
Practical Bayesian Optimization for Scientific Discovery

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Abstract

1 Bayesian optimization (BO) is a standard tool for experimental scientific discovery,
2 where evaluations are costly and candidate spaces are vast. Classical formula-
3 tions often rely on methods that scale poorly with data size and are ill-suited
4 to discrete sequences and molecules. Scientific foundation models now provide
5 rich, transferable representations for these domains. However, it remains unclear
6 how to best leverage them with BO in lab-in-the-loop campaigns, or how this
7 approach compares with LLMs and generative modeling, two leading paradigms in
8 AI-for-science. We investigate these questions across proteins, DNA, RNA, and
9 small molecules through 61 regression tasks drawn from established experimental
10 benchmarks. This constitutes, to our knowledge, the most extensive cross-domain
11 study of foundation-model driven Bayesian optimization to date. We systemati-
12 cally ablate foundation models, surrogates, acquisition functions, and fine-tuning
13 regimes under both sequential and batched selection. We find that Gaussian pro-
14 cess surrogates are consistently outperformed by neural alternatives paired with
15 Thompson sampling, particularly MLP ensembles and variational Bayesian last
16 layers. We further find that smaller batch sizes reach peak performance faster
17 and recover more elite candidates under the same total experimental budget, a
18 trend that is consistent across tasks and surrogate choices. Finally, we show that
19 foundation-model driven BO outperforms both an in-context LLM surrogate and a
20 guided discrete diffusion model.

21 1 Introduction

22 In experimental discovery campaigns, candidates are cheap to propose and are often expensive to
23 measure [98, 88]. Protein engineering, regulatory genomics, RNA design, and molecular optimization
24 therefore share a common decision problem: given prior measurements and a limited budget, which
25 candidates should be tested next? Bayesian optimization (BO) addresses expensive black-box
26 optimization in settings like these by explicitly balancing exploration of uncertain regions against
27 exploitation of regions predicted to perform well. This balance is typically mediated by a probabilistic
28 surrogate model whose posterior uncertainty quantifies the potential value of each candidate evaluation
29 [92, 85]. Gaussian process (GP) surrogates remain a principled default because they provide closed-
30 form posterior predictions and support provable regret guarantees [79].

31 Scientific discovery, however, has characteristics that distinguish it from the continuous low-
32 dimensional benchmarks on which classical BO is often applied. Proteins, RNA, DNA, and small
33 molecules each require their own specialized representations, and a hand-designed kernel does not
34 transfer between them [83, 32]. The GP also scales cubically in the number of observations and
35 requires elaborate batch approximations [21, 31, 105], which becomes prohibitive at the batch sizes
36 typical of experimental campaigns. Coupling FM representations with BO is appealing, but existing
37 approaches are fragmented. For instance, prior work has used FM embeddings as kernel features

38 for a GP [55, 78], as inputs to a Random Forest [47], or as in-context tokens for an LLM-driven
39 acquisition step [59], with limited head-to-head comparison of which choices matter in practice.

40 In the broader literature on AI-for-science, two alternative paradigms are the subject of active
41 investigation. The first treats LLMs as in-context surrogates, prompting the model with the history
42 of measurements and asking it to score the remaining candidate pool directly [59, 16, 77]. This
43 avoids explicit surrogate training, but it asks the acquisition step to act on outputs that are not
44 calibrated posterior uncertainties. Several lines of evidence reinforce this concern: miscalibration
45 introduced by instruction tuning and RLHF [107, 97, 50], insensitivity to experimental feedback
46 in genetic perturbation and molecular property tasks [35], and weak in-context performance on
47 continuous-valued regression [65]. The second treats experimental design as conditional generation,
48 training or steering a generative model so that its samples are themselves the proposed candidates
49 [93, 108, 103, 80, 40]. However, this is complicated by the fact that guidance toward high-reward
50 regions can collapse sample diversity [6] and push samples off the data manifold [52], and when the
51 steering signal is a learned reward, optimization pressure can exploit reward-model errors rather than
52 producing genuinely high-fitness candidates [109].

53 In this study, we aim to clarify how foundation models should be used within Bayesian optimization
54 for scientific discovery. We study frozen and adapted foundation-model embeddings as task represen-
55 tations, sample-efficient surrogate heads as uncertainty-aware predictors, and batch-aware acquisition
56 as the mechanism for selecting experiments under realistic laboratory scenarios. This framing allows
57 us to ask which components of foundation-model-augmented BO matter most, how these choices
58 interact under experimentally relevant constraints, and how the resulting approach compares with
59 the leading paradigms of in-context LLM surrogates and steered generative design. We make the
60 following contributions:

- 61 1. *A practical Bayesian optimization framework* (SciOpt) that unifies proteins, RNA, DNA, and
62 small molecules in a single modular pipeline of frozen foundation-model embeddings and a
63 sample-efficient surrogate head, with backbone, head, acquisition, and fine-tuning regime (frozen,
64 supervised fine-tuning, self-supervised fine-tuning) as independent design axes.
- 65 2. *A systematic empirical study* on 61 real-data regression tasks across protein, chemistry, RNA, DNA
66 benchmarks, ablating nine surrogates, two FM backbones per modality, three acquisition functions,
67 three fine-tuning regimes, and across five batch sizes. We find that VBLL with Thompson sampling
68 is the unique upper-right Pareto point of optimal performance and coverage on chemistry, RNA,
69 and DNA, while MLP Ensemble leads on protein.
- 70 3. *Head-to-head comparison against two leading AI-for-science paradigms*. SciOpt beats an in-
71 context LLM surrogate (Qwen3.6-35B) on Top-5% coverage for a representative dataset in every
72 modality, and beats a steered masked-diffusion generative model (SGPO) on the combinatorially
73 complete GB1, TrpB, and PhoQ protein datasets.

74 2 Technical Overview

75 SciOpt (Figure 1) functions as a closed-loop selector over a finite candidate pool. A scientific
76 foundation model maps each candidate to an embedding z ; a surrogate trained on accumulated
77 measurements \mathcal{D}_t predicts a mean and uncertainty; and an acquisition rule selects the next candidate
78 or batch for experimental evaluation. The new measurements are added to the labelled set, the
79 surrogate is retrained, and the loop repeats.

80 We organize this loop around four design axes: the foundation-model backbone, the surrogate head,
81 the acquisition rule, and the fine-tuning regime. Each axis is exposed as a separate component in the
82 configuration, so any compatible (FM, head, acquisition, regime) tuple can be run without changing
83 the rest of the pipeline. This factorization lets us compare one choice at a time while holding the
84 other axes fixed.

85 **Foundation-model backbones.** For the main sweep, we use one primary FM per modality: ESM-C
86 600M [26] for proteins, RNA-FM [17] for RNA, NTv3-650M [8] for DNA, and ChemFM-1B [15]
87 for chemistry. In the frozen setting, the FM block in Figure 1 acts only as a feature extractor:
88 embeddings are precomputed once per (FM, task) pair, and the BO loop trains only the surrogate
89 head. Alternative backbones, pooling choices, and pseudo-likelihood calculations for the zero-shot
90 baseline are described in Appendix A and Appendix E.

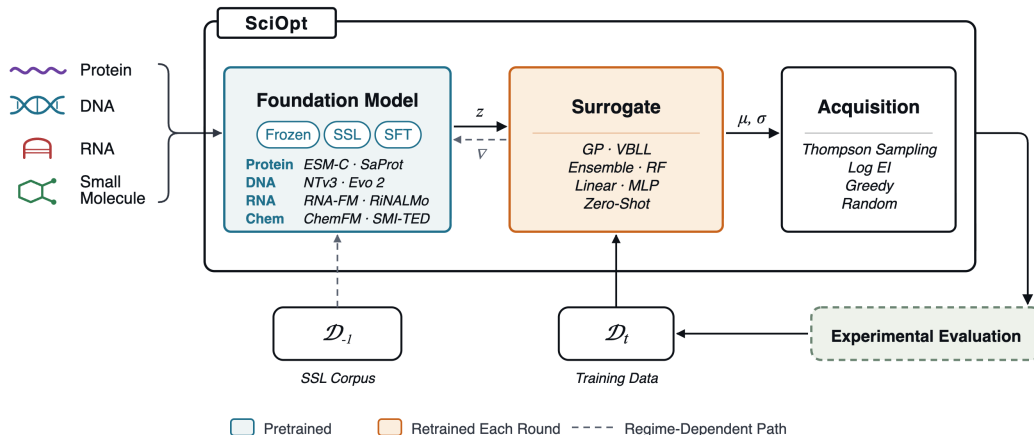


Figure 1: **SciOpt**. A modular Bayesian optimization framework that couples a frozen scientific foundation model to a learned surrogate head and a batch-aware acquisition. Each node lists the choices studied across four modalities (protein, DNA, RNA, chemistry). Solid arrows indicate the BO loop, in which the surrogate is retrained on accumulated data D_t and proposes the next batch. Dashed arrows denote optional configurations such as self-supervised pretraining on a domain corpus D_1 and supervised fine-tuning via surrogate gradients (∇).

91 **Surrogate heads.** The surrogate heads consume the representations from the FM in order to
 92 predict the property of interest (e.g. binding affinity, promoter expression), fall into three groups.
 93 *Non-adaptive baselines* do not learn from experimental feedback: Random samples uniformly and
 94 *Zero_Shot* ranks candidates by the FM prior alone. *Greedy methods* train a deterministic head
 95 on the labelled set each round and select by predicted mean, with no per-candidate uncertainty:
 96 this group includes the random-forest EvolvePro configuration [47], a linear head, and an MLP.
 97 *Uncertainty-aware methods* expose a per-candidate uncertainty estimate to the acquisition step and
 98 we include classical algorithms: a random forest, an exact GP, an MLP ensemble. We also include
 99 variational Bayesian last layer which have been shown to be competitive with exact GP’s [39, 11].
 100 Implementation details and hyperparameters are in Appendix B.

101 **Acquisition functions.** Three acquisition rules cover the methods in Table 1. *Greedy* selects
 102 the candidate with the largest predicted value, or the largest pseudo-likelihood for *Zero_Shot*.
 103 *LogEI* scores candidates by expected improvement using the surrogate’s predictive uncertainty [1].
 104 *Thompson sampling* samples a possible score function and selects its maximizer over the heldout
 105 pool [85]. For batch construction at size k , non-Thompson methods take the top- k candidates under
 106 the round-start acquisition score. Thompson methods draw one posterior sample per batch member;
 107 the additional VBLL diversity rule is given in Appendix C.3.

108 **Fine-tuning regimes.** The regime-dependent paths in Figure 1 specify which FM parameters, if
 109 any, are updated during the BO loop. In the *Frozen* regime, embeddings are cached and only the
 110 surrogate head is trained. This is the regime used for the full 61-task surrogate sweep, as it is the
 111 most computationally tractable. The *Supervised Fine-Tuning* regime lets the FM adapt to measured
 112 labels through LoRA adapters [45]; at each round, the adapters and head are reinitialized and then
 113 trained on the current labelled set. The *Self-Supervised Fine-Tuning* regime continues pretraining
 114 the FM prior to running experiments, by using the pretraining objective on related data. This is
 115 applied in protein tasks as shown in ESM-1v and ProteinTTT [63, 14], where there is a wild-type
 116 sequence you wish to mutate and you can enhance your FM embeddings by continuing pretraining
 117 with a masked-language-model objective on related protein sequences according to multi-sequence
 118 alignment (MSA). Details and results for fine-tuning regimes are in Appendix F.

119 3 Results

120 **Problem setup.** Let \mathcal{X} be a finite candidate pool of size N and $f : \mathcal{X} \rightarrow \mathbb{R}$ an unknown black-
 121 box objective. At round t the learner has noisy measurements $\mathcal{D}_{t-1} = \{(x_s, y_s)\}_{s < t}$. Sequential

Table 1: **Summary of methods compared in the main results.** All methods consume the same per-task FM embeddings. The table lists the surrogate/acquisition pair used in the main sweep; implementation details and hyperparameters are in Appendix B.

Method	Acquisition	Role in comparison
<i>Non-adaptive baselines</i>		
Random Zero-Shot	Random Likelihood	Uniform random sampling without feedback. Ranks candidates by the FM’s pseudo-likelihood without fitting to labels.
<i>Greedy heads</i>		
Random Forest	Greedy	EvolvePro-style random forest on frozen FM embeddings [47].
Linear	Greedy	Linear probe on FM embeddings; tests whether a shallow head is sufficient.
MLP	Greedy	Nonlinear deterministic head trained on labelled data each round.
<i>Uncertainty-aware heads</i>		
Random Forest	LogEI	Adds exploration to Random Forest using variance across trees.
Gaussian Process	LogEI	Classical Bayesian surrogate baseline on FM embeddings [79].
MLP Ensemble	Thompson	Uses variation across independently trained MLP heads as a function posterior [56, 81].
V BLL	Thompson	Variational Bayesian last-layer surrogate with analytic posterior sampling [39].

122 BO selects one candidate per round while batch BO selects k candidates without intermediate
 123 observations. Each campaign is initialized with a round 0 of 96 candidates drawn uniformly from
 124 below the median of the marginal label distribution, mimicking a low-fitness starting library, and runs
 125 for $T = 100$ rounds in the sequential setting or batch rounds of $T \in \{32, 16, 8, 4, 2\}$ at batch sizes
 126 $k \in \{24, 48, 96, 192, 384\}$ respectively for a total of $N = 768$ candidates each. Every (task, method)
 127 tuple is run with 5 BO seeds, with round 0 candidates shared within a (task, seed) pair for fair
 128 comparison between methods.

129 **Tasks and metrics.** Our study contains 61 real-data scientific regression tasks across proteins
 130 ($n_P=18$), chemistry ($n_C=12$), RNA ($n_R=20$), and DNA ($n_D=11$). Tasks are included when they
 131 have a deduplicated candidate pool of at least 2,000 sequences or molecules and fit within the
 132 primary FM’s context window. Large datasets are deterministically subsampled when needed to
 133 10,000 candidates, with the same runtime pool shared across all surrogate baselines and BO seeds,
 134 so aggregate metrics are more comparable. Per-task data sources, splits, and preprocessing are in
 135 Appendix D.

136 We track two primary metrics:

$$\text{NBSF}(t) = \max_{s \leq t} \frac{y_s - y_{\min}}{y_{\max} - y_{\min}}, \quad \text{Top-5\%}(t) = \sum_{s \leq t} \mathbf{1}[y_s \geq y_{0.95}]$$

137 where y_{\min} , y_{\max} , and $y_{0.95}$ denote the minimum, maximum, and 95th percentile of the labels
 138 over the full candidate pool \mathcal{X} . NBSF measures how close the campaign has come to the global
 139 maximum. Top-5% count measures how many distinct elite candidates have been recovered, so it
 140 captures coverage rather than only peak performance. For uncertainty-aware heads, we also compute
 141 cumulative expected calibration error (ECE) on heldout candidates to evaluate whether predictive
 142 uncertainty is calibrated over the course of the campaign.

143 3.1 Sequential Bayesian Optimization

144 Sequential BO is the cleanest setting for comparing surrogate and acquisition choices. After each
 145 selected candidate is measured, the surrogate is retrained on the updated labeled set before the next
 146 decision. This removes batch-construction effects and tests how well each method turns frozen FM
 147 embeddings into one-step acquisition scores.

148 Figure 2 shows the final NBSF and Top-5% count by modality. The upper frontier is dominated
 149 by neural heads. V BLL is the strongest overall uncertainty-aware method, sitting at or near the
 150 upper-right frontier in every modality and leading clearly on chemistry and RNA. Protein is the main
 151 exception on coverage: MLP_Ensemble recovers the most Top-5% candidates, with MLP (Greedy)

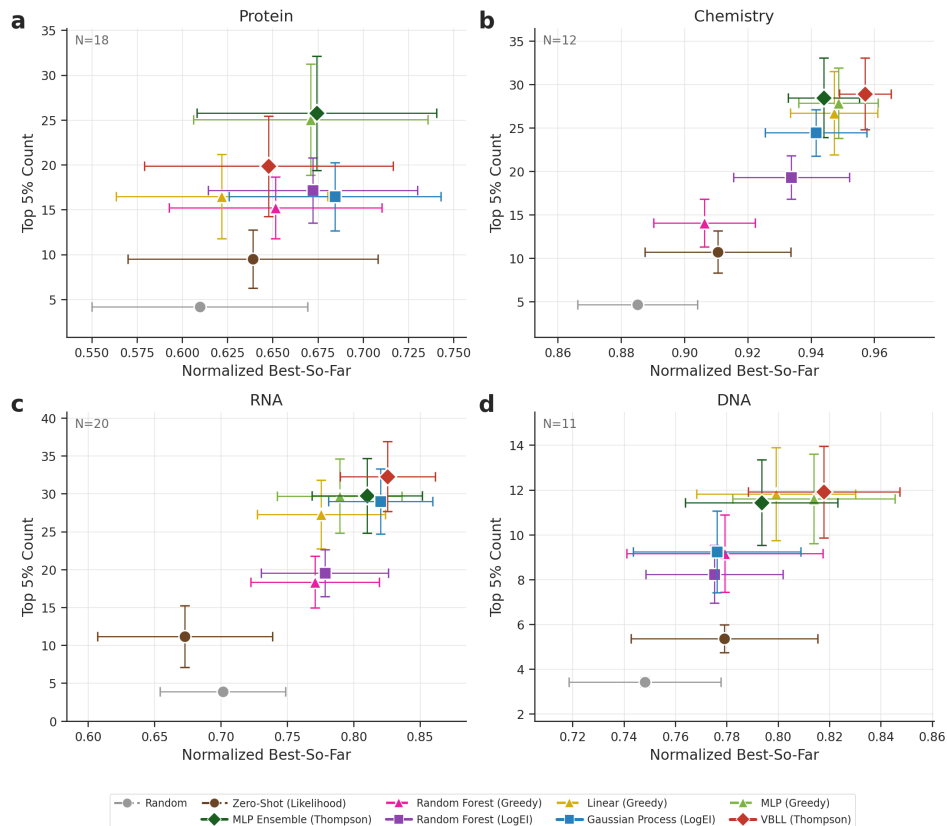


Figure 2: **Per-modality Pareto frontier of NBSF against Top-5% count, sequential BO** ($T=100$, $k=1$). Each marker is one method aggregated over tasks and seeds; error bars are ± 1 SEM. VBLL (red diamond) is the unique upper-right frontier point on chemistry, RNA, and DNA. On protein tasks, MLP_Ensemble (dark green diamond) leads with MLP_Greedy (light green triangle) following close behind. The middle cluster of Linear (yellow triangle), the simple greedy baseline, and GP (blue square), the classical BO surrogate, are one tier below. RF_Greedy (pink triangle), also known as EvolvePro, is generally outperformed by the other methods, including RF_LogEI (purple square) which adds in some exploration to the search. Zero-Shot (brown circle) slightly outperforms Random, which performs the worst of all methods.

152 also competitive and VBLL trailing on that axis despite comparable NBSF. DNA shows a compact
 153 upper tier with VBLL, MLP, MLP Ensemble, and Linear all close within error bars.

154 The middle tier is formed mostly by Linear, GP, and the random-forest variants, although the exact
 155 ordering varies by modality. Linear and GP are often close, which suggests that much of the predictive
 156 signal is already present in the FM embedding. The exact GP remains a useful calibrated baseline,
 157 but it does not translate that calibration into the best optimization performance. RF (Greedy), the
 158 EvolvePro-style recipe, generally falls below the neural heads; adding LogEI to the same random-
 159 forest posterior generally boosts performance in most settings but does not move it to the frontier.
 160 Zero-Shot improves over Random but remains well below learned surrogates, showing that the FM
 161 prior alone is not enough for reliable adaptive optimization.

162 The strong performance of MLP (Greedy) is worth noting. Although its acquisition rule is greedy,
 163 the head is reinitialized and retrained each round, so stochastic optimization can introduce a form
 164 of implicit exploration. This can be viewed intuitively as a form of implicit Thompson sampling:
 165 the trained weights at each acquisition step are approximately a draw an implicit posterior over
 166 MLP weights induced by the initial distribution plus the optimizer trajectory on a finite dataset [61].
 167 We therefore view MLP (Greedy) as a strong simple baseline rather than as a purely exploitative
 168 control. Still, the most consistent frontier methods are the ones with explicit uncertainty or sampling,
 169 especially VBLL and MLP Ensemble. Calibration results are given in Appendix G.2.

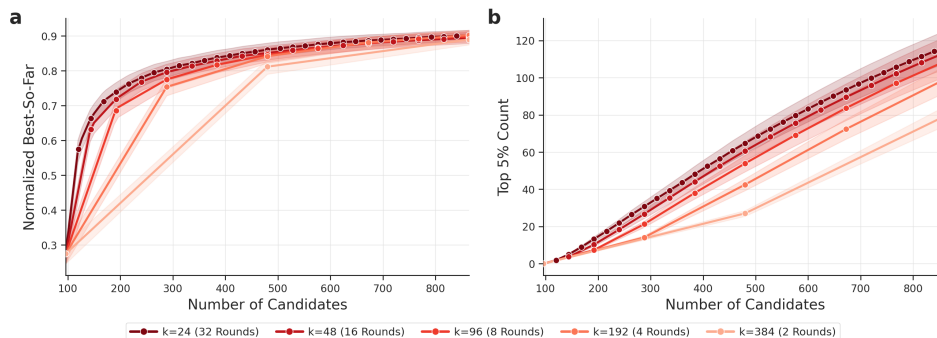


Figure 3: **Batch-size scaling at fixed budget.** NBSF (left) and Top-5% count (right) vs. cumulative candidates measured across multiple batch sizes with a common total budget. Curves aggregate across 61 tasks, 9 surrogates, and 5 seeds. Bands are ± 1 SEM over the 61 tasks and quite narrow, indicating that the batch-size effect is highly conserved across tasks and methods. Smaller batches dominate at low cumulative data and curves converge as the surrogate posterior tightens, albeit at a significantly slower rate for Top-5% count.

170 We evaluate fine-tuning on selected representative protein tasks, as it is computationally intractable to
 171 do across all datasets. Supervised LoRA fine-tuning can improve sequential performance for some
 172 heads, while MSA-based self-supervised fine-tuning has mixed, task- and head-dependent effects:
 173 aggregate NBSF changes are small, but Top-5% coverage can improve for some neural heads and
 174 degrade for others. Detailed fine-tuning results are given in Appendix F.

175 3.2 Batch Bayesian Optimization

176 Experimental campaigns rarely get to choose candidates one at a time. Protein engineering, MPRA
 177 screens, RNA assays, and small-molecule screens are usually organized around batches of candidates
 178 tested each tested over a period of weeks to months. Running larger batches improves throughput,
 179 amortizes setup cost, and can be necessary when reagents, cell lines, instruments, or personnel are
 180 available only within a limited window. The statistical cost is that BO receives less feedback: the
 181 surrogate must choose all k candidates in a batch before observing any of their labels.

182 We quantify this tradeoff with a fixed total budget of candidates. After the shared 96-candidate
 183 initialization, we evaluate batch sizes $k \in \{24, 48, 96, 192, 384\}$ for $T \in \{32, 16, 8, 4, 2\}$
 184 rounds, respectively, giving the same acquisition budget of 768 new candidates in every setting. Each
 185 surrogate uses its native batch rule, and curves are aggregated over all 61 tasks, 9 methods, and 5
 186 seeds.

187 Figure 3 shows a consistent batch-size effect. Smaller batches reach high NBSF earlier because labels
 188 are incorporated into the surrogate more often. The final NBSF gap narrows by the end of the budget,
 189 which means peak best-so-far performance is relatively forgiving of moderate batching. Top-5%
 190 count behaves differently: smaller batches recover elite candidates at a higher rate throughout the
 191 campaign, and the gap remains visible even at the final budget. This suggests that coverage of the
 192 high-fitness set depends more strongly on the number of feedback rounds than on the total number
 193 of candidates measured. We include the full per-modality Pareto frontier of NBSF against Top-5%
 194 count for the practical $k=96$ setting in Figure 13 in Appendix H.

195 3.3 Comparison to In-Context Learning with LLMs

196 **Experimental setup.** In this paradigm, we compare SciOpt to the use of LLMs as in-context
 197 surrogates for experimental design. In this setting, each BO round is a single forward pass over a
 198 prompt containing the running history of measured candidates and the remaining candidate pool;
 199 the model returns one candidate ID, with no fitted surrogate, no embedding head, and no explicit
 200 acquisition function [59, 16, 66]. We use Qwen3.6-35B-A3B-FP8 [75] as the representative LLM
 201 baseline. Full prompt format, inference settings, parsing rules, and contamination controls are given
 202 in Appendix I.

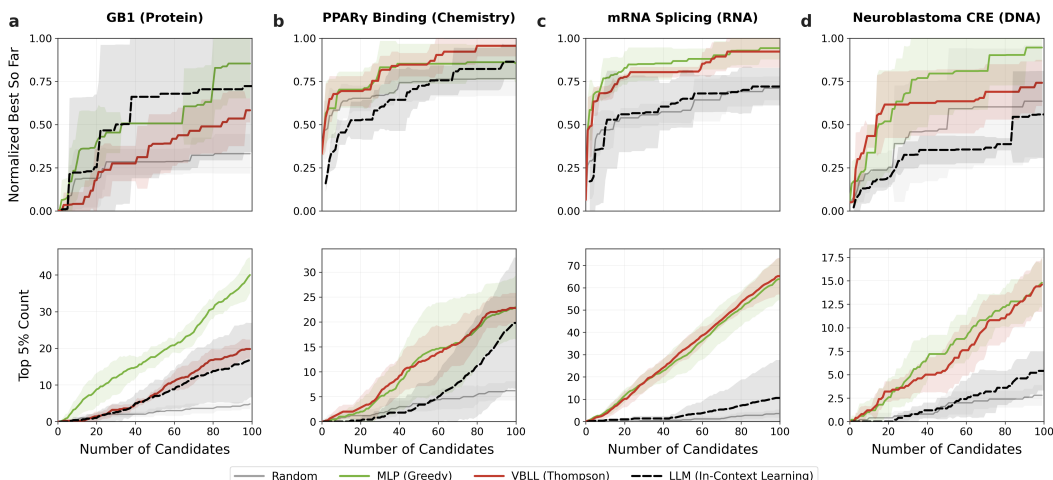


Figure 4: **SciOpt vs. LLM in-context selection.** Columns show one task per modality: gb1 (protein), pparg (chemistry), ke_mrna (RNA), and gosai_sknsh (DNA). Top row: NBSF. Bottom row: Top-5% count. All methods run sequential selection for 100 rounds after a shared 96-candidate below-median initialization; shaded regions show ± 1 s.d. over 5 seeds. LLM (In-Context Learning) selects one candidate per round from a prompt containing the visible pool and the full measurement history. MLP and VBLL use the modality-default FM embeddings.

203 We evaluate one representative task per modality from the 61-task benchmark. The full protein and
 204 DNA pools are too large to provide in context, so for gb1 and gosai_sknsh we use deterministic
 205 subsamples of size 1,500 and 2,100, respectively. We rerun the SciOpt methods on these subsampled
 206 datasets for a fair comparison. This setup gives the LLM the full visible candidate pool whenever
 207 context permits, and uses identical starting data across methods.

208 **Results on representative tasks from each modality.** Figure 4 shows that the LLM baseline can find
 209 high-scoring candidates on some tasks, but it is much less reliable than SciOpt as an optimizer. On
 210 NBSF, the LLM trails the stronger SciOpt surrogate on every task, but the identity of that surrogate
 211 is task-dependent. The gap is modest on pparg (LLM 0.864, MLP 0.861, VBLL 0.956) and gb1
 212 (LLM 0.722, MLP 0.853, VBLL 0.582; VBLL’s drop here likely reflects the smaller candidate pool),
 213 and widens substantially on ke_mrna (LLM 0.720 vs both surrogates ≥ 0.92 , essentially at random
 214 0.711) and on gosai_sknsh (LLM 0.558 vs MLP 0.946 and VBLL 0.742, below random 0.635).

215 The Top-5% count separates the methods more clearly. On the two matched-pool tasks, the LLM
 216 recovers fewer elite candidates than SciOpt: 19.8 versus 22.8 on pparg, and 10.6 versus 63.8 and
 217 65.2 on ke_mrna. On gb1 and gosai_sknsh, absolute Top-5% counts are affected by the smaller
 218 LLM-visible pools, so we treat those comparisons as conservative diagnostics rather than matched-
 219 pool estimates. The qualitative pattern is still consistent across tasks: the LLM occasionally identifies
 220 a good region, but it does not cover the elite set at the same rate as a learned surrogate.

221 Together, the two metrics suggest that the LLM is not failing simply because it cannot understand
 222 the task; reasoning traces (Appendix I) show coherent, domain-grounded selection rationales on
 223 every task. It often improves NBSF, especially when an early high-fitness mode is enough to make
 224 progress. The failure mode is coverage: the model tends to return candidates near regions it has
 225 already identified rather than spreading measurements across distinct high-fitness regions. This
 226 behavior is consistent with prior reports that instruction-tuned LLMs can behave like strong priors
 227 but poor calibrated surrogates under small experimental budgets [86, 107, 97]. In this role, a learned
 228 surrogate provides a more reliable decision step than in-context selection alone, though the strongest
 229 surrogate is task-dependent.

230 3.4 Comparison to Steered Generation

231 **Experimental setup.** In this paradigm, we elect to compare against Steered Generation for Protein
 232 Optimization (SGPO). The authors conduct a broad sweep over generative priors and steering

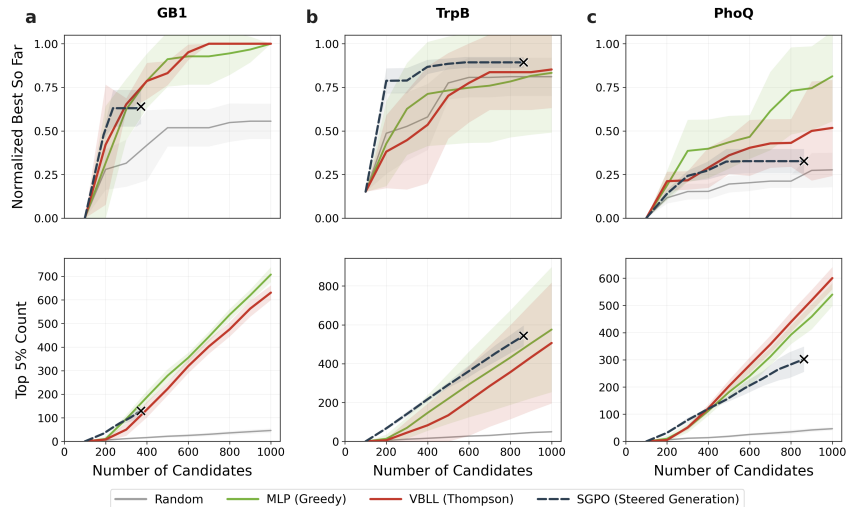


Figure 5: **SciOpt vs. Steered Generative Modeling.** Columns show three combinatorially complete protein landscapes GB1, TrpB, and PhoQ. Top row: NBSF. Bottom row: Top 5% count. SciOpt is evaluated with MLP and VBLL heads on ESM-C embeddings. SGPO samples high fitness candidates via steered generation, as discussed in 3.4. **X** marks the point after which SGPO can no longer propose unique candidate sequences, resulting in diversity collapse

233 strategies, benchmarked on protein fitness optimization, from which we select the strongest reported
 234 configuration [108]. The results are summarized in Figure 5.

235 SGPO samples from a masked diffusion language model (MDLM), $p_\theta(x)$, trained on the target-
 236 family MSA, and uses decoupled annealing posterior sampling (DAPS) with an ensemble of one-hot
 237 MLP value functions $g_{\phi,t}$ trained on \mathcal{D}_{t-1} . Informally, this steers generation toward a reward-tilted
 238 distribution of the form $p_t(x) \propto p_\theta(x) \exp(\beta g_{\phi,t}(x))$, with each generated sample guided by a
 239 Thompson-style draw from the ensemble surrogate.

240 We benchmark on three combinatorially complete protein landscapes with full experimental fitness
 241 maps: GB1 IgG-Fc binding, TrpB enzymatic activity, and PhoQ-PhoP interface signaling [106, 48,
 242 71]. This removes the use of the surrogate-oracle used in SGPO, which can guide sampling toward
 243 sequences that have not been experimentally measured. Thus, every proposal from either method is
 244 scored against the same measured ground truth. More details about the set up can be found in J.

245 **Results on combinatorially complete protein landscapes.** SciOpt, evaluated with MLP_Greedy and
 246 VBLL on ESMC embeddings, matches or exceeds SGPO on Top-5% Count and NBSF on GB1 and
 247 PhoQ. On TrpB, SGPO retains a Top-5% lead throughout its active phase, and SciOpt MLP_Greedy
 248 draws roughly even by the budget cap. SciOpt VBLL shows wider seed-level variance than the
 249 MLP_Greedy variant due to a subset of seeds failing to escape early local optima.

250 Diversity collapse is universal across the three protein tasks, but most acutely present in the GB1 task
 251 [6]. At the four assayed positions, the natural-homolog distribution for GB1 concentrates $\sim 65\%$ of
 252 its mass on the wild-type combination VDGV, compared with $\sim 2\%$ (AVST) for PhoQ and $\sim 10\%$
 253 (VFVS) for TrpB. This constitutes a failure mode of an otherwise strong evolutionary prior for protein
 254 design. The GB1 assayed positions coincide with the prior’s mode, so the majority of proposals from
 255 $p_\theta(x)$ duplicate sequences labeled in rounds 0 and 1, leading to mode collapse.

256 Finally, the PhoQ MSA is the shallowest of the three targets, which limits the SGPO prior coverage
 257 of high-fitness regions. This leads it to perform marginally better than random on NBSF as well as
 258 Top 5% Count. On the other hand, TrpB has the deepest MSA of the three targets. As expected,
 259 SGPO performs the best overall on this task and the benefit of the rich prior is apparent by the steep
 260 early rise in the NBSF curve.

261 4 Discussion

262 In summary, SciOpt unifies Bayesian optimization across proteins, DNA, RNA, and small molecules.
263 In a systematic evaluation across dozens of tasks, we demonstrate that frozen scientific representations,
264 when paired with lightweight neural surrogates and posterior-sampling acquisitions, is a practical
265 approach to sequential experimental design that efficiently identifies promising candidates and is
266 highly competitive with alternative paradigms in AI-for-Science.

267 **Limitations.** The main limitation is that our evaluation is retrospective. All campaigns considered
268 optimize over fixed candidate pools with known experimental labels. This design enables controlled
269 comparison across methods, but it abstracts away experimental challenges. SciOpt also assumes
270 that a candidate pool already exists. It selects from this pool rather than generating new proteins,
271 molecules, RNA sequences, or regulatory elements, so its performance depends on the quality,
272 diversity, and coverage of the upstream candidate generator. Several modeling choices further bound
273 the scope of the study. We use a below-median initialization protocol, which makes the starting
274 library deliberately challenging but does not fully separate the effect of initialization quality from
275 surrogate quality. We use one primary foundation model per modality in the main sweep, with broader
276 backbone comparisons left to the Appendix E. Finally, the benchmark is single-objective, while real
277 campaigns often balance potency, selectivity, stability, synthesis, delivery, cost, and other constraints
278 [41].

279 The comparisons to adjacent AI-for-science paradigms should also be interpreted narrowly. The
280 LLM experiment evaluates direct in-context candidate selection from a visible pool, not frontier
281 agentic systems with retrieval, tool use, multi-step planning, or external simulators [7, 60, 96, 34,
282 64]. The SGPO comparison evaluates a representative steered generative workflow on complete
283 protein landscapes, but does not rule out stronger priors or improved diversity control. Furthermore,
284 mutations on combinatorial protein landscapes were limited to 4 positions and does not reflect protein
285 engineering settings where biochemical knowledge of the target identifies is highly limited without
286 known a tractable set of plausible positions such as active-site residues, contact maps, or prior deep
287 mutational scans.

288 **Practical takeaways.** Despite these limitations, SciOpt provides a simple recipe for running Bayesian
289 optimization over scientific candidate pools, requiring only three common components across domains.
290 Neural surrogates paired with posterior sampling, especially VBLL and MLP ensembles, occupied
291 the leading Pareto frontier. However, notably, a reinitialized greedy MLP emerged as a strong simple
292 baseline, suggesting that stochastic training can provide useful implicit exploration even without an
293 explicit uncertainty model.

294 The batch size scaling experiments showed, at fixed total budget, smaller batches incorporate feedback
295 more frequently, reaching strong NBSF values earlier and recovering more Top-5% candidates. This
296 suggests that for sequential experimental design, there exists a tradeoff between model learnability and
297 per-round scale. However, fortunately, the default well-plate size of 96 showed strong convergence in
298 both peak candidate identification and elite coverage.

299 **Future directions.** The most important next step is validation in closed wet-lab loops [13, 88, 98].
300 Live experimental campaigns would expose the operational constraints that fixed-pool benchmarks
301 cannot capture, and would test whether the batch-size scaling trends remain useful as practical
302 planning curves. A related direction is multi-objective, constrained, and multi-fidelity BO, since
303 practical discovery campaigns rarely optimize a single scalar endpoint. Extending SciOpt to reason
304 over multiple assay readouts, heterogeneous measurement costs, and proxy-to-validation assay
305 hierarchies would make the framework closer to real campaign decisions.

306 More broadly, our findings point toward a complementary view of AI-for-science. The SGPO
307 generative baseline can propose strong candidates early, but our complete-landscape evaluation
308 also shows that its supply of unique proposals can mode collapse under optimization pressure or
309 a misaligned prior. This motivates closed-loop systems in which generative models expand the
310 candidate set, while BO surrogates and acquisition functions can promote diverse sampling over
311 shared foundation-model latent space. LLMs may be better positioned at a higher level of abstraction:
312 retrieving and synthesizing biochemical knowledge from the literature, imposing constraints on
313 search spaces, and automating the workflow that connects design, measurement, and model updating.

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713 A Foundation models

714 The frozen main sweep fixes one primary foundation model (FM) per modality and holds it constant
 715 across every surrogate head and acquisition rule in App. B. For each (FM, task) pair we precompute
 716 two quantities offline: a D -dimensional pooled embedding per candidate, and a length-normalized
 717 log-likelihood-style score that we call the model’s pseudo-likelihood (PLL). The BO loop never
 718 instantiates the FM: learned surrogates consume the precomputed embedding, and the Zero-Shot
 719 surrogate consumes the precomputed PLL. This decouples the comparison from FM inference
 720 throughput and lets us swap FMs on a fixed candidate pool without changing anything else.

721 A.1 Models considered

722 For every modality we use one primary FM in the 61-task sweep and pair it against one principal
 723 alternative for the backbone-sensitivity sweep (App. E). The primary FMs are domain-specific, pub-
 724 licly released, and compatible with the raw candidate representation in the corresponding benchmark.
 725 Each alternative varies the choice along the dimension most likely to matter in that modality: a
 726 structure-aware tokenizer for proteins (SaProt 650M vs. ESM-C 600M), a different RNA-encoder
 727 family at larger scale (RiNALMo-giga vs. RNA-FM), an autoregressive decoder vs. an encoder for
 728 DNA (Evo2-1B vs. NTv3-650M), and an encoder/decoder reconstruction model vs. a causal SMILES
 729 decoder for chemistry (SMI-TED vs. ChemFM-1B). Table 2 summarizes the eight models.

Table 2: **Foundation models used in this work.** Primary models are used for the 61-task surrogate sweep; alternatives are used in the paired backbone-sensitivity sweep (App. E). D is the pooled embedding dimension consumed by every learned surrogate. *PLL family* indicates which scoring procedure in §A.3 produces the cached prior score. “WT-marginal” is single-pass marginal scoring under a masked-LM head in the style of [63]; “ K -stripe masked” is a K -pass batched masking scheme used for U-Net-style nucleotide models (§A.3); “AR” is left-to-right next-token log-likelihood; “Recon.” is encoder/decoder reconstruction cross-entropy. Length normalization divides the per-sequence log-probability by the number of scored non-special tokens.

Modality	Model	Role	Architecture	Params	D	PLL family
Protein	ESM-C 600M [26]	primary	encoder, transformer (rotary, SwiGLU)	600M	1152	WT-marginal
Protein	SaProt 650M (AF2) [95]	alternative	encoder, MLM (446-vocab AA \times 3Di bigrams)	650M	1280	WT-marginal, AA-marg.
RNA	RNA-FM [17]	primary	encoder, BERT-style MLM	100M	640	WT-marginal
RNA	RiNALMo-giga [69]	alternative	encoder, transformer (RoPE, SwiGLU)	650M	1280	WT-marginal
DNA	NTv3-650M [8, 18]	primary	nucleotide encoder, U-Net + transformer	650M	1536	K -stripe masked
DNA	Evo2-1B [10]	alternative	decoder, StripedHyena [73]	1B	1920	AR
Chemistry	ChemFM-1B [15]	primary	decoder, Llama-family causal LM	970M	2048	AR
Chemistry	SMI-TED [89]	alternative	encoder/decoder	289M	768	Recon.

730 A.2 Embedding extraction protocol

731 Each FM is run in inference mode using its native tokenizer. Inputs come from the curated task tables
 732 in App. D: protein, RNA, and DNA strings are uppercased before tokenization, while molecules are
 733 kept in their curated SMILES form. Rows with non-finite targets, empty inputs, or inputs longer than
 734 the model context window are dropped from that FM’s candidate pool, and the BO comparisons within
 735 a modality use the intersection pool so that primary and alternative FMs see identical candidates.
 736 Inference uses bfloat16 mixed-precision autocast on GPU.

737 The pooled embedding is the mean of the final-layer hidden states over non-special tokens, where
 738 the special set is taken from each tokenizer’s mask and includes BOS/CLS, EOS/SEP, PAD, MASK,
 739 UNK, and model-specific equivalents. We apply the same mean-over-non-special-tokens rule to every
 740 FM in Table 2 so that pooling is not a confound in the comparison, with two exceptions dictated by
 741 the model itself. For SMI-TED we use the autoencoder bottleneck vector that the decoder is trained
 742 to reconstruct from, since that is the representation the model is designed to expose. For NTv3 we
 743 pool the hidden state at the LM-head input rather than the post-skip output, so that the embedding
 744 stays on the same surface the model uses internally; the corresponding prior score is computed under
 745 the masking scheme below to avoid a trivial-copy path through the U-Net’s skip connection. For
 746 Evo2 we additionally retain an intermediate Hyena-block representation alongside the final-layer

747 pool, because several near-final block outputs are empirically degenerate and pooling at those depths
748 would silently degrade the embedding.

749 **A.3 Pseudo-likelihood and log-likelihood scoring**

750 The cached prior is the model’s length-normalized log-probability of the candidate under its native
751 head, averaged over non-special tokens. For autoregressive decoders this is the standard one-token-
752 shift log-likelihood. For encoder masked-LMs we use the single-pass wild-type-marginal scoring
753 of [63], which approximates the true pseudo-log-likelihood of [102, 87] at one forward pass per
754 candidate and is the standard cheap surrogate for protein-LM zero-shot variant scoring [63, 43]. For
755 SMI-TED we use the model’s native reconstruction objective: the per-token log-probability under the
756 autoencoder decoder, averaged over the non-special positions. We refer to all four scalars uniformly
757 as the PLL, and the Zero-Shot surrogate ranks candidates by this scalar with no further modeling.

758 Two FMs require a non-standard construction. SaProt’s vocabulary is a 446-token product of amino-
759 acid and 3Di structural tokens, so a direct gather would conflate sequence and structure preferences;
760 we instead marginalize the bigram softmax over the 3Di axis within each input amino-acid letter, so
761 the score reflects the model’s distribution over the channel that varies in our candidates. NTv3 is a
762 U-Net encoder [84] whose full-resolution skip connection feeds a transform of the token embeddings
763 into the pre-LM-head representation, making a single unmasked forward dominated by a trivial-copy
764 identity rather than the trunk’s predictions; we instead use a K -pass masked scheme that masks $1/K$
765 of the positions on each pass and reads log-probabilities only at the masked positions, with $K=7$
766 chosen to match the $\approx 15\%$ MLM training rate of [22].

767 **B Surrogate heads**

768 All surrogates in the main sweep consume the same per-task FM embeddings, cached once per (FM,
769 task) pair as a parquet of fixed-size float vectors (Sec. 2, App. A). The only thing that varies across
770 rows of Table 1 is the surrogate head and its acquisition rule. Any gap in NBSF or Top-5% count
771 between two methods isolates the head, not the representation. This appendix records the eight
772 surrogates compared in the main results, the exact hyperparameters used for each, and the ablations
773 we ran when picking those settings.

774 **B.1 Random (Random)**

775 Uniform sampling without replacement from the heldout pool. The configuration omits both the
776 surrogate and the acquisition blocks and sets `batch_strategy=random` on the optimizer. The
777 featurizer is set to `identity` so no FM forward pass is performed.

778 **B.2 Zero-Shot (Zero_Shot)**

779 The zero-shot baseline ranks the heldout pool by the FM’s own pseudo-likelihood at each candidate,
780 with no labelled-data fit and no parameter update over the campaign. This is the natural “FM-prior-
781 only” control: it isolates how much of the optimization signal is already in the FM’s pretraining
782 likelihood, before any task-specific learning takes place. For protein and RNA assays this baseline is
783 well-known to correlate with measured fitness for many DMS landscapes [67, 63], which is what
784 makes it a meaningful anchor rather than a trivial floor.

785 The cached score column is the per-FM PLL constructed by the scoring procedures of App. A.3:
786 WT-marginal scoring for the masked-LM encoders (ESM-C 600M, RNA-FM), K -stripe masked PLL
787 for NTv3-650M, and autoregressive log-likelihood for ChemFM-1B. All three are length-normalised
788 so candidates of different sizes sit on the same scale and higher always means more likely under the
789 FM. Acquisition is `ArgMax` on this scalar. Because the score is fixed at parquet-creation time and
790 the surrogate has no parameters, the ranking of the heldout pool never changes between BO rounds;
791 the loop simply removes each round’s pick from the heldout set and selects the next-highest-scoring
792 candidate. This is the sense in which `zero_shot` is open-loop: measured labels are recorded but
793 ignored.

794 **B.3 Random Forest (RF_Greedy, RF_LogEI)**

795 Sklearn’s RandomForestRegressor with 100 trees and standardized targets, fed the raw FM
796 embedding as a fixed-size feature vector. Tree-level hyperparameters are sklearn’s defaults:
797 `criterion=friedman_mse`, unbounded depth, `min_samples_leaf=1`, and `max_features=1.0`
798 (every split considers all features). The random-state seed is fixed at 42 so tree splits are deterministic
799 across methods and seeds; the only stochasticity in the baseline is the BO loop. We use the predictive
800 mean of the forest (`rf.predict`) as the surrogate mean and the variance of the per-tree predictions
801 as a heteroscedastic uncertainty estimate.

802 This recipe matches the EvolvePro setup [47]: a frozen protein-FM embedding, an unconstrained
803 sklearn random forest with 100 estimators, and a greedy step that picks the candidate with the largest
804 forest mean. We also report the LogEI-on-tree-variance variant in the same row of Table 1, which
805 uses the tree variance as a posterior variance under BoTorch’s LogExpectedImprovement [1] with
806 f^* set to the running maximum on the labelled set. LogEI adds an exploration term but does not
807 change the surrogate; the comparison between the two acquisitions inside this row isolates the effect
808 of variance-aware exploration on top of an EvolvePro-style head.

809 **B.4 Linear (Linear)**

810 A single linear layer on the raw FM embedding, $f(x) = w^\top z + b$ with $z \in \mathbb{R}^D$, trained end-to-end
811 with SGD rather than the closed-form ridge solution. Training is identical to the mlp head described
812 next: AdamW (`lr=3e-4`, `wd=1e-3`), batch size 32, gradient clip 1.0, MSE loss against standardized
813 targets, up to 3000 epochs per BO round with `patience=100` early stopping on the per-epoch training
814 loss. The head is reinitialized at every BO round before retraining, so nothing carries between rounds
815 beyond the labelled set. Acquisition is ArgMax.

816 We use this SGD-trained linear head rather than a closed-form ridge solution so the only architectural
817 difference between `linear` and `mlp` is the head depth, with optimizer, loss, schedule, and reinitial-
818 ization protocol all matched. This isolates the effect of the nonlinearity in the MLP from the effect of
819 the optimization recipe.

820 **B.5 MLP (MLP_Greedy)**

821 A 2-layer MLP head on the raw FM embedding, with `hidden_features=128`, `num_layers=1`,
822 `activation=elu`. Training uses AdamW (`lr=3e-4`, `wd=1e-3`), mini-batch 32, gradient clip 1.0,
823 MSE on standardized targets, up to 3000 epochs with `patience=100` early stopping on the per-epoch
824 training loss. Acquisition is ArgMax on the predictive mean.

825 The head is reinitialized at every BO round before retraining; the model weights, the optimizer
826 moments, and any learning-rate state are all dropped between rounds. This matters for the result in
827 Sec. 3.1: the converged weights of an SGD-trained MLP from a fresh init can be intuitively read
828 as an approximate draw from the implicit posterior over heads induced by the init distribution and
829 the optimizer trajectory on the current labelled set, so an ArgMax on those weights is effectively a
830 single-sample Thompson rule with the sampler hidden in the optimizer.

831 **B.6 MLP Ensemble (MLP_Ensemble)**

832 Five MLP heads with the same architecture and optimizer recipe as `mlp`, trained jointly on the labelled
833 set with summed MSE loss. The diversity comes from initialization, not from data: each head’s linear
834 weights are Kaiming-uniform initialized under a per-head seed (`torch.manual_seed(k * 1337)` for
835 the k -th head), so the five heads start at different points in weight space and converge to different
836 solutions under the same SGD trajectory. We do not bootstrap or subsample the labelled data. All
837 five heads are reinitialized at the start of every BO round.

838 The predictive mean is the average of the head outputs and the predictive variance is the em-
839 pirical variance across the five outputs, both de-standardized before being passed to BoTorch’s
840 LogExpectedImprovement. We performed an ablation for this surrogate with LogEI and Thomp-
841 son Sampling and found that Thompson Sampling performs far better. For batch BO the ensemble
842 exposes a Thompson rule: each batch slot draws one head index uniformly and selects the candidate
843 with the largest predicted mean under that head.

844 **B.7 Gaussian Process** (Gaussian Process)

845 An exact GP from BoTorch with a constant mean, a scaled Matérn-5/2 ARD kernel directly on the raw
 846 FM embedding, and a Gaussian likelihood, fit by `fit_gpytorch_mll` [4]. Inputs are mapped to the
 847 unit cube (`Normalize`) and targets are standardized (`Standardize`). The kernel is initialized with
 848 output scale 1.0, lengthscale 1.0, and noise variance 1.0 under the constraint $\sigma_y^2 \geq 10^{-3}$, with the
 849 L-BFGS optimizer using a learning rate of 0.2 on the GP hyperparameters. Acquisition is BoTorch’s
 850 `LogExpectedImprovement` [1] with f^* set to the running maximum.

851 The default `Gaussian Process` runs the kernel on the full D -dimensional FM embedding (e.g.
 852 $D=1152$ for ESM-C 600M). We also tested a shallow deep-kernel variant (`gp_bottleneck`) that
 853 prepends a trainable `Linear` ($D \rightarrow 128$) + ELU projector before the kernel and co-trains the projector
 854 with the GP hyperparameters by marginal likelihood, using a separate AdamW parameter group
 855 at `lr=1e-3` and `wd=1e-3` (the kernel still uses `lr=0.2`). The bottleneck shape mirrors the VBLL
 856 projection exactly so any GP-vs-VBLL difference attributable to the projector is held fixed. Across the
 857 cohort the bottleneck variant performed worse than the no-projection `Gaussian Process`, consistent
 858 with the well-known DKL overfitting failure mode at small labelled-set sizes [68], so we report the
 859 no-projection GP as our headline GP baseline.

860 **B.8 Variational Bayesian Last Layer** (VBLL)

861 **Generative model.** A Bayesian linear regression head sits on top of a learned `Linear` ($D \rightarrow d$) + ELU
 862 projection $\phi_\theta : \mathbb{R}^D \rightarrow \mathbb{R}^d$ of the FM embedding z with $d = 128$ [39]. Writing $\phi_i = \phi_\theta(z_i)$ for
 863 brevity, the joint generative model on the labelled set $\mathcal{D}_t = \{(z_i, y_i)\}_{i=1}^{|\mathcal{D}_t|}$ is

$$y_i | \phi_i, w, \sigma_y^2 \sim \mathcal{N}(w^\top \phi_i, \sigma_y^2) \quad (\text{likelihood}), \quad (1)$$

$$w \sim \mathcal{N}(0, s_w I_d) \quad (\text{weight prior}), \quad (2)$$

$$\sigma_y^2 \sim \mathcal{W}^{-1}(\nu, s_\Sigma) \quad (\text{noise prior}), \quad (3)$$

864 where the scalar Inverse-Wishart on σ_y^2 reduces to an Inverse-Gamma in our single-output regression
 865 setting. The variational posterior factorizes as $q(w, \sigma_y^2) = q(w) q(\sigma_y^2)$ with a Gaussian $q(w) =$
 866 $\mathcal{N}(\mu, \Sigma)$ on the weights (full $d \times d$ covariance) and a deterministic $q(\sigma_y^2)$ parameterized by a single
 867 learned log-scale; the latter behaves as a MAP estimate of the noise variance under the Inverse-Wishart
 868 prior.

869 **ELBO.** Under this conjugate structure both the data-term expectation and $\text{KL}(q||p)$ are available in
 870 closed form, giving a deterministic per-batch ELBO:

$$\begin{aligned} \mathcal{L}(\theta, q) = \frac{1}{|\mathcal{D}_t|} \sum_{(z_i, y_i) \in \mathcal{D}_t} & \left[\underbrace{\log \mathcal{N}(y_i; \mu^\top \phi_i, \sigma_y^2)}_{\text{predictive log-likelihood}} - \underbrace{\frac{1}{2} \phi_i^\top \Sigma \phi_i / \sigma_y^2}_{\text{weight-uncertainty penalty}} \right] \\ & + \lambda_t \cdot \left[\underbrace{\nu \log \sigma_y^{-2} - \frac{1}{2} s_\Sigma \sigma_y^{-2}}_{\text{Inverse-Wishart prior log-density on } \sigma_y^2} - \underbrace{\text{KL}(\mathcal{N}(\mu, \Sigma) || \mathcal{N}(0, s_w I_d))}_{\text{weight KL}} \right]. \end{aligned} \quad (4)$$

871 The data term is the closed-form expectation $\mathbb{E}_{q(w)}[\log \mathcal{N}(y_i; w^\top \phi_i, \sigma_y^2)]$, which decomposes into
 872 $\log \mathcal{N}(y_i; \mu^\top \phi_i, \sigma_y^2)$ minus the weight-uncertainty penalty $\frac{1}{2} \phi_i^\top \Sigma \phi_i / \sigma_y^2$. The Inverse-Wishart term
 873 acts as a regulariser on the noise variance under the deterministic $q(\sigma_y^2)$, preventing collapse to
 874 $\sigma_y^2 \rightarrow 0$. σ_y^2 inside the ELBO denotes the current variational point estimate.

875 **Predictive distribution.** For a candidate x with embedding $z(x)$, the posterior predictive over the
 876 noiseless function value $f(x) = w^\top \phi_\theta(z(x))$ is closed-form Gaussian:

$$p(f(x) | \mathcal{D}_t) = \mathcal{N} \left(\underbrace{\mu^\top \phi_\theta(z(x))}_{\text{predictive mean}}, \underbrace{\phi_\theta(z(x))^\top \Sigma \phi_\theta(z(x))}_{\text{predictive variance}} \right). \quad (5)$$

877 The mean is the linear readout under the variational mean μ , and the variance is the quadratic form
 878 of the projected feature against the posterior covariance Σ (with the noise variance σ_y^2 added if a

879 predictive over y is required). This gives any variance-aware acquisition rule a mean and variance per
 880 candidate without Monte Carlo sampling.

881 **Hyperparameters.** Table 3 lists the head’s hyperparameters, grouped by role.

Table 3: **VBLL head hyperparameters.** Grouped by role. The same settings are used across every task, modality, and FM in the main sweep; the only quantity that changes between rounds is the regularisation weight λ_t , which is rescaled by the current dataset size.

Group	Hyperparameter	Value
Architecture	Projection width d	128
	Activation	ELU
	Covariance parameterisation of $q(w)$	dense ($d \times d$)
Priors	Weight prior scale s_w	$1/d$
	Noise prior scale s_Σ	10
	Degrees of freedom ν	10
ELBO weighting	Regularisation weight λ_t	$1/ \mathcal{D}_t $ (per round)
Optimisation	Optimiser	AdamW
	Learning rate	10^{-3}
	Weight decay	10^{-3}
	Mini-batch size	64
Schedule	Gradient clip (max norm)	1.0
	Warmup	5 epochs, linear
	Decay	cosine to zero
	Max epochs / round	3000 (patience 100, smoothing 0.5)
Per-round reset	Target standardisation	yes
	FM-embedding normalisation	no
	Head / projector reinit each round	yes

882 C Acquisition functions

883 The acquisition rule turns the surrogate’s predictive distribution at each candidate into a single
 884 score and selects the candidate (sequentially) or batch of candidates (under batched selection) that
 885 maximizes it. Three rules cover every method in Table 1: *Greedy* on the predictive mean, *LogEI* on
 886 the predictive mean and variance, and *Thompson sampling* on a posterior draw. This appendix gives
 887 the sequential form of each rule and the batch construction we pair with it.

888 C.1 Sequential acquisition rules

889 Let $\mu_t(x)$ and $\sigma_t^2(x)$ denote the posterior predictive mean and variance produced by the surrogate at
 890 round t . The sequential acquisition selects $x_t = \arg \max_{x \in \mathcal{X} \setminus \mathcal{D}_{t-1}} \alpha_t(x)$, where α_t is one of:

891 **Greedy.** $\alpha_t(x) = \mu_t(x)$, which selects the candidate with the largest predicted mean. For Zero-Shot
 892 this reduces to the FM’s pseudo-likelihood, since the surrogate is the precomputed PLL itself; for the
 893 deterministic heads (Linear, MLP, RF_Greedy) it is the predicted scalar with no variance term. This
 894 is the only rule available to surrogates without an uncertainty estimate.

895 **LogEI.** $\alpha_t(x) = \log \mathbb{E}[(f(x) - f^*)_+]$, the logarithm of the expected improvement over
 896 the running maximum $f^* = \max_{s \leq t-1} y_s$. We use BoTorch’s numerically stabilised
 897 LogExpectedImprovement [1] under the surrogate’s predictive Gaussian, with $\mu_t(x)$ and $\sigma_t^2(x)$
 898 supplied by the head: the marginal predictive of the GP [79], the empirical mean and across-head
 899 variance of the MLP ensemble (de-standardized before being passed to the acquisition), and the
 900 predictive mean and tree-variance of the random forest for RF_LogEI. LogEI converts to expected
 901 improvement under a strict monotone transform, so the argmax of LogEI matches that of EI; the
 902 log form simply avoids the floating-point underflow that EI suffers when f^* is far above the current
 903 posterior mode [1].

904 **Thompson sampling.** $\alpha_t(x) = \tilde{f}_t(x)$, where \tilde{f}_t is one draw from the surrogate’s posterior over
 905 functions, and $x_t = \arg \max_x \tilde{f}_t(x)$ is the maximizer of that single draw [85]. This matches the
 906 Thompson rule’s regret guarantees and yields exploration without an explicit acquisition trade-off
 907 term: a candidate is selected because it is the optimum of *some* plausible function under the posterior,
 908 not because it has high mean or high variance per se.

909 For VBLL, the predictive in Eq. 5 is closed-form Gaussian, and a function draw is obtained by drawing
 910 the last-layer weights once: $\tilde{w} \sim \mathcal{N}(\mu, \Sigma)$ via the Cholesky factor of Σ , with $\tilde{f}_t(x) = \tilde{w}^\top \phi_\theta(z(x))$
 911 scored over the pool by a single matrix-vector product. For the MLP ensemble, a function draw is
 912 obtained by sampling one head index $k \sim \text{Uniform}\{1, \dots, M\}$ and taking $\tilde{f}_t(x) = m_k(x)$, where
 913 m_k is the k -th head’s prediction. The two constructions are not interchangeable: VBLL exposes an
 914 explicit weight posterior so each call is a fresh continuous draw, whereas the ensemble draws from a
 915 discrete posterior over M trained heads.

916 Thompson sampling is in principle also available for the GP, by drawing a joint posterior sample over
 917 the candidate pool from the GP’s N -dimensional predictive Gaussian and taking its argmax [42, 104].
 918 We do not use this rule in the main results because each draw requires a Cholesky factorization
 919 of an $N \times N$ kernel matrix at every BO round, which is $O(N^3)$ in the candidate pool size and
 920 prohibitive at the pool sizes considered here (N up to $\sim 10K$) when run across 61 tasks, 5 seeds, and
 921 $T = 100$ sequential rounds; the GP is therefore paired with LogEI throughout. The deterministic
 922 heads (Linear, MLP, RF_Greedy) and the random forest expose neither a weight posterior nor an
 923 ensemble of trained functions, so they are paired with ArgMax or LogEI rather than Thompson.

924 C.2 Batch construction

925 Batch BO at size k requires the surrogate to commit to k candidates without intermediate observations.
 926 The challenge is that the round-start posterior is the only information available for every member
 927 of the batch, so the natural single-step argmax of any acquisition concentrates the batch on a single
 928 mode of the posterior unless the batching rule explicitly diversifies.

929 We use the natural batch construction for each acquisition family. For Thompson sampling on VBLL
 930 and the MLP ensemble, batch members are independent posterior draws and their argmaxes; for
 931 VBLL we additionally apply a *projection-residual* diversity rule (App. C.3) that rejects redundant
 932 draws in covariance-weighted feature space. For the LogEI methods (GP, MLP ensemble paired
 933 with LogEI, RF paired with LogEI), the batch is the top- k candidates by the round-start LogEI score
 934 (App. C.4), since the surrogate’s hyperparameters and f^* are not refit between picks within a single
 935 batch. For greedy methods the batch is the top- k candidates by predictive mean, and for the random
 936 baseline it is a uniform sample without replacement.

937 C.3 VBLL: Thompson sampling with projection-residual diversity

938 Sequential Thompson sampling under VBLL is exact (App. B.8): a single Cholesky factorization
 939 of Σ followed by an inner product over the candidate pool. The natural batch extension at size k
 940 draws k independent posterior samples $\tilde{w}^{(1)}, \dots, \tilde{w}^{(k)} \sim q(w)$ and selects the argmax of each over
 941 the remaining heldout pool. This is correct when the posterior is broad, but for a sharp posterior
 942 the k argmaxes can concentrate on the same region of design space because every draw lies near
 943 the posterior mean. We layer a *projection-residual* diversity rule on top of the independent-sample
 944 construction to mitigate this collapse without changing the underlying Thompson semantics.

945 The rule operates in covariance-weighted feature space. For a candidate x , define $z(x) = L^\top \phi_\theta(x)$,
 946 where L is the Cholesky factor of the posterior covariance Σ (so $\|z(x)\|^2 = \phi_\theta(x)^\top \Sigma \phi_\theta(x)$ is the
 947 head’s predictive variance at x , up to noise). After committing batch members $X_j = \{x_{(1)}, \dots, x_{(j)}\}$,
 948 we maintain an orthonormal basis $Q \in \mathbb{R}^{r \times d}$ for $\text{span}\{z(x_{(1)}), \dots, z(x_{(j)})\}$ and accept the $(j+1)$ -th
 949 proposal x^* iff its residual-energy ratio

$$\rho(x^*) = \frac{\|z(x^*)\|^2 - \|Qz(x^*)\|^2}{\|z(x^*)\|^2 + \varepsilon} \quad (6)$$

950 exceeds a fixed threshold δ . The numerator is the squared length of $z(x^*)$ orthogonal to the span of
 951 already-committed members; $\rho \rightarrow 1$ when $z(x^*)$ is fully orthogonal to that span (the candidate carries
 952 information about a new direction in the posterior covariance), and $\rho \rightarrow 0$ when it is essentially

Algorithm 1 VBLL Batch Thompson Sampling with Projection-Residual Diversity

Require: Posterior $q(w) = \mathcal{N}(\mu, \Sigma)$, projection ϕ_θ , candidate pool \mathcal{X} , batch size k , max resamples R , threshold δ , tolerance ε

- 1: $L \leftarrow \text{Cholesky}(\Sigma)$
- 2: $X_0 \leftarrow \emptyset, Q \leftarrow \emptyset$
- 3: **for** $j = 0, 1, \dots, k - 1$ **do**
- 4: **for** attempt = 0, 1, \dots, R **do**
- 5: Draw $\tilde{w} \sim \mathcal{N}(\mu, \Sigma)$
- 6: $x^* \leftarrow \arg \max_{x \in \mathcal{X} \setminus X_j} \tilde{w}^\top \phi_\theta(x)$
- 7: $z \leftarrow L^\top \phi_\theta(x^*)$
- 8: **if** $Q = \emptyset$ **or** $\|z\|^2 \leq \varepsilon$ **or** attempt = R **then**
- 9: accept \leftarrow **true**
- 10: **else**
- 11: $\rho \leftarrow (\|z\|^2 - \|Qz\|^2) / (\|z\|^2 + \varepsilon)$
- 12: accept $\leftarrow (\rho \geq \delta)$
- 13: **end if**
- 14: **if** accept **then**
- 15: $X_{j+1} \leftarrow X_j \cup \{x^*\}$
- 16: Append the unit-normalized residual of z against Q to Q (Gram–Schmidt)
- 17: **break**
- 18: **end if**
- 19: **end for**
- 20: **end for**
- 21: **return** X_k

953 redundant. If $\rho(x^*) < \delta$ we draw a fresh posterior sample and a fresh argmax, up to R resamples,
954 after which we accept the last candidate as a fallback so the batch budget is always filled. On
955 accept, Q is extended by Gram–Schmidt orthogonalization of $z(x^*)$ against the current basis. The
956 numerical tolerance ε avoids division by zero; if $\|z(x^*)\|^2 \leq \varepsilon$ the head reports essentially no
957 posterior uncertainty at x^* and the candidate is accepted unconditionally so that diversity filtering
958 does not block batch completion. We use $\delta = 10^{-3}$, $R = 5$, and $\varepsilon = 10^{-8}$ in all experiments.

959 The per-batch cost is $O(k(d^2 + Nd) + k^2d)$: a single Cholesky reused across all draws, k posterior
960 draws plus pool scorings, and a Gram–Schmidt update that grows linearly in the basis size. This
961 is independent of $|\mathcal{D}_{t-1}|$ and of the FM size, since the FM enters only through the precomputed
962 embedding z .

963 **Ablation against plain Thompson sampling.** We compared this rule against the plain independent-
964 sample construction (the same algorithm with $\delta = 0$, equivalent to skipping the residual check) at
965 every batch size $k \in \{24, 48, 96, 192, 384\}$ used in the main batch sweep. Across the cohort, the
966 projection-residual variant slightly improved both NBSF and Top-5% count over plain Thompson
967 sampling, with the gap most visible at the largest batch sizes where the posterior is sharpest and the
968 redundancy mode is most pronounced. The improvement is small enough on aggregate that we report
969 only the projection-residual variant in the main results, but the ablation justifies it as the default and
970 is consistent with prior reports that Thompson batches benefit from explicit redundancy filtering at
971 large k [11].

972 C.4 LogEI surrogates: top- k acquisition argmax

973 For LogEI on the GP, the LogEI variant of the MLP ensemble, and RF_LogEI, the batch is the
974 top- k candidates by the round-start LogEI score over the heldout pool. Within a single batch we
975 do not refit the surrogate or update f^* between picks; the predictive mean, predictive variance, and
976 improvement target are all held at their round-start values. This is by construction equivalent to
977 the constant-liar batch rule with the model’s posterior mean as the lie [30, 105]: the lie does not
978 change the LogEI score at the remaining points because the surrogate is not refit, so sequentially
979 appending $(x^{(j)}, \mu_t(x^{(j)}))$ and recomputing the argmax produces the same ordering as a single sort
980 by the original LogEI values. We use this top- k form in the main results because the equivalence is
981 exact and the implementation is $O(N \log k)$ instead of $O(kN)$.

982 This batch rule does not encode any explicit diversity: at large k all k picks come from a single
983 round-start posterior, and they tend to cluster around the same posterior maximum. The collapse is
984 most visible on the GP, whose predictive variance is small in the well-explored part of the pool, and
985 is the failure mode underlying the GP’s poor scaling at large batch in Sec. 3.2.

986 **Sequential kriging-believer ablation.** We additionally tested a true sequential kriging-believer
987 variant for the GP [30], in which after each pick the GP is conditioned on the pseudo-observation
988 $(x^{(j)}, \mu_t(x^{(j)}))$ via Gaussian conditioning (no hyperparameter refit) and the LogEI is recomputed on
989 the remaining pool. Because conditioning lowers the predictive variance near $x^{(j)}$, this rule diversifies
990 the batch at the cost of k posterior conditionings per round. On our cohort the sequential variant
991 actually performed slightly worse than top- k LogEI, and the runtime was substantially larger. We
992 therefore report top- k LogEI as the headline GP batch rule.

993 C.5 Greedy and random surrogates

994 The greedy heads (Linear, MLP, RF_Greedy, Zero-Shot) have no per-candidate uncertainty and no
995 posterior to sample from. Their batch construction is top- k on the predictive mean (ArgMax on μ_t),
996 with no diversity term. This matches their sequential rule one-to-one: nothing about the surrogate
997 changes between members of the batch, so the k best candidates under the round-start posterior are
998 exactly the k candidates the rule would select if run sequentially without intermediate observations.
999 The Random baseline samples k candidates uniformly without replacement from the heldout pool,
1000 independently of the surrogate.

1001 D Datasets

1002 The main benchmark contains 61 fixed-pool scalar optimization tasks: 18 protein, 12 chemistry, 11
1003 DNA, and 20 RNA. The broader benchmark collection contains additional audit, ablation, and legacy
1004 tasks; the selected cohort below is the one used for the paper’s aggregate figures. Each task is treated
1005 as a finite candidate pool with a measured or computed scalar objective, and all methods compare on
1006 the same candidate set for that task.

1007 **Selection criteria.** We include tasks that satisfy four constraints. First, the input is a discrete
1008 scientific object that can be passed to the modality FM without changing the representation: amino-
1009 acid sequence, DNA sequence, RNA sequence, or SMILES. Second, the target is a scalar regression
1010 objective with a well-defined optimization direction; ordinal or classification-only datasets such
1011 as `nucb` and `vapdiff` are excluded. Third, the deduplicated candidate pool is large enough for a
1012 96-candidate initialization plus a 100-round sequential campaign without exhausting the landscape.
1013 Fourth, the source task is from an established benchmark or primary assay collection with enough
1014 provenance to reproduce the curated task. The selected set therefore emphasizes real biological assays
1015 and standard molecular-property benchmarks, while excluding chemistry reaction-procedure tasks
1016 whose natural-language inputs are not comparable to the SMILES-only chemistry FM pipeline, very
1017 small panels, deprecated duplicate tasks, and context-length edge cases.

1018 **Preprocessing and target convention.** Preprocessing removes rows with missing inputs or missing
1019 labels, canonicalizes the input representation, drops exact duplicate candidates when the source
1020 permits, and keeps one scalar target per task. All tasks are maximization tasks except `enamine10k`,
1021 where lower docking score is better. For each seed, the initial 96 candidates are drawn from the below-
1022 median half of the task’s target distribution, forcing every method to improve from a deliberately
1023 weak starting set.

1024 **Subsampling policy.** Subsampling is deterministic and task-level, never method-level. When a
1025 source landscape is much larger than the campaign budget, the runtime CSV is a fixed subsample,
1026 usually stored as `<task>_10k.csv` and generated with seed 42; the full source files remain on
1027 disk for ablations when available. Other selected tasks use the full curated assay table because it is
1028 already a finite benchmark pool and embeddings were cached for the full CSV; the exact runtime
1029 N is reported in the tables. For the SGPO comparison, we use the full combinatorially complete
1030 landscapes for `gb1`, `phoq`, and `trpb_4site`, so every sequence proposed by either method can be
1031 scored against the complete experimental map. Separate LLM-context subsamples, such as `gb1_1500`
1032 and `gosai_skns_h_2100`, are not part of the 61-task BO cohort.

1033 **Protein tasks.** Protein tasks combine FLIP [19], FLIP2 [23], EvolvePro / ProteinGym [67], and
 1034 complete combinatorial landscapes used for the SGPO comparison. The optimized properties
 1035 cover viral packaging, binding, enzymatic activity, viral fitness, protein stability, and genetic-circuit
 1036 signaling.

Table 4: **Protein benchmark tasks.** N_{orig} is the original curated dataset size before any campaign subsampling.

Task	Benchmark Suite	N_{orig}	Dataset description	Original citation
aav	FLIP	283,775	AAV2 capsid VP1-region DMS; maximize viral packaging viability.	Bryant et al., 2021 [12]
alpha_amylase	FLIP2	7,467	Single-mutant <i>Bacillus</i> alpha-amylase assay; maximize DP3 substrate-hydrolysis activity.	van der Flier et al., 2024 [100]
brenan	EvolvePro ProteinGym	6,810	Human MAPK1 / ERK2 kinase DMS; maximize SCH-condition kinase signaling activity.	Brenan et al., 2016 [9]
cas12f	EvolvePro	7,942	AsCas12f1 miniature CRISPR nuclease DMS; maximize genome-editing / DNA-cleavage efficiency.	Hino et al., 2023 [44]
doud	EvolvePro ProteinGym	10,716	H1N1 influenza hemagglutinin DMS; maximize viral replicative fitness.	Doud and Bloom, 2016 [25]
gb1	FLIP ProteinGym	149,361	Four-position GB1 combinatorial DMS; maximize IgG-Fc binding fitness.	Wu et al., 2016 [106]
giacomelli	EvolvePro ProteinGym	7,448	Human TP53 DMS under etoposide selection; maximize tumor-suppressor function.	Giacomelli et al., 2018 [29]
haddox	EvolvePro ProteinGym	12,863	HIV-1 Env DMS; maximize viral infectivity / replicative fitness.	Haddox et al., 2018 [38]
hydro	FLIP2	24,935	HIS3 ortholog combinatorial DMS; maximize fitness across hydrophobic-core mutations.	Pokusaeva et al., 2019 [72]
ired	FLIP2	10,905	Imine reductase DMS; maximize catalytic fitness on the active substrate.	Gantz et al., 2024 [27]
jones	EvolvePro ProteinGym	7,800	Human beta-2 adrenergic receptor DMS; maximize agonist-dependent signaling activity.	Jones et al., 2020 [49]
lee	EvolvePro ProteinGym	10,754	H3N2 influenza hemagglutinin DMS; maximize viral replication capacity.	Lee et al., 2018 [57]
meltome_human	FLIP	9,792	Human proteome melting-temperature dataset; maximize protein thermostability (T_m).	Jarzab et al., 2020 [46]
meltome_mixed	FLIP	23,340	Mixed-species proteome melting-temperature dataset; maximize protein thermostability (T_m).	Jarzab et al., 2020 [46]
phoq	PhoQ landscape	140,517	PhoQ four-site histidine-kinase landscape; maximize signaling fitness.	Podgornaia and Laub, 2015 [71]
stiffler	EvolvePro ProteinGym	4,978	TEM-1 beta-lactamase DMS; maximize ampicillin-resistance fitness.	Stiffler et al., 2015 [94]
trpb_4site	FLIP2	159,129	Four-site PflTrpB combinatorial landscape; maximize beta-replacement reaction fitness.	Johnston et al., 2024 [48]
zikv_E	EvolvePro ProteinGym	9,577	Zika-virus envelope-protein DMS; maximize viral growth / replication fitness.	Sourisseau et al., 2019 [91]

1037 **Chemistry tasks.** The chemistry cohort is SMILES-only. It includes three GOLLuM molecular-
 1038 property tasks [78] and nine MoleculeACE activity-cliff panels [101]. Reaction-yield tasks with
 1039 procedure text are intentionally excluded from the main cohort because they use a different input
 1040 representation.

Table 5: **Chemistry benchmark tasks.**

Task	Benchmark Suite	N_{orig}	Dataset description	Original citation
d3r_dopamine	MoleculeACE	3,651	Dopamine D3 receptor ligands; maximize pChEMBL / pK_i binding affinity.	van Tilborg et al., 2022 [101]
delta_opioid	MoleculeACE	2,598	Delta-opioid receptor ligands; maximize pChEMBL / pK_i binding affinity.	van Tilborg et al., 2022 [101]

Task	Benchmark Suite	N_{orig}	Dataset description	Original citation
enamine10k	GOLLuM DOCKSTRING	10,449	Enamine REAL molecules docked to a target receptor; minimize docking score.	García-Ortegón et al., 2022 [28]
f2_thrombin	MoleculeACE	2,750	Thrombin / coagulation factor II inhibitors; maximize pChEMBL potency.	van Tilborg et al., 2022 [101]
fx_factor_x	MoleculeACE	3,093	Factor Xa inhibitors; maximize pChEMBL potency.	van Tilborg et al., 2022 [101]
hrh3_histamine	MoleculeACE	2,862	Histamine H3 receptor ligands; maximize pChEMBL / pK_i binding affinity.	van Tilborg et al., 2022 [101]
kappa_opioid	MoleculeACE	2,603	Kappa-opioid receptor ligands; maximize pChEMBL / pK_i binding affinity.	van Tilborg et al., 2022 [101]
laser_multi10k	GOLLuM	10,000	Laser / photonic candidate molecules; maximize computed fluorescence oscillator strength.	Pollice et al., 2021 [74]
mor_mu_opioid	MoleculeACE	3,142	Mu-opioid receptor ligands; maximize pChEMBL / pK_i binding affinity.	van Tilborg et al., 2022 [101]
photovoltaics_pce10k	GOLLuM CEP	2,322,849	Organic photovoltaic donor molecules; maximize simulated power-conversion efficiency.	Hachmann et al., 2011 [37]
pparg	MoleculeACE	2,349	PPAR-gamma ligands; maximize pChEMBL activity / potency.	van Tilborg et al., 2022 [101]
serotonin_5ht1a	MoleculeACE	3,317	Serotonin 5-HT1A receptor ligands; maximize pChEMBL / pK_i binding affinity.	van Tilborg et al., 2022 [101]

1041 **DNA tasks.** DNA tasks are MPRA or promoter-expression datasets. They are grouped into random/synthetic promoter benchmarks, DeepSTARR enhancer activity, Gosai human cis-regulatory
1042 element activity, and PARM / Barbadilla promoter MPRA tasks. The five `barbadilla_*` tasks are
1043 derived from the same promoter-fragment library and differ only in the expression or perturbation
1044 target.
1045

Table 6: **DNA benchmark tasks.**

Task	Benchmark Suite	N_{orig}	Dataset description	Original citation
barbadilla_hepg2	PARM MPRA	4,449,234	Human promoter-fragment MPRA in HepG2 cells; maximize basal expression.	Barbadilla-Martínez et al., 2026 [5]
barbadilla_hepg2_nutlin3a_lfc	PARM MPRA	4,449,234	Same promoter-fragment library in HepG2; maximize Nutlin-3a perturbation log-fold change.	Barbadilla-Martínez et al., 2026 [5]
barbadilla_k562	PARM MPRA	4,449,234	Human promoter-fragment MPRA in K562 cells; maximize basal expression.	Barbadilla-Martínez et al., 2026 [5]
barbadilla_k562_heatshock_lfc	PARM MPRA	4,449,234	Same promoter-fragment library in K562; maximize heat-shock perturbation log-fold change.	Barbadilla-Martínez et al., 2026 [5]
barbadilla_k562_pma_lfc	PARM MPRA	4,449,234	Same promoter-fragment library in K562; maximize PMA perturbation log-fold change.	Barbadilla-Martínez et al., 2026 [5]
deepstarr_dev	DeepSTARR	484,052	Drosophila STARR-seq enhancer library; maximize developmental-enhancer activity.	de Almeida et al., 2022 [20]
deepstarr_hk	DeepSTARR	484,052	Same enhancer library; maximize housekeeping-enhancer activity.	de Almeida et al., 2022 [20]
dream	DREAM	7,413,183	Random synthetic yeast promoters; maximize measured promoter expression.	Rafi et al., 2025 [76]
gosai_hepg2	Gosai MPRA	CRE 798,064	Human cis-regulatory elements assayed in HepG2 cells; maximize regulatory activity.	Gosai et al., 2024 [33]
gosai_k562	Gosai MPRA	CRE 798,064	Human cis-regulatory elements assayed in K562 cells; maximize regulatory activity.	Gosai et al., 2024 [33]

Task	Benchmark Suite	N_{orig}	Dataset description	Original citation	
gosai_ sknsh	Gosai MPRA	CRE	798,064	Human cis-regulatory elements assayed in SK-N-SH cells; maximize regulatory activity.	Gosai et al., 2024 [33]

1046 **RNA tasks.** The RNA cohort is dominated by RNAgym [3] ribozyme and tRNA fitness landscapes,
1047 with tasks spanning self-cleavage, splicing, aptamer binding, mRNA expression, and tRNA suppression.
1048 Several sources contain multiple assays on related ribozyme families; these are kept as separate
1049 tasks when they have distinct candidate pools or distinct measured targets.

Table 7: RNA benchmark tasks.

Task	Benchmark Suite	N_{orig}	Dataset description	Original citation
andreasson_ ribozyme	RNAgym	7,343	Cofactor-dependent <i>glmS</i> self-cleaving ribozyme variants; maximize cleavage activity.	Andreasson et al., 2020 [2]
cpeb3_ ribozyme	RNAgym	111,417	Human CPEB3 HDV-like ribozyme DMS; maximize self-cleavage activity.	Zhang et al., 2020 [111]
domingo_ trna	RNAgym	4,175	Yeast tRNA fitness landscape; maximize translation / aminoacylation fitness.	Domingo et al., 2018 [24]
hairpin_ ribozyme	RNAgym	22,578	Hairpin self-cleaving ribozyme DMS; maximize cleavage activity.	Roberts et al., 2023 [82]
hammerhead_ ribozyme	RNAgym	9,046	Type-III hammerhead ribozyme mutational library; maximize self-cleavage activity.	Roberts et al., 2023 [82]
hdv_ ribozyme	RNAgym	33,930	Hepatitis-delta-virus ribozyme DMS; maximize self-cleavage activity.	Roberts et al., 2023 [82]
ke_ mrna	RNAgym	5,559	mRNA exon-definition saturation mutagenesis; maximize splicing-reporter expression.	Ke et al., 2018 [51]
mcrae_5tu_ ribozyme	RNAgym	74,942	5TU catalytic subunit of a triplet polymerase ribozyme (TPR); maximize polymerase activity.	McRae et al., 2024 [62]
mcrae_t1_ ribozyme	RNAgym	47,503	t1 scaffolding subunit of a triplet polymerase ribozyme (TPR); maximize polymerase activity.	McRae et al., 2024 [62]
nelfe_ aptamer	RNAgym	2,652	RNA aptamer variants selected against NELF-E; maximize protein-binding activity.	Tome et al., 2014 [99]
osa_twister_ ribozyme	RNAgym	10,296	<i>Oryza sativa</i> twister-class ribozyme variants; maximize self-cleavage activity.	Kobori and Yokobayashi, 2016 [54]
peri_ ribozyme	RNAgym	16,383	Azoarcus group-I ribozyme activity landscape; maximize activity score.	Peri et al., 2022 [70]
pistol_ aptazyme	RNAgym	16,383	Pistol aptazyme saturation library; maximize log-enrichment / cleavage activity.	Kobori et al., 2017 [53]
soo_ ribozyme	RNAgym	63,430	Tetrahymena group-I intron self-splicing ribozyme fitness landscape; maximize splicing activity.	Soo et al., 2021 [90]
sup4_ trna_tyr	RNAgym	25,491	SUP4-oc tRNA-Tyr DMS; maximize amber-suppression / RTD-survival function.	Guy et al., 2014 [36]
trna_ arg	RNAgym	65,537	Yeast SUP4-o tRNA-Arg(UCU) saturation landscape; maximize suppression-based fitness.	Li et al., 2016 [58]
twister_ ribozyme	RNAgym	10,296	Twister self-cleaving ribozyme DMS; maximize cleavage activity.	Roberts et al., 2023 [82]
zhang_line1_ full_ribozyme	RNAgym	69,583	Full LINE1-associated twister-sister-like self-cleaving ribozyme library; maximize cleavage activity.	Zhang et al., 2024 [110]
zhang_line1_ mini_ribozyme	RNAgym	149,710	Minimized LINE1-associated twister-sister-like ribozyme library; maximize cleavage activity.	Zhang et al., 2024 [110]
zhang_or4k15_ ribozyme	RNAgym	61,393	OR4K15-associated twister-sister-like self-cleaving ribozyme library; maximize cleavage activity.	Zhang et al., 2024 [110]

1050 E Foundation-model comparison per modality

1051 To isolate the effect of the foundation-model backbone, we rerun the entire surrogate sweep with the
 1052 alternative FM swapped in for each modality (Table 2) while holding the task list, the BO loop, the
 1053 seeds, and every surrogate hyperparameter fixed. The pairings are ESM-C 600M vs. SaProt 650M
 1054 (protein), RNA-FM vs. RiNALMo-giga (RNA), NTv3-650M vs. Evo2-1B (DNA), and ChemFM-1B
 1055 vs. SMI-TED (chemistry). Each modality is evaluated on the intersection of candidate pools that both
 1056 FMs admit so that any difference is attributable to the representation rather than to coverage. For
 1057 every (FM, surrogate, task, seed) tuple we record two BO outcomes: the normalized best-so-far at the
 1058 end of the budget, and the cumulative count of acquired candidates whose true objective lies above
 1059 the 95th percentile of the pool.

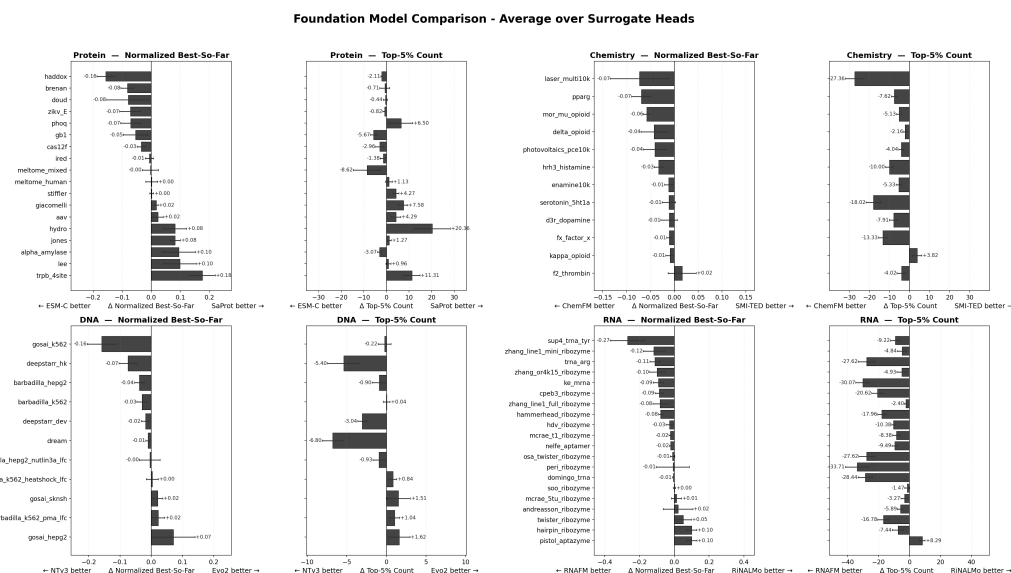


Figure 6: **Backbone sensitivity per modality.** Two panels per modality (normalized best-so-far on the left, top-5% acquired count on the right) report a per-task signed difference between the primary FM and its principal alternative (Table 2), averaged over surrogate heads and seeds. Each horizontal bar corresponds to one task; the sign indicates which FM is preferred (the labels under each axis name the winning side), and the magnitude reports the size of the gap on that metric. ESM-C 600M and SaProt 650M trade wins task by task and end up roughly on par overall, indicating that the structure-aware 3Di vocabulary helps on some landscapes but does not displace the sequence-only encoder as a default. Chemistry and RNA show clearer separations in favor of the primaries (ChemFM over SMI-TED, RNA-FM over RiNALMo-giga), with RNA exhibiting the largest and most uniform per-task gap despite RiNALMo-giga’s higher parameter count. DNA is consistent with the rest: NTv3-650M is preferred over Evo2-1B across most tasks on both metrics, validating the encoder choice for sequences whose downstream signal is dominated by short-range regulatory motifs. The takeaway is that scale alone does not predict suitability for BO; the encoder vs. decoder distinction and the alignment between the pretraining objective and the candidate space matter at least as much.

1060 F Fine-Tuning

1061 The main results in Section 3 freeze the foundation model and train only the surrogate head on cached
 1062 embeddings. This appendix reports the two regimes that update the FM itself: *supervised* LoRA
 1063 fine-tuning on the labelled BO set, and *self-supervised* LoRA pretraining on a target-family MSA.
 1064 Both are evaluated on protein tasks; the SSL regime requires a wild-type sequence and an alignable
 1065 family, which has no clean equivalent in the other modalities.

1066 **F.1 Supervised Fine-Tuning**

1067 In the Supervised regime, LoRA adapters [45] are co-trained with the surrogate head on \mathcal{D}_{t-1}
 1068 each round; adapters and head are reinitialized between rounds. We test three representative heads:
 1069 MLP_Greedy, VBLL, and GP_LogEI, the last reproducing the deep-kernel-GP-with-LoRA recipe from
 1070 GoLLuM [78] with FM, LoRA rank, and acquisition matched to the frozen baseline.

1071 Figure 7 shows that gains are head-dependent: MLP_Greedy and VBLL both improve with co-training,
 1072 especially on Top-5%. GP_LogEI does not run to completion (cross marker, GP panel): backpropa-
 1073 gating the marginal likelihood through both the kernel matrix and the adapter exhausts GPU memory
 1074 partway through every protein task. This is intrinsic to the GoLLuM-style recipe at our FM scale, not
 1075 a tuning issue, and motivates our focus on variational and deterministic heads for SFT.

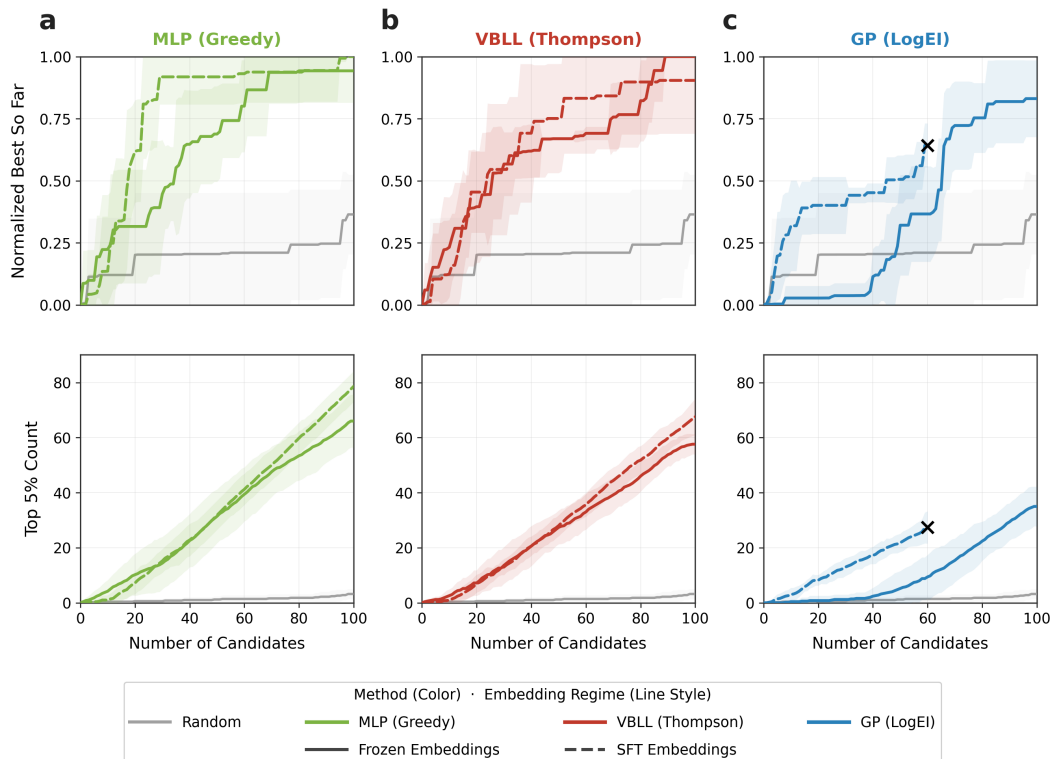


Figure 7: **Supervised LoRA fine-tuning on representative protein tasks.** NBSF (top) and Top-5% count (bottom) over $T=100$ sequential rounds for MLP_Greedy, VBLL, and GP_LogEI. Solid lines: frozen embeddings. Dashed lines: supervised LoRA. Bands are ± 1 SEM across tasks and seeds. Gains are largest for MLP_Greedy and VBLL; GP_LogEI ends up consistently breaking at that step due to memory issues.

1076 **F.2 Self-Supervised Fine-Tuning**

1077 In the Self-Supervised regime, a single LoRA adapter is pretrained once *before* the BO loop using a
 1078 masked-language-model objective on a target-family MSA, in the style of ESM-1v [63]. For each task,
 1079 the wild-type sequence is used as a query for a sequence-database search, hits are clustered at 80%
 1080 identity, and training samples are weighted by inverse cluster frequency to prevent over-representation
 1081 of dense regions of sequence space. The pretrained adapter is then loaded in place of a random init
 1082 and frozen, so SSL acts as a *target-aware feature-extractor delta* on top of the base FM. We evaluate
 1083 this regime on 15 of the 18 protein tasks; the remaining three (combinatorial-library or ortholog-panel
 1084 datasets) lack a single wild-type query sequence, so the family-MSA construction step does not apply.

1085 Figures 8 and 9 report per-task Δ NBSF and Δ Top-5% for each (task, head) pair. The picture is
 1086 strongly heterogeneous: SSL is clearly beneficial on a subset of tasks (large green bars) and clearly
 1087 harmful on another (large red bars), with the sign and magnitude depending on both task and head.

1088 Aggregating across tasks, mean NBSF changes are small and within 1 SEM for every method,
 1089 while Top-5% coverage tends to improve for the simpler greedy heads (Zero_Shot, RF_Argmax,
 1090 Linear_Argmax, MLP_Argmax, RF_LogEI) and stays roughly flat for the stronger uncertainty-aware
 1091 heads (MLP_Ensemble, GP, VBLL). Tasks where the wild type is already a high-fitness reference, and
 1092 where the family MSA is dense and well-aligned, are the most consistent winners. We therefore
 1093 do *not* adopt SSL as a default in the main results; it is a useful task-conditional lever rather than a
 1094 uniform improvement.

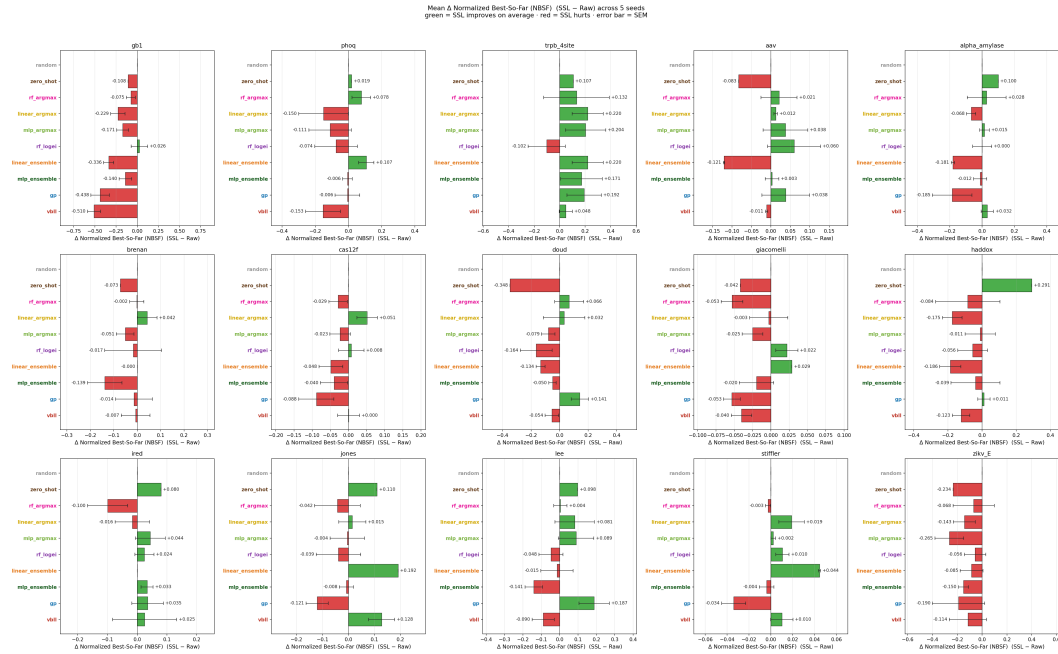


Figure 8: Per-task Δ NBSF (SSL – original), 15 protein tasks. One panel per task; bars are method-level differences, green for SSL improving, red for SSL degrading. Error bars are ± 1 SEM across seeds. Aggregate NBSF changes are within 1 SEM, but per-task swings are large and bidirectional.

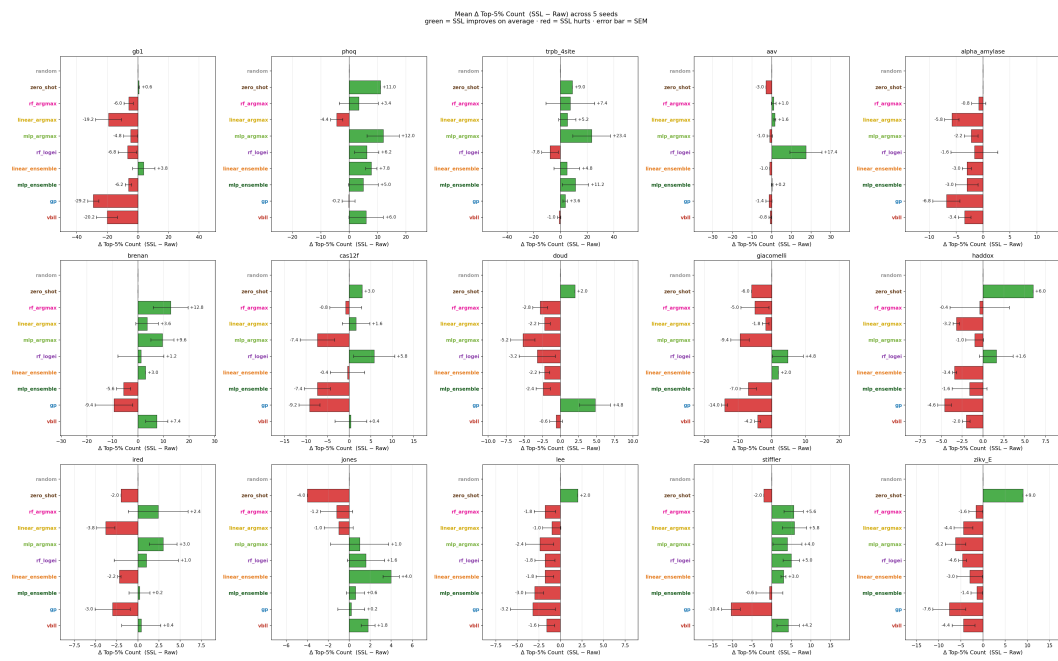


Figure 9: **Per-task Δ Top-5% (SSL - original), 15 protein tasks.** Same layout as Figure 8 for elite-candidate coverage. Greedy heads gain most often; uncertainty-aware heads are roughly unchanged on aggregate.

1095 **G Sequential Bayesian Optimization**

1096 This appendix expands on the sequential results in §3.1. We first show the across-task Pareto frontier
 1097 and the round-by-round learning curves that produce it, then turn to the variance side via expected
 1098 calibration error (ECE) for the uncertainty-aware heads.

1099 **G.1 Detailed Results**

1100 Figure 10 pools all 61 tasks into a single endpoint summary per method, with both metrics evaluated
 1101 at the end of the $T=100$ -round budget. MLP Ensemble (Thompson) and VBLL (Thompson) sit
 1102 at the upper-right frontier, MLP (Greedy) is essentially tied with them on best-so-far and only
 1103 marginally behind on top-5% count, and Gaussian Process (LogEI) matches the leaders on best-
 1104 so-far but acquires meaningfully fewer top-5% candidates. Linear (Greedy), Random Forest
 1105 (LogEI), and Random Forest (Greedy) form the middle tier, while Zero-Shot (Likelihood)
 1106 and Random are dominated on both axes. Figure 11 unrolls those endpoints over rounds and splits by
 1107 modality: rows are protein, chemistry, RNA, and DNA, the left column is normalized best-so-far,
 1108 and the right column is top-5% count. The two columns behave differently in time. Best-so-far gaps
 1109 narrow late as most methods eventually find a near-optimum, while top-5% gaps keep widening for
 1110 the remainder of the budget, because that metric rewards continuing to acquire high-value designs
 1111 after the first one is in hand. Random and Zero-Shot (Likelihood) stay roughly linear throughout,
 1112 consistent with non-adaptive sampling.

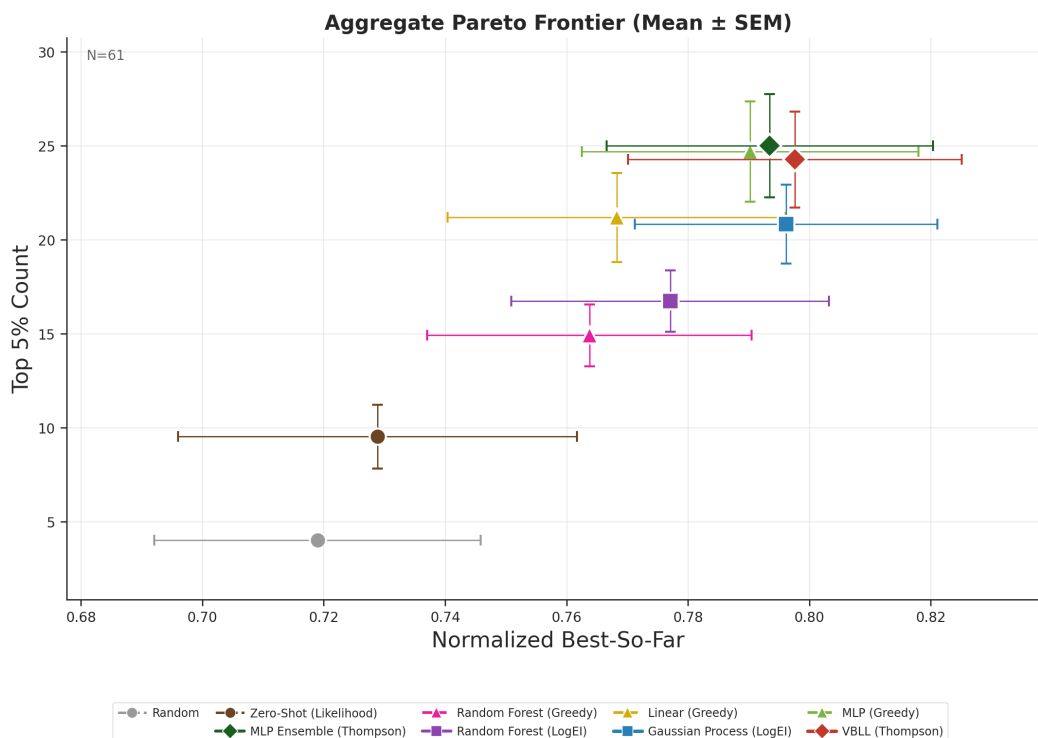


Figure 10: **Aggregate Pareto frontier of normalized best-so-far vs. top-5% count, pooled across all 61 sequential tasks ($T=100, k=1$).** Each marker is one method aggregated over tasks and seeds; error bars are ± 1 SEM. The upper-right corner is the joint optimum.

Sequential BO — aggregate by modality (\pm SEM)

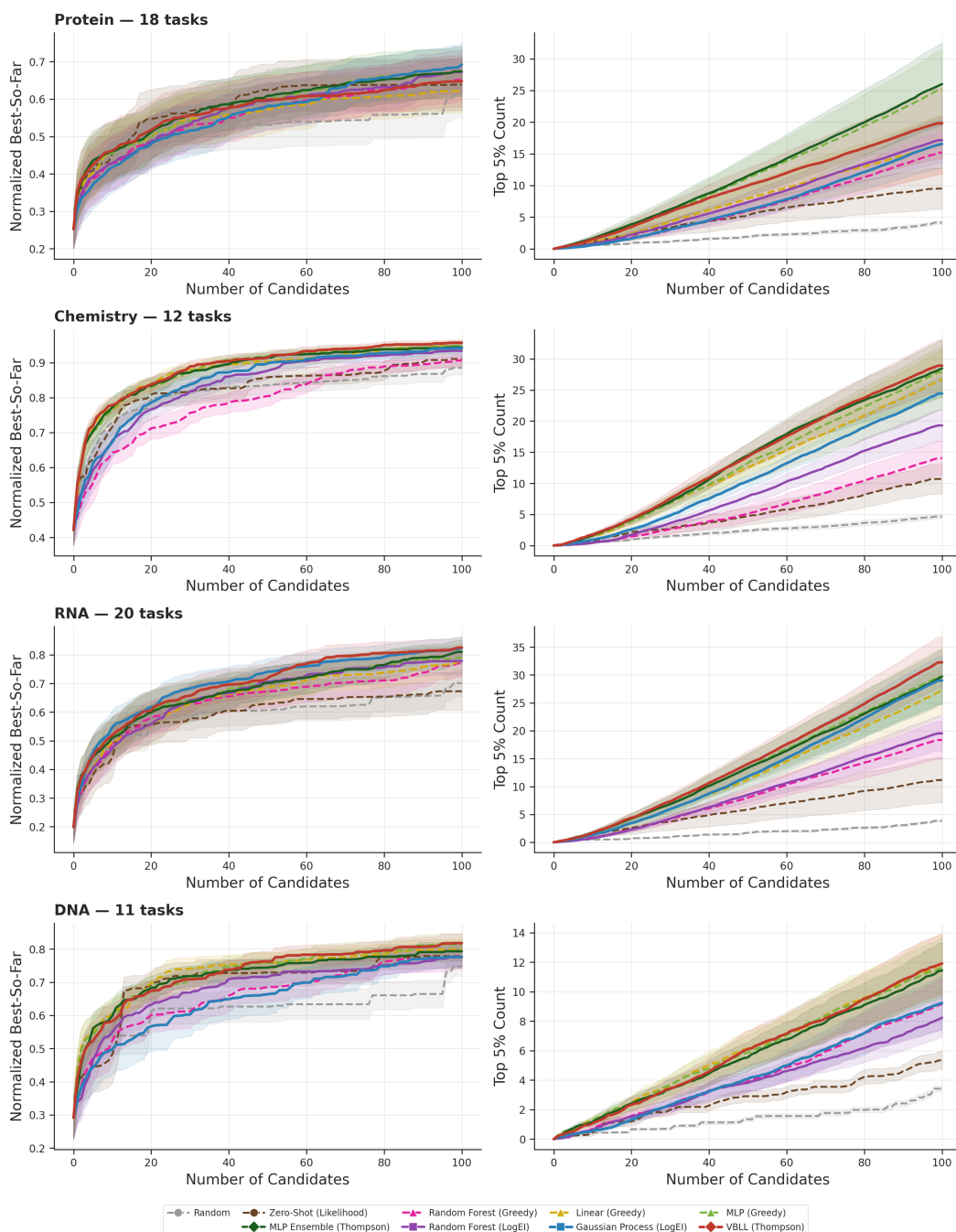


Figure 11: **Per-modality sequential learning curves.** Rows are protein (18 tasks), chemistry (12), RNA (20), and DNA (11); the left column is normalized best-so-far and the right column is top-5% count, both as a function of round t . Bands are ± 1 SEM across tasks and seeds. Best-so-far gaps tighten as the budget grows; top-5% gaps widen.

1113 **G.2 Calibration**

1114 For the three surrogates that expose a closed-form Gaussian predictive distribution (Gaussian
 1115 Process (LogEI), VBLL (Thompson), and MLP Ensemble (Thompson)) we additionally track
 1116 cumulative expected calibration error (ECE) on the heldout pool, recomputed at every BO round.
 1117 ECE is the standard binned reliability gap between predicted and empirical coverage; a perfectly
 1118 calibrated regression posterior would drive it to zero as the loop accumulates labels. The exact GP
 1119 is the calibration reference by construction. VBLL starts uncalibrated but tightens within the first
 1120 ~ 20 rounds and then trails the GP by a roughly constant offset for the remainder of the budget. The
 1121 MLP ensemble stays badly miscalibrated throughout: the disagreement signal across heads does not
 1122 match the true predictive variance and barely improves with more data. The cold-start MLP (Greedy)
 1123 and the random-forest heads are omitted because their uncertainty is either implicit (round-to-round
 1124 reinitialization) or non-Gaussian (tree variance), and ECE under a Gaussian assumption is not the
 1125 right diagnostic for them.

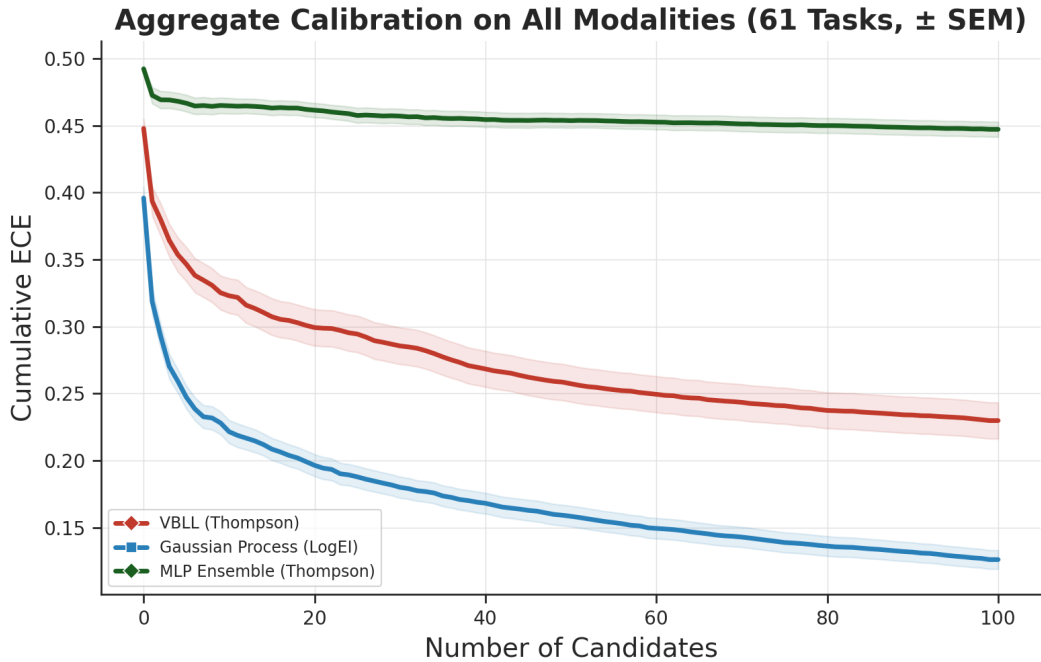


Figure 12: **Aggregate cumulative ECE over all 61 sequential tasks (\pm SEM).** Lower is better. Gaussian Process (LogEI) is the calibration ceiling. VBLL (Thompson) tightens quickly and trails the GP by a roughly constant offset. MLP Ensemble (Thompson) stays nearly flat at high ECE.

1126 The surprising takeaway is that calibration quality and BO performance are essentially decoupled
 1127 in this regime. The MLP ensemble has by far the worst ECE in Figure 12, yet it sits on the Pareto
 1128 frontier in Figure 10 and matches or beats the GP on top-5% count across modalities in Figure 11.
 1129 The GP, conversely, is the best-calibrated method by a wide margin and still loses on the acquisition
 1130 metric. What appears to matter for discrete BO over a fixed candidate pool is whether the posterior
 1131 preserves the *ranking* of high-value candidates and supplies enough disagreement to keep Thompson
 1132 sampling exploratory; faithfully reproducing posterior coverage is neither necessary nor sufficient for
 1133 that. A natural interpretation is that ECE is computed over the entire heldout pool, whereas BO only
 1134 ever queries the upper tail, so a head whose variances are globally miscalibrated can still produce
 1135 a useful ordering of the candidates that actually get acquired. The two axes should therefore be
 1136 read together; the calibration plot is informative about the posterior, but it is not a reliable proxy for
 1137 downstream optimization performance.

1138 **H Batch Bayesian Optimization**

1139 This appendix expands on the batch results in §3.2. We fix the total acquisition budget at 768
 1140 candidates and sweep batch sizes $k \in \{24, 48, 96, 192, 384\}$ over $T \in \{32, 16, 8, 4, 2\}$ rounds. At
 1141 the practical $k=96$ setting (one 96-well plate per round), we report the Pareto frontier of NBSF
 1142 against Top-5% count both pooled and split by modality, then show the round-by-round curves
 1143 underlying the scaling result of Figure 3.

1144 **H.1 Detailed Results**

1145 Figure 13 pools across all 61 tasks at $k=96$, and Figure 14 disaggregates by modality. The qualitative
 1146 picture closely matches the sequential setting (§G.1): VBLL and MLP_Ensemble occupy the upper-
 1147 right frontier with MLP_Greedy adjacent, the random-forest, linear, and GP variants form the middle
 1148 tier, and Random/Zero-Shot trail. The main batching effect is on coverage: the Top-5% axis
 1149 compresses for every method relative to sequential, since the surrogate cannot incorporate within-
 1150 batch labels before committing all k picks. Figure 15 shows the round-by-round trajectories at each
 1151 k . Smaller batches reach a given NBSF level in fewer cumulative candidates, and the gap on Top-5%
 1152 count remains visible at the end of the budget; the curves converge slowly as k grows, consistent with
 1153 elite-set coverage being feedback-round-limited rather than candidate-budget-limited.

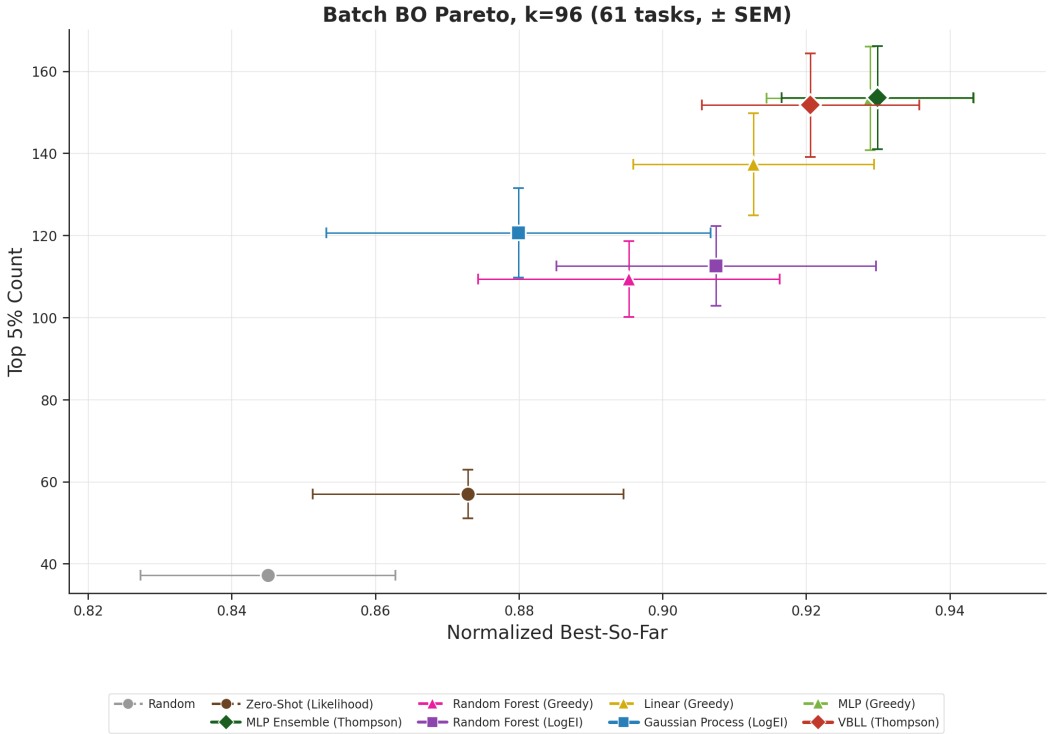


Figure 13: **Pareto frontier of NBSF vs. Top-5% count, pooled across all 61 tasks (batch, $k=96$, $T=8$).** Each marker is one method aggregated over tasks and seeds; error bars are ± 1 SEM. The frontier ordering matches the sequential setting (Figure 10); absolute Top-5% counts are lower because batches commit k picks per posterior update.

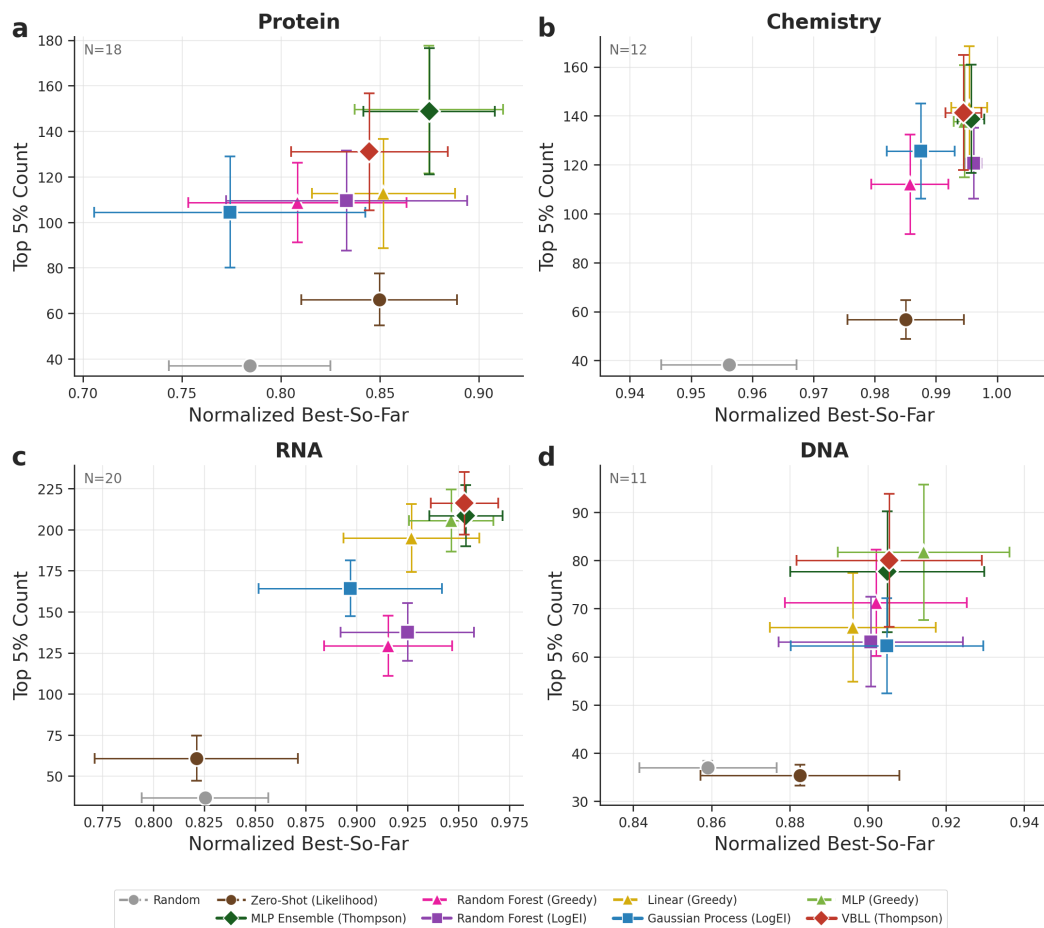


Figure 14: **Per-modality Pareto frontier at $k=96$, $T=8$.** Same axes as Figure 13 split by modality. VBLL leads on chemistry, RNA, and DNA; MLP_Ensemble and MLP_Greedy are most competitive on protein, mirroring the sequential per-modality picture.

Batch BO (k=96) — aggregate by modality (± SEM)

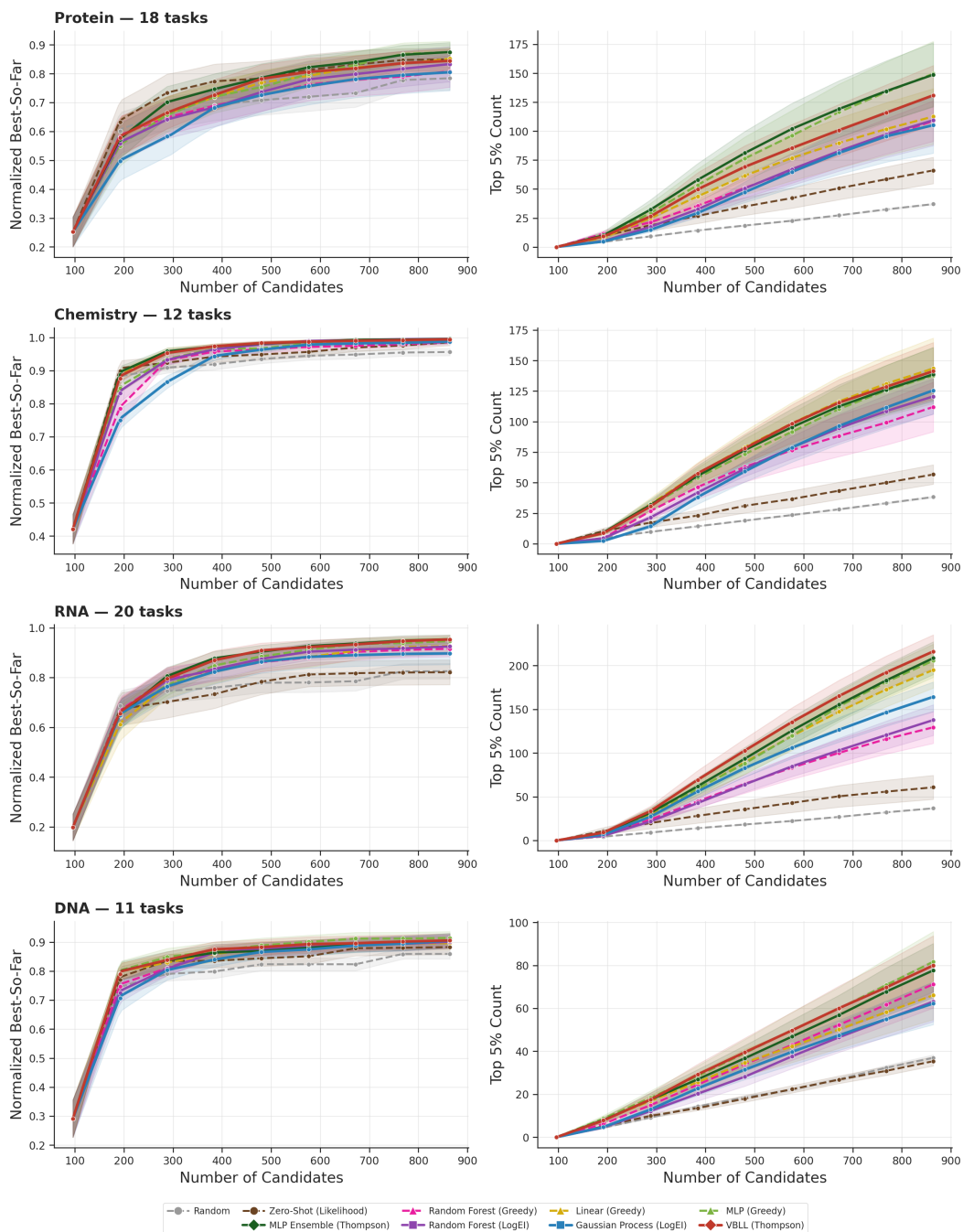


Figure 15: **Round-by-round batch curves at fixed total budget.** NBSF (top) and Top-5% count (bottom) vs. cumulative candidates measured for $k \in \{24, 48, 96, 192, 384\}$. Aggregated over 61 tasks, 9 methods, and 5 seeds. Bands are ± 1 SEM. Smaller k dominates throughout on Top-5% and converges with larger k on NBSF by end-of-budget.

1154 I Comparison to LLM

1155 This appendix documents reproducibility details for the LLM-ICL baseline used in §3.3. None of the
1156 choices below are load-bearing for the paper’s claim, but reviewers and reimplementors will want
1157 them.

1158 **Prompt structure.** The prompt is fully pool-stable: the candidate pool is rendered once, sorted
1159 by candidate ID, and never re-permuted. This is critical for serving cost. vLLM’s prefix cache
1160 survives round to round, only the appended selection row needs cold prefill at each step, and round 2
1161 wall-clock is roughly an order of magnitude faster than round 1. The prompt contains six sections in
1162 fixed order:

- 1163 • **## Pool:** stable, listing (*id*, sequence) for unobserved candidates and never the fitness label
1164 (the central no-leakage invariant).
- 1165 • **## Initial Screen:** all 96 below-median initial candidates with their measured fitness,
1166 sorted by the task metric.
- 1167 • **## Selections:** append-only table of (*id*, sequence, fitness) tuples for rounds 1 through
1168 $t-1$.
- 1169 • **## Tested IDs:** append-only list, used by the model to filter its own candidate set.
- 1170 • **## Progress:** summary of best-so-far, the top-5 selections, and the number of remaining
1171 candidates.
- 1172 • **## Task:** defines the two BO objectives (NBSF and top-5% count) and the balanced ex-
1173 ploit/explore framing.

1174 **Coverage-aware framing.** The **## Task** block defines the two objectives and instructs the model in
1175 language that does not bias toward either strategy: “*Both exploitation (refining within a known high-*
1176 *fitness region) and exploration (probing a distinct cluster) can be productive [...] balance the two*
1177 *based on what the data suggests.*” The model is then required to emit a brief **## diversity_check ##**
1178 block stating which strategy it has chosen and why, followed by **## selected_id ## N**. The
1179 diversity-check block is a forcing function for the model to commit to a stated strategy each round,
1180 which in turn anchors its selection.

1181 **Contamination controls.** The task-description block never names the source paper, the bench-
1182 mark suite, the original authors, or the assay year, and identifies only the underlying biology in
1183 domain-generic terms: “*GB1 protein B₁-domain*”; “*MPRA for human enhancers in the SK-N-SH*
1184 *neuroblastoma line*”; “*synthetic 5' UTR plus start-codon library driving an mRNA reporter*”; “*small-*
1185 *molecule agonists of PPAR γ , a ligand-activated nuclear receptor*”. Specific receptor or library
1186 identities are retained because they are pre-existing public knowledge that any domain expert would
1187 also have, and excluding them would render the task uninterpretable to the model. We did not
1188 implement an additional purge of the pretraining corpus: the LLM may have seen the underlying
1189 datasets indirectly through derivative literature, which is the residual contamination concern noted in
1190 §3.3.

1191 **Strict parser.** We use a strict parser that strips the `<think>...</think>` block and then the
1192 **## diversity_check ##** block before scanning for **## selected_id ## N**. If the delimiter is
1193 missing, the parser returns one of four failure flags (`no_delimiter`, `ambiguous`, `out_of_pool`,
1194 `tested`) rather than a silent integer match, and the round is logged as `parse_failure` for post-hoc
1195 audit. We do not use a “last integer in the response” fallback (which would silently match an integer
1196 in the diversity-check sentence or a position number in the reasoning). Failed rounds fall back to
1197 a uniform random pick from the untested pool, so parse failure does not bias the LLM toward any
1198 sequence region but does cap the upper bound on its top-5% recall. Per-task parse-success rates
1199 ranged from 84.6% (`gosai_sknsh`) to 92.2% (`ke_mrna`); detailed per-seed counts appear in Table 9.

1200 **Inference.** Inference uses vLLM with `max_model_len=262,144` tokens, `max_tokens=32,768`,
1201 FP8 KV cache, prefix caching enabled, and a single H100 GPU under FP8 weights (35B-parameter
1202 MoE, 3B active per token). Sampling follows the Qwen3.6-recommended thinking-mode settings:
1203 `temperature=1.0`, `top_p=0.95`, `top_k=20`, `presence_penalty=1.5`. A multi-seed wrapper
1204 loads model weights once and warms up DeepGEMM kernels once, then resets the prefix cache and
1205 BO state between seeds (no weight reload, no warmup repeat).

1206 **Task selection rationale.** We selected one task per modality from the 61-task benchmark using three
 1207 criteria: (i) the task is in our benchmark and has a competitive surrogate baseline (so any LLM gap
 1208 reflects a hard regime, not a poorly-tuned baseline); (ii) the pool is small enough to fit in context
 1209 with $\geq 25\text{K}$ reasoning tokens of headroom at round 100 under the empirical Qwen tokenizer; (iii)
 1210 within (ii), we prefer the largest pool that fits, since the comparison is most informative when the
 1211 LLM is given as much context as it can use. Long-protein and long-RNA tasks (over 400 residues
 1212 or nucleotides) overflow the 256K-token window once the pool exceeds a few hundred candidates
 1213 and were dropped from the LLM-eligible cohort entirely. For chemistry (pparg, $N=2,349$) and
 1214 RNA (ke_mrna, $N=5,559$) the entire dataset fits in context. For protein and DNA the full 10K-row
 1215 datasets are too large, so we deterministically subsample (seed 12345, applied identically across
 1216 methods on the LLM-side runs) to $N=1,500$ for gb1 and $N=2,100$ for gosai_sknsh.

1217 **Pool-size confound on top-5% count.** The top-5% threshold is the 95th percentile of the full task
 1218 dataset, computed identically for the LLM and the SciOpt baselines. For the matched-pool tasks
 1219 (pparg, ke_mrna) both methods see the same candidates, so absolute count is directly comparable.
 1220 For gb1 and gosai_sknsh the LLM sees a subsample and SciOpt sees the full dataset, so the LLM
 1221 has fewer top-5% candidates available in its visible pool (Table 8). On these two tasks the absolute-
 1222 count comparison mechanically caps the LLM’s top-5% count by roughly $5\times$, so we additionally
 1223 check the recall rate (hits divided by available top-5% in each method’s pool); the LLM still trails on
 1224 coverage rate everywhere except gb1.

Table 8: Pool sizes and top-5% availability per task per method.

Task	LLM-ICL		SciOpt	
	Pool Size	Top-5% avail	Pool Size	Top-5% avail
gb1	1,500	79	10,000	500
pparg	2,349	131	2,349	131
ke_mrna	5,559	277	5,559	277
gosai_sknsh	2,100	98	10,000	500

1225 **Per-seed results.** Table 9 reports NBSF, top-5% count, and parse-failure count for each (task, seed)
 1226 at round 100. Run-to-run variance is large for LLM-ICL on every task, often comparable to or
 1227 exceeding the mean. On gb1 two of five seeds reach NBSF 0.254 and 0.358 while the other three
 1228 reach 1.000, reflecting the mode-collapse pattern discussed in §3.3.

Table 9: Per-seed final-round (round 100) results for LLM-ICL on the four paper-slate tasks. T5 = top-5% count; PF = parse-failure count out of 100 rounds.

Seed	gb1			pparg			ke_mrna			gosai_sknsh		
	NBSF	T5	PF	NBSF	T5	PF	NBSF	T5	PF	NBSF	T5	PF
1	1.000	28	10	0.830	18	10	0.643	4	6	0.420	5	11
2	1.000	18	9	0.780	9	10	0.752	3	5	1.000	3	18
3	0.254	5	12	0.774	6	24	0.894	41	8	0.420	7	12
4	1.000	25	17	0.934	29	6	0.626	1	15	0.539	8	16
5	0.358	8	11	1.000	37	8	0.685	4	5	0.413	4	20
Mean	0.722	16.8	11.8	0.864	19.8	11.6	0.720	10.6	7.8	0.558	5.4	15.4
S.d.	0.382	10.1	3.1	0.100	13.1	7.4	0.109	17.0	4.1	0.252	2.1	3.8

1229 **Random-baseline note for unmatched-pool columns.** For gb1 and gosai_sknsh, the random
 1230 baseline in Figure 4 is computed on the SciOpt full pool ($N=10,000$), not the LLM’s subsample. A
 1231 random search on the LLM’s pool would have a slightly different baseline NBSF, since both pools
 1232 share the same biology but differ in absolute fitness range. For the matched-pool tasks (pparg,
 1233 ke_mrna) the random baseline is directly comparable to the LLM.

1234 **Reasoning examples.** Figures 16–19 display one structured response per task from rounds
 1235 where LLM-ICL selected a global top-5% candidate. Each example contains the model’s full
 1236 `## reasoning ##`, `## diversity_check ##`, and `## selected_id ##` blocks (the `<think>` chain-
 1237 of-thought is omitted since the model emits an explicit final reasoning section). The reasoning
 1238 is consistently grounded in domain biology (FMN-binding J-helix in GB1; tetralin-carboxylate

1239 scaffolds with halogen substitution for PPAR γ ; conserved core motifs with 5' UTR variation for
 1240 ke_mrna; high-GC neuronal-enhancer architecture for gosai_sknsh), which is consistent with the
 1241 paradigm-appeal claim in Liu et al. 2024 [59]. Despite this reasoning quality, the run-level metrics in
 1242 Table 9 show that grounded chains-of-thought do not translate to surrogate-competitive performance
 1243 under tight measurement budgets.

LLM-ICL on GB1 — One Round of In-Context Learning

Owen3.0-35B-A3B-FP8 · round 38 of 100 · selected ID 737 → fitness 4.916, top-5%

STEP 1 · Optimization setup

You are an expert protein biochemist performing iterative experimental optimization:

Your goal: discover high-performing amino acid sequence variants. We score you on TWO objectives, and both matter:

- **Best-so-far**** – the single highest Fitness you find across all selections.
- **Coverage**** – how many of the top 5% of the full library you discover (top_5_count).

Both exploitation (refining within a known high-fitness region) and exploration (probing a distinct cluster) can be productive. Exploitation is most useful when a high-fitness pattern in your selections hasn't been fully mapped yet; exploration is most useful when your top selections cluster narrowly and other high-fitness regions likely remain undiscovered. Balance the two based on what the data suggests. After each selection you will receive the measured fitness. You have a budget of 100 rounds.

About this experiment:
 GB1 protein B1-domain. Fitness measures binding affinity to IgG-Fc.

About the data format:
 Sequences use amino acid single-letter code. Key properties:
 Hydrophobic (A, V, L, I, W, F, M, P), polar (S, T, Y, N, Q),
 charged (D, E, K, R, H), special (C disulfide, G flexible, P rigid).

Reasoning budget guidance: keep your private reasoning concise and decision-oriented. ****Never re-write a candidate's full sequence in your reasoning – refer to candidates ONLY by their integer ID number.**** The pool is shown above; you can locate any ID instantly. Verbose sequence enumeration in <think> wastes the response budget and risks truncating before the final **** selected id **** block. Aim for s2-3 K tokens of reasoning before committing.

STEP 2 · Iteration state (abridged for display)

```
## Pool (1404 total candidates, sorted by ID)
## Initial Screen (Round 0 – 96 candidates from the low-fitness region, sorted by Fitness)
| ID | Sequence | Fitness |
|----|-----|-----|
| 57 | MOYKLLNGKTLKGETTTEAVDAATAEKVFKQYANDNGRFRKENTYDDATK... | 0.000 |
| 14 | MOYKLLNGKTLKGETTTEAVDAATAEKVFKQYANDNGRFRKENTYDDATK... | 0.000 |
| 18 | MOYKLLNGKTLKGETTTEAVDAATAEKVFKQYANDNGRFRKENTYDDATK... | 0.000 |
| 73 | MOYKLLNGKTLKGETTTEAVDAATAEKVFKQYANDNGRFRKENTYDDATK... | 0.000 |
| 94 | MOYKLLNGKTLKGETTTEAVDAATAEKVFKQYANDNGRFRKENTYDDATK... | 0.000 |
Round 0 distribution: mean=0.000, median=0.000, min=0.000, max=0.000, stdev=0.000.

## Selections (Rounds 1-38)
| Round | ID | Sequence | Fitness |
|----|-----|-----|-----|
| 2 | 200 | MOYKLLNGKTLKGETTTEAVDAATAEKVFKQYANDNGRFRKENTYDDATK... | 0.000 |
| 3 | 196 | MOYKLLNGKTLKGETTTEAVDAATAEKVFKQYANDNGRFRKENTYDDATK... | 0.000 |
| 4 | 1150 | MOYKLLNGKTLKGETTTEAVDAATAEKVFKQYANDNGRFRKENTYDDATK... | 0.000 |
[... +33 more selections ...]

## Tested IDs (37 – exclude from your selection)
96, 100, 106, 111, 130, 141, 143, 200, ... (37 total)

## Progress
Round: 38 / 100
Untested candidates remaining: 1367
Best Fitness so far: 1.000 (ID 833, Round 22)
Selections so far: n=36, mean=0.049, stdev=0.179
Top-5 of your selections (Top-5 table elided for figure; see ## Selections above) –

## Task
Analyze the patterns in your selections (and the top of Round 0). Consider which sequence features correlate with high Fitness.

**select ONE candidate ID from '## Pool' whose ID is NOT in '## Tested IDs'.** That candidate should be:
1. **Likely high-Fitness** – features consistent with your top selections.
2. **A deliberate strategic choice** – either exploitation (reinforcing a productive pattern in your top-5 selections to refine an under-mapped region) or exploration (probing a sequence-distinct region of sequence space).

Choose exploitation when a clear high-fitness pattern is emerging and there is room to refine it. Choose exploration when your top selections cluster narrowly and additional similar picks would yield diminishing returns. Both objectives – best-so-far AND top_5_count – benefit from the right balance.

[response format spec – see Step 3]
```

STEP 3 · Model reasoning + selection

```
## reasoning ##
Analyzing the top performers, I notice a key structural distinction: **ID 833** (fitness 1.0) uniquely has the pattern 'ANDNGRAEEWYDDATKFTFTHTE' – specifically, it carries a rare 'KTFTH' variant (position 37 shows H instead of the more common E/T/N). Meanwhile, many moderately performing sequences share 'KTFFE' or 'KTFTH' but differ in their central motif.

The critical variable region spans approximately positions 31-34 ('XXE WTY'). My highest performers cluster around motifs like 'RAEE', 'FWLE', 'SDDE', 'VLQE'. These all contain polar or charged side chains (E, D) which likely contribute to IgG-Fc binding surface complementarity.

My current coverage is poor – I've only tested 37 of 1404 candidates despite needing to find top 5% (~70 sequences). With one sequence hitting 1.0 and another at 0.42, there's clearly under-mapped space. Rather than exploit the narrow 'KTFTH' region further, I should probe nearby untested motifs with similar physicochemical properties.

I'll select **ID 737** (ANDNGWDNEWYDDATKFTFPTTE) – this carries 'WDNE' motif (aromatic W + polar D/N), which structurally mirrors features of my top performers. While its 'KTFTP' variant differs slightly from the best performer's 'KTFTH', the motif composition in the critical 31-34 region is promisingly similar to the successful 'RAEE'/'FWLE'/'SDDE' classes.

## diversity check ##
This pick is **exploration** – probing a different motif region (WDNE vs RAEE/FWLE/SDDE) while maintaining favorable physicochemical properties (polar/aromatic character), targeting a largely unexplored cluster in sequence space rather than reinforcing the narrow KTFTH pattern of our single best hit.

## selected id ##
737
```

STEP 4 · Measured fitness returned to the model (next round's prompt)

After Step 3, the B0 loop measures the fitness of the chosen variant and concatenates the measurement onto the running **** Selections **** block at the start of round 39:

Round	ID	Sequence	Fitness
38	737	MOYKLLNGKTLKGETTTEAVDAATAEKVFKQYANDNGRFRKENTYDDATKFTFIT...	0.080

That single row is the entire feedback signal – no surrogate, no acquisition function. The model's only learning channel is re-reading its own past selections and their measured fitness.

Figure 16: Reasoning example: GB1 (Protein). Round 38 of seed 2 on the gb1_1500 pool. LLM-ICL selects ID 737, fitness 4.916 (top-5%). The model identifies physicochemical motif clusters (RAEE / FWLE / SDDE) shared across high-fitness sequences and explicitly chooses to probe a parallel WDNE motif as exploration of an under-mapped region of sequence space.

42

LLM-ICL on PPAR γ — One Round of In-Context Learning

Owen3.6-35B-A3B-FP8 · round 73 of 100 · selected ID 1079 → pIC₅₀ 1.745, global max

STEP 1 · Optimization setup

You are an expert medicinal chemist performing iterative experimental optimization.

Your goal: discover high-performing molecule variants. We score you on two objectives, and both matter:

- **Best-so-far**** — the single highest pIC₅₀ (PPAR γ) you find across all selections.
- **Coverage**** — how many of the top 5% of the full library you discover (top_5_count).

Both exploitation (refining within a known high-fitness region) and exploration (probing a distinct cluster) can be productive. Exploitation is most useful when a high-fitness pattern in your selections hasn't been fully mapped yet; exploration is most useful when your top selections cluster narrowly and other high-fitness regions likely remain undiscovered. Balance the two based on what the data suggests. After each selection you will receive the measured fitness. You have a budget of 160 rounds.

About this experiment:
Optimization of small-molecule agonists of PPAR γ (peroxisome-proliferator activated receptor γ), a ligand-activated nuclear receptor. Fitness measures pIC₅₀ (negative log of half-maximal inhibitory concentration). A carboxylate or acidic head paired with a lipophilic tail is the canonical PPAR γ -binding motif; halogen substitutions and substitution-position patterns modulate affinity.

About the data format:
Molecules are represented as SMILES strings. Aromatic rings use lowercase (c1ccccc1), branches in parentheses, double bonds with =. Functional groups, ring systems, and electronic effects drive properties.

Reasoning budget guidance: keep your private reasoning concise and decision-oriented. ****Never** rewrite a candidate's full sequence in your reasoning — refer to candidates **ONLY** by their integer ID number. ****** The pool is shown above; you can locate any ID instantly. Verbose sequence enumeration in **<think>** wastes the response budget and risks truncating before the final **** selected id **** block. Aim for s2-3 K tokens of reasoning before committing.

STEP 2 · Iteration state (abridged for display)

```
## Pool (2253 total candidates, sorted by ID)

## Initial Screen (Round 0 — 96 candidates from the low-fitness region, sorted by pIC50 (PPARγ))
| ID | SMILES | pIC50 (PPARγ) |
|-----|-----|-----|
| 68 | COC1OC2CC(O)C3C(C2C(=O)NIC(=O)NC1CCCC1)OC1=CC(O)=C1 | 0.334 |
| 57 | CCCOC1OC2CCC(O)C2CC(C1)CC2C1CCC1CCC1CCC1(C(=O)O)C2=O | 0.328 |
| 59 | Cn1c(COC2CCCC(C(=O)O)C2)nc2cccc(O)C3CC(C1)cn3 | 0.328 |
| 44 | CCCOC1CCC(C(C)C(C(=O)O)CC1)CC(C(=O)O)C1CCC(C(F)(F)F)CC1 | 0.324 |
| 73 | CCCCCC1(C)Cn1c2cccc(NS1=O)C1CCC(C(C)C(C)C)CC1 | 0.319 |
Round 0 distribution: mean=0.239, median=0.252, min=0.092, max=0.334, stdev=0.060.

## Selections (Rounds 1-73)
| Round | ID | SMILES | pIC50 (PPARγ) |
|-----|-----|-----|
| 2 | 966 | O=C(O)[C@H](Cc1ccccc1)O1CCCC1C2CCCC2(C(F)(F)F)CC1 | 0.118 |
| 3 | 514 | O=C(O)C1CCCC(O)C1C2CCCC(C(F)(F)F)CC1C3CCCC3 | 0.297 |
| 4 | 1789 | ClOC1C2CCCC(C1)CC2)nc1CCOC1CCCC1(C)C(=O)N(C)C1 | 0.212 |
[... +68 more selections ...]

## Tested IDs (72 — exclude from your selection)
106, 109, 118, 127, 136, 152, 168, 171, ... (72 total)

## Progress
Round: 73 / 160
Untested candidates remaining: 2181
Best pIC50 (PPARγ) so far: 0.741 (ID 1617, Round 71)
Selections so far: n=71, mean=0.324, stdev=0.162
Top-5 of your selections (Top-5 table elided for figure; see ## Selections above) —

## Task
Analyze the patterns in your selections (and the top of Round 0). Consider which smiles features correlate with high pIC50 (PPARγ).

**Select ONE candidate ID from '## Pool' whose ID is NOT in '## Tested IDs'.** That candidate should be:
1. **Likely high-pIC50 (PPARγ)** — features consistent with your top selections.
2. **A deliberate strategic choice** — either exploitation (reinforcing a productive pattern in your top-5 selections to refine an under-mapped region) or exploration (probing a sequence-distinct region of molecular space).

Choose exploitation when a clear high-fitness pattern is emerging and there is room to refine it. Choose exploration when your top selections cluster narrowly and additional similar picks would yield diminishing returns. Both objectives — best-so-far AND top_5_count — benefit from the right balance.

[response format spec — see Step 3]
```

STEP 3 · Model reasoning + selection

```
## reasoning ##

My top performers share two key structural motifs:

1. **Fused bicyclic scaffold with carboxylic acid** — IDs 1367 (0.671), 1714 (0.626), 1453 (0.576) all follow the pattern 'CCC(C(=O)O)C1CCC2cc(...)ccc21': a tetralin-like fused system with a 3-methylbutanoic acid side chain, connected via an ether linker (OCC) to a heteroaromatic ring (oxazole/thiazole) bearing a distal phenyl substituent.

2. **Variation in the distal phenyl group**: unsubstituted phenyl gave 0.671 (ID 1367), unsubstituted ring gave 0.626 (ID 1714), CF3-phenyl gave 0.576 (ID 1453). The trend suggests that moderate lipophilicity/electronic modulation on the distal group is beneficial but excessive hydrophobicity (CF3) may penalize.

ID 1079 ('CCC(C(=O)O)C1CCC2cc(O)CC3nc(-c4ccc(Cl)cc4C)oc3C)ccc21') is an **exploitation** pick using the identical scaffold, but substituting the distal phenyl with a dichloro-phenyl. Halogen substitutions are known to fine-tune PPAR $\gamma$  affinity through both electronic effects and van der Waals contacts in the ligand-binding pocket. The dichloro variant probes whether increased lipophilicity/bulk beyond phenyl improves affinity without crossing into the penalty region observed with CF3.

## diversity check ##

Exploitation: This candidate uses the exact same fused-bicyclic-tetralin scaffold as my top-3 performers, varying only the distal phenyl substituent from H/C/H3 to dichloro. This refines the under-mapped parameter space of halogen substitution within the proven high-fitness pattern.

## selected id ##

1079
```

STEP 4 · Measured fitness returned to the model (next round's prompt)

After Step 3, the BO loop measures the pIC₅₀ of the chosen variant and concatenates the measurement onto the running **** Selections **** block at the start of round 74:

Round	ID	Sequence	Fitness
73	1079	CCC(C(=O)O)C1CCC2cc(O)CC3nc(-c4ccc(Cl)cc4C)oc3C)ccc21	0.437

That single row is the entire feedback signal — no surrogate, no acquisition function. The model's only learning channel is re-reading its own past selections and their measured fitness.

Figure 17: Reasoning example: PPAR γ Binding (Chemistry). Round 73 of seed 1 on the pparg_full pool. LLM-ICL selects ID 1079, pIC₅₀ 1.745 (global maximum). The model identifies a fused-bicyclic-tetralin scaffold with a carboxylate head shared by its top performers, and exploits the under-mapped halogen-substitution dimension on the distal aromatic group.

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LLM-ICL on ke_mrna — One Round of In-Context Learning

Owen3.6-35B-A3B-FP8 · round 9 of 100 · selected ID 4244 → DMS score 5.21, top-5%

STEP 1 · Optimization setup

You are an expert RNA biologist performing iterative experimental optimization.

Your goal: discover high-performing RNA sequence variants. We score you on TWO objectives, and both matter:

- Best-so-far** — the single highest mRNA Expression you find across all selections.
- Coverage** — how many of the top 5% of the full library you discover (top_5_count).

Both exploitation (refining within a known high-fitness region) and exploration (probing a distinct cluster) can be productive. Exploitation is most useful when a high-fitness pattern in your selections hasn't been fully mapped yet; exploration is most useful when your top selections cluster narrowly and other high-fitness regions likely remain undiscovered. Balance the two based on what the data suggests. After each selection you will receive the measured fitness. You have a budget of 100 rounds.

About this experiment:
Optimization of a synthetic 5' UTR + start-codon context library driving an mRNA reporter. Fitness measures relative protein output (translation efficiency × mRNA stability). Kozak-context strength, 5'-end secondary structure, upstream open reading frames (uORFs), and start-codon accessibility modulate expression.

About the data format:
RNA sequences use nucleotide single-letter code (A, C, G, U). Base pairing (A-U, G-C, G-U wobble) drives secondary structure. Sequence context affects folding, stability, and catalytic activity.

Reasoning budget guidance: keep your private reasoning concise and decision-oriented. **Never** re-write a candidate's full sequence in your reasoning — refer to candidates ONLY by their integer ID number. The pool is shown above; you can locate any ID instantly. Verbose sequence enumeration in <think> wastes the response budget and risks truncating before the final **# selected id #** block. Aim for <2-3 K tokens of reasoning before committing.

STEP 2 · Iteration state (abridged for display)

```
## Pool (5463 total candidates, sorted by ID)

## Initial Screen (Round 0 — 96 candidates from the low-fitness region, sorted by mRNA Expression)
| ID | Sequence | mRNA Expression |
|----|-----|-----|
| 30 | AGUUGAAGAGGGAGGCUCCAGCACAGUGAAUUGGACUAGGGCAGAGCA | 0.065 |
| 60 | AGUUGAAGAGGGAGGCUCCAGCACAGUGAAUUGGACAGAGGGCAGAGCA | 0.063 |
| 89 | AGUUGAAGAGGGAGGCUCCAGCACAGUGAAUUGGACAGAGGGCAGAGCA | 0.062 |
| 0 | AGUUGAAGAGGGAGGCUCCAGCACAGUGAAUUGGACAGAGGGCAGAGCA | 0.062 |
| 43 | AGUUGGCGCCUAAGCUCAGCACAGUGAAUUGGACAGAGGGCAGAGCA | 0.062 |
Round 0 distribution: mean=0.014, median=0.006, min=0.000, max=0.065, stdev=0.018.

## Selections (Rounds 1-9)
| Round | ID | Sequence | mRNA Expression |
|----|----|-----|-----|
| 2 | 2443 | AGUUGAAGAGGGAGGCUCCAGCACAGUGAAUUGGACAGAGGGCAGAGCA | 0.125 |
| 3 | 3967 | AGUUACACCGGGAGCUCAGCACAGUGAAUUGGACAGAGGGCAGAGCA | 0.038 |
| 4 | 4242 | AGUUGACACCGGGAGCUCAGCACAGUGAAUUGGACAGAGGGCAGAGCA | 0.245 |
[... +4 more selections ...]

## Tested IDs (0 — exclude from your selection)
2443, 3317, 3967, 4242, 4243, 4245, 4247, 4289

## Progress
Round: 9 / 100
Untested candidates remaining: 5455
Best mRNA Expression so far: 0.305 (ID 4243, Round 6)
Selections so far: n=7, mean=0.229, stdev=0.098
Top-5 of your selections (Top-5 table elided for figure; see ## Selections above) -

## Task
Analyze the patterns in your selections (and the top of Round 0). Consider which sequence features correlate with high mRNA Expression.

**Select ONE candidate ID from '## Pool' whose ID is NOT in '## Tested IDs'.** That candidate should be:
1. **Likely high-mRNA Expression** — features consistent with your top selections.
2. **A deliberate strategic choice** — either exploitation (reinforcing a productive pattern in your top-5 selections to refine an under-mapped region) or exploration (probing a sequence-distinct region of sequence space).

Choose exploitation when a clear high-fitness pattern is emerging and there is room to refine it. Choose exploration when your top selections cluster narrowly and additional similar picks would yield diminishing returns. Both objectives — best-so-far AND top_5_count — benefit from the right balance.

[response format spec — see Step 3]
```

STEP 3 · Model reasoning + selection

```
## reasoning ##
Analysis of the top 5 performers (IDs 4242-4289) reveals a highly consistent core motif: 'CUCCAGCACAGUGAAUUGGACAGAGGGCAGAGCAA'. All five share this exact backbone. They differ primarily in their 5' termini, with successful variants starting with 'AGUU' followed by diverse intermediate sequences (e.g., 'UGAAGAGCGS', 'CUUCUCGGG', 'UGAACACGG'). The consensus indicates that the core sequence is essential for high expression, while the 5' region can tolerate significant variation—likely affecting ribosome accessibility, secondary structure, or initiation efficiency.

Given only 7 total selections and a clear signal emerging around this conserved core, exploitation is the right move. By selecting another candidate that preserves the winning core but varies the 5' region, I can map the neighborhood of this high-fitness peak more thoroughly. Candidate 4244 matches the core perfectly ('CUCCAGCACAGUGAAUUGGACAGAGGGCAGAGCAA') and has a GC-rich 5' start ('AGUUGACGAAAGG') distinct from the 5' variants already tested in rounds 2-8. This targeted exploitation should either identify a better local optimum or confirm the boundaries of the current peak.

## diversity check ##
Exploitation — selecting a candidate with the same proven core motif but a different 5' sequence to refine the mapped high-fitness region before broader exploration.

## selected id ##
4244
```

STEP 4 · Measured fitness returned to the model (next round's prompt)

After Step 3, the B0 loop measures the dms score of the chosen variant and concatenates the measurement onto the running **# Selections #** block at the start of round 10:

Round	ID	Sequence	Fitness
9	4244	AGUUACACCGGGAGCUCAGCACAGUGAAUUGGACAGAGGGCAGAGCAA	0.298

That single row is the entire feedback signal — no surrogate, no acquisition function. The model's only learning channel is re-reading its own past selections and their measured fitness.

Figure 18: Reasoning example: mRNA Splicing (RNA). Round 9 of seed 3 on the ke_mrna_full pool. LLM-ICL selects ID 4244, DMS score 5.21 (top-5%). The model identifies a conserved 36-nt core motif (CUCCAGCACAGUGAAUUGGACAGAGGGCAGAGCAA) preserved across the top performers and exploits within the 5'-end variation neighborhood of the existing high-fitness peak.

LLM-ICL on gosai_sknsH — One Round of In-Context Learning

Owen3.6-35B-A3B-FB8 · round 67 of 100 · selected ID 1106 → STARR-seq 2.93, top-5 %

STEP 1 · Optimization setup

You are an expert regulatory genomicist performing iterative experimental optimization.

Your goal: discover high-performing DNA sequence variants. We score you on TWO objectives, and both matter:

- **Best-so-far**** – the single highest Enhancer Activity (SK-N-SH) you find across all selections.
- **Coverage**** – how many of the top 5% of the full library you discover (top_5_count).

Both exploitation (refining within a known high-fitness region) and exploration (probing a distinct cluster) can be productive. Exploitation is most useful when a high-fitness pattern in your selections hasn't been fully mapped yet; exploration is most useful when your top selections cluster narrowly and other high-fitness regions likely remain undiscovered. Balance the two based on what the data suggests. After each selection you will receive the measured fitness. You have a budget of 160 rounds.

About this experiment:
MPRA for human enhancers in SK-N-SH neuroblastoma cells. Fitness measures STARR-seq signal. NEUROD, ASCL1, and POU3F2 motifs are characteristic of neuronal enhancers.

About the data format:
DNA sequences use nucleotide single-letter code (A, T, C, G). Base pairing (A-T, G-C) drives structure. Motifs like TATA boxes, GC content, and transcription factor binding sites affect function.

Reasoning budget guidance: keep your private reasoning concise and decision-oriented. ****Never re-write a candidate's full sequence in your reasoning – refer to candidates ONLY by their integer ID number.**** The pool is shown above; you can locate any ID instantly. Verbose sequence enumeration in `<think>` wastes the response budget and risks truncating before the final `## selected id ##` block. Aim for s2-3 K tokens of reasoning before committing.

STEP 2 · Iteration state (abridged for display)

```
## Pool (2084 total candidates, sorted by ID)

## Initial Screen (Round 0 – 96 candidates from the low-fitness region, sorted by Enhancer Activity (SK-N-SH))
| ID | Sequence | Enhancer Activity (SK-N-SH) |
|----|-----|-----|
93 | CTCCTGCACAGAGGACACTTGTATCCTTATGGATTGATGAGT... | 0.059 |
85 | GGGTGTGGTGGAGGCTGGTATGGTGGCTGGGGTGGGGTGGAGAC... | 0.047 |
24 | AAATTAGCGGGGCTGGTGGGGGGCCCTGATGCCAGCTACTGGAG... | 0.046 |
88 | TTTTITTTTTTAAATAGCCAAGTAAGCCAGGATGGCTATGCC... | 0.046 |
84 | CTAAKCCGTACCCCATTTGGTGGCTGGGGGGGGCTGCTTTATT... | 0.046 |
Round 0 distribution: mean=0.026, median=0.026, min=0.000, max=0.050, stdev=0.013.

## Selections (Rounds 1-67)
| Round | ID | Sequence | Enhancer Activity (SK-N-SH) |
|----|-----|-----|
2 | 122 | AAATTAATGGATGCTATTGTGTAAGCTTGGGCTGATGGGGCAGAC... | 0.011 |
3 | 183 | GCTTATTAGGTGAAGAAACTATCTCCAGGTGGACTTGGGATGGGA... | 0.004 |
4 | 111 | AGGATTCATACAGTATTCTAGACCCAGGGCTTATATCTATGATCCA... | 0.002 |
[... +62 more selections ...]

## Tested IDs (66 – exclude from your selection)
101, 103, 111, 112, 113, 122, 151, 242, ... (66 total)

## Progress
Round: 67 / 160
Untested candidates remaining: 1938
Best Enhancer Activity (SK-N-SH) so far: 0.420 (ID 1207, Round 25)
Selections so far: n=65, mean=0.180, stdev=0.092
Top-5 of your selections (Top-5 table elided for figure; see ## Selections above) -

## Task
Analyze the patterns in your selections (and the top of Round 0). Consider which sequence features correlate with high Enhancer Activity (SK-N-SH).

**Select ONE candidate ID from '## Pool' whose ID is NOT in '## Tested IDs'.** That candidate should be:
1. **Likely high-Enhancer Activity (SK-N-SH)** – features consistent with your top selections.
2. **A deliberate strategic choice** – either exploitation (reinforcing a productive pattern in your top-5 selections to refine an under-mapped region) or exploration (probing a sequence-distinct region of sequence space).

Choose exploitation when a clear high-fitness pattern is emerging and there is room to refine it. Choose exploration when your top selections cluster narrowly and additional similar picks would yield diminishing returns. Both objectives – best-so-far AND top_5_count – benefit from the right balance.

[response format spec – see Step 3]
```

STEP 3 · Model reasoning + selection

```
## reasoning ##
Top performers (IDs 1207, 1935, 825, 2010, 1398) consistently feature high GC content, dense purine/pyrimidine tracts, and shared regulatory cores (e.g., 'GGGAGGCAGAGGTTGCAGTGAG', 'CACACAC'). These motifs strongly align with neuronal enhancer architecture expected in SK-N-SH cells. With 33 rounds remaining, exploitation is optimal: refining within this high-fitness sequence neighborhood can reveal additive context effects and potentially push activity past 0.420. ID 1106 preserves the exact high-value core modules seen in my top-5 while presenting novel upstream/downstream flanks, making it a precise target for performance calibration.

## diversity_check ##
Exploitation. This pick directly targets the high-GC/multimeric enhancer pattern dominating the top-5, aiming to refine motif spacing and flanking context rather than branching into a divergent sequence regime.

## selected_id ##
1106
```

STEP 4 · Measured fitness returned to the model (next round's prompt)

After Step 3, the BO loop measures the starr-seq of the chosen variant and concatenates the measurement onto the running `## Selections ##` block at the start of round 68:

Round	ID	Sequence	Fitness	
67	1106	GCTAGGCGTGGTGGCTGCTGCTGCTAATCCAGCTACTCGGGAGGCTGAGGTAGG...	0.182	- TOP-5%

That single row is the entire feedback signal – no surrogate, no acquisition function. The model's only learning channel is re-reading its own past selections and their measured fitness.

Figure 19: **Reasoning example: Neuroblastoma CRE (DNA).** Round 67 of seed 1 on the gosai_sknsH subsample. LLM-ICL selects ID 1106, STARR-seq activity 2.93 (top-5%). The model identifies a high-GC architecture with shared regulatory cores (GGGAGGCAGAGGTTGCAGTGAG, CACACAC) characteristic of neuronal enhancers in the SK-N-SH line, and exploits the motif-spacing neighborhood of its current top performers.

45

1244 J Comparison to SGPO

1245 J.1 Experimental Setup

1246 We evaluate on three combinatorially complete four-site libraries: GB1 (positions 39, 40, 41, 54),
1247 TrpB4 (positions 34, 35, 78, 79), and PhoQ (positions 50, 51, 54, 55). For each seed, all methods
1248 share an identical cold-start set of 100 sequences drawn uniformly from the subset of the labeled
1249 pool whose true fitness lies below the 0.5 quantile, as described in the main text. The total labeling
1250 budget is $T = 1000$ sequences per seed, allocated as 100 initial points followed by 9 acquisition
1251 rounds of 100 candidates each. This protocol matches the iterative SGPO setting of [108] up to one
1252 additional acquisition round, included to align the budget across all methods compared in this work
1253 (their reported budget is $T = 900$). Each method is run for five independent seeds ($\{0, 1, 2, 3, 4\}$);
1254 shaded regions denote ± 1 sample standard deviation across seeds. We compare the ESM-C backbone
1255 under the MLP and VBLL SciOpt configurations, together with a uniform-random baseline.

1256 J.2 SGPO Configuration

1257 We adopt the configuration that [108] identify as strongest overall (their Section 5): a masked-diffusion
1258 language-model prior steered by decoupled annealing posterior sampling (DAPS), with Thompson
1259 sampling over an ensemble of value functions. At each round t , the value functions are retrained on
1260 the accumulated set of measured candidates \mathcal{D}_{t-1} . We use the bolded “ideal” DAPS hyperparameters
1261 from their Table A3 together with the unreported repository defaults (Table 10); the $5\times$ oversampling
1262 cap on per-round generation is the hard-coded default in their `iterativeBO.py`. For each dataset,
1263 the `data-config.residues` field is set to the four combinatorially varied positions; this field is the
1264 upstream scope-restriction mechanism consumed by their `sampling/base.py` and used by DAPS to
1265 constrain the Metropolis–Hastings proposal scope, so the assignment is a configuration choice rather
1266 than a modification of the method.

Table 10: DAPS hyperparameters used in all SGPO experiments.

Parameter	Value	Description
$1/\beta$	128	Guidance strength (<code>alpha</code>)
K	50	Annealing steps (<code>num_steps</code>)
Euler steps	20	ODE solver steps (<code>ode_steps</code>)
MH steps	1,000	MH steps per annealing step
<code>max_dist</code>	1	Mutations per MH proposal
Iteration cap	$5\times$	Per-round oversampling limit

1267 We observe substantial per-seed variability in the cumulative number of unique candidates selected,
1268 consistent with mode collapse in the diffusion prior. At the terminal round, the cumulative unique-
1269 candidate counts across the five seeds are

$$\begin{aligned} \text{GB1:} & \quad [333, 412], \quad 371 \pm 38; \\ \text{TrpB:} & \quad [771, 914], \quad 865 \pm 57; \\ \text{PhoQ:} & \quad [782, 952], \quad 863 \pm 76. \end{aligned}$$

1270 For each task, the SGPO trajectory is summarized as the cross-seed mean of cumulative unique
1271 candidates, with a cross marker denoting the trajectory endpoint.

1272 K Contamination audit

1273 The benchmark labels are wet-lab measurements that no pretraining corpus contains directly, so a
1274 literal (x, y) leak is implausible. The realistic risks are (a) *sequence-level* memorization, where the
1275 FM has seen the candidate x and assigns it an unusually informative likelihood, and (b) *narrative*
1276 memorization, where a chat-tuned LLM has read the assay paper and carries a prior over high-fitness
1277 motifs or scaffolds. Channel (a) is what `Zero_Shot` would exploit; channel (b) is what LLM-ICL
1278 would exploit.

1279 **FM-side: candidate pools vs. pretraining corpora.** Each primary FM has been pretrained on a
1280 corpus that overlaps the candidate space at the wild-type level but not at the variant level. ESM-
1281 C 600M [26] sees UniRef parents but not the combinatorial DMS variants; RNA-FM [17] sees
1282 RNACentral but not the synthetic UTR / ribozyme libraries; NTV3-650M [8] sees multi-species
1283 genomes but not the 200 bp MPRA libraries; ChemFM-1B [15] is trained on PubChem and so is the
1284 highest-overlap modality, with plausible exact-molecule overlap on the GOLLuM-derived chemistry
1285 tasks.

1286 **Implications for Zero_Shot.** Zero_Shot ranks candidates by the FM’s pseudo-likelihood without
1287 ever seeing labels (§B.2), so it is the surrogate most exposed to channel (a). If pretraining contam-
1288 ination were producing a useful fitness prior, Zero_Shot would be expected to dominate Random,
1289 especially on chemistry. Empirically it sits on or below the random-search frontier on every modality
1290 (Figure 2), consistent with the FM prior tracking sequence naturalness rather than the assay-specific
1291 target.

1292 **LLM-side: Qwen3.6 web-text overlap.** Qwen3.6-35B-A3B-FP8 [75] has a knowledge cutoff
1293 postdating every benchmark publication on our slate, so the model has plausibly read each source
1294 paper and derivative literature. We mitigate the most direct path via the prompt controls in App. I:
1295 the task block names only the underlying biology in domain-generic terms (never the source paper,
1296 benchmark, authors, or assay year), and the prompt never includes unobserved fitness labels. We
1297 did not perform a corpus purge, so this is a soft control. The empirical pattern is again inconsistent
1298 with a useful narrative leak: LLM-ICL trails learned surrogates on NBSF on every task, the gb1
1299 mode-collapse (two of five seeds end at NBSF 0.254 and 0.358) and high gosai_sknsh parse-failure
1300 rate (84.6% parse-success) match the prior-collapse failure mode documented for instruction-tuned
1301 LLMs under tight budgets [86, 107, 97], and the reasoning traces in App. I are domain-grounded but
1302 generic enough to come from background knowledge alone.

1303 **Direction of any residual leak.** Residual contamination would inflate the leaked baseline, not the
1304 SciOpt result: a more contaminated FM helps Zero_Shot, which already trails the learned surrogates,
1305 and a more contaminated LLM helps LLM-ICL, which already trails them too. The main-paper gaps
1306 are therefore conservative with respect to leakage. Two honest caveats: (i) PubChem overlap may
1307 give every method on chemistry a uniform lift, so absolute NBSF on pparg should be read as “with
1308 PubChem-overlap allowed,” and (ii) the LLM’s gb1 mode-collapse may be partly memorization-
1309 driven, which would make the favorable gb1 LLM number a less informative comparison than the
1310 other three tasks.

1311 **NeurIPS Paper Checklist**

1312 The checklist is designed to encourage best practices for responsible machine learning research,
1313 addressing issues of reproducibility, transparency, research ethics, and societal impact. Do not remove
1314 the checklist: **The papers not including the checklist will be desk rejected.** The checklist should
1315 follow the references and follow the (optional) supplemental material. The checklist does NOT count
1316 towards the page limit.

1317 Please read the checklist guidelines carefully for information on how to answer these questions. For
1318 each question in the checklist:

- 1319 • You should answer [Yes], [No], or [N/A].
- 1320 • [N/A] means either that the question is Not Applicable for that particular paper or the
1321 relevant information is Not Available.
- 1322 • Please provide a short (1–2 sentence) justification right after your answer (even for [N/A]).

1323 **The checklist answers are an integral part of your paper submission.** They are visible to the
1324 reviewers, area chairs, senior area chairs, and ethics reviewers. You will also be asked to include it
1325 (after eventual revisions) with the final version of your paper, and its final version will be published
1326 with the paper.

1327 The reviewers of your paper will be asked to use the checklist as one of the factors in their evaluation.
1328 While [Yes] is generally preferable to [No], it is perfectly acceptable to answer [No] provided a
1329 proper justification is given (e.g., error bars are not reported because it would be too computationally
1330 expensive” or “we were unable to find the license for the dataset we used”). In general, answering
1331 [No] or [N/A] is not grounds for rejection. While the questions are phrased in a binary way, we
1332 acknowledge that the true answer is often more nuanced, so please just use your best judgment and
1333 write a justification to elaborate. All supporting evidence can appear either in the main paper or the
1334 supplemental material, provided in appendix. If you answer [Yes] to a question, in the justification
1335 please point to the section(s) where related material for the question can be found.

1336 **IMPORTANT, please:**

- 1337 • **Delete this instruction block, but keep the section heading “NeurIPS Paper Checklist”,**
- 1338 • **Keep the checklist subsection headings, questions/answers and guidelines below.**
- 1339 • **Do not modify the questions and only use the provided macros for your answers.**

1340 **1. Claims**

1341 Question: Do the main claims made in the abstract and introduction accurately reflect the
1342 paper’s contributions and scope?

1343 Answer: [Yes]

1344 Justification: We highlight the three main contributions of the paper in the introduction
1345 where we state we provide a practical foundation-model driven BO framework, a systematic
1346 empirical study of this framework across 61 different experimental regression tasks, and a
1347 head to head comparison with leading AI-for-science paradigms.

1348 Guidelines:

- 1349 • The answer [N/A] means that the abstract and introduction do not include the claims
1350 made in the paper.
- 1351 • The abstract and/or introduction should clearly state the claims made, including the
1352 contributions made in the paper and important assumptions and limitations. A [No] or
1353 [N/A] answer to this question will not be perceived well by the reviewers.
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1355 much the results can be expected to generalize to other settings.
- 1356 • It is fine to include aspirational goals as motivation as long as it is clear that these goals
1357 are not attained by the paper.

1358 **2. Limitations**

1359 Question: Does the paper discuss the limitations of the work performed by the authors?

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Answer: [Yes]

Justification: We have a long section in the discussion regarding limitations of the paper. We mention things ranging from some of the choices made in the evaluation to limitations regarding the choice of LLM we compared against and lack of wet-lab experiments.

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1450 Answer: [No]

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1640 **subjects**

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