# Advancing Fluorescence Detection and Ranging in Scattering Media with Mixture-of-Experts and Evidential Critics

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39th Conference on Neural Information Processing Systems (NeurIPS 2025) Workshop: The 3rd Workshop on Imageomics: Discovering Biological Knowledge from Images Using AI.

## Abstract

Attention-based models dominate sequence transduction, yet in medical time-series datasets they often misallocate focus to irrelevant regions while missing critical context. We present EvidenceMoE, a Mixture-of-Experts architecture that assigns experts based on prior physics knowledge and refines their outputs through an Evidential Dirichlet feedback mechanism providing per-expert reliability scores. In our work on fluorescence lifetime-guided cancer surgery, we assigned expert models to relevant time-series segments encoding tumor depth and microenvironment based tumor delineation knowledge from physics (i.e., the radiative transport equation for photon propagation in tissue), rather than learned only from data. Unlike other prior models that address either depth (e.g., Fluorescence LiDAR) or fluorescence decay (fluorescence lifetime or FLI for drug–target binding), EvidenceMoE jointly captures both within a unified framework, achieving errors as low as 0.030 NRMSE for depth and 0.074 NRMSE for FLI on simulated and experimental datasets, closely matching ground-truth measurements.


## 1 Introduction

Fluorescence-guided surgery (FGS) enhances intraoperative tumor visualization, enabling surgeons to achieve more precise resections while sparing healthy tissue (1; 2; 3). Despite its promise, current FGS systems face two fundamental limitations. First, intensity-based imaging alone often fails to delineate tumor boundaries accurately, as fluorescence accumulation can occur passively and generate misleading signals (4; 5). Second, it provides only 2D surface fluorescence intensity map, leaving surgeons without information about tumor depth (tumor location beneath the tissue surface) (6).

A natural solution to the first limitation is fluorescence lifetime imaging (FLI), which leverages fluorescence decay information rather than intensity alone to robustly distinguish specific molecular interactions from nonspecific probe accumulation (5; 7; 8). However, FLI being indirect computational imaging method requires time-resolved fluorescence images acquisition following solving ill-posed inverse problems, resulting in computationally expensive pipelines that limit its clinical translation (9; 10). To address the second limitation, fluorescence detection and ranging (FLiDAR) has been proposed for depth estimation (11; 12). In ideal conditions, where scattering and absorption are absent or known, FLiDAR can localize fluorescence probes with high accuracy. Yet, in real surgical environments, biological tissue introduces highly variable scattering and absorption, severely degrading performance unless prior knowledge of optical properties is provided (13; 6; 14; 11; 8; 14).

In this work, we demonstrate that time-resolved fluorescence sequences alone contain sufficient information to jointly infer both depth and lifetime without requiring any auxiliary measurements of tissue optical properties. Our approach builds on the physics of photon transport in scattering media (biological tissues), where different temporal regions of the fluorescence decay sequence encode distinct aspects of the underlying tissue–fluorophore interaction (15; 12; 16). By learning to attend selectively to these physics-relevant regions, our model achieves accurate depth localization and robust lifetime estimation in complex tissue environments, paving the way toward clinically viable FGS systems with depth-resolved molecular contrast.

Herein, we introduce a Physics-guided Mixture-of-Experts (MoE) architecture, where expert roles are pre-defined using knowledge from photo-physics rather than learned from data. Each expert generates a prediction, which is evaluated and corrected by an evidence-based critic serving as an internal quality assessor. This reduces expert domination (17) and allows a Decider Network to intelligently fuse these reviewed contributions into a final, reliable estimate of depth and lifetime (Figure 1). Note that "physics-guided" here is distinct from physics-informed approaches.

The principal contributions of this work are:

1. A direct framework for jointly estimating fluorescence depth and lifetime from raw time-resolved fluorescence image sequences without requiring tissue optical properties.
2. An uncertainty-aware inference scheme using evidential Dirichlet correction to quantify model reliability.
3. A Mixture-of-Experts architecture leveraging the knowledge from photon transport equation to attend to temporal segments, with adaptive fusion for FLiDAR inference.

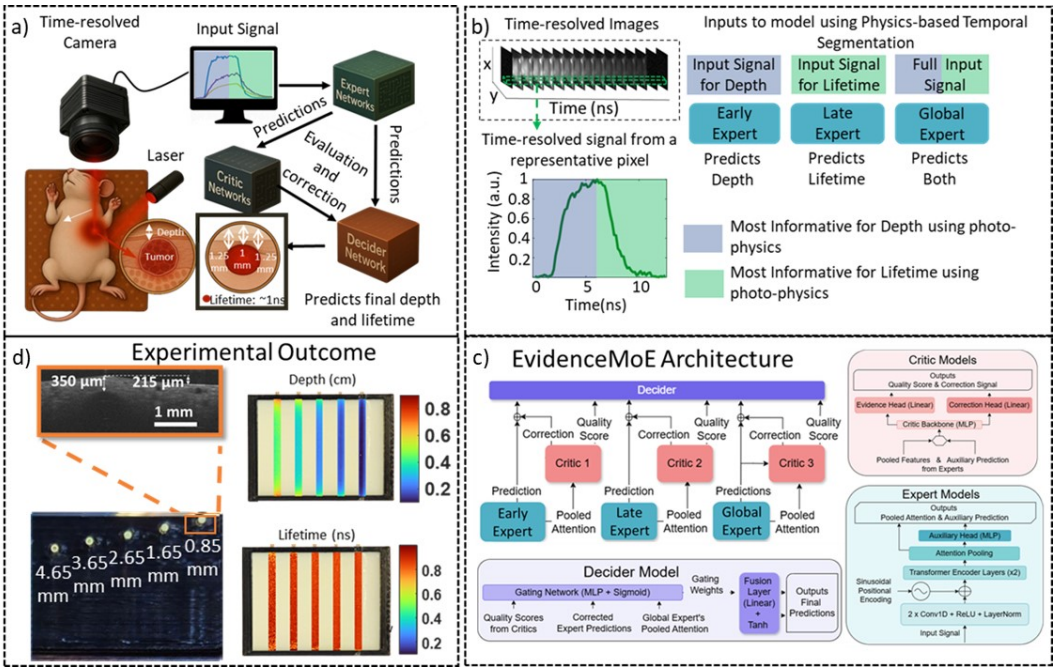


Figure 1: **End-to-end EvidenceMoE Workflow for FLiDAR-based Tumor Lifetime and Depth Estimation.** (a) A laser excites the fluorescent tumor target, and the resulting photons are captured by a time-resolved camera to generate temporal decay images. (b) These images are processed by physics-guided experts that specialize on early photon arrivals for depth, late decay dynamics for lifetime, and the full signal for global context. (c) Within the EvidenceMoE architecture, evidential critics assess expert reliability and provide corrections, while the decider fuses these pathways into final robust estimates of tumor depth and fluorescence lifetime. (d) The framework is validated on a tissue-mimicking phantom with inclusions at varying depths.

## 2 Model Architecture

Our proposed EvidenceMoE framework is designed to jointly estimate the fluorescence probe depth and fluorescence lifetime directly from raw time-resolved fluorescence image sequences. The framework targets biological samples in which the fluorescent inclusion is located at depths of 1–5 mm beneath the tissue surface. Subsequent subsections will provide descriptions of the specialized expert networks, the Evidence-Based Dirichlet Critics (EDCs), and the Decider network.

### 2.1 High-Level Overview and Signal Flow

EvidenceMoE model, illustrated in Figure 1 (c), processes an input time-resolved fluorescence images through a sequence of specialized, interconnected modules. Each input signal is represented as a vector $\mathbf{x} \in \mathbb{R}^L$, where $L$ denotes the total number of discrete time bins capturing the temporal distribution of detected photons for the respective pixel.

**Expert pathways** The framework utilizes three parallel expert pathways, each tailored to different aspects of the signal: (1) an Early Expert $E_e$, (2) a Late Expert $E_l$, and (3) a Global Expert $E_g$. Each pathway is specialized to extract information from distinct temporal regions of the fluorescence decay and to produce auxiliary predictions.

**Critic pathways** Each expert is paired with a dedicated critic that evaluates the reliability of the expert's auxiliary prediction, quantifies uncertainty, and generates a corrective residual, to account for the stochasticity inherent in photon transport and signal noise in scattering media.

**Decider network** The final module adaptively fuses corrected expert predictions, critic-derived quality scores, and global contextual features of entire signal into a single robust estimate of fluorescence depth and lifetime.

### 2.2 Physics-Guided Mixture-of-Experts: Temporal Specialization

Our proposed MoE architecture leverages the understanding that early-arriving photons in the FLiDAR images are predominantly correlated with the target depth, whereas the decay characteristics

of the later portion of the time-resolved images are more significantly influenced by the material's intrinsic fluorescence lifetime. Consequently, each expert network processes a designated portion of the input (cf. Figure 1(b)).

**Architecture details** Each expert shares a common backbone, as detailed in Appendix C: 1D convolutional layers to capture local temporal features, a transformer encoder to model long-range dependencies, an attention pooling mechanism to extract a compact feature vector $\phi_k \in \mathbb{R}^H$, and multi-layer perceptron (MLP) head generates the final prediction $y_{\text{aux},k}$.

### 2.3 Evidence-Based Dirichlet Critics (EDCs)

Each EDC is paired with a specific expert and receives a rich input representation that includes both the expert's pooled internal feature vector and its auxiliary prediction. These are concatenated into a single input vector, allowing the critic to consider both the latent activations and initial predictions when evaluating reliability.

**Architecture details.** Given an expert's pooled features and auxiliary prediction, concatenated as $z_k = \text{concat}(\phi_k, y_{\text{aux},k})$ where $z_k \in \mathbb{R}^{H+D_k}$, the critic applies a shared MLP backbone followed by two heads. The first, an *evidence head*, that estimates the parameters $\{\alpha_{k,d}, \beta_{k,d}\}$ of independent Beta distributions, modeling the uncertainty associated with each output dimension. The second, a *correction head*, produces a residual vector $\Delta_k \in \mathbb{R}^{D_k}$, which is used to refine the expert's auxiliary output.

**Critic score.** In the absence of direct supervision, training the evidence head requires a proxy for an expert's prediction quality. For each dimension $d$, the target score is given by

$$q_{k,d}^{\text{target}} = \frac{1}{1 + \kappa \cdot \text{MAE}_{k,d}} \quad \text{with} \quad \text{MAE}_{k,d} = \frac{1}{N} \sum_{i=1}^{N} \left| y_{aux,k,d}^{(i)} - y_{true,k,d}^{(i)} \right|, \tag{1}$$

where $N$ represents the batch size and $\kappa$ is a scaling hyperparameter controlling sensitivity. This formulation enables the critic to learn a continuous notion of reliability directly grounded in the expert's observed performance.

## 3 Decider Network: Adaptive and Informed Fusion

The Decider architecture ($F$, parameterized by $\theta_F$), illustrated in Figure 1 (c), consists of a gating mechanism and a fusion layer.

**Architecture details.** The network employs a gating mechanism that assigns dynamic weights to the early, late, and global experts through a two-layer MLP with sigmoid activation: $w = \sigma(W_{g2} \cdot \text{ReLU}(W_{g1} u_{\text{gate}} + b_{g1}) + b_{g2})$, where $(W_{g1}, b_{g1}, W_{g2}, b_{g2})$ are learnable parameters within $F$ that determine the relative influence of each expert branch. The gated expert contributions are computed as $y_{\text{gated}} = [y_{\text{aux},e} \cdot w_e, y_{\text{aux},l} \cdot w_l, y_{\text{aux},g,d} \cdot w_g, y_{\text{aux},g,l} \cdot w_g] \in \mathbb{R}^{D_{\text{experts}}}$ and concatenated with the decider feature $\phi_g$. This combined vector is passed through a linear fusion layer to produce the raw 2D output: $y_{raw} = H_{\text{fus}}(\text{concat}(y_{\text{gated}}, \phi_g); \theta_F)$. Finally, the raw output $y_{\text{raw}}$ is transformed via a $\tanh$ activation to yield the final predictions for depth $y_d$ and fluorescence lifetime $y_l$.

## 4 Empirical Studies

This section details empirical validation of the EvidenceMoE framework, highlighting the critical role of physics-guided temporal segmentation for accurate depth and lifetime measurement while managing photon stochasticity using EDCs. We evaluate the framework using both simulated datasets and experimental phantom data. For simulation studies, datasets were partitioned into 80% training, 20% validation, and 100 test samples. Data generation is explained in detail in Appendix D, briefly to generate realistic FLiDAR data, we leveraged Monte Carlo (MC) simulation, a robust methodology for simulating photon transport in scattering biological tissues (18; 19), using the Monte Carlo eXtreme (MCX) tool (19) following established workflows (20; 21; 22).

**Performance of the Full EvidenceMoE Framework** In the evaluation of our proposed EvidenceMoE model, we set the hyperparameter $\kappa = 2$ (see Equation 1) while training the EDCs. This parameter influences how prediction errors are translated into the target quality scores that the EDCs learn to predict. Our choice of $\kappa = 2$ was made to ensure a balanced and interpretable relationship between error and quality, where, for example, a 20% prediction error yields around a 70% quality score. As reported in Table 2 (row *Full model ($\kappa = 2$)*), this framework demonstrates strong performance.

The accuracy of these estimations is further illustrated in Figure 2, demonstrating lifetime predictions (Figure 2 b) exhibit high precision, closely aligning with the ground truth. While depth predictions (Figure 2 a) also show strong agreement, they display a slightly larger spread compared to lifetime; yet, the maximum depth errors remain small, around 0.07 cm (0.7 mm), indicating a high degree of accuracy. Notably, the predicted depth quality scores (Figure 2 c) average around 95%, while the lifetime quality scores (Figure 2 d) average around 96.5%. This observation suggests the slightly higher quality scores for lifetime correspond with its marginally better predictive precision compared to depth, underscoring the utility of the EDC-generated quality scores in reflecting prediction reliability. Beyond overall performance metrics, we conduct targeted evaluations and ablation studies (see subsection D.3) to validate that each architectural component performs its intended function according to our design principles.

**Leveraging Prior Knowledge from Physics for Expert Assignment** The physics-guided design assigns each expert to distinct temporal segments of the FLiDAR signal: the Early expert focuses on initial photon arrivals (depth), while the Late Expert targets later decay characteristics (lifetime). Attention maps from each expert, visualized in Figure 3, confirm this specialization: the depth focused expert emphasizes the signal's rising edge, while the fluorescence lifetime focused expert concentrates on the falling edge, validating that each expert captures specific features relevant to its task.

**The Challenge of Stochasticity** Accurate parameter estimation from FLiDAR signals in scattering media is complicated by the inherent stochasticity of photon transport, which introduces significant noise and variability. To explicitly account for the varying uncertainty in the expert output, heteroscedastic loss was also used in isolated experts, our results (Table 2, *Heteroscedastic experts only*) show that this approach converges more slowly, requiring ∼500 epochs versus 70 for EvidenceMoE, and yields lower performance on depth estimation (D.NRMSE: 0.036 vs. 0.030). This demonstrates that, without dynamic expert assessment and fusion, basic uncertainty prediction alone is insufficient to address the intricacies of FLiDAR signal analysis, motivating our more comprehensive EvidenceMoE architecture.

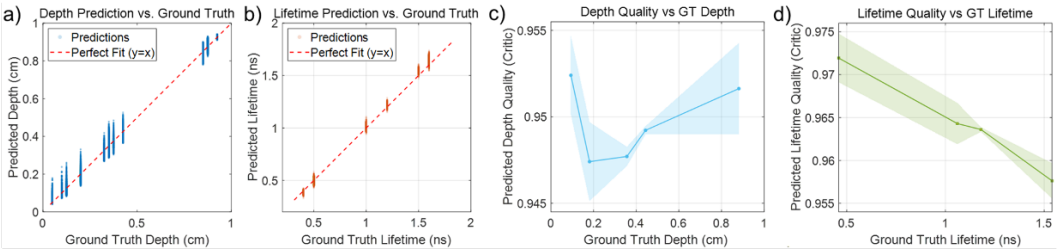


Figure 2: Performance results of EvidenceMoE model

**Experimental Validation** To bridge the gap between simulation and real-world application, we conducted experimental validation using a tissue-mimicking phantom The phantom was fabricated from 1% agar to replicate tissue structure, with intralipid incorporated to induce scattering properties analogous to biological tissue. Five capillary tubes, filled with a 10 µM concentration of the near-infrared fluorophore Alexa Fluor 700 (AF700), were embedded within the phantom. The tubes were arranged in a stepwise depth configuration, with each subsequent tube placed 1 $mm$ deeper than the last, creating a controlled ground truth for depth assessment as shown in Figure 1 (d). Our model achieved depth estimation errors $\leq 0.09$ cm and lifetime errors $\leq 0.13$ ns across all inclusions (Table 1). Using optical coherence tomography (OCT) as a validation benchmark for depth, we confirmed that our method could localize all five buried inclusions, whereas OCT itself visualized only the shallowest target within it's limit of 2mm resolution in highly scattering media.

**Implementation for Real-Time Inference** To evaluate its clinical feasibility, the EvidenceMoE framework was benchmarked on an NVIDIA H100 GPU with 80GB of HBM3 memory. The model processed a full 500×250 pixel frame in 1.375 seconds. Crucially, practical applications like tumor imaging often focus on a smaller region of interest (approximately 1/4 of the total field of view), which reduces latency to a sub-second timeframe suitable for near real-time feedback. This performance confirms a viable pathway for deploying the framework on dedicated hardware to support low-latency, uncertainty-aware surgical guidance.

| Tube Number | Predicted Depth | Actual Depth | Lifetime* |
|---|---|---|---|
| 1 | 0.11 cm $\pm$ 0.05 | 0.09 cm | 0.87 ns $\pm$ 0.03 |
| 2 | 0.18 cm $\pm$ 0.06 | 0.17 cm | 0.87 ns $\pm$ 0.02 |
| 3 | 0.26 cm $\pm$ 0.08 | 0.27 cm | 0.87 ns $\pm$ 0.02 |
| 4 | 0.37 cm $\pm$ 0.09 | 0.37 cm | 0.88 ns $\pm$ 0.03 |
| 5 | 0.53 cm $\pm$ 0.11 | 0.47 cm | 0.88 ns $\pm$ 0.06 |

*While the manufacturer's reported lifetime for Alexa Fluor 700 dye is $\approx$ 1 ns in solution (23), in scattering media, with a traditional least squares solver estimating it at 0.9 ns.

Table 1: Experimental validation results of EvidenceMoE framework on tissue-mimicking phantom with stepwise depth configuration.

## 5 Conclusion and Discussion

In this work, we introduced EvidenceMoE, a Mixture-of-Experts architecture that integrates physics-based prior knowledge with sequential data learning for time-resolved fluorescence imaging. Through ablation studies and validation on both Monte Carlo simulations and tissue-mimicking phantom experiments, we showed that EvidenceMoE achieves accurate depth and lifetime estimation. Notably, it could locate fluorescence probes at depths up to 5 mm in experimental scattering media, surpassing the $\approx 2mm$ limit of established optical methods such as Optical Coherence Tomography. These results highlight the clinical translation potential of EvidenceMoE for fluorescence-guided surgery, where precise depth and molecular information are essential for reliable tumor delineation and resection. In a nutshell, EvidenceMoE combines photophysics knowledge with Mixture-of-Experts learning to deliver accurate depth and lifetime estimates in time-resolved fluorescence imaging, enabling clinically translatable guidance. Moving forward, we will extend our study to *ex vivo* and *in vivo* samples to capture the complexity of biological tissues, and pursue embedded hardware implementations to satisfy real-time surgical constraints. This work represents a step toward depth-resolved, lifetime-enabled fluorescence imaging in the operating room, bridging physics, machine learning, and clinical needs.

## Acknowledgments and Disclosure of Funding

This work was supported by IBM through the IBM-Rensselaer Future of Computing Research Collaboration. The authors thank Professor Edoardo Charbon and the AQUA Lab for providing the state-of-art SwissSPAD cameras.

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# A Principles of Time-Resolved FLiDAR, Photon Scattering, and Fluorescence Lifetime

Fluorescence LiDAR (FLiDAR) is a specialized technique that extends LiDAR capabilities by analyzing light-induced fluorescence in scattering media, where LiDAR performance degrades by photon scattering. When photons from the laser pulse are absorbed by specific molecules (fluorophores) within the target material, these molecules transition to an excited electronic state. They subsequently relax to their ground state, partly by emitting photons, a process known as *fluorescence* (24; 7; 5). Time-resolved camera systems are designed to detect and temporally resolve this fluorescence emission. The characteristic rate at which the fluorescence intensity declines after excitation follows an exponential curve, and is termed the *fluorescence lifetime* ($\tau$). This lifetime is an intrinsic property of the fluorophore and is sensitive to its local chemical and structural environment (7; 24). Consequently, fluorescence lifetime serves as a useful contrast parameter with applications in biomedical diagnostics to differentiate tissue states (such as healthy or cancerous tissue (25)) or in environmental science for vegetation analysis (26).

Accurately retrieving depth and fluorescence lifetime using FLiDAR in scattering media presents distinct challenges. Firstly, the laser pulse for excitation and basic ranging experiences scattering en route to the target (27; 28). Secondly, photons that are emitted by the target fluorophores will also propagate through the scattering medium to reach the time-resolved camera. During this transit, these fluorescence photons are subject to similar scattering processes. This additional scattering means that the temporal profile of the fluorescence decay, as recorded by the detector, is not solely governed by the intrinsic fluorescence lifetime of the molecule. Instead, the observed decay profile becomes a convolution of the intrinsic exponential decay with the temporal dispersion effects introduced by photon scattering within the medium.

Therefore, the signal acquired by FLiDAR in such conditions is a composite, reflecting both the target's range and its fluorescence decay properties, each distorted by scattering. Disentangling these convolved effects to estimate the true depth and the intrinsic fluorescence lifetime accurately requires sophisticated signal processing. Despite these complexities, specific temporal characteristics of the signal provide differential information:

- **Early photons:** Early-arriving photons to the time-resolved camera, having statistically undergone fewer scattering events, correlate more strongly with the shortest path length to the target, thus primarily encoding depth information (15).
- **Late photons:** The decay characteristics of the later portion of the signal are more significantly influenced by the fluorescence lifetime.

# B Background and Related Work

Our proposed framework integrates concepts from Mixture-of-Experts, uncertainty quantification, and evidential reasoning, all applied to the specific challenges of interpreting time-resolved FLiDAR images from scattering media. We briefly review these foundational areas and position our contributions within their context.

## B.1 Physics-Guided Inductive Biases for FLiDAR Temporal Segmentation

With a finite training set, a model's ability to generalize to new inputs depends on the preferences or assumptions it encodes, its inductive biases, which narrow the set of solutions consistent with the observed data(29). These inductive biases are the inherent assumptions within a model architecture that guide its learning process and ability to generalize from finite data (30). For complex data such as FLiDAR images from scattering media, where distinct temporal segments like early and late photon arrivals convey different physical information (15), the choice of inductive bias substantially impacts learning outcomes. An effective inductive bias guides the learning algorithm by incorporating domain knowledge about the signal, such as by structuring the model to process these physically meaningful segments differentially. This targeted approach constrains the hypothesis space, directing the model to focus on relevant features and relationships that align with known physical principles. Consequently, such guidance can lead to more efficient model training, including faster convergence and improved sample efficiency, as the model is steered away from learning spurious correlations, such as noise, ultimately enhancing its ability to interpret the underlying signal characteristics.

### B.2 Mixture-of-Experts (MoE)

Mixture-of-Experts (MoE) models (31; 32) implement a divide-and-conquer strategy by routing each input to a small subset of expert subnetworks via a gating network. In MoE, the gate selects experts through sparse routing to balance computation across the model. This paradigm has been applied to both multi-representation sensing and temporal forecasting. In LiMoE, features from range images, voxels, and point clouds are fused through an MoE layer for LiDAR perception in air (33). ME-ODAL applies MoE routing to 3D object detection in point clouds (34). Across these applications, expert specialization, where each expert learns a distinct function or handles a particular data subset, underpins model behavior (32).

Existing temporal MoE methods process each sequence holistically, relying on auxiliary objectives (e.g., load balancing) to promote expert diversity and expecting the gate to infer segment relevance from raw inputs (35). Such approaches do not exploit known signal physics. Our Physics-guided MoE instead assigns one expert to each of the predefined temporal segments, reflecting the physics of photon transport. This segment-based assignment embeds an inductive bias: each expert models the dynamics specific to its interval.

### B.3 Limitations of Standard Uncertainty Quantification in Deep Learning

The challenging nature of FLiDAR-based parameter estimation in scattering media, stemming from distorted and convolved signals, elevates the importance of providing reliable uncertainty estimates alongside deep learning predictions. Common approaches of uncertainty estimation include Monte Carlo Dropout (36), Deep Ensembles (37), and Bayesian Neural Networks (BNNs) (38). While effective, these methods can suffer from limitations (39): MC Dropout's estimates may not always be well-calibrated; Deep Ensembles incur significant computational overhead during training and inference (37); and approximate inference in BNNs can be complex to implement and tune (40). Furthermore, these methods primarily capture aleatoric (data) uncertainty or epistemic (model) uncertainty (41; 42), but do not explicitly model the quality of a specific prediction based on input evidence and do not provide correction signals based on the uncertainty.

### B.4 Evidential Deep Learning

Evidential Deep Learning (EDL) trains a deterministic network, for example, a stack of standard MLP layers, to output the parameters of a higher-order evidential distribution, rather than placing priors on weights as in BNNs with Bayesian layers (43; 44). Training of EDL models generally relies on loss functions that combine a negative log-likelihood term with regularizers (e.g. KL divergence to a noninformative prior or evidence penalties). Our Evidence-Based Dirichlet Critic (EDC) module acts as an evaluator for each expert. Inspired by actor-critic frameworks in reinforcement learning (45), though adapted for supervised regression, the critic assesses the actor's (expert's) output.

## C Detailed Model Architecture for Reproducibility

### C.1 Physics-Guided Mixture-of-Experts

Each expert ($E_k$) $k \in \{e, l, g\}$, parameterized by $\theta_E = \{\theta_{E_e}, \theta_{E_l}, \theta_{E_g}\}$, shares a common internal architecture optimized for feature extraction, consisting of three main stages:

1. **Hybrid CNN-Transformer Encoder:** The input segment $x_k \in \mathbb{R}^{L_k}$ is initially processed by a sequence of 1D convolutional layers (kernel size $K$, with residual connections, Layer Normalization, and GELU activation). This allows the network to explicitly capture localized characteristics of the time resolved signal, such as:
   - The sharpness and timing of the initial rising edge related to photon arrival time (depth).
   - Local decay rates or changes in slope within short segments of the fluorescence tail (lifetime).
   - The presence and shape of small secondary peaks or instrumental response function artifacts within the window.

   This extraction of local waveform motifs precedes the subsequent components. The output of the CNN block is then augmented with sinusoidal Positional Encoding before being passed to a multi-layer Transformer encoder. The Transformer utilizes self-attention mechanisms to model long-range temporal dependencies and contextual relationships across the entire input segment $\mathbf{x}_k$. The encoder outputs a sequence of refined feature vectors $h_k^{enc} \in \mathbb{R}^{L_k \times H}$, where $H$ is the hidden dimension size.

2. **Pooling Layer ($f_k$):** To obtain a fixed-size representation from the variable-length output sequence of the encoder, an Attention Pooling mechanism is employed. This layer learns attention weights over the time steps of $h_k^{enc}$ and computes a weighted sum, producing a single feature vector $\phi_k \in \mathbb{R}^H$. This vector summarizes the relevant information from the expert's input segment.

$$\phi_k = \text{AttentionPool}(h_k^{enc}; \theta_{E_k}) \tag{2}$$

3. **Auxiliary Prediction Head ($h_k$):** A small Multi-Layer Perceptron (MLP) with non-linear activation ( ReLU) maps the pooled feature vector $\phi_k$ to the expert's specific auxiliary prediction $y_{aux,k}$ (dimension $D_k = 1$ for early/late, $D_k = 2$ for global).

$$y_{aux,k} = h_k(\phi_k; \theta_{E_k}) \tag{3}$$

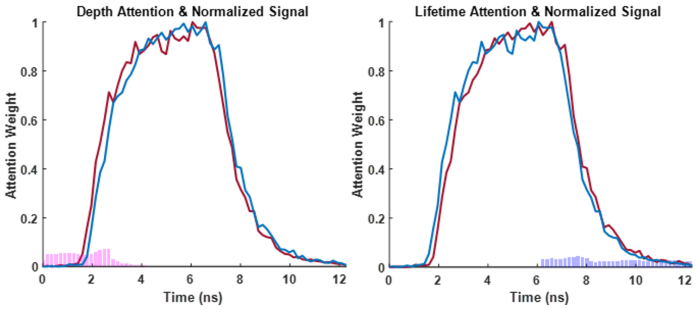


Figure 3: Visualization of Pooled Attention Weights Over Time for Both Depth and Lifetime Experts, Computed Over a Batch Size of 512.

**Role of Global Expert Features:** Beyond its auxiliary prediction $y_{aux,g}$, the pooled feature vector $\phi_g$ from the global expert serves a dual purpose. It acts as the primary source of global context for the downstream fusion mechanism within the Final Decider Head, informing the gating decisions.

### C.2 Evidence-Based Dirichlet Critics (EDC)

To assess the reliability of each expert's auxiliary prediction and provide a mechanism for refinement, we employ a dedicated critic network $C_k$ for each expert $k \in \{e, l, g\}$, parameterized by $\theta_C = \{\theta_{C_e}, \theta_{C_l}, \theta_{C_g}\}$. We adopt the Evidential Deep Learning (EDL) framework (44) to enable the critics to quantify uncertainty in their quality assessments.

**Critic Input Features:** To enable an informed reliability assessment by the critic $C_k$, we provide it with an input representation $z_k$. This input concatenates the pooled feature vector $\phi_k$ from the expert's encoder (Equation 2) with the expert's auxiliary prediction $y_{aux,k}$ (Equation 3):

$$z_k = \text{concat}(\phi_k, y_{aux,k}) \tag{4}$$

**Critic Architecture:** Each critic $C_k$ utilizes an identical architecture comprising a shared MLP backbone ($b_k$) followed by two separate linear heads:

1. **Shared Backbone ($b_k$):** The concatenated input $z_k$ is processed by a shared MLP backbone, $b_k$. A relatively shallow architecture (two layers) with moderate hidden dimensions [32, 16] is employed to keep the critic computationally lightweight while providing sufficient capacity to extract relevant features from the input $z_k$. The backbone outputs a shared latent feature representation $h_k \in \mathbb{R}^{16}$.

$$h_k = b_k(z_k; \theta_{C_k}) \tag{5}$$

2. **Evidence Head ($evi_k$):** A dedicated linear layer, $evi_k$, maps the shared features $h_k$ to the raw evidence outputs $e_k \in \mathbb{R}^{2 \times D_k}$ (one positive and one negative evidence value per output dimension $D_k$ of the corresponding expert).

$$e_k = evi_k(h_k; \theta_{C_k}) \tag{6}$$

To ensure the parameters of the resulting Beta/Dirichlet distribution are strictly positive and greater than one (required for a well-defined distribution and stable calculation of variance and KL divergence terms), the raw evidence is transformed using the $\text{softplus}(x) =$

$\log(1 + e^x)$ function followed by adding 1:

$$\alpha_{k,d} = \text{softplus}(e_{k,pos,d}) + 1 \tag{7}$$

$$\beta_{k,d} = \text{softplus}(e_{k,neg,d}) + 1 \tag{8}$$

For each dimension $d = 1..D_k$, where $e_{k,pos}$ and $e_{k,neg}$ are the corresponding slices of $e_k$. The resulting $\alpha_{k,d}, \beta_{k,d} > 1$ parameterize $D_k$ independent Beta distributions. The total evidence $S_{k,d} = \alpha_{k,d} + \beta_{k,d}$ represents the precision or concentration parameter of the distribution, quantifying the amount of evidence gathered from the data supporting the quality prediction; a higher $S_{k,d}$ indicates greater confidence (lower variance) in the quality estimate.

3. **Correction Head ($corr_k$):** A separate linear layer maps $h_k$ to the correction signal $\Delta_k \in \mathbb{R}^{D_k}$.

$$\Delta_k = corr_k(h_k; \theta_{C_k}) \tag{9}$$

The critic's forward pass thus yields $(\alpha_k, \beta_k, \Delta_k)$. The mean of the predicted Beta distribution serves as the point estimate for quality score $q_k$:

$$q_{k,d} = \frac{\alpha_{k,d}}{\alpha_{k,d} + \beta_{k,d}} \tag{10}$$

These mean quality scores (specifically $q_e, q_l$, and the two components of $q_g$, forming $q_{full} \in \mathbb{R}^4$) are utilized by the downstream decider head.

### C.3 Decider Network: Adaptive and Informed Fusion

To synthesize the multiple, quality-assessed predictions from the expert pathways into a unified estimation of depth and lifetime, the EvidenceMoE architecture incorporates a Decider network. The Decider architecture $F$, illustrated in Figure 1 (c) consists of a gating mechanism and a fusion layer.

**Gating mechanism for dynamic expert weighting** A core component of the Decider is a learned gating network $G$. The gate's decision $w$ is informed by a concatenation of the corrected auxiliary predictions, $u_{gate} = \text{concat}(y_{aux,k}, \phi_g, q_{full})$, the global decider feature, and the full quality scores $q_{full}$, a vector containing the mean quality scores derived from the EDCs for all relevant output dimensions of the experts. The gating network $G$ outputs gating weights, $w_e$, $w_l$, and $w_g$ for early, late, and global experts respectively.

$$w = \sigma(W_{g2} \cdot \text{ReLU}(W_{g1} u_{\text{gate}} + b_{g1}) + b_{g2}) \tag{11}$$

where $(W_{g1}, b_{g1}, W_{g2}, b_{g2})$ are learnable parameters within $F$. These weights determine the relative influence of each expert branch.

**Fusion and final prediction**

The gated expert contributions are concatenated with the decider feature $\phi_g$:

$$y_{\text{gated}} = [y_{\text{aux},e} \cdot w_e, y_{\text{aux},l} \cdot w_l, y_{\text{aux},g,d} \cdot w_g, y_{\text{aux},g,l} \cdot w_g] \in \mathbb{R}^{D_{\text{experts}}} \tag{12}$$

This vector of gated expert contributions, $y_{\text{gated}}$, is then concatenated with the $\phi_g$ and passed through a final fusion layer ($H_{fus}$), a linear layer, to produce the raw 2D output $y_{raw} \in \mathbb{R}^2$:

$$y_{raw} = H_{fus}(\text{concat}(y_{gated}, \phi_g); \theta_F) \tag{13}$$

Finally, this raw output $y_{raw}$ is transformed via an $\tanh$ activation to yield the final predictions for depth $y_d$ and fluorescence lifetime $y_l$.

### C.4 Decider Head and Fusion Mechanism

The final stage of the model is the Decider Head ($F$, parameterized by $\theta_F$), which performs a learned, context-aware fusion of the information streams originating from the three expert branches. This head utilizes a gating network ($G$) that processes the potentially corrected auxiliary predictions ($y_{aux,k}$), the critics' reliability estimates ($q_{full}$), and global contextual features ($\phi_g$) to compute dynamic, input-dependent weights ($w$) for each expert branch. These weighted expert contributions are then combined with the global context in a subsequent fusion layer ($H_{fus}$) to generate the final, refined 2D prediction $y_d, y_l$.

**Inputs to the Decider Head:** The head receives three primary inputs per sample:

1. **Corrected Auxiliary Predictions ($y_{aux}$):** This is the set of auxiliary predictions from the experts, adjusted by the correction signals provided by the critics (Equation 9), $y_{aux} = \{y_{aux,e} \in \mathbb{R}^1, y_{aux,l} \in \mathbb{R}^1, y_{aux,g} \in \mathbb{R}^2\}$.

2. **Decider Feature ($\phi_g$):** This is the pooled feature vector $\phi_g \in \mathbb{R}^H$ from the global expert's encoder (Equation 2).
3. **Full Quality Scores ($q_{full}$):** A vector containing the mean quality estimates derived from the Evidence Critics for all four quality dimensions: $q_{full} = [q_e, q_l, q_{g,d}, q_{g,l}] \in \mathbb{R}^4$ (Equation 10).

**Gating Network ($G$):** The core of the fusion mechanism is a learned gating network $G$, designed to adaptively weight the contributions of the three expert branches based on the specific input characteristics. The gate's decision is informed by the corrected predictions $y_{aux}$, the global context $\phi_g$, and the critics' full quality assessments $q_{full}$. The combined input $u_{gate}$ is defined as:

$$u_{gate} = \text{concat}(y_{aux,k}, \phi_g, q_{full}) \tag{14}$$

The gating network architecture consists of a two-layer MLP with a ReLU activation after the first layer and a final Sigmoid activation applied after the second layer (mapping to the 3 expert weights):

$$w = \sigma(W_{g2} \cdot \text{ReLU}(W_{g1} u_{gate} + b_{g1}) + b_{g2}) \tag{15}$$

where $\sigma(\cdot)$ is the Sigmoid function, and $(W_{g1}, b_{g1}, W_{g2}, b_{g2})$ are learnable parameters within $\theta_F$. Additionally, gating dropout may apply dropout to $w_g$ during training as a regularization technique.

**Applying Gates:** The gating weights $w$ modulate the corrected auxiliary predictions $y_{aux,k}$:

$$y_{gated,e} = y_{aux,e} \cdot w_e \tag{16}$$

$$y_{gated,l} = y_{aux,l} \cdot w_l \tag{17}$$

$$y_{gated,g} = y_{aux,g} \cdot w_g \tag{18}$$

**Fusion Layer ($H_{fus}$):** The gated expert contributions are concatenated with the decider feature $\phi_g$ and passed through a final linear fusion layer $H_{fus}$ to produce the raw 2D output $y_{raw}$:

$$y_{gated_concat} = [y_{gated,e}, y_{gated,l}, y_{gated,g}] \tag{19}$$

$$u_{fus} = [y_{gated_concat}, \phi_{decider_fus}] \tag{20}$$

$$y_{raw} = H_{fus}(u_{fus}; \theta_F) \tag{21}$$

# D Training Methodology

## D.1 Realistic Data Generation

For an AI model to perform reliably in real-world scenarios, especially in complex fields like medical imaging, it must be trained on data that closely mirrors experimental conditions. This section explains how we generated such realistic training data for our study on Fluorescence LiDAR (FLiDAR) in biological tissue. Our goal was to generate representative data that captures the nuances of how light travels through tissue and how our specific camera system detects it. The realistic data generation allows us to incorporate its experimentally determined Instrument Response Function (IRF), representing the system's intrinsic temporal response to a laser pulse, and its documented noise profile into our data generation process (46; 47).

This experimentally determined IRF represents the system's intrinsic temporal response to a laser pulse, and we incorporate system's documented noise profile into data generation flow. Using directly measured IRF is critical as it ensures that the temporal dispersion characteristics embedded in our simulated data faithfully replicate those of the imaging apparatus. Similarly, integrating the camera's documented noise profile is essential for ensuring that our simulations' stochastic variations and statistical fidelity of photon counts accurately reflect those of the physical sensor.

Furthermore, to realistically model the complex interactions of light within the tissue, we utilized Monte Carlo (MC) simulations, a well-established and robust methodology in biomedical optics for simulating photon transport in scattering media (18; 19). Our simulations were performed using Monte Carlo eXtreme (MCX) (19), adopting a two-stage approach to generate time-resolved fluorescence signals. The MC data generation workflow is further detailed in (20; 21). Moreover, given that the noise profile of the specific time-resolved camera was also characterized and its parameters defined in the camera's documentation, we introduced these system-specific noises (photon (shot) noise, dark counts, afterpulsing, and read noise) into the `MCXLab`-generated signals. By applying these characterized noise sources to the initial MCX simulation outputs and utilizing the noise-free and noise-integrated datasets, our training and validation procedures are grounded in data that realistically reflect the detector's behavior.

### D.2 Loss Function

The model parameters, partitioned into expert ($\theta_E$), critic ($\theta_C$), and final head ($\theta_F$) groups, are concurrently trained by minimizing a composite, multi-component loss function $\mathcal{L}_{total}$. This loss function is designed to achieve several simultaneous objectives: optimizing the final prediction accuracy ($y_{pred}$), encouraging the experts to learn informative intermediate representations ($\phi_k$) and generate reasonable auxiliary predictions ($y_{aux,k}$), training the Evidence Critics to produce quality estimates (represented by $\alpha_k, \beta_k$) and correction signals ($\Delta_k$) that approximate the experts' scaled residual errors ($\Delta_k \approx (y_{true,k'} - y_{aux,k})/\lambda_{damp}$), and applying specific regularization terms (such as KL divergence for evidence and an evidence-weighted penalty for corrections). The overall loss is a weighted sum of these individual components:

$$\mathcal{L}_{total} = \lambda_{pri}\mathcal{L}_{primary} + \lambda_{aux}\mathcal{L}_{aux} + \lambda_{crit_q}\mathcal{L}_{quality} + \lambda_{corr}\mathcal{L}_{corr} + \lambda_{pen}\mathcal{L}_{penalty} \tag{22}$$

where the weights $\lambda_{(\cdot)}$ are scalar hyperparameters controlling the relative importance of each term, as defined in the configuration. Each loss component is detailed below.

**Primary Loss ($\mathcal{L}_{primary}$):** This is the main objective function driving the overall prediction task. It measures the discrepancy between the final fused prediction $y_{pred} \in \mathbb{R}^2$ and the ground truth $y_{true} \in \mathbb{R}^2$ (containing depth and lifetime). We use the Mean Absolute Error (L1 loss):

$$\mathcal{L}_{primary} = \mathrm{MAE}(y_{pred}, y_{true}) = \frac{1}{D_{out}} \sum_{j=1}^{D_{out}} \mathbb{E}_{\text{batch}} \left[ |y_{pred,j} - y_{true,j}| \right] \tag{23}$$

where $D_{out} = 2$ (depth and lifetime dimensions) and $\mathbb{E}_{\text{batch}}$ denotes the expectation (mean) over the batch samples.

**Auxiliary Loss ($\mathcal{L}_{aux}$):** To foster expert specialization and enhance training stability, an auxiliary loss term, $\mathcal{L}_{aux}$, provides direct supervision to each individual expert network $E_k$. This loss computes the L1 distance between the expert's auxiliary prediction ($y_{aux,e}$ for depth, $y_{aux,l}$ for lifetime, $y_{aux,g}$ for both) and the corresponding ground truth targets ($y_{true,k'}$). Enforcing this intermediate accuracy encourages each expert to learn representations directly relevant to its specific task domain (temporal segment and target variable).

$$\mathcal{L}_{aux} = \frac{1}{N_{exp}} \sum_{k \in \{e,l,g\}} \mathbb{E}_{\text{batch}}[\mathrm{L1}(y_{aux,k}, y_{true,k'})] \tag{24}$$

where $N_{exp} = 3$.

**Critic Quality Loss ($\mathcal{L}_{quality}$):** This loss component is responsible for training the evidence head parameters $(\alpha, \beta)$ of each Evidence Critic $C_k$. It employs the Evidential Deep Learning (EDL) formulation specifically to learn a calibrated predictive distribution (parameterized by $\alpha_k, \beta_k$) over the quality score associated with the corresponding expert's auxiliary prediction, $y_{aux,k}$. The training objective aims to align the mean of this predicted distribution, $q_k = \alpha_k/(\alpha_k + \beta_k)$, with a target quality score $q_{gt,k}$ derived from the expert's actual error (Equation 26), while simultaneously using the evidential variance and KL divergence terms (Equations 27, 28) to ensure the distribution's concentration (total evidence $S_k = \alpha_k + \beta_k$) reflects the true uncertainty or reliability. The target quality $q_{gt,k}$ is calculated using the $y_{aux,k}$:

$$MAE_{k,d} = \frac{1}{N} \sum_{i=1}^{N} \left| y_{aux,k,d}^{(i)} - y_{true,k,d}^{(i)} \right| \tag{25}$$

$$q_{gt,k,d} = (1 + \kappa \cdot \mathrm{MAE}_{k,d} + \epsilon)^{-1} \tag{26}$$

where $\kappa$ is the hyperparameter and $\epsilon$ prevents division by zero.

The quality loss combines the Evidential Regression loss ($\mathcal{L}_{evi}$) and a KL divergence regularizer ($\mathcal{L}_{KL}$), summed over the four quality dimensions $(k, d)$ corresponding to (early, depth), (late, lifetime),

(global, depth), (global, lifetime):

$$\mathcal{L}_{evi}(\alpha, \beta, q_{gt}) = \underbrace{(q_{gt} - \frac{\alpha}{\alpha+\beta+\epsilon})^2}_{\text{MSE Term}} + \underbrace{\frac{\alpha\beta}{(\alpha+\beta+\epsilon)^2(\alpha+\beta+1+\epsilon)}}_{\text{Variance Term}} \tag{27}$$

$$\begin{aligned}\mathcal{L}_{KL}(\alpha, \beta) &= \mathrm{KL}(\mathrm{Beta}(\alpha, \beta) || \,\mathrm{Beta}(1, 1)) \\ &= \mathrm{lgamma}(\alpha + \beta) - \mathrm{lgamma}(\alpha) - \mathrm{lgamma}(\beta) \\ &\quad + (\alpha - 1)(\digamma(\alpha) - \digamma(\alpha + \beta)) \\ &\quad + (\beta - 1)(\digamma(\beta) - \digamma(\alpha + \beta))\end{aligned} \tag{28}$$

$$\mathcal{L}_{quality} = \mathbb{E}_{\text{batch}} \left[ \sum_{k,d} \left( \mathcal{L}_{evi}(\alpha_{k,d}^{loss}, \beta_{k,d}^{loss}, q_{gt,k,d}) + \lambda_{KL} \max(0, \mathcal{L}_{KL}(\alpha_{k,d}^{loss}, \beta_{k,d}^{loss})) \right) \right] \tag{29}$$

The $\mathcal{L}_{evi}$ term drives the mean predicted quality towards the target while penalizing high confidence for incorrect predictions via the variance term. The $\mathcal{L}_{KL}$ term regularizes the learned distribution, preventing collapse and encouraging uncertainty quantification. Gradients from $\mathcal{L}_{quality}$ only update critic parameters $\theta_C$.

**Correction Loss ($\mathcal{L}_{corr}$):** This loss component trains the correction head of each critic $C_k$ to output a signal $\Delta_k$ (Equation 9) that aims to reduce the error in the expert's auxiliary prediction $y_{aux,k}$. Specifically, it minimizes the Huber loss between the damped corrected prediction ($y_{aux,k} + \lambda_{damp}\Delta_k$) and the ground truth target $y_{true,k'}$.

$$\mathcal{L}_{corr} = \mathbb{E}_{\text{batch}} \left[ \sum_{k \in \{e,l,g\}} \mathrm{Huber}(y_{aux,k} + \lambda_{damp}\Delta_k, y_{true,k'}) \right] \tag{30}$$

This loss is calculated using the auxiliary predictions $y_{aux,k}$ and correction signals $\Delta_k$ generated during the standard forward pass. Consequently, the gradients derived from $\mathcal{L}_{corr}$ backpropagate to update both the critic parameters $\theta_{C_k}$ (through $\Delta_k$) and the expert parameters $\theta_{E_k}$.

$$\mathcal{L}_{corr} = \frac{1}{N_{exp}} \sum_{k \in \{e,l,g\}} \mathbb{E}_{\text{batch}} \left[ \mathrm{Huber}(y_{aux,k} + \lambda_{damp}\Delta_k, y_{true,k'}) \right] \tag{31}$$

**Evidence Penalty Loss ($\mathcal{L}_{penalty}$):** To further regulate the correction mechanism and promote robustness, we use an evidence-weighted penalty term, $\mathcal{L}_{penalty}$. This loss component links the confidence of the critic's quality assessment (as measured by the total evidence $S_{k,d}^{loss} = \alpha_{k,d}^{loss} + \beta_{k,d}^{loss}$) to the magnitude of the correction signal $\Delta_k^{loss}$ it proposes. The rationale is to discourage the critic from making large adjustments to the expert's prediction when its own assessment of the expert's quality is uncertain (i.e., when the evidence $S$ is low). This is achieved by penalizing the squared L2 norm of the correction signal, inversely weighted by the total evidence:

$$\mathcal{L}_{penalty} = \mathbb{E}_{\text{batch}} \left[ \sum_{k,d} \gamma \frac{(\Delta_{k,d}^{loss})^2}{S_{k,d}^{loss} + \epsilon} \right] \tag{32}$$

where $\gamma$ is the hyperparameter, the sum is over the relevant output dimensions $(k, d)$, and $\epsilon$ ensures numerical stability. This loss is calculated using the parameters $\alpha^{loss}, \beta^{loss}, \Delta^{loss}$ derived from the critic inputs ($z_k^{loss}$), ensuring that its gradients only update the critic parameters $\theta_C$. This evidence-aware regularization encourages more cautious corrections under uncertainty compared to standard L2 regularization on $\Delta_k$ alone.

### D.2.1 Phased Training Strategy

A three-phased training strategy was utilized to stabilize training.

1. **Phase 1 (Expert Pretraining):** Initially, only the expert parameters ($E$) are trained for a set number of epochs ($N_1$). Here, the primary learning signal comes from the auxiliary loss $\mathcal{L}_{\text{aux}}$ (detailed in Appendix D) associated with each expert, while the critic ($C$) and decider ($F$) components remain frozen.
2. **Phase 2 (Critic and Decider Integration):** In the second phase, the expert parameters ($E$) are frozen. The critic ($C$) and decider ($F$) parameters are then trained for $N_2$ epochs, utilizing the full

Table 2: Ablation studies for proposed model.

| Configuration | D.NRMSE ↓ | D.AbsRel↓ | D.RMSE$_{\log}$ ↓ | L.NRMSE(f) ↓ | Q.Depth ↑ | Q.Life ↑ |
|---|---|---|---|---|---|---|
| Damping factor $d = 0.5$ | $0.032 \pm 0.009$ | $0.164 \pm 0.160$ | $0.170 \pm 0.150$ | $0.063 \pm 0.023$ | $0.954 \pm 0.001$ | $0.966 \pm 0.007$ |
| Damping factor $d = 1.0$ | $0.034 \pm 0.010$ | $0.202 \pm 0.240$ | $0.189 \pm 0.180$ | $0.058 \pm 0.018$ | $0.952 \pm 0.004$ | $0.966 \pm 0.006$ |
| Critic quality-loss $\lambda_{cq} = 4$ | $0.034 \pm 0.011$ | $0.150 \pm 0.120$ | $0.169 \pm 0.130$ | $0.071 \pm 0.022$ | $0.949 \pm 0.003$ | $0.962 \pm 0.009$ |
| Phased training (1 / 6) | $0.033 \pm 0.009$ | $0.171 \pm 0.180$ | $0.175 \pm 0.150$ | $0.064 \pm 0.014$ | $0.951 \pm 0.002$ | $0.964 \pm 0.008$ |
| Phased training (5 / 15) | $0.032 \pm 0.008$ | $0.153 \pm 0.130$ | $0.174 \pm 0.140$ | $\mathbf{0.058 \pm 0.010}$ | $0.951 \pm 0.003$ | $0.962 \pm 0.008$ |
| Phased training (3 / 8) | $0.034 \pm 0.009$ | $0.153 \pm 0.130$ | $0.166 \pm 0.130$ | $0.059 \pm 0.017$ | $0.952 \pm 0.002$ | $0.968 \pm 0.005$ |
| Phased training (10 / 10) | $0.036 \pm 0.013$ | $0.198 \pm 0.200$ | $0.383 \pm 0.520$ | $0.083 \pm 0.026$ | $0.949 \pm 0.000$ | $0.963 \pm 0.006$ |
| No evidential correction | $0.035 \pm 0.009$ | $0.206 \pm 0.240$ | $0.193 \pm 0.180$ | $0.063 \pm 0.018$ | $0.951 \pm 0.001$ | $0.964 \pm 0.007$ |
| No quality gating | $0.032 \pm 0.009$ | $0.143 \pm 0.110$ | $0.167 \pm 0.120$ | $0.074 \pm 0.028$ | $0.950 \pm 0.002$ | $0.963 \pm 0.009$ |
| No decider features | $0.032 \pm 0.006$ | $0.160 \pm 0.150$ | $0.172 \pm 0.140$ | $0.077 \pm 0.030$ | $0.947 \pm 0.001$ | $0.959 \pm 0.008$ |
| No decider fusion | $0.034 \pm 0.011$ | $0.181 \pm 0.180$ | $0.179 \pm 0.150$ | $0.059 \pm 0.015$ | $0.953 \pm 0.004$ | $0.965 \pm 0.006$ |
| No gating dropout | $0.033 \pm 0.007$ | $0.169 \pm 0.170$ | $0.171 \pm 0.150$ | $0.072 \pm 0.017$ | $0.951 \pm 0.001$ | $0.961 \pm 0.007$ |
| No phased training | $0.031 \pm 0.010$ | $0.145 \pm 0.120$ | $0.159 \pm 0.130$ | $0.063 \pm 0.023$ | $0.948 \pm 0.002$ | $0.964 \pm 0.008$ |
| Mean pooling | $0.036 \pm 0.010$ | $0.170 \pm 0.150$ | $0.174 \pm 0.140$ | $0.069 \pm 0.024$ | $0.949 \pm 0.006$ | $0.968 \pm 0.007$ |
| Heteroscedastic experts only | $0.036 \pm 0.011$ | $0.139 \pm 0.093$ | $0.164 \pm 0.110$ | $0.063 \pm 0.051$ | – | – |
| Full model ($\kappa = 2$) | $\mathbf{0.030 \pm 0.007}$ | $\mathbf{0.140 \pm 0.120}$ | $\mathbf{0.155 \pm 0.120}$ | $0.074 \pm 0.022$ | $0.950 \pm 0.003$ | $0.965 \pm 0.006$ |

composite loss $\mathcal{L}_{total}$ (detailed in Appendix D) to learn how to evaluate the pre-trained experts and fuse their outputs.

3. **Phase 3 (Joint Training):** Finally, all model parameters $(E, C, F)$ are jointly fine-tuned for the remaining $N_3$ epochs using the complete loss function $\mathcal{L}_{total}$. This phase incorporates a gradual unfreezing schedule for the expert learning rates.

The specific number of epochs allocated to each phase $(N_1, N_2, N_3)$ was subject to variation in some experiments, as further detailed in the ablation studies (Table 2).

### D.3 Ablation Studies

To evaluate the distinct contributions of its architectural elements and design choices, we conducted a series of ablation studies on the EvidenceMoE framework. These studies systematically assessed the impact of individual mechanisms on depth and lifetime estimation by creating model variants with specific components removed or altered. Key aspects investigated included the necessity of evidential correction, quality gating, decider features, and decider fusion. Additionally, we explored the influence of hyperparameter settings, phased training schedules, and pooling mechanisms. Each ablated configuration was evaluated on the same test dataset. Table 2 presents comprehensive ablation results for our primary model configuration with $\kappa = 2$, while Table 3 shows additional ablation studies conducted with $\kappa = 8$ to evaluate the sensitivity of our approach to this hyperparameter. The implementation of EvidenceMoE is publicly available on GitHub (48). [1].

Table 3: Ablation study for $\kappa = 8$.

| Configuration | D.NRMSE ↓ | D.AbsRel↓ | D.RMSE$_{\log}$ ↓ | L.NRMSE(f) ↓ | Q.Depth ↑ | Q.Life ↑ |
|---|---|---|---|---|---|---|
| Critic quality-loss $\lambda_{cq} = 4$ | $0.033 \pm 0.011$ | $0.146 \pm 0.110$ | $0.181 \pm 0.130$ | $0.058 \pm 0.012$ | $0.856 \pm 0.025$ | $0.900 \pm 0.034$ |
| No evidential correction | $0.036 \pm 0.015$ | $0.148 \pm 0.100$ | $0.182 \pm 0.130$ | $0.060 \pm 0.011$ | $0.859 \pm 0.012$ | $0.869 \pm 0.044$ |
| No quality gating | $0.033 \pm 0.010$ | $0.146 \pm 0.110$ | $0.176 \pm 0.130$ | $0.056 \pm 0.012$ | $0.868 \pm 0.024$ | $0.886 \pm 0.031$ |
| No decider features | $0.032 \pm 0.011$ | $0.146 \pm 0.110$ | $0.184 \pm 0.130$ | $0.067 \pm 0.025$ | $0.865 \pm 0.014$ | $0.892 \pm 0.037$ |
| No decider fusion | $0.035 \pm 0.013$ | $0.167 \pm 0.160$ | $0.182 \pm 0.140$ | $0.073 \pm 0.015$ | $0.828 \pm 0.020$ | $0.879 \pm 0.022$ |
| Uniform gating | $0.034 \pm 0.010$ | $0.157 \pm 0.120$ | $0.191 \pm 0.150$ | $0.066 \pm 0.018$ | $0.861 \pm 0.021$ | $0.879 \pm 0.034$ |
| No gating dropout | $0.041 \pm 0.014$ | $0.215 \pm 0.180$ | $0.373 \pm 0.400$ | $0.073 \pm 0.022$ | $0.865 \pm 0.015$ | $0.866 \pm 0.029$ |
| No phased training | $0.037 \pm 0.015$ | $0.181 \pm 0.150$ | $0.269 \pm 0.260$ | $0.076 \pm 0.021$ | $0.862 \pm 0.007$ | $0.890 \pm 0.037$ |
| Mean pooling | $0.034 \pm 0.009$ | $0.155 \pm 0.130$ | $0.173 \pm 0.130$ | $0.075 \pm 0.027$ | $0.818 \pm 0.069$ | $0.866 \pm 0.058$ |
| No auxiliary MAE | $0.037 \pm 0.014$ | $0.172 \pm 0.130$ | $0.234 \pm 0.180$ | $0.063 \pm 0.018$ | $0.850 \pm 0.009$ | $0.850 \pm 0.034$ |
| Model trained with ($\kappa = 8$) | $0.040 \pm 0.013$ | $0.216 \pm 0.230$ | $0.202 \pm 0.180$ | $\mathbf{0.055 \pm 0.011}$ | $0.857 \pm 0.023$ | $0.896 \pm 0.023$ |
| Full model ($\kappa = 2$) | $\mathbf{0.030 \pm 0.007}$ | $\mathbf{0.140 \pm 0.120}$ | $\mathbf{0.155 \pm 0.120}$ | $0.074 \pm 0.022$ | $0.950 \pm 0.003$ | $0.965 \pm 0.006$ |

[1] `https://github.com/ismailerbas/EvidenceMoE/blob/main/EvidenceMoE.ipynb`

## NeurIPS Paper Checklist

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

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