# Probabilistic Deep Learning with GammaTPC

## Low-Energy Electron-Track Imaging for a Liquid Argon Time-Projection Chamber Compton Telescope

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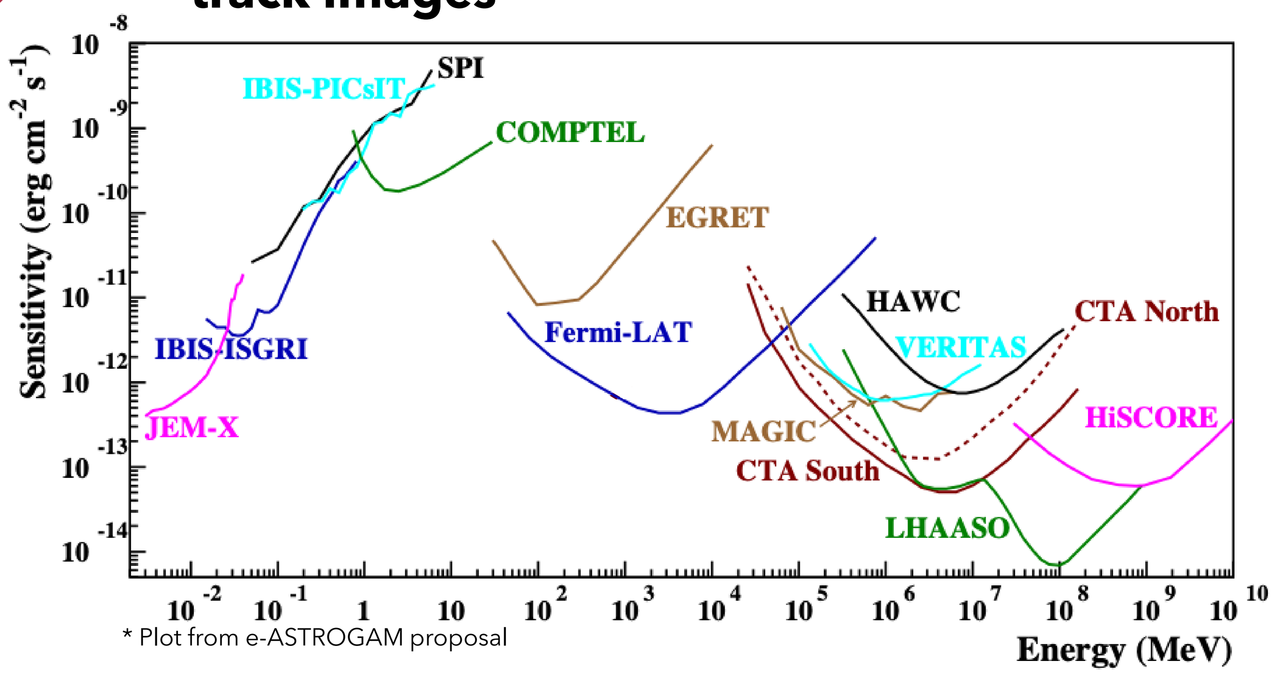
* Simulation/Analysis team only

## Science case for GammaTPC

- **0.5-50 MeV sky** is poorly measured
  - **Great opportunity** for new instrument
- Measure **galactic evolution** and **particle content**
  - Use **nuclear transition lines**
- Identify **transient sources**
  - In synchrony with gravitational waves for **multi-messenger astronomy**
- **Catalog steady sources**

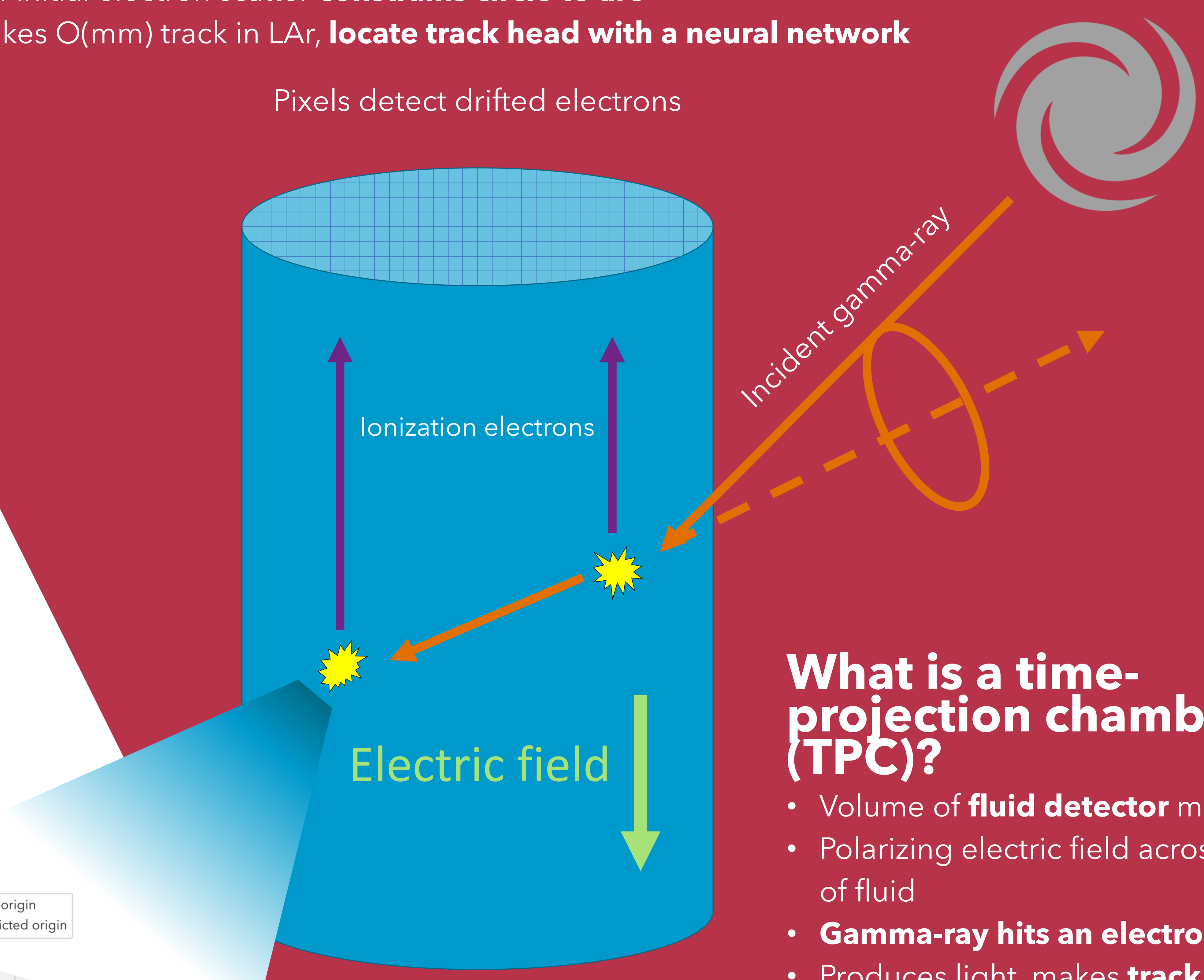
## Technical Goals

- **1000x sensitivity improvement** over COMPTEL
- Factor of **$10^5$ increase in known sources**
- **Precisely reconstruct** electron scatters from **track images**




## How to find a gamma-ray source with a TPC

- **Location** of two scatters + **energy** deposited in first scatter constrains gamma-ray origin to **circle on sky**
- **Direction** of initial electron scatter **constrains circle to arc**
- Electron makes O(mm) track in LAr, **locate track head with a neural network**



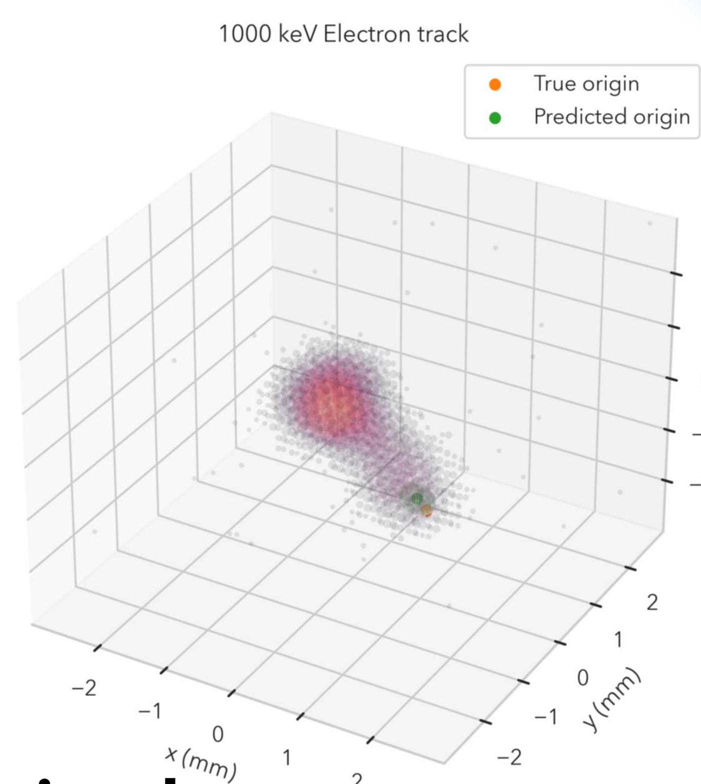

## What is a time-projection chamber (TPC)?

- Volume of **fluid detector** material
- Polarizing electric field across extent of fluid
- **Gamma-ray hits an electron**
- Produces light, makes **track of ionized electrons**

- **Light** immediately detected, **gives time** of interaction
- **Ionization electrons drift** to end of detector, **collected with pixels**
  - **Energy** of scatter **measured** directly from light and charge
    - **Pixel samples create 3D image** of electron track, enabling pos./dir. reconstruction

## Project design

- **This project is purely for track analysis**
  - Hardware/electronics design happening in parallel
- Proof of **DL technique** to **reconstruct electron track head** and **initial direction**
- Proof of **DL technique** to **estimate uncertainty**
- **Evaluate performance** on gamma-ray sources from industry-standard MEGAlib simulator

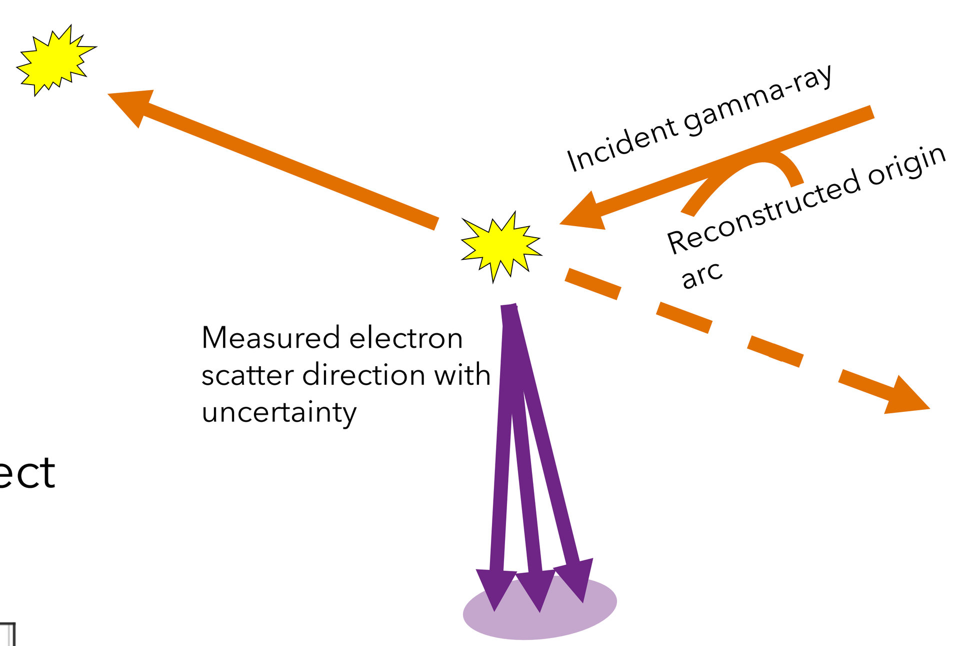


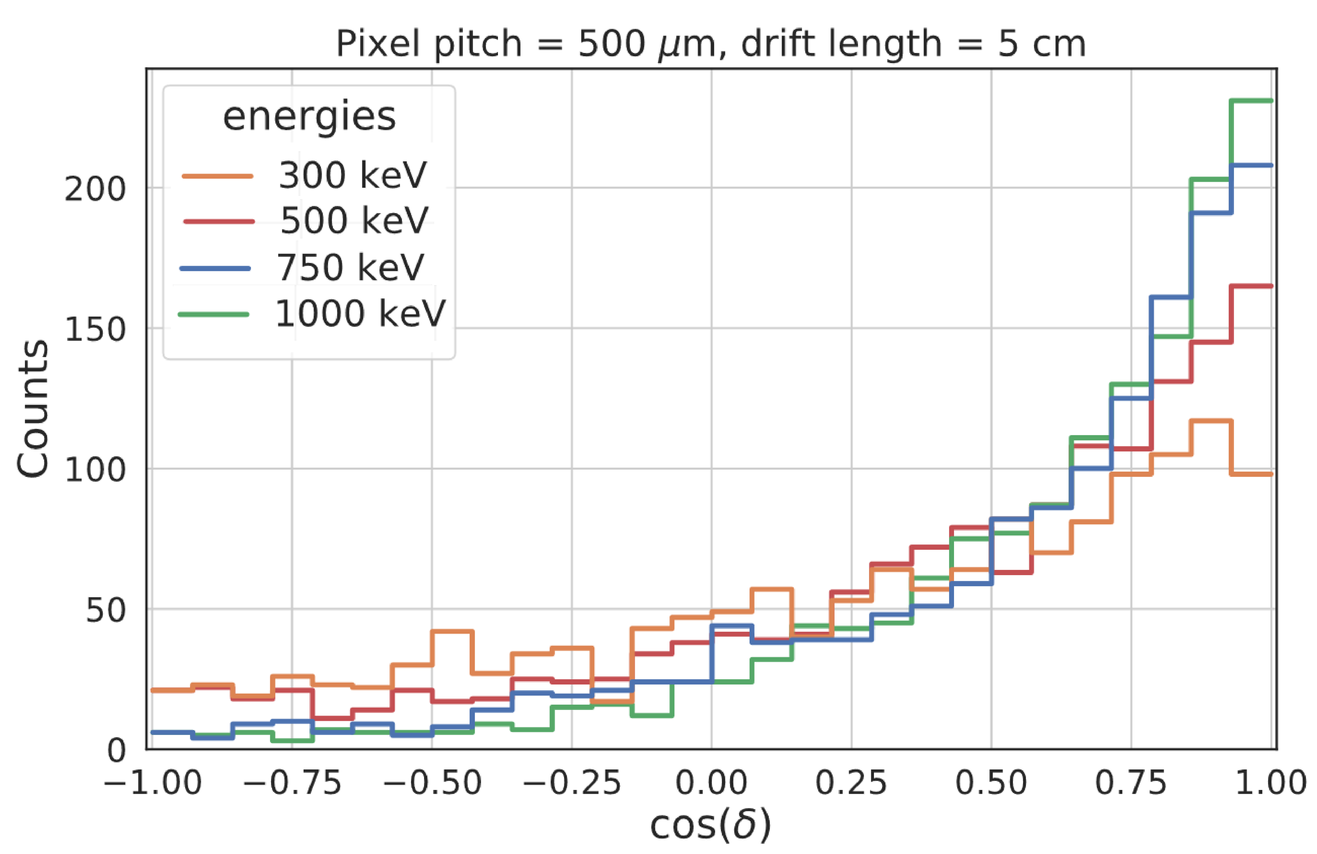

**Example electron track**

- Small colored **circles** → **charge** collected
- **Ellipse** around predicted origin → **prediction uncertainty**

## Direction reconstruction with a convolutional neural network (CNN)

- **Perfect measurement of initial electron scatter** completely determines kinematics
  - **Points directly to gamma-ray source**
- In practice, there is **uncertainty in measurement**
  - **Constrains** reconstructed source **circle to arc**
- Use **3D CNN** to **reconstruct initial direction**
  - Does not provide uncertainty estimation: future project

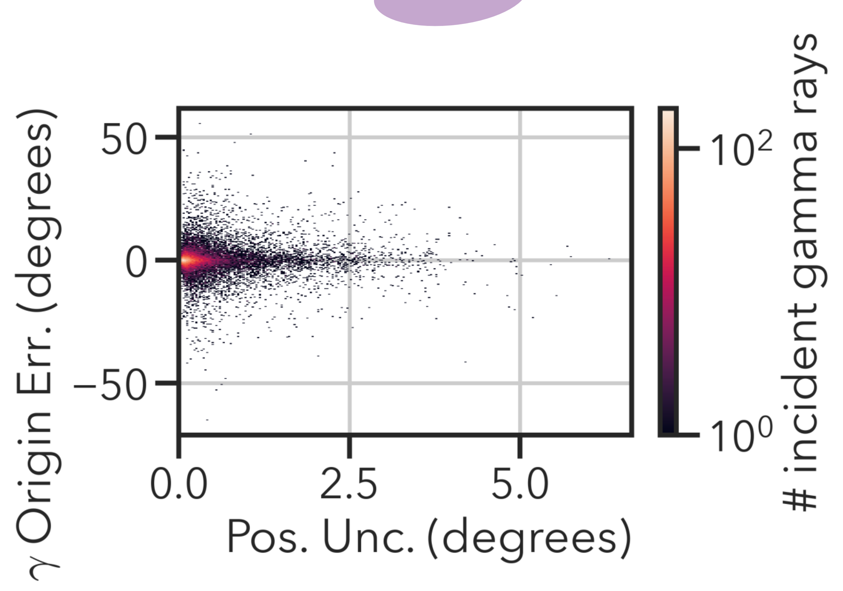



- **Figure of merit:** Cosine of angle between true and reconstructed gamma-ray origin
- **Perfect reconstruction at cos(δ) = 1**, flat distribution → no power
- Distribution is peaked near cos(δ) = 1 → **e⁻ scatter directions are** generally **reconstructed correctly!**

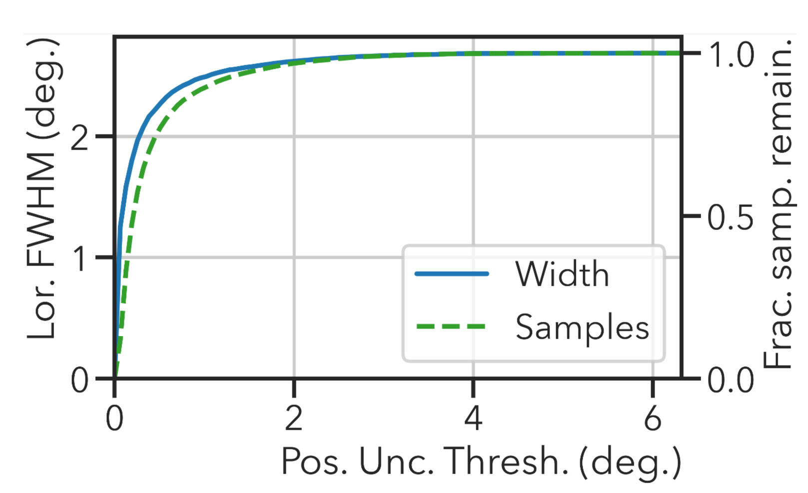
## Position reconstruction with Evidential Deep Learning

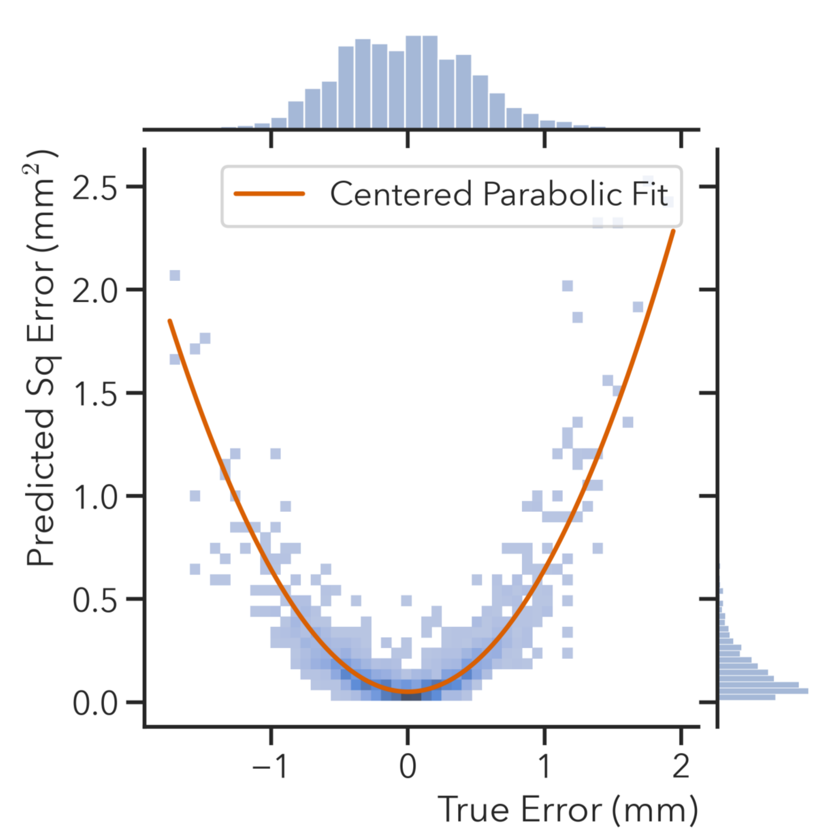
- Neural networks can be trained to maximize **Gaussian likelihood**
  - Does not give prediction uncertainty
- Place **normal inverse-gamma prior** over Gaussian parameters
- Maximize **"model evidence"**
  - Bayesian posterior marginalized over likelihood parameters
- **Posterior mean/std. dev.** for normal component give **prediction/uncertainty**




## We achieve accurate position and uncertainty predictions

- **Below right:** True error and predicted squared error follow **parabolic relationship**
- **Left:** Pointing error vs. uncertainty in e⁻ scatter position
  - Y-projection is ~Lorentz
  - **Below left:** Lorentz FWHM shrinks as threshold on position uncertainty is applied
  - Can **use uncertainty** estimation to **improve pointing!**

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**Paper posted to arXiv soon!**