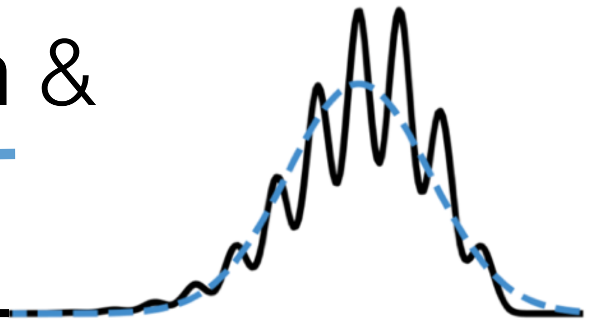
Novel detector response modelling

High pileup event reconstruction &



Single photon statistics

in cryogenic scintillating calorimeters

Philipp Schreiner

Zaragoza, June 1st, 2026

IDM2026
ZARAGOZA

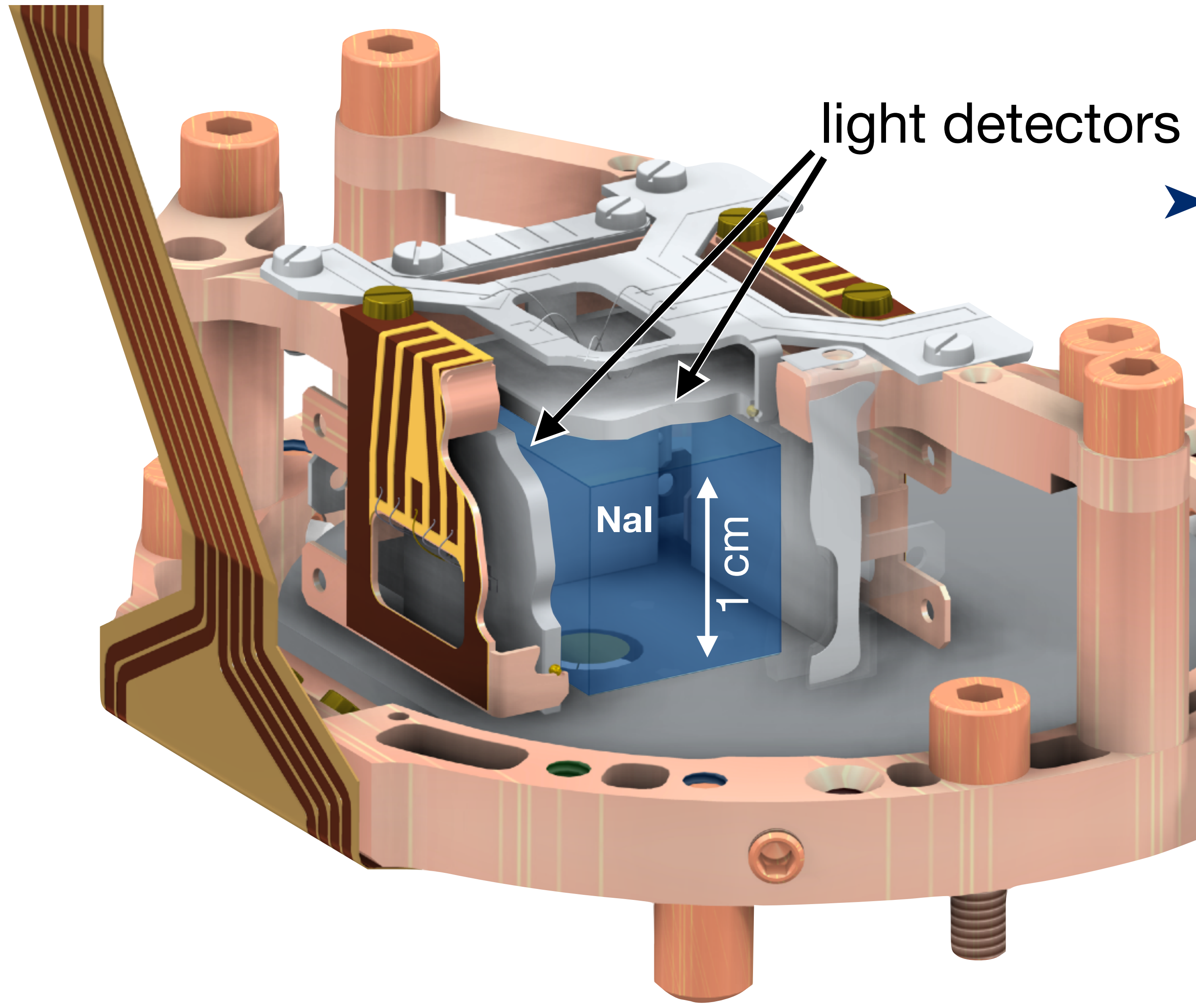
COSINUS

Cryogenic **O**bservatory for **SI**gnatures seen in **N**ext generation **U**nderground **S**earches

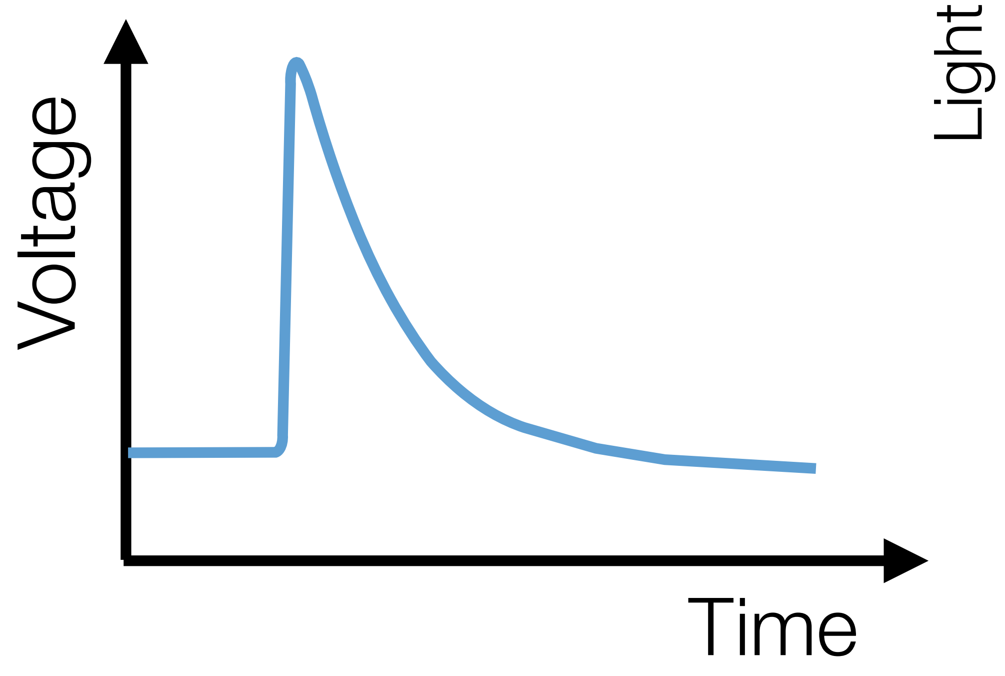
TECHNISCHE UNIVERSITÄT WIEN
MBI
G S S I
MAX-PLANCK-INSTITUT FÜR PHYSIK
HELSINKI INSTITUTE OF PHYSICS
INFN LNGS Istituto Nazionale di Fisica Nucleare Laboratori Nazionali del Gran Sasso
Since 1928 SICCAS

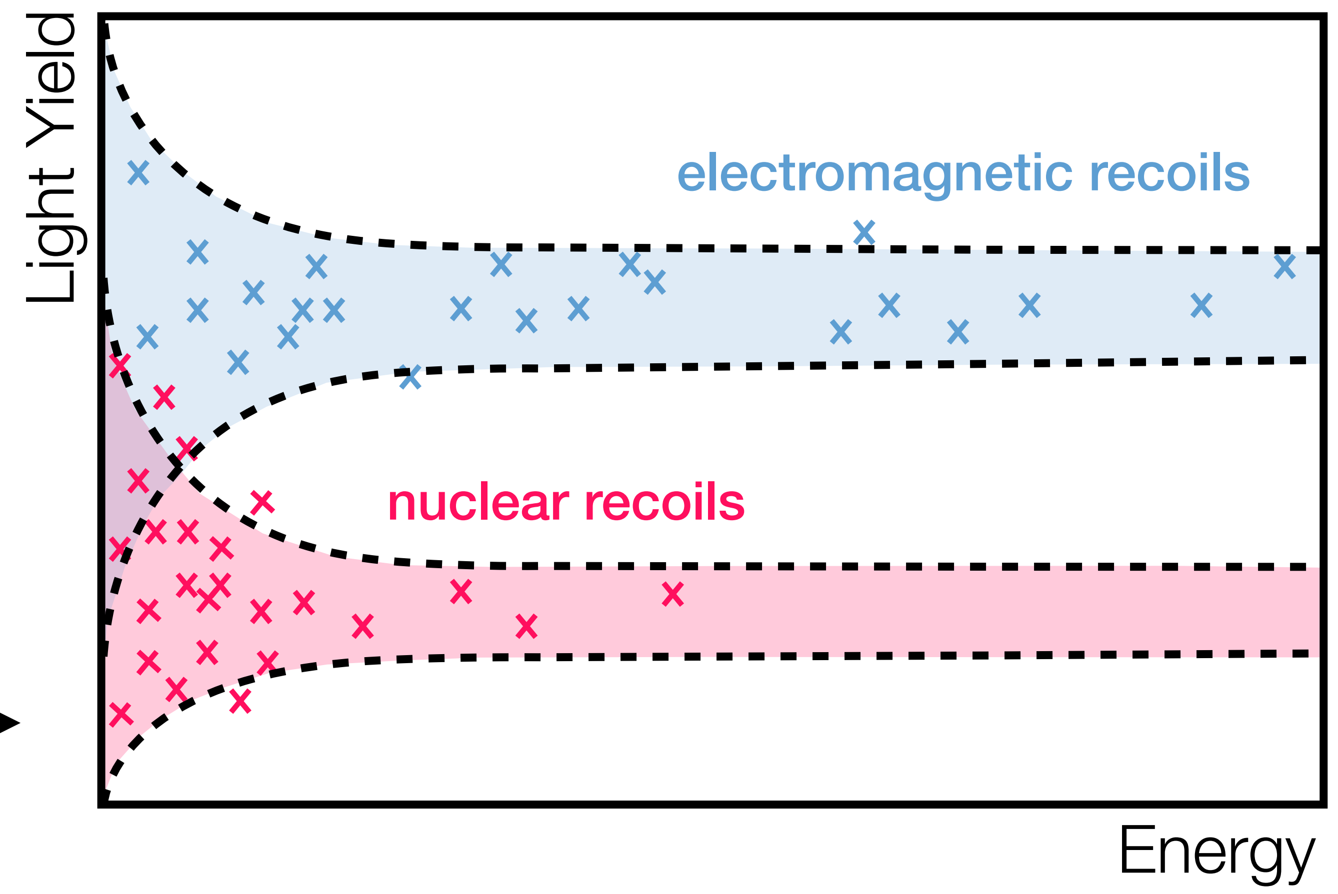
Cryogenic scintillating calorimeters (CSC)

- **Scintillating target** material like $CaWO_4$ or NaI (few cm^3 in size) used as cryogenic calorimeters to measure phonons after particle interaction.
- **Light detector** to collect scintillation light (e.g. Si) which makes up $\lesssim 10$ % of total deposited energy.
- Both detectors read out with **Transition edge sensors** (TES): small temperature change (μK) = measurable resistance change (mΩ).
- Measuring total recoil energy allows for **absolute** energy **calibration** and the ratio between light and phonon energy (**light yield**) allows for **particle discrimination** on event-by-event basis.
- The present detector module (**“NaIm”**) **required revisiting** existing **detector response models** for both raw voltage pulses and scintillation light output.



➤ see talk by Lutz Ziegele on Wednesday for details on detector module

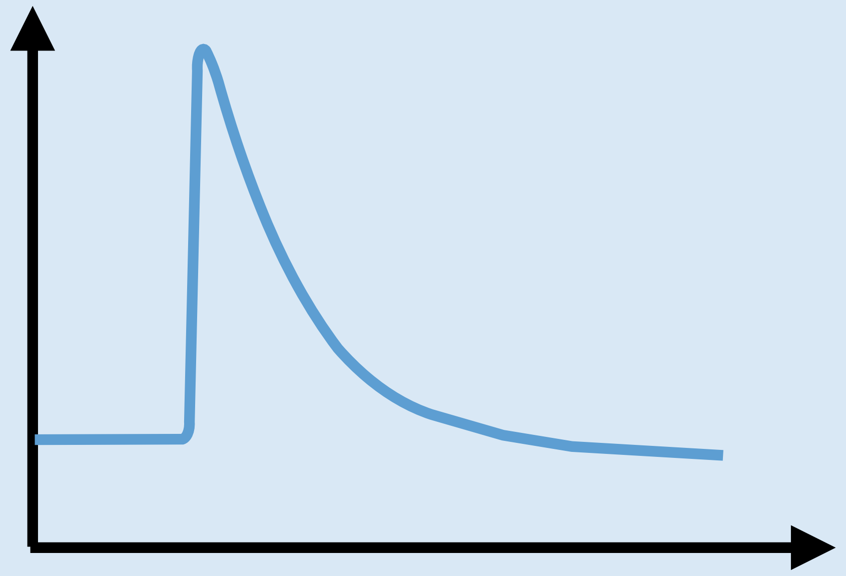




Generalized optimum filtering

arXiv:26xx.xxxx

revisiting pulse
reconstruction:



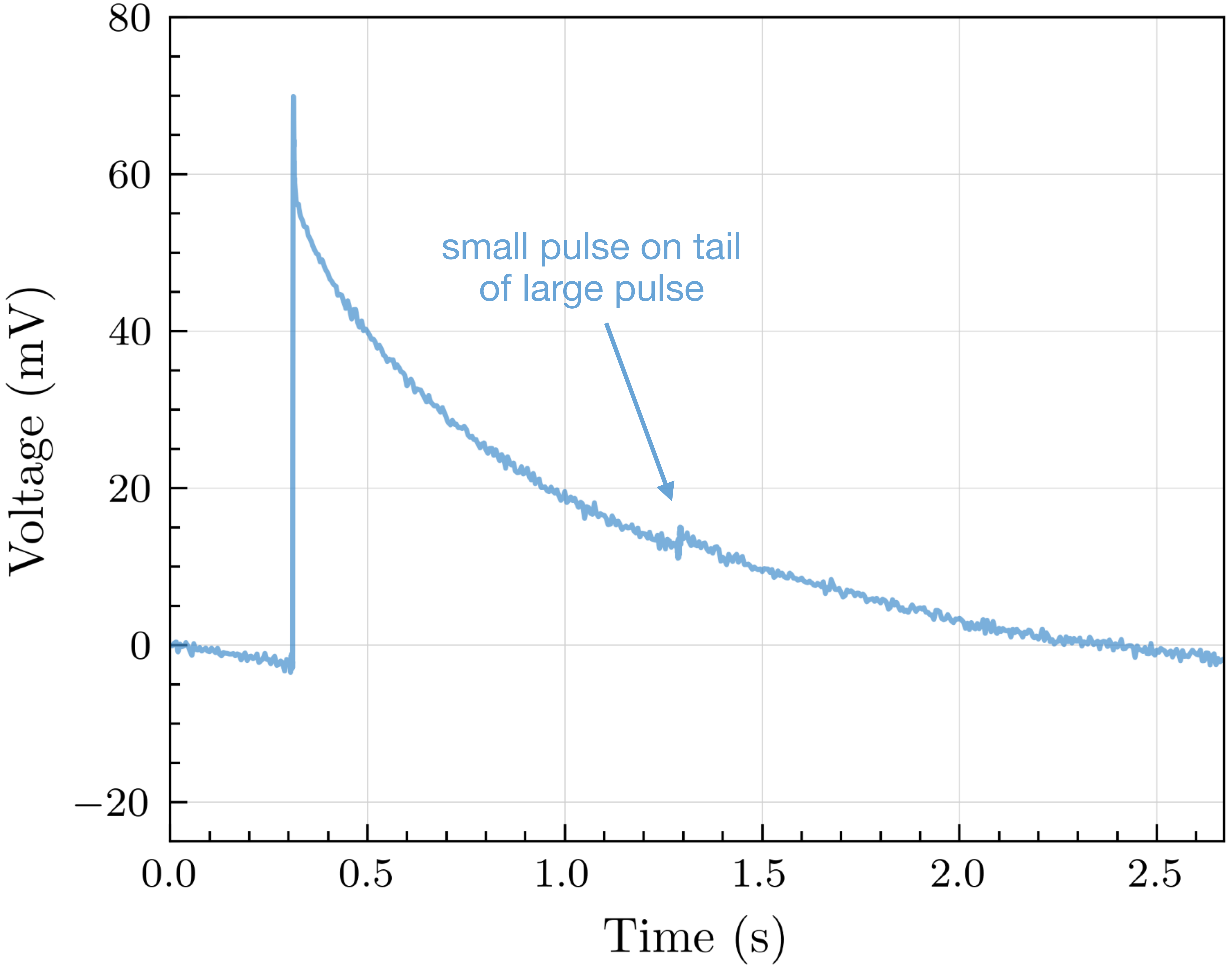
Motivation

- Current COSINUS NaI detectors have **pulses** that **decay** on the order of **seconds**. For above ground prototype measurements, the **event rate** is usually of order **Hz**.

- State of the art energy reconstruction for TES-based calorimeters is the **optimum filter (OF)** which struggles with non-flat baselines (the bias that they introduce to the filter response can be calculated).

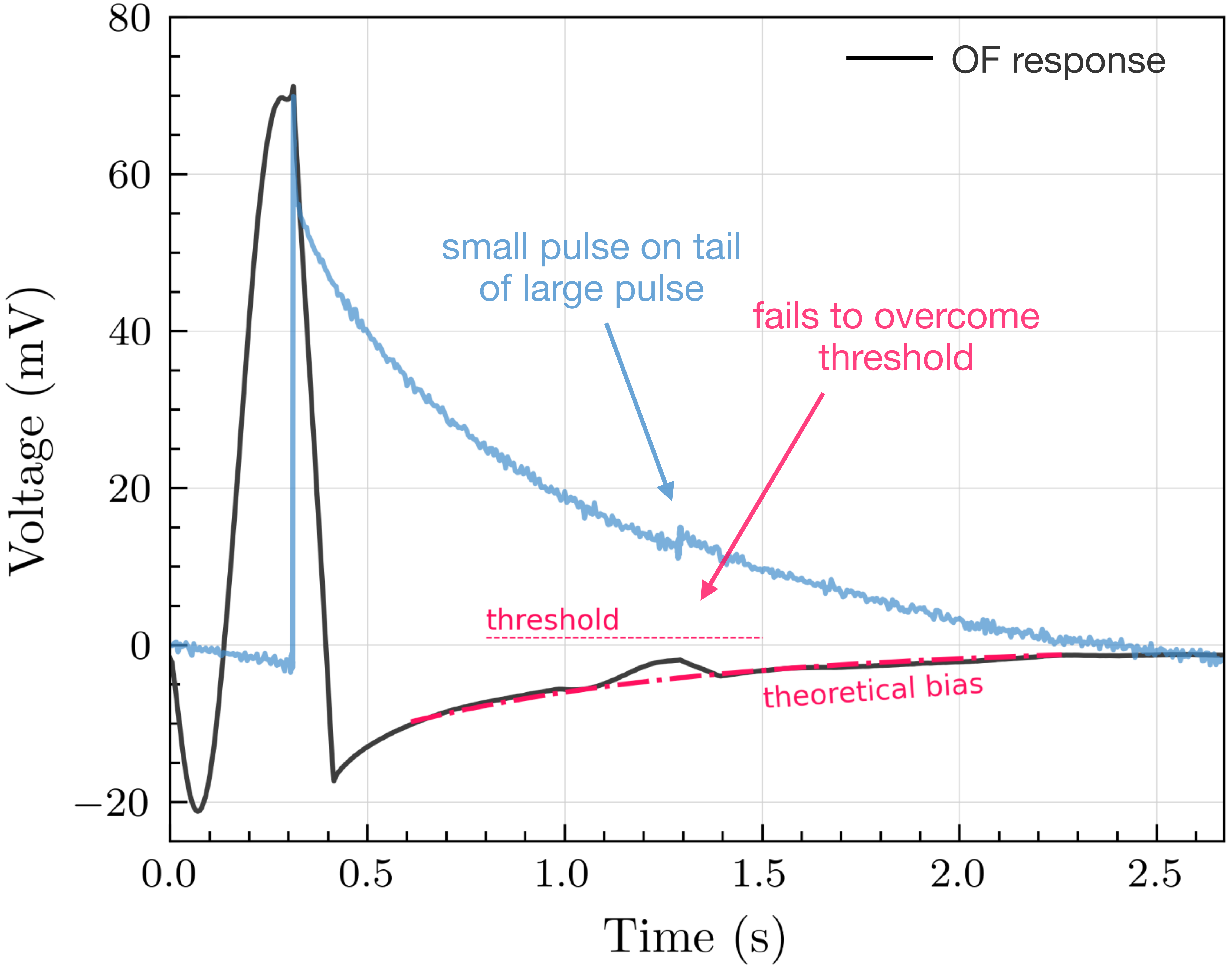
- Issues both in triggering (**high effective threshold**) and energy reconstruction (**bias** and line **broadening**).

- Both can be mitigated by explicitly modelling a varying baseline in the filter construction.
  → **generalized optimum filter (GOF)**



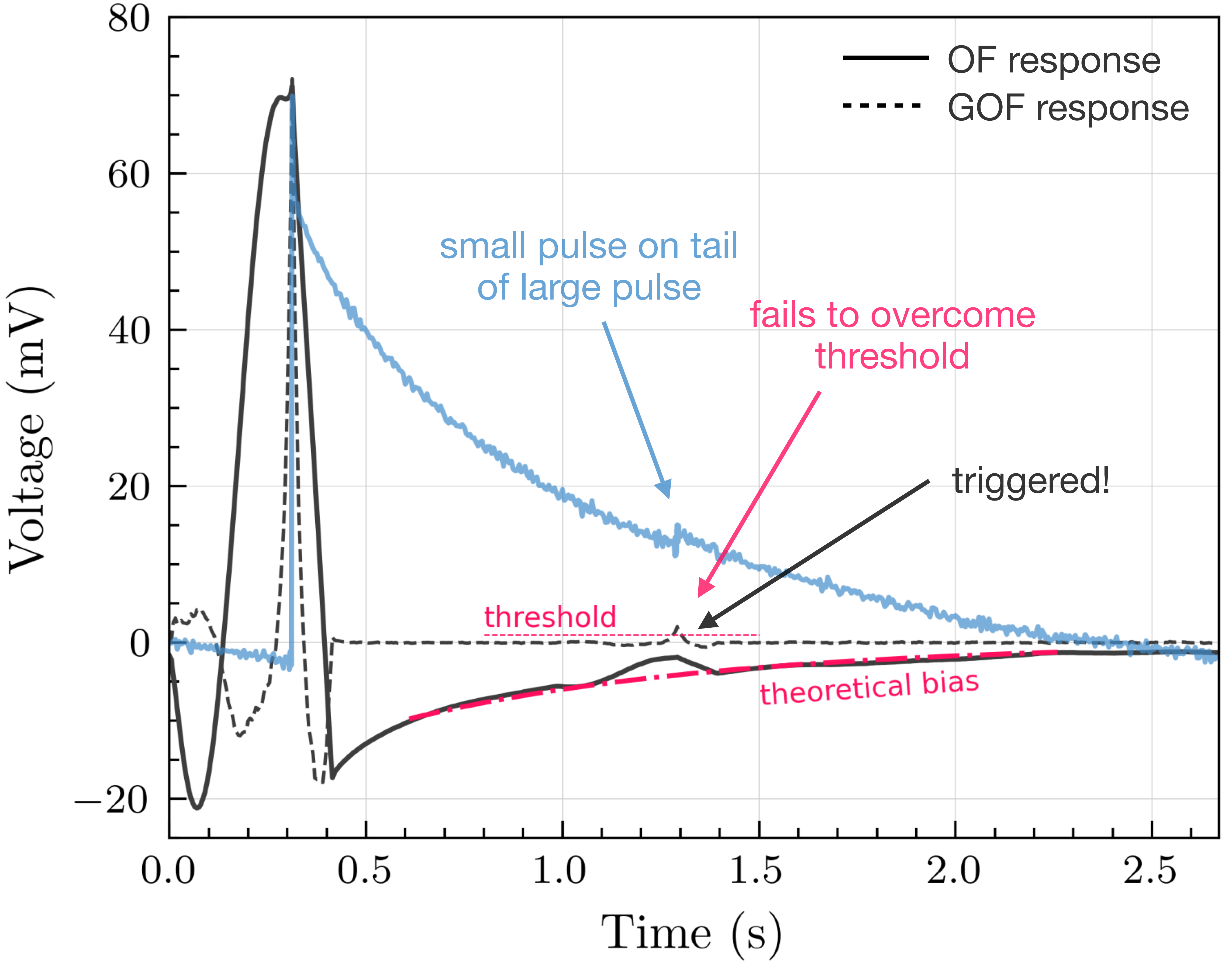
Motivation

- Current COSINUS NaI detectors have **pulses** that **decay** on the order of **seconds**. For above ground prototype measurements, the **event rate** is usually of order **Hz**.
- State of the art energy reconstruction for TES-based calorimeters is the **optimum filter (OF)** which struggles with non-flat baselines (the bias that they introduce to the filter response can be calculated).
- Issues both in triggering (**high effective threshold**) and energy reconstruction (**bias** and line **broadening**).
- Both can be mitigated by explicitly modelling a varying baseline in the filter construction.
  → **generalized optimum filter (GOF)**



Motivation

- Current COSINUS NaI detectors have **pulses** that **decay** on the order of **seconds**. For above ground prototype measurements, the **event rate** is usually of order **Hz**.
- State of the art energy reconstruction for TES-based calorimeters is the **optimum filter (OF)** which struggles with non-flat baselines (the bias that they introduce to the filter response can be calculated).
- Issues both in triggering (**high effective threshold**) and energy reconstruction (**bias** and line **broadening**).
- Both can be mitigated by explicitly modelling a varying baseline in the filter construction.
  → **generalized optimum filter (GOF)**



Model construction

- Instead of modelling the detector response as a (scaled) template plus noise, we **explicitly include** a (polynomial) **baseline description**.
- Then, the log-likelihood is constructed — expressed in terms of the noise-weighted inner product in frequency space (for convenience).
- Finally, the **maximum likelihood** (ML) **estimator** and its variance for the pulse amplitude are derived.
- *Interpretation:* Generalized optimum filtering is equivalent to projecting the baseline contributions out of the template used.
- *Observation:* The **filter resolution worsens** for larger polynomial degrees. The strength of this effect depends on the template overlap with the baseline model.

model for standard optimum filter

$$\boldsymbol{d} = A\boldsymbol{s} + \boldsymbol{n}$$

amplitude template noise

extended model

$$\boldsymbol{d} = A\boldsymbol{s} + \mathbf{B}\boldsymbol{a} + \boldsymbol{n} = A\boldsymbol{s} + a_j\boldsymbol{b}^{(j)} + \boldsymbol{n}, \quad j = 0, ..., k$$

polynomial basis

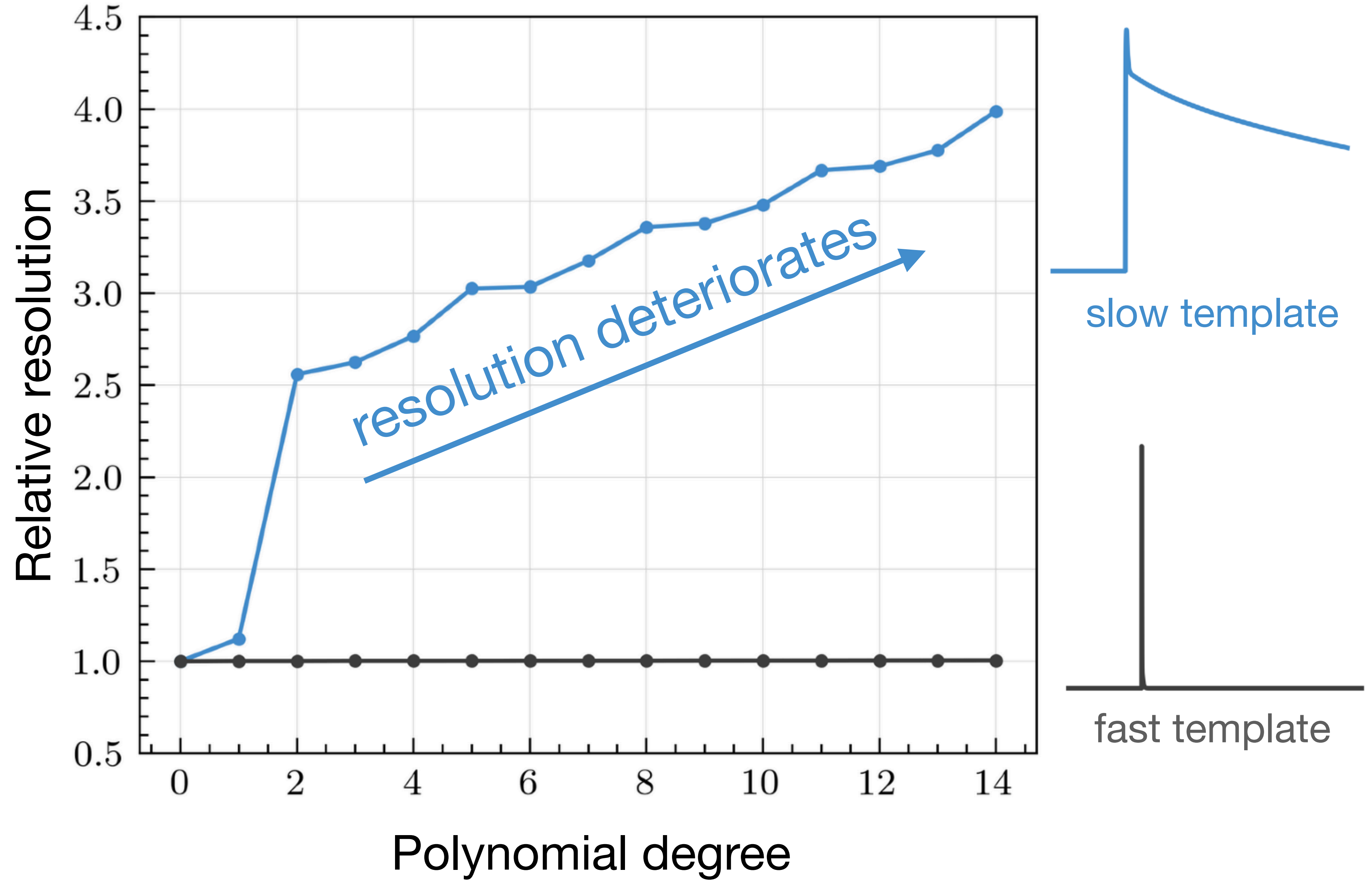
Model construction

- Instead of modelling the detector response as a (scaled) template plus noise, we **explicitly include** a (polynomial) **baseline description**.
- Then, the log-likelihood is constructed — expressed in terms of the noise-weighted inner product in frequency space (for convenience).
- Finally, the **maximum likelihood** (ML) **estimator** and its variance for the pulse amplitude are derived.
- *Interpretation:* Generalized optimum filtering is equivalent to projecting the baseline contributions out of the template used.
- *Observation:* The **filter resolution worsens** for larger polynomial degrees. The strength of this effect depends on the template overlap with the baseline model.

ML amplitude estimator and its variance

$$\hat{A} = \frac{\langle \tilde{\boldsymbol{s}}|\tilde{\boldsymbol{d}}\rangle - \boldsymbol{\sigma}^T \mathbf{G}^{-1}\boldsymbol{\delta}}{\langle \tilde{\boldsymbol{s}}|\tilde{\boldsymbol{s}}\rangle - \boldsymbol{\sigma}^T \mathbf{G}^{-1}\boldsymbol{\sigma}} \qquad \mathrm{Var}(\hat{A}) = (\boldsymbol{\Gamma}^{-1})_{AA} = \frac{1}{\langle \tilde{\boldsymbol{s}}|\tilde{\boldsymbol{s}}\rangle - \boldsymbol{\sigma}^T \mathbf{G}^{-1}\boldsymbol{\sigma}}$$

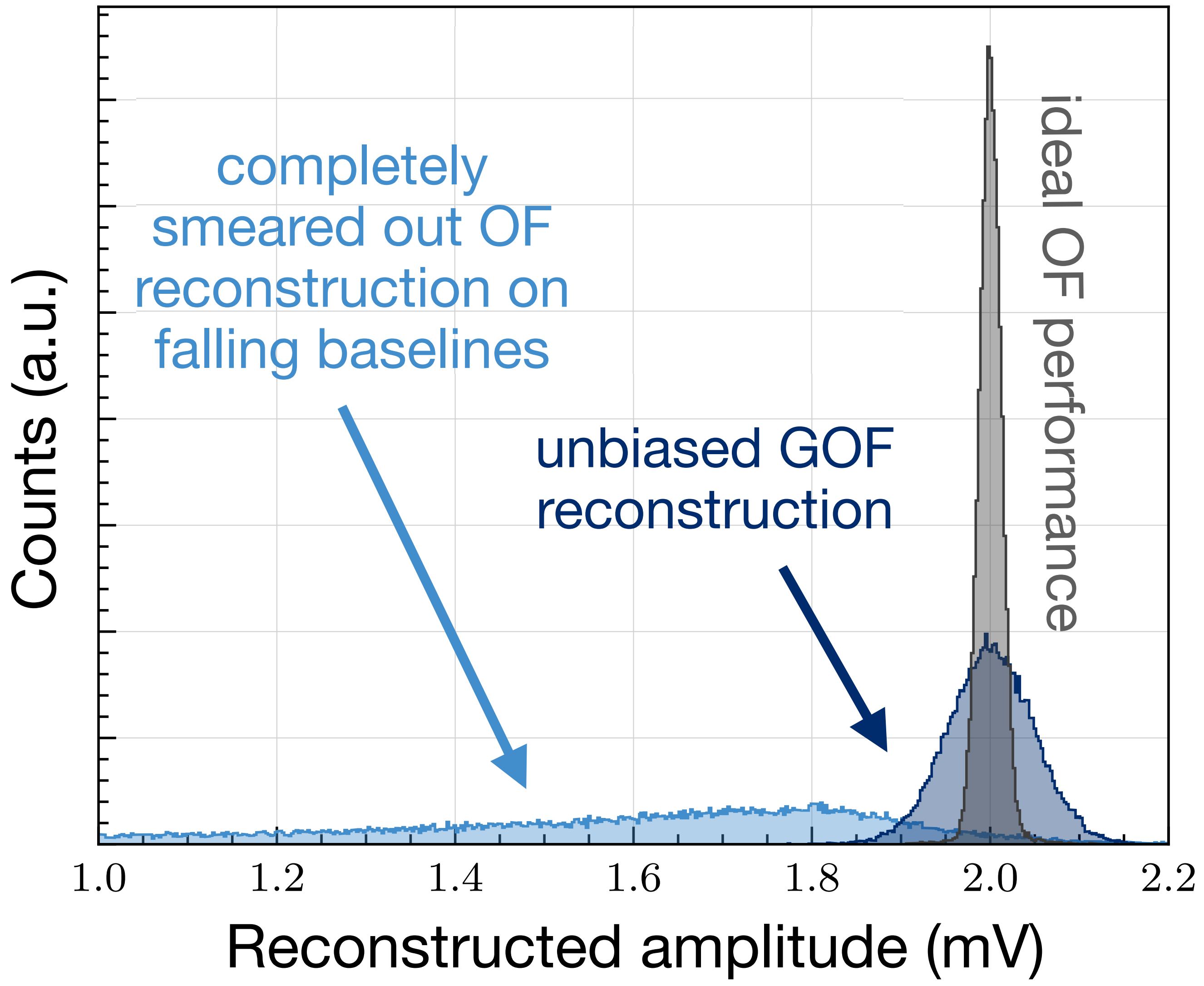
(symbols explained in backup)



NaIm prototype data

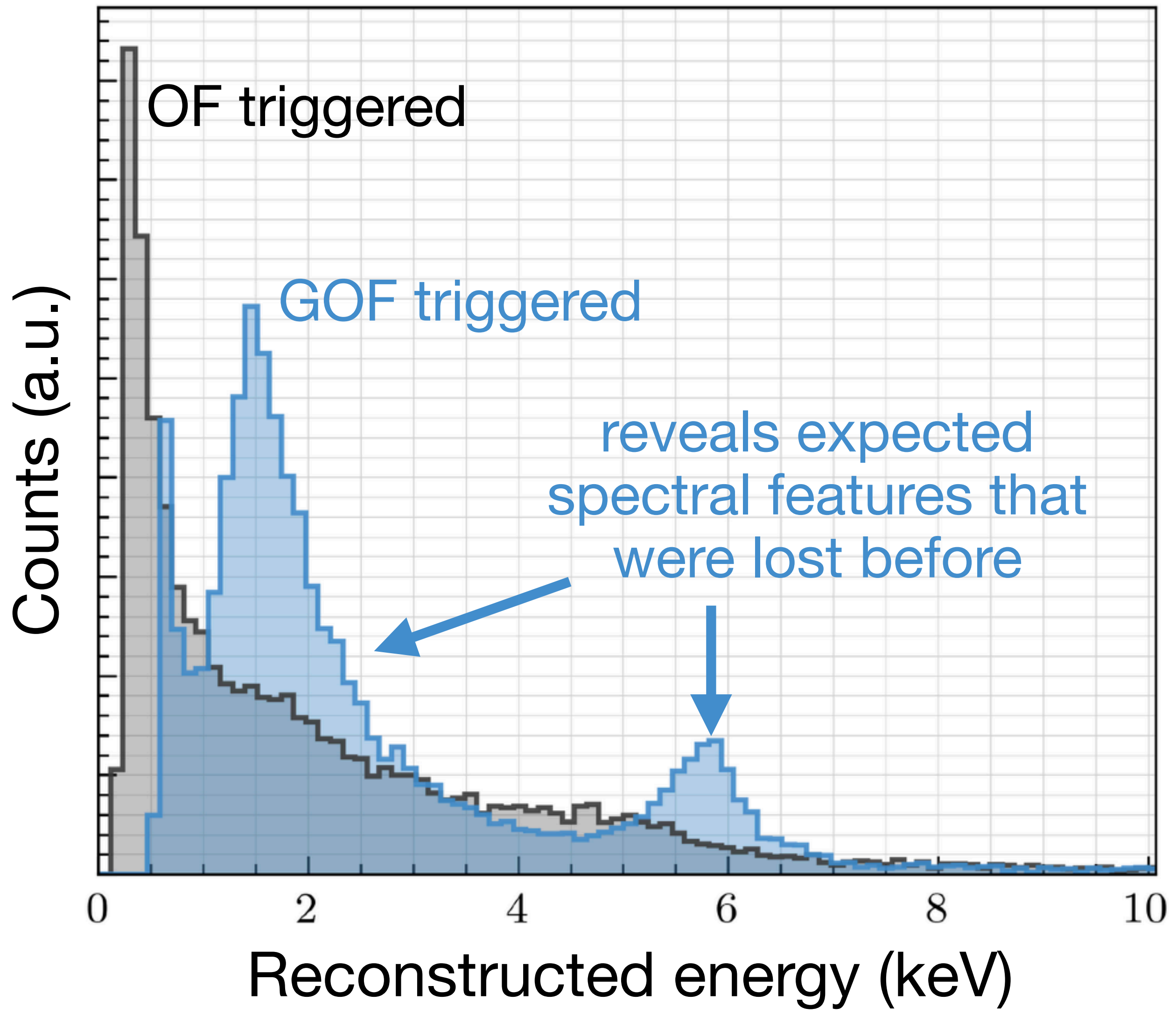
COSINUS

- Despite the worse resolution, the **GOF scores** in terms of **reconstruction fidelity** in high count rate scenarios.
- **Spectral features** that were washed out by the OF reconstruction are **recovered** using the GOF.
- This way, the “effective resolution” could be reduced from **~400 eV to 140 eV**.
- Which in turn improved the **detection threshold** from **~5 keV to <1 keV**!
- Furthermore, the theoretical scaling derived for the filter resolution lets us extrapolate to the underground operation (low count rate). *Prediction:* 50 eV baseline resolution.



(for pulses with 2.0 mV simulated amplitude)

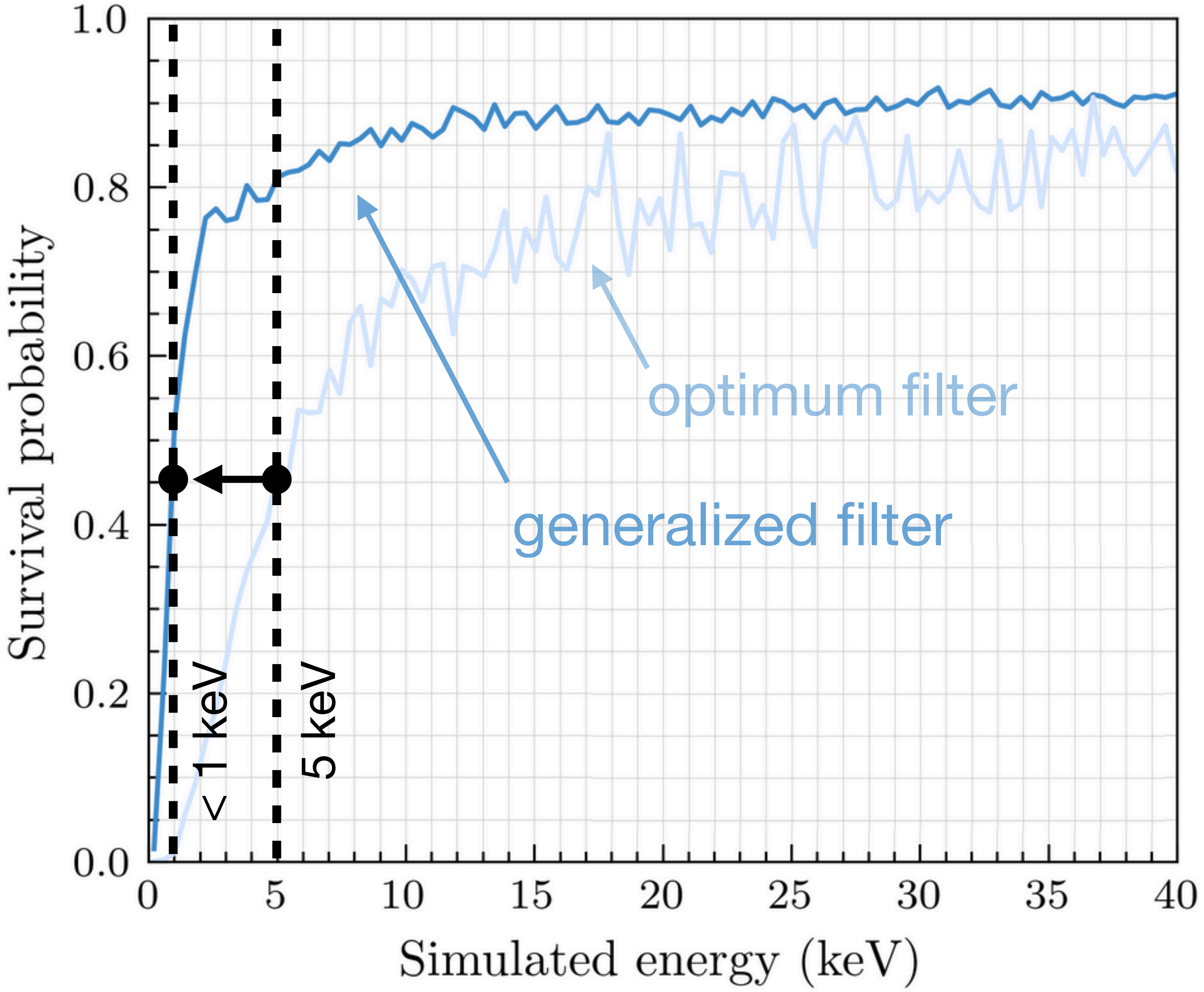
Raw spectra after triggering



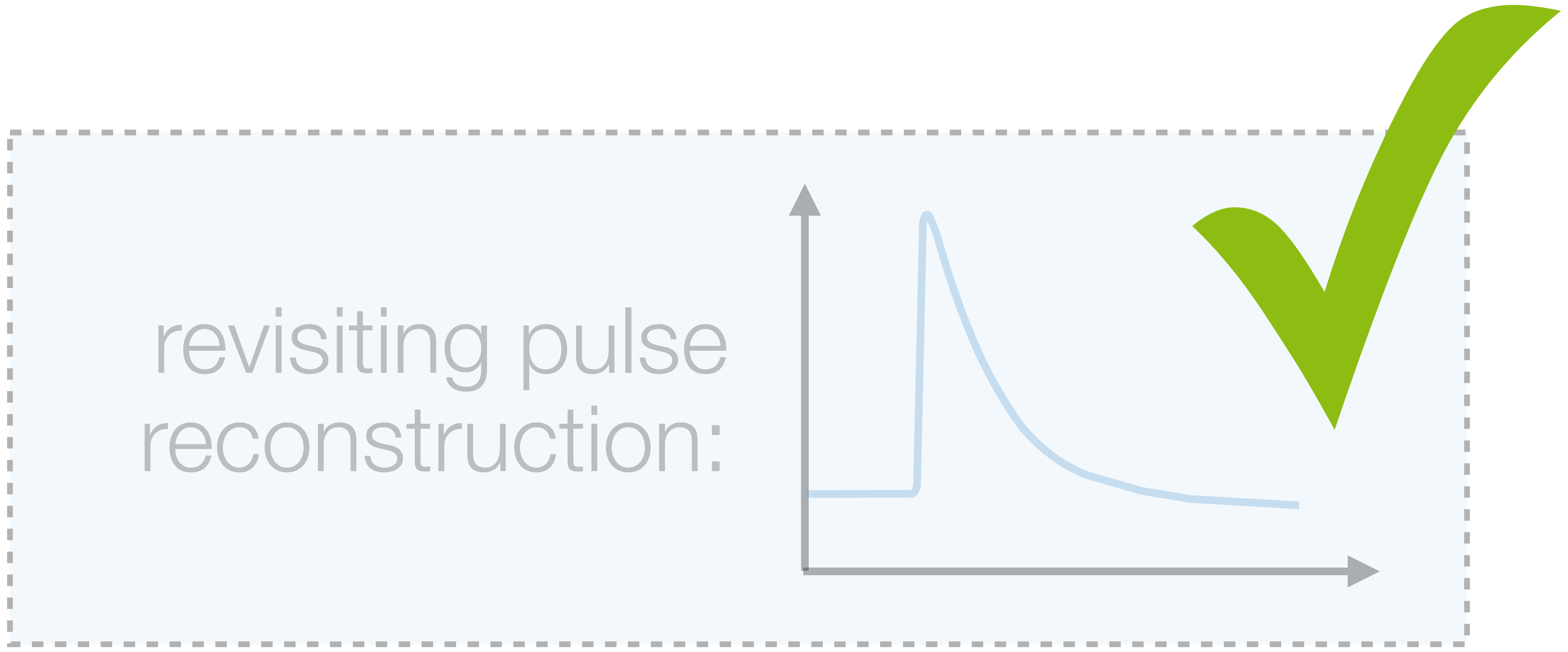
NaIm prototype data

COSINUS

- Despite the worse resolution, the **GOF scores** in terms of **reconstruction fidelity** in high count rate scenarios.
- **Spectral features** that were washed out by the OF reconstruction are **recovered** using the GOF.
- This way, the “effective resolution” could be reduced from **~400 eV to 140 eV**.
- Which in turn improved the **detection threshold** from **~5 keV to <1 keV**!
- Furthermore, the theoretical scaling derived for the filter resolution lets us extrapolate to the underground operation (low count rate). *Prediction:* 50 eV baseline resolution.



Summary



revisiting pulse reconstruction:

- Use **OF wherever possible** (better resolution).
- **When decaying baselines distort** the **amplitude** reconstruction, the **GOF** is an easy to use fix to many of the problems.
- Relevant **especially for above ground** measurements but also in presence of calibration sources underground (elevated rate)!

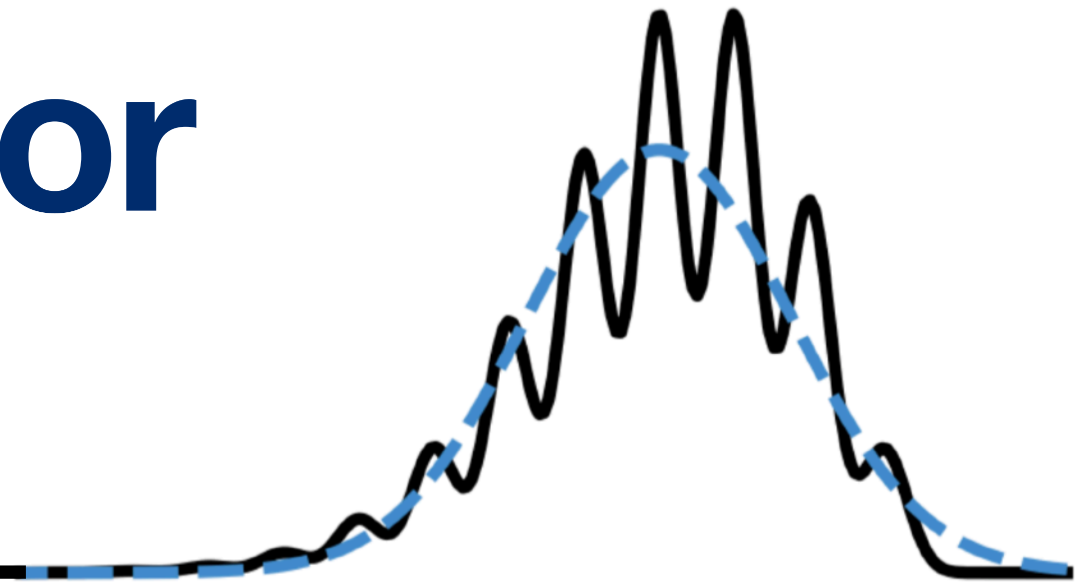
Connection to other fields using similar technique in (slightly) different contexts:

- gravitational waves detection, e.g. PRD 58, 063001 (1998)
- TES-based X-ray spectroscopy, e.g. ApJS 219 35 (2015)
- TES-based neutrino experiments, e.g. EPJC 82, 5 (2022)

- It is implemented in cait (starting from 1.3.0)!

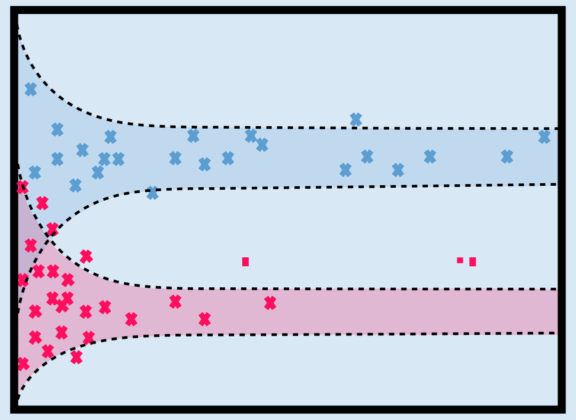
cait.readthedocs.io

Compound Poissonian detector response model



arXiv:26xx.xxxx

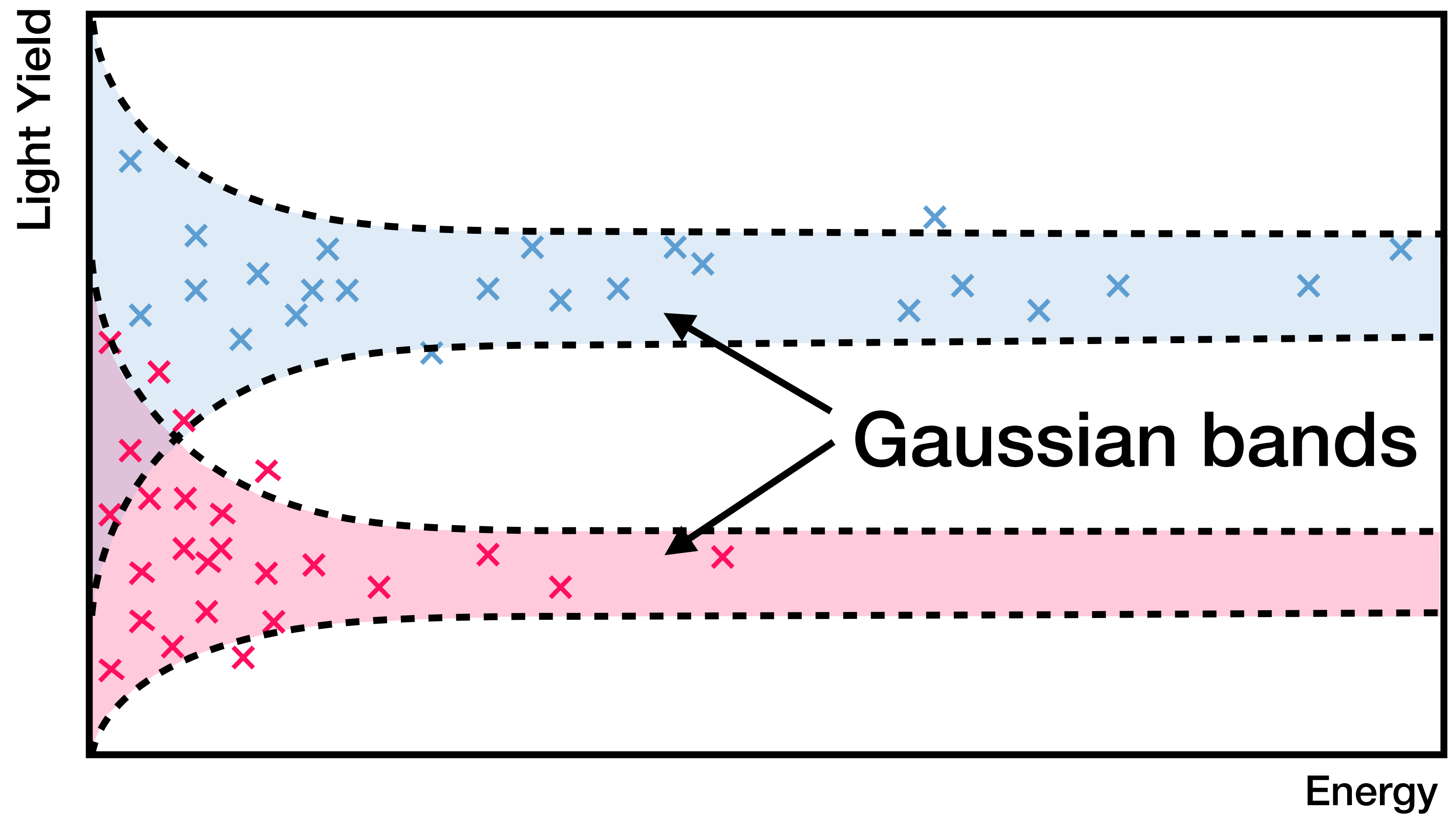
revisiting light
detector statistics:

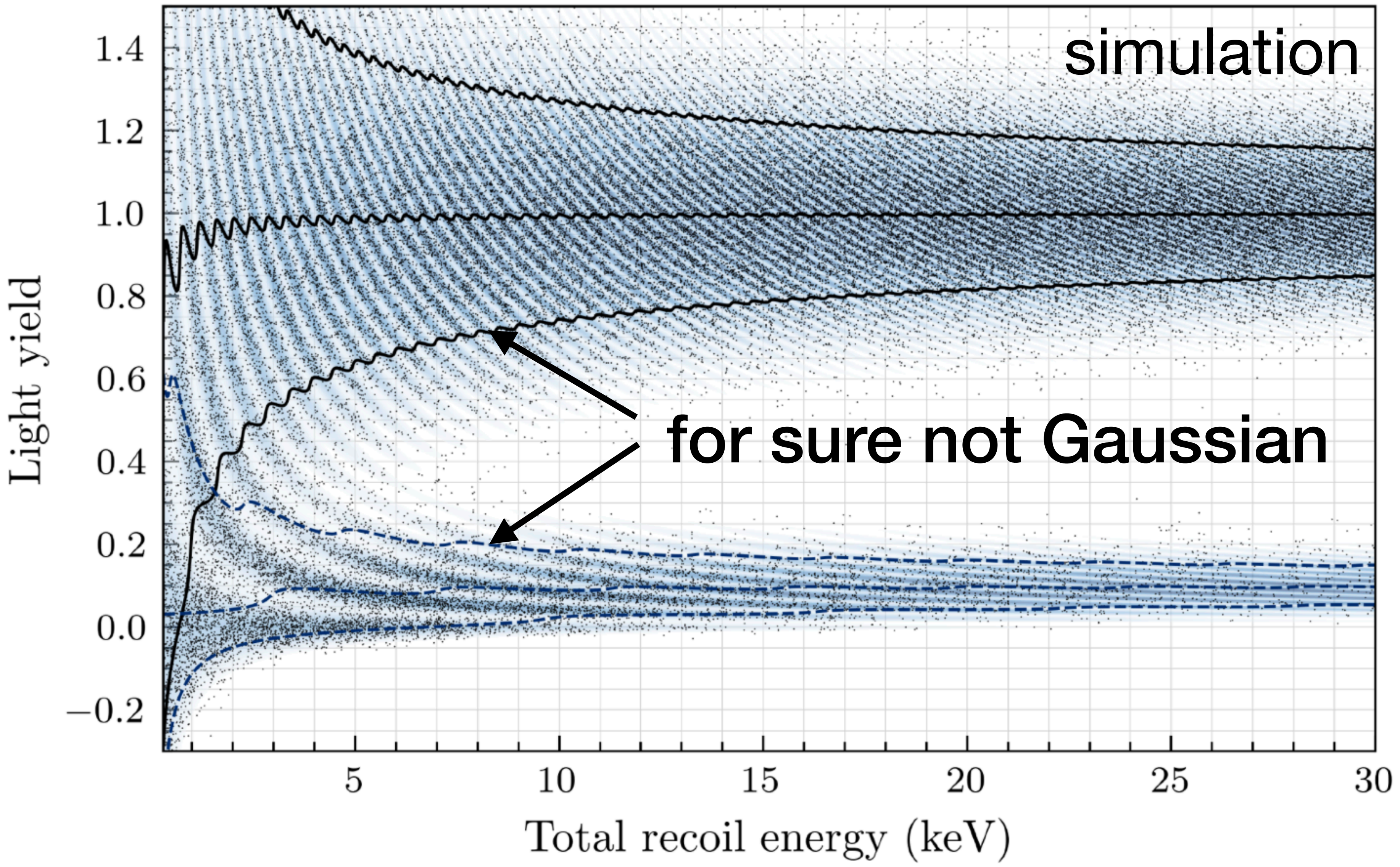


Motivation

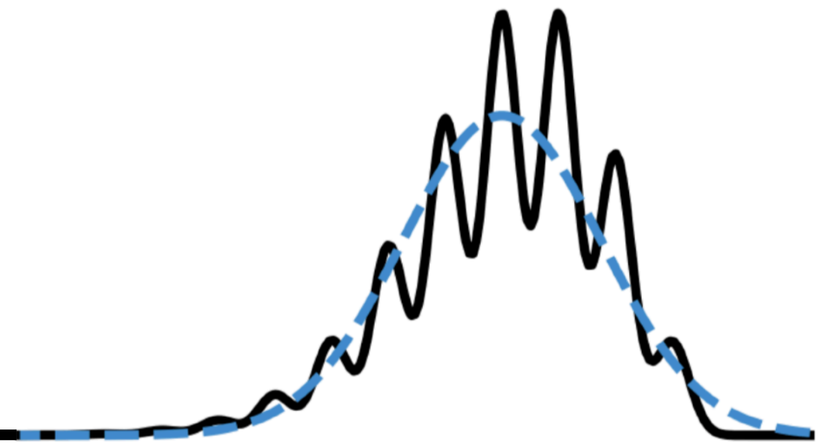
- Cryogenic scintillating calorimeters (CSCs) enable **recoil-type discrimination** via light yield bands.
- Statistical modelling of the scintillation response is essential.
- Single photon resolution introduces **Poissonian features** such as skewness and **sub-band structure**.

- These effects are expected in future underground NaIm measurements with higher statistics.
- **Single photon resolution** in a sapphire CSC has already been demonstrated by **CRESST**.

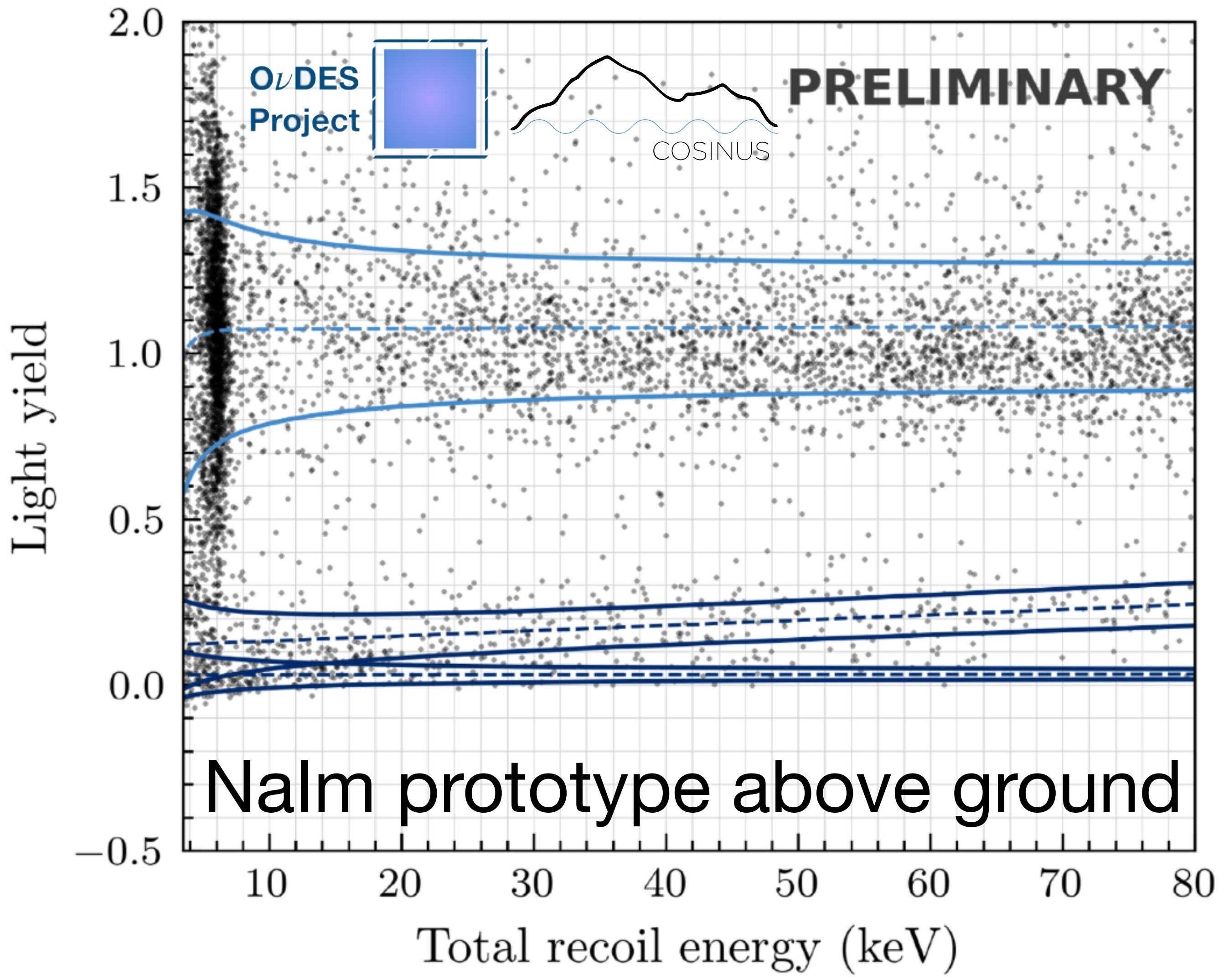




Motivation

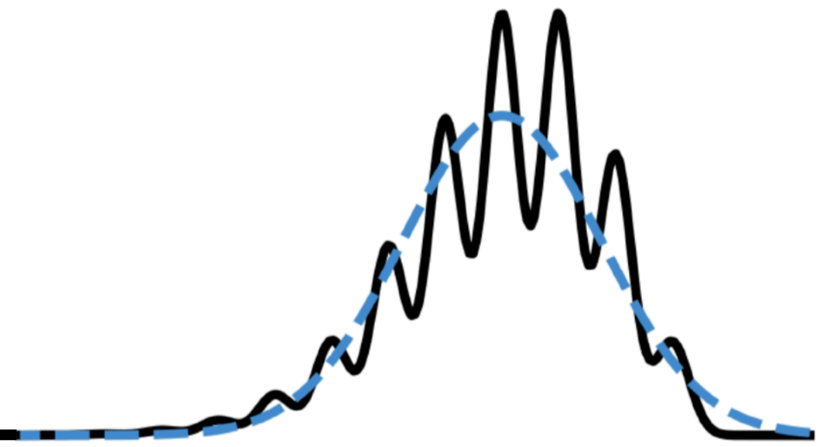


- Cryogenic scintillating calorimeters (CSCs) enable **recoil-type discrimination** via light yield bands.
- Statistical modelling of the scintillation response is essential.
- Single photon resolution introduces **Poissonian features** such as skewness and **sub-band structure**.



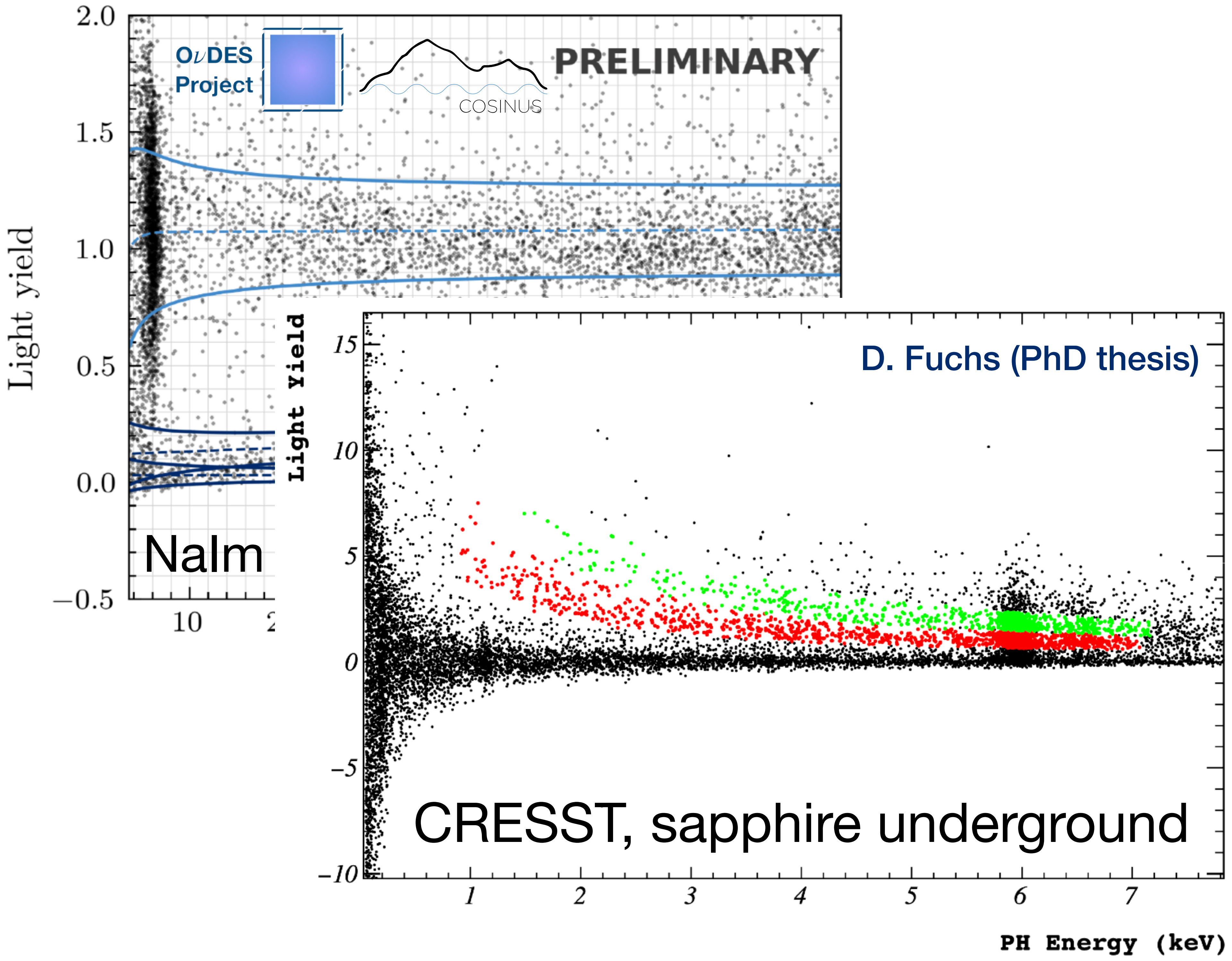
- These effects are expected in future underground NaIm measurements with higher statistics.
- **Single photon resolution** in a sapphire CSC has already been demonstrated by **CRESST**.

Motivation



- Cryogenic scintillating calorimeters (CSCs) enable **recoil-type discrimination** via light yield bands.
- Statistical modelling of the scintillation response is essential.
- Single photon resolution introduces **Poissonian features** such as skewness and **sub-band structure**.

- These effects are expected in future underground NaIm measurements with higher statistics.
- **Single photon resolution** in a sapphire CSC has already been demonstrated by **CRESST**.

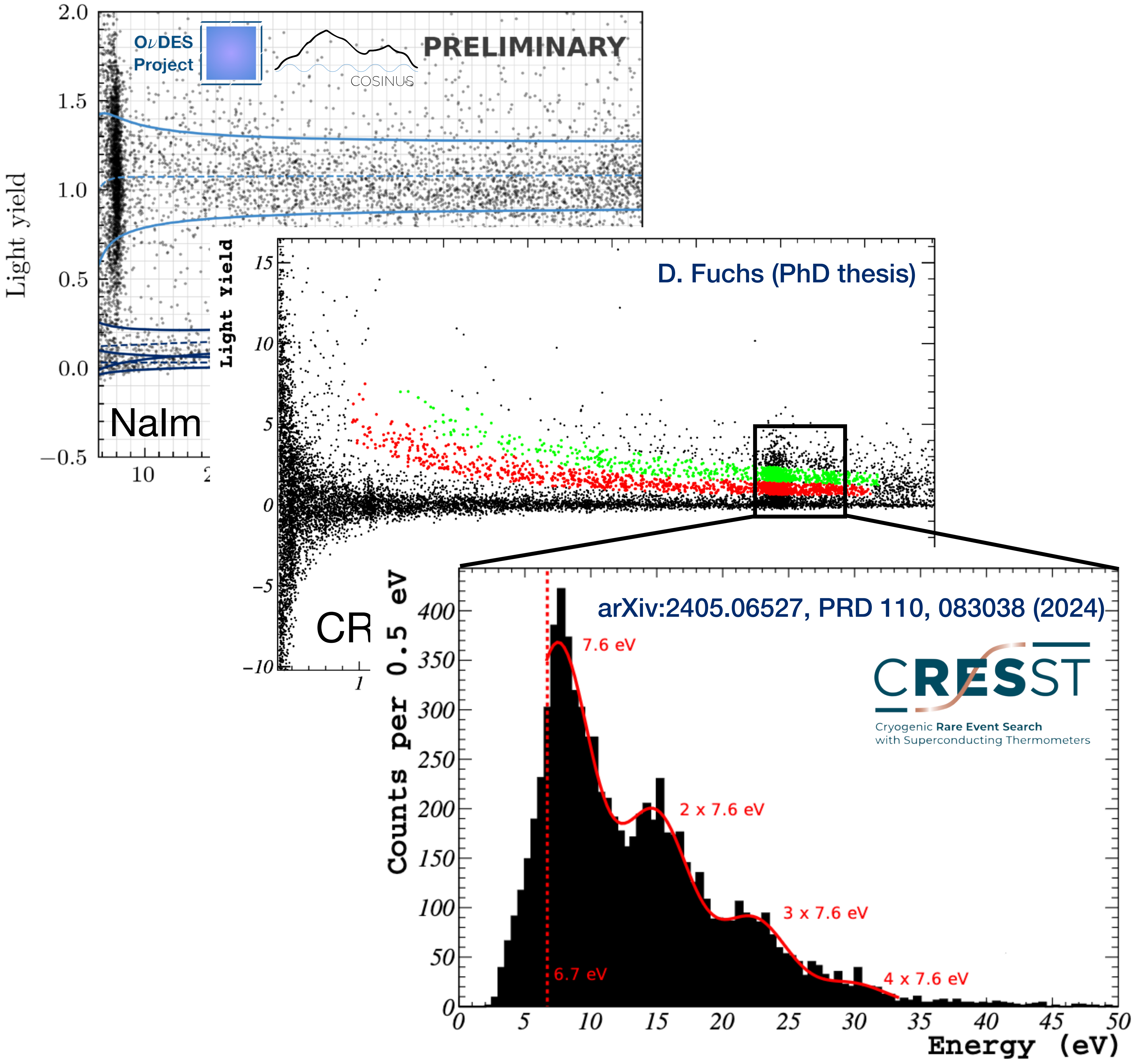


D. Fuchs (PhD thesis)

Motivation

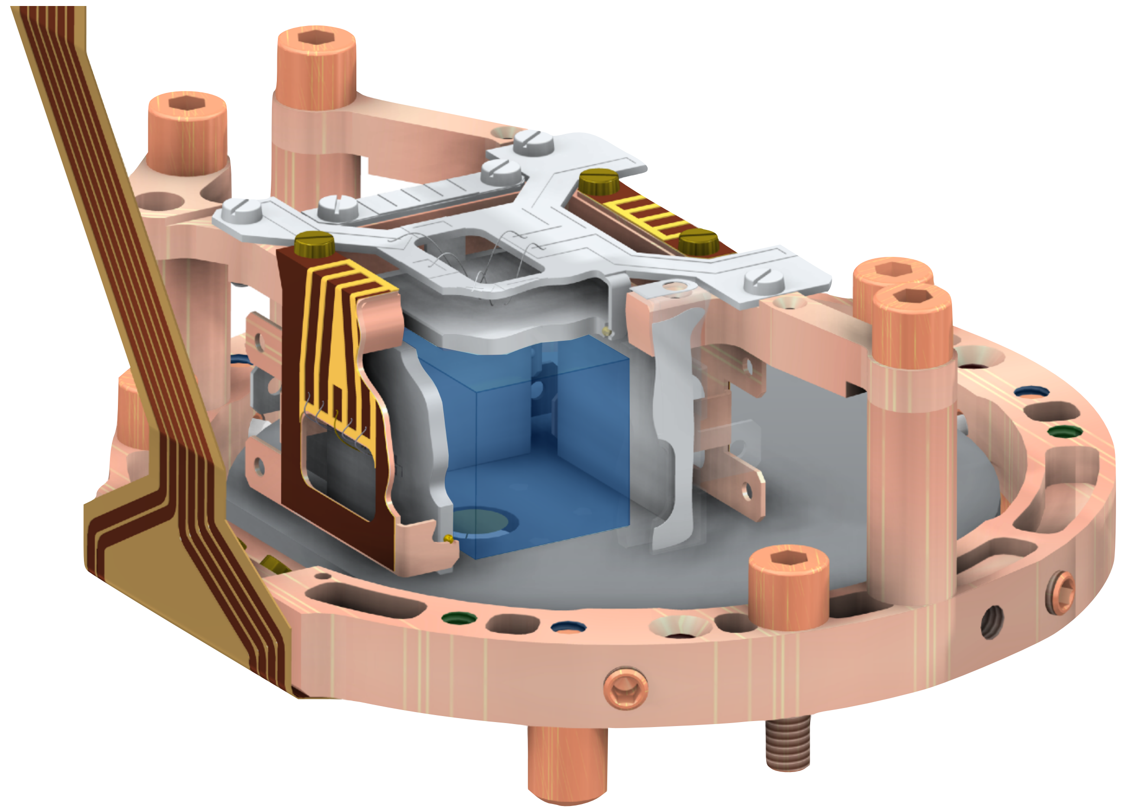
- Cryogenic scintillating calorimeters (CSCs) enable **recoil-type discrimination** via light yield bands.
- Statistical modelling of the scintillation response is essential.
- Single photon resolution introduces **Poissonian features** such as skewness and **sub-band structure**.

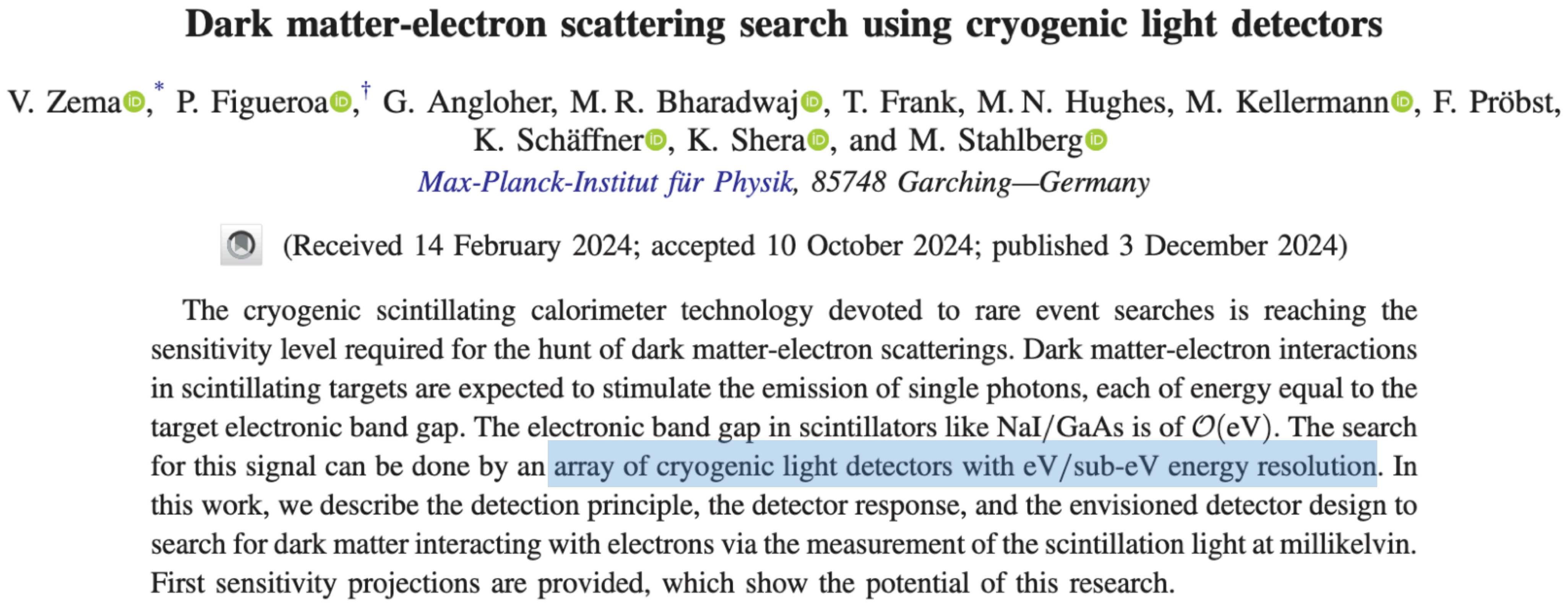
- These effects are expected in future underground NaIm measurements with higher statistics.
- **Single photon resolution** in a sapphire CSC has already been demonstrated by **CRESST**.



Motivation

- Enables **DM electron scattering** searches, where the n-**photon peaks** are the **signature** (OνDES project).
- Envisioned detector design: That of NaIm.
- Have to **understand scintillation** well, especially if the scintillation spectrum is energy dependent and/or non-mono-energetic.



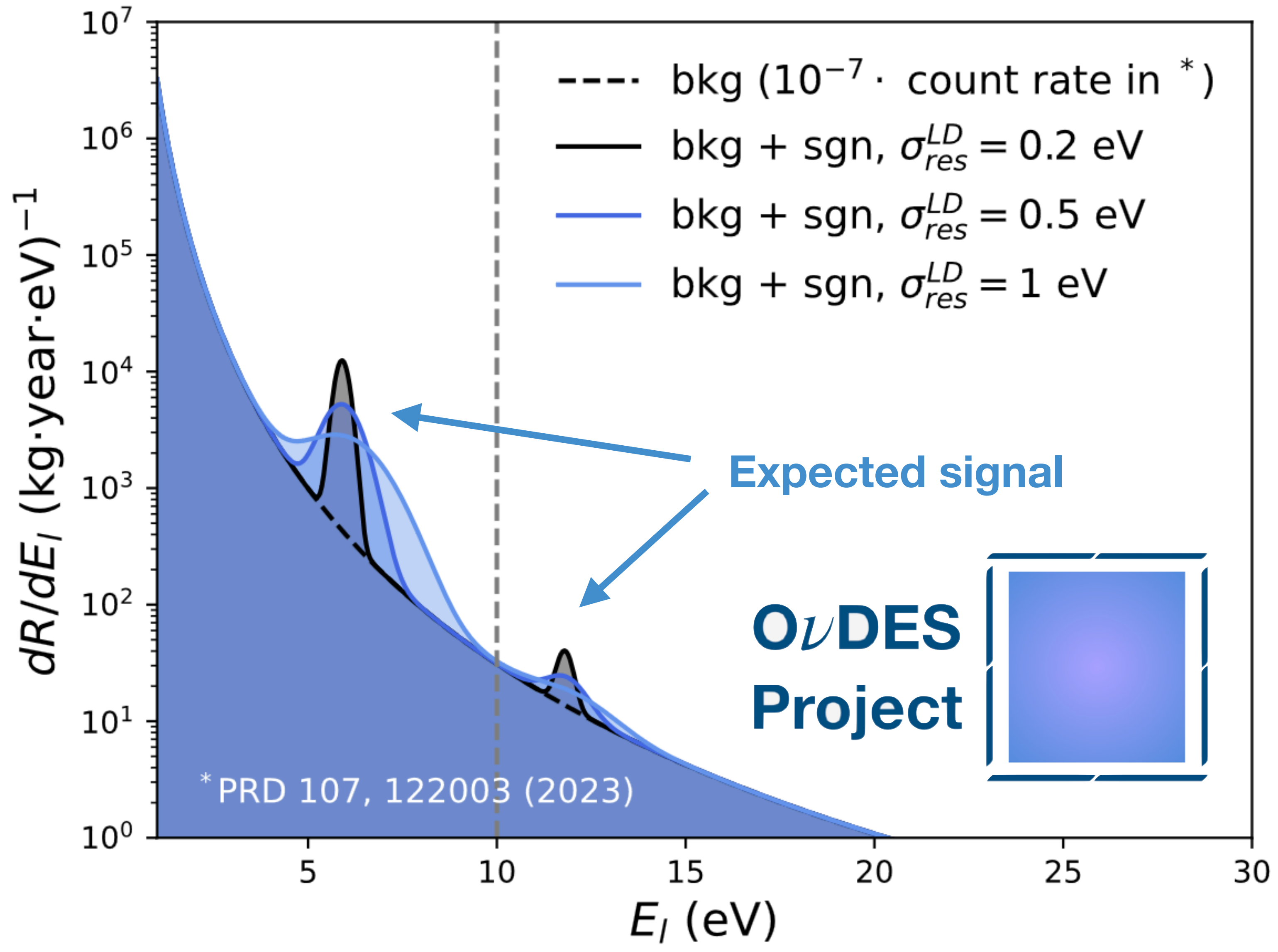


Dark matter-electron scattering search using cryogenic light detectors

V. Zema,[*] P. Figueroa,[†] G. Angloher, M. R. Bharadwaj, T. Frank, M. N. Hughes, M. Kellermann, F. Pröbst,
K. Schäffner, K. Shera, and M. Stahlberg
Max-Planck-Institut für Physik, 85748 Garching—Germany

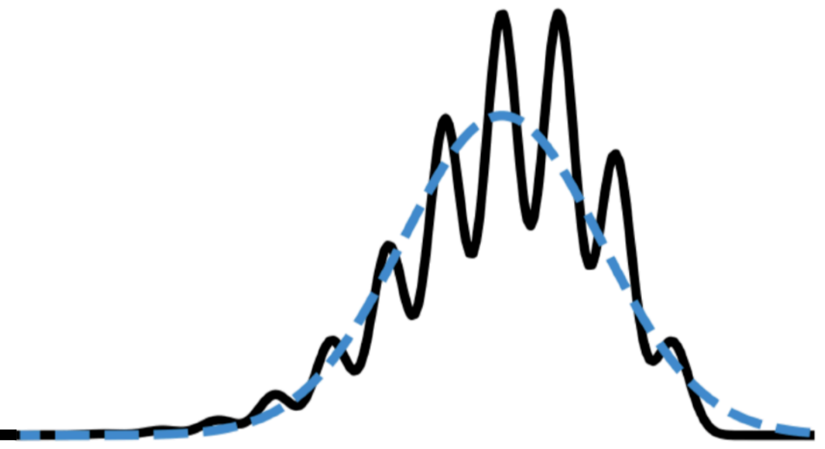
(Received 14 February 2024; accepted 10 October 2024; published 3 December 2024)

The cryogenic scintillating calorimeter technology devoted to rare event searches is reaching the sensitivity level required for the hunt of dark matter-electron scatterings. Dark matter-electron interactions in scintillating targets are expected to stimulate the emission of single photons, each of energy equal to the target electronic band gap. The electronic band gap in scintillators like NaI/GaAs is of $\mathcal{O}$(eV). The search for this signal can be done by an array of cryogenic light detectors with eV/sub-eV energy resolution. In this work, we describe the detection principle, the detector response, and the envisioned detector design to search for dark matter interacting with electrons via the measurement of the scintillation light at millikelvin. First sensitivity projections are provided, which show the potential of this research.

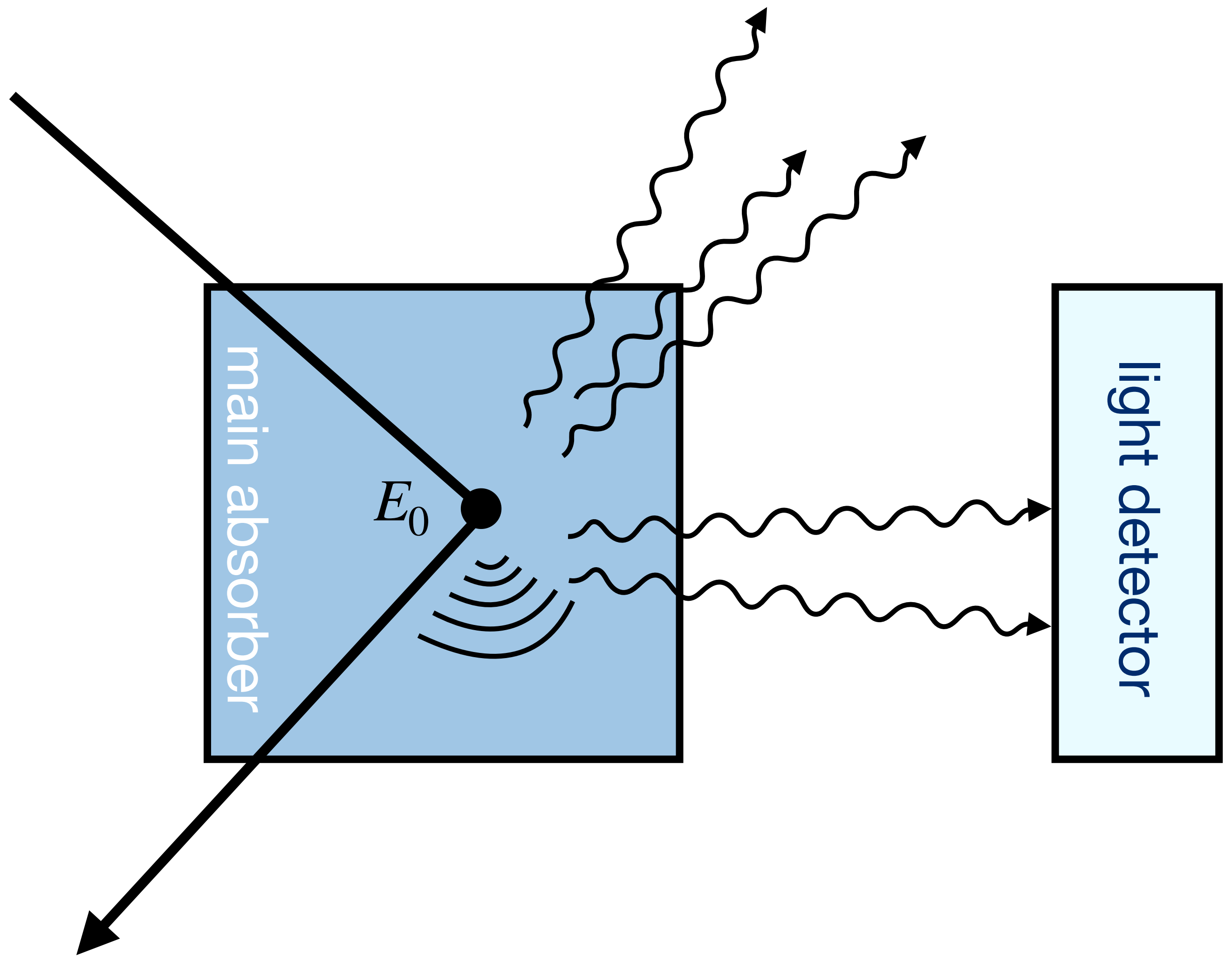


arXiv:2402.01395, PRD 110, 123012 (2024)

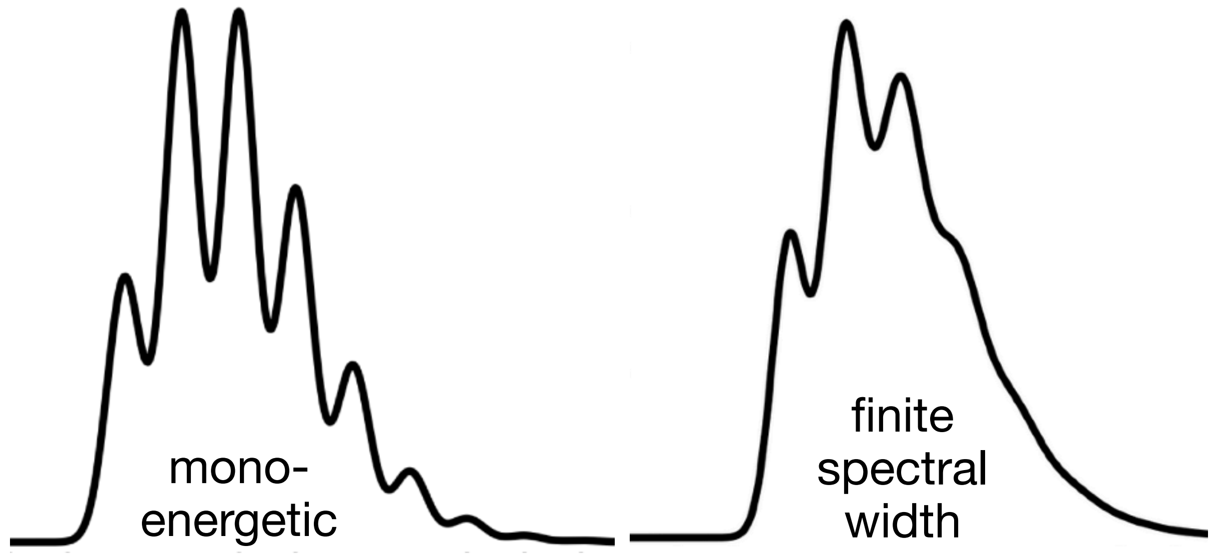
Model construction



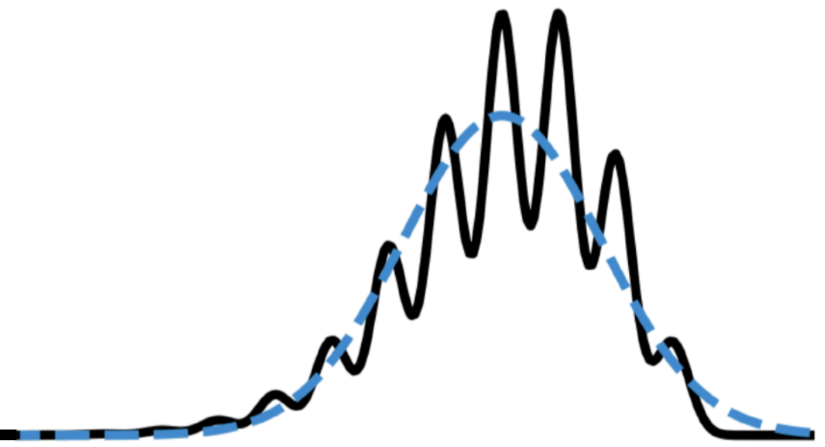
- Suppose that a particle deposits energy in the **main absorber** which **produces photons** from an **arbitrary** scintillation **spectrum**. The energy not converted to photons remains in the main absorber.
- With some probability, those photons are **captured in** the **light detector**.
- Both phonon and light detector suffer from **Gaussian** measurement **noise**.
- This setup defines two random variables, whose joint probability distribution can be written in closed form using characteristic functions (“Fourier transform of PDF”).
- In the following, we **consider the light detector** only.



light detector response $$= \exp\left(\overbrace{-\frac{1}{2}\sigma_{\mathrm{L}}^2 t_{\mathrm{L}}^2}^{\text{Gaussian noise}} + \overbrace{p\lambda_r(E_0)[\underbrace{\varphi_\Gamma}_{\text{scintillation spectrum}}(t_{\mathrm{L}}; E_0) - 1]}^{\text{compound Poissonian}}\right)$$

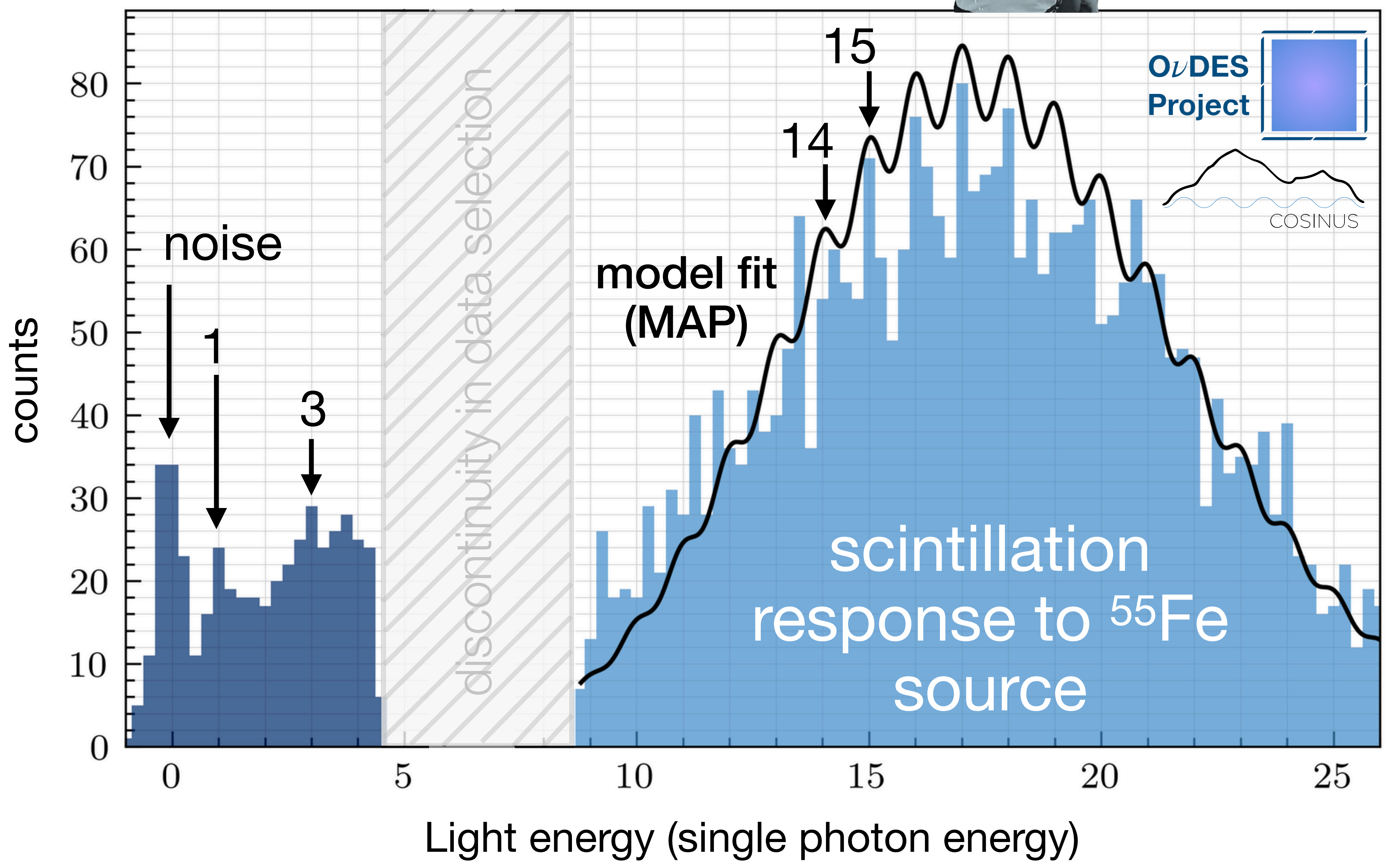


NaIm prototype data

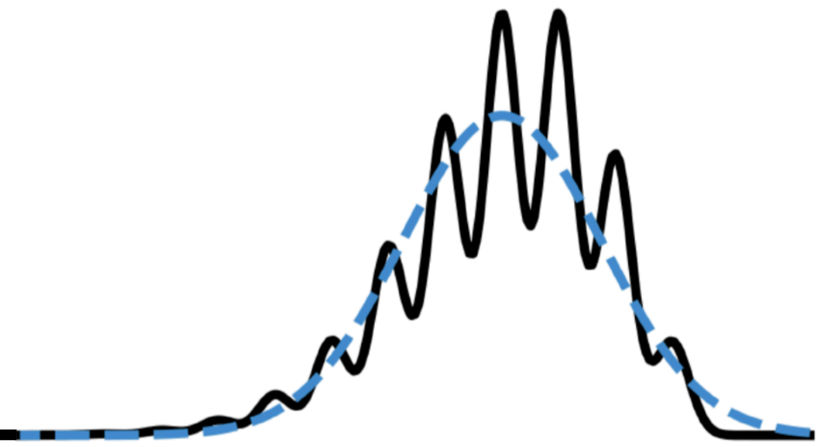


- **Hints for peak structure** but as mentioned before: not yet fully convincing.
- *Disclaimer:* No calibration source at low energies, i.e. no possibility to independently determine single photon energy. **Low statistics**, **above ground** measurement! Consider graph as **“proof of principle”**.
- … will soon be measured underground, with more stable operation and higher statistics! **Stay tuned!**
- One conclusion that we can draw, however: Peaks appear to still be visible at large photon counts: **Suggests fairly mono-energetic** scintillation **spectrum**.

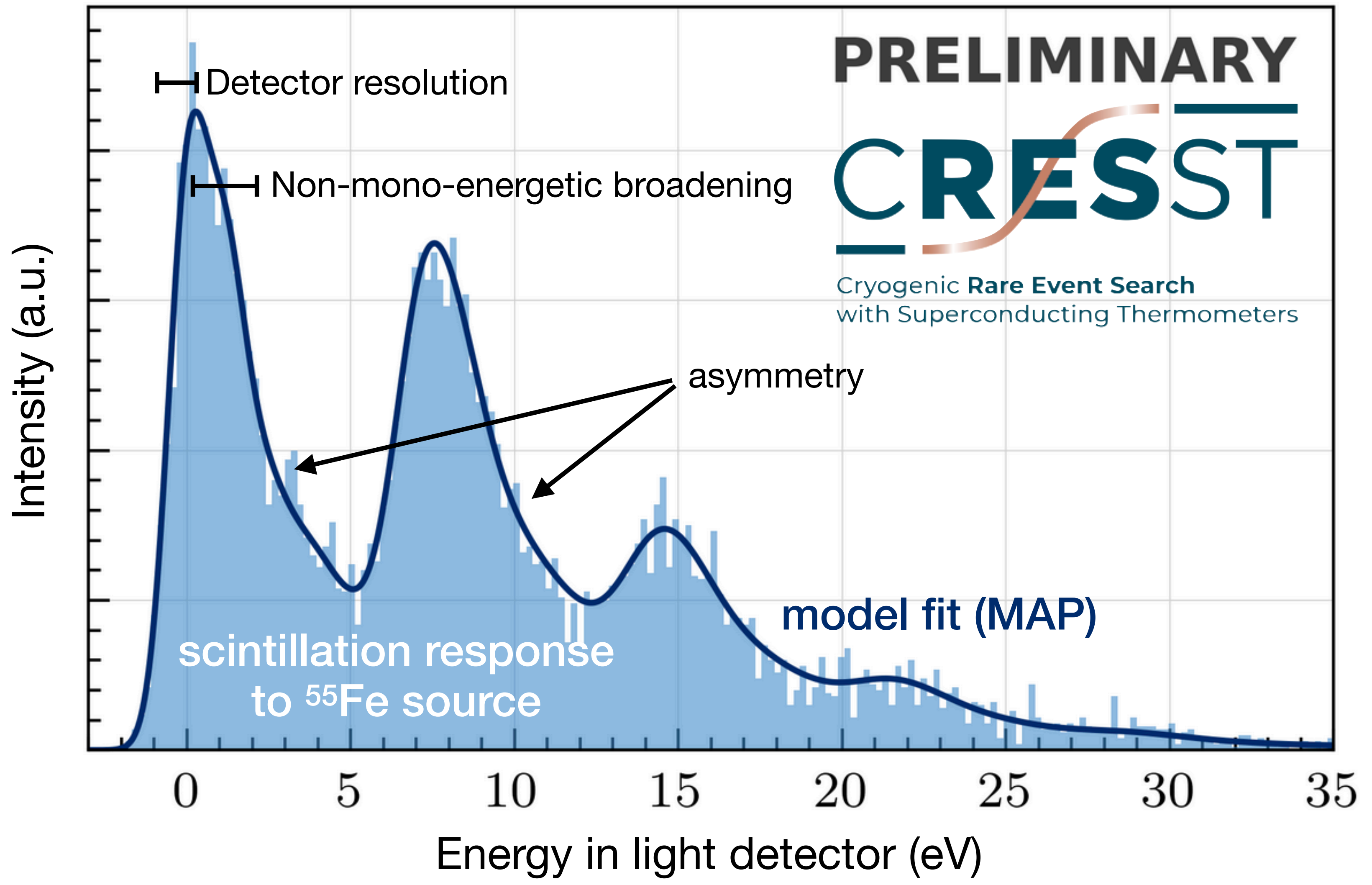
take fit with a grain of salt

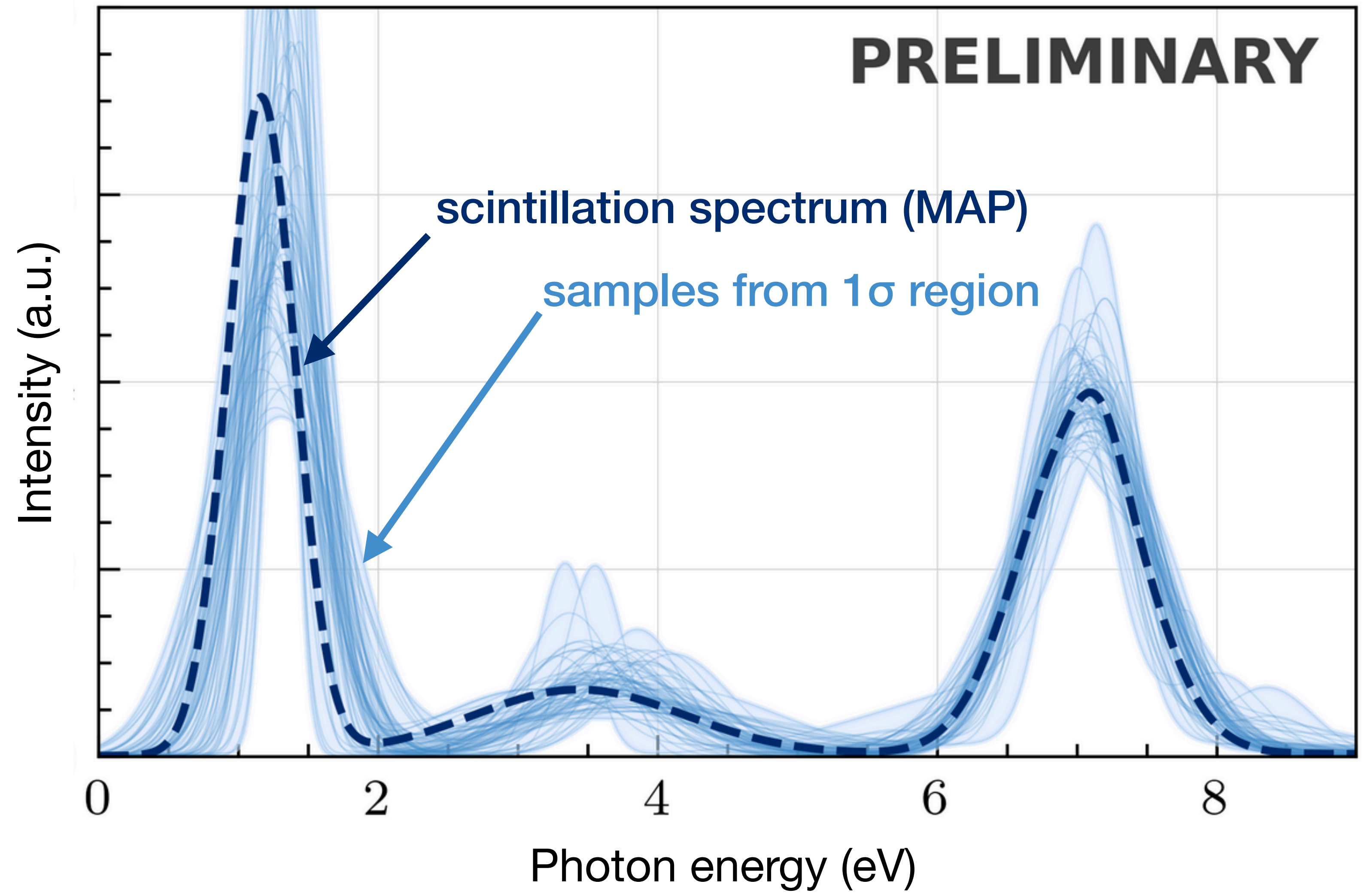


CRESST sapphire data



- **Asymmetry** of photon peaks clearly visible: Suggests a scintillation spectrum that is **not mono-energetic**.
- Gaussian mixture with 5 components was assumed and inferred from a **Bayesian fit** (unbinned; nested sampling).
- In addition to the **7.6 eV** emission line previously used by CRESST for calibration (PRD 110, 083038 (2024)), a feature around **3-4 eV** appears which is **qualitatively consistent** with literature measurements of the sapphire luminescence spectrum. The feature at <2 eV needs further studies.
- Model is **sensitive to intrinsic spectrum** and allows in-situ measurement.
- ***Opportunity:*** With appropriate calibration one could probe the scintillation response as a function of energy and for different recoil types, e.g. with LEDs and reactor neutrons (CRAB)!



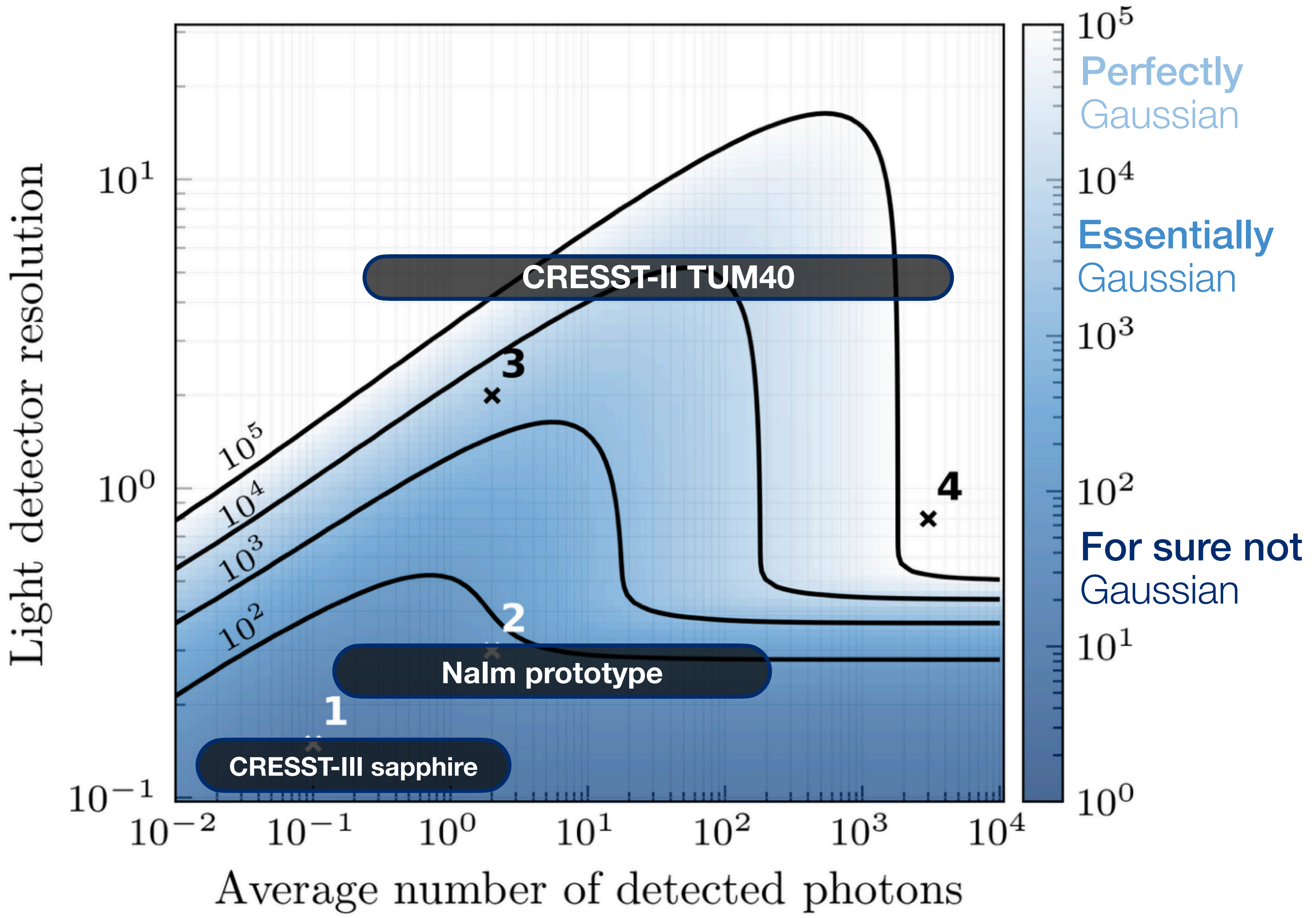


Summary

- Better detectors require **better models**!

- We’re at a point where CSCs can **probe single photon scintillation** spectra which would enable in-situ spectroscopy at cryogenic temperatures.
- Future measurements of the NaIm module will let us **characterize NaI scintillation**.
- Important to mention: Most **past measurements** were **sufficiently Gaussian**.

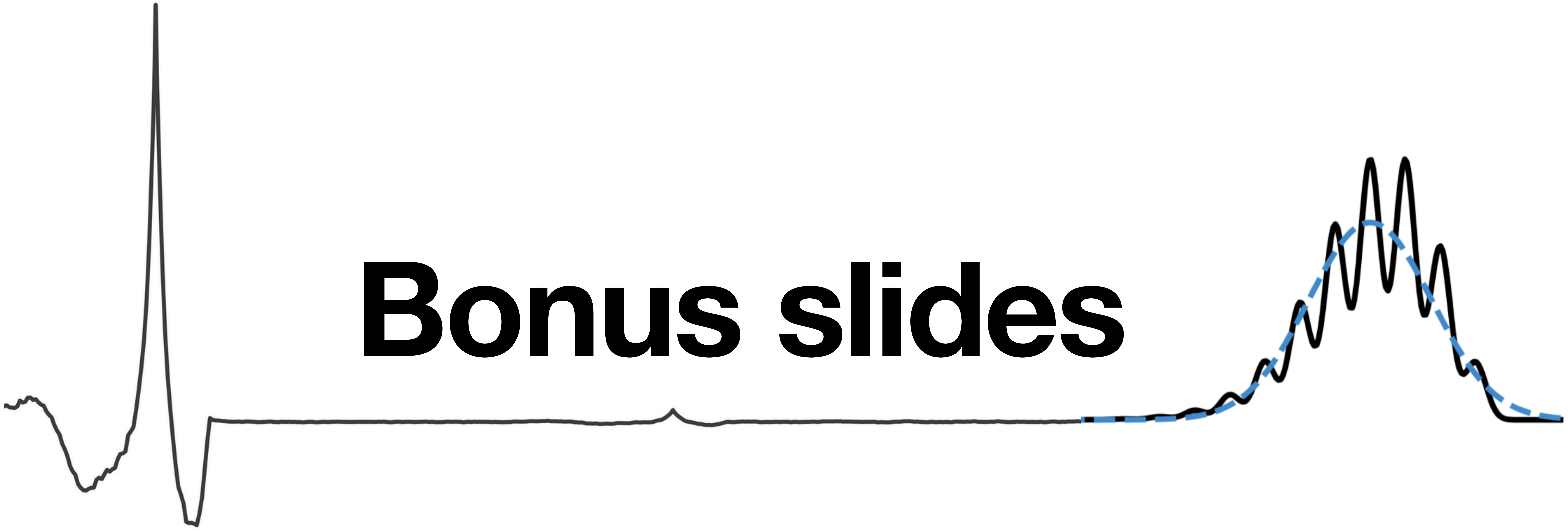
- The **generalized optimum filter** solved a fundamental analysis problem of our **slow NaI pulses**.
- It has become the default reconstruction tool for NaI prototypes, especially above ground where we observed a **factor 5 reduction in threshold**.



Stay tuned!

Questions?

Bonus slides



Generalized filter (details)

Optimum filter amplitude (kernel notation)

$$\hat{A}_0 = \frac{\langle \tilde{\boldsymbol{d}} | \tilde{\boldsymbol{s}} \rangle}{\langle \tilde{\boldsymbol{s}} | \tilde{\boldsymbol{s}} \rangle}$$

data-template overlap

template norm

$$\tilde{h}_k \equiv \frac{2\Delta t}{\langle \tilde{\boldsymbol{s}} | \tilde{\boldsymbol{s}} \rangle} \frac{\tilde{s}_k^*}{S_1(f_k)}$$

conjugate FT of template

noise power spectral density

generalization: $$\tilde{h}_k = \frac{2\Delta t}{\langle \tilde{\boldsymbol{s}} - \tilde{\boldsymbol{s}}_p | \tilde{\boldsymbol{s}} \rangle} \frac{(\tilde{\boldsymbol{s}} - \tilde{\boldsymbol{s}}_p)_k^*}{S_1(f_k)}$$

conjugate FT of template with polynomial part projected out

log-likelihood

$$\lambda(\boldsymbol{d}\,|\,A) = -\frac{1}{2}\langle \tilde{\boldsymbol{d}} - A\tilde{\boldsymbol{s}} - \mathbf{B}\tilde{\boldsymbol{a}}\,|\,\tilde{\boldsymbol{d}} - A\tilde{\boldsymbol{s}} - \mathbf{B}\tilde{\boldsymbol{a}} \rangle + \text{const}\,.$$

Symbols used in main slides

$$\delta_j \equiv \langle \tilde{\boldsymbol{b}}^{(j)} | \tilde{\boldsymbol{d}} \rangle\,, \quad \sigma_j \equiv \langle \tilde{\boldsymbol{b}}^{(j)} | \tilde{\boldsymbol{s}} \rangle\,, \quad G_{jl} \equiv \langle \tilde{\boldsymbol{b}}^{(j)} | \tilde{\boldsymbol{b}}^{(l)} \rangle$$

data projection coefficients to baseline

template projection coefficients to baseline

Gram matrix

Theoretical amplitude reconstruction bias of regular optimum filter

$$\Delta \hat{A}_0 \equiv \frac{\langle A\tilde{\boldsymbol{s}} + \tilde{\boldsymbol{b}} | \tilde{\boldsymbol{s}} \rangle}{\langle \tilde{\boldsymbol{s}} | \tilde{\boldsymbol{s}} \rangle} - \hat{A}_0 = \frac{\langle \tilde{\boldsymbol{b}} | \tilde{\boldsymbol{s}} \rangle}{\langle \tilde{\boldsymbol{s}} | \tilde{\boldsymbol{s}} \rangle} = T e^{-\frac{t'}{\tau}} \frac{\langle \mathrm{RFFT}(e^{-\boldsymbol{t}/\tau}) | \tilde{\boldsymbol{s}} \rangle}{\langle \tilde{\boldsymbol{s}} | \tilde{\boldsymbol{s}} \rangle}$$

amplitude of previous pulse

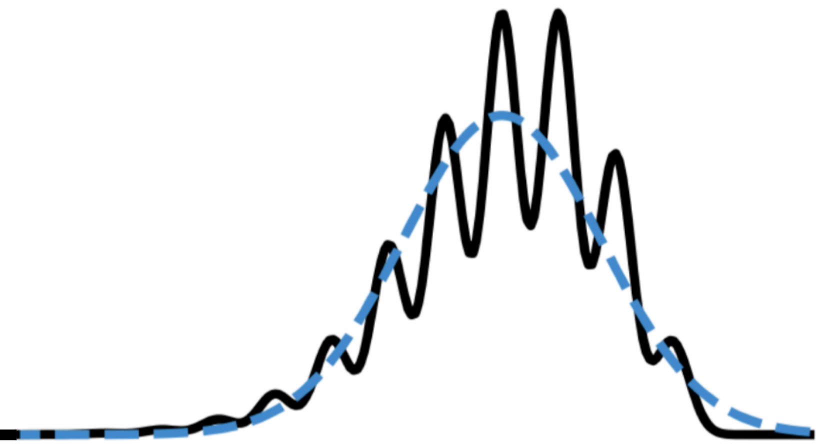
decay time of previous pulse

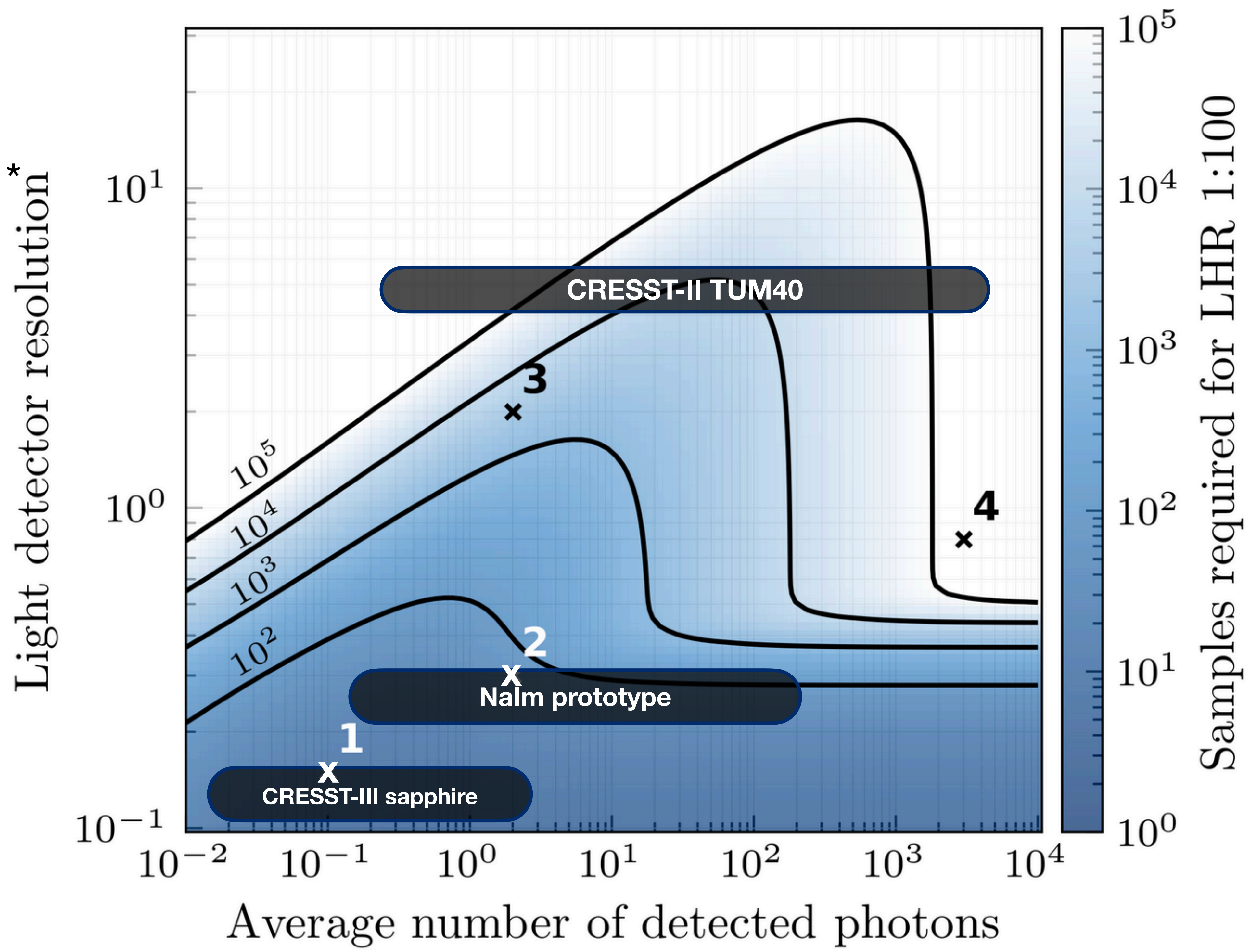
time since previous pulse

Fourier domain noise-weighted inner product

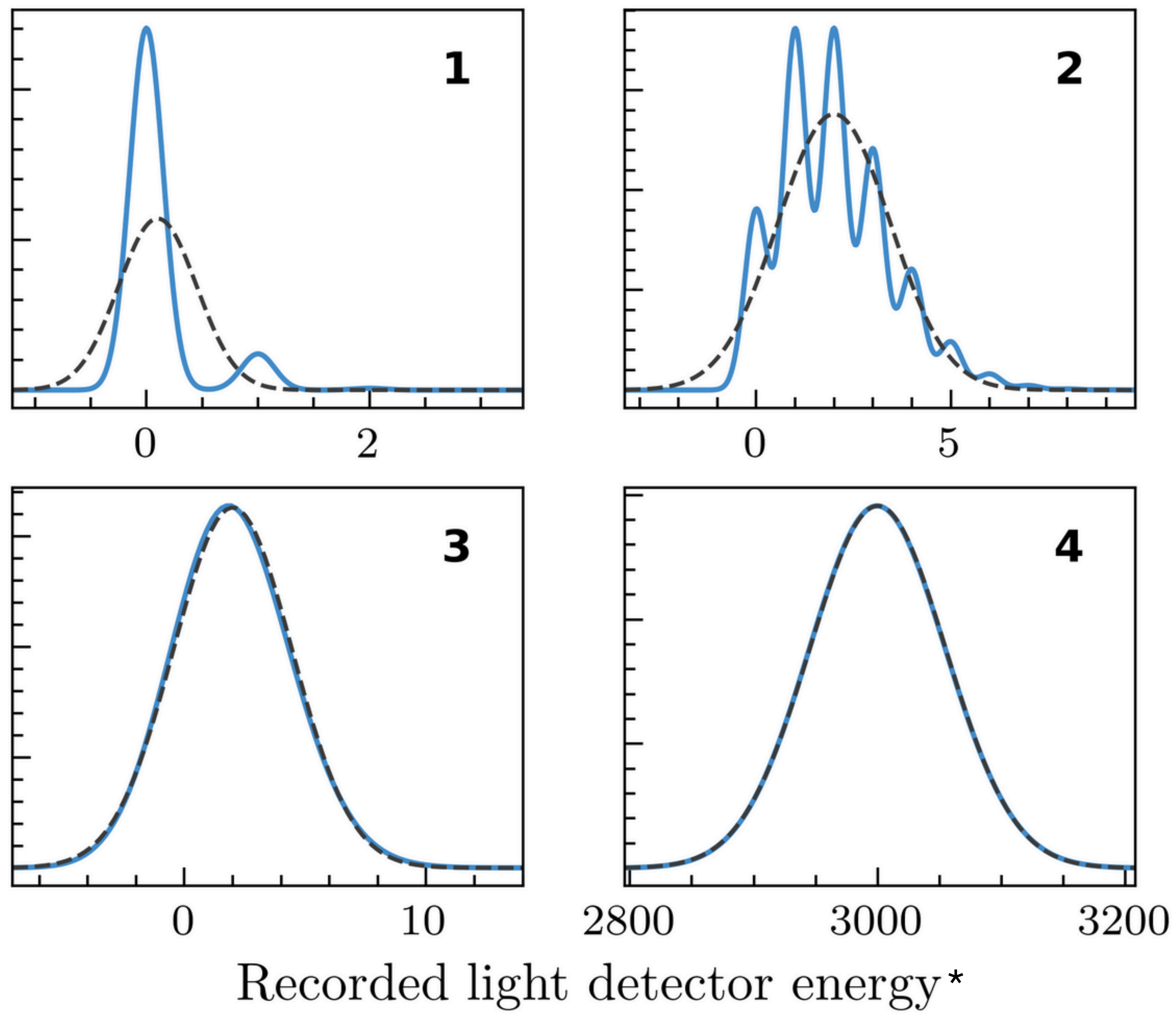
$$\langle \tilde{\boldsymbol{x}} | \tilde{\boldsymbol{y}} \rangle \equiv \frac{2\Delta t}{N} \sum_{k=0}^{N/2} \omega_k \frac{\tilde{x}_k^* \tilde{y}_k}{S_1(f_k)}, \qquad \omega_k = \begin{cases} 1, & k = 0,\ N/2 \\ 2, & \text{else} \end{cases}$$

Gaussian vs. Poissonian model



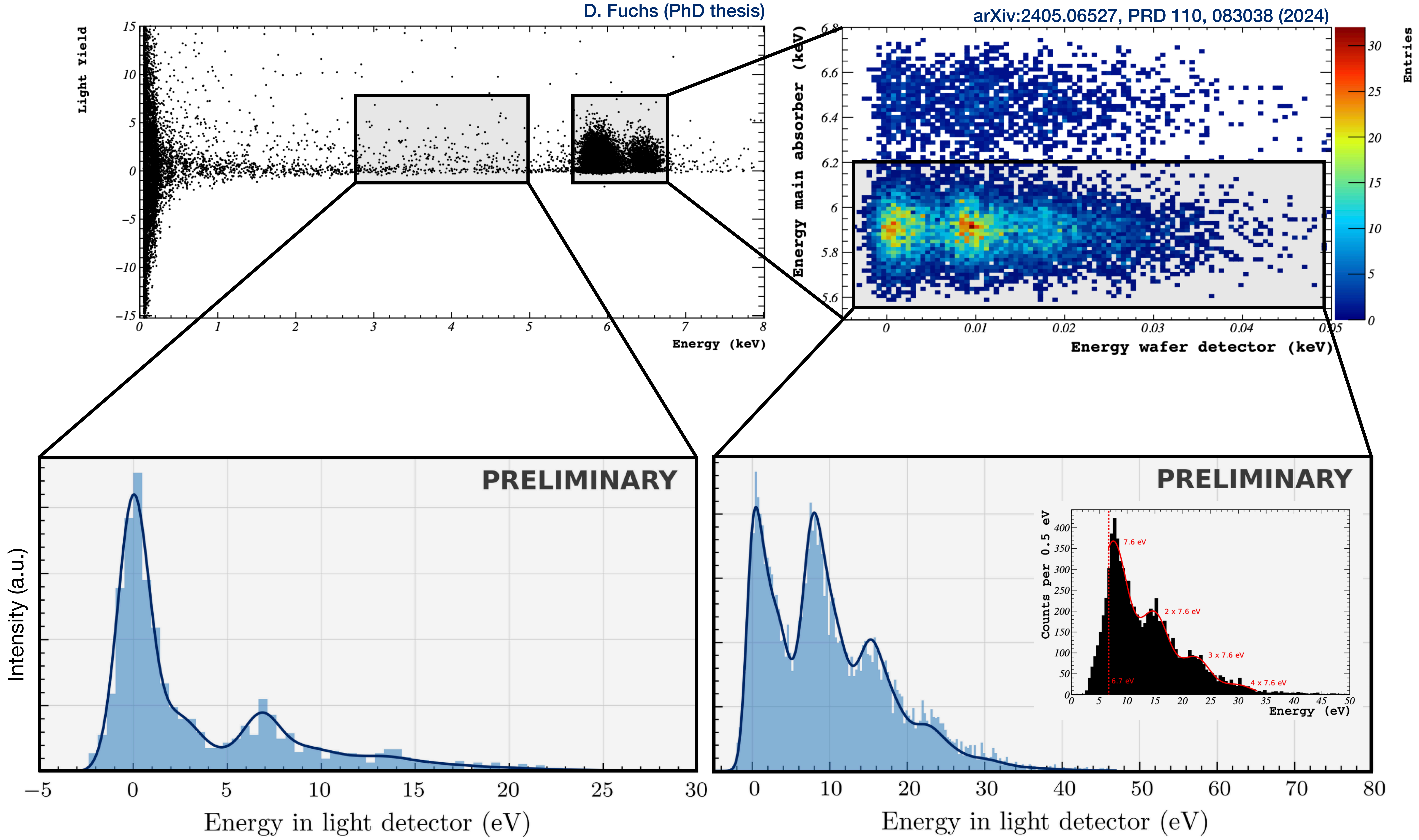


Photon energy assumed for NaI: 4.2 eV, CaWO₄: 2.9 eV, sapphire: 7.6 eV



* in units of single photon energy

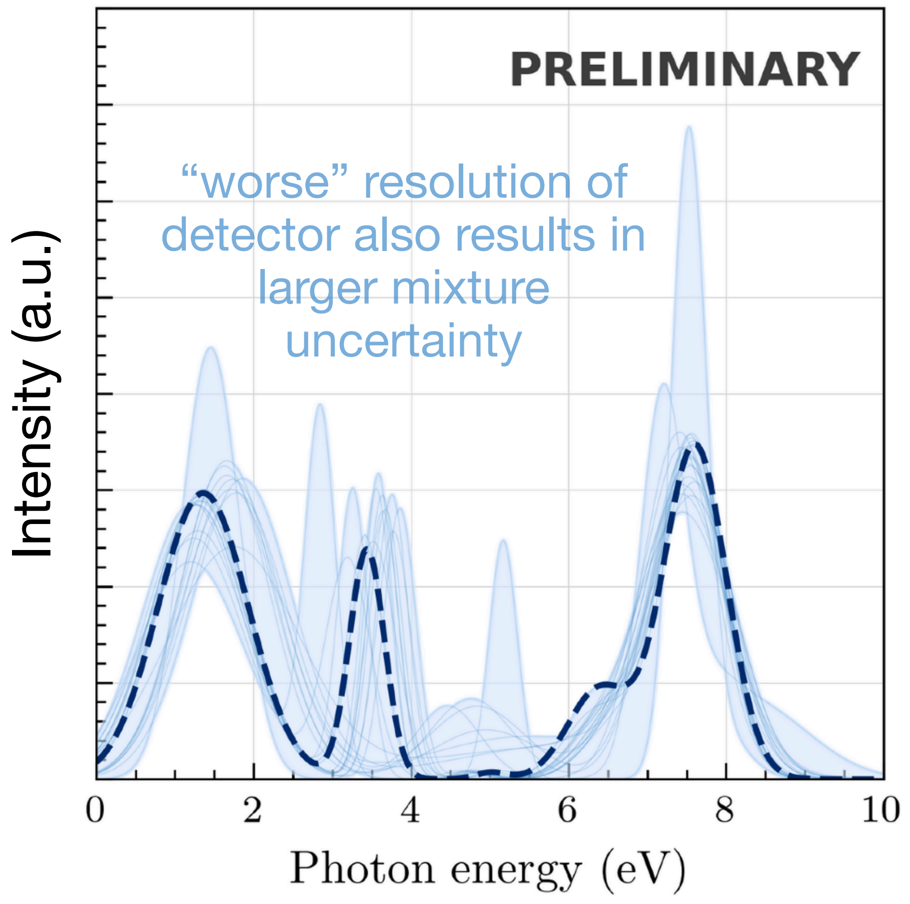
More sapphire fits


D. Fuchs (PhD thesis)

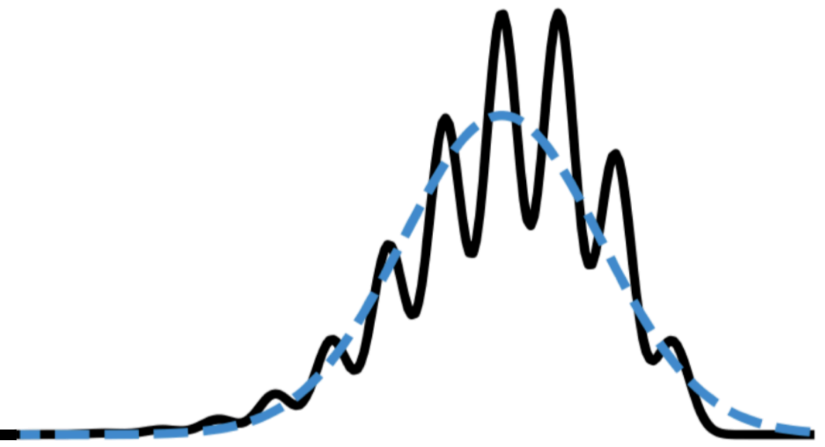
arXiv:2405.06527, PRD 110, 083038 (2024)

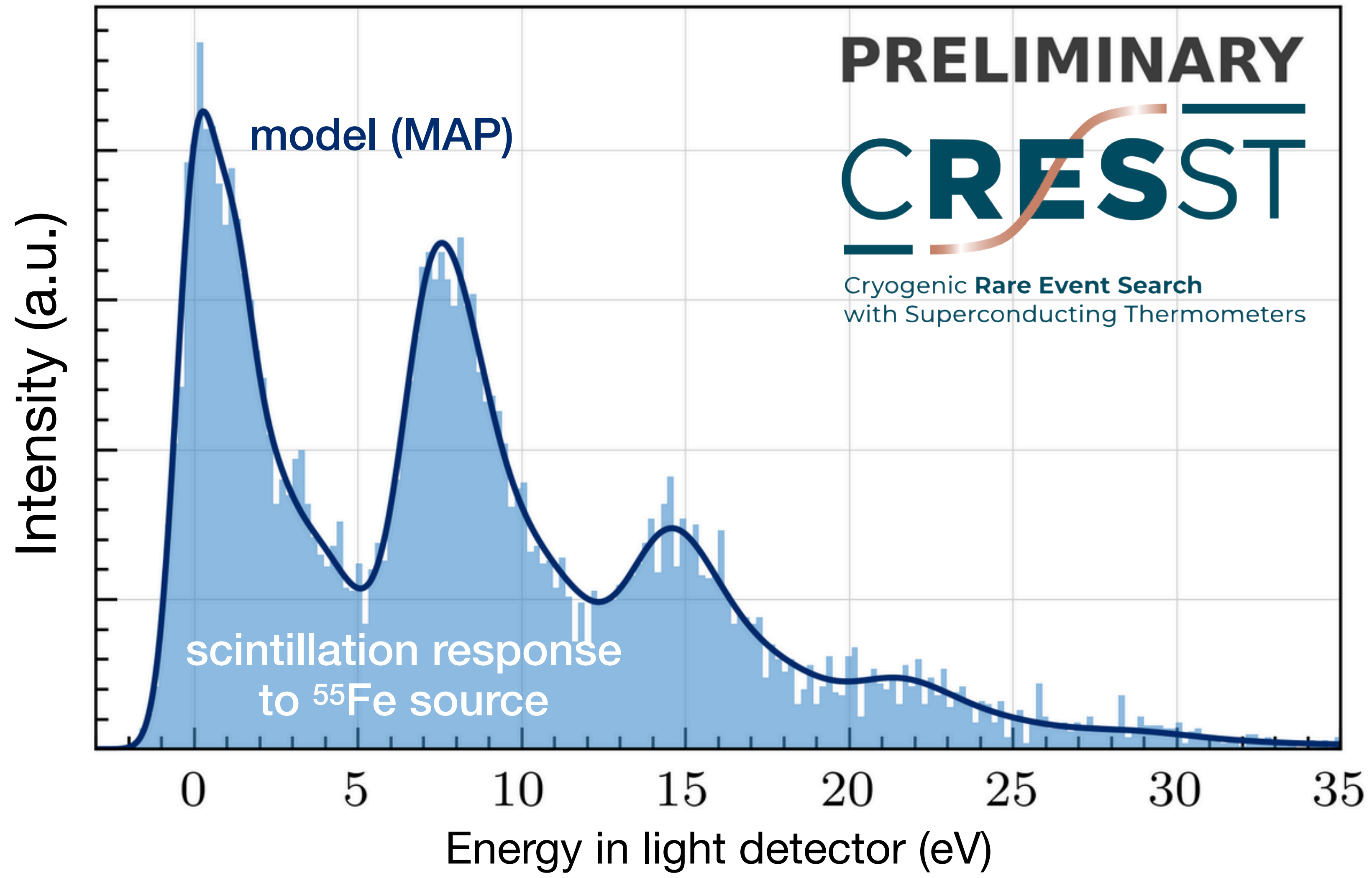
CRESST

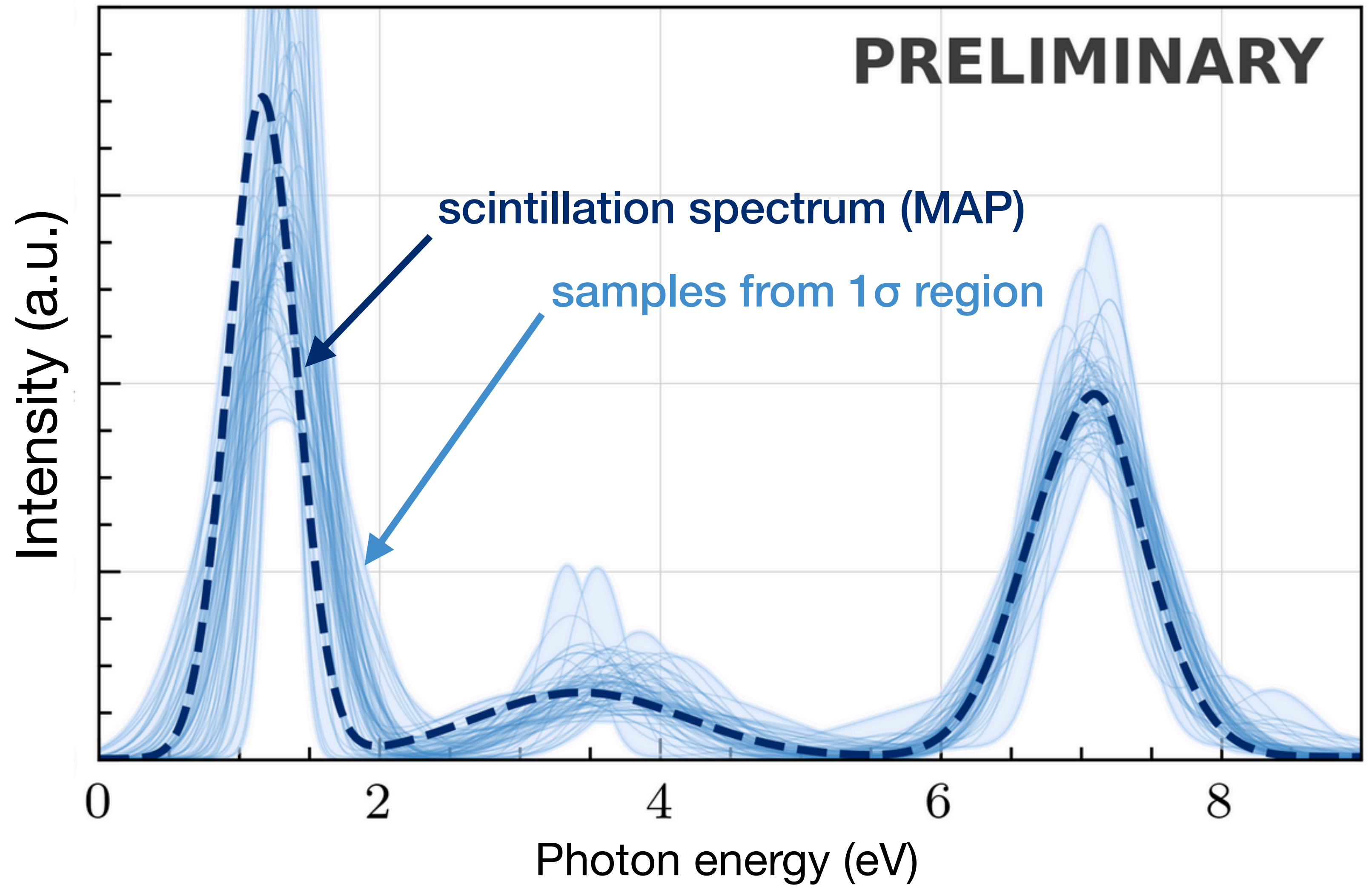
Cryogenic **Rare Event Search**
with Superconducting Thermometers


“worse” resolution of detector also results in larger mixture uncertainty

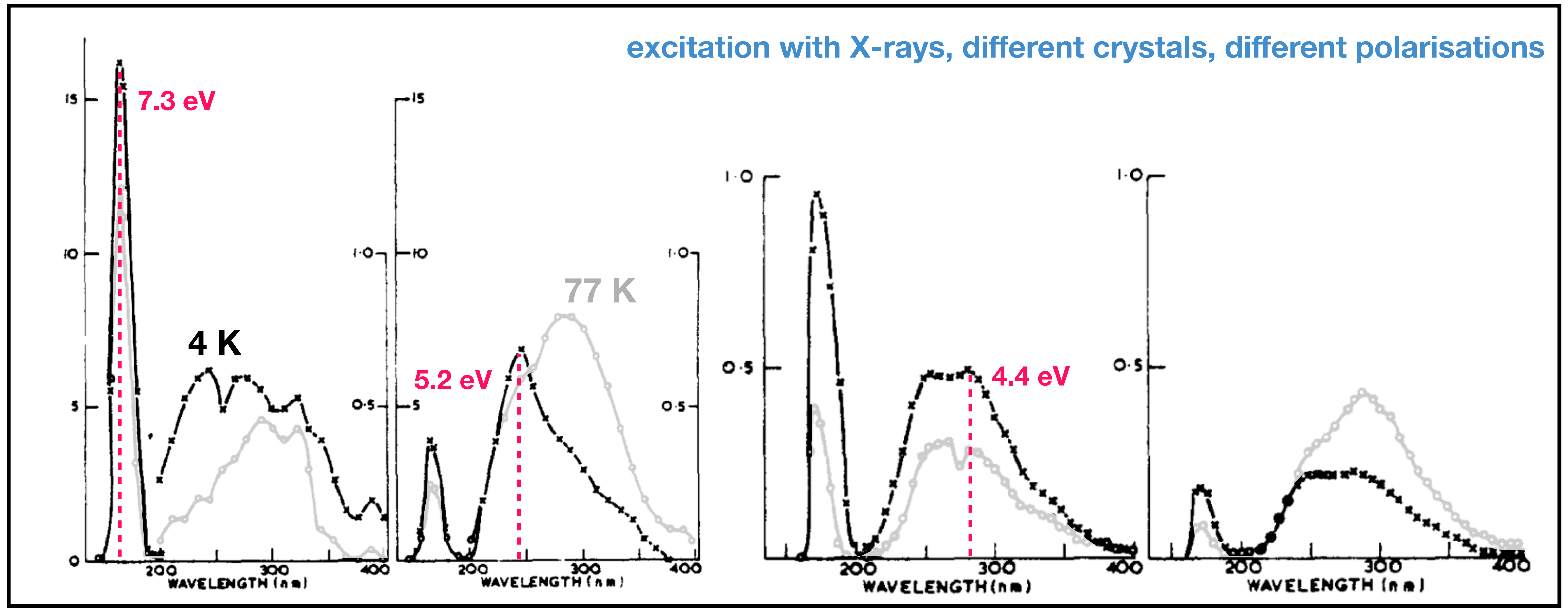
Sapphire scintillation spectra







Solid State Comm. 6, 8 (1968)



Phys. Rev. B 60, 502 (1999)