

THE QUALIPHIDE-FIR DARK MATTER EXPERIMENT & **LOW-ENERGY EXCESS**

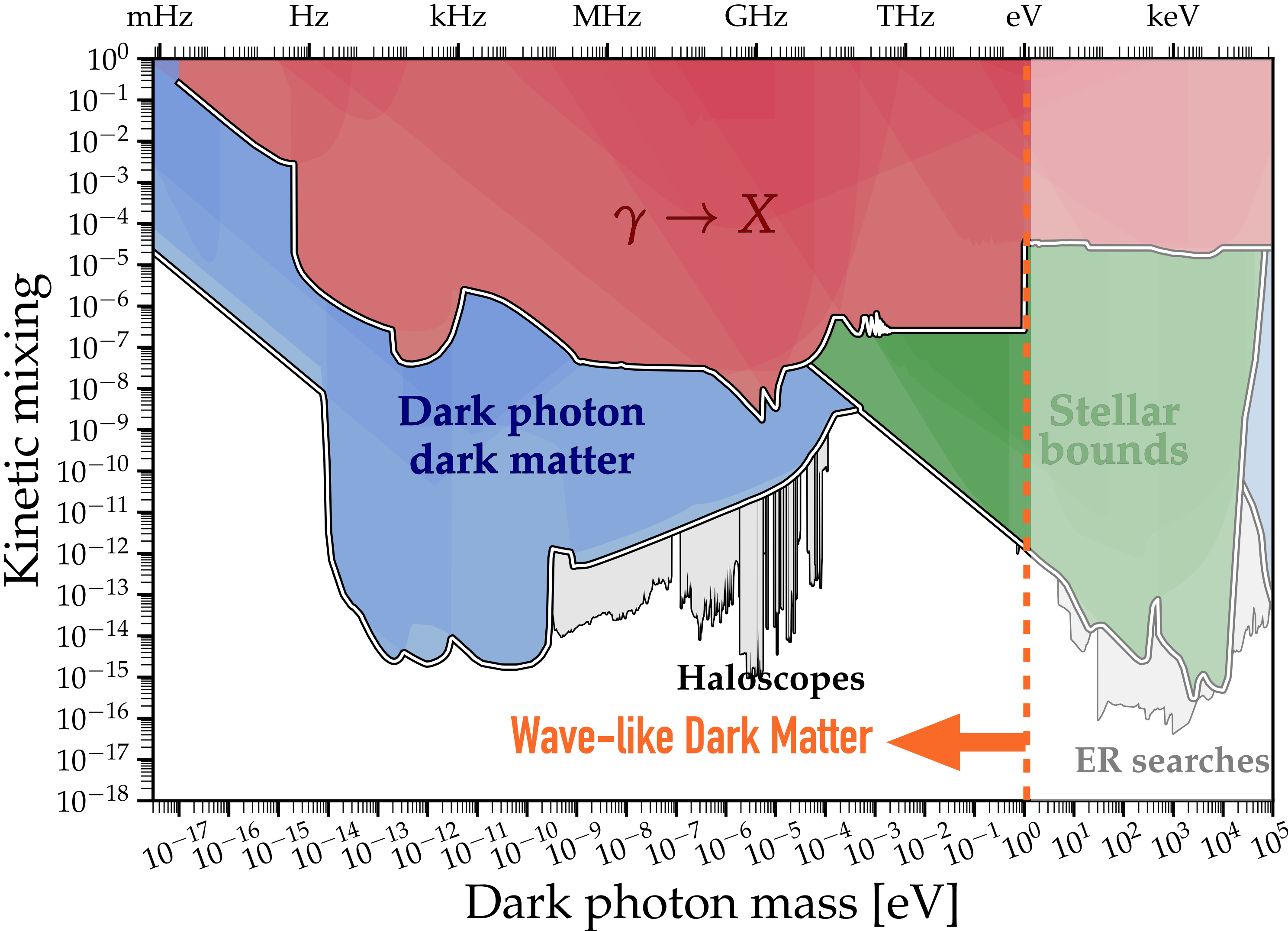
Lanqing Yuan, on behalf of the QUALIPHIDE collaboration

June 16, 2026, RISQ

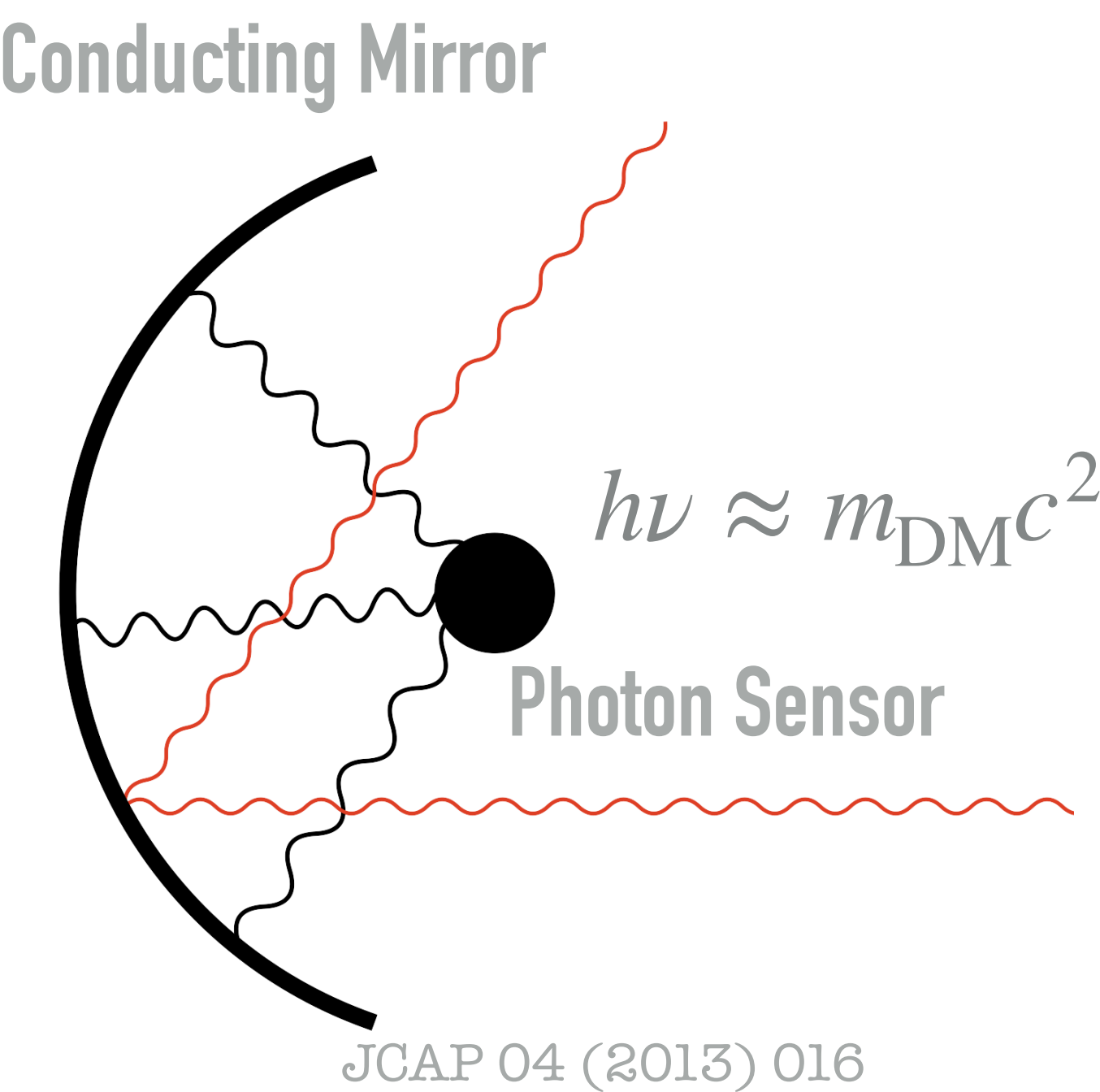


QUALIPHIDE-FIR DARK MATTER EXPERIMENT

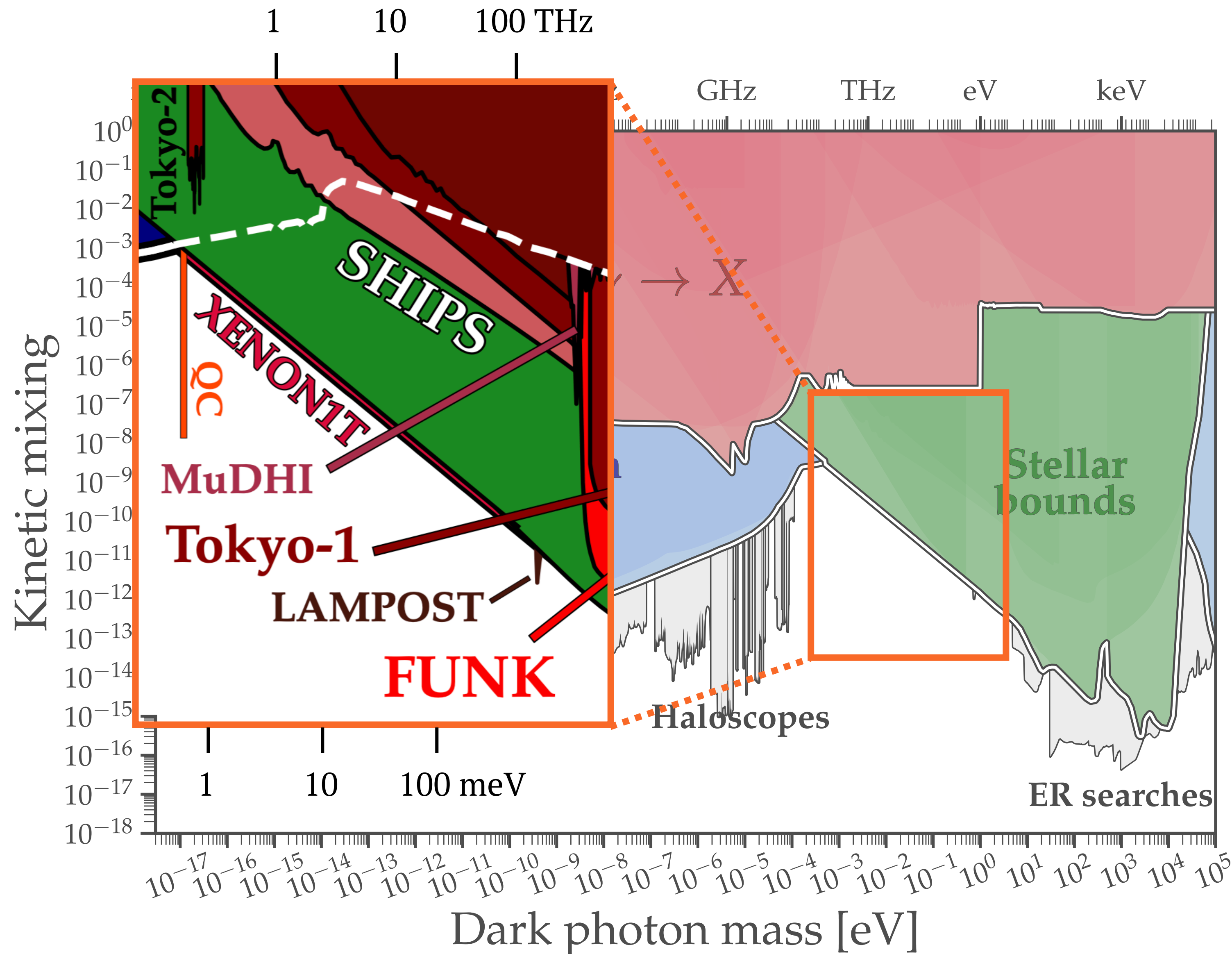
SETUP



Phys.Rev.D 104 (2021) 9, 095029



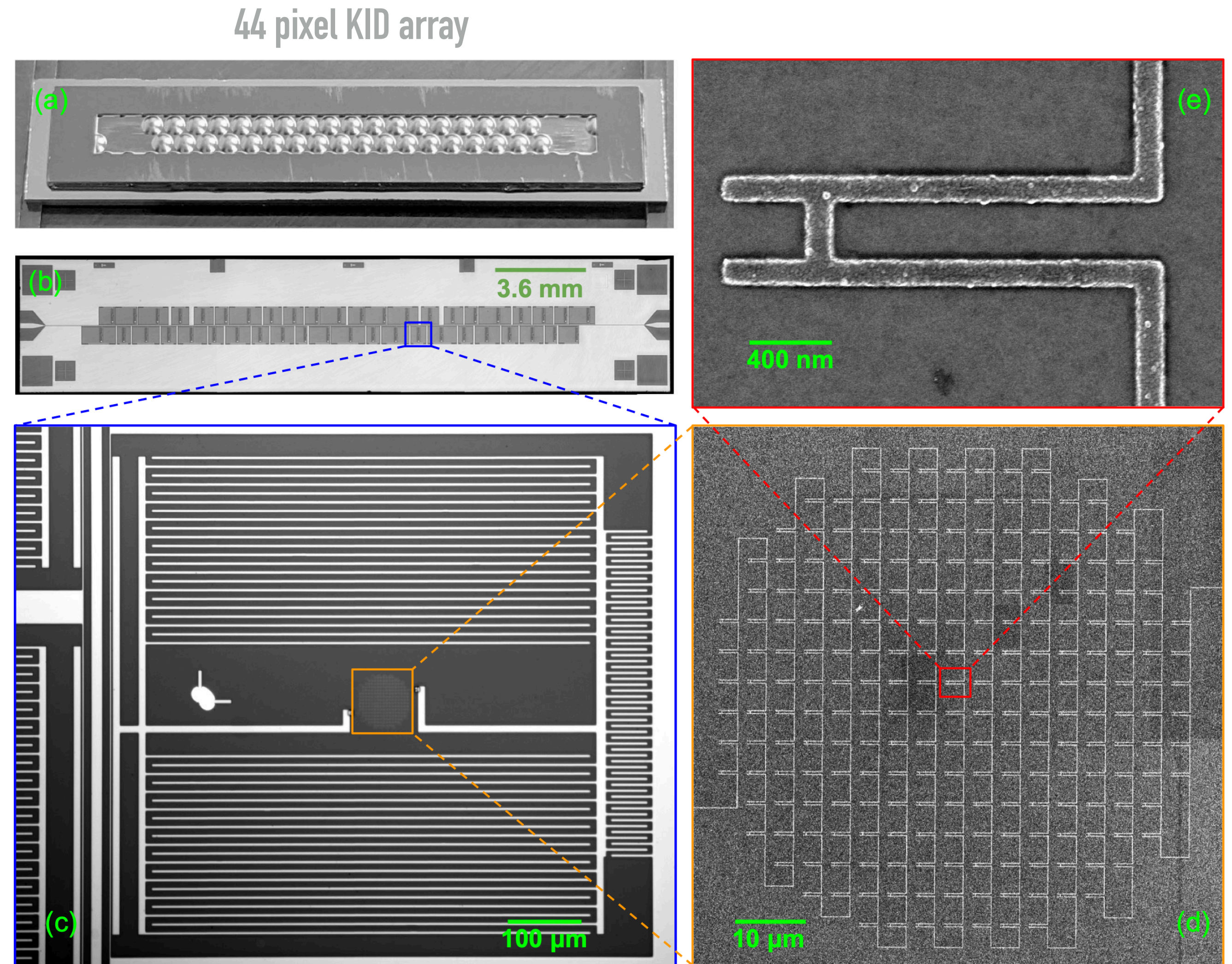
We can search for dark photon here using dish antenna detectors!



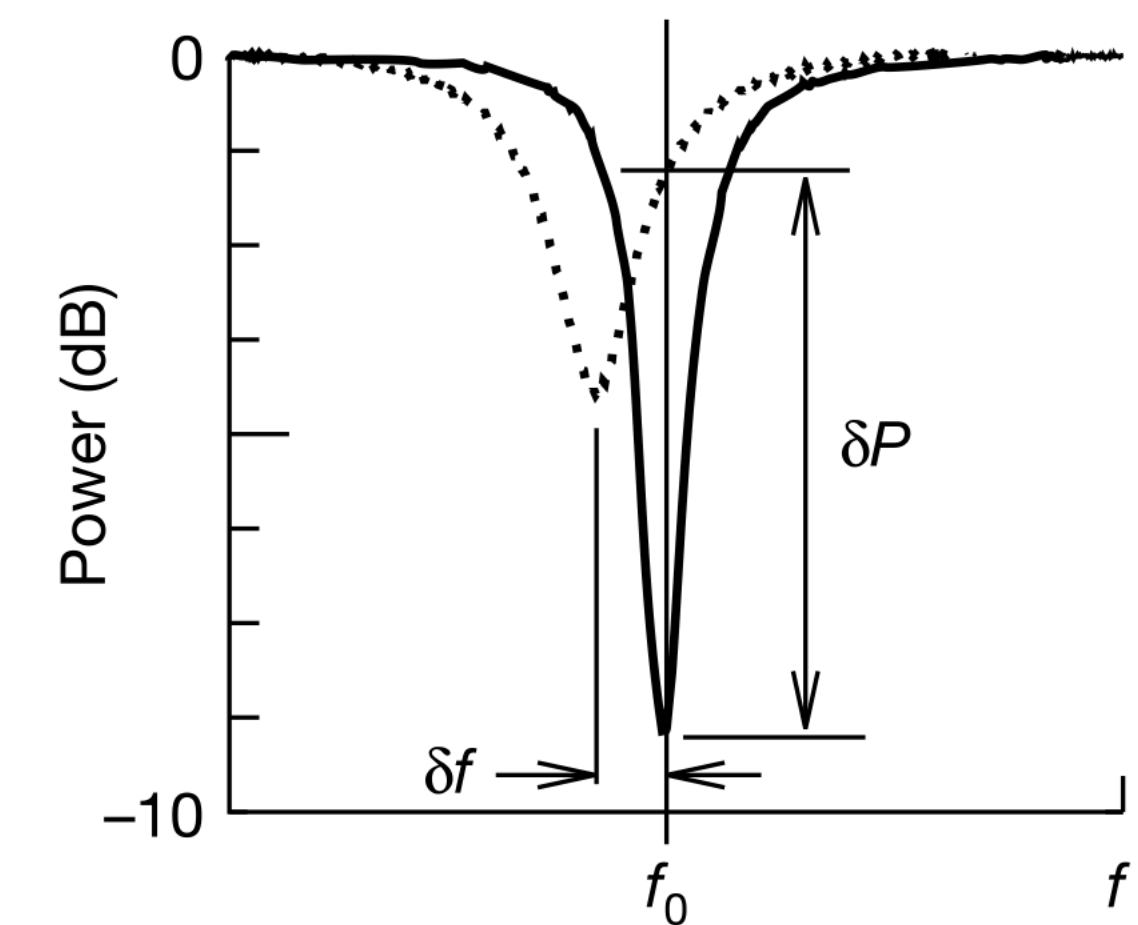
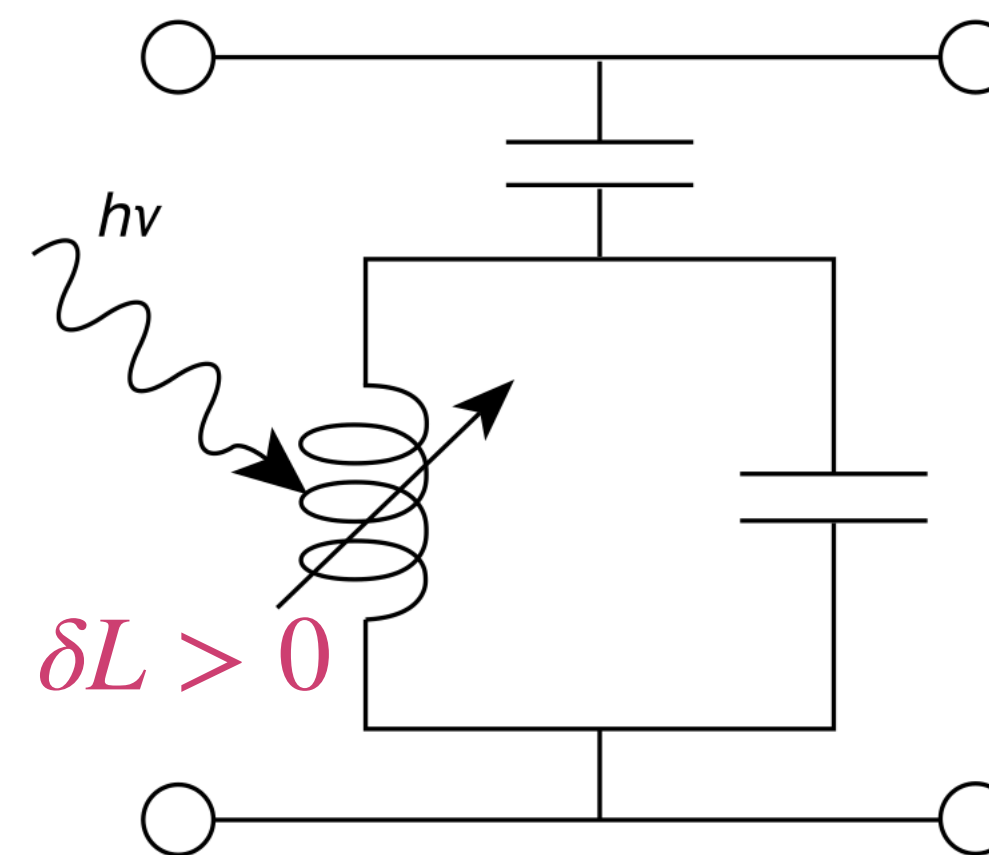
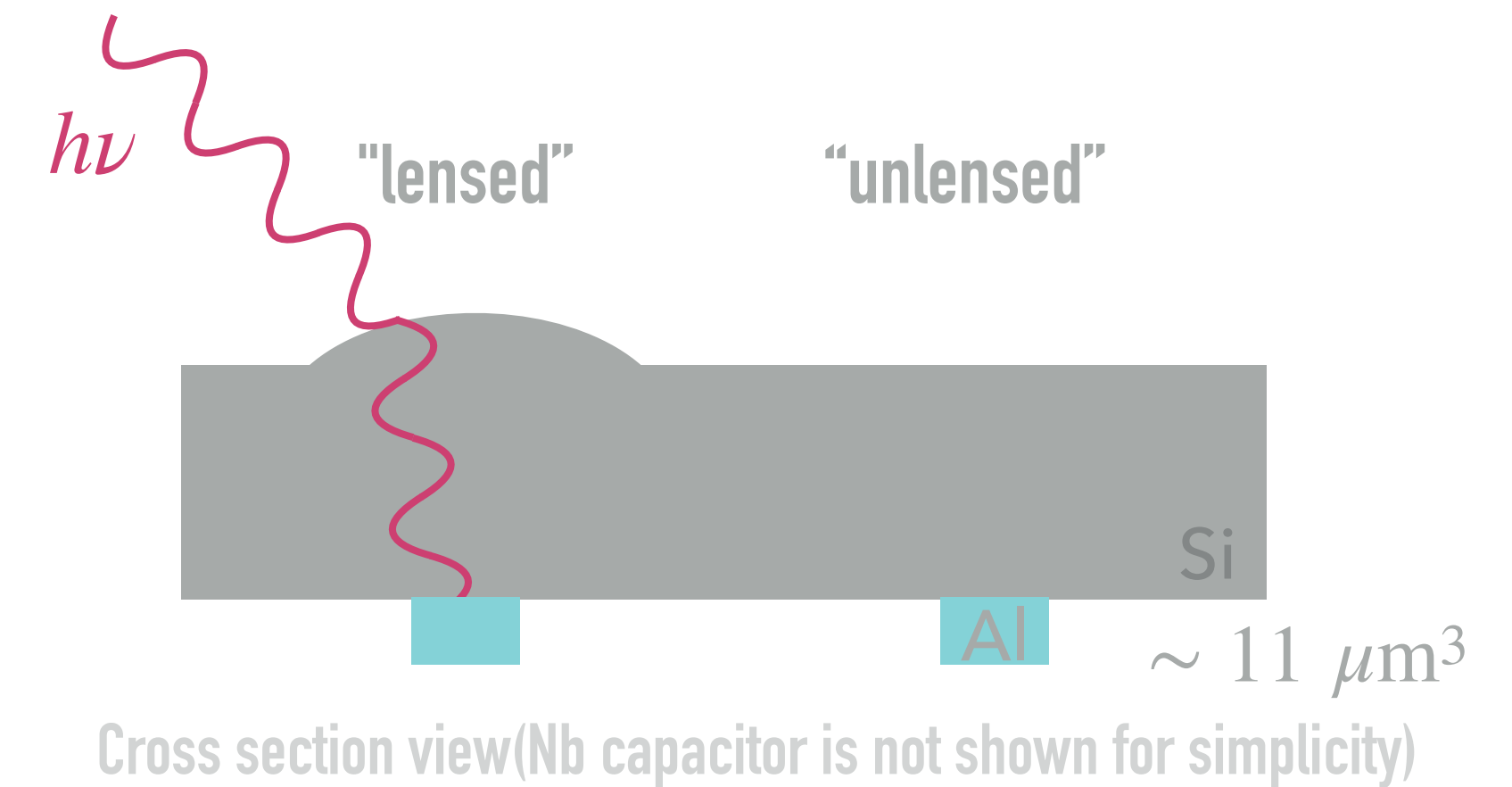
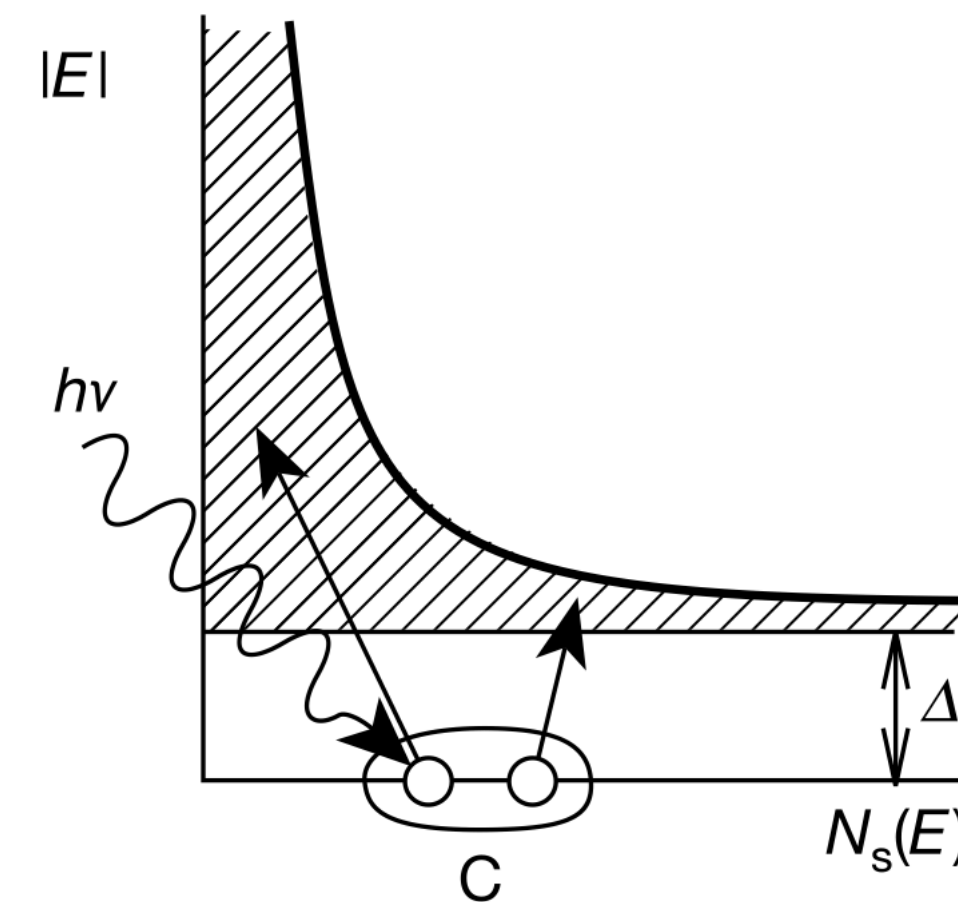
Phys.Rev.D 104 (2021) 9, 095029

- ▶ **"The far-infrared (FIR) desert"**: Absence of lab search constraint in FIR frequency range ($0.1 \sim 100$ THz). **Photon readout is a central challenge**
 - ▶ Volume scaling problem in resonant cavity experiments
 - ▶ Noise problem in heterodyne readout at FIR
 - ▶ Threshold problem in electronic recoil experiments
- ▶ Ideally, we want an experiment in the FIR range:
 - ▶ **Broadband sensitivity**: wide search range
 - ▶ **Single photon-counting**: Beyond Standard Quantum Limit
 - ▶ **Energy resolution**: extra background rejection
 - ▶ **Background modeling**: enable discovery power

- ▶ Kinetic inductance detectors (KIDs) are nano-fabricated superconducting LC resonator
- ▶ Using Al superconducting inductor as photon absorber
- ▶ Working principle:
 - ▶ Photons focused by Si micro-lenslet
 - ▶ Photon/Phonon breaks Cooper pairs
 - ▶ Kinetic inductance increased
 - ▶ Resonance frequency and quality factor decreases
- ▶ At low energy, resonance frequency shift is linear to the absorbed energy

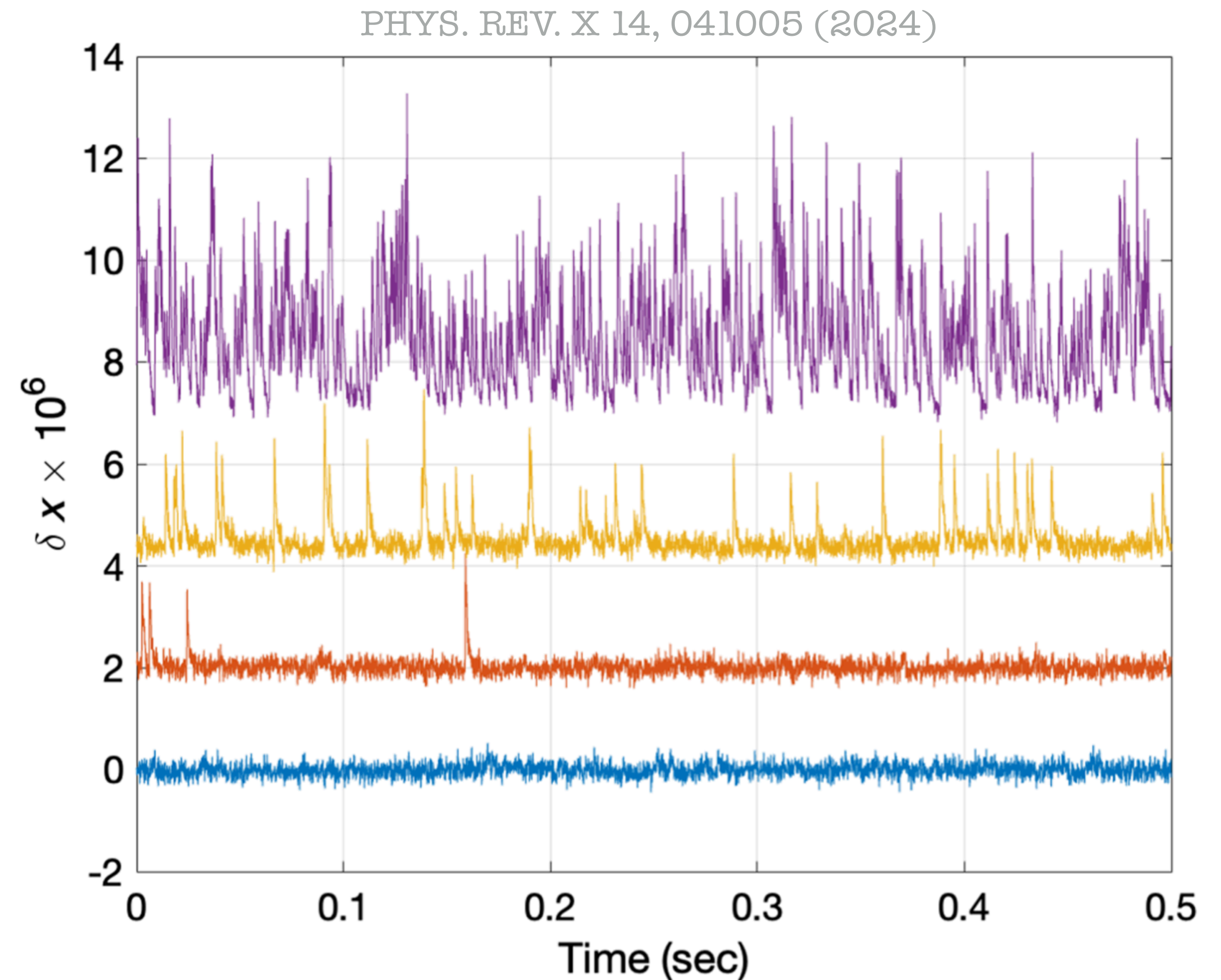


- ▶ Kinetic inductance detectors (KIDs) are nano-fabricated superconducting LC resonator
- ▶ Using Al superconducting inductor as photon absorber
- ▶ Working principle:
 - ▶ Photons focused by Si micro-lenslet
 - ▶ Photon/Phonon breaks Cooper pairs
 - ▶ Kinetic inductance increased
 - ▶ Resonance frequency and quality factor decreases
- ▶ At low energy, resonance frequency shift is linear to the absorbed energy

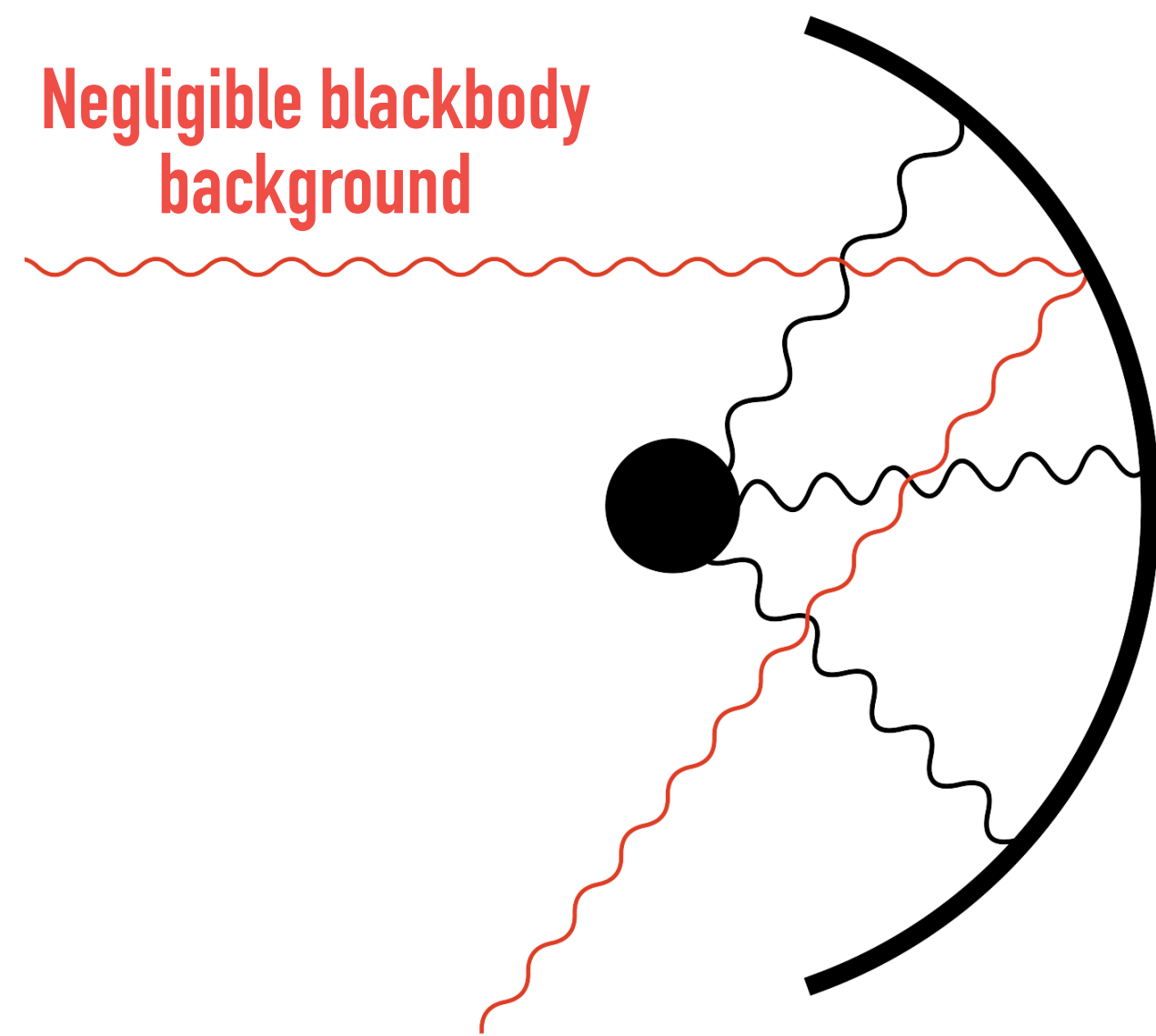


Nature 425 (2003) 6960, 817-821

- ▶ Kinetic inductance detectors (KIDs) are nano-fabricated superconducting LC resonator
- ▶ Using Al superconducting inductor as photon absorber
- ▶ Working principle:
 - ▶ Photons focused by Si micro-lenslet
 - ▶ Photon/Phonon breaks Cooper pairs
 - ▶ Kinetic inductance increased
 - ▶ Resonance frequency and quality factor decreases
- ▶ At low energy, resonance frequency shift is linear to the absorbed energy

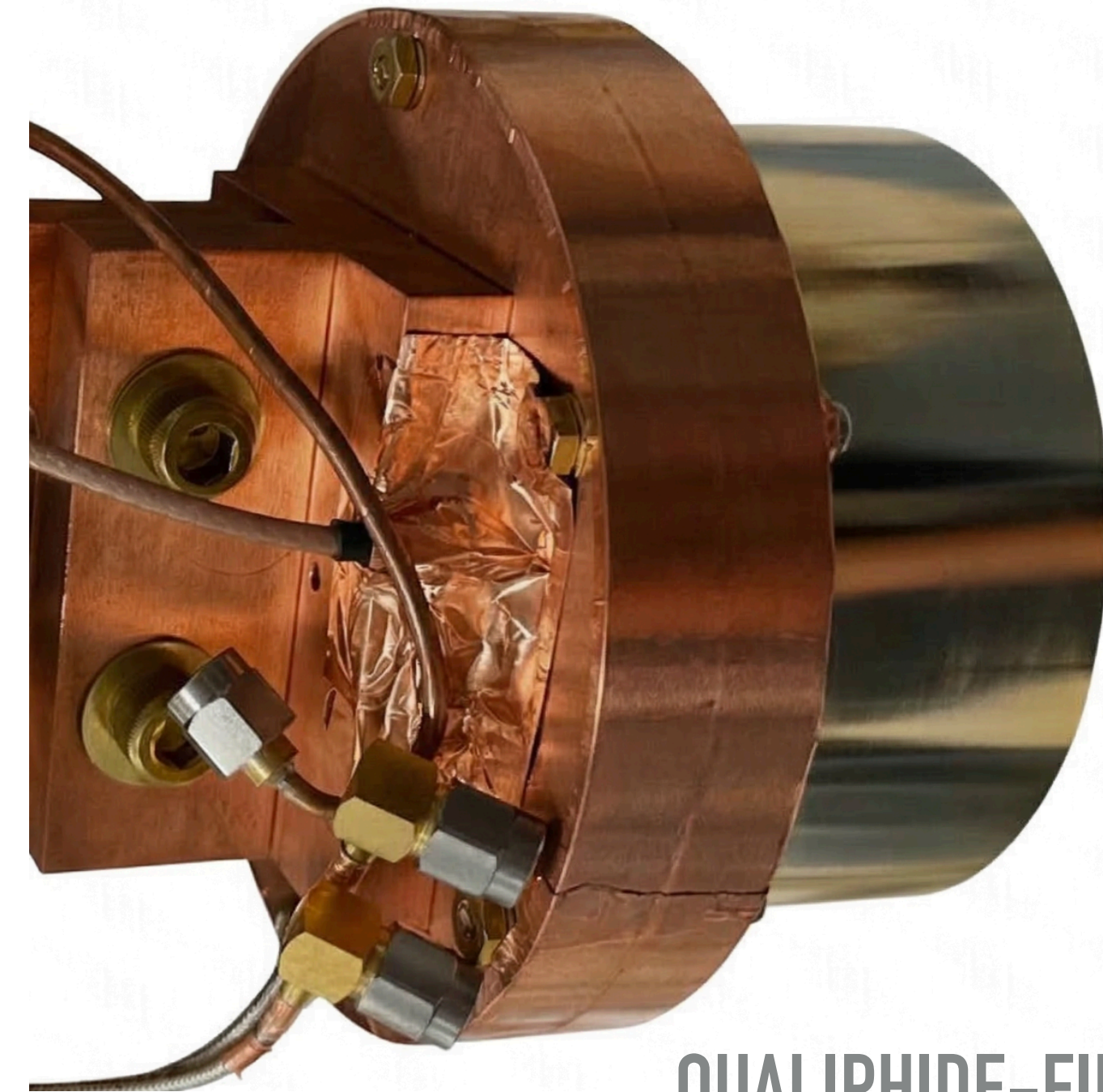


Single photon response:
$$\delta x \equiv \frac{f_{r,0} - f_r}{f_{r,0}} \propto \delta N_{\text{qp}} / V_{\text{sc}} \propto E_{\text{abs}} / V_{\text{sc}}$$



JCAP 04 (2013) 016

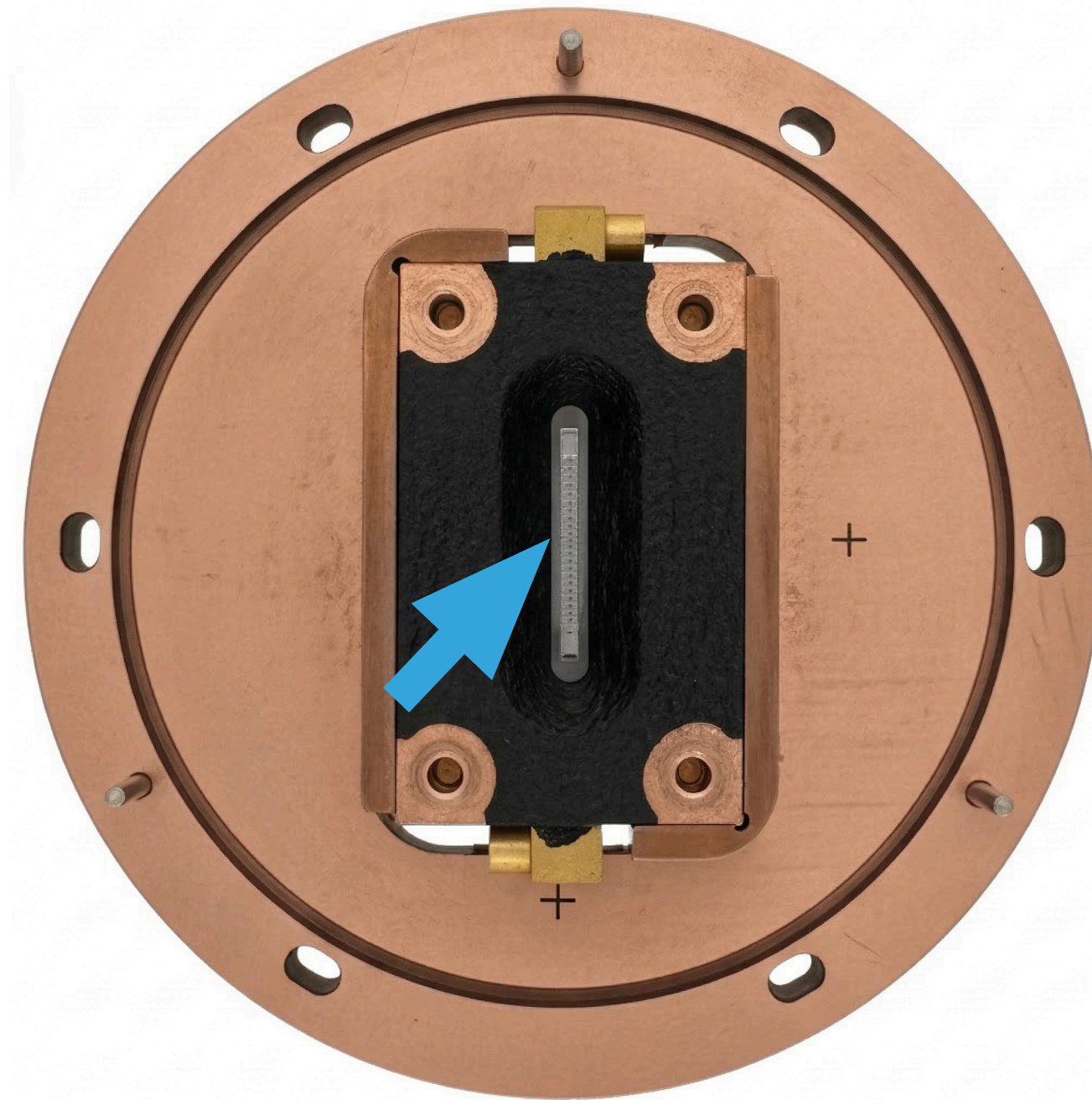
- ▶ Science data taken at 125 mK → blackbody radiation background is negligible
- ▶ ~20 hours of exposure
- ▶ Timestream data taking at 38 kHz sampling rate with all 41 channels on



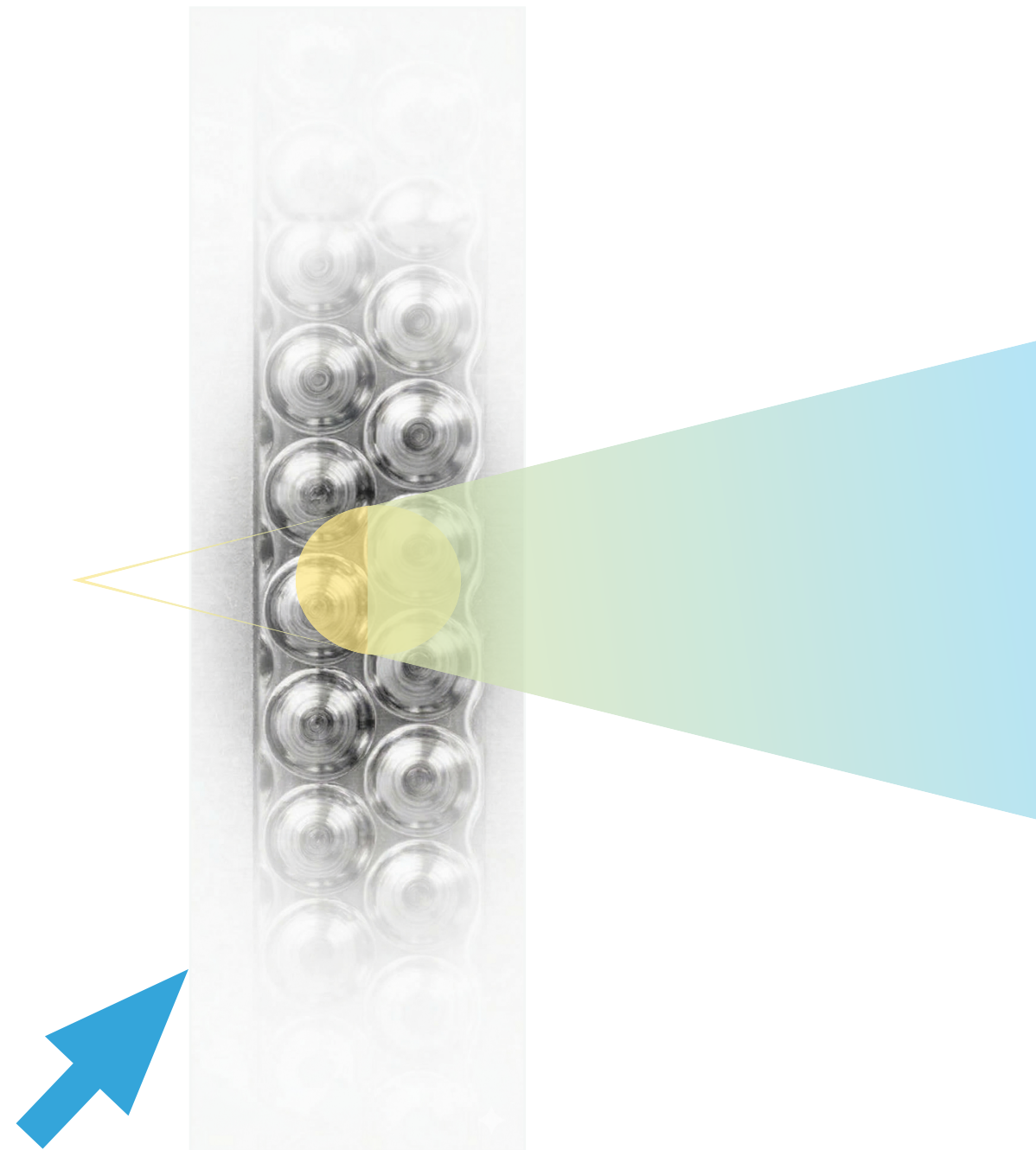
QUALIPHIDE-FIR

- ▶ Gold-coated spherical mirror with radius 4 cm and area 52 cm²
- ▶ Used a 41-channel FIR KID array (8 unlensed)
- ▶ Displaced focus of the spherical mirror so the central 4 central pixels form the DP signal channels

Sensor array is mounted using epoxy



KID array



Zoom-in around the 4 signal channels

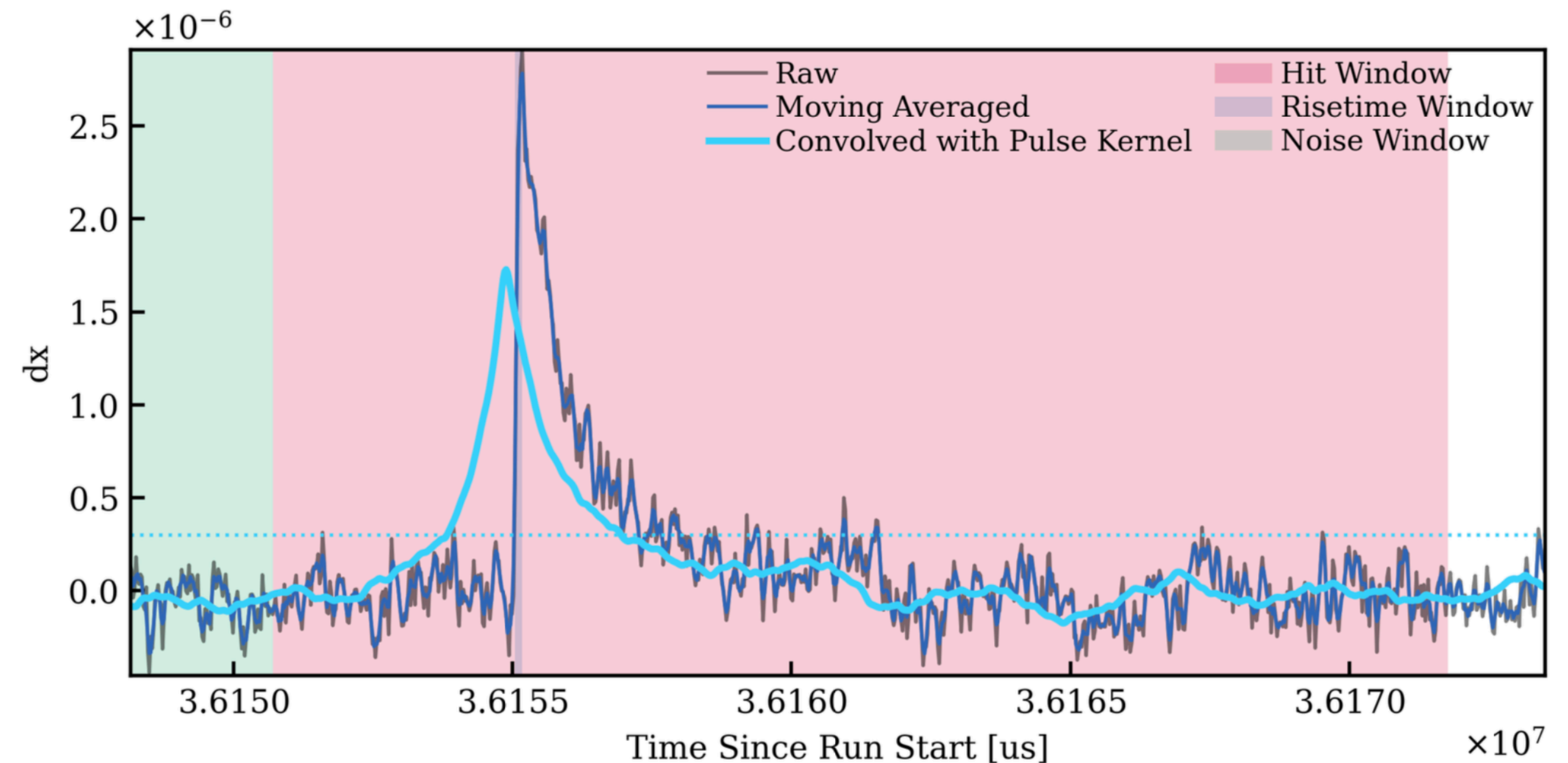


Gold-plated mirror

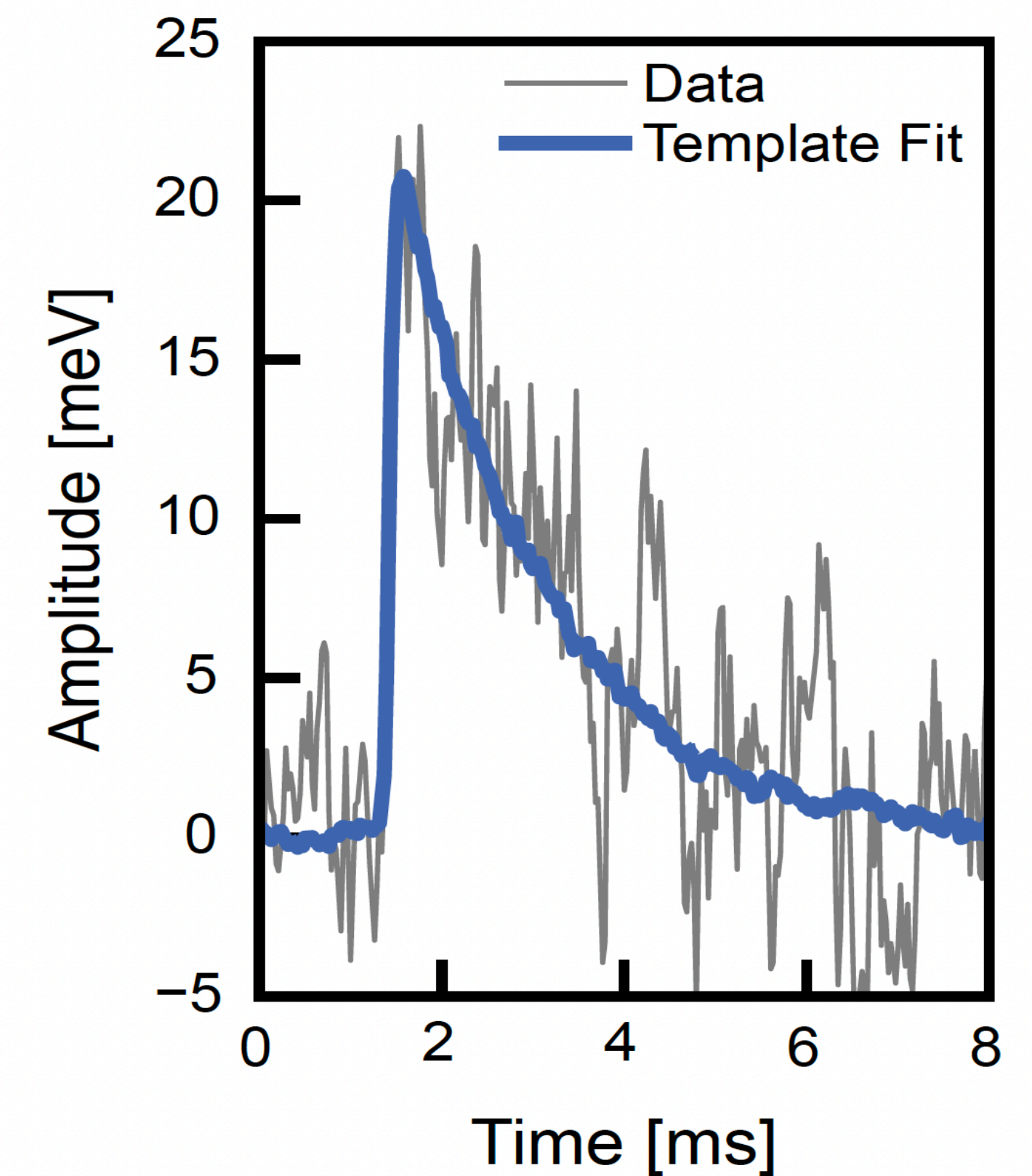
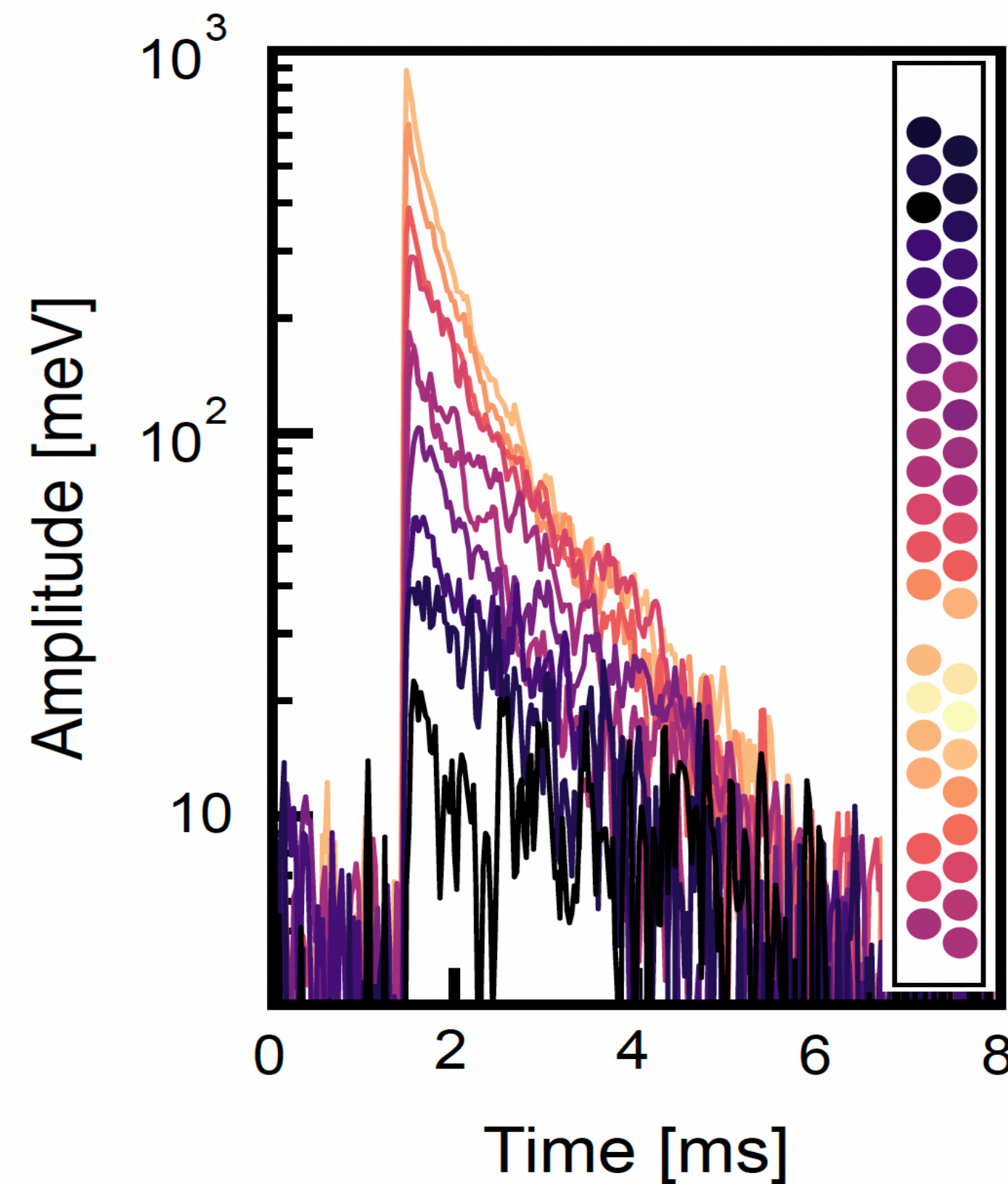
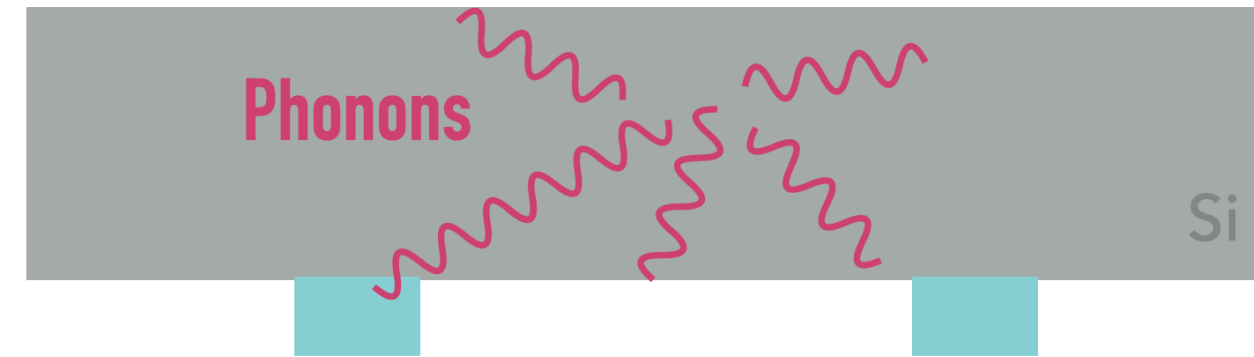
- ▶ Science data taken at 125 mK → blackbody radiation background is negligible
- ▶ ~20 hours of exposure
- ▶ Timestream data taking at 38 kHz sampling rate with all 41 channels on

- ▶ Gold-coated spherical mirror with radius 4 cm and area 52 cm²
- ▶ Used a 41-channel FIR KID array (8 unlensed)
- ▶ Displaced focus of the spherical mirror so the central 4 central pixels form the DP signal channels

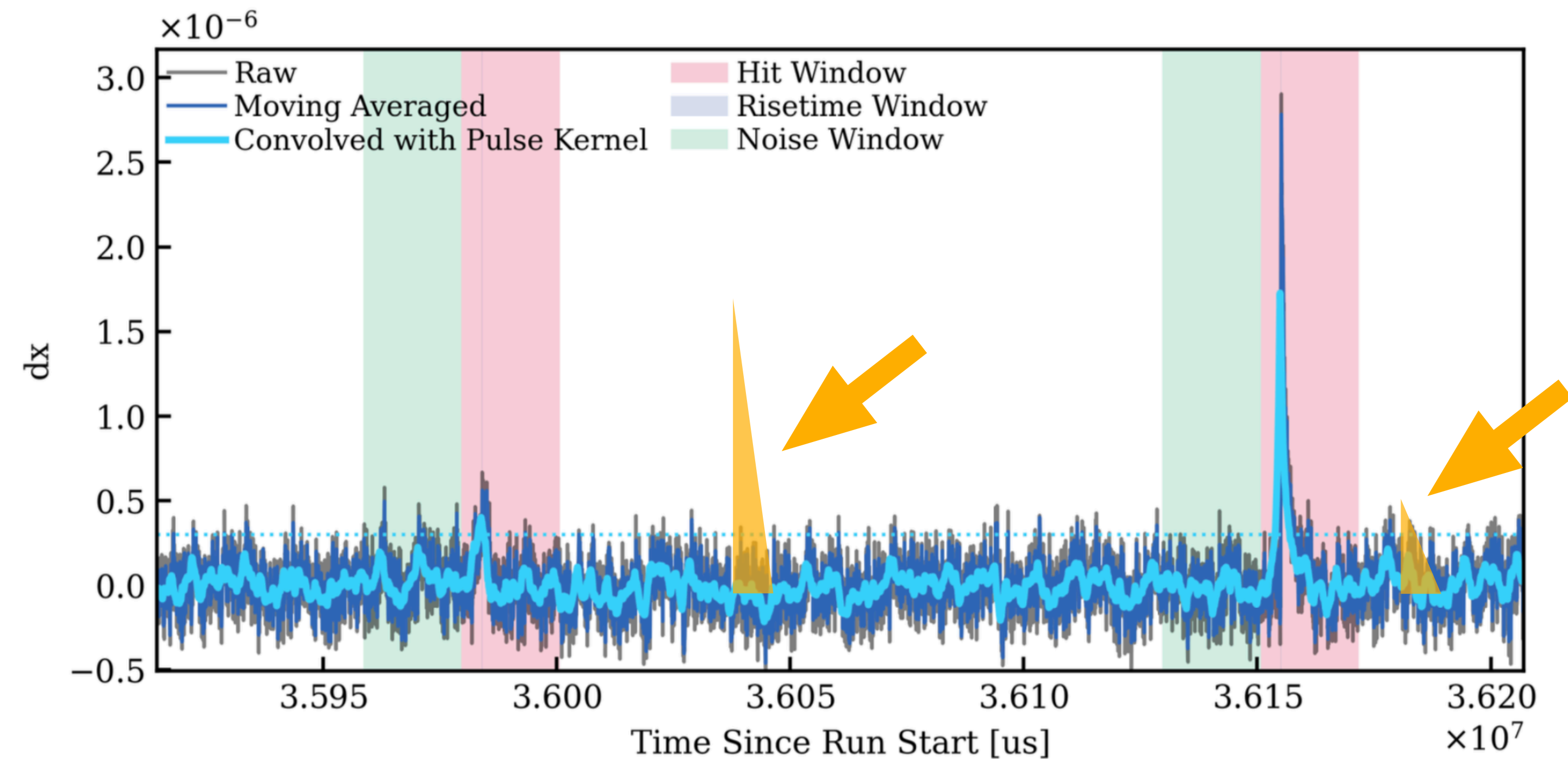
- ▶ Hit finding using filtered δx waveforms, then impose pulse shape quality selections
- ▶ #coincidence hit >5 (within 0.2 ms) is classified as substrate-like events, and the rest as photon-like events
- ▶ Energy reconstruction in two regimes:
 - ▶ < 70 meV: by optimal filtering using data-driven pulse shape template
 - ▶ >70 meV: by raw amplitude, scaled from 50 meV template
- ▶ Evaluated photon-like event analysis efficiency by a salting-based simulation pipeline



- ▶ Hit finding using filtered δx waveforms, then impose pulse shape quality selections
- ▶ #coincidence hit >5 (within 0.2 ms) is classified as substrate-like events, and the rest as photon-like events
- ▶ Energy reconstruction in two regimes:
 - ▶ < 70 meV: by optimal filtering using a data-driven pulse shape template
 - ▶ >70 meV: by raw amplitude, scaled from 50 meV template
- ▶ Evaluated photon-like event analysis efficiency by a salting-based simulation pipeline

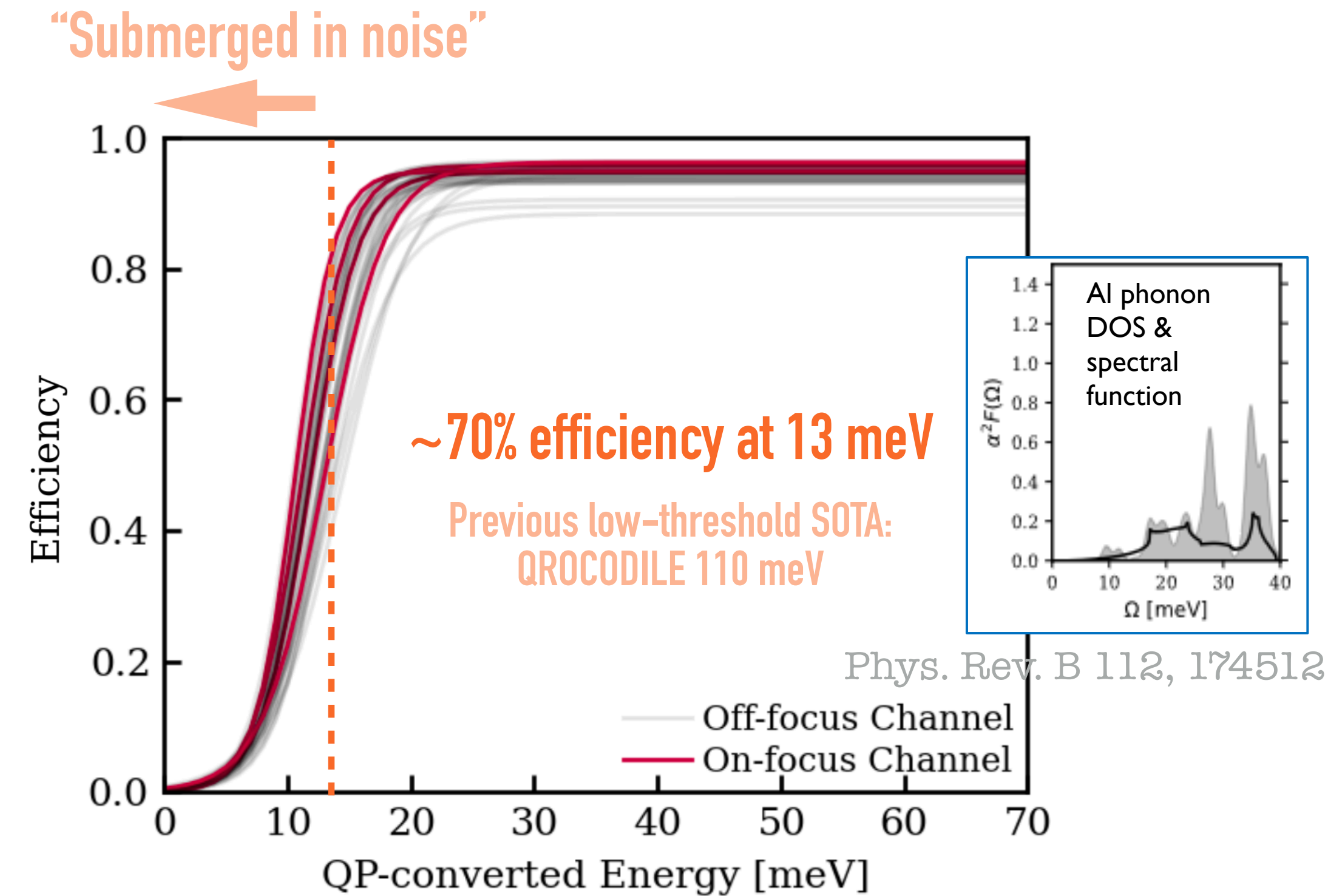
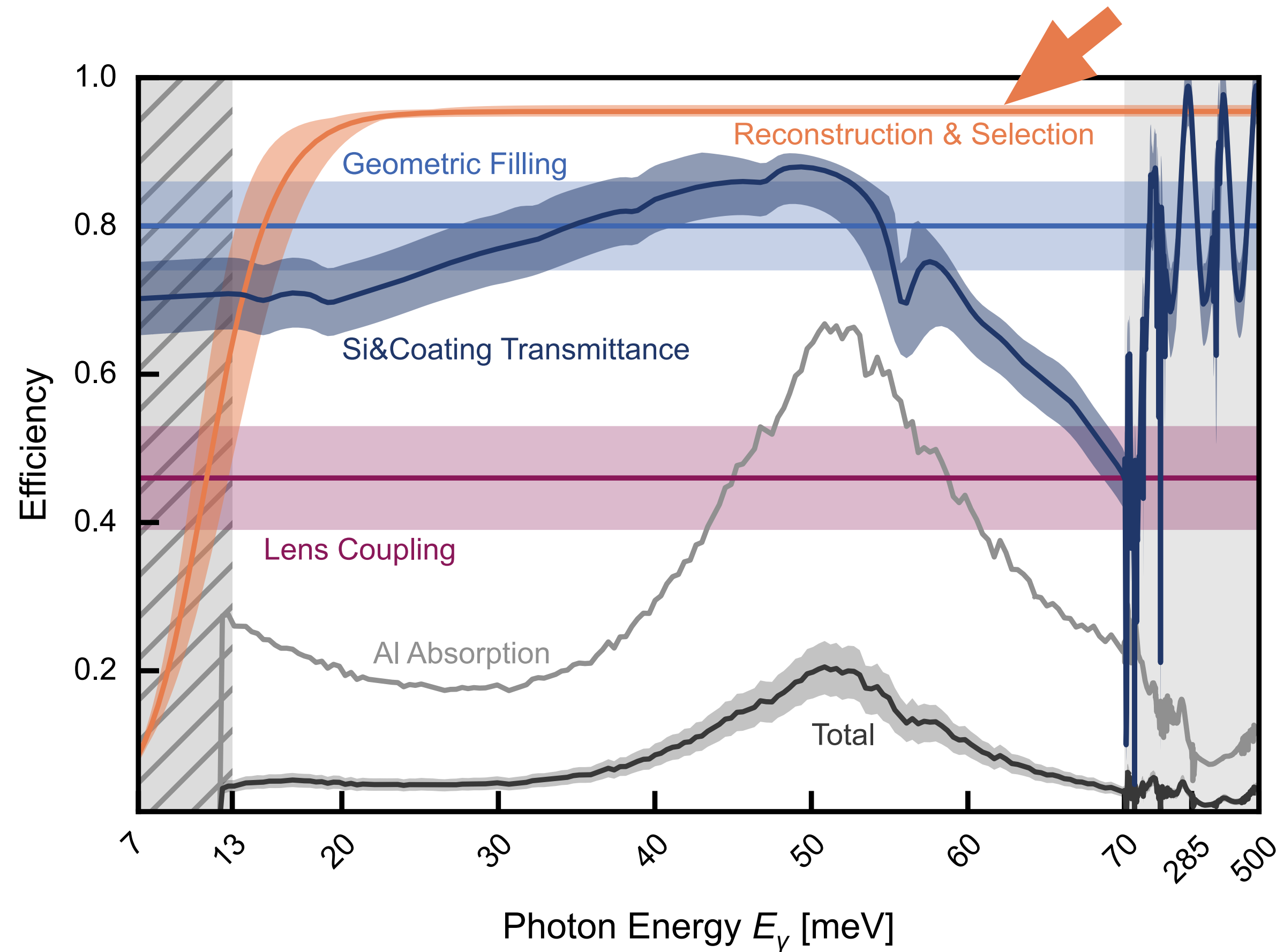


- ▶ Hit finding using filtered δx waveforms, then impose pulse shape quality selections
- ▶ #coincidence hit >5 (within 0.2 ms) is classified as substrate-like events, and the rest as photon-like events
- ▶ Energy reconstruction in two regimes:
 - ▶ < 70 meV: by optimal filtering using a data-driven pulse shape template
 - ▶ >70 meV: by raw amplitude, scaled from 50 meV template
- ▶ Evaluated photon-like event analysis efficiency by a salting-based simulation pipeline

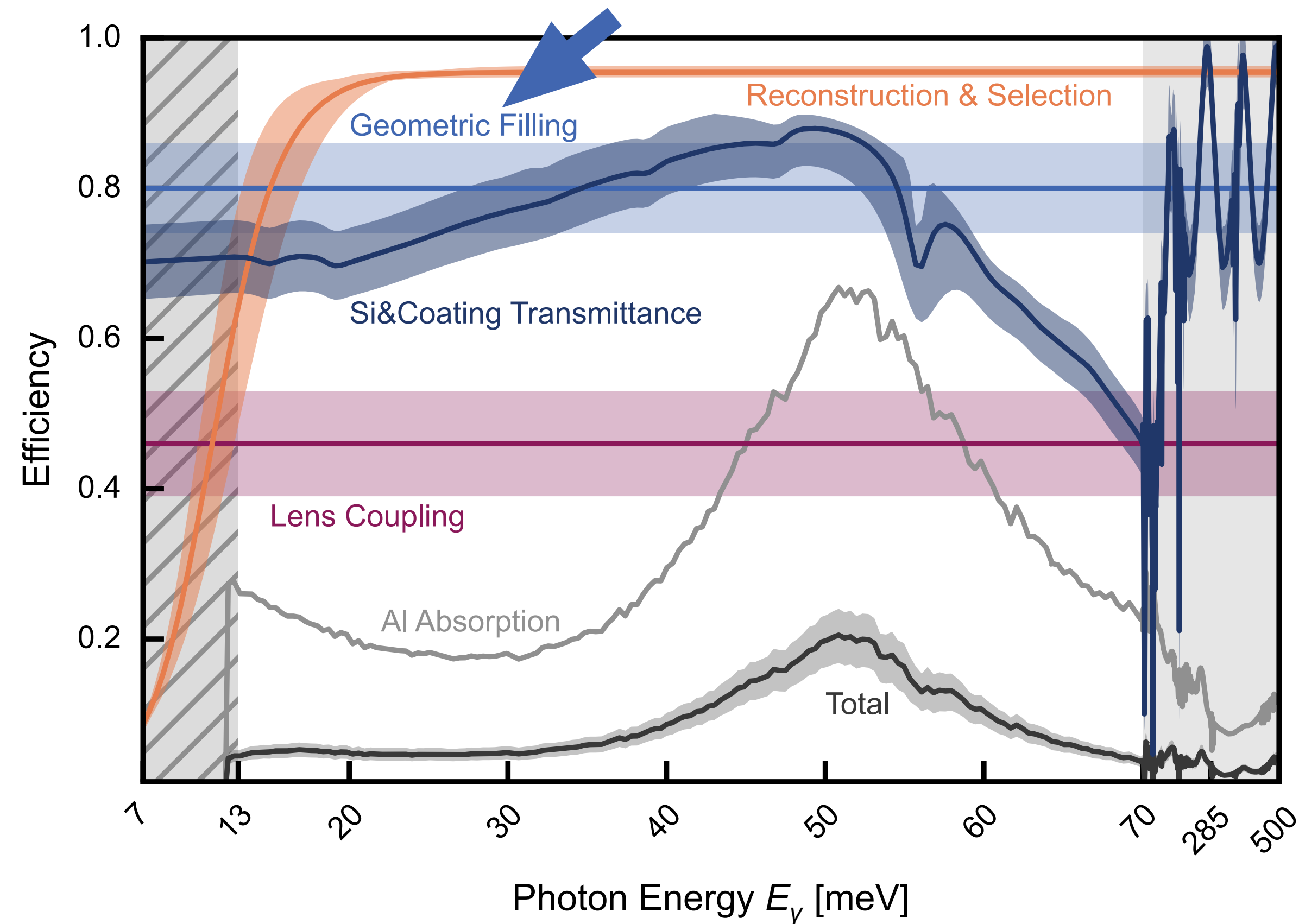


“salt” pulse with known true energy

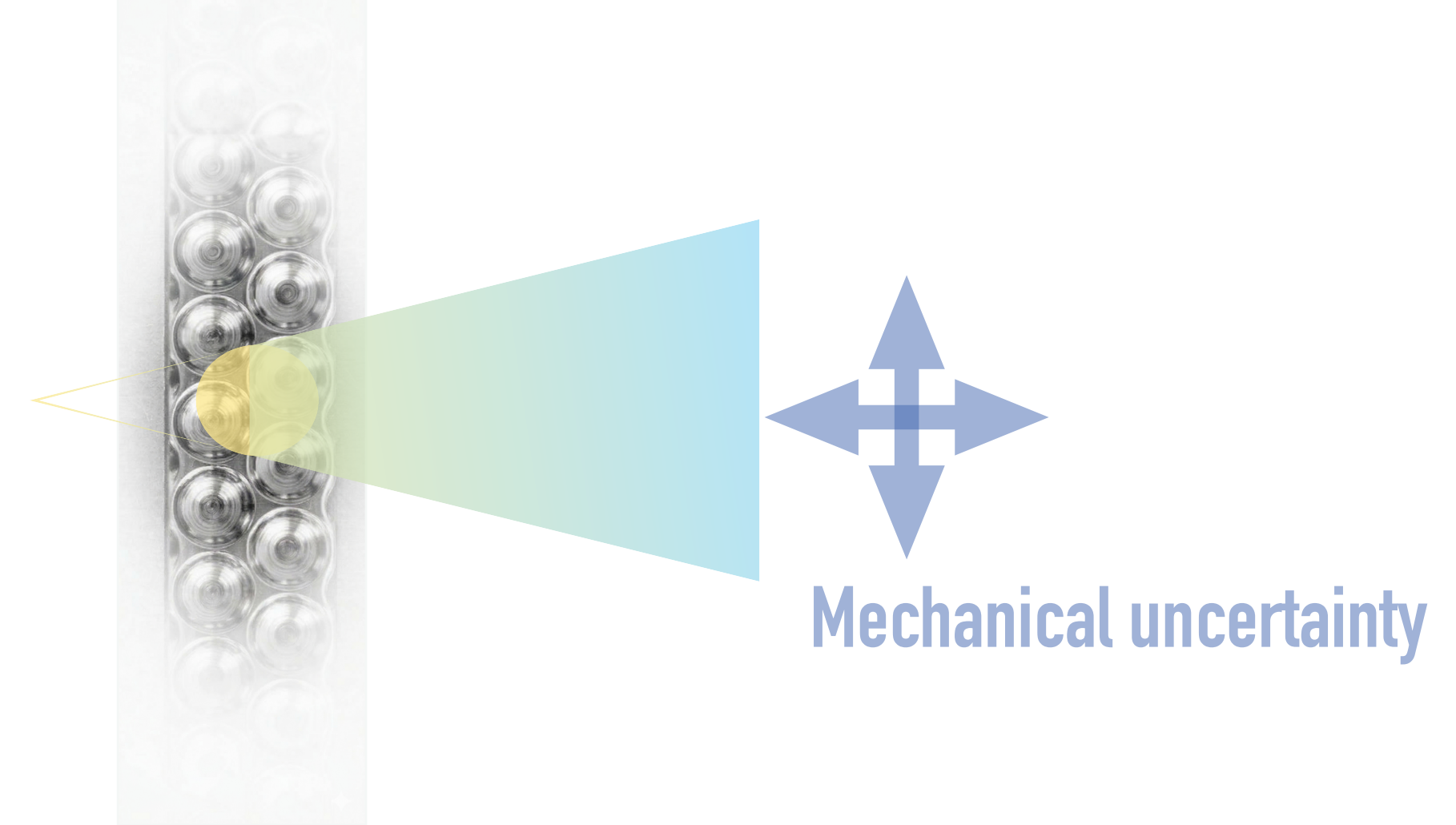
Energy threshold is dominated by “baseline fluctuations”



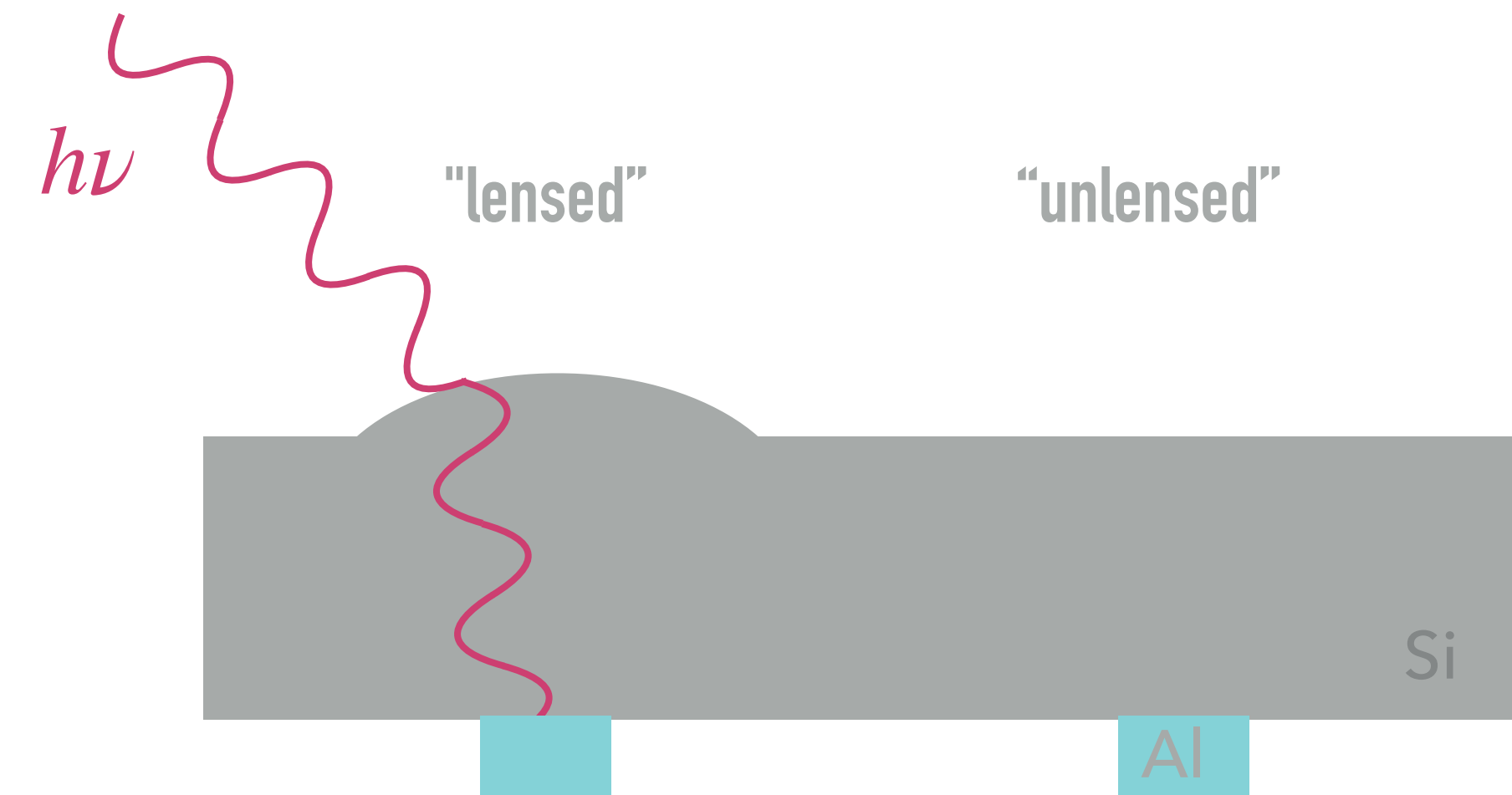
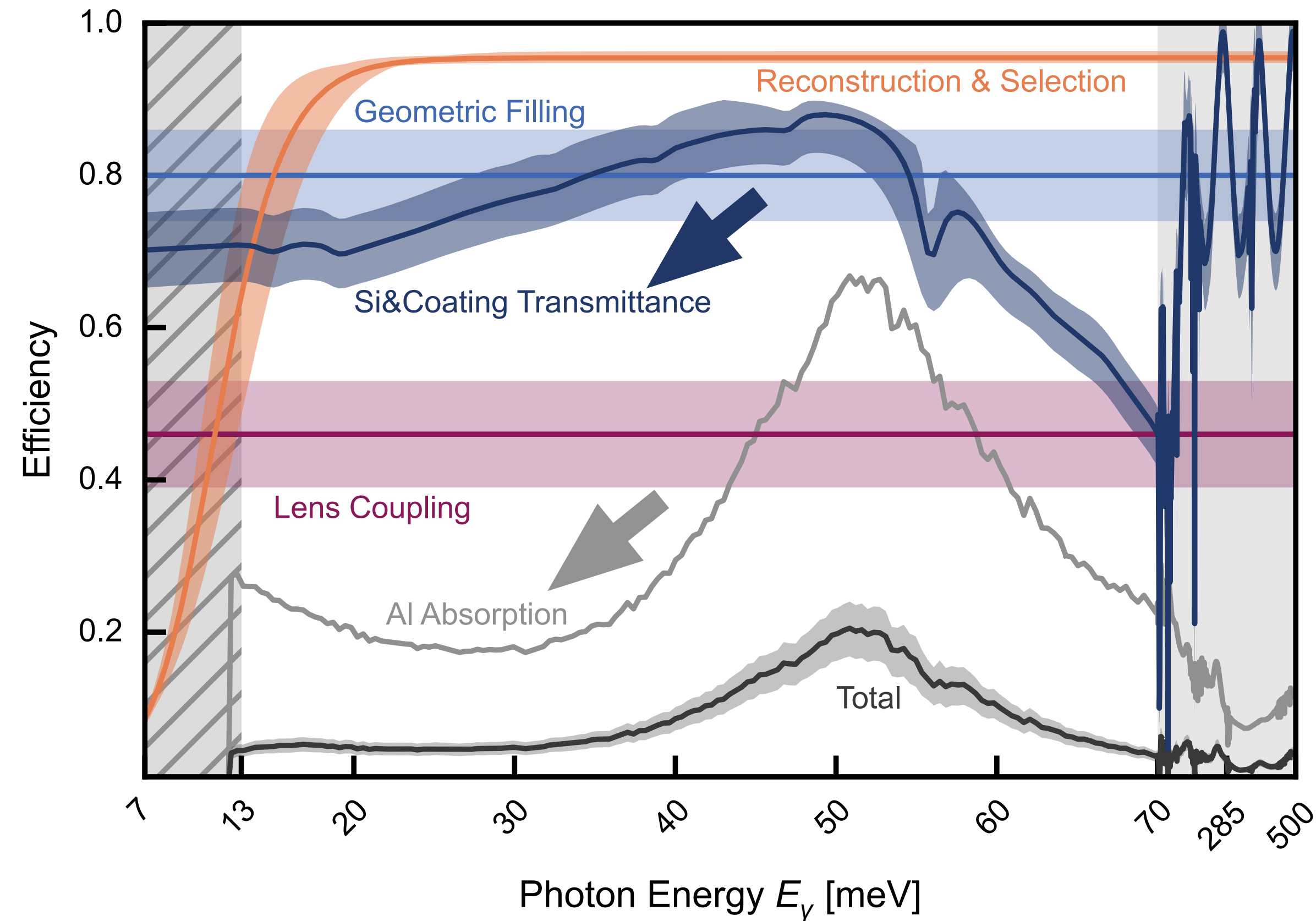
- ▶ **Reconstruction & selection:** estimated by a salting based simulation on a per-channel basis
- ▶ Geometric filling: estimated by ray-tracing simulation
- ▶ Absorption & transmittance: measured by Fourier transform spectrometer
- ▶ Lens coupling: estimated by scaling predicted rate to measured in black-body calibration (25 μm)



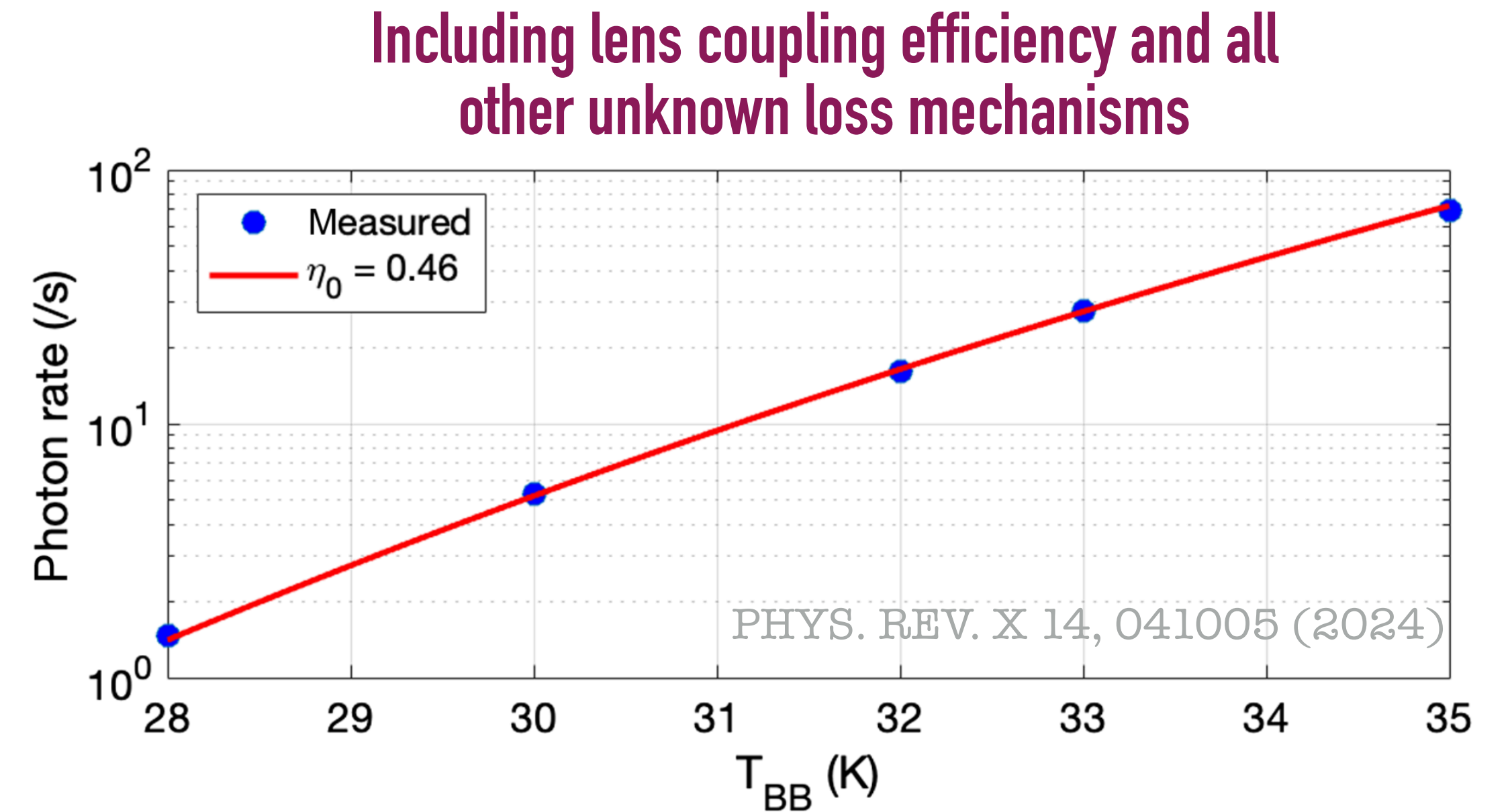
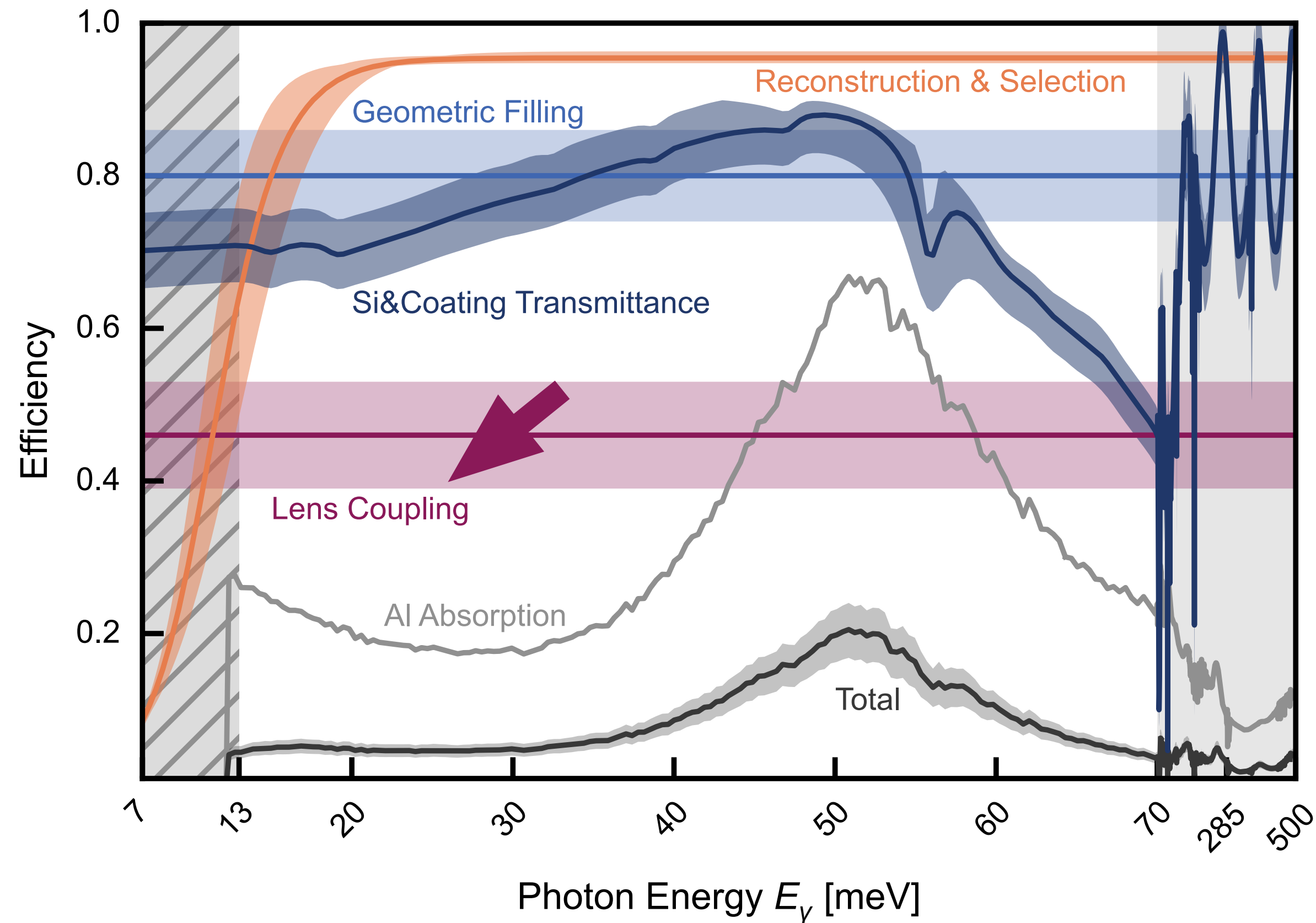
80% optical coverage



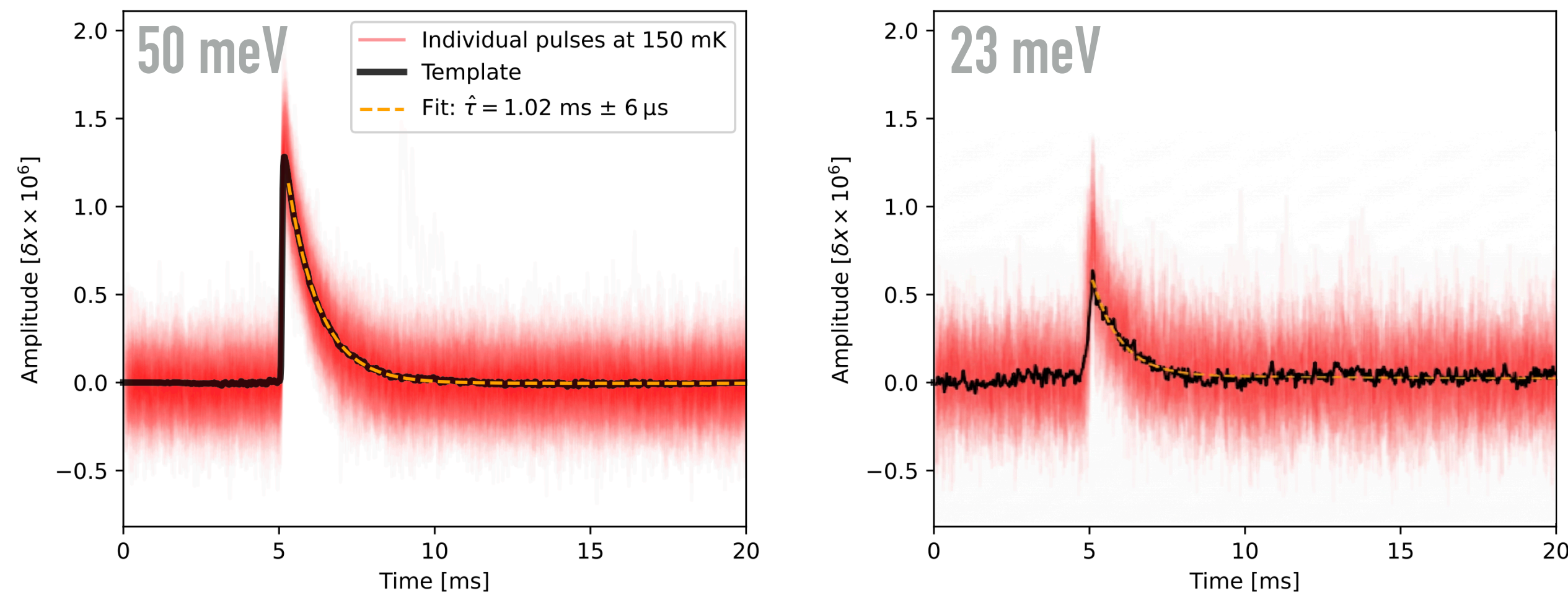
- ▶ Reconstruction & selection: estimated by a salting based simulation on a per-channel basis
- ▶ **Geometric filling**: estimated by ray-tracing simulation
- ▶ Absorption & transmittance: measured by Fourier transform spectrometer
- ▶ Lens coupling: estimated by scaling predicted rate to measured in black-body calibration (25 μm)



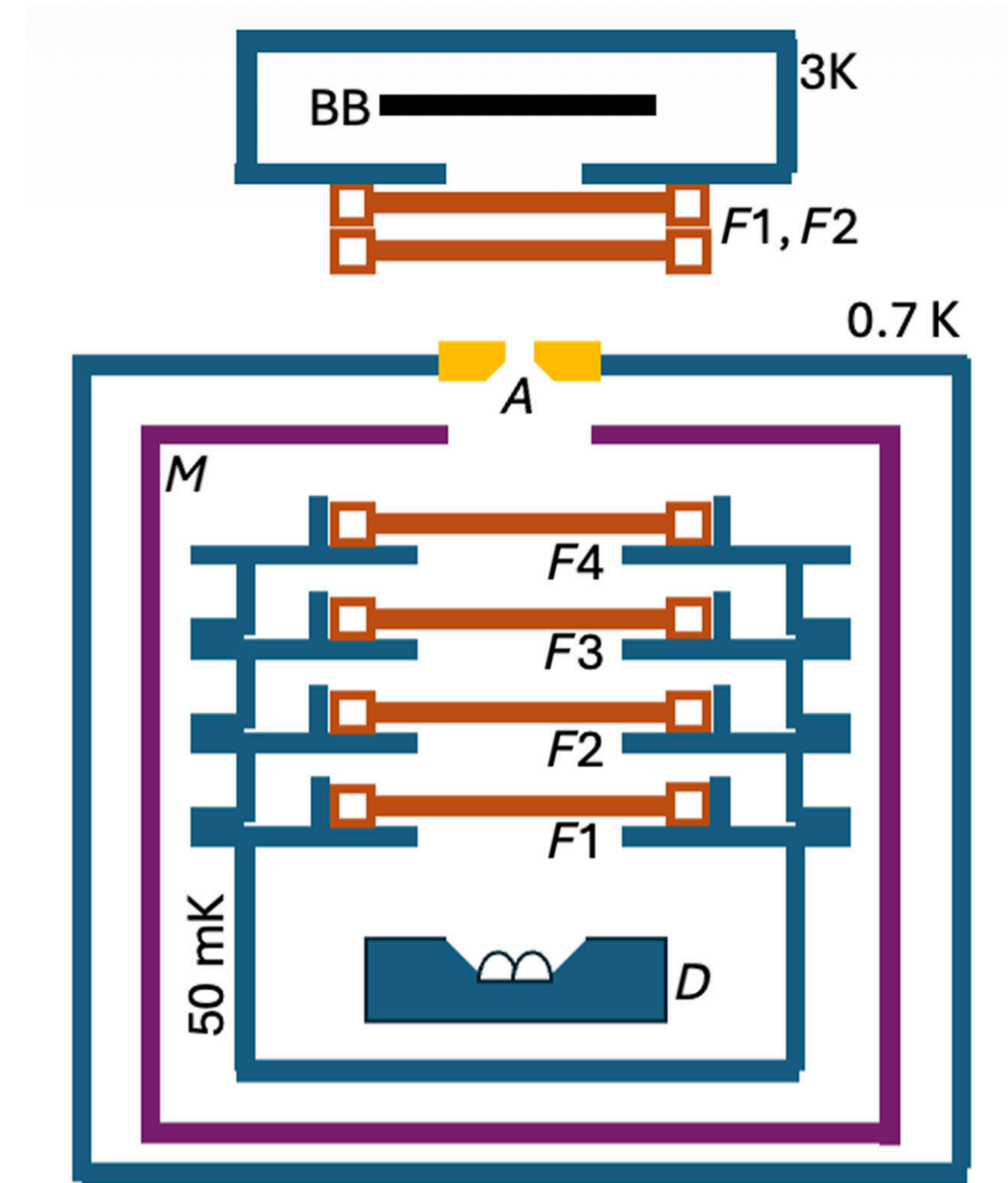
- ▶ Reconstruction & selection: estimated by a salting based simulation on a per-channel basis
- ▶ Geometric filling: estimated by ray-tracing simulation
- ▶ Absorption & **transmittance**: measured by Fourier transform spectrometer
- ▶ Lens coupling: estimated by scaling predicted rate to measured in black-body calibration (25 μm)

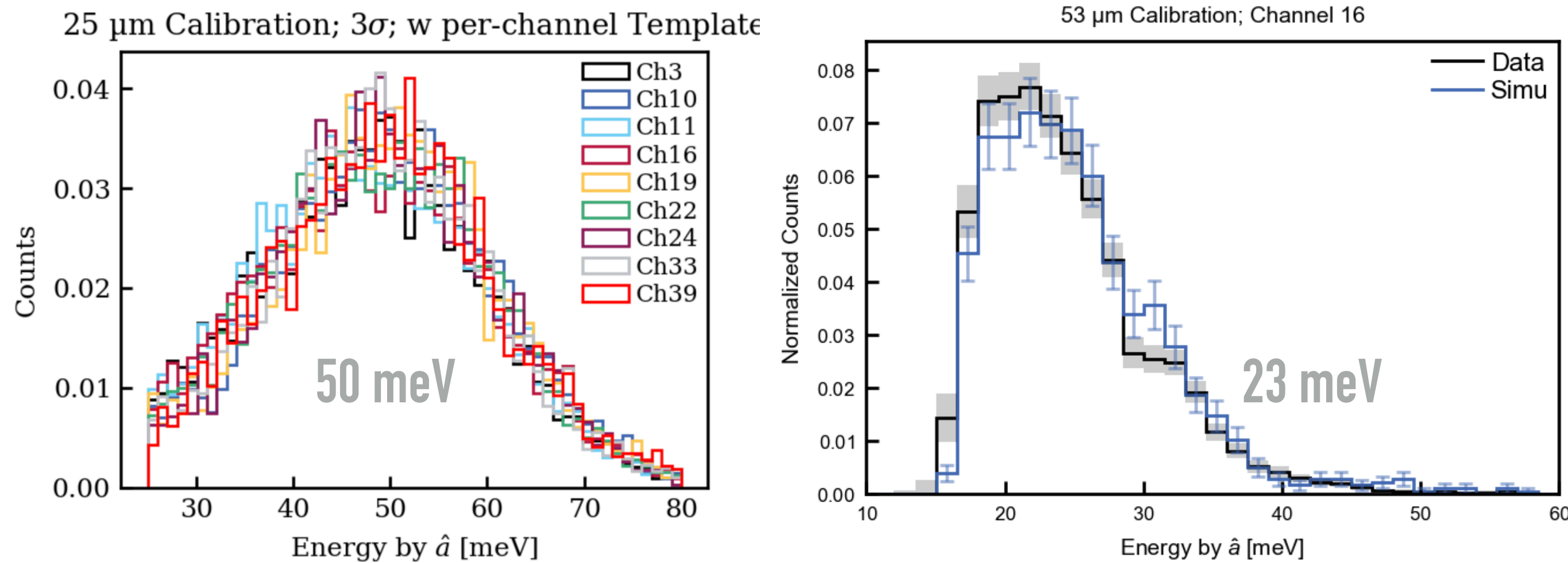


- Reconstruction & selection: estimated by a salting based simulation on a per-channel basis
- Geometric filling: estimated by ray-tracing simulation
- Absorption & transmittance: measured by Fourier transform spectrometer
- Lens coupling**: estimated by scaling predicted rate to measured in black-body calibration (25 μm)

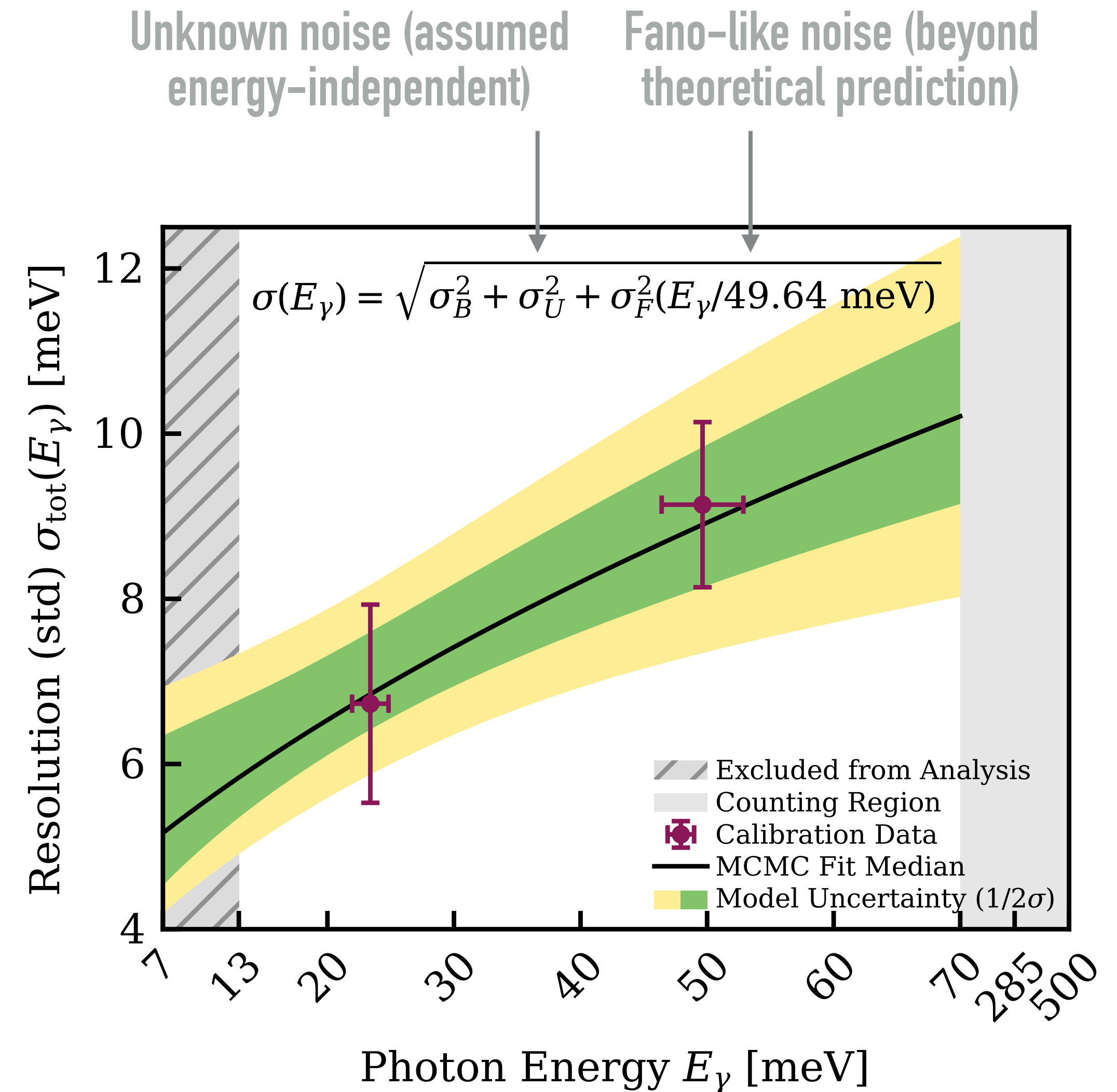


- Two mono-energetic calibrations by blackbody source + bandpass filter ($25 \mu\text{m}$ and $53 \mu\text{m}$)
- Resolution uncertainties given by Markov chain Monte Carlo fit of the calibration points to an empirical model





- Two mono-energetic calibrations by blackbody source + bandpass filter (25 μm and 53 μm)
- Resolution uncertainties given by Markov chain Monte Carlo fit of the calibration points to an empirical model





QUALIPHIDE-FIR DARK MATTER
EXPERIMENT

BACKGROUND

PRELIMINARY!!!

ENERGY SPECTRUM

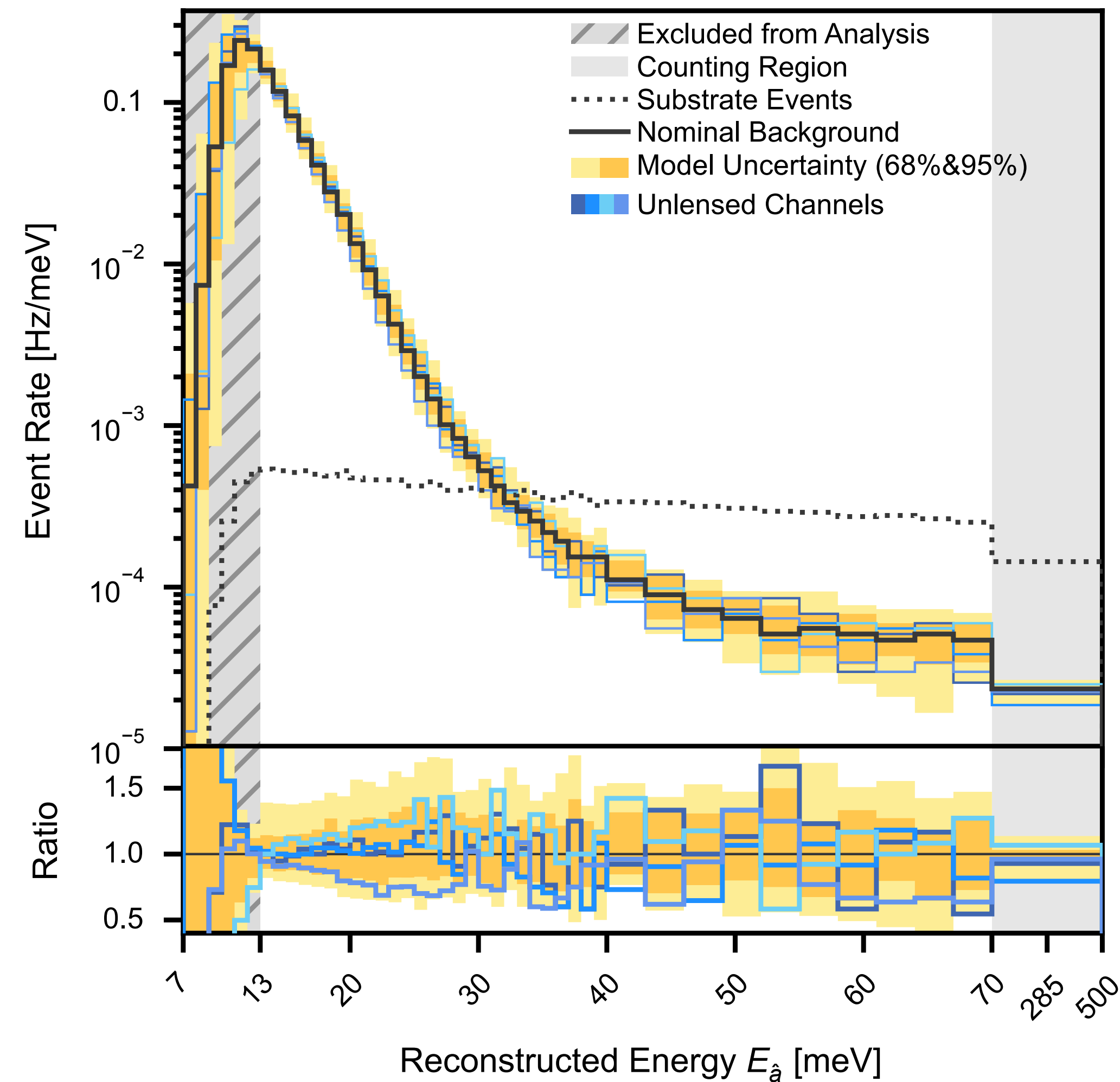
TIME TREND

PULSE SHAPE

SPATIAL PATTERN

1. SPECTRUM: PHOTON-LIKE HAS TWO COMPONENTS

21



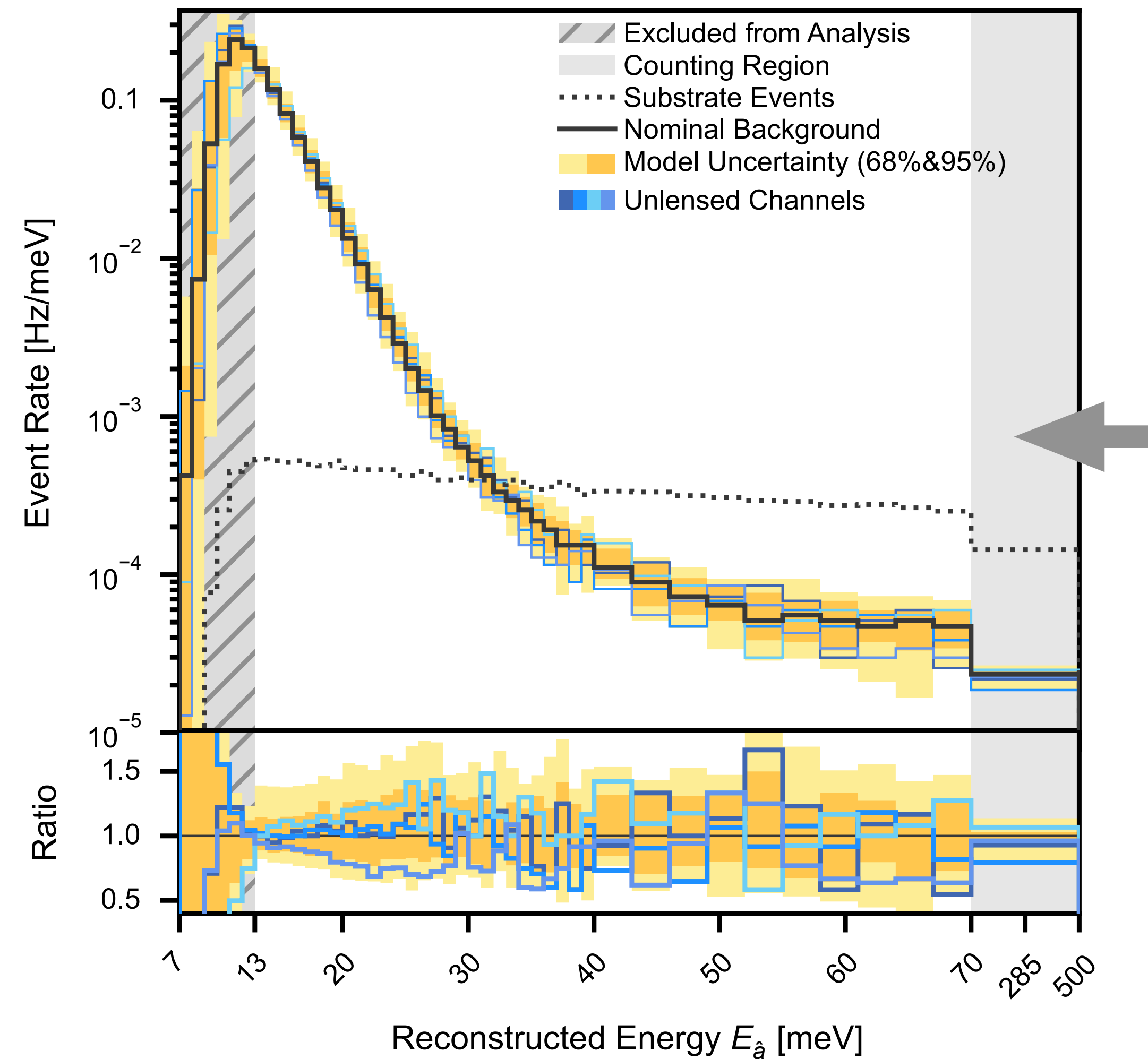
Yellow band: rate variation among channels

Solid black line: Median among channels

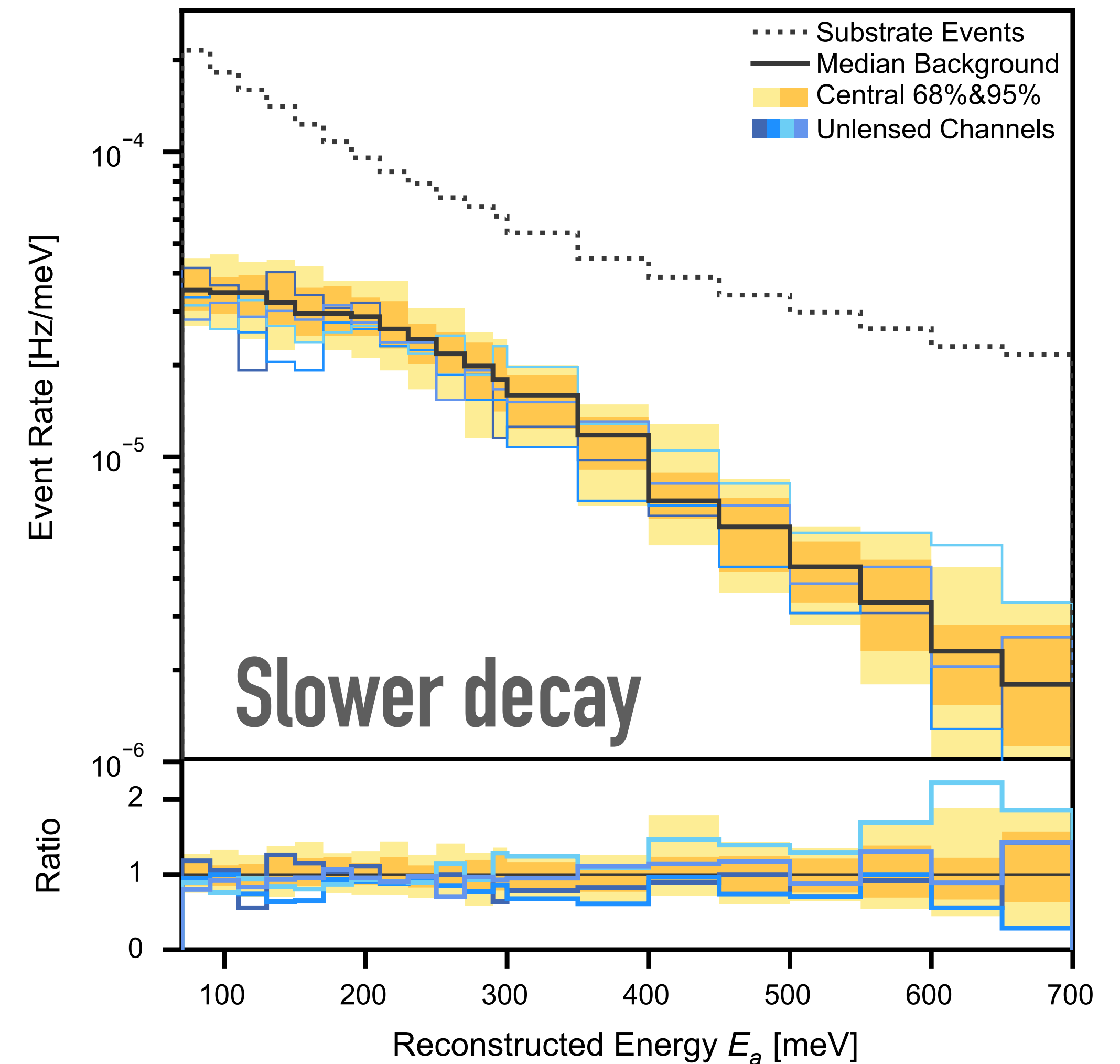
**Exponentially decaying peak < 40 meV
in photon-like events,
but not in substrate-like ones**

1. SPECTRUM: PHOTON-LIKE HAS TWO COMPONENTS

22



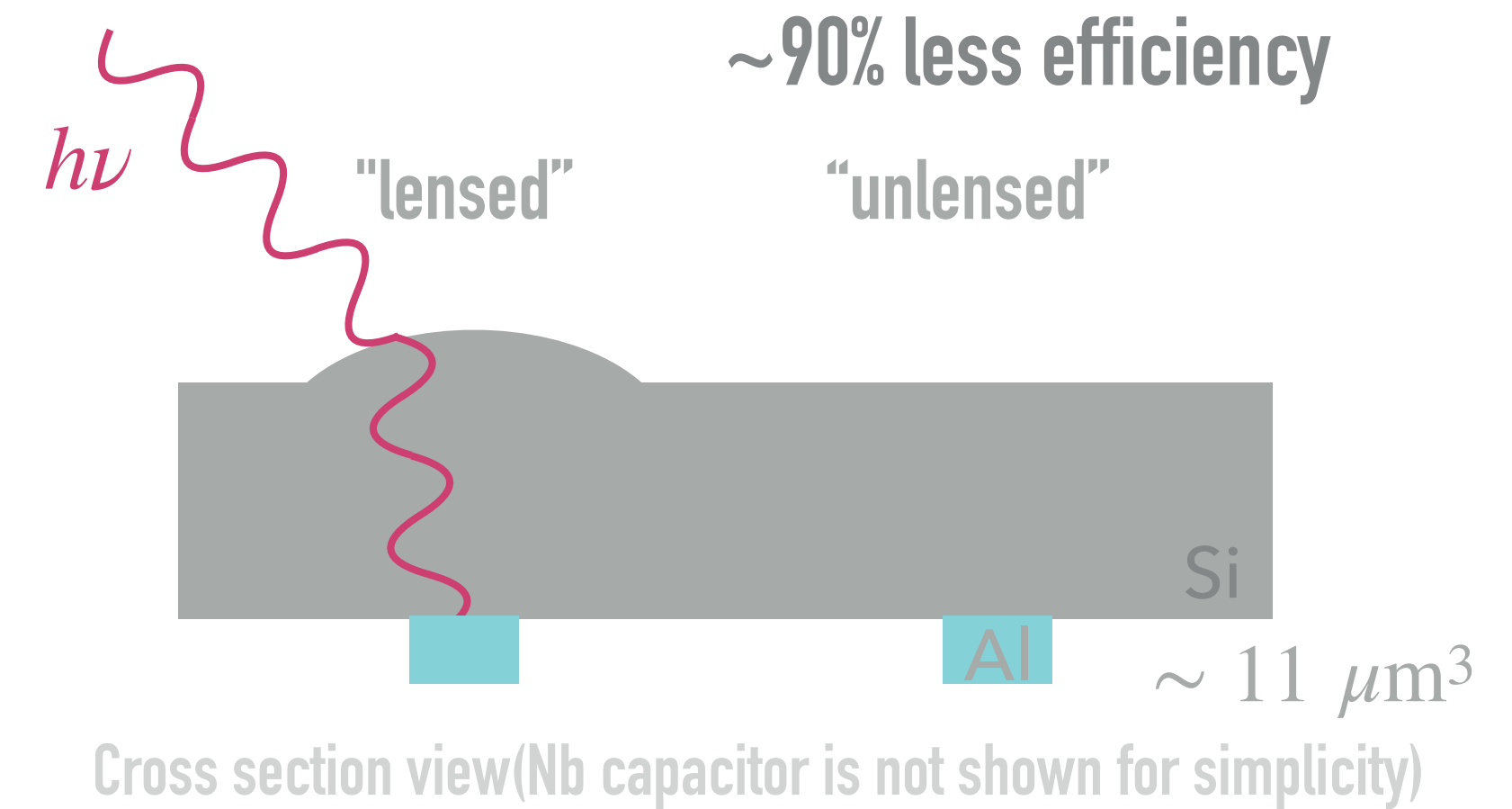
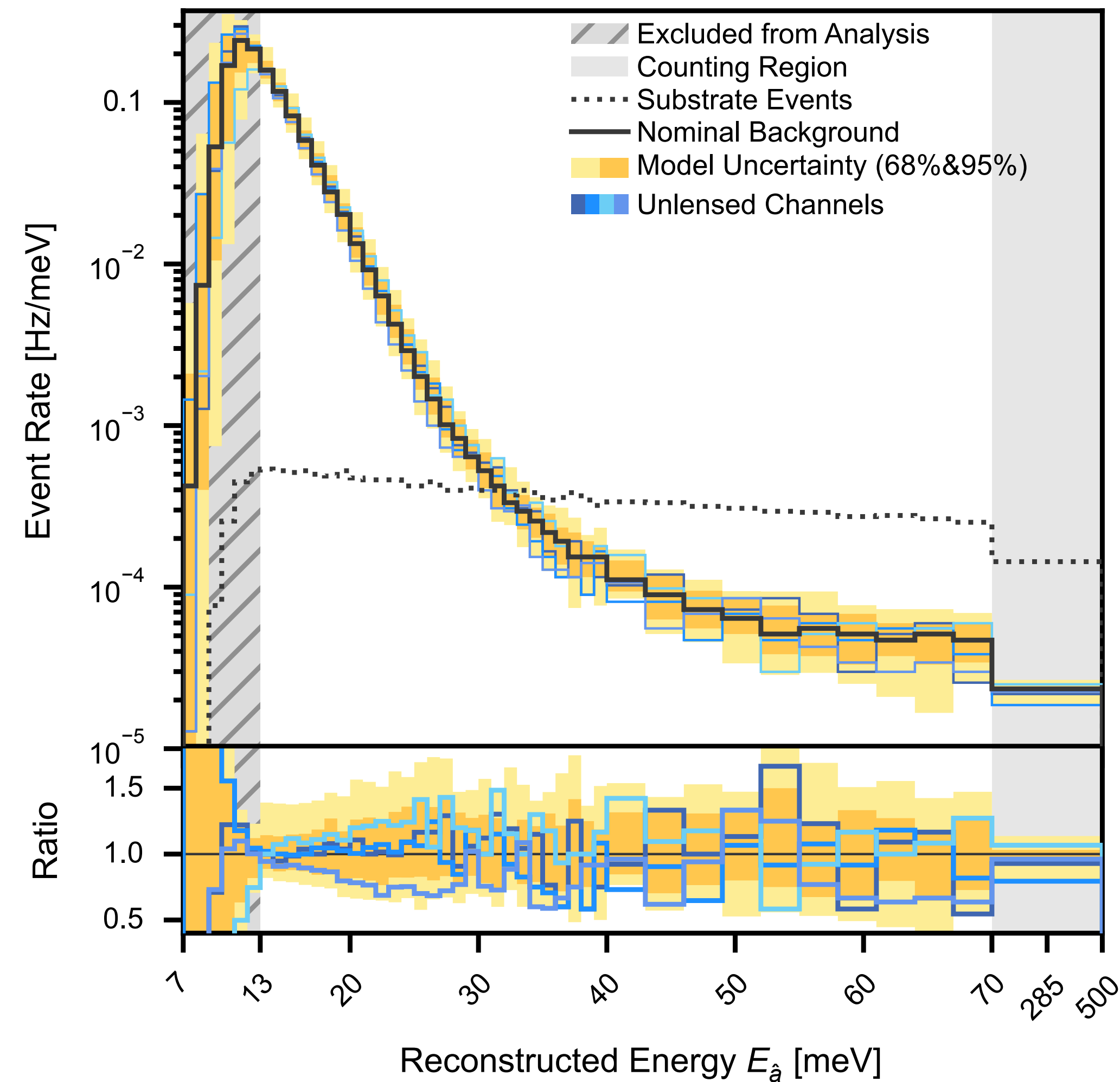
Low-energy reconstruction by optimal filtering



High-energy reconstruction by raw amplitude

2. SPECTRUM: PHOTON-LIKE RATE AGREE BETWEEN WITH/WITHOUT LENS

23



Photon-like events are likely phonons within Al thin film

Caveat: Very difficult to estimate theoretically how much photons we should detect with/without lens

3. SPECTRUM: SUBSTRATE-LIKE SHOWS POWER LAW

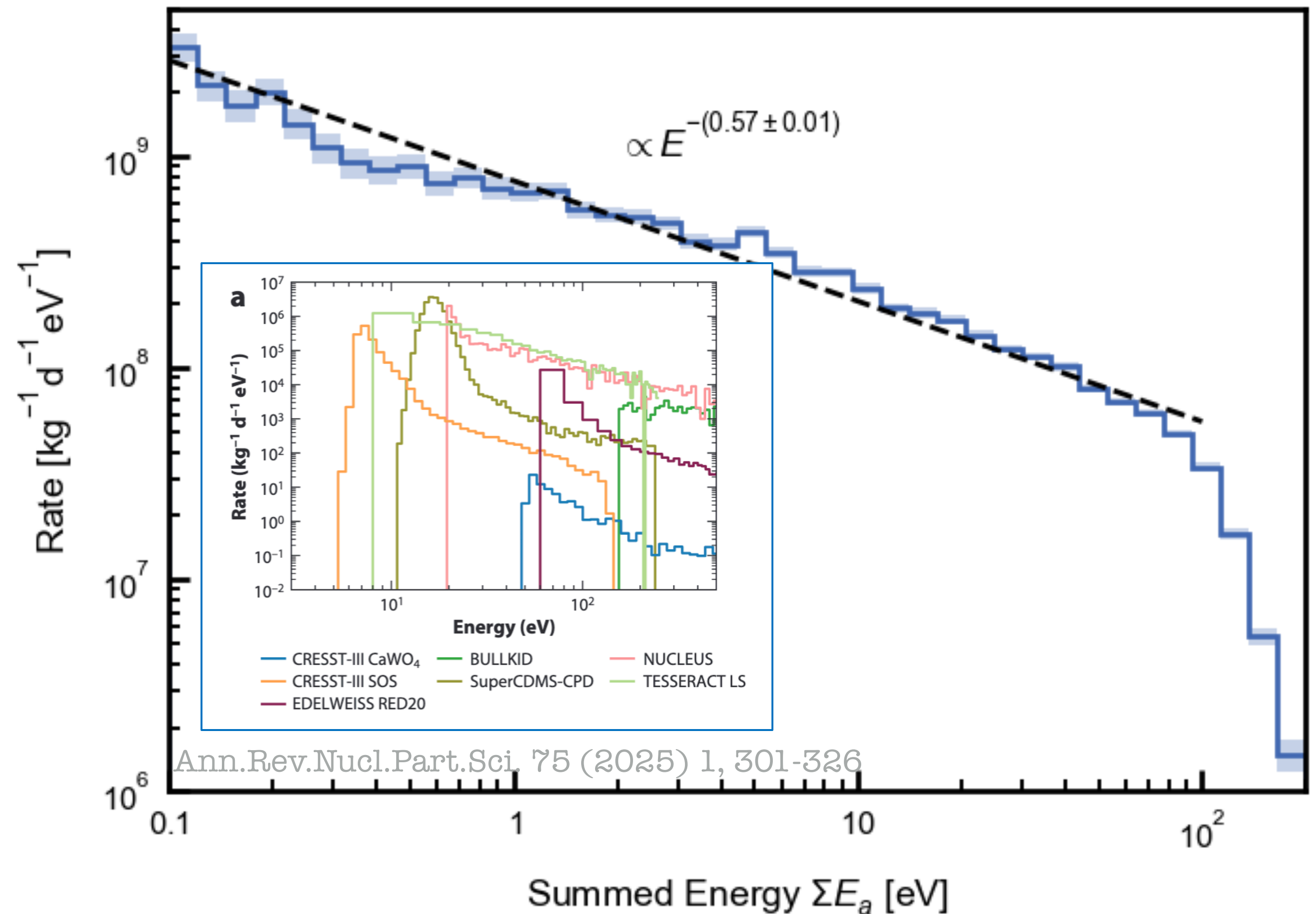
24

Similar behavior to LEE literature
But elevated rate. Hypotheses:

Chip gluing

Radiogenic background

Photon absorption in Si



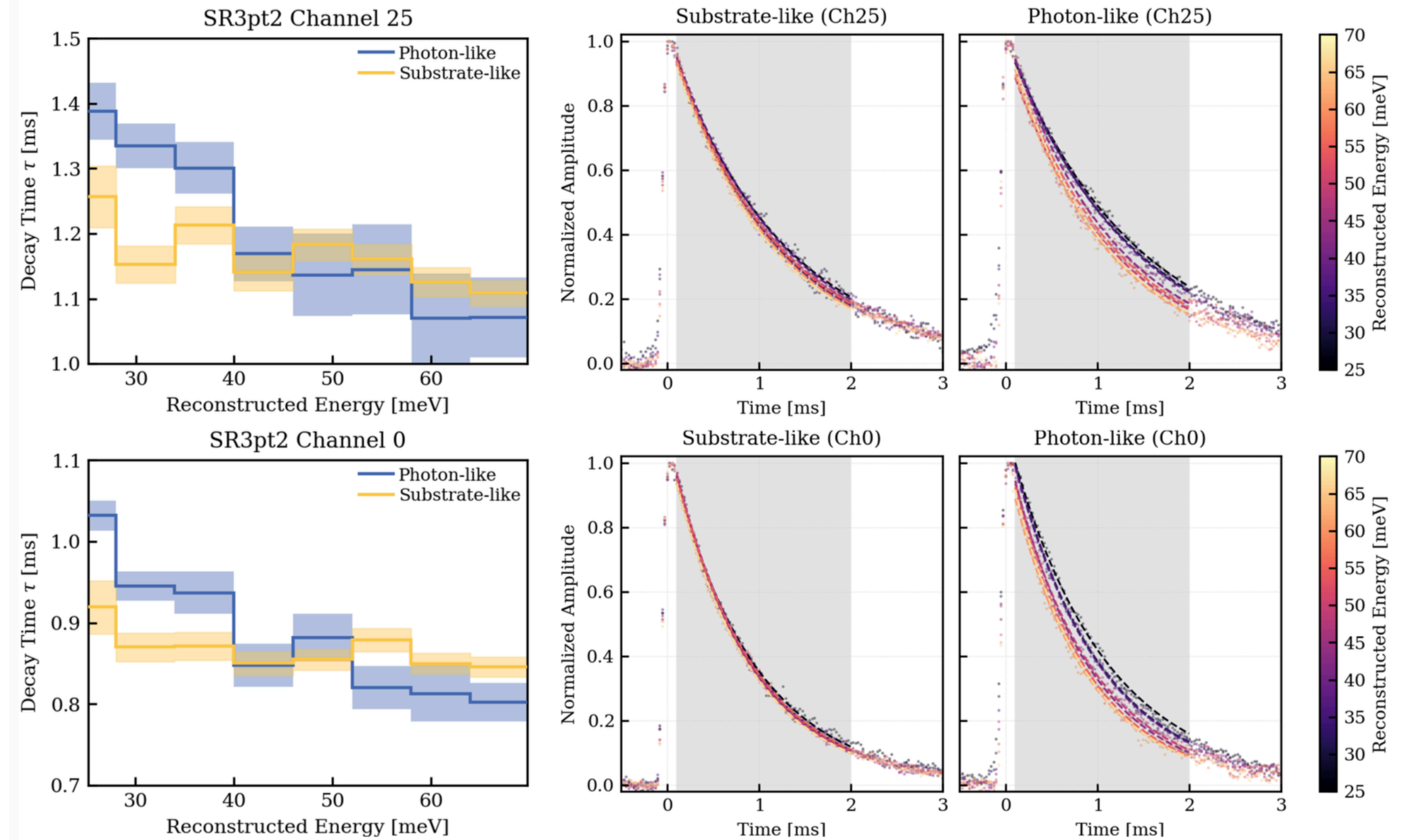
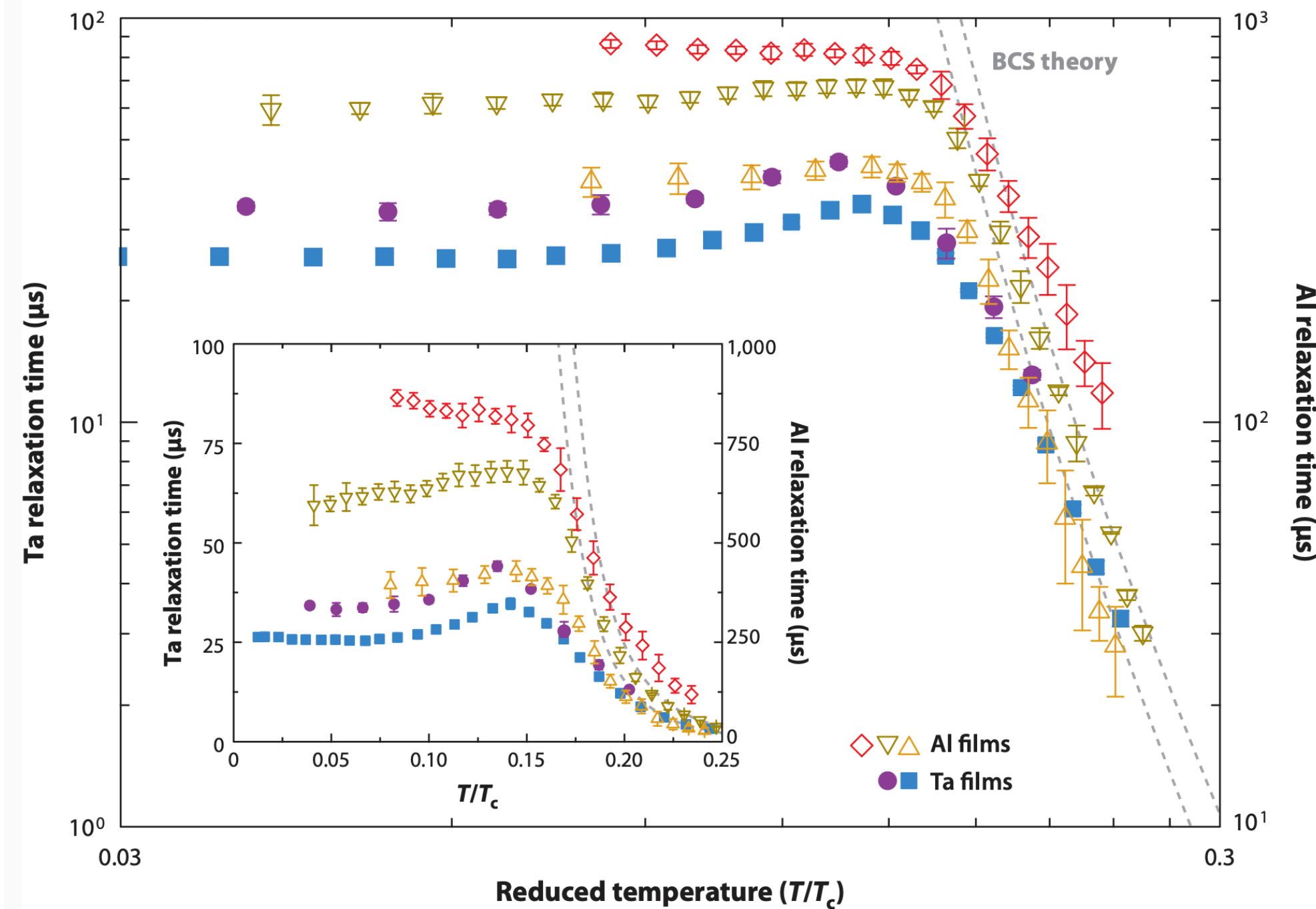
Caveat: we don't have photon-collection efficiency estimation yet; Guess: $\mathcal{O}(1\%)$

4. PULSE SHAPE: ABSENCE OF $\tau_{\max}$ IN PHOTON-LIKE EVENTS

25

Effective quasiparticle lifetime encoded in pulse shape

$$\tau_{qp} = \frac{\tau_{\max}}{1 + n_{qp}/n^*}$$



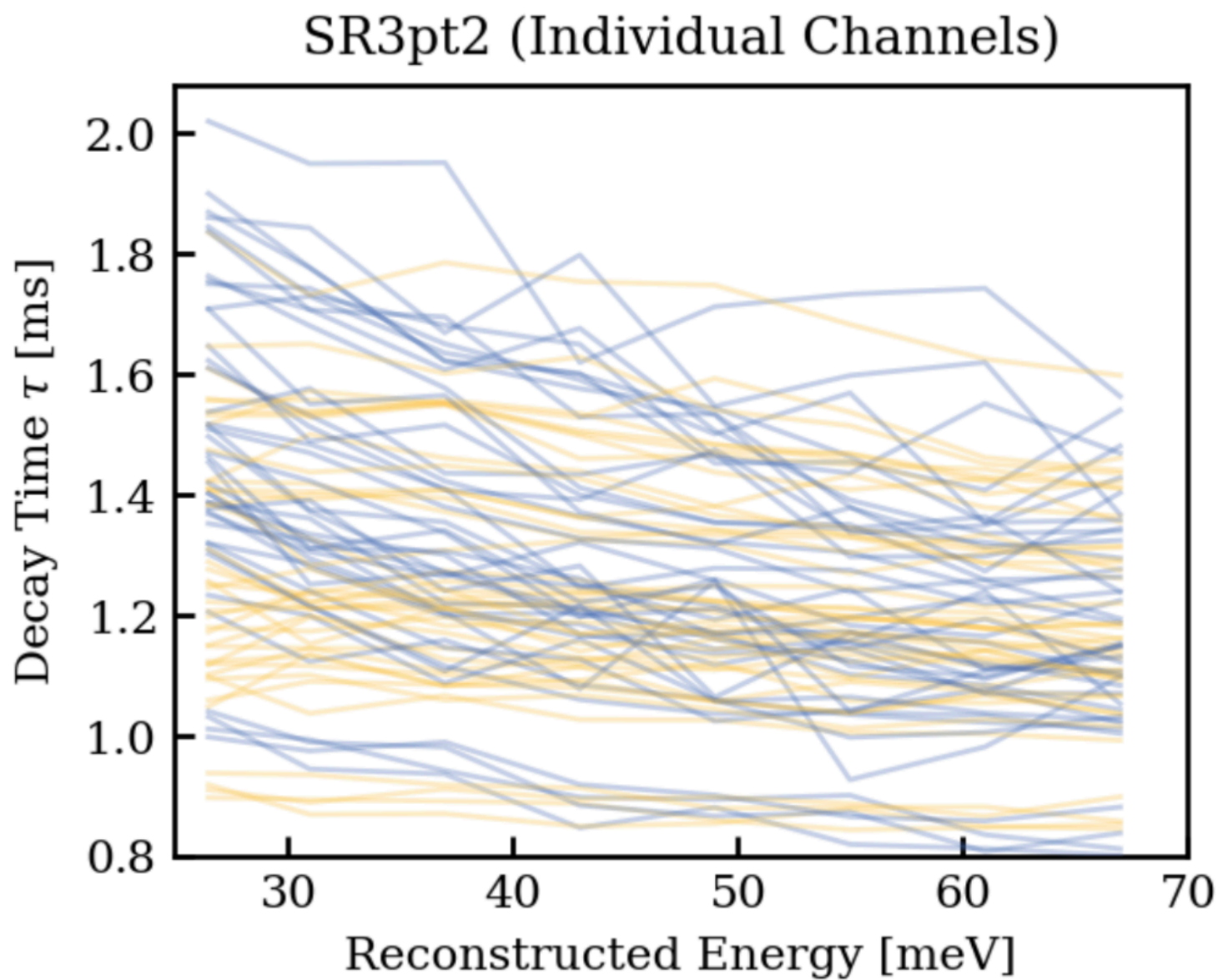
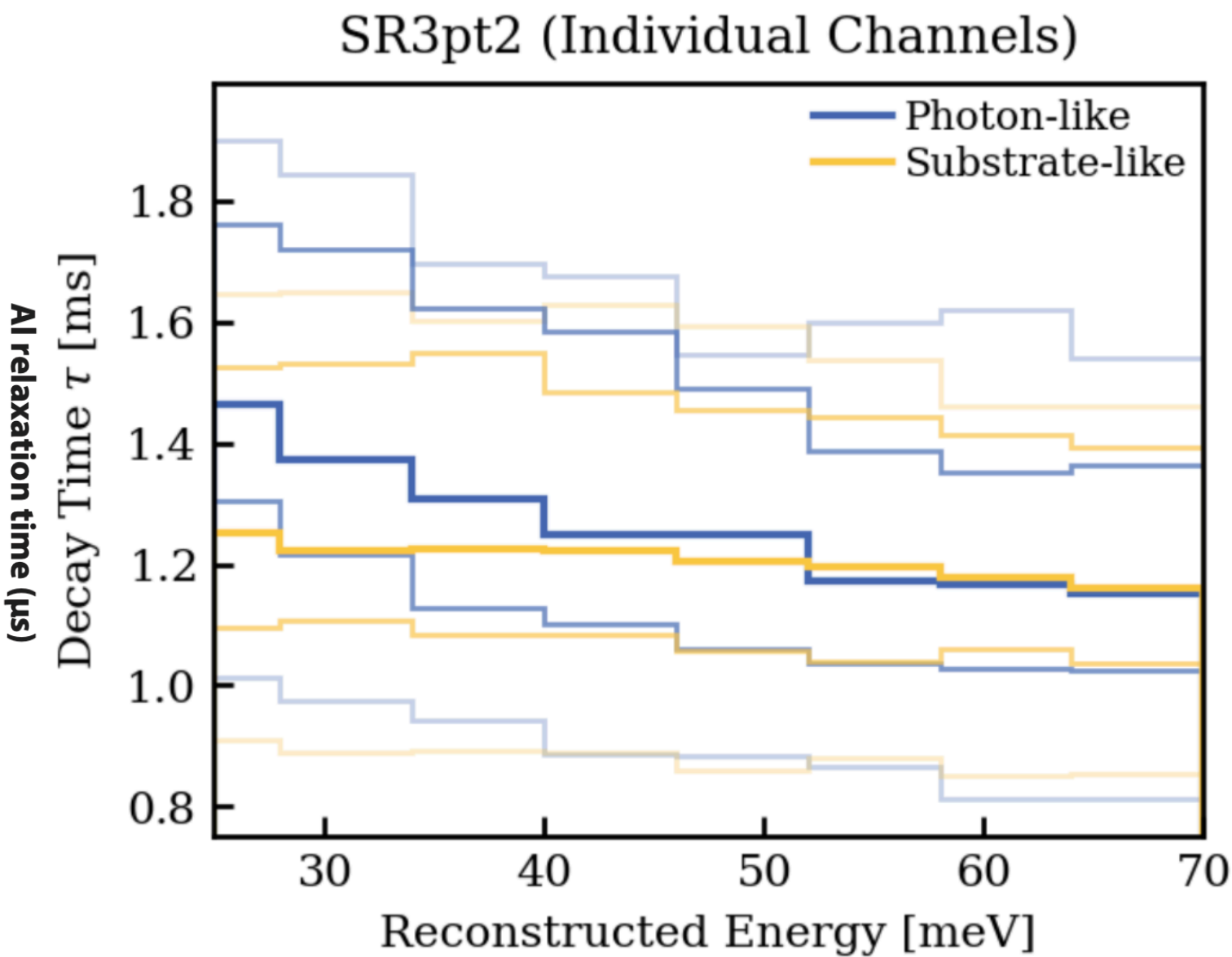
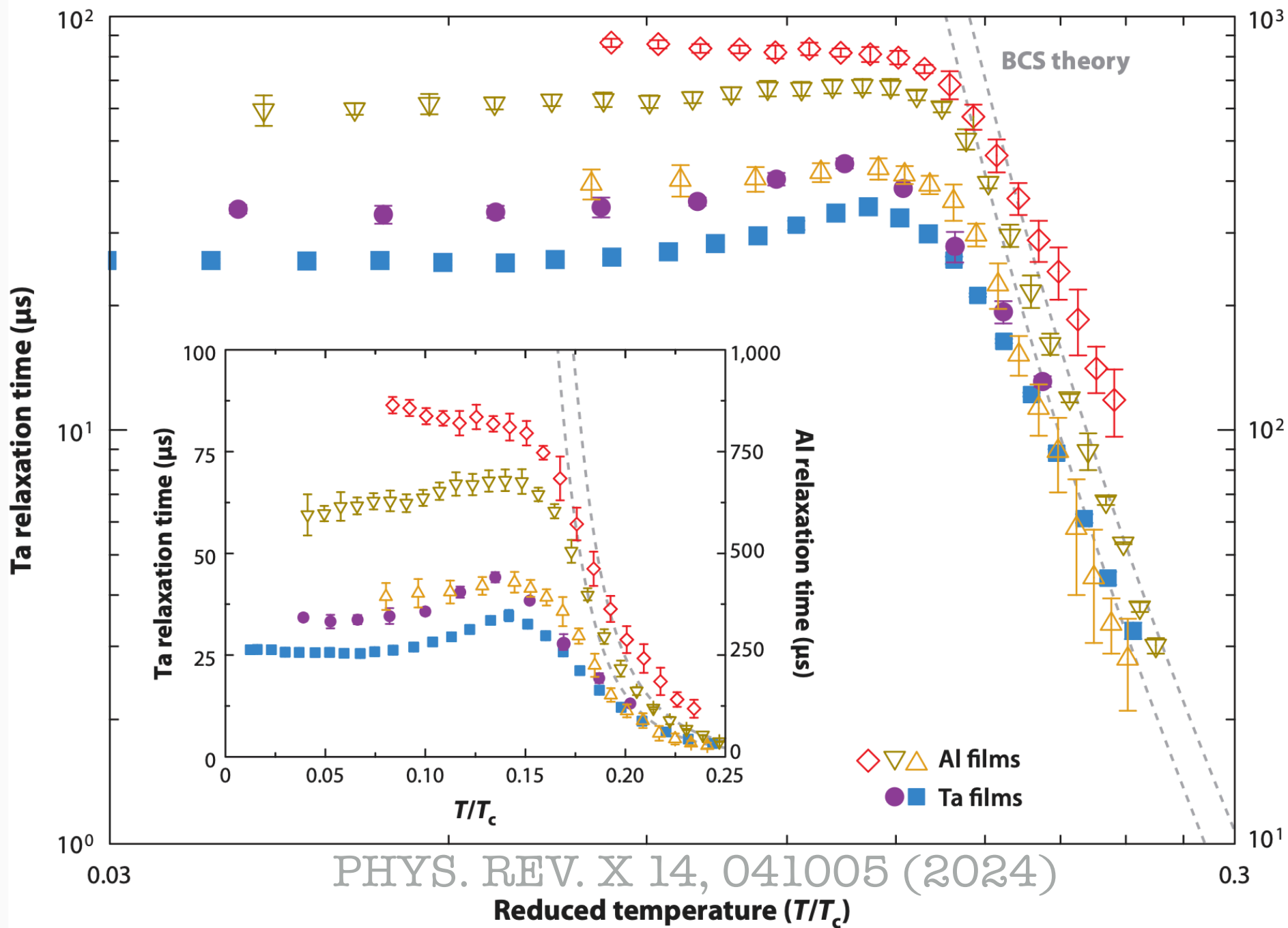
All literature reports a phenomenological $\tau_{\max}$
Which suggests unknown a universal unknown
mechanism for quasiparticle loss

$\tau_{\max}$ shows up in substrate events,
but not photon-like events!?

4. PULSE SHAPE: ABSENCE OF τ_{max} IN PHOTON- LIKE EVENTS

Effective quasiparticle lifetime encoded in pulse shape

$$\tau_{qp} = \frac{\tau_{\text{max}}}{1 + n_{qp}/n^*}$$

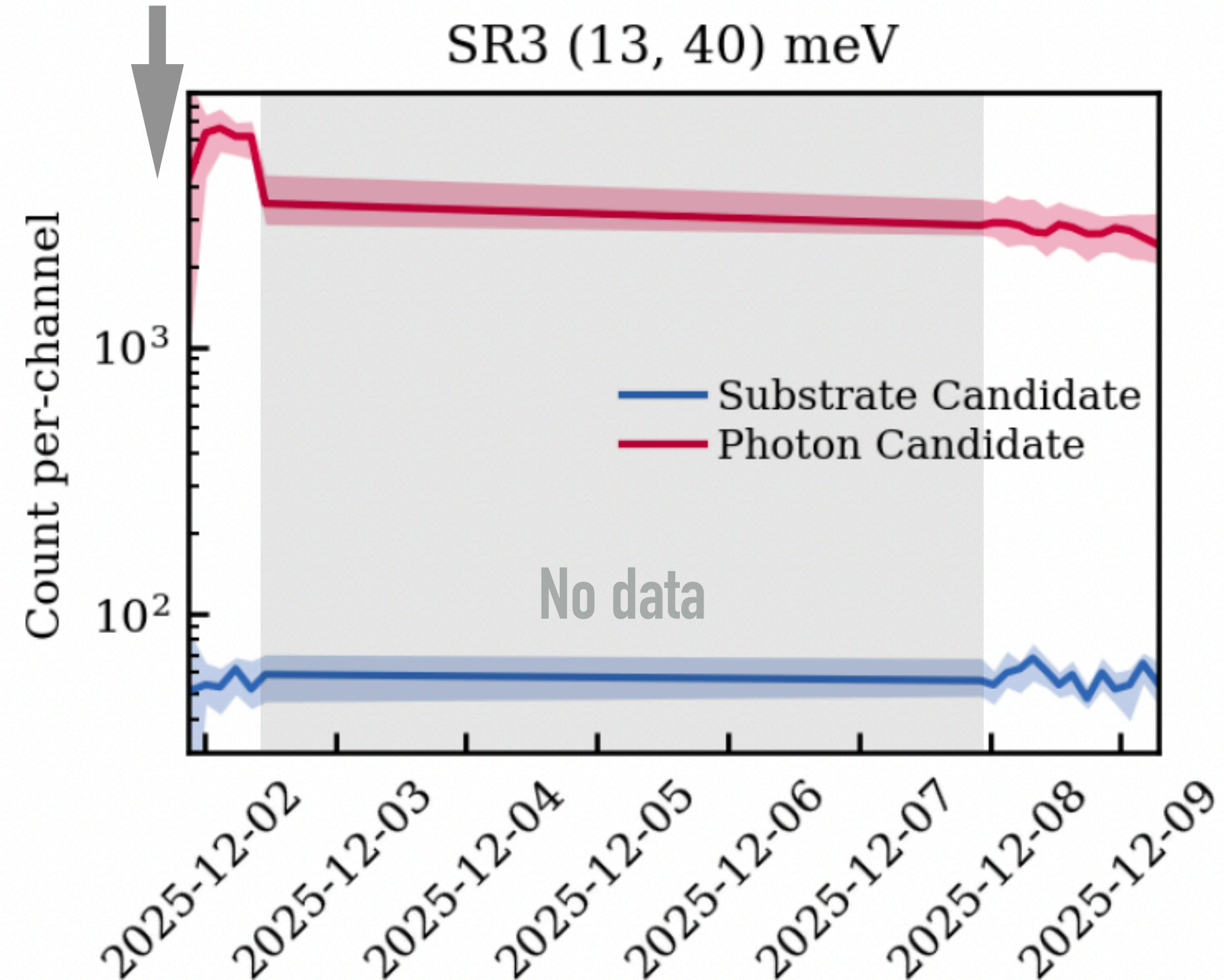


All literature reports a phenomenological τ_{max}
Which suggests unknown a universal unknown
mechanism for quasiparticle loss

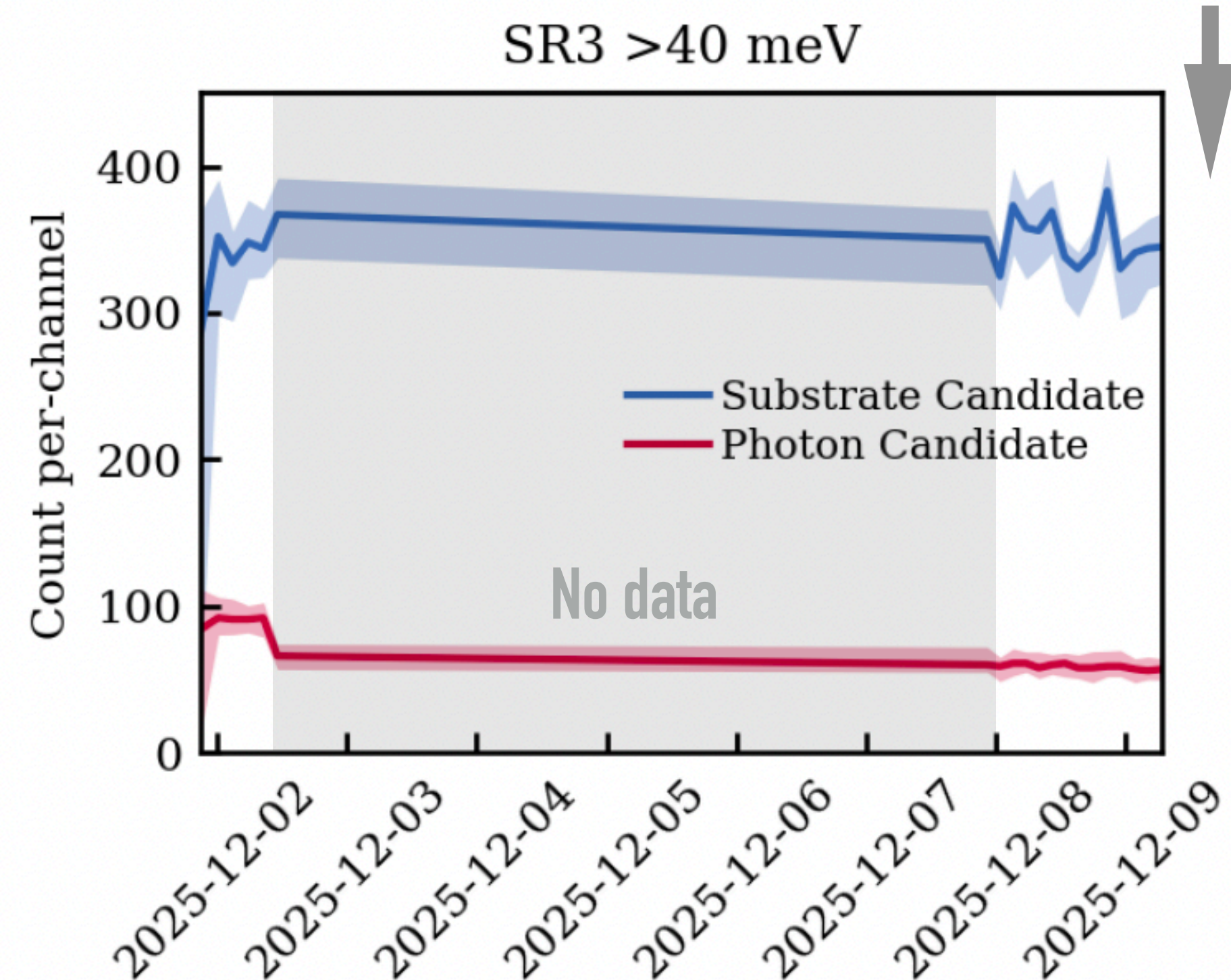
τ_{max} shows up in substrate events,
but not photon-like events!?

5. WEEK-SCALE TIME EVOLUTION: YES IN PHOTON-LIKE, NO IN SUBSTRATE-LIKE²⁷

7 days after cool-down



14 days after cool-down



Substrate-like shows no significant trend after 7 days since cool-down

But photon-like rate does drop ~50% after a 5.5 day gap

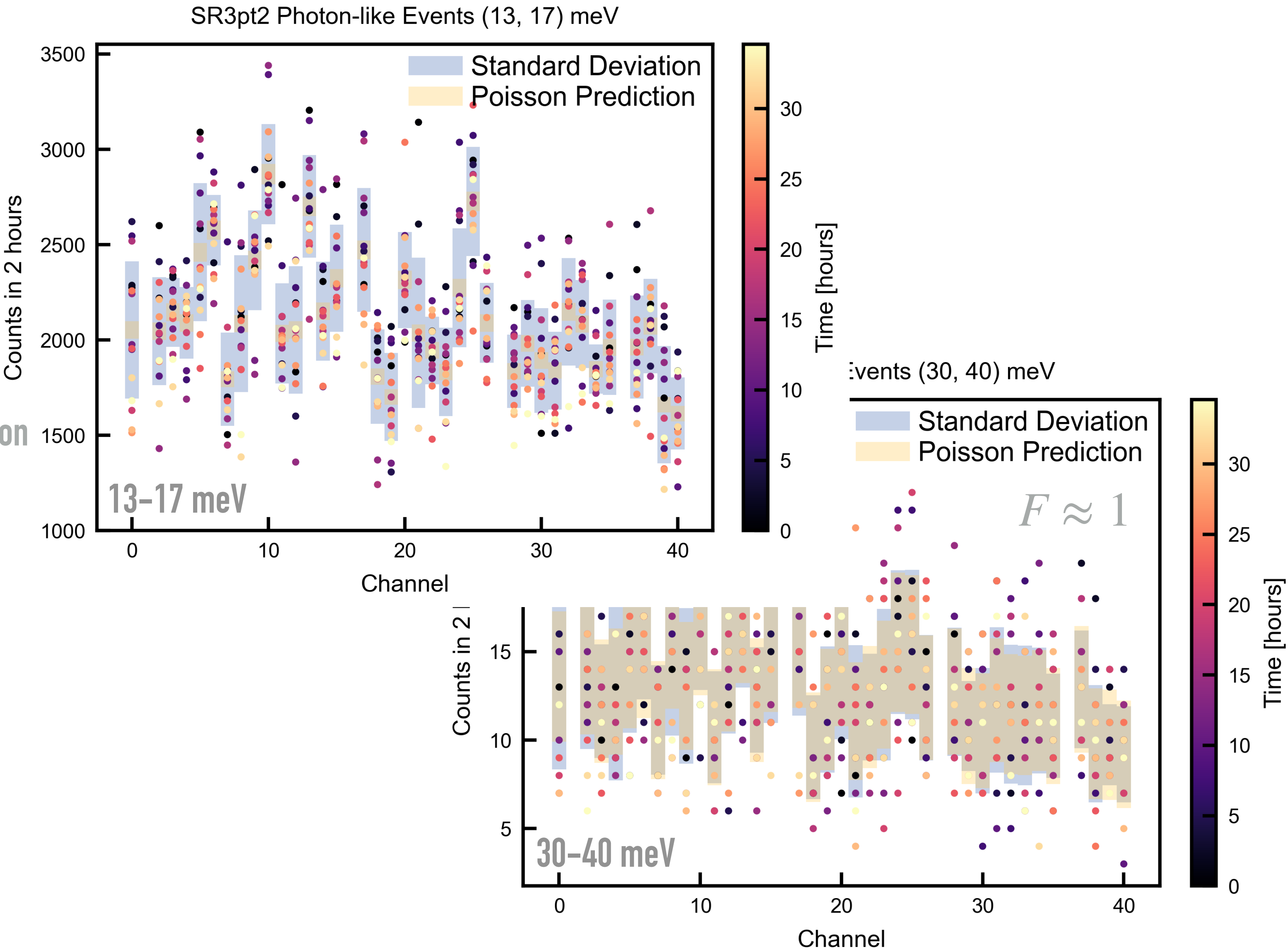
6. HOUR-SCALE TIME EVOLUTION: ENERGY-DEPENDENT SUPER-POISSON FLUCTUATION

Yellow band: std by Poisson estimation over full 21 hours

Blue band: measured std over full 21 hours

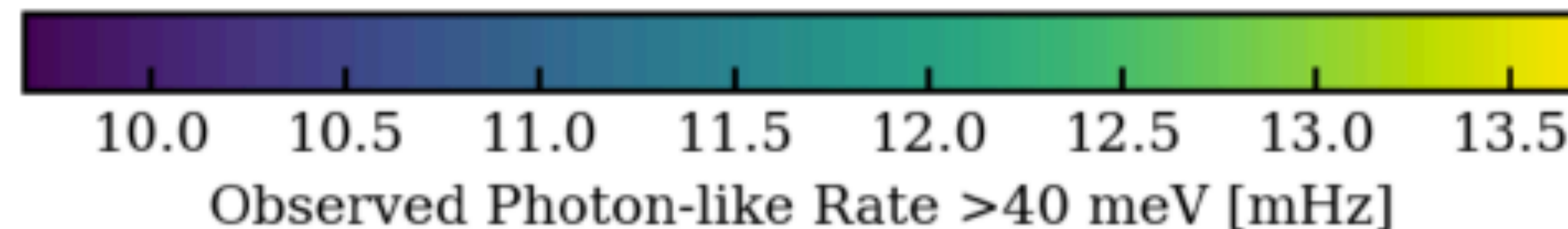
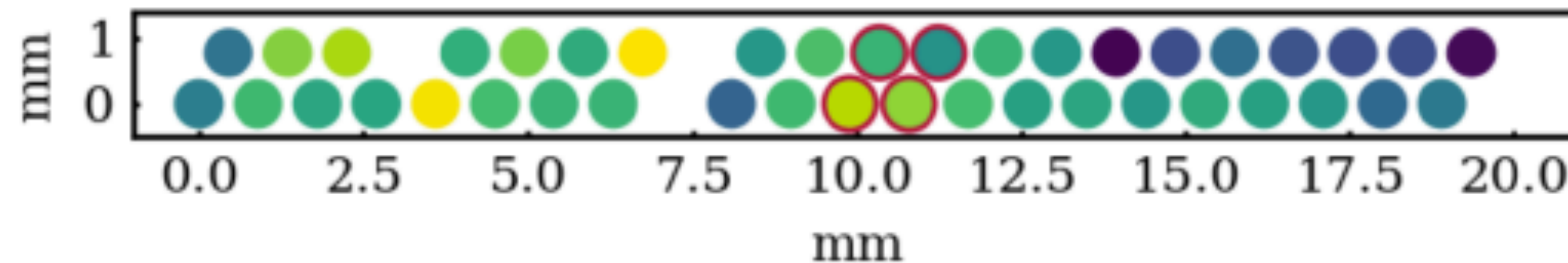
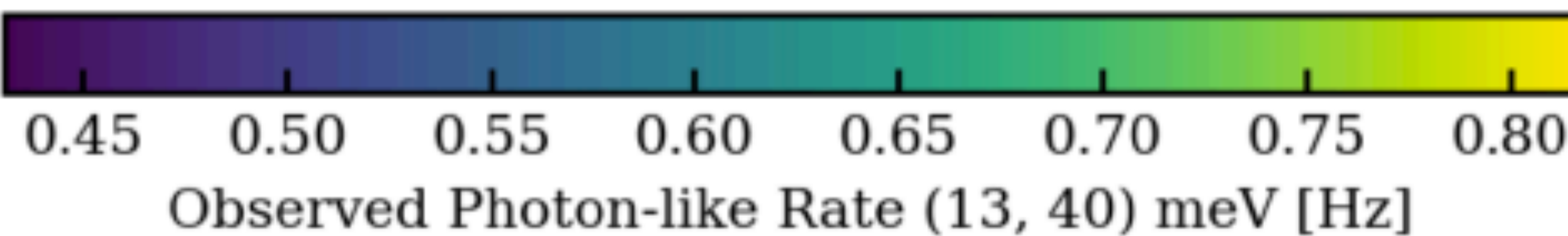
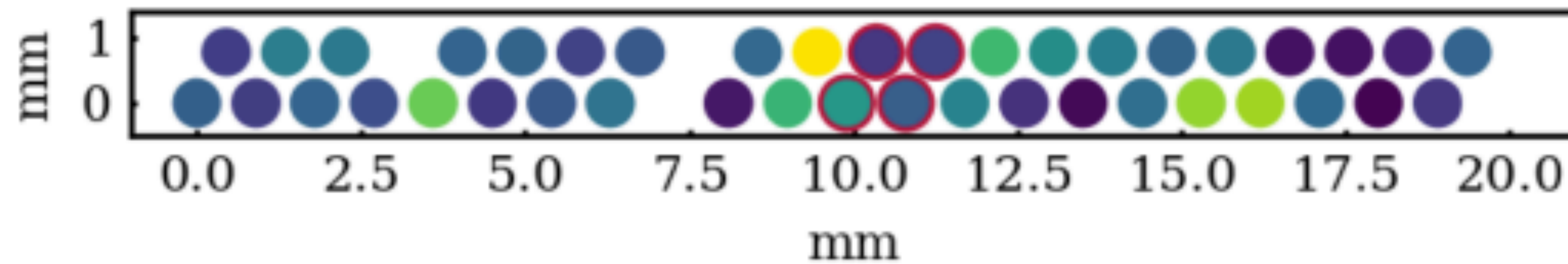
A disagreement means beyond-Poisson fluctuation

Low-energy photon-like events have some self-triggering mechanism!



7. POSITION DEPENDENCE: PHOTON-LIKE IS UNIFORM

29



No clear spatial dependence in low-energy photon-like events

Maybe a pattern in higher energy? Could be IR leak?

MAYBE ENOUGH TO DOWN-SELECT PHYSICAL MECHANISMS?

ENERGY SPECTRUM

TIME TREND

PULSE SHAPE

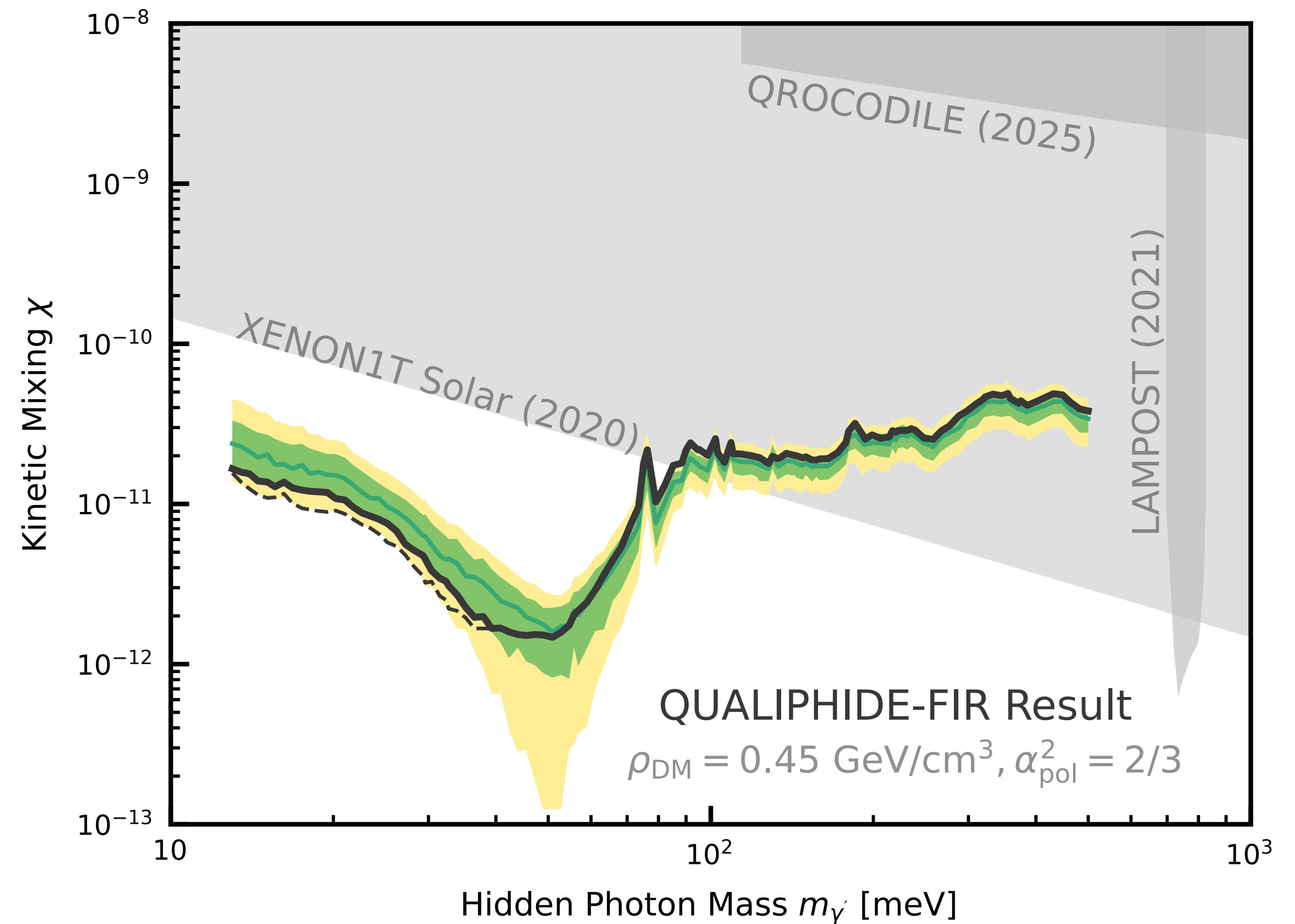
SPATIAL PATTERN



QUALIPHIDE-FIR DARK MATTER
EXPERIMENT

DARK MATTER RESULT

- ▶ We adopted the profiled-likelihood ratio frequentist framework from WIMP detection community
 - ▶ Blind analysis
 - ▶ No excess (local significance $< 3.0\sigma$)
 - ▶ Modeled systematic uncertainties via nuisance parameters: low/high energy background rate, efficiency uncertainty and resolution uncertainty
 - ▶ Implicitly performed “background subtraction” through extended unbinned Poisson likelihood
 - ▶ Gaussian constraints on nuisance parameters
- ▶ **World leading constraint in (13,90) meV**
 - ▶ First dish antenna experiment with discovery potential



Phonon-dominated background

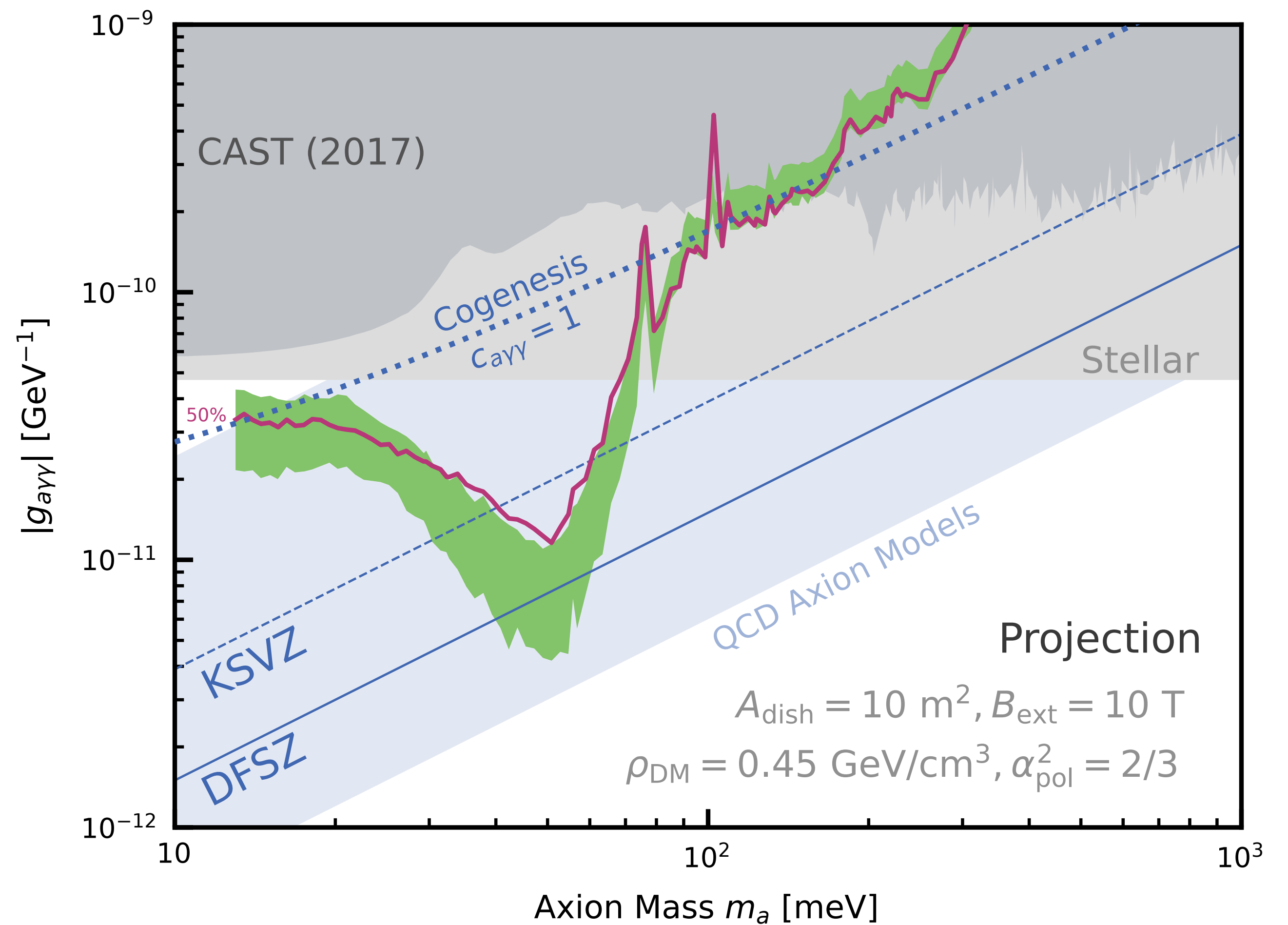
→ Expect the same background spectra inside BREAD

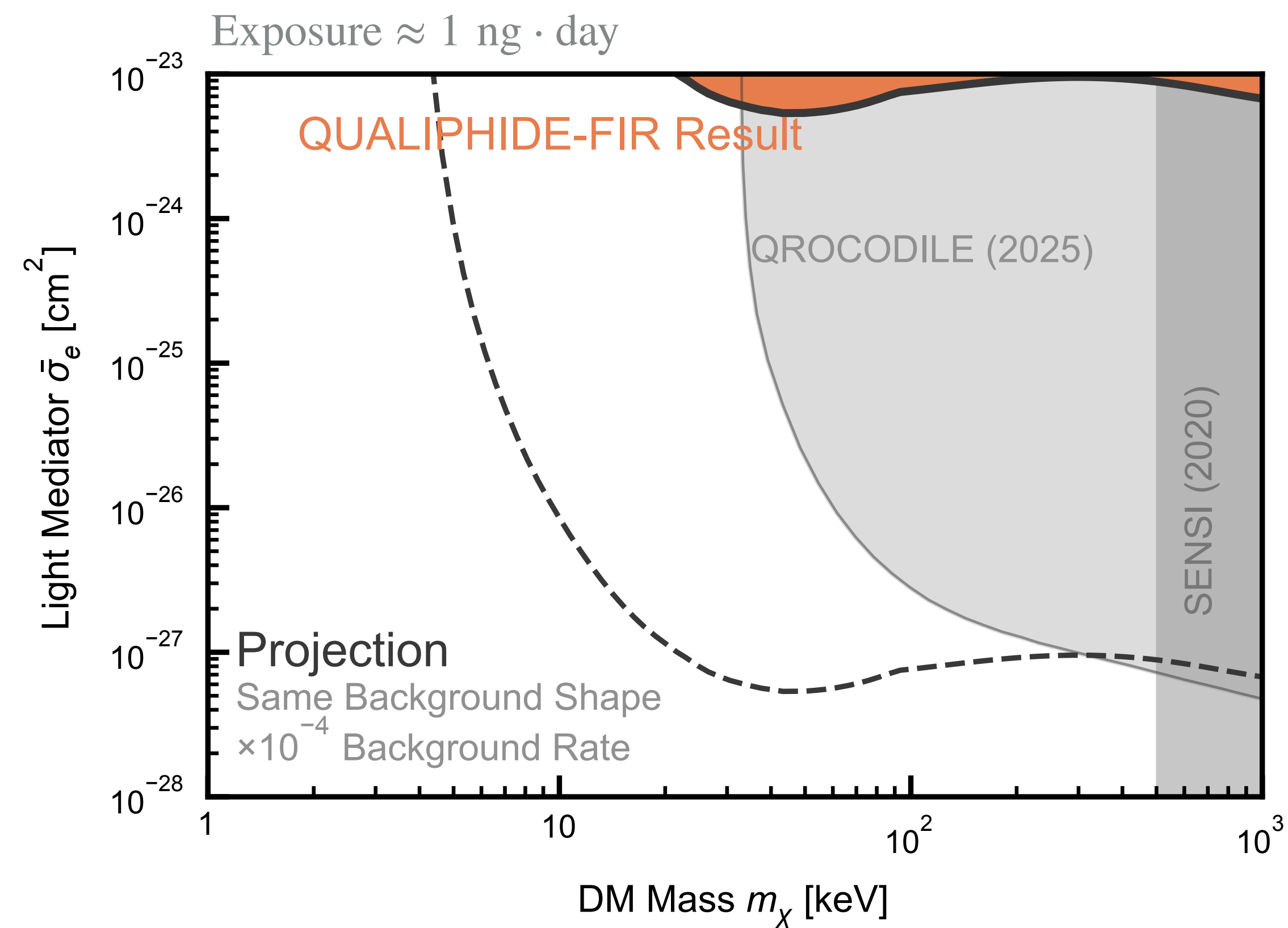
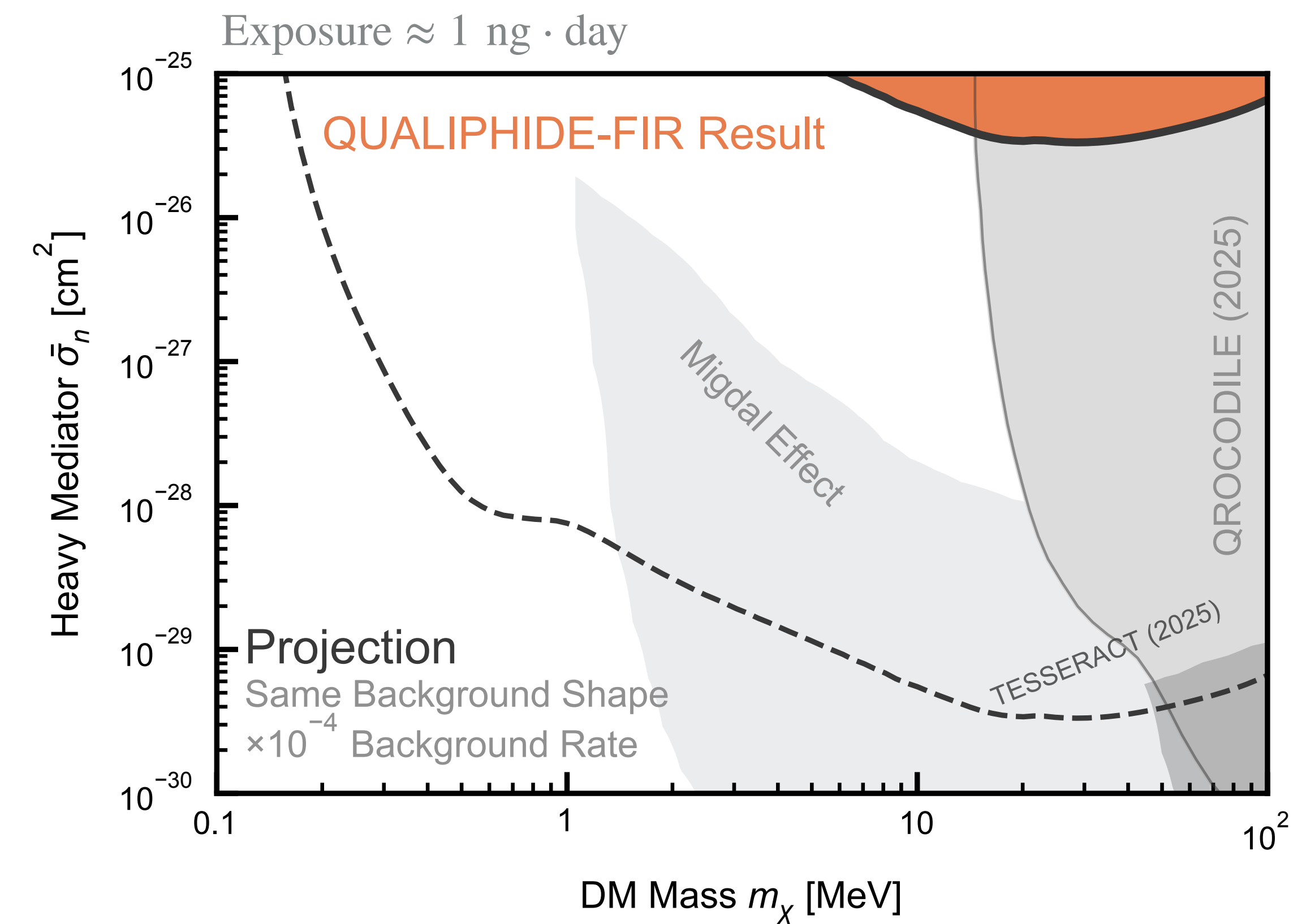
Discovery potential at KSVZ & DFSZ!



Phys.Rev.Lett. 128 (2022) 13, 131801

Next: how can KID dance with a $B_{\text{ext}} = 10 \text{ T}$?





Phys.Rev.D 106 (2022) 3, 036019

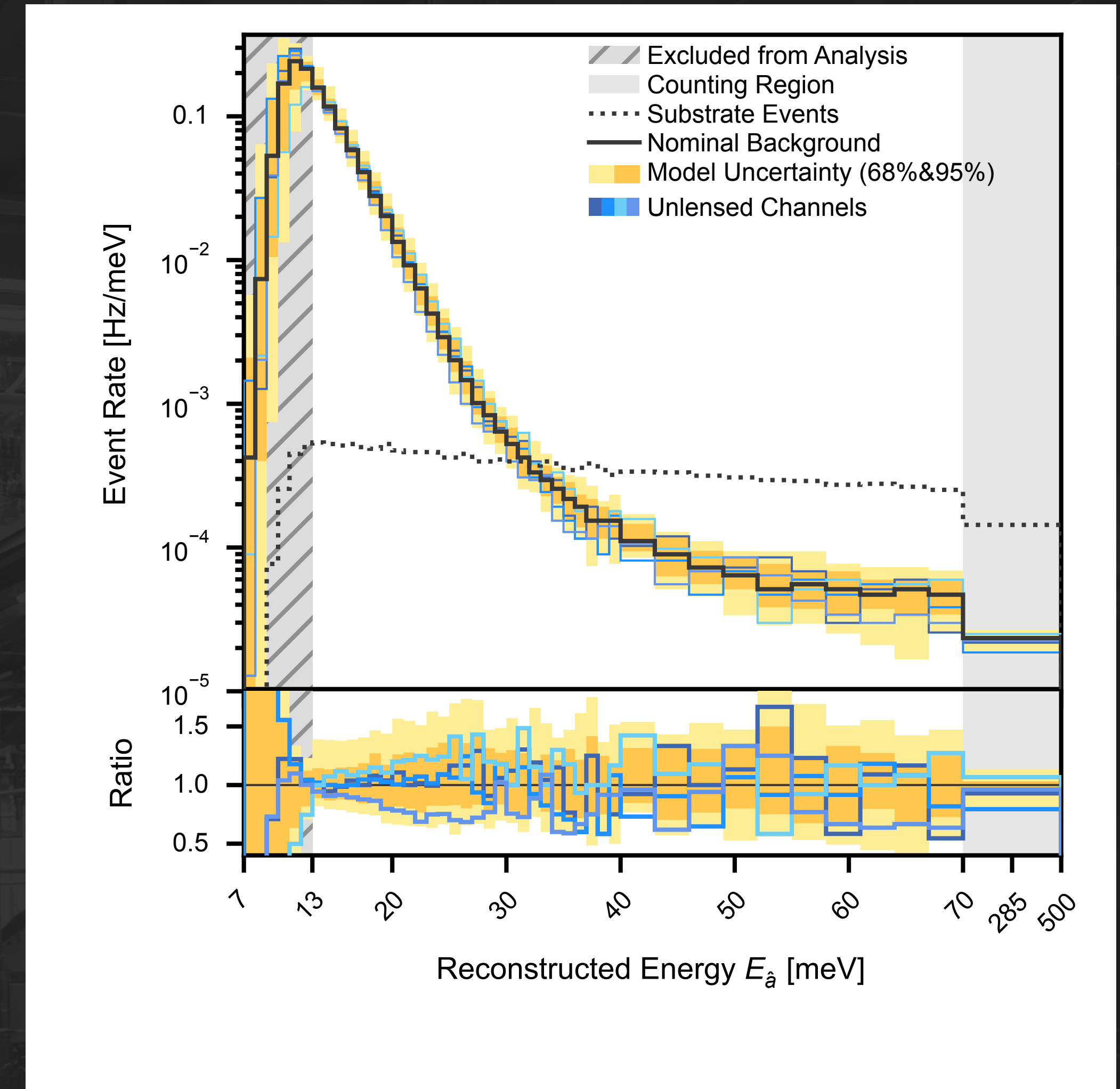
Phys.Rev.D 105 (2022) 1, 015014

Phonons within superconducting volume from electronic/nuclear scattering by dark matter can also break Cooper pairs

Phonon maximum energy $< 40 \text{ meV}$ in Al $\rightarrow$ **We can in principle detect scattering from single phonon production!**

Lowest mass probed at a terrestrial experiment (Previous dark matter experiment with lowest threshold: 110 meV) Phys. Rev. Lett. 135, 081002

- ▶ QUALIPHIDE-FIR: A pathfinder experiment of dish antenna + energy-resolved photon counting FIR-KID
 - ▶ World-leading constraints on dark photon (blind analysis) and light dark matter scatterings
- ▶ Preliminary investigation of background origin
 - ▶ Substrate-like:
 - ▶ Observed power law in spectrum $p \approx -1/2$
 - ▶ Photon-like:
 - ▶ Exponential decay peak (<40 meV) & slower decay (> 40 meV)
 - ▶ QP lifetime keeps increasing as energy decreases, while substrate-like hits a $\tau_{\max}$ first
 - ▶ Observed week-scale trend since cool-down, and hour-scale super-Poisson fluctuation <30 meV
 - ▶ ~Same rate between lensed and unlensed channels → likely to be phonon-dominated
- ▶ ~First principle microphysical modeling ongoing; More measurements being done



QUALIPHIDE Collaboration



Karthik Ramanathan (PI)
Lanqing Yuan (PD)
Jacob Harris (GS)
Christopher Cappiello (PD)
Andrew Bear (UG)
Drew Smersfelt (UG)

Caltech

Ritoban Basu Thakur (PI)
Christopher Albert (GS)



Alejandro Simon (GS)



Peter Day (PI)
Byeong Ho Eom (SS)
Andrew Beyer (SS)
Henry LeDuc (SS)
Christopher Curwen (SS)



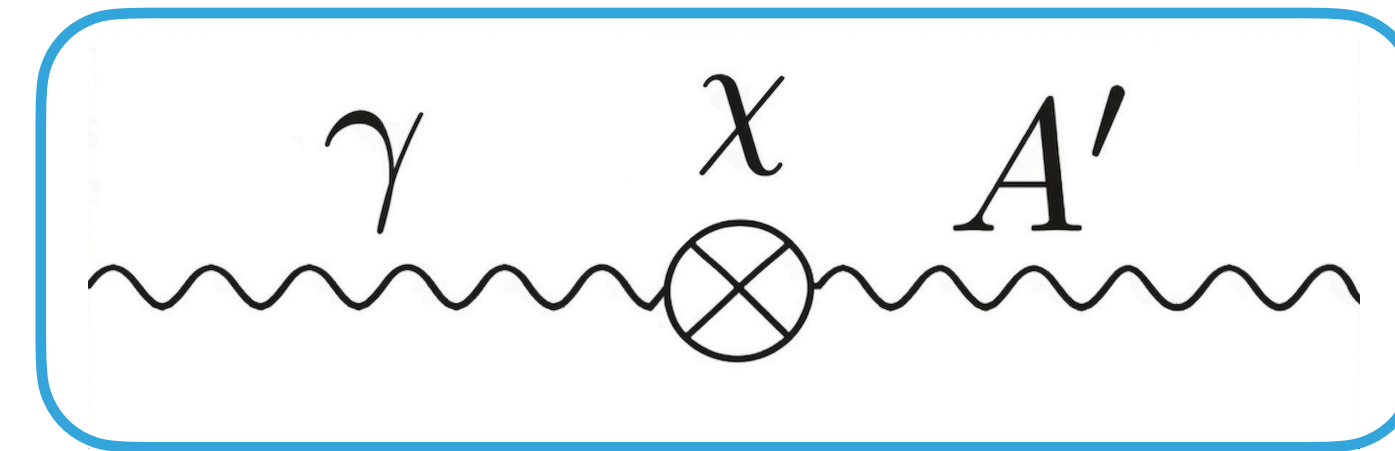
Nikita Klimovich (PD)



Arjun Ghosh (GS)

► Dark photon (DP)

- Simplest possible addition to Standard Model
- Kinetic mixing (χ) with Standard Model photon
- Wave-like DP ($\lesssim 1$ eV) effectively modifies Maxwell Equation
- Dish antenna detector
 - Continuity of $E_{\perp}$ at conducting surface forces an emission of photons
 - A metallic dish focuses these DP induced photons onto a sensor
 - A lower detected power P_{det} suggests a more stringent constraint on DP

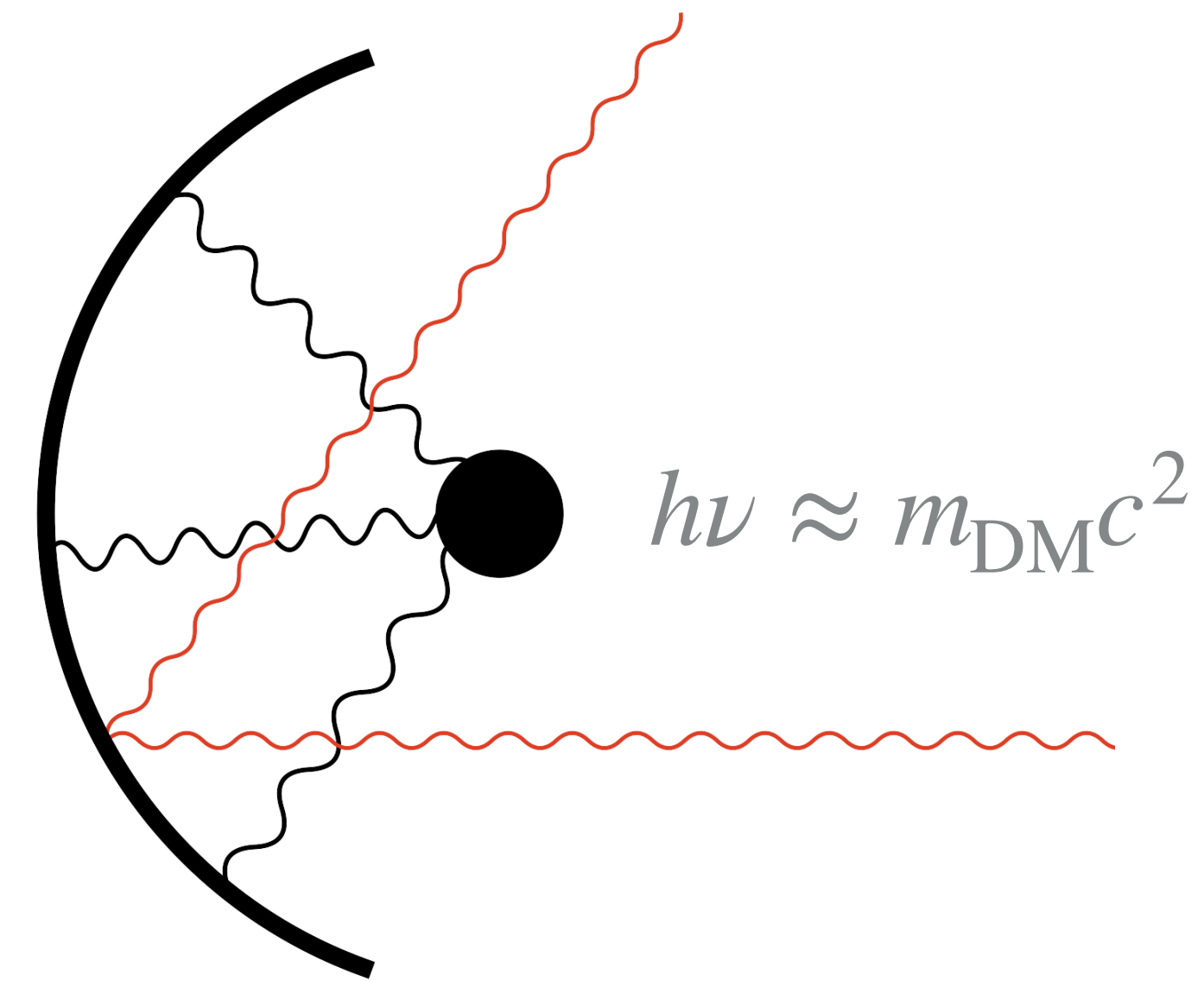
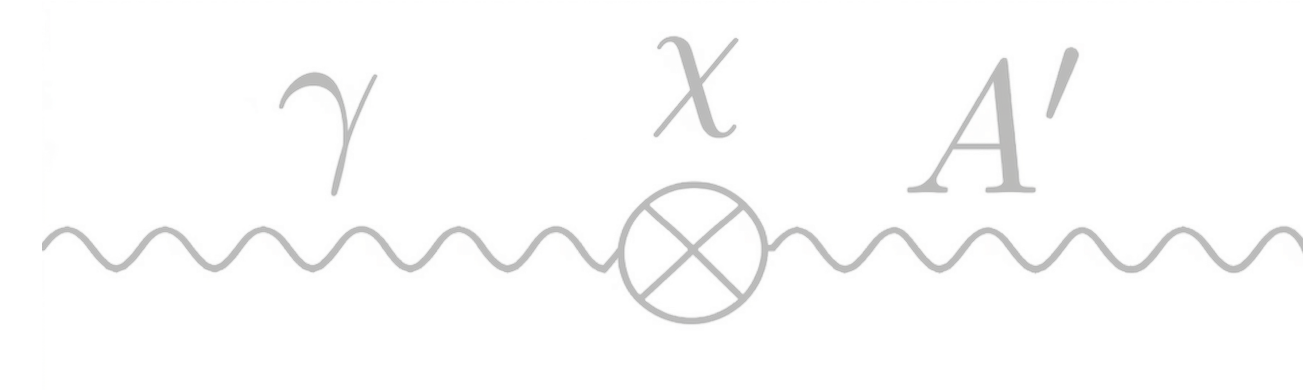


$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + J^{\mu}A_{\mu}$$

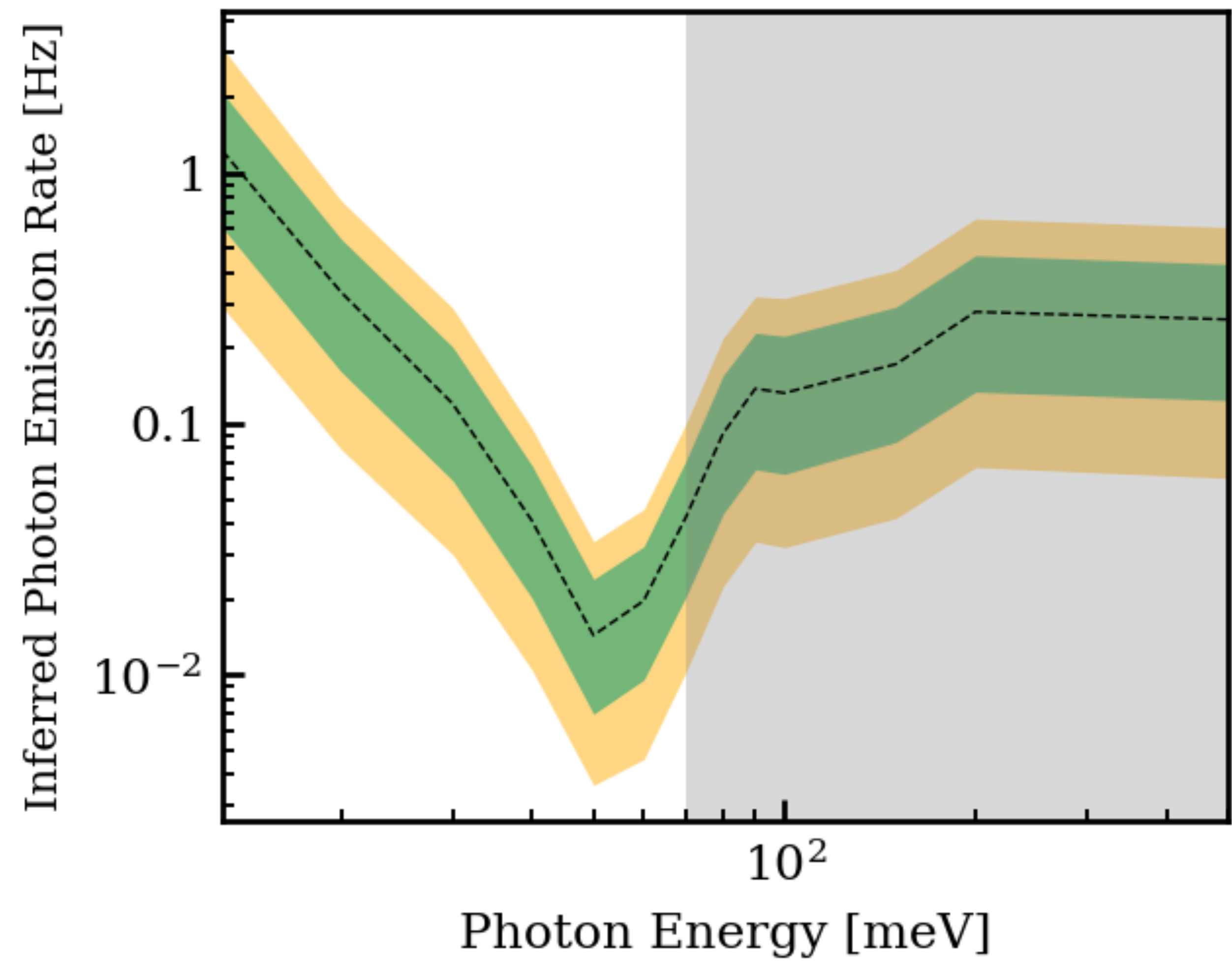
$$-\frac{1}{4}\tilde{X}_{\mu\nu}\tilde{X}^{\mu\nu} + \frac{m_{\gamma'}^2}{2}\tilde{X}_{\mu}\tilde{X}^{\mu}$$

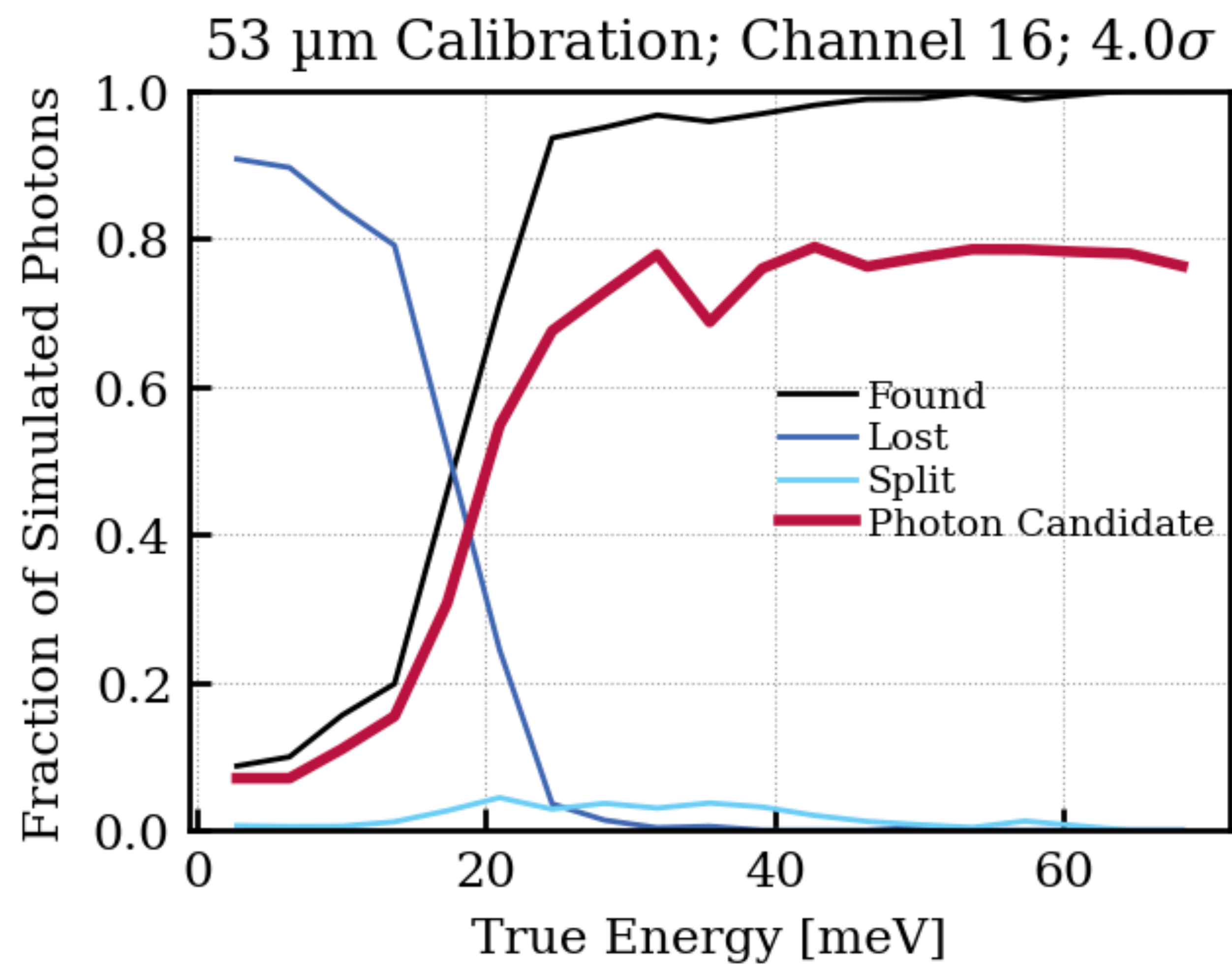
$$-\frac{\chi}{2}F_{\mu\nu}\tilde{X}^{\mu\nu}$$

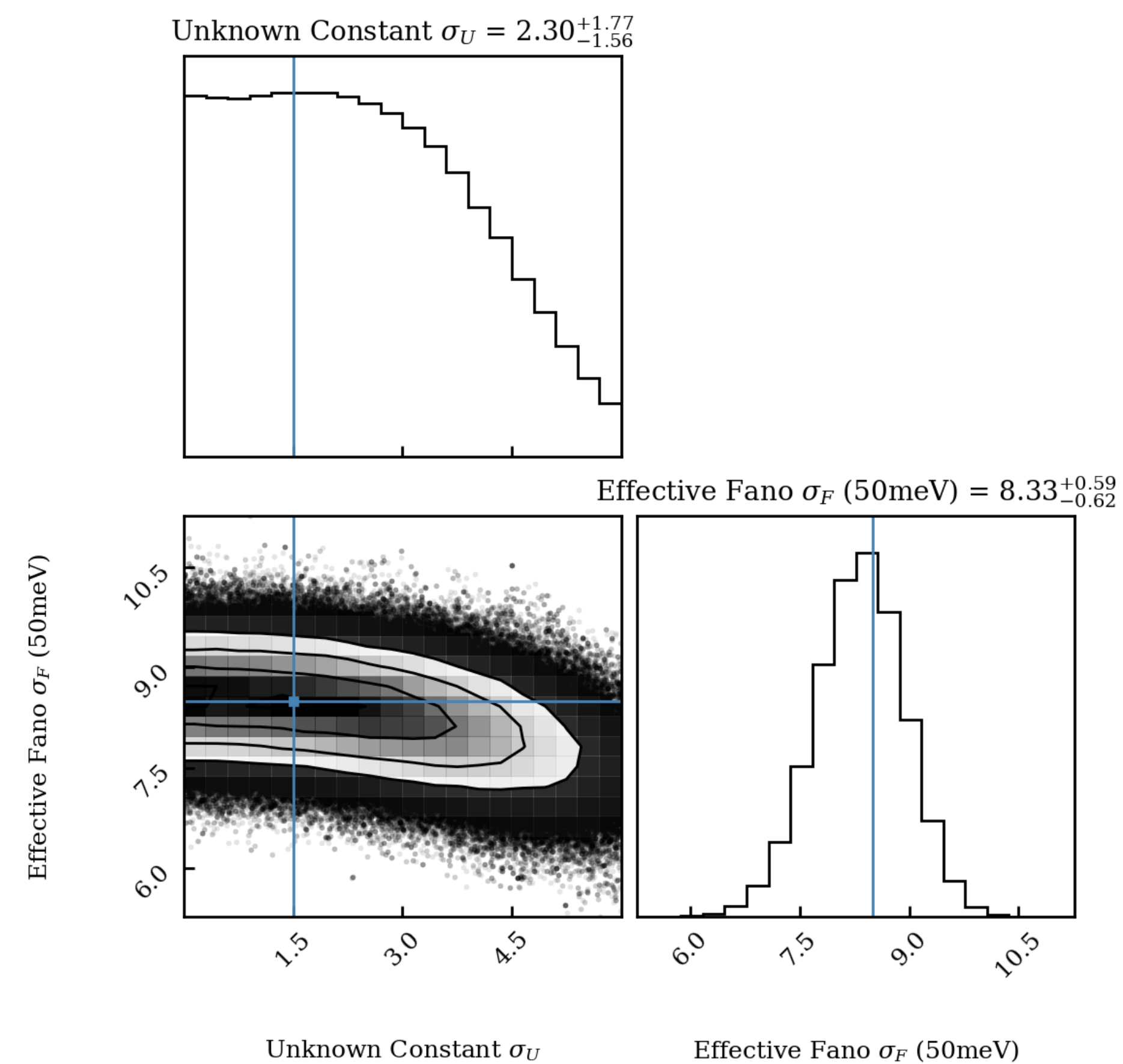
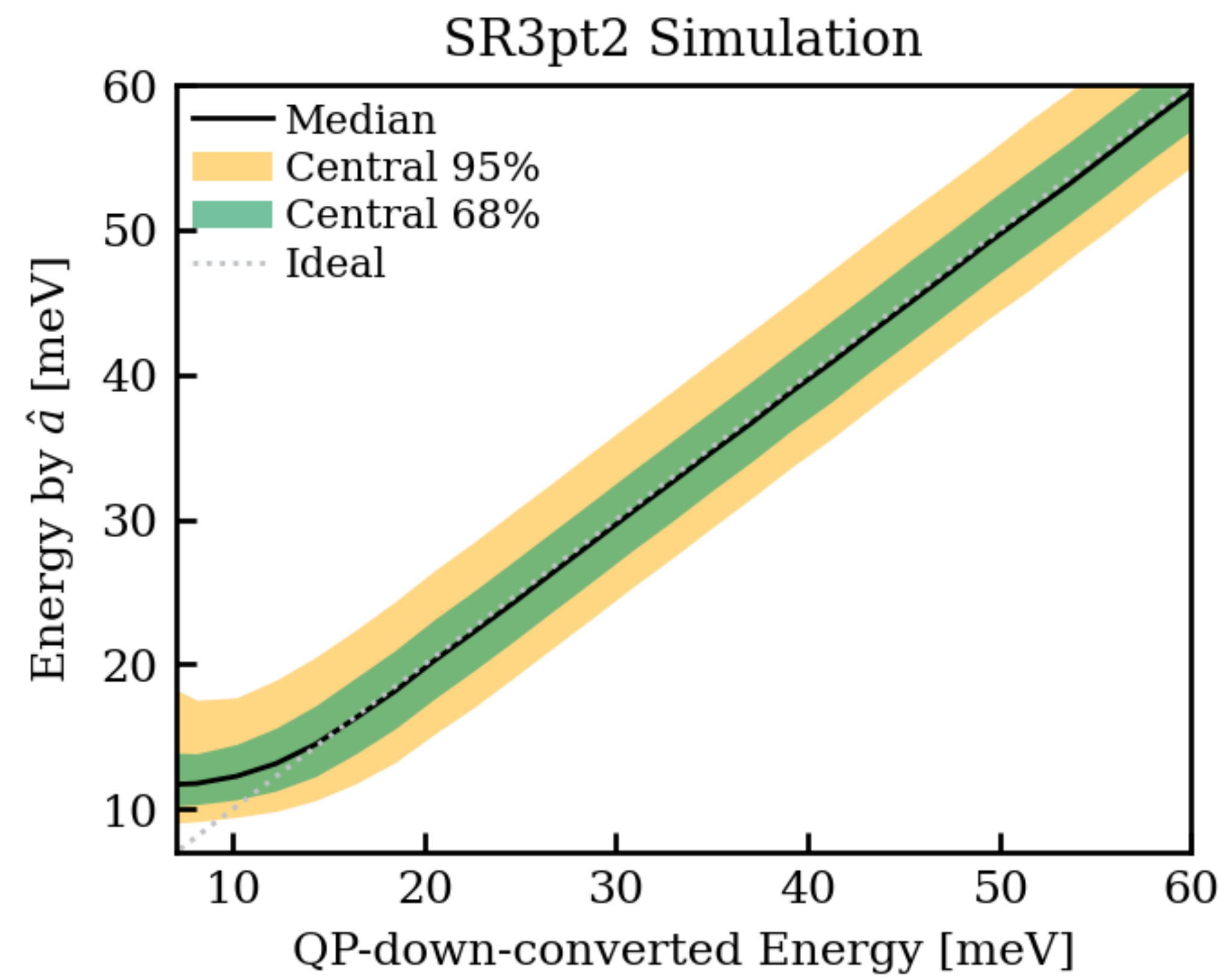
- ▶ Dark photon (DP)
 - ▶ Simplest possible addition to Standard Model
 - ▶ Kinetic mixing (χ) with Standard Model photon
 - ▶ Wave-like DP ($\lesssim 1$ eV) effectively modifies Maxwell Equation
- ▶ **Dish antenna detector**
 - ▶ Continuity of $E_{\perp}$ at conducting surface forces an emission of photons
 - ▶ A metallic dish focuses these DP induced photons onto a sensor
 - ▶ A lower detected power P_{det} suggests a more stringent constraint on DP

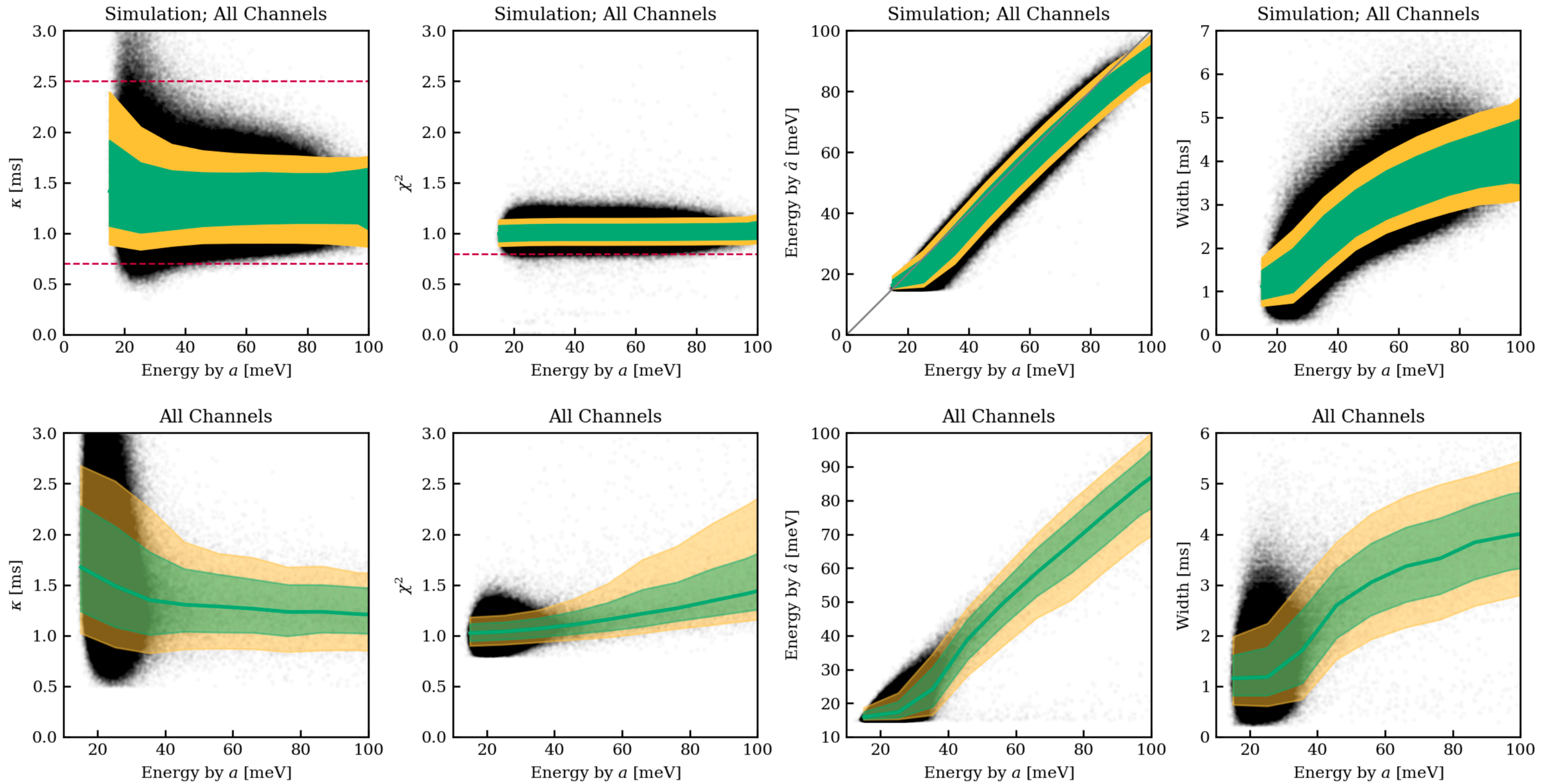


$$P_{\text{det}} \propto \chi^2 \rho_{\text{DM}} A_{\text{Dish}}$$



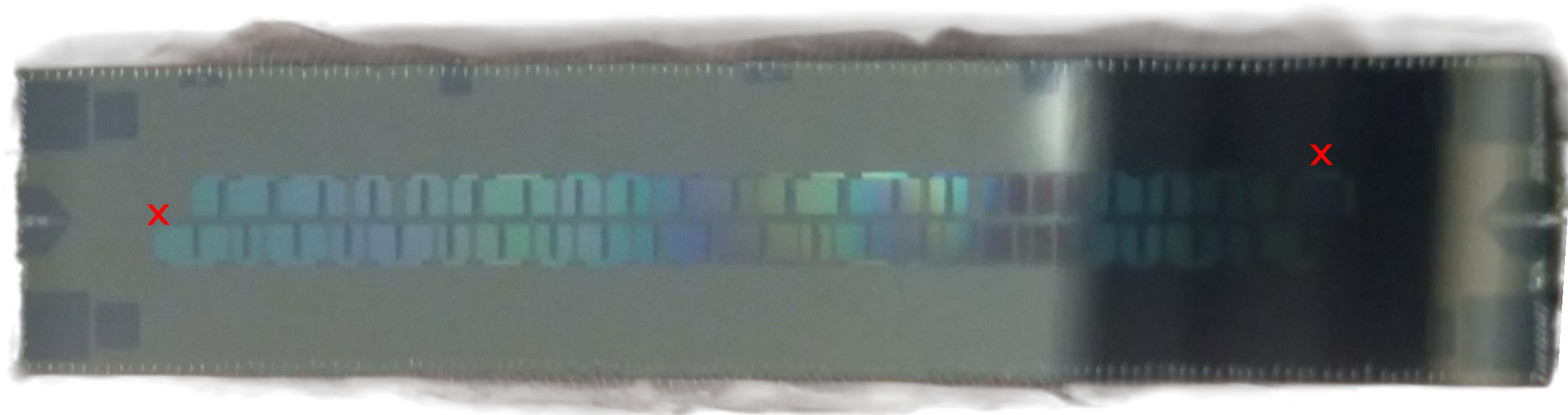
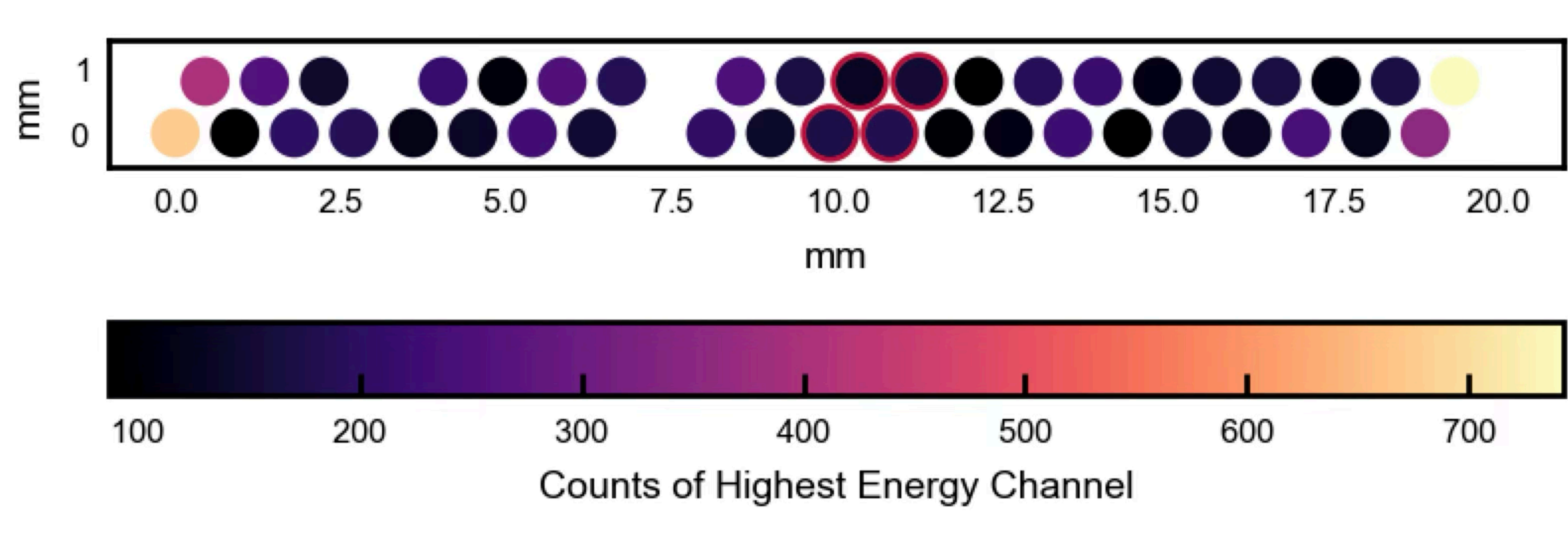


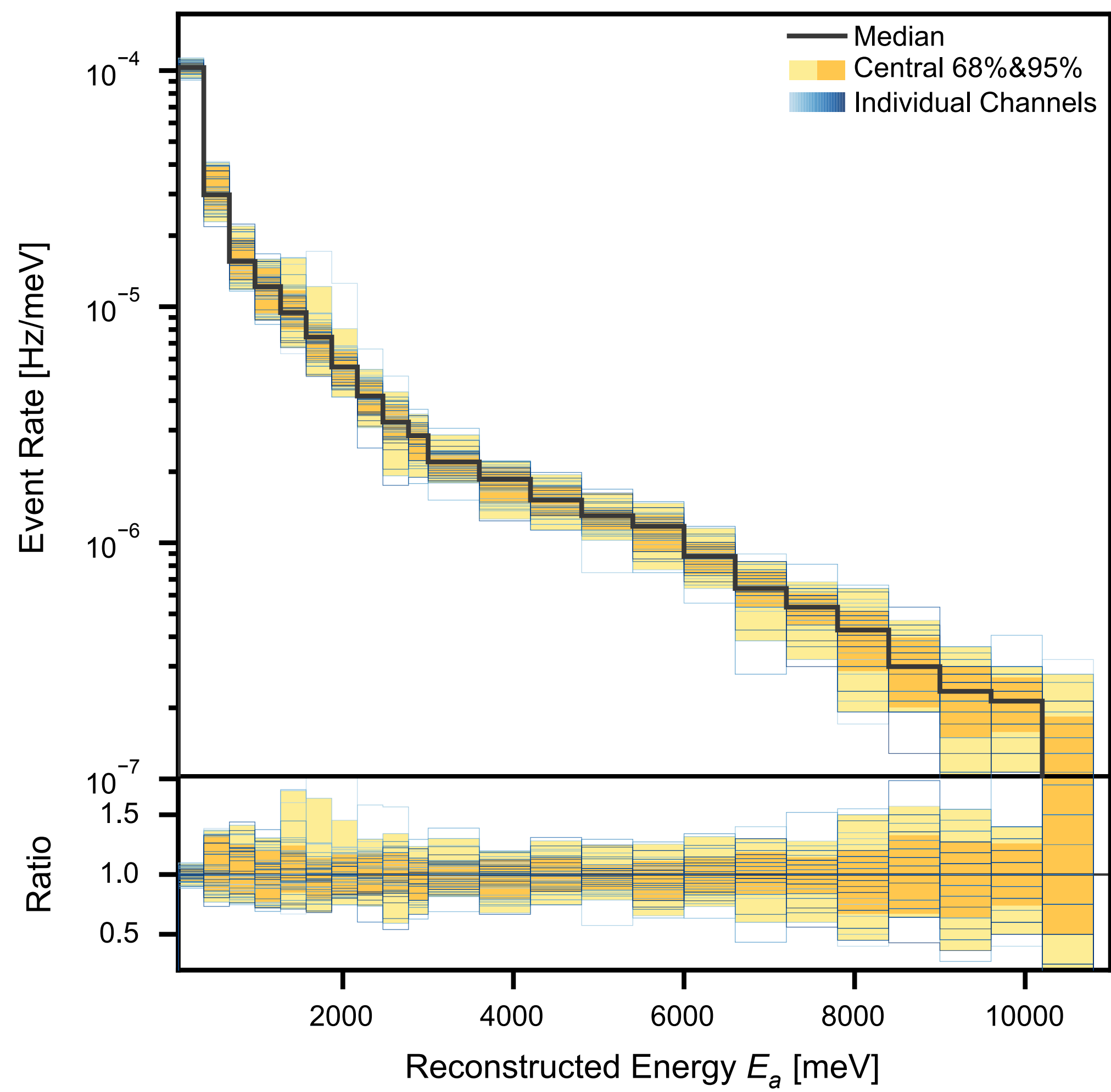




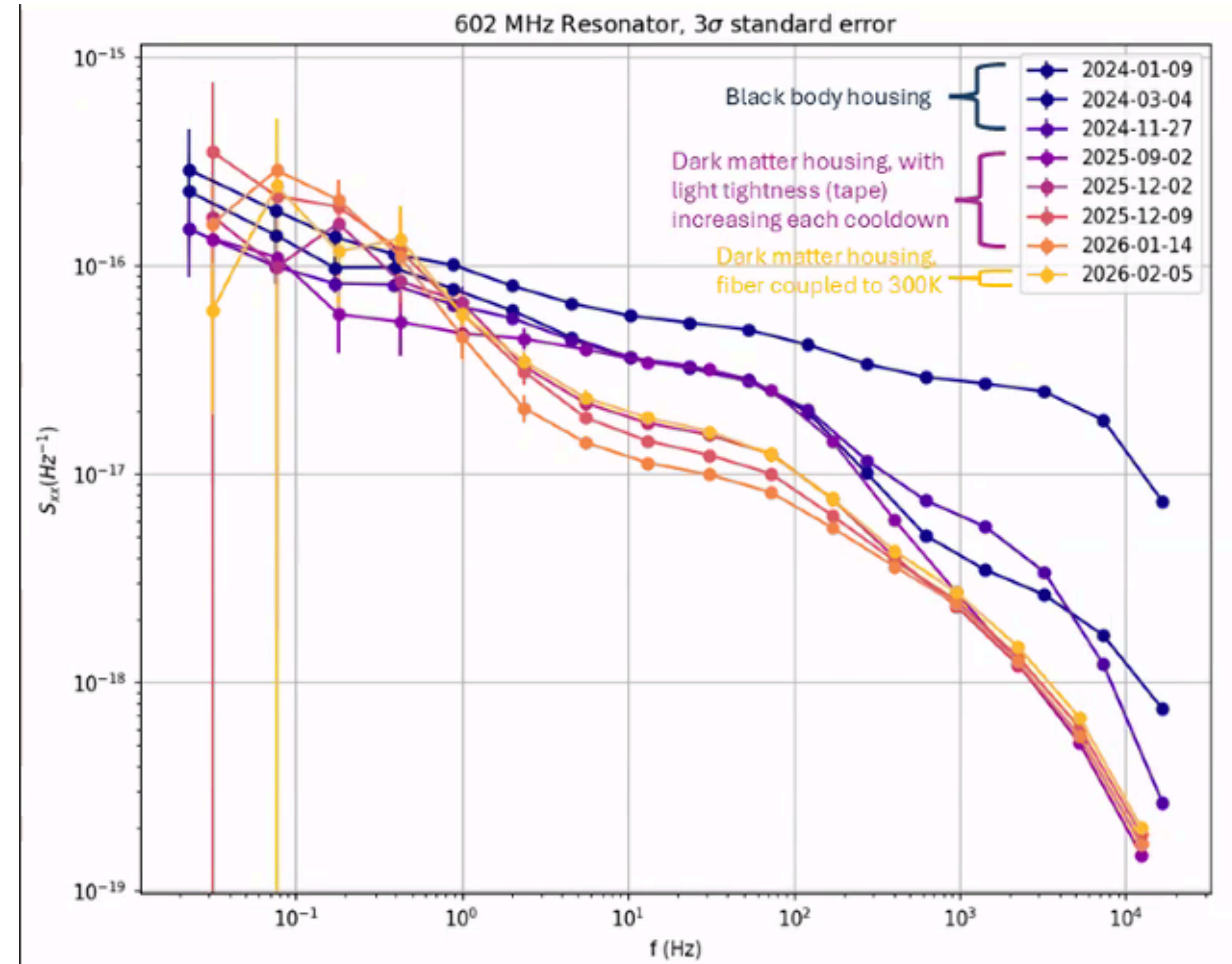
$$q \equiv -2 \ln \frac{\mathcal{L}(\chi, \hat{\boldsymbol{\theta}})}{\mathcal{L}(\hat{\chi}, \hat{\boldsymbol{\theta}})}$$

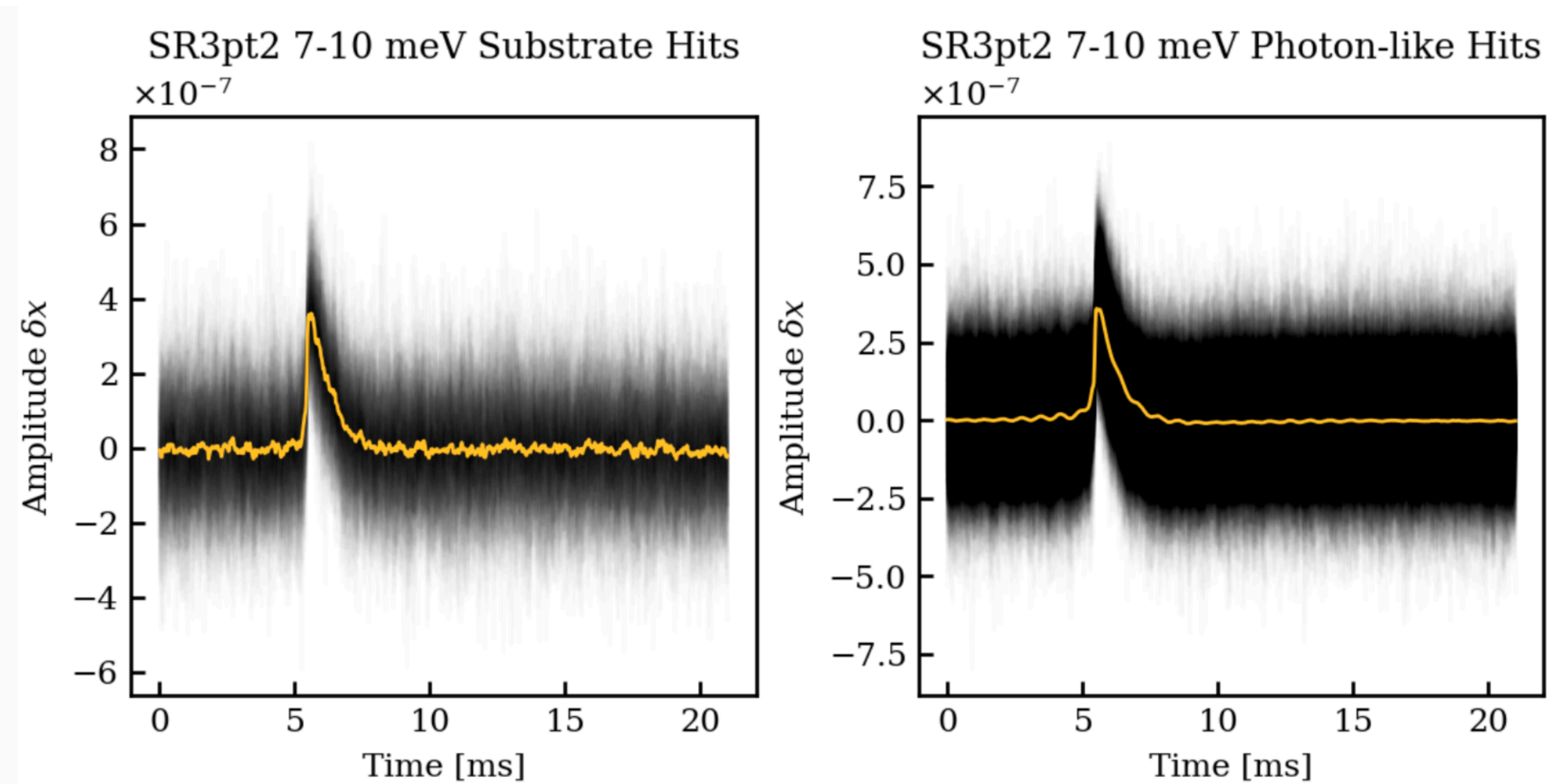
$$\begin{aligned} \ln \mathcal{L}(\chi \mid \boldsymbol{\theta}) = & \ln \left(\text{Pois} \left(N \mid \mu_{\text{tot}}(\chi, \boldsymbol{\theta}) \right) \cdot \prod_{i=1}^N \left[\sum_{\mathbf{c}} \frac{\mu_{\mathbf{c}}(\chi, \boldsymbol{\theta})}{\mu_{\text{tot}}(\chi, \boldsymbol{\theta})} \cdot f_{\mathbf{c}} \left(\vec{x}_i \mid \boldsymbol{\theta} \right) \right] \right) \\ & + \sum_m \ln \left(\mathcal{L}_m(\theta_m) \right) \end{aligned}$$





- ▶ PSD of time-series, lower the level the better (higher SNR)
- ▶ Holder type (i.e. blackbody calibration configuration and dark matter housing) and progressive addition of copper tape can make up to an order of magnitude difference
- ▶ Future runs will house device in a “stub-filter” housing (based on LBNL design)





Low-energy photon-like events are mutually UNCORRELATED across channels: detrended $\bar{r} \approx 0$, far from the $r \approx 0.9$ of a global drive

