PRELIMINARY RESULTS FROM DARK PHOTON & LIGHT DARK MATTER SEARCHES WITH THE **QUALIPHIDE-FIR** EXPERIMENT

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on behalf of the QUALIPHIDE collaboration

IDM
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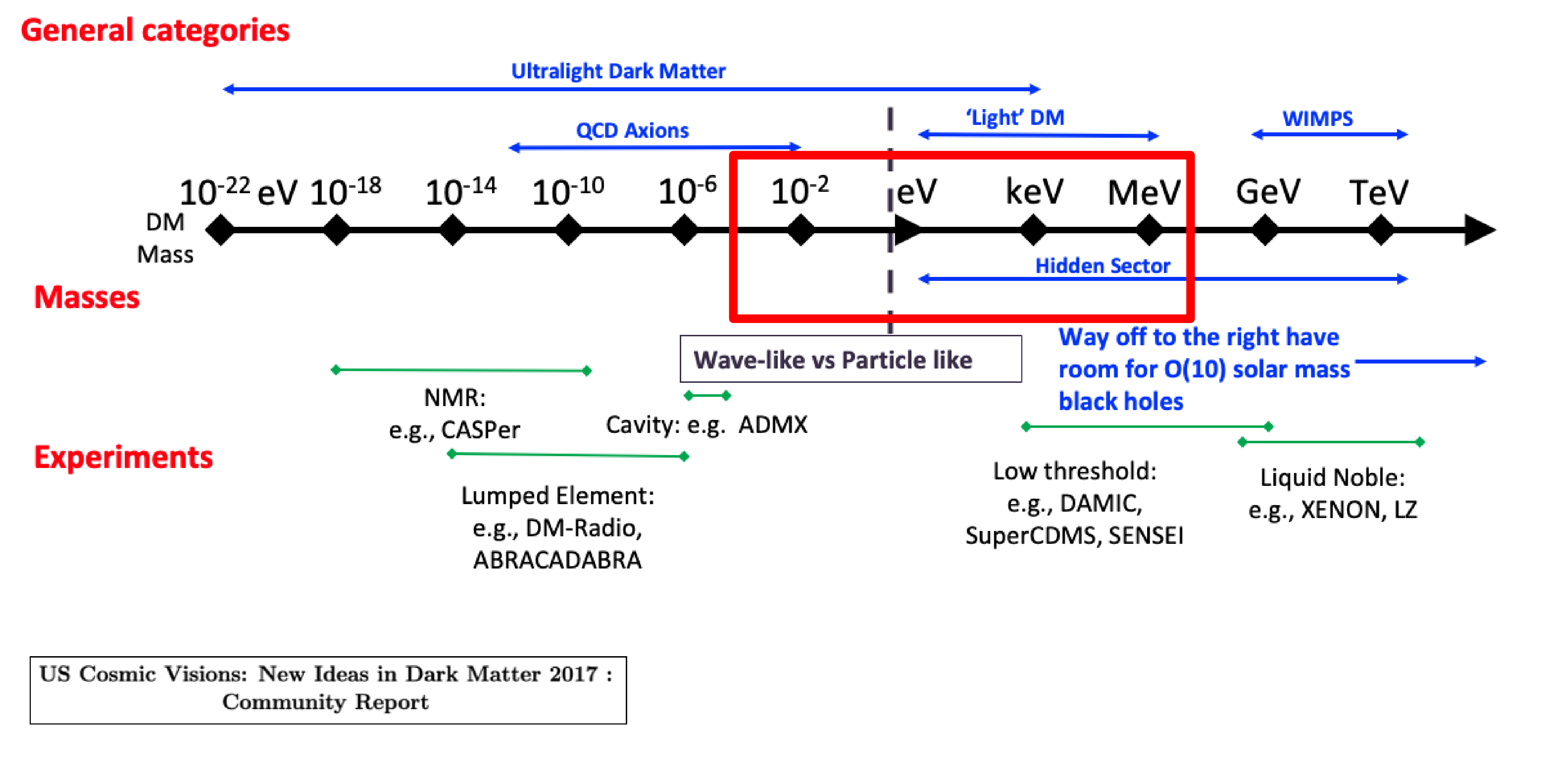
Image courtesy of JPL Microdevices Laboratory

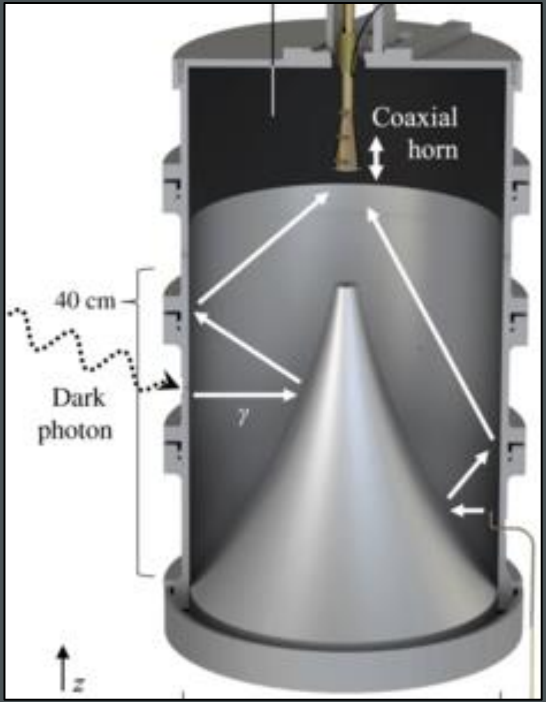
DM Parameter Space



Shared technical overlap in sensing DM

Wave-like

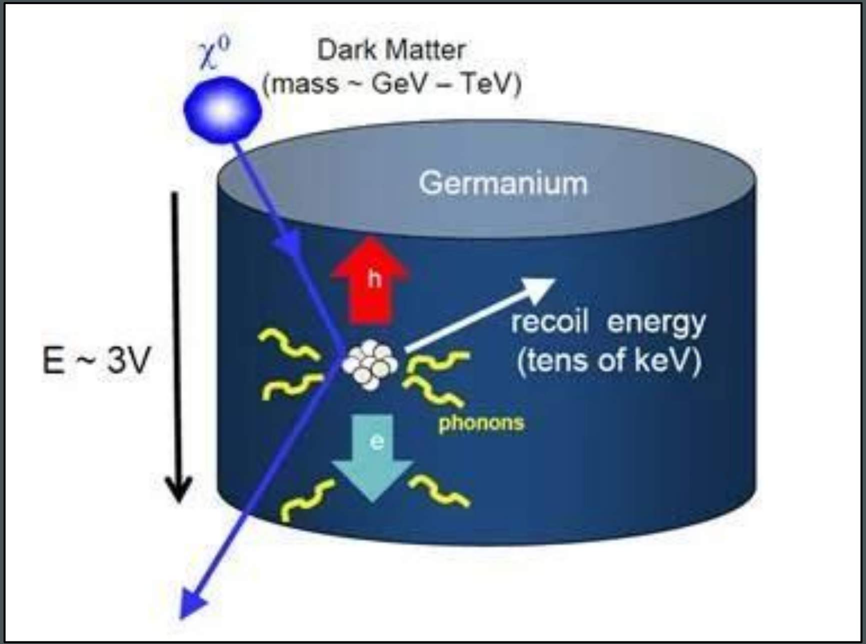
- e.g. Dark Photons
- large occupation numbers
- may generate a single **photon**
- **How do you detect photons of few meV (THz)?**



BREAD
Phys. Rev. Lett. **132**, 131004

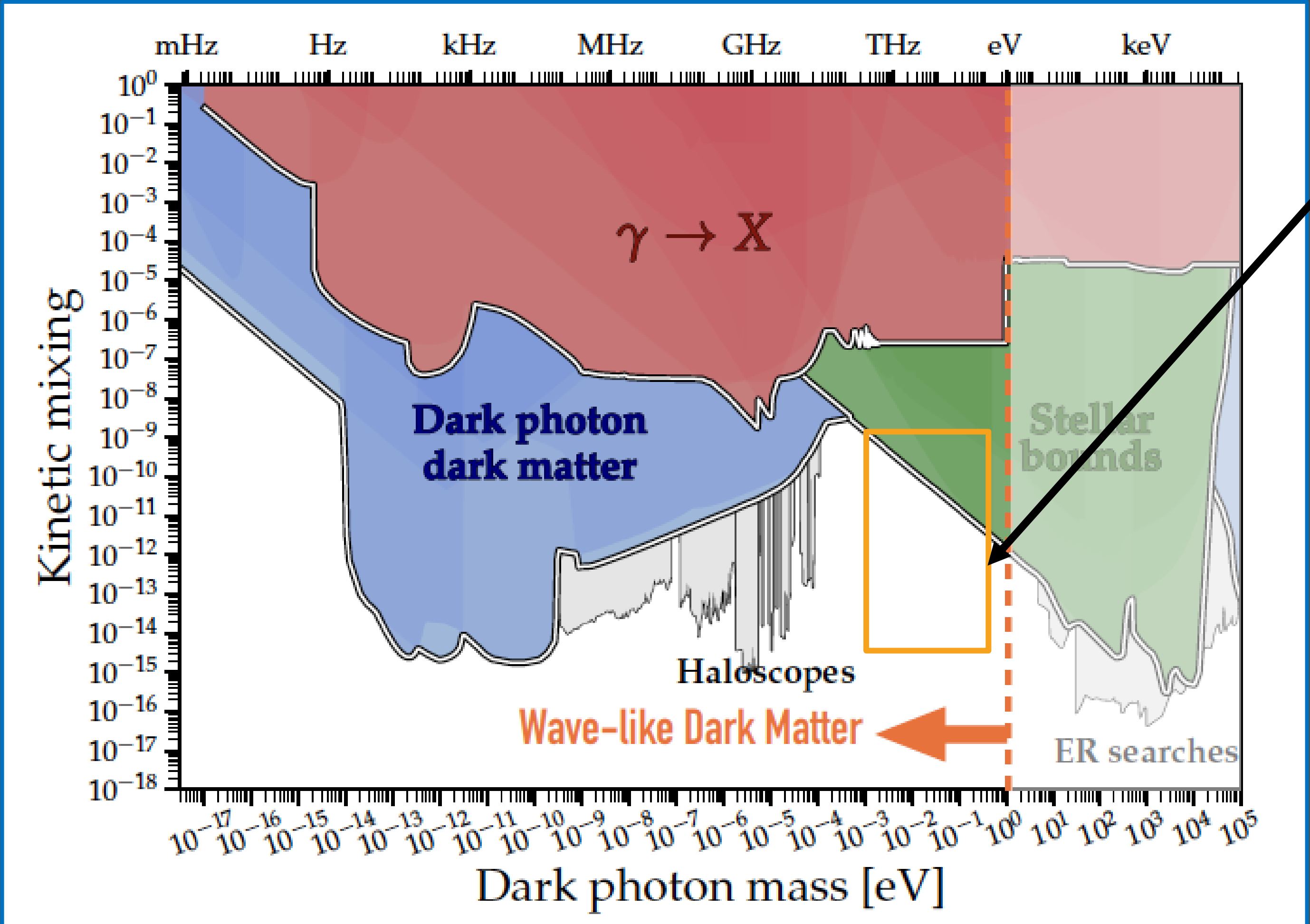
Particle-like

- e.g. LDM
- single particle scattering or absorption
- generate collective excitations like a **phonon**
- **How do you detect a 10 meV energy deposit?**



SuperCDMS schematic

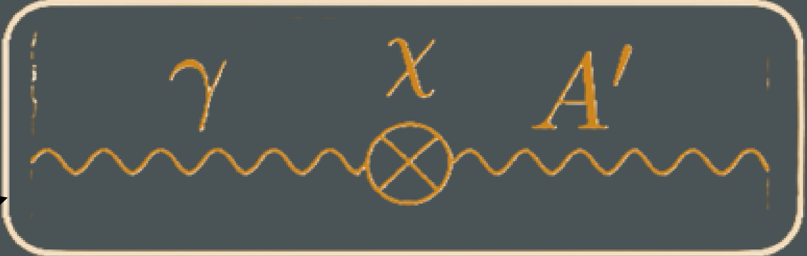
Wave-like Dark Matter & the Far-IR Desert



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

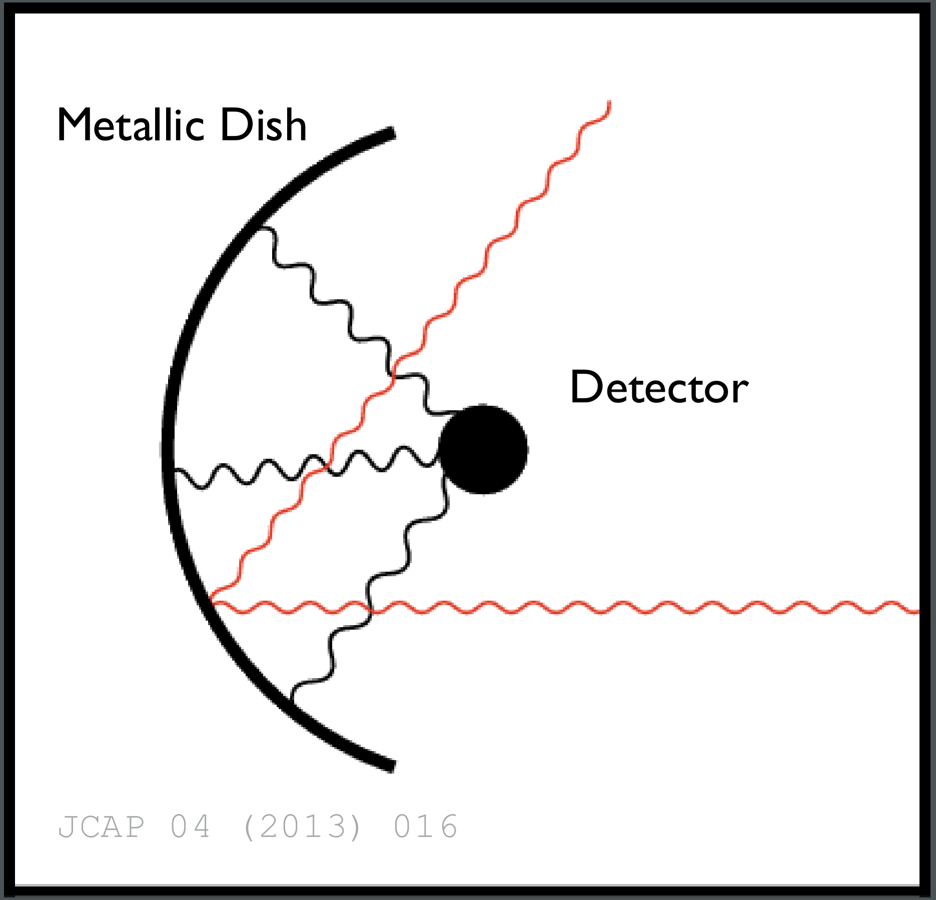
"The far-infrared (FIR) desert":

- Absence of lab search constraint in FIR frequency range (~THz). Photon readout is a central challenge
  - Volume scaling problem in resonant cavity experiments
  - Noise & bandwidth issues in heterodyne readout
  - Threshold problem in electronic recoil experiments



"kinetic mixing" with Standard Model photon

Dish Antenna DM experiments



Wideband approach: interchange detectors at the geometric focus.

If wave-like DM has a tiny effective electric field from SM coupling → tangential boundary condition on any conducting surface sources small amount of perpendicularly emitted radiation.

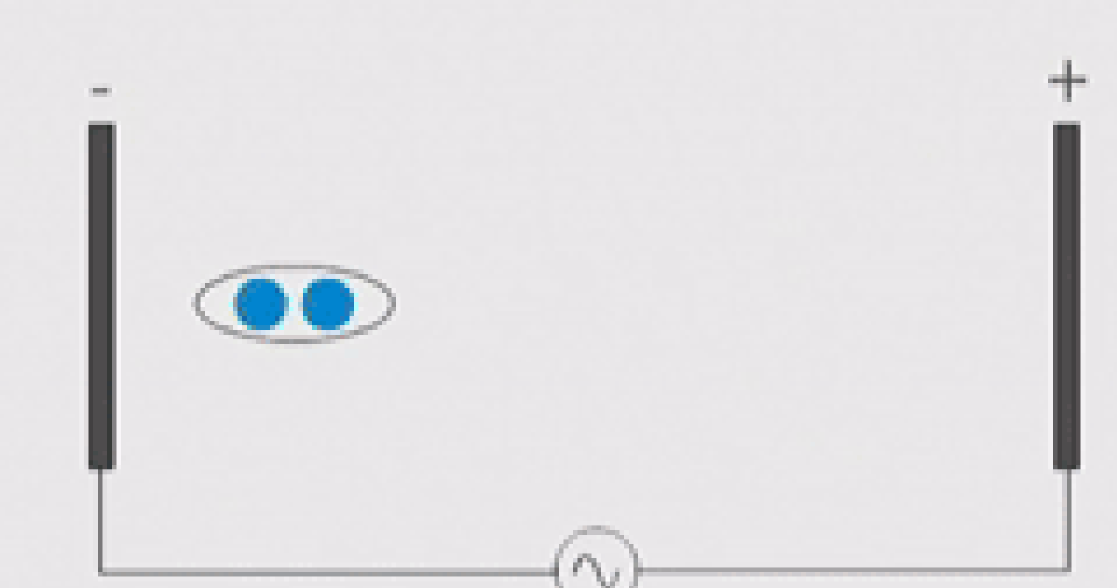
Also benefit from:

- Single photon counting: better than field detection >10 GHz and not "standard quantum limited"
- Energy resolution: allows background rejection
- Background modeling: enables discovery power

Microwave Kinetic Inductance Detectors

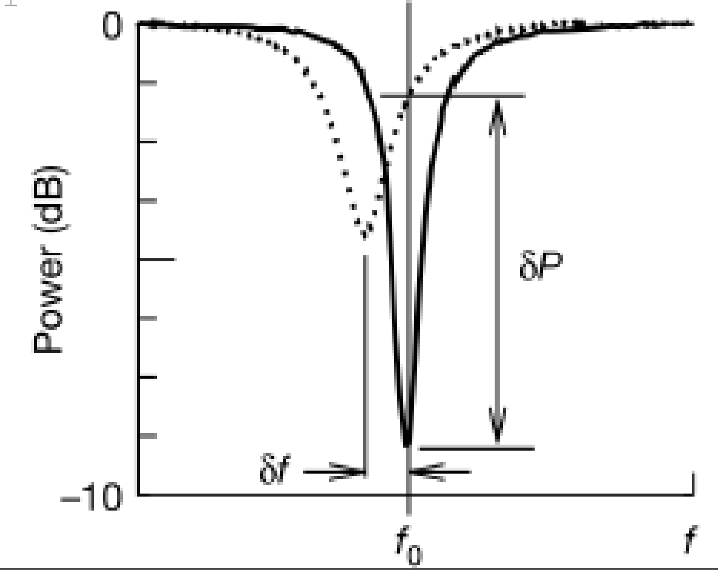
- Inductance arising from inertia of Cooper pairs in a superconductor as they respond to an external field → stored energy in the kinetic movement rather than a magnetic field

In a superconductor: $$L_{sc} = L_{geo} + L_K$$



Mazin, 2015

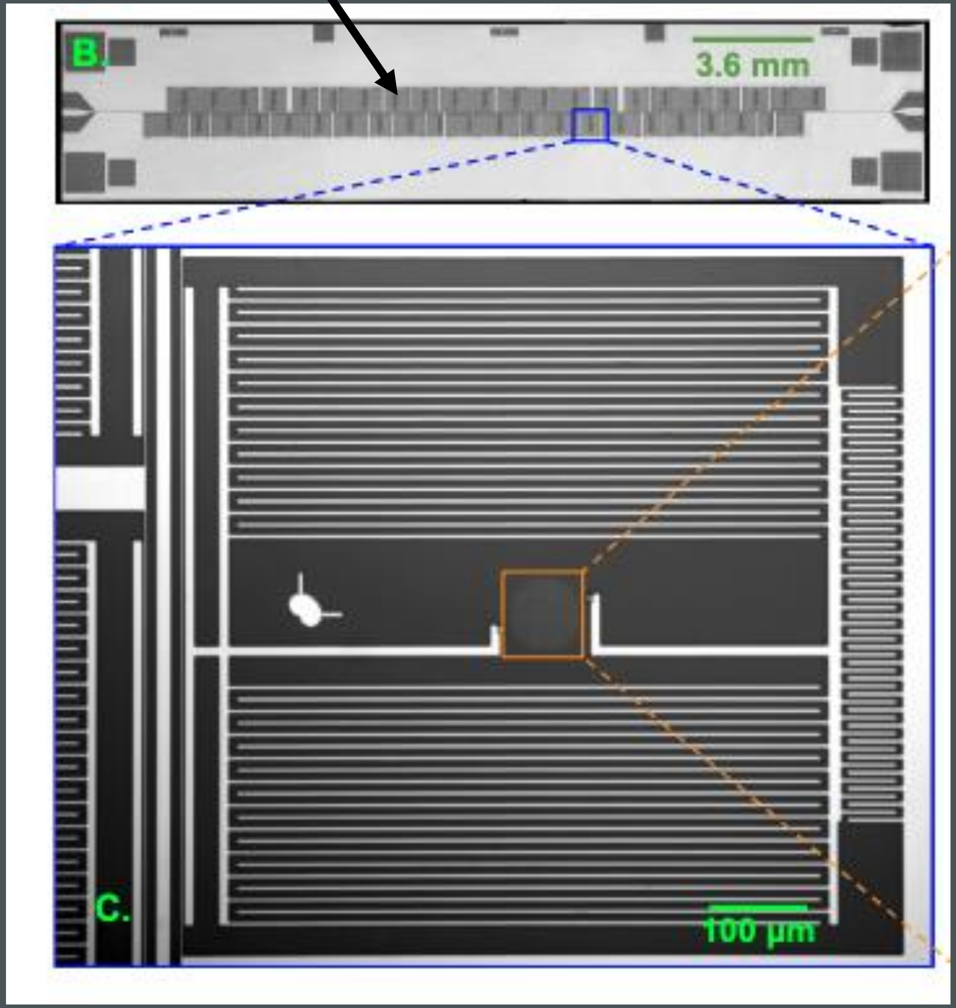
Nature 425 (2003) 6960, 817-821



- Pattern superconductor into an LC resonator
- Measure RF transmission across resonator → how is CP density changing in the inductor?
- Very high resonator Qs (10^6) achievable, so thousands of O(GHz) resonators can be chained on a single feedline with O(kHz) linewidths → simple cryogenic multiplexing

Single Photon Counting THz KIDs

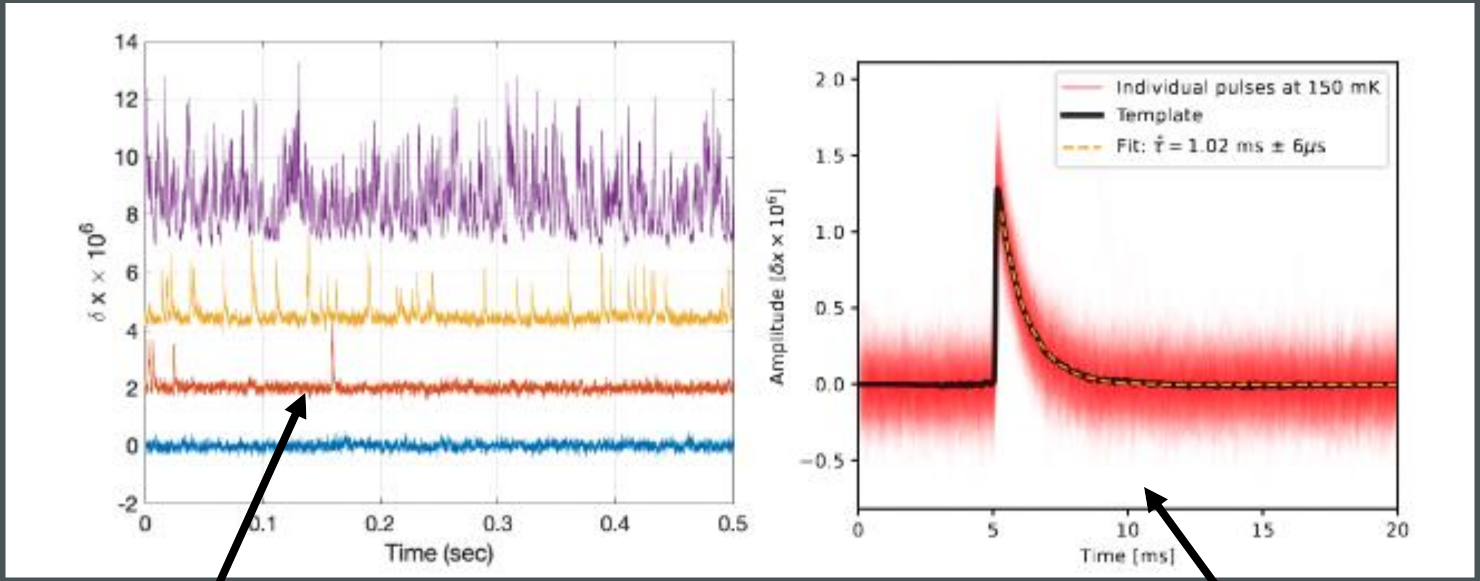
Array of 44 KIDs; Resonators on one side, lenses on the other



KIDs developed for far-IR telescope mission: successful demonstration of single photon counting in the 5-15 THz regime, mHz dark count rate

$$\mathrm{NEP} \sim h\nu\sqrt{\mathrm{DCR}} \approx 5 \times 10^{-22}\mathrm{W}/\sqrt{\mathrm{Hz}}$$

https://doi.org/10.1103/PhysRevX.14.041005

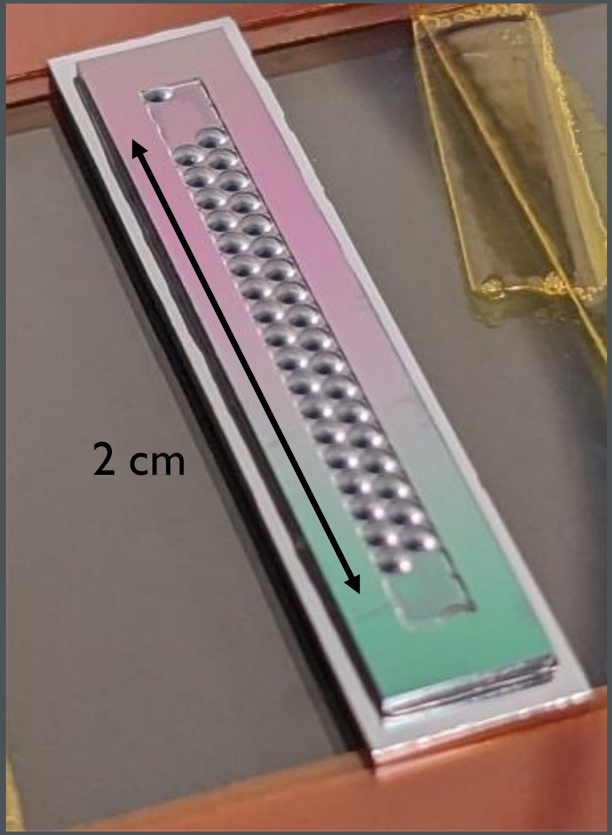


Single 12 THz photon counts under variable temperature blackbody illumination loads

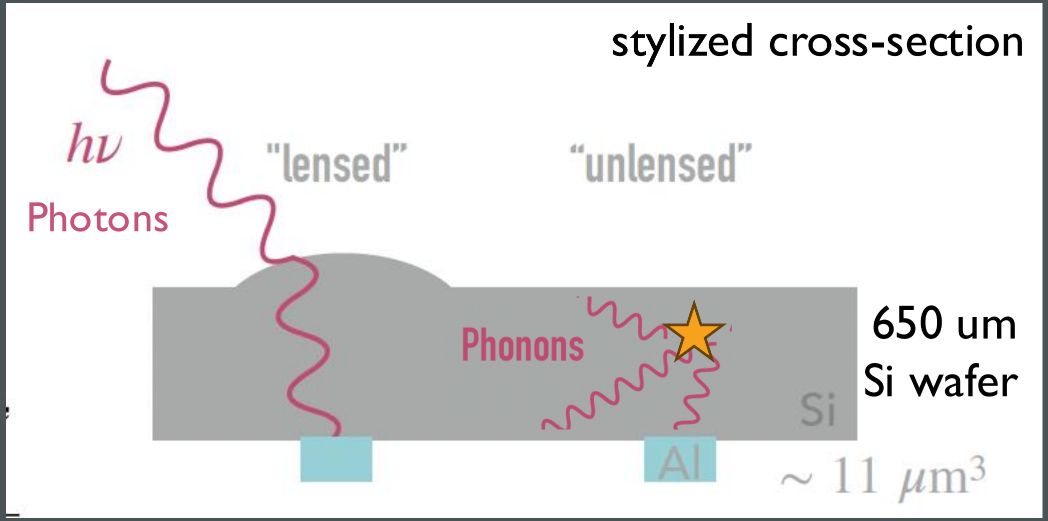
Pulse with fitted template

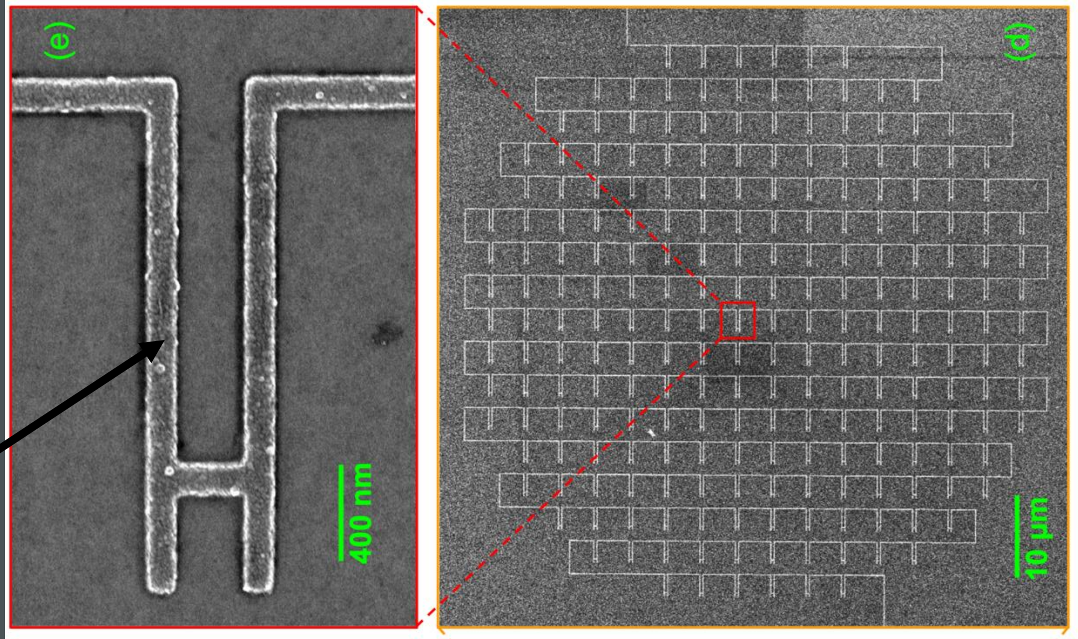
The 44-pixel lensed array

- Al inductor (11 um^3) with Nb resonators and capacitors
- Etched Si-microlenslets on backside of wafer



- 41 working pixels, 8 of which are unlensed
- Mounted onto holder PCB with GE varnish



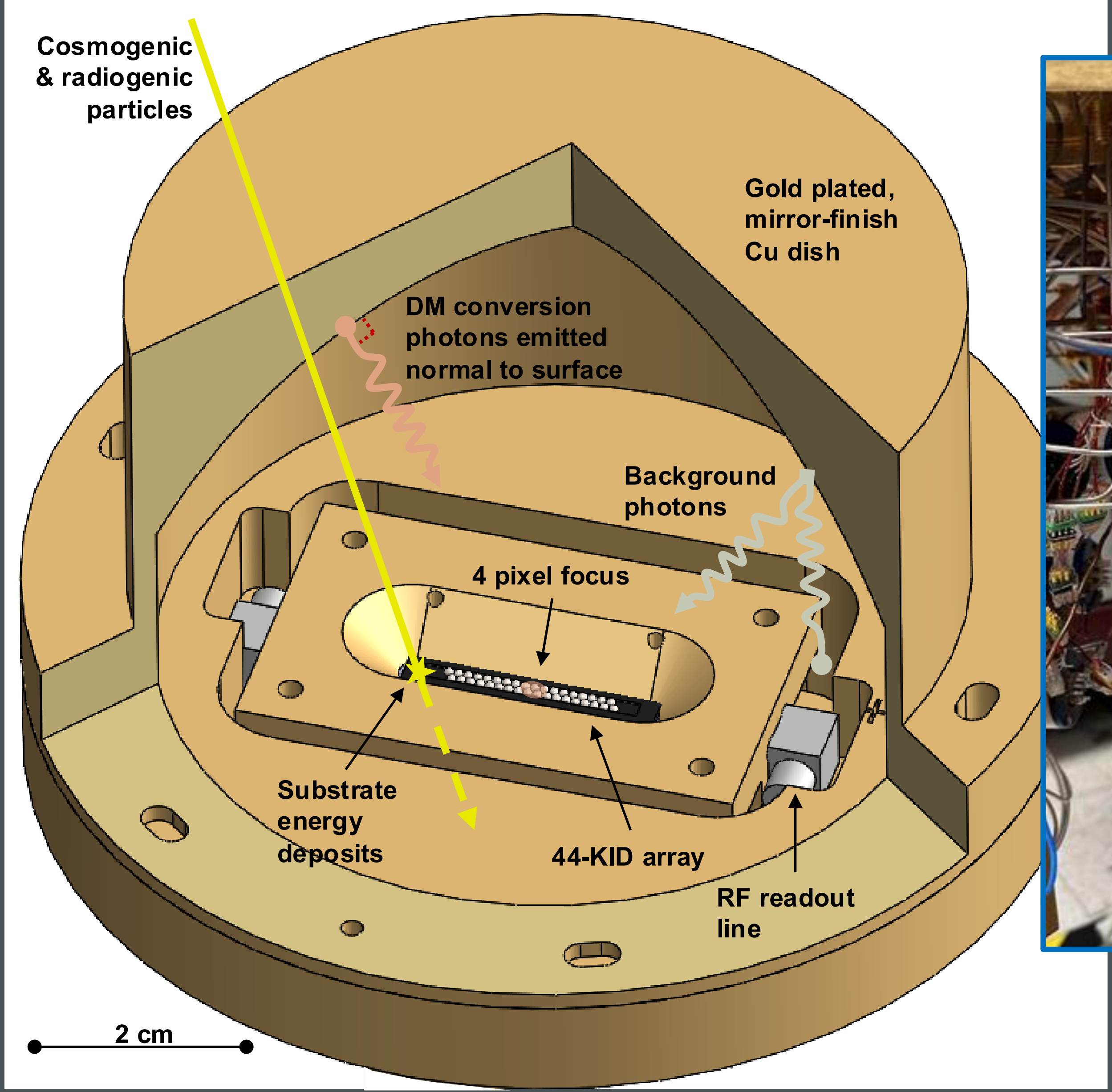


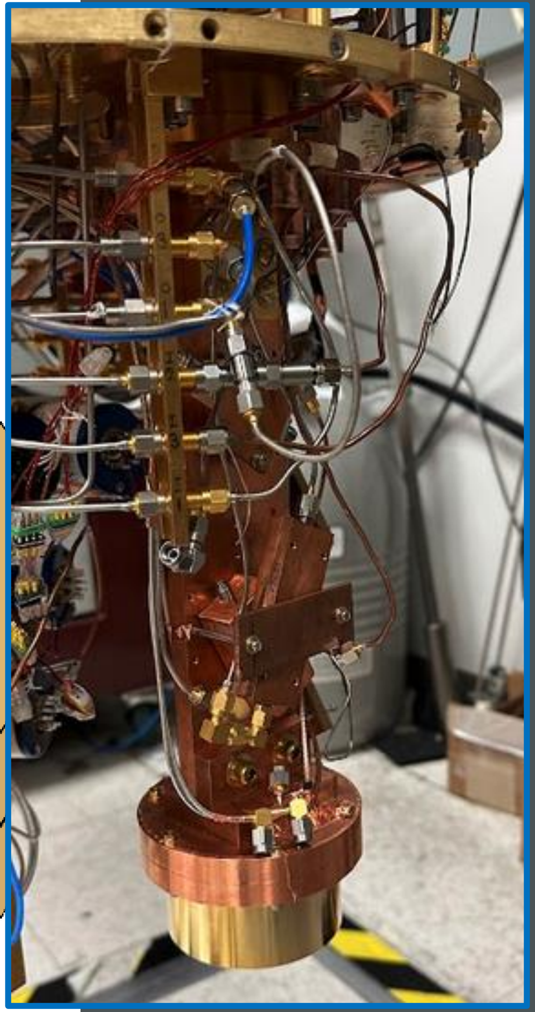
Hairpin inductor geometry optimized for band around 12 THz

QUAntum LImited PHotons In the Dark Experiment

Put all the pieces together:

- Gold plated copper dish, with internal hemispherical surface
- Geometric focus on 4 pixels of FIR KID pixels
- Goal: look for excess rate on focus vs. off-focus pixel background → signal of DPs
- First (?) DP experiment with discovery potential



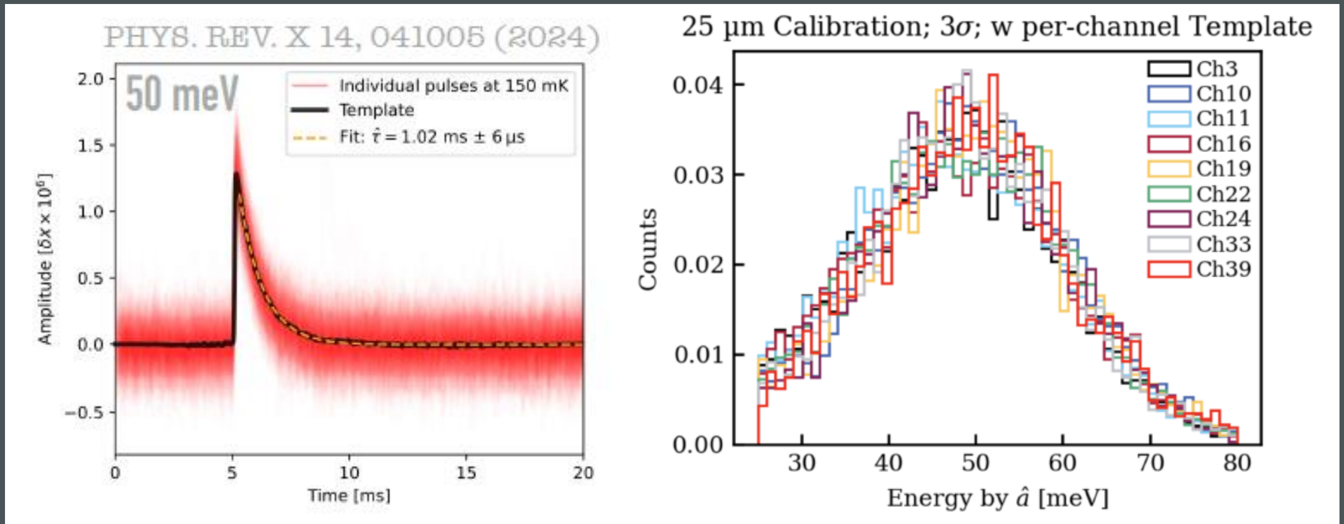


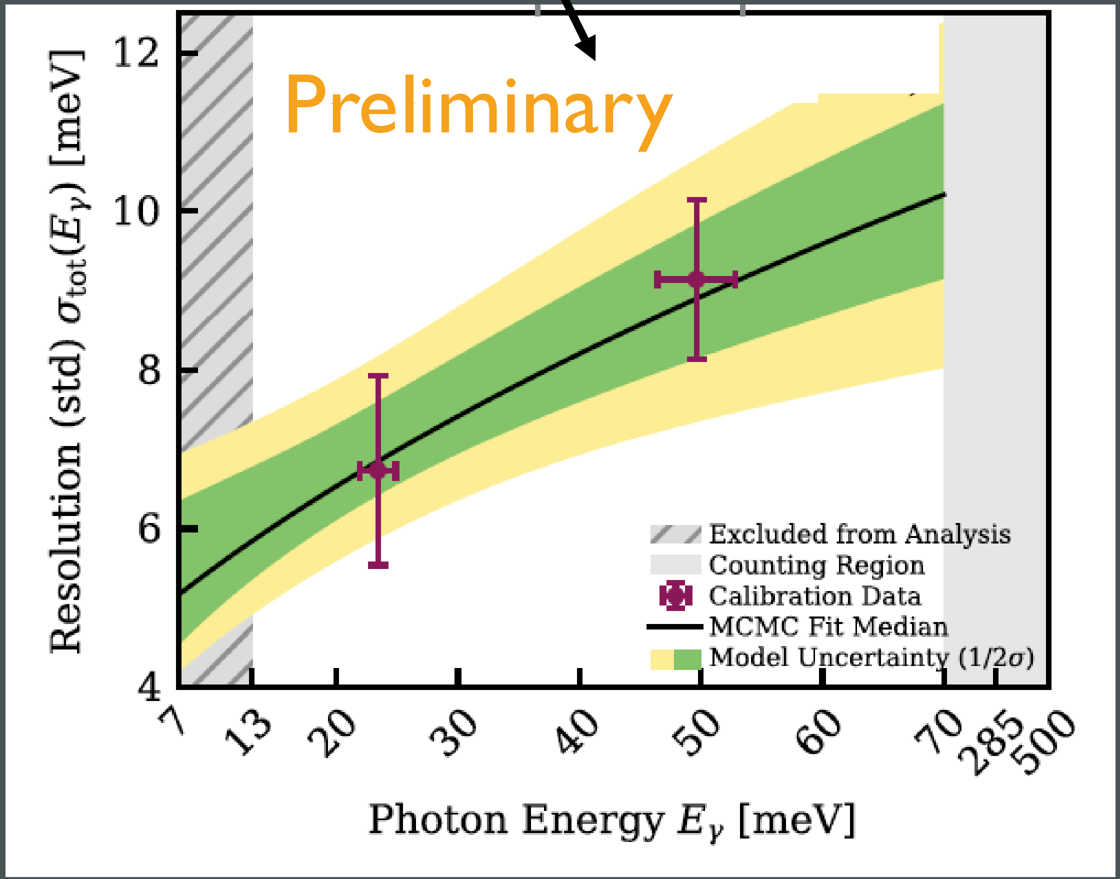
- Science data taken at 125 mK
- ~20 hrs exposure
- Data taken parasitically to other experiments, during multi-week cooldown
- Simultaneous readout of 41 pixels, sampled at 38 kHz, using to.technology CRS platform

Calibration & Energy Resolution

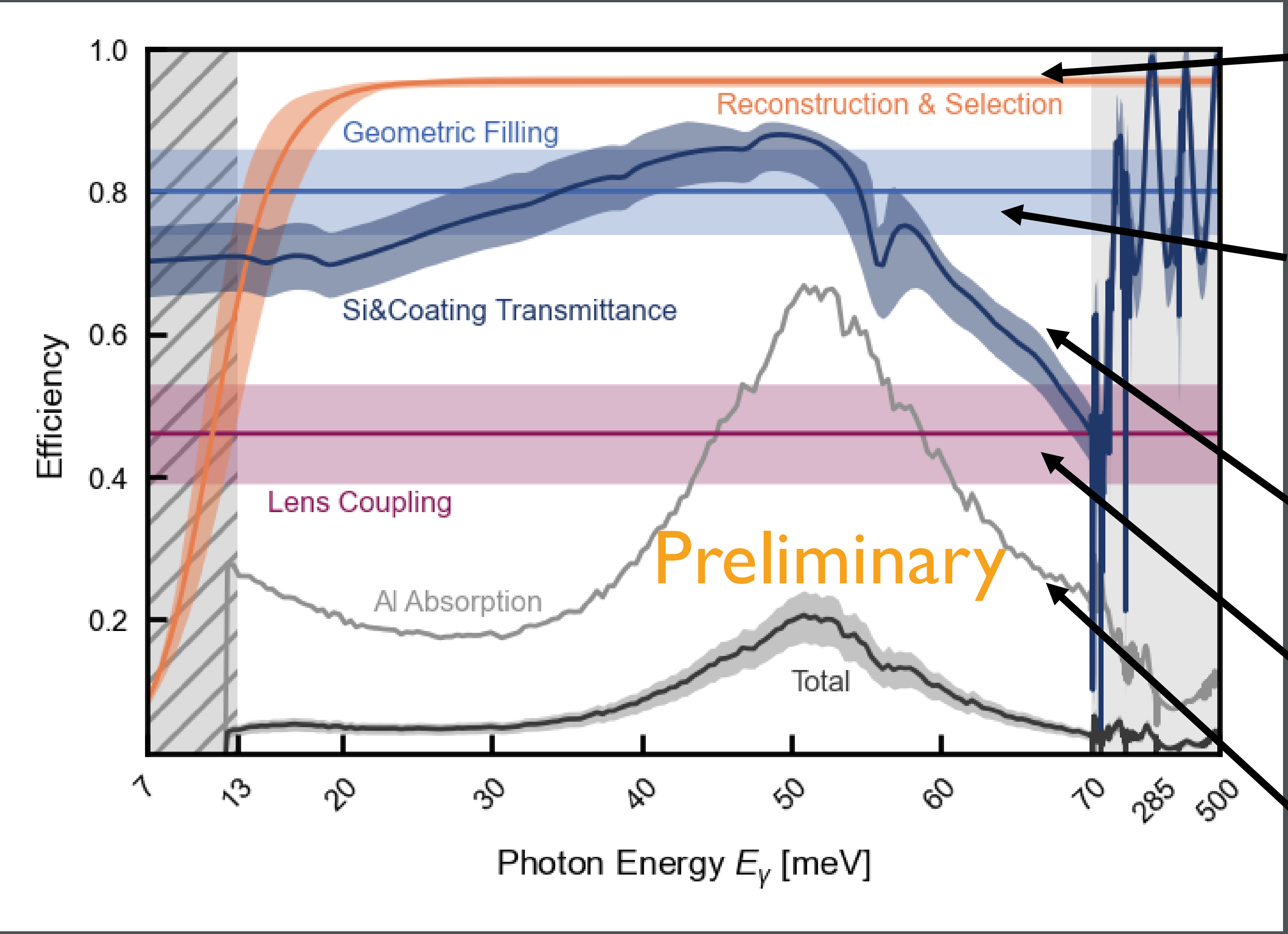
- Energy reconstruction by optimal filtering → σ_B = 3 meV
- Calibration via blackbody source & bandpass filter @ 25 um (12 THz, 50 meV) and 53 um (5.6 THz, 24 meV)
- Resolution uncertainties given by MCMC fits to calibration points
- Above 70 meV → non-linear response and no calibration → combine into one bin

Allows for unknown excess resolution component along with elevated Fano factor





Detection efficiency



Reconstruction and selection efficiency: estimated via simulation and reconstruction, ~70% at 13 meV

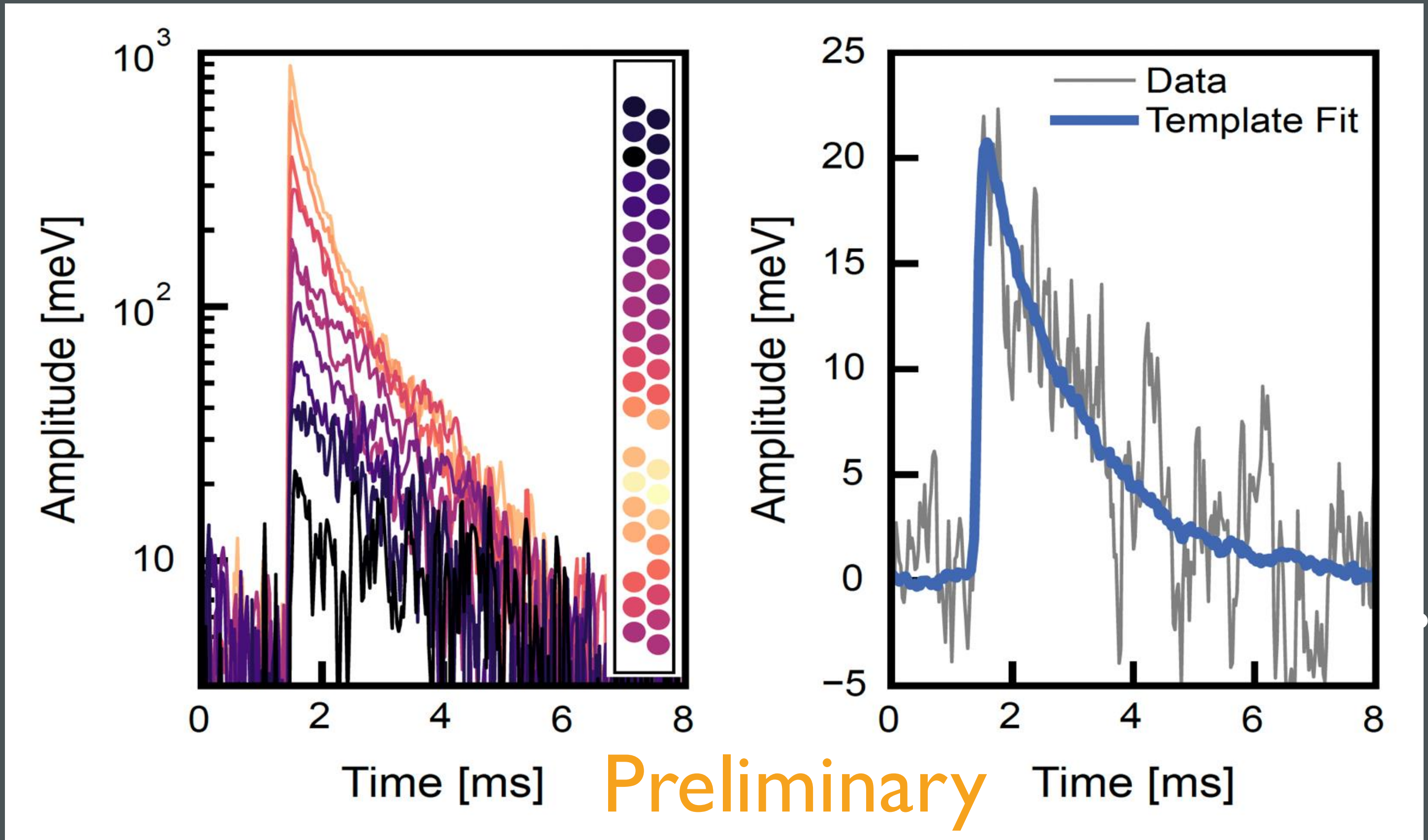
Geometric filling: estimated by ray-tracing simulation, accounting for mechanical mounting uncertainty and de-focusing, ~80%

Wafer & Coatings: computed from literature spectra for Si & antireflection material

Optical: combination of measurement & simulation based losses

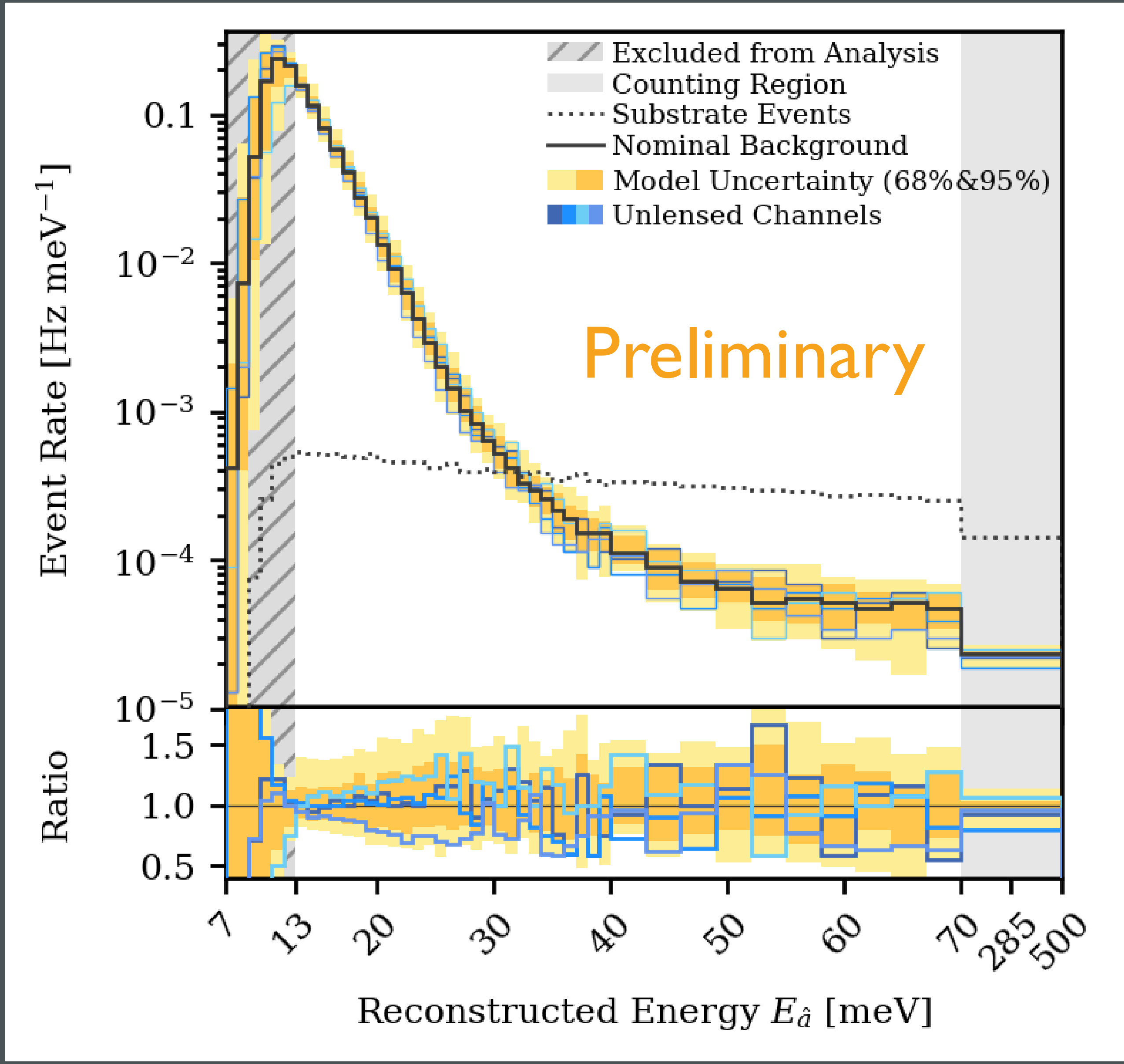
Absorption: measured by Fourier transform spectrometer

Pulse fitting, selection, and definitions



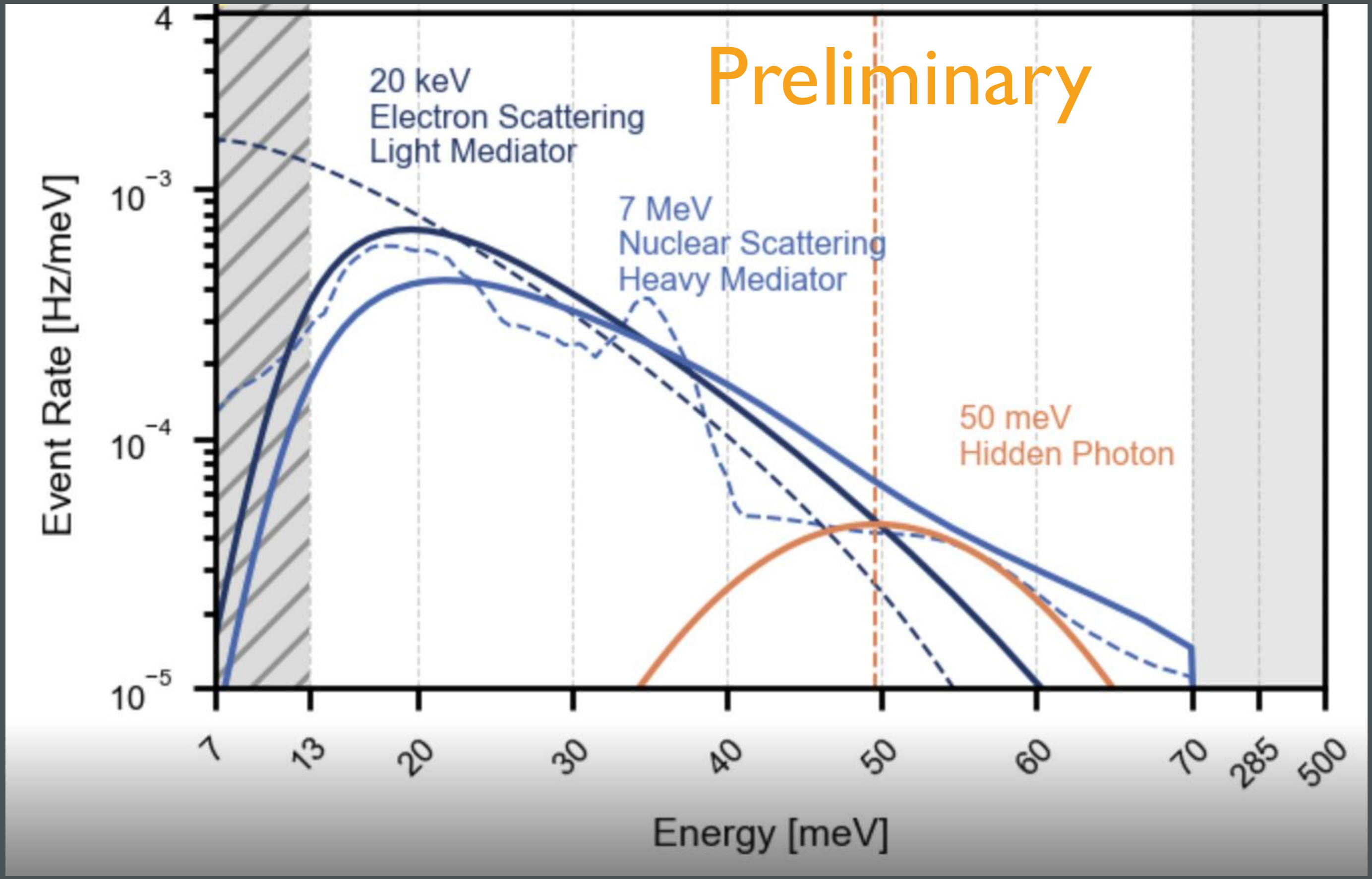
- Events split into two families: "photon-like" and "substrate-like".
  - Photon-like: single event in a pixel, no coincidences (events within 200 us) → Used for DM search
  - Substrate-like: at least 5 pixels triggered within coincidence window
- 3 energy regimes:
  - <13 meV: threshold, complicated/no efficiencies
  - 13-70 meV: energy reconstruction feasible with R~3
  - >70 meV: non-linear pulses and no robust calibration

Background Model

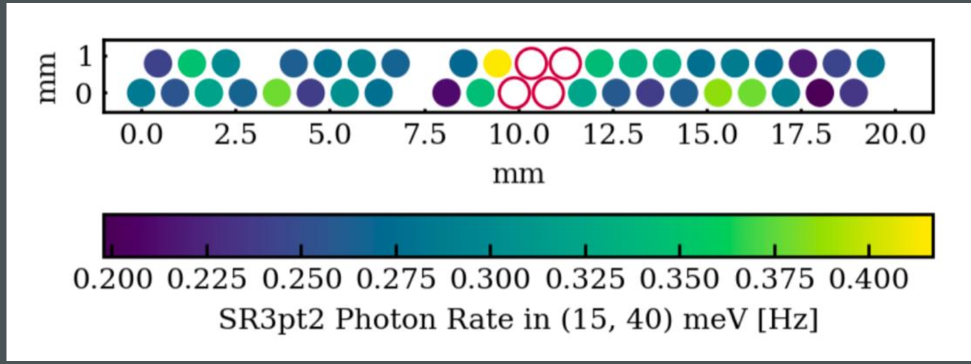


- Above threshold event rate of ~500 mHz, consistent across pixels, including lensed and un-lensed channels(yellow-bands: 1 & 2 sigma spread of all channels)
- Distinct spectral difference between photon-like and substrate-like events
    - Photon-like events rise continually at low-energies
    - Substrate-like events are much flatter

Modeling

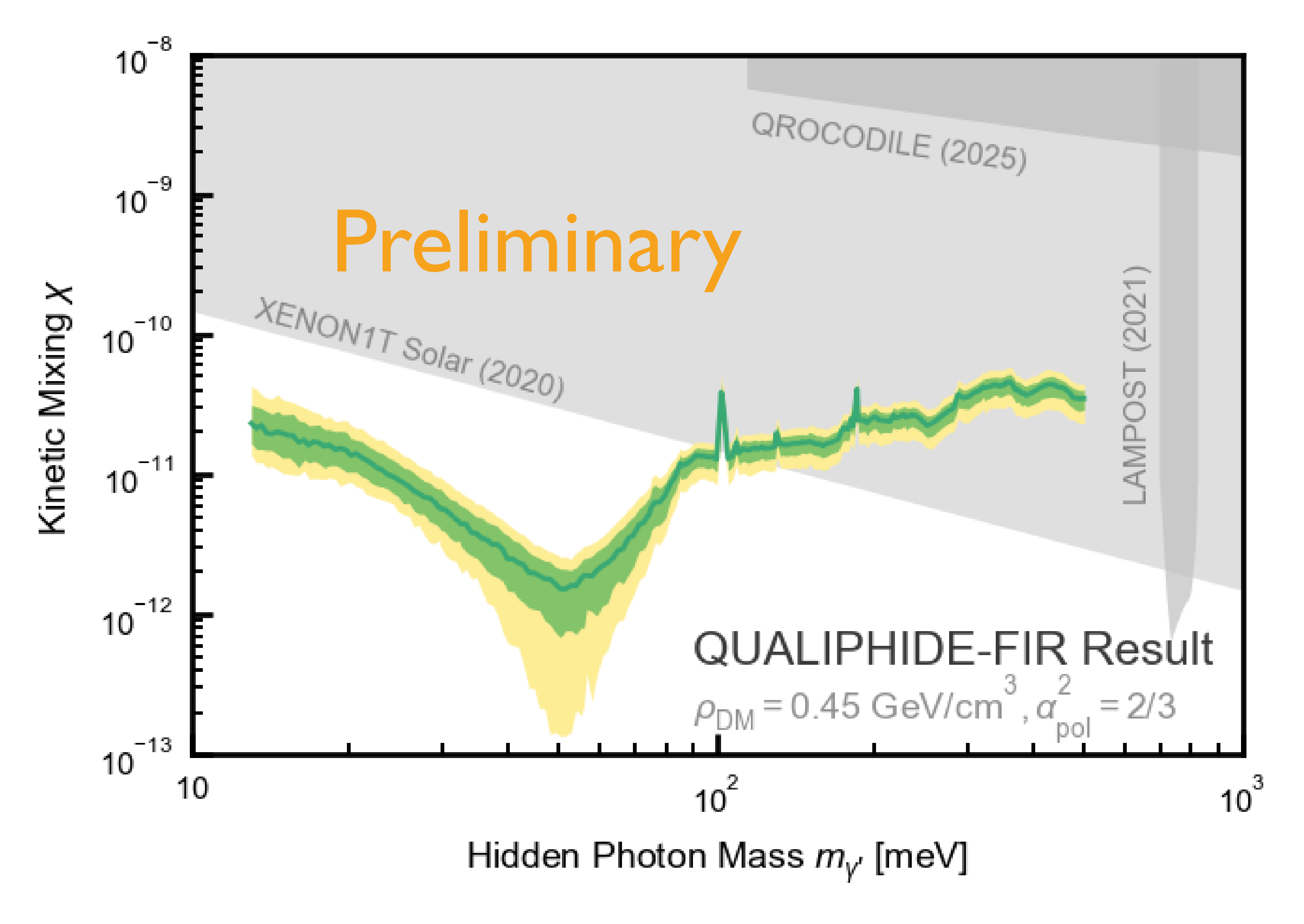


- Dispersion (coming from dish and DM effects) is << 1% → spread dominated by energy resolution
  - Between 13-70 meV: use calibration model
  - >70 meV: no resolution, counting events



Discovery potential: blinded the 4 signal channels, designed data selection criteria and built data-driven background model with 37 channels

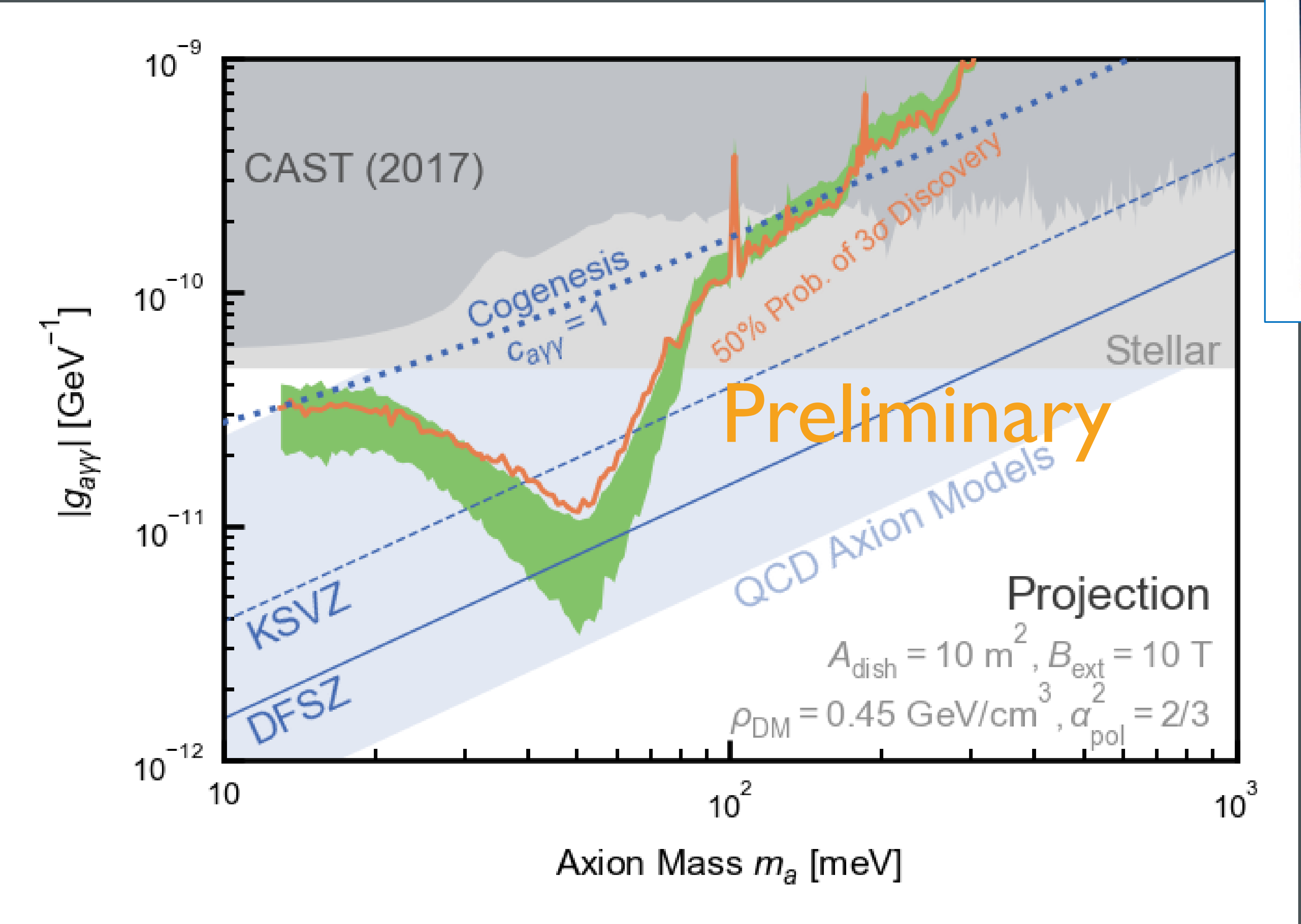
Dark Photon Limits

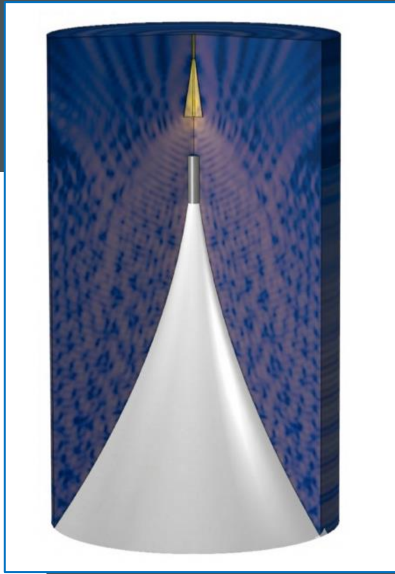


- Sensitivity and limits computed with a profiled-likelihood ratio frequentist framework (from WIMP community)
- Modeled systematic uncertainties via nuisance parameters: folding in background rate, efficiency and resolution uncertainty
- Implicit "background subtraction" through extended unbinned Poisson likelihood with Gaussian constraints on nuisance parameters.

→ Results on arXiv soon!

Axion Projection

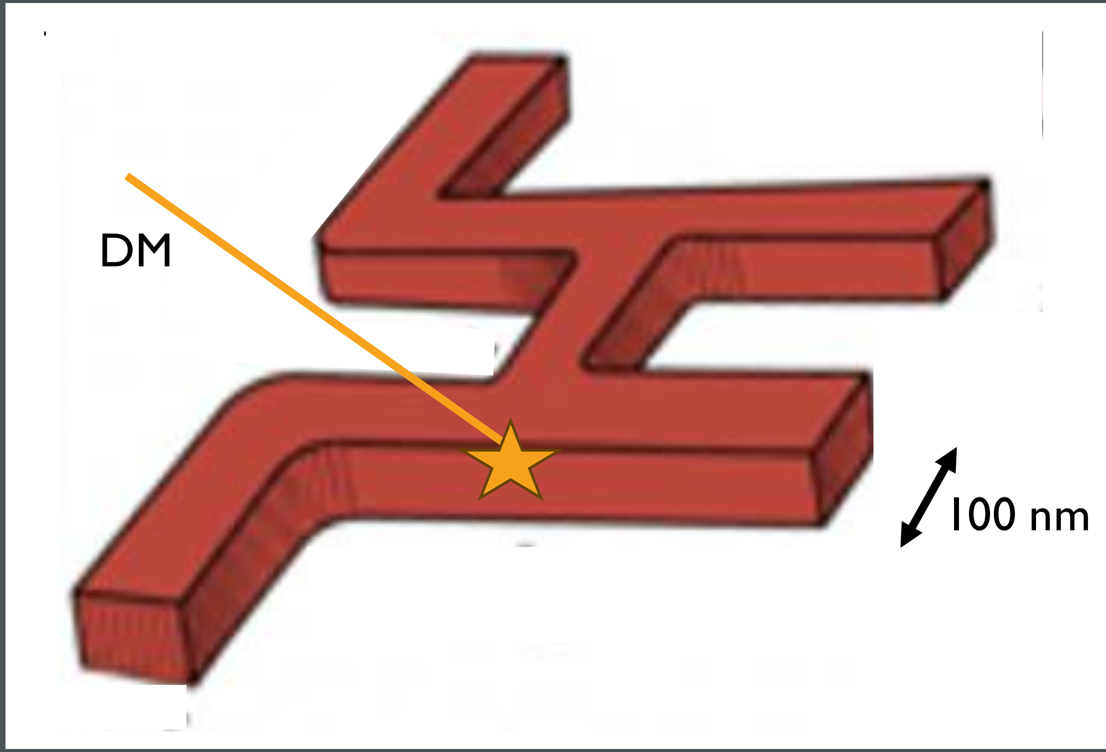


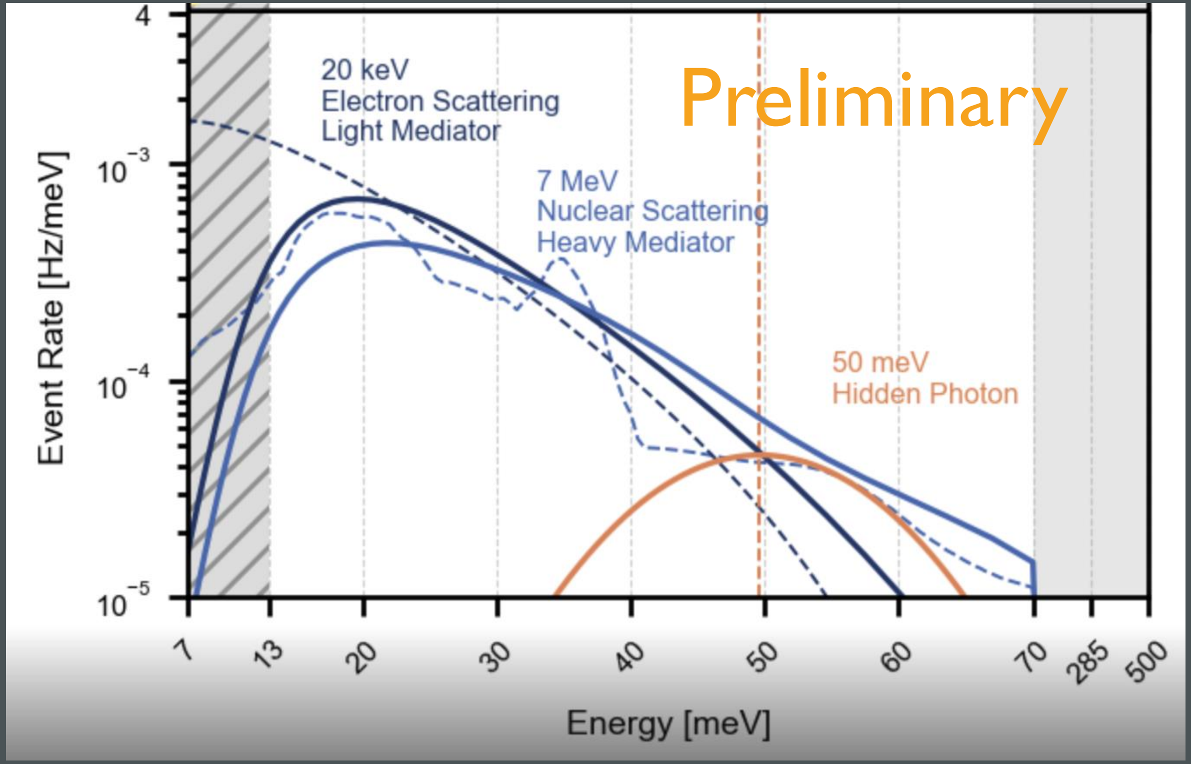


BREAD experiment Phys.Rev.Lett. 128 (2022) 13, 131801

Projection placing same detector array within a larger experiment with B-field (assuming similar photon coupling) for same ~1 day exposure & background → DFSZ sensitivity

Direct Scattering

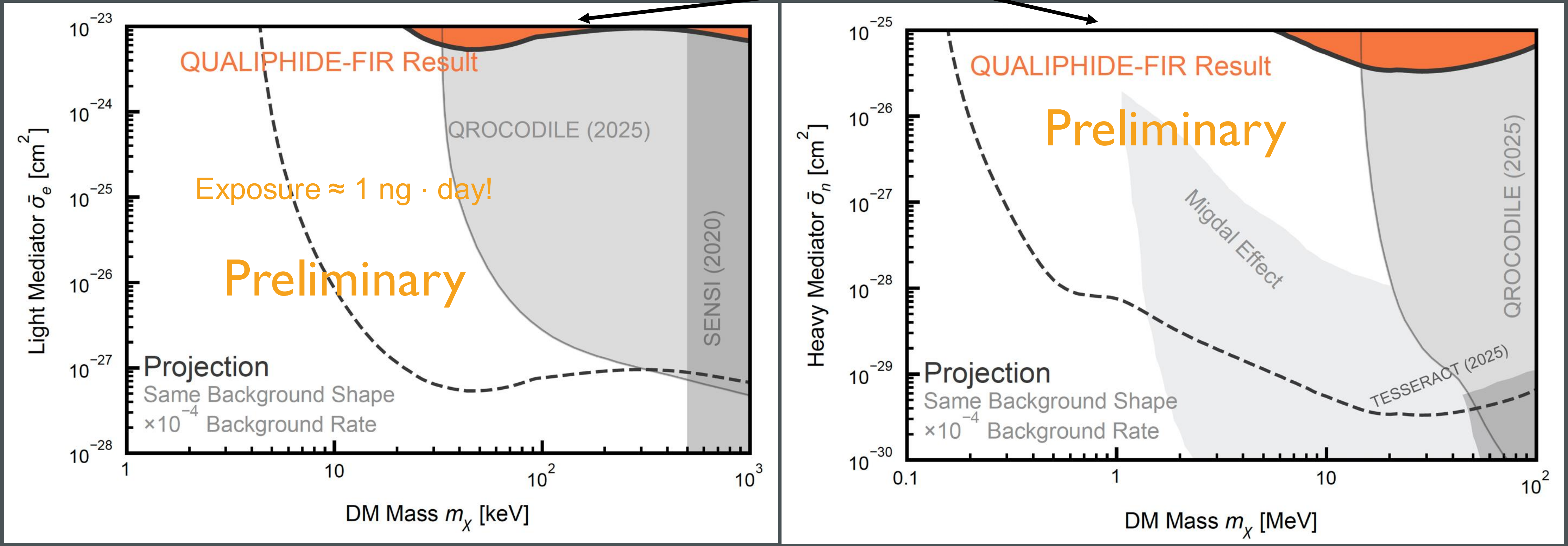




- Direct scattering (electronic, nuclear) within small volume Al inductor → directly probe MeV/sub-MeV DM
- Use formalism and modeling from DarkELF (Phys. Rev. D **105**, 015014) & recent SNSPD / QROCODILE work (Phys. Rev. Lett. 135, 081002)
- No background model → can only constrain models

Direct Scattering Limits

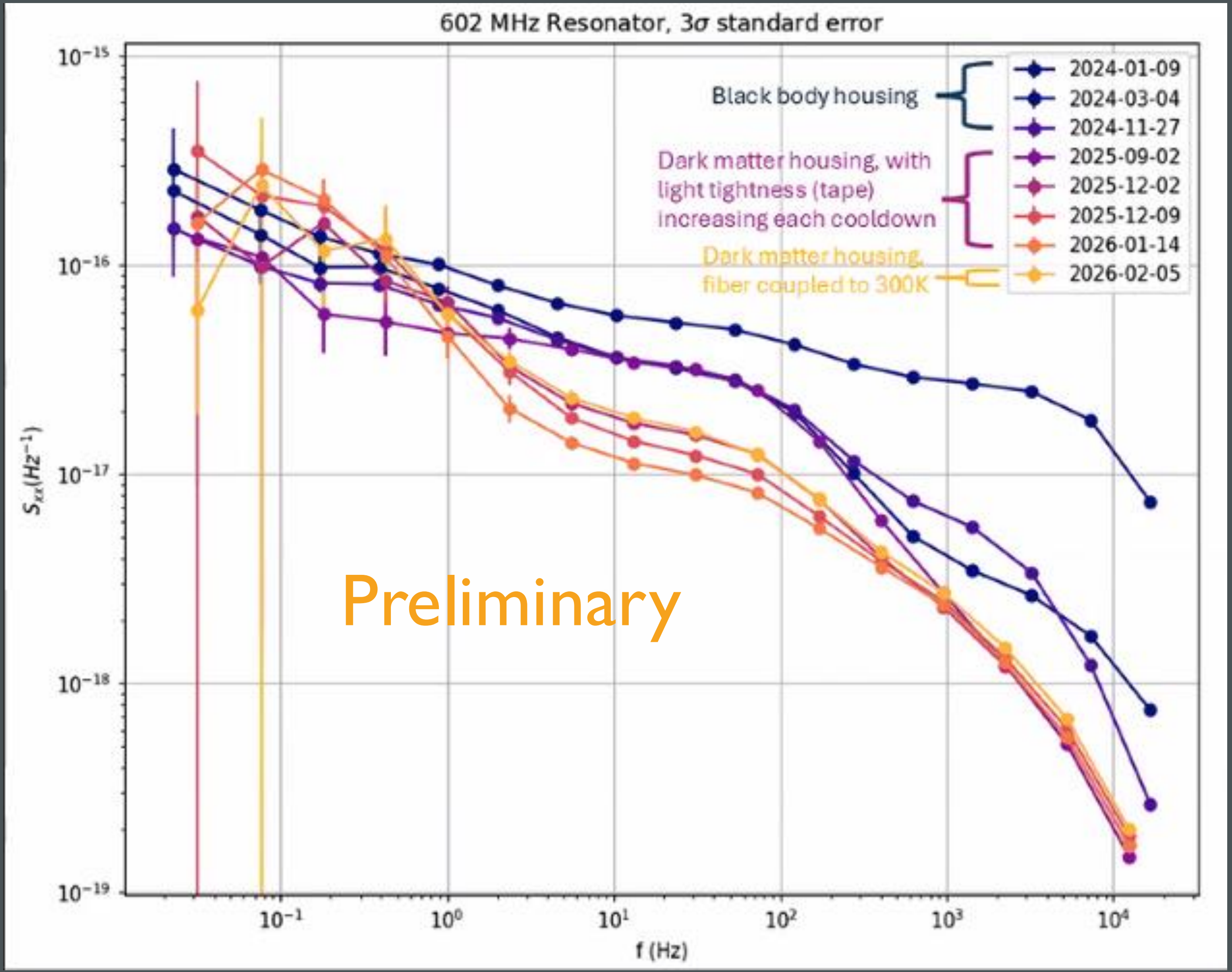
Atmospheric overburden limits larger cross-sections



- Lowest mass models ever probed by a terrestrial experiment
- Phonon spectrum in Al is <40 meV → in principle detect scattering from single phonons
- Background rate is biggest limiting factor, 10^4x reduction → probe keV/sub-MeV models

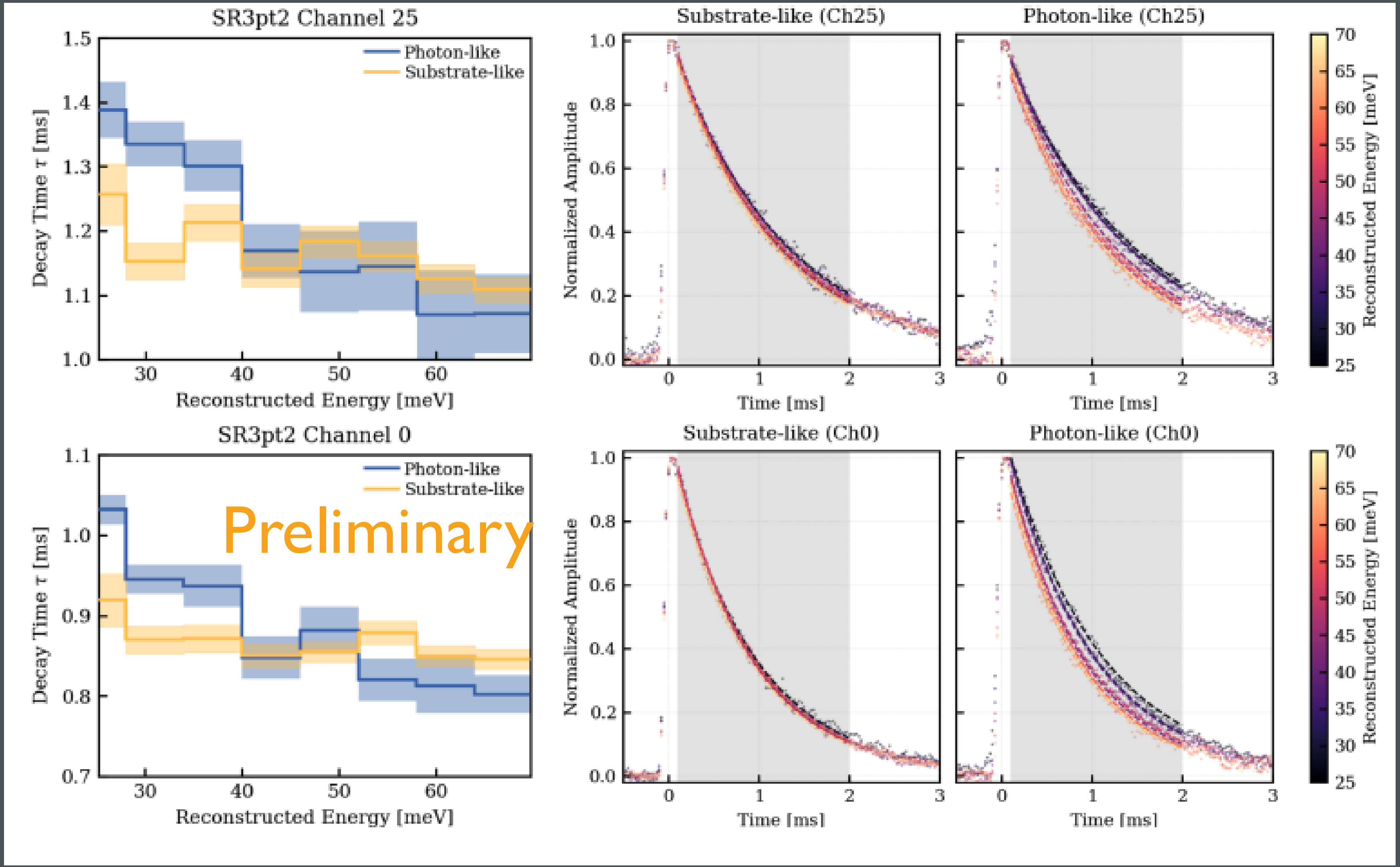
Background Rate Reduction

- 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 already → we are likely still suffering from background IR - another O(10)?
- Future runs will house device in a "stub-filter" housing (based on LBNL design)



Rich dataset for future studies

- Statistically significant difference in pulse fall-times between photon-like and substrate-like events
- Substrate-like → fairly constant with energy
- Photon-like → longer at lower energies (and compared to substrate-like) and shorter at higher energies
- No plateauing of time-constant!



Could photon-like be arising from film itself?

QUALIPHIDE Collaboration

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THANKS! QUESTIONS?

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