

C. Albert<sup>1,2</sup>, R. Basu Thakur<sup>1,2</sup>, P. Day<sup>2</sup>, B. Eom<sup>2</sup>, H. LeDuc<sup>2</sup>, K. Ramanathan<sup>3</sup>  
<sup>1</sup>California Institute of Technology, Pasadena, CA 91125, USA, <sup>2</sup>Jet Propulsion Laboratory, Pasadena, CA 91107, USA, <sup>3</sup>Washington University in St. Louis, St. Louis, MO 63130, USA

### Hidden Photon Dark Matter Searches

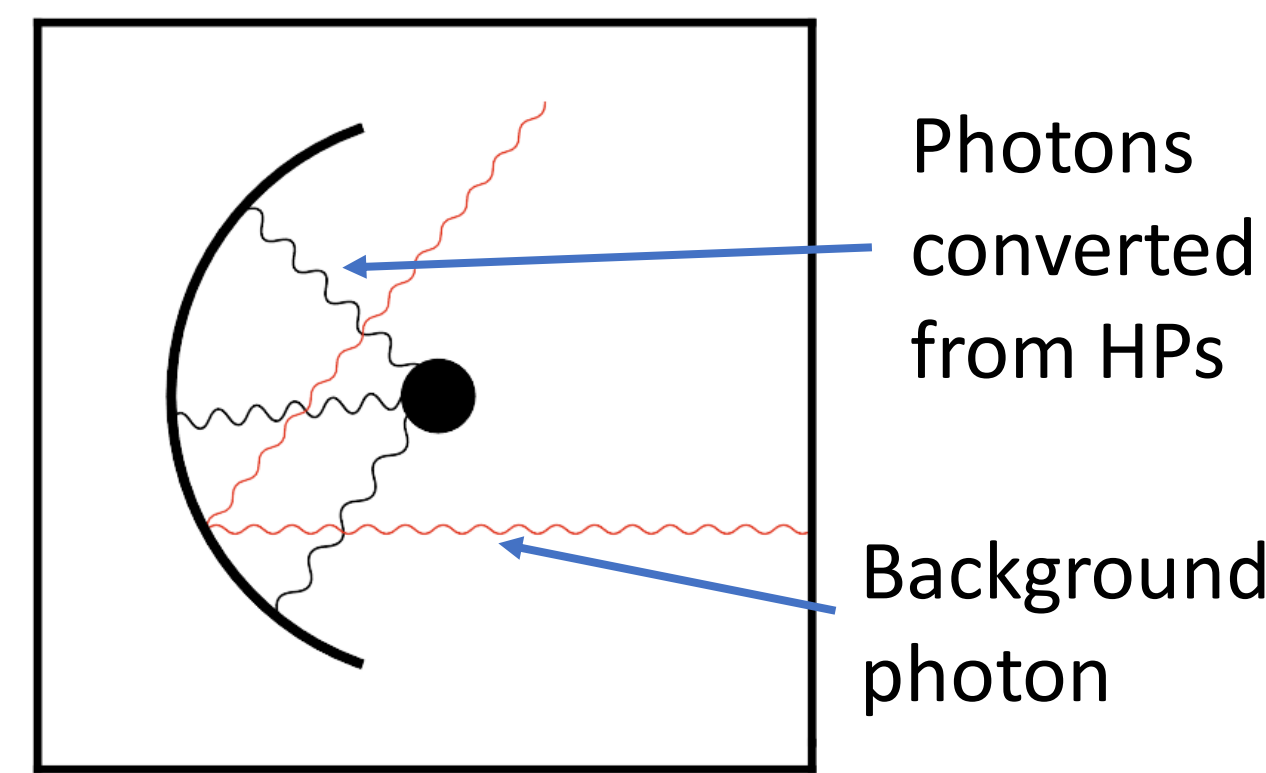
- Hidden photons (HPs)/dark photons are hypothetical dark matter candidates that weakly couple to the Standard Model though kinetic mixing, the dominant interaction being with the electromagnetic (EM) field. They could be the entirety of dark matter or be the mediator to a dark sector.

$$\mathcal{L} \supset \frac{m_{\gamma'}^2}{2} X_\mu X^\mu - \frac{\chi}{2} F_{\mu\nu} X^{\mu\nu} - \frac{1}{2} F_{\mu\nu} F^{\mu\nu}$$

HP mass, kinetic mixing parameter, HP field tensor, EM field tensor, HP vector potential

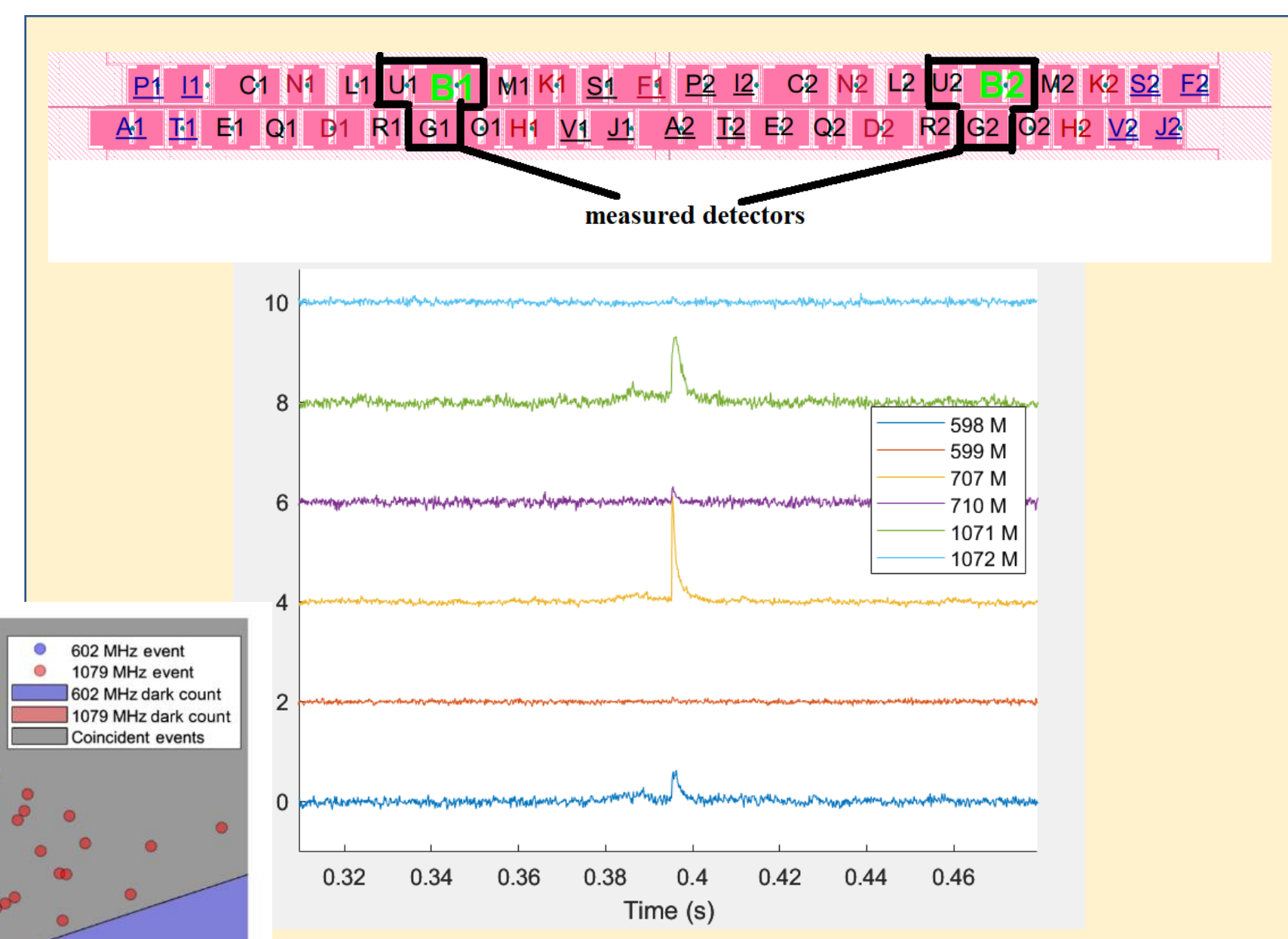
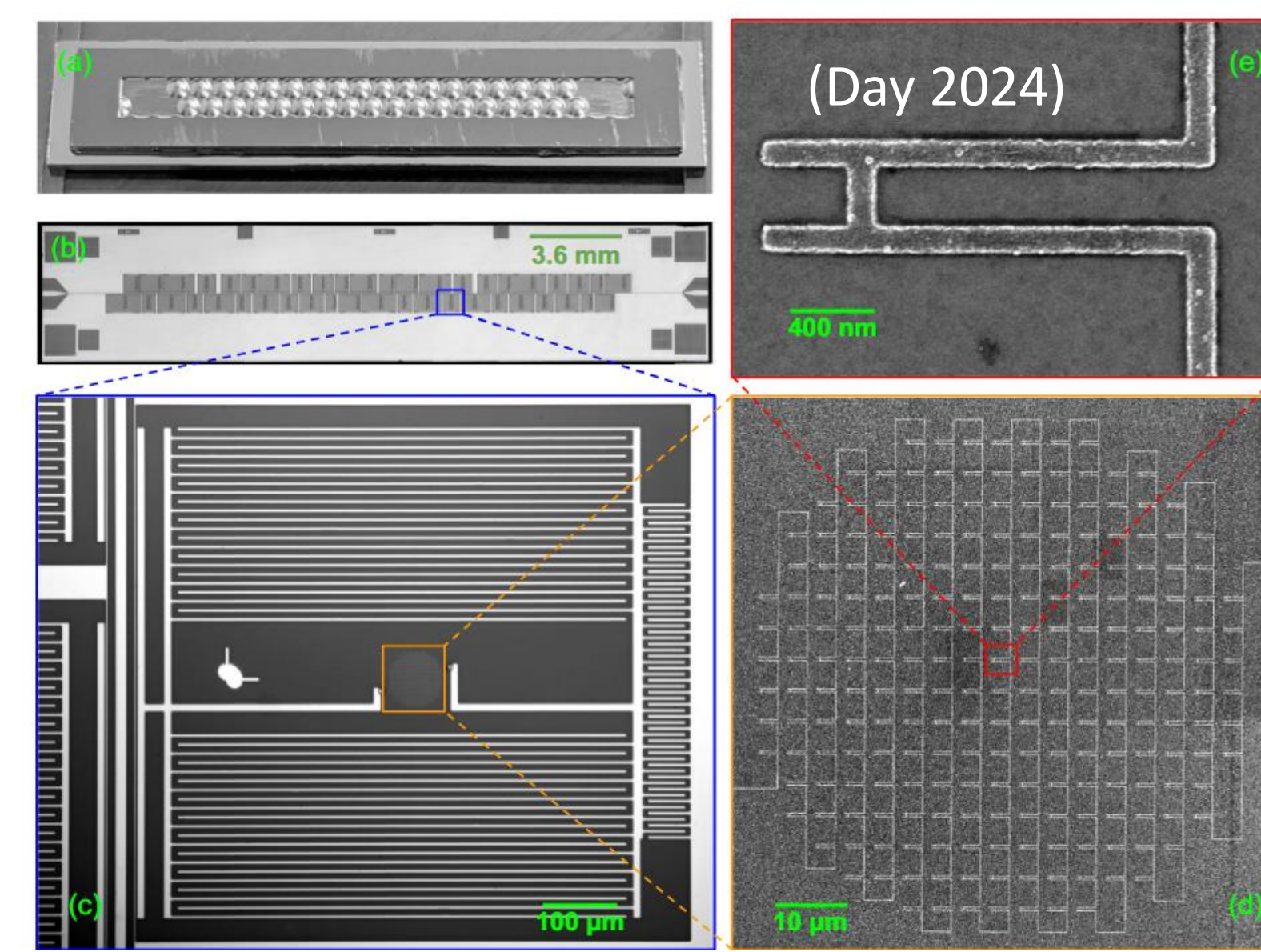
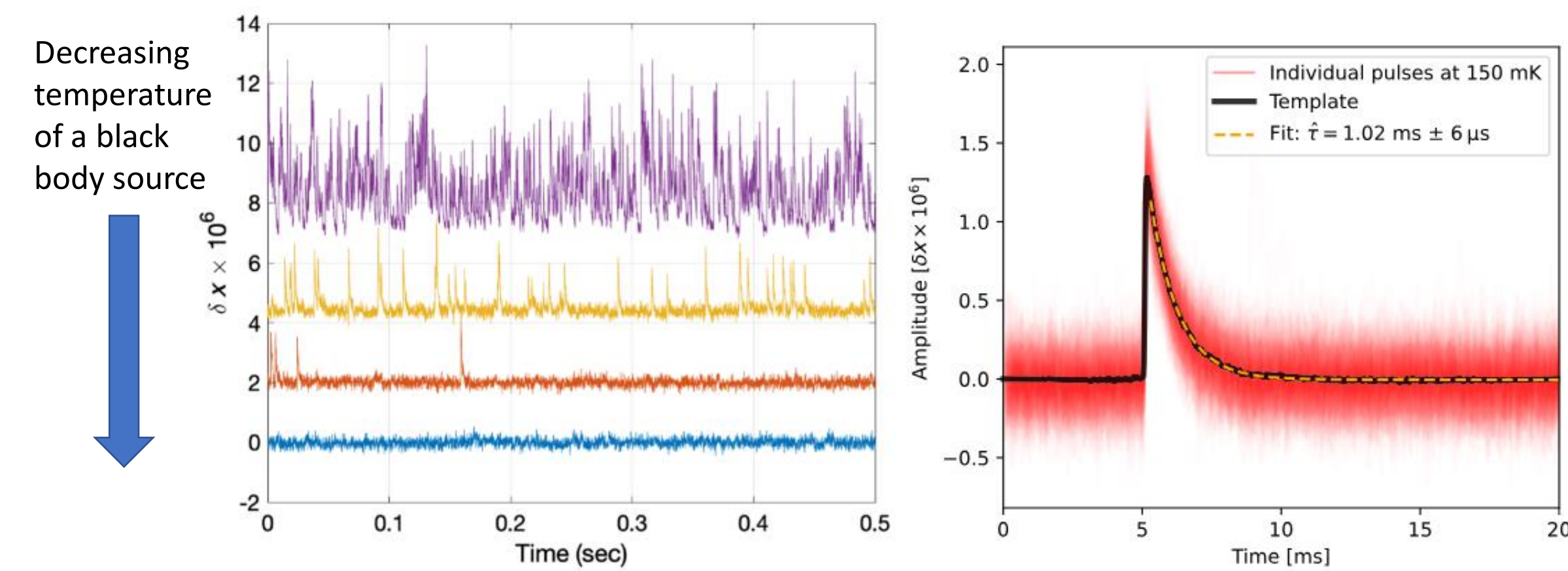
- E-field boundary conditions at a conducting surface require that any photons generated by kinetic mixing with the HP field will propagate normal to the surface. This is the basis of dish antenna searches (Horns 2013), where a detector is placed at the focal point of a hemispherical dish.
- Sensitivity to the kinetic mixing parameter for a photon counting dish antenna experiment (Horns 2013):

$$\chi_{\text{sens}} = 5.6 \times 10^{-12} \left( \frac{R_{\gamma, \text{det}}}{1 \text{ photon/s}} \right)^{\frac{1}{2}} \left( \frac{m_{\gamma'}}{\text{eV}} \right)^{\frac{1}{2}} \left( \frac{0.3 \text{ GeV/cm}^3}{\rho_{\text{CDM, halo}}} \right)^{\frac{1}{2}} \left( \frac{1 \text{ m}^2}{A_{\text{dish}}} \right)^{\frac{1}{2}} \left( \frac{\sqrt{2/3}}{\alpha} \right)$$

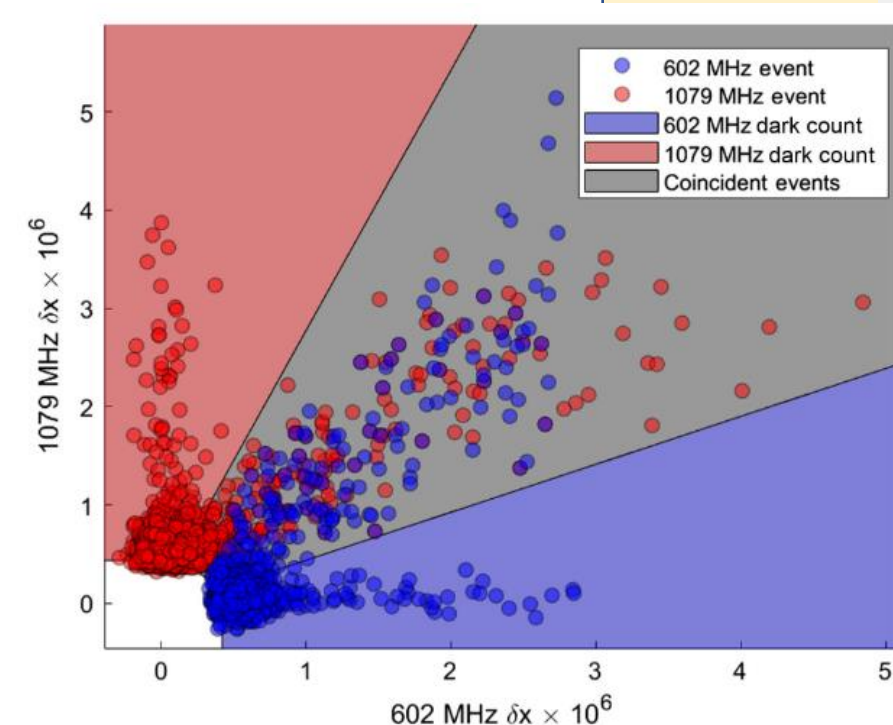


### Single Photon Counting Kinetic Inductance Detectors

- Kinetic Inductance Detectors (KIDs) are superconducting inductor-capacitor resonators that experience a resonance shift, detected with a microwave probe tone, when an energy deposition event breaks Cooper pairs in the inductive element to lower the device's kinetic inductance.
- Ultra-sensitive far infrared (IR) KIDs made for the PRobe Far-Infrared Mission for Astrophysics (PRIMA) have demonstrated photon noise limited performance down to 70 zW absorbed power and a limiting noise equivalent power of  $4.6 \times 10^{-20} \text{ W/Hz}^{-1}$  at 1 Hz (Day 2024).
- At low enough loading ( $\sim < 200$  photons/s), individual photon pulses are resolvable.

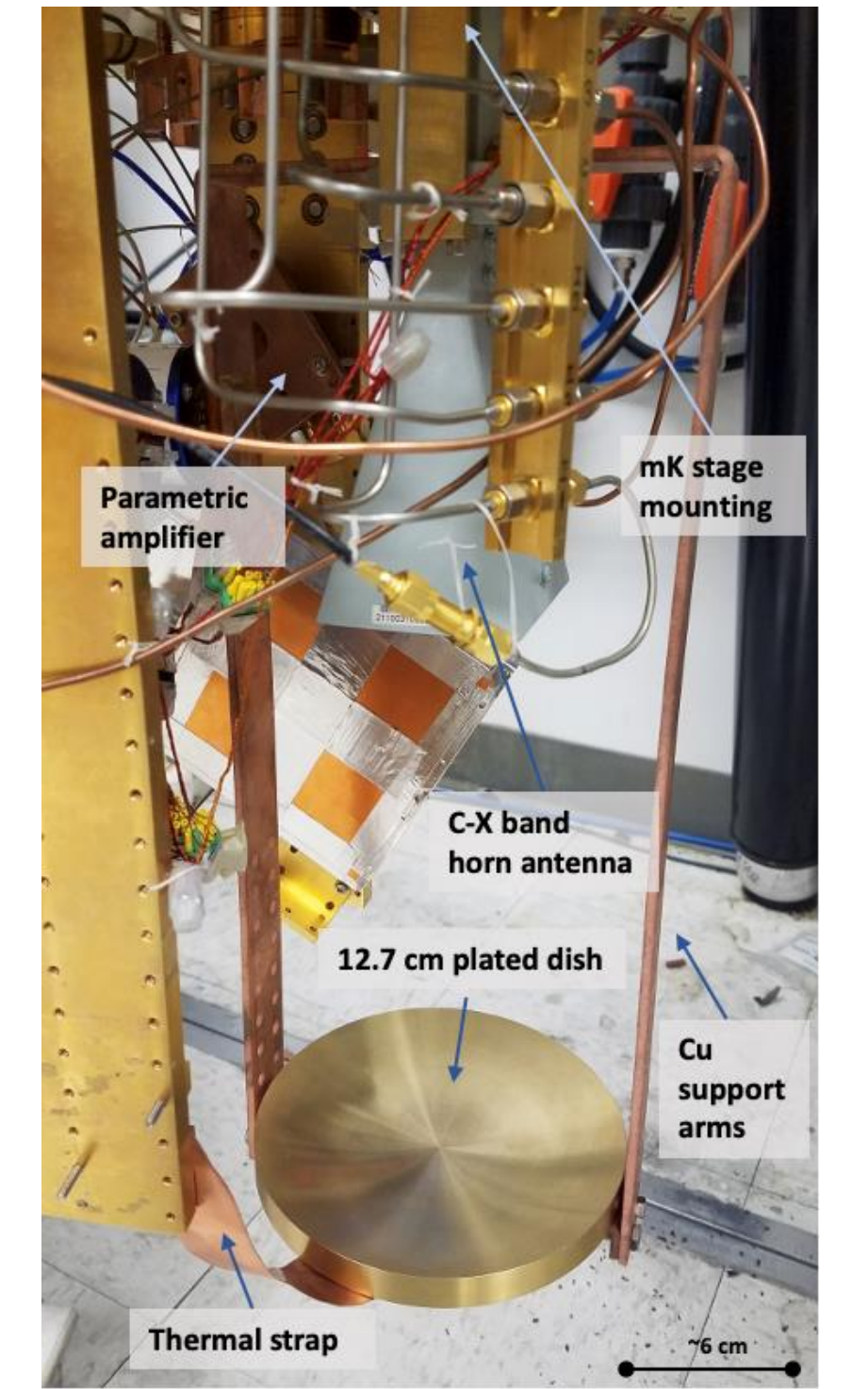
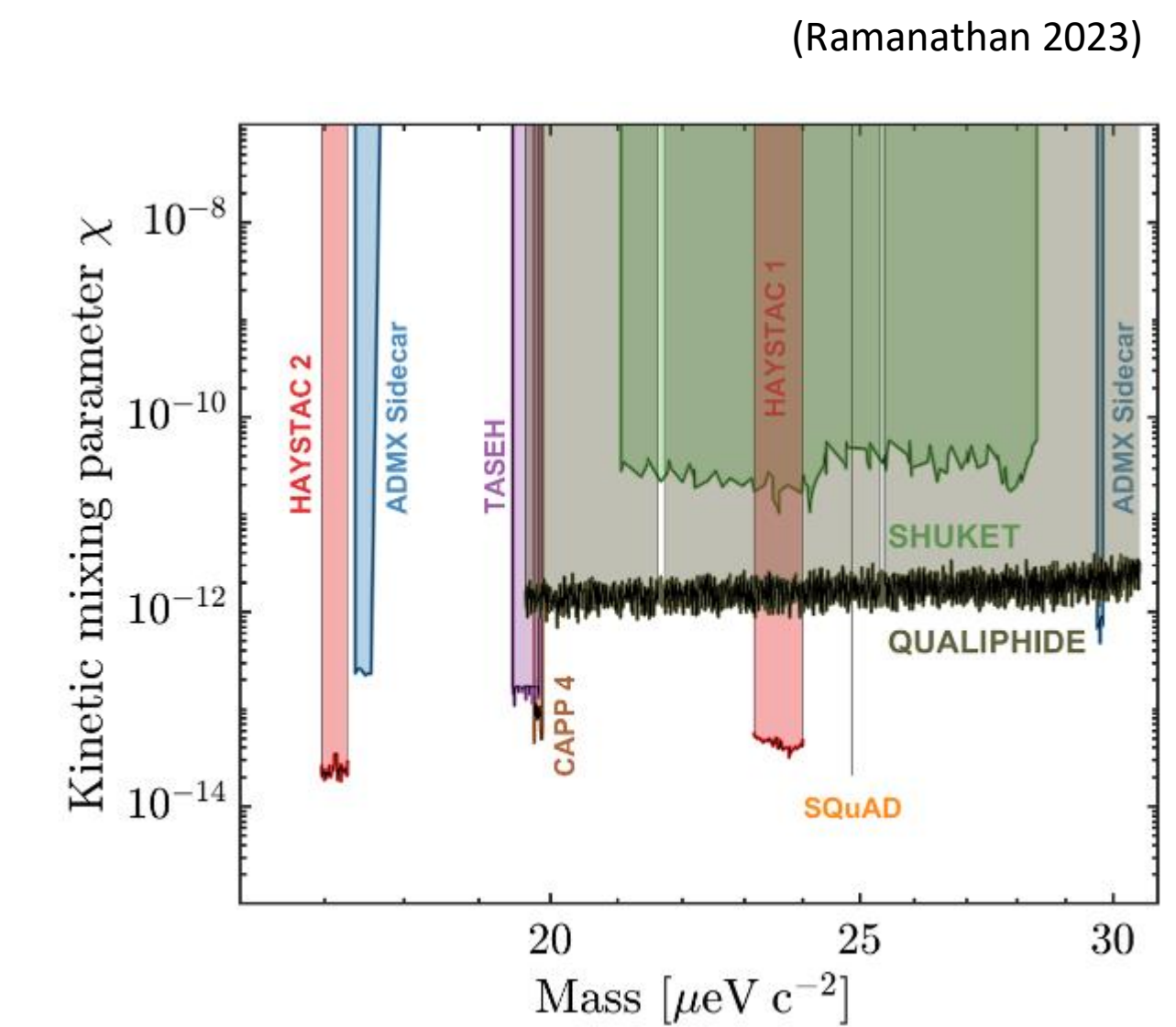


- Coincidence Triggering:** By reading out multiple pixels simultaneously, we can learn about a pulse's origin:
  - Pulse in only one pixel  $\rightarrow$  far-IR photon
  - Pulse in multiple pixels  $\rightarrow$  phonons from substrate excited by a cosmic ray
- Day et al. (2024) found 4.4 mHz dark count rate (DCR) with 2 pixel coincidence triggering and the device in a black body optical enclosure.
- In a dark enclosure with 6 pixel triggering (right plot)  $\rightarrow$  **1 mHz DCR**



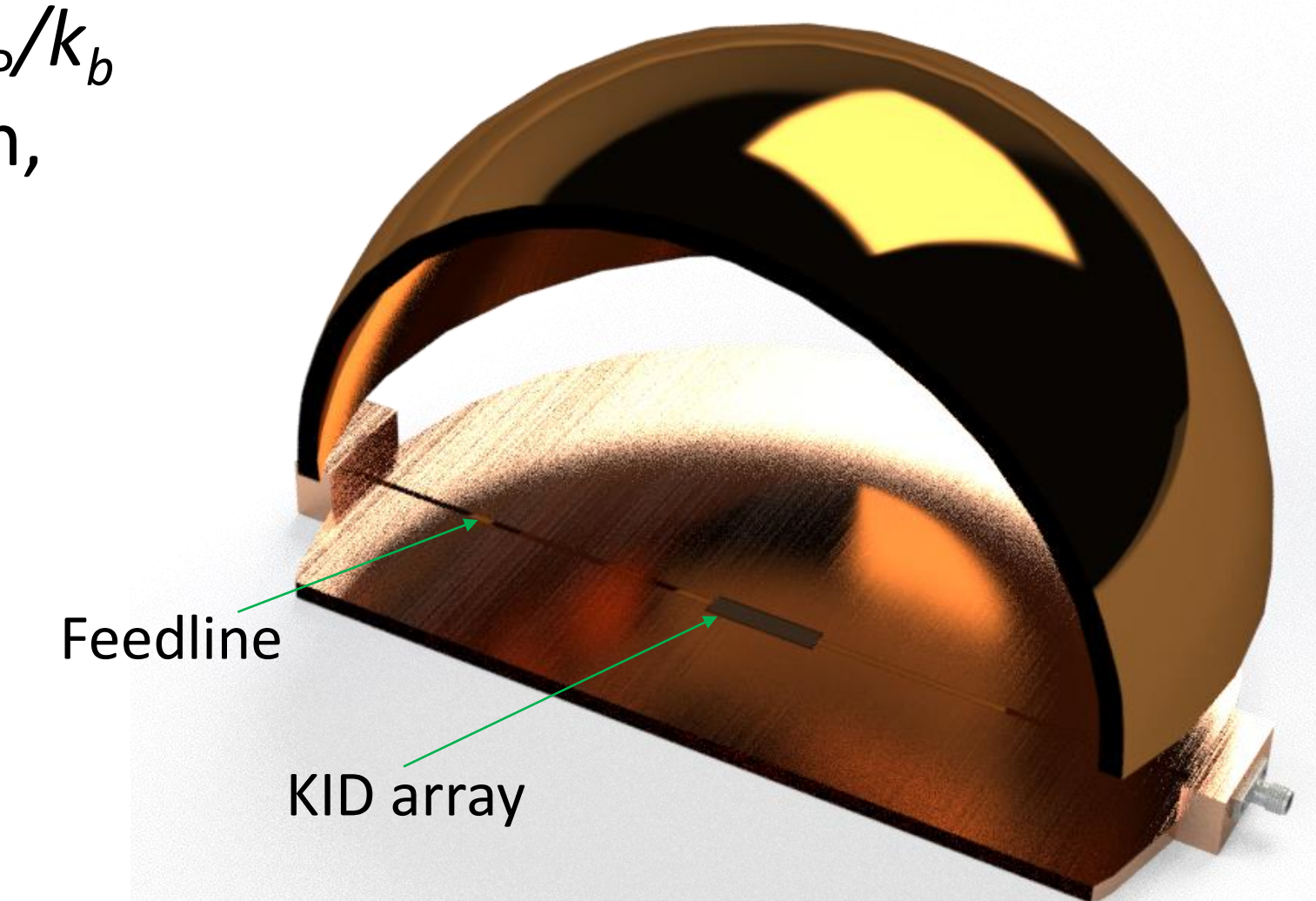
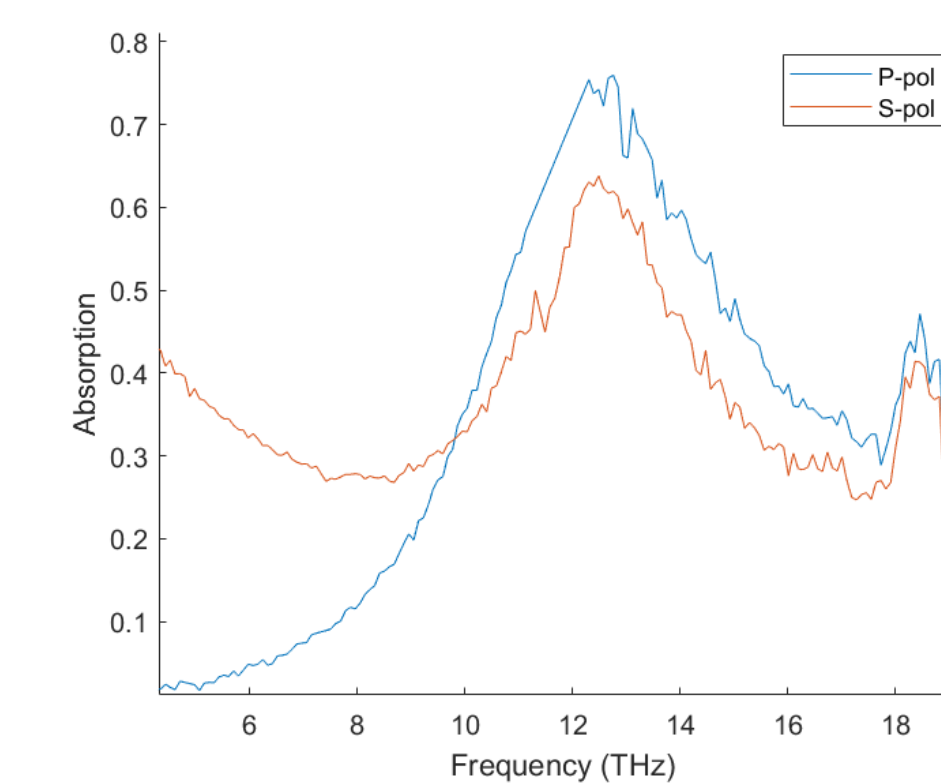
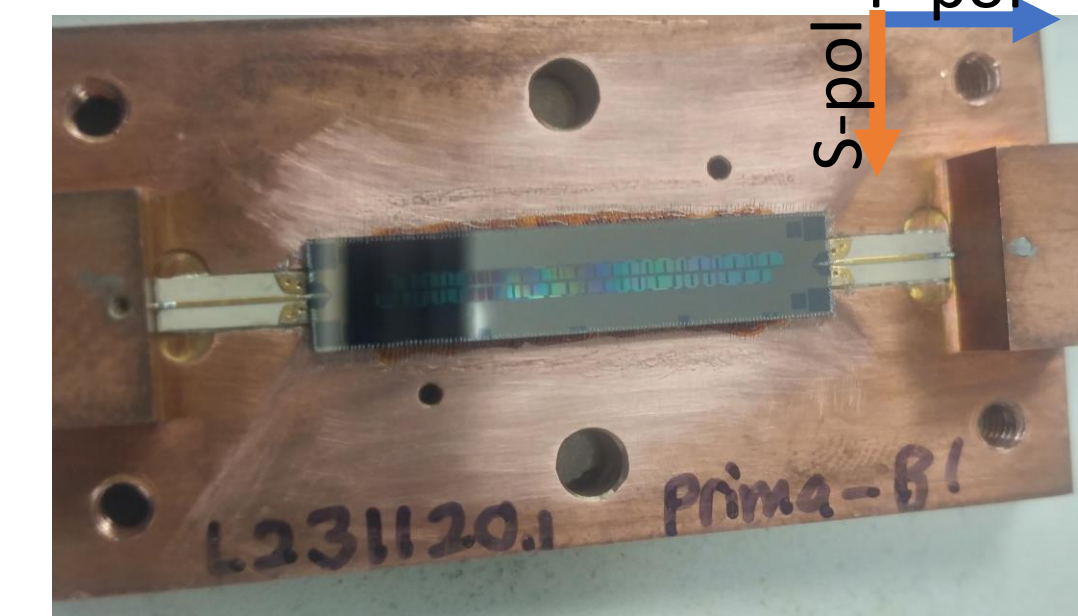
### QUALIPHIDE Background

- First generation of QUALIPHIDE searched for hidden photons with masses 20-30  $\mu\text{eV } c^{-2}$  using a horn antenna coupled to a 4-8 GHz parametric amplifier (Ramanathan 2023).
- The parametric amplifier was operated at 20 mK and allowed for measurements nearly at the Standard Quantum Limit (SQL), at which only one quanta of noise is added to the signal during amplification.
- Kinetic mixing parameter was probed down to  $\chi \approx 10^{-12}$



### Experiment and Expected Results

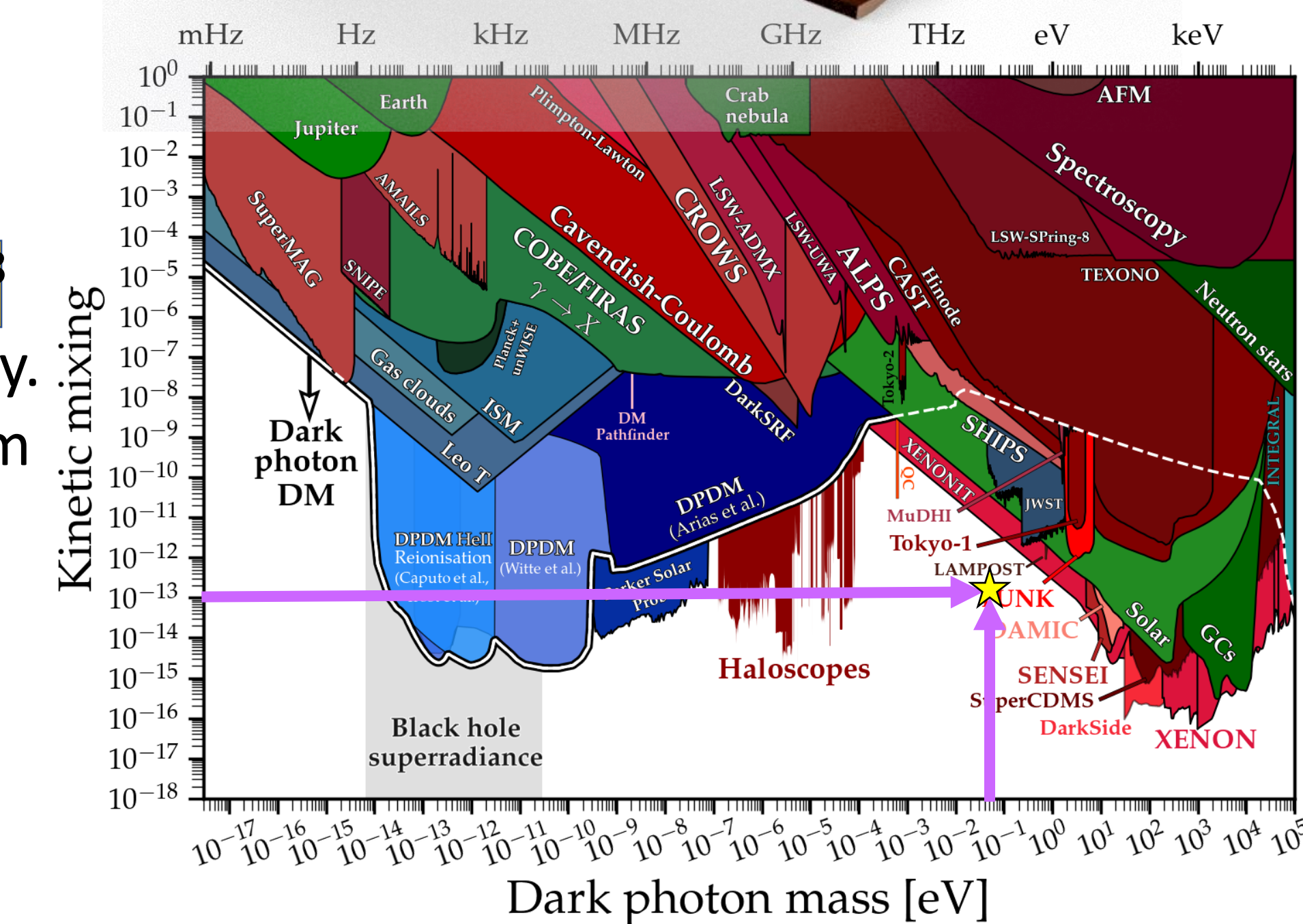
- No need for a parametric amplifier in this current experiment.
  - Operating in a photon counting mode instead of power detection means that we are no longer photon noise limited.
  - The KID absorbers are sensitive to 8-20 THz photons, thus could not achieve SQL performance even if we were measuring power because  $T_{\text{sys}} = 150 \text{ mK} \ll h\nu_{\text{HP}}/k_b$
- KID array placed in the center of  $r=10 \text{ cm}$  hemispherical dish, acting as the lid to the light-tight detector housing.
  - 1-3 central pixels in the focus of the dish.
- Peak KID absorption at 12 THz  $\rightarrow m_\alpha = 50 \text{ meV } c^{-2}$



- With DCR of  $R_{\gamma, \text{det}} = 1 \text{ mHz}$ , at 12 THz we can reach  $\chi \approx 10^{-13}$ 
  - Less sensitive when farther from peak absorber efficiency.
- Careful pulse tagging blocks detector noise fluctuations from being counted  $\rightarrow$  only stray IR photons contribute to DCR.

### Future Experiments

- Modifying KIDs to absorb 1 THz (4 meV) photons
  - Cannot directly absorb 1 THz photons with the inductor anymore because the structure's volume limits us. We could instead couple Nb antennas to Al inductors.
- QUALIPHIDE aims to be an R&D platform leading into future large scale dish antenna searches.



### References

- Horns, D., et al. "Searching for WISPy cold dark matter with a dish antenna", *Journal of Cosmology and Astroparticle Physics*, vol. 2013, no. 4, Art. no. 016, IOP, 2013.
- Day, P. K., et al. "A 25-micrometer Single-Photon-Sensitive Kinetic Inductance Detector", *Physical Review X*, vol. 14, no. 4, Art. no. 041005, APS, 2024.
- Ramanathan, K., et al. "Wideband Direct Detection Constraints on Hidden Photon Dark Matter with the QUALIPHIDE Experiment", *Physical Review Letters*, vol. 130, no. 23, Art. no. 231001, APS, 2023.