Targeted Searches for Gravitational Waves from Supermassive Black Hole Binaries

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Mingarelli et al. for the NANOGrav Collaboration

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Background

NANOGrav has observed 67 millisecond pulsars for 15 years to search for nanohertz gravitational waves (GWs). In 2023, NANOGrav announced evidence for a stochastic GW background (GWB), believed to result from a population of supermassive black hole binaries (SMBHBs) [1]. Deterministic GW signals from individual SMBHBs, however, are too quiet to be resolved from the background at low frequencies.

While previous searches for deterministic GW signals have considered all frequencies across the entire sky, **targeted searches fix the frequency, sky location, and distance of a potential GW source** and are expected to improve sensitivity dramatically. This work is the first systematic catalog of targeted searches.

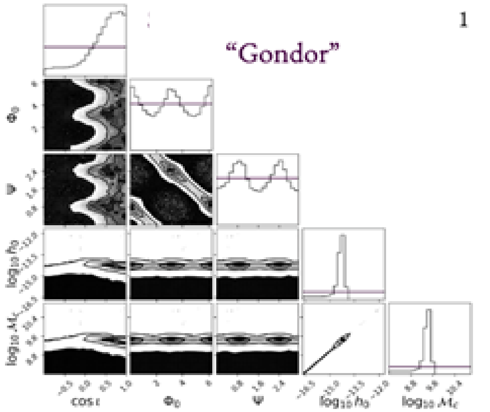
EM Signatures

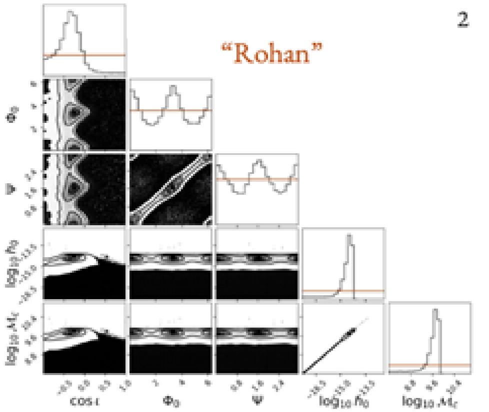
Hydrodynamic simulations predict that AGN hosting **SMBHBs may have periodic variability in their optical light curves** [3]. Optical periods can be anywhere from one to six times the GW period, depending on orbital eccentricity. Other models predict periodic radio variability in AGN with jets, again corresponding loosely to the GW period [6].

Locating these signatures in optical and radio surveys gives sky locations and distances at which to search. Using the EM period to predict the GW frequency, we can further constrain our search and potentially detect a quieter signal from a particular source.

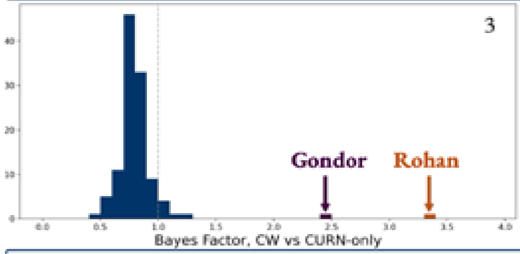
Binaries in the PTA band have orbital periods of several years, so candidates require decades of monitoring to establish periodicity.

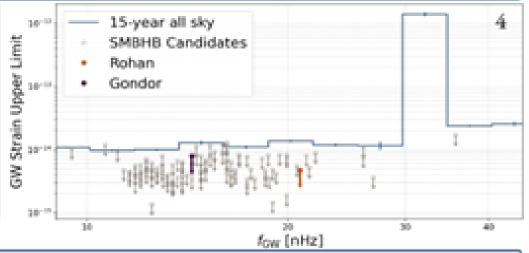
Results



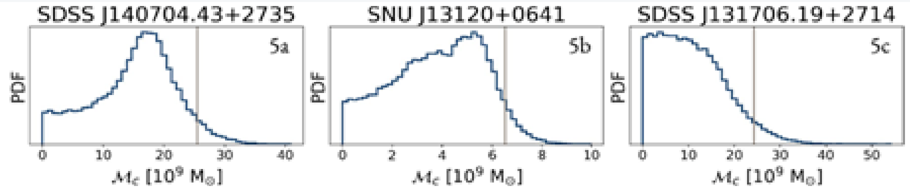


For 111 targets, the evidence disfavors or narrowly favors the binary model. "Gondor" (Fig. 1) and "Rohan" (Fig. 2) are **two targets standing out at 5σ and 8σ** (Fig. 3), moderately preferring the binary model. We highlight these for further investigation. Figs. 1 and 2 show posterior distributions for inclination ι, phase Φ_0, polarization ψ, strain amplitude h_0, and chirp mass M_c for these two targets. Uniform priors on all parameters are shown as colored lines.





Targeted searches deliver more constraining mass upper limits: **a median improvement of 57% over all-sky searches.** Three distinct classes of chirp mass posteriors are observed. Fig. 5 shows three examples from the 113 studied: "Peak" (5a), "Hill" (5b), and "Cliff" (5c). Vertical lines represent the 95% mass upper limit.



Targets

We perform targeted searches for 111 AGN from the Catalina Real-time Transient Survey (CRTS) [5], plus two quasars with radio variability from the Owens Valley Radio Observatory 40m telescope monitoring program (OVRO) [6, 7].

Population models suggest that about 1% of AGN may host binaries [4], and the CRTS sample in particular might include around 1 genuine binary.

Conclusions & Outlook

This catalog includes no confident detections, but two interesting candidates with Bayes factors of 2.4 and 3.3, at 5σ and 8σ, suggest a need for more investigation. Upper limits on binary masses for individual targets were also reduced by a median of 57% over limits derived from all sky searches. Improvements indicate that detections could be within reach in the near future. The upcoming NANOGrav 20 year and IPTA DR3 data releases will be the most sensitive PTAs to date, and upcoming EM surveys will produce many more candidates.

Meanwhile, detection criteria have not been established, and the significance of these results is not known. Next steps include recovering injected GW signals from simulated binaries to better understand sensitivity, characterize signals, and calculate false alarm probabilities.

References

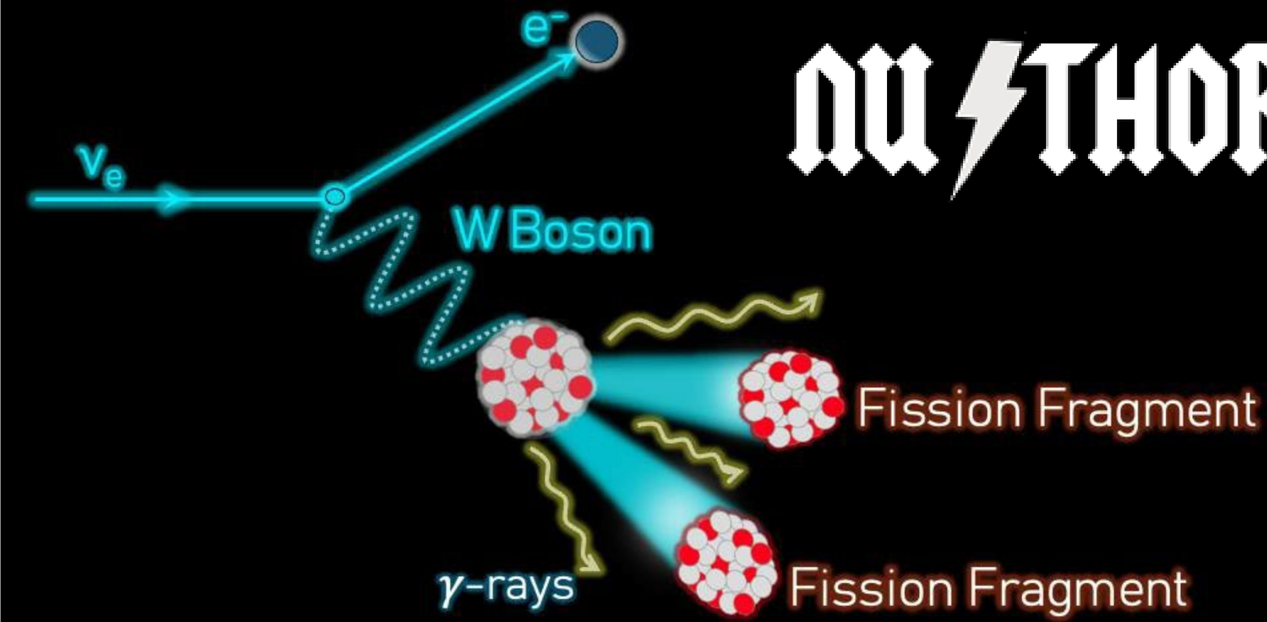
[1] Agazie, G., et al. 2023, ApJL, 951, L50.
[2] Arzoumanian, Z., et al. 2020, ApJ, 900, 102.
[3] Farris, B. D., et al. 2014, ApJ, 783, 134.
[4] Casey-Clyde, J. A., et al. 2025, ApJ, in press.
[5] Graham, M. J., et al. 2015, MNRAS, 453, 1562.
[6] O'Neill, S., et al. 2022, ApJL, 926, L35.
[7] de la Parra, P. V., et al. 2024, arXiv:2408.02645.

Forrest Hutchison

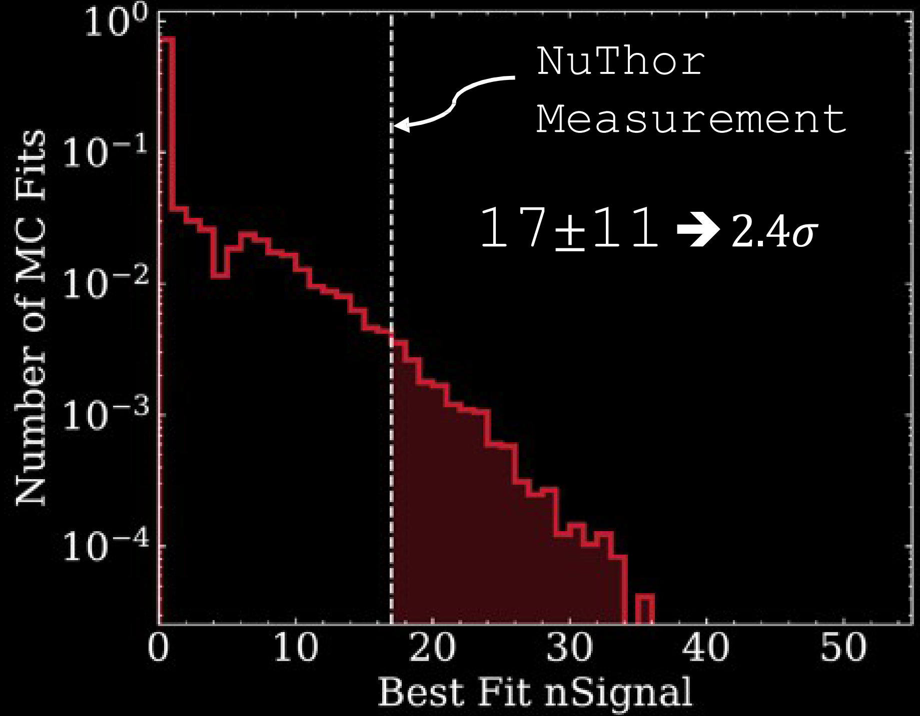
Rohan Shivakumar

Bjorn Larsen

The First Indication of Neutrino-Induced Nuclear Fission



NU THOR

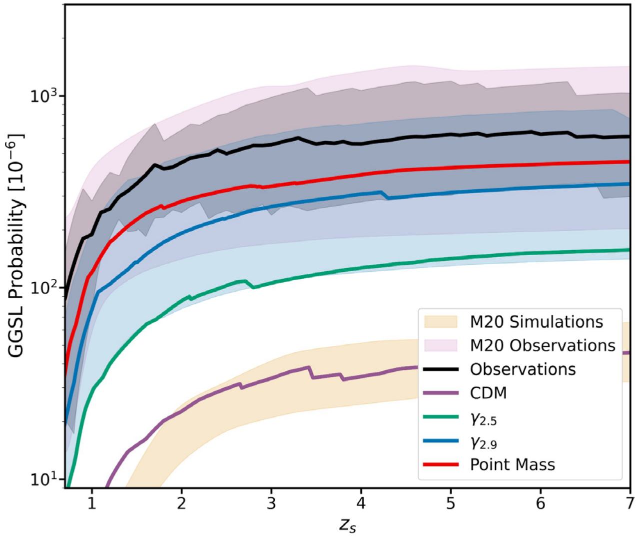


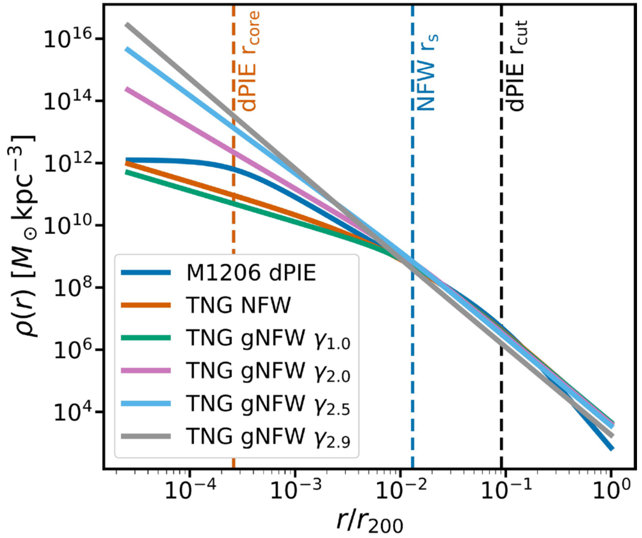
Self-Interacting Dark Matter, Core Collapse, and the Galaxy-Galaxy Strong Lensing Discrepancy

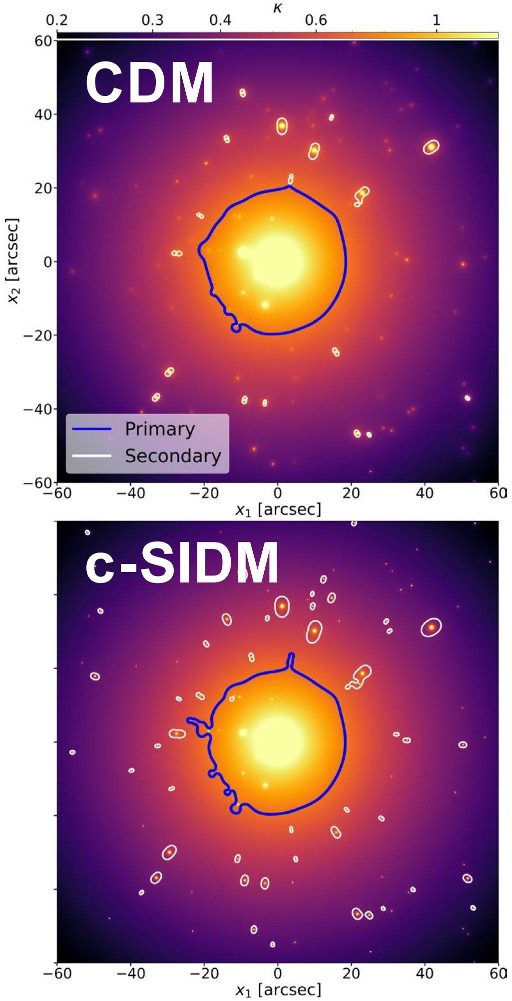
Isaque Dutra[1], Priyamvada Natarajan[1,2], Daniel Gilman[3]

[1]Department of Physics, Yale University; [2]Department of Astronomy, Yale University; [3]Department of Astronomy & Astrophysics, University of Chicago

- Our best models predict that galaxy-galaxy strong lensing (GGSL) probability by cluster subhalos in the real universe is an **order of magnitude stronger** than CDM simulations
- GGSL is extremely sensitive to the inner density profile shape (how mass is distributed within the subhalos)
- Enhancement of the mass density by four orders of magnitude in the inner region appears to resolve this tension
- Core-collapsed SIDM offers a natural scenario for this level of steepening







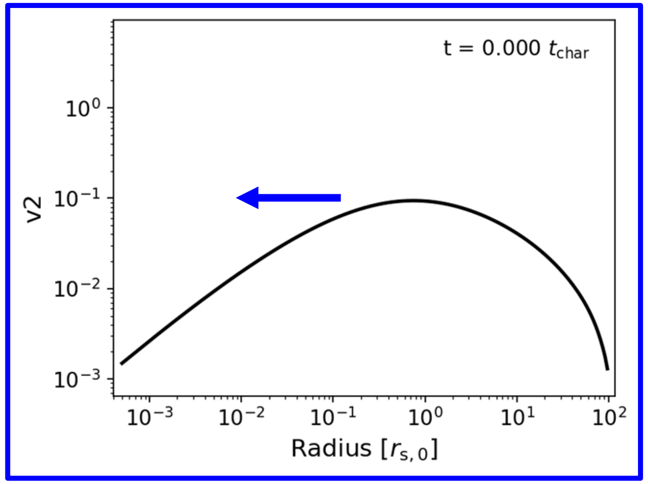
(Dutra et al 2024)

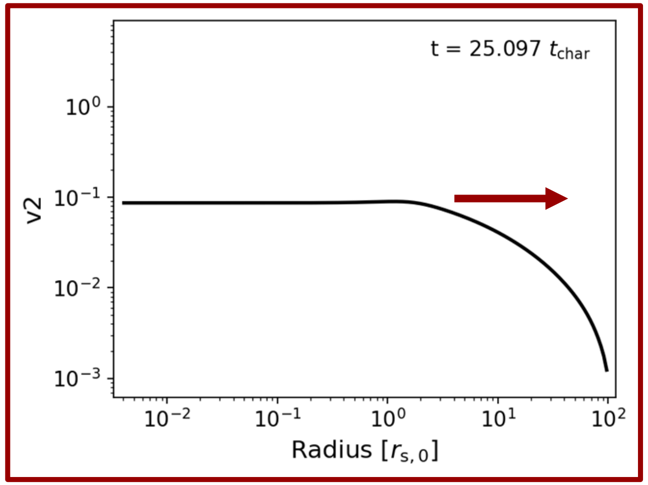
Core-collapsed SIDM halos as massive SMBH seeds

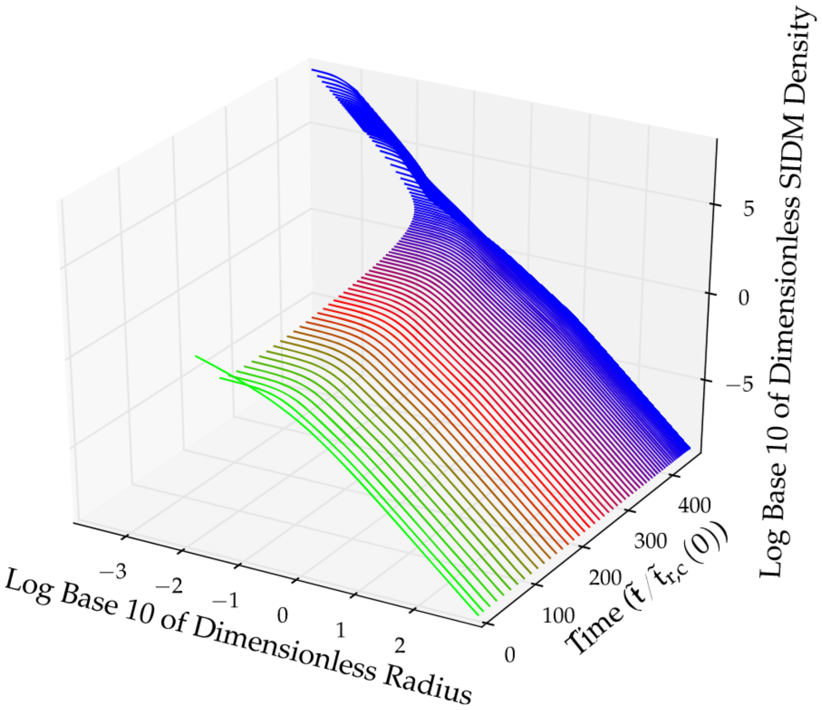
Yarone Tokayer PI: van den Bosch

- **Self-interacting dark matter** originally proposed to explain diversity of halo density profiles (Spergel & Steinhardt 2000)
- Early stages: heat flows *inward* → create core
  - Conduction is collision-limited ($O(t_r)$)
- Late stages: heat flows *outward* →gravothermal catastrophe
  - Conduction is mean free path-limited ($O(100 \times t_r)$)
- Can core-collapsed SIDM halo populations in the early universe seed SMBHs? (Jiang+25, Shen+25)
- How do encounters/interactions affect collapse timescales?

$$t_r = \mathcal{O}\left(\frac{\lambda}{v}\right) = \mathcal{O}\left(\frac{1}{\rho \sigma v}\right)$$

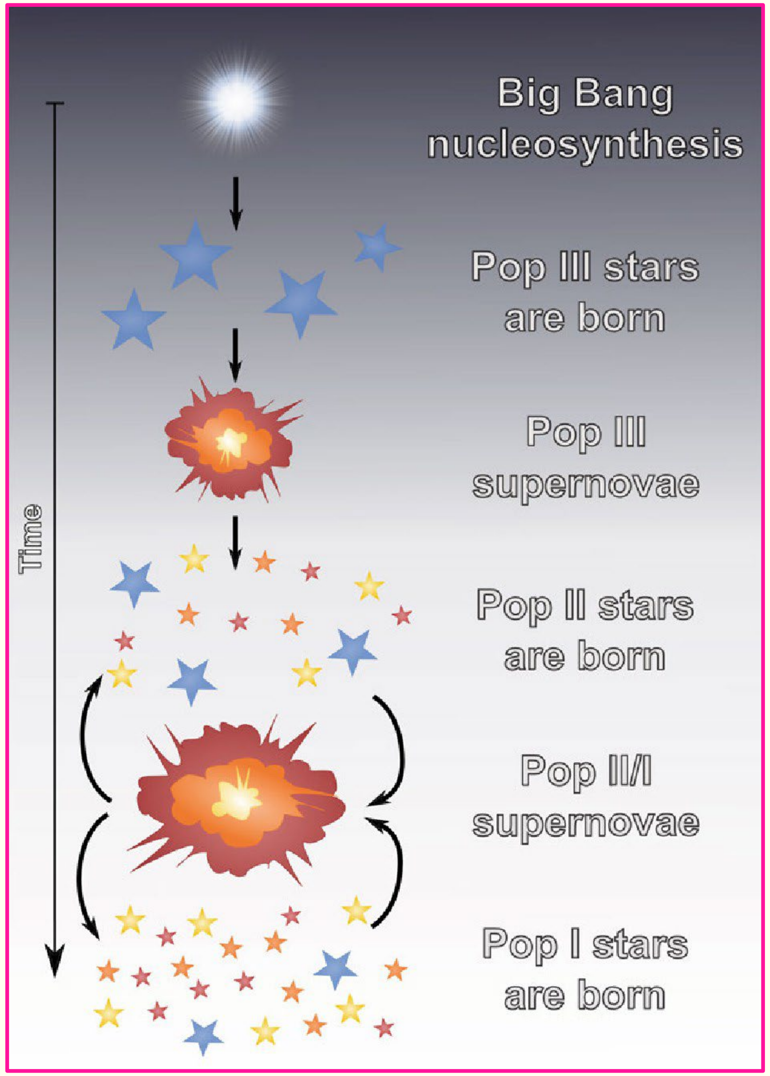




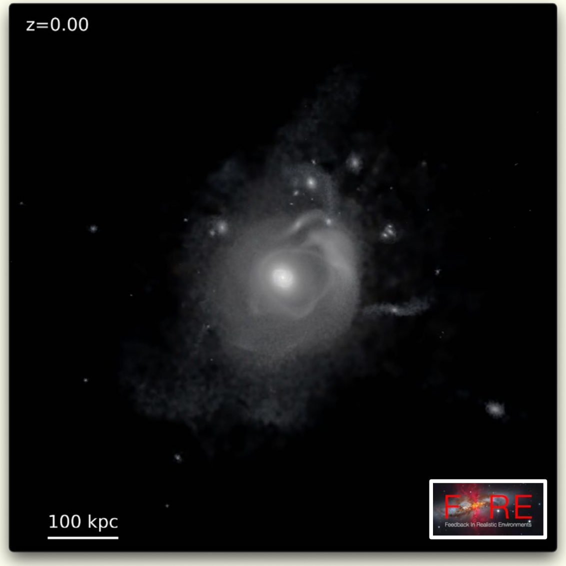


(figure: Pollack+15)

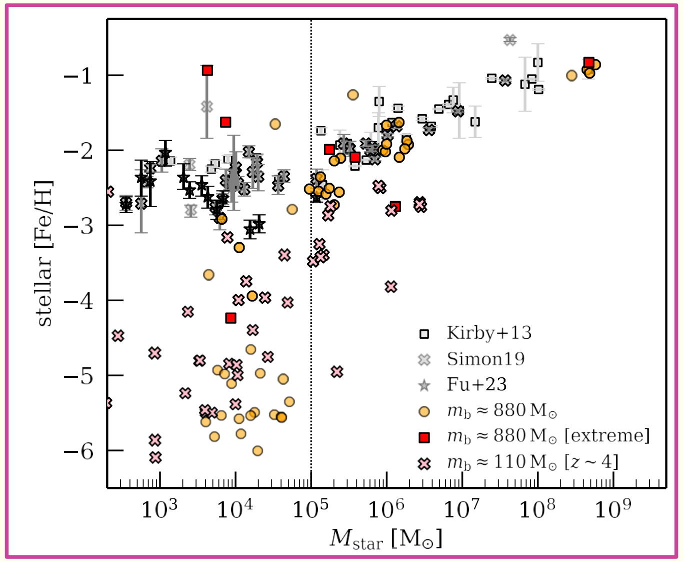
Studying popIII feedback using ultra-faint galaxies



Jessica Till



Gandhi et al., in prep

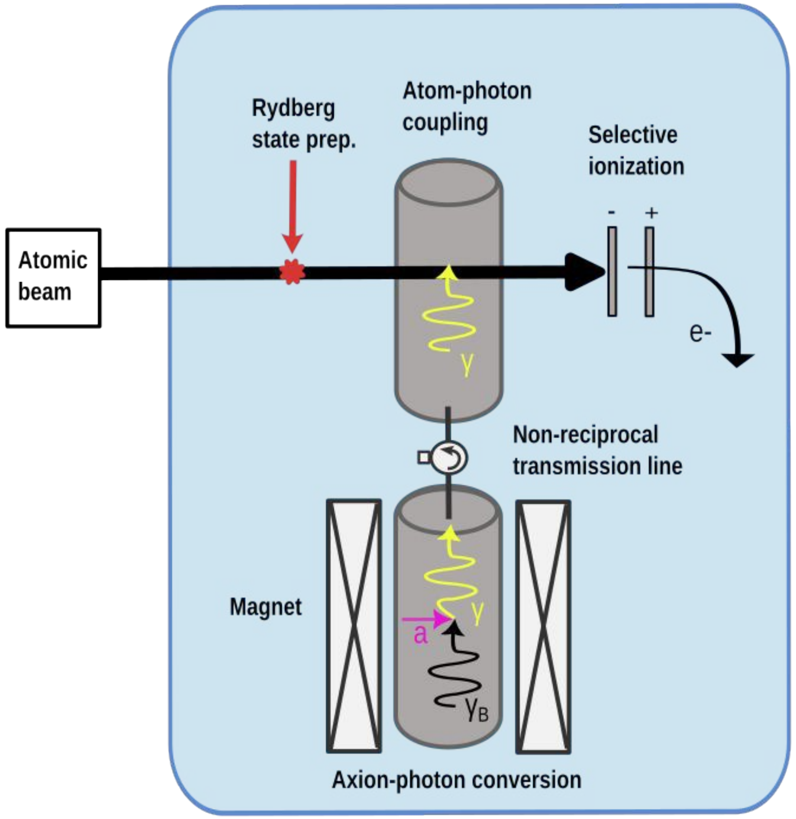


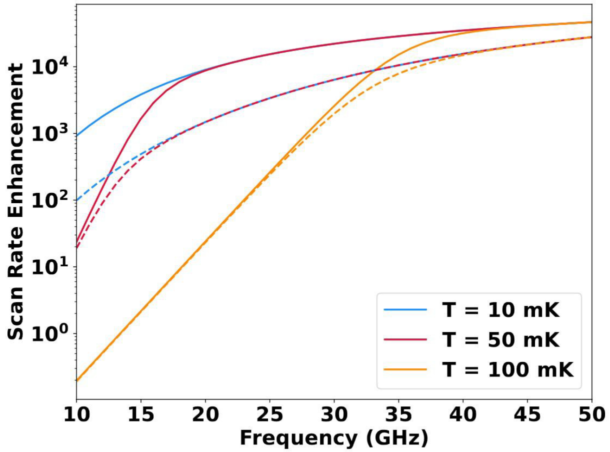
Rydberg/Axions at Yale (RAY)

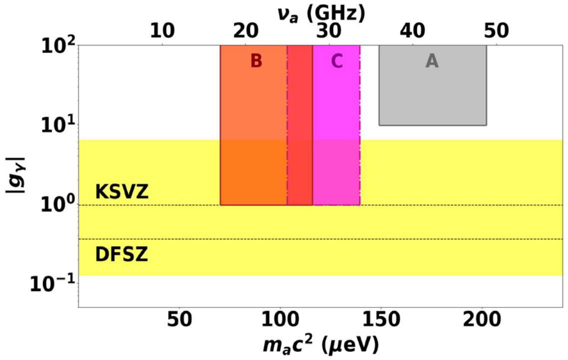
Building a **microwave single-photon detector** out of ^{39}K **Rydberg atoms** for **dark matter axion searches**

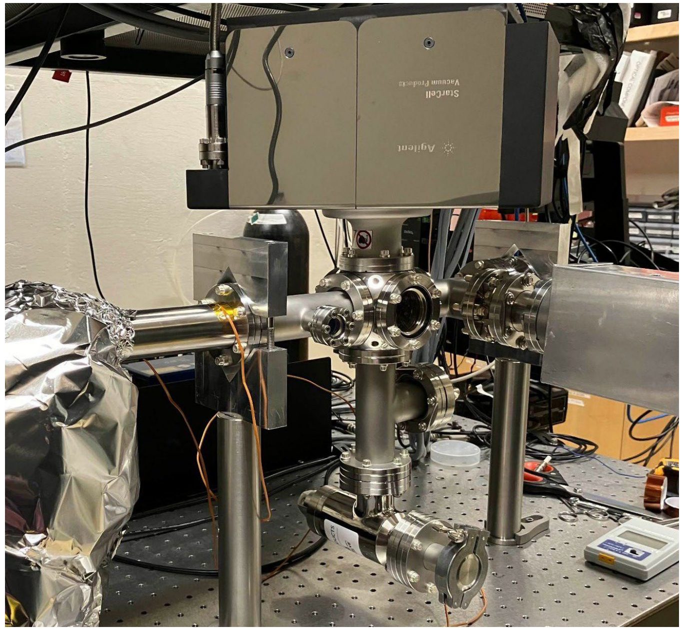
E. Graham et al, Phys. Rev. D 109, 032009 (2024)

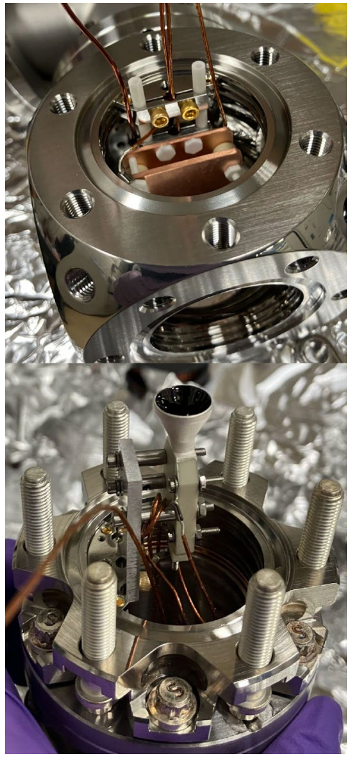
alpha ray

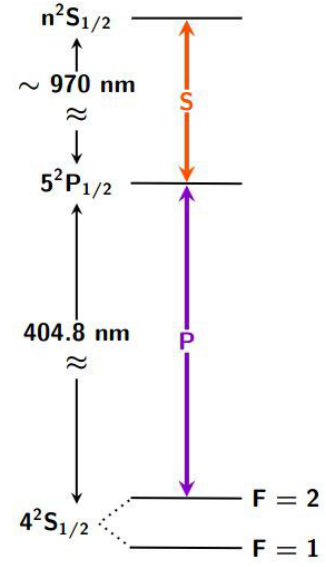




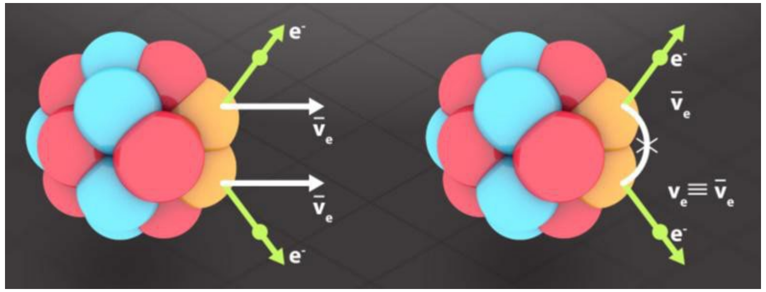




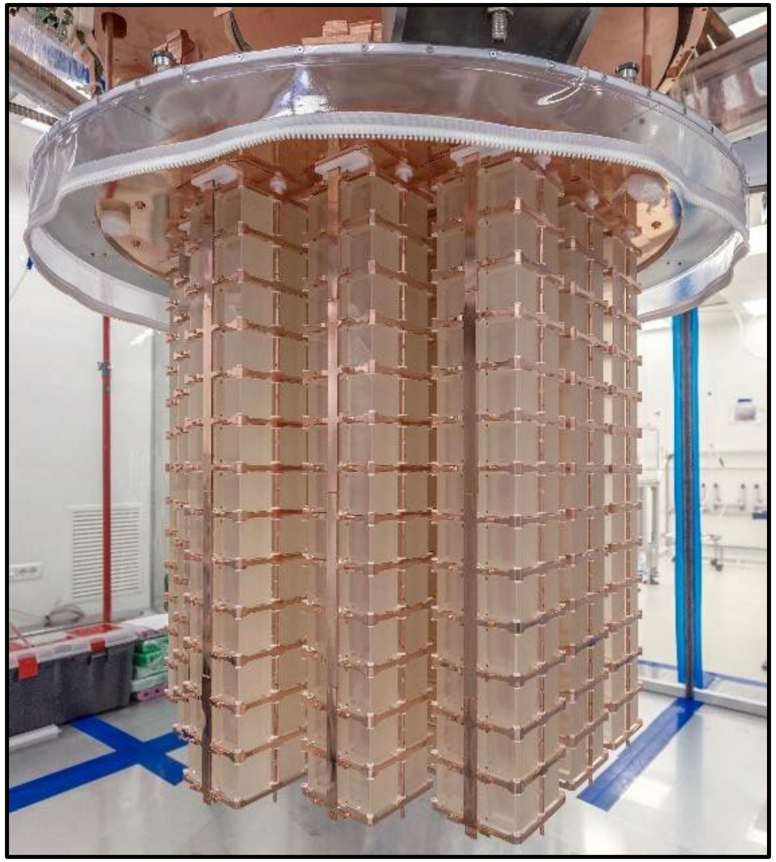


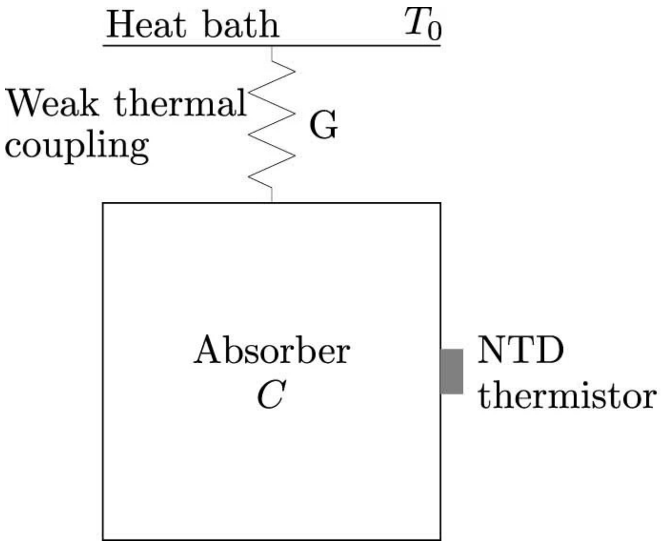


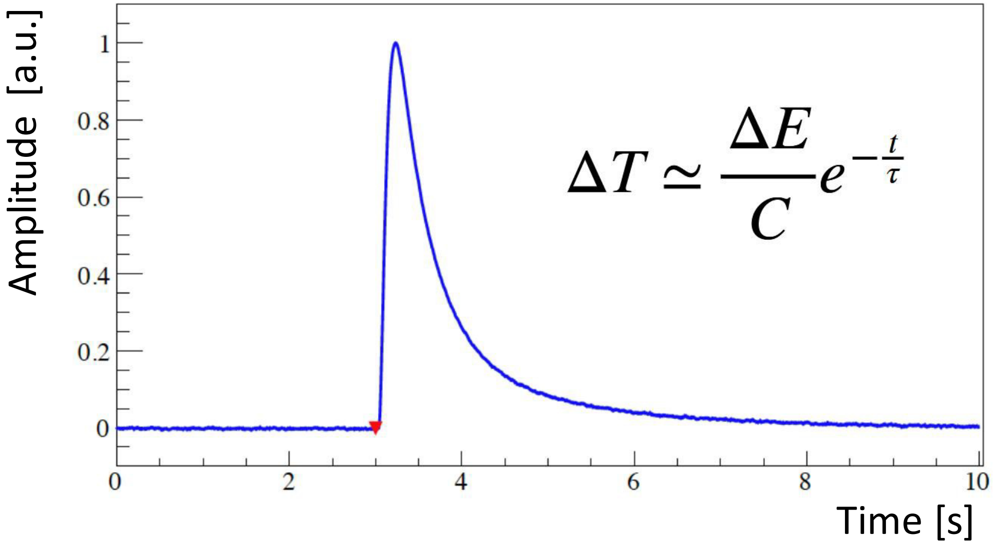
Cryogenic Underground Observatory for Rare Events



- Array of 988 TeO_2 crystals (742 kg) at O(10 mK)
- Neutrinoless double beta decay can help explain matter-antimatter asymmetry and neutrino mass generation
- CUORE is a search for neutrinoless double beta decay
  - Taking data since 2019, and
  - Setting the world-leading limit on ^{130}Te $0\nu\beta\beta$ half-life: $>3.8\times10^{25}$ yr
- Low backgrounds enable searches for other rare physics
  - e.g. axions, decay to excited nuclear states



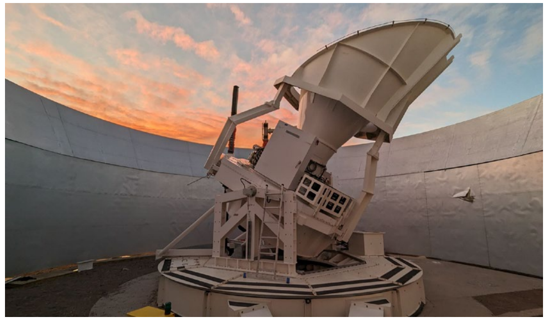


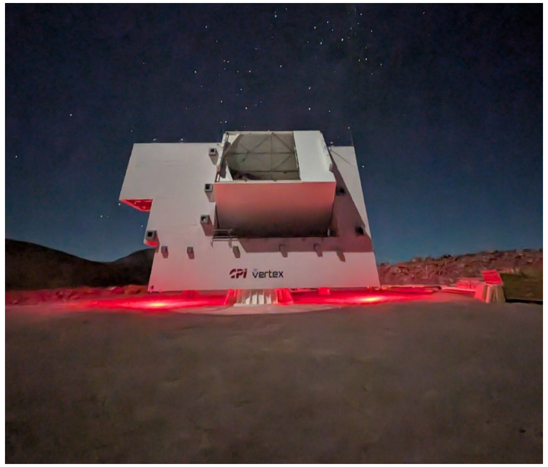


Yale Wright Laboratory

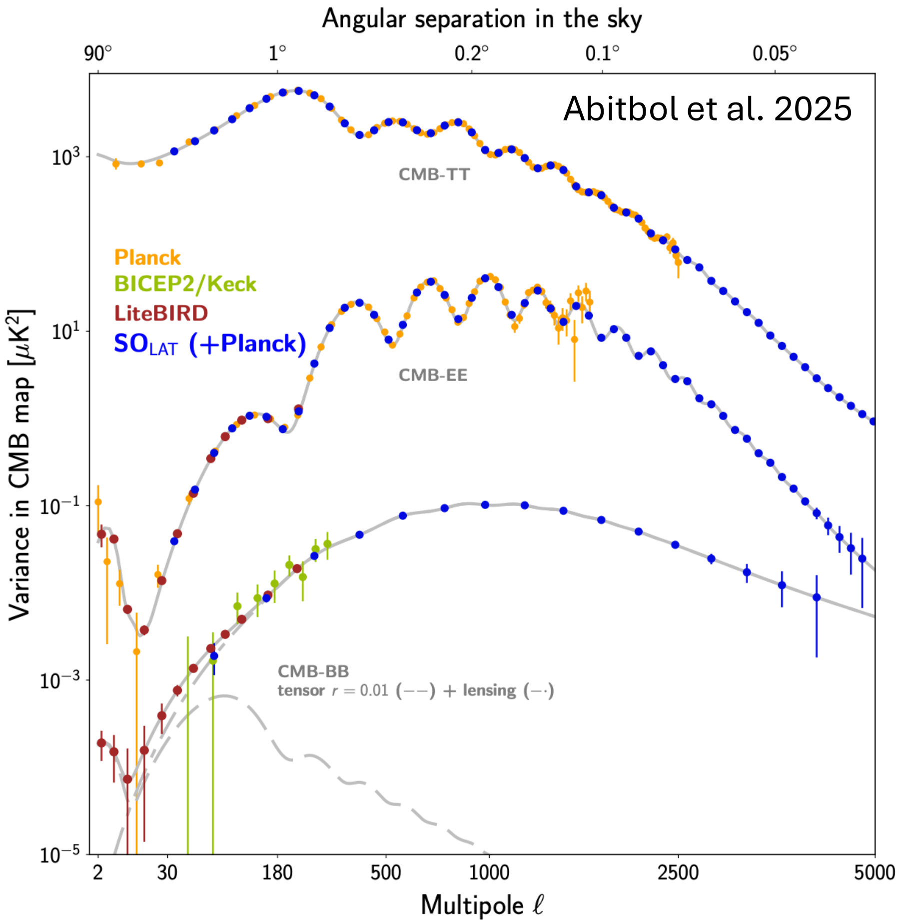
The Simons Observatory

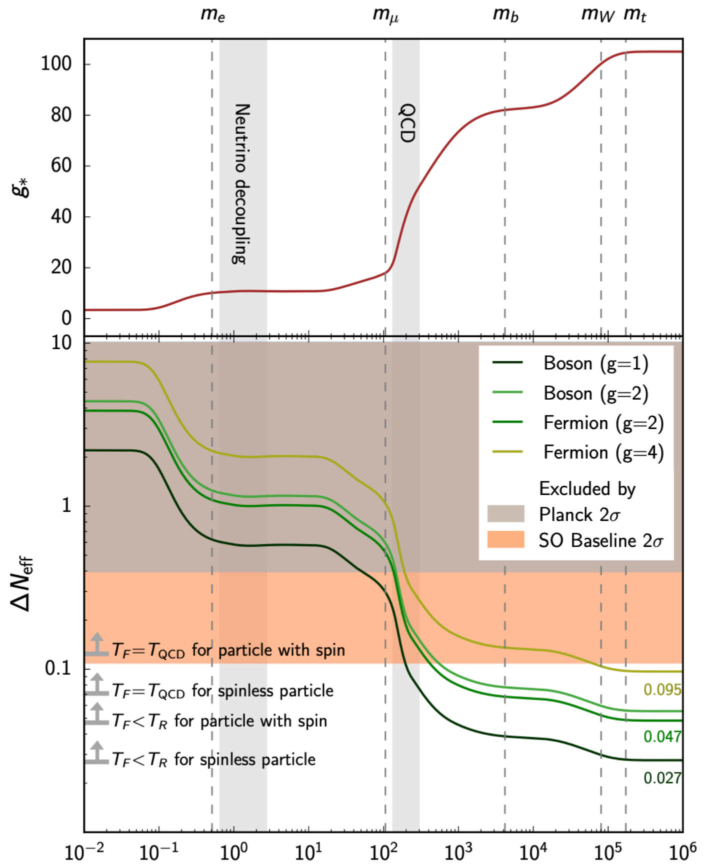
Credit: Nicholas Galitzki





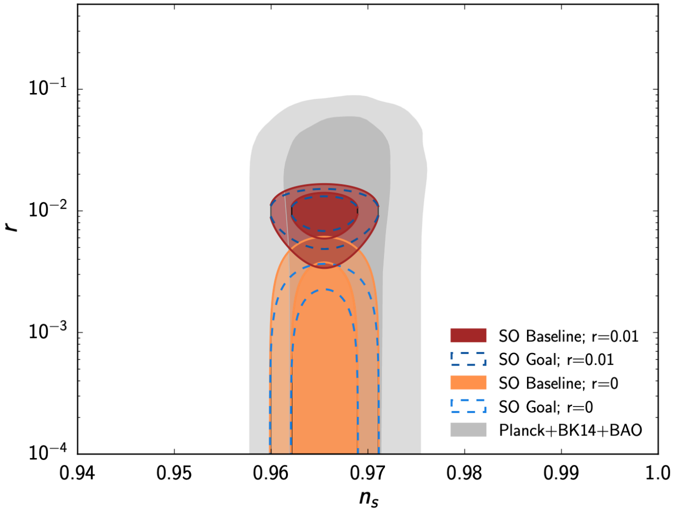
Credit: Mark Devlin

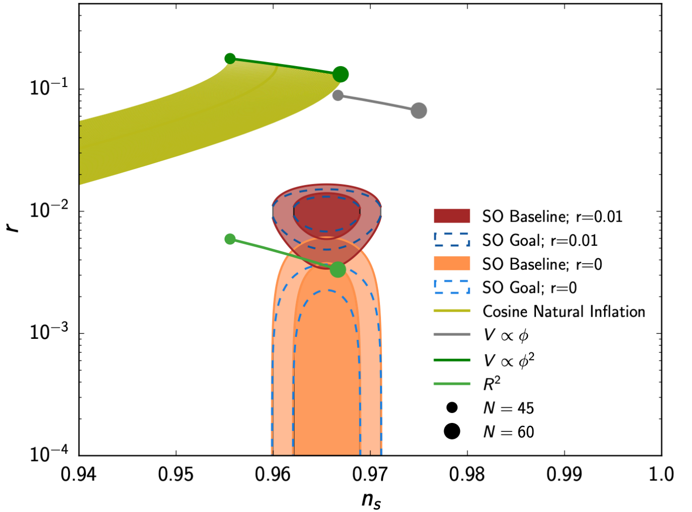




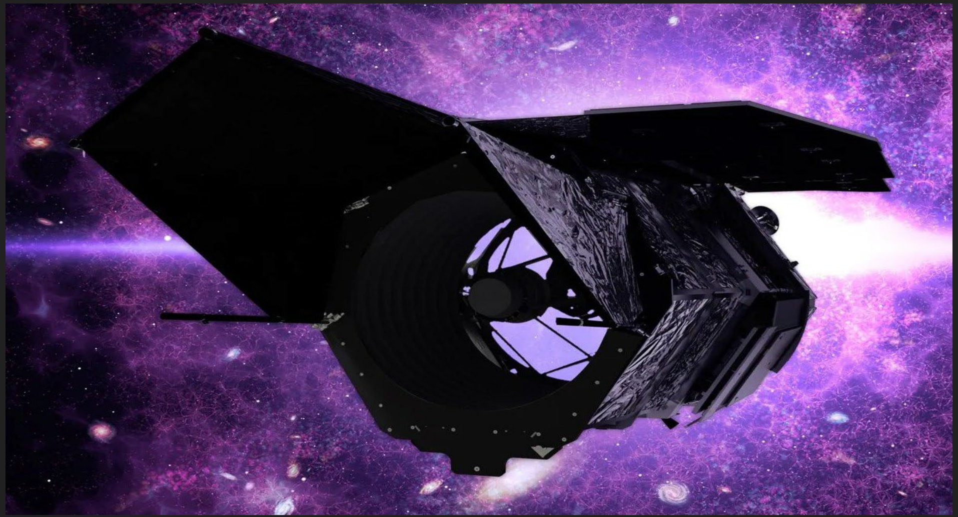
Ade et al. 2019

- ❑ 0.5 m **Small Aperture Telescopes** (x3)
- ❑ 6 m **Large Aperture Telescope**
- ❑ 27, 39, 93, 145, 225, 280 GHz





Searching for Dark Energy with Roman



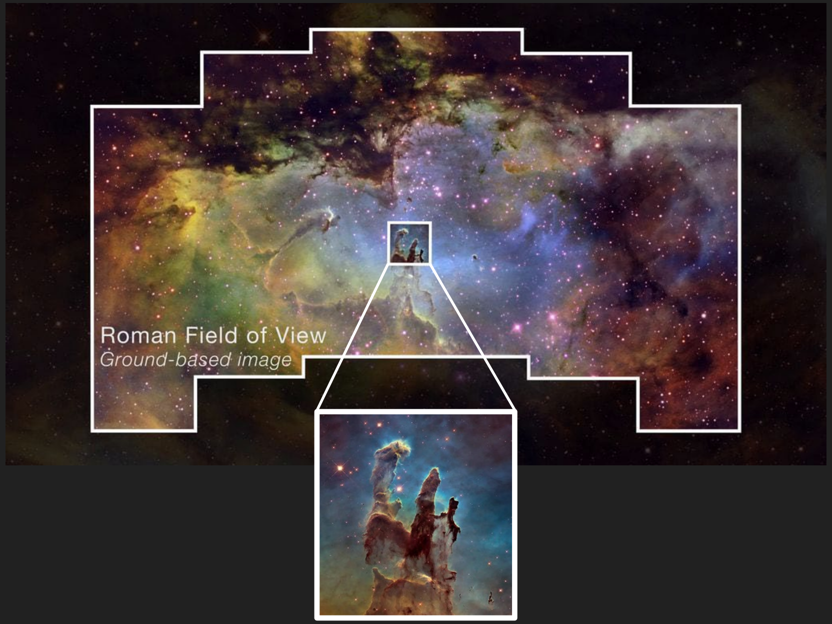
High Latitude Wide Area Survey

- ➔ 2000 square degrees
  - ◆ Notably smaller than DESI or Euclid
  - ◆ Much greater number density
  - ◆ Better magnitude limit by 2 vs. Euclid
- ➔ Probe LSS with BAO, LyA forest, higher-point statistics ⇒ **Track expansion throughout cosmic time**

Launch:
Fall 2026

Hubble mirror (2.4m) ⇒ 100x FOV

Wide Field Instrument and **Coronagraph**



Calibration & Systematics

Redshift Interlopers

- ➔ Objects with incorrect redshifts can bias BAO measurement
- ➔ Developed a method to self calibrate this effect out ⇒

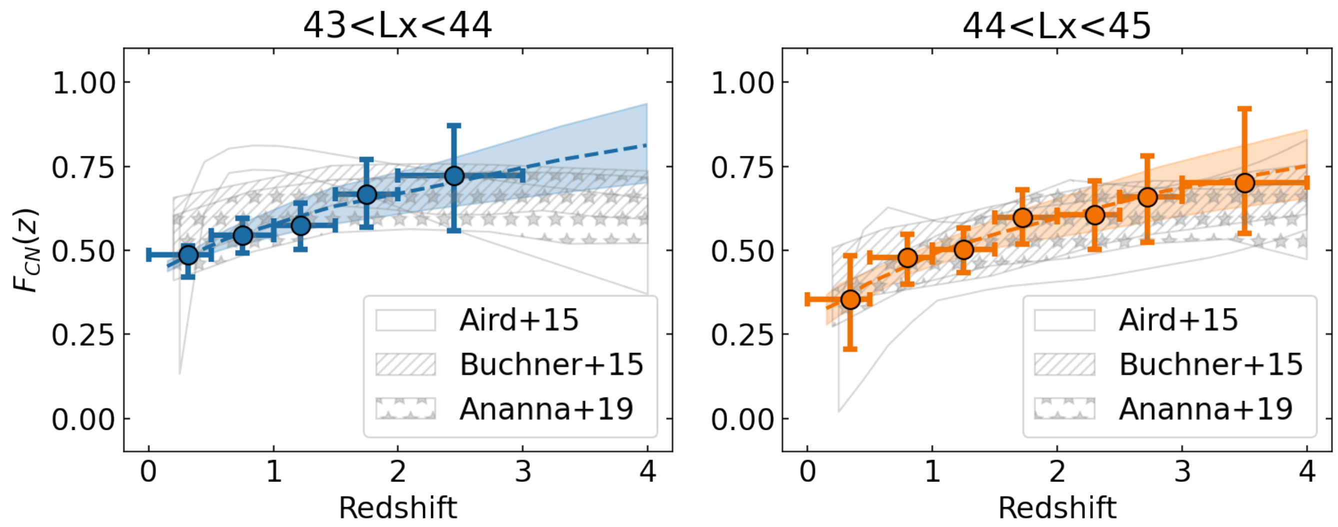
Relative Flux Calibration

- ➔ Correct for spatial and/or wavelength dependent detector response

Why are high-redshift JWST AGN so different?

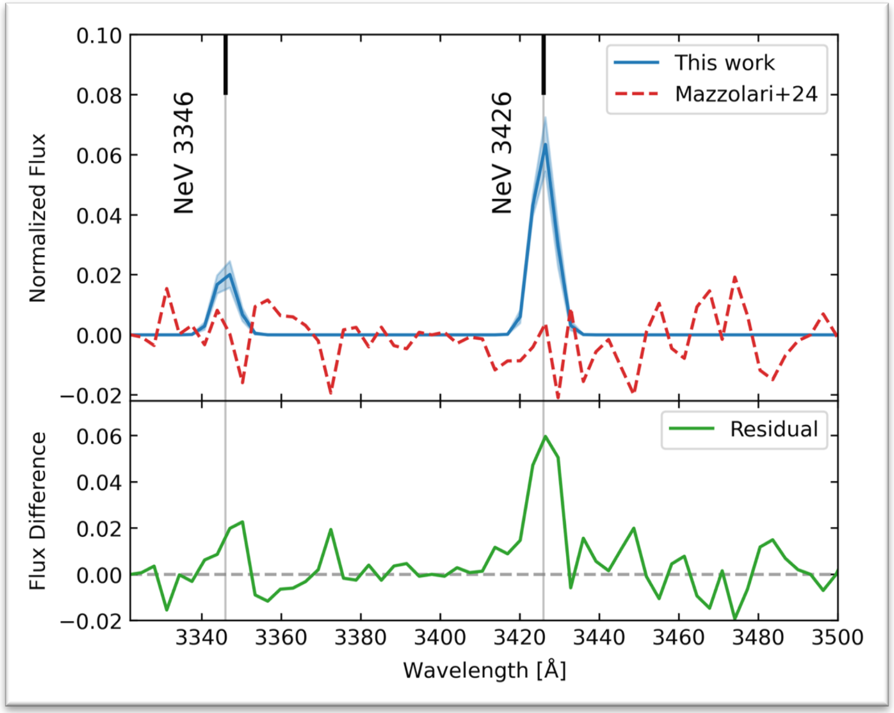
We EXPECT high-z AGN to be heavily obscured, with a major contribution coming from the host galaxy's ISM

But is this enough to explain the **X-ray weakness**?



Peca et al. (2023)

JWST AGN (2 < z < 9) lack [NeV] λ3426



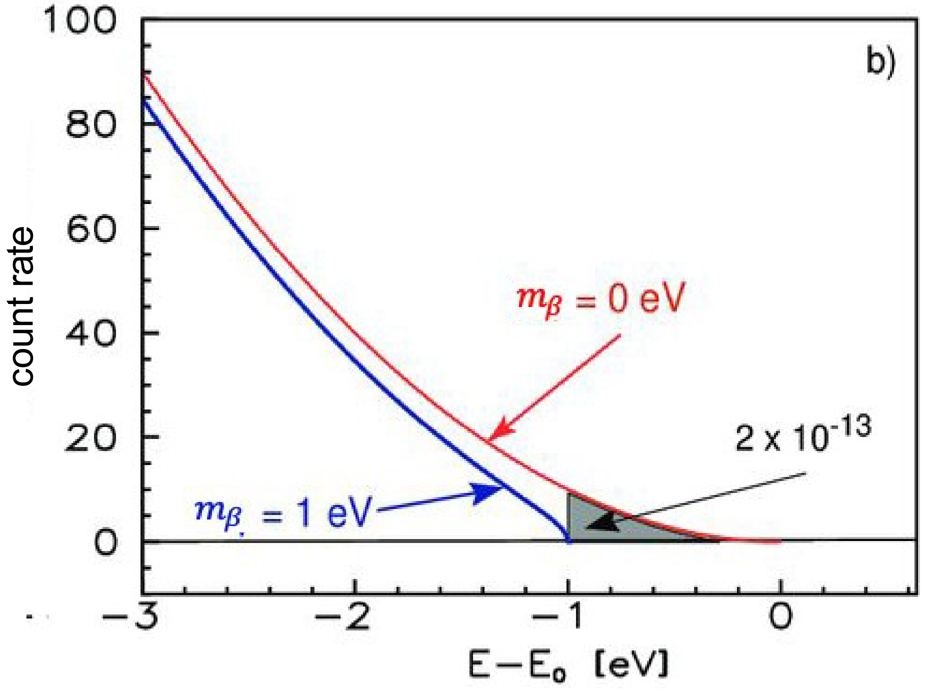
Peca et al. (submitted)

Eureka Scientific

Project 8 simulation development

P. L. Slocum, K. M. Heeger, T. E. Weiss, Wright Laboratory, Yale

Energy spectrum of electrons emitted from tritium β⁻ decay

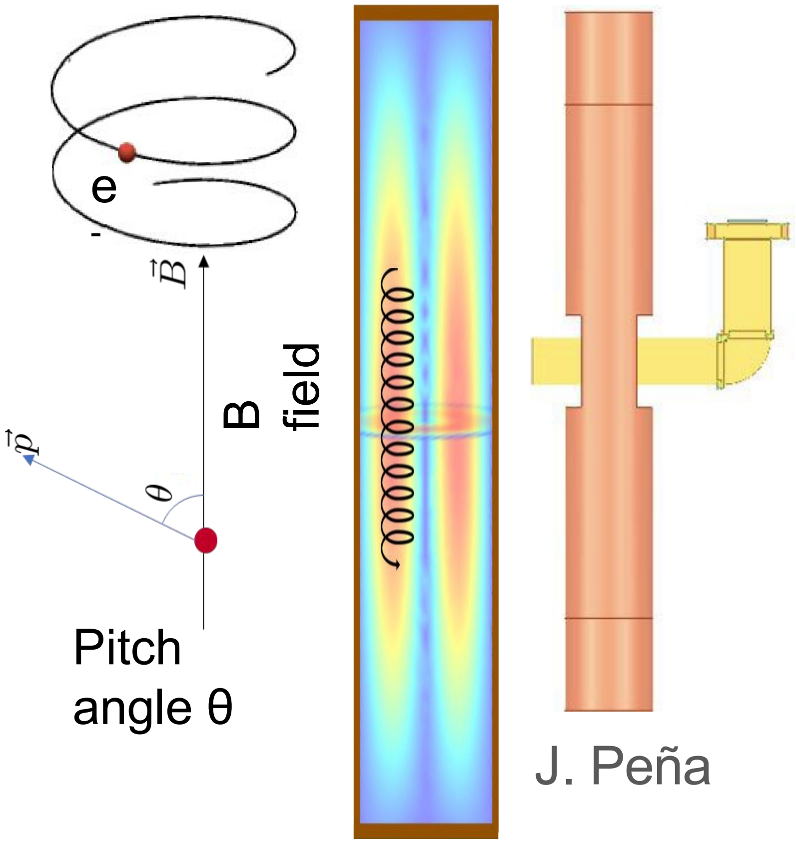


Direct neutrino mass measurement using tritium beta decay, targeting 40 meV sensitivity.

Cyclotron radiation emission spectroscopy (CRES)*

Simulation challenge: Model multiple unique subsystems that are tightly coupled by EM fields.

Simulation purpose: Generate data to examine feasibility and performance of the experiment.



*Monreal and Formaggio, Phys. Rev. D 80 (2009) 051301

nEXO: A Search for Neutrinoless Double Beta Decay

Liquid xenon TPC searching for $0\nu\beta\beta$ in ^{136}Xe

Evidence for Majorana neutrinos and origin of mass

Observation of a process that produces more matter than antimatter