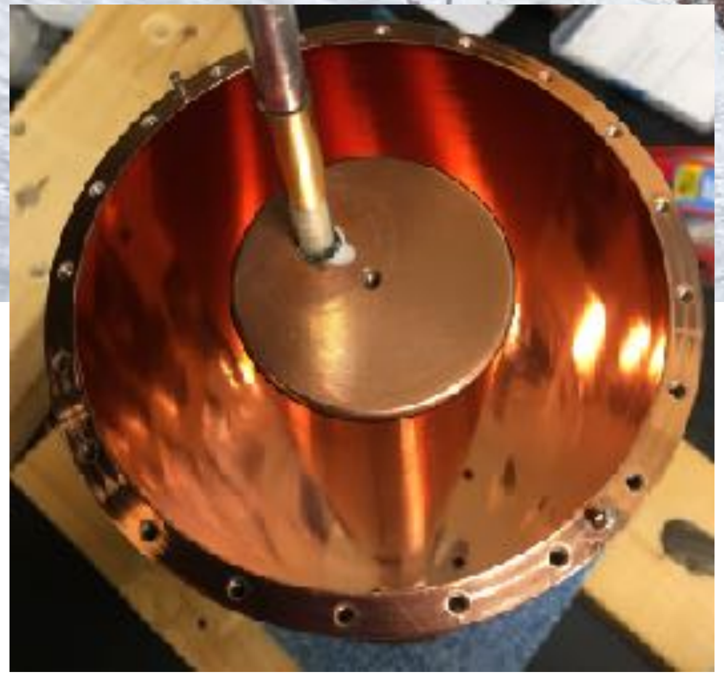
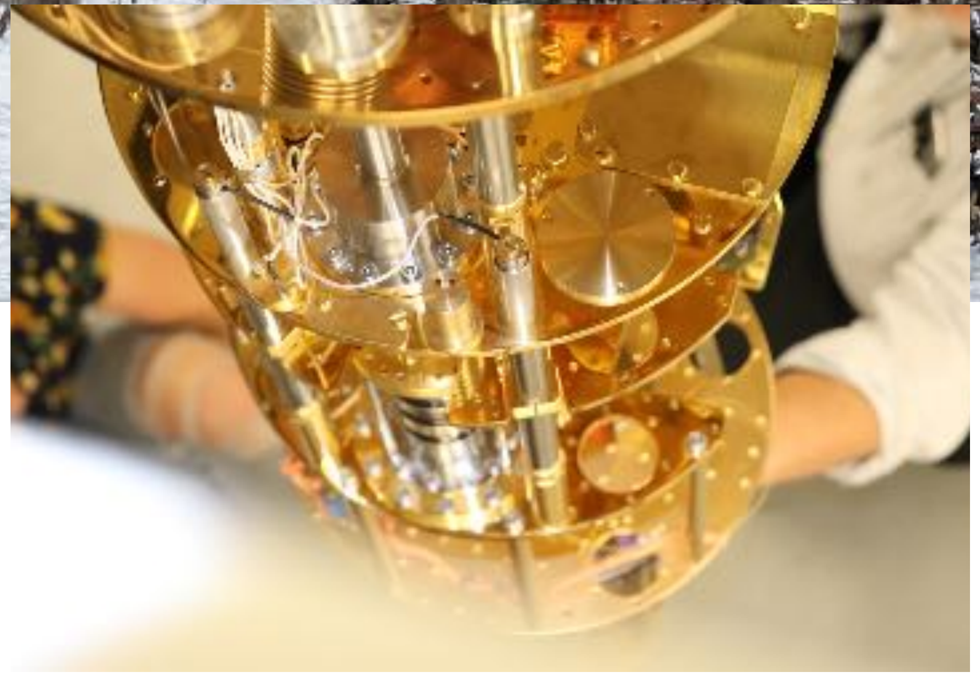
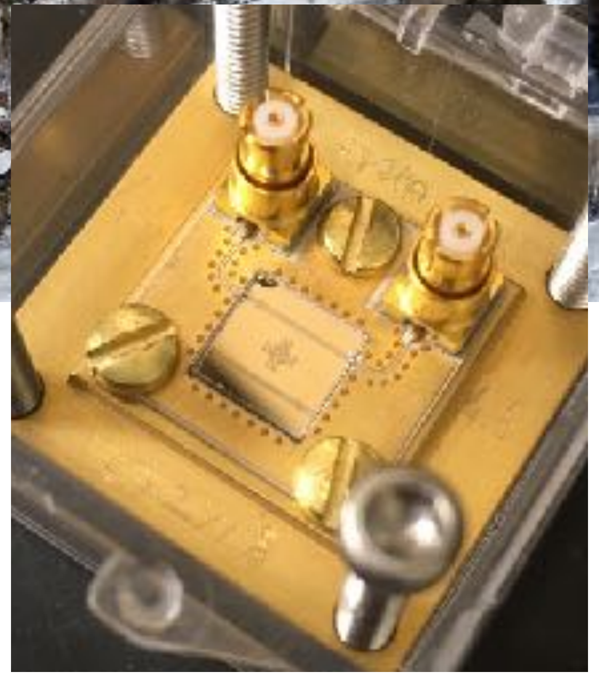
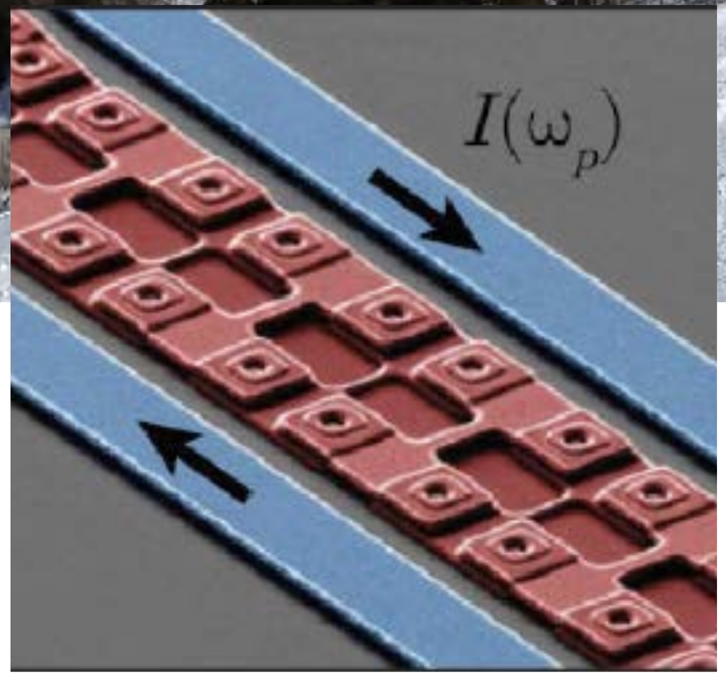
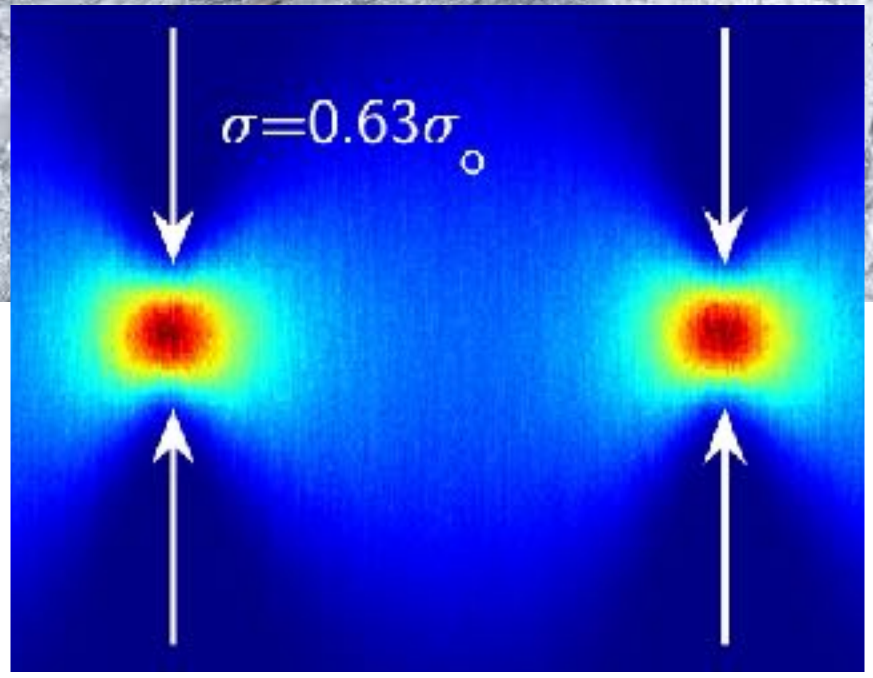
Neutrinos and Dark Matter



Reina Maruyama
Yale University

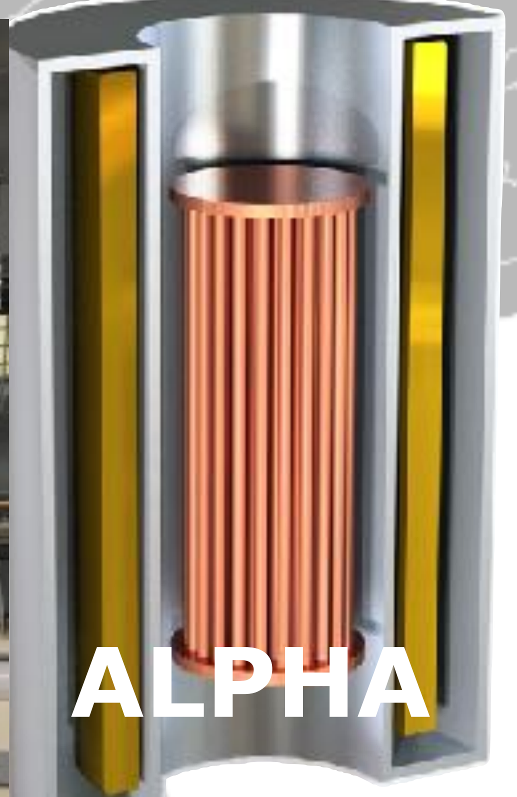
MPP Colloquium
Max Planck Institut Für Physik
May 17, 2024

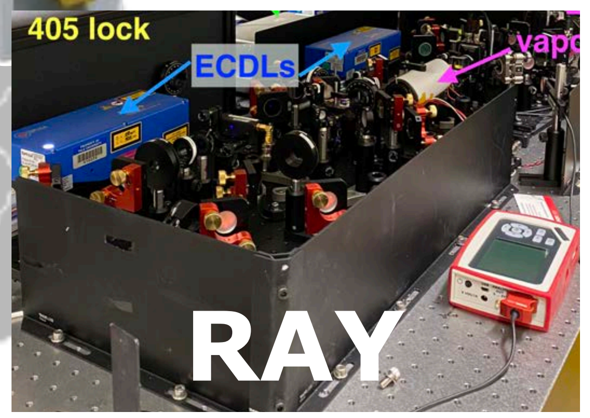
Research @ Yale

Wright Laboratory

http://maruyama-lab.yale.edu

- Physics Beyond the Standard Model of Particle Physics
- Neutrinos and Dark Matter





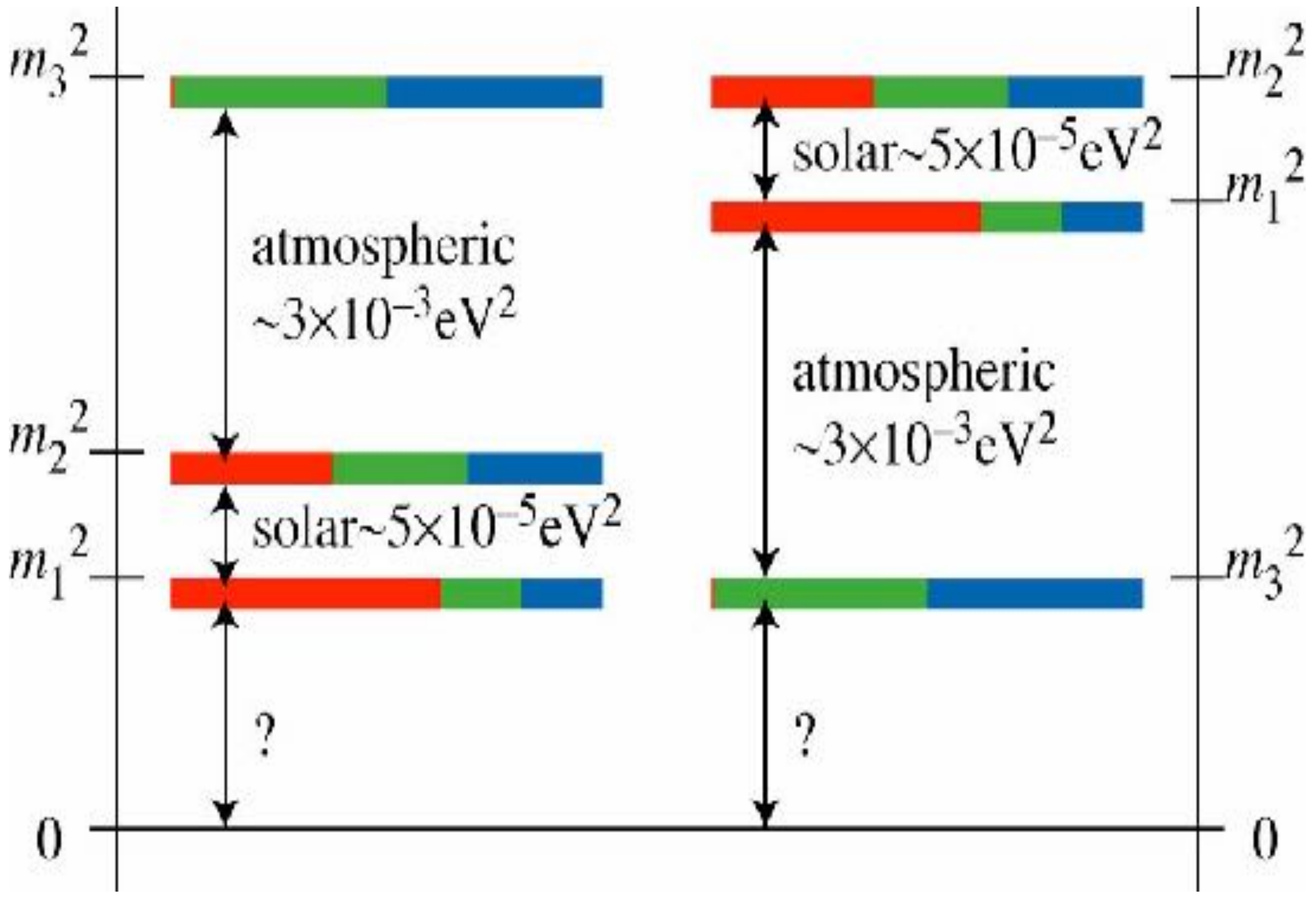
- Is DAMA really seeing dark matter?
- Does dark matter = axions?

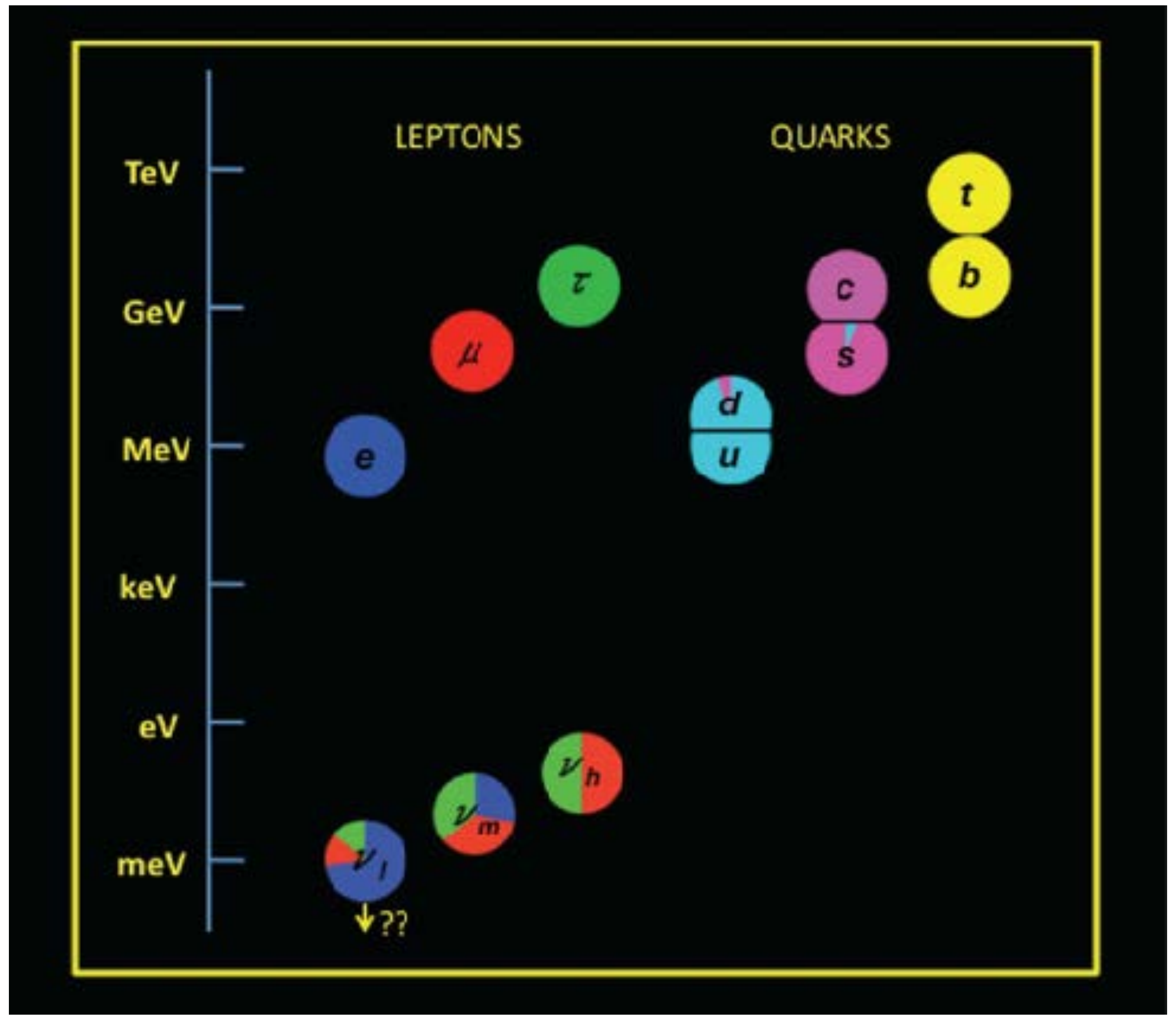
- Neutrinoless double beta decay
- Are neutrinos their own anti-particles? Are they Majorana particles?

Yale SSGF STEWARDSHIP SCIENCE GRADUATE FELLOWSHIP WISCONSIN ICECUBE PARTICLE ASTROPHYSICS CENTER U.S. DEPARTMENT OF ENERGY Office of Science ALFRED P. SLOAN FOUNDATION 1934 NSF

Neutrinoless Double Beta Decay

Open Questions

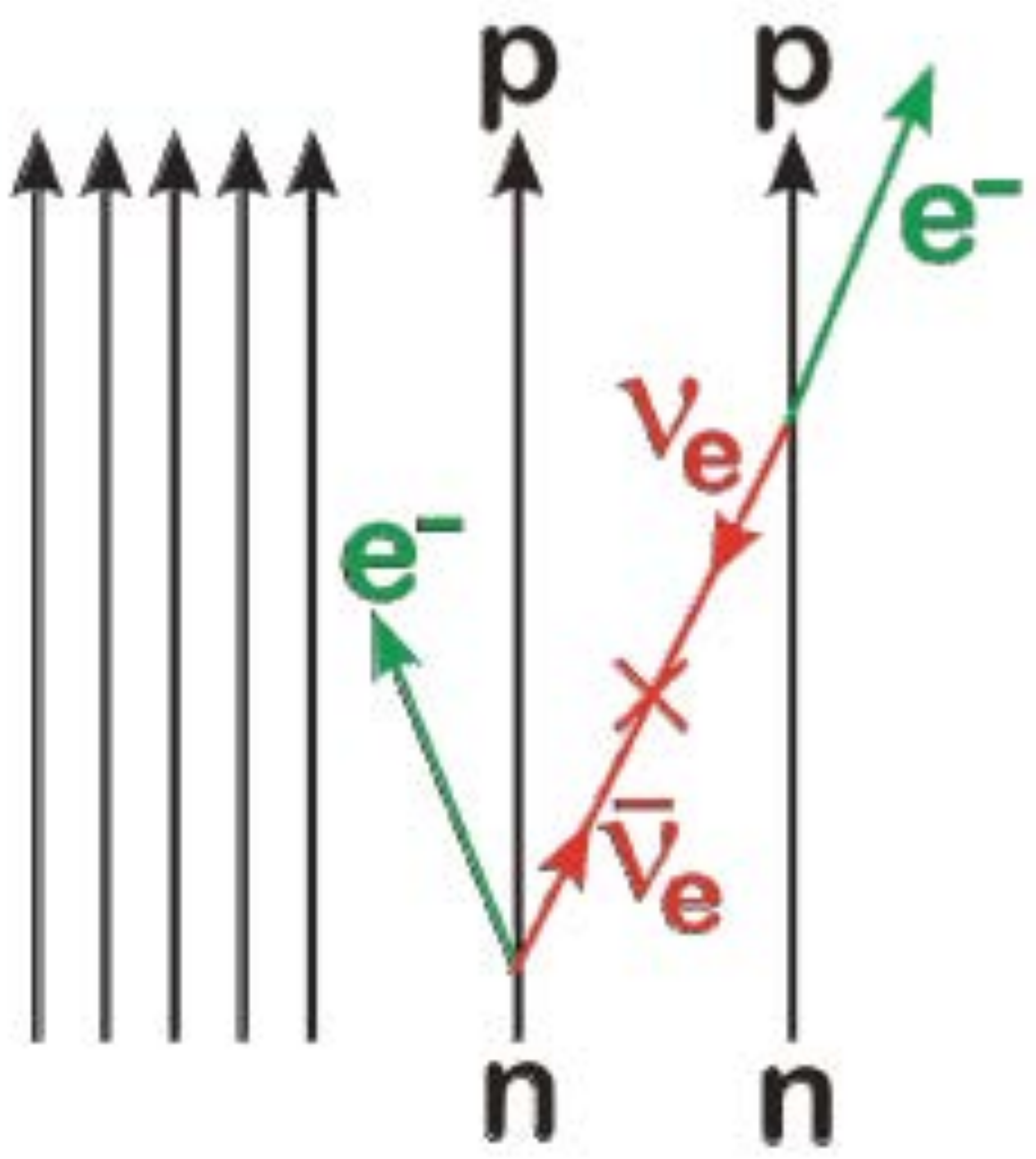




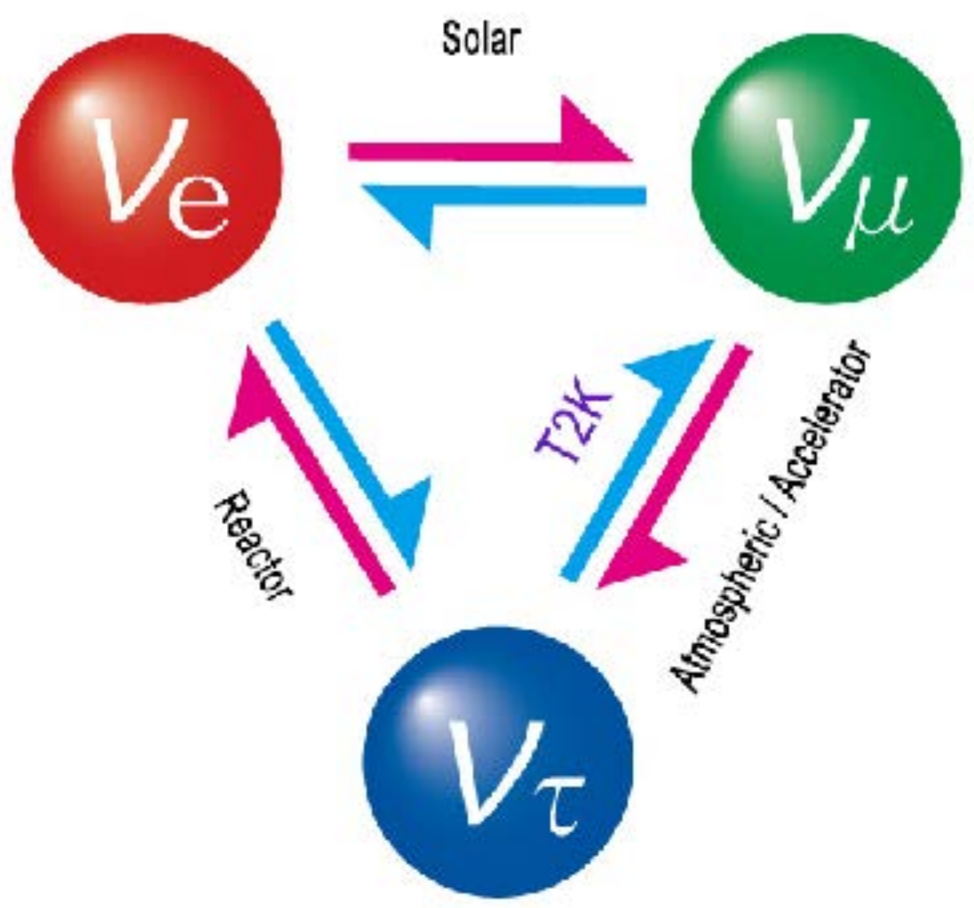
Where do neutrino masses come from?

What is the origin of leptonic mixing?

Are neutrinos their own antiparticles?



$\nu=\bar{\nu}$?

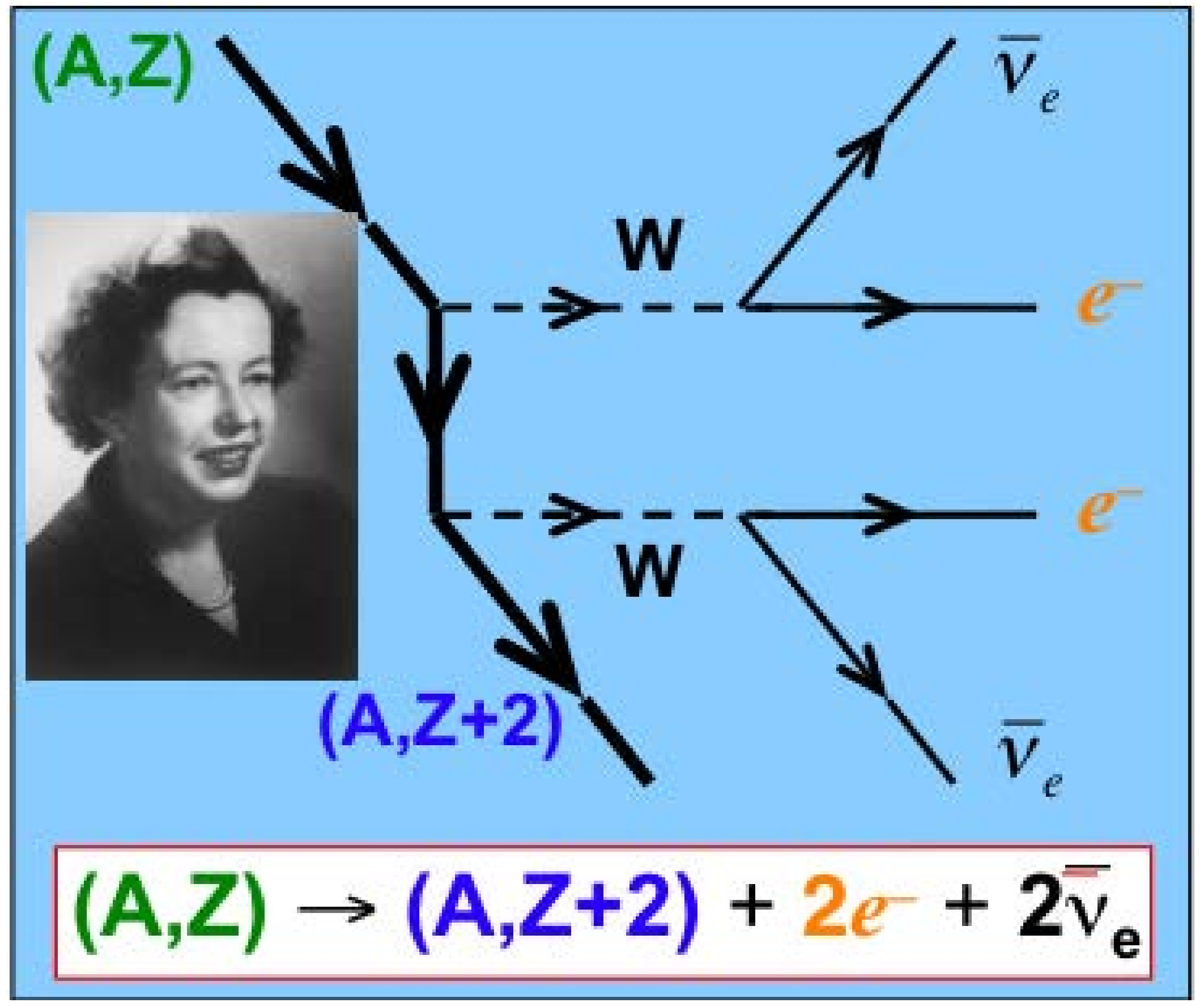


Major discoveries ahead

Understanding Neutrino Mass from Double Beta Decay

Nuclei as a laboratory to study lepton number violation at low energies

$2\nu\beta\beta$



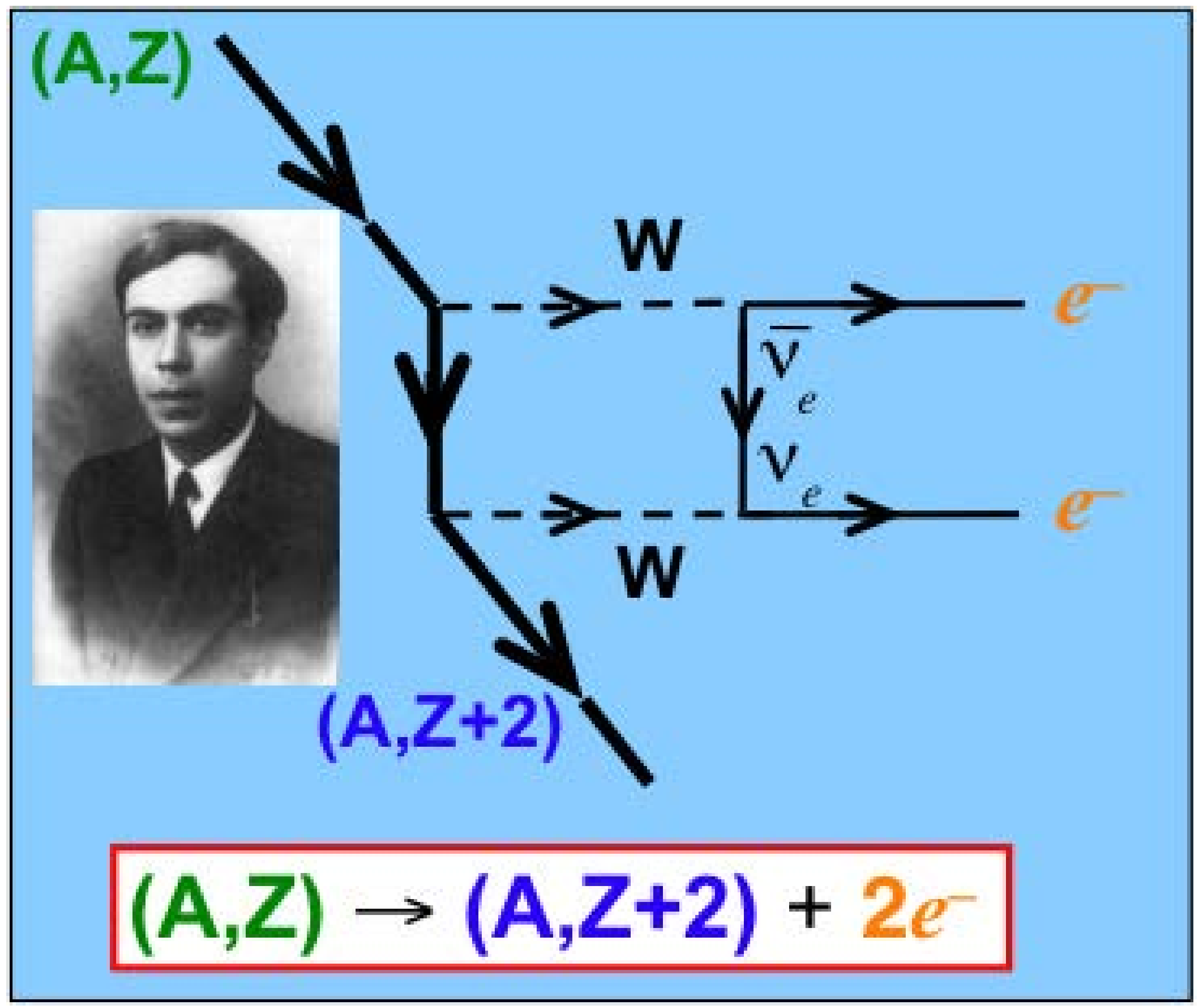
Proposed in 1935 by Maria Goeppert-Mayer

Observed in several nuclei

$T_{1/2} \sim 10^{19} - 10^{21}$ yrs

$$\Gamma_{2\nu} = G_{2\nu} \, | M_{2\nu} |^2$$

$0\nu\beta\beta$



Proposed in 1937 by Ettore Majorana

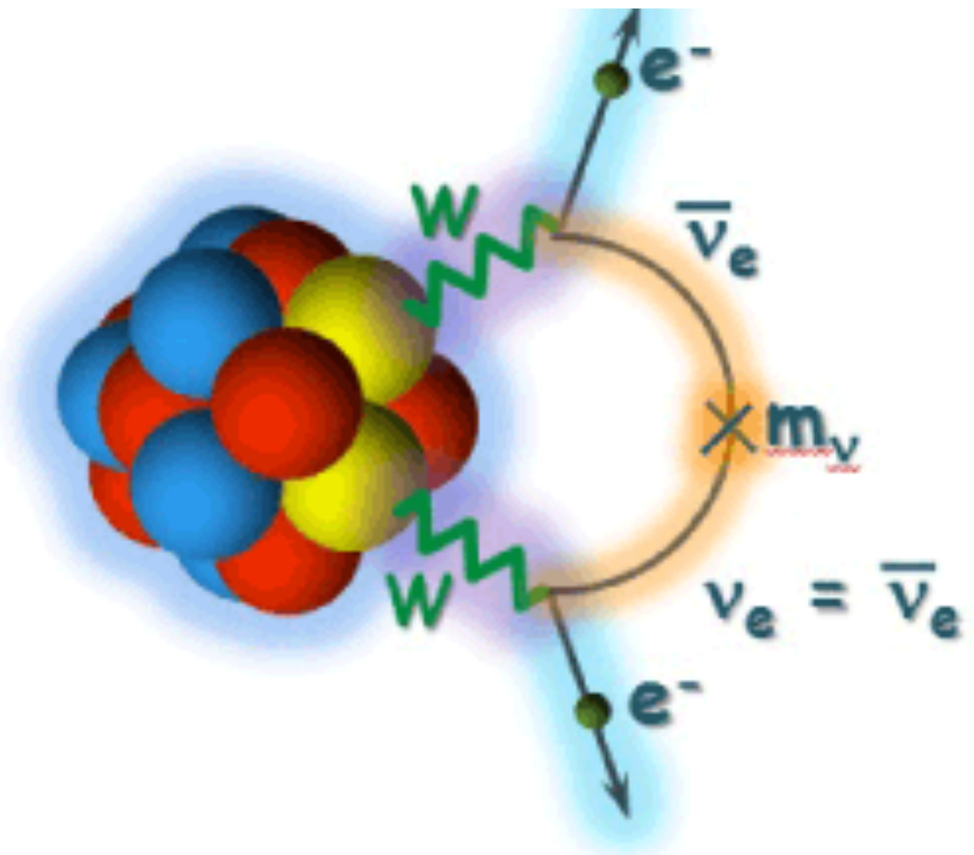
Not observed yet

$T_{1/2} \geq 10^{25}$ y

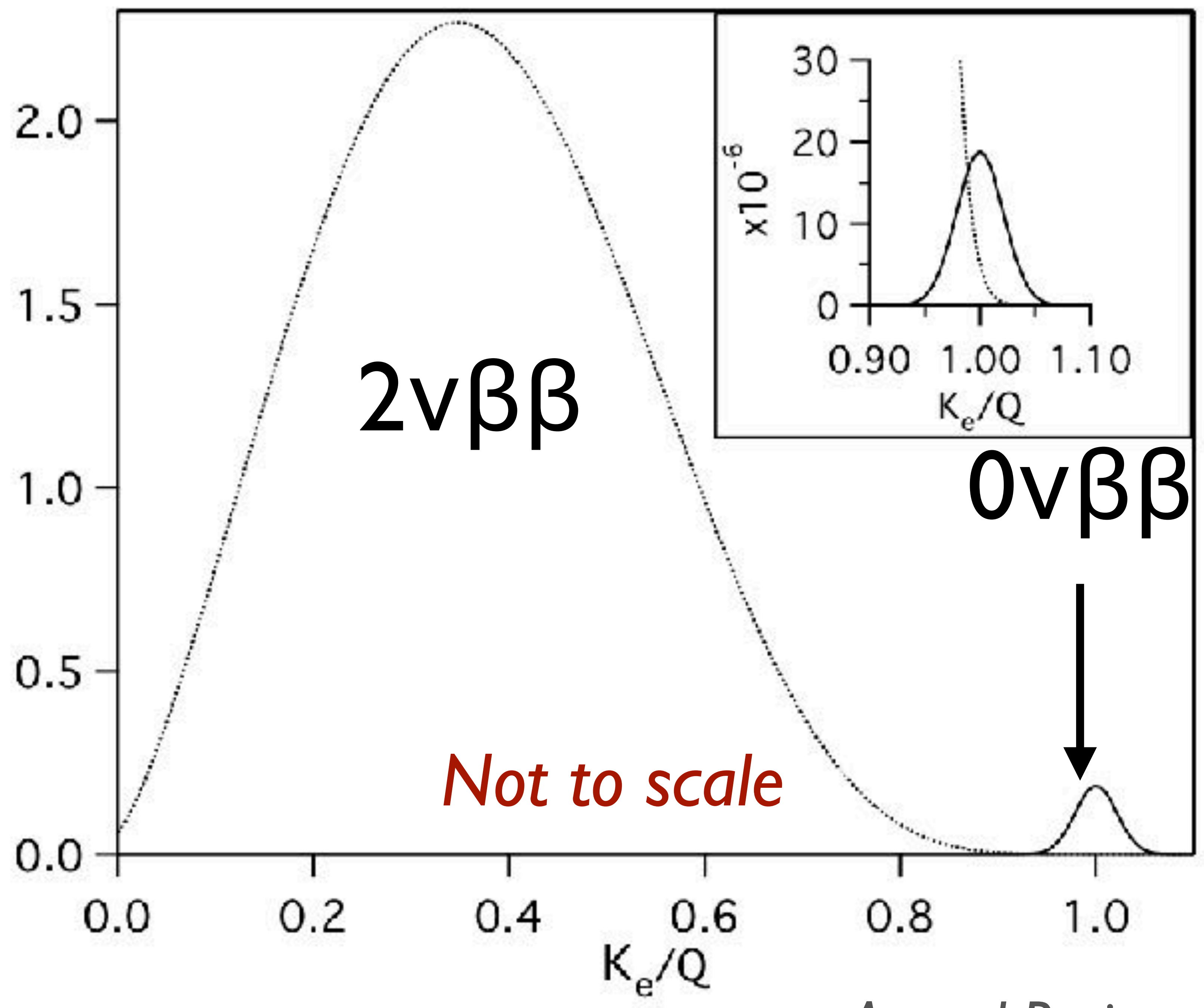
$$\Gamma_{0\nu} = G_{0\nu} \, | M_{0\nu} |^2 \left\langle m_{\beta\beta} \right\rangle^2$$

$0\nu\beta\beta$ would imply
- lepton number non-conservation
- Majorana nature of neutrinos

Neutrinoless Double Beta Decay (0νββ)

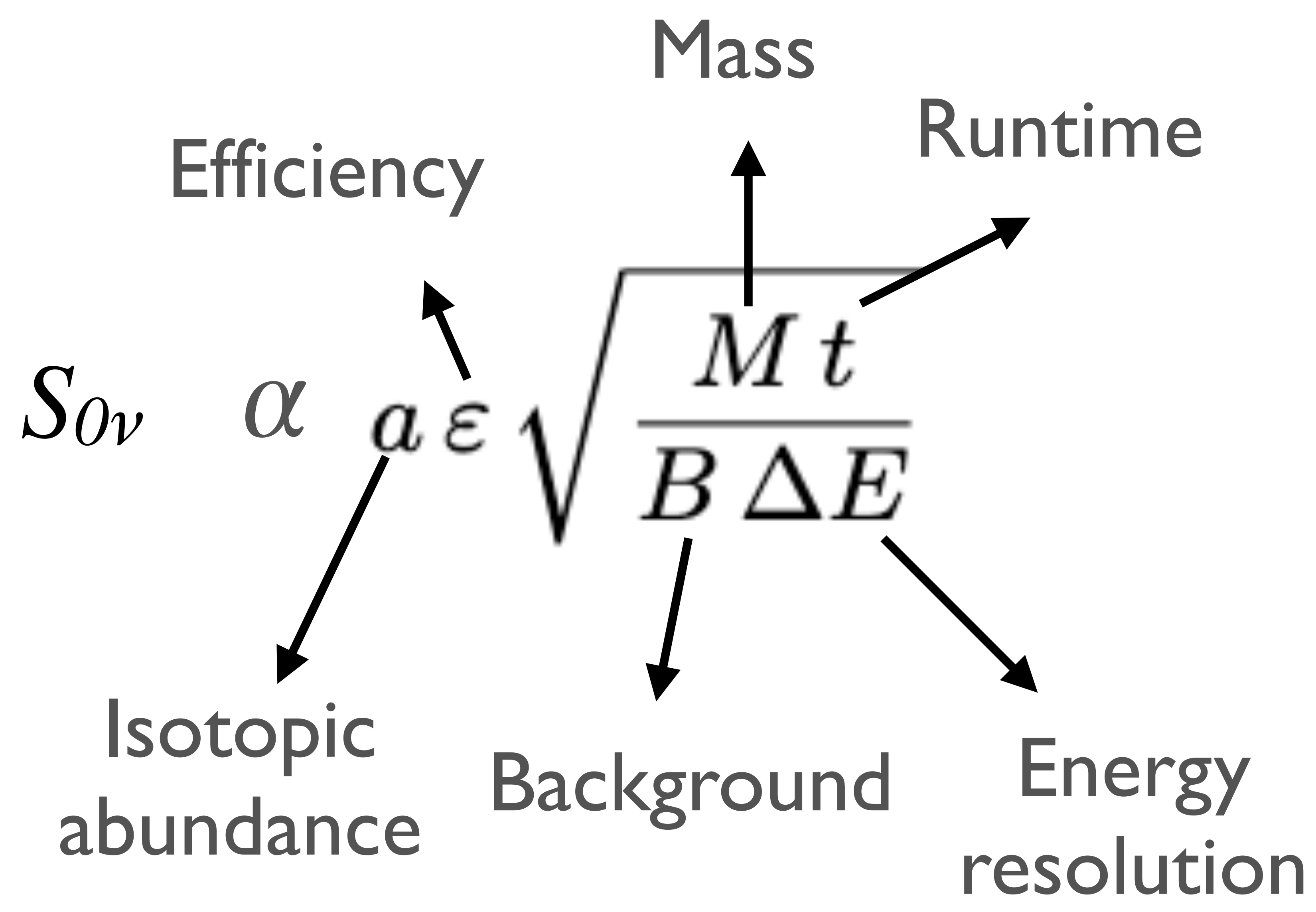


Neutrinoless
double beta decay



Annual Reviews: 52:115-151

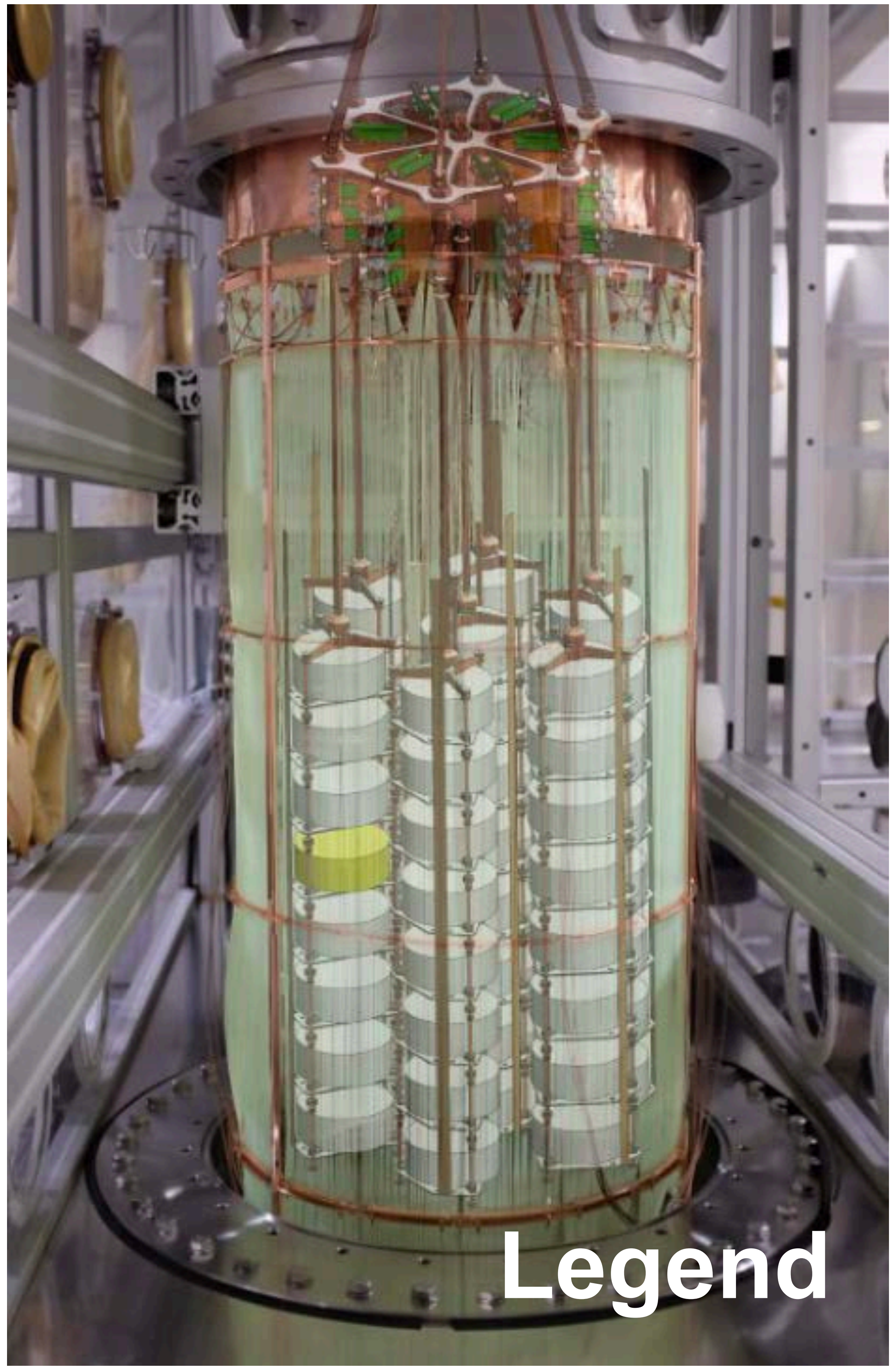
Sensitivity

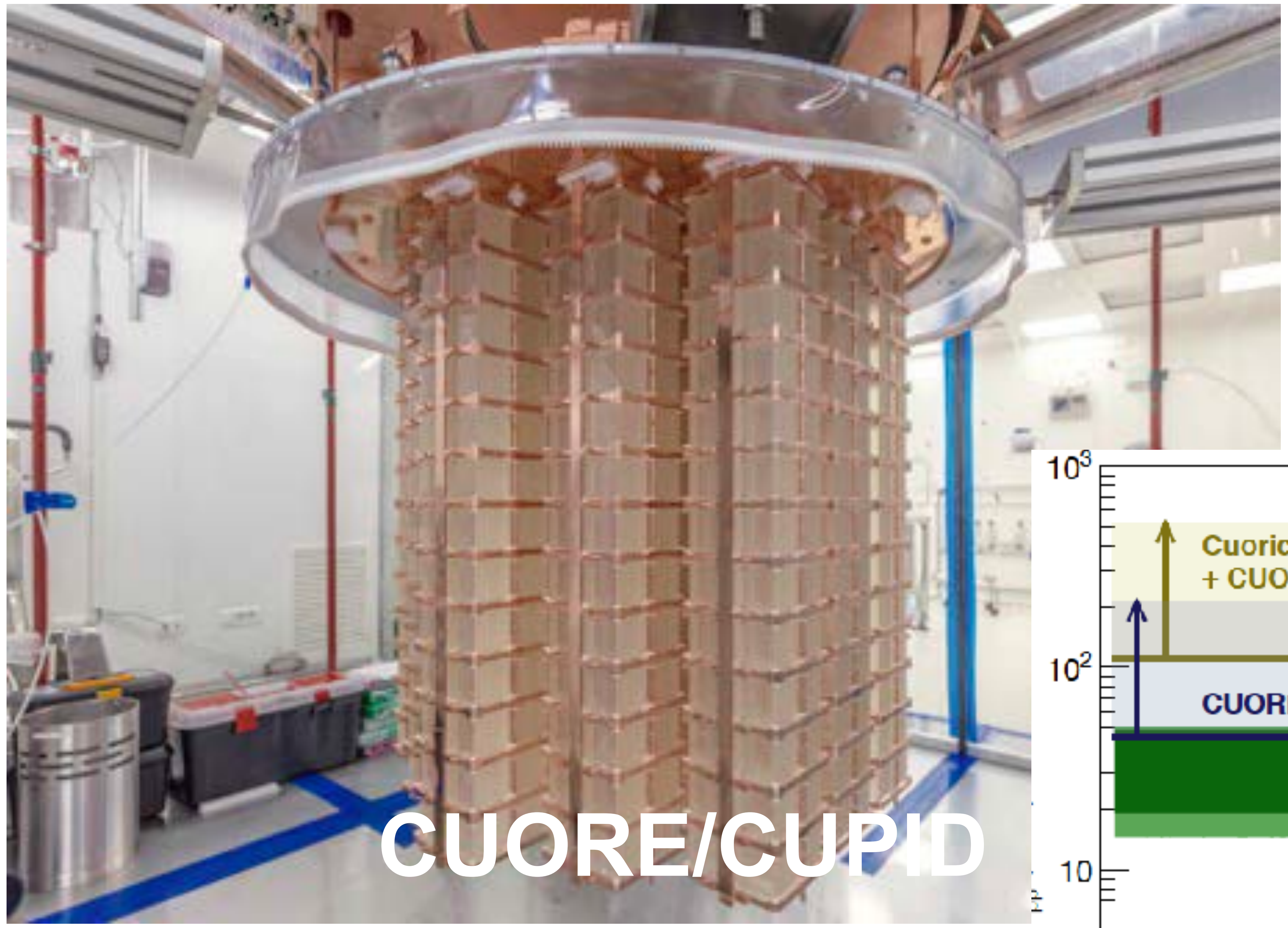


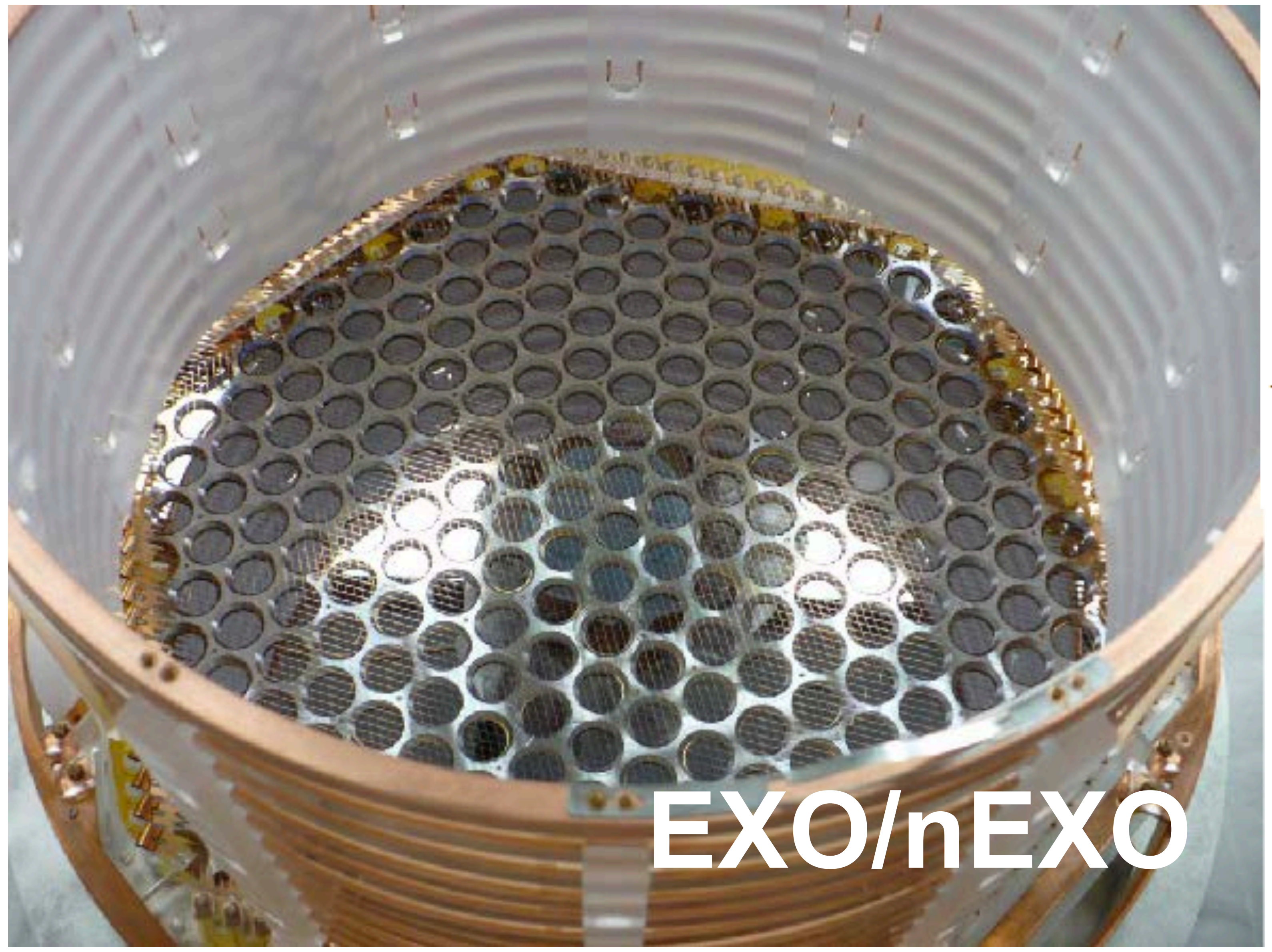
Search for peak search at the Q value of the decay

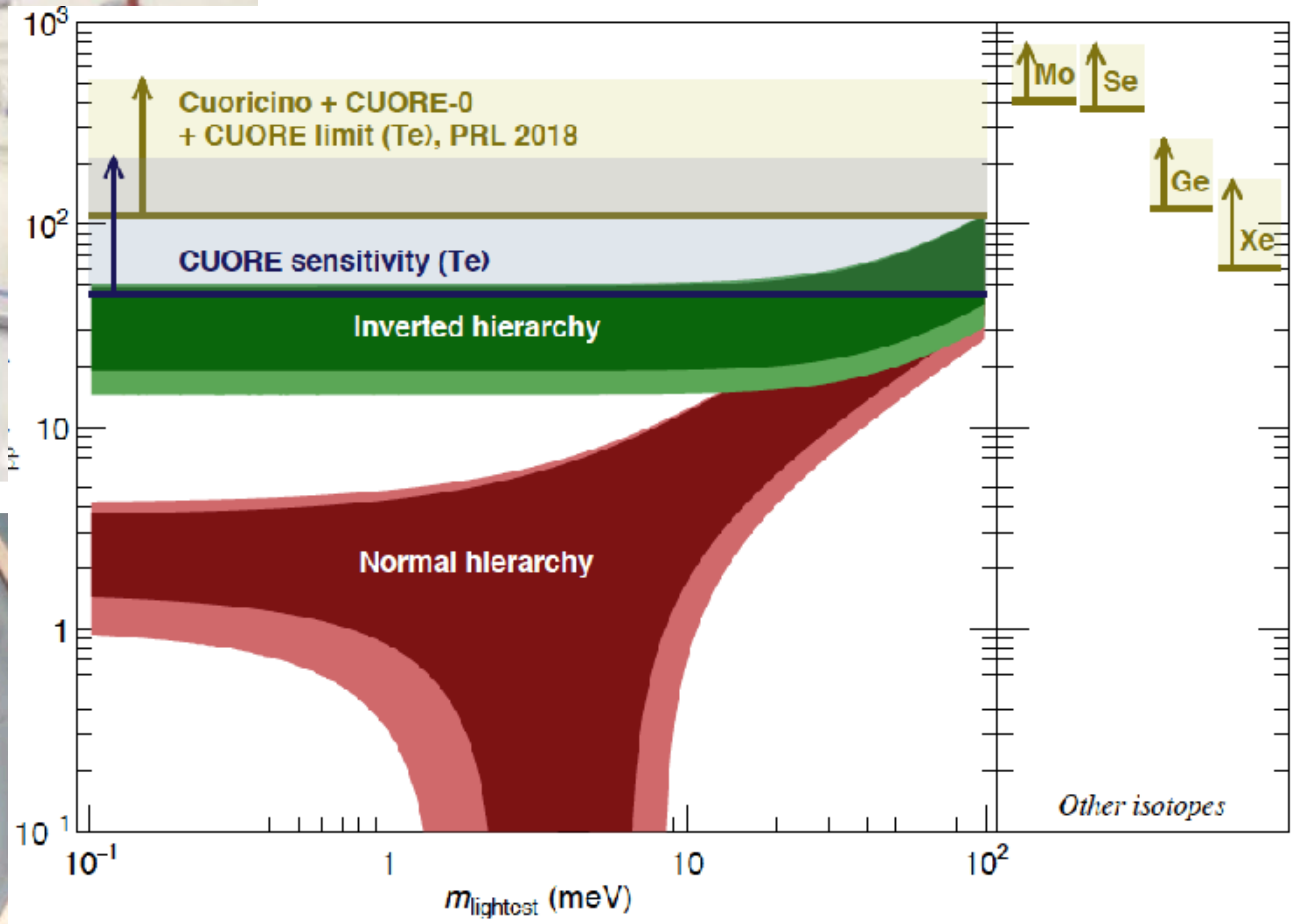
Energy peak is necessary and sufficient signature to claim a discovery.
Additional signatures from signal topology etc

0νββ Searches



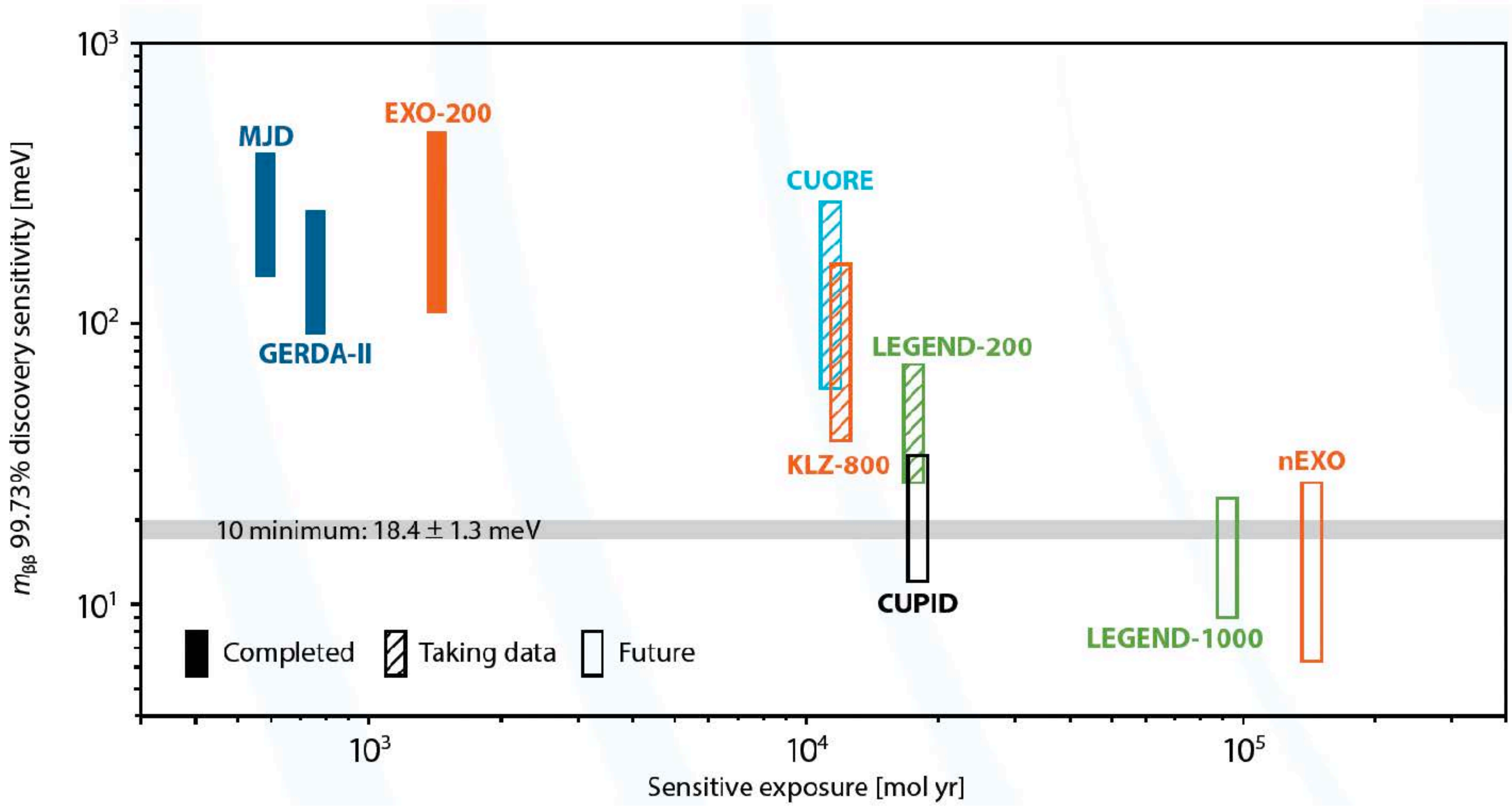






pushing limits towards inverted hierarchy

Discovery Sensitivity of CUORE and CUPID



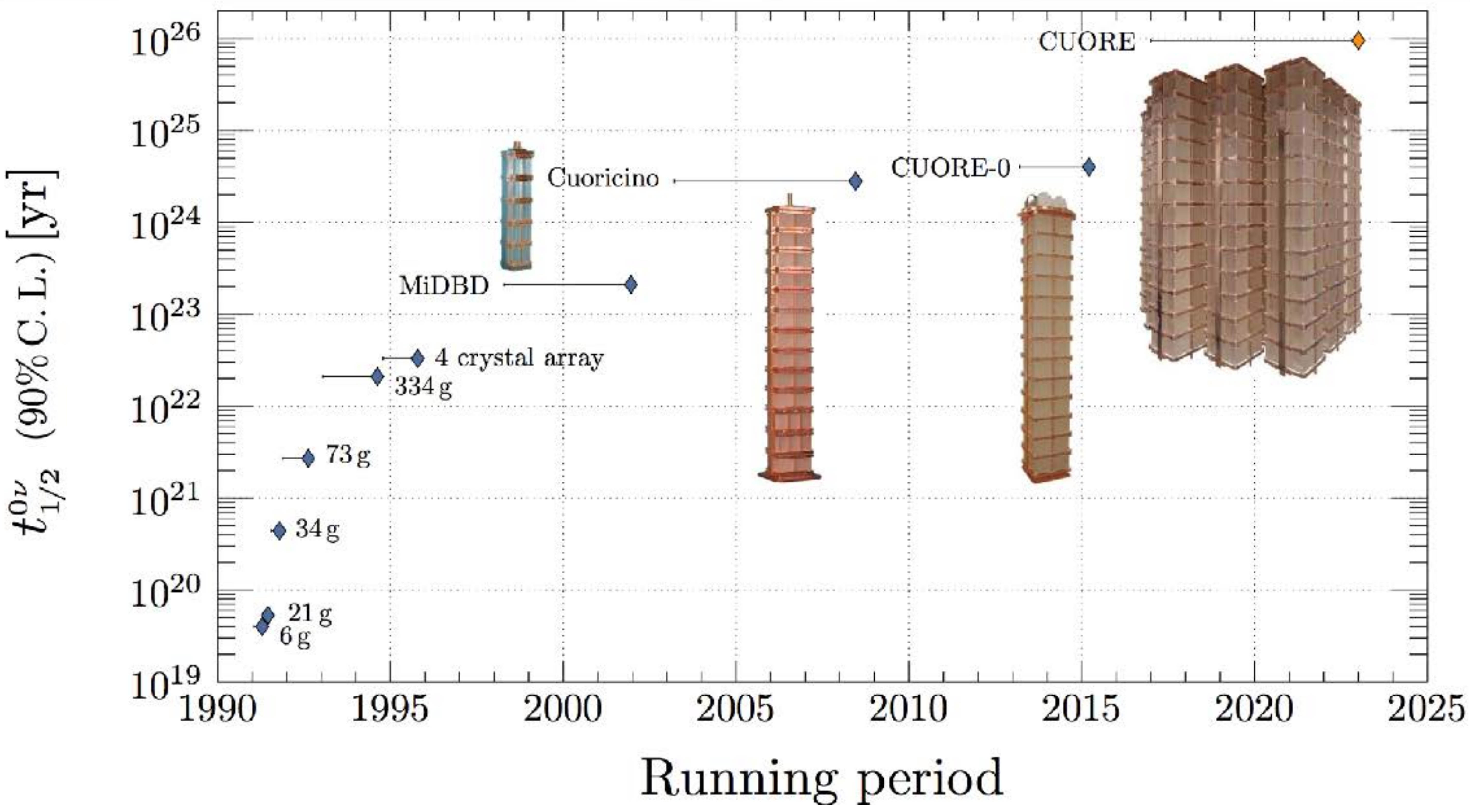
2023 Nuclear Physics Long Range Plan

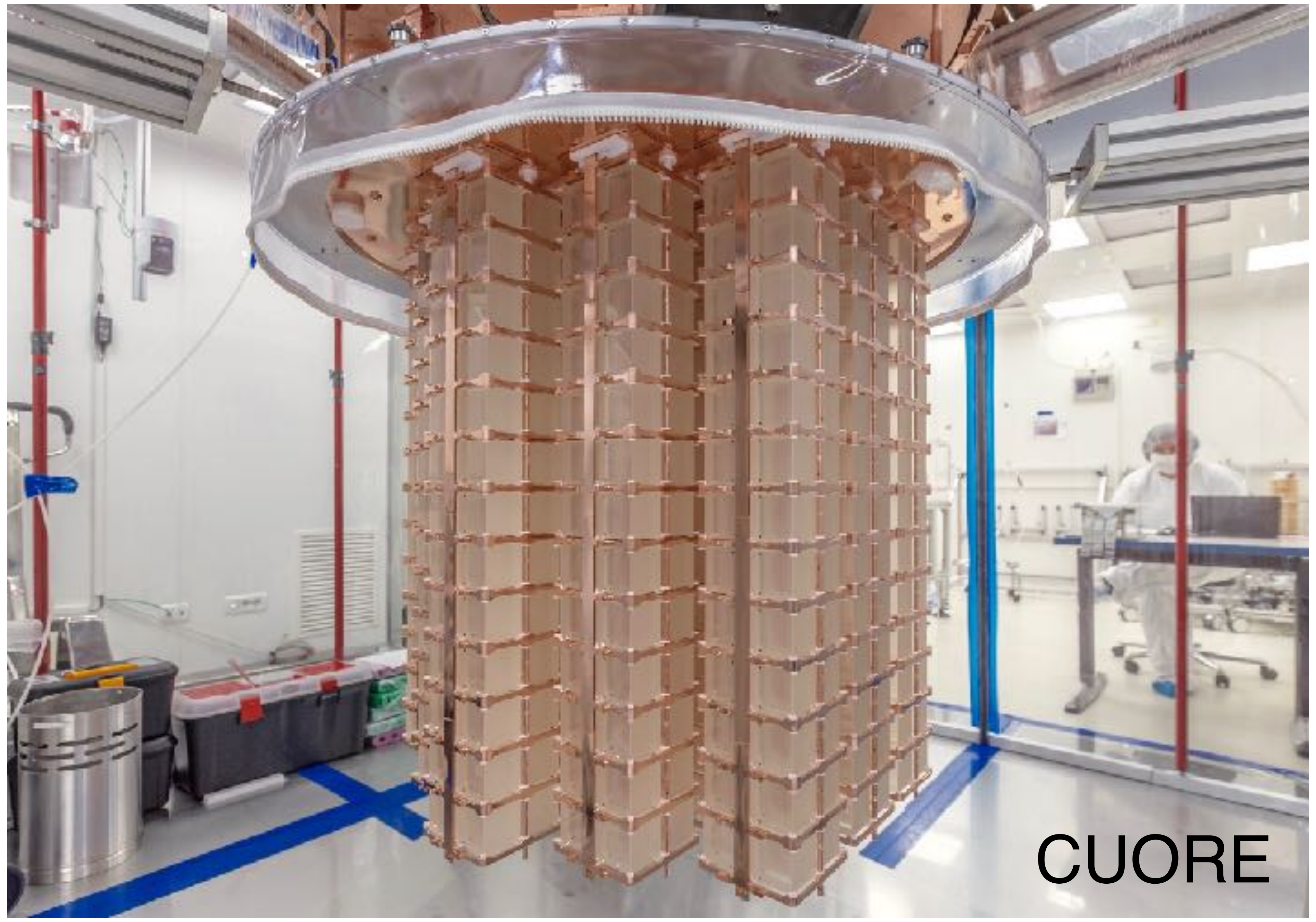
CUORE → CUPID Collaboration

We would like to acknowledge support from the U.S. Department of Energy Office of Science contract No. DE-SC0019368 and DE-SC0012654 and the National Science Foundation Graduate Research Fellowship Program under Grant No. DGE-1752134.

History of Bolometer Experiments

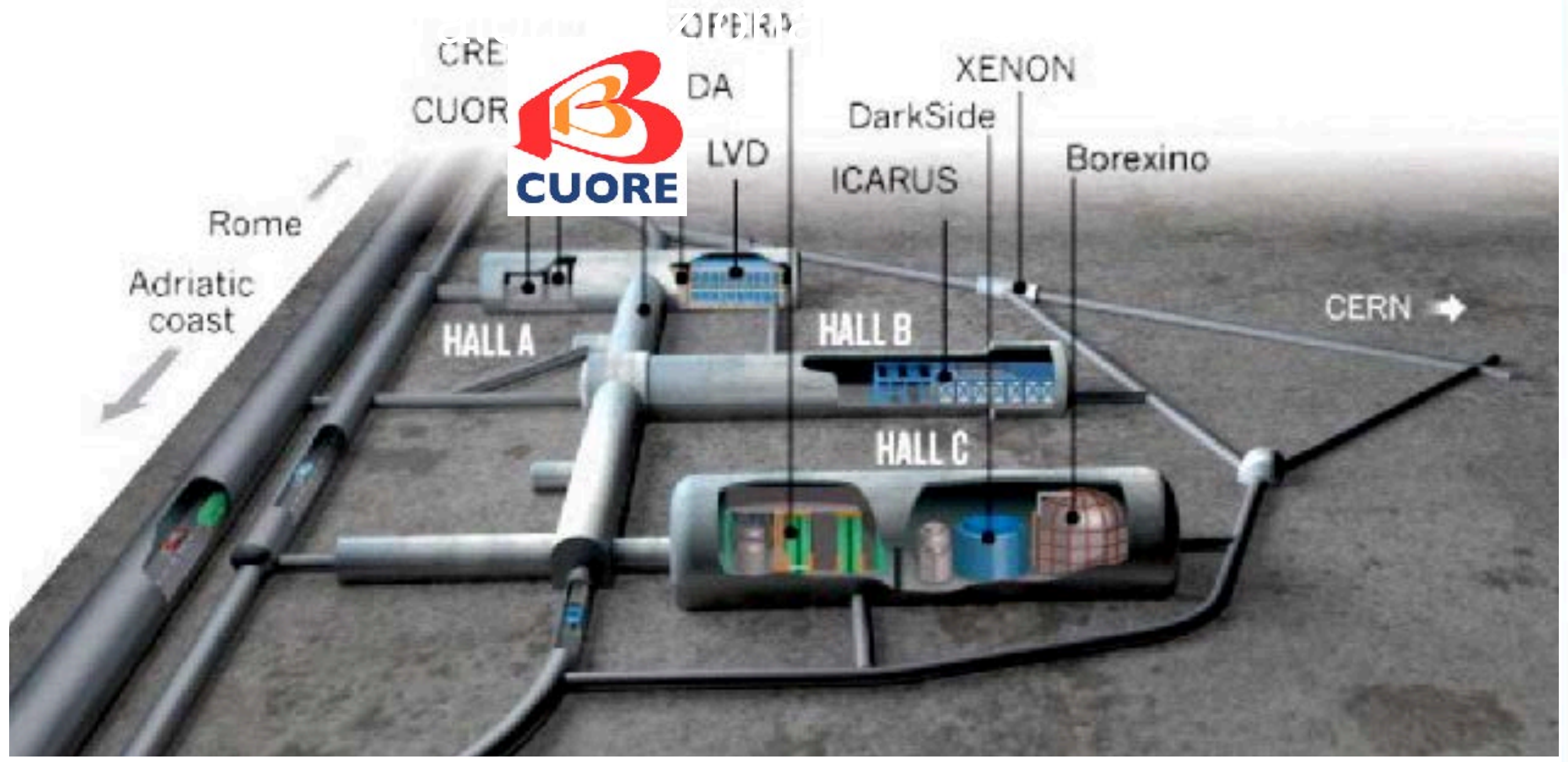
CUORE is in a long series of experiments: a few grams to 742 kg of detector material

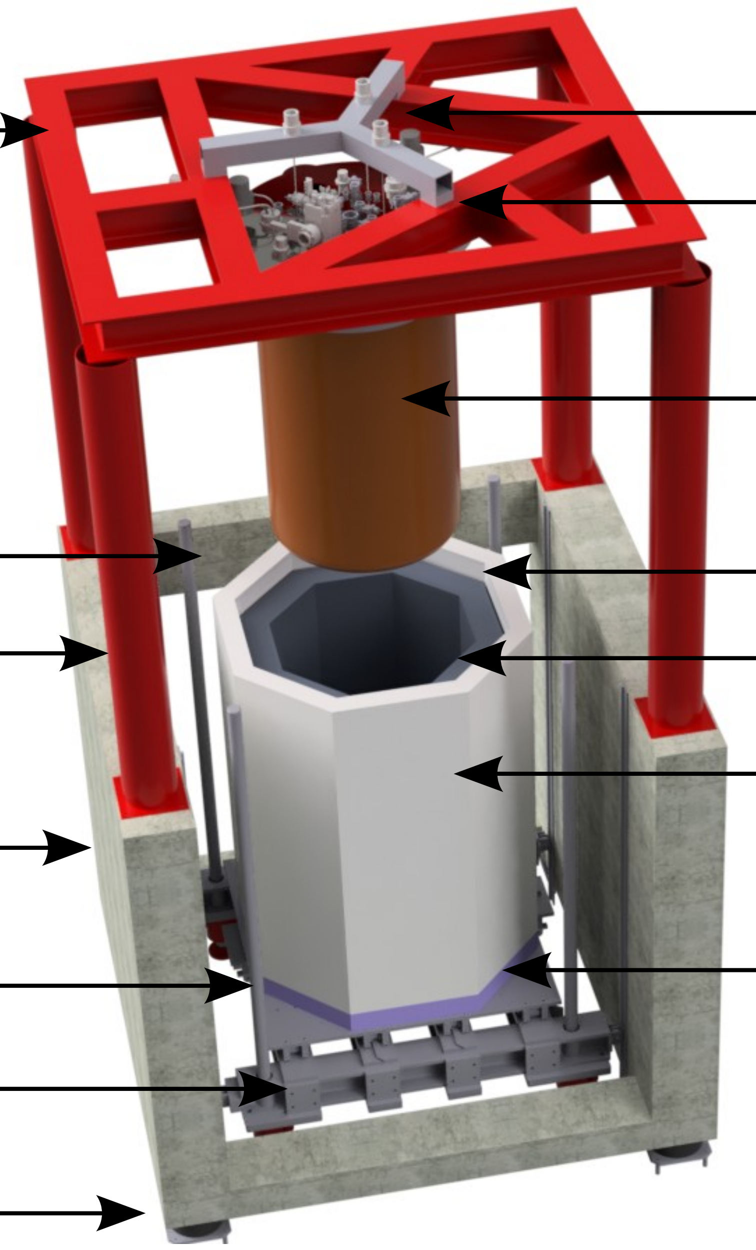


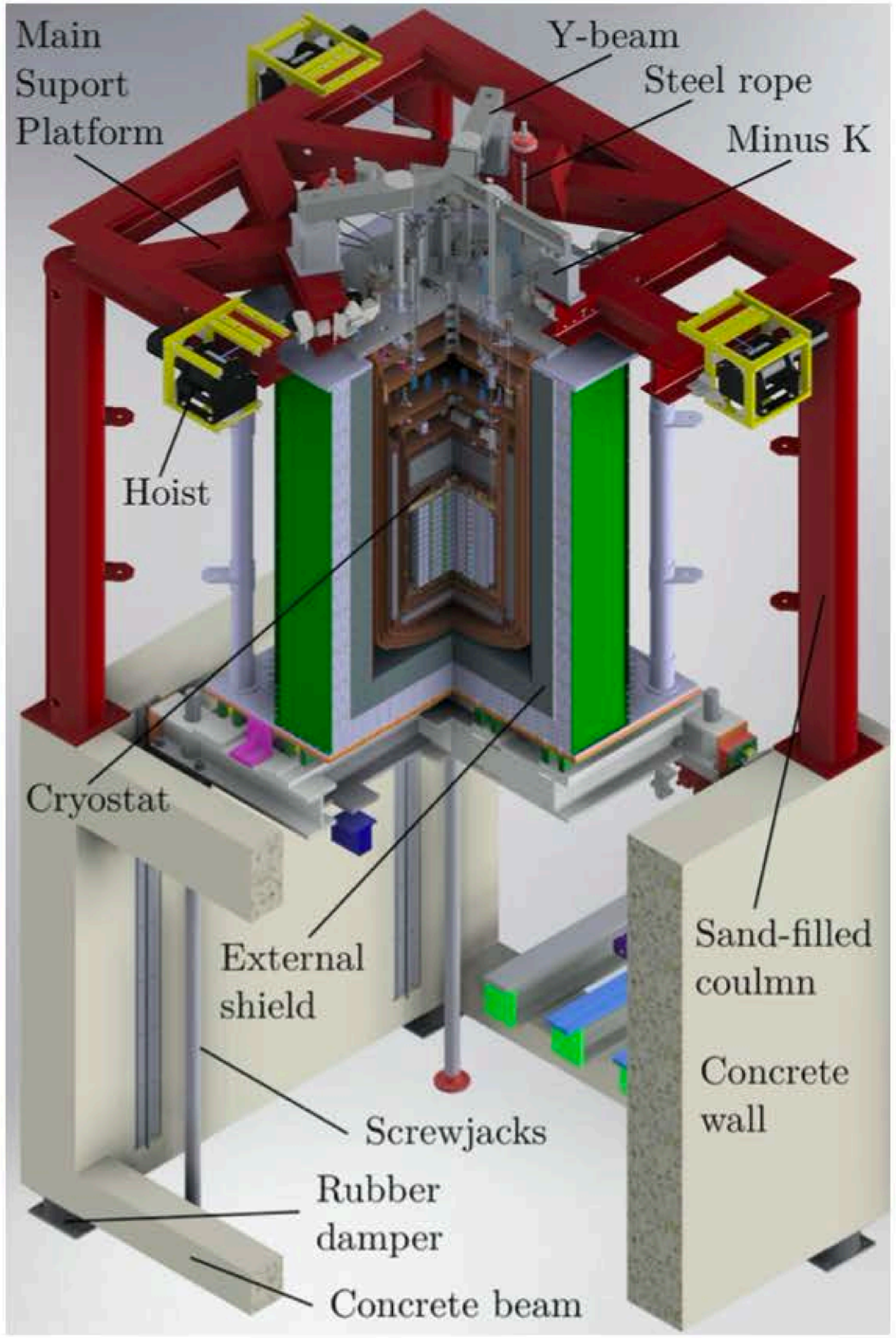


Brofferio, C. and Dell'Oro, S., Rev. Sci. Inst. 89, 121501 (2018)

Experimental Site







Unique cryogenic infrastructure.

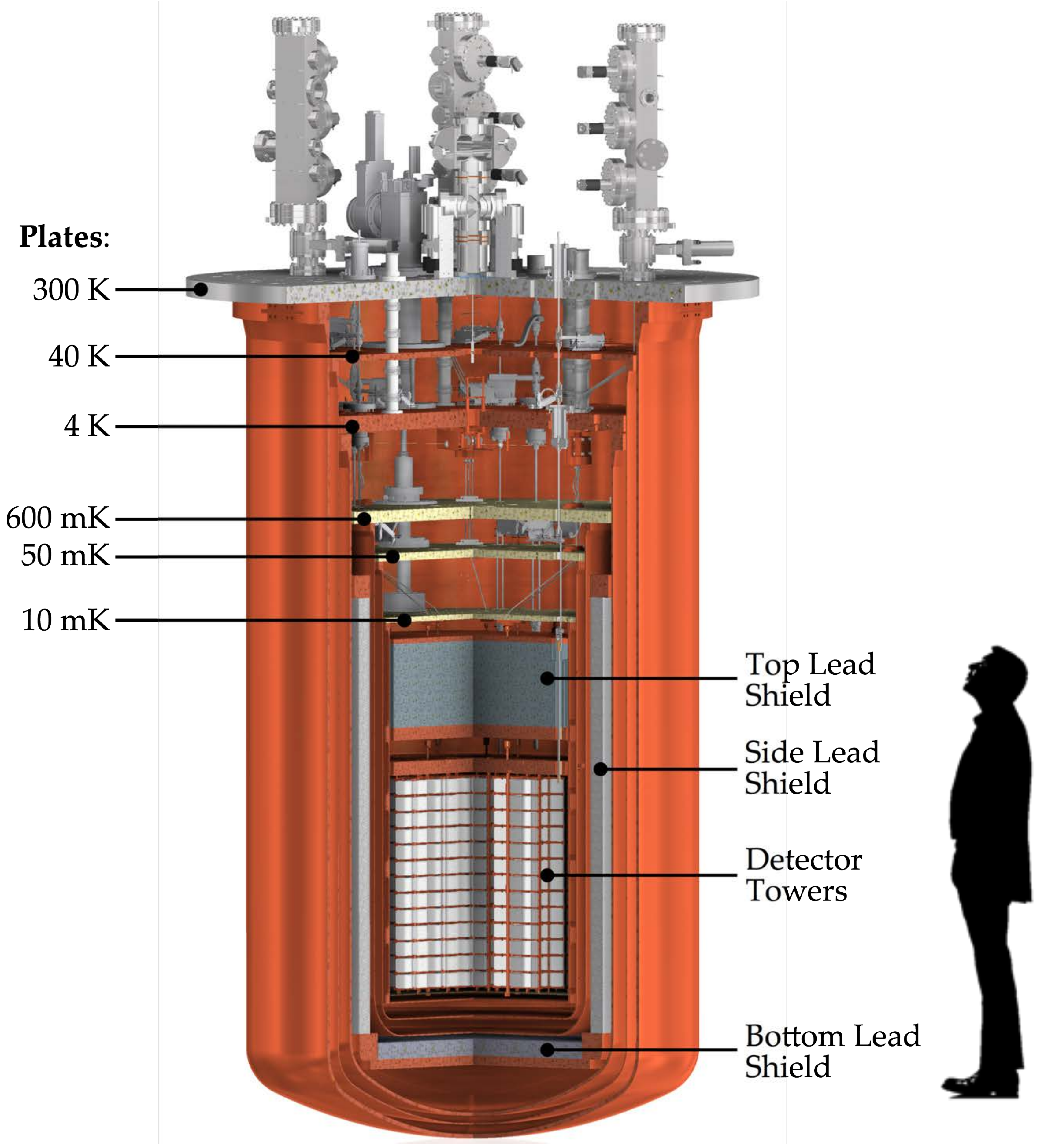
CUORE - *Coldest Cubic Meter in the Known Universe*

CUORE cryostat

- Multistage cryogen-free
- cryostat
- Cooling systems: fast cooling
- system, Pulse Tubes (PTs), and
- Dilution Unit (DU)
- ~15 tons @ < 4 K
- ~ 3 tons @ < 50 mK
- Mechanical vibration isolation
- Active noise cancelling

CUORE (passive) shielding

- Roman Pb shielding in cryostat
- External Pb shielding
- H_3BO_3 panels + polyethylene

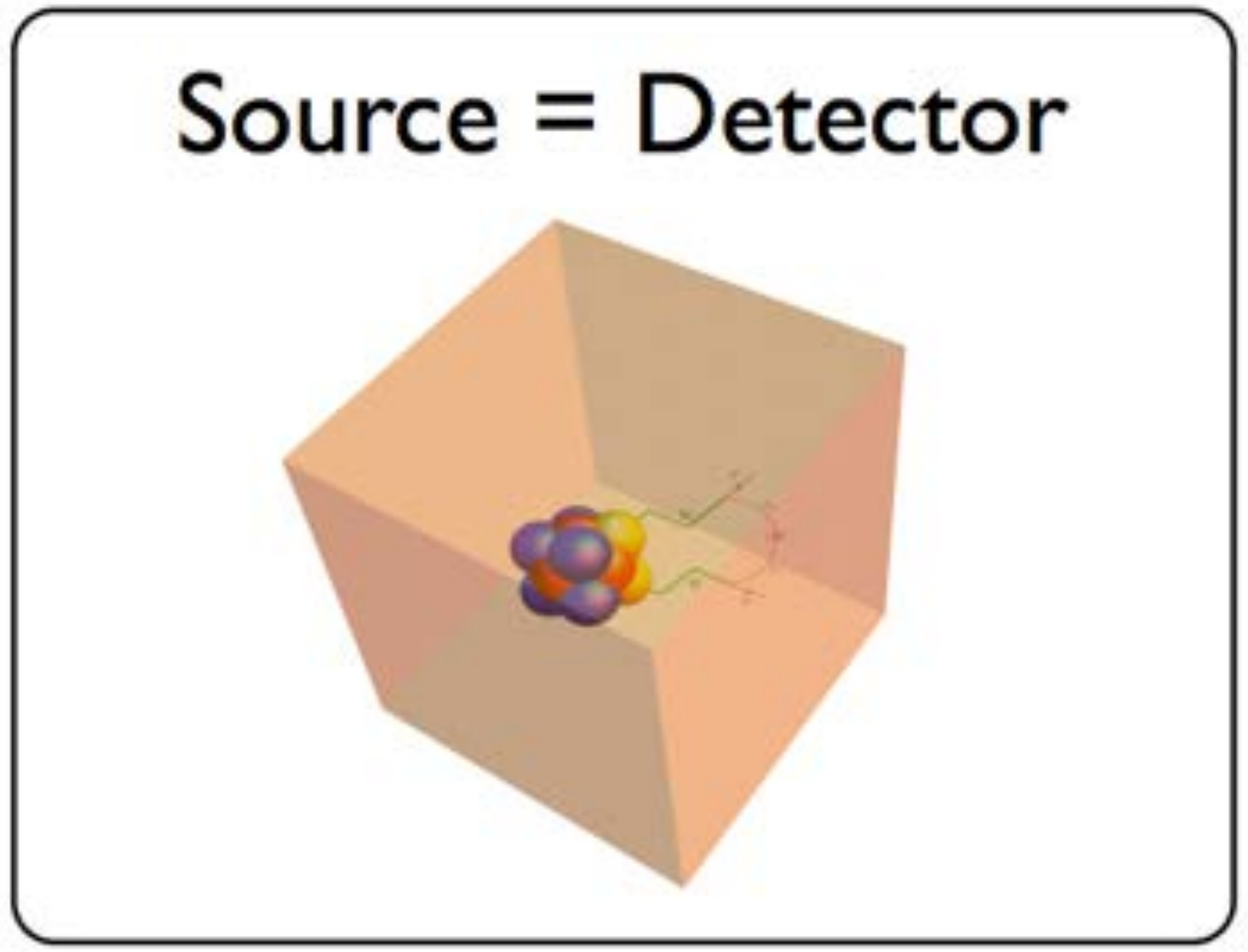


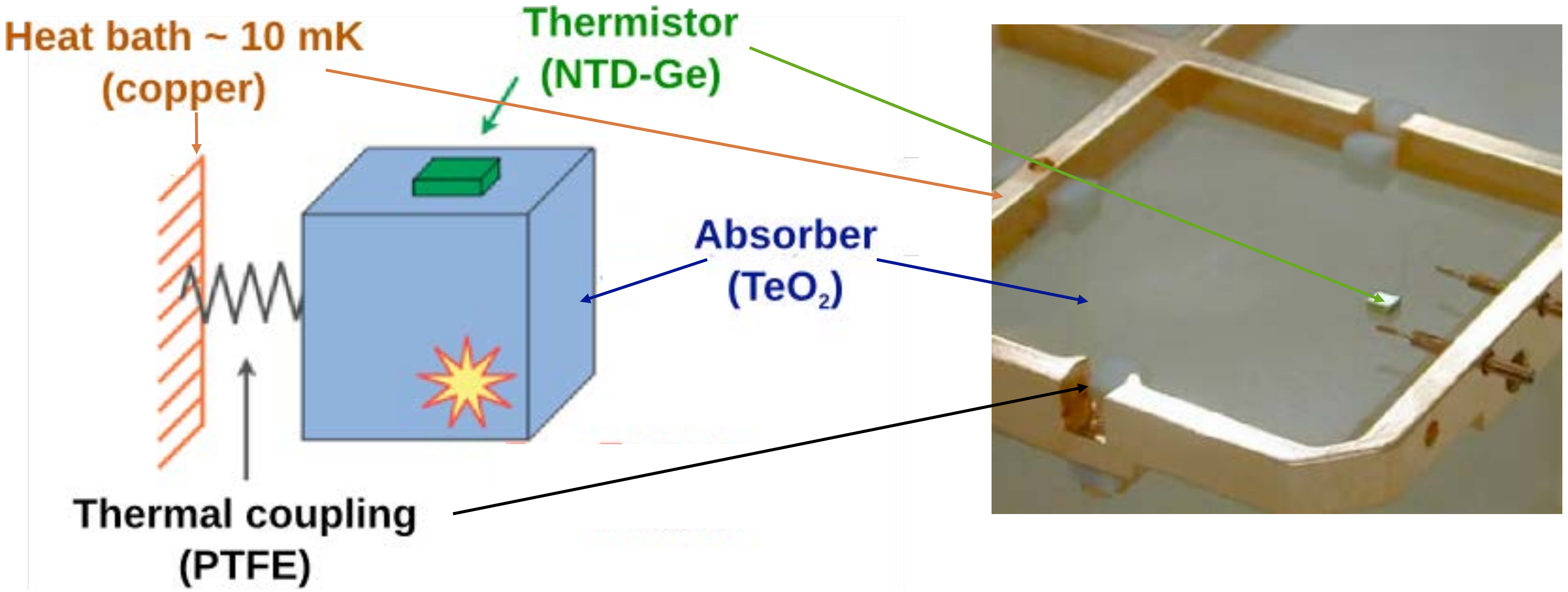
Roman lead ingots

70 tonne of lead, 7 tonne of cold lead

Careful material selection: Ancient Lead and low radioactive copper

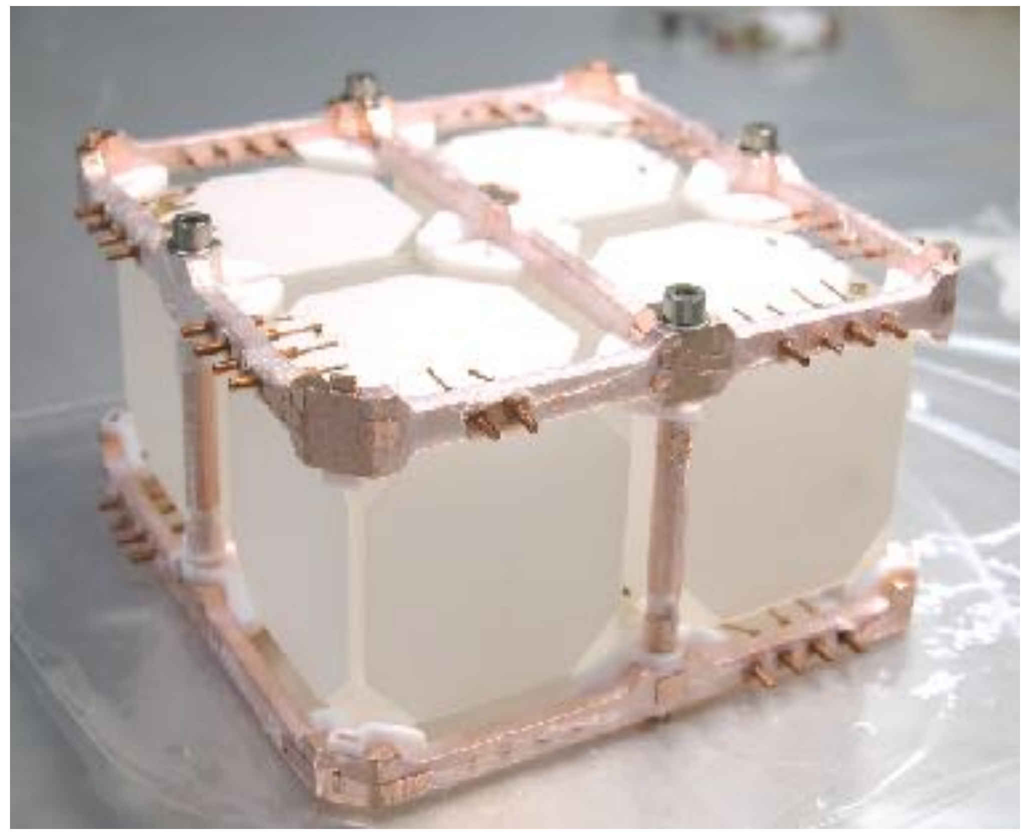
Bolometric Search for 0νββ

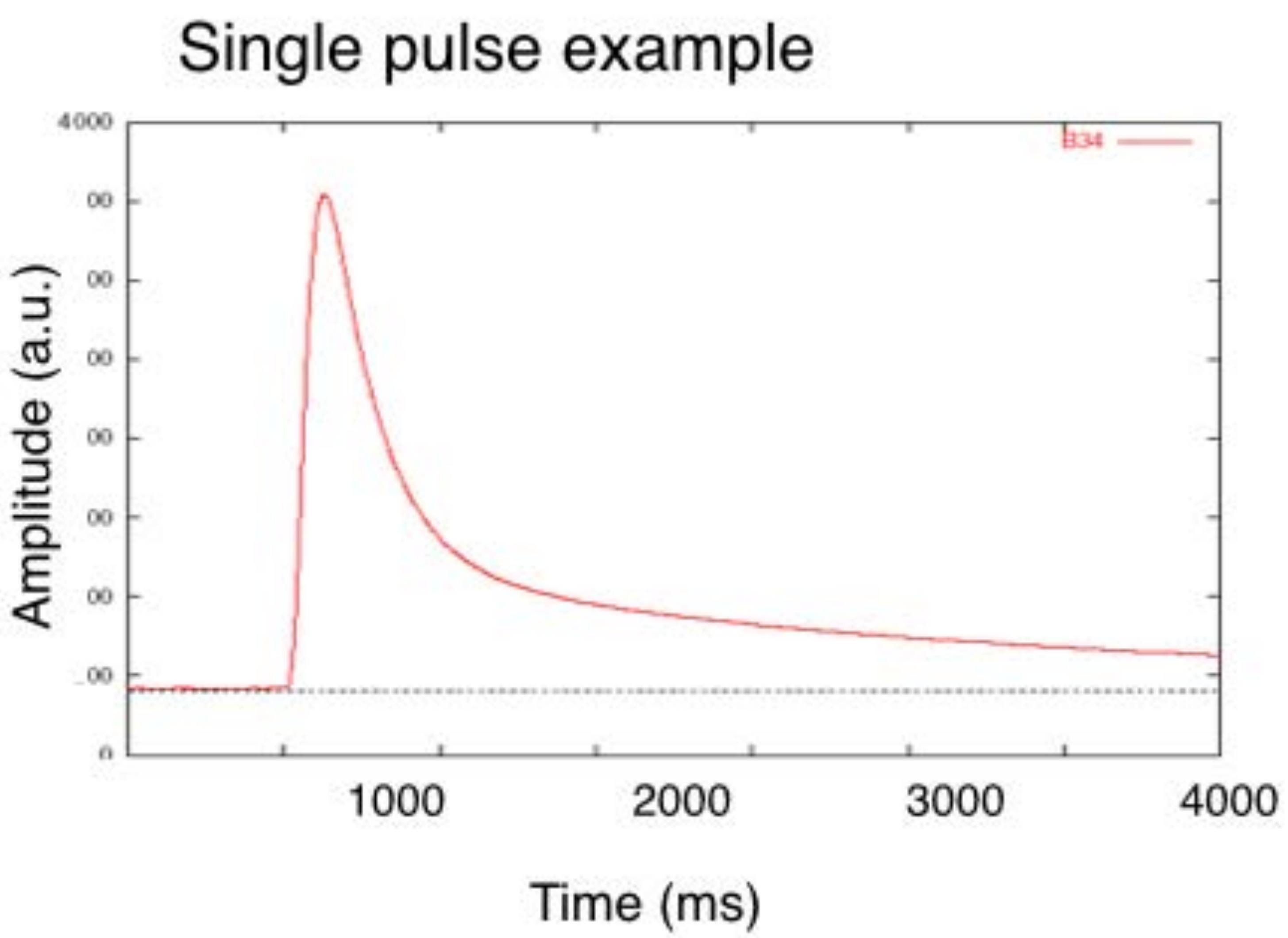


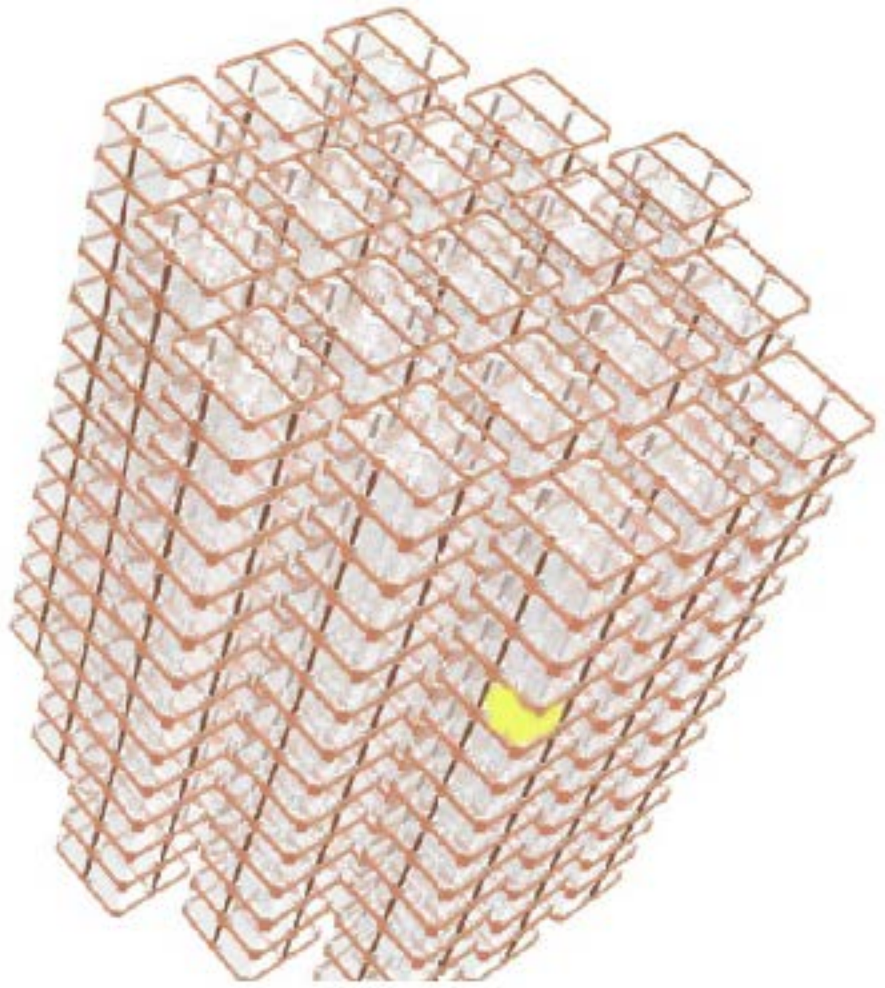


$^{130}Te \rightarrow ^{130}Xe + 2e^-$

Q = (2527.518 +/- 0.013) keV







single hit, monochromatic event

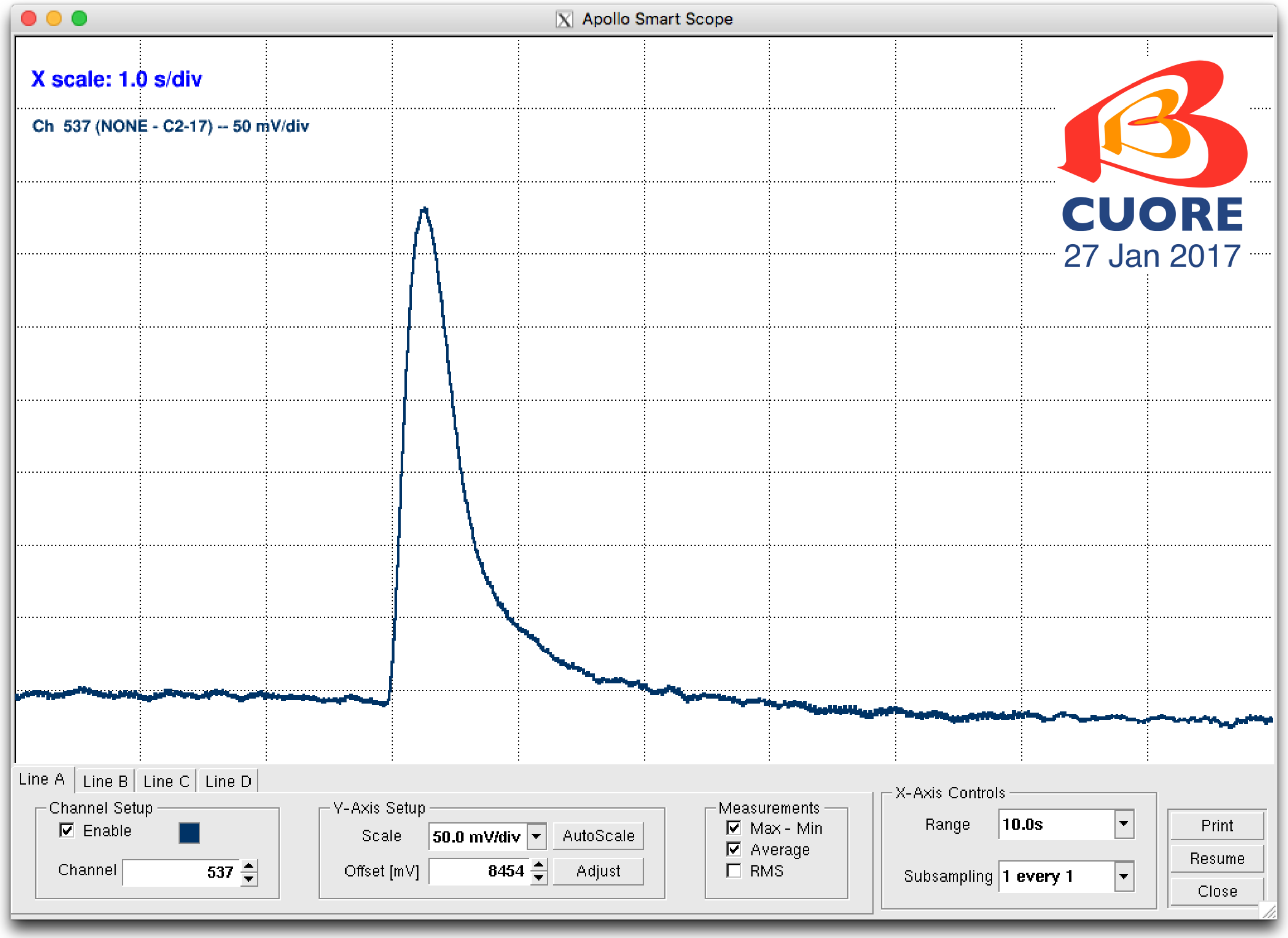
CUORE Detector

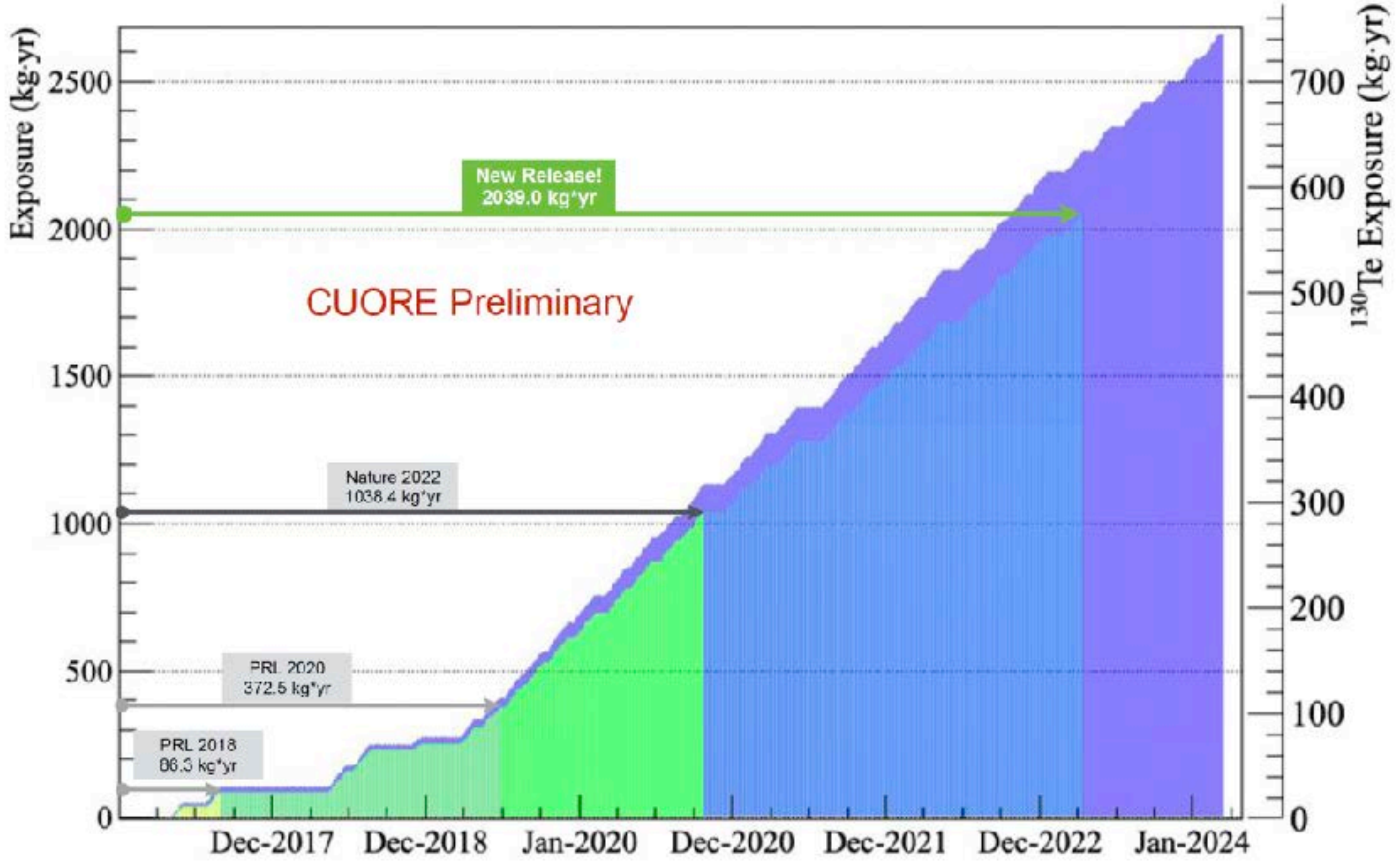
CUORE Data

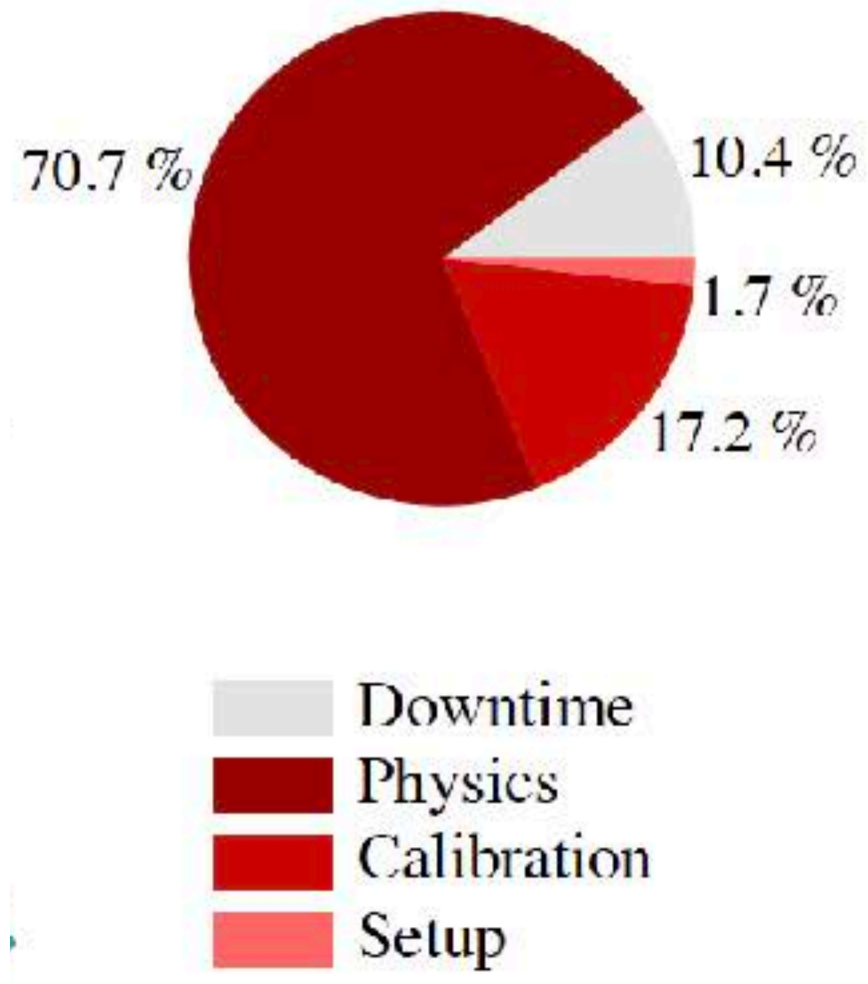
Cooldown tarted in Dec 2016

~1 month cool down

First data in Jan 2017







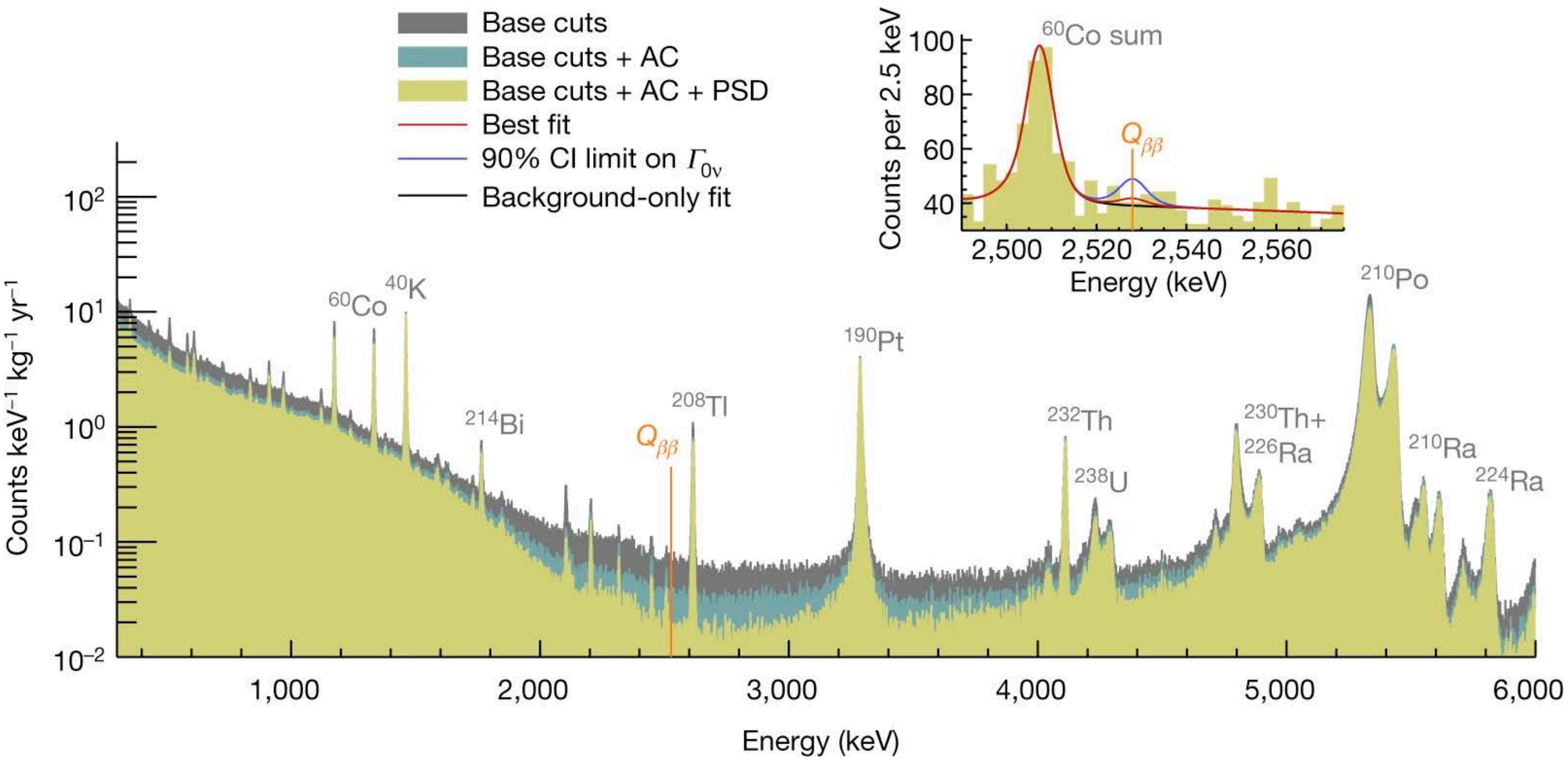
CUORE Data Taking

- Stable operations and data taking
- 984/988 channels active (> 99%),
- uptime ~90%
- >2.2 ton-yr high-quality data collected

CUORE Run Plan

Goal: 3 ton-yr in 2025

CUORE 1-tonne Year Spectrum



Adams, D.Q. et al. (CUORE Collaboration), *Nature* **604**, 53-58 (2022)

Background in Region of Interest (ROI)

α region

fit flat background in [2650,3100] keV
1.40(2) 10^{-2} counts/(keV kg yr)

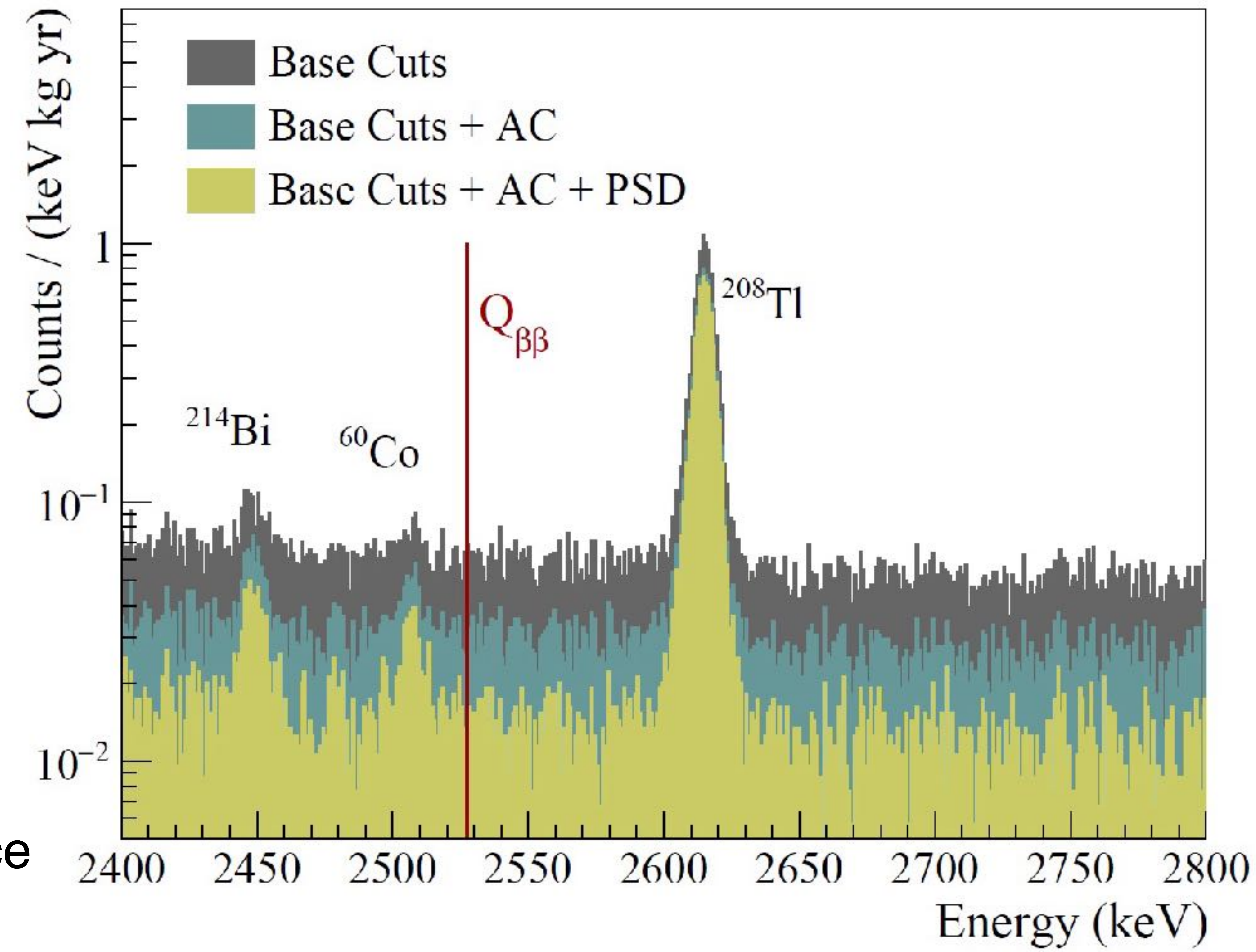
$Q_{\beta\beta}$ region

fit background + ^{60}Co peak in [2490,2575] keV
1.49(4) 10^{-2} counts/(keV kg yr)

source

~90% of the background in the ROI is given by degraded alpha interactions

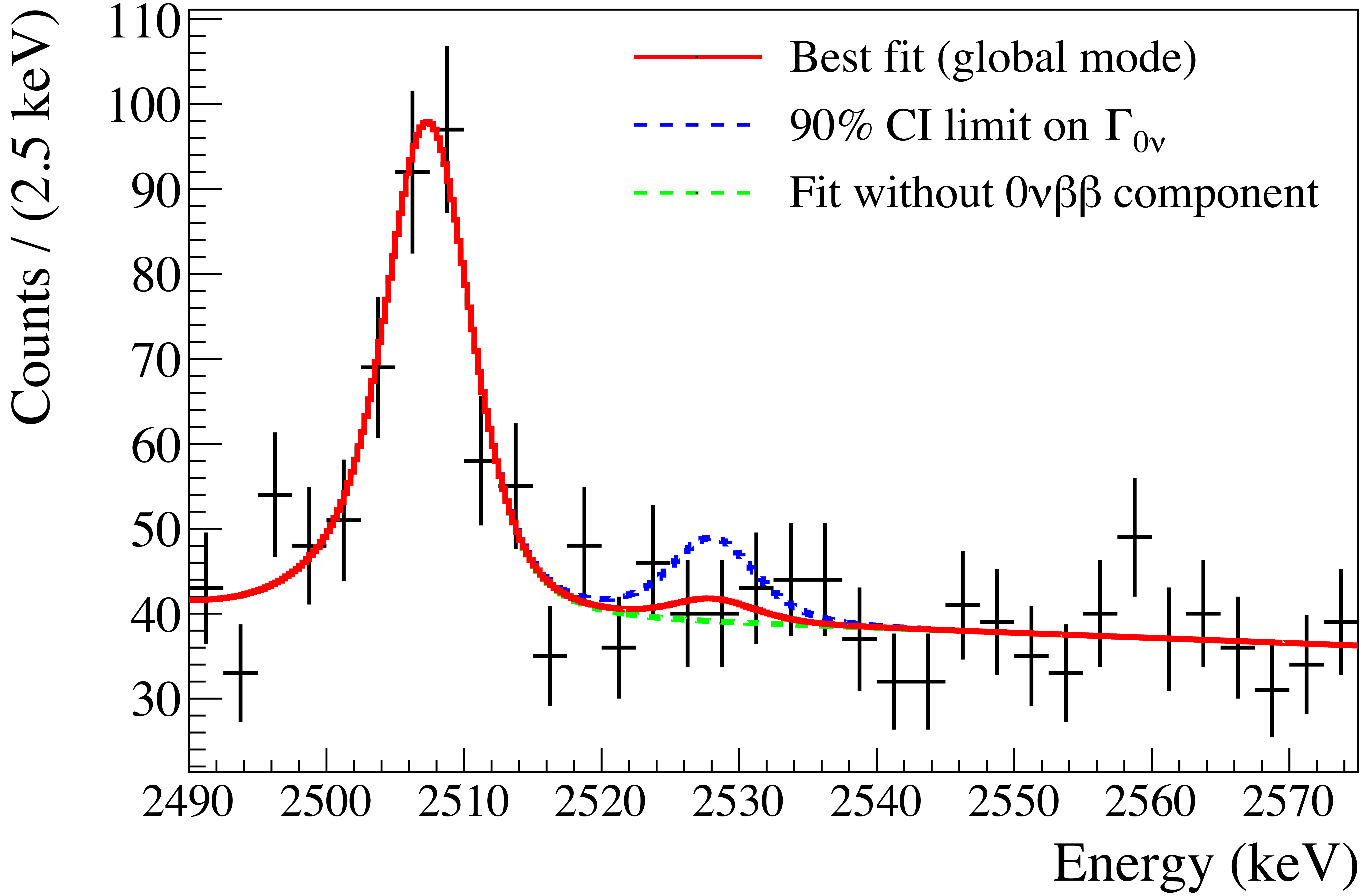
Muons are the next dominant background source



CUORE uses ^{130}Te with 34% natural isotopic abundance, $Q_{\beta\beta}$ (2528 keV)

Adams, D.Q. et al. (CUORE Collaboration), *Nature* **604**, 53-58 (2022)

CUORE Fit



No evidence of 0νββ

Best fit rate: **$(0.9 \pm 1.4) \times 10^{-26}$** yr

Background index = **$1.49(4) \times 10^{-2}$** cts/keV/kg/yr

$T^{0\nu}_{1/2}$ > **2.2×10^{25}** yr at 90% C.L.

Adams, D.Q. et al. (CUORE Collaboration), *Nature* **604**, 53-58 (2022)

CUORE 0νββ Limit and Sensitivity

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)\,|M^{0\nu}|^2\,\frac{|\langle m_{\beta\beta}\rangle|^2}{m_e^2}$$

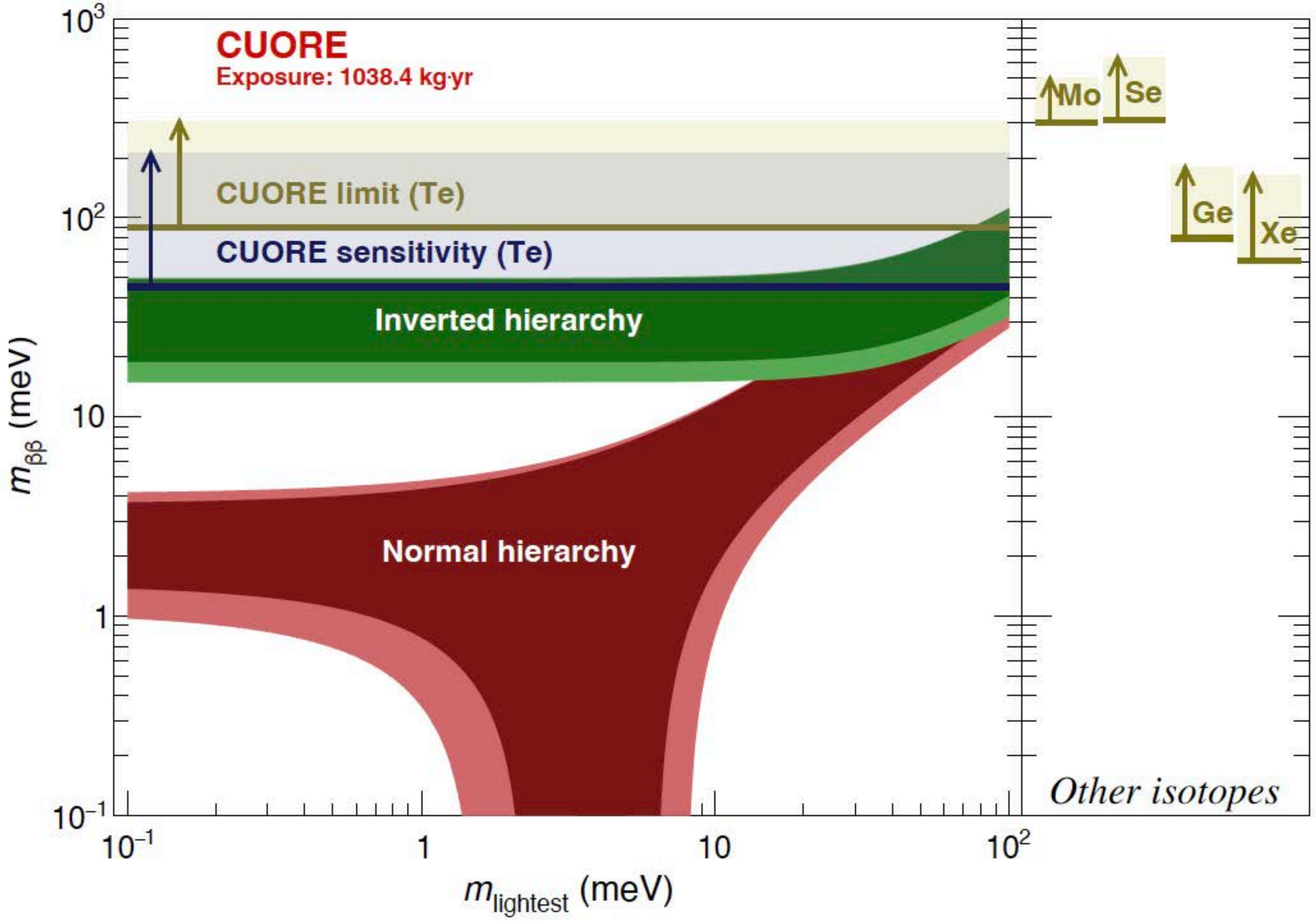
- Phase Space Factor
- Nuclear Matrix element
- Effective Majorona mass: a weighted sum of different ν flavors masses

CUORE 1 Tonne Limit:

$m_{\beta\beta}$< 90-305 meV

CUORE Sensitivity (5 yrs)

$m_{\beta\beta}$ < 50 - 130 meV

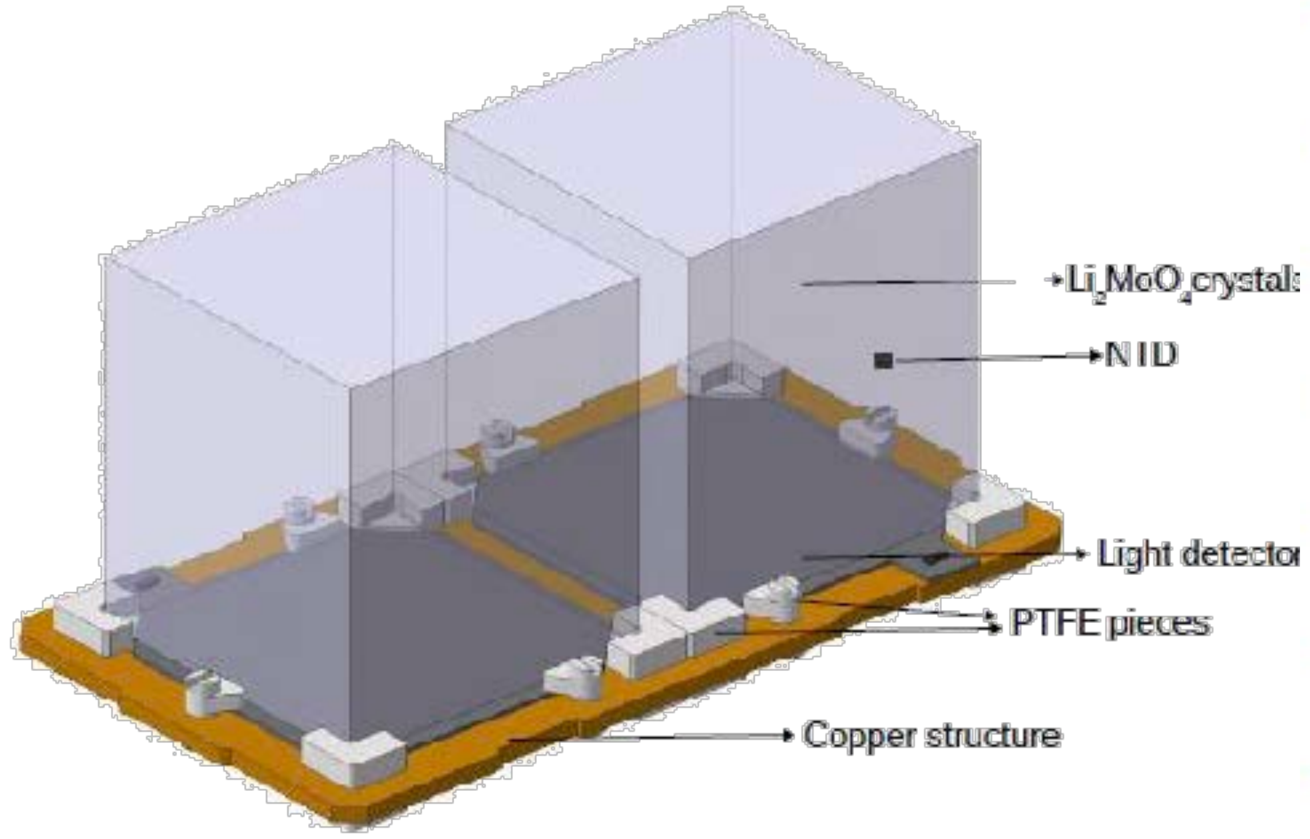


CUPID Detector

Single Detector

$Li_2{}^{100}MoO4$, 45x45x45 mm, 280 g

Ge light detector as in CUPID-Mo, CUPID-0



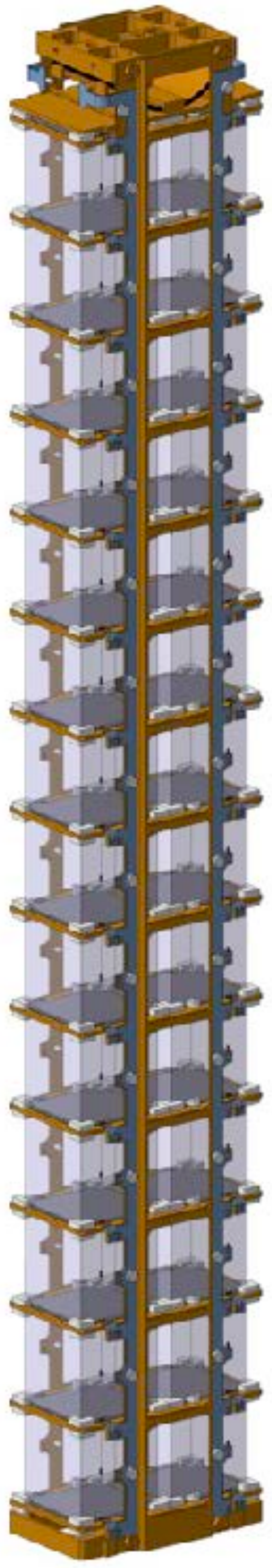
Gravity stacked structure
Crystals thermally interconnected

Detector Array

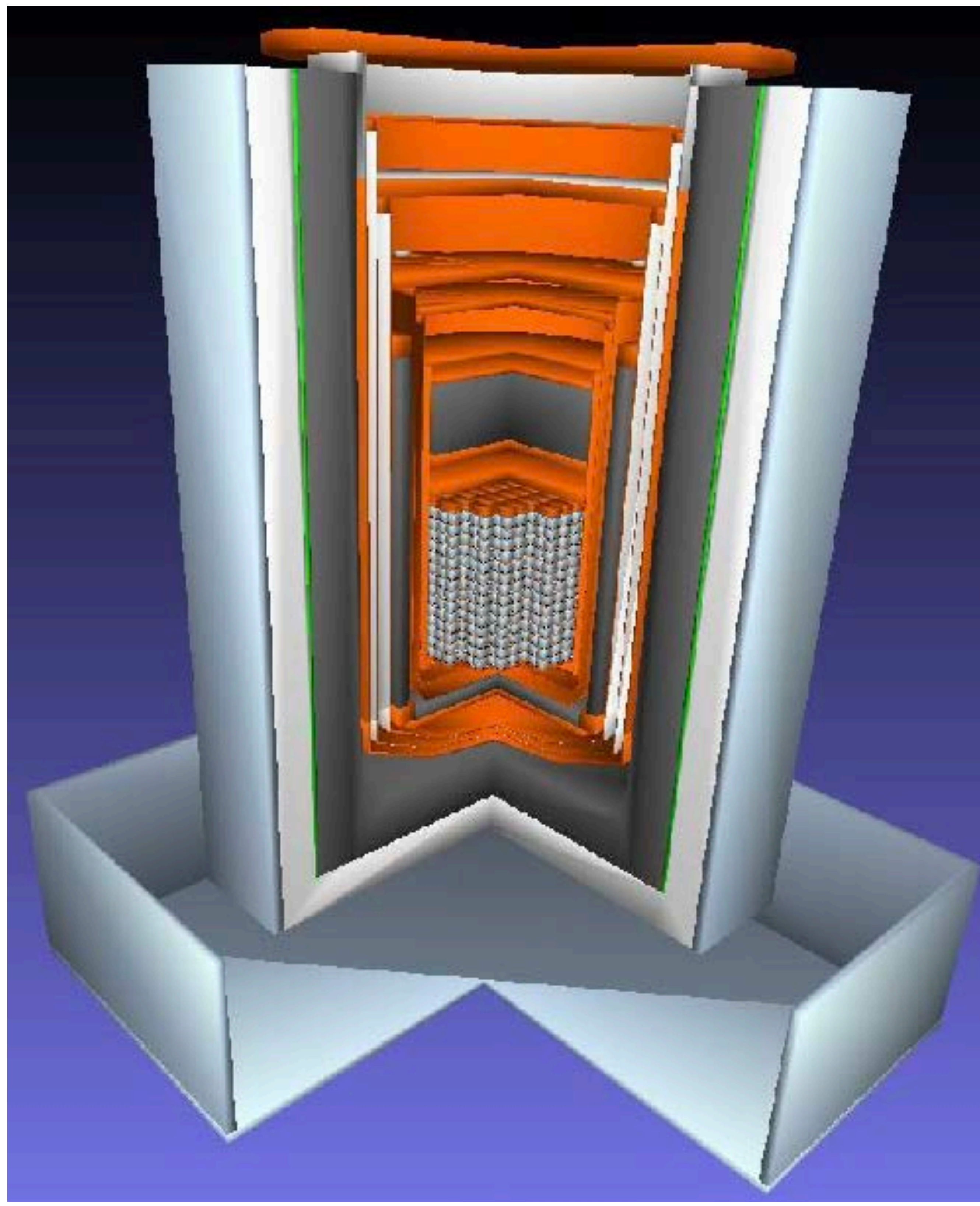
~240 kg of ^{100}Mo with >95% enrichment

~1.6.10^{27} ^{100}Mo atoms

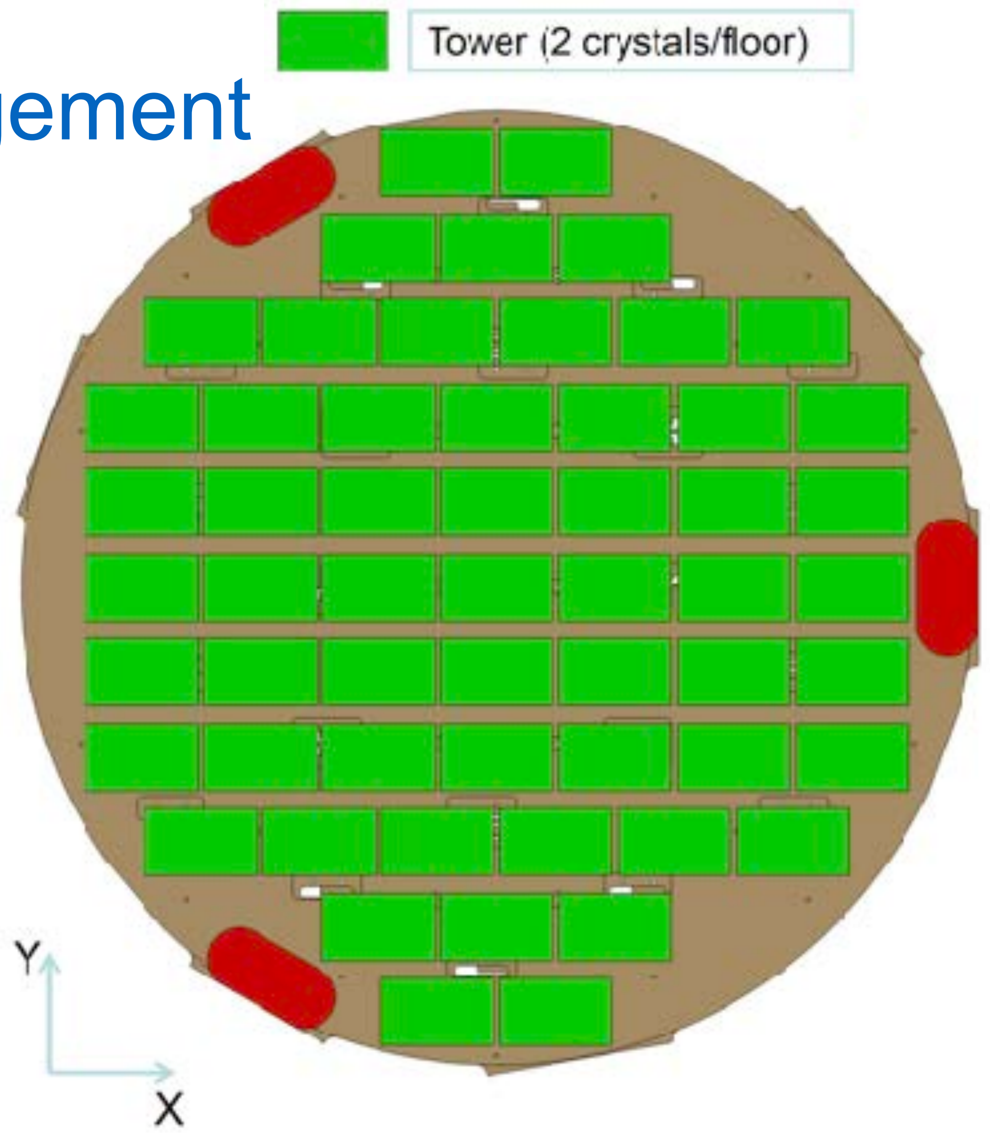
57 towers of 14 floors with 2 crystals each, 1596 crystals



Tower



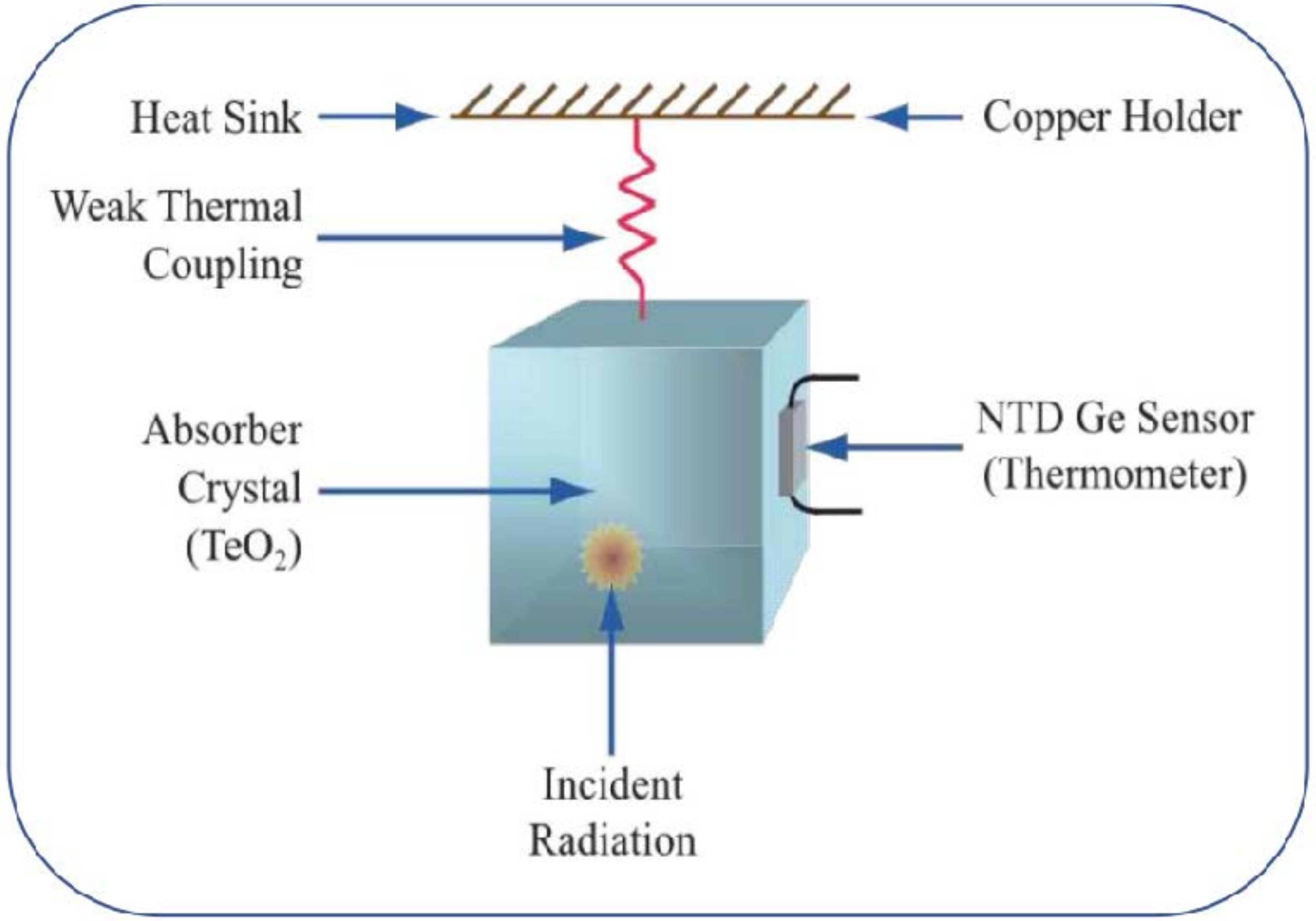
Tower Arrangement



Opportunity to deploy multiple isotopes, phased deployment

CUPID detector technology

CUORE ^{130}Te
pure thermal detector
(bolometer)

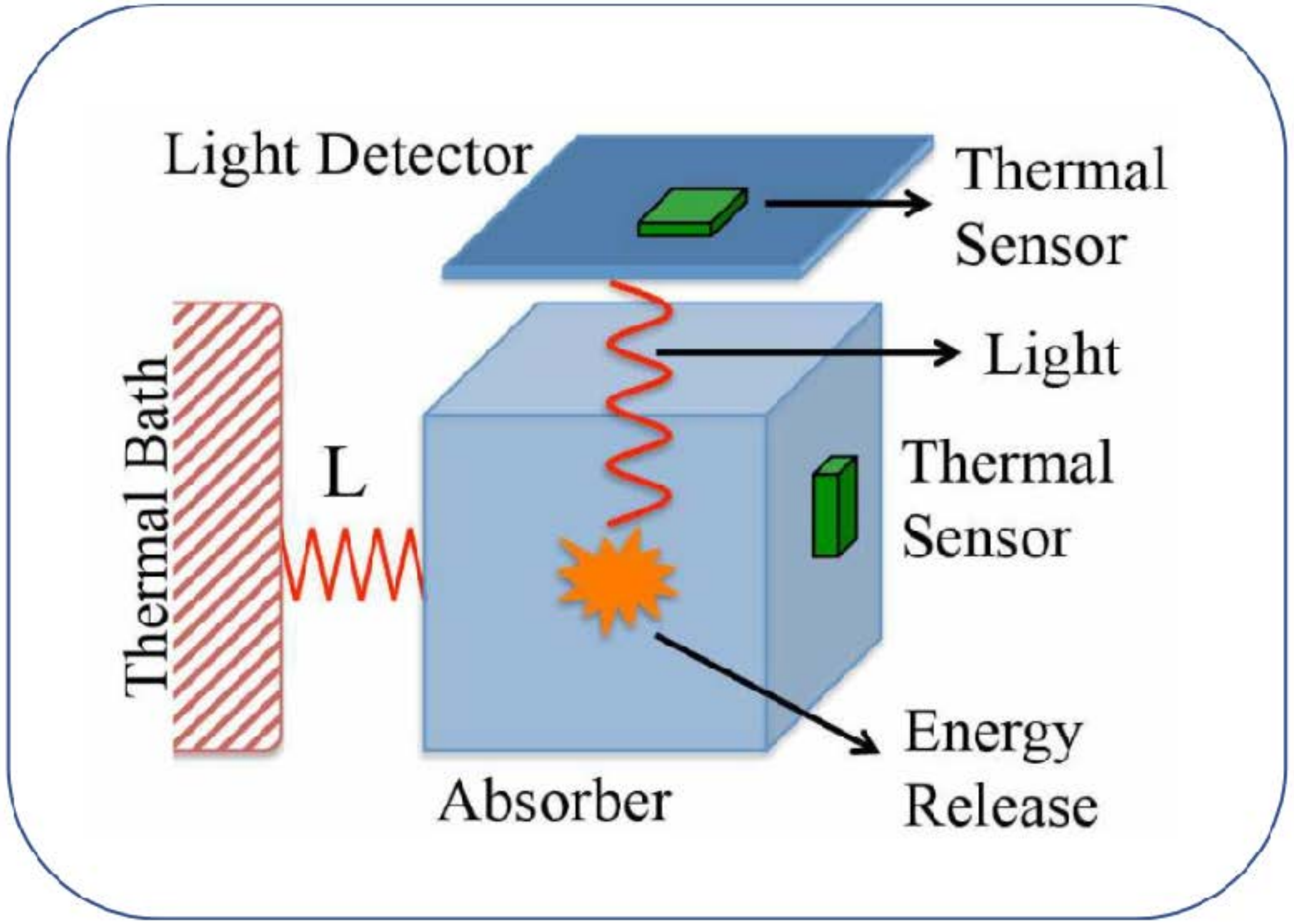


No PID
Q = 2527 keV **< 2615 keV**

PID → remove α

high Q → remove γ

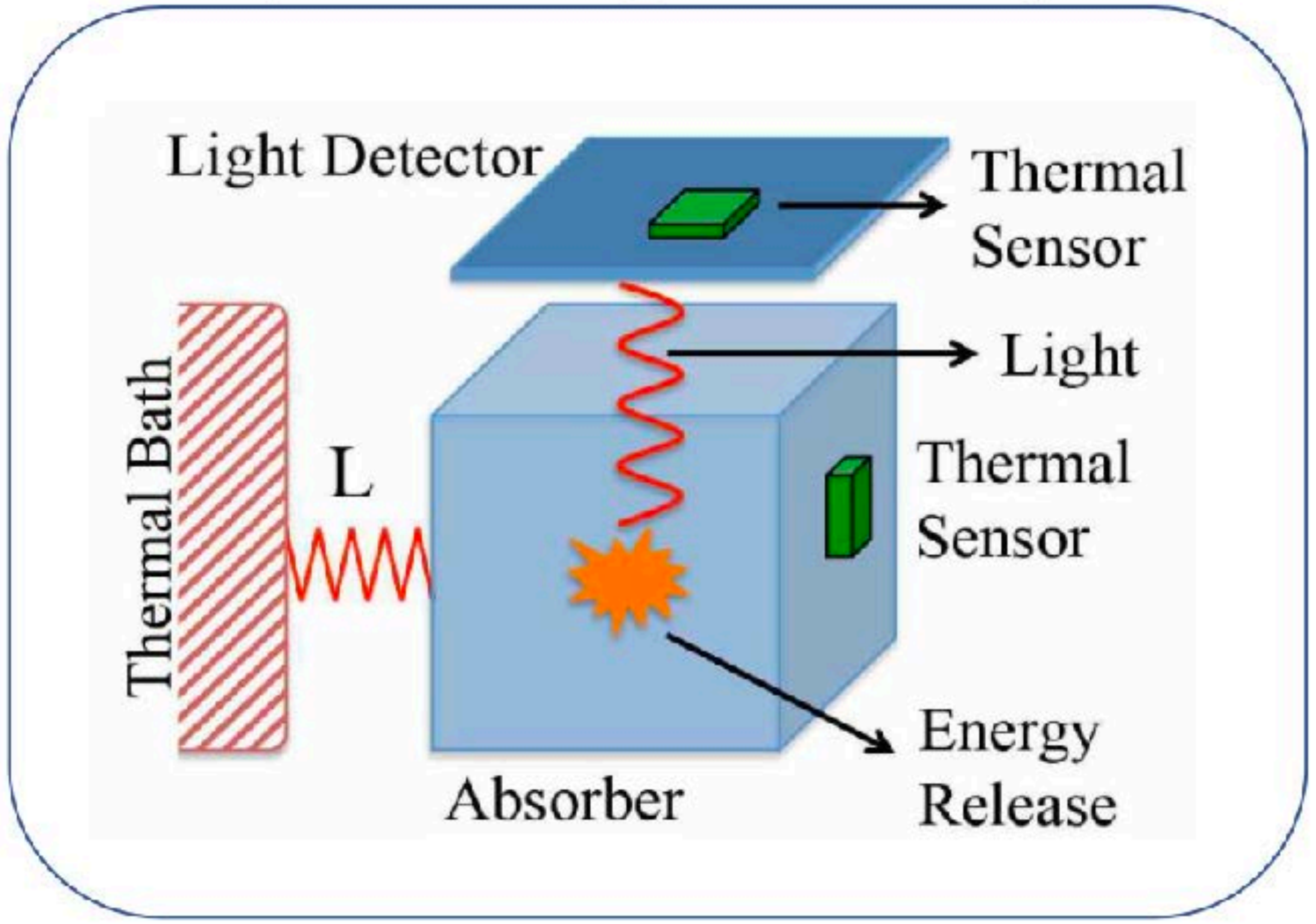
CUPID ^{100}Mo
heat + light
(scintillating bolometer)

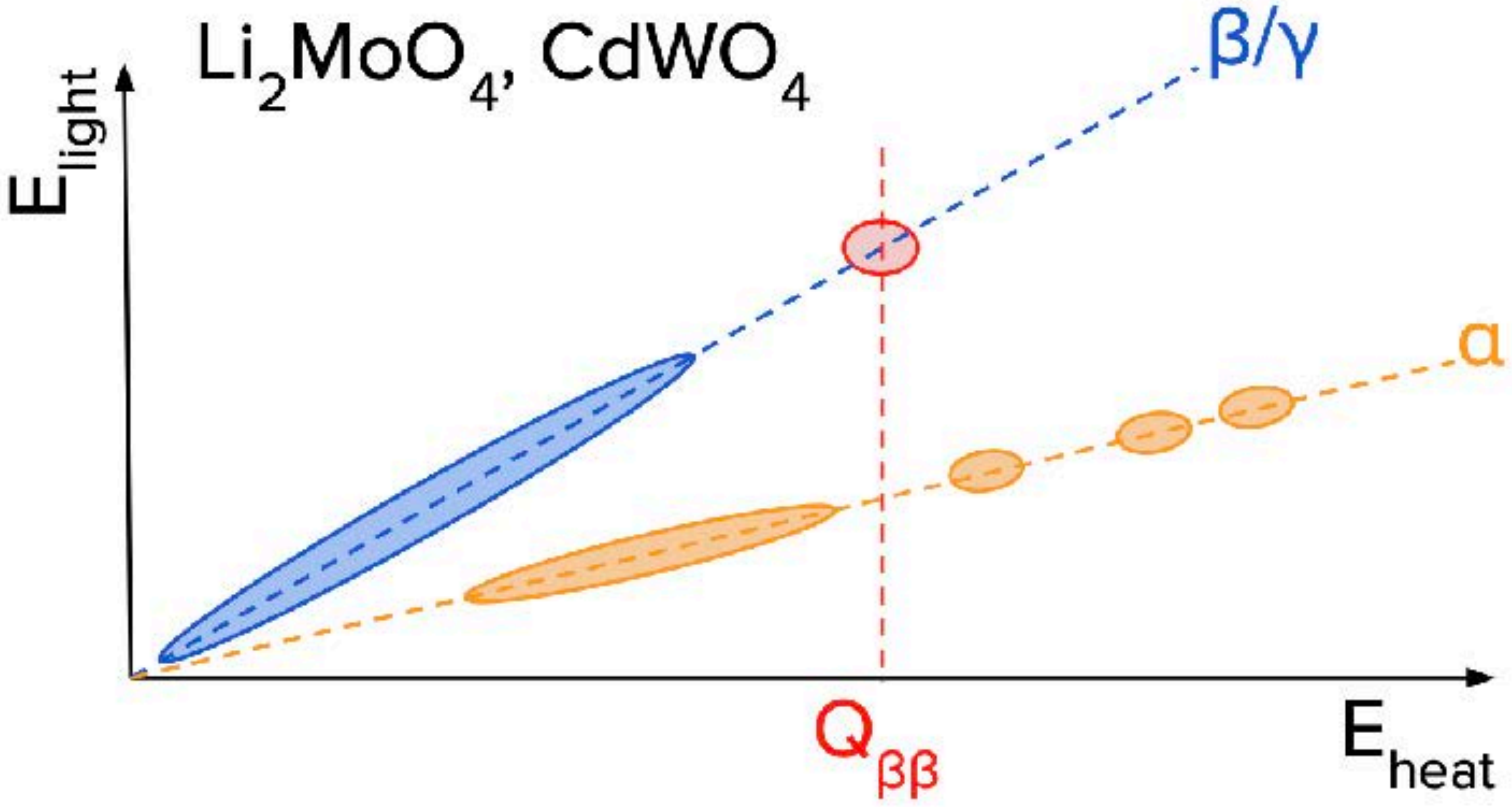


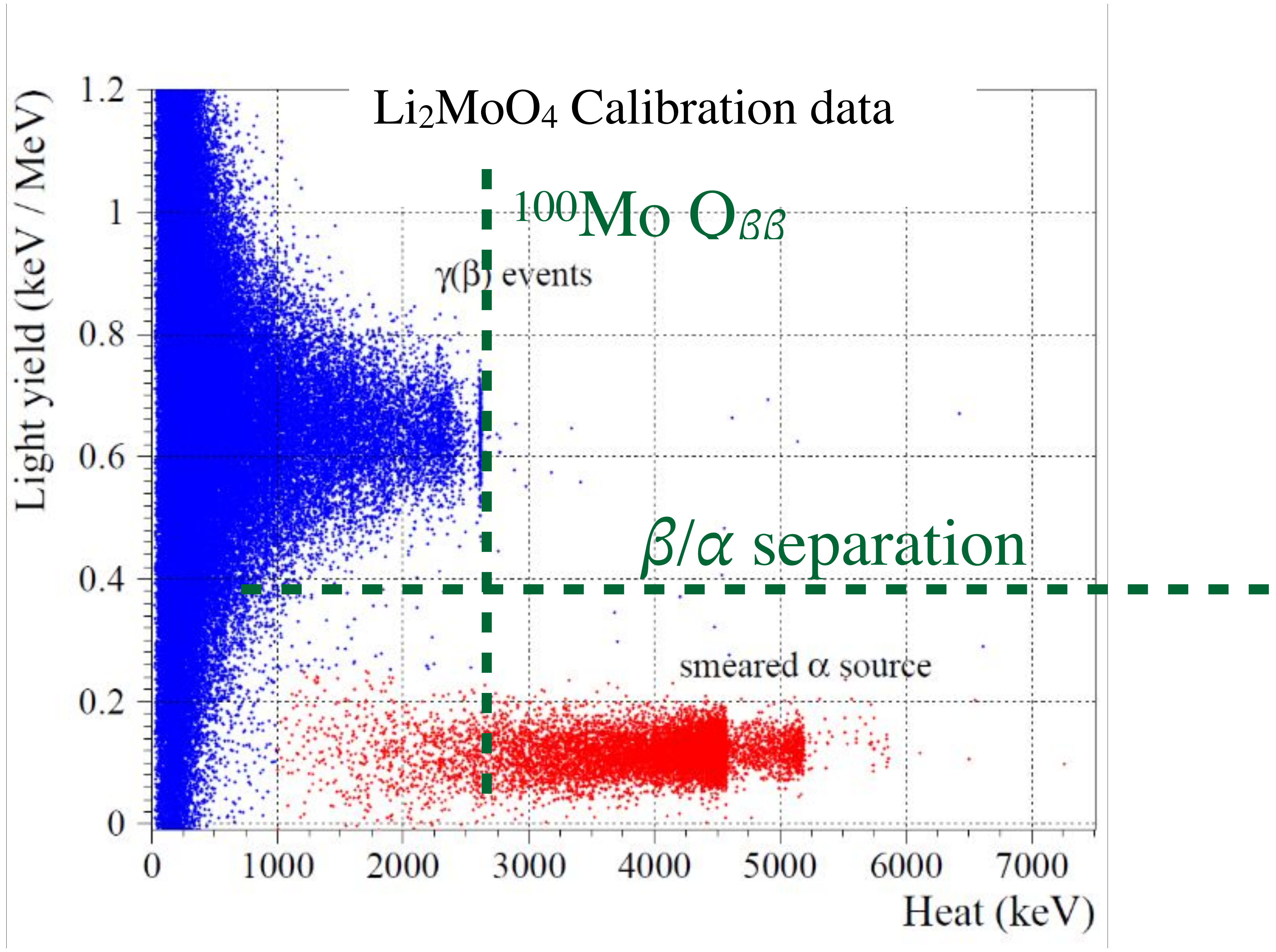
^{100}Mo **Q-value: 3034 keV**: β/γ background significantly reduced

CUPID Concept

CUPID ^{100}Mo
heat + light
(scintillating bolometer)







Measure heat and light from energy deposition

Heat is particle independent, but light yield depends on particle type

Actively discriminate α using measured light yield

CUPID Sensitivity to 0νββ

Baseline

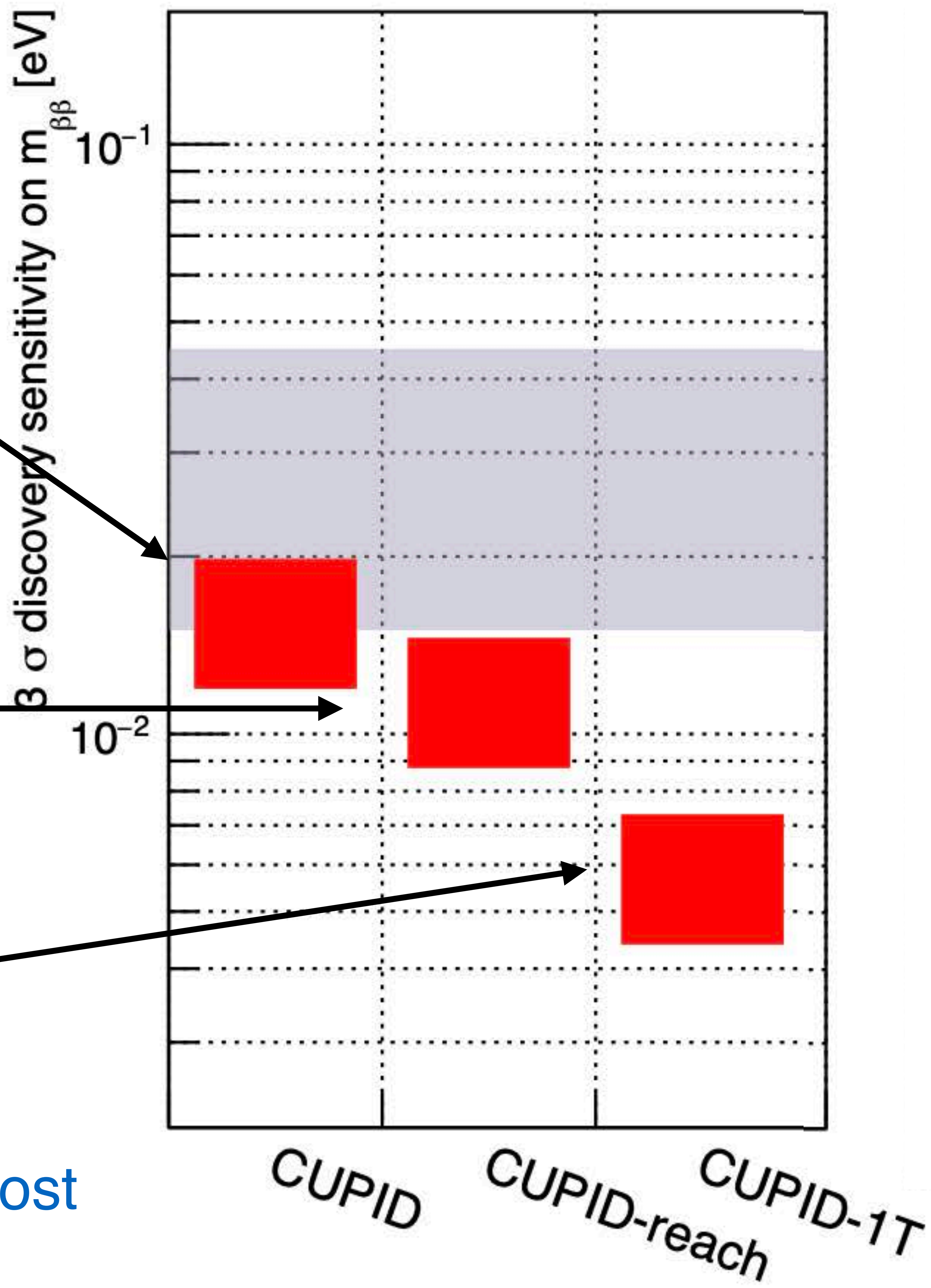
- Mass: 450 kg (**240 Kg**) of $Li_2{}^{100}MoO_4$(^{100}Mo) for **10** yrs
- Energy resolution: **5 keV** FWHM
- Background: **10^{-4}** cts/keV.kg.yr
- Discovery sensitivity **$T_{1/2} > 1.1\times10^{27}$ yr (3σ)**
- Conservative, limited R&D

Reach

- R&D for further background reduction by radio purity and reduce pileup background
- Discovery sensitivity **$T_{1/2} > 2\times10^{27}$ yr (3σ)**

1-Ton

- 1000 kg of ^{100}Mo
- Discovery sensitivity **$T_{1/2} > 8\times10^{27}$ yr (3σ)**



CUPID-1T is within technical reach, limited by timeline and cost

CUPID Sensitivity to 0νββ

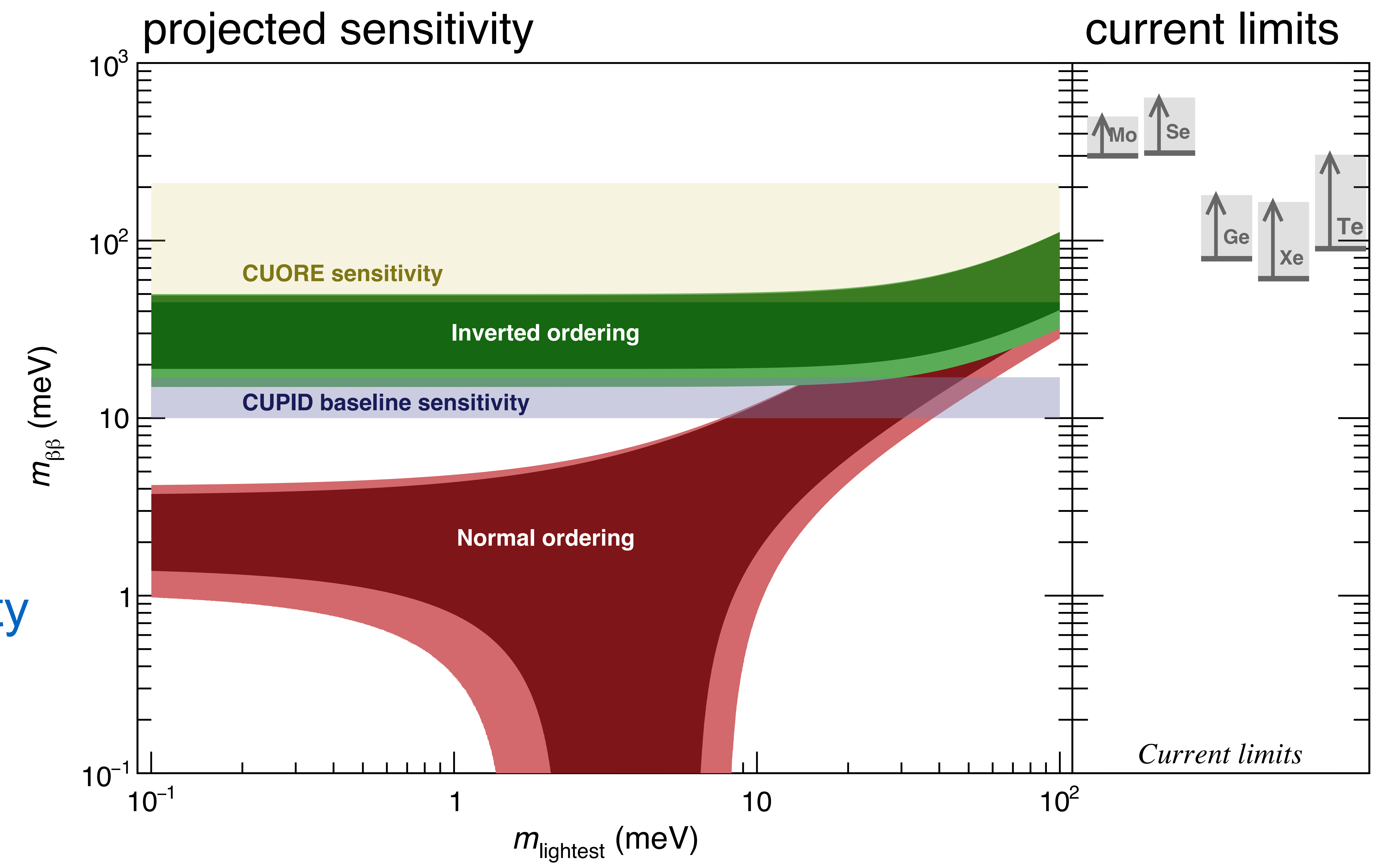
CUPID Baseline

- Mass: 472 kg (**240 Kg**) of $Li_2{}^{100}MoO_4$(^{100}Mo)
- **10** yr runtime
- Energy resolution: **5 keV** FWHM
- Background: **10^{-4}** cts/keV.kg.yr

CUPID Baseline Discovery Sensitivity

$T_{1/2}$ > **1.1×10^{27} yrs (3σ)**

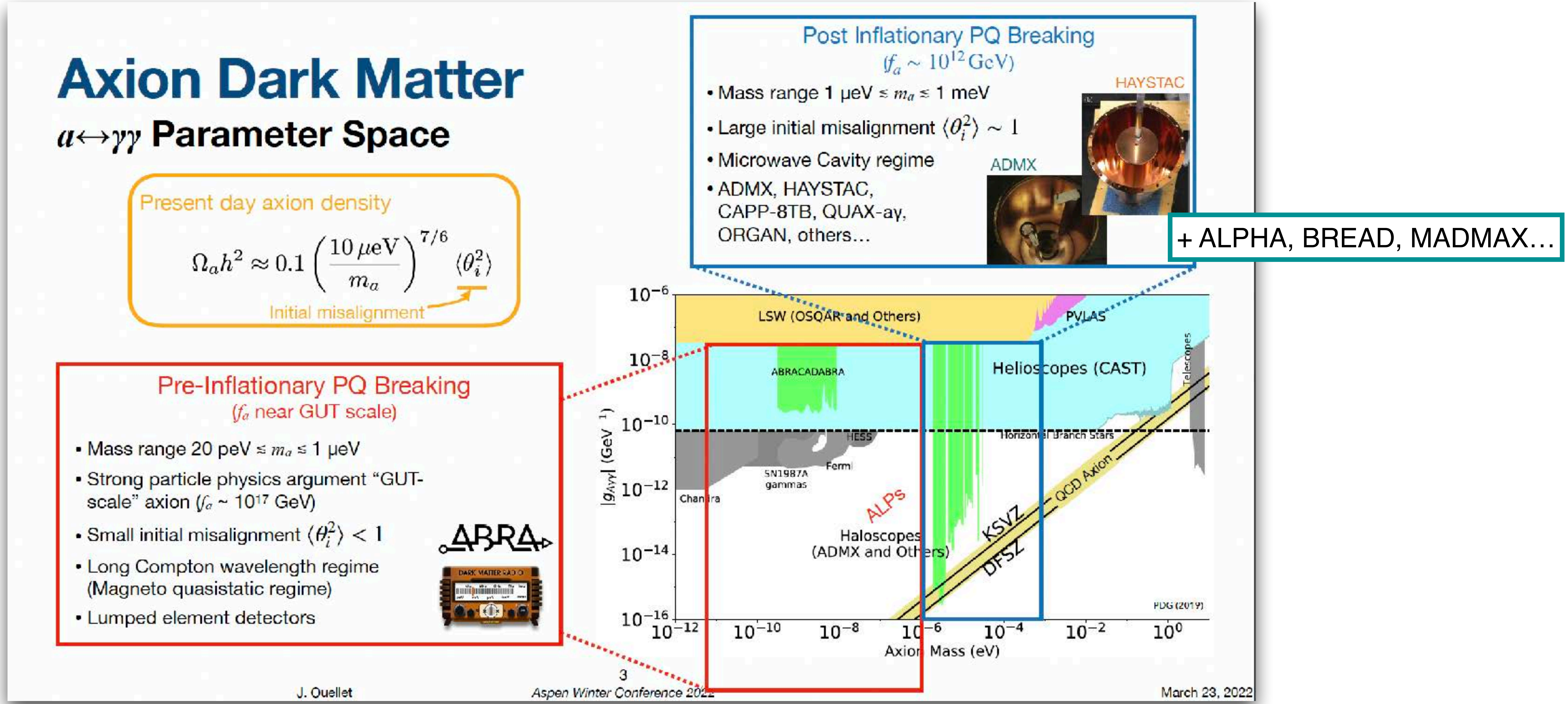
$m_{\beta\beta}$ ~ **12-20 meV**



CUPID aims to cover the inverted hierarchy and a fraction of normal ordering

Axions

Axions are well motivated



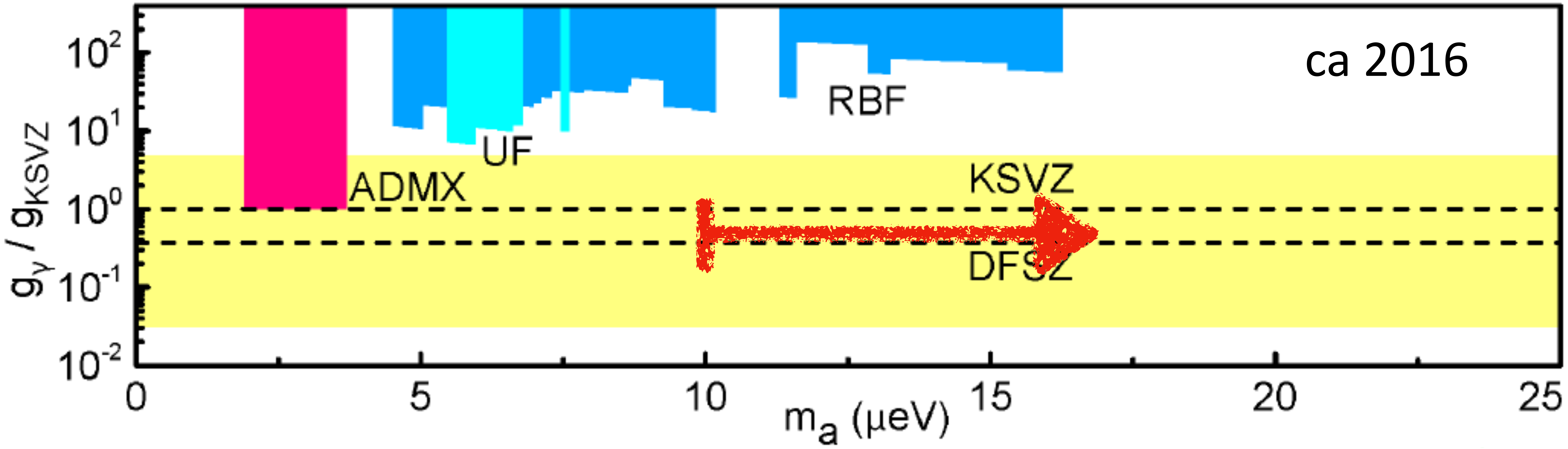
J. Ouellet, Aspen 2022

HAYSTAC's Aim: Going high

- Innovation testbed for axion searches in QCD band > 10 µeV (~2.5 GHz)
- Challenges:
  - Photon detection, noise
  - Scan rate: $V \propto \nu^{-2}$, $\frac{d\nu}{dt} \propto V^2$, $\frac{d\nu}{dt} \propto \nu^{-4}$

Borsanyi et al (2016) PQ symmetry broken after inflation: m_a > 10 µeV

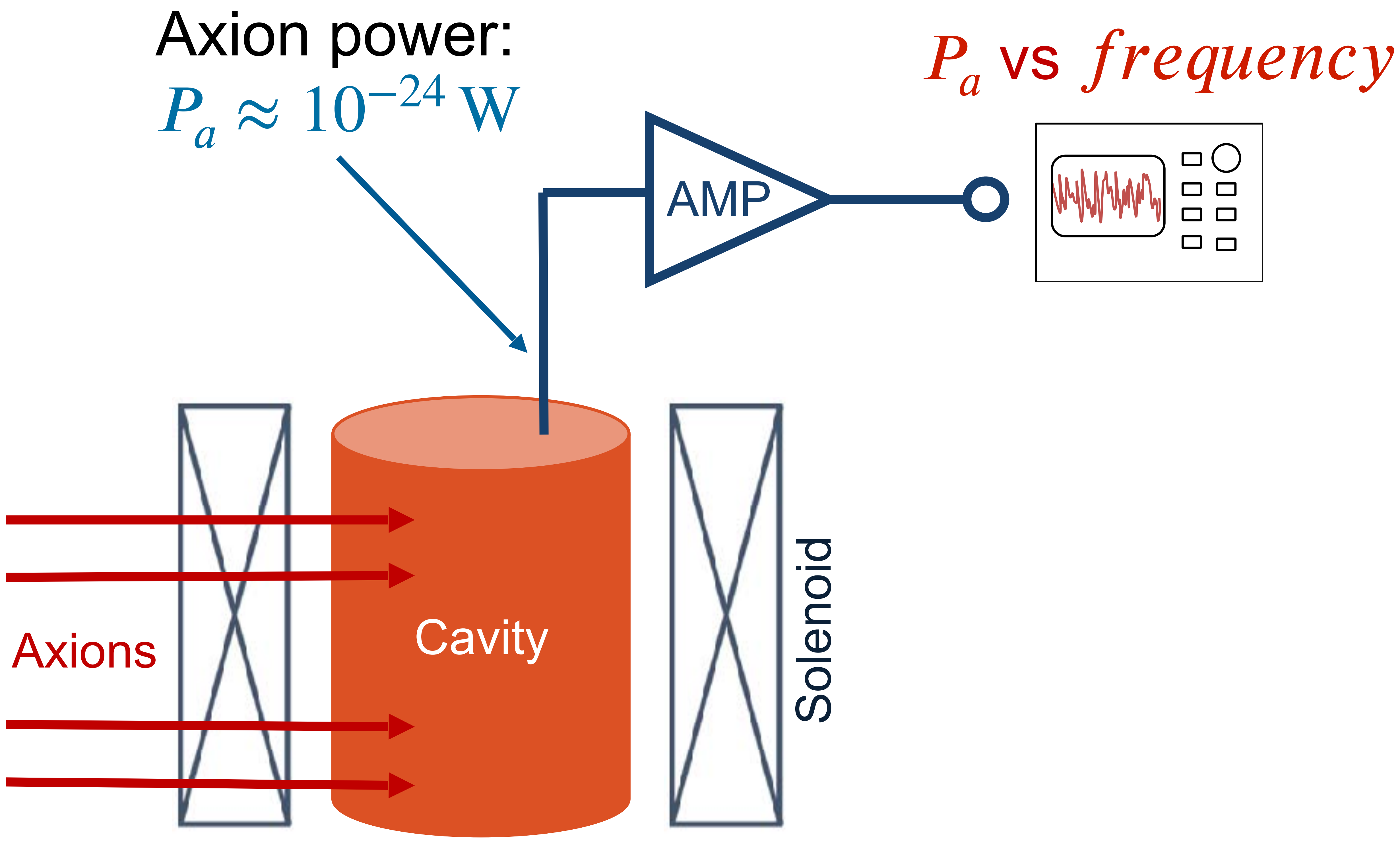
Klaer & Moore (2017); 26.2 ± 3.4 µeV



Buschmann, et al. (2022): 40 µeV [65 ± 6 µeV, q=1; scale invariant spectrum]

* In $\Omega_A \sim f_A^\alpha$, the best fit α = 1.24 ± 0.04
Rather than analytical 1.187

Detecting Axions: Sikivie’s Haloscope



Interaction of interest: $\mathcal{L} \supset g_{a\gamma\gamma} a \boldsymbol{E} \cdot \boldsymbol{B}$

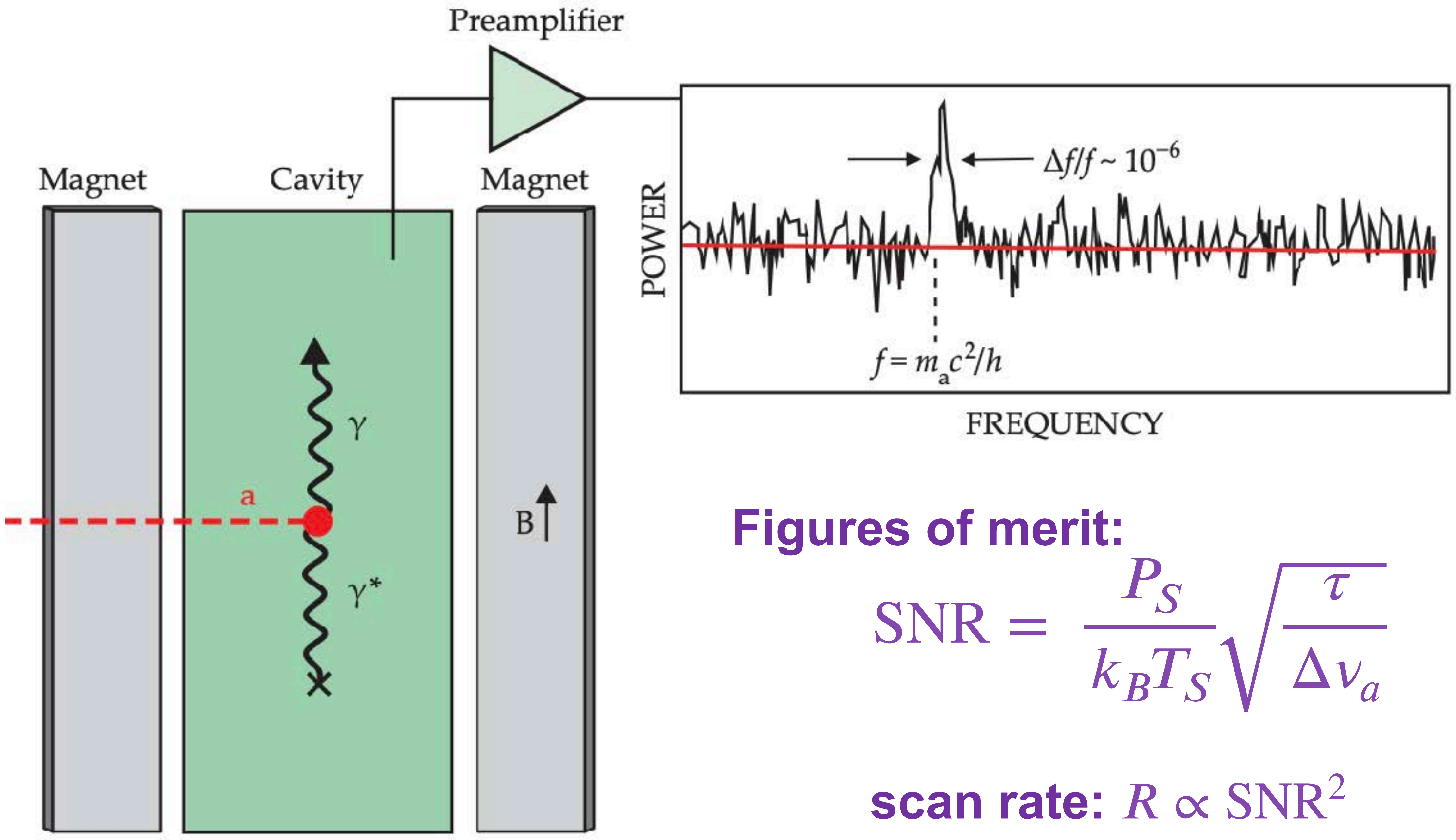
ADMX

HAYSTAC

Haloscope principle: P. Sikivie, *Phys. Rev. Lett.*, **51**, 1415 (1983)

HAYSTAC detector: Nucl. Instrum. Methods A 854, 11 (2017)

Detecting Axions: the Haloscope Principle



Figures of merit:

$$\mathrm{SNR} = \frac{P_S}{k_B T_S}\sqrt{\frac{\tau}{\Delta \nu_a}}$$

scan rate: $R \propto \mathrm{SNR}^2$

Scaling:

Signal power:

$$P = \kappa \mathcal{G} V \frac{Q}{m_a} \rho_a g_{a\gamma}^2 B_e^2$$

m_a = (4.1 μeV) × (f / GHz)

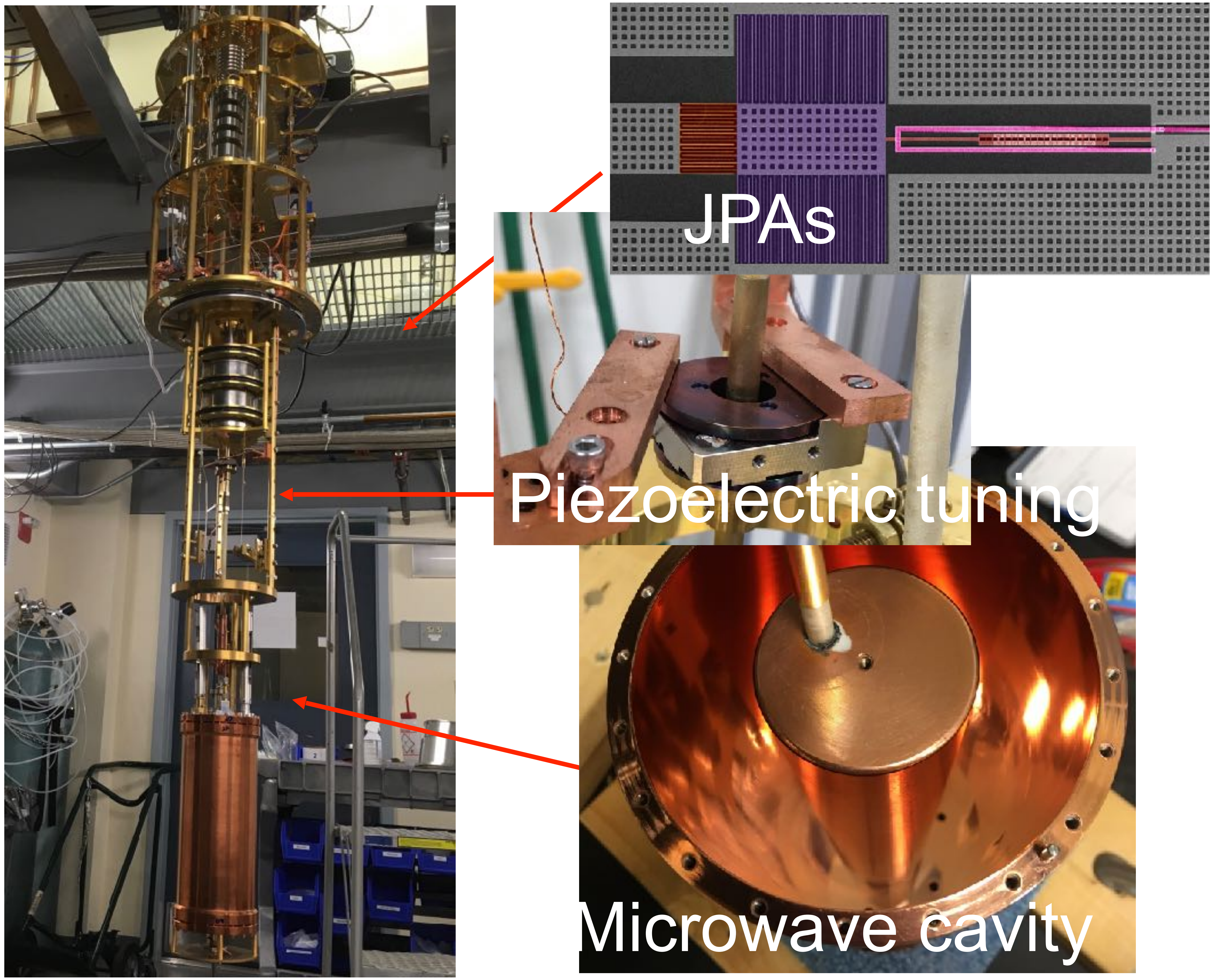
$$(f)_{TM_{010}} = \frac{2.405}{2\pi a\sqrt{\mu_0 \epsilon_0}} = \frac{0.115}{a}\ \mathrm{GHz}$$

Standard quantum limit: $kT_N \geq h\nu$

For f = 10 GHz, cavity of ~1.15 cm

Physics Today 72, 6, 48 (2019)

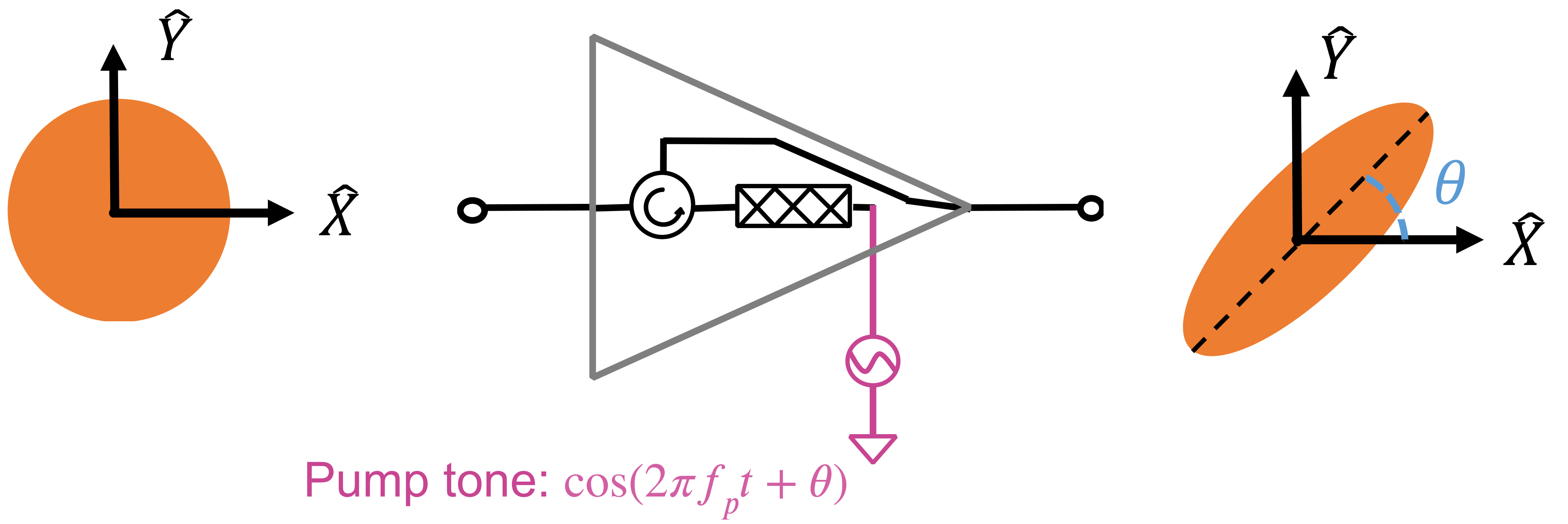
HAYSTAC Experiment

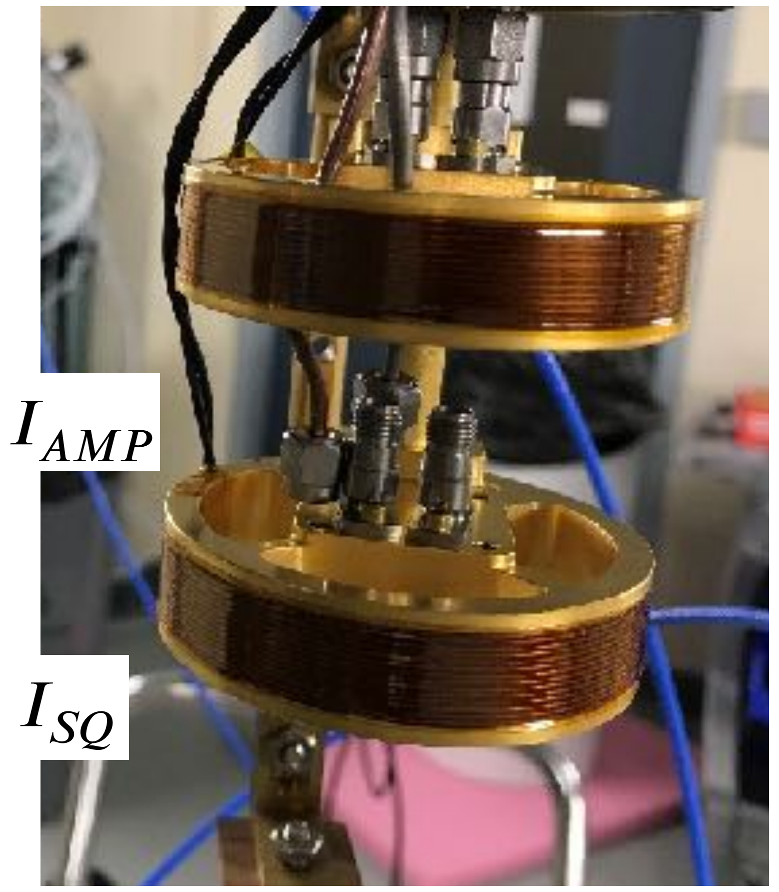


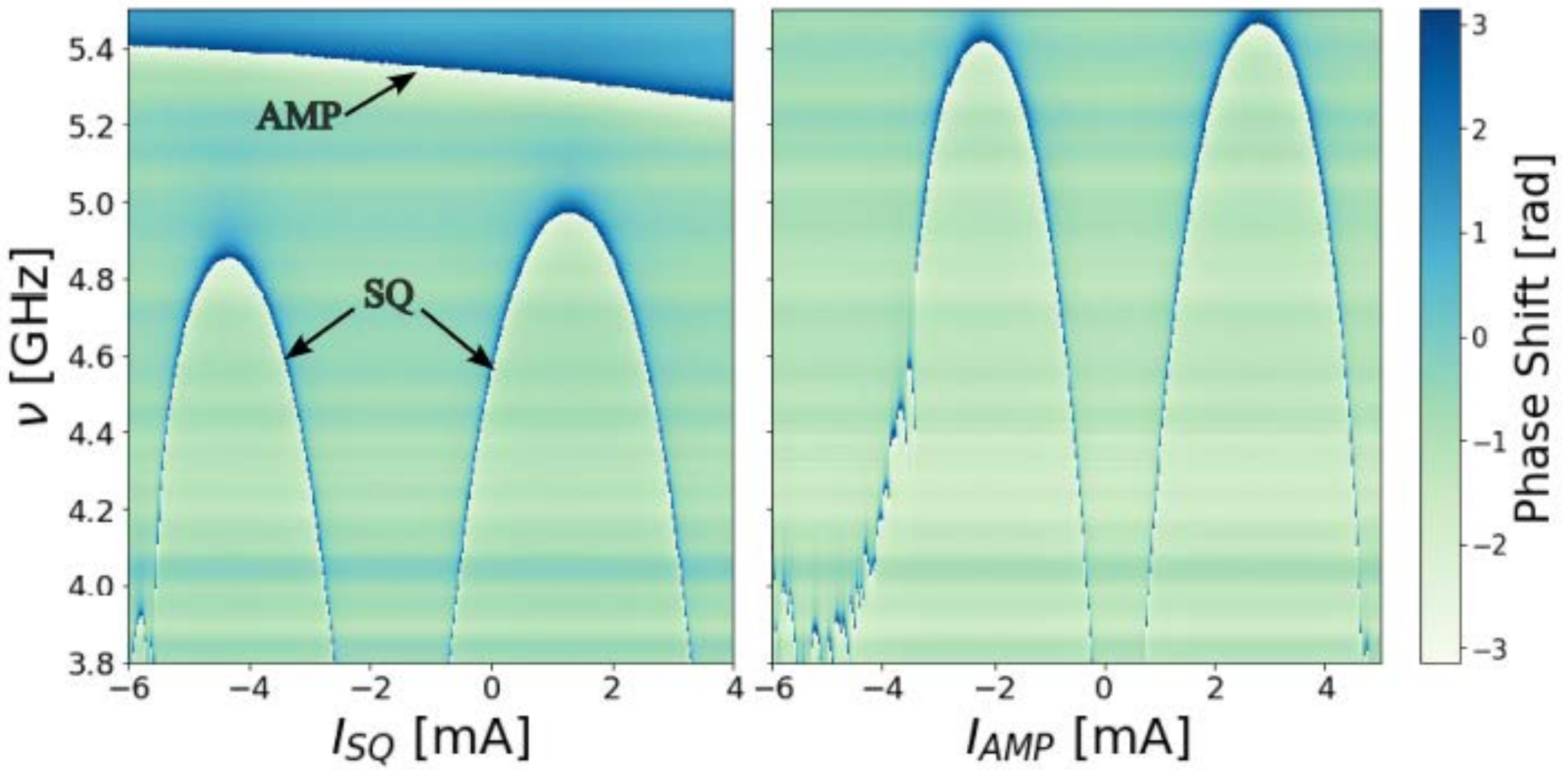
Brubaker et al., [PRL 118 061302 (2017)]

HAYSTAC's Innovations: Phase 1

- Use JPAs to lower the system noise
- Tunable LC resonators
- Near Quantum Limited Noise
- Can Operate in Phase Sensitive mode



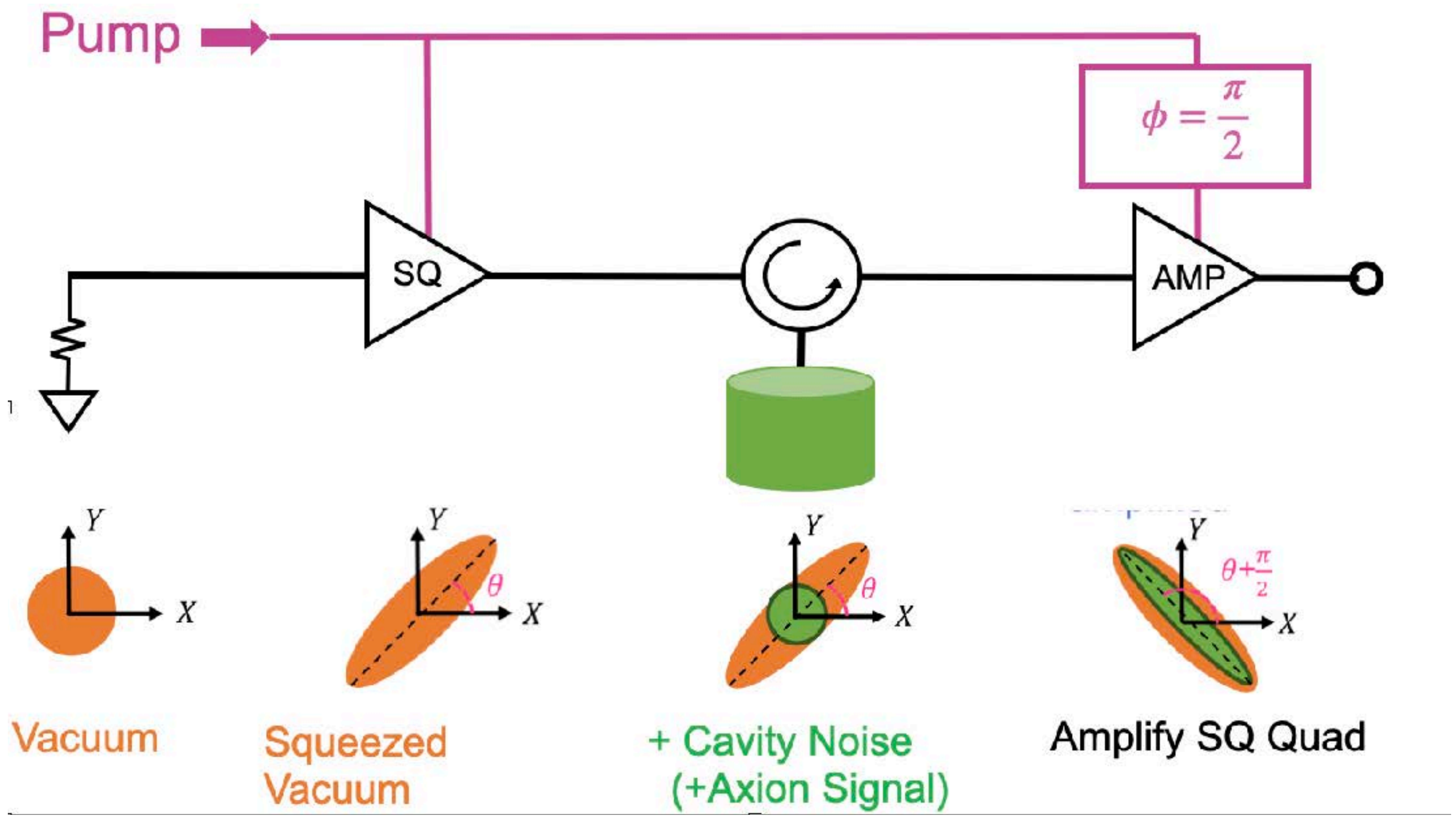




Malnou et al., Phys. Rev. X 9, 021023 (2019)

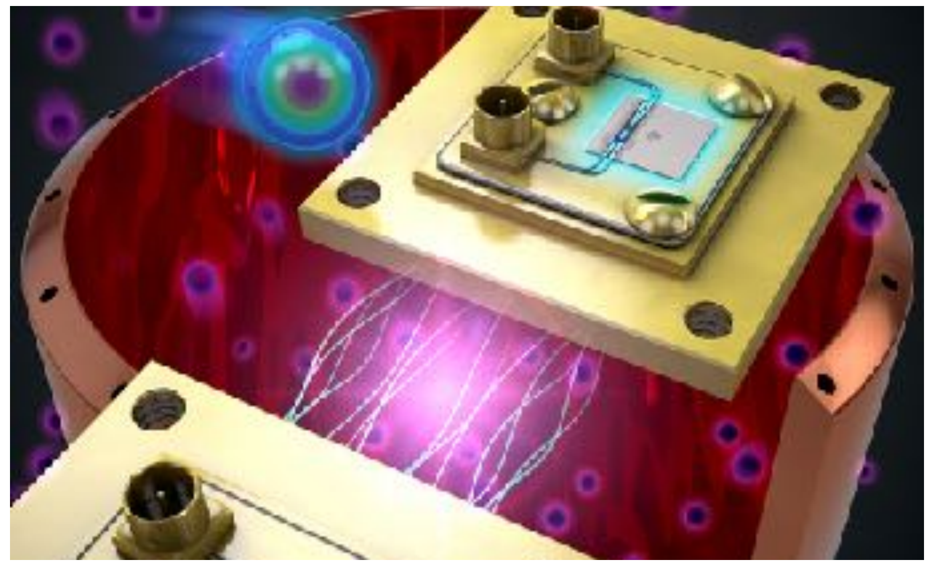
HAYSTAC Innovation Phase 2: Squeezing

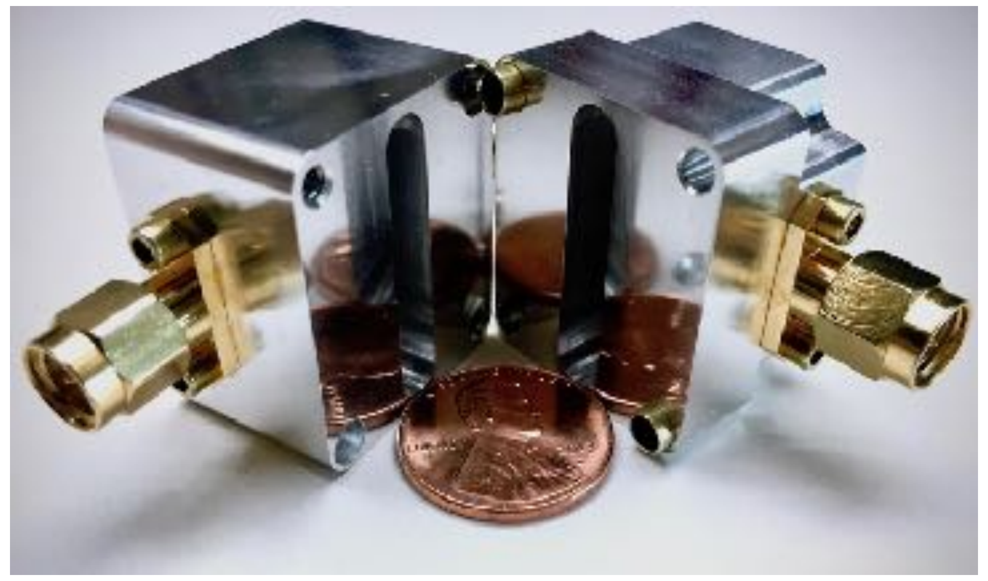
- 2 JPAs in tandem can even beat the Quantum Limit
- Squeezed State Receiver



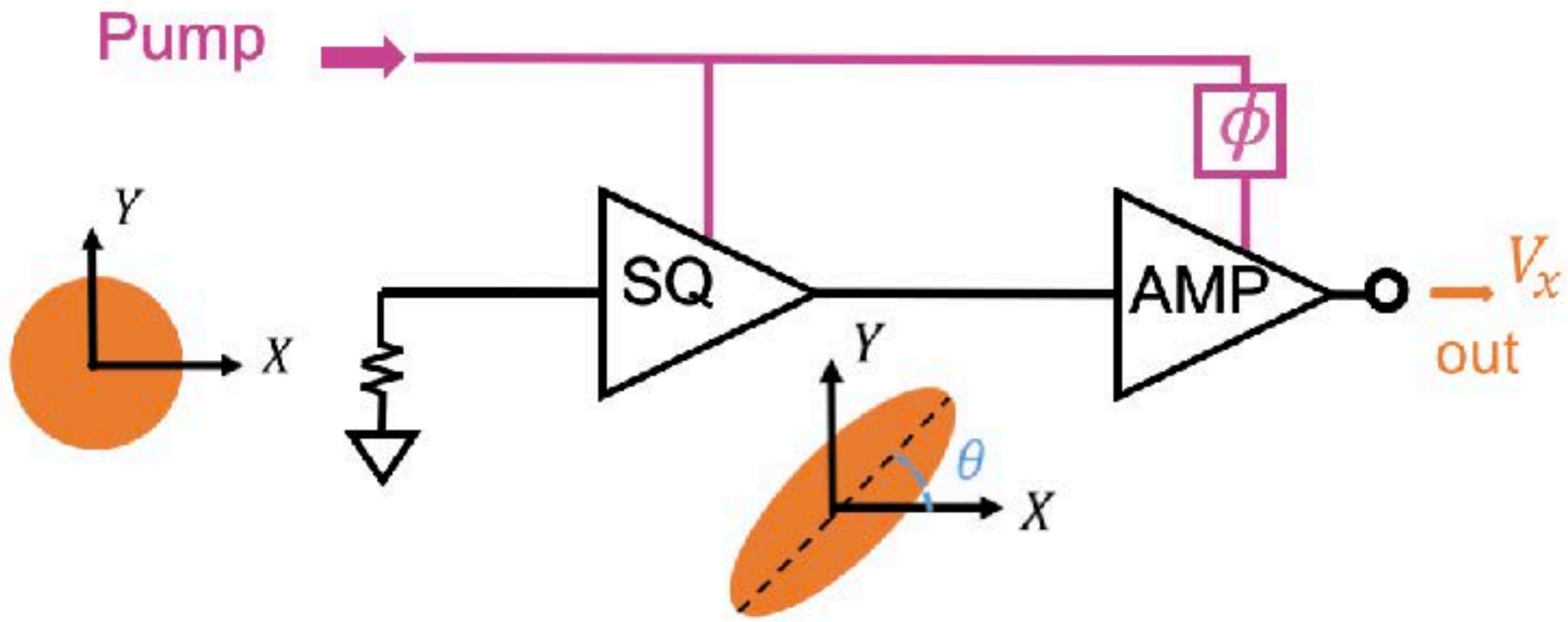
[Backes et al., Nature, **590,** 238 (2021)]

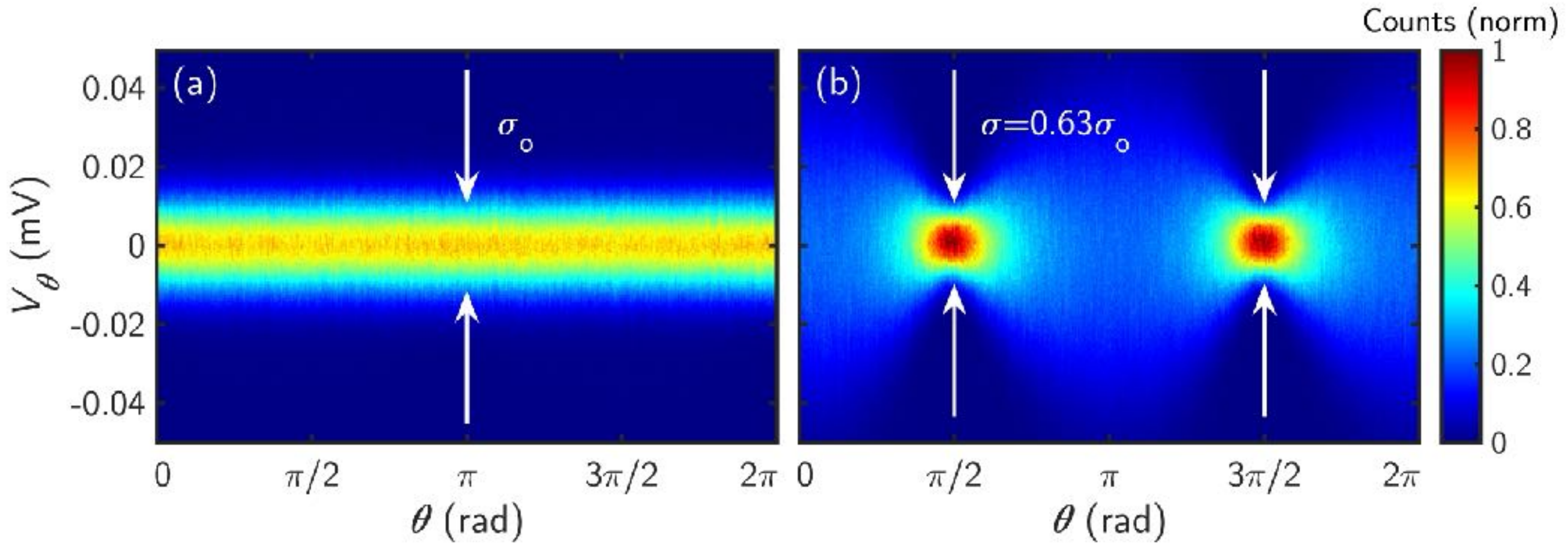
HAYSTAC: Phase 2





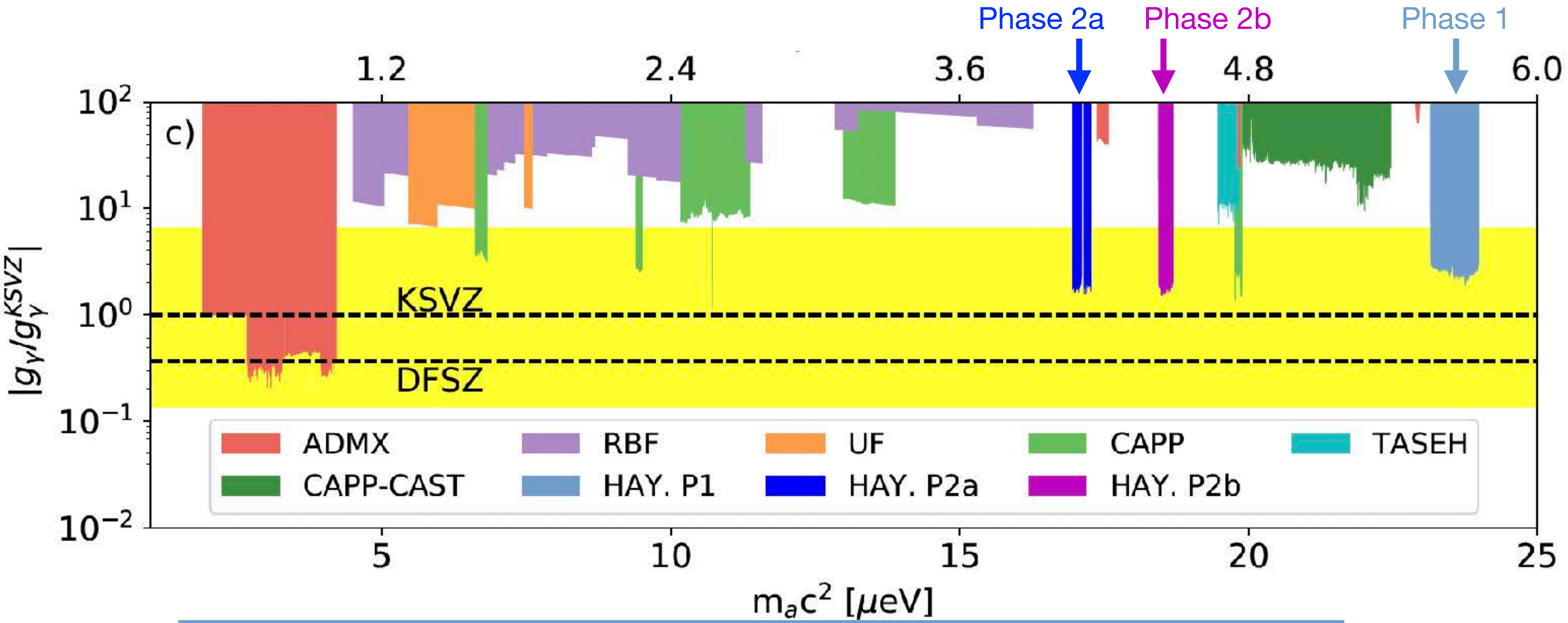
- Dark matter search enhanced by quantum squeezing
- Josephson Parametric Amplifier source squeezed states
- Squeezed state receiver operation
- -4dB noise reduction
- x2 speedup





Reina Maruyama, Yale University

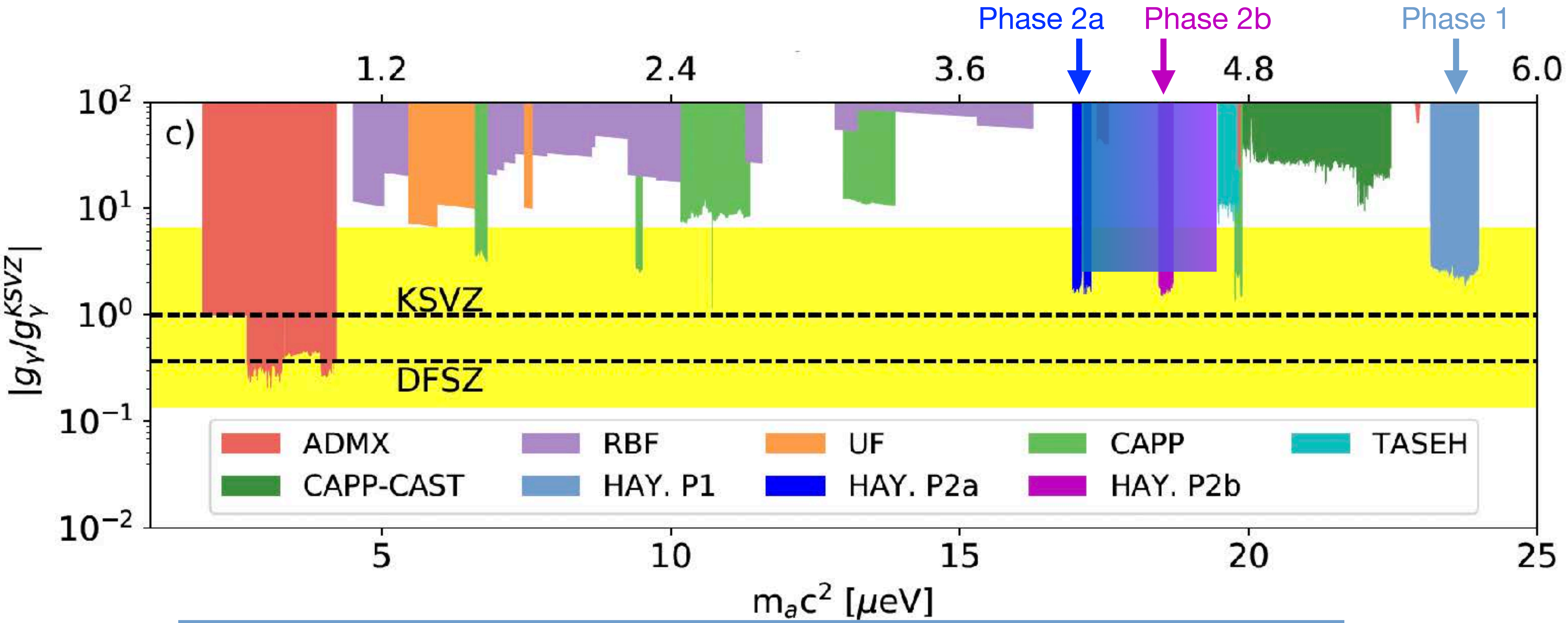
HAYSTAC: Results so far



~330MHz of parameter space in the QCD band between 4.1-5.8 GHz

- Brubaker et al., PRL 118 061302 (2017), Axion search with Quantum limited Noise
- Zhong et al., PRD 97, 092001 (2018)
- Backes et al., Nature, 590, 238–242 (2021), reach below the SQL
- Jewell et al., PRD, 107, 072007 (2023)

HAYSTAC: Phase 2 Projected



~330MHz of parameter space in the QCD band between 4.1-5.8 GHz

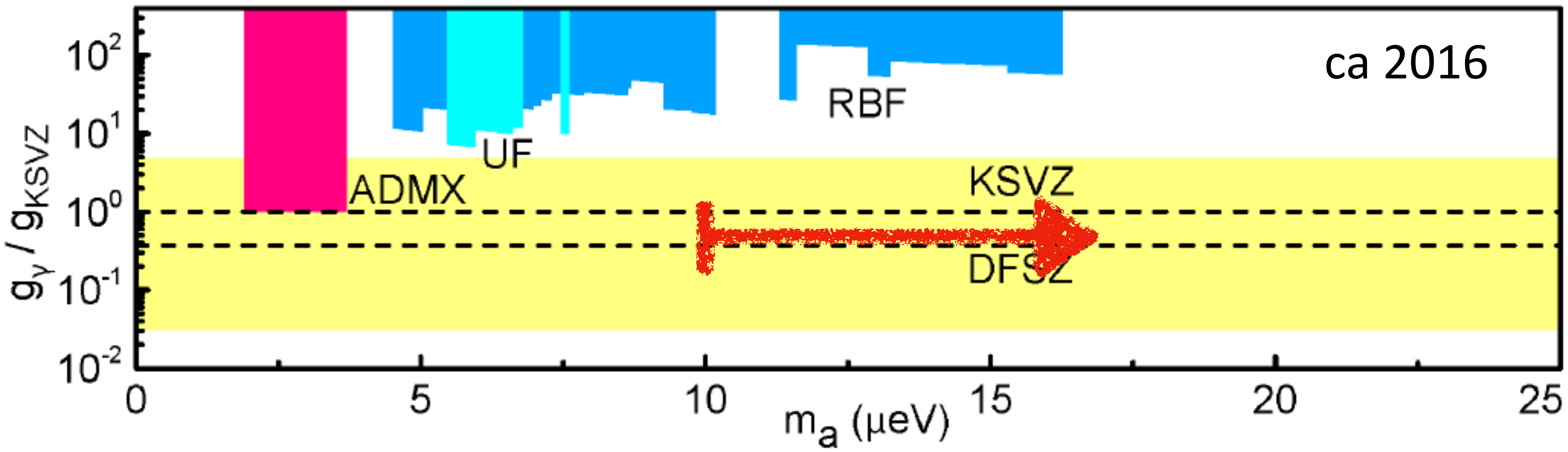
- Brubaker et al., PRL 118 061302 (2017), Axion search with Quantum limited Noise
- Zhong et al., PRD 97, 092001 (2018)
- Backes et al., Nature, 590, 238–242 (2021), reach below the SQL
- Jewell et al., PRD, 107, 072007 (2023)

HAYSTAC & ALPHA: Going higher

- Axion searches in QCD band > 10 μeV -> (~2.5 GHz)
- Challenges:
  - Photon detection, noise
  - Scan rate: $V \propto \nu^{-2}$, $\frac{d\nu}{dt} \propto V^2$, $\frac{d\nu}{dt} \propto \nu^{-4}$

Borsanyi et al (2016) PQ symmetry broken after inflation: m_a > 10 μeV

Klaer & Moore (2017); 26.2 ± 3.4 μeV

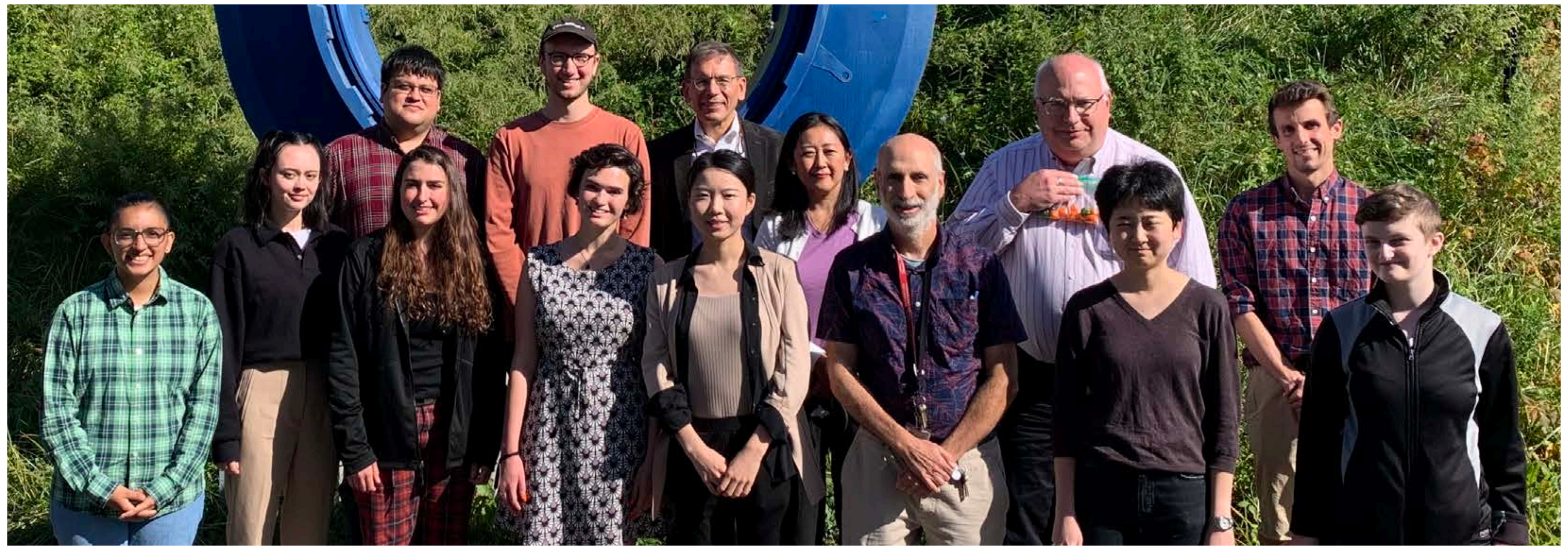


Buschmann, et al. (2022): 40 μeV [65 ± 6 μeV, q=1; scale invariant spectrum]

* In $\Omega_A \sim f_A^\alpha$, the best fit α = 1.24 ± 0.04
Rather than analytical 1.187

https://axion-dm.yale.edu/

Haystac



Yale (host), UC Berkeley, CU-Boulder, & Johns Hopkins

U.S. DEPARTMENT OF ENERGY | Office of Science

QuantiSED

NSF

Wright Laboratory

Yale

ALPHA

Yale (host), ASU, UC Berkeley, Cambridge, Colorado (Boulder), Iceland, ITMO, JHU, MIT, ORNL, Stockholm, and Wellesley.

SIMONS FOUNDATION

Knut and Alice Wallenberg Foundation

Rymdstyrelsen Swedish National Space Agency

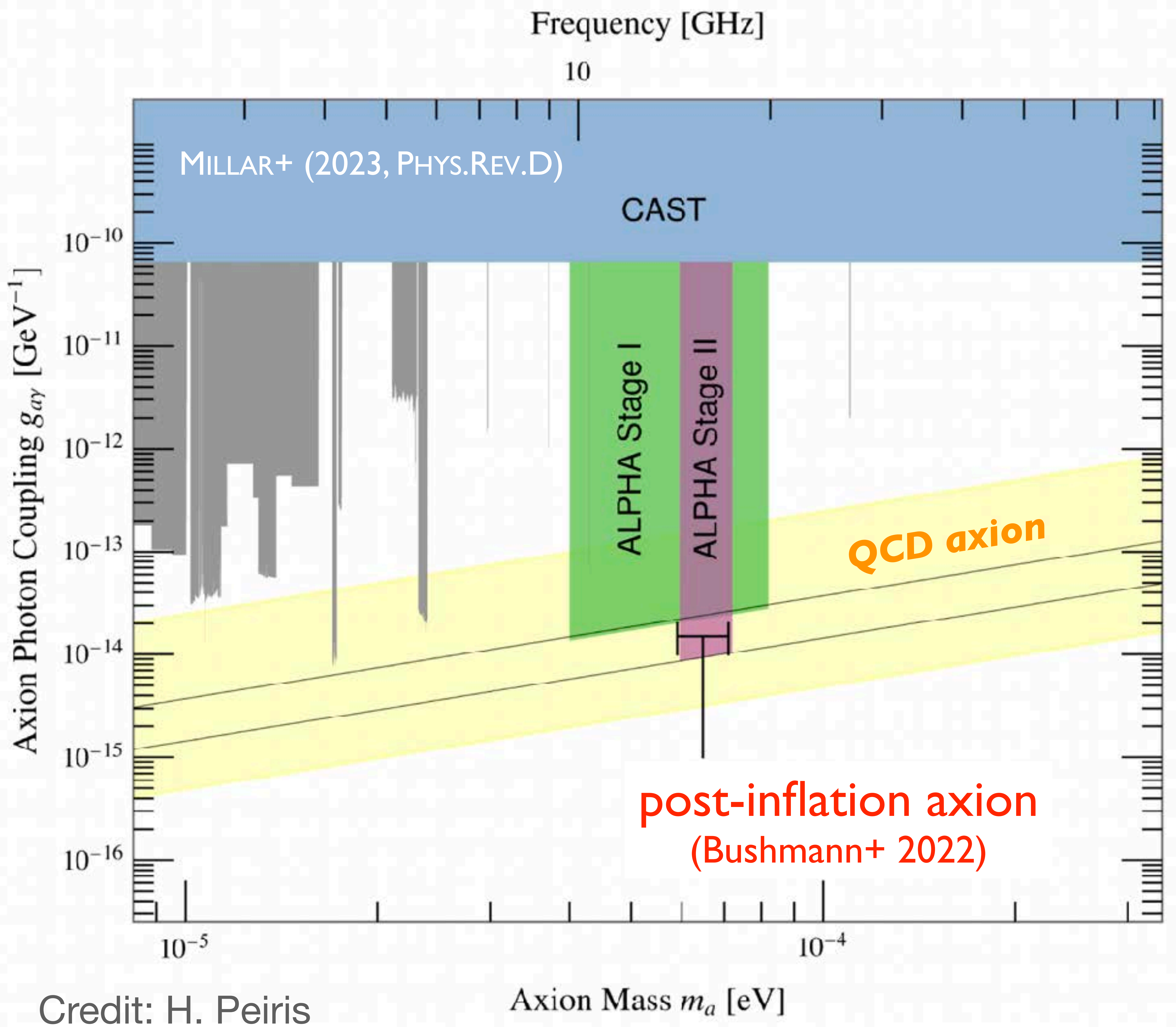
JOHN TEMPLETON FOUNDATION *Inspiring Awe & Wonder*

Swedish Research Council

Funded by the European Union

erc

ALPHA

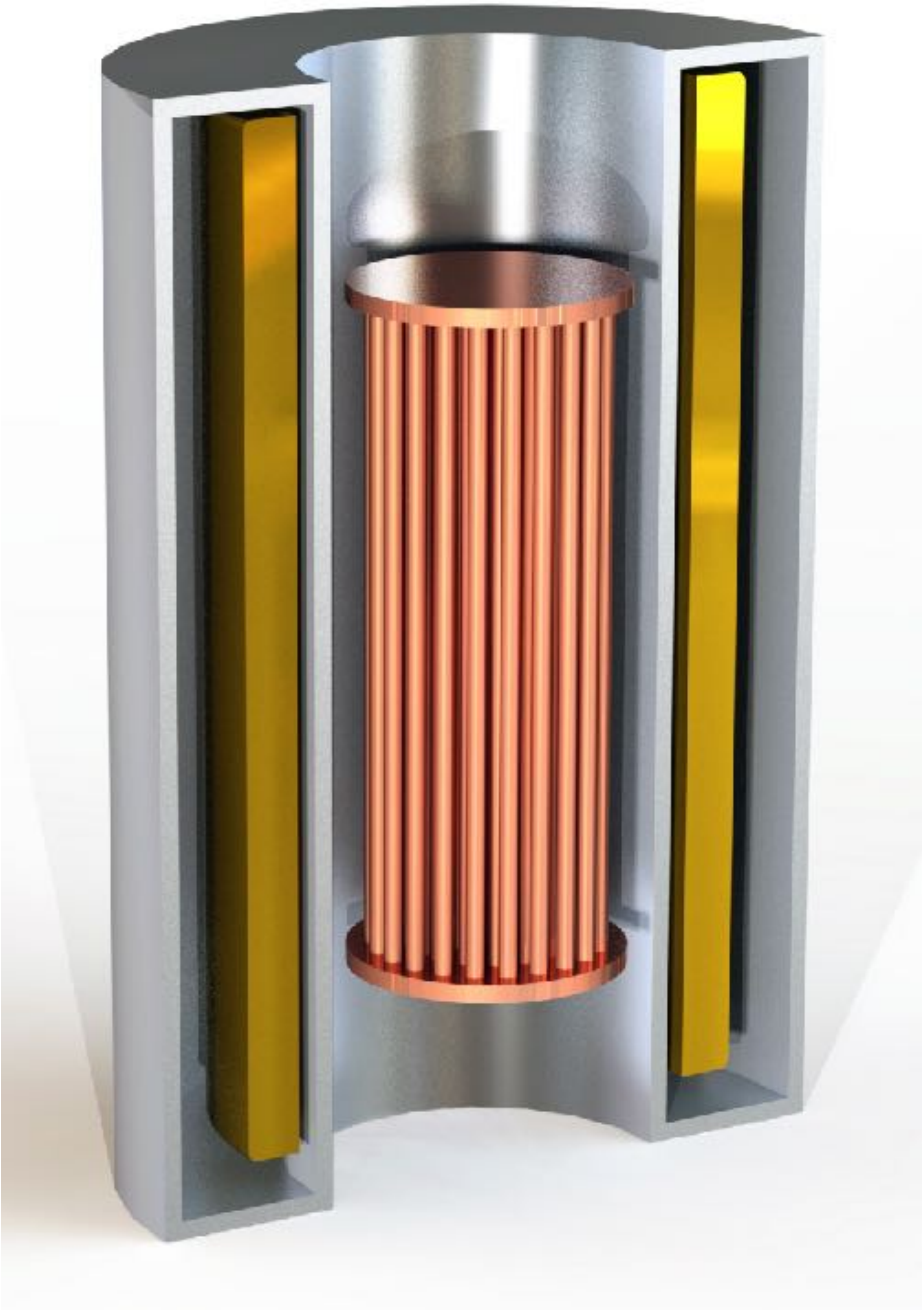


Credit: H. Peiris

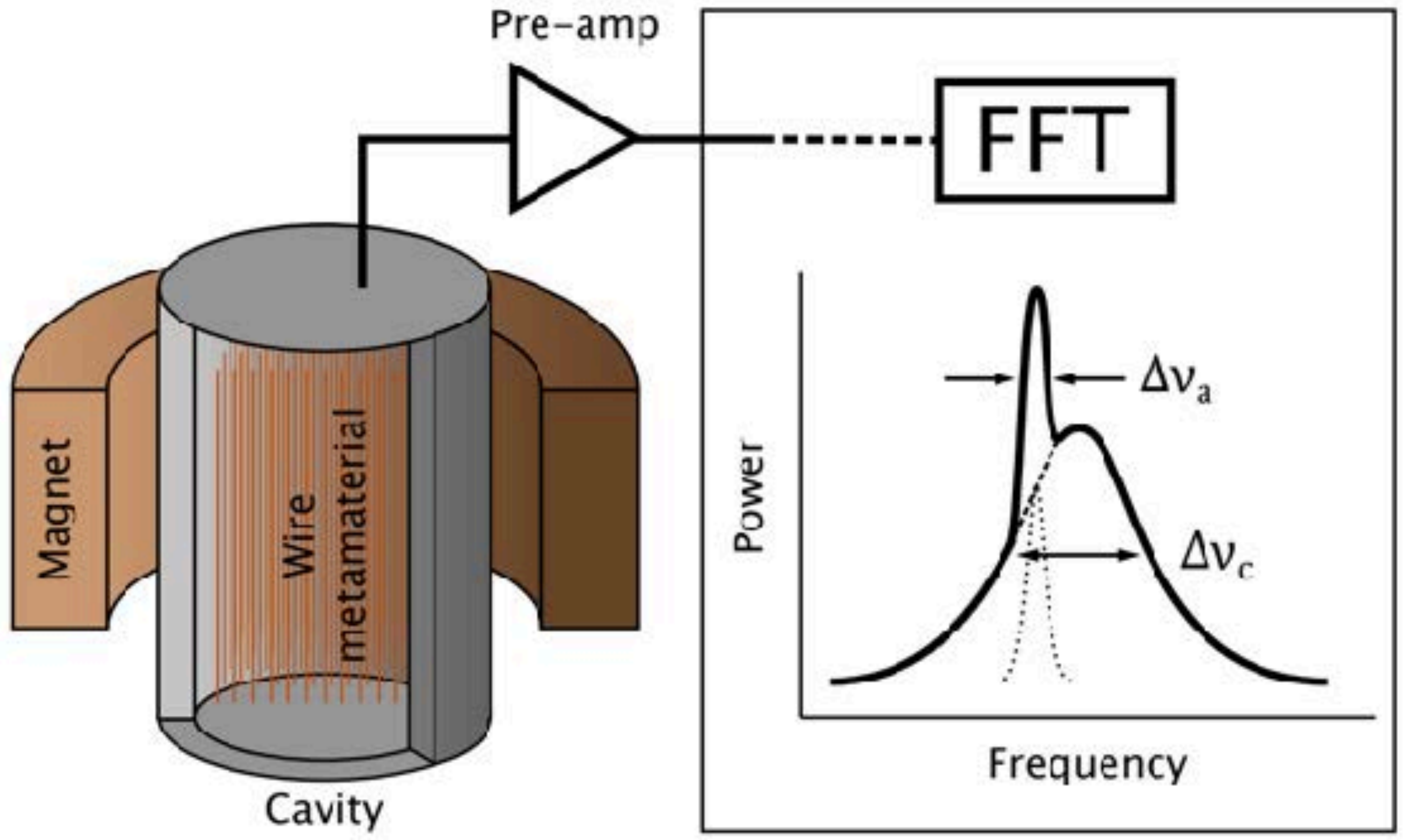
- **Post-inflation axion**: one of two well-motivated mass ranges.
- Mass is uniquely determined, limited only by computation.
- Recent calculations: **~15 GHz/65 μeV** (Buschmann+ 2022)
- Out of reach of conventional cavities but accessible to plasma haloscope
- Construction of **ALPHA** underway, experiment hosted at Yale

YALE (HOST); ASU; UC BERKELEY; CAMBRIDGE; COLORADO (BOULDER); ICELAND; ITMO; JHU; MIT; ORNL; STOCKHOLM, WELLESLEY.

Concept: Tunable Axion Plasma Haloscopes

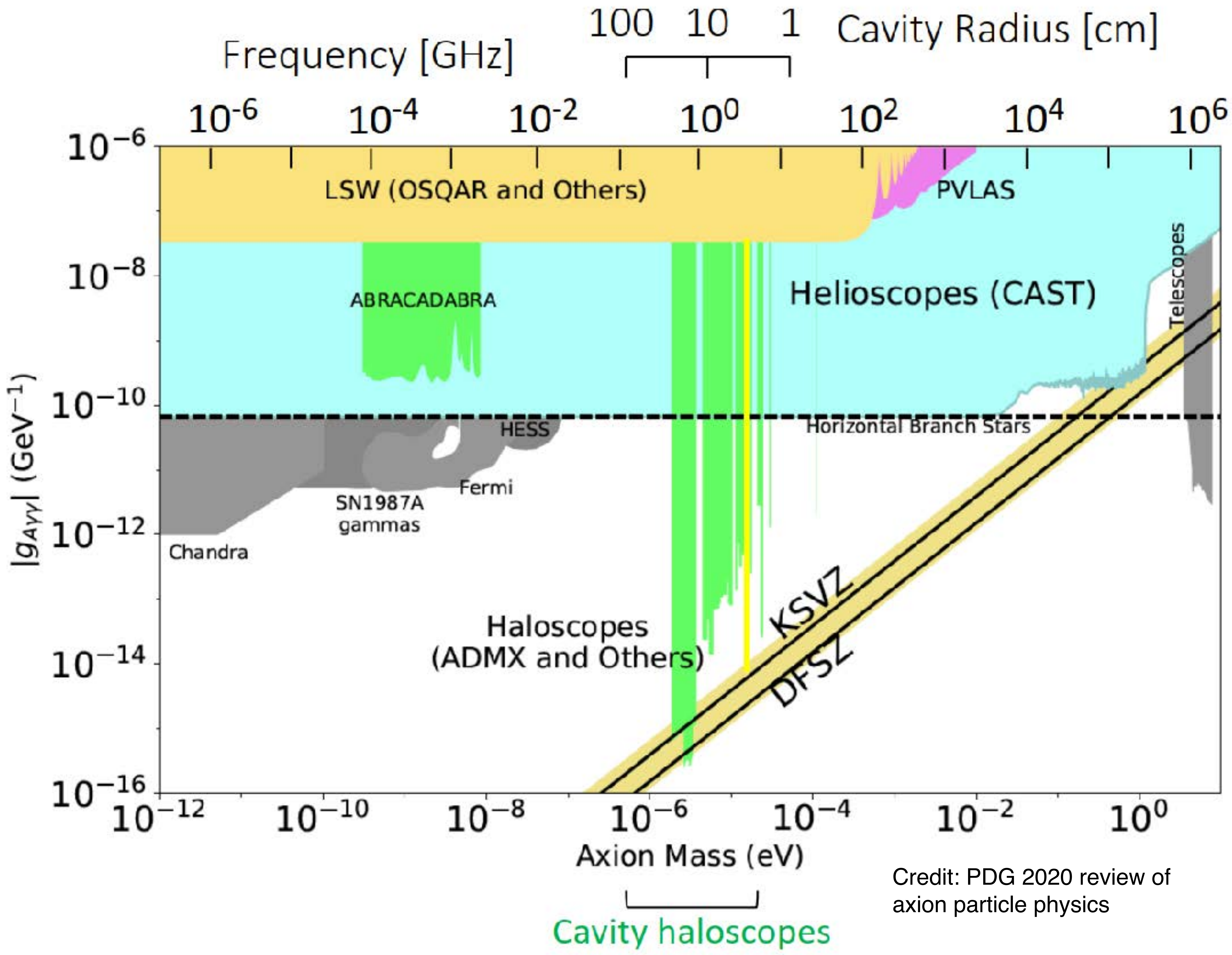


- Idea in Lawson, Millar, Pancaldi, Vitagliano & Wilczek, Phys. Rev. Lett. 123 (2019)
- Allows for larger volumes/higher power for high frequencies than traditional approaches
- + HAYSTAC-like quantum detectors for readout



Kowit et al, *Phys.Rev.Applied* 20 (2023)

Large mass → small volume

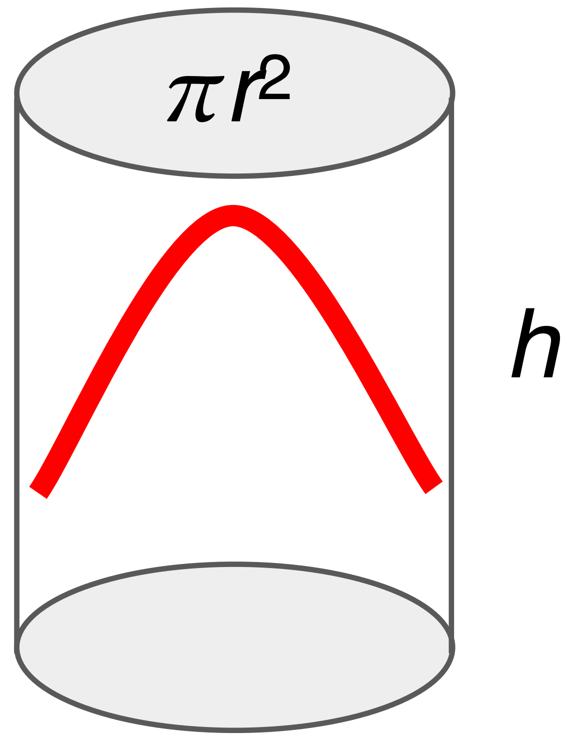


Credit: PDG 2020 review of axion particle physics

The power produced in a haloscope:

$$P = \kappa \mathcal{G} V \frac{Q}{m_a} \rho_a g_{a\gamma}^2 B_e^2$$

Volume = $h\pi r^2$



m_a = (4.1 µeV) ⨉ (f / GHz)

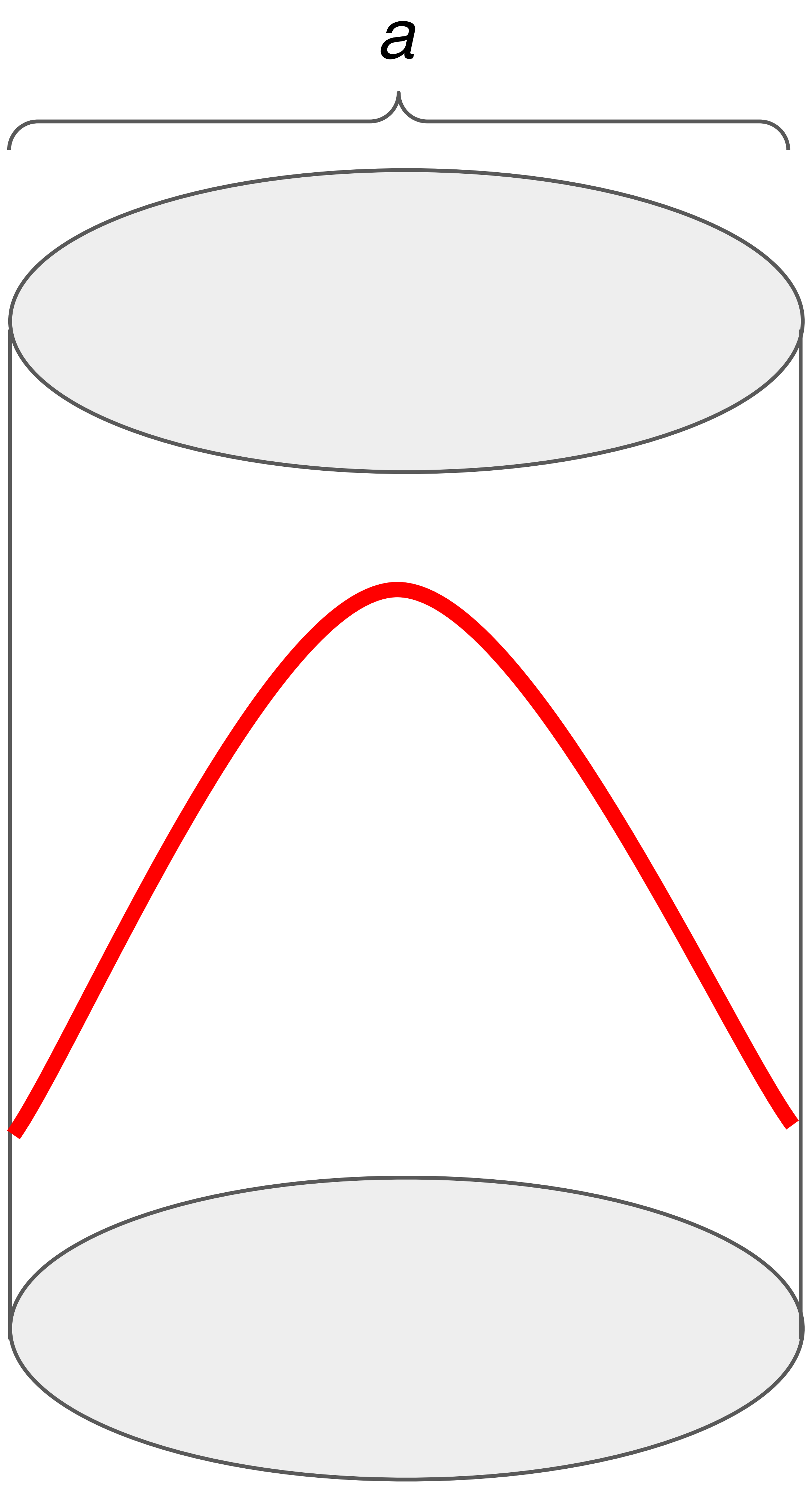
$$(f)_{TM_{010}} = \frac{2.405}{2\pi a\sqrt{\mu_0\epsilon_0}} = \frac{0.115}{a}\ \mathrm{GHz}$$

For a = 1.15 cm, we get f = 10 GHz

Credit: J. Gudmundsson

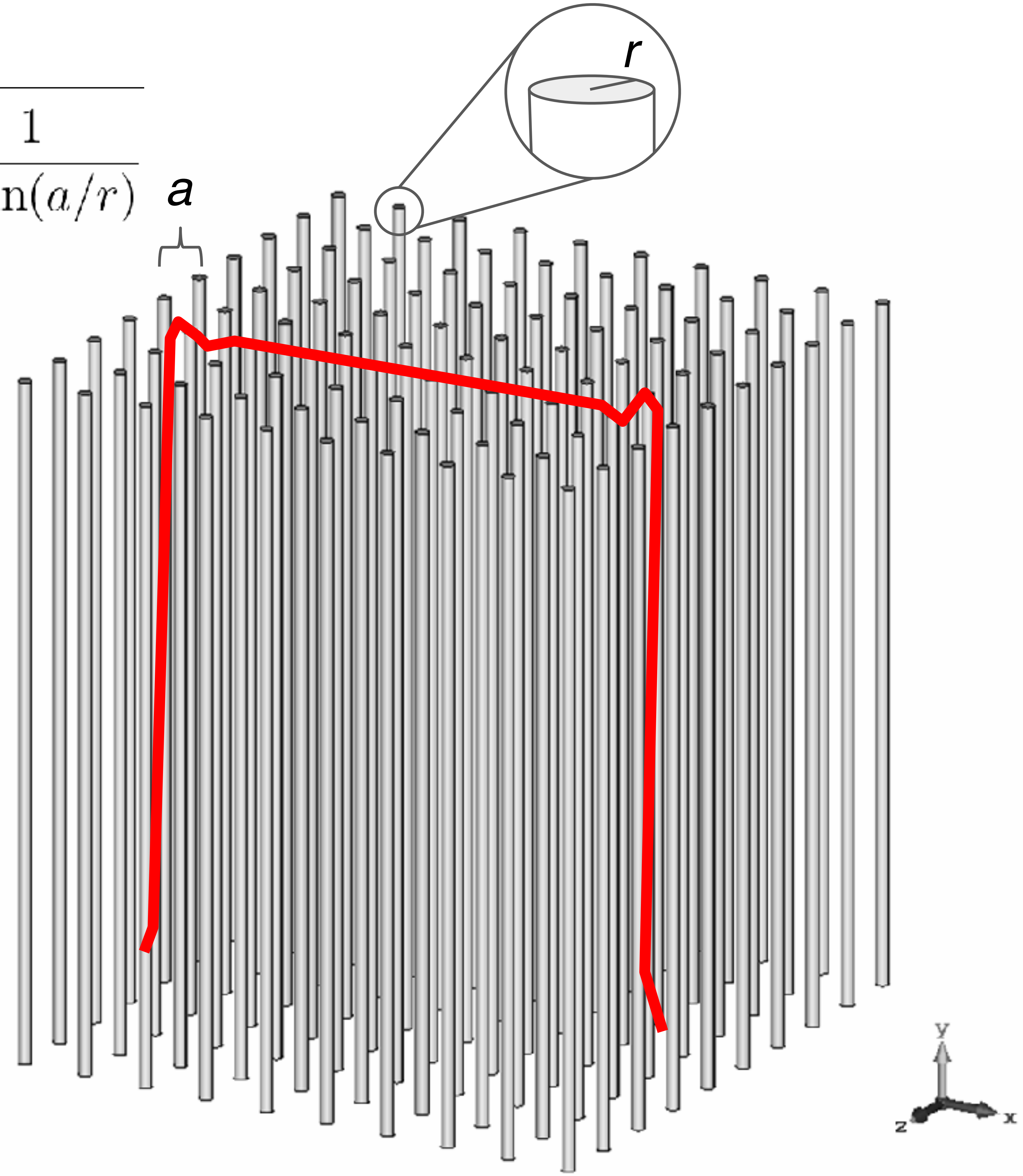
Solution: plasmonic resonance

$$f = \frac{2.405}{2\pi a\sqrt{\mu_0\epsilon_0}}$$



Sikivie (1983), PRL

$$f = \frac{c}{a}\sqrt{\frac{1}{2\pi\ln(a/r)}}$$



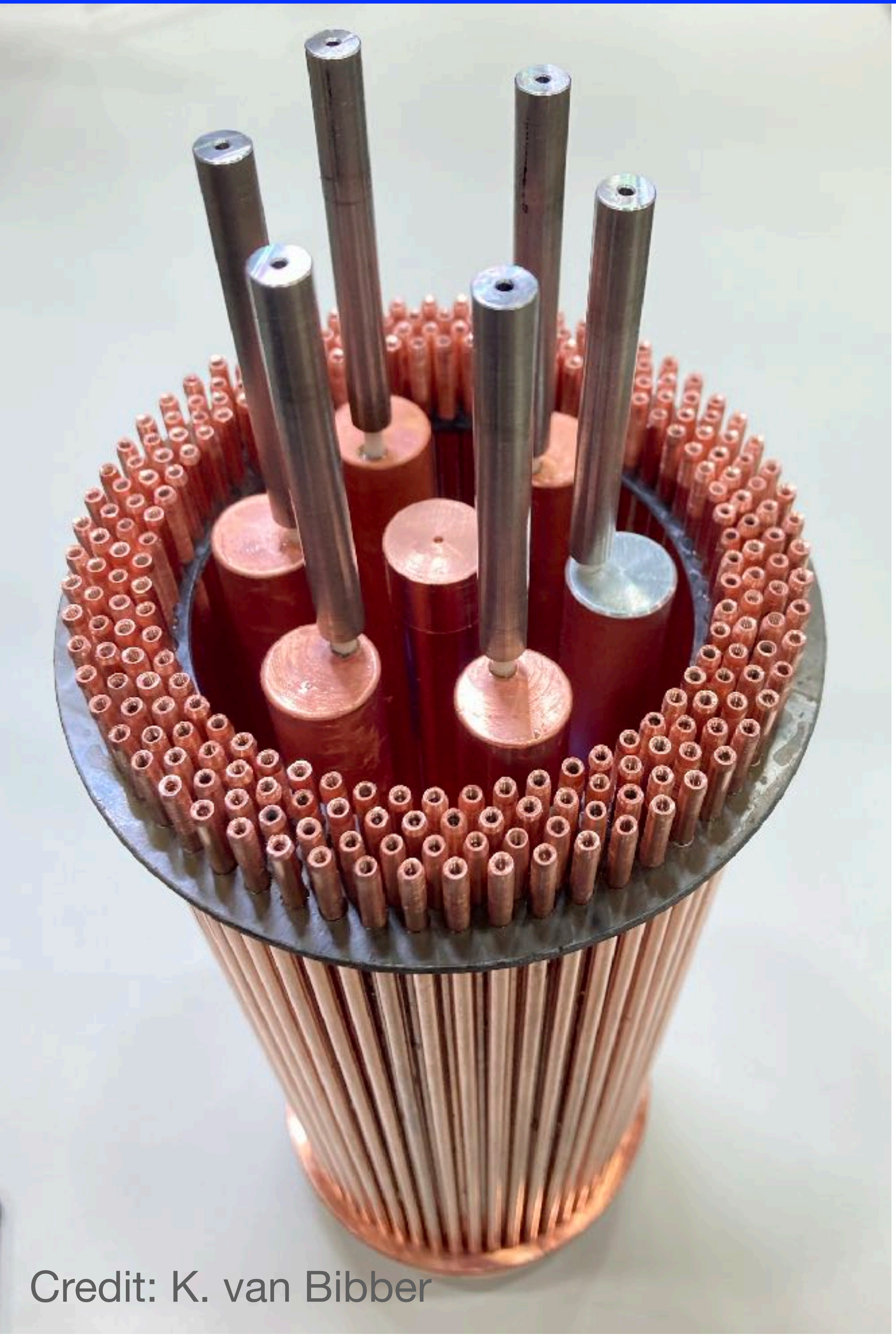
Lawson et al. (2019), PRL

Credit: J. Gudmundsson

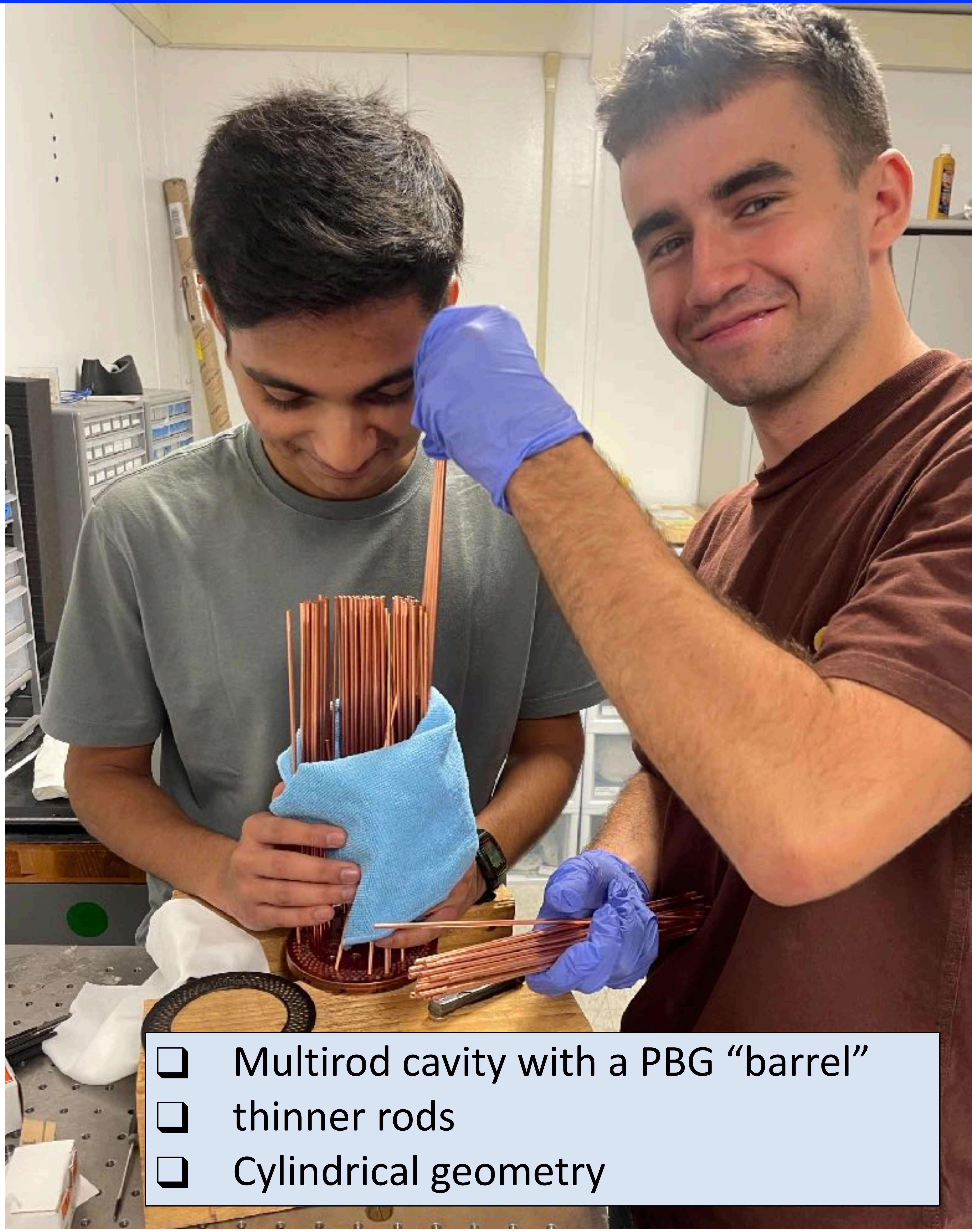
Berkeley resonator prototype


Stockholm resonator prototype

ALPHA resonators will require incorporating Photonic Band Gap structues

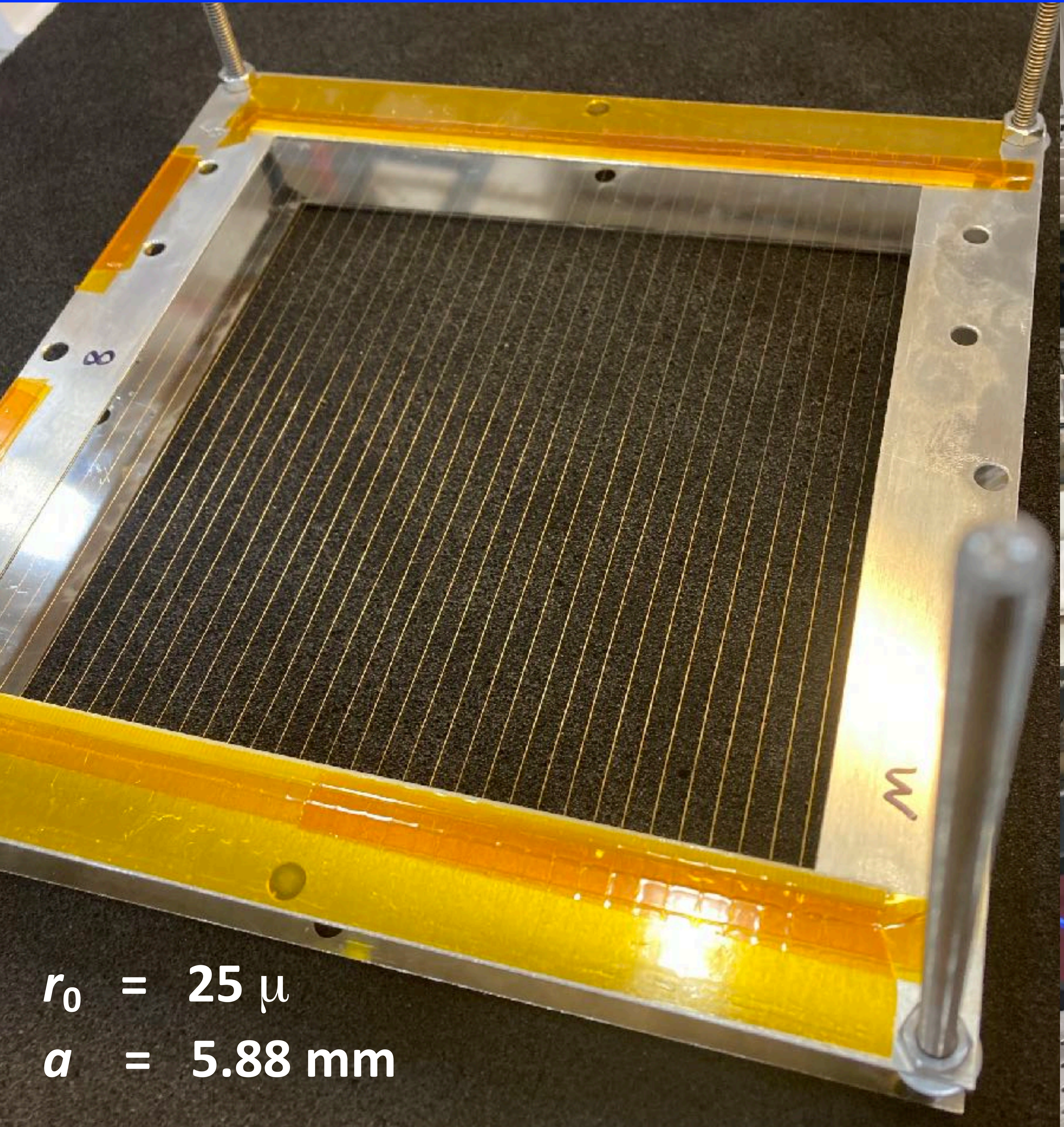


Credit: K. van Bibber



- ❑ Multirod cavity with a PBG "barrel"
- ❑ thinner rods
- ❑ Cylindrical geometry

Resonators for >20 GHz will require superconducting wire array metamaterials

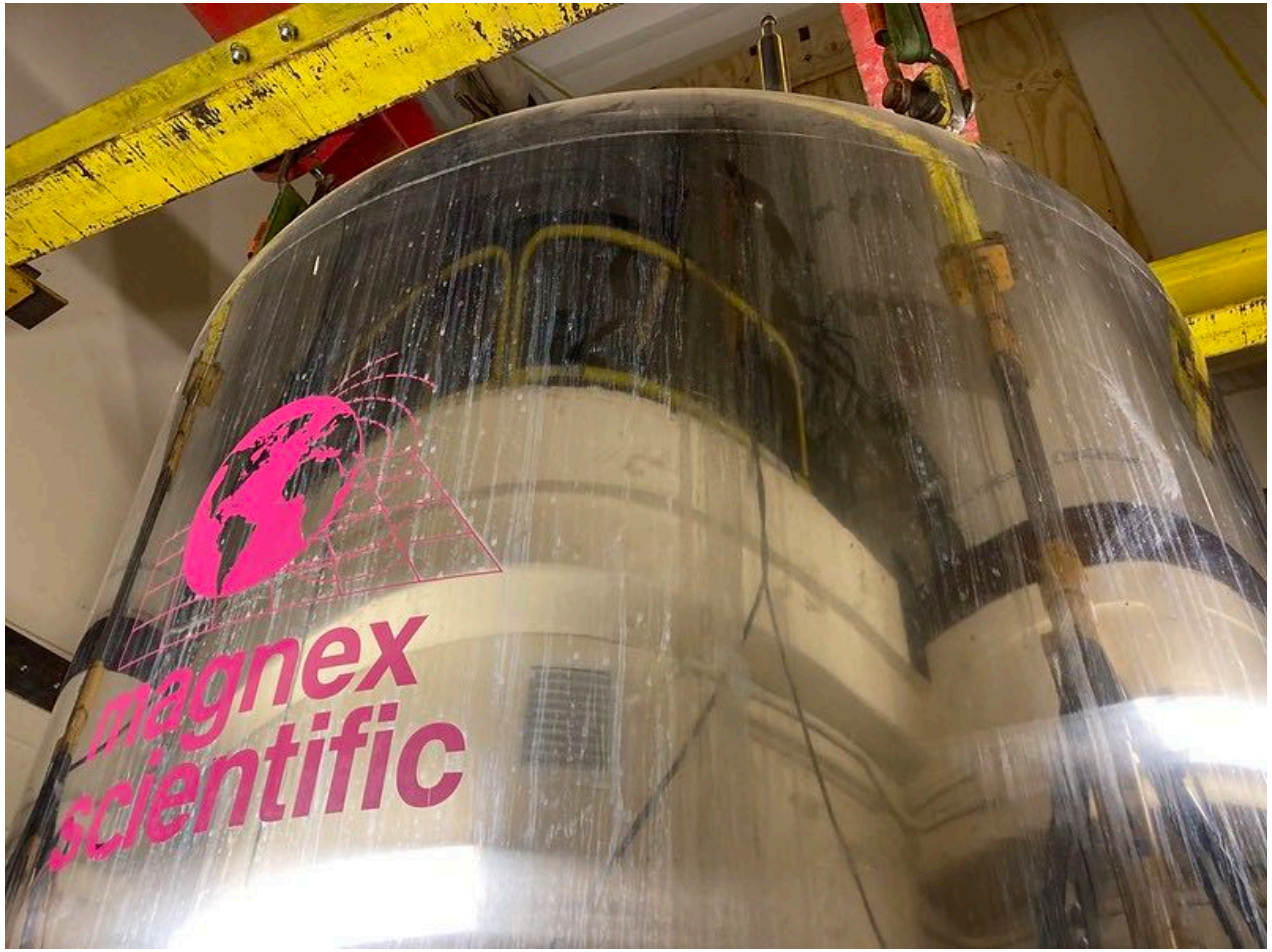


Credit: K. van Bibber

Site: Wright Lab @ Yale

Yale Wright Laboratory

Magnet

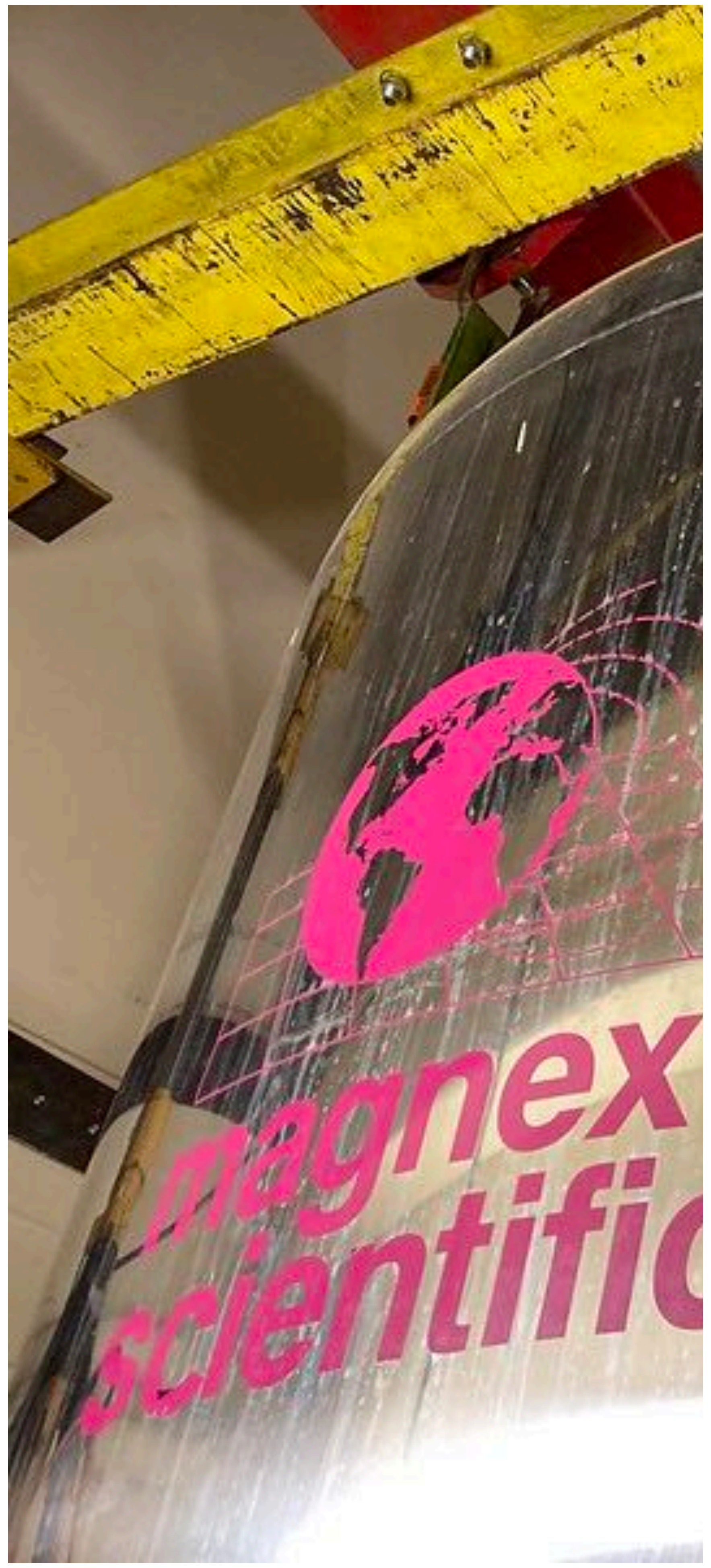


Magnet

Magnet

Magnet

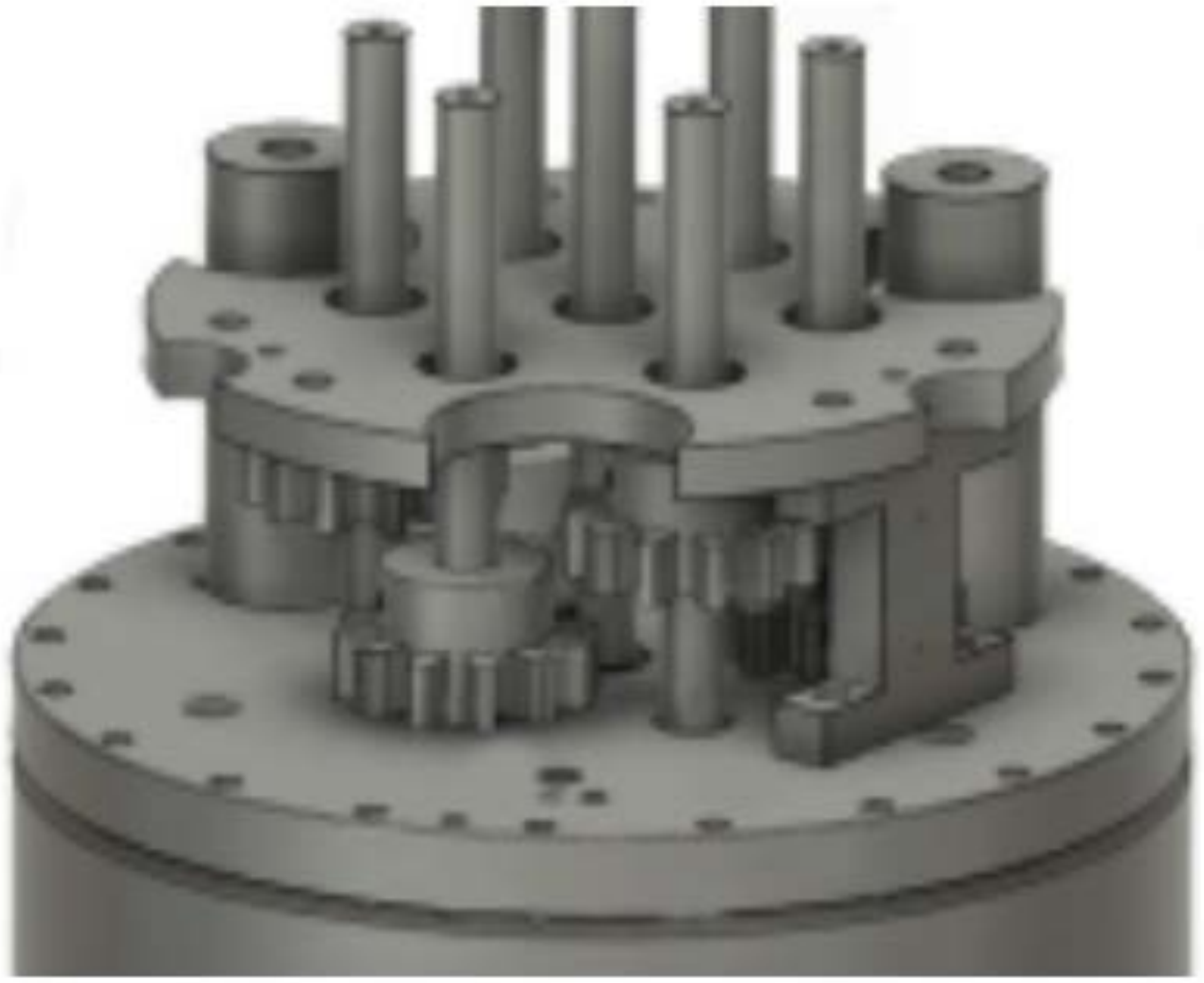
Magnet



Next set of innovations

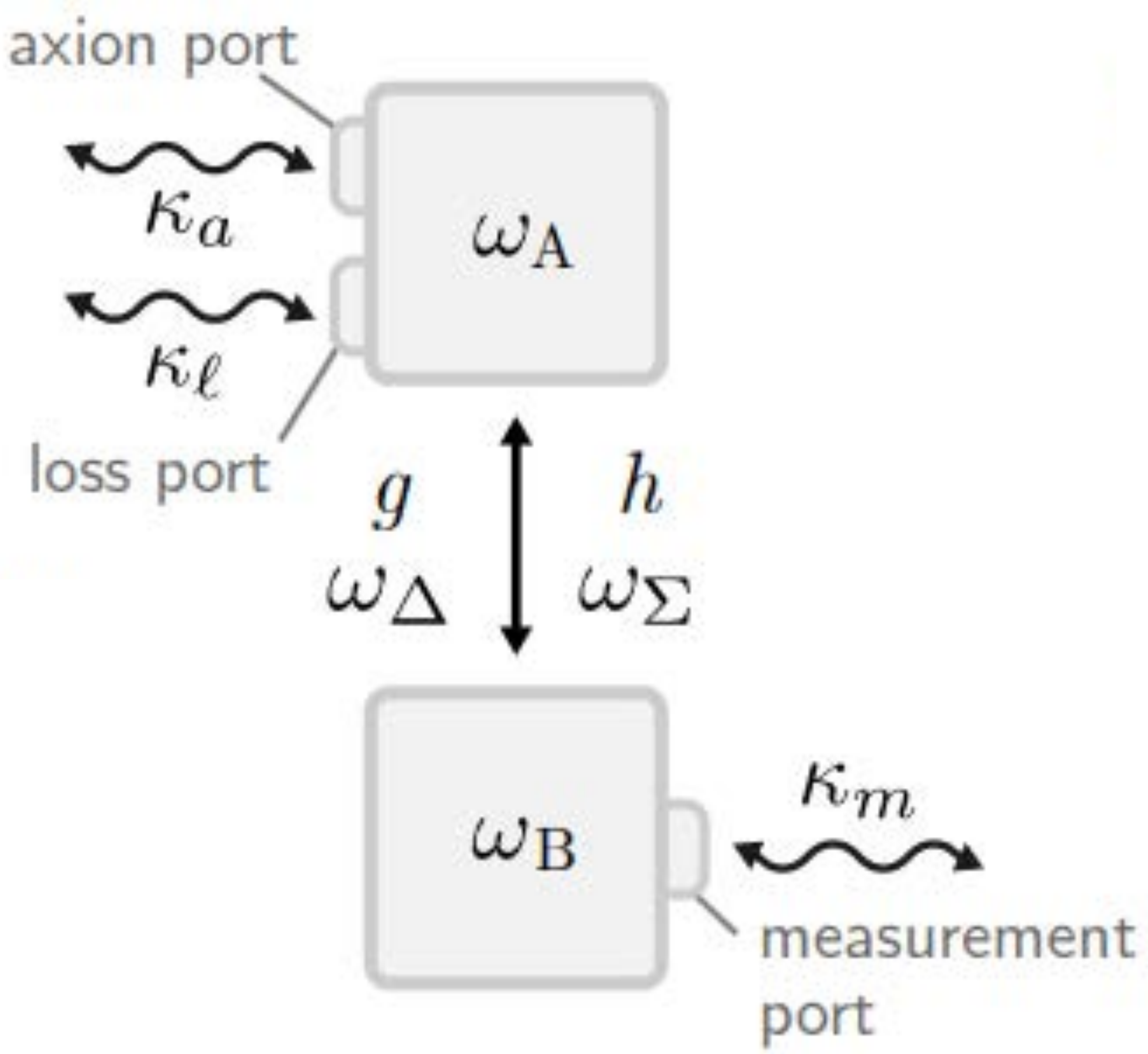
Multi-Rod Cavity

Same Radius but extend >6GHz



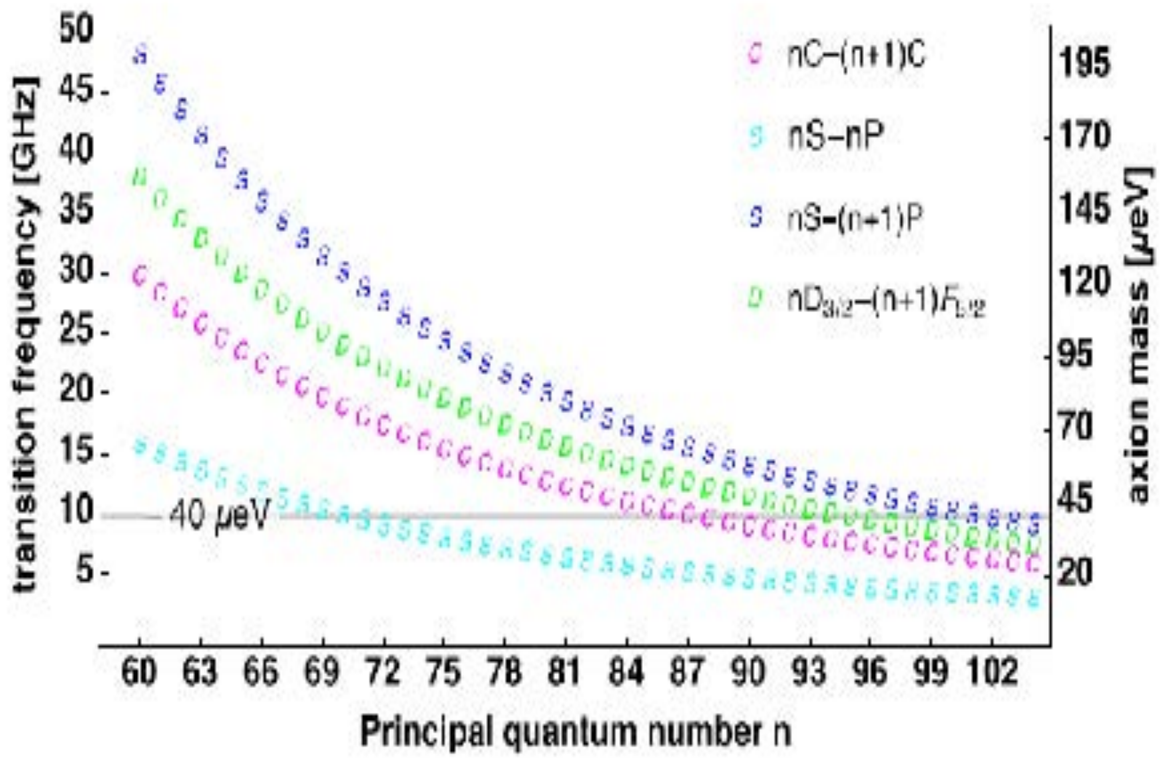
CEASEFIRE

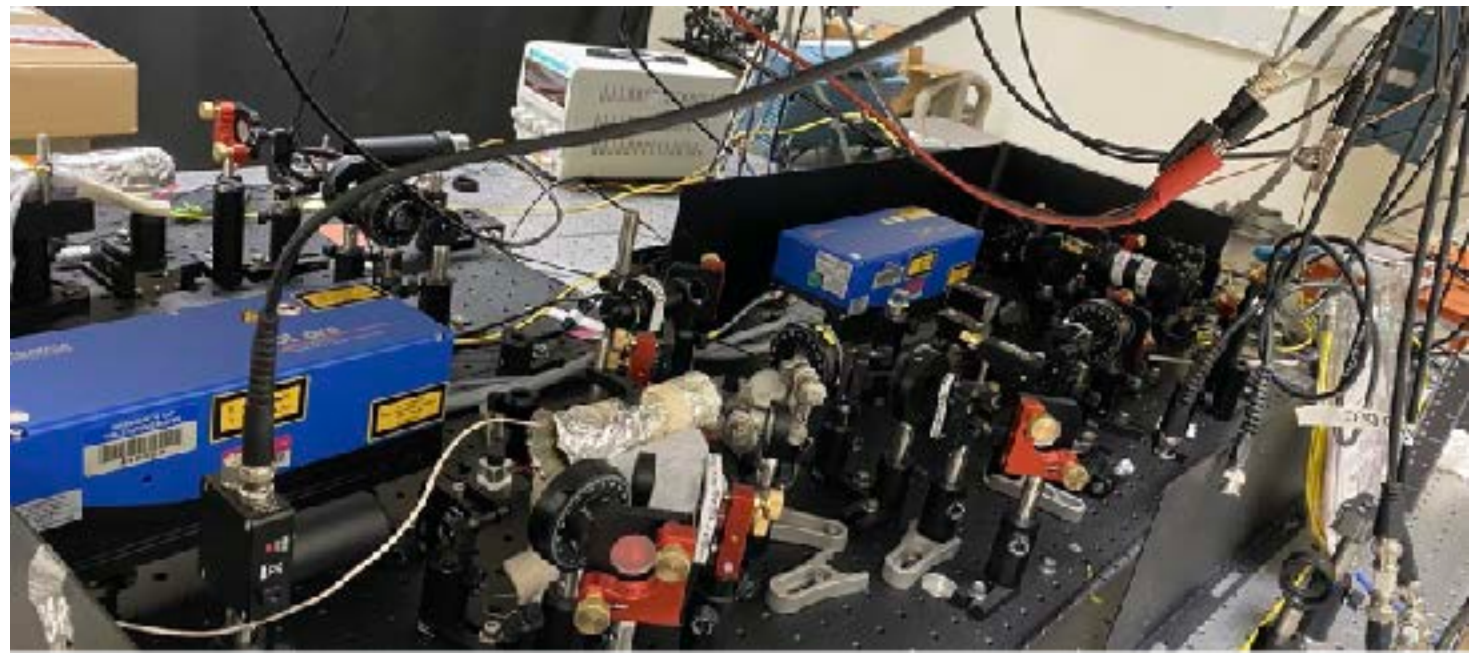
Improve the level of squeezing we achieve



RAY

Use Rydberg atoms as single photon counters for > 10GHz



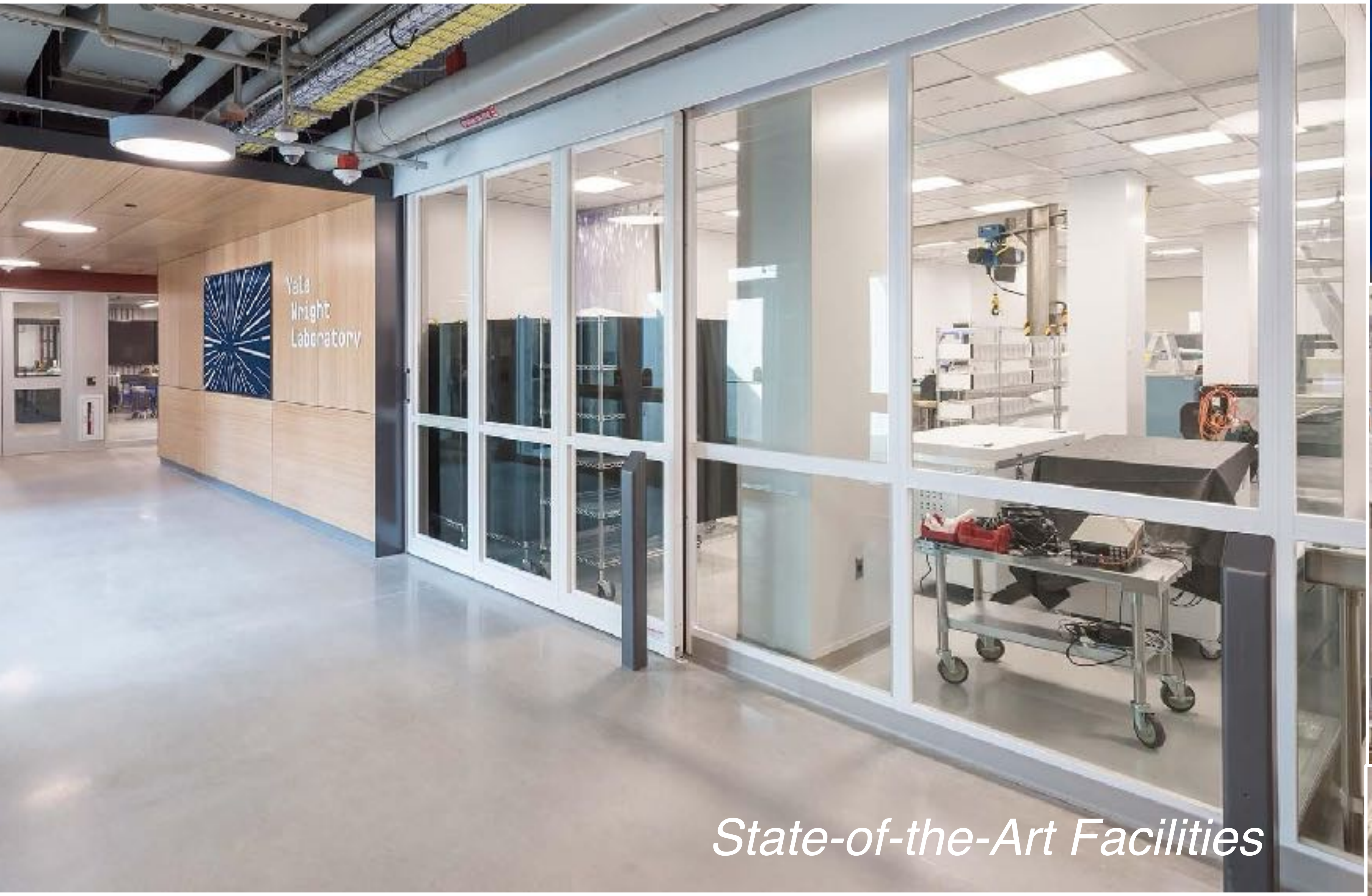


Credit: M. Jewell

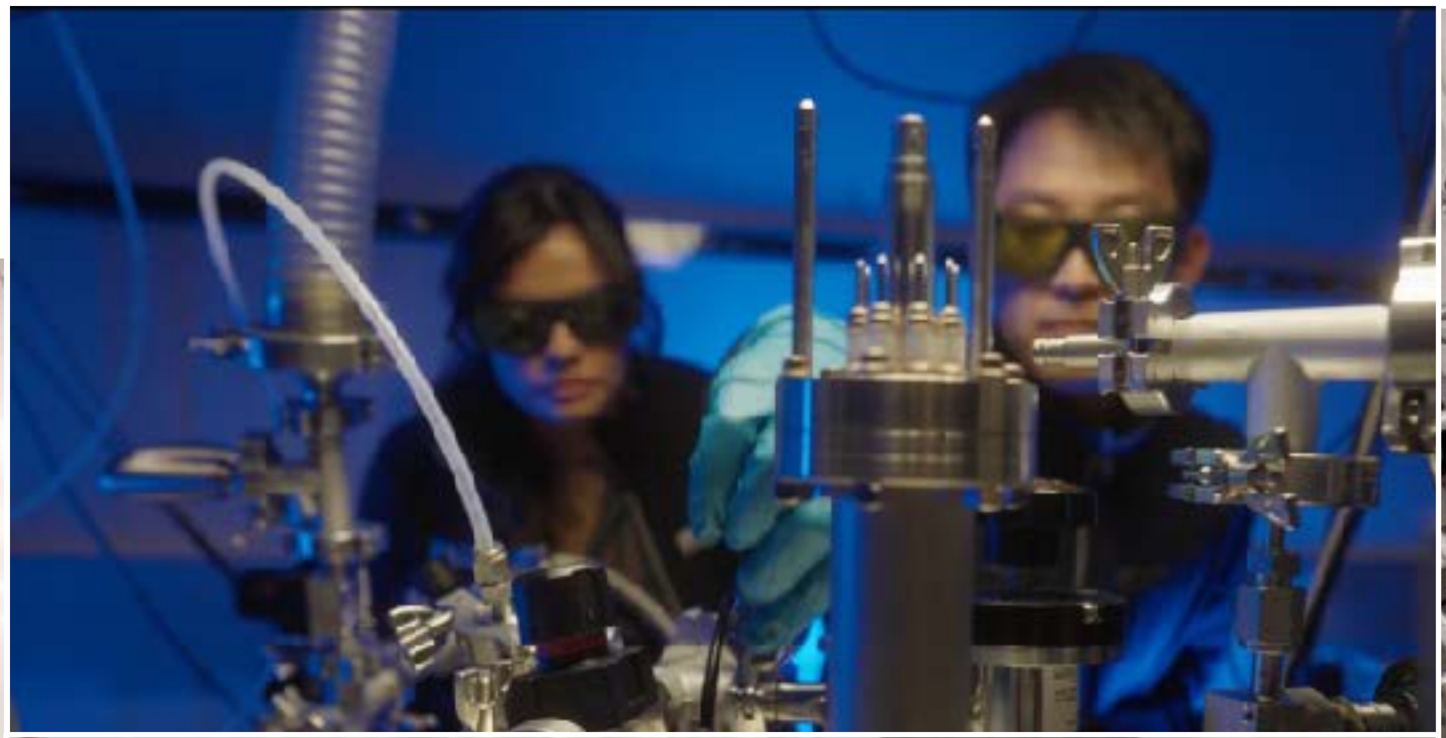
Yale Wright Laboratory

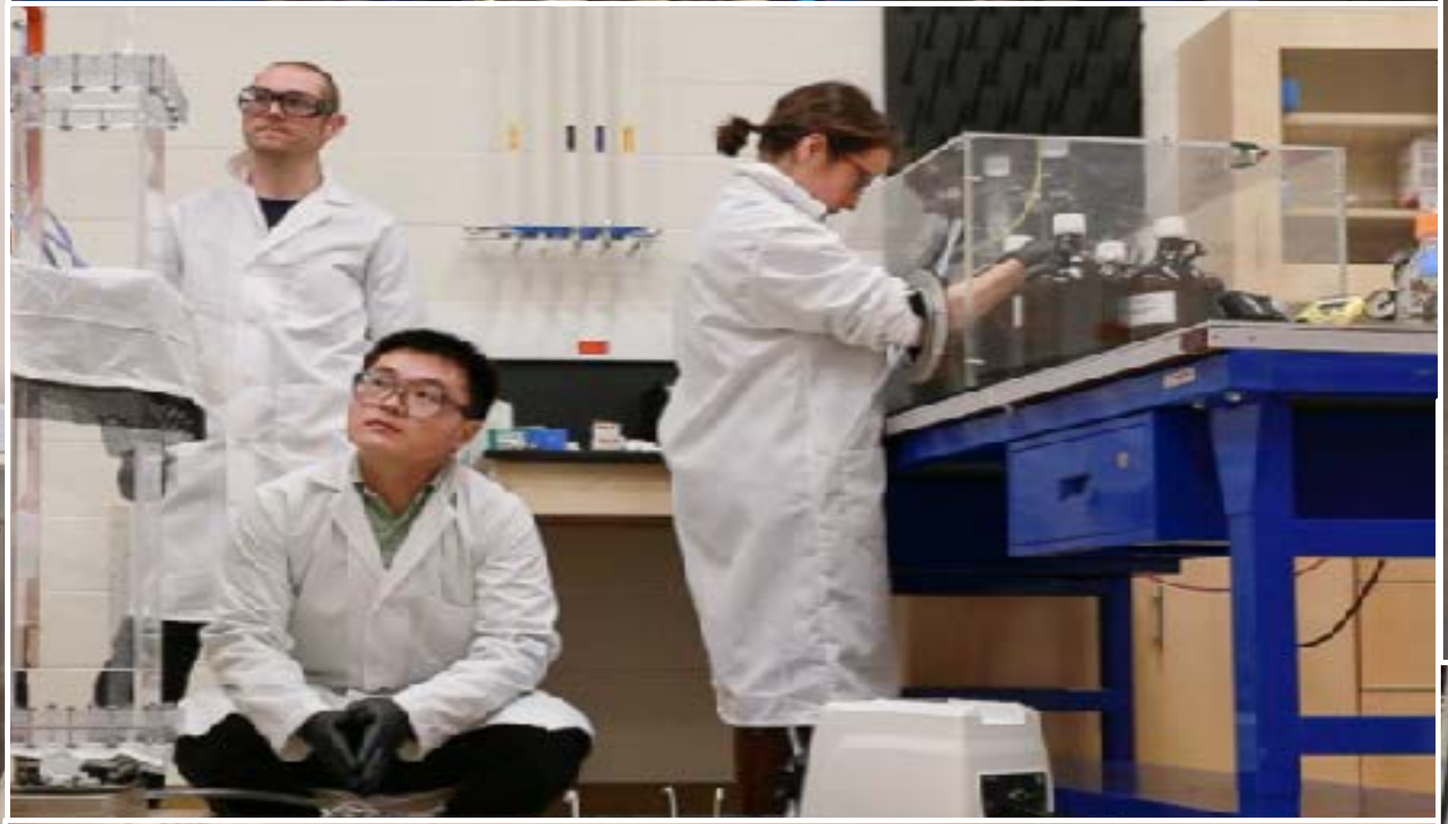
Developing Tools for Discoveries

Exploring the Invisible Universe

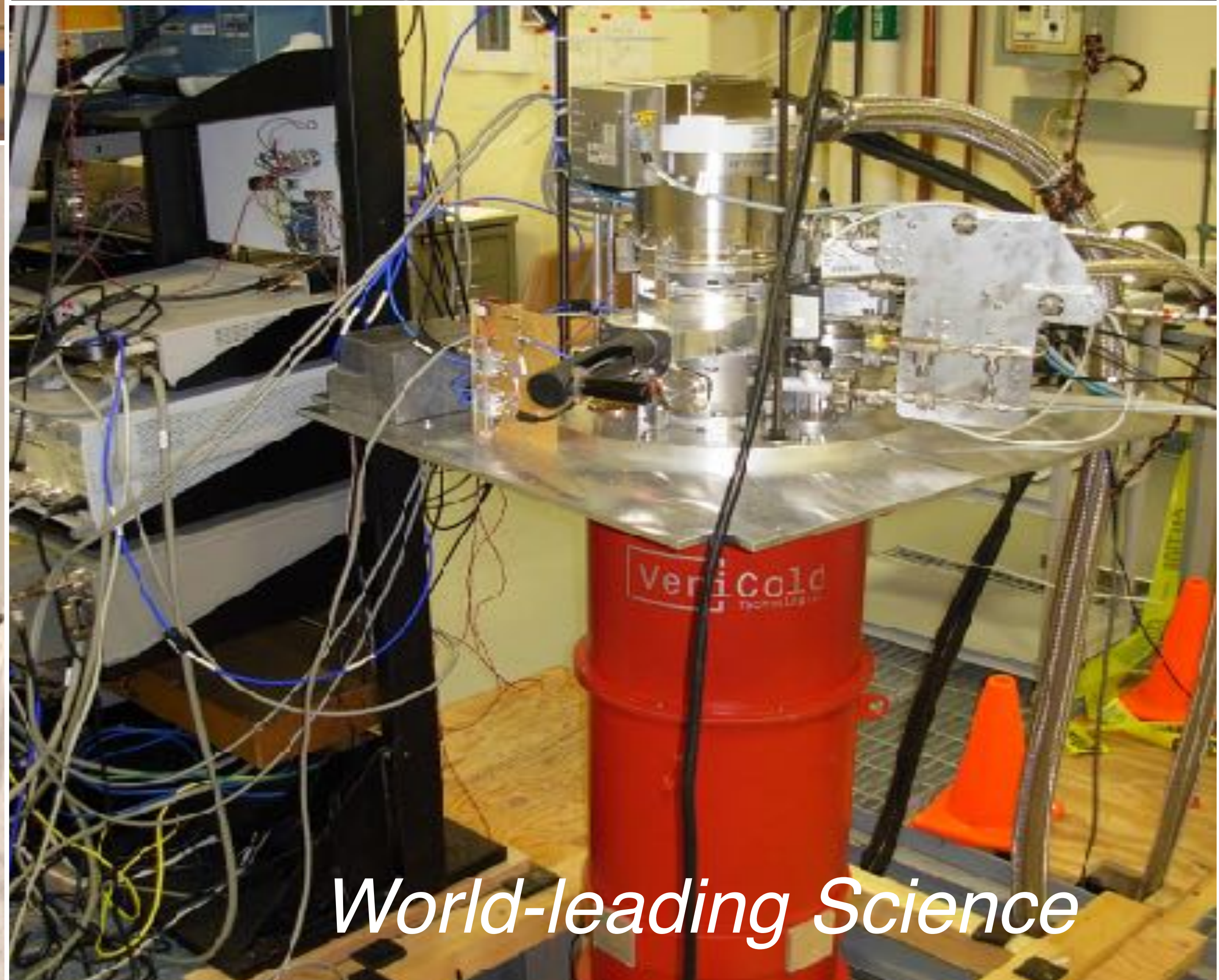


State-of-the-Art Facilities






Training Future Scientists

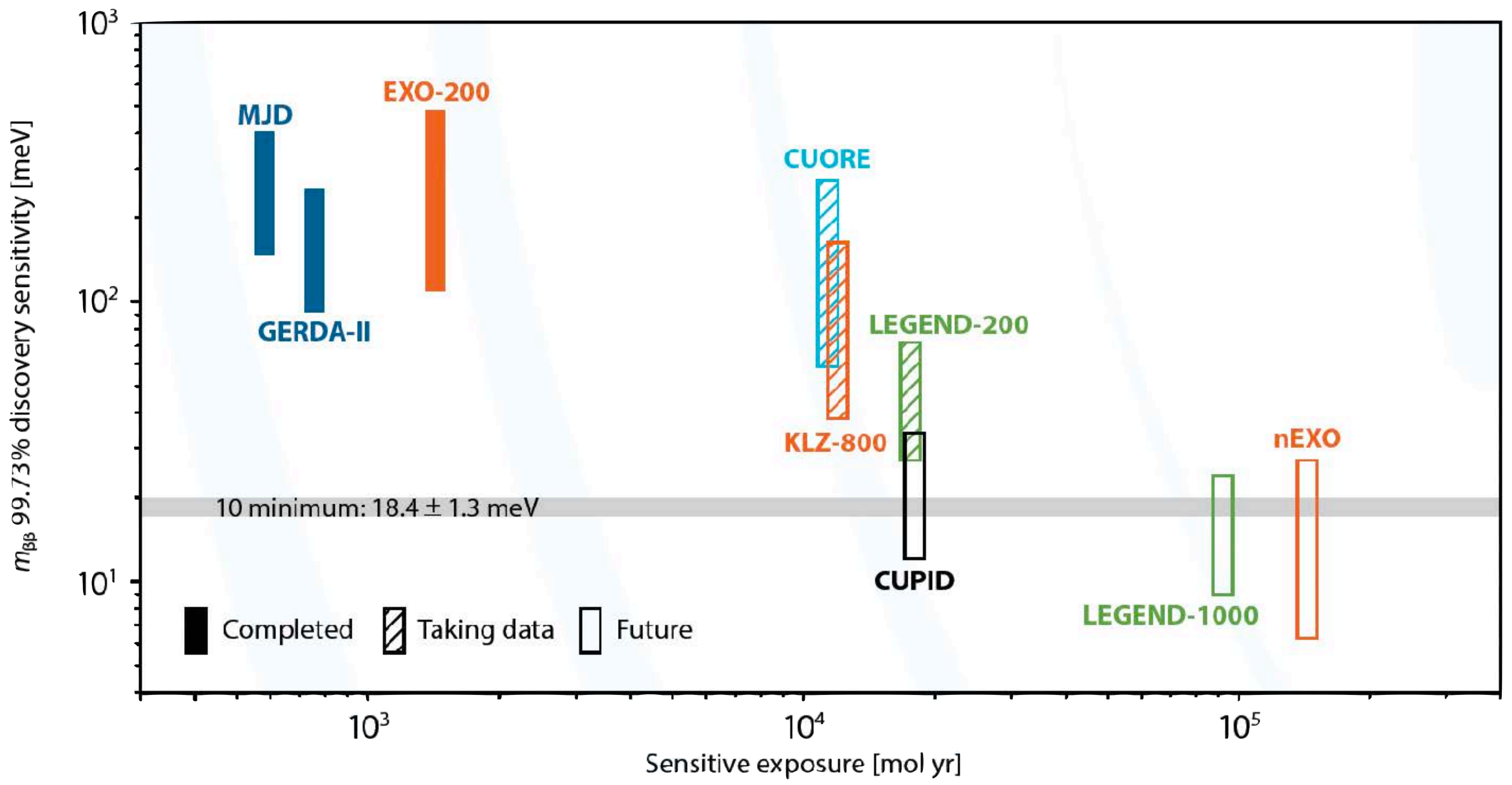


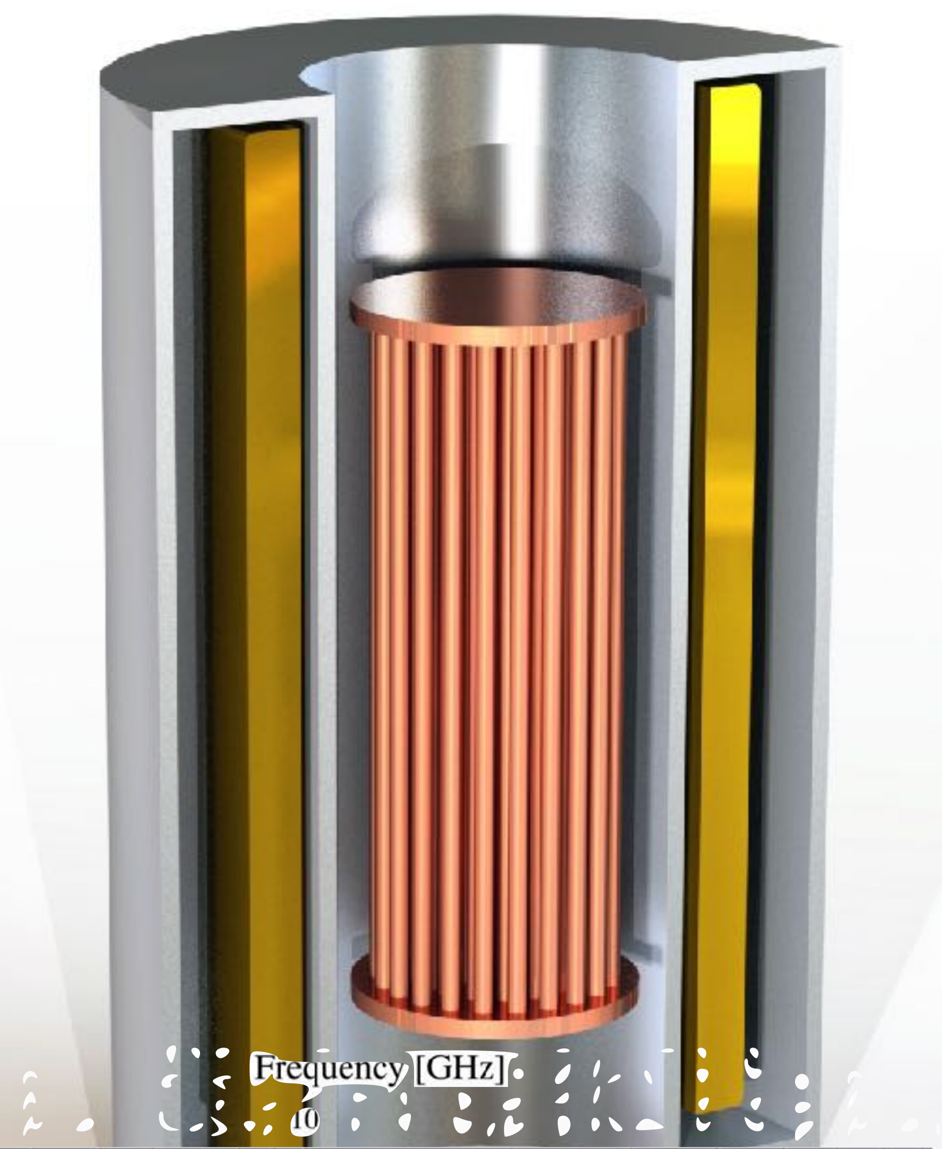
World-leading Science

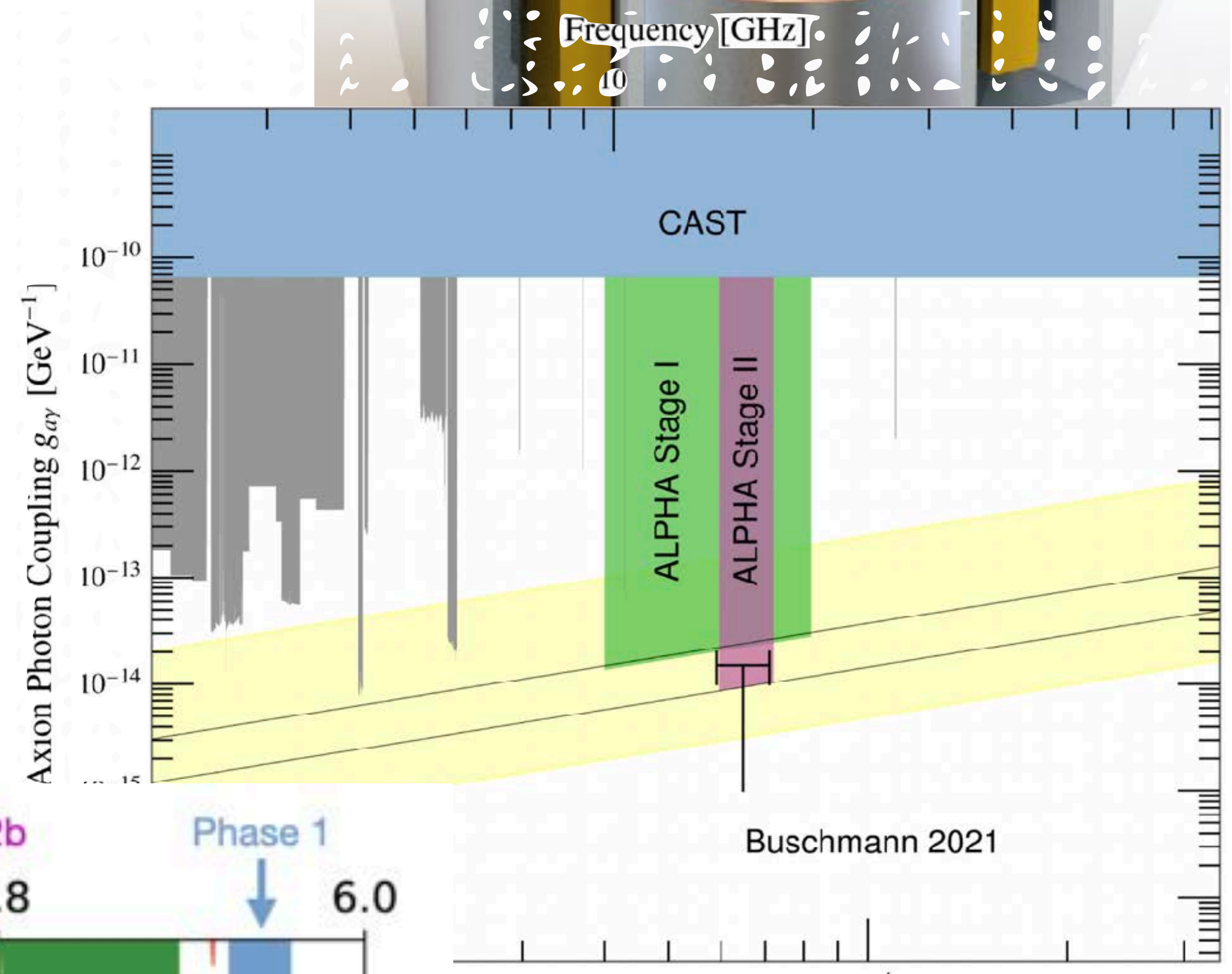
Advancing frontiers of nuclear, particle, and astrophysics including studies of **neutrinos**; searches for **dark matter**; understanding **matter**; exploration of **quantum science** and observations of **the early Universe**.

https://wlab.yale.edu

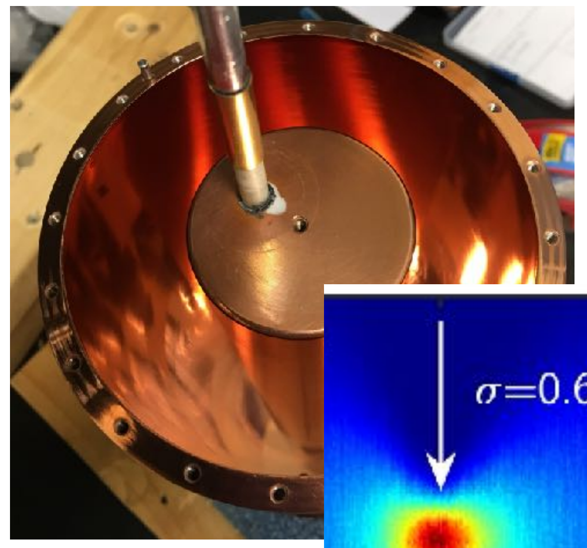
Summary & Outlook

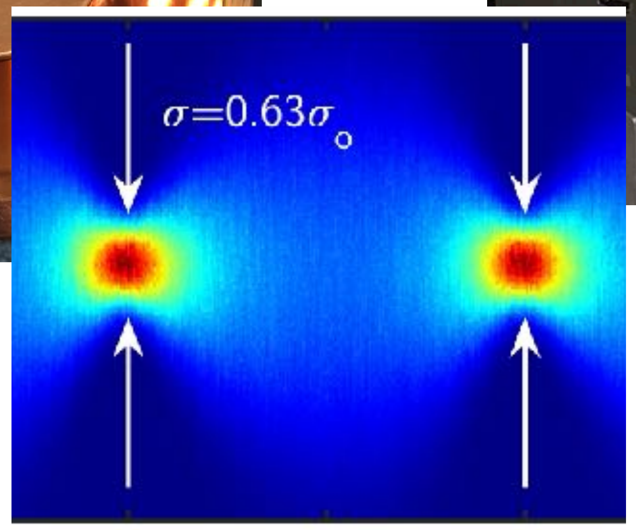


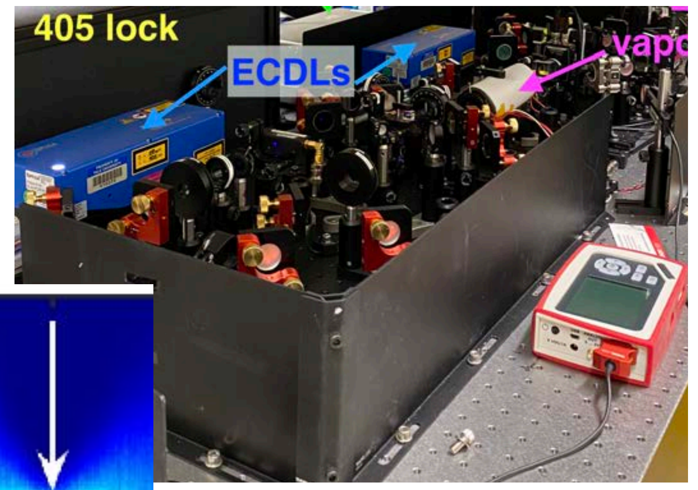


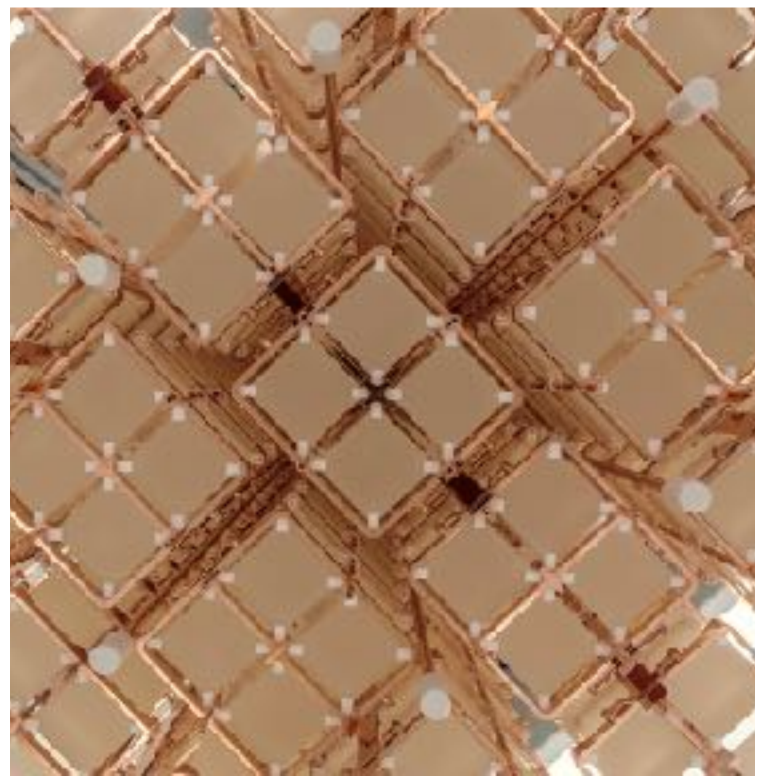


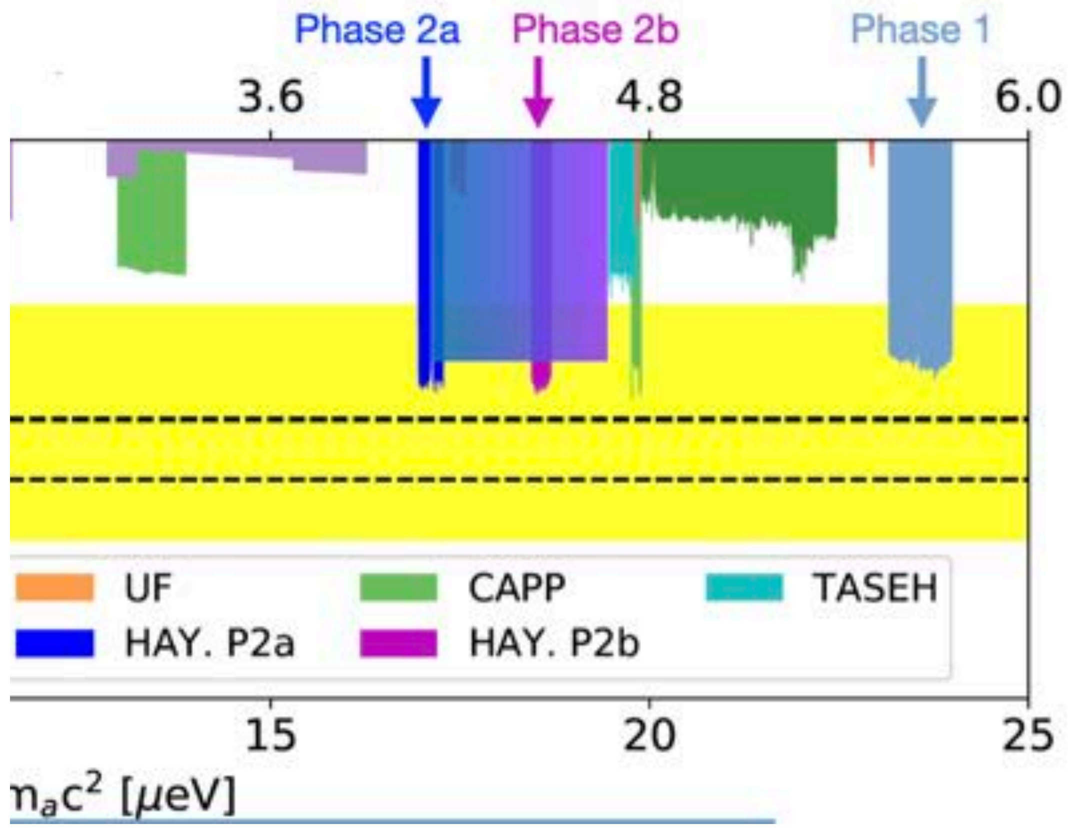
- Neutrinos
  - Neutrinoless double beta (0νββ) is a powerful probe of lepton number violation
- Exciting developments in dark matter
  - Is DAMA seeing dark matter?
  - Axions: New experiments, new ideas, new people

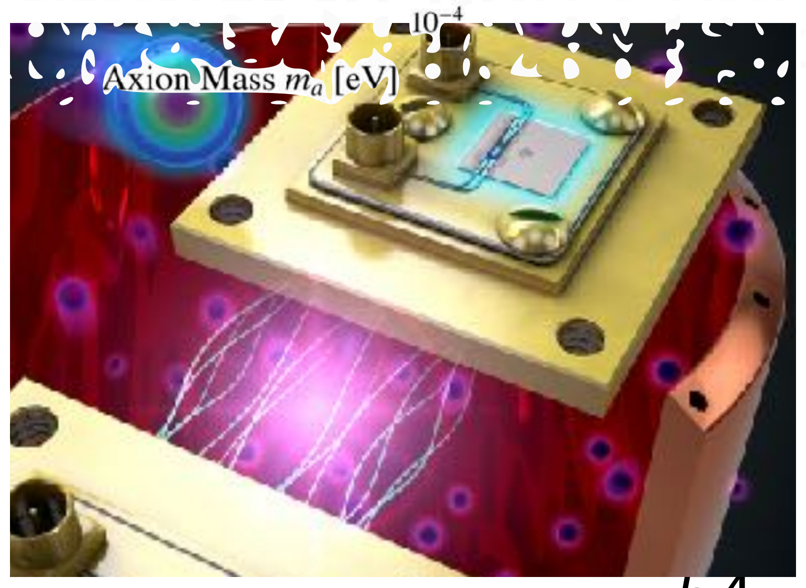













COSINE62
John Barton Building
Dark Matter Research