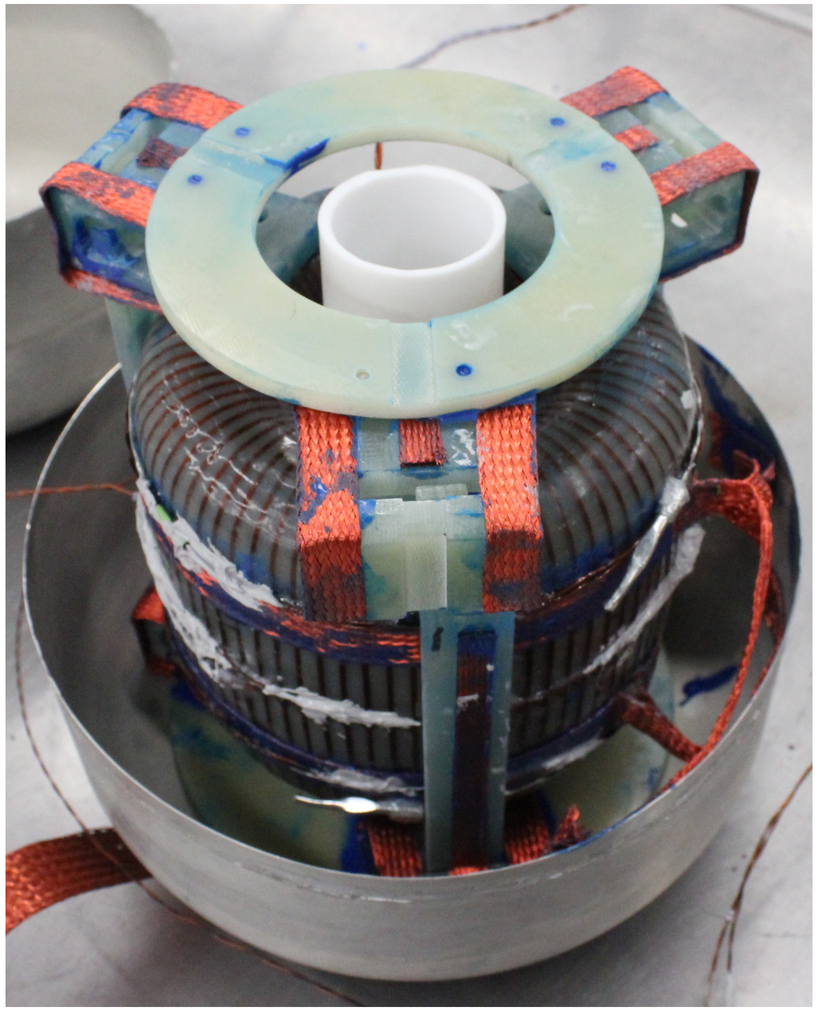
THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

TUNL



A Tale of Two Axion Searches

Reyco Henning
University of North Carolina at Chapel Hill
Triangle Universities Nuclear Laboratory

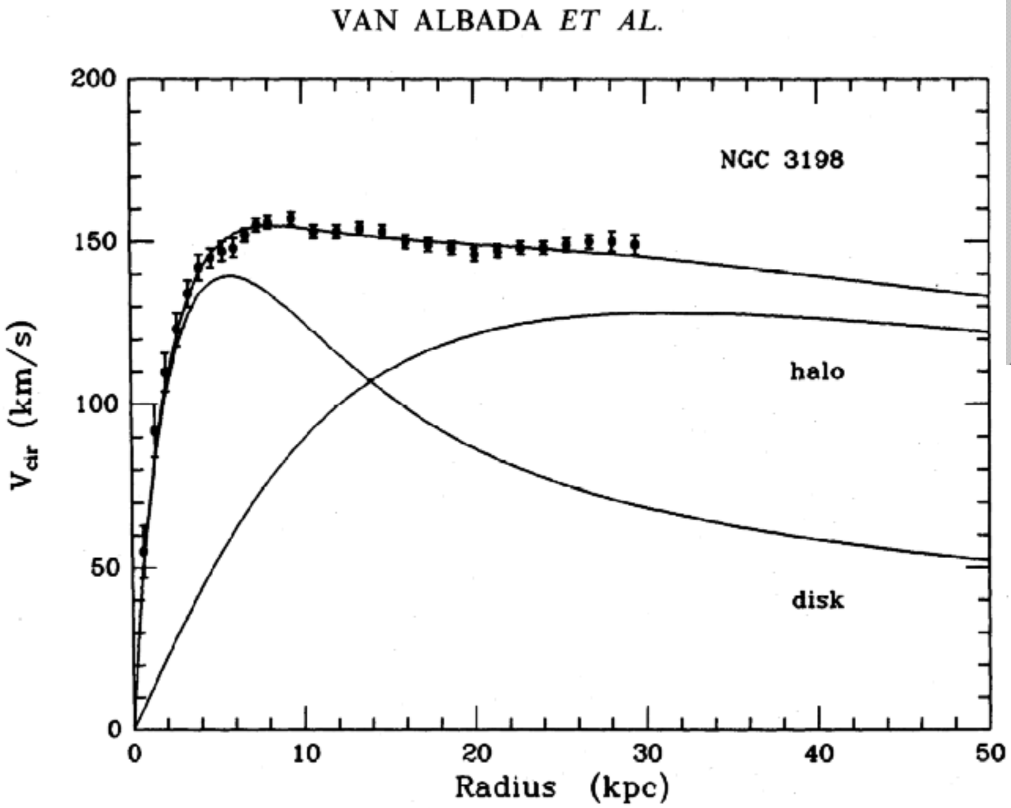
Outline

- Brief History and Motivation for Axions
- ABRACADABRA
  - Concept
  - Results from 10cm prototype
  - Future Plans
- MAJORANA DEMONSTRATOR
  - Neutrinoless Double Beta Decay
  - Experimental Description
  - Searches for Bosonic Dark Matter
- Conclusions

Evidence for Dark Matter is Gravitational

- Galactic Rotation Curves
- Peculiar velocities of galaxies in clusters
- X-Ray emission of hot gas in clusters.
- Weak gravitational lensing
- Cosmic Microwave background (indirect)

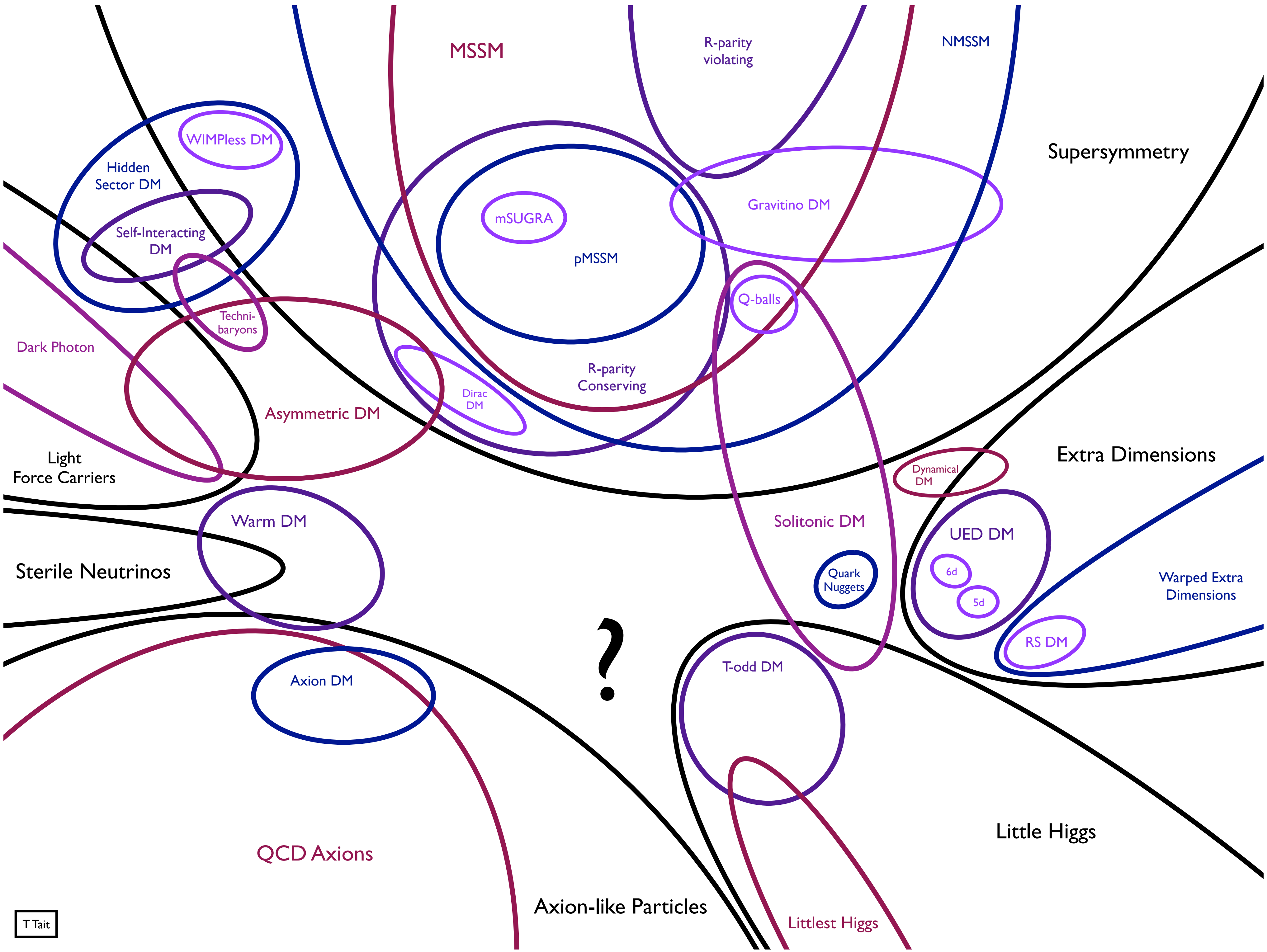
- Big Bang Nucleosynthesis predicts it cannot be baryonic




Vera Rubin


Fritz Zwicky

DM Candidates



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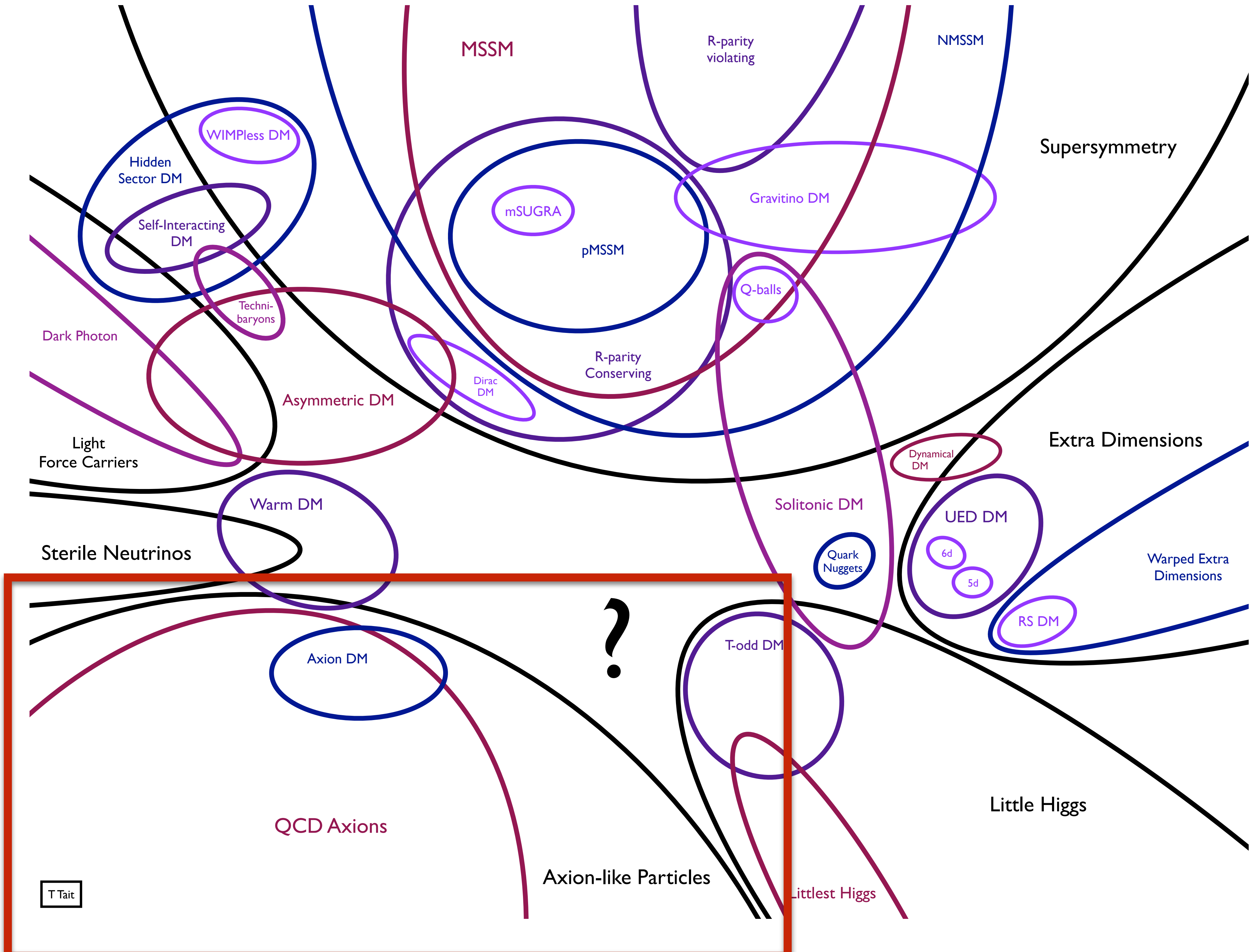


Original Axion Motivation: Strong CP Problem

- Strong interaction does not intrinsically conserve *CP*
- Neutron should have Electric Dipole Moment $d_n \sim 10^{-15}$ e.cm
- Experimentally $d_n < 1.8\times10^{-26}$ e.cm Phys. Rev. Lett. 124, 8, 081803 (2020)
- Requires "unpleasant" fine-tuning of QCD — set arbitrary CP violating phase equal to effectively zero.
- Hint at new physics mechanism?

Peccei-Quinn Mechanism

wikipedia

- Trivial explanation: One quark is massless. Inconsistent with experiment.

aps.org

- Spontaneous Symmetry breaking at high mass scale (f_a) leads to CP conservation.

  PRL 38, 1440 (1977); PRD 16, 1791 (1977)

- Wilczek & Weinberg: Leads to new particle: **Axion** PRL 40, 223 (1978); PRL 40, 279 (1978).

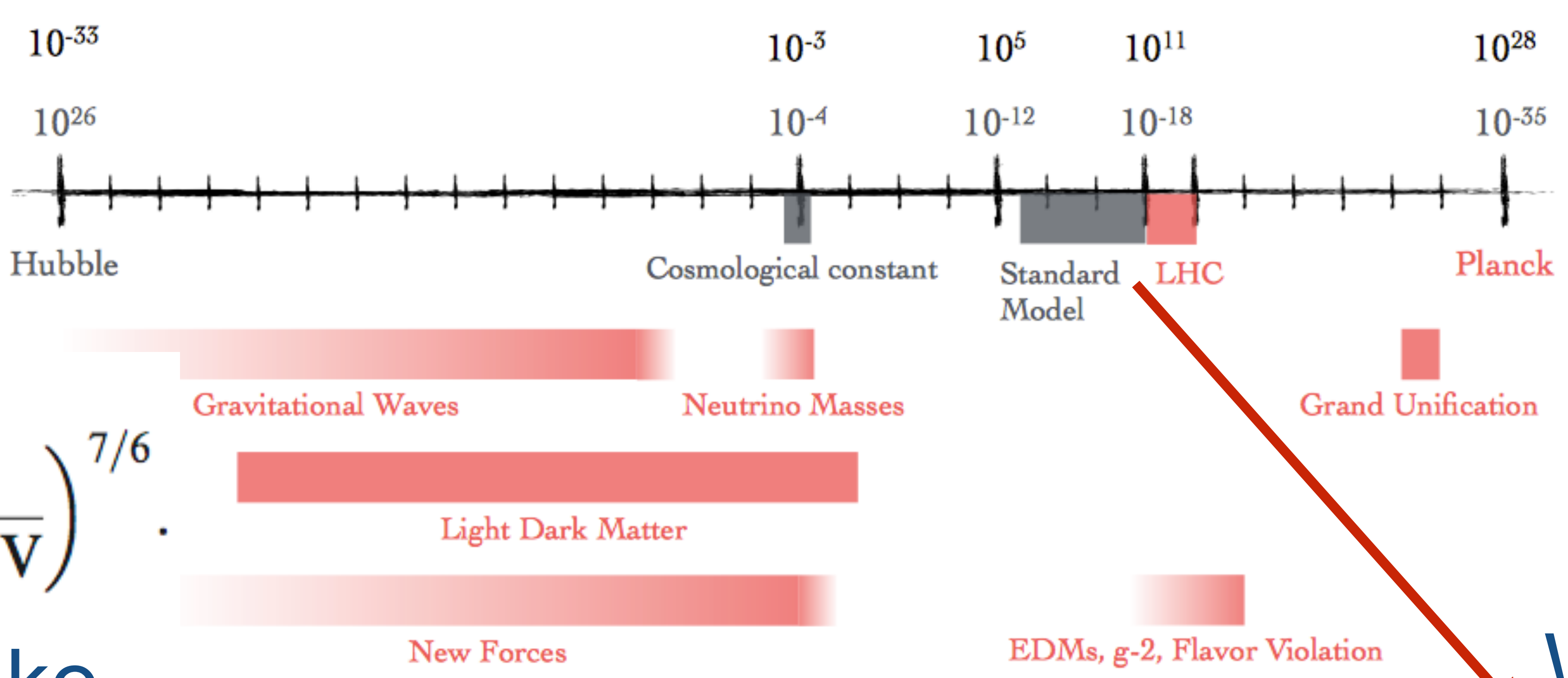
nobelprize.org

MIT

- Discover Axion, solve Strong CP problem

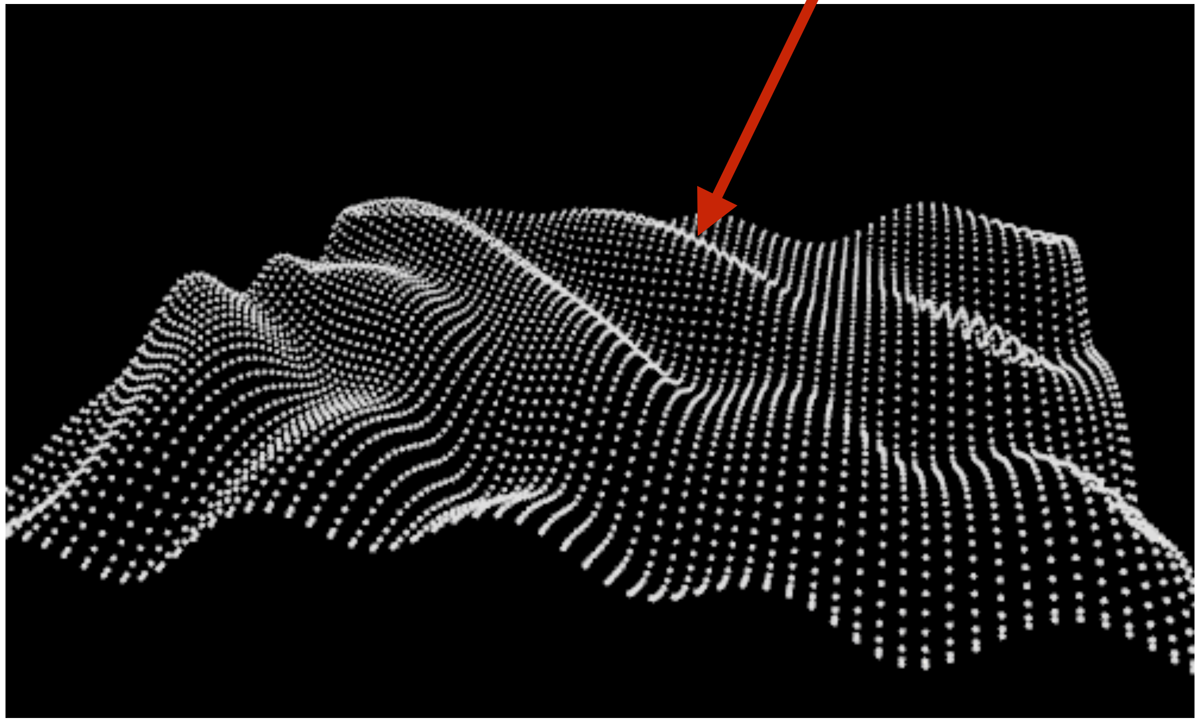
Axion can also be DM

Arvanitaki

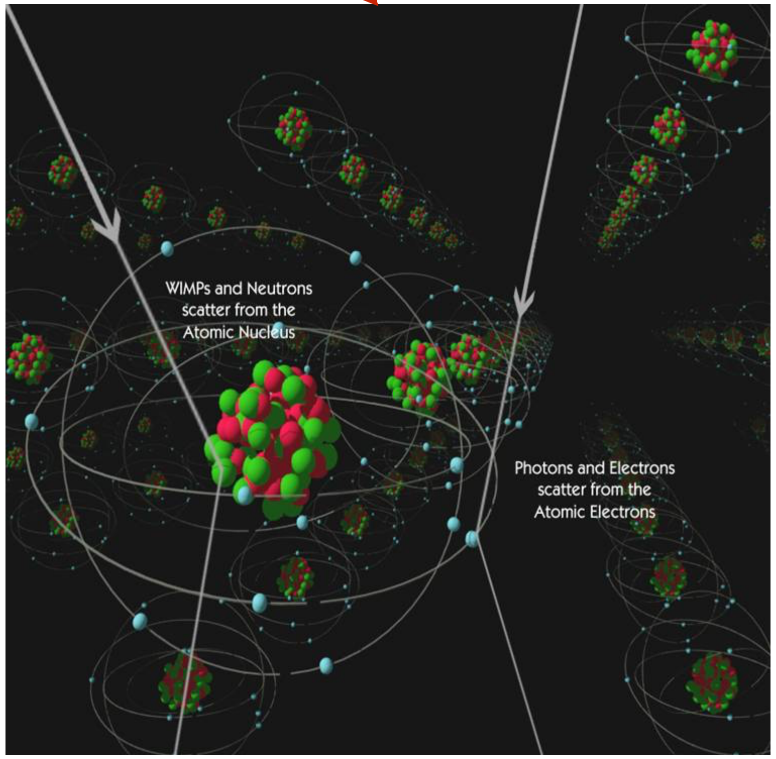


$$\Omega_a \sim \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{7/6}.$$

Wavelike



WIMPs

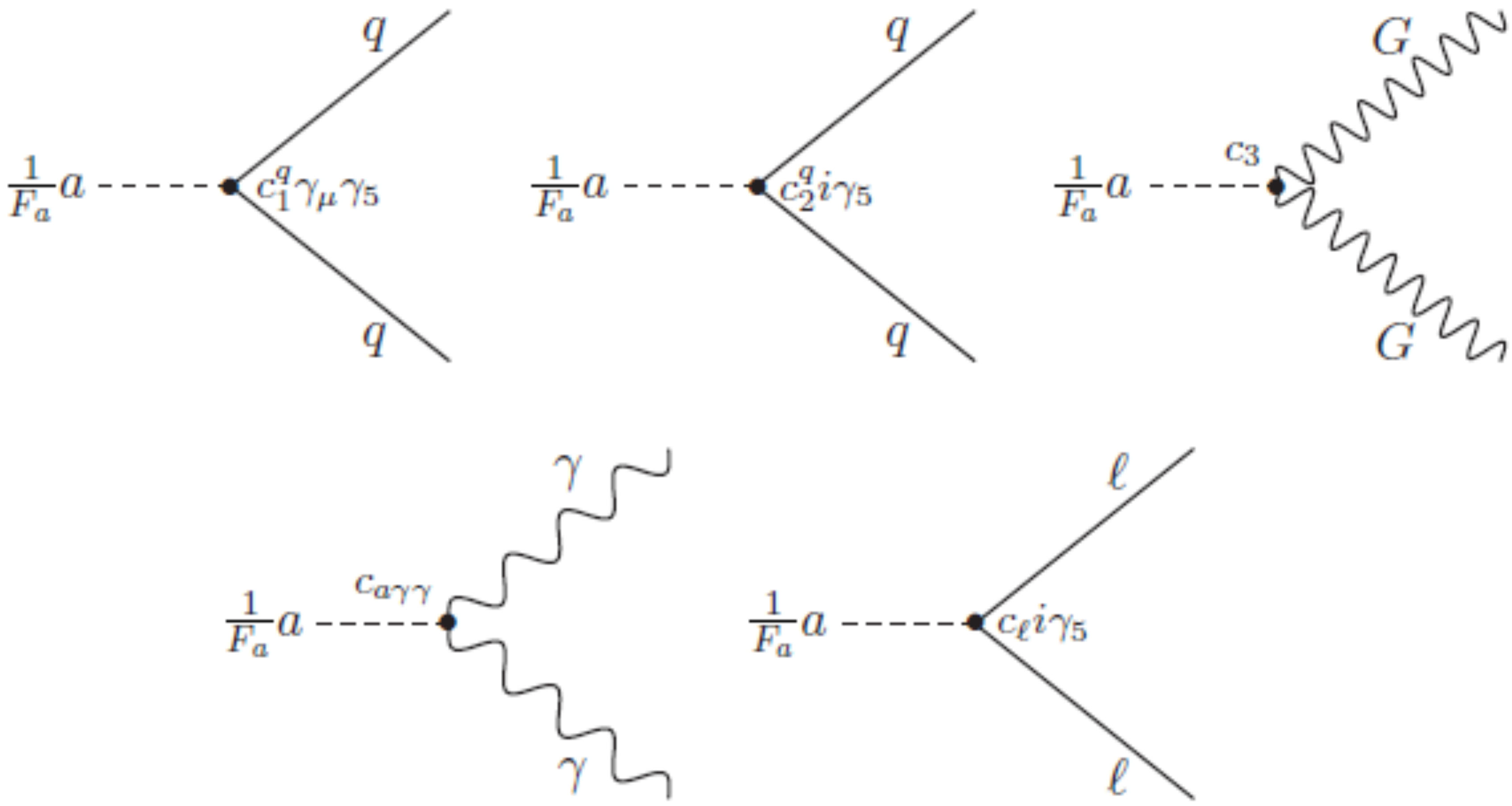


QCD Axion Properties

$$m_a \simeq 0.6\,\text{eV}\,\frac{10^7\,\text{GeV}}{f_a}$$

f_a : PQ Symmetry Breaking Scale
Relationship Model-dependent

Rev.Mod.Phys. 82 (2010) 557



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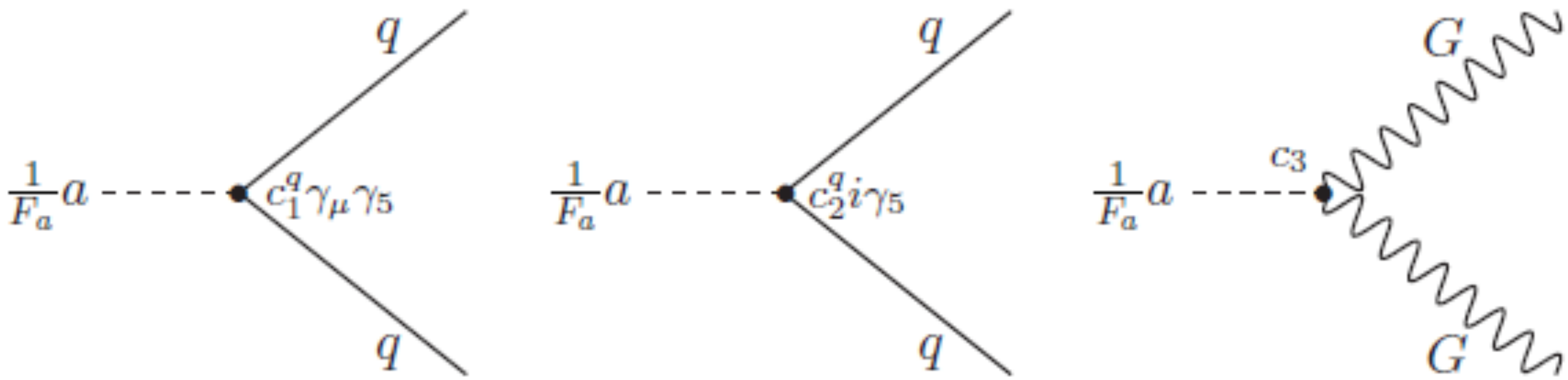
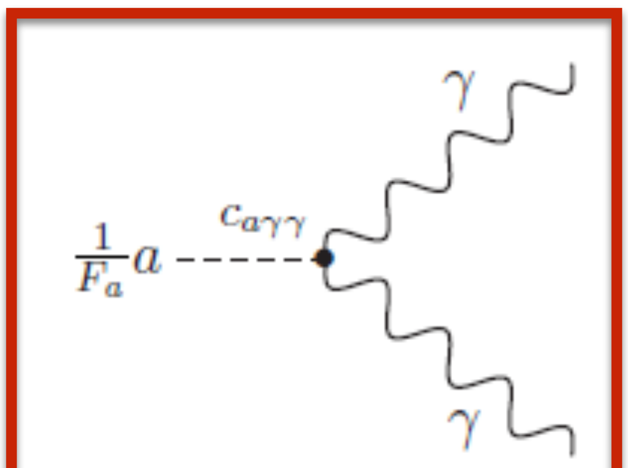


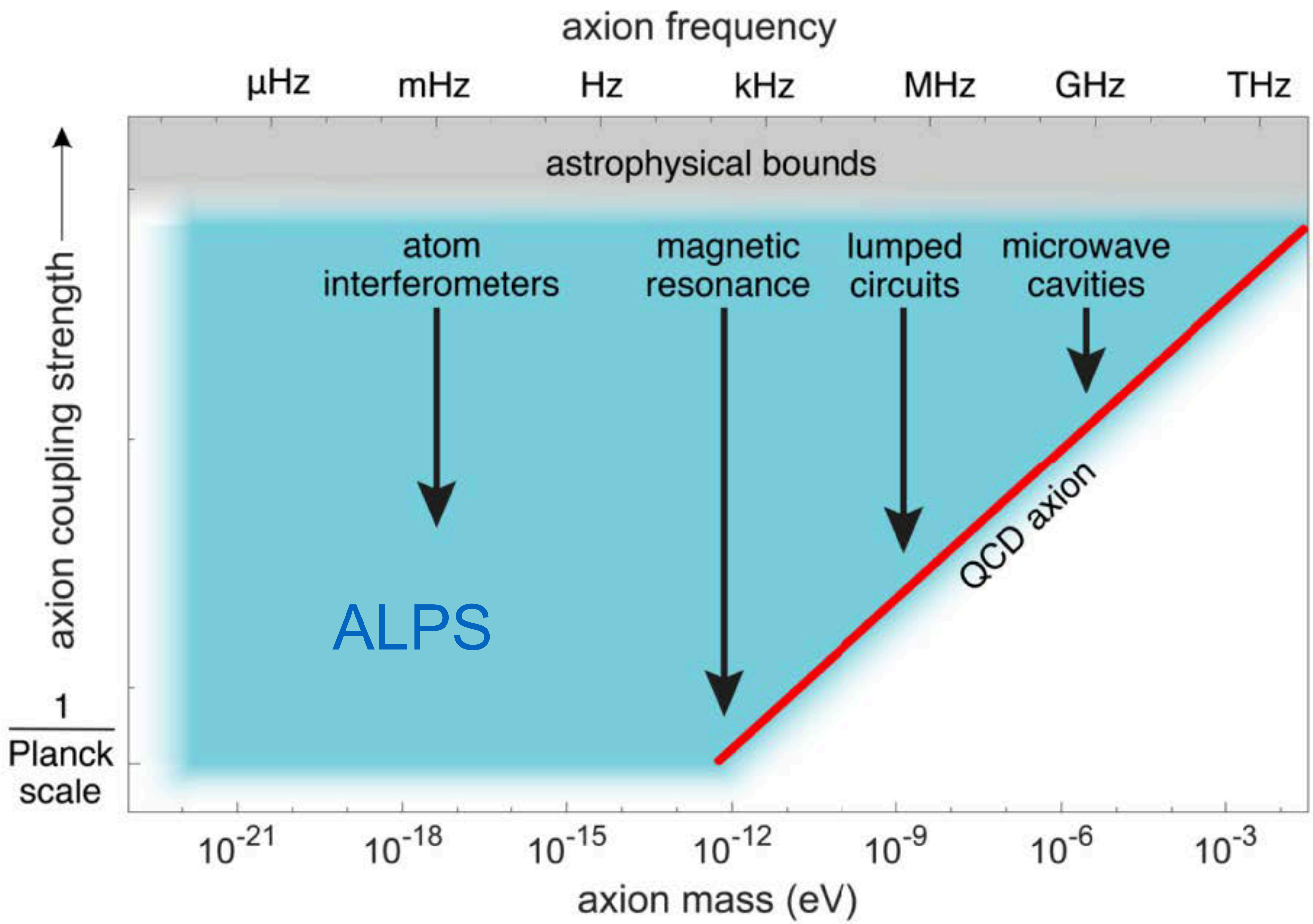


$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4}g_{a\gamma\gamma}aF_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$= -g_{a\gamma\gamma}a\vec{E}\cdot\vec{B}$$

$$g_{a\gamma\gamma} \propto \frac{\alpha_{\mathrm{EM}}}{f_a}$$

Axion Experimental Landscape



2018 DOE HEP Basic Research needs for Dark Matter Small Projects Report

Axions-like particles (ALPS) arise naturally in string theories.

Do not solve Strong CP problem

Much less constrained: PRD 81, 123530 (2010),…

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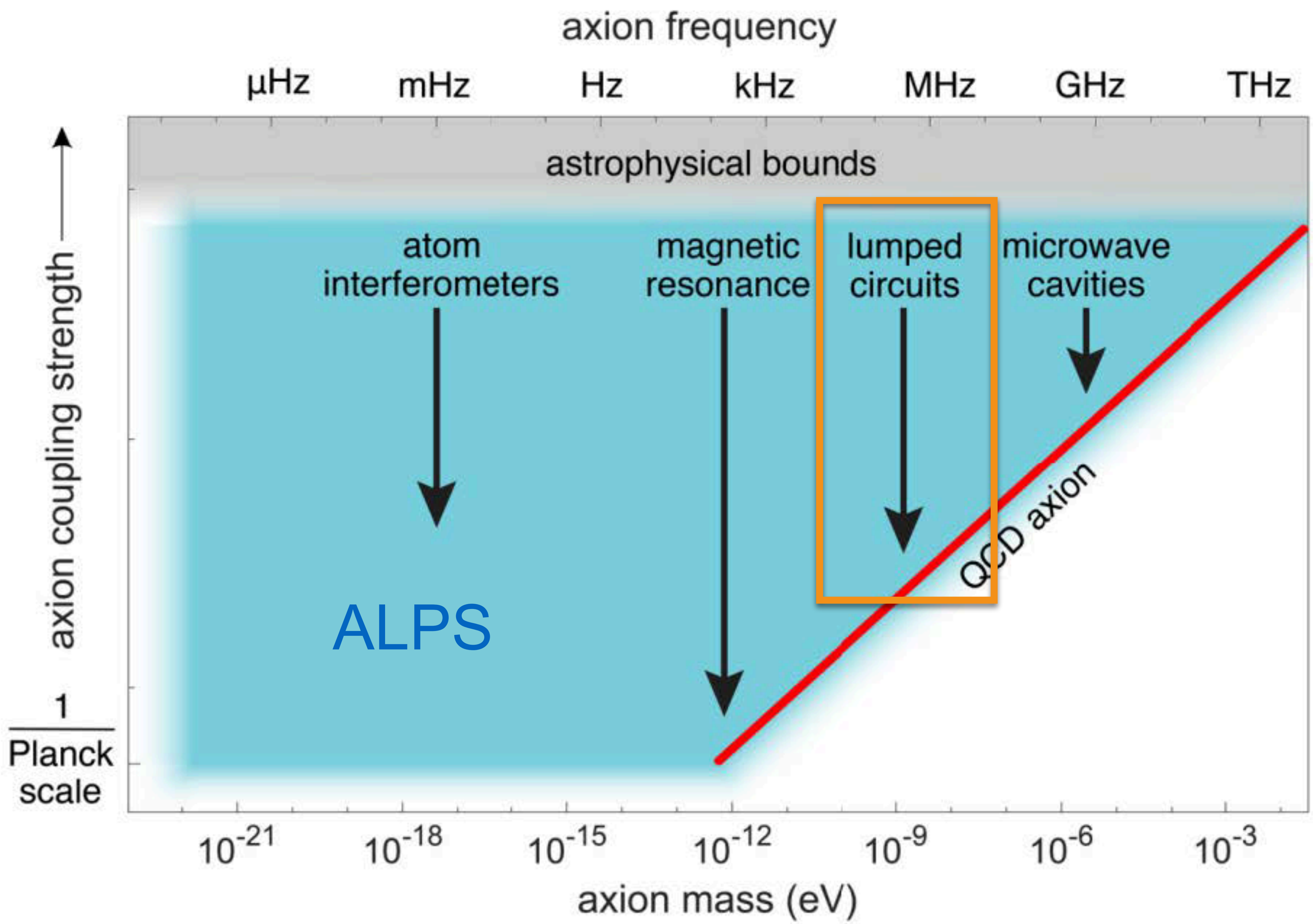
Axion Experimental Landscape



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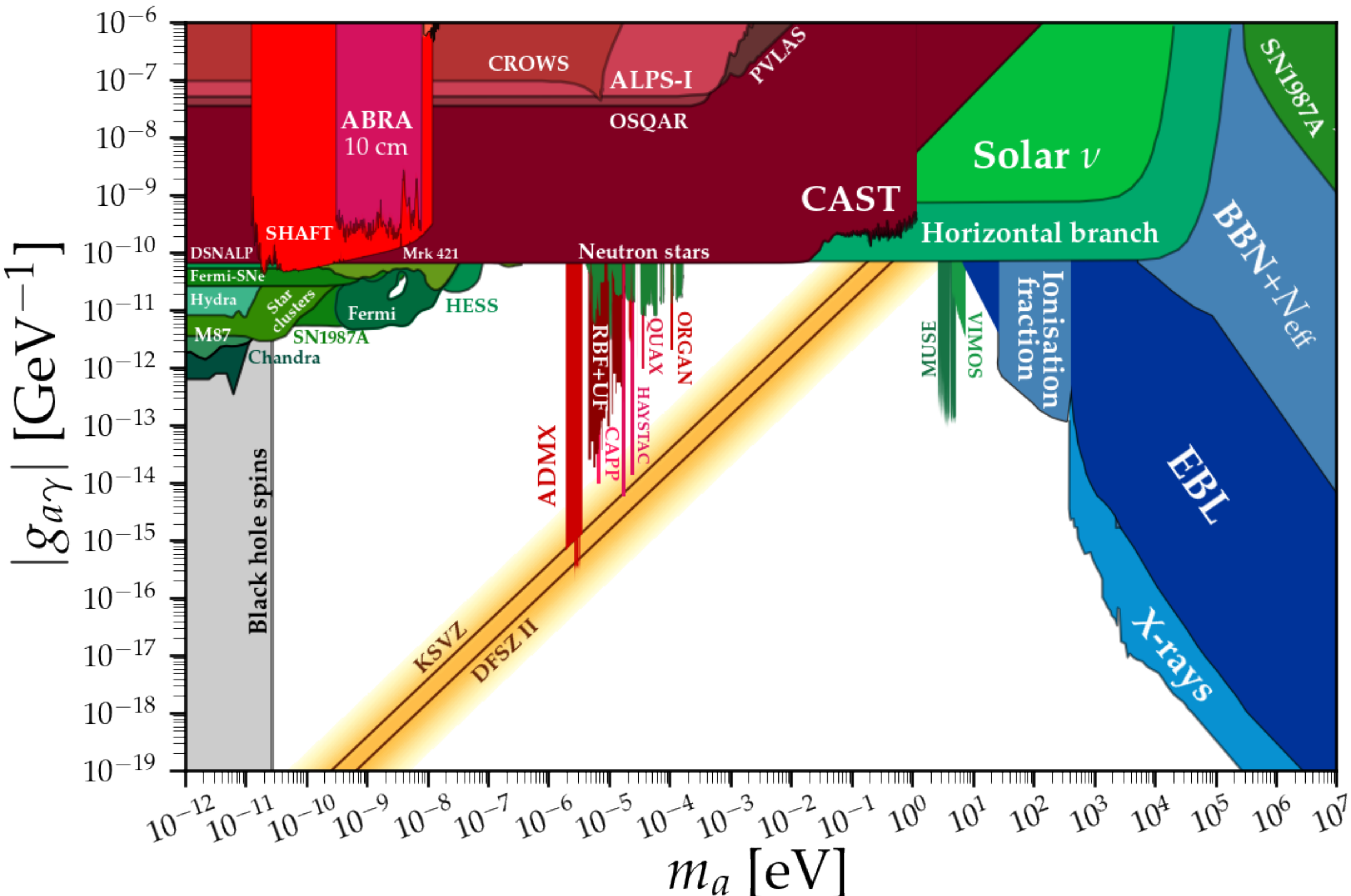
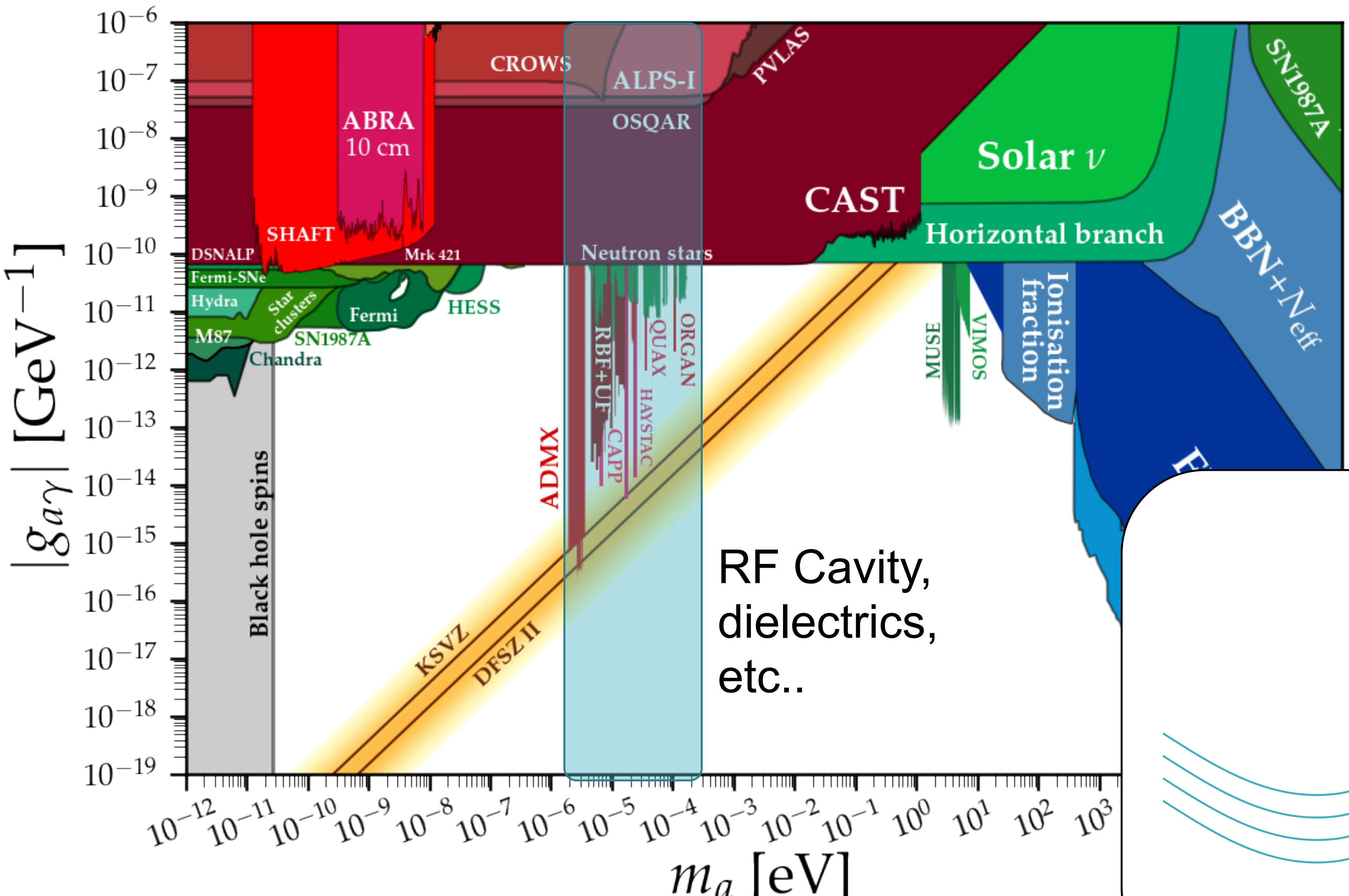


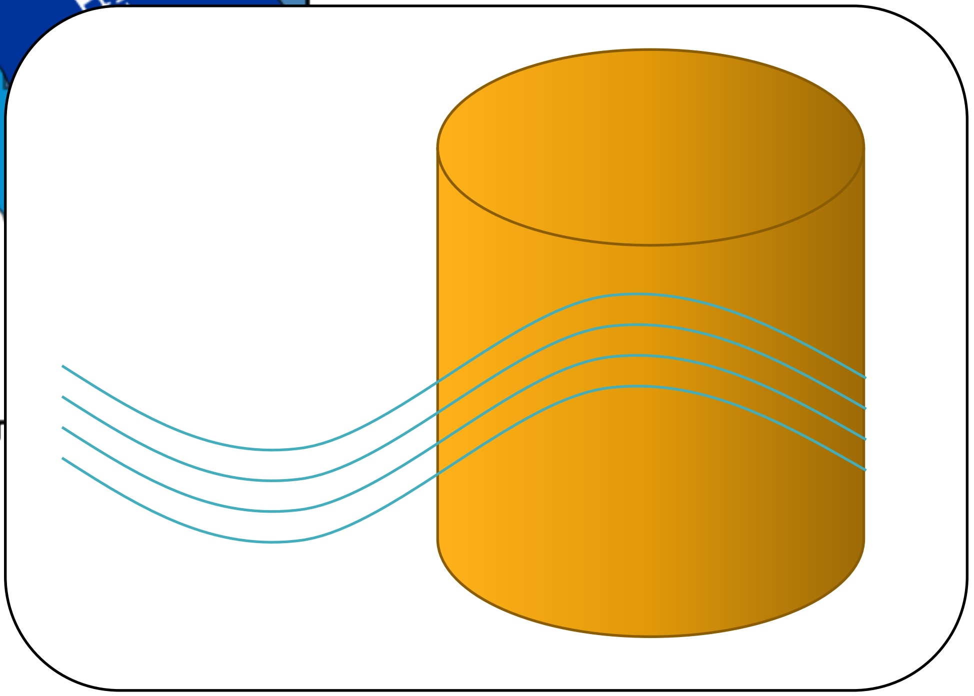
C. O'Hare

Experimental Landscape



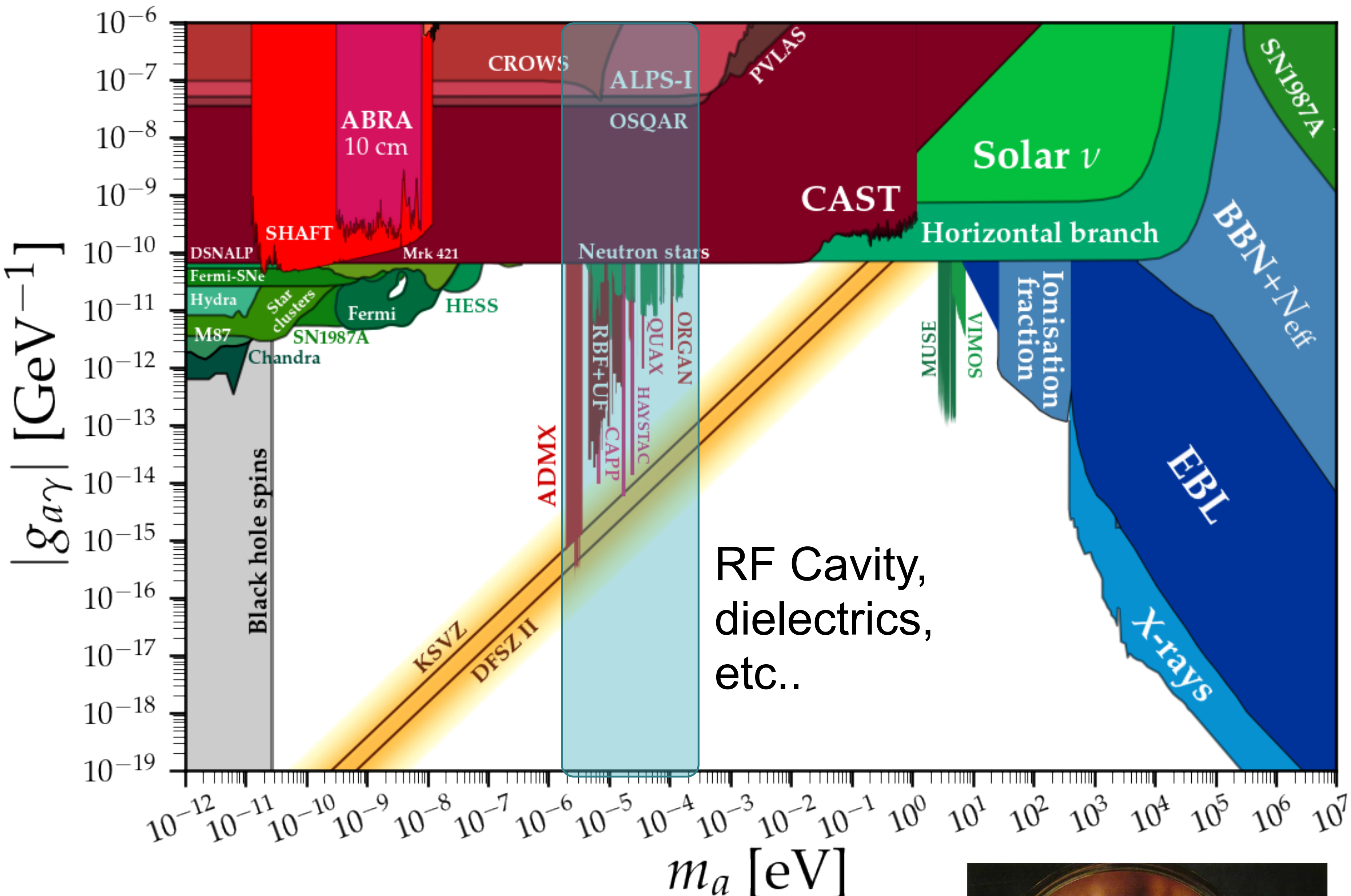
C. O'Hare

RF Cavity, dielectrics, etc..



Axion Compton Wavelength ~ size of detector (cm to meters)

Experimental Landscape



C. O'Hare

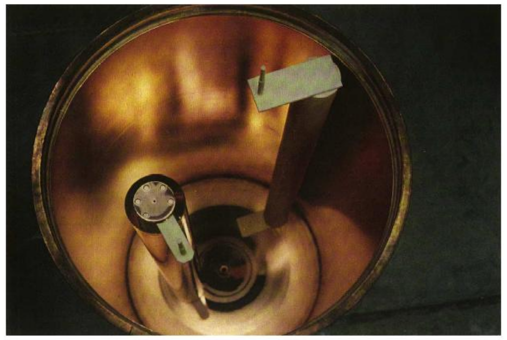
Resonant conversion of DM axion in high-Q cavity in magnetic field

Sikivie PRL 51(1983) 1415

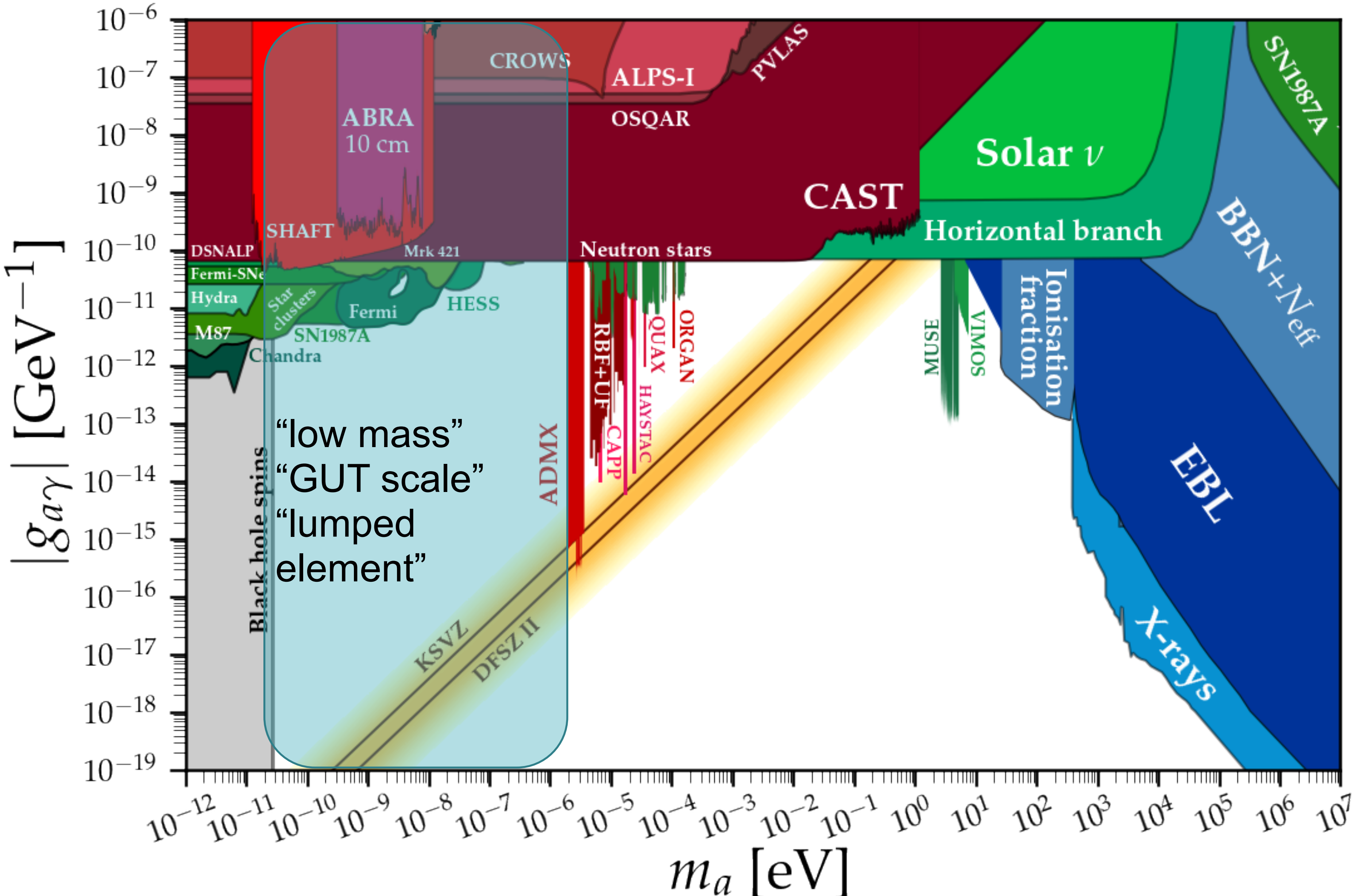
Dielectric Haloscopes: MADMAX

HAYSTAC

ADMX



Experimental Landscape



C. O'Hare

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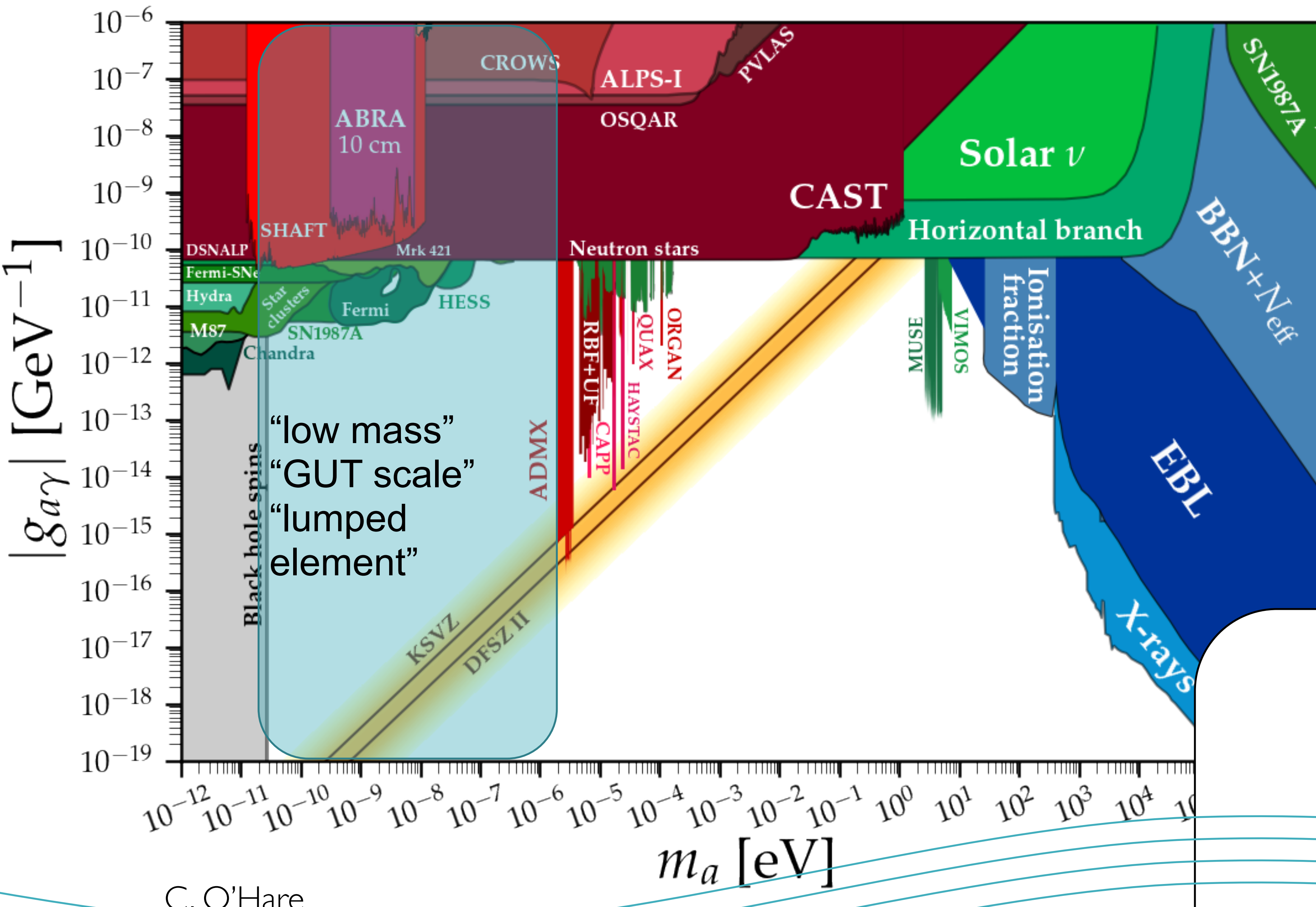
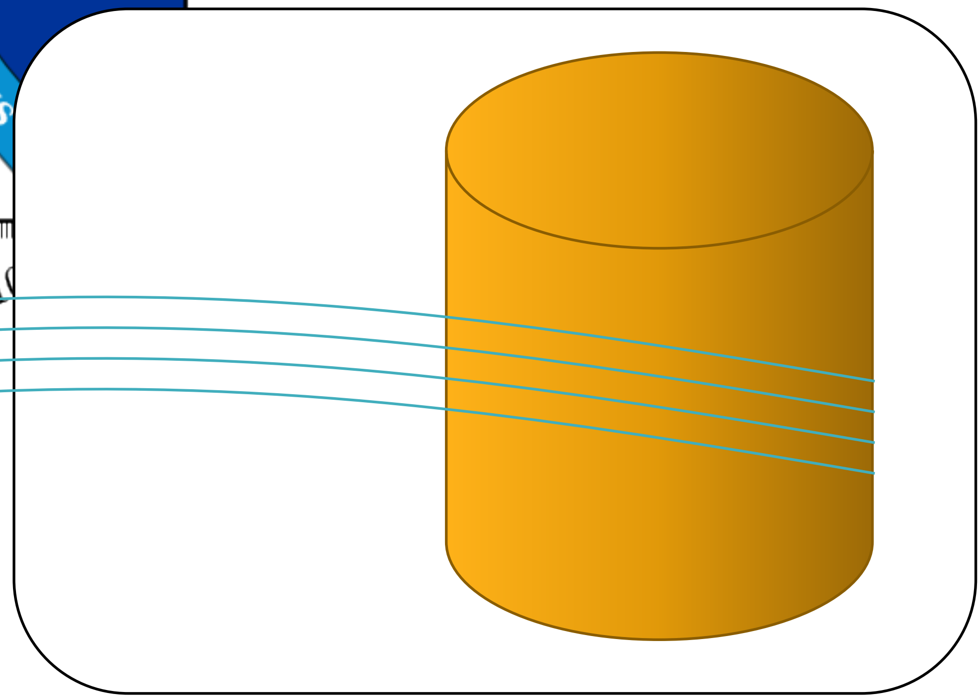




Axion Compton Wavelength >> size of detector

DM QCD Axions Below 1μeV

- Pre-inflation PQ symmetry breaking allows DM axion masses 10^{-12} to 10^{-4} eV or even beyond
- GUT Scale Axion at ~ 1 neV ($f_a \sim 10^{15}$ GeV) generic feature of String Theories
- Many proposals exist for removing fine tuning required for $m_a << 1\mu$eV. Typically require new particles.
- Or can just require long-scale inflation, e.g. Phys. Rev. D 98, 035017 (2018)

Max Tegmark, Anthony Aguirre, Martin J. Rees, and Frank Wilczek. Dimensionless constants, cosmology, and other dark matters. *Phys. Rev. D*, 73:023505, Jan 2006.

Luca Visinelli and Paolo Gondolo. Axion cold dark matter in nonstandard cosmologies. *Phys. Rev. D*, 81:063508, March 2010.

Raymond T. Co, Francesco D'Eramo, and Lawrence J. Hall. Gravitino or Axino Dark Matter with Reheat Temperature as high as 10^{16} GeV. *JHEP*, 03:005, 2017.

Hooman Davoudiasl, Dan Hooper, and Samuel D. McDermott. Inflatable Dark Matter. *Phys. Rev. Lett.*, 116(3):031303, 2016.

Prateek Agrawal, Gustavo Marques-Tavares, and Wei Xue. Opening up the QCD axion window. *JHEP*, 03:049, 2018.

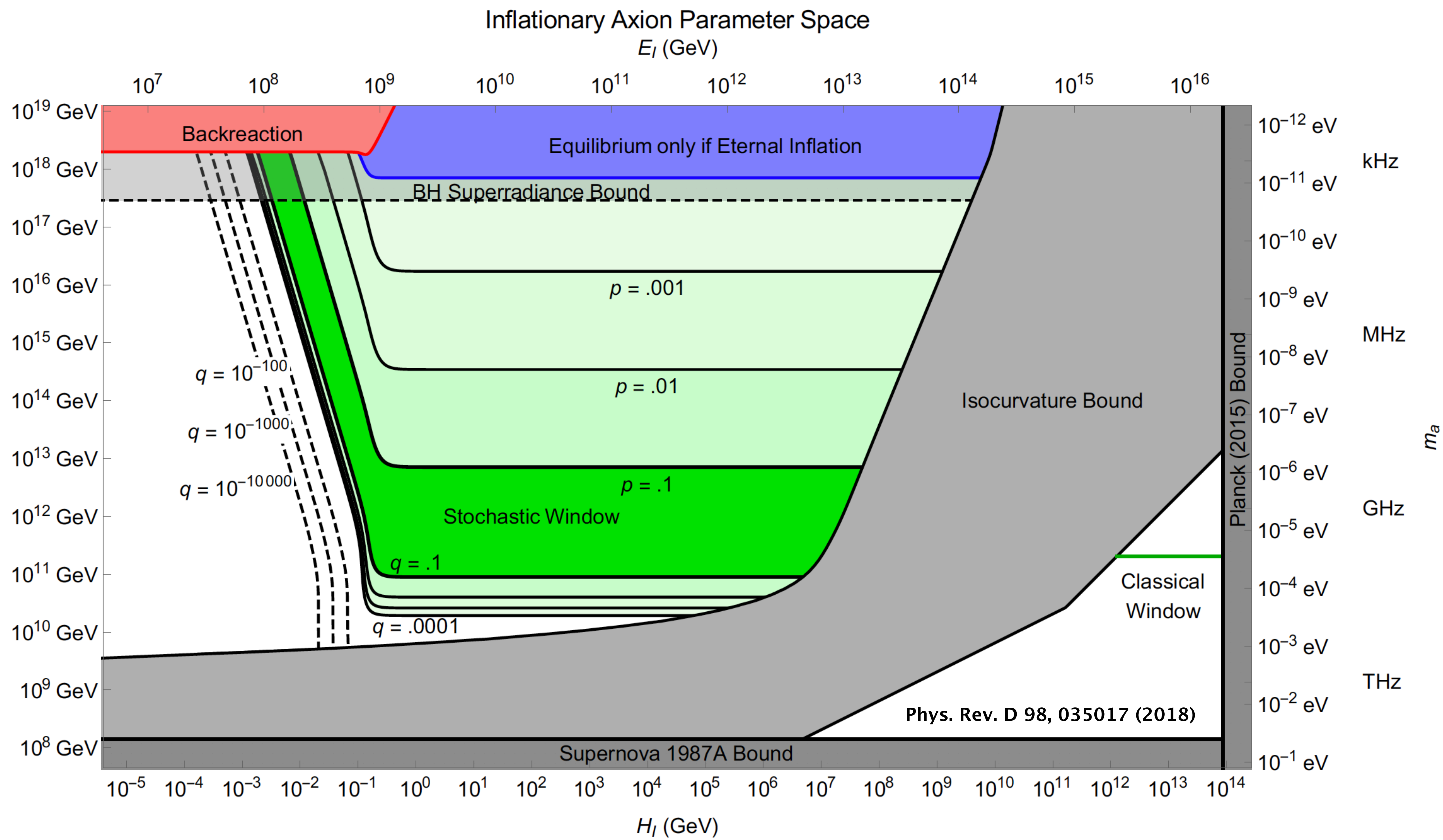
Peter W. Graham and Adam Scherlis. Stochastic axion scenario. *Phys. Rev. D*, 98:035017, Aug 2018.

Manuel A. Buen-Abad and JiJi Fan. Dynamical axion misalignment with small instantons. https://arxiv.org/abs/1911.05737, 2019.

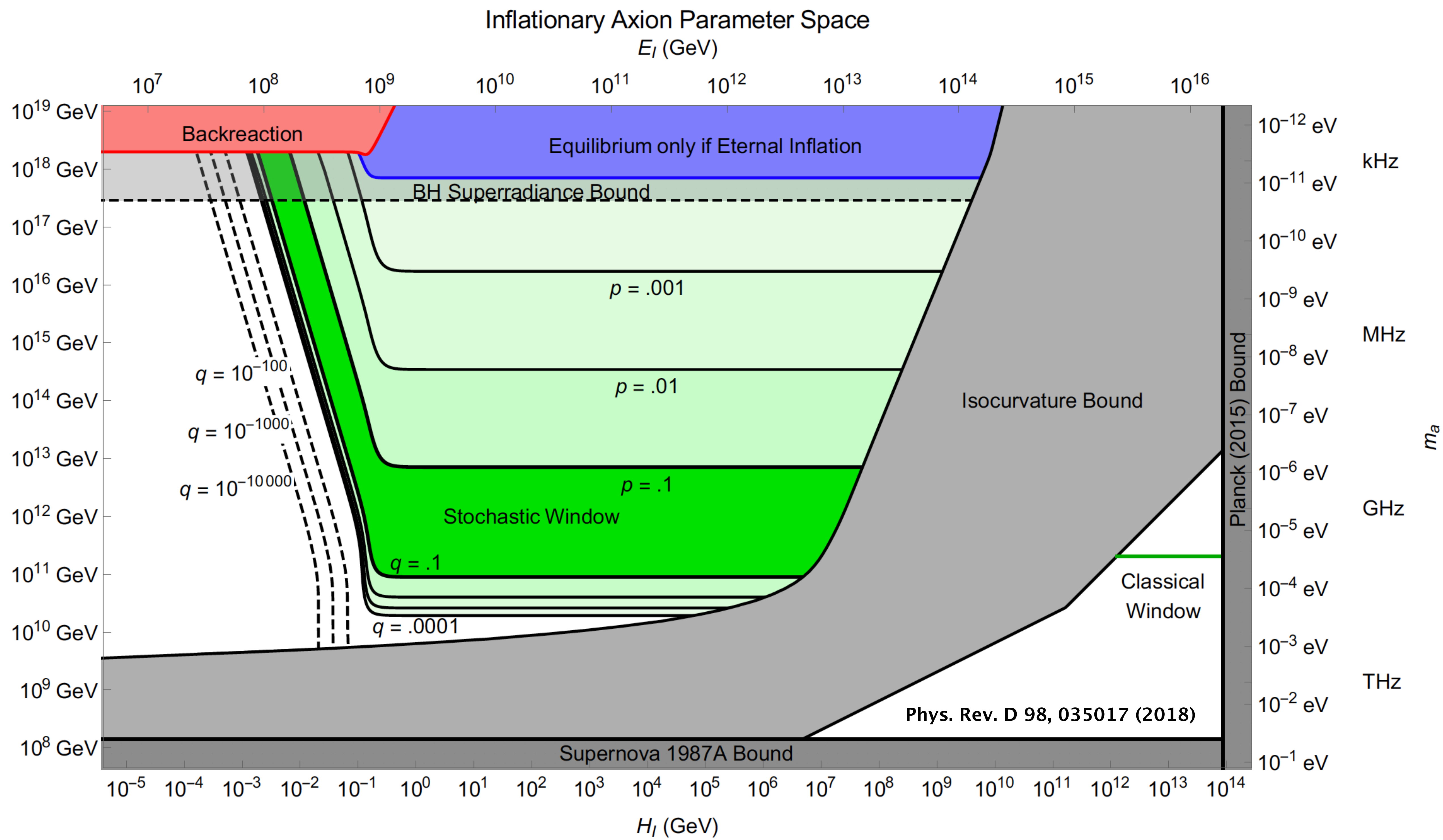
Takeshi Kobayashi and Lorenzo Ubaldi. Inflaxion dark matter. *Journal of High Energy Physics*, 2019:147, 2019.

Tommi Tenkanen and Luca Visinelli. Axion dark matter from higgs inflation with an intermediate $h*$. *Journal of Cosmology and Astroparticle Physics*, 2019:033–033, 2019.

Raymond T. Co, Eric Gonzalez, and Keisuke Harigaya. Axion misalignment driven to the bottom. *Journal of High Energy Physics*, 2019:162, 2019.



Inflationary Axion Parameter Space
E_I (GeV)
10^7 10^8 10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14} 10^{15} 10^{16}
10^{19} GeV
10^{18} GeV
10^{17} GeV
10^{16} GeV
10^{15} GeV
10^{14} GeV
10^{13} GeV
10^{12} GeV
10^{11} GeV
10^{10} GeV
10^9 GeV
10^8 GeV
Backreaction
Equilibrium only if Eternal Inflation
BH Superradiance Bound
$p = .001$
$p = .01$
$p = .1$
$q = 10^{-100}$
$q = 10^{-1000}$
$q = 10^{-10\,000}$
Stochastic Window
$q = .1$
$q = .0001$
Isocurvature Bound
Planck (2015) Bound
Classical Window
Phys. Rev. D 98, 035017 (2018)
Supernova 1987A Bound
10^{-5} 10^{-4} 10^{-3} 10^{-2} 10^{-1} 10^0 10^1 10^2 10^3 10^4 10^5 10^6 10^7 10^8 10^9 10^{10} 10^{11} 10^{12} 10^{13} 10^{14}
H_I (GeV)
10^{-12} eV
10^{-11} eV
10^{-10} eV
10^{-9} eV
10^{-8} eV
10^{-7} eV
10^{-6} eV
10^{-5} eV
10^{-4} eV
10^{-3} eV
10^{-2} eV
10^{-1} eV
kHz
MHz
GHz
THz
m_a



Axions with masses below 1μeV require serious consideration

ABRACADABRA

A Search for Low-Mass Axion Dark Matter*

"A Broadband or Resonant Approach to Cosmic Axion Detection with an Amplifying *B*-field Ring Apparatus"

*PRL 117 (2016) 141801

ABRA Concept

Treat ultralight axion DM as coherent field

$$a(t) = \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m_a} \sin(m_a t)$$

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Generic axion modifies Ampere's Law:

$$\nabla \times \mathbf{B} = \frac{\partial \mathbf{E}}{\partial t} - g_{a\gamma\gamma}(\mathbf{E} \times \nabla a - \mathbf{B}\frac{\partial a}{\partial t})$$

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Magnetoquasistatic limit

E=**0**, DM *v* ~10^{-3}

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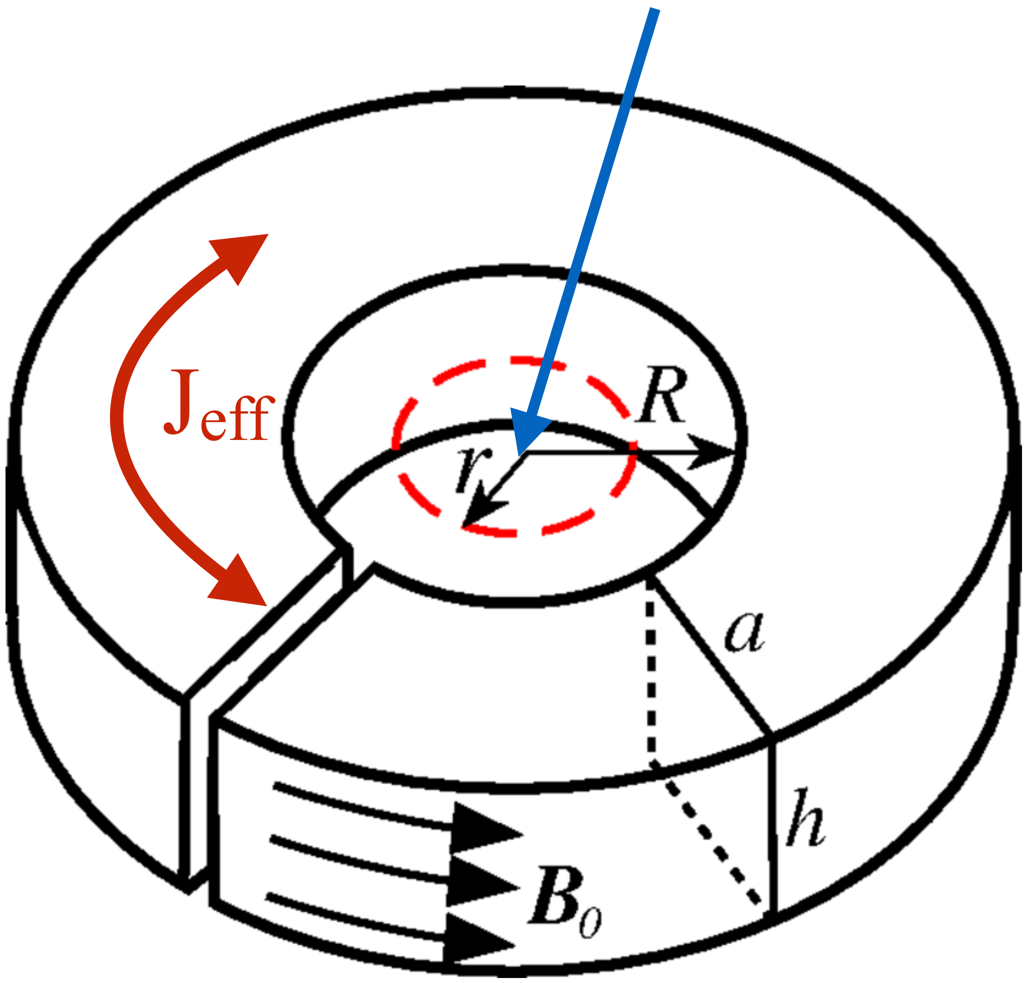
Yields axion-induced effective current:

$$\mathbf{J}_{\rm eff} = g_{a\gamma\gamma}\sqrt{2\rho_{\rm DM}}\cos(m_a t)\mathbf{B_0}$$

Zero DC Field



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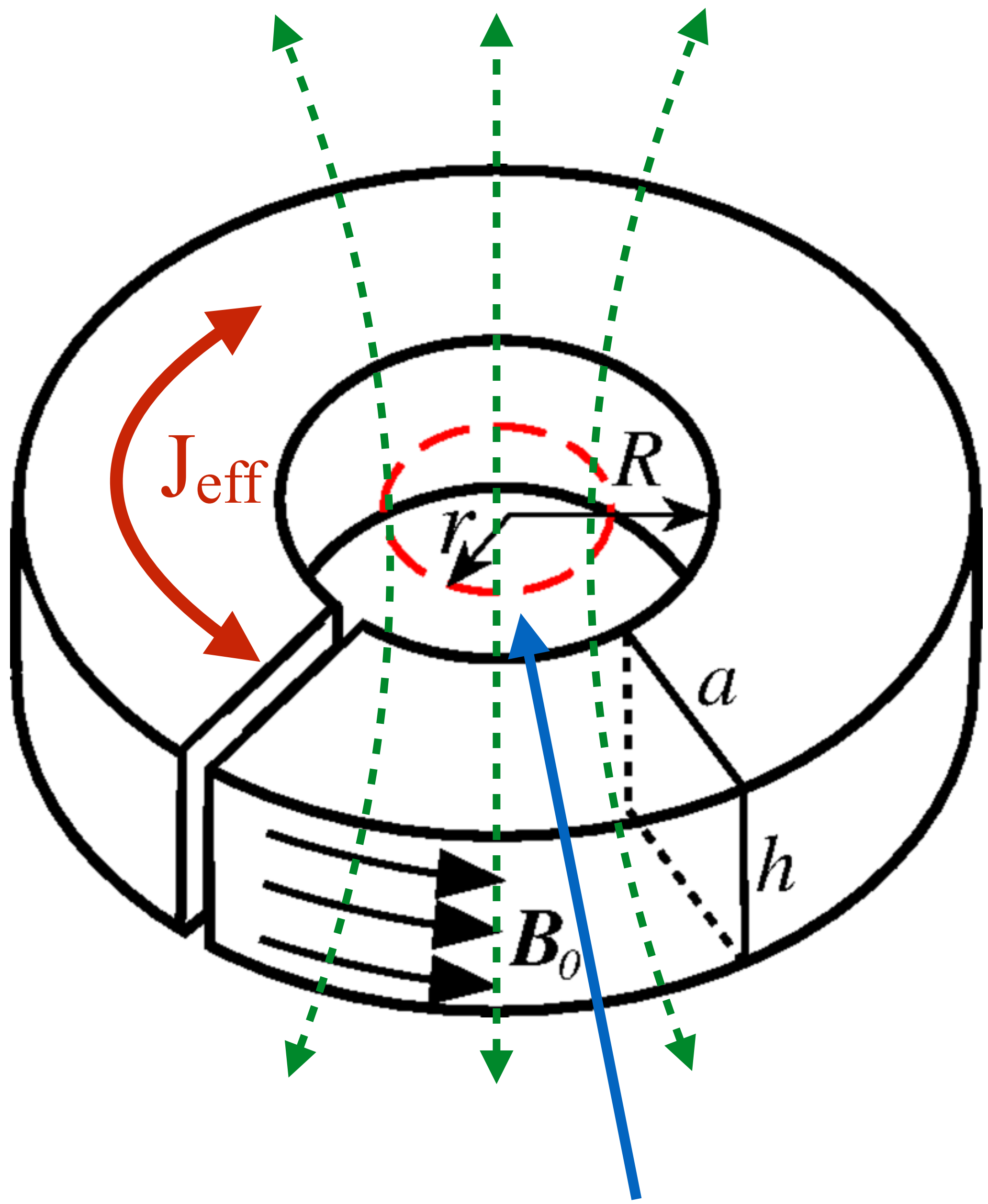
Induces oscillating magnetic field in torus

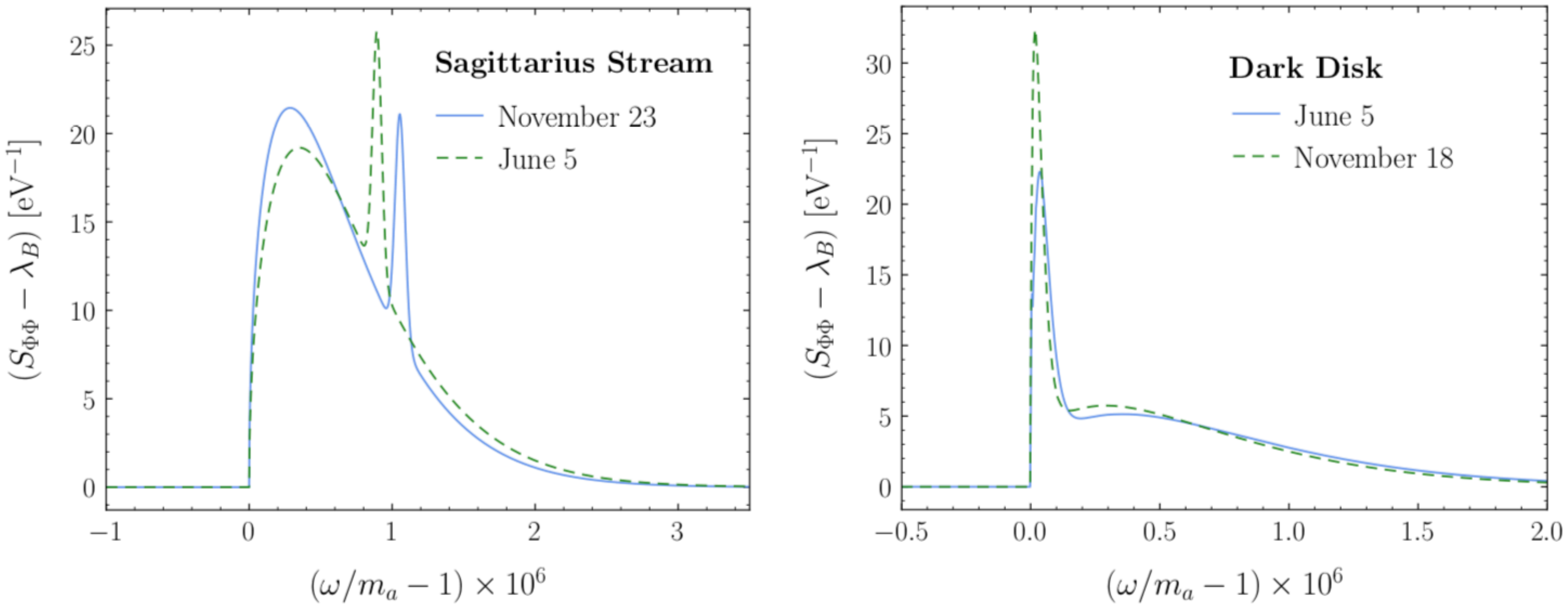
Induced B-field



Measure induced field using pickup loop
DC B-field free

DM Axion Signal

PRD 97 (2018) 12



- Standard halo model with width $\Delta f/f \sim 10^{-6}$
- Possible substructure

Two Readout Strategies

Broadband

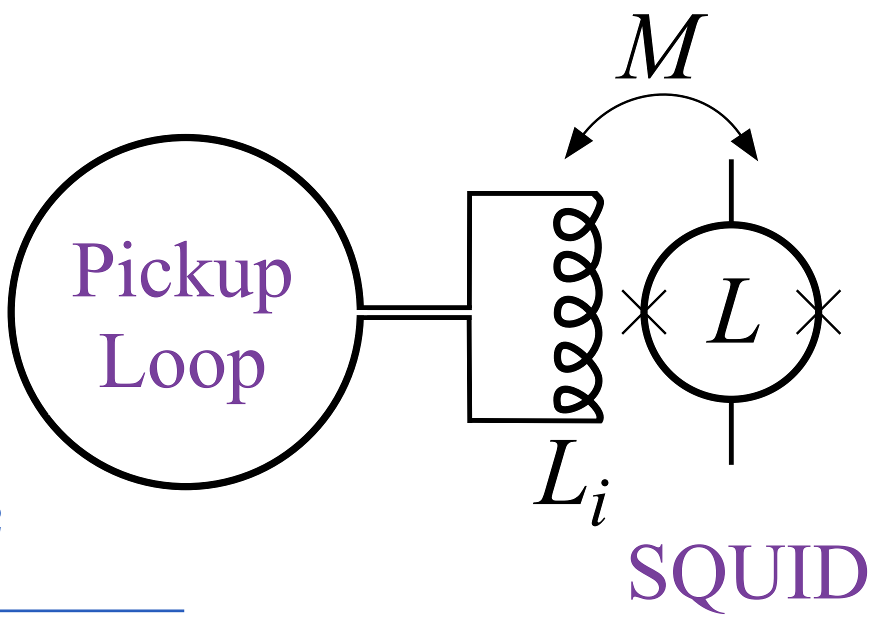
Scan all frequencies simultaneously

> ~50 Hz dominated by flux noise in SQUID magnetometer:

$$S_{\Phi,0}^{1/2} \sim 10^{-6}\Phi_0/\sqrt{\mathrm{Hz}}$$

< ~50Hz 1/f noise dominates

Broadband Sensitivity: > ~50 Hz $\quad g_{a\gamma\gamma} \propto (\frac{m_a}{t})^{\frac{1}{4}} \frac{S_{\Phi,0}^{1/2}}{B_{\max} G V_B \sqrt{\rho_{\mathrm{DM}}}}$



Resonant

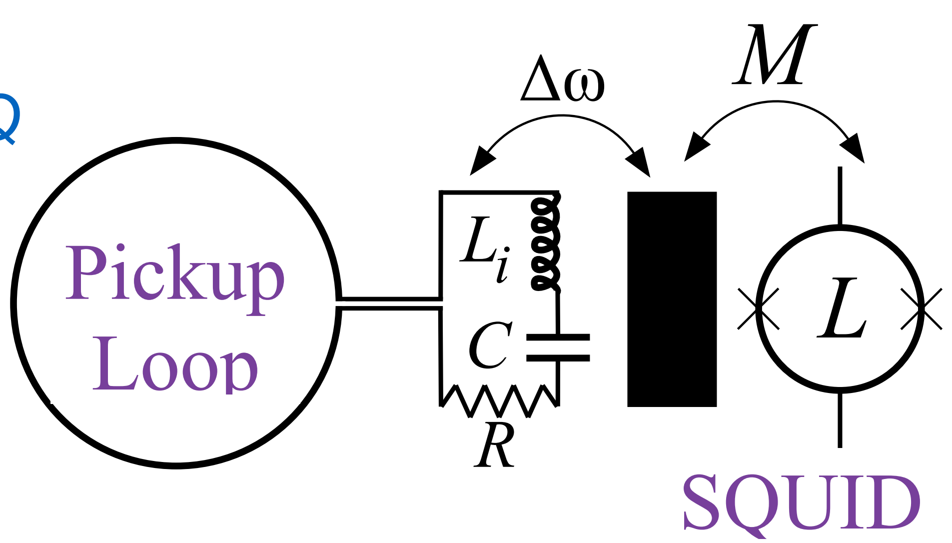
Resonance enhancement by adding capacitor with high-Q

Scan across frequencies

Thermal noise in pickup loop dominates

Resonance Mode Sensitivity:

$$g_{a\gamma\gamma} \propto \sqrt{L_T}(\frac{1}{m_a t})^{\frac{1}{4}} \frac{1}{B_{\max} G V_B}\sqrt{\frac{k_B T}{\rho_{\mathrm{DM}} Q_0}}$$



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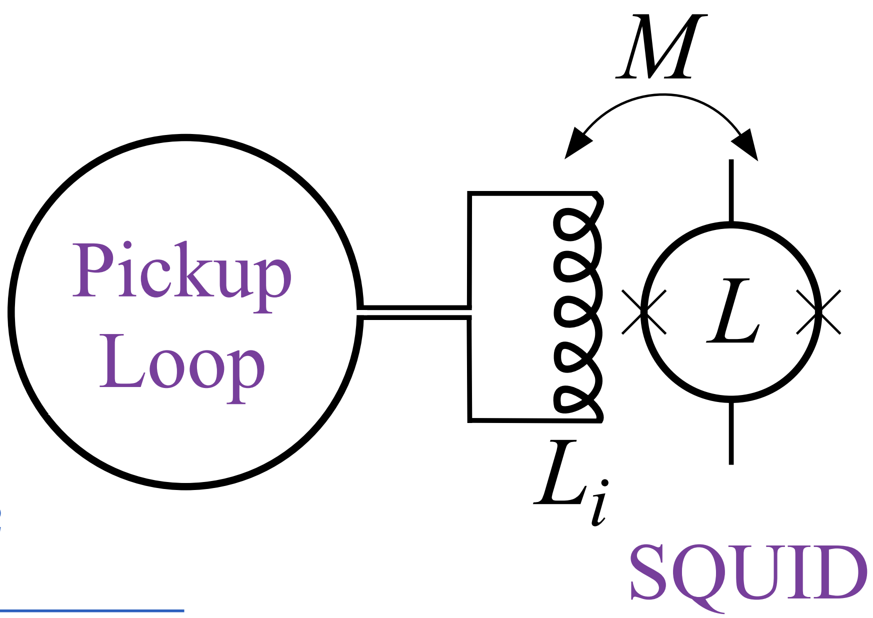
Current



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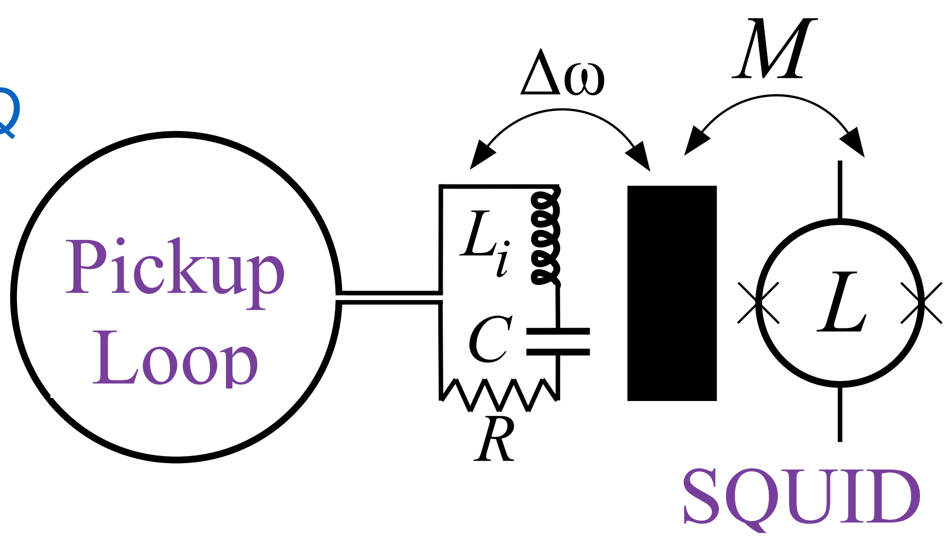
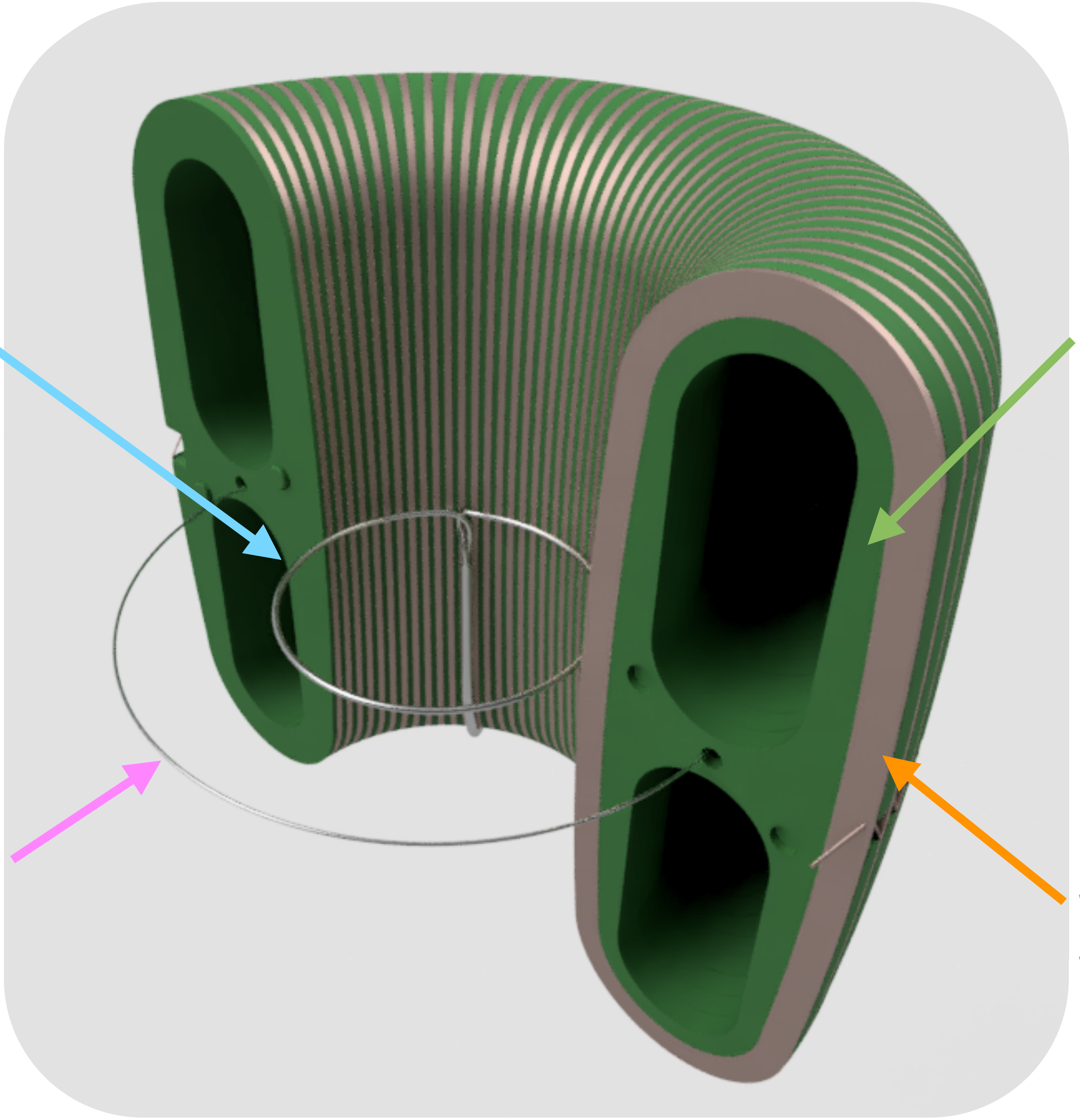
Future (DMRadio)



ABRACADABRA-10 cm

PRD 99 (2019) 052012, PRL 122 (2019) 121802

Dissecting ABRACADABRA-10 cm



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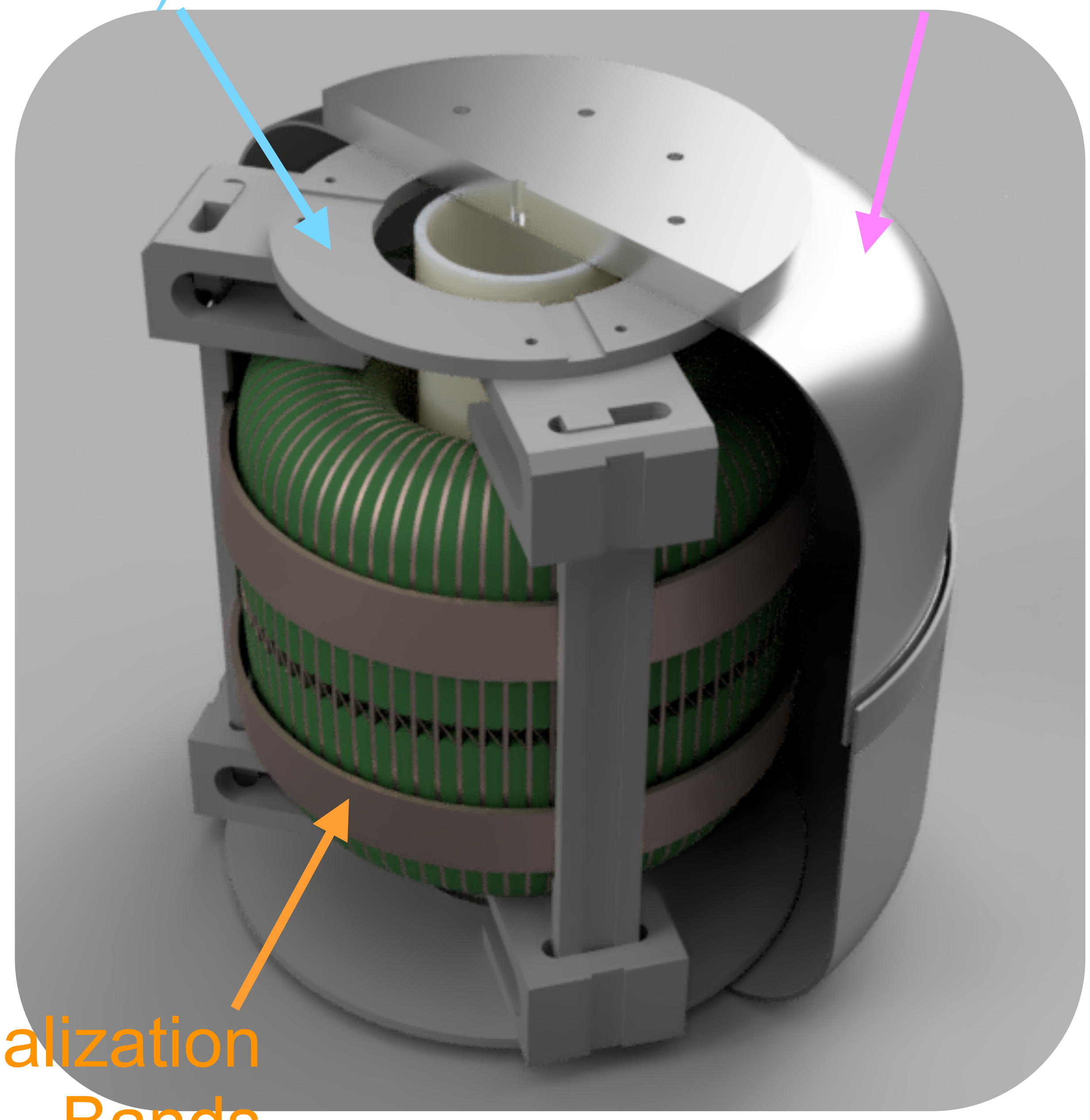
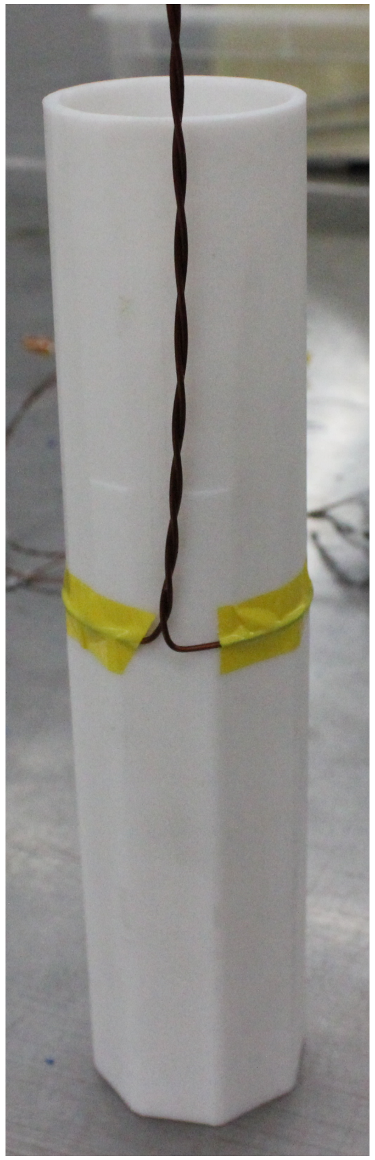
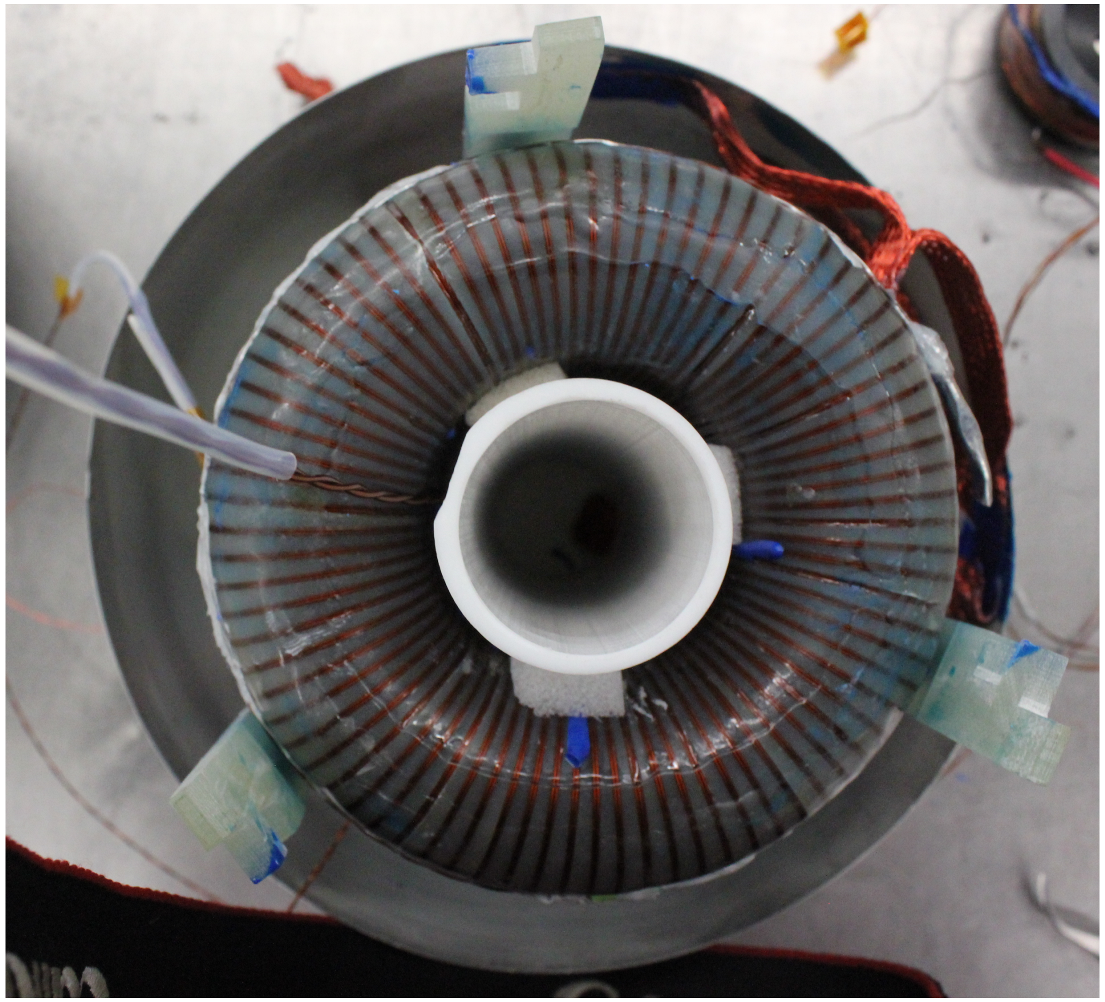
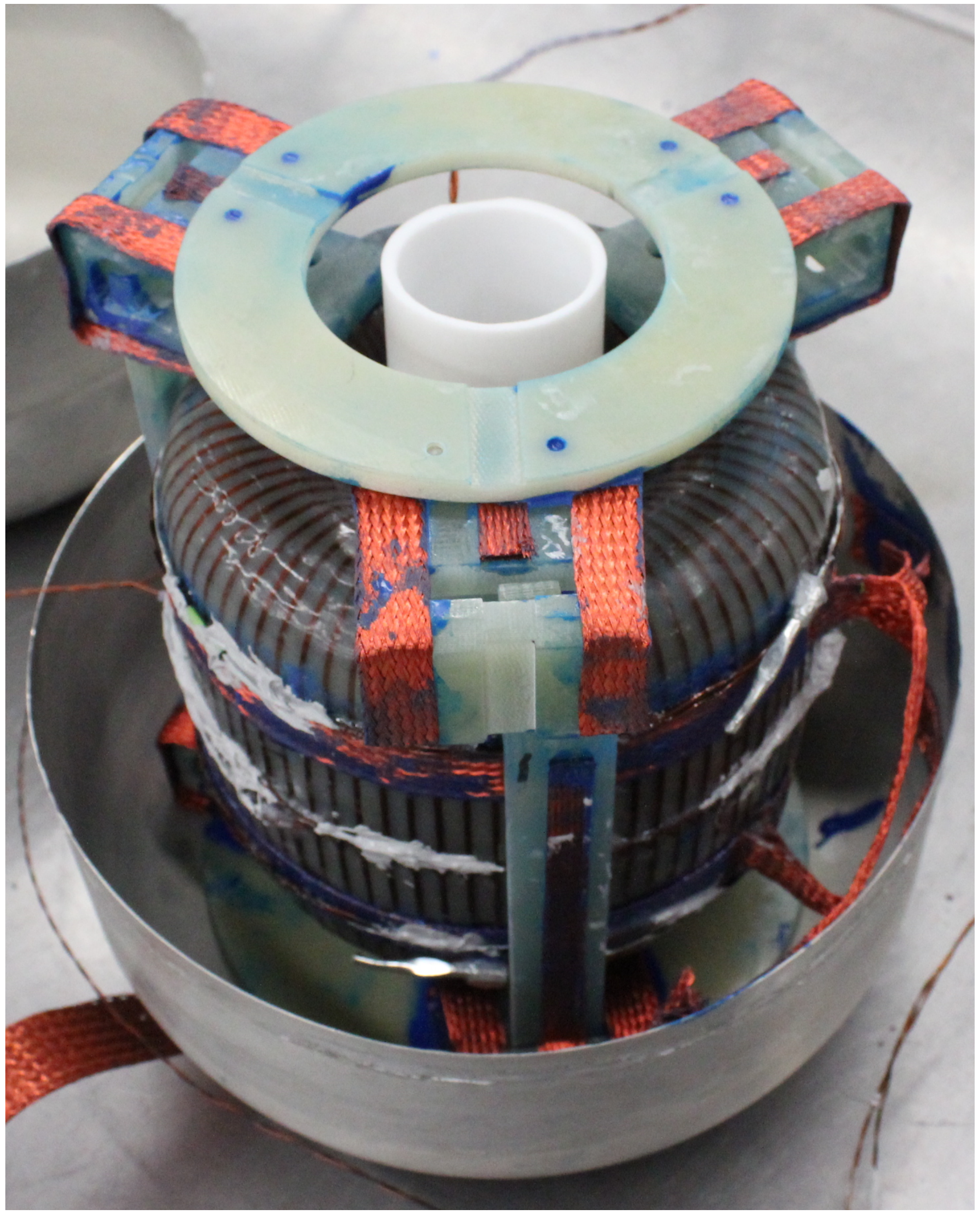


Assembling ABRACADABRA-10 cm

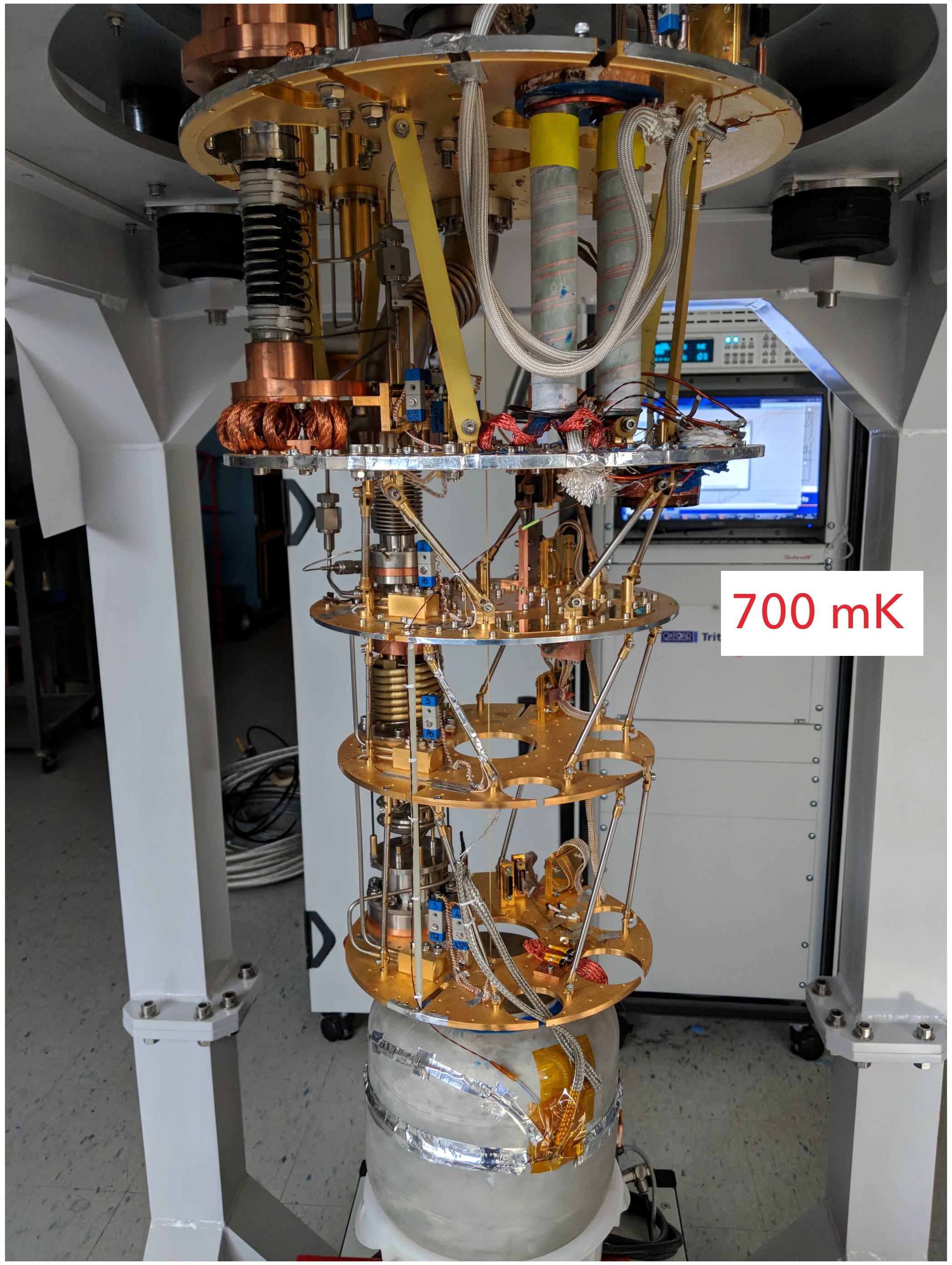
Pickup Loop



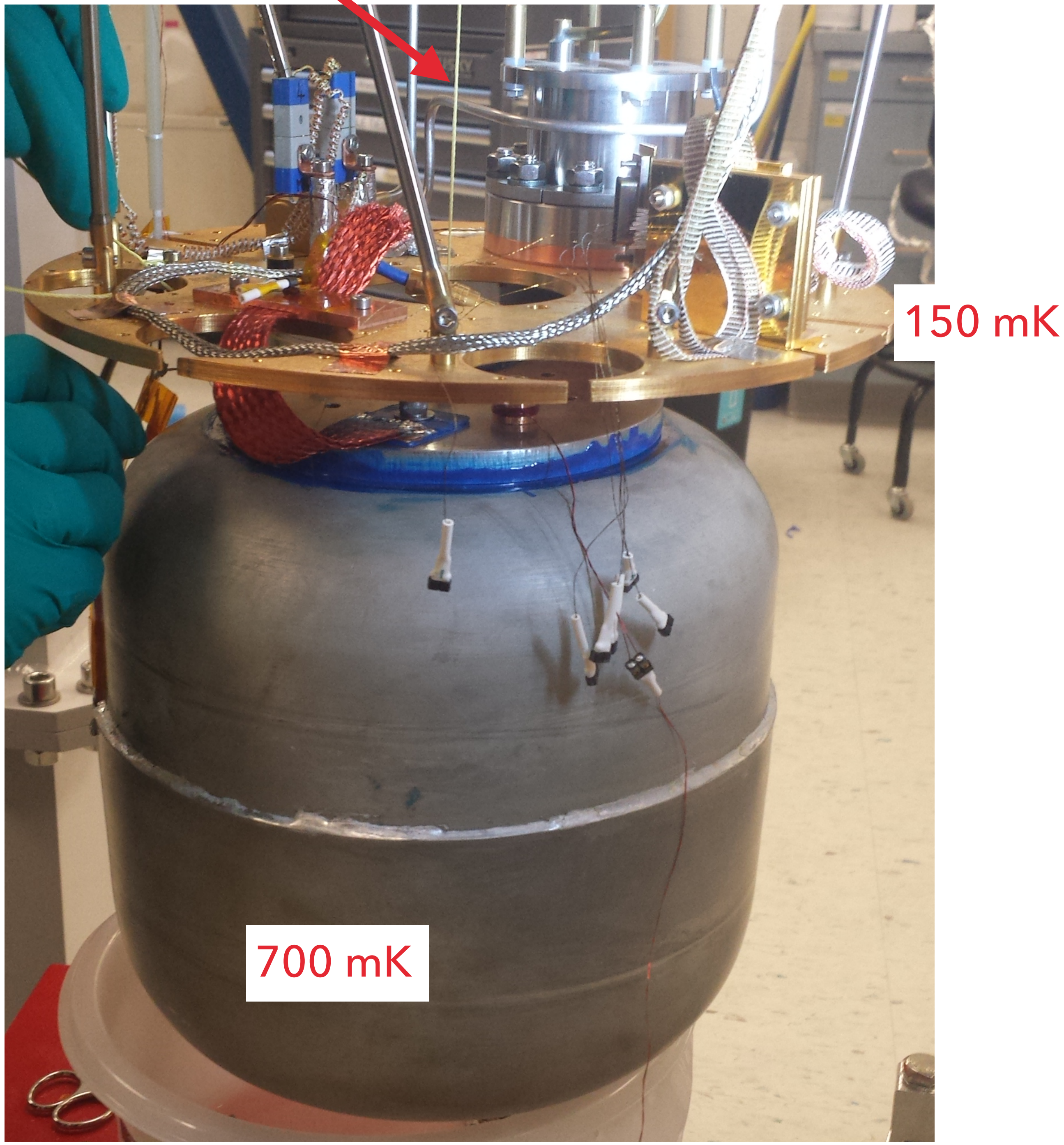




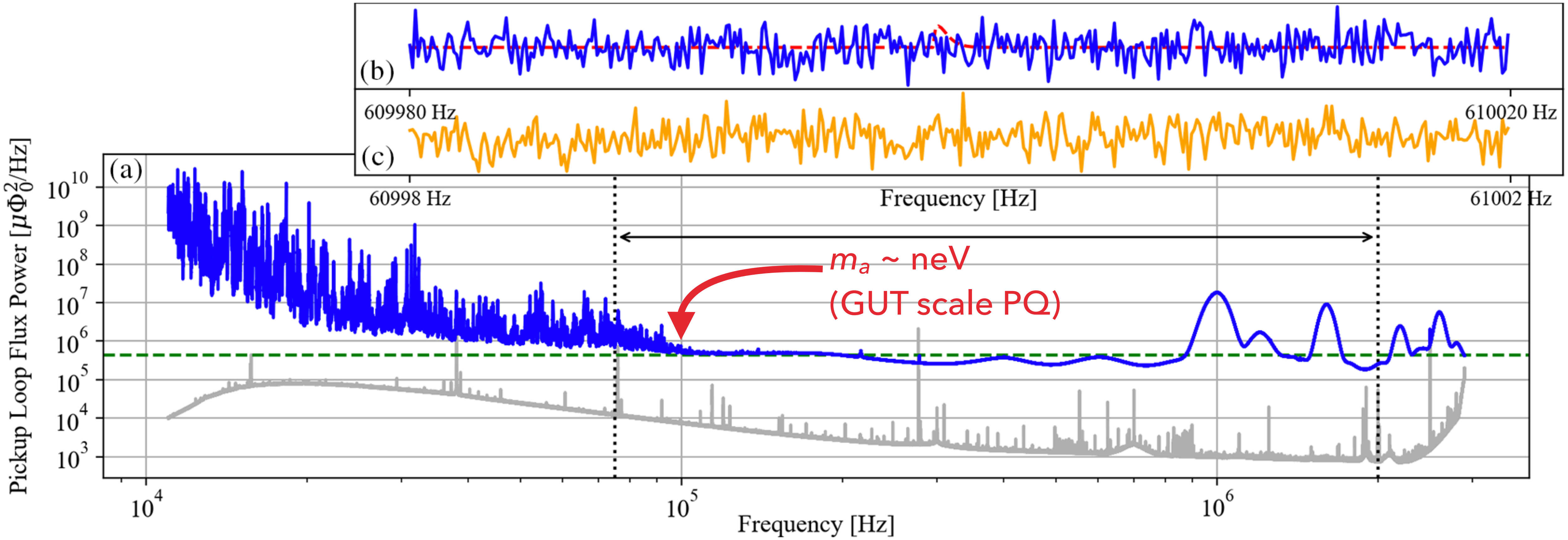
Mechanical Suspension System



Kevlar Support



Example Spectrum

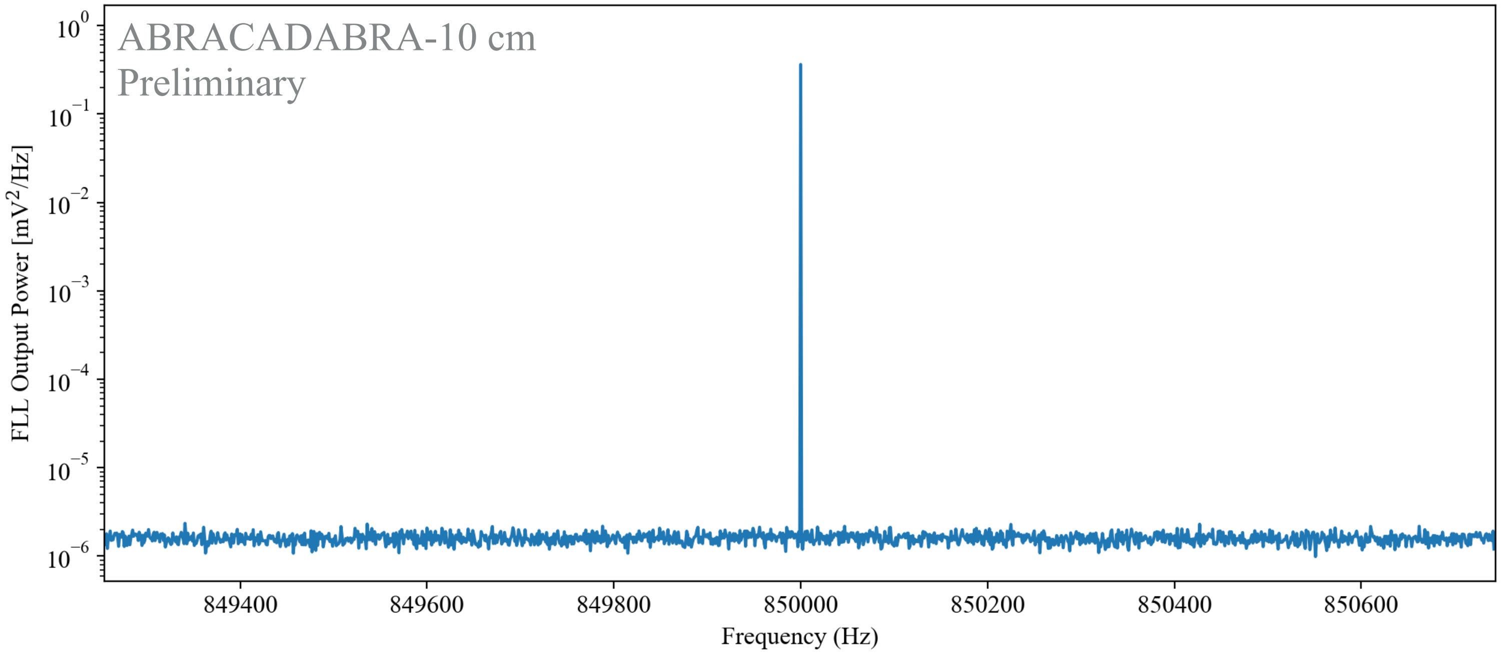


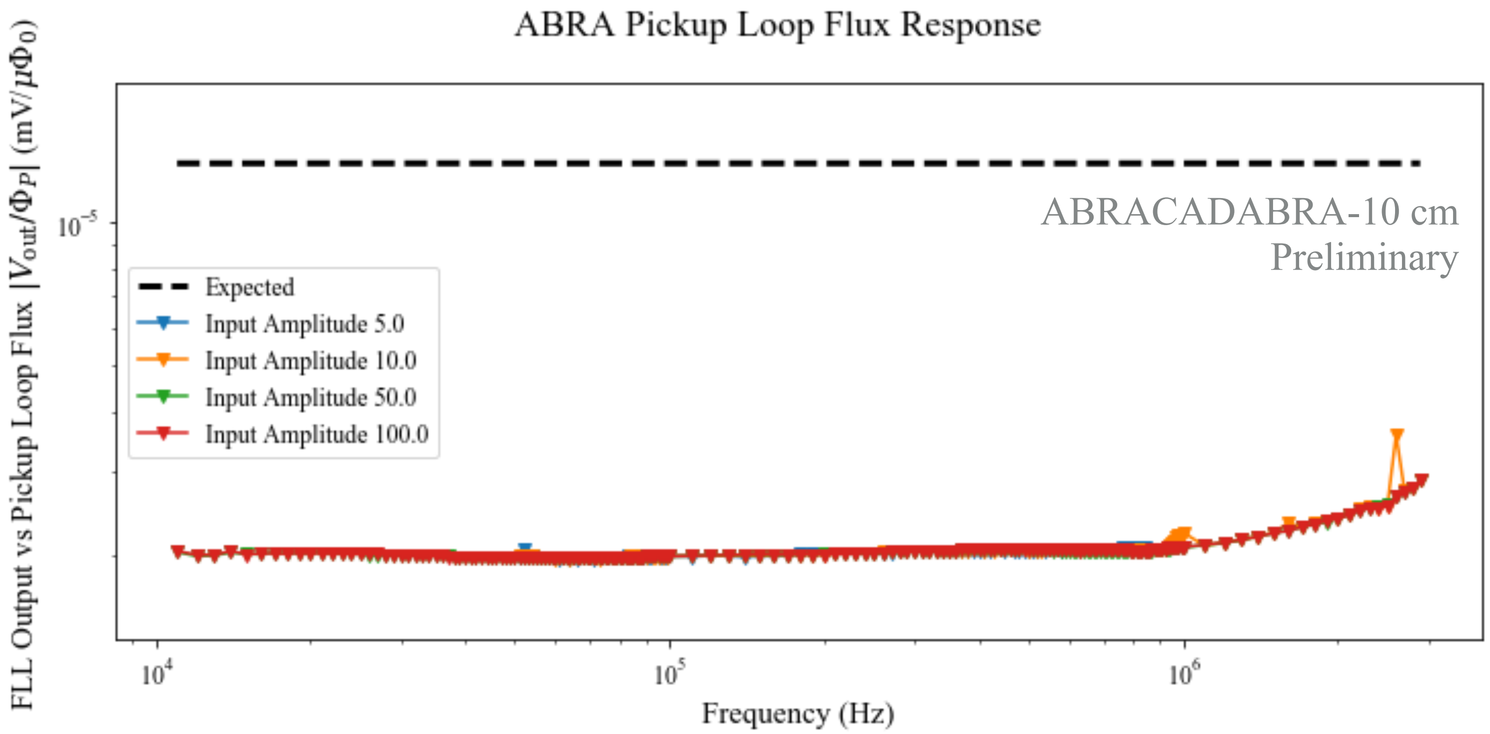
- 10 kHz high-pass and 1.9MHz anti-aliasing filters before digitizer
- Digitizer-only data show spurious noise spikes that were vetoed.

ABRACADABRA-10cm Axion Search Run 1

Calibration

- Calibrate by injecting AC current into the calibration loop
- Fine scan from 10 kHz - 3 MHz at multiple amplitudes
- Gain lower than expected by a factor of ~6.5. Corrected for next phase





Broadband Data Collection Procedure

- Collected data with magnet on continuously for 4 weeks from July - August
- AlazarTech ATS9870 8-bit Digitizer locked to a Rb oscillator frequency standard
- 10 MS/s for 2.4×10^6 seconds (25T samples total)
- Apply FFTW on-the-fly on DAQ machine to compute Power Spectral Distributions (PSD)
- Acquisition (currently) limited to 1 cpu and 8 TB max data size

10 MS/s Sampling → Down Sample → 1 MS/s Sampling → Down Sample → 100 kS/s Sampling

10 MS/s Sampling ↓

Compute PSDs of 10 s waveforms

Average 80 PSDs, write to disk

$\Delta f = 100$ mHz

1 MS/s Sampling ↓

Compute PSDs of 100 s waveforms

Average 16 PSDs, write to disk

$\Delta f = 10$ mHz

100 kS/s Sampling ↓

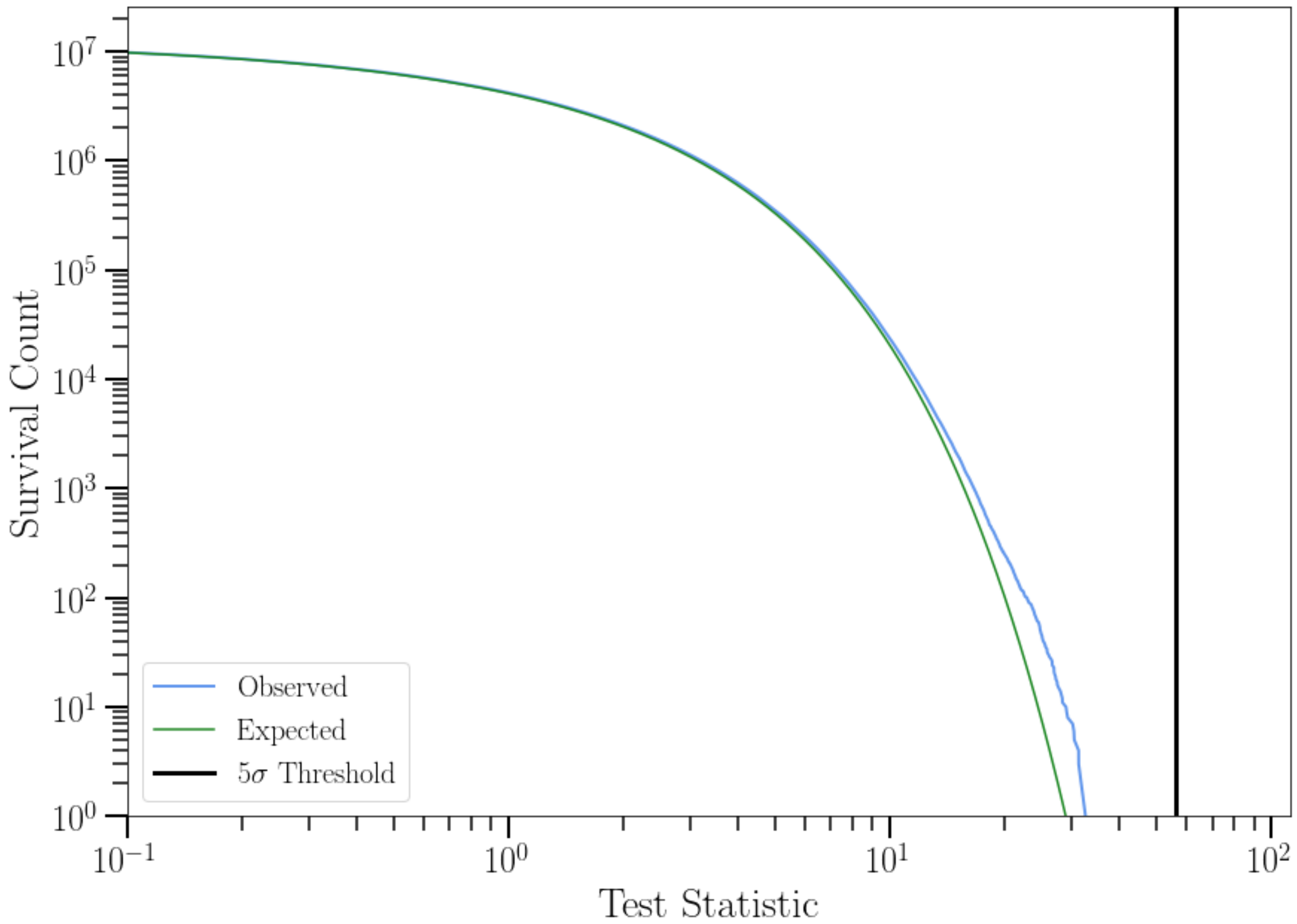
Written directly to disk

2,452,000 seconds total

$\Delta f \approx 408$ nHz

Axion Search Approach

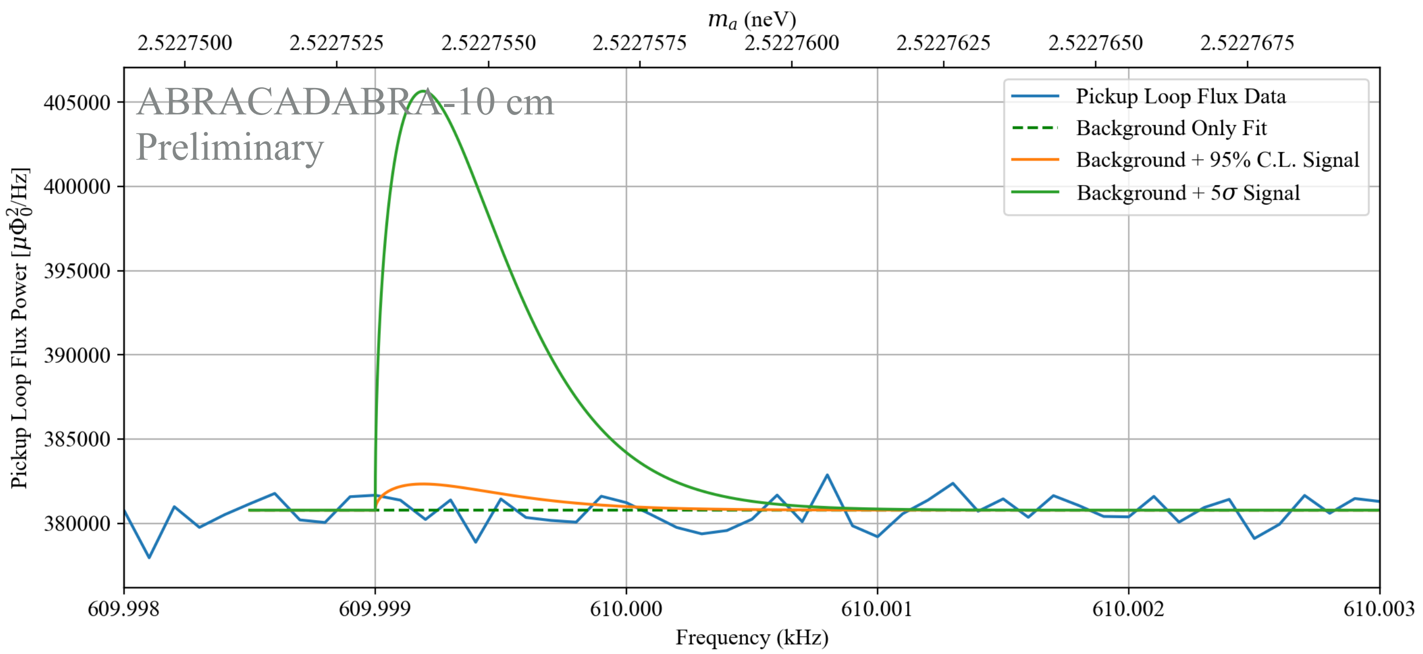
- Search range to 75 kHz - 2 MHz (m_a in 0.31 — 8.1 neV).
- 8.6 million mass points
- For each mass point, calculate a likelihood function
- Axion discovery search based on a log-likelihood ratio test, between the best fit and the null hypothesis
- 5σ discovery threshold: TS>56.1
- Accounts for Look Elsewhere Effect.

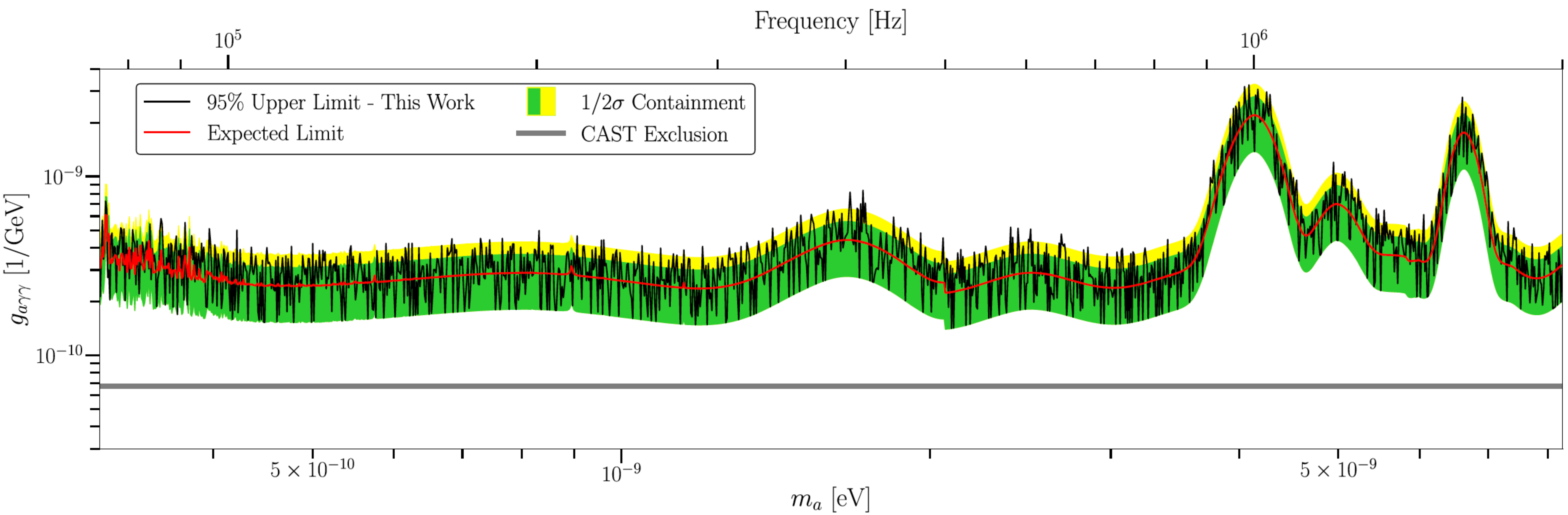


For details, see: PRD 97 (2018) 123006

Axion Limits

- We saw no 5σ excesses that were not vetoed by Magnet off or digitizer data
- 87 (0) mass points were vetoed in the 10MS/s (1MS/s) data
- We place 95% C.L. upper limits using a similar log-likelihood ratio approach

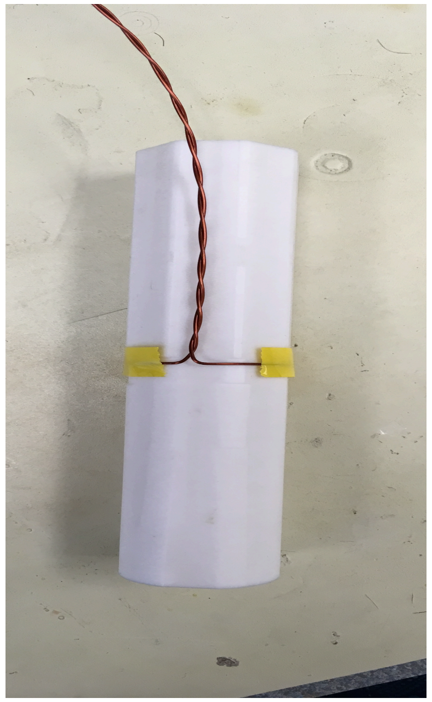


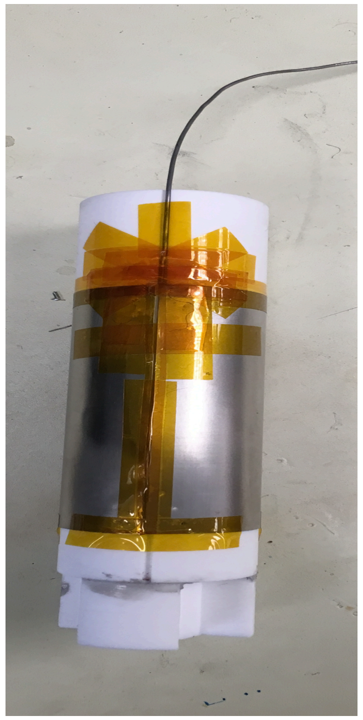


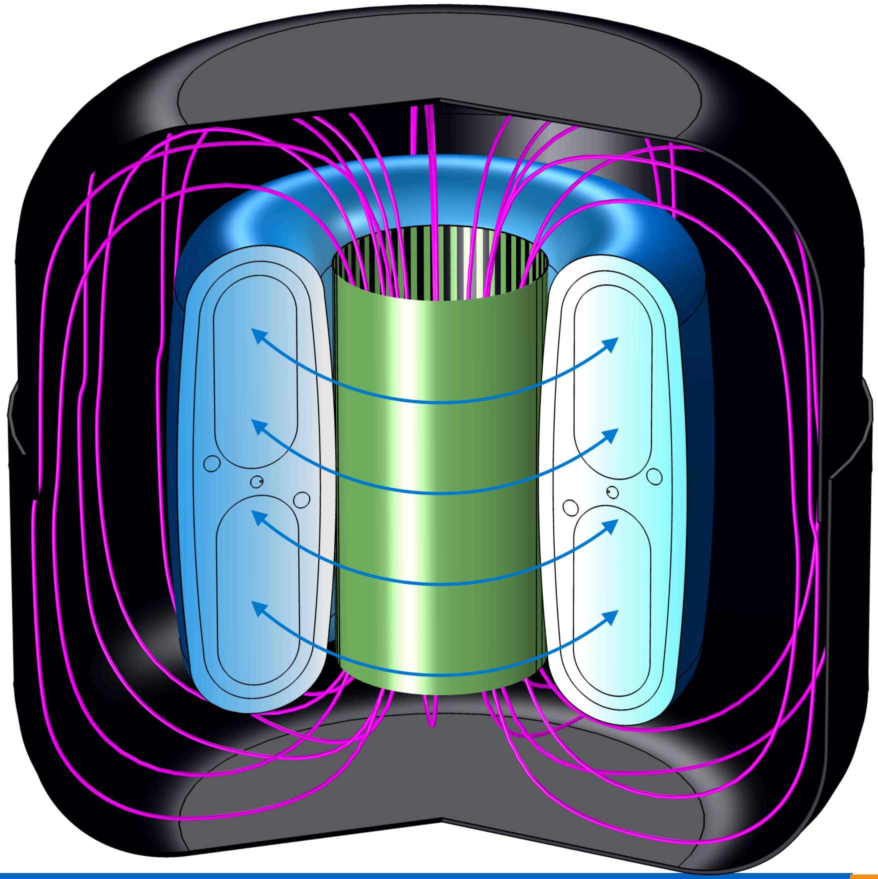
PRD 99 (2019) 052012, PRL 122 (2019) 121802

ABRA-10 cm Run 2

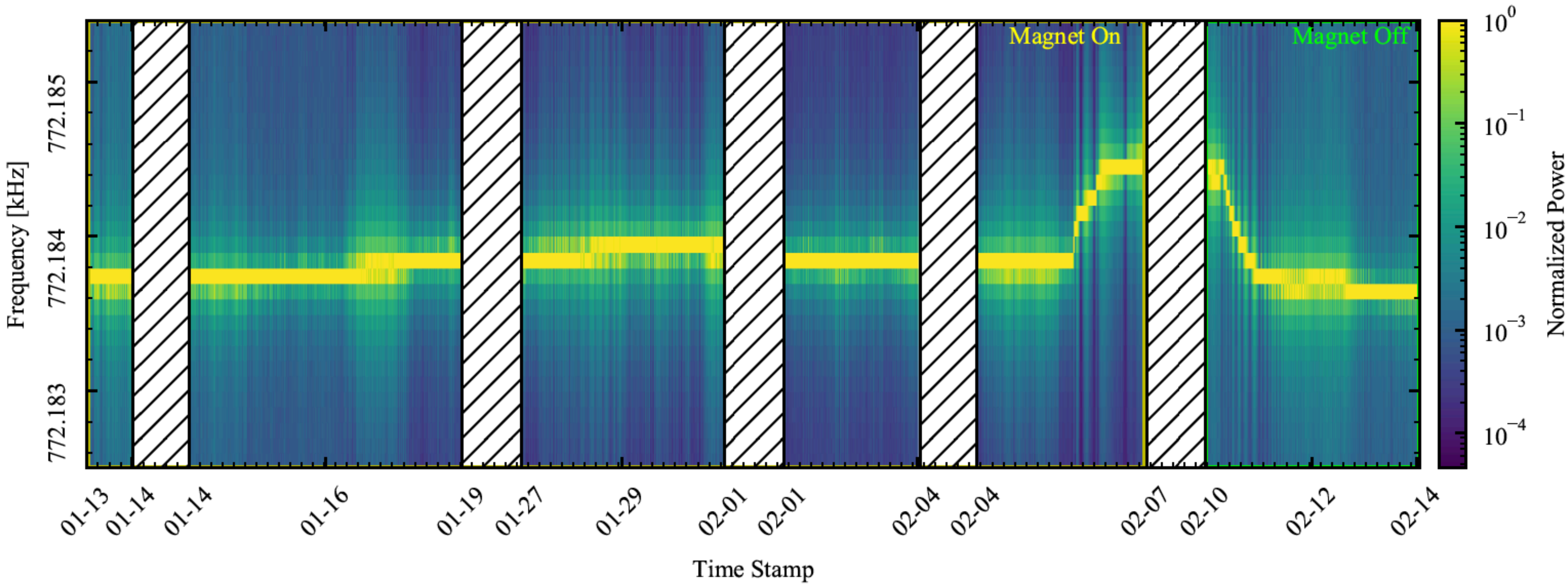
- Reduced wiring lengths — reduced parasitic inductances
- Cylindrical Pickup loop to reduce loop inductance
- Boosted gain by factor ~10
- Had to implement active feedback to reduce noise <1kHz
- Results submitted for publication 2102.06722





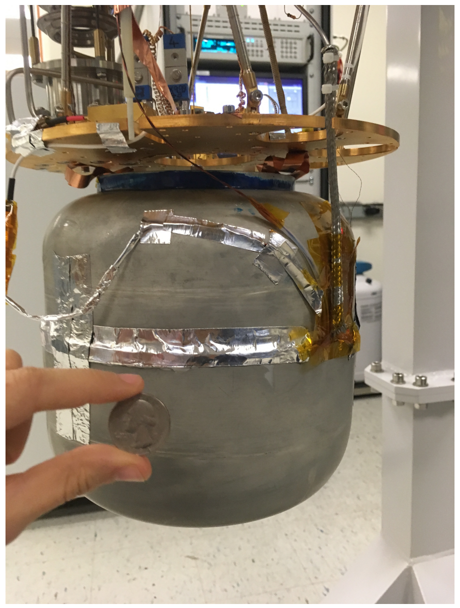


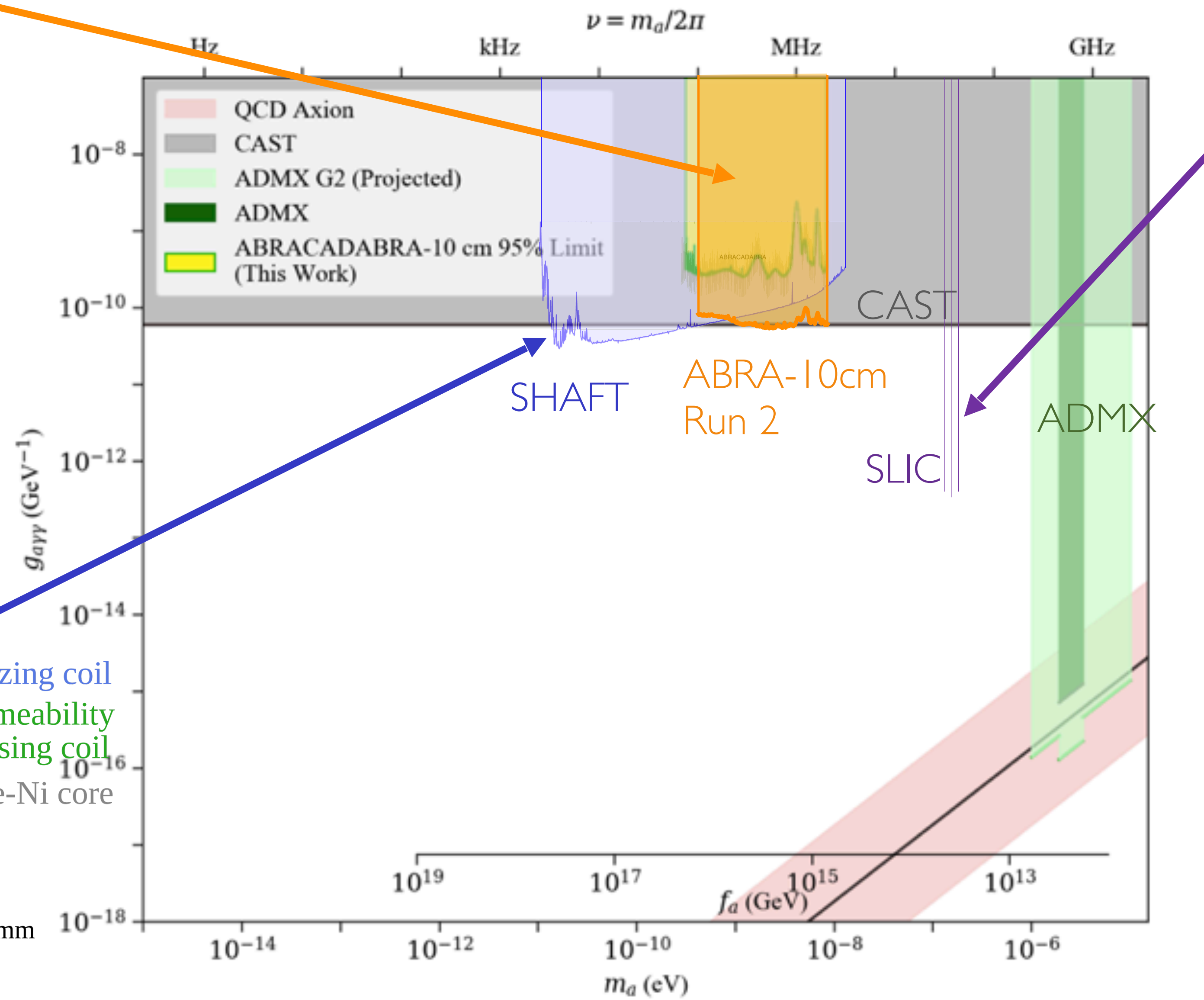
Run 2 Data Cleaning

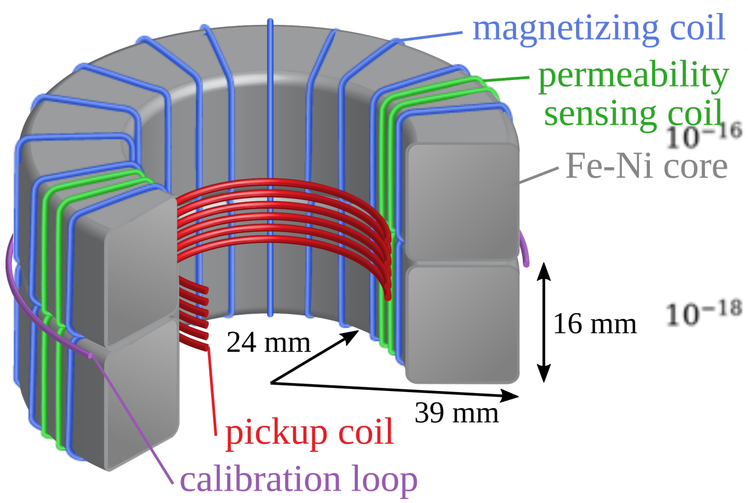


Ex: Remove peaks that drift in time
Technique developed by A. Gavin (UNC)

Summary of Recent Results

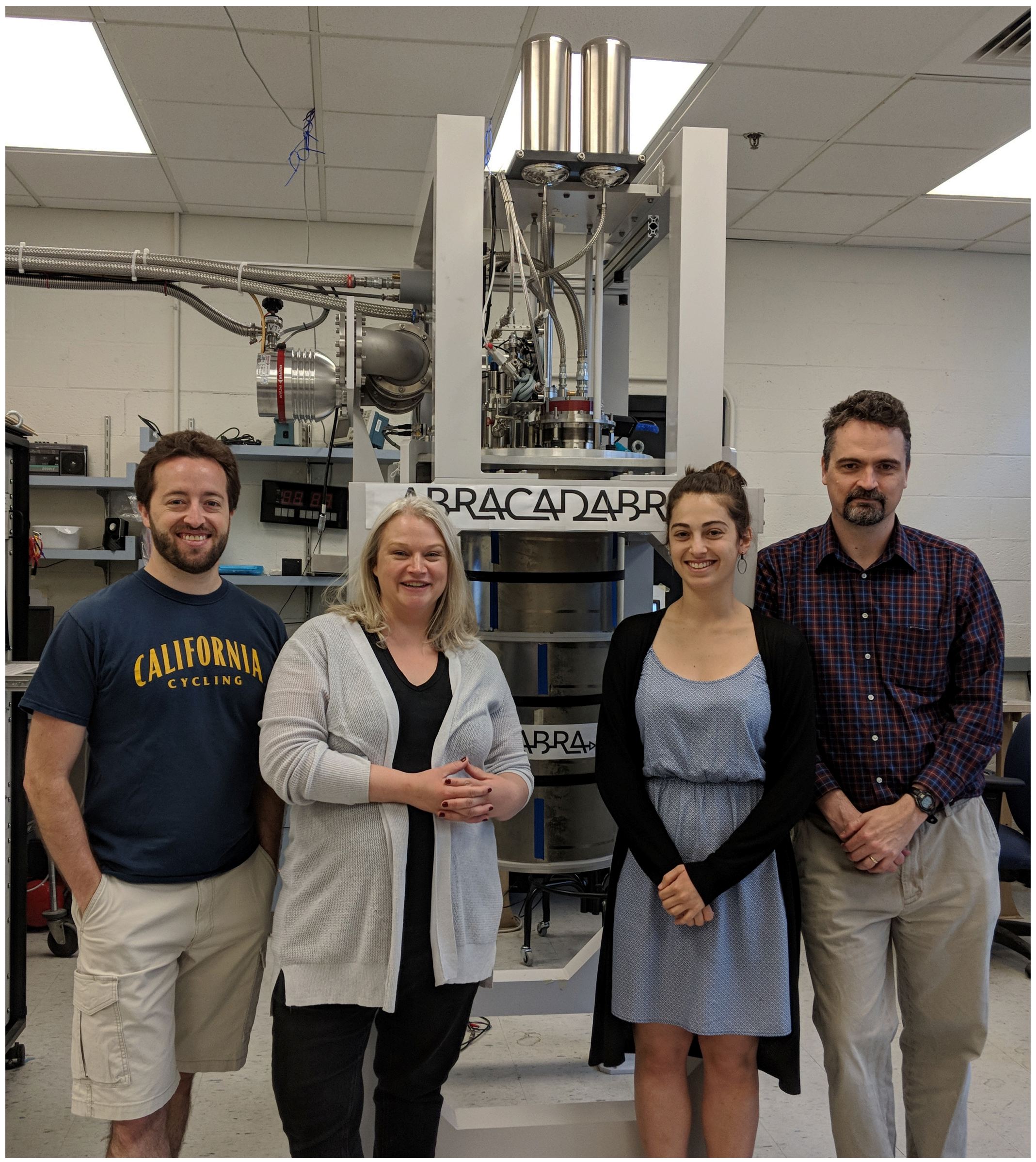






C. Salemi

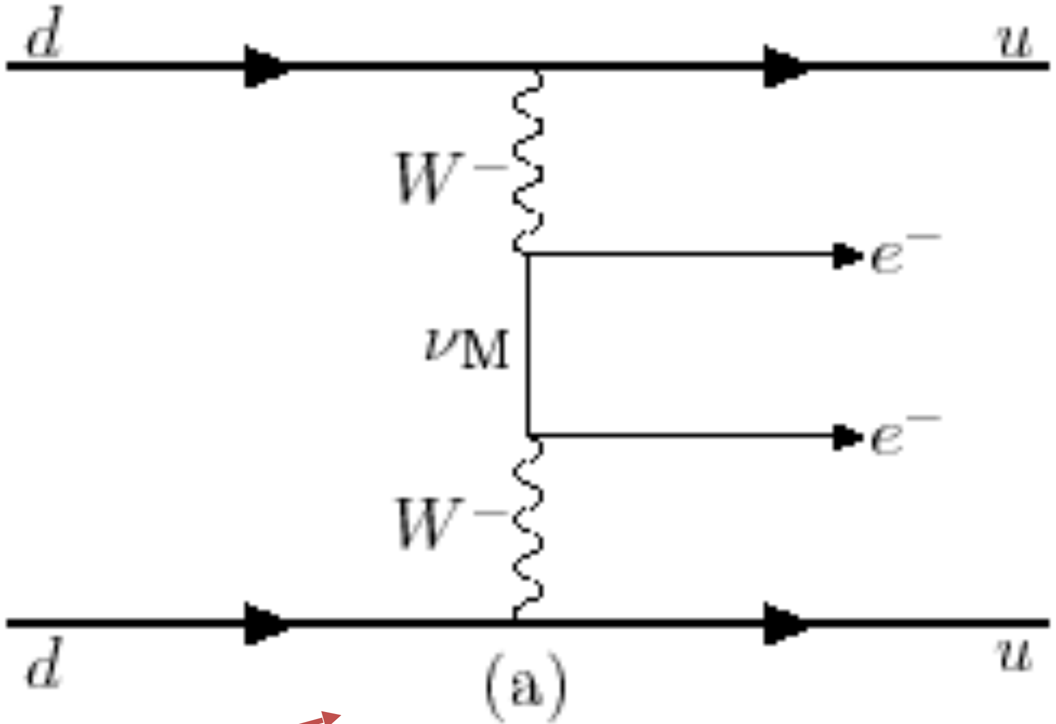
ABRACADABRA



The MAJORANA DEMONSTRATOR

Motivation for *0υββ* Search

- Implications of discovery:
  - Neutrino is Majorana* (own antiparticle)
  - Total lepton number is not conserved
  - Neutrinos have mass* (known)
  - Absolute neutrino mass.
- 0υββ nuclear decay may occur via several processes (SUSY, RH currents, etc)
- Canonical example: Exchange of virtual Majorana neutrino

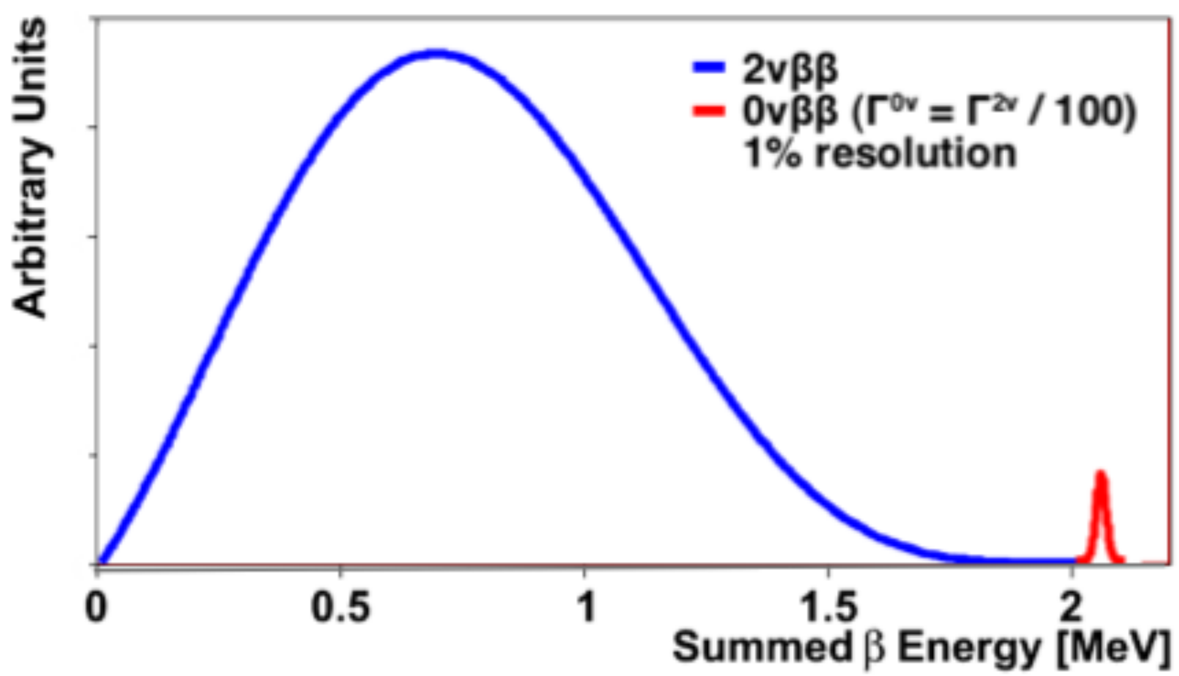


* Schechter et al, Phys. Rev. D**25**, 2951 (1982)

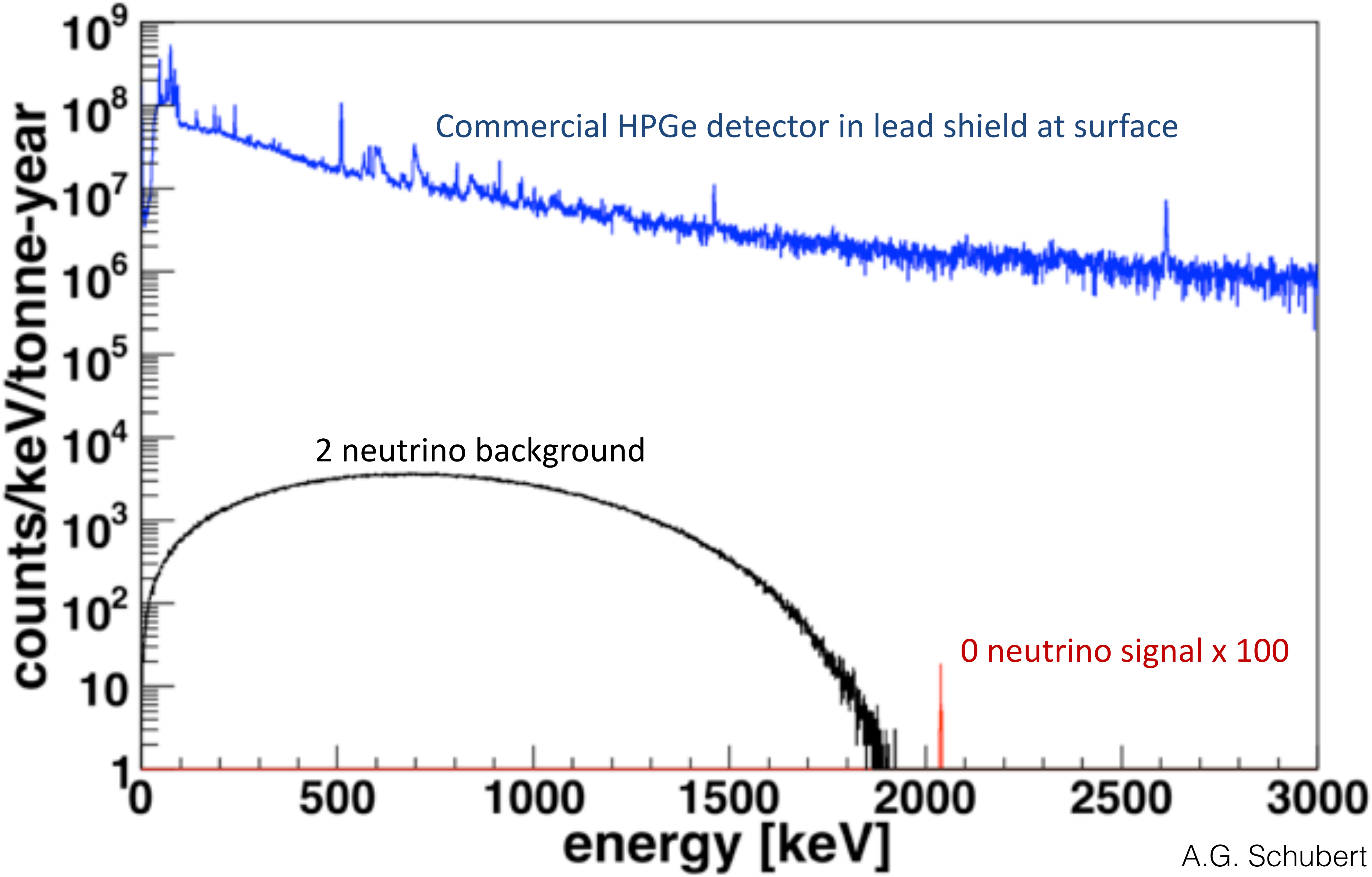
Experimental Considerations

- Measure ***extremely*** rare decay rates :
- $T_{1/2} \sim 10^{26}$-10^{27} years ~ few decays per tonne per year.
- Large, highly efficient source mass.
- Extremely low (near-zero) backgrounds in the $0\nu\beta\beta$ peak region-of-interest (ROI)

1. High *Q* value
2. Best possible energy resolution
   - Minimize $0\nu\beta\beta$ peak ROI to maximize S/B
   - Separate $2\nu\beta\beta/0\nu\beta\beta$



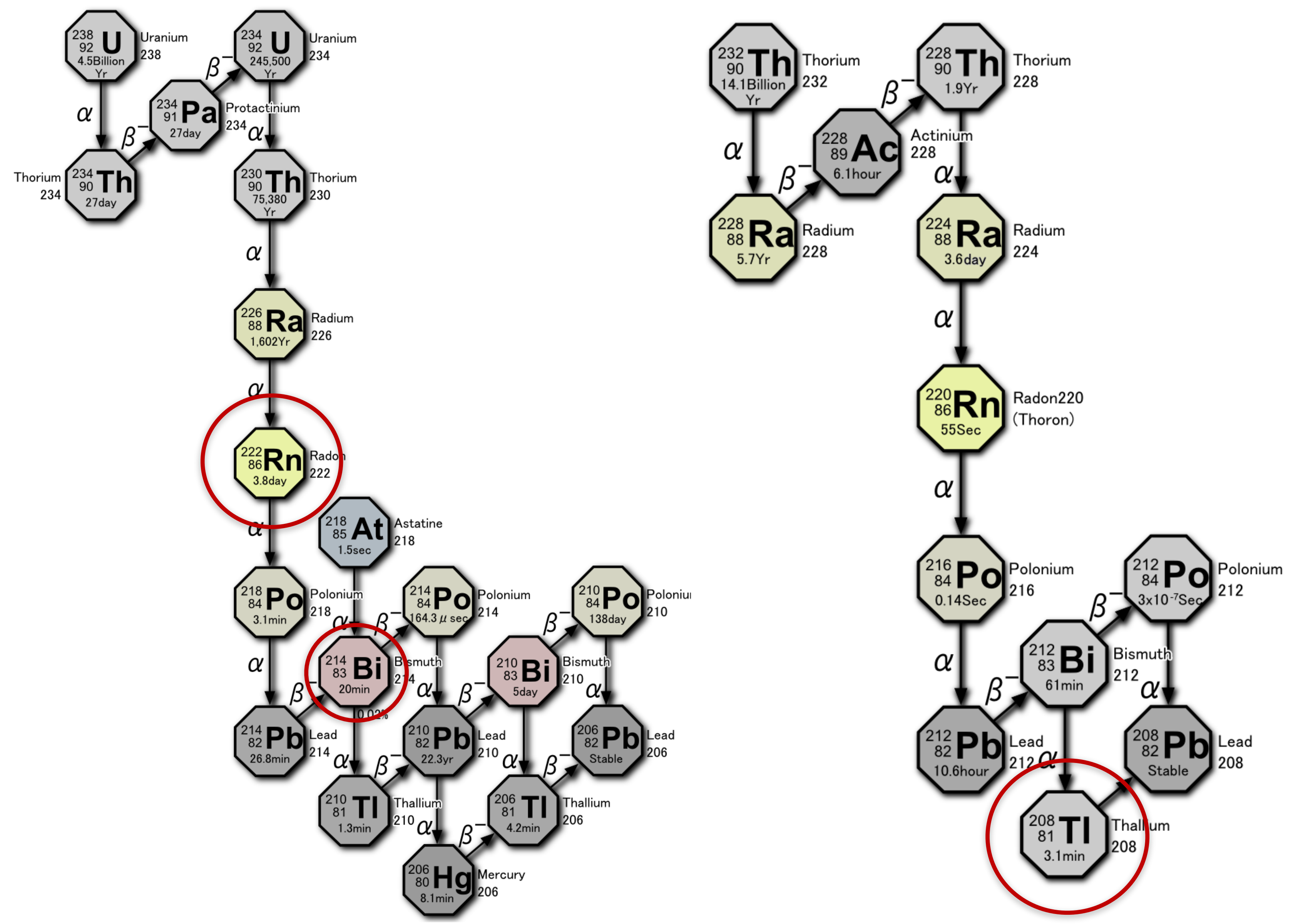
Background Reduction Challenges



A.G. Schubert

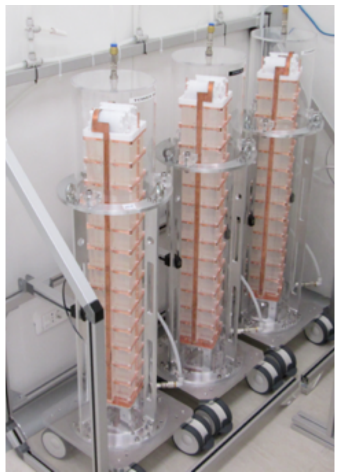
Background Identification

- Natural isotope chains:
  - ^{232}Th, ^{235}U, ^{238}U, Rn
- $2\nu\beta\beta$-decays
- Cosmic Rays:
  - Activation at surface
  - Hard neutrons from cosmic rays in rock and shield.
  - Prompt
- Pushing limits in ICP-MS, materials science, radio-assay. Ie. Ultra-low radioactive background, fast, low-noise electronics

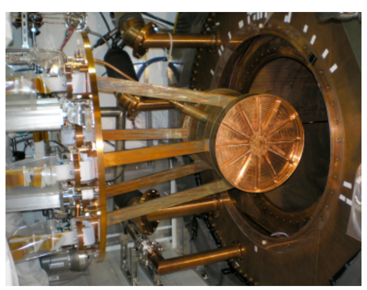


0νββ decay Experiments - Efforts Underway

CUORE



EXO200

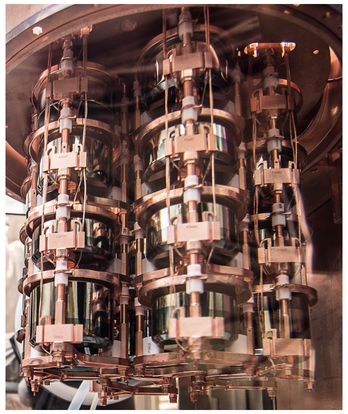


KamLAND Zen

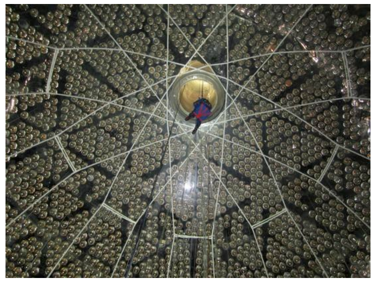
Collaboration	Isotope	Technique	mass (0νββ isotope)	Status
CANDLES	Ca-48	305 kg CaF_2 crystals - liq. scint	0.3 kg	Construction
CARVEL	Ca-48	$^{48}CaWO_4$ crystal scint.	~ ton	R&D
GERDA I	Ge-76	Ge diodes in LAr	15 kg	Complete
GERDA II	Ge-76	Point contact Ge in LAr	31	Operating
MAJORANA DEMONSTRATOR	Ge-76	Point contact Ge	25 kg	Operating
LEGEND	Ge-76	Point contact with active veto	**~ ton**	R&D
NEMO3	Mo-100 Se-82	Foils with tracking	6.9 kg 0.9 kg	Complete
SuperNEMO Demonstrator	Se-82	Foils with tracking	7 kg	Construction
SuperNEMO	Se-82	Foils with tracking	100 kg	R&D
LUCIFER (CUPID)	Se-82	ZnSe scint. bolometer	18 kg	R&D
AMoRE	Mo-100	$CaMoO_4$ scint. bolometer	1.5 - 200 kg	R&D
LUMINEU (CUPID)	Mo-100	$ZnMoO_4$ / Li_2MoO_4 scint. bolometer	1.5 - 5 kg	R&D
COBRA	Cd-114,116	CdZnTe detectors	10 kg	R&D
CUORICINO, CUORE-0	Te-130	TeO_2 Bolometer	10 kg, 11 kg	Complete
CUORE	Te-130	TeO_2 Bolometer	**206 kg**	Operating
CUPID	Te-130	TeO_2 Bolometer & scint.	**~ ton**	R&D
SNO+	Te-130	0.3% ^{nat}Te suspended in Scint	**160 kg**	Construction
EXO200	Xe-136	Xe liquid TPC	79 kg	Operating
nEXO	Xe-136	Xe liquid TPC	**~ ton**	R&D
KamLAND-Zen (I, II)	Xe-136	2.7% in liquid scint.	**380 kg**	Complete
KamLAND2-Zen	Xe-136	2.7% in liquid scint.	**750 kg**	Upgrade
NEXT-NEW	Xe-136	High pressure Xe TPC	5 kg	Operating
NEXT-100	Xe-136	High pressure Xe TPC	100 kg - **ton**	R&D
PandaX - III	Xe-136	High pressure Xe TPC	~ **ton**	R&D
DCBA	Nd-150	Nd foils & tracking chambers	20 kg	R&D

GERDA

MAJORANA



SNO+

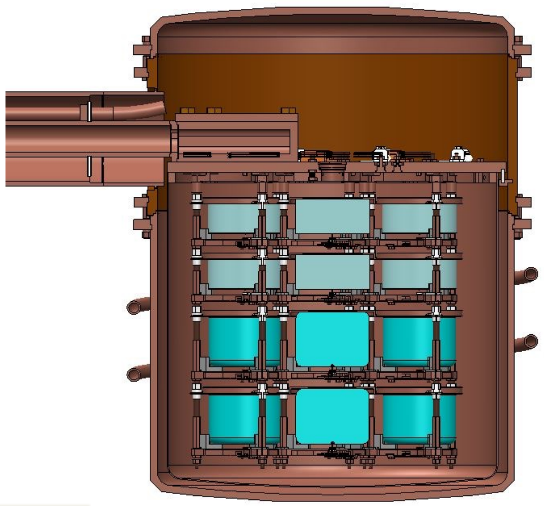


J.F. Wilkerson

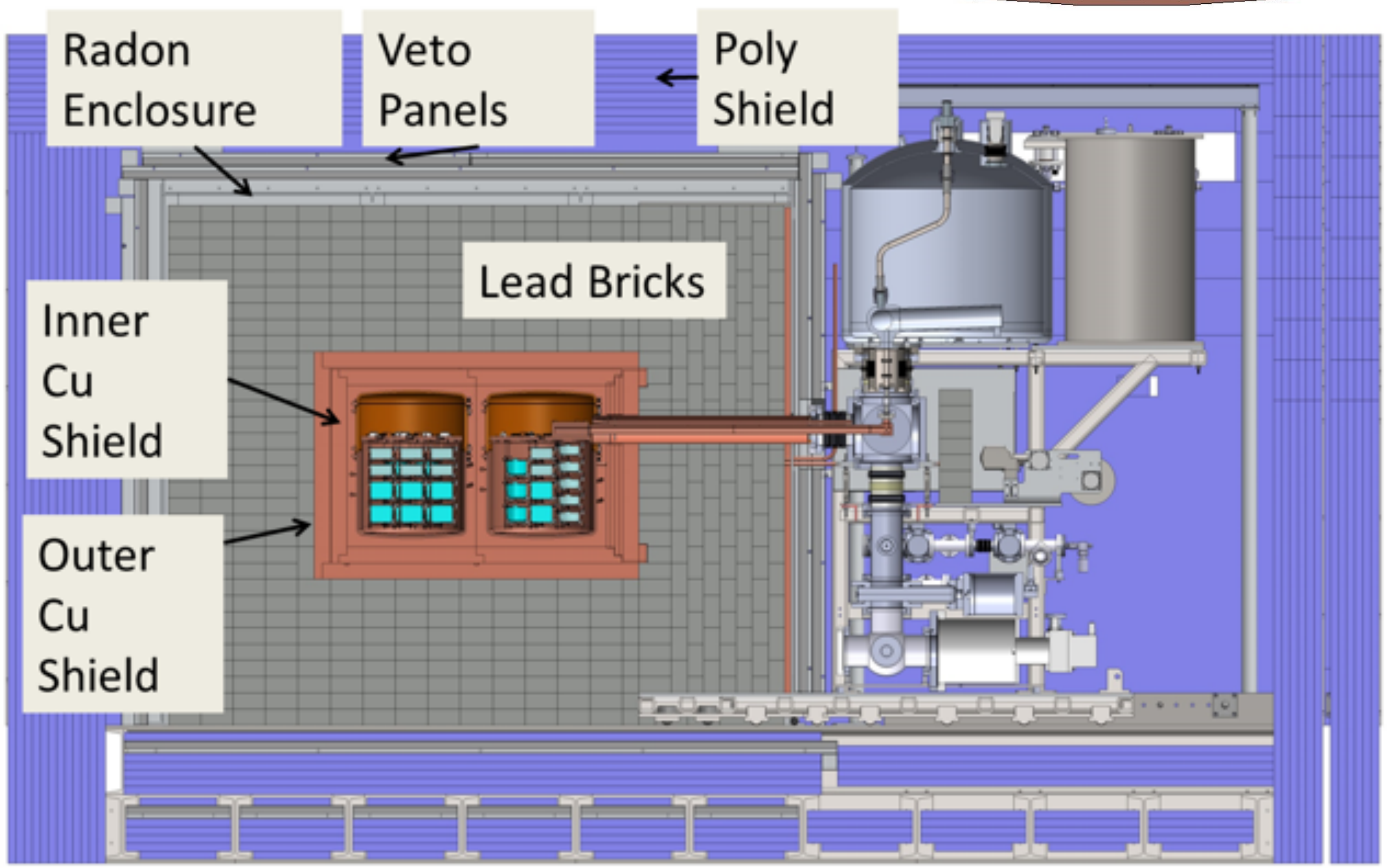
The MAJORANA DEMONSTRATOR

Funded by DOE Office of Nuclear Physics, NSF Particle Astrophysics, & NSF Nuclear Physics with additional contributions from international collaborators.

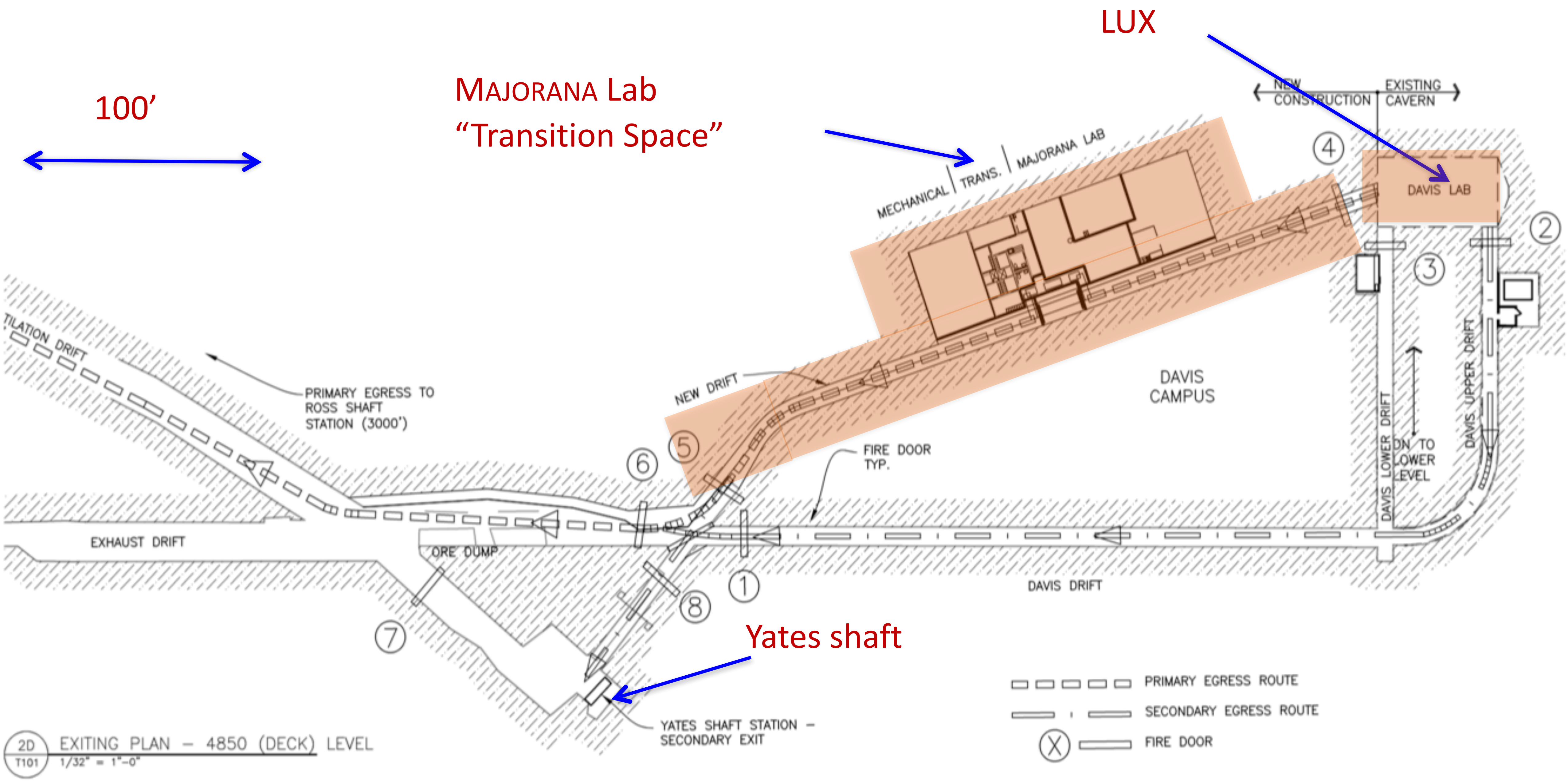
Goals: - Demonstrate backgrounds low enough to justify building a tonne scale experiment.
- Establish feasibility to construct & field modular arrays of Ge detectors.
- Searches for additional physics beyond the standard model.



- Located underground at 4850' Sanford Underground Research Facility
- Background Goal in the $0\nu\beta\beta$ peak region of interest (4 keV at 2039 keV)
- 44.1-kg of Ge detectors
  - 29.7 kg of 88% enriched ^{76}Ge crystals
  - 14.4 kg of ^{nat}Ge
  - Detector Technology: P-type, point-contact.
- 2 independent cryostats
  - ultra-clean, electroformed Cu
  - 22 kg of detectors per cryostat
  - naturally scalable
- Compact Shield
  - low-background passive Cu and Pb shield with active muon veto

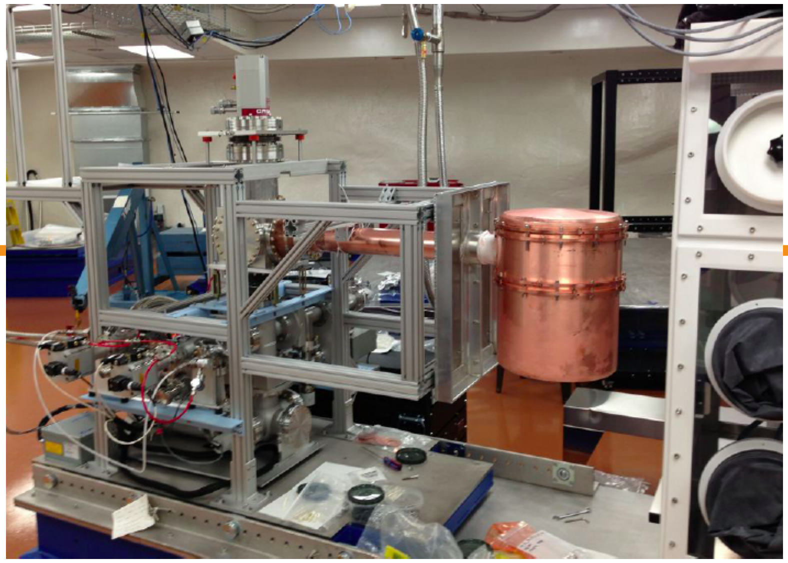


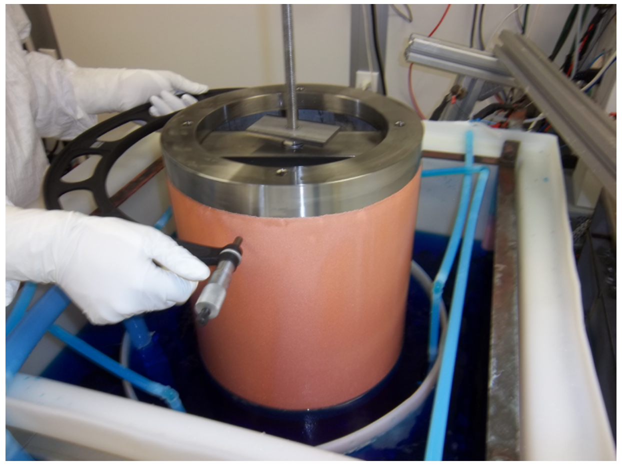
Underground Location of MAJORANA Laboratory



Davis Campus, 4850' level, near Yates shaft

MJD Construction





Electroformed Cu and enriched Ge

Fig: Courtesy M. Kapust

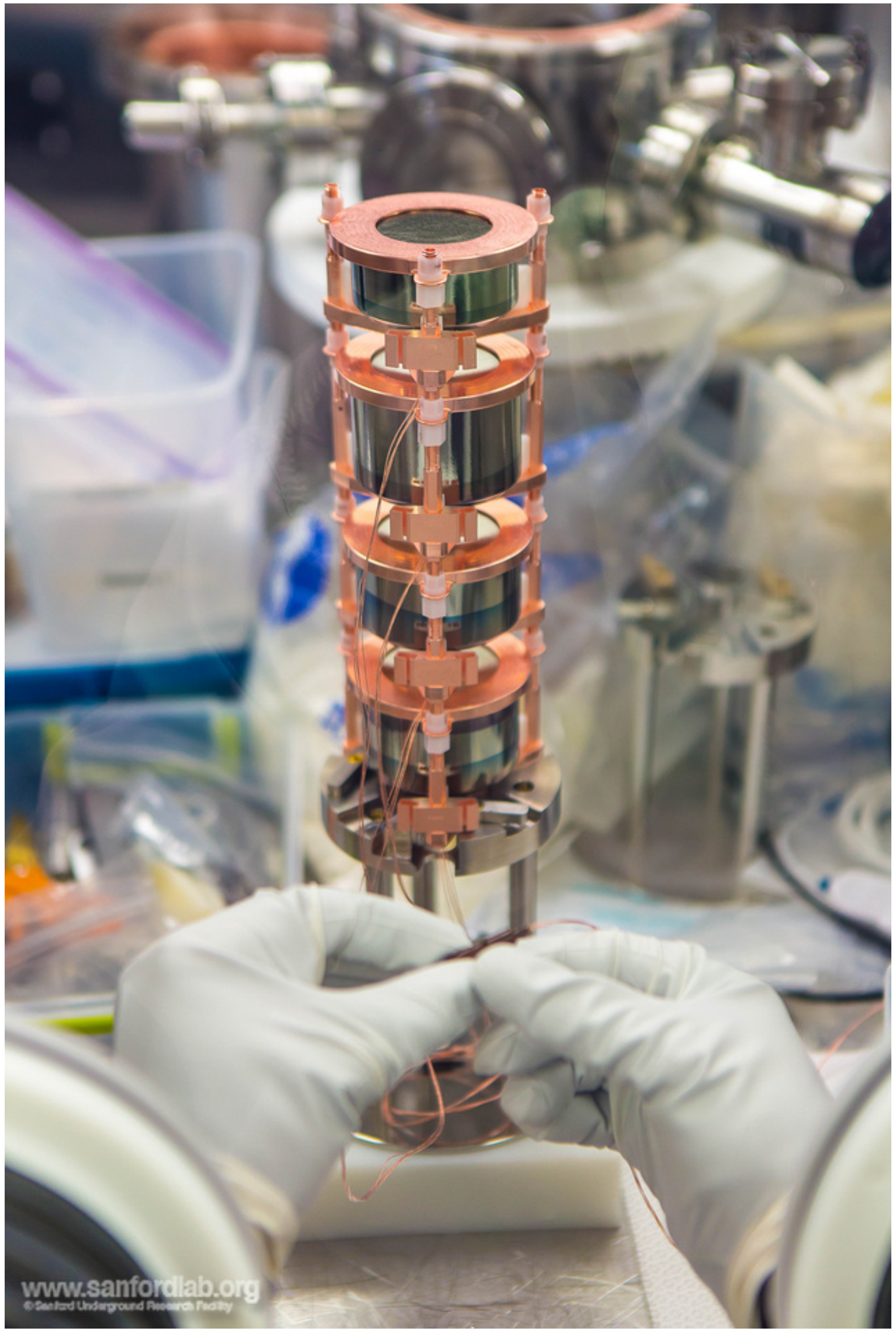
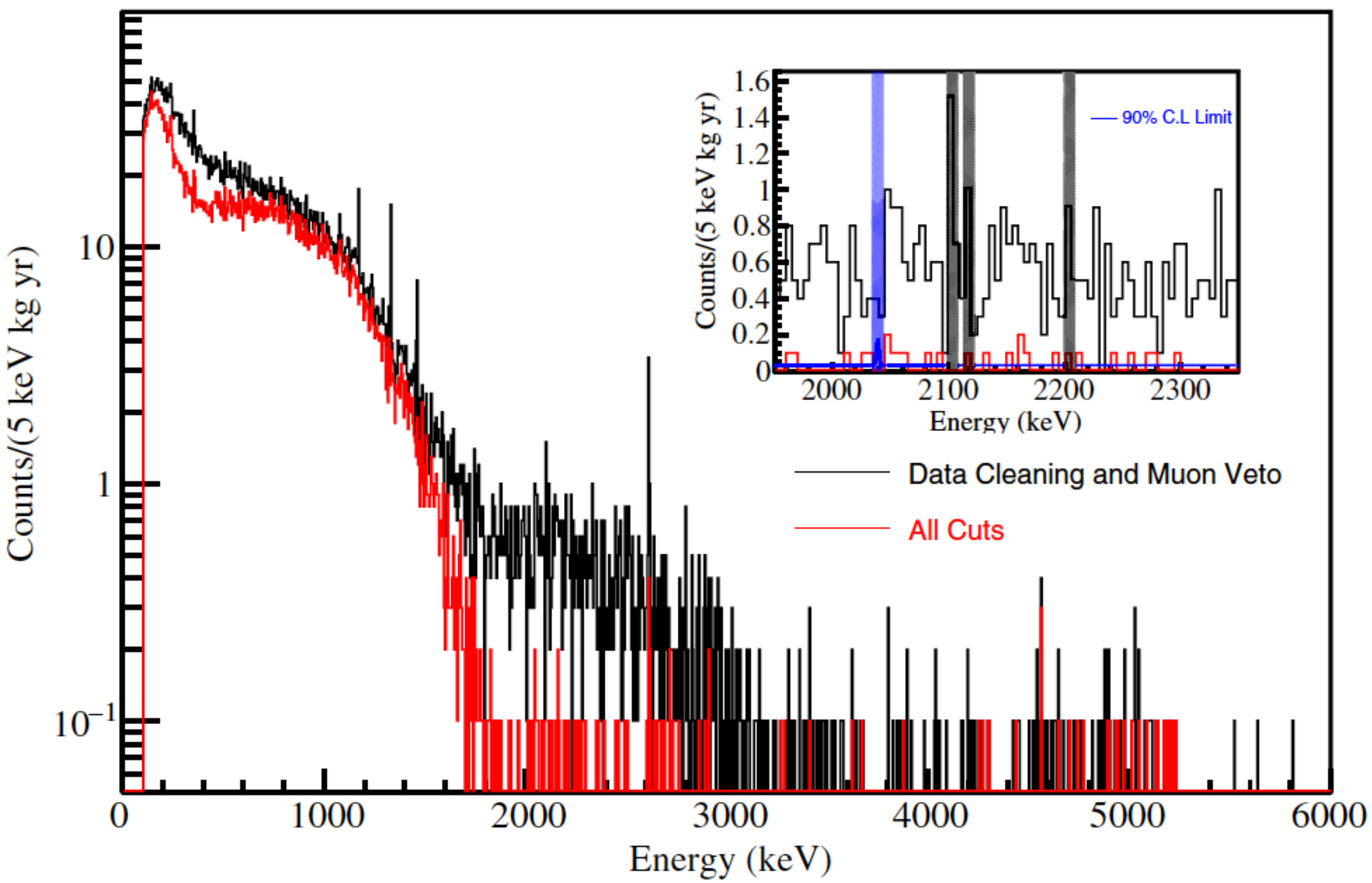


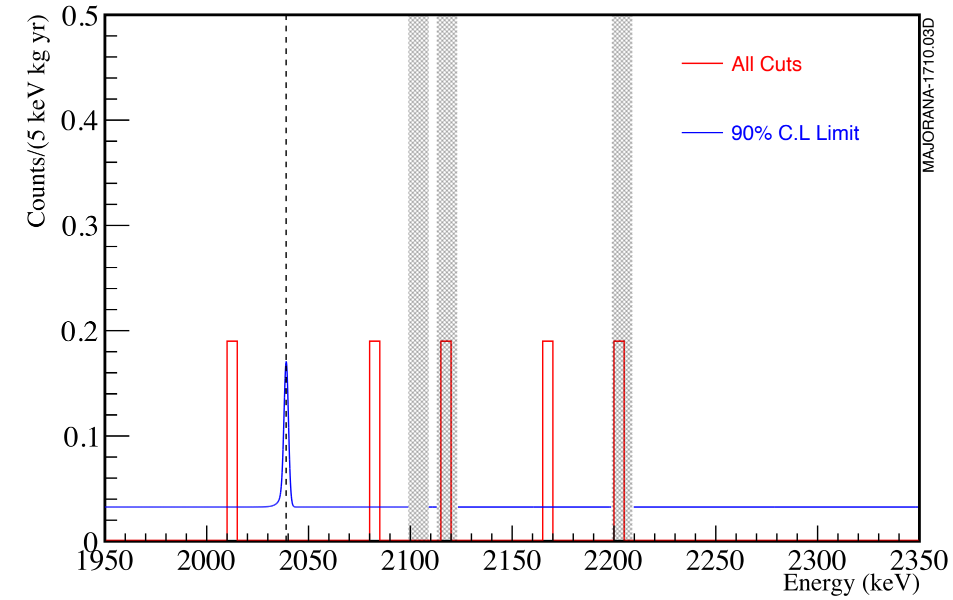
Fig: Courtesy M. Kapust

MAJORANA Results

PHYSICAL REVIEW LETTERS 120, 132502 (2018)

Editors' Suggestion | Featured in Physics





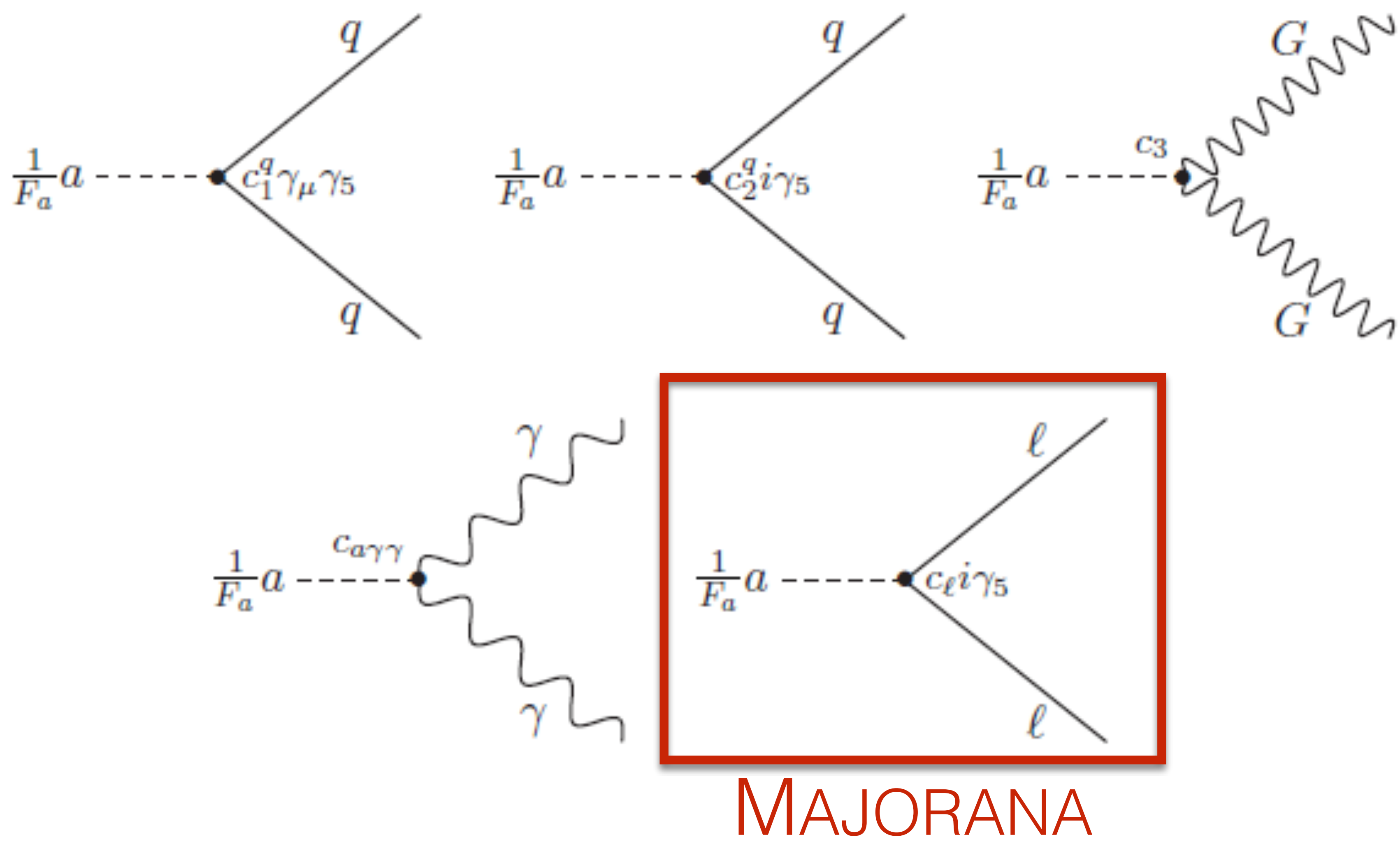
$T_{1/2} > 1.9\times10^{25}$ years

QCD Axion Properties

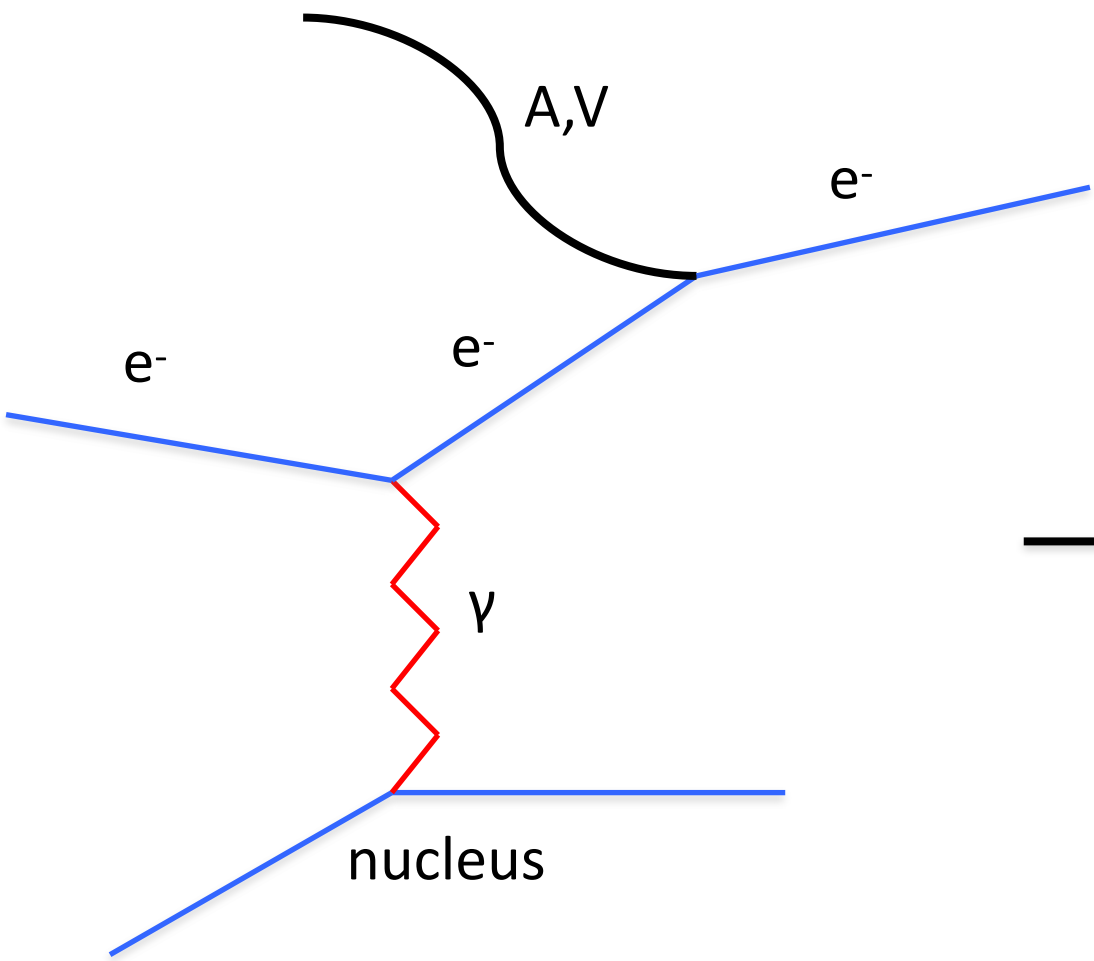
$$m_a \simeq 0.6\,\mathrm{eV}\,\frac{10^7\,\mathrm{GeV}}{f_a}$$

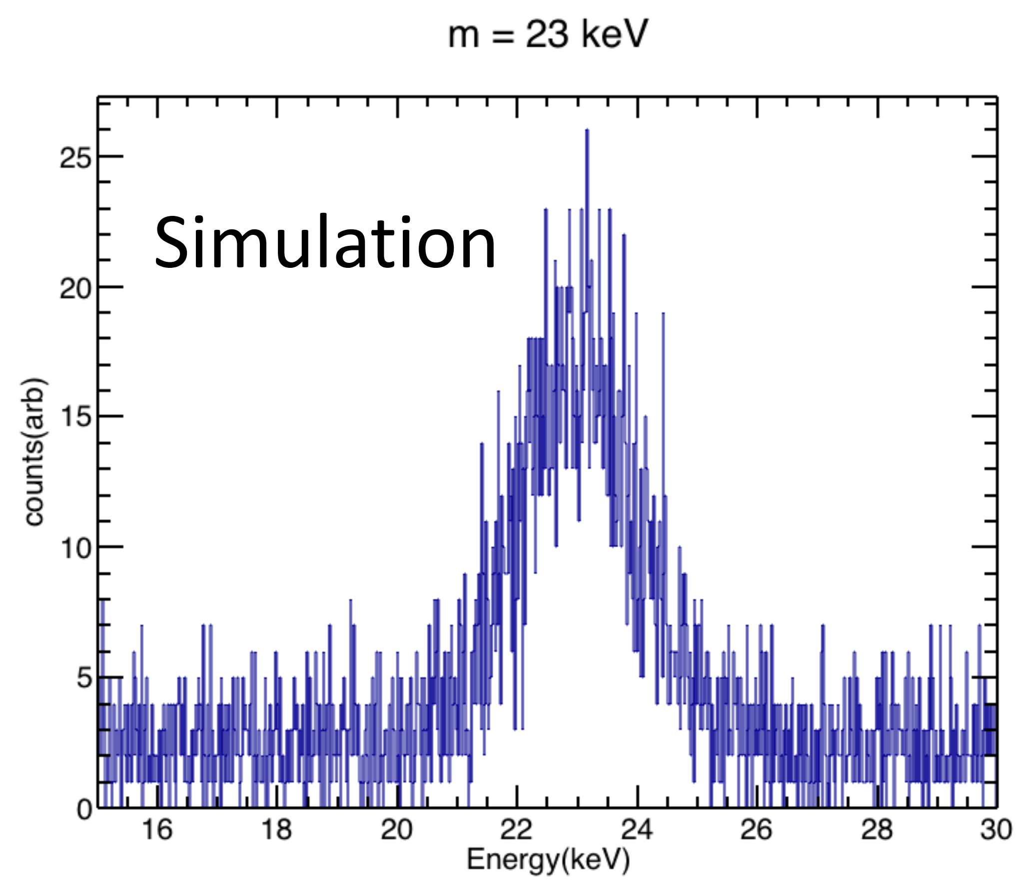
f_a : PQ Symmetry Breaking Scale
Relationship Model-dependent

Rev.Mod.Phys. 82 (2010) 557



Other BSM Physics: Light (1-100 keV-scale) Bosonic DM





ρ_{DM} = 0.3 GeV/cm^3 $\beta = v/c \sim 0.001$

- Low threshold PPC Ge detectors well suited for keV-scale DM search
- Pseudoscalar (ALPs) or Vector DM could deposit rest mass-energy in detector
- See: M. Pospelov, A. Ritz, and M. Voloshin, Phys. Rev. D, 78, 115012 (2008).

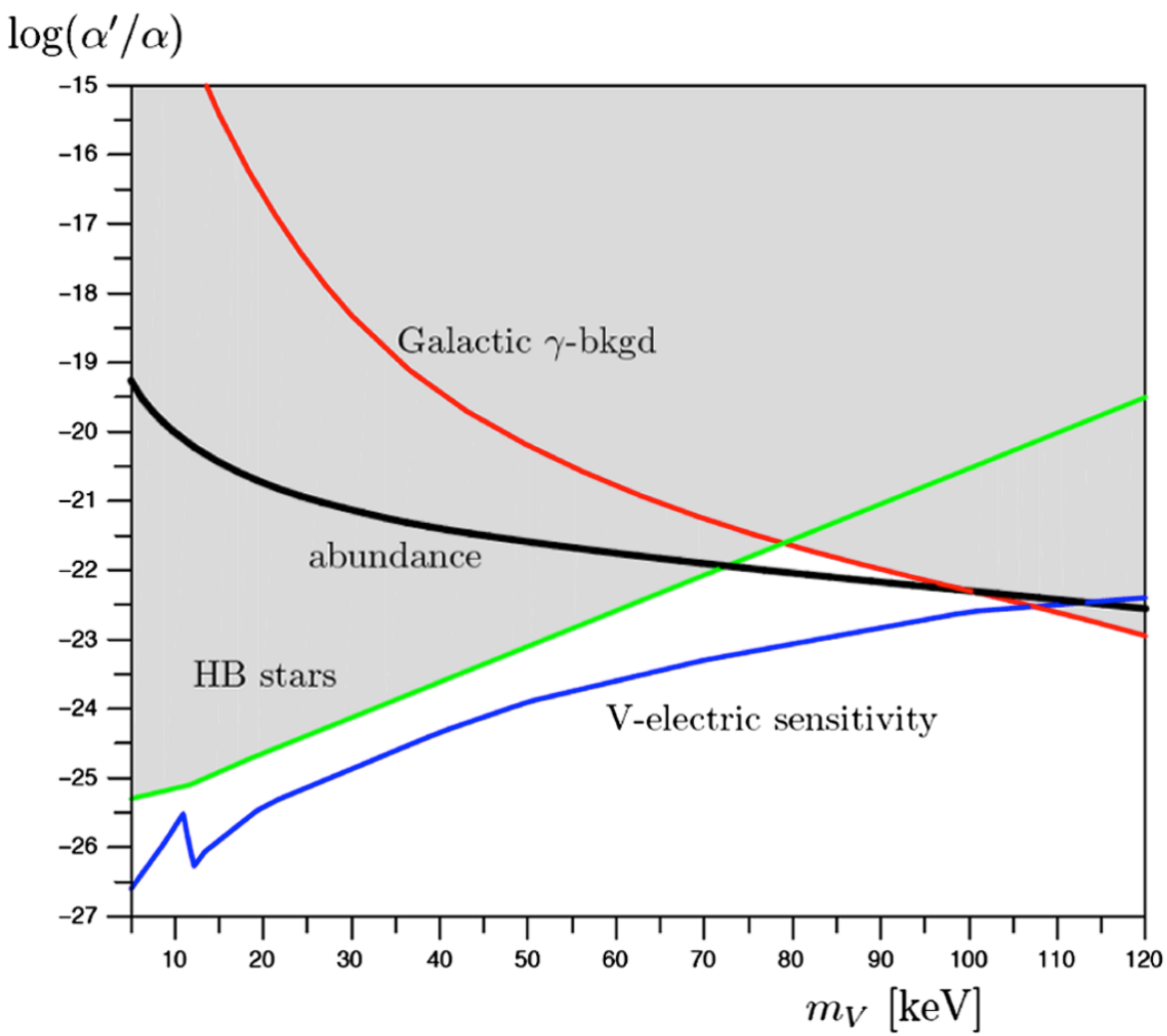
PHYSICAL REVIEW D **78,** 115012 (2008)

Bosonic super-WIMPs as keV-scale dark matter

Maxim Pospelov,[1,2] Adam Ritz,[1] and Mikhail Voloshin[3,4]

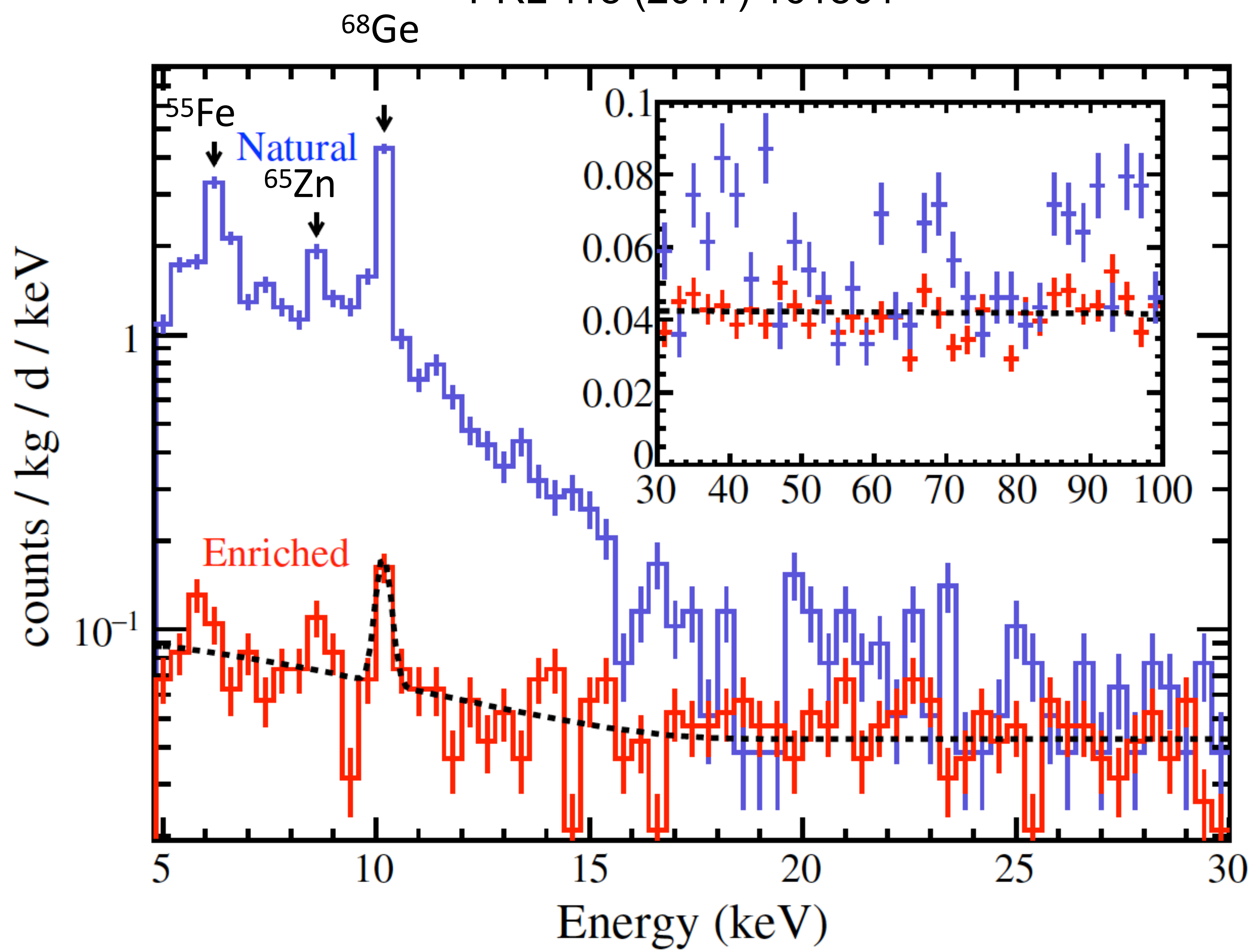
[1]*Department of Physics and Astronomy, University of Victoria, Victoria, British Colombia, V8P 1A1 Canada*
[2]*Perimeter Institute for Theoretical Physics, Waterloo, Ontario, N2J 2W9, Canada*
[3]*William I. Fine Theoretical Physics Institute, University of Minnesota, Minneapolis, Minnesota 55455, USA*
[4]*Institute of Theoretical and Experimental Physics, Moscow, 117218, Russia*

(Received 15 August 2008; published 16 December 2008)



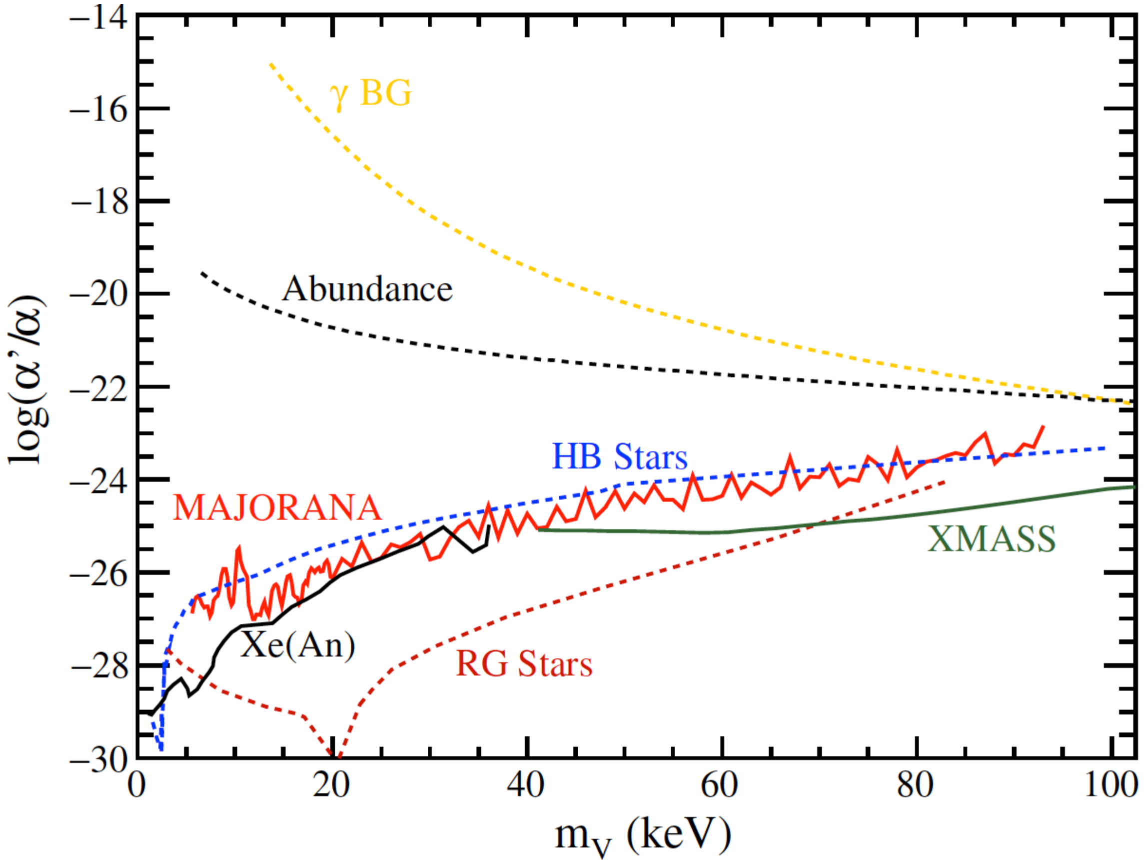
Low-energy backgrounds world-leading for Ge in commissioning data!

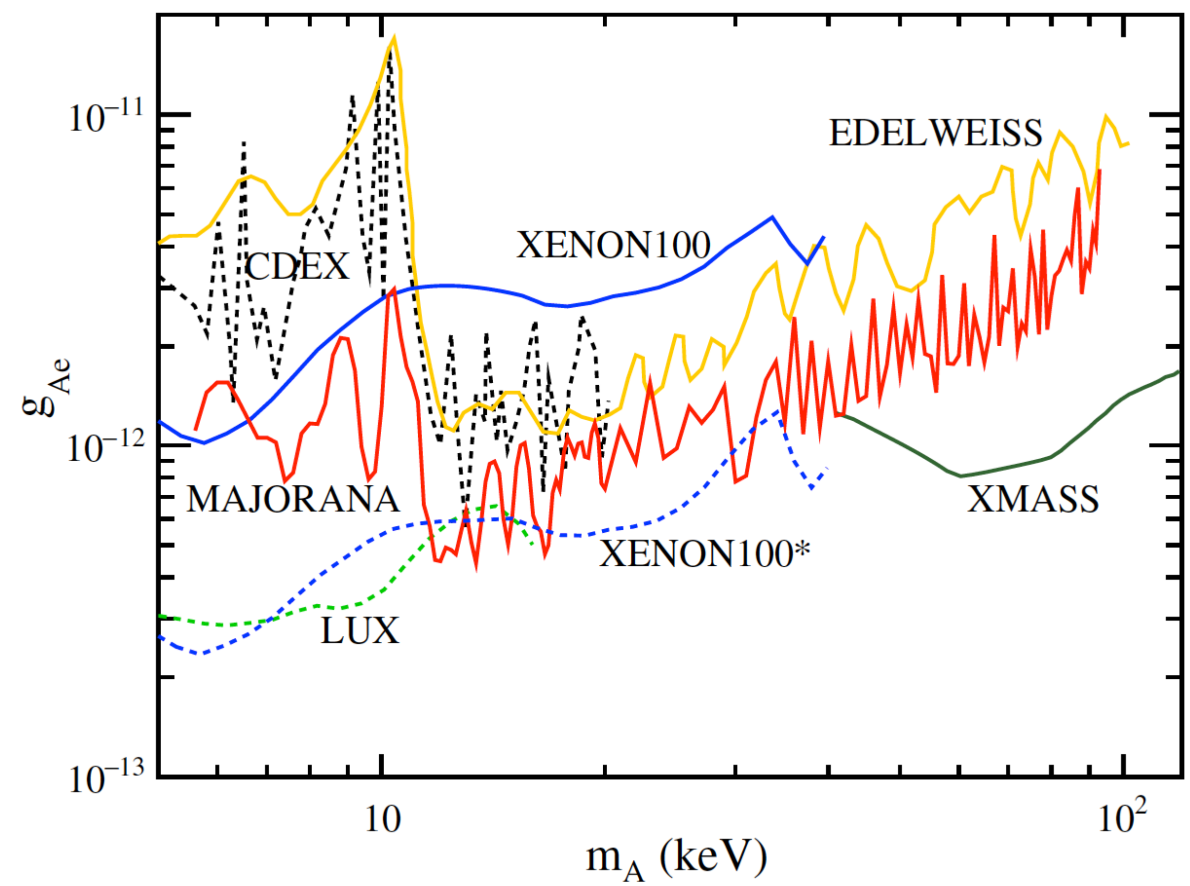
PRL 118 (2017) 161801



Bosonic DM limits

PRL 118 (2017) 161801





Pseudoscalar ALP-like DM

Vector DM electron coupling α'

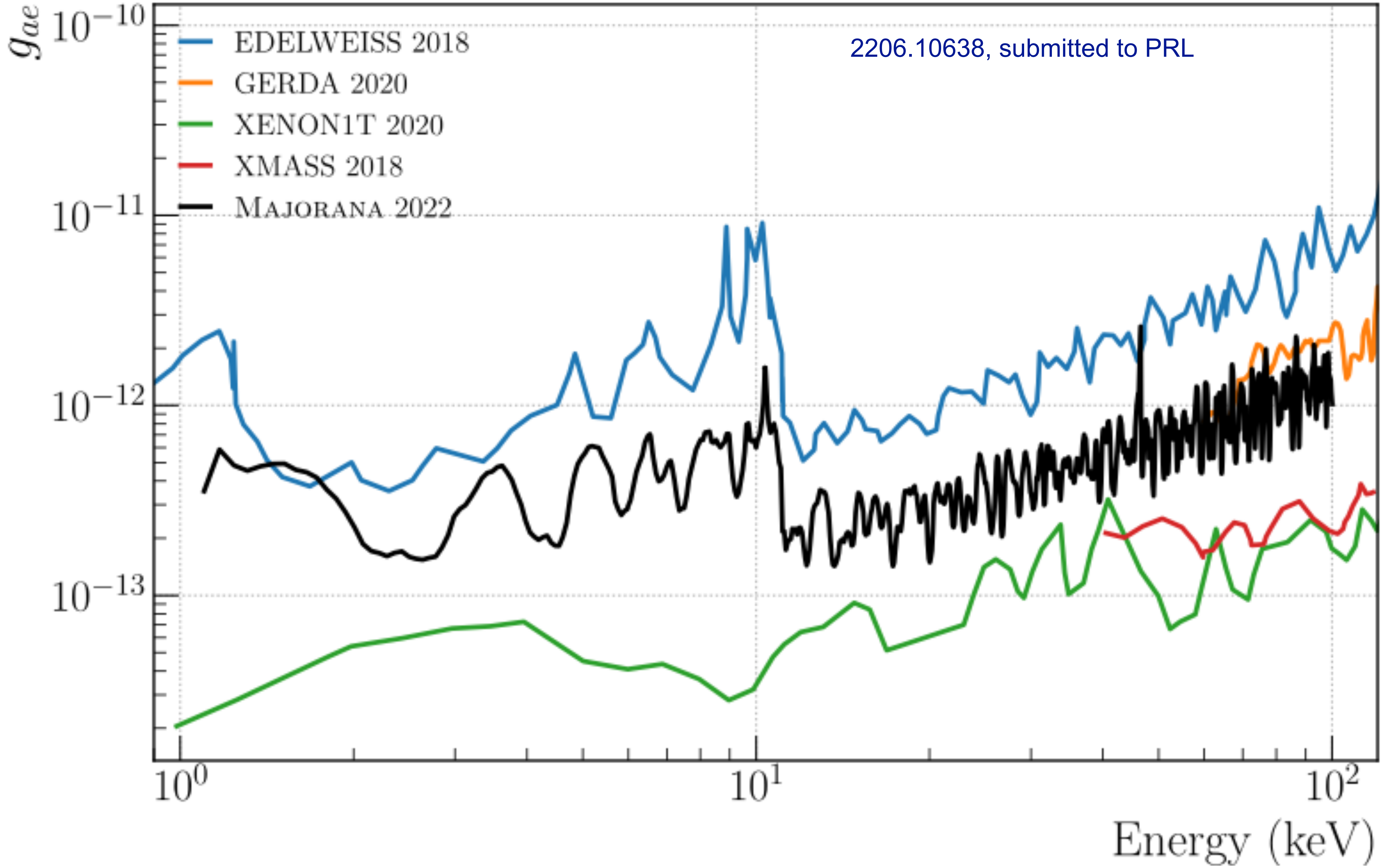
$$g_{Ae} < 4.5 \times 10^{-13}$$

$$\left(\frac{\alpha'}{\alpha}\right) < 9.7 \times 10^{-28}$$

$$S(E) \approx g_{A_e}^2 \left(\frac{m_A}{\text{keV}}\right) \left(\frac{\sigma_{pe}}{\text{barn}}\right) \frac{1.2 \times 10^{-19}}{A}$$

$$\Phi_{\text{DM}}(m_V)\sigma_{Ve}(m_V) = \frac{4 \times 10^{23}}{m_V} \left(\frac{\alpha'}{\alpha}\right) \frac{\sigma_{pe} m_V}{A}$$

Updated limits



The MAJORANA Collaboration

U.S. DEPARTMENT OF ENERGY | Office of Science

Sanford Underground Research Facility

Black Hills State University · Duke University · ITEP · Joint Institute for Nuclear Research · Berkeley Lab · Los Alamos National Laboratory · Max-Planck-Gesellschaft · Massachusetts Institute of Technology

NC State University · Oak Ridge National Laboratory · 大阪大学 Osaka University · Pacific Northwest National Laboratory (Proudly Operated by Battelle Since 1965) · Princeton University · Queen's University · South Dakota School of Mines & Technology · Technische Universität München

Tennessee Tech · TUNL · The University of North Carolina at Chapel Hill · University of South Carolina · University of South Dakota · The University of Tennessee Knoxville · W

Bonus slides

Other Limits

PRL 118 (2017) 161801

Three additional limits obtained:

- **Solar axion coupling** (14.4 keV ^{57}Fe M1)

  Low-mass limit. 90% UL.

  $$g_{AN}^{\mathrm{eff}} \times g_{Ae} < 3.8 \times 10^{-17}$$

- **Non-Paulian transition** in Ge:

  $$a_i a_j^\dagger - q\ a_j^\dagger a_i = \delta_{ij}$$
  $$q = -1 + \beta^2$$

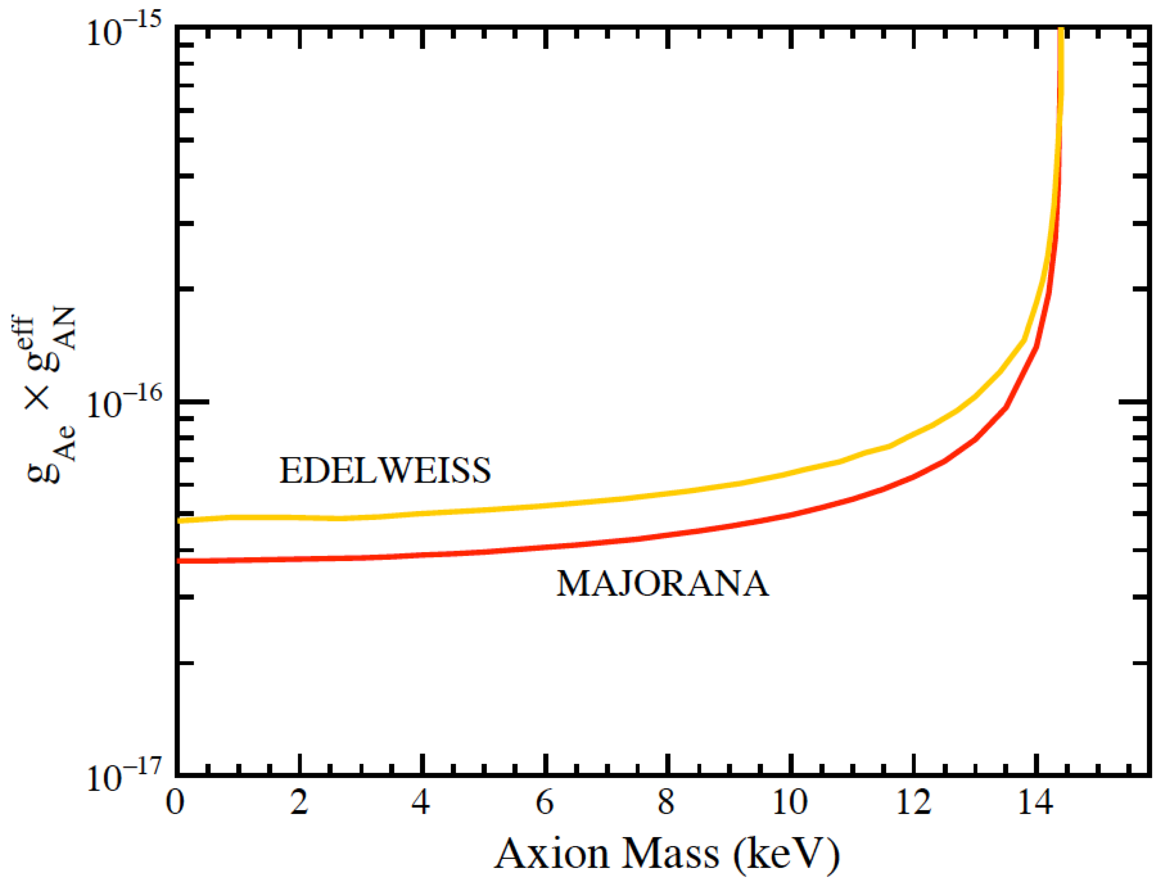
  Binned likelihood study for peak at 10.6 keV

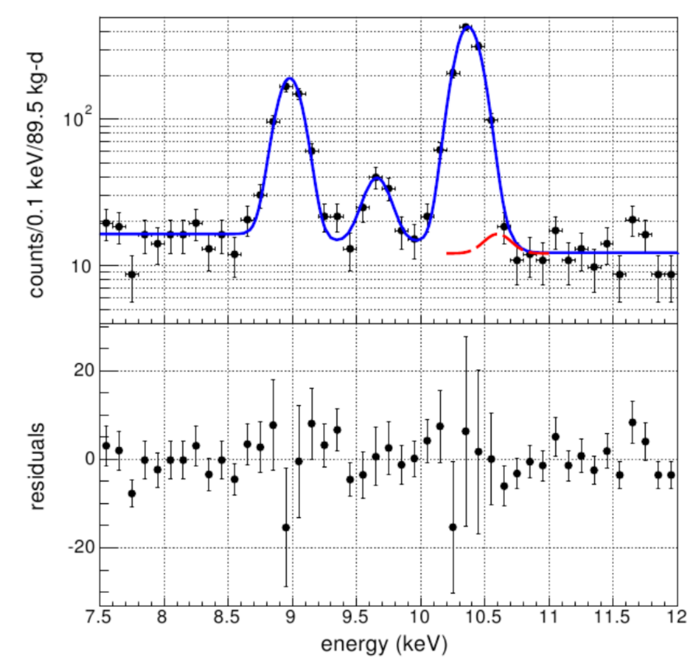
  $1/2\ \beta^2 < 8.5 \times 10^{-48}$ (90% CL UL)

- **Electron decay**

  Binned likelihood for peak at 11.1 keV

  $$e^- \to \nu\ \bar{\nu}\ \nu$$
  $\tau_e > 1.2 \times 10^{24}$ yr (90% CL UL)





0νββ Rate and Neutrino Mass

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu}(E_0,Z)\left|\langle m_{\beta\beta}\rangle\right|^2\left|M^{0\nu}\right|^2$$

$T_{1/2}^{0\nu}$: Half-life

$G^{0\nu}$: Phase Space (Known)

$M^{0\nu}$: Nuclear Matrix Element (large uncertainty)

$$\left|< m_{\beta\beta} >\right| = \left|\sum_i \left|U_{ei}\right|^2 m_{\nu_i} e^{i\alpha_i}\right|$$

Effective Majorana electron neutrino mass*

- ☞ $0\upsilon\beta\beta$ decay can probe **absolute** neutrino mass scale and mixing.
- ☞ Current neutrino experiments measure mass squared differences: Δm^2.

*Assumes ν_m exchange

Neutrino Flavor Mixing

Mass eigenstates different than flavor eigenstates.

$\Longrightarrow$ Propagating neutrinos undergo flavor oscillations.

Mass to flavor relationship described by neutrino mixing matrix

Parameter	best-fit	3σ
Δm^2_{21} [10^{-5} eV ^{2}]	7.37	6.93 – 7.97
$\lvert\Delta m^2\rvert$ [10^{-3} eV ^{2}]	2.50 (2.46)	2.37 – 2.63 (2.33 – 2.60)
$\sin^2\theta_{12}$	0.297	0.250 – 0.354
$\sin^2\theta_{23}$, $\Delta m^2 > 0$	0.437	0.379 – 0.616
$\sin^2\theta_{23}$, $\Delta m^2 < 0$	0.569	0.383 – 0.637
$\sin^2\theta_{13}$, $\Delta m^2 > 0$	0.0214	0.0185 – 0.0246
$\sin^2\theta_{13}$, $\Delta m^2 < 0$	0.0218	0.0186 – 0.0248
δ/π	1.35 (1.32)	(0.92 – 1.99) ((0.83 – 1.99))

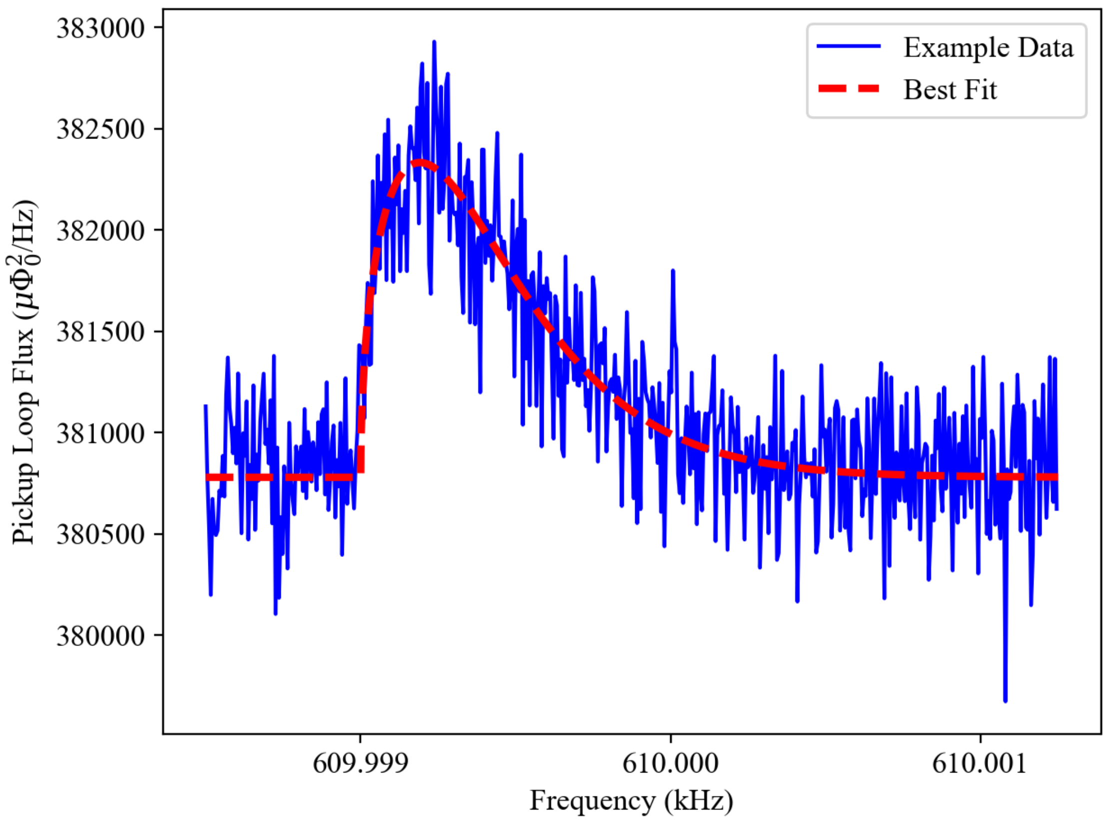
$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & e^{i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} e^{i\alpha_1} & 0 & 0 \\ 0 & e^{i\alpha_2} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

$c_{ij} = \cos\theta_{ij}$ $s_{ij} = \sin\theta_{ij}$

CP Phase

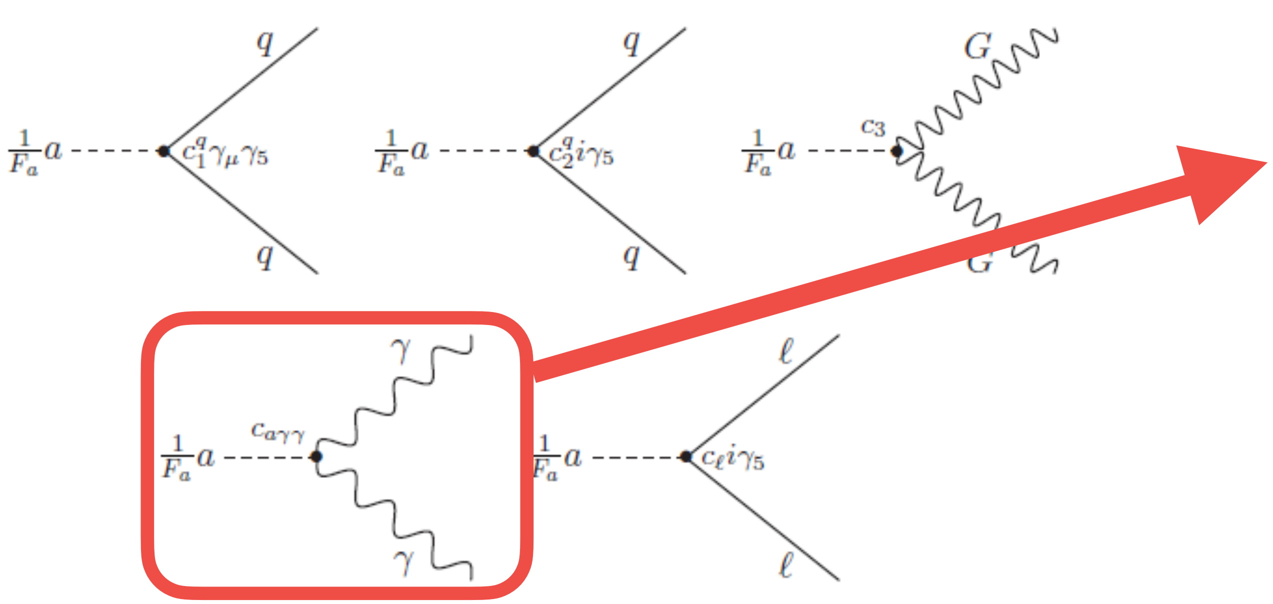
Axion Search Approach

- Rebin the data into 53 (24) of our 10 MS/s (1 MS/s) spectra that span the data taking period
- Limit our search range to 75 kHz - 2 MHz (m_a in 0.31 — 8.1 neV)
- For each mass point, we calculate a likelihood function
- Power bins are Erlang distributed with shape parameter N_{avg} (average over N_{avg} exponential distributions) and mean $s_{i,k}+b_i$
- Depends only on $g_{a\gamma\gamma}$ and nuisance parameters, b_i, which are assumed to be constant across the axion signal, but can vary slowly in time



Axion Interactions with the Standard Model

- In addition to canceling the CP violating term, the axion also adds a lot of interactions with the SM!



Axion Interactions with the Standard Model

- New QED Lagra[...]n leads to new Maxwell's equations

Modified Source-Free Maxwell's Equations

$$
\begin{aligned}
\nabla \cdot \mathbf{E} &= \underbrace{-g_{a\gamma\gamma}\mathbf{B} \cdot \nabla a}_{\approx 0} \\
\nabla \cdot \mathbf{B} &= 0 \\
\nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t} \\
\nabla \times \mathbf{B} &= \underbrace{\frac{\partial \mathbf{E}}{\partial t}}_{\approx 0} - g_{a\gamma\gamma}\left(\underbrace{\mathbf{E} \times \nabla a}_{\approx 0} - \frac{\partial a}{\partial t}\mathbf{B}\right)
\end{aligned}
$$

Ouellet & Bogorad
(arXiv:1809.10709)

Industrial Assay Programs

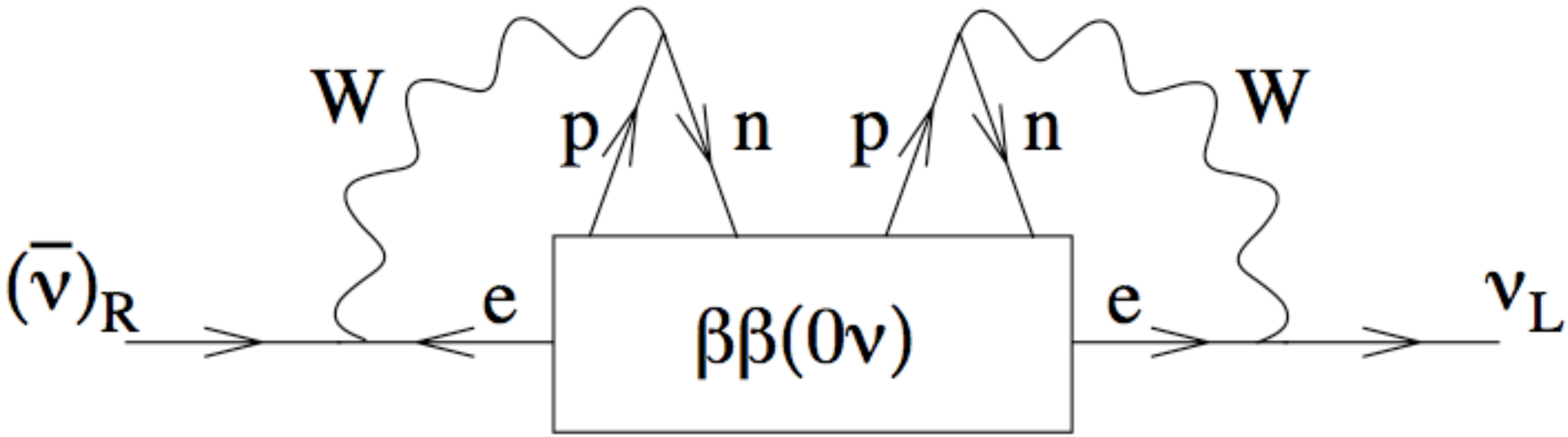
Abgrall et al. NIM A 828 (2016) 22

Table 3
Radioactive isotope levels within various materials and their 68% CL uncertainties. Values for K were not always provided by the analysis.

#	Material	Method	K (10^{-9} g/g)	^{232}Th (10^{-12} g/g)	^{238}U (10^{-12} g/g)
	Metals				
1	Cu electroformed stock sample	ICPMS		<0.17	
2	Cu electroformed stock sample	ICPMS		0.011 ± 0.005	0.017 ± 0.003
3	Cu electroformed stock sample	GDMS	<2.2	<50	<70
4	Cu electroformed stock sample	ICPMS		<0.029	<0.008
5	Cu electroformed stock sample	ICPMS		<0.029	<0.009
6	Cu electroformed stock sample	ICPMS		<0.029	<0.008
7	Cu electroformed stock sample	ICPMS		<0.030	<0.009
8	Cu Electroformed, machined part, guide clip	ICPMS		0.330 ± 0.022	0.123 ± 0.005
9	Cu Electroformed, machined part, guide clip	ICPMS		0.112 ± 0.009	0.078 ± 0.002
10	Cu Electroformed, machined part, guide clip	ICPMS		0.170 ± 0.008	0.087 ± 0.002
11	Cu Electroformed, machined part, spring clip	ICPMS		0.215 ± 0.009	0.130 ± 0.010
12	Cu Electroformed, machined part, hex bolt	ICPMS		0.118 ± 0.011	0.035 ± 0.004
13	Cu Electroformed, machined part, hex bolt	ICPMS		0.119 ± 0.014	0.041 ± 0.003
14	Cu Electroformed, machined part, hex bolt	ICPMS		0.148 ± 0.021	0.051 ± 0.002
15	Cu, C10100 cake stock, (source for Rows 16, 17)	ICPMS		0.46 ± 0.06	0.21 ± 0.06
16	Cu, C10100 2.5 in plate stock, exterior sample	ICPMS		0.27 ± 0.05	0.10 ± 0.02
17	Cu, C10100 2.5 in plate stock, interior sample	ICPMS		0.27 ± 0.05	0.12 ± 0.02
18	Cu, C10100 1 in plate stock, saw cut (same stock Row 19)	ICPMS		10.2 ± 1.0	6.62 ± 0.58
19	Cu, C10100 1 in plate stock, machined surfaces	ICPMS		1.88 ± 0.45	3.11 ± 0.39
20	Cu, C10100 1 × 2 in bar stock, machined surfaces	ICPMS		2.12 ± 0.39	2.25 ± 0.15
21	Cu, C10100 1 in plate stock	ICPMS		<0.029	0.013 ± 0.002
22	Cu, C10100 2.5 in plate stock	ICPMS		<0.030	0.017 ± 0.003
23	Cu, C10100 2.5 in plate stock	ICPMS		0.049 ± 0.010	0.061 ± 0.006
24	Cu, C10100 0.5 in plate stock	ICPMS		<0.030	0.009 ± 0.001
25	Cu wire, California Fine Wire	ICPMS	<25 000	<87	<40
26	Pb, smelted from virgin ore, Sullivan Metals	γ count	<60	<100	<30
27	Pb, UW	γ count	<190	<200	<500
28	Pb, UW	γ count	<160	<170	<400
29	Pb, smelted from virgin ore, Sullivan Metals	γ count	<160	<173	<241
30	Pb, smelted from virgin ore, Sullivan Metals	GDMS	4 ± 2	<10	<10
31	Pb, UW	GDMS	23 ± 11	<8	<10
32	Pb, UW	GDMS	<0.4	<8	<9
33	Pb, archeological ingot, UChicago	GDMS	<0.3	<9	<9
34	Pb, archeological sample prepared by Mifer Brick	GDMS	<0.2	<8	<10
35	Pb (Average from Brick samples)	ICPMS		1.3 ± 1.3	2.9 ± 2.0
36	Sn, sample of unknown origin	γ count	800 ± 450	<760	<137
37	Sn, sample of unknown origin	ICPMS	<108	940 ± 50	1190 ± 170
38	Sn, sample supplied by Canberra	ICPMS	<108	760 ± 70	1150 ± 350
39	6-way SS conflat intersection, MDC Vac. Prod., LLC	γ count	<840	3200 ± 1000	<400
40	TIG-Ce welding rods	γ count	$(1.60 \pm 0.14) \times 10^5$	$(1.68 \pm 0.31) \times 10^7$	<72 000
41	TIG-Zr welding rods	γ count	5500 ± 4600	$(1.08 \pm 0.05) \times 10^5$	19 300 ± 1600
42	Cr, stock used for vapor depositions	ICPMS	<7000	<20 000	<5000
43	Au, sputtering target	ICPMS	<270		570 ± 130
44	Au (4 N8), sputtered at LBNL	ICPMS	47 000 ± 1000	1980 ± 370	2000 ± 300
45	Al, sputtered, sample film provided by ORTEC	ICPMS	$(1.42 \pm 0.51) \times 10^7$	2000 ± 250	5730 ± 300
46	Al, sputtered, sample film provided by ORTEC	ICPMS	$(1.10 \pm 0.01) \times 10^5$	2210 ± 460	4390 ± 340
47	Ge, sputtered, sample film provided by ORTEC	ICPMS	<430	207 ± 38	843 ± 62
48	Ge, sputtered, sample film provided by ORTEC	ICPMS	<215	349 ± 80	1340 ± 120
49	amorphous Ge, sputtered at LBNL	ICPMS	4800 ± 230	2370 ± 690	1680 ± 350
50	Cr, sputtered at LBNL	ICPMS	<1900	5240 ± 1290	5030 ± 700
51	Ti film, sputtered at LBNL	ICPMS		<400	<100
	Plastics				
52	Teflon® TE-6742	NAA	0.15 ± 0.02	0.025 ± 0.002	<0.4
53	Peek®, Victrex®	NAA	180 ± 110	<400	<5100

… 170 entries …

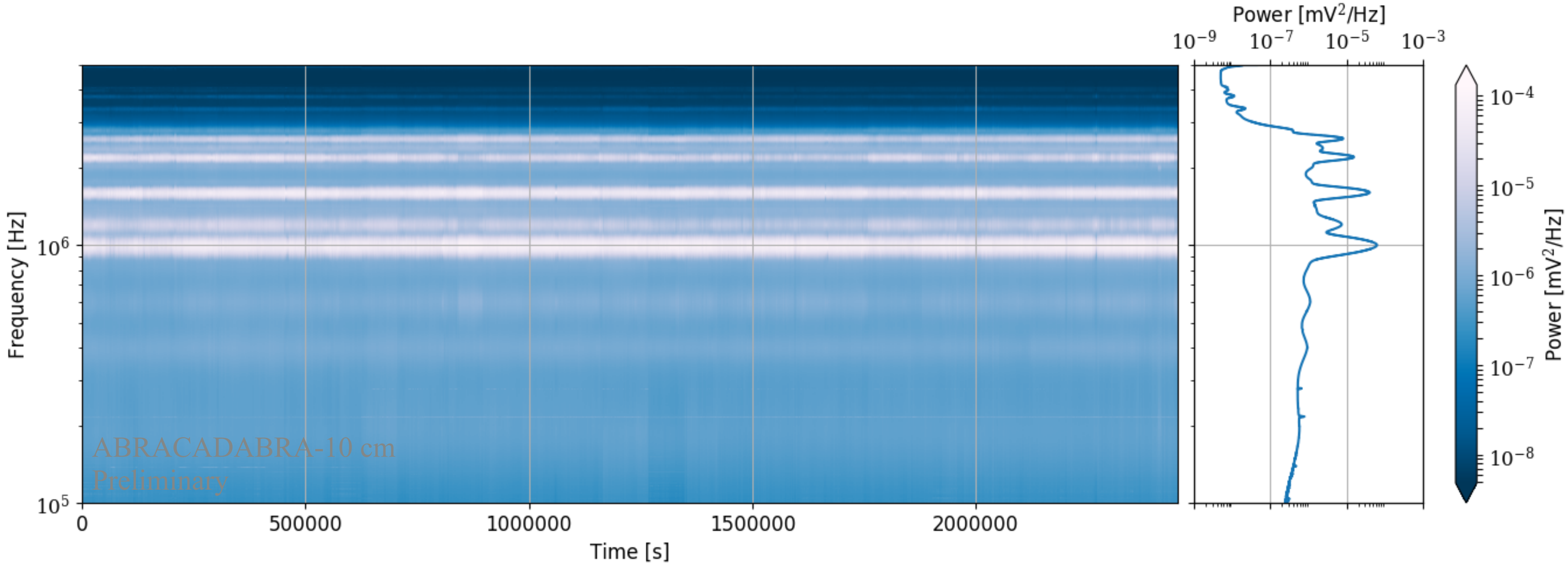
$0\nu\beta\beta$–decay and Majorana Neutrinos



Schechter et al, Phys. Rev. D**25**, 2951 (1982)

Majorana nature verification ***independent*** of process that mediates $0\nu\beta\beta$ decay!

ABRACADABRA-10 cm First Dataset



	10 MS/s Dataset	1 MS/s Dataset
Integrated Time	471 h	427h
Individual Spectra	2120	960
Frequency Range	500 kHz - 3 MHz	75 kHz - 500 kHz

GERDA

- Direct immersion of enriched Ge detectors in LAr
- Phase I (Nov 2011- May 2013)
- Phase II (Dec 2015- ongoing)

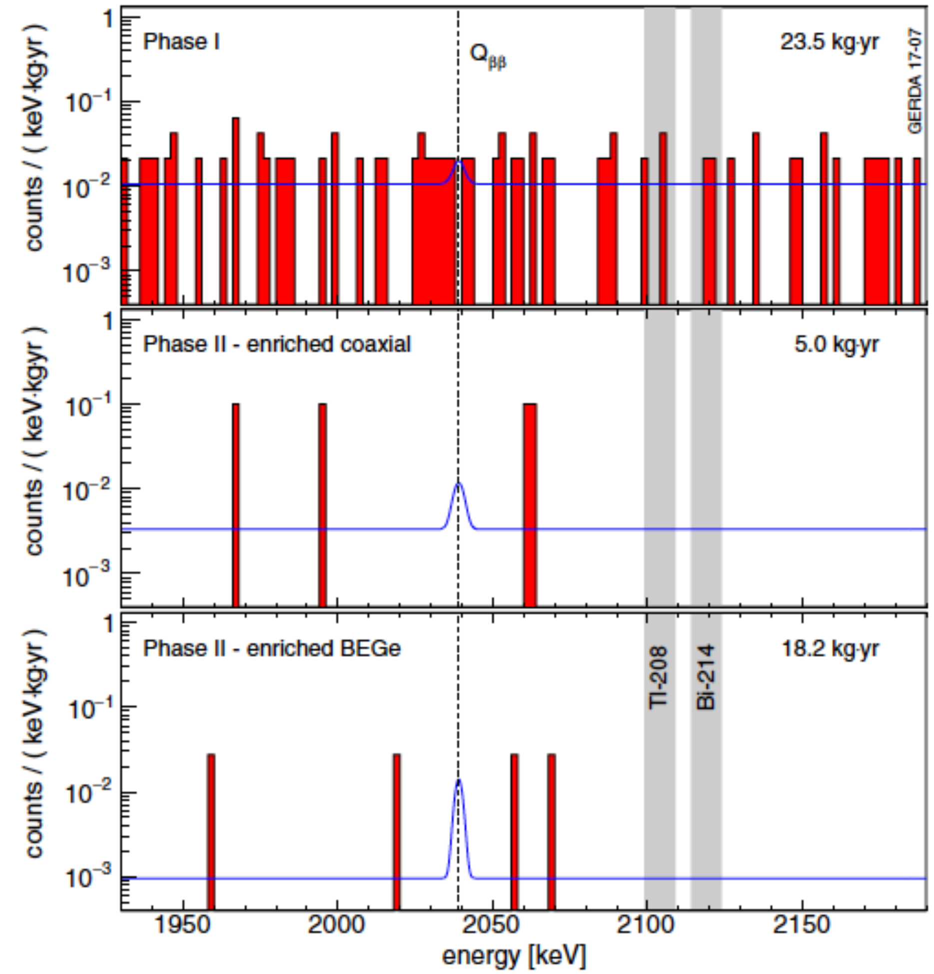
GERDA Results

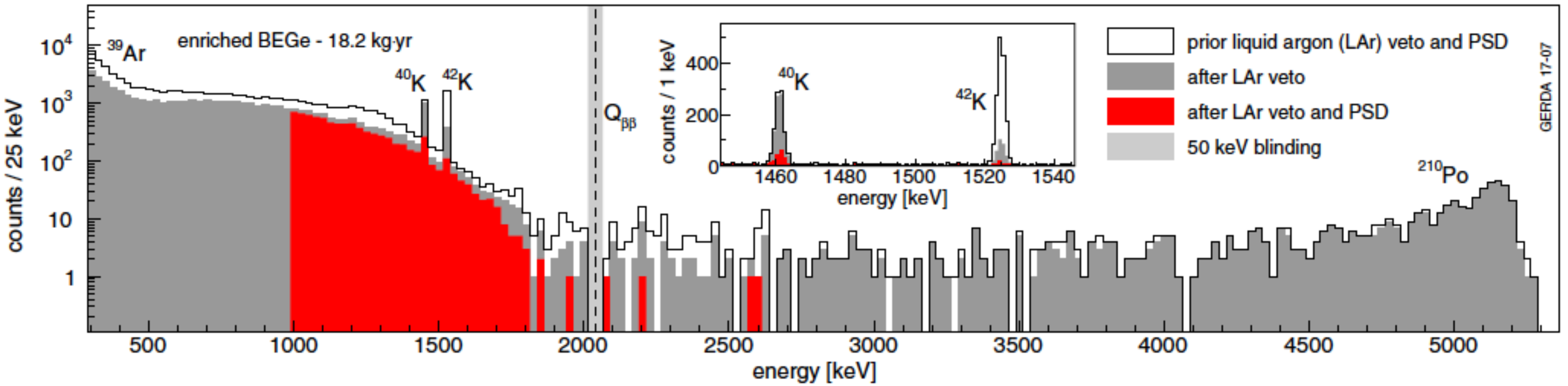
PHYSICAL REVIEW LETTERS 120, 132503 (2018)

Editors' Suggestion | Featured in Physics

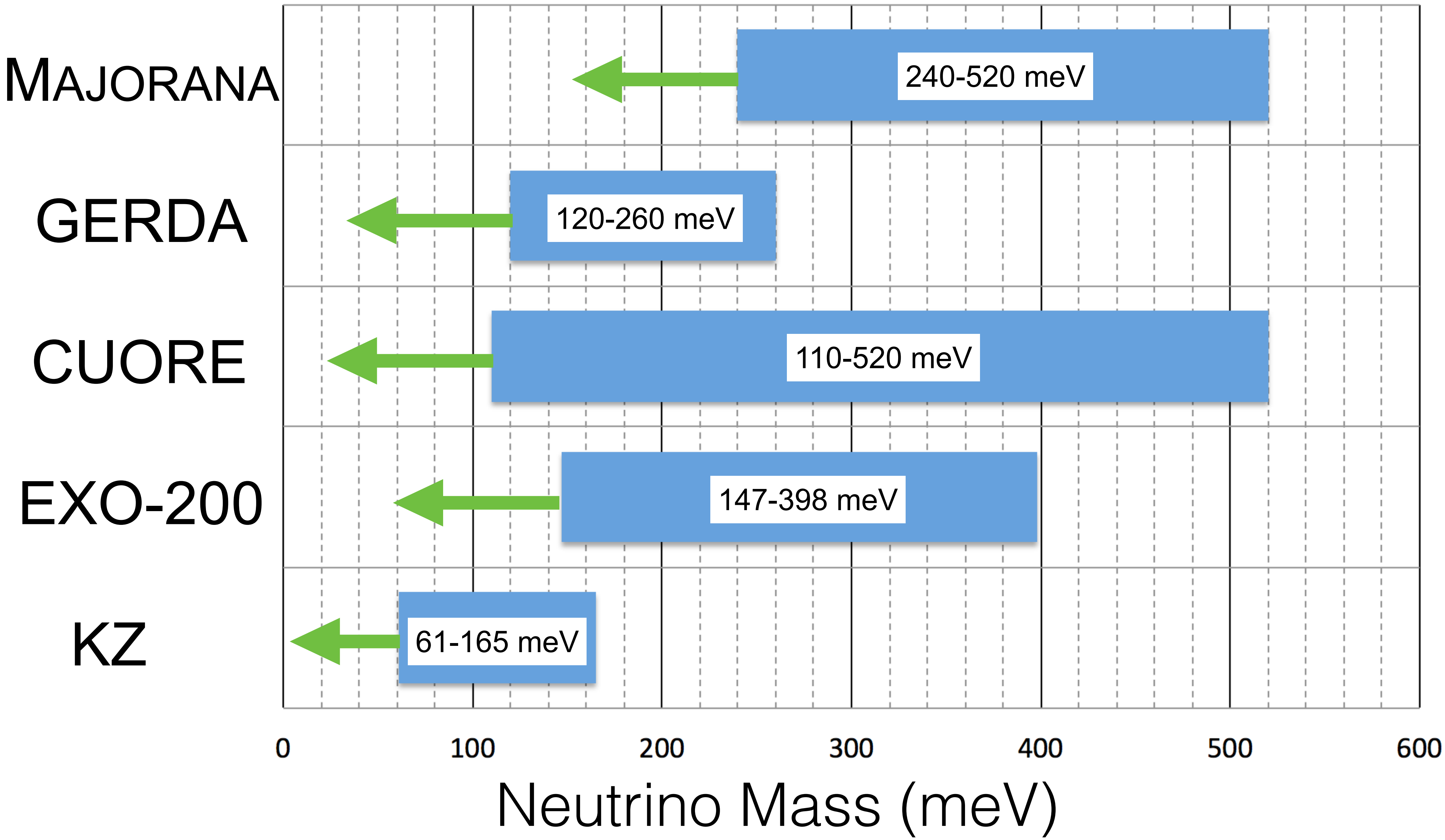
Improved Limit on Neutrinoless Double-β Decay of ^{76}Ge from GERDA Phase II

$T_{1/2} > 8.0\times10^{25}$ years





Mass Limit Summary



LEGEND ^{76}Ge

Large Enriched Germanium Experiment for Neutrinoless Double Beta Decay

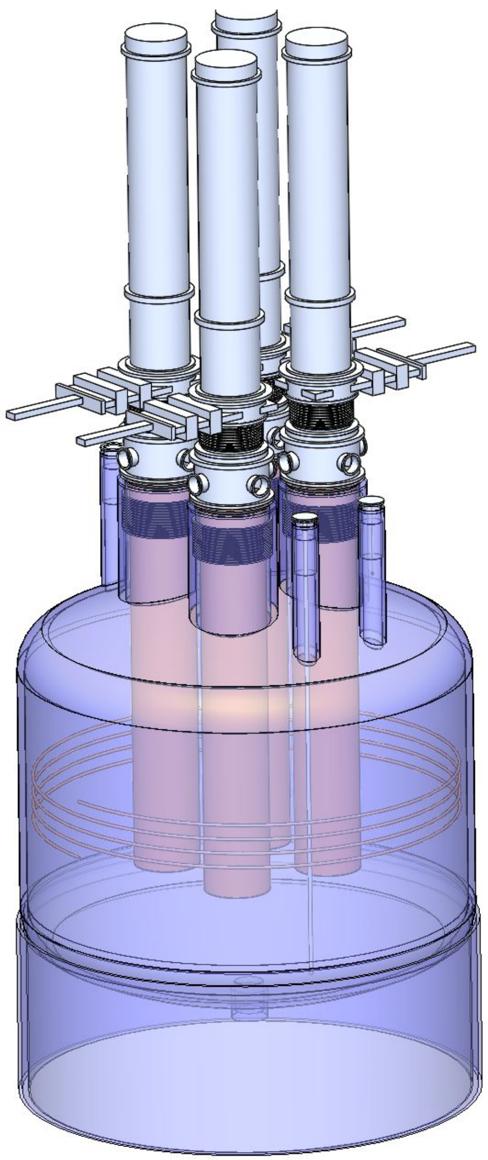
LEGEND mission: "The collaboration aims to develop a phased, ^{76}Ge based double-beta decay experimental program with **discovery potential** at a half-life beyond 10^{28} years, using existing resources as appropriate to expedite physics results."

First Stage:

- (up to) 200 kg ^{76}Ge in upgrade of existing infrastructure at LNGS
- BG goal
  0.6 cts/(FWHM t yr)
- Data start ~2021
- Will use existing MAJORANA & GERDA detectors
- Proposal submitted to LNGS in March 2018
- Have funding for 130 of the 200 kg in place.

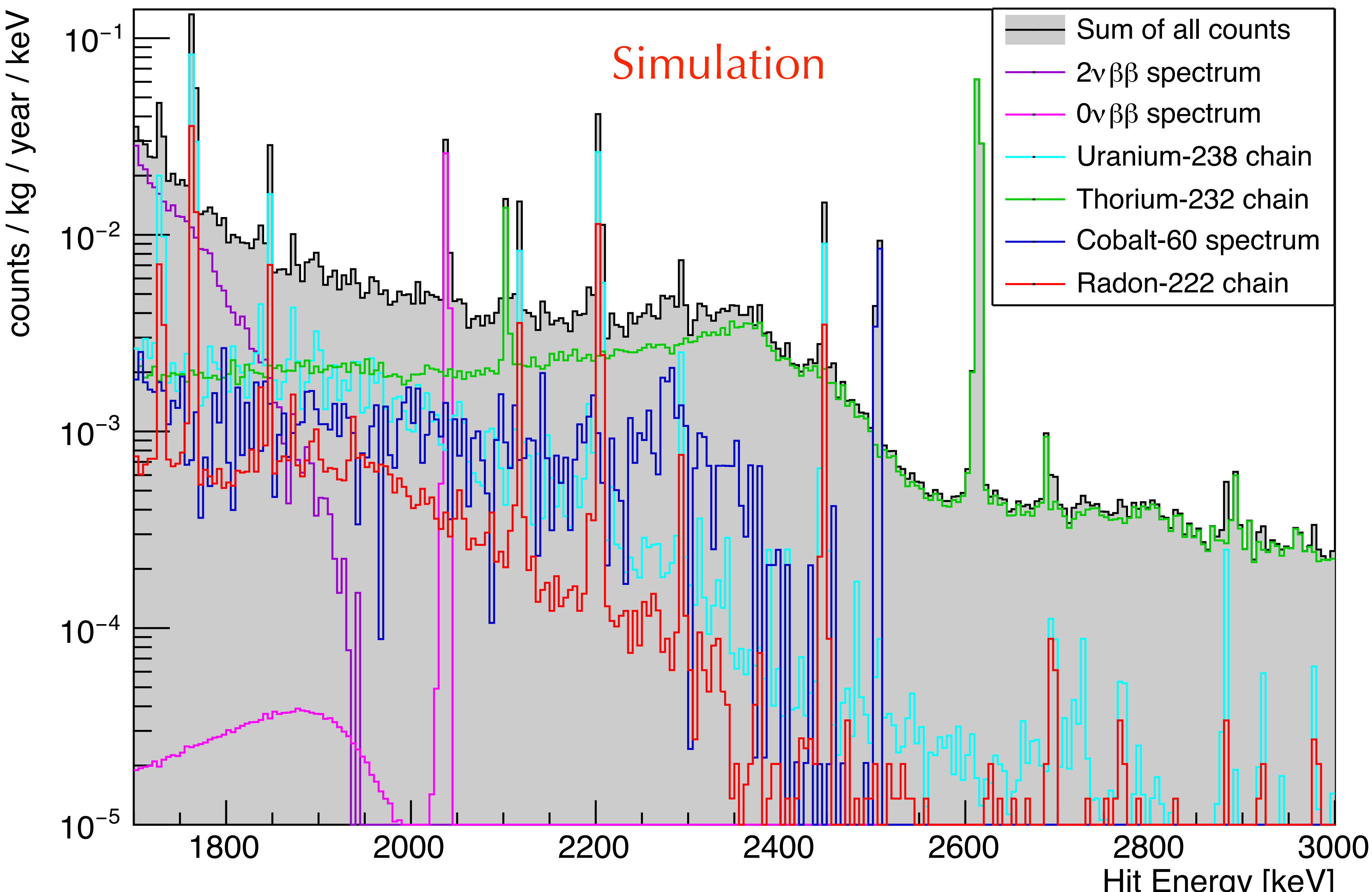
Subsequent Stages:

- 1000 kg ^{76}Ge (staged)
- Timeline coordinated with First Stage
- BG goal
  0.1 cts/(FWHM t yr)
- Location tbd
- Required depth (Ge-77m) under investigation



Backgrounds, resolution, discovery

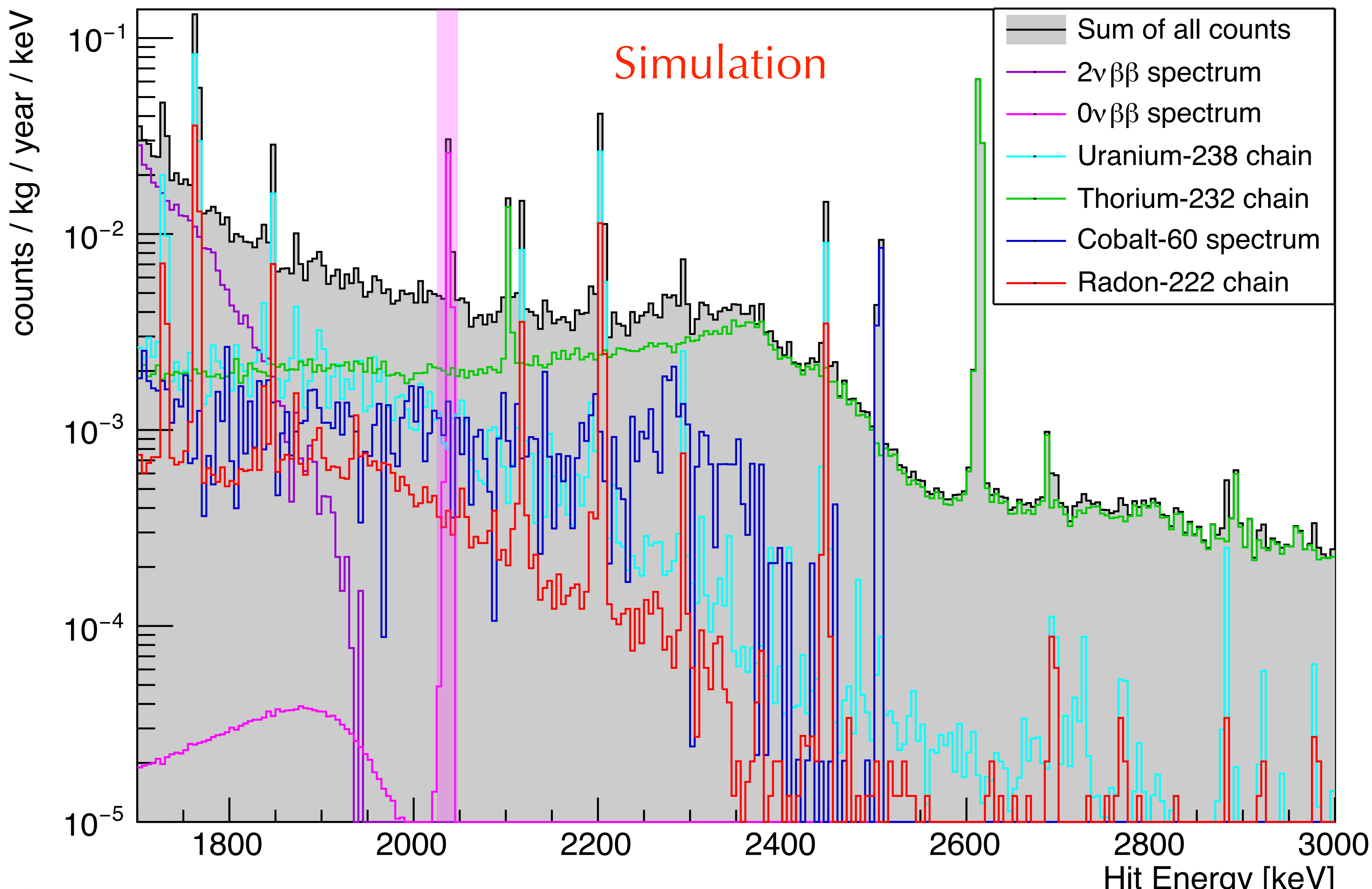
Resolution@2039keV: 2.5 keV, 0νββ HL: ~2e25 y



M. Buuck/J.F. Wilkerson

Backgrounds, resolution, discovery

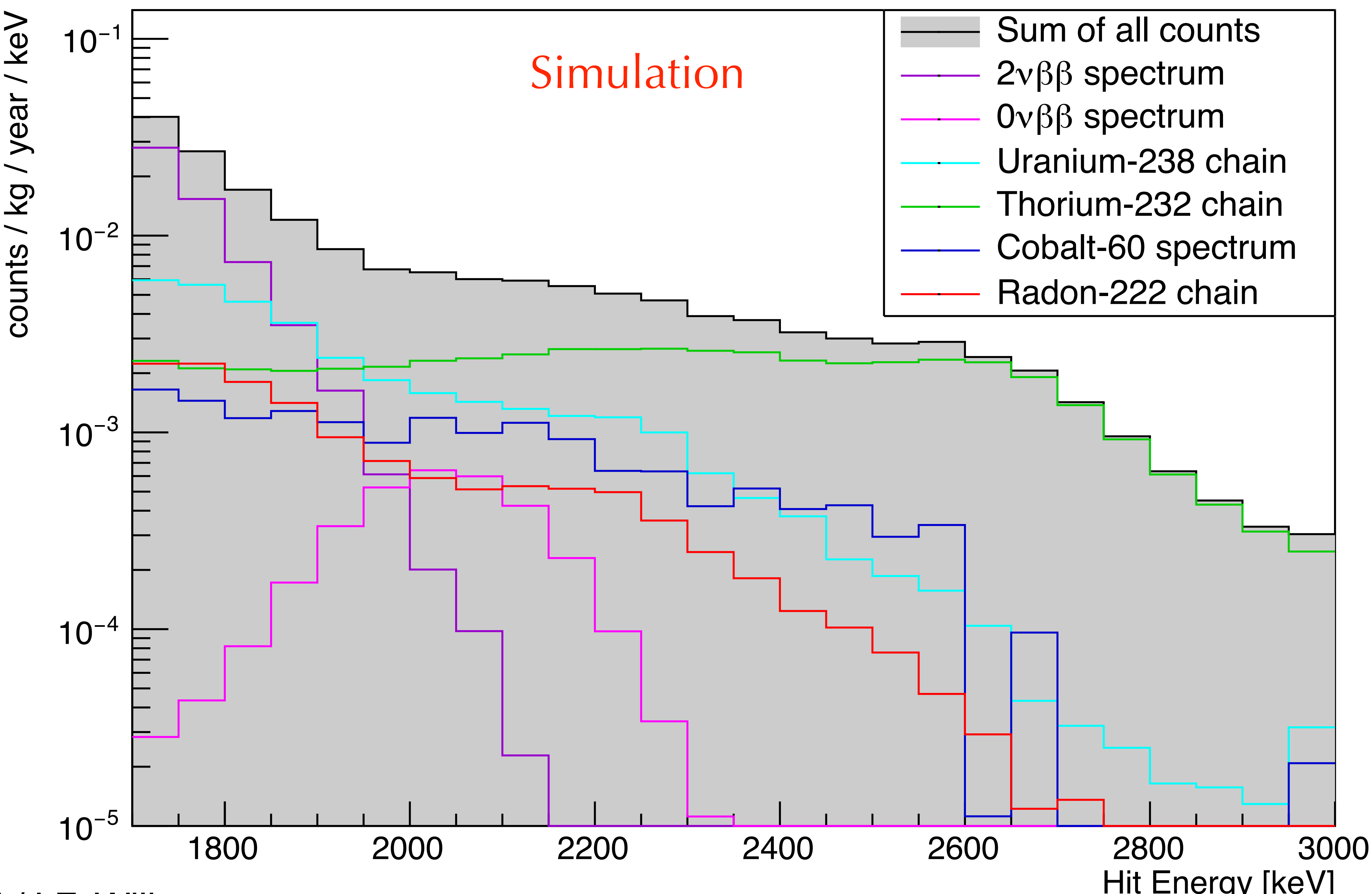
Resolution@2039keV: 2.5 keV, 0νββ HL: ~2e25 y



M. Buuck/J.F. Wilkerson

Backgrounds, resolution, discovery

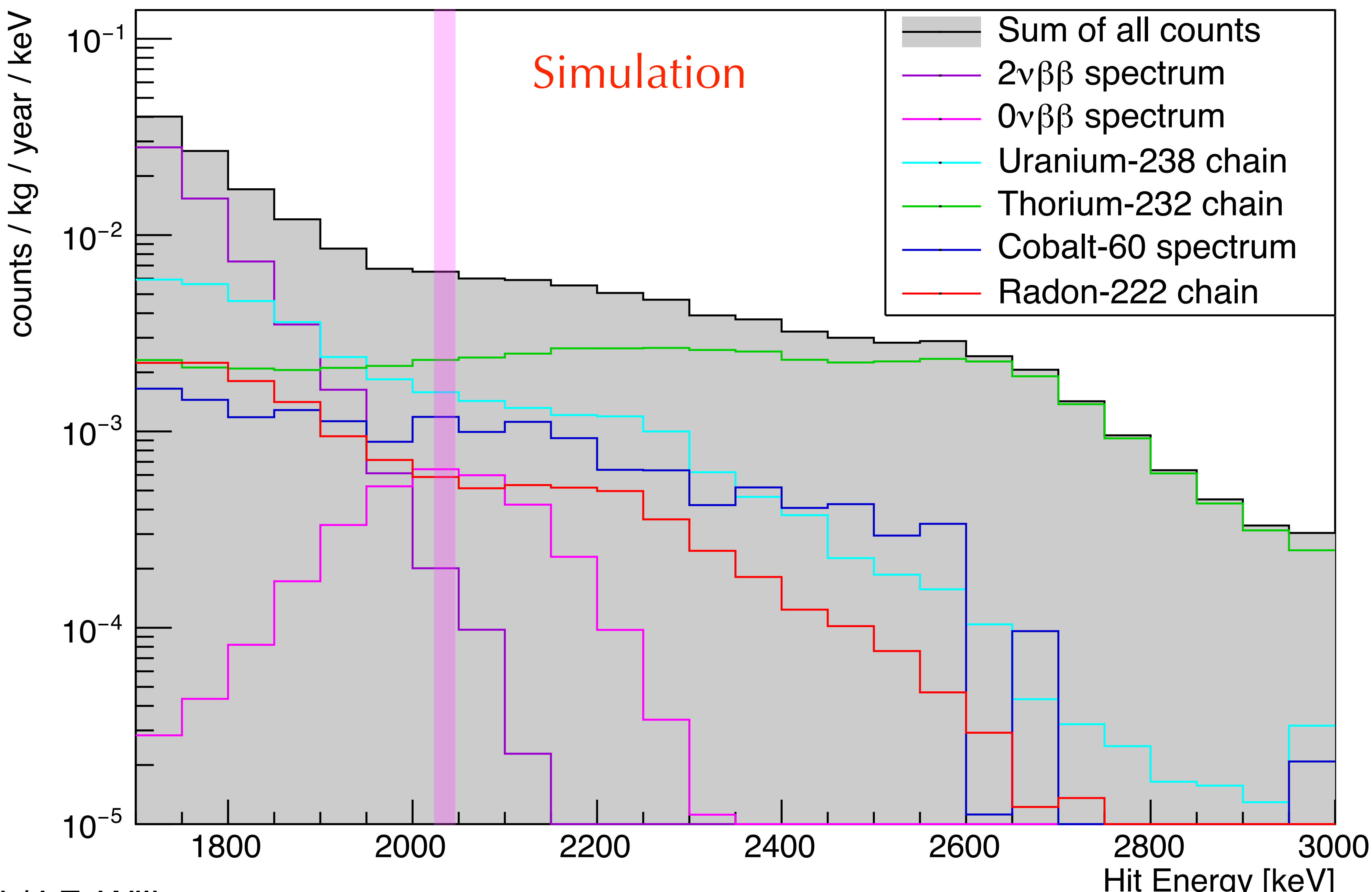
Resolution@2039keV: 250 keV, 0νββ HL: ~2e25 y



M. Buuck/J.F. Wilkerson

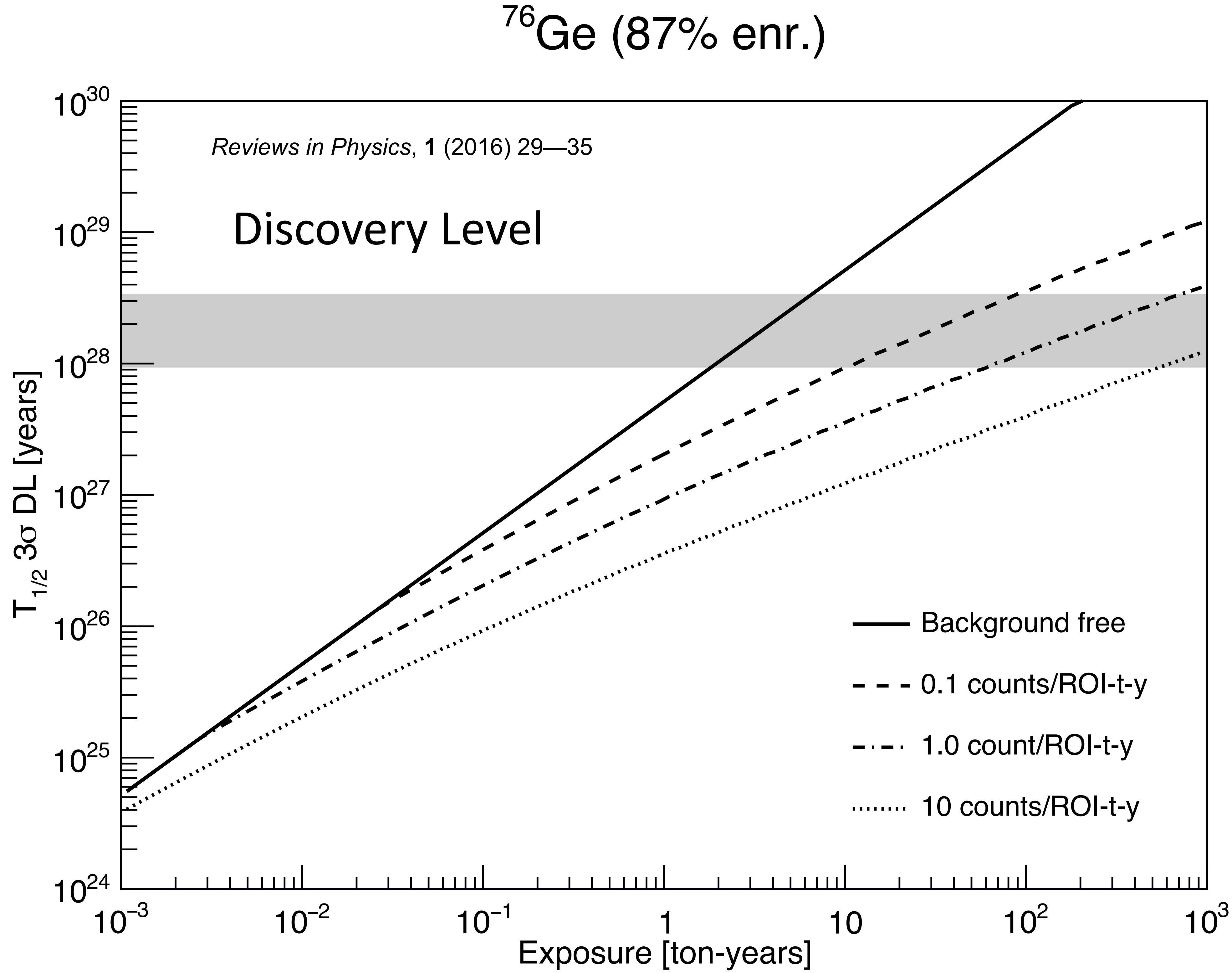
Backgrounds, resolution, discovery

Resolution@2039keV: 250 keV, 0νββ HL: ~2e25 y

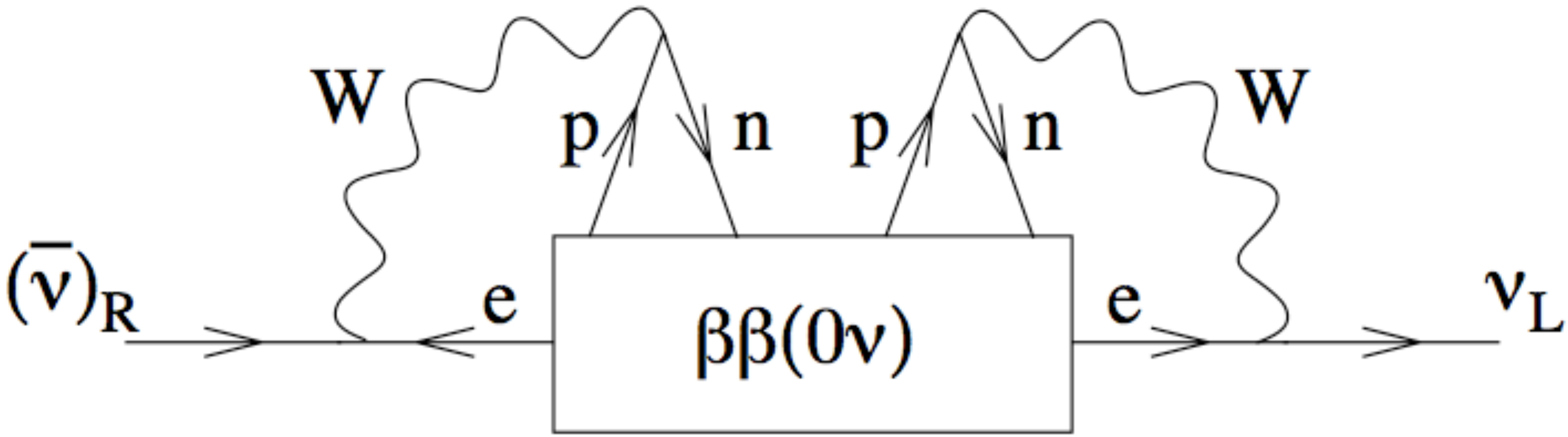


M. Buuck/J.F. Wilkerson

Sensitivity, Background and Exposure



0νββ–decay and Majorana Neutrinos



Schechter et al, Phys. Rev. D**25**, 2951 (1982)

Majorana nature verification ***independent*** of process that mediates 0νββ decay!

More about Majorana vs. Dirac

Note: Only valid if neutrinos are massive.

Lorentz Boost

ν_+ $\overline{\nu}_-$ $\overline{\nu}_+$ ν_-

CPT

$\nu \neq \overline{\nu}$

CPT

Lorentz Boost

ν^M_- ν^M_+

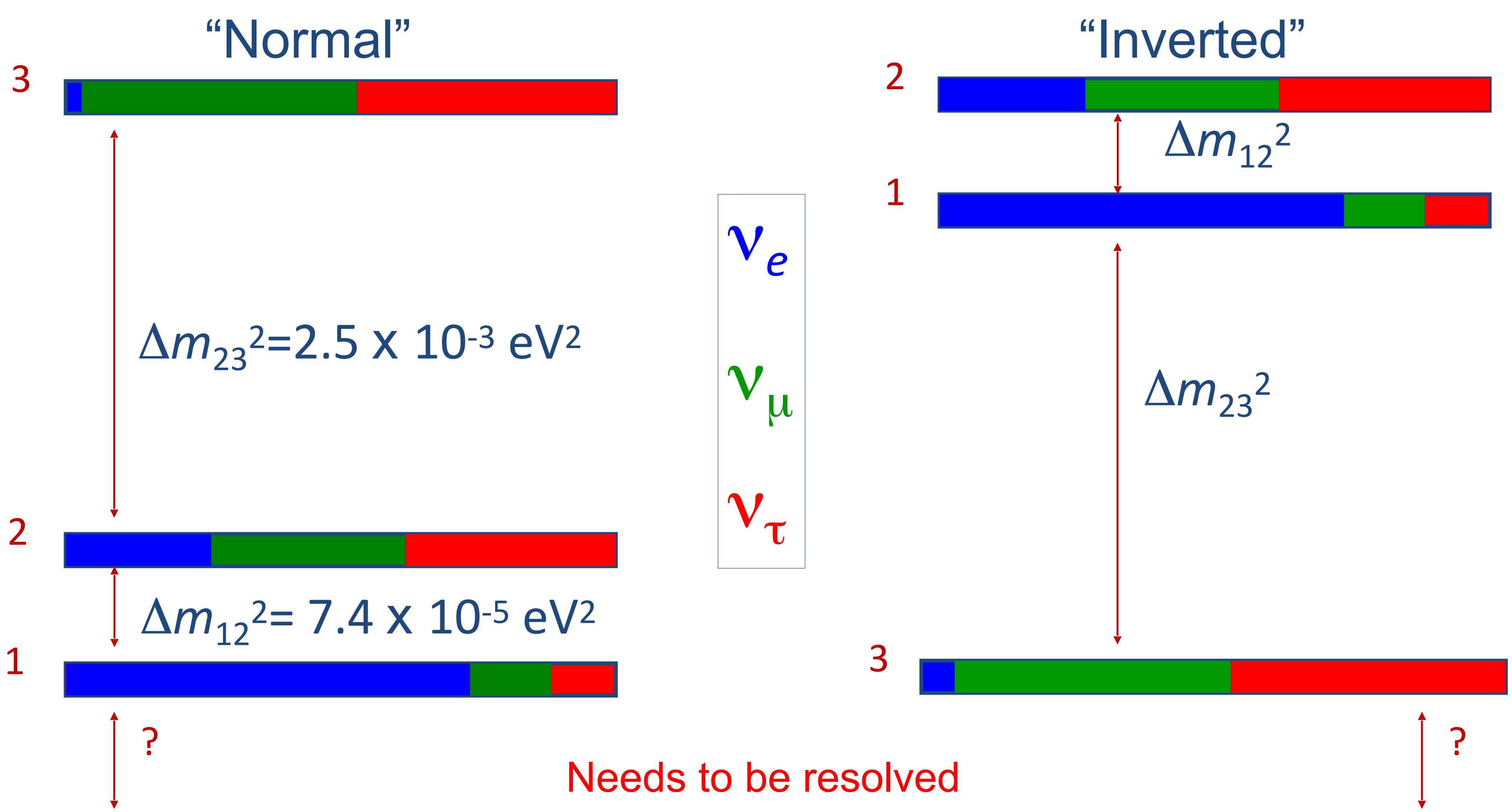
CPT

$\nu = \overline{\nu} = \nu^M$

Original argument by Kayser, 1985

Neutrino Masses

- Absolute masses weakly constrained, < 1eV.
- Relative mass-squared differences known.
- Three possible scenarios: Quasi-degenerate, also:



Needs to be resolved

Origin of Matter

Majorana neutrinos

Required by

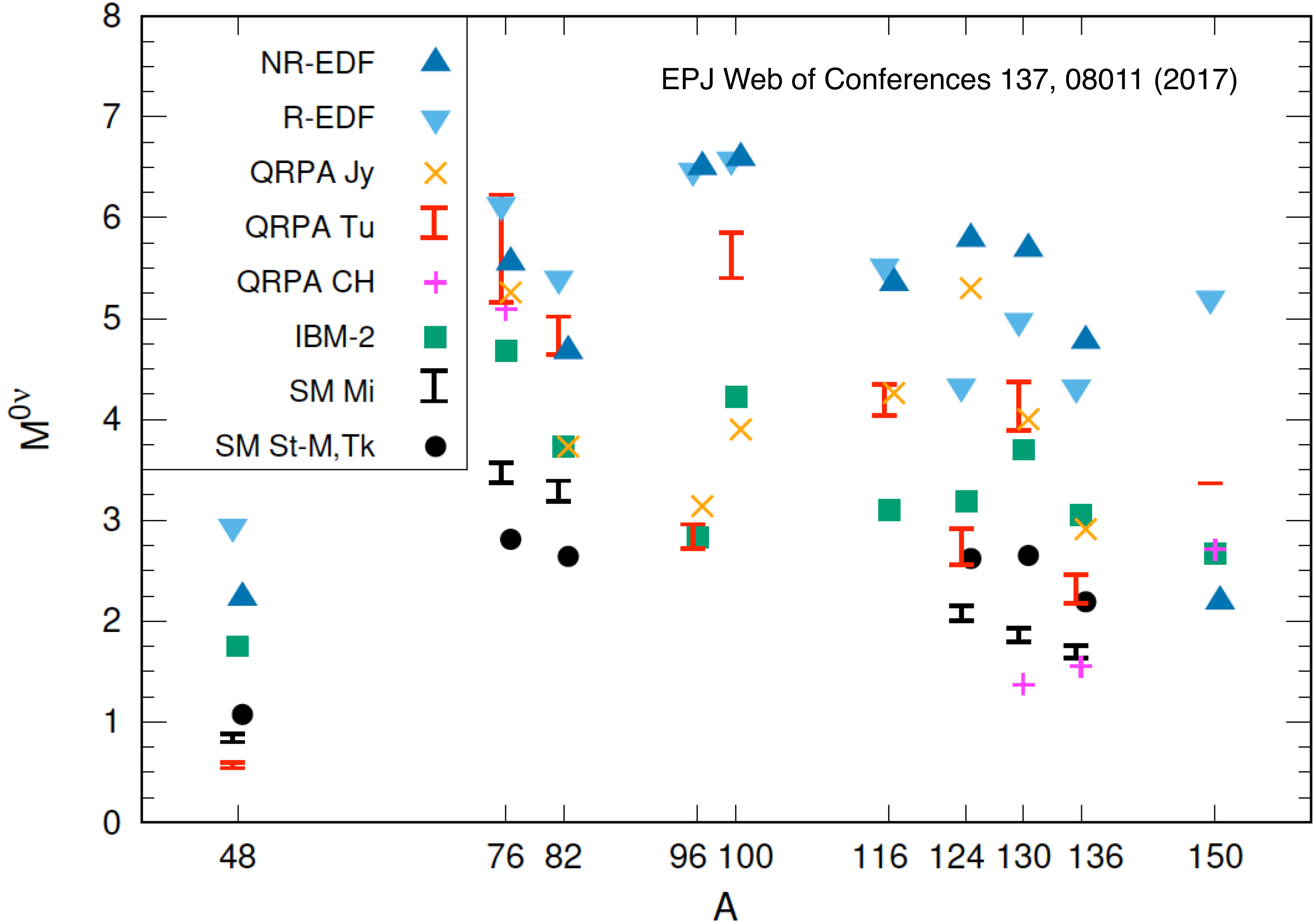
See-Saw mass-generating mechanism

Required (in general) by

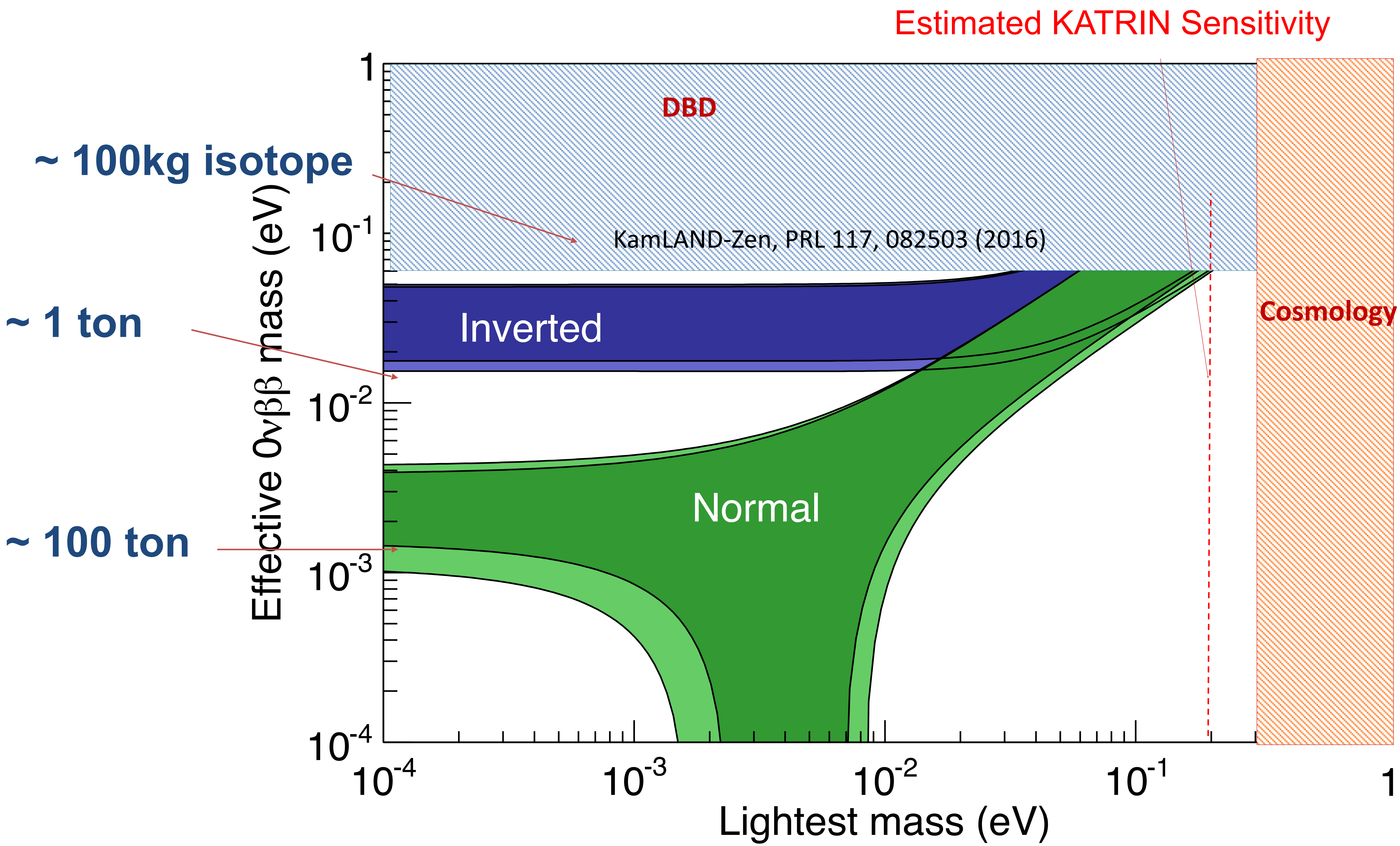
Leptogenesis

Matter dominated universe?

Matrix Elements



Combined Mass Limits



0νββ Rate and Neutrino Mass

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu}(E_0, Z)\left|\langle m_{\beta\beta}\rangle\right|^2 \left|M^{0\nu}\right|^2$$

$T_{1/2}^{0\nu}$: Half-life

$G^{0\nu}$: Phase Space (Known)

$M^{0\nu}$: Nuclear Matrix Element (large uncertainty)

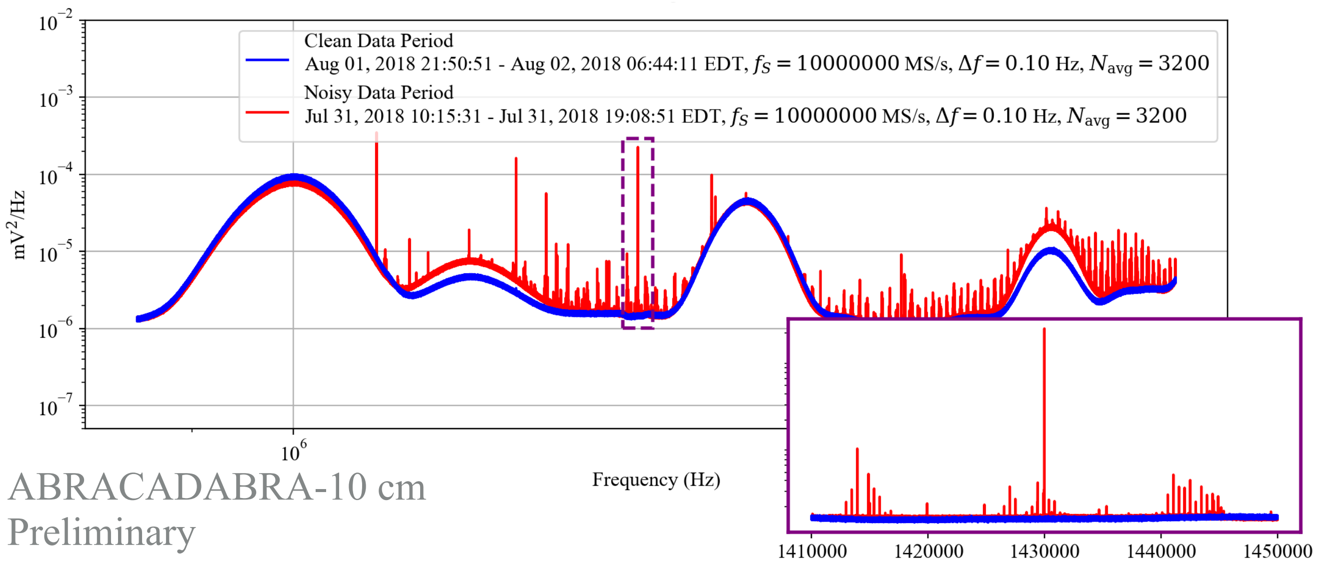
$$\left|< m_{\beta\beta} >\right| = \left|\sum_i \left|U_{ei}\right|^2 m_{\nu_i} e^{i\alpha_i}\right|$$

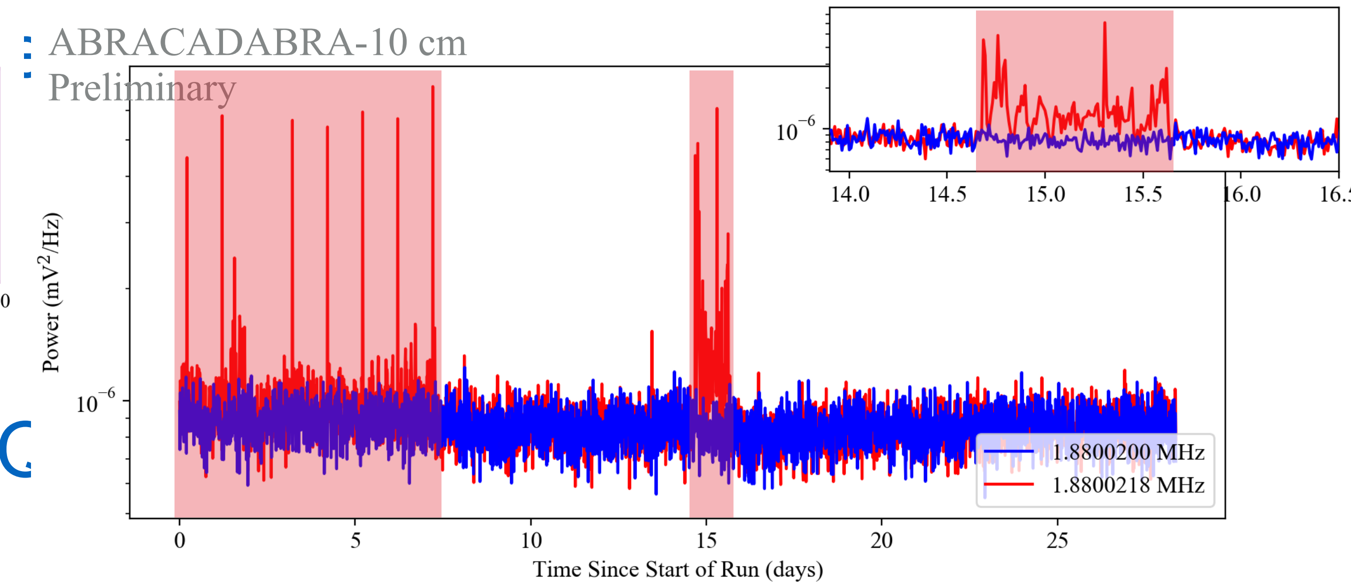
Effective Majorana electron neutrino mass*

- ☞ 0υββ decay can probe **absolute** neutrino mass scale and mixing.
- ☞ Current neutrino experiments measure mass squared differences: Δm^2.

*Assumes ν_m exchange

Transient Noise at High Frequency



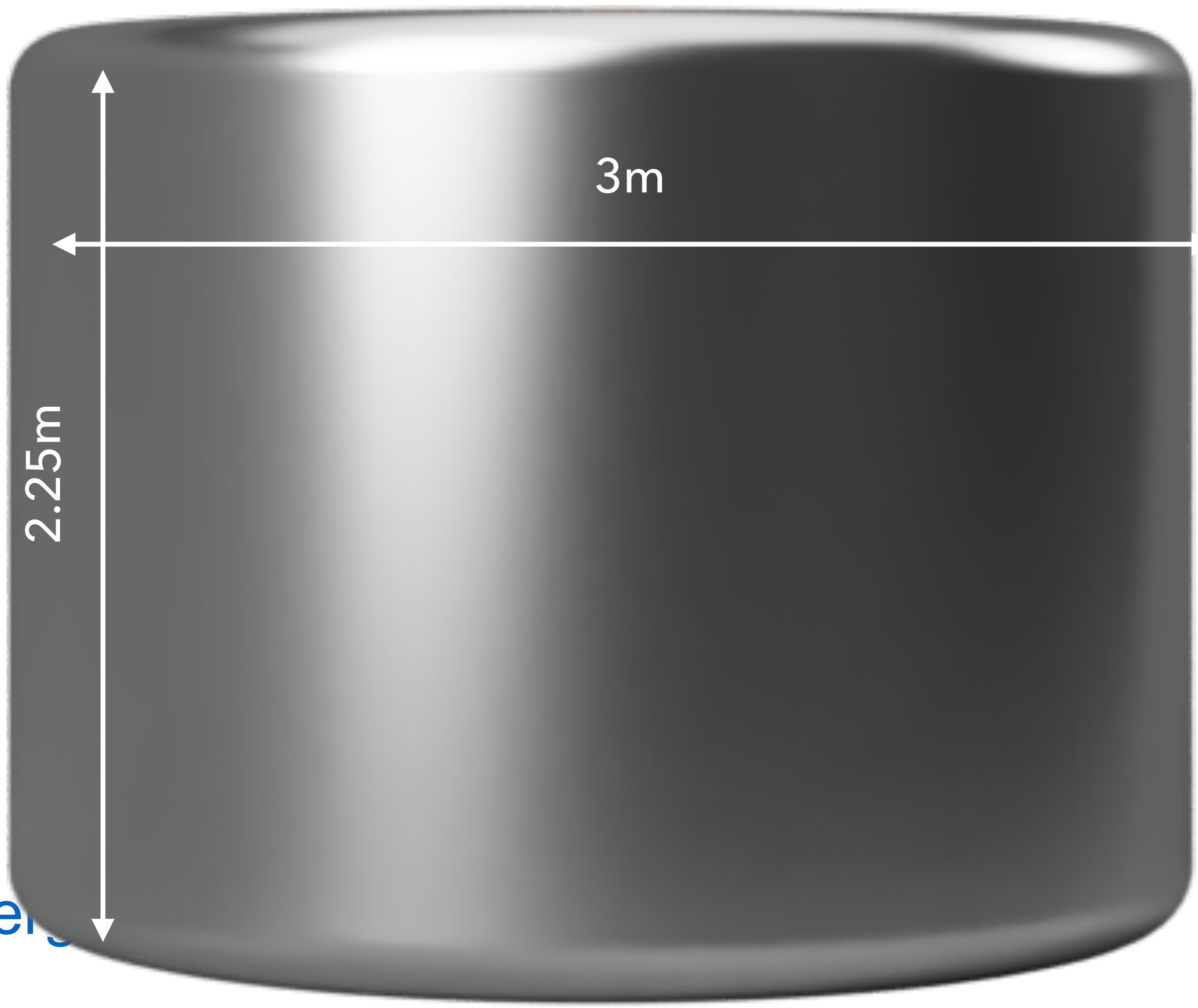


- Investigating the digitizer/DAC shielding, etc…

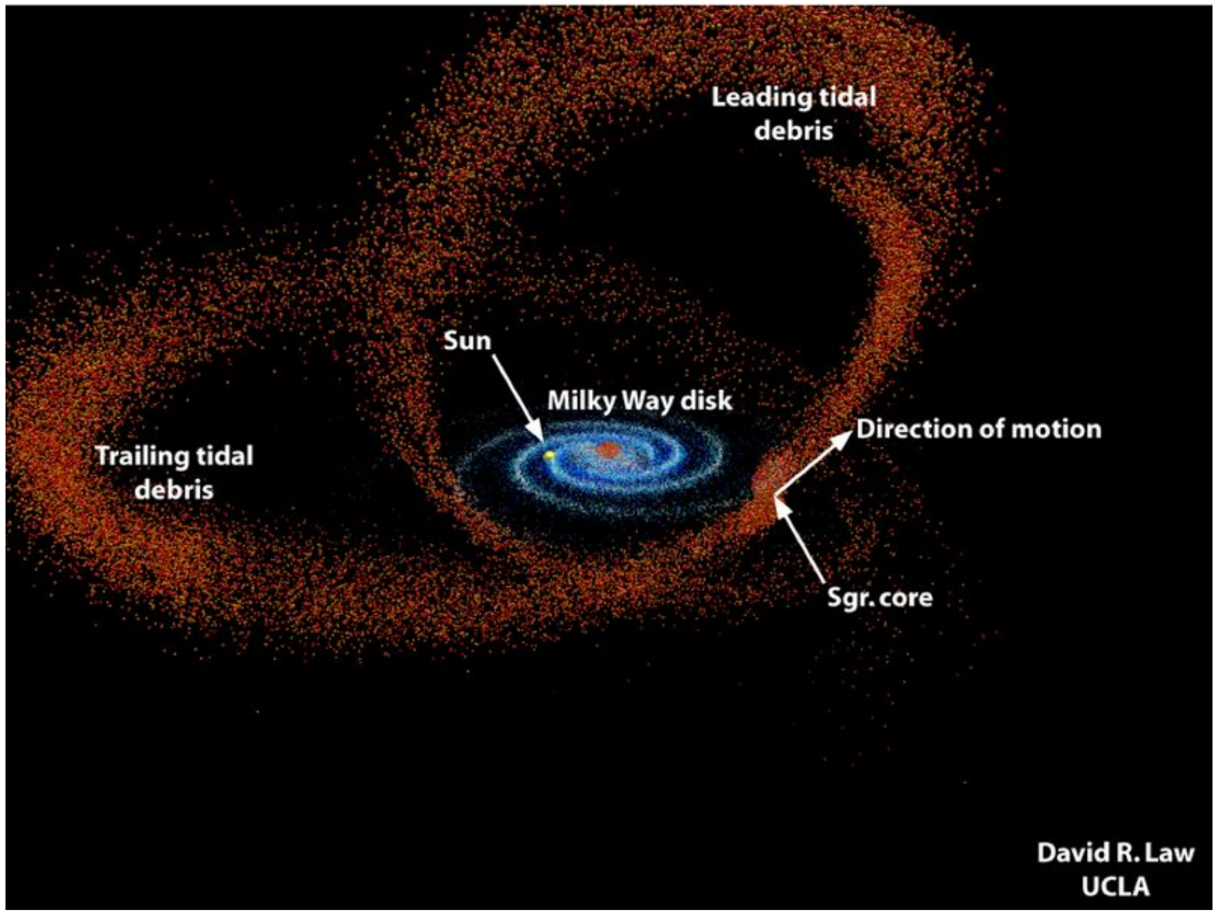
- In the present analysis, we had to discard ~30% of the data

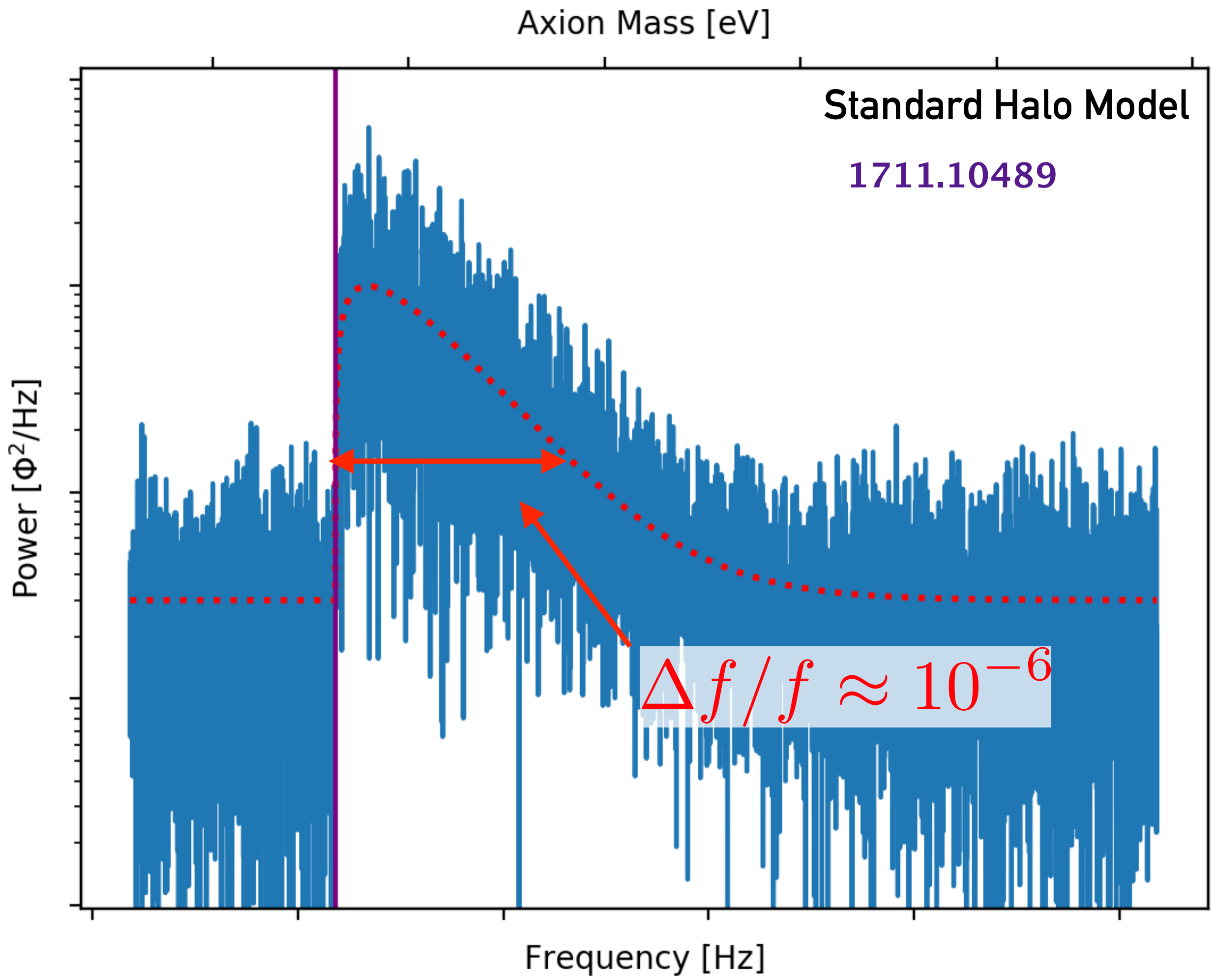
ABRACADABRA-75 cm

- $R_{in} = R_{out}/2 = h/3 = 75$ cm
- $B_0 = 1 - 5$ T
- Resonant Goals:
  - Quality factor of 10^6
  - Thermal noise limited at 100
- ABRACADABRA Magnet
  - Approx. 2 - 50 MJ stored ener
- Ultimate goal: ABRA-QCD — Probe GUT-scale QCD axion



Axion Astrophysics





Axion Astrophysics