www.sanfordlab.org

Test of Collapse Models with the MAJORANA DEMONSTRATOR

Inwook Kim
2022-11-03

Sanford Underground Research Facility

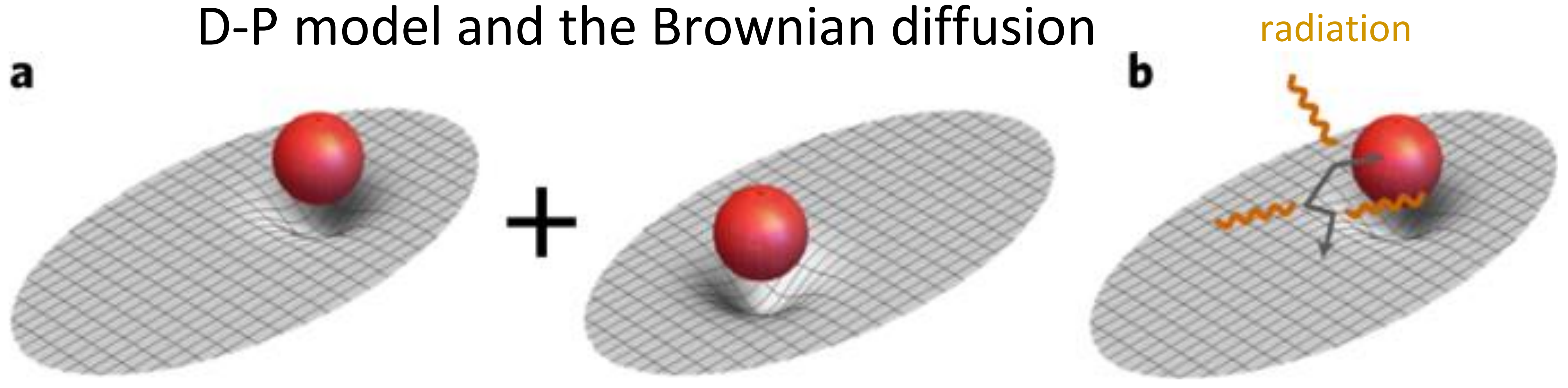
U.S. DEPARTMENT OF ENERGY | Office of Science

NSF

Objective Collapse Models

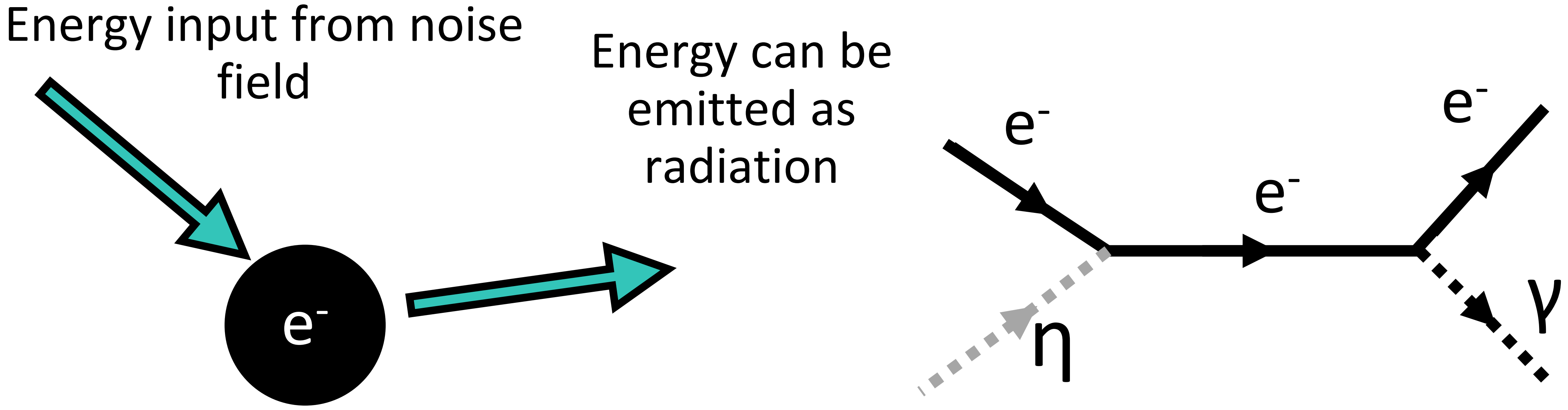
Objective collapse models are possible explanations of why and how quantum measurements give definite outcomes

- Ghirardi–Rimini–Weber (GRW) model [Phys. Rev. D 34, 470, Phys. Rev. D 36, 3287]
- Continuous spontaneous localization (CSL) model [Phys. Rev. A 39, 2277]
- Diósi–Penrose (DP) model [Phys. Rev. A 40, 1165, Gen. Relativ. Gravit. 28, 581]



D-P model and the Brownian diffusion

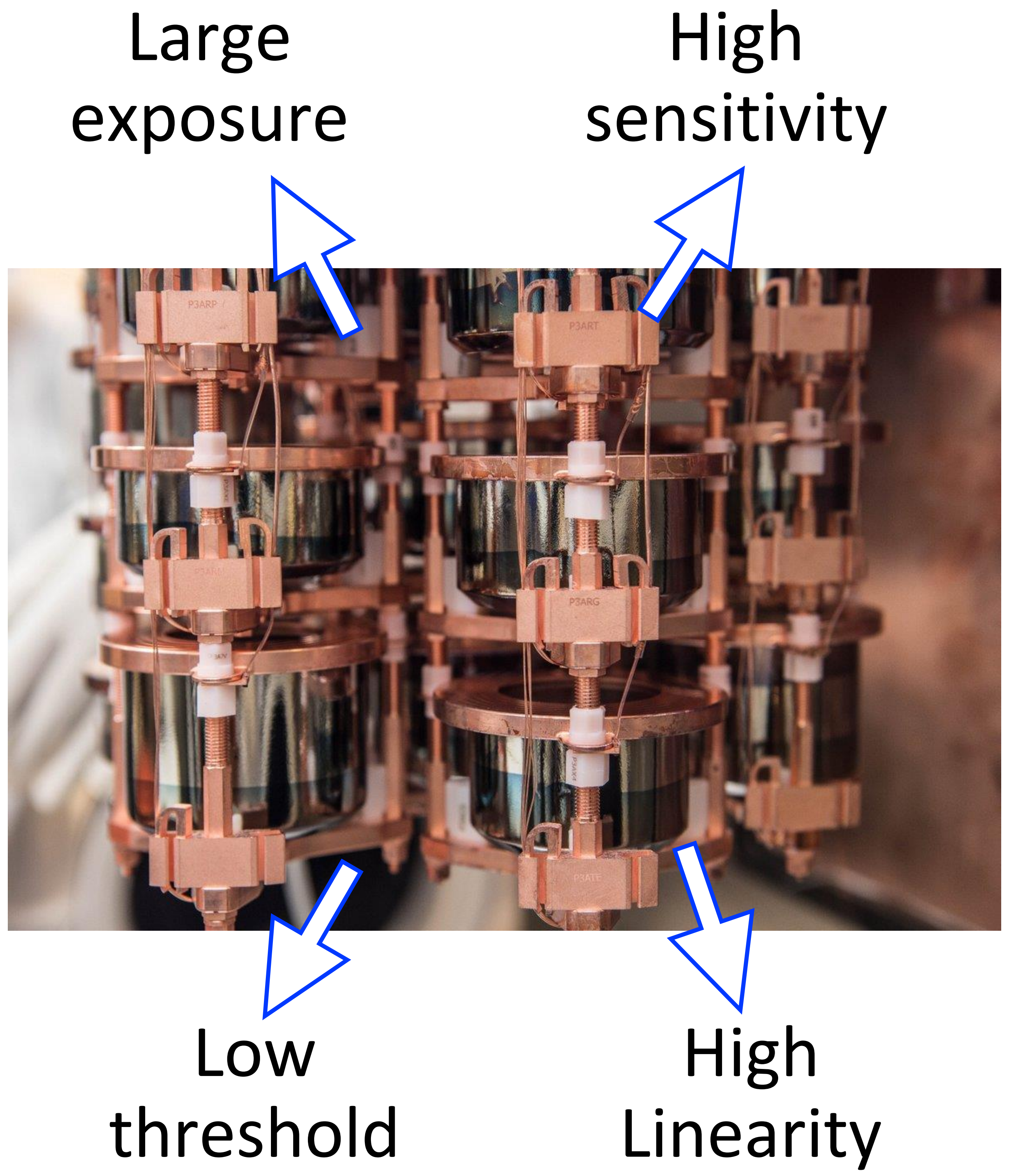
[Nature Physics **17**, 74–78 (2021)]



Energy input from noise field

Energy can be emitted as radiation

Detectable with HPGe detectors!



Large exposure

High sensitivity

Low threshold

High Linearity

Signature of WFC:

$$\frac{d\Gamma(E)}{dE} \propto \frac{\lambda}{r_C^2}\frac{1}{E}$$

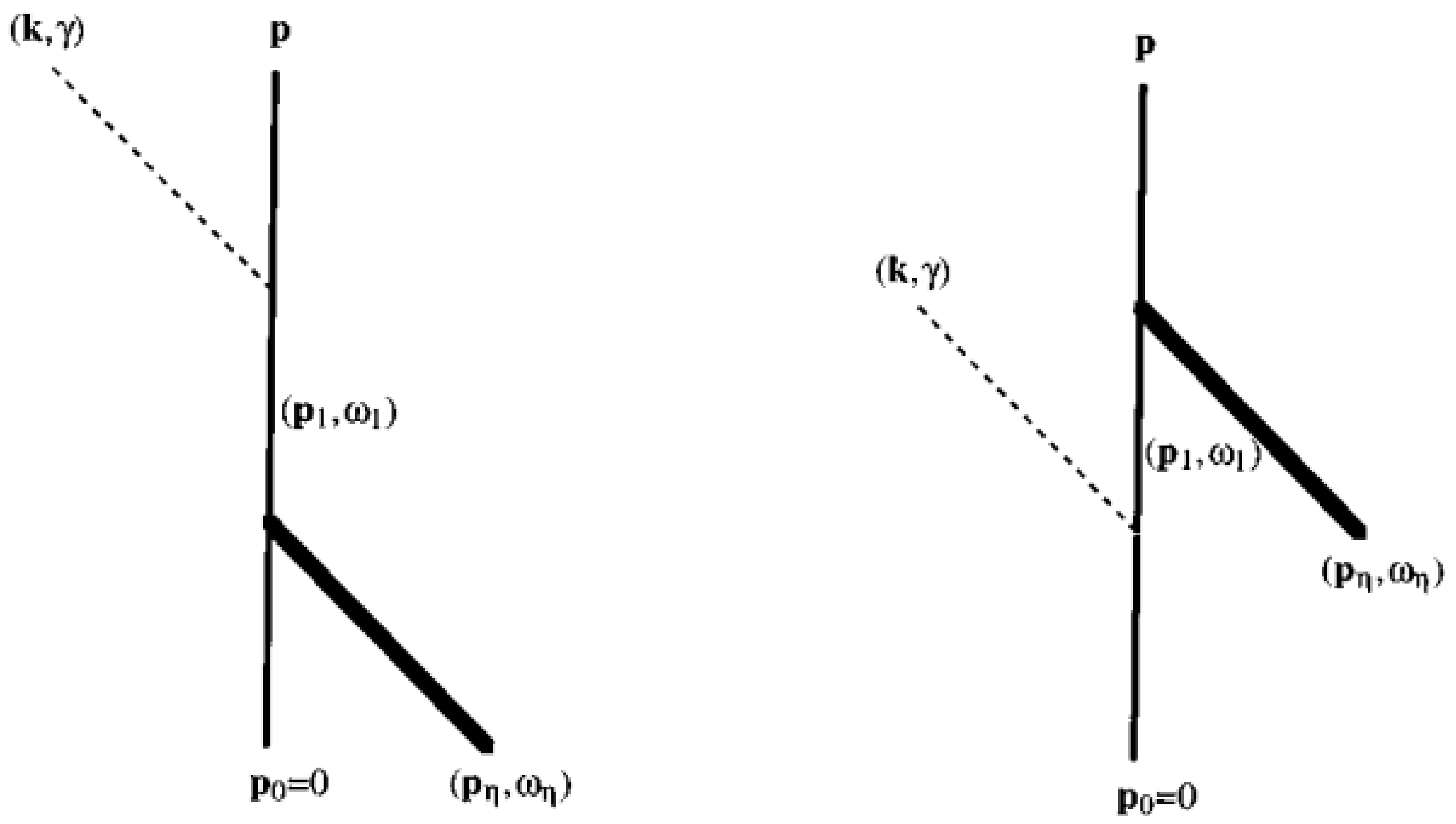
λ : collapse rate

r_C : correlated radius

$1/E$: spectral shape

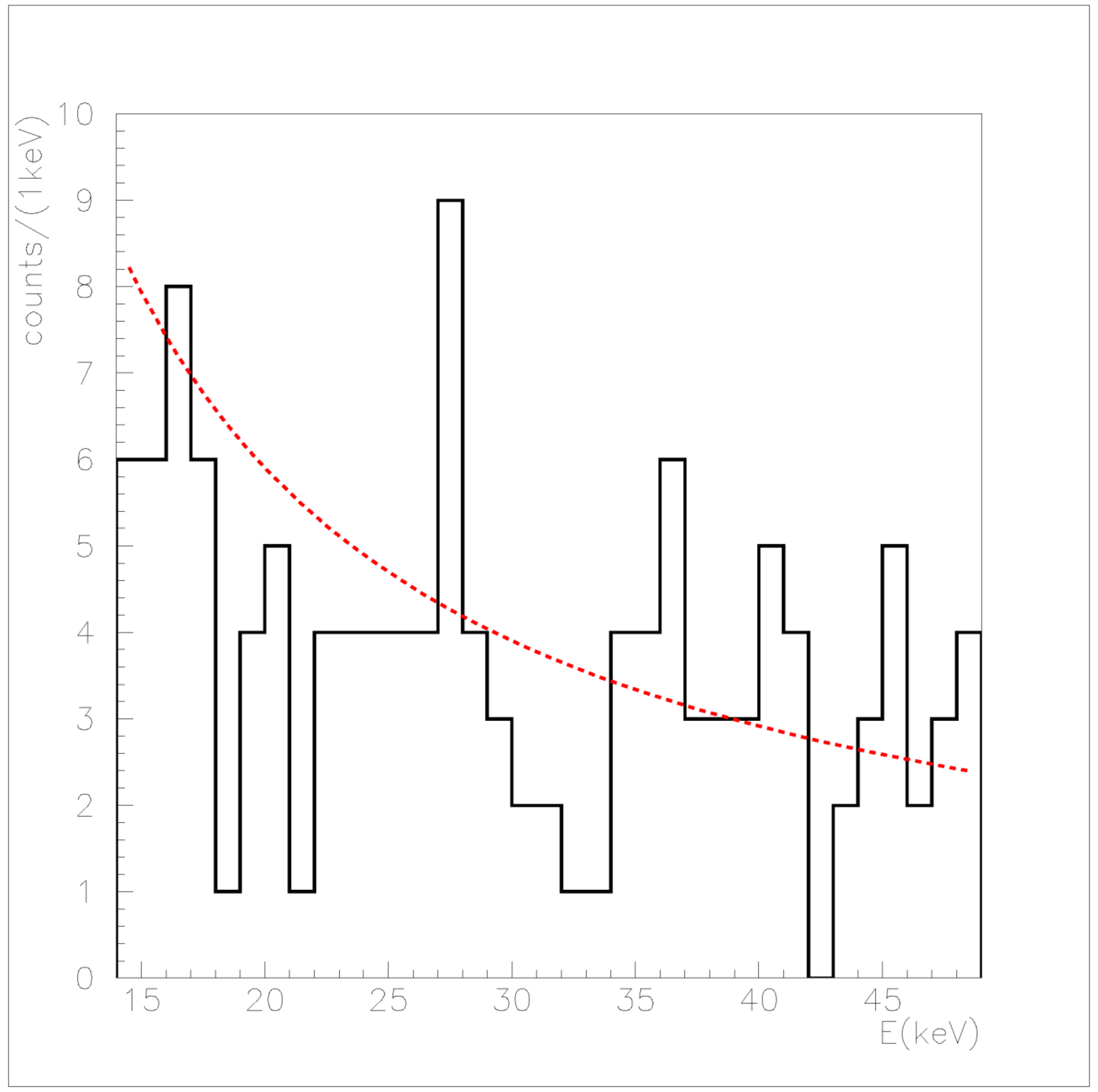
X-ray Radiation from Collapse

Objective collapse models predict stochastic energy exchange between a particle and the collapse field



Q. Fu
Phys. Rev. A **56**, 1806 (1997)

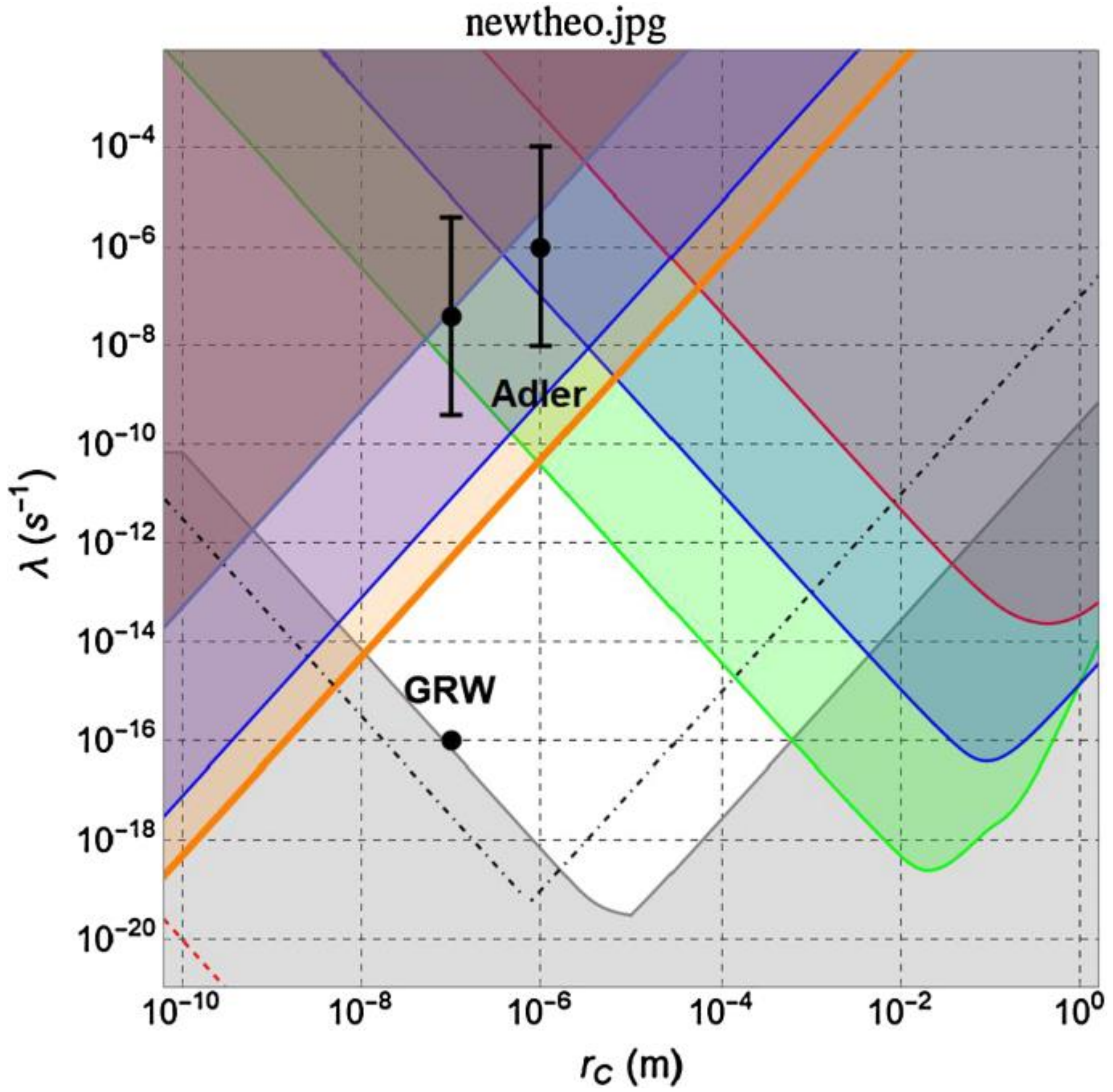
Proposed using germanium-based neutrino experiments to detect a CSL signature of X-ray emission



K. Piscicchia et al.
Entropy **2017**, 19(7), 319 (2017)

Analysis of IGEX[1,2] data

[1] Phys. Rev. C **1999**, 59, 2108.
[2] Phys. Lett. B **2002**, 532, 8–14.



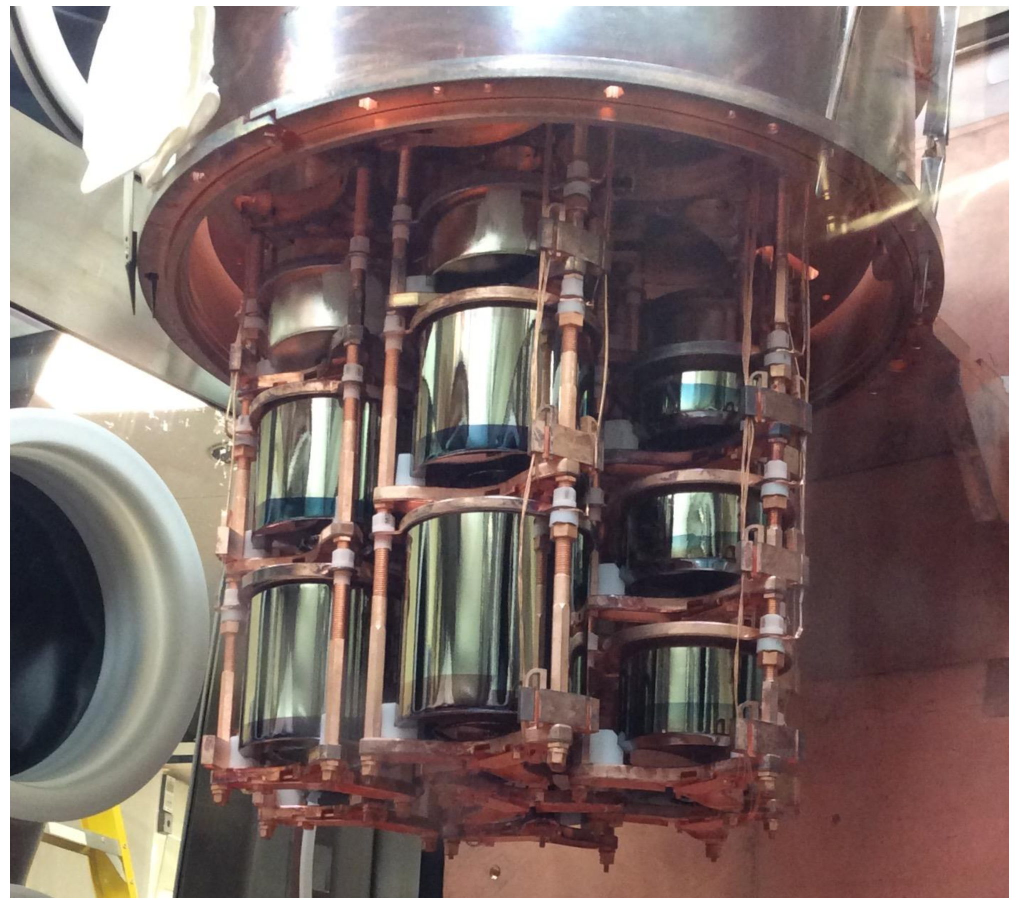
S. Donadi et al.
Nature Physics **17**, 74–78 (2021)
EPJ. C. **81**, 773 (2021)

Coherent emission from nucleus

MAJORANA DEMONSTRATOR

Searching for neutrinoless double-beta decay of ^{76}Ge in HPGe detectors, probing additional physics beyond the standard model, and informing the design of the next-generation LEGEND experiment

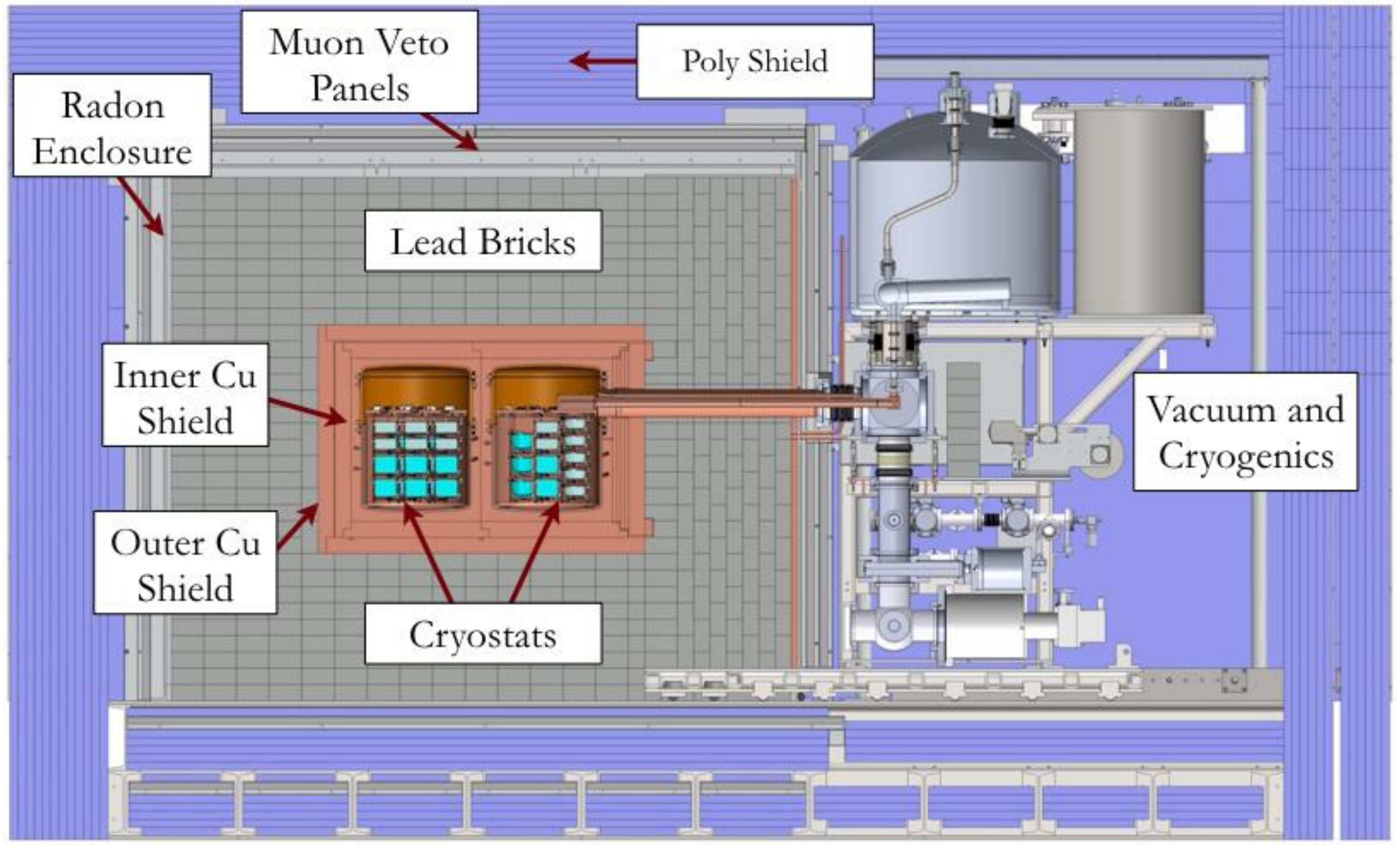
Source & Detector: Array of p-type, point contact detectors
30 kg of 88% enriched ^{76}Ge crystals - 14 kg of natural Ge crystals
Included 6.7 kg of ^{76}Ge inverted coaxial, point contact detectors in final run



Excellent Energy Resolution: 2.5 keV FWHM @ 2039 keV
and **Analysis Threshold:** 1 keV

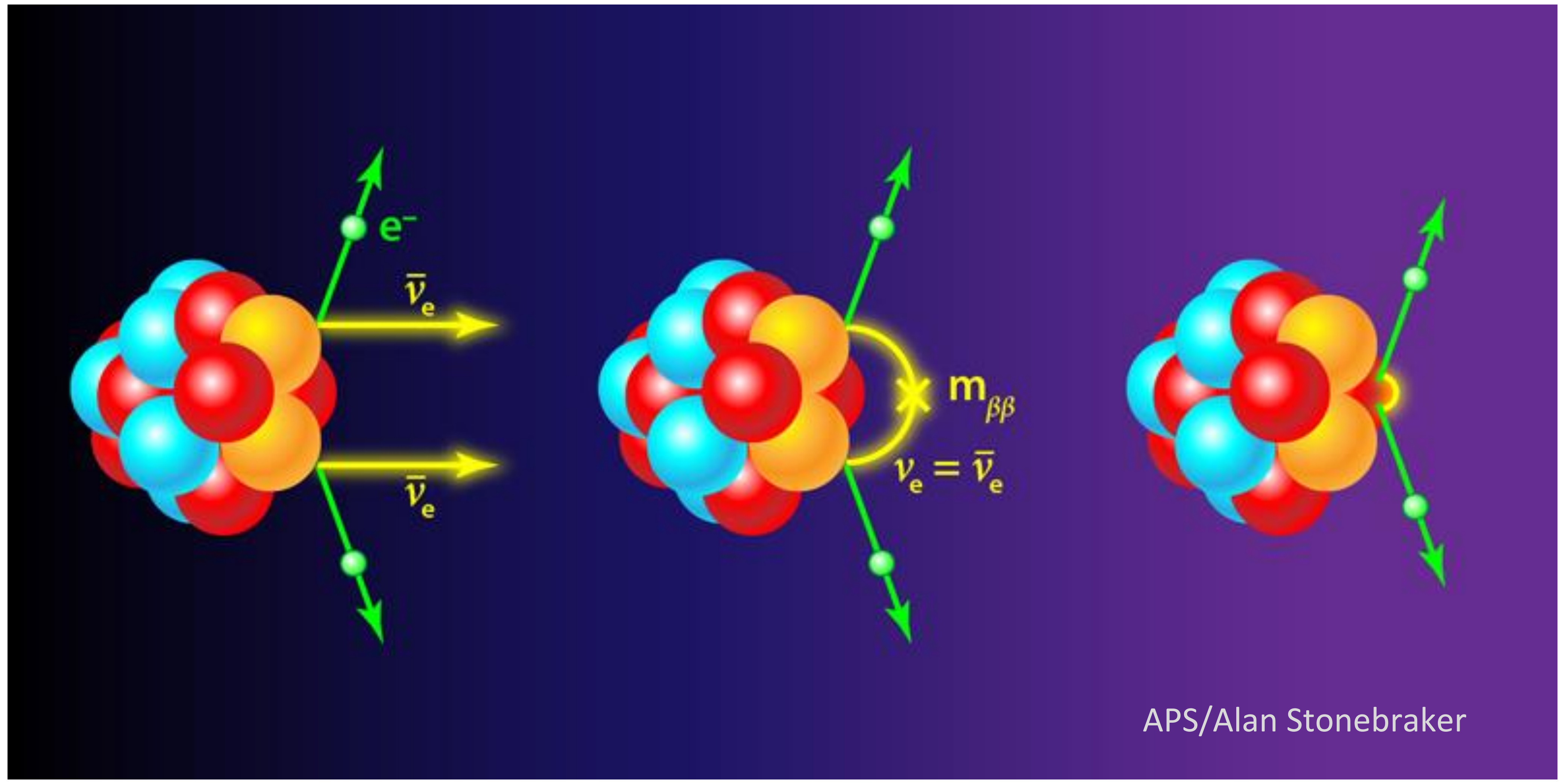
Low Background: 2 modules within a compact graded shield and active muon veto using ultra-clean materials

Reached an exposure of ~65 kg-yr before removal of the enriched detectors for the LEGEND-200 experiment at LNGS

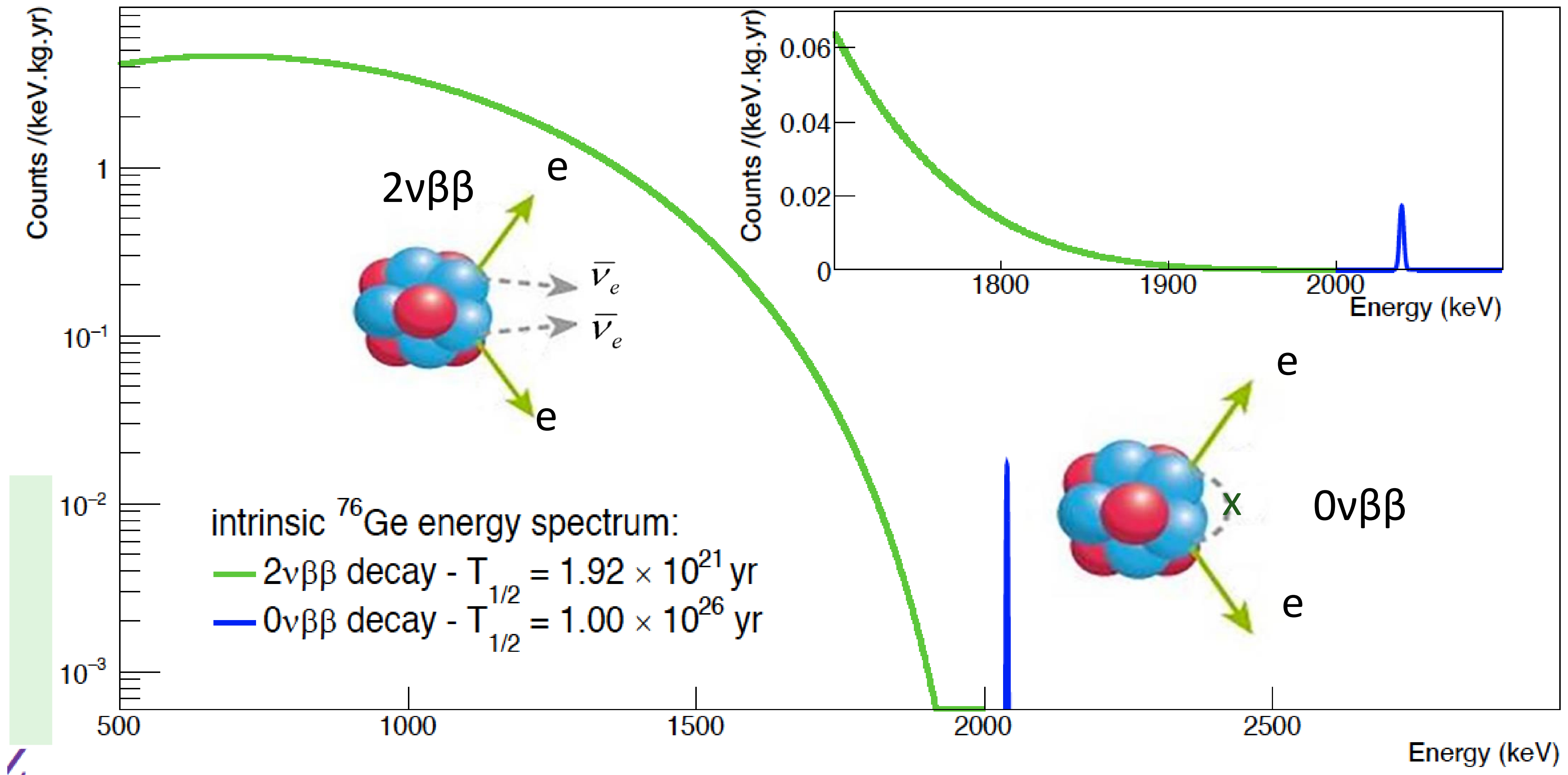


Continuing to operate at the Sanford Underground Research Facility with natural detectors for background studies and other physics

Neutrinoless Double Beta Decay with the DEMONSTRATOR



APS/Alan Stonebraker



(Two-neutrino) Double Beta Decay (2vββ)

- rare decay process that is possible when the single beta decay is energetically forbidden
- Two electrons and two anti-neutrinos are emitted

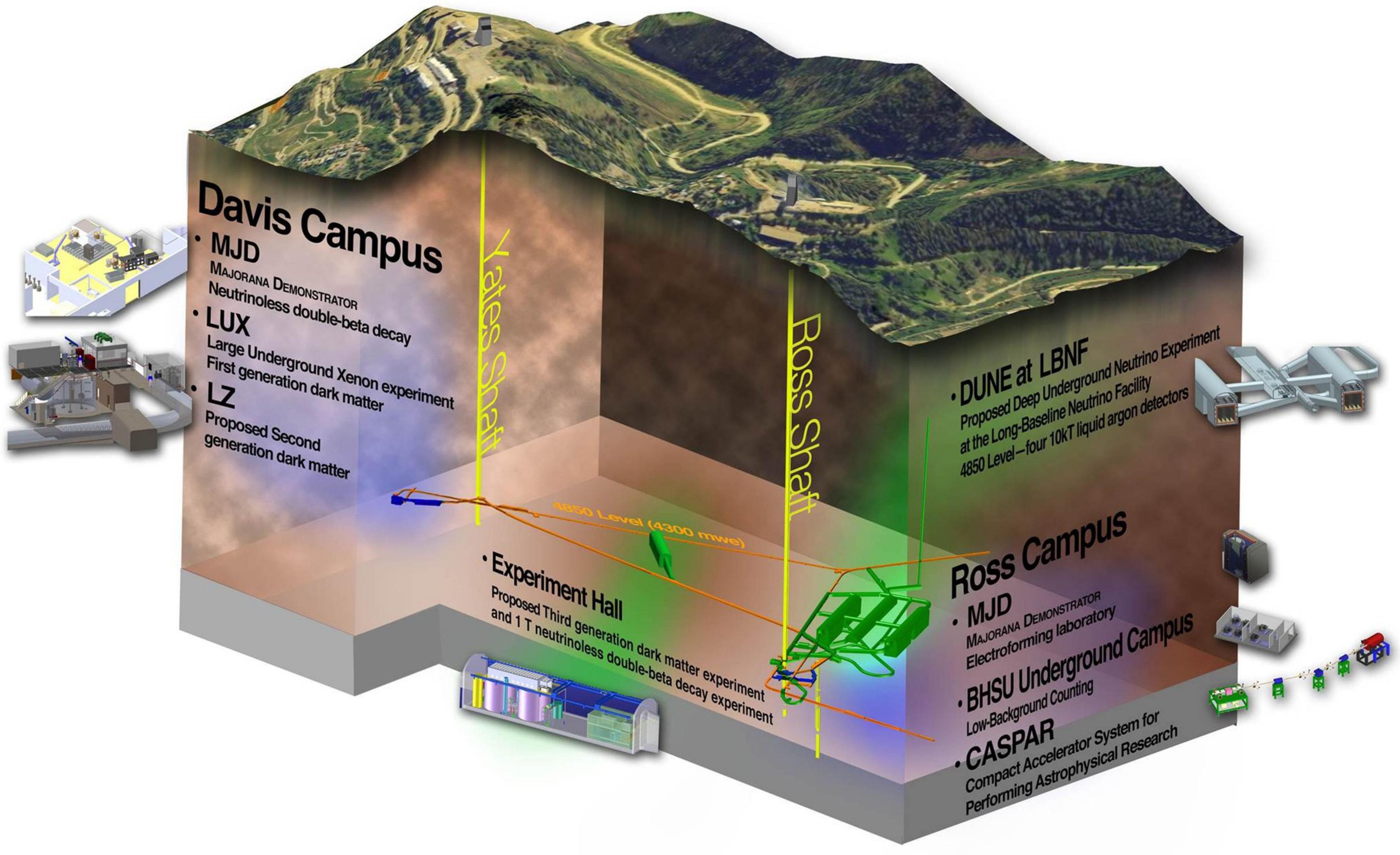
Neutrinoless Double Beta Decay (0vββ)

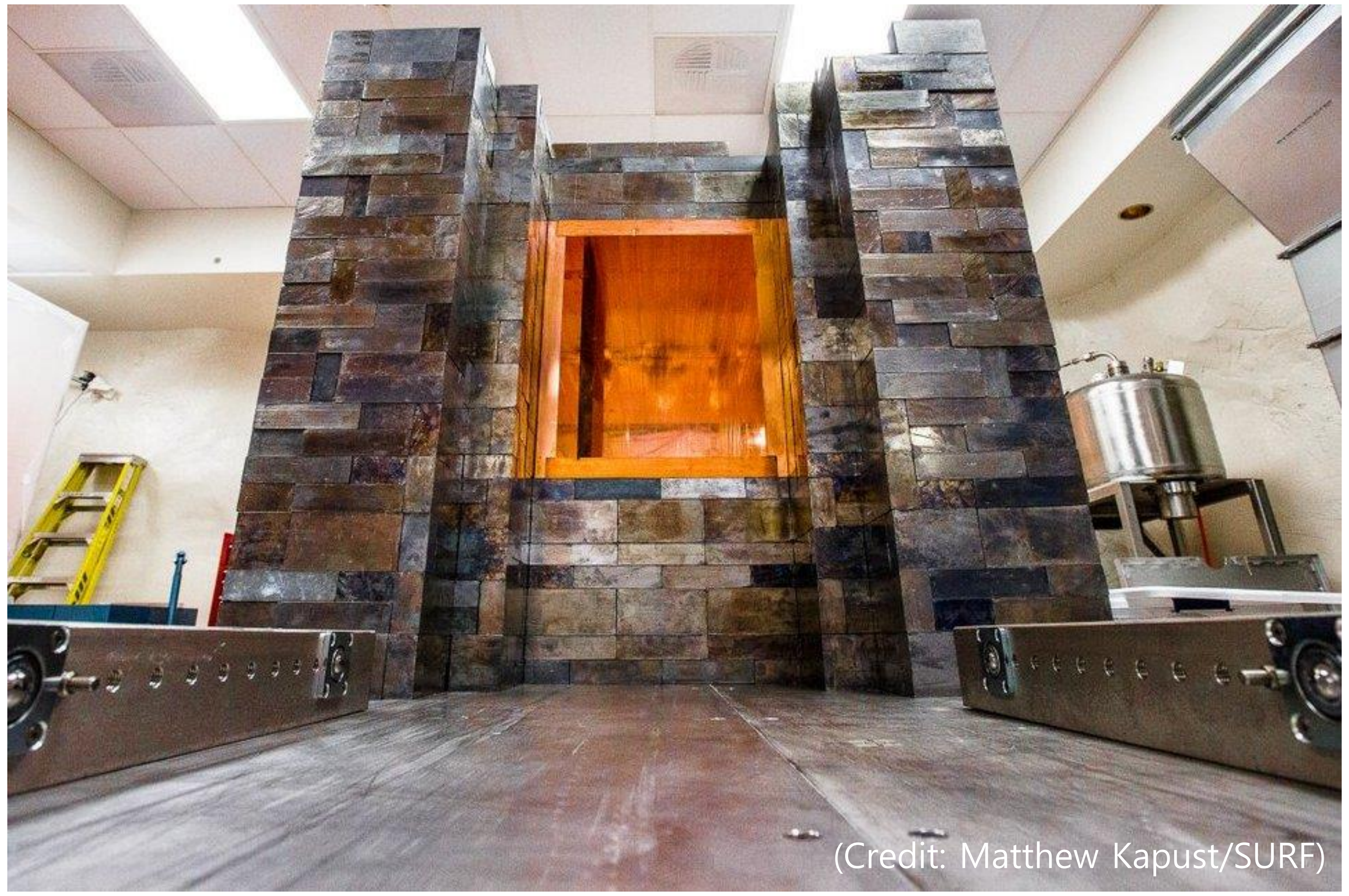
- ββ-decay associated with no anti-neutrinos
- Only allowed if neutrinos are *Majorana particles*
- As the decay energy does not escape, the detection signature of the 0vββ is a peak at the *Q*-value of the 2vββ decay spectrum

Requirements for the 0vββ detection

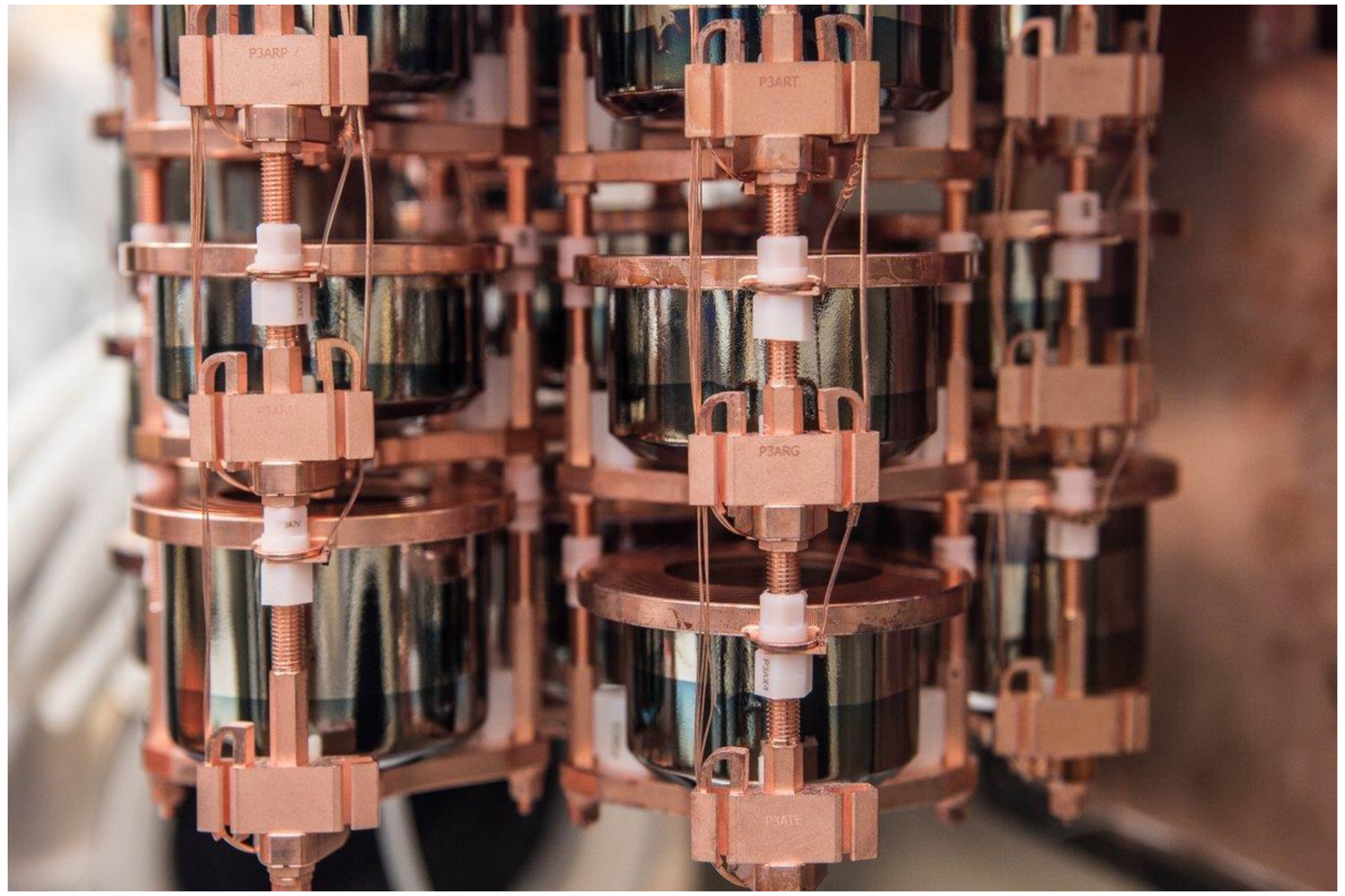
- Large exposure
- High detection efficiency
- Low background
- High energy resolution

Neutrinoless Double Beta Decay with the DEMONSTRATOR

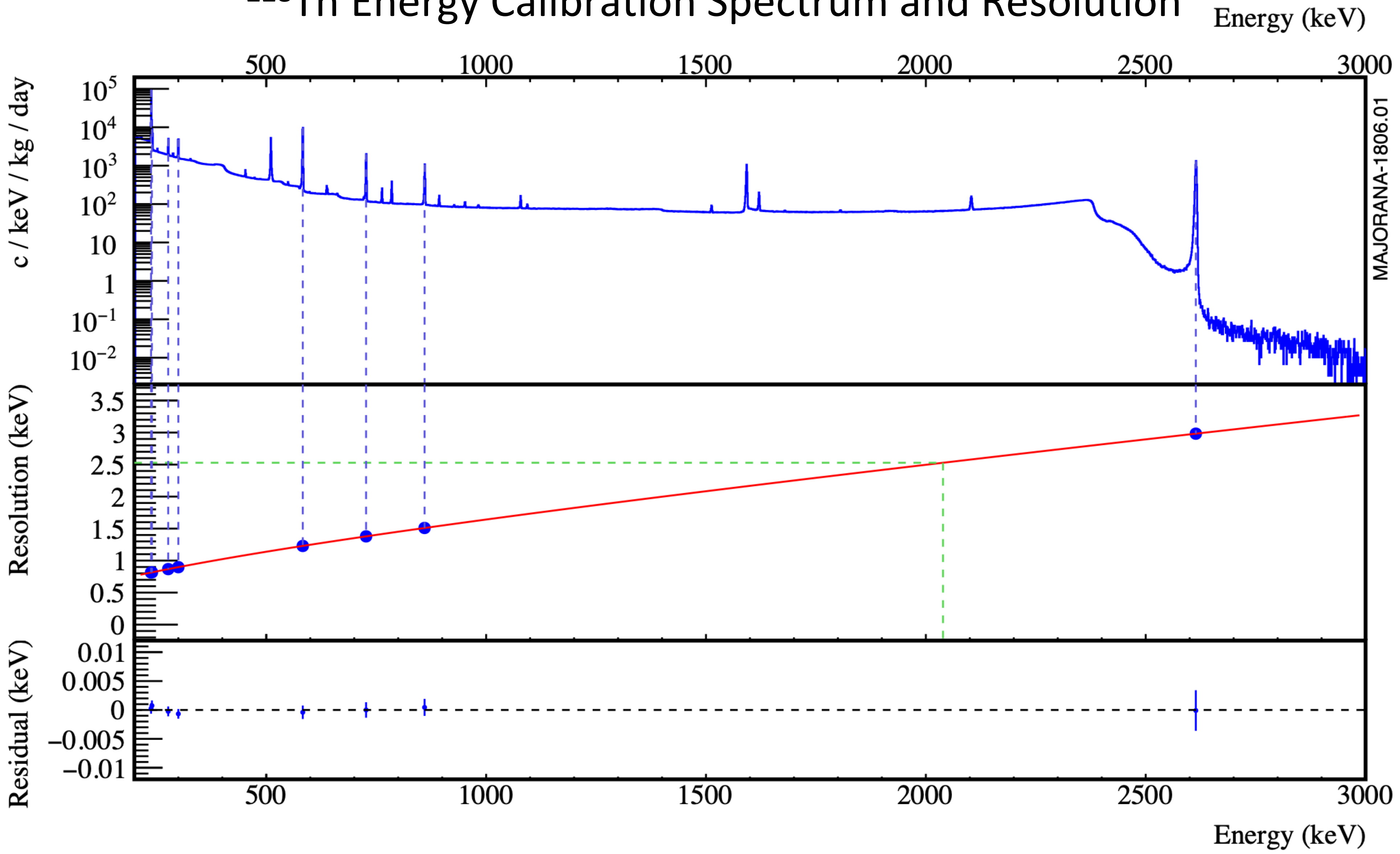




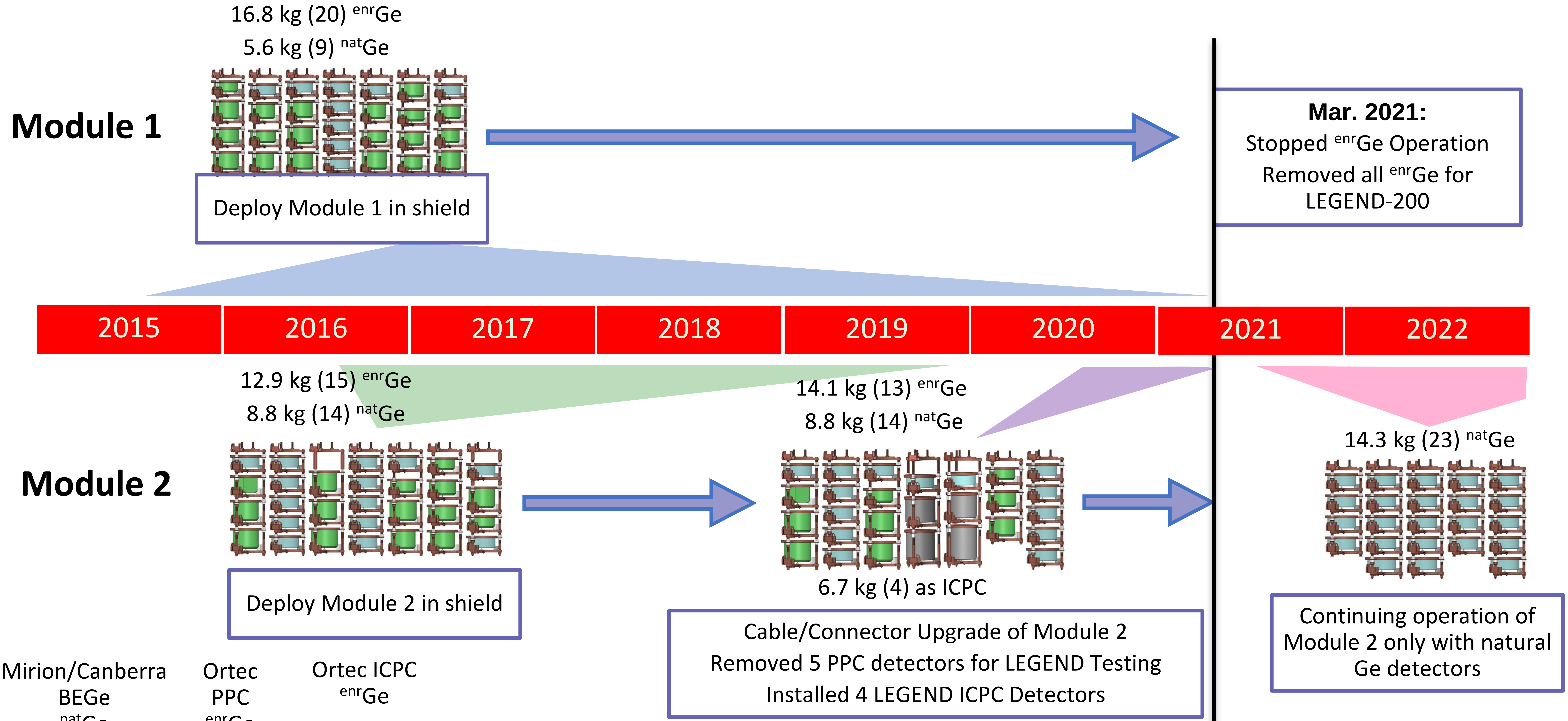
(Credit: Matthew Kapust/SURF)



^{228}Th Energy Calibration Spectrum and Resolution



MAJORANA Run Configuration & Timeline



16.8 kg (20) ^{enr}Ge
5.6 kg (9) ^{nat}Ge

Module 1

Deploy Module 1 in shield

Mar. 2021:
Stopped ^{enr}Ge Operation
Removed all ^{enr}Ge for LEGEND-200

12.9 kg (15) ^{enr}Ge
8.8 kg (14) ^{nat}Ge

Module 2

Deploy Module 2 in shield

14.1 kg (13) ^{enr}Ge
8.8 kg (14) ^{nat}Ge

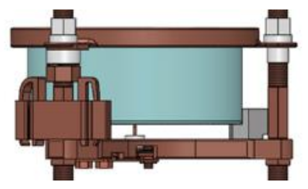
6.7 kg (4) as ICPC

Cable/Connector Upgrade of Module 2
Removed 5 PPC detectors for LEGEND Testing
Installed 4 LEGEND ICPC Detectors

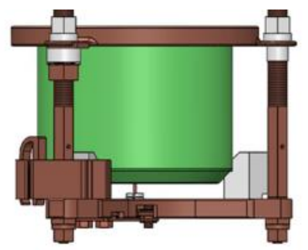
14.3 kg (23) ^{nat}Ge

Continuing operation of Module 2 only with natural Ge detectors

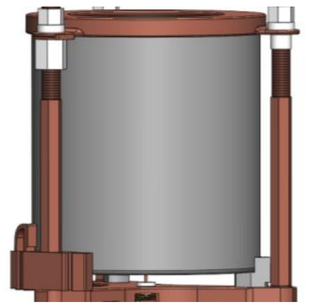
Mirion/Canberra BEGe
^{nat}Ge



Ortec PPC
^{enr}Ge



Ortec ICPC
^{enr}Ge



Searches for Beyond Standard Model Physics

With **low cosmogenic activation**, **excellent energy resolution**, and **~1 keV thresholds**,

MAJORANA is well-positioned to look for Beyond-SM physics **(especially at low energy):**

Tests of Fundamental Symmetries and Conservation Laws

- Lepton number violation via neutrinoless double beta decay $(0\nu\beta\beta)$
- $0\nu\beta\beta$ decay to excited states
- Baryon number violation
- Pauli Exclusion Principle violation

Low-mass dark matter signatures

- Pseudoscalar (axionlike) dark matter
- Vector (dark photon) dark matter
- Fermionic dark matter
- Sterile neutrino dark matter
- Primakoff solar axion
- 14.4-keV solar axion

MAJORANA DEMONSTRATOR
Excellent energy performance,
and low backgrounds
in broad energy regions

Standard Model Physics, and particular backgrounds

- In situ cosmogenics
- (alpha, n) reactions
- Cosmic ray muons

Exotic Physics

- Quantum Wavefunction collapse
- Lightly ionizing particles

Rich and Broad Physics Program

On the Cover

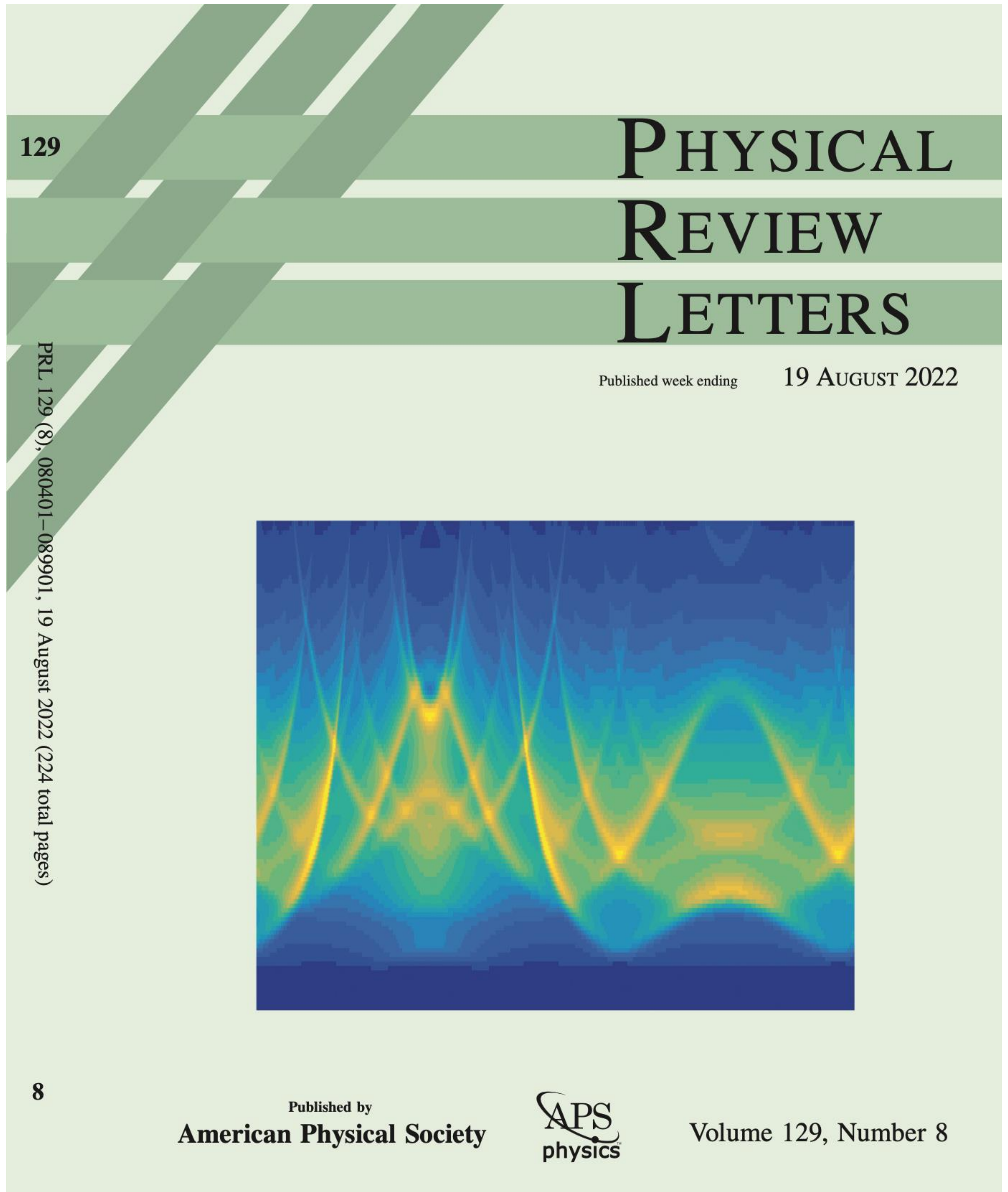
Axion signatures from coherent Primakoff-Bragg scattering over a 24-hour period.

From the article:

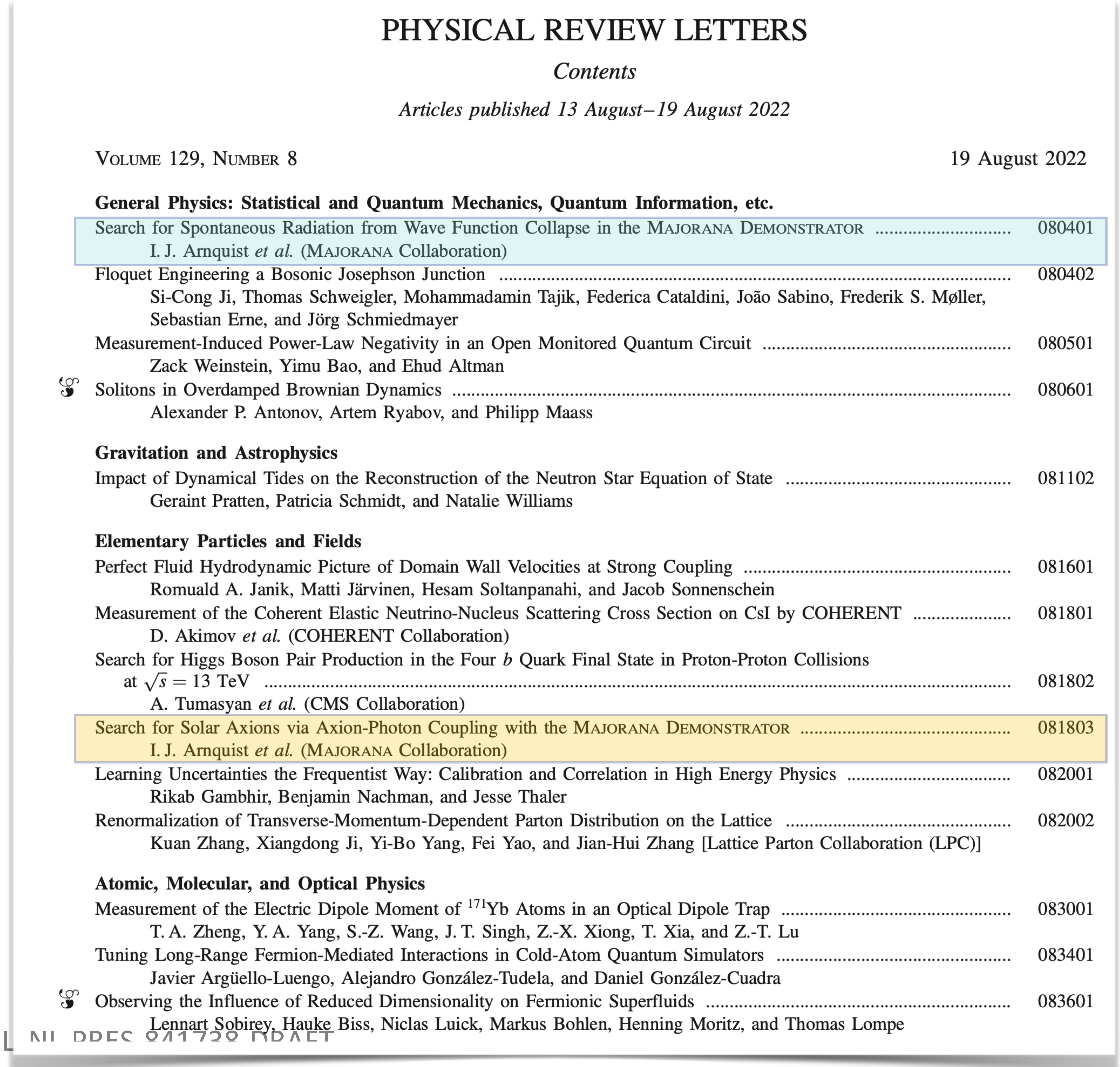
Search for Solar Axions via Axion-Photon Coupling with the MAJORANA DEMONSTRATOR

I.J. Arnquist *et al.* (MAJORANA Collaboration)

Phys. Rev. Lett. **129**, 081803 (2022)



https://journals.aps.org/prl/issues/129/8



PHYSICAL REVIEW LETTERS

Contents

Articles published 13 August–19 August 2022

VOLUME 129, NUMBER 8 — 19 August 2022

General Physics: Statistical and Quantum Mechanics, Quantum Information, etc.

Search for Spontaneous Radiation from Wave Function Collapse in the MAJORANA DEMONSTRATOR 080401
I. J. Arnquist *et al.* (MAJORANA Collaboration)

Floquet Engineering a Bosonic Josephson Junction 080402
Si-Cong Ji, Thomas Schweigler, Mohammadamin Tajik, Federica Cataldini, João Sabino, Frederik S. Møller, Sebastian Erne, and Jörg Schmiedmayer

Measurement-Induced Power-Law Negativity in an Open Monitored Quantum Circuit 080501
Zack Weinstein, Yimu Bao, and Ehud Altman

Solitons in Overdamped Brownian Dynamics 080601
Alexander P. Antonov, Artem Ryabov, and Philipp Maass

Gravitation and Astrophysics

Impact of Dynamical Tides on the Reconstruction of the Neutron Star Equation of State 081102
Geraint Pratten, Patricia Schmidt, and Natalie Williams

Elementary Particles and Fields

Perfect Fluid Hydrodynamic Picture of Domain Wall Velocities at Strong Coupling 081601
Romuald A. Janik, Matti Järvinen, Hesam Soltanpanahi, and Jacob Sonnenschein

Measurement of the Coherent Elastic Neutrino-Nucleus Scattering Cross Section on CsI by COHERENT 081801
D. Akimov *et al.* (COHERENT Collaboration)

Search for Higgs Boson Pair Production in the Four b Quark Final State in Proton-Proton Collisions at $\sqrt{s} = 13$ TeV 081802
A. Tumasyan *et al.* (CMS Collaboration)

Search for Solar Axions via Axion-Photon Coupling with the MAJORANA DEMONSTRATOR 081803
I. J. Arnquist *et al.* (MAJORANA Collaboration)

Learning Uncertainties the Frequentist Way: Calibration and Correlation in High Energy Physics 082001
Rikab Gambhir, Benjamin Nachman, and Jesse Thaler

Renormalization of Transverse-Momentum-Dependent Parton Distribution on the Lattice 082002
Kuan Zhang, Xiangdong Ji, Yi-Bo Yang, Fei Yao, and Jian-Hui Zhang [Lattice Parton Collaboration (LPC)]

Atomic, Molecular, and Optical Physics

Measurement of the Electric Dipole Moment of ^{171}Yb Atoms in an Optical Dipole Trap 083001
T. A. Zheng, Y. A. Yang, S.-Z. Wang, J. T. Singh, Z.-X. Xiong, T. Xia, and Z.-T. Lu

Tuning Long-Range Fermion-Mediated Interactions in Cold-Atom Quantum Simulators 083401
Javier Argüello-Luengo, Alejandro González-Tudela, and Daniel González-Cuadra

Observing the Influence of Reduced Dimensionality on Fermionic Superfluids 083601
Lennart Sobirey, Hauke Biss, Niclas Luick, Markus Bohlen, Henning Moritz, and Thomas Lompe

Cleaning up the Low Energy spectrum (1-100 keV)

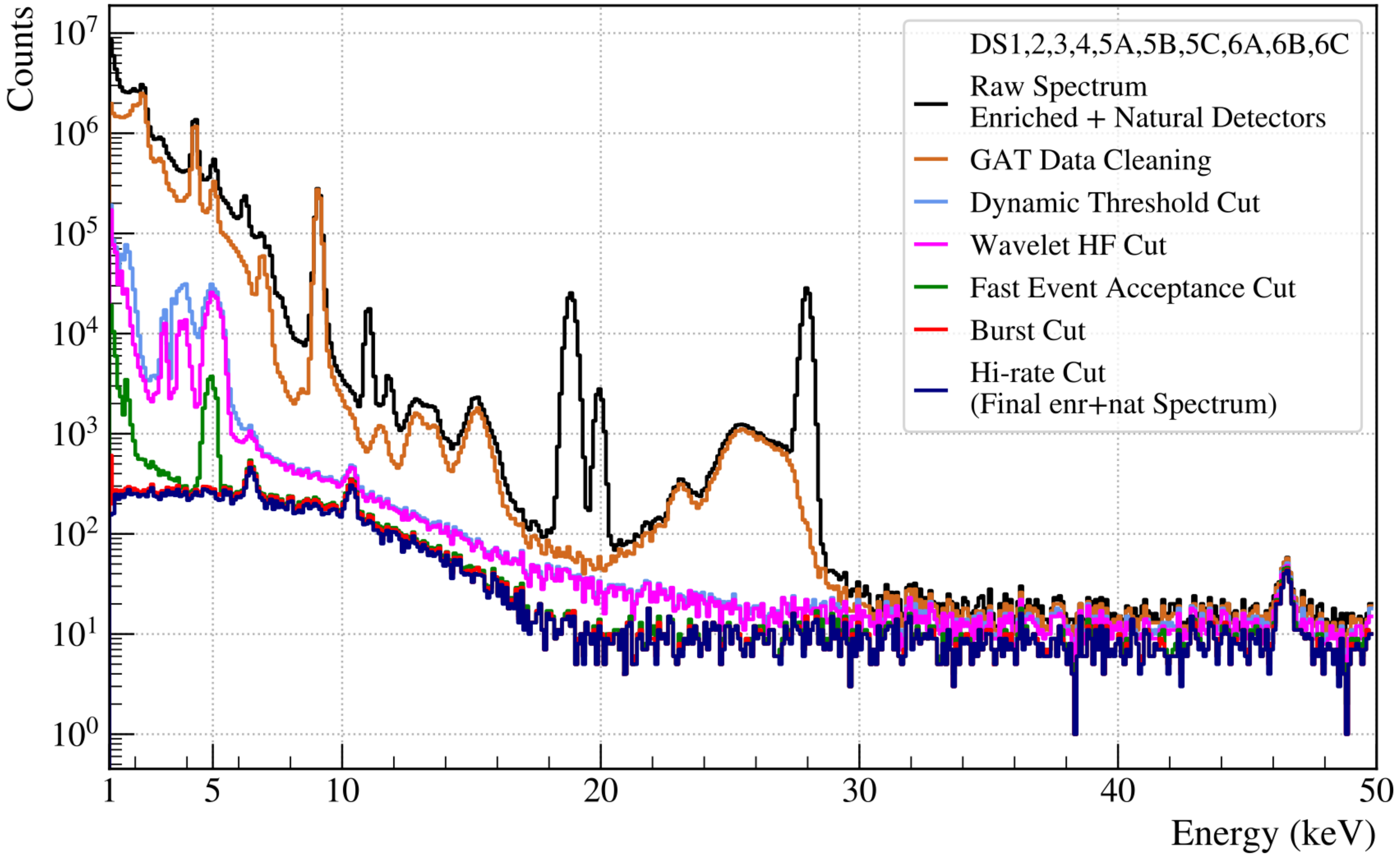
Many populations of low-energy noise initially obscured spectral features under 100 keV.

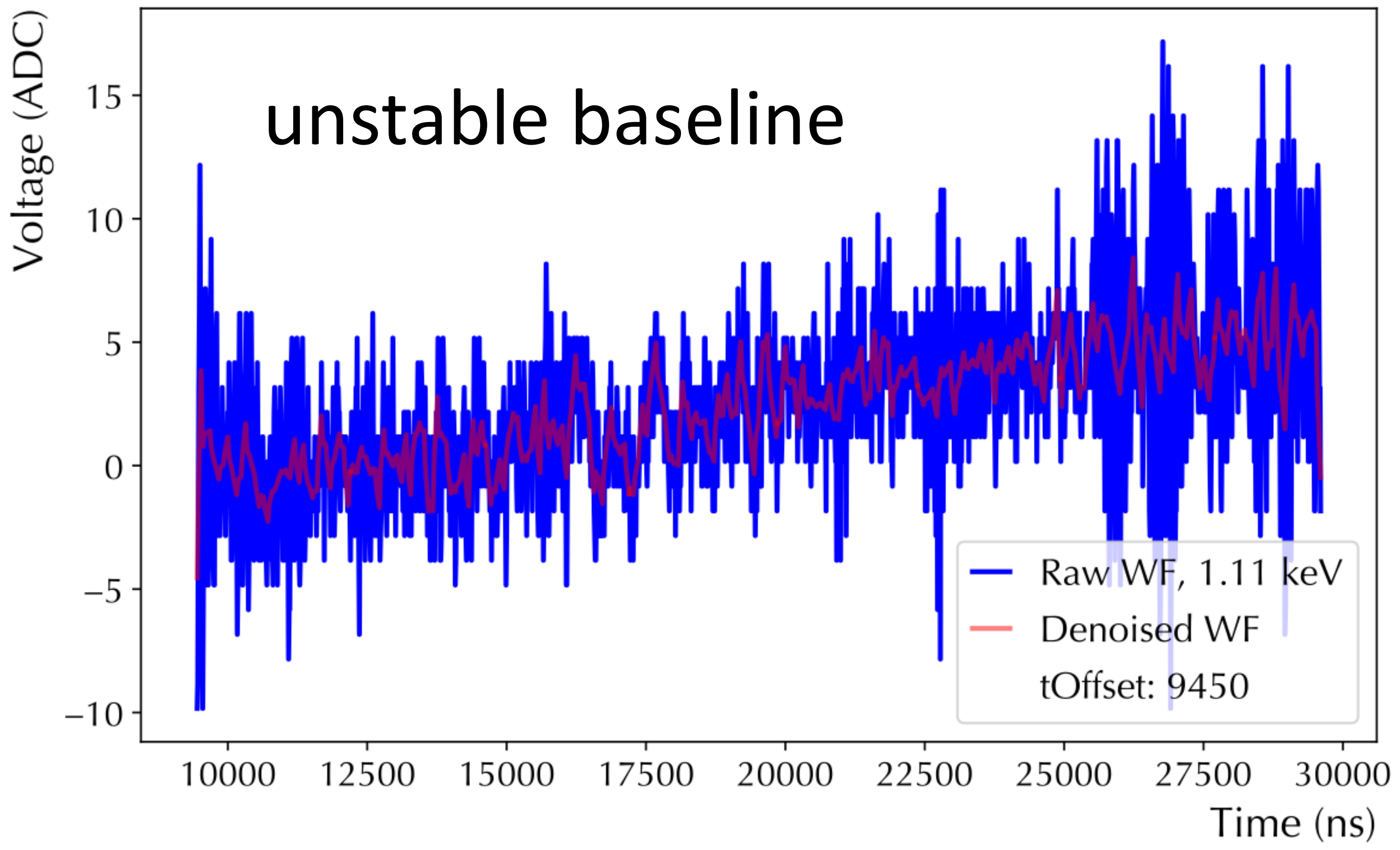
Careful cuts based on waveform fitting, wavelet de-noising, and other parameters were trained on ^{228}Th calibration data.

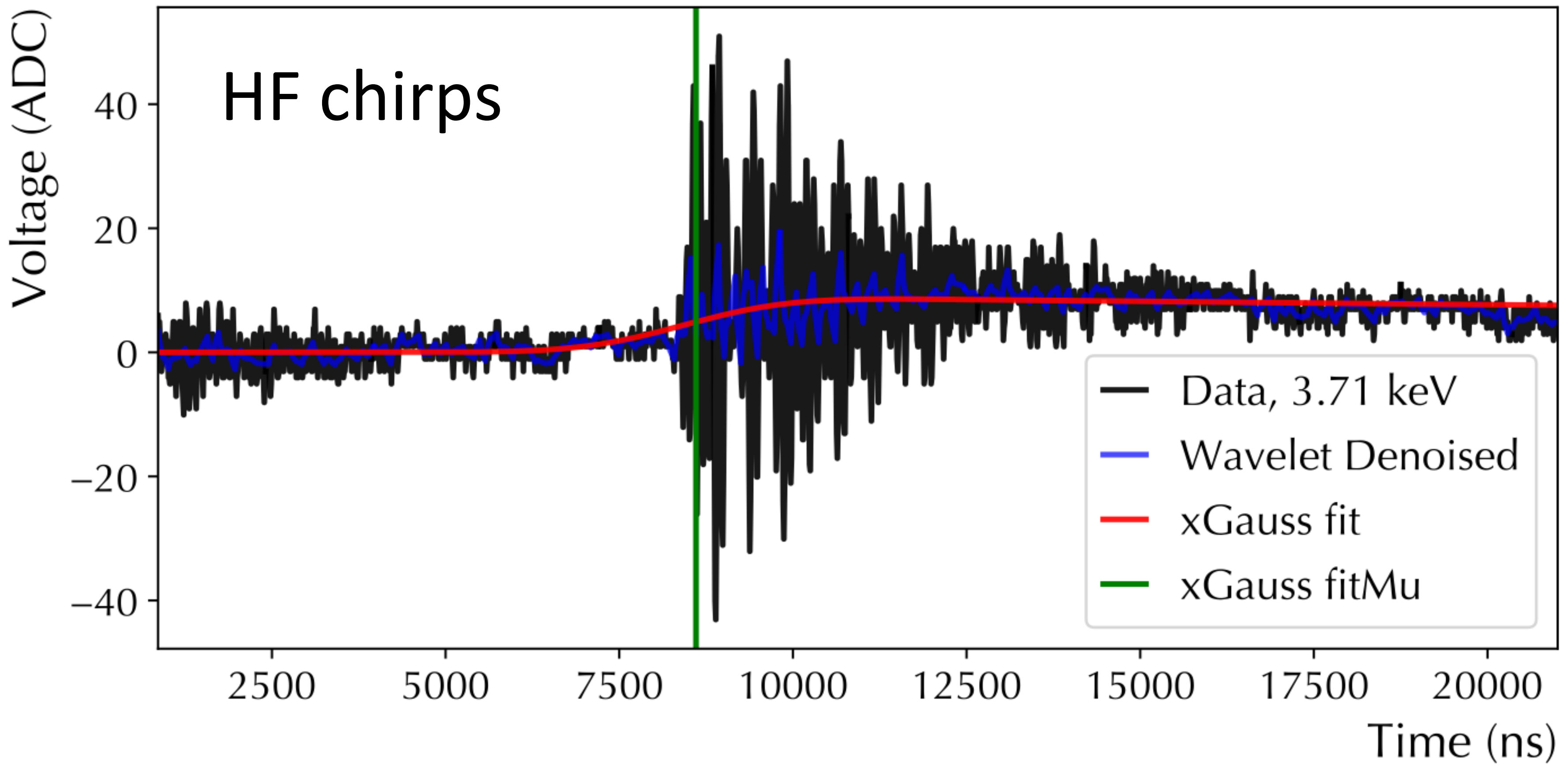
Data taking milestones:

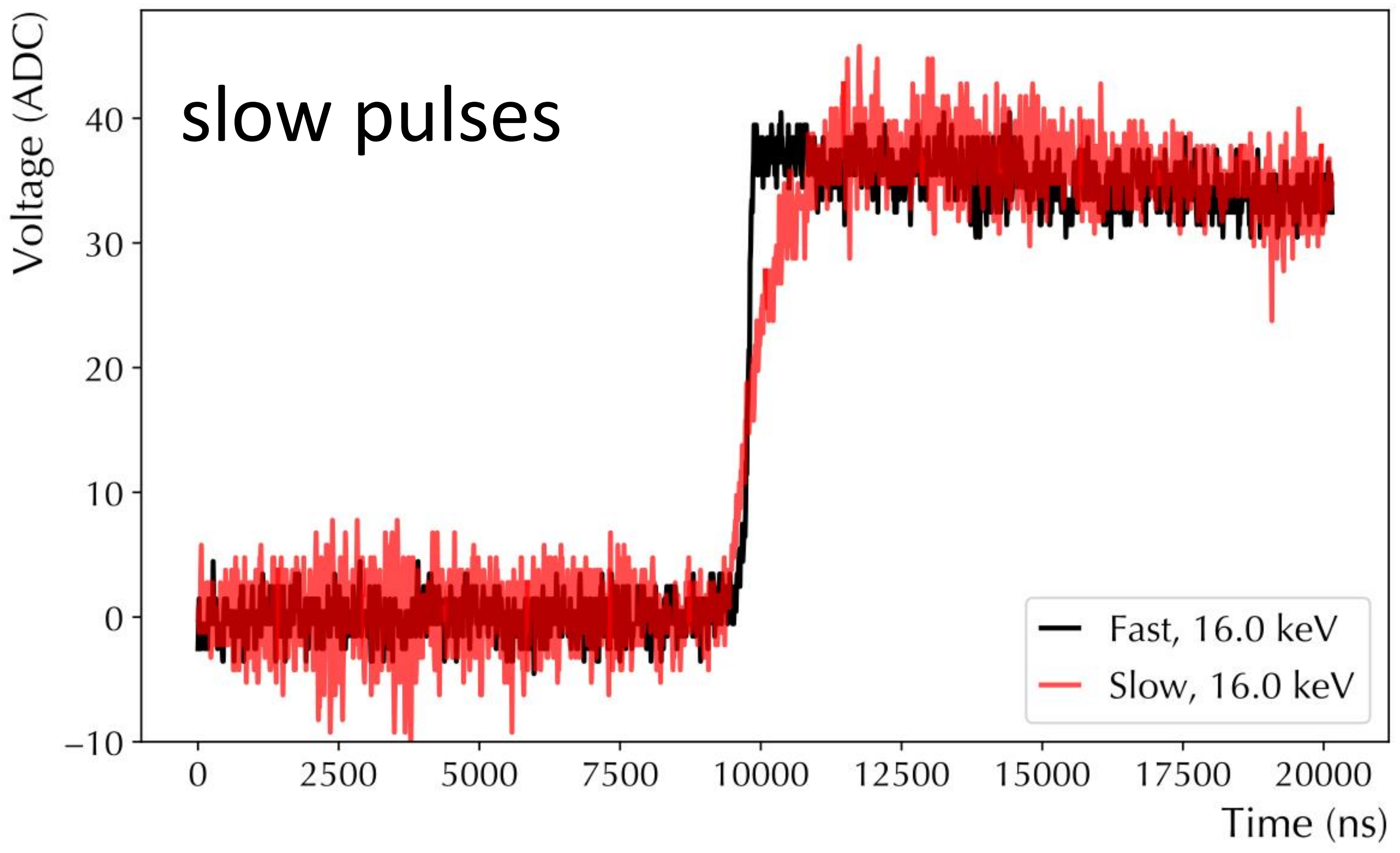
- **June 2015:** commissioning dataset taken
- **Nov 2019:** End of the “Low-E” data set (6C)
- **2021:** ^{enr}Ge detectors removed, ^{nat}Ge detectors running

After 4 years of operation, our analysis achieves a **5 order of magnitude noise reduction** in the low E spectrum!





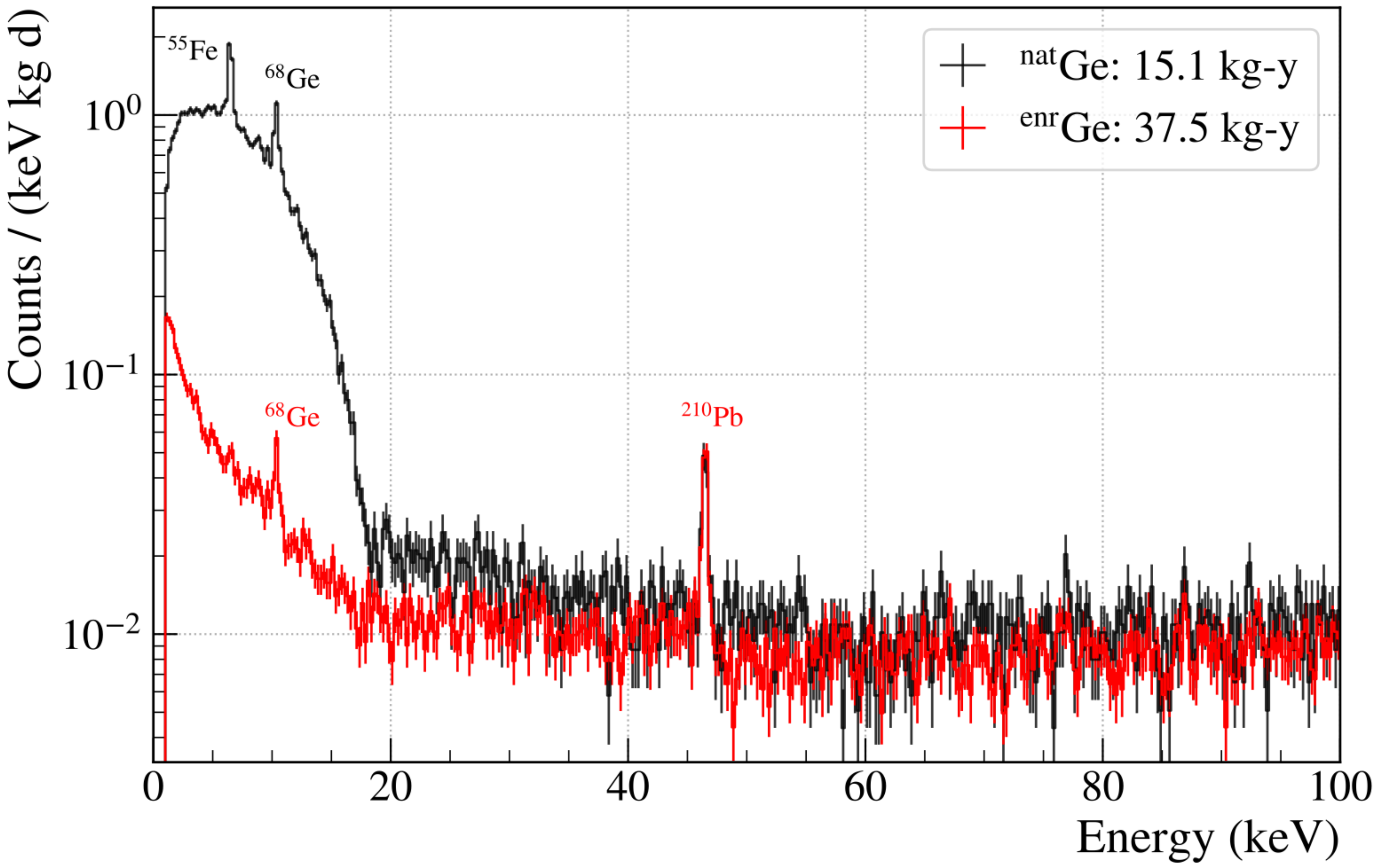


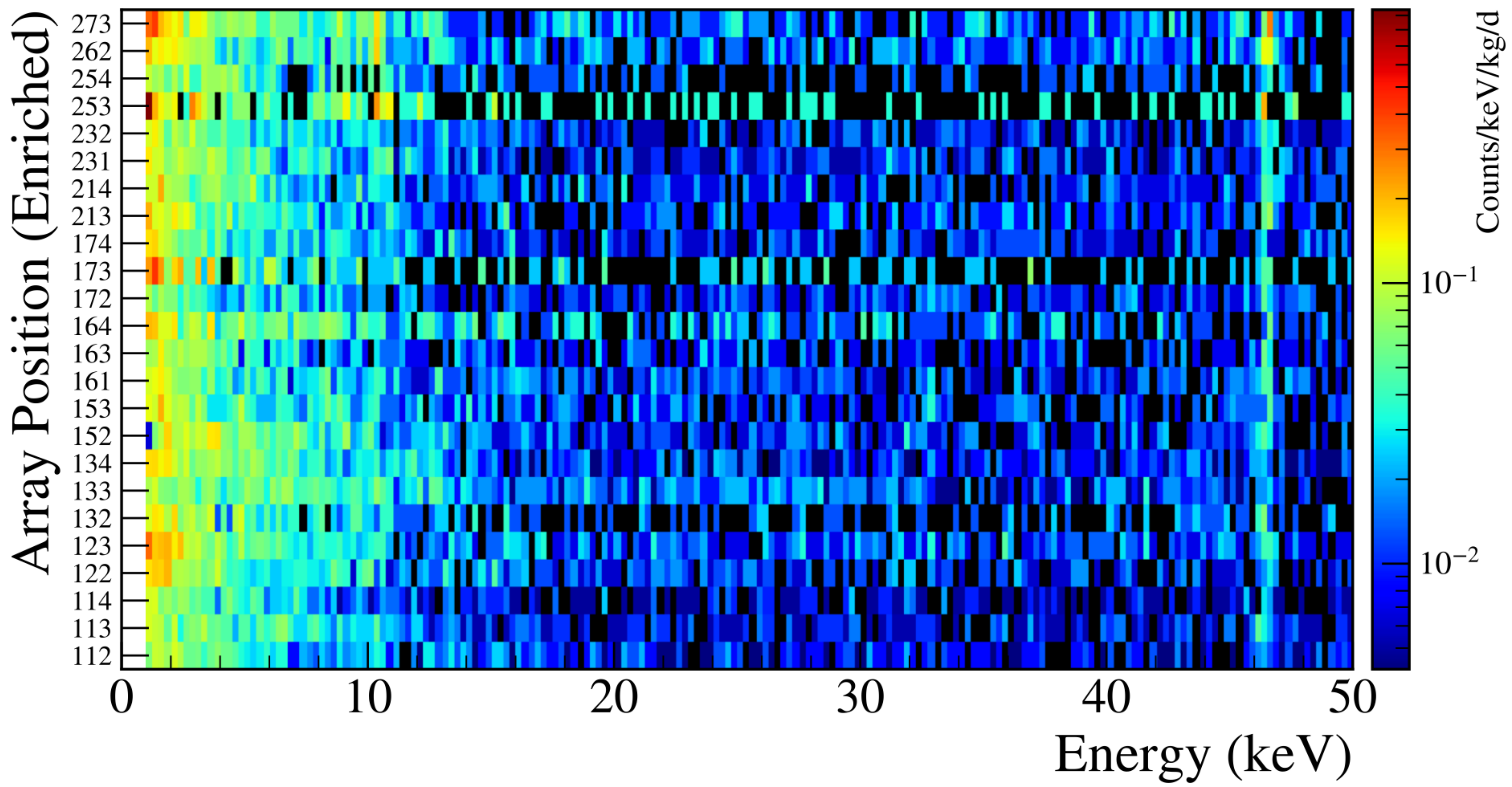


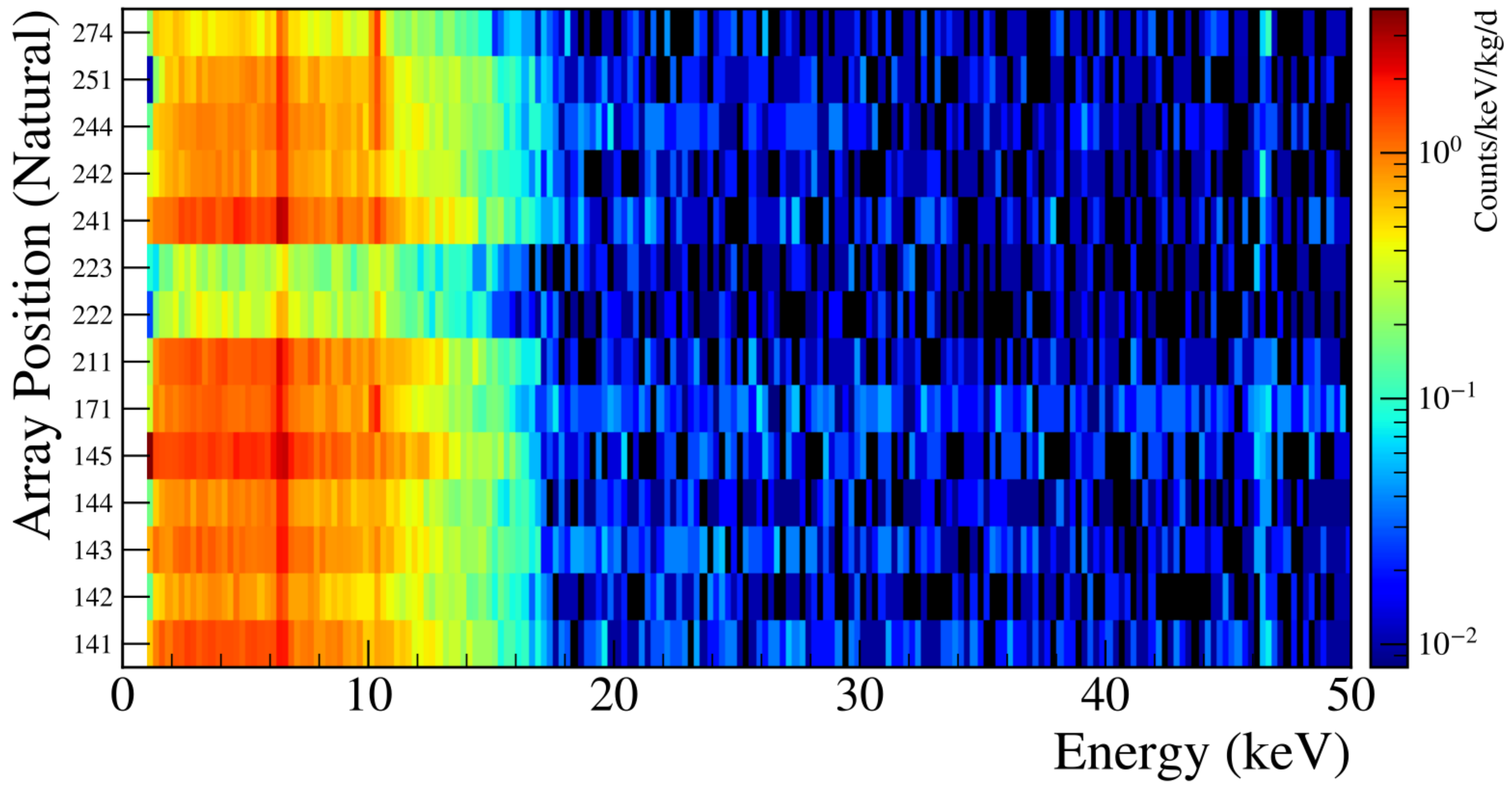
The Low-E spectrum

After spectrum is cleaned:

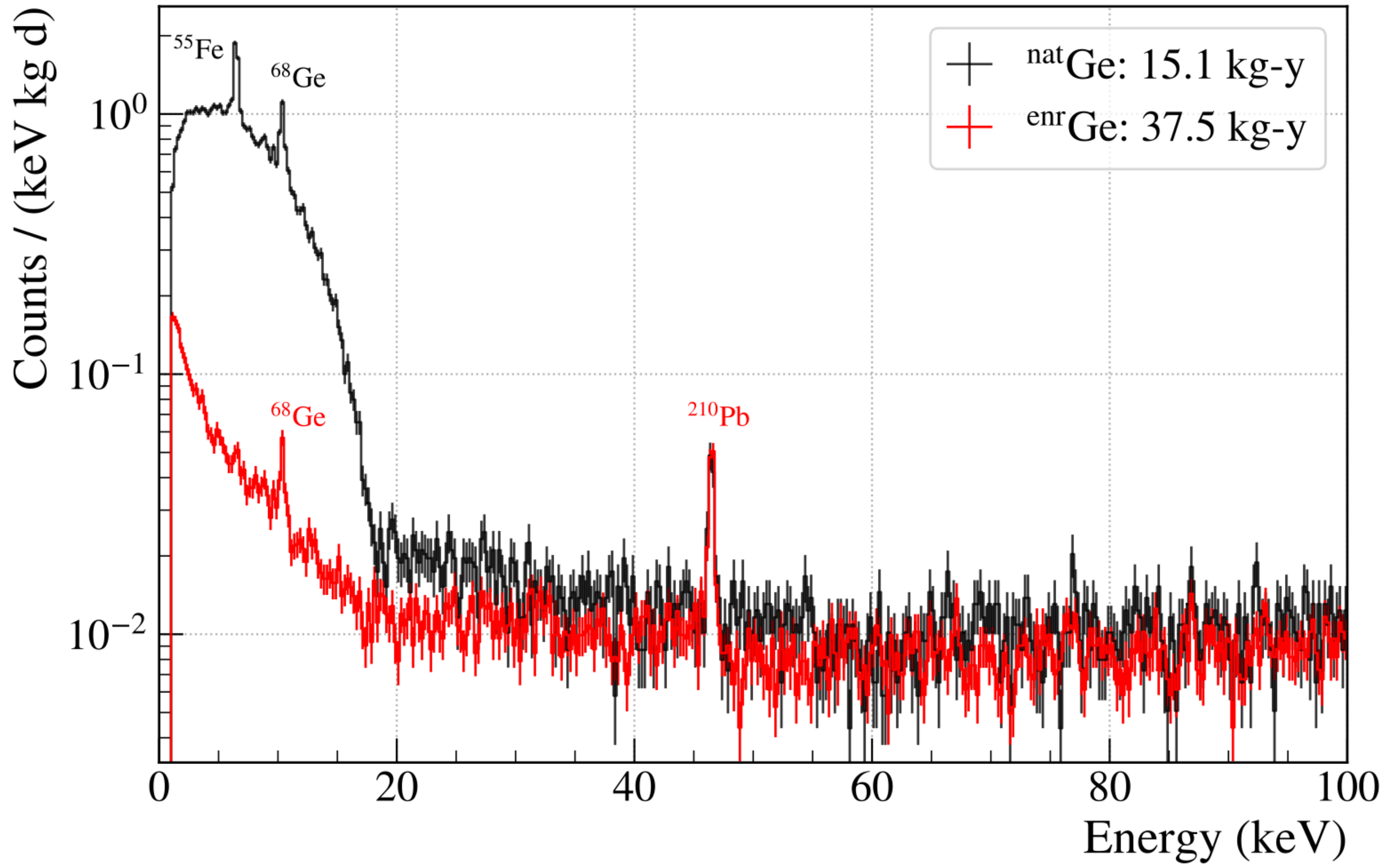
- 37.5 kg-y ^{enr}Ge, 15.1 kg-y ^{nat}Ge
- ^{210}Pb line at 46 keV @ same rate in both sets
- Minimal cosmogenic activation in ^{enr}Ge
- ^{enr}Ge rising shape likely from Rn progeny
- Reduced cosmogenics in two ^{nat}Ge detectors



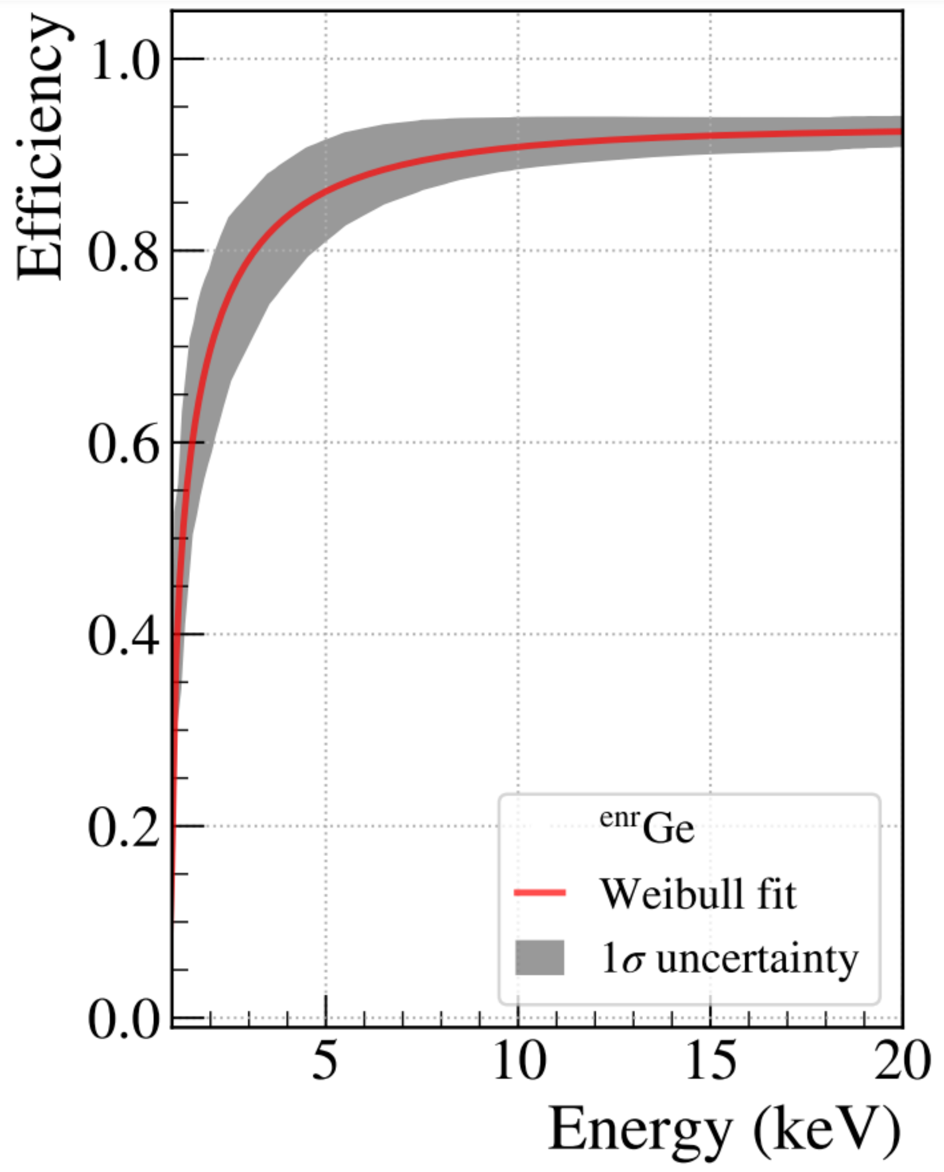




Search for wave function collapse PRL 129 080401 (2022)



MAJORANA Low energy spectrum



Detection Efficiency

For the CSL model,

$$\frac{d\Gamma(E)}{dE} = A_f \times \frac{\hbar\lambda}{4\pi^2\varepsilon_0 m_0^2 c^3 r_C^2 E}$$

For the DP model,

$$\frac{d\Gamma(E)}{dE} = \frac{2}{3}\frac{e^2 G Z^2 N_{\text{Ge}} M}{\pi^{3/2}\varepsilon_0 c^3}\frac{1}{R_{\text{DP}}^3}\frac{1}{E}$$

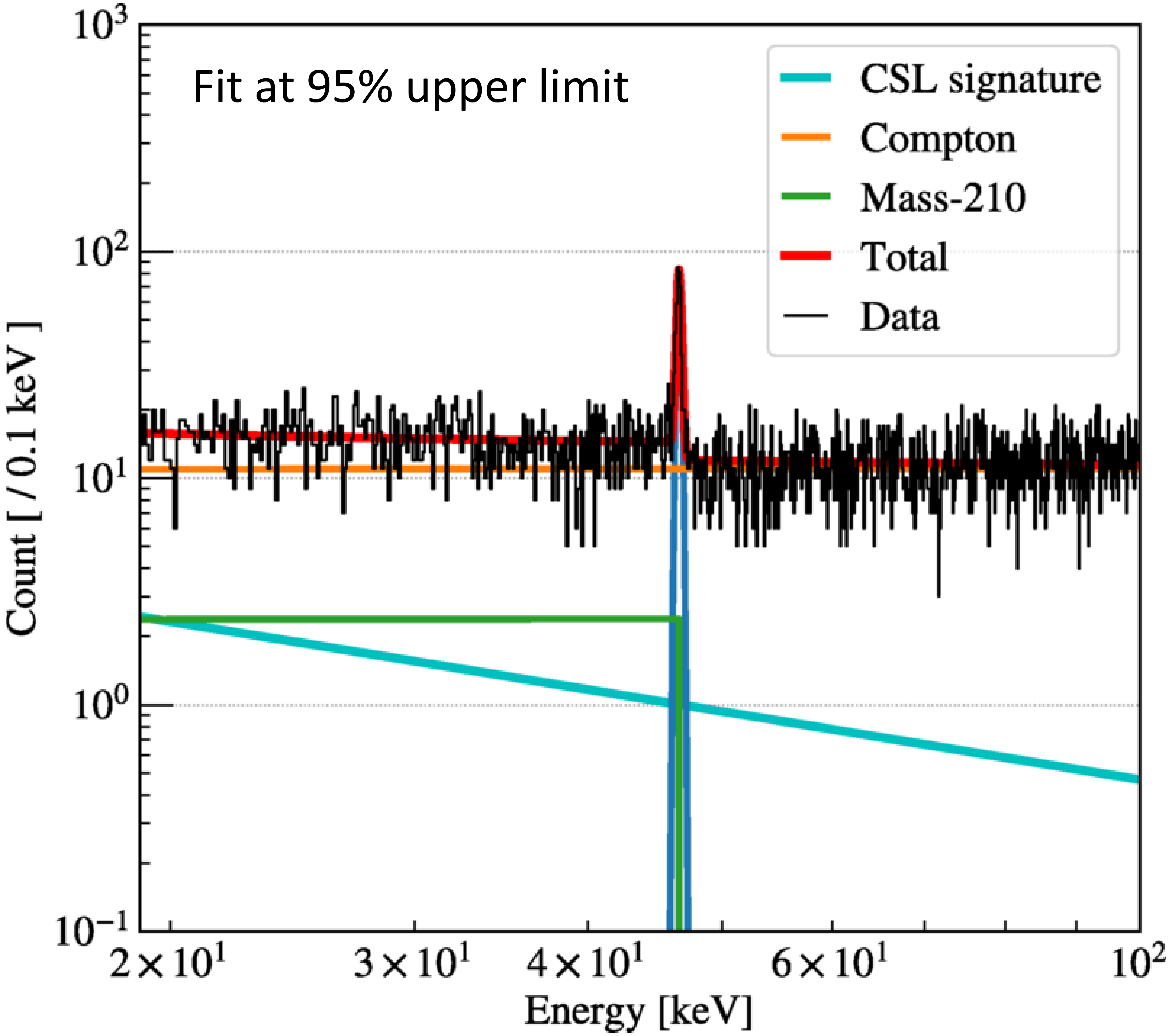
Total PDF:

$$T(E) = \varepsilon(E) \times \left[sW(E) + \sum_i b_i B_i(E) \right]$$

MAJORANA Low-E search for the collapse signature

Exposure: 37.5 kg-y (2015.12.31 – 2019.11.27)
Region of Interest: 19—100 keV (to avoid the ^{3}H continuum)
Background level: 0.01 counts/(keV kg d) at 20 keV
Detection efficiency: (92.4±1.5)% at 20 keV.
Known background PDFs: Compton, ^{210}Pb, mass-210 continuum

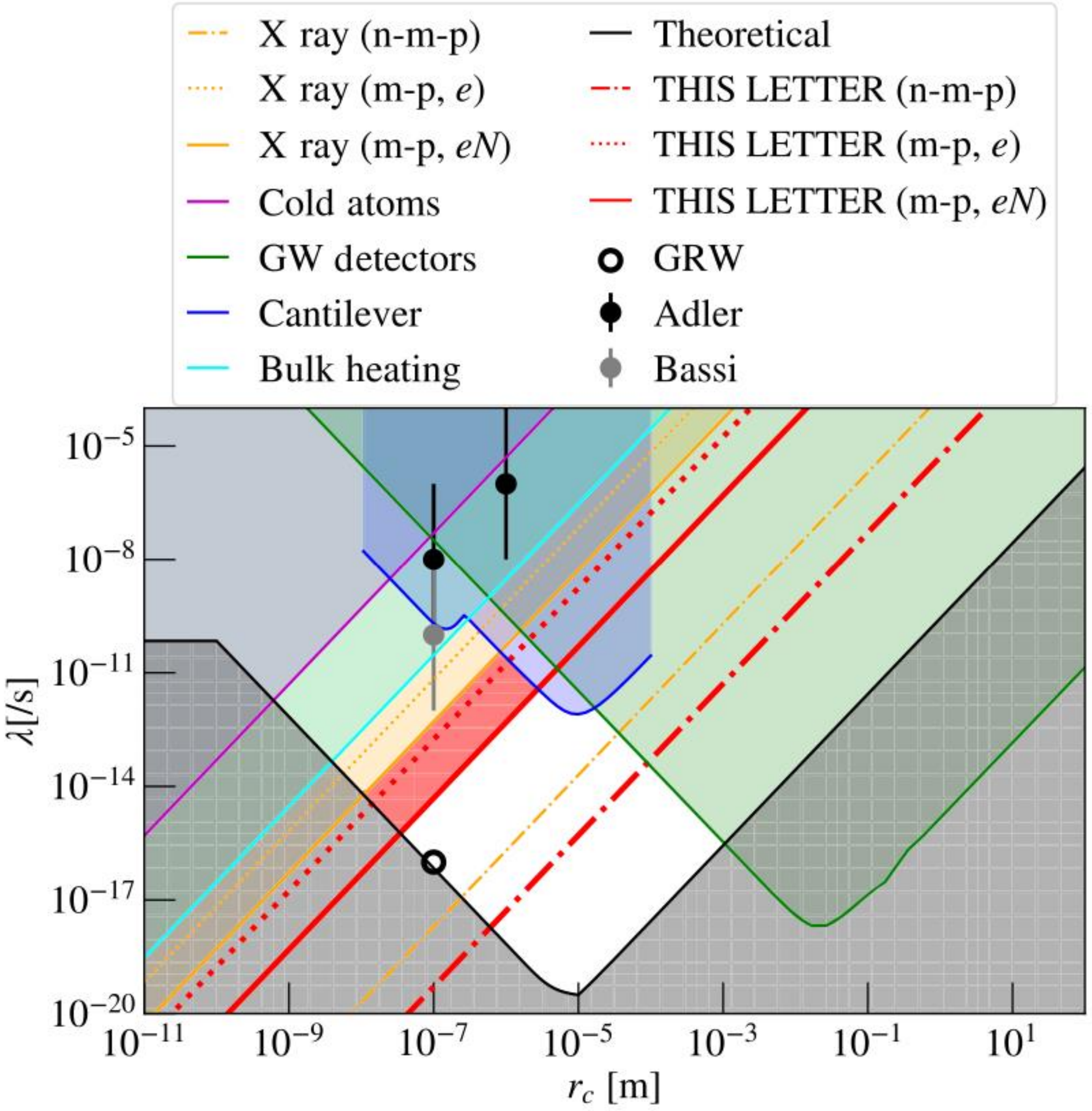
Search for wave function collapse PRL 129 080401 (2022)



Rate of the 1/E signature: 0.0368±0.0011/(kg-d) (95% CL)

Systematics	Value
Energy determination	0.3%
Efficiency	3.1%

Search for wave function collapse PRL 129 080401 (2022)



Model	Parameter	95%CL limit
CSL (n-m-p)	λ/r_C^2	$< (5.15 \pm 0.16) \times 10^{-6}\ s^{-1}\ m^{-2}$
CSL (m-p, e)	λ/r_C^2	$< (17.4 \pm 0.5)\ s^{-1}\ m^{-2}$
CSL (m-p, eN)	λ/r_C^2	$< (4.94 \pm 0.15) \times 10^{-1}\ s^{-1}\ m^{-2}$
DP	R_{DP}	$> (4.5 \pm 0.1) \times 10^{-10}$ m

The Majorana Collaboration

Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain:
Clara Cuesta

Duke University, Durham, NC, and TUNL:
Matthew Busch

Indiana University, Bloomington, IN:
Walter Pettus

Joint Institute for Nuclear Research, Dubna, Russia:
Sergey Vasilyev

Lawrence Berkeley National Laboratory, Berkeley, CA:
Yuen-Dat Chan, Alan Poon

Los Alamos National Laboratory, Los Alamos, NM:
Pinghan Chu, Steven Elliott, In Wook Kim, Ralph Massarczyk, Samuel J. Meijer, Keith Rielage, Danielle Schaper, Brian Zhu

National Research Center '*Kurchatov Institute' Institute of Theoretical and Experimental Physics, Moscow, Russia:*
Alexander Barabash

North Carolina State University, Raleigh, NC and TUNL:
Matthew P. Green, Ethan Blalock, Rushabh Gala

Oak Ridge National Laboratory, Oak Ridge, TN:
Vincente Guiseppe, José Mariano Lopez-Castaño, David Radford, Robert Varner, Chang-Hong Yu

Osaka University, Osaka, Japan:
Hiroyasu Ejiri

Pacific Northwest National Laboratory, Richland, WA:
Isaac Arnquist, Maria-Laura di Vacri, Eric Hoppe, Richard T. Kouzes

Queen's University, Kingston, Canada:
Ryan Martin

South Dakota Mines, Rapid City, SD:
Cabot-Ann Christofferson, Sam Schleich, Ana Carolina Sousa Ribeiro, Jared Thompson

Technische Universität München, and Max Planck Institute, Munich, Germany:
Susanne Mertens

Tennessee Tech University, Cookeville, TN:
Mary Kidd

University of North Carolina, Chapel Hill, NC, and TUNL:
Kevin Bhimani, Brady Bos, Thomas Caldwell, Morgan Clark, Julieta Gruszko, Ian Guinn, Chris Haufe, Reyco Henning, David Hervas, Aobo Li, Eric Martin, Gulden Othman, Anna Reine, Jackson Waters, John F. Wilkerson

University of South Carolina, Columbia, SC:
Franklin Adams, Frank Avignone, Thomas Lannen, David Tedeschi

University of South Dakota, Vermillion, SD:
C.J. Barton, Laxman Paudel, Tupendra Oli, Wenqin Xu

University of Tennessee, Knoxville, TN:
Yuri Efremenko

University of Washington, Seattle, WA:
Micah Buuck, Jason Detwiler, Alexandru Hostiuc, Nick Ruof, Clint Wiseman

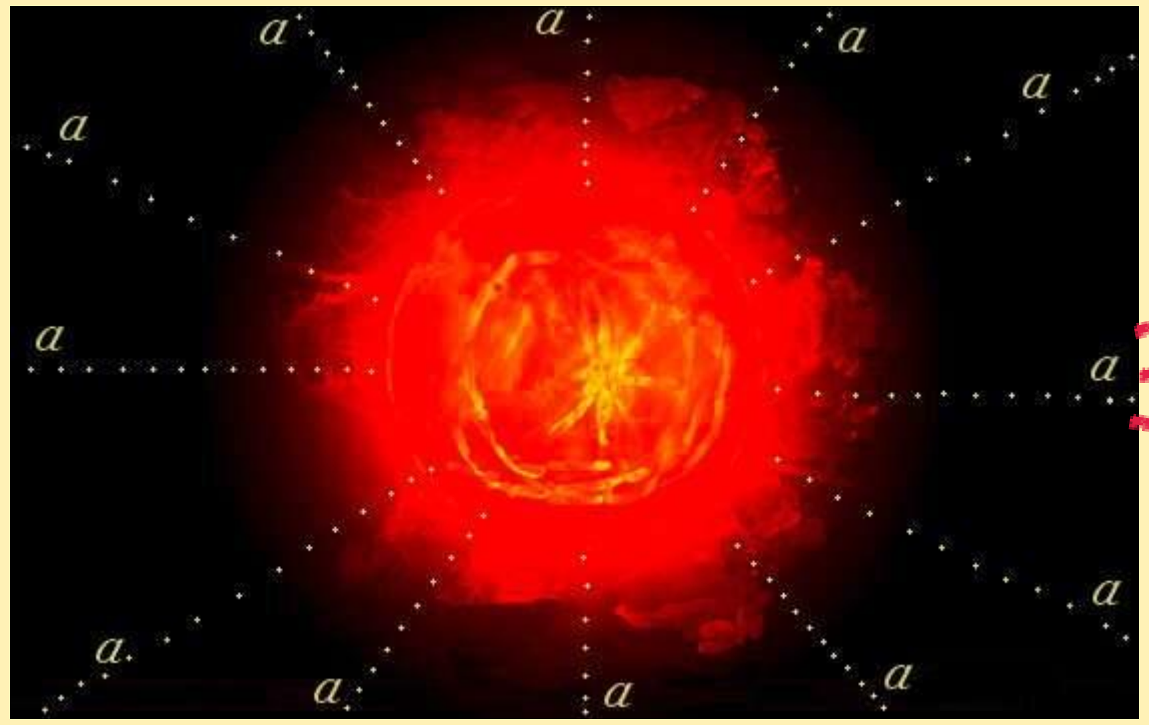
Williams College, Williamstown, MA:
Graham K. Giovanetti

*students

Backup

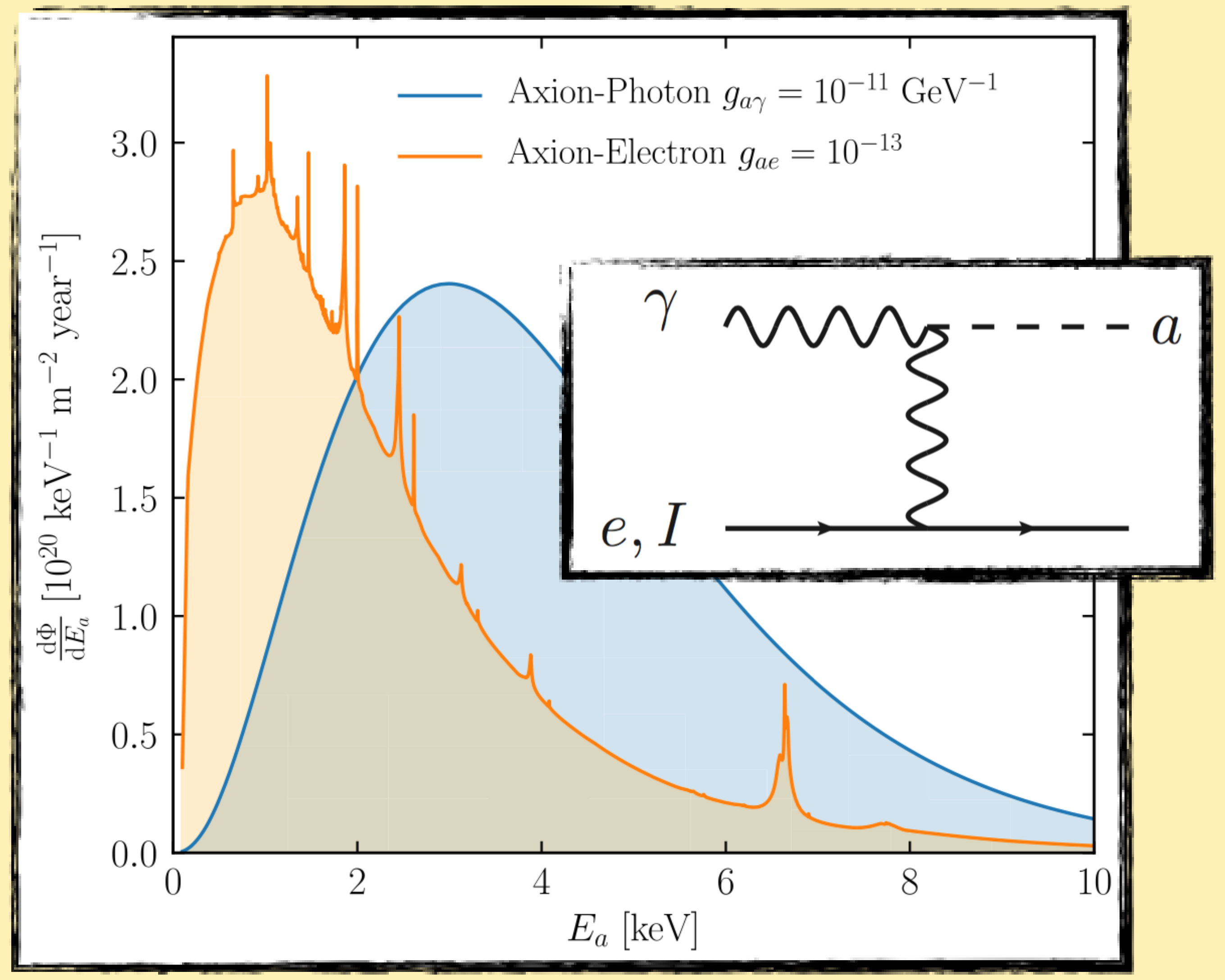
Search for solar axions (a-γ coupling)

Solar Axion Production



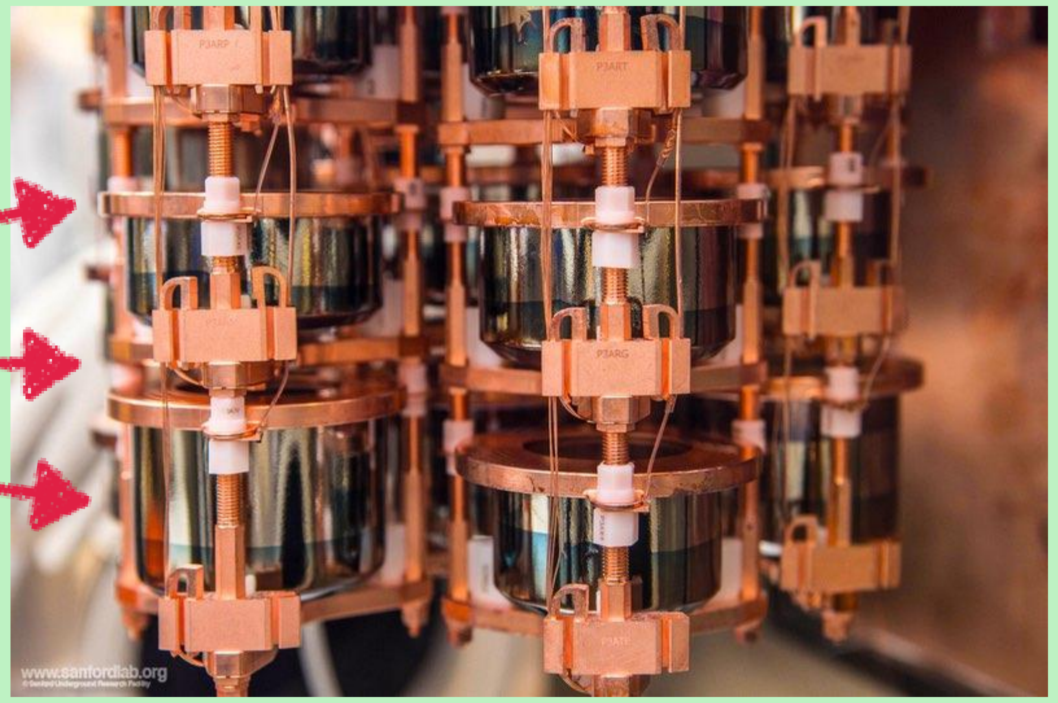
$$\gamma + \gamma_{\text{virtual}} \rightarrow a$$

Primakoff effect: production of axions



PhysRevD.99.035037 (2019)

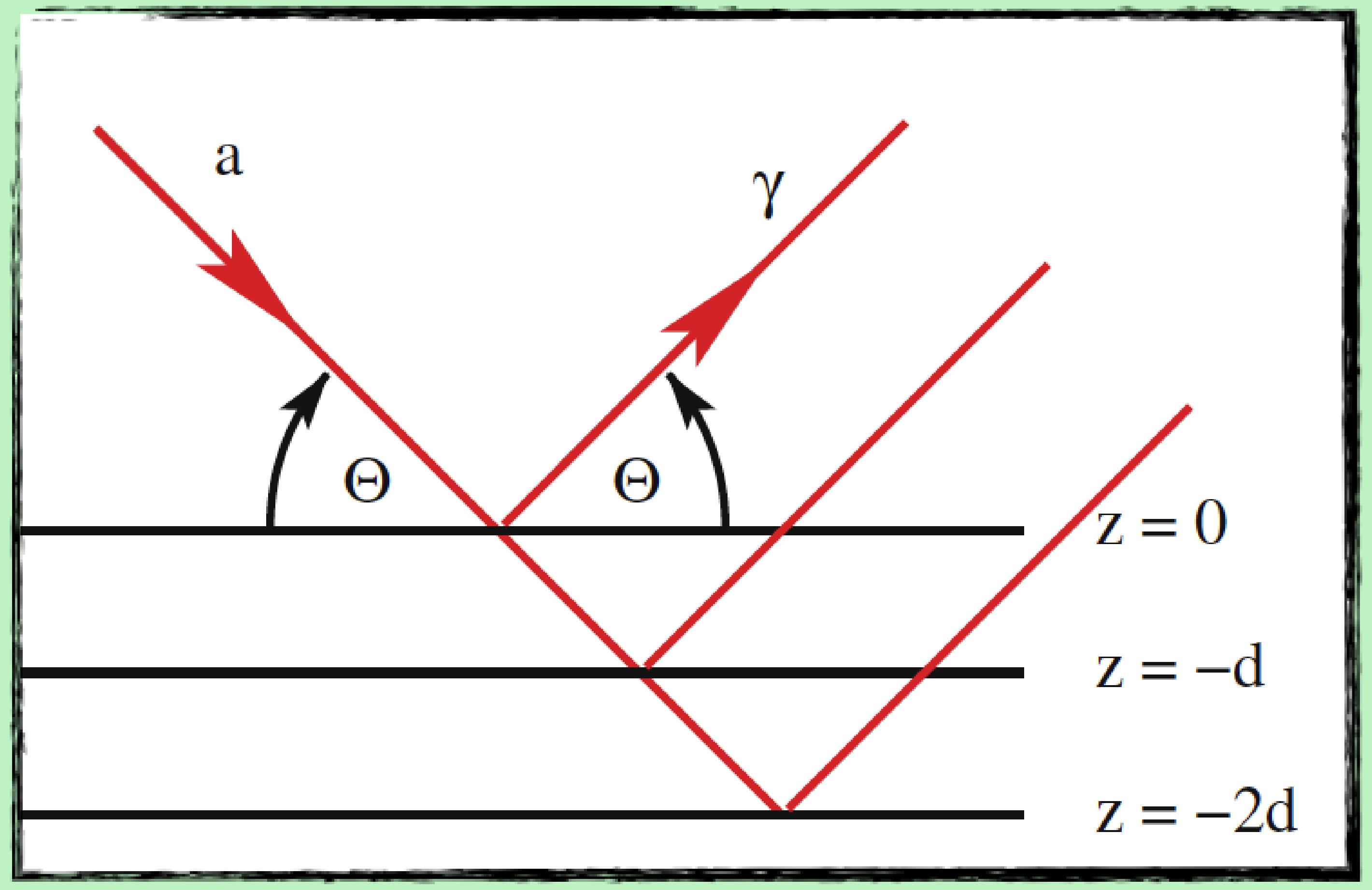
Detection Mechanism



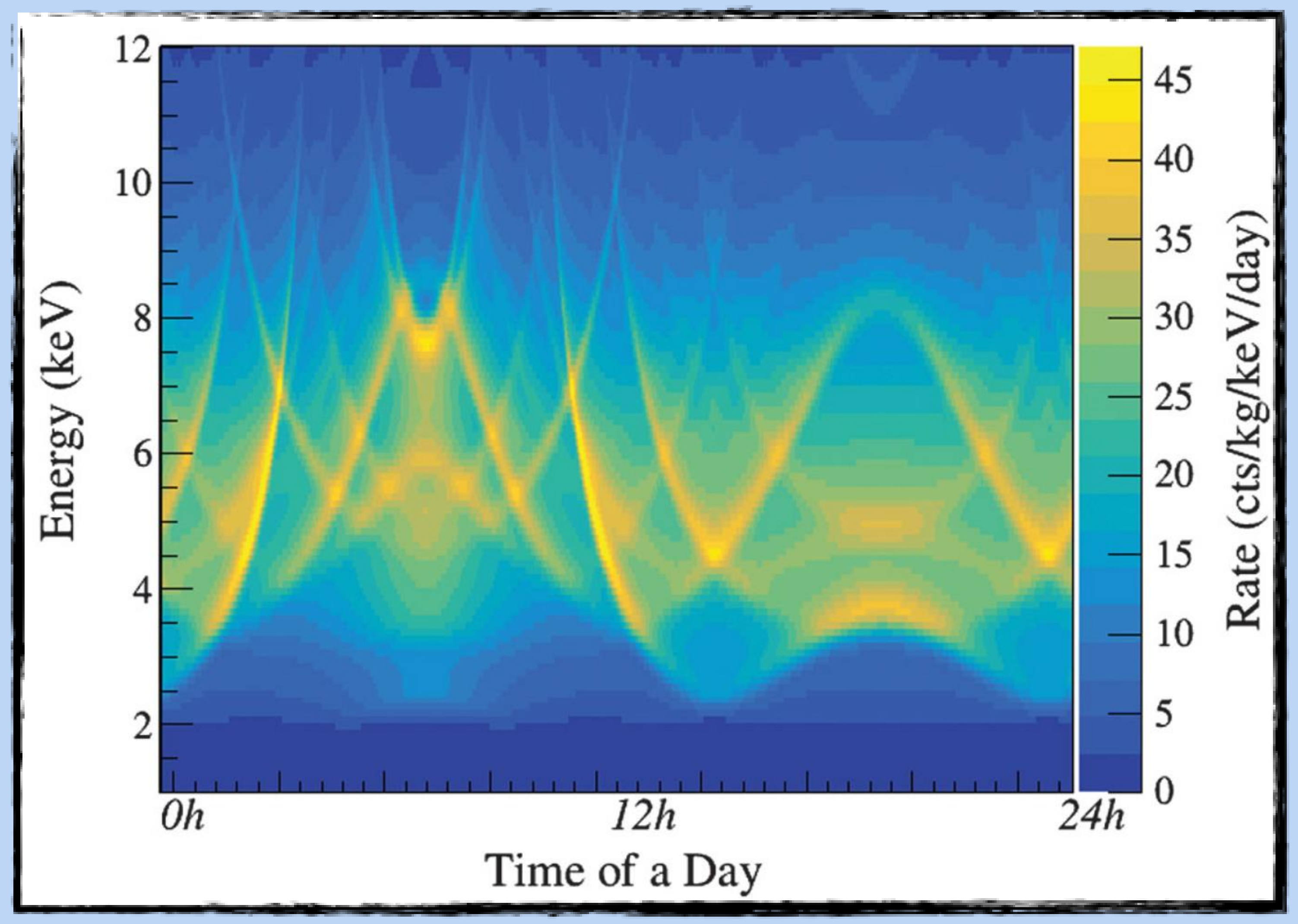
$$a + \gamma_{\text{virtual}} \rightarrow \gamma$$

Inverse Primakoff effect: detection of axions

Enhanced by coherent Bragg diffraction



Time-dependent Signature



The axion signal is enhanced when it aligns with the Ge crystal axes (Bragg)

Reduced sharpness if some crystal axes are unknown, but with enough detectors, still able to see time-dependence

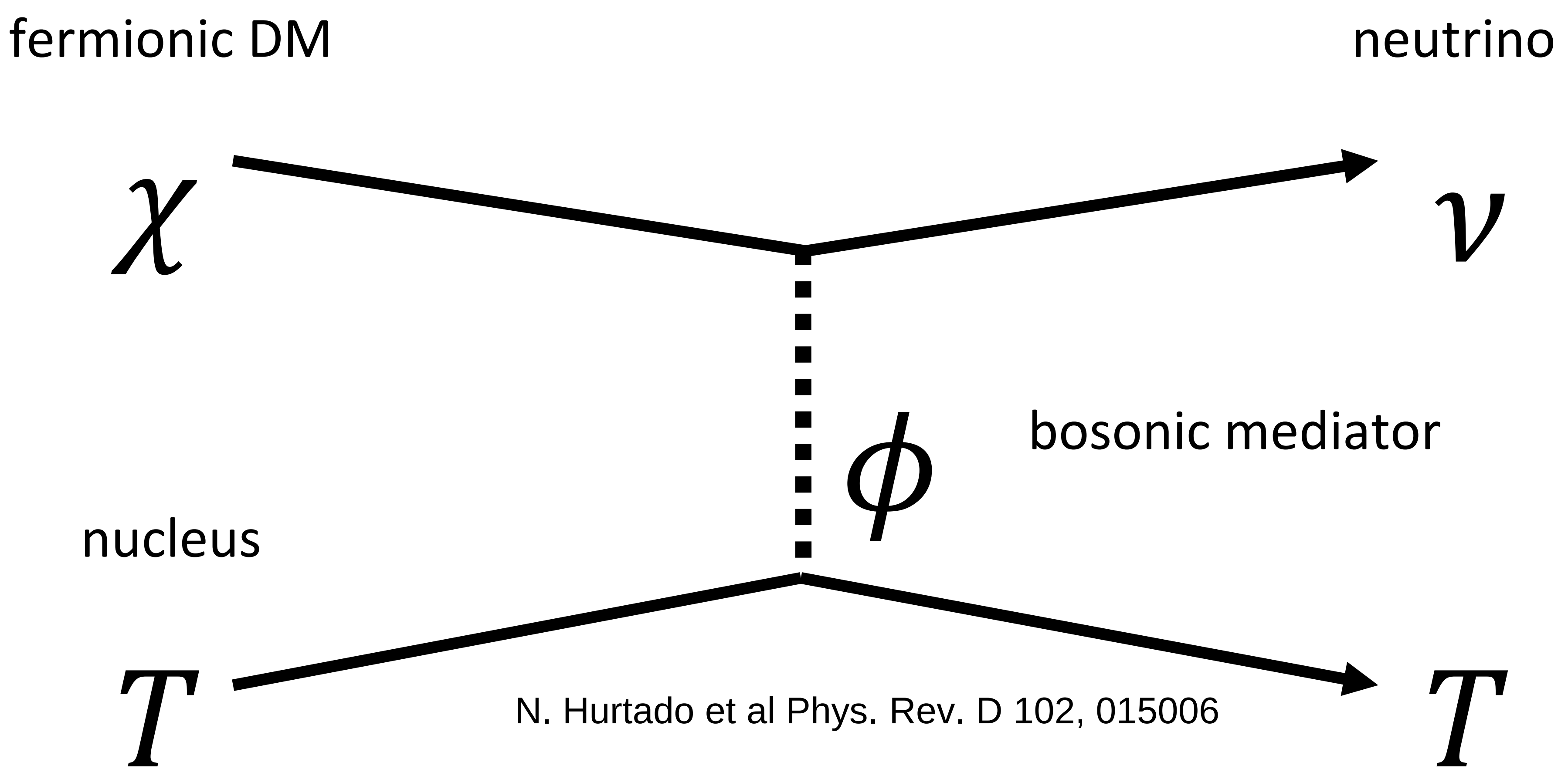
Distinct time dependence is a key strength for discovery!

Search for fermionic dark matter

Dror, arXiv:1905.12635

Fermionic dark matter interacts with a nucleus through a bosonic mediator, converting into standard neutrinos through a **2-2 neutral current (NC, Yukawa-like) interaction**

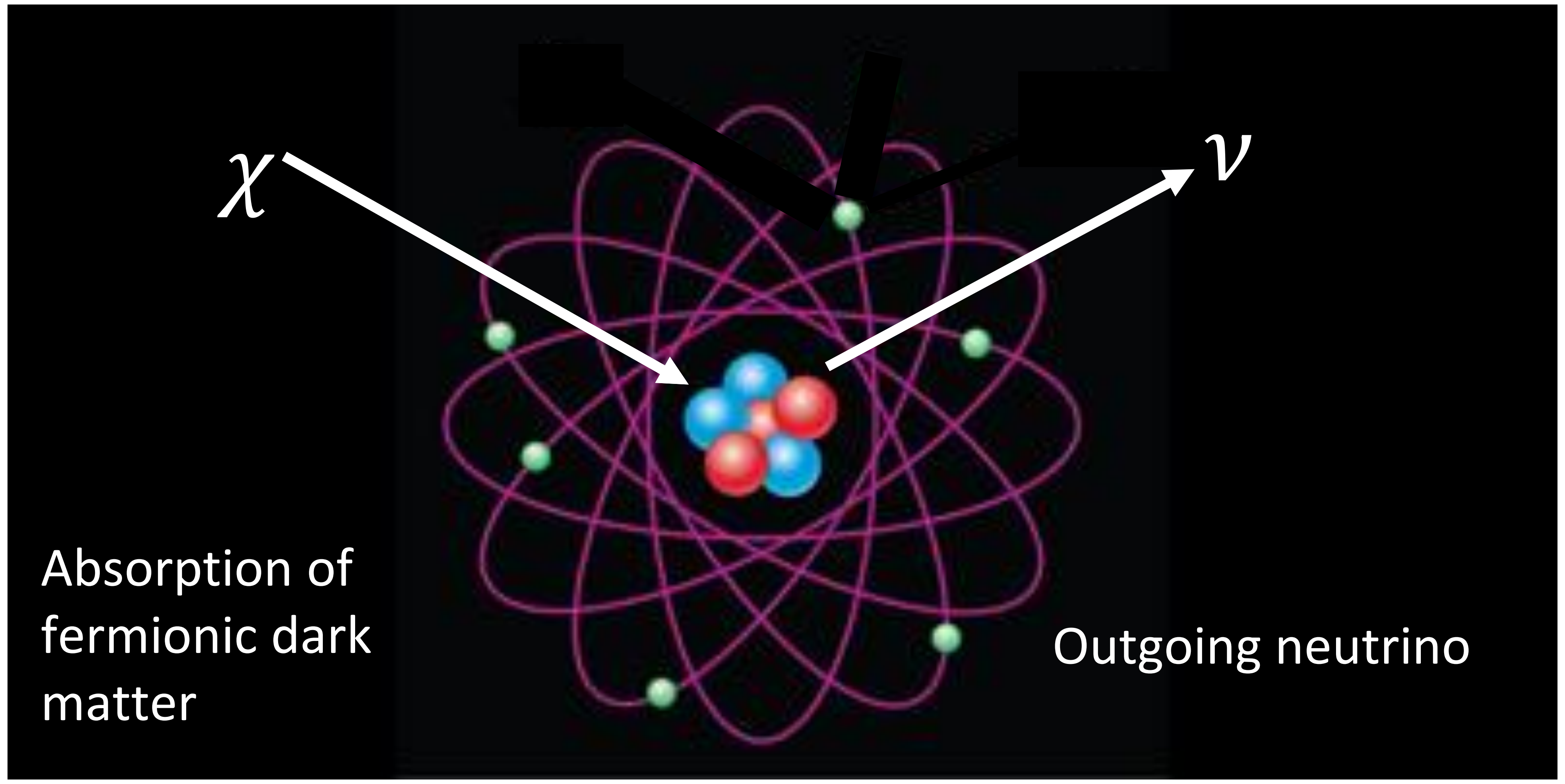
If incoming DM is nonrelativistic, the **conversion gives a peak** at $E_R \simeq m_\chi^2/2M$, where M is the target atom mass



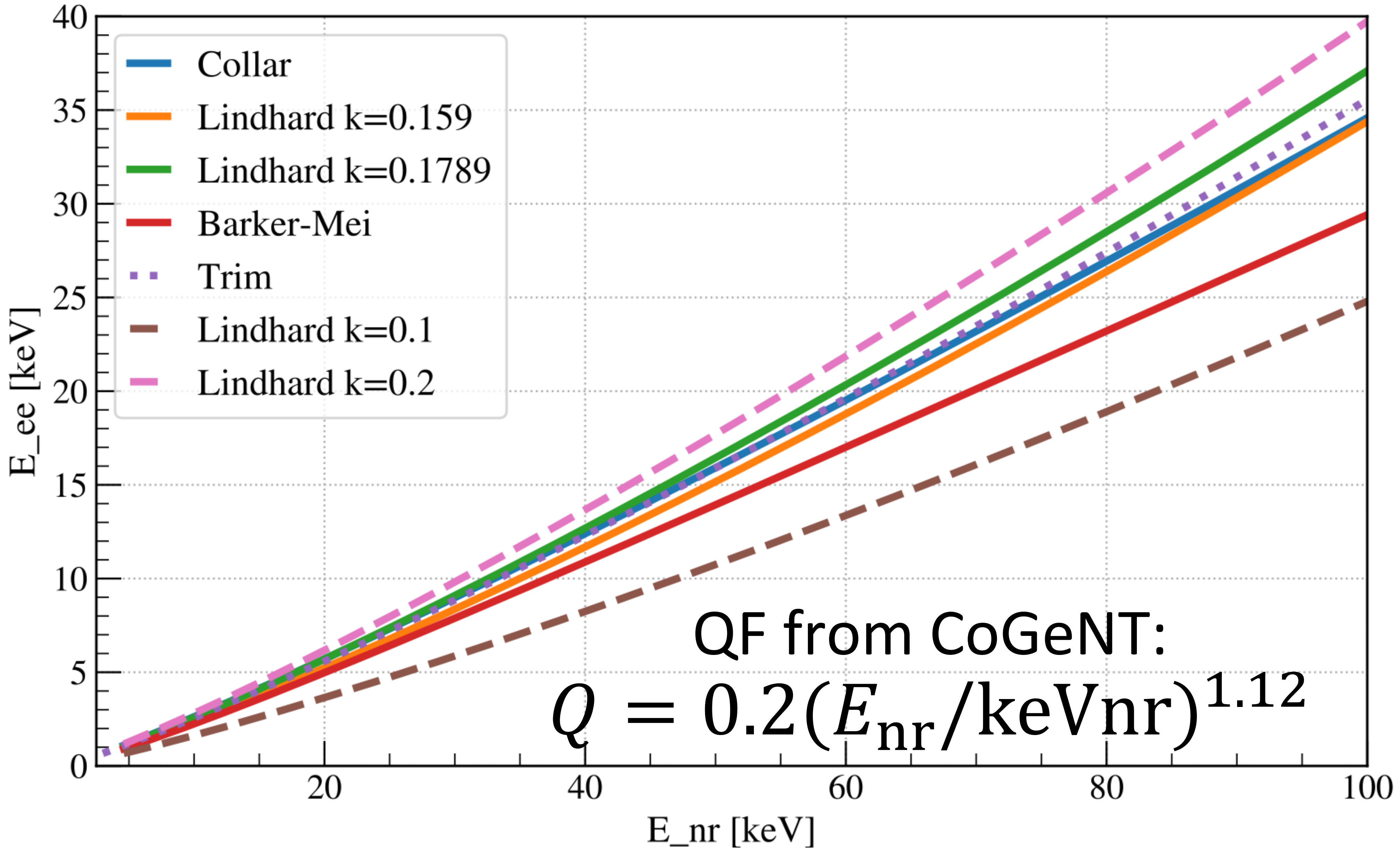
N. Hurtado et al Phys. Rev. D 102, 015006

Interaction is with the nucleus! We choose a **Ge ionization quenching factor suitable for 1—100 keV,** rather than newer results optimized for < 1 keV

$$\boxed{\chi + T \rightarrow \nu + T}$$



Adapted from APS / Carin Cain



Search for fermionic dark matter, II

We set new limits on the DM-nucleon scattering cross section σ_{NC} using our rare event search method:

1 keVee energy threshold

4.5 keVnr nuclear recoil threshold

25.5 MeV minimum dark matter mass

$$\frac{N_U}{MT} = \frac{\rho_\chi}{m_\chi}\sigma_{\mathrm{NC}}\sum_j N_{Tj}A_j^2 F_j(m_\chi)^2\Theta(E_{R,j} - E_{\mathrm{th}})$$

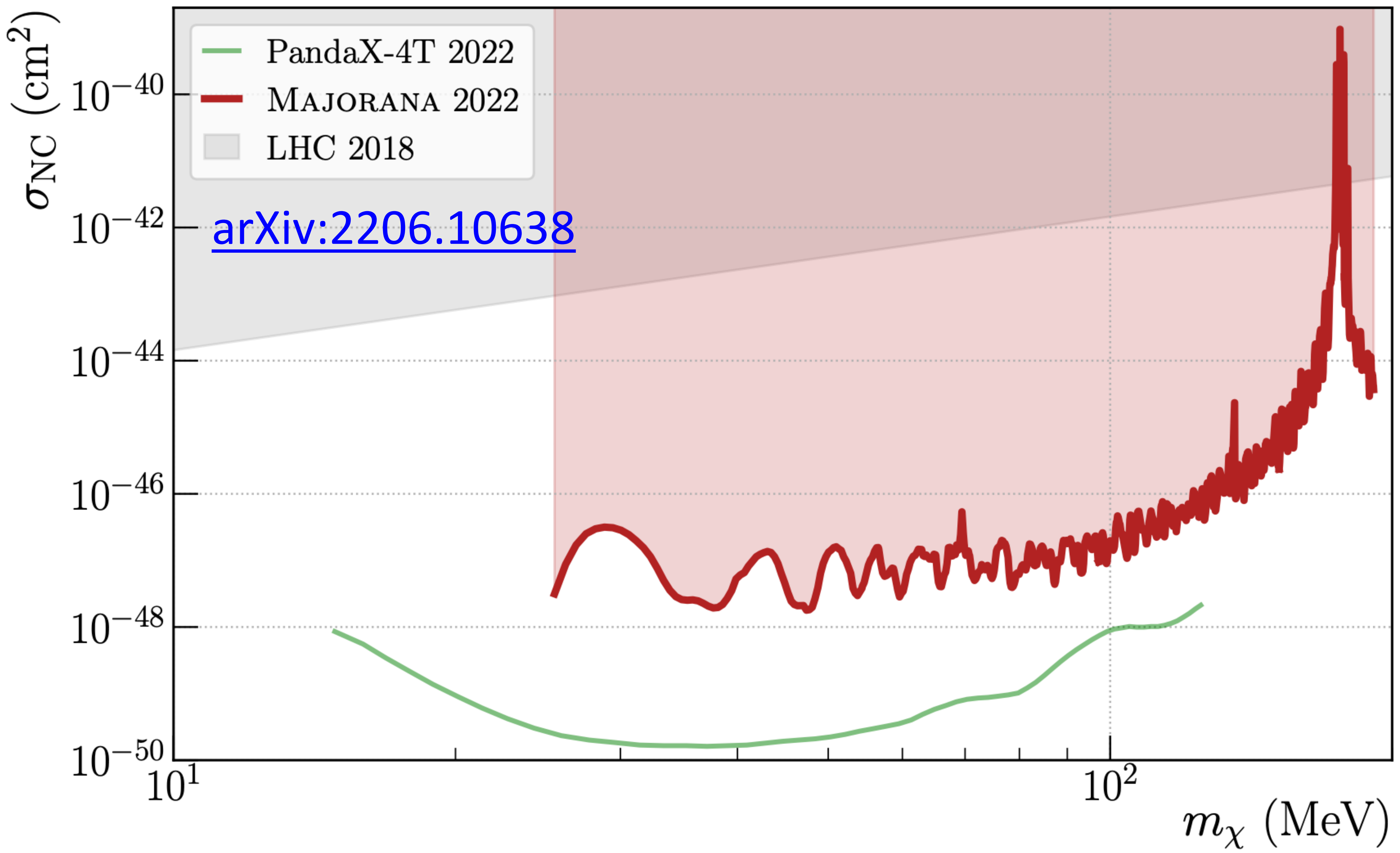
absorption rate

neutral-current cross-section

different Ge isotopes

interaction with nucleus, involving Helm form factor F and mass number A

recoil energy threshold



arXiv:2206.10638

Peaks due to cosmogenic lines and Helm form factor

Our result improves on Z₀ monojet results from the LHC by ~4 orders of magnitude!

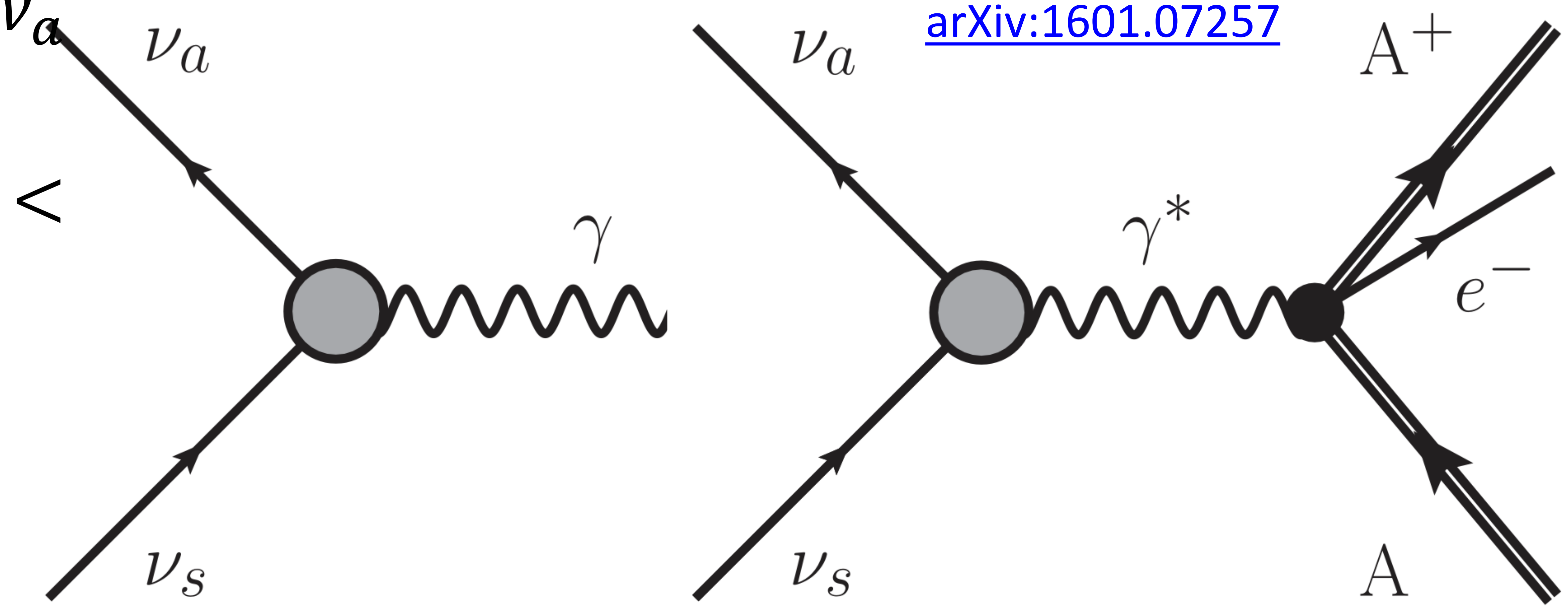
Other recent results: PandaX-4T, EXO-200 … much interest!

Belyaev 2018, arXiv:1807.03817

Sterile neutrino transition magnetic moment

Radiative decay of sterile neutrinos into active neutrinos $\nu_s \rightarrow \nu_a$ (or inverse) can have a **nonzero magnetic moment** μ_{sa} Current best limits are obtained from Borexino's data on $\nu_\mu \rightarrow \nu_s$, $\mu_{\mu s} < 7 \times 10^{-11} \mu_B$

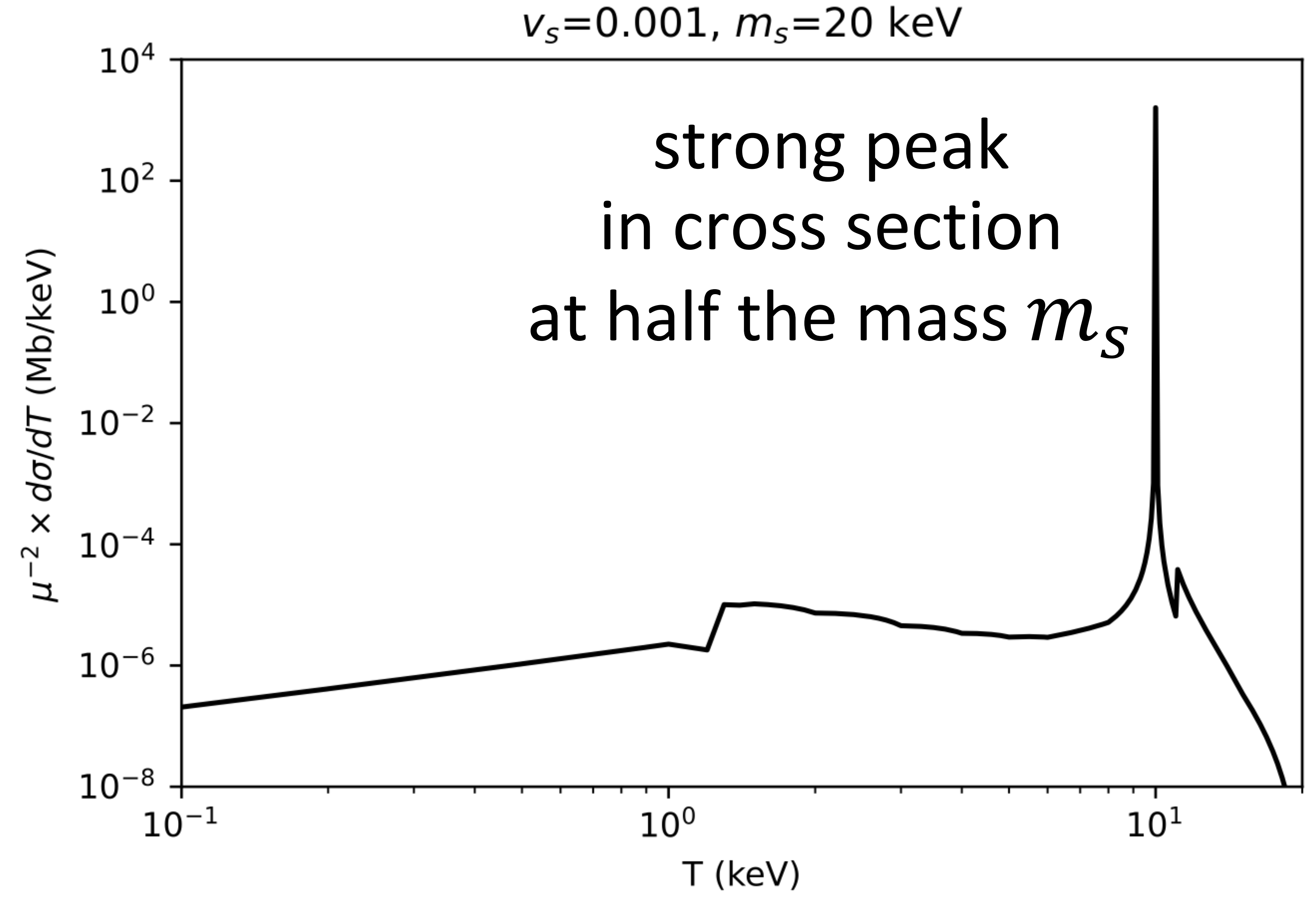
$$\boxed{\nu_s + A \rightarrow \nu_a + A^+ + e^-}$$



Chen 2016, arXiv:1601.07257

We consider an enhancement from atomic ionization, when the virtual photon interacts coherently with a target atom A, approaching $q^2 \rightarrow 0$ in the equivalent photon approximation (EPA).

- The interaction cross section is enhanced by orders of magnitude at half the sterile neutrino mass, $m_s/2$, plateauing in the region $E = (m_s \pm |\vec{k}_s|)/2$, producing a peak-like signature in HPGe detectors.
- Amplified differential cross section: $\dfrac{d\sigma(m_s, v)}{dT} \approx \left(\dfrac{\mu_{sa}}{2m_e}\right)^2 \dfrac{\alpha}{2n_A} \dfrac{m_s^2}{|v|^2}$



strong peak in cross section at half the mass m_s

Sterile neutrino transition magnetic moment

Sterile neutrinos with keV-scale masses have been proposed as a dark matter candidate.

Initially, many thought they could explain the XENON1T excess.

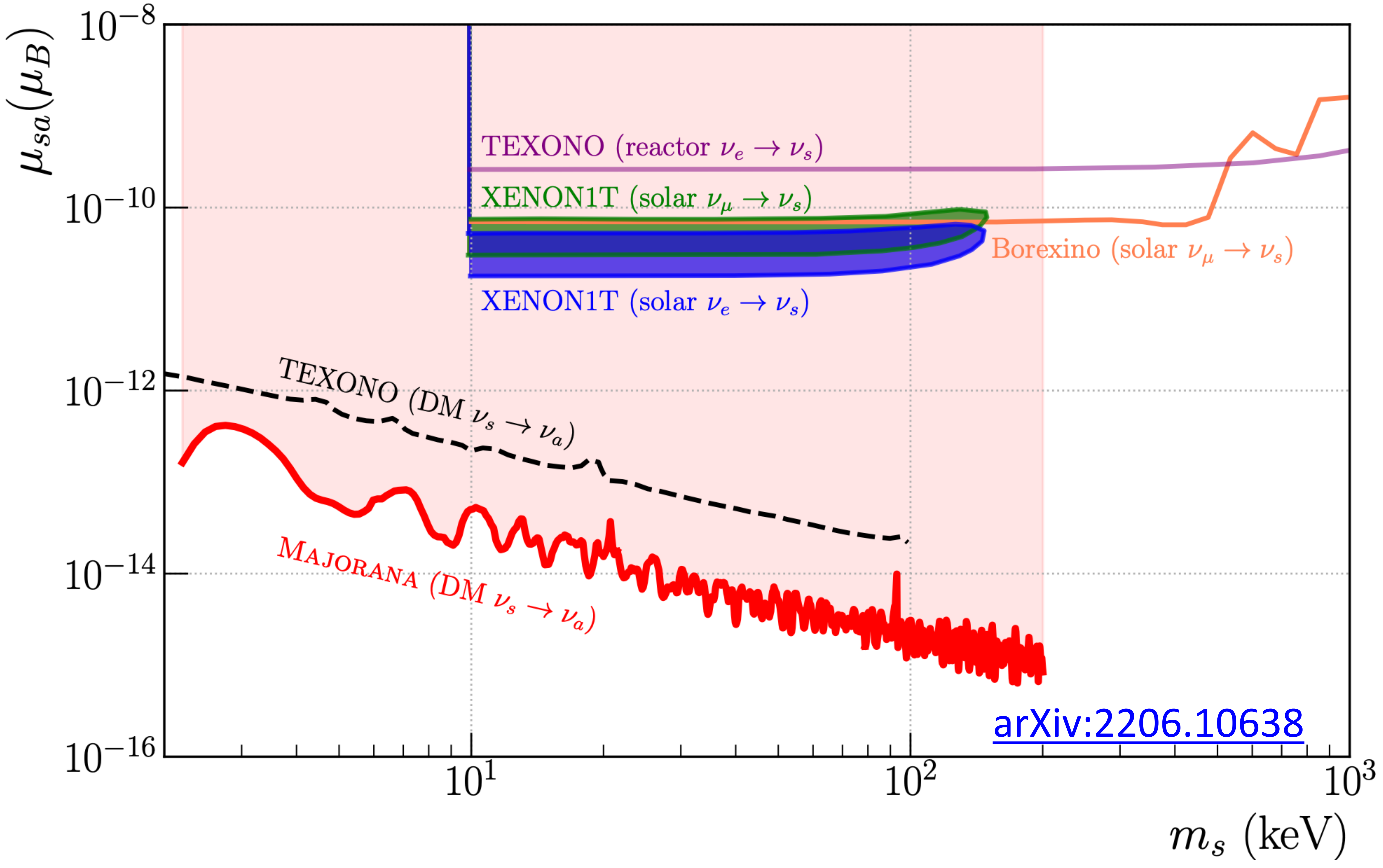
XENON1T excess has been ruled out by XENONnT, but the Majorana result is still world-leading …

arXiv:2207.11330

- Assuming local DM halo density $\rho_\chi = 0.4$ GeV/cm^3, we compute the expected rate of sterile-to-active transitions:

$$R = \frac{N_U}{MT} = \frac{\rho_\chi}{m_A}\left(\frac{\mu_{sa}}{2m_e}\right)^2 \frac{\alpha}{2n_A} m_s^2$$

- This assumes the cross section is flat in the peak region, $E = m_s/2$ (taking the equivalent photon approximation, EPA)



arXiv:2206.10638

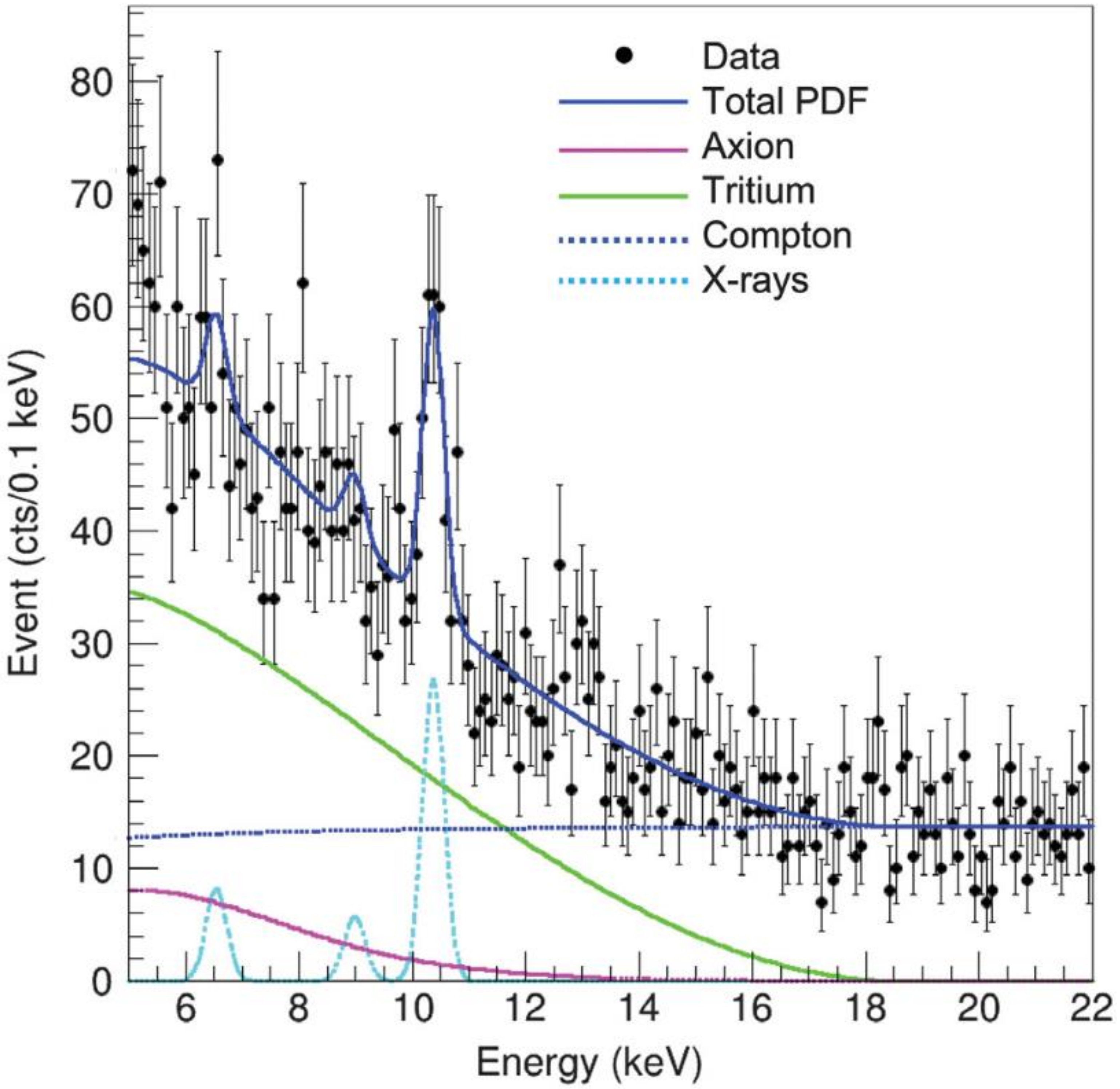
(alternate models are still possible, for example Shoemaker 2020, arXiv:2007.05513)

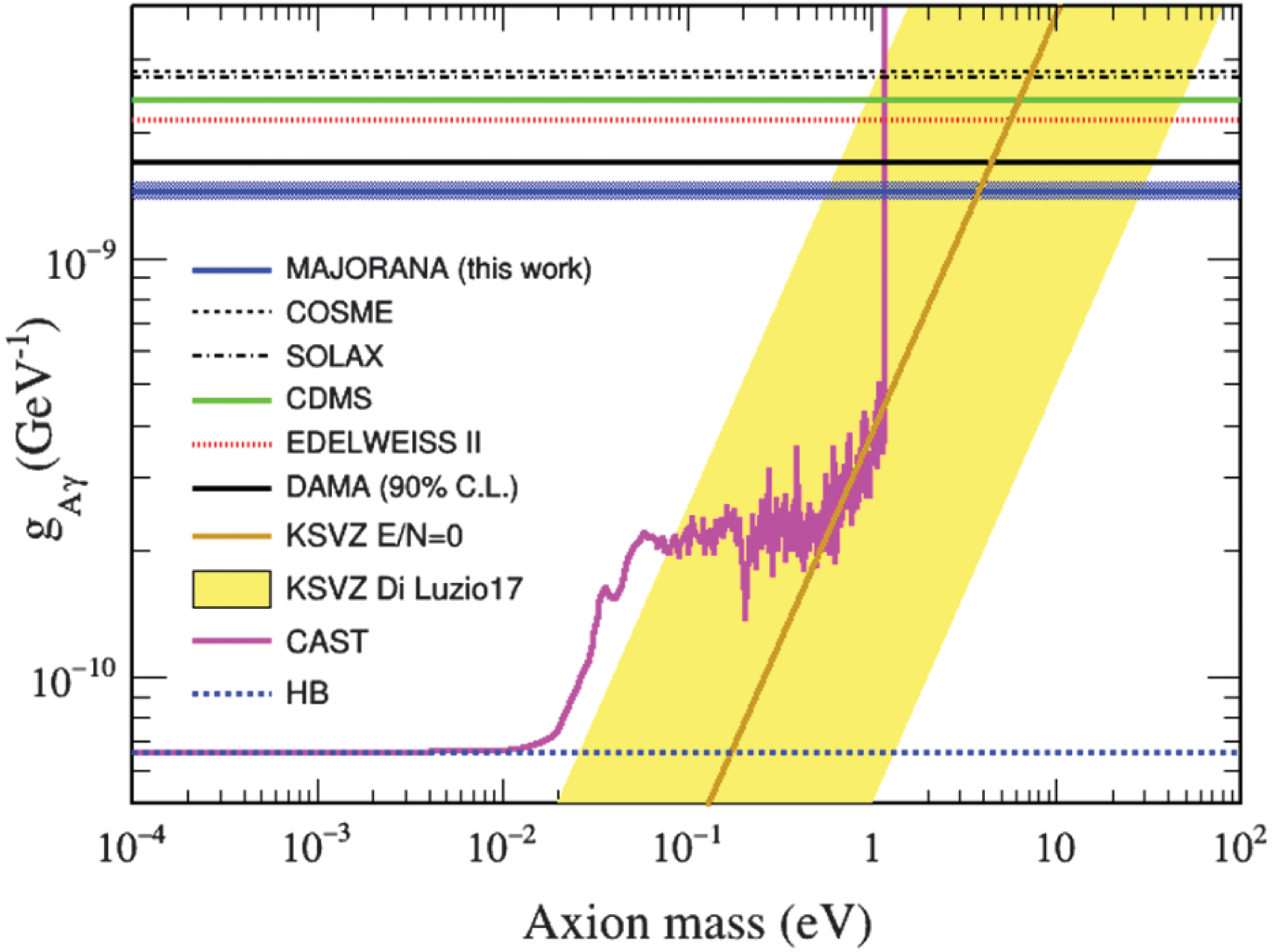
New limits on axion-γ coupling PRL 129 081803 (2022)

We perform an energy- and time-dependent analysis, 5 minute precision over a 3 year data set.

The solar axion flux is consistent with zero within 2.2σ.

Our limit on the axion-photon coupling: $g_{a\gamma} < 1.45 \times 10^{-9}\mathrm{GeV}^{-1}(95\%\mathrm{CL})$ Surpasses previous best lab-based limit for 21 years (DAMA, 90% CL) with a 95% CL limit, in the 1-100 eV mass range





Search for rare peaks from “exotic” dark matter

There are **many DM models** (alternative to WIMPs) that would create a **sharp peak in Ge detectors.**
Some examples: **Axionlike particles, dark photons, fermionic DM, sterile neutrino conversion**, etc.

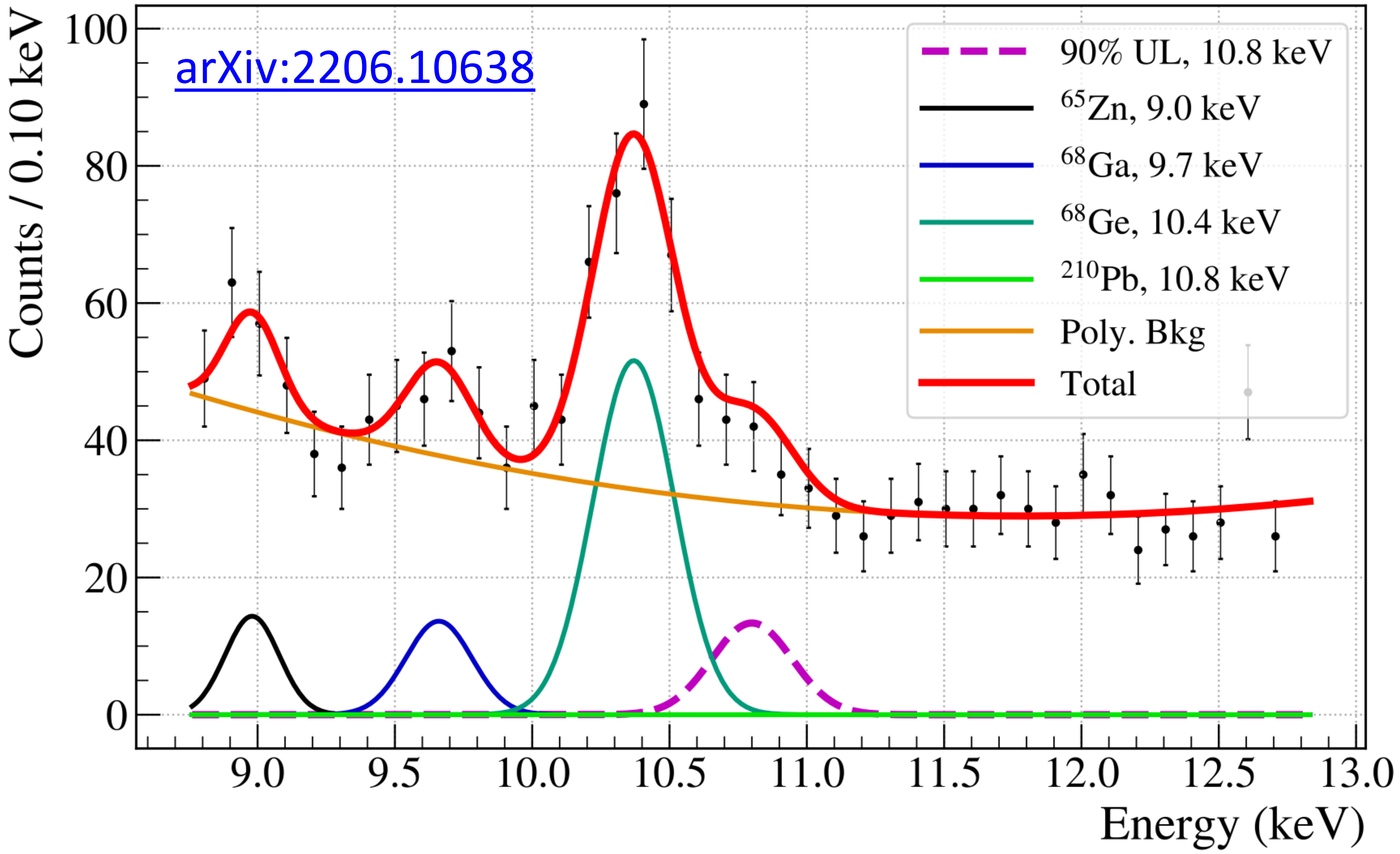
A common “bump hunt” strategy: set a 90% upper limit on counts attributable to the DM peak (N_U),
by scanning a small moving window 1-100 keV. If signal peak overlaps w/ bkg, all strength goes to signal.

Adapted from ESA/Hubble & NASA

arth travels through the dark matter halo of the Milky Way, seeing a flux:

$$\Phi_{DM} = \frac{\rho_{DM} v_\chi}{m_\chi}$$

$$\frac{dN}{dE} = \underset{\substack{\uparrow \\ \text{DM flux}}}{\Phi_{\mathrm{DM}}}(m_\chi)\underset{\substack{\uparrow \\ \text{cross section}}}{\sigma}(m_\chi)\underset{\substack{\uparrow \\ \text{efficiency}}}{\eta}(E)\underset{\substack{\uparrow \\ \text{rare peak}}}{P_{\mathrm{rare}}}(E)\underset{\substack{\uparrow \\ \text{exposure}}}{MT}$$



$$P(E_i) = n_0 P_{\mathrm{pol2}} + \sum^{n_{\mathrm{pks}}} n_i P_{G,i} + N_U P_{\mathrm{DM}}$$

(Fit peaks with Gaussians, fit continuum w/ pol2)