Exotic dark matter searches (and other BSM physics!) with the MAJORANA DEMONSTRATOR

CENPA
Center for Experimental Nuclear Physics and Astrophysics

Clint Wiseman, University of Washington
CIPANP 2022

NSF
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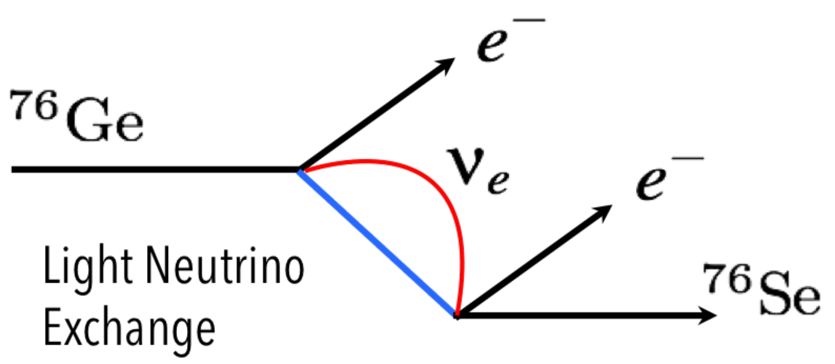
The Majorana Demonstrator

Searching for neutrinoless double-beta decay of ^{76}Ge, additional physics beyond the Standard Model, and informing the design of the next-generation LEGEND experiment



Source & Detector: Array of p-type, point contact Ge detectors.

30 kg of 88% enriched ^{76}Ge crystals, 14 kg of natural Ge crystals.

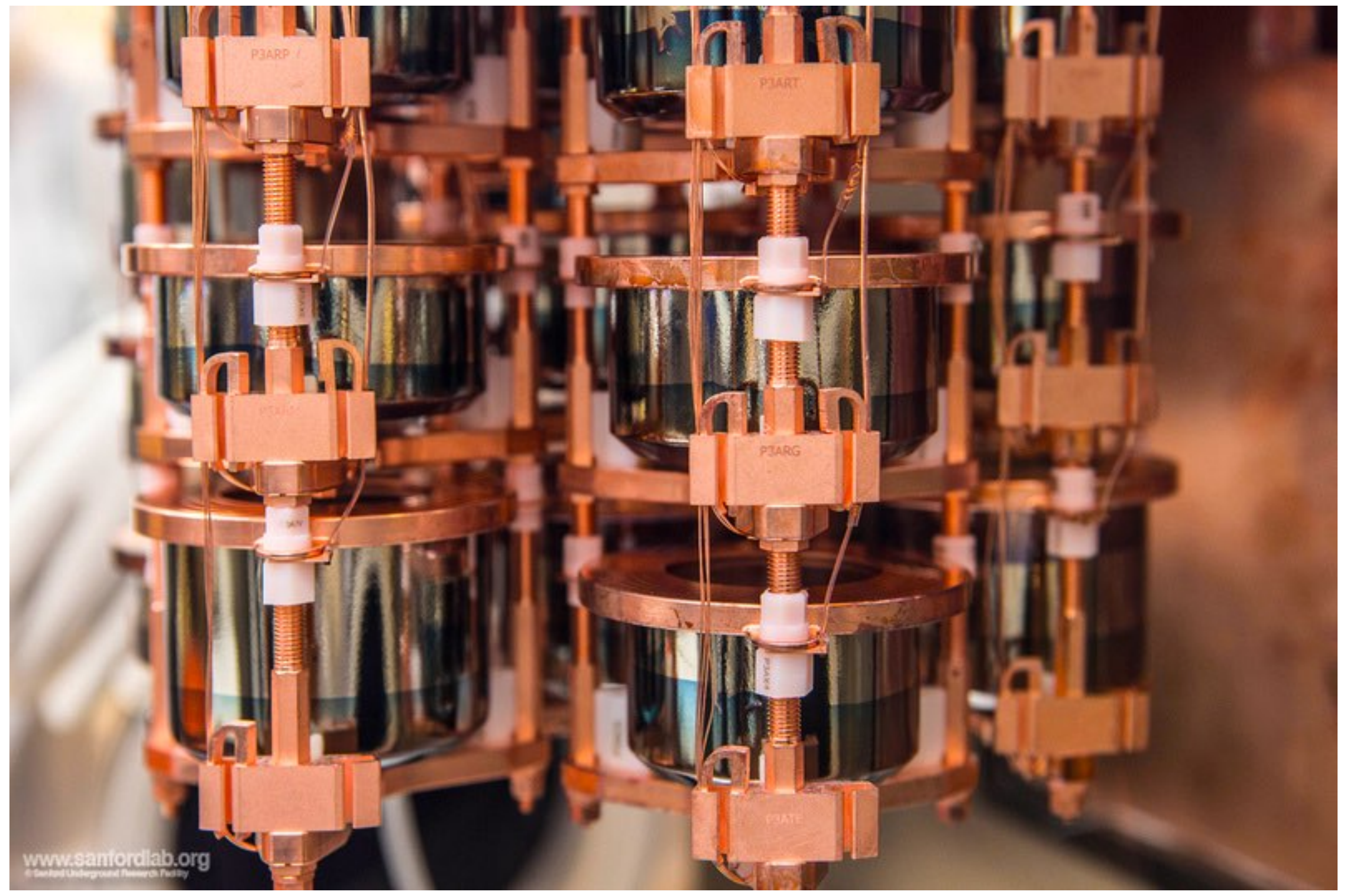
Included 6.7 kg of ^{76}Ge inverted-coax detectors in final run

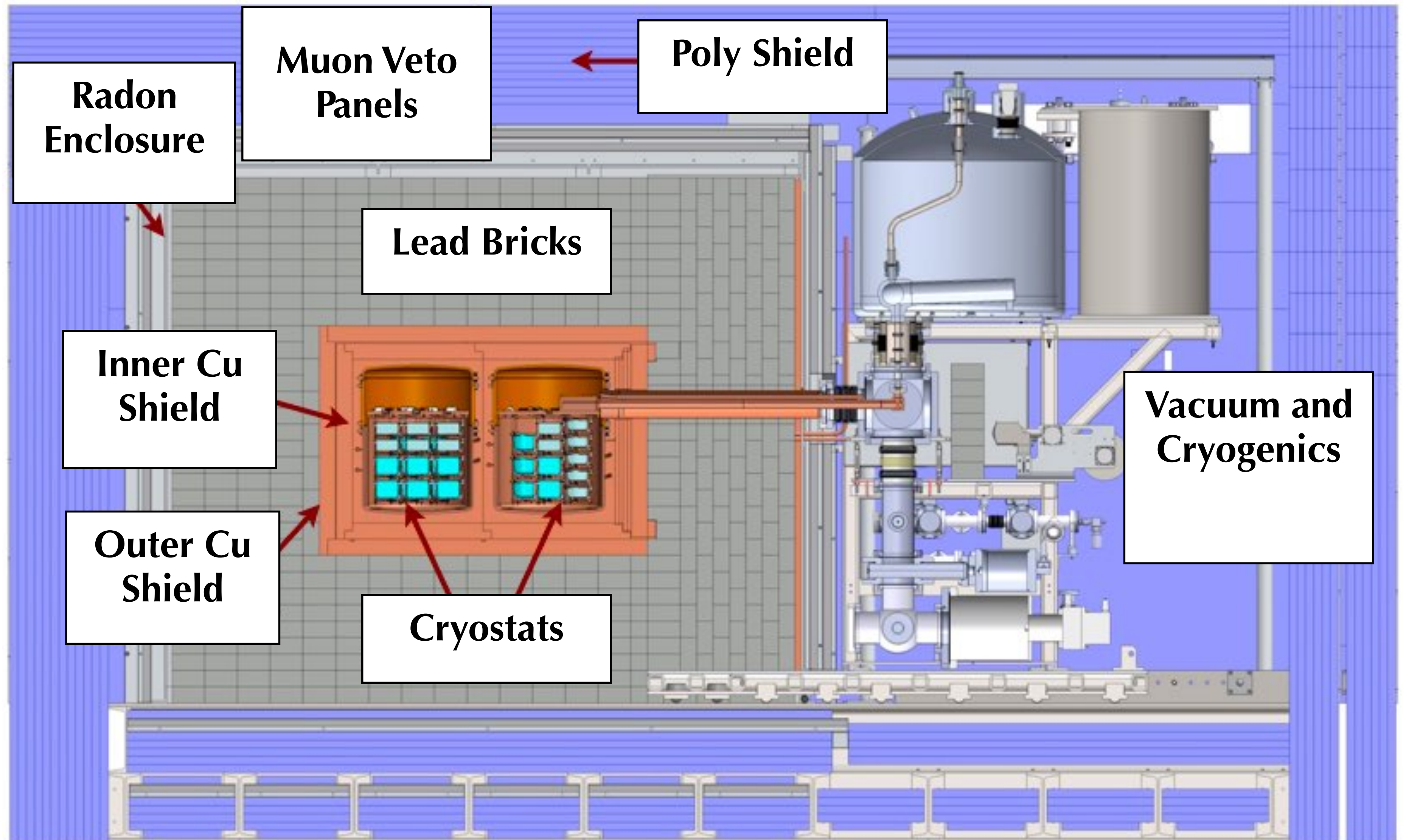
Excellent energy resolution: 2.5 keV FWHM @ 2039 keV (world-leading!)

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

Low Thresholds: As low as 1 keV for significant data taking periods

Total Exposure: Reached **~65 kg-yr** before removal of the ^{76}Ge detectors for the LEGEND-200 experiment at LNGS

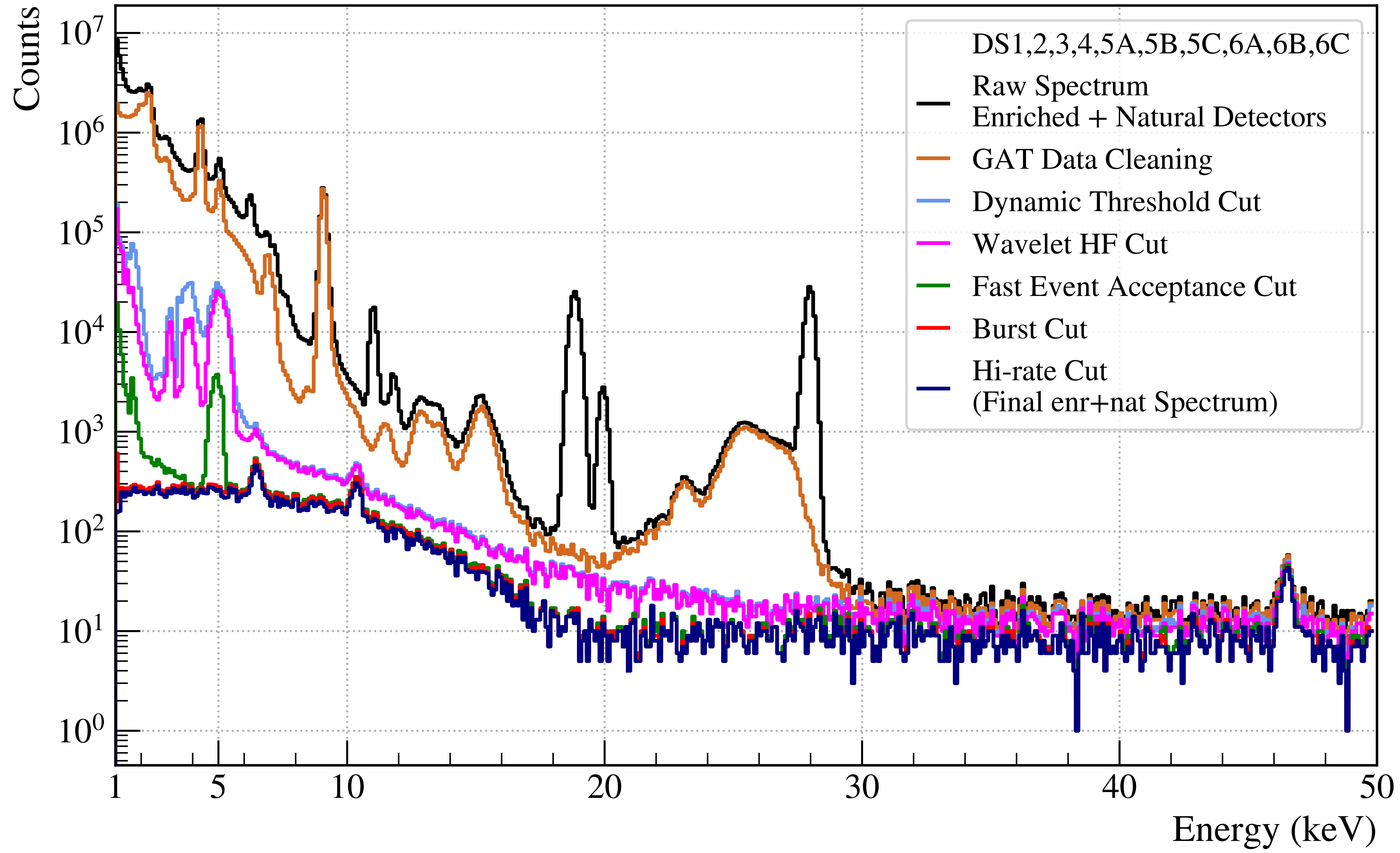




Cleaning up the Low Energy spectrum (1-100 keV)

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

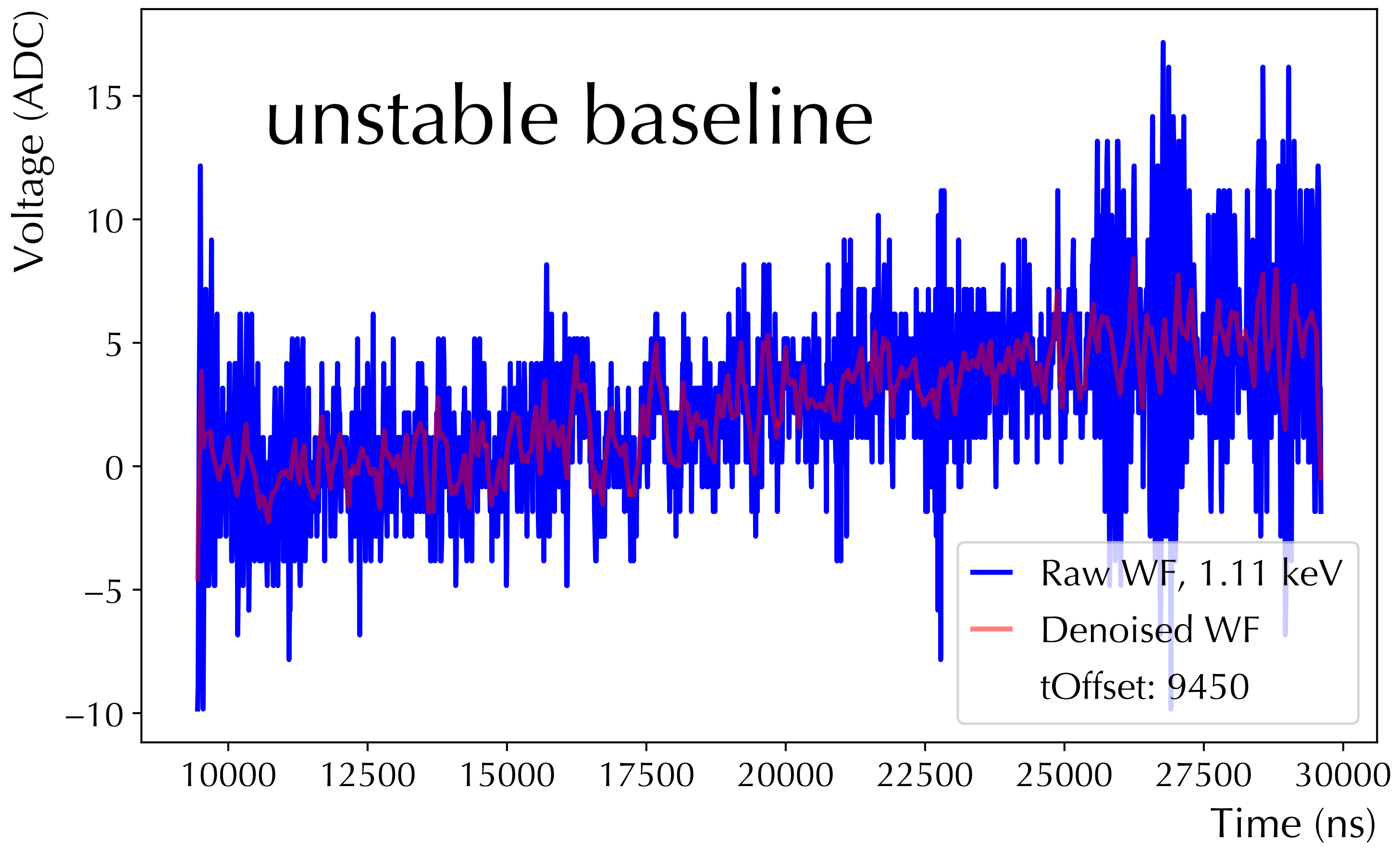
Careful cuts based on waveform fitting, wavelet denoising, and other parameters were trained on ^{228}Th calibration data.

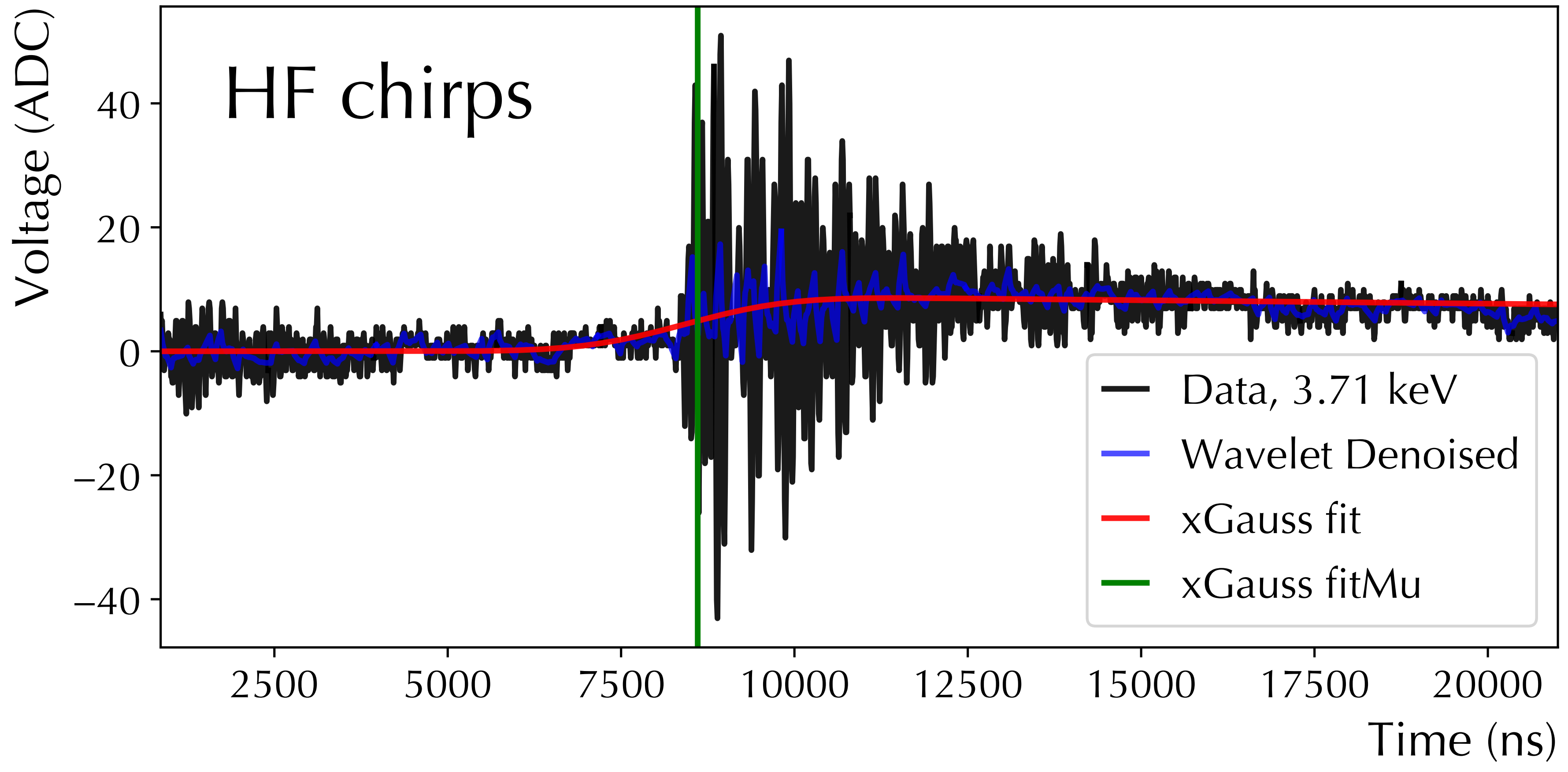


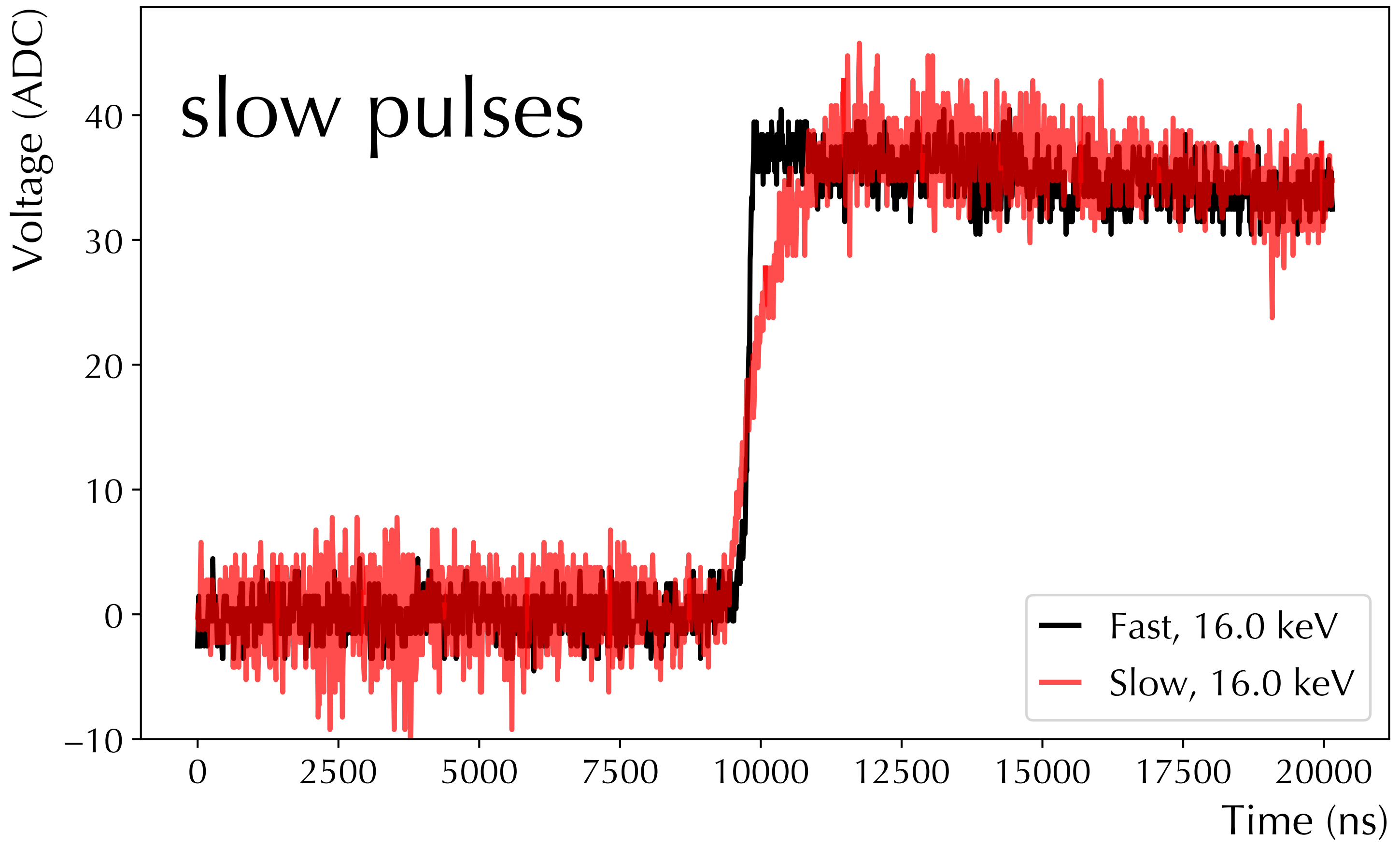
Data taking milestones:

- **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!



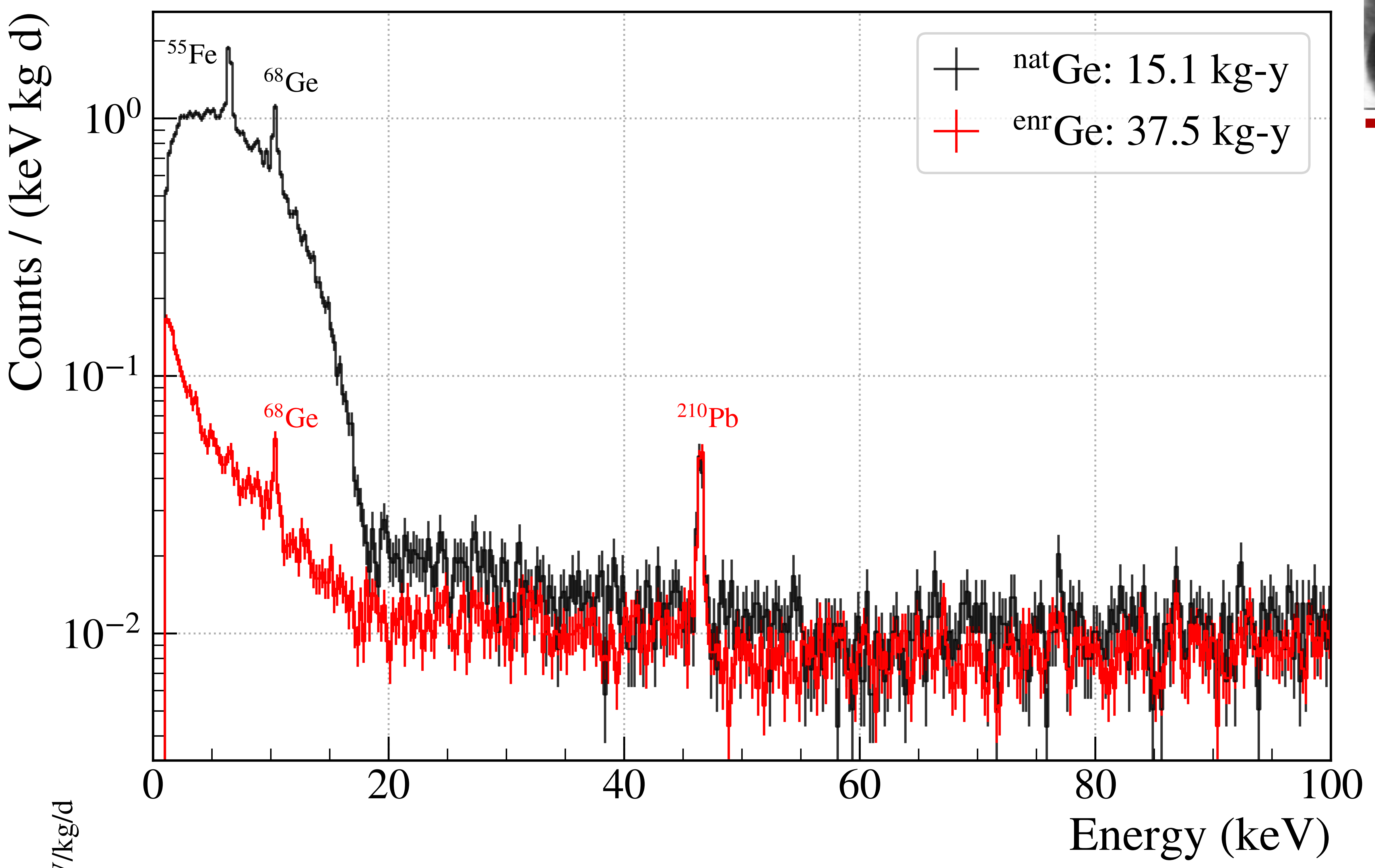


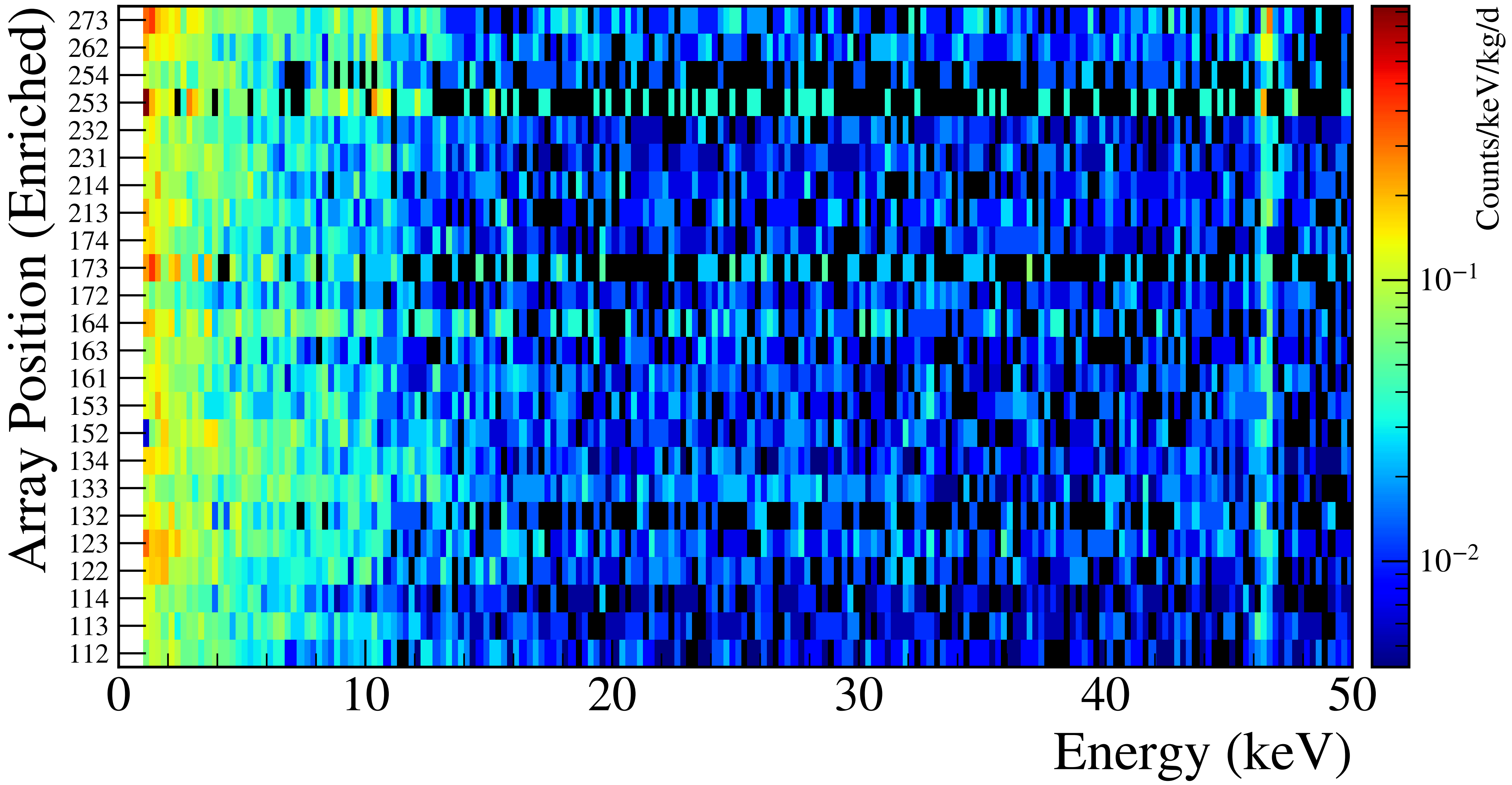


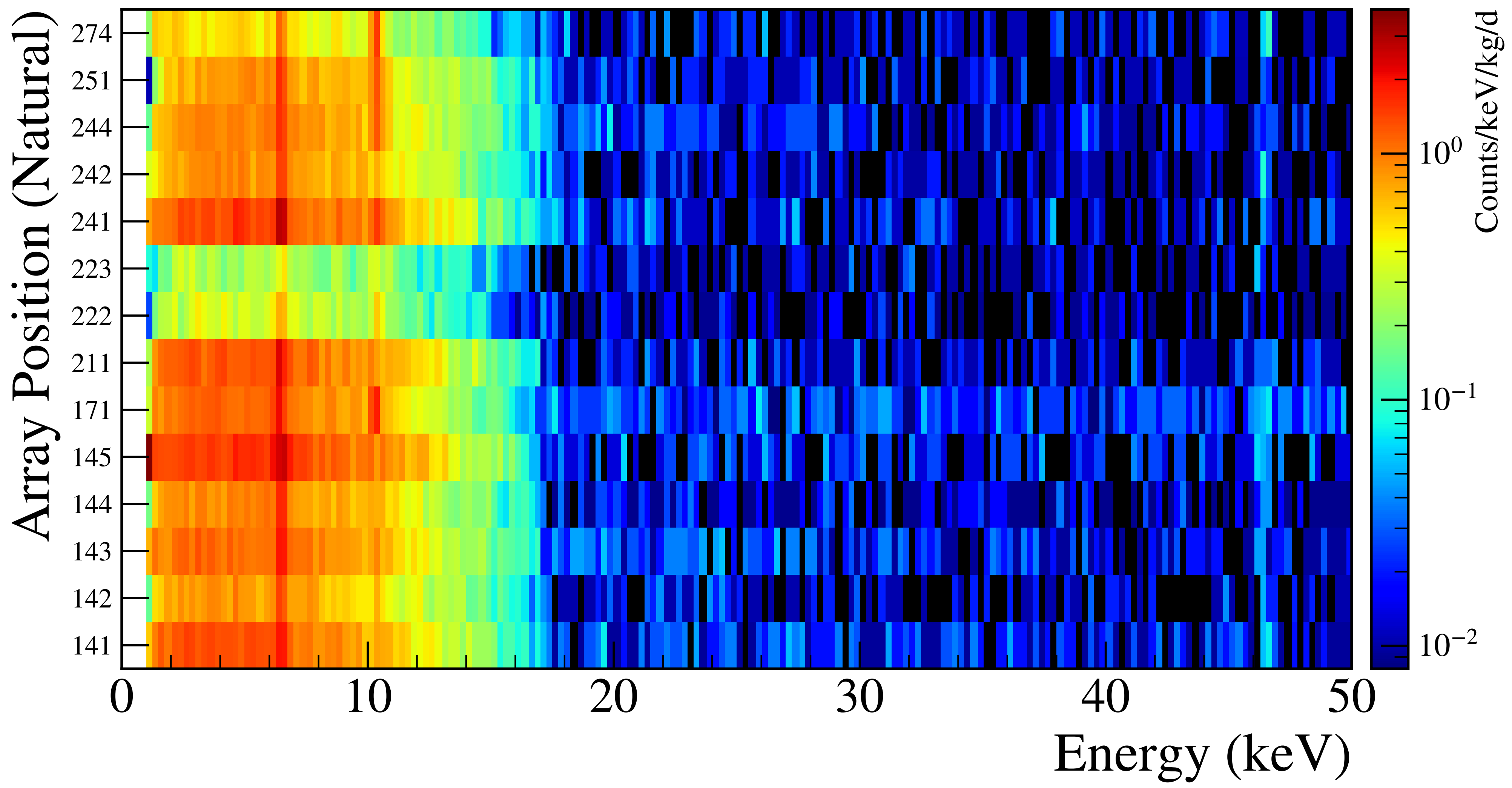
The Low-E spectrum

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







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

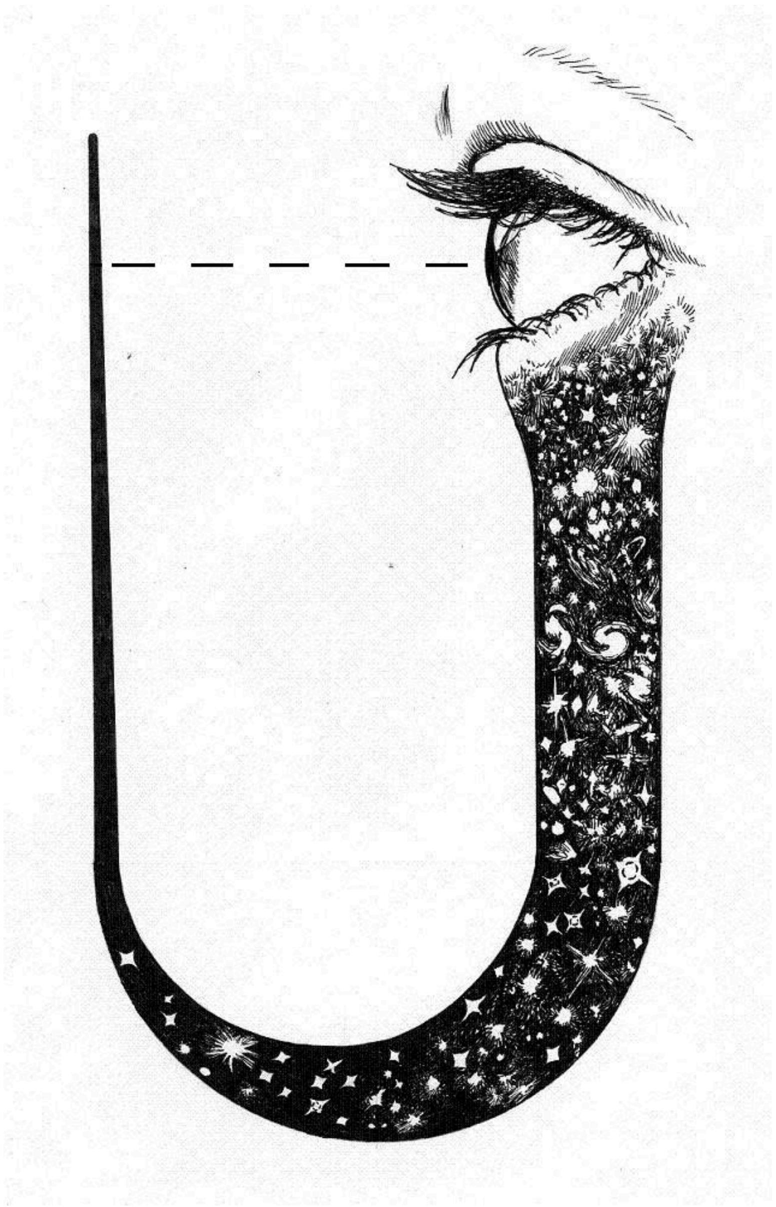
- Quantum Wavefunction collapse
- Lightly ionizing particles

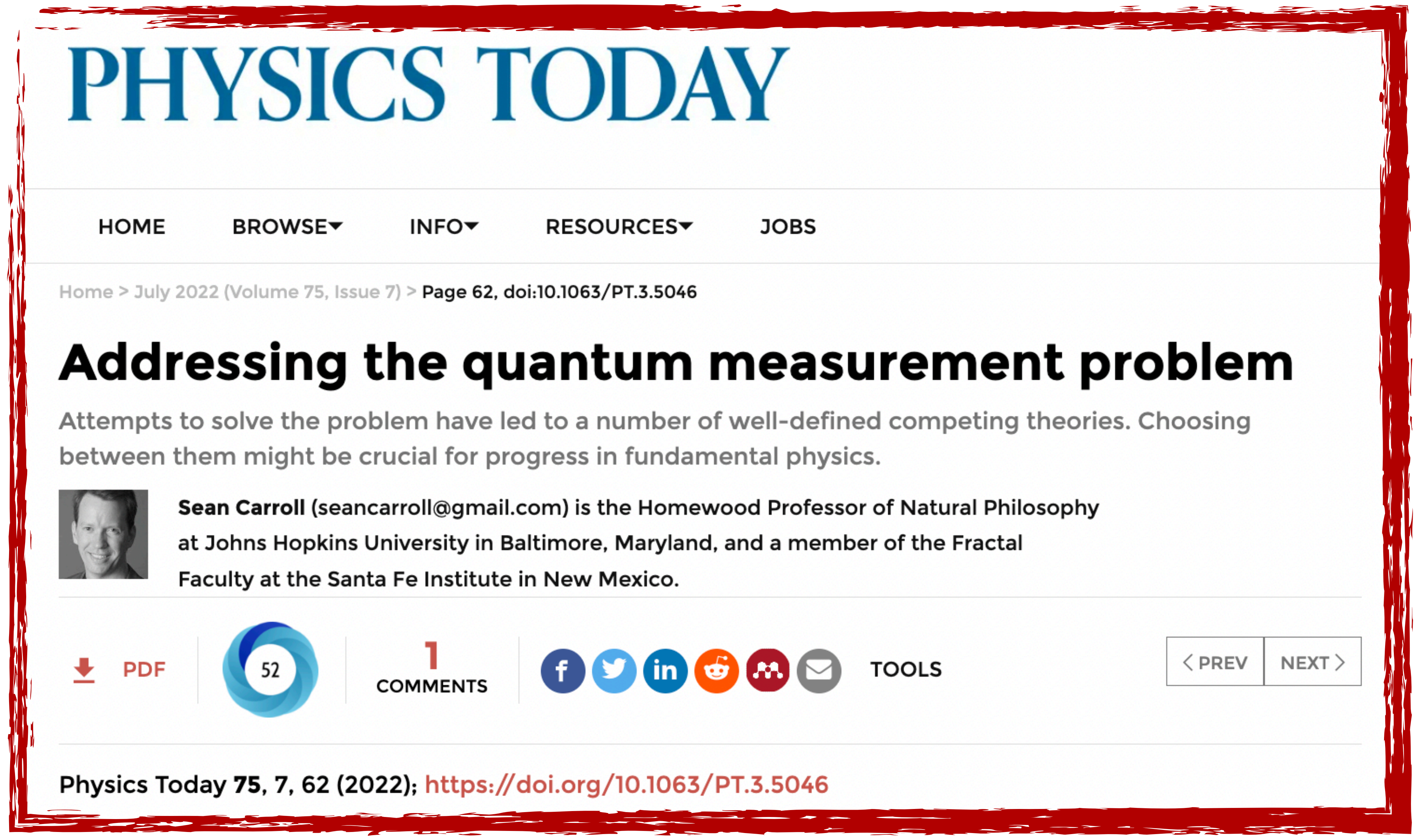
Do wave functions collapse?

What happens when a quantum measurement is performed?

- Does the wave function collapse? Does it have observable effects?
- Can collapse be explained by nonlinear terms in the Schrodinger equation?
- Continuous Spontaneous Localization (CSL) is a well-motivated model

An interesting, interdisciplinary problem we can probe with the germanium detectors in the MAJORANA DEMONSTRATOR …





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Addressing the quantum measurement problem

Attempts to solve the problem have led to a number of well-defined competing theories. Choosing between them might be crucial for progress in fundamental physics.

Sean Carroll (seancarroll@gmail.com) is the Homewood Professor of Natural Philosophy at Johns Hopkins University in Baltimore, Maryland, and a member of the Fractal Faculty at the Santa Fe Institute in New Mexico.

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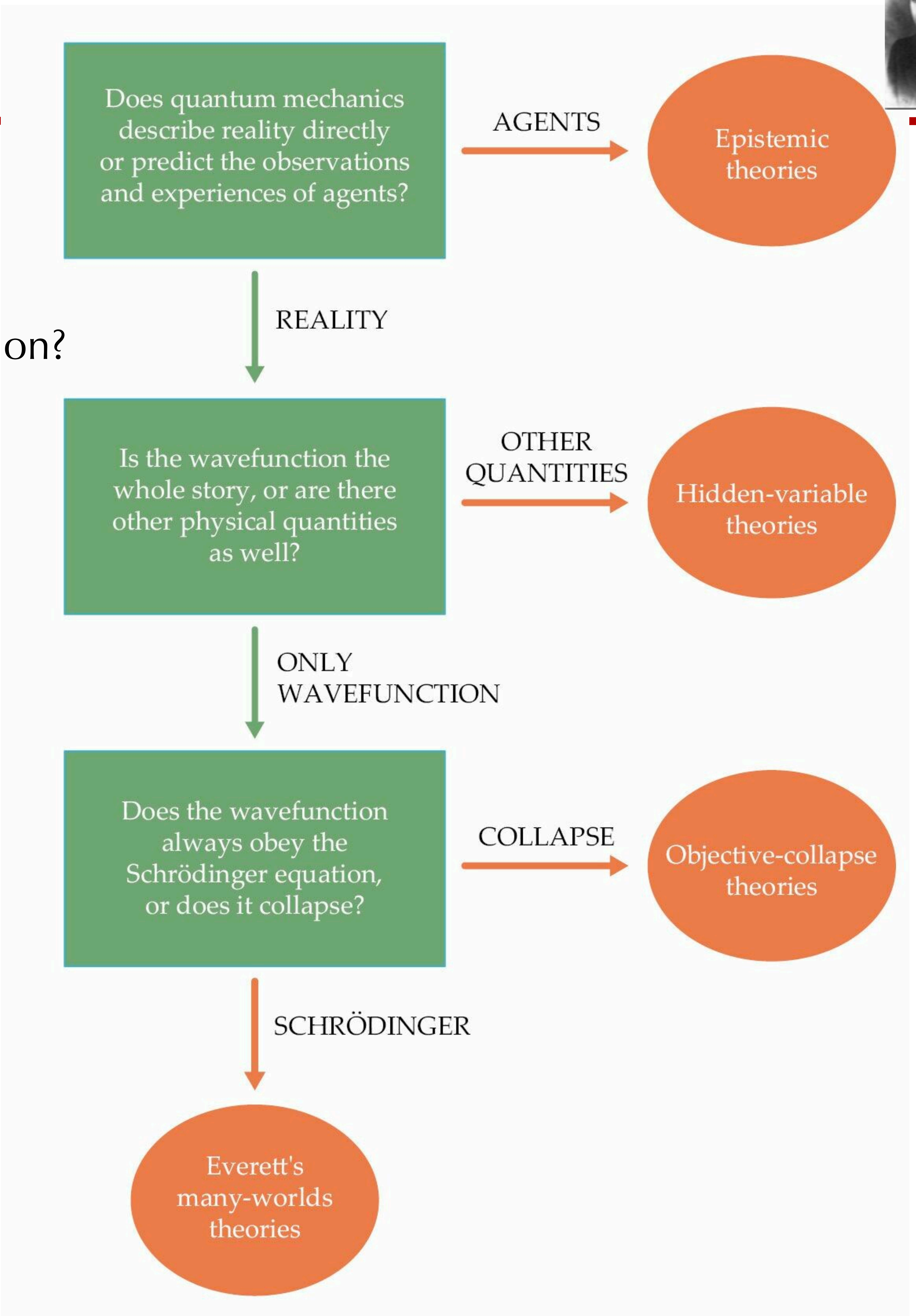
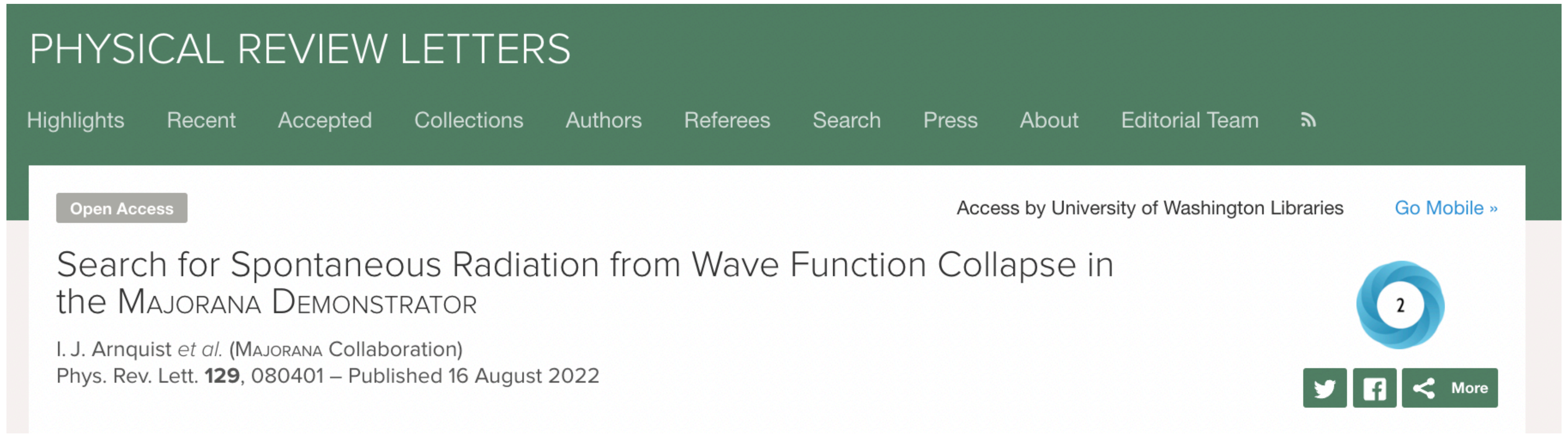
Physics Today **75**, 7, 62 (2022); https://doi.org/10.1063/PT.3.5046



Search for wave function collapse PRL 129 080401 (2022)

Spontaneous WF collapse models try to solve the measurement problem by adding nonlinear terms to the Schrodinger equation

In the CSL model, particles continuously interact with a noise field and emit X-rays (1/E distribution)



MAJORANA improves previous limits by orders of magnitude!

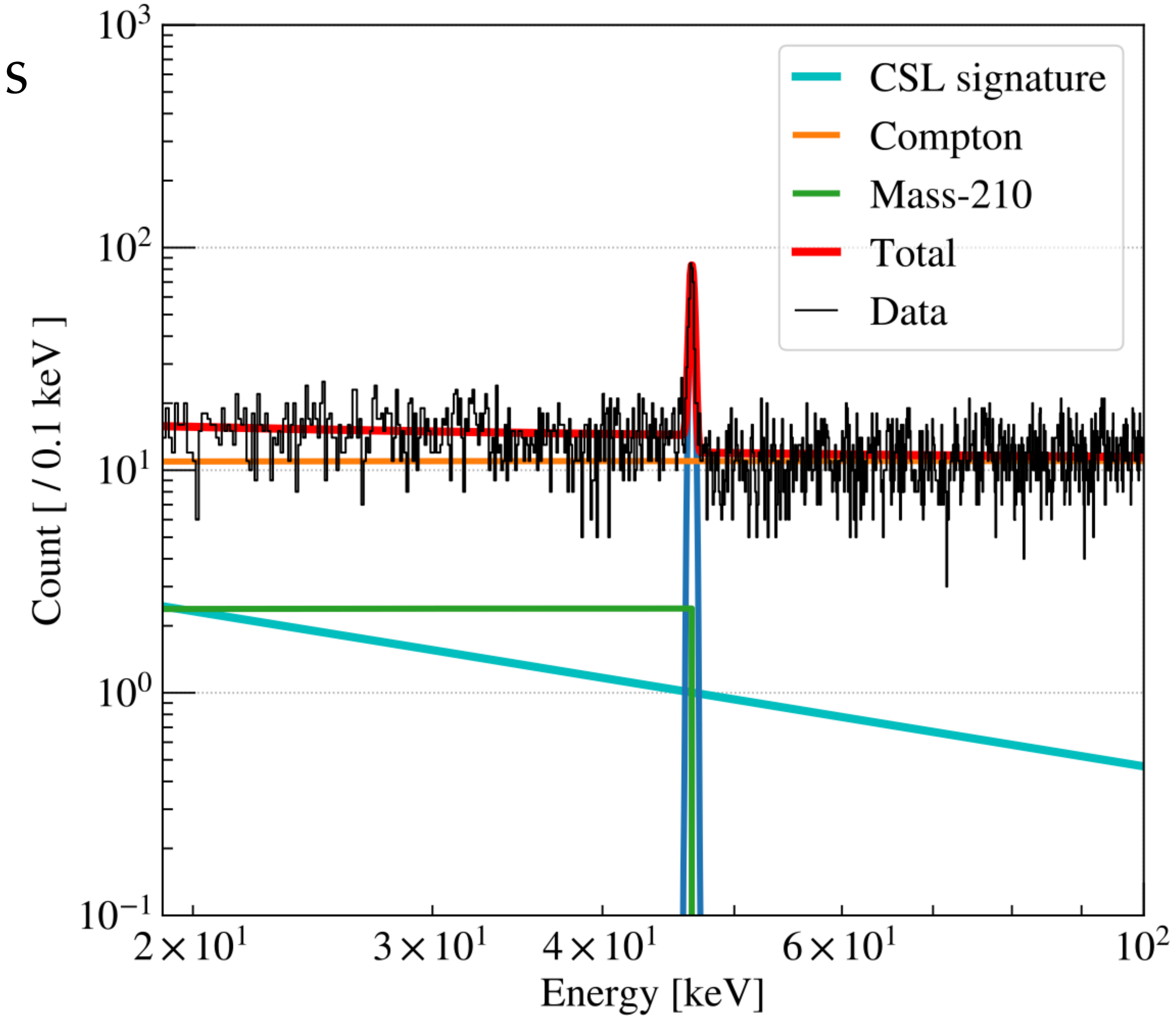
Signature of WFC:

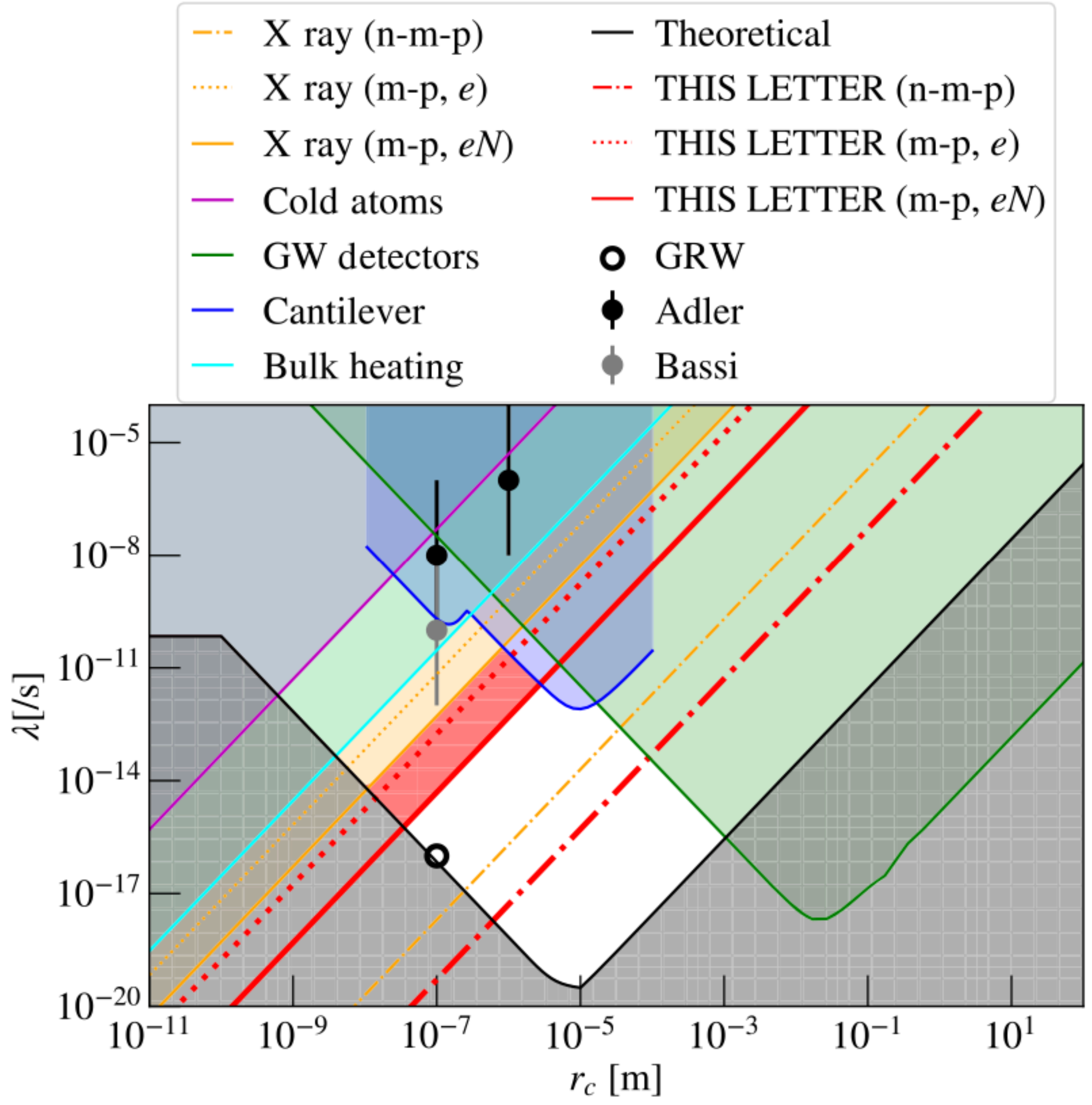
$$\frac{d\Gamma(E)}{dE} \propto \frac{\lambda}{r_C^2}\frac{1}{E}$$

λ : collapse rate

r_C : correlated radius

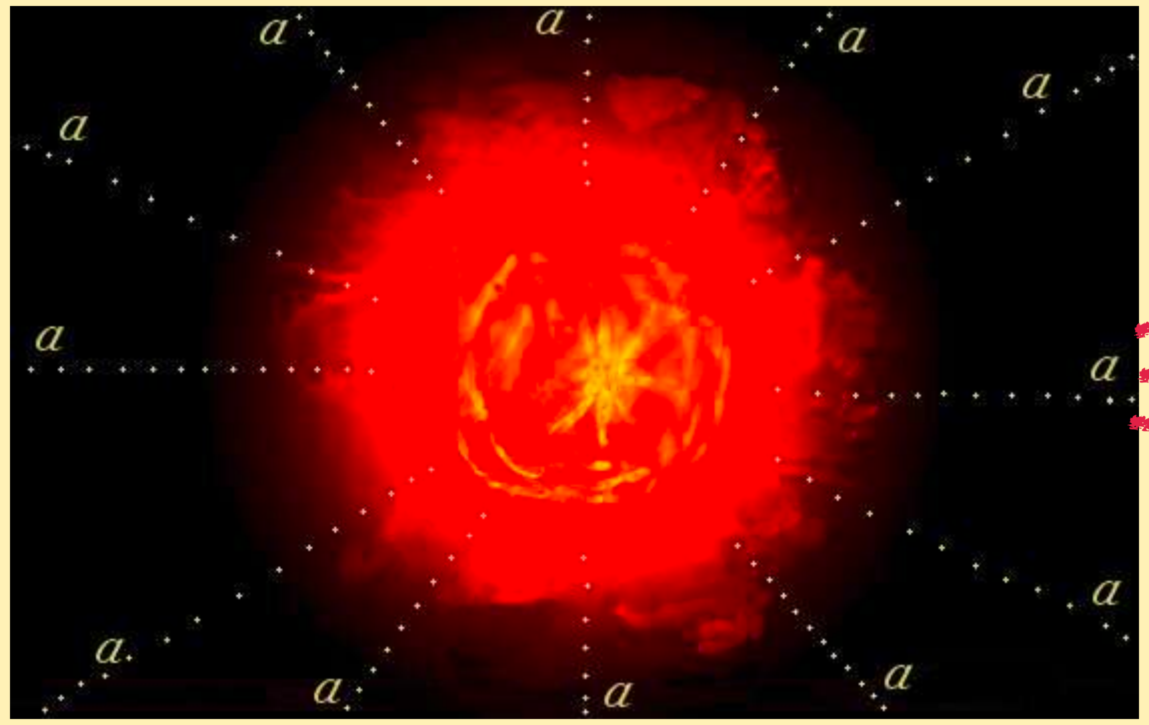
$1/E$: spectral shape





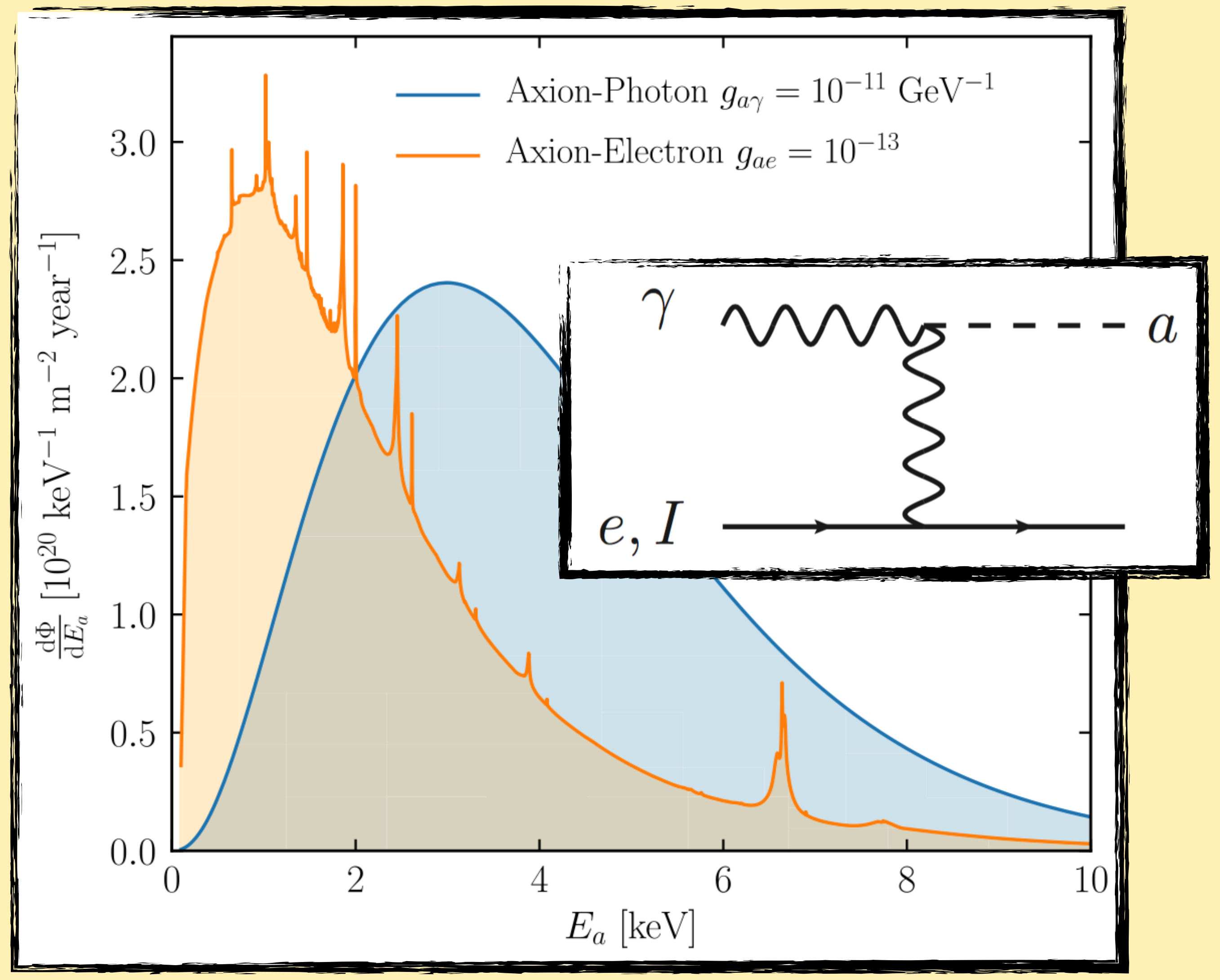
Search for solar axions (a-γ coupling)

Solar Axion Production



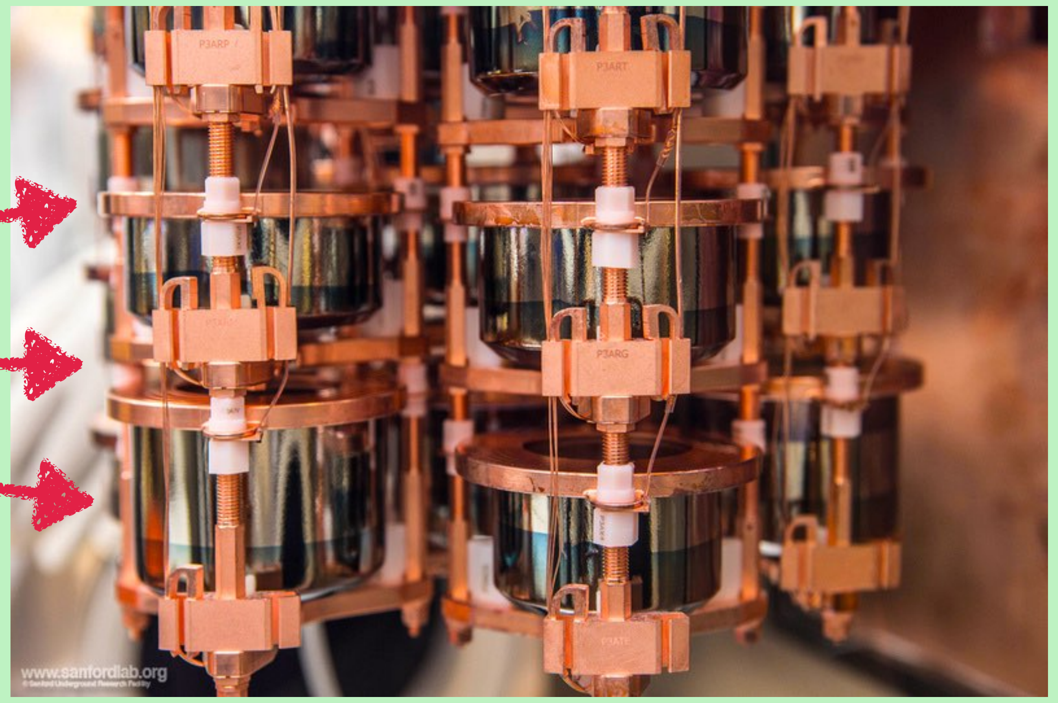
$$\gamma + \gamma_{\text{virtual}} \rightarrow a$$

Primakoff effect: production of axions



PhysRevD.99.035037 (2019)

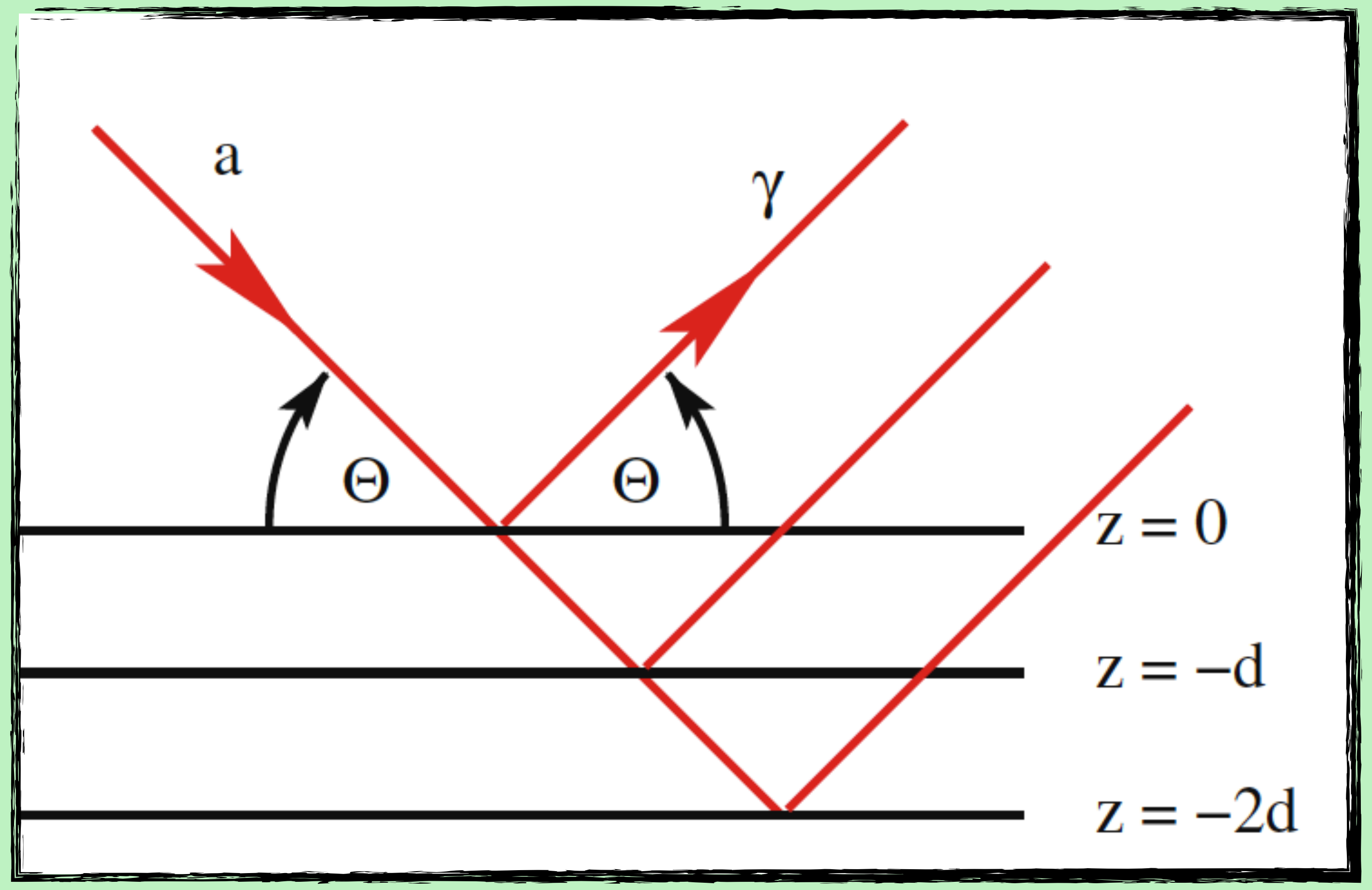
Detection Mechanism



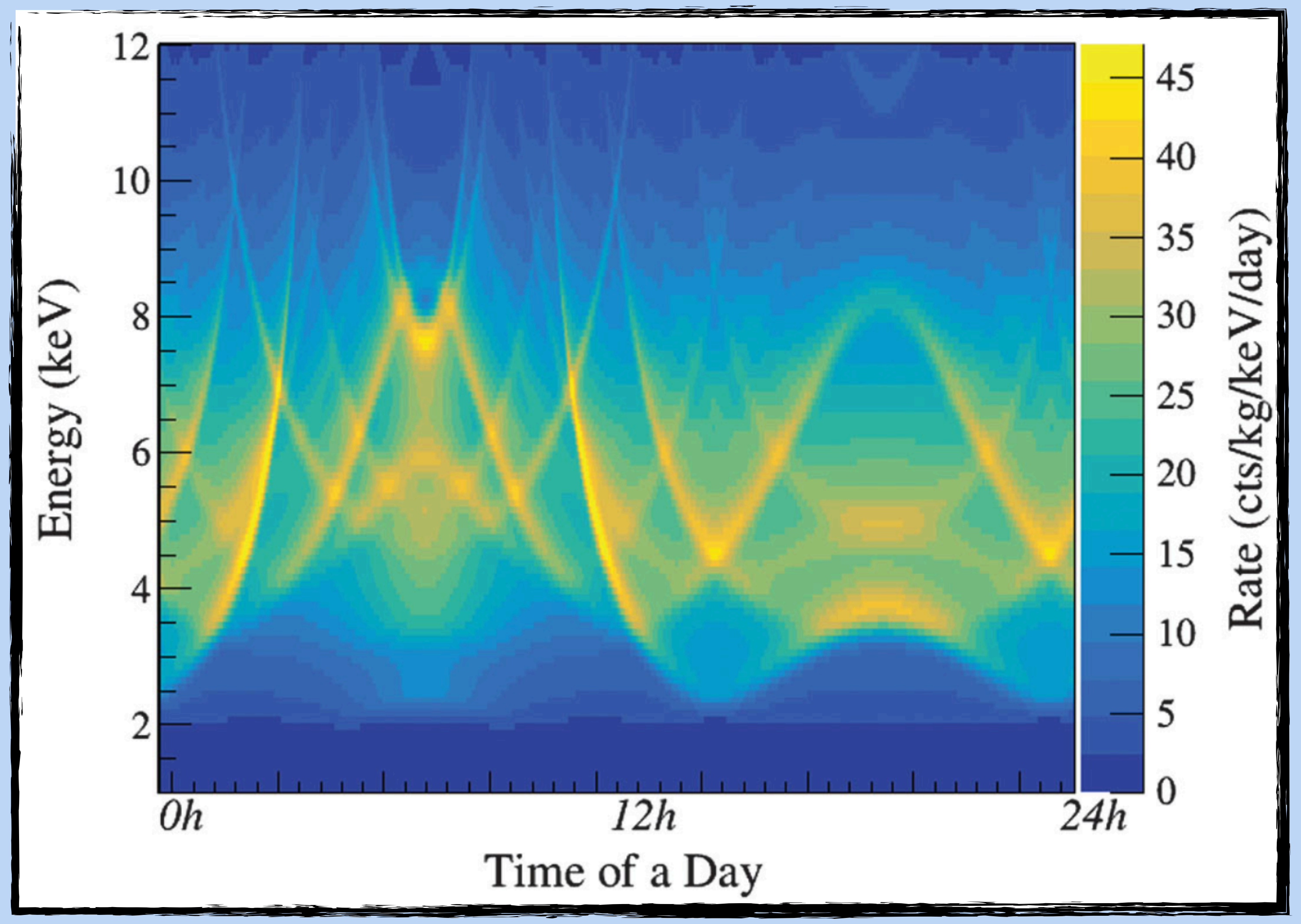
$$a + \gamma_{\text{virtual}} \rightarrow \gamma$$

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!

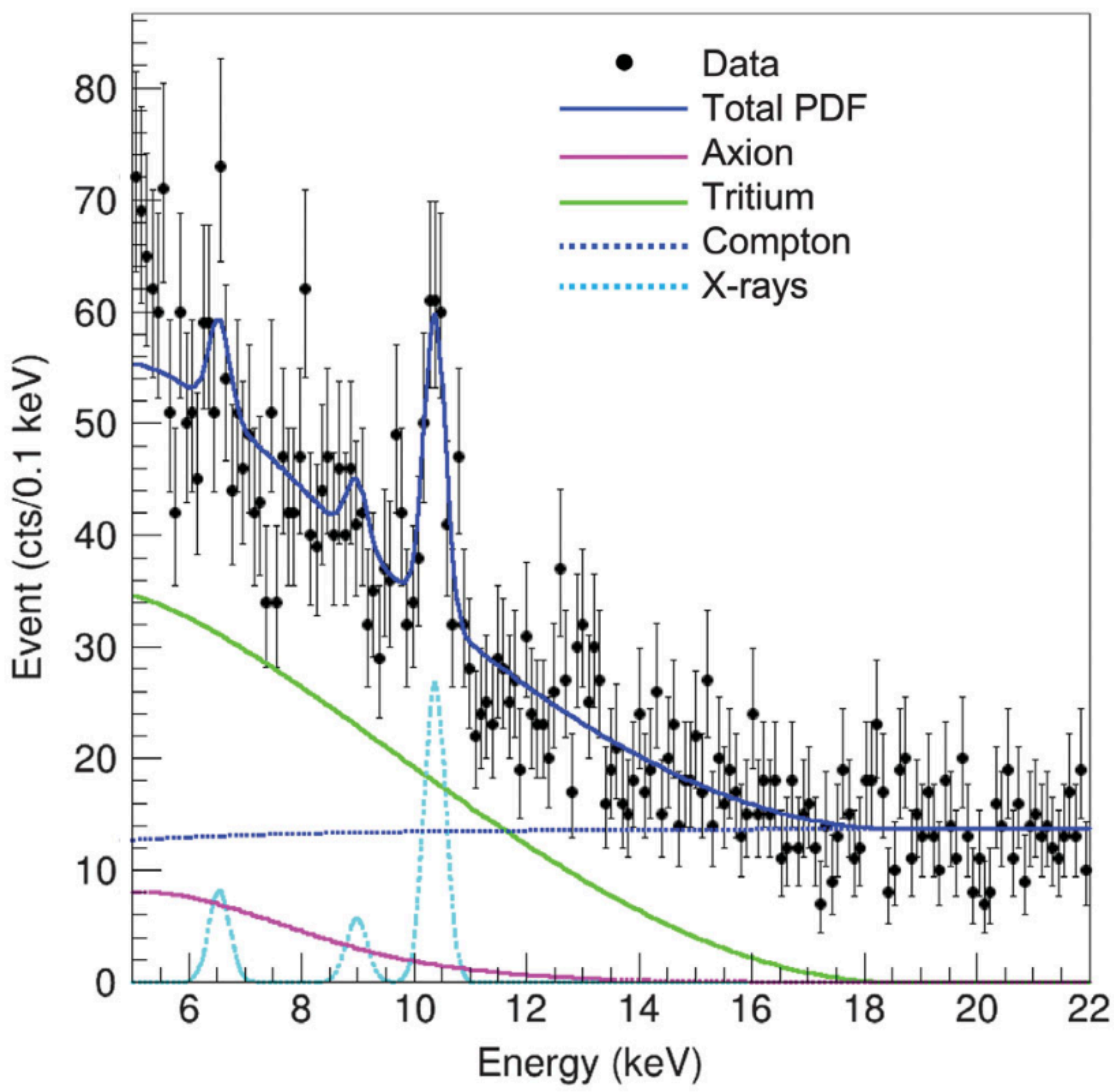
New limits on axion-γ coupling

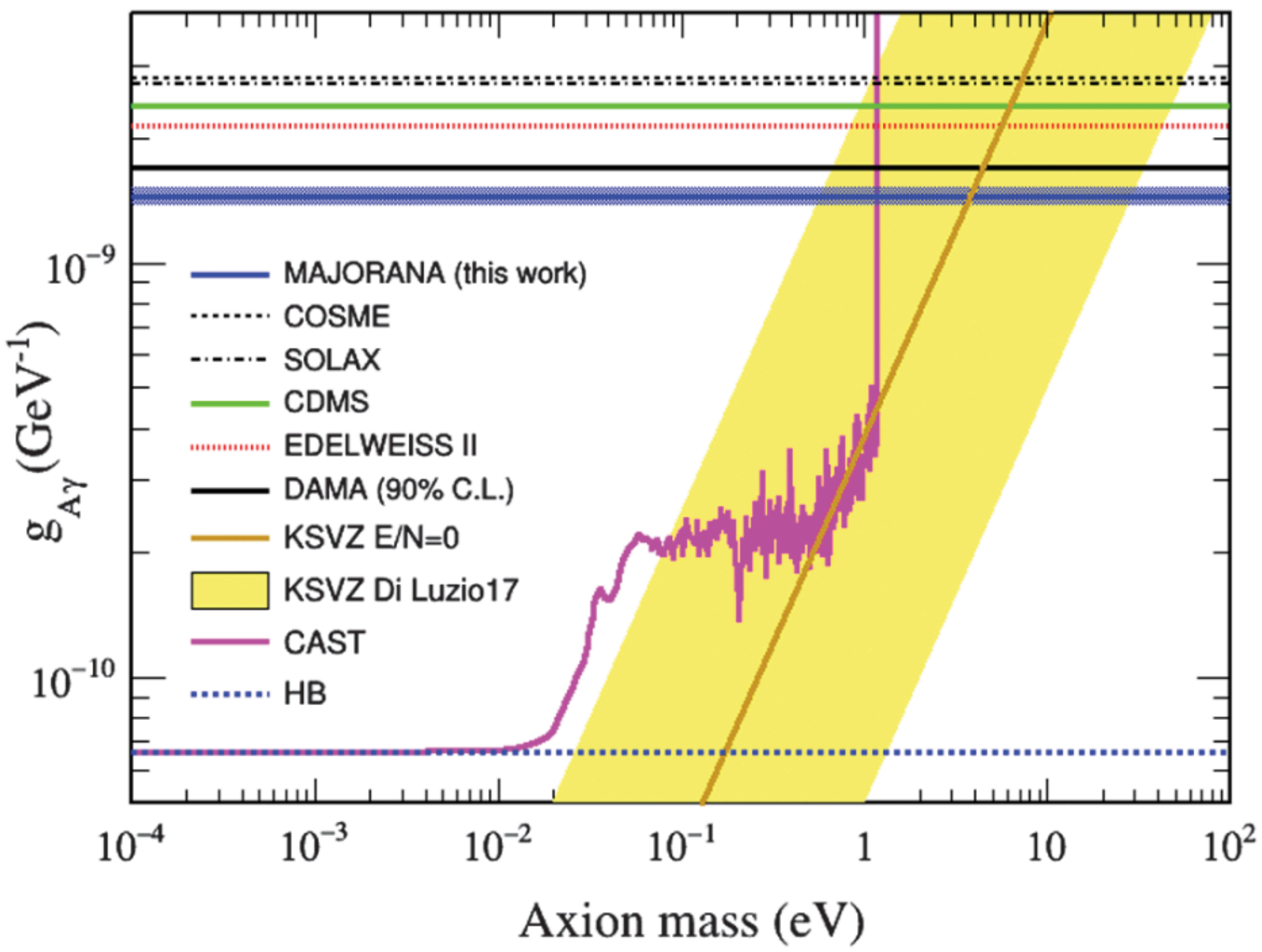
PRL 129 081803 (2022)

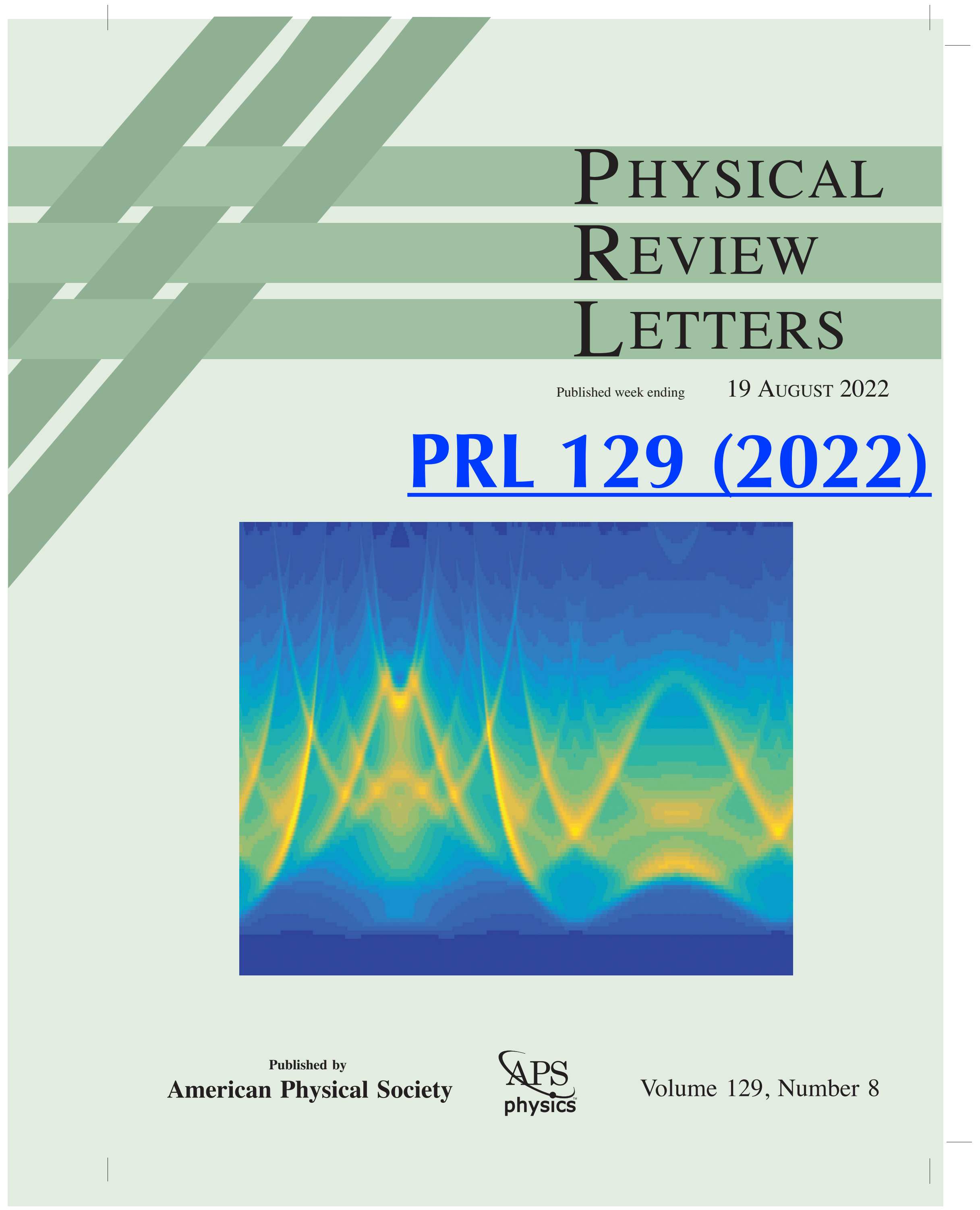
We perform an energy- and time-dependent analysis, 5 minute precision over a 3 year data set.

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

Our limit on the axion-photon coupling: $g_{a\gamma} < 1.45 \times 10^{-9}$ GeV^{-1} (95 % 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







PRL 129 (2022)

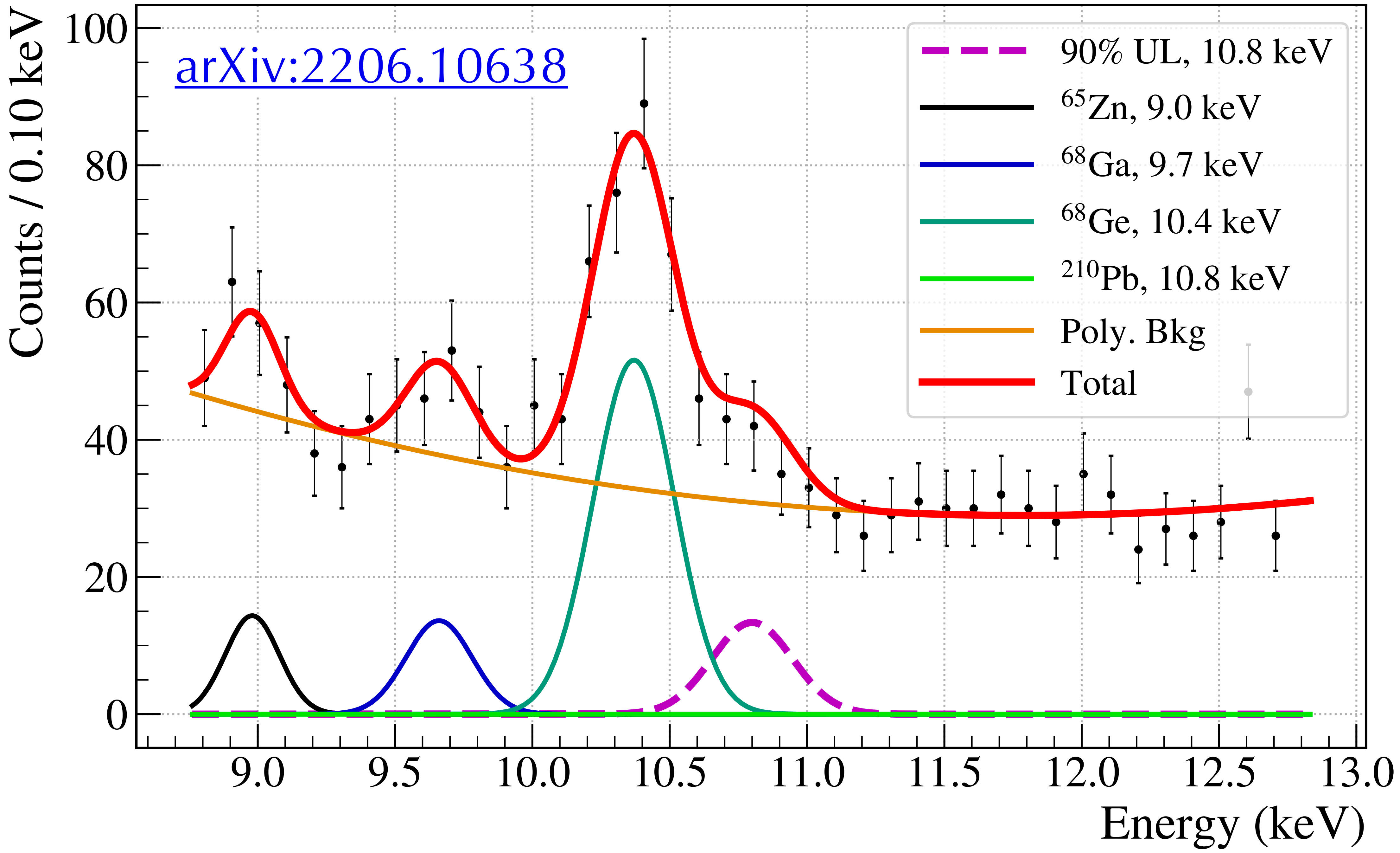
Search for rare peaks from “exotic” dark matter

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.

$$\frac{dN}{dE} = \Phi_{\mathrm{DM}}(m_\chi)\ \sigma(m_\chi)\ \eta(E)\ P_{\mathrm{rare}}(E)\ MT$$

DM flux ↑ cross section ↑ efficiency ↑ rare peak ↑ exposure ↑



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

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

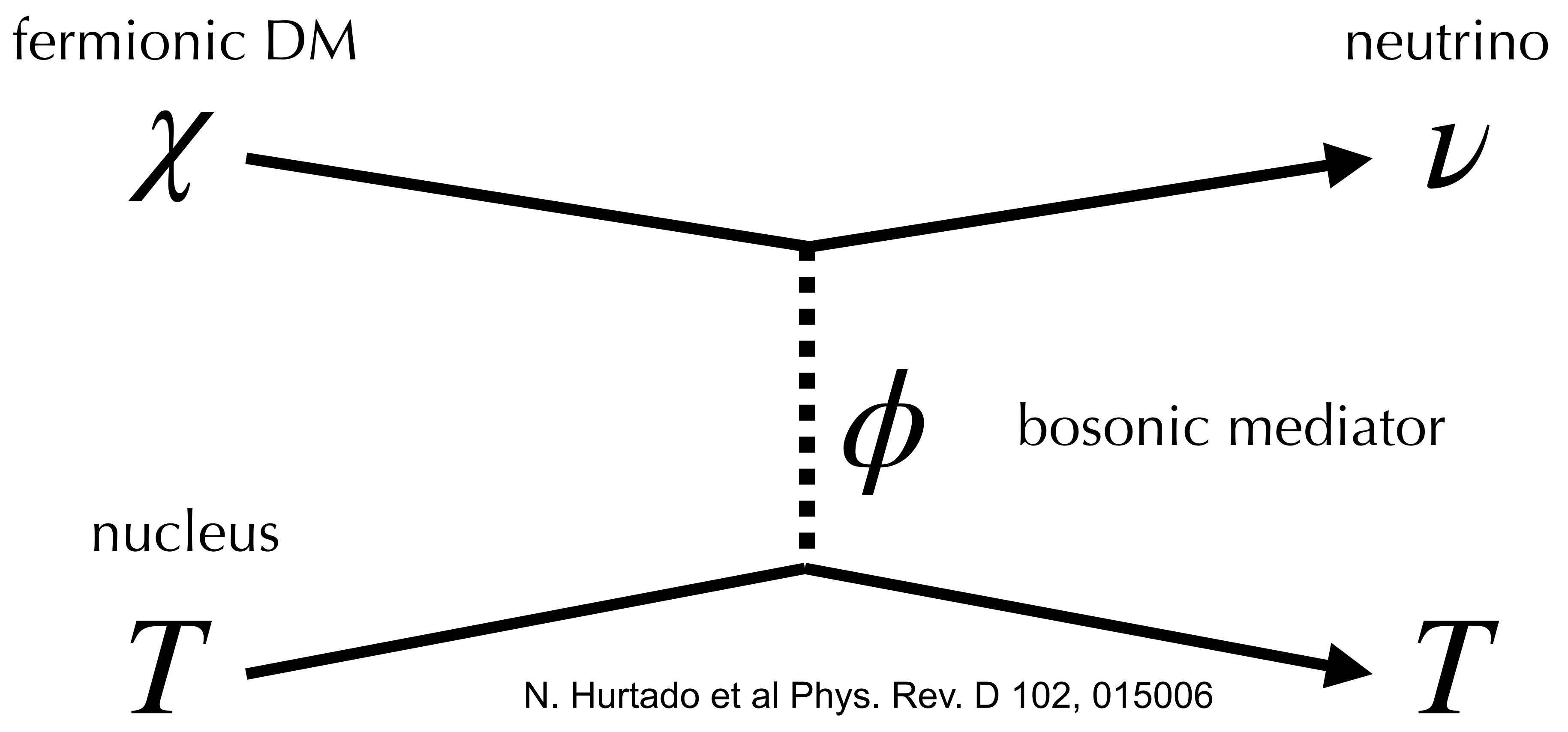
C. Wiseman

Search for fermionic dark matter

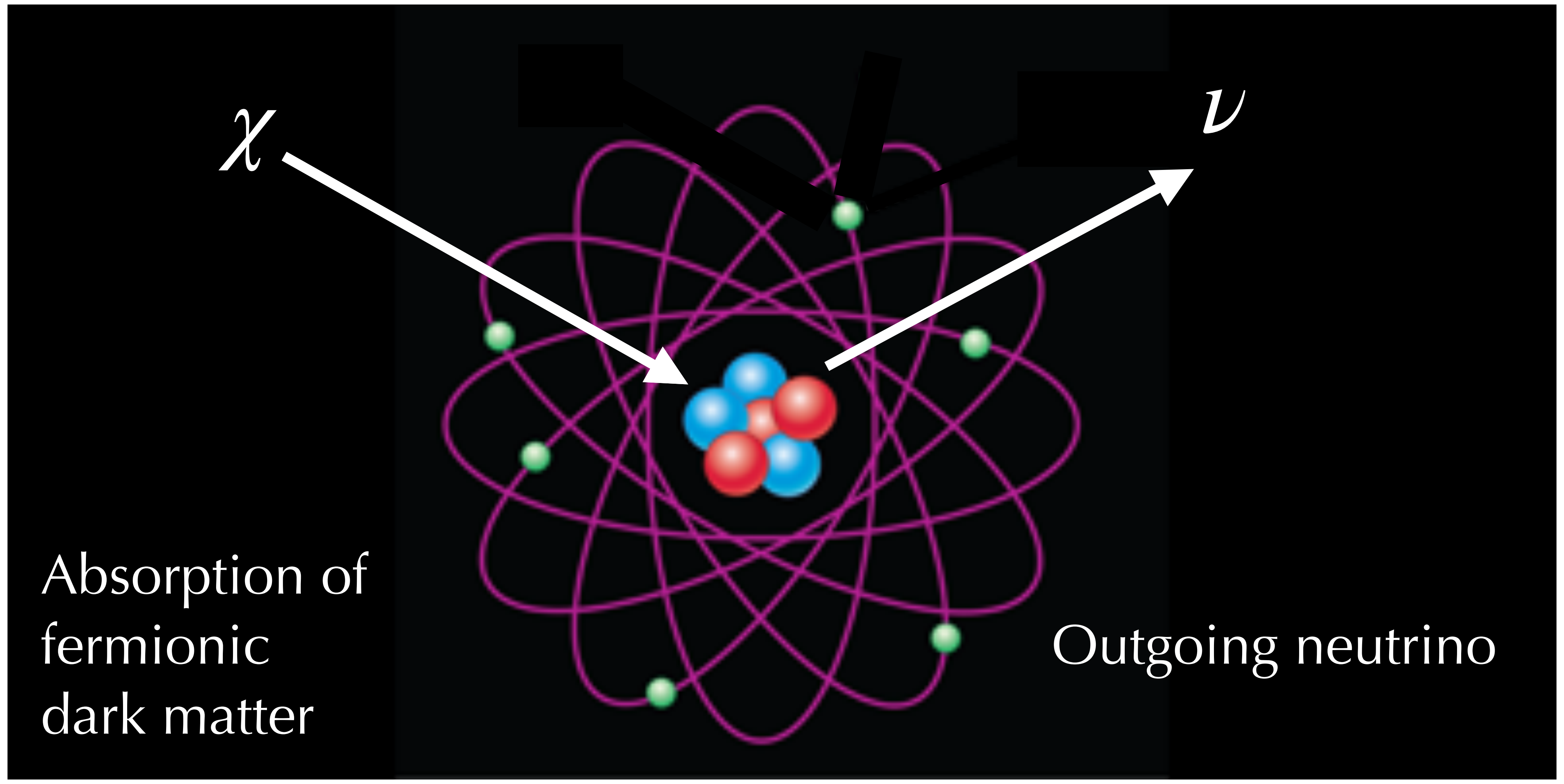
[Dror, arXiv:1905.12635](#)

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

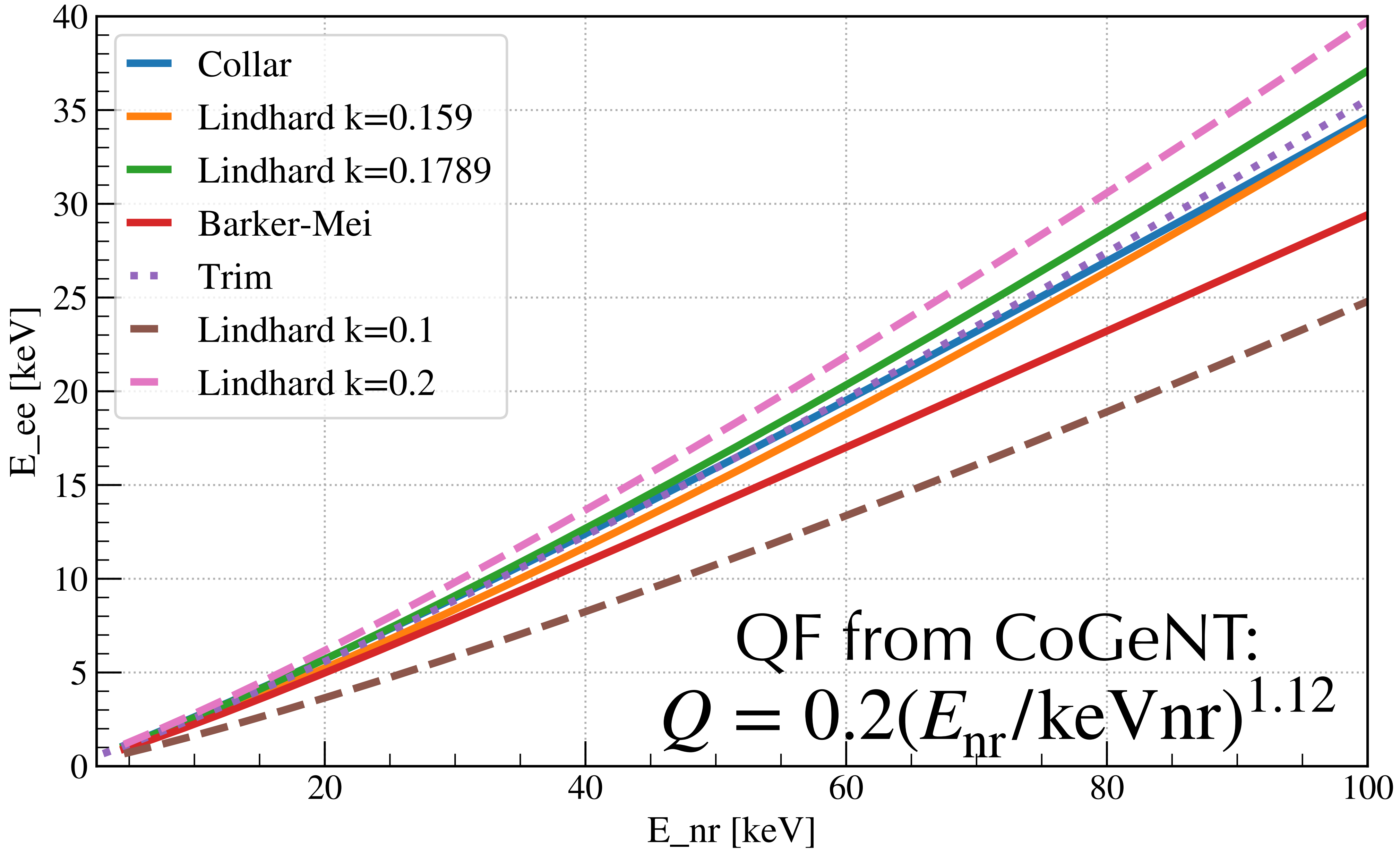


$$\chi + T \rightarrow \nu + T$$



Adapted from APS / [Carin Cain](#)

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



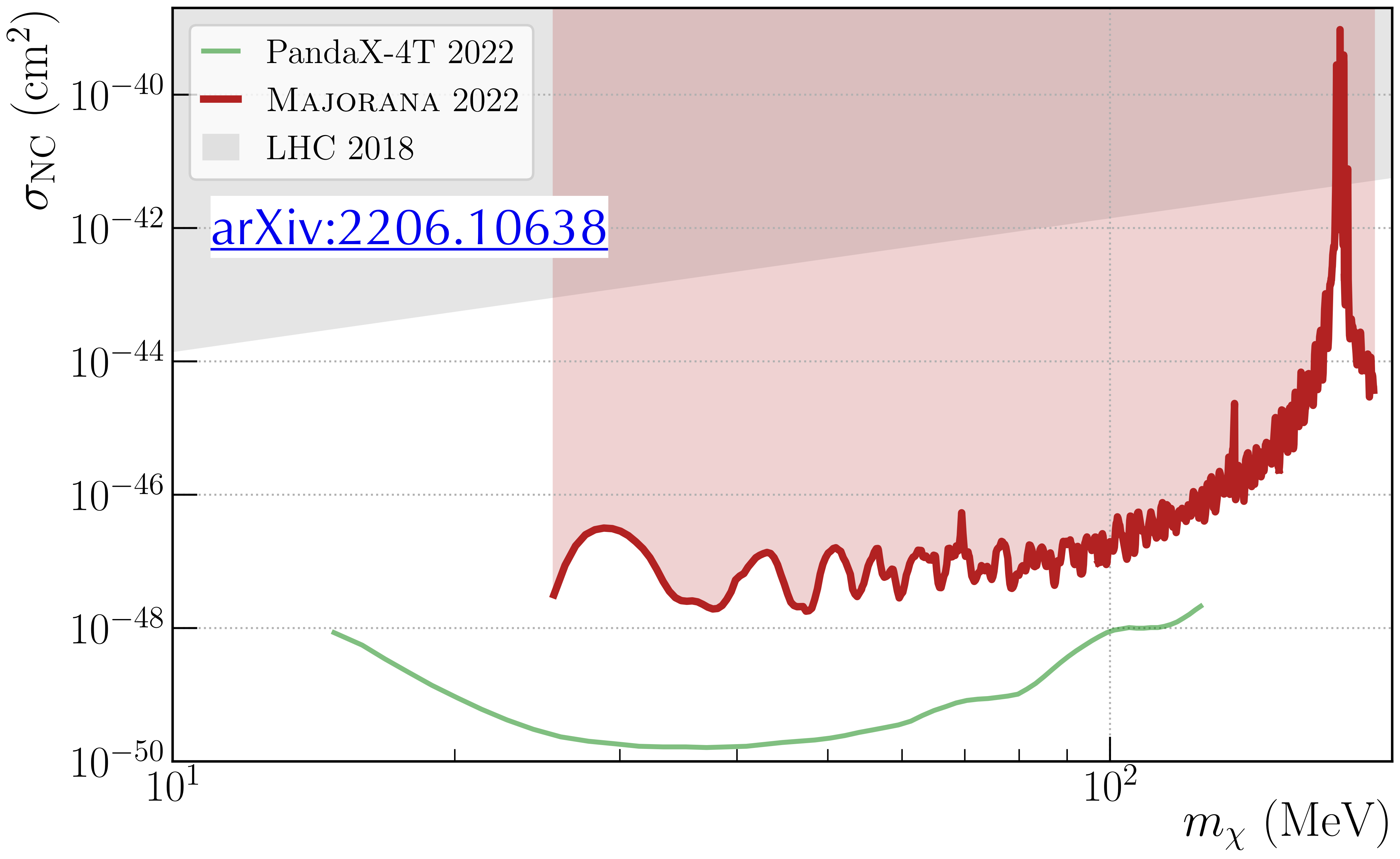
Search for fermionic dark matter, II

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

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

- N_U/MT: absorption rate
- σ_{NC}: neutral-current cross-section
- $\sum_j$: different Ge isotopes
- $N_{Tj} A_j^2 F_j(m_\chi)^2$: interaction with nucleus, involving Helm form factor F and mass number A
- $\Theta(E_{R,j} - E_{\mathrm{th}})$: recoil energy threshold



Peaks due to cosmogenic lines and Helm form factor

Our result improves on Z_0 monojet results from the LHC by ~4 orders of magnitude!

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

Belyaev 2018, arXiv:1807.03817

Search for bosonic dark matter (ALP, dark γ)

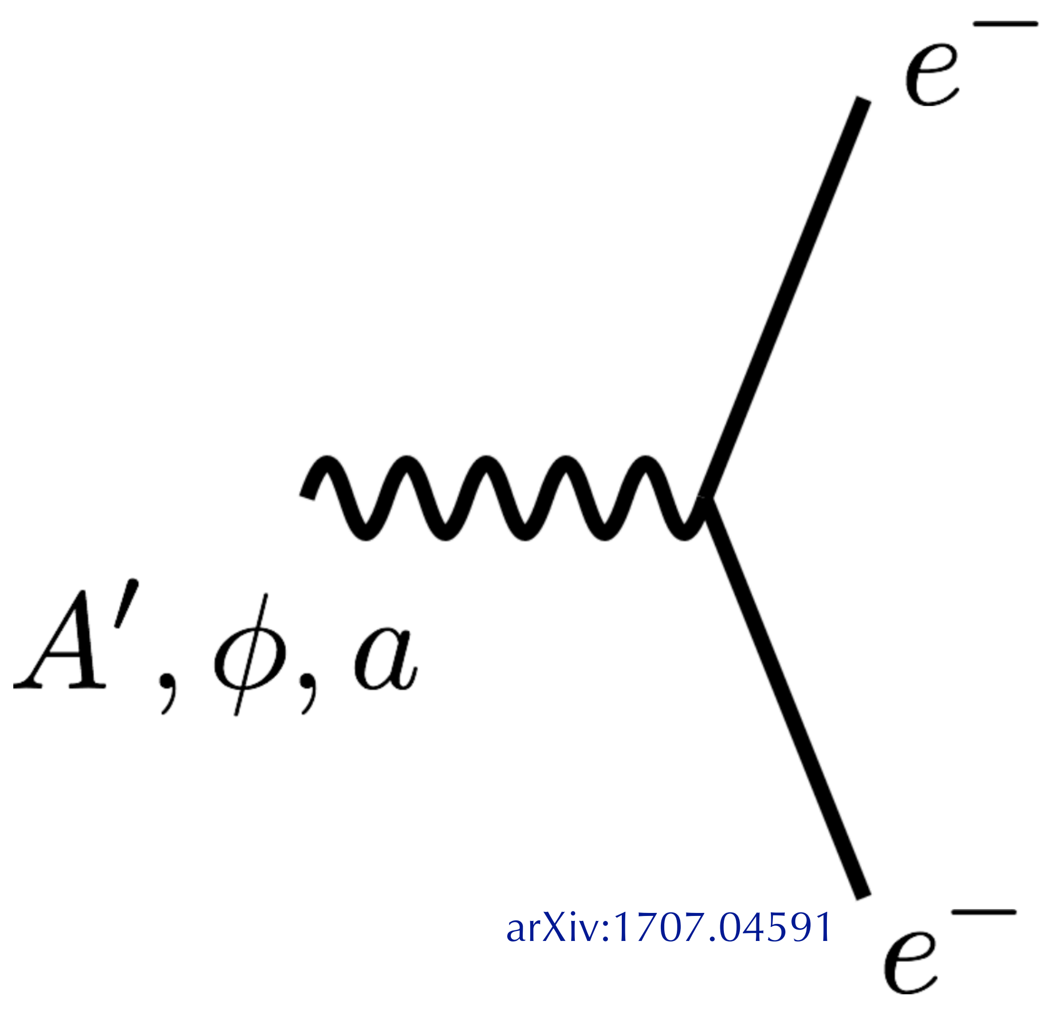
Bosonic dark matter can be pseudoscalar (axionlike) or vector (dark photons).

- MAJORANA released first results in 2017 from commissioning data
- Interaction is via the axioelectric effect
- Non-relativistic, peak at rest mass energy
- Coupling of interest is axion-electron

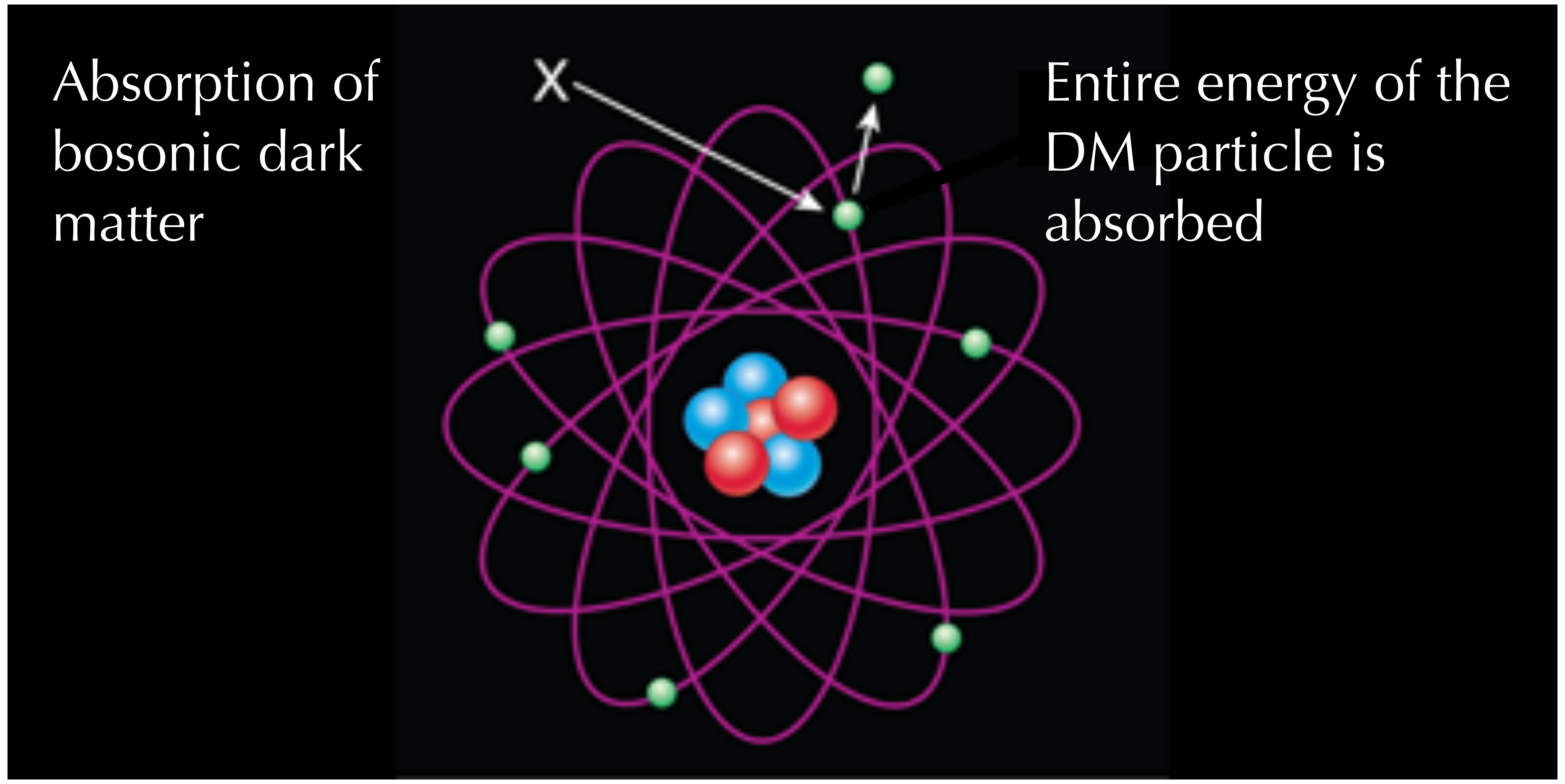
(add'l results for dark photon search in paper)

$$\sigma_{ae}(E) = g_{ae}^2 \frac{E^2 \sigma_{pe}(E)}{\beta} \left(\frac{3}{16\pi\alpha m_e^2} \right)$$

$$|g_{ae}| \leq \left(\frac{N_U\ m_\chi}{MT\ (7.8 \times 10^{17})\ \sigma'_{ae}(m_\chi)} \right)^{1/2}$$



arXiv:1707.04591



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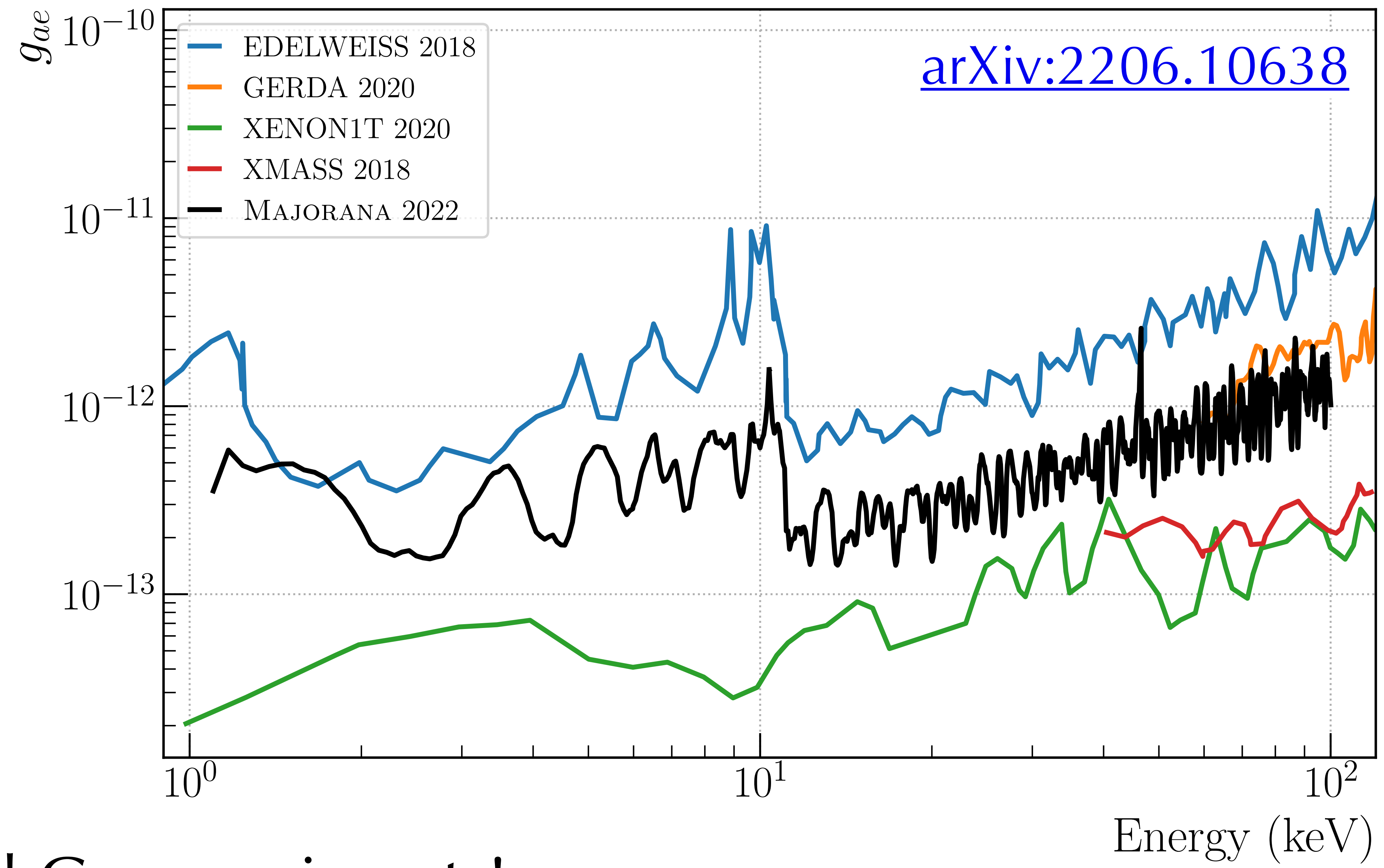


Best limit 1—100 keV of all Ge experiments!

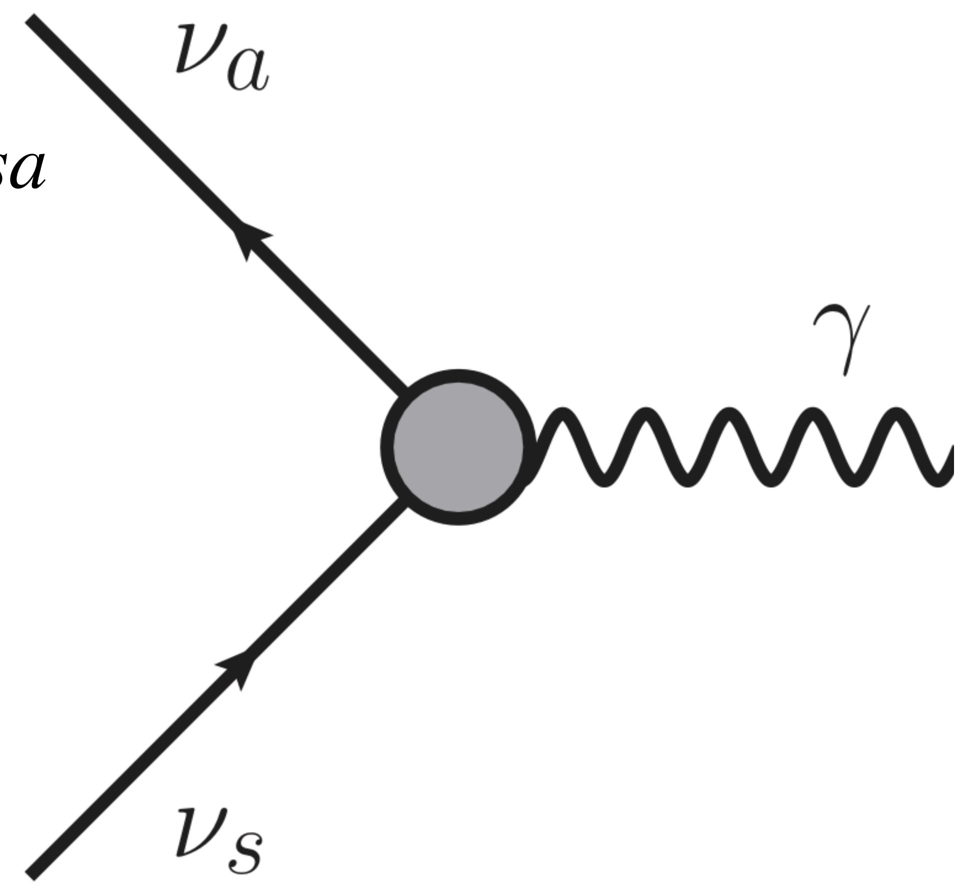
Sterile neutrino transition magnetic moment

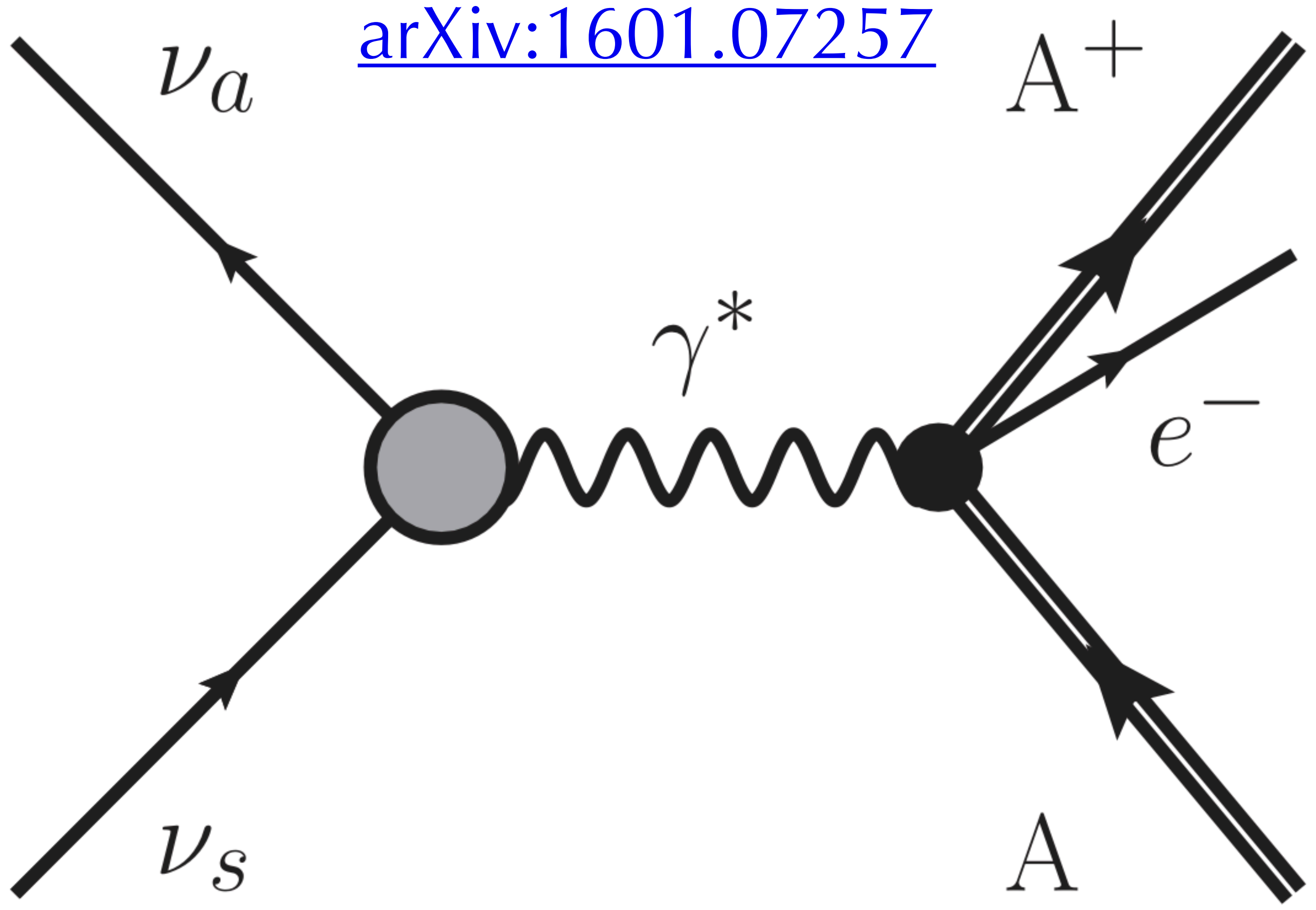
Radiative decay of sterile neutrinos into active neutrinos $\nu_s \to \nu_a$ (or inverse) can have a **nonzero magnetic moment** μ_{sa}

Current best limits are obtained from Borexino's data on $\nu_\mu \to \nu_s$, $\mu_{\mu s} < 7 \times 10^{-11}\ \mu_B$

$$\nu_s + A \to \nu_a + A^+ + e^-$$

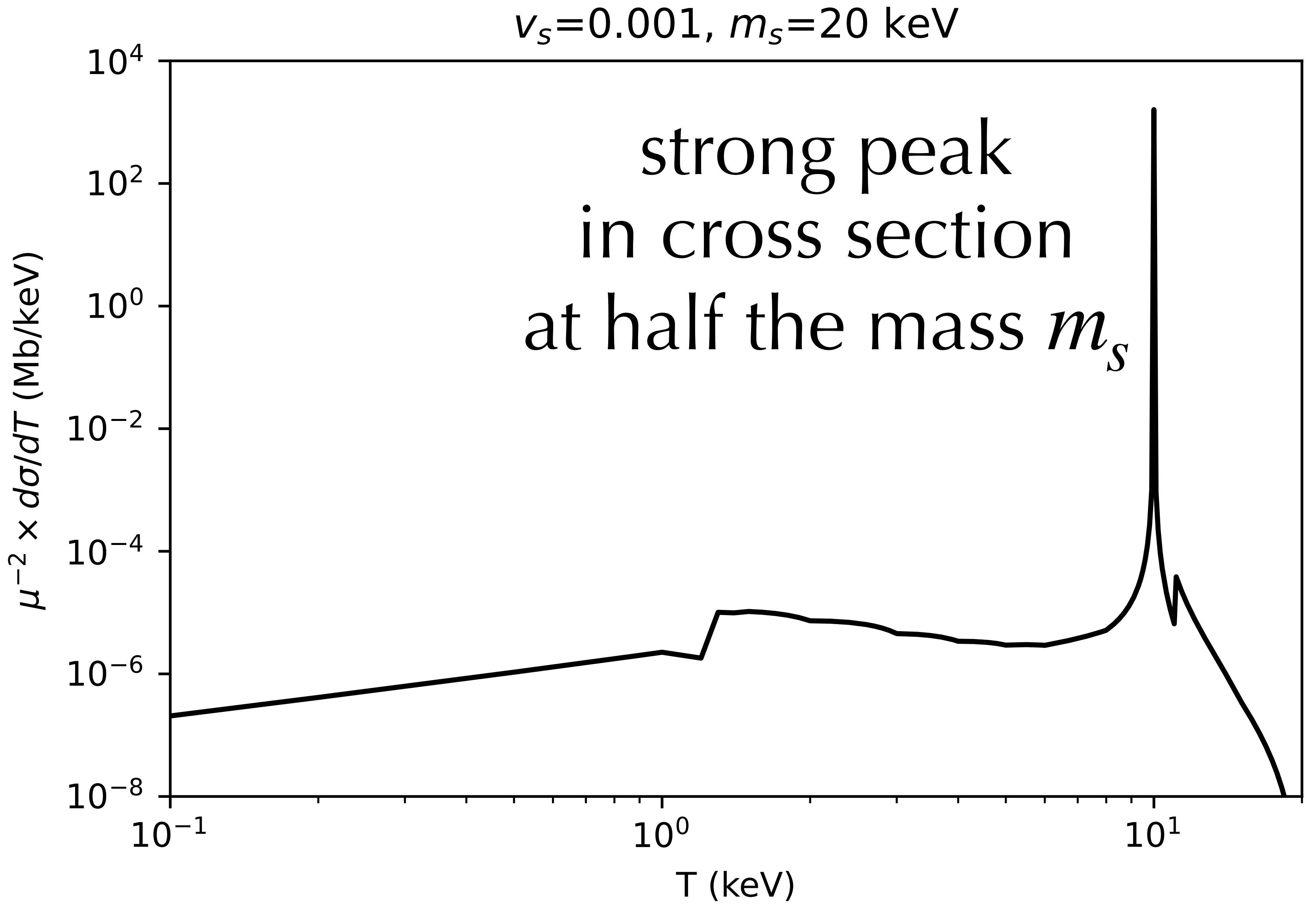
[Chen 2016, arXiv:1601.07257](https://arxiv.org/abs/1601.07257)





We consider an enhancement from atomic ionization, when the virtual photon interacts coherently with a target atom A, approaching $q^2 \to 0$ 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: $\dfrac{d\sigma(m_s, v)}{dT} \approx \left(\dfrac{\mu_{sa}}{2m_e}\right)^2 \dfrac{\alpha}{2n_A} \dfrac{m_s^2}{|v|^2}$



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.

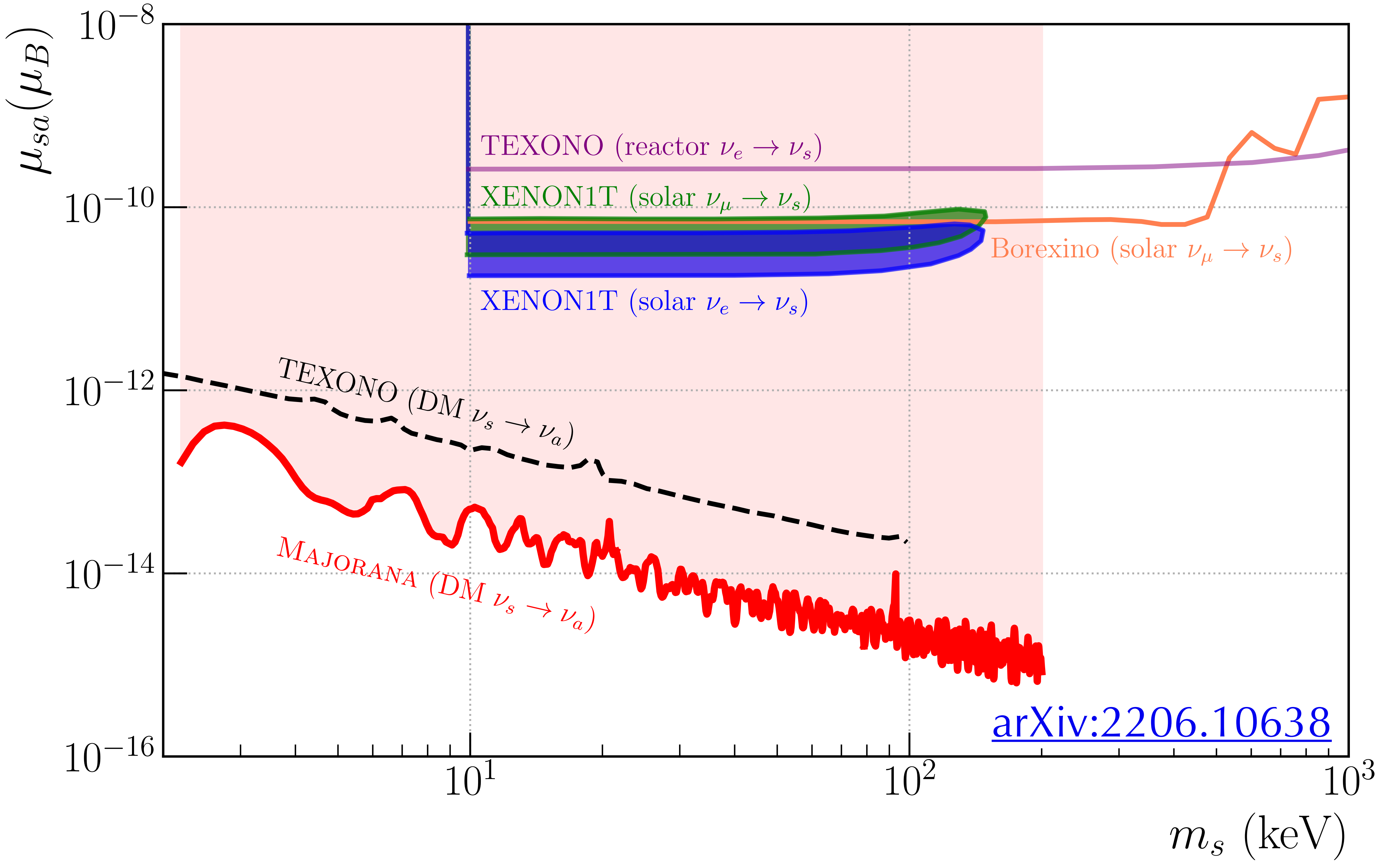
XENON1T excess has been ruled out by XENONnT, but the Majorana result is still world-leading …

arXiv:2207.11330

- Assuming local DM halo density $\rho_\chi = 0.4$ GeV/cm³, 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)



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

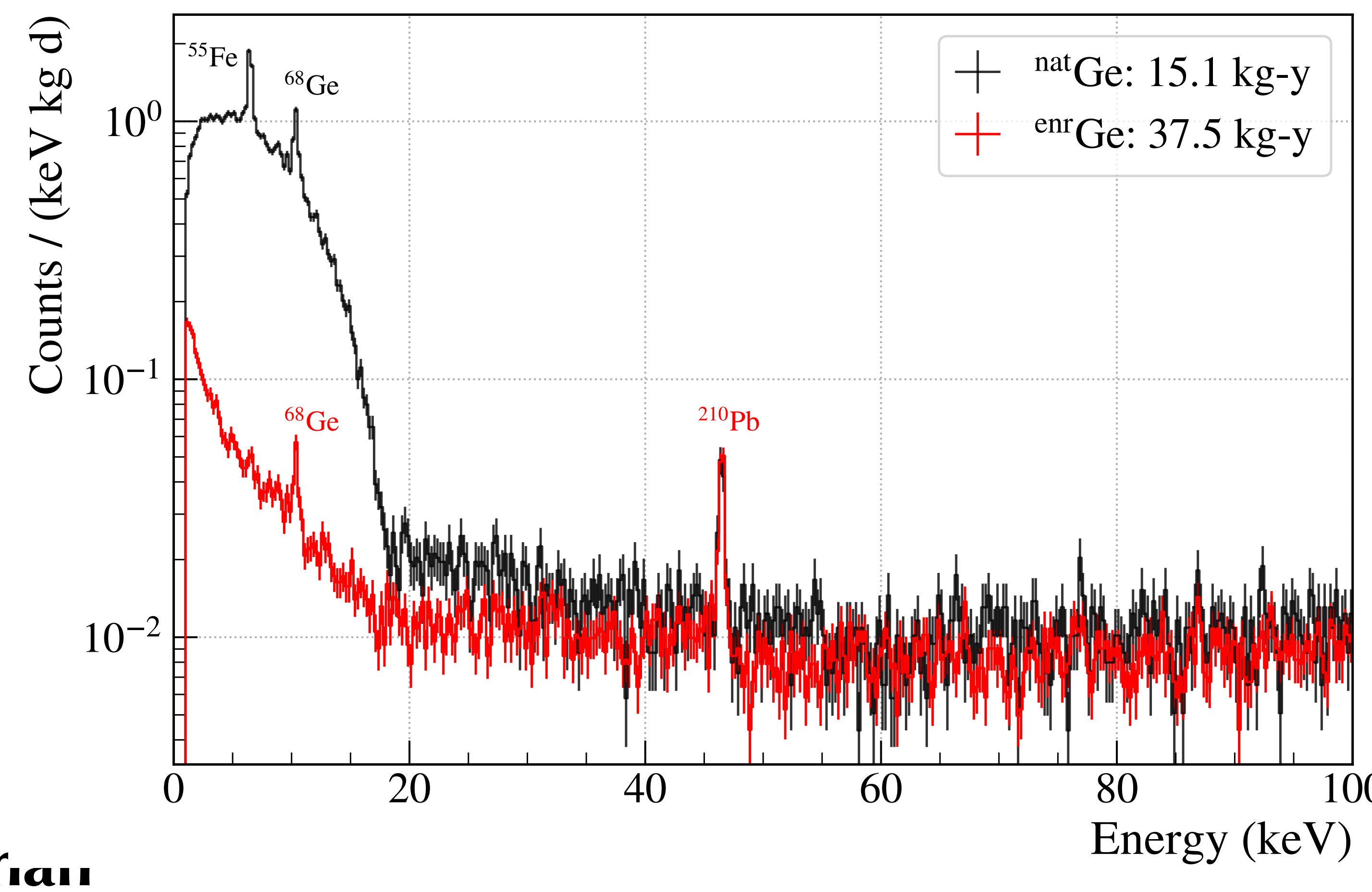
Conclusions, take-aways …

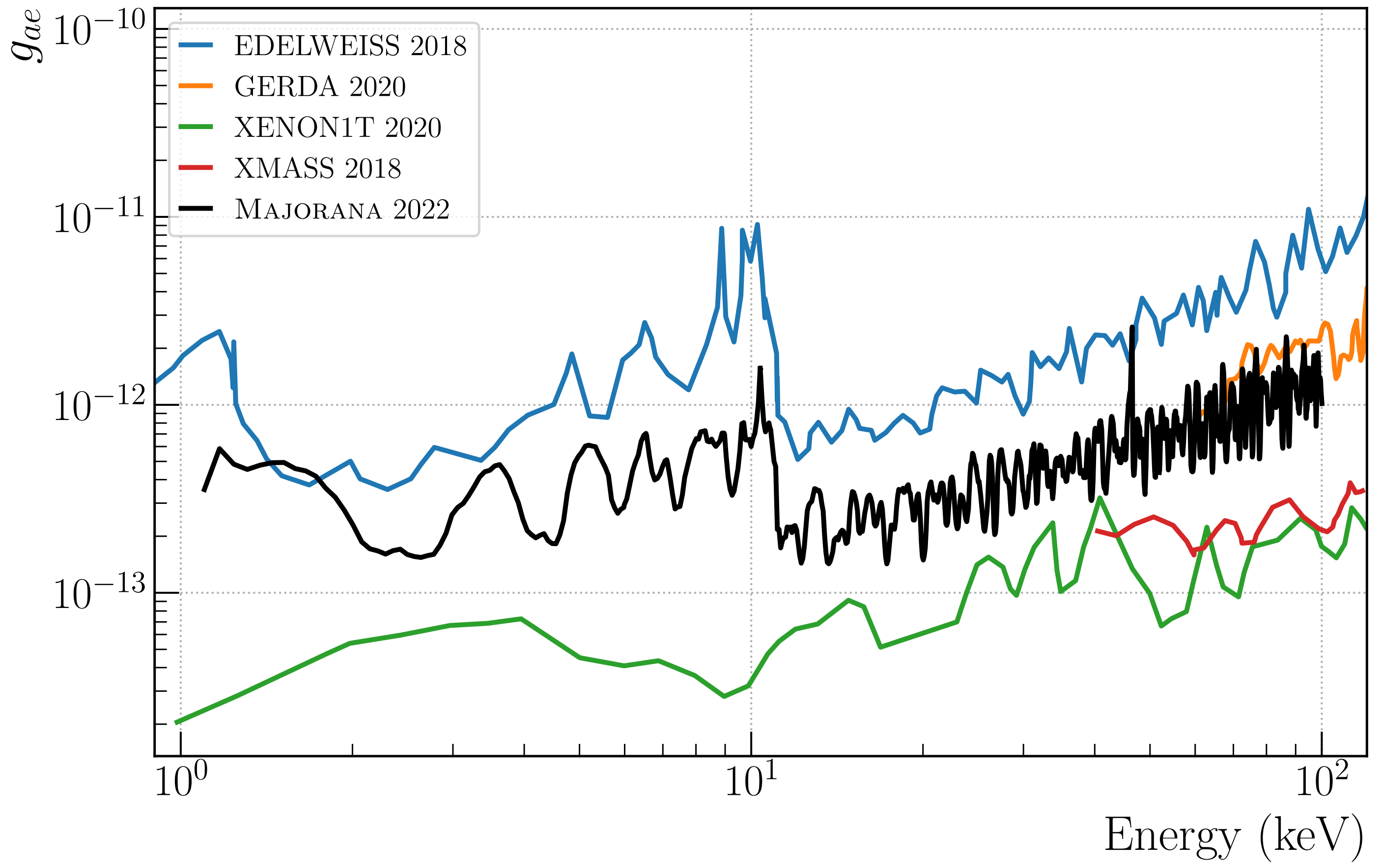
With **low cosmogenic activation, excellent energy resolution, and ~1 keV thresholds,**

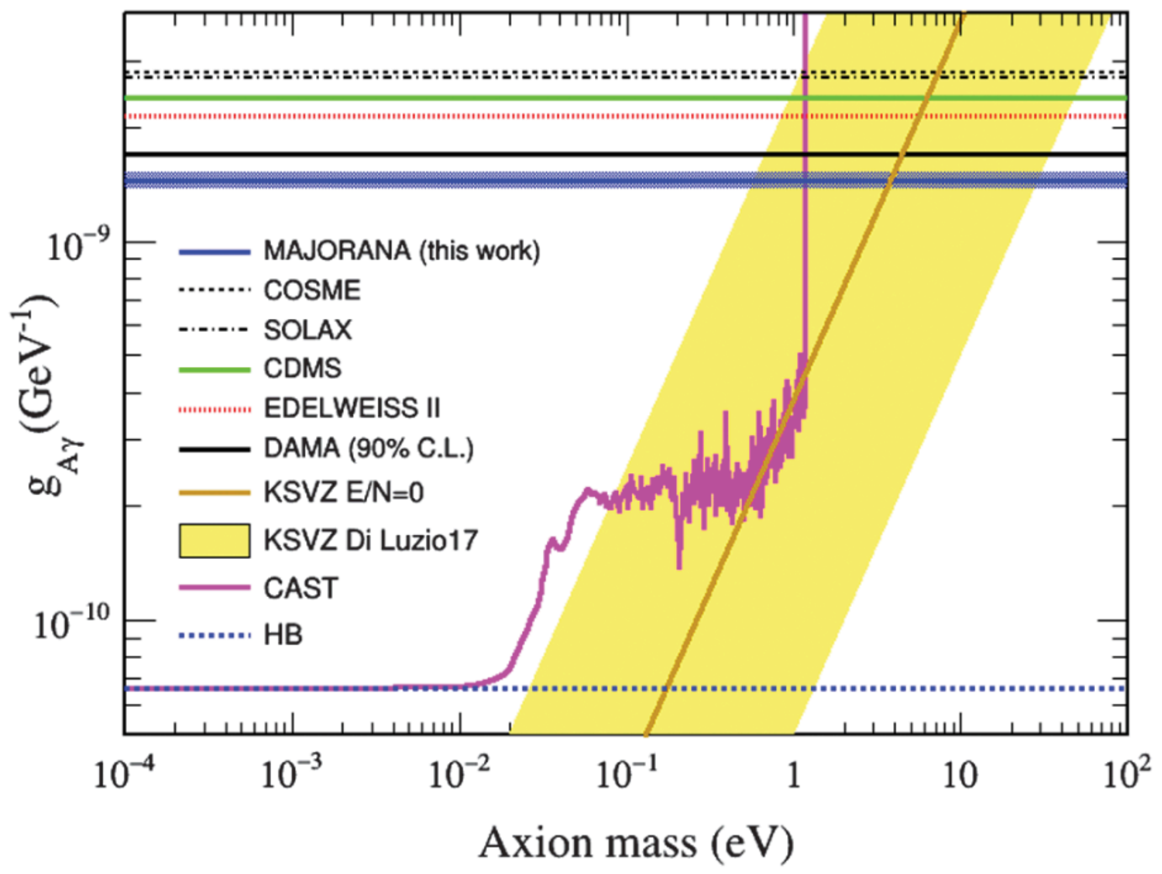
the DEMONSTRATOR is well-positioned to look for Beyond Standard Model physics at low energy:

- Solar axion-photon coupling, wavefunction collapse (PRL 2022, 2 articles!)
- Bosonic, fermionic, and other exotic dark matter (PRL 2017, update in review)
- Lightly ionizing (fractionally-charged) particles (PRL 2018)
- 14.4 keV solar axions, electron decay (PRL 2017)

MAJORANA results can inform Low-E BSM searches in LEGEND! New background models needed.







More MAJORANA & LEGEND talks at CIPANP!

Walter Pettus (IU), "Final Results from the Majorana Demonstrator"
3 Sep, 8 am, Palm Ballroom 1

Laxman Paudel (USD), "Pulse-Shape-Based Analysis using Machine Learning in the Majorana Demonstrator" 30 Aug, 3:50pm, Palm Ballroom 3

Wenqin Xu (USD), "The search for $0\nu\beta\beta$ and the LEGEND Experiment"
3 Sep, 3:30 pm, Camelia/Dogwood room

Clay Barton (USD), "An update on muon-induced backgrounds in LEGEND-1000"
30 Aug, 4:10 pm, Palm Ballroom 3

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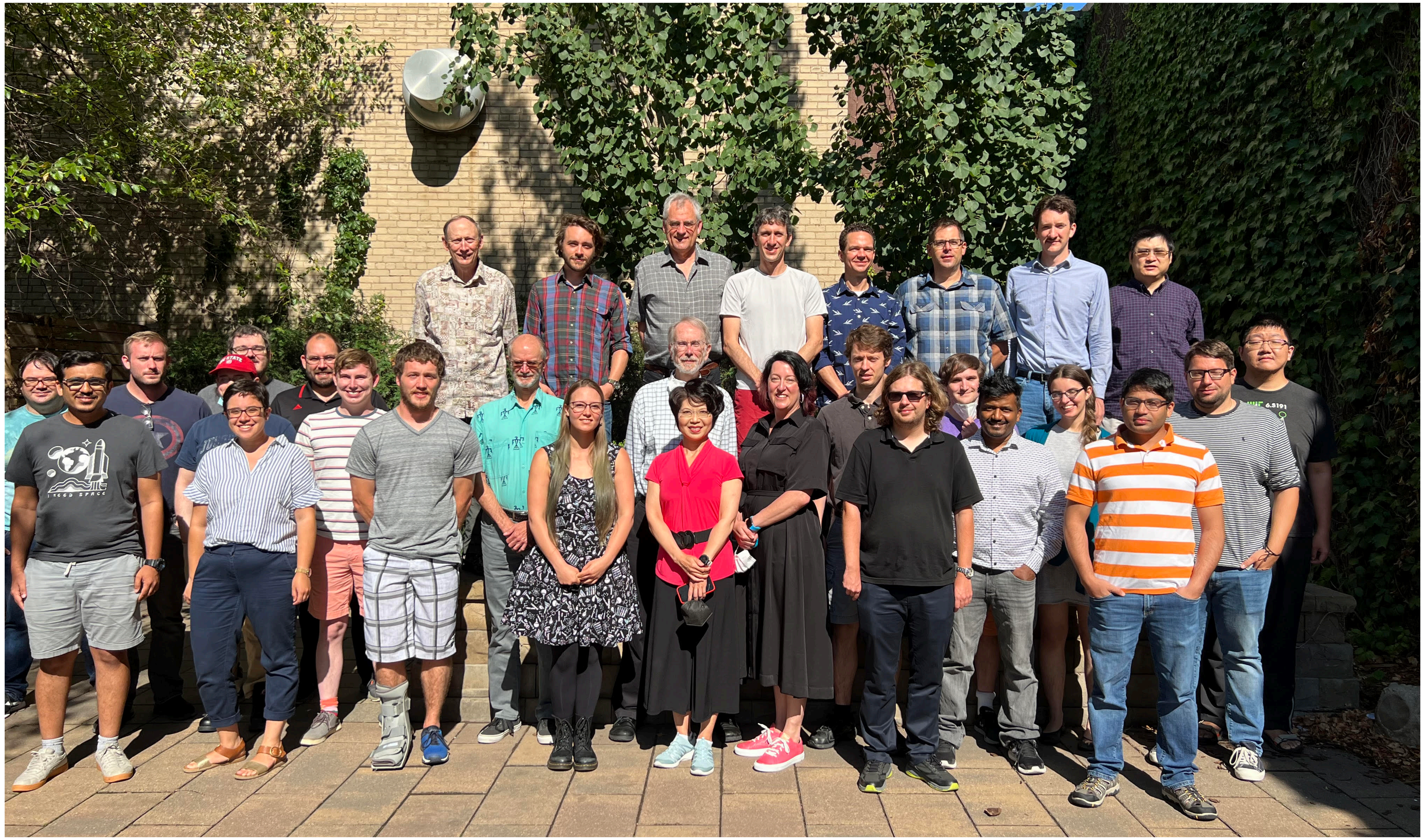

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Kevin Bhimani, Brady Bos, Thomas Caldwell, Morgan Clark, Aaron Engelhardt, Julieta Gruszko, Ian Guinn, Chris Haufe, Reyco Henning, David Hervas, Aobo Li, Eric Martin, Gulden Othman, Anna Reine, Jackson Waters, John Wilkerson

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

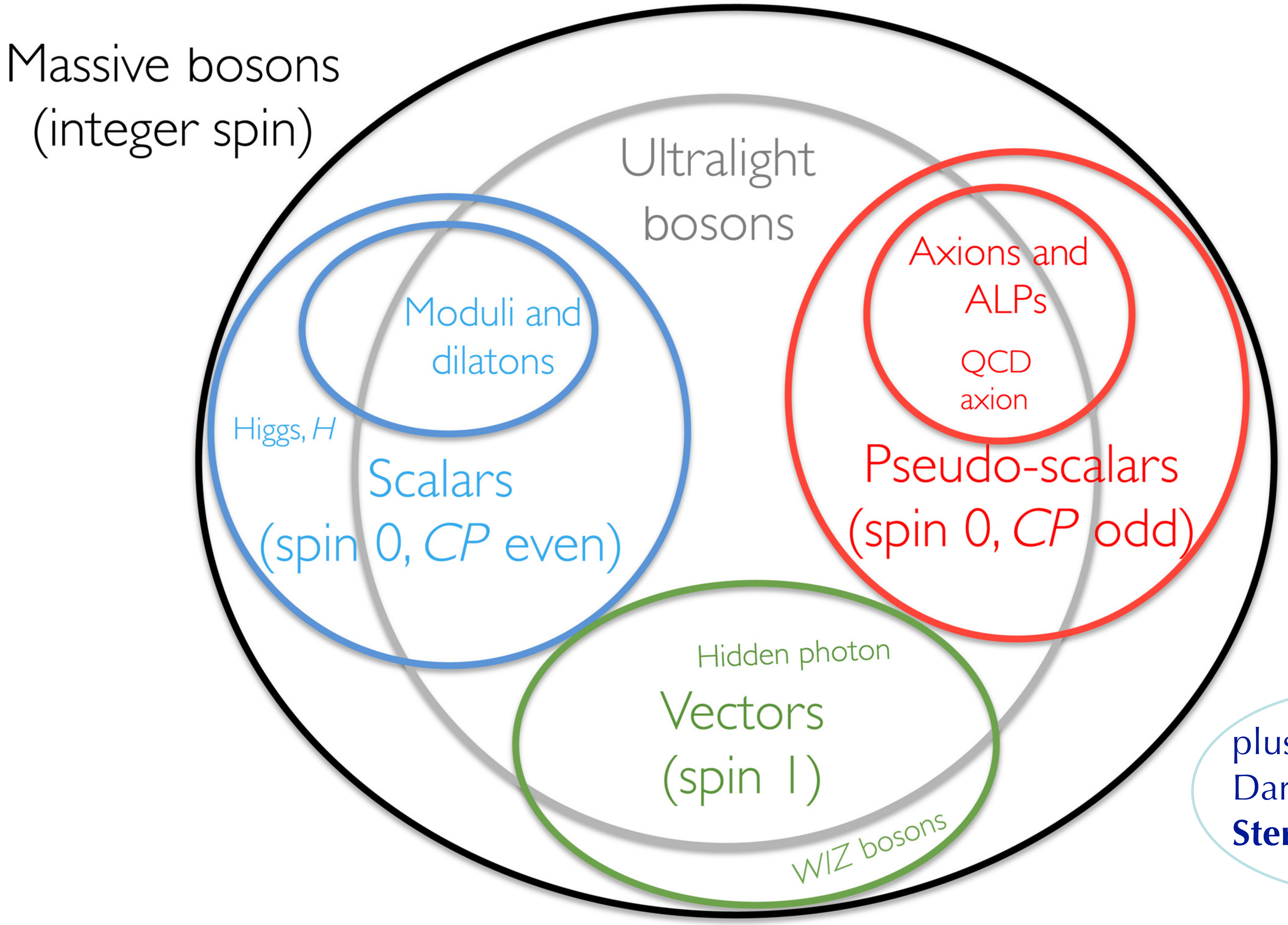
University of Tennessee, Knoxville, TN:
Yuri Efremenko

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

Williams College, Williamstown, MA:
Graham K. Giovanetti

backups

The DM model space is huge!



plus **Fermionic** Dark Matter and **Sterile Neutrinos**

science.org/doi/10.1126/sciadv.abj3618

Recent and upcoming papers!

Several papers utilizing the Low-Energy (1—100 keV) data set are coming off the typewriters:

Wave Function Collapse (arXiv:2202.01343) — Test of quantum measurement problem. **Pub in PRL!**

Solar Axion Search (arXiv:2206.05789) — Best new limit in 21 years since DAMA. **Cover of PRL!**

Exotic Dark Matter Search (arXiv:2206.10638) — Bosonic, fermionic, sterile neutrino. **In review…**

Pauli Exclusion Principle Violation & Charge Conservation — Tests of quantum mechanical principles

MAJORANA Low-E Analysis Paper — Analysis techniques, data cleaning, efficiency determination

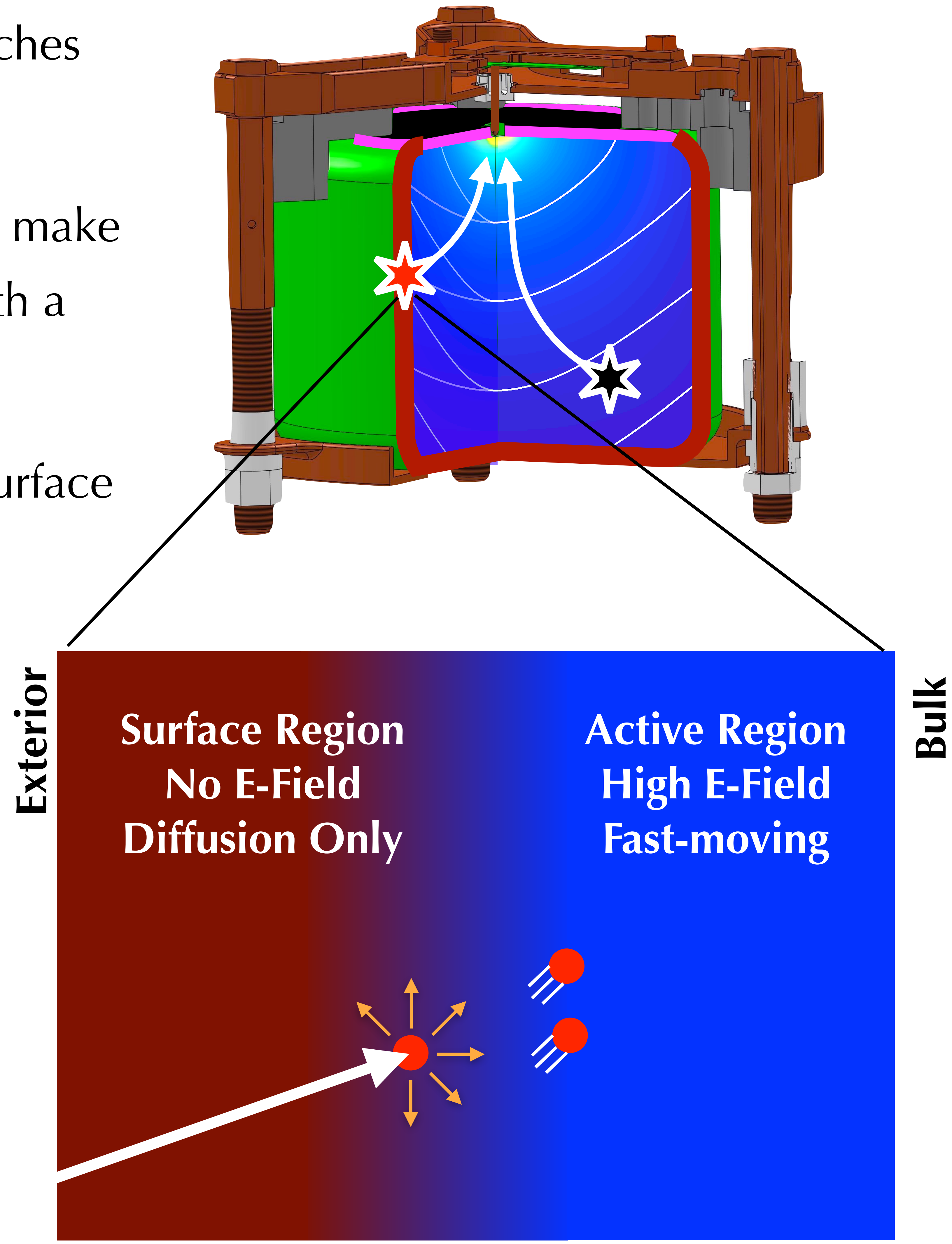
enriched Ge Cosmogenics — Surface exposure calculation and comparison to measured rates

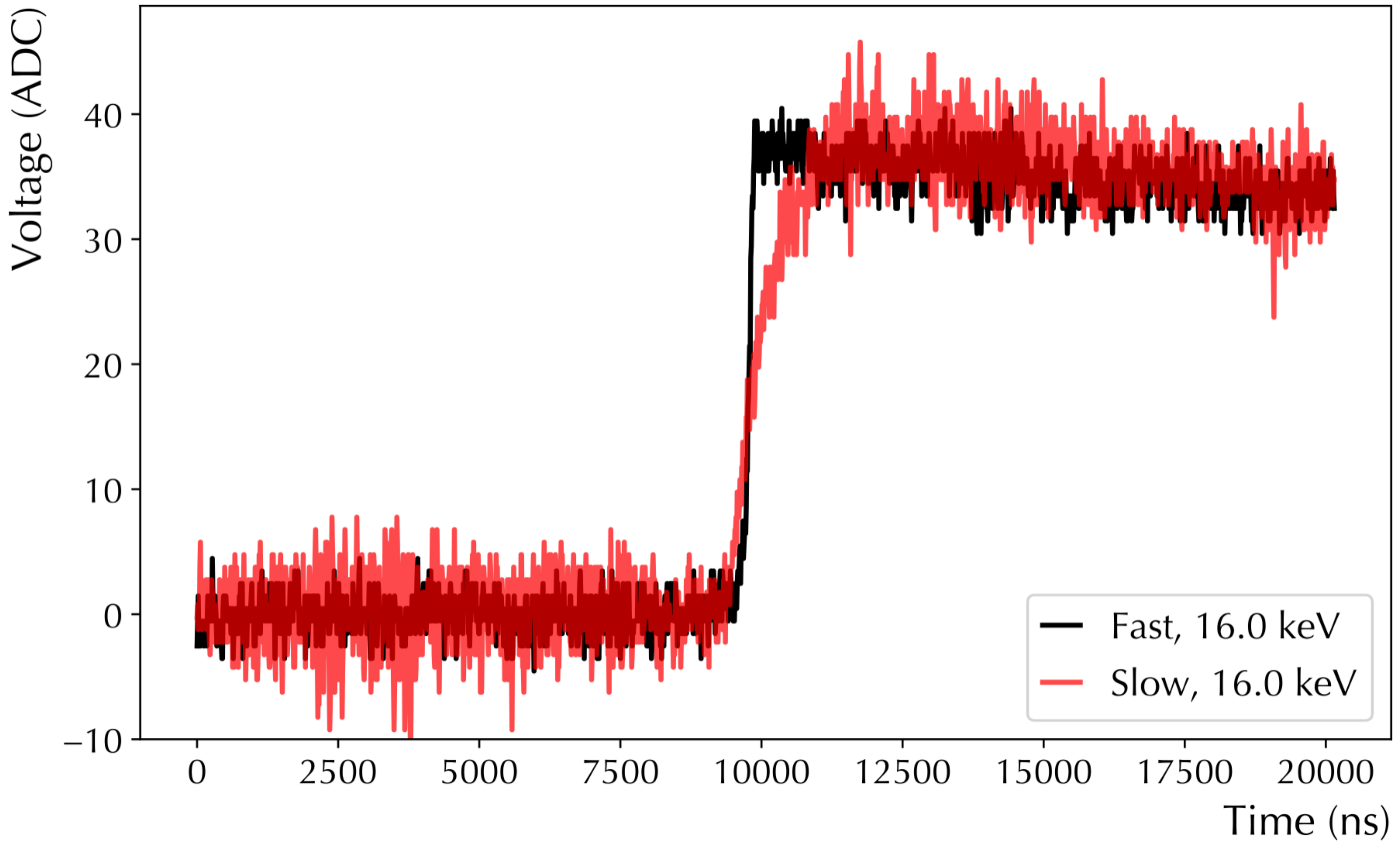
Surface Events in HPGe Detectors

Energy-degraded events from near the n+ surface are a challenging background for low-energy rare event searches with PPC HPGe detectors **(CoGeNT, CDEX, MALBEK, …)**

Charges slowly diffuse through the Ge/Li layer, and some make it to the bulk region after a delay, producing pulses with a measurably slower rise time

Degradation at the passivated surface is also possible. Surface charge @ passivated surface causes non-perp field



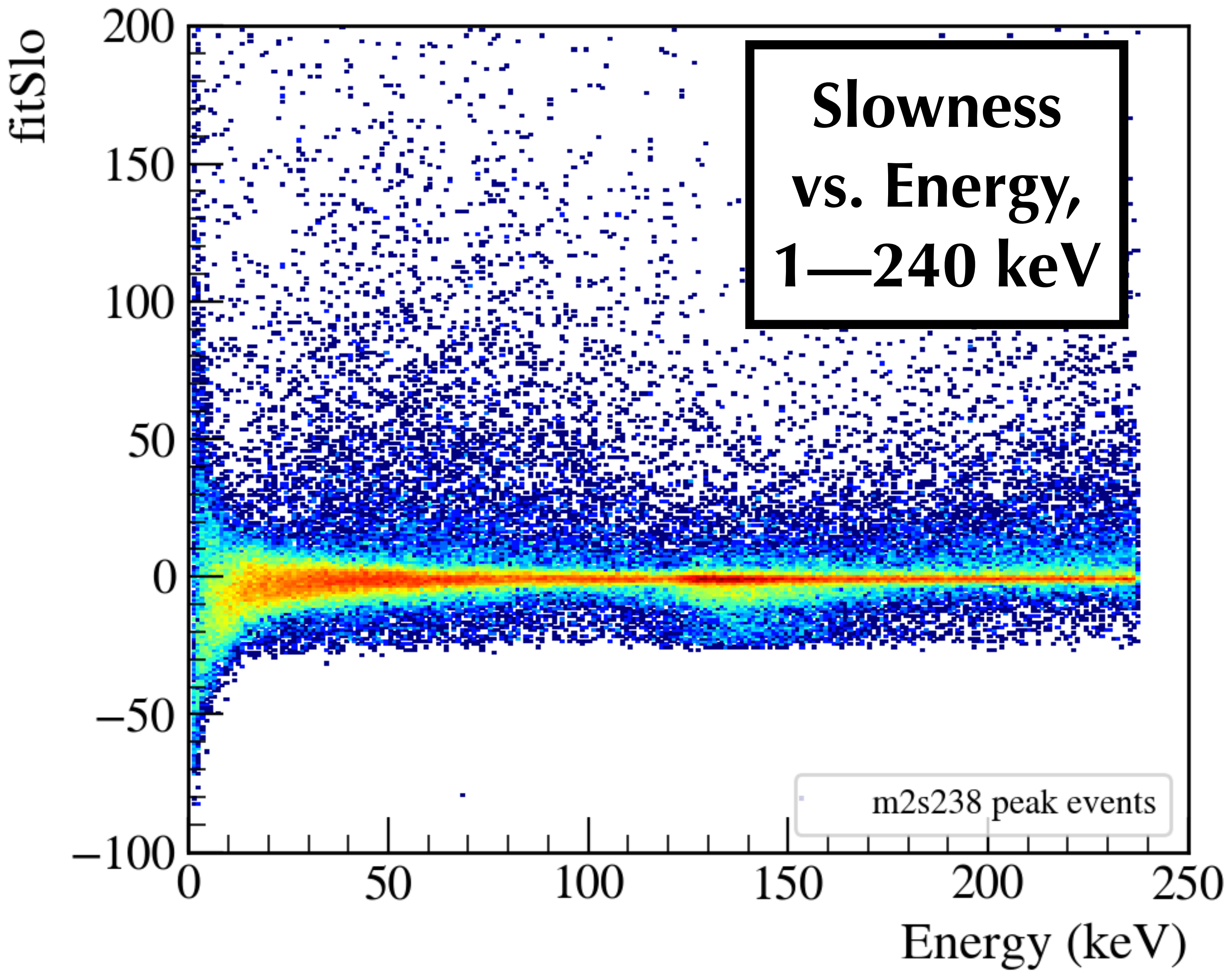


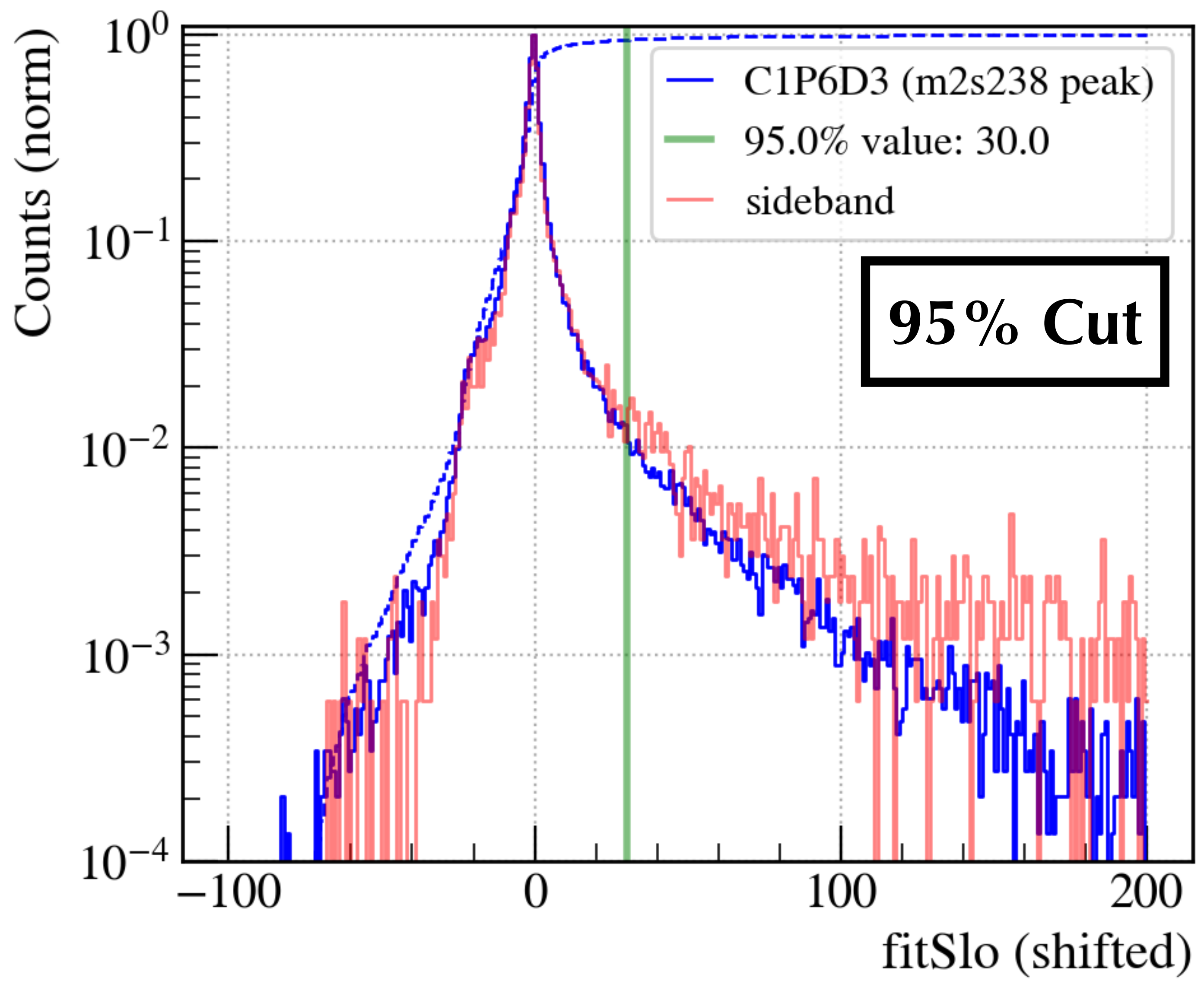
Measuring Slow Pulse Cut Efficiency

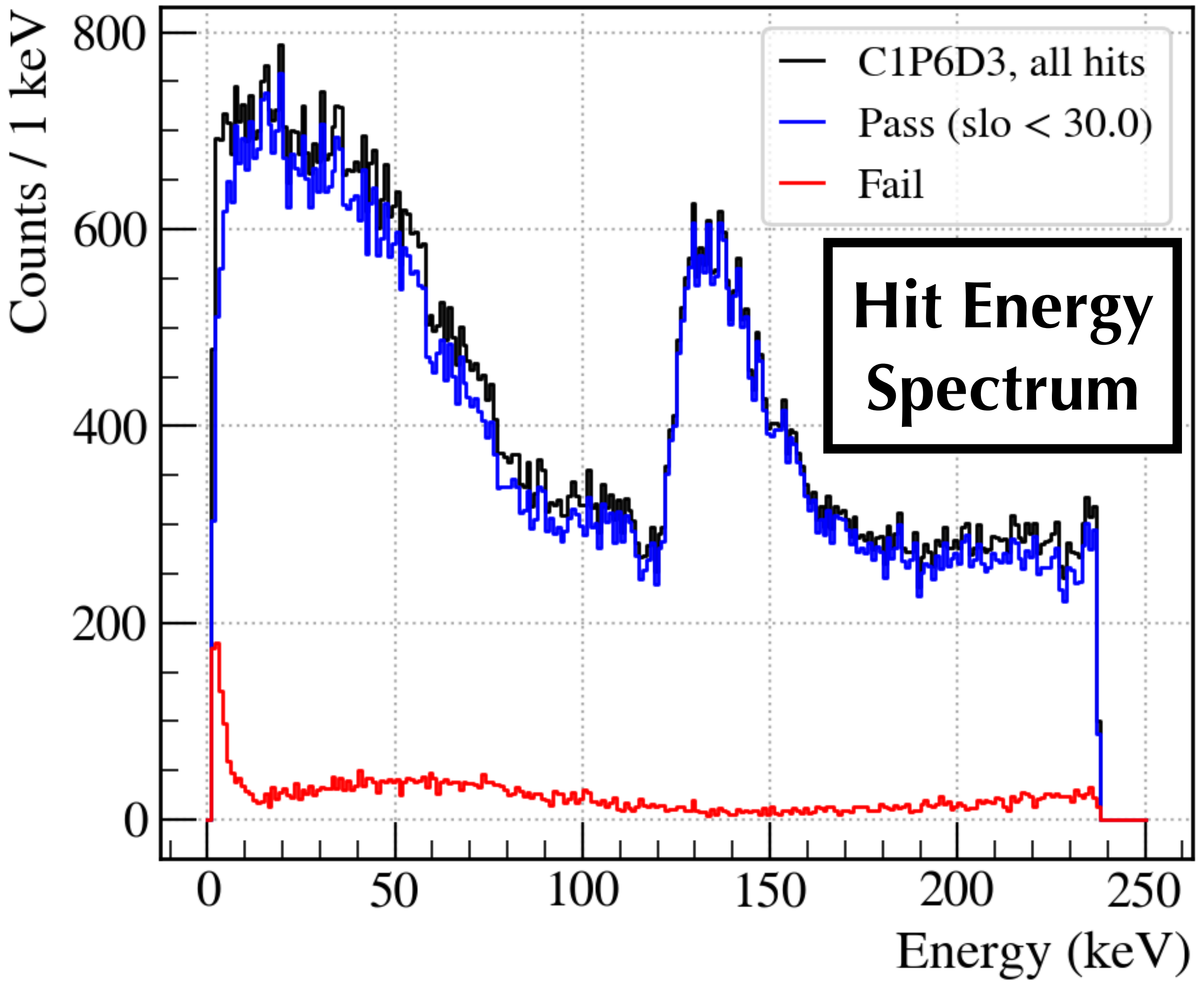
Efficiency is measured for each detector w/ Compton data, each detector is exposure-weighted.

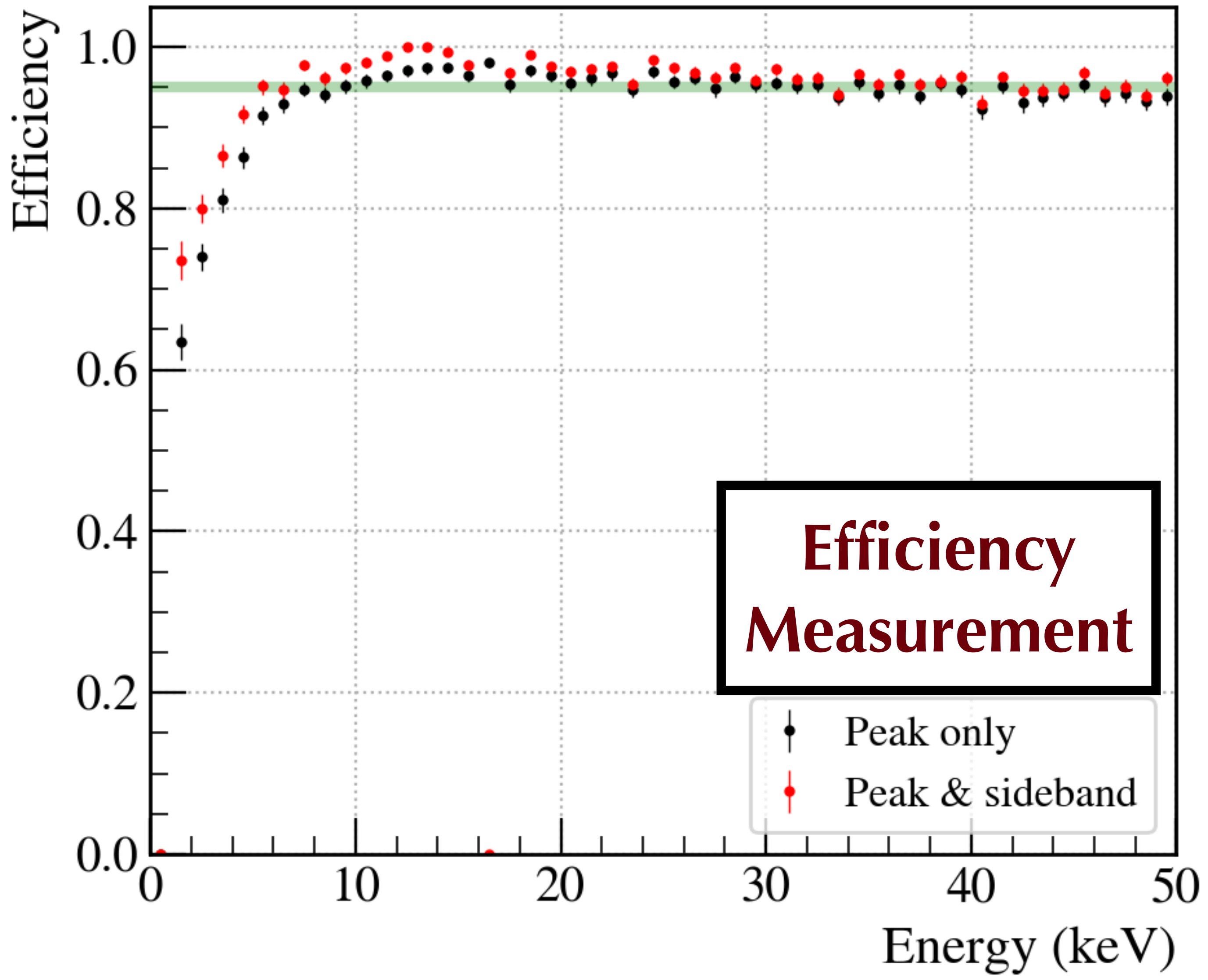
We tune the cut to accept 95% of the Compton detector hits (which sum to 238 keV) and then compute efficiency for each energy:

$$\epsilon(E) = \frac{N_{pass}(E) - \tau B_{pass}(E)}{N_{tot}(E) - \tau B_{tot}(E)}$$









^{enr}Ge and ^{nat}Ge Detector Cut Efficiency

Final cut efficiency is obtained from convolving our energy-dependent slow pulse (red) and threshold (green) curves.

We apply an additional flat 95% efficiency from a high-frequency noise cut.

Threshold efficiency shows most detectors active at ~2 keV. Slow pulse efficiency uncertainty is larger in natural detectors due to positions in array. Final efficiency uncertainty is still being assessed.