Searches for New Physics with the MAJORANA DEMONSTRATOR

Reyco Henning
U. Of North Carolina at Chapel Hill and Triangle Universities Nuclear Laboratory
On behalf of the MAJORANA Collaboration
March 19, 2023

57th Rencontres de Moriond 2023

The MAJORANA DEMONSTRATOR

Searched for neutrinoless double-beta decay ($0\nu\beta\beta$)of ^{76}Ge in HPGe detectors, probing additional physics beyond the standard model, and informing the design of the next-generation LEGEND experiment

Continuing to operate at the Sanford Underground Research Facility with natural detectors to search for decay of ^{180m}Ta

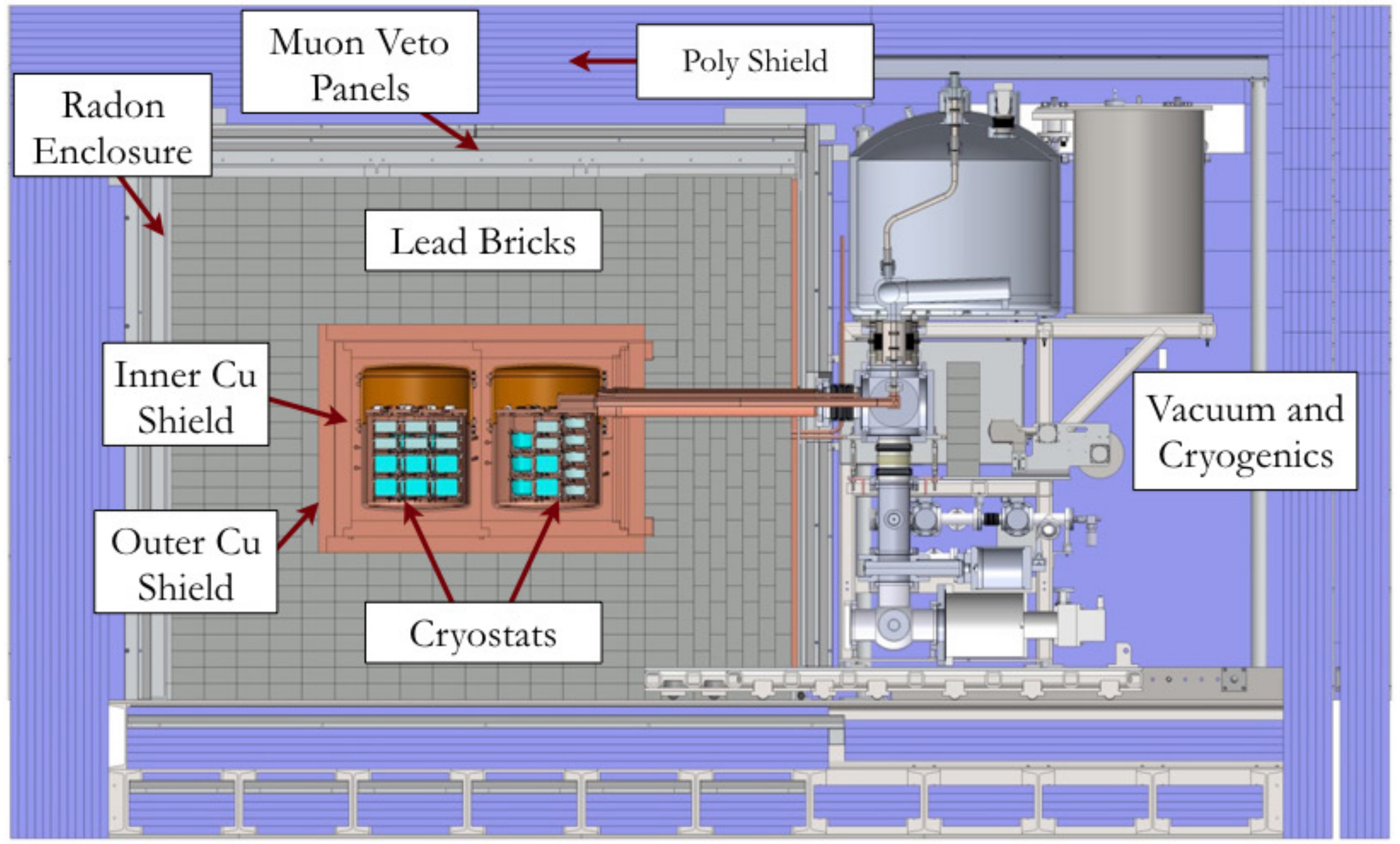
Source & Detector: Array of p-type, point contact detectors

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

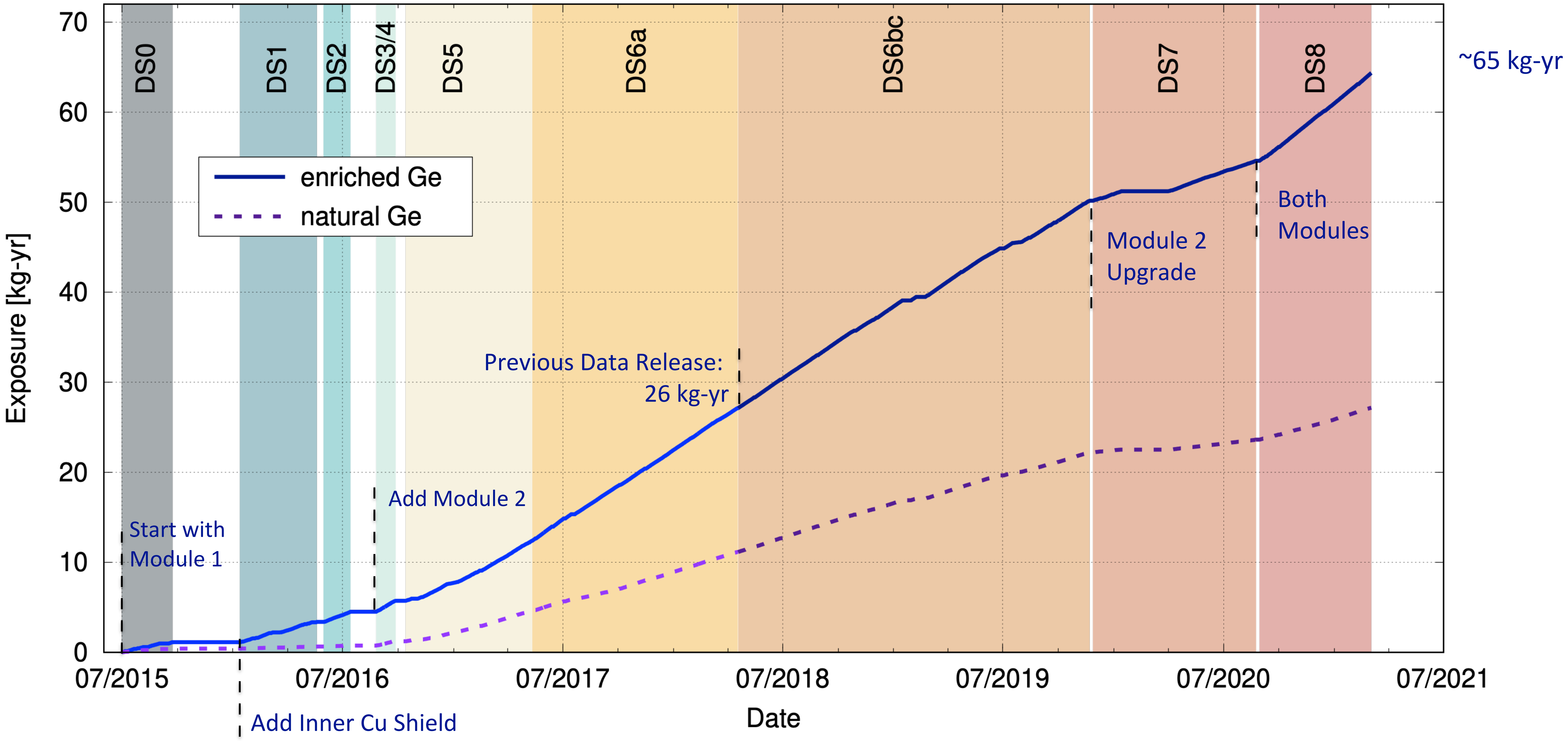
Included 6.7 kg of ^{76}Ge inverted coaxial, point contact detectors in final run

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

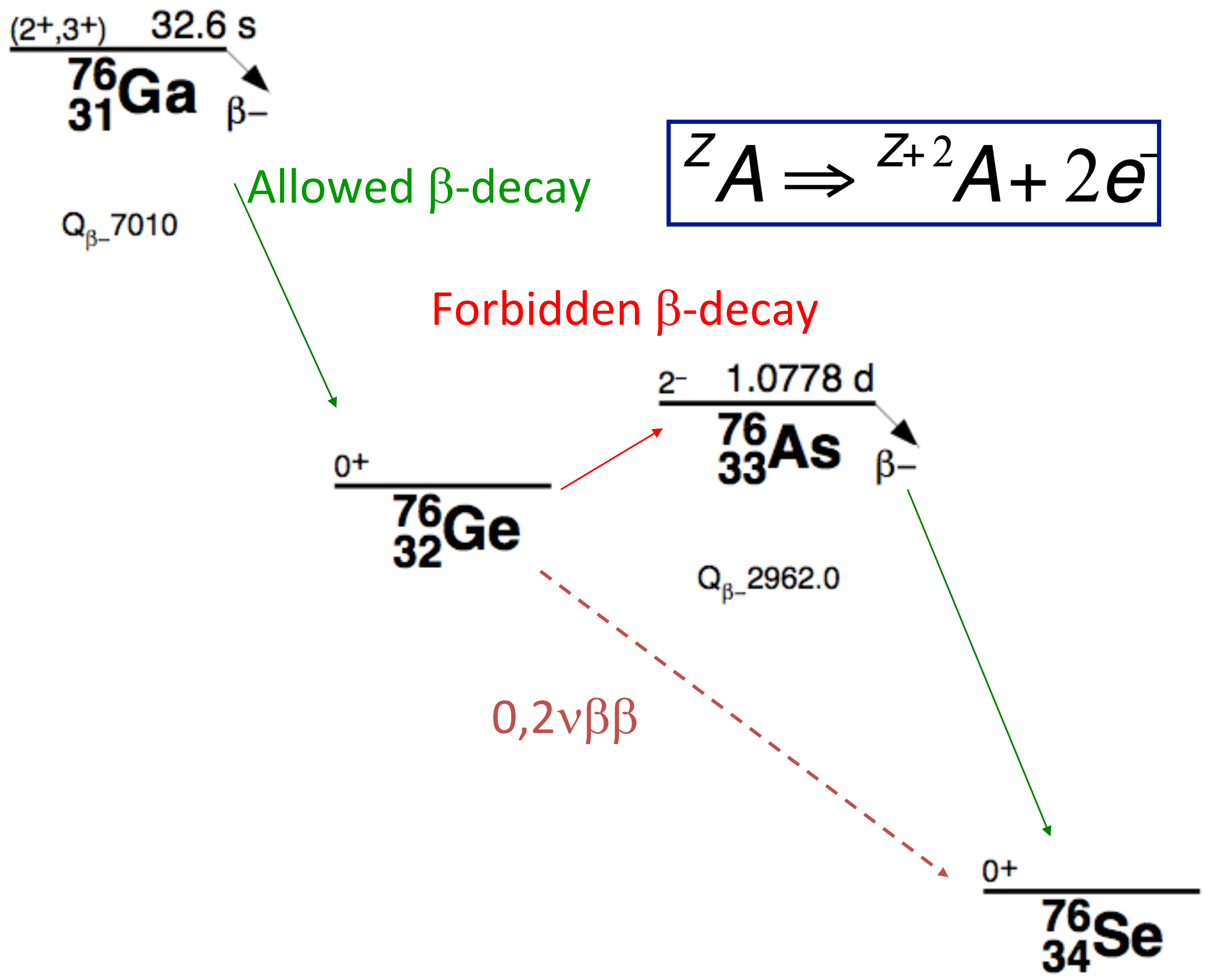


MAJORANA Total Exposure



Motivation for *0νββ* Search

$$^{Z}A \Rightarrow {}^{Z+2}A + 2e^{-}$$



Implications of discovery:

L, *B-L* is not conserved

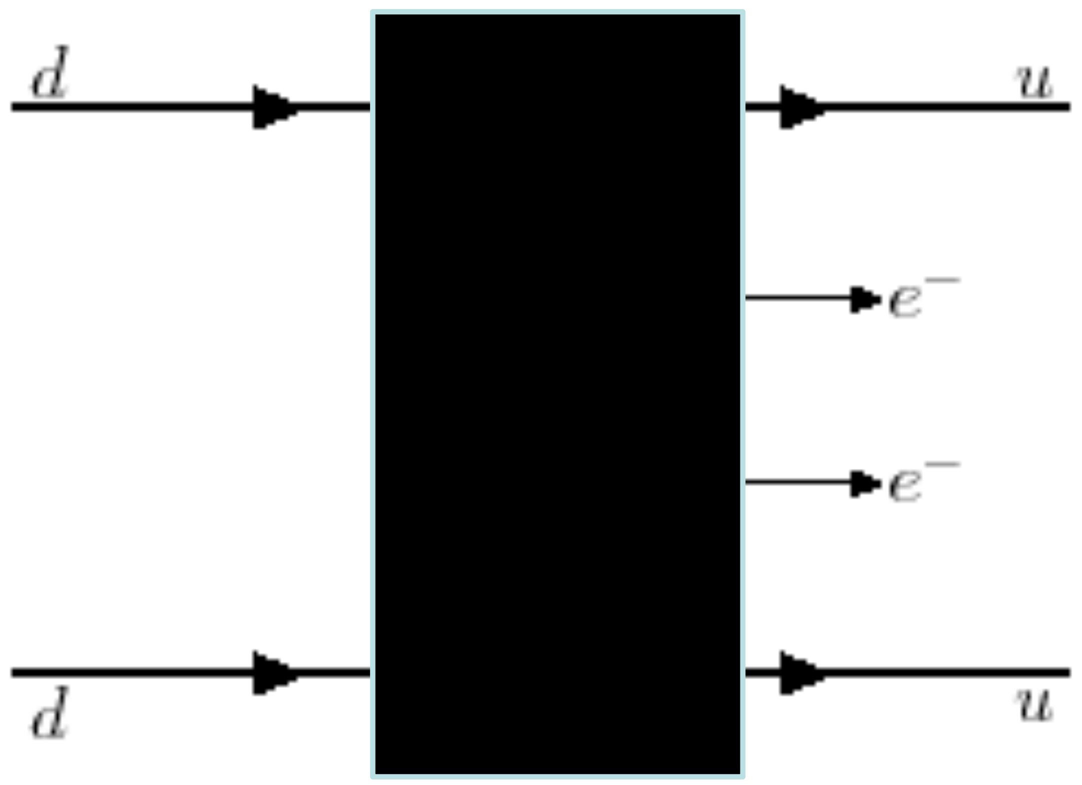
Neutrino is Majorana* (own antiparticle)

Neutrinos have Majorana Mass Term

Probes absolute neutrino mass scale

0νββ nuclear decay may occur via several processes (SUSY, RH currents, etc)

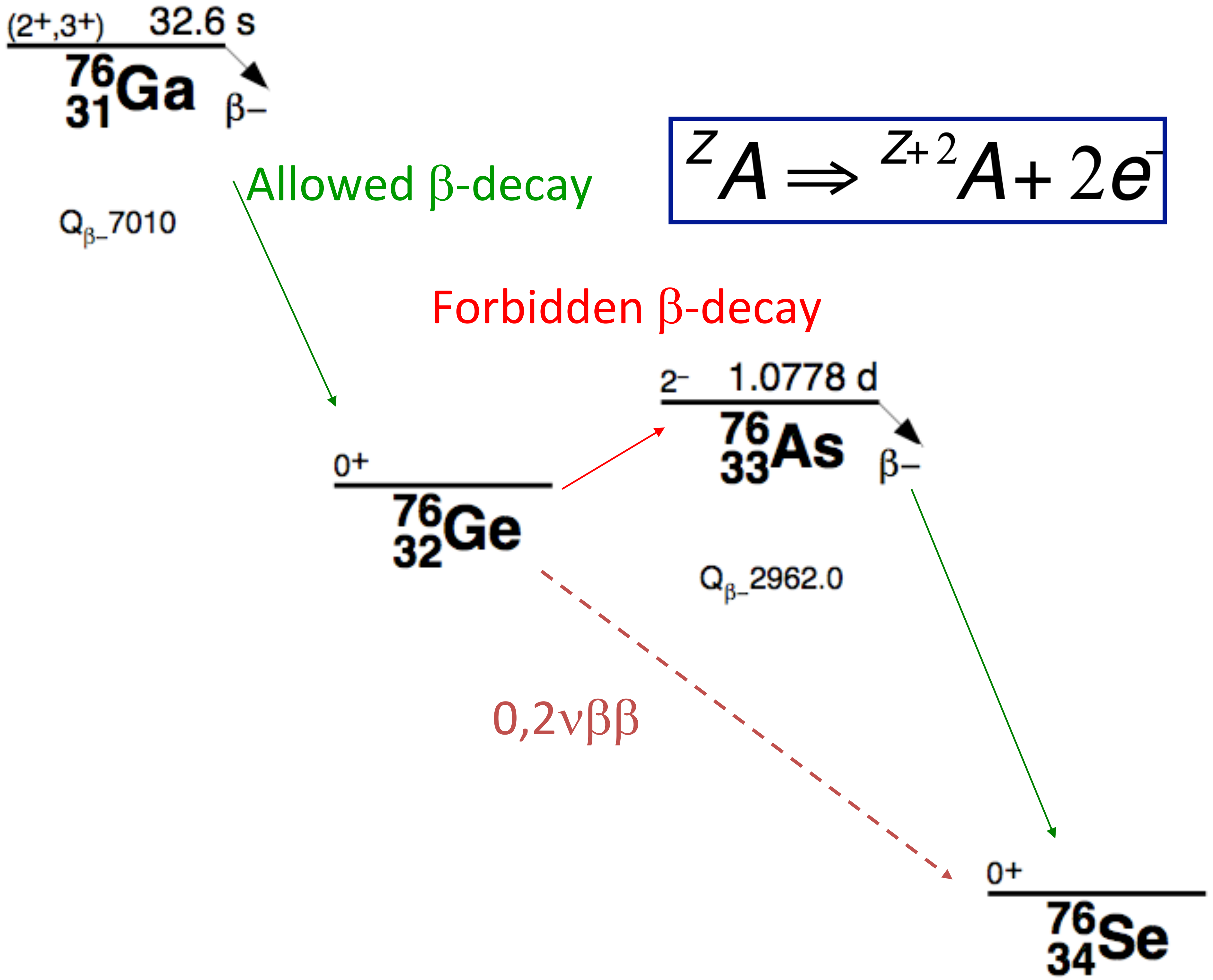
* Schechter et al, Phys. Rev. D**25**, 2951 (1982)



Signal: Peak at Q-value of decay

Motivation for *0νββ* Search

$$^{Z}A \Rightarrow {}^{Z+2}A + 2e^{-}$$



Implications of discovery:

- *L, B-L* is not conserved
- Neutrino is Majorana* (own antiparticle)
- Neutrinos have Majorana Mass Term
- Probes absolute neutrino mass.

0νββ nuclear decay may occur via several processes (SUSY, RH currents, etc)

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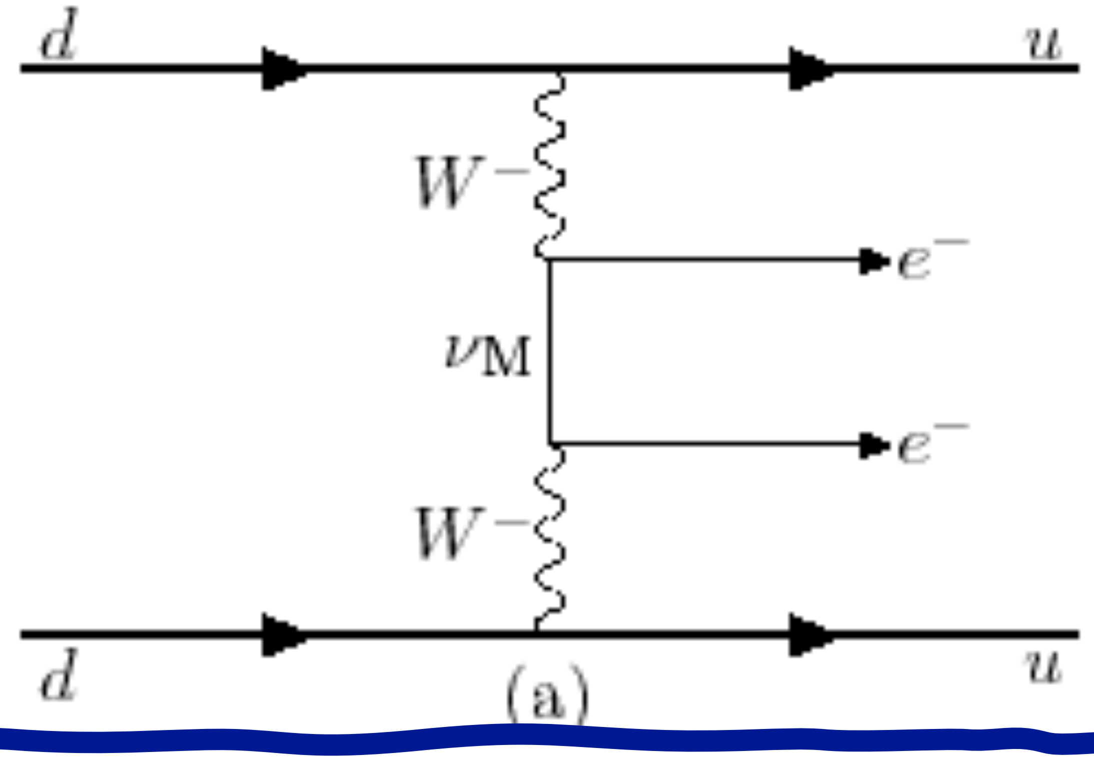
Canonical example: Exchange of virtual Majorana neutrino + helicity flip



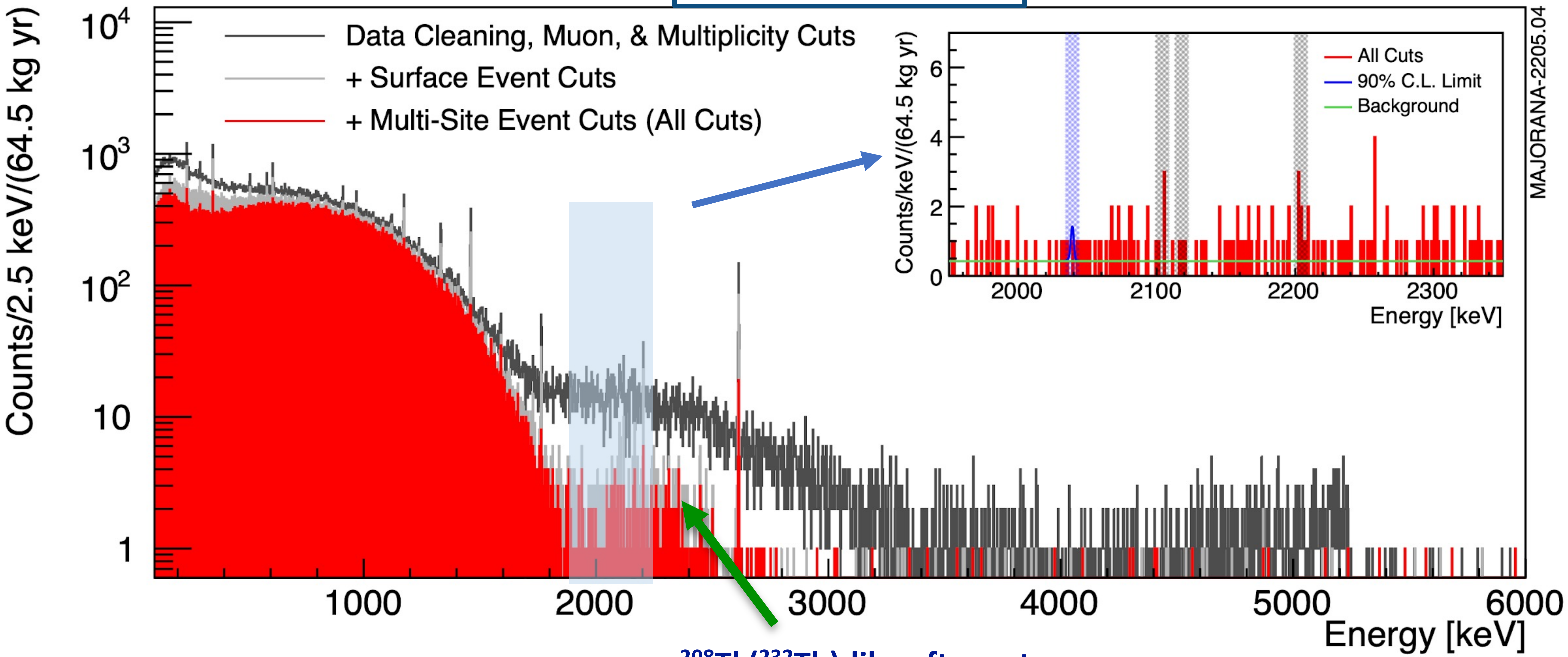
$$\left[T_{1/2}^{0\nu}\right]^{-1} = G^{0\nu}(E_0,Z)\left|\langle m_{\beta\beta}\rangle\right|^{2}\left|M^{0\nu}\right|^{2}$$

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

MAJORANA DEMONSTRATOR Final *0νββ* Result

Operating in a low background regime and benefiting from excellent energy resolution

PRL 130 062501 (2023)



^{208}Tl (^{232}Th)-like after cuts

Final enriched detector active exposure:

64.5 ± 0.9 kg-yr

Background index at 2039 keV in lowest background configuration

15.7 ± 1.4 cts/(FWHM t yr)

Second lowest background index by any 0νββ search to date!

MAJORANA DEMONSTRATOR Final $0\nu\beta\beta$ Result

Background Index: $(15.7 \pm 1.4) \times 10^{-3}$ cts/(FWHM kg yr)

Expect 1.5 background counts in 3.8 keV ROI; measured 1 count

Frequentist Limit:

65 kg-yr Exposure Limit: $T_{1/2} > 8.3 \times 10^{25}$ yr (90% C.I.)

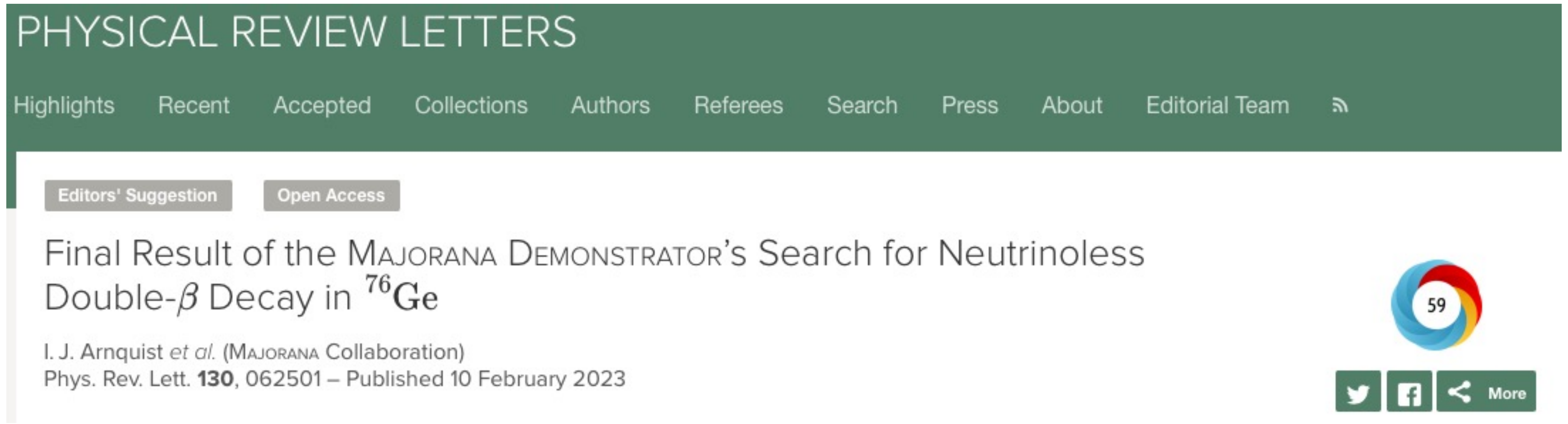
Median $T_{1/2}$ Sensitivity: 8.1×10^{25} yr (90% C.I.)

Bayesian Limit: (flat prior on rate)

65 kg-yr Exposure Limit: $T_{1/2} > 7.0 \times 10^{25}$ yr (90% C.I.)

$m_{\beta\beta} < 113 - 269$ meV

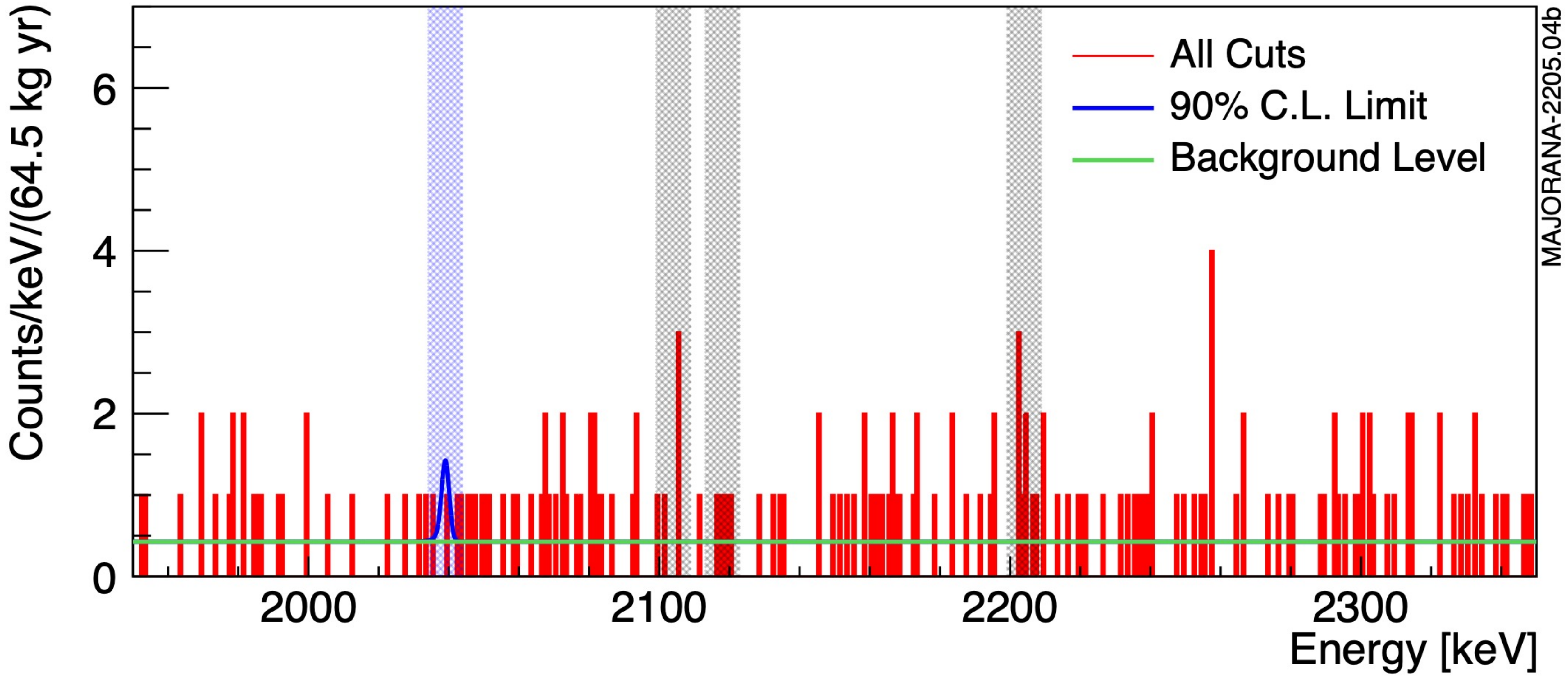
Using $M_{0\nu} = 2.66 - 6.34$



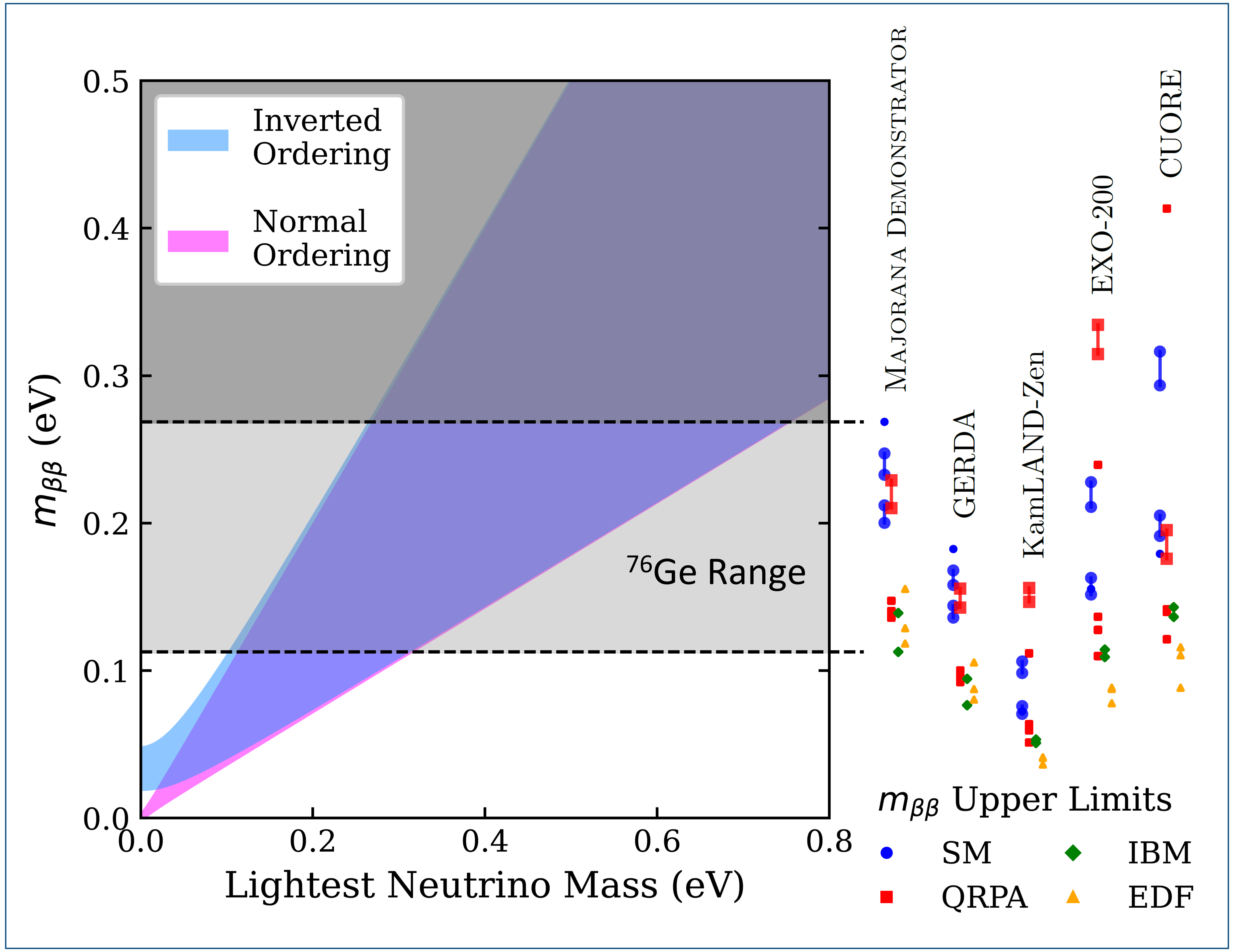
PHYSICAL REVIEW LETTERS

Final Result of the MAJORANA DEMONSTRATOR's Search for Neutrinoless Double-β Decay in ^{76}Ge

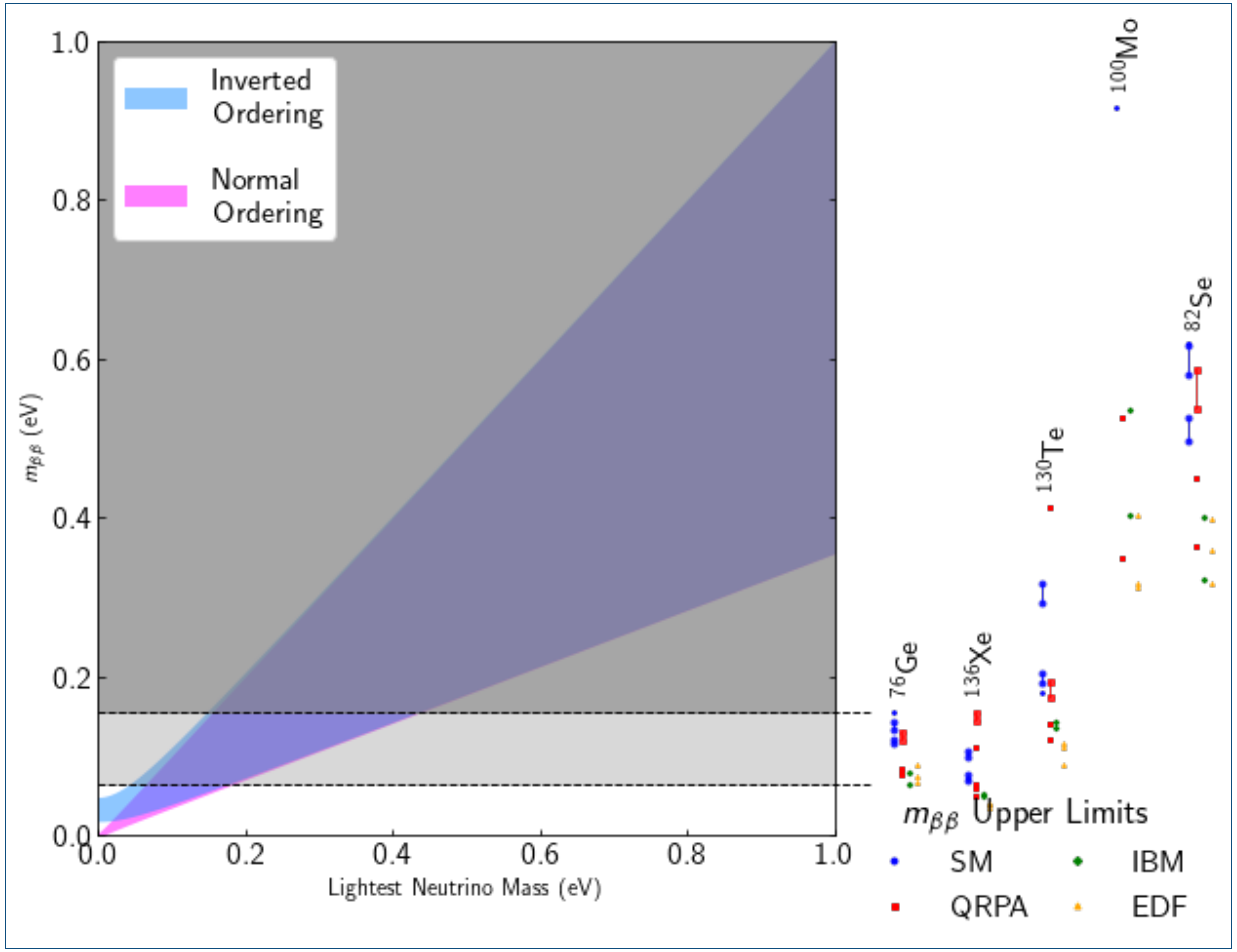
I. J. Arnquist *et al.* (MAJORANA Collaboration)
Phys. Rev. Lett. **130**, 062501 – Published 10 February 2023



Current Limits



Experimental Limits



Combined Limits per Isotope

Rich and Broad Physics Programs

Majorana Demonstrator
Excellent energy resolution
High Granularity
Low Backgrounds

Fundamental Symmetries
- *B, L, Q* violation
- Pauli Exclusion Principle violation

Standard Model
- In-situ cosmogenic productions
- $2\nu\beta\beta$ decays

Dark Matter Signatures
- Pseudoscalar dark matter
- Vector dark matter
- Fermionic dark matter
- Sterile neutrino
- Solar Axions

Exotic Physics
- Quantum Wavefunction collapse
- Lightly ionization particles

Rich and Broad Physics Programs

Fundamental Symmetries

B, L, Q violation

Pauli Exclusion Principle violation

PRC **100** 025501 (2019)

PRC **103** 015501 (2021)

PRD **99** 072004 (2019)

arXiv:2203.02033 (2022)

Standard Model

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PRC **105** 014617 (2022)

PRC **105** 064610 (2022)

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PRL **118** 161801 (2017)

PRL **129** 081803 (2022)

arXiv:2206.10638 (2022)

Exotic Physics

Quantum Wavefunction collapse

Lightly ionization particles

PRL **129** 080401 (2022)

PRL **120** 211804 (2018)

Rich and Broad Physics Programs

On the Cover

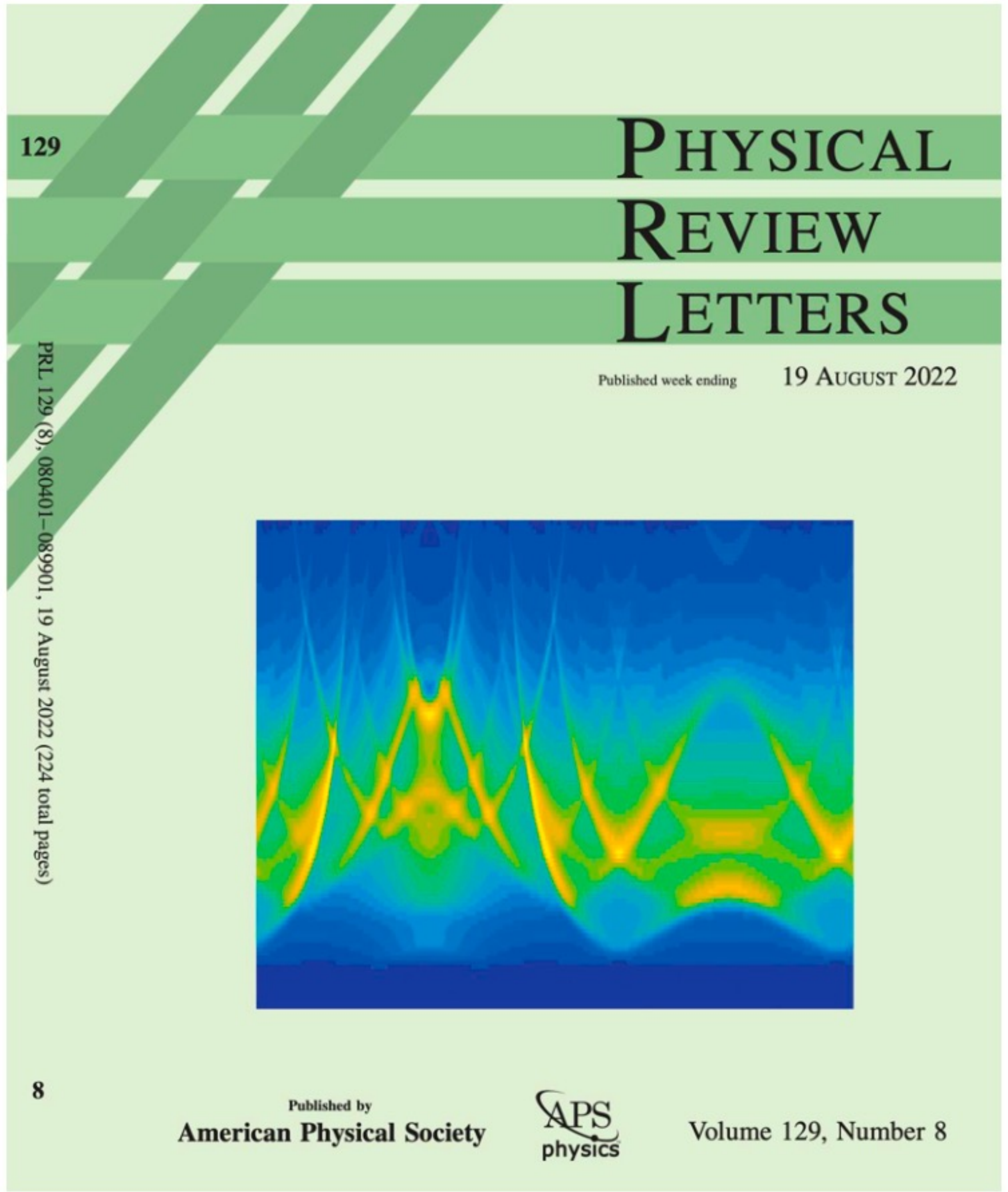
Axion signatures from coherent Primakoff-Bragg scattering over a 24-hour period.

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)



129

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PRL 129 (8), 080401–089901, 19 August 2022 (224 total pages)

8

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Volume 129, Number 8

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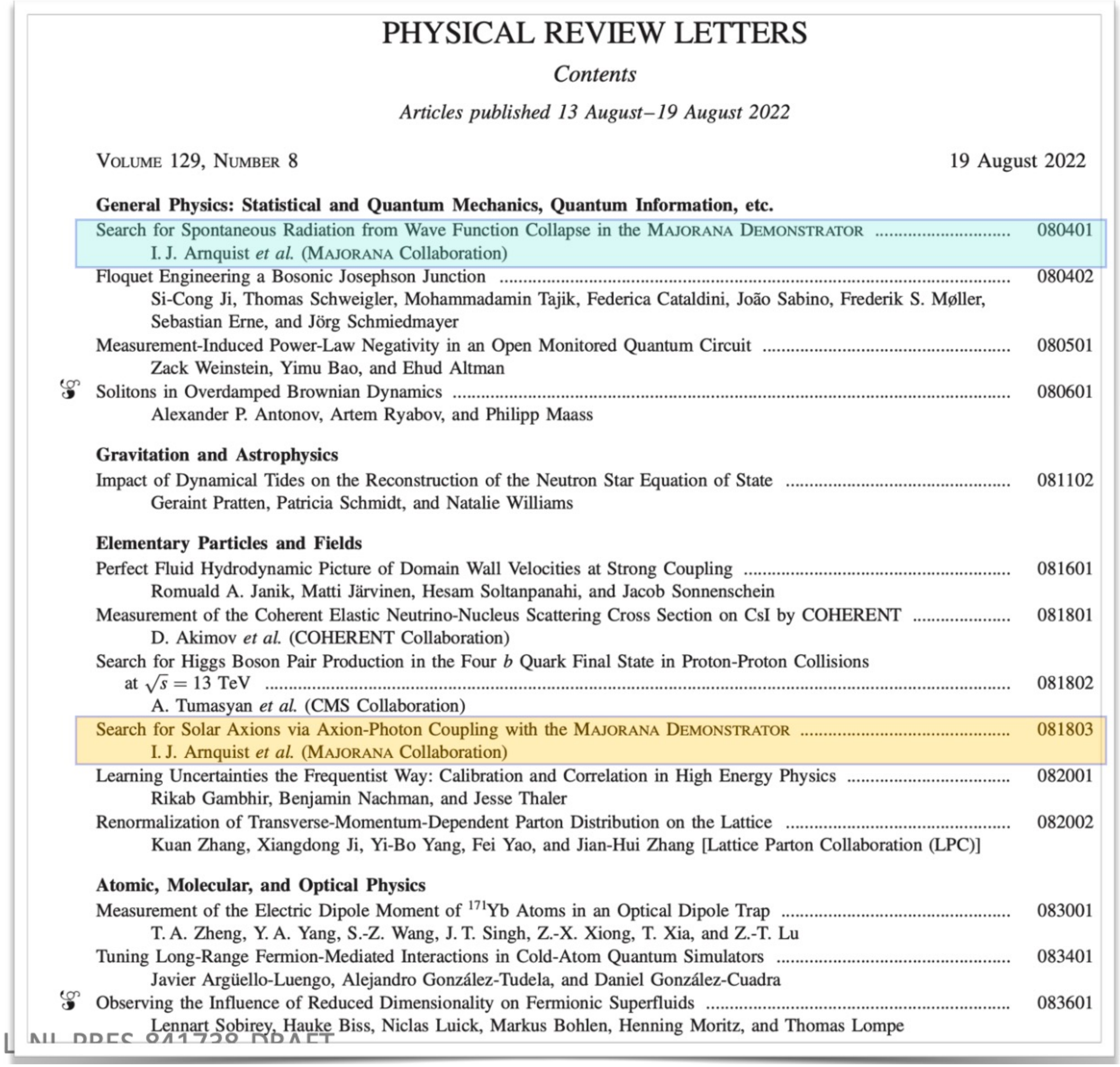

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Lightly ionization particles

PRL **129** 080401 (2022)
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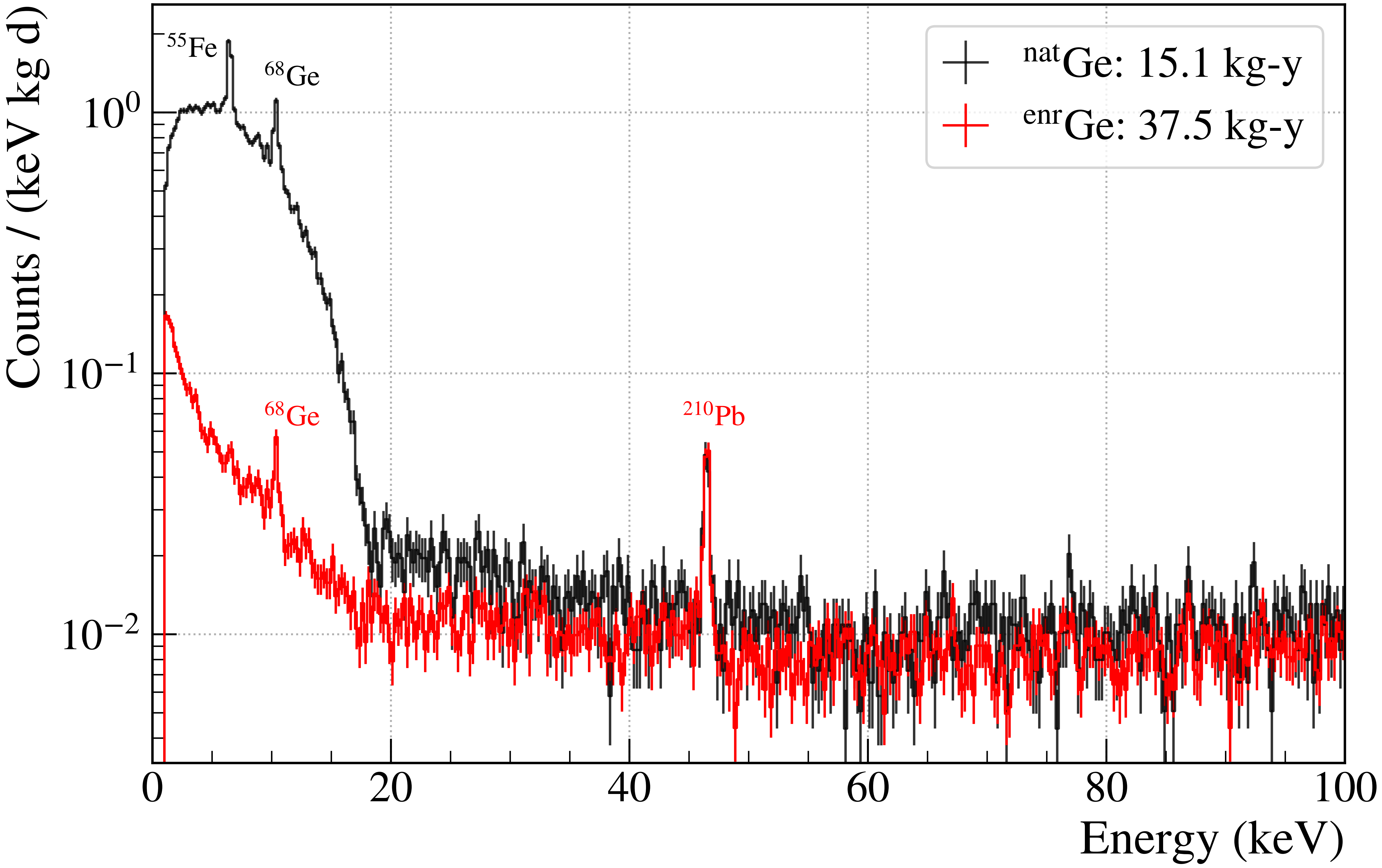
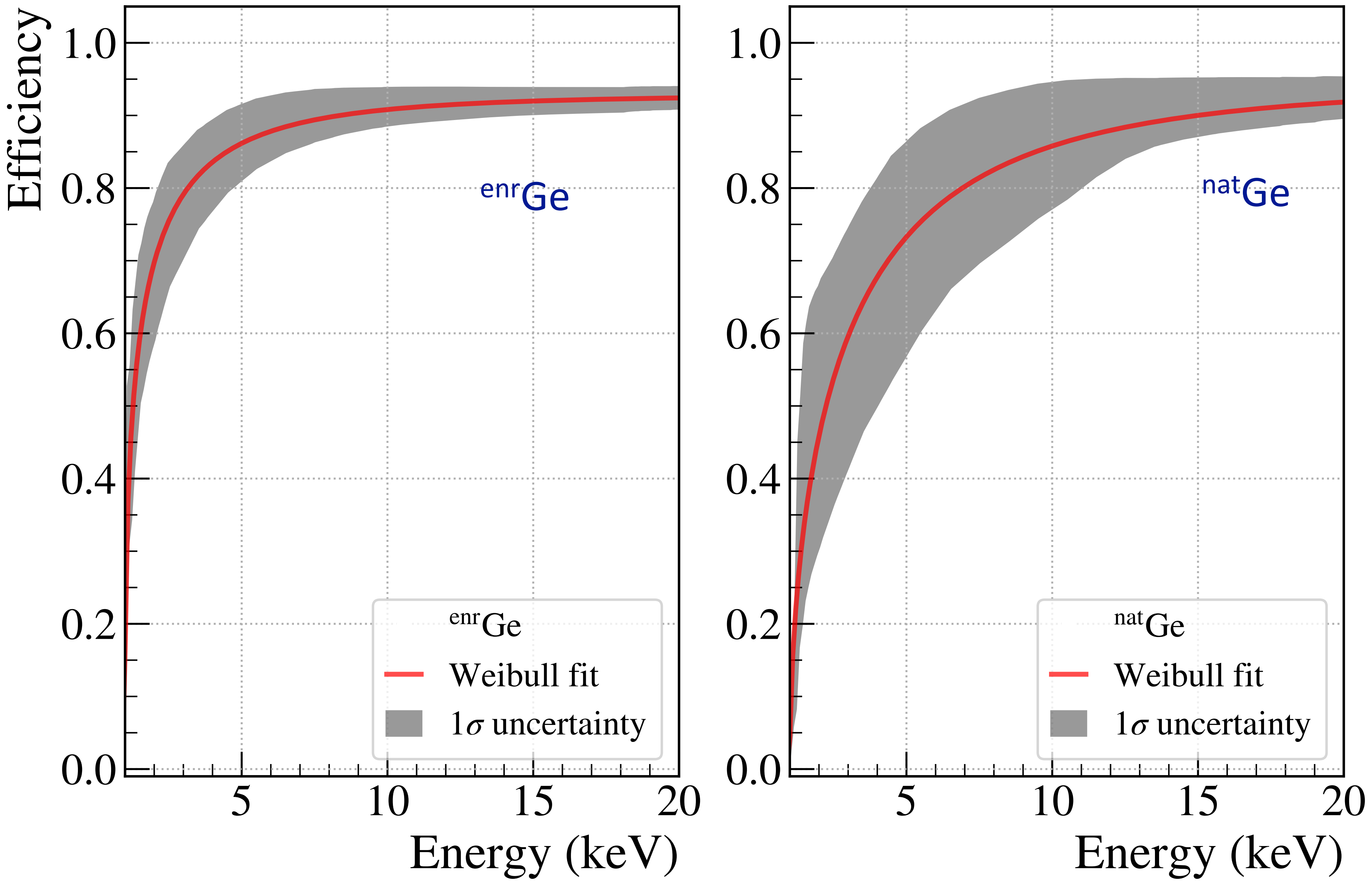
Beyond the Standard Model Searches

- Low detector capacitance and low-noise electronics
  - Excellent energy resolution: ~0.4 keV FWHM at 10.4 keV
  - 1 keV Analysis Threshold
- Low electron recoil background (for solid state)
  - Low background materials and construction
  - Controlled surface exposure of enriched material minimized cosmogenics

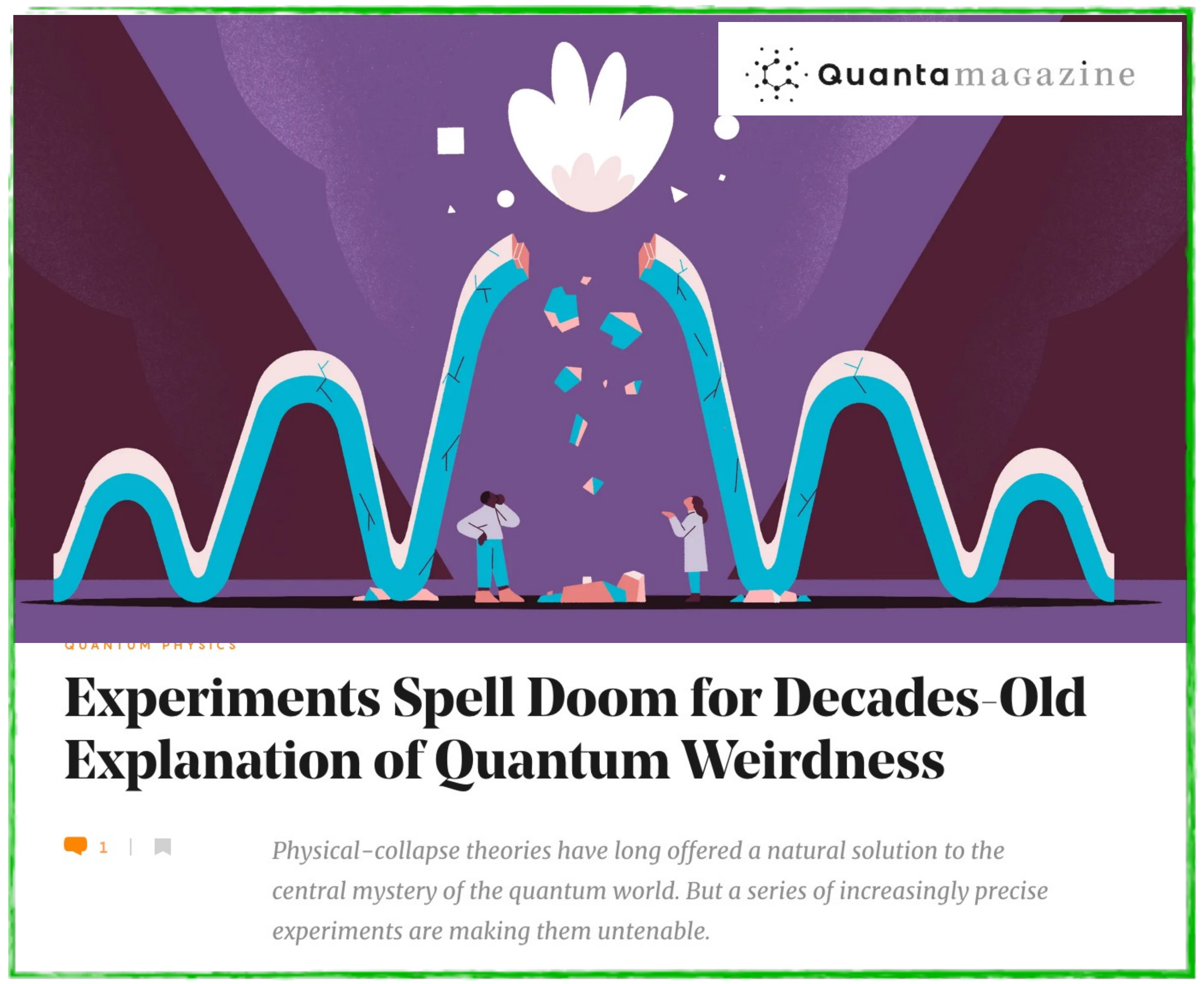
IEEE trans. Nucl. Sci. 36 , 926 (1989)
JCAP 0709 (2007)
JINST 17 (2022) 05, T05003





2206.10638, submitted to PRL

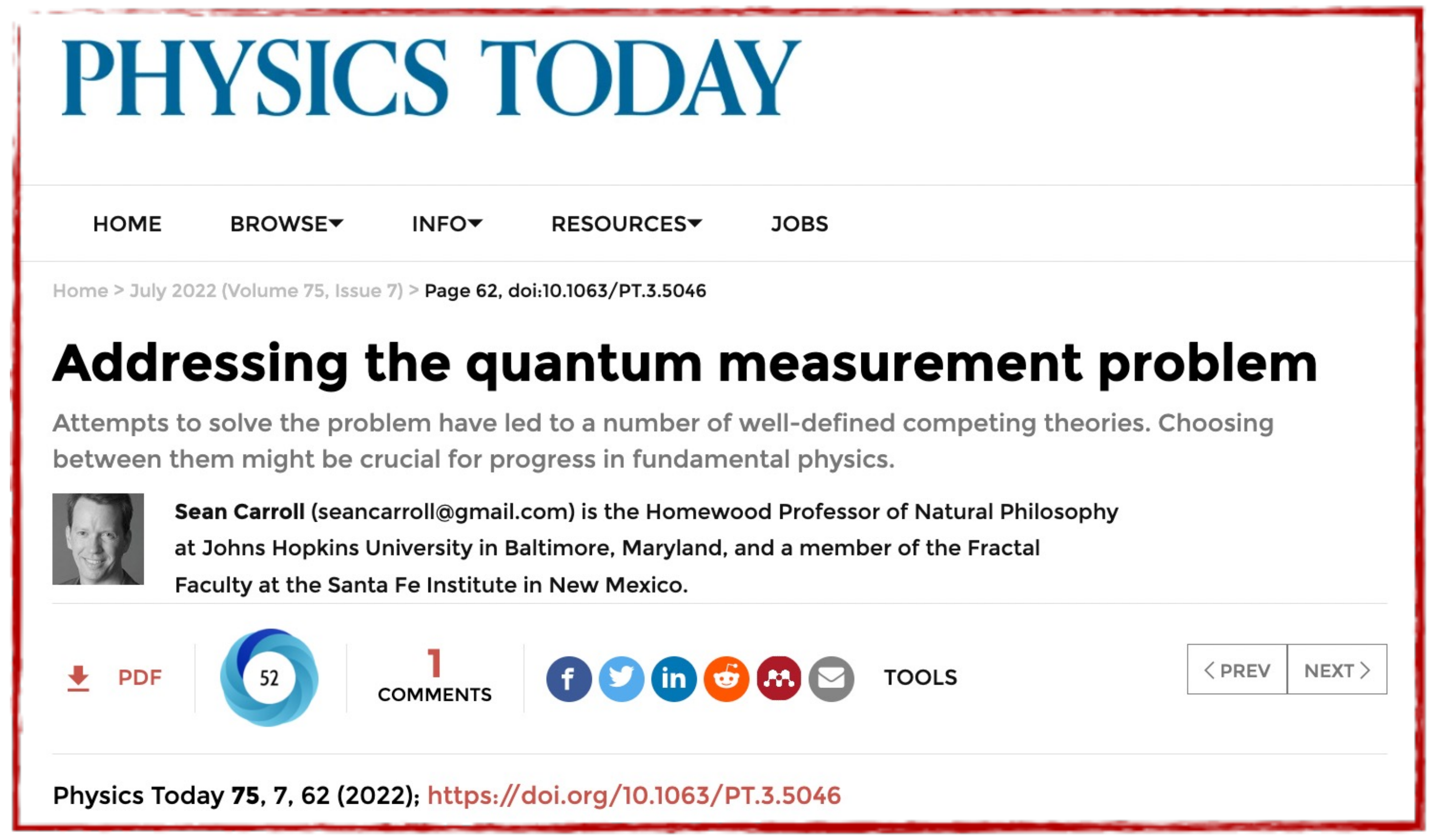
Quantum Wavefunction Collapse (WFC)



Experiments Spell Doom for Decades-Old Explanation of Quantum Weirdness

Physical-collapse theories have long offered a natural solution to the central mystery of the quantum world. But a series of increasingly precise experiments are making them untenable.

A timely result for MAJORANA with interdisciplinary appeal! Featured in Quanta magazine, Oct 2022. Article by Sean Carroll highlights broader interest from the community for this style of test.



Home > July 2022 (Volume 75, Issue 7) > Page 62, doi:10.1063/PT.3.5046

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.

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

Schrödinger Equation and Time Evolution in QM is Linear

Wave-function Collapse is non-Linear Process

Microscopic systems can exist in superposition but macroscopic objects do not.

No ”smooth” transition from quantum to classical in Copehagen interpretation.

Properties of WFC Models:

- Non-linear
- Stohastic
- Amplification/Scaling
- No superluminal Signaling

Non-linear interaction with cosmological

noise field (gravity?)

For review see, Rev Mod Phys **85** 471 (2013)

X-ray Emission Signature of WFC in Continuous Spontaneous Localization Models (CSL):

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

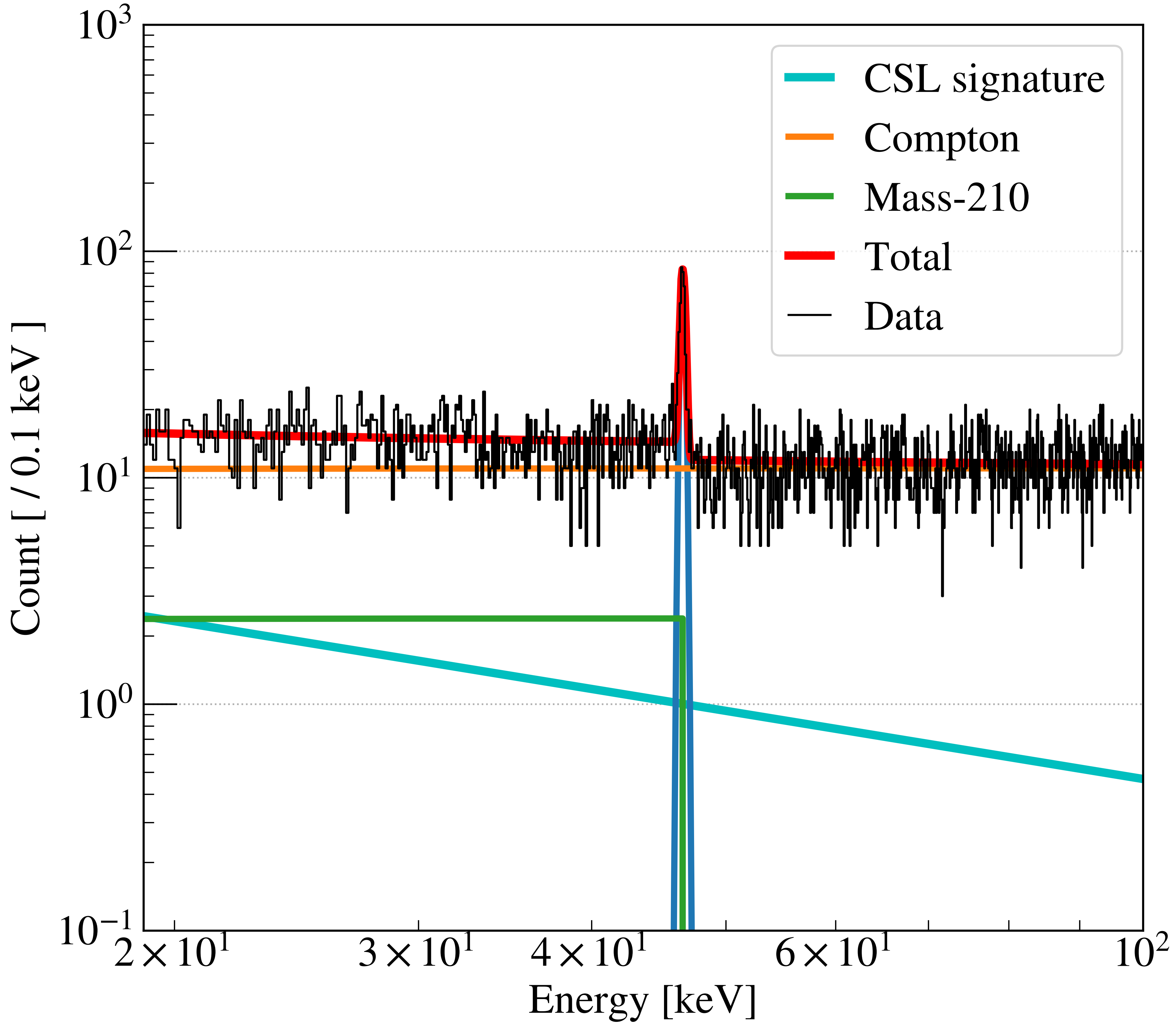
λ : collapse rate

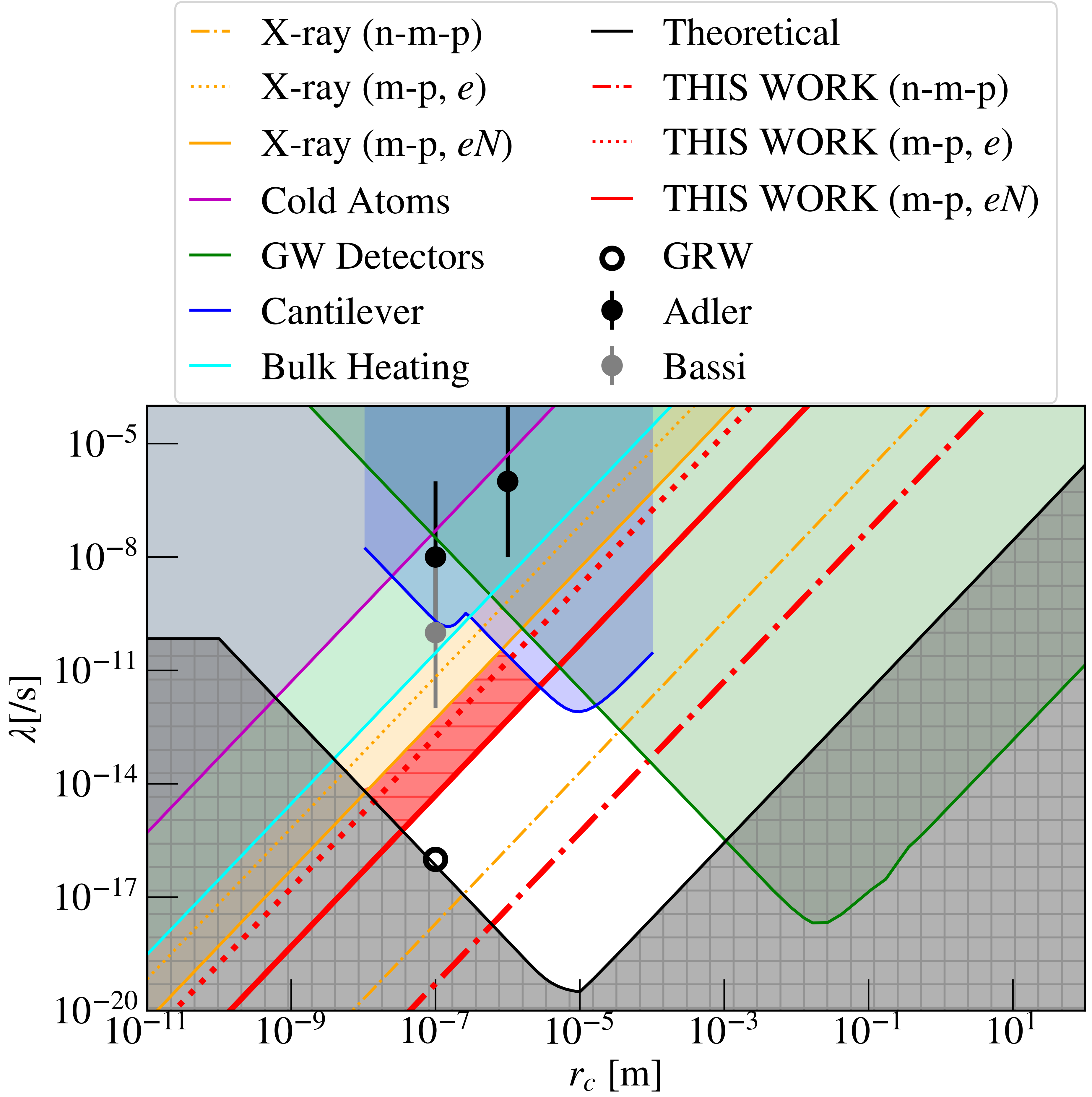
r_C : correlated radius

$1/E$: spectral shape

Quantum Wavefunction Collapse (WFC)

PRL **129** 080401 (2022)



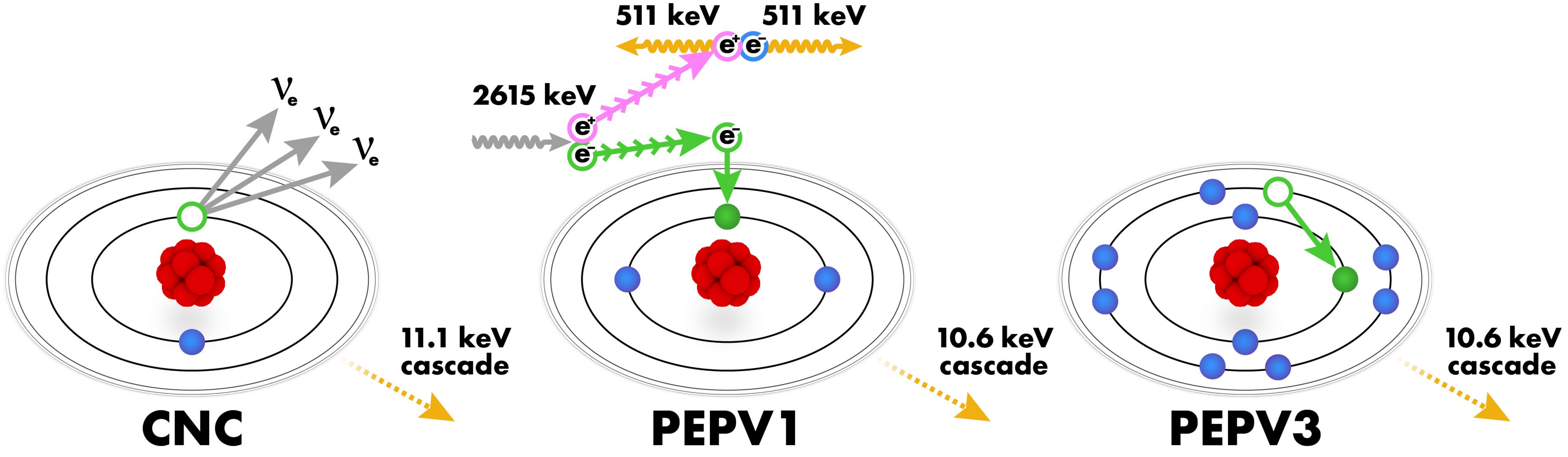


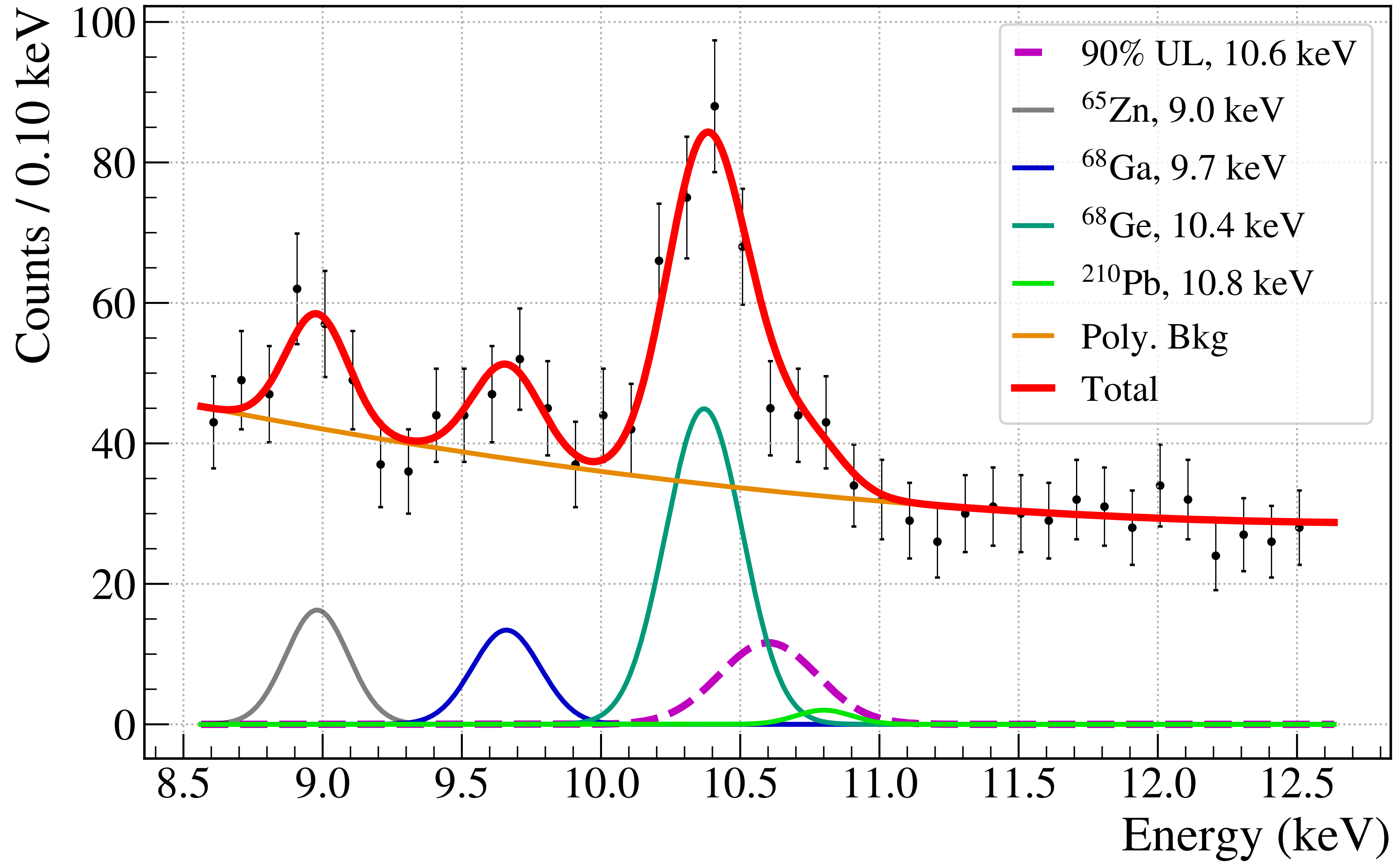
Test Pauli Exclusion Principle Violation

Pauli Exclusion Principle (PEP)

- Two identical fermions cannot occupy the same quantum state
- *e.g.*: Two electrons on the K-shell makes it full. A third electron is forbidden

arXiv:2203.02033 (2022)
Submitted to *Nature Phys.*





- Limit $\frac{1}{2}\beta^2 = \frac{\text{rate of PEP violating transition}}{\text{rate of PEP transition}} = \frac{\text{K−transition lifetime}}{\text{PEP violating K−transition lifetime}} < 1.0\times10^{-49}$ (90% CL)

Most stringent upper limit

Three types of PEP violating searches (Foundations of Physics **42** 1015 (2012))

Also set limit for terrestrial PEPV1 search: $\frac{1}{2}\beta^2 < 1.0\times10^{-3}$ (99.7% CL)

And electron lifetime: $\tau > 3.2\times10^{25}$ years (90% CL)

LEGEND

(1709.01980, 2107.11462)

Mission: “The collaboration aims to develop a phased, **Ge-76 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**.”

Select best technologies, based on what has been learned from GERDA and the MAJORANA DEMONSTRATOR, as well as contributions from other groups and experiments.

MAJORANA

- Radiopurity of nearby parts (FETs, cables, Cu mounts, etc.)
- Low noise electronics improves PSD
- Low energy threshold (helps reject cosmogenic background)

GERDA

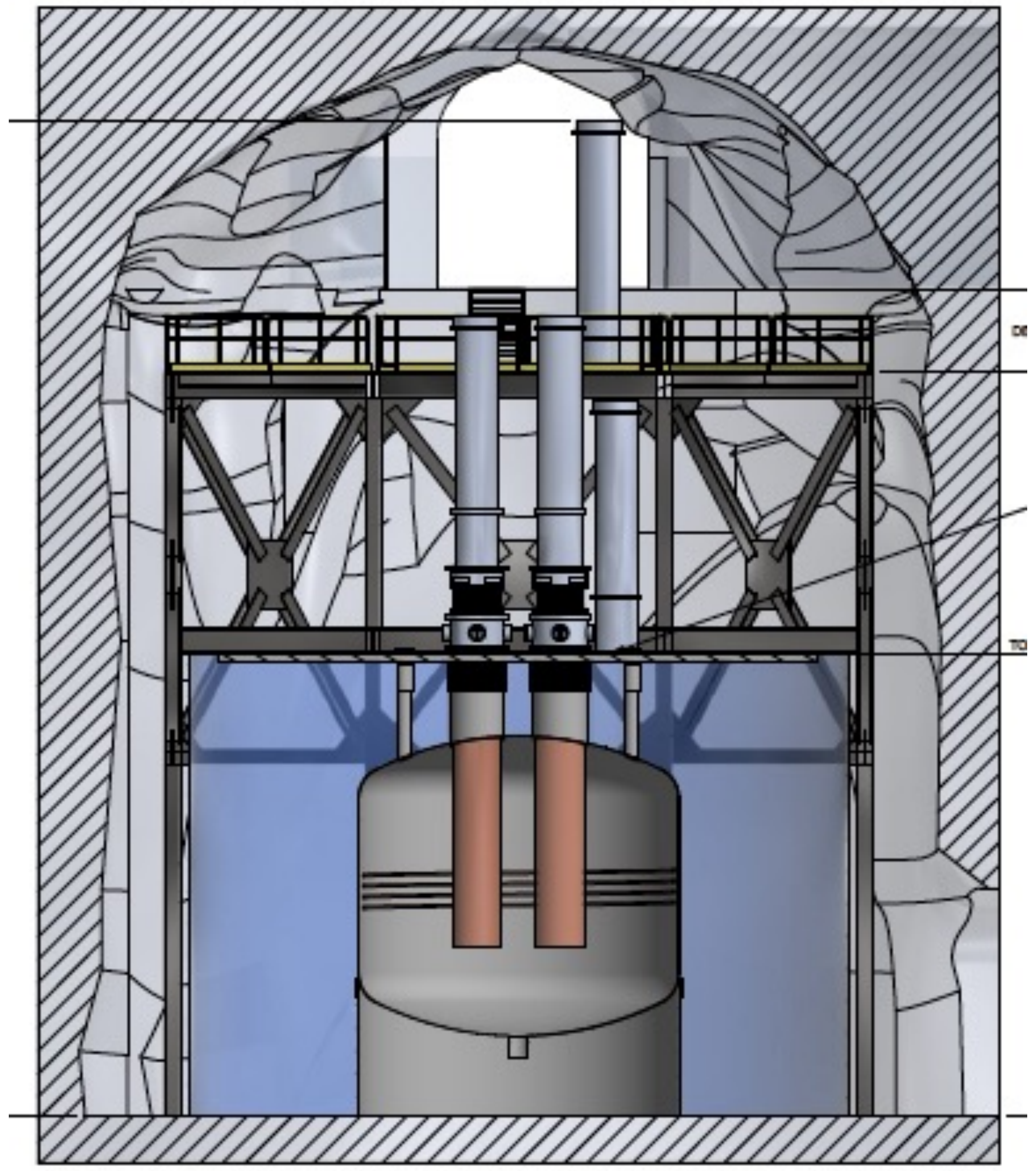
- LAr veto
- Low-A shield, no Pb

Both

- Clean fabrication techniques
- Control of surface exposure
- Development of large point-contact detectors
- Lowest background and best resolution $0\nu\beta\beta$ experiments

First phase:

- (up to) 200 kg in upgrade of existing infrastructure at LNGS
- BG goal: <0.6 c /(FWMH t y)
- Discovery sensitivity at a half-life of 10^{27} years
- Currently Taking Data



Subsequent stages:

- 1000 kg, staged via individual payloads
- Timeline connected to review process
- Background goal <0.03 cts/(FWHM t yr)
- Location to be selected

(1709.01980, 2107.11462)

Physics	**Signature**	**Energy Range**
Bosonic dark matter	Peak at DM mass	< 1 MeV
Electron decay	Peak at 11.8 keV	~ 10 keV
Pauli exclusion principle violation	Peak at 10.6 keV	~ 10 keV
Solar axions	Peaked spectra, daily modulation	$2 - 10$ keV
Majoron emission	$2\nu\beta\beta$ spectral distortion	$< Q_{\beta\beta}$
Exotic fermions	$2\nu\beta\beta$ spectral distortion	$< Q_{\beta\beta}$
Lorentz violation	$2\nu\beta\beta$ spectral distortion	$< Q_{\beta\beta}$
Exotic currents in $2\nu\beta\beta$ decay	$2\nu\beta\beta$ spectral distortion	$< Q_{\beta\beta}$
Time-dependent $2\nu\beta\beta$ decay rate	Modulation of $2\nu\beta\beta$ spectrum	$< Q_{\beta\beta}$
WIMP and related searches	Exponential excess, annual modulation	< 10 keV
Baryon decay	Timing coincidence	> 10 MeV
Fractionally charged cosmic-rays	Straight tracks	few keV
Fermionic dark matter	Nuclear recoil/deexcitation	$<$ few MeV
Inelastic boosted dark matter	Positron production	$<$ few MeV
BSM physics in Ar	Features in Ar veto spectrum	ECEC in ^{36}Ar

+ many more…

The Majorana Collaboration

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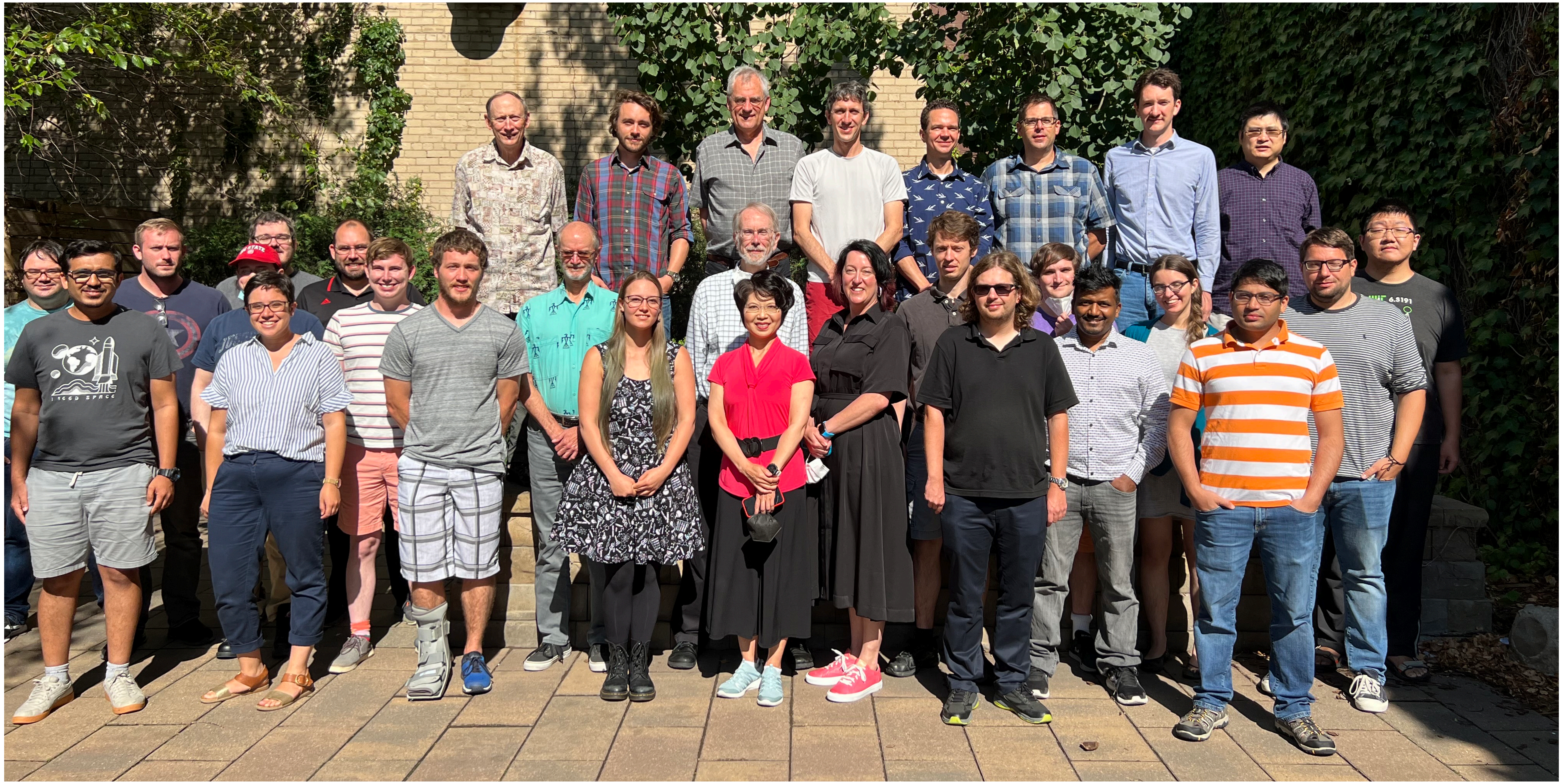
The MAJORANA Collaboration

NSF

Sanford Underground Research Facility



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Technische Universität München

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TUNL

THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

UNIVERSITY OF SOUTH CAROLINA

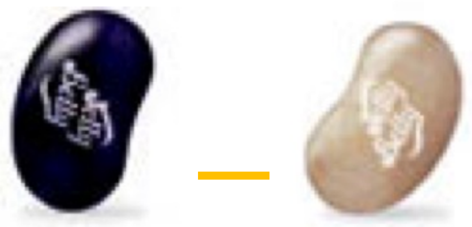
UNIVERSITY OF SOUTH DAKOTA

THE UNIVERSITY of TENNESSEE KNOXVILLE

Williams

Backup

Majorana vs. Dirac



Majorana fermions are their own anti-particles.

Dirac fermions are not.

No fermions are known to be Majorana.

- Electrically charged fermions have good QM # to distinguish particle/anti-particles, hence are Dirac

Experimental evidence consistent with both Majorana and Dirac neutrinos.

Verification difficult due to small neutrino masses and handedness of weak interaction.

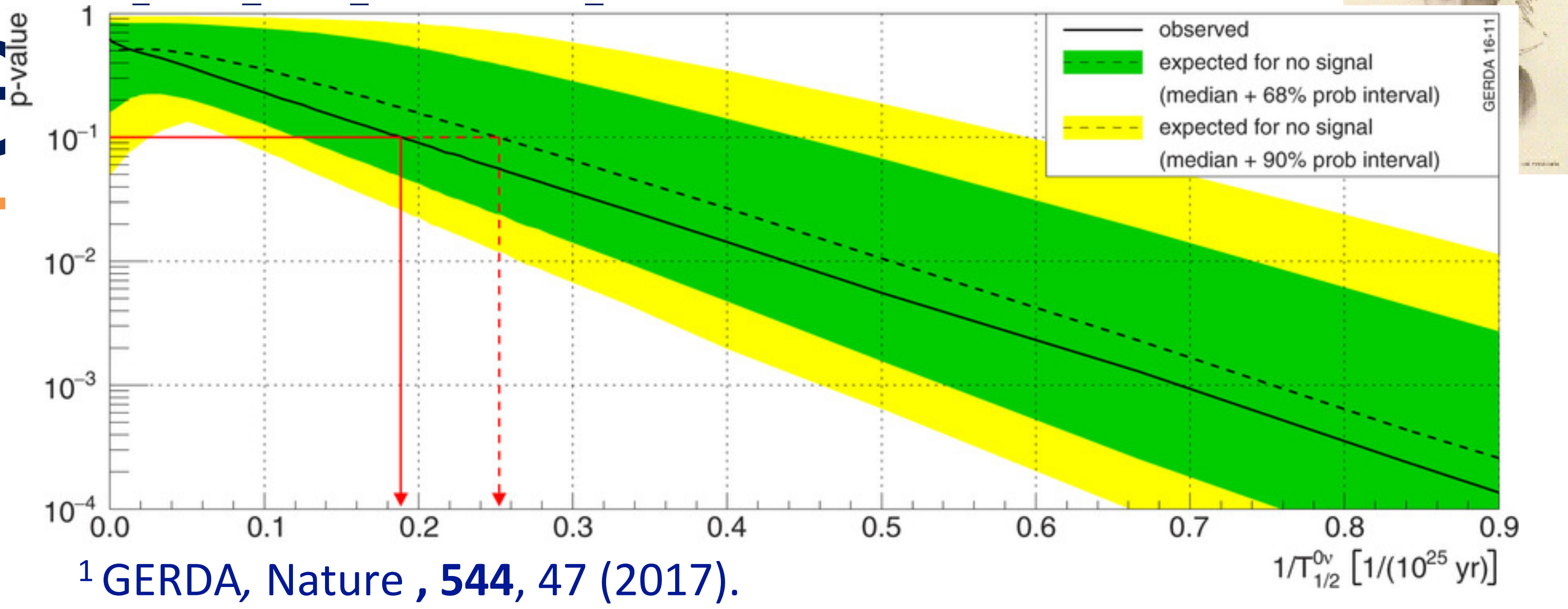
Fotografia di Ettore Majorana tratta dalla tessera universitaria datata 3 novembre 1923.

Ettore Majorana

Paul Dirac

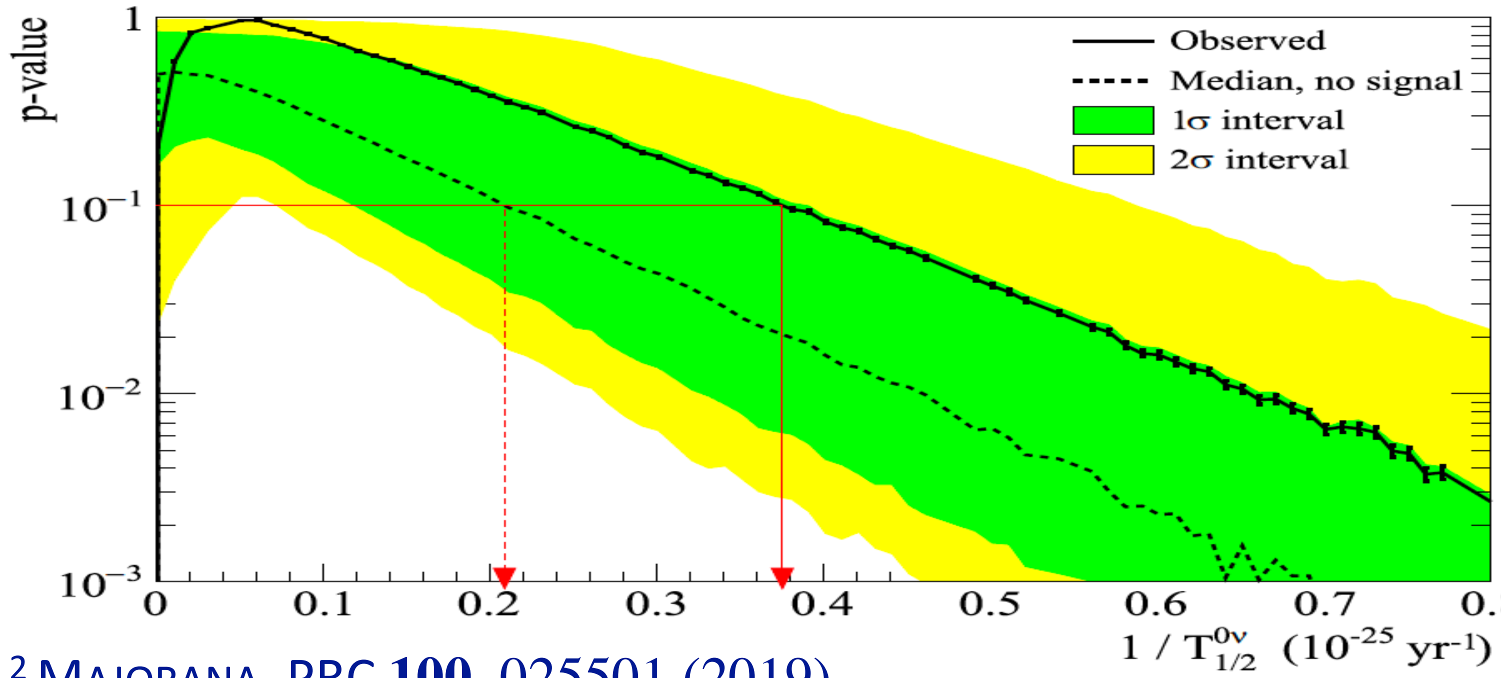
Neutrinoless double-beta decay is the only practical process that can resolve this mystery.

Approximate ^{76}Ge Combine



[1] GERDA, Nature , **544**, 47 (2017).

- A calculation was performed to understand the behavior of the combined final Majorana and GERDA limits.
- The calculation was based on the profile likelihood method, in a fashion consistent with both GERDA[1] and Majorana[2] publications. It was implemented in RooFit/RooStats.



[2] Majorana, PRC **100**, 025501 (2019).

Simplifications and approximations in this calculation of combined limit:

1. The GERDA final analysis divides each detector in GERDA phase II into partitions. This analysis simplifies by dividing GERDA phase II detectors into two groups of BEGes and non-BEGes.
2. The actual energies of GERDA phase I events are approximated from the spectrum histogram in Fig. 1 of PRL 111, 122503 (2013), *i.e.* an energy value within the 1 keV bin of the spectrum histogram is randomly chosen.
3. Due to the statistics-dominated nature of the results and a lack of knowledge on detector-by-detector uncertainties for GERDA phase II, systematic uncertainties are removed here.

Data sets	**Lower limit on the half-life in this calculation**	**Published final limits and prediction for the combined limit**
Majorana final	$T_{1/2} > 0.83\text{x}10^{26}$yr	$T_{1/2} > 0.83\text{x}10^{26}$yr [arXiv:2207.07638]
GERDA final, phase I + phase II	$T_{1/2} > 1.6\text{x}10^{26}$yr (see simplifications and approximations)	$T_{1/2} > 1.8\text{x}10^{26}$yr [PRL 125, 252502 (2020)]
Combined	$T_{1/2} > 2.3\text{x}10^{26}$yr, 4% lower than the sum of the two	$T_{1/2} > (0.96)\text{x}(0.8+1.8)\text{x}10^{26}$yr = $2.5\text{x}10^{26}$yr

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

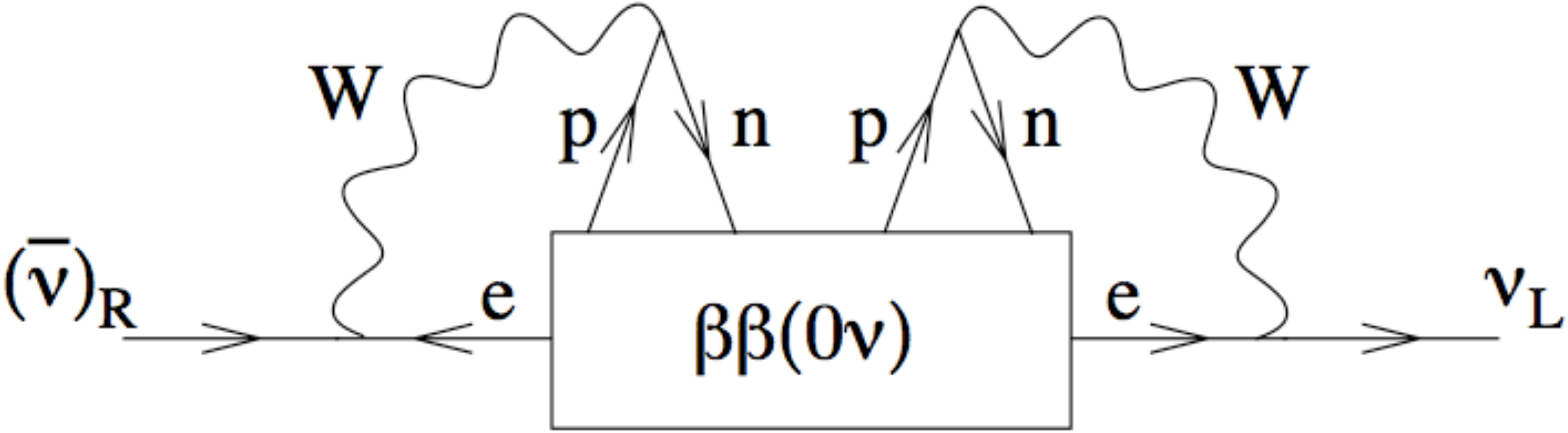
History

1935: Double beta decay postulated by Maria Goeppert-Mayer *Phys. Rev. 48 (1935) 512*

1937: Ettore Majorana formulates theory with no distinction between ν and anti-ν. *Nuovo Cimento 14 (1937) 171*

1937: Giulio Racah suggests zero-neutrino double-beta decay as test for Majorana’s theory. *Nuovo Cimento 14 (1937) 322*

0νββ–decay and Majorana Neutrinos

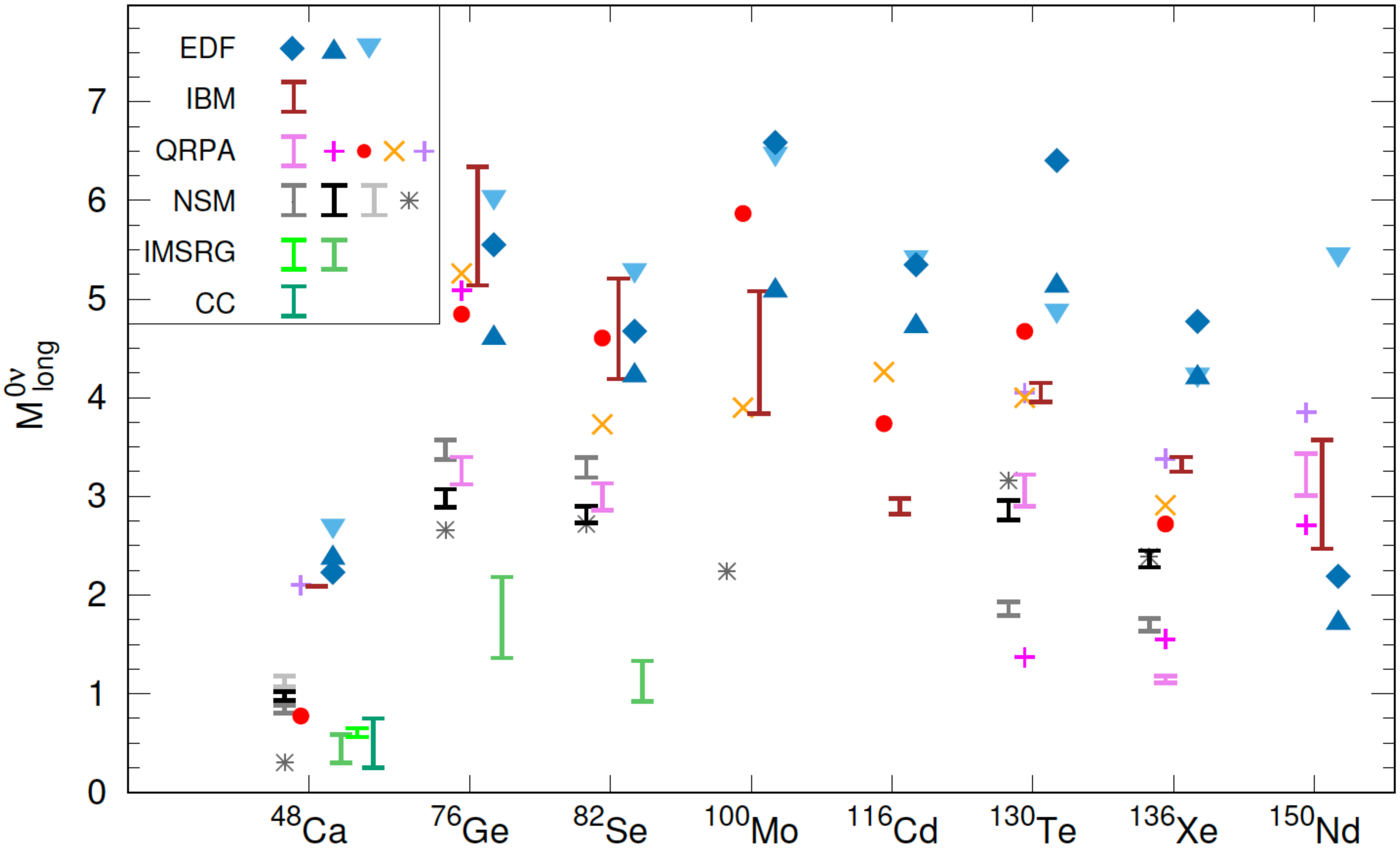


Schechter et al, Phys. Rev. D**25**, 2951 (1982)

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

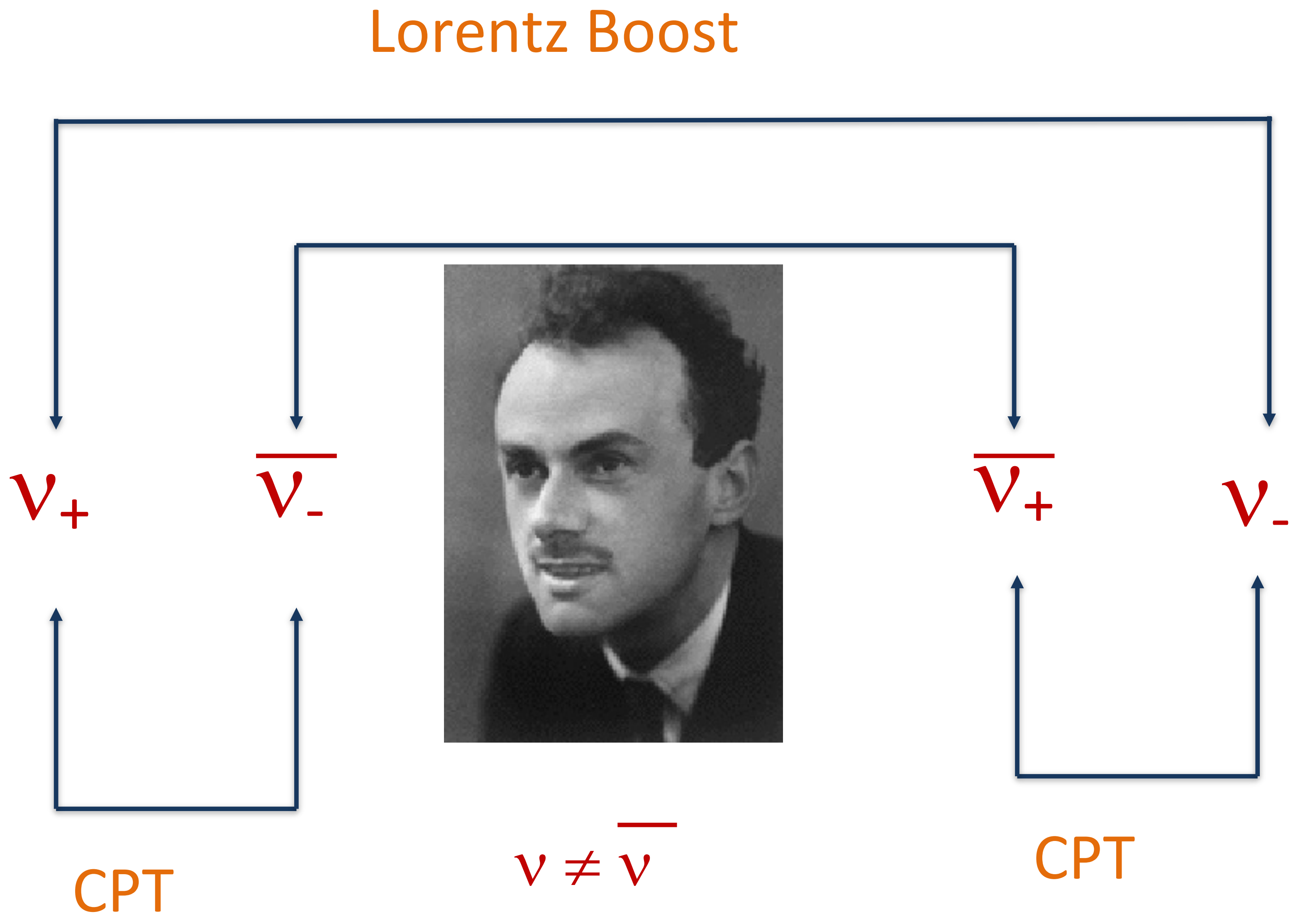
Matrix Elements

arXiv:2202.01787



More about Majorana vs. Dirac

Note: Only valid if neutrinos are massive.



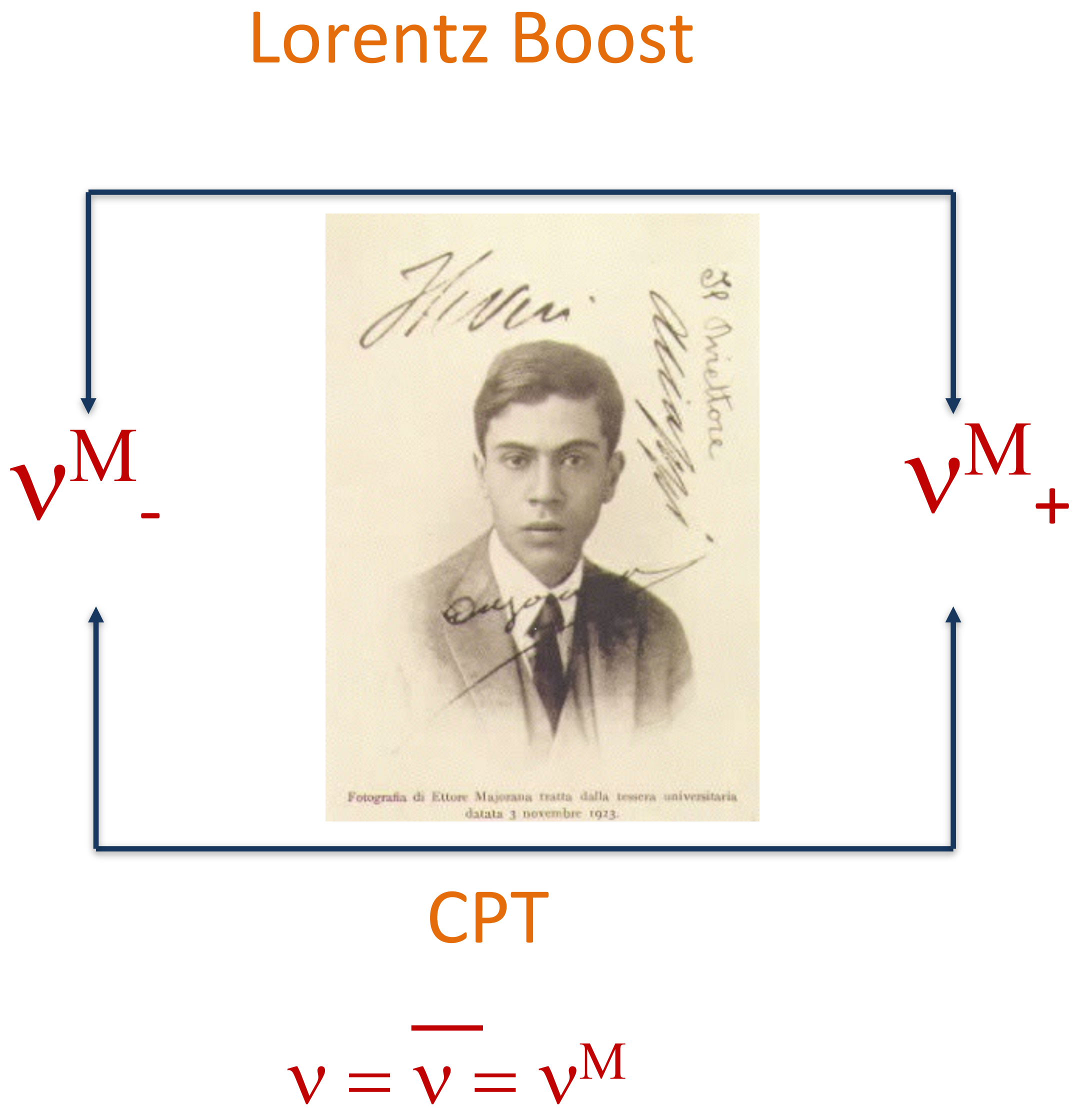
Lorentz Boost

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

CPT

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

CPT



Lorentz Boost

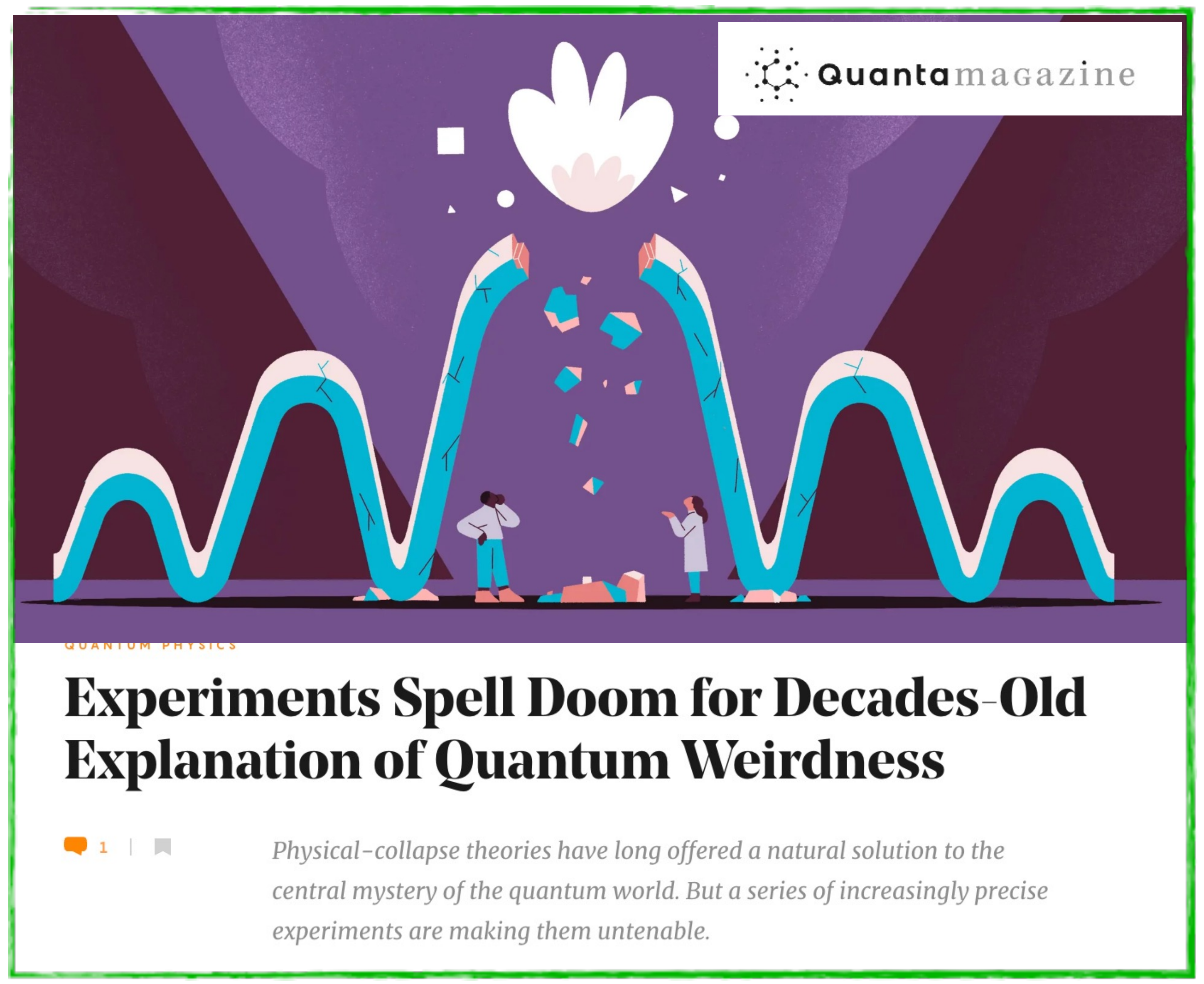
ν^M_- ν^M_+

CPT

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

Original argument by Kayser, 1985

Search for wave function collapse PRL 129 080401 (2022)



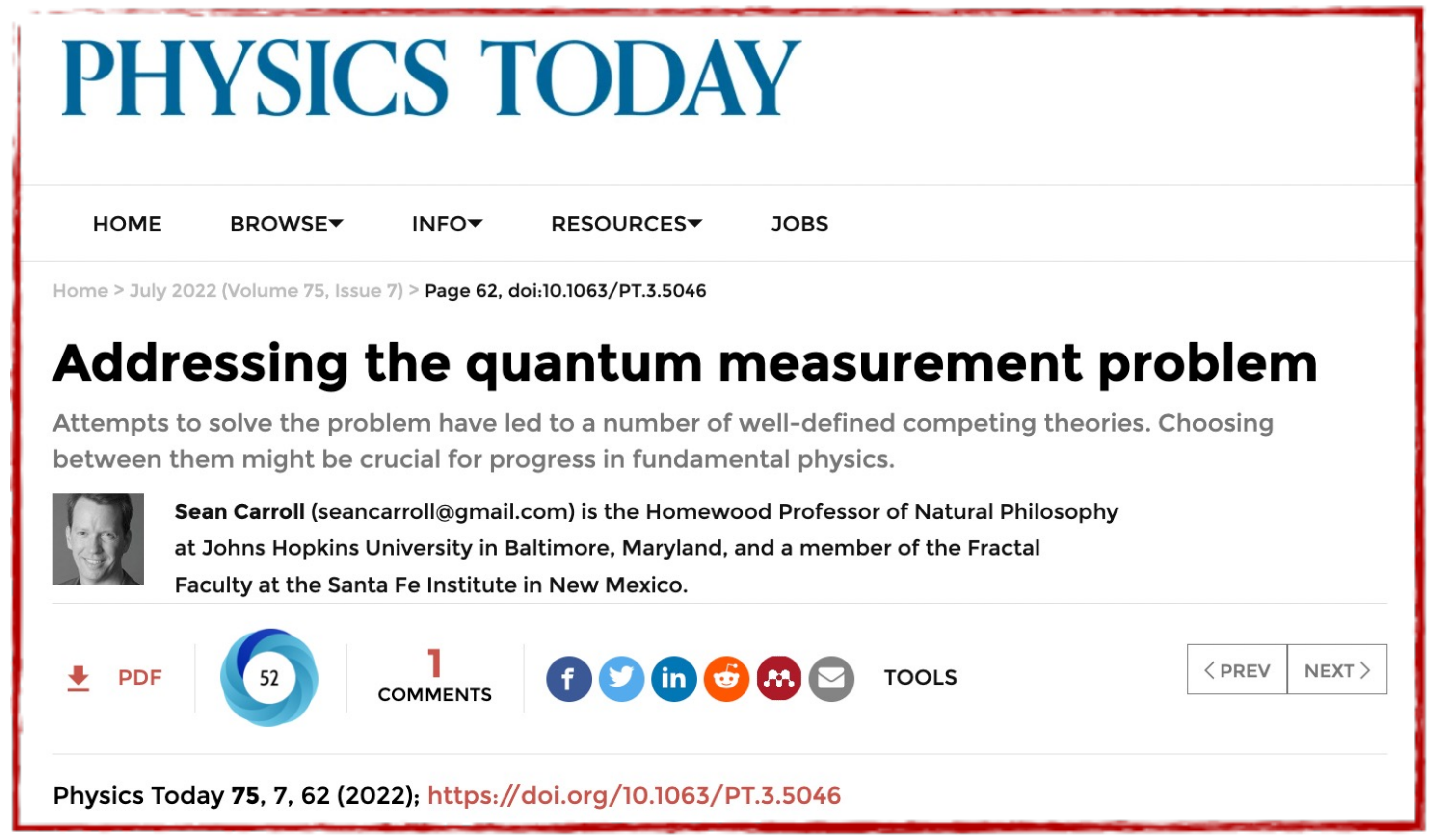
QUANTUM PHYSICS

Experiments Spell Doom for Decades-Old Explanation of Quantum Weirdness

1

Physical-collapse theories have long offered a natural solution to the central mystery of the quantum world. But a series of increasingly precise experiments are making them untenable.

A timely result for MAJORANA with interdisciplinary appeal! Featured in Quanta magazine, Oct 2022. Article by Sean Carroll highlights broader interest from the community for this style of test.



PHYSICS TODAY

HOME BROWSE▾ INFO▾ RESOURCES▾ JOBS

Home > July 2022 (Volume 75, Issue 7) > Page 62, doi:10.1063/PT.3.5046

Addressing the quantum measurement problem

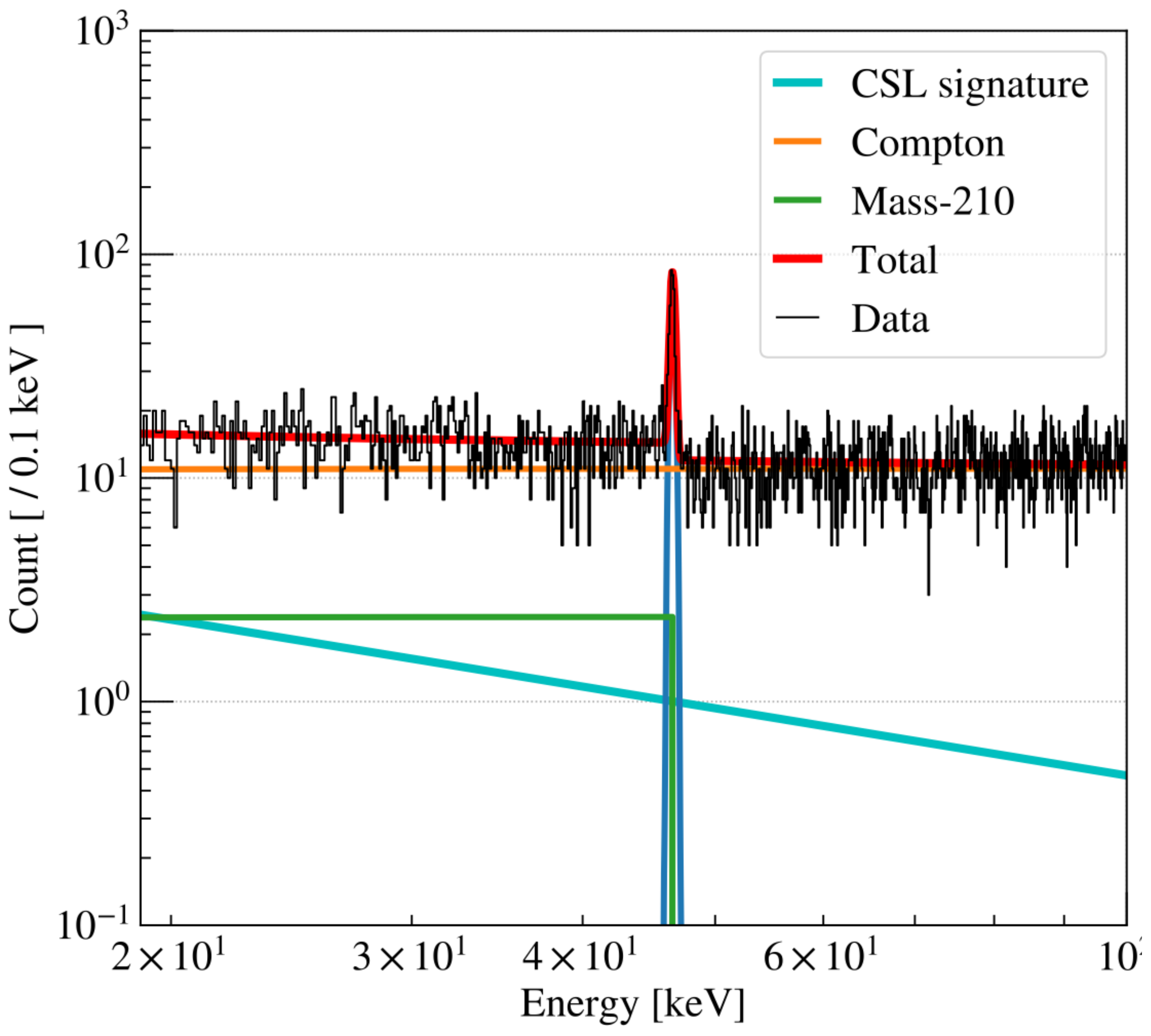
Attempts to solve the problem have led to a number of well-defined competing theories. Choosing between them might be crucial for progress in fundamental physics.

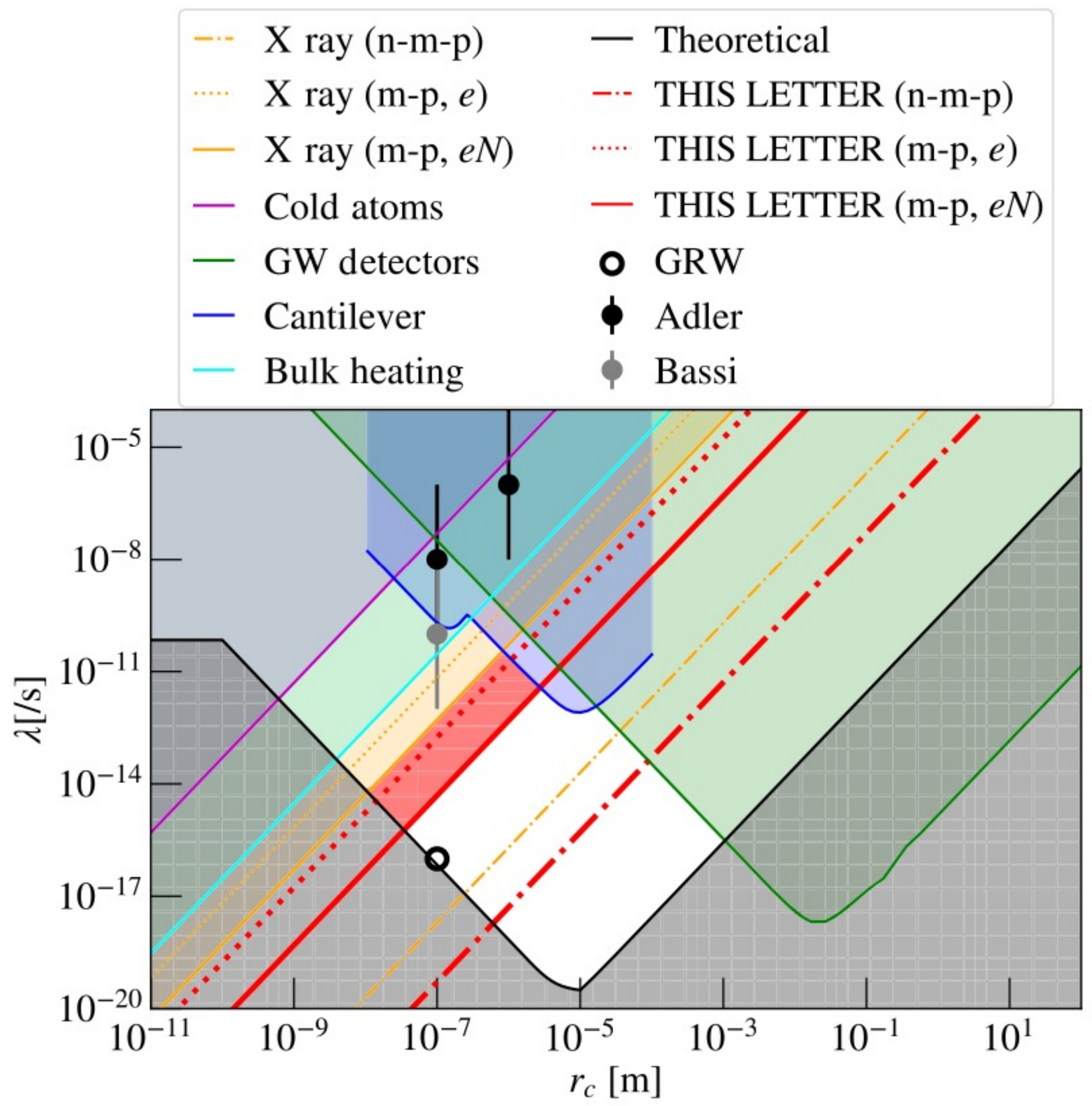
Sean Carroll (seancarroll@gmail.com) is the Homewood Professor of Natural Philosophy at Johns Hopkins University in Baltimore, Maryland, and a member of the Fractal Faculty at the Santa Fe Institute in New Mexico.

PDF 52 1 COMMENTS TOOLS ‹ PREV NEXT ›

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

- Where is the border between the microscopic and macroscopic worlds?
  - How does the wave function collapse when a quantum system interacts with its surroundings?
  - Or is it “continuously spontaneously localized” (CSL) ?
  - Objective WFC models add **nonlinear terms** to the Schrodinger equation.
- Is there a detectable signature of WFC for a large, low-background, low-threshold experiment?
  - In the CSL model, particles continuously interact with a noise field and **emit low-E X-rays.**





PHYSICAL REVIEW LETTERS

Search for Spontaneous Radiation from Wave Function Collapse in the MAJORANA DEMONSTRATOR

I. J. Arnquist *et al.* (MAJORANA Collaboration)
Phys. Rev. Lett. **129**, 080401 – Published 16 August 2022

Signature of WF

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

λ : collapse rate

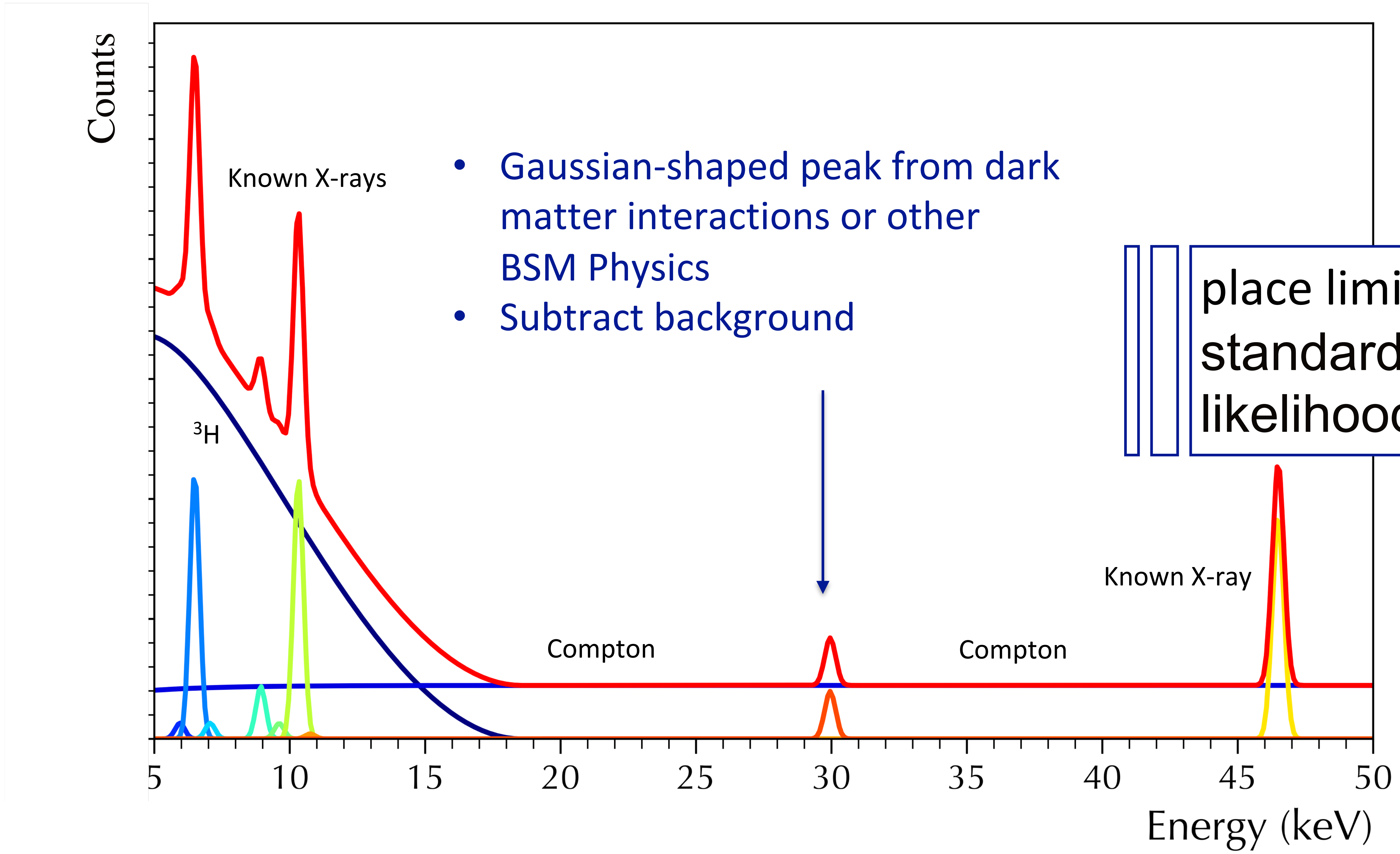
r_C : correlated ra

$1/E$: spectral s

MAJORANA improves previous limits by orders of magnitude!

We expect similar searches from Xe experiments such as LZ, XENON-nT, and PandaX

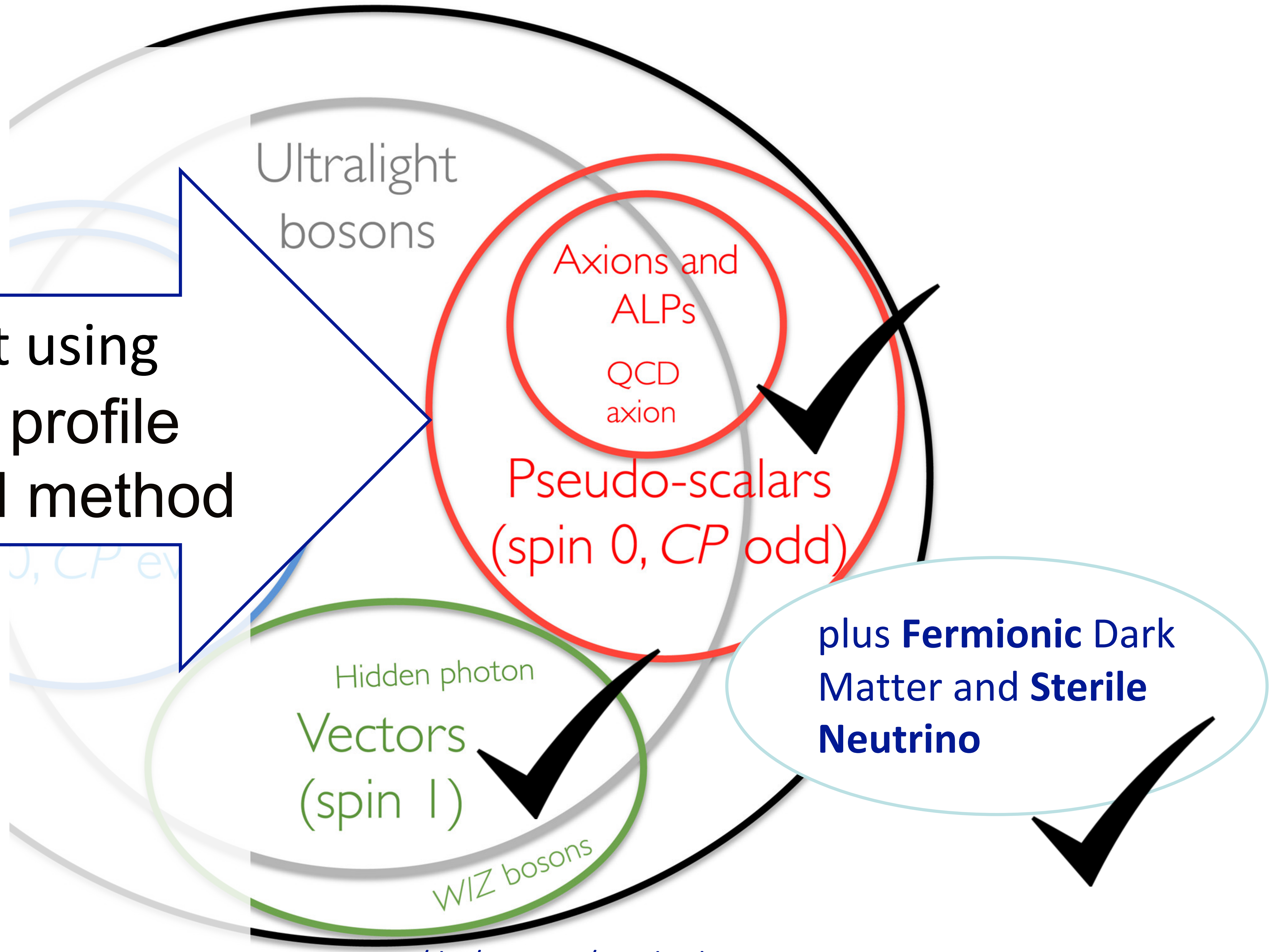
Common Theme: BSM Peak Searches in Energy Spectrum



- Gaussian-shaped peak from dark matter interactions or other BSM Physics
- Subtract background

place limit using standard profile likelihood method

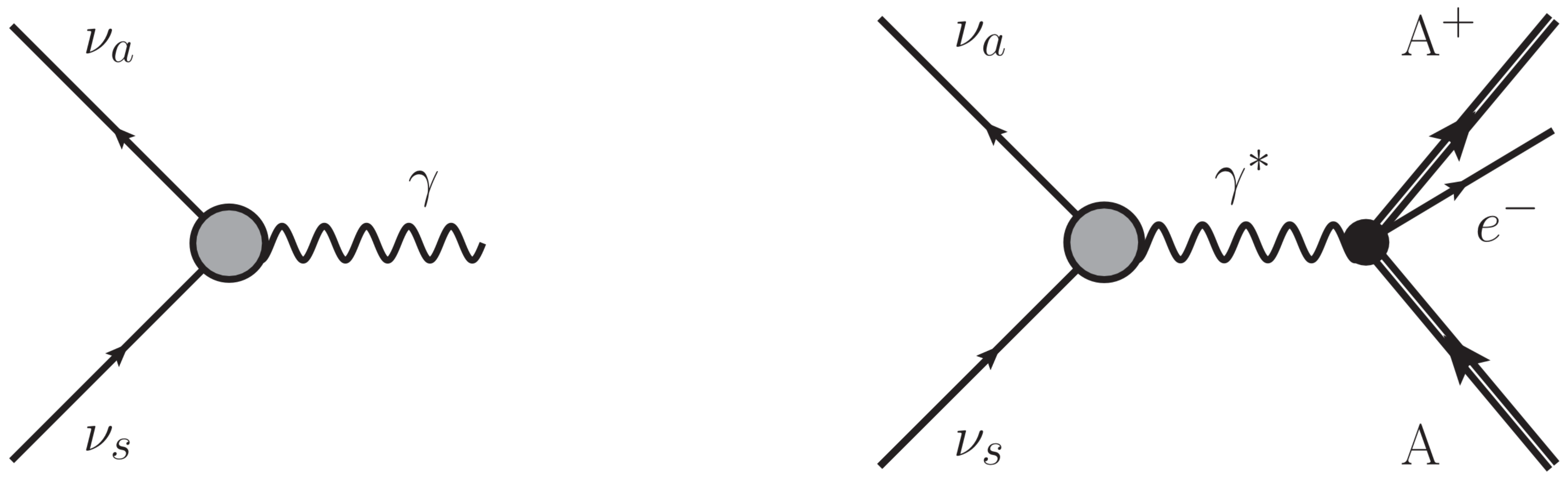
Dark Matter candidates



plus **Fermionic** Dark Matter and **Sterile Neutrino**

science.org/doi/10.1126/sciadv.abj3618

$\nu_s - \nu_a$ Sterile-to-Active Transition Magnetic Moment

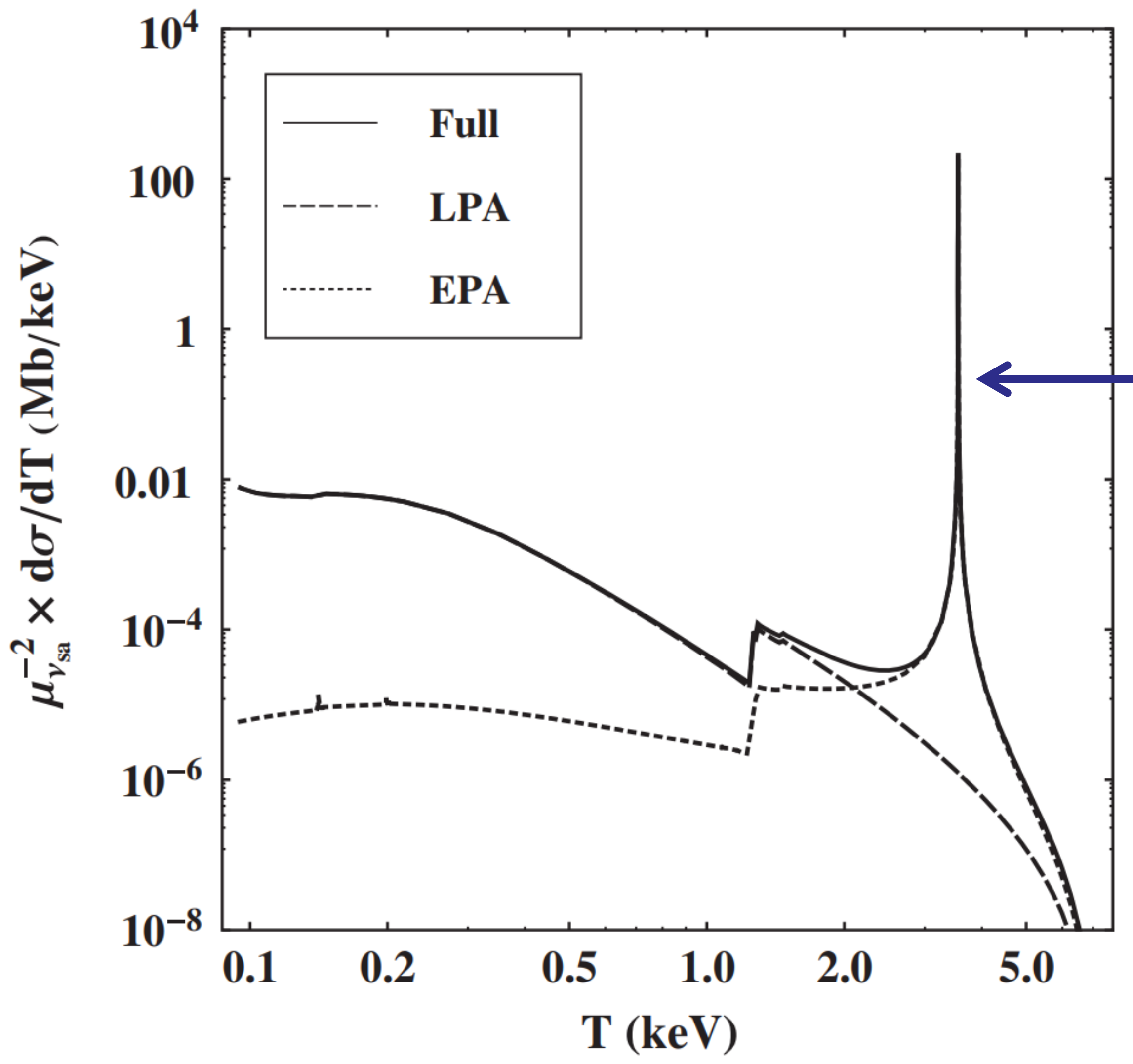


- Transition magnetic moment (TMM) could induce a sterile-to-active transition
- DM sterile neutrinos can ionize atom A: *[Phys. Rev. D 93, 093012 (2016)]*

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

- Cross section enhanced greatly at energy transfer of $m_s/2$, leading to a peak-like signature.
- MAJORANA searched for sterile neutrino DM peak-like signature
- **<u>The limit established by MAJORANA is the best limit so far</u>**
- The local galactic halo is considered as the source of incoming ν_s
- Implication: If the DM halo consists of the keV-scale sterile neutrinos, then the μ_{sa} is too weak to produce the XENON1T excess

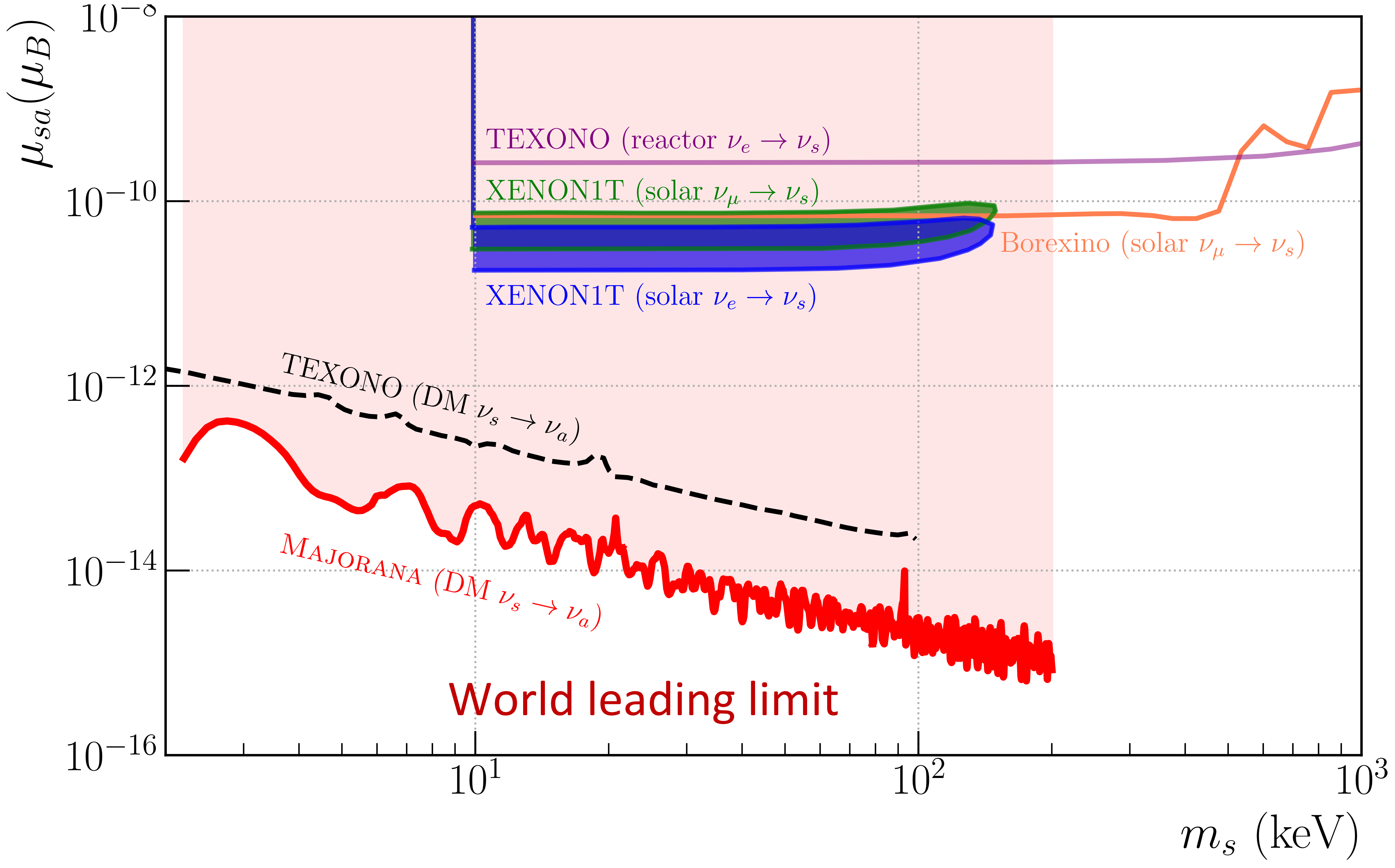
PRD **93**, 093012 (2016)



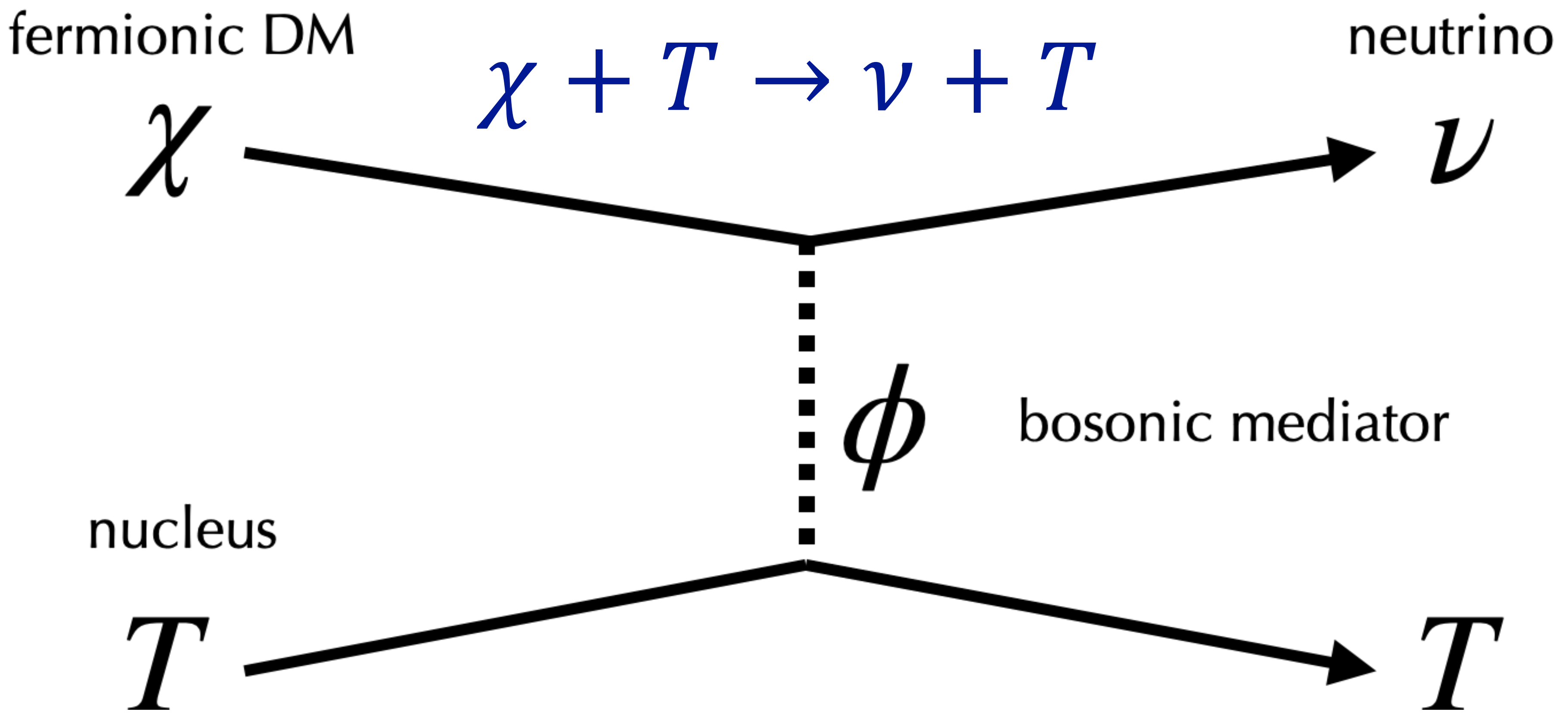
$$\frac{d\sigma(m_s, v)}{dT} \approx \left(\frac{\mu_{sa}}{2m_e}\right)^2 \frac{\alpha}{2n_A} \frac{m_s^2}{|v|^2}$$

v^{-2} amplification

2206.10638, submitted to PRL

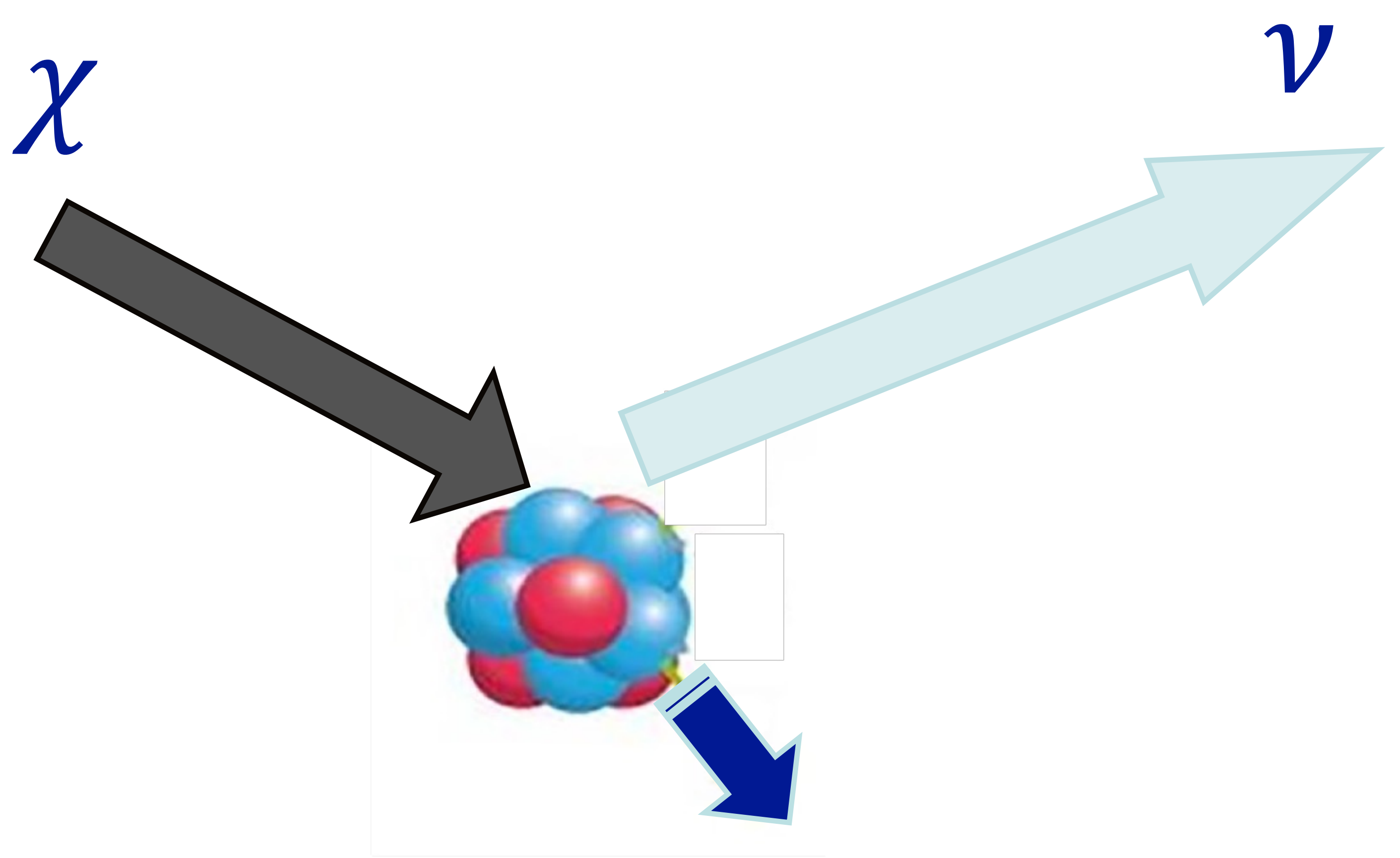


Fermionic Dark Matter Searches



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

- Fermionic DM χ has a Yukawa-like neutral-current (NC) interaction with nucleus *T*
- 2→2 scattering with a neutrino in the final state, leading to a fixed energy transfer to nucleus *T* and the absorption of Fermionic DM χ
- Recoil energy of nucleus *T* generates a monogenetic peak



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

cross section

different Ge isotopes

Ge Helm form factor

Detector threshold

- 1 keVee energy threshold
- 4.5 keVnr nuclear recoil threshold
- 25.5 MeV minimum dark matter mass

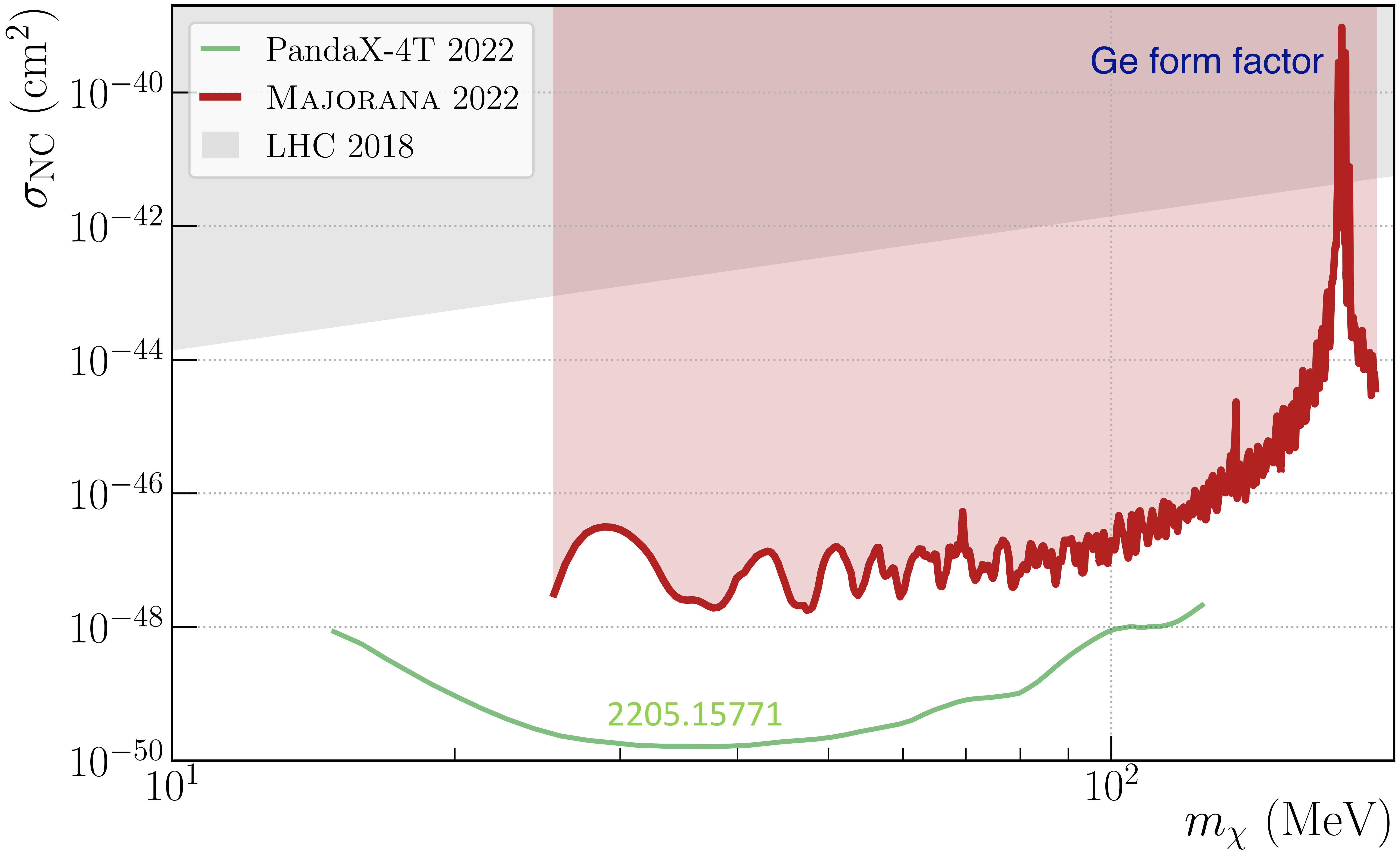
➢ little dependence on the choice of quenching factor

Fermionic Dark Matter Searches

Fermionic: 2→2 neutral-current (NC) interaction

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

2206.10638, submitted to PRL



3→2 Scattering Dark Matter Searches

Also: 3→2 scattering with nucleus *T*, with a new dark matter ψ in the final state

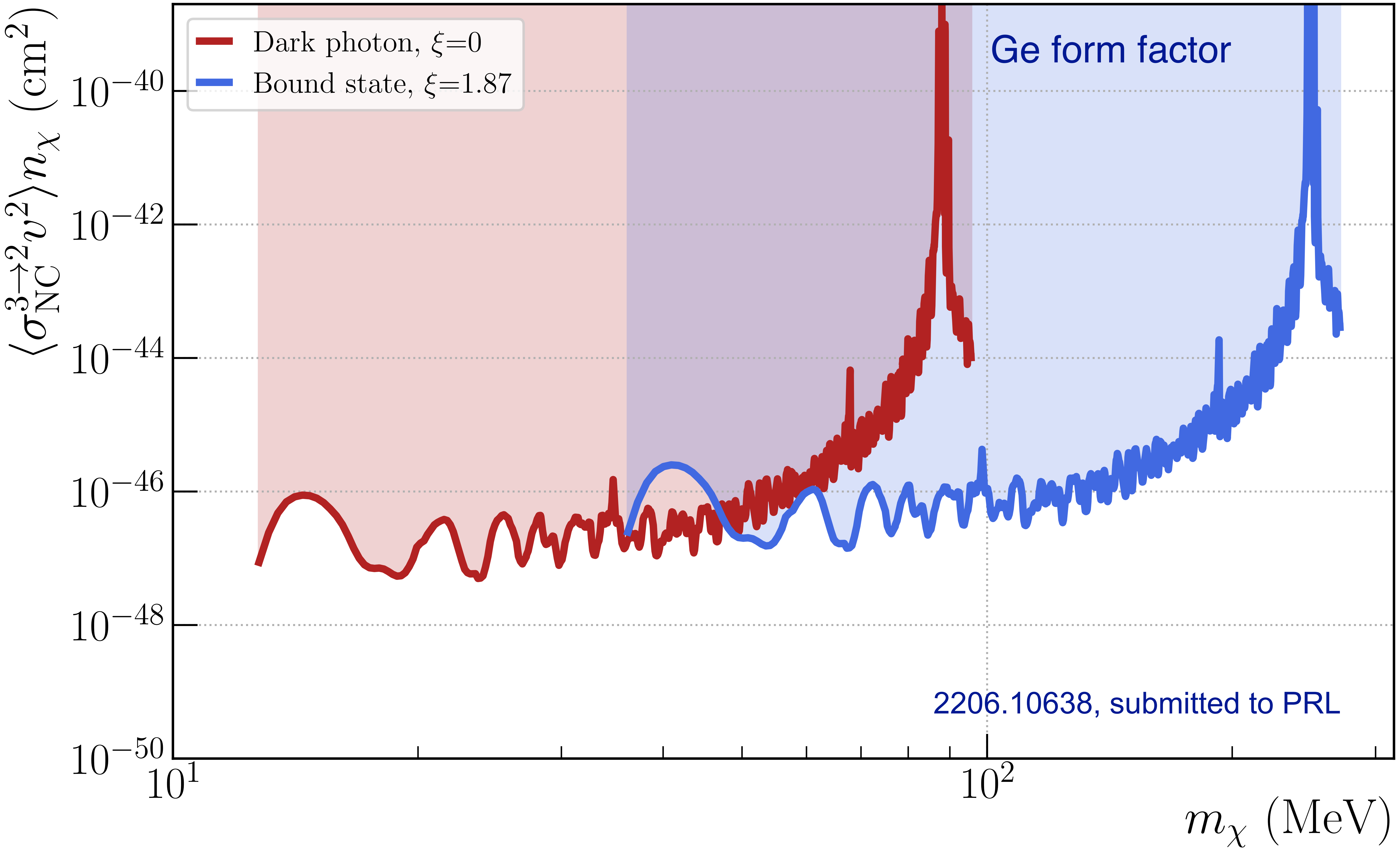
$$\chi + \chi + T \rightarrow \psi + T$$

Signature: Monoenergetic peak depending on mass ratio ξ of ψ and χ

Limits are calculated for massless and bound final dark matter states

Massless final dark matter state: ψ is dark photon, $\xi = 0$

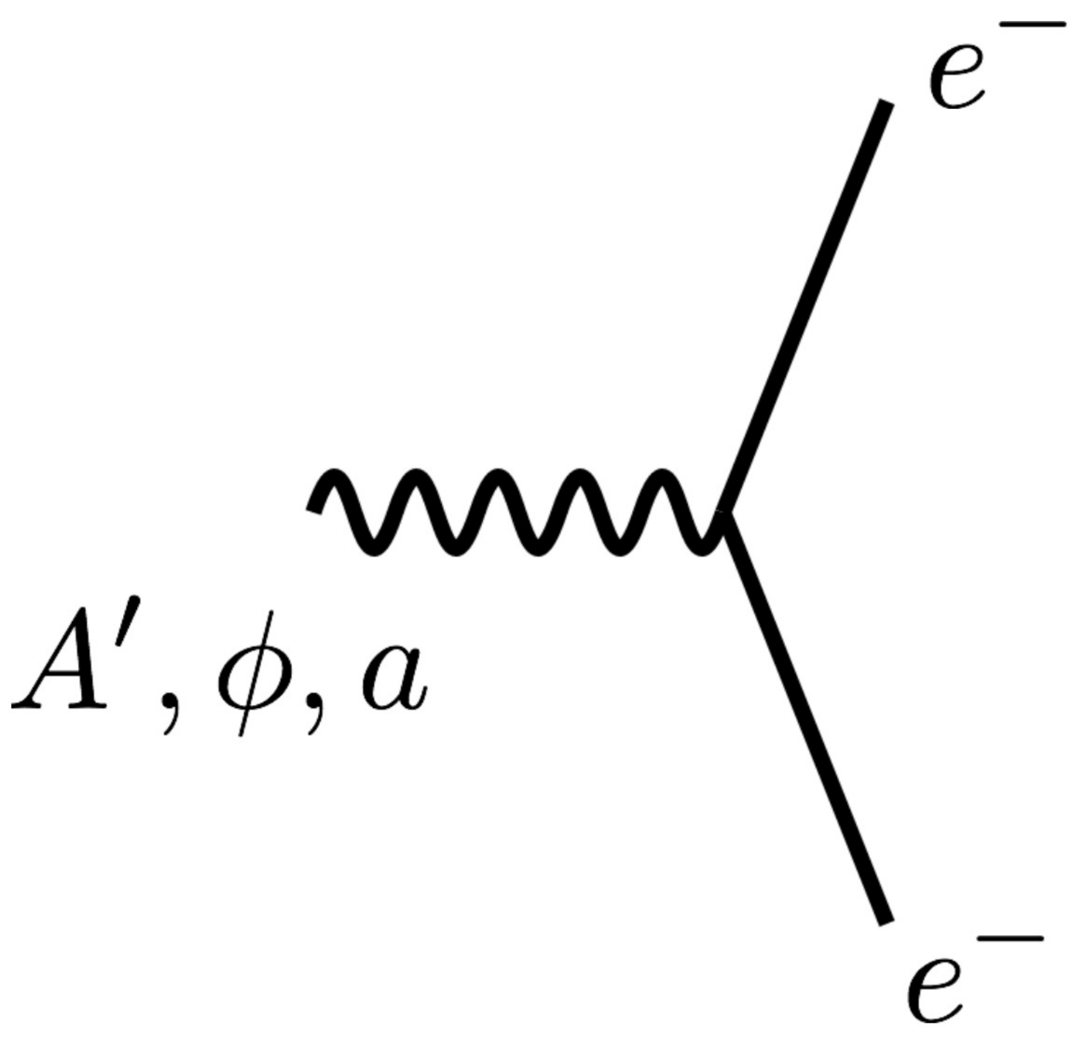
Bound final dark matter state $\xi = 1.87$

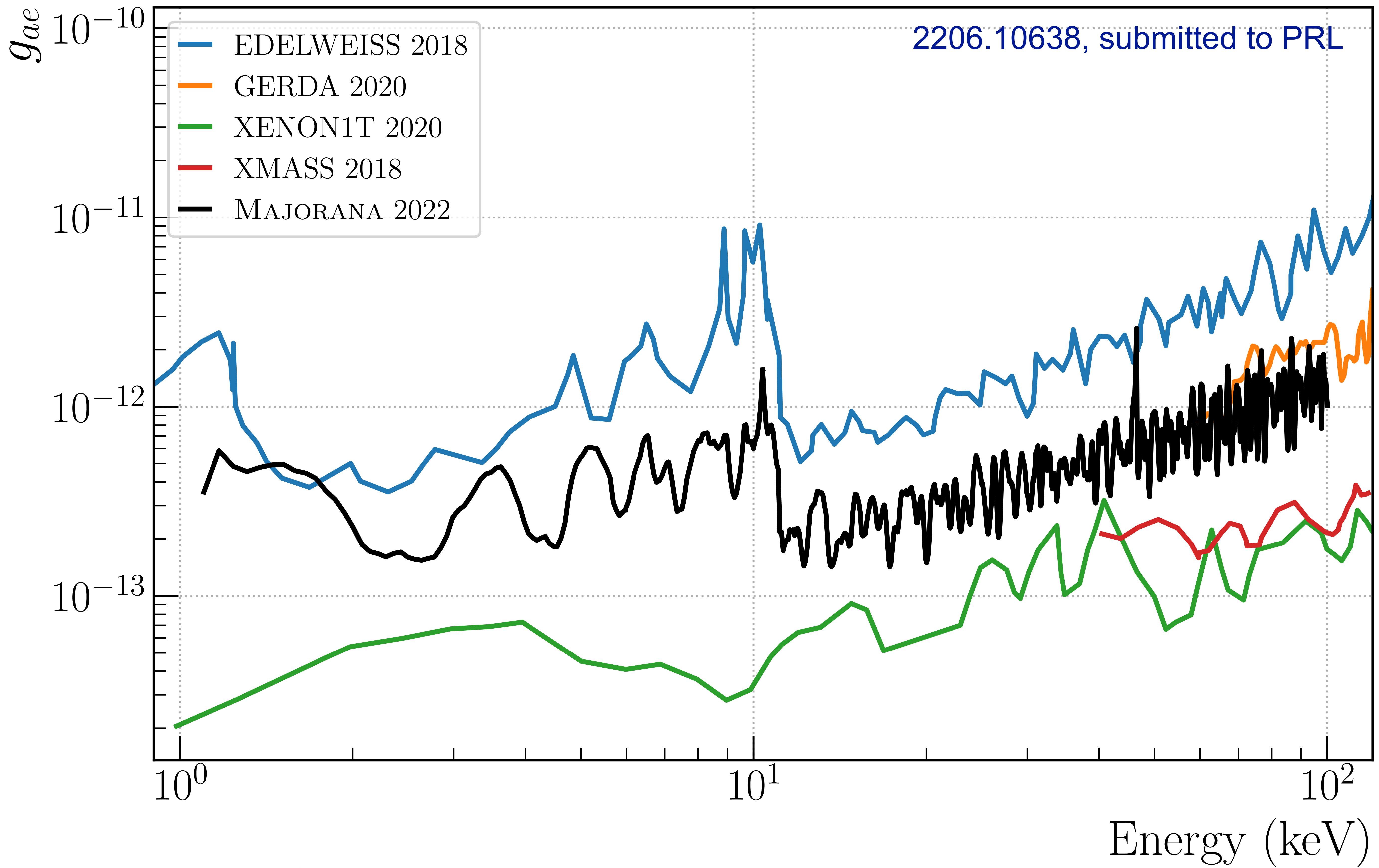


2206.10638, submitted to PRL

Pseudoscalar Bosonic Dark Matter Searches

- Pseudoscalar Particles (spin-0, axion-like particles)
  - Absorption of bosonic dark matter via electron coupling in axio-electric effect
  - Similar to the photo-electric effect
  - Peak at rest mass





2206.10638, submitted to PRL

- Axioelectric cross section σ_{ae} relates to the photoelectric cross section σ_{pe} via ${g_{Ae}}^2$

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

Best limit in germanium detectors
Ruled out by astrophysics > 5 keV: PRL. **128**, 221302, (2022)

Solar Axion Search

Combine time and energy into a 2-dimensional analysis

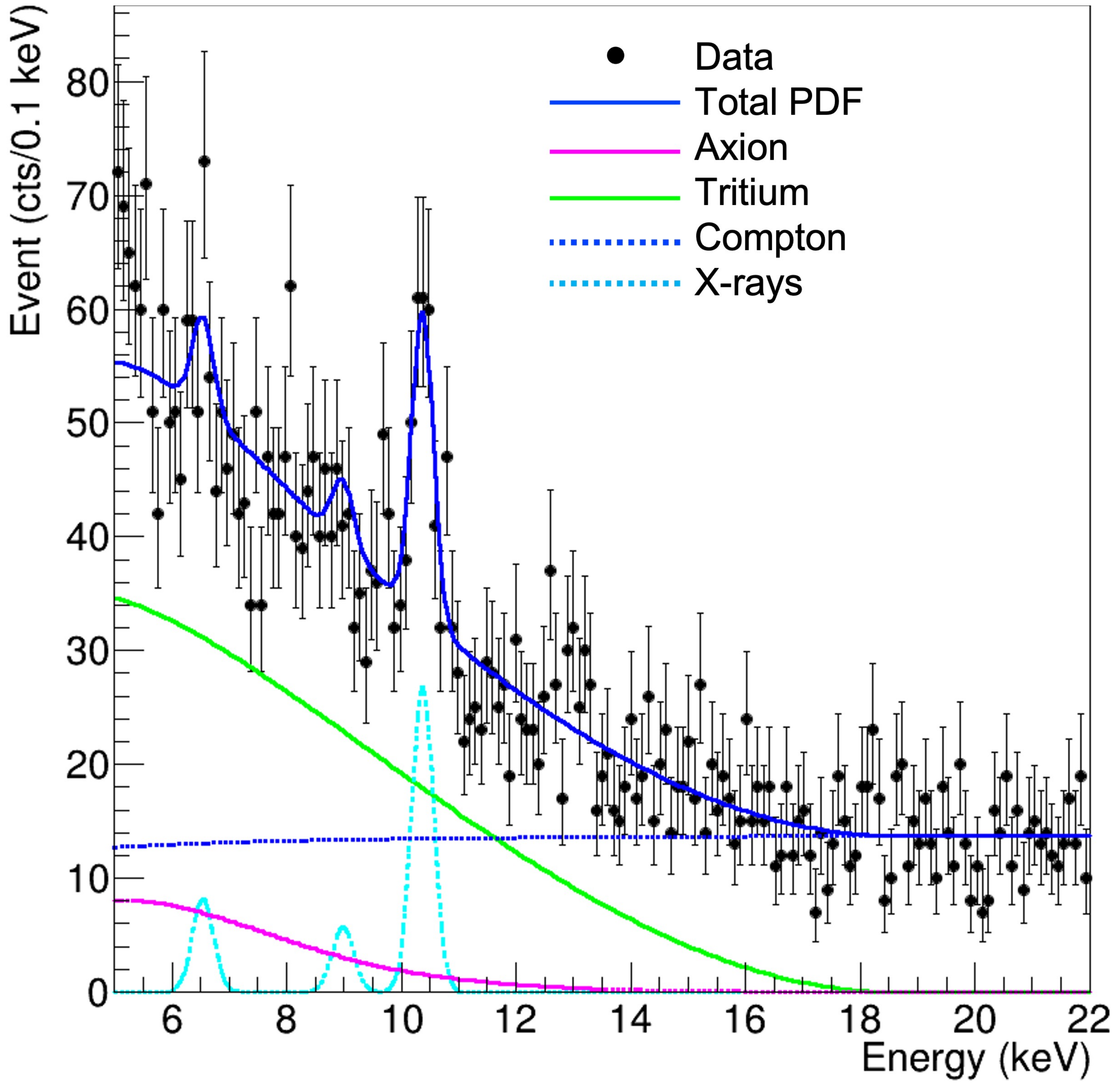
All PDFs have both energy and time dependence (5-min precision over 3 years)

Only the energy dimension shown

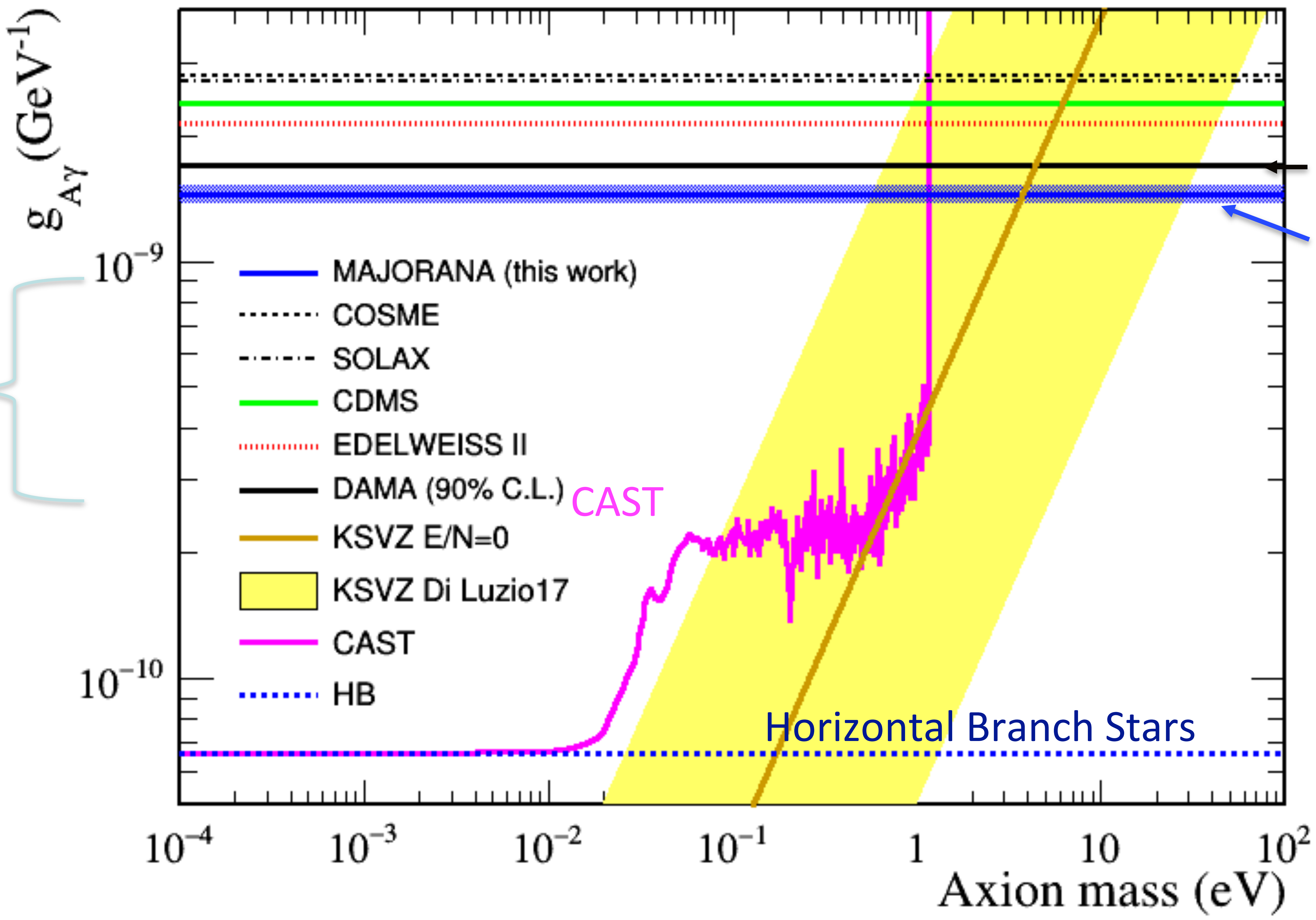
Solar axion flux consistent with zero within 2.1σ

2206.05789, submitted to PRL

$g_{A\gamma} < 1.45\times10^{-9}\mathrm{GeV}^{-1}$ (95% Bayesian CI) improves the best lab-based limit between 1.2 eV and 100 eV solar axion mass



Exp. w/. similar technique



Previous best 90% limit for 21 years by DAMA

This work, 95% limit, blind analysis

SOLAX, Phys. Rev. Lett., 81:5068, 1998, DAMA, Phys. Lett. B, 515:6, 2001 , COSME, Astropart. Phys., 16:325, 2002, CDMS, Phys. Rev. Lett., 103:141802, 2009 EDELWEISS II, JCAP11 (2013) 067

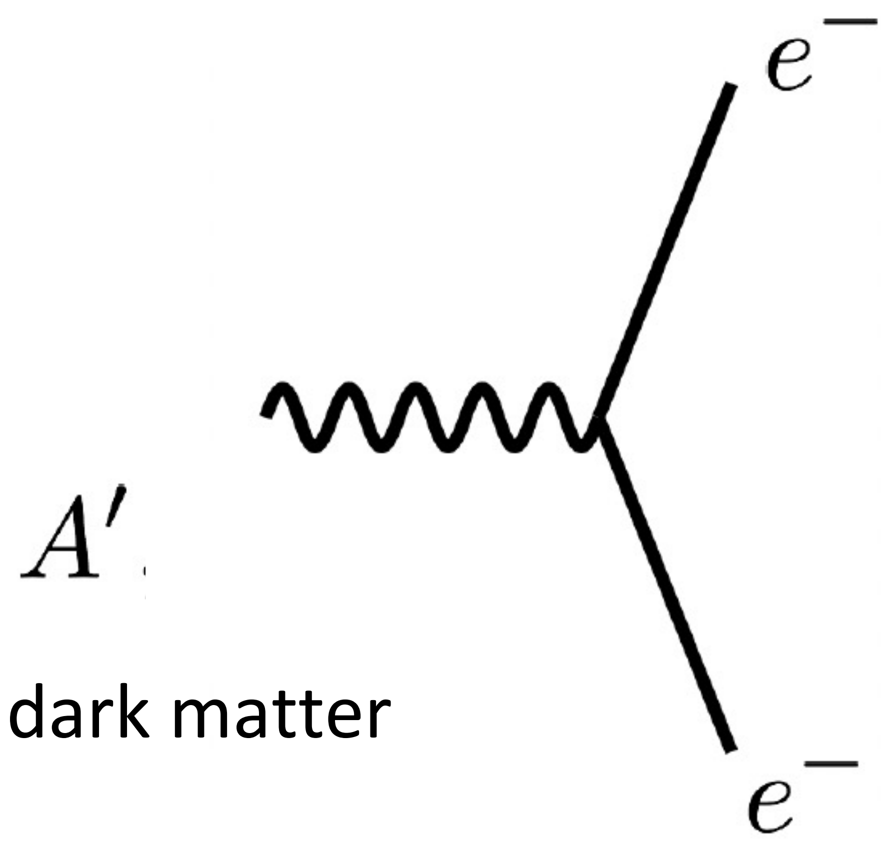
Vector Bosonic Dark Matter Searches

BSM Physics

Peak Search

Vector Bosonic Dark Matter (spin-1, dark photons)

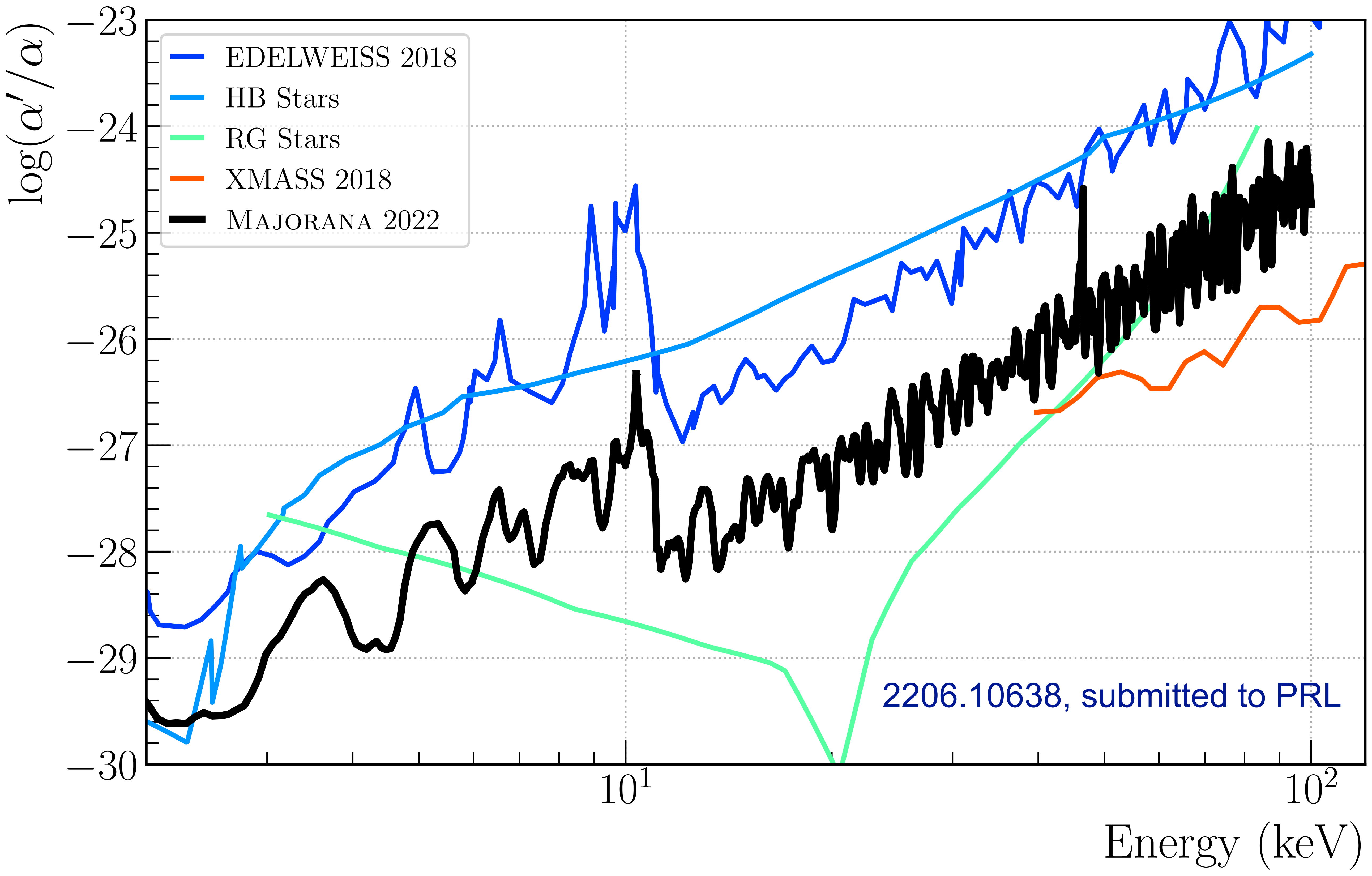
- Very similar to the detection of the pseudoscalar DM



Vector dark matter

- DM to electron coupling constant α' relates to the fine structure constant α

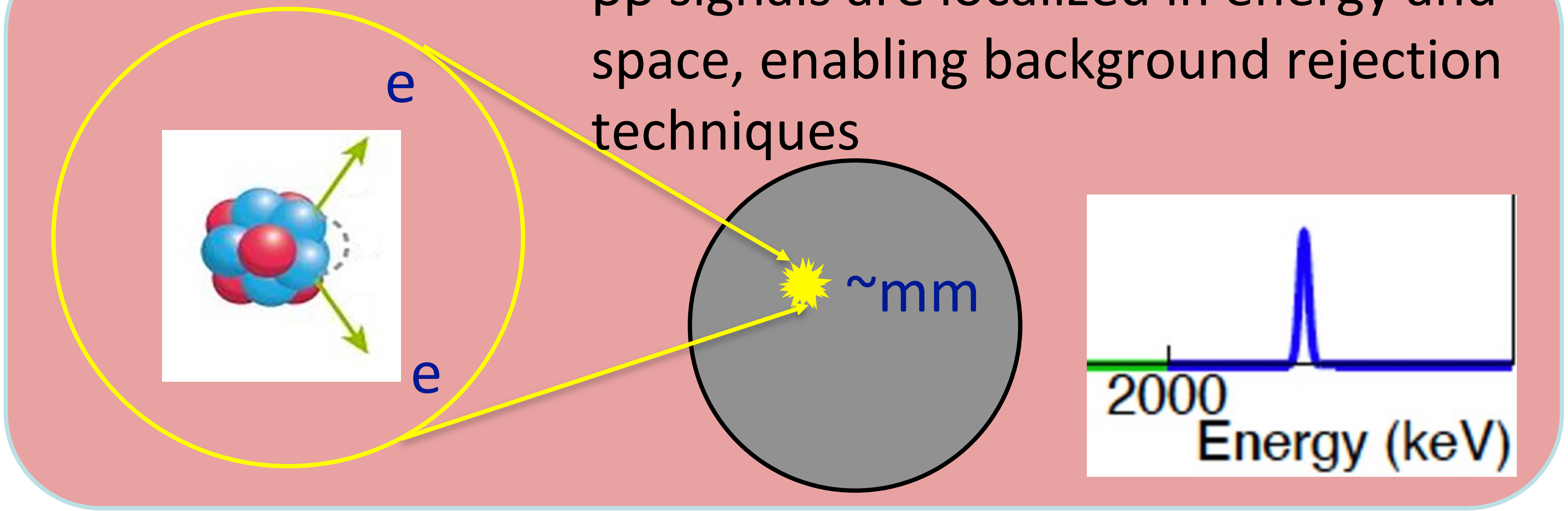
$$\Phi_{DM}\ \sigma_{ve} = \left(\frac{4\times 10^{23}}{m_v}\right)\left(\frac{\alpha'}{\alpha}\right)\frac{\sigma_{pe}(m_v)}{A}$$



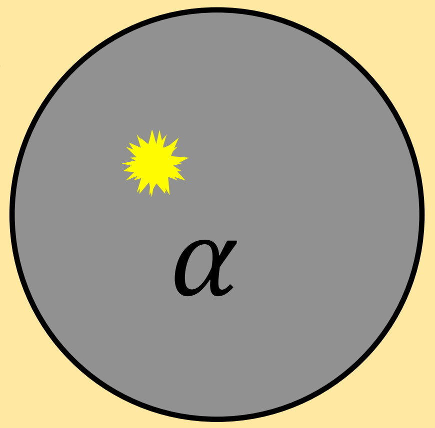
2206.10638, submitted to PRL

Best limit in germanium detectors

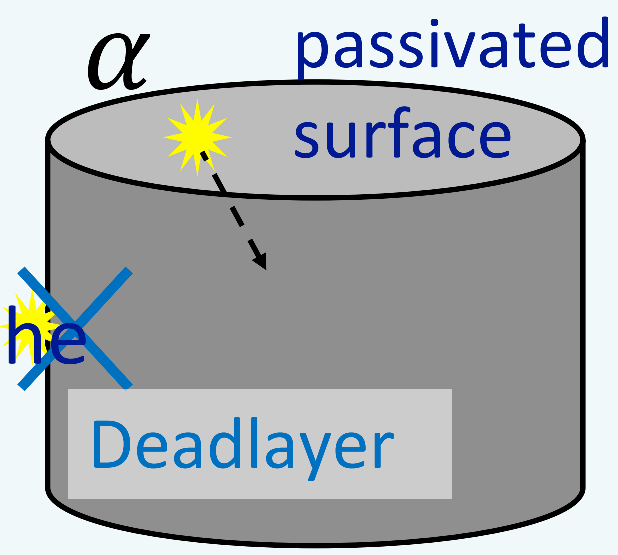
Signal and Backgrounds



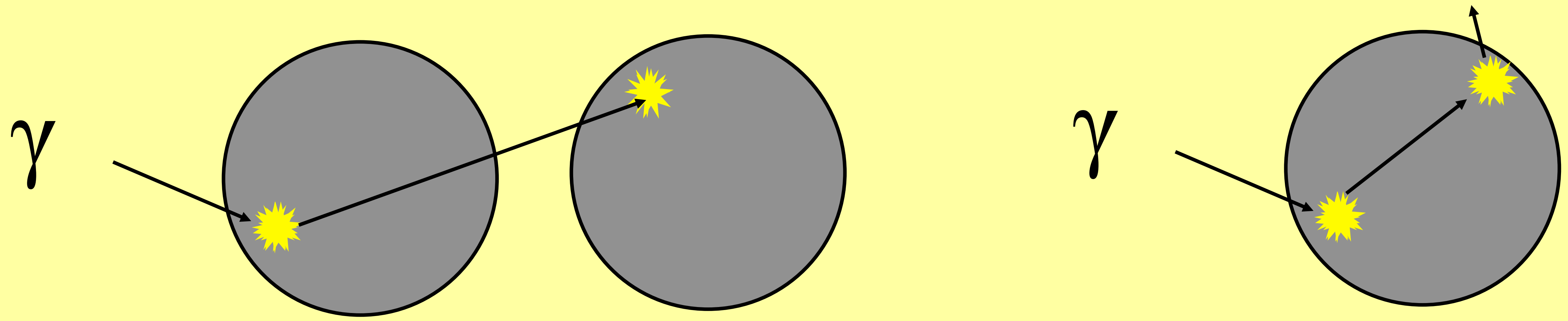
ββ signals are localized in energy and space, enabling background rejection techniques



Internal alpha particle background:
- different energies
- never observed

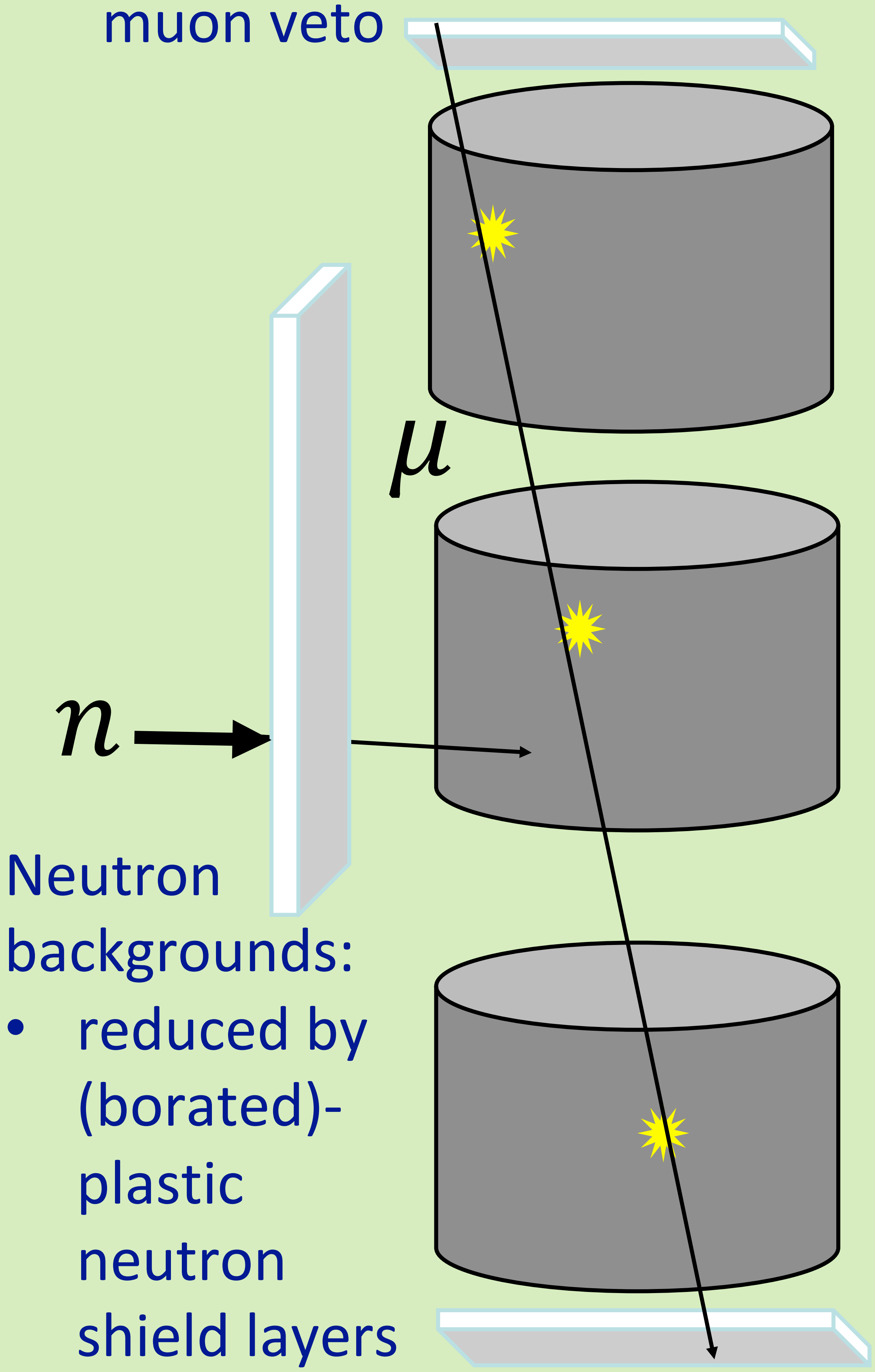


External alpha particle background:
- reduced by radio purity
- stopped by ~1mm dead layer everywhere except on the passivated surface
- rejected by pulse shape discrimination



Photon background:
- reduced by radio purity + shielding + radon purge
- rejected by single detector requirement and pulse shape discrimination

Main backgrounds requiring analysis cuts



Cosmic ray backgrounds:
- reduced by being 4850’ underground
- rejected by high efficient muon veto

Neutron backgrounds:
- reduced by (borated)-plastic neutron shield layers

Excellent Energy Performance

Calibrated on weekly ^{228}Th calibration data

Energy estimated via optimized trapezoidal filter of ADC-nonlinearity-corrected* traces with charge-trapping correction and fixed-time pickoff

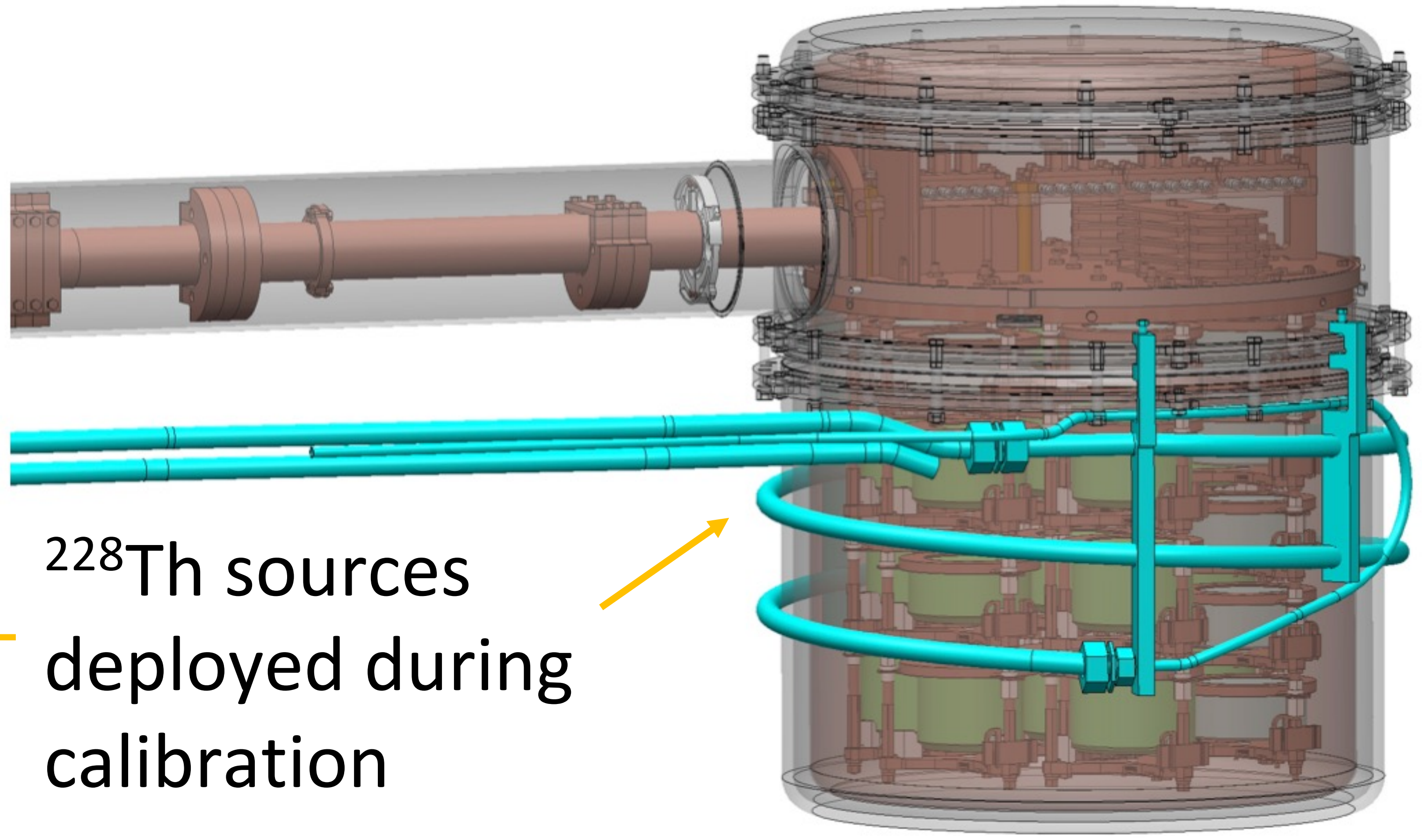
* IEEE Trans. on Nuc Sci 10.1109/TNS.2020.3043671

FWHM (2.5 keV) and linearity (<0.2 keV up to 3 MeV) a record for neutrinoless double-beta decay searches

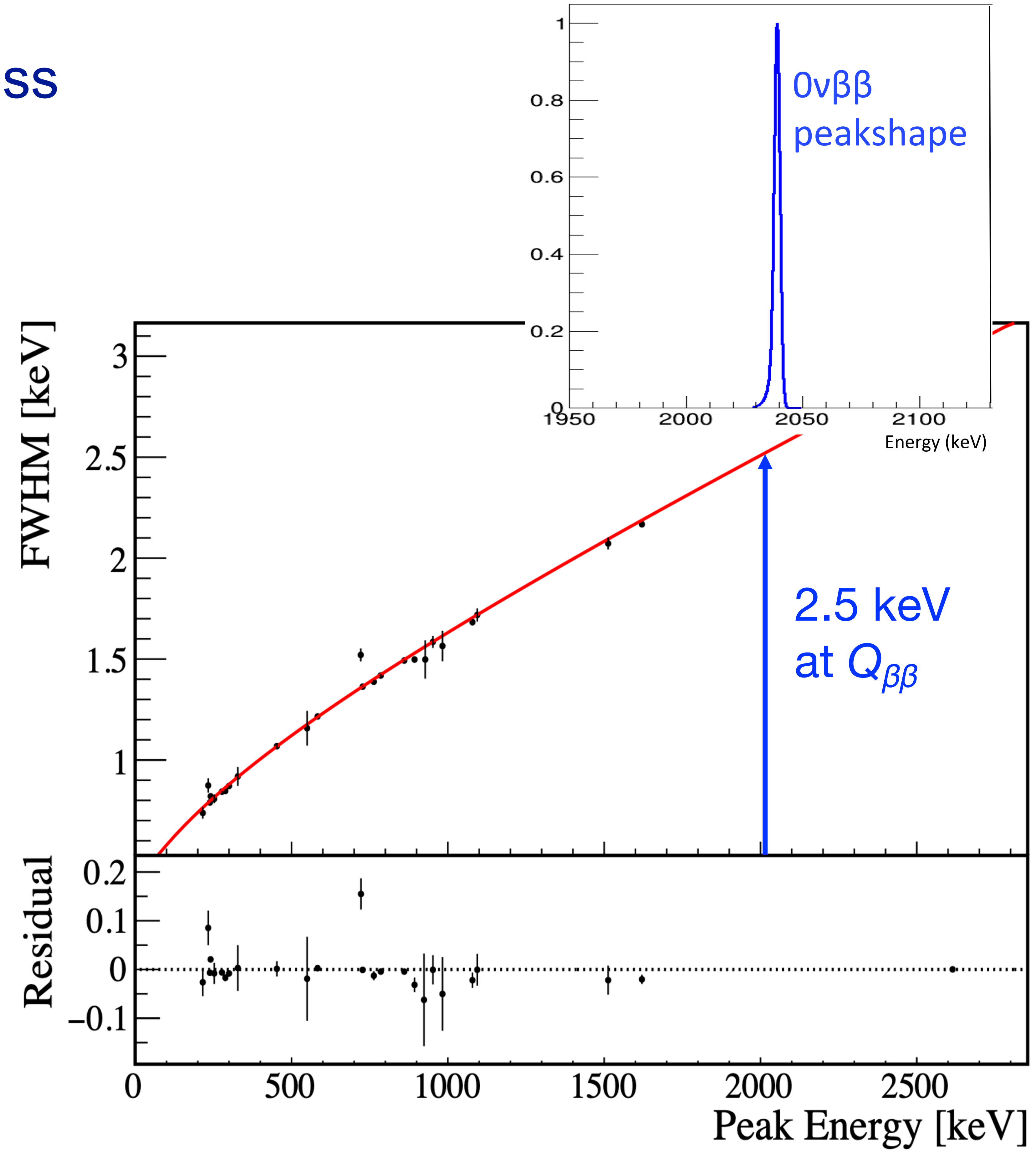
- Less than 0.1 keV energy scale offset at low energy 1 keV~10keV

NIMA **872** (2017) 16

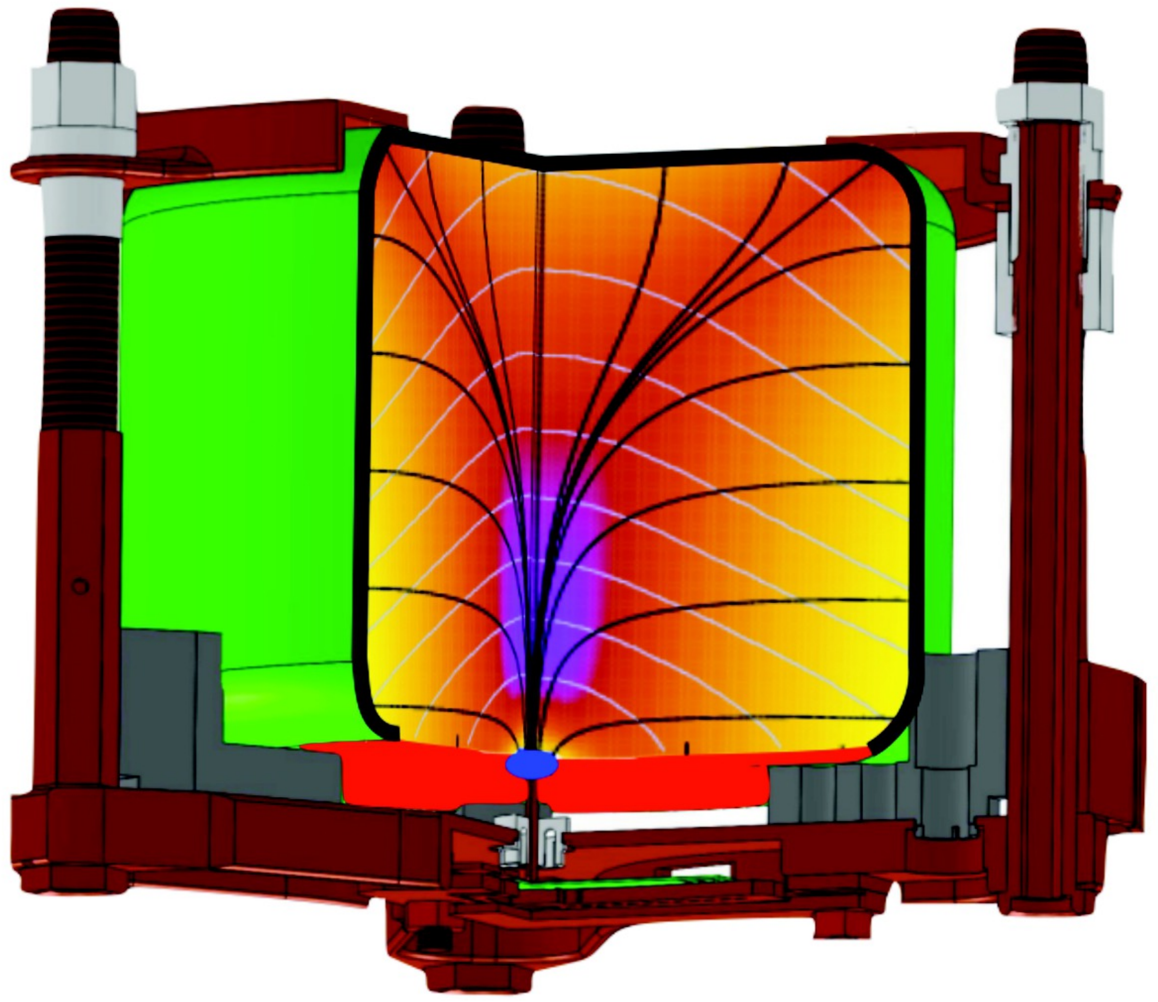
^{228}Th sources deployed during calibration



as-built geometry

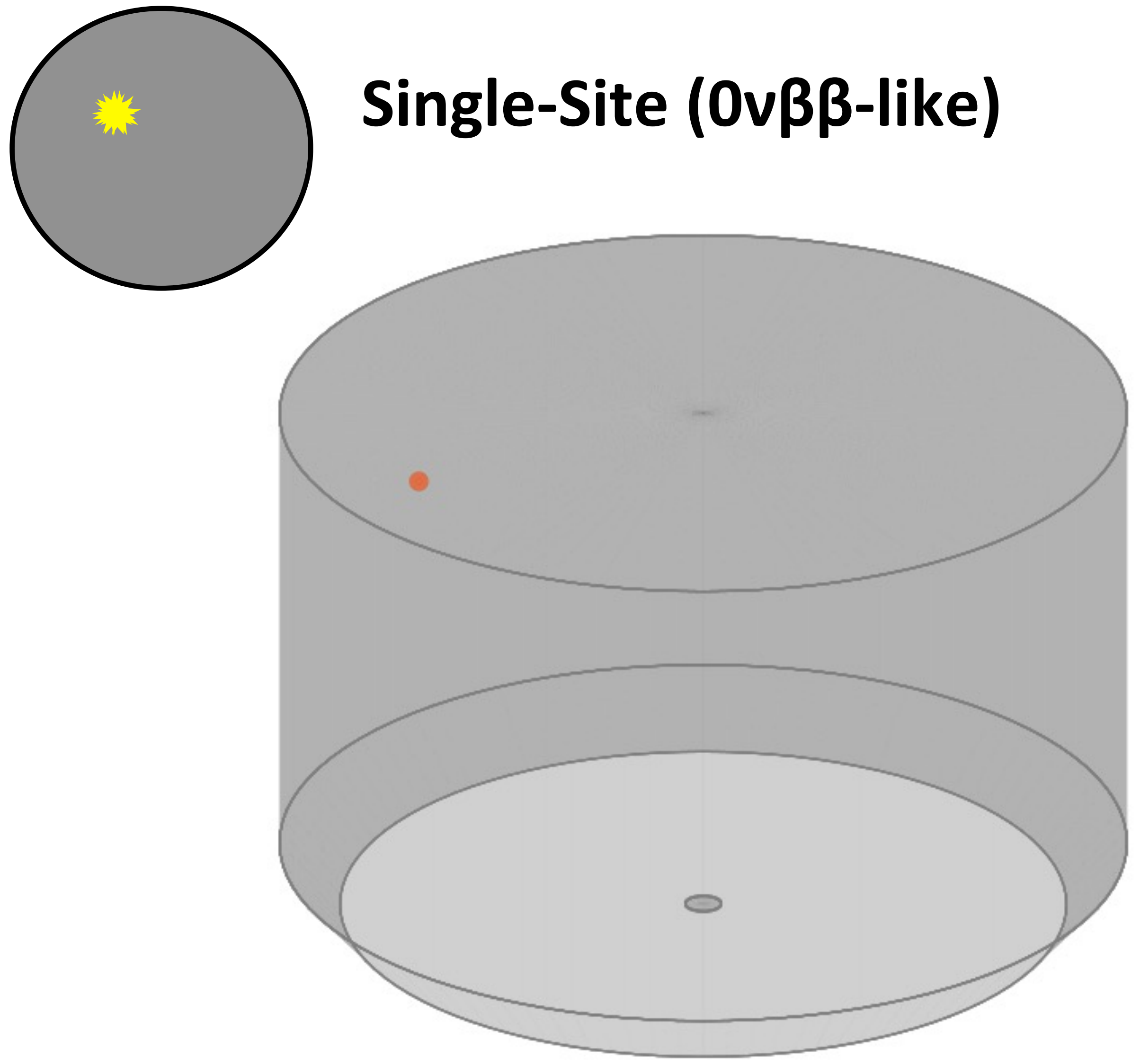


Timing Information Accessed by Pulse Shape

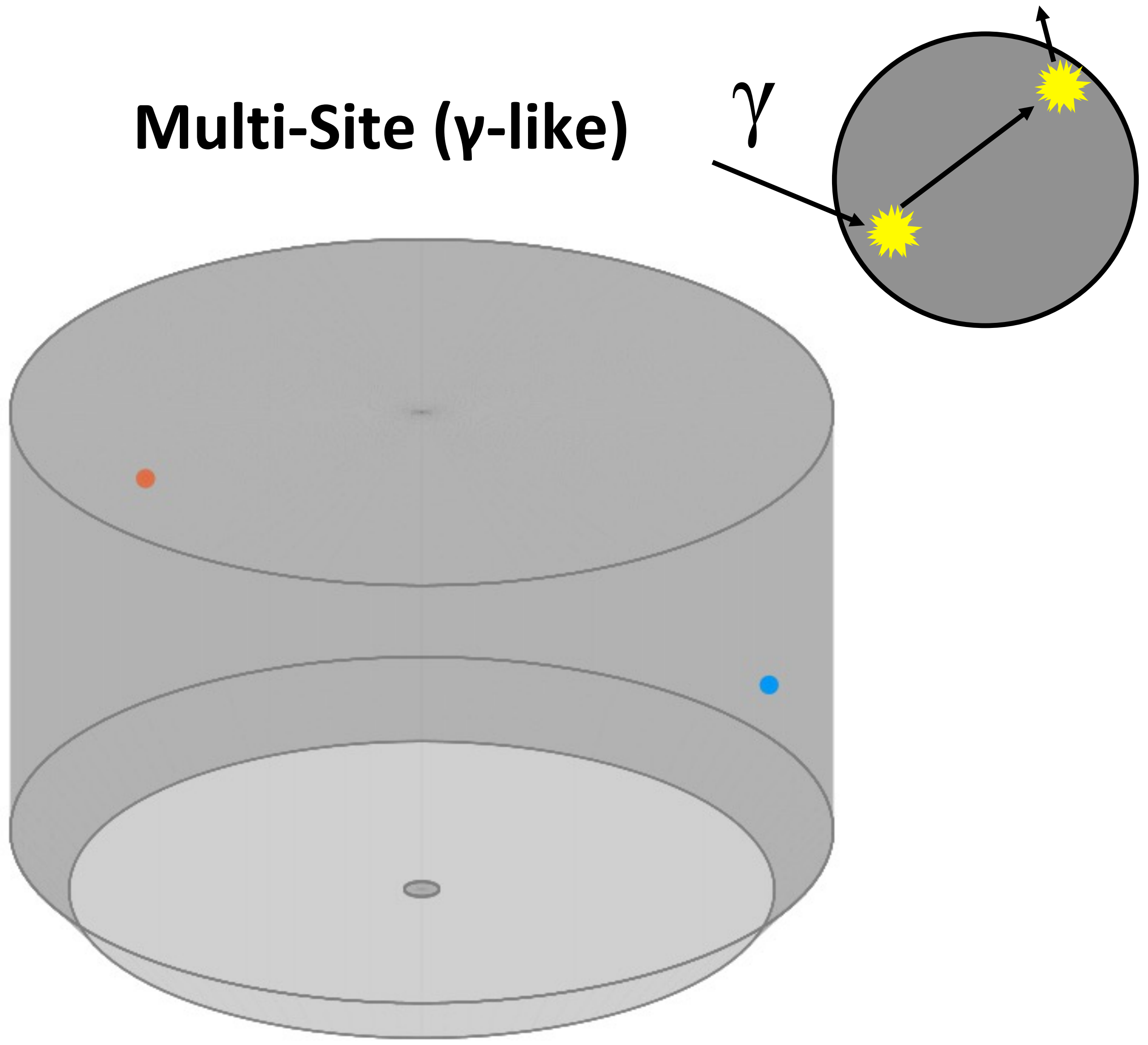


🟦 p+ Point Contact (Ge)
🟩 n+ Outer Contact (Li)
🟧 Active (Intrinsic) Volume
🟥 Passivated Surface
⬛ Transition Layer (~1mm)

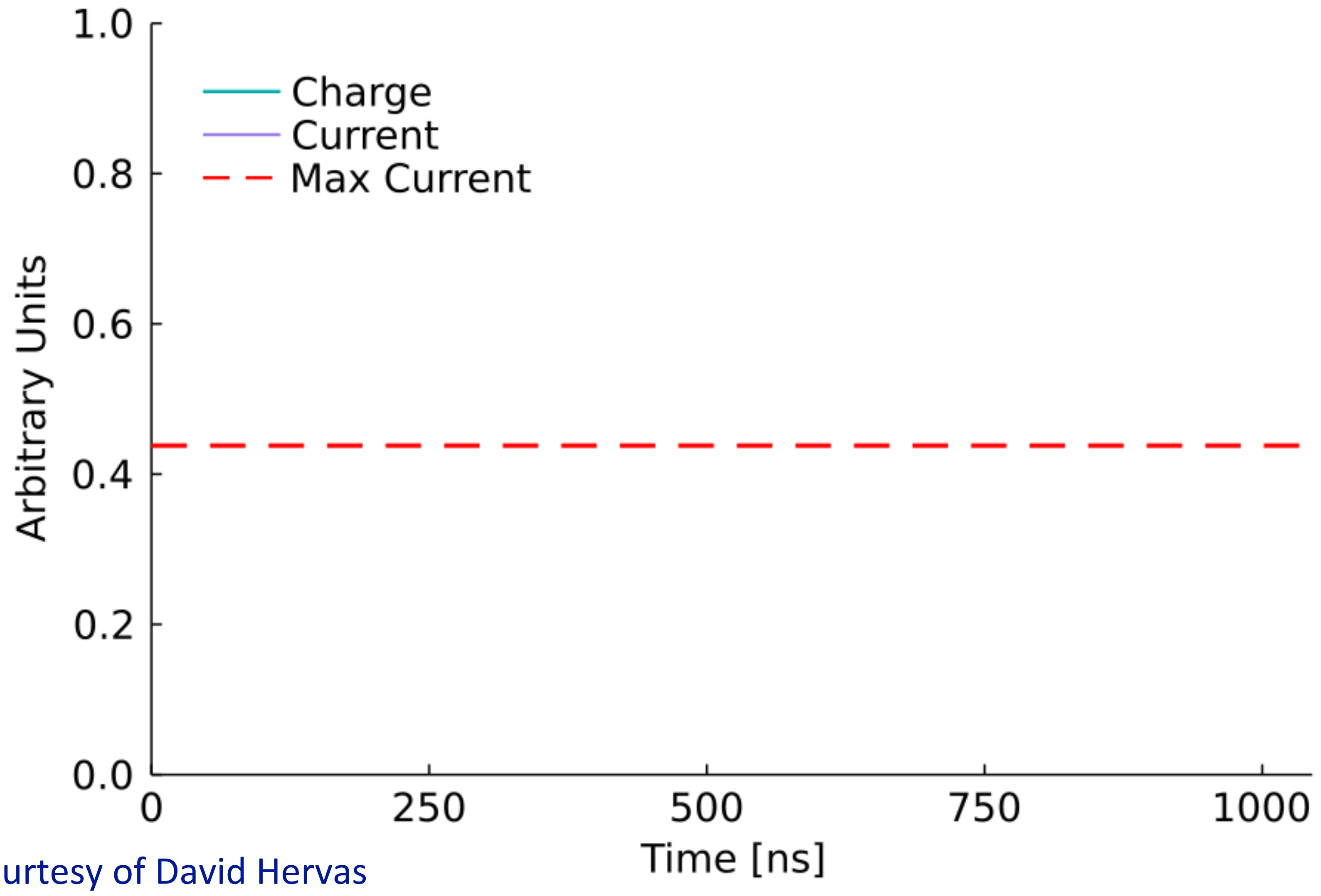
Amplitude of current pulse is suppressed for a multi-site event compared to a single-site event of the same event **E**nergy (AvsE) PRC **99** 065501 (2019)

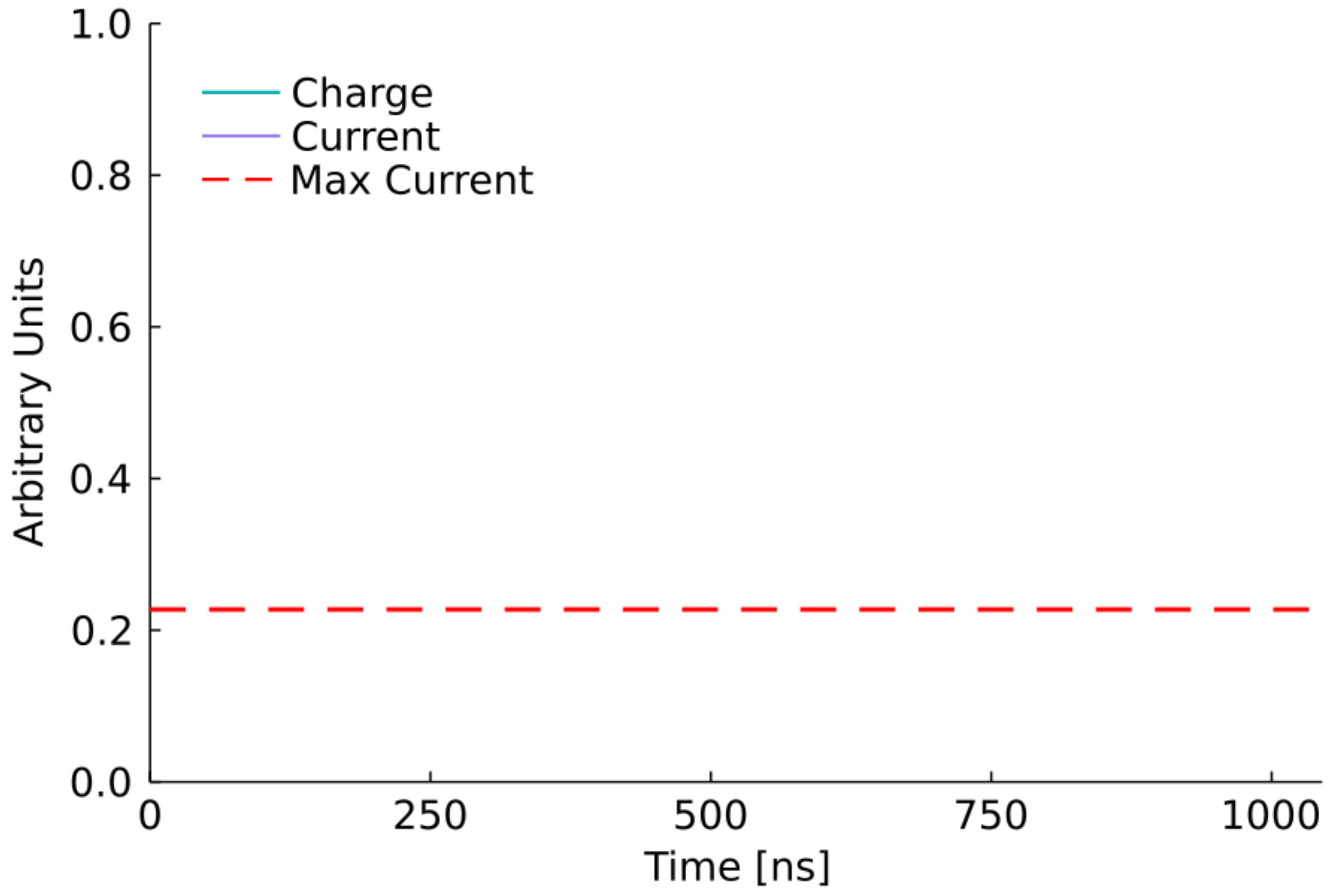


Single-Site (0νββ-like)



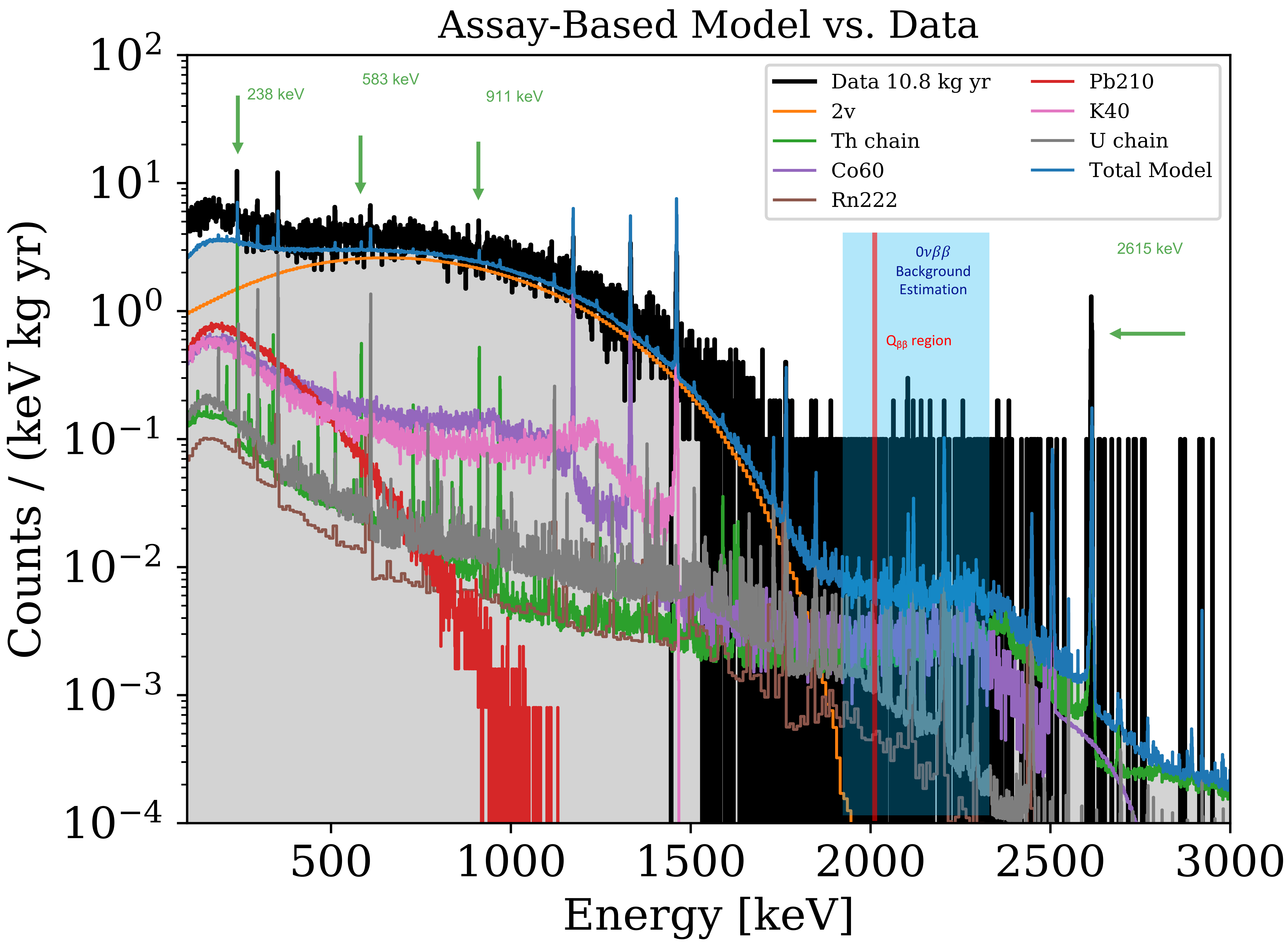
Multi-Site (γ-like)





courtesy of David Hervas

Background Modeling and Investigation



Investigating observed background near $Q_{\beta\beta}$

Assay-based prediction: 2.9 ± 0.14 cts/(FWHM t y) at $Q_{\beta\beta}$

Measured Background: 11.9 ± 2.0 cts/(FWHM t y)

PRC **100** 025501 (2019)

Characteristics of background excess:

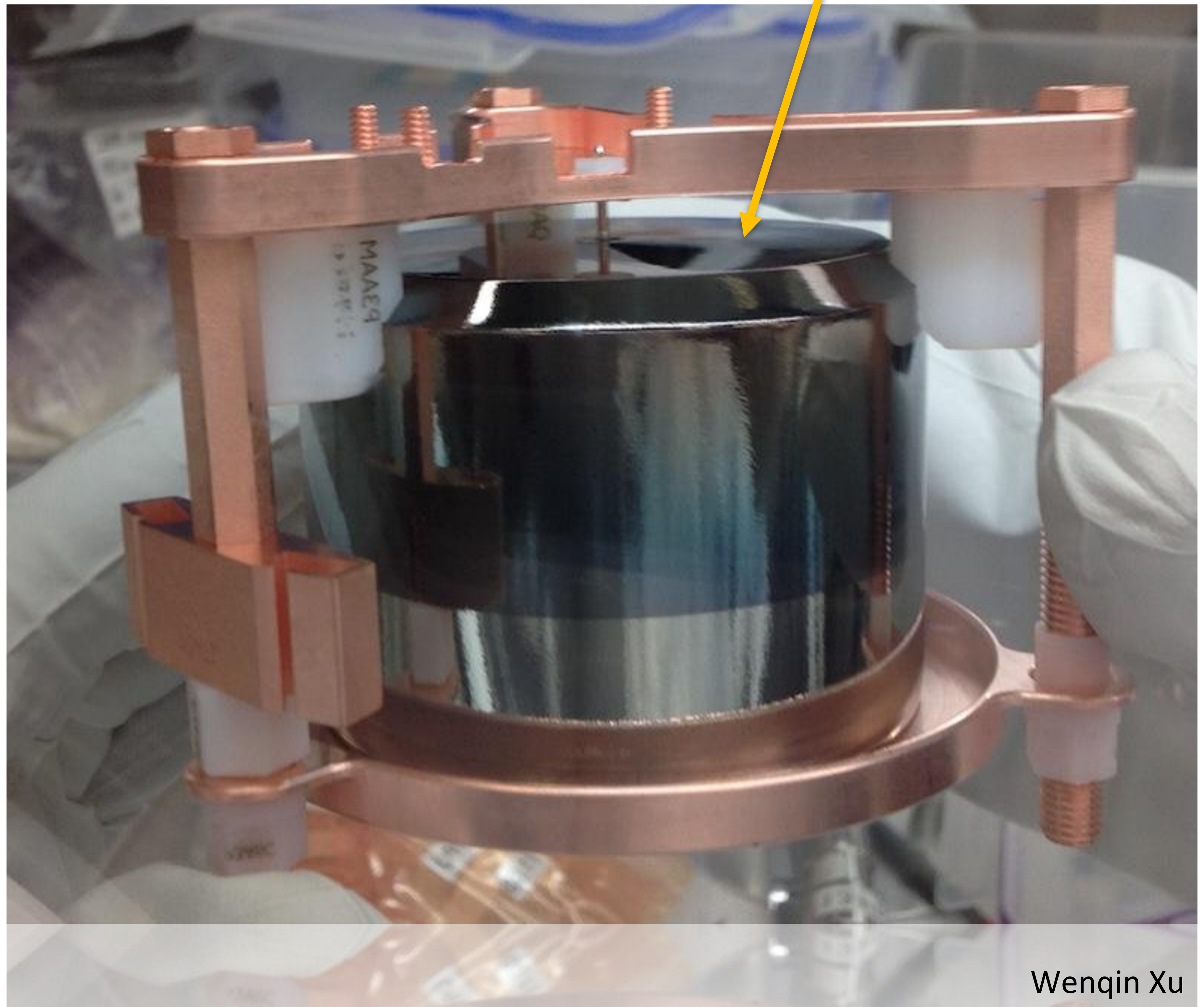
- Dominated by ^{232}Th decay chain
- Higher in Module 1 than Module 2
- Some evidence that Module 1 has higher rates at top of array compared to bottom
- The observed ^{232}Th excess is not consistent with either a point or uniformly distributed source in the near-detector components --- This is an important finding for LEGEND-200 which uses similar materials for near-detector components

Backgrounds: Surface Alpha Rejection

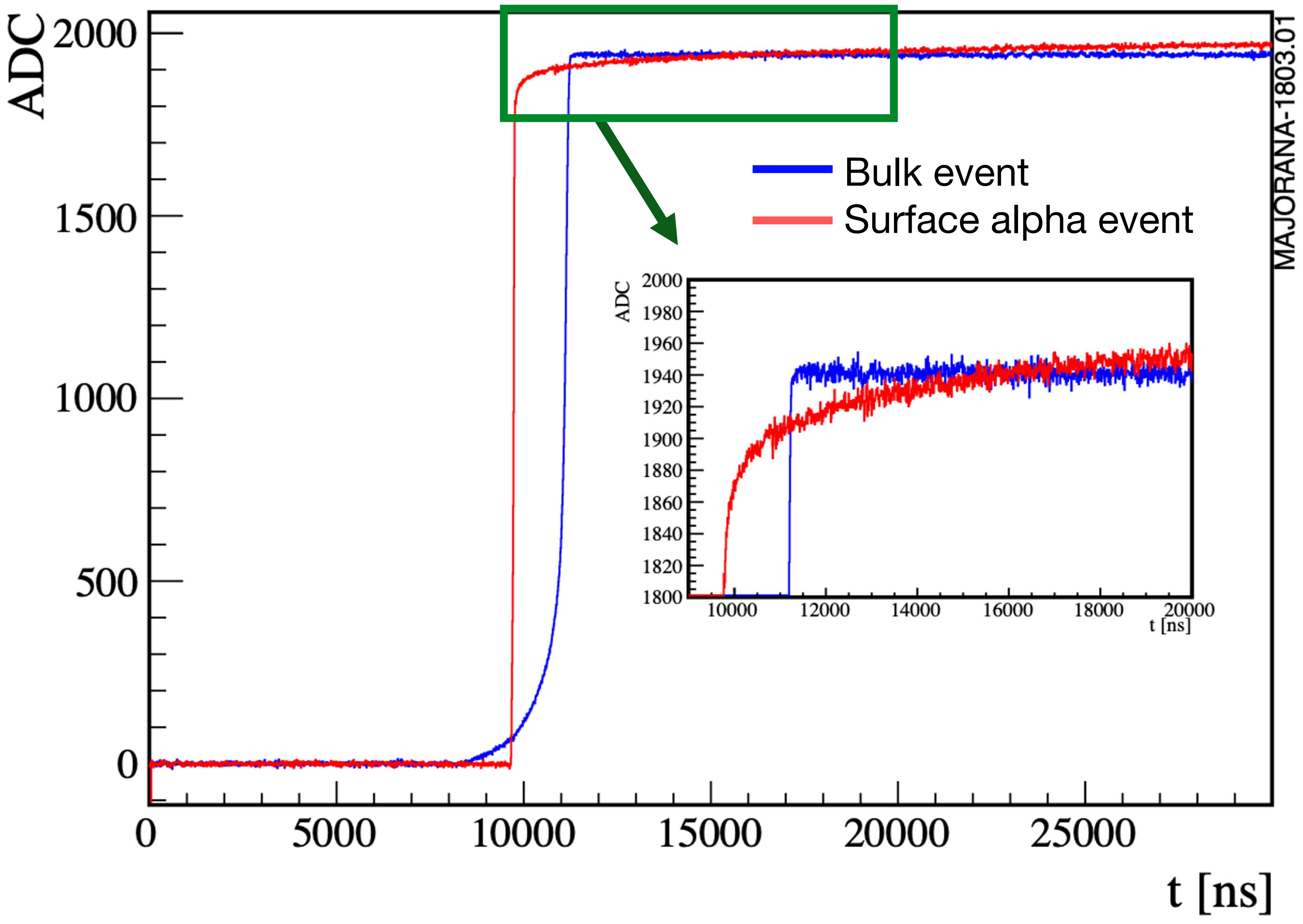
Alpha background with degraded energies observed; charge trapped at passivated surface, slowly released into bulk: *delayed charge recovery* (DCR) EPJC 82 (2022) 226

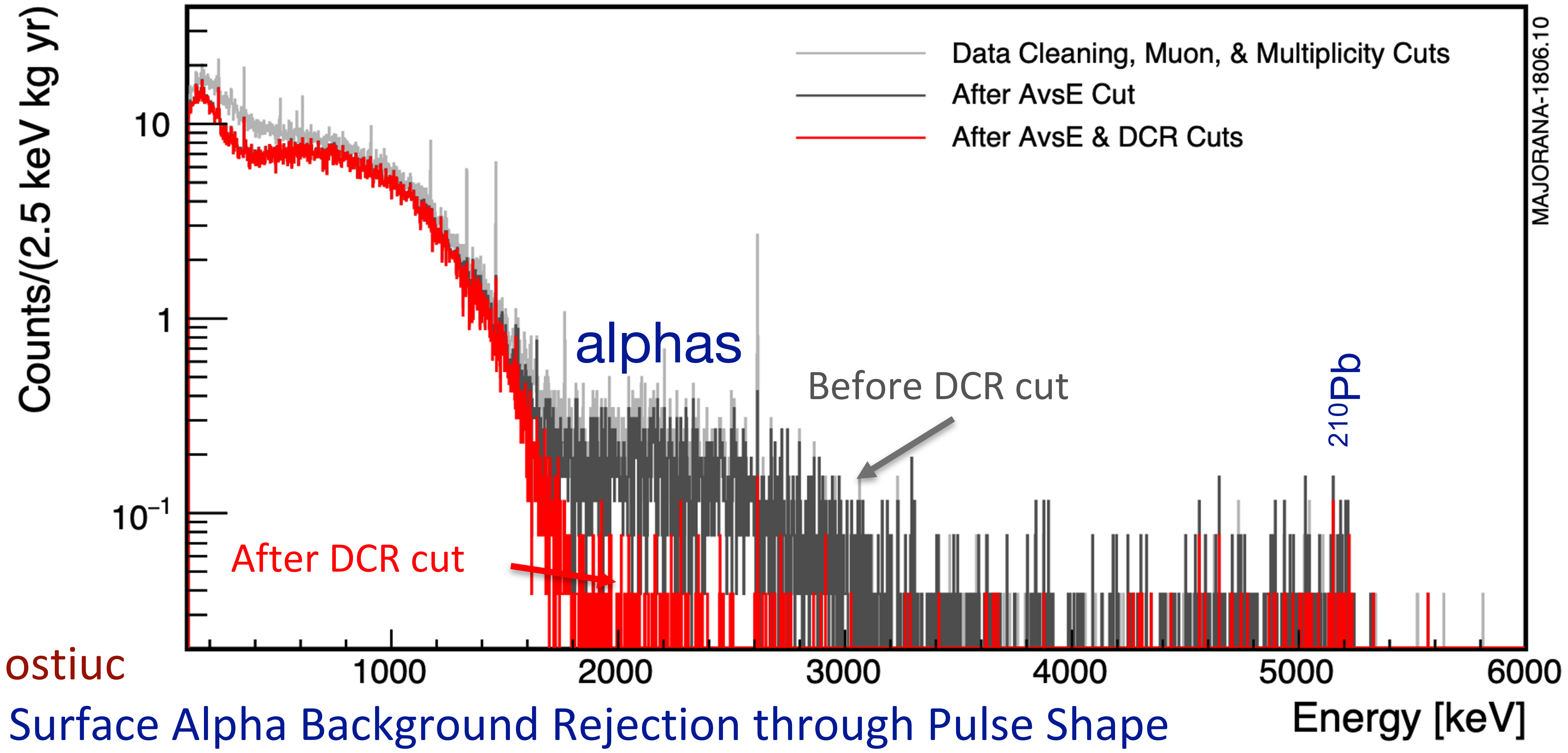
- Cut with a parameter related to slope of tail after the rising edge
- Retains 99% of the β/γ events, evaluated based on ^{228}Th data

Suspect α contamination near passivated surface ^{210}Po from ^{222}Rn exposure



Wenqin Xu

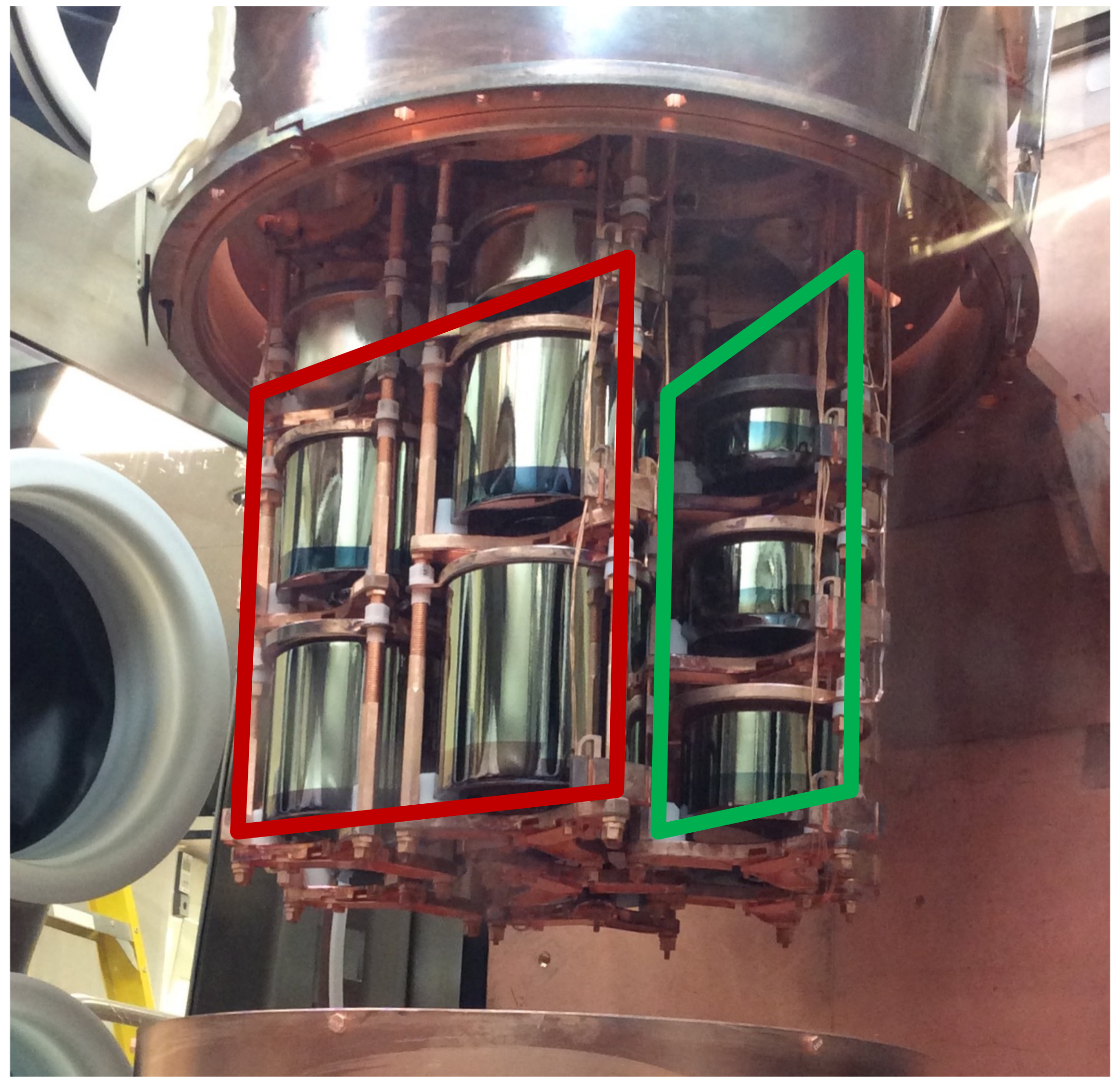




Alexandru Hostiuc

B14.00005 : Surface Alpha Background Rejection through Pulse Shape Discrimination in the MAJORANA DEMONSTRATOR

ICPC Detectors



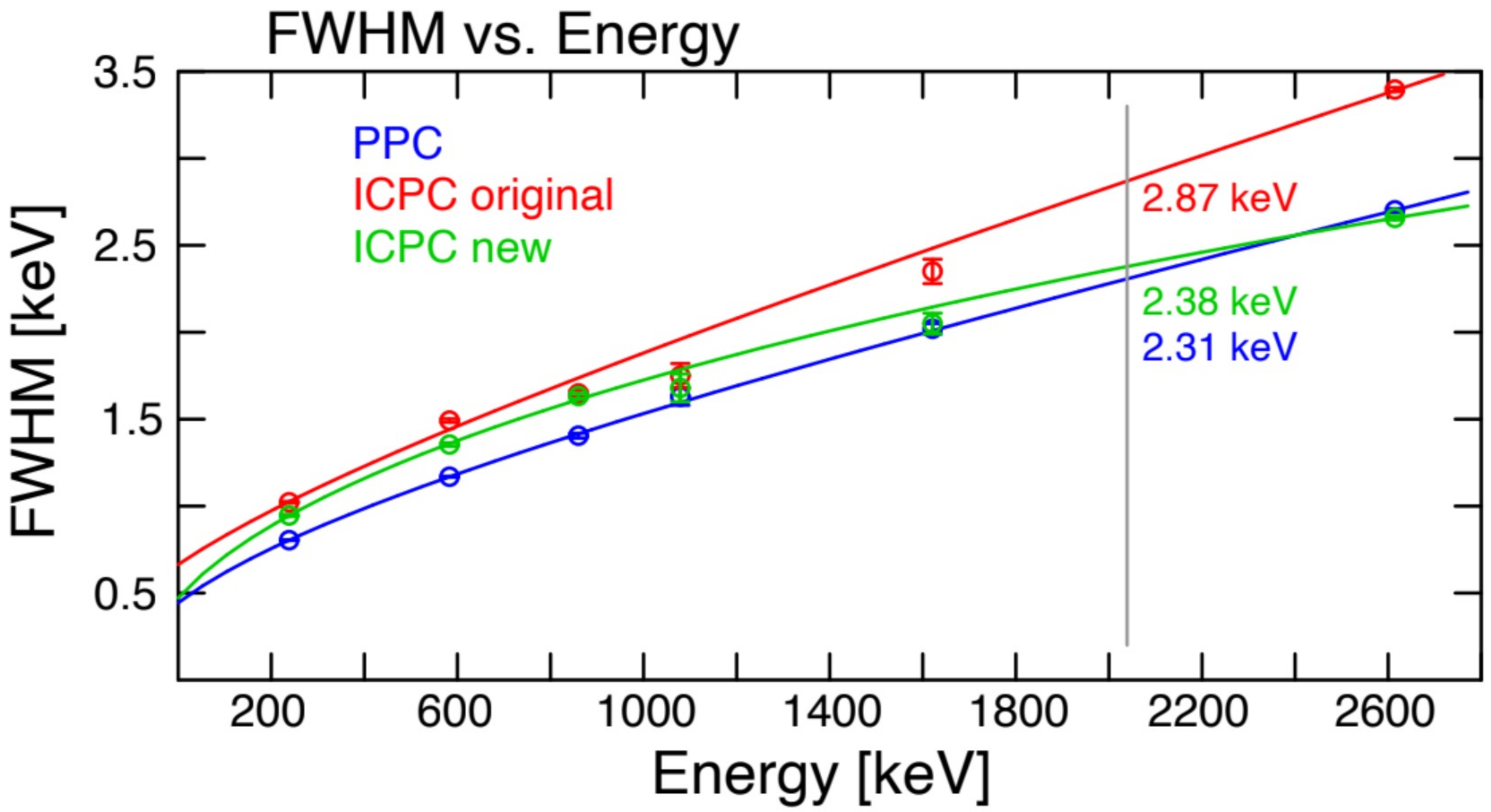
The size of the **ICPC detectors** is larger than **PPC detectors**

- Highly beneficial for background reduction in LEGEND
- Larger range of drift time in ICPC detectors.
- Charge trapping correction in PPC turn inaccurate for ICPC detectors

Proper algorithms have been developed for ICPC analysis

- Drift-charge-time (DT) correction used to develop new energy parameters
- A/E is used for multiple site event rejection
- Slope of the waveform tail is used to calculate late charge (LQ), as an extra PSD tool

The energy resolution achieved for ICPC detectors with new algorithms are comparable with PPC detectors

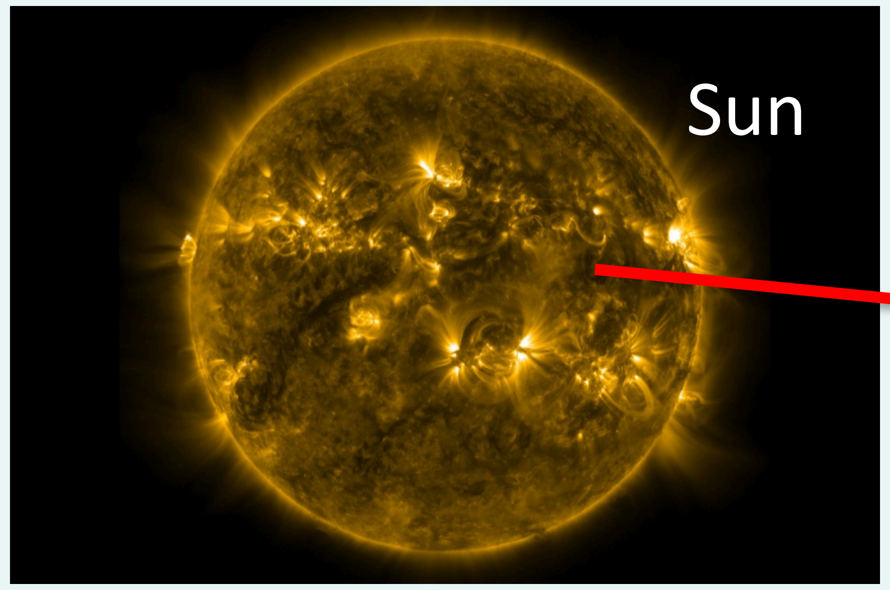


Solar Axion Search via Photon Coupling

BSM Physics

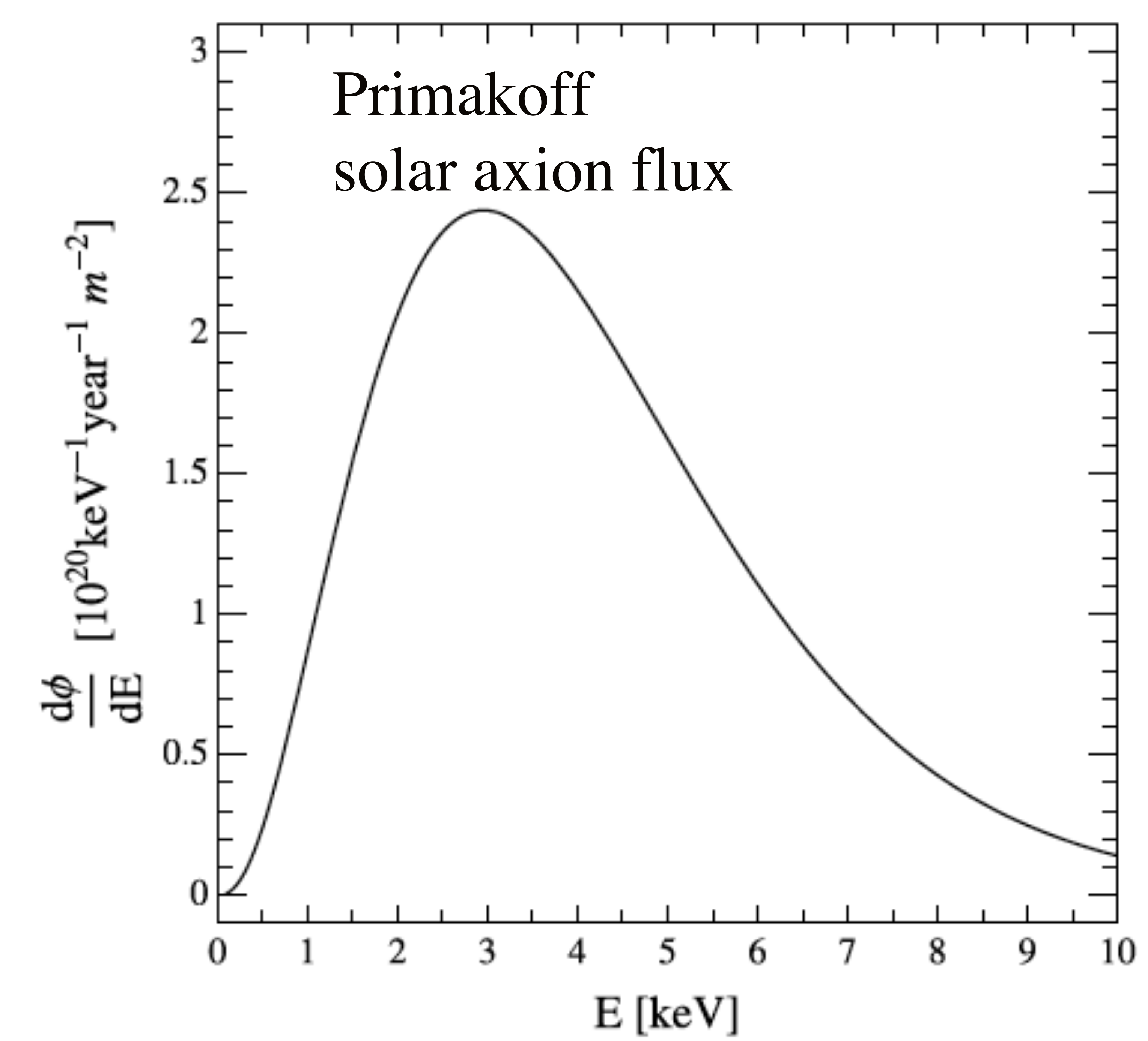
Energy-Time 2-D analysis

Production



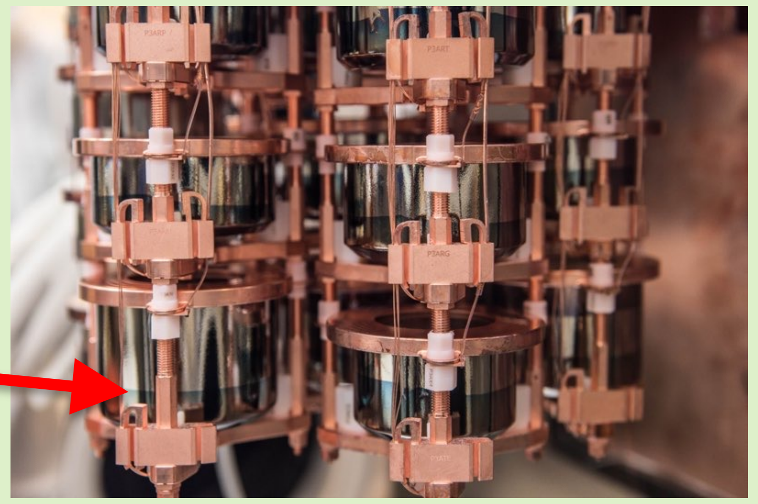
$\gamma + \gamma \rightarrow Axion$ Primakoff axions

axion-photon coupling (reverse Primakoff effect)



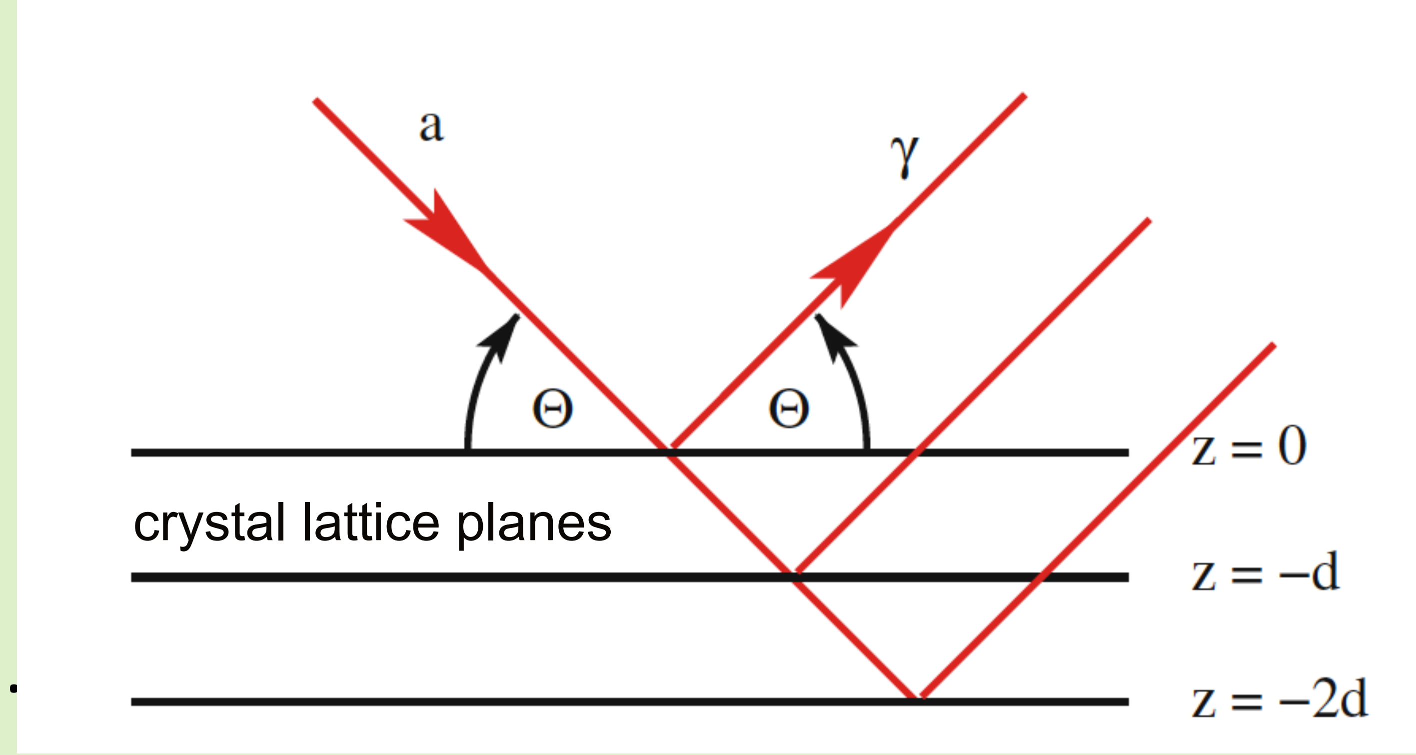
Progress in Particle and Nuclear Physics
102 (2018) 89–159

Detection



$Axion + \gamma_{virtual} \rightarrow \gamma$

- axion-photon coupling (Primakoff effect)
- enhanced by coherent Bragg diffraction

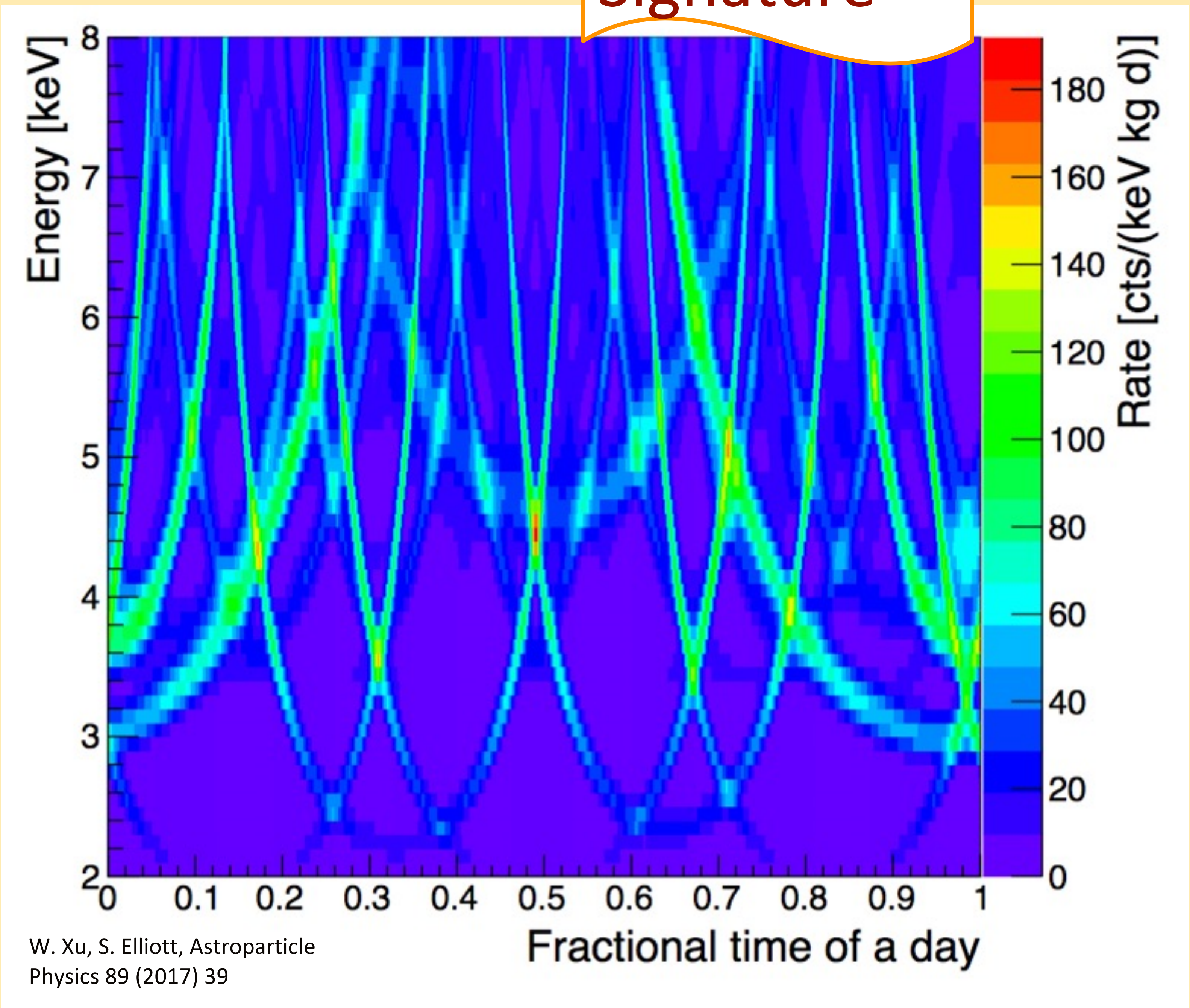


Axion signals:

- enhanced at certain incident angles for certain energy --- the Bragg condition
- follow Sun's movement over time

R. Battesti et al. Lect. Notes Phys. 741, 199–237 (2008)

Signature



W. Xu, S. Elliott, Astroparticle Physics 89 (2017) 39

plot for $g_{A\gamma} = 10^{-8} GeV^{-1}$, $g_{Ae} = 0$

- ➢ Distinct time dependence is a key strength for discovery
- ➢ Reduced sharpness if crystal orientations on the horizontal plane are unknown, but still good for analysis