New Results from the MAJORANA DEMONSTRATOR

Inwook Kim, on behalf of MAJORANA collaboration

2022-06-08

Sanford Underground Research Facility

U.S. DEPARTMENT OF ENERGY | Office of Science

NSF

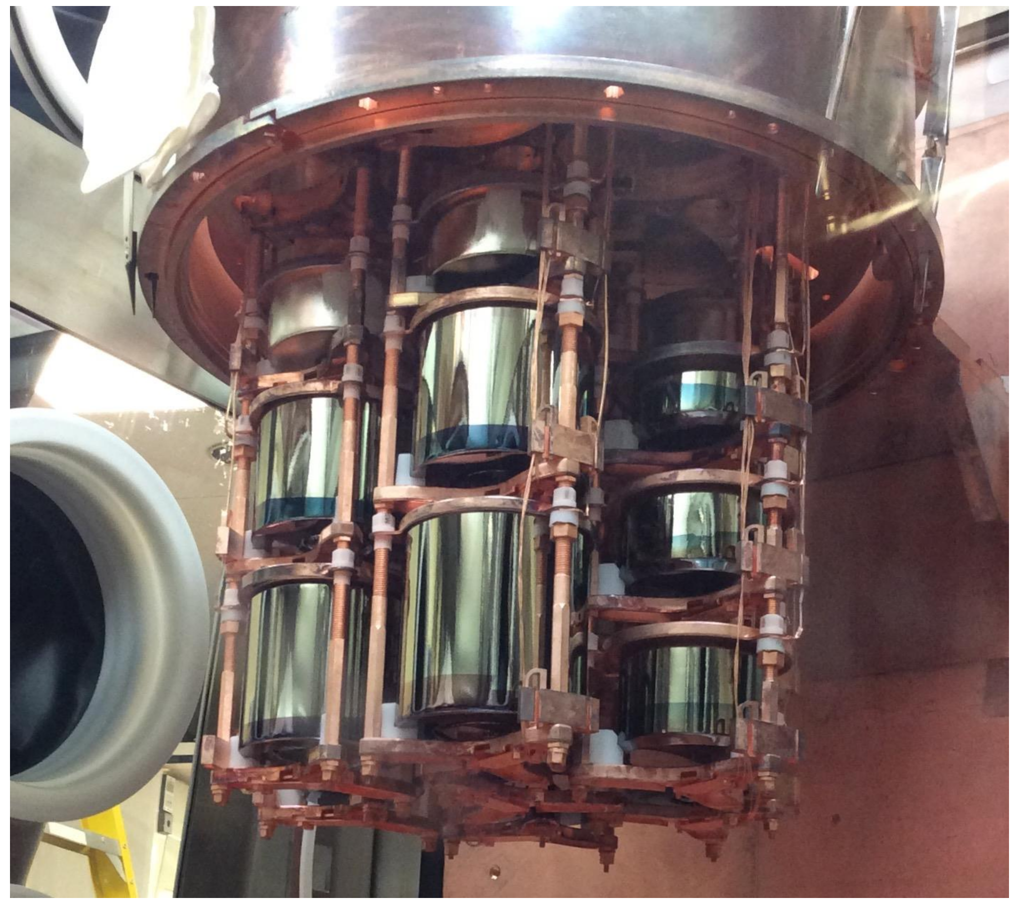
MAJORANA DEMONSTRATOR

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

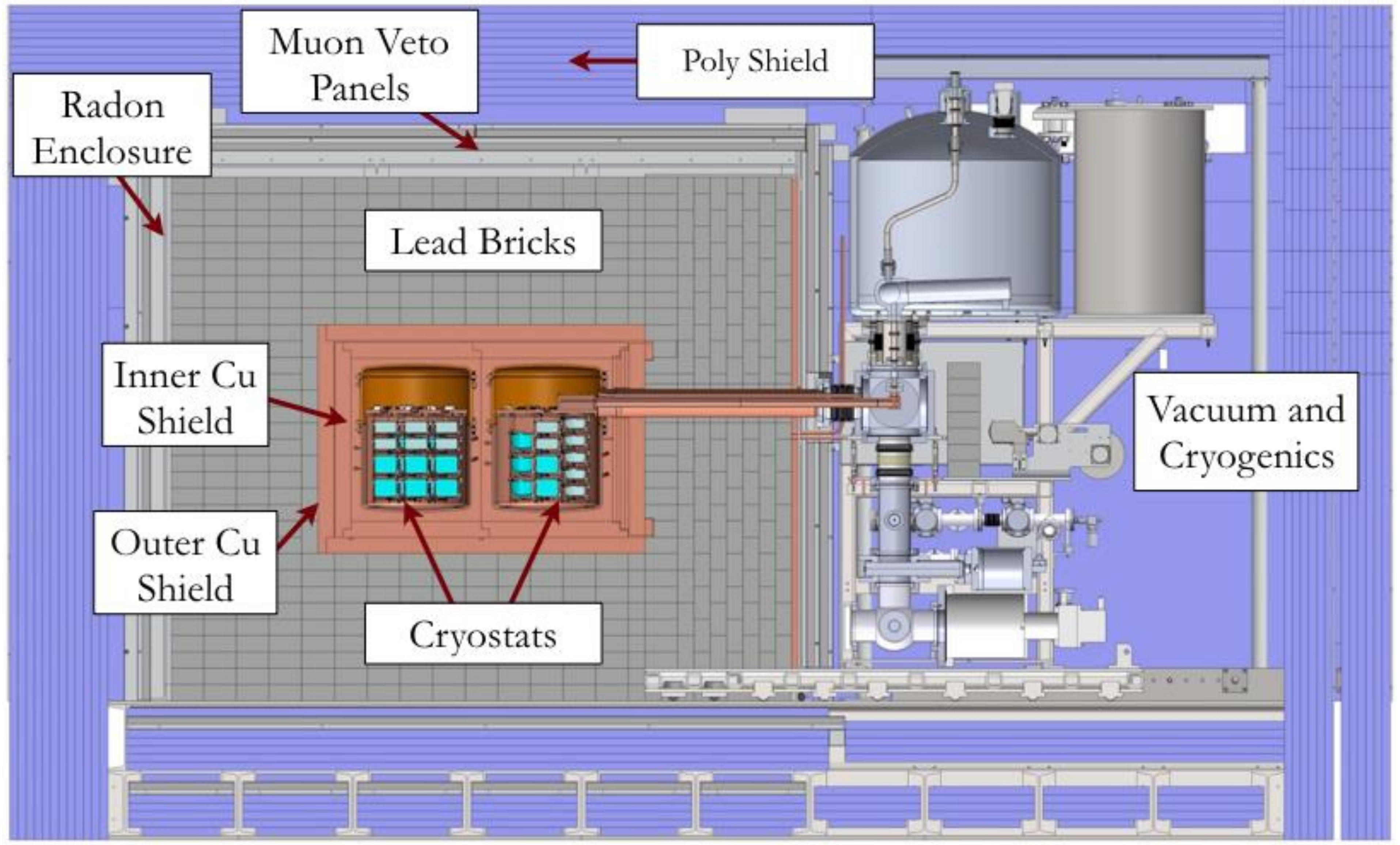
Source & Detector: Array of p-type, point contact detectors
30 kg of 88% enriched ^{76}Ge crystals - 14 kg of natural Ge crystals
Included 6.7 kg of ^{76}Ge inverted coaxial, point contact detectors in final run

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



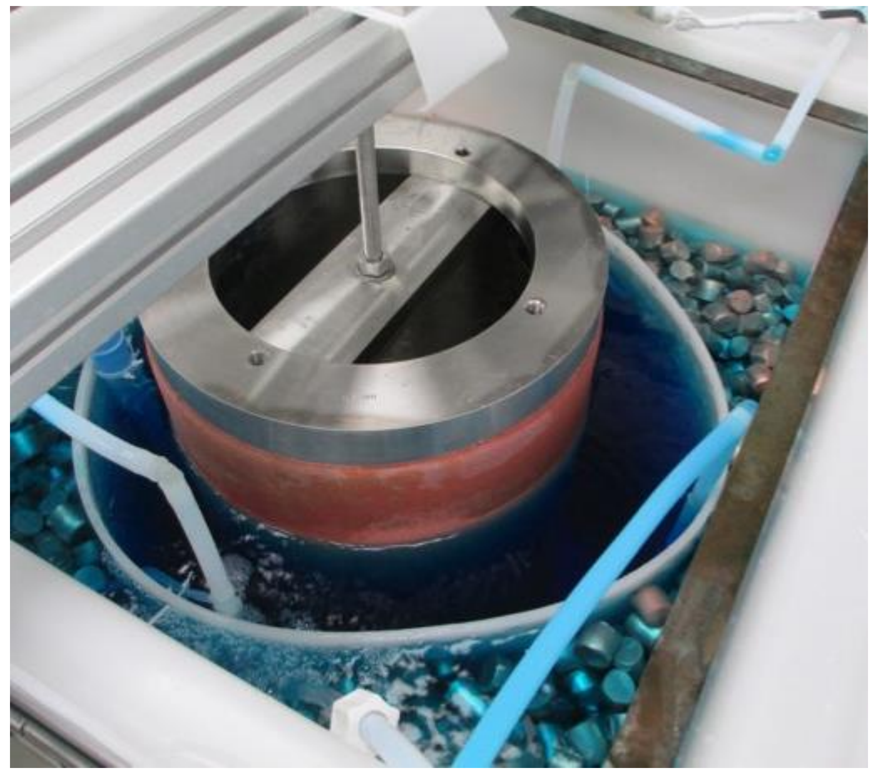
Continuing to operate at the Sanford Underground Research Facility with natural detectors for background studies and other physics

MAJORANA Approach to Backgrounds

P-type point contact detectors low intrinsic backgrounds, excellent energy resolution, pulse-shaped based background suppression PRC **100** 025501 (2019)

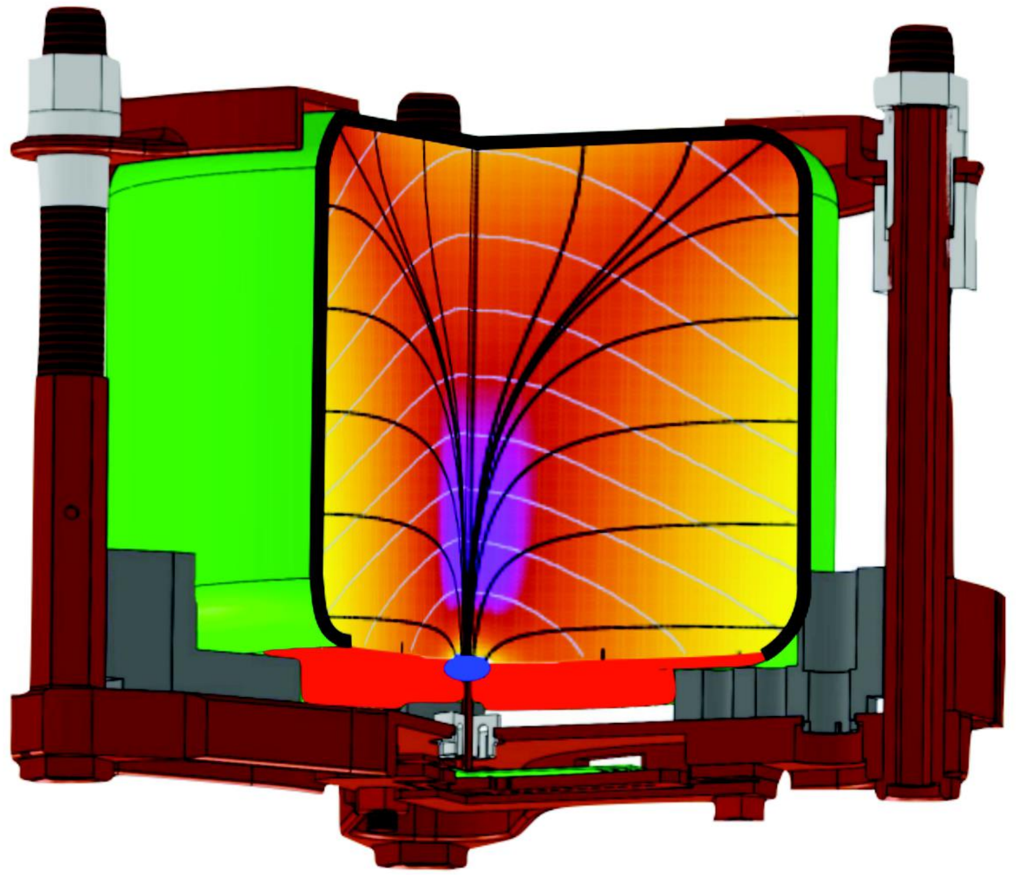
- Ge enrichment, zone-refining and crystal pulling processes enhance purity NIM A **877** 314 (2018)
- Limit above-ground exposure to prevent cosmic activation.
- Slow drift of ionization charge carriers allows separation of multiple interactions inside a detector.

Array components and passive shielding fabricated from ultra-pure materials with extremely low radio-isotope content NIM A **828** 22 (2016)



Rejection of backgrounds

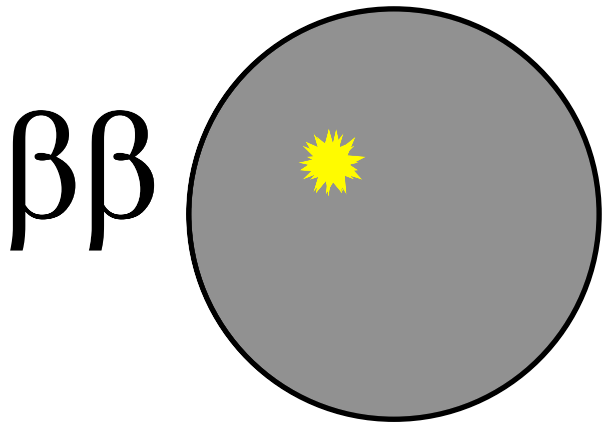
- Muon Veto: reject events coincident with muons Astropart. Phys. **93** 70 (2017)
- Granularity: multiple detectors hit
- Pulse shape discrimination: no multiple hits, reject surface events



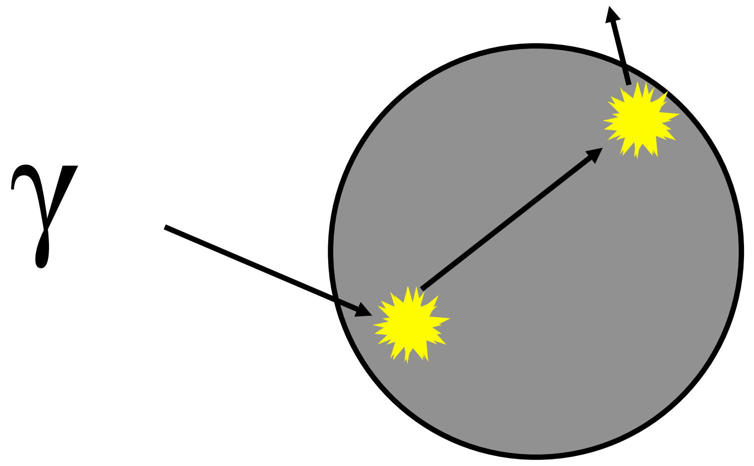
PRC **99** 065501 (2019)

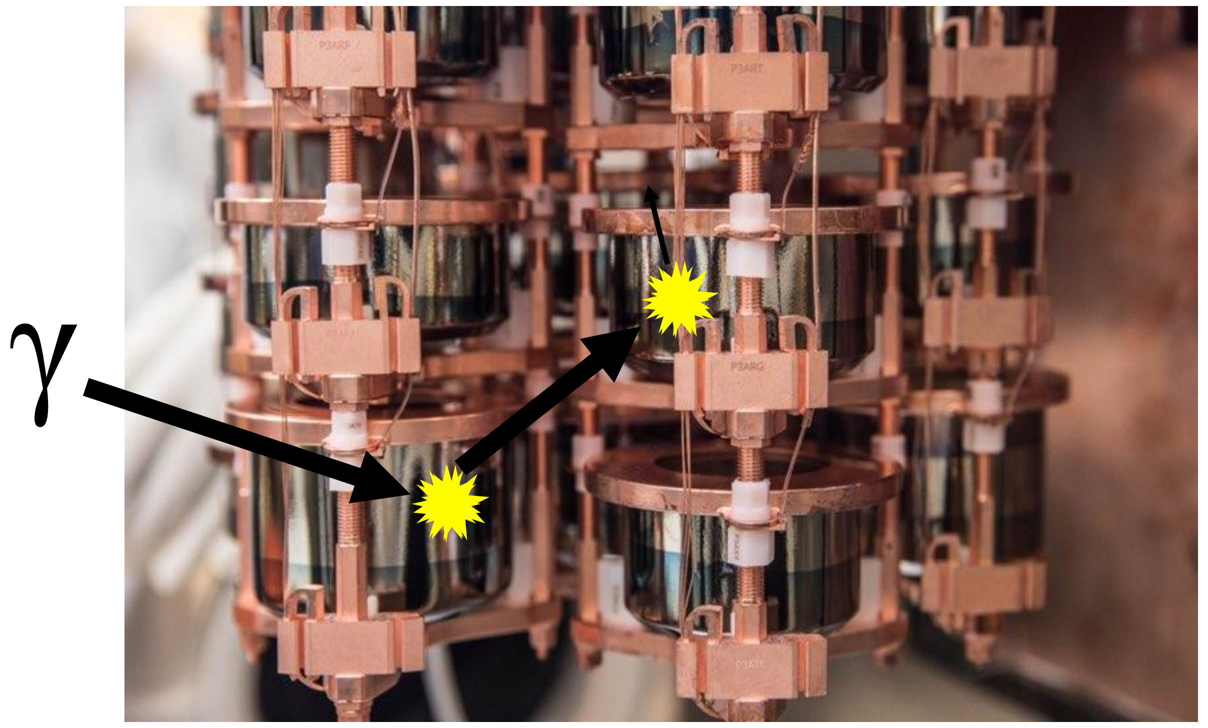
Eur. Phys. J. C **82,** 226 (2022)

Single-site event



Multi-site event





Analysis Techniques for Reducing Backgrounds

0νββ is most likely single-site and located in the bulk of the detector.

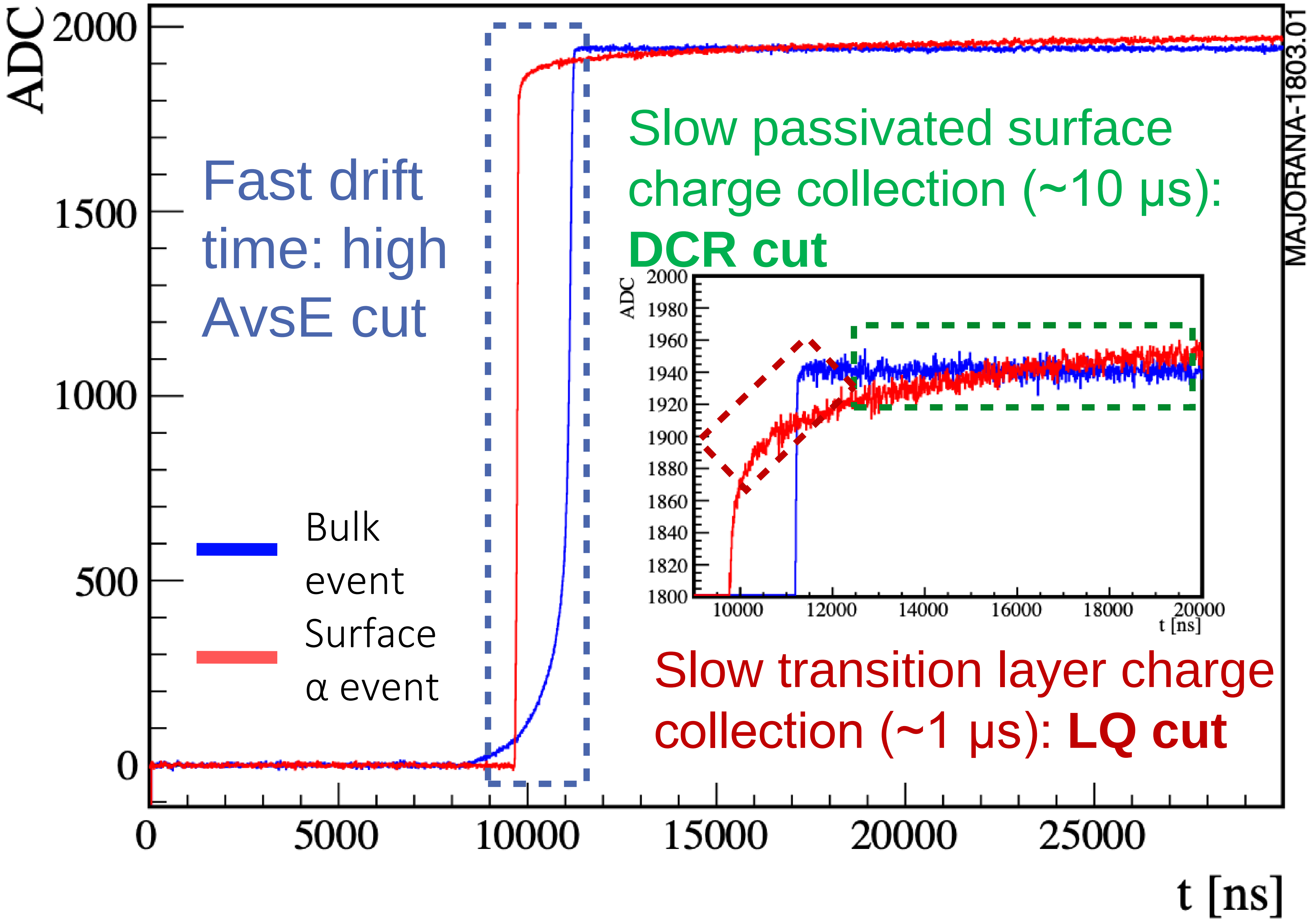
Many backgrounds are multi-site or located near detector surfaces.
Pulse-shape discrimination is used to distinguish between these event topologies.

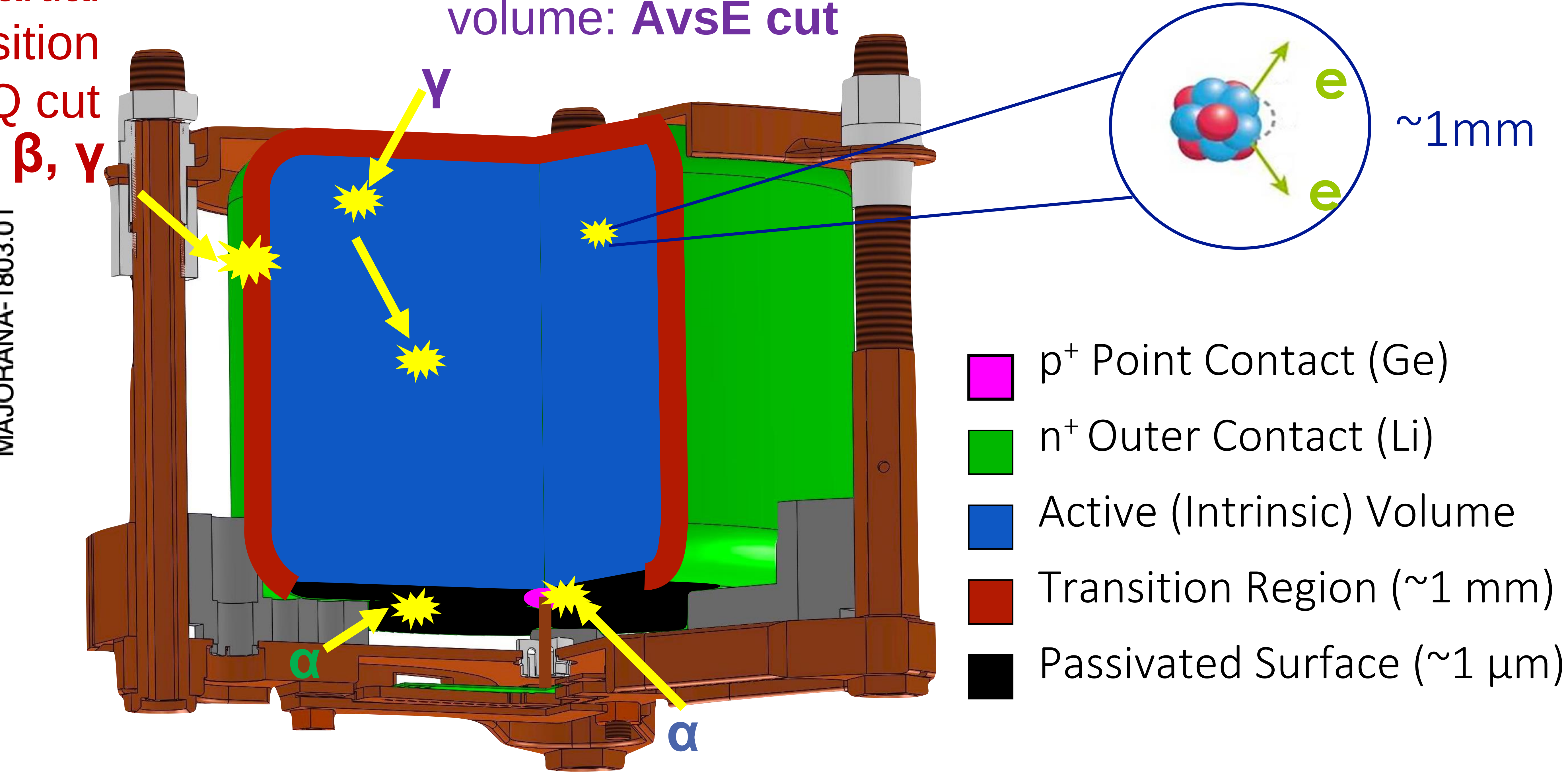
PRC **99** 065501 (2019)

EPJC 82 (2022) 226

Detector surface: for partial charge deposition in transition dead layer: LQ cut

Multi-site events in active volume: **AvsE cut**





Detector surface - for particle incident on passivated surface: **DCR cut**

Detector surface - for particle incident on surface near point contact: **high AvsE cut**

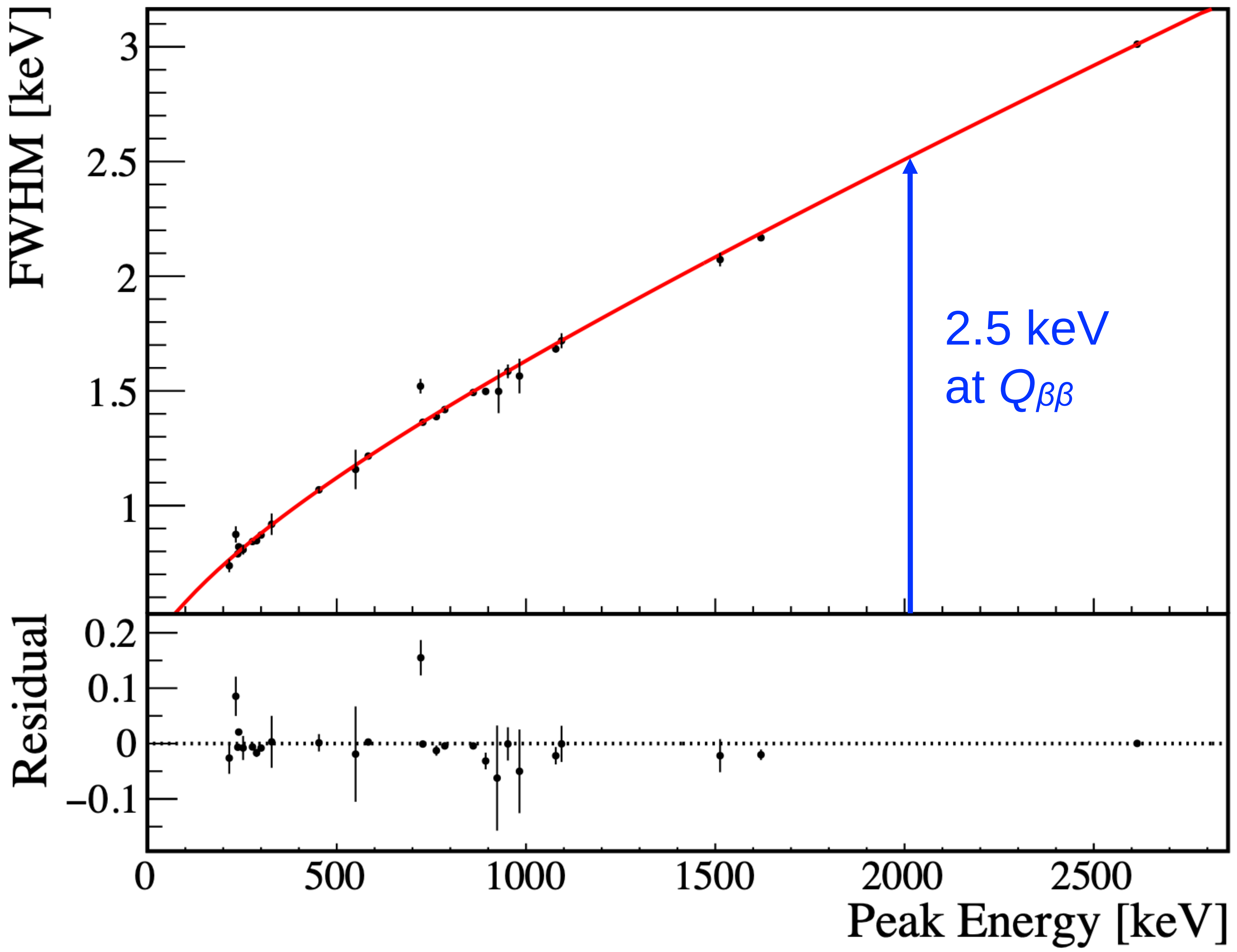
Excellent Energy Performance

Calibrated on weekly ^{228}Th calibration data, retuned on full data set

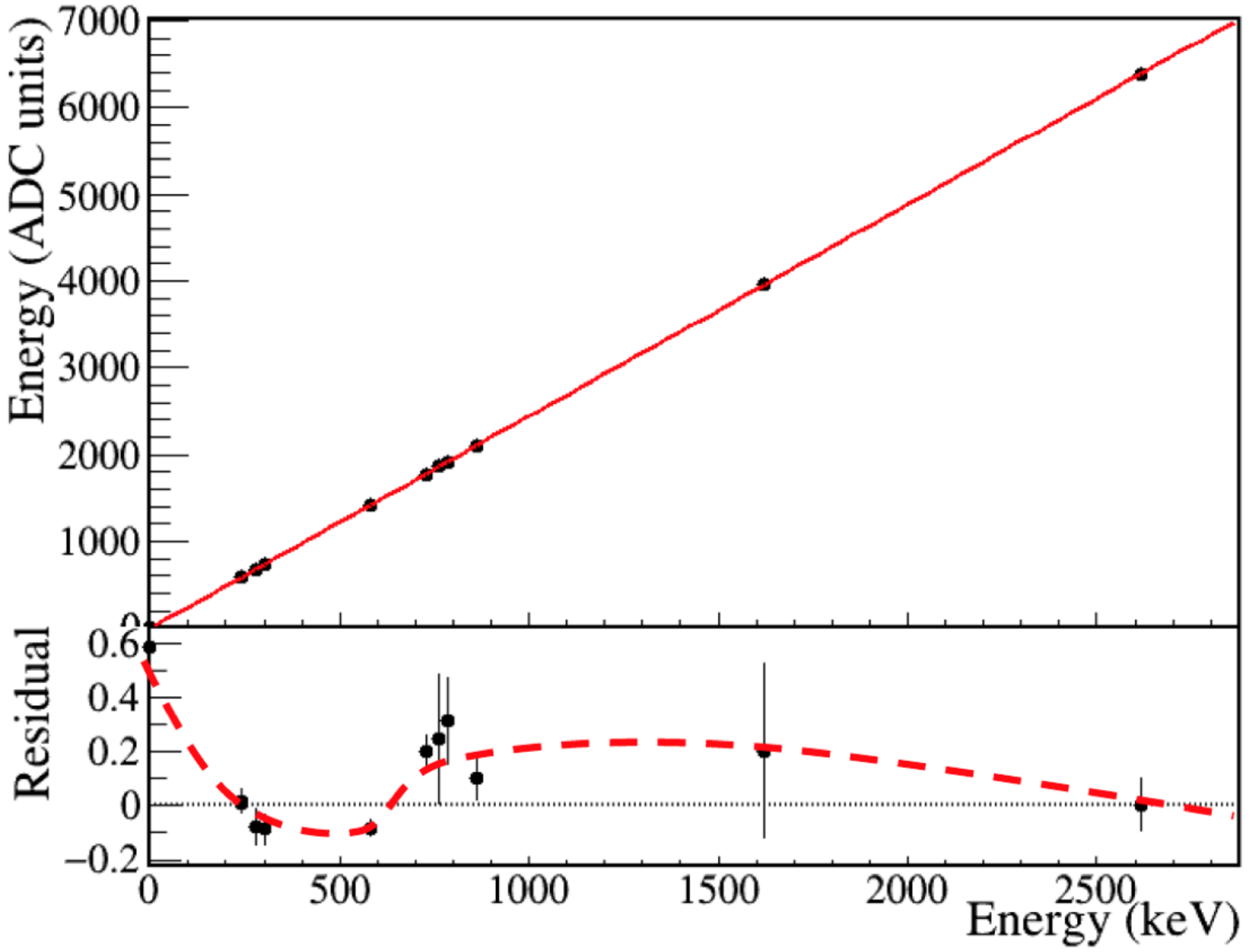
Energy estimated via optimized trapezoidal filter of ADC-nonlinearity-corrected* traces with charge-trapping correction and fixed-time pickoff from "t_0"

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

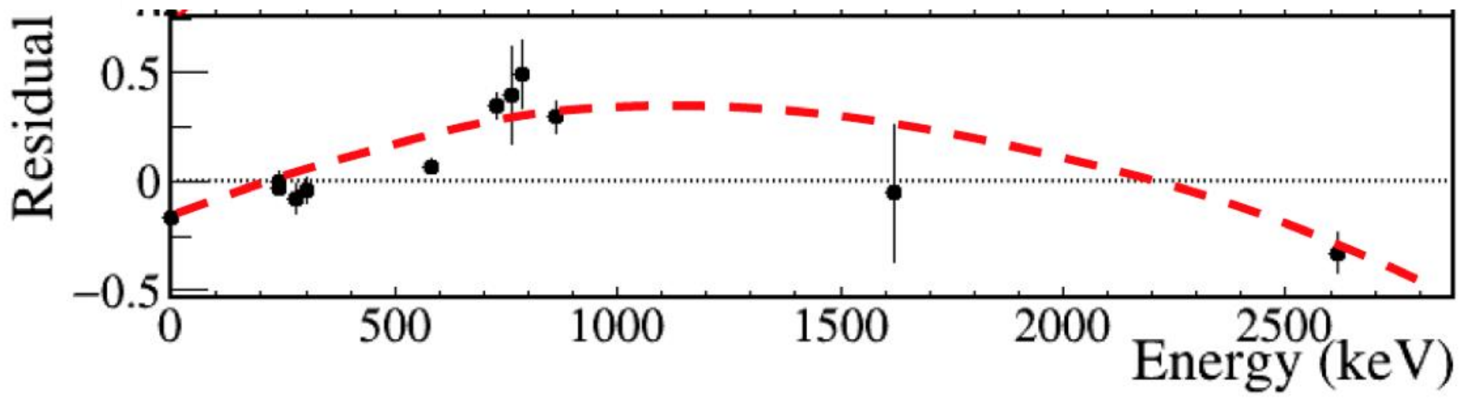
Less than 0.1 keV energy scale offset at low energy 1 keV~10keV



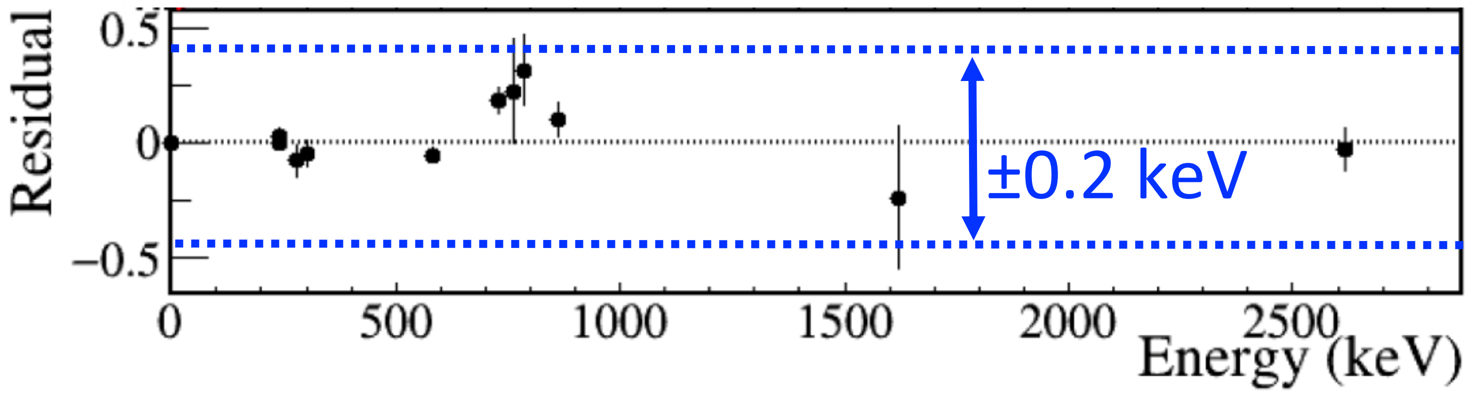
E calibration with no t_0 correction



Linear *E* calibration with t_0 correction



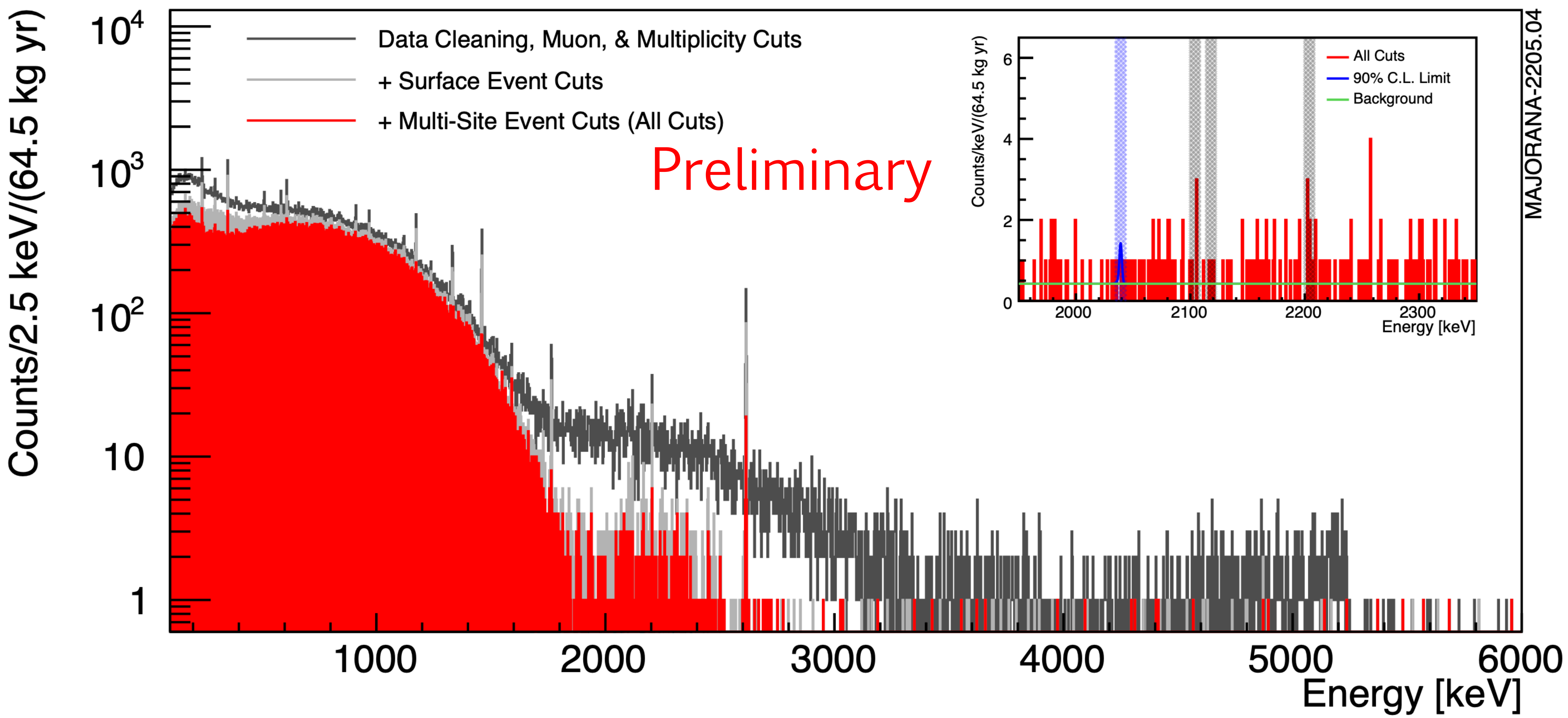
Quadratic *E* calibration with t_0 correction



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

MAJORANA DEMONSTRATOR 2022 0νββ Result

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



Final enriched detector active exposure:

64.5 ± 0.9 kg-yr data

Background index at 2039 keV in lowest background configuration

15.7 ± 1.4 cts/(FWHM t yr)

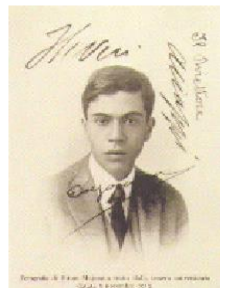
Background index in Module 1

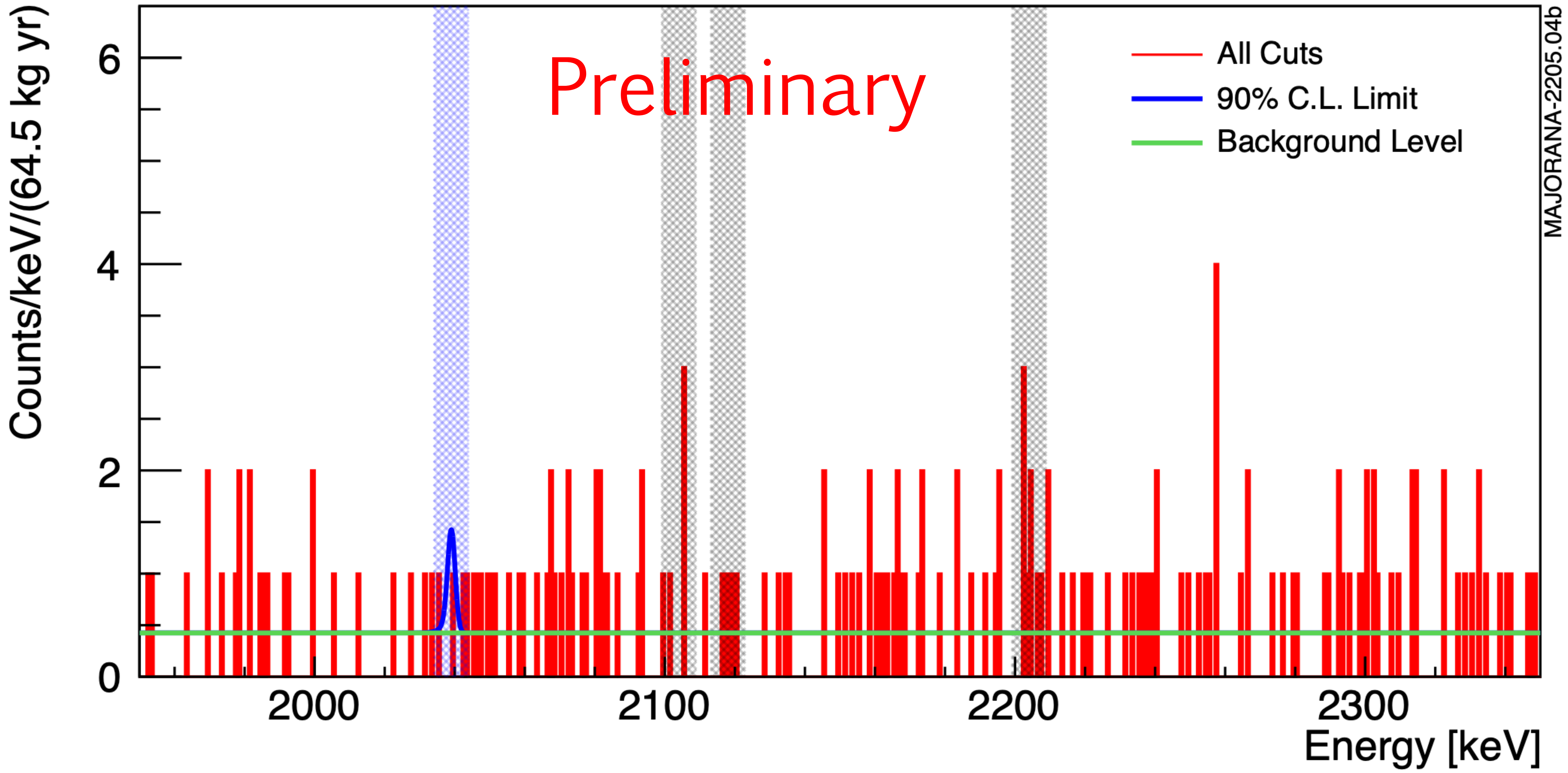
18.6 ± 1.8 cts/(FWHM t yr)

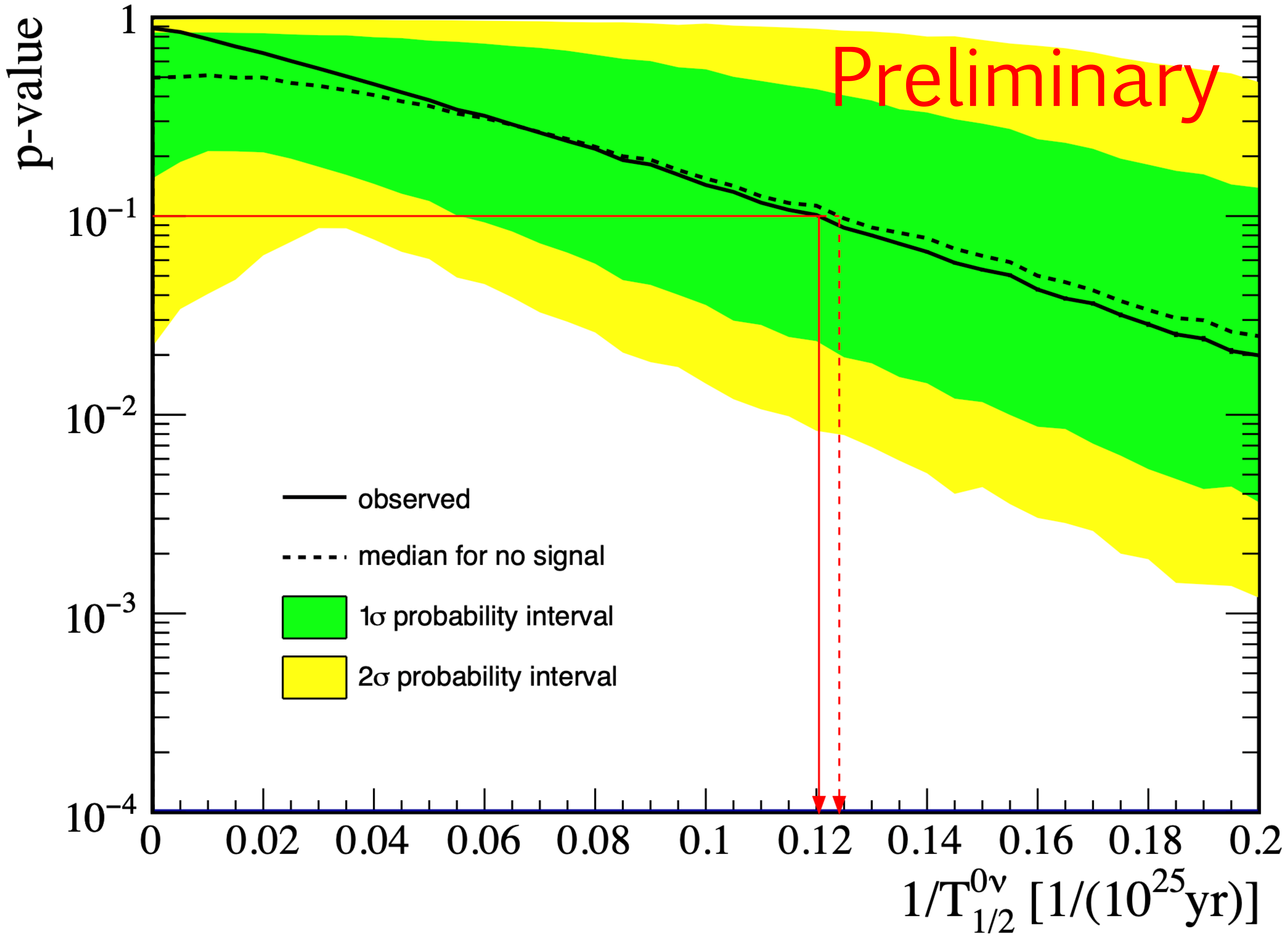
Background index in Module 2

$8.4^{+1.9}_{-1.7}$ cts/(FWHM t yr)

MAJORANA DEMONSTRATOR 2022 0νββ Result







Background Index:

$(6.2 \pm 0.6) \times 10^{-3}$ cts/(keV kg yr)

Energy resolution: 2.5 keV FWHM @ $Q_{\beta\beta}$

Frequentist Limit:

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

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

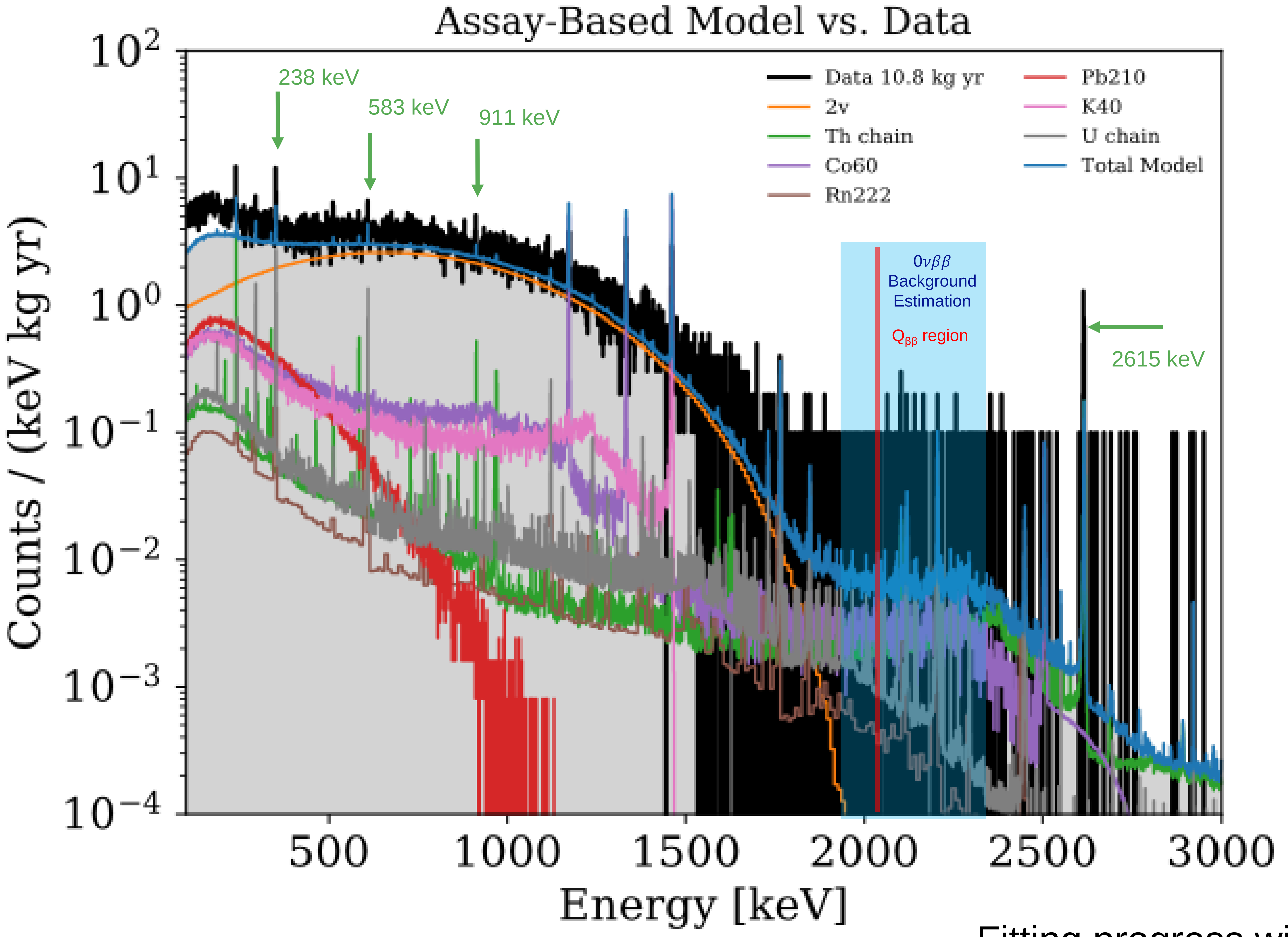
Bayesian Limit: (flat prior on rate)

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

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

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

Background Modeling and Investigation



Assay-based prediction: 2.9 ± 0.14 cts/ (FWHM t y)

- Updated to match as-built geometry, new assay information, and more refined uncertainties

Measured Background in lowest background configuration: 15.7 ± 1.4 cts/(FWHM t y) [PRELIMINARY]

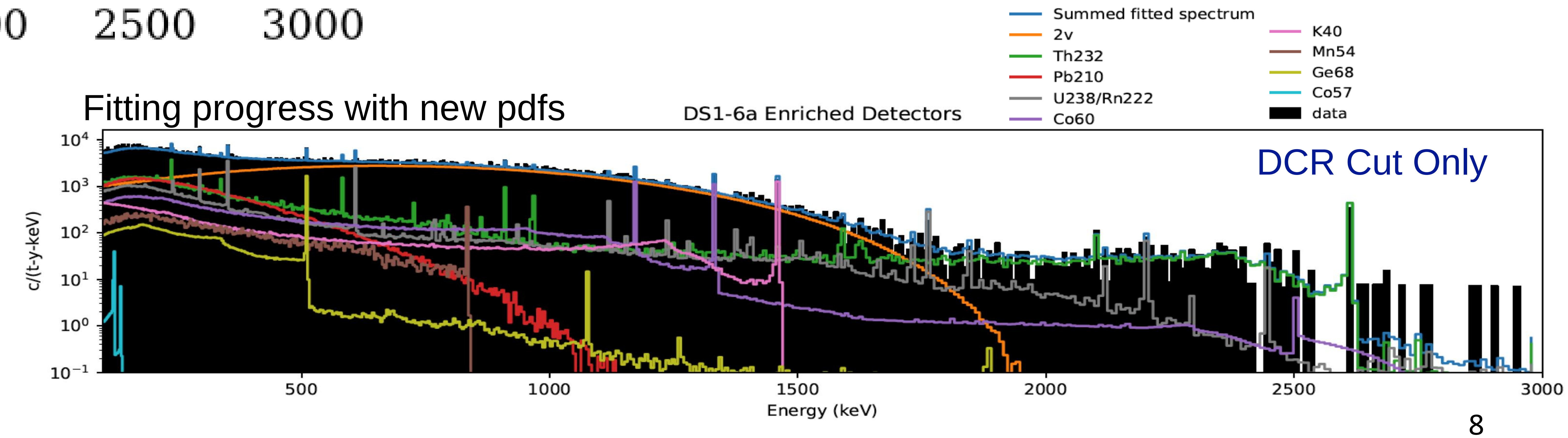
- Module 1: 18.6 ± 1.8 cts/(FWHM t yr)
- Module 2: $8.4^{+1.9}_{-1.7}$ cts/(FWHM t yr)

Characteristics of background excess:

- Dominated by ^{232}Th decay chain — excess apparent at ^{208}Tl, especially 238 keV and 2615 keV
- Does not indicate a source within the Ge detector array (front end electronics, detector holders, etc.).

Improved Frequentist and Bayesian fitting efforts underway in order to more precisely locate source of excess ^{232}Th background and complete the background model

Fitting progress with new pdfs



Rich and Broad Physics Programs

Beyond double beta decay

Standard Model Physics

BSM Physics

Tests of Fundamental Symmetries and Conservations
- Lepton number violation via neutrinoless double beta decay
- Baryon number violation
- Pauli Exclusion Principle violation

PRC **100** 025501 (2019)

PRC **103** 015501 (2021)

PRD **99** 072004 (2019)

arXiv:2203.02033 (2022)

MAJORANA DEMONSTRATOR

Excellent energy performance

Low backgrounds

in broad energy regions

Standard Model Physics, particular backgrounds
- In situ cosmogenics
- (alpha, n) reactions

PRC **105** 014617 (2022)

arXiv:2203.14228 (2022)

Low-mass dark matter signatures
- Pseudoscalar dark matter
- Vector dark matter
- Fermionic dark matter
- Sterile neutrino
- Primakoff solar axion
- 14.4-keV solar axion

PRL **118** 161801 (2017)

arXiv:220x.xxxxx (2022) **x3**

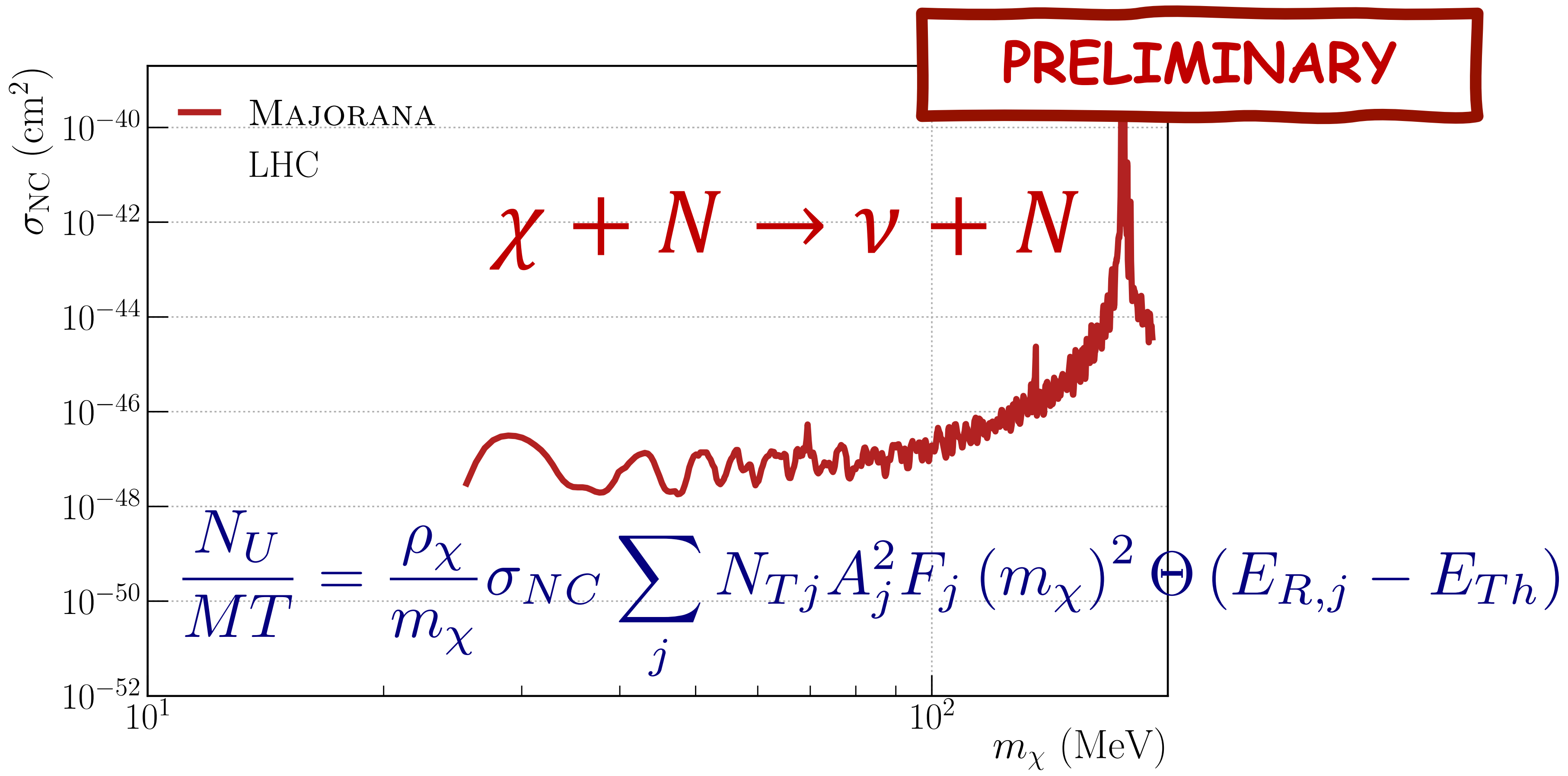
Exotic Physics
- Quantum Wavefunction collapse
- Lightly ionizing particle

arXiv:2202.01343 (2022)

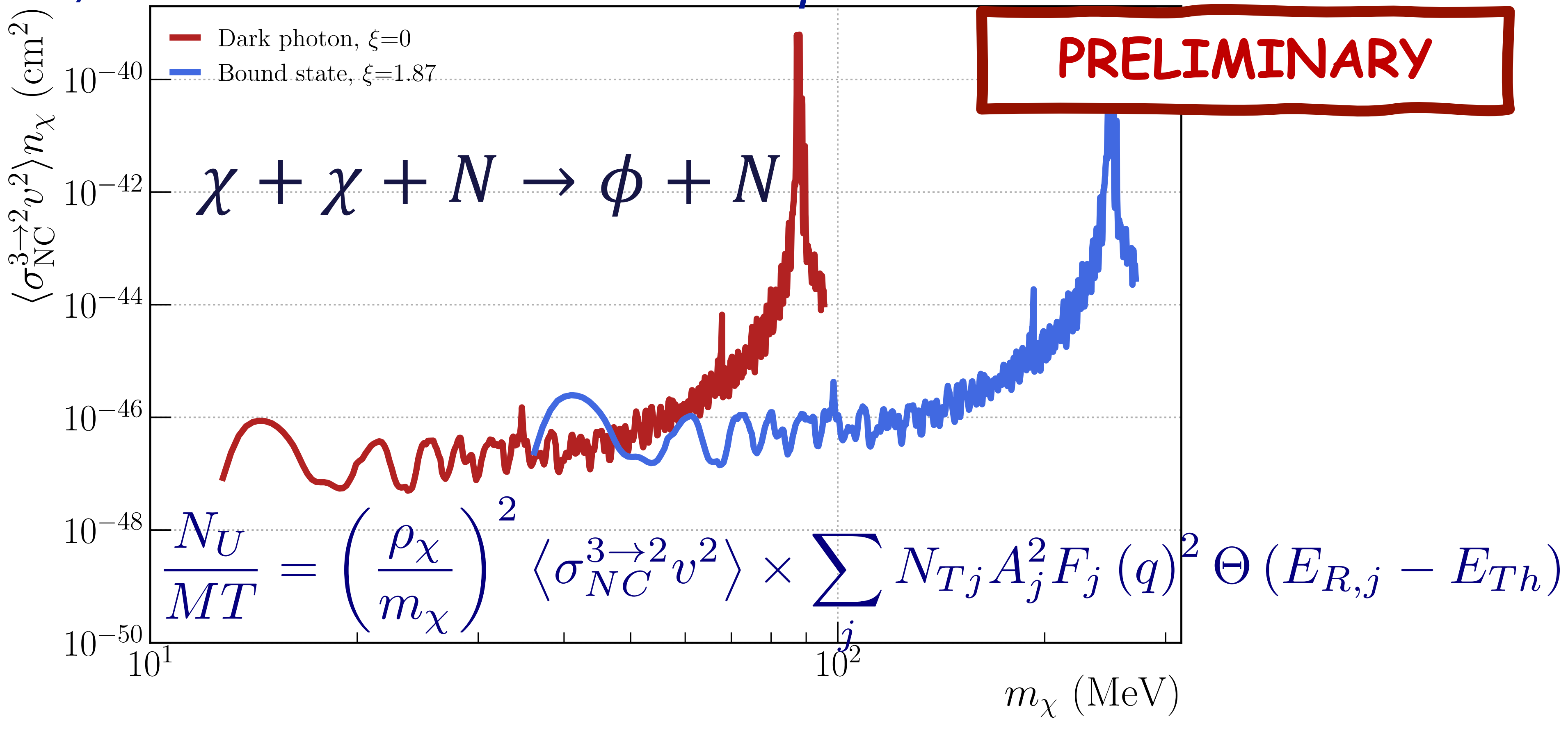
PRL **120** 211804 (2018)

Dark Matter Searches

- **Fermionic DM absorption**: 2→2 neutral-current (NC) interaction with nucleus N, characterized by a cross-section



- **Sub-GeV DM-nucleus scattering**: If 3→2 scattering with nucleus N, with a new dark matter ϕ in the final state

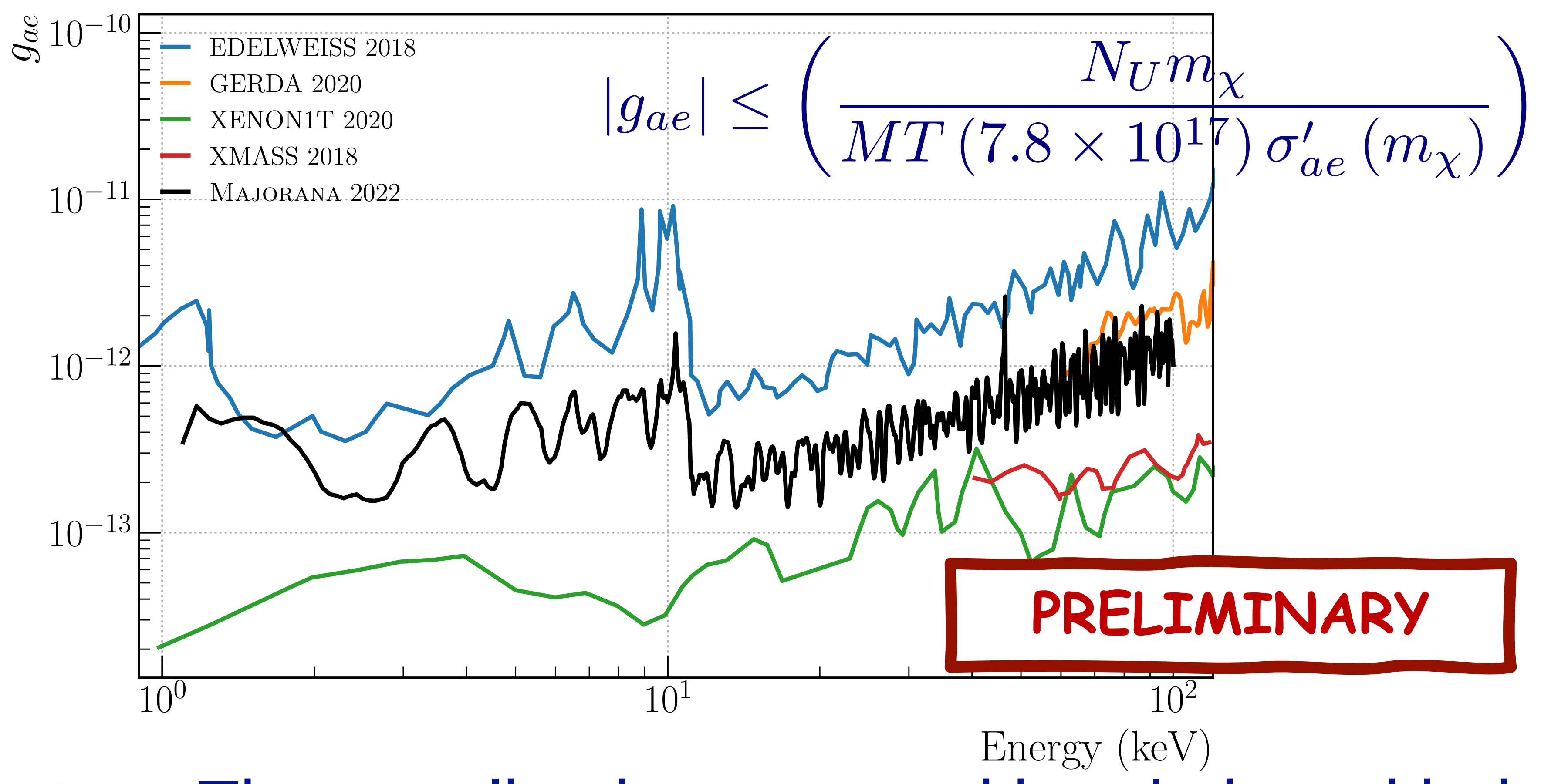


New Results

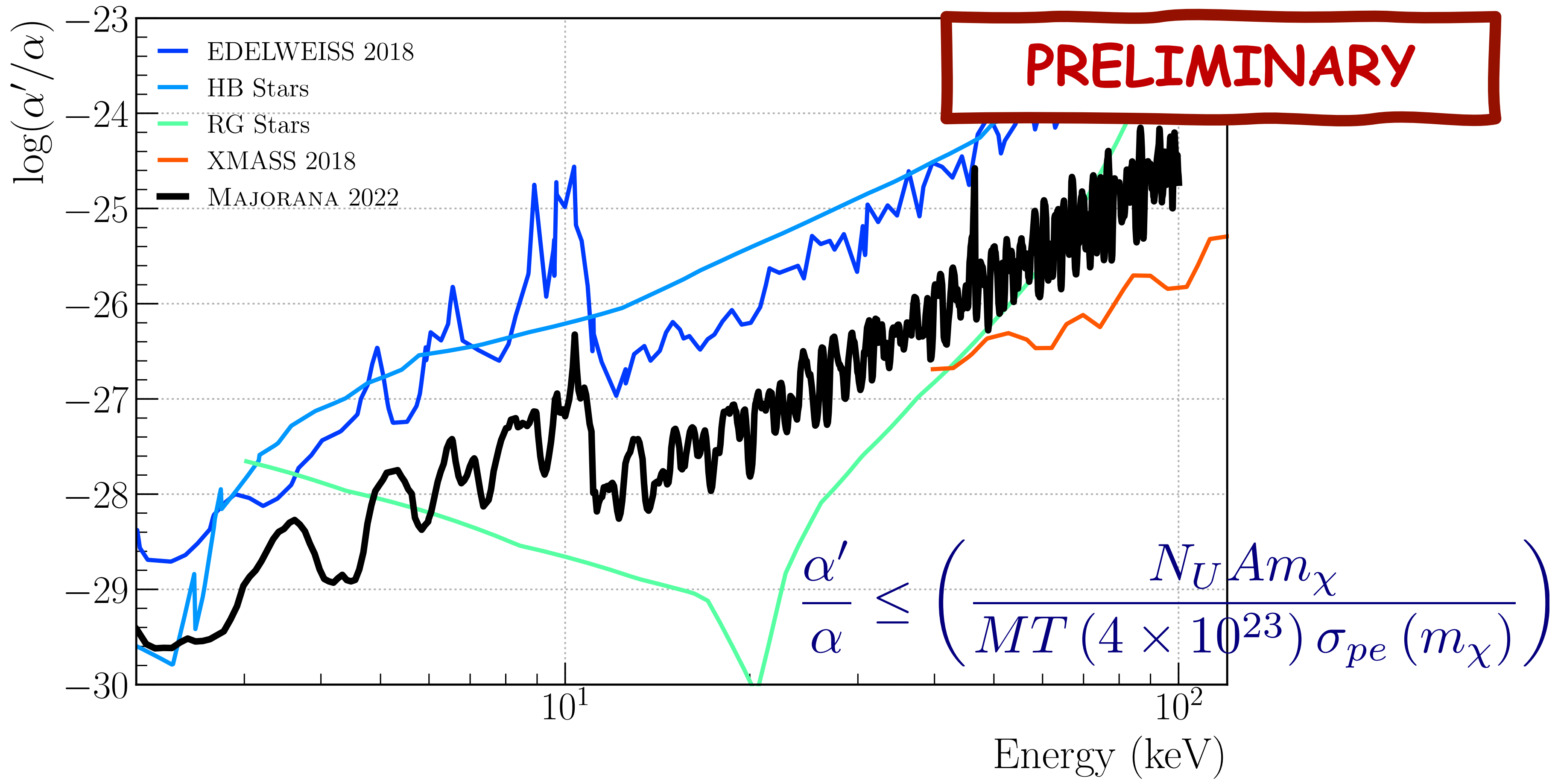
Best among germanium experiments

Bosonic DM via electron coupling

- **Axion-like particles**: Coupling proportional to the cross-section

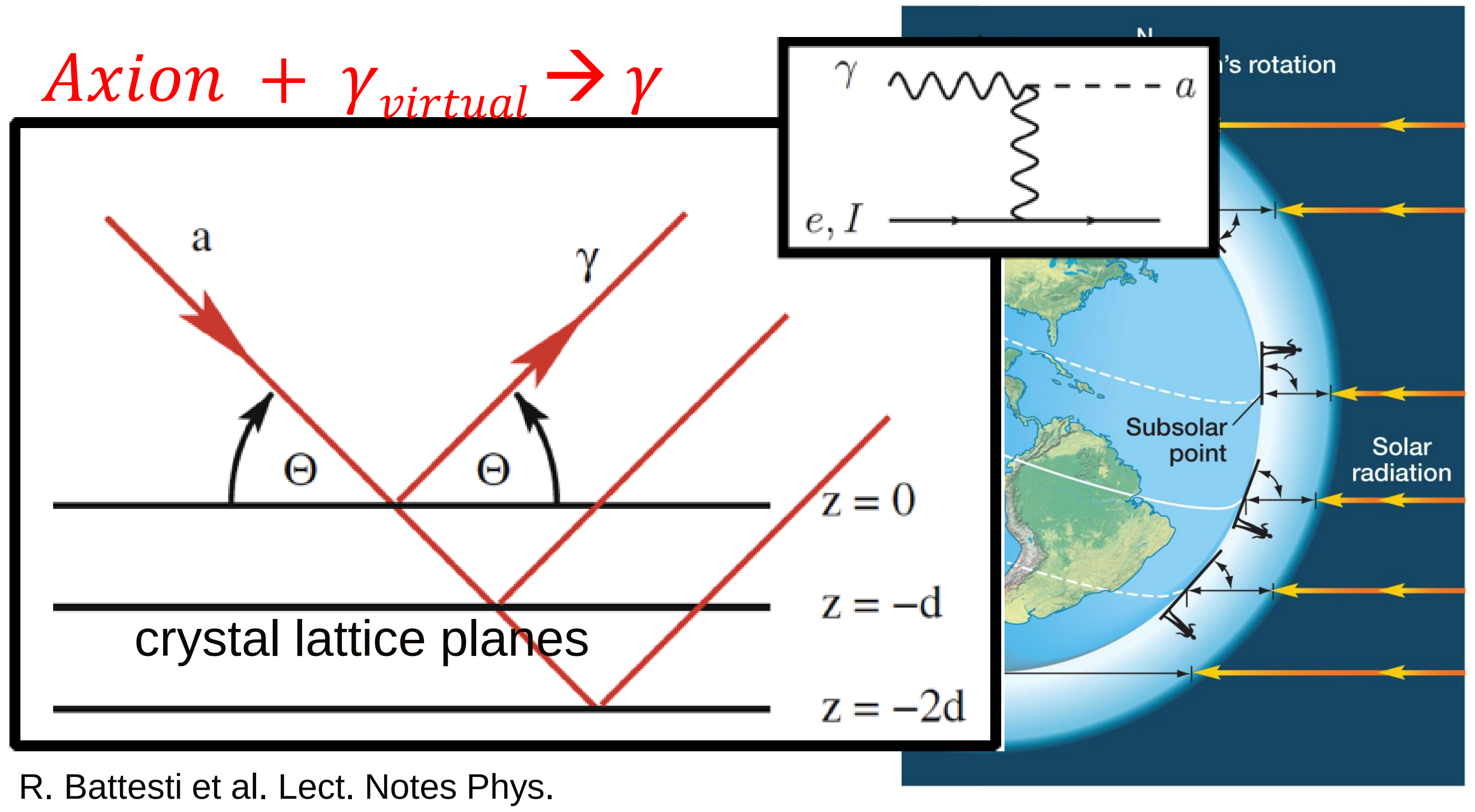


- **Dark photon**: The coupling is measured in relation with the fine structure constant, α



SOLAR AXIONS

Axion-photon coupling via inverse Primakoff conversions



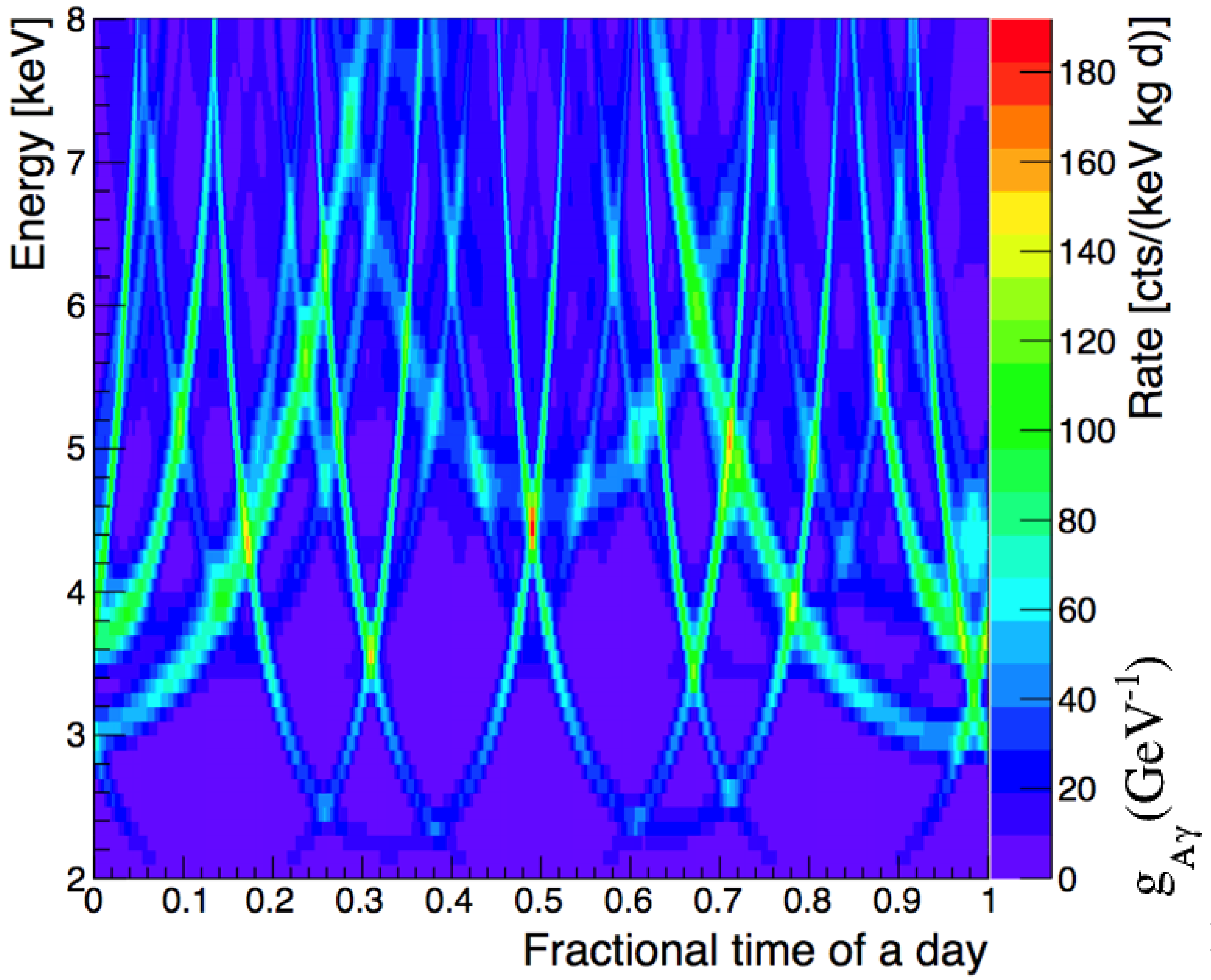
R. Battesti et al. Lect. Notes Phys. 741, 199–237 (2008)

Bragg diffraction: coherent scattering on the crystal planes when Bragg condition is met.

pioneered by R. J. Creswick, et al., PLB 427 (1998) 235-240

Axion signals:

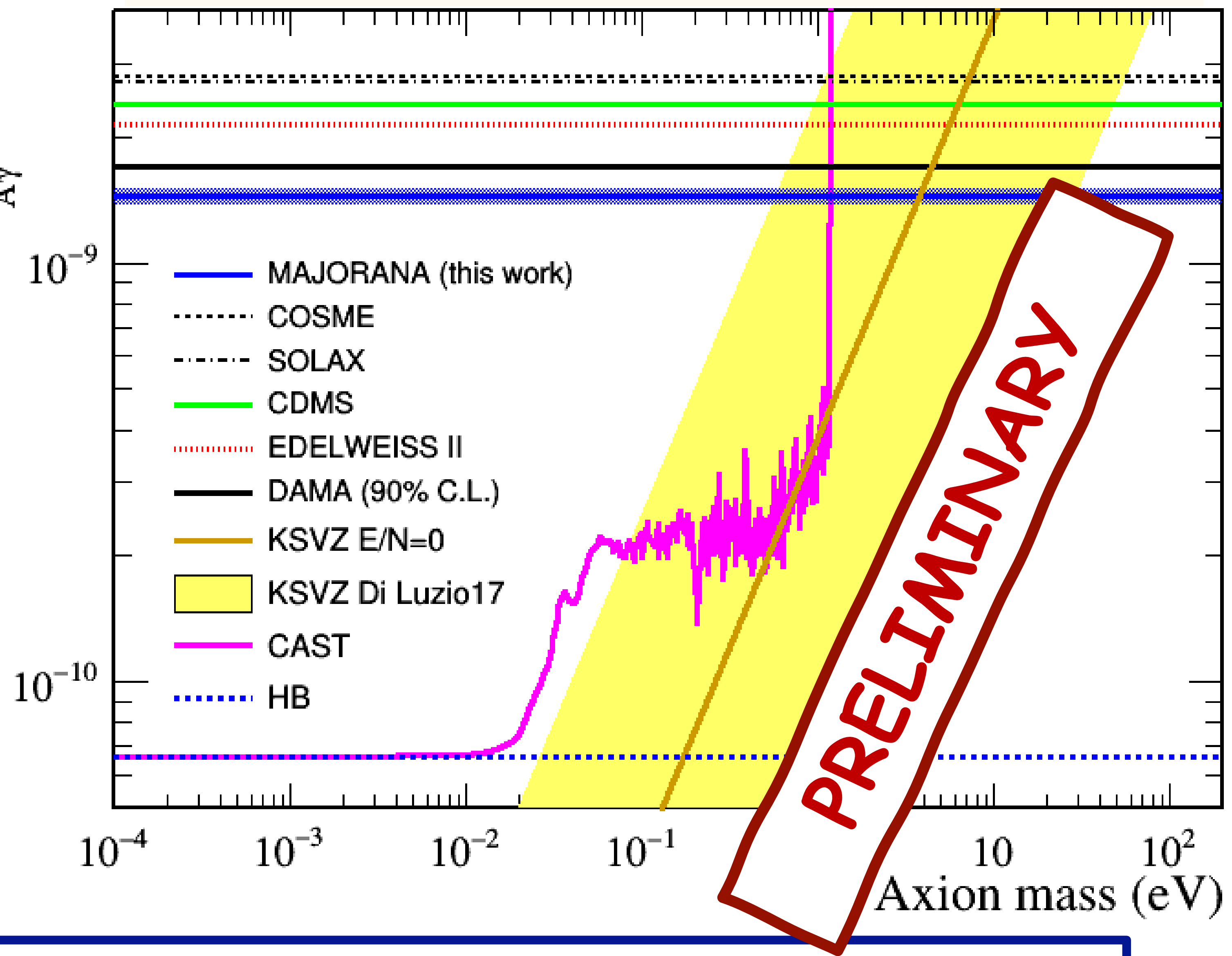
- enhanced at certain angles for certain energy
- depend on time, following Sun's movement
- Explored by a series of experiment



- Distinct time dependence is a key strength for discovery
- Unknown angles of crystal planes can be averaged over, e.g. in Bayesian marginalization step

- The energy dimension of the energy-time 2-dimensional analysis
- Axion model is signal averaged over crystal plane angles

SOLAX, Phys. Rev. Lett., 81:5068, 1998
DAMA, Phys. Lett. B, 515:6, 2001 – best 90% limit
COSME, Astropart. Phys., 16:325, 2002
CDMS, Phys. Rev. Lett., 103:141802, 2009
EDELWEISS II, JCAP11 (2013) 067 – best 95% limit



$$g_{a\gamma} < 1.45 \times 10^{-9}\ \mathrm{GeV}^{-1}\ \ (95\%\ \mathrm{C.L.})$$

WAVEFUNCTION COLLAPSE

Measurement problem

- When/how does the WF collapse occur?
- How does the measurement affect the physical world?

Spontaneous Radiation

- Various WF collapse models (CSL, D-P model, etc) predict Beyond-SM 1/E dependent X-ray radiation
- Free charged particle gains energy from interaction with stochastic noise field, and 'shaken' by the field

→ EM radiation from charged particle [Fu, Phys. Rev. A 1997, 56, 1806]

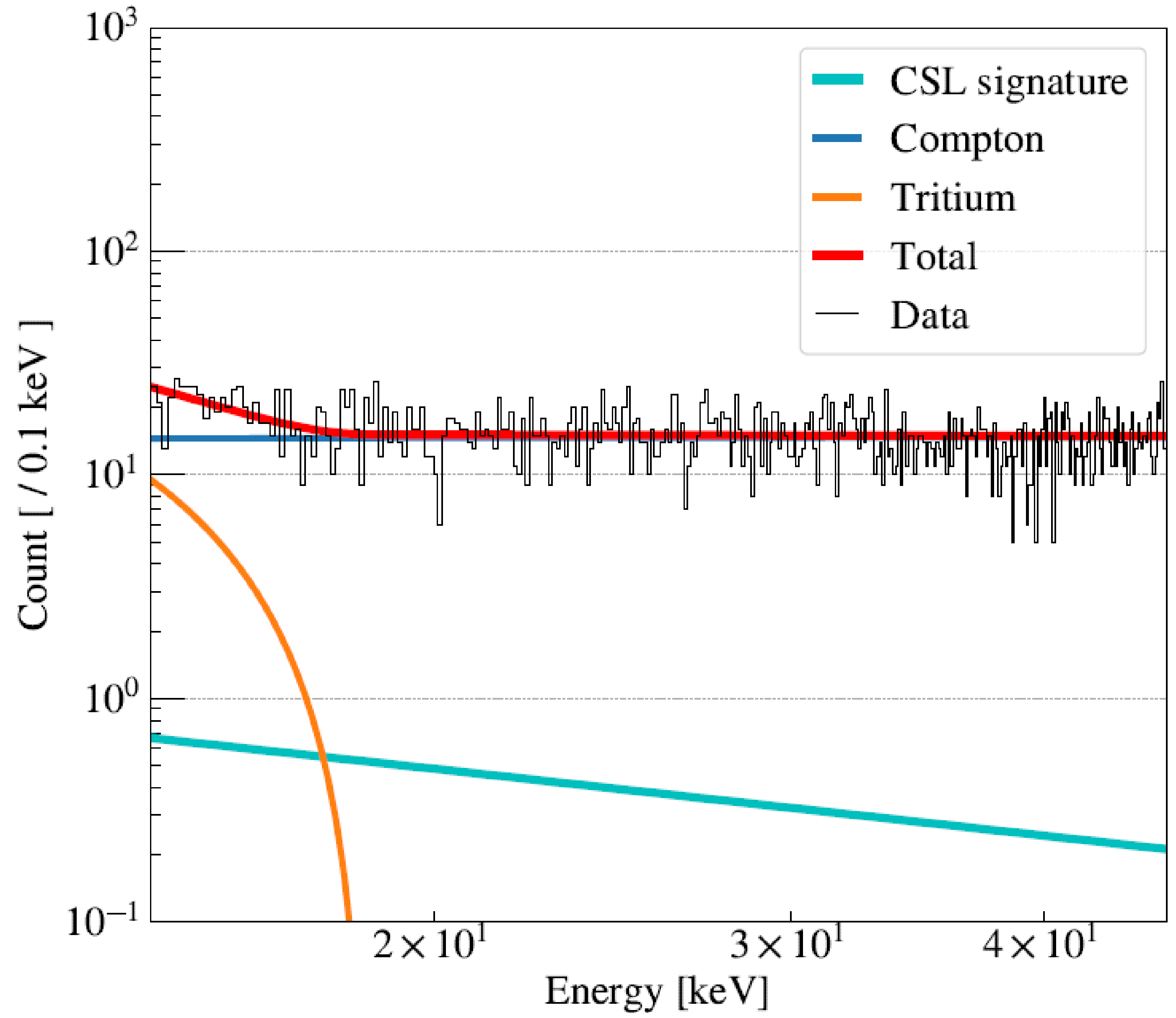
- Detection of the Beyond-SM radiation is a signature of the CSL

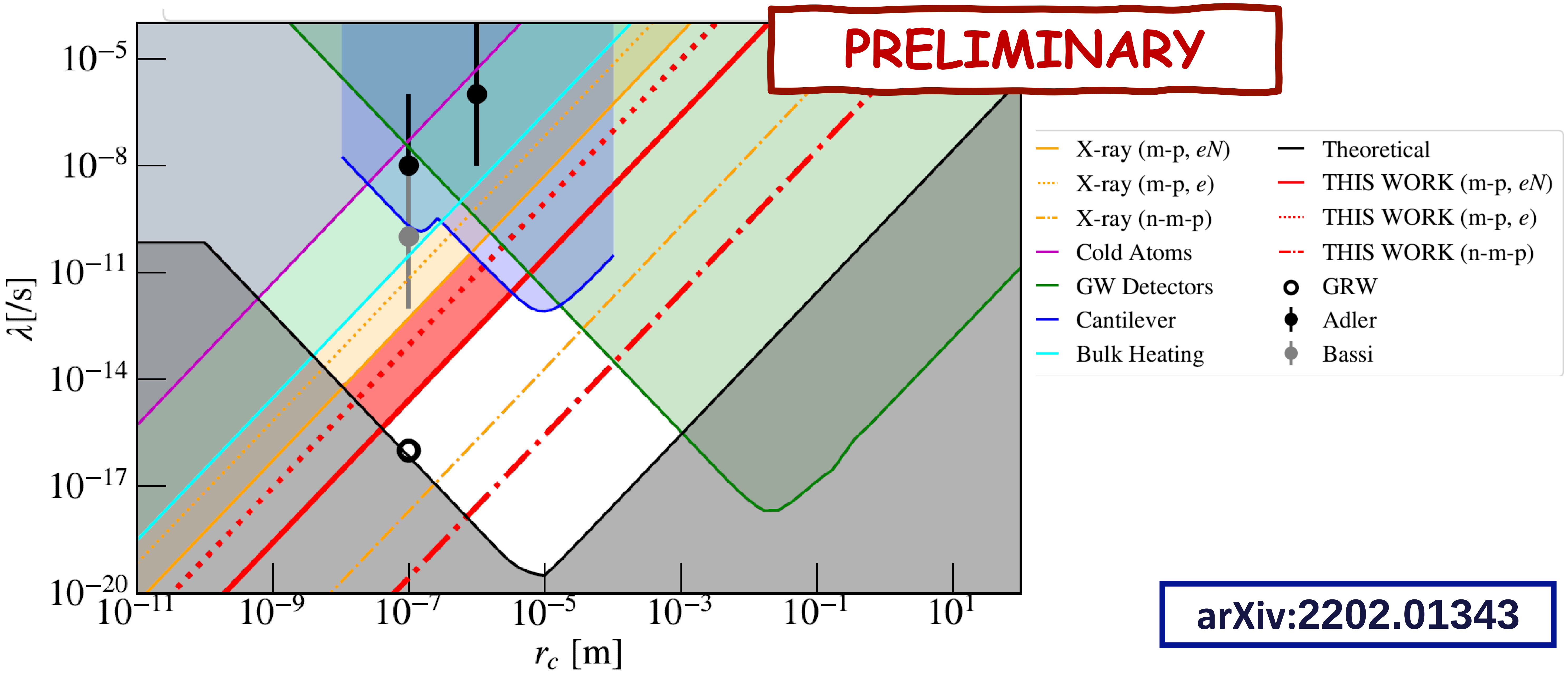
$$\frac{d\Gamma(E)}{dE} = \frac{\alpha\lambda}{\pi r_C^2 m_e^2 E}\tilde{f}(E)$$

Re-expression of (Entropy **2017**, 19, 319) and (Eur. Phys. J. D (2018) 72: 159)

MAJORANA Improves previous limits by orders of magnitudes

λ/r_C^2 (m-p CSL)	$<(2.6\pm0.1)\times10^{-1}\ s^{-1}m^{-2}$
R_{DP} (DP model)	$>(5.6\pm0.1)\times10^{-10}$ m





arXiv:2202.01343

MAJORANA DEMONSTRATOR Summary and Outlook

- Started taking data with first module in 2015 and has completed enriched Ge data-taking in 2021
  - Excellent energy resolution of 2.5 keV FWHM @ 2039 keV, best of all $0\nu\beta\beta$ experiments
  - **Latest limit on $0\nu\beta\beta$ of $T_{1/2} > 8.3 \times 10^{25}$ yr (90% C.I.) from 64.5 kg-yr exposure**
  - Leading limits in the search for double-beta decay of ^{76}Ge to excited states
- Background model being investigated and refined
  - Initial background fits are informing possible distribution of background sources
- Low background + energy resolution + multiple years of high-quality data allows for broad physics program, yielding many new results
  - BSM physics results extracted in wide energy range with various analysis techniques
  - Search for neutron and cosmogenic signatures at high energy
- Continuing operation with natural detectors for background studies and other physics (e.g. decay of ^{180m}Ta)
- The technologies, analysis techniques, and people involved in MAJORANA will continue to play a major role in searching for $0\nu\beta\beta$ with LEGEND

This material is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, the Particle Astrophysics and Nuclear Physics Programs of the National Science Foundation, and the Sanford Underground Research Facility.

The MAJORANA Collaboration

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, Charlie Havener, 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, Jessica Peterson, 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, Aaron Engelhardt, 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, Clara Cuesta, Jason Detwiler, Alexandru Hostiuc, Nick Ruof, Clint Wiseman

Williams College, Williamstown, MA:
Graham K. Giovanetti

*students

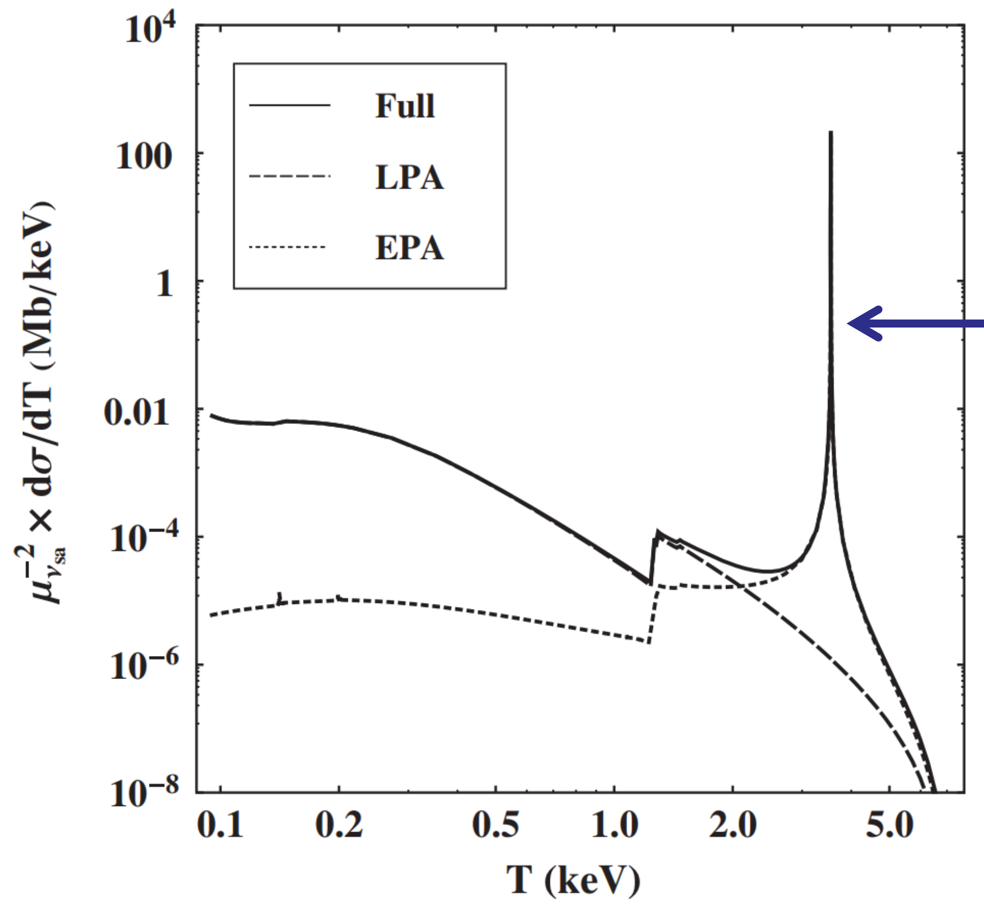
$\nu_s - \nu_a$ Transition Magnetic Moment

Search for neutral DM candidates in MAJORANA (1 keV-100 keV)

- Non-zero transition magnetic moment (TMM) could induce a sterile-to-active transition
- DM sterile neutrinos can be searched for by considering a non-standard interaction, where an atom A is ionized by incoming sterile neutrino:

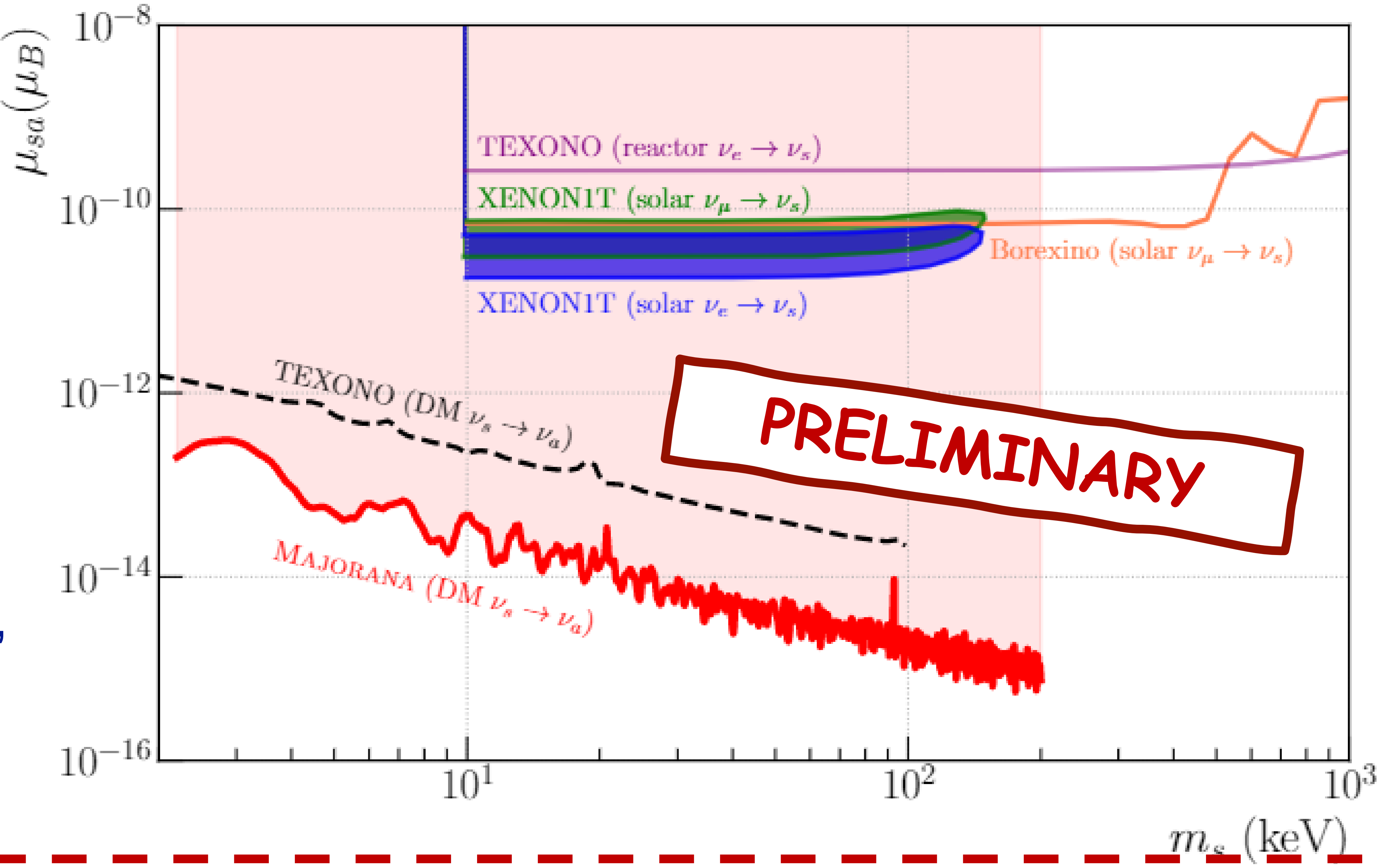
$$\nu_s + A \rightarrow \nu_a + A^+ + e^-$$ *[Phys. Rev. D 93, 093012 (2016)]*

- Cross section enhance greatly at energy transfer of $m_s/2$, leading to a peak-like signature in the low energy spectrum
- MAJORANA can set a limit on TMM (μ_{sa}) of DM sterile neutrino by searching for the 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 neutrino, then the μ_{sa} is too weak to produce the XENON1T excess



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

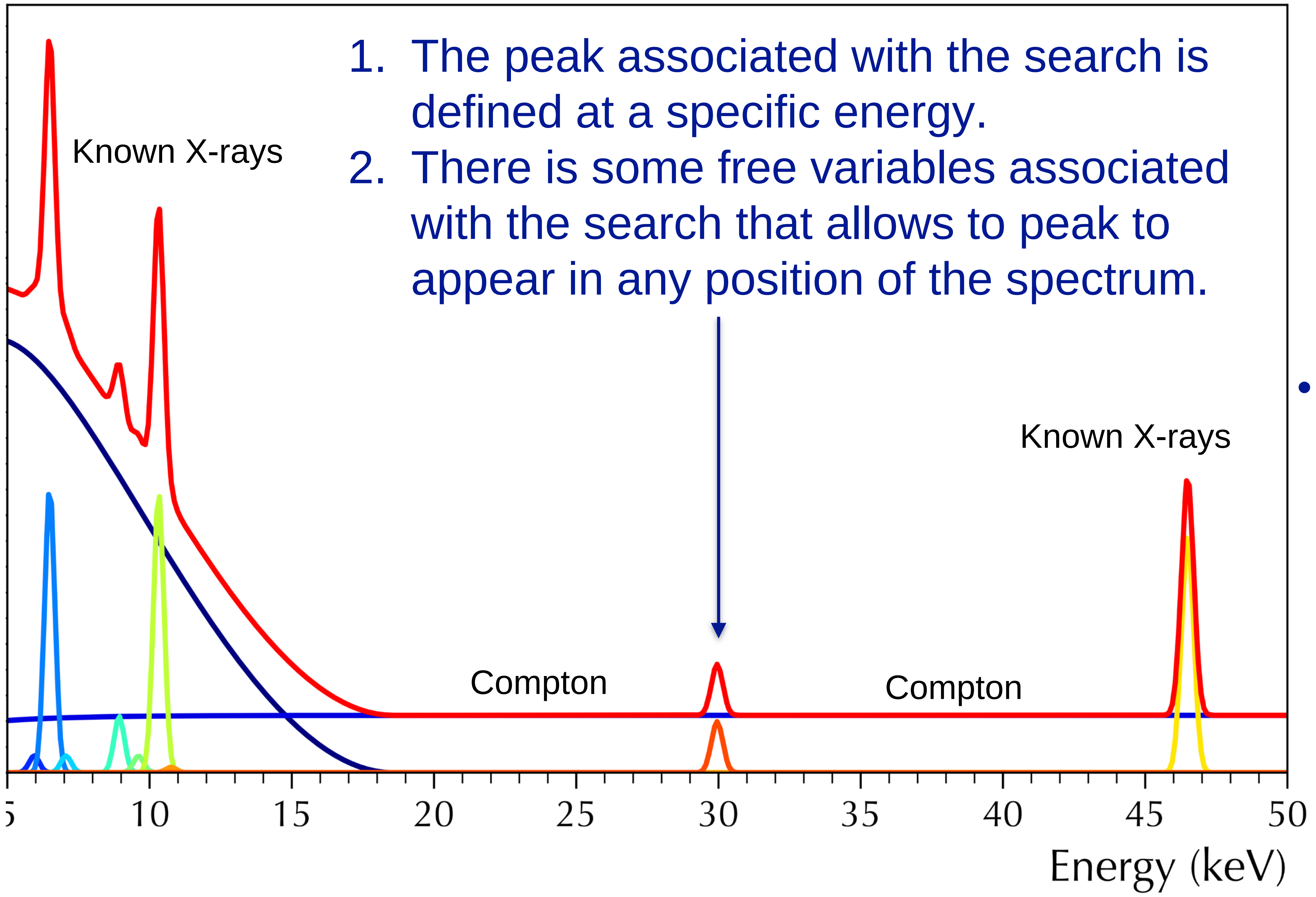
v^{-2} amplification



World leading limit

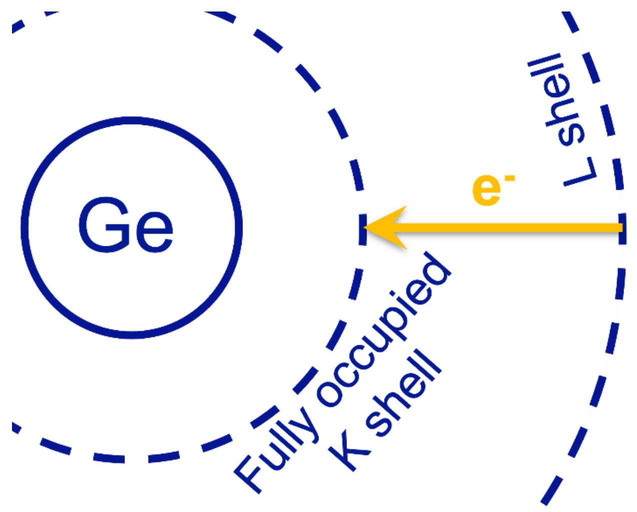
Low energy search mechanism

The mechanism for searching beyond the Standard Model physics in the MAJORANA data is to search for signatures that appear as peak between 1 keV and 100 keV.



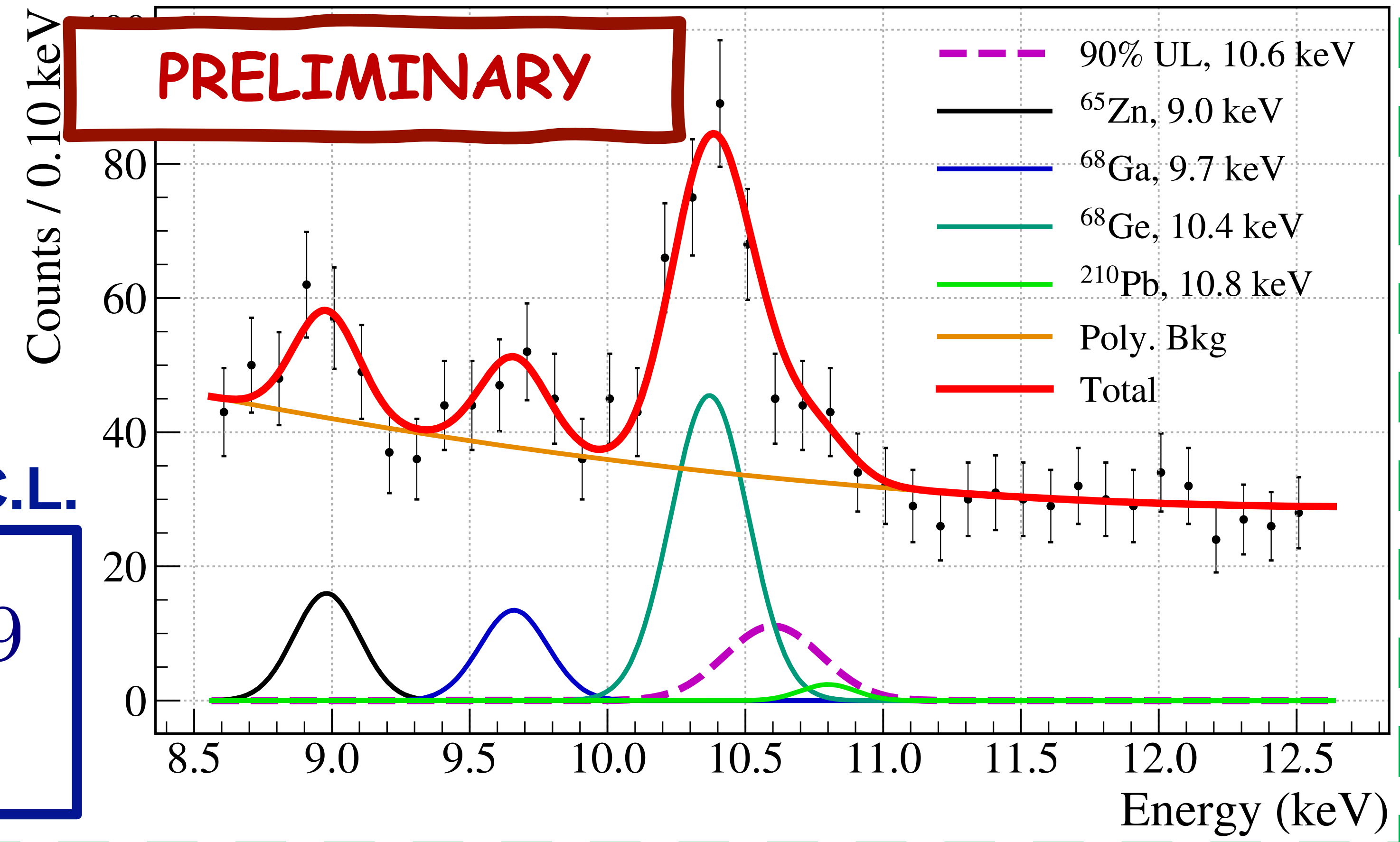
1. The peak associated with the search is defined at a specific energy.
2. There is some free variables associated with the search that allows to peak to appear in any position of the spectrum.

- Looking for the PEP-forbidden transition of an electron in the L shell to the fully occupied K shell in ^{76}Ge (10.6 keV)



90% C.L.

$$\frac{1}{2}\beta^2 < 9.6 \times 10^{-49}$$

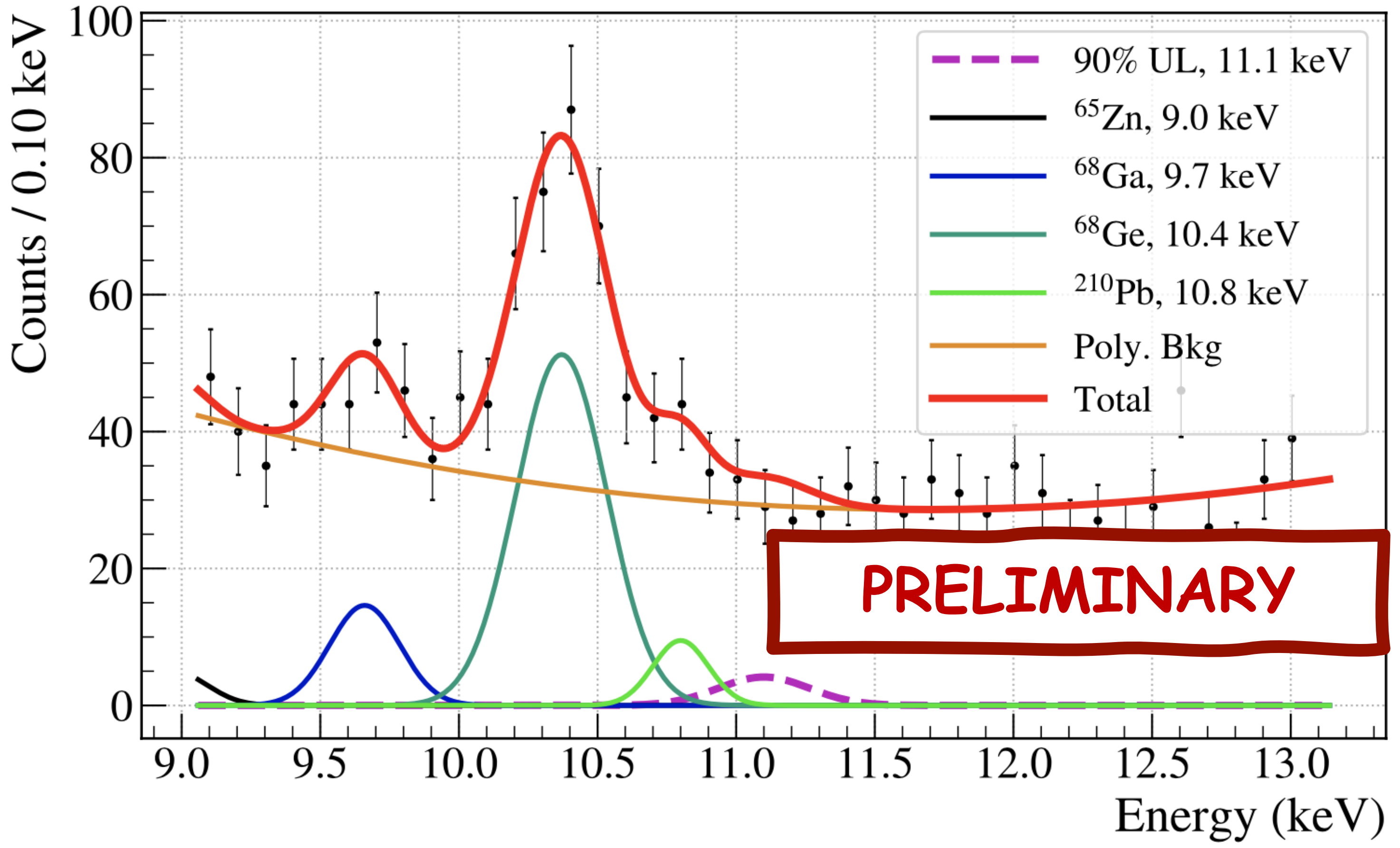


Best among germanium experiments

- Looking for an electron decay without charge conservation which would generate a peak at 11.1 keV

90% C.L.

$$\tau\left(e^- \to \nu\nu\bar{\nu}\right) > 3.2 \times 10^{25}$$



World leading limit

Beyond the Standard Model Searches

Excellent energy resolution: ~0.4 keV FWHM at 10.4 keV

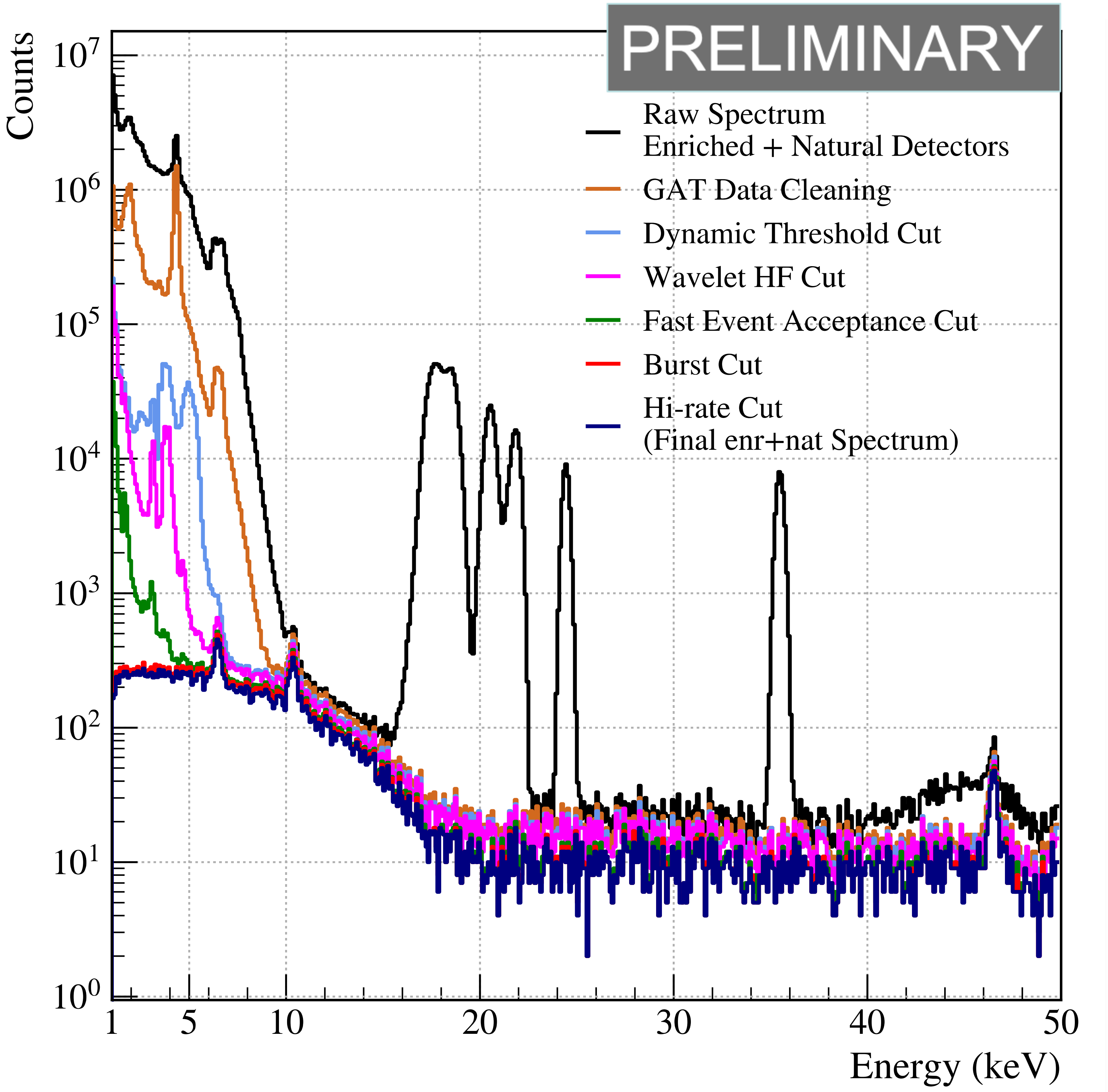
- Progress towards a low-E background model

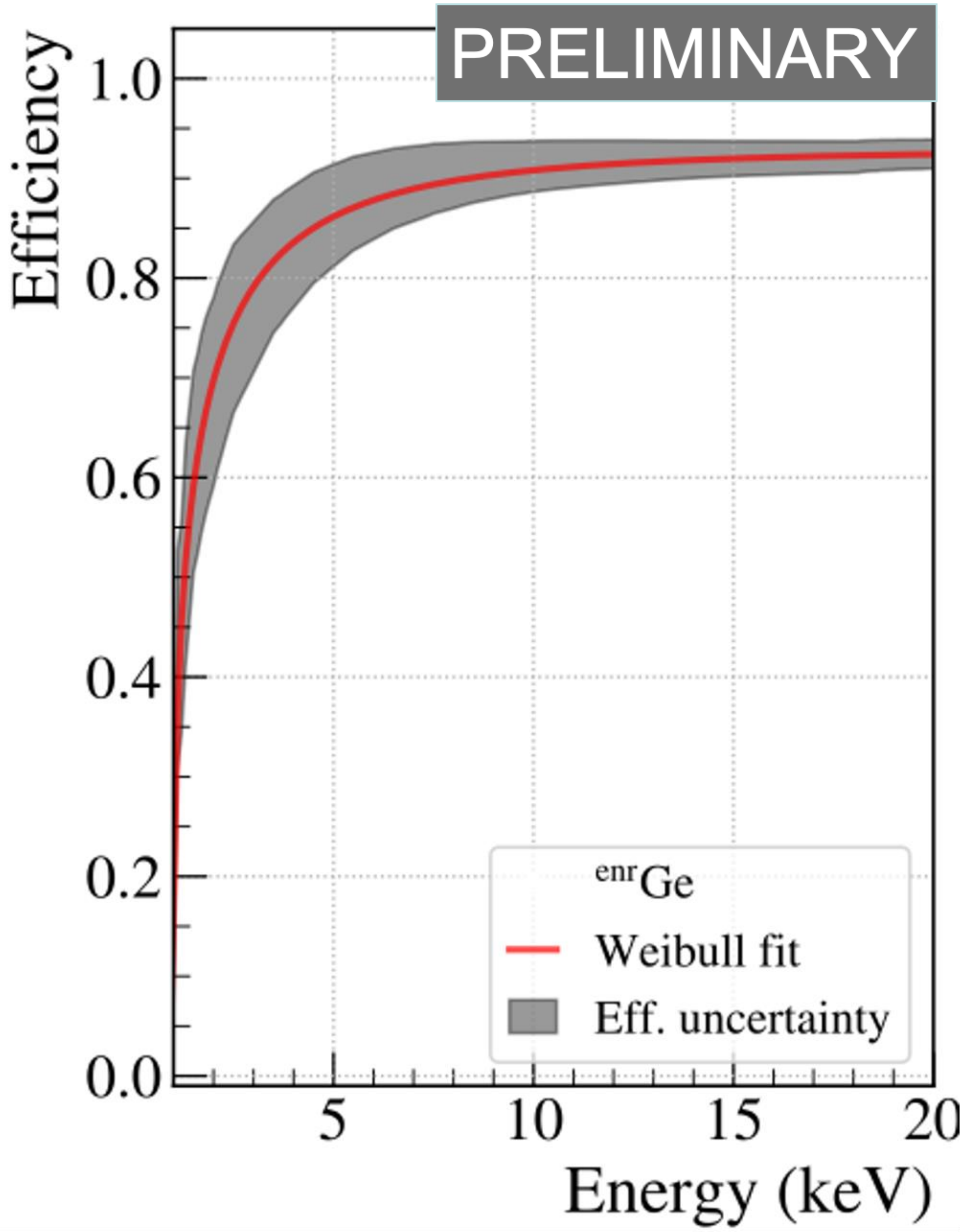
The low backgrounds, low threshold, high resolution spectra allows additional physics searches

- Controlled surface exposure of enriched material to minimize cosmogenics

Low Energy Physics is enabled by low-capacitance of PPC detectors and low-noise electronics

JINST 17 (2022) 05, T05003





- 5 orders of magnitude noise reduction under 5 keV
- 1 keV threshold achieved with novel analysis cuts
- Blind analysis implemented