The broad physics program of the MAJORANA DEMONSTRATOR at SURF: Final results and new directions

Ian Guinn, UNC & TUNL
Anna Reine, UNC & TUNL
Clint Wiseman, UW & CENPA
Ralph Massarczyk, LANL
On behalf of the MAJORANA collaboration

Outline: Final Results and New Directions

Ian Guinn (UNC & TUNL)

- Overview of MAJORANA, and final neutrinoless double beta decay result

Anna Reine (UNC & TUNL)

- Studies of radioactive backgrounds and development of a full background model

Clint Wiseman (UW & CENPA)

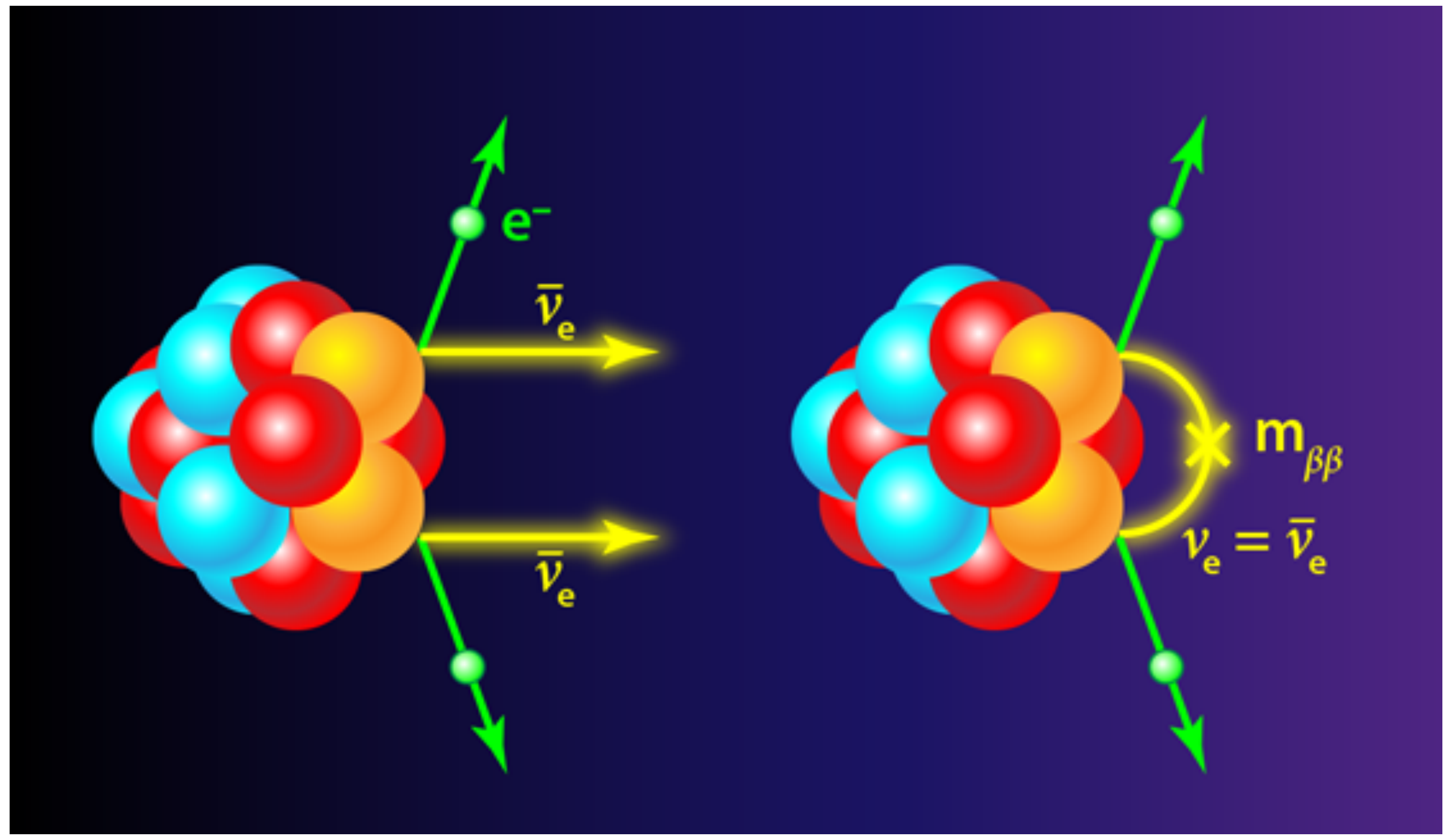
- Search for beyond standard model physics, dark matter

Ralph Massarczyk (LANL)

- First results from a search for the decay of nature's rarest isotope - Tantalum-180

Neutrinoless Double-β Decay

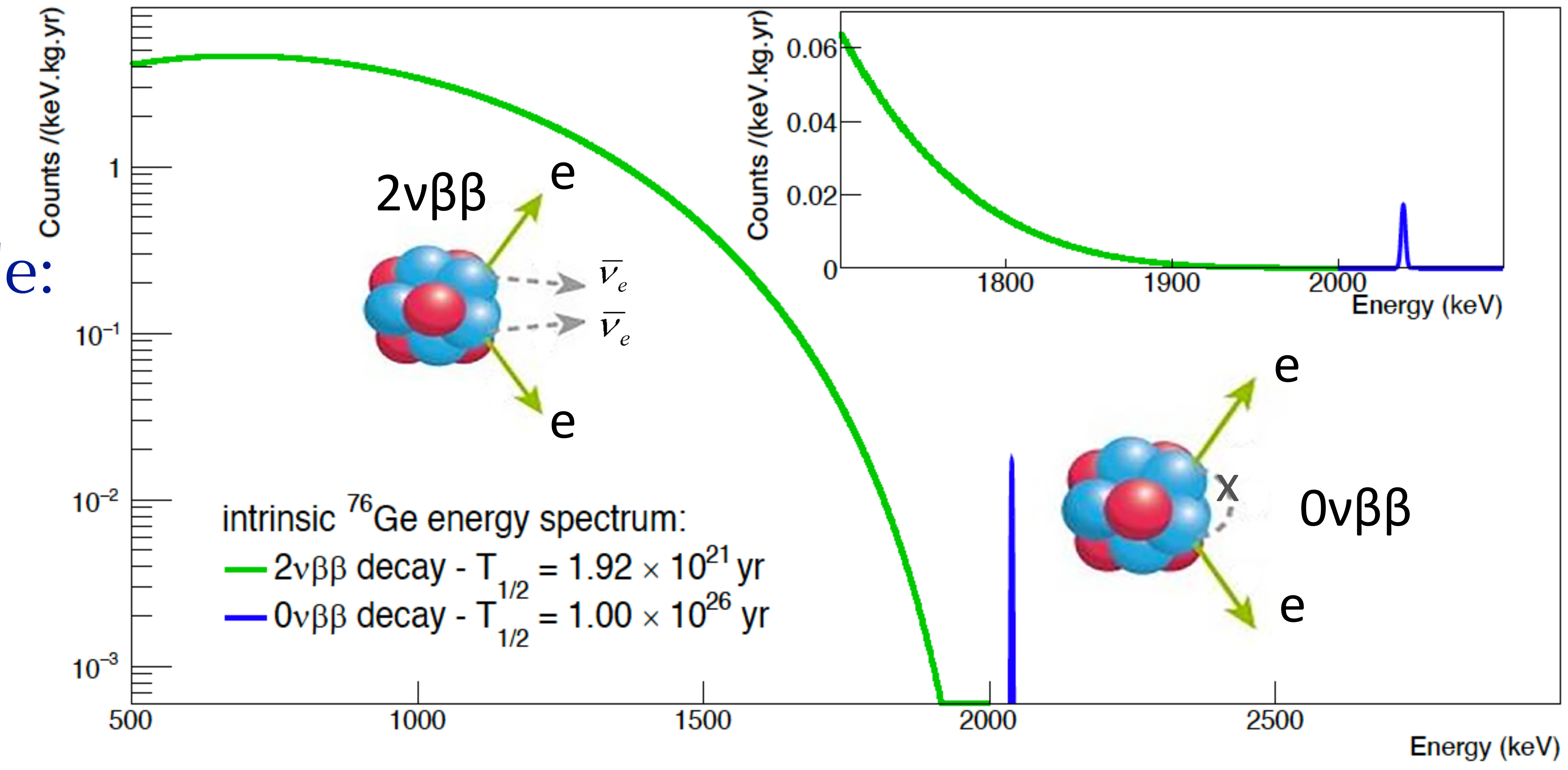
Neutrinoless double-β decay (0νββ) is a hypothetical, ultra-rare process that converts 2 neutrons into 2 protons, 2 electrons and no neutrinos



Discovery of neutrinoless double-β decay would provide:

- Proof that the neutrino is a Majorana fermion
- An explanation for the tiny mass of the neutrino
- A direct observation of lepton number non-conservation
- A mechanism to explain excess of matter over anti-matter
- A pathway to extending the standard model

Unambiguous detection signature in Germanium: peak at the end-point of a 2νββ spectrum



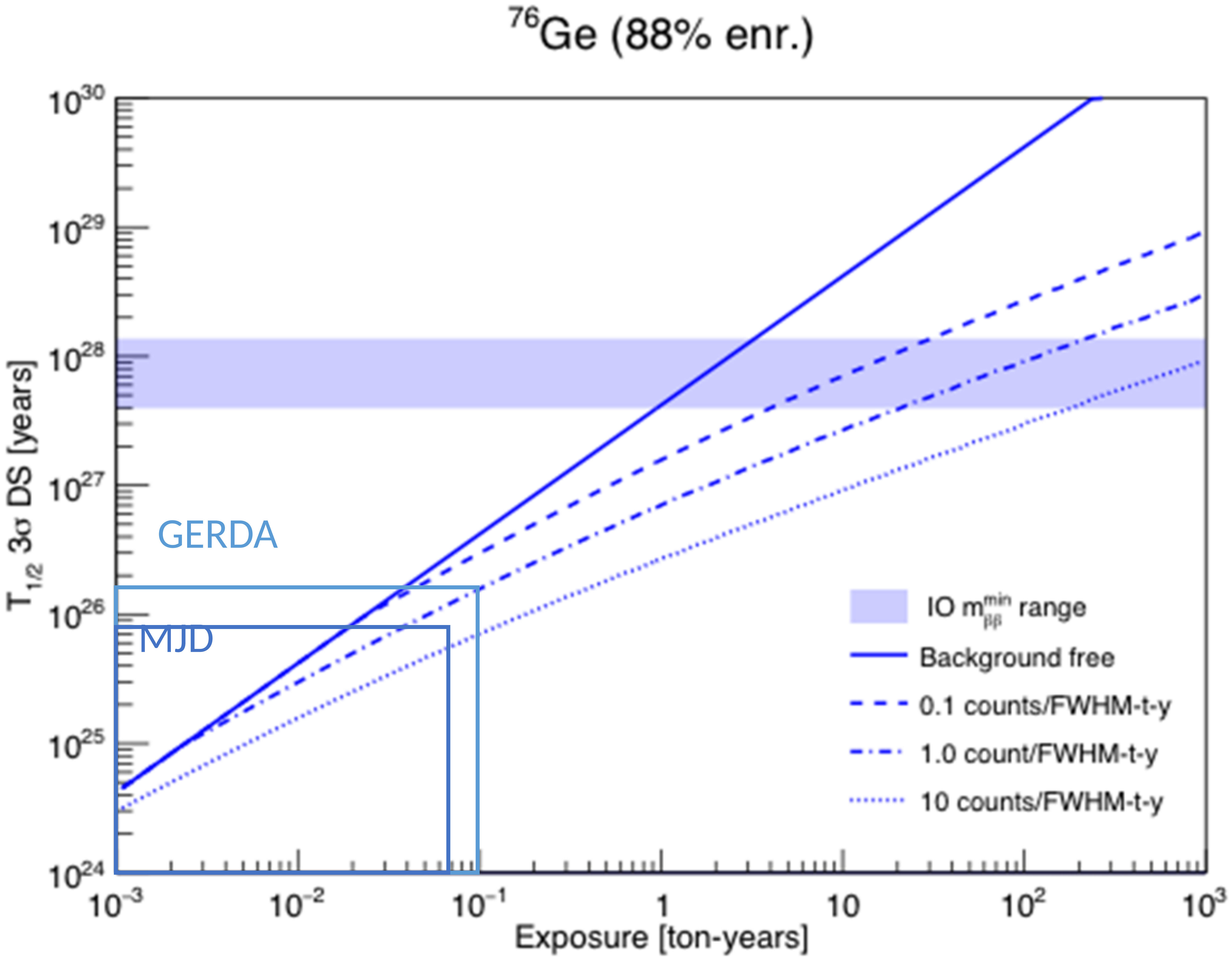
Searching for 0νββ in ^{76}Ge

Current limits on the 0νββ half-life in ^{76}Ge are around 10^{26} yrs

This was achieved with quasi-background-free measurements with ~100 kg-yrs of exposure

High purity germanium detectors have many advantages in this search:

- Well understood technology
- High detection efficiency
- Low intrinsic backgrounds
- Excellent energy resolution
- Background rejection techniques using pulse-shape analysis
- Long history of 0νββ searches



The MAJORANA DEMONSTRATOR

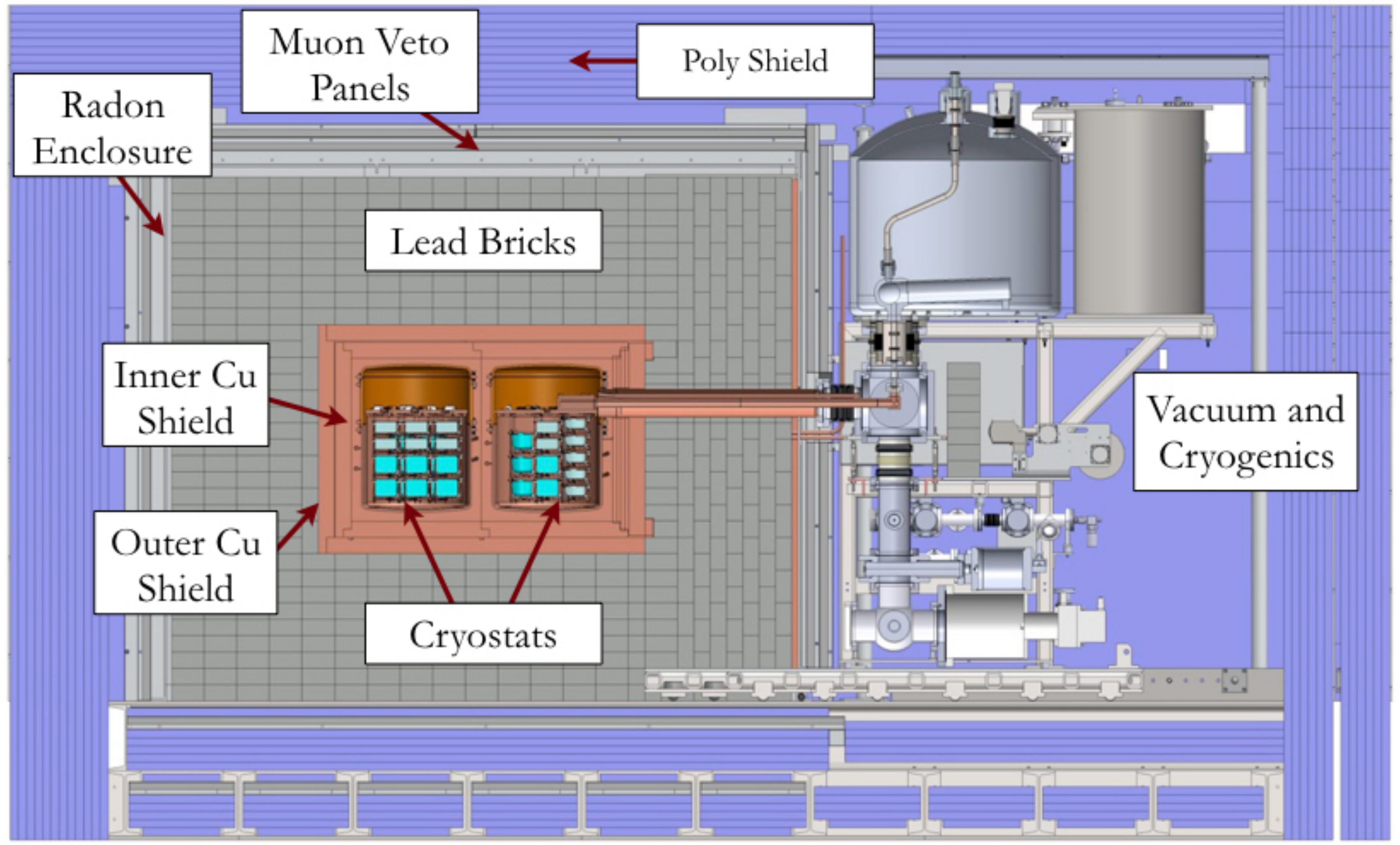
Searching for neutrinoless double-beta decay of ^{76}Ge in HPGe detectors, probing additional physics beyond the standard model, and informing the design of the next-generation LEGEND experiment

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

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



The MAJORANA Collaboration

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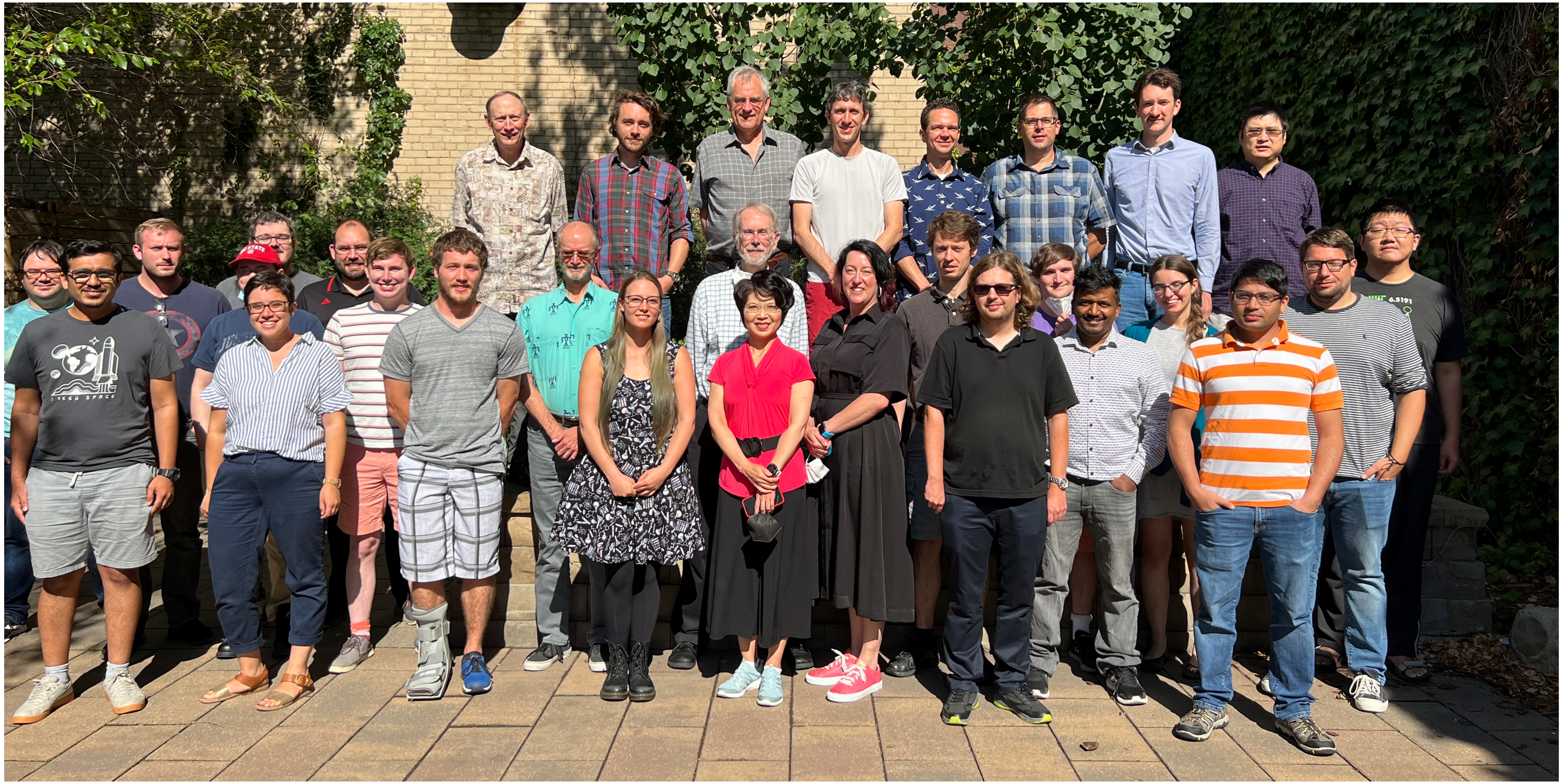
The MAJORANA Collaboration

NSF

Sanford Underground Research Facility



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UNIVERSITY OF SOUTH CAROLINA

UNIVERSITY OF SOUTH DAKOTA

THE UNIVERSITY of TENNESSEE KNOXVILLE

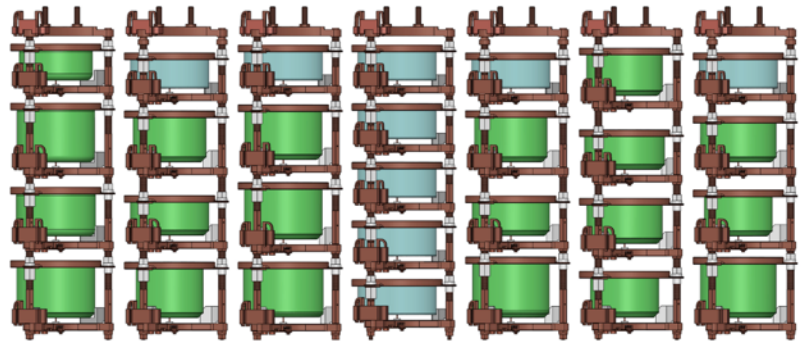
W

Williams

A History of the MAJORANA DEMONSTRATOR

Module 1

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



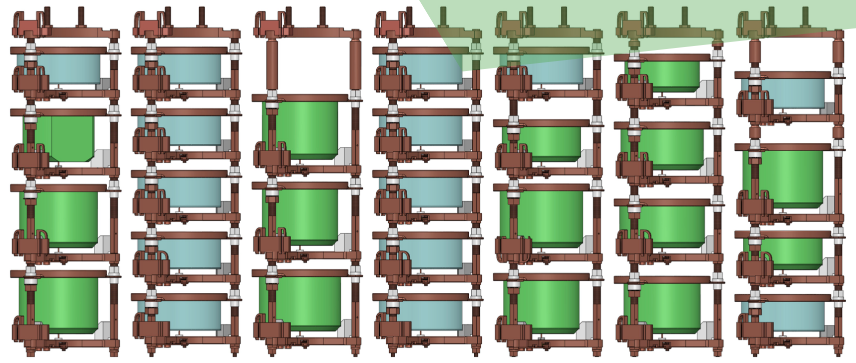
Deployed Module 1 in shield

Mar. 2021:
Stopped ^{enr}Ge Operation with 65 kg-yr of exposure
Removed all ^{enr}Ge for LEGEND-200

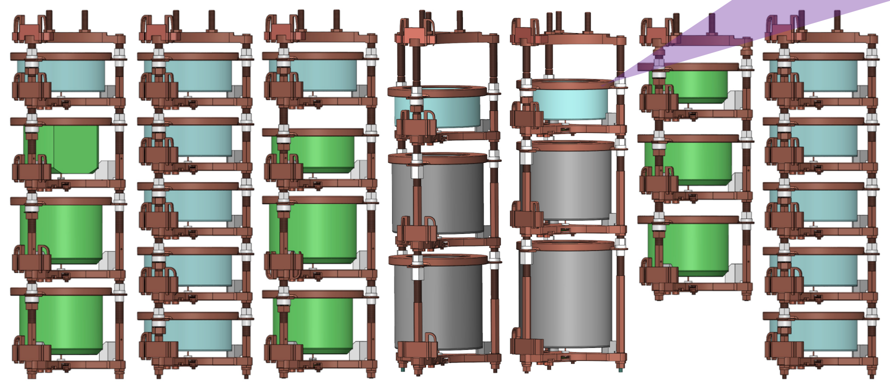
2015	2016	2017	2018	2019	2020	2021	2022	…

Module 2

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

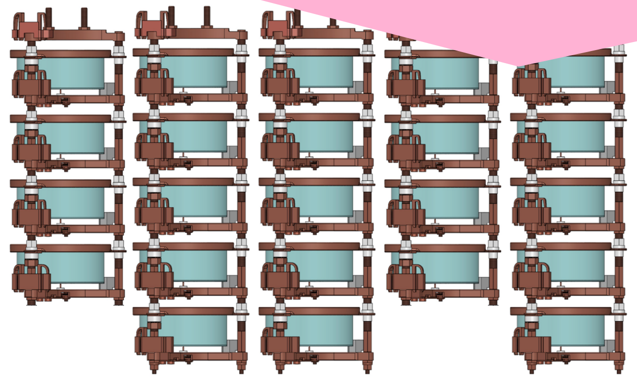


Deployed Module 2 in shield



14.1 kg (13) ^{enr}Ge
6.7 kg (4) as ICPC
8.8 kg (14) ^{nat}Ge

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

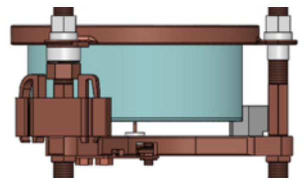


14.3 kg (23) ^{nat}Ge

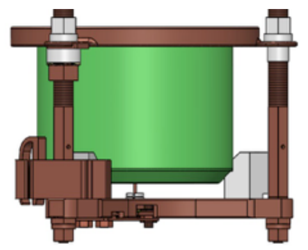
Continued operation of Module 2 only with natural Ge detectors

Currently measuring half-life of ^{180m}Ta

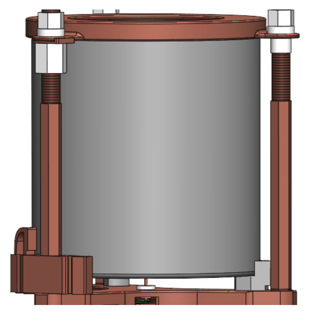
Mirion/Canberra BEGe
^{nat}Ge



Ortec PPC
^{enr}Ge



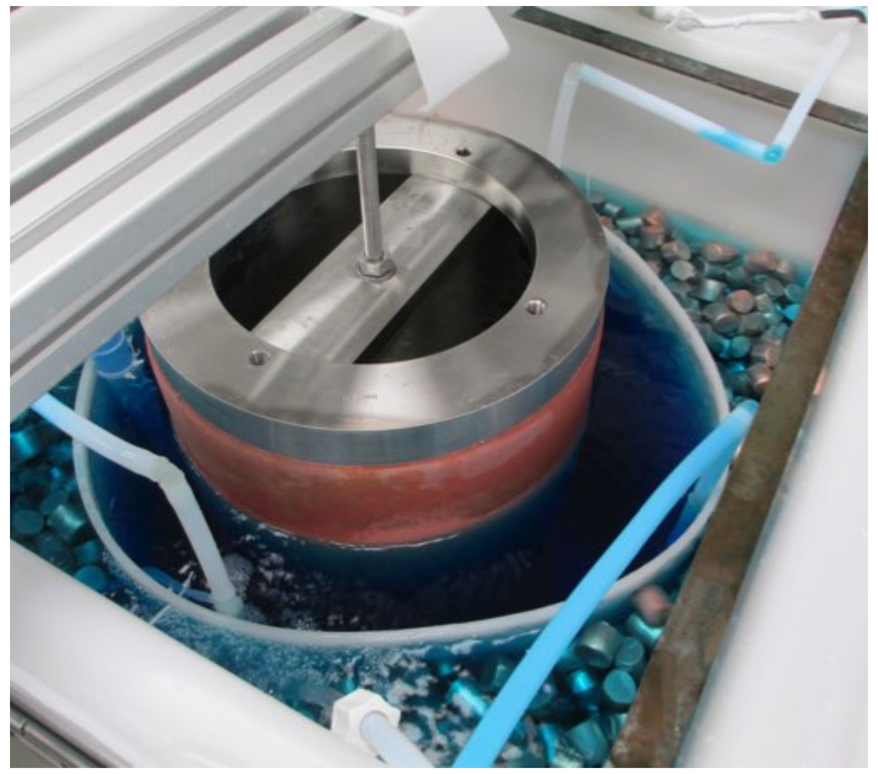
Ortec ICPC
^{enr}Ge

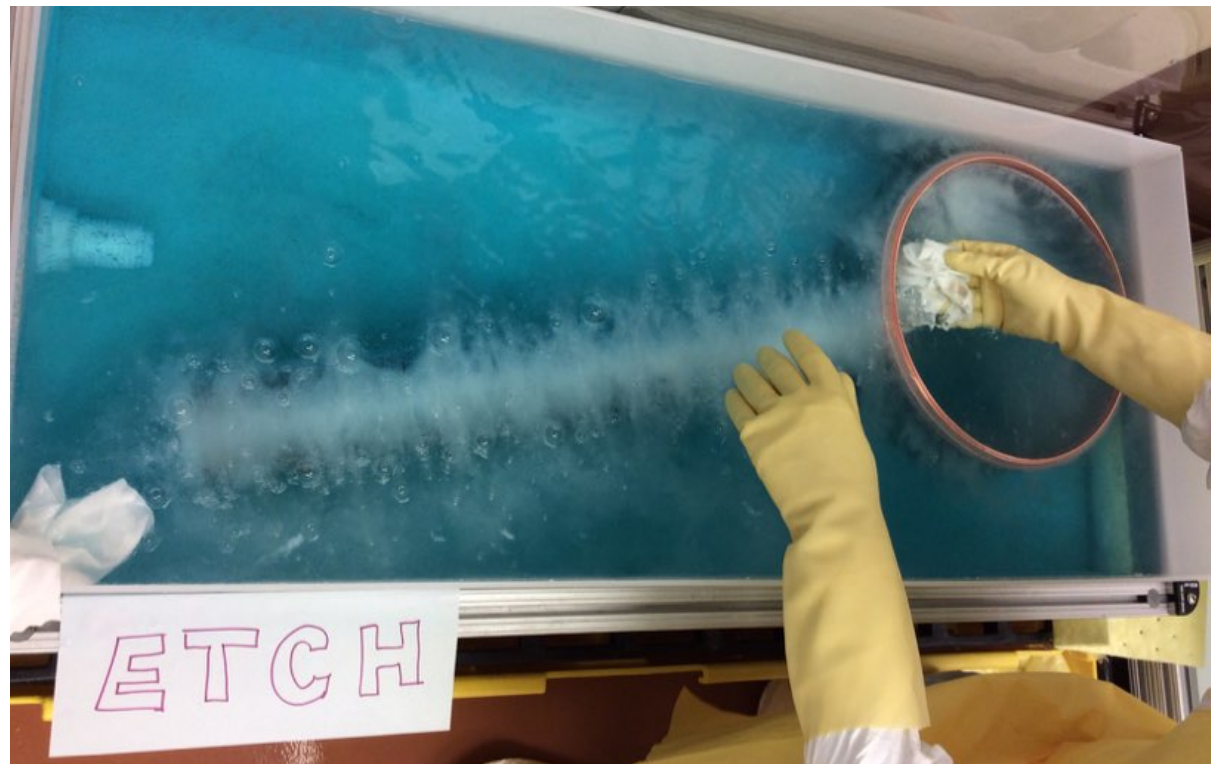


Achieving Low Backgrounds

Ultra-pure materials

- Low-mass design NIM A 828 22 (2016)
- Custom cable connectors and front-end boards
- Selected plastics and low-mass Cu coax cables
- Underground electroformed copper NIM A 775 93 (2015)



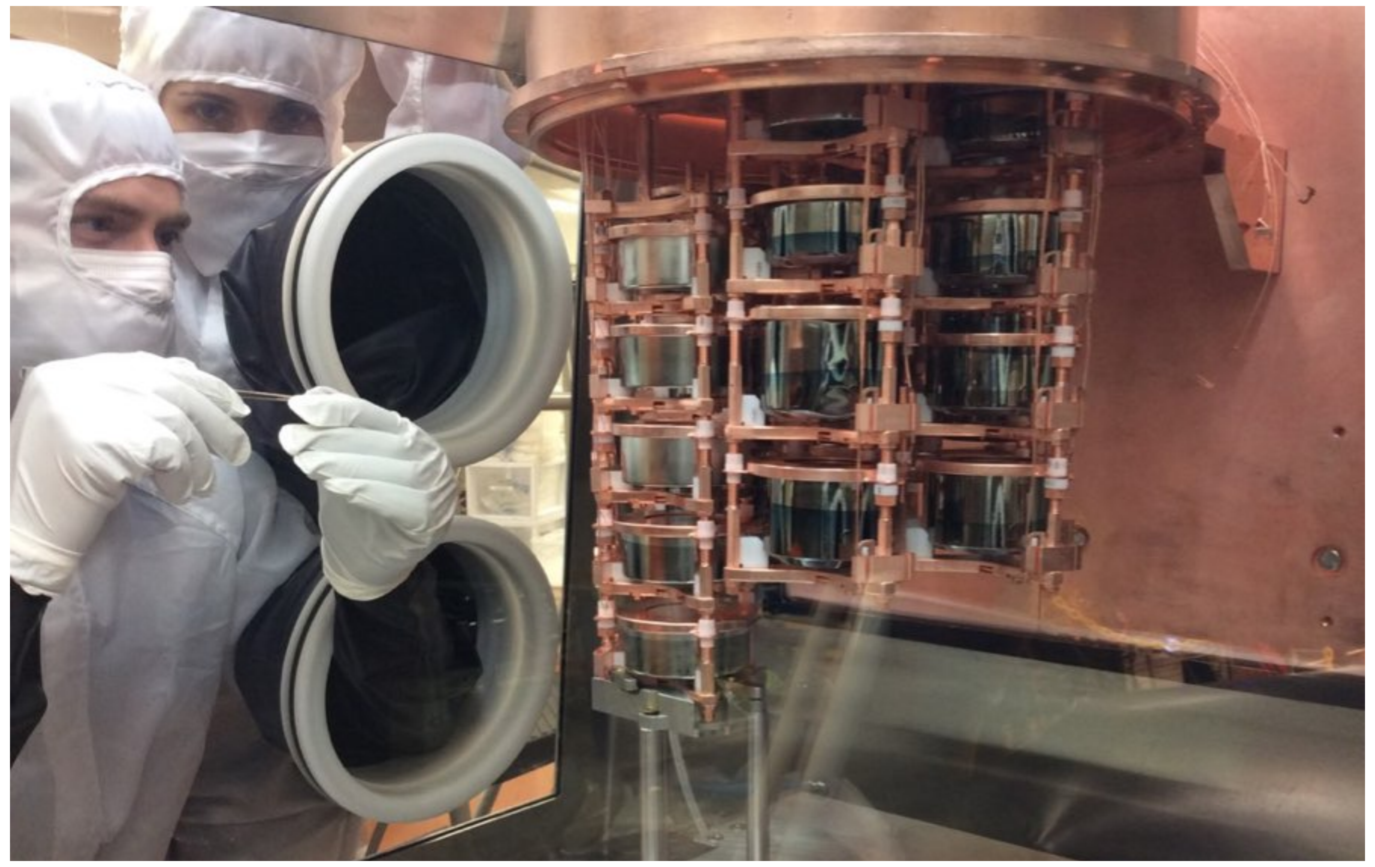


Cosmogenic backgrounds

- Limit and track Ge above-ground exposure to prevent cosmic activation. NIM A 877 314 (2018) NIM A 779 52 (2015)
- Veto events coincident with muons Astropart. Phys. 93 70 (2017)

Machining, cleaning, and assembly

- Cu machining in an underground cleanroom
- Cleaning of Cu parts by acid etching and passivation
- Nitric leaching of plastic parts
- Dedicated glove boxes with a purged N2 environment



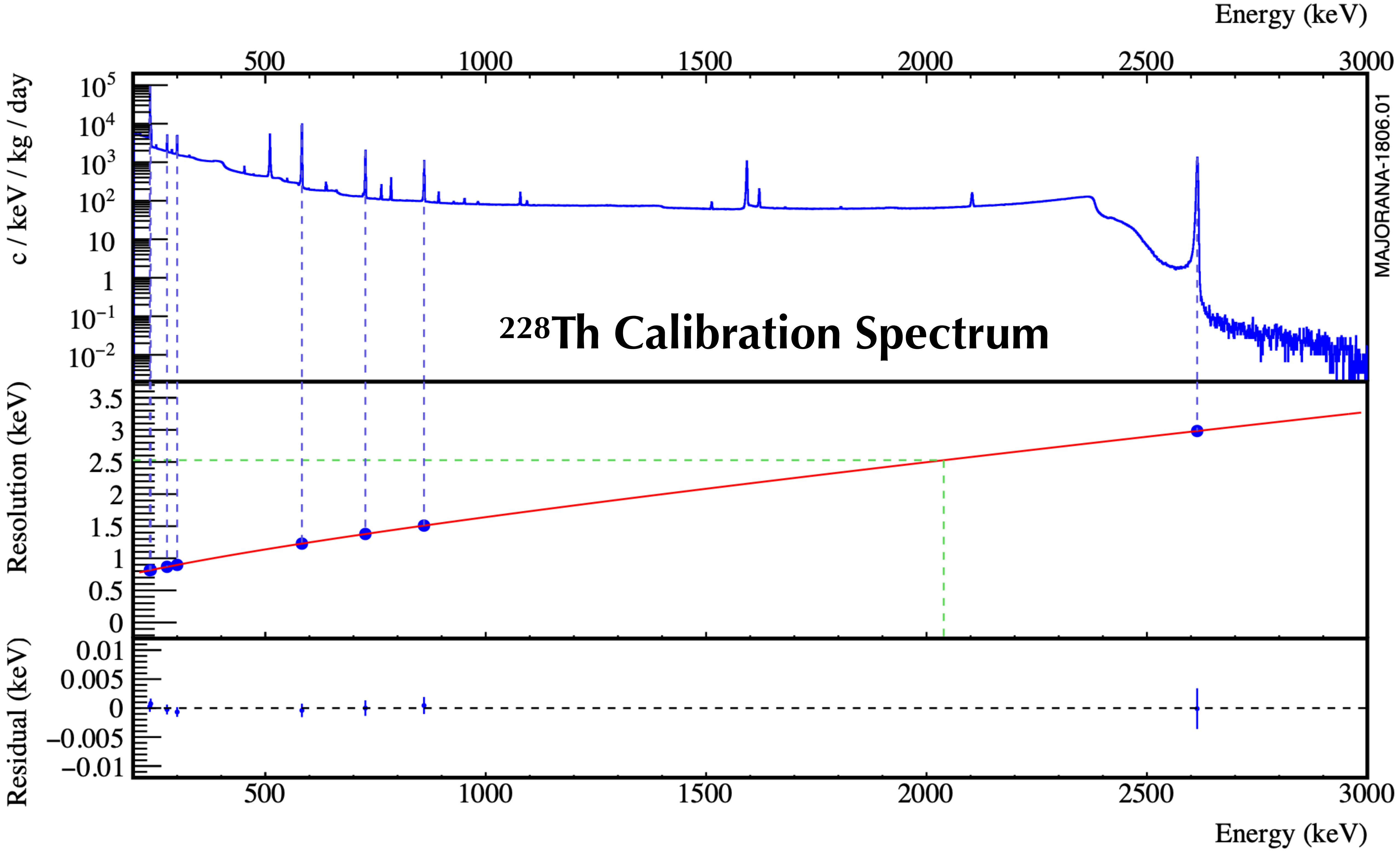
Excellent Energy Resolution

Energy estimated via optimized trapezoidal filter of ADC-nonlinearity-corrected[1] traces with charge-trapping correction[2]

FWHM of 2.5 keV at $Q_{\beta\beta}$ of 2039 keV (0.12%) is a record for $0\nu\beta\beta$ searches

- Charge trapping correction improves FWHM at 2039 keV from 4 keV to 2.5 keV
- Calibrated on weekly ^{228}Th calibration data[3,4]

^{228}Th line source deployed during calibration



FWHM of combined enriched detectors in the MAJORANA DEMONSTRATOR, measured using ^{228}Th calibration data

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

2. arXiv:2208.03424 (accepted PRC)

3. NIMA **872** (2017) 16

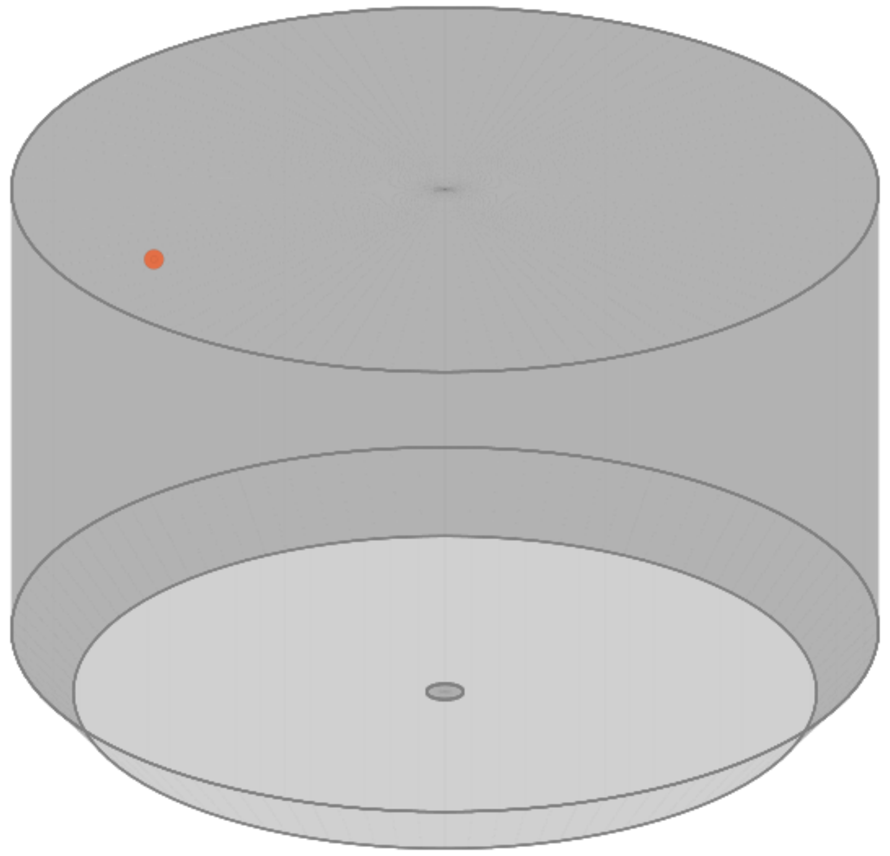
4. Calibration Procedure Paper to appear soon

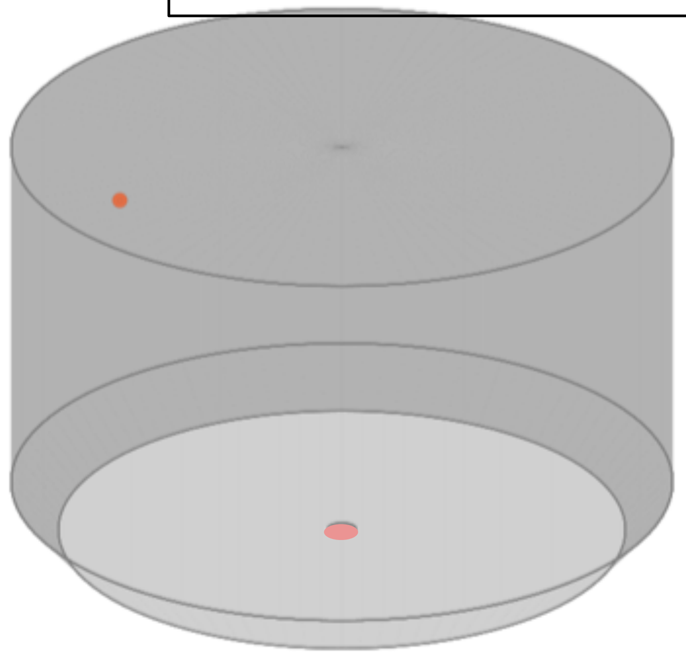
P-Type Point Contact Detectors

Advantages of P-type Point-Contact detector geometries

- Low capacitance for improved energy resolution and low thresholds
- Drift time highly dependent on position of charge deposition due to slow charge drift and highly localized weighting potential

IEEE Trans. on Nuc. Sci., 36, 1, 926-930 (1989)

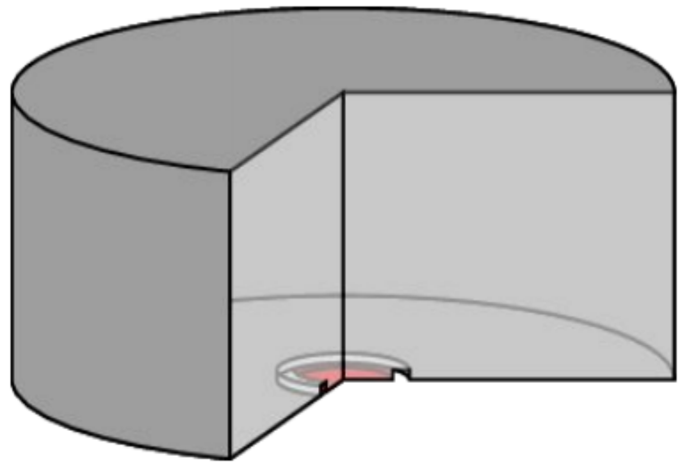




PPC

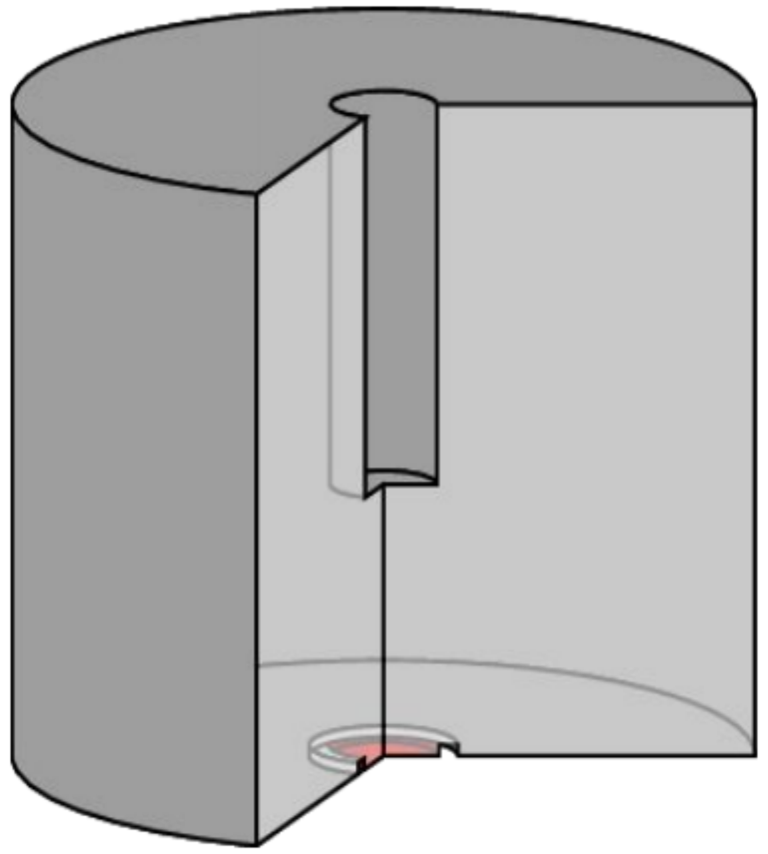
JCAP 09 (2007) 009

- Small mass (< 1 kg)
- Excellent background rejection



BeGe

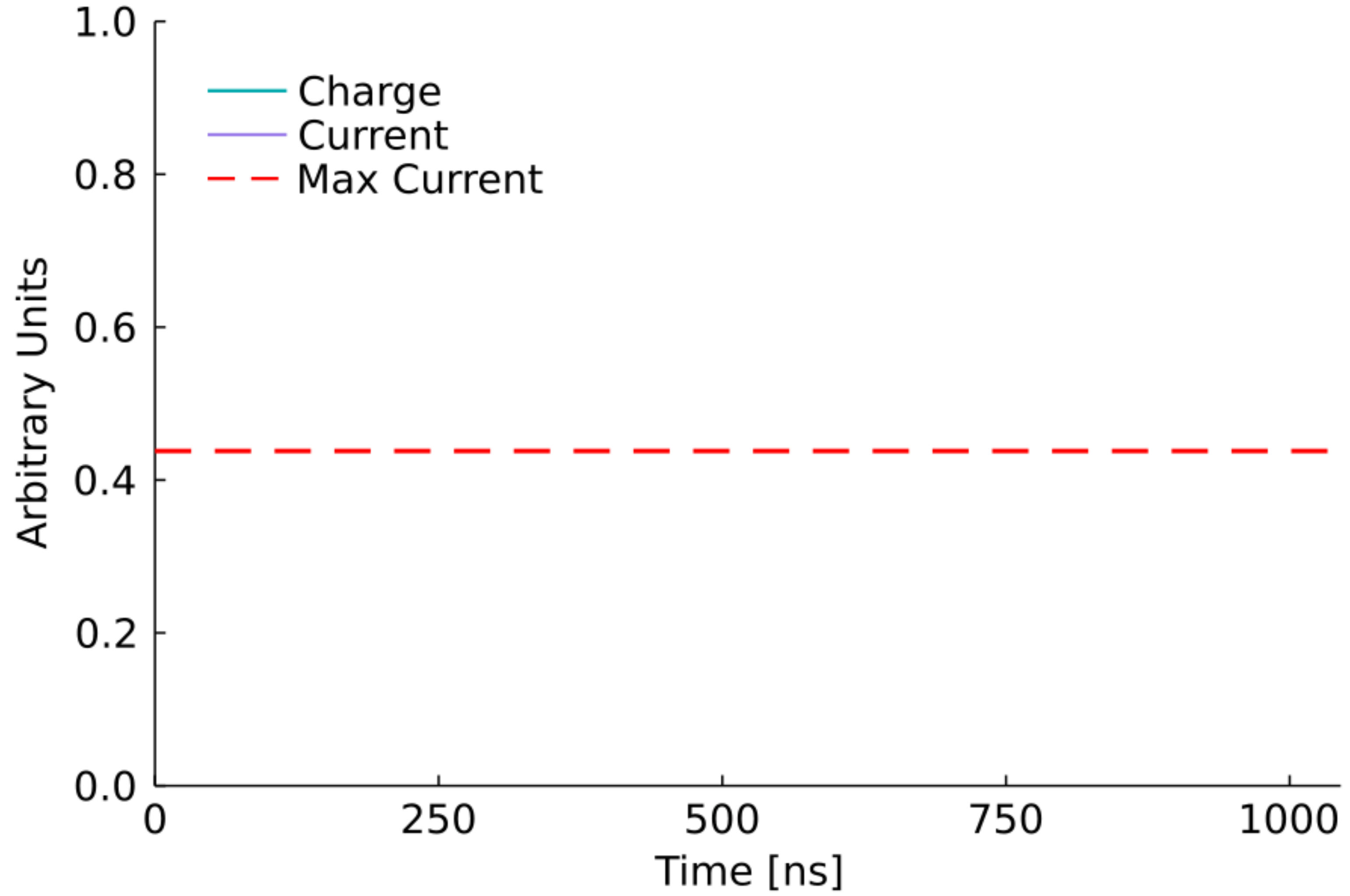
Eur. Phys. J. C 79, 978 (2019)



Inverted-Coaxial

NIMA ,665, 25-32, (2011)

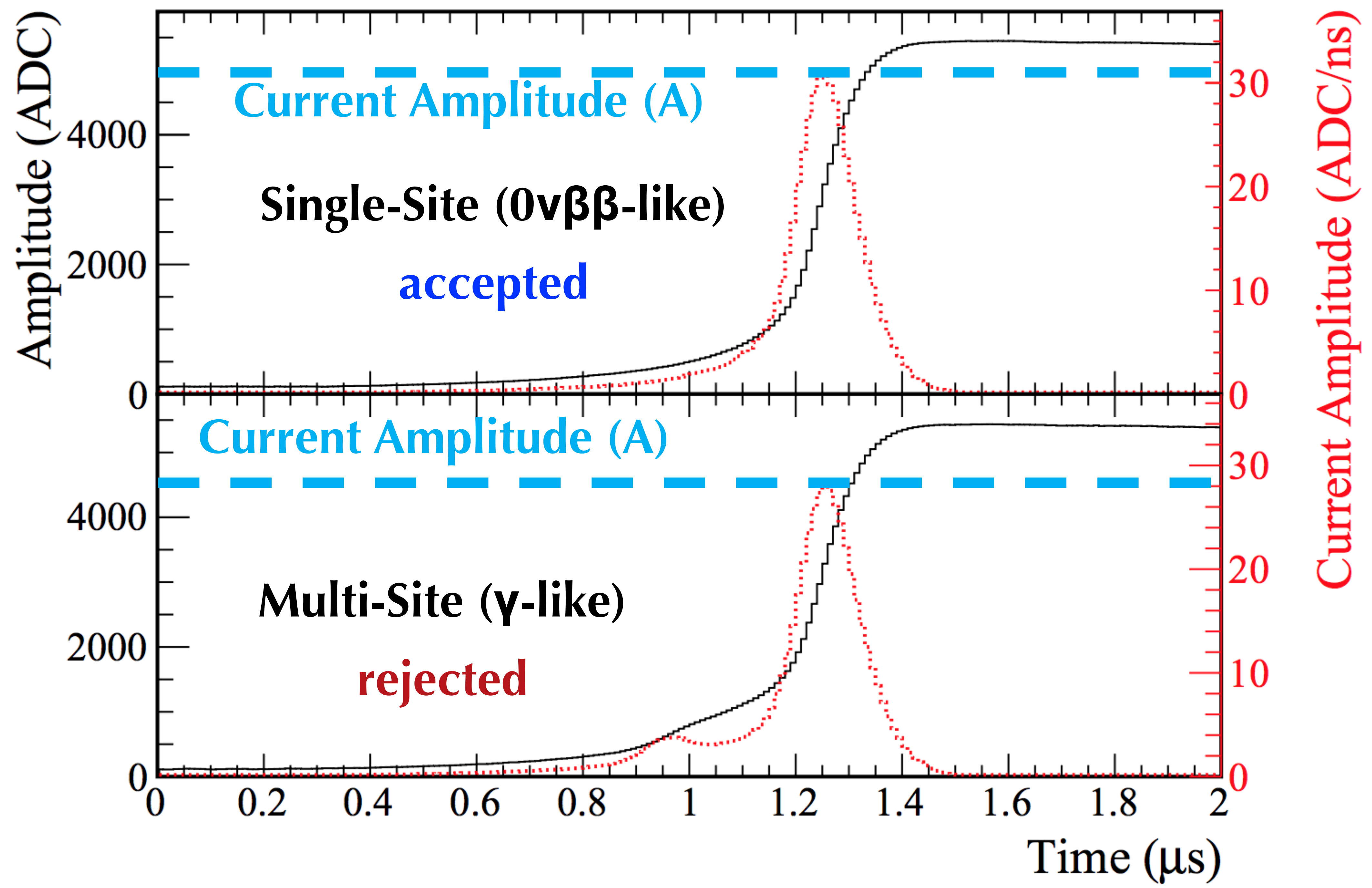
- Newly developed for LEGEND
- Large mass (up to 4 kg)
- Excellent background rejection

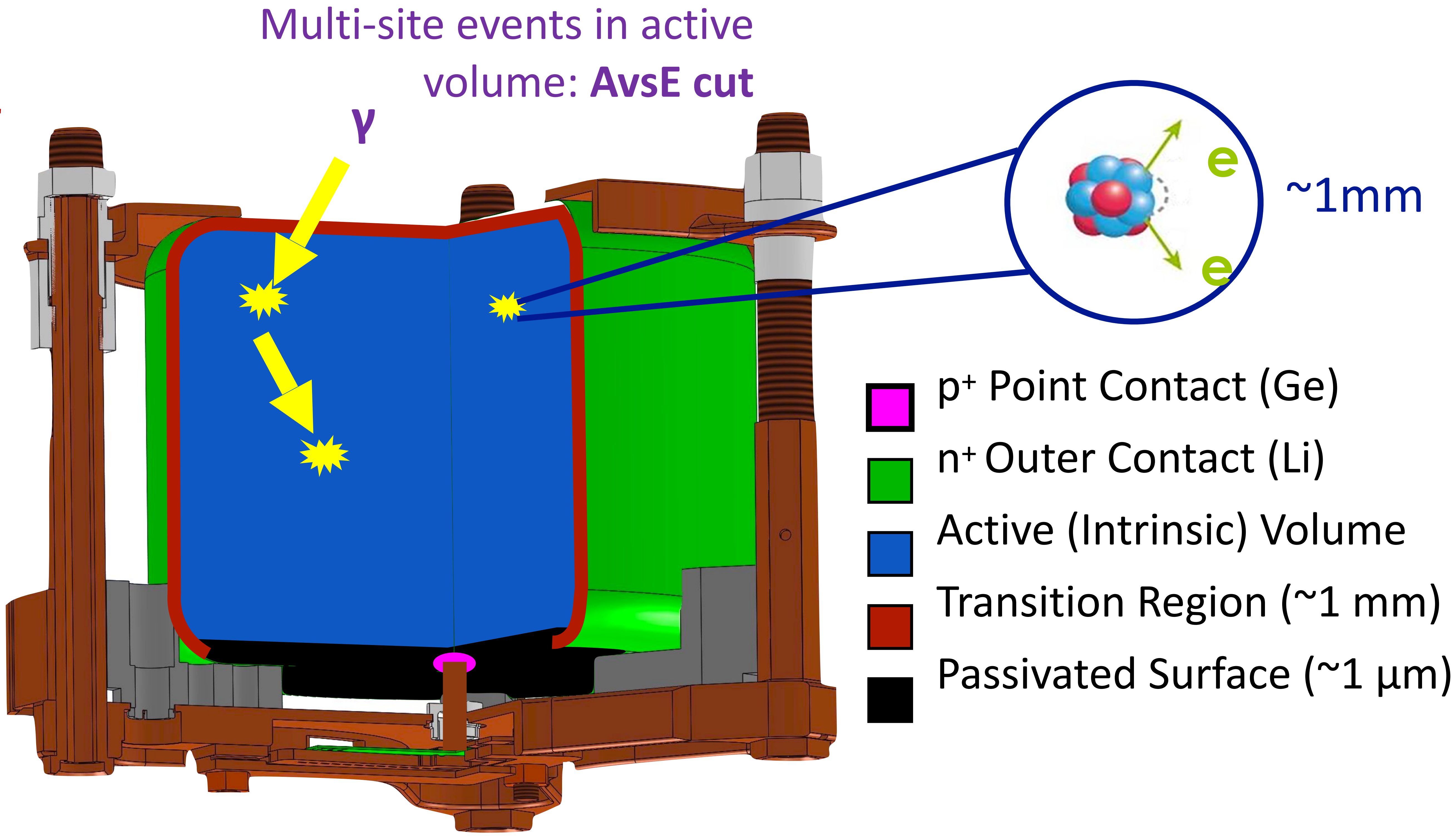


Pulse Shape Analysis: Multi-Site Events

$0\nu\beta\beta$ is localized within ~1 mm (i.e. single-site). Many backgrounds are multi-site

- Reject by comparing current amplitude to pulse height (AvsE)
- Tuned on ^{228}Th calibration data to accept 90% of single-site DEP events. Rejects >50% of the Compton continuum near $Q_{\beta\beta}$





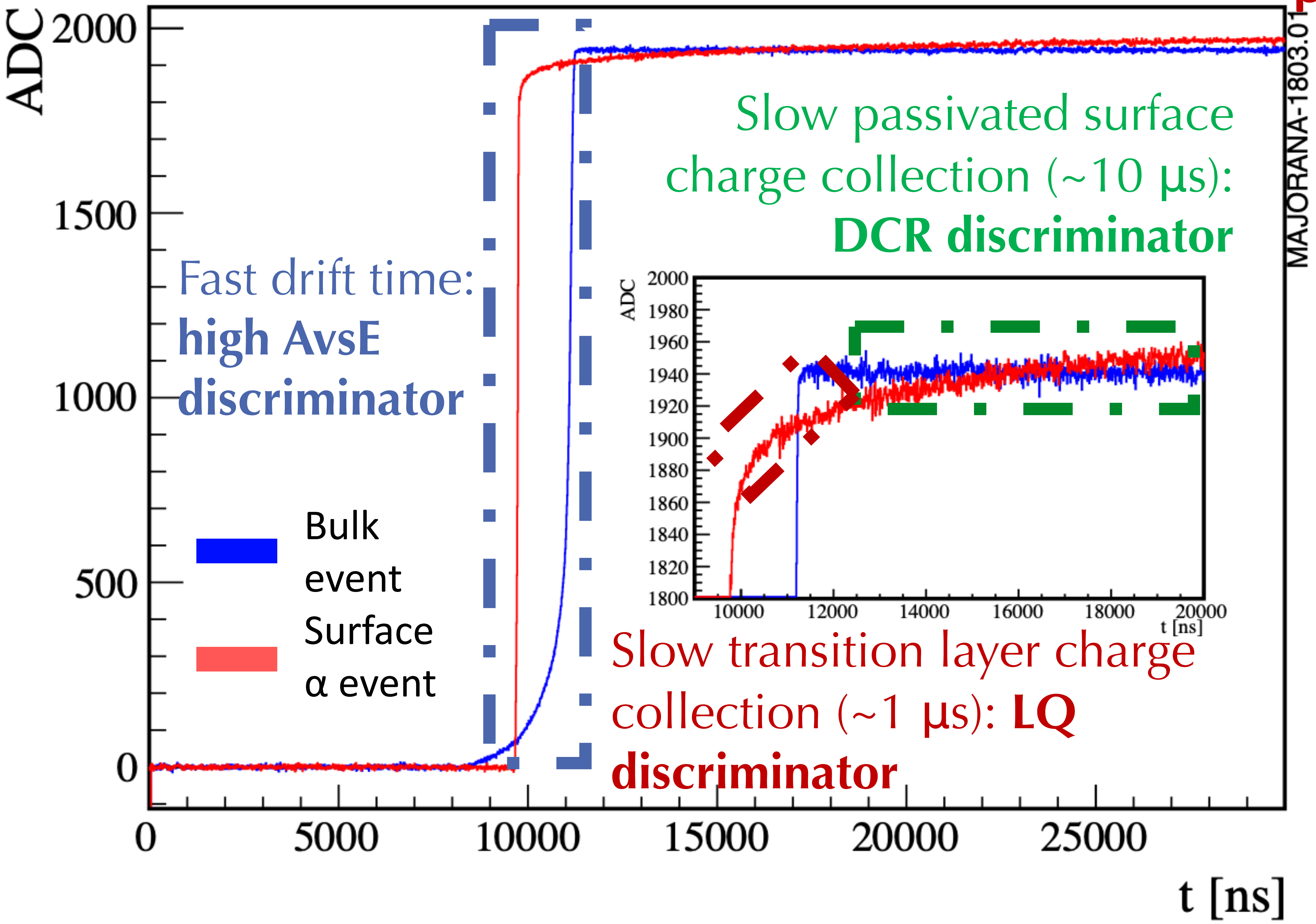
New to 2022 result: Improved uniformity and stability, increased signal acceptance by 6%

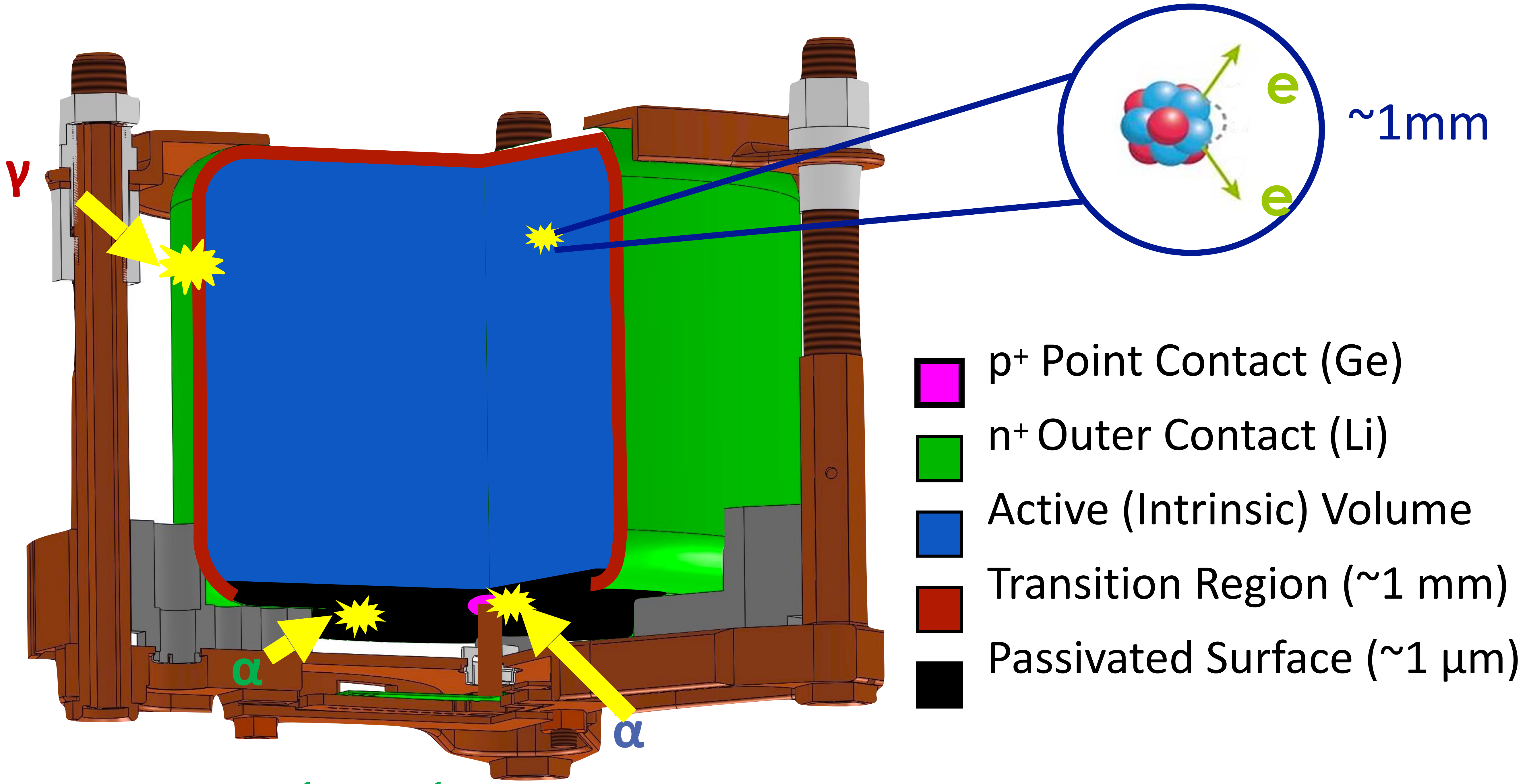
Pulse Shape Analysis: Surface Events

$0\nu\beta\beta$ is most likely located in the bulk of the detector. Many backgrounds are located near detector surfaces. Pulse-shape discrimination can distinguish between these topologies.

EPJC 82 (2022) 226

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





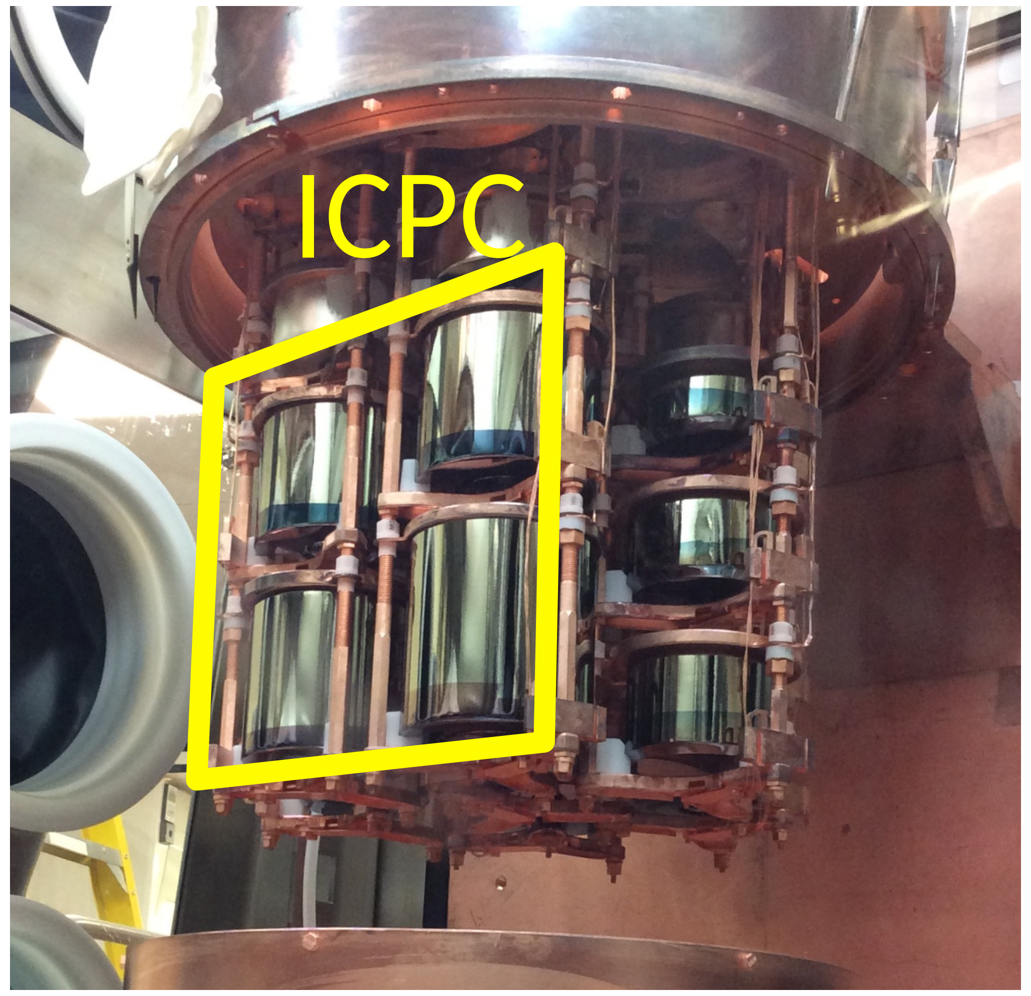
Detector surface - for particle incident on passivated surface: **DCR discriminator**

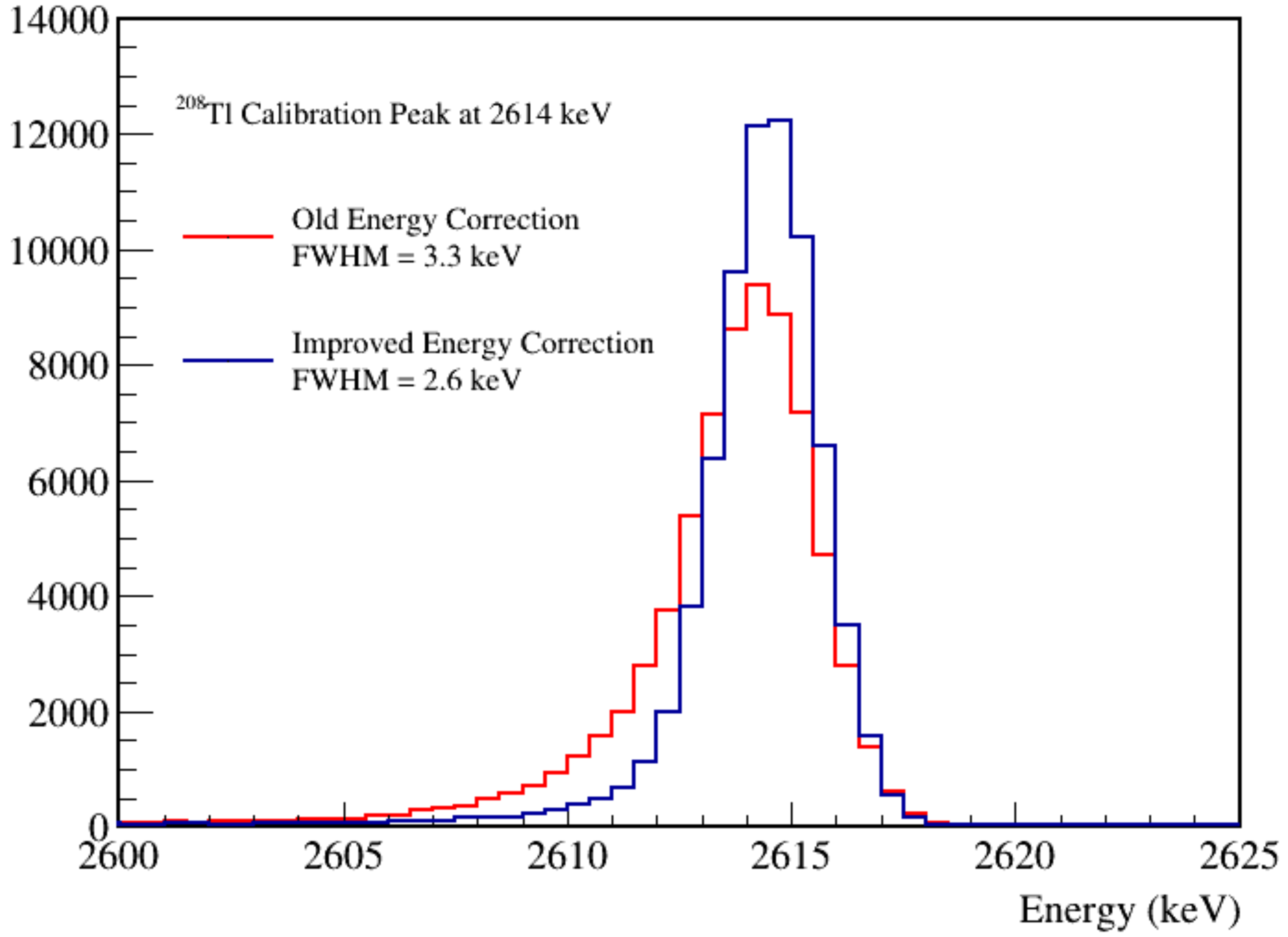
Detector surface - for particle incident on surface near point contact: **high AvsE discriminator**

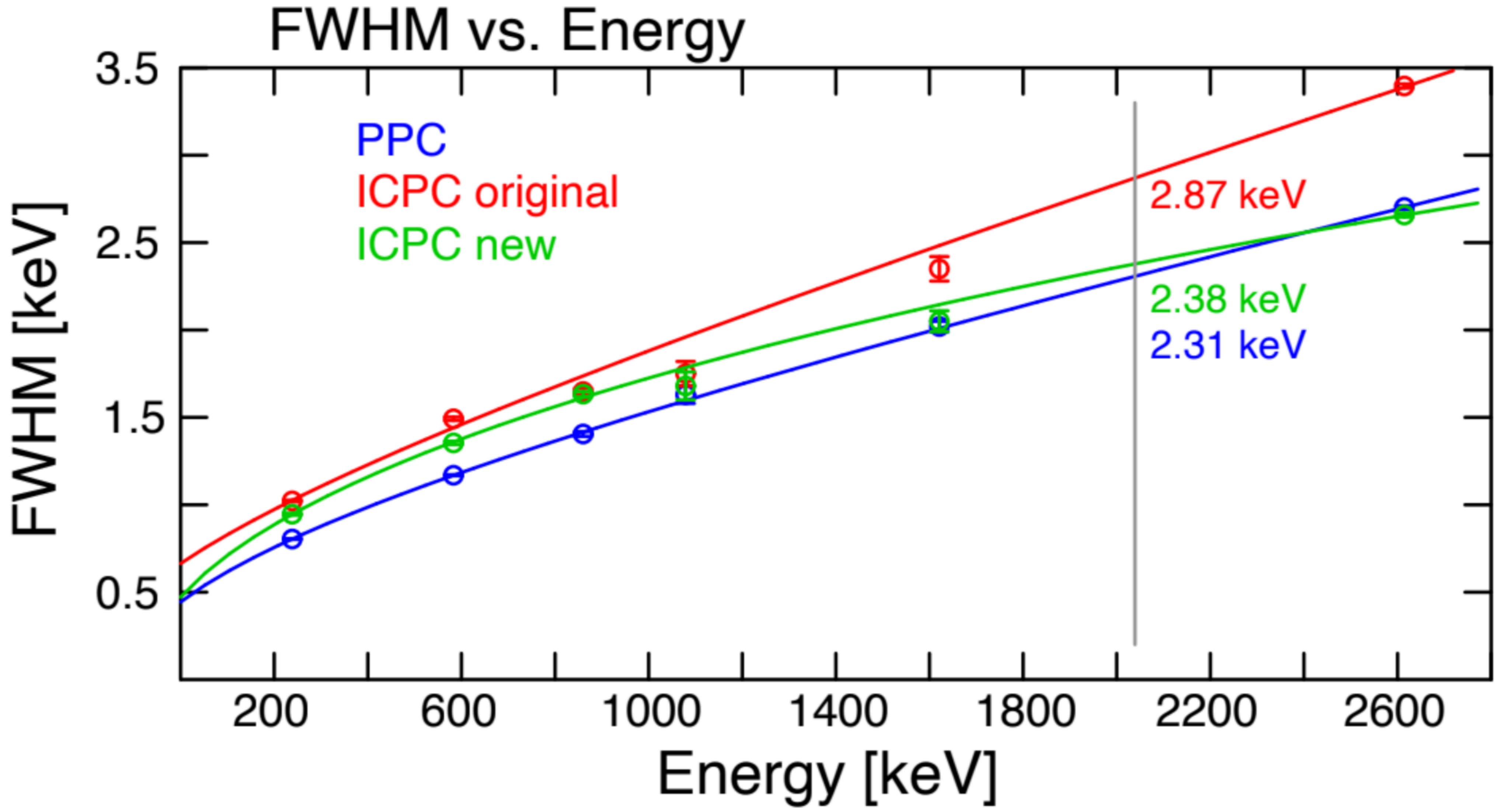
Inverted Coaxial Point Contact Detectors

Inverted coaxial point contact (ICPC) detectors are larger (1.4 – 4 kg) than PPC detectors (0.6 – 1.2 kg). MAJORANA operated 4 ICPCs from Aug. 2020 to Mar 2021

- Beneficial for background reduction in LEGEND
- Larger range of drift times requires more refined analysis techniques
- MAJORANA has demonstrated comparable performance with ICPCs and PPCs. Best energy resolution for ICPCs to date!





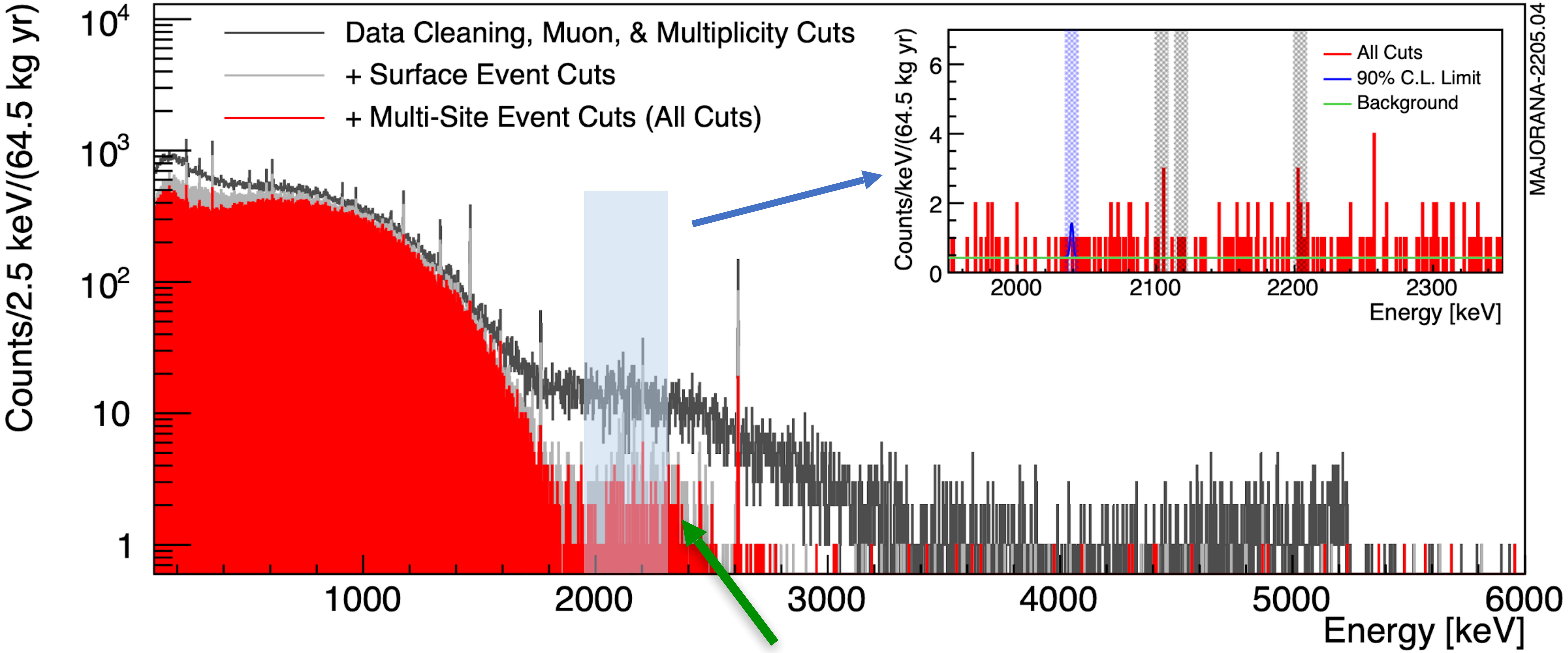


New analysis techniques improve combined energy resolution of ICPCs from 2.9 keV to 2.4 keV FWHM at 2039 keV

MAJORANA DEMONSTRATOR Final Result

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

PRL 130 062501 (2022)



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

Final enriched detector active exposure:

64.5 ± 0.9 kg-yr

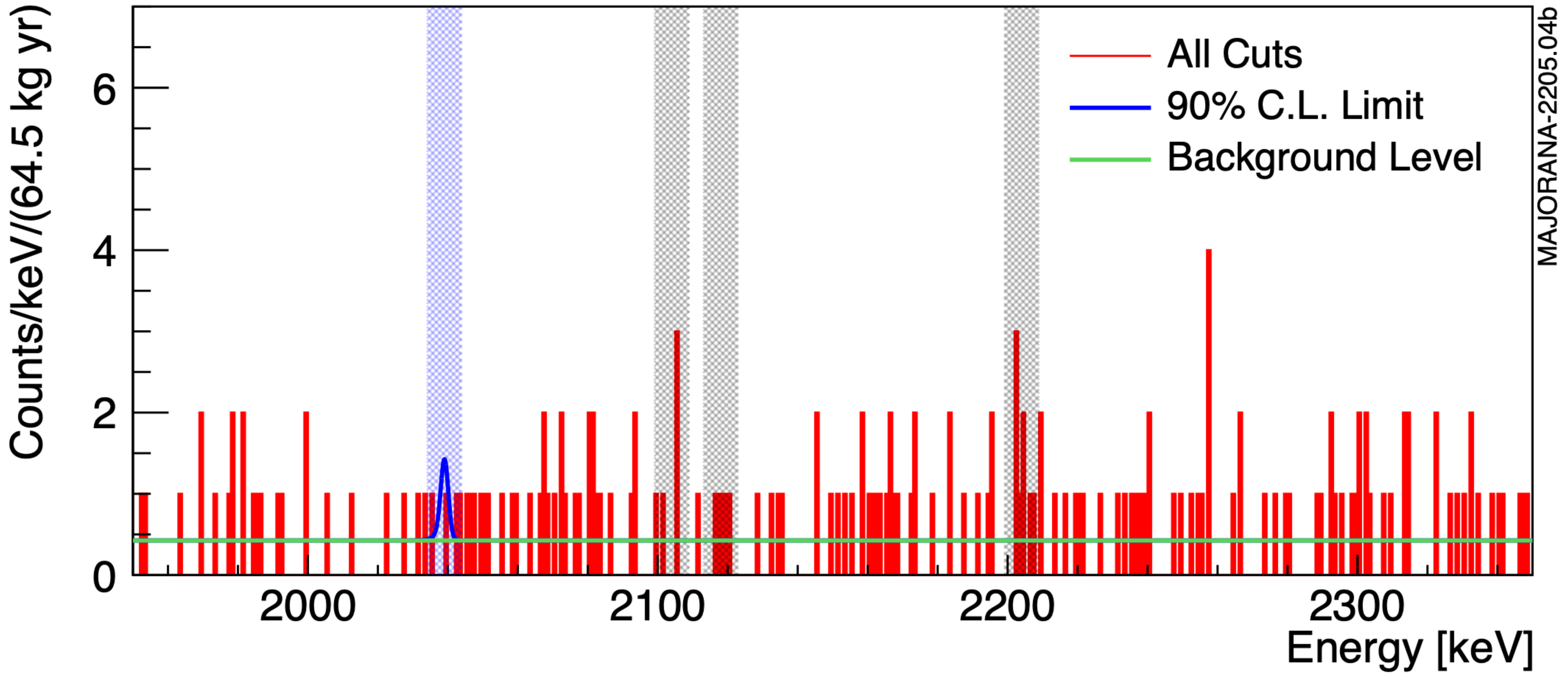
Background index at 2039 keV in lowest background configuration

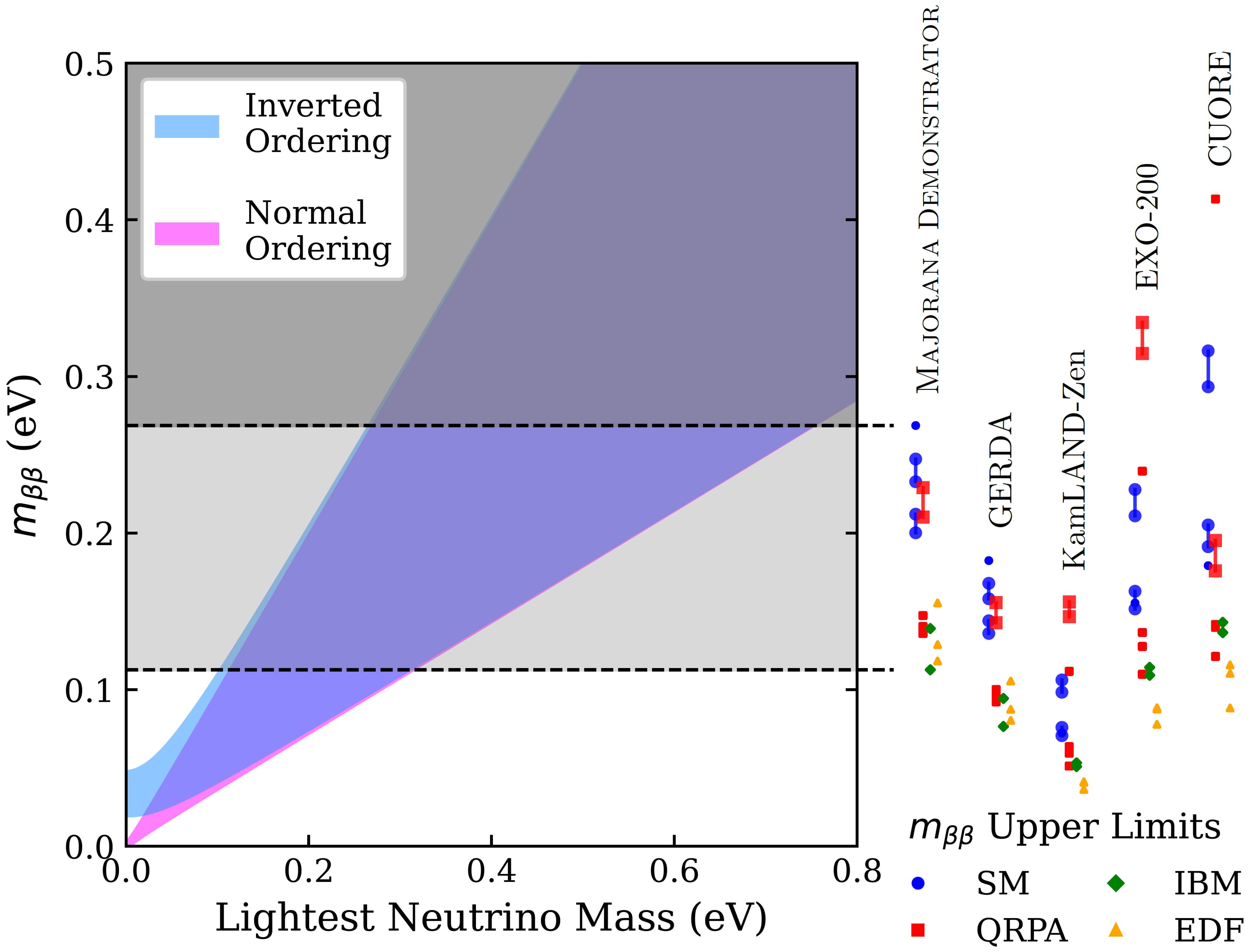
15.7 ± 1.4 cts/(FWHM t yr)

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

MAJORANA DEMONSTRATOR Final 0νββ Result

PRL **130** 062501 (2022)





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

Expect 1.5 background counts in 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 $M_{0\nu} = 2.66 - 6.34$

Next Steps in the Search for $0\nu\beta\beta$

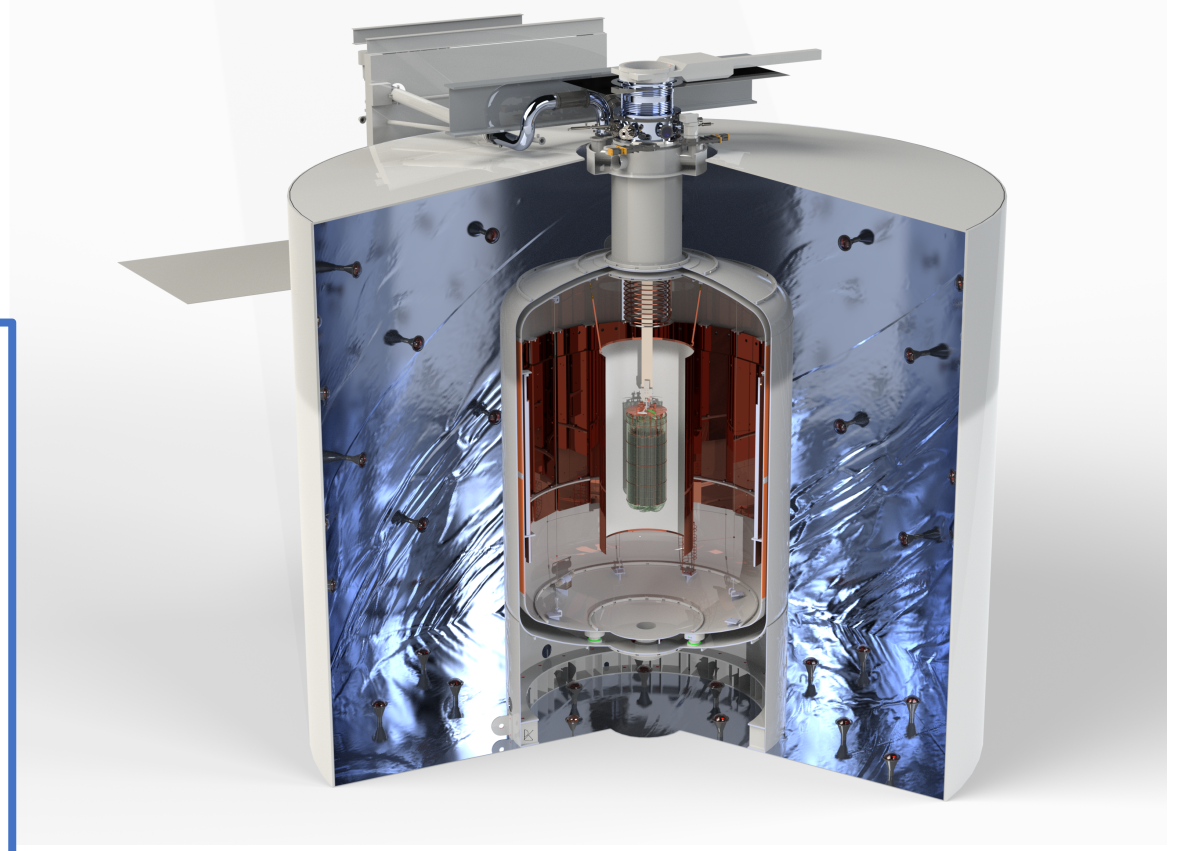
The MAJORANA DEMONSTRATOR achieved the second lowest backgrounds of any $0\nu\beta\beta$ to date, benefitting from:

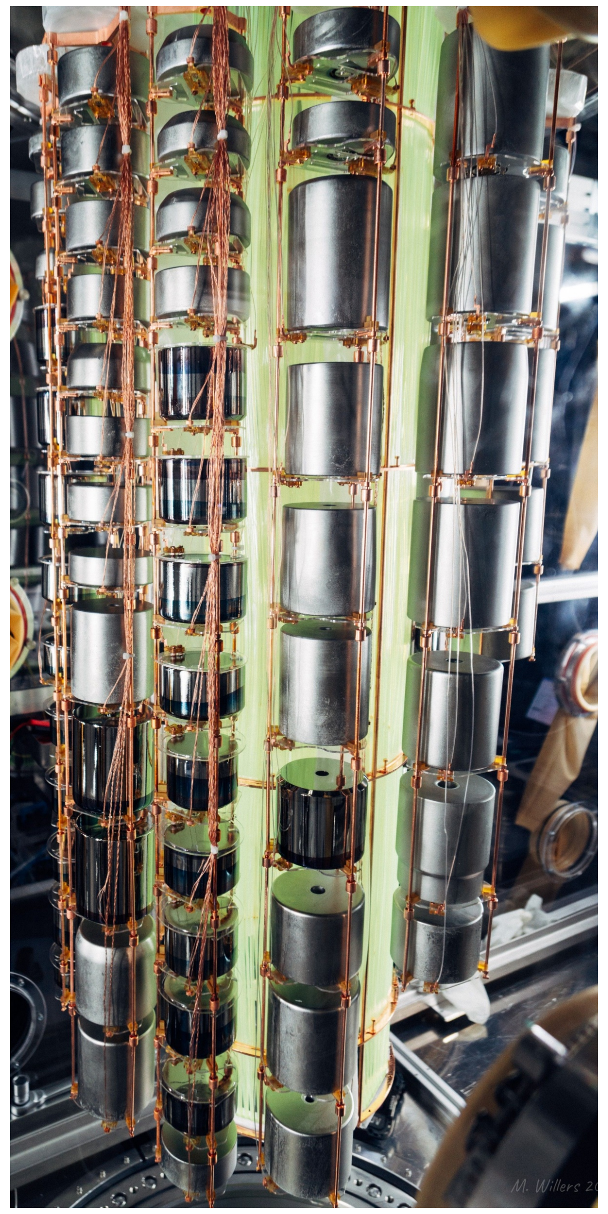
- Clean materials and techniques
- Control of surface exposure
- P-type Point-Contact detectors
- Radiopurity of components near detectors
- Best energy resolution of any $0\nu\beta\beta$ to date
- Low noise electronics, for low energy thresholds and more powerful cuts

Next step: the LEGEND collaboration will continue a phased search for $0\nu\beta\beta$ in ^{76}Ge, with an ultimate discovery potential of 10^{28} yr half-life

- Combine the people, materials and techniques from GERDA (lowest BGs) and MAJORANA (second lowest BGs)

The MAJORANA DEMONSTRATOR	GERDA
PRL **130** 062501 (2022)	PRL **125** 252502 (2020)
Backgrounds: 16 cts/(FWHM t yr)	Backgrounds: 1.5 cts/(FWHM t yr)
Exposure: 65 kg-yr exposure	Exposure: 104 kg-yr exposure
Limit: $T_{1/2} > 8.3 \times 10^{25}$ yr (90% C.I.)	Limit: $T_{1/2} > 1.8 \times 10^{26}$ yr (90% C.I.)





LEGEND-200 is currently operating, with an expected half-life discovery potential of 10^{27} yrs after 5 years

Final steps for MAJORANA: build a background model

Outline: Final Results and New Directions

Ian Guinn (UNC & TUNL)

- Overview of MAJORANA, and final neutrinoless double beta decay result

Anna Reine (UNC & TUNL)

- Studies of radioactive backgrounds and development of a full background model

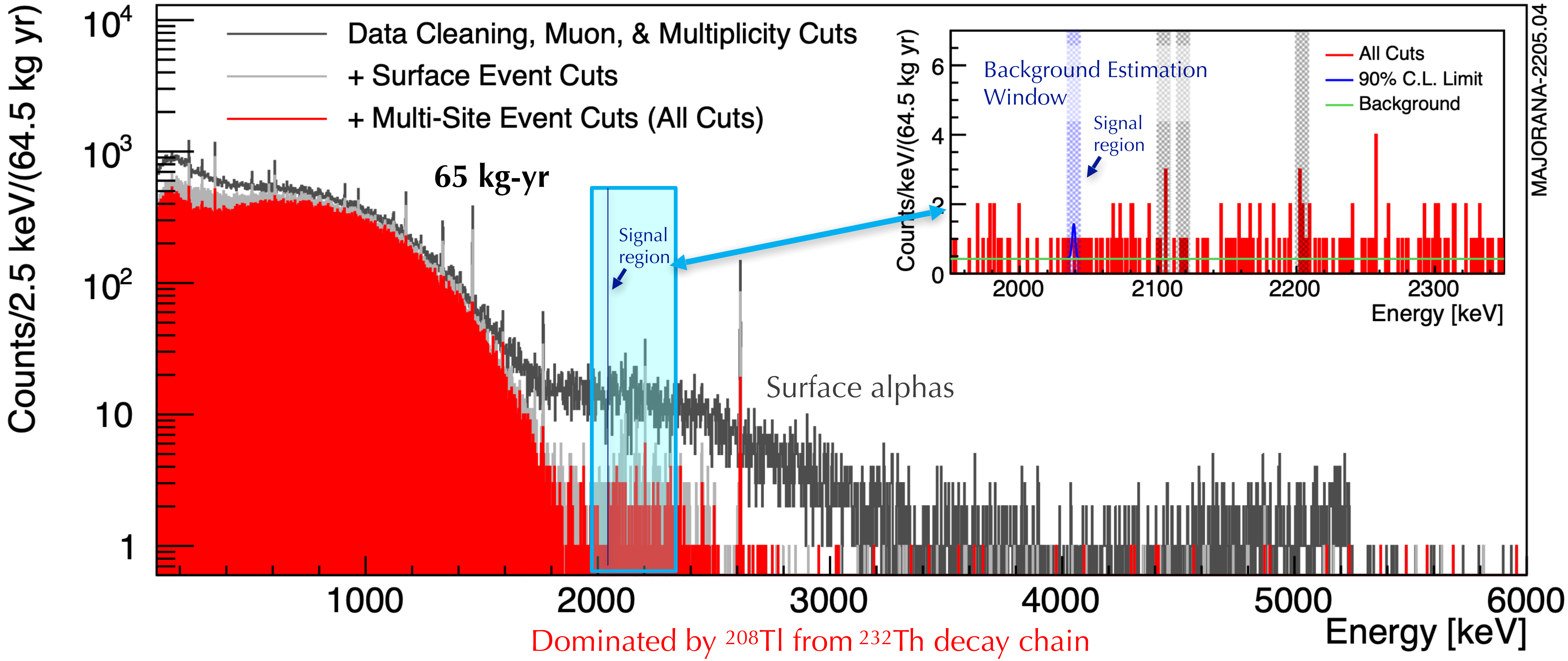
Clint Wiseman (UW & CENPA)

- Search for beyond standard model physics, dark matter

Ralph Massarczyk (LANL)

- First results from a search for the decay of nature's rarest isotope - Tantalum-180

Backgrounds in the MAJORANA DEMONSTRATOR



Dominated by ^{208}Tl from ^{232}Th decay chain

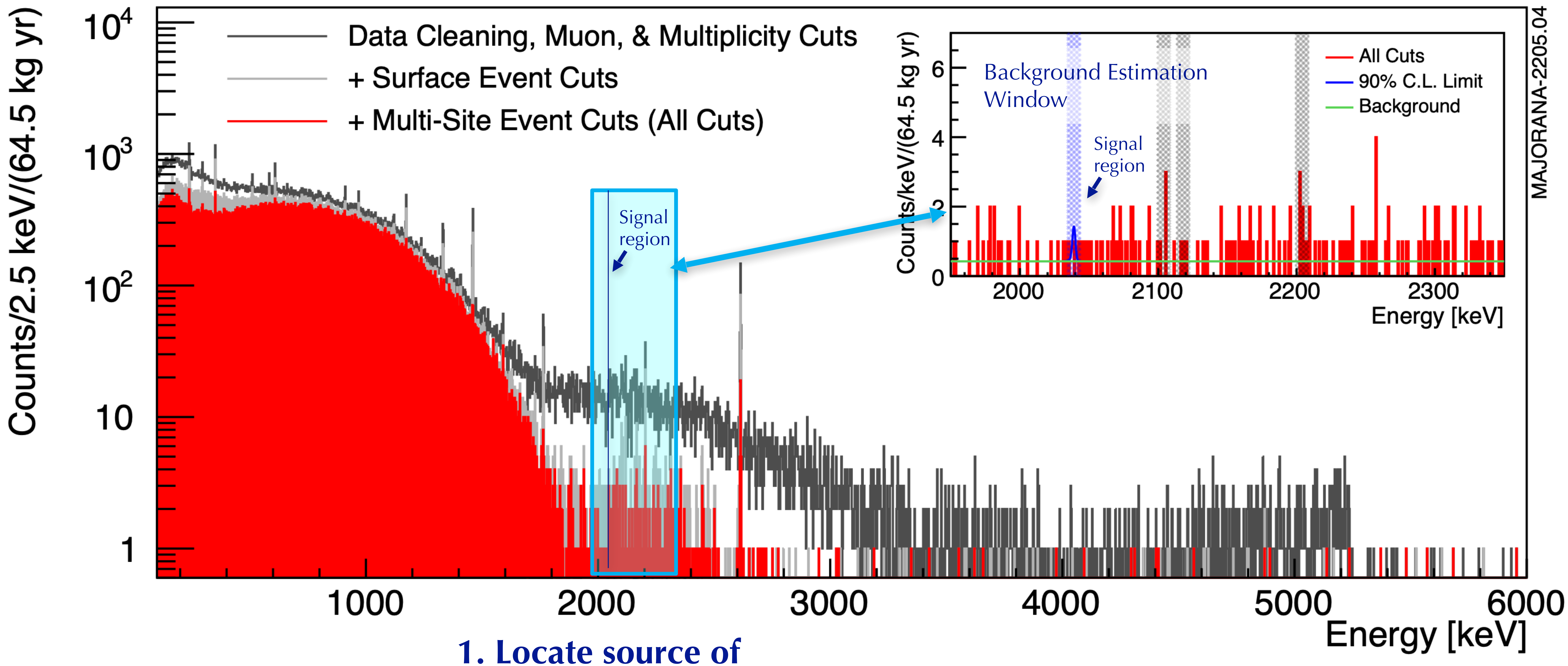
Rates in Background Estimation Window (after cuts):

Measured background*:
15.7 ± 1.4 cts/(FWHM t y)

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

*Excludes higher background commissioning data

Background Modeling Goals



1. Locate source of background ^{232}Th excess

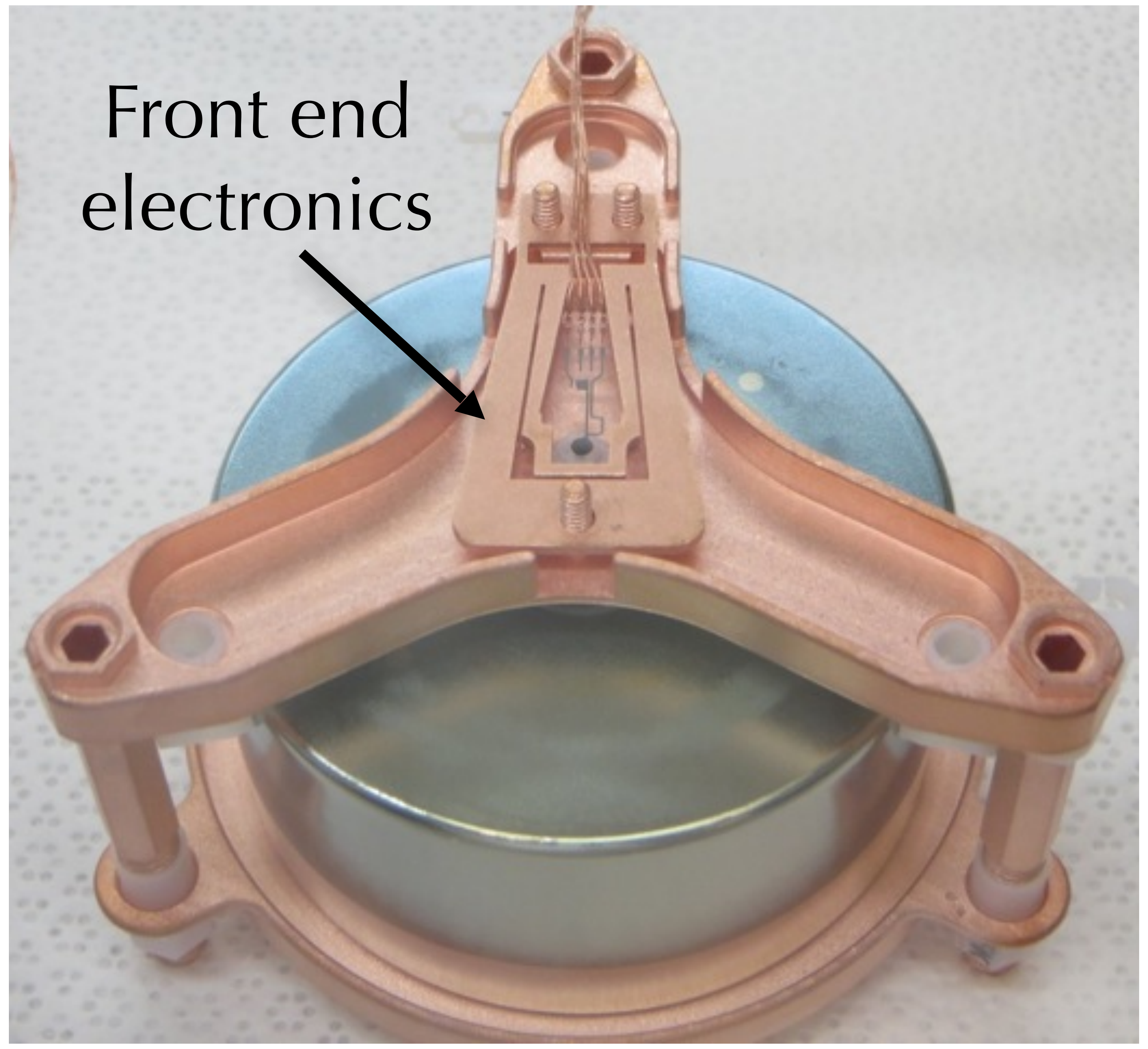
Evaluate effect on LEGEND

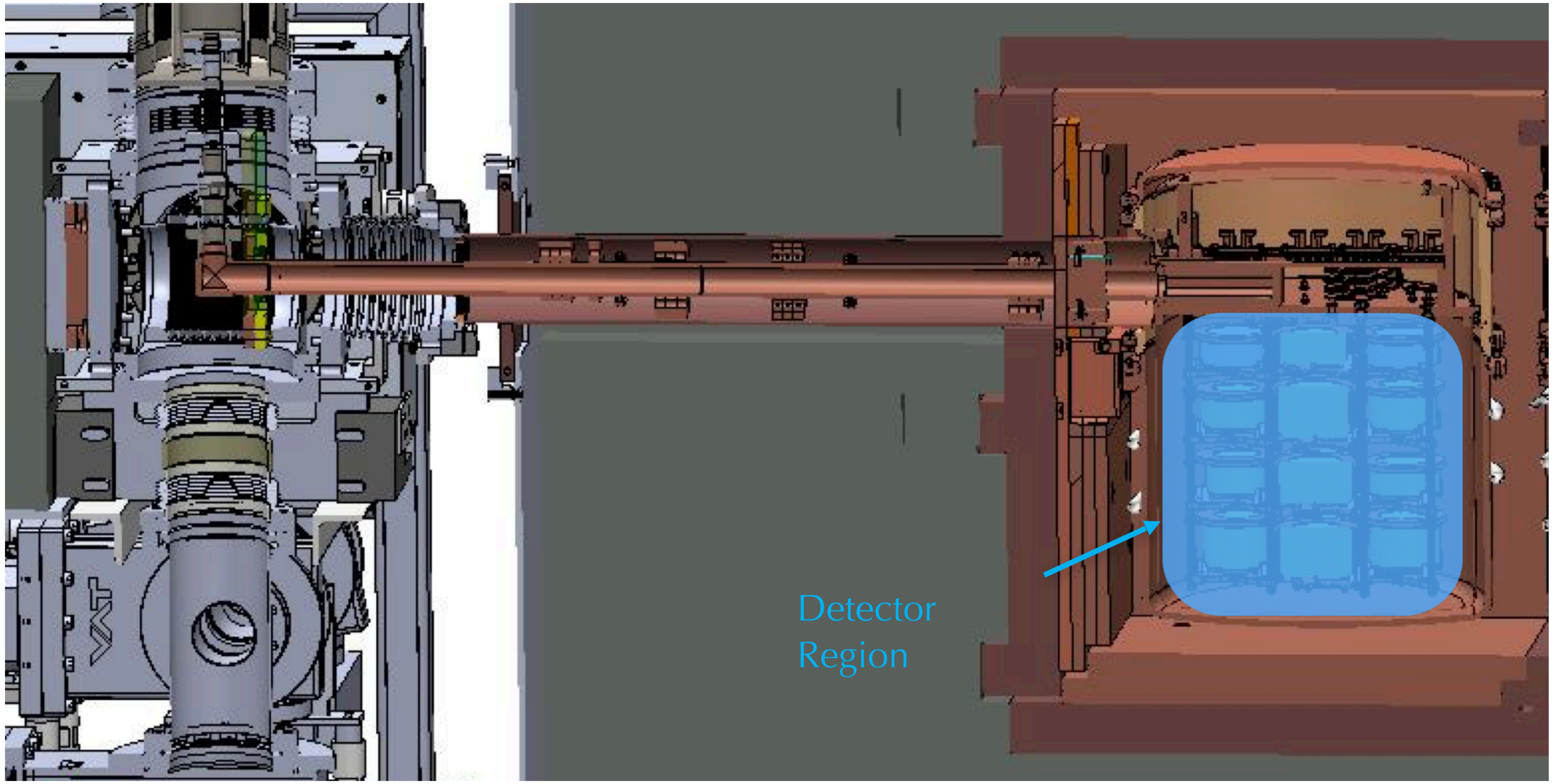
^{232}Th Excess Implications for LEGEND

LEGEND design builds on radiopurity of near-detector parts in MAJORANA

- Front end electronics
- Electroformed copper

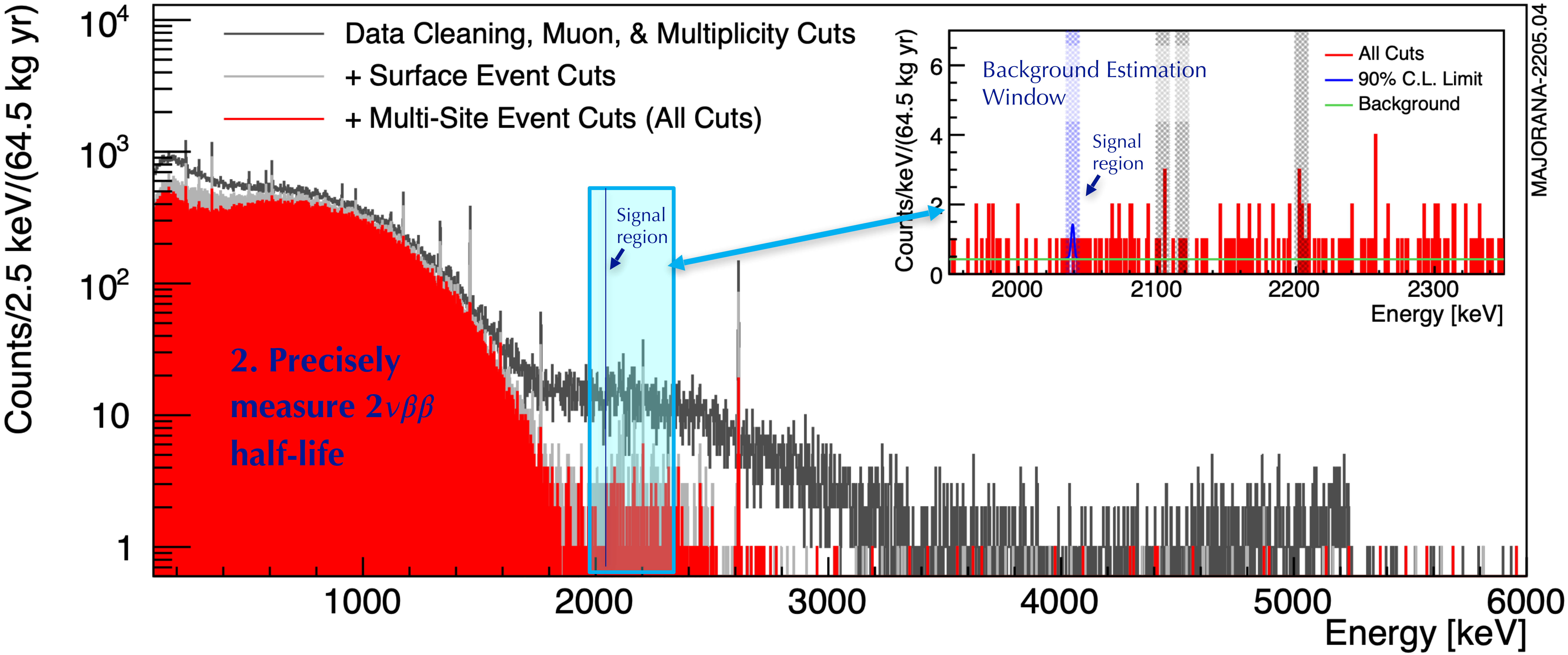
Radiopurity requirements are essential for near-detector components where LAr veto is less efficient





Determining how much of the DEMONSTRATOR's observed background excess originates in near-detector components has been critically important for LEGEND

Background Modeling Goals



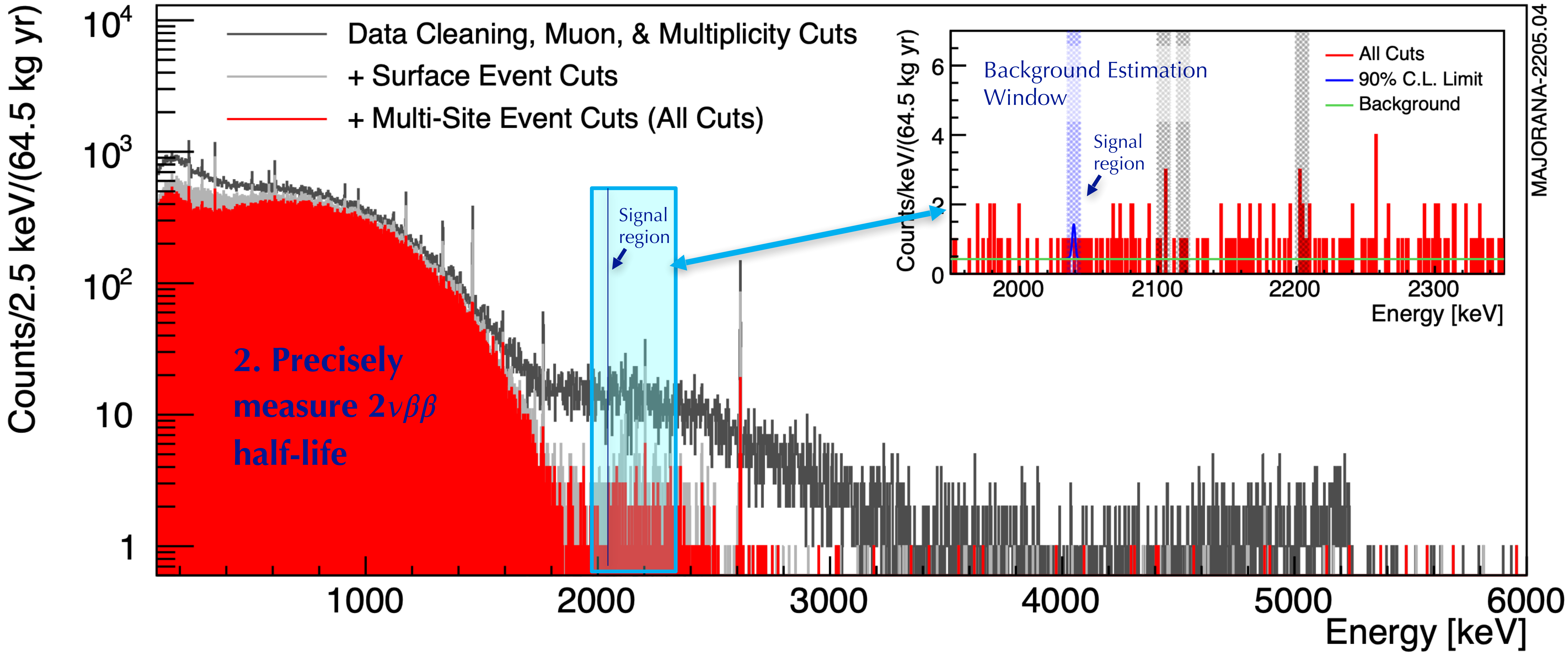
1. Locate source of background ^{232}Th excess

Evaluate effect on LEGEND

Background Modeling Goals

3. Model backgrounds across wide energy range for use in searches for BSM processes

Ex: deviations of the $2\nu\beta\beta$ spectral shape



1. Locate source of background ^{232}Th excess

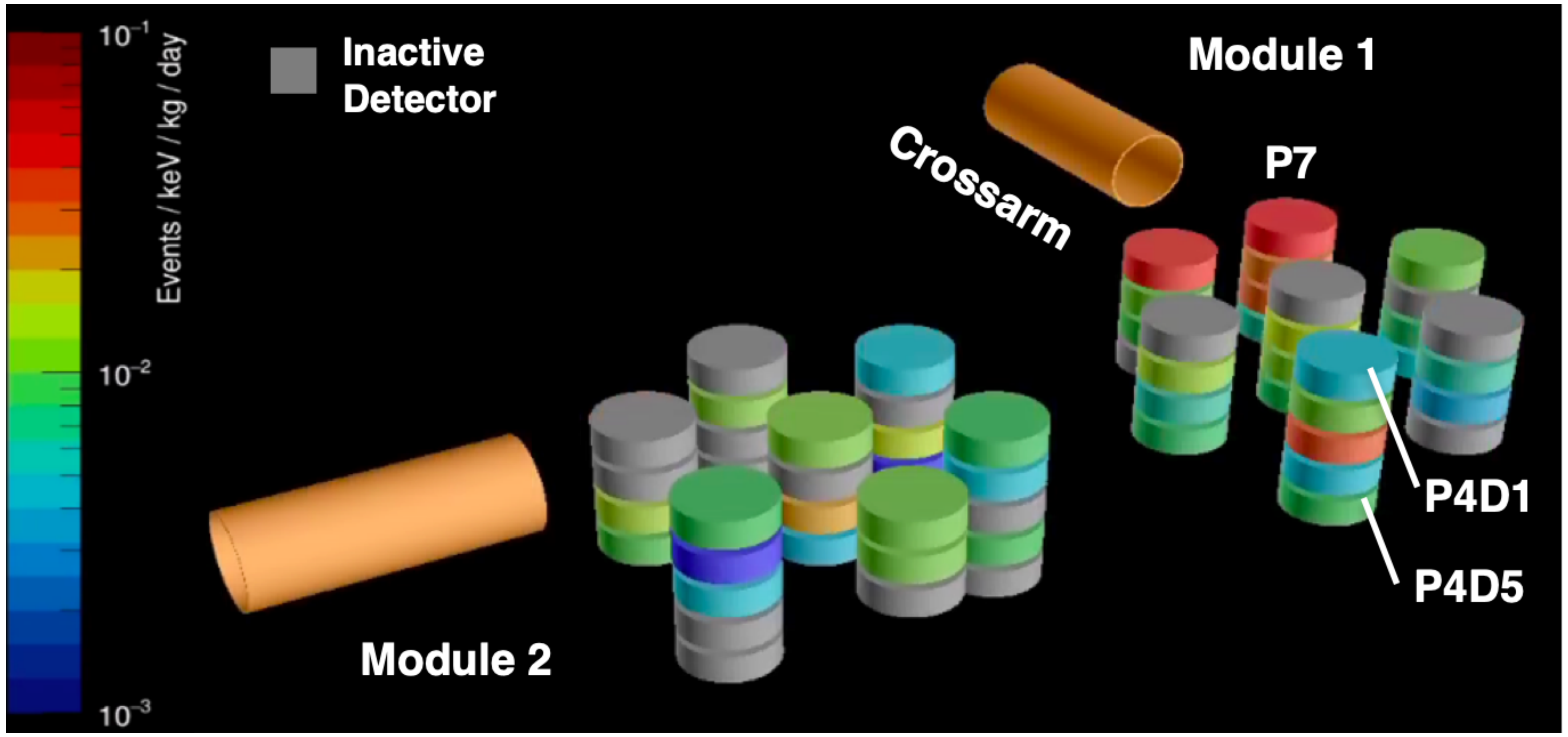
Evaluate effect on LEGEND

Spatial Non-Uniformity of Observed Backgrounds

Background Index for Enriched Detectors:

Module 1: 18.6 ± 1.8 cts/ (FWHM t yr)

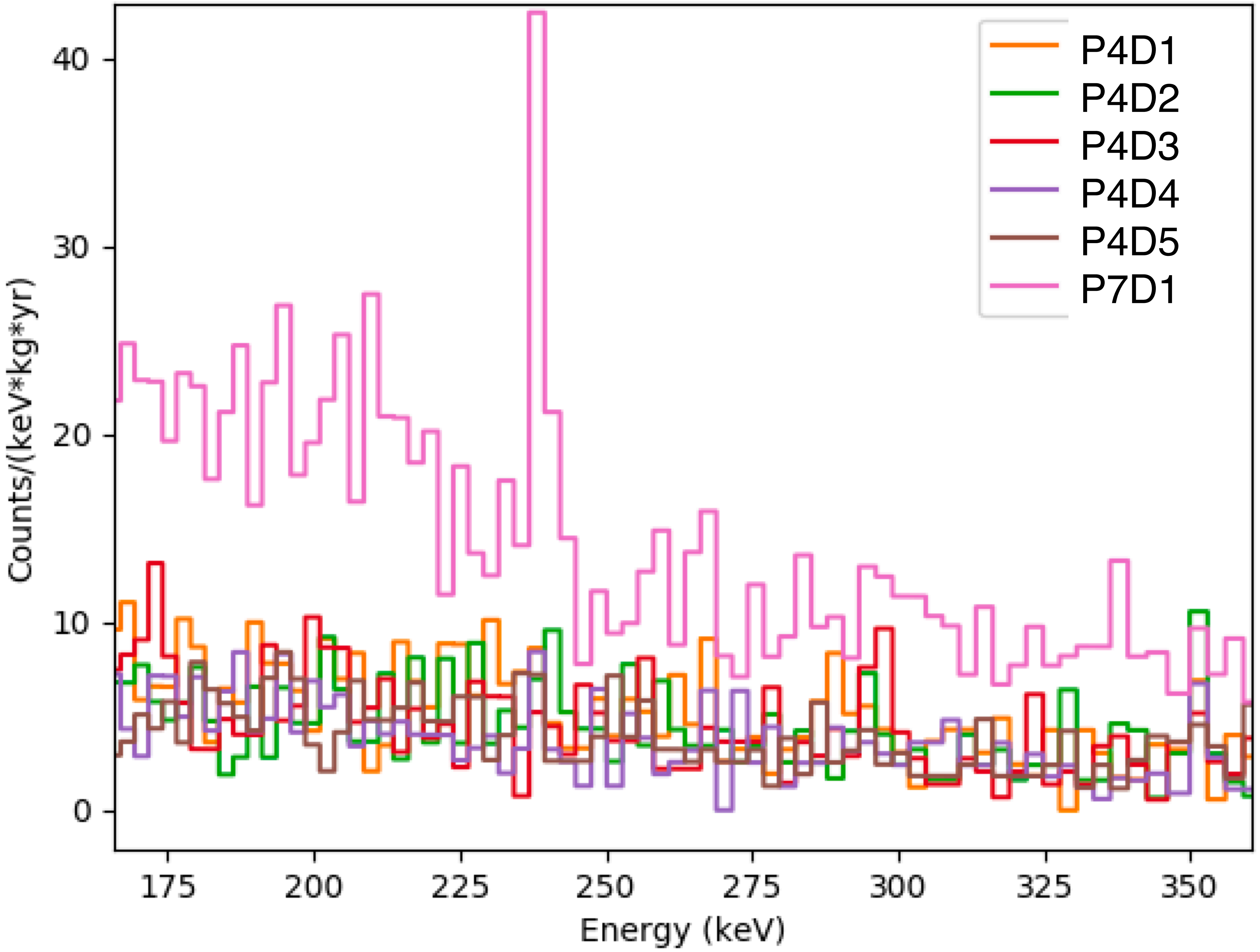
Module 2: $8.4^{+1.9}_{-1.7}$ cts/ (FWHM t yr)



2615 keV rate in datasets prior to upgrade*

***Excluding high background commissioning data**

238 keV ^{212}Pb Peak (from ^{232}Th Chain) in Module 1 Natural Detectors**



****One detector that was biased down early omitted due to low statistics**

Background originates near the crossarm region, separated from two hot detectors by a small amount of shielding

Strengthens conclusion from earlier studies that excess cannot be dominated by contamination uniformly distributed in a near-detector component group and is not a problem for LEGEND

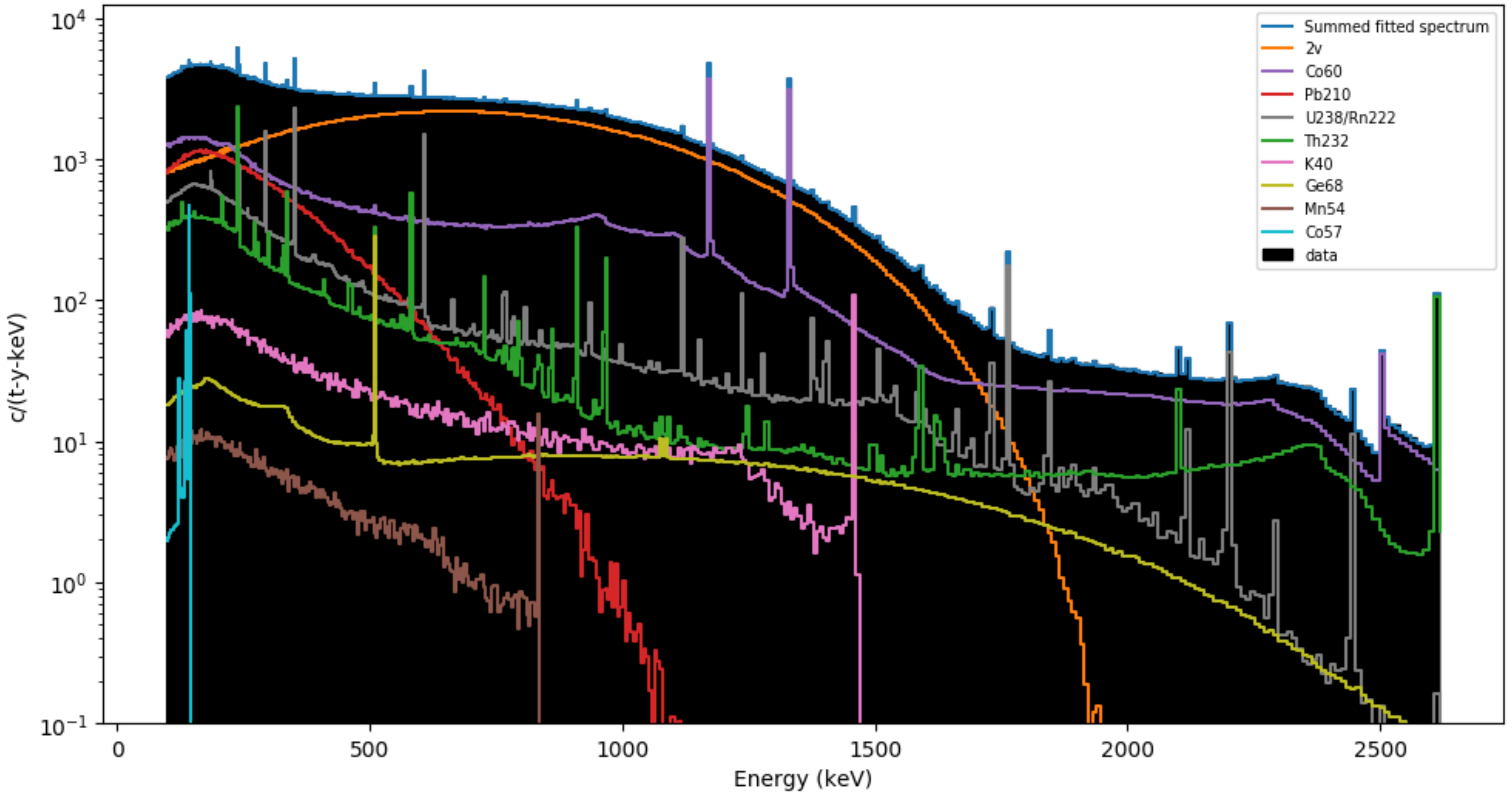
Spectral Fitting Algorithm

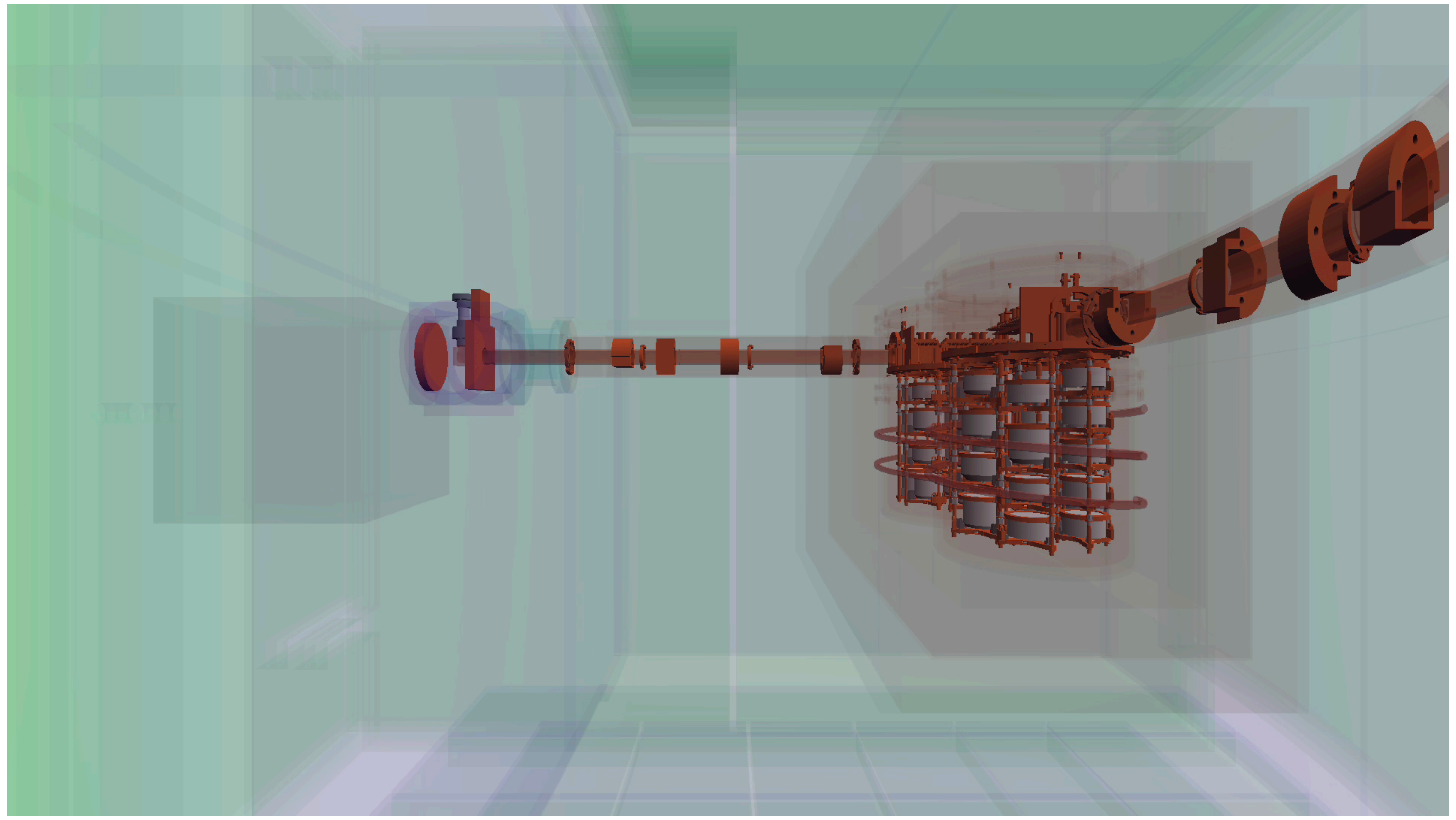
Simulation details

MaGe/Geant Monte Carlo simulations

- Approximately 4000 parts, combined into 27 component groups
- 9 decay chains or isotopes

- ^{76}Ge ($2\nu\beta\beta$)	- ^{57}Co	- ^{40}K
- ^{232}Th chain	- ^{68}Ge	- ^{60}Co
- ^{238}U chain	- ^{210}Pb	- ^{222}Rn





Frequentist fitting details

- Binned likelihood fits over a wide energy range (from 100 keV to above 2615 keV peak)
- Multiple spectra simultaneously fit
  - Detectors divided into groups based on module and enrichment
- ~100 activities floated during fits

Simulated Datasets

Does the fitting algorithm perform as expected?

How precisely can we measure the $2\nu\beta\beta$ half-life?

How precisely can we pinpoint origin of ^{232}Th excess?

How much are we limited by the low statistics of the DEMONSTRATOR?

Simulated datasets provide a testbed where "true" parameter values are known

To produce: data randomly sampled from model constructed from ~100 simulated spectra

Results:

High statistics simulated datasets

⬇

Validated algorithm performance

MAJORANA statistics simulated datasets

⬇

$2\nu\beta\beta$ half-life determined with <0.5% statistical uncertainty*

*Does not account for systematic effects

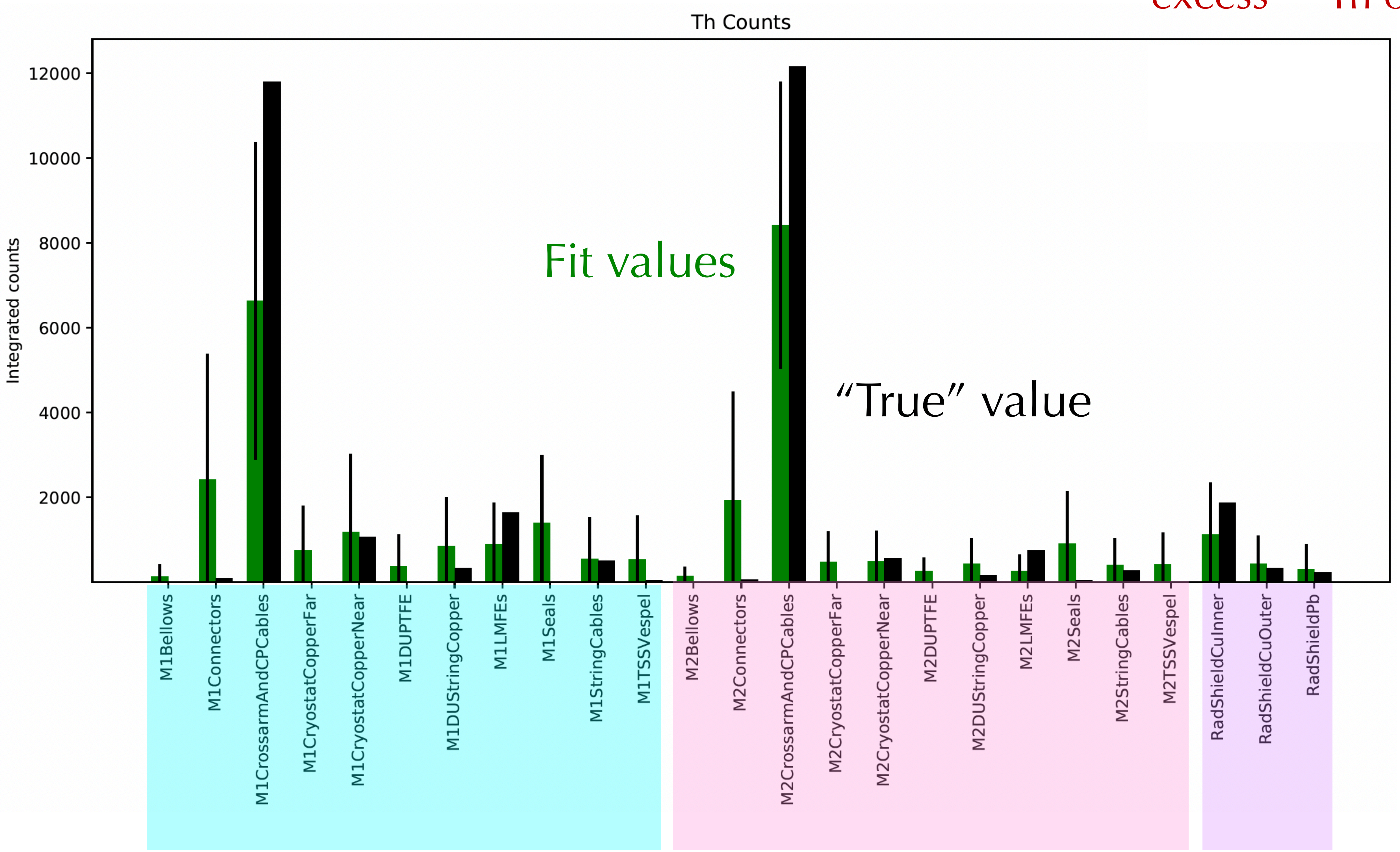
Statistical Limitations of Fitting

How precisely can we pinpoint origin of ^{232}Th excess?

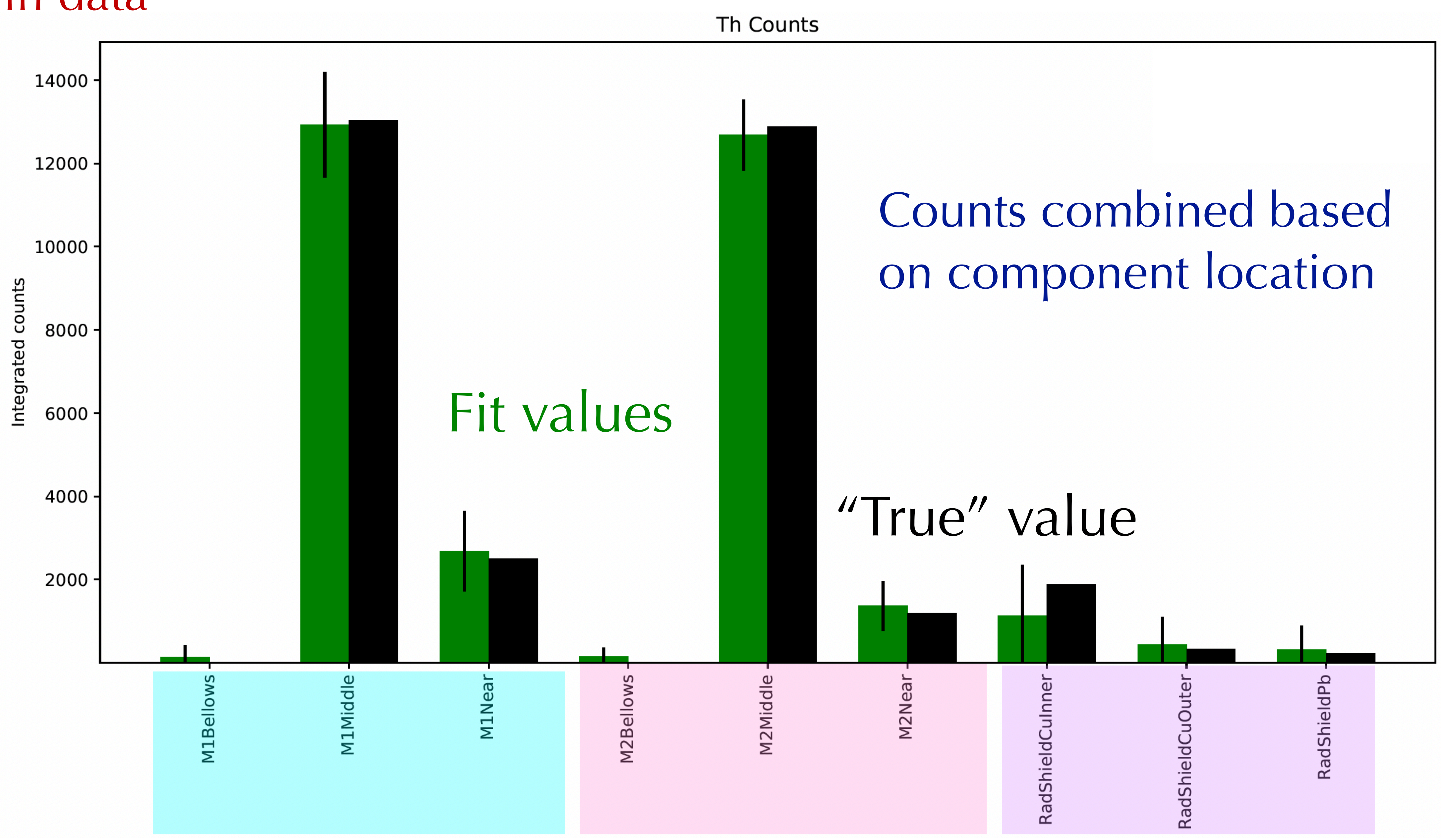
Tested with simulated datasets using approximately **the DEMONSTRATOR's true exposure**

How much are we limited by the low statistics of the DEMONSTRATOR?

Assuming 1-2 components responsible for excess ^{232}Th observed in data



Module 1 Components Module 2 Components Common



Module 1 Module 2 Common

50 fits to 50 simulated datasets with same parameters

- Central value based on mean
- Error bars based on standard deviation

Can determine region but not component responsible for excess

Fits to Subsets of Data

Data cleaning and some surface event cuts applied to data

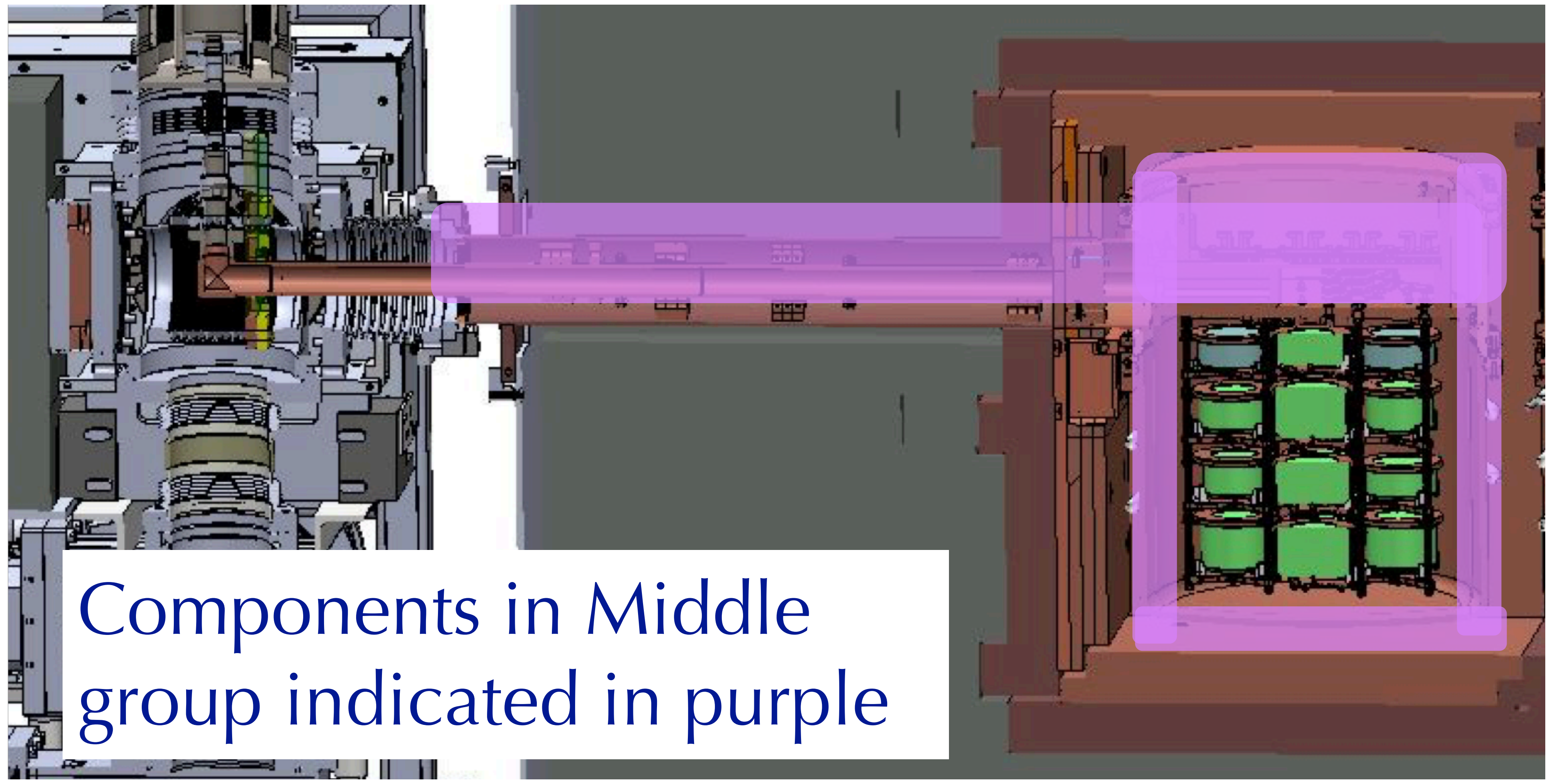
Fit to open data confirm earlier studies indicated that the source of the ^{232}Th excess **cannot be due to a uniform distribution in a component group within the detector array**

A contamination for a component in middle region would not pose a problem for LEGEND

Fits to be performed with final exposure to complete the background model

Systematics studies to fully quantify uncertainties

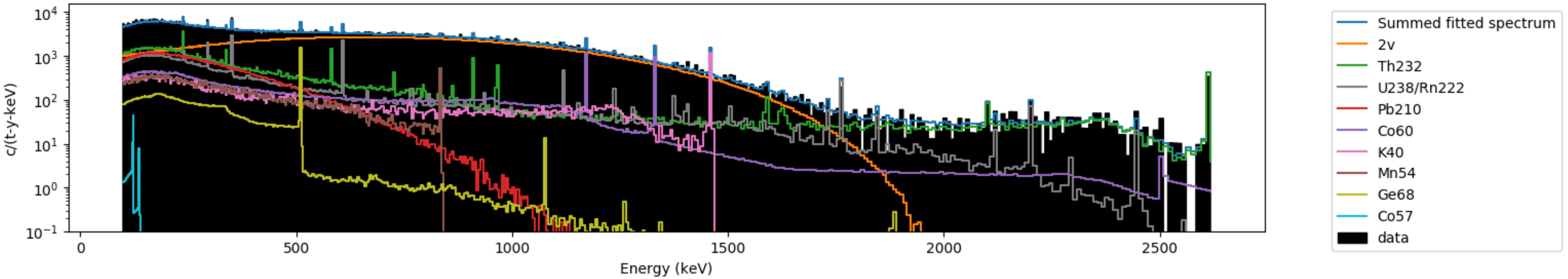
Ongoing assay measurements of components from suspect regions



Components in Middle group indicated in purple

Summary of Backgrounds

- The MAJORANA DEMONSTRATOR achieved the **second lowest background** of all neutrinoless double beta decay experiments but observed a significant **excess over assay-based projections**
- Background excess is due to **^{232}Th** decay chain and is **distributed non-uniformly** between the two modules, with an excess near the Module 1 crossarm region
- Spectral fits point to a ^{232}Th background **excess that does not originate within the detector array**
  - Background excess does **not pose a problem for the next-generation LEGEND-200** experiment, which uses similar materials near the detectors
- Working towards a final paper including fits with the DEMONSTRATOR's full exposure and evaluations of systematic uncertainties



Outline: Final Results and New Directions

Ian Guinn (UNC & TUNL)

- Overview of MAJORANA, and final neutrinoless double beta decay result

Anna Reine (UNC & TUNL)

- Studies of radioactive backgrounds and development of a full background model

Clint Wiseman (UW & CENPA)

- Search for beyond standard model physics, dark matter

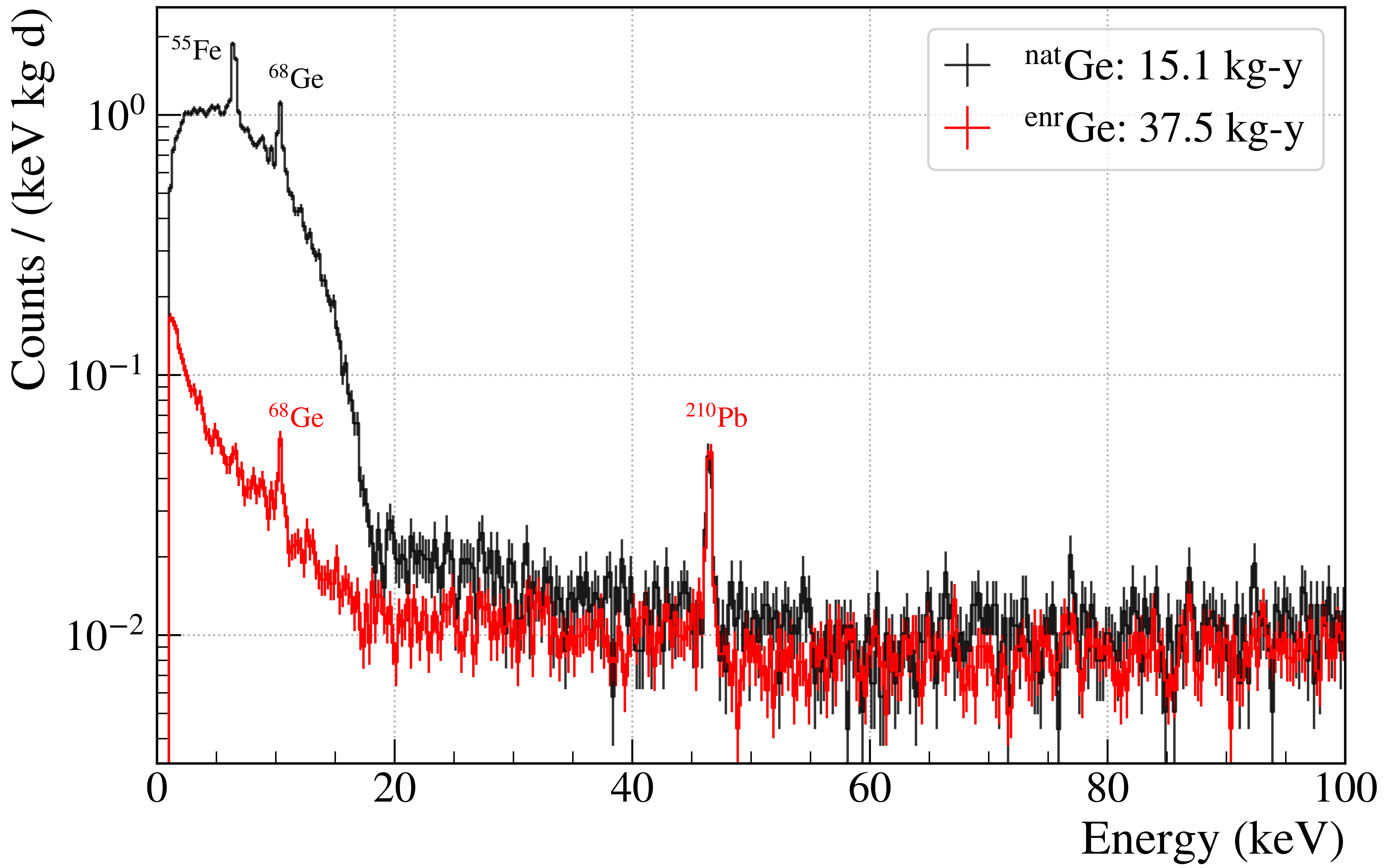
Ralph Massarczyk (LANL)

- First results from a search for the decay of nature's rarest isotope - Tantalum-180

The MAJORANA Low-Energy Program

The MAJORANA Low-E program is founded on four important aspects:

- Ultra-low backgrounds (0.01 cts/kev/kg-d at 20 keV)
- Substantial effort during design & construction to optimize electronics readouts
- Pre-MJ studies (MALBEK, CoGeNT) showing ways to reject surface event backgrounds
- Advanced data cleaning developed based on waveform fitting & wavelet denoising



We have opened up a **new frontier** in sensitivity to fundamental physics signatures in underground, low-background experiments!

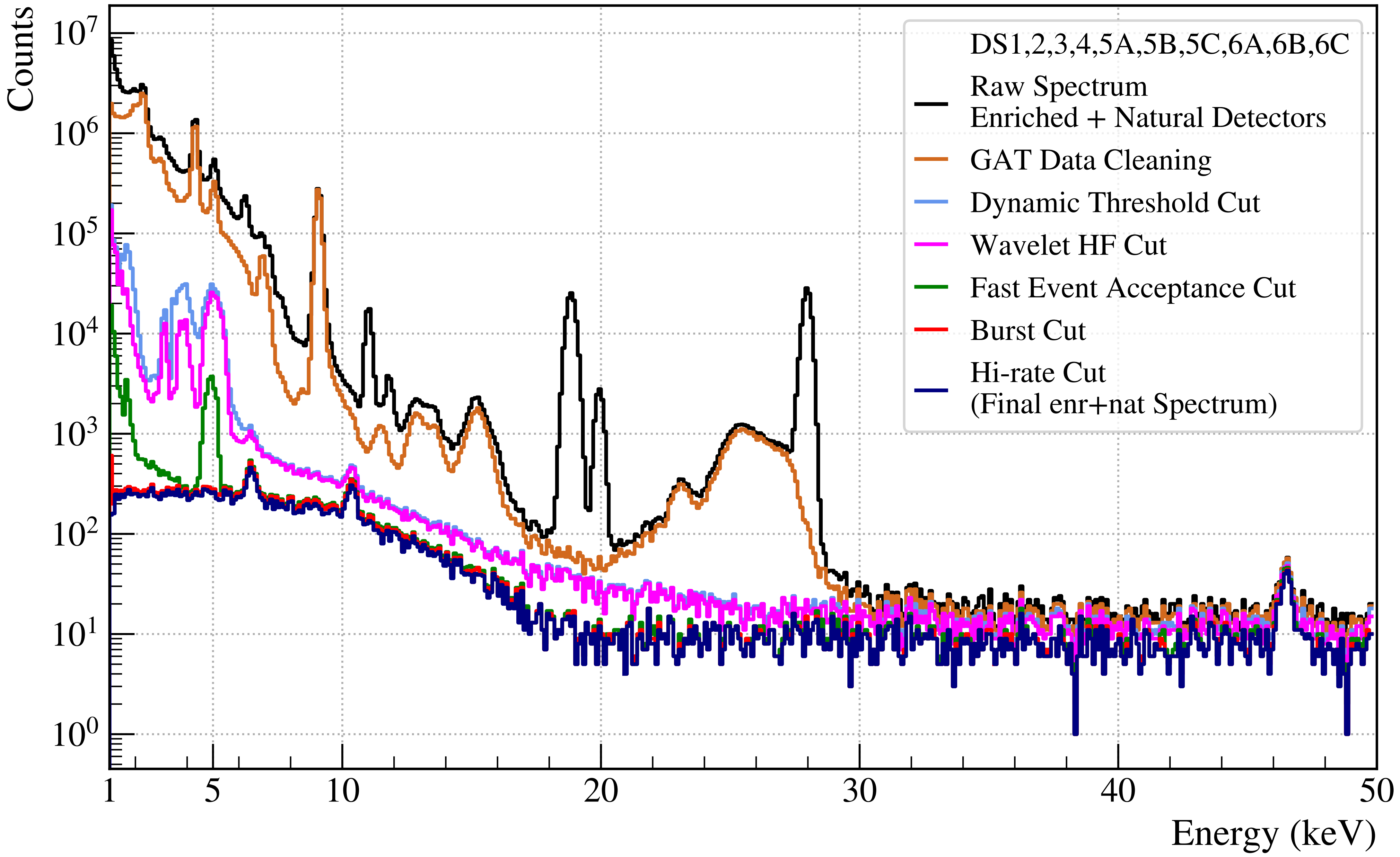
Cleaning up the data set

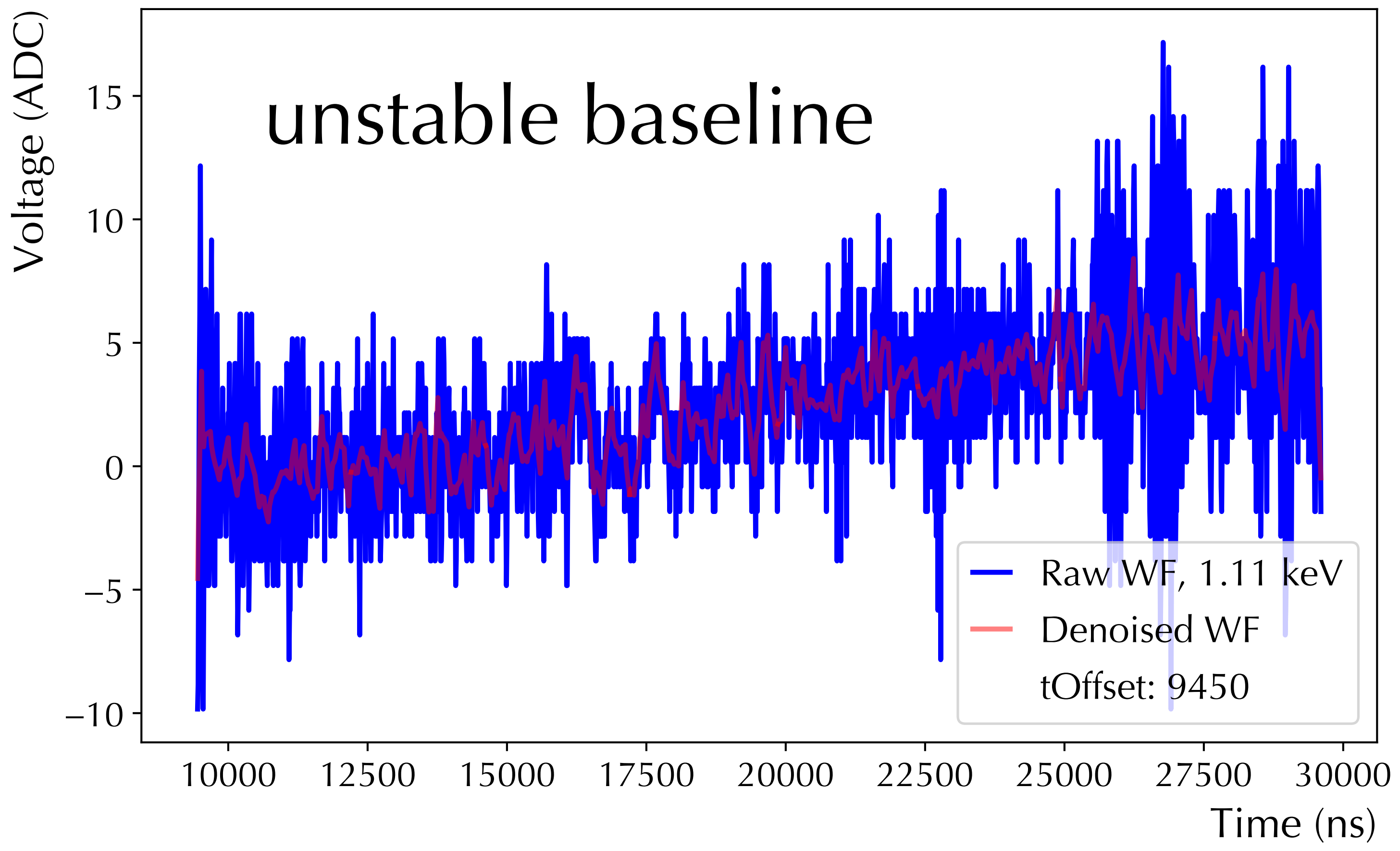
Advanced data cleaning techniques were applied: waveform fitting, wavelet denoising & more!

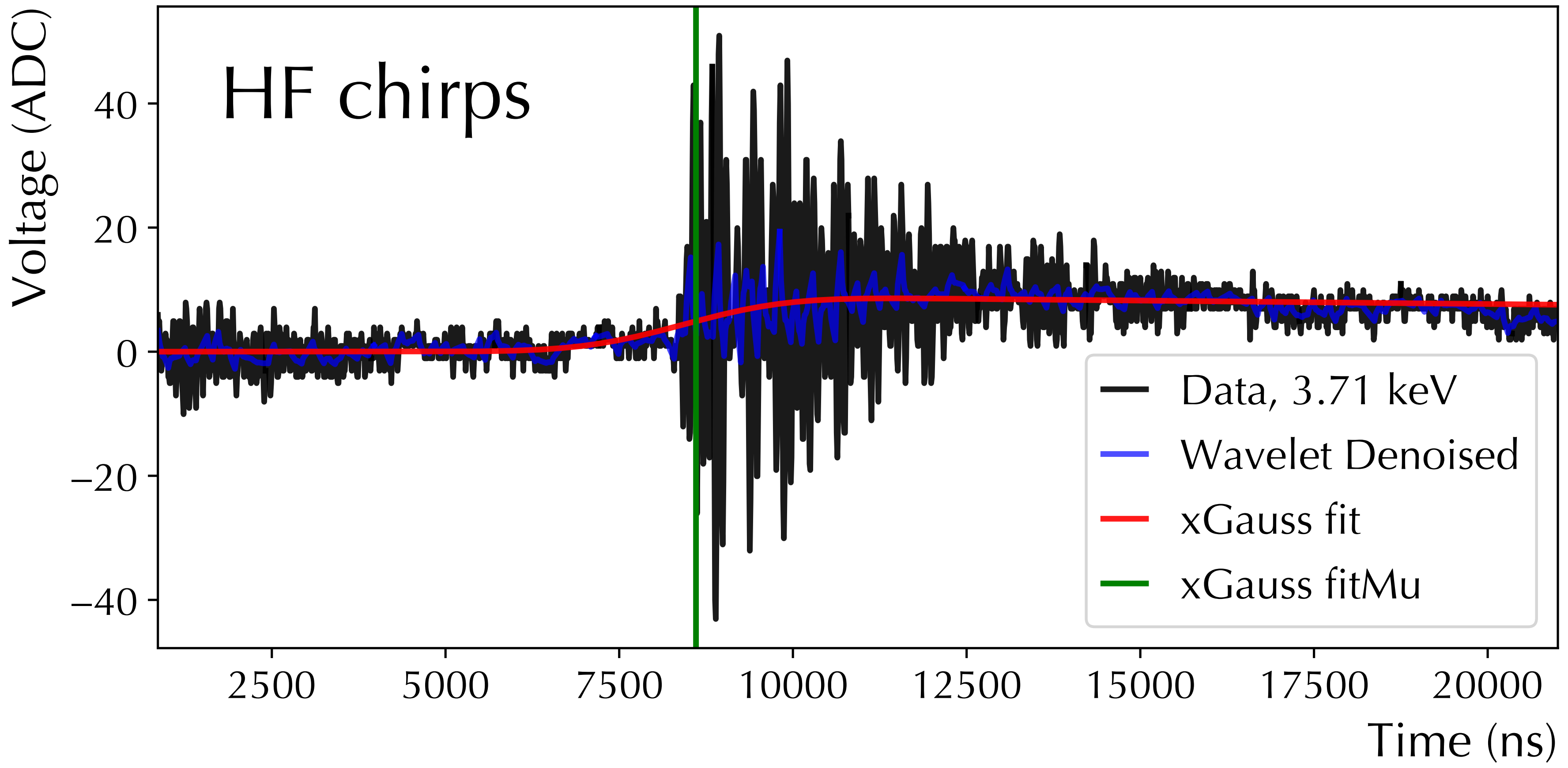
Data taking milestones for Low-Energy:

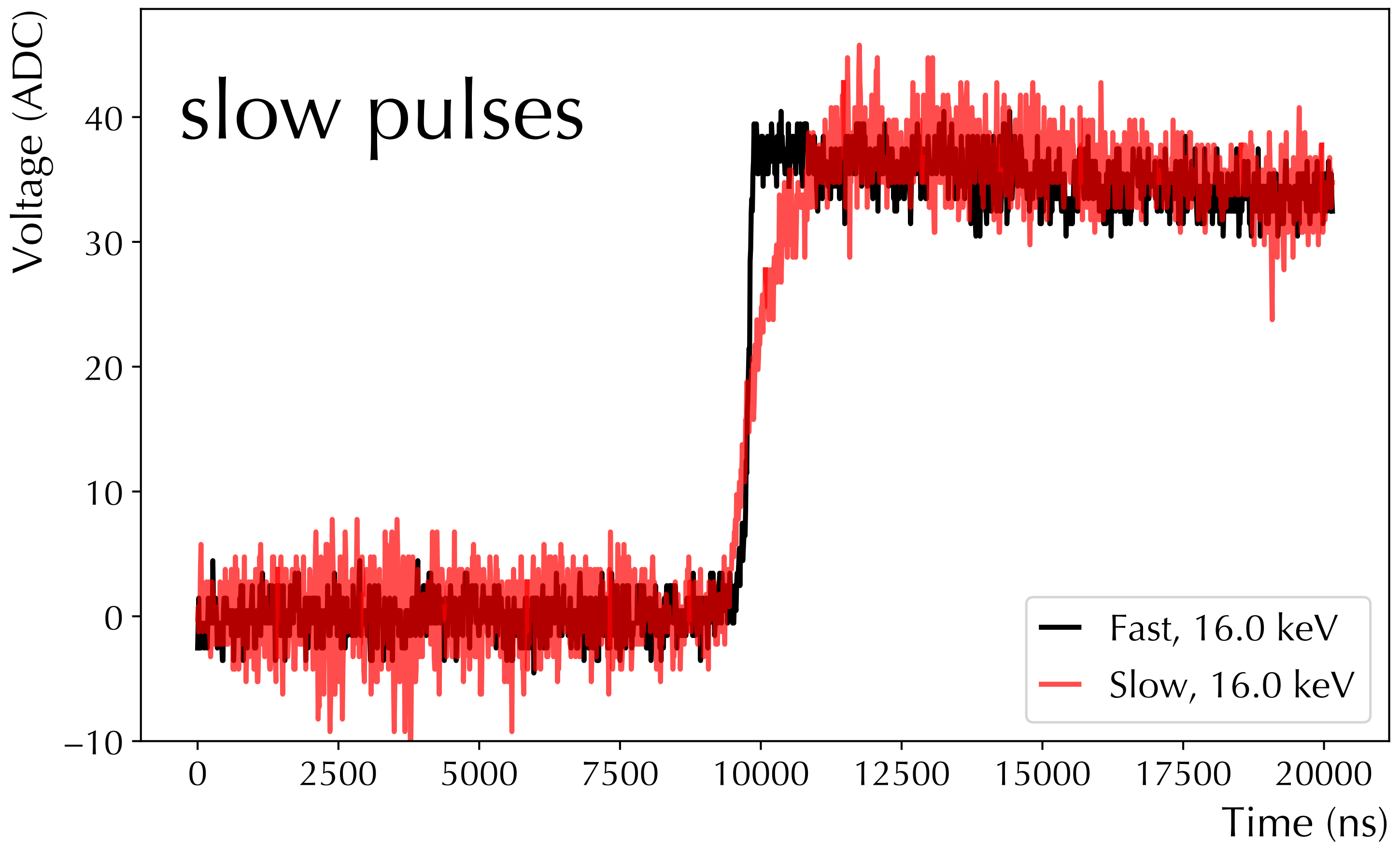
- **June 2015:** commissioning dataset taken
- **Nov 2019:** End of the “Low-E” data set (6C)
- **2021:** ^{enr}Ge detectors removed, ^{nat}Ge detectors running

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









“a rich and broad physics program”

Tests of Fundamental Symmetries and Conservation Laws

- Lepton number violation via neutrinoless double beta decay ($0\nu\beta\beta$)
  arXiv:2207.07638 (2022)
- $0\nu\beta\beta$ decay to excited states
  PRC **100** 025501 (2019)
- Baryon number violation
  PRD **99** 072004 (2019)
- Pauli Exclusion Principle violation
  arXiv:2203.02033 (2022)

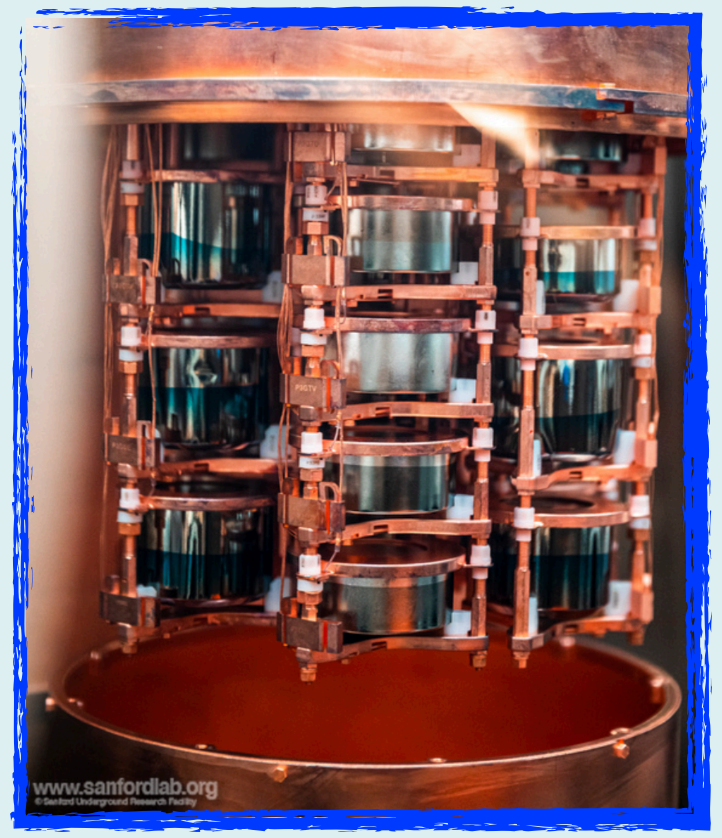
MAJORANA DEMONSTRATOR
Excellent energy performance,
and low backgrounds
in broad energy regions

Low-mass dark matter signatures

- Pseudoscalar (axionlike) dark matter
- Vector (dark photon) dark matter
  PRL **118** 161801 (2017)
- Fermionic dark matter
- Sterile neutrino dark matter
  arXiv:2206.10638 (2022)
- Primakoff solar axion
- 14.4-keV solar axion
  PRL **129** 081803 (2022)

Standard Model Physics, and particular backgrounds

- In situ cosmogenics
  PRC **103** 015501 (2021)
- (alpha, n) reactions
  PRC **105** 014617 (2022)
- Cosmic ray muons
  PRC **105** 064610 (2022)



Exotic Physics

- Quantum wavefunction collapse
  PRL **129** 080401 (2022)
- Lightly ionizing particles
  PRL **120** 211804 (2018)

“a rich and broad physics program”

On the Cover

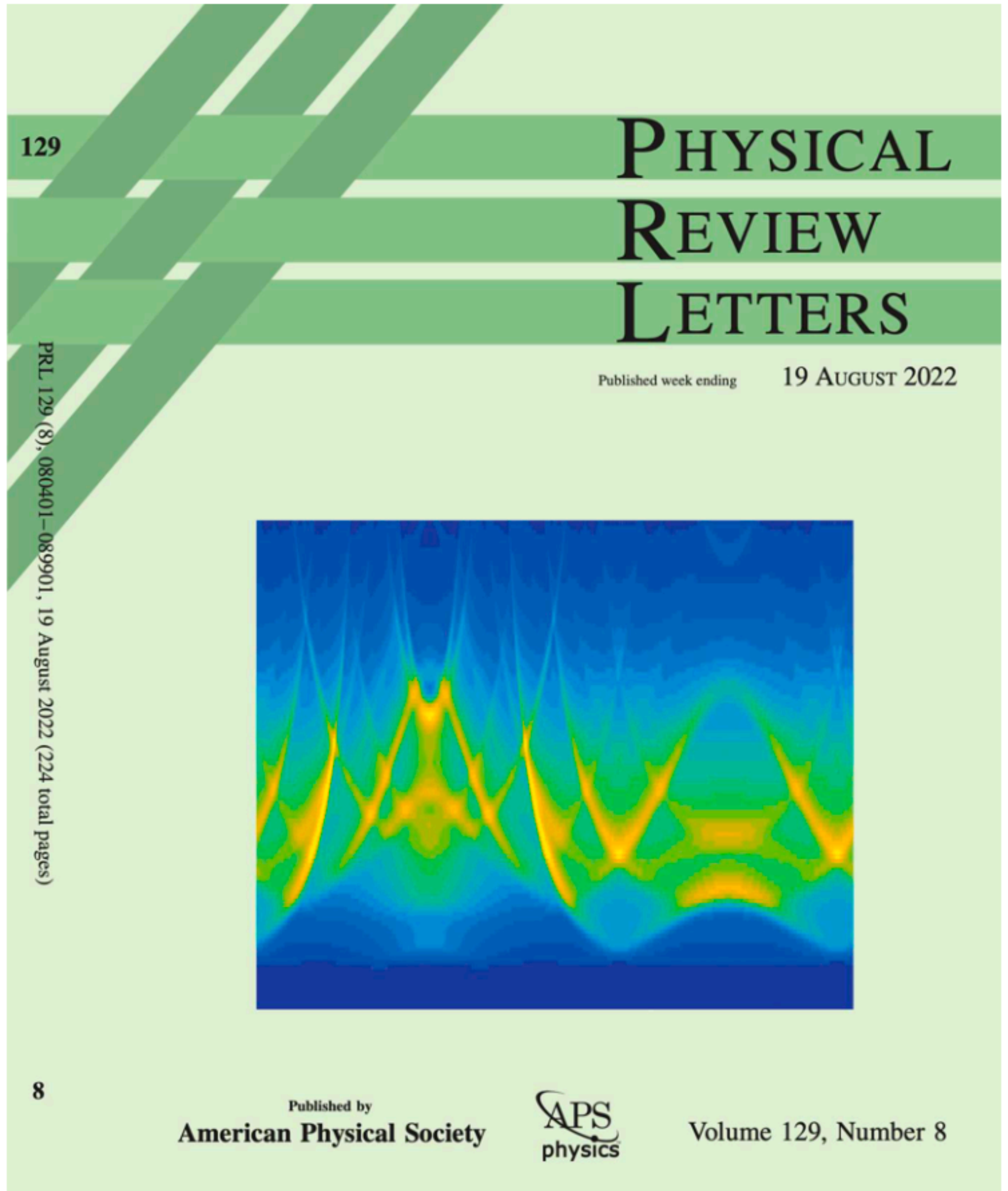
Axion signatures from coherent Primakoff-Bragg scattering over a 24-hour period.

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

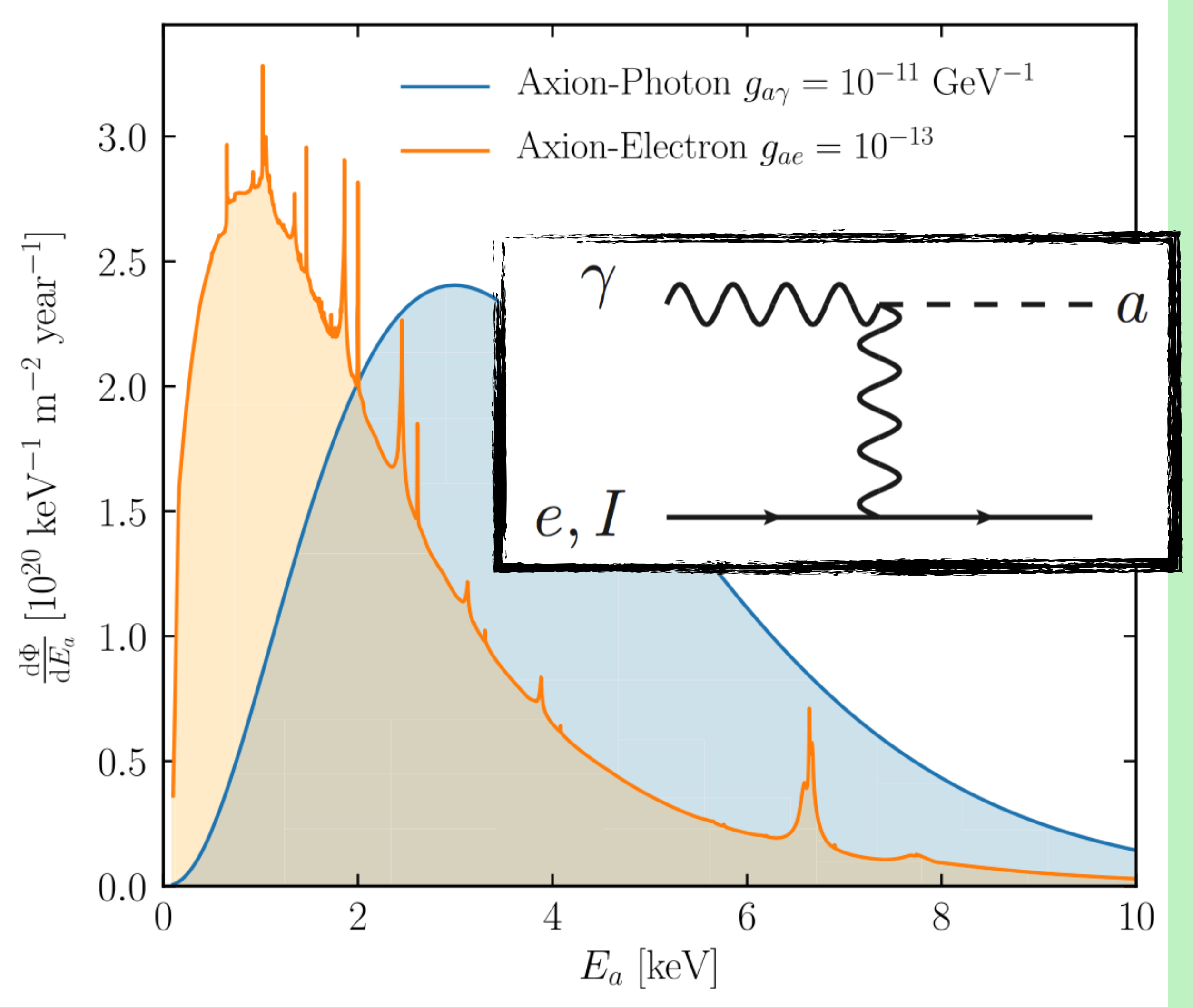
LNL PRES 841738 DRAFT

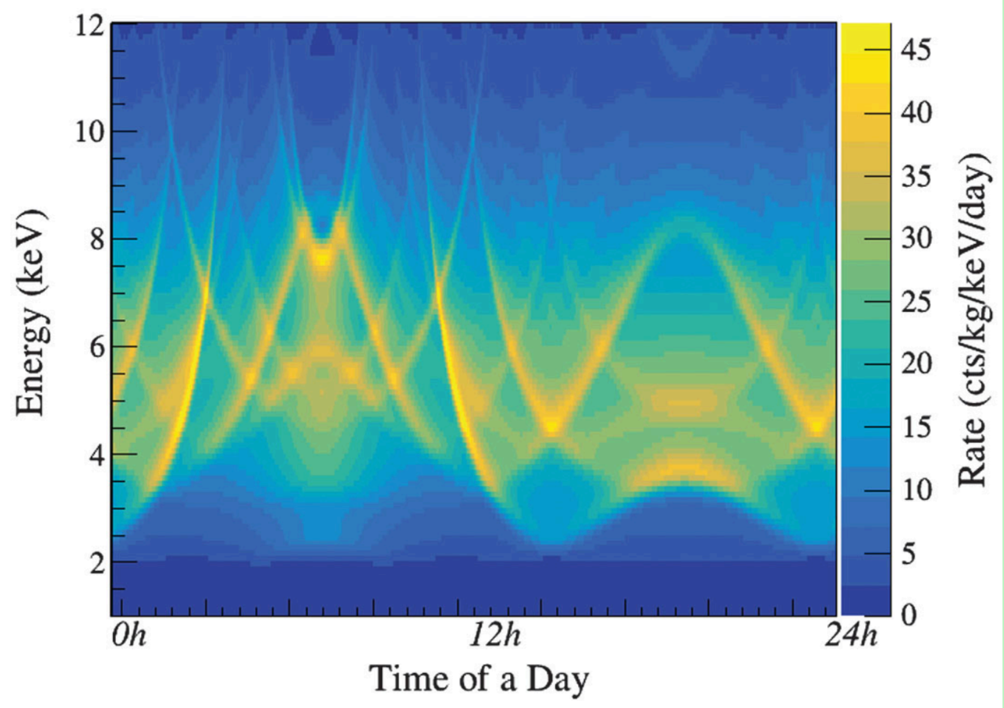
New limits on axion-gamma coupling

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 % 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

Solar Axion production & detection mechanism



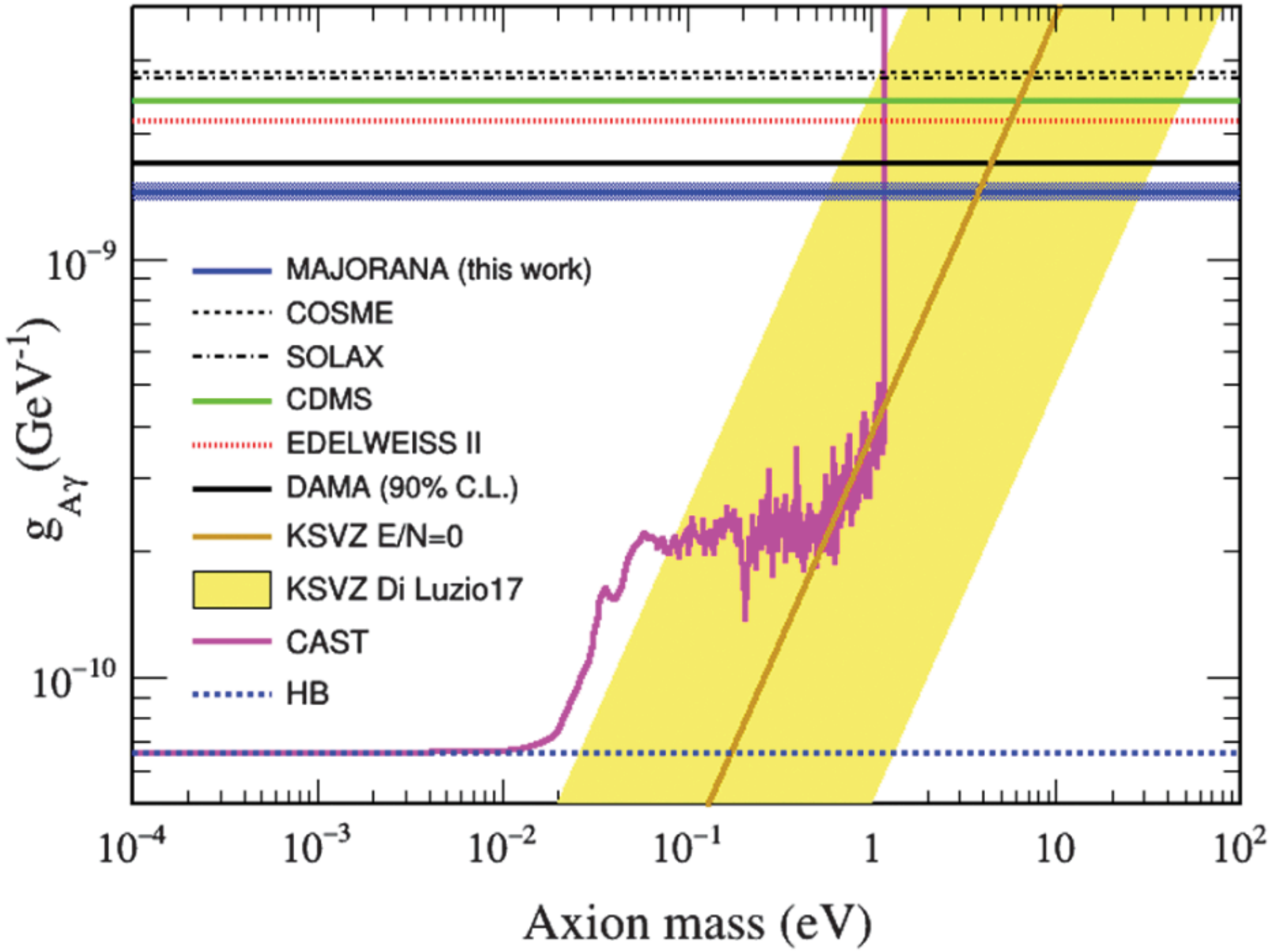


Highly time-dependent signal moves w/ crystal axes!

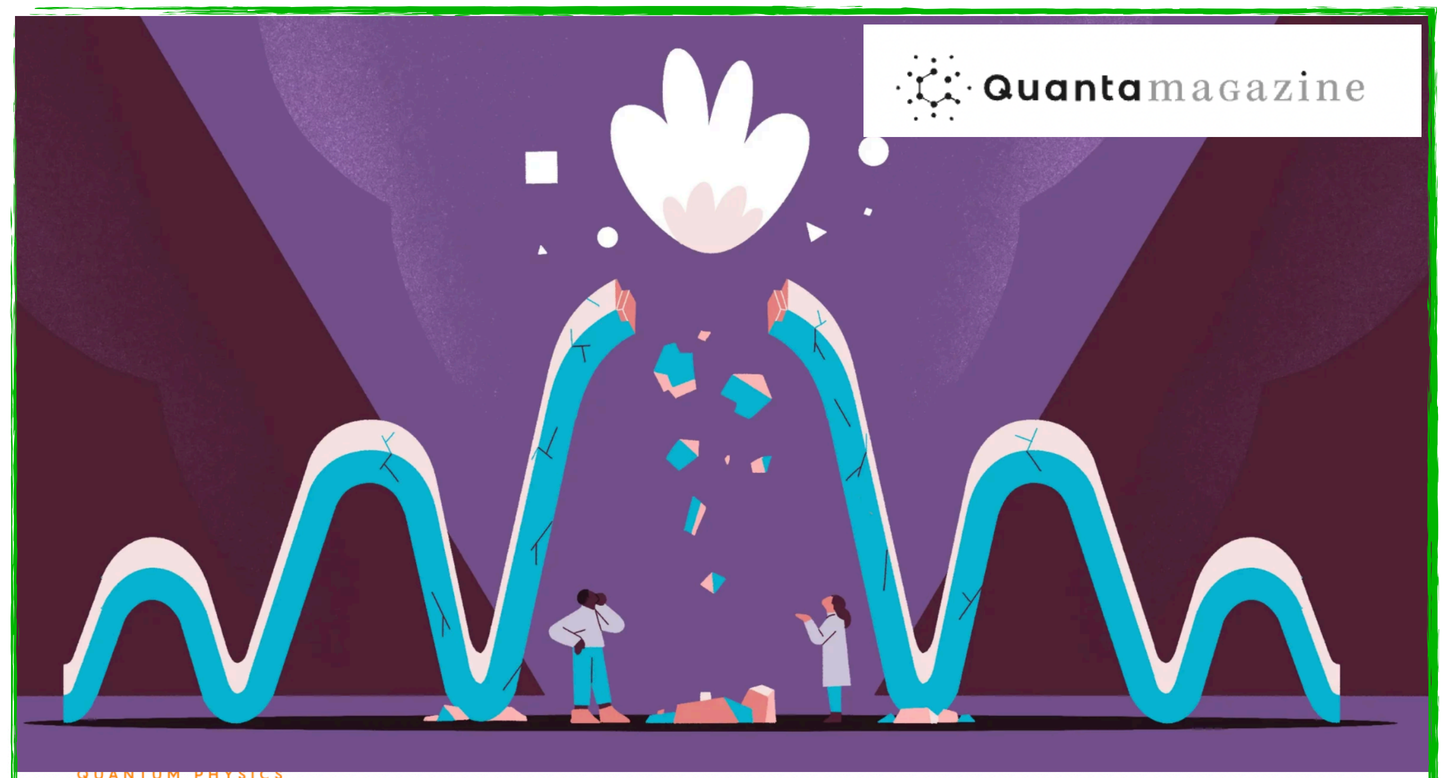
Production: Primakoff.
$\gamma + \gamma_{\mathrm{virtual}} \to a$

Detection: inverse Primakoff
$a + \gamma_{\mathrm{virtual}} \to \gamma$

PRL 129 081803 (2022)



Search for wave function collapse PRL 129 080401 (2022)



QUANTUM PHYSICS

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.

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 >

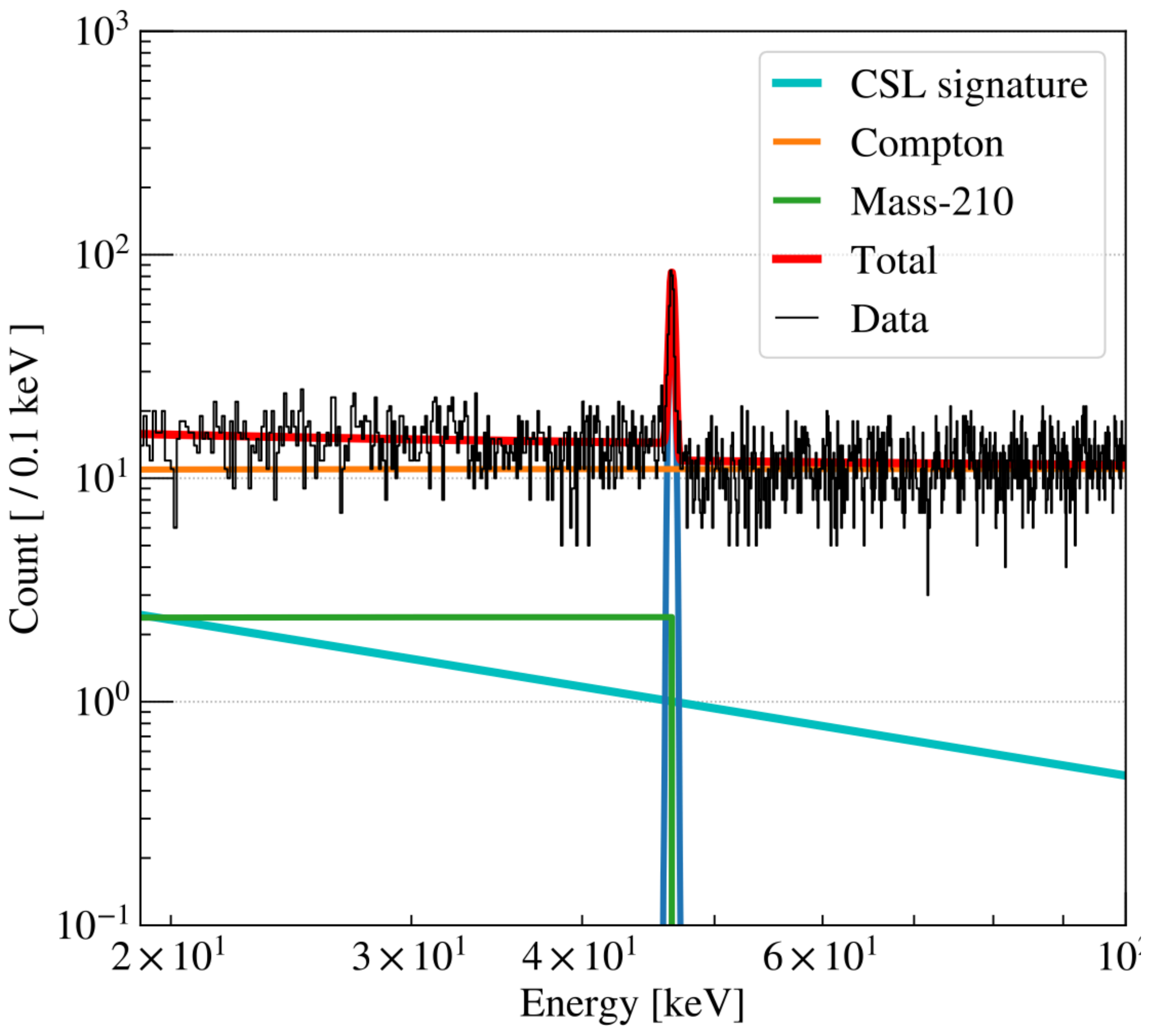
Physics Today **75**, 7, 62 (2022); https://doi.org/10.1063/PT.3.5046

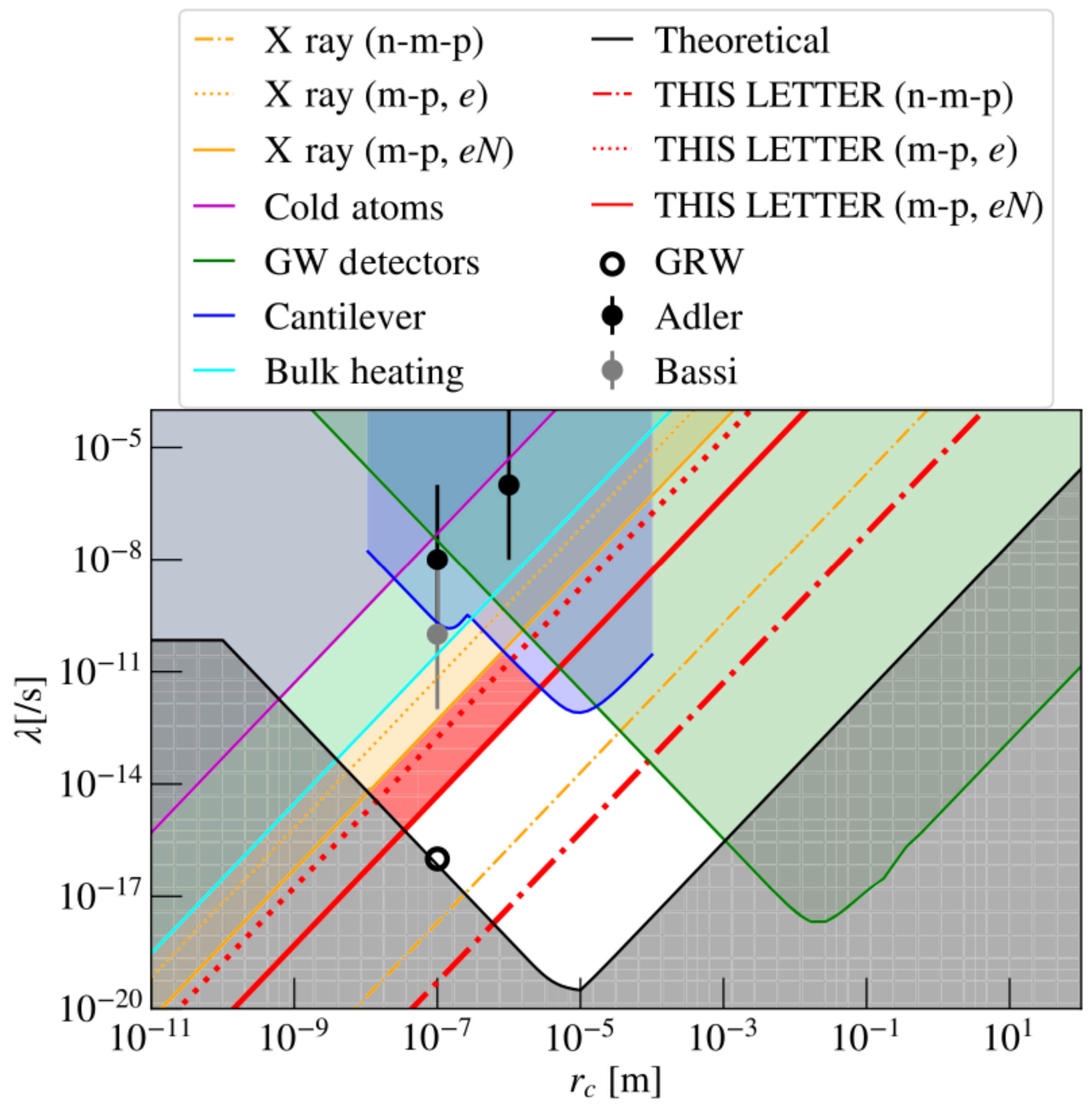
Where is the border between the microscopic and macroscopic worlds?

- 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 WFC:

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

λ : collapse rate

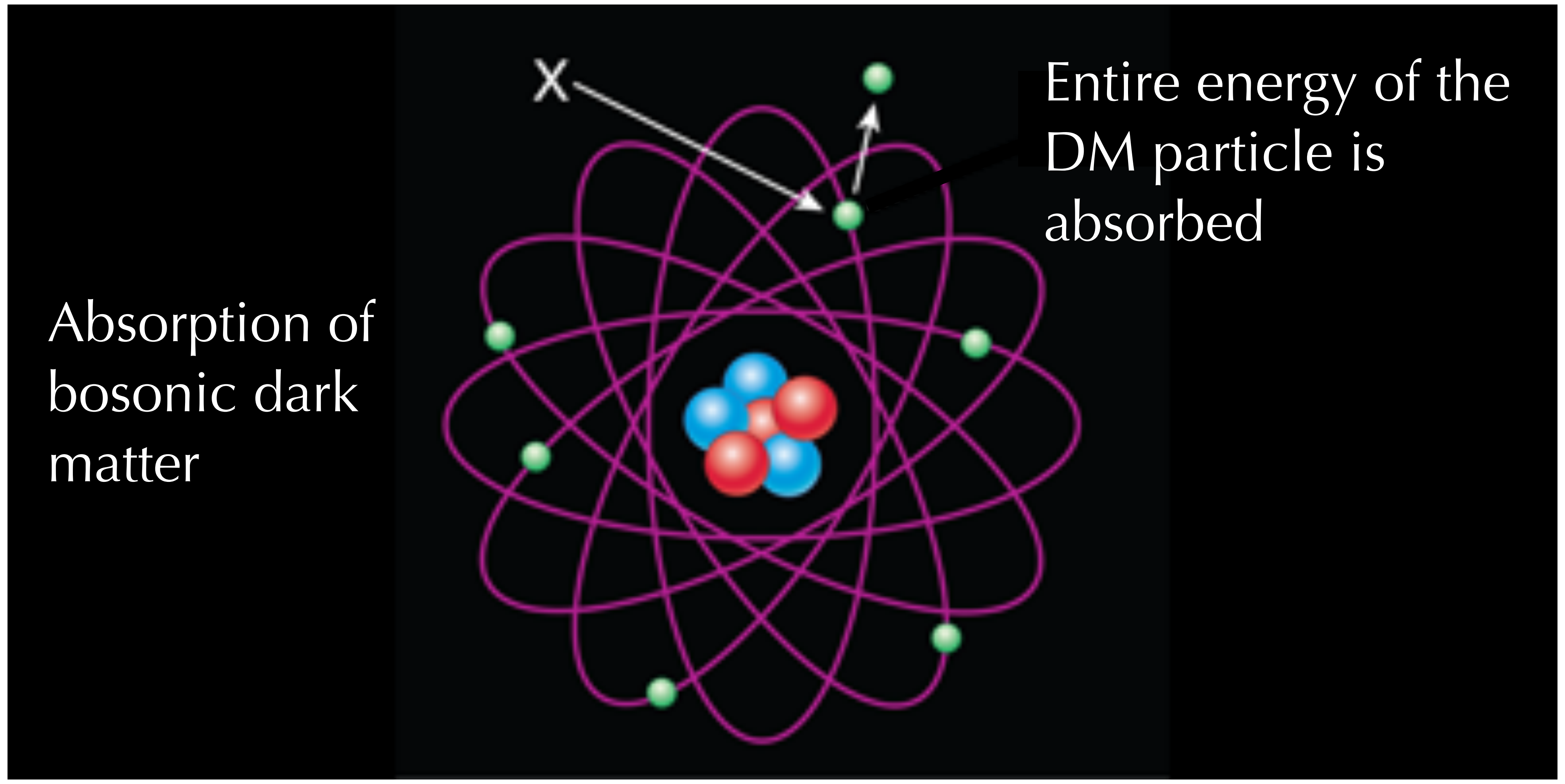
r_C : correlated radius

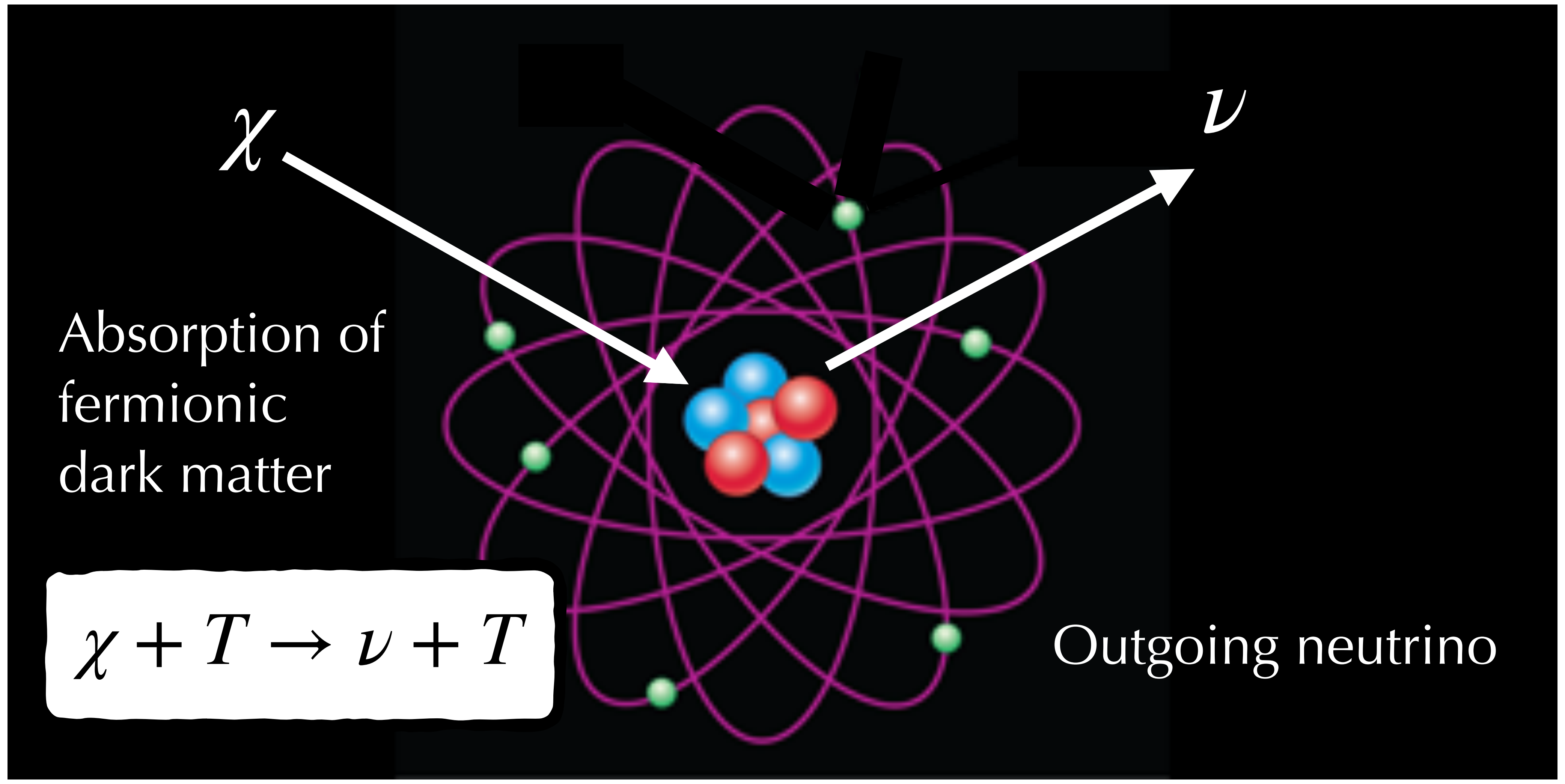
$1/E$: spectral shape

MAJORANA improves previous limits by orders of magnitude!

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

Search for rare peaks & exotic dark matter

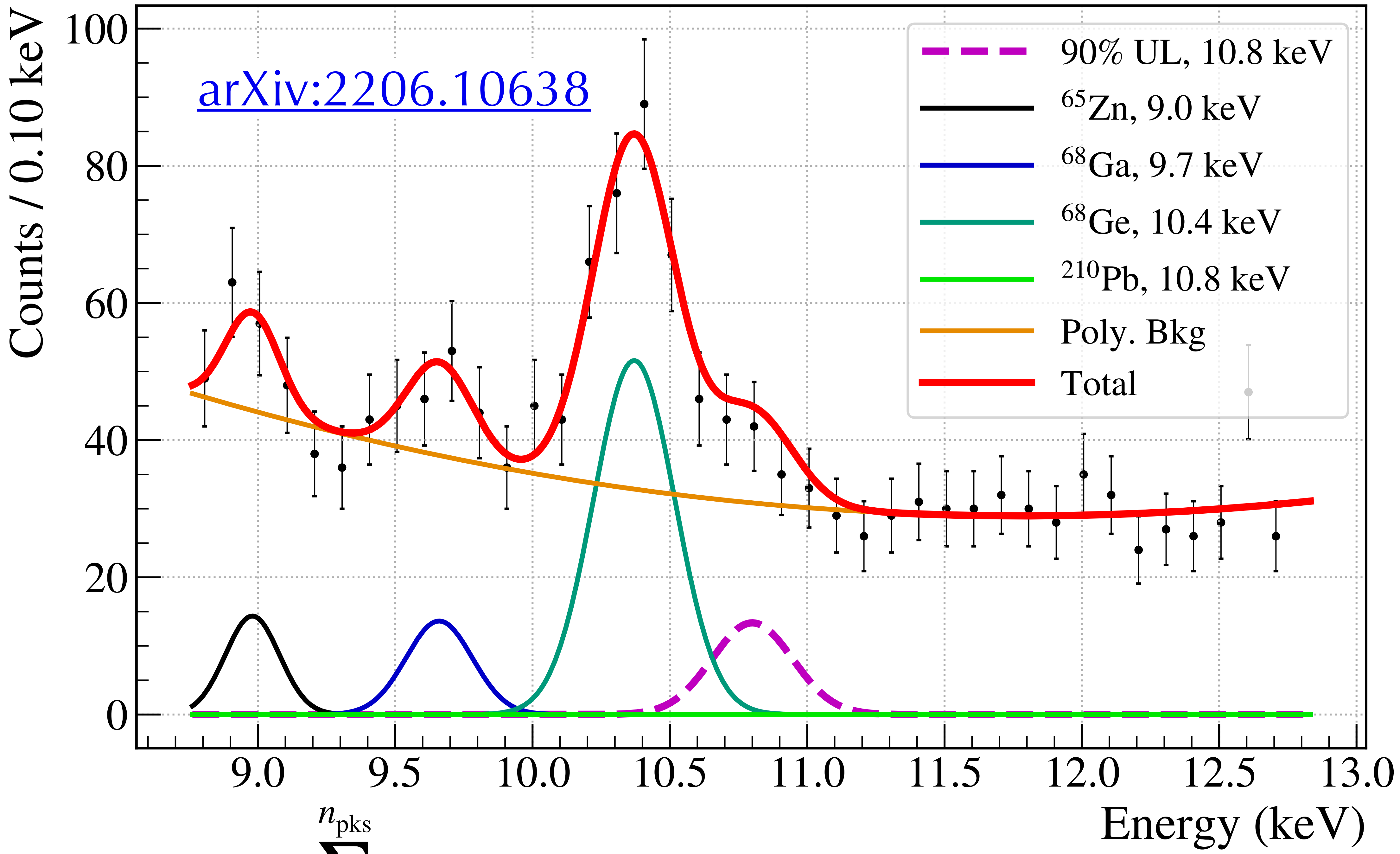




Adapted from APS / [Carin Cain]

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.

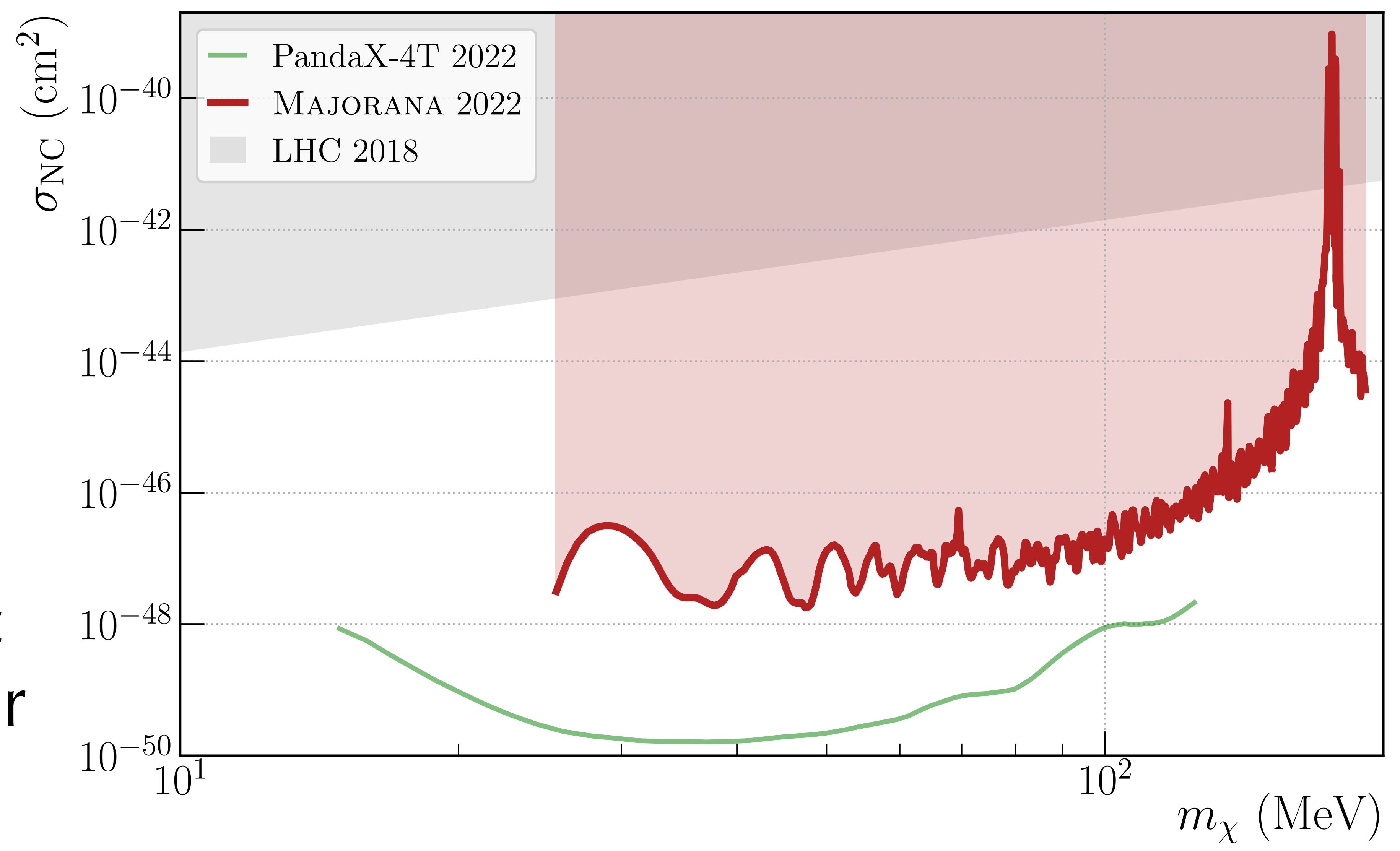


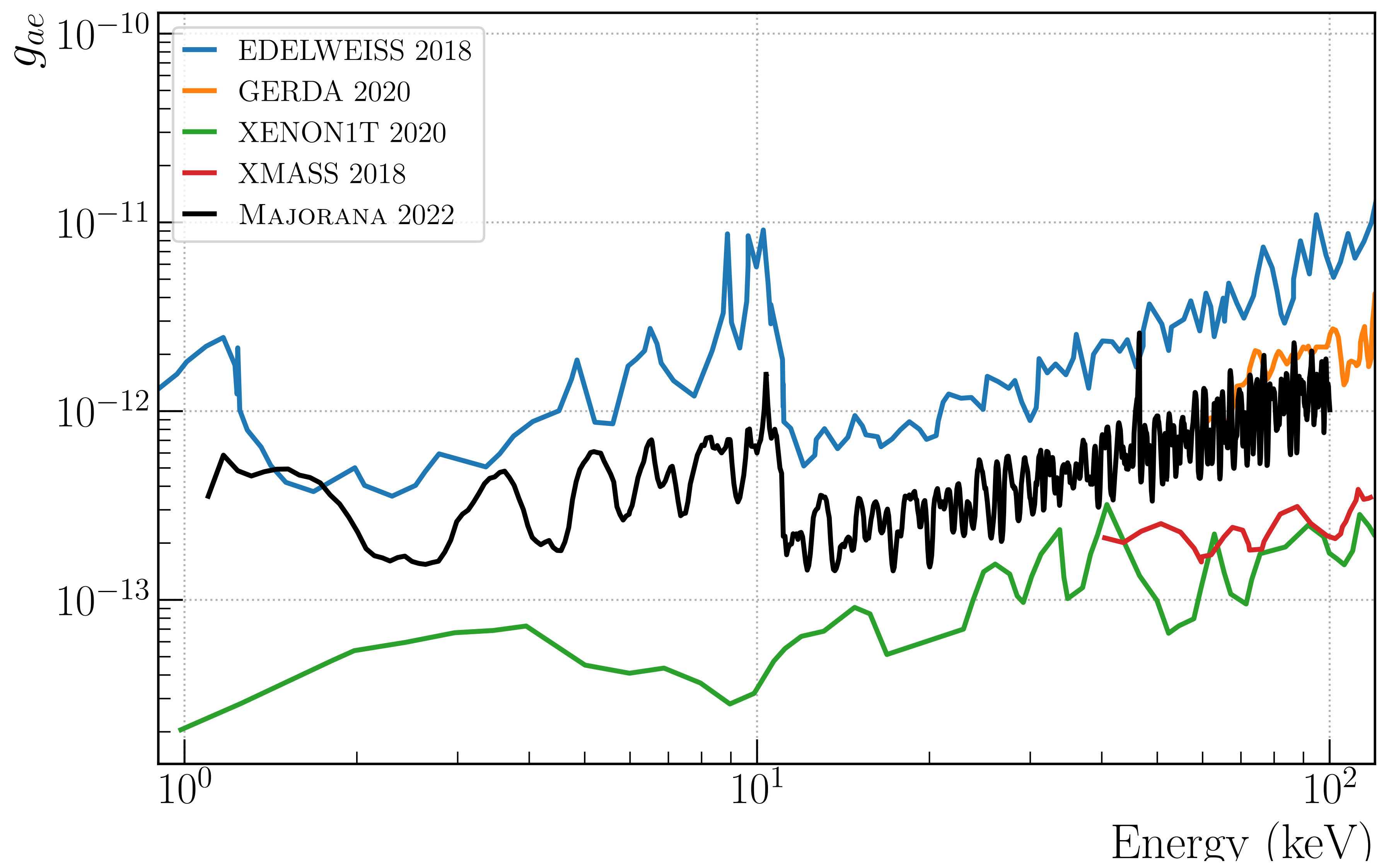
$$P(E_i) = n_0 P_{\text{pol2}} + \sum^{n_{\text{pks}}} n_i P_{G,i} + N_U P_{\text{DM}}$$

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

Results from exotic DM search

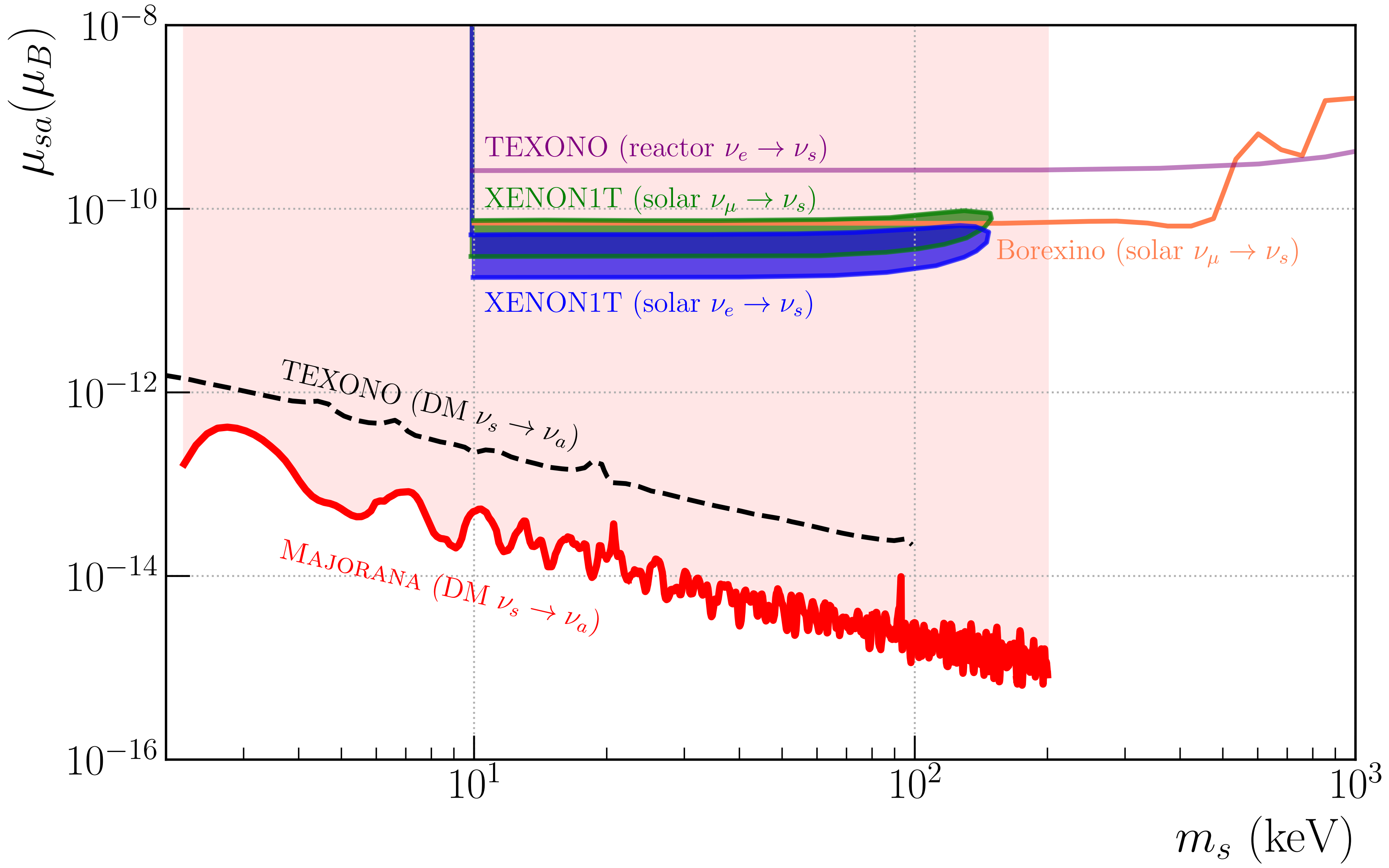
Fermionic dark matter

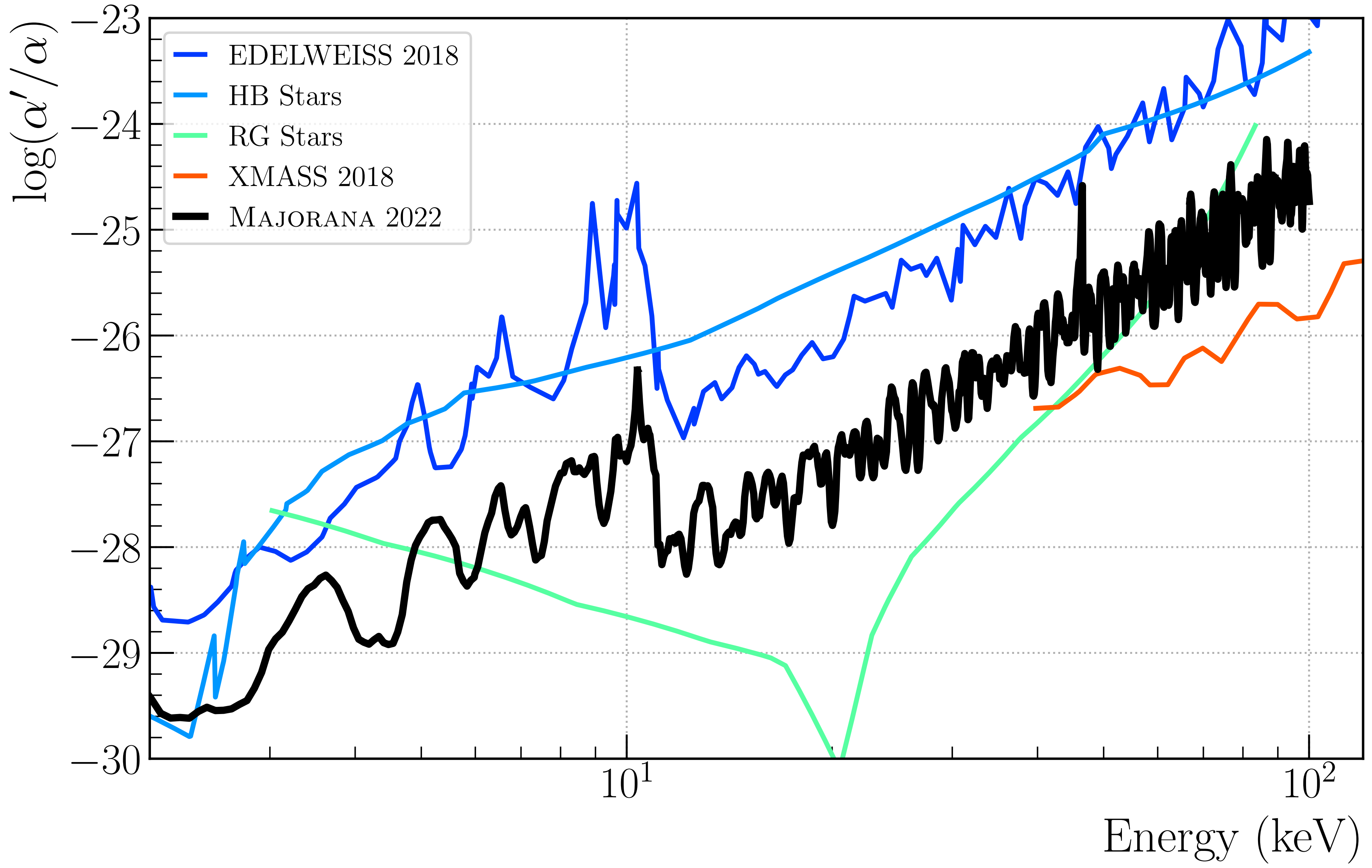




Bosonic dark matter, pseudoscalar (axionlike)

Sterile neutrino transition magnetic moment





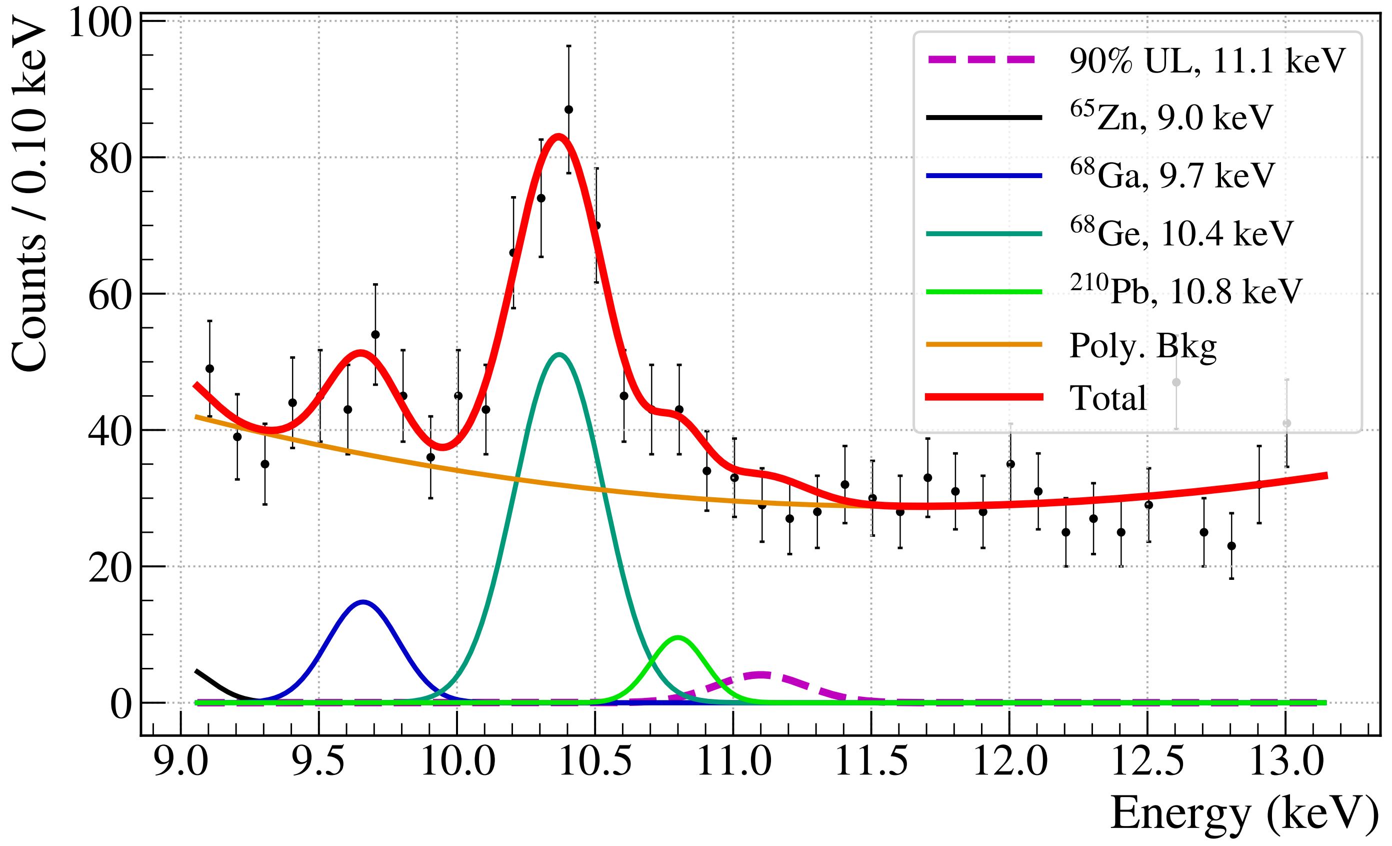
Bosonic dark matter, vector (dark photon)

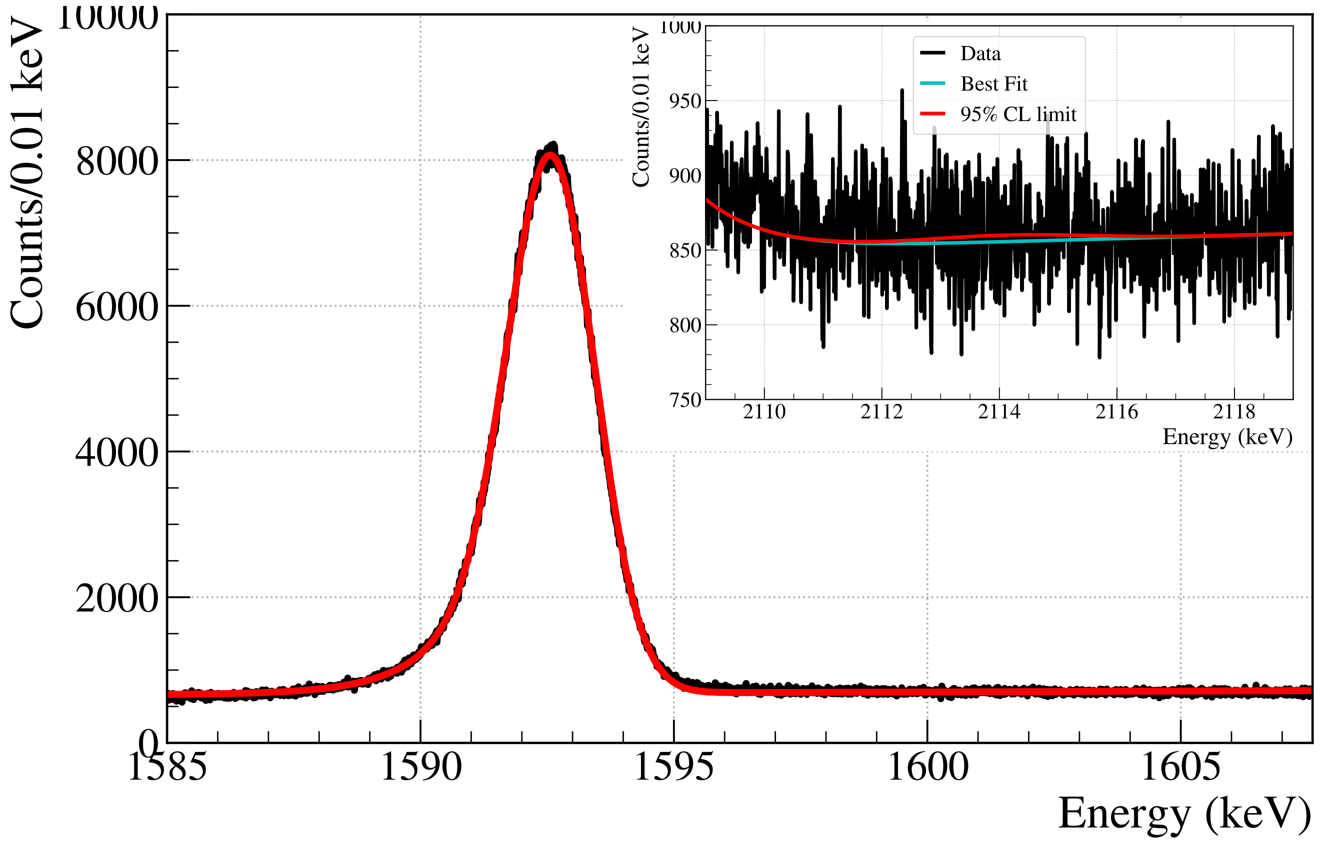
C. Wiseman

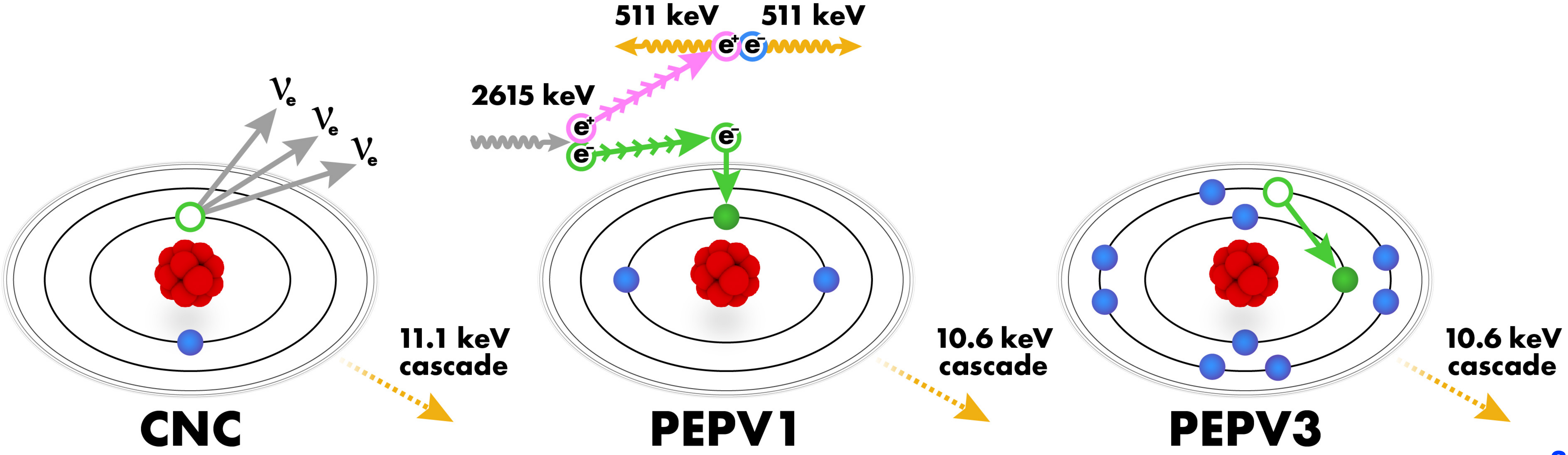
Coming Soon: Charge Conservation & PEP Violation

Another search for rare peaks, in the low-e exposure and in the ^{228}Th calibration data.

- This paper is another "interdisciplinary" result and test of QM.
- Best CNC result in 22 years for this mode







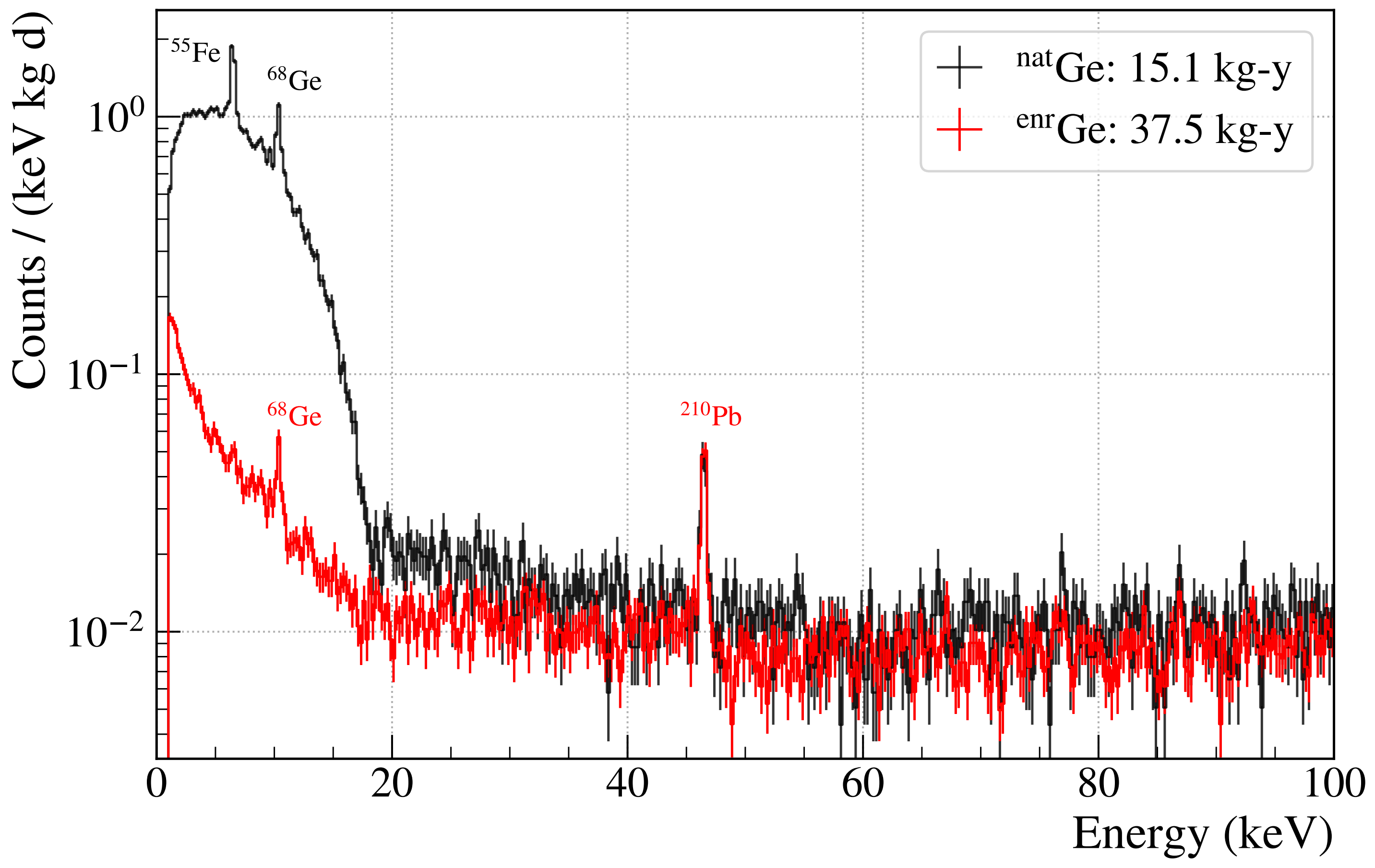
Take-aways from the Low-E program

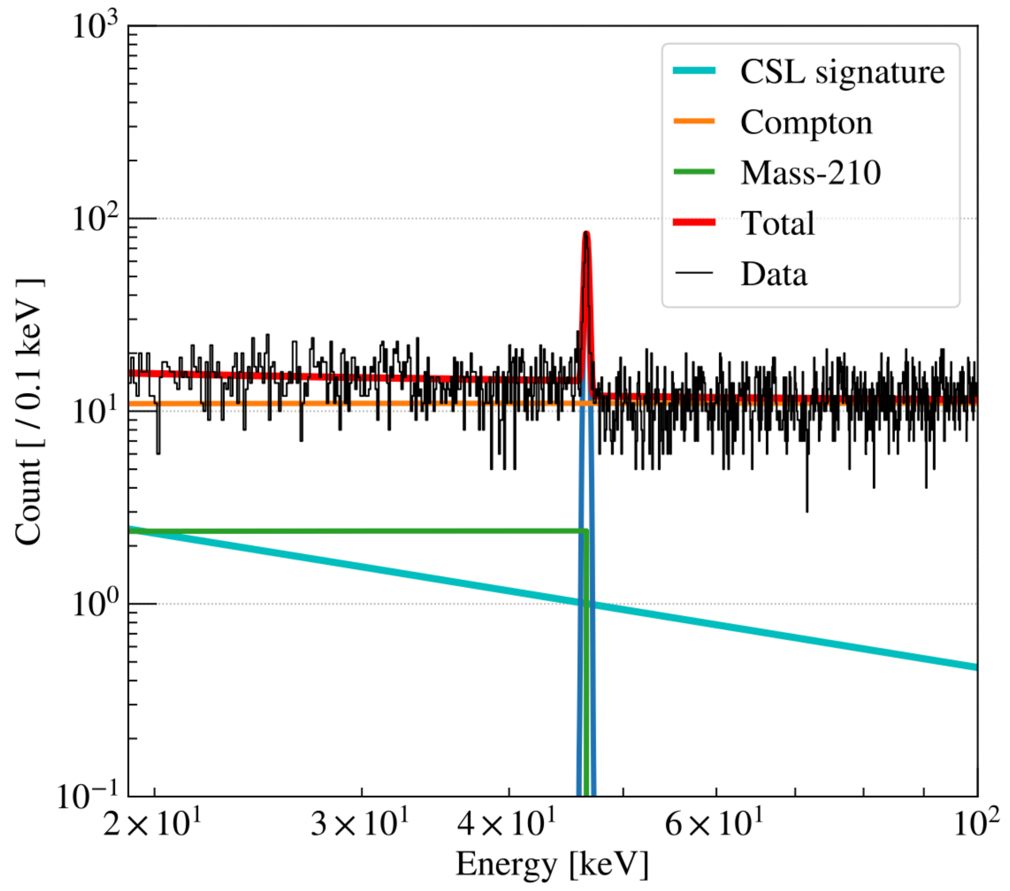
With **low cosmogenic activation, excellent energy resolution, and ~1 keV thresholds,** the DEMONSTRATOR is well-positioned to look for Beyond Standard Model physics at low energy:

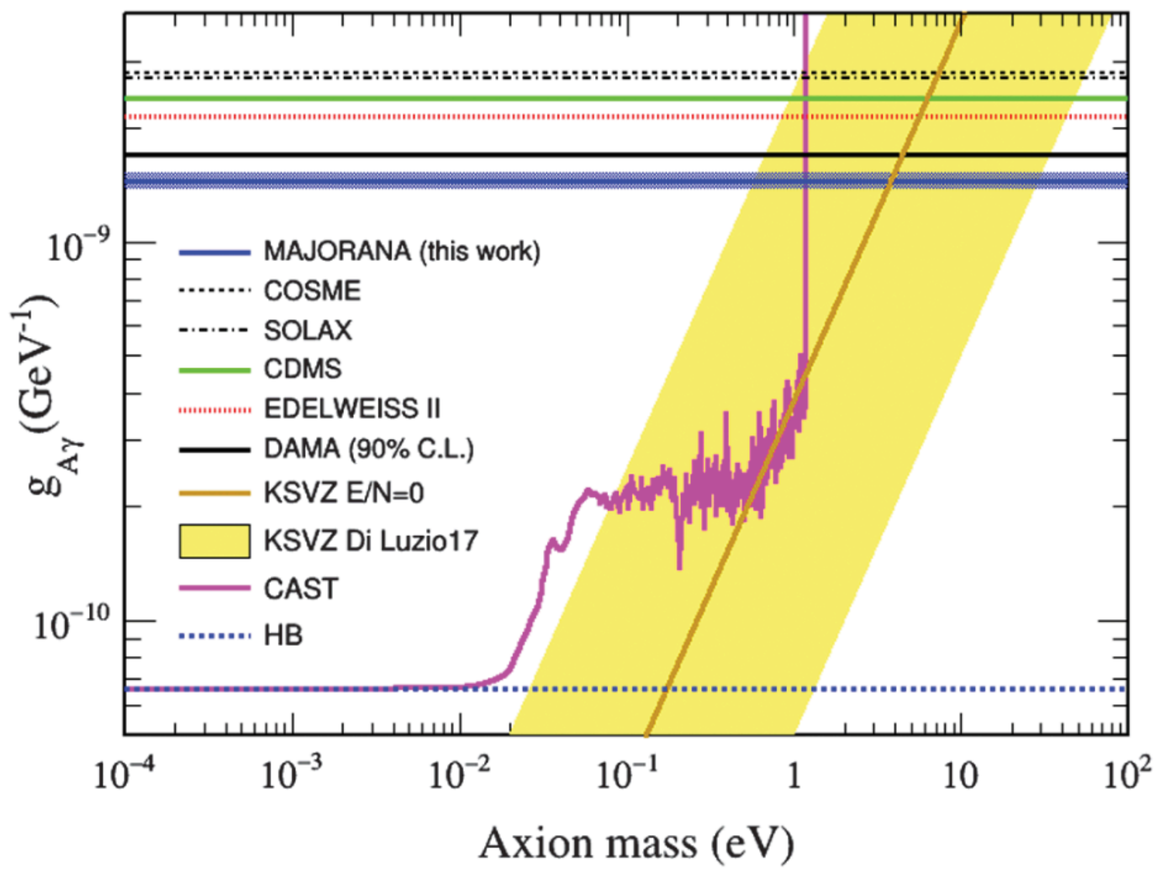
- Solar axion-photon coupling, wavefunction collapse (PRL 2022, 2 articles!)
- Bosonic, fermionic, and other exotic dark matter (PRL 2017, [**arXiv:2206.10638 (2022)**]())
- Lightly ionizing (fractionally-charged) particles (PRL 2018)
- 14.4 keV solar axions, electron decay (PRL 2017)

MAJORANA results can inform Low-E BSM searches in next generation ^{76}Ge: LEGEND!

- Advances in background modeling, pulse shape analysis, extensive physics topics list ….







Outline: Final Results and New Directions

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- Overview of MAJORANA, and final neutrinoless double beta decay result

Anna Reine (UNC & TUNL)

- Studies of radioactive backgrounds and development of a full background model

Clint Wiseman (UW & CENPA)

- Search for beyond standard model physics, dark matter

Ralph Massarczyk (LANL)

- First results from a search for the decay of nature's rarest isotope - Tantalum-180

Physics of isomers … context

- All physical systems tend to be in the lowest energetic state **(ground-state)**
- Frederick Soddy, *Nature 99 (1917)*

> *"We can have isotopes with identity of atomic weight, as well as of chemical character, which are different in their stability and mode of breaking up."*

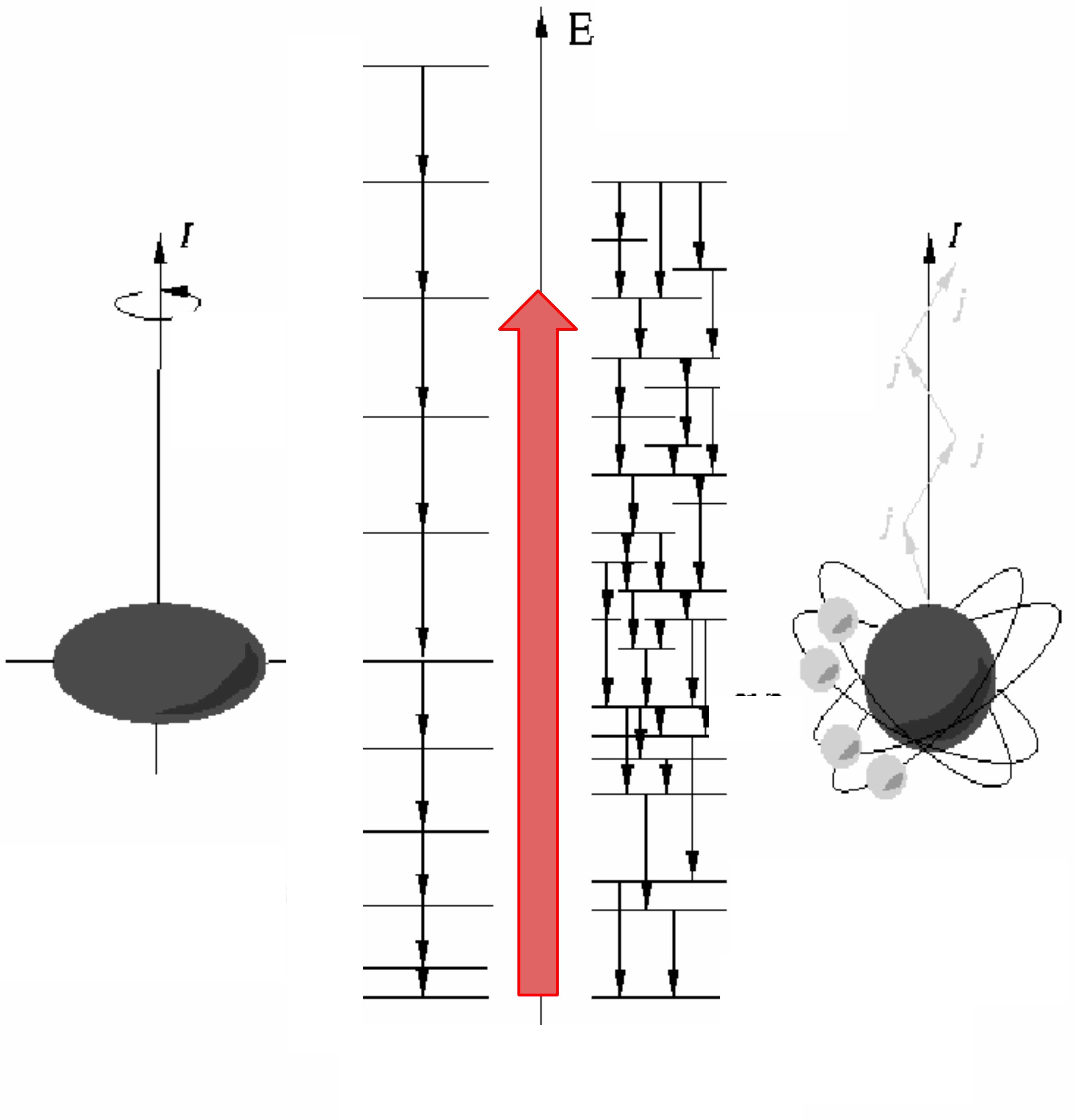
Chemistry Nobel prize 1921

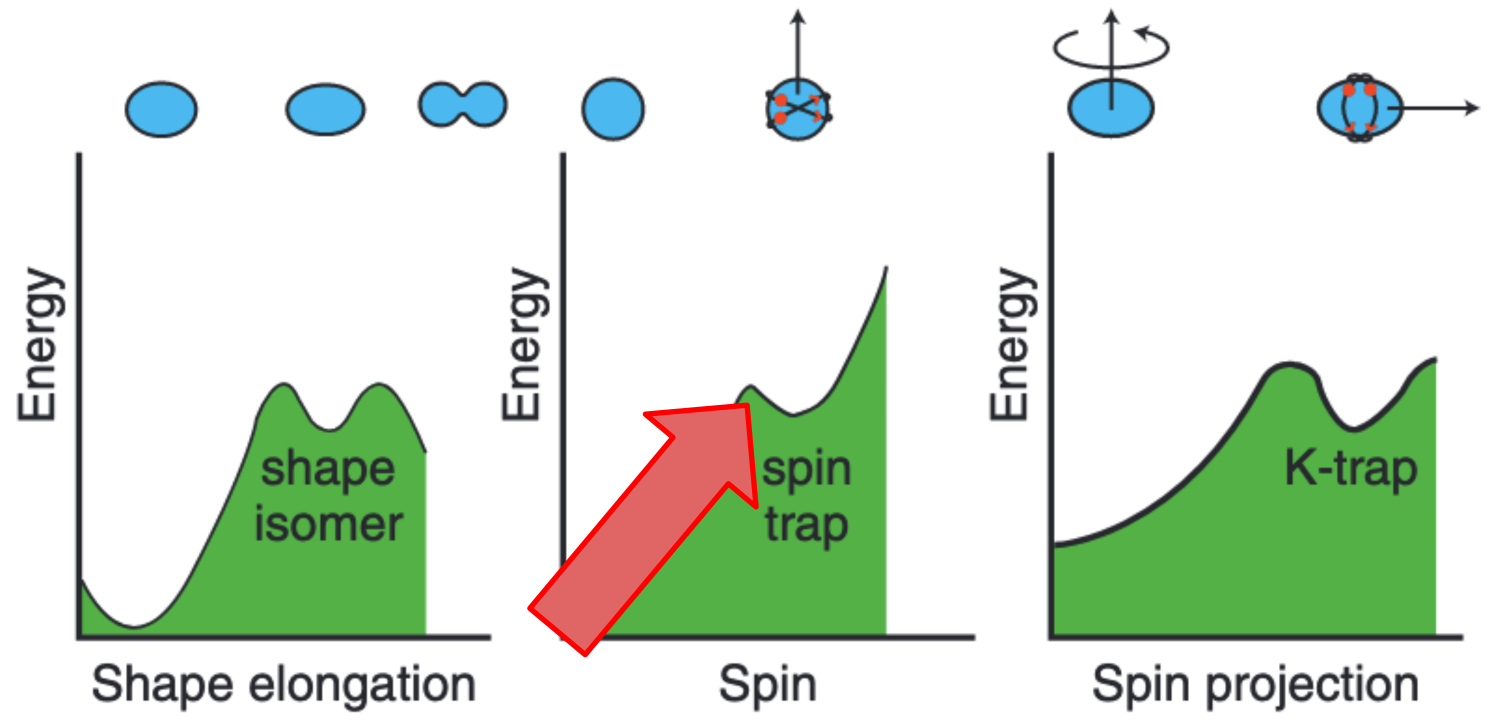
- Carl von Weizsäcker 1936:

> *Spin is the important quantity*

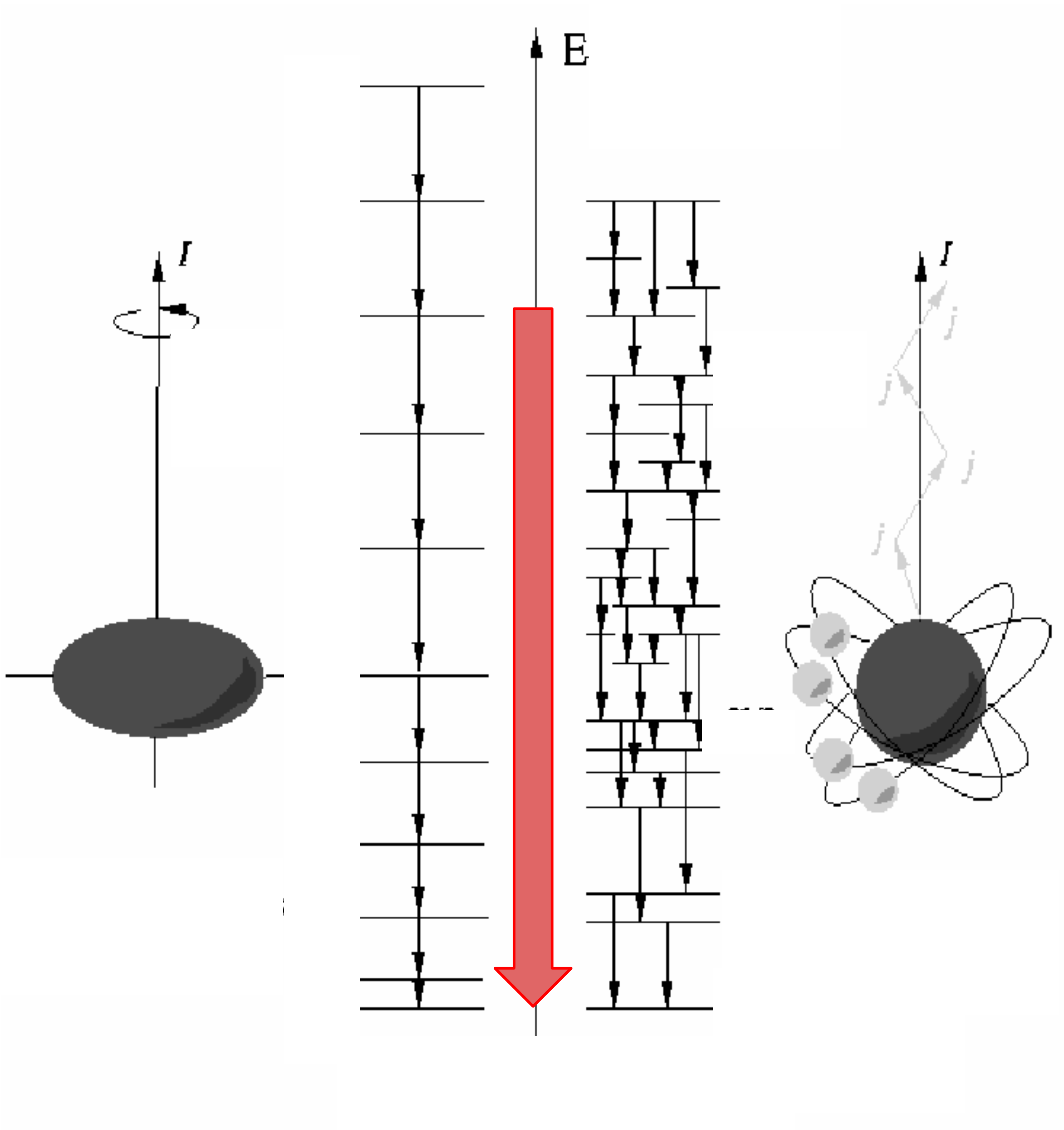
Today isomers we have found from 10^{-9} seconds … $>10^{16}$ years

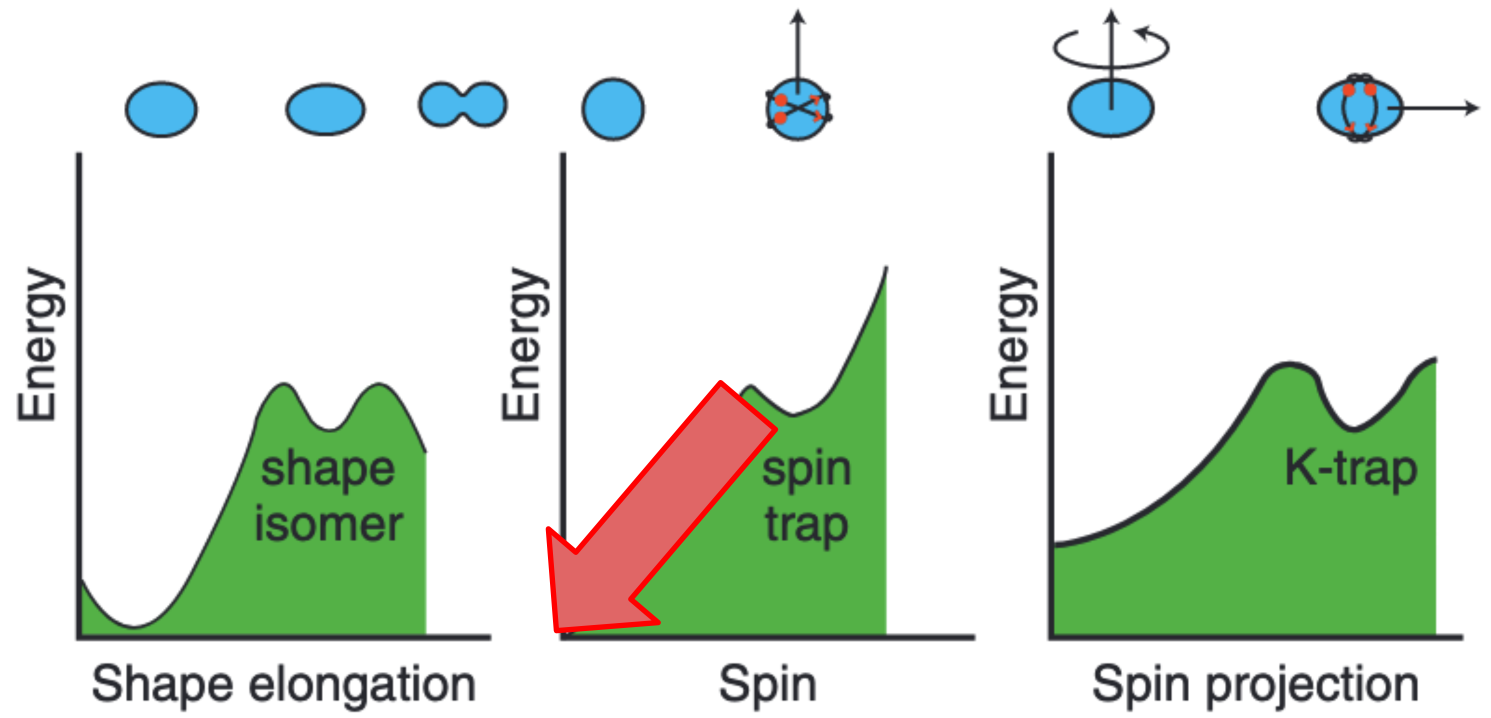
Physics of isomers…excitation



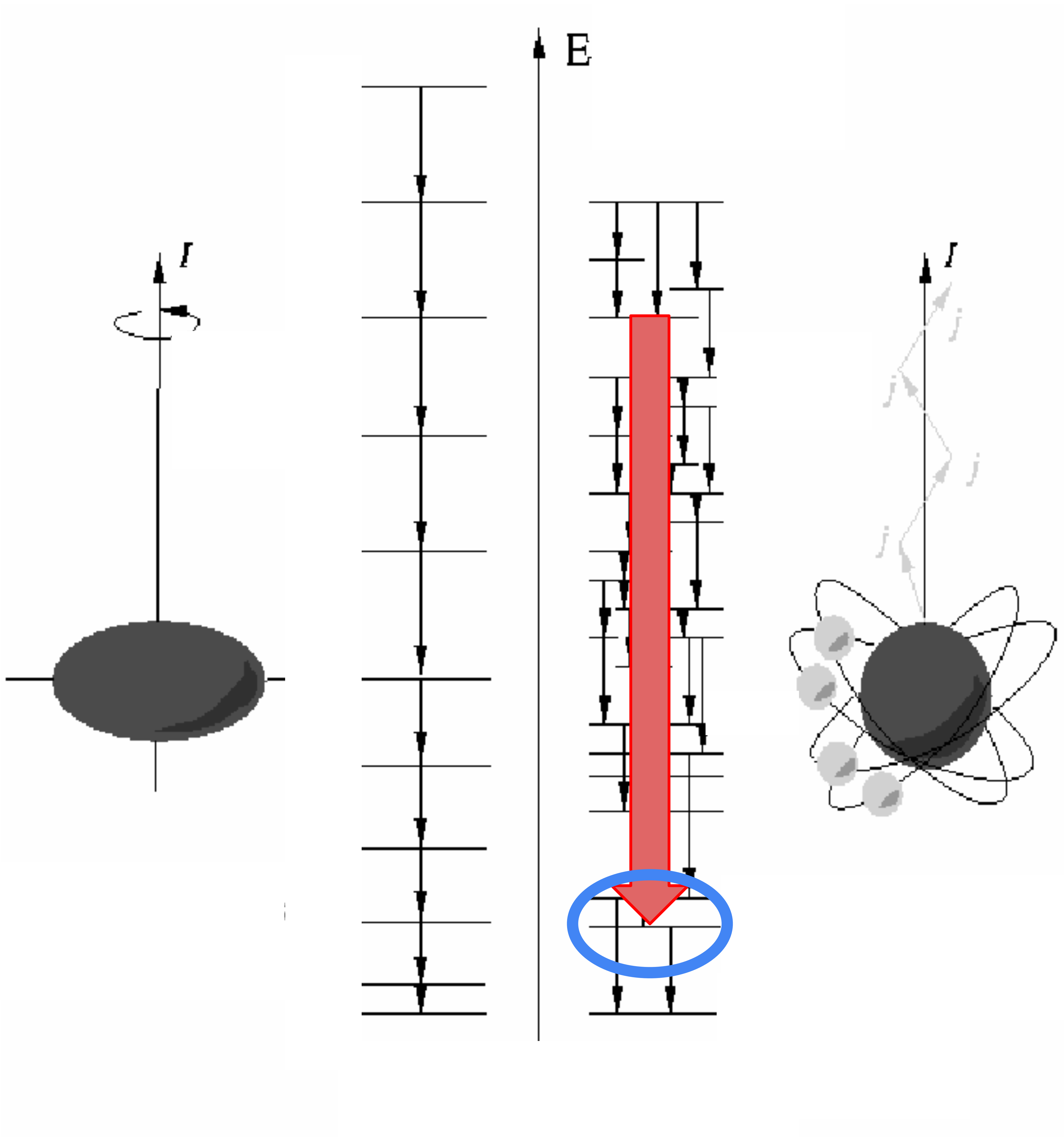


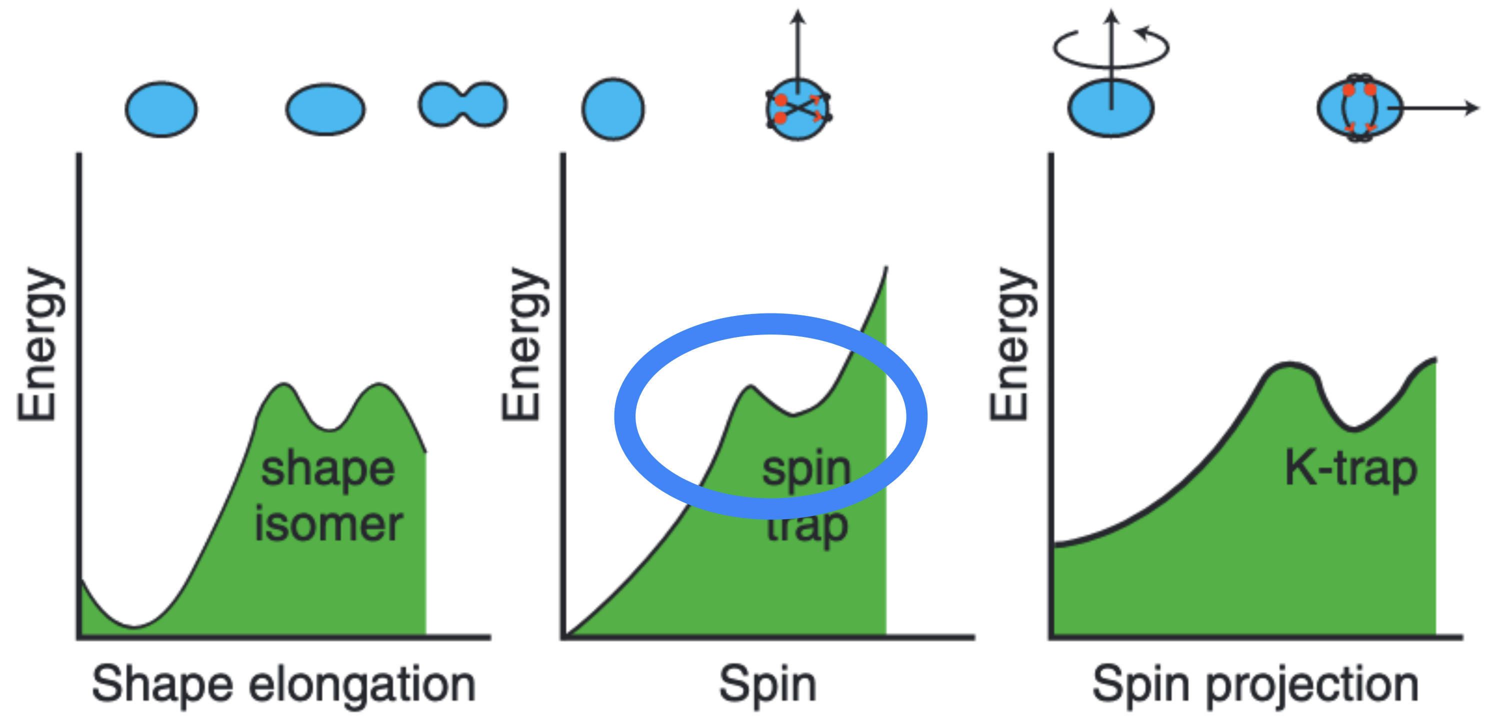
Physics of isomers…deexciation

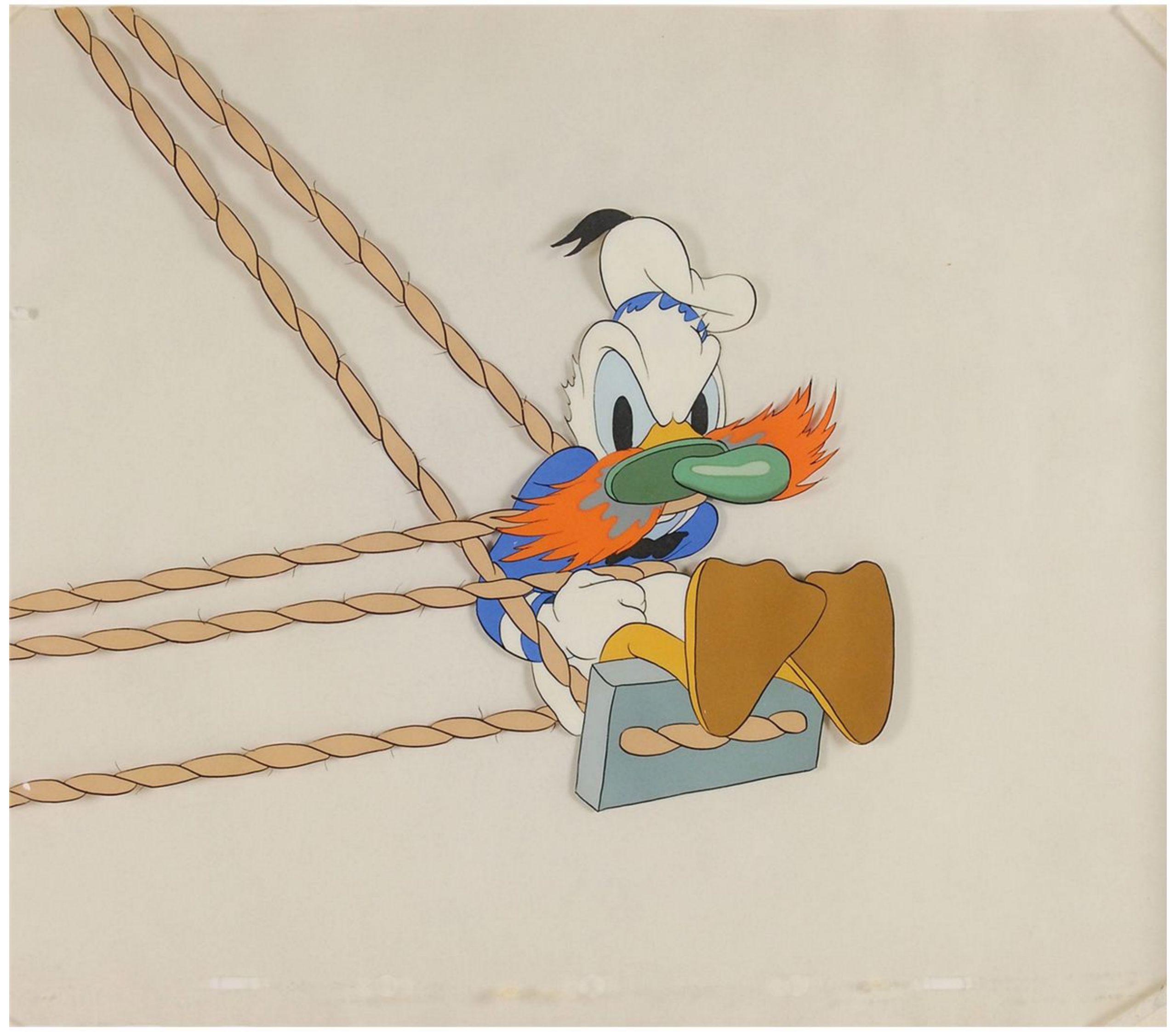




Physics of isomers…but sometimes



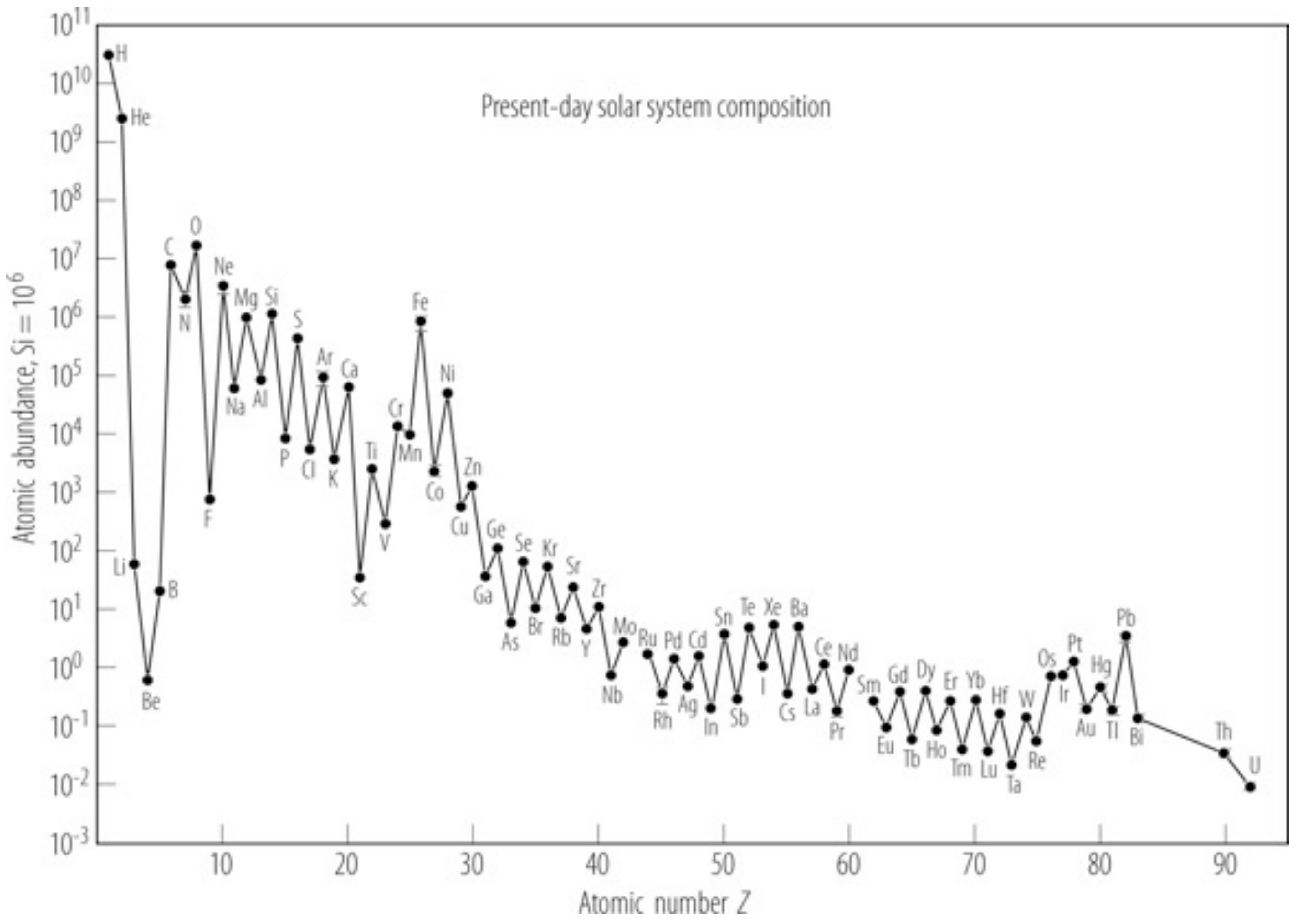




The Tantalum problem

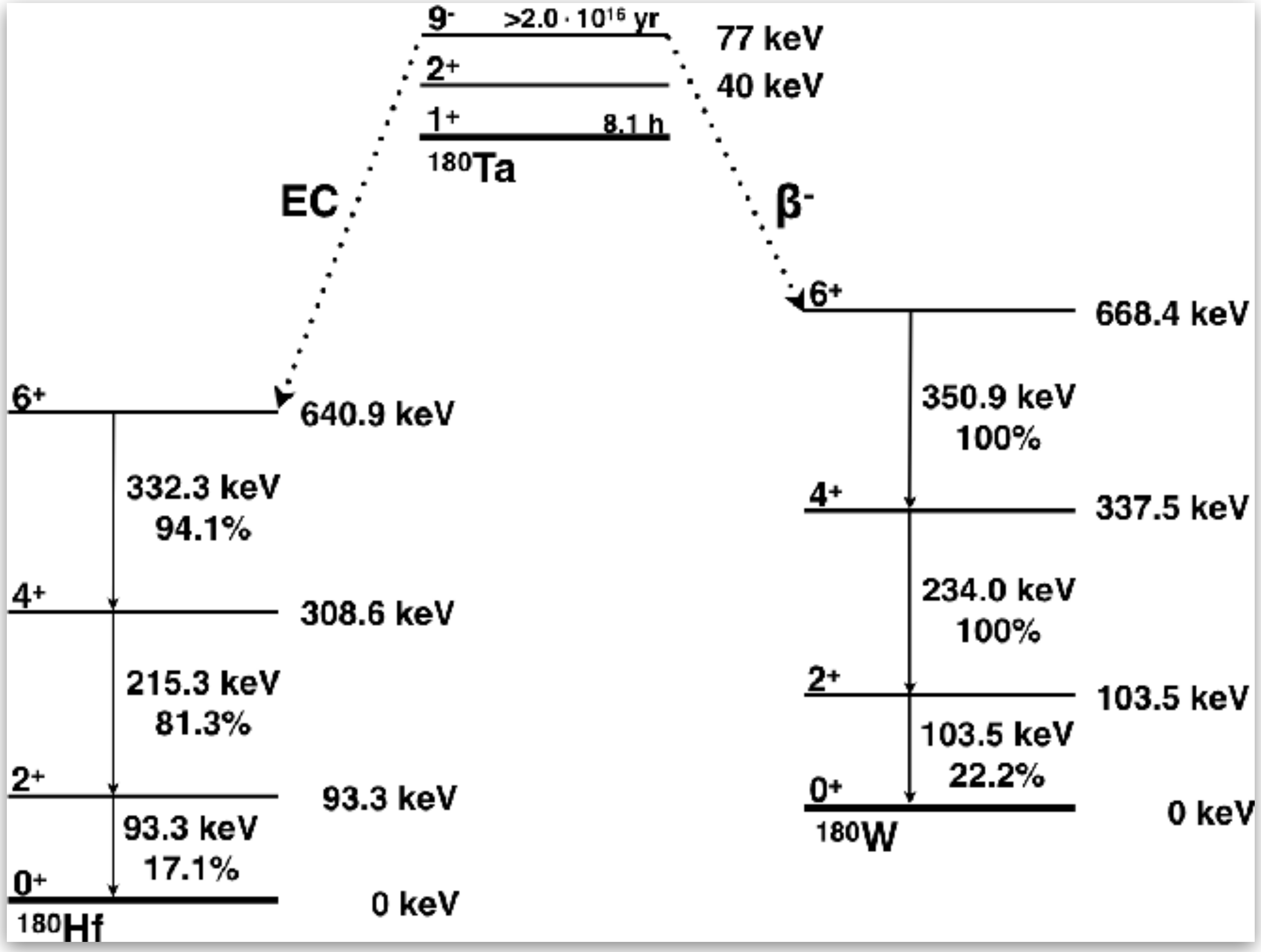
- 1 - 2 ppm of earth's crust is Ta
- 99.98% is ^{181}Ta
- Best previous measurement used ~1kg of ^{nat}Ta (~0.2 g of ^{180m}Ta)
- ^{180}Ta ground state has a half-life of 8 hours
- All the ^{180}Ta is metastable:

the only naturally occurring long-lived isomer

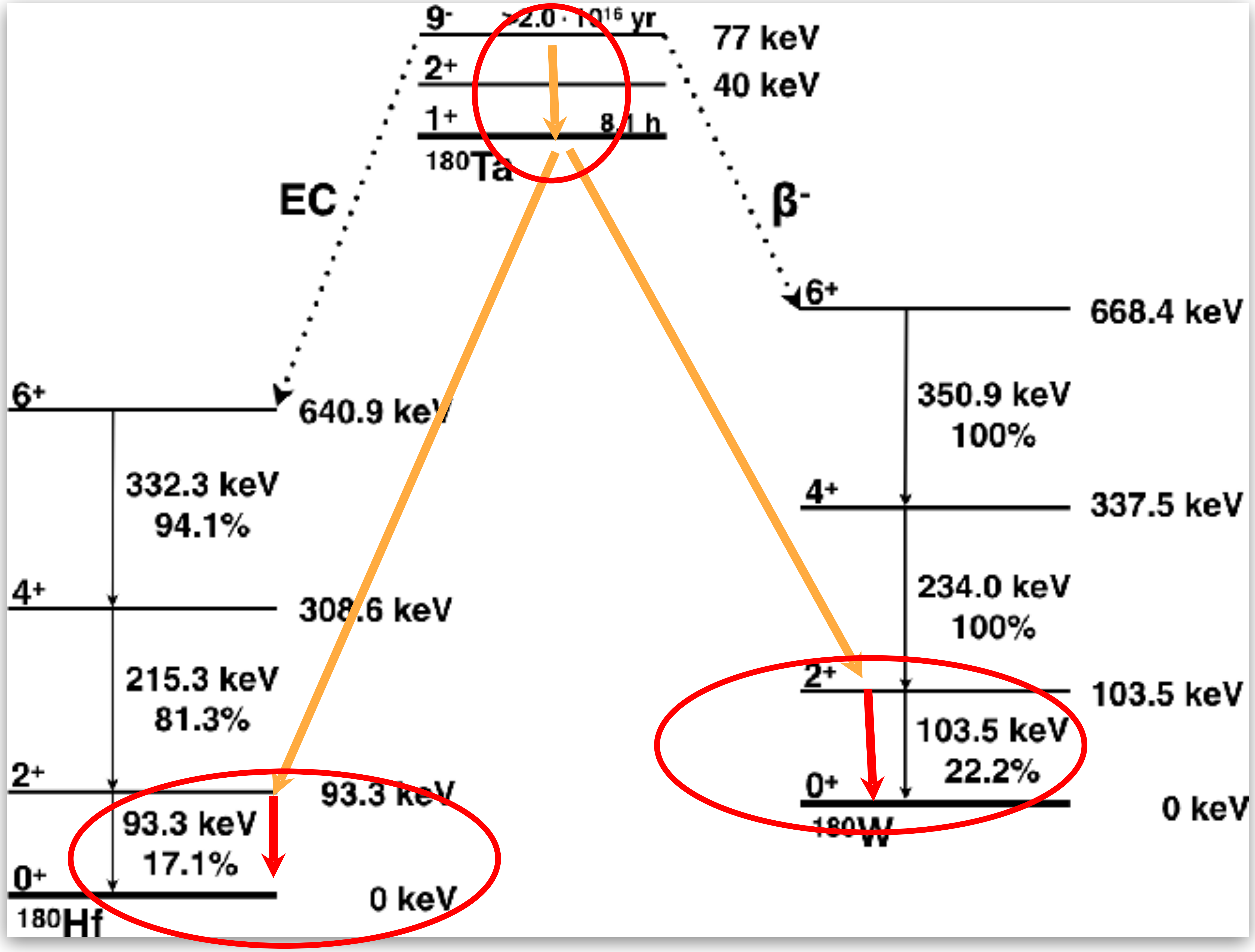


Testing basic nuclear physics on the extremes

Tantalum… the longest living isomer



Tantalum… the longest living isomer

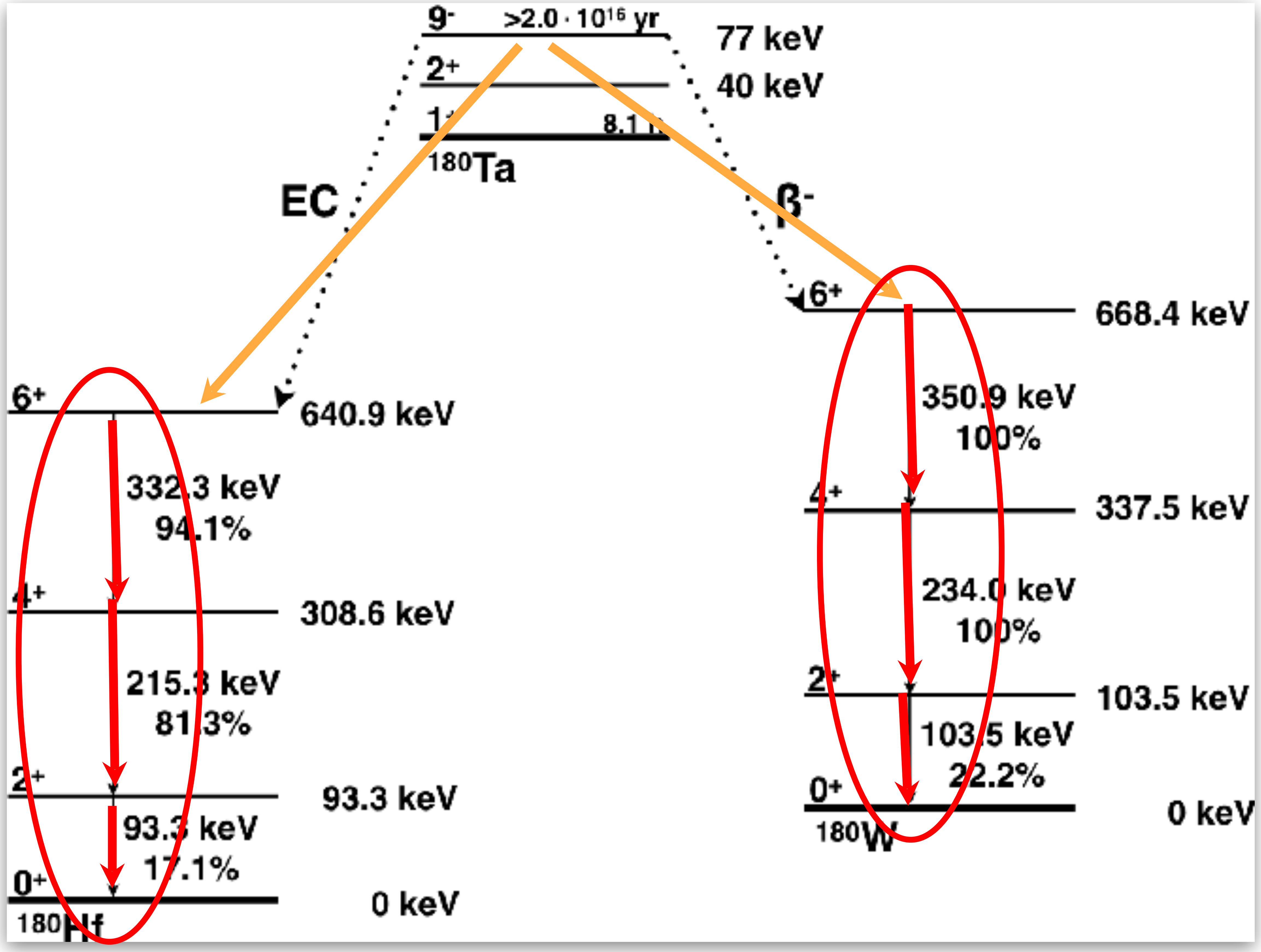


- $^{180m}Ta \rightarrow {}^{180}Ta$ g.s.

  Single peak at 93/103 keV

  (and 77, 40, 37 keV)

Tantalum… the longest living isomer



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  Transition into excited state

  Coincidence measurement

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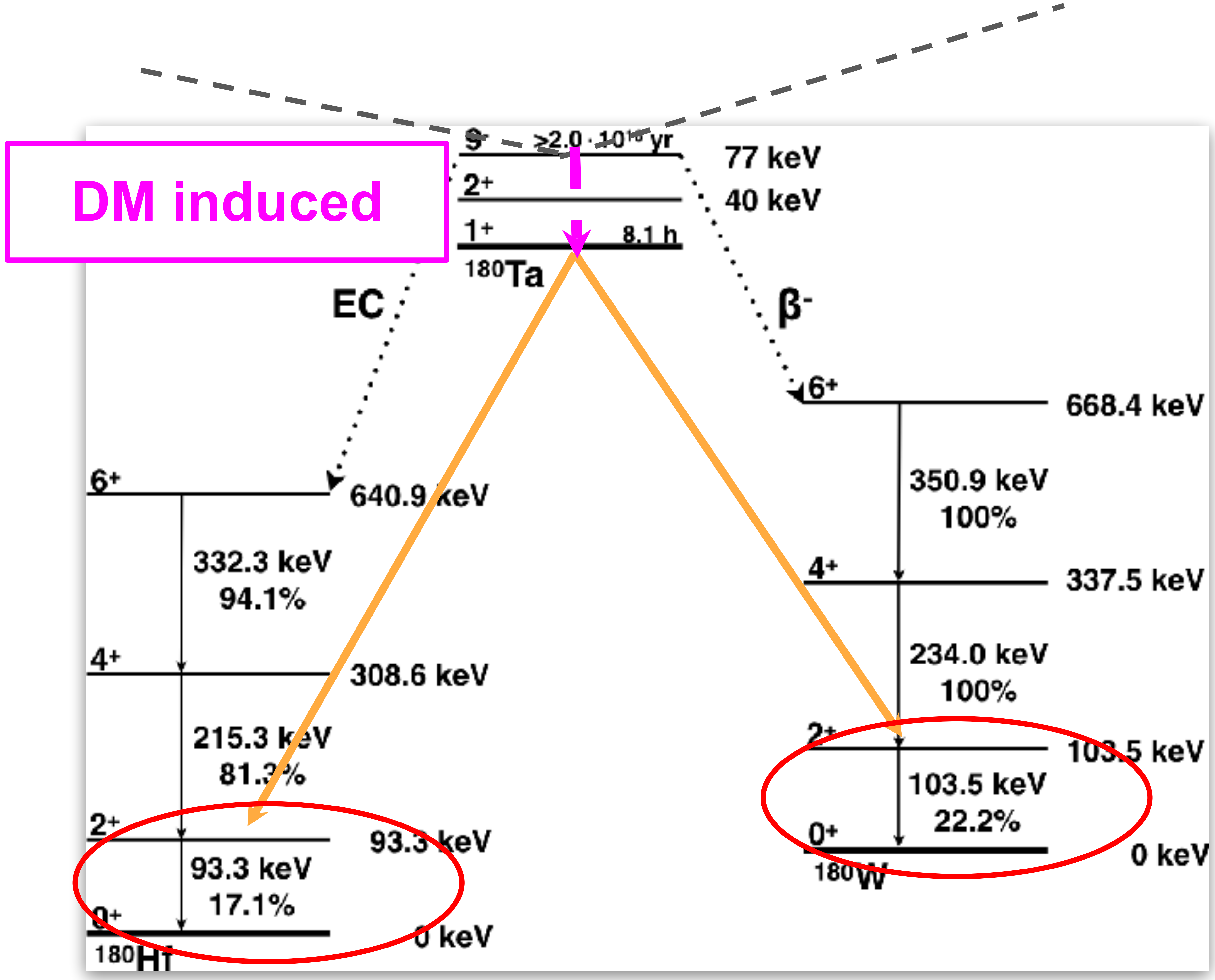

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  (and 77, 40, 37 keV)

- ^{180m}Ta → ^{180}Hf* / ^{180}W*

  Transition into excited state

  Coincidence measurement

- ^{180m}Ta interacts with DM

A bit of history…

Measurement	half-life EC	half-life β	half-life *via gs*
theory expectation	$5.4 \cdot 10^{23}$	$1.4 \cdot 10^{20}$	$1.4 \cdot 10^{31}$ (γ);10^{18}-10^{19} (IT)
Bauminger 1958	$2.3 \cdot 10^{13}$	$2.7 \cdot 10^{13}$	$>2.3 \cdot 10^{13}$
Norman 1981	$5.6 \cdot 10^{13}$	$5.6 \cdot 10^{13}$	–
Cumming 1985	$3.0 \cdot 10^{15}$	$1.9 \cdot 10^{15}$	–
Hult 2006	$1.7 \cdot 10^{16}$	$1.2 \cdot 10^{16}$	$>1.8 \cdot 10^{14}$
Hult 2009	$4.5 \cdot 10^{16}$	$3.6 \cdot 10^{16}$	$>3.7 \cdot 10^{14}$
Lehnert 2017	$2.0 \cdot 10^{17}$	$5.8 \cdot 10^{16}$	–
MJD Dec 2022	… a few more slides		

What is needed for a good measurement ?

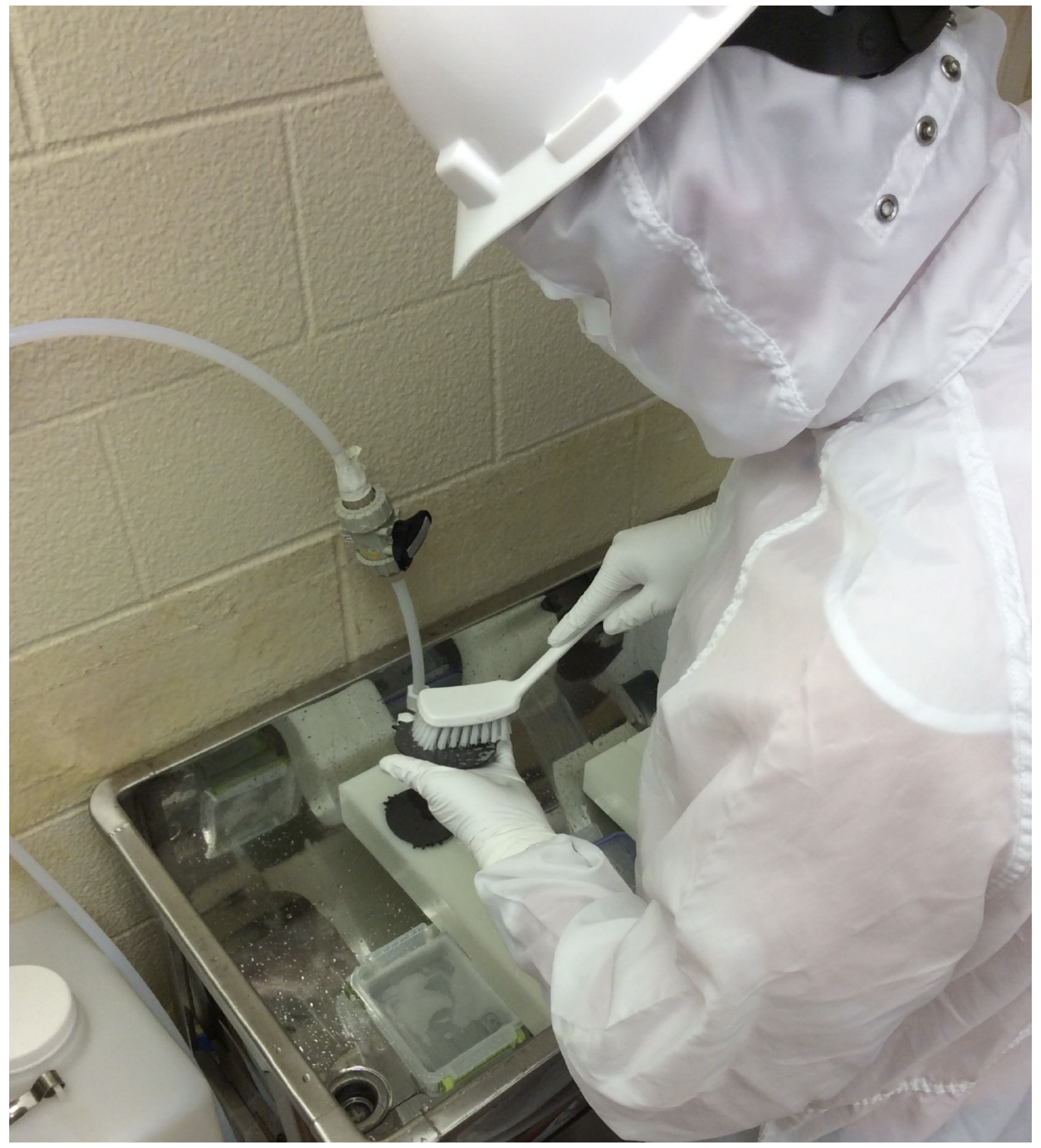
- A lot of material
- Detector with excellent energy resolution
- If possible multiple detectors that can detect coincidences
- A clean, ultra low-background system and environment

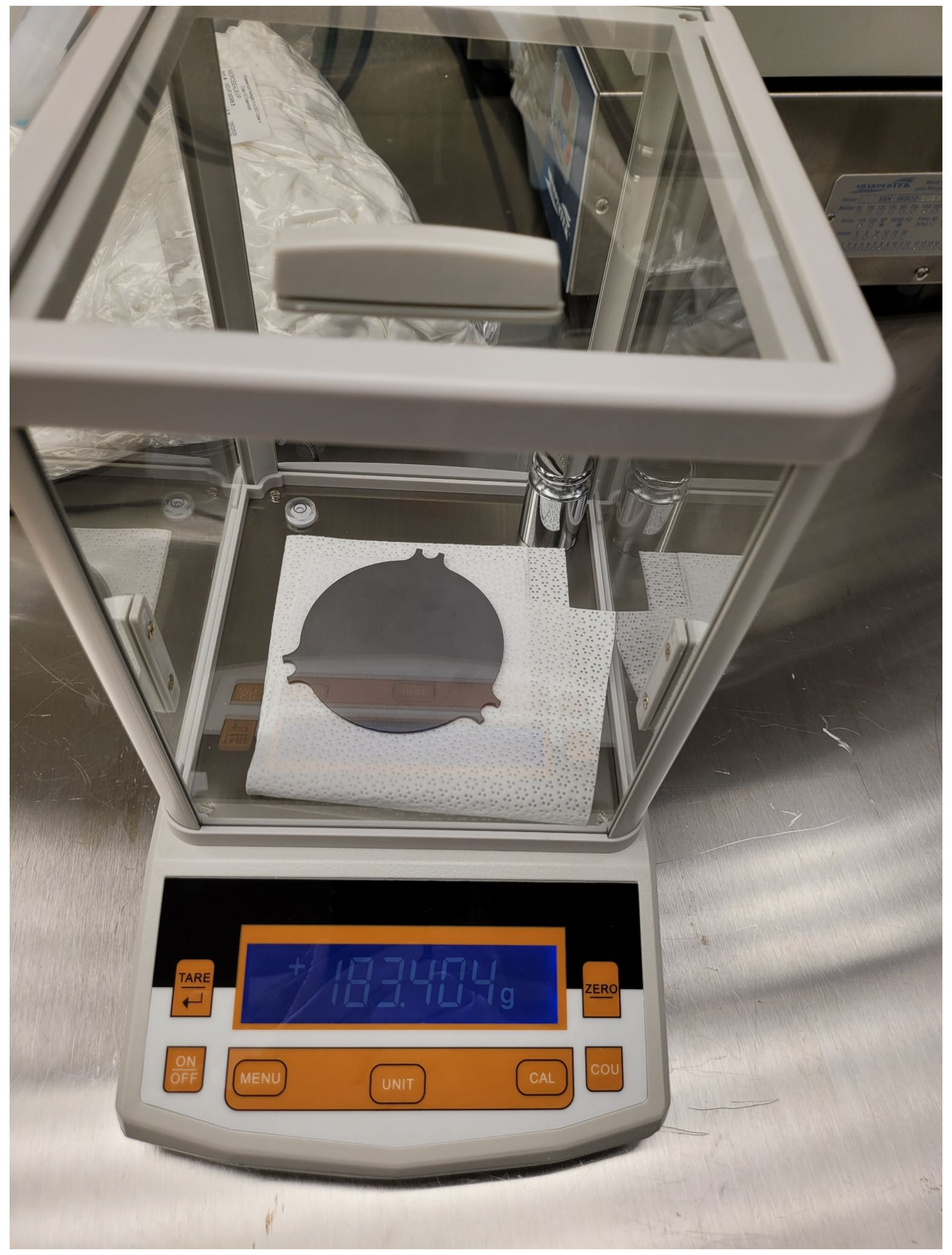
Perfect use of MJD facility after enriched detector removal

Installation and preparation

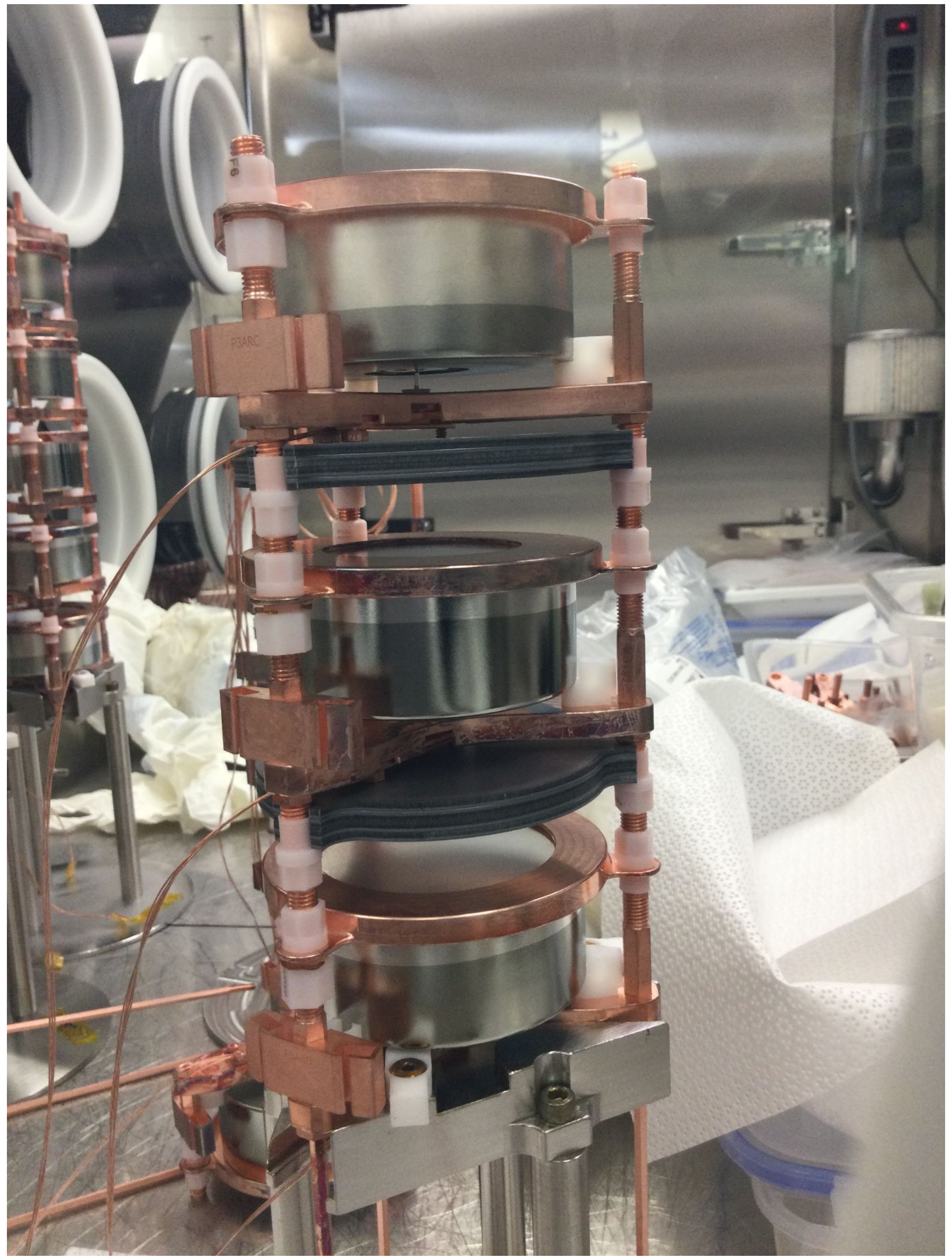
- Material cleaning following MJD standards

- 120 disks, 99.999% pure



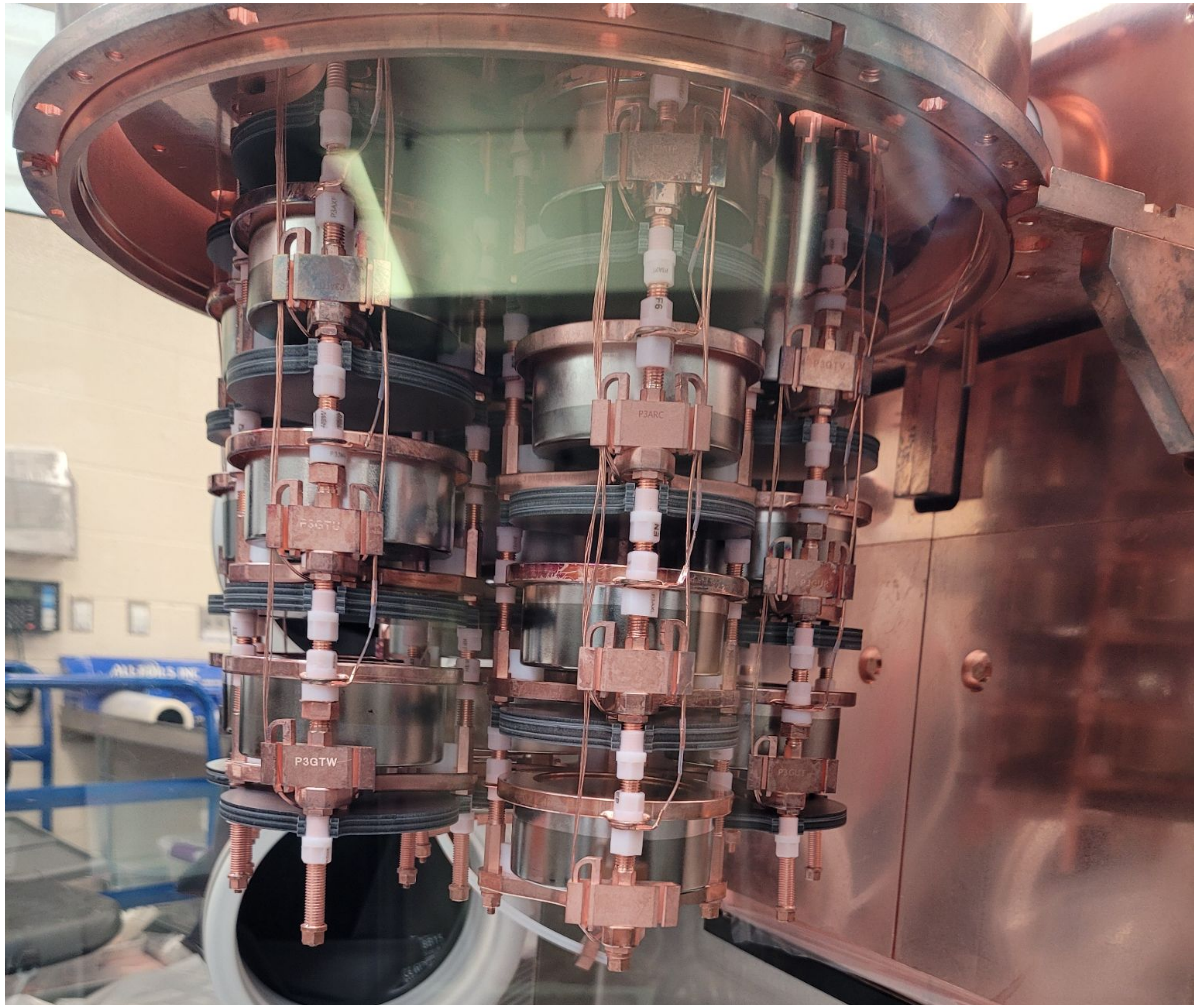


Installation



Installation and run time

- **17.39 kg installed**
  ~ 2 g ^{180m}Ta
- 23 active detectors
- Detectors and Ta arranged to maximize efficiency
- Start of data taking: 05/2022
- Today: first data release:
  - 229 days of data
  - 225.5 days of ^{180m}Ta data (97.7% life time)



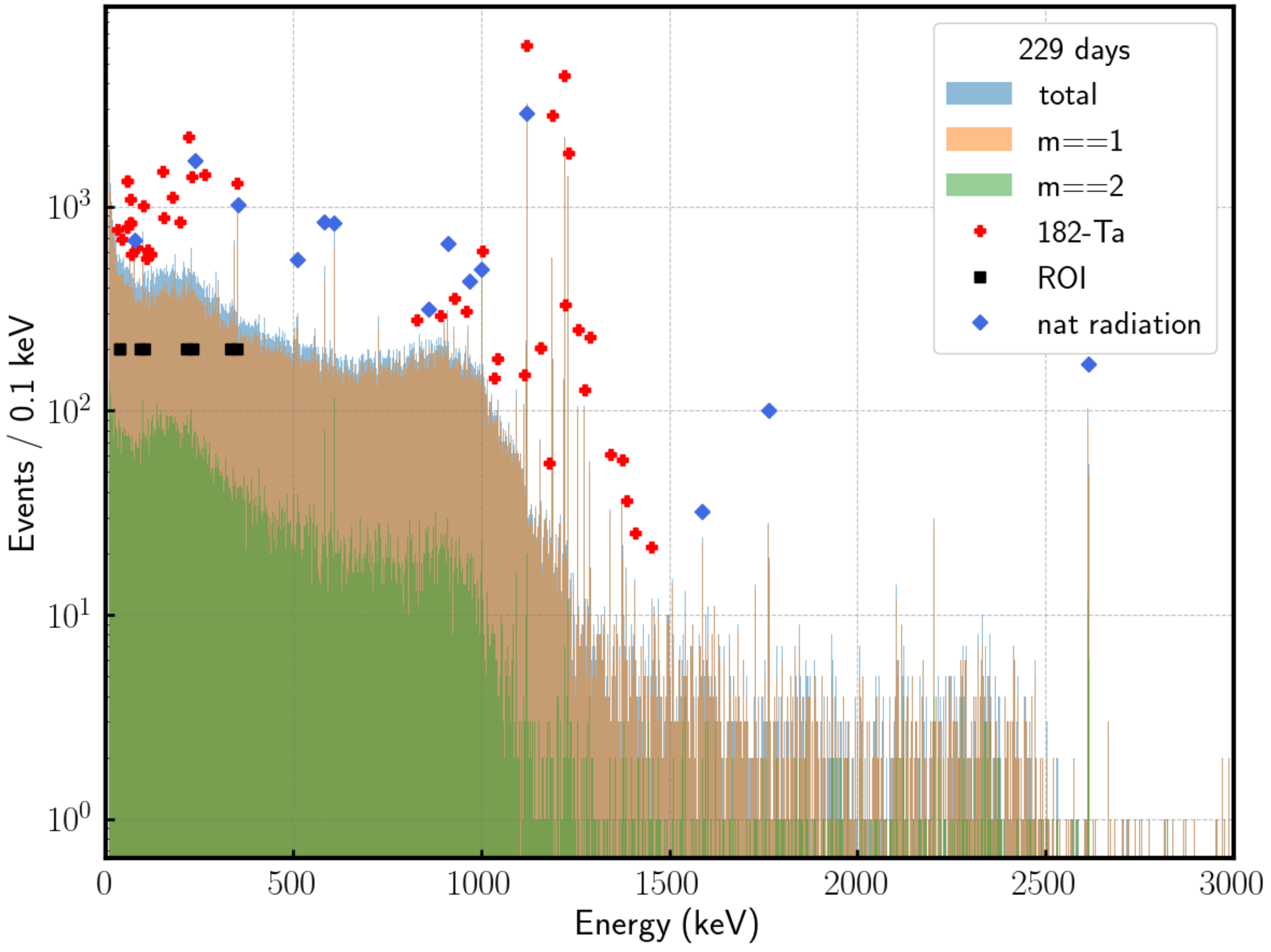
Spectral analysis

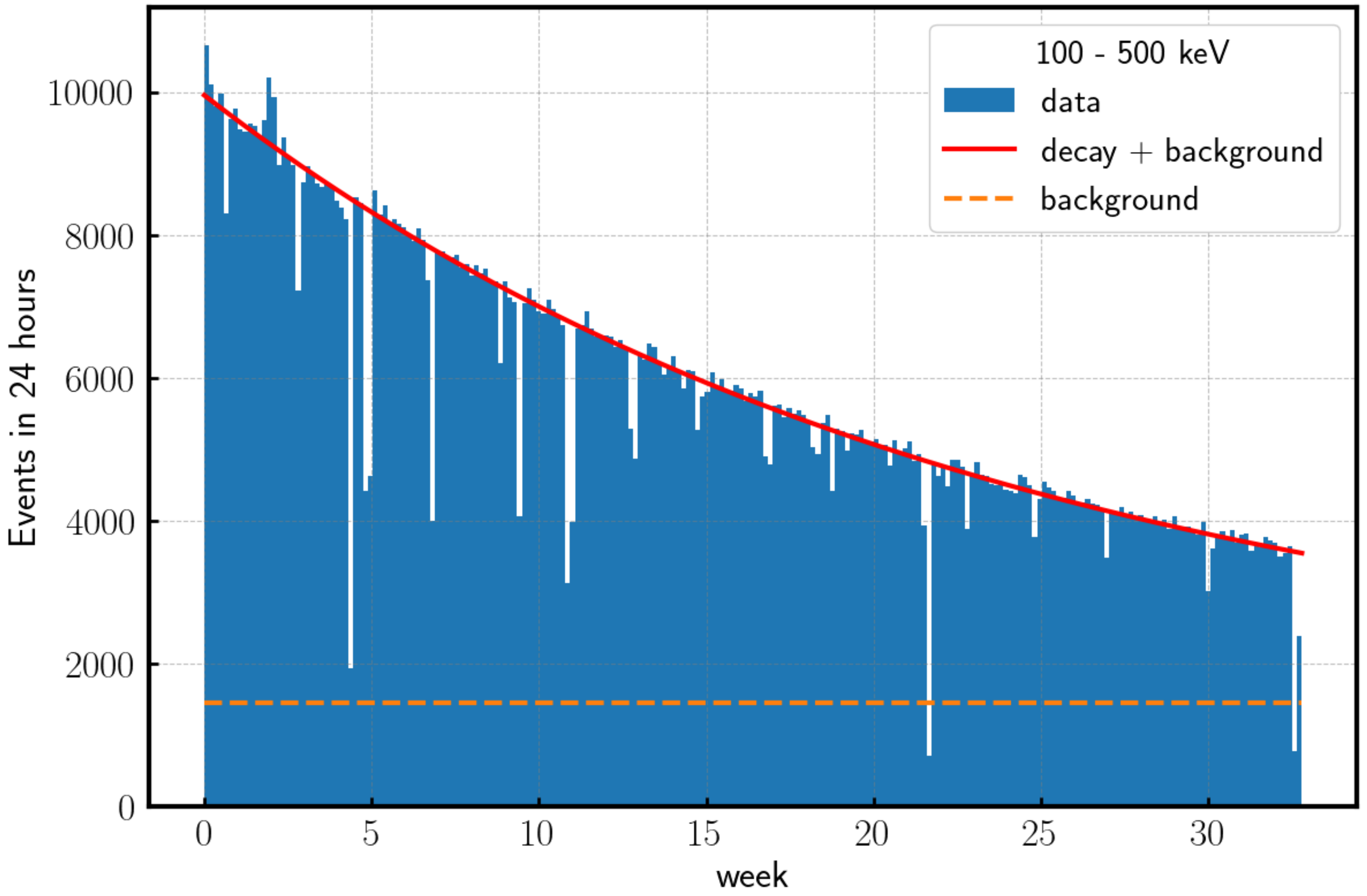
- First look at blinded data

- Low contributions from natural radioactivity (< 0.5 mBq/kg_{Ta})

- Contributions from surface activation in Ta
  - ^{182}Ta - 114 days half-life
  - ^{175}Hf - 70 days half-life

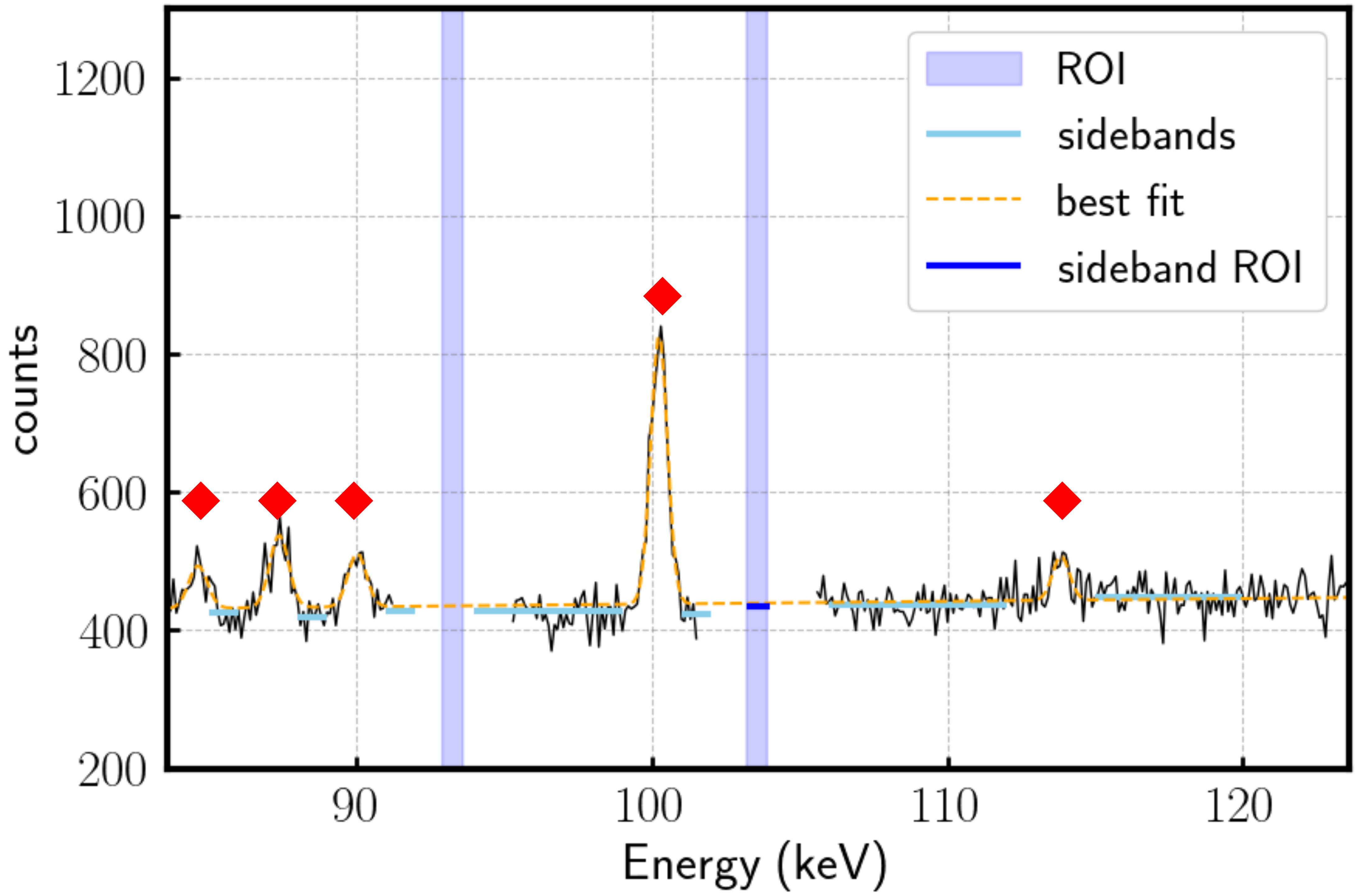
- Background improving over time



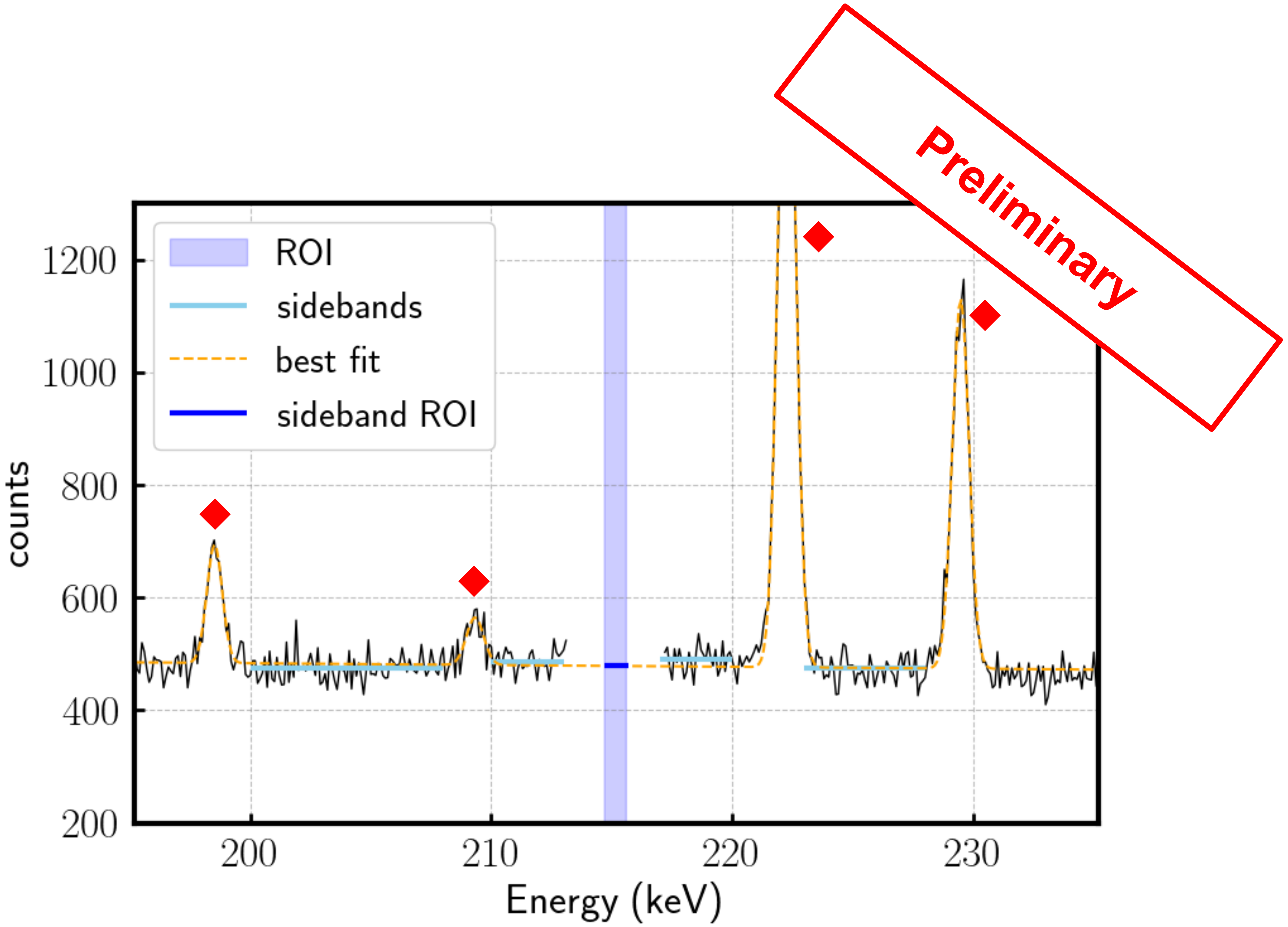


*Note: blinding regions are 4 keV wide

Unblinding… (almost live)



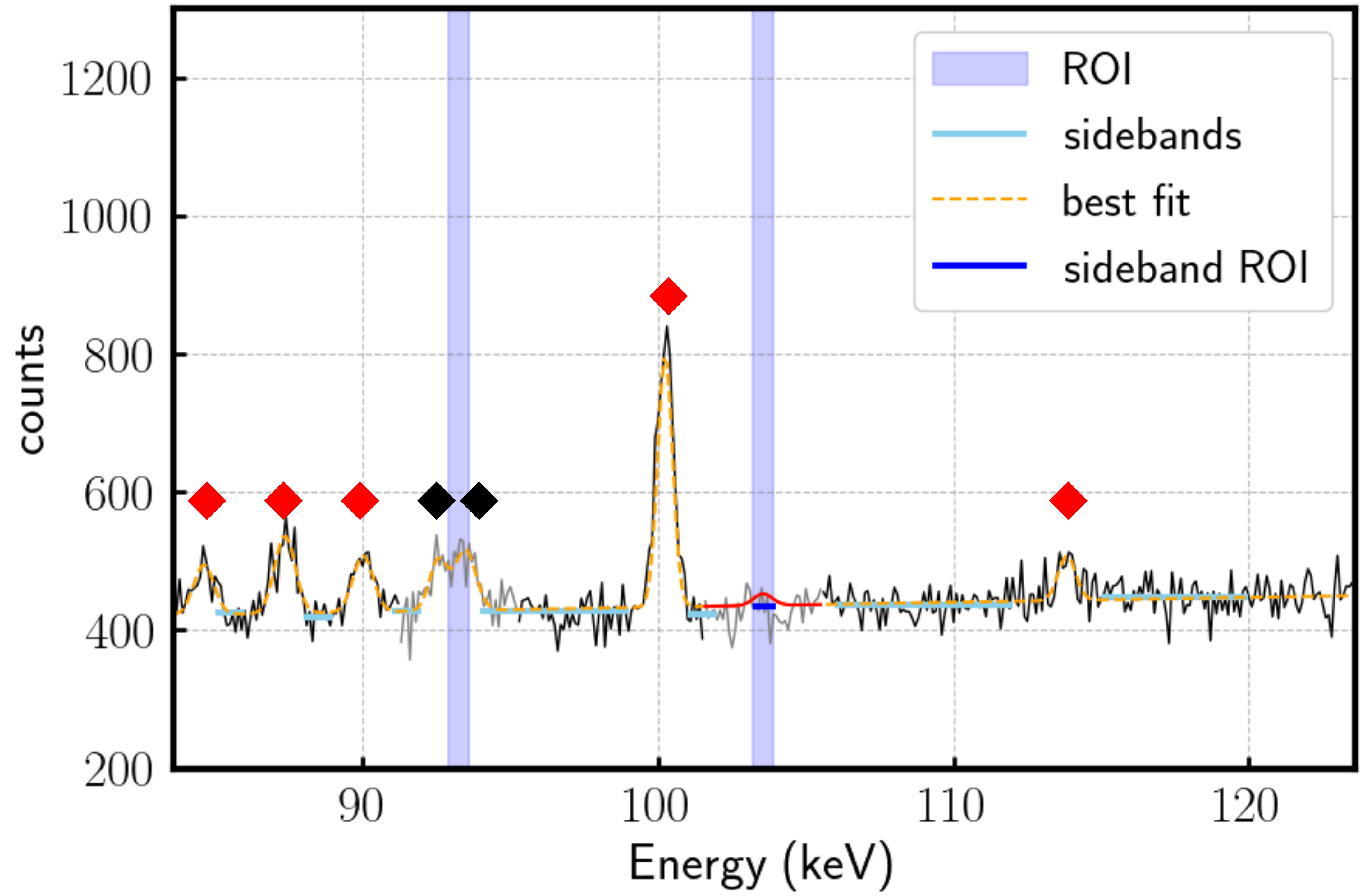
Signal region for deexcitations after β-decay



Signal region for deexcitations after electron capture

- ^{182}Ta
- U/Th decay chain

Unblinding… (almost live)



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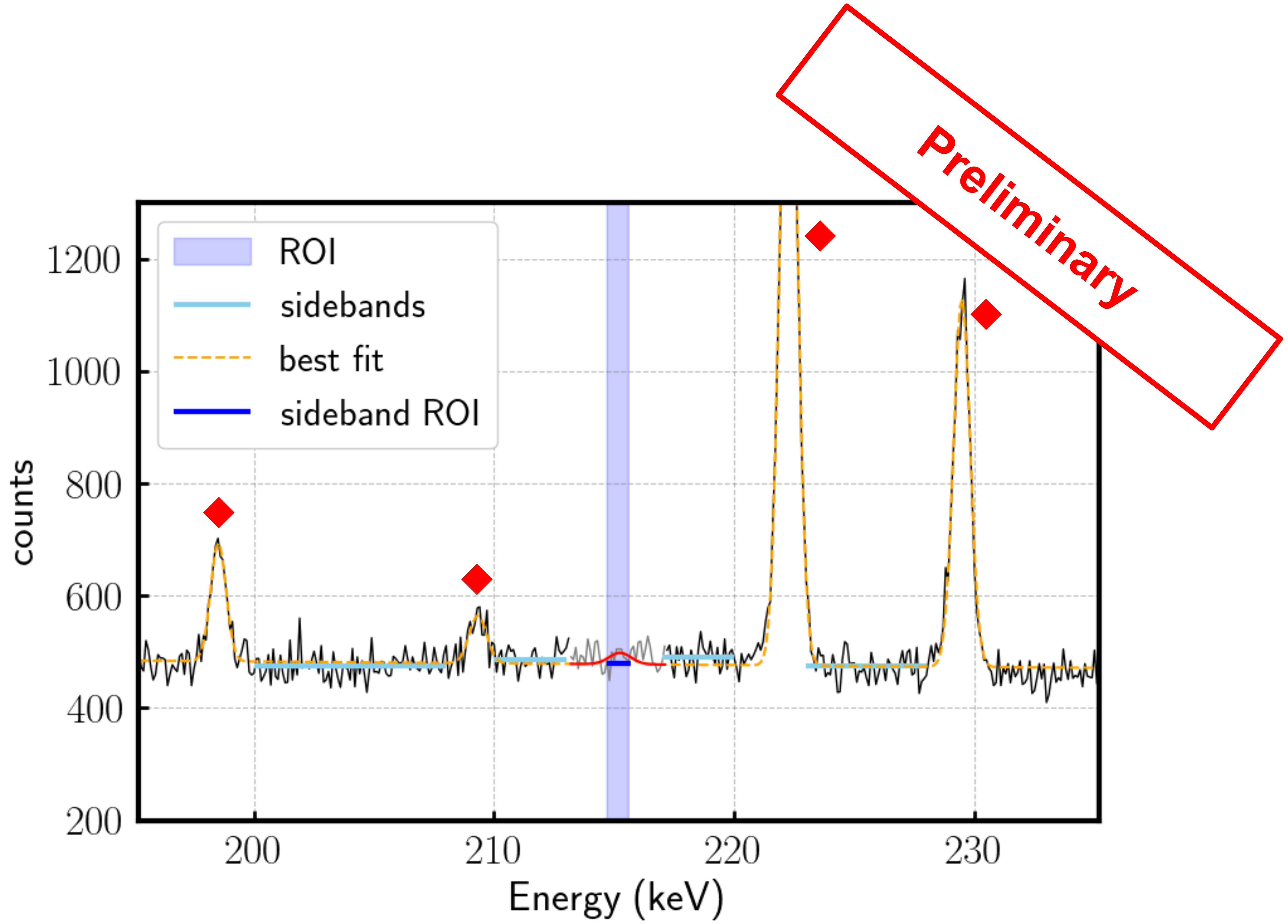

Signal region for deexcitations after electron capture

- ◆ ^{182}Ta
- ◆ U/Th decay chain

Results

- Background of early data (with ^{182}Ta) comparable with previous efforts

- Main improvements
  - Efficiency (x2-3)
  - Mass (x12)
  - Detector number (23)
  - Background

- multiplicity analysis
  - Not done in past
  - Significant background improvement

Measurement	half-life *EC*	half-life β	half-life *via gs*
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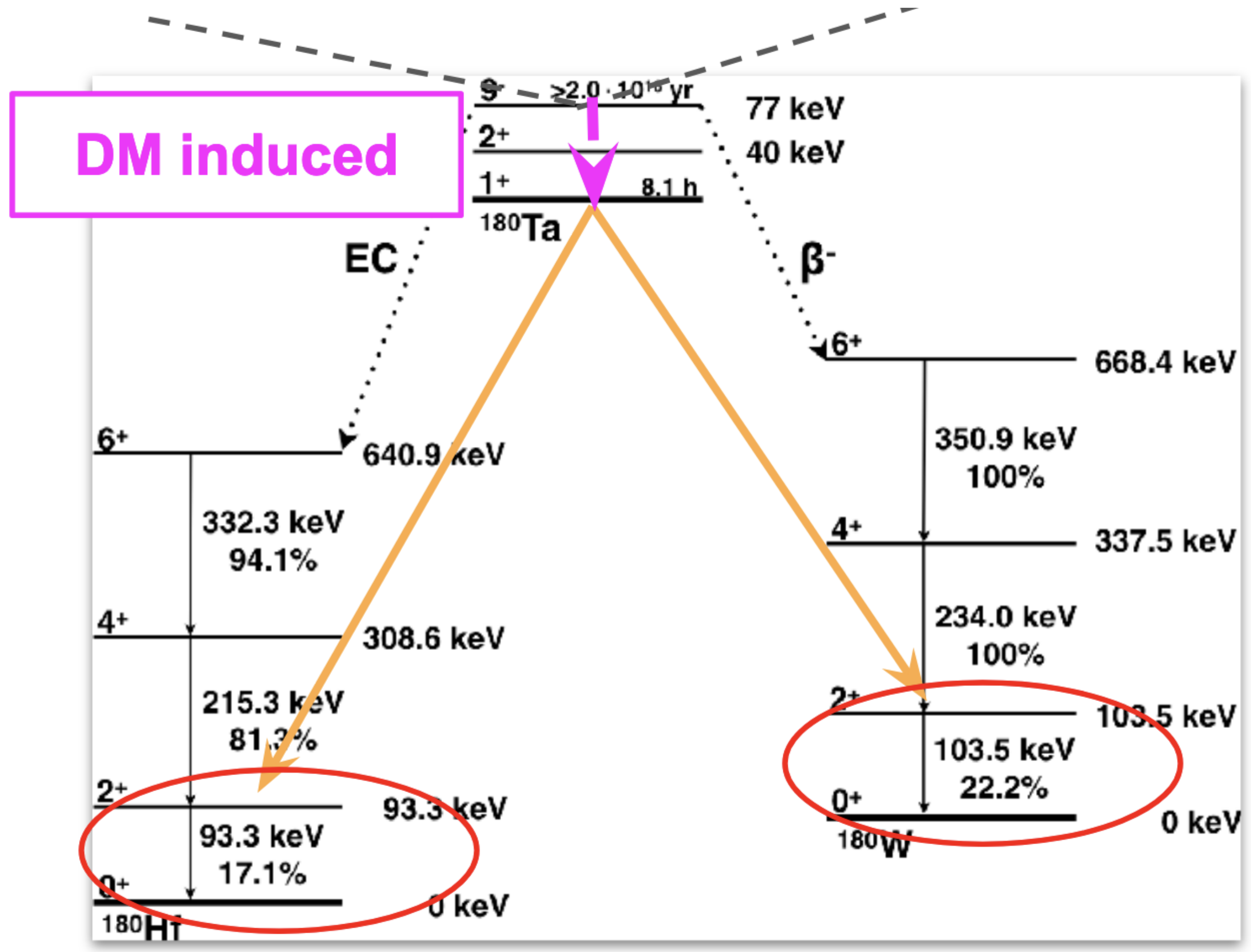
Preliminary
Paper in preparation

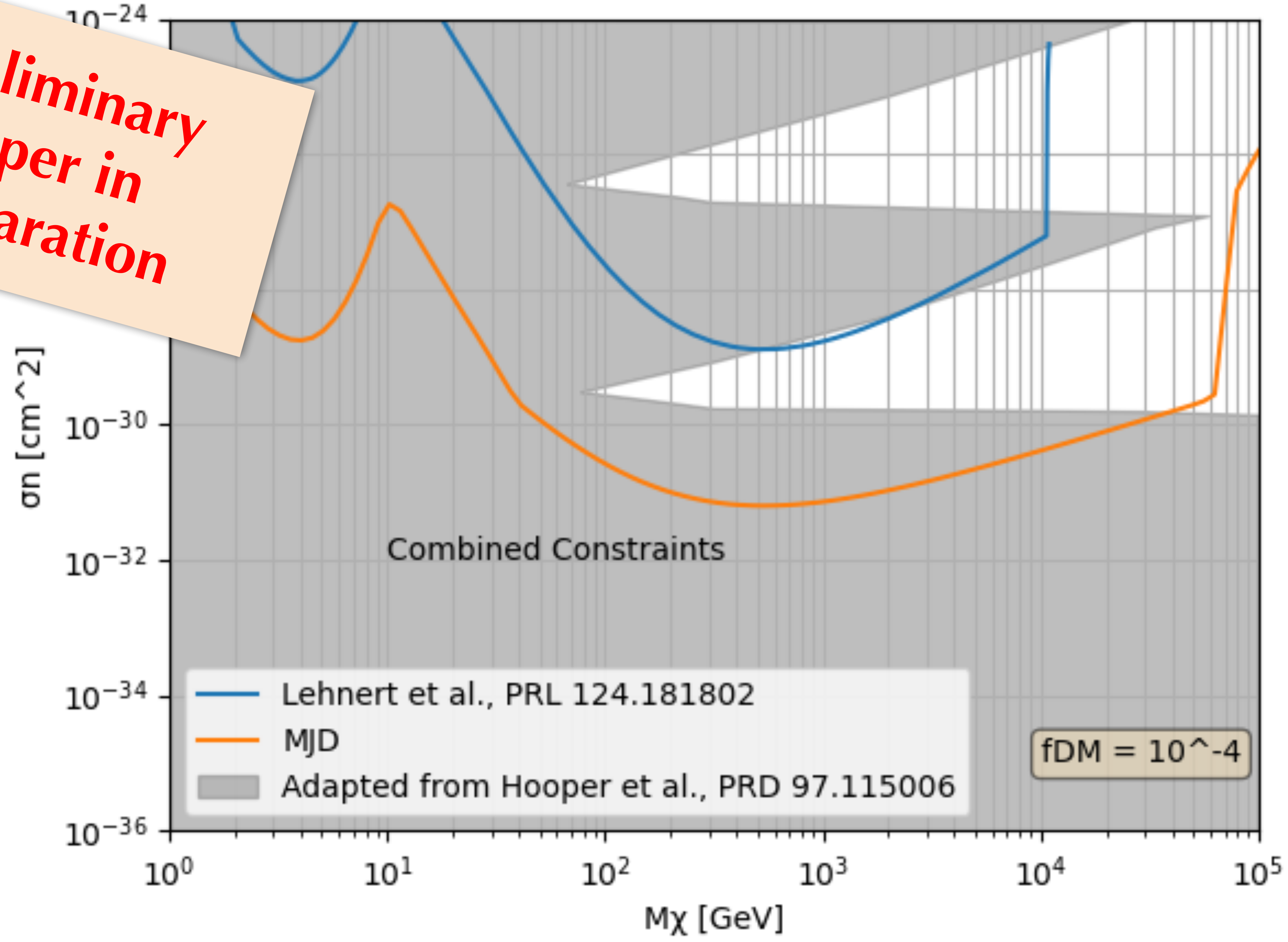
First half-life sensitivities for classic
β-decays and electron captures > 10^{19} years
(only some α and $\beta\beta$ longer)

Improvements of 2-3 orders of magnitude

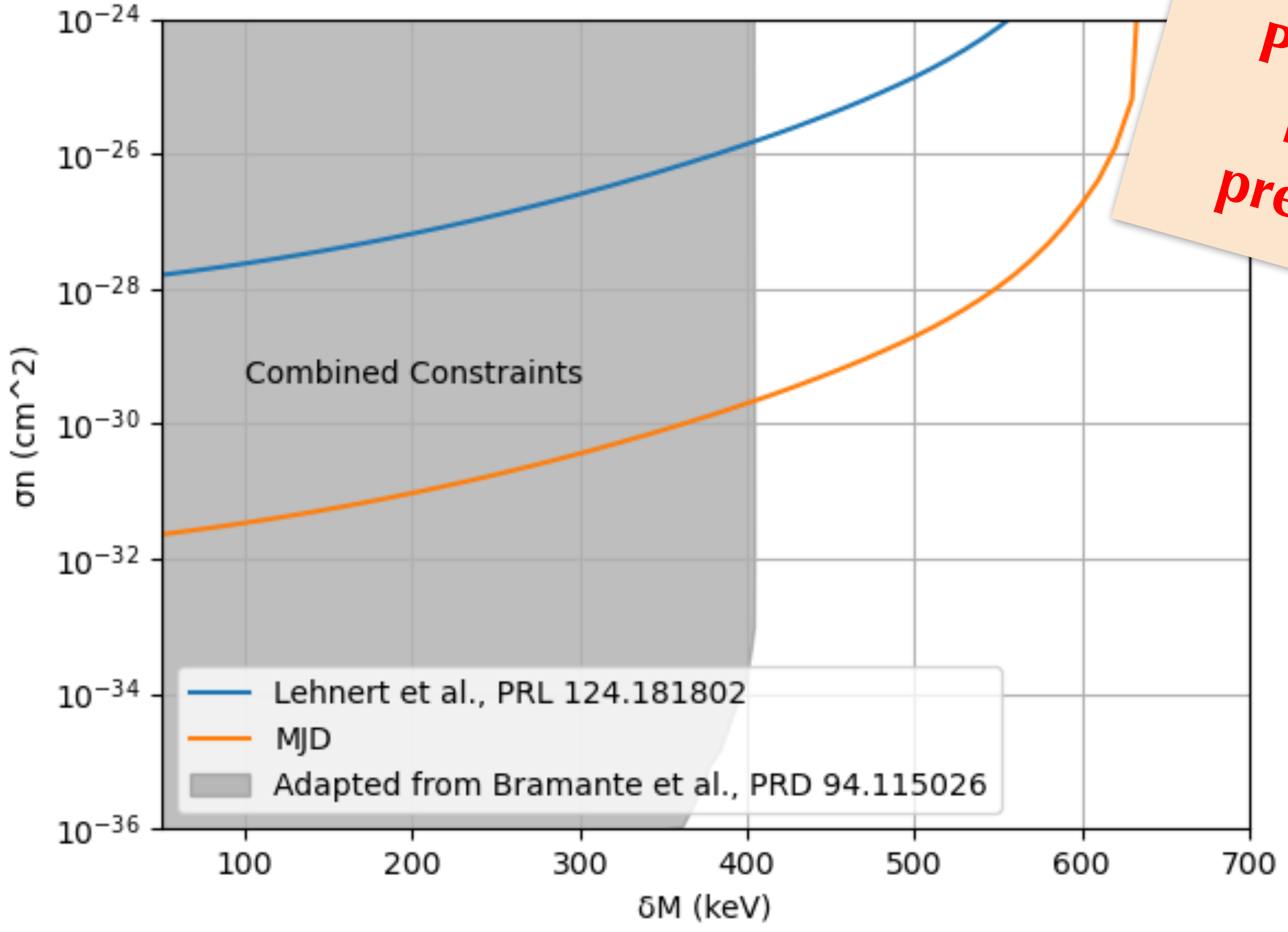
Dark matter induced deexcitation

- No observation of ^{180m}Ta decay → no DM-induced decay
- Improved sensitivities to DM models that couple to nuclei (left)
- Additional sensitivities to more complex DM with multiple states and or particles (right)





Preliminary Paper in preparation



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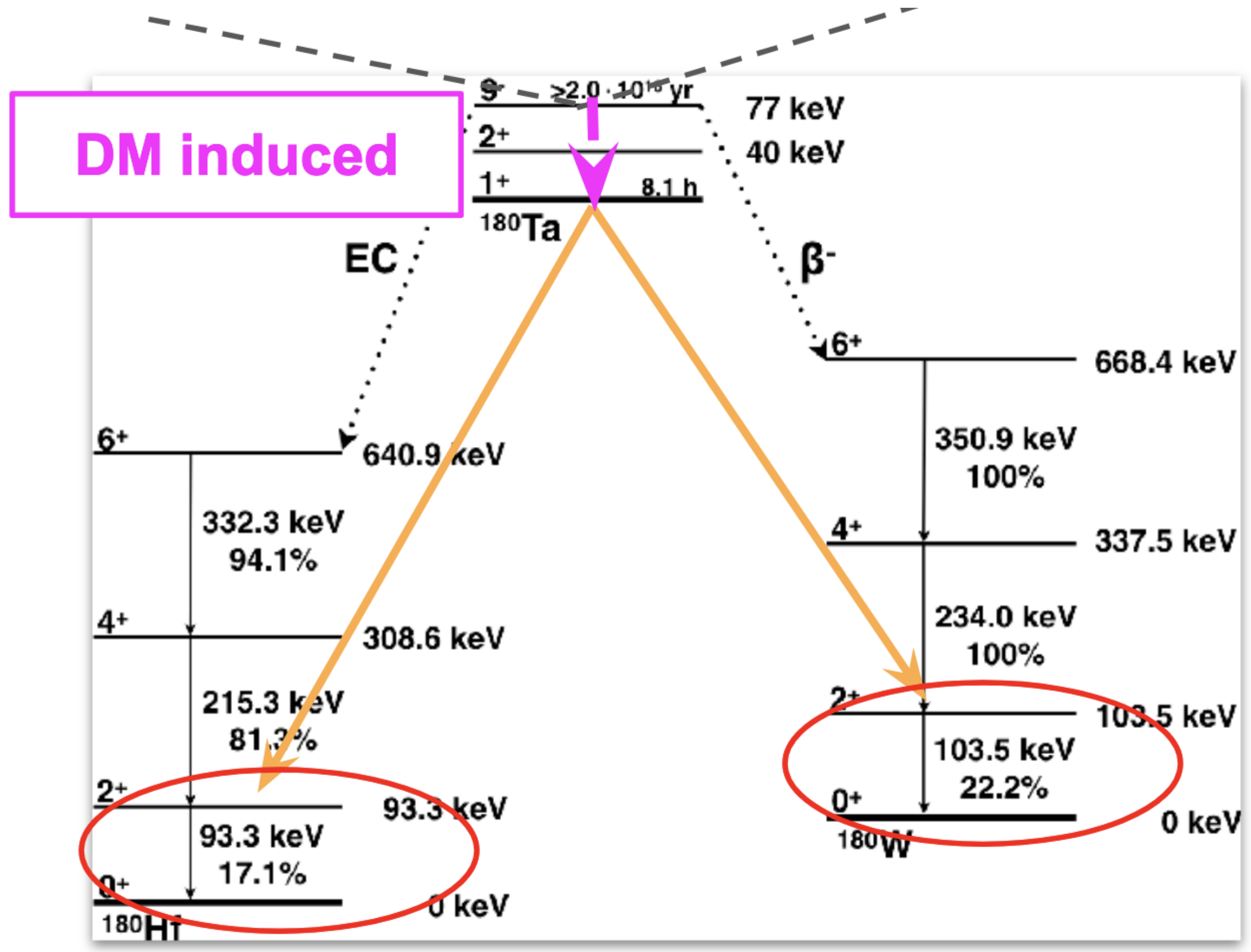

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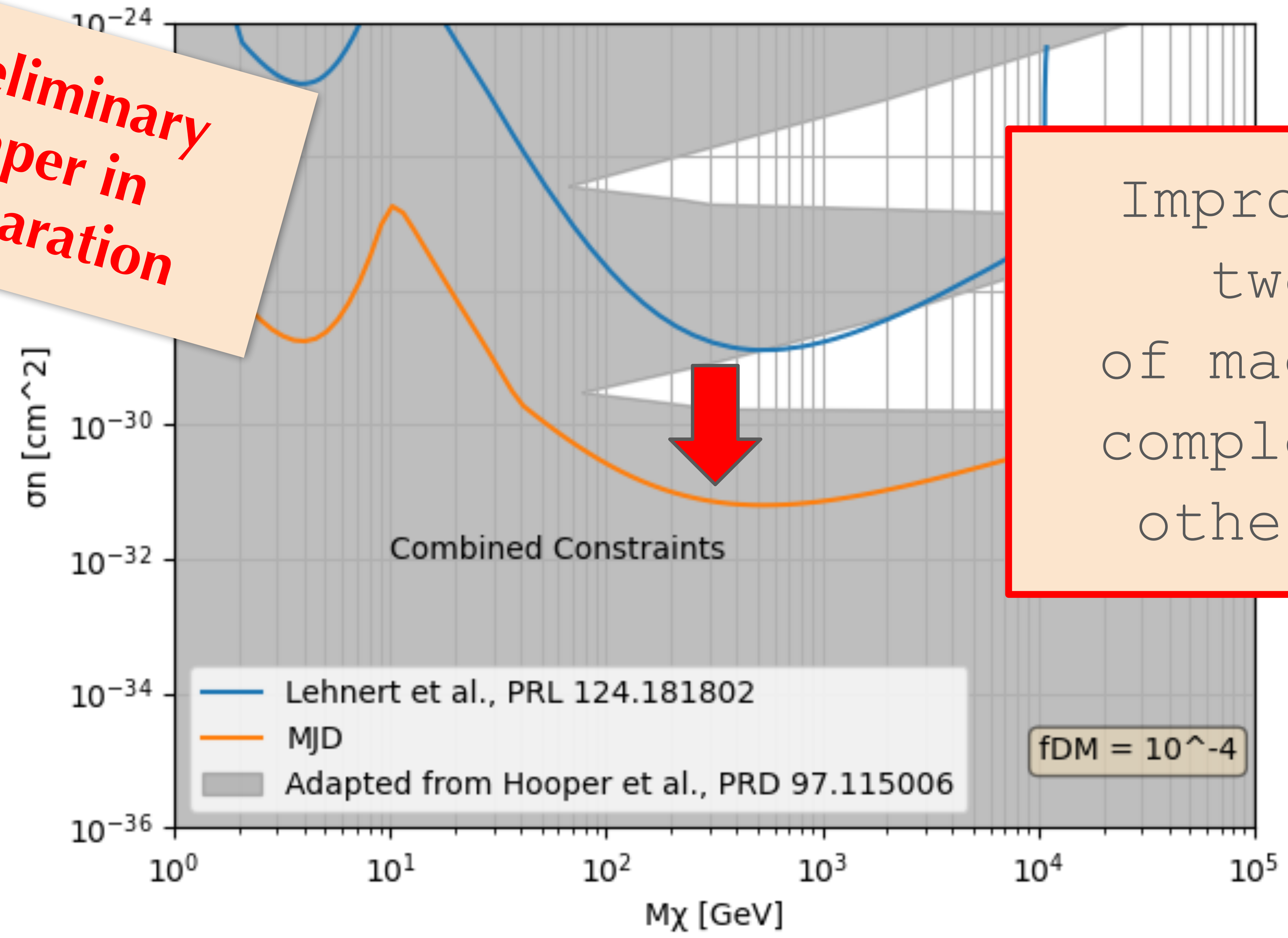
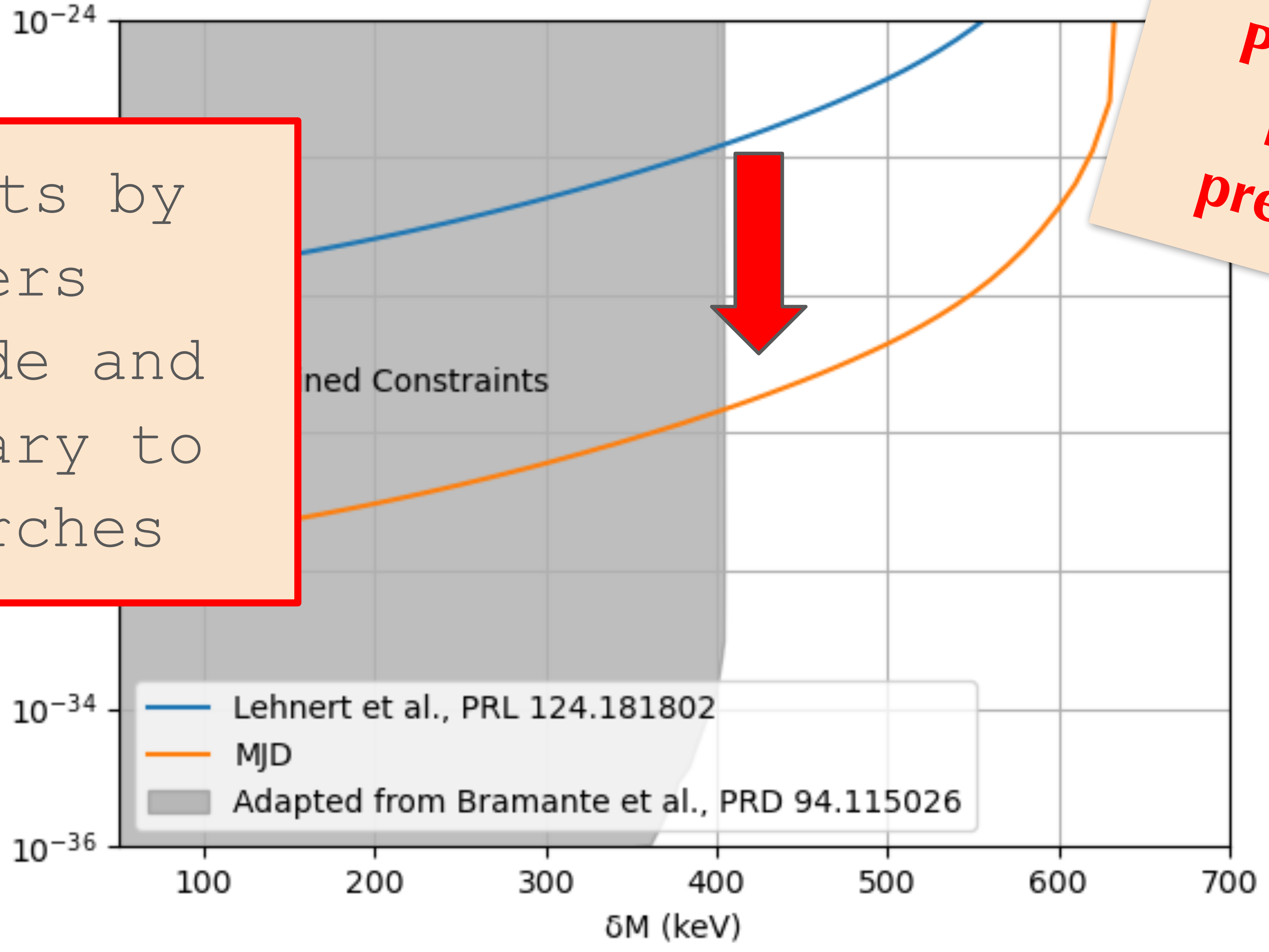


Improvements by two orders of magnitude and complementary to other searches



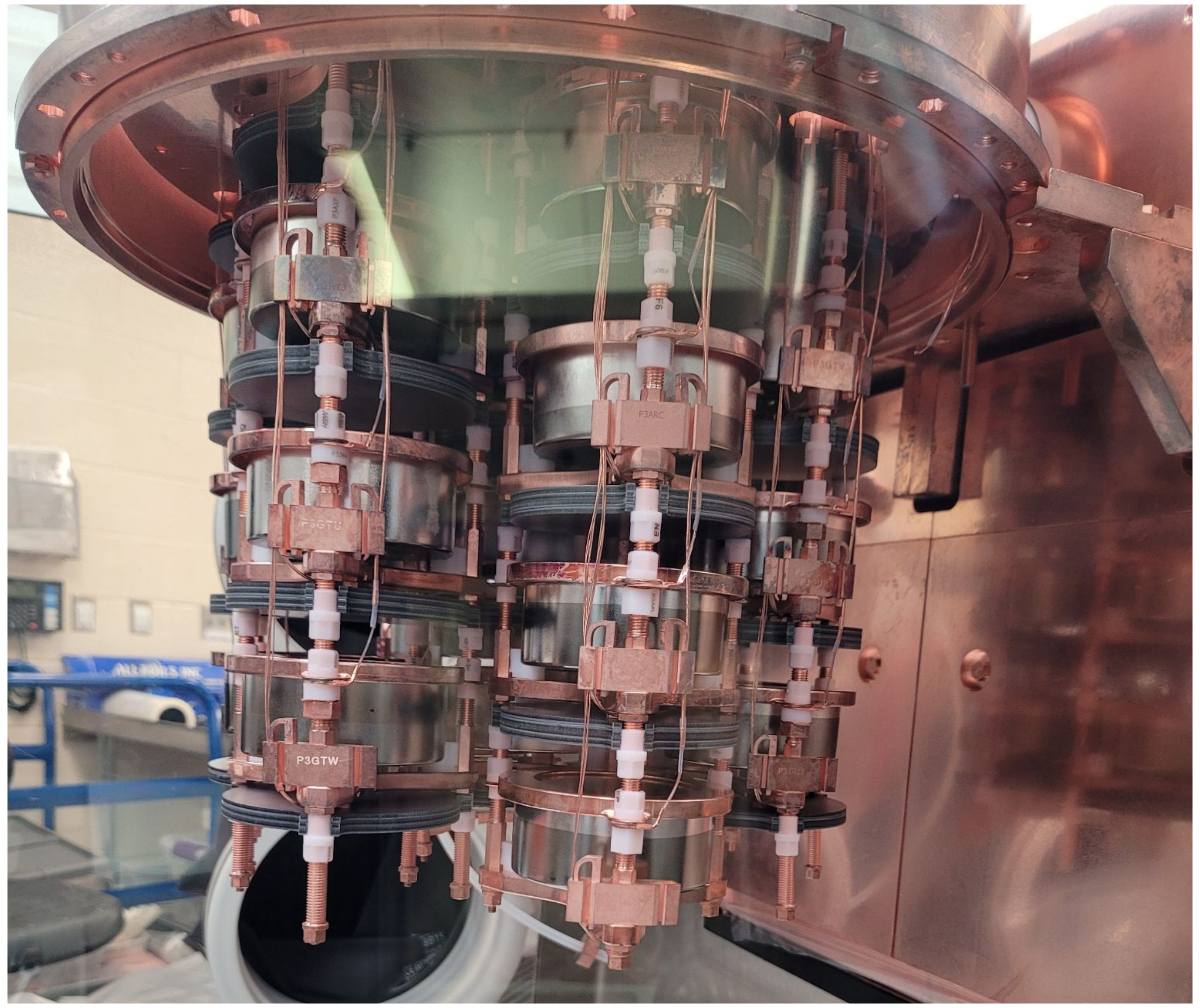
Preliminary Paper in preparation

Summary

- Most sensitive search for half-life measurements in isomers world-wide
  - First data improved previous measurements by **2-3 orders of magnitude**
  - Background continues to improve
  - Estimated **final sensitivity of 10^{19} years** <u>in all channels</u> has the potential to discover the decay
- Made possible by
  - The unique facility at SURF
  - The cleanliness procedures and performance of the Majorana experiment
  - LANL LDRD - LA-UR-23-21726

Los Alamos
NATIONAL LABORATORY
EST.1943

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT



Review, summary, and thanks!

Overview of MAJORANA, and final neutrinoless double beta decay result

- Established methods & techniques for the next generation of Ge experiments

Studies of radioactive backgrounds and developing a background model

- Developed a better understanding of background sources

Search for beyond standard model physics, including dark matter

- Auxiliary searches increase the impact of large underground arrays

First results from a search for the decay of nature's rarest isotope - Tantalum-180

- Continuing to get excellent science from the MAJORANA DEMONSTRATOR!

We thank the support of 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. We thank the LANL LDRD support for the Ta research.