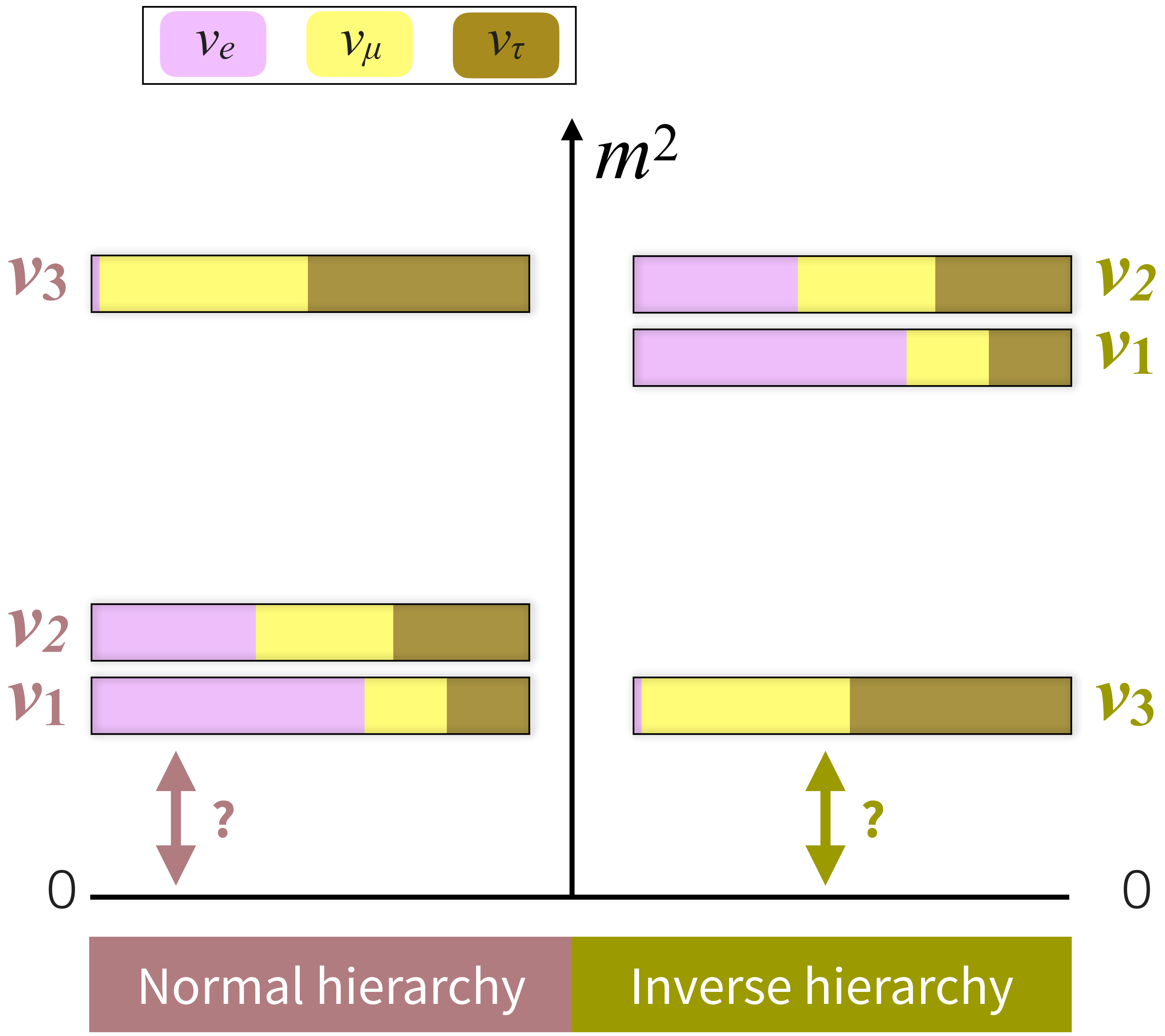
Science and Technology Facilities Council

Neutrinoless double-beta decay

Cheryl Patrick STFC Ernest Rutherford Fellow, University of Edinburgh

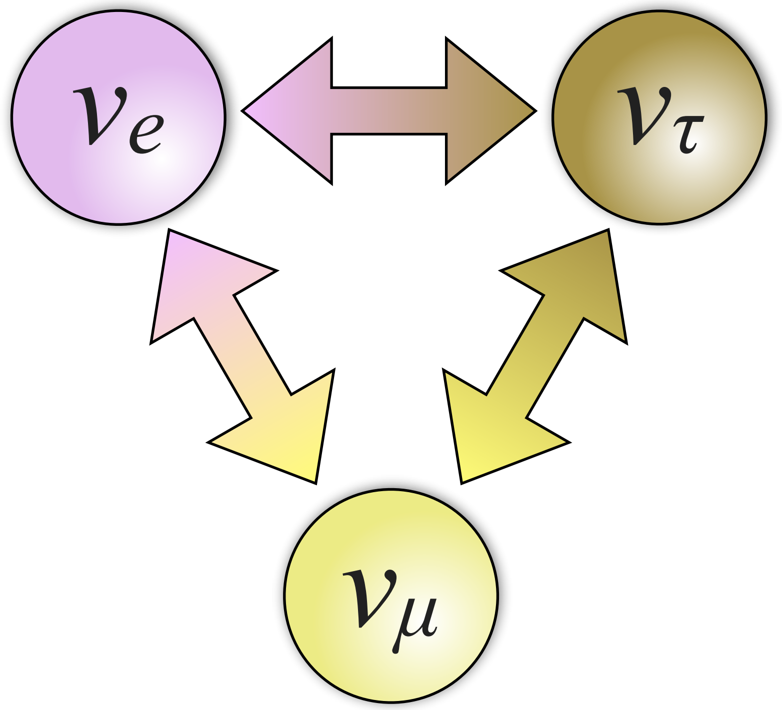
THE UNIVERSITY of EDINBURGH

Neutrinos - unanswered questions



Which neutrino is lightest?

Do neutrinos violate CP symmetry?

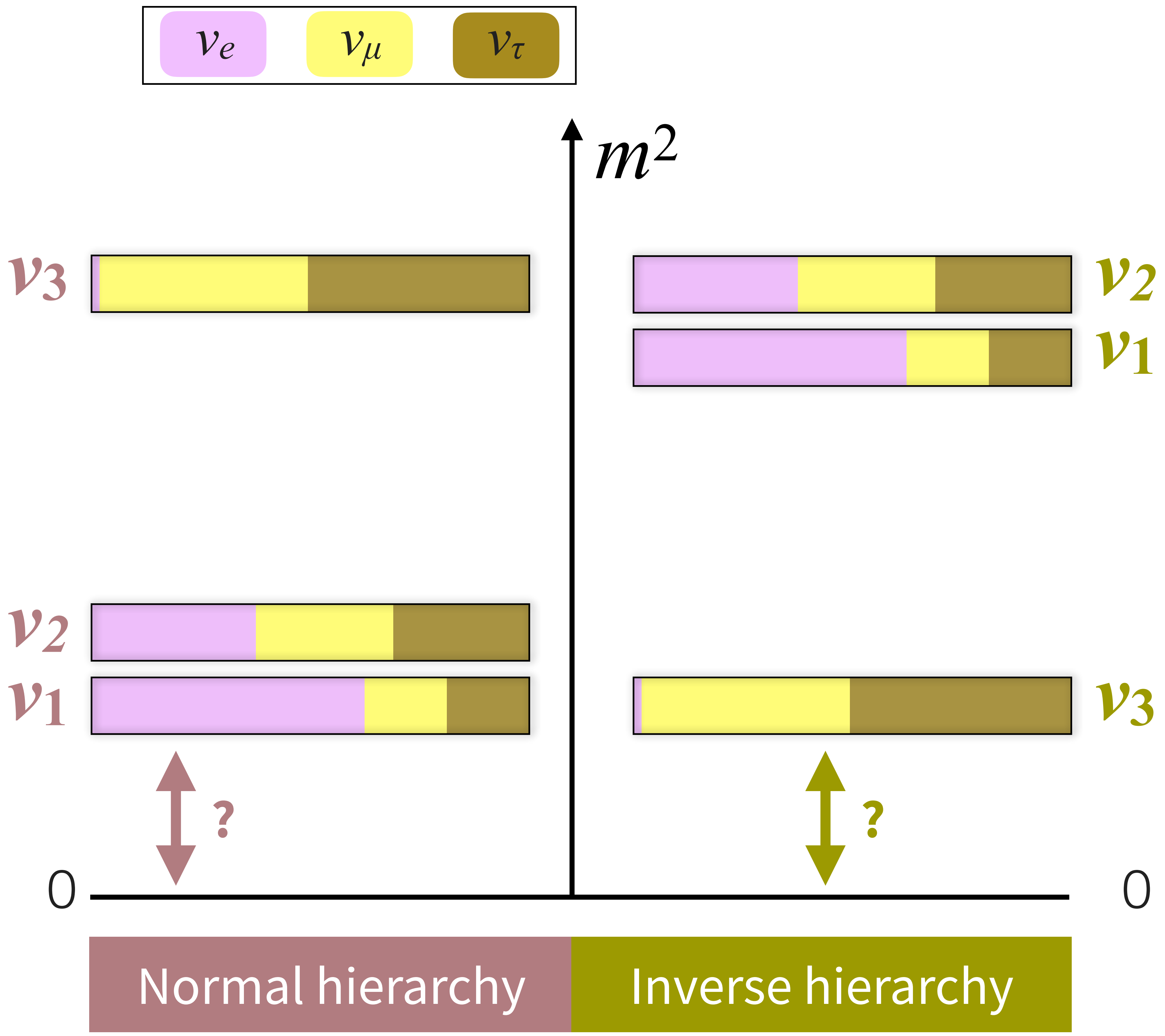


Neutrino oscillations

What's the absolute mass scale?

How do neutrinos get their mass?

Neutrinos - unanswered questions



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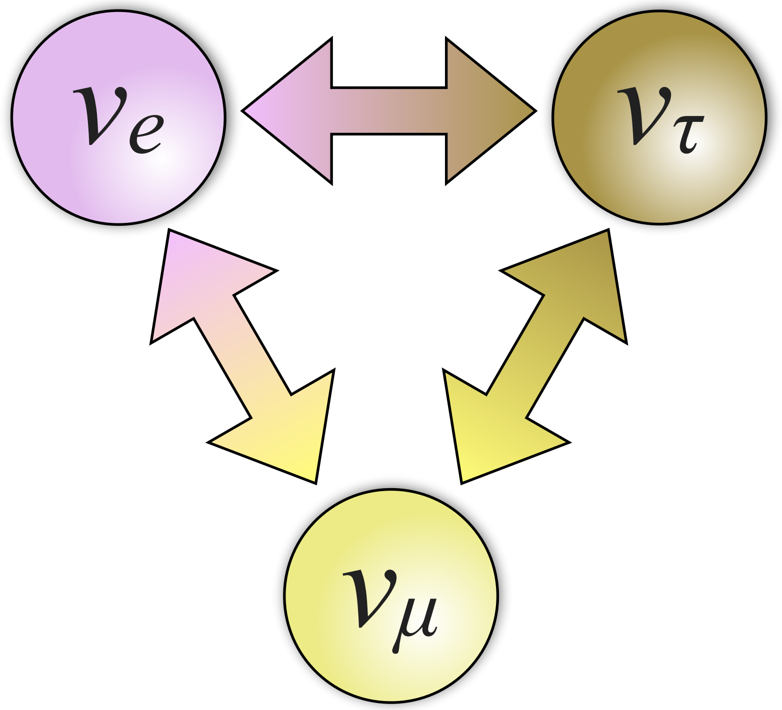

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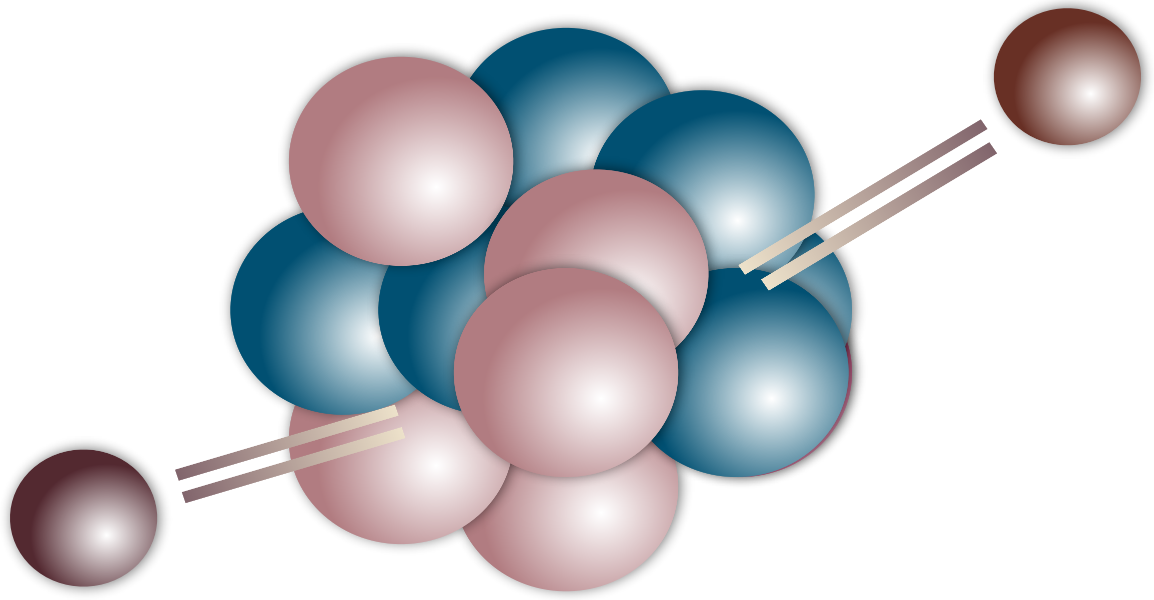
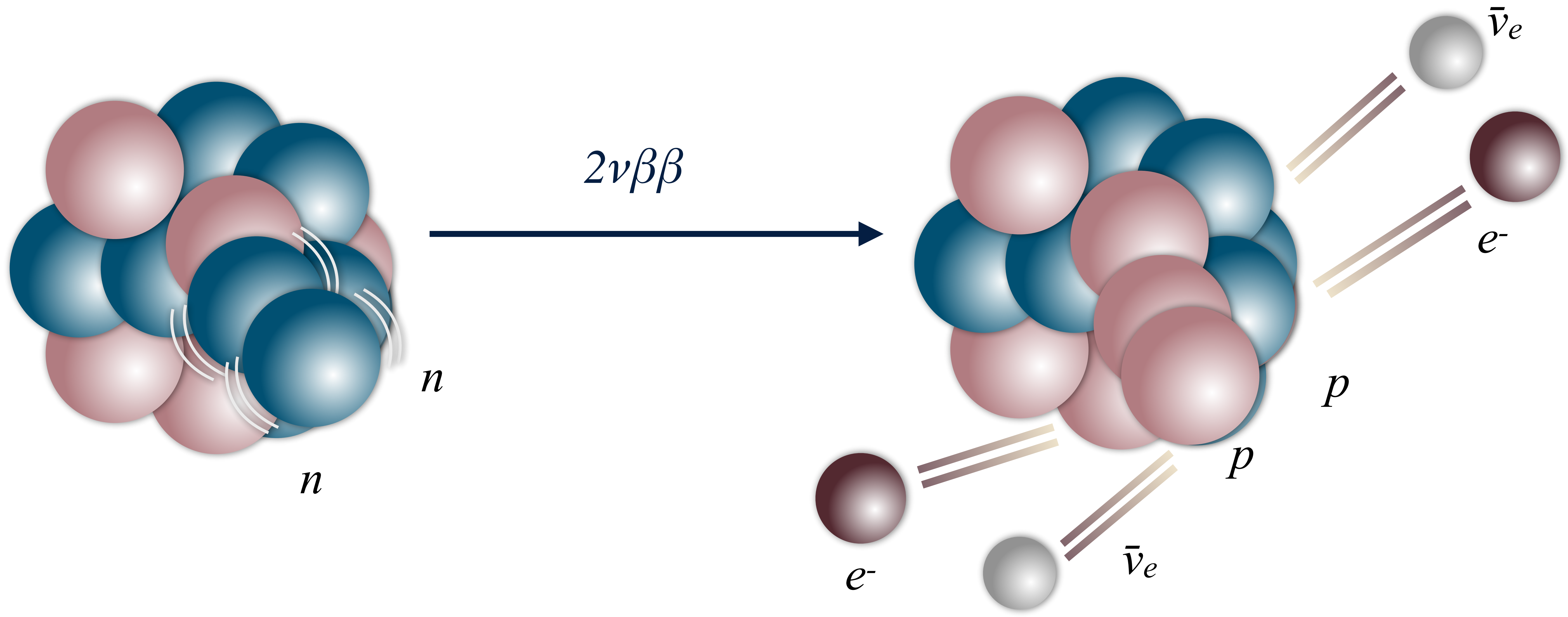
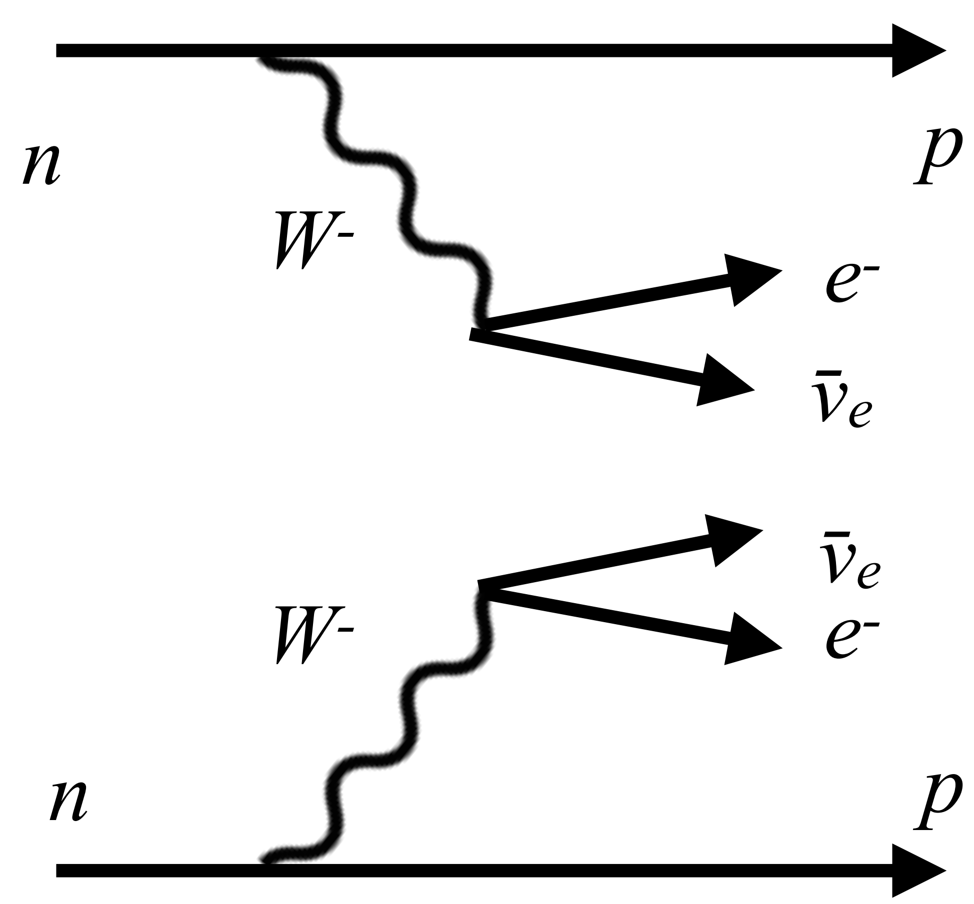


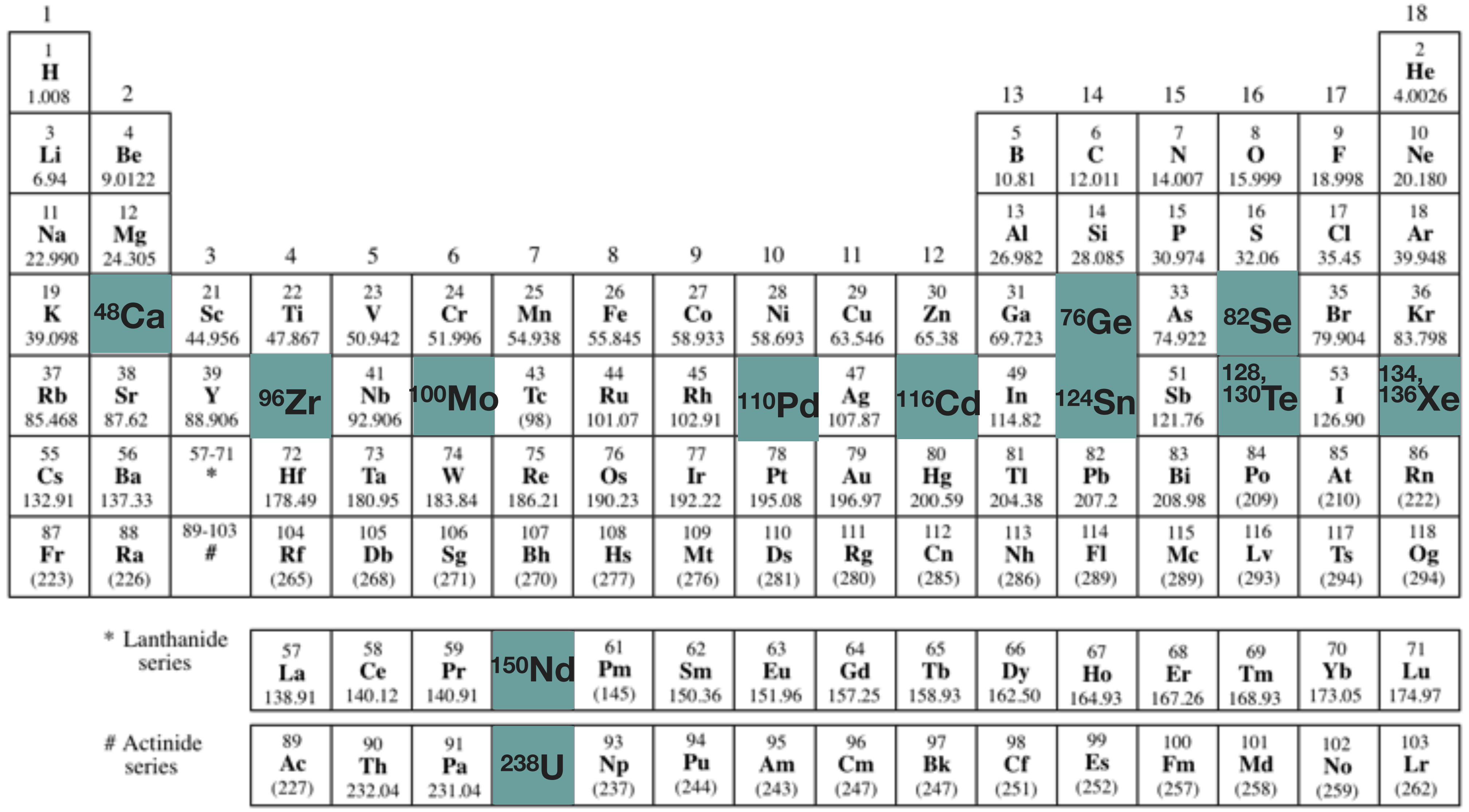
Neutrinoless double-beta decay

Standard-model double-beta decay *($2\nu\beta\beta$)*





- Standard Model process
- Lepton number conserved
- Doubly weak = long half-life
- Observed in several isotopes; $T_{½}$ ~ 10^{20} years



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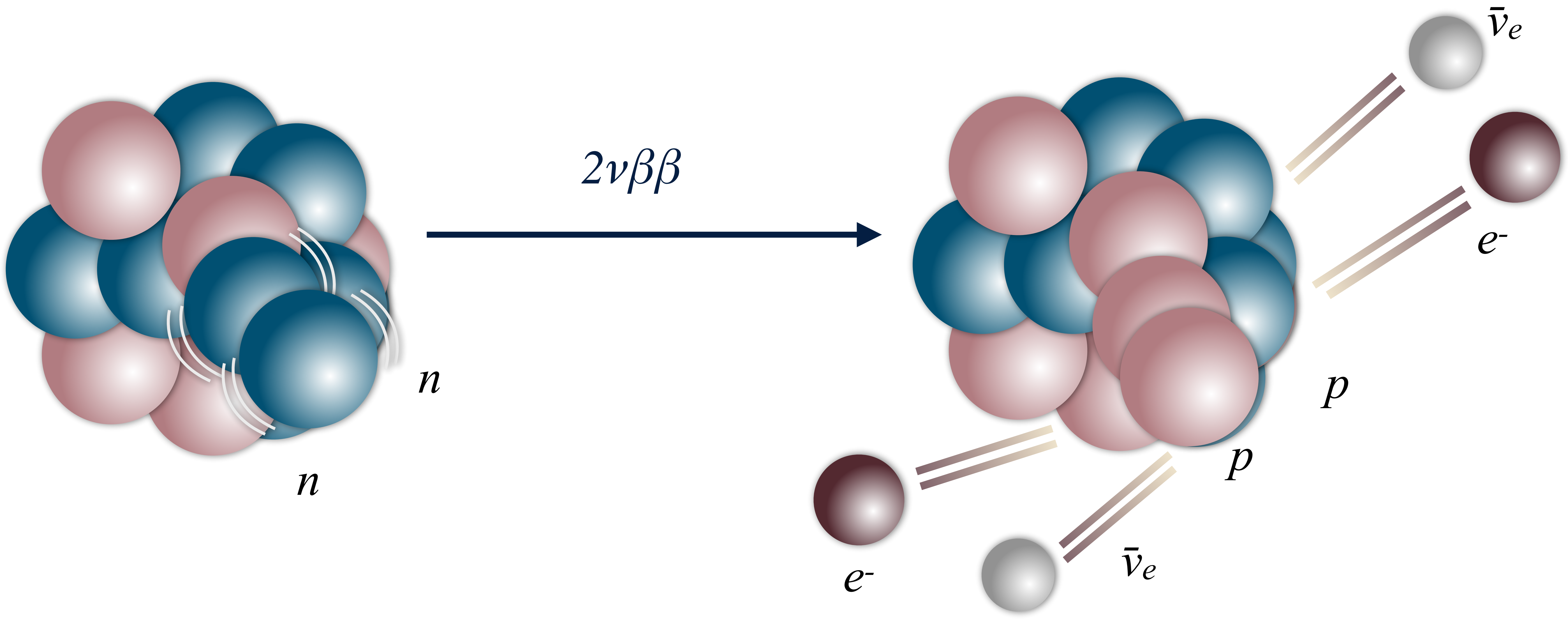

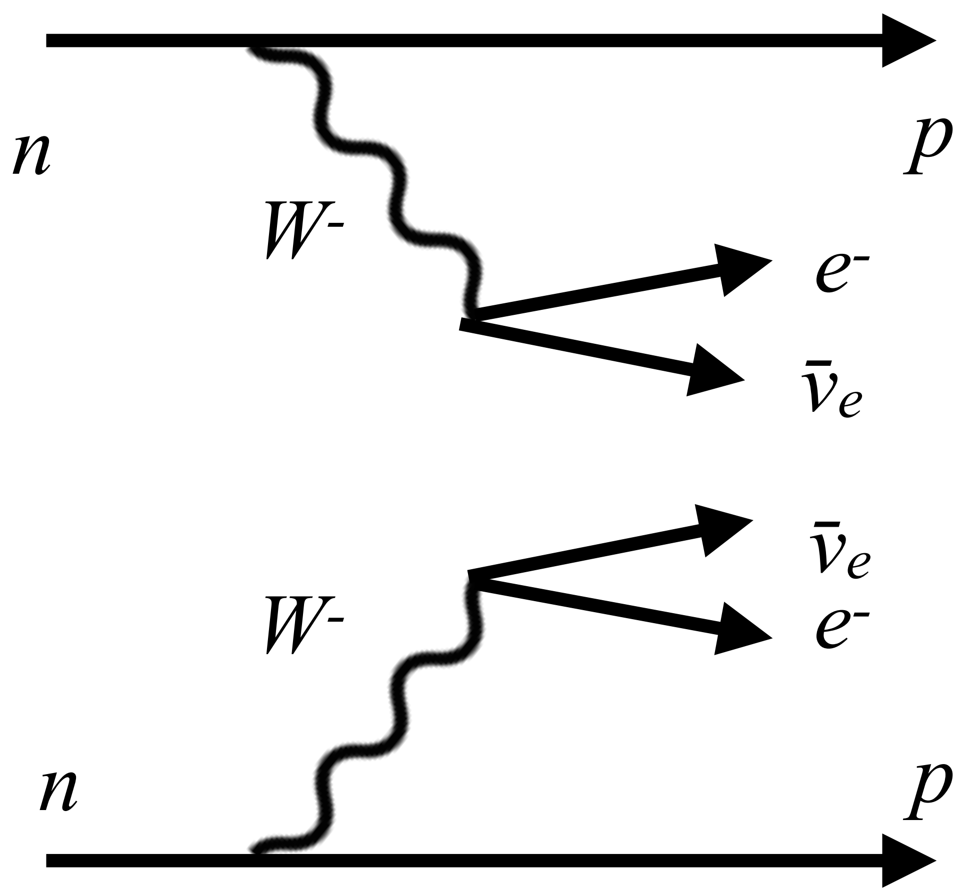

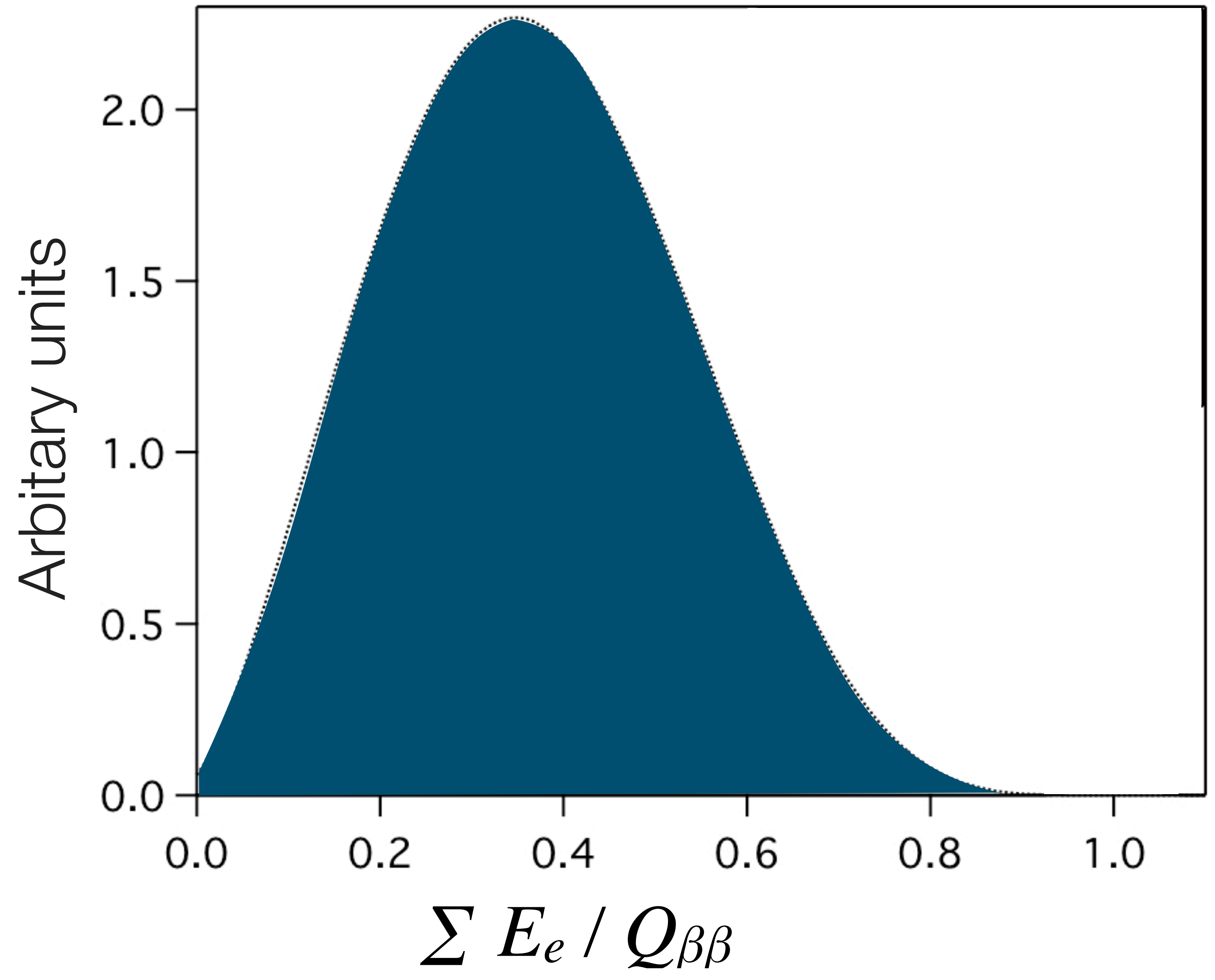

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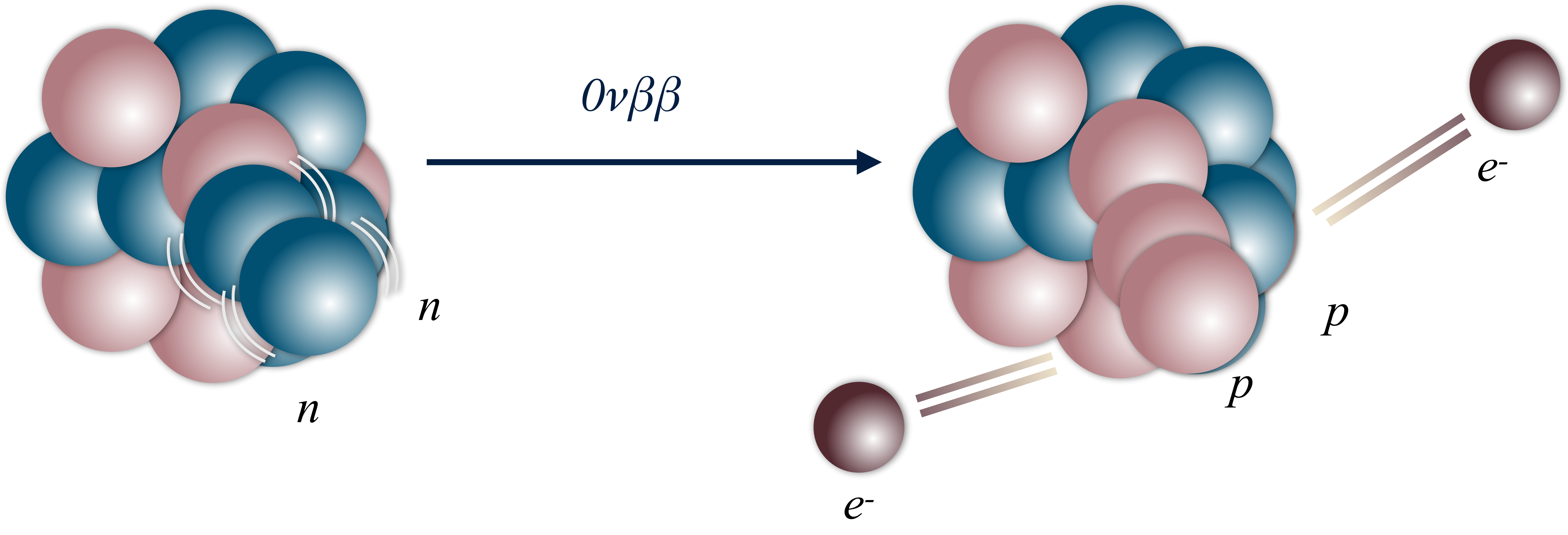
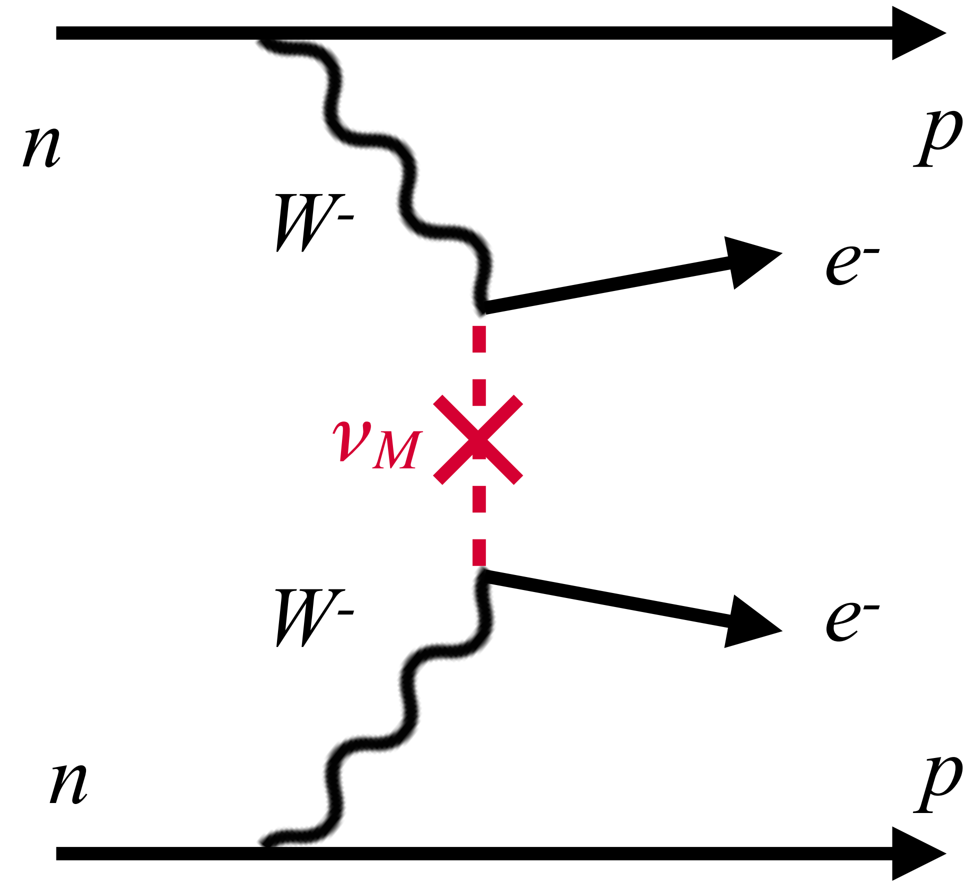
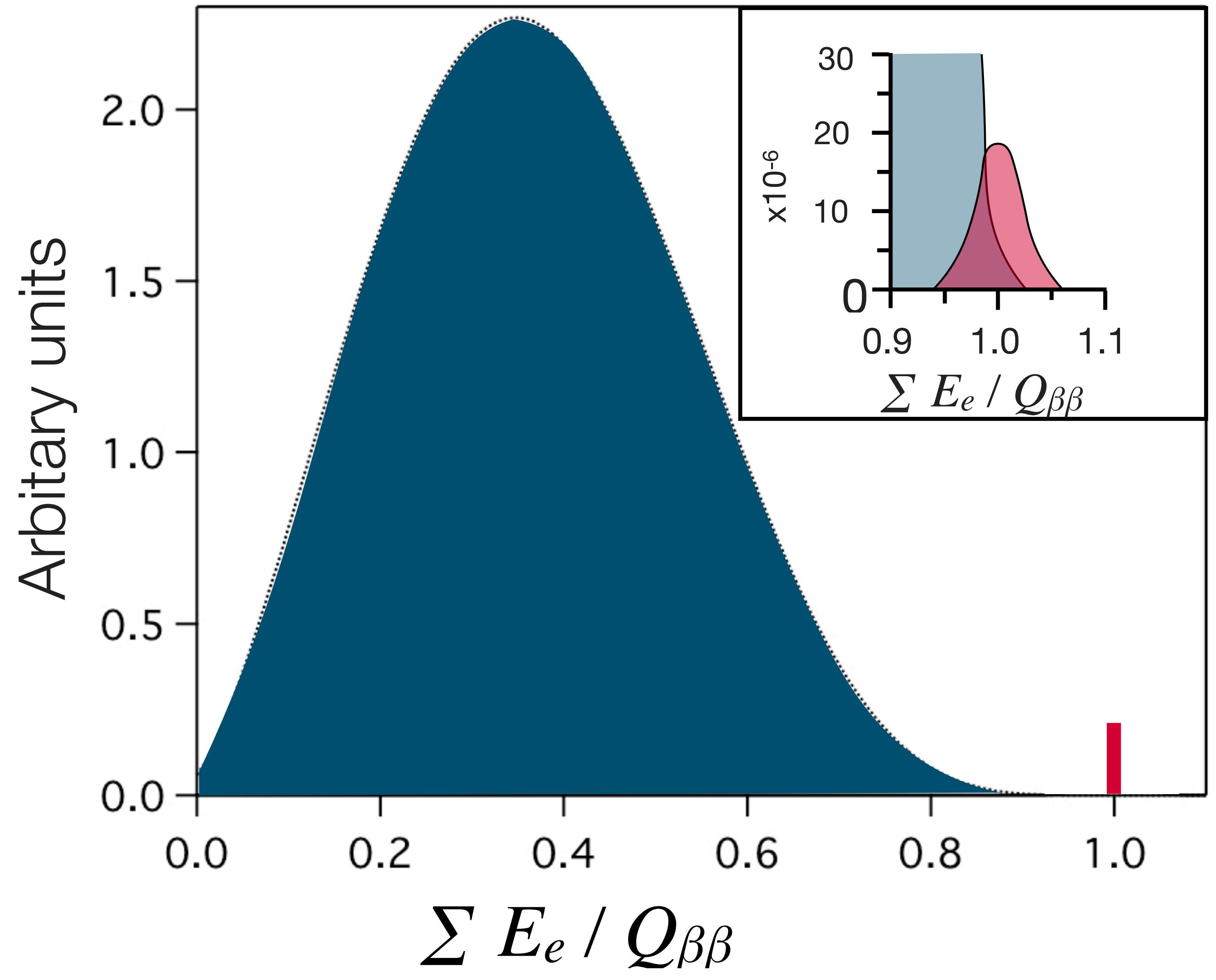
Neutrinoless double-beta decay ($0\nu\beta\beta$)

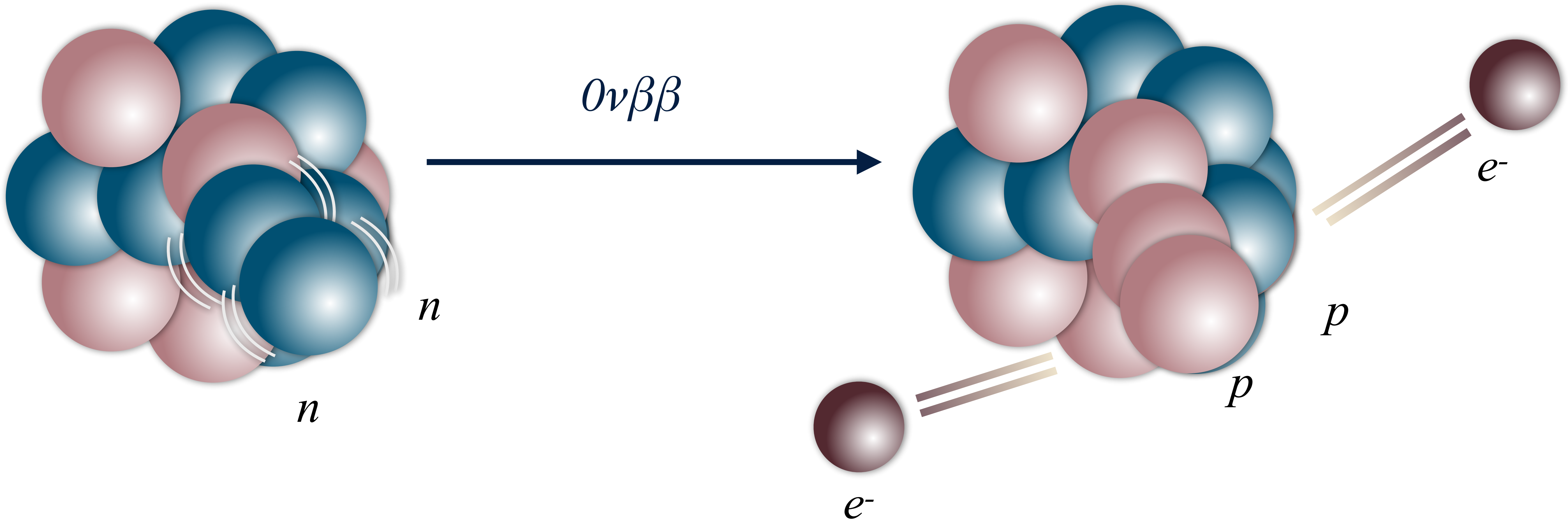


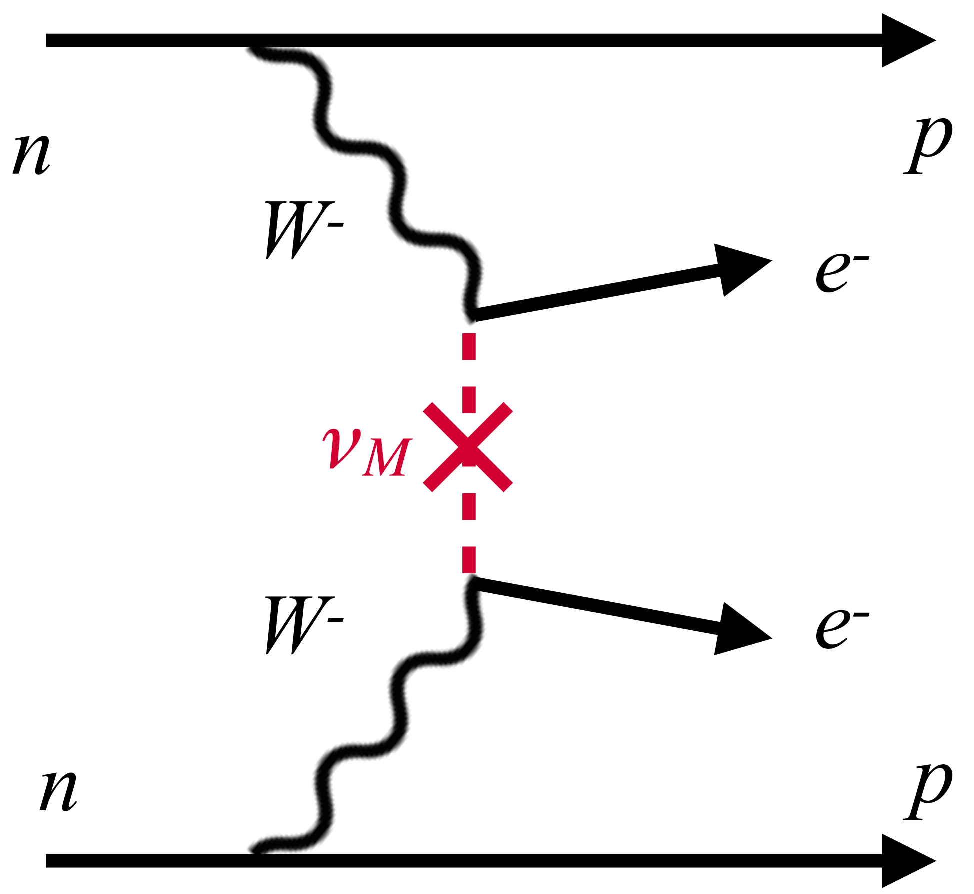


- No neutrinos in final state
- Virtual Majorana neutrino exchanged (various models available)
- All $2\nu\beta\beta$ isotopes are $0\nu\beta\beta$ candidates
- Not yet observed - $T_{½} > 10^{24}$ - 10^{26} years



Neutrinoless double-beta decay *($0\nu\beta\beta$)*





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If seen, $0\nu\beta\beta$ would:
- be the first process observed to create matter without antimatter
- prove that neutrinos are Majorana fermions
- tell us about absolute neutrino mass

$0\nu\beta\beta$ and neutrino mass

$0\nu\beta\beta$ rate

$$\frac{1}{T_{1/2}^{0\nu\beta\beta}} = G_{0\nu}(Q_{\beta\beta}, Z) g_A^4 |M_{0\nu}|^2 \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2}$$

Isotope-dependent

$0\nu\beta\beta$ and neutrino mass

$0\nu\beta\beta$ rate $$\frac{1}{T_{1/2}^{0\nu\beta\beta}} = G_{0\nu}(Q_{\beta\beta}, Z) g_A^4 |M_{0\nu}|^2 \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2}$$

Mixing fractions (known from oscillations)

$$m_{\beta\beta} = c_{12}^2 c_{13}^2 m_{\nu_1} + s_{12}^2 c_{13}^2 m_{\nu_2} e^{i\phi_{12}} + s_{13}^2 m_{\nu_3} e^{i\phi_{13}}$$

Individual neutrino masses

CP-violating Majorana phases (unknown)

$0\nu\beta\beta$ and neutrino mass

$0\nu\beta\beta$ rate $$\frac{1}{T_{1/2}^{0\nu\beta\beta}} = G_{0\nu}(Q_{\beta\beta}, Z) g_A^4 |M_{0\nu}|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

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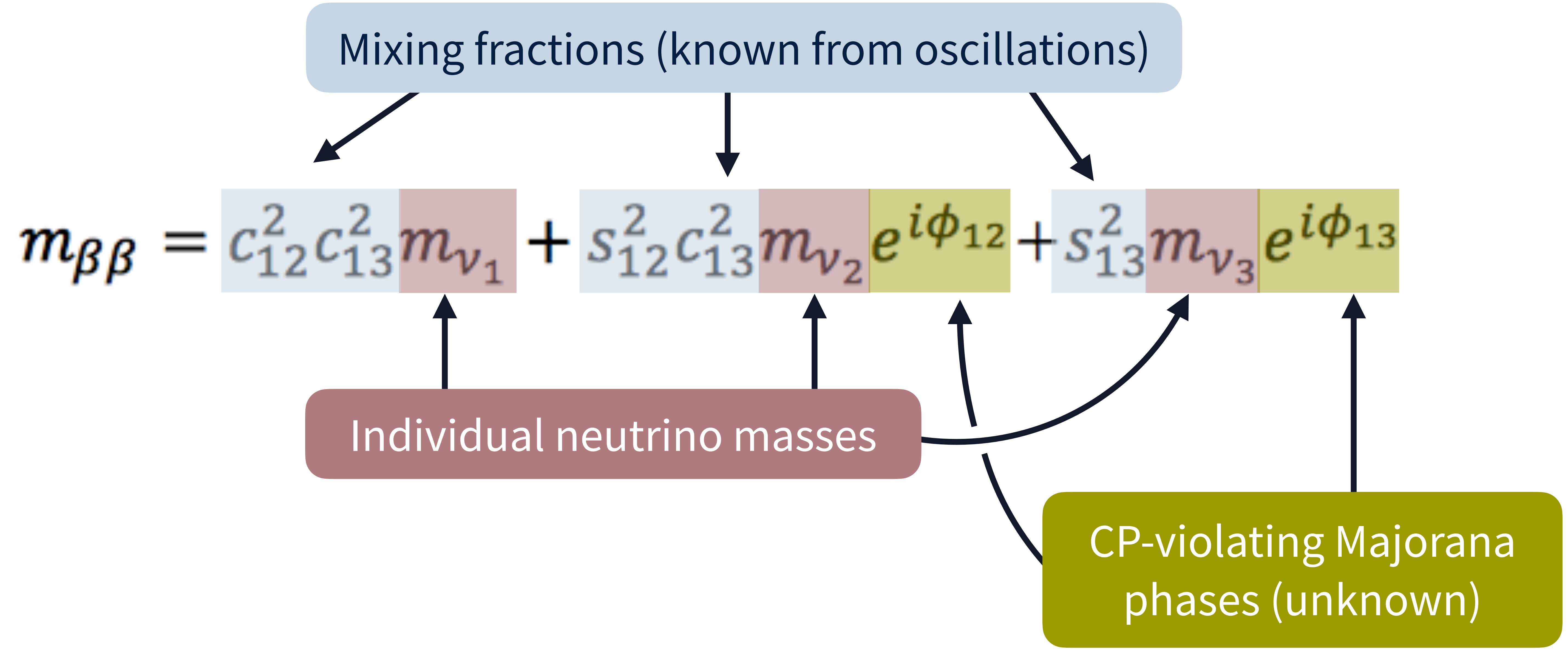
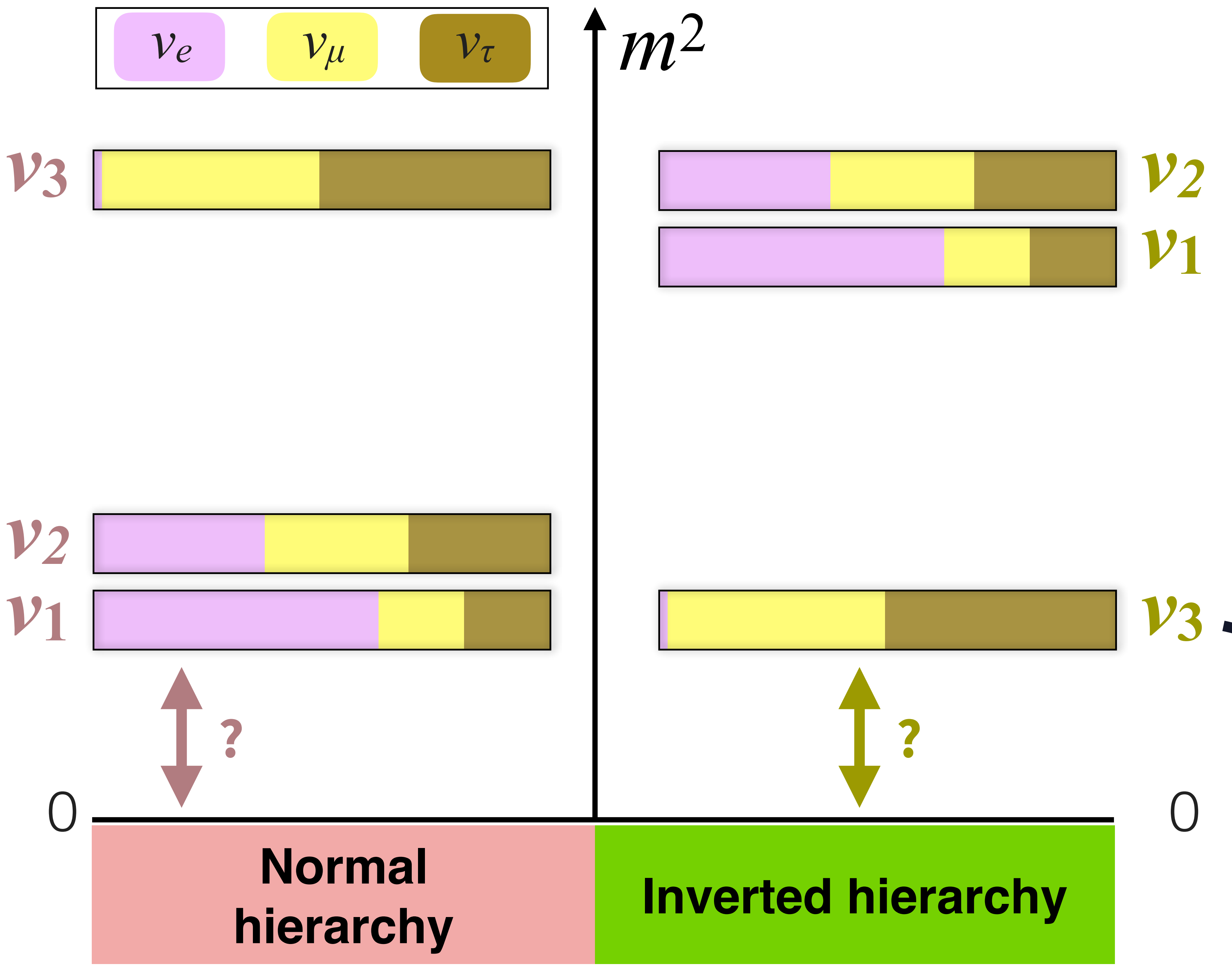


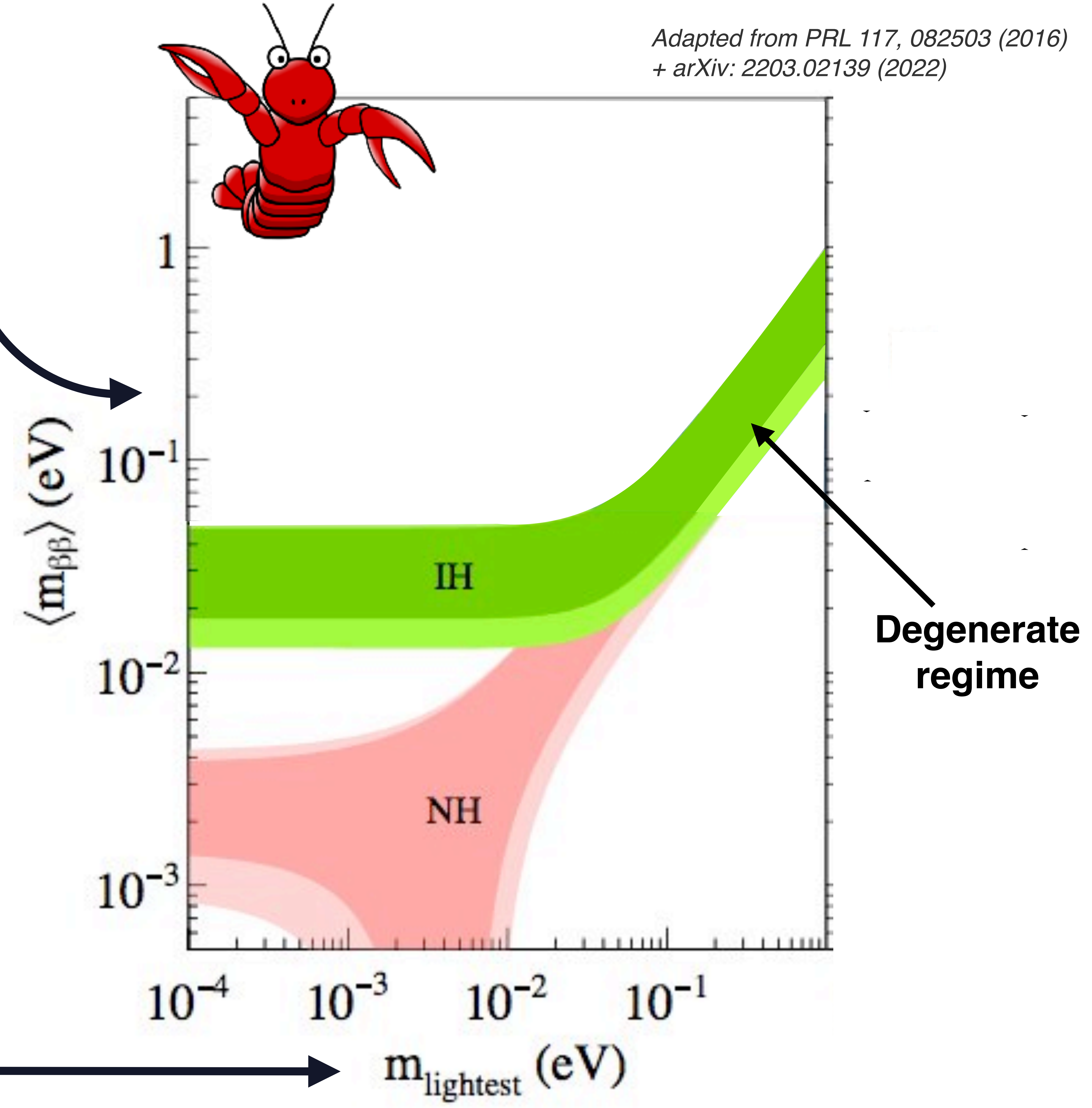
Complementary to:

- Oscillations
- Cosmology
- β decay endpoints

$0\nu\beta\beta$ and neutrino mass

$0\nu\beta\beta$ rate
$$\frac{1}{T_{1/2}^{0\nu\beta\beta}} = G_{0\nu}(Q_{\beta\beta}, Z) g_A^4 |M_{0\nu}|^2 \frac{\langle m_{\beta\beta} \rangle^2}{m_e^2}$$





Adapted from PRL 117, 082503 (2016)
+ arXiv: 2203.02139 (2022)

$0\nu\beta\beta$ and neutrino mass

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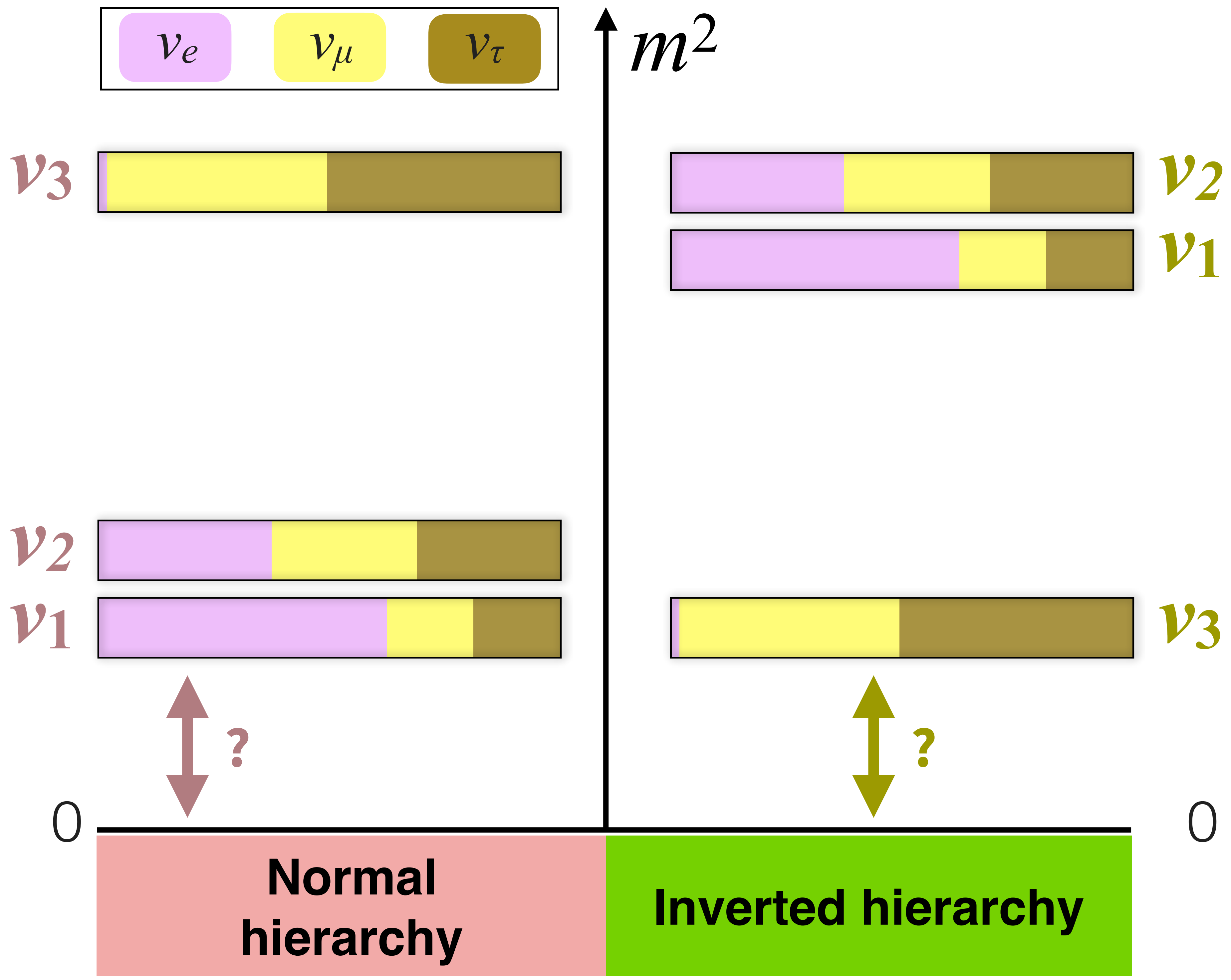

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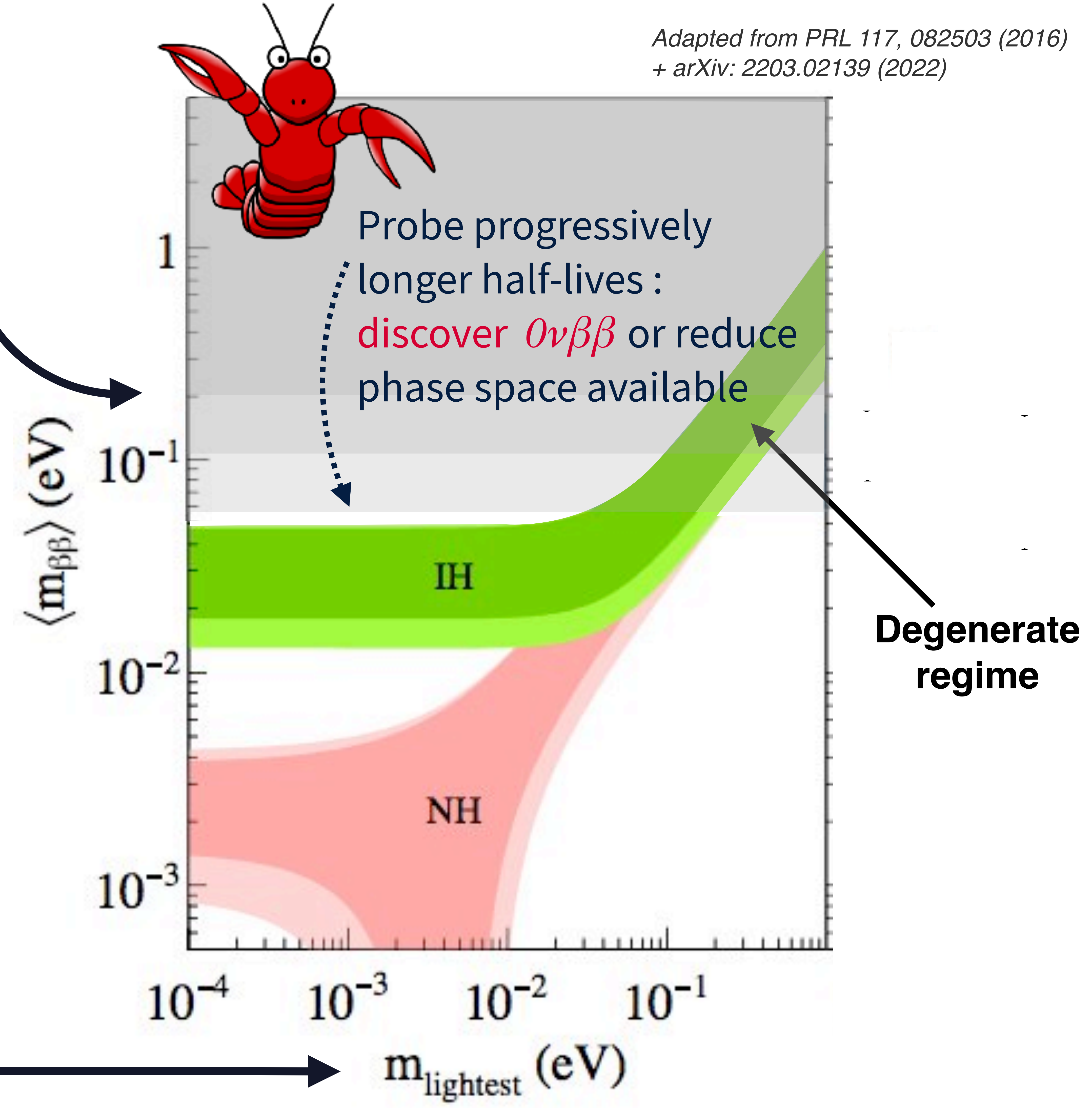

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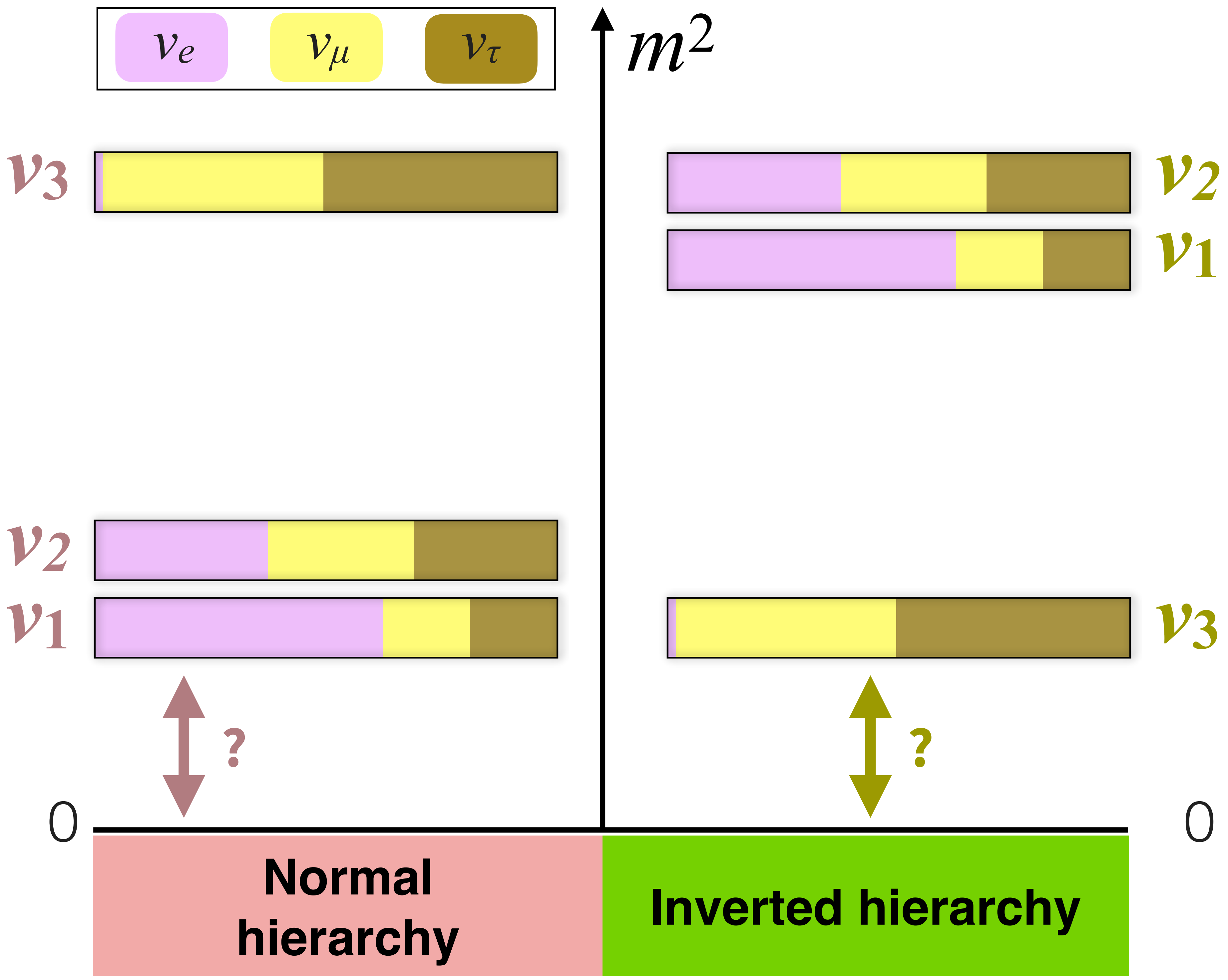

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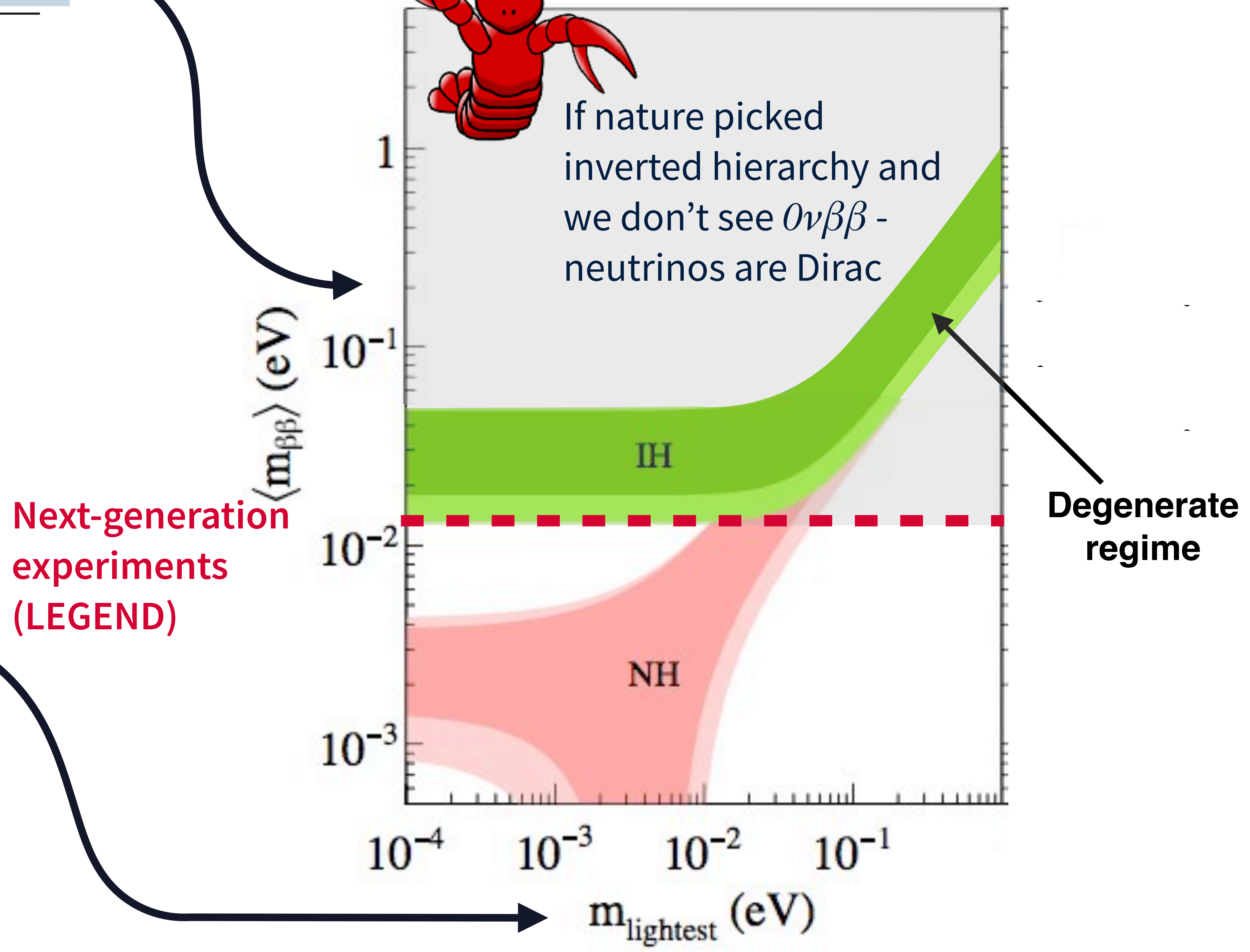
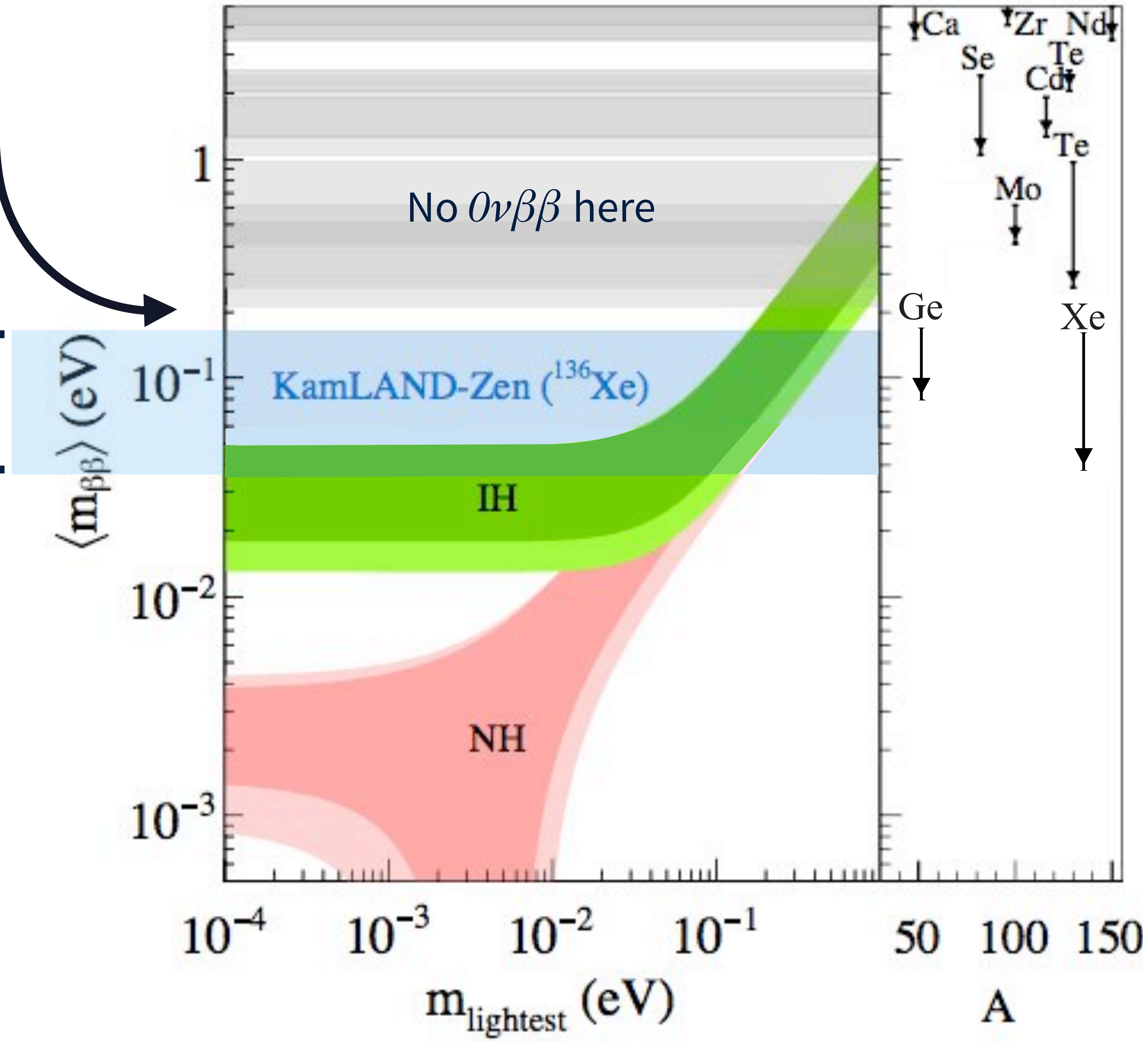


What do we know?

$0\nu\beta\beta$ rate
$$\frac{1}{T_{1/2}^{0\nu\beta\beta}} = G_{0\nu}(Q_{\beta\beta}, Z) g_A^4 |M_{0\nu}|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

Current best $m_{\beta\beta}$ limit

Adapted from PRL 117, 082503 (2016) + arXiv: 2203.02139 (2022)



What do we know? And what don't we know?

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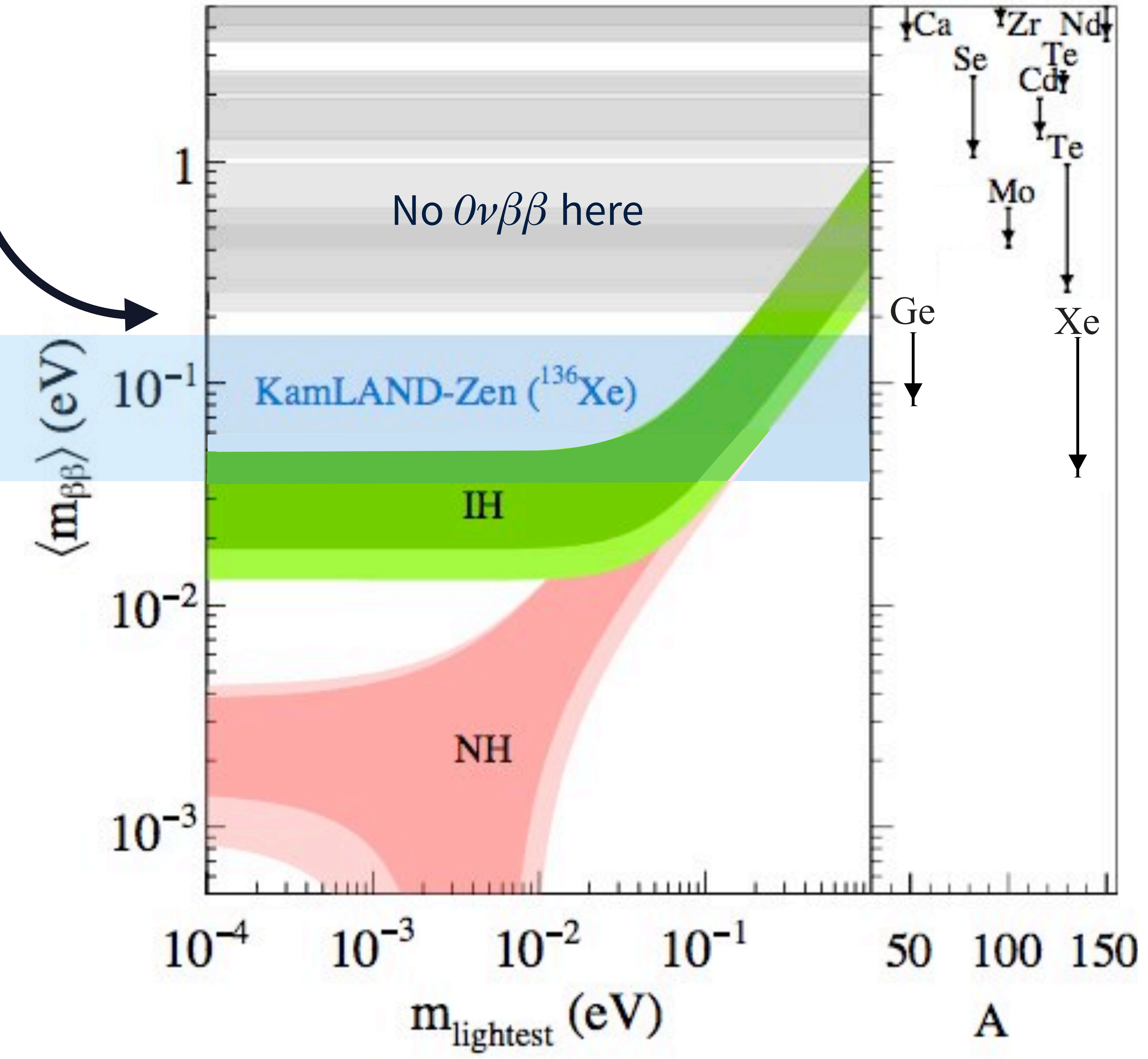

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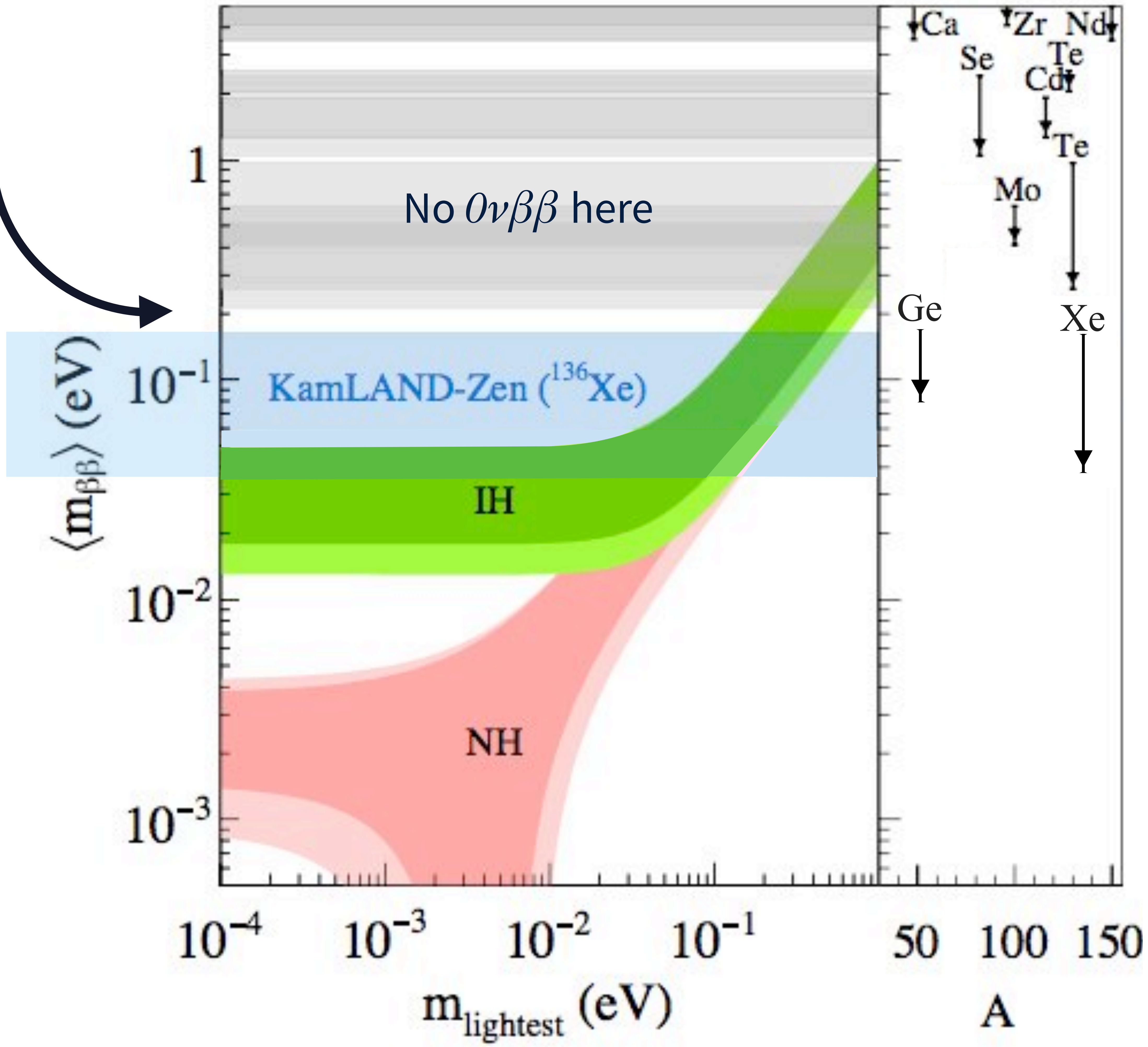

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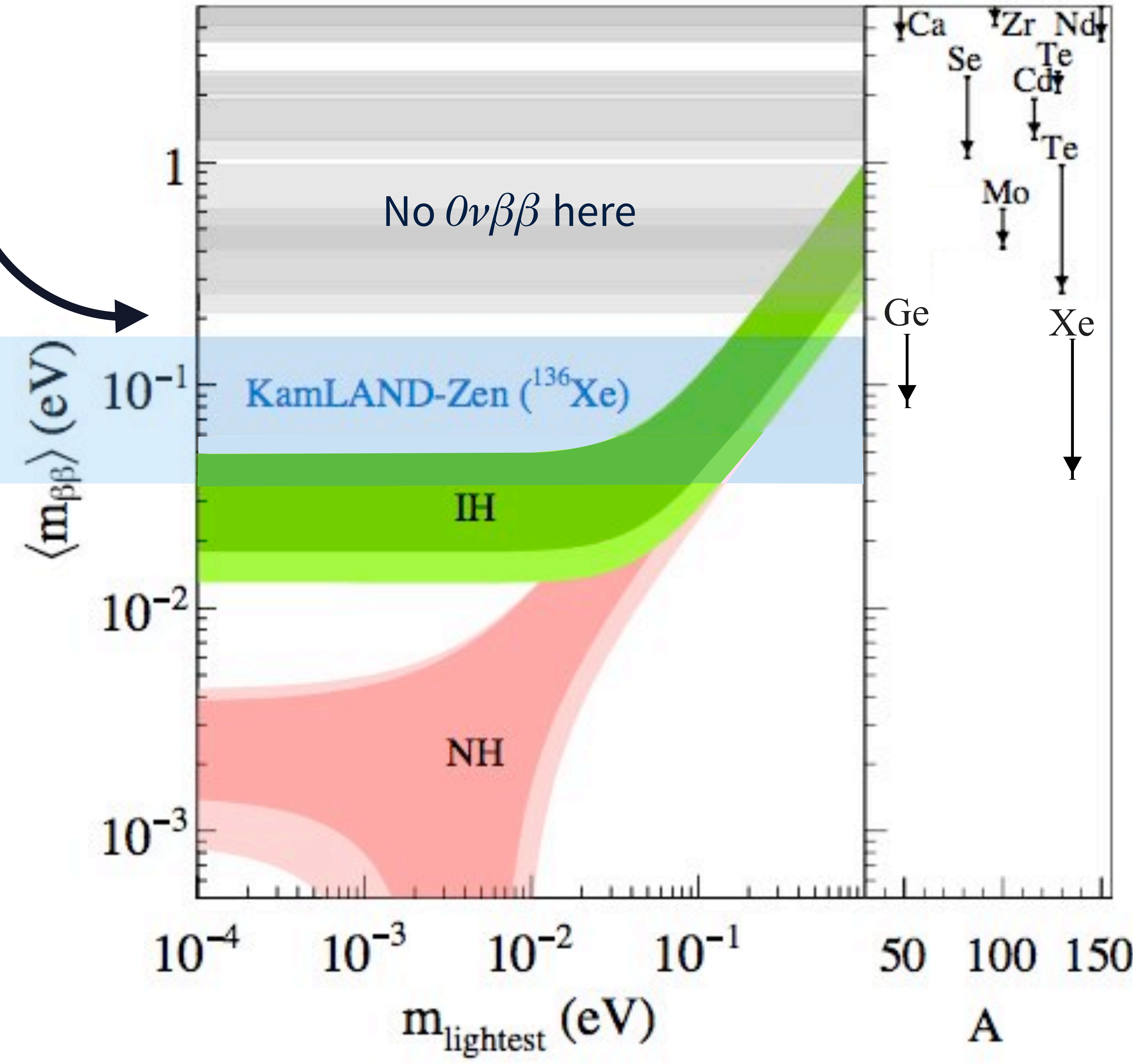

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Uncertainty on nuclear matrix element leads to broad $m_{\beta\beta}$ band

Current best $m_{\beta\beta}$ limit

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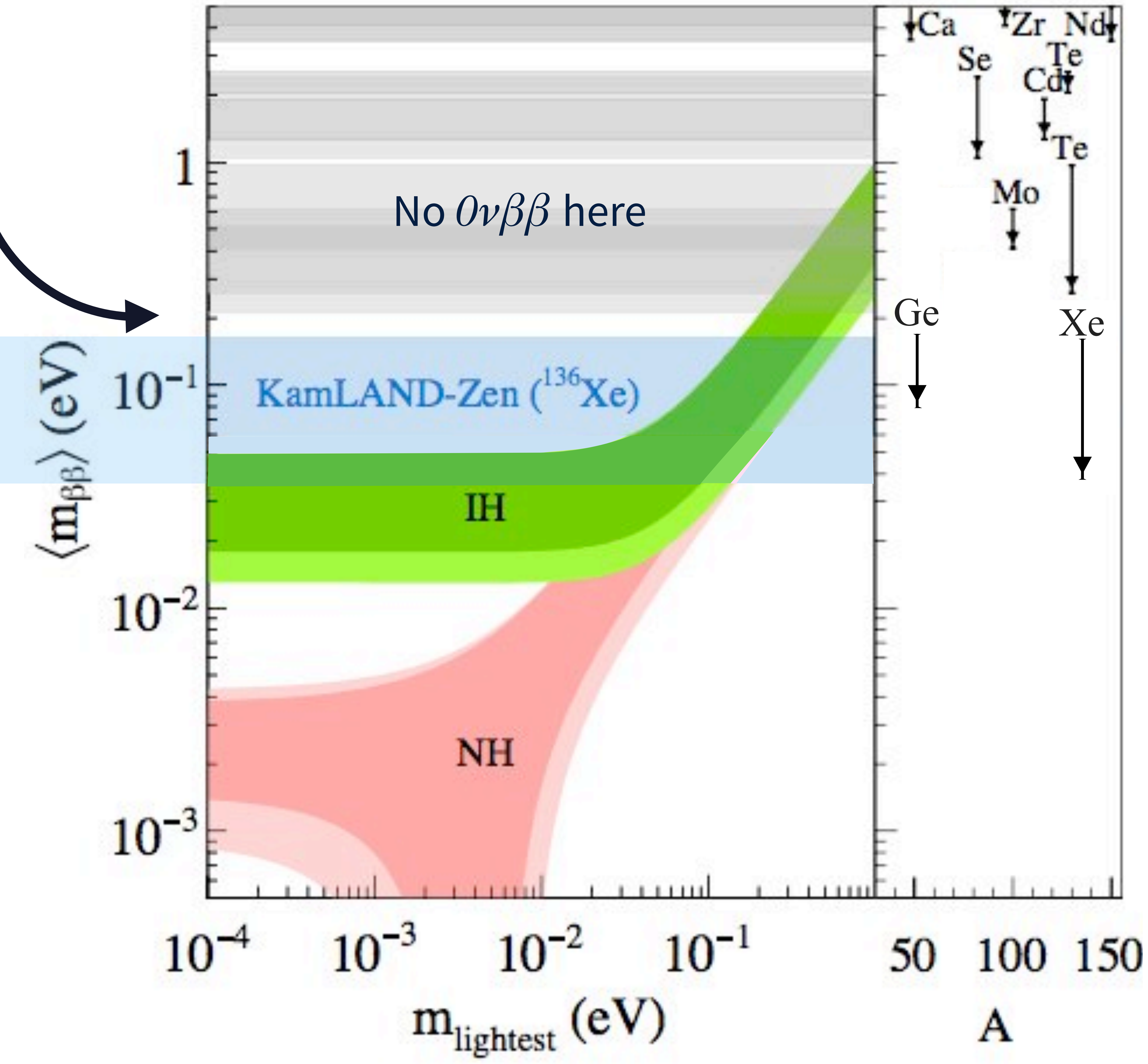

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The UK's strategic approach

Core UK strategy

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The UK's strategic approach

Core UK strategy

LEGEND: a discovery machine to explore the full inverted hierarchy regime

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The UK's strategic approach

Core UK strategy

LEGEND: a discovery machine to explore the full inverted hierarchy regime

SNO+: a scalable technology that could take us to even lower mass limits

SuperNEMO: a technique to probe $0\nu\beta\beta$ mechanism and nuclear effects

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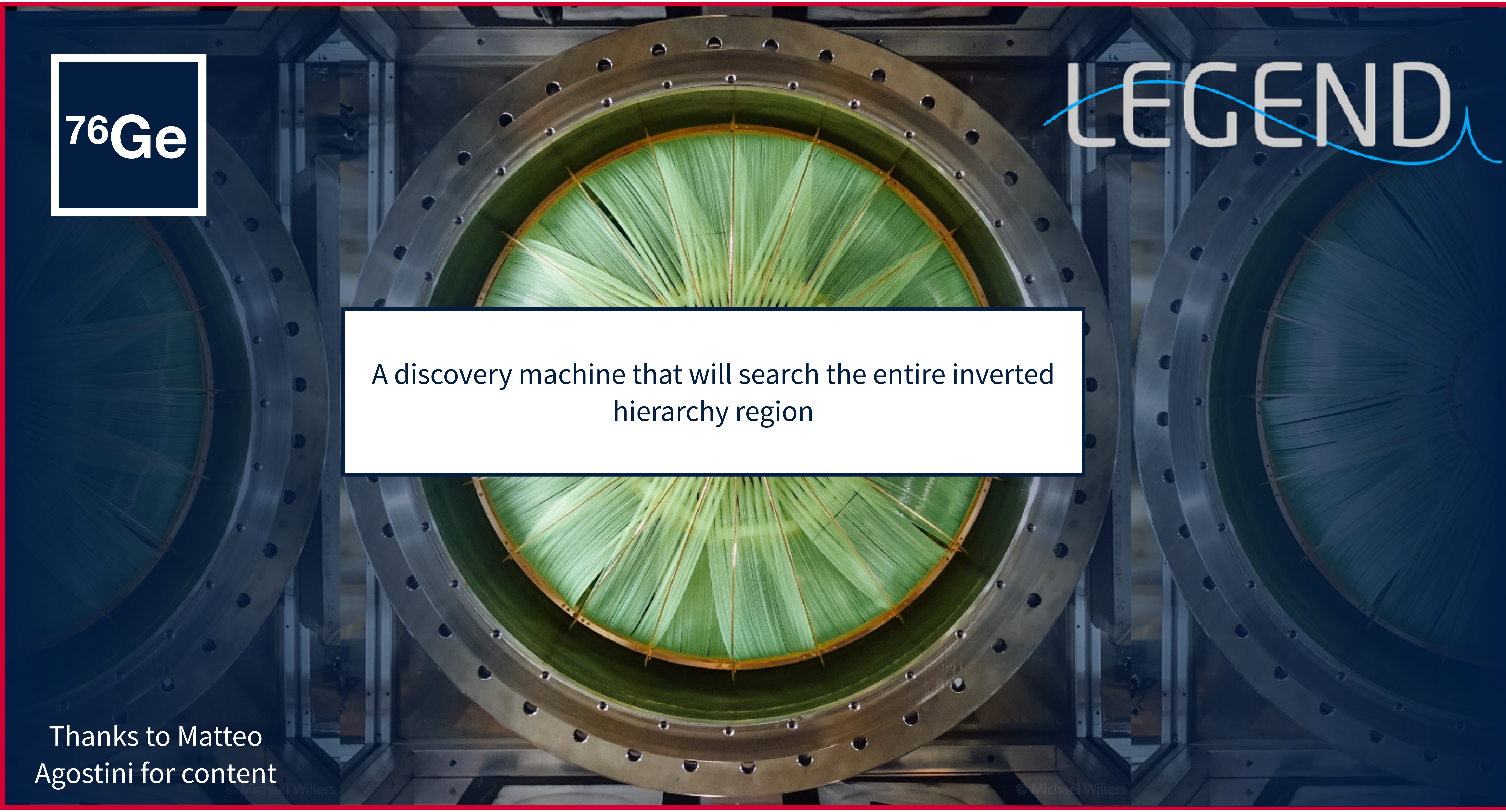
LEGEND at LNGS, Italy (so far…)

UCL

Lancaster University

UNIVERSITY OF LIVERPOOL

WARWICK
THE UNIVERSITY OF WARWICK



^{76}Ge

LEGEND

A discovery machine that will search the entire inverted hierarchy region

Thanks to Matteo Agostini for content

How does LEGEND work?

Semiconductor HPGe Detectors:
- solid state TPC
- mm-scale event topology

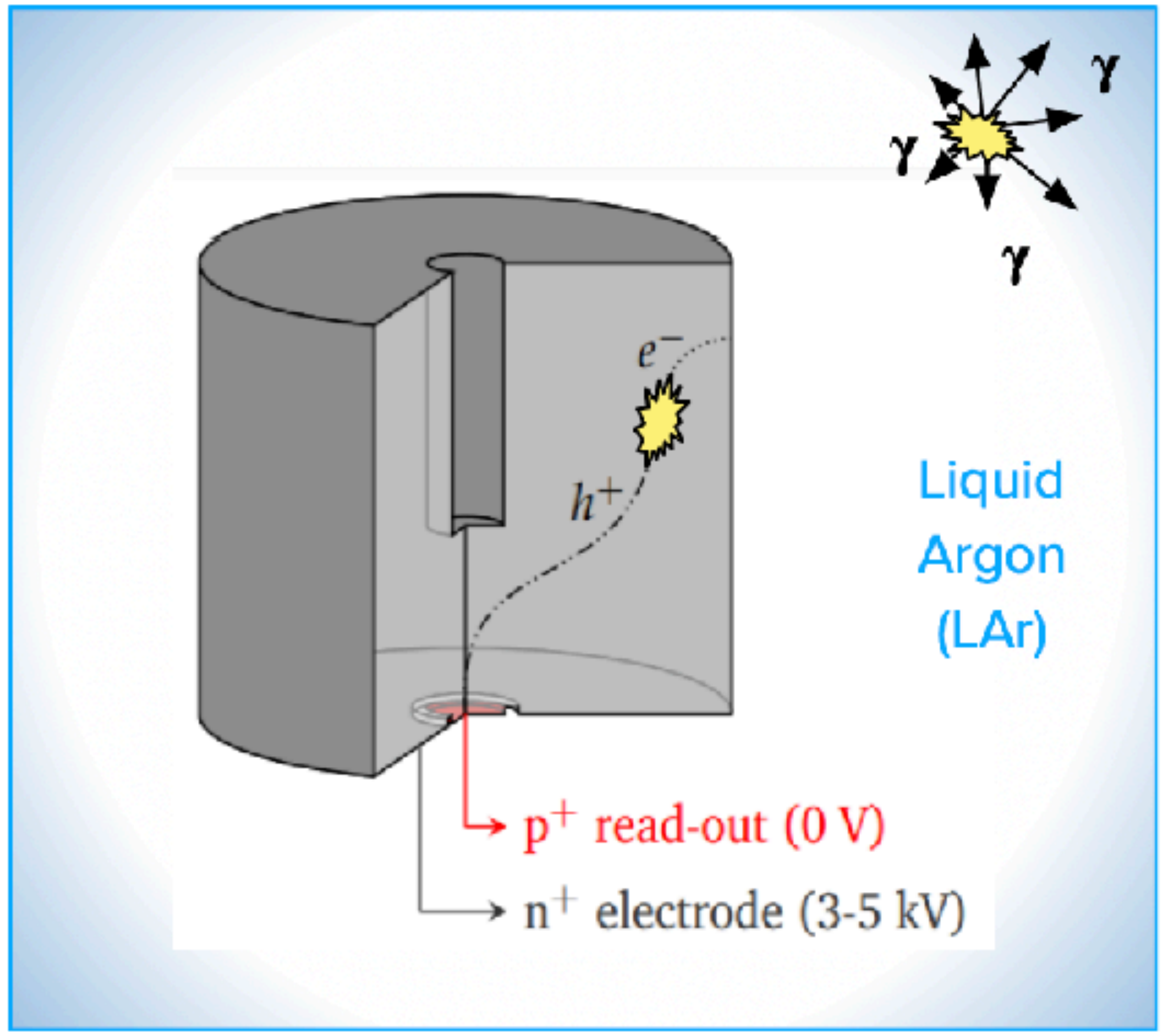
How does LEGEND work?

Semiconductor HPGe Detectors:

- solid state TPC
- mm-scale event topology

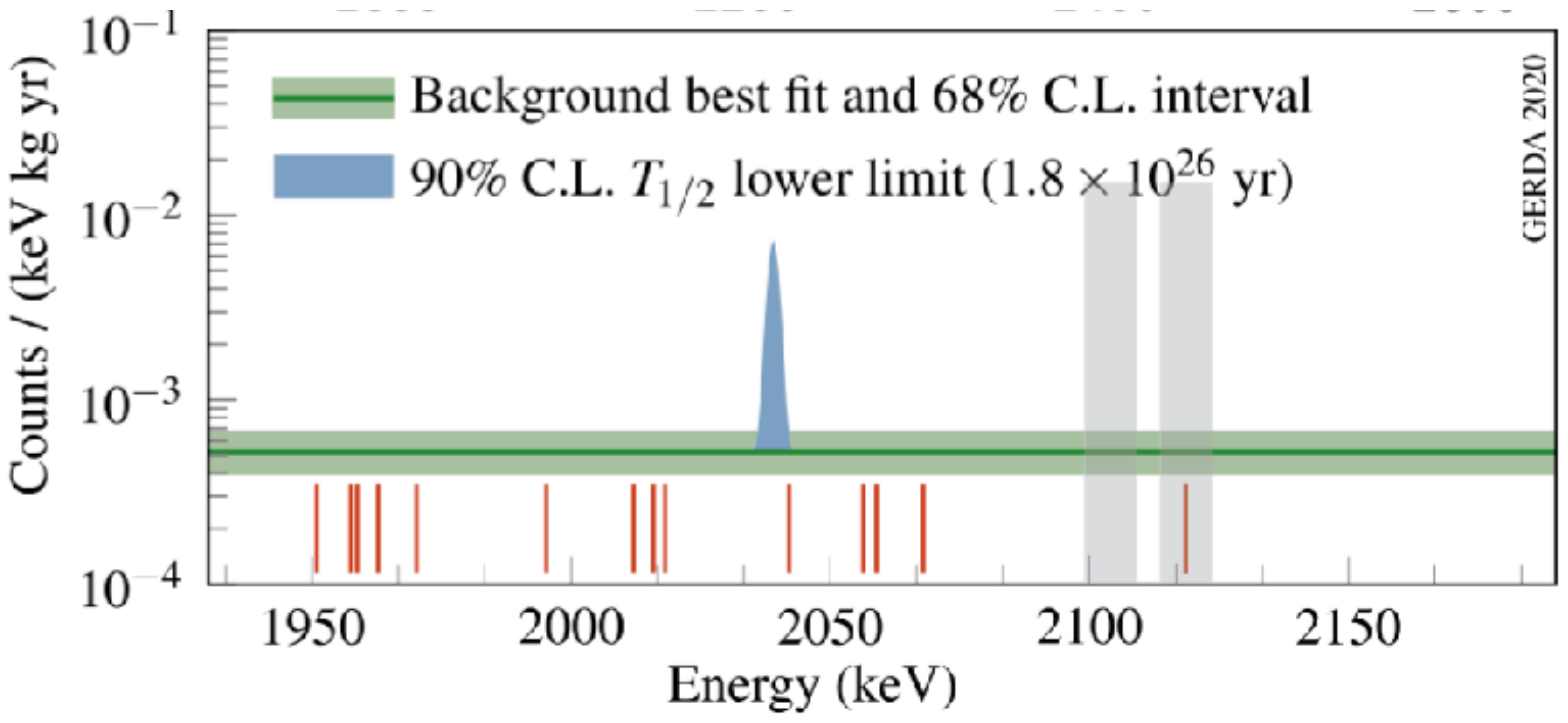
Liquid-argon Scintillation Detector:

- ultra-clean, cryogenic liquid
- isotropic emission of XUV photons
- calorimetric energy measurement

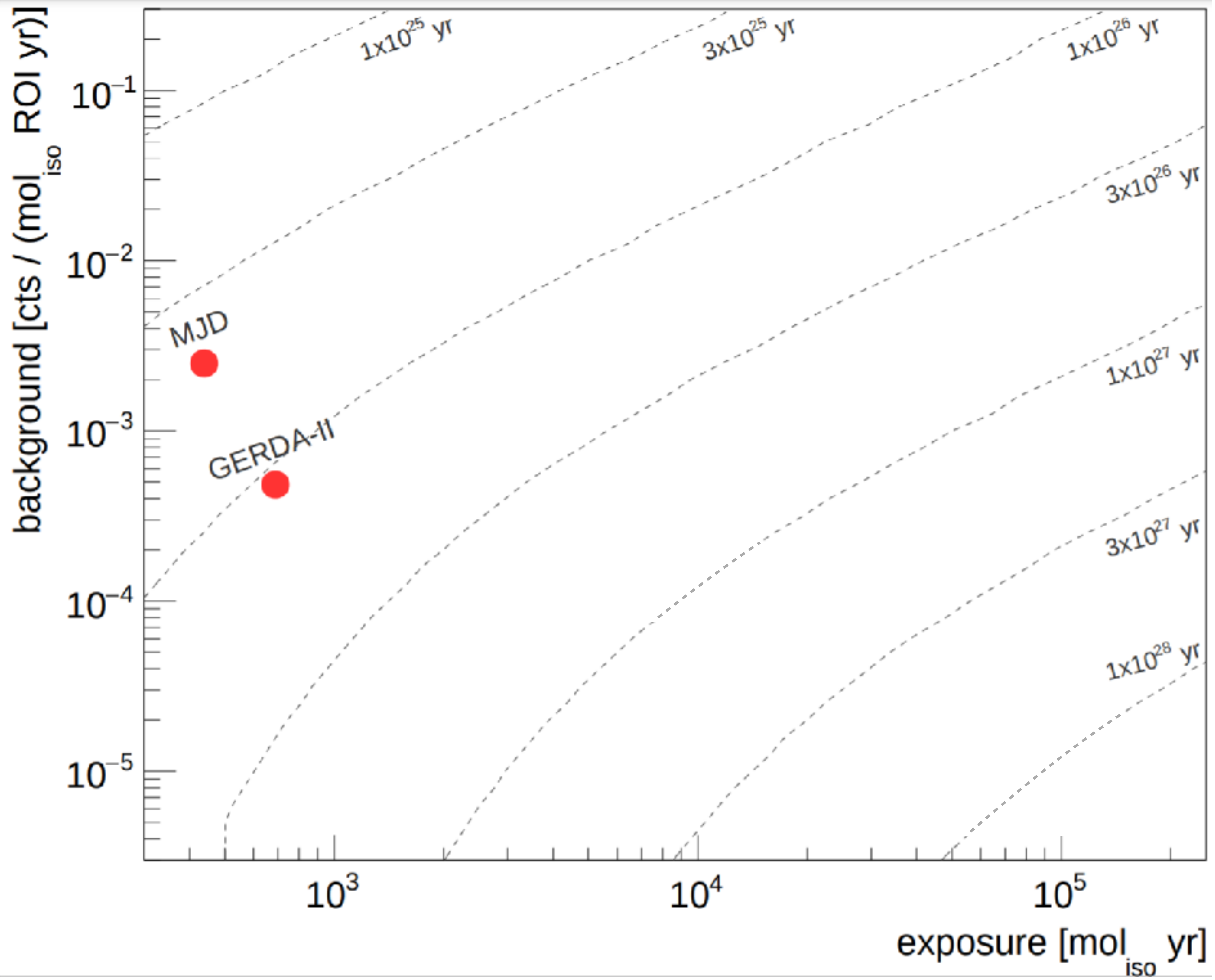


GERDA/MAJORANA (40/30 kg)

- **Lowest background** level in the field
- Best **energy resolution** in the field
- Best **discovery power** so far



Phys.Rev.Lett. 125 (2020) 25, 252502



^{76}Ge - innovation and breakthroughs: past, present

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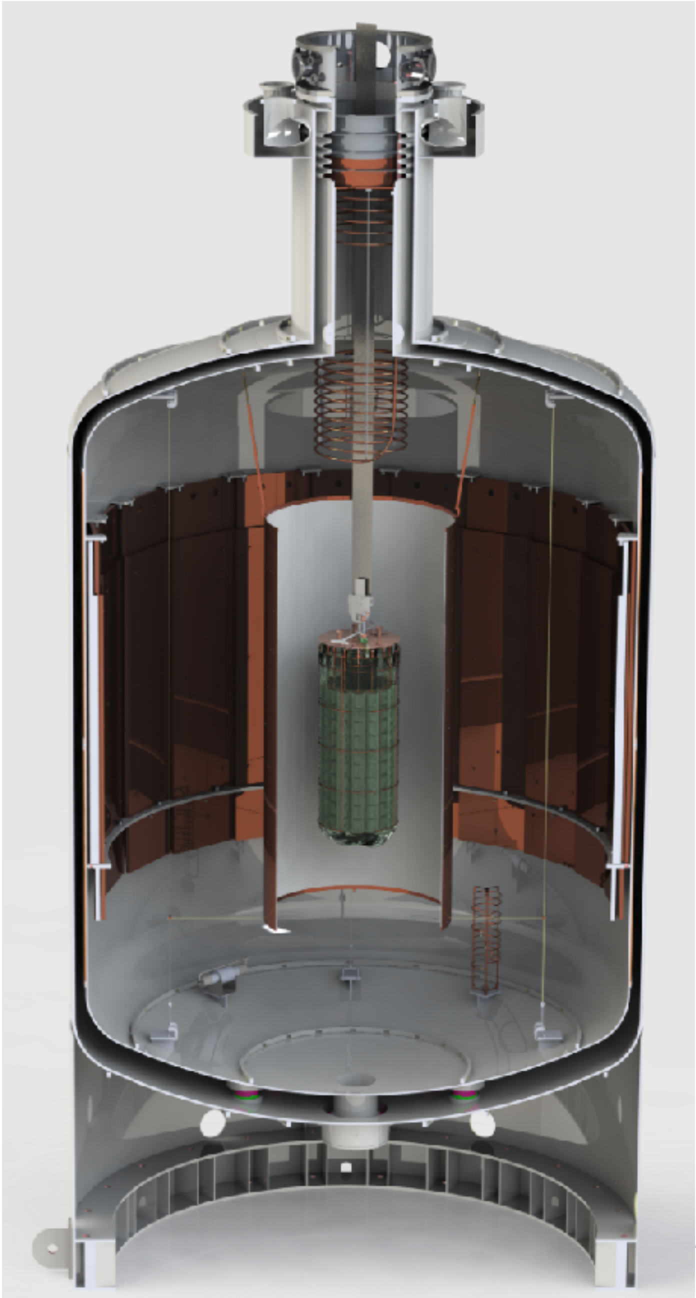
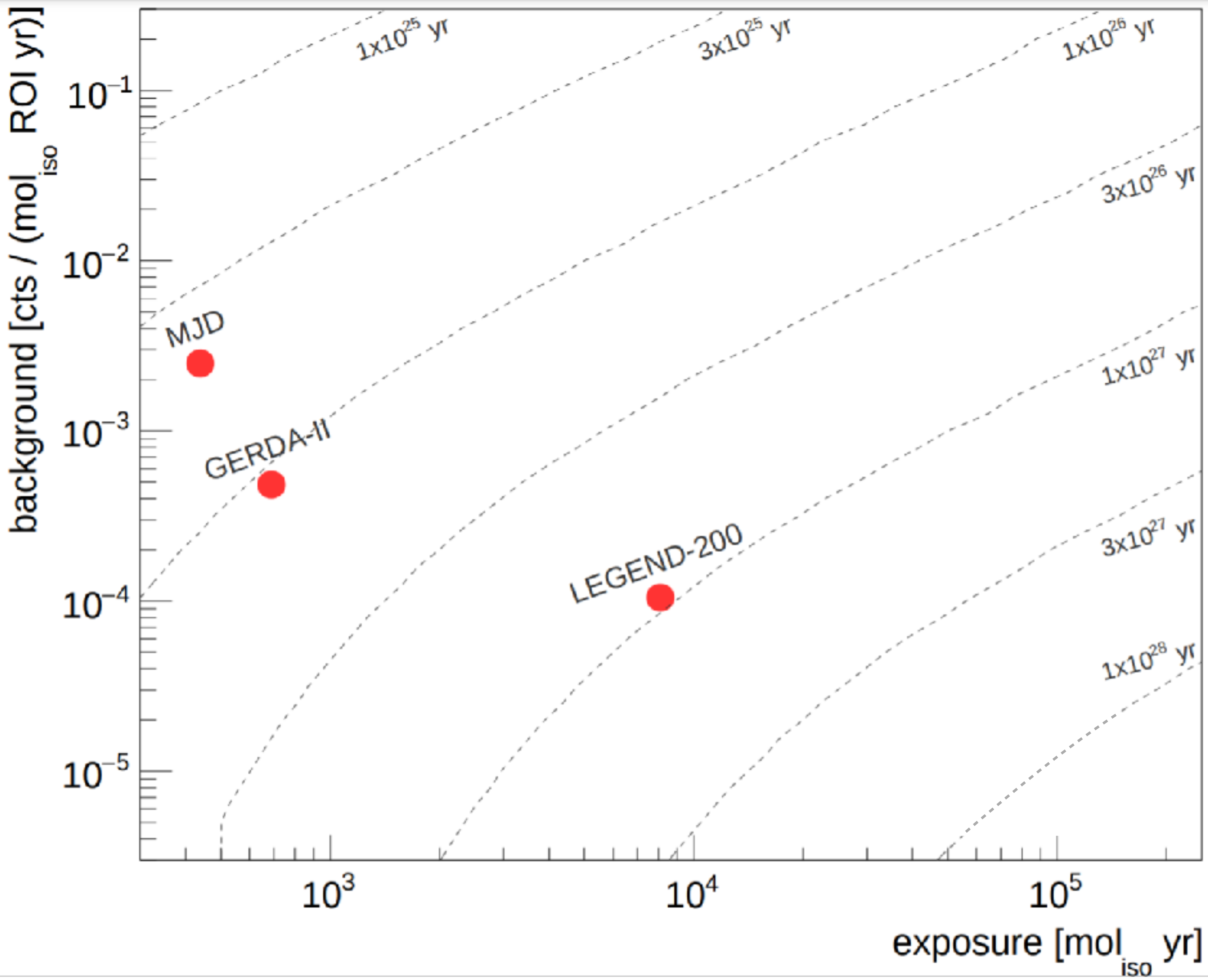
LEGEND-200 (200 kg)

- Approaching physics data taking
- Leading experiment for the next 5 years





^{76}Ge - innovation and breakthroughs: past, present, and future

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LEGEND-200 (200 kg)

- Approaching physics data taking
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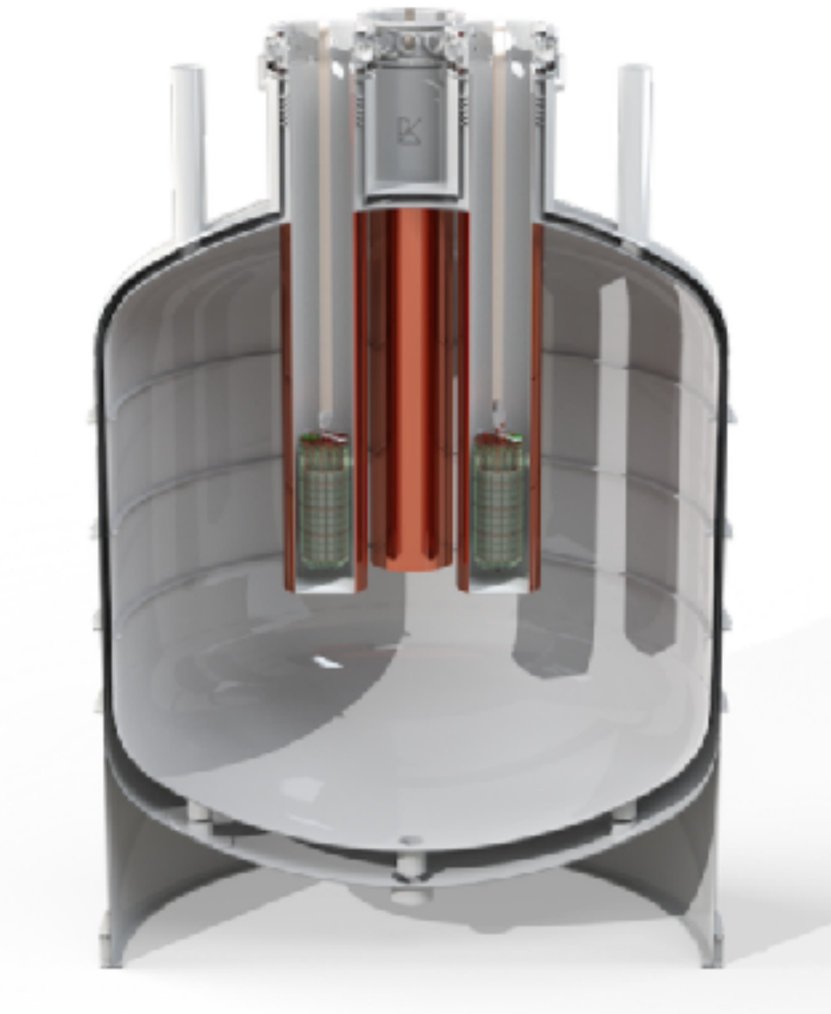
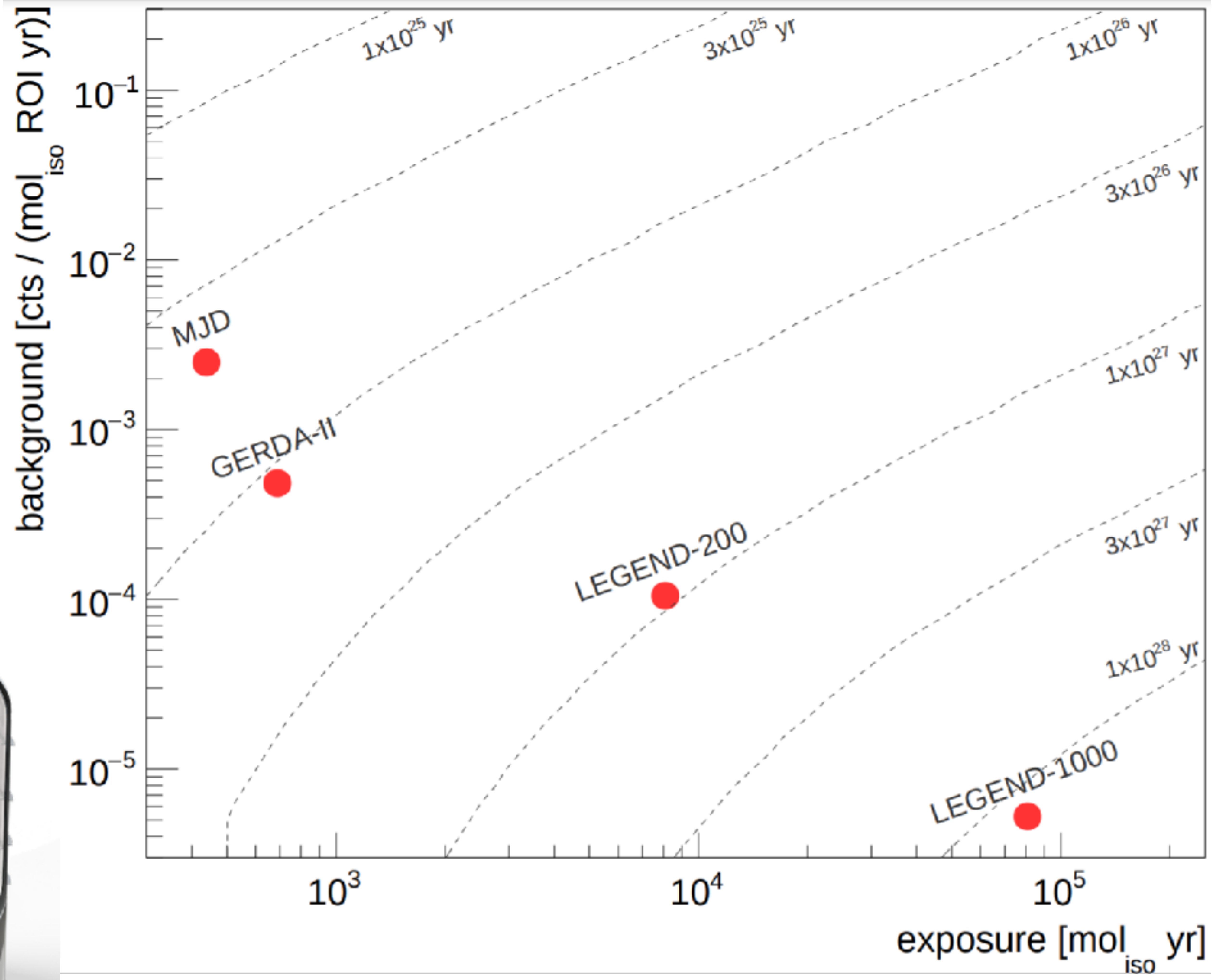
LEGEND-1000 (1 ton)

- Inverted-hierarchy explorer: $m_{\beta\beta}$=18 meV
- Only experiment in both the EU APPEC roadmap and DOE long term plan

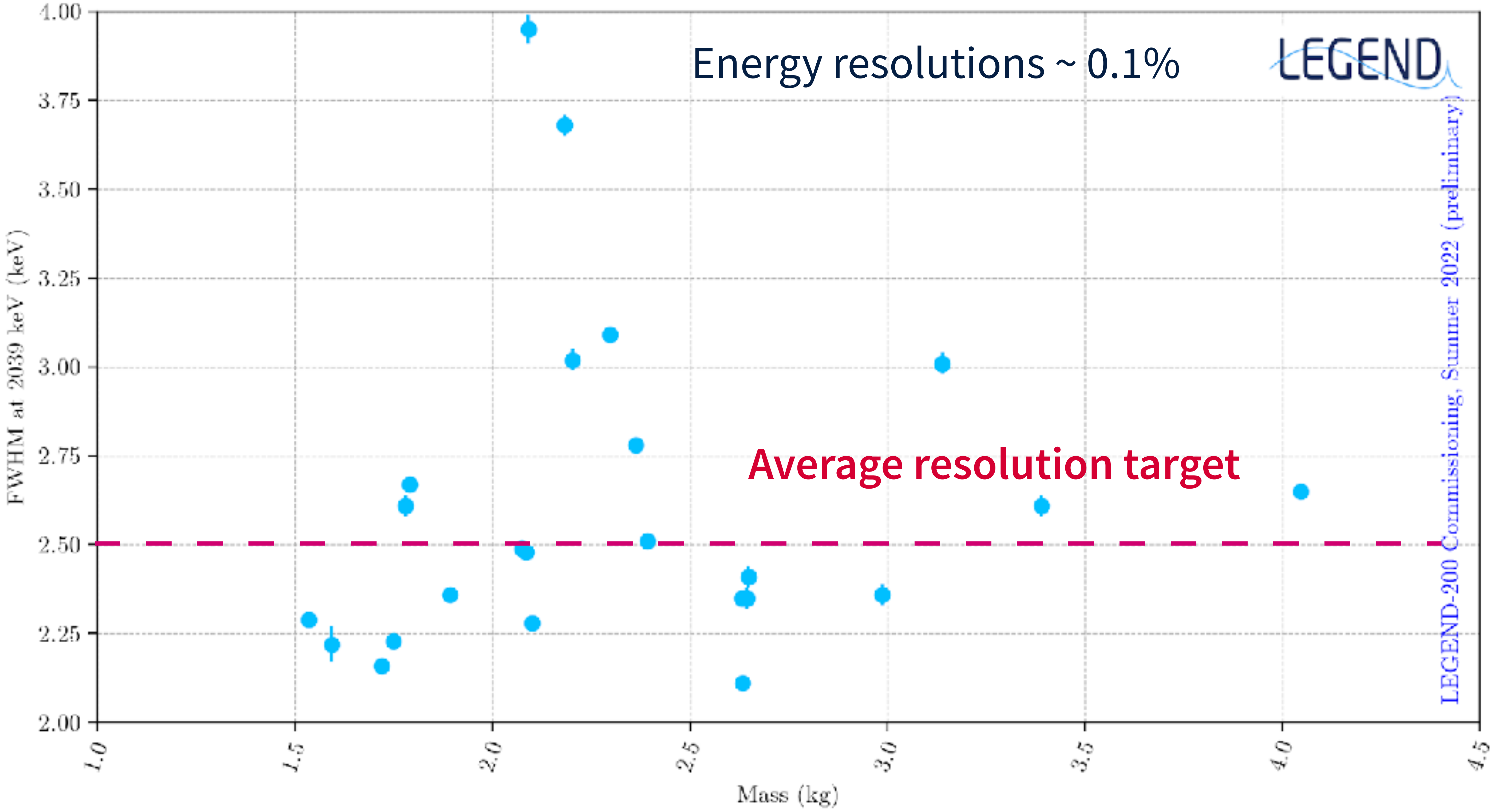




LEGEND-200

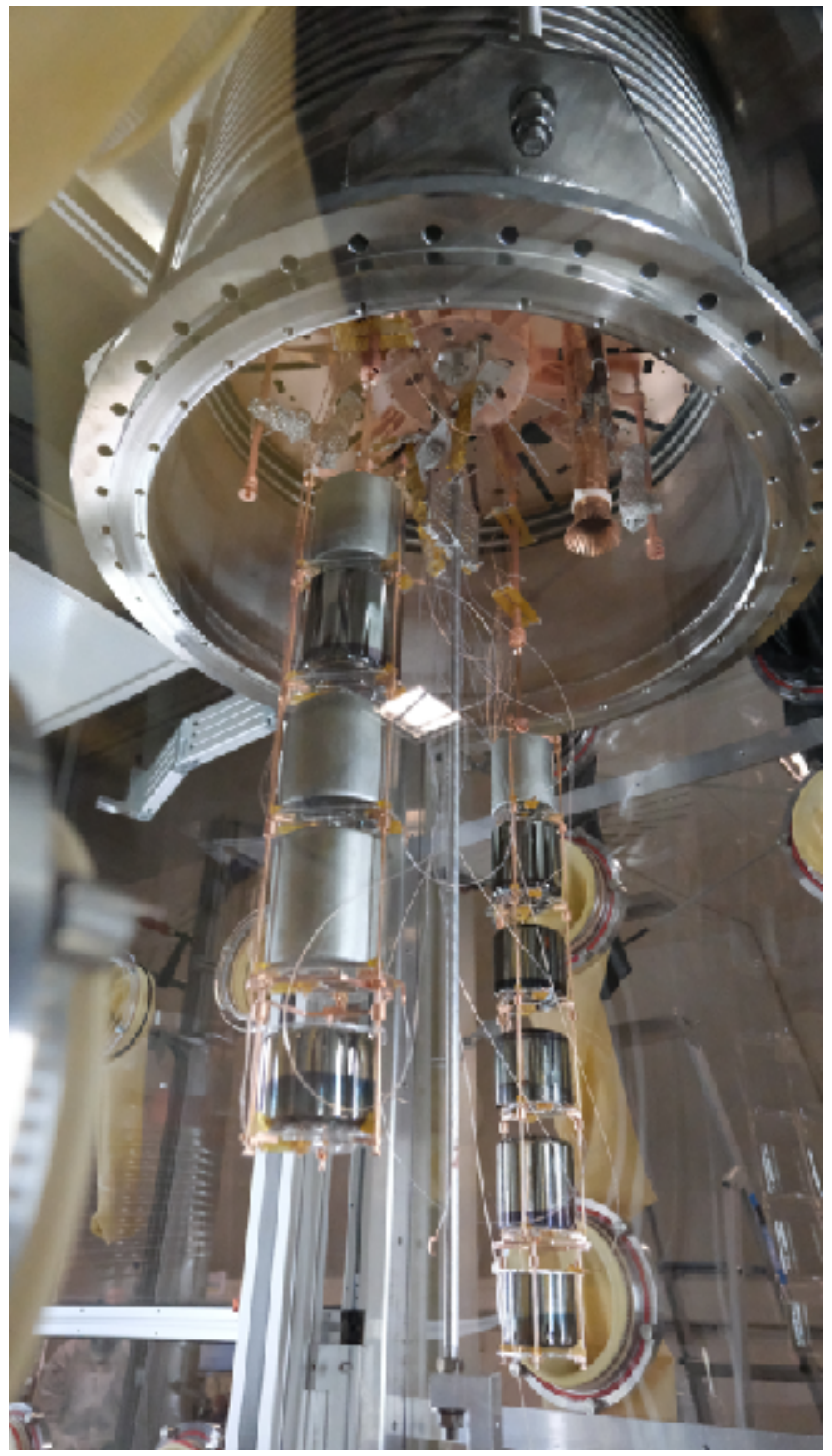
Summer 2022 LEGEND-200 integration runs:

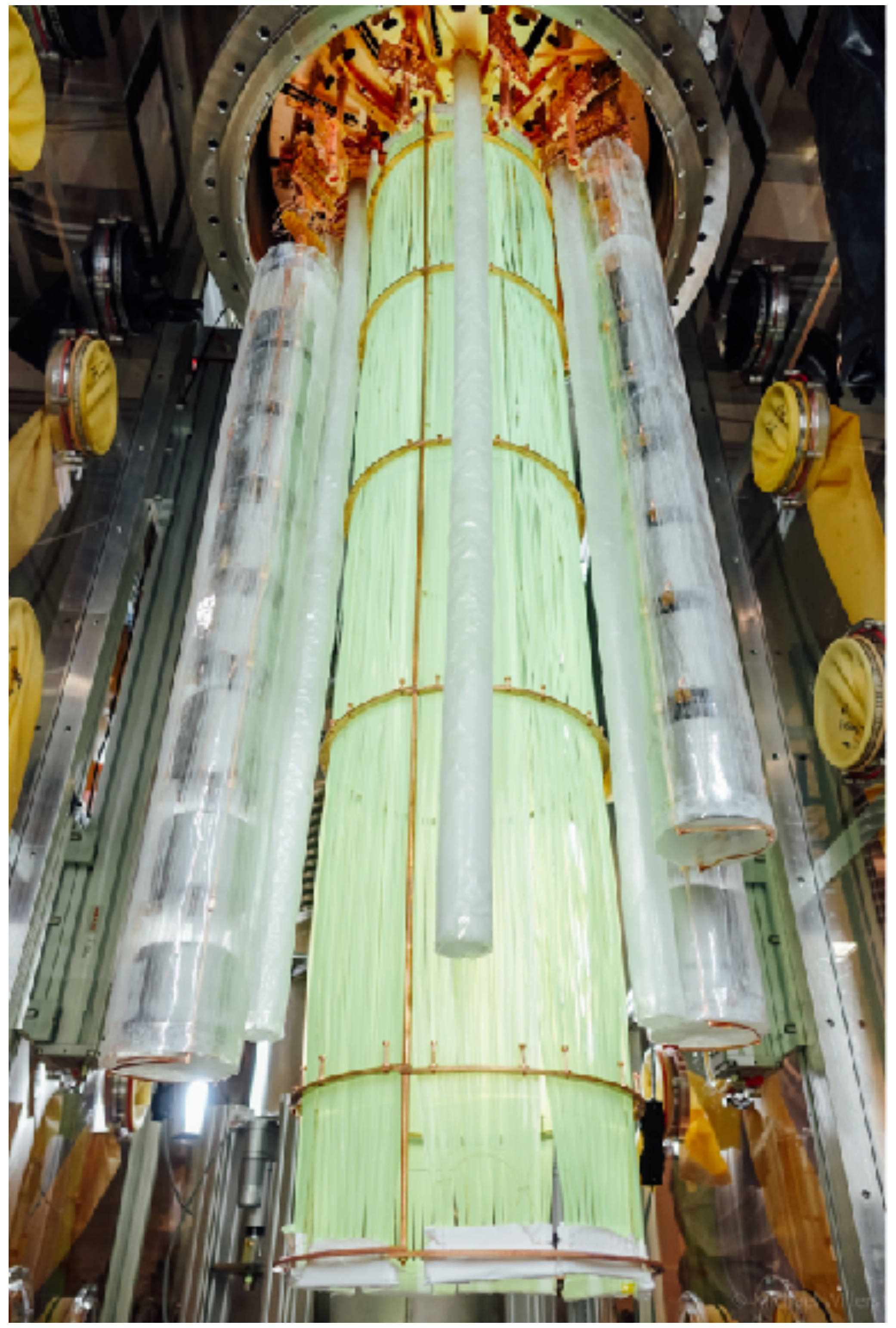
- 24 detectors (60kg) used for background studies

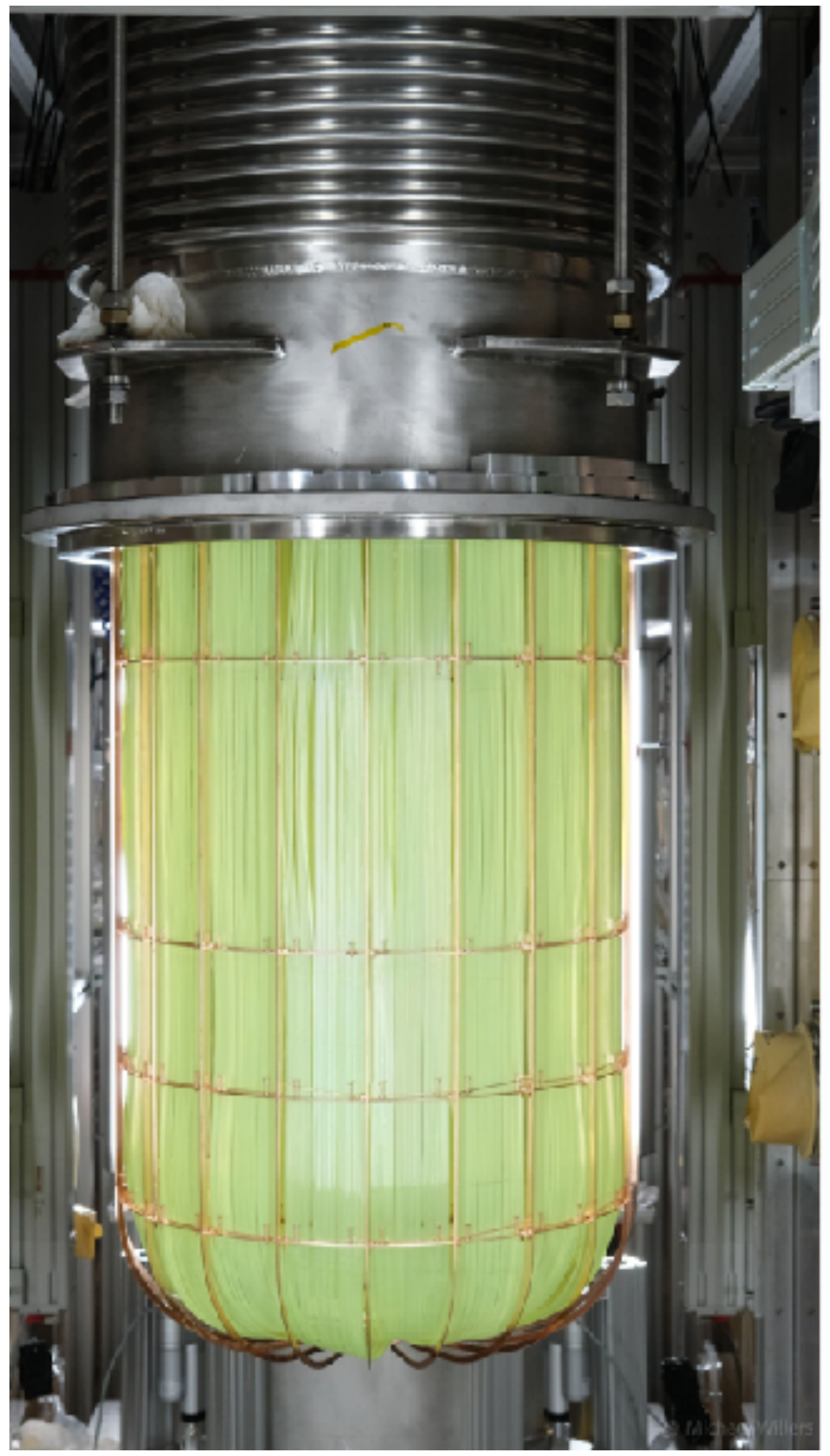


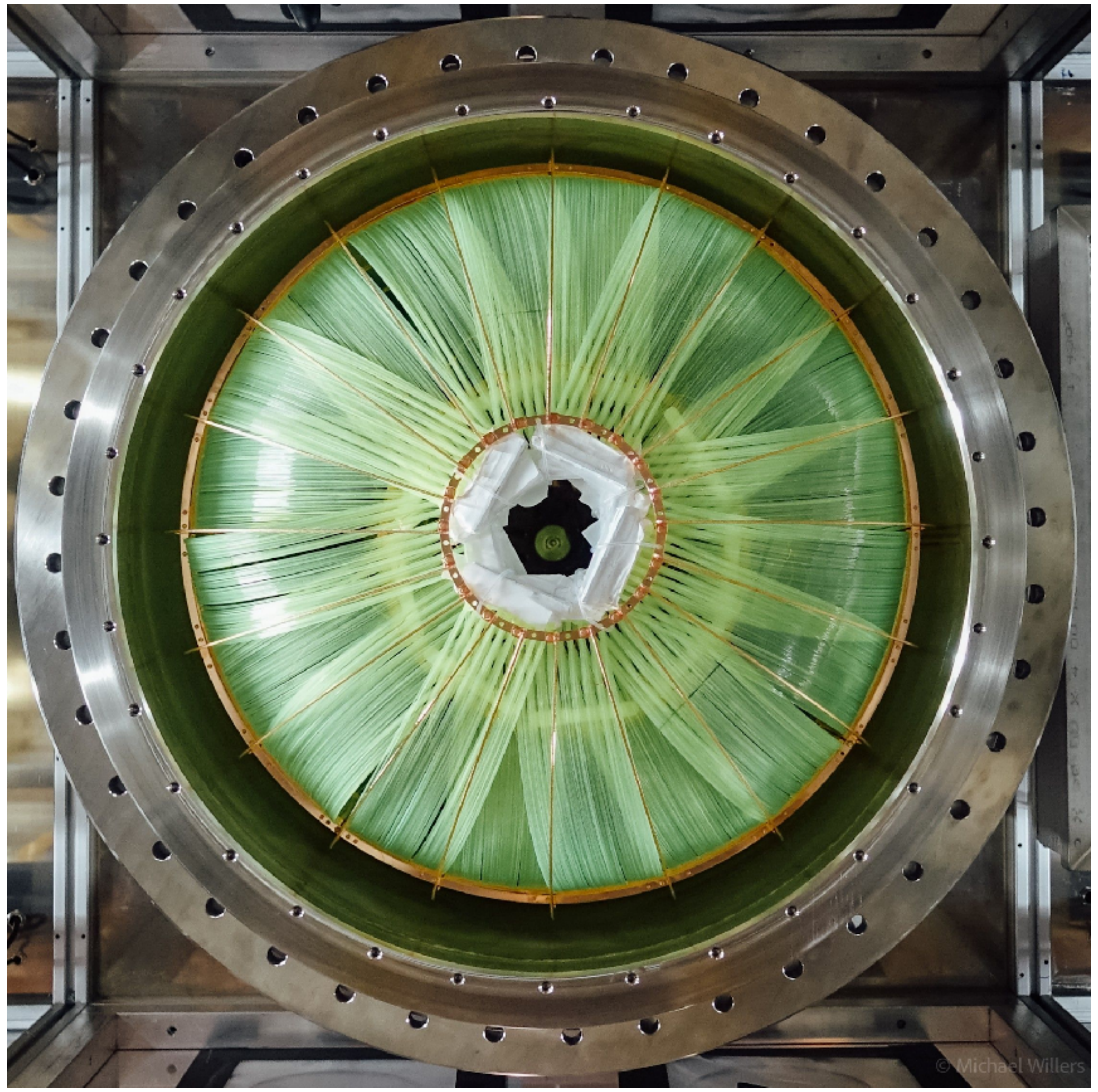
Summer 2022 LEGEND-200 integration runs:

- 24 detectors (60kg) used for background studies
- Ge and LAr detectors, electronics & DAQ





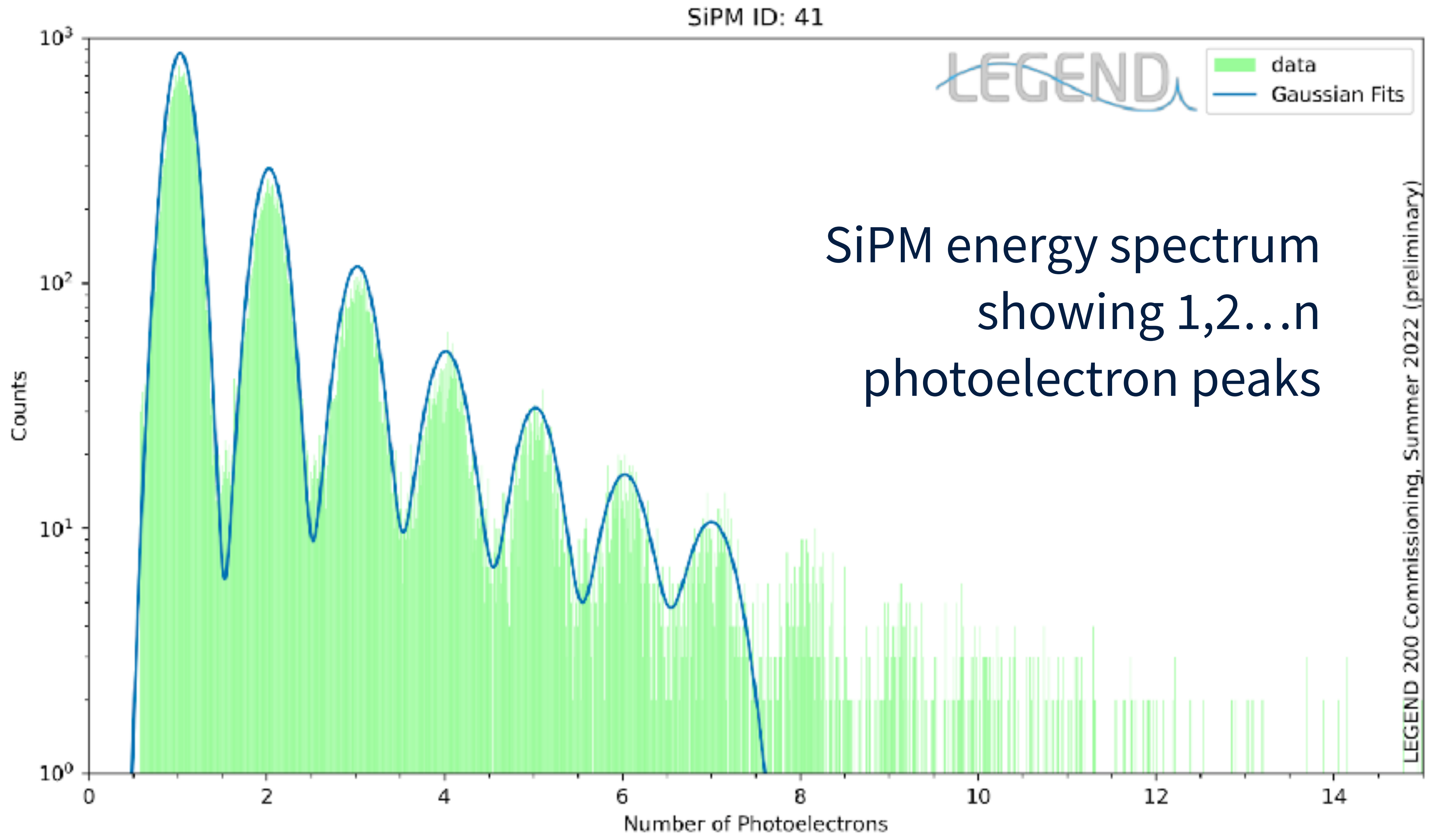




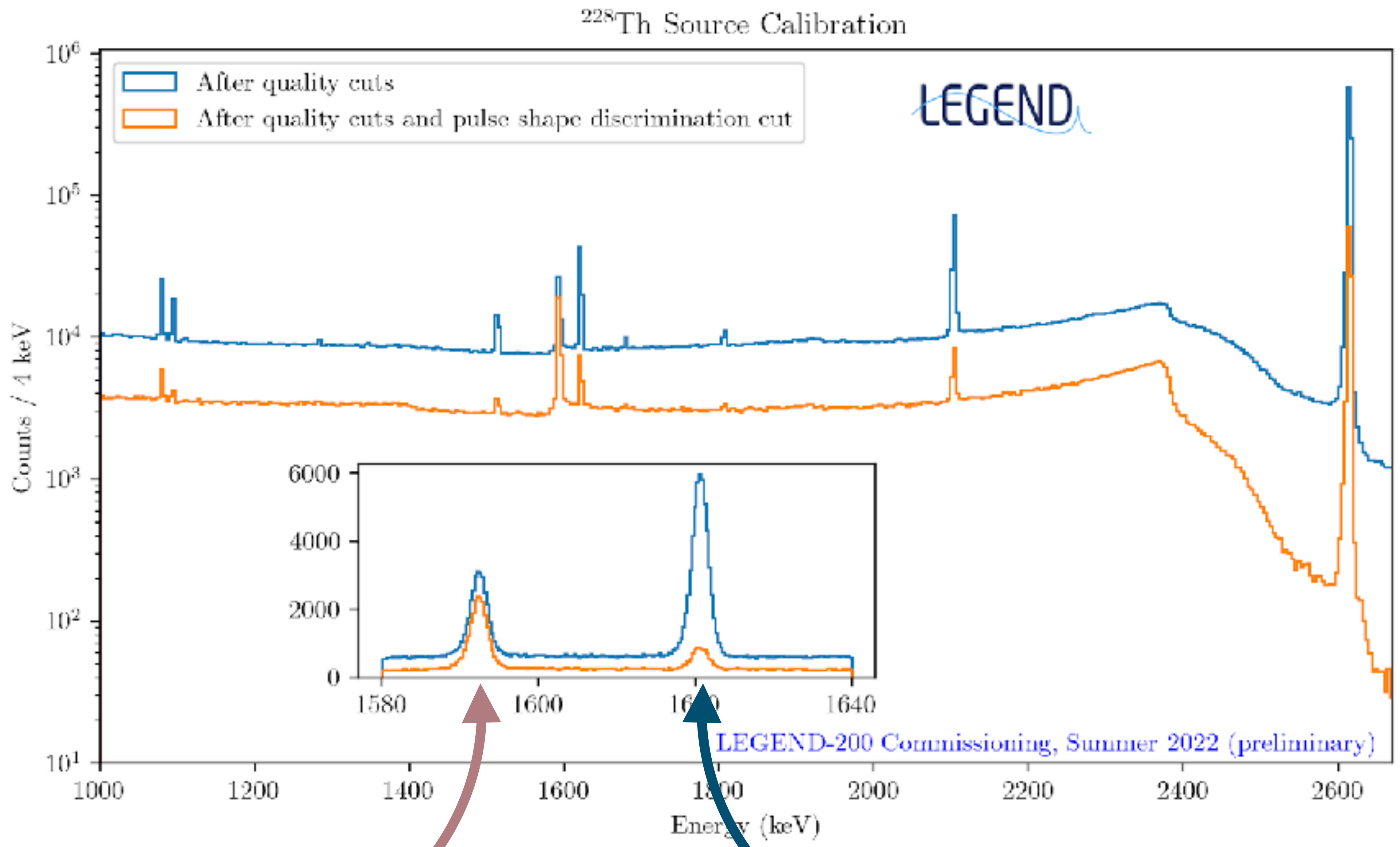
LEGEND-200

Summer 2022 LEGEND-200 integration runs:

- 24 detectors (60kg) used for background studies
- Ge and LAr detectors, electronics & DAQ
- Analysis pipeline



SiPM energy spectrum showing 1,2…n photoelectron peaks



Signal-like events are kept

^{208}Tl double-escape peak ($\beta\beta$-proxy)

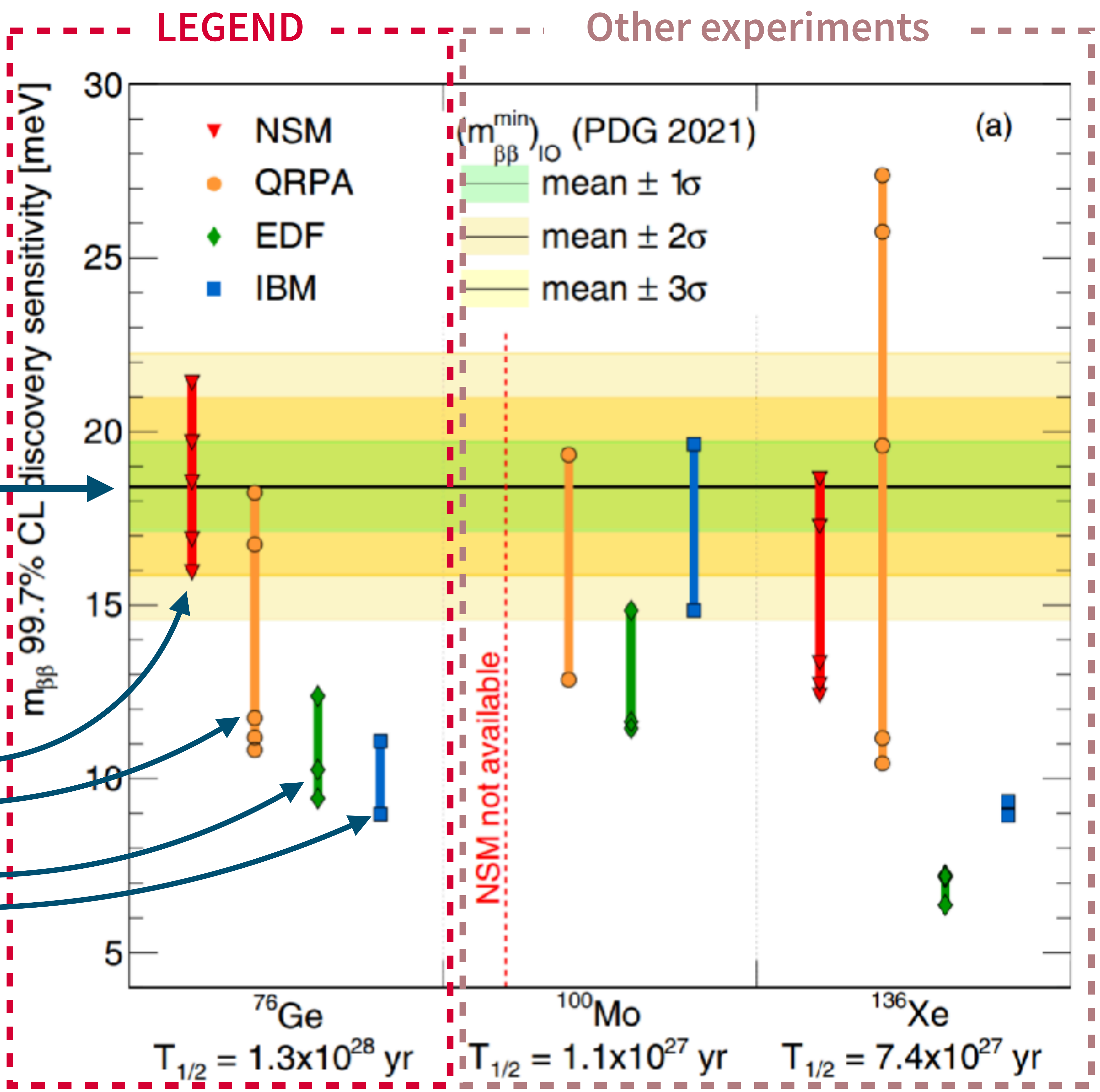
Background-like (multi-site) events are cut

(^{214}Bi full-energy escape peak)

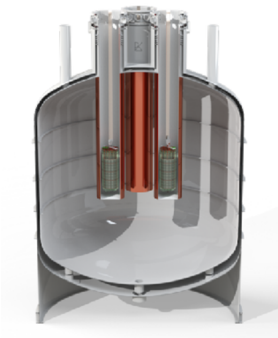
LEGEND capability

Bottom of inverted hierarchy

LEGEND-1000's $m_{\beta\beta}$ sensitivity (different nuclear models)



LEGEND-200 (under construction, first data this year)



LEGEND-1000 (construction 2023-2030, first data in 2028, 10 years of operations)

LEGEND won DOE portfolio review

- DOE fully committed to LEGEND and will prioritise it over any other $0\nu\beta\beta$ experiments
- CD1 and CD3 review next year

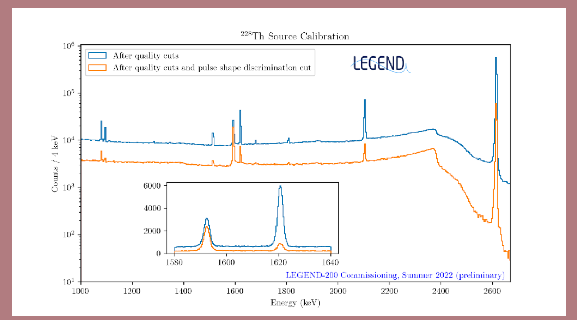
LEGEND-UK

Germanium **detector R&D**

Leadership

(Physics coordinator, WBS level 2 managers)

Analysis and simulation



LEGEND-UK interested group (13 institutions; common SOI this autumn)

New scintillating **materials**

Radiopurity assays

Supported by both particle- and nuclear-physics communities

SNO+ at Sudbury, Canada

University of Oxford

King's College London

Lancaster University

University of Sussex

University of Liverpool

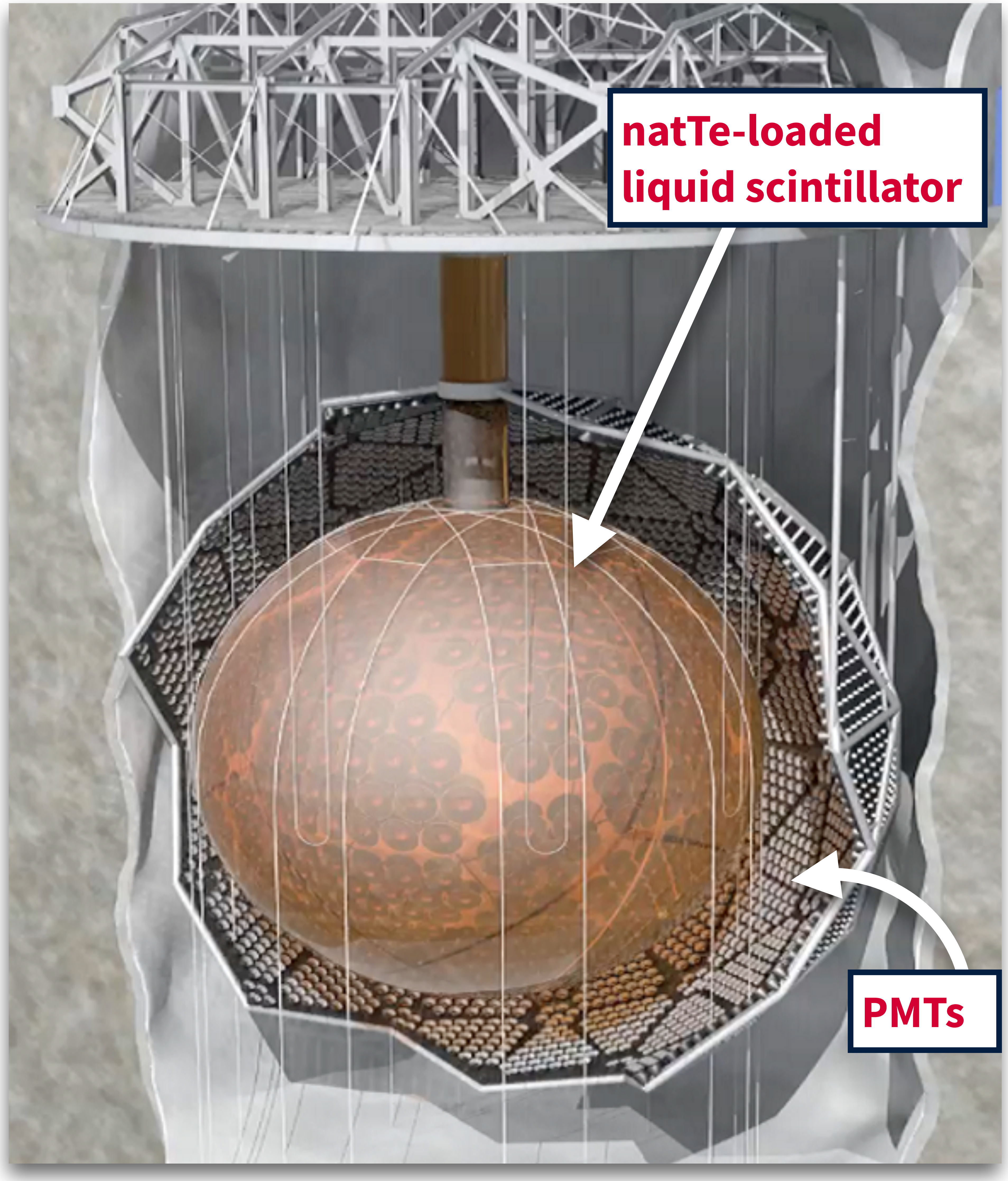
SNO+

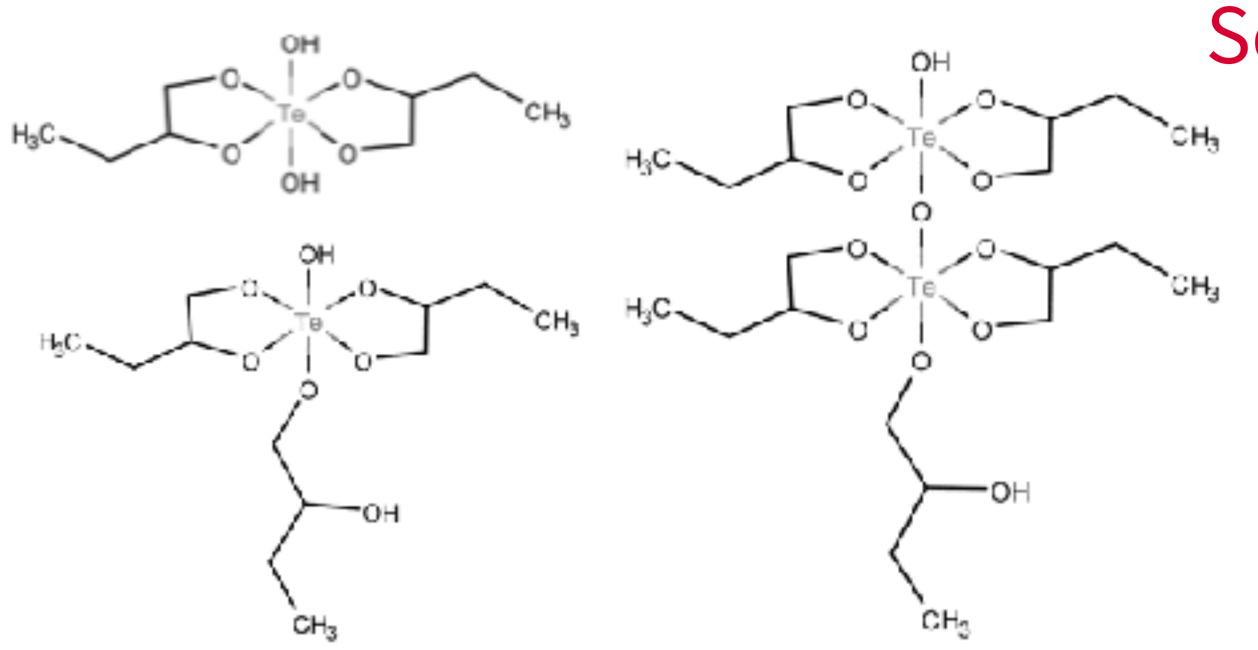
Thanks to Steve Biller for content

A highly scalable, cost-effective and sensitive approach to $0\nu\beta\beta$ (concept developed in the UK)

^{130}Te

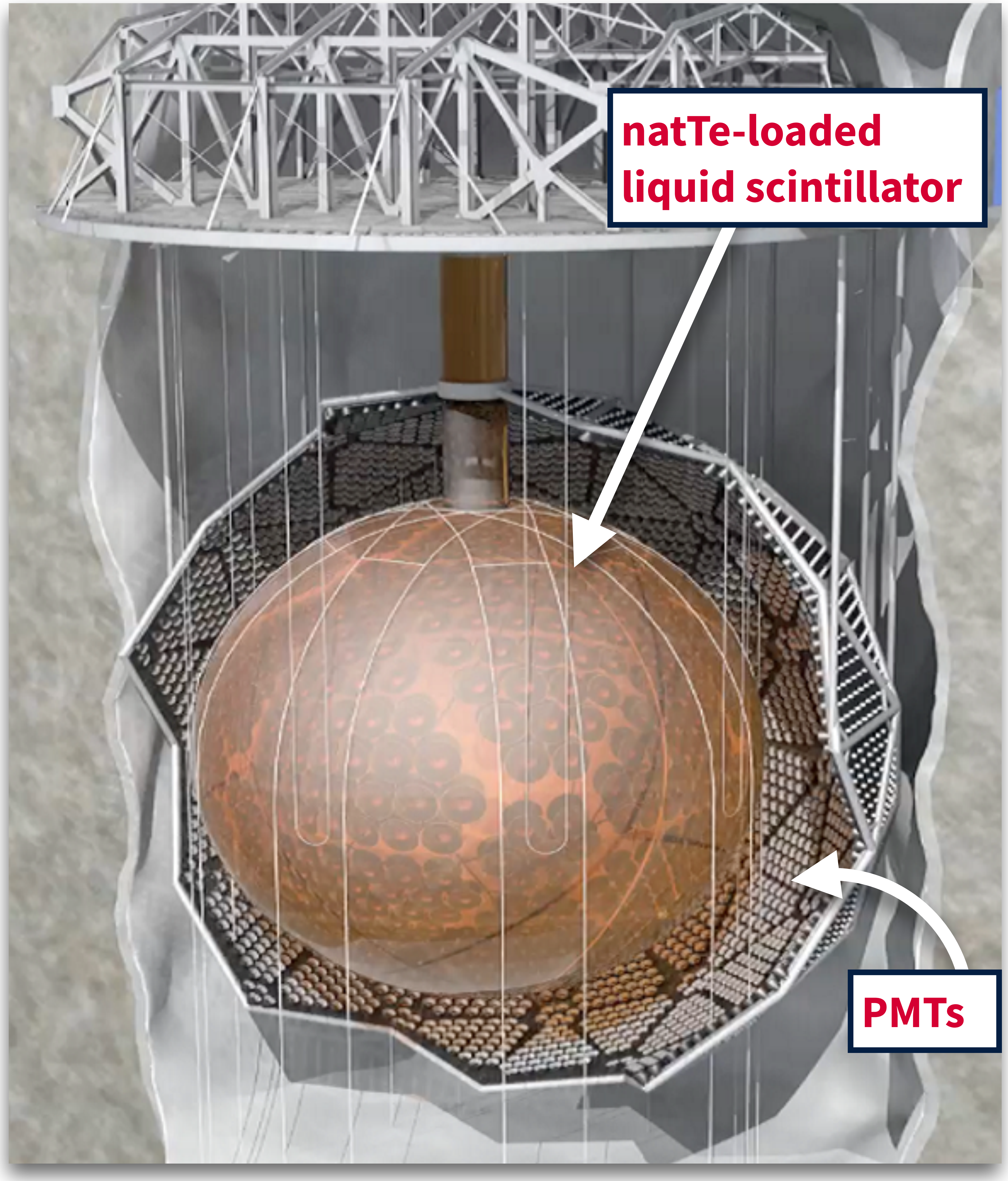
How SNO+ works

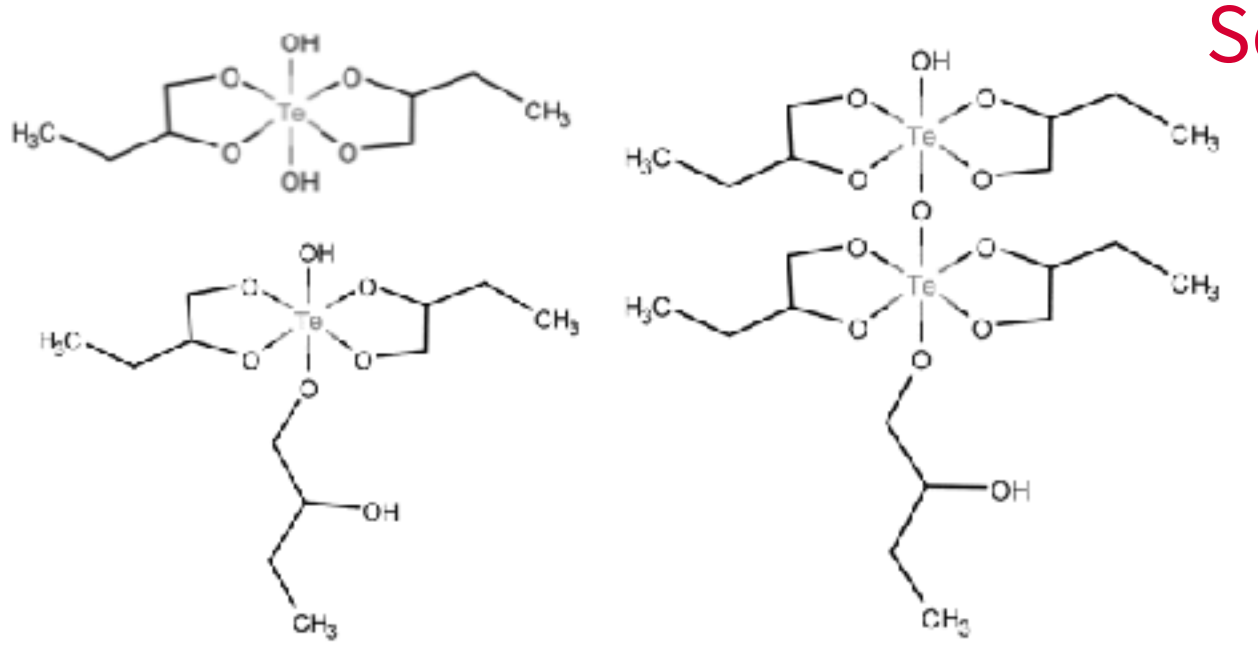




Diol Loading of ^{130}Te in Liquid Scintillator (developed in UK)

How SNO+ works



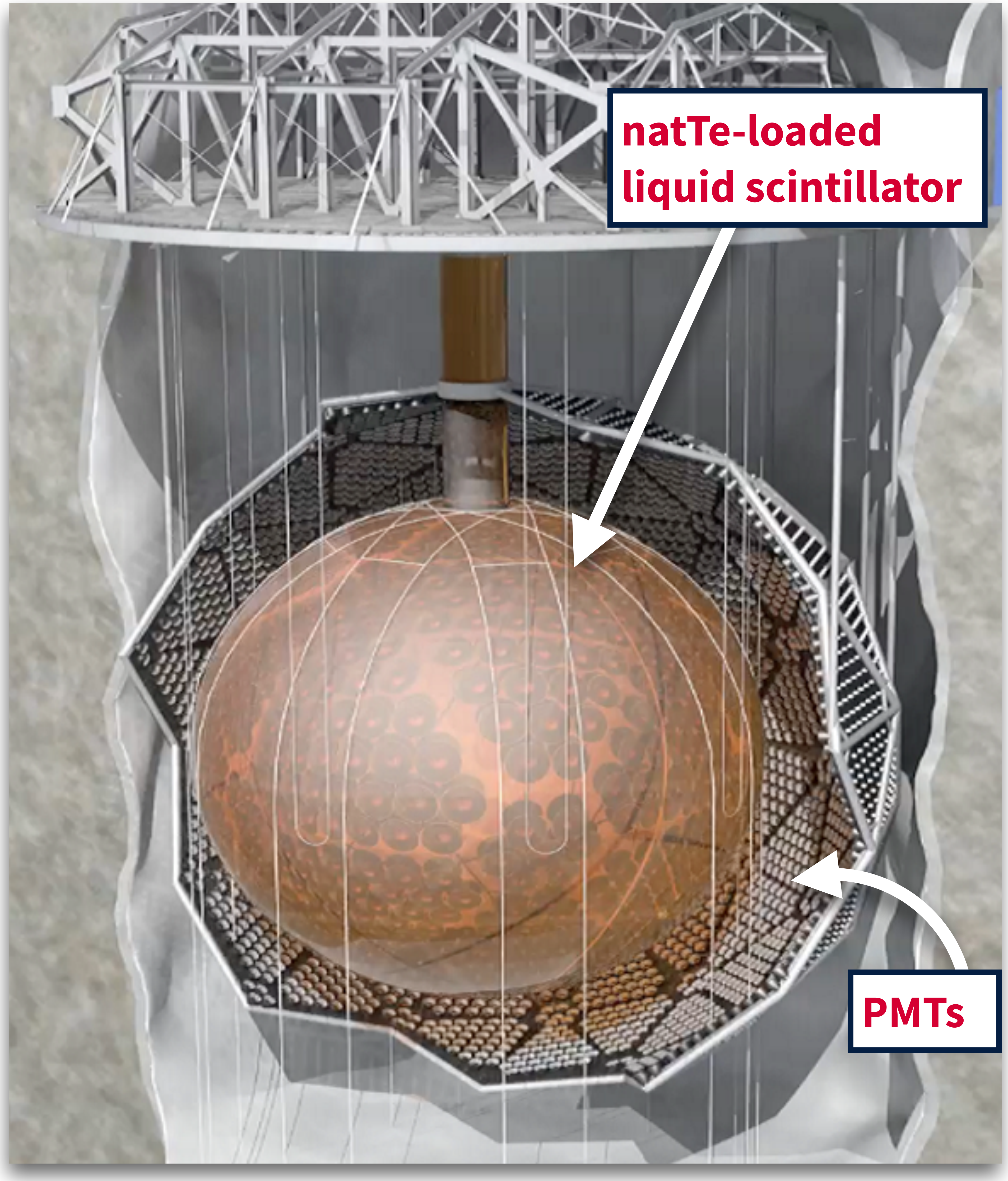


Diol Loading of ^{130}Te in Liquid Scintillator (developed in UK)

Cost-effective

- $\beta\beta$ isotope has high (34%) natural abundance
- Liquid scintillator is also economical

How SNO+ works



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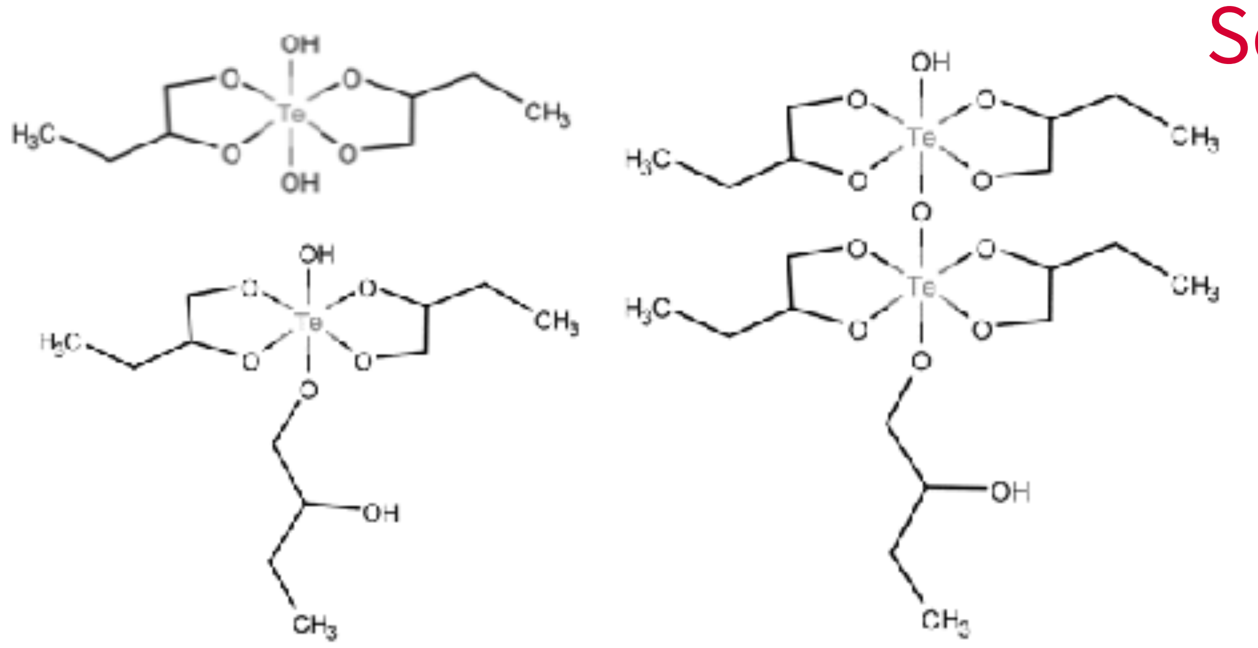

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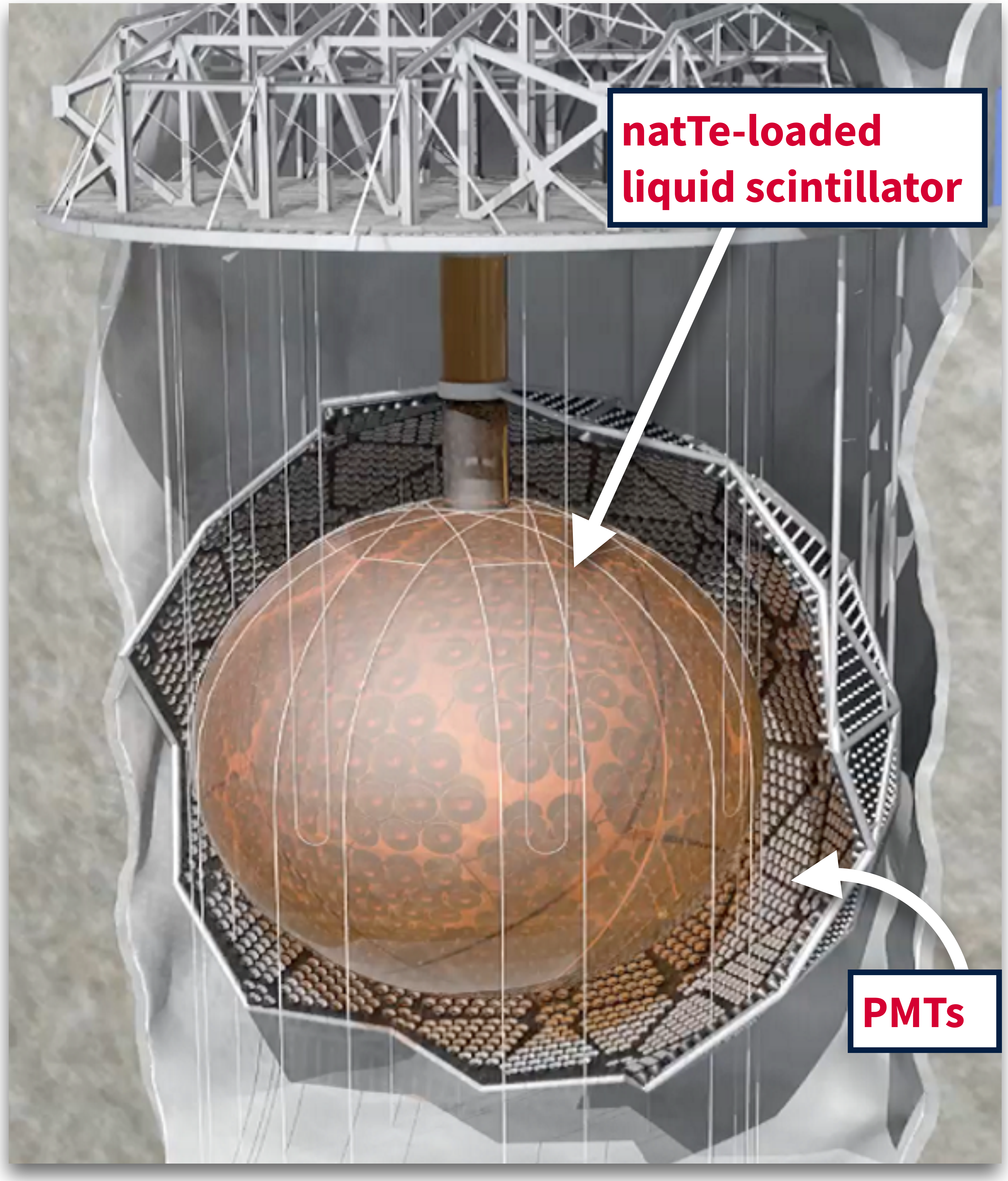
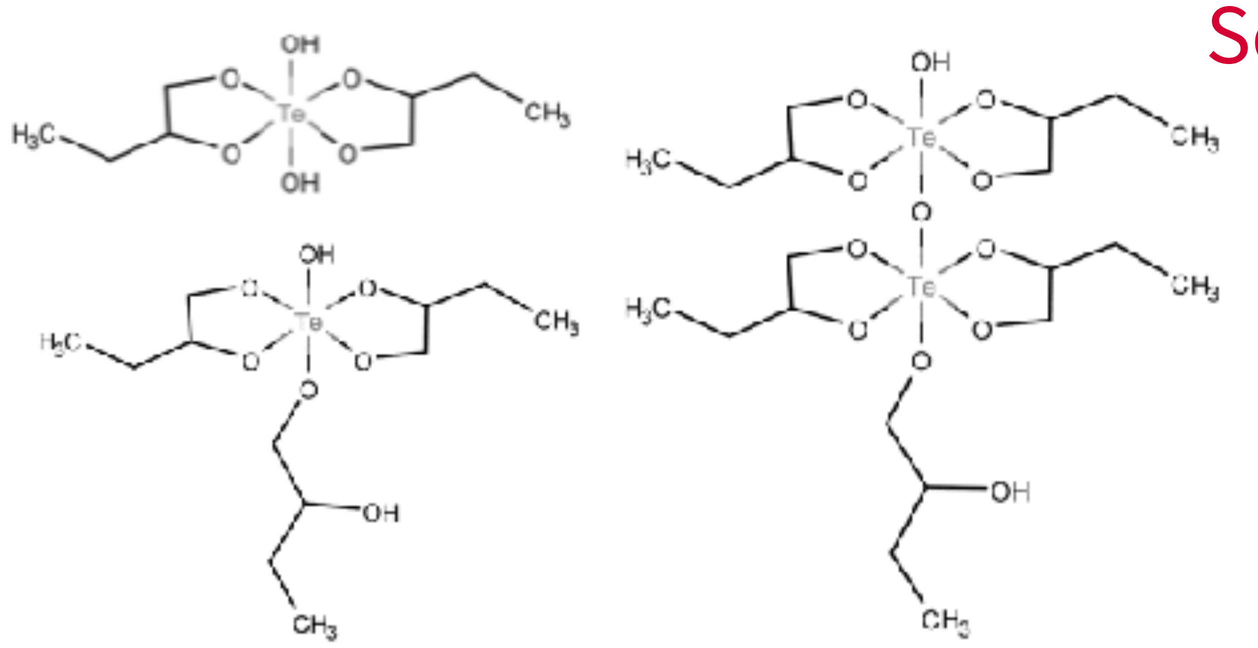
Scalable

- Detector **design** can be scaled up dramatically
- UK-developed techniques can increase **tellurium loading**





Diol Loading of ^{130}Te in Liquid Scintillator (developed in UK)

Cost-effective

- $\beta\beta$ isotope has high (34%) natural abundance
- Liquid scintillator is also economical

Scalable

- Detector **design** can be scaled up dramatically
- UK-developed techniques can increase **tellurium loading**

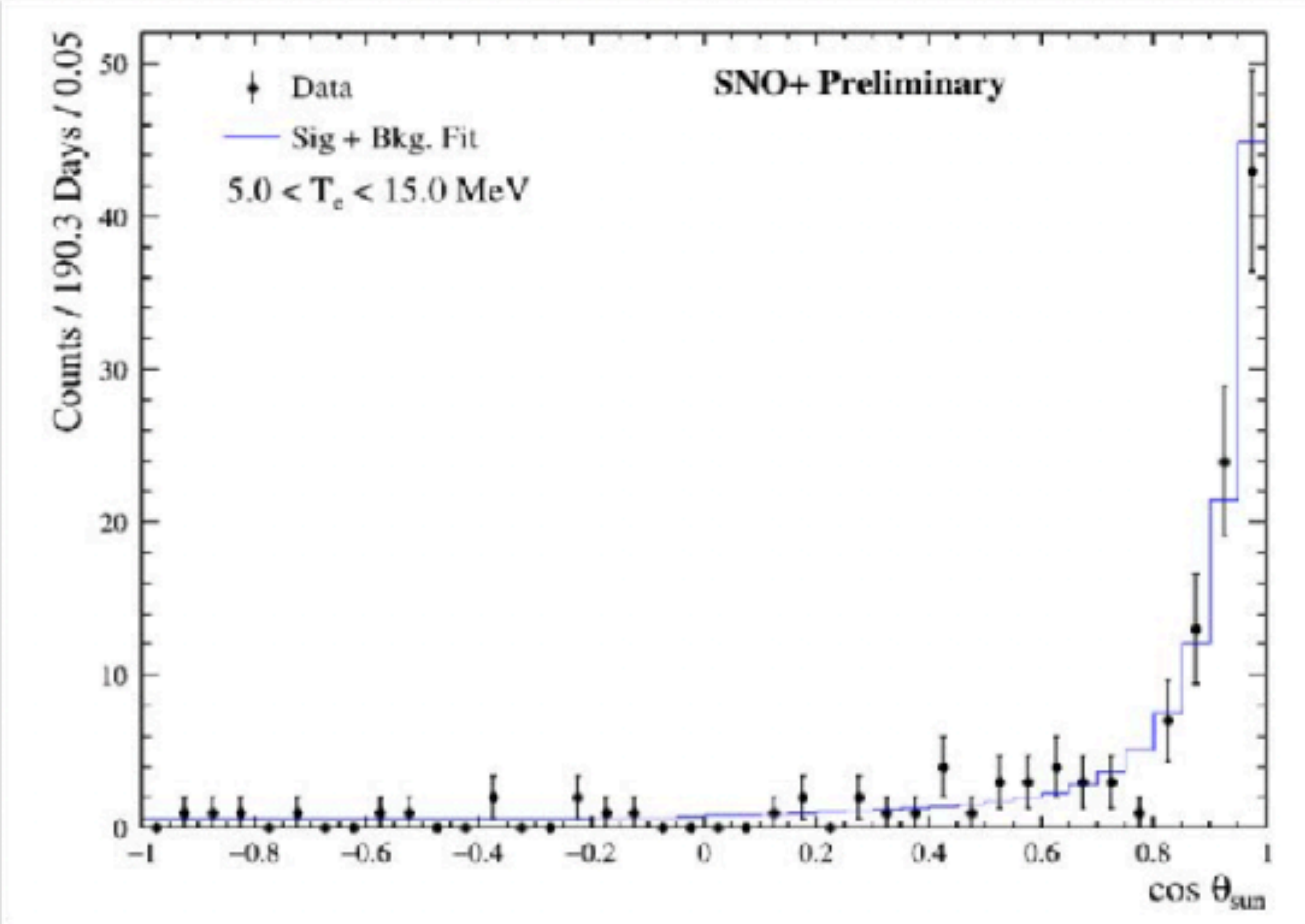
Sensitive

- Single- vs multi-site discrimination keeps backgrounds low

NIM, 943, 162420 (2019)

SNO+ without tellurium

Initial phase - water-Cherenkov detector



^{8}B solar neutrinos with extremely low backgrounds!

Since April 2021- full liquid-scintillator detector

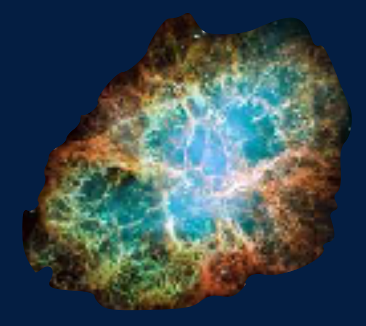
Solar neutrinos

Reactor neutrinos

Up-scattered dark matter

Geo-neutrinos

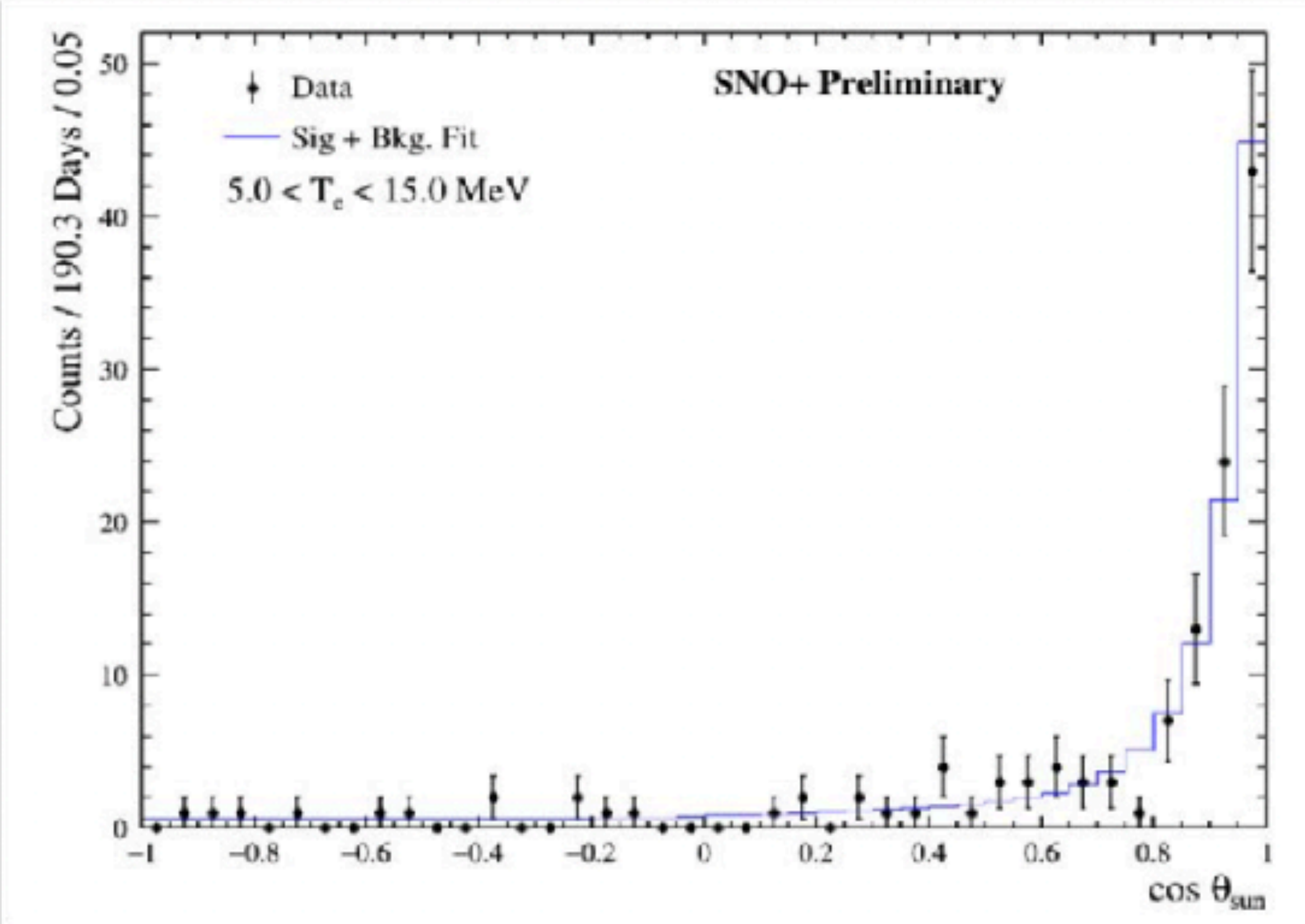
Supernova neutrinos



"Invisible" nucleon decay

SNO+ without tellurium

Initial phase - water-Cherenkov detector



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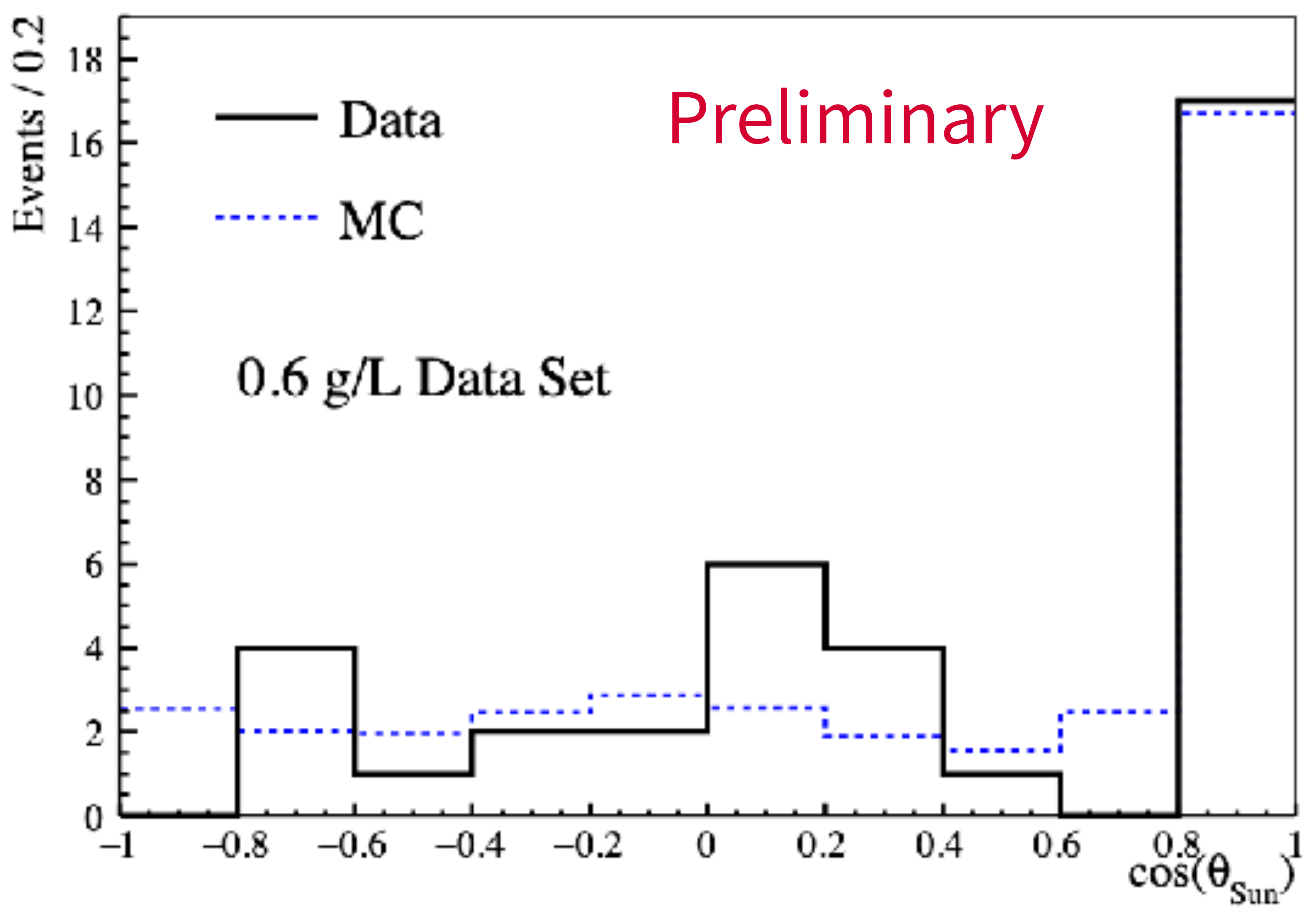
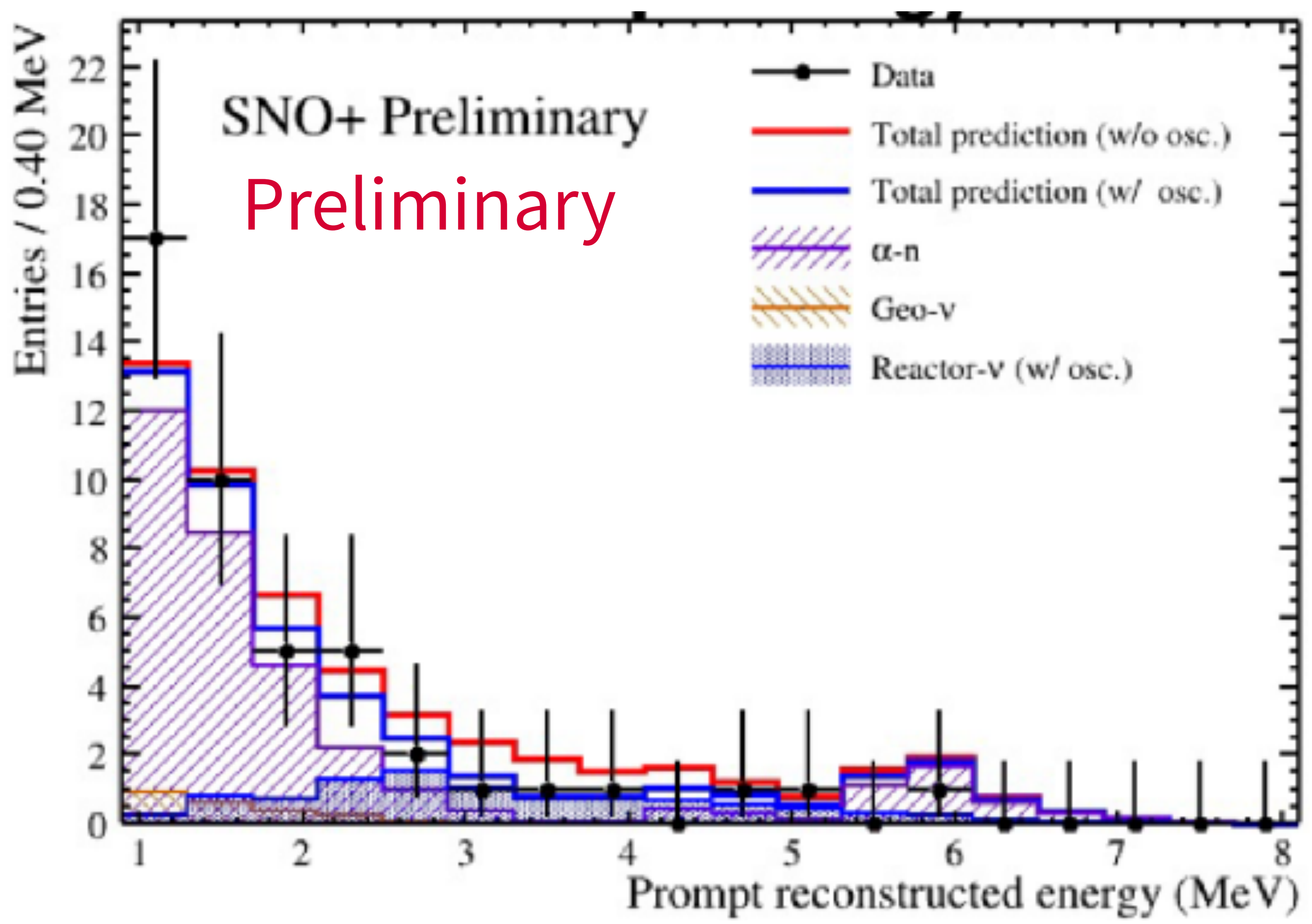
Solar neutrinos



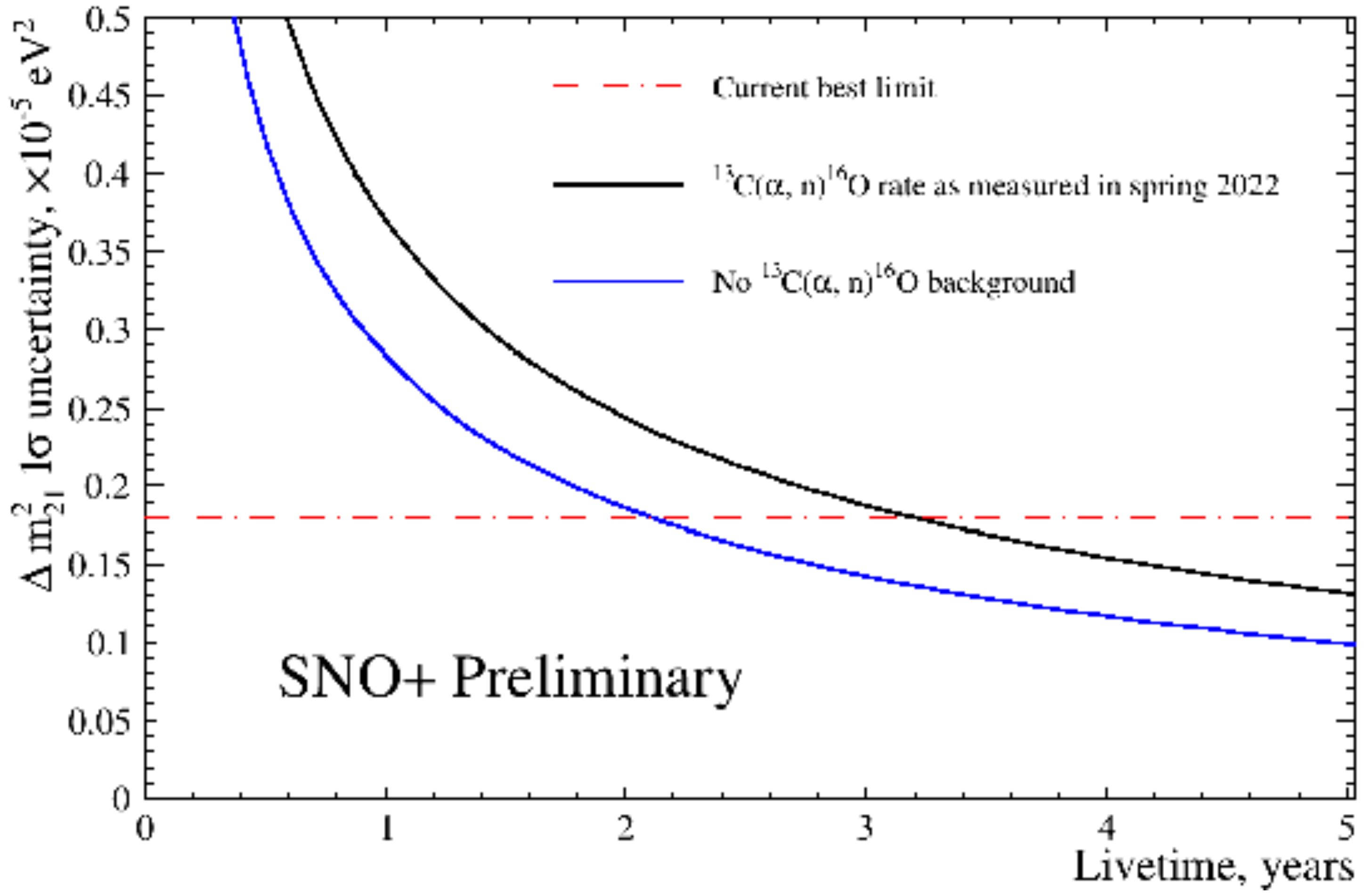
First ever demonstration of event-by-event solar ν directional reconstruction in high light-yield LS

Reactor neutrinos



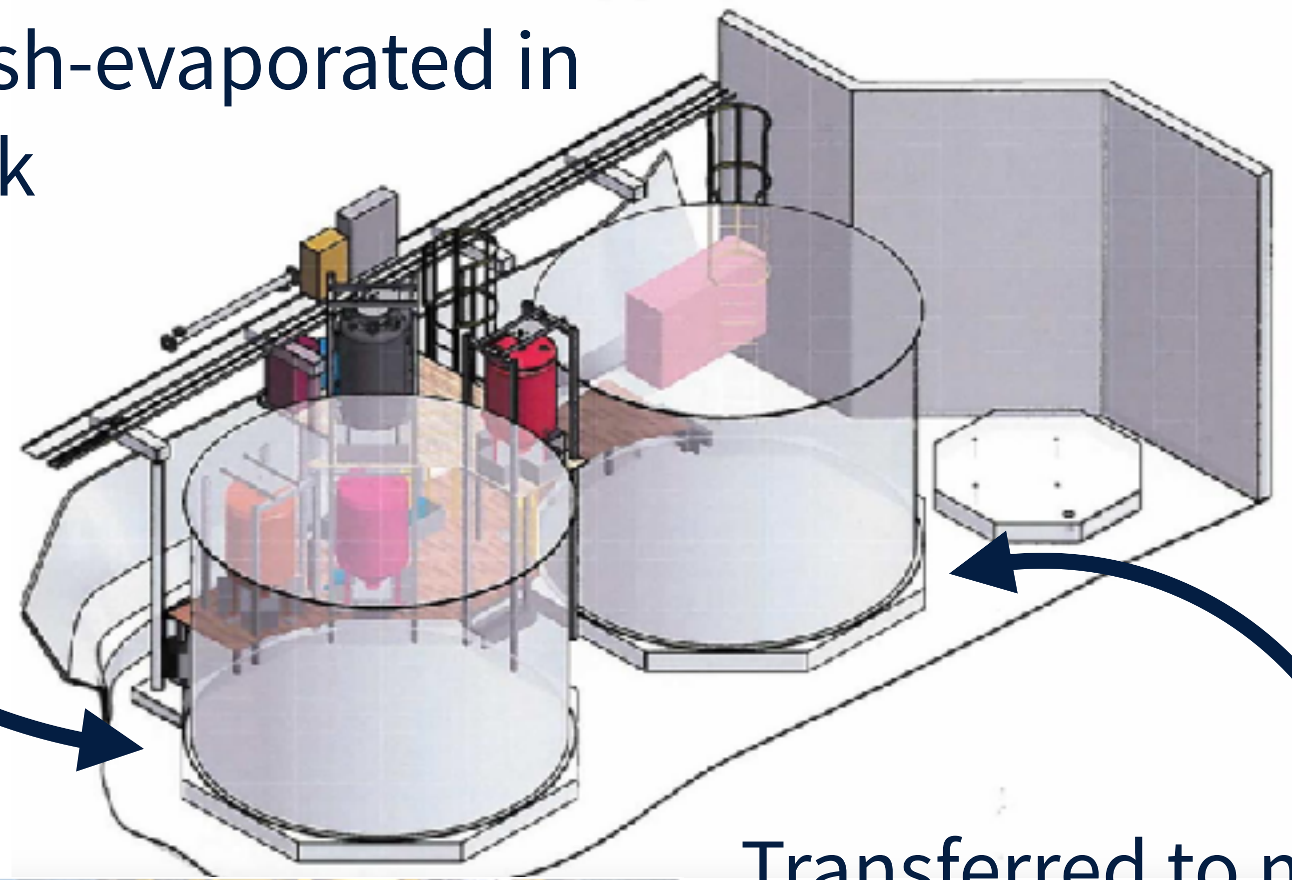
Initial SNO+ observation of reactor $\bar{\nu}$ oscillation

Best Δm^2_{12} constraints within a couple of years!



Preparing for $\beta\beta$-decay

Mixture of telluric acid in water and distilled butanediol is heated while water is flash-evaporated in the synthesis tank



Transferred to mixing tank near solubility point to combine with LAB and 0.25mol DDA to complete solubilisation

Te purification and loading systems constructed and starting commissioning

Delays to Te deployment:

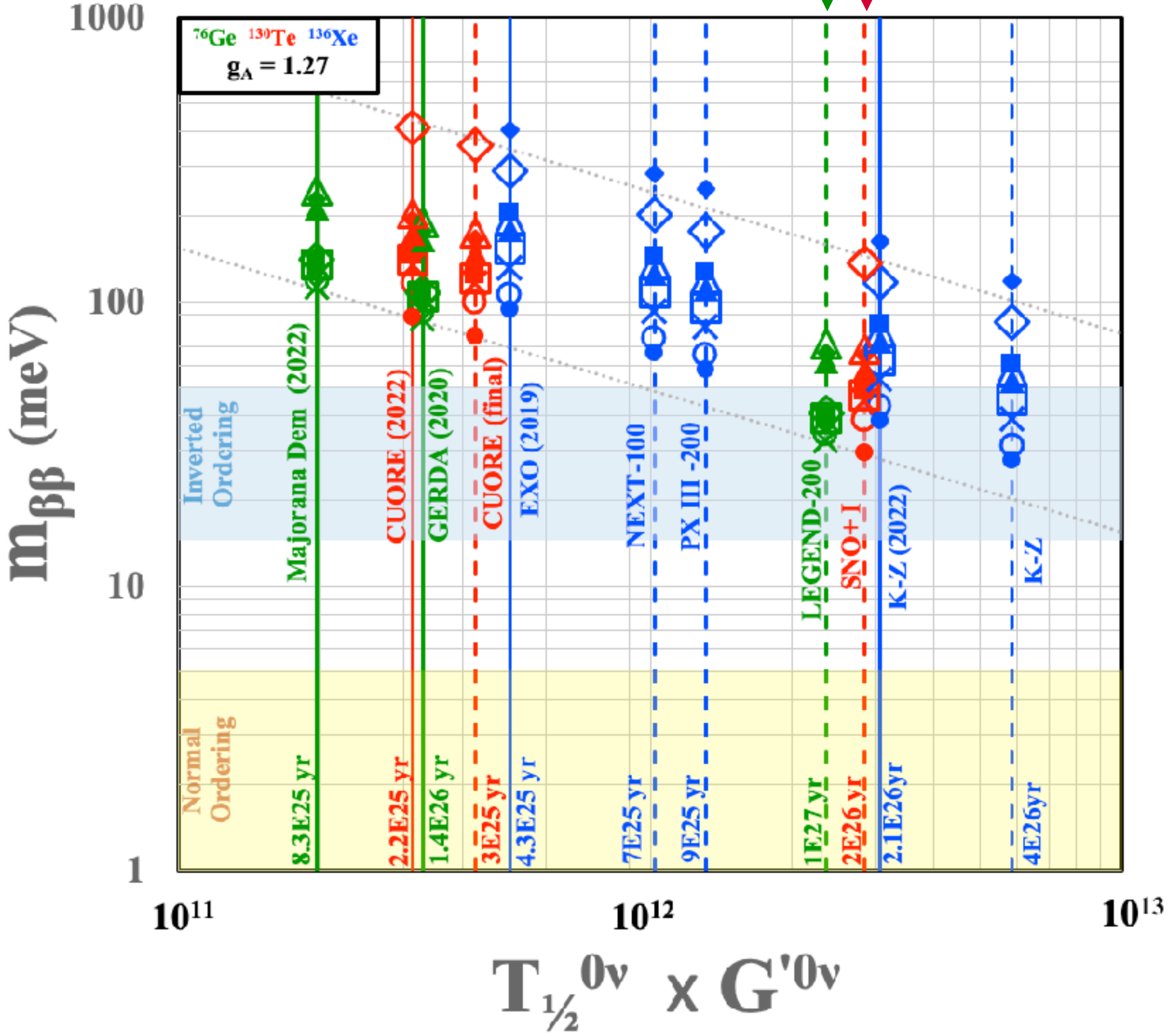
- COVID disruption of supply chains
- Loss of key engineers at SNOLAB
- Extended commissioning & safety review
- Site access limitations

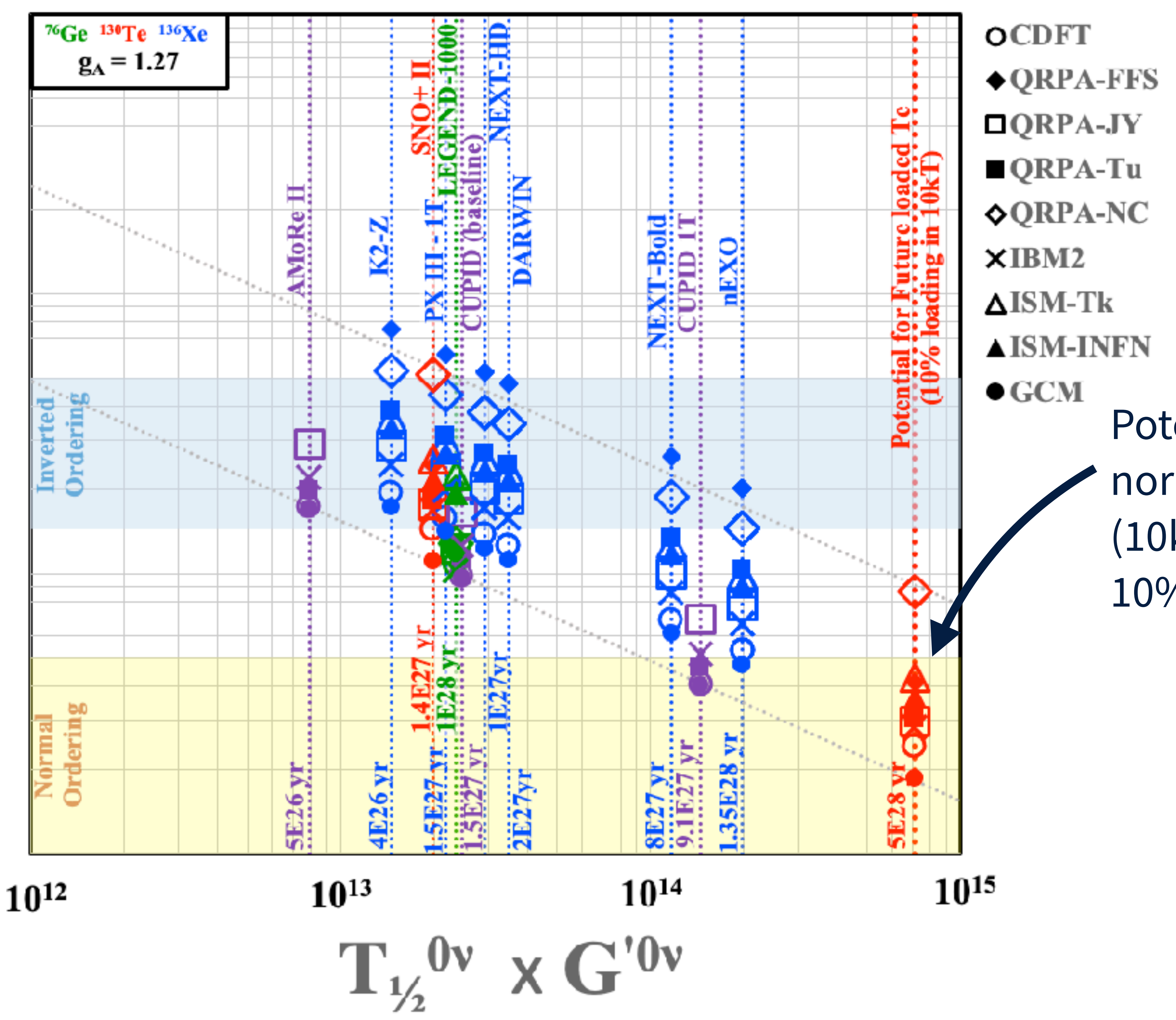
Loading to start in late 2024/early 2025

SNO+ sensitivity

SNO+ I comparable to LEGEND-200

SNO+ II well into inverted hierarchy





Potential to probe normal hierarchy (10kT detector with 10% Te loading)

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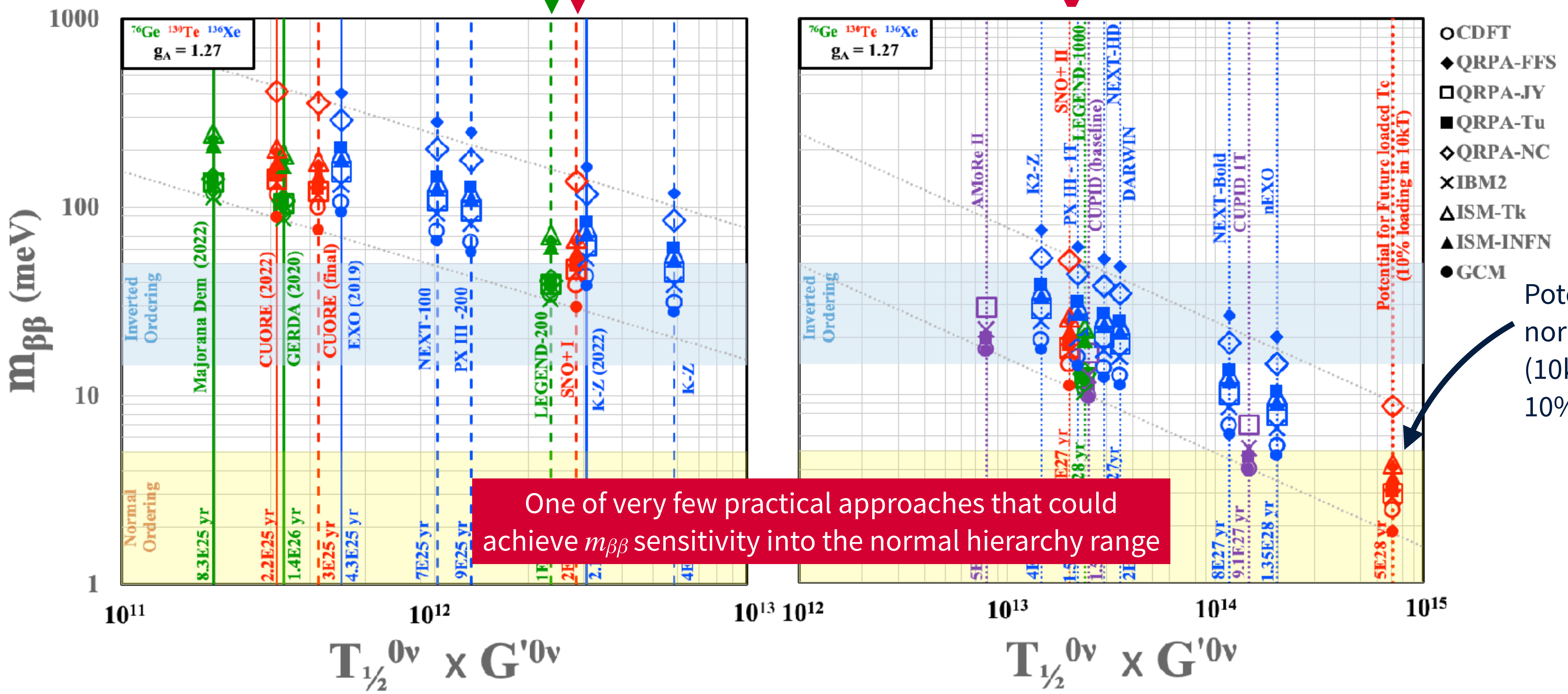


Potential to probe normal hierarchy (10kT detector with 10% Te loading)

One of very few practical approaches that could achieve $m_{\beta\beta}$ sensitivity into the normal hierarchy range

SuperNEMO, at LSM, French Alps

THE UNIVERSITY of EDINBURGH

UCL

WARWICK
THE UNIVERSITY OF WARWICK

MANCHESTER 1824
The University of Manchester

Imperial College London

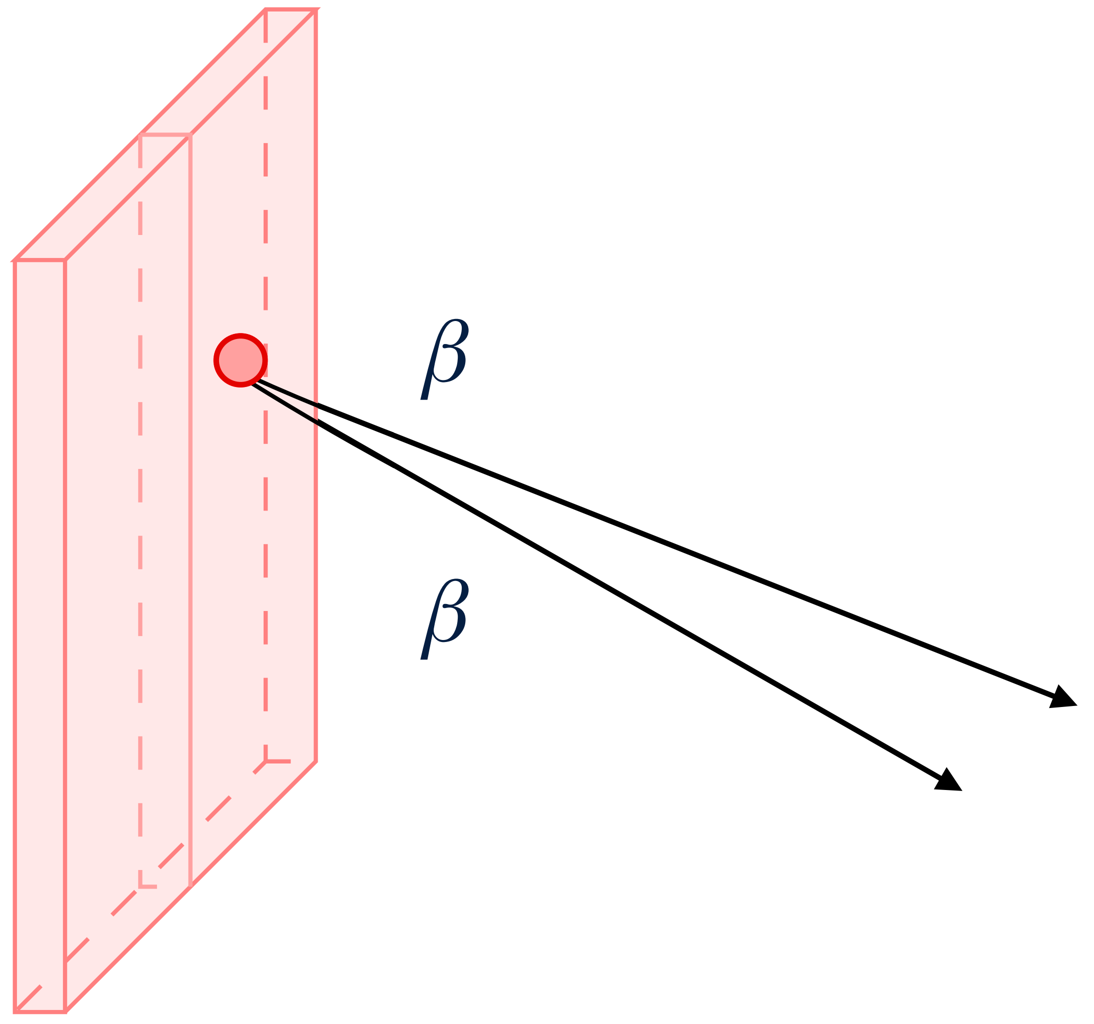
^{82}Se

supernemo collaboration

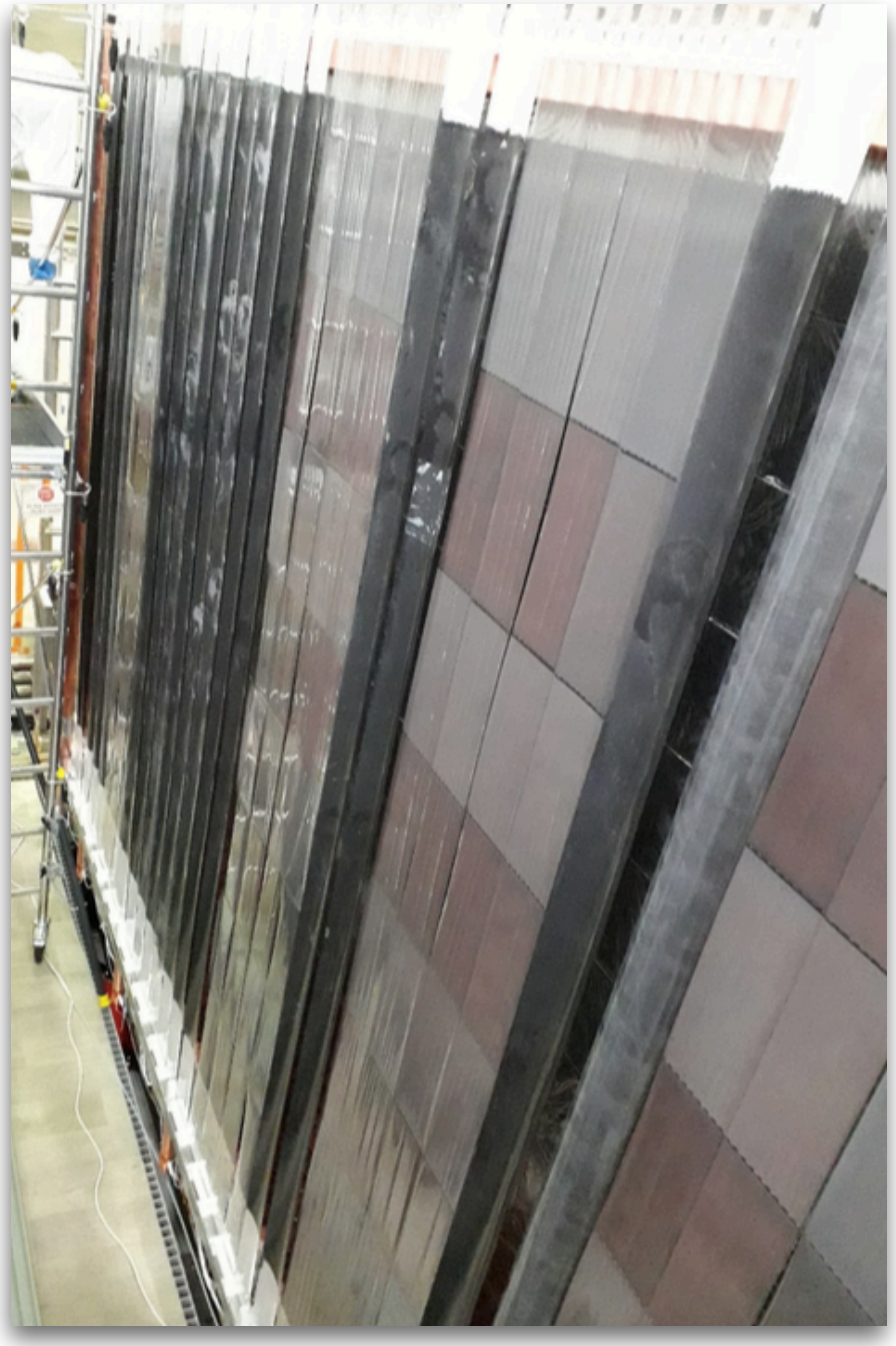
An isotope-agnostic technique to distinguish individual particles, and probe $0\nu\beta\beta$ mechanisms and nuclear effects

The NEMO principle

$\beta\beta$ source



Any solid $\beta\beta$ isotope

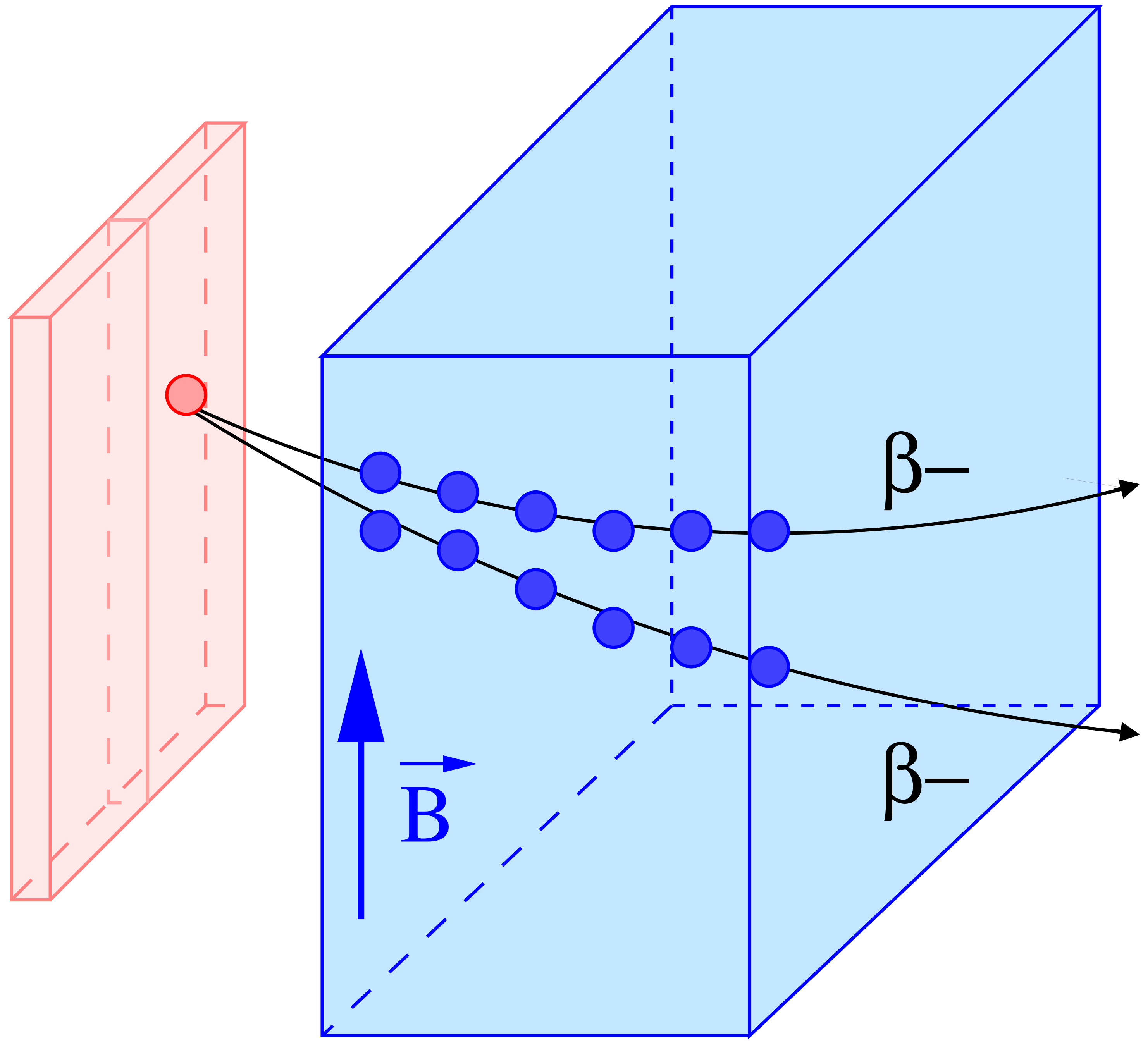


SuperNEMO Demonstrator - 6.23kg ^{82}Se

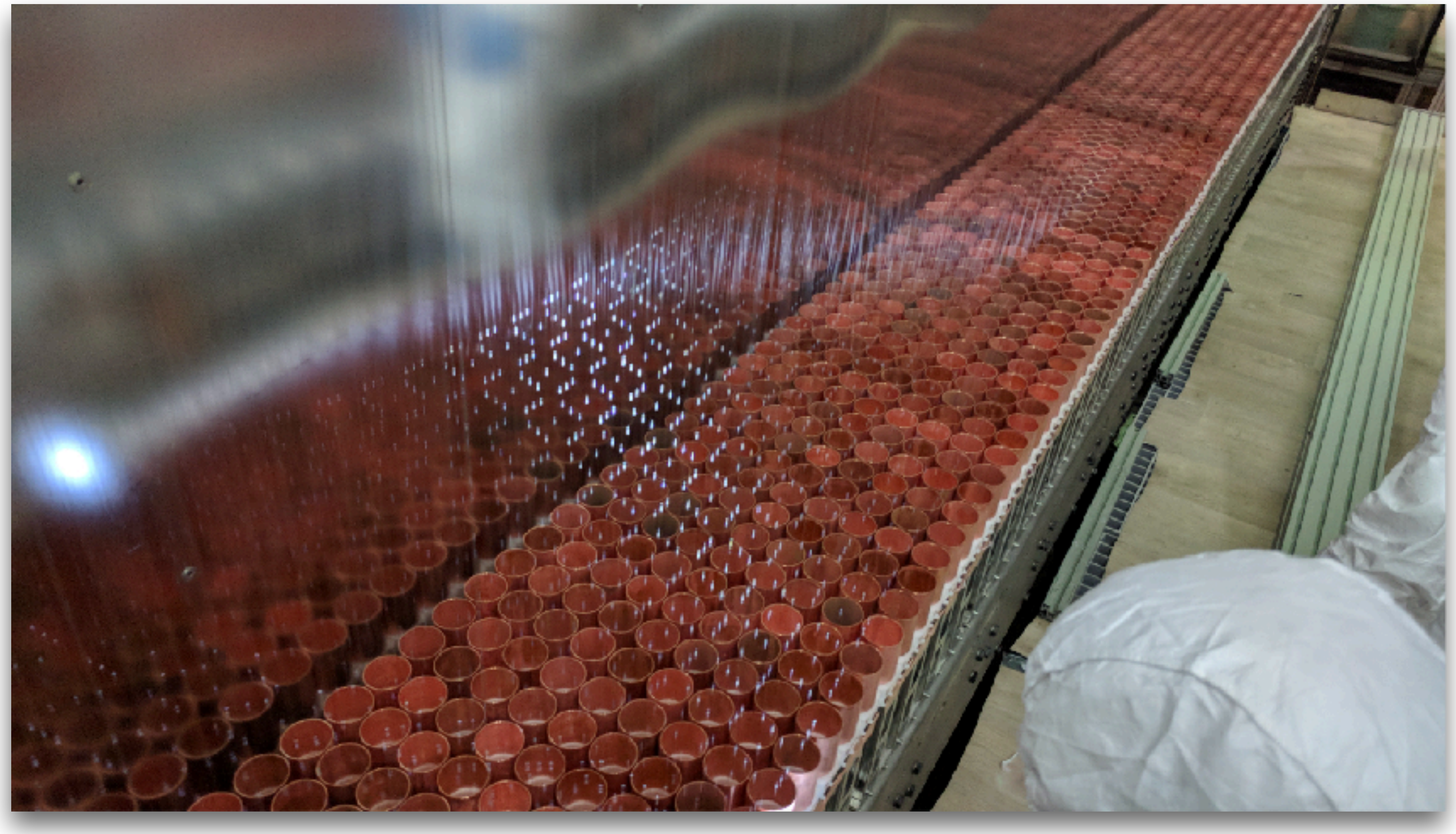
The NEMO principle

$\beta\beta$ source

High-granularity tracker

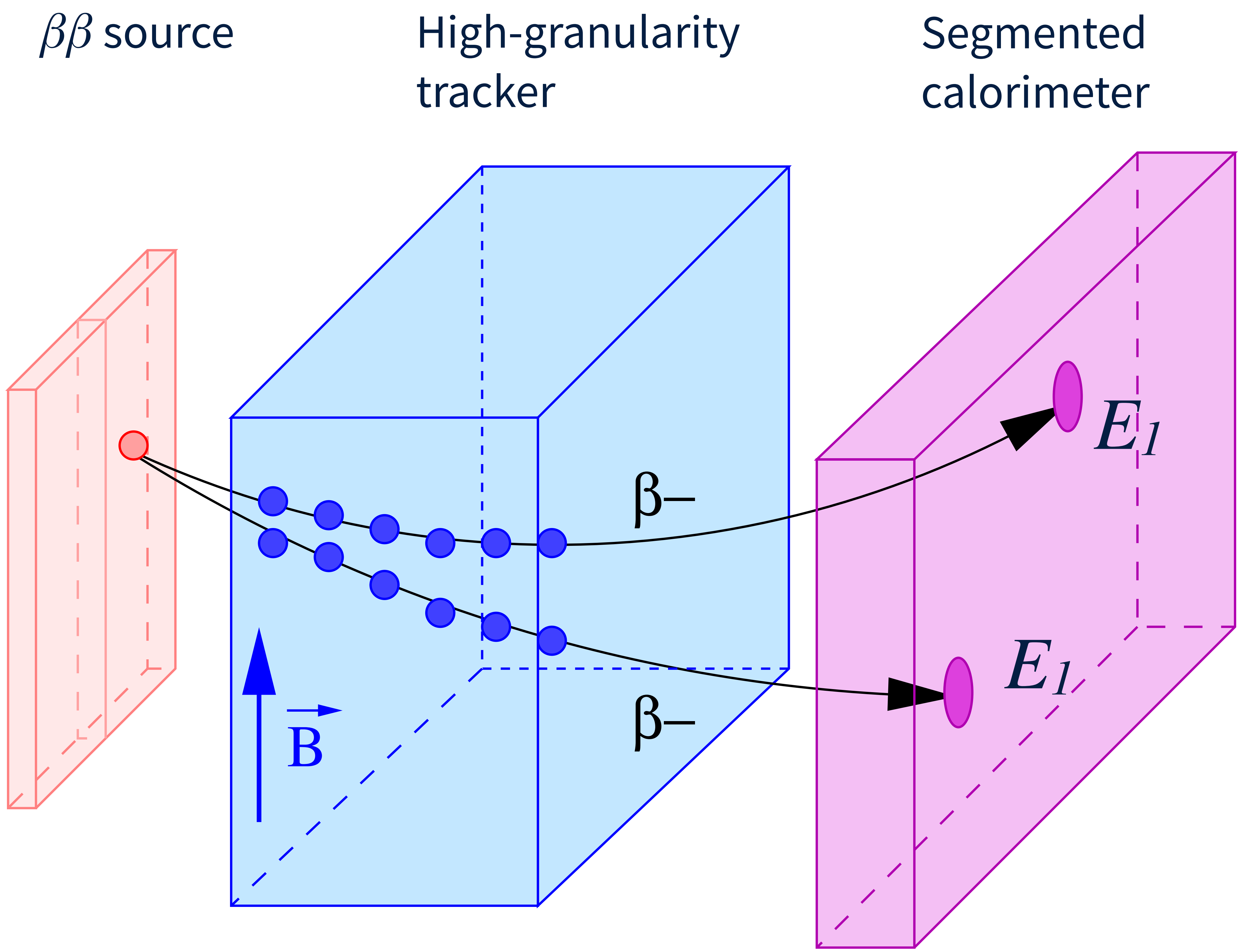


Angle between tracks

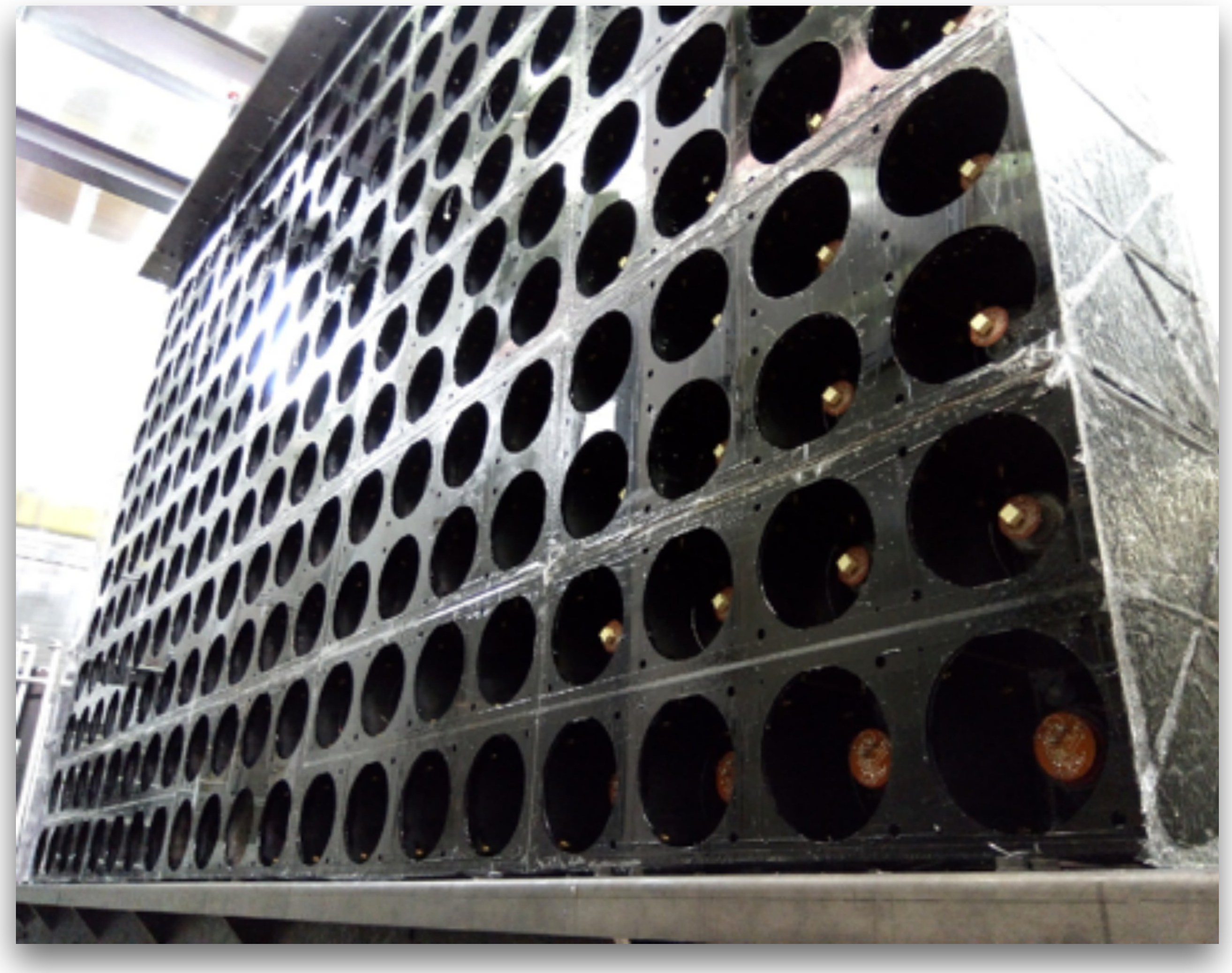


SuperNEMO Demonstrator - 2034 Geiger cells

How SuperNEMO works



Angle between tracks + Individual energies & times



712 optical modules

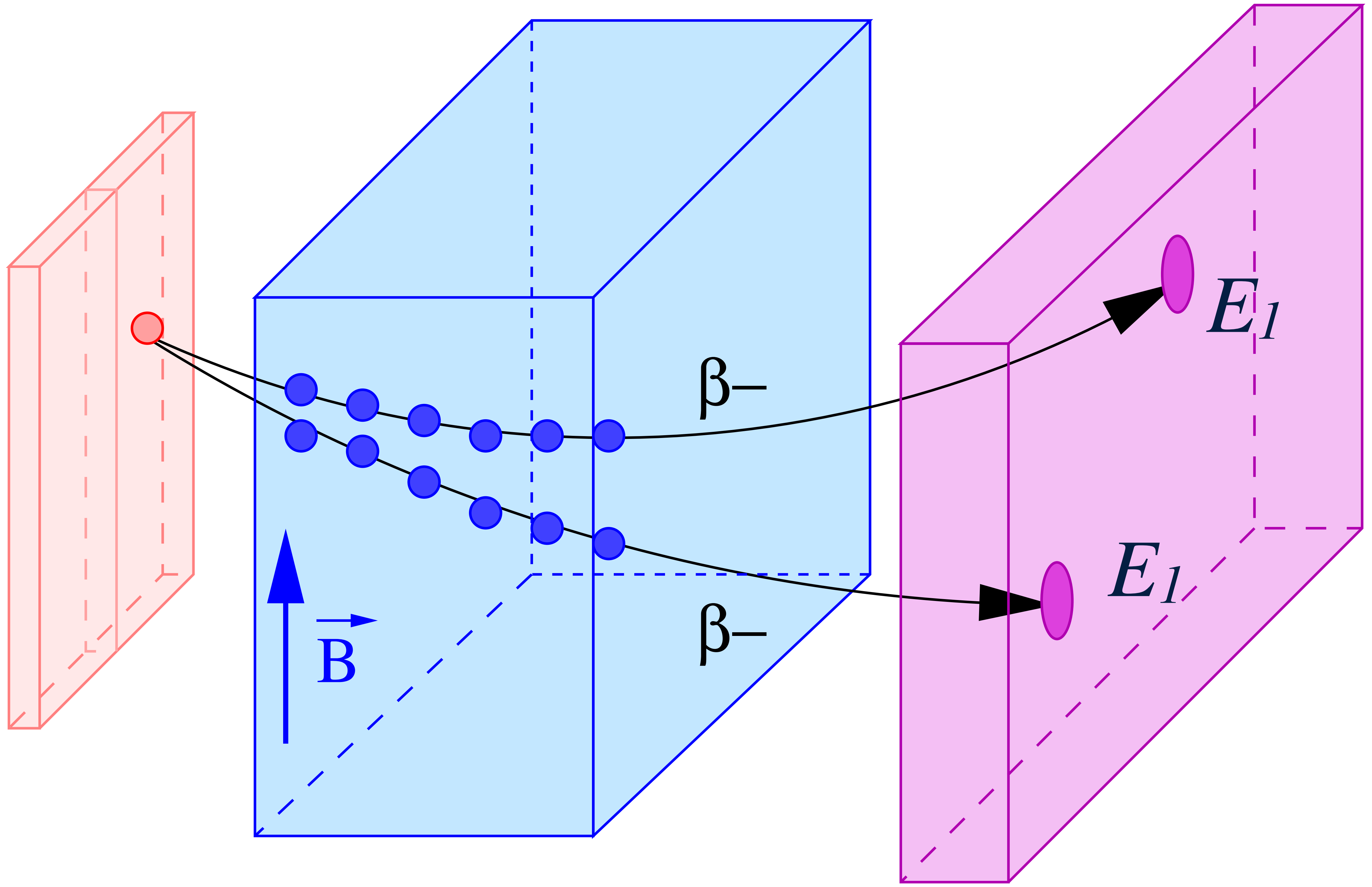
σ/E 1.8% at 3 MeV

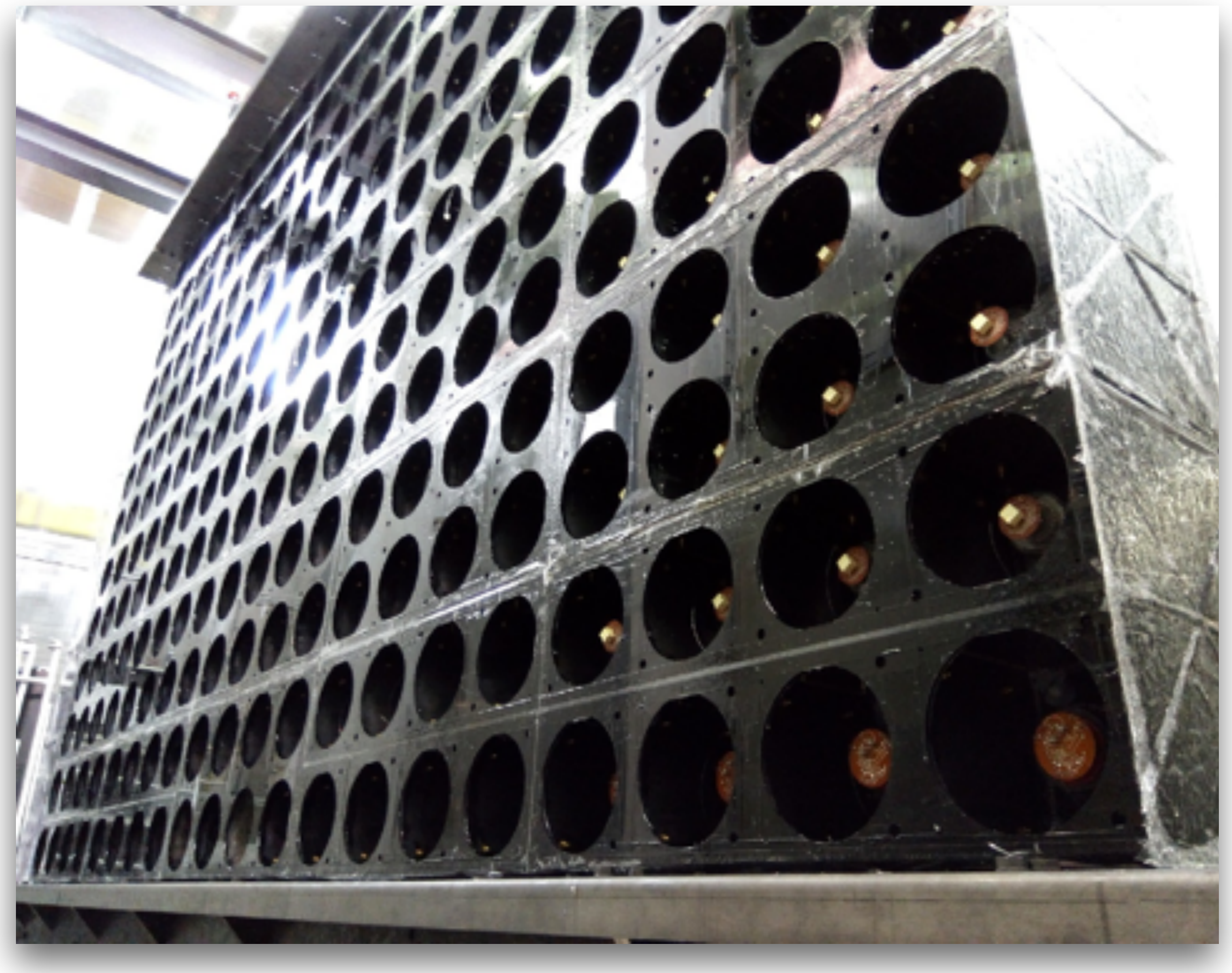
How SuperNEMO works

$\beta\beta$ source

High-granularity tracker

Segmented calorimeter





712 optical modules

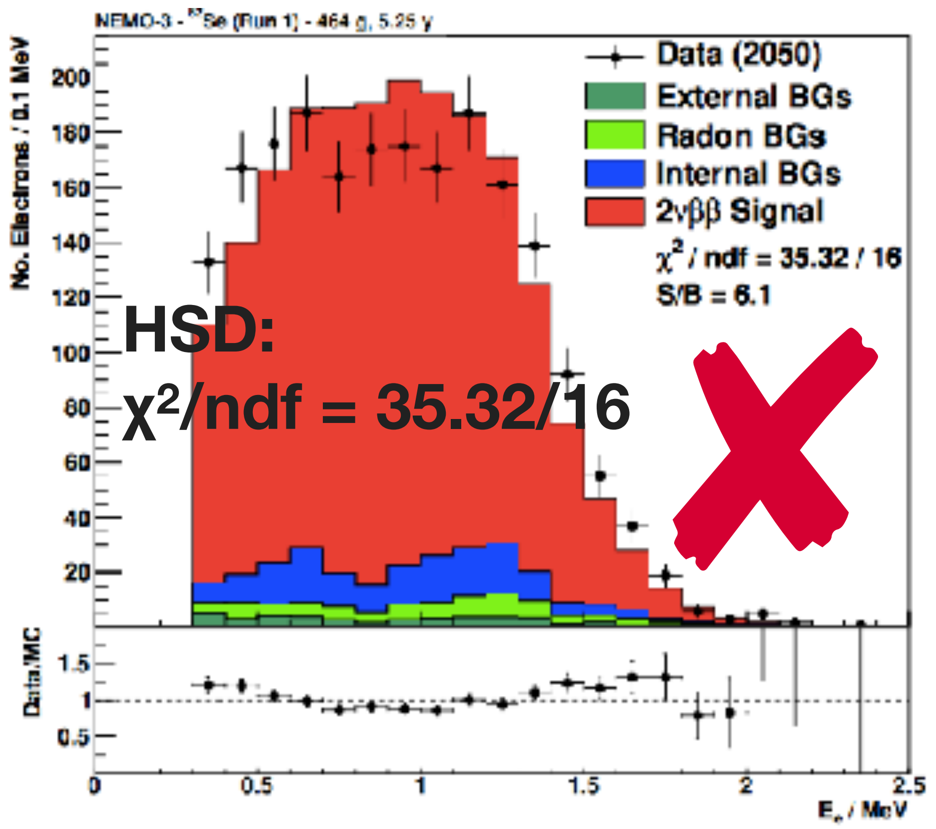
σ/E 1.8% at 3 MeV

Angle between tracks + Individual energies & times = discrimination between $\beta\beta$ mechanisms and nuclear effects; background rejection

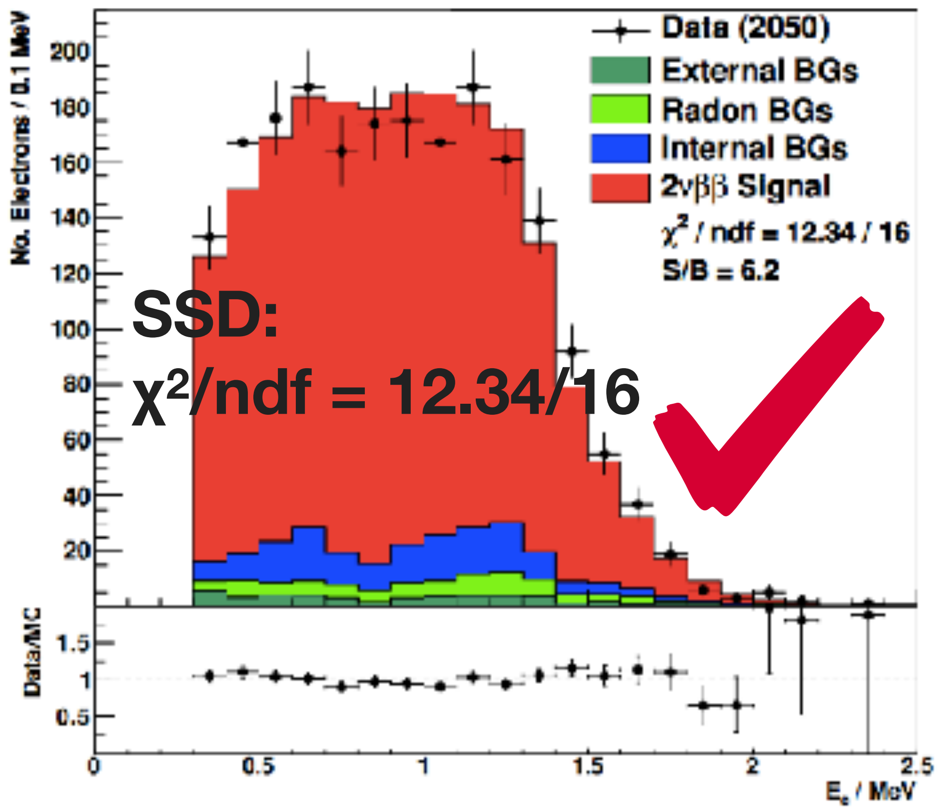
SuperNEMO for nuclear effects

Intermediate states in $2\nu\beta\beta$ decay

Eur. Phys. J. C (2018) 78: 821



Various excited states



Mostly ground state

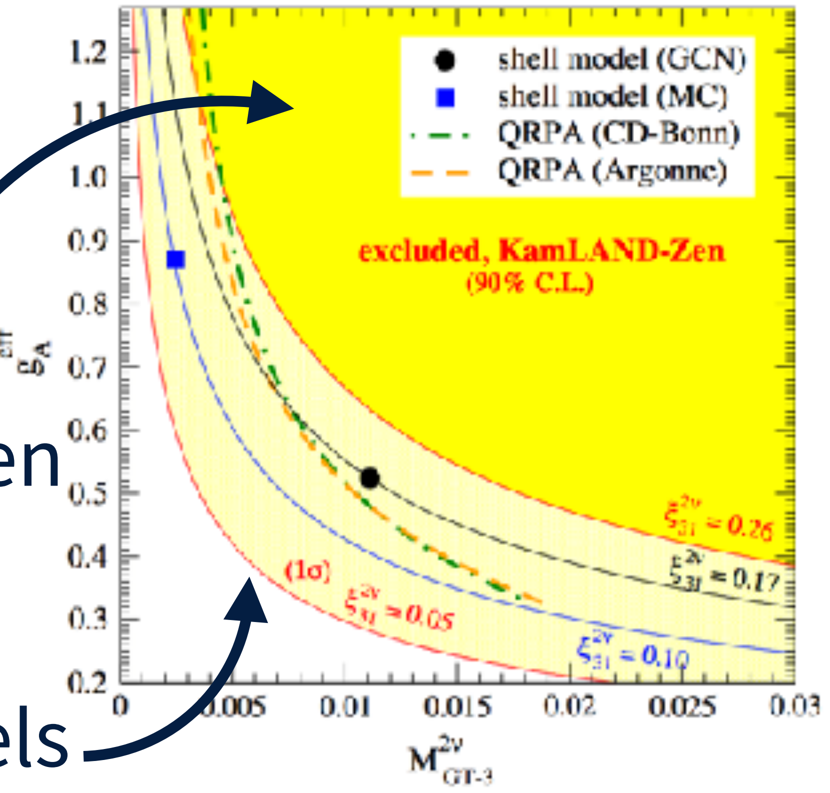
SuperNEMO will have 5σ sensitivity

g_A quenching

Phys Rev Lett 122, 192501 (2019)

SuperNEMO's individual e^- spectrum will be more sensitive

Excluded by KamLAND-Zen

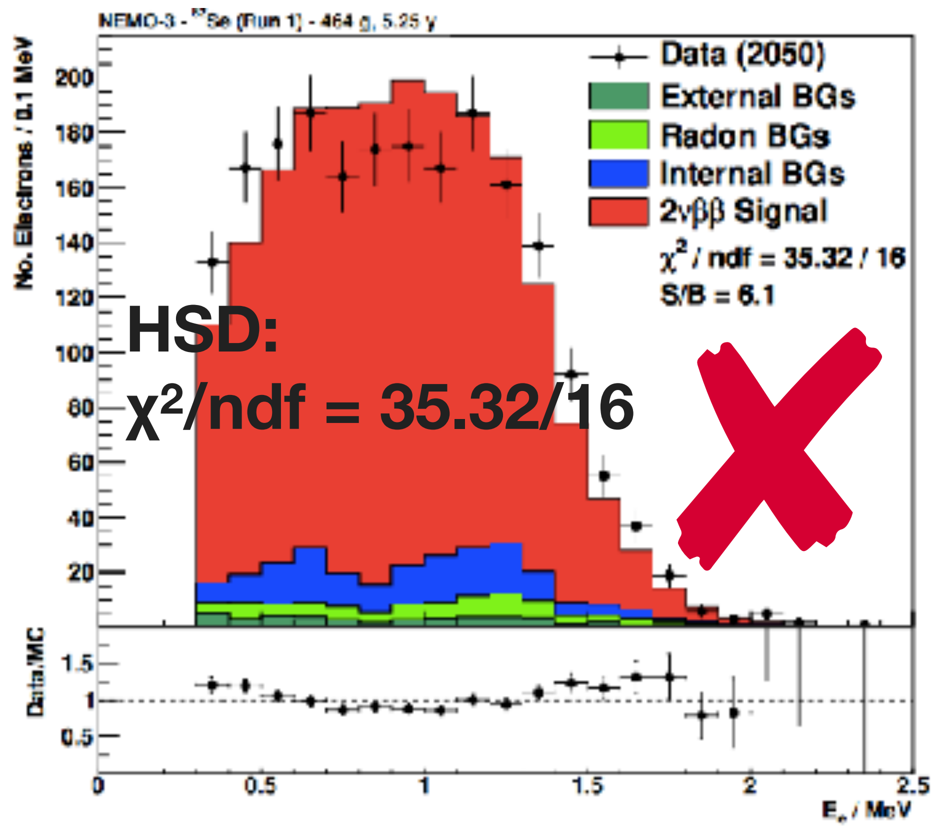


Lines and points → nuclear models

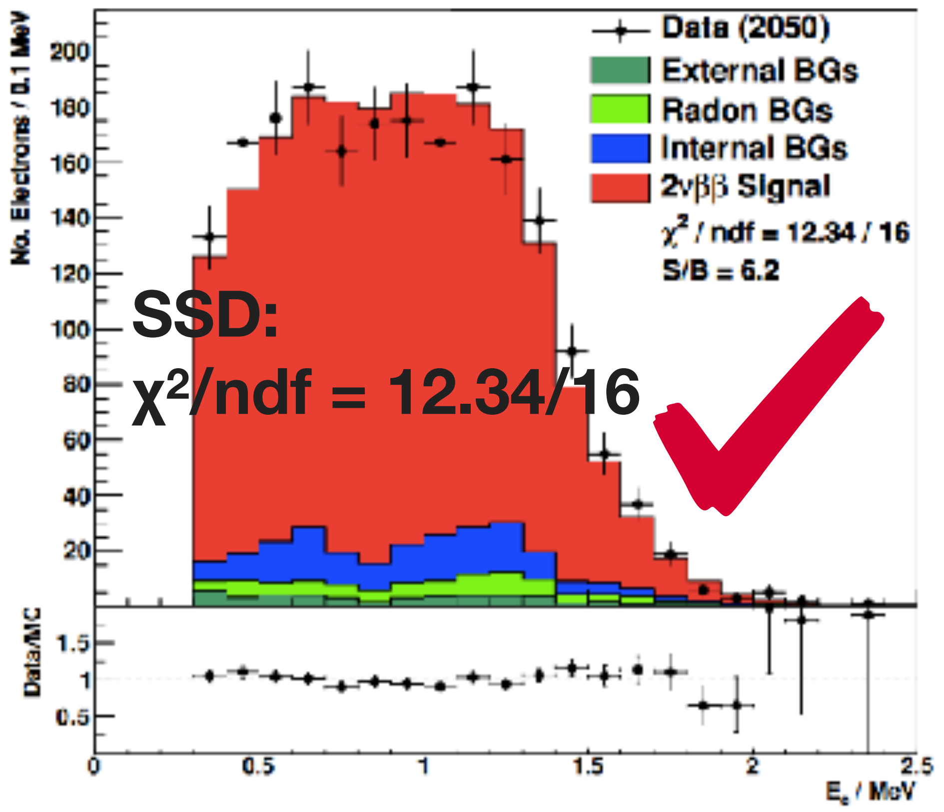
SuperNEMO for nuclear effects … and exotic physics

Intermediate states in $2\nu\beta\beta$ decay

Eur. Phys. J. C (2018) 78: 821



Various excited states



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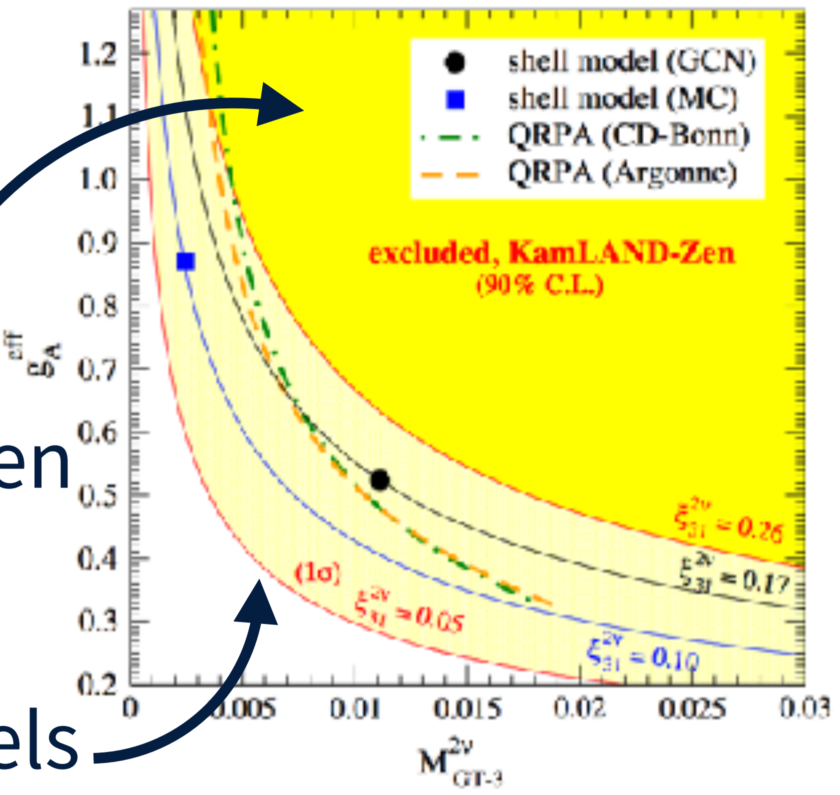
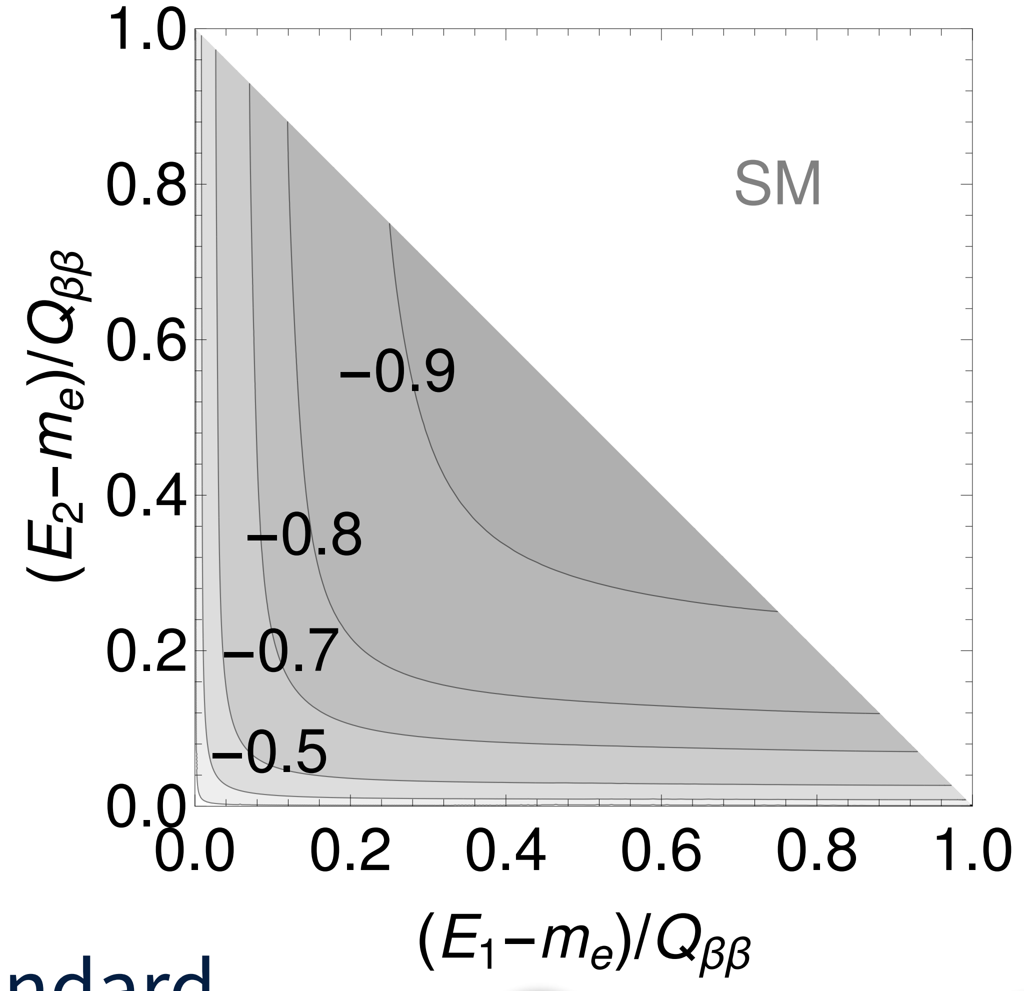


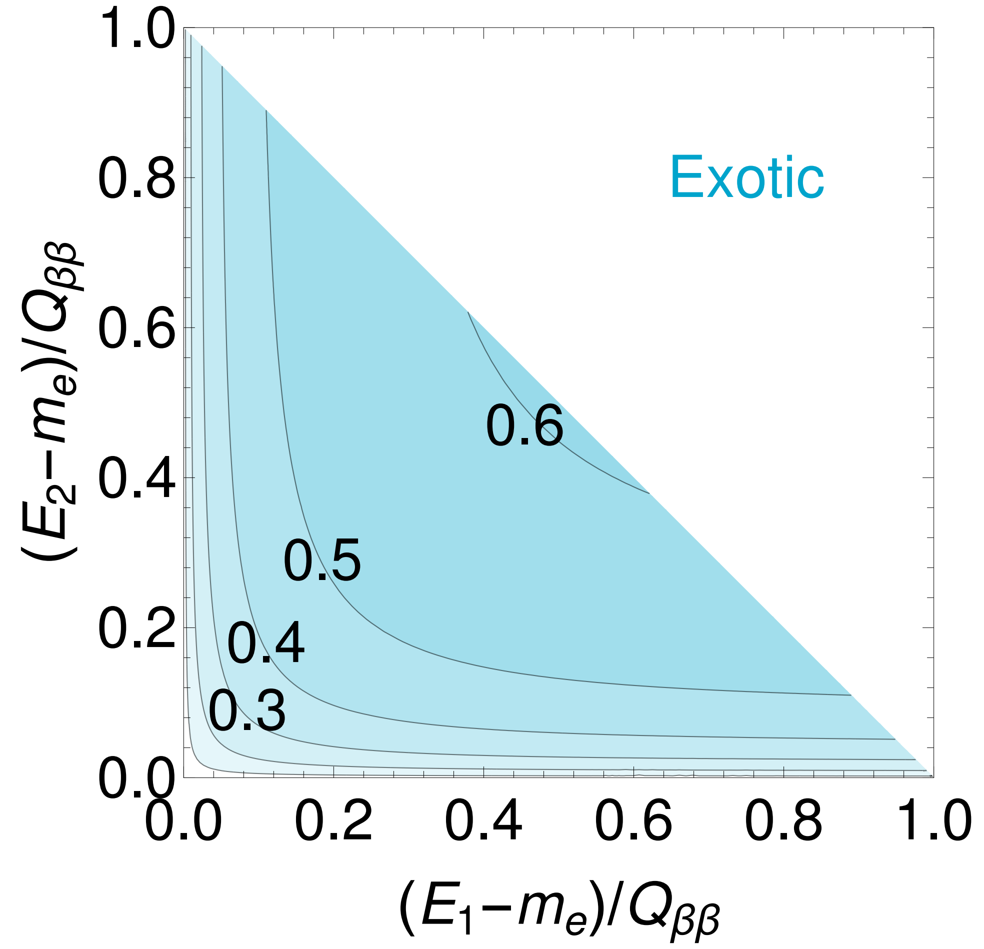
Lines and points → nuclear models

Precision $2\nu\beta\beta$ measurements can reveal BSM effects…

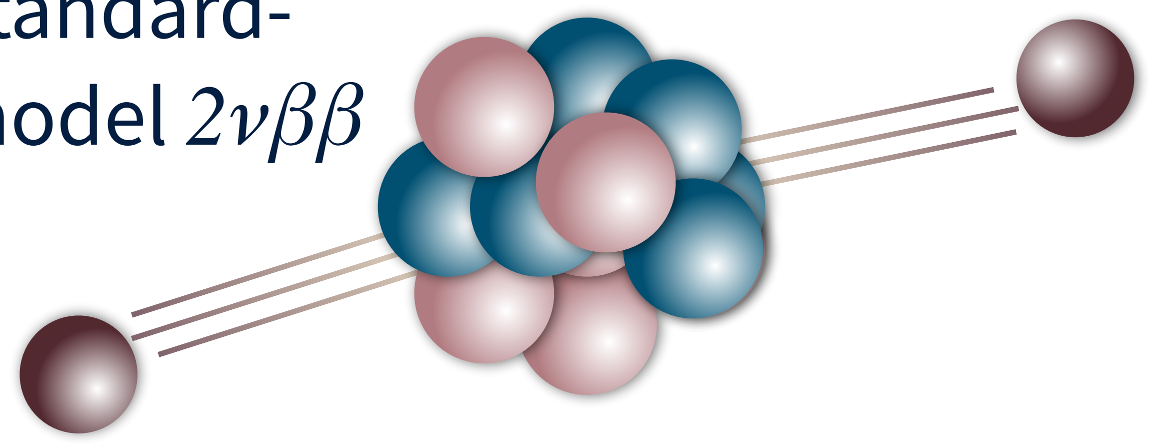
- Lorentz-invariance violation
- Exotic $0\nu\beta\beta$ mechanisms
- Right-handed neutrinos (see below)
- Scalar currents…

Phys. Rev. Lett. 125, 171801 (2020) (UK-led study)

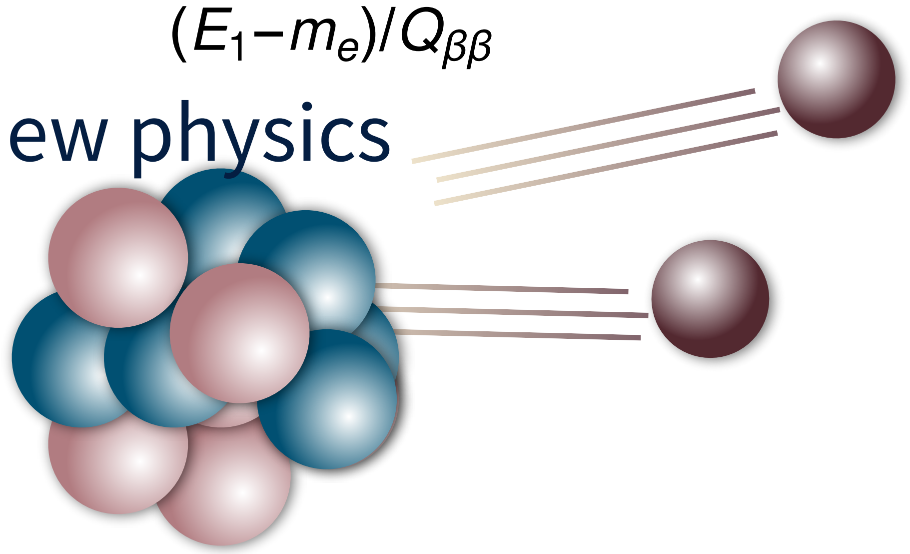




Standard-model $2\nu\beta\beta$



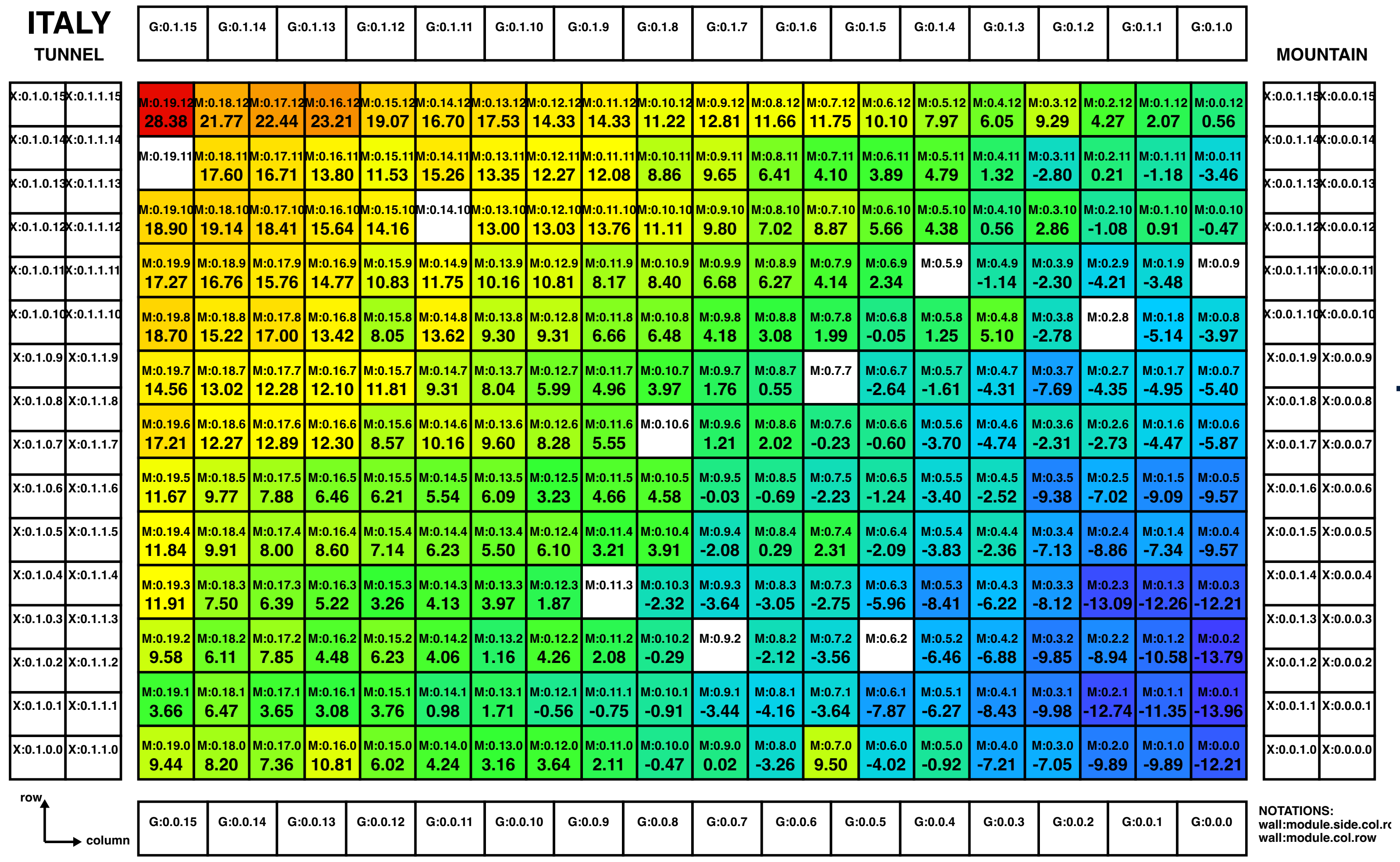
New physics



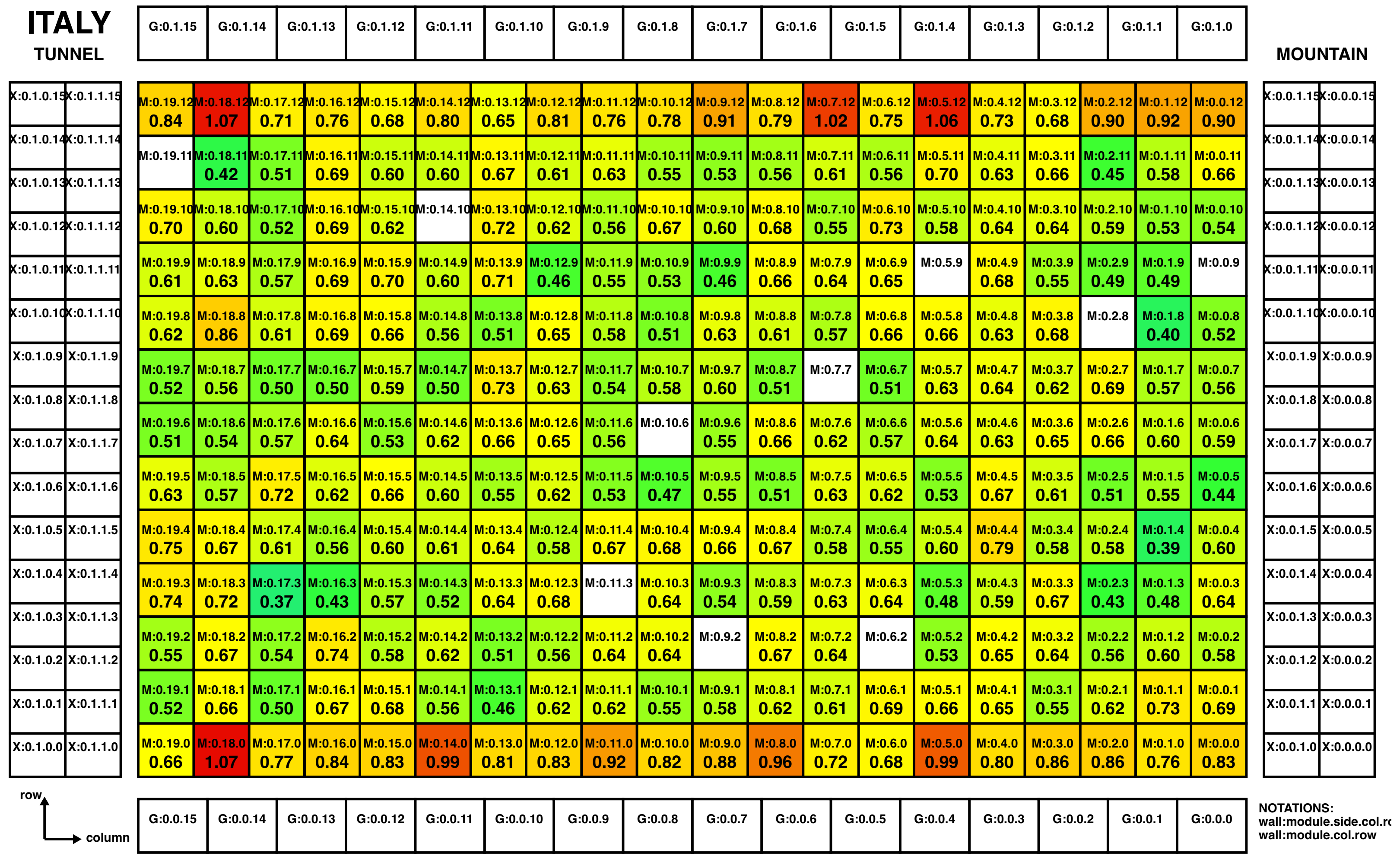
Best technology to understand $0\nu\beta\beta$ mechanism if it's discovered

SuperNEMO Demonstrator status: Calorimeter calibration

Timing

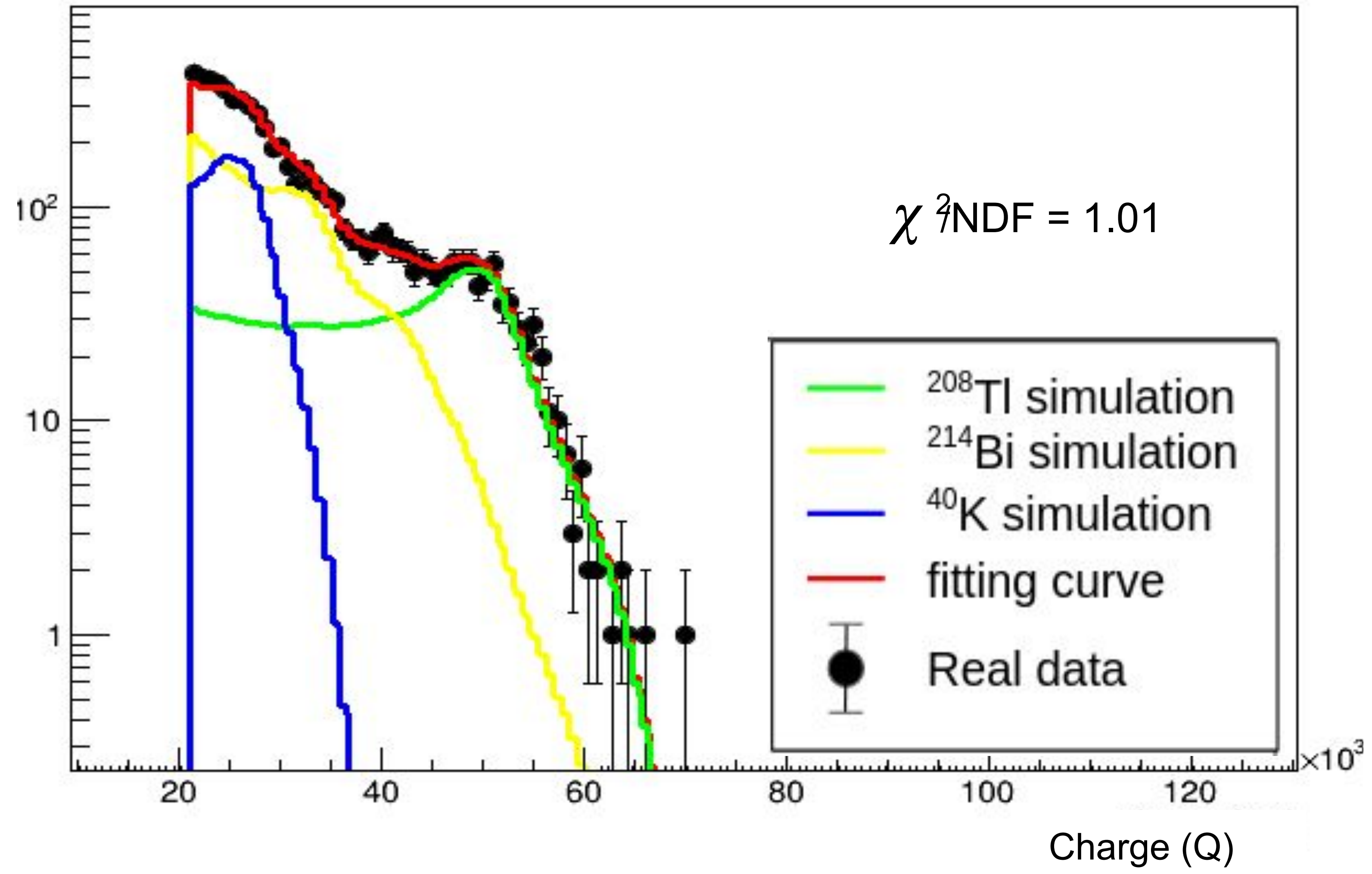


Time-delay calibration

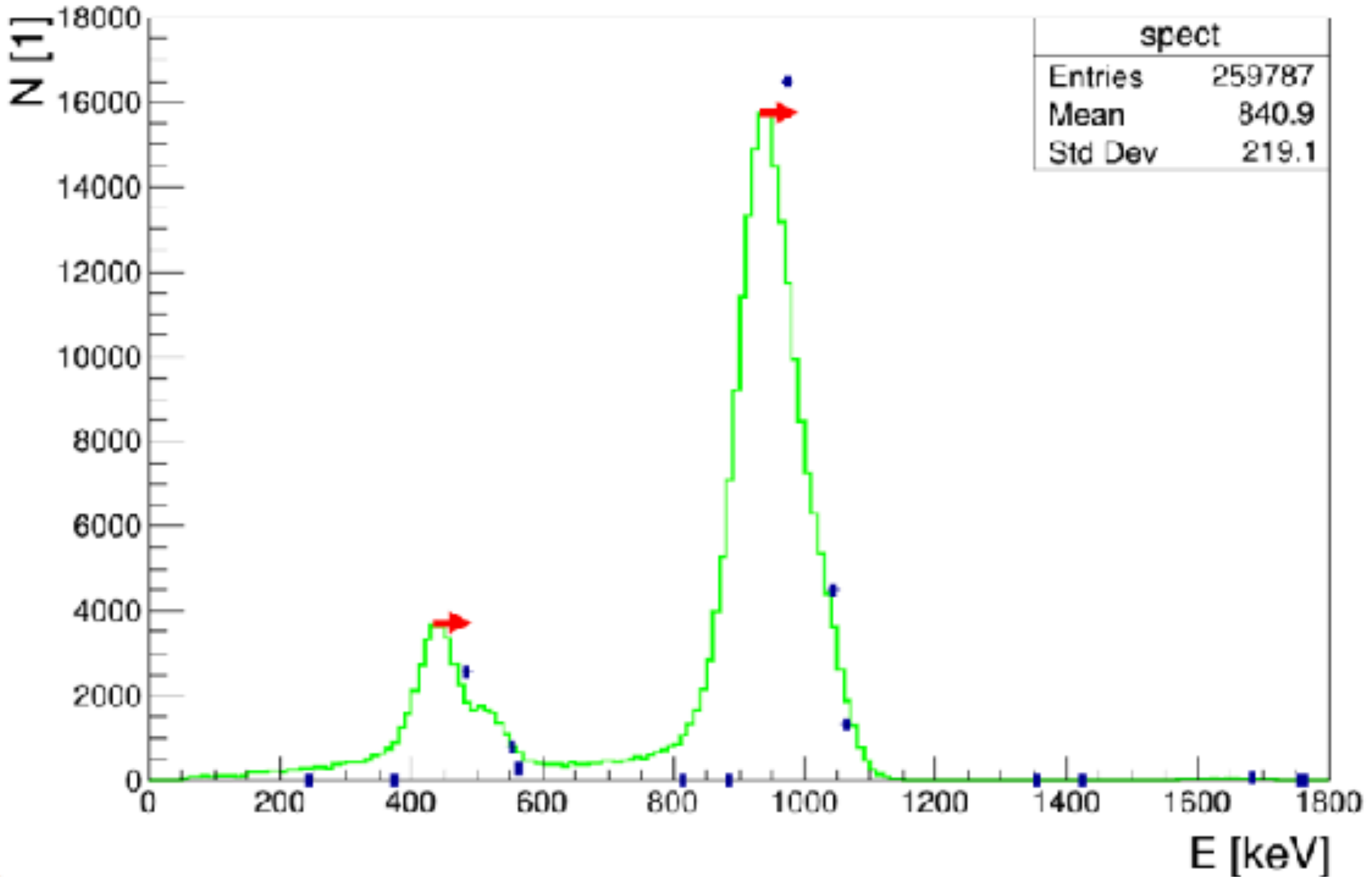


Timing resolution:
σ ~ 0.6ns (at 1 MeV)

Energy calibration

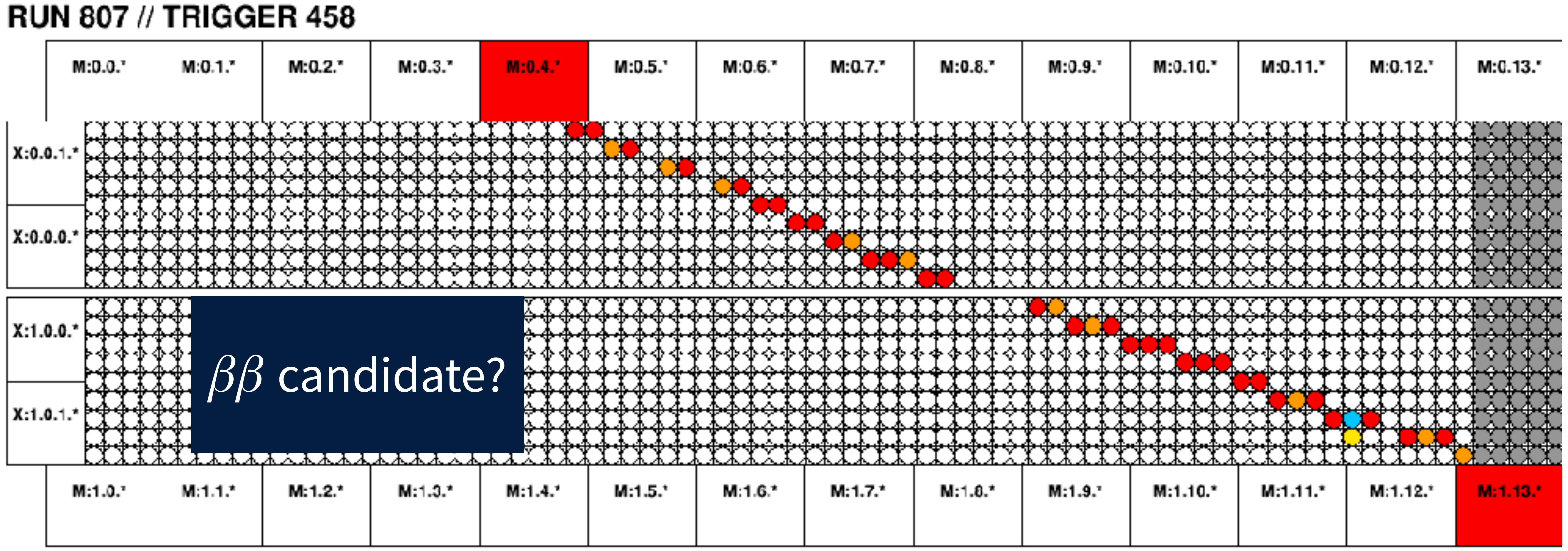


… with ambient sources

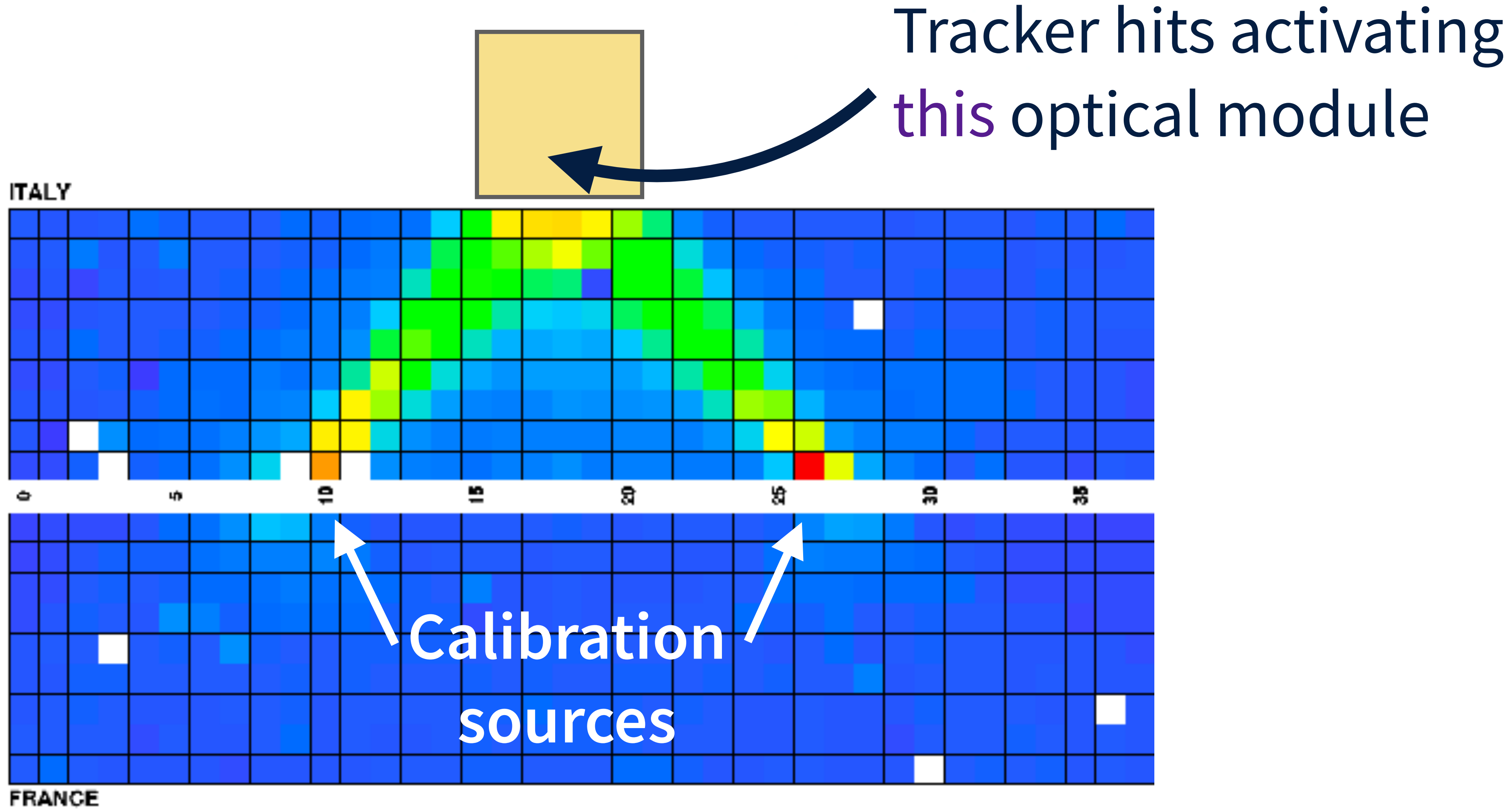


… with our automatic ^{207}Bi source deployment system

SuperNEMO Demonstrator status: Tracker

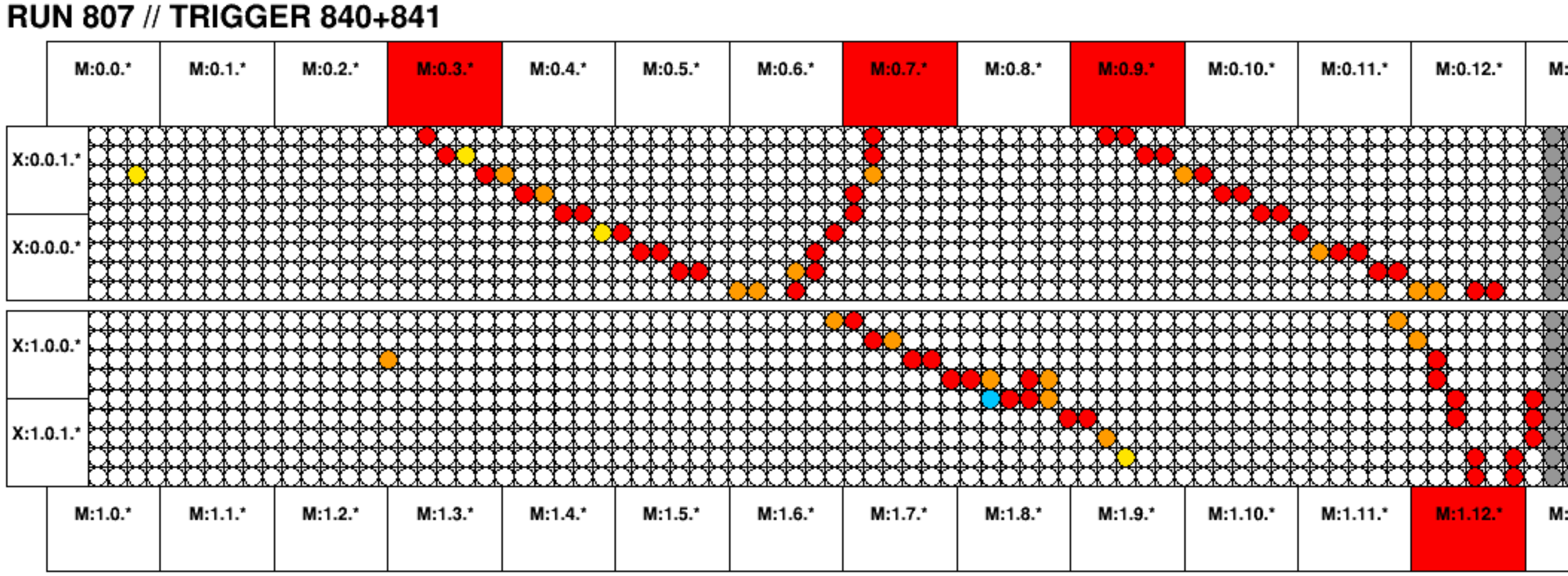


- **Dramatic progress** over the last year after setbacks due to Covid, faulty hardware…
- **Entire tracker successfully tested** at high voltage
- 2/3 of detector undergoing commissioning / calibration
- Final 1/3 to be connected shortly
- **~99% of connected channels operational**

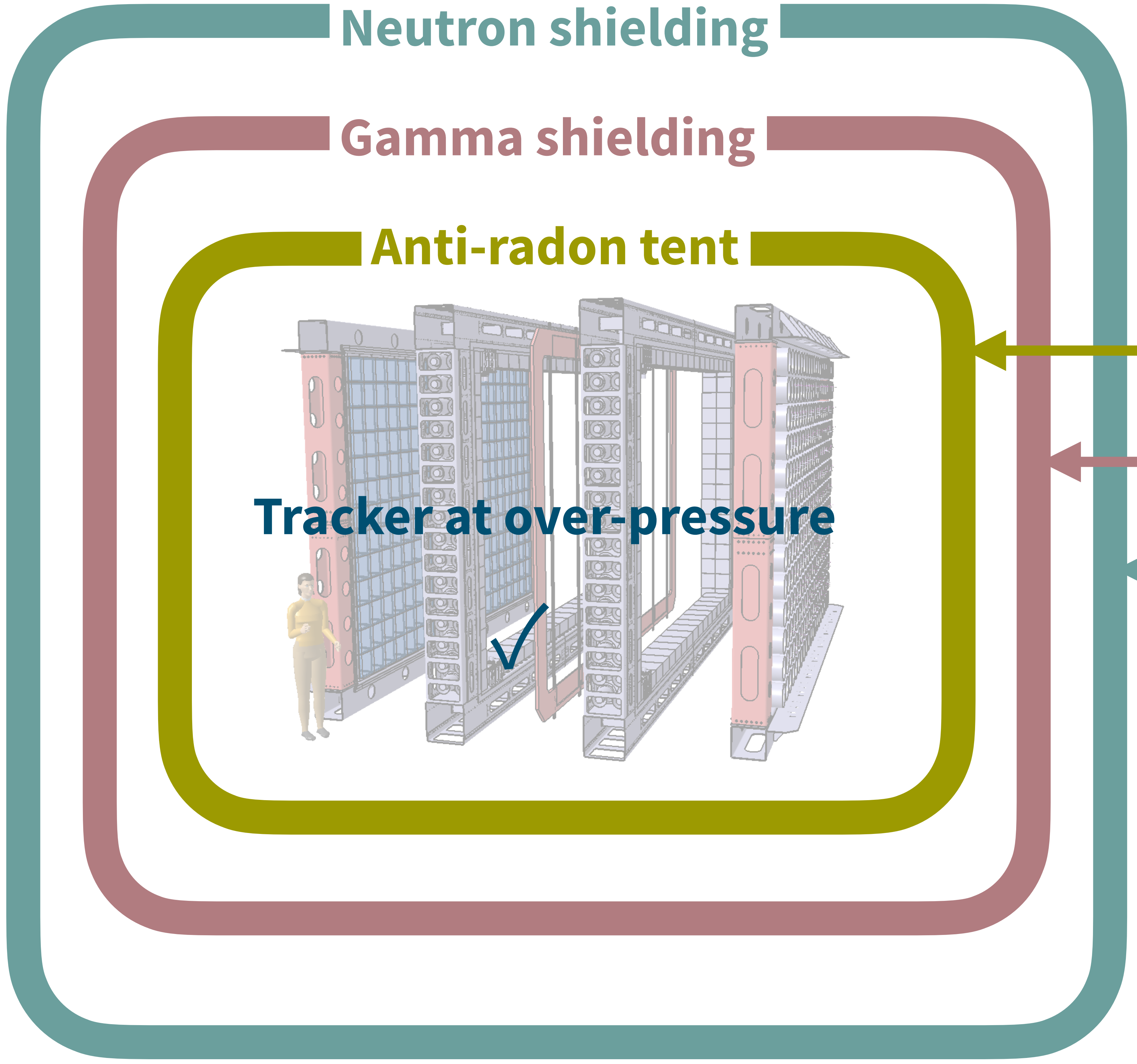


Automatic ^{207}Bi calibration system in action

Real tracker-calorimeter data!



Getting ready for physics data



Under construction

Iron shielding ordered; quality control looking promising

Polyethylene / water design in final review

Getting ready for physics data

2022 | 2023 | 2024 | 2025

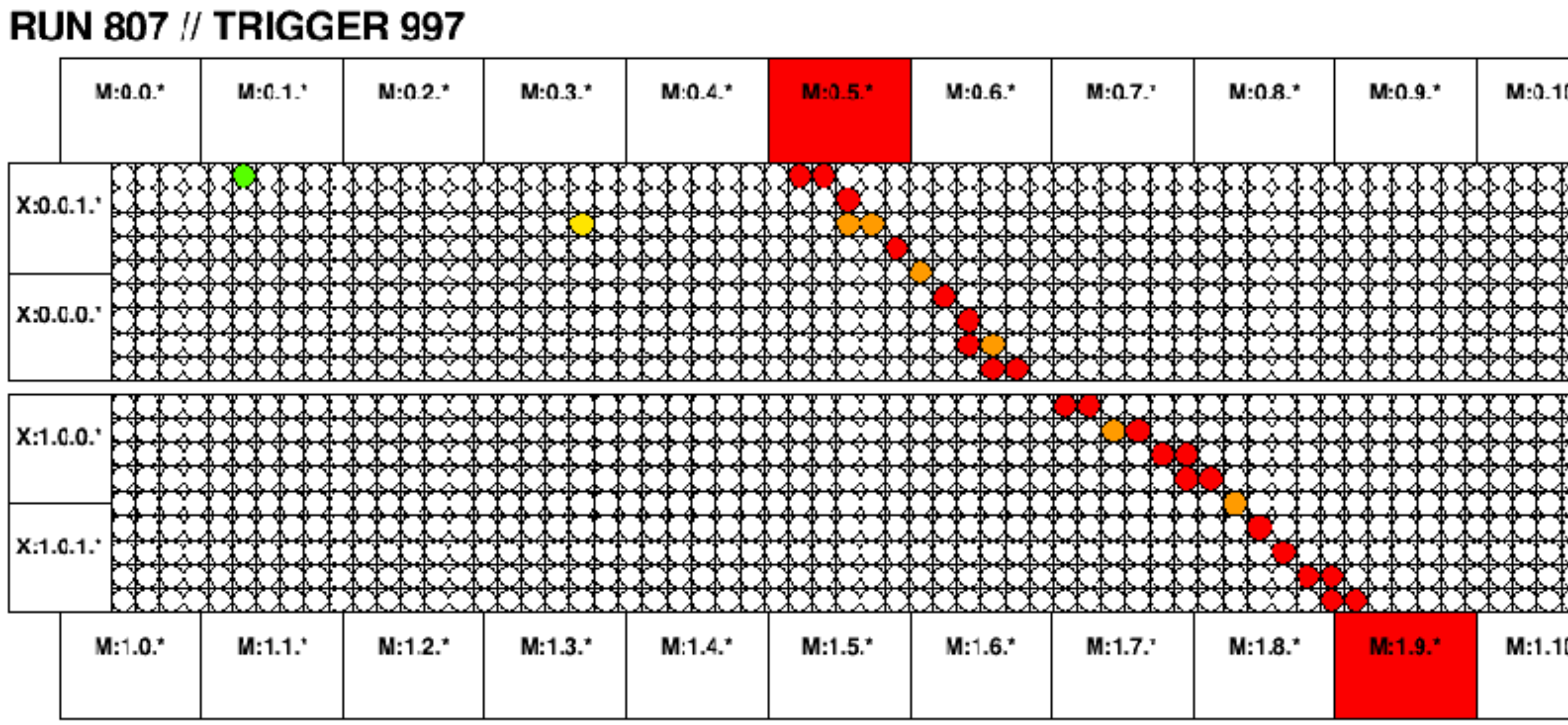
Shielding purchase/installation

Detector installation/ commissioning

No-shielding data to measure backgrounds

2.5 years $\beta\beta$ data taking ($0\nu\beta\beta$ search; $2\nu\beta\beta$ studies)

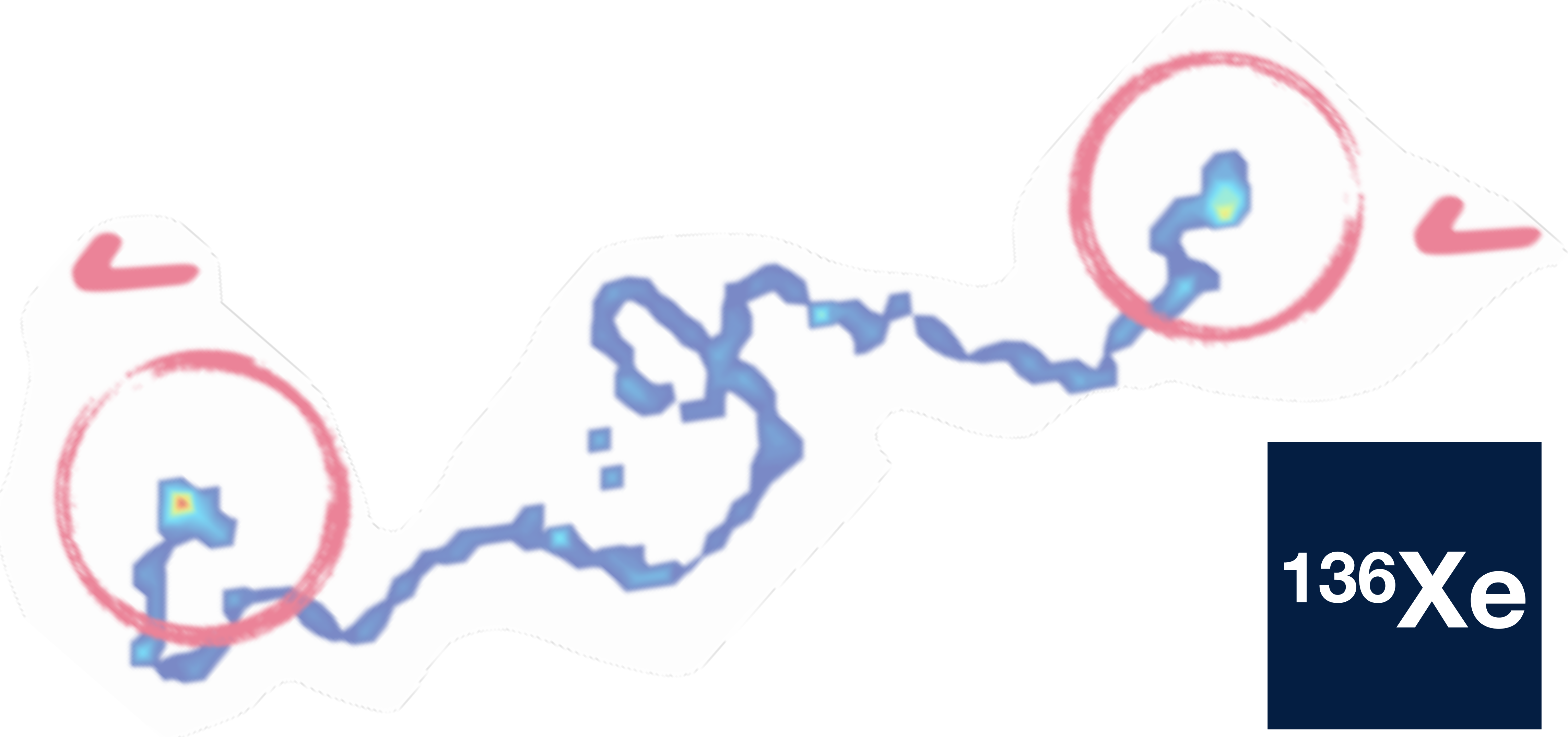
Currently transitioning to continuous data-taking phase!



Other UK activities

next

MANCHESTER 1824
The University of Manchester



^{136}Xe

Thanks to Roxanne Guenette for content

LZ

^{134}Xe

Thanks to Sally Shaw for content

THE UNIVERSITY of EDINBURGH

UCL

UNIVERSITY OF OXFORD

UNIVERSITY OF LIVERPOOL

UKRI Science and Technology Facilities Council
Rutherford Appleton Laboratory

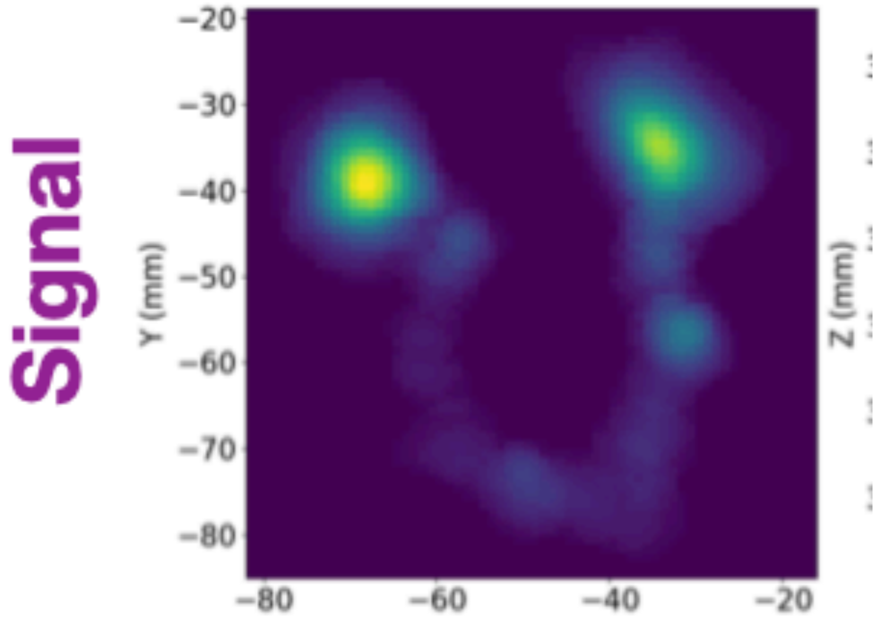
The University Of Sheffield.

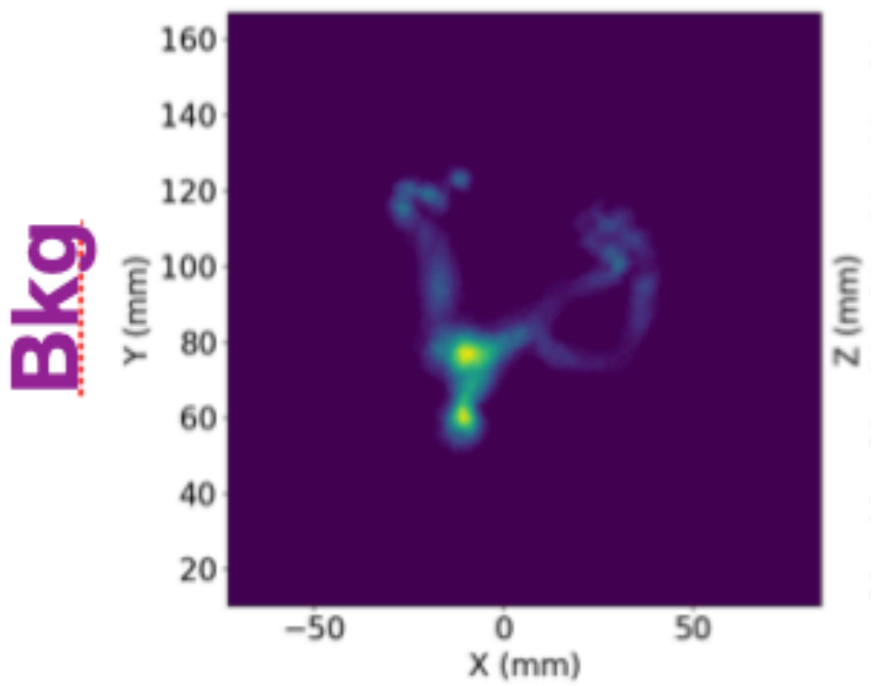
ROYAL HOLLOWAY UNIVERSITY OF LONDON

Imperial College London

NEXT high-pressure gaseous ^{136}Xe TPC

Topological Identification

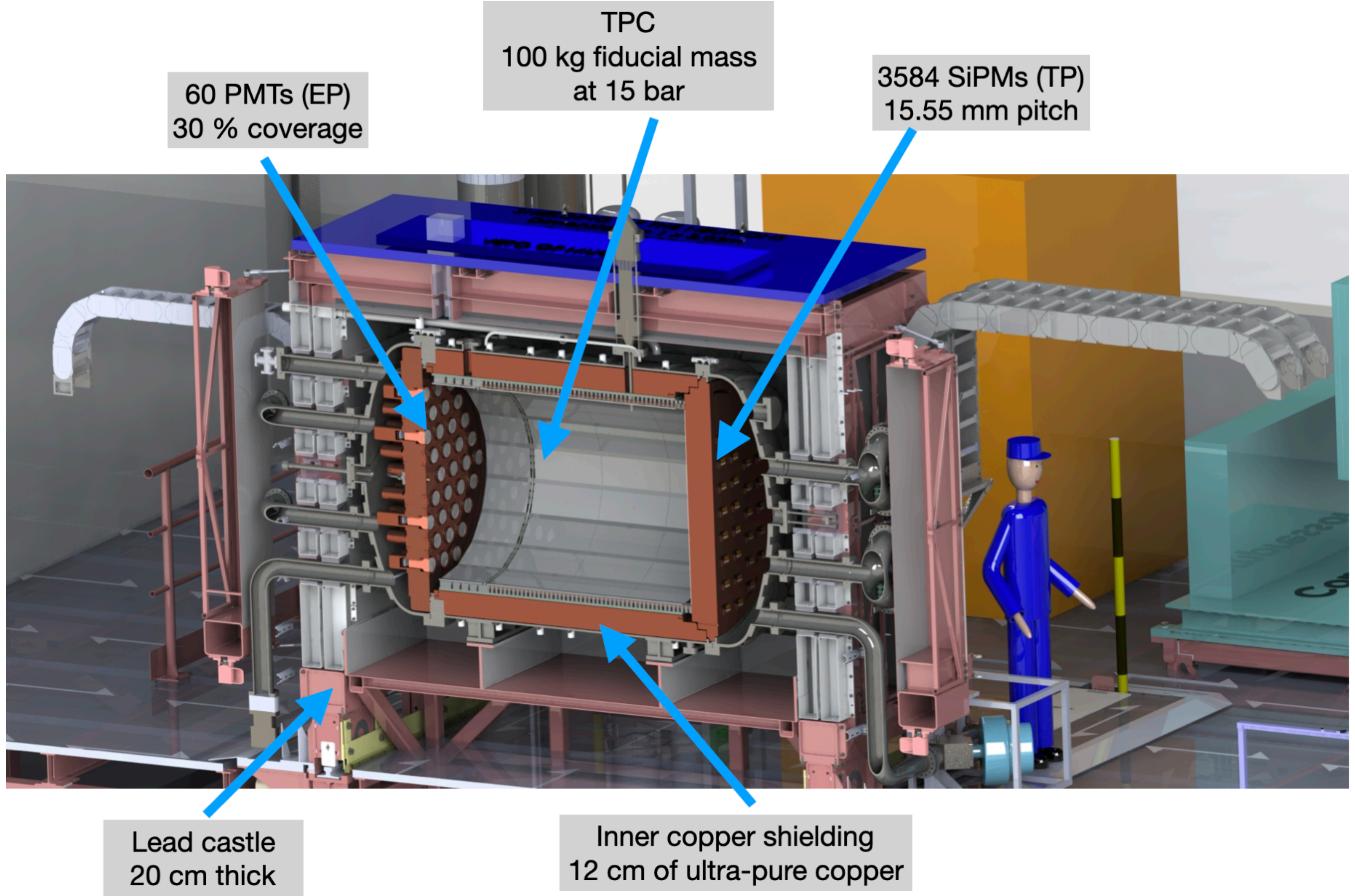




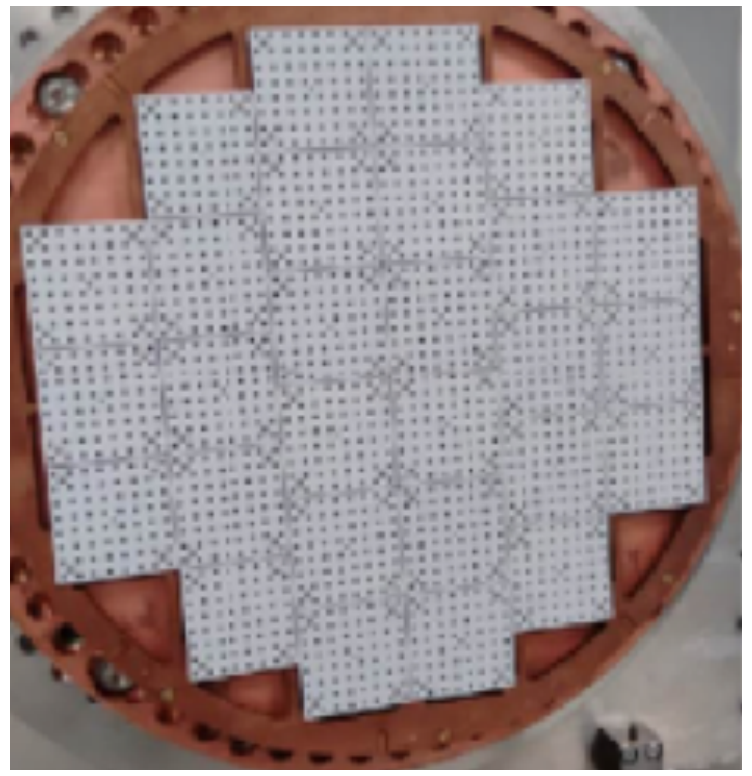
NEXT Collaboration, JHEP 01 (2021) 189

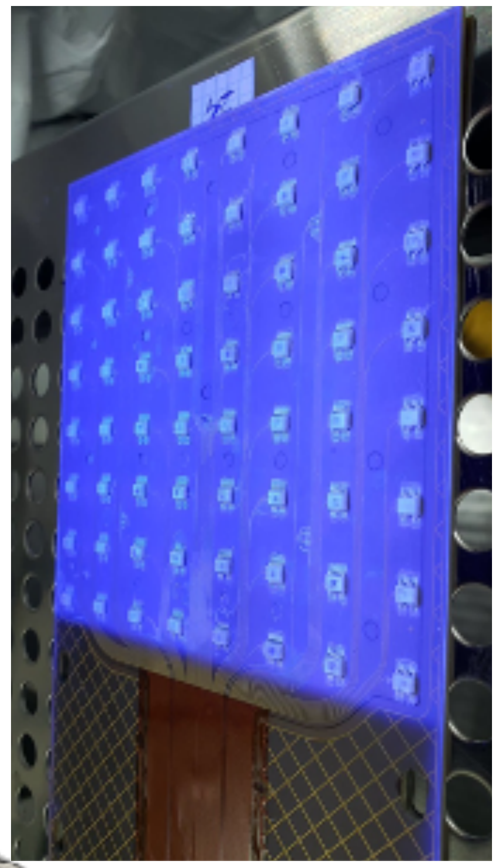
NEXT Collaboration, JHEP 10 (2019) 052

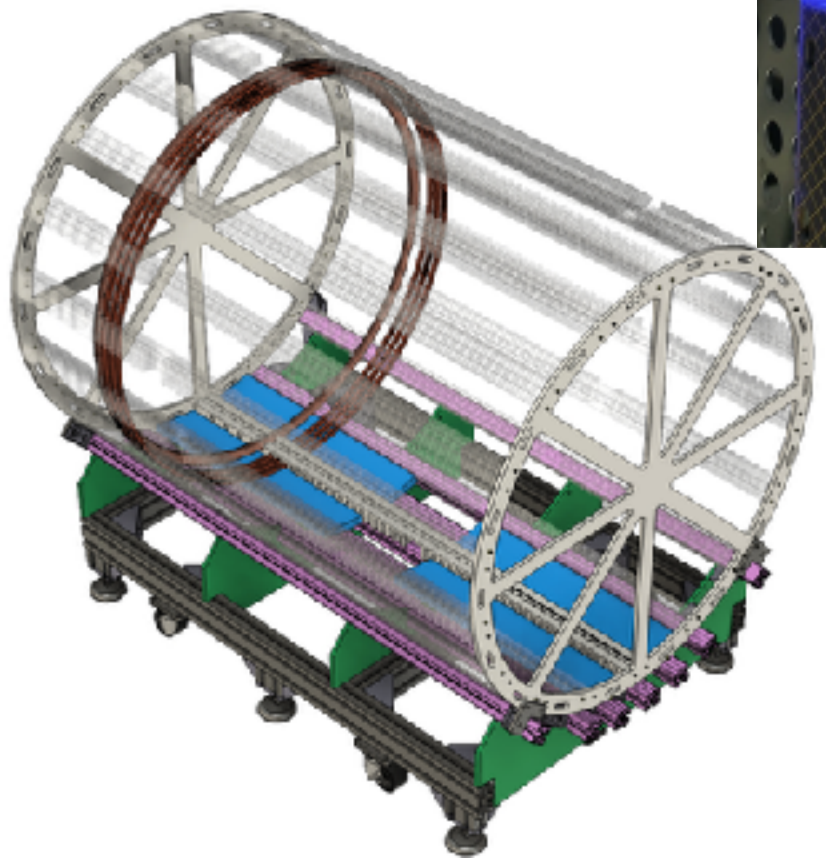
NEXT-100 (2022-2025) proves scalability



R&D on new tracking and energy plane with SiPMs



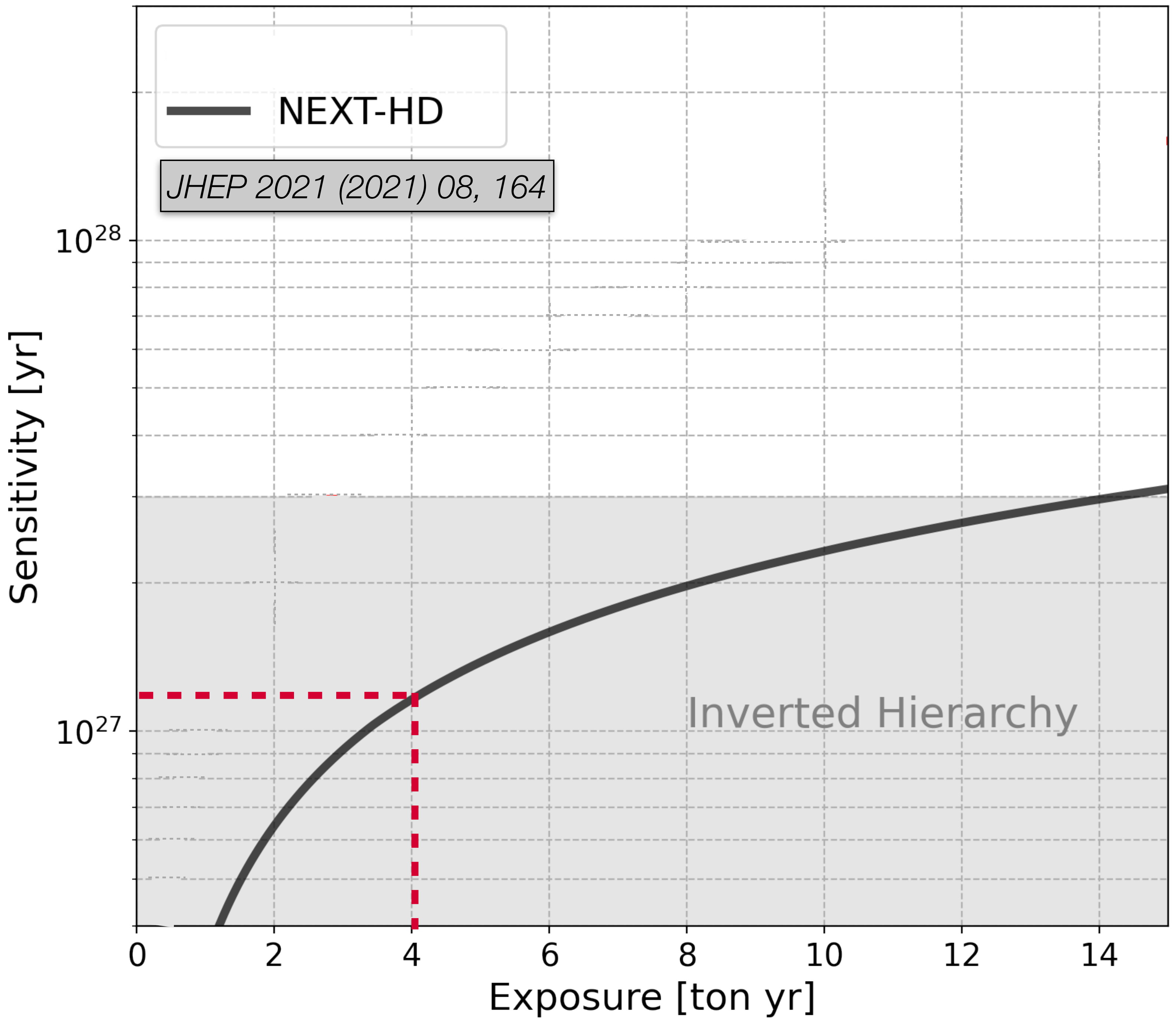




TPC installation UK-led

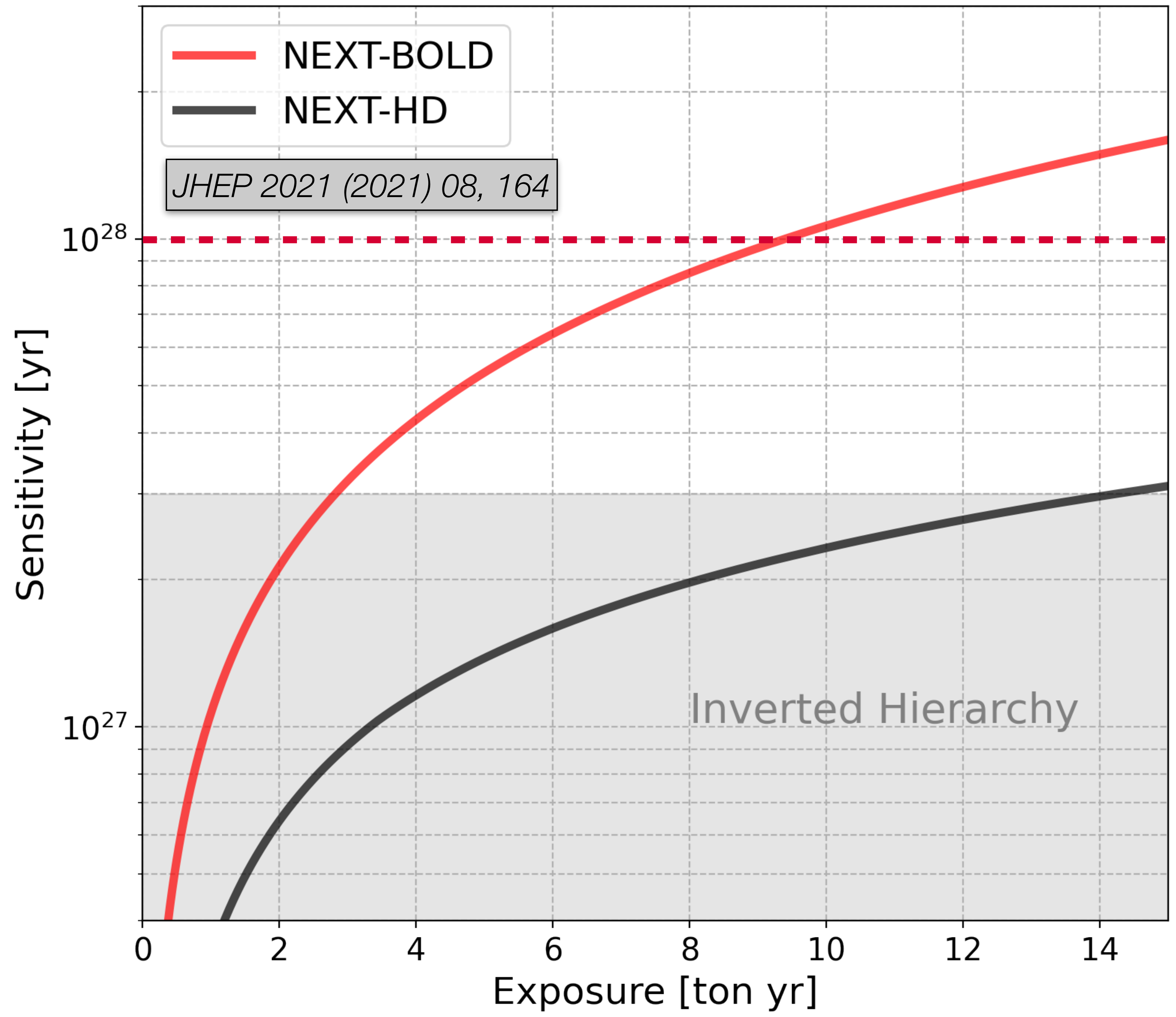
NEXT ton-scale and beyond

- NEXT-HD's first module can reach $T_{½}$ > **10^{27} yr** $0\nu\beta\beta$ sensitivity with **4 ton.yr** exposure



NEXT ton-scale and beyond

- NEXT-HD's first module can reach $T_{1/2}$ > **10^{27} yr** $0\nu\beta\beta$ sensitivity with **4 ton.yr** exposure
- NEXT-BOLD: seeks 10^{28}-year sensitivity through **barium tagging technology**



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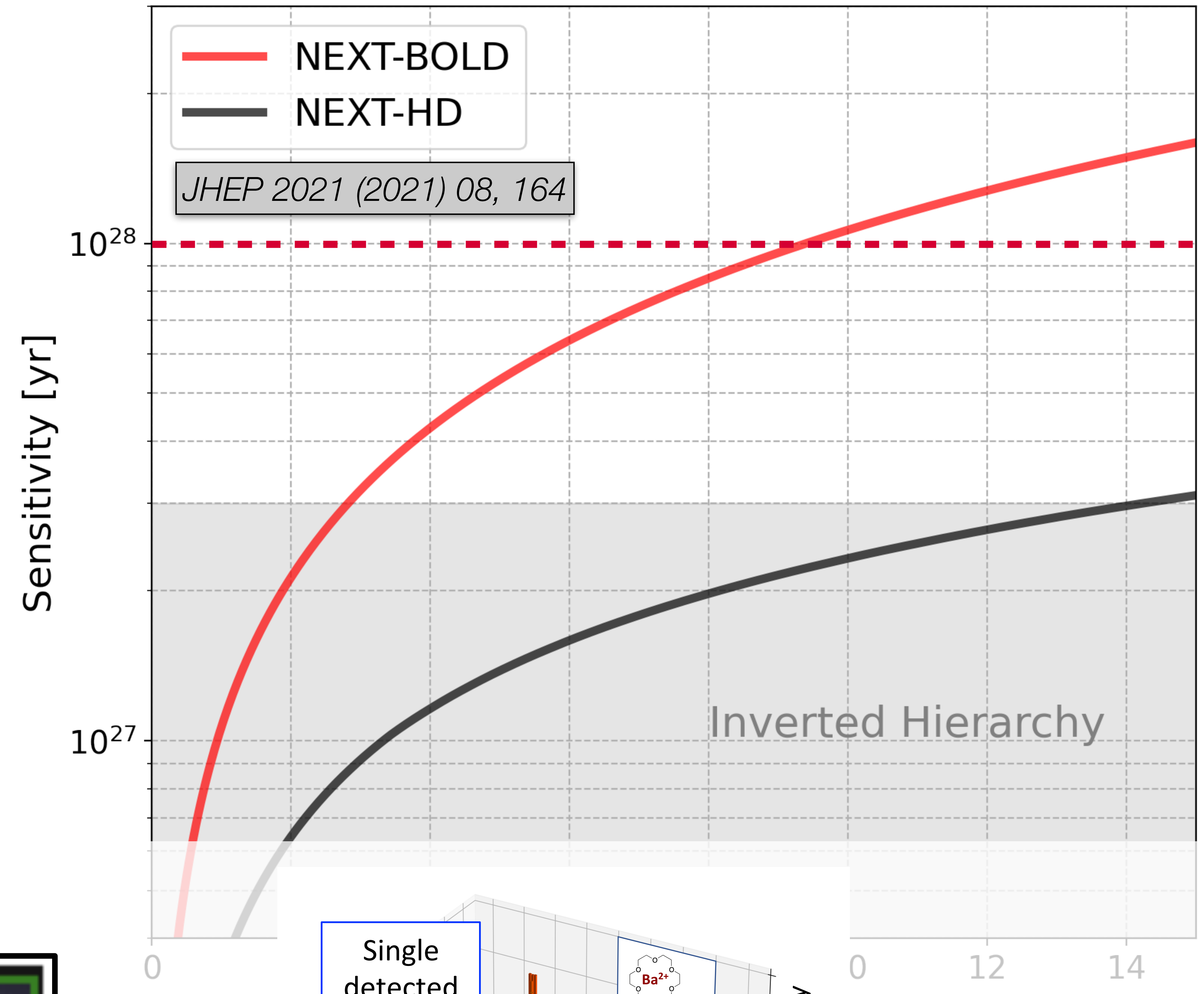
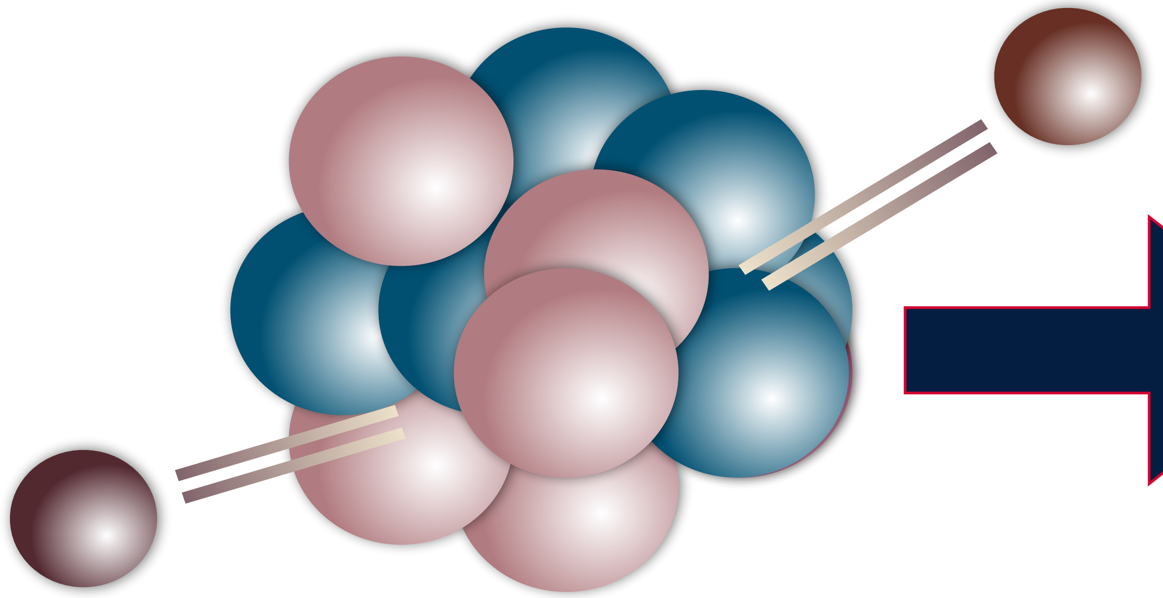
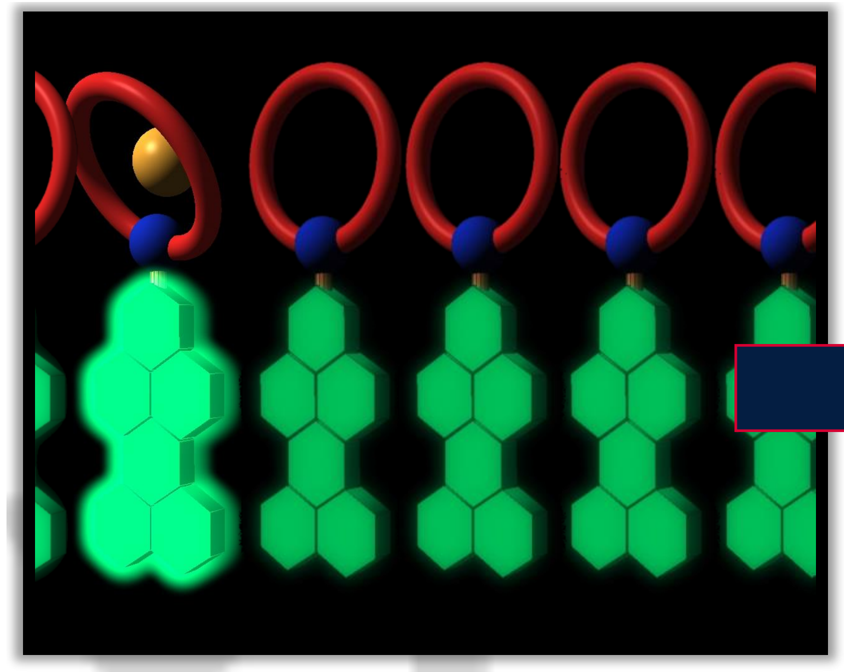


J. Phys.Conf.Ser 650 (2015) 1, 012002;
JINST 11 (2016) 12, P12011;
Phys.Rev.Lett 120 (2018) 13 132504;
Sci.Rep. 9 (2019) 1, 15097;
Nature 583 (2020) 7814 48-54;
ACS Sens. (2021) 6, 1, 192-202;
arXiv:2201.09099;
arXiv:2109.05902

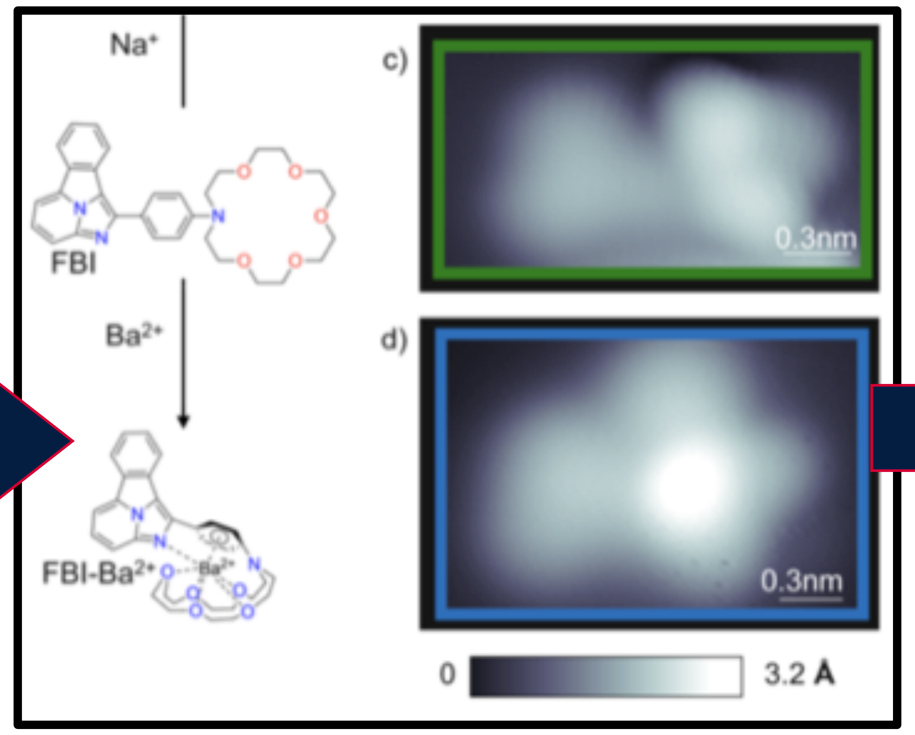
Ba^{2+} $\beta\beta$ decay product

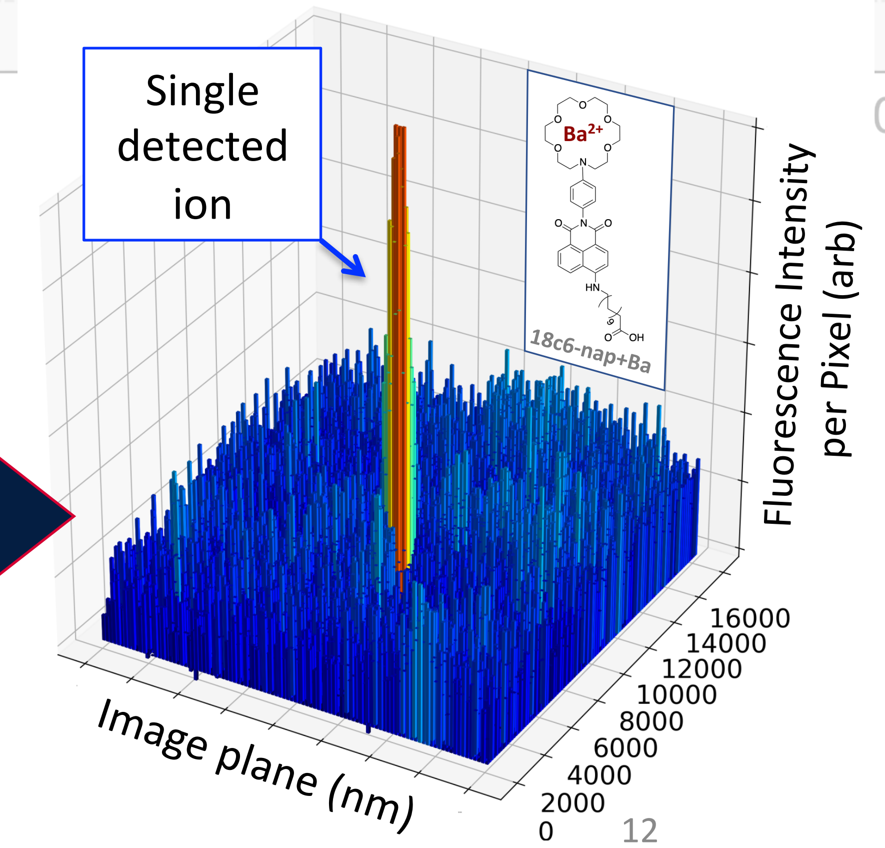


Ba^{2+} chelation



Molecule fluoresces

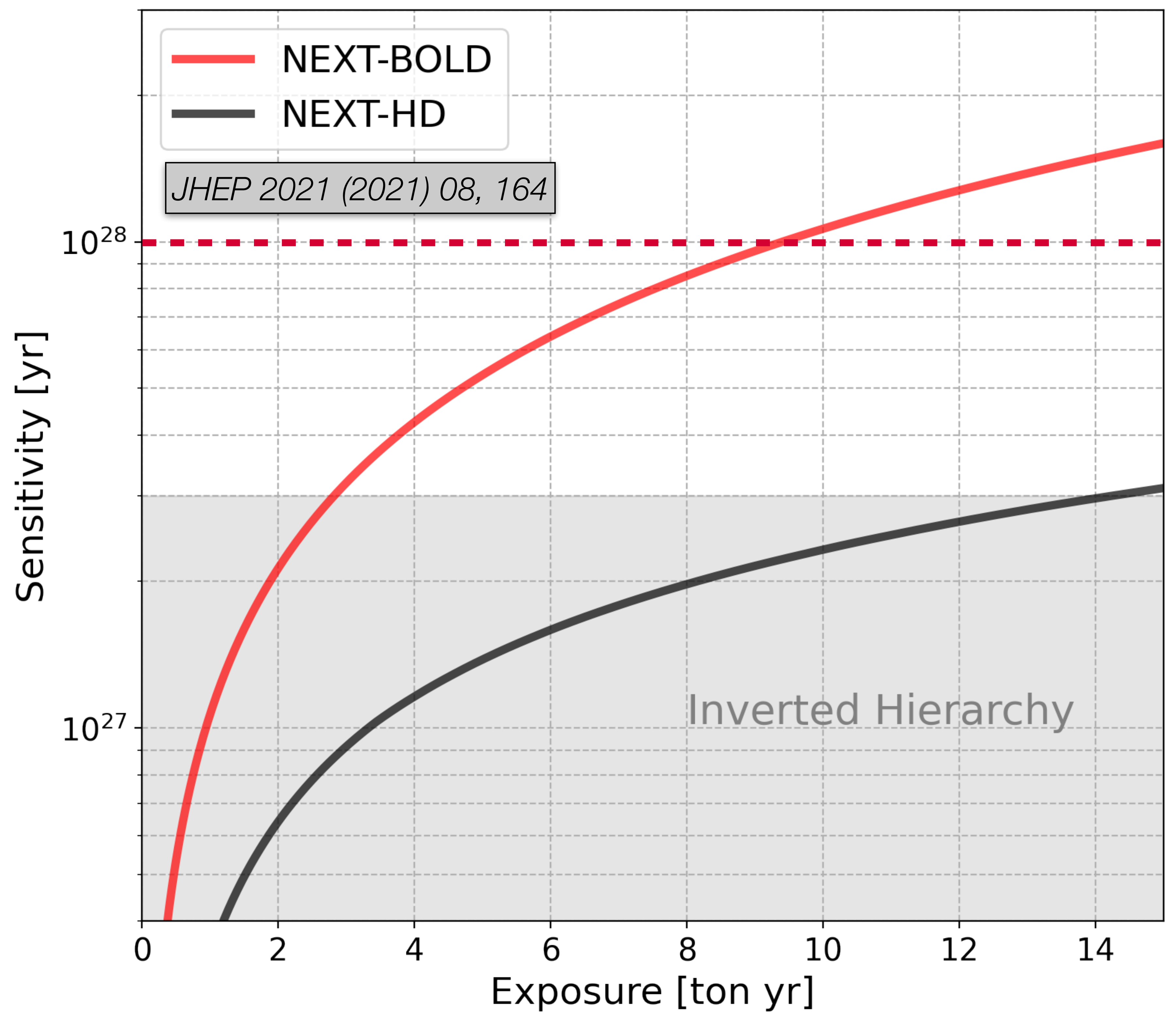




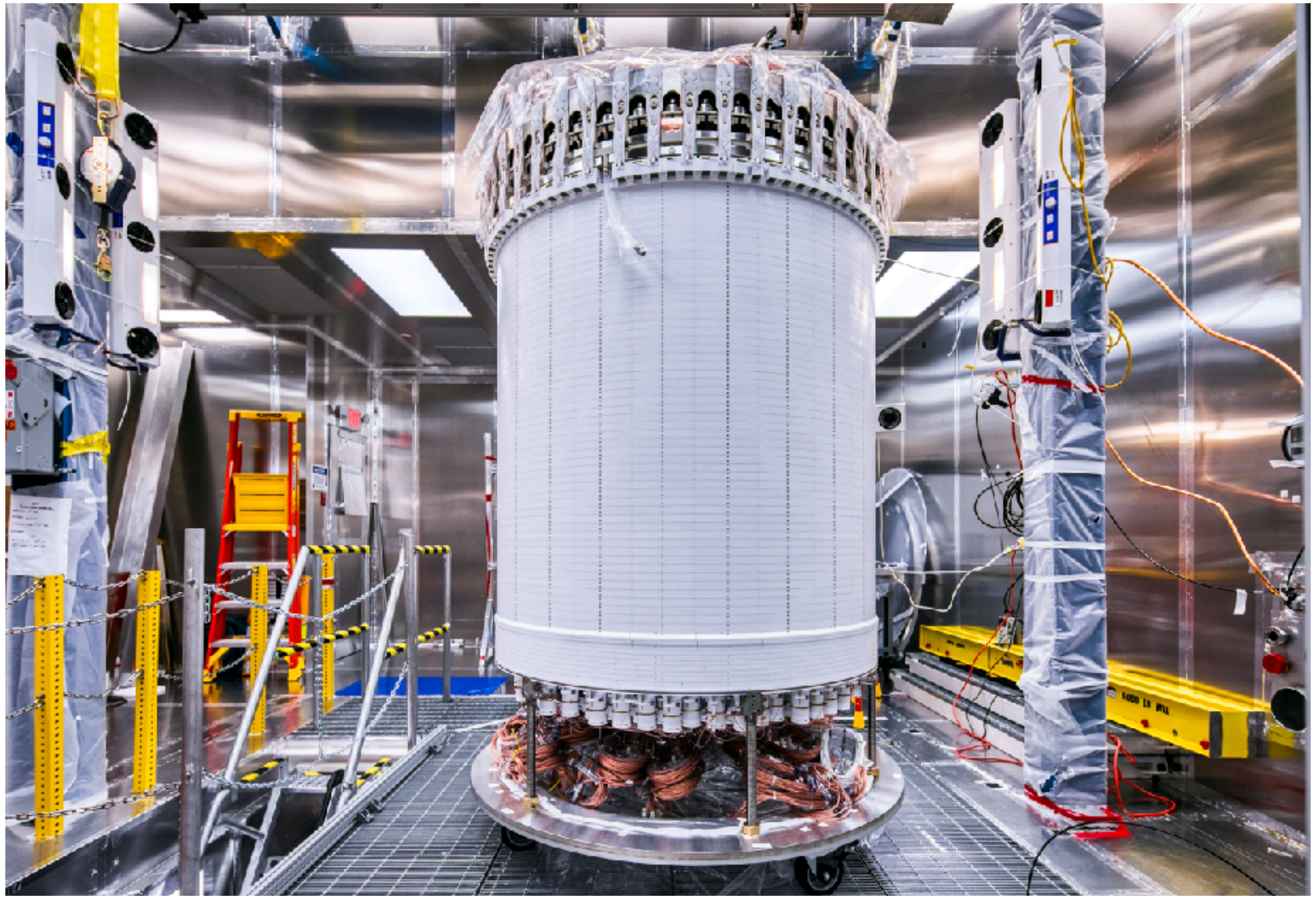
Single fluorescent ion detected

NEXT ton-scale and beyond

- NEXT-HD's first module can reach $T_{½}$ > **10^{27} yr** $0\nu\beta\beta$ sensitivity with **4 ton.yr** exposure
- NEXT-BOLD: seeks 10^{28}-year sensitivity through **barium tagging technology**
- Unambiguous signature for $\beta\beta$ → background free
- R&D needed to scale up to 1-ton detectors…



LUX-ZEPLIN dark-matter detector



The day job:

- 7-ton liquid-xenon TPC for direct dark-matter detection

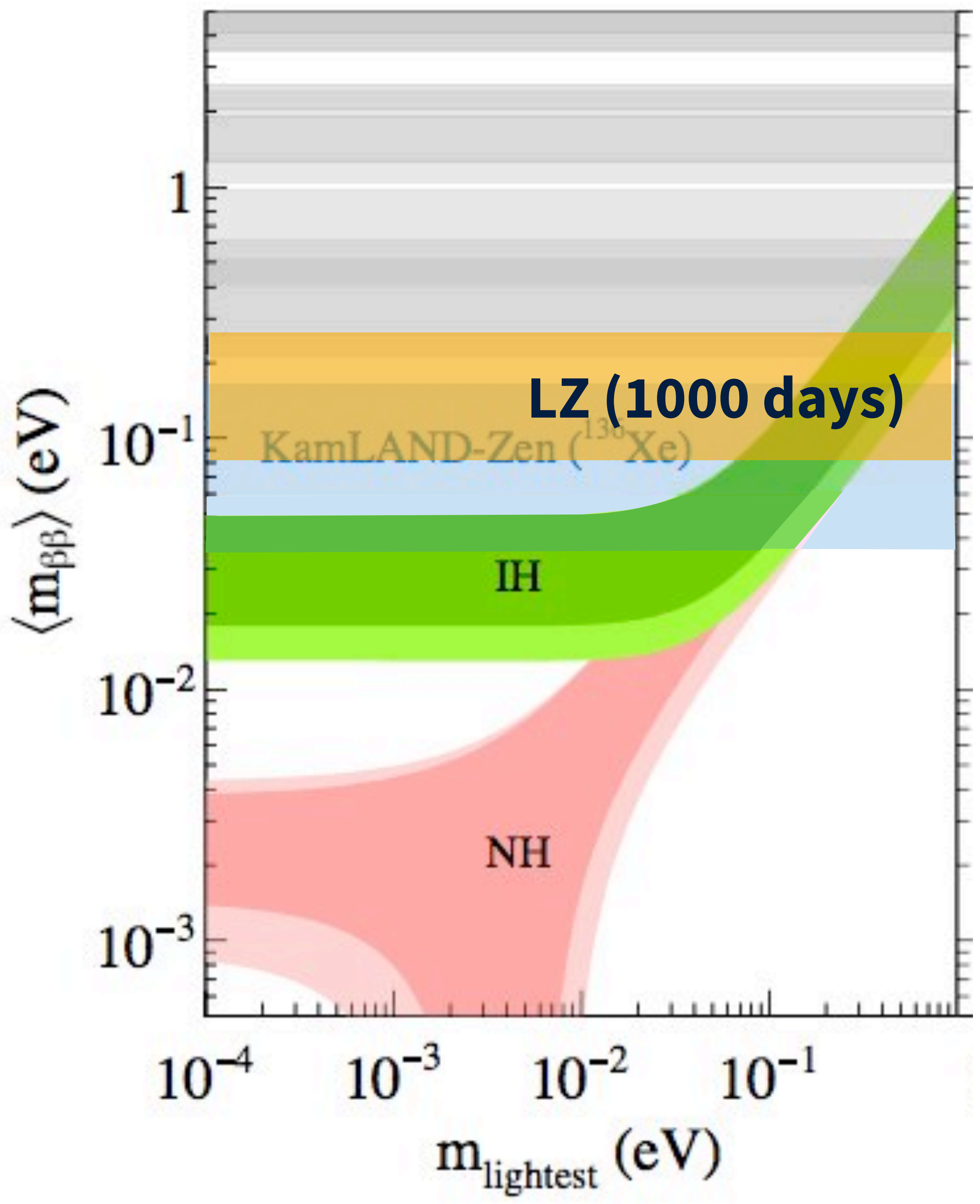
The side hustles:

- Two $\beta\beta$ xenon isotopes: ^{134}Xe and ^{136}Xe

^{136}Xe at LZ

Phys. Rev. C 102, 014602 (2020)

Current LZ xenon detector
(8.9% ^{136}Xe) won't see $0\nu\beta\beta$



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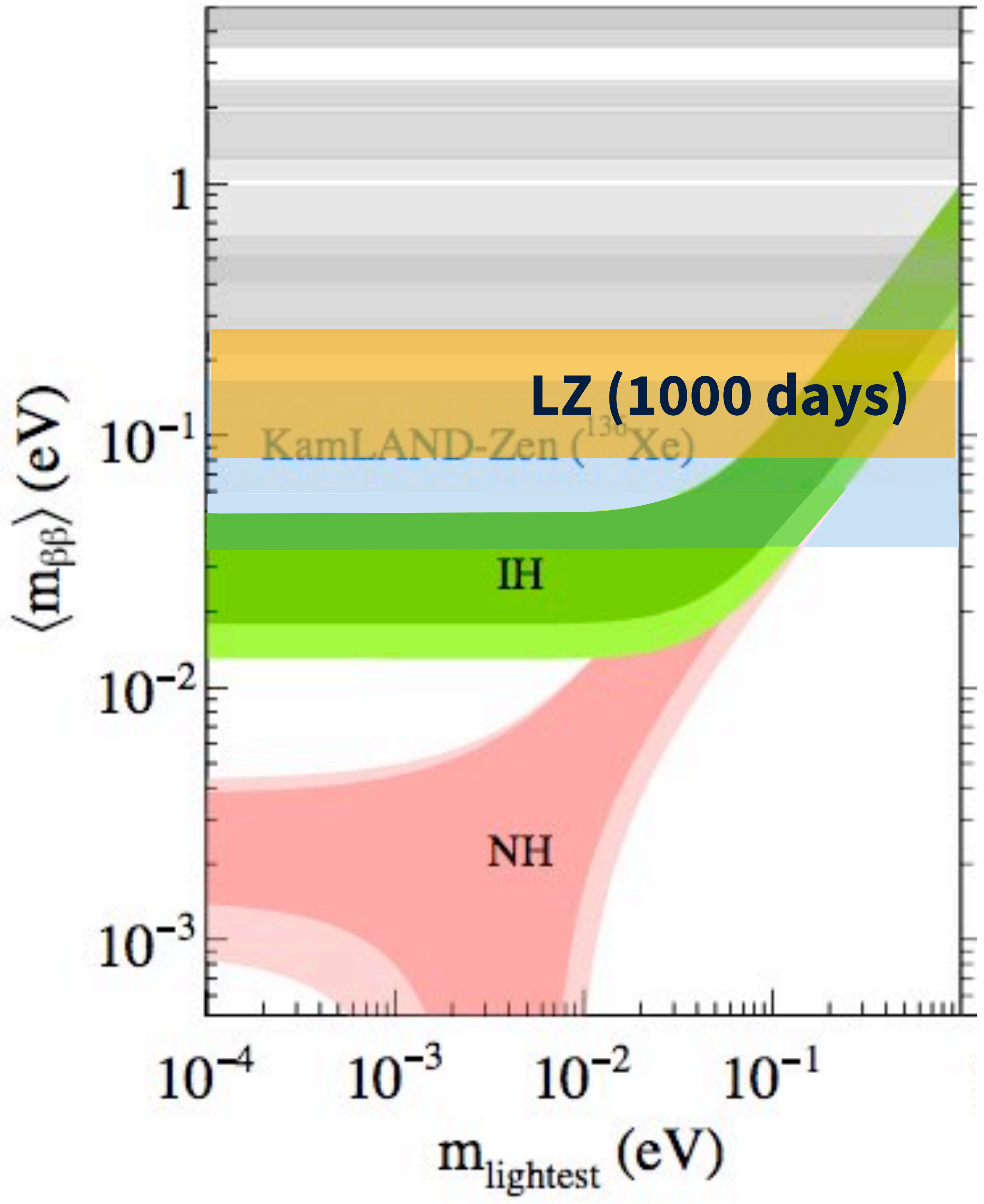
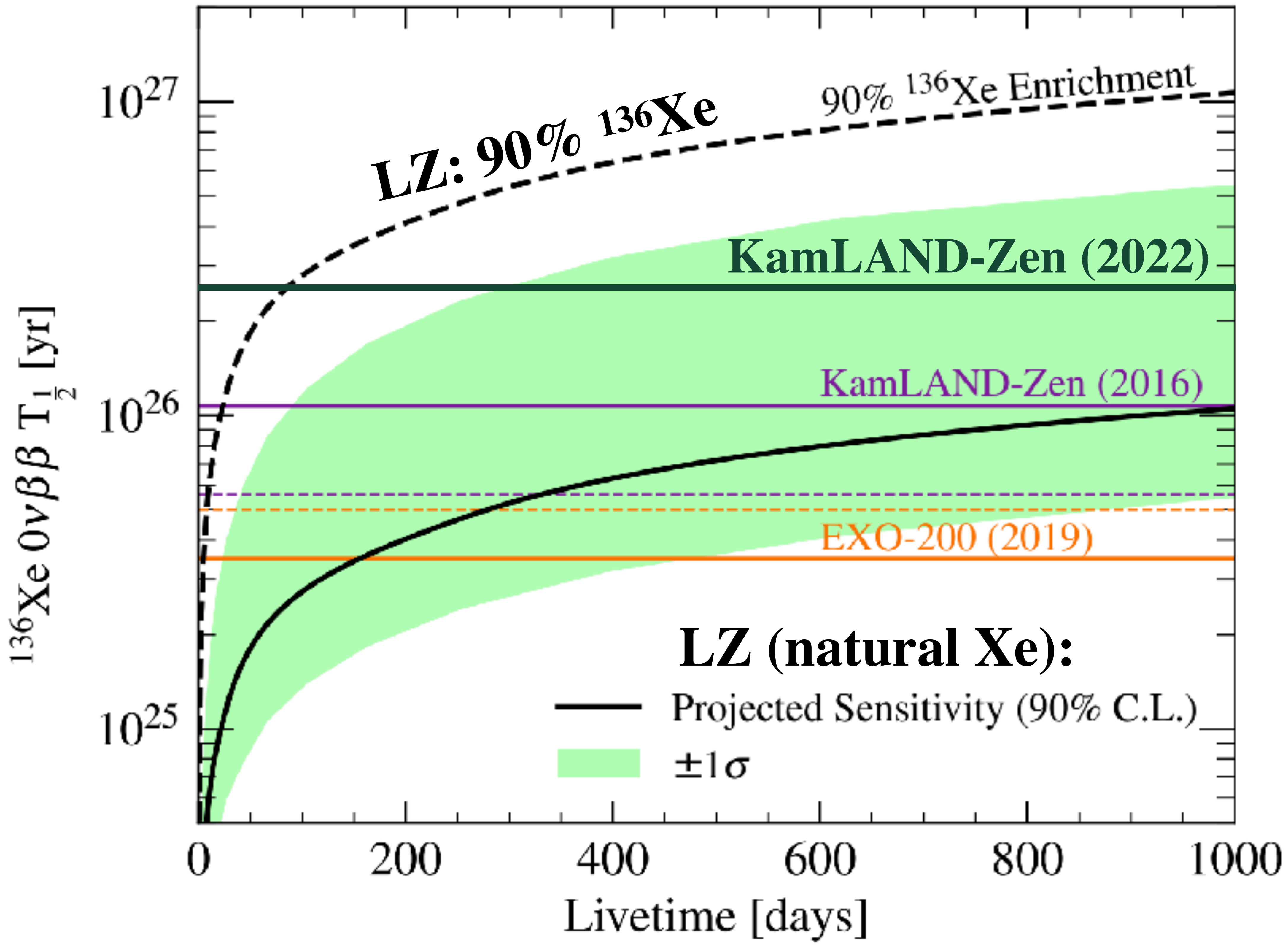


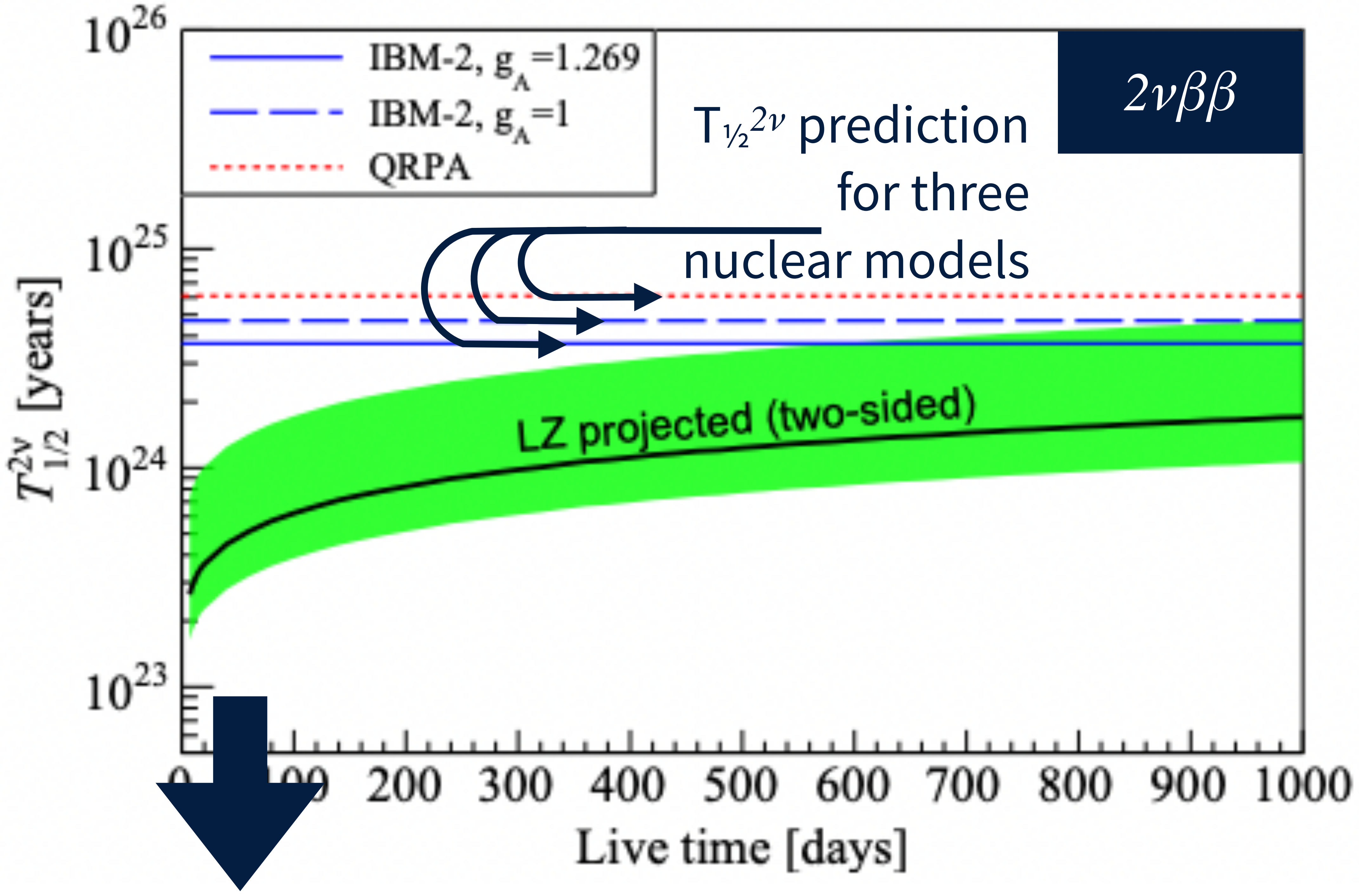
- **After WIMP search**: enrich with 90% ^{136}Xe?
- Potential for 10^{27}-year sensitivity - beyond current best limit



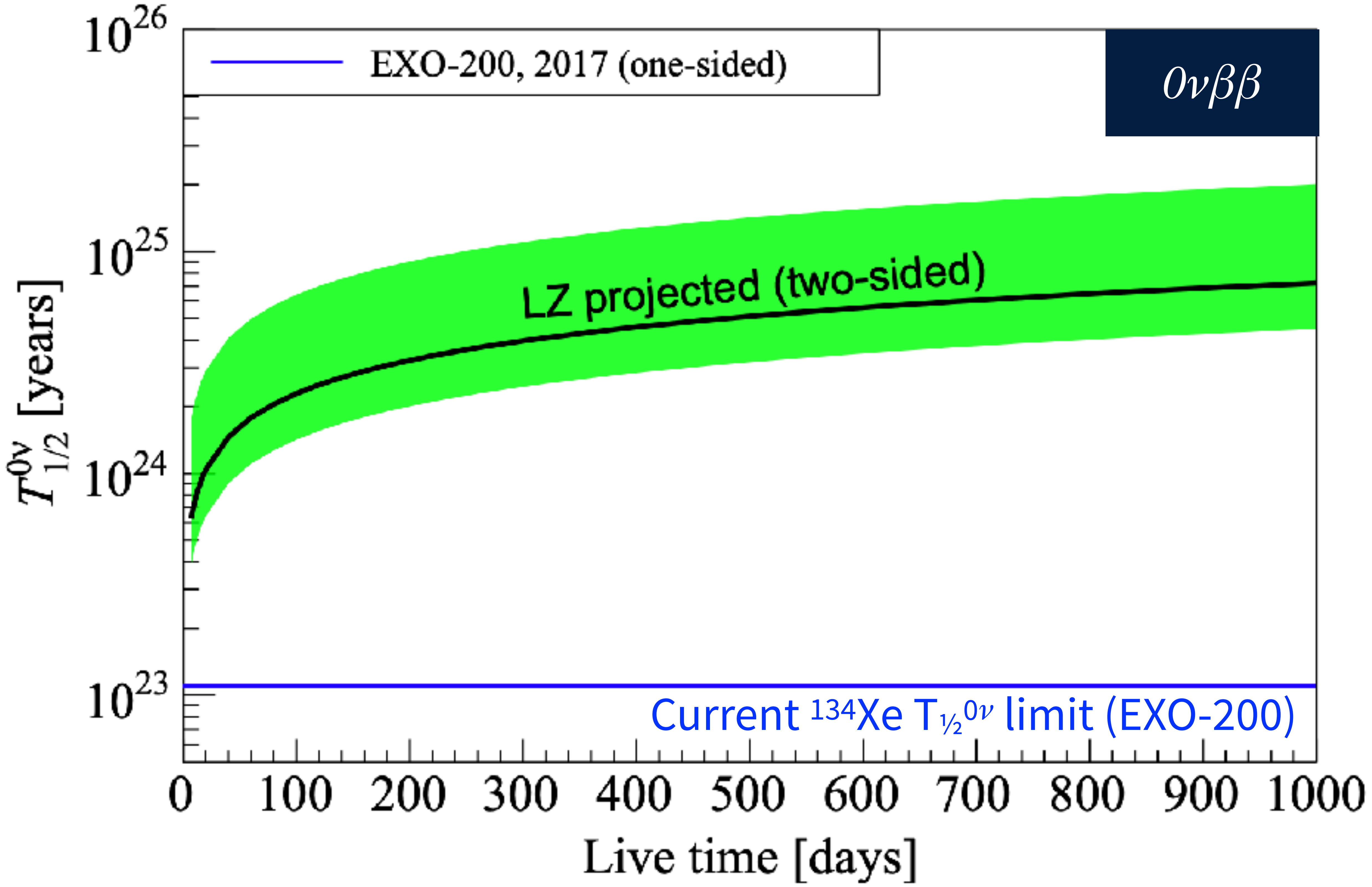
^{134}Xe at LZ

- Abundance 10.4%
- ***2νββ* predicted with very long half-life**
- Experimental limit $T_{1/2}^{2\nu}$ > 8.7×10[20] years (EXO-200)

LZ's nautral-Xe detector could improve the limit at short exposure for *2νββ* and *0νββ*



Experimental limit 100 times shorter



arXiv:2104.13374 [physics.ins-det]

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3) R&D: new techniques to go beyond inverted hierarchy

- Isotope-loaded liquid scintillator (SNO+ technique) especially promising
- and…?