Science and Technology Facilities Council

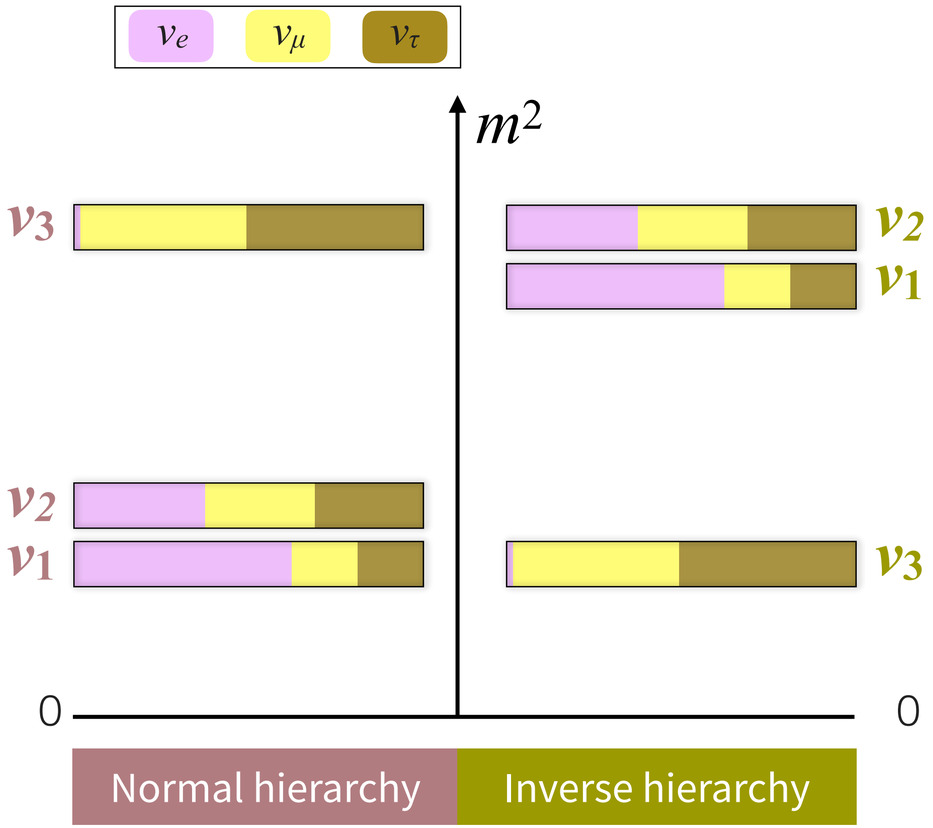
UK HEP forum, November 23, 2022

Neutrinoless double-beta decay

Cheryl Patrick STFC Ernest Rutherford Fellow, University of Edinburgh

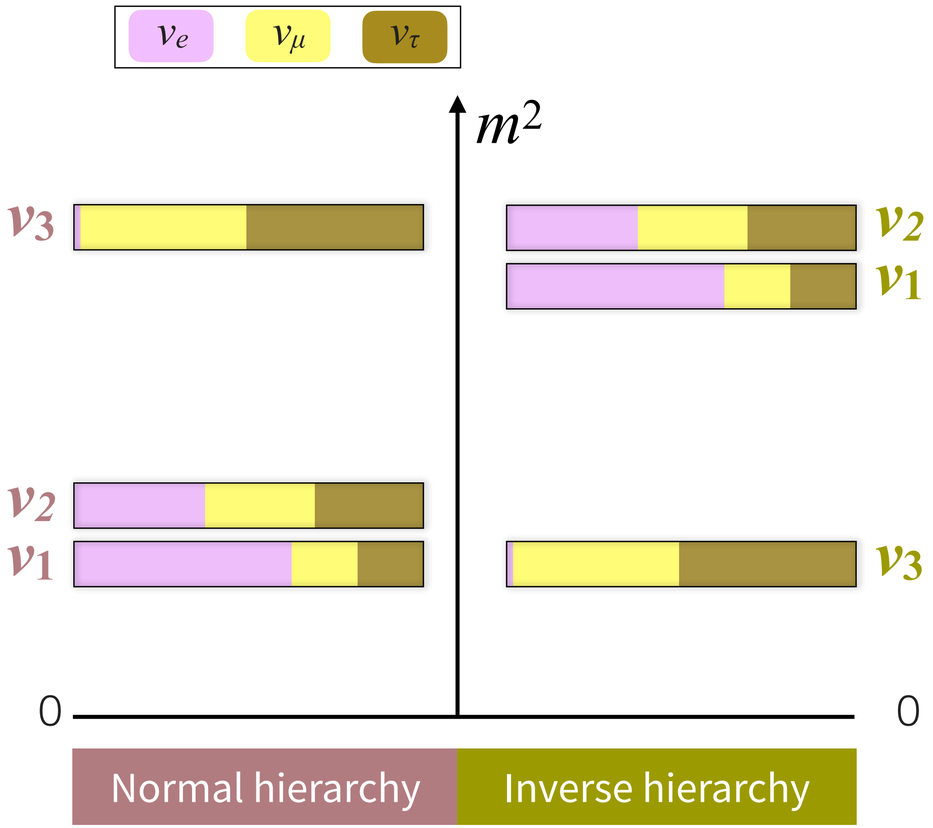
THE UNIVERSITY of EDINBURGH

Neutrinos - unanswered questions



Which neutrino is lightest?

Neutrinos - unanswered questions



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Do neutrinos violate CP symmetry?

Do ν and $\bar{\nu}$ behave the same?

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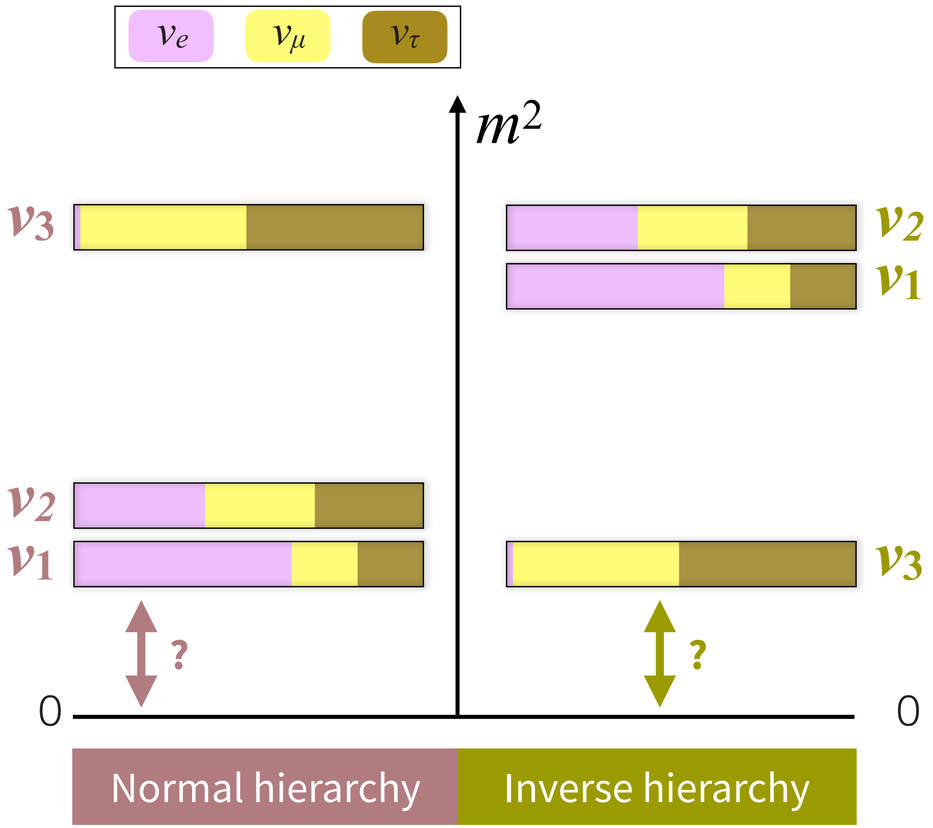

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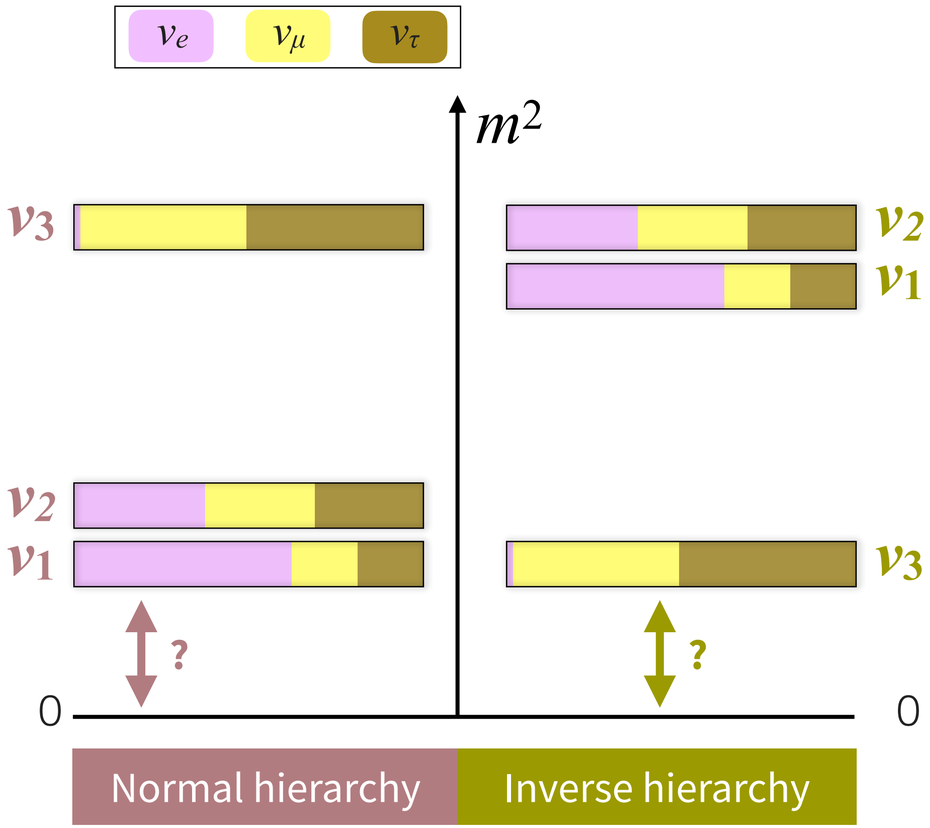

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How do neutrinos get their mass?

Majorana mechanism

$$\mathcal{L}_{m_L} = -\frac{m_L}{2}\overline{(\nu_L^0)^c}\nu_L^0 + \text{ h. c.}$$

$$\nu = \bar{\nu}$$

- ν and ν̄ differ only in **helicity**
- Elegant explanation for light neutrinos (see-saw mechanisms; various options available)
- Allows lepton number violation!

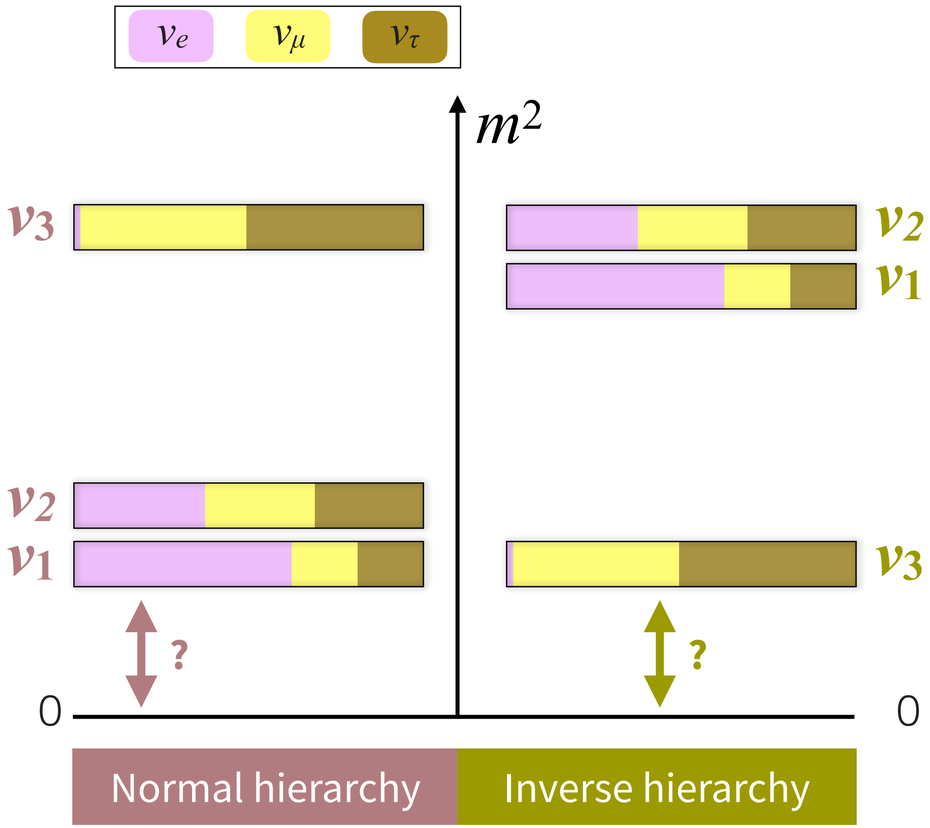
Dirac mechanism

$$\mathcal{L}_D = -m_D\overline{\nu_R^0}\nu_L^0 + \text{ h. c.}$$

$$\nu \neq \bar{\nu}$$

- Suspiciously weak coupling needed to explain light neutrino
- Requires right-handed neutrino
- … allowing both Dirac & Majorana to exist concurrently…
- … with neutrinos Majorana particles!

Neutrinos - unanswered questions



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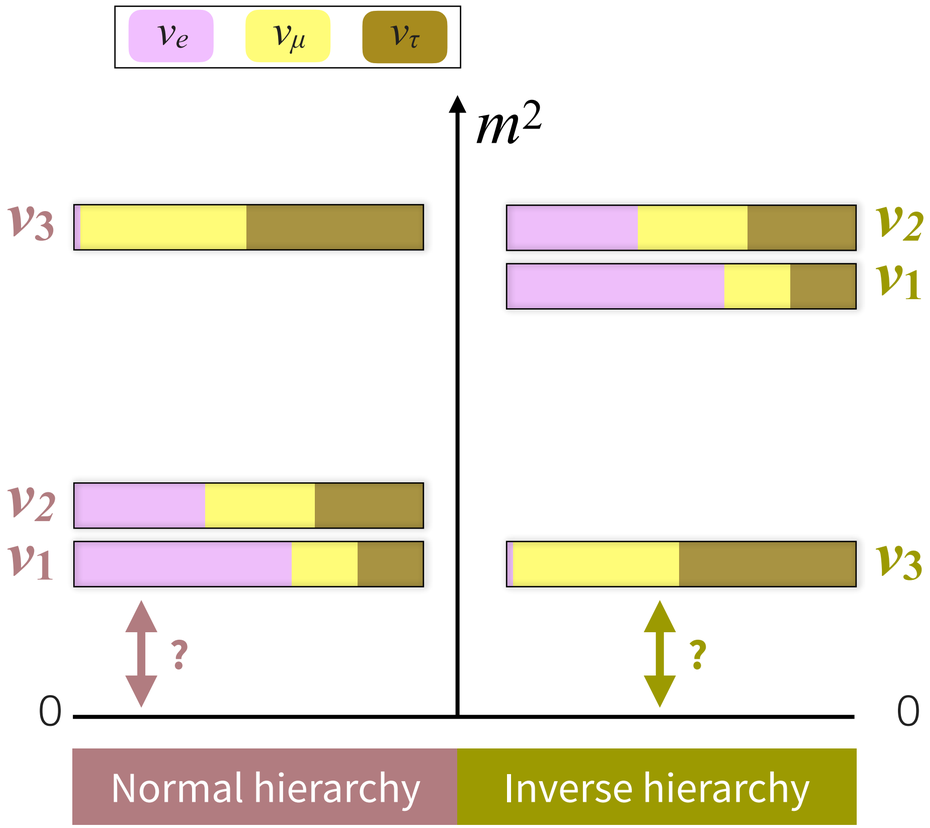
Matter-antimatter asymmetry

Neutrinos - unanswered questions



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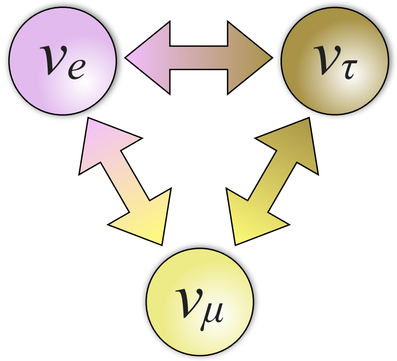

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What's the absolute mass scale?

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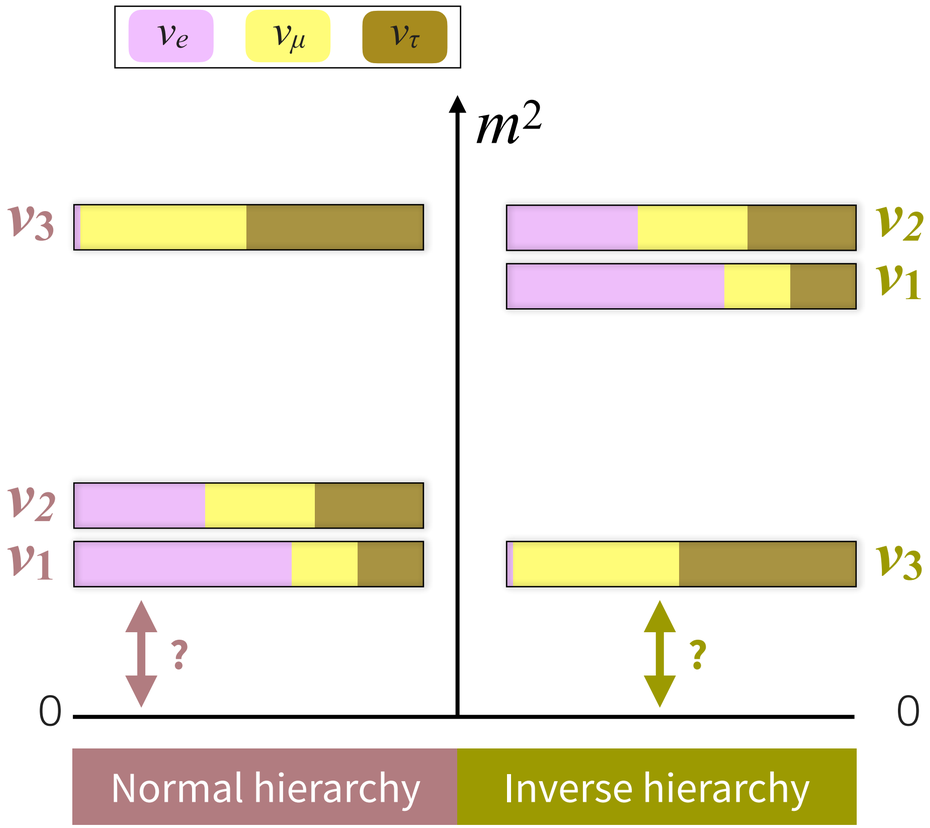
Neutrinos - unanswered questions



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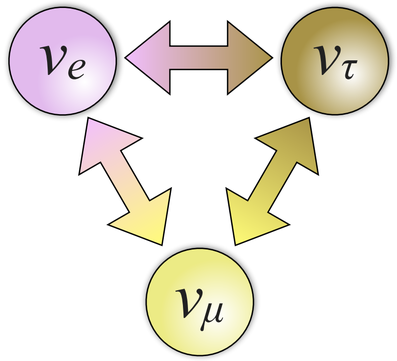

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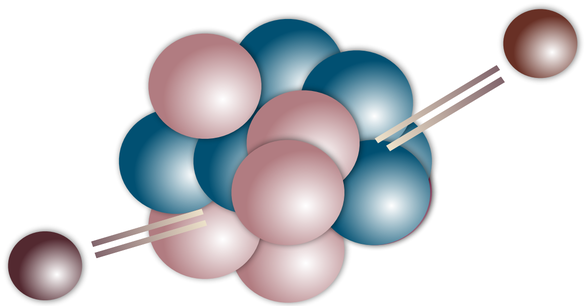
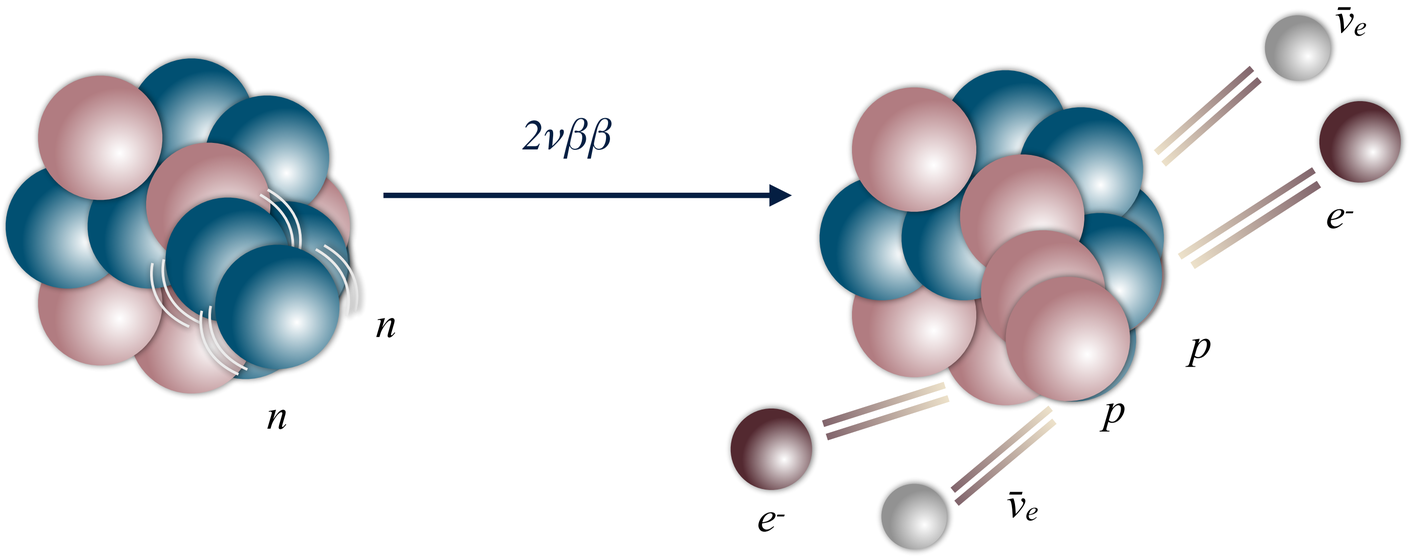
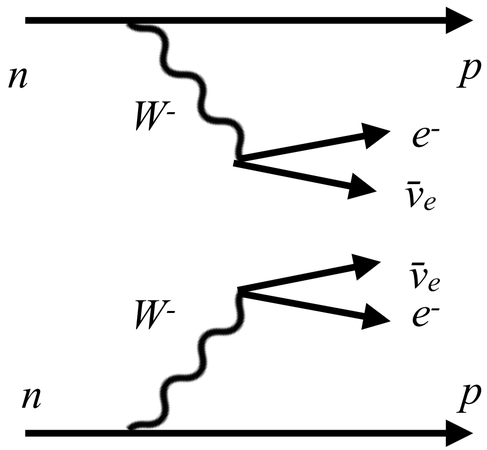


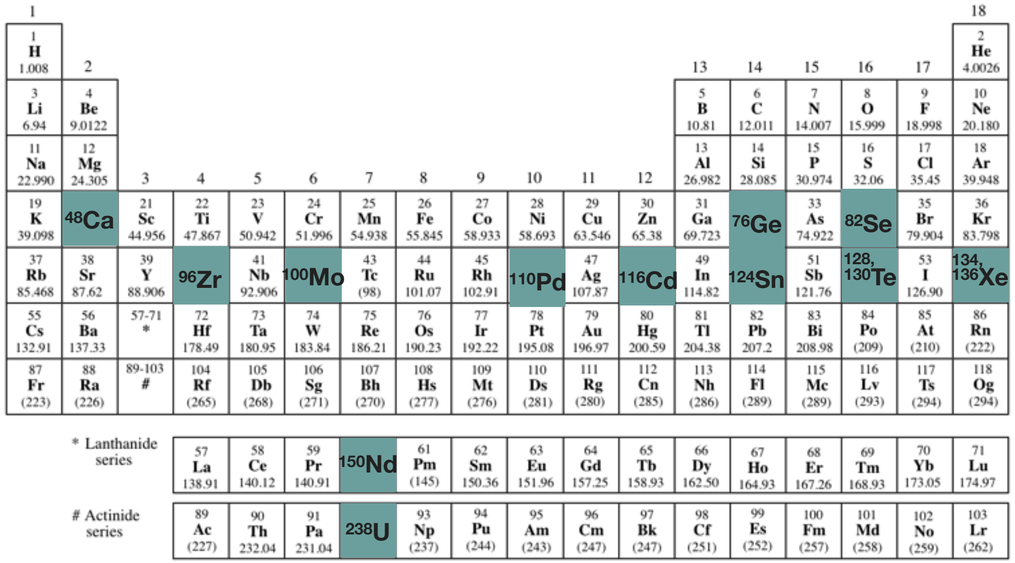
Neutrinoless double-beta decay

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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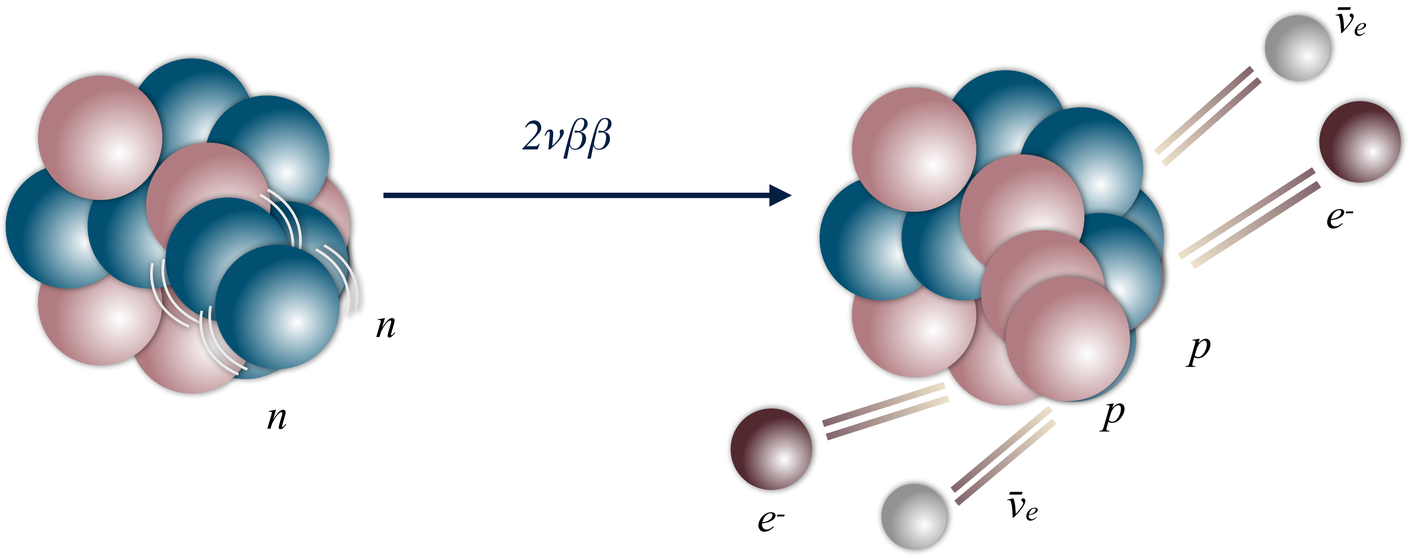

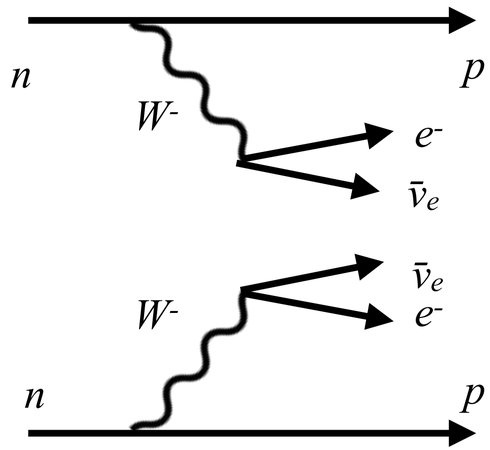

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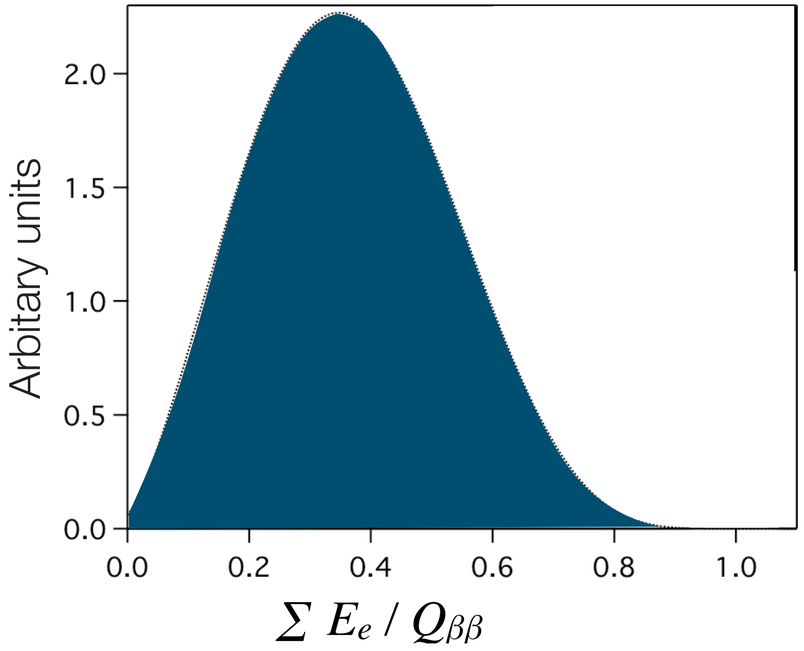

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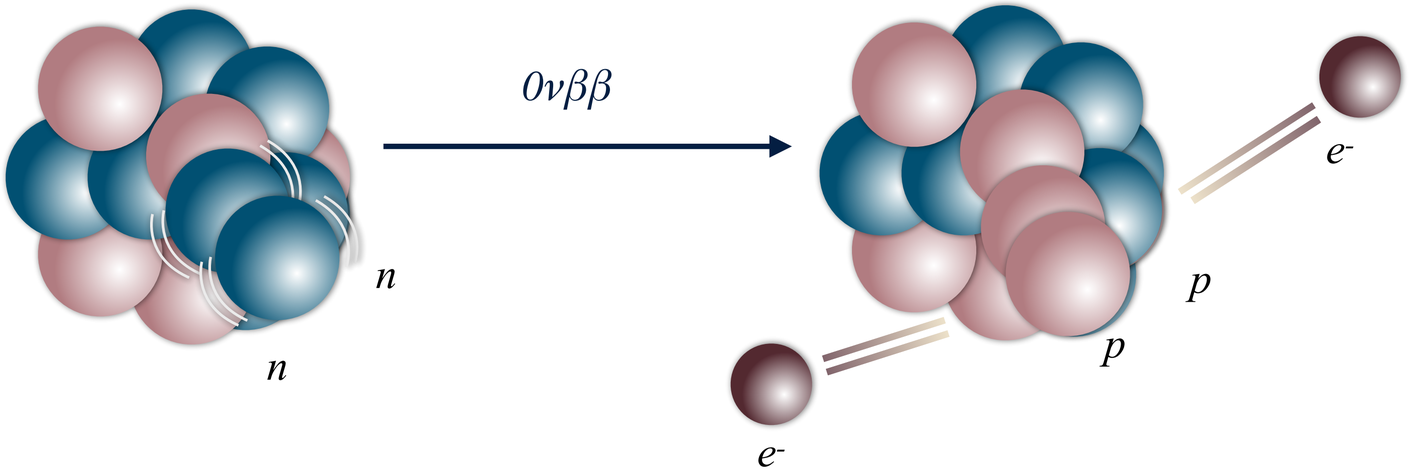
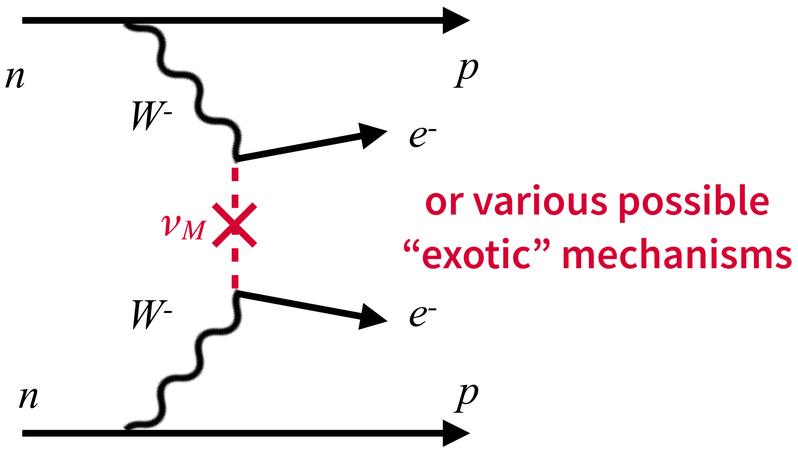
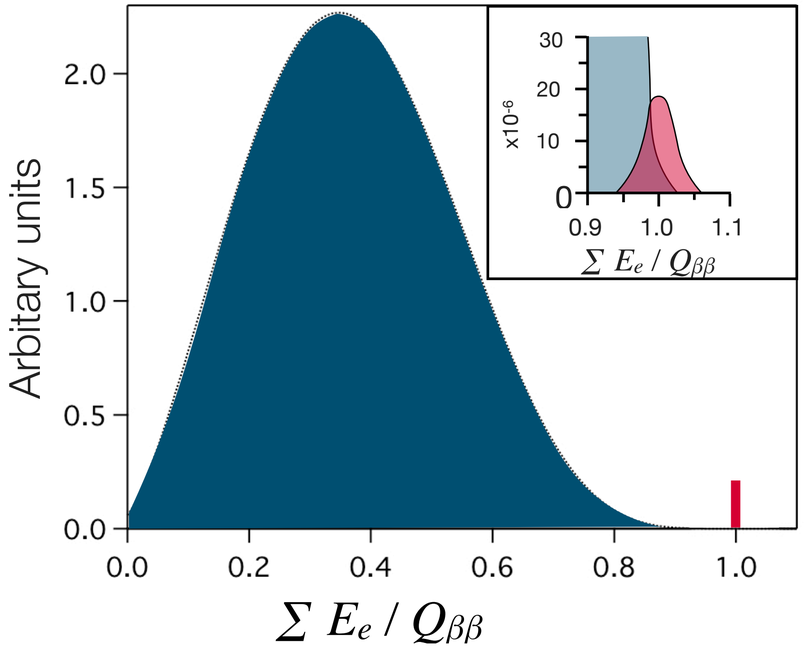




- No neutrinos in final state
- Virtual Majorana neutrino exchanged (various models available)
- All $2\nu\beta\beta$ isotopes are $0\nu\beta\beta$ candidates
- Not yet observed - $T_{½}$ > 10^{24} - 10^{26} years
  - Need great energy resolution…
  - …and background rejection



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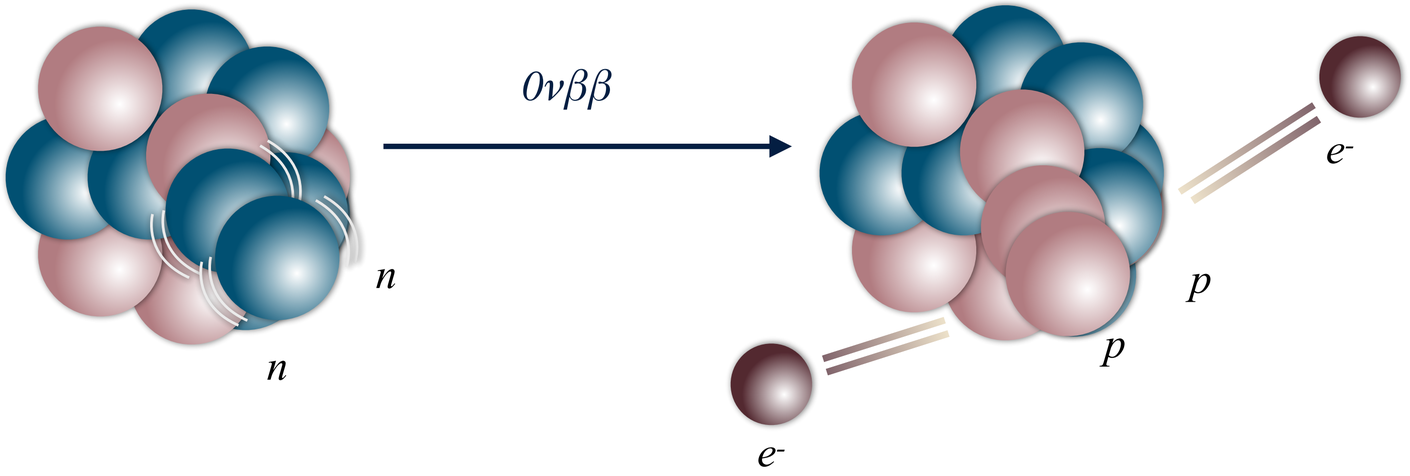

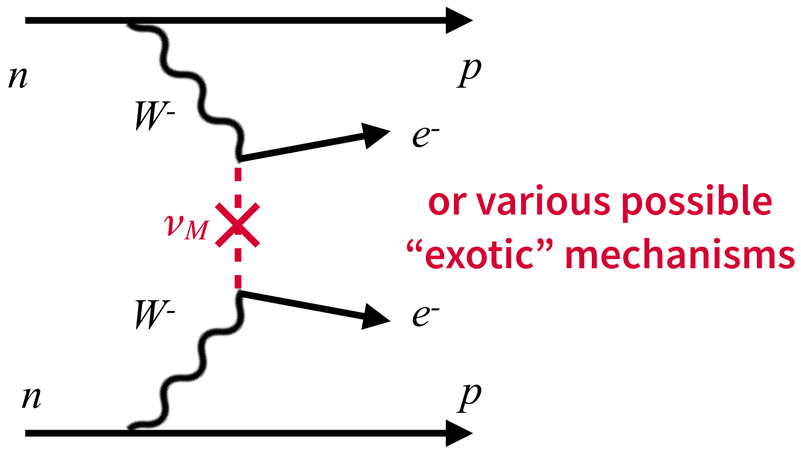

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If seen, $0\nu\beta\beta$ would:
- be the first process observed to create matter without antimatter
- prove that neutrinos are Majorana fermions
- tell us about absolute neutrino mass

$0\nu\beta\beta$ 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

Effective "ν_e" mass

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

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Effective "ν_e" mass

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)

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Individual neutrino masses

CP-violating Majorana phases (unknown)

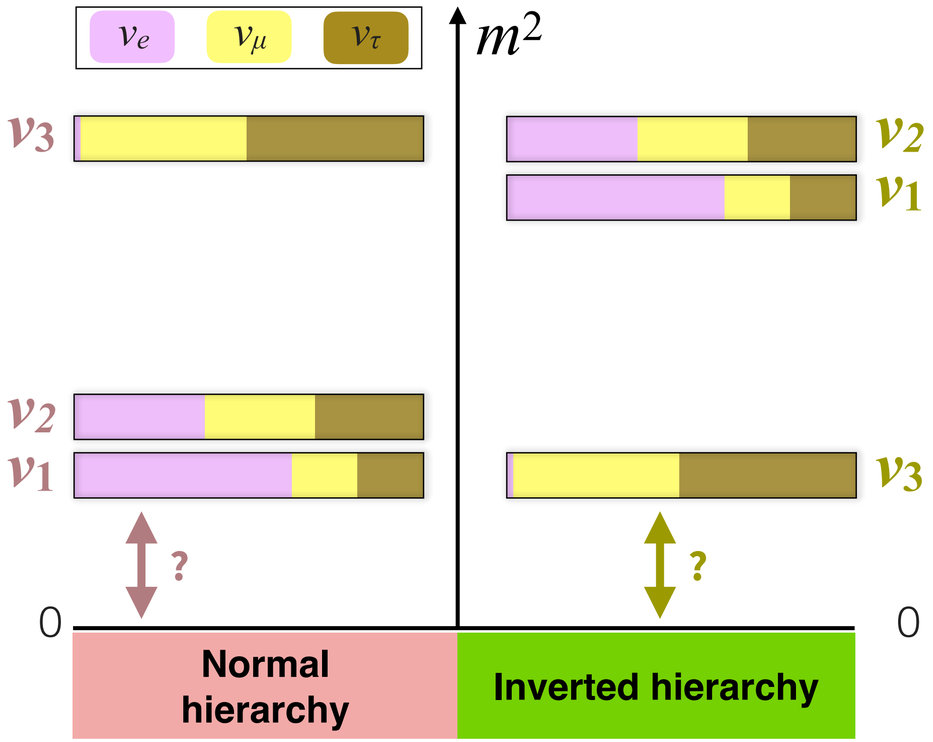
Complementary to:

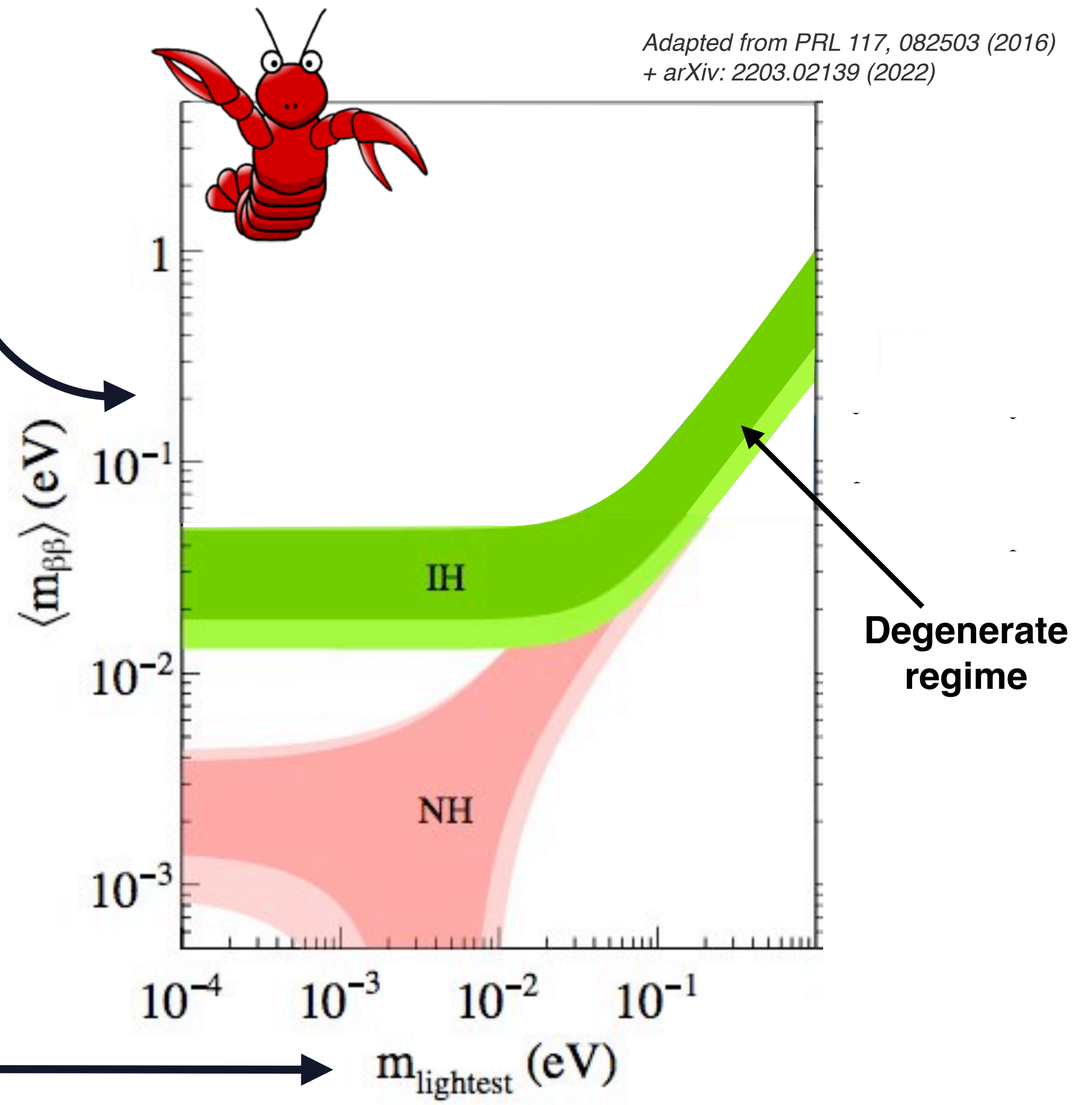
- Oscillations (Δm^2)
- Cosmology Σm
- β decay endpoints (m_β :different "ν_e" mass)

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

$0\nu\beta\beta$ rate

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





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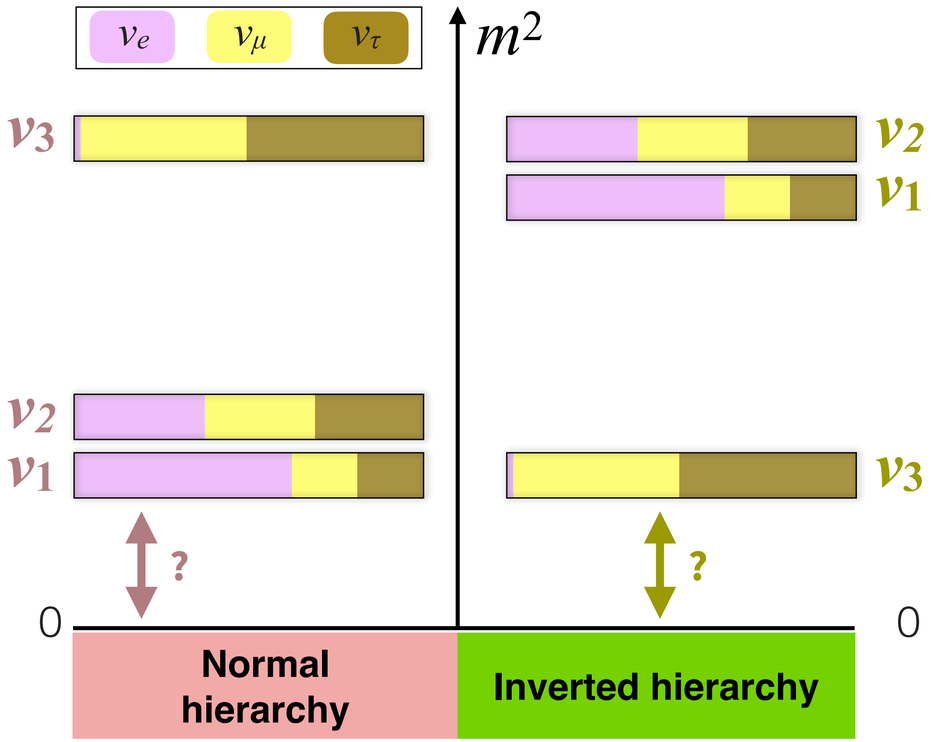

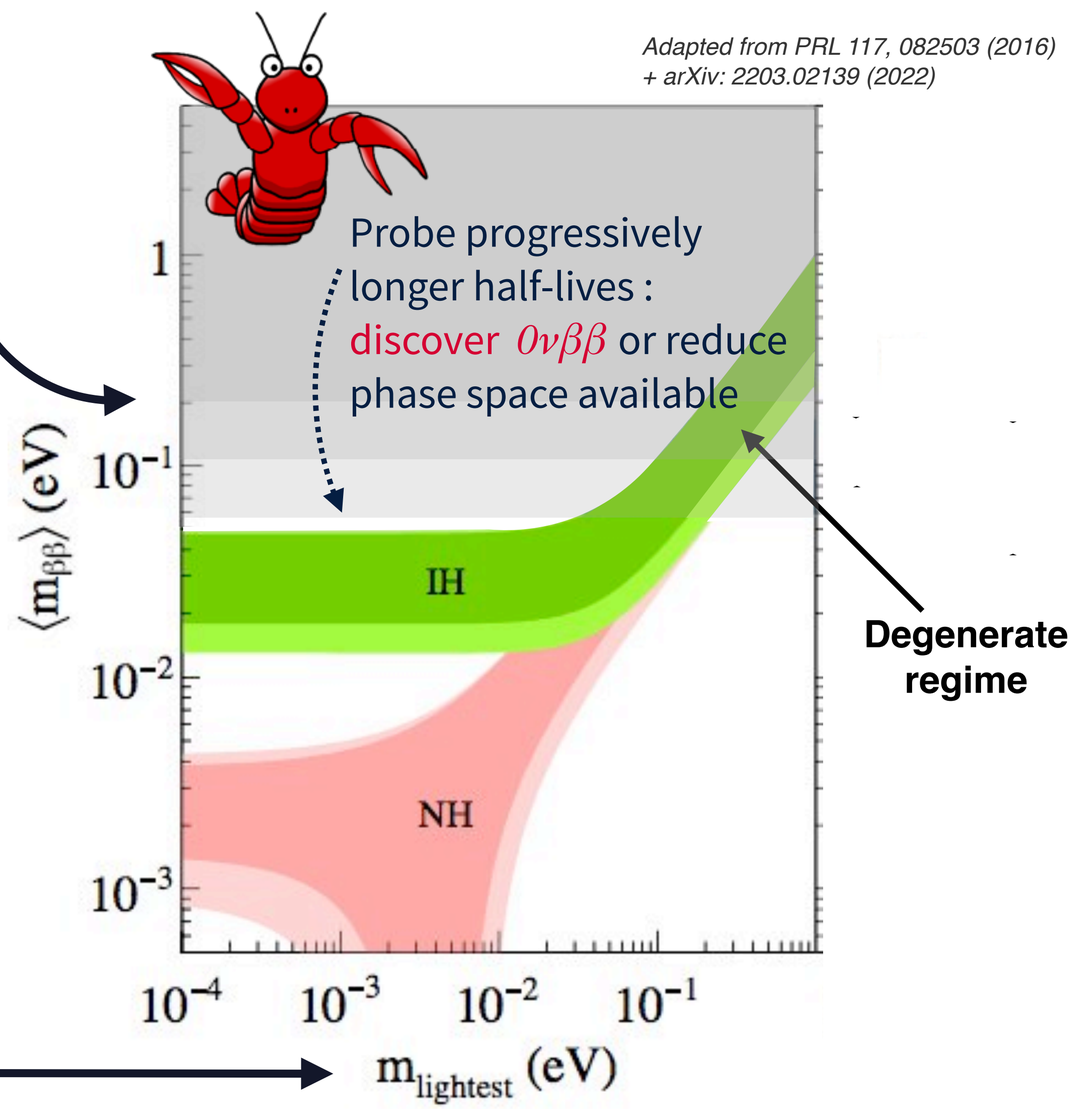

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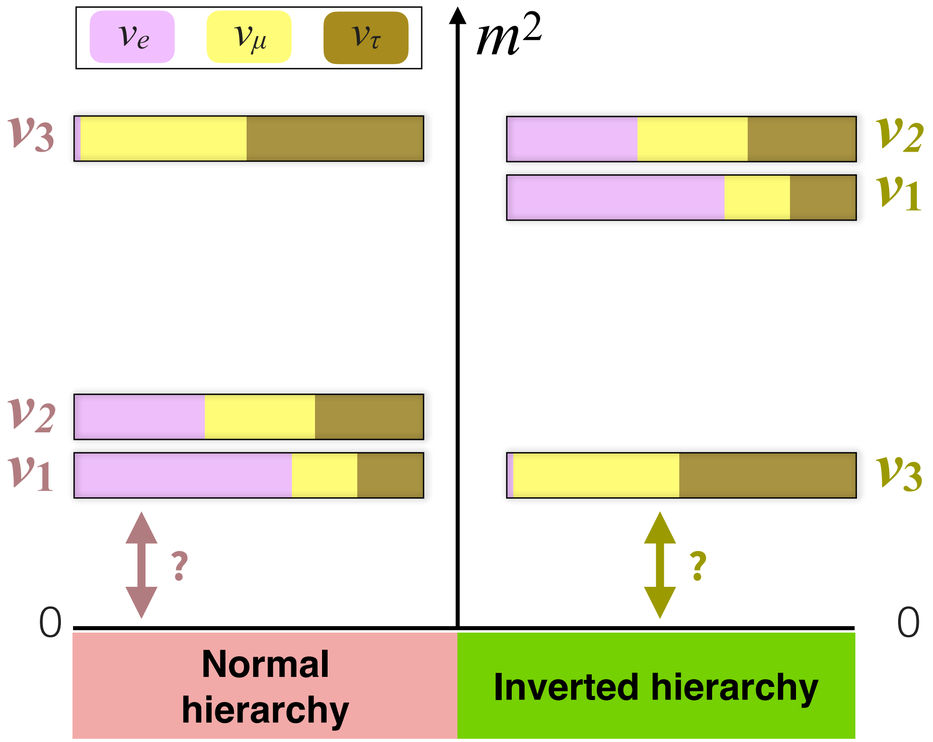

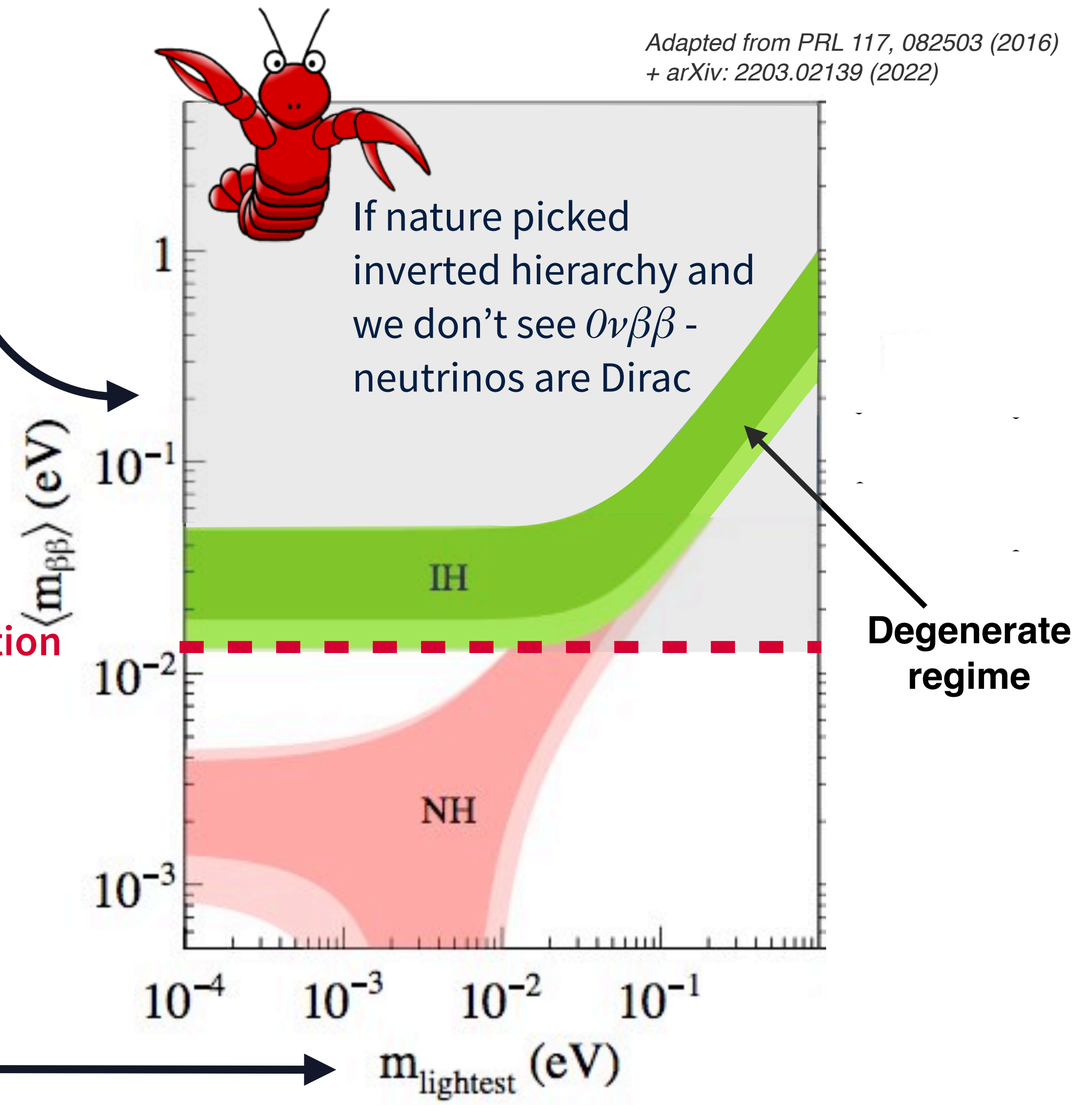

The state of the art

$0\nu\beta\beta$ rate

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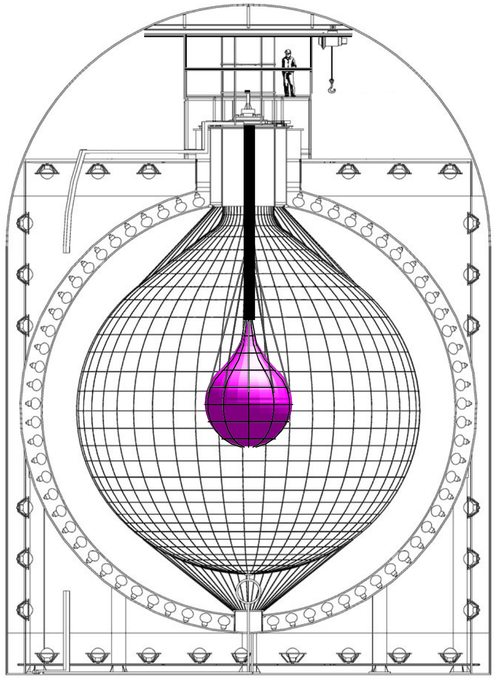


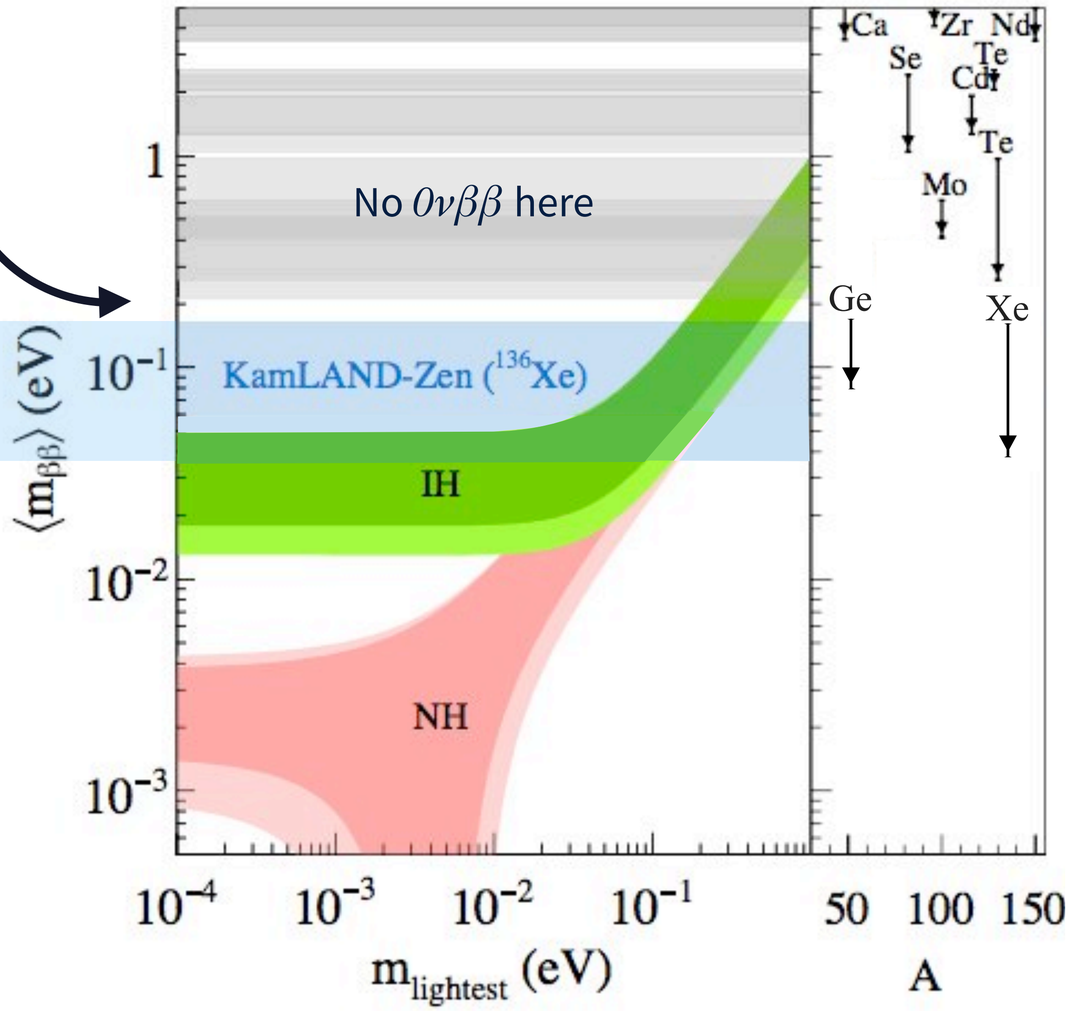
KamLAND-Zen (Japan):
750 kg ^{136}Xe in liquid scintillator

$T_{1/2}^{0\nu} > 2.3 \times 10^{26}$ years

$m_{\beta\beta}$ < 36-156 meV

arXiv:2203.02139 **[hep-ex]**

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



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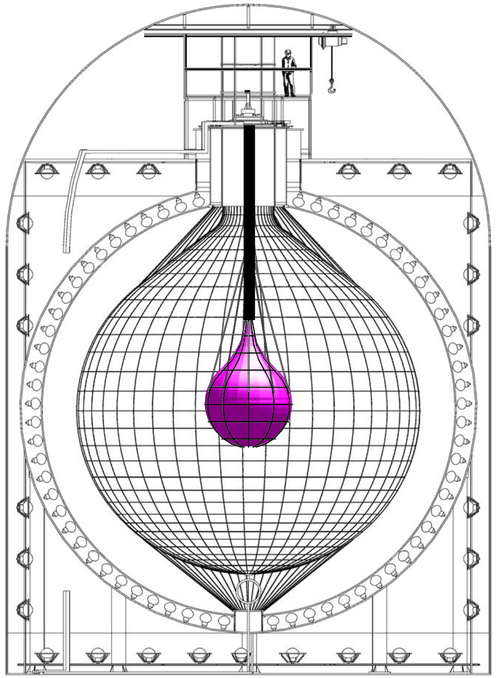
Uncertainty on nuclear matrix element leads to broad $m_{\beta\beta}$ band

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



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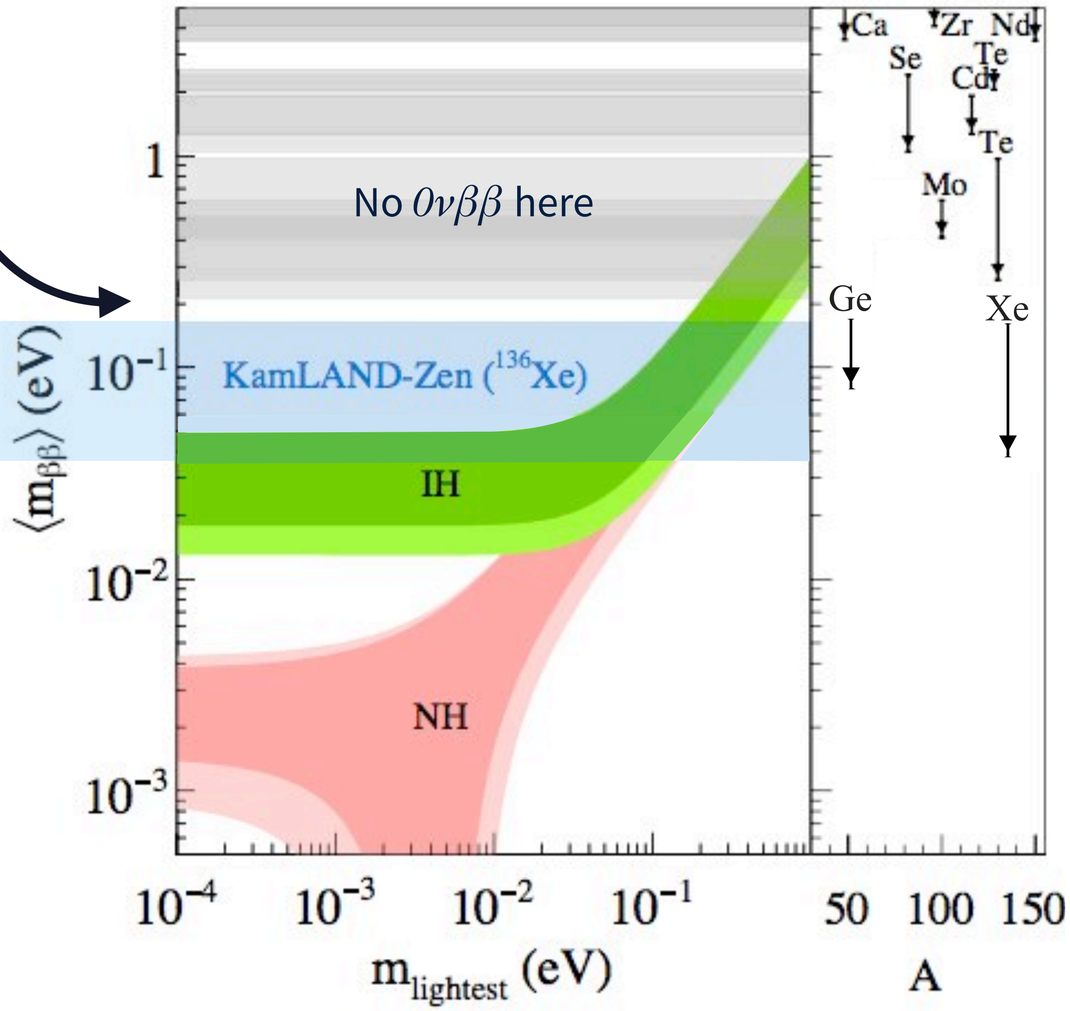

Double-beta decay and the nucleus

0νββ 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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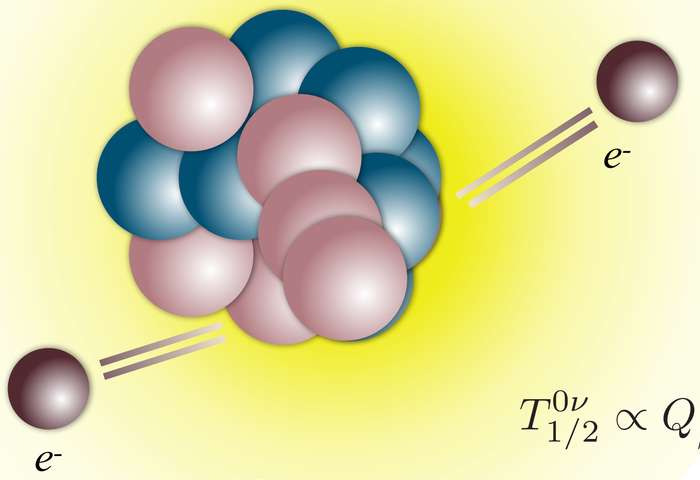
Phase space factor



$$T_{1/2}^{0\nu} \propto Q_{\beta\beta}^{-5}$$

Isotope-dependent:

- Phase-space volume (Q-dependent)
- Coulomb effects of the nucleus on emitted electrons (Z-dependent)

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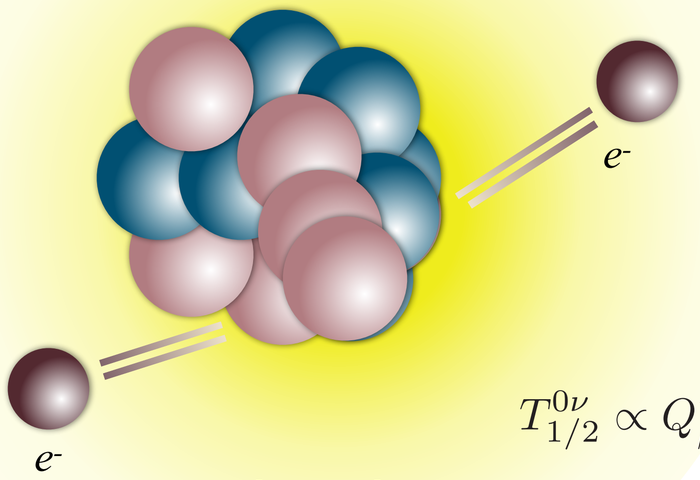

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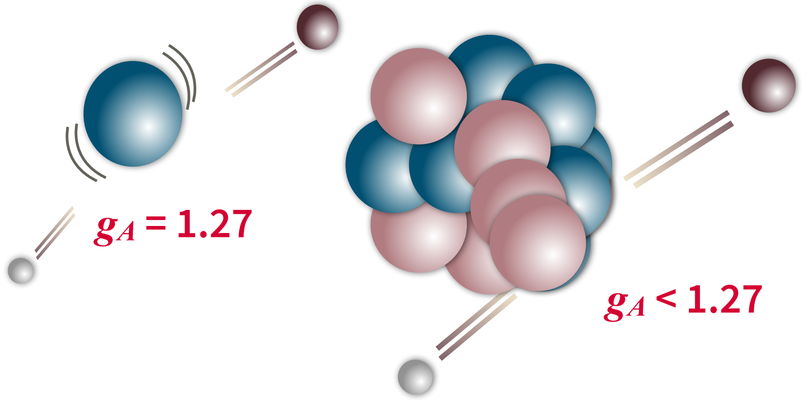

Axial vector coupling constant appears quenched in heavy nuclei

Due to multinucleon effects

"Fudge" for inaccurate assumptions in matrix element…

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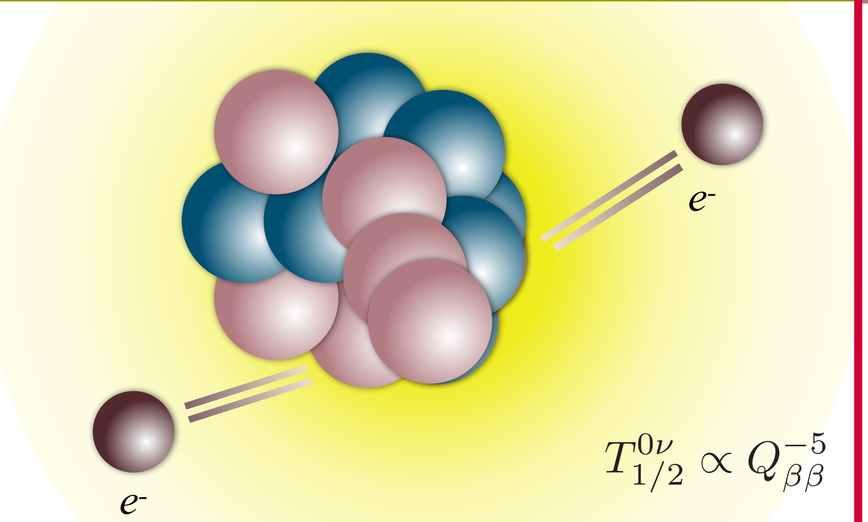

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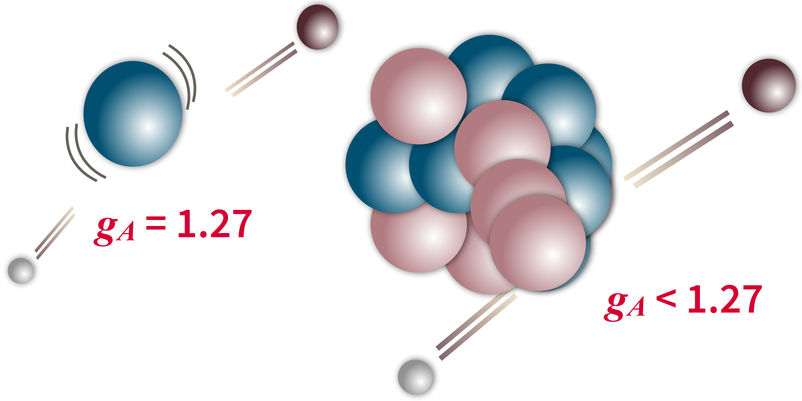

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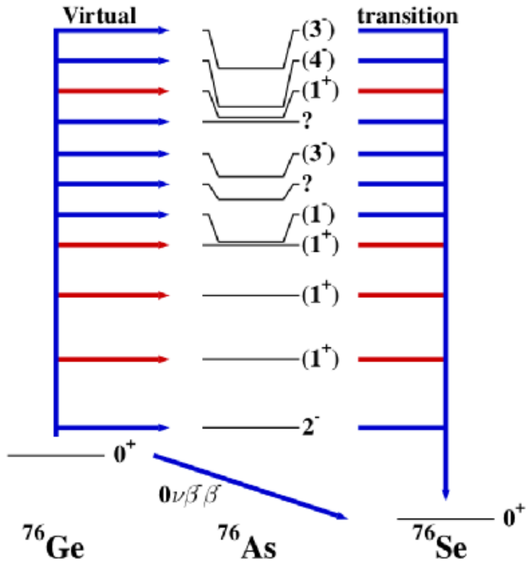
Nuclear matrix element



Nuclear structure effects of the parent, daughter, and intermediate nuclei

IPPP/05/56, DCPT/05/114

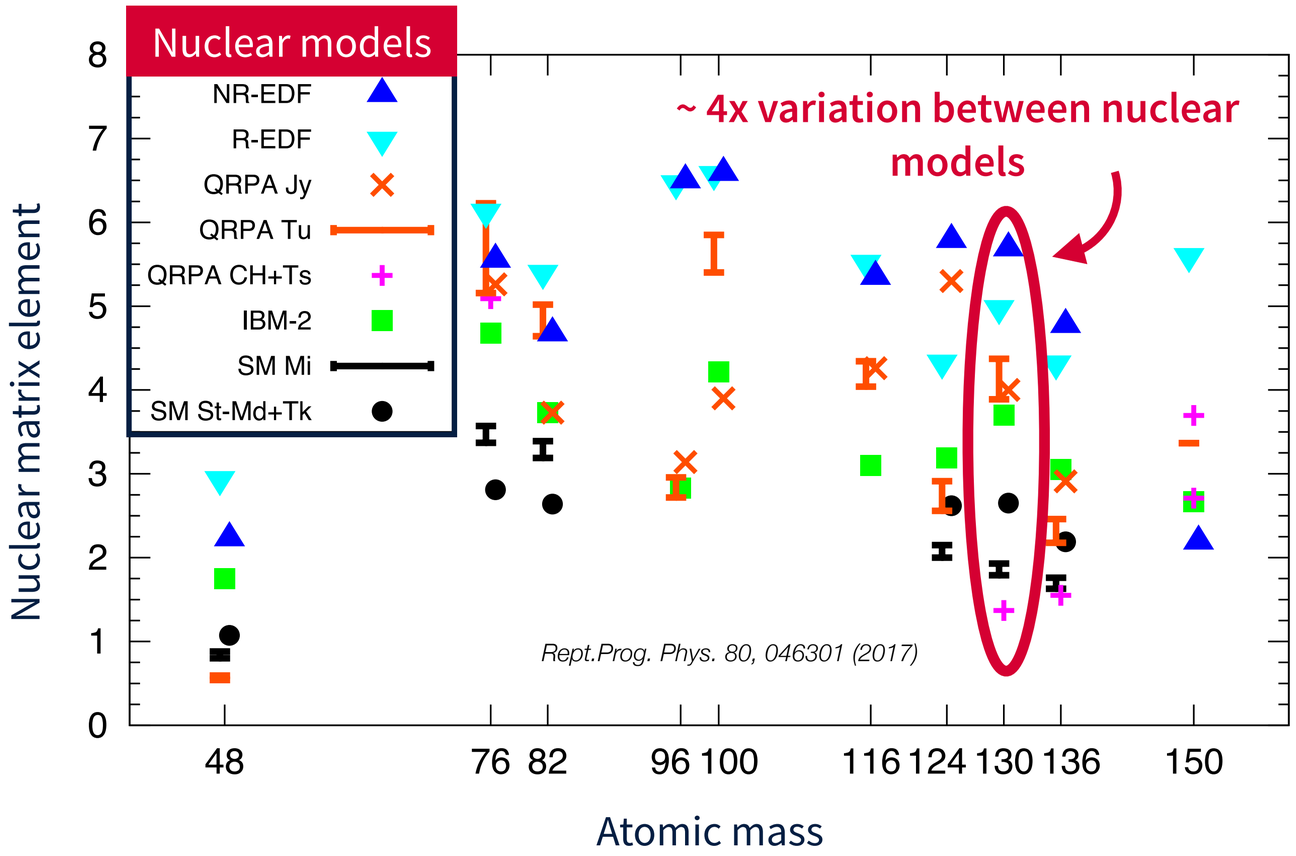
Nuclear matrix elements are hard to calculate

$0\nu\beta\beta$ rate

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

Neutrino mass $\propto$ $0\nu\beta\beta$ rate $\otimes$ Nuclear model

Understanding the nucleus is key to interpreting $0\nu\beta\beta$ measurements



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- At what mass scale it could show up
- The $0\nu\beta\beta$ mechanism
- Nuclear effects on $m_{\beta\beta}$ calculation

UK strategy for double-beta decay

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LEGEND

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

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- Nuclear effects on $m_{\beta\beta}$ calculation

UK strategy for double-beta decay

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

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

We still don't know:

- Whether $0\nu\beta\beta$ exists at all (are neutrinos Majorana?)
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UK strategy for double-beta decay

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

We still don't know:

- Whether $0\nu\beta\beta$ exists at all (are neutrinos Majorana?)
- At what mass scale it could show up
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- Nuclear effects on $m_{\beta\beta}$ calculation

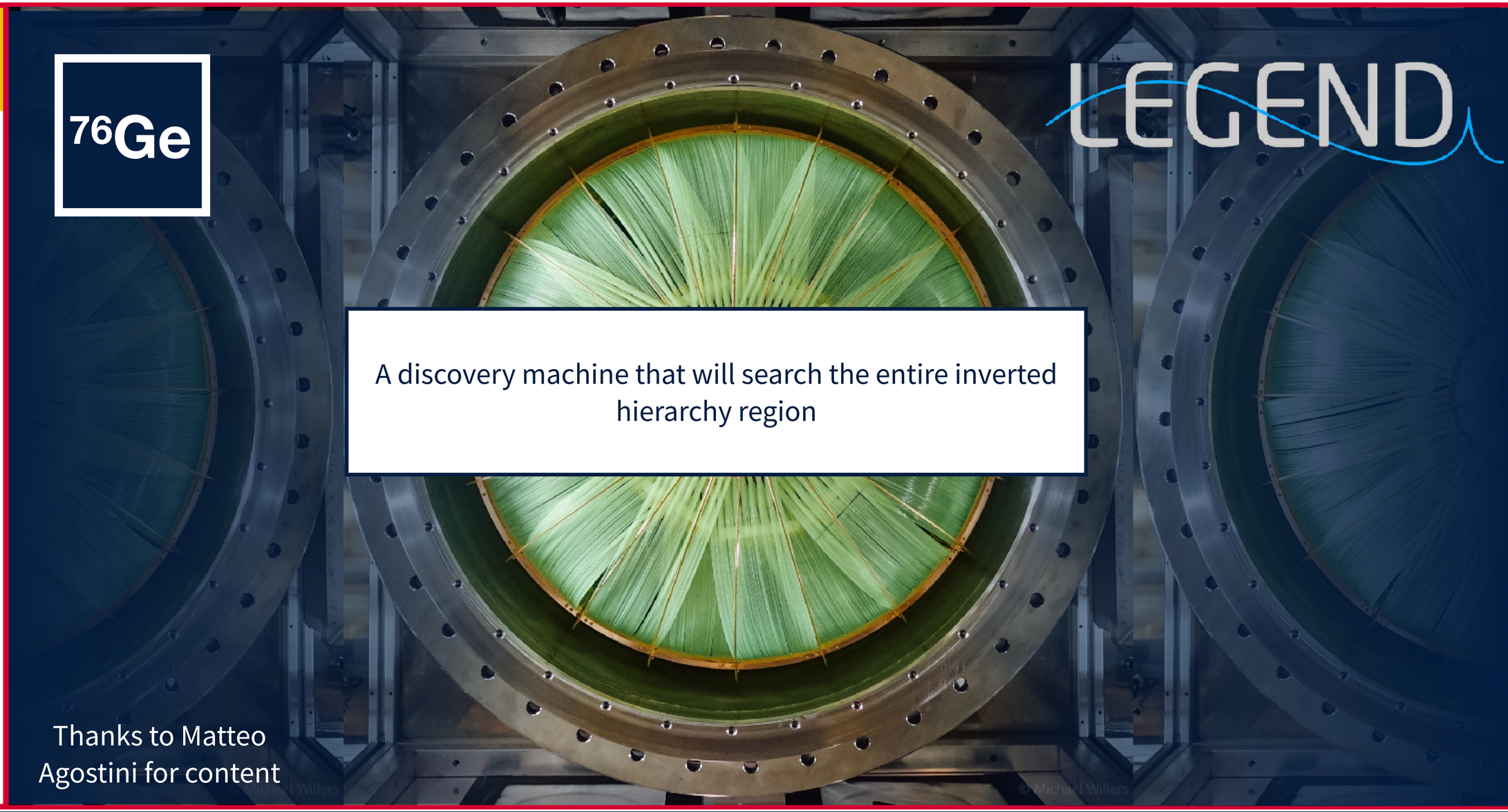
LEGEND at LNGS, Italy (so far…)

UCL

Lancaster University

UNIVERSITY OF LIVERPOOL

WARWICK
THE UNIVERSITY OF WARWICK



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
- calorimetric energy measurement

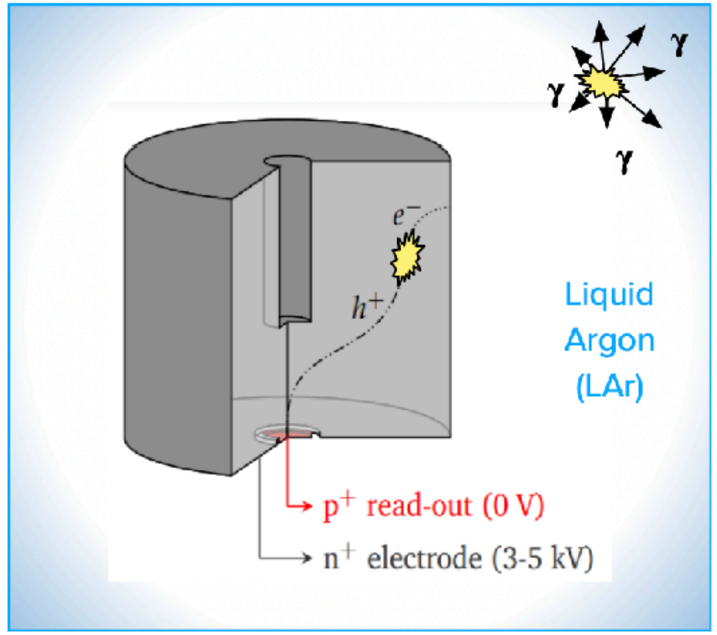
How does LEGEND work?

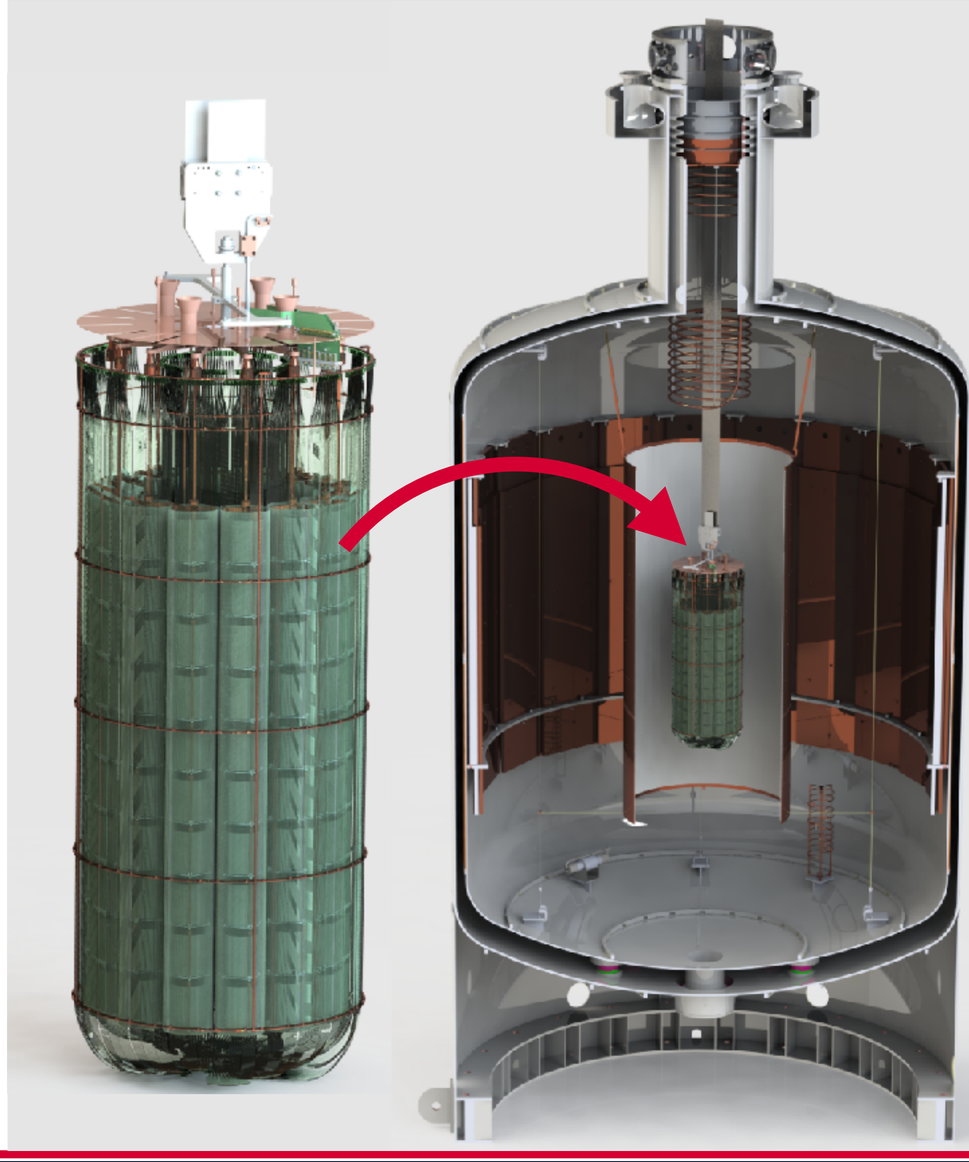
Semiconductor HPGe detectors:

- solid state TPC
- mm-scale event topology
- calorimetric energy measurement

Liquid-argon scintillation detector:

- background veto
- ultra-clean, cryogenic liquid
- isotropic emission of XUV photons

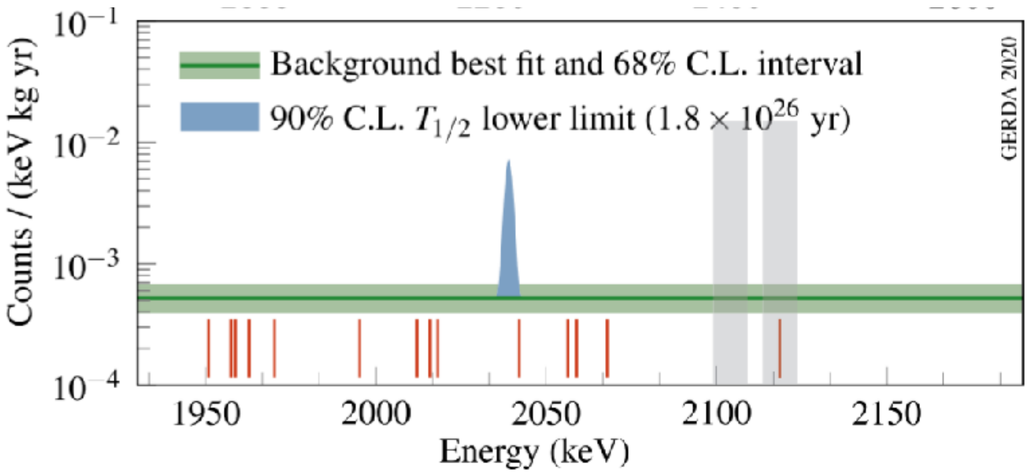




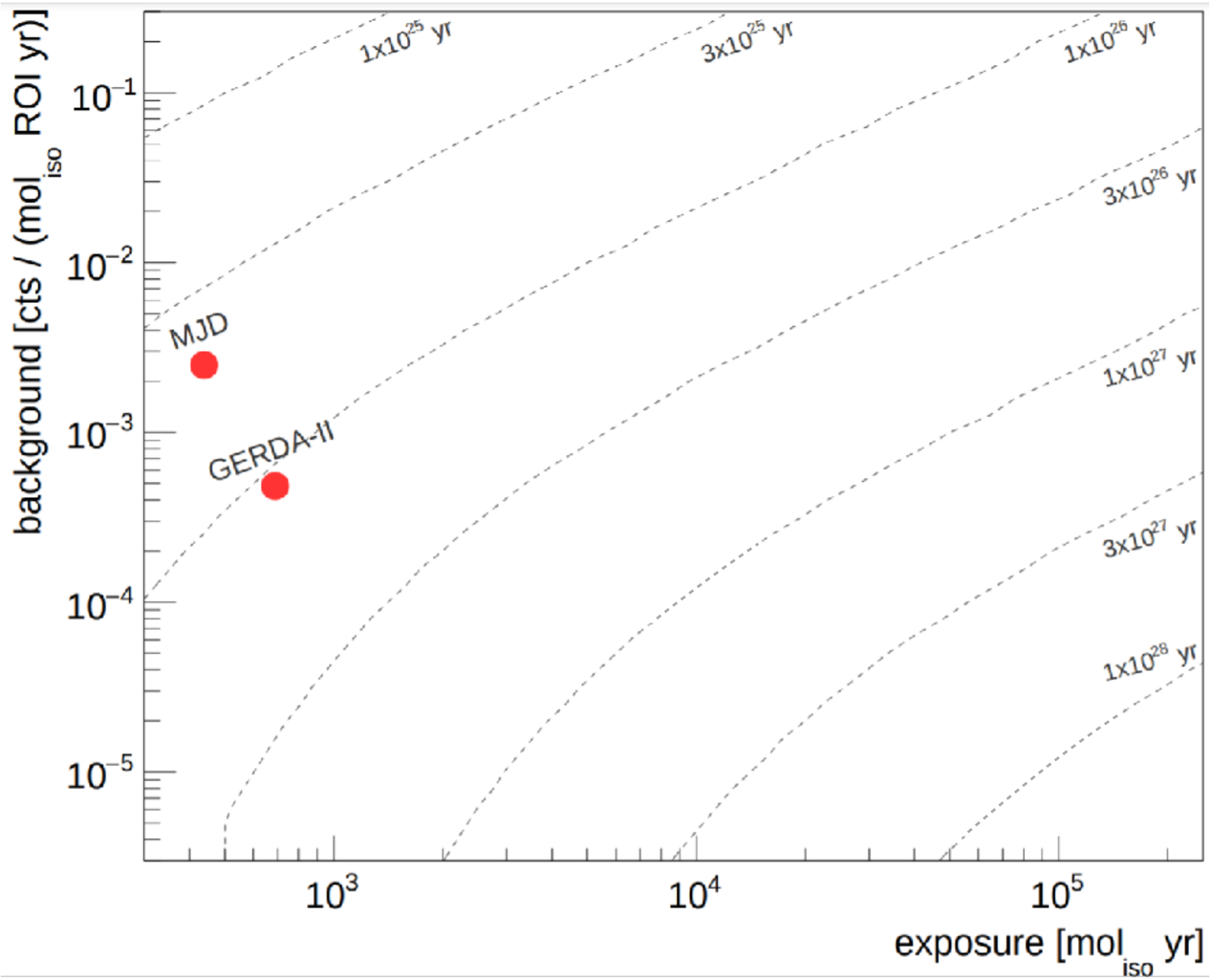
^{76}Ge - innovation and breakthroughs: past

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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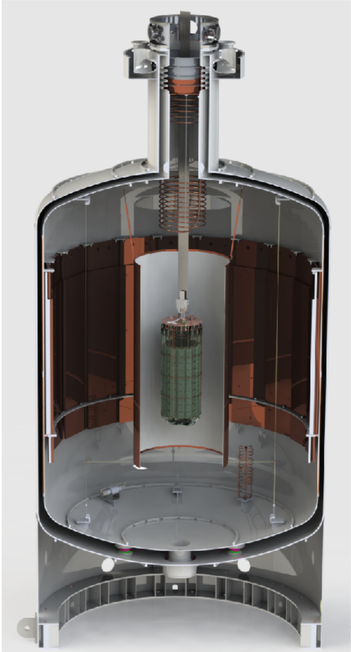
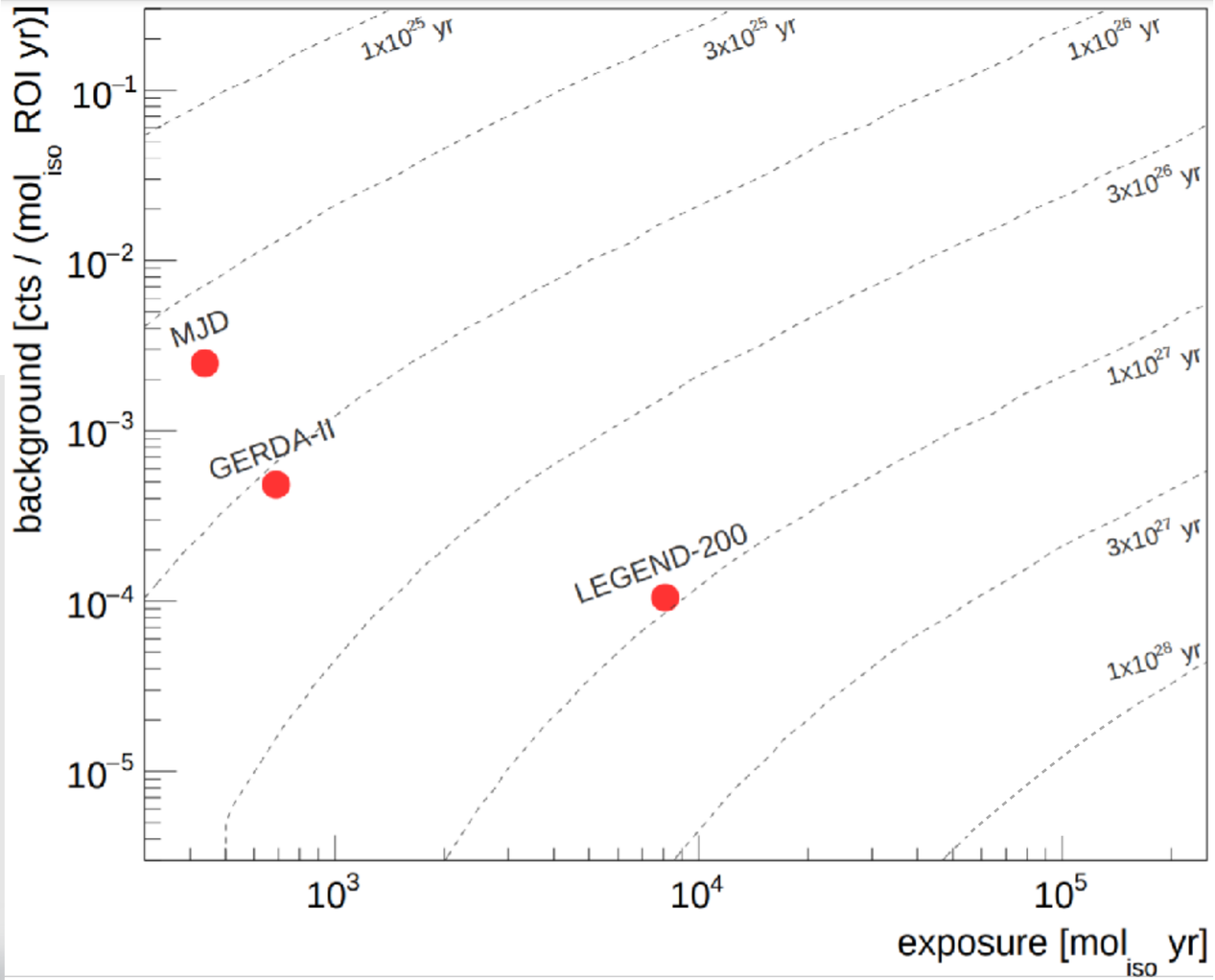
LEGEND-200 (200 kg)

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





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

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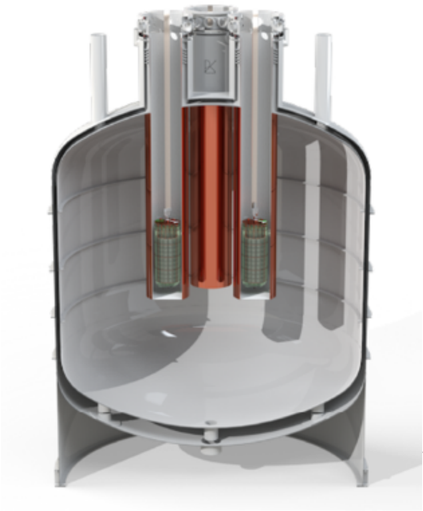
- **Lowest background** level in the field
- Best **energy resolution** in the field
- Best **discovery power** so far

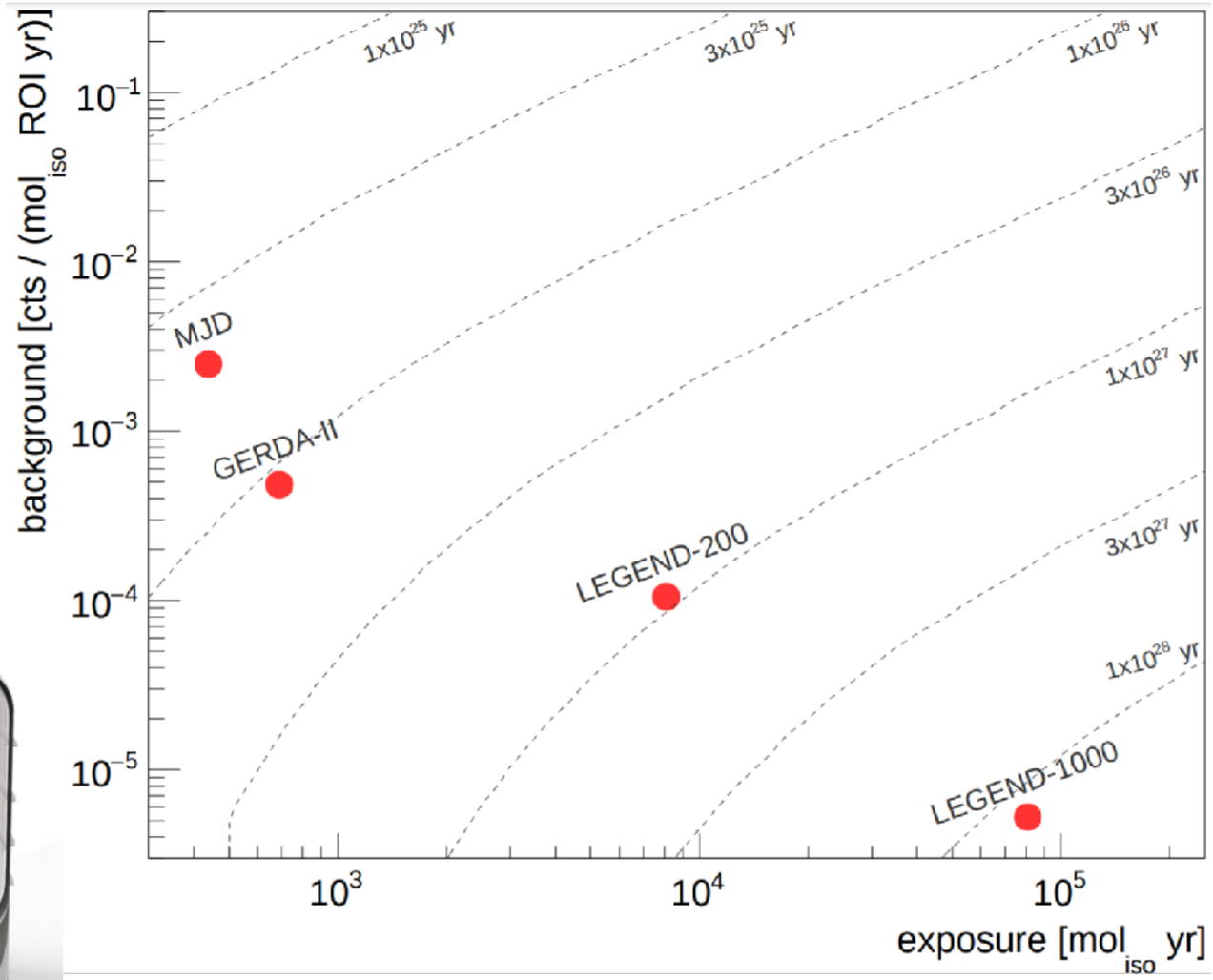
LEGEND-200 (200 kg)

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

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

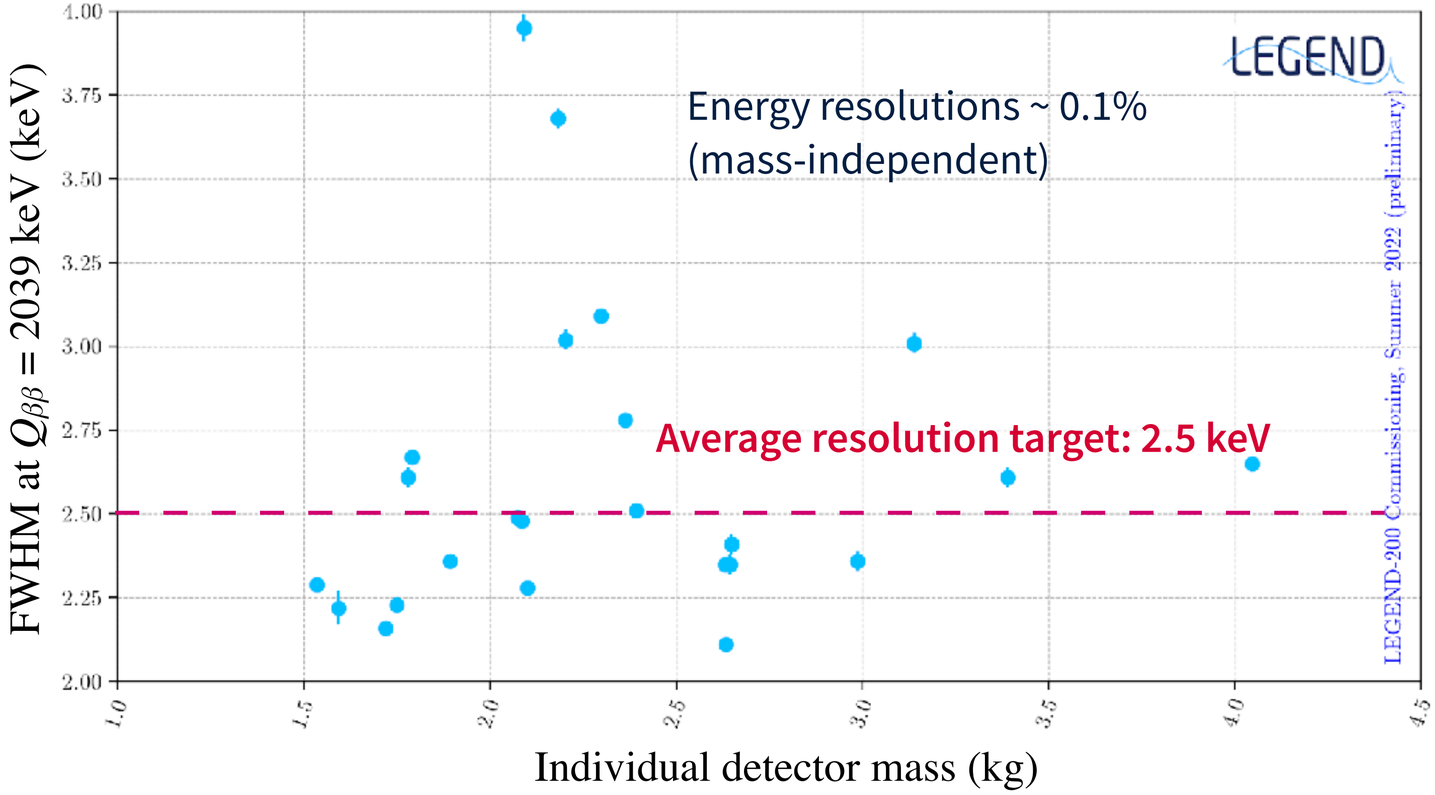




LEGEND-200

Summer 2022 LEGEND-200 integration runs:

- 24 detectors (60kg) used for background studies



LEGEND-200

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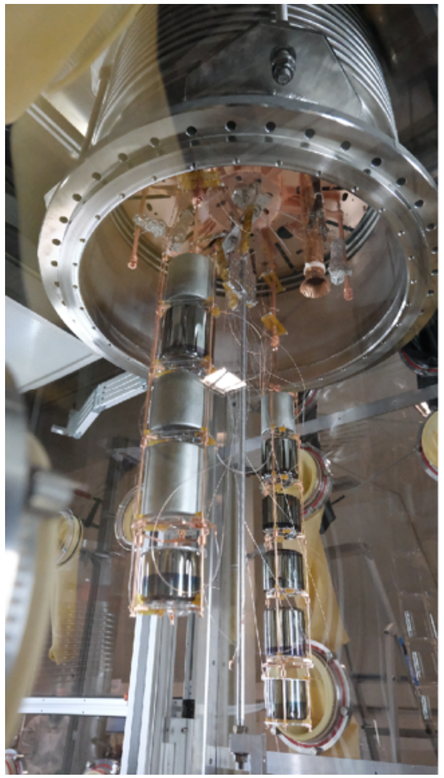

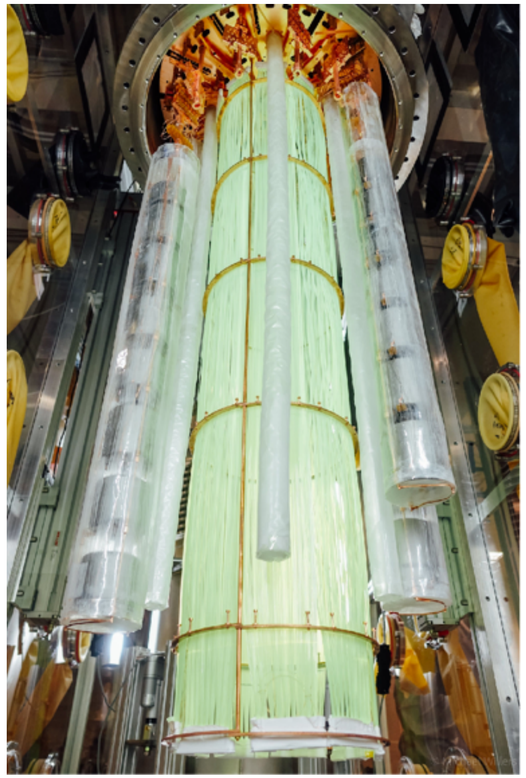

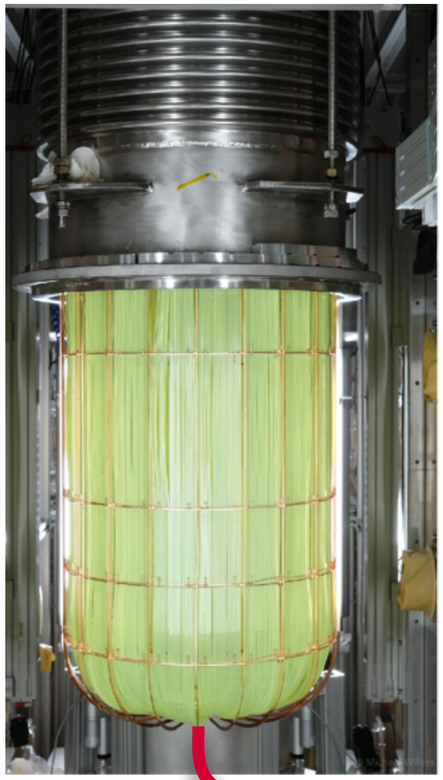

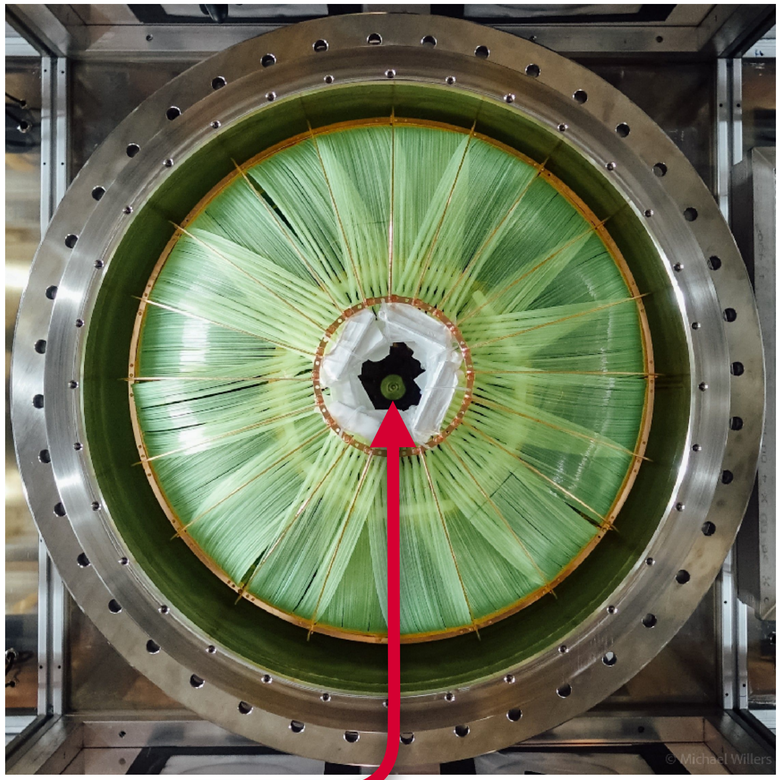

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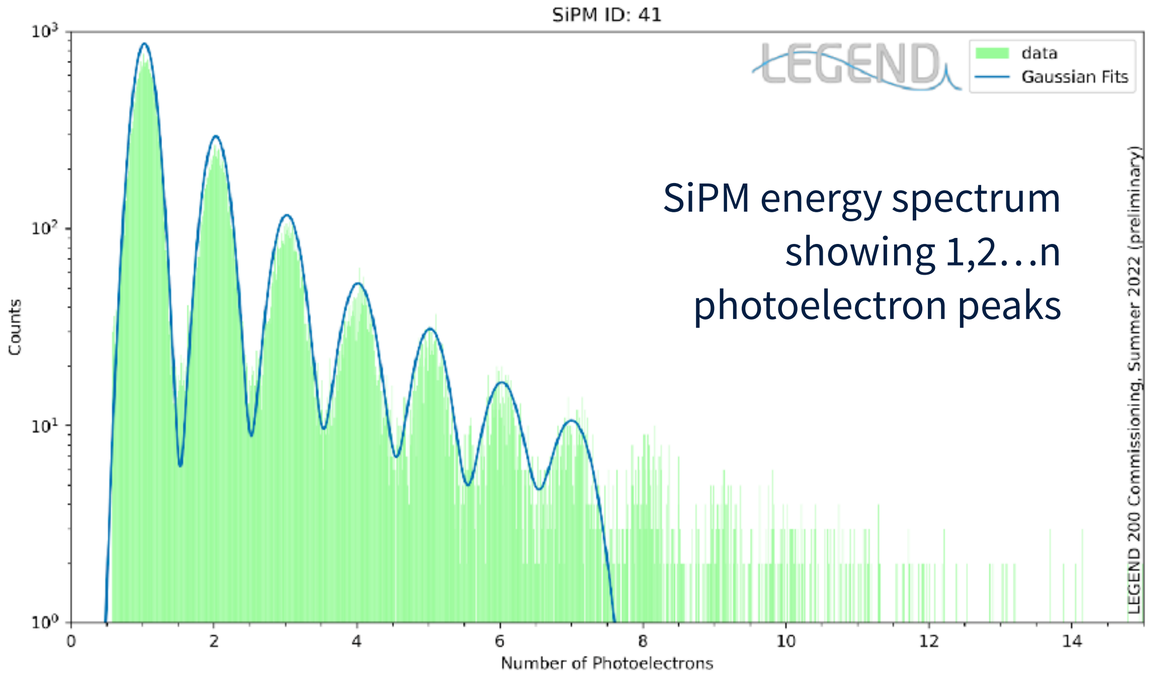
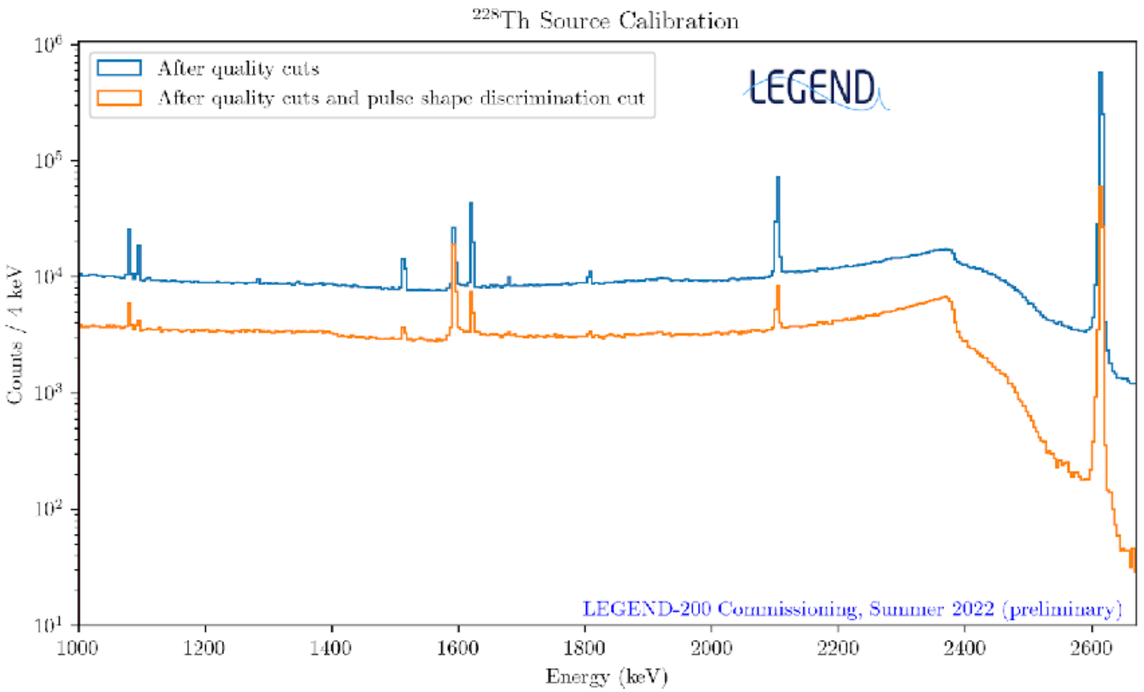


SiPM energy spectrum showing 1,2…n photoelectron peaks



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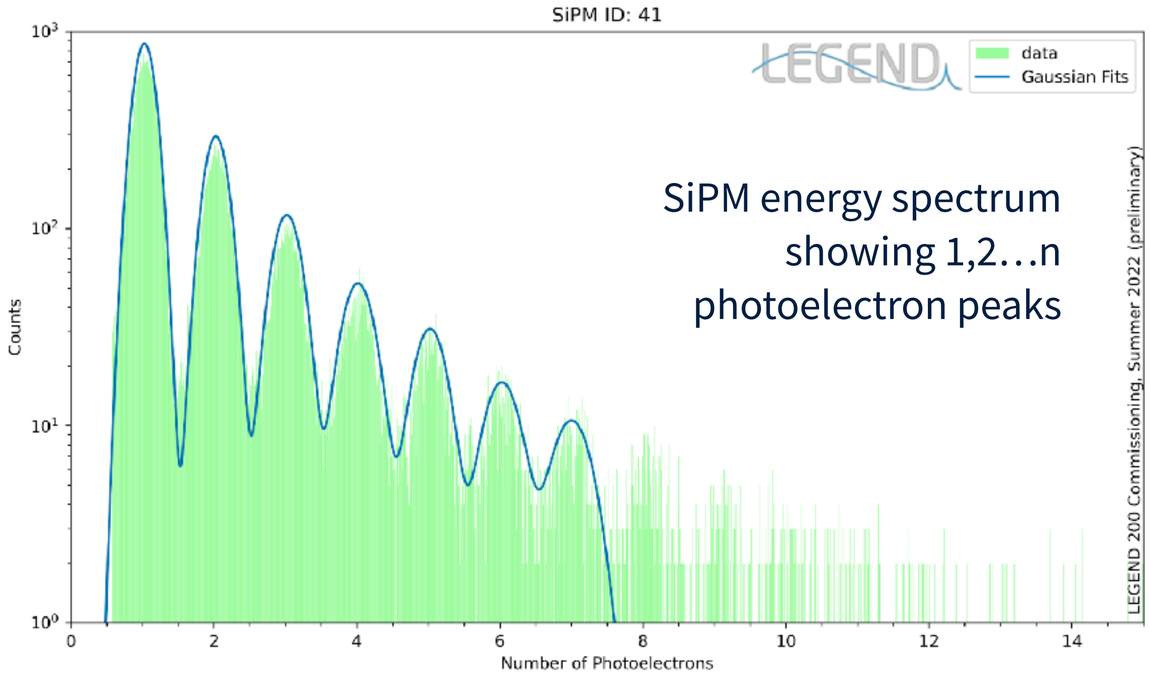

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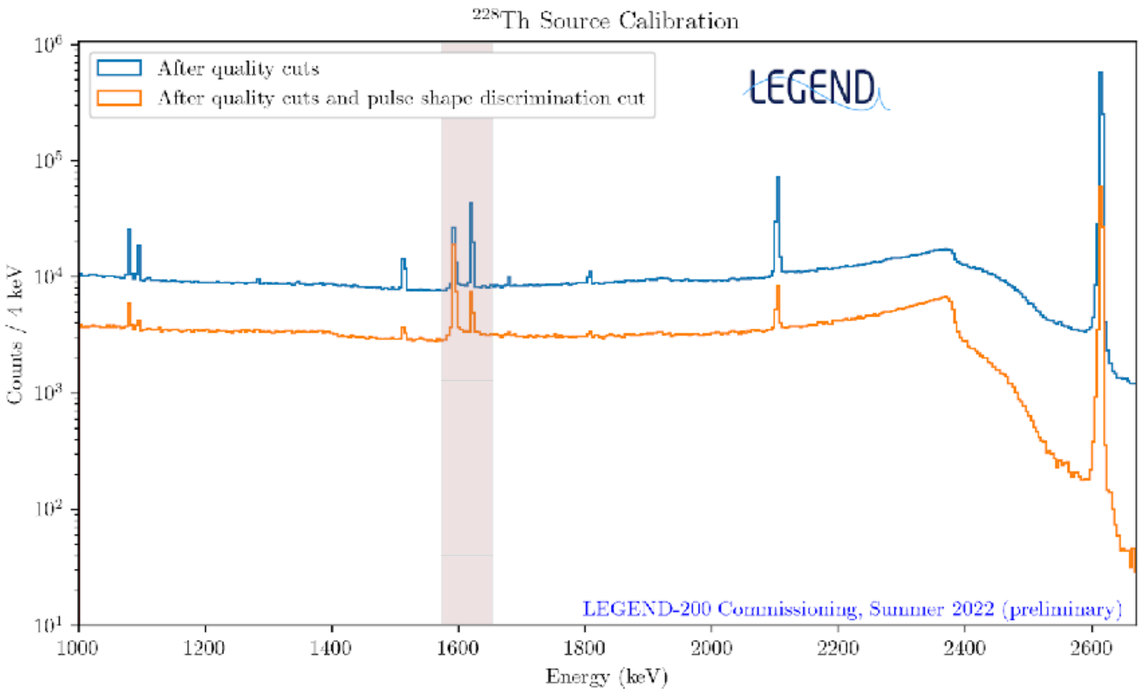

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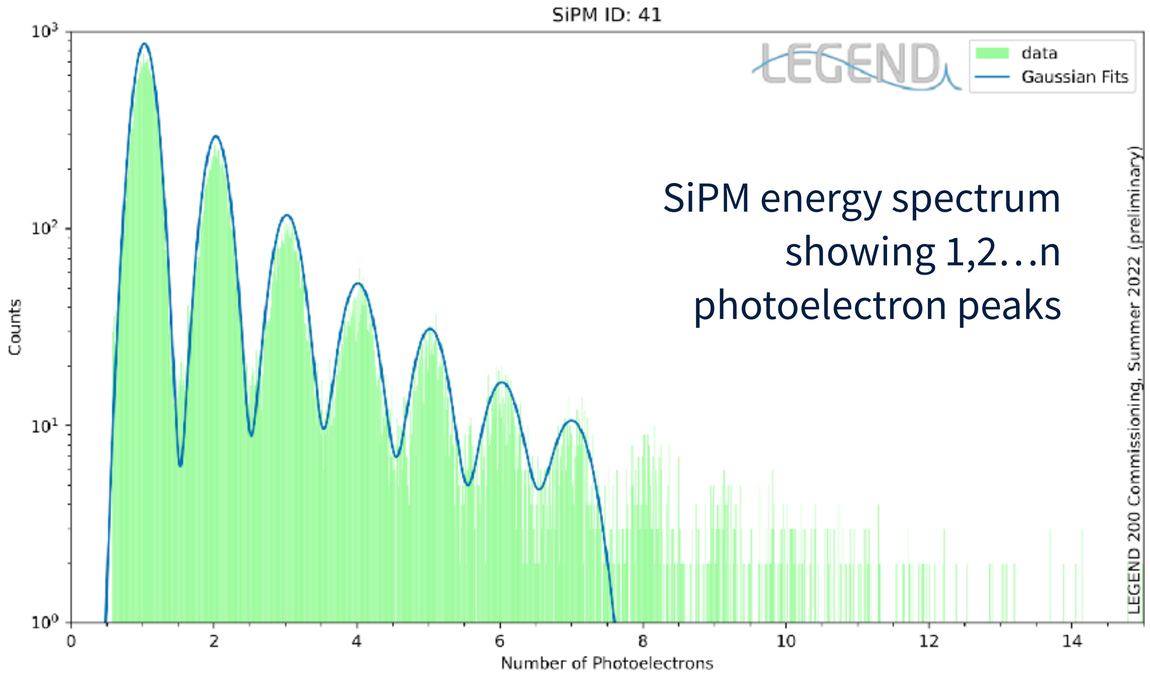

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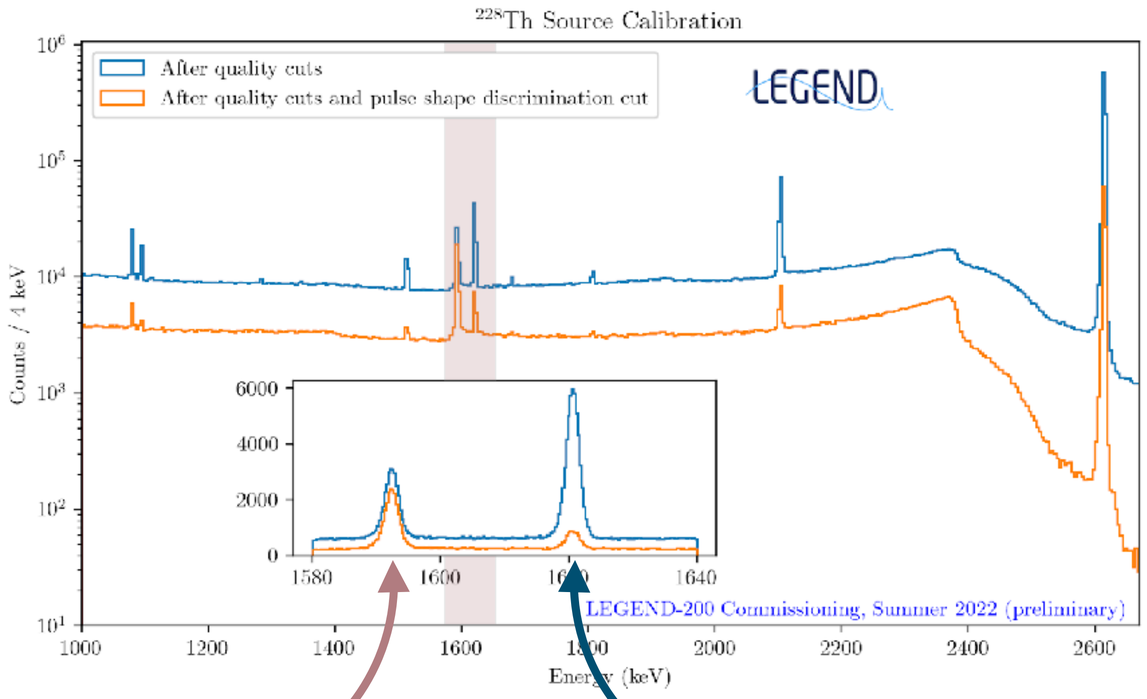
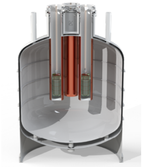


Signal-like events are kept
^{208}Tl double-escape peak (ββ-proxy)

Background-like (multi-site) events are cut
(^{212}Bi full-energy escape peak)

LEGEND status

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

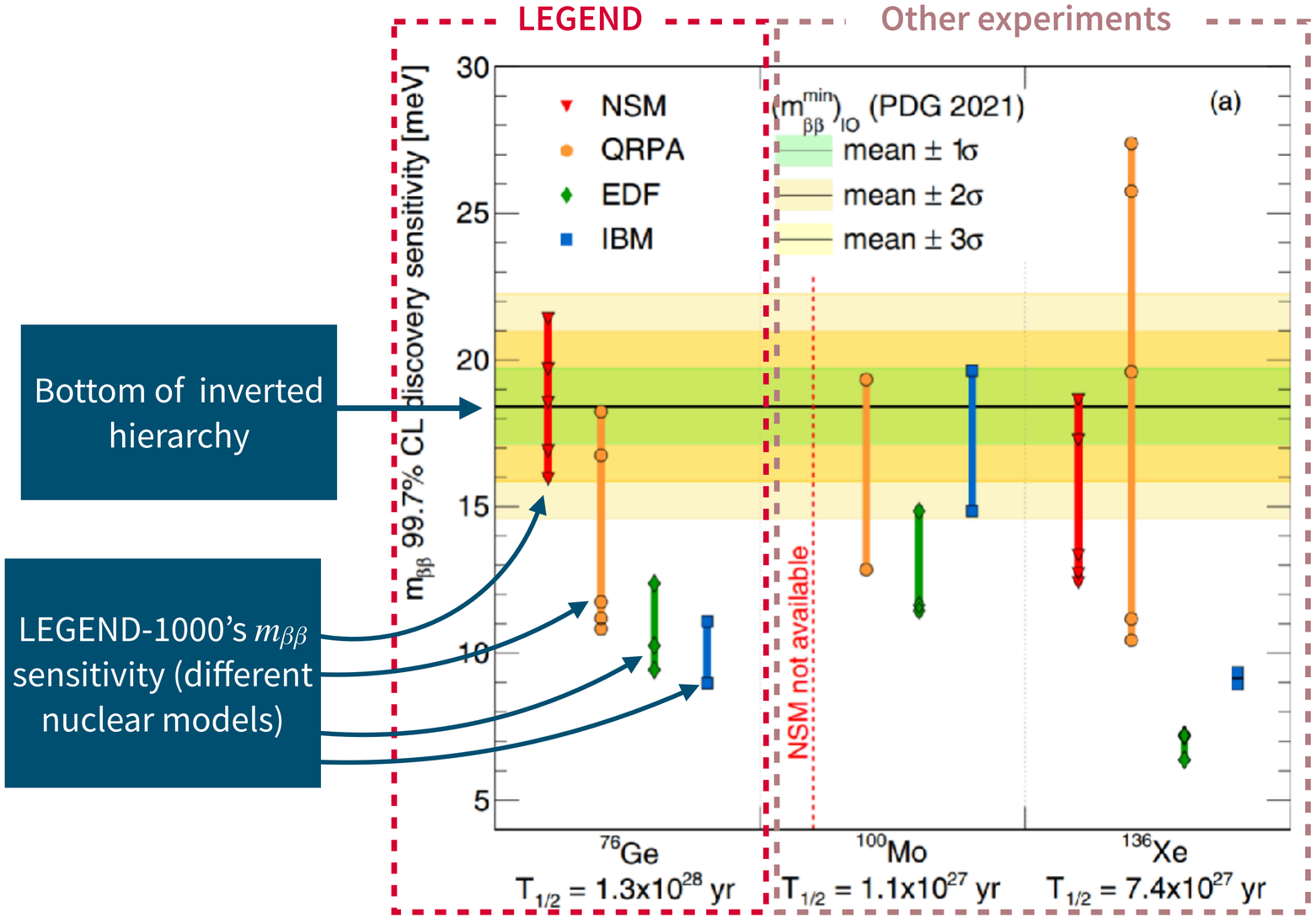


LEGEND-1000 (construction 2023-2030, first data in 2028, 10 years of operations)

LEGEND won DOE portfolio review

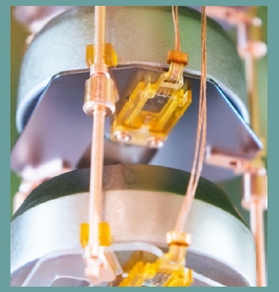
- DOE fully committed to LEGEND and will prioritise it over any other $0\nu\beta\beta$ experiments
- CD1 and CD3a review next year

LEGEND-1000 capability



LEGEND-UK statement of interest

Underground detector assembly and characterisation



Radiopurity assays

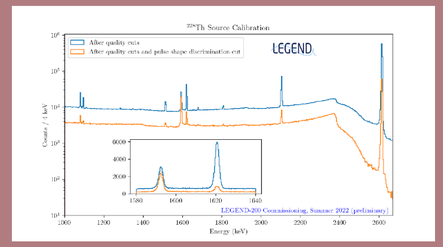
Cryogenic infrastructure

9 universities

UKRI Science and Technology Facilities Council

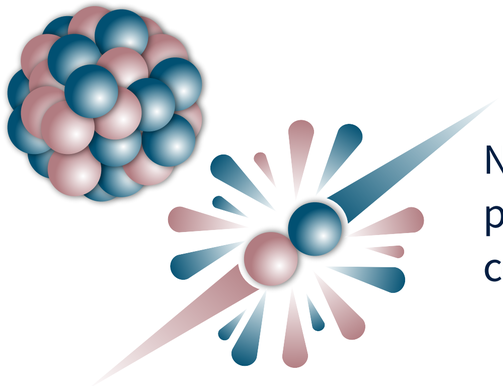
2 national labs

Computing, software, simulation and theory calculations



Data acquisition system

Isotope/ HPGe detector procurement



Nuclear- and particle- physics communities

SNO+ at Sudbury, Canada

UNIVERSITY OF OXFORD

KING'S College LONDON

Lancaster University

UNIVERSITY OF SUSSEX

UNIVERSITY OF LIVERPOOL

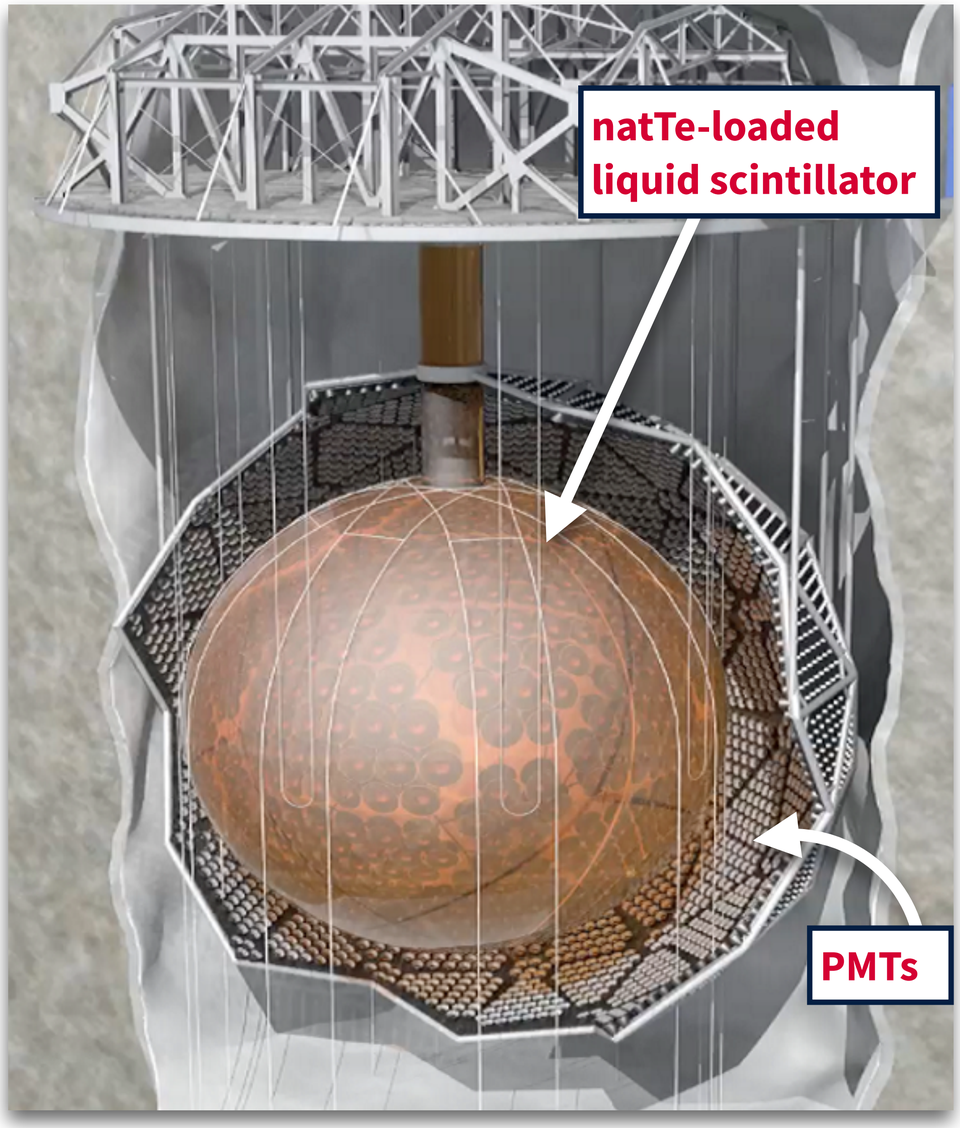
SNO+

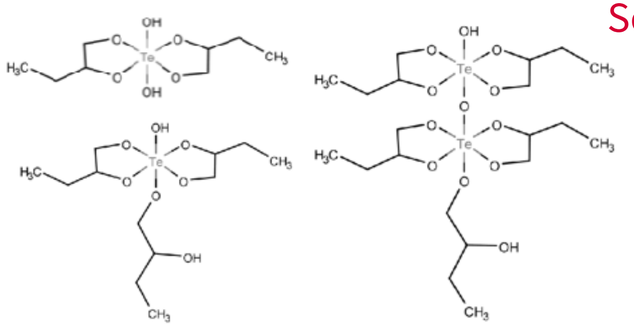
Thanks to Steve Biller for content

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

^{130}Te

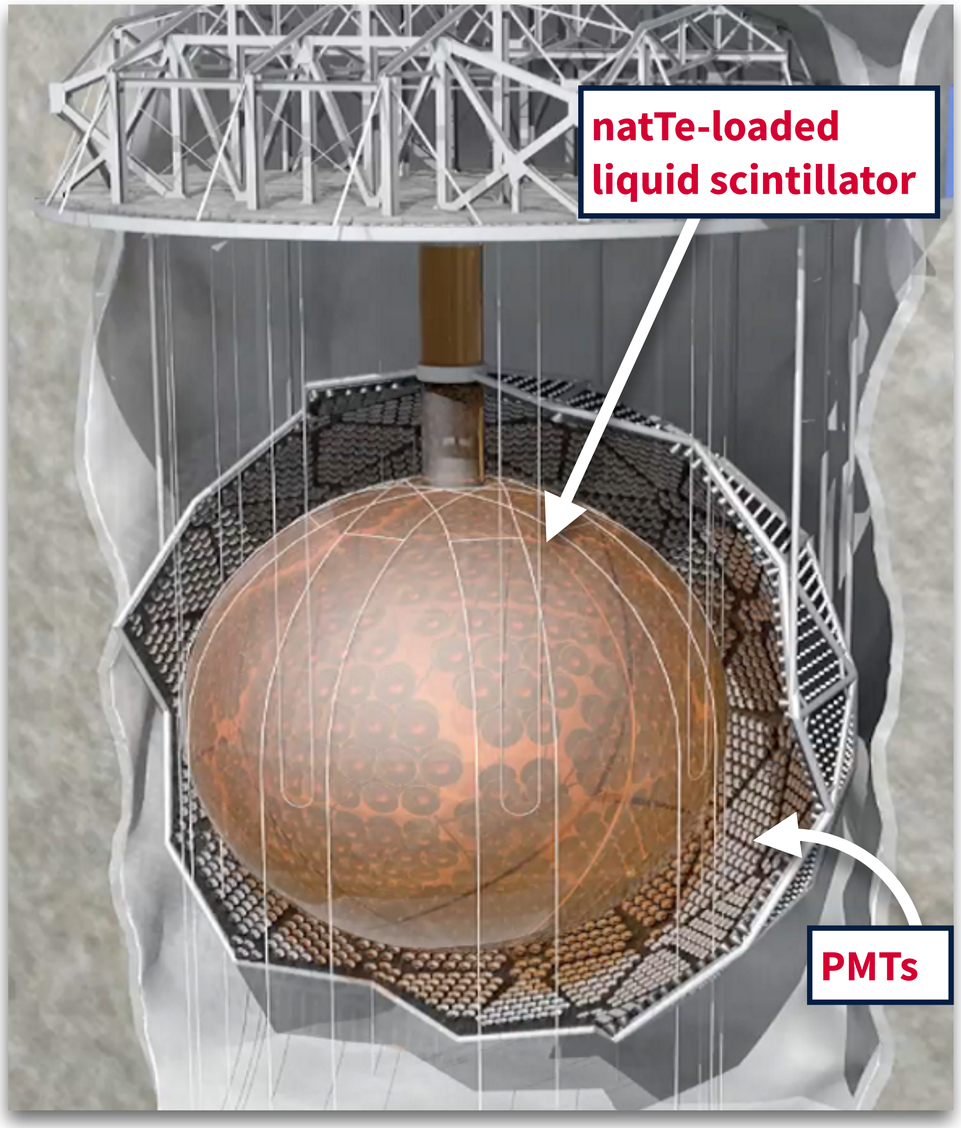
How SNO+ works

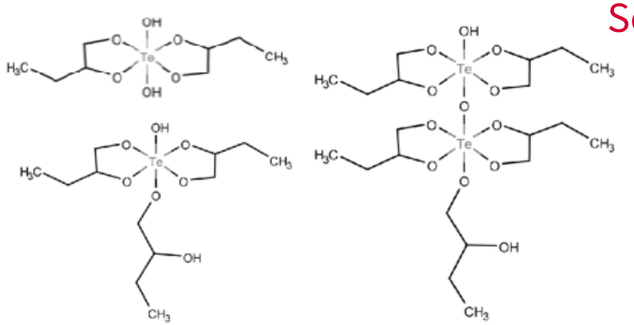




Diol Loading of ^{130}Te in Liquid Scintillator (developed in UK)

How SNO+ works



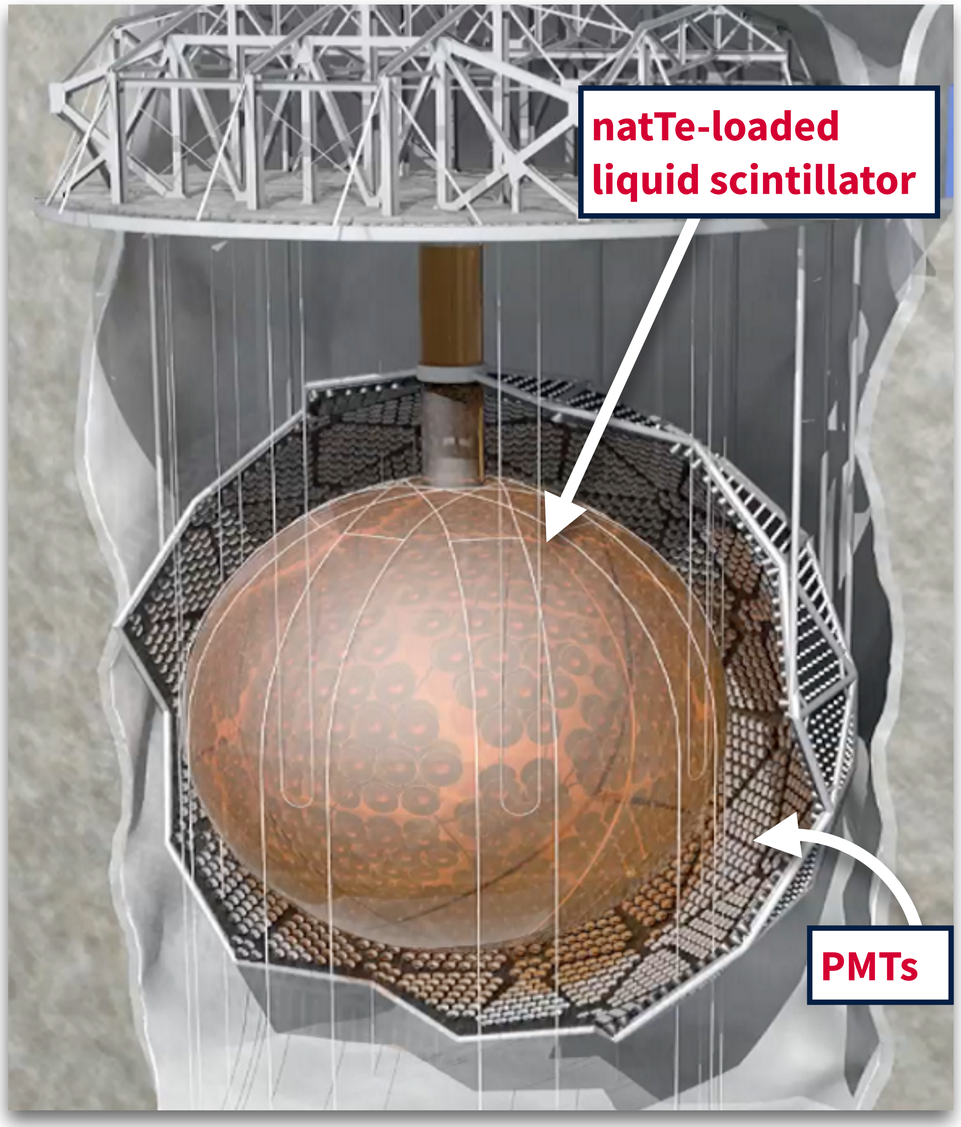


Diol Loading of ^{130}Te in Liquid Scintillator (developed in UK)

Cost-effective

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

How SNO+ works



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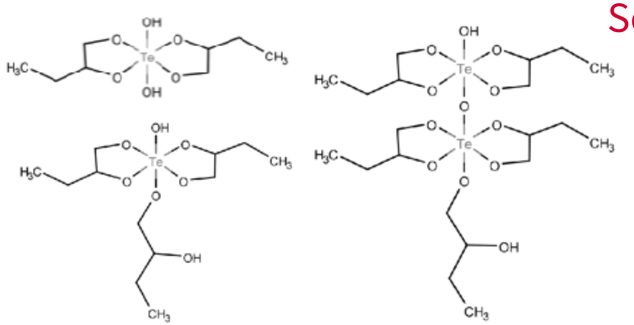

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Scalable

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

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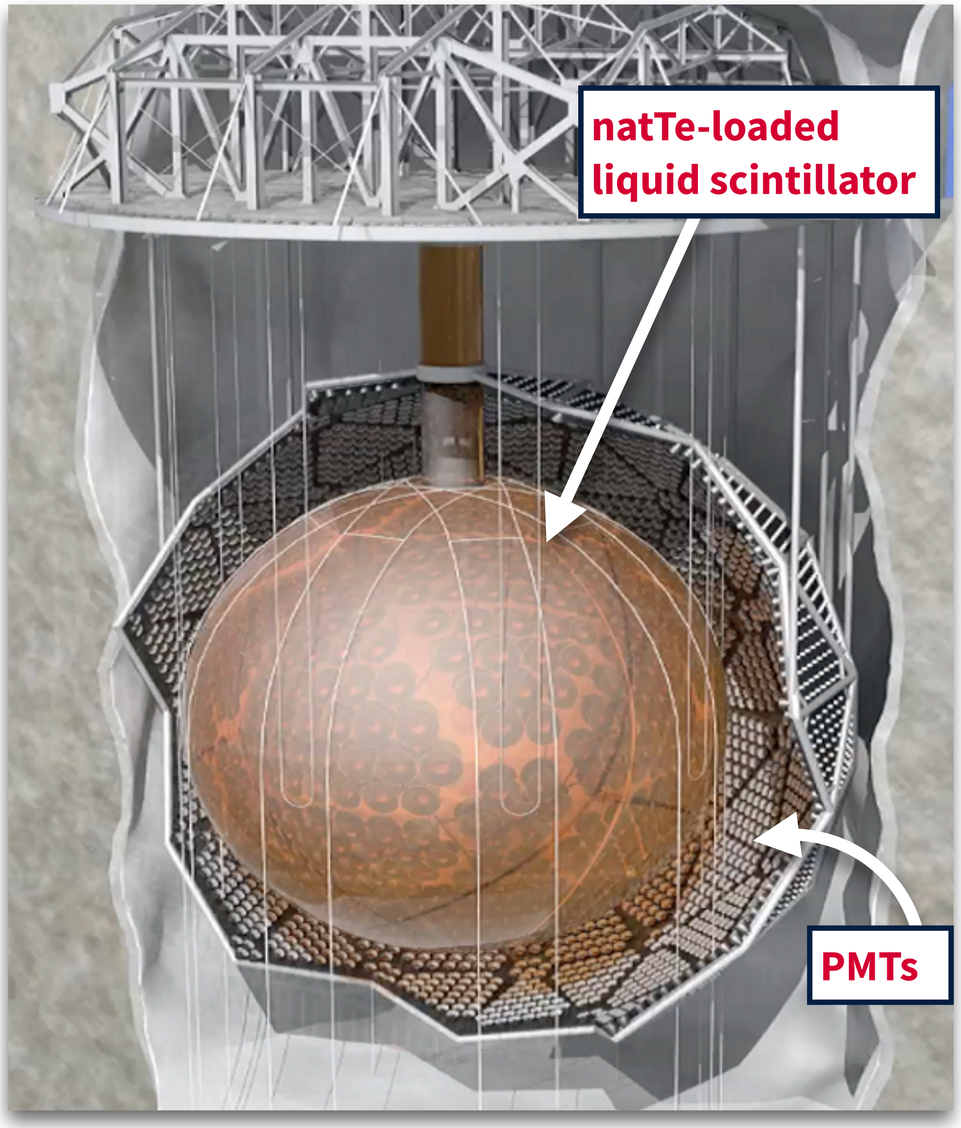

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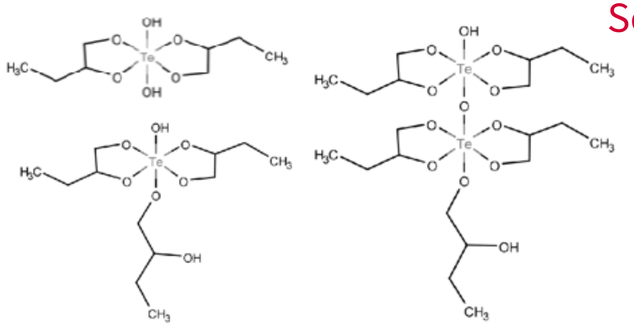

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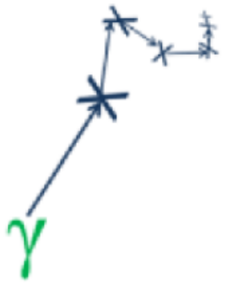
Sensitive

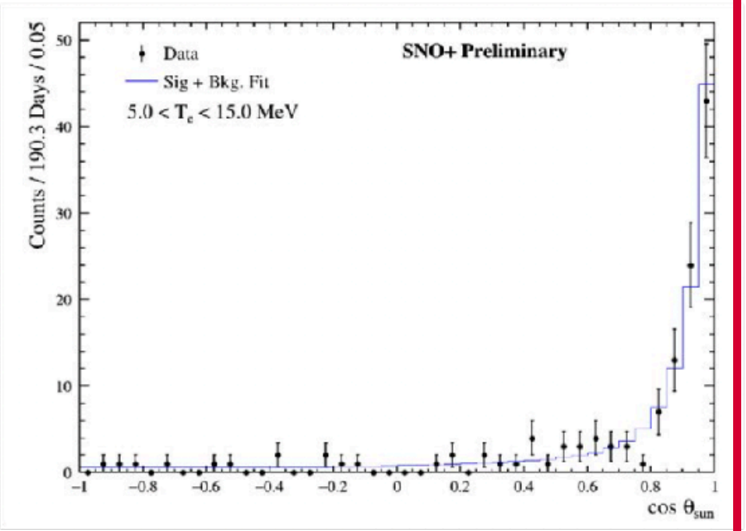
- Single- vs multi-site discrimination keeps backgrounds low



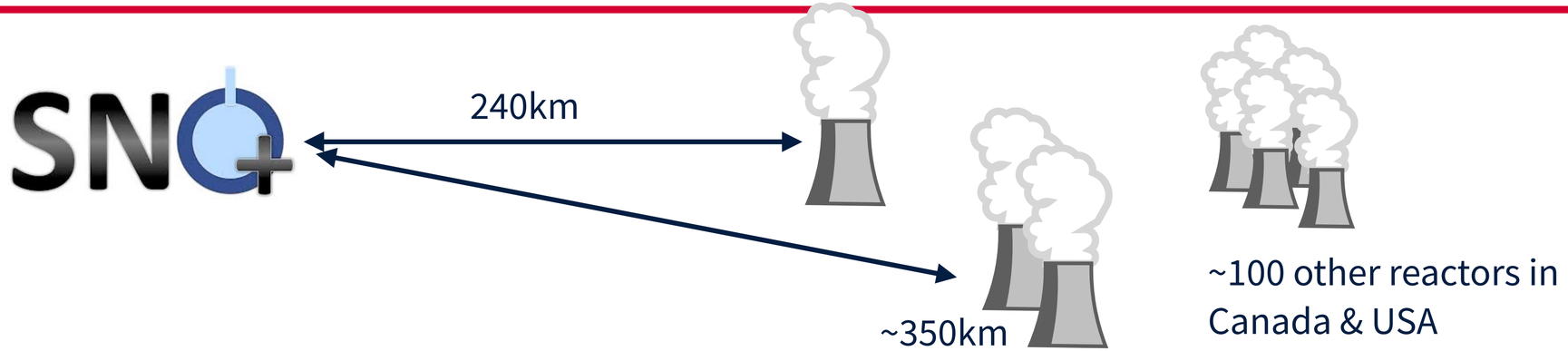
NIM, 943, 162420 (2019)

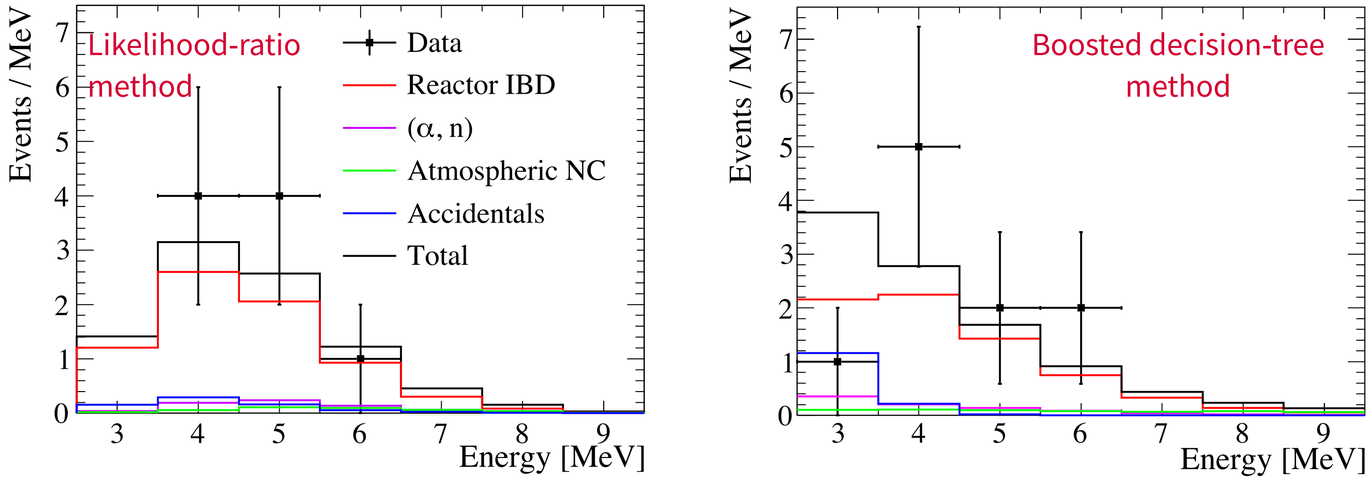
SNO+ initial phase - water-Cherenkov detector

^{8}B solar neutrinos



Extremely low backgrounds!



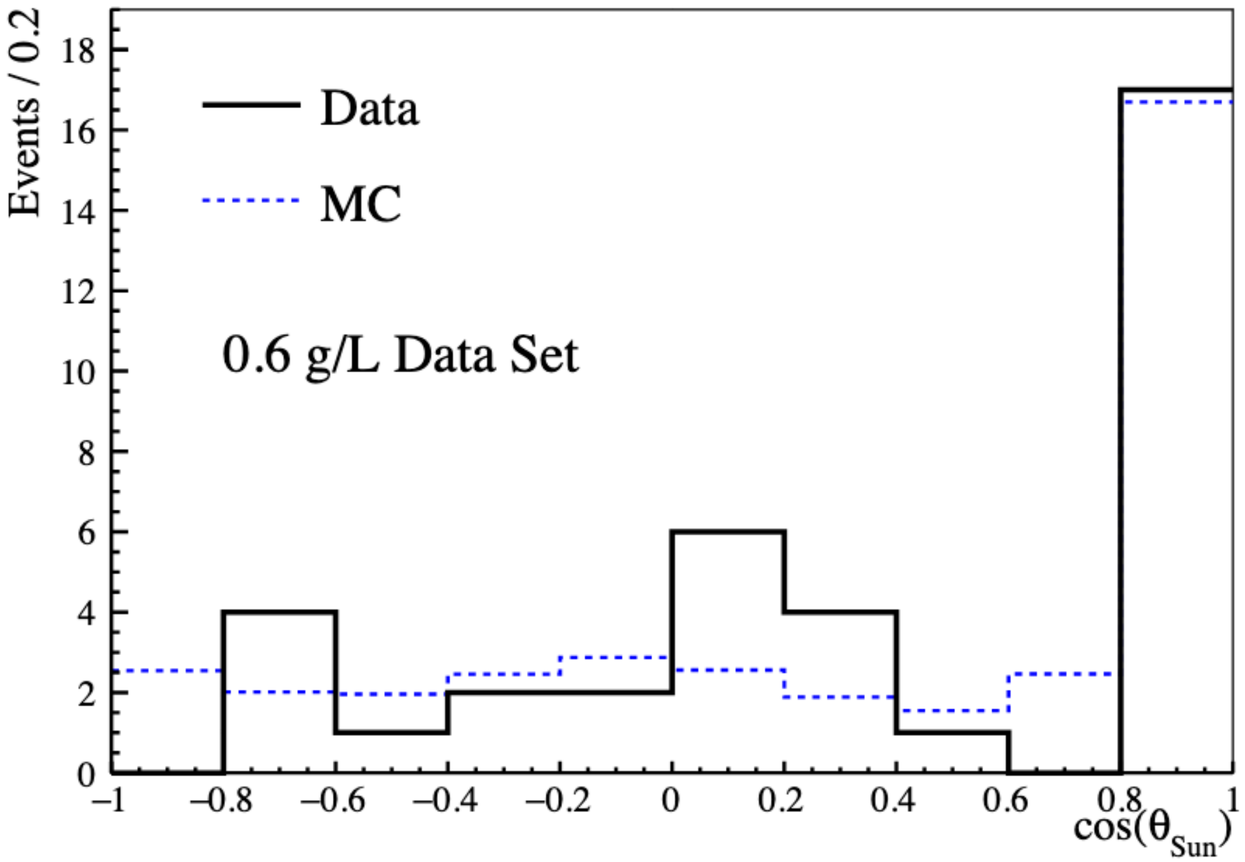


Two independent methods detect $\bar{\nu}_e$ with 3.5σ significance

arXiv 2210.14154 [nucl-ex]

Lowest-energy reactor antineutrinos seen by a water Cherenkov detector

Since April 2021 - full liquid-scintillator detector

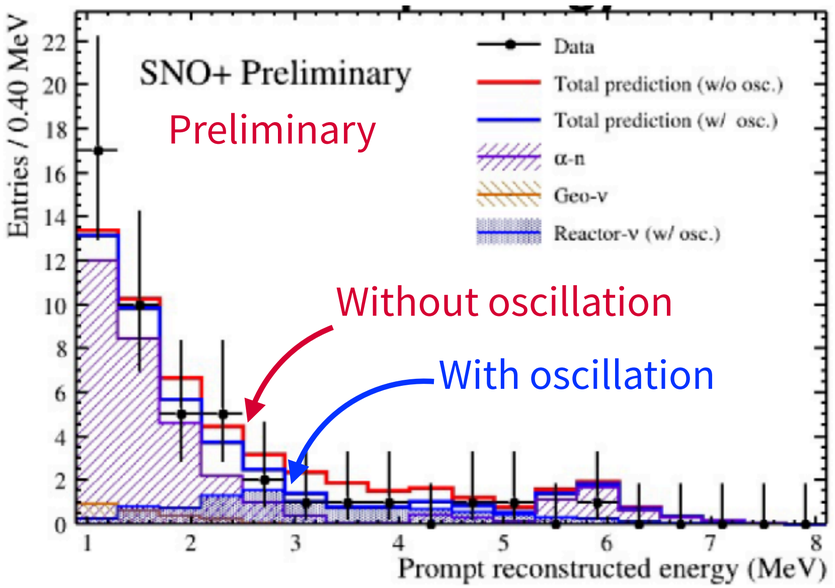


First ever demonstration of event-by-event solar ν directional reconstruction in high light-yield LS

Since April 2021 - full liquid-scintillator detector

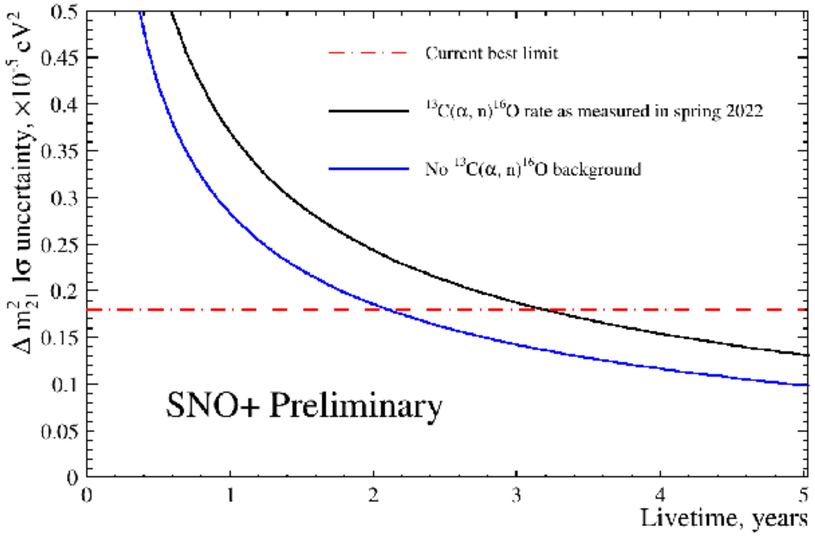
Solar neutrinos

Reactor neutrinos



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

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



Since April 2021 - full liquid-scintillator detector

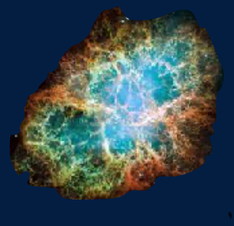
Solar neutrinos

Geo- neutrinos

Up-scattered dark matter

Reactor neutrinos

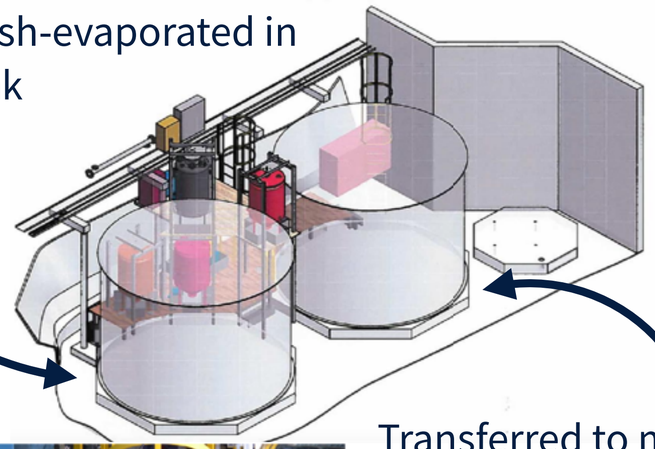
Supernova neutrinos



"Invisible" nucleon decay

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:

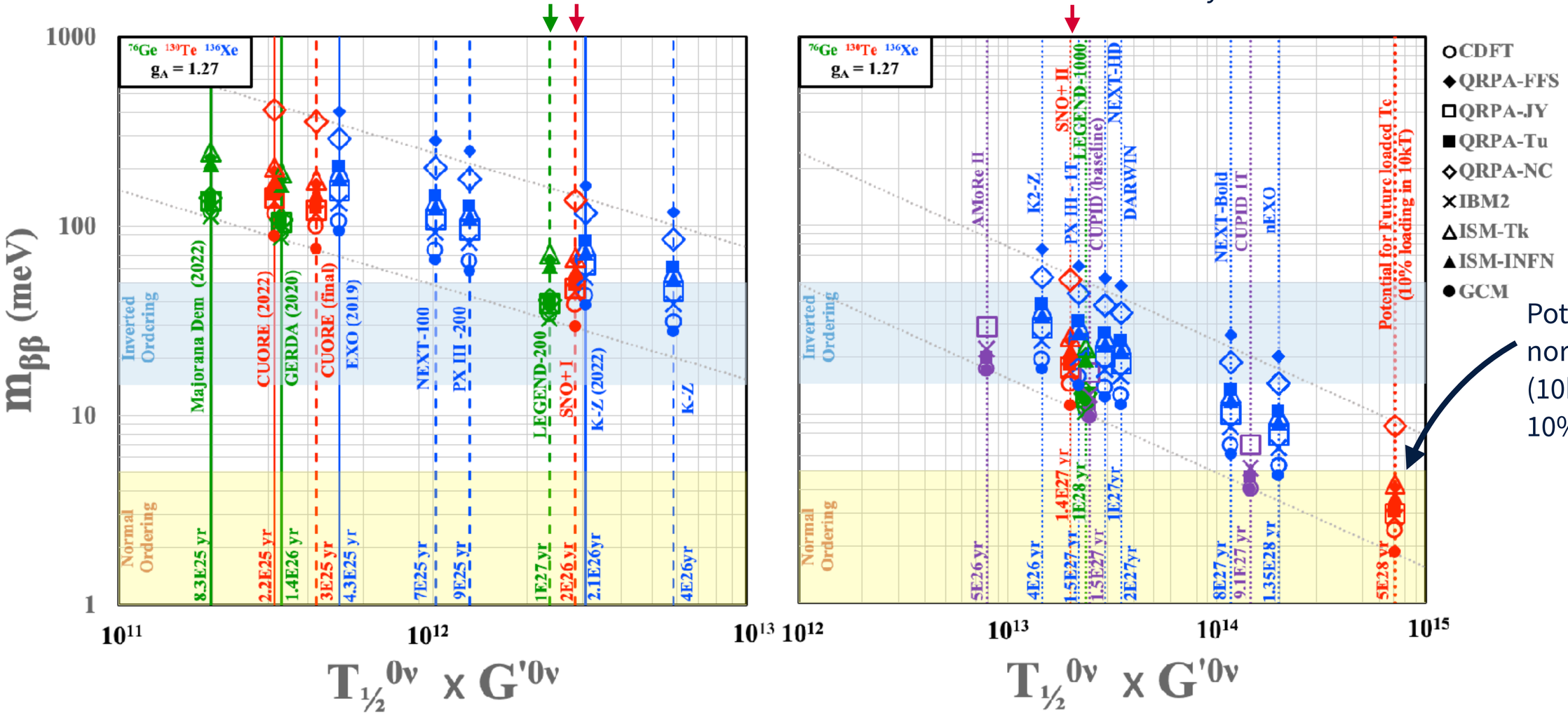
- COVID disruption of supply chains
- Loss of key engineers at SNOLAB
- Extended commissioning & safety review
- Site access limitations

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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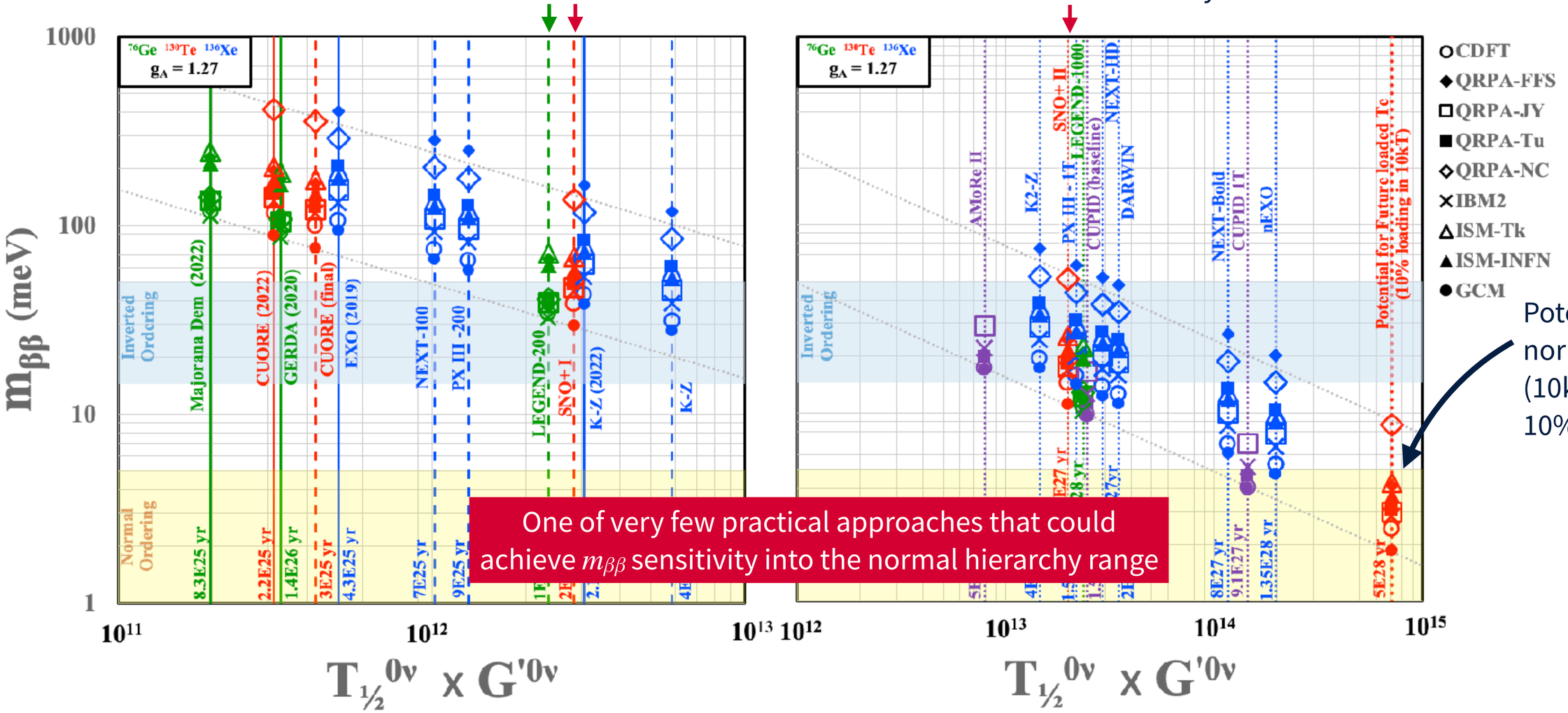
SNO+ II well into inverted hierarchy



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

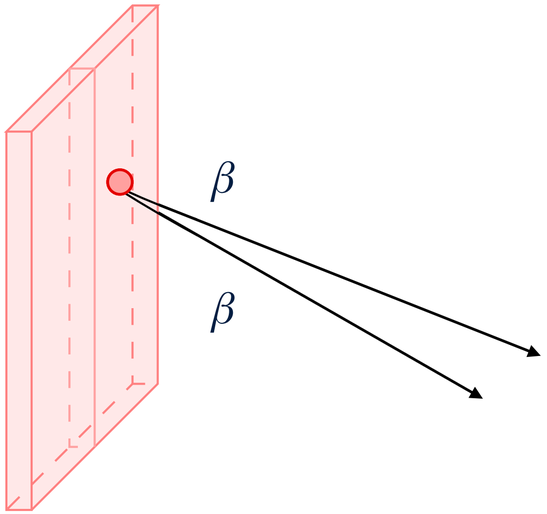
^{82}Se

supernemo collaboration

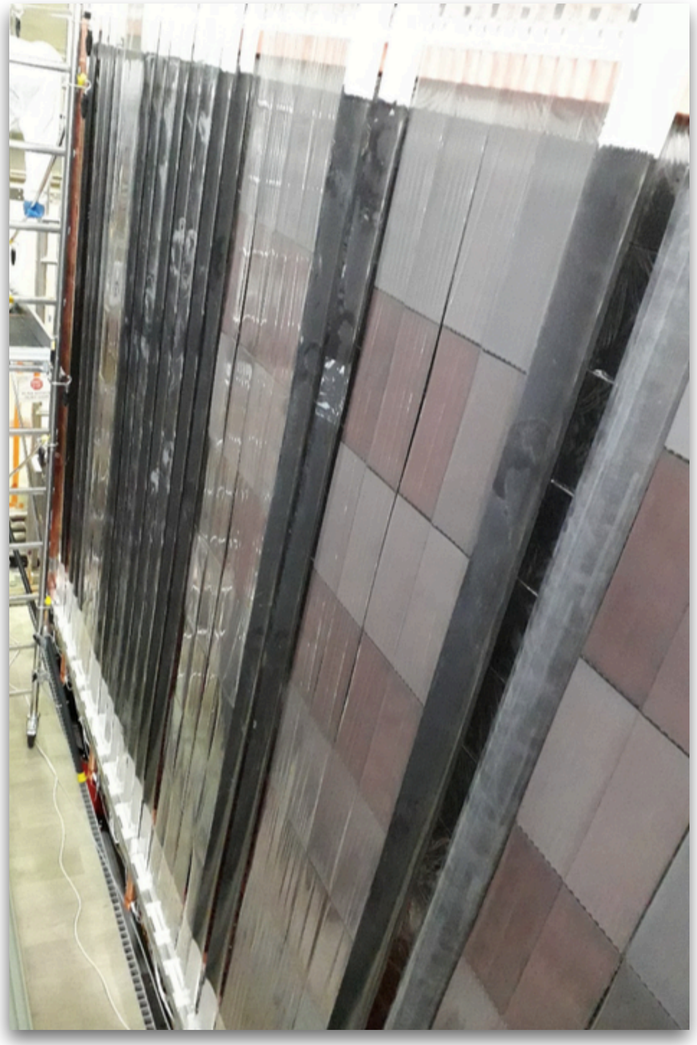
An isotope-agnostic technique to distinguish individual particles, and probe $0\nu\beta\beta$ mechanisms and nuclear effects

The NEMO principle

$\beta\beta$ source



Any solid $\beta\beta$ isotope

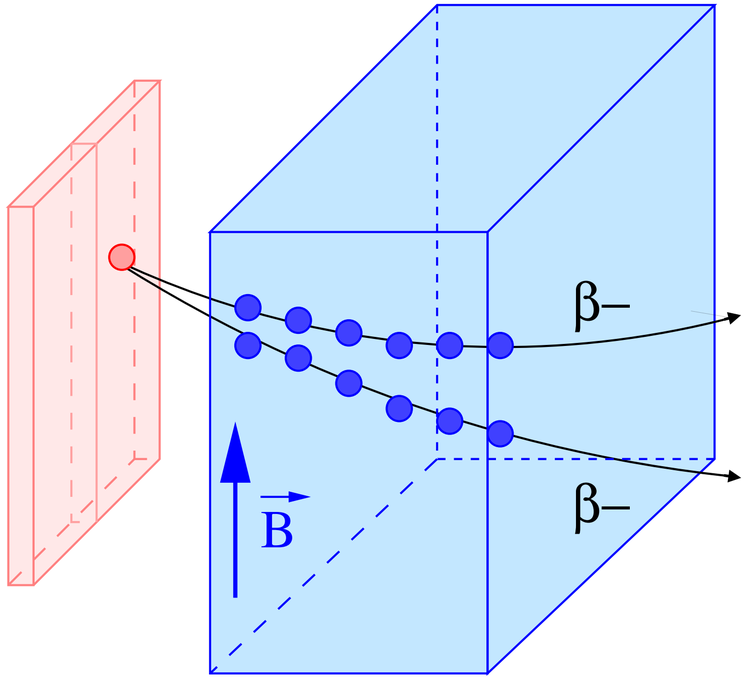


SuperNEMO Demonstrator - 6.23kg ^{82}Se

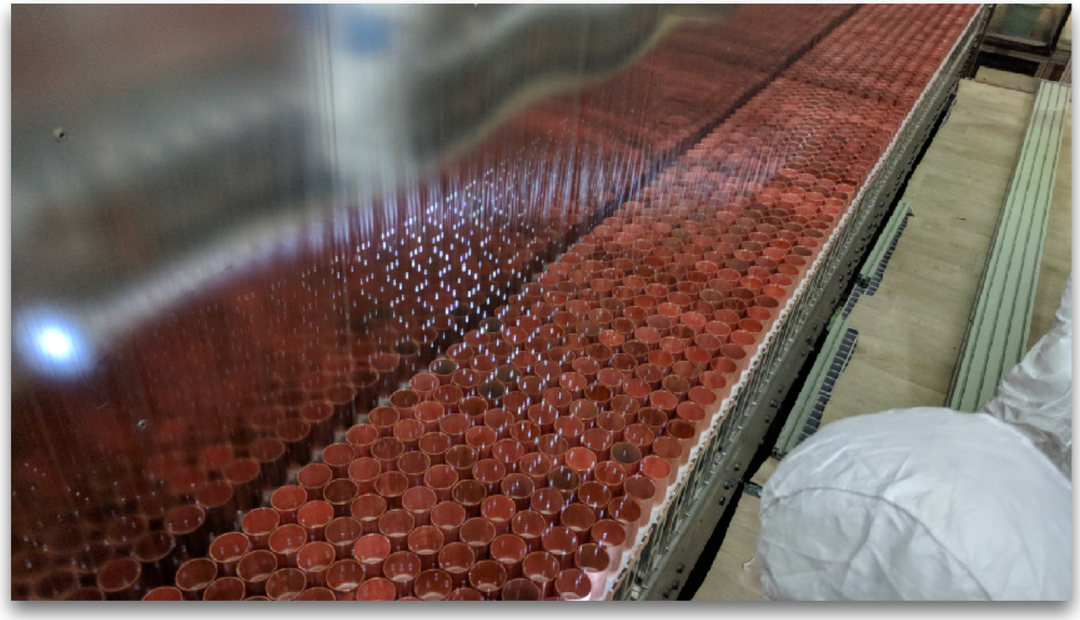
The NEMO principle

$\beta\beta$ source

High-granularity tracker

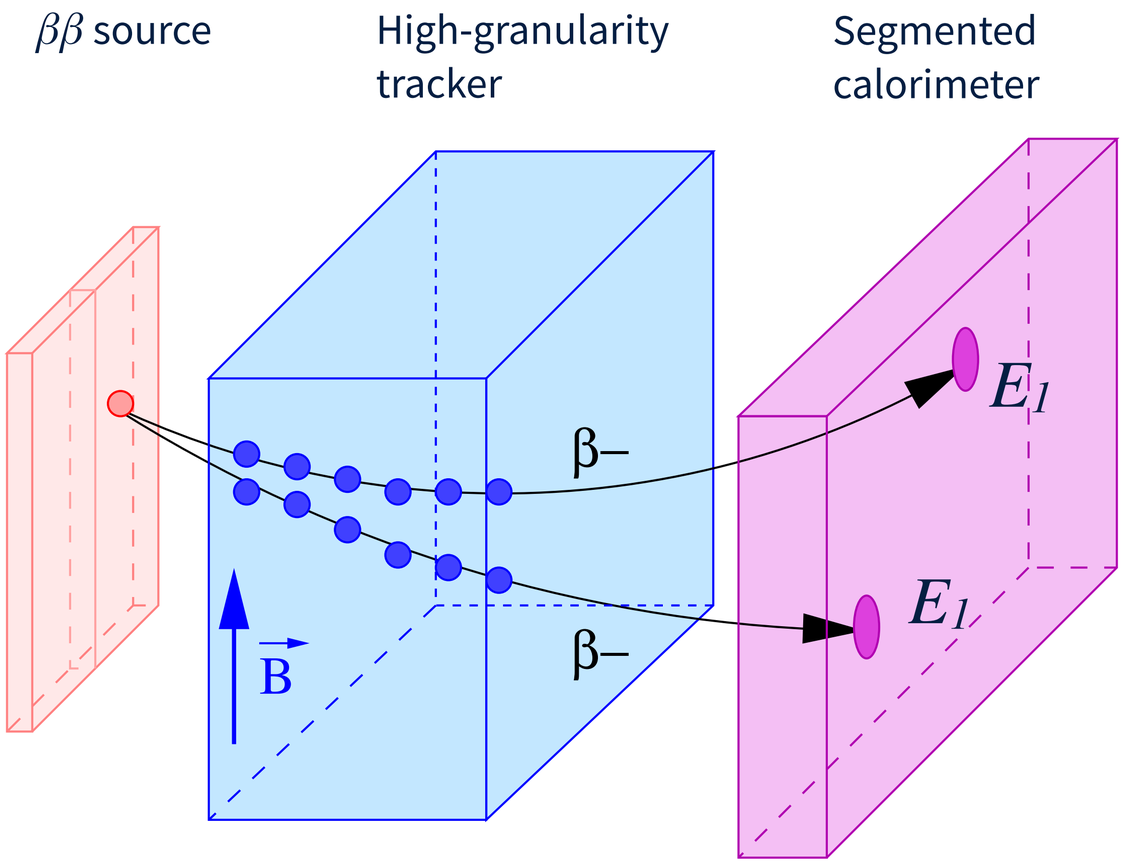


Angle between tracks
+ charge ID

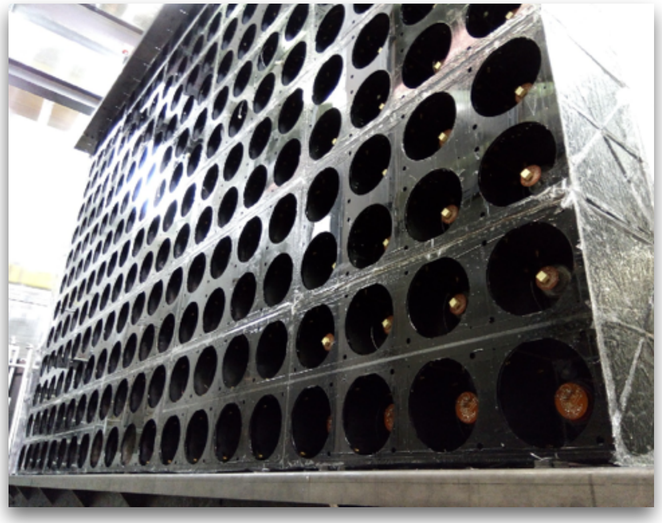


SuperNEMO Demonstrator - 2034 Geiger cells

How SuperNEMO works



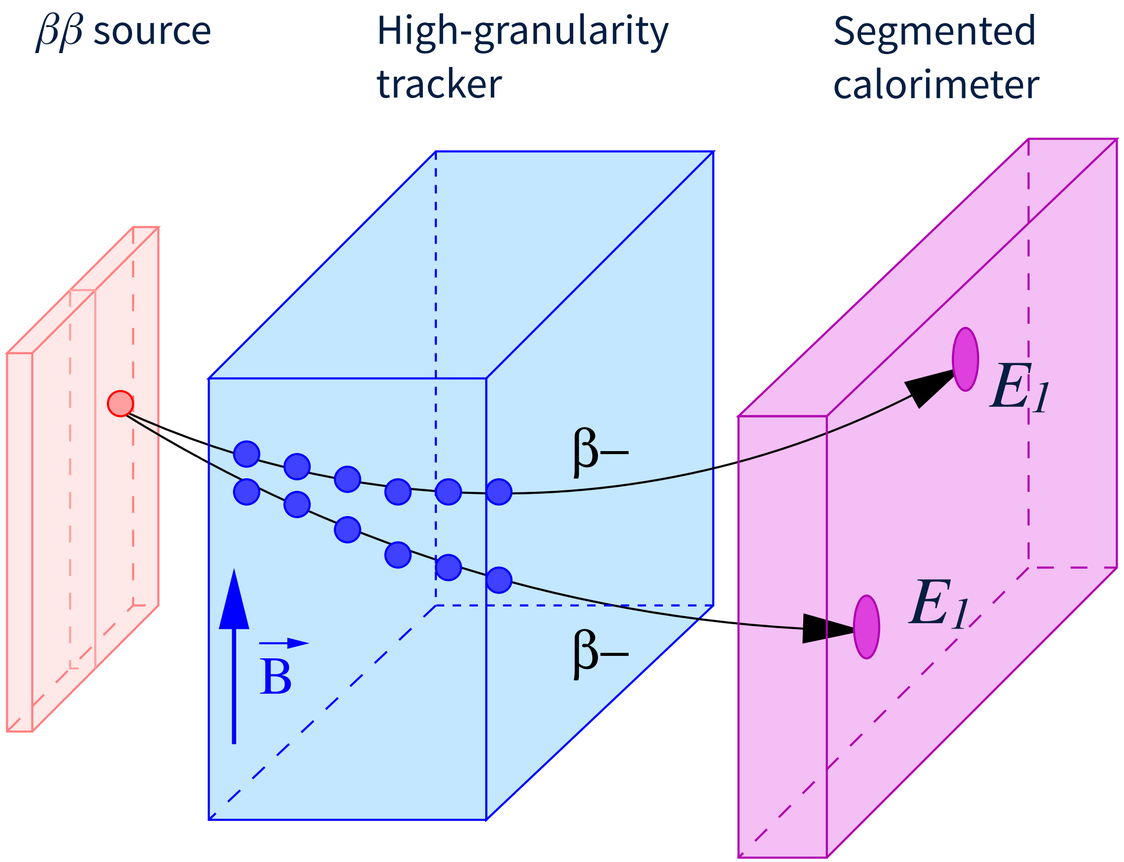
Angle between tracks + charge ID + Individual energies & times

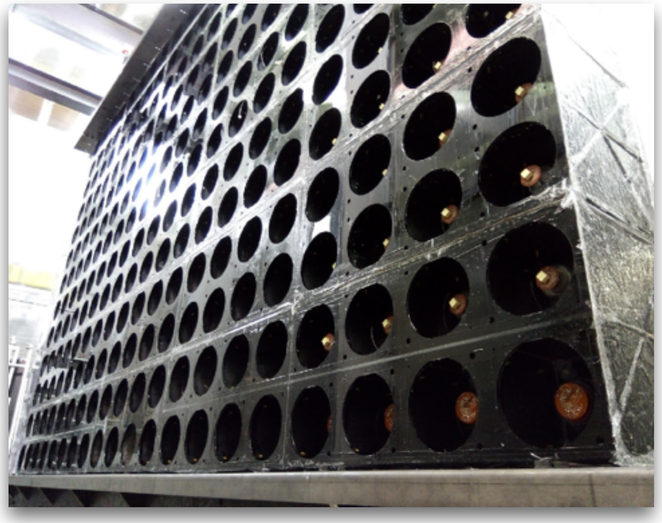


712 optical modules

σ/E 1.8% at 3 MeV

How SuperNEMO works





712 optical modules

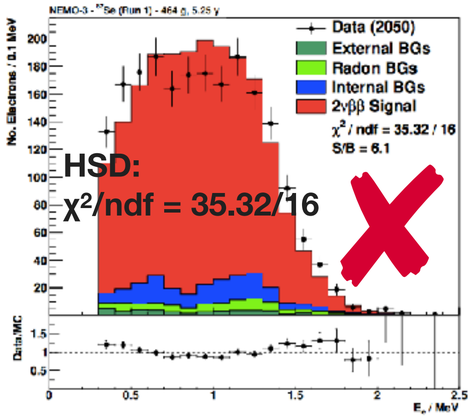
σ/E 1.8% at 3 MeV

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

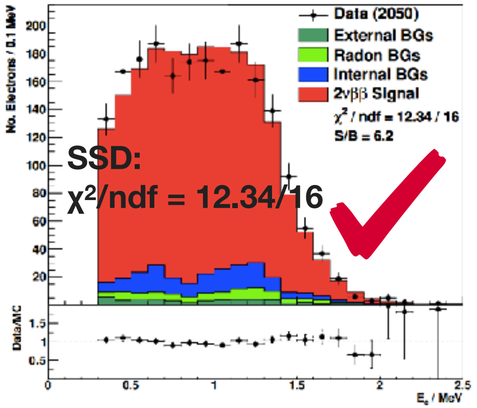
SuperNEMO for nuclear effects with 2νββ

NEMO-3 studied intermediate states

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



Various excited states



Mostly ground state

Individual e^- spectrum identifies intermediate states in 2νββ decay

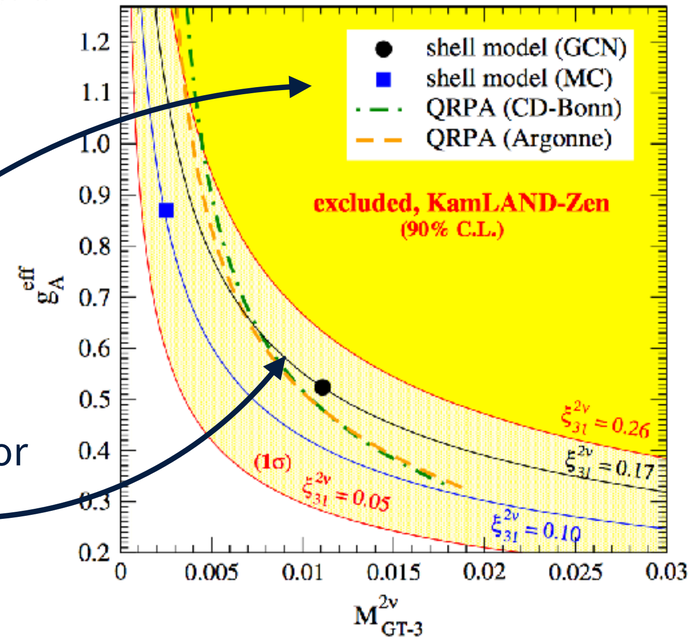
SuperNEMO's improved stats and technology will give 5σ SSD/HSD sensitivity in < 2.5 years

KamLAND-Zen studied g_A quenching

Phys Rev Lett 122, 192501 (2019)

Excluded by KamLAND-Zen

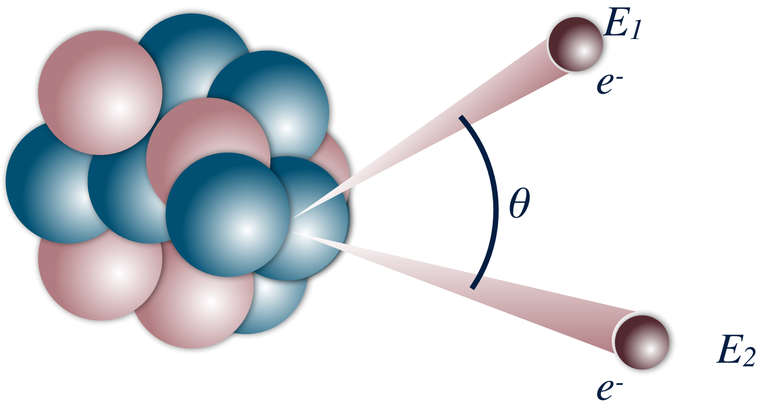
Nuclear models → lines or points in plane



SuperNEMO's individual e^- spectrum is more sensitive than KamLAND-Zen's summed energy spectrum

SuperNEMO is the best technology for reducing nuclear uncertainties in ββ decay

SuperNEMO physics - looking for new physics with 2νββ

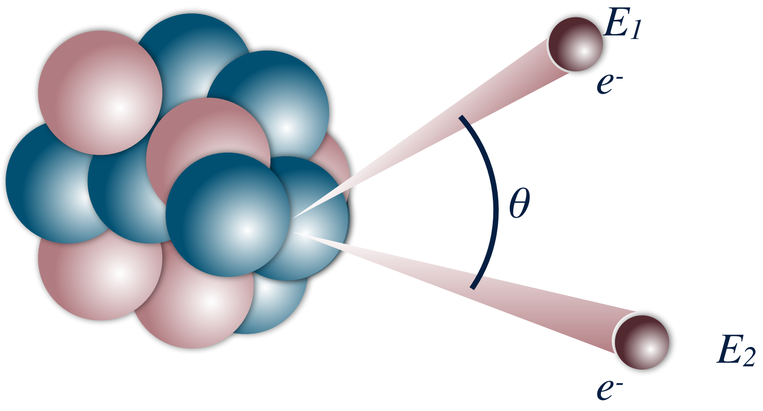


Precision 2νββ measurements can reveal BSM effects…

- Lorentz-invariance violation
- Exotic 0νββ mechanisms
- Right-handed neutrinos (see right)
- Scalar currents…

… and SuperNEMO's topological measurements could also distinguish 0νββ mechanism!

SuperNEMO physics - looking for new physics with 2νββ



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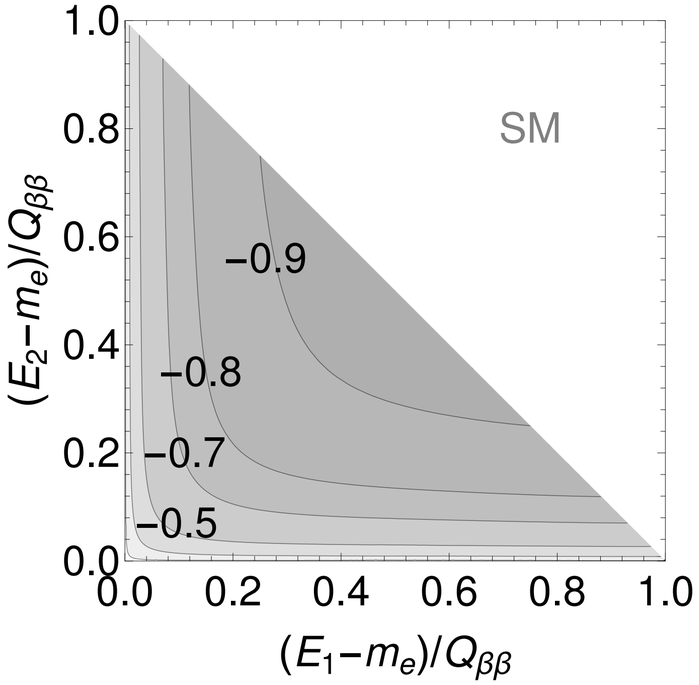
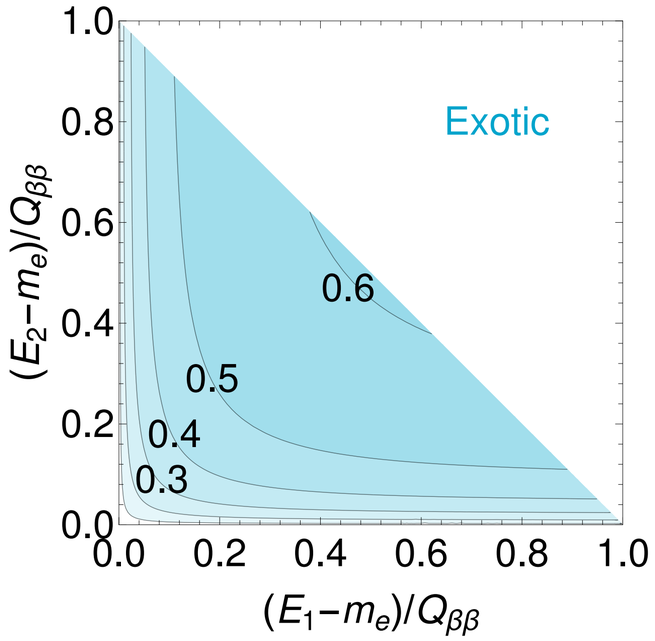
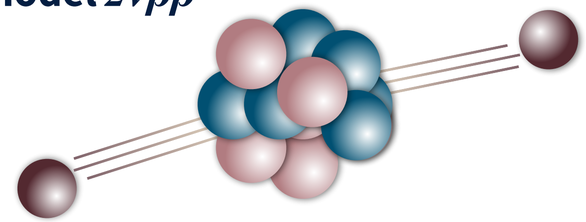
Phys. Rev. Lett. 125, 171801 (2020)

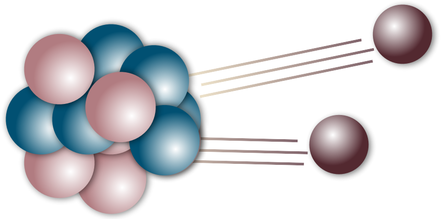




Standard-model *2νββ*

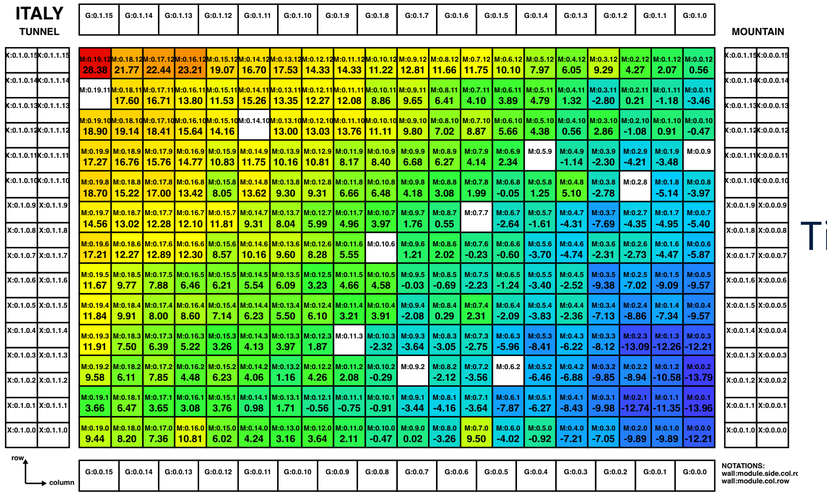


New physics

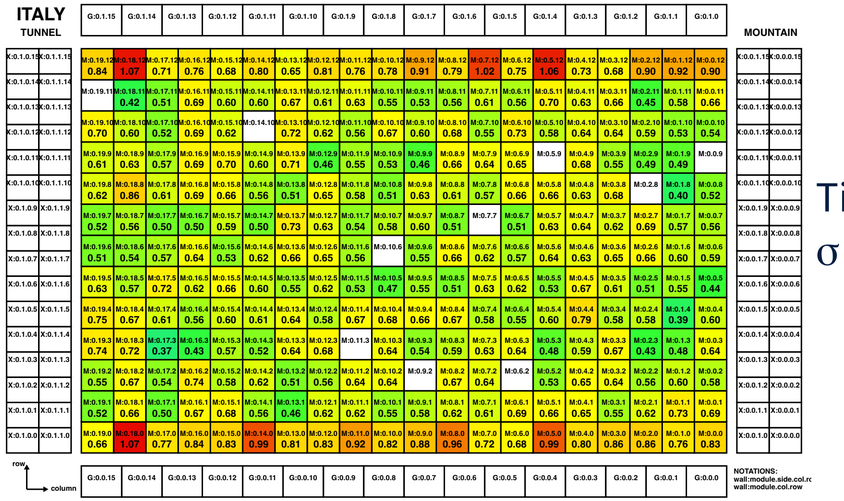


SuperNEMO Demonstrator status: Calorimeter calibration

Timing

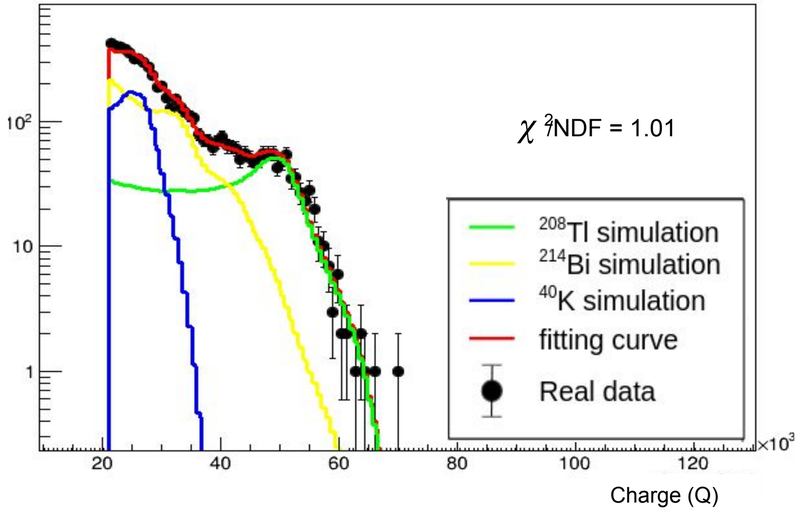


Time-delay calibration

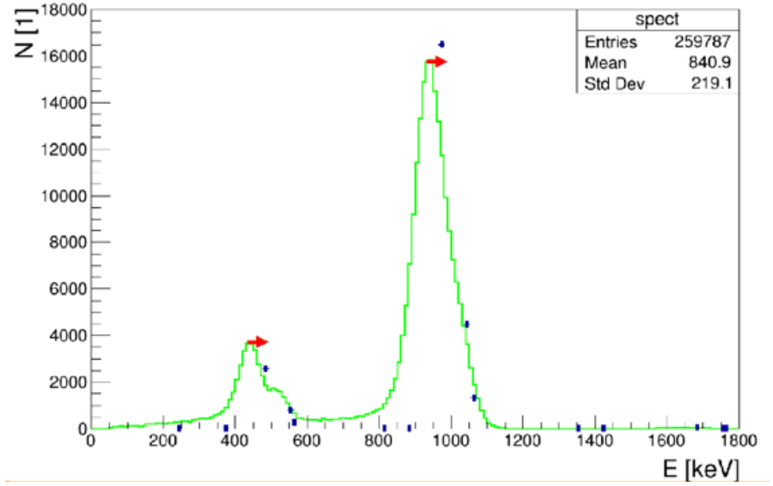


Timing resolution:
σ ~ 0.6ns (at 1 MeV)

Energy calibration

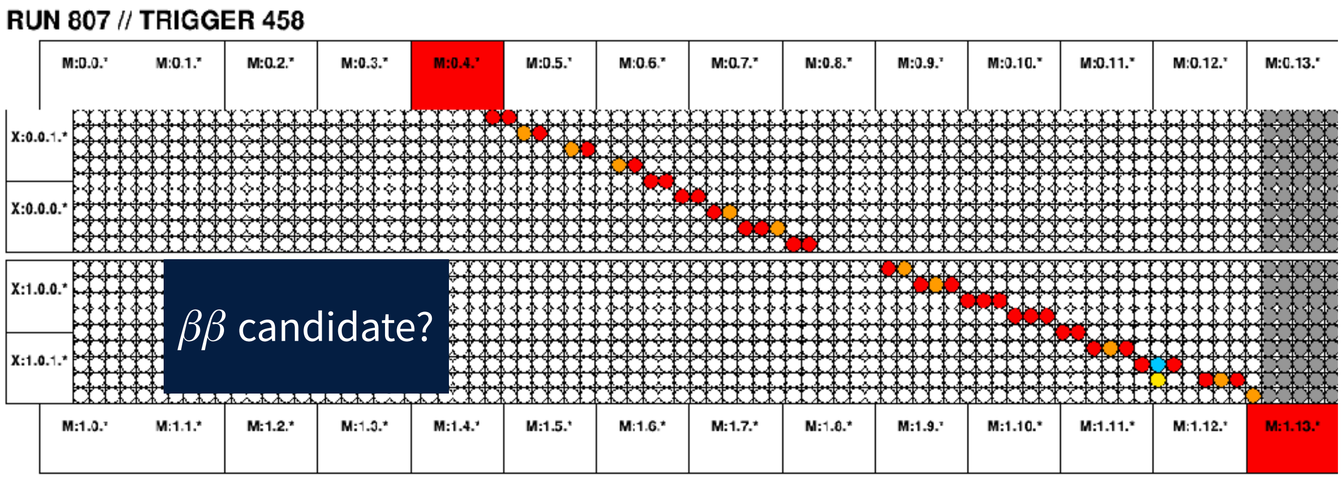


… with ambient sources



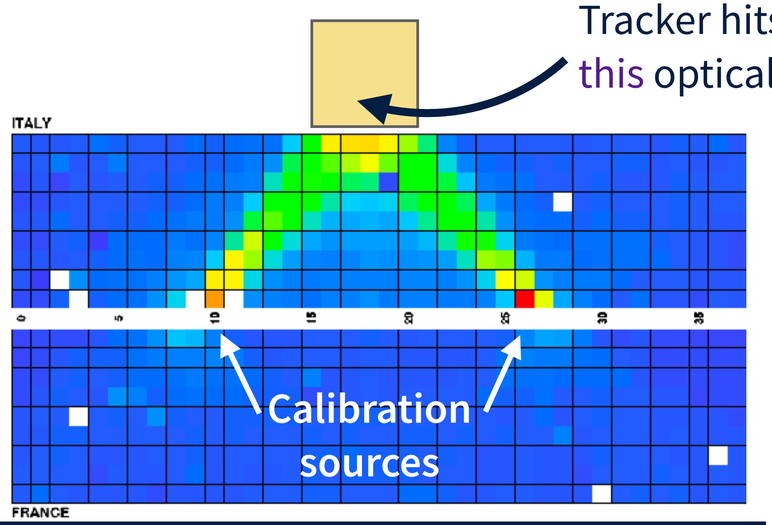
… with our automatic ^{207}Bi source deployment system

SuperNEMO Demonstrator status: Tracker



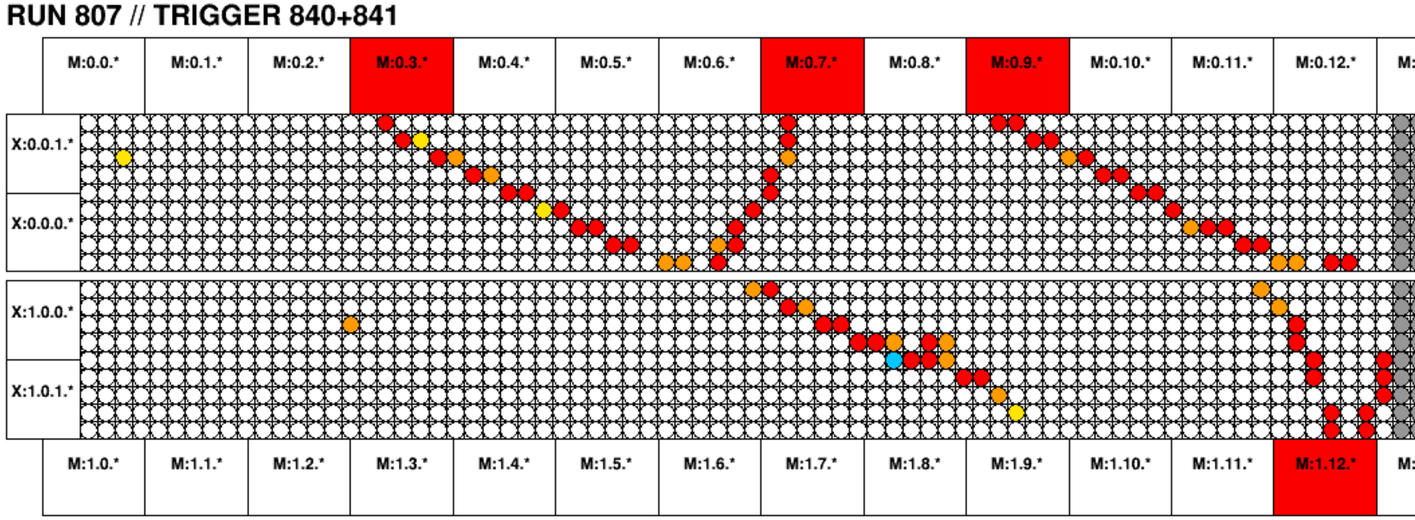
- **Dramatic progress** over the last year after setbacks due to Covid, faulty hardware…
- **Entire tracker successfully tested** at high voltage
- 2/3 of detector undergoing commissioning / calibration
- Final 1/3 currently being connected
- **~99% of connected channels operational**

Tracker hits activating this optical module



Automatic ^{207}Bi calibration system in action

Real tracker-calorimeter data!

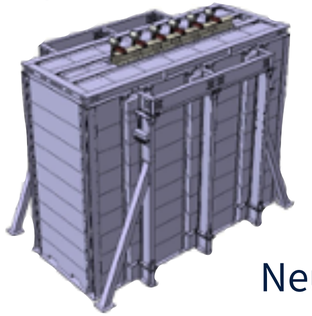


Getting ready for physics data!

2022	2023	2024	2025

Anti-radon tent

γ shielding (iron)



Neutron shield (water/polyethylene)

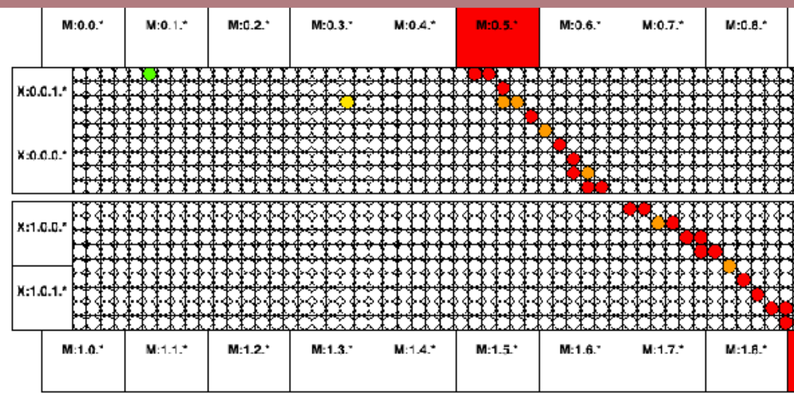
Shielding purchase/installation

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!

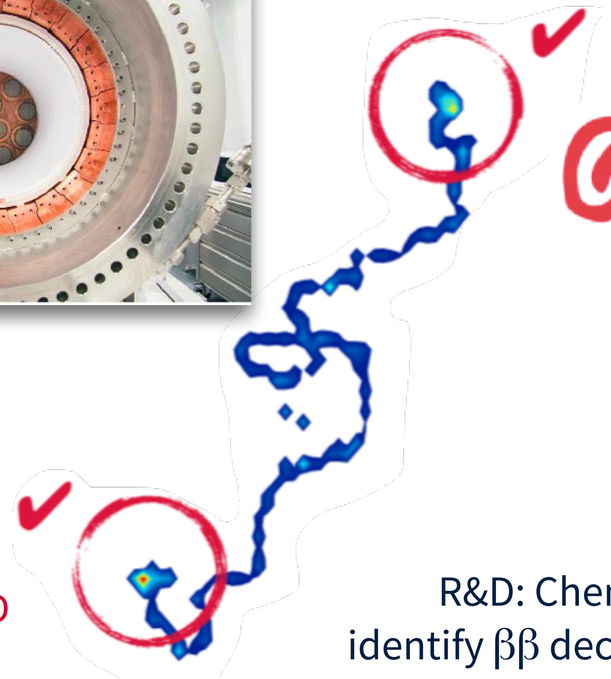


Techniques beyond the UK strategy

^{136}Xe time-projection chambers

EXO (USA) PANDA-X (China)

+ dark-matter detectors (LZ, DARWIN, XENON…?)



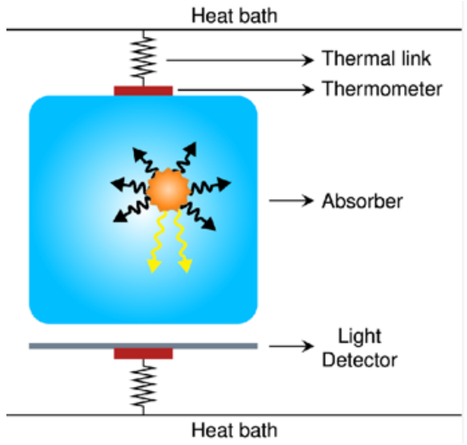
Individual electron ID

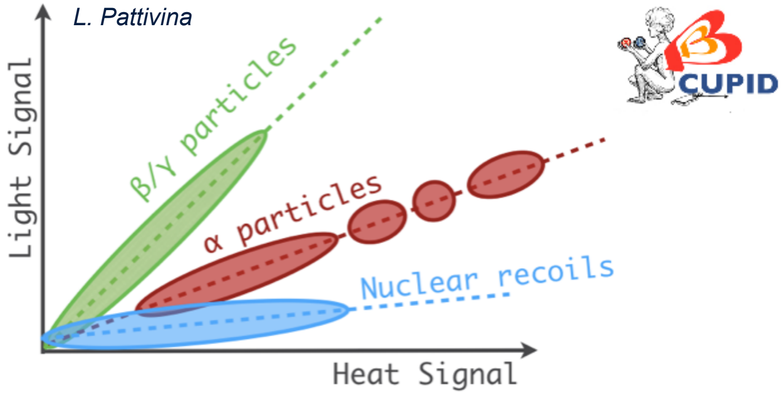
next (Spain)

MANCHESTER 1824 The University of Manchester

R&D: Chemical tagging to identify ββ decay product Ba^{2+}

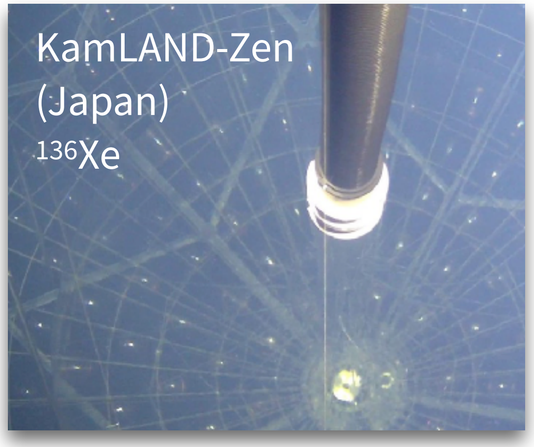
Scintillating bolometers (CUPID)





Ultra-cold Li_2MoO_4 crystal produces heat and light when ^{100}Mo decays

Liquid scintillator + ?



Neutrinoless double-beta decay:

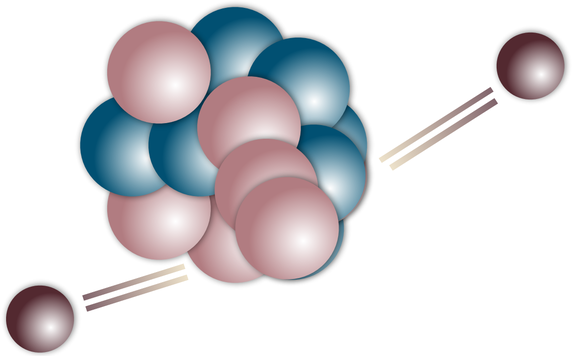
What?

Where from?

Where to?

Neutrinoless double-beta decay:

What?



Never-seen nuclear decay that creates matter without antimatter

Where from?

Where to?

Neutrinoless double-beta decay:

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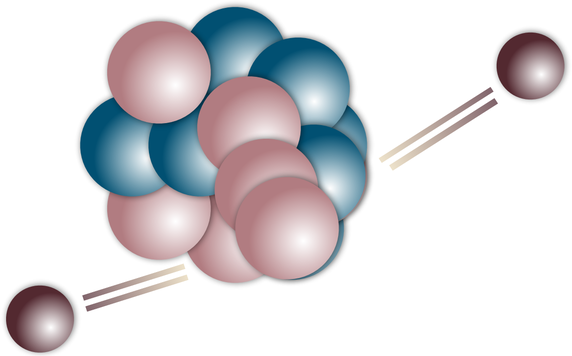

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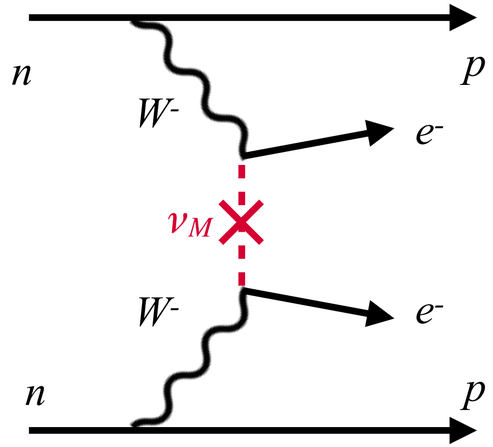
If neutrinos are Majorana fermions (ν = ν̄)



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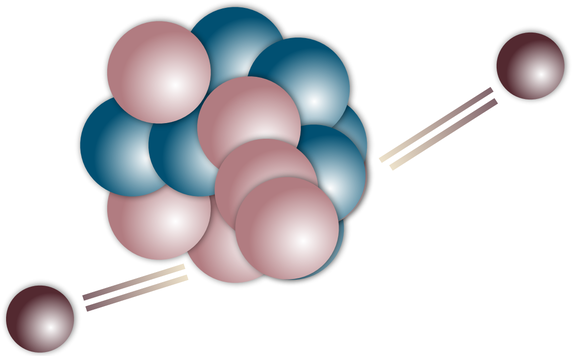

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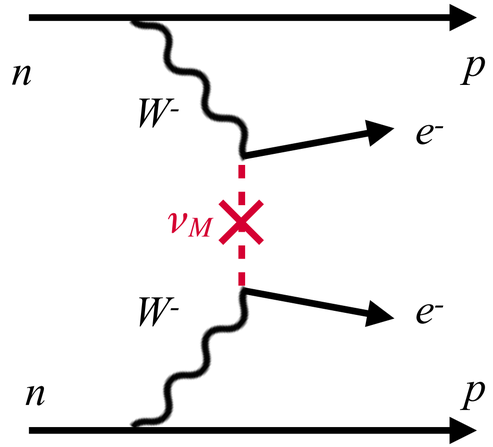
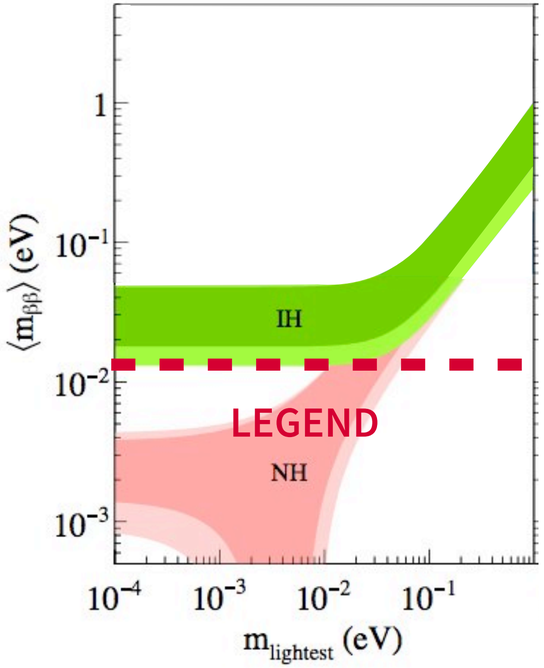


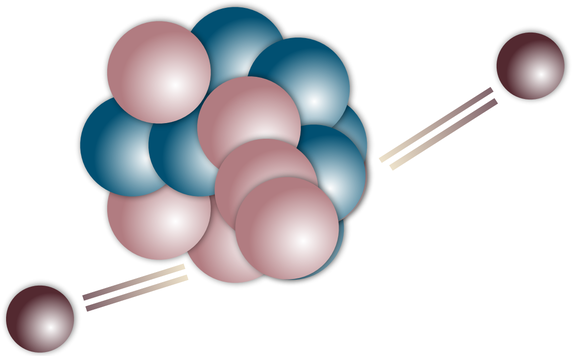
Where to?

Full inverted-hierarchy discovery power with LEGEND



Neutrinoless double-beta decay:

What?



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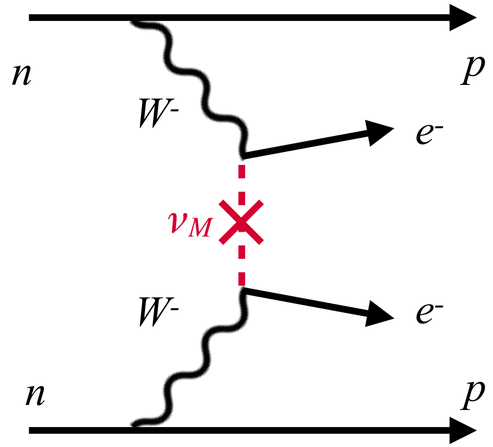

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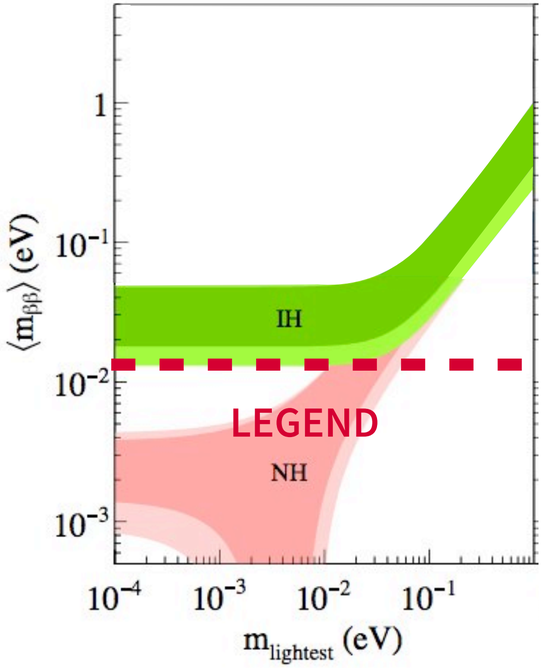
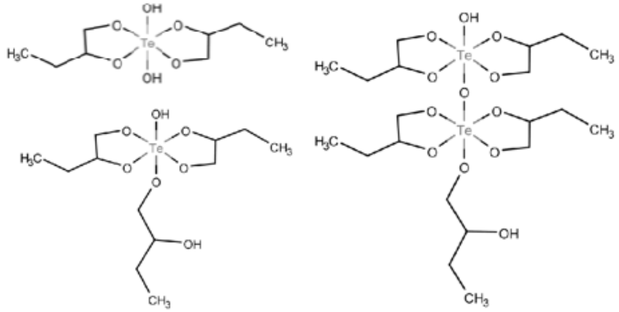
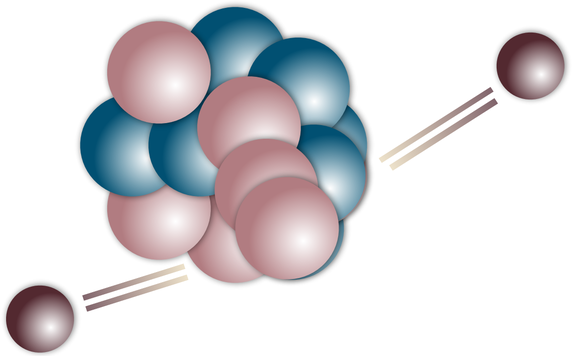




Towards even lower masses with novel techniques from SNO+

Neutrinoless double-beta decay:

What?



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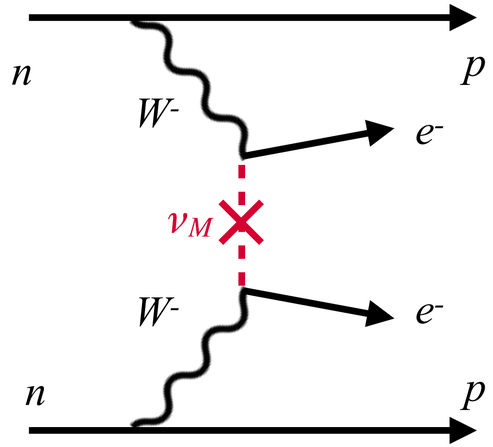

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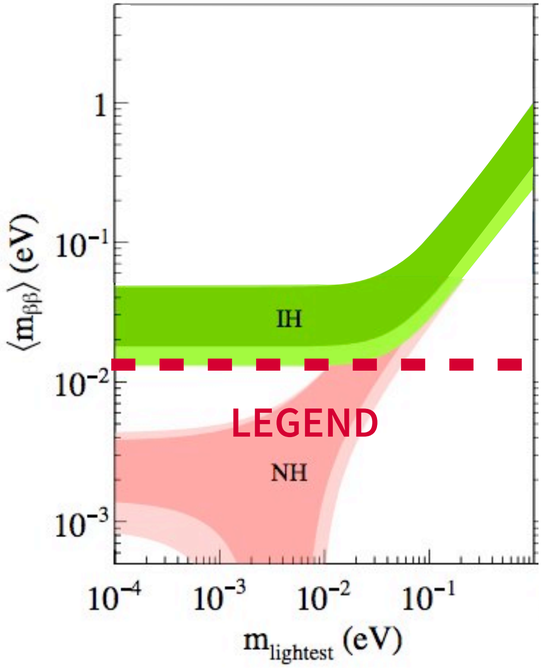

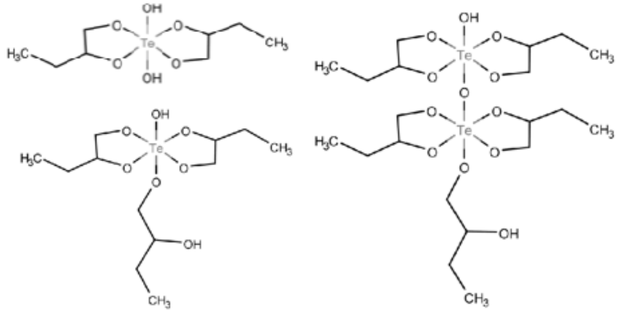

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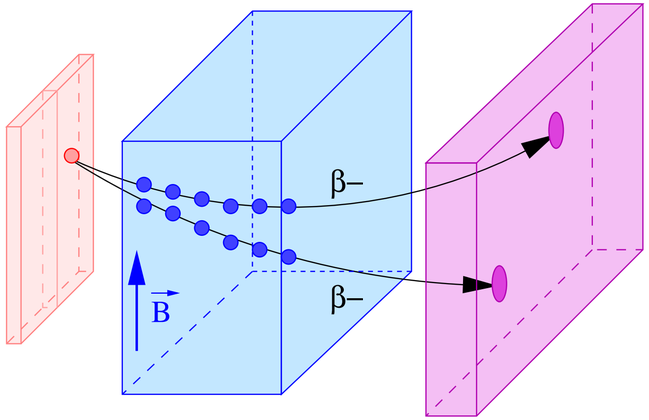
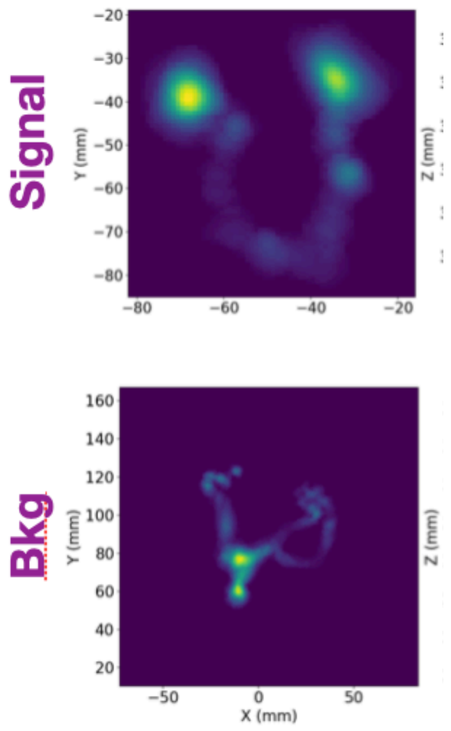


Understanding nuclear effects and $\beta\beta$ decay mechanisms with SuperNEMO collaboration

Backup slides

NEXT high-pressure gaseous ^{136}Xe TPC

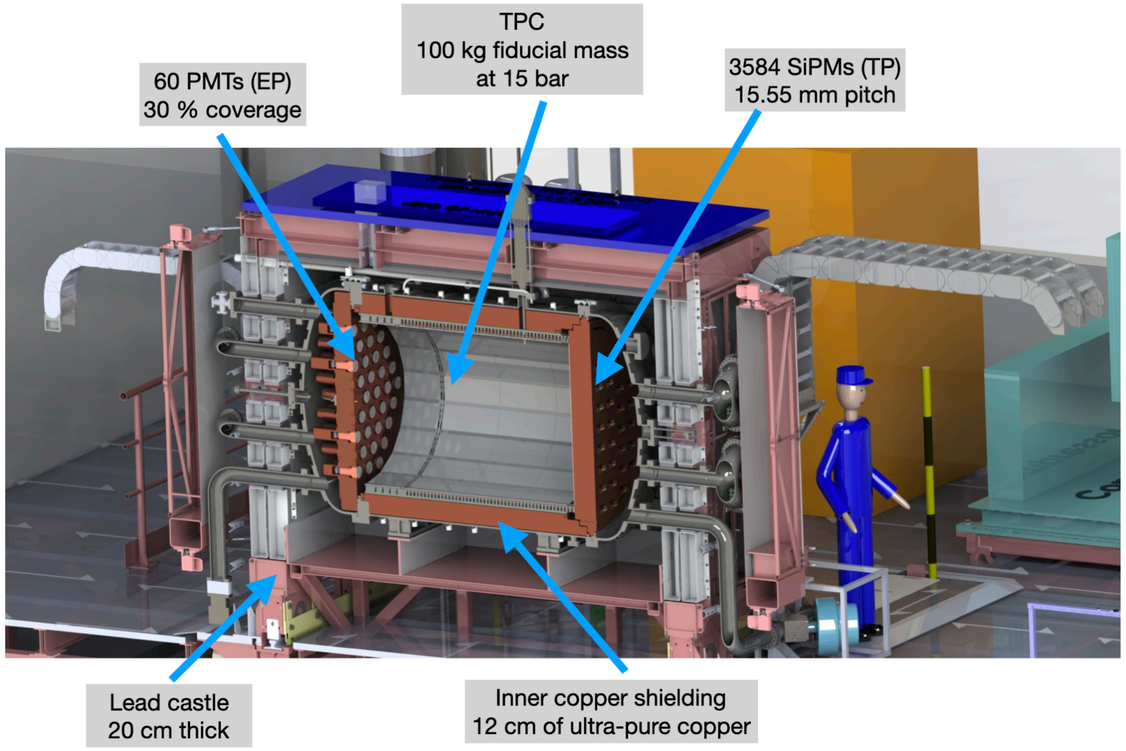
Topological Identification



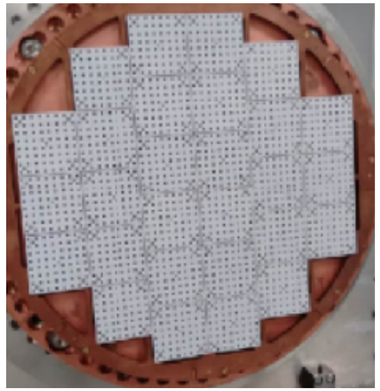
NEXT Collaboration, JHEP 01 (2021) 189

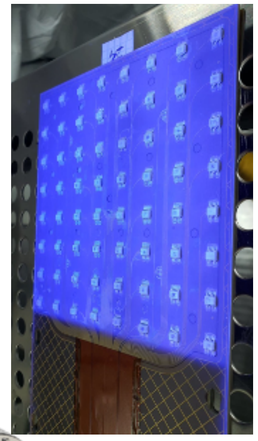
NEXT Collaboration, JHEP 10 (2019) 052

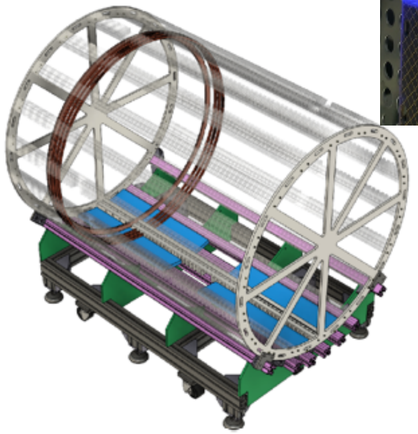
NEXT-100 (2022-2025) proves scalability



R&D on new tracking and energy plane with SiPMs



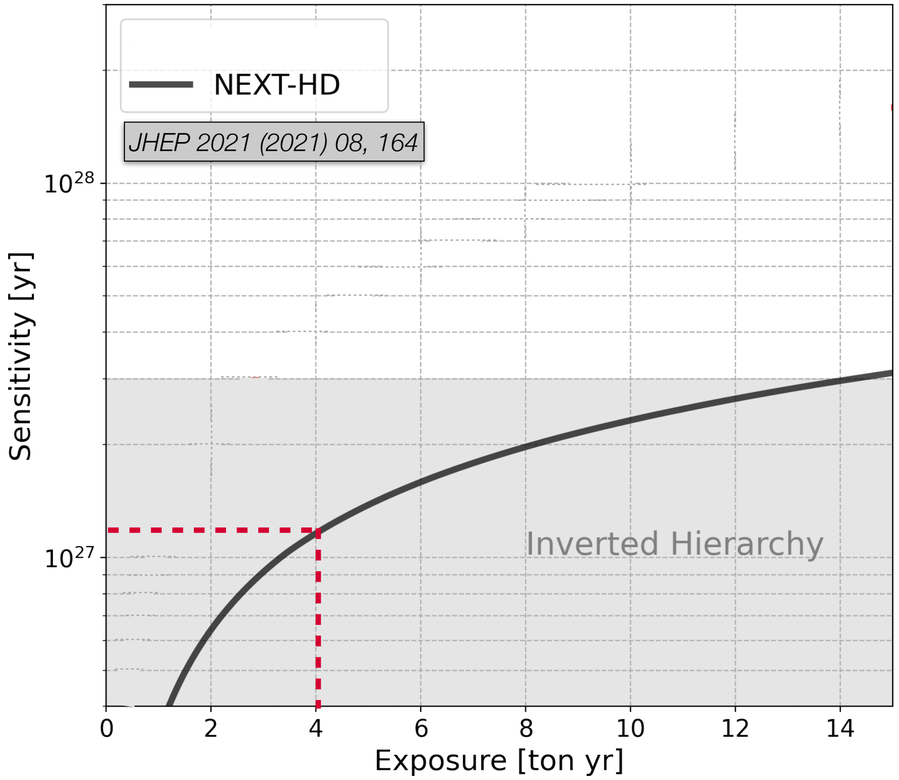




TPC installation UK-led

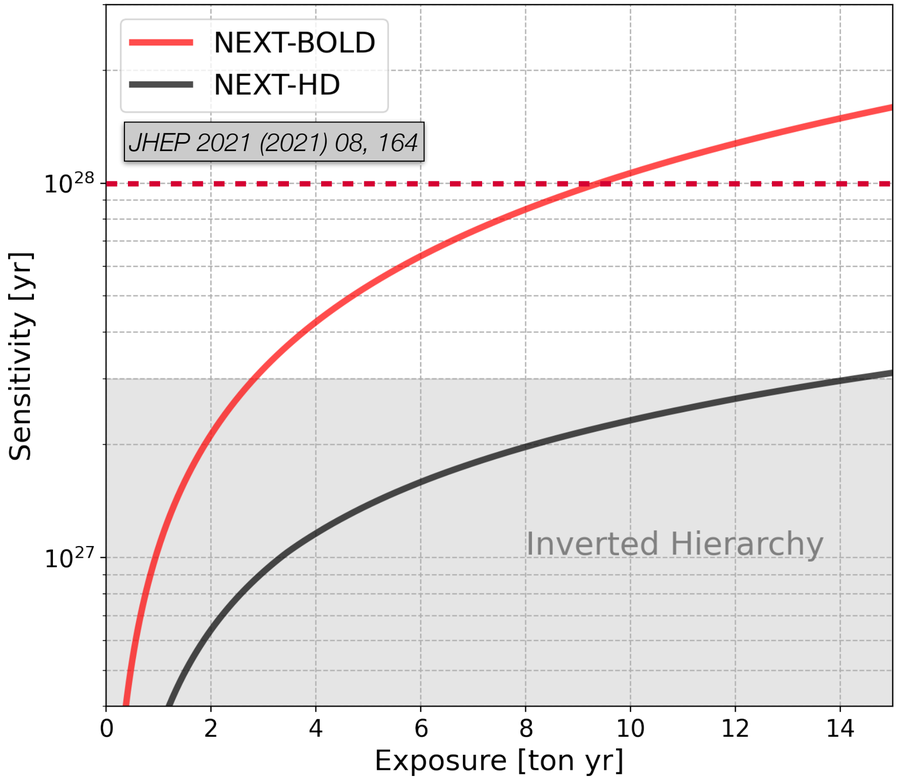
NEXT ton-scale and beyond

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



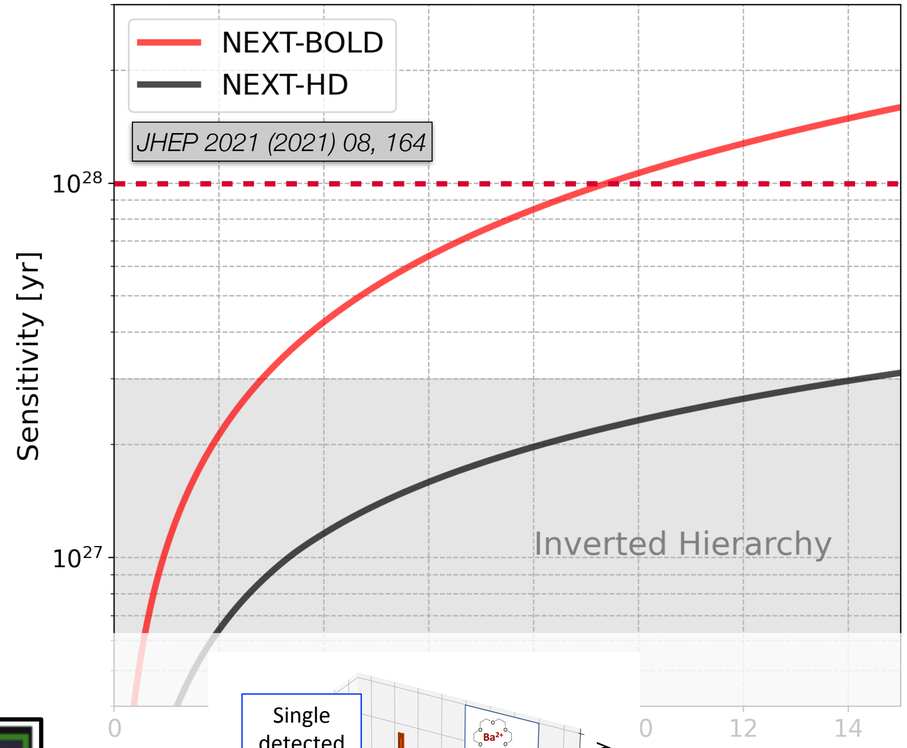
NEXT ton-scale and beyond

- NEXT-HD's first module can reach $T_{½}$ > **10^{27} yr** $0\nu\beta\beta$ sensitivity with **4 ton.yr** exposure
- NEXT-BOLD: seeks 10^{28}-year sensitivity through **barium tagging technology**



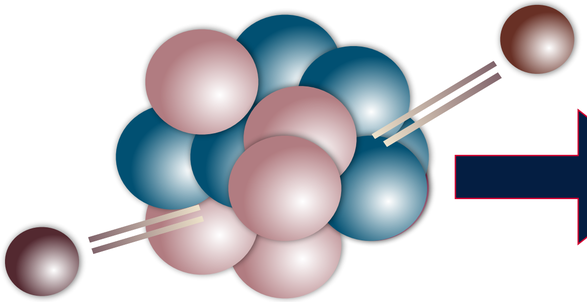
NEXT ton-scale and beyond

- 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**

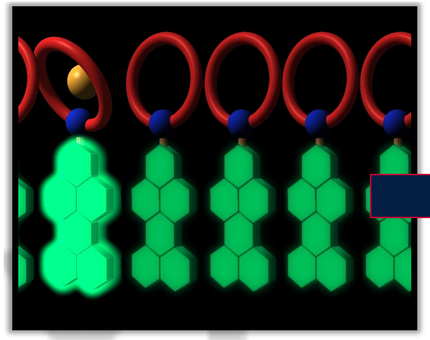


J. Phys.Conf.Ser 650 (2015) 1, 012002;
JINST 11 (2016) 12, P12011;
Phys.Rev.Lett 120 (2018) 13 132504;
Sci.Rep. 9 (2019) 1, 15097;
Nature 583 (2020) 7814 48-54;
ACS Sens. (2021) 6, 1, 192-202;
arXiv:2201.09099;
arXiv:2109.05902

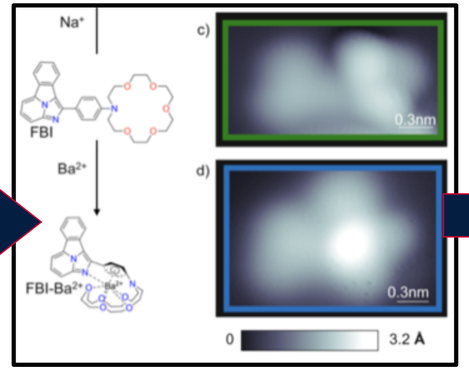
Ba^{2+} $\beta\beta$ decay product

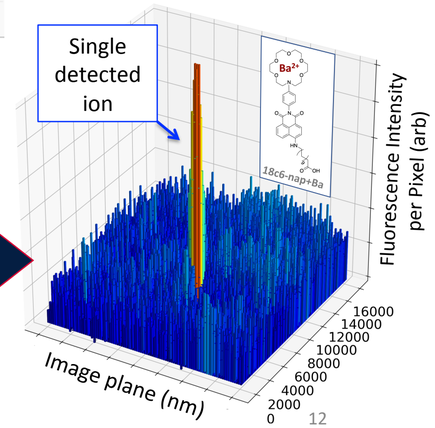


Ba^{2+} chelation



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…