Searching for the Creation of Matter (Without Antimatter!) in the Laboratory

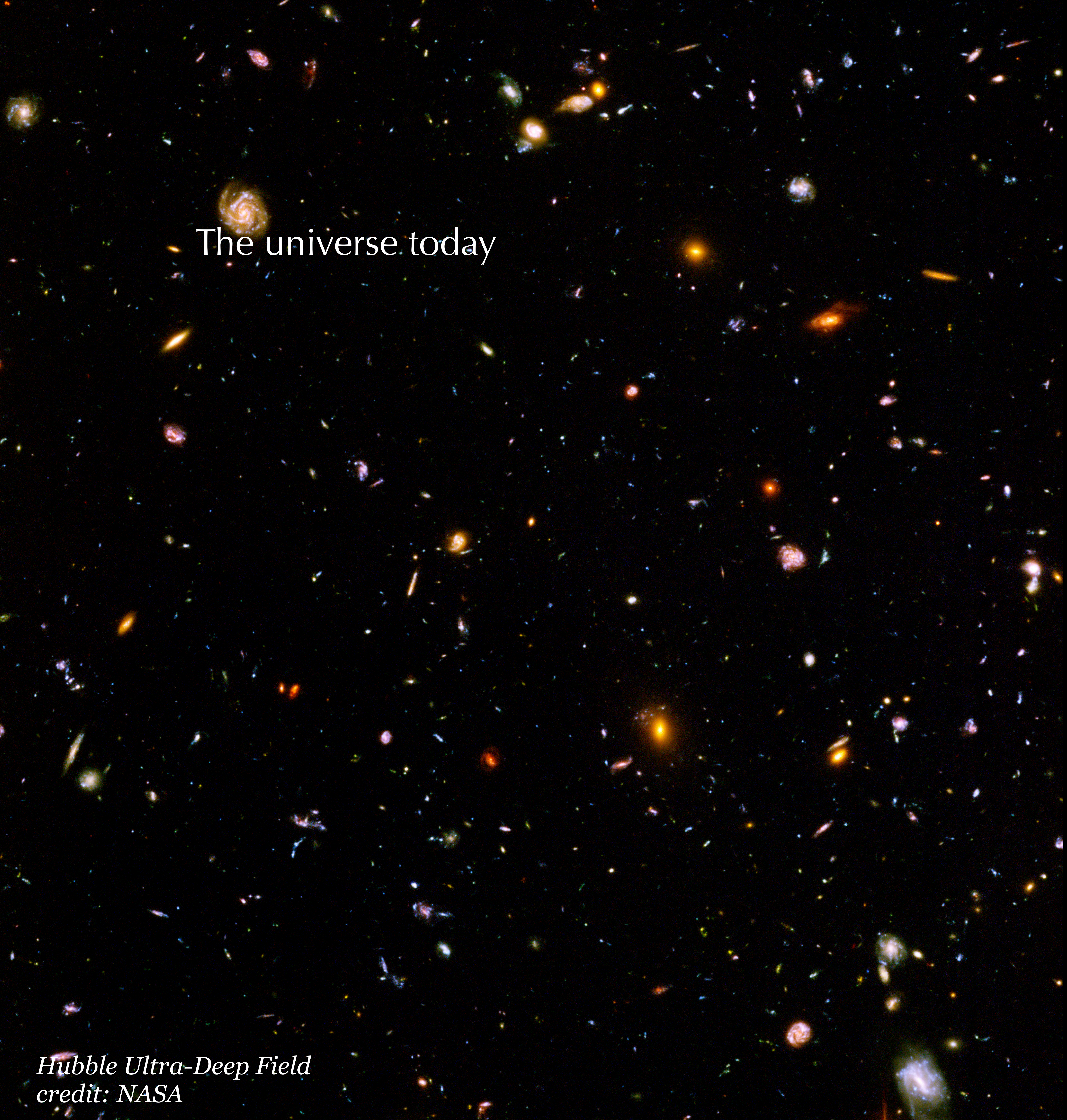
Jason Detwiler, University of Washington
BNL Physics Colloquium, 21 March 2023

Outline

- Introduction: a Creator's cookbook
- The global hunt for a "Little Bang"
- Searching for 0νββ decay in CUPID, nEXO, and LEGEND

Hubble Ultra-Deep Field
credit: NASA

The Bullet Cluster
credit: NASA



Hubble Ultra-Deep Field
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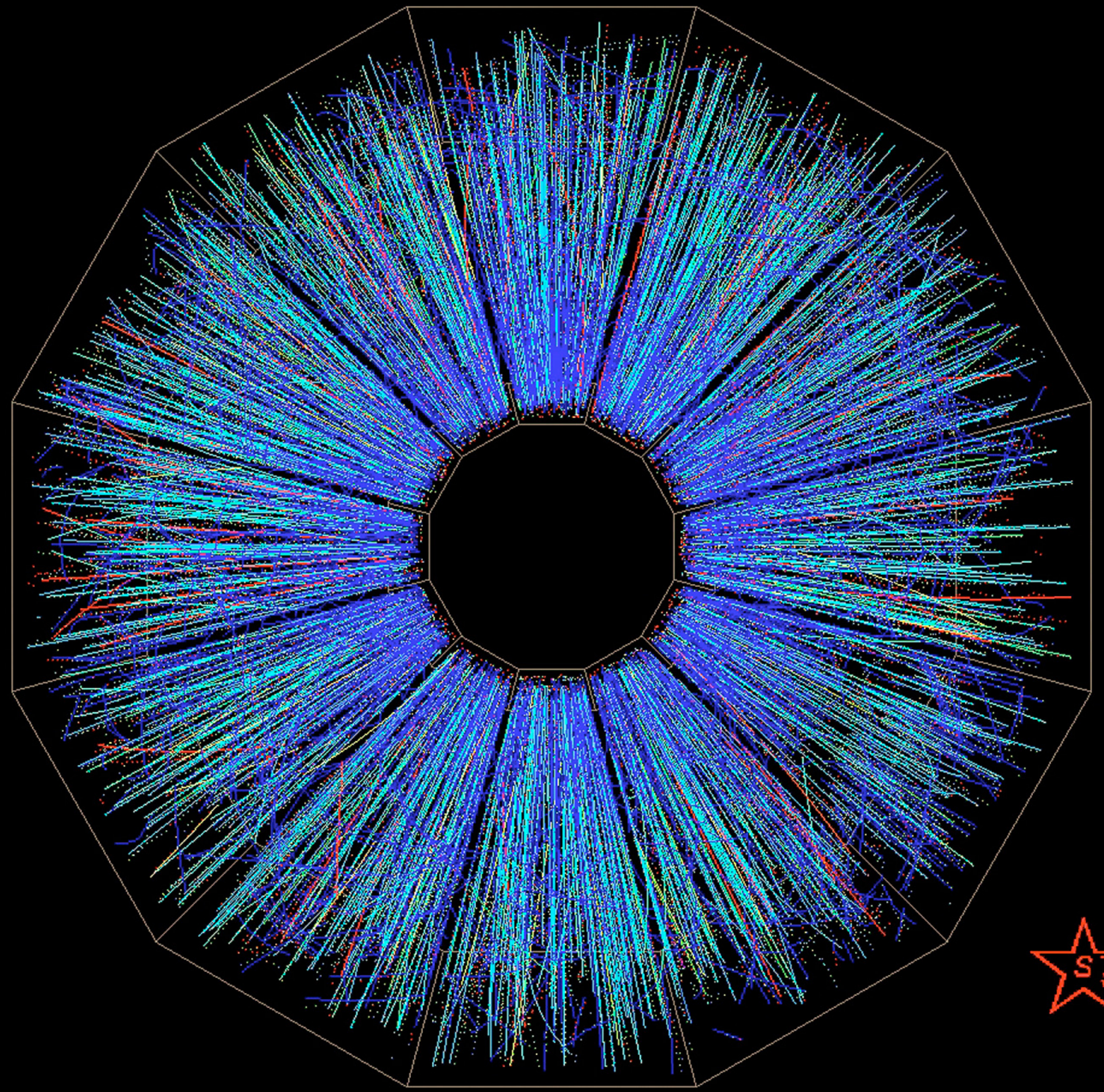
The universe
~0.00001 seconds
after the Big Bang

Temperature:
4,000,000,000,000 K



Matter and antimatter are
always created in pairs.

Pb-Pb collisions in STAR at RHIC
credit: Brookhaven National Lab

Hubble Ultra-Deep Field
credit: NASA

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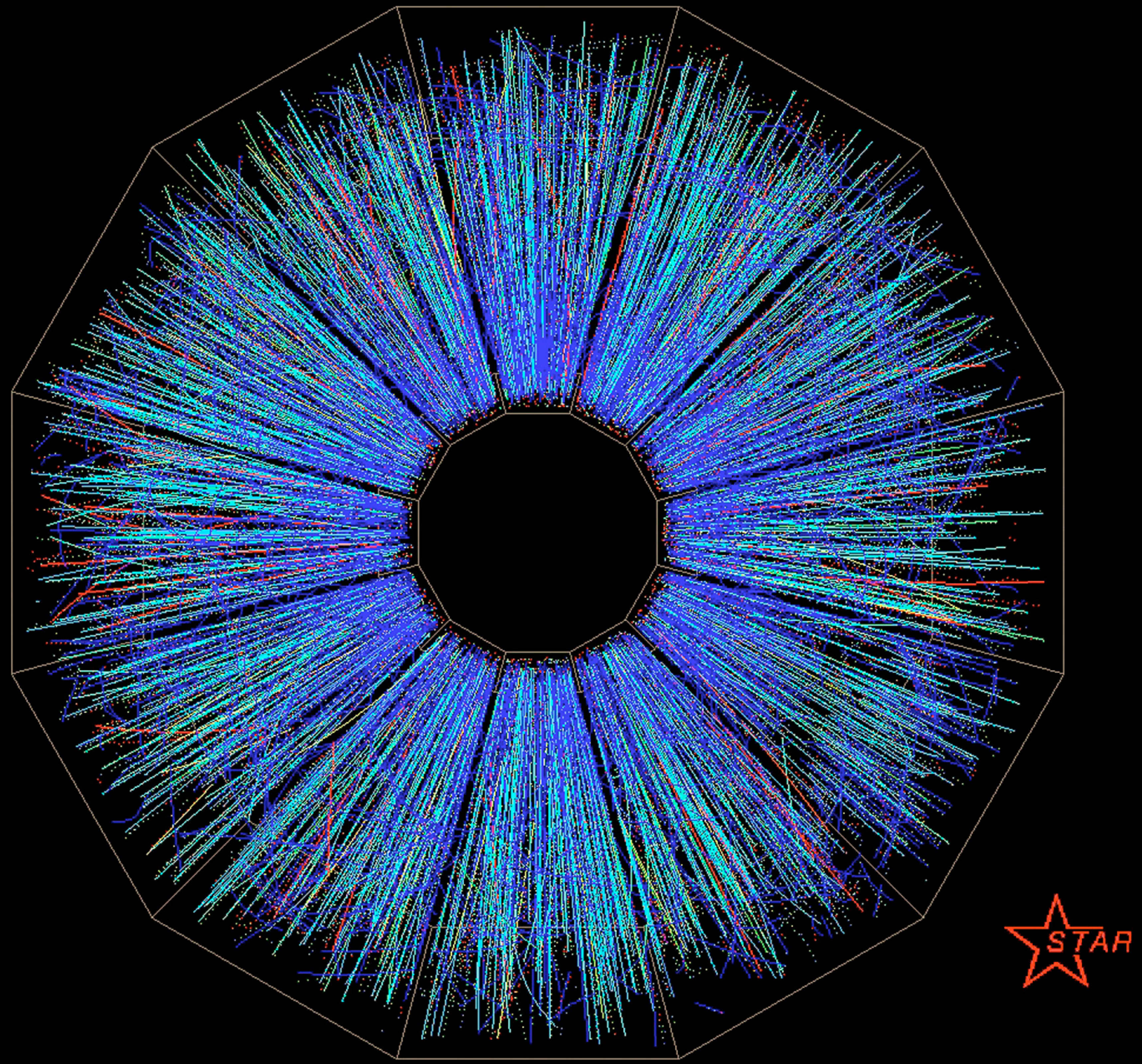

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Pb-Pb collisions in STAR at RHIC
credit: Brookhaven National Lab

Matter and Antimatter

Early Universe

1,000,000,001
particles

for every

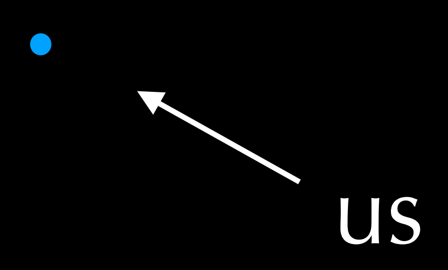
1,000,000,000
anti-particles

J. Detwiler

Following H. Murayama

Matter and Antimatter

Current Universe



"The Great Annihilation"

Sakharov Conditions

- Baryon number violation (baryogenesis)
- C (charge) and CP (charge-parity) violation
  - Creation of more baryons than anti-baryons
- Interactions out of thermal equilibrium
  - More creation than annihilation of baryons

A. Sakharov, JETP 5, 24 (1967).

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  - $B \leftrightarrow L$ processes (sphalerons)
  - CKM complex phases
  - Weak vs strong couplings

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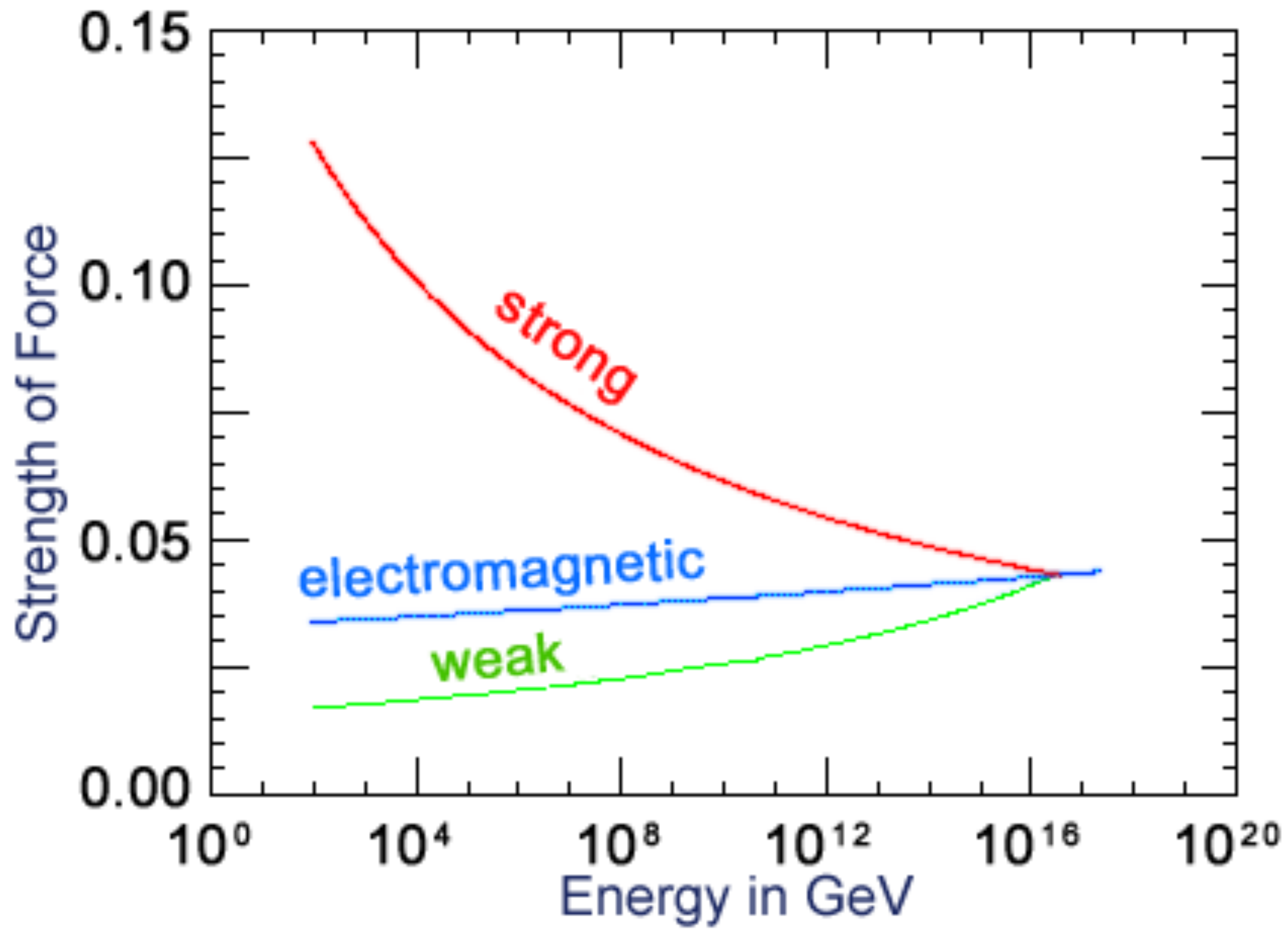
…but in insufficient quantities

A. Sakharov, JETP 5, 24 (1967).

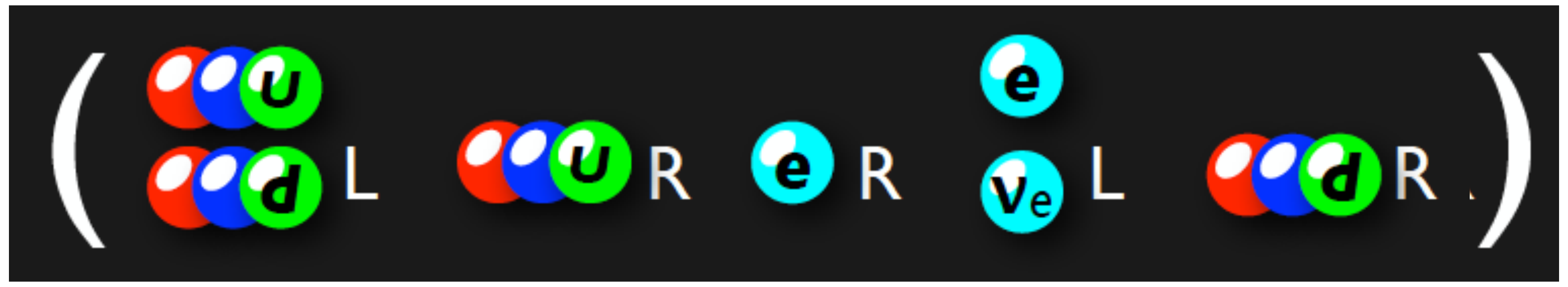
Grand Unification Theory

- Strong and electroweak forces appear to merge at high energy
- Implies some larger gauge symmetry that is spontaneously broken at high energy
- The SM would be the low-energy EFT of this more general theory



GUT Groups

- SM: U(1) x SU(2) x SU(3)



GUT Groups

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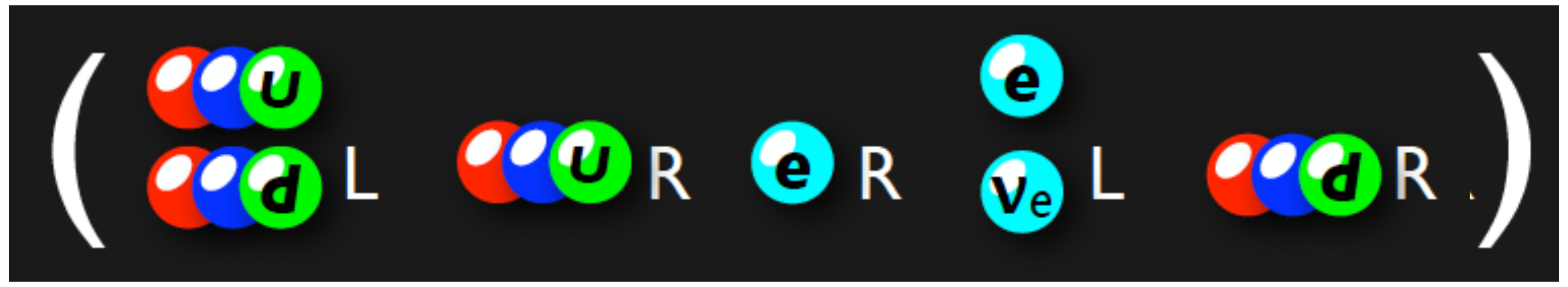
- SU(5): smallest group containing the SM
  - Predicted proton decay rates (mostly) ruled out by Kamiokande and other experiments
  - Also: does not accommodate ν mass



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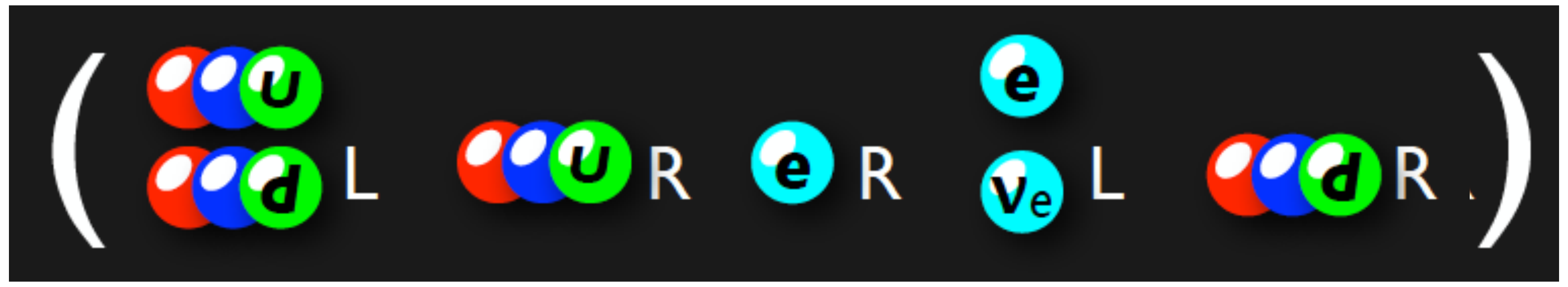
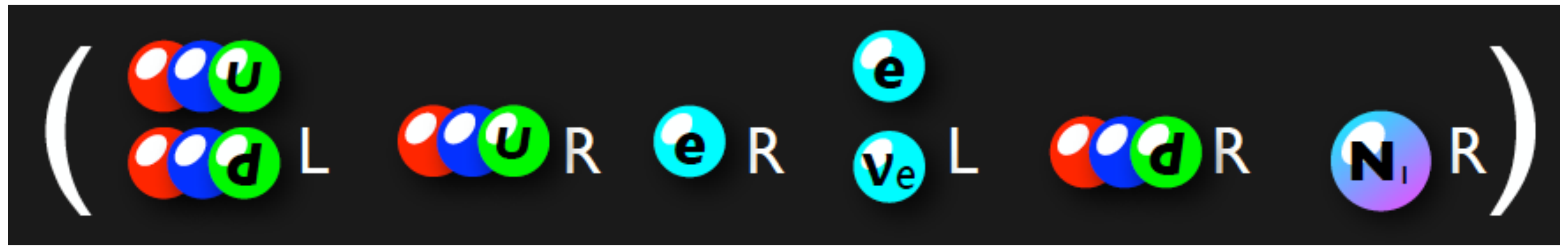
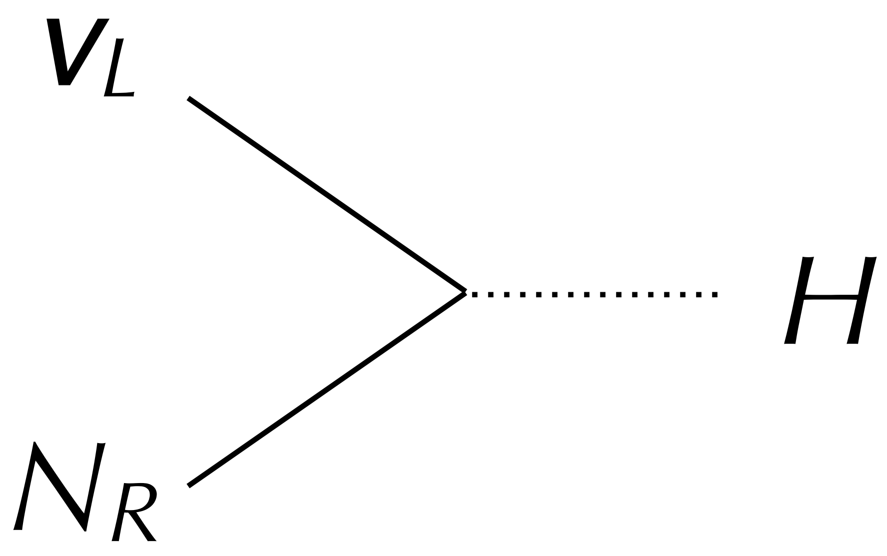
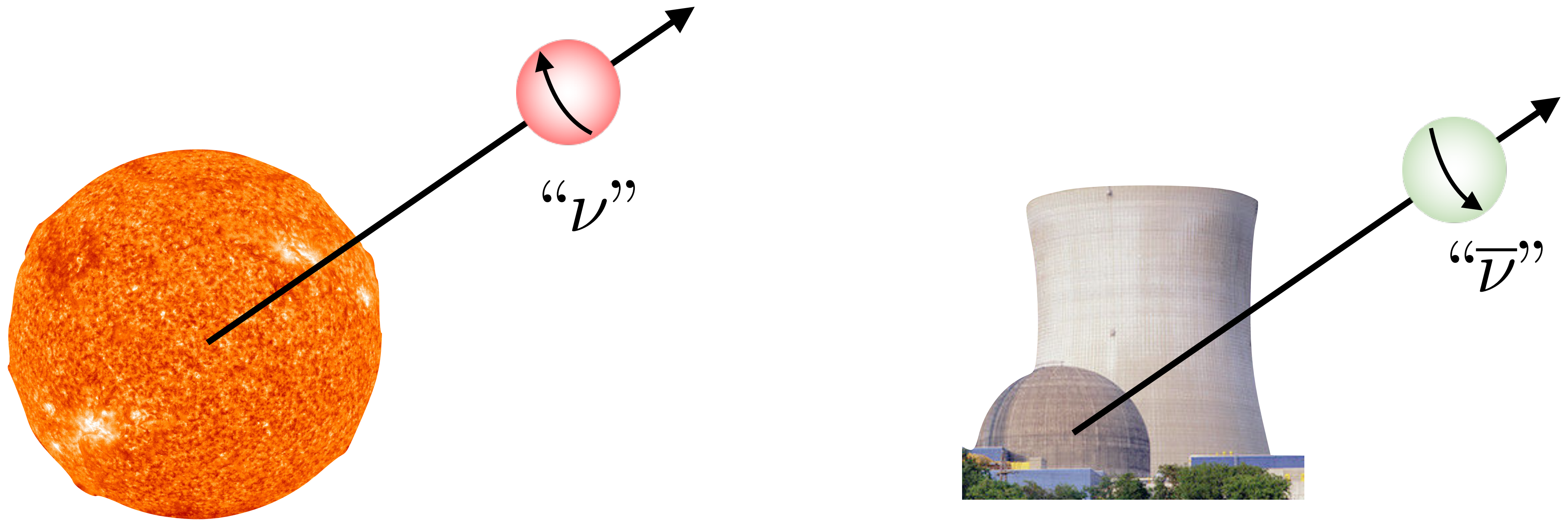


- SU(5): smallest group containing the SM
  - Predicted proton decay rates (mostly) ruled out by Kamiokande and other experiments
  - Also: does not accommodate ν mass
- Next smallest: SO(10) — add N_R
  - Not ruled out
  - Accommodates ν mass ("νSM")
  - Predicts proton decay may be seen in future experiments





Neutrino Mass



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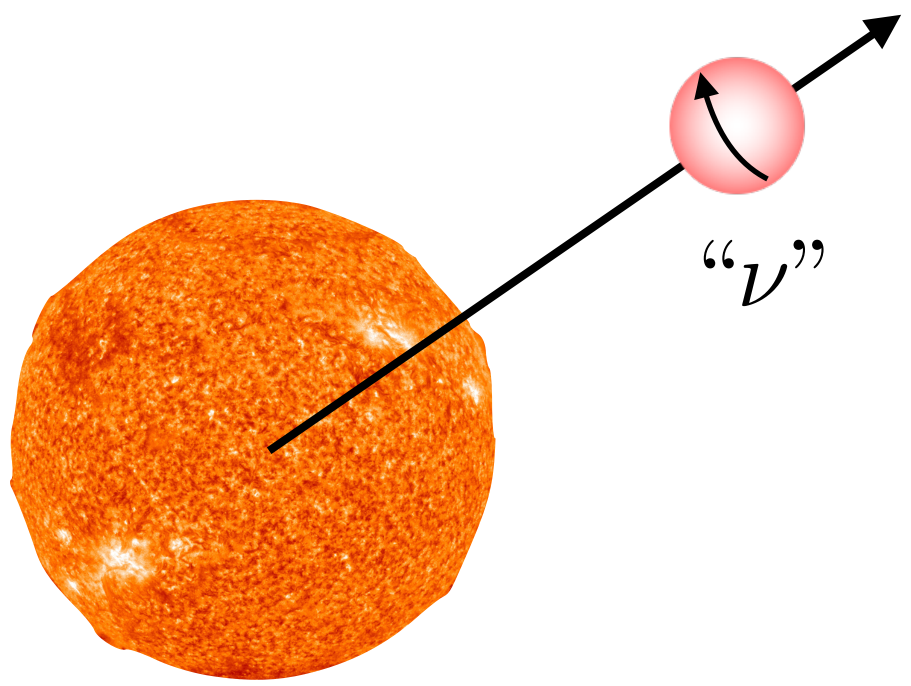
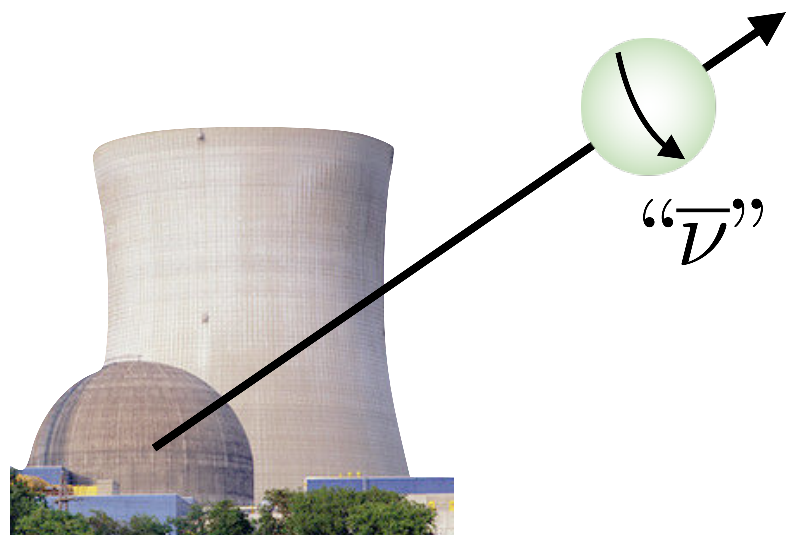
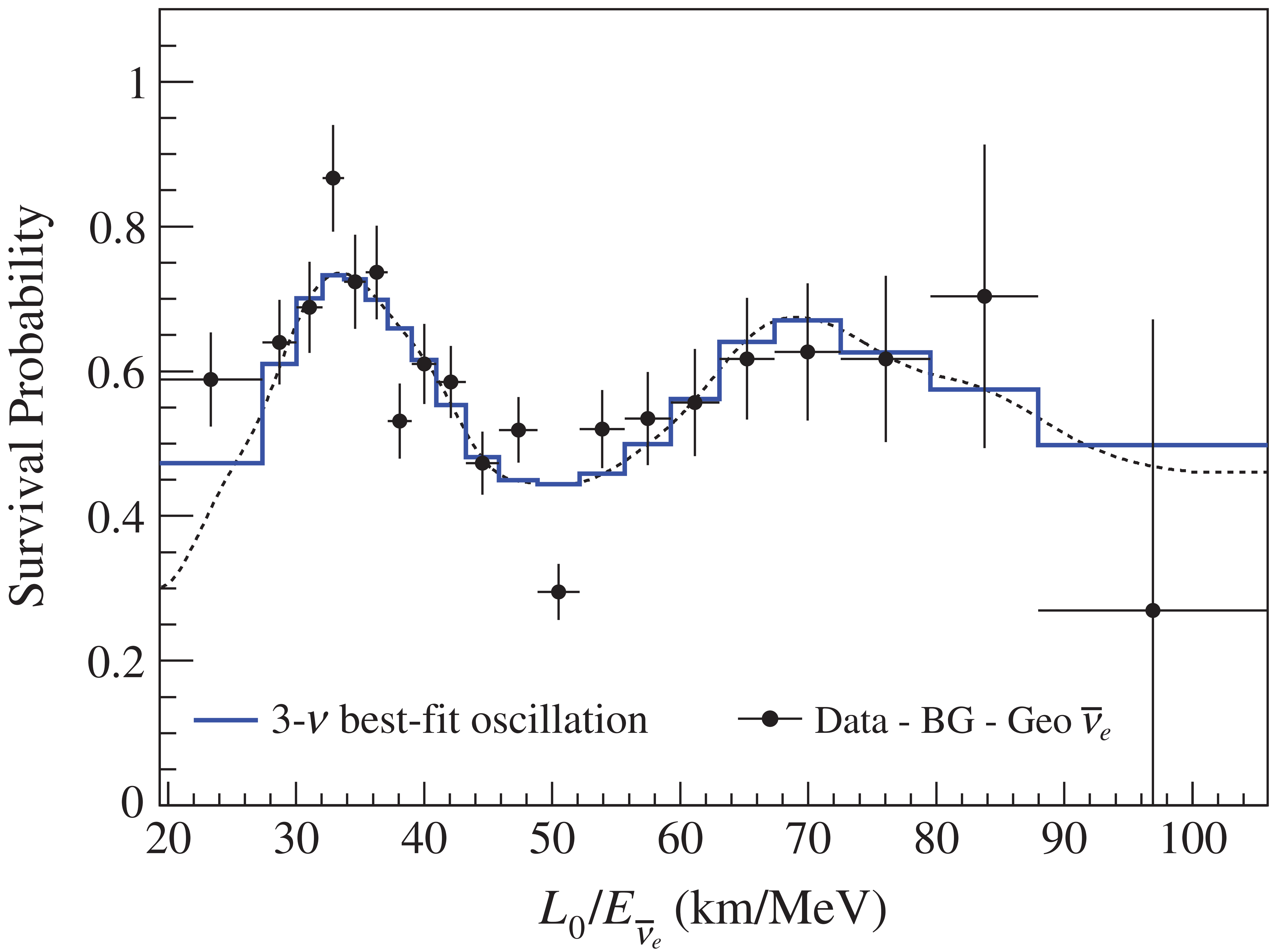
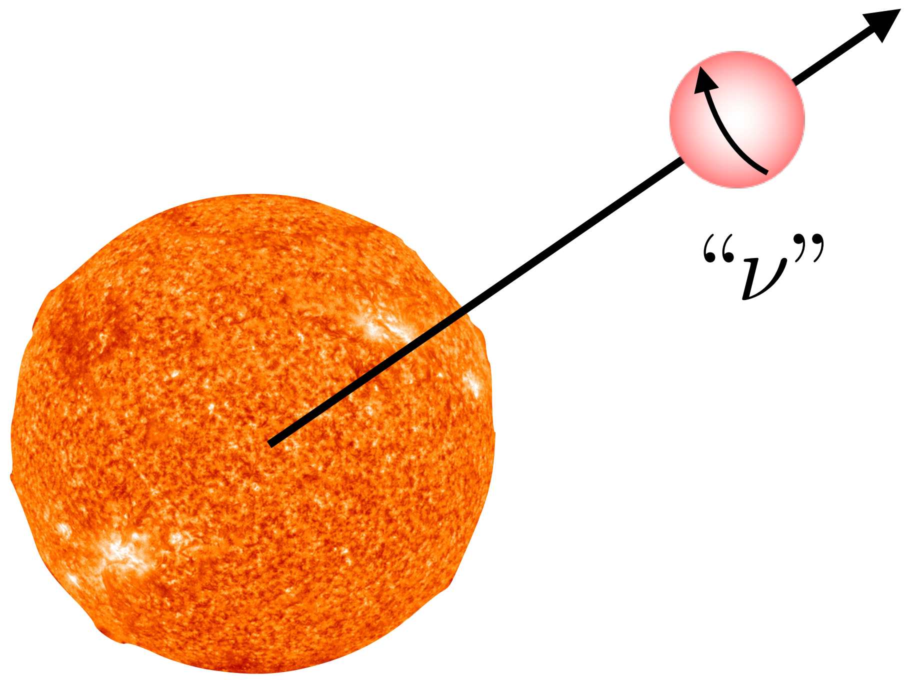


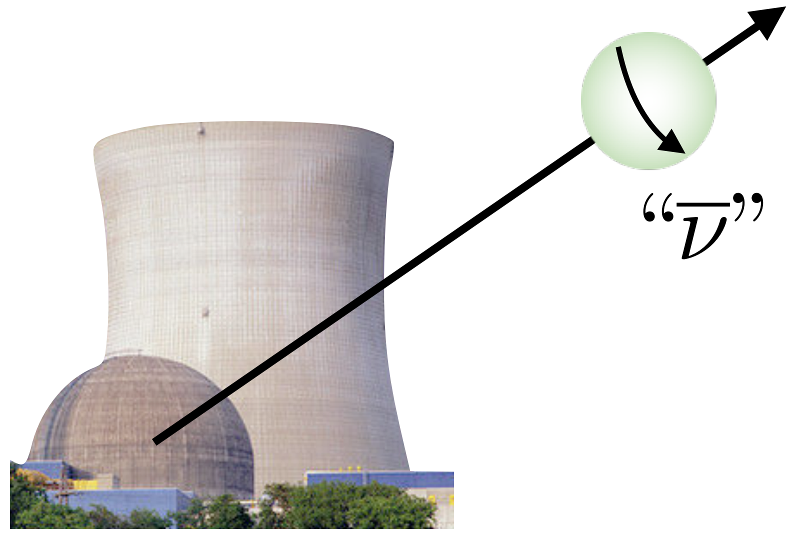


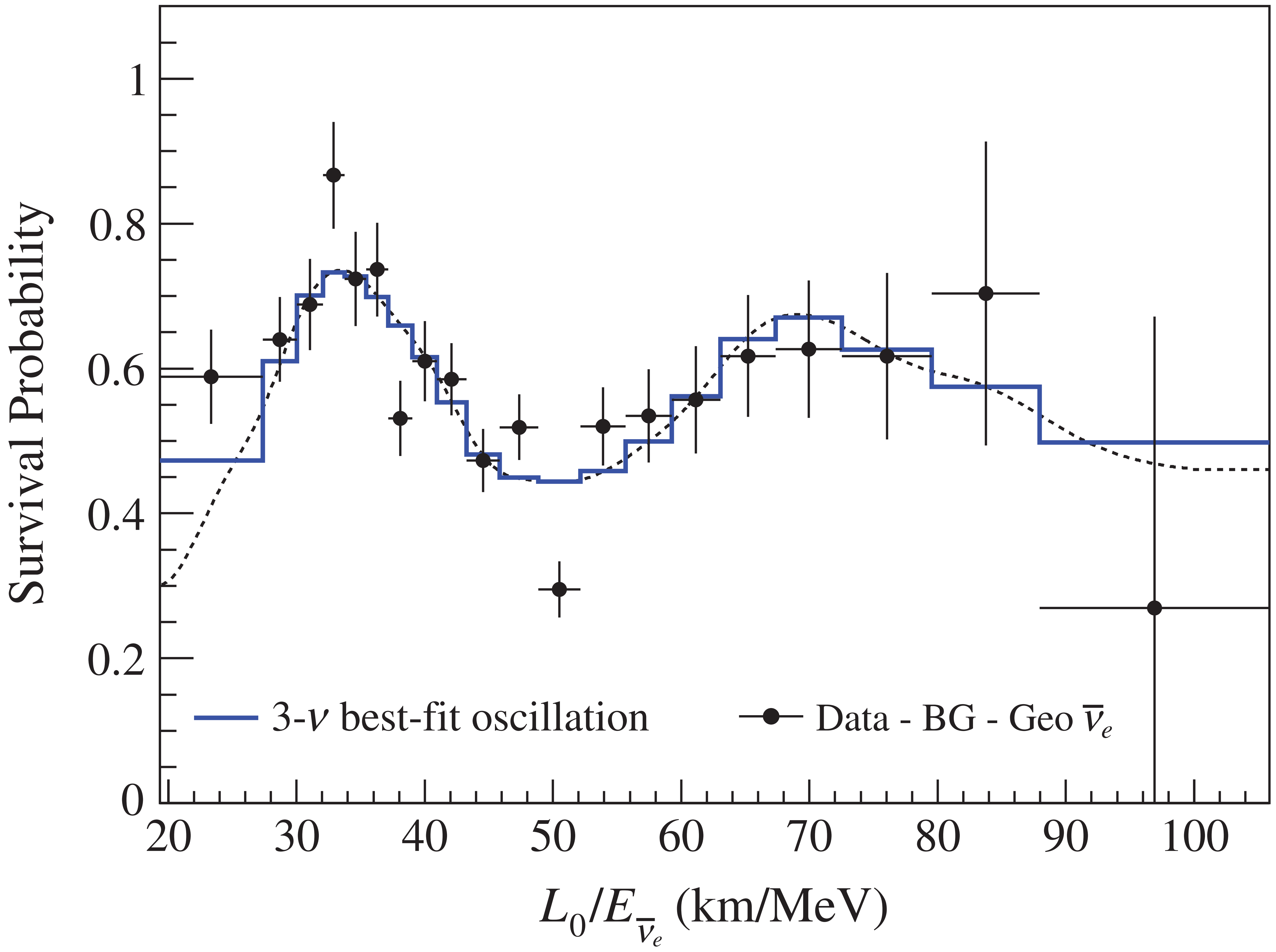


KamLAND, PRD **88**, 033001 (2013)

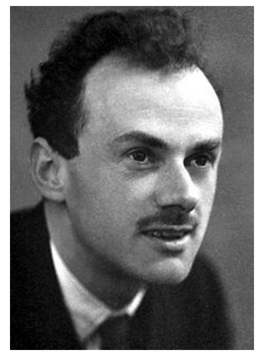
Neutrino Mass







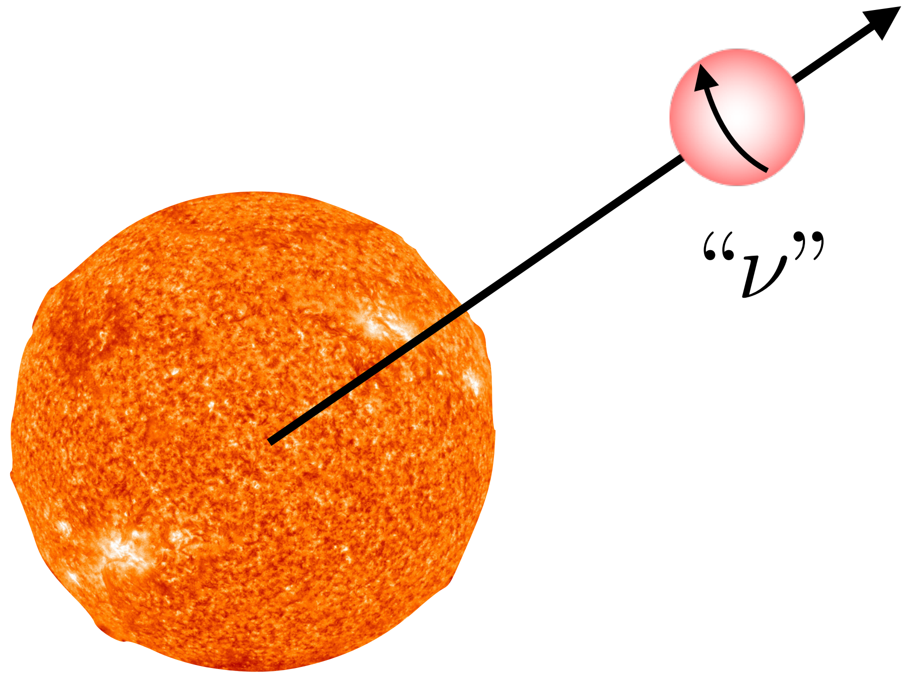
In the neutrino’s rest frame:

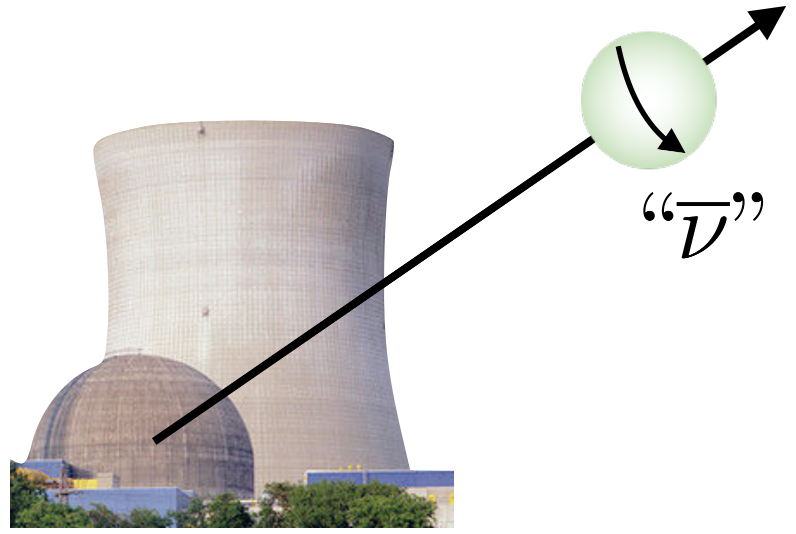


Dirac

Two sterile components? …

Neutrino Mass





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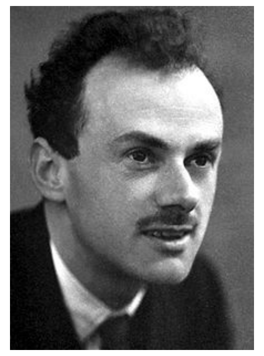

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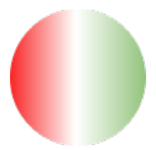
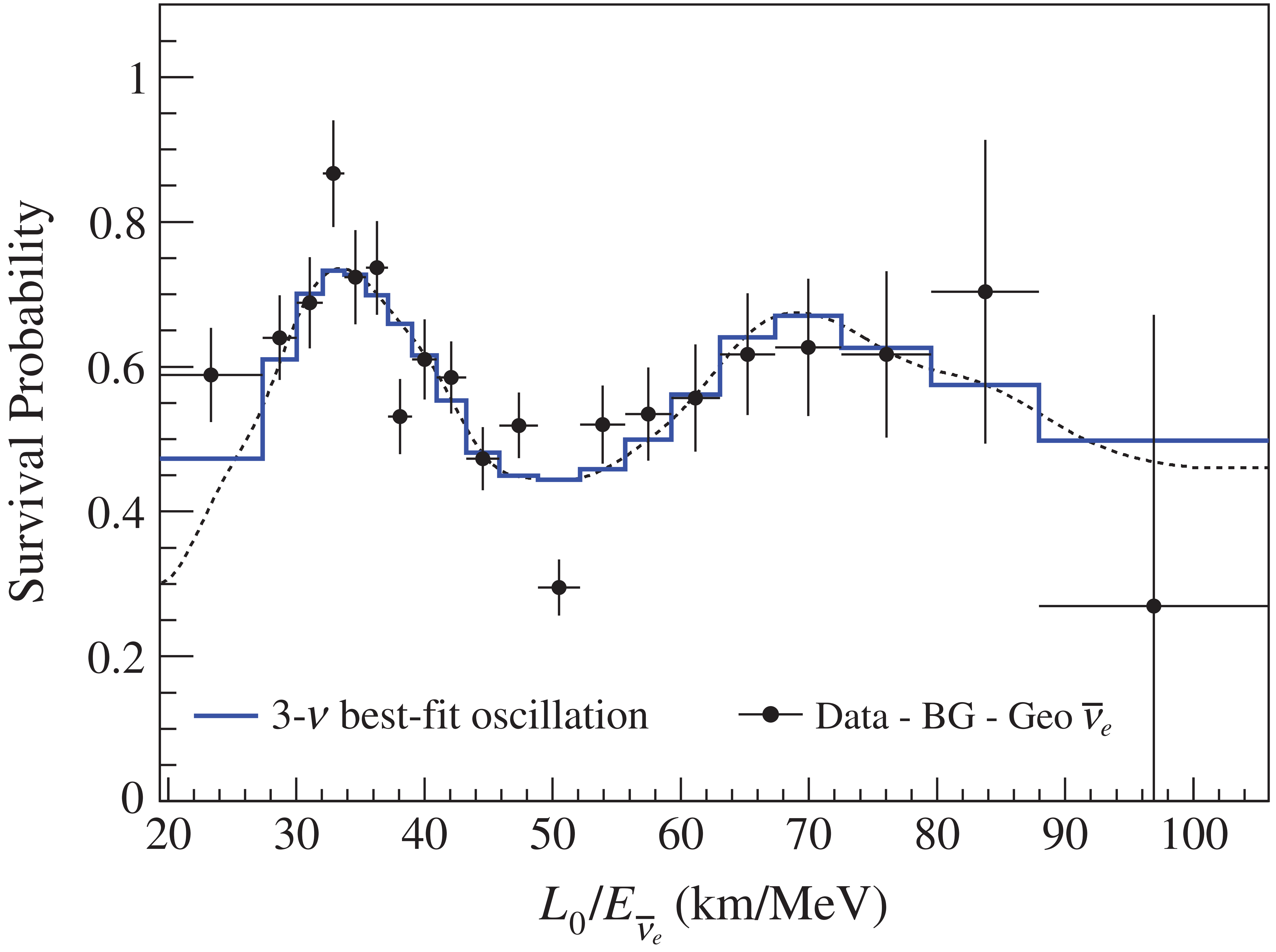


Majorana

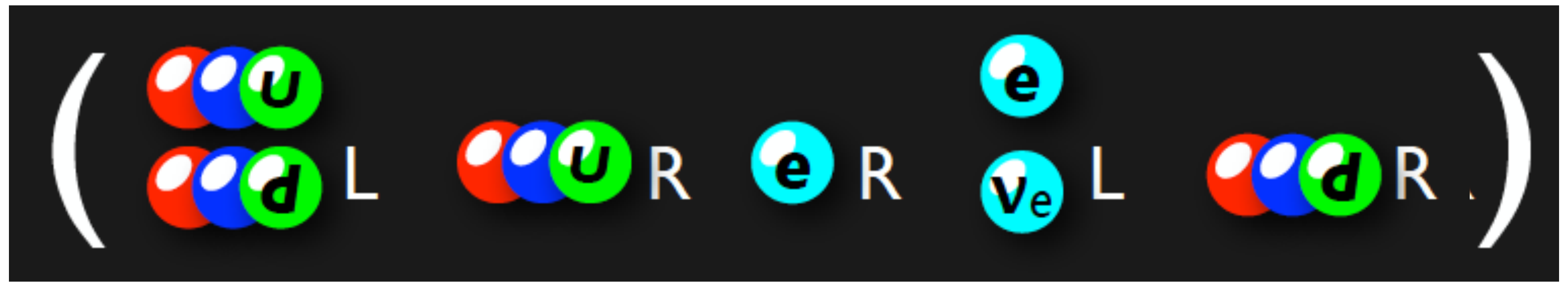
Two sterile components? …

… or a new type of particle?

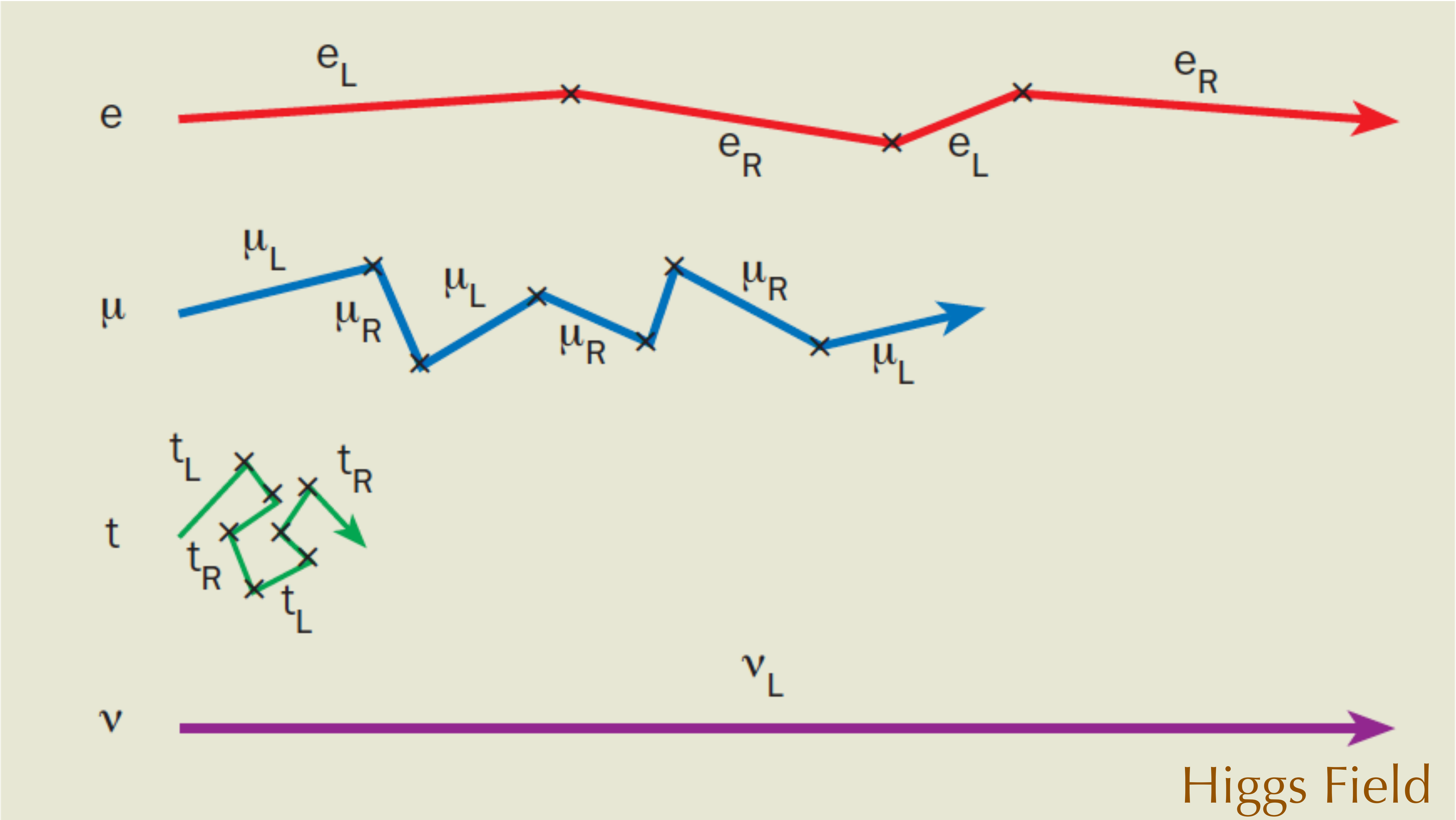


KamLAND, PRD **88**, 033001 (2013)

The SM and ν Mass

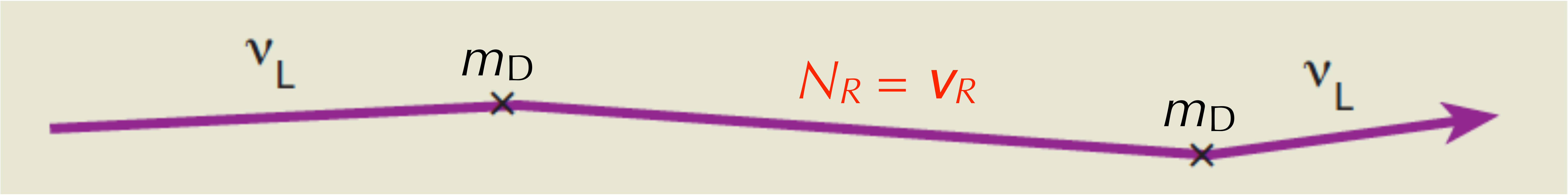


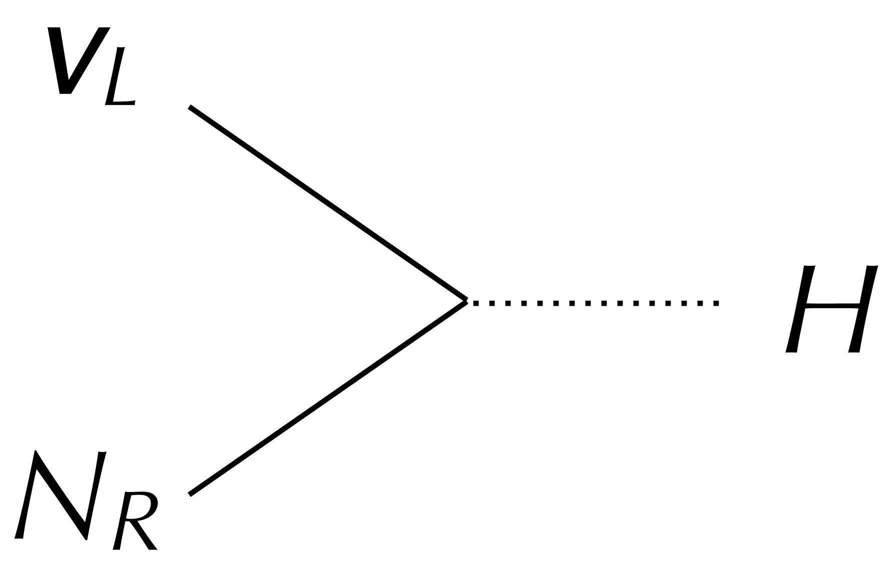
- No ν_R to give the neutrino a Dirac mass
- Majorana mass violates SU(2) symmetry: $e^- \neq e^+$



 H. Murayama, Physics World (May 2002).

N_R and Dirac Masses





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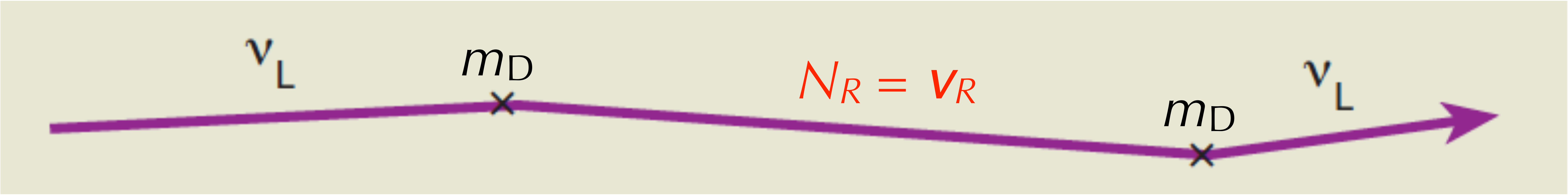

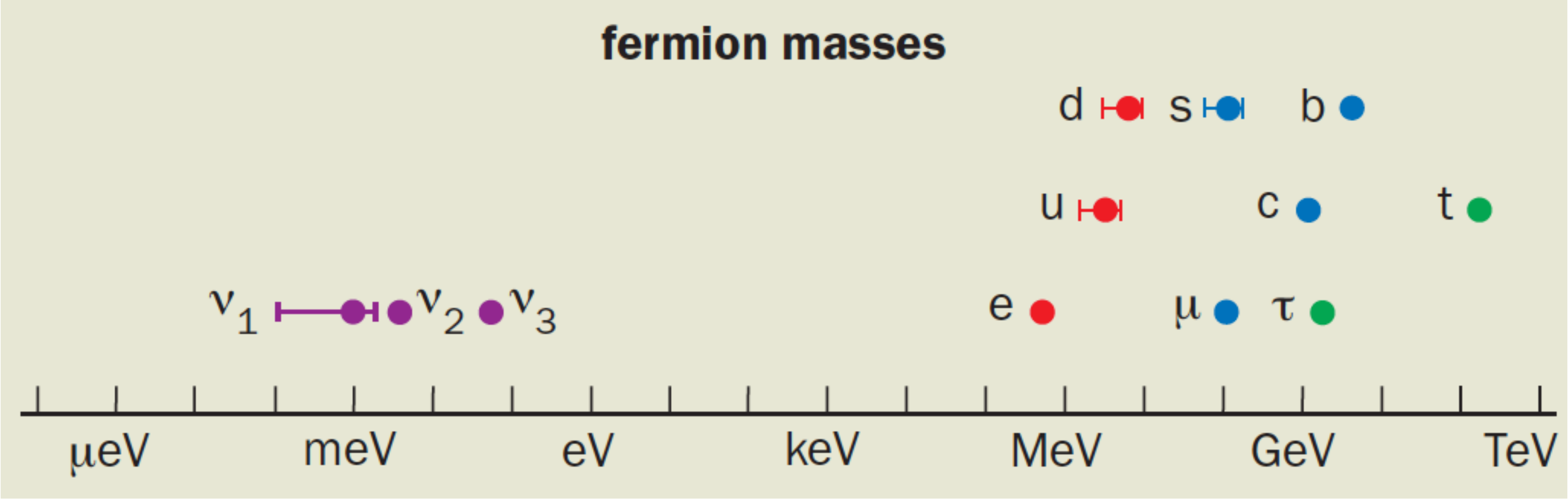

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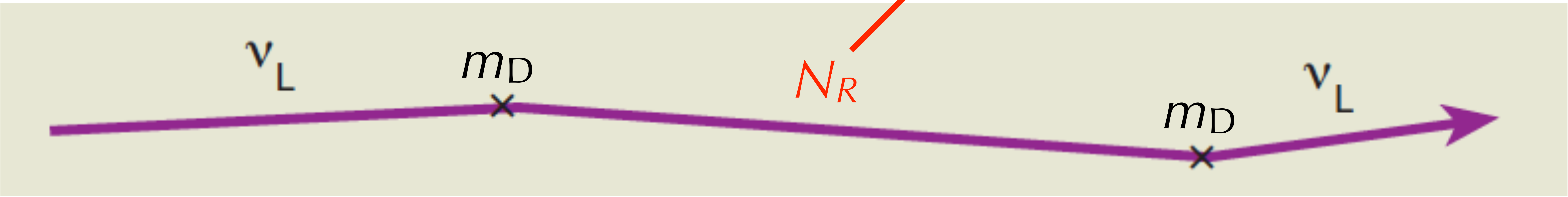
The Seesaw Mechanism

Majorana mass M_R, $\tau \sim 1/M_R$



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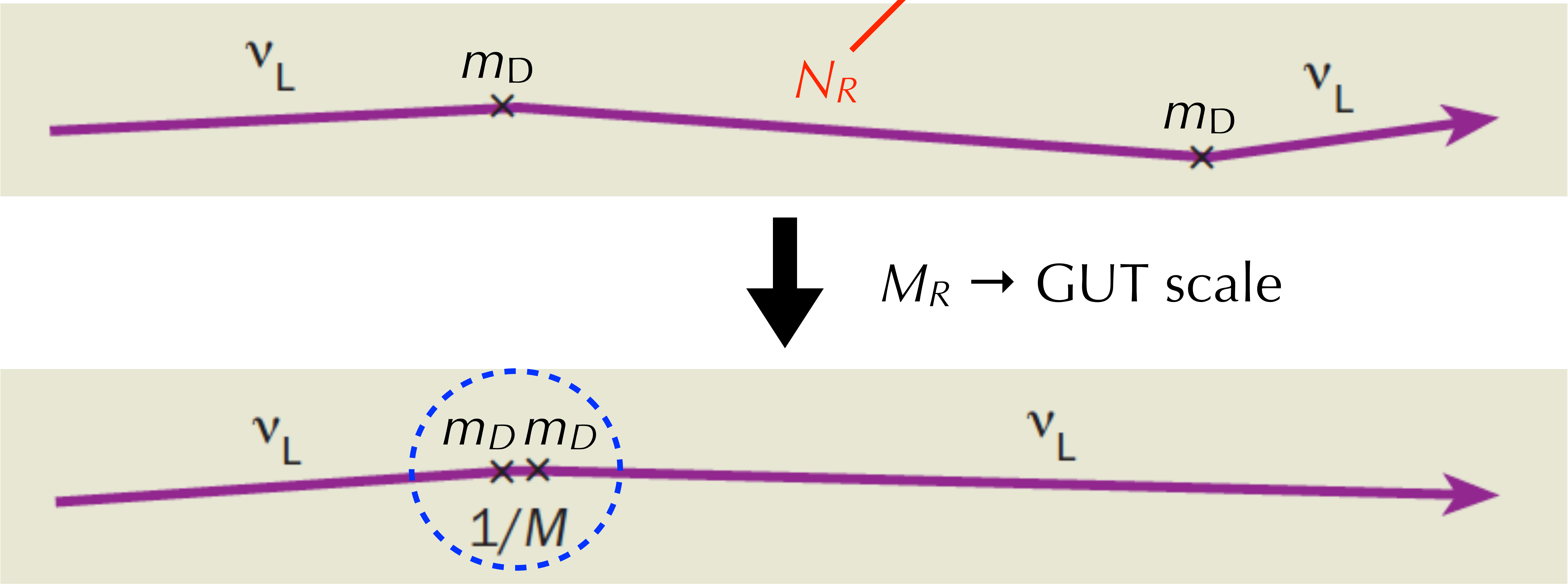
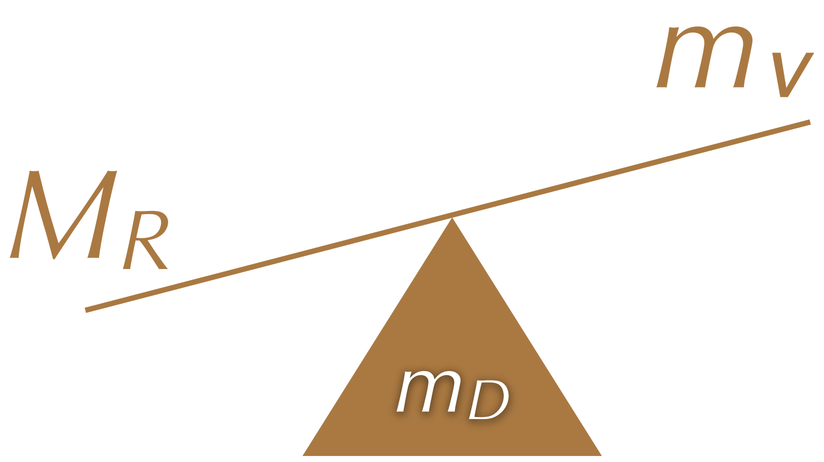


M_R → GUT scale

Majorana mass term $m_\nu \sim m_D^2/M_R$



m_D ~ weak scale, M_R → GUT scale: m_ν ~ meV

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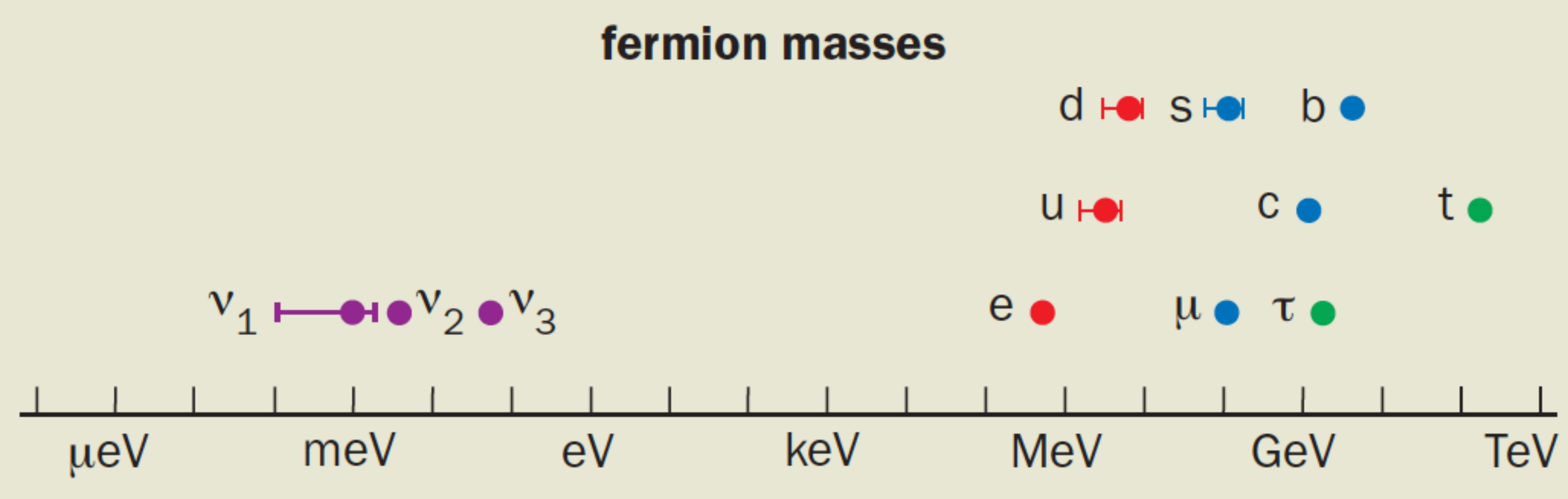

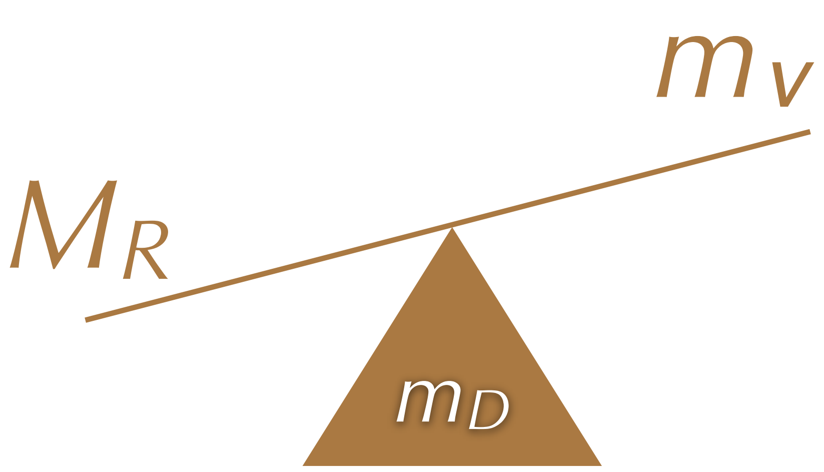

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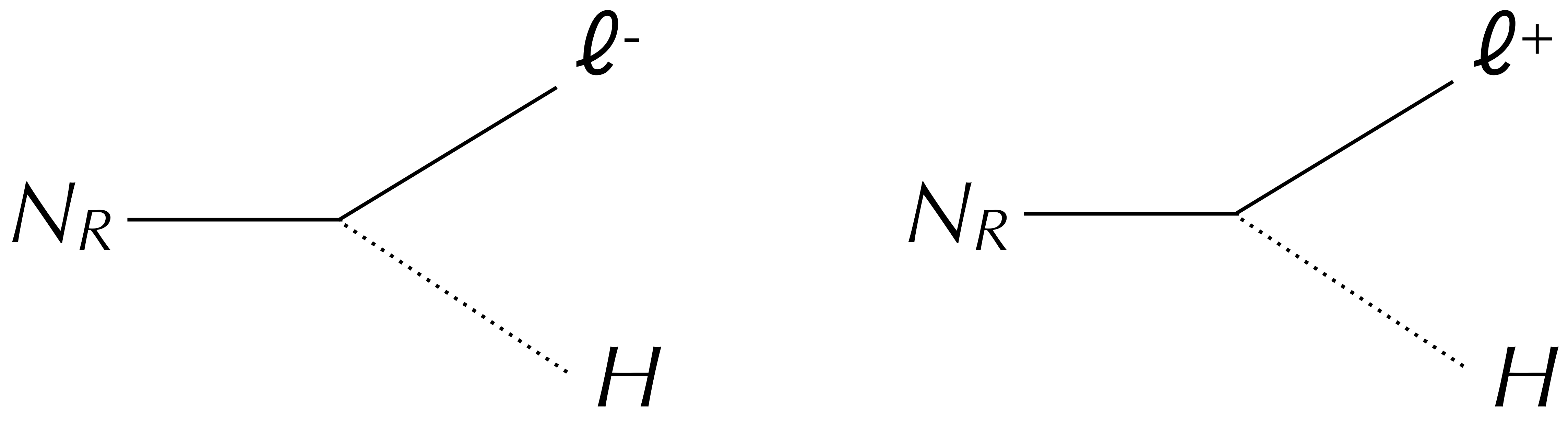
Leptogenesis

- Heavy N_R produced in Big Bang, decays into leptons ($\ell^{\pm}$) and Higgs (H):



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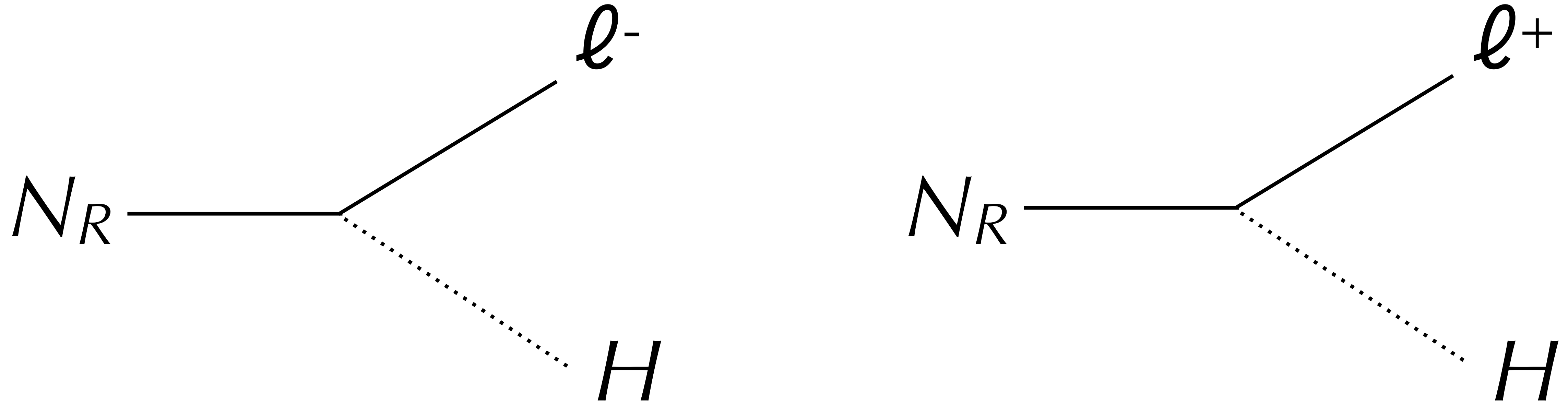

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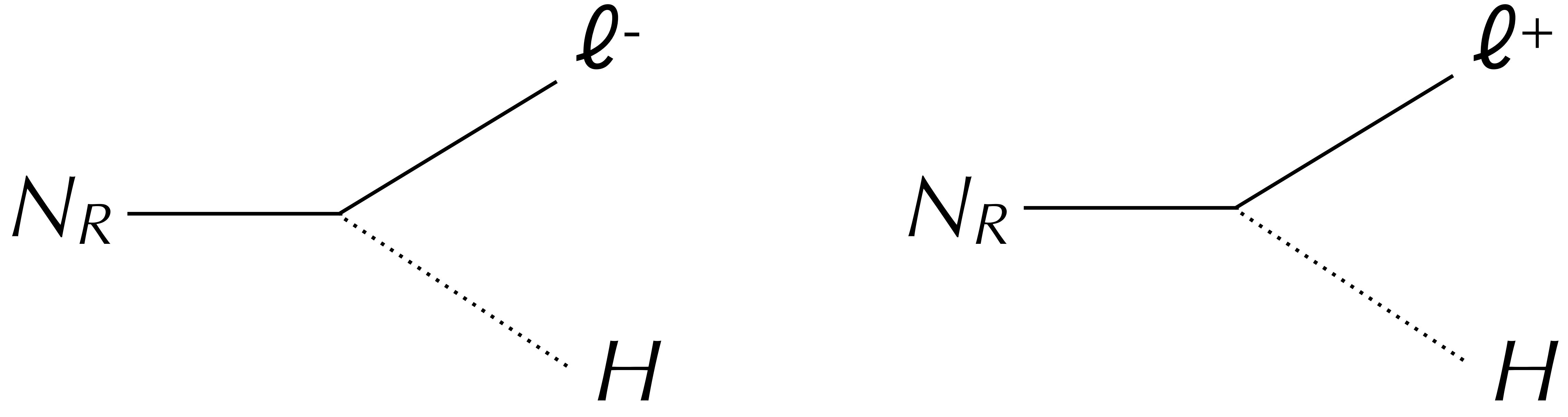

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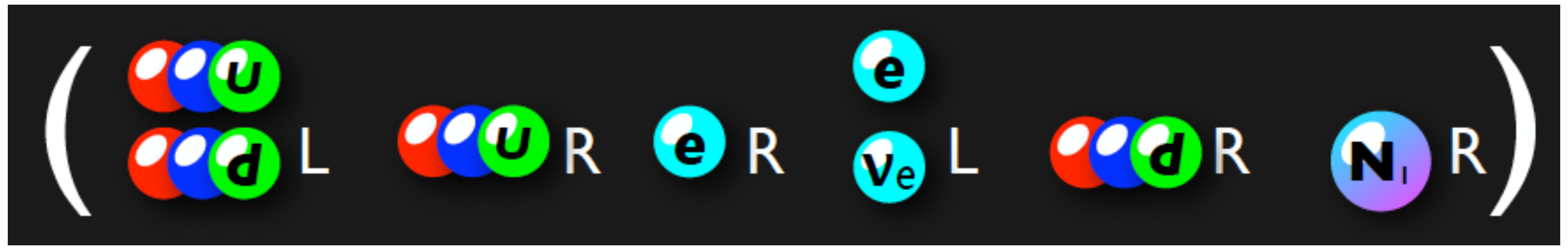
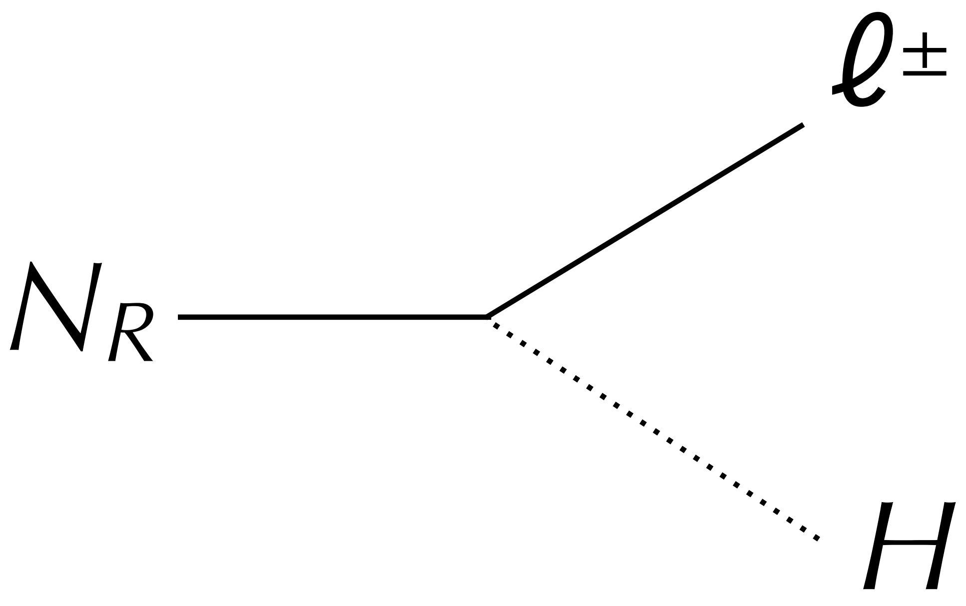
Triple-Role of N_R

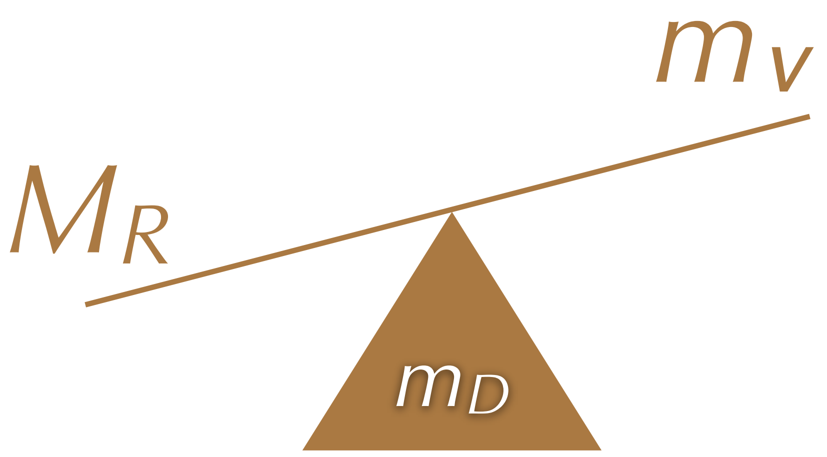
- Completes SO(10) GUT, unifying quarks and leptons



- CPV decay in the early universe provides leptogenesis



- Generates a naturally small Majorana mass term for SM neutrinos (see-saw mechanism)



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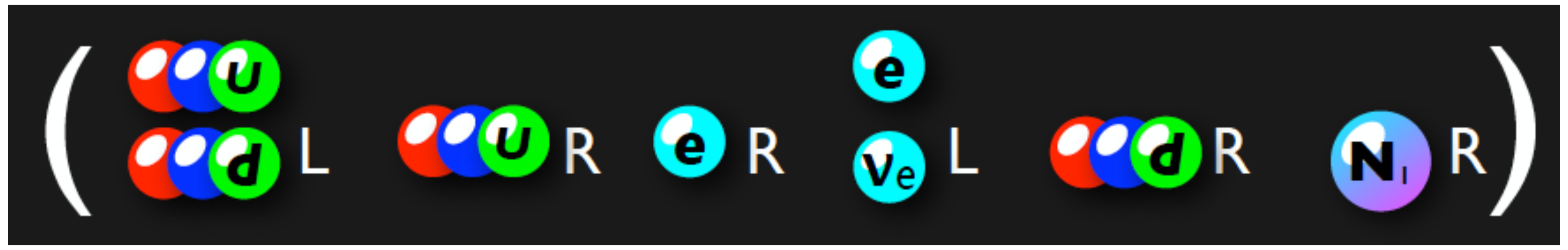

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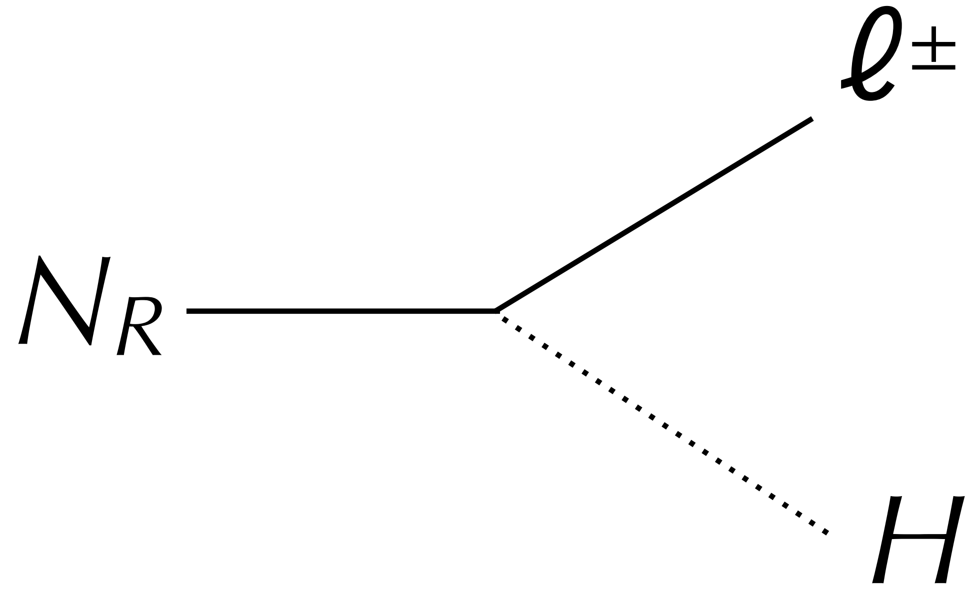

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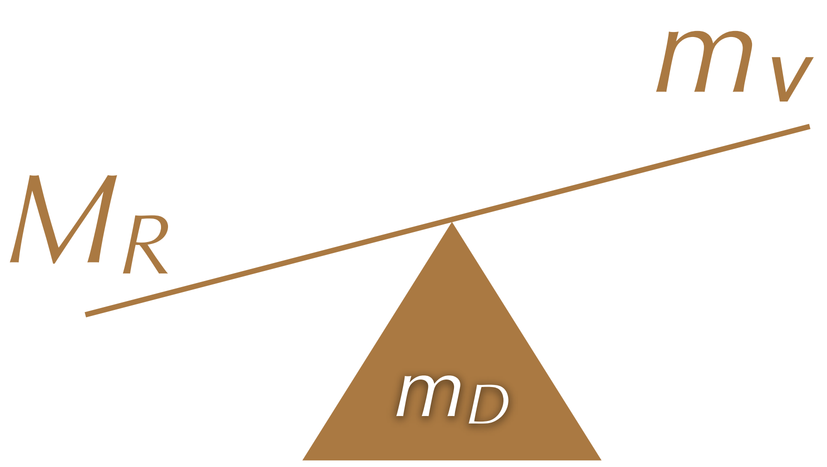
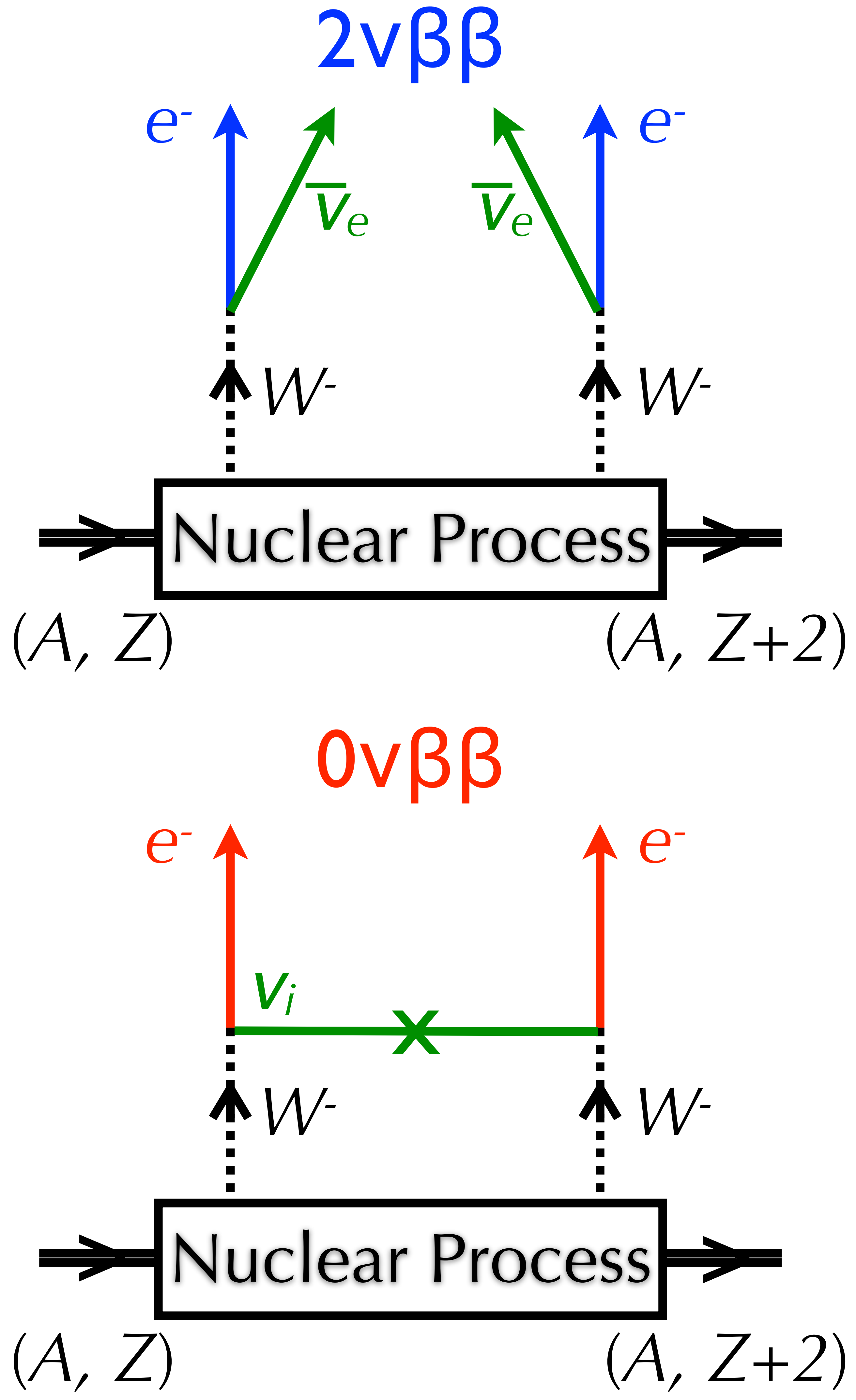
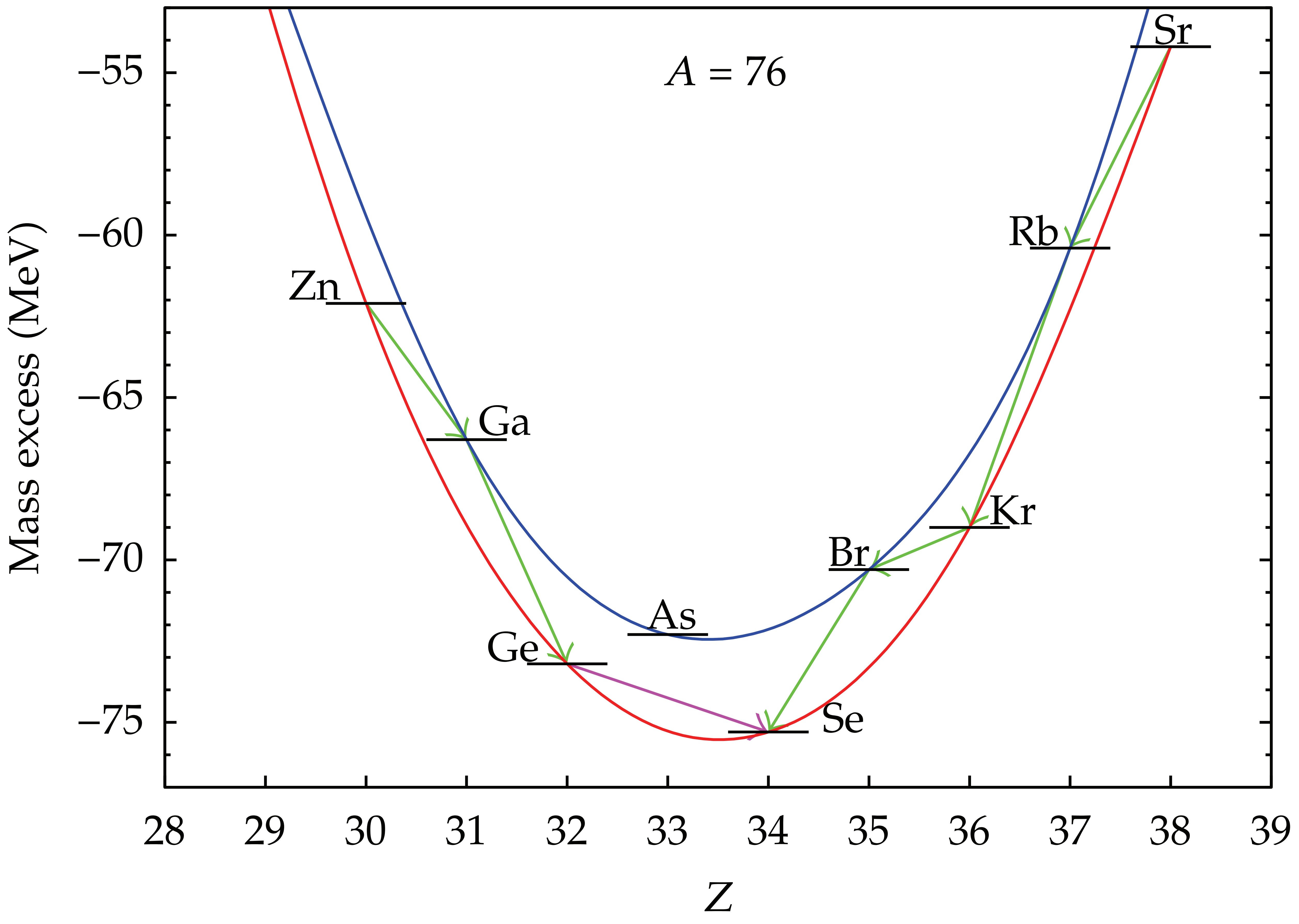


Prediction: Majorana SM neutrinos can mediate a "Little Bang" in the laboratory!

Neutrinoless Double Beta Decay





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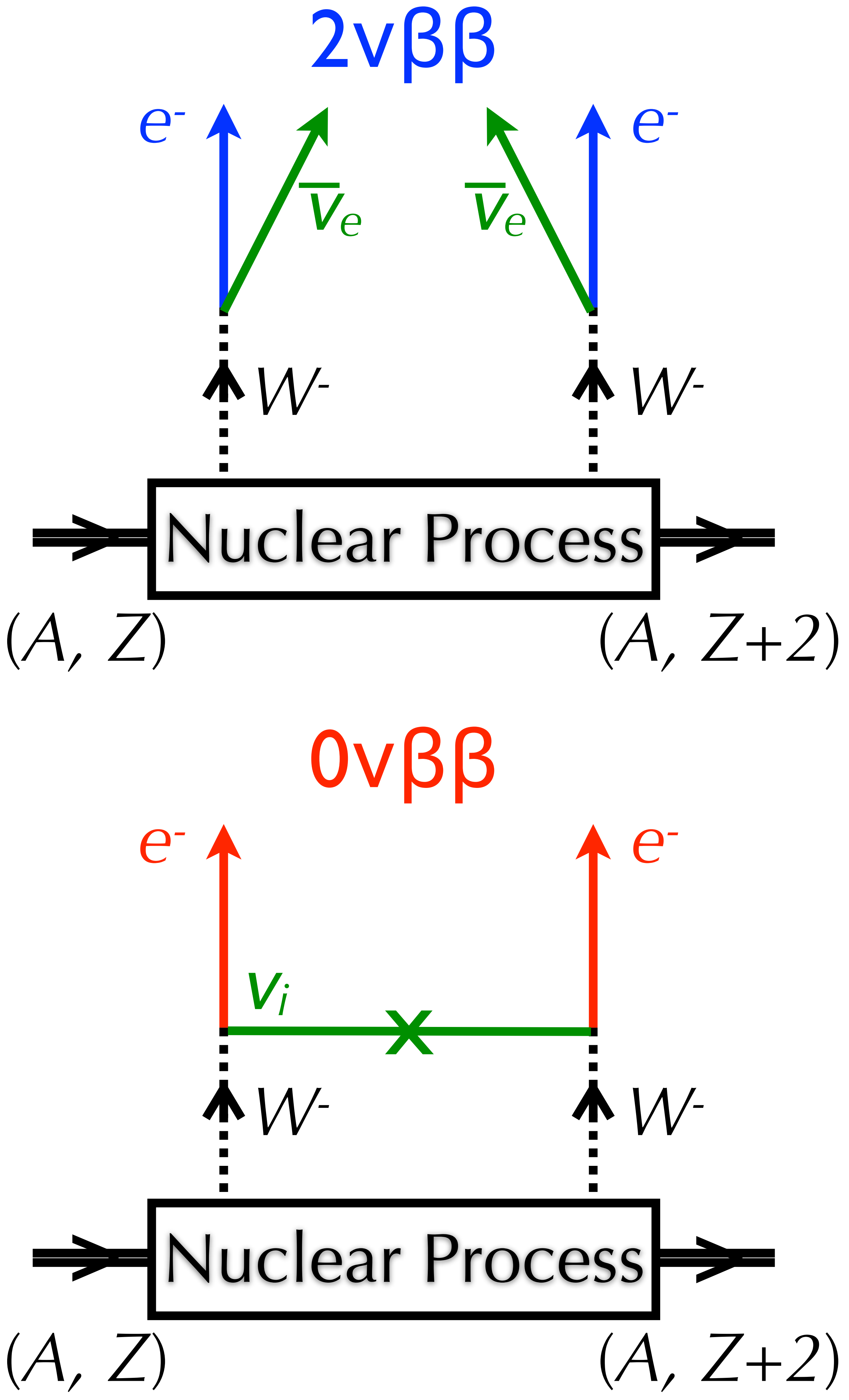
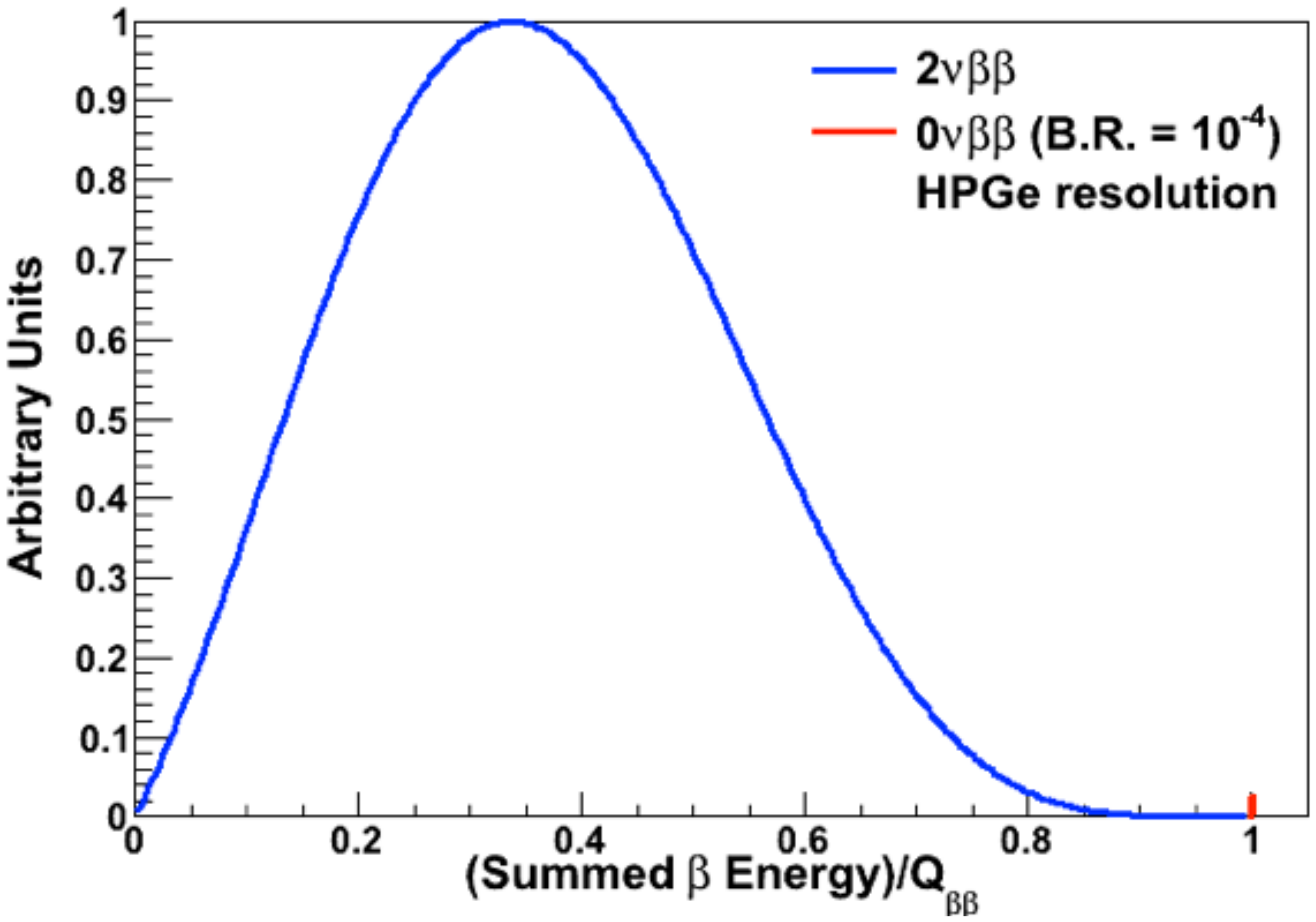
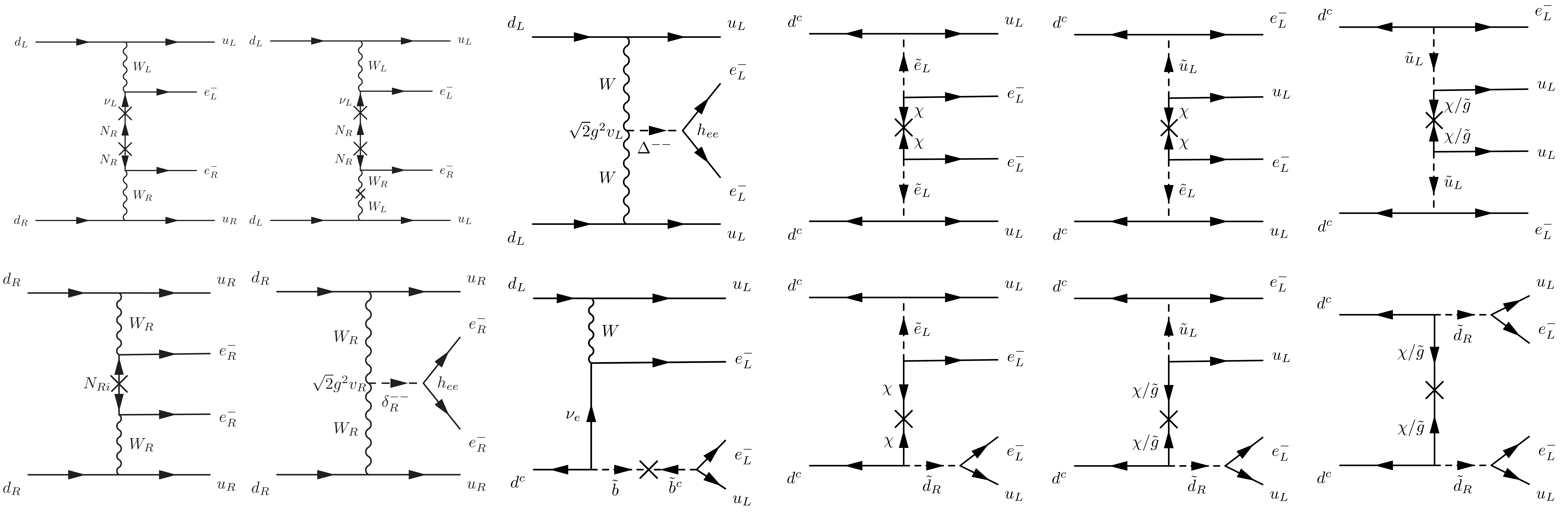




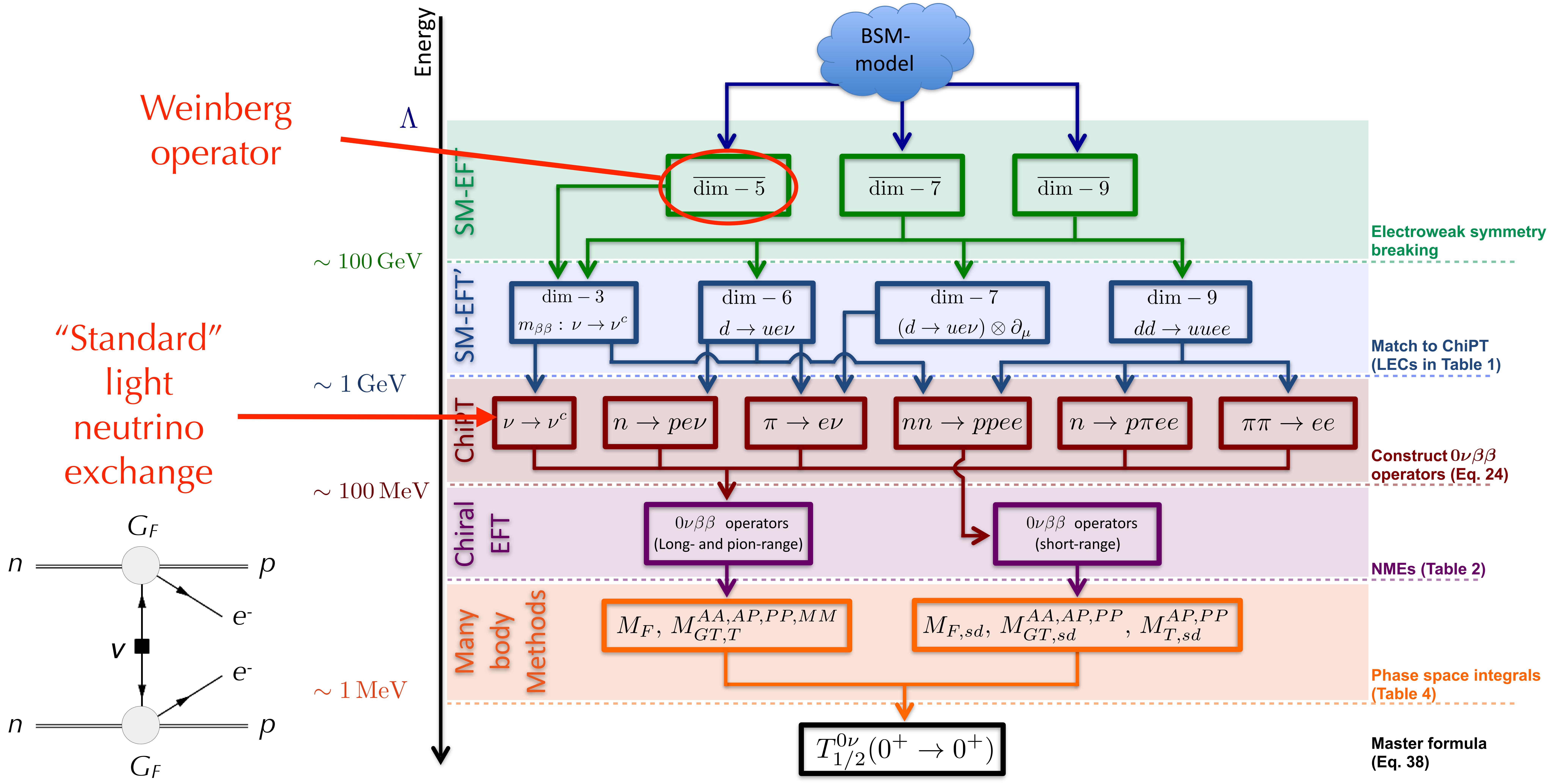
Alternative Exchange Mechanisms

N_R exchange, Left-Right Symmetric Models, Higgs Triplets, RPV SUSY…



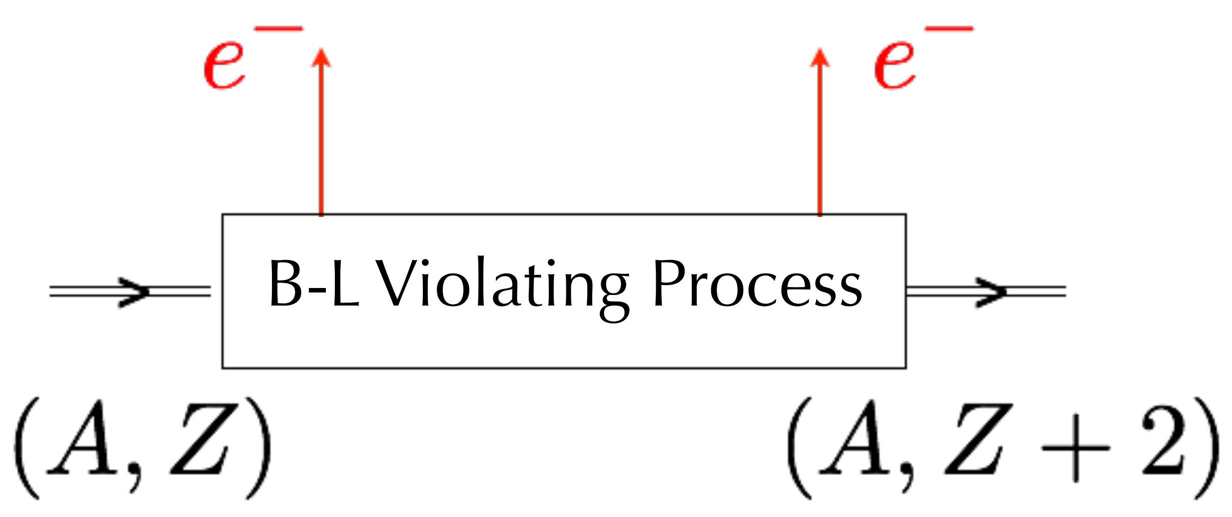
Tello *et al.*, PRL **106**, 151801 (2011)
Rodejohann, Int. J. Mod. Phys. E **20**, 1833 (2011)

Systematic Classification of 0νββ Mediators



0νββ Decay, Generically

- Creates two new particles of matter but no antimatter
  - Violates not just *L* but *B-L*: the last accidentally conserved quantity in the SM
  - This is important whether or not leptogenesis, SO(10), the seesaw mechanism, etc. are realized in nature



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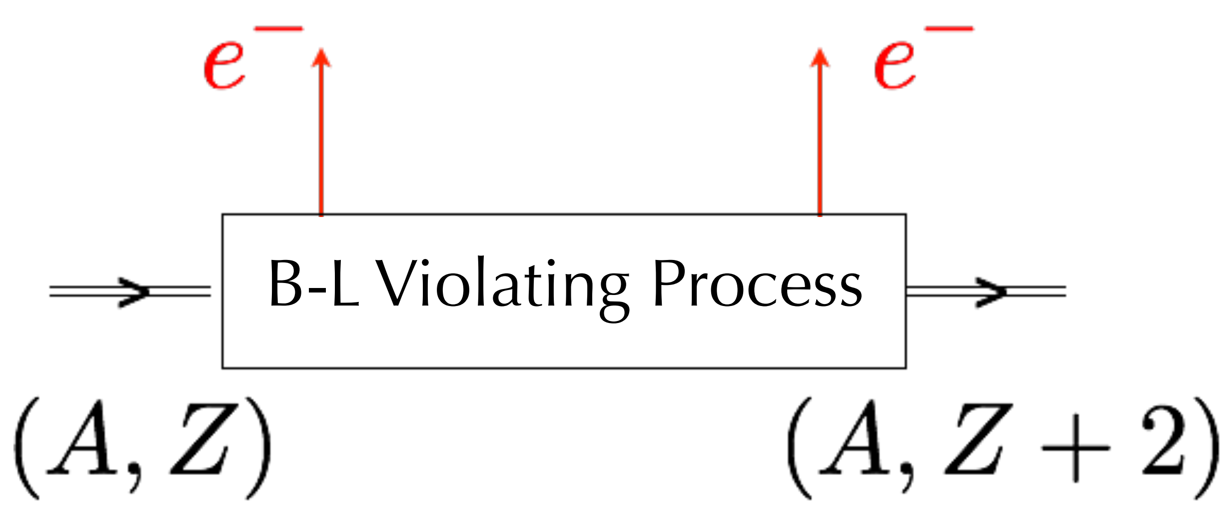
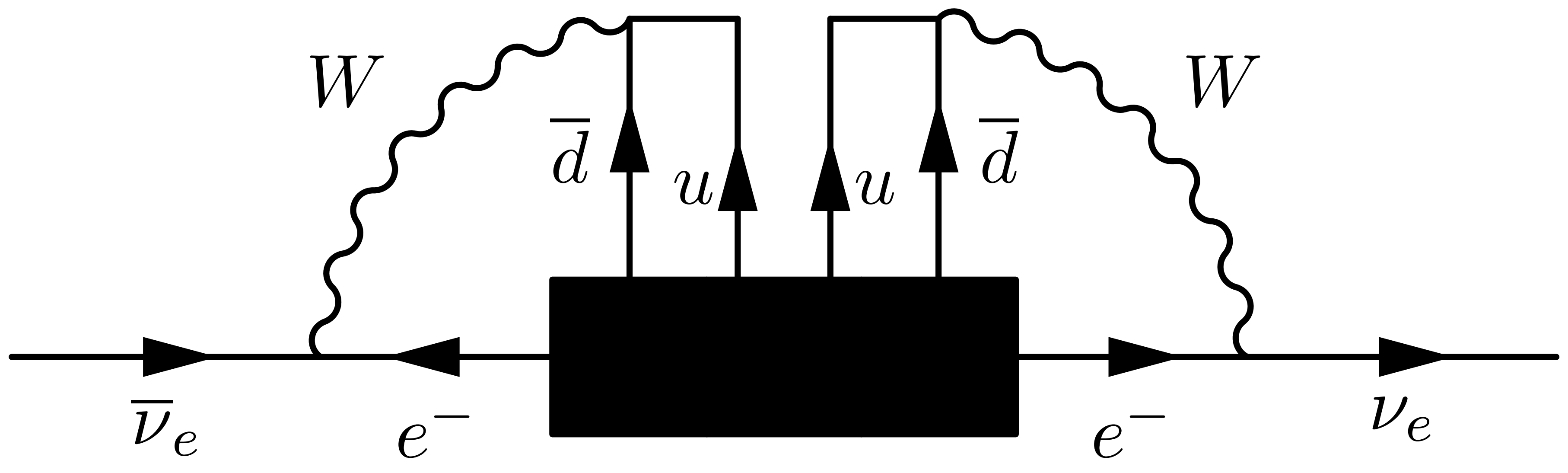
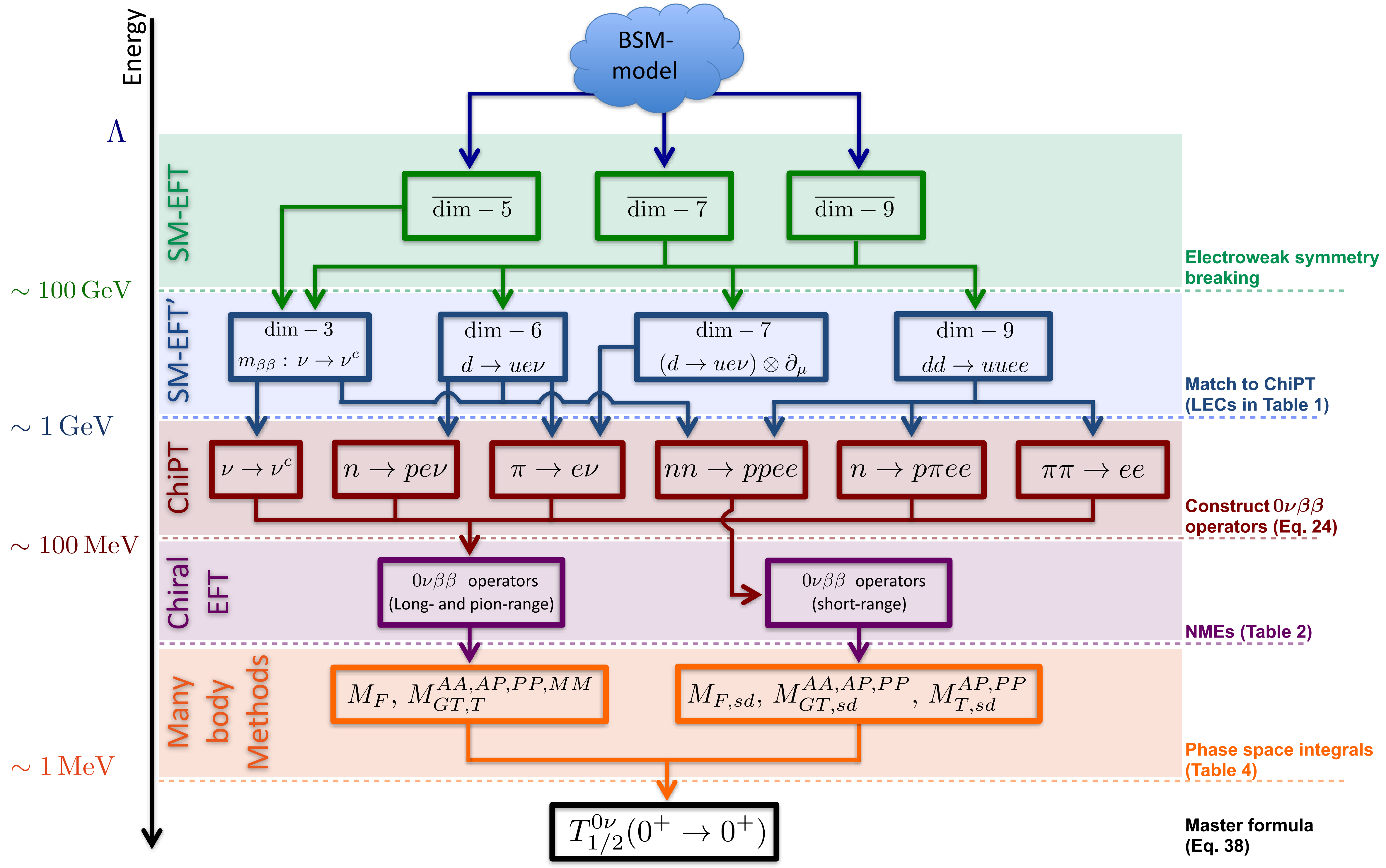


- The existence of 0νββ decay implies that neutrinos are (likely) Majorana particles
  - Schecter-Valle: all 0νββ exchange mechanisms induce Majorana masses (PRD **25**, 2951 (1982))…
  - … but they are many orders of magnitude smaller than Δm^2_{sol} (Duerr, Lindner, Merle, JHEP **2011**, 91 (2011)) …
  - … but if BSM physics mediates 0νββ decay, it is rather "unnatural" for the neutrino to be left "mostly Dirac"



The “Modern Orthodoxy”

- It is “natural” for light left-handed neutrino exchange to dominate the 0νββ decay rate.



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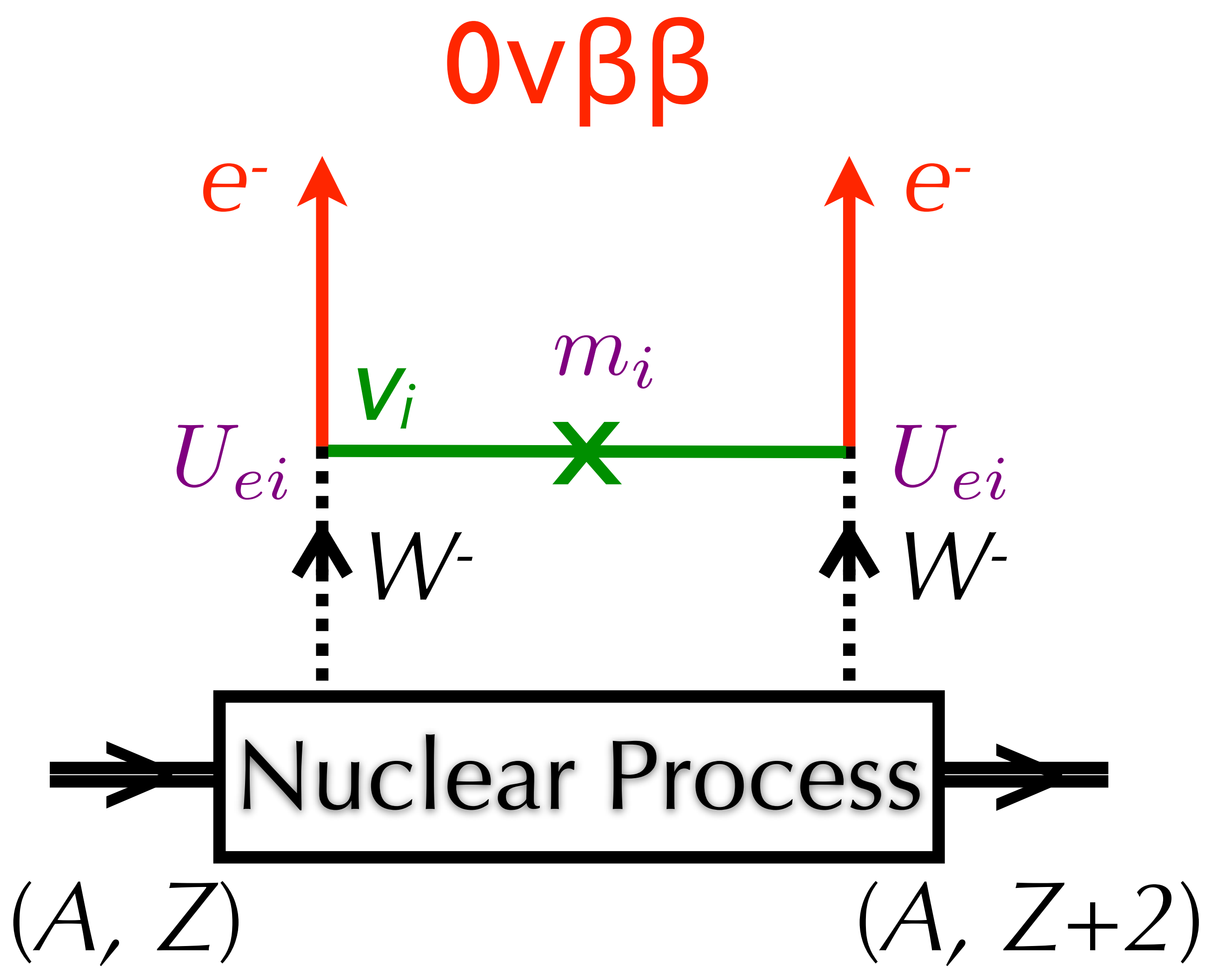

$$\Gamma^{0\nu} = G^{0\nu} \left|M^{0\nu}\right|^2 m_{\beta\beta}^2$$

$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right|$$

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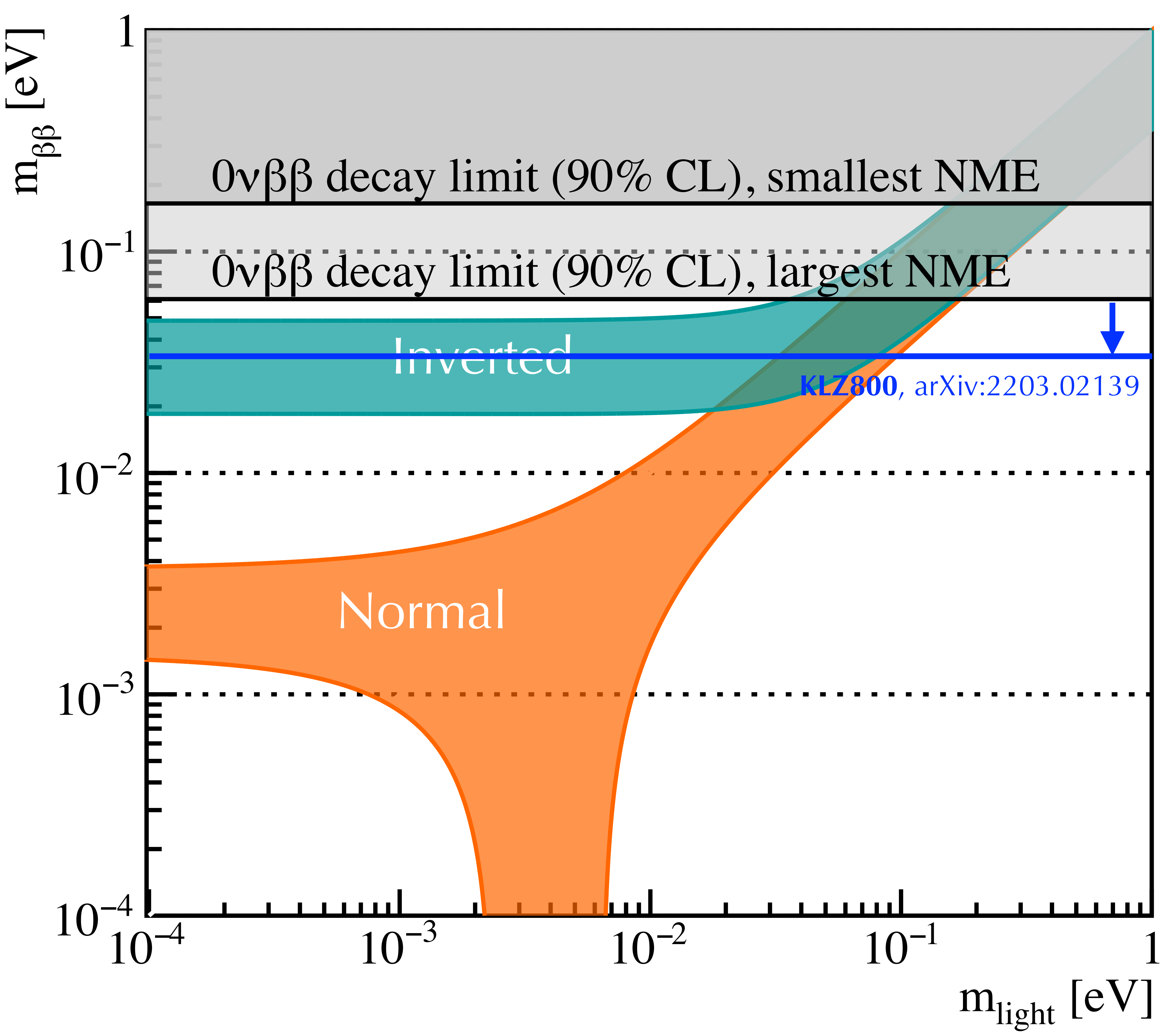
- Light left-handed neutrino exchange is a “minimalistic” extension of the Standard Model: it requires no specific new field or symmetry, only a Majorana mass term for the SM neutrino.
- Light left-handed neutrino exchange sets clear experimental goal posts:
    - IO: $T_{1/2} \lesssim 10^{28}$ years (10^{18} times the age of the universe)
    - NO: $T_{1/2} \lesssim 10^{30}$ years, modulo cancellations / flavor symmetries, etc.



Agostini, Benato, Detwiler, Menendez, and Vissani, arXiv:2202.01787

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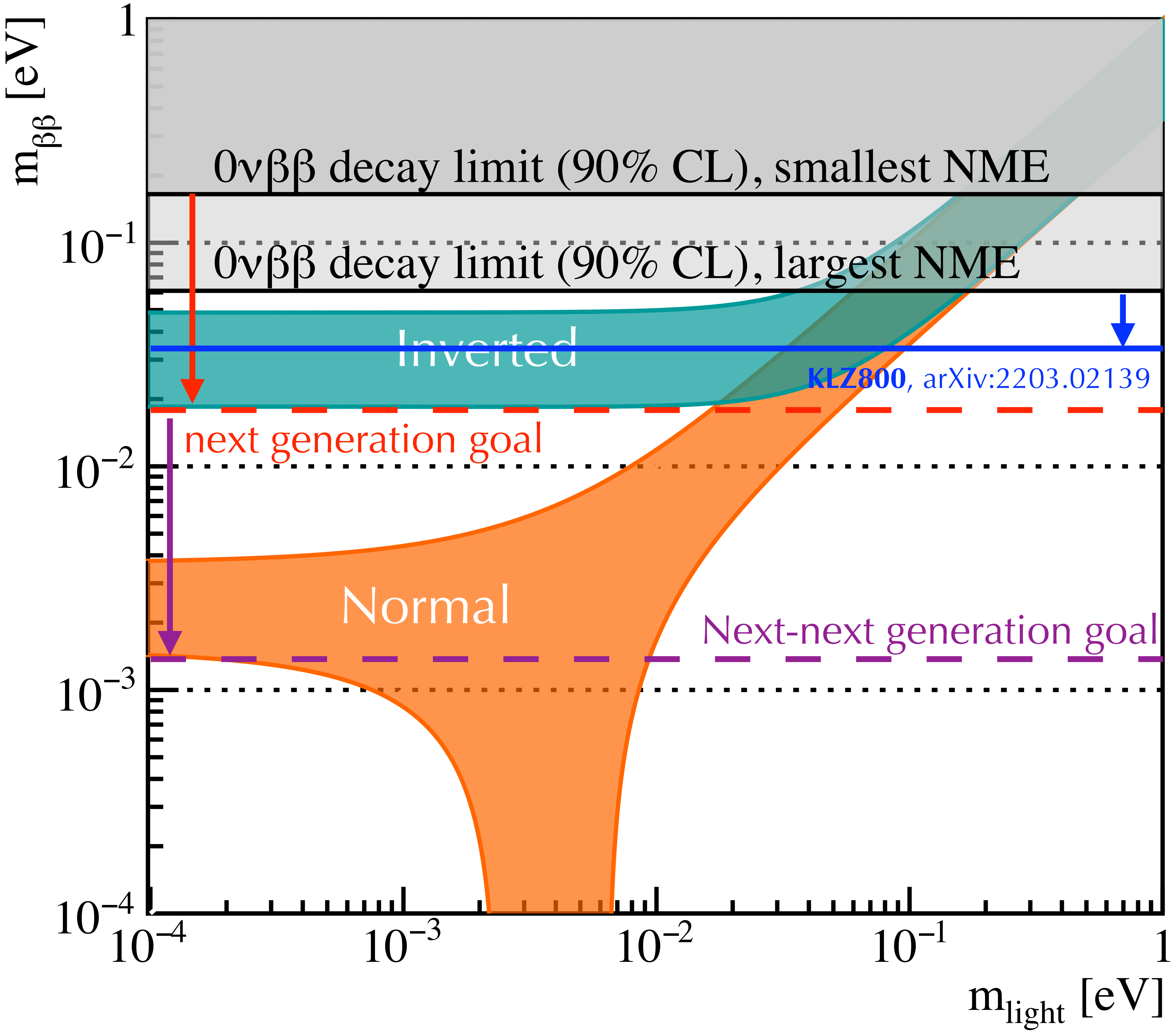
- Light left-handed neutrino exchange is a "minimalistic" extension of the Standard Model: it requires no specific new field or symmetry, only a Majorana mass term for the SM neutrino.
- Light left-handed neutrino exchange sets clear experimental goal posts:
  - IO: $T_{1/2} \lesssim 10^{28}$ years (10^{18} times the age of the universe)
  - NO: $T_{1/2} \lesssim 10^{30}$ years, modulo cancellations / flavor symmetries, etc.



Agostini, Benato, Detwiler, Menendez, and Vissani, arXiv:2202.01787

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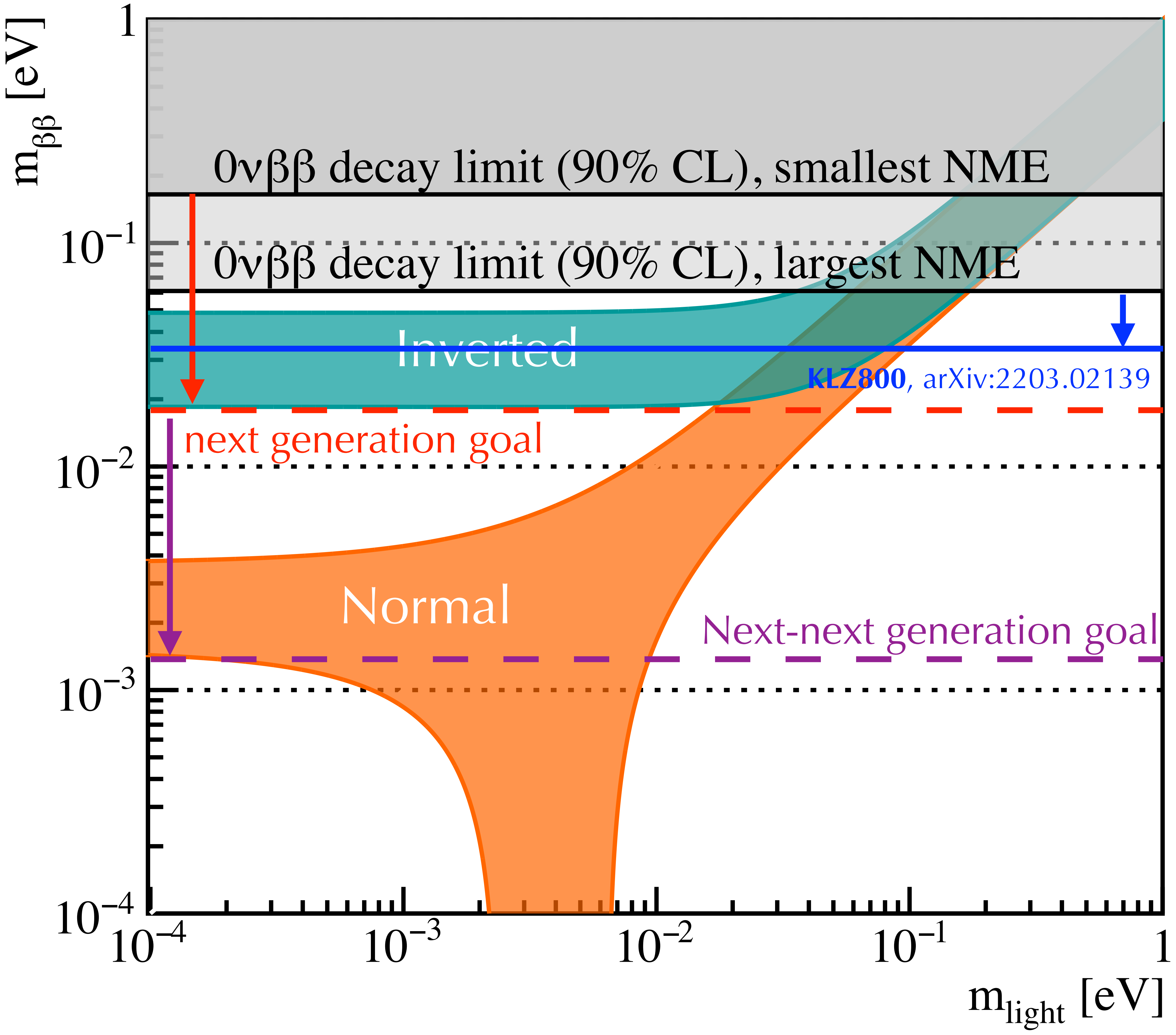
- A discovery will be most readily first interpreted in terms of light left-handed neutrino exchange, until evidence is available to suggest another mechanism may play a non-negligible role.



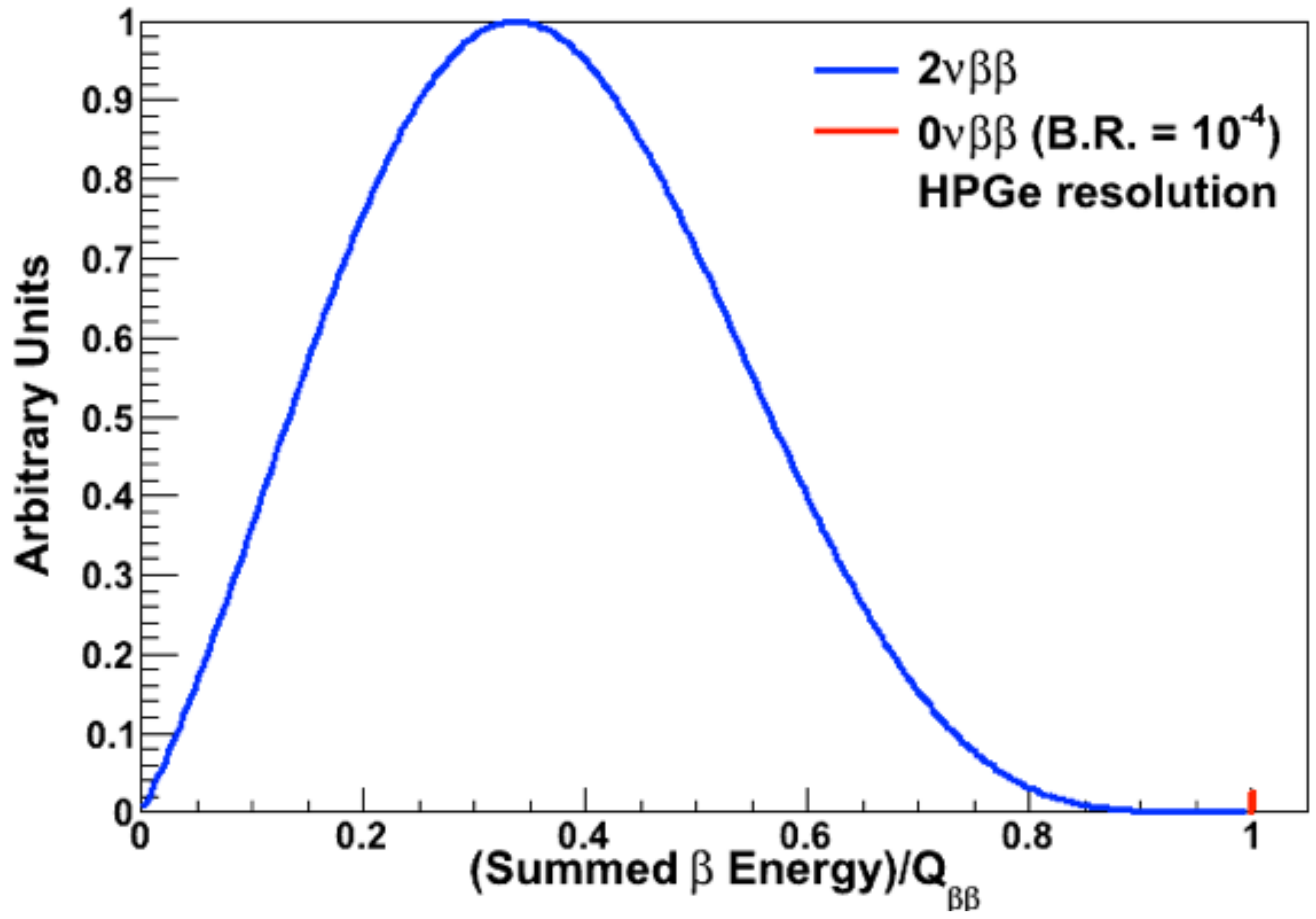
Agostini, Benato, Detwiler, Menendez, and Vissani, arXiv:2202.01787

Outline

- Introduction: a Creator's cookbook
- The global hunt for a "Little Bang"
- Searching for 0νββ decay in CUPID, LEGEND, and nEXO

Neutrinoless Double-Beta Decay

- *Must* measure summed electron kinetic energy to distinguish from Standard-Model 2ν process: search for a peak at $Q_{\beta\beta}$
- The peak in the plot exceeds current limits by ~1 order of magnitude



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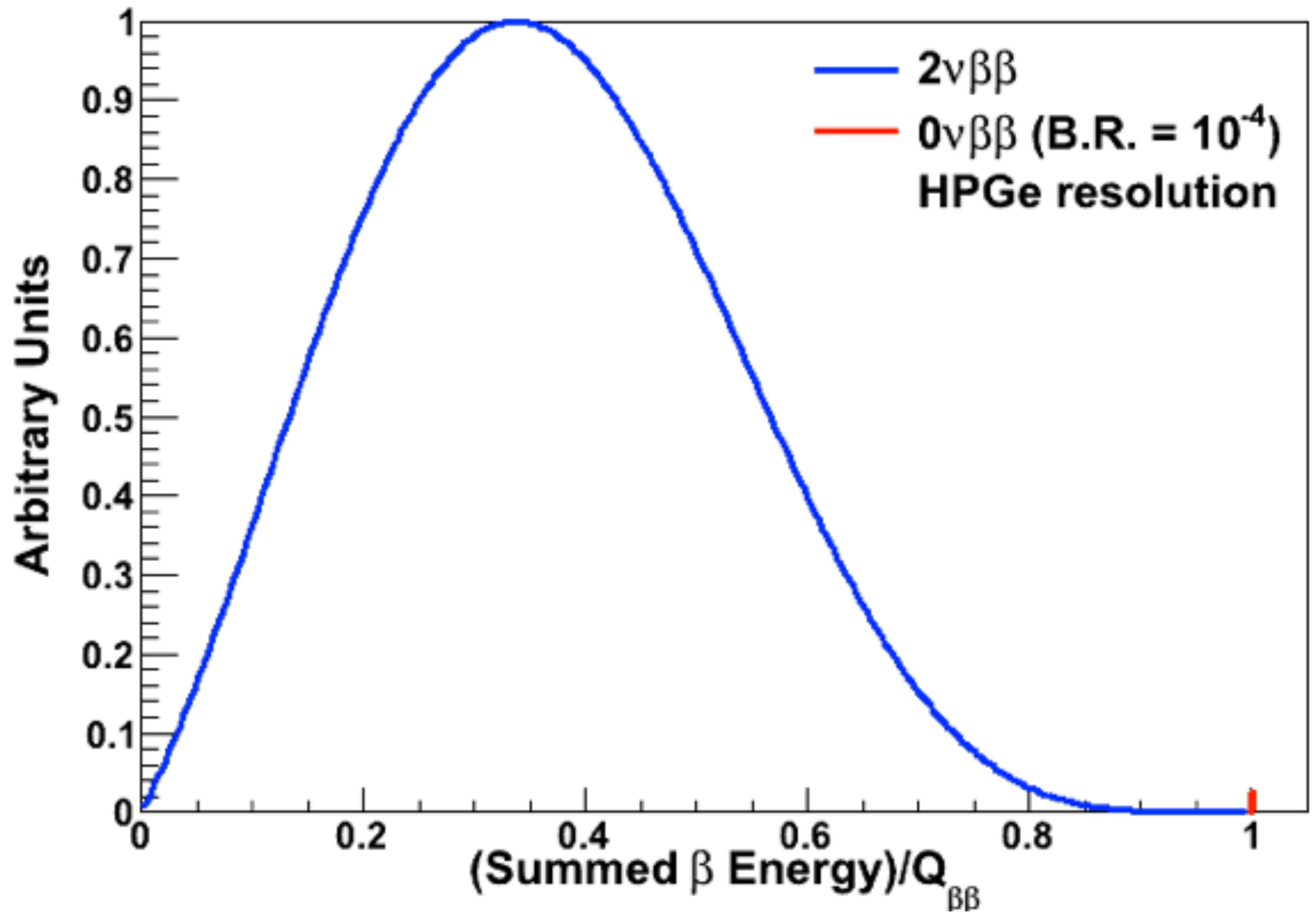
  - Get ~1 ton of ββ isotope 🤑
  - Instrument it so that it can detect 0νββ decay with good efficiency 🧙
  - Eliminate all random events that can mimic 0νββ 🤫
  - Wait 10 years 😑



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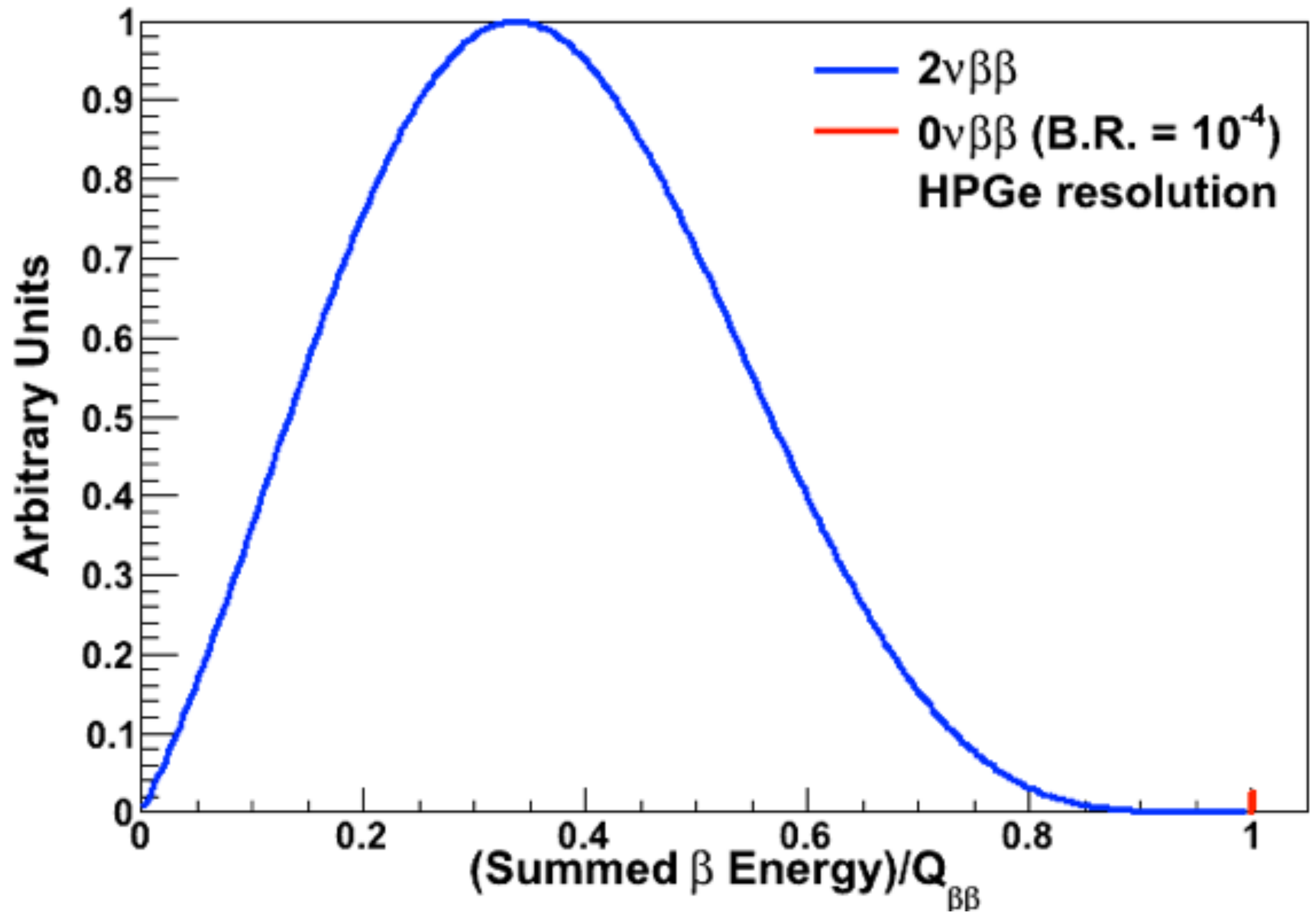
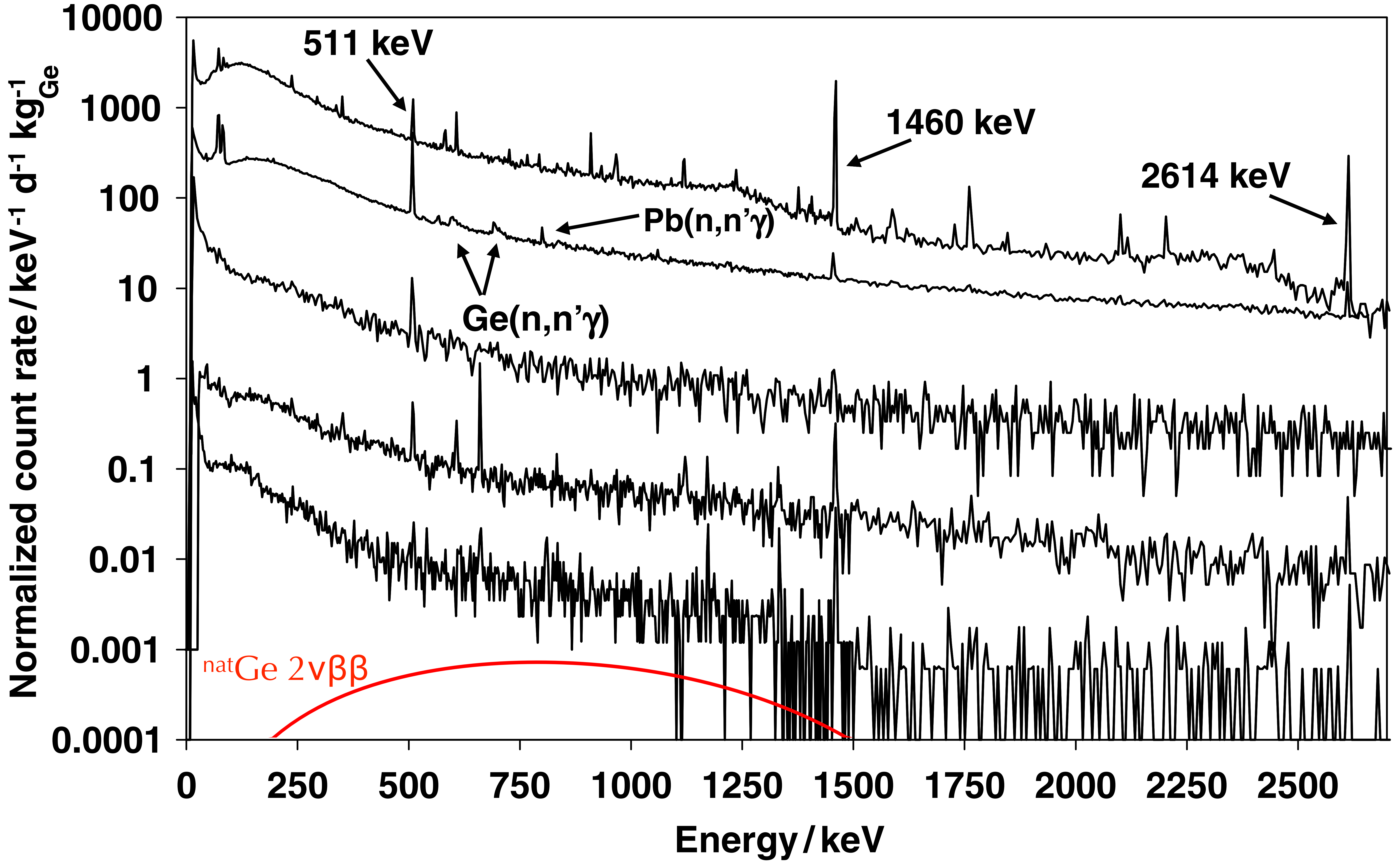


The Background Problem



Typical surface detector (HPGe): natural radioactivity dominates

Low-bg surface detector: muon and primary n cosmic rays

Low-bg detector, 125 mwe: muons

Low-bg detector, 500 mwe: muons + natural radioacitivity

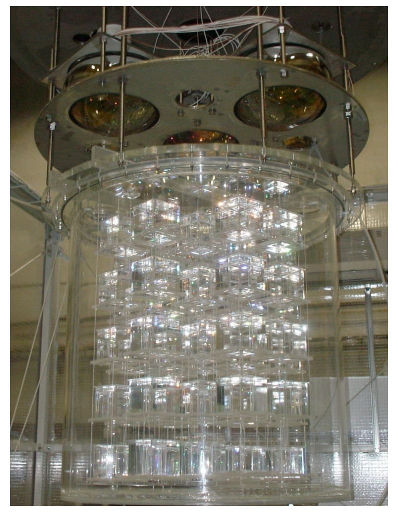
Ultra-low-bg detector, 3400 mwe: natural radioacitivity

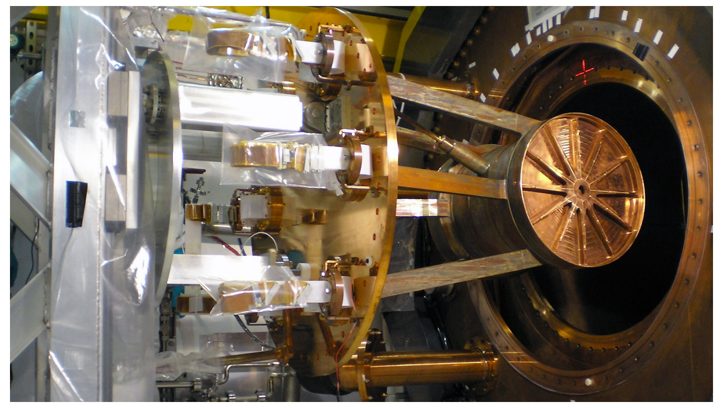
Need an underground detector made of pure materials, and typically need enrichment.

Experimental Techniques

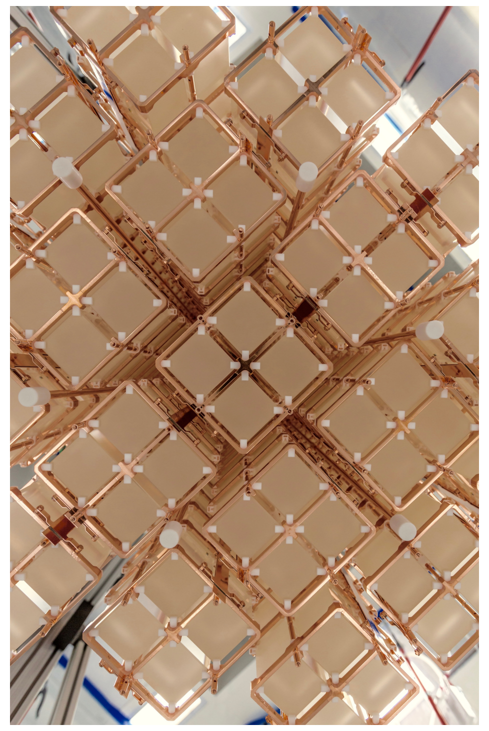
- Bolometers (CUORE/CUPID, AMoRE, CANDLES IV)
  - Measure *E* (σ ~ 0.1-0.3%) from phonons; granularity gives position info
  - Instrumenting with photon detectors for background rejection
- External trackers (NEMO3, SuperNEMO)
  - Trackers + calorimeters, measure *E* (σ ~ 3-10%) + tracks / positions + PID
- Scintillators (KamLAND-Zen, SNO+, CANDLES-III, Theia, ZICOS)
  - Measure *E* (σ ~ 3-10%) + position from scintillation light; some PID
- Semiconductors (COBRA, MAJORANA, GERDA, LEGEND)
  - Measure *E* (σ ~ 0.05-0.3%) from ionization; some tracking / position sensitivity
- TPCs (EXO, NEXT, PandaX, AXEL, NvDEx, DARWIN, LZ)
  - Collect scintillation + ionization: measure *E* (σ ~0.4-3%) + tracks / position + PID

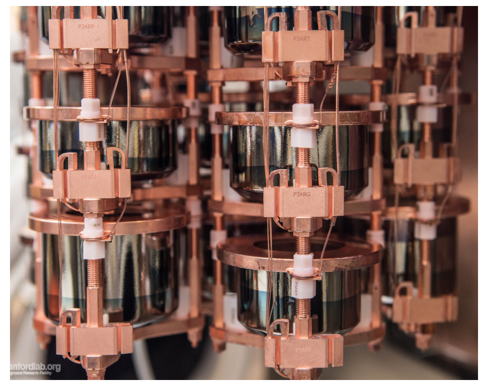

KamLAND-Zen

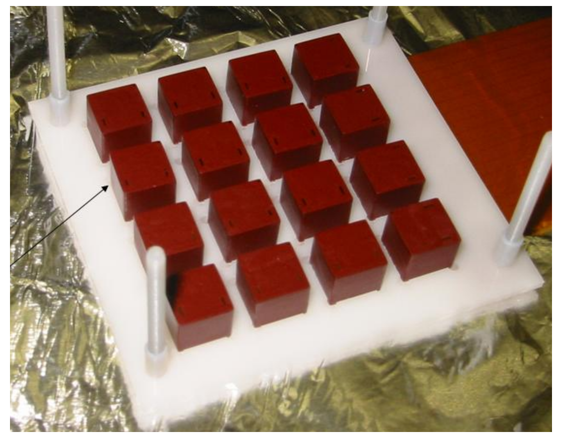

CANDLES

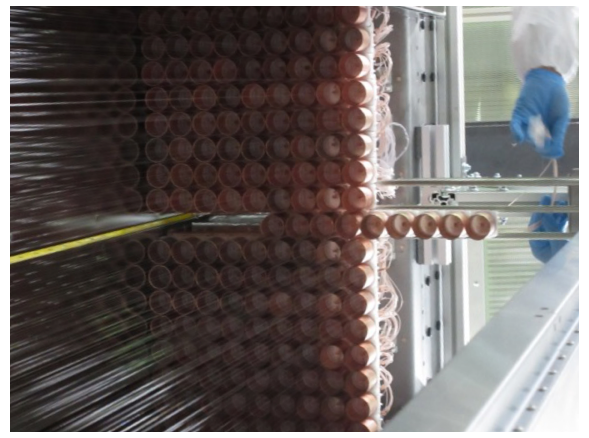

EXO-200


NEXT-100


CUORE


MAJORANA


COBRA


SuperNEMO


NEMO3

Experimental Sensitivity

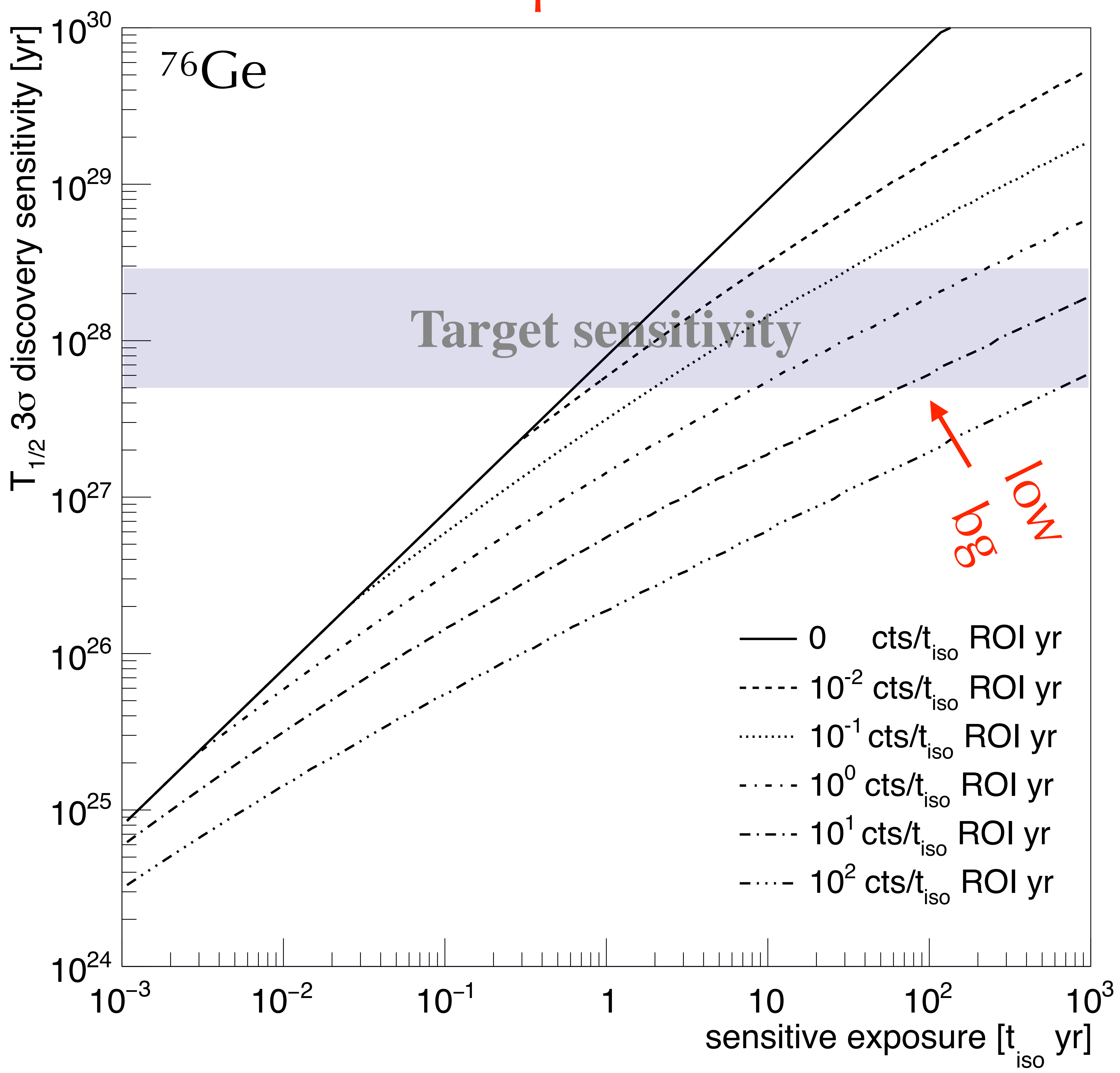
- Effectively a Poisson counting experiment near $Q_{\beta\beta}$
- Relevant parameters: sensitive exposure and sensitive background

$$\mathcal{E} = \epsilon \, m_{iso}^{FV} t \qquad \mathcal{B} = N_{bg}/\mathcal{E}$$

- Discovery sensitivity: the value of $T_{1/2}$ for which an experiment has a 50% chance to observe a signal above background with 3σ significance:

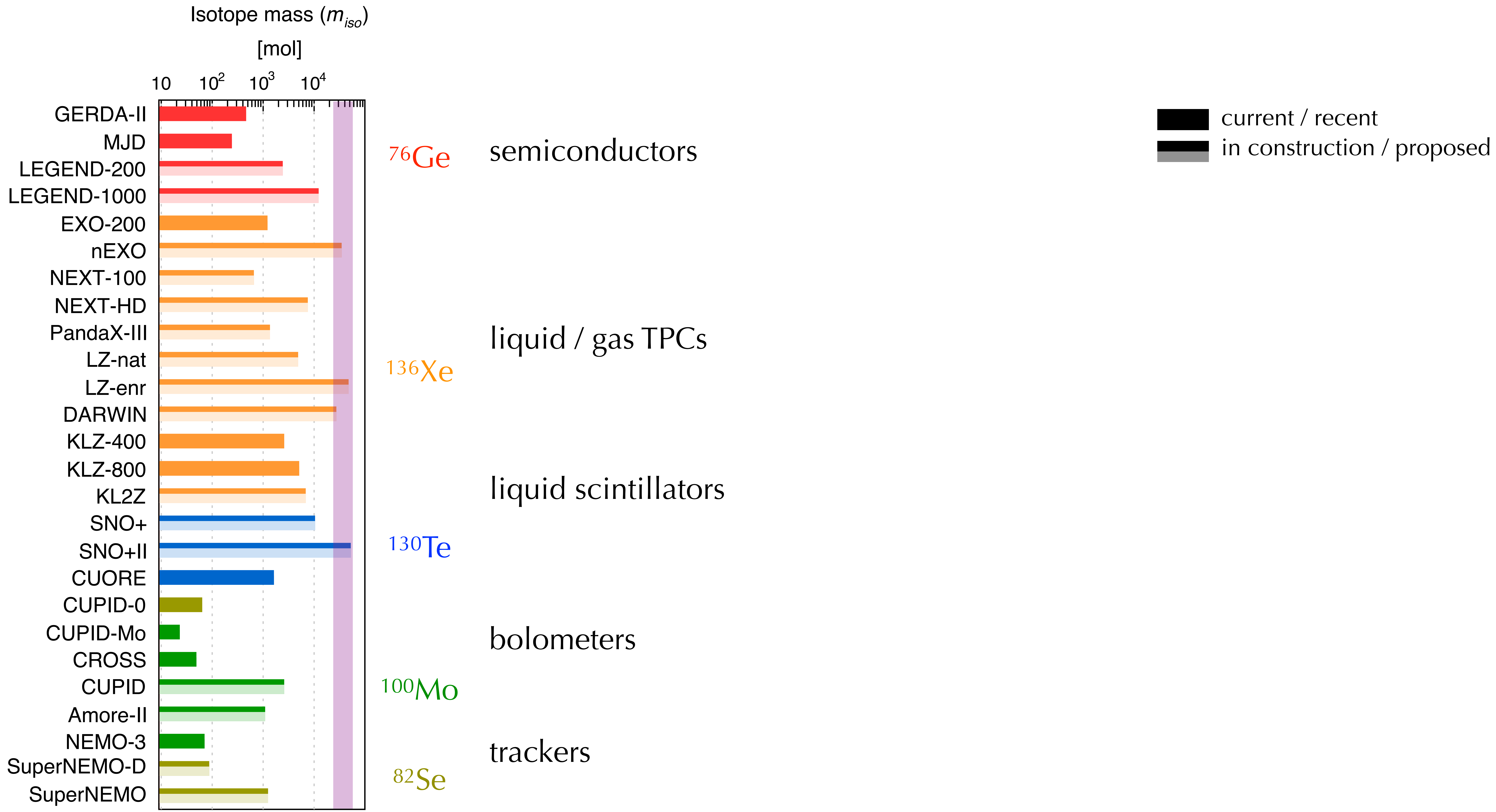
$$T_{1/2}^{3\sigma} = \ln 2 \frac{N_A \mathcal{E}}{m_a S_{3\sigma}(\mathcal{B}\mathcal{E})}$$

Requirements:

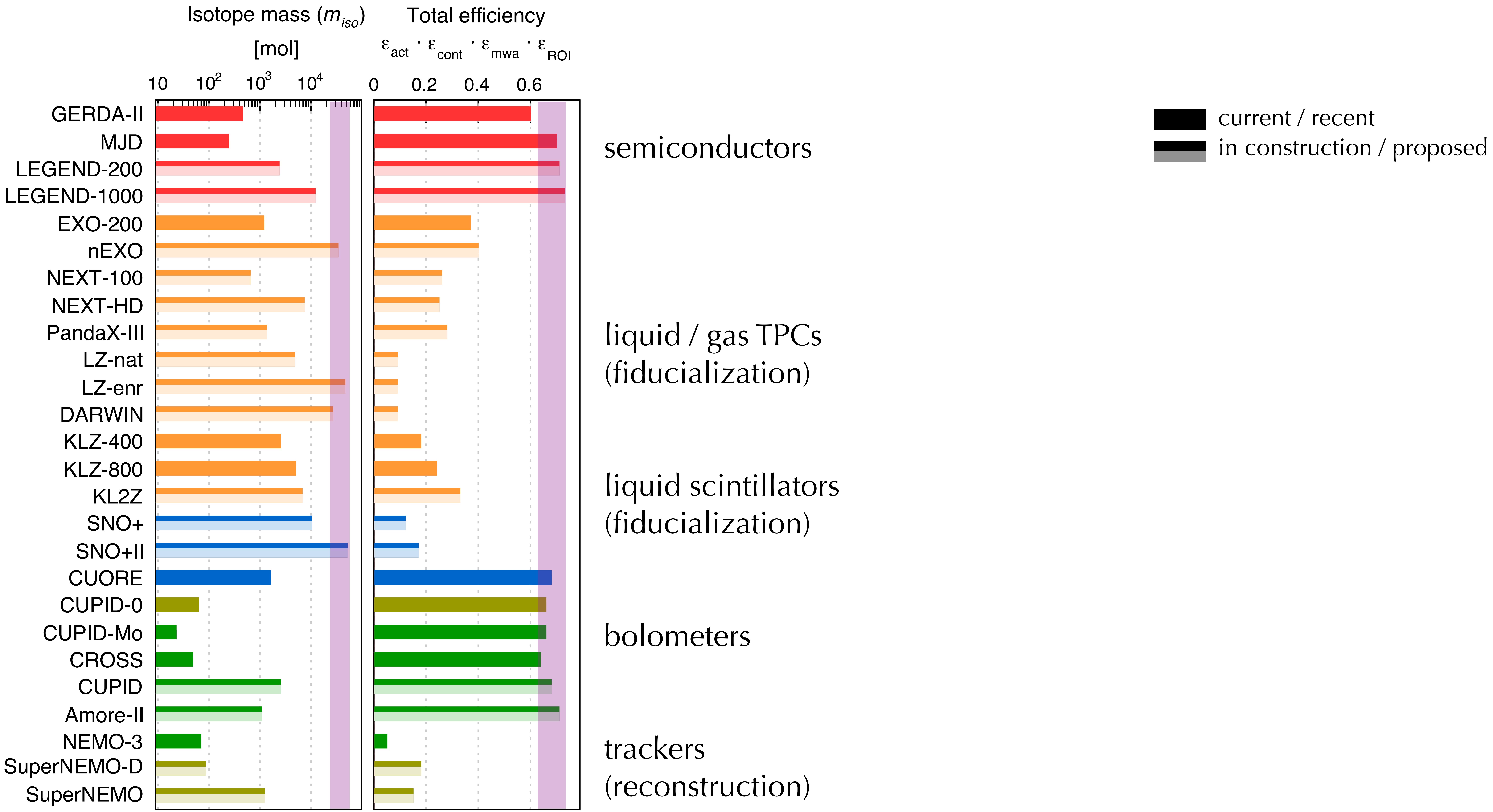


high exposure →

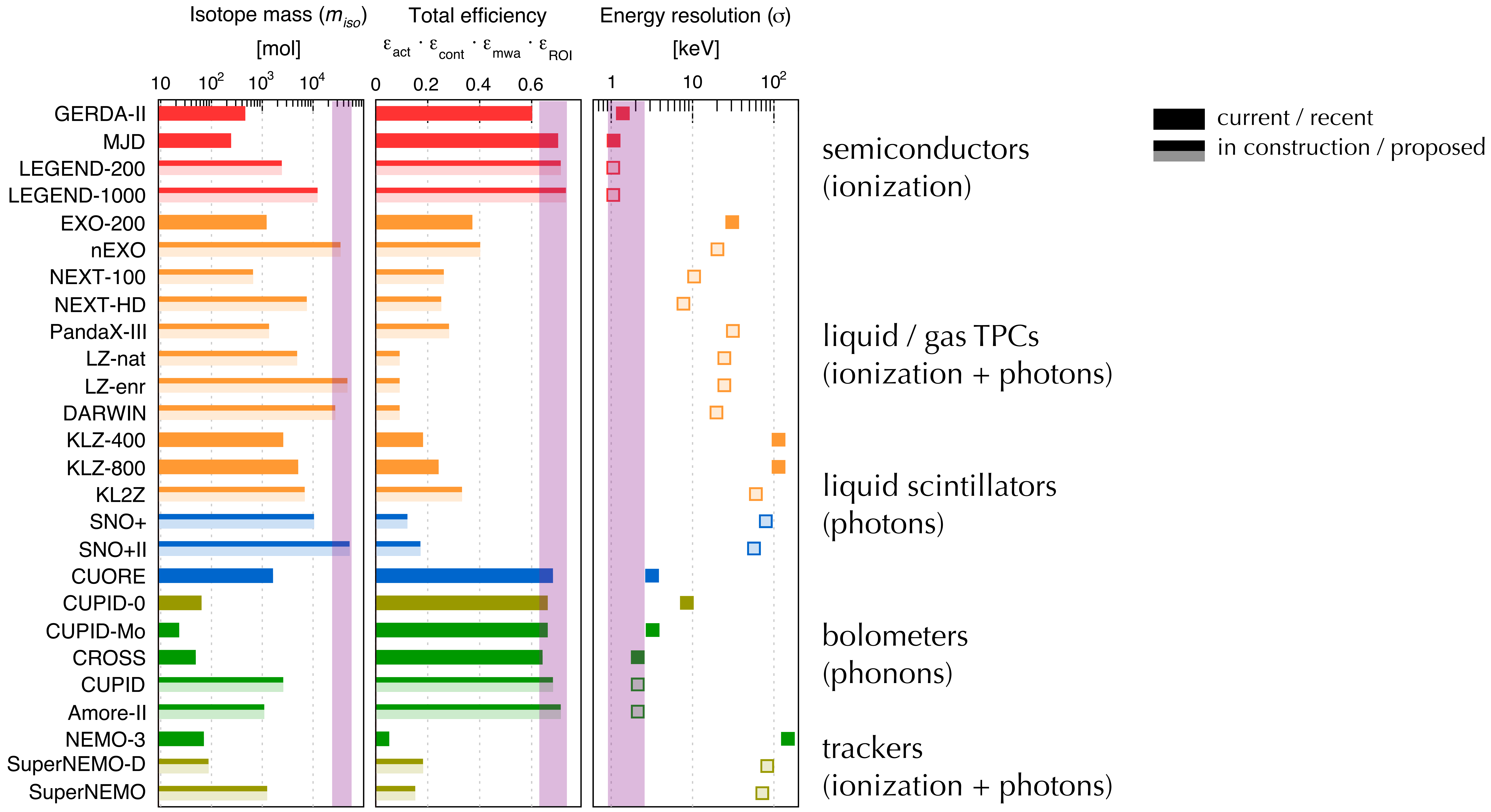
Agostini, Benato, Detwiler, PRD **96**, 053001 (2017)



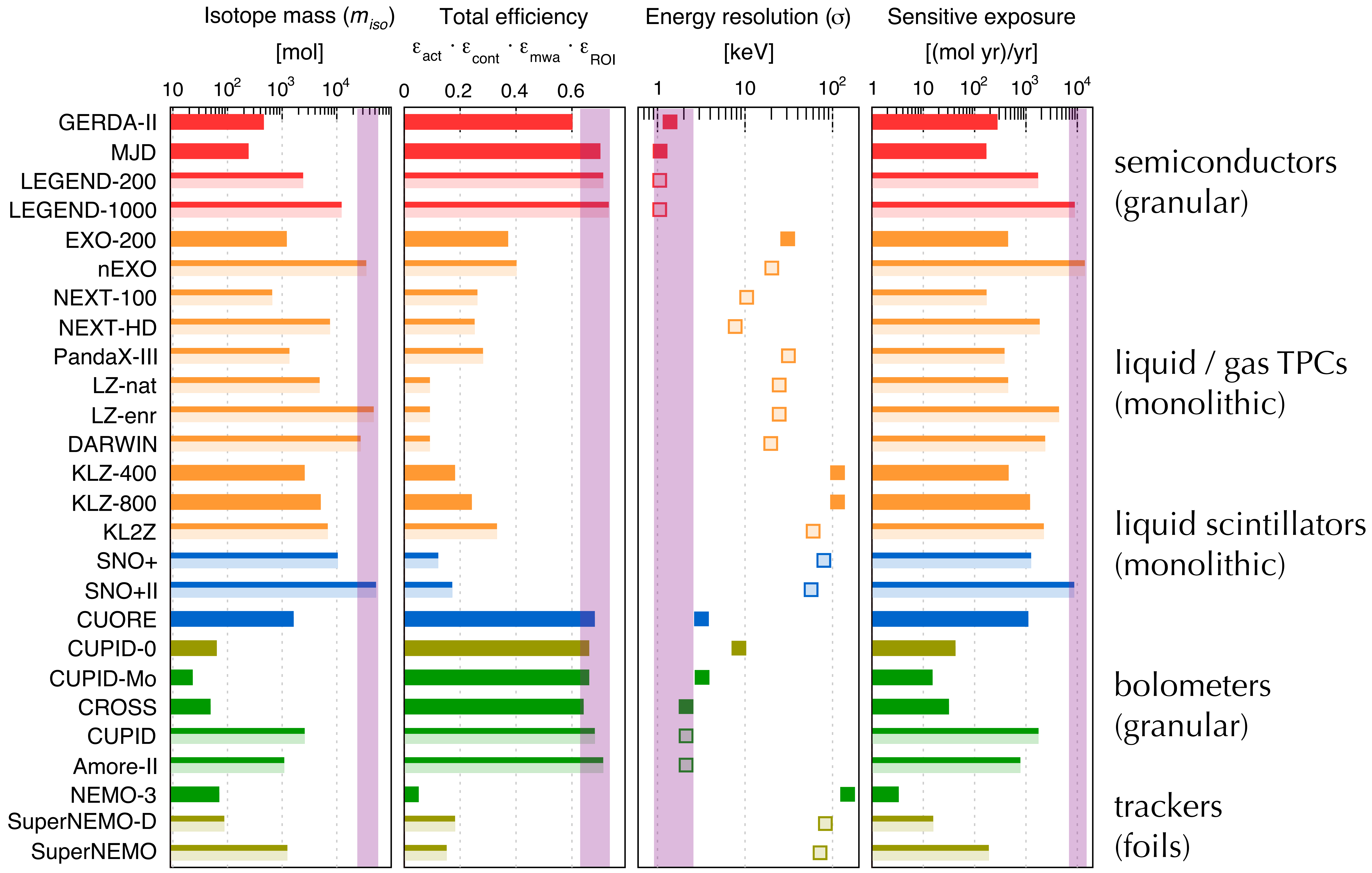
Agostini, Benato, Detwiler, Menendez, and Vissani, arXiv:2202.01787



Isotope mass (m_{iso})
[mol]
Total efficiency
$\varepsilon_{act} \cdot \varepsilon_{cont} \cdot \varepsilon_{mwa} \cdot \varepsilon_{ROI}$
10
10^2
10^3
10^4
0
0.2
0.4
0.6
GERDA-II
MJD
LEGEND-200
LEGEND-1000
EXO-200
nEXO
NEXT-100
NEXT-HD
PandaX-III
LZ-nat
LZ-enr
DARWIN
KLZ-400
KLZ-800
KL2Z
SNO+
SNO+II
CUORE
CUPID-0
CUPID-Mo
CROSS
CUPID
Amore-II
NEMO-3
SuperNEMO-D
SuperNEMO
semiconductors
liquid / gas TPCs
(fiducialization)
liquid scintillators
(fiducialization)
bolometers
trackers
(reconstruction)
current / recent
in construction / proposed



Agostini, Benato, Detwiler, Menendez, and Vissani, arXiv:2202.01787



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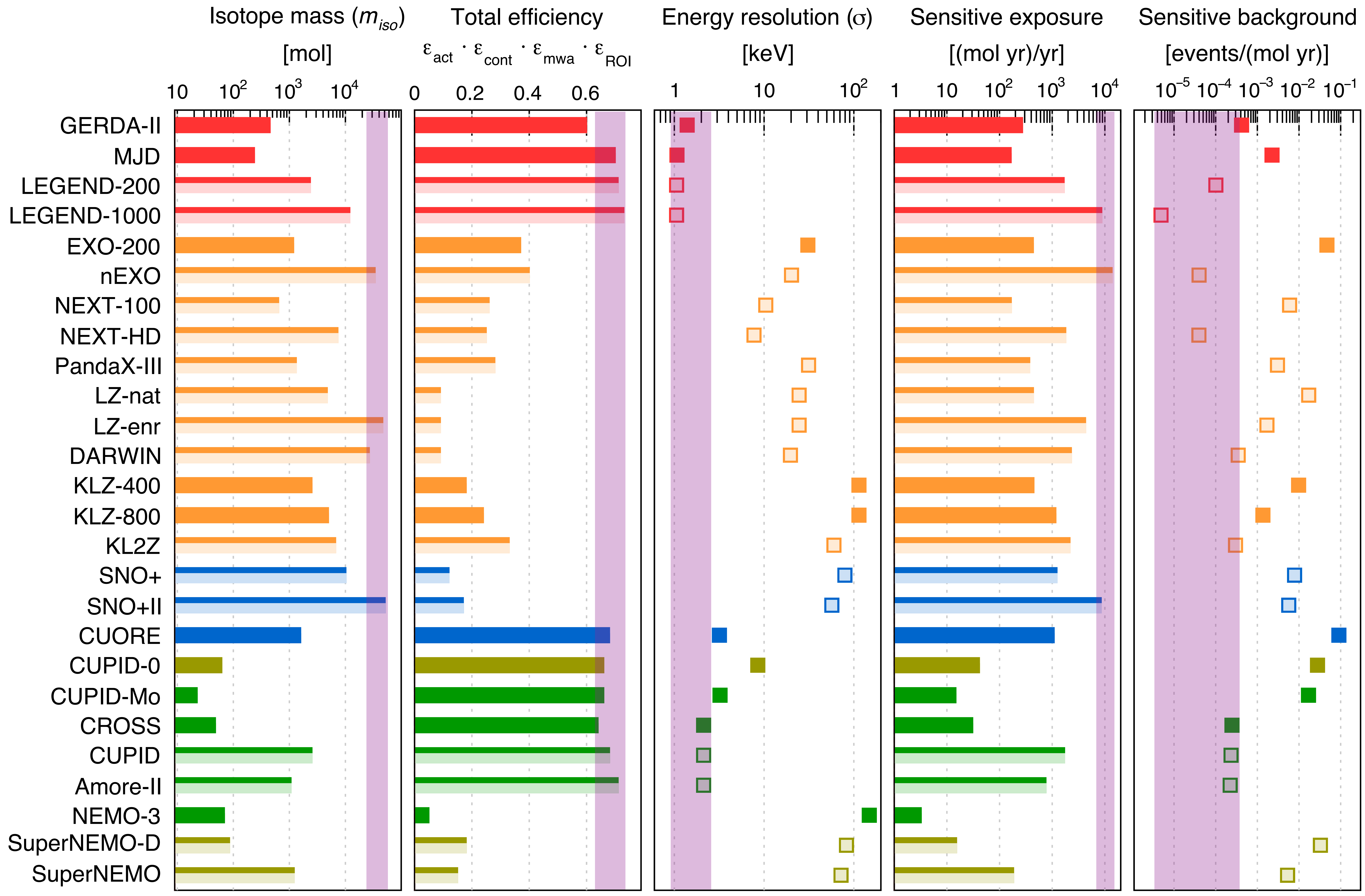
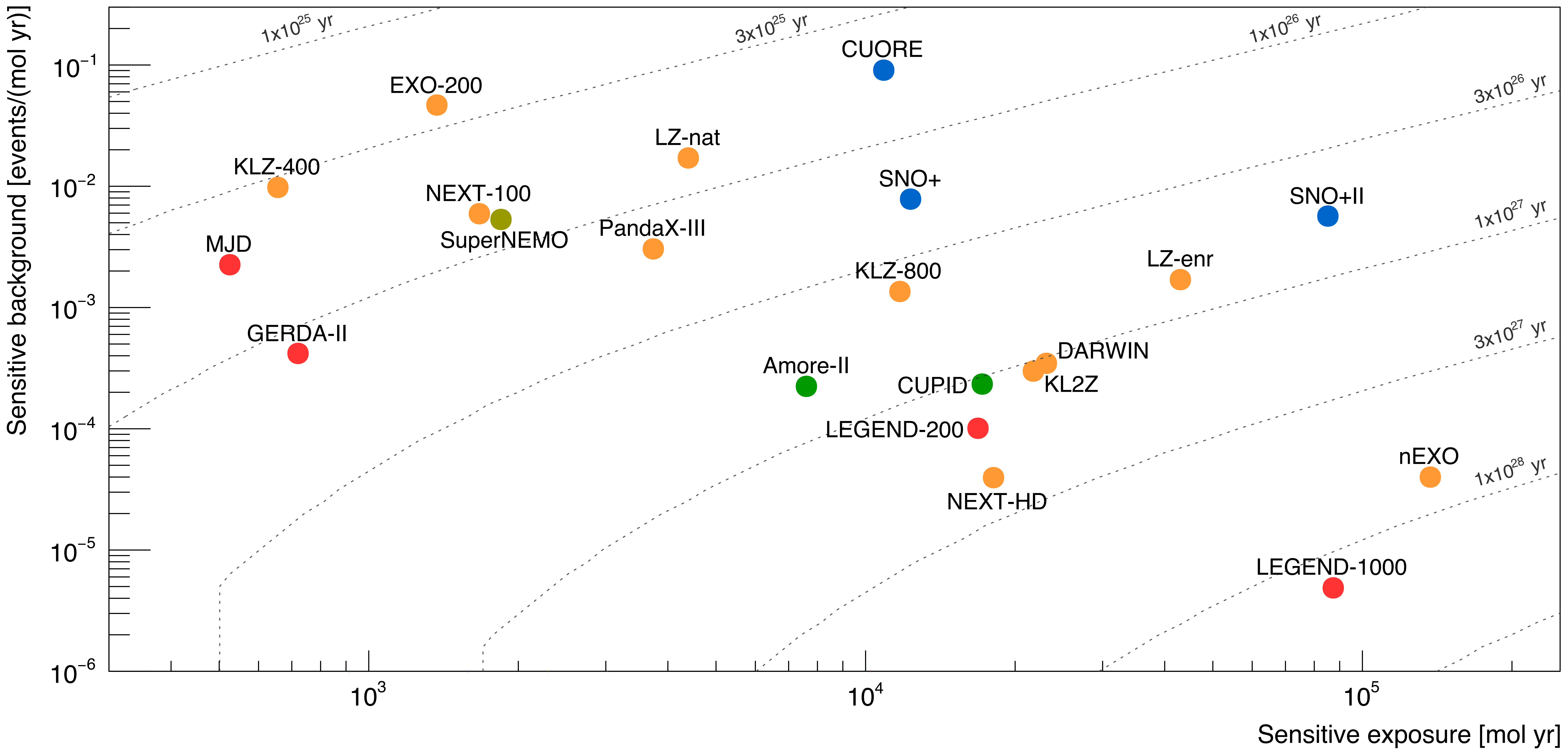


Isotope mass (m_{iso})
[mol]
Total efficiency
$\varepsilon_{act} \cdot \varepsilon_{cont} \cdot \varepsilon_{mwa} \cdot \varepsilon_{ROI}$
Energy resolution (σ)
[keV]
Sensitive exposure
[(mol yr)/yr]
Sensitive background
[events/(mol yr)]
10
10^2
10^3
10^4
0
0.2
0.4
0.6
1
10
10^2
1
10
10^2
10^3
10^4
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
GERDA-II
MJD
LEGEND-200
LEGEND-1000
EXO-200
nEXO
NEXT-100
NEXT-HD
PandaX-III
LZ-nat
LZ-enr
DARWIN
KLZ-400
KLZ-800
KL2Z
SNO+
SNO+II
CUORE
CUPID-0
CUPID-Mo
CROSS
CUPID
Amore-II
NEMO-3
SuperNEMO-D
SuperNEMO

Discovery Sensitivities

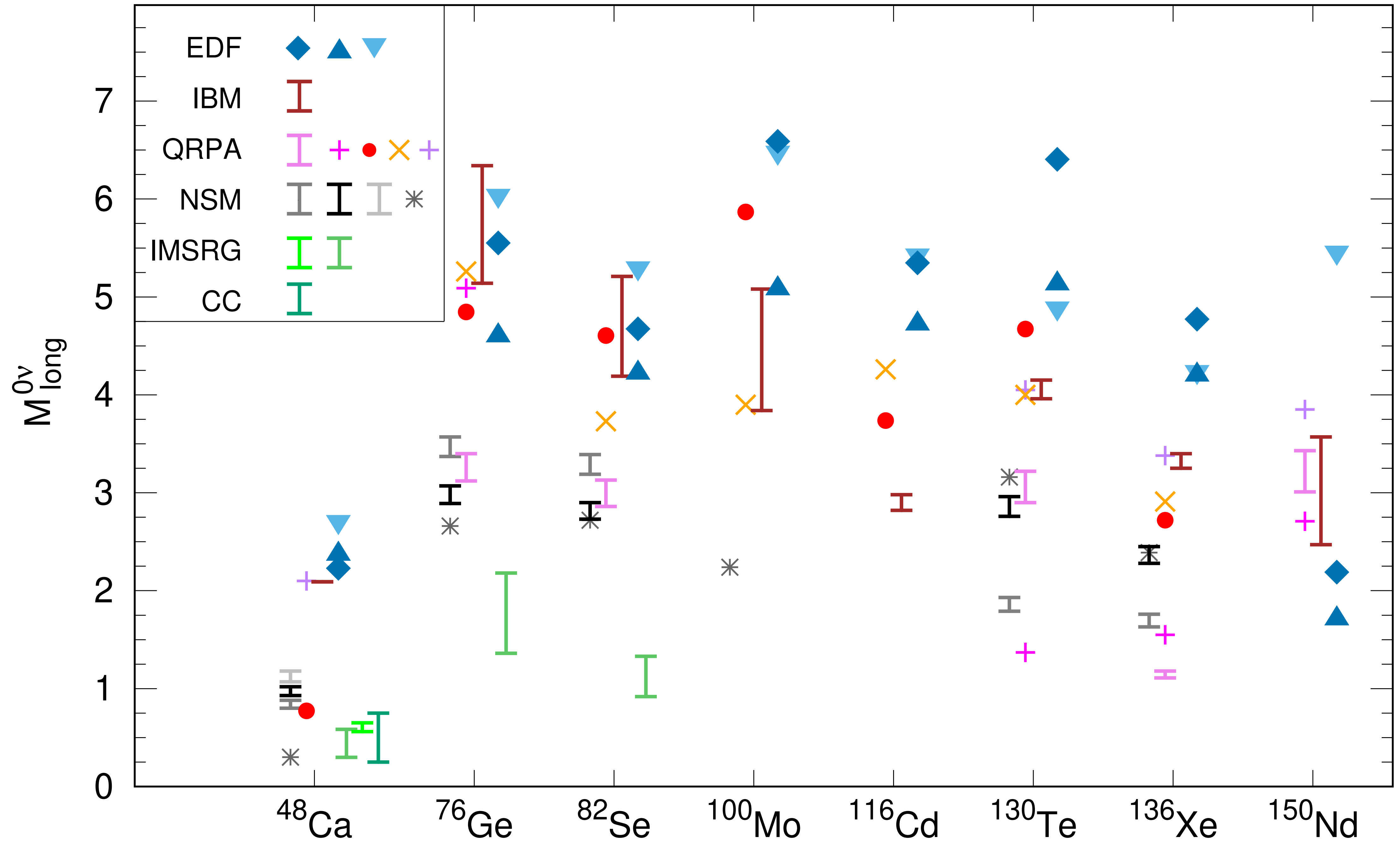


Agostini, Benato, Detwiler, Menendez, and Vissani, arXiv:2202.01787

Nuclear Matrix Elements

- Historically:
  - Large disagreements (factor of ~3)
  - Limited computation ability
  - Unknown "quenching"
  - Limited uncertainty characterization

$$\Gamma^{0\nu}_{1/2} = G^{0\nu} \, | M^{0\nu} |^2 m^2_{\beta\beta}$$



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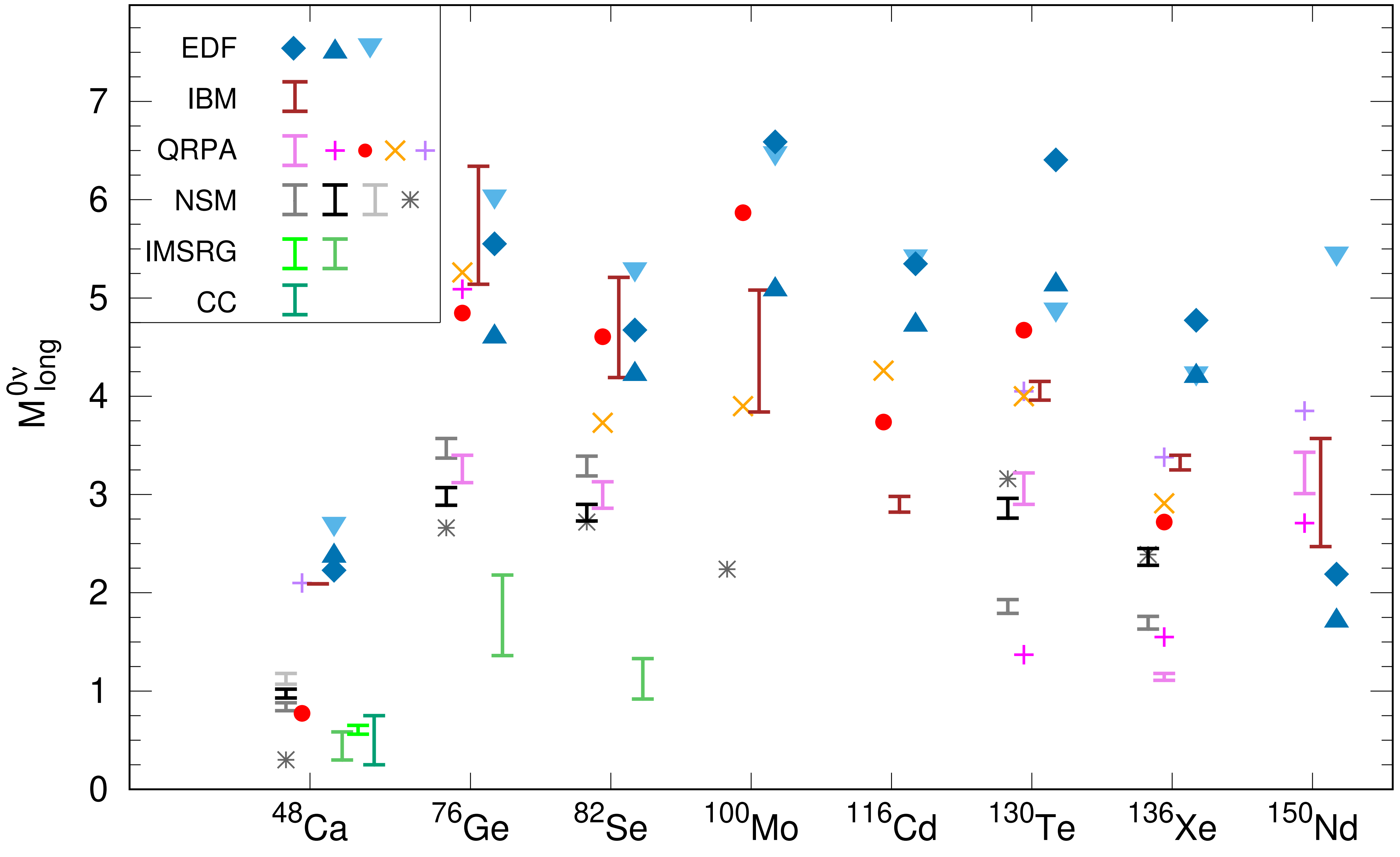

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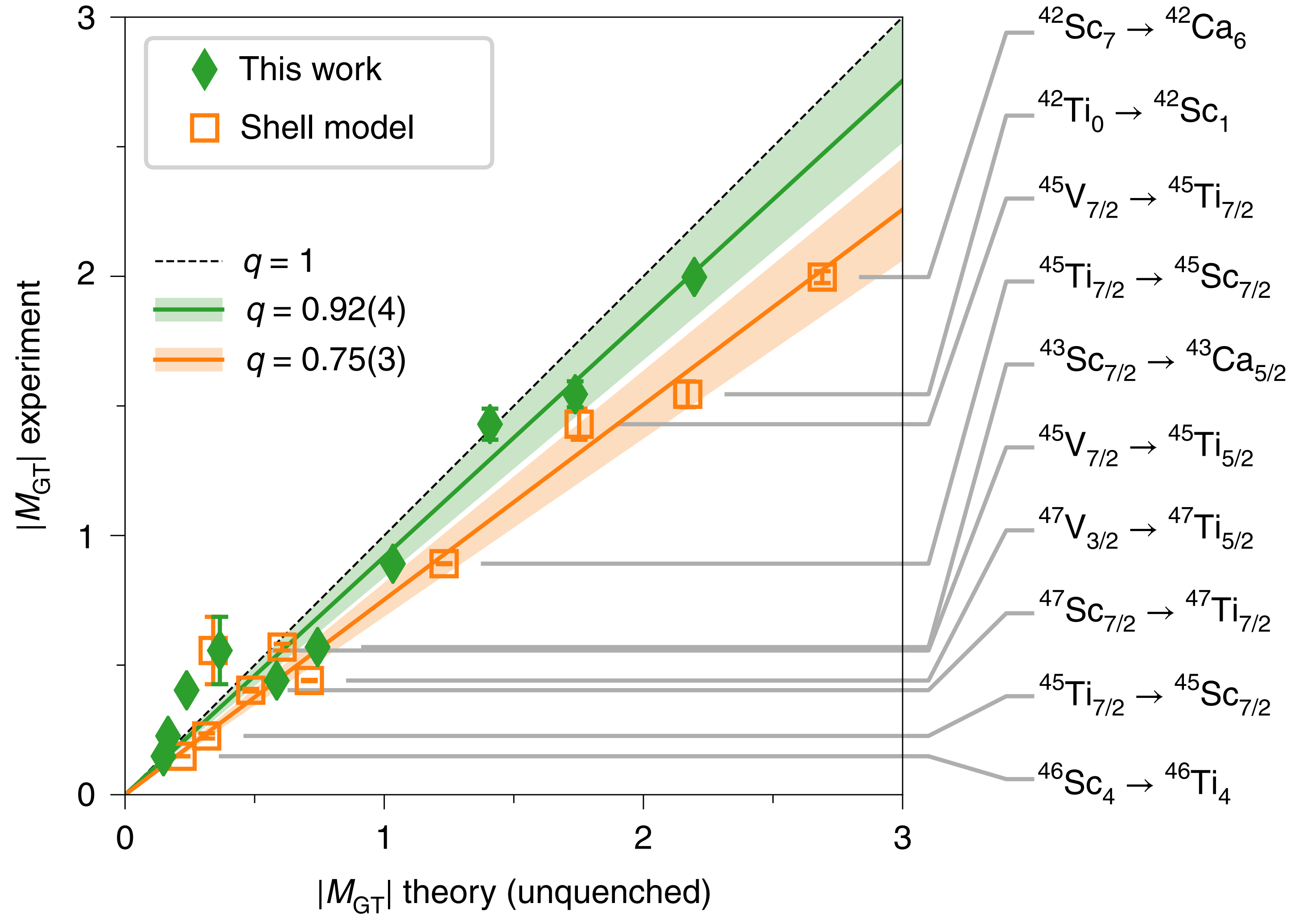
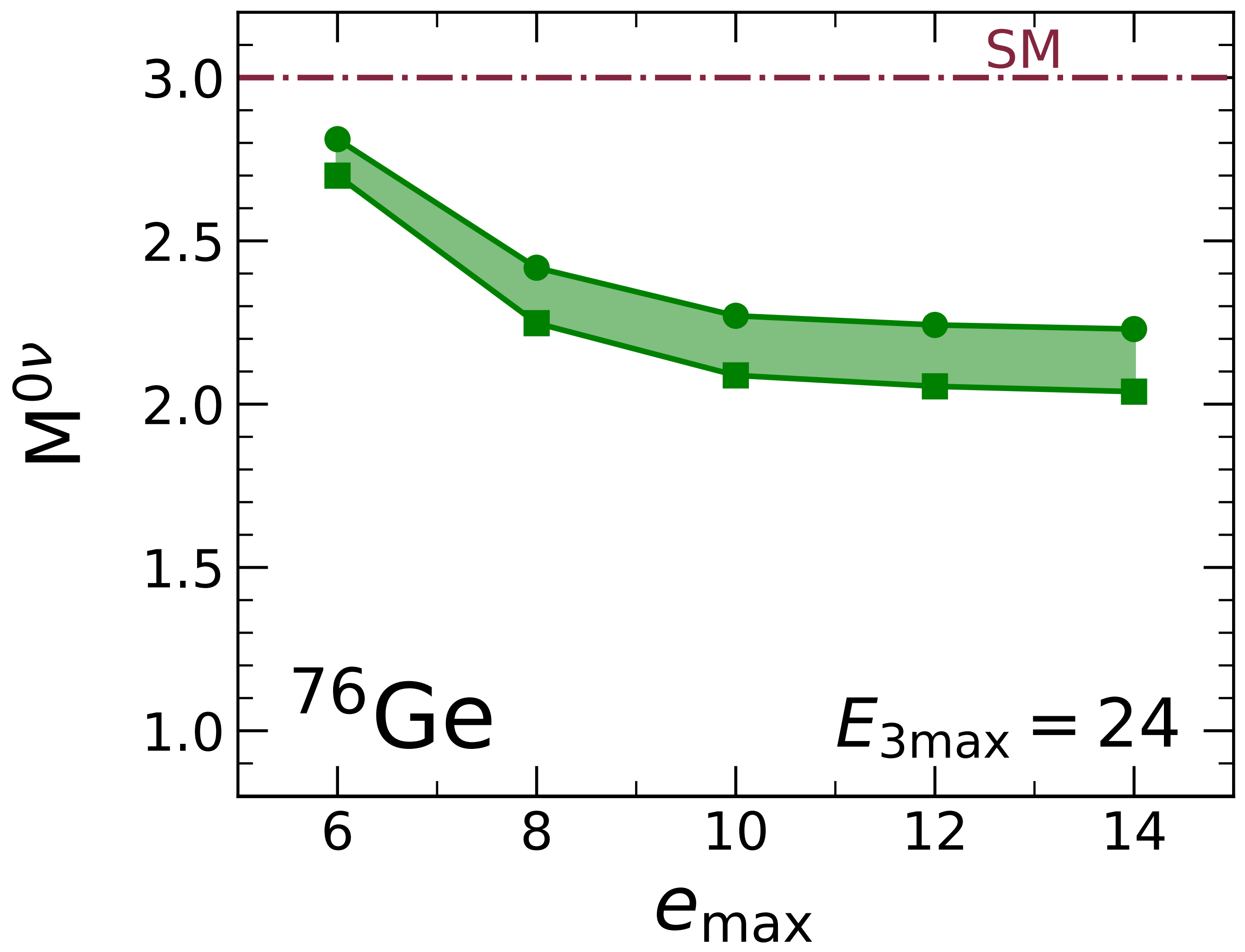
    - First 0νββ estimates: O(30%) reduction





Gysbers *et al.*, Nature Phys. **15**, 428 (2019); Belle *et al.*, PRL **126**, 042502 (2021)

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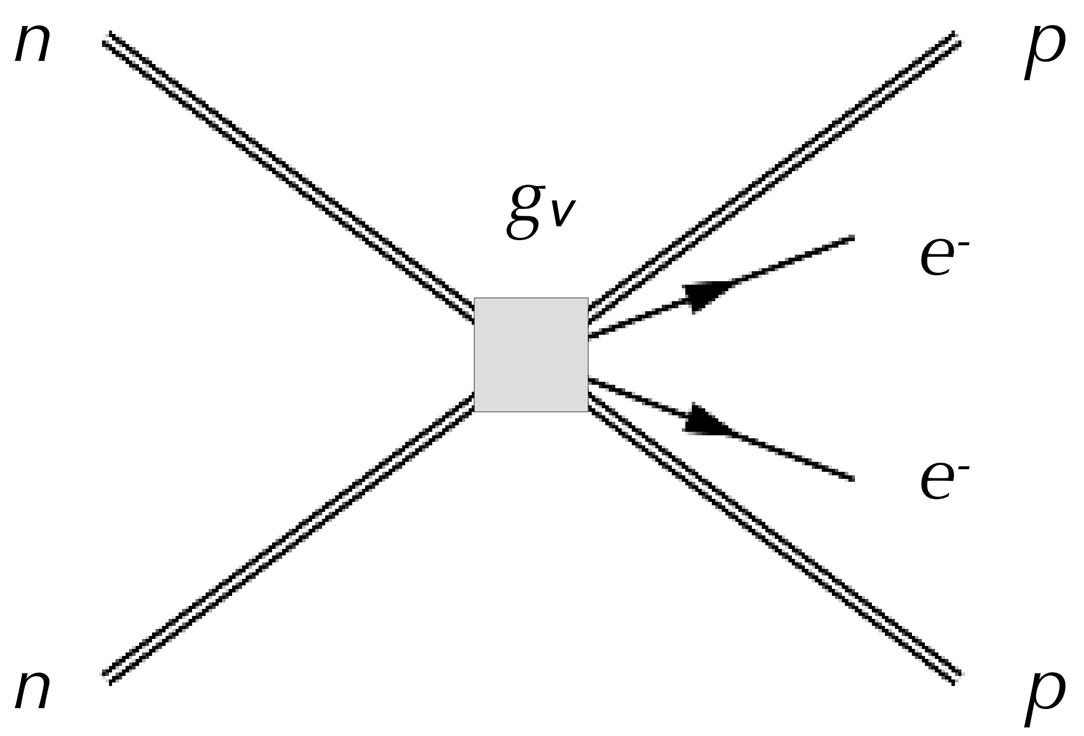
    - First 0νββ estimates: O(30%) reduction
  - Identified a new contribution (“contact term”)
    - First estimates: O(30%) increase

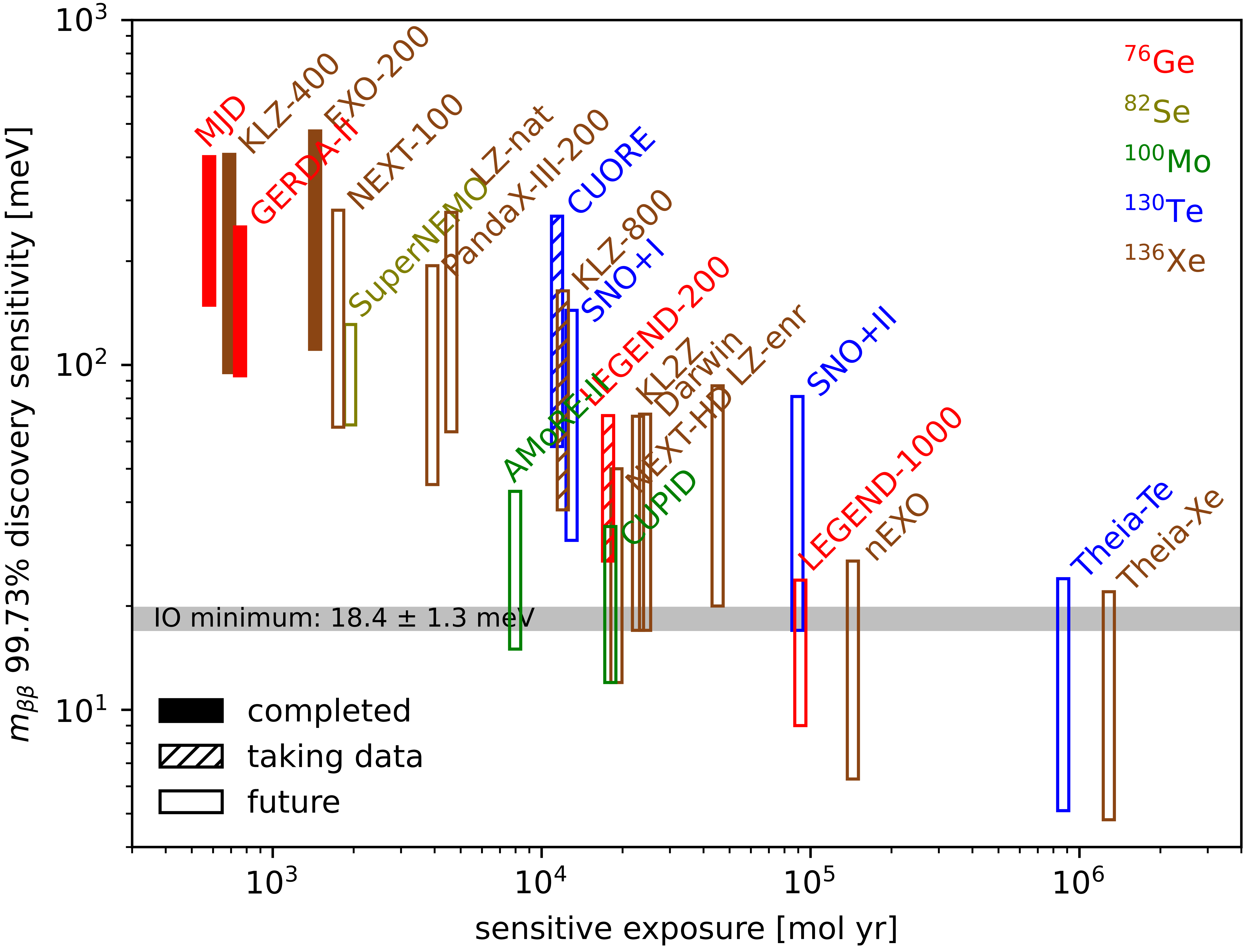


$$T_{1/2}^{-1} = G_{01}\, g_A^4 \left| M_{\text{long}}^{0\nu} + M_{\text{short}}^{0\nu} \right|^2 \frac{m_{\beta\beta}^2}{m_e^2}$$

Nucleus	pnQRPA			NSM		
	$M_{\rm L}^{0\nu}$	$M_{\rm S}^{0\nu}$	$M_{\rm S}^{0\nu}/M_{\rm L}^{0\nu}(\%)$	$M_{\rm L}^{0\nu}$	$M_{\rm S}^{0\nu}$	$M_{\rm S}^{0\nu}/M_{\rm L}^{0\nu}(\%)$
^{48}Ca				0.96 − 1.05	0.22 − 0.65	23 − 62
^{76}Ge	4.72 − 5.22	1.49 − 3.80	32 − 73	3.34 − 3.54	0.52 − 1.49	15 − 42
^{82}Se	4.20 − 4.61	1.27 − 3.24	30 − 70	3.20 − 3.38	0.48 − 1.38	15 − 41
^{96}Zr	4.22 − 4.63	1.24 − 3.19	29 − 69			
^{100}Mo	3.40 − 3.95	1.66 − 4.26	49 − 108			
^{116}Cd	4.24 − 4.57	1.10 − 2.80	26 − 61			
^{124}Sn	4.72 − 5.29	1.69 − 4.28	36 − 81	3.20 − 3.41	0.54 − 1.58	17 − 46
^{128}Te	3.92 − 4.50	1.37 − 3.45	35 − 77	3.56 − 3.80	0.61 − 1.76	17 − 46
^{130}Te	3.46 − 3.89	1.18 − 3.05	34 − 77	3.26 − 3.48	0.57 − 1.64	17 − 47
^{136}Xe	2.53 − 2.80	0.76 − 1.95	30 − 70	2.62 − 2.79	0.45 − 1.31	17 − 47

Cirigliano *et al.*, PRL **120**, 202001 (2018); Jokiniemi *et al.*, PLB **823**, 136720 (2021)

Discovery Sensitivities



ABDMV, arXiv:2202.01787; Saldanha; 0νββ whitepaper

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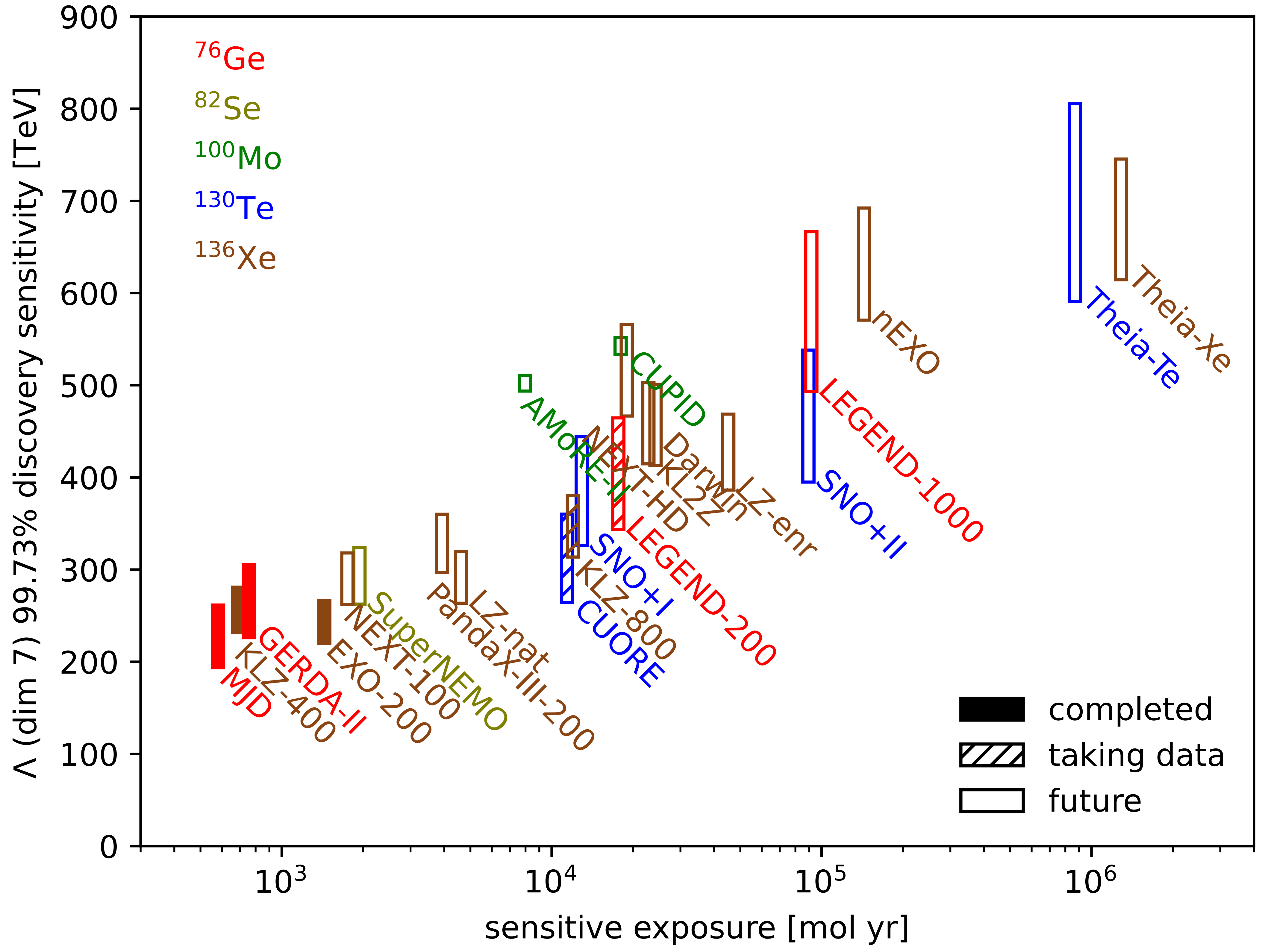

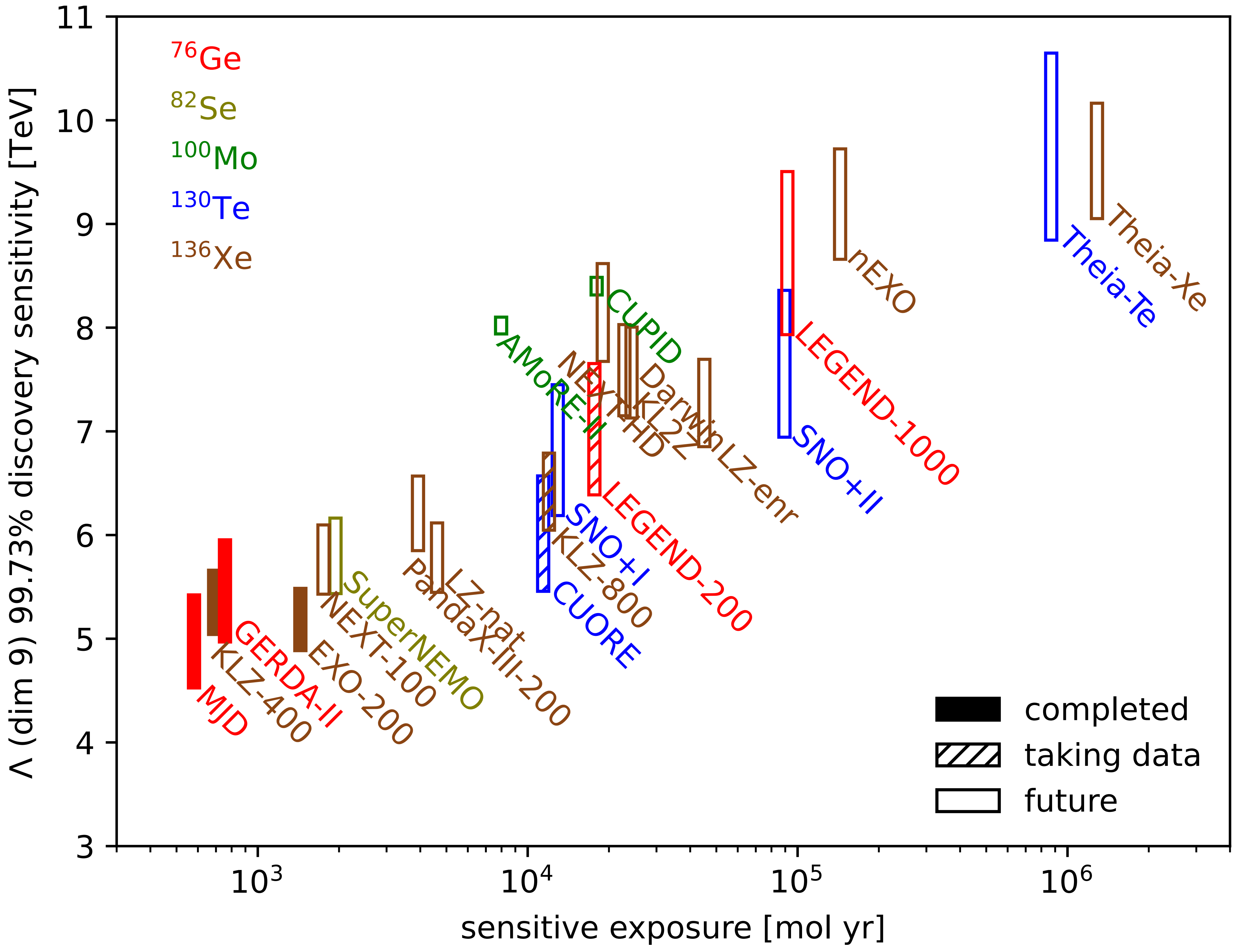

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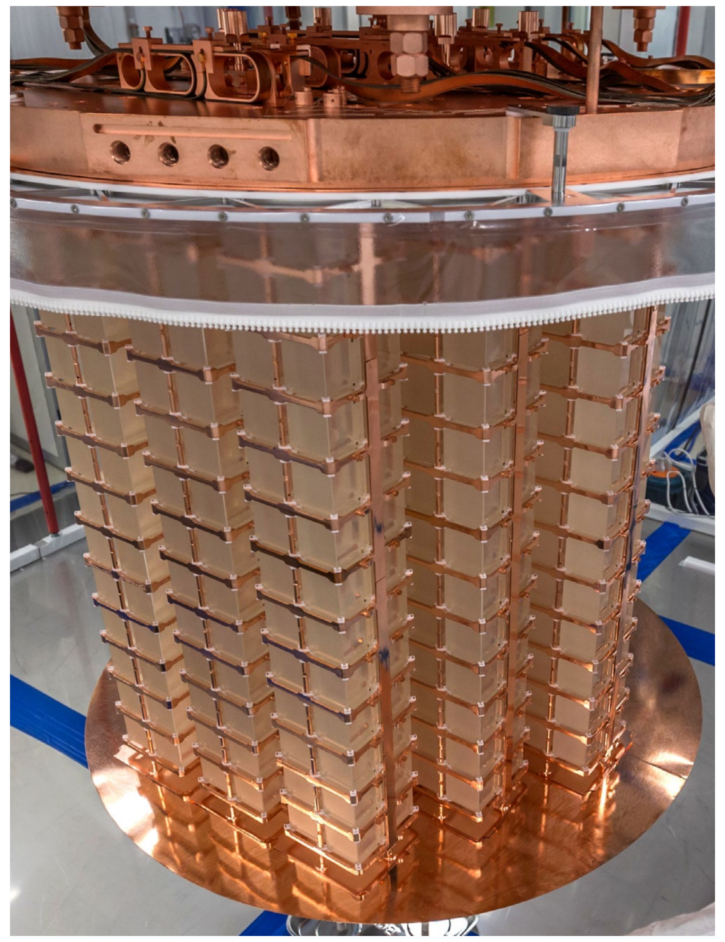
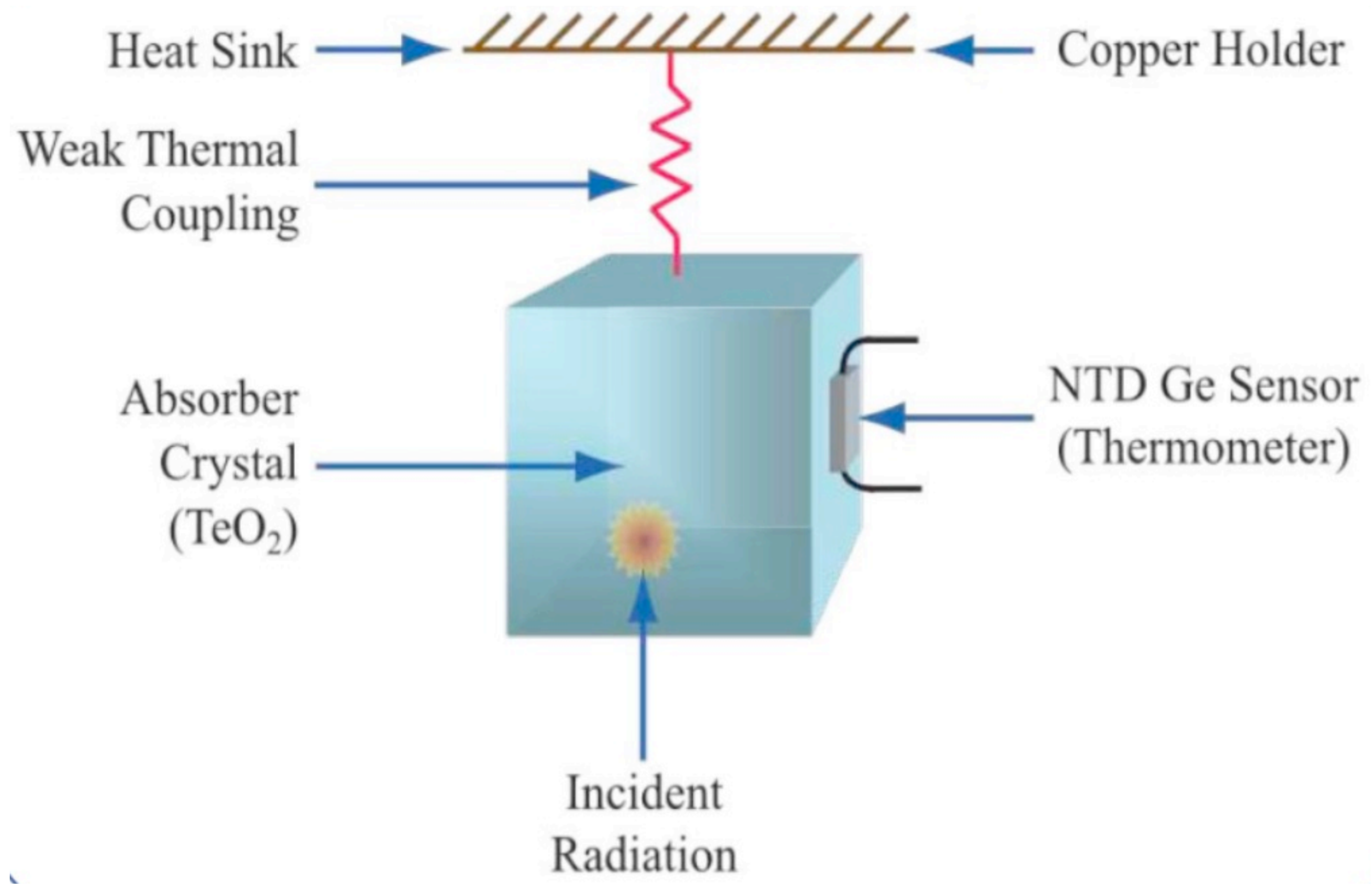
A Few Slides on Each Experiment

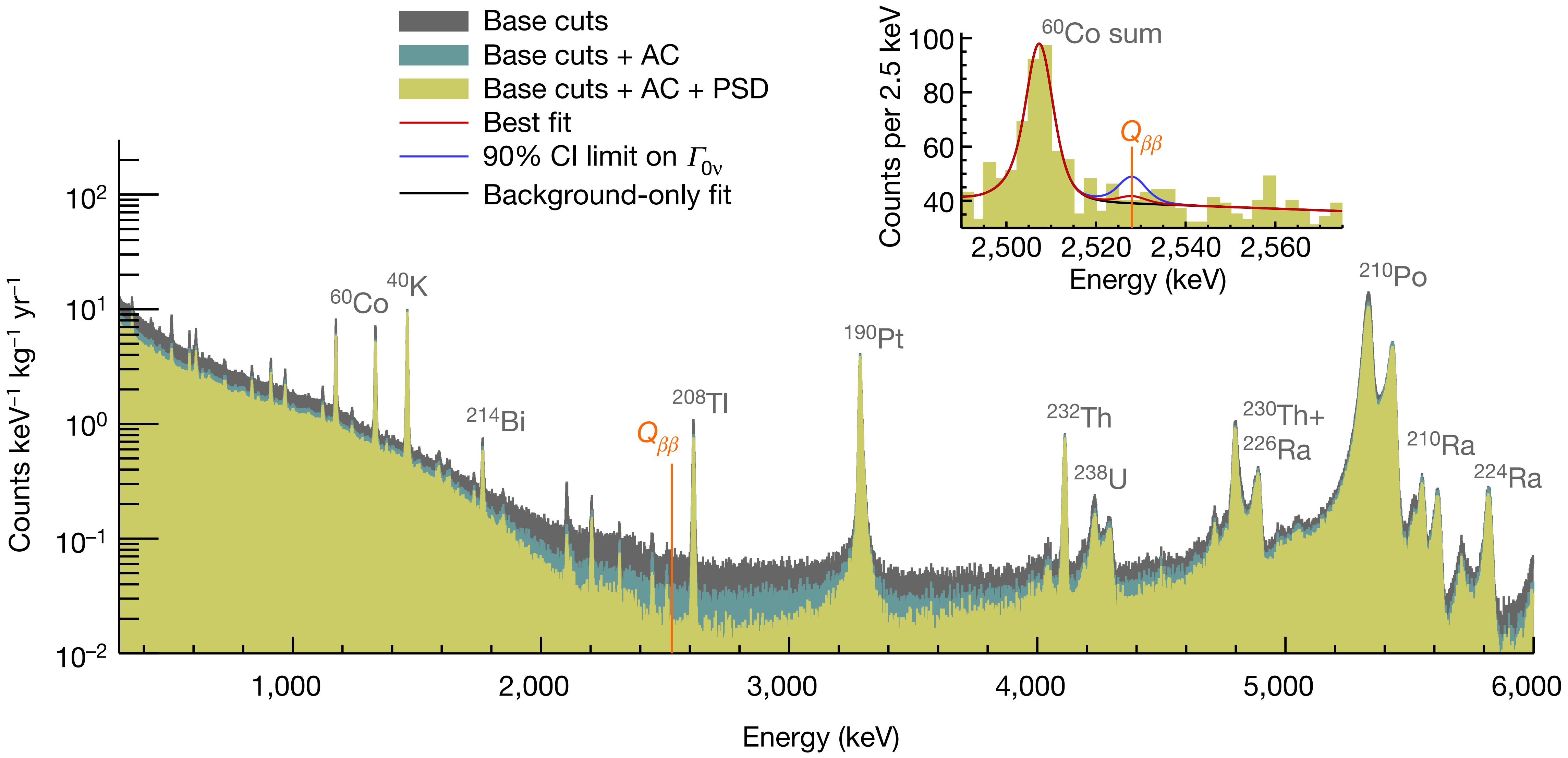
- Based on content collected by D. Hertzog for the FSNN Town Hall Meeting, Dec. 2022
- Focus:
    - Achievements and challenges of the previous generation
    - Basic design concept and strategy for optimizing sensitivity
    - What a discovery would look like
- Will not cover cost, schedule, risks (including obtaining isotope), etc.

CUPID Predecessor: CUORE

- Large array of TeO_2 bolometric crystals
  - High energy resolution
  - Takes advantage of large natural abundance of ^{130}Te
  - High $Q_{\beta\beta}$ = 2527 keV
- Latest results
  - 206 kg ^{130}Te deployed,
    290 kg yr (>1 ton-yr TeO_2) collected.
  - BG dominated by degraded U/Th chain alphas impingement on the crystal surfaces
  - $T_{1/2} > 2.2 \times 10^{25}$ yr, $m_{\beta\beta} <$ 90-305 meV
- Running through 2024 at LNGS
  - Projected sensitivity reaches the top of the IO "bulk"



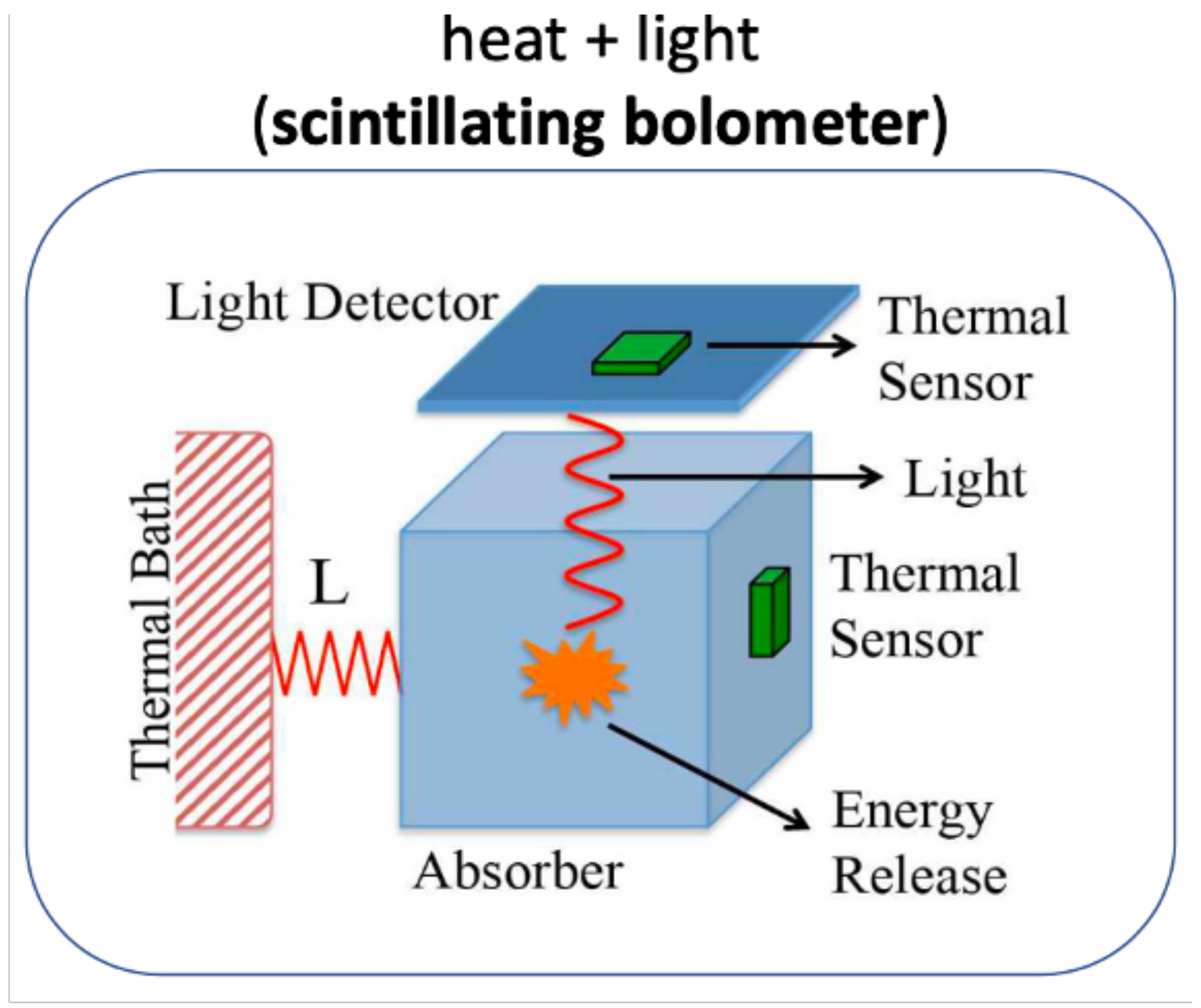


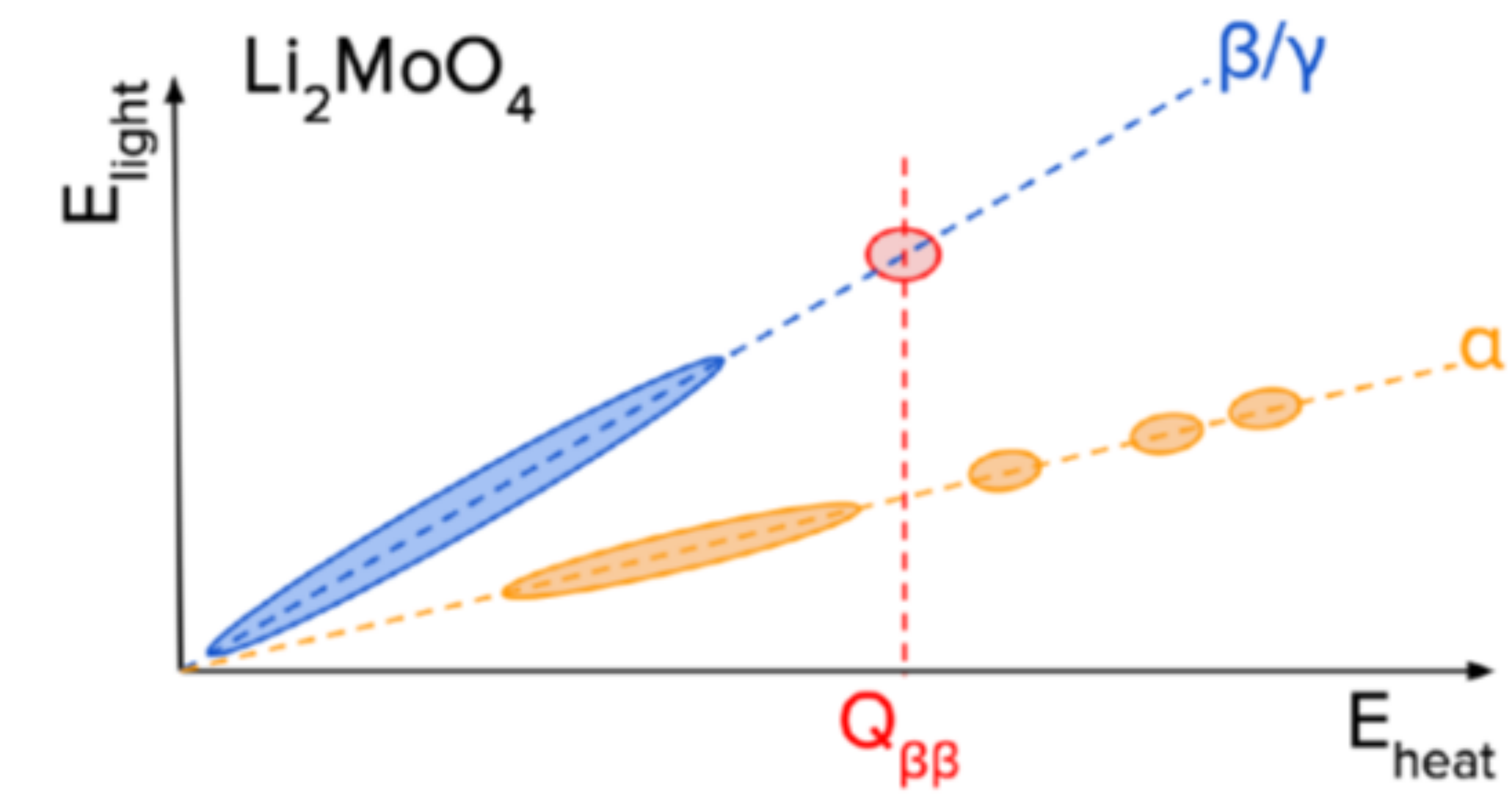


Nature **604**, 53 (2022)

CUPID: CUORE Upgrade with Particle ID

- Replace CUORE TeO_2 array with scintillating 500 kg of Li_2MoO_4 crystals (240 kg of ^{100}Mo)
  - ^{100}Mo Q-value: 3034 keV, well above natural U/Th lines
  - Instrument with light sensors to eliminate surface (α) background observed in CUORE





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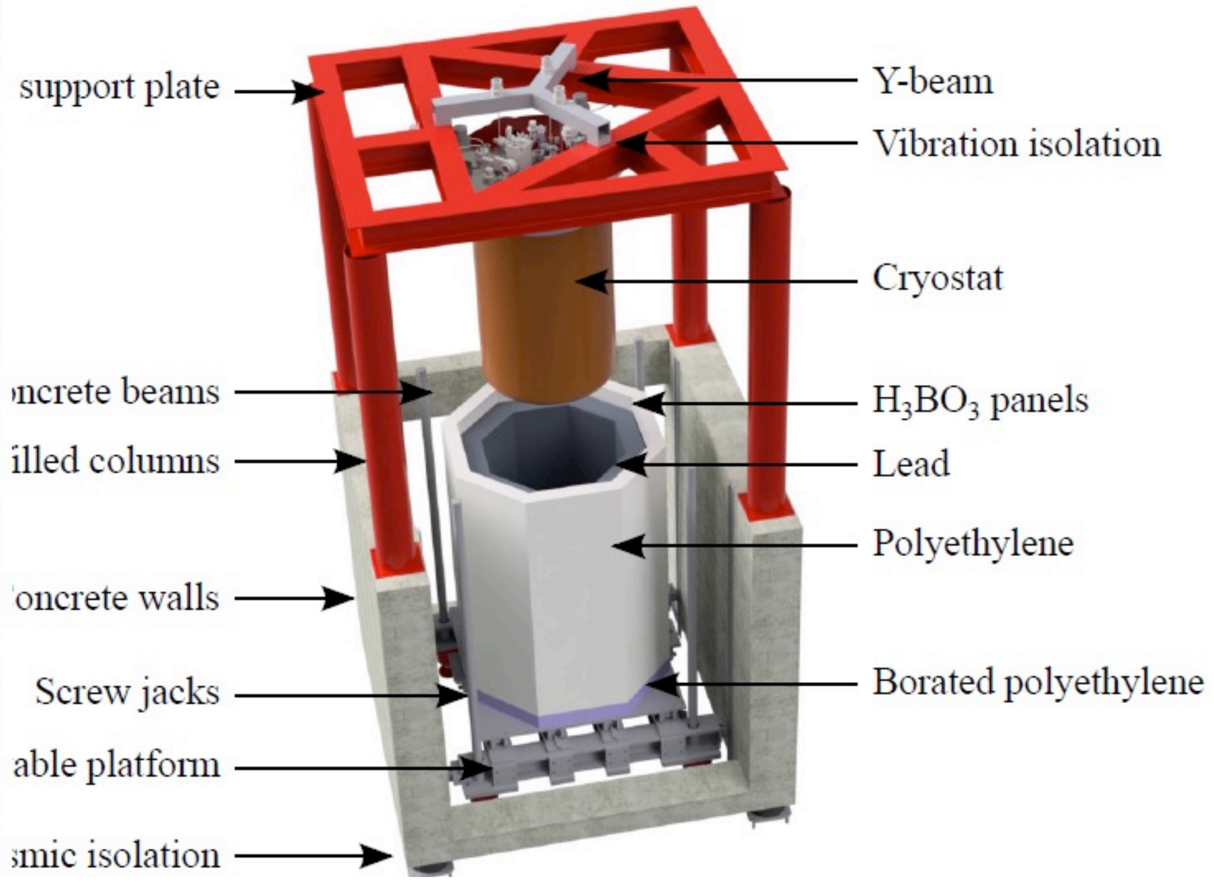
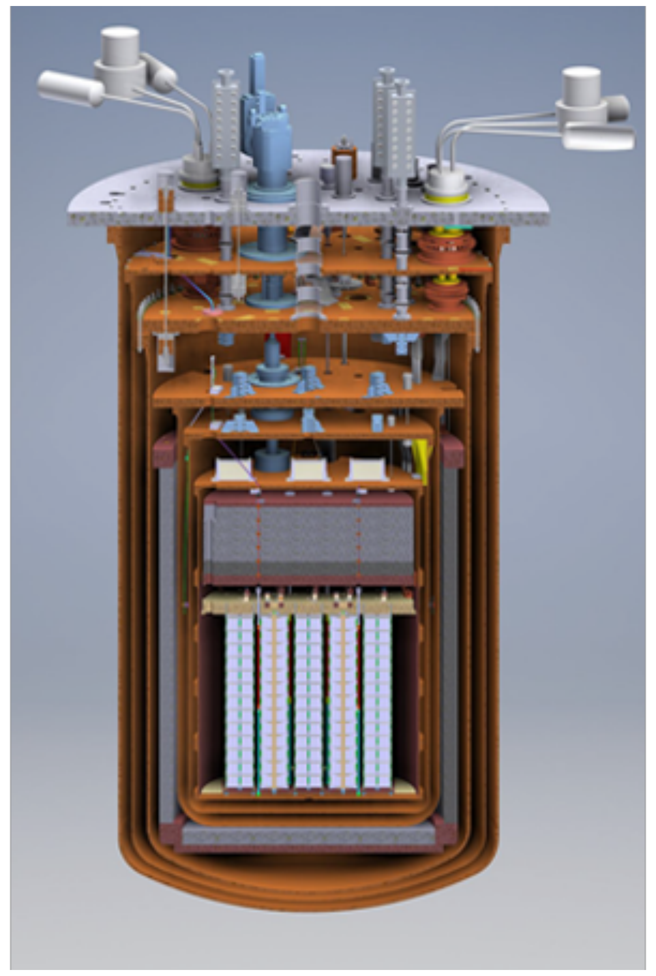
  - 1 ton payload in a single dilution refrigerator at LNGS





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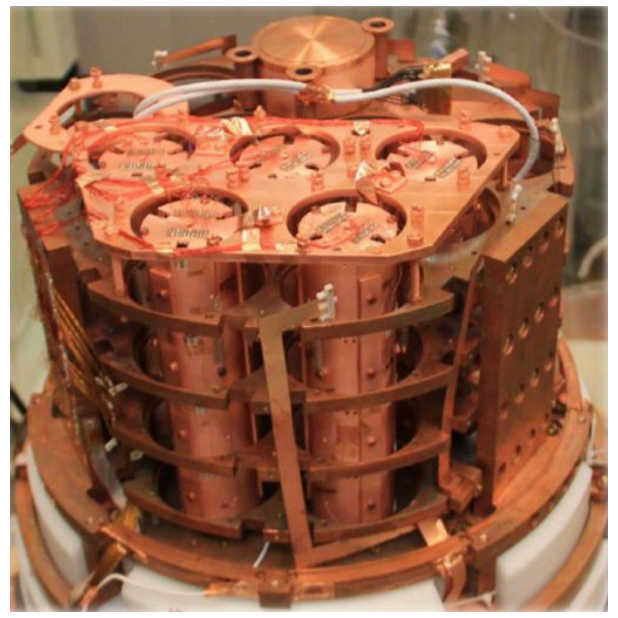
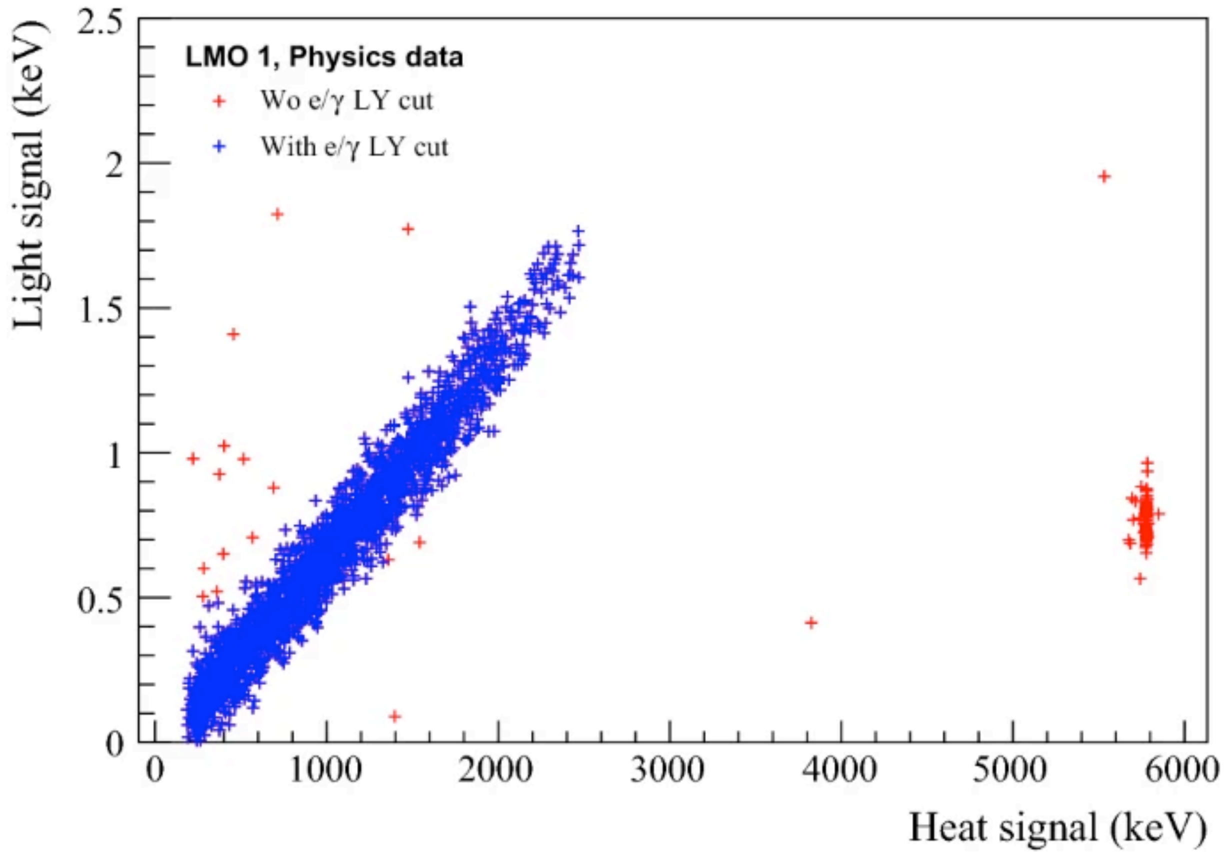
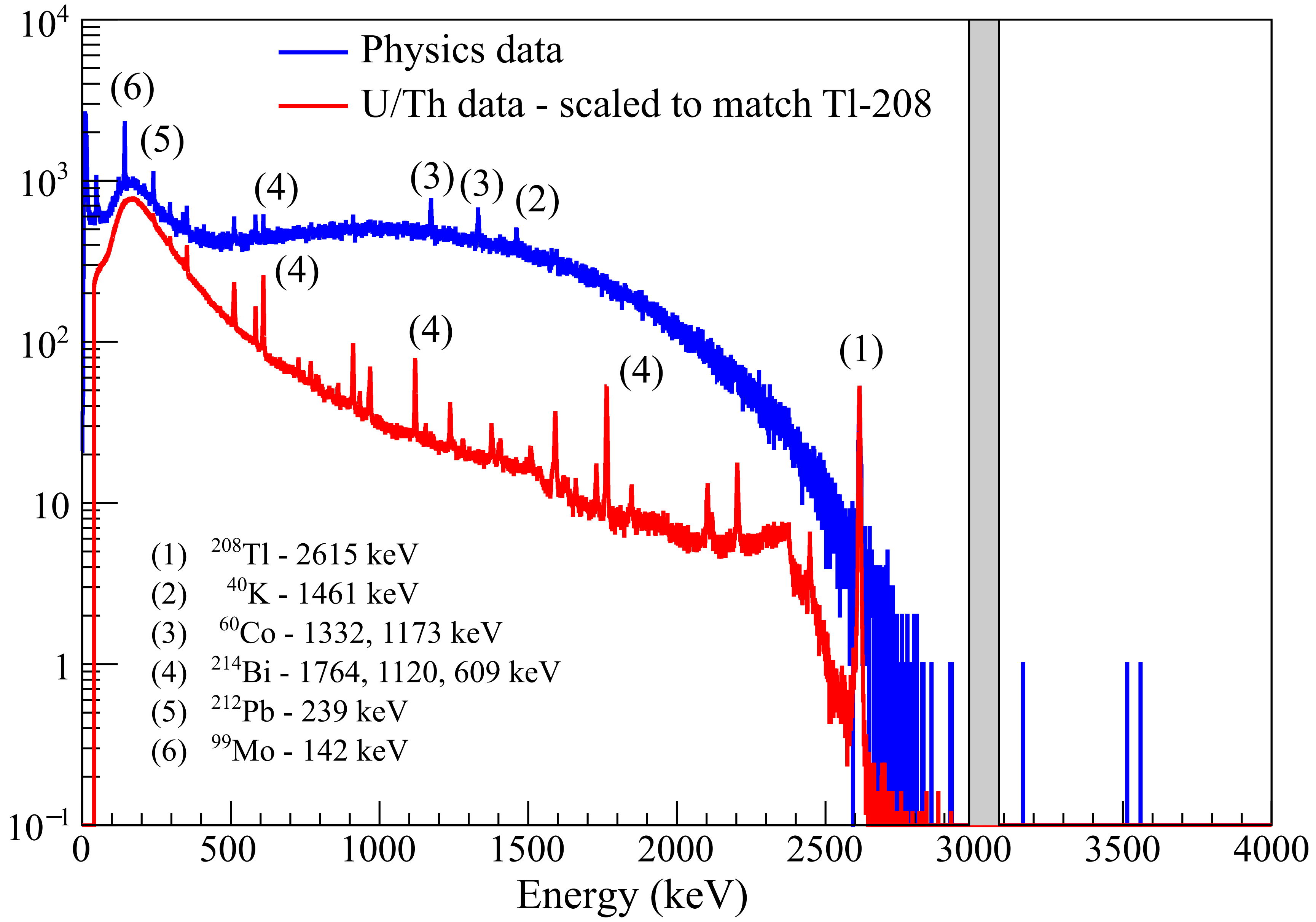
  - Instrument with light sensors to eliminate surface (α) background observed in CUORE
- Reuses CUORE infrastructure
  - 1 ton payload in a single dilution refrigerator at LNGS
- CUPID-Mo at LSM has demonstrated the needed background suppression, and has already set leading limits with ^{100}Mo



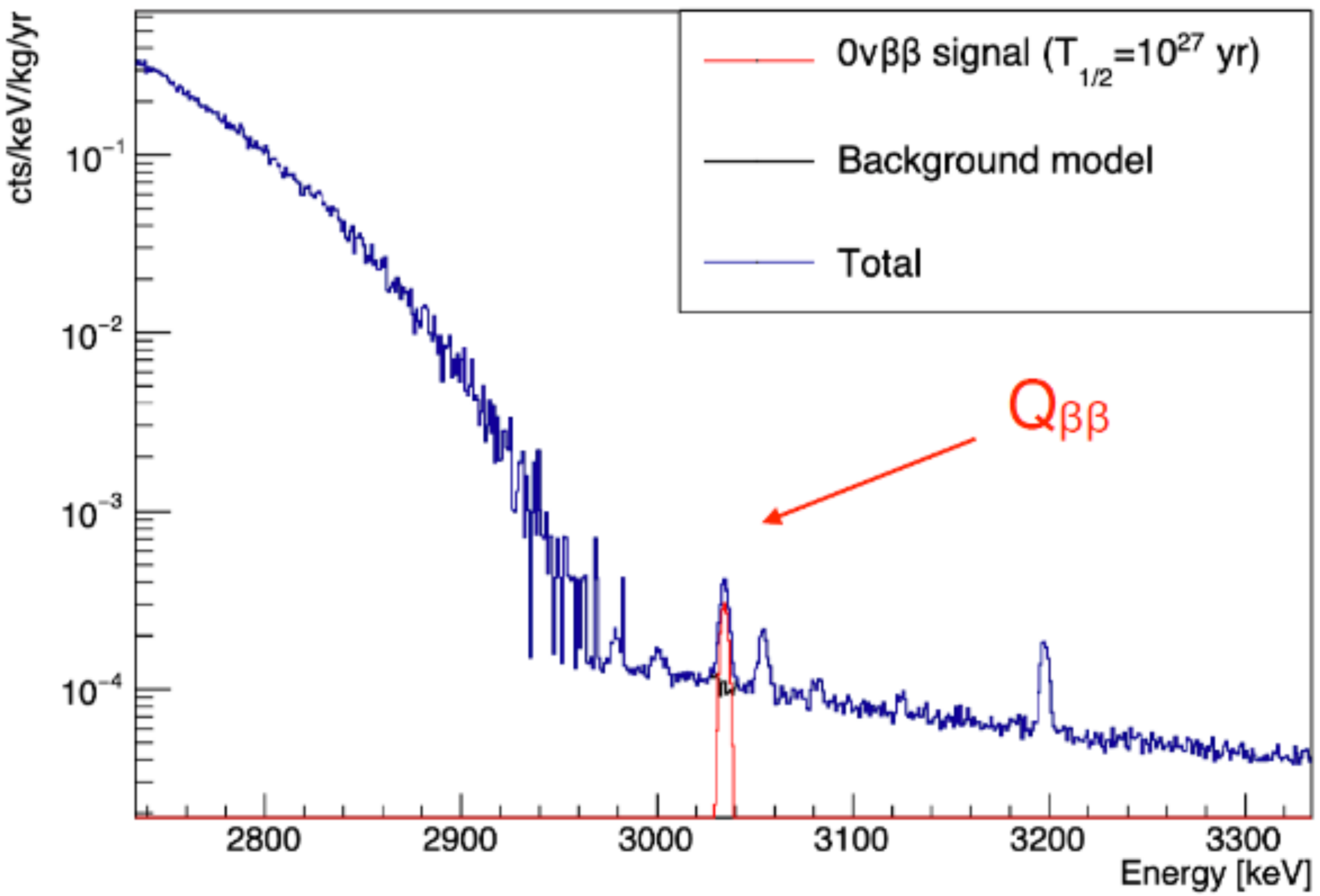




EPJC **80**, 44 (2020); PRL **126**, 181802 (2021)

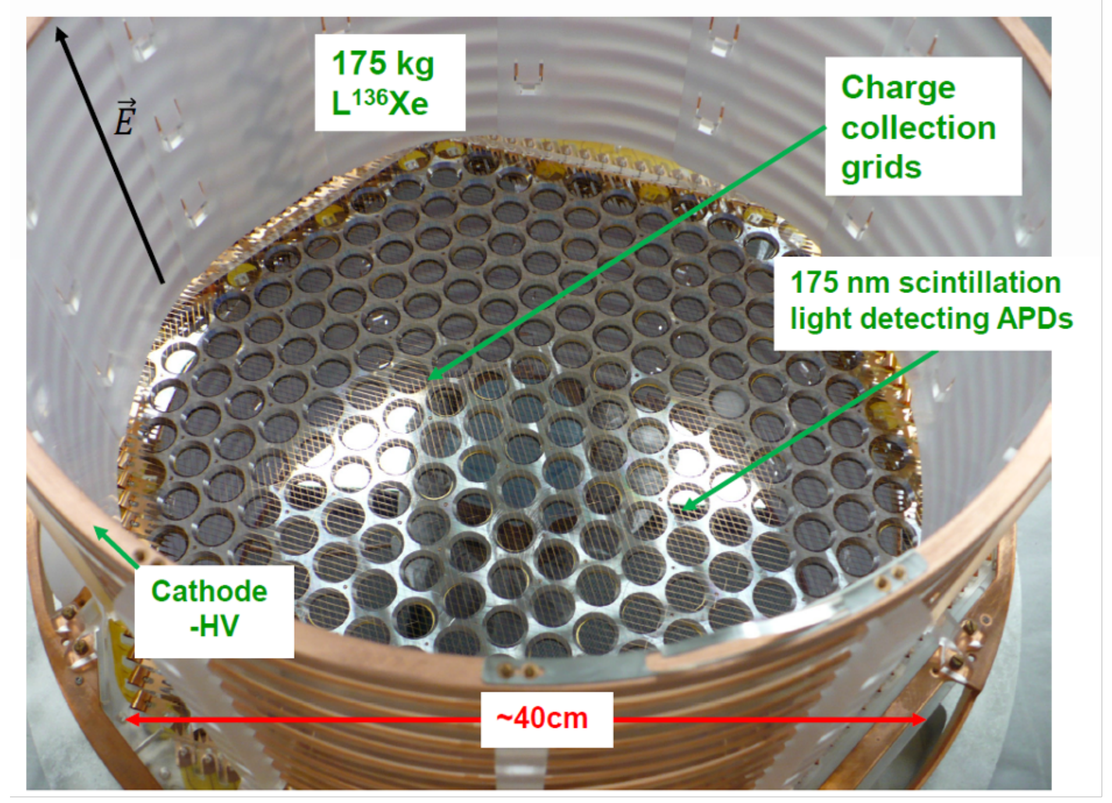
CUPID: What would a discovery look like?

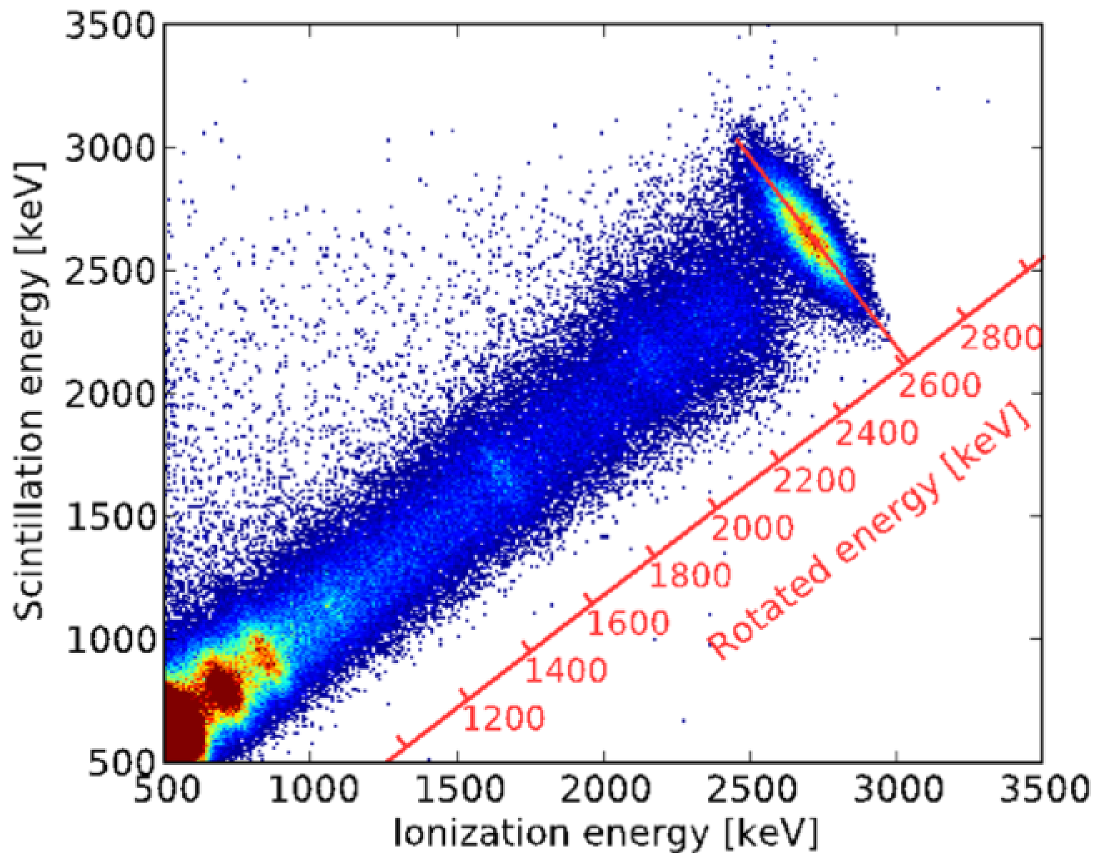
- Simulated 10-year exposure with $T_{1/2} = 10^{27}$ yr
- High $Q_{\beta\beta}$ of ^{100}Mo plays an important role
  - Large phase space factor: lower $T_{1/2}$ (less exposure) required to reach the IO_{min}
  - Region-of-interest is well-separated from strong natural radioactive backgrounds
  - Dominant expected background is from pileup of ^{100}Mo 2νββ! O(~Hz)

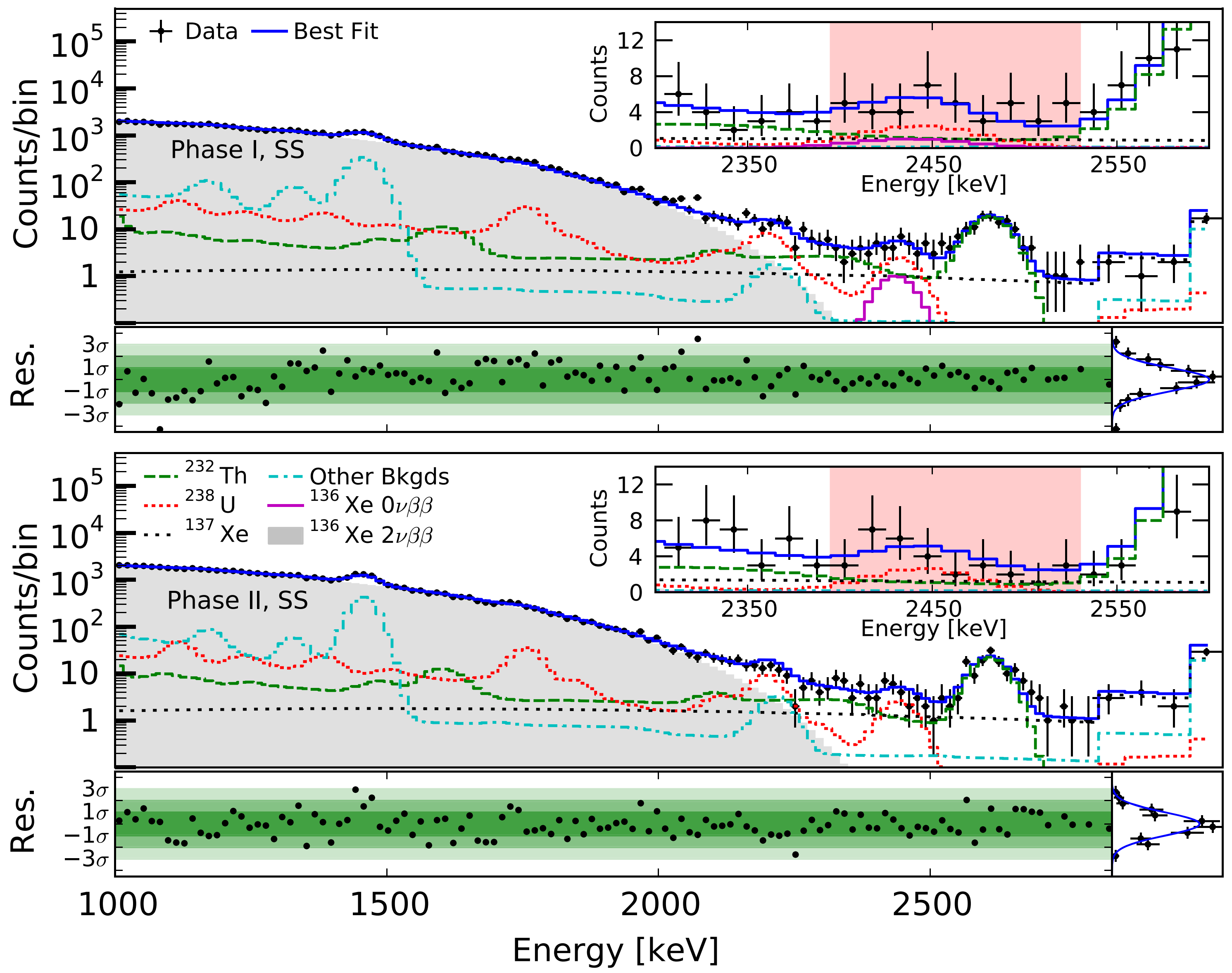


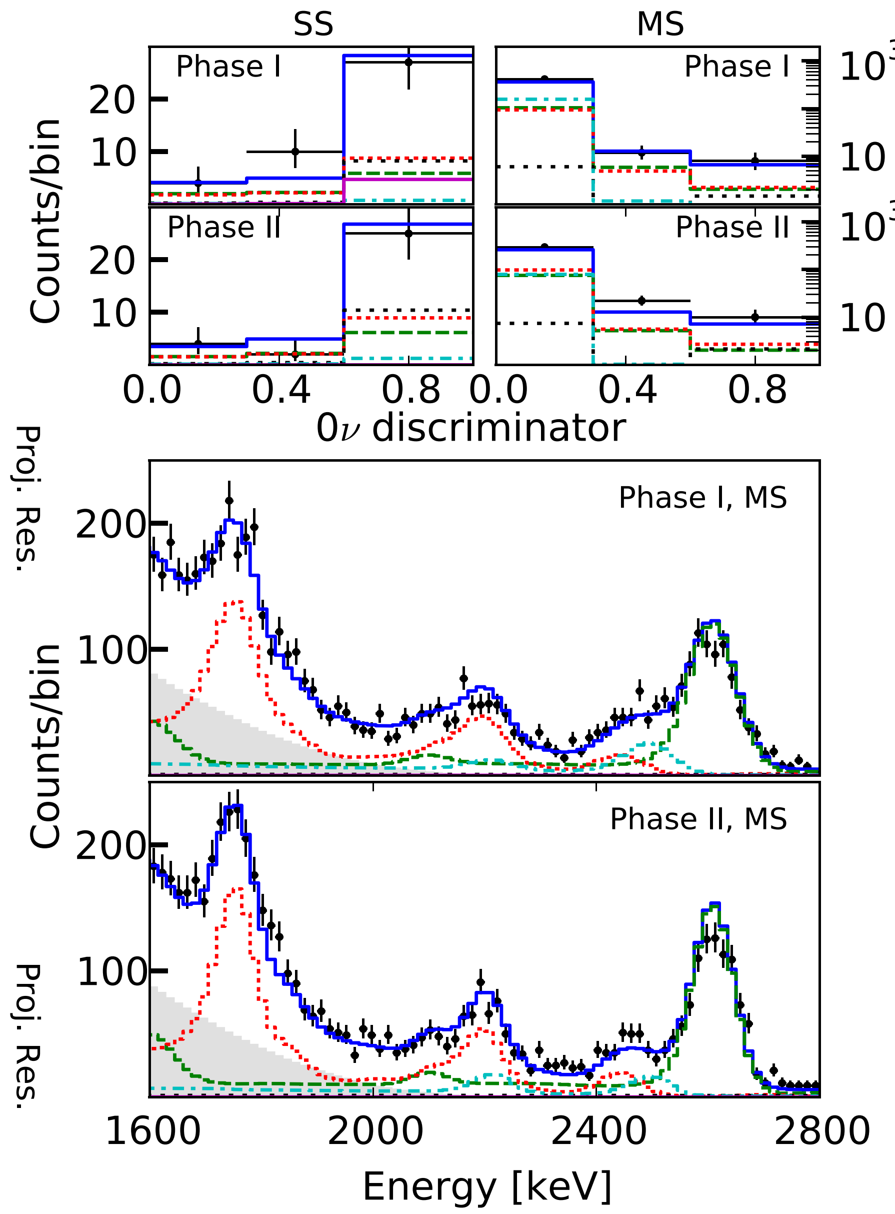
nEXO Predecessor: EXO-200

- LXe TPC with scintillation + ionization readout
  - Monolithic and compact
  - Enhanced resolution
  - Event topology reconstruction
- Final results
  - 160 kg ^{136}Xe deployed, 234 kg yr collected
  - Background dominated by natural radioactivity
  - $T_{1/2} > 3.5 \times 10^{25}$ yr, $m_{\beta\beta} < 93$-286 meV









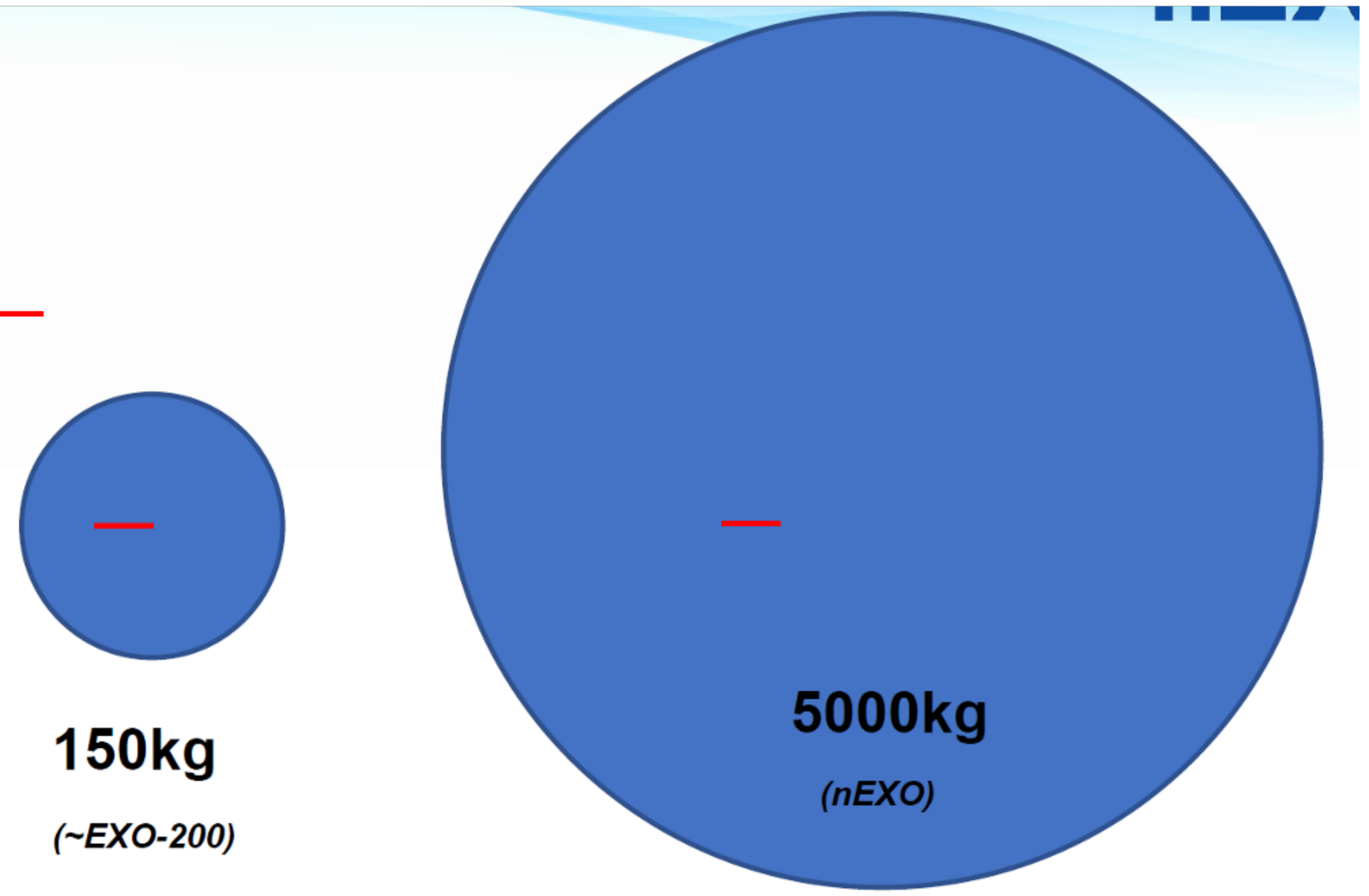
arXiv:1805.11142 [physics.ins-det]; PRL **123**, 161802 (2019)

nEXO Strategy and Design

- Top EXO-200 background fiducializes away as size increases

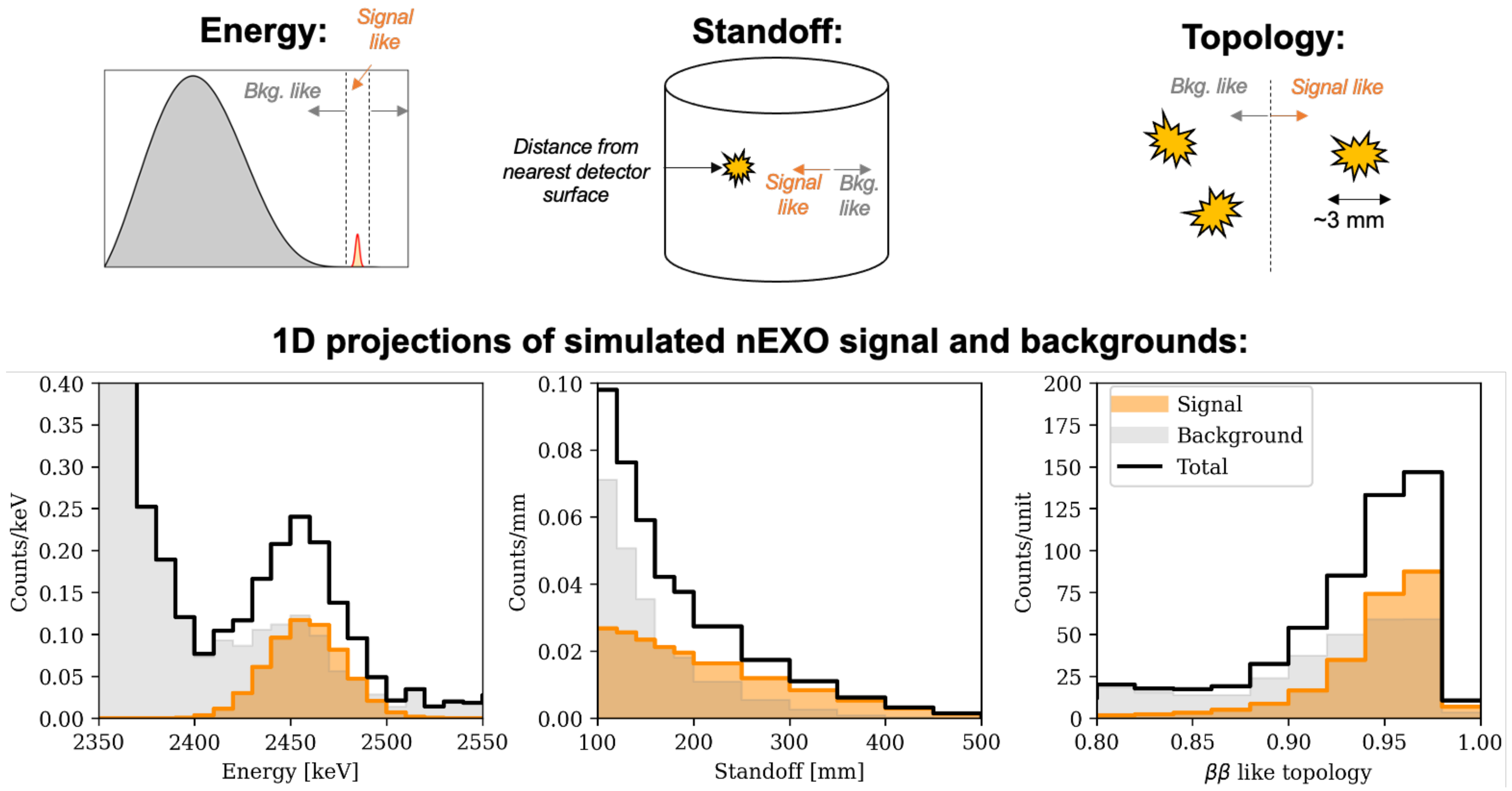
LXe mass (kg)	Diameter or length (cm)
5000	130
150	40
5	13

2.5 MeV γ attenuation length 8.7cm = —



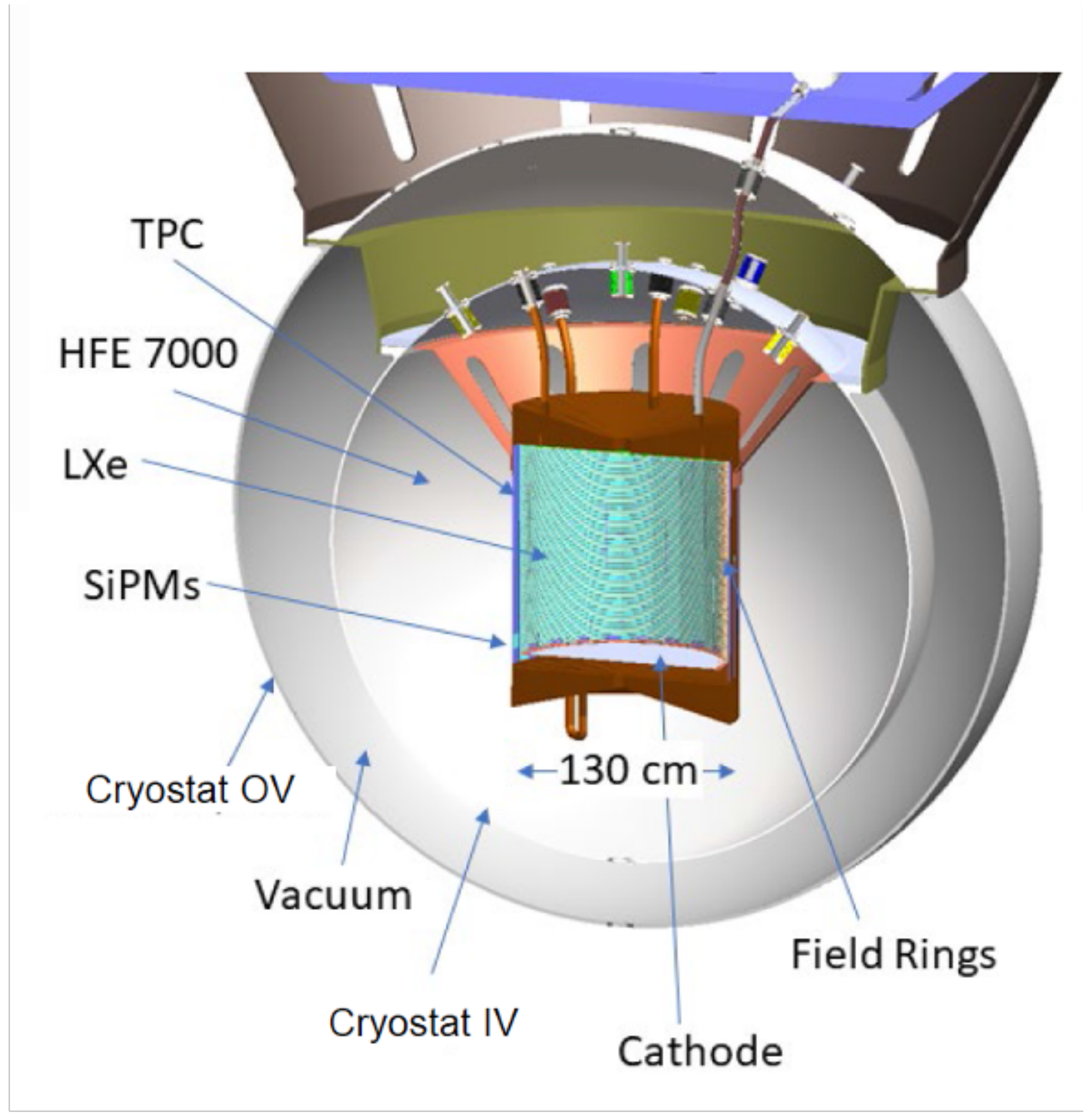
nEXO Strategy and Design

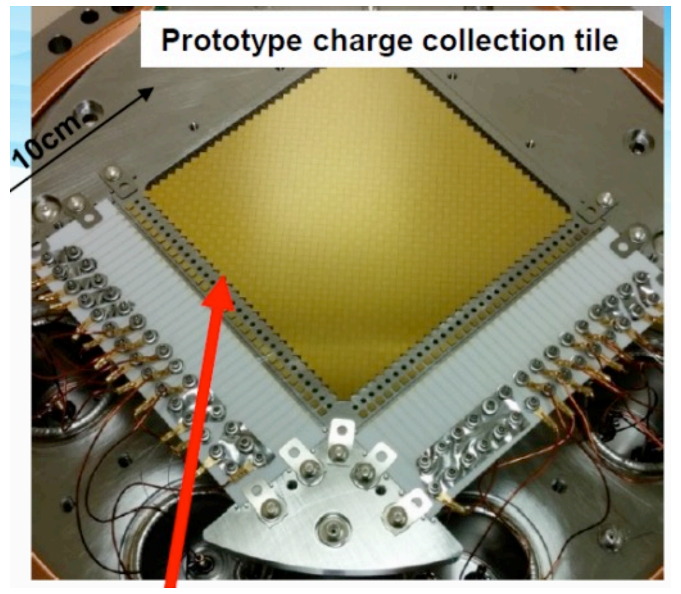
- Top EXO-200 background fiducializes away as size increases
- Fully exploit position and topology in addition to energy to pin backgrounds and optimize sensitivity

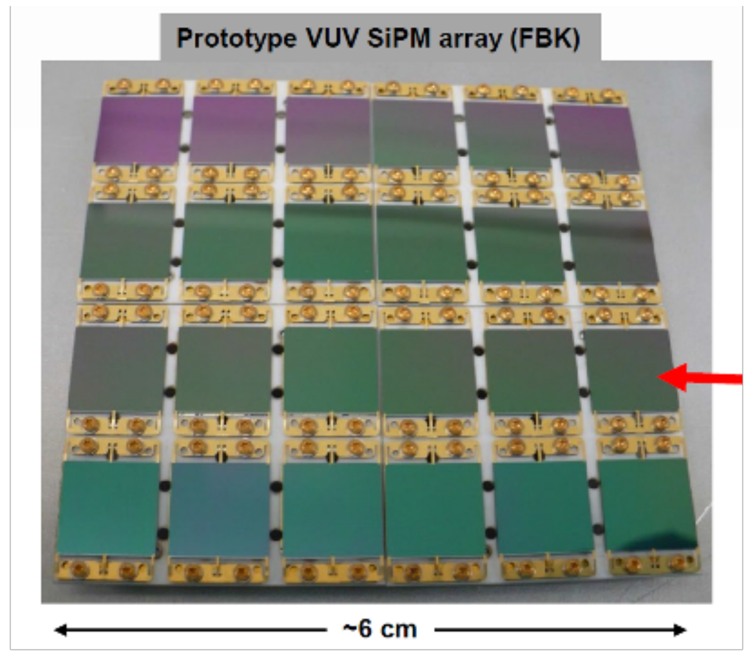


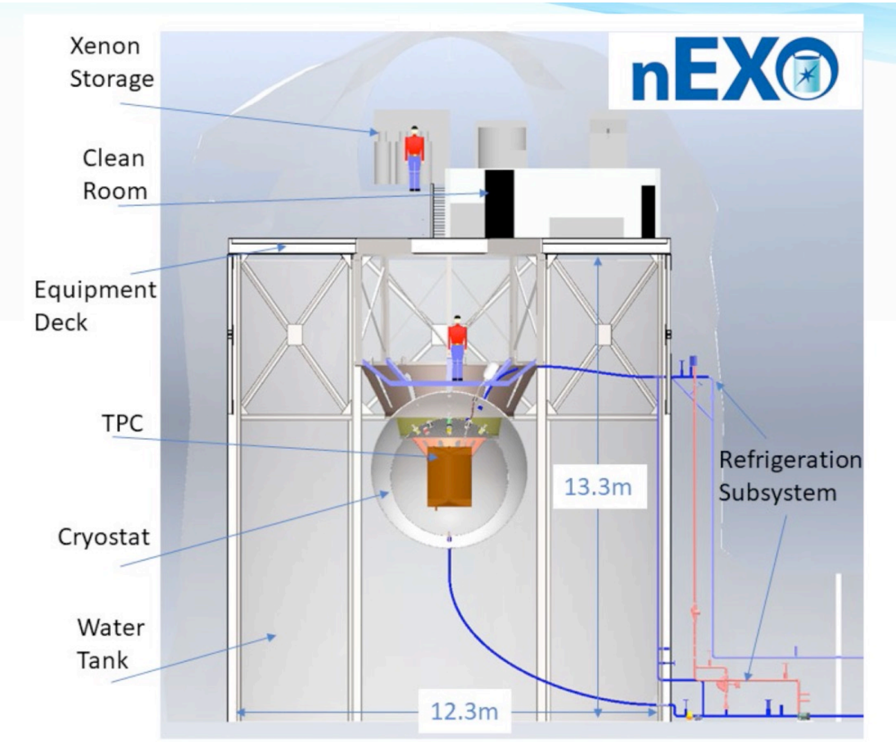
nEXO Strategy and Design

- Top EXO-200 background fiducializes away as size increases
- Fully exploit position and topology in addition to energy to pin backgrounds and optimize sensitivity
- Design: single drift volume, silica tile ionization readout, VUV-sensitive SiPMs on the walls. TPC is suspended in large water veto in the SNOLAB cryopit



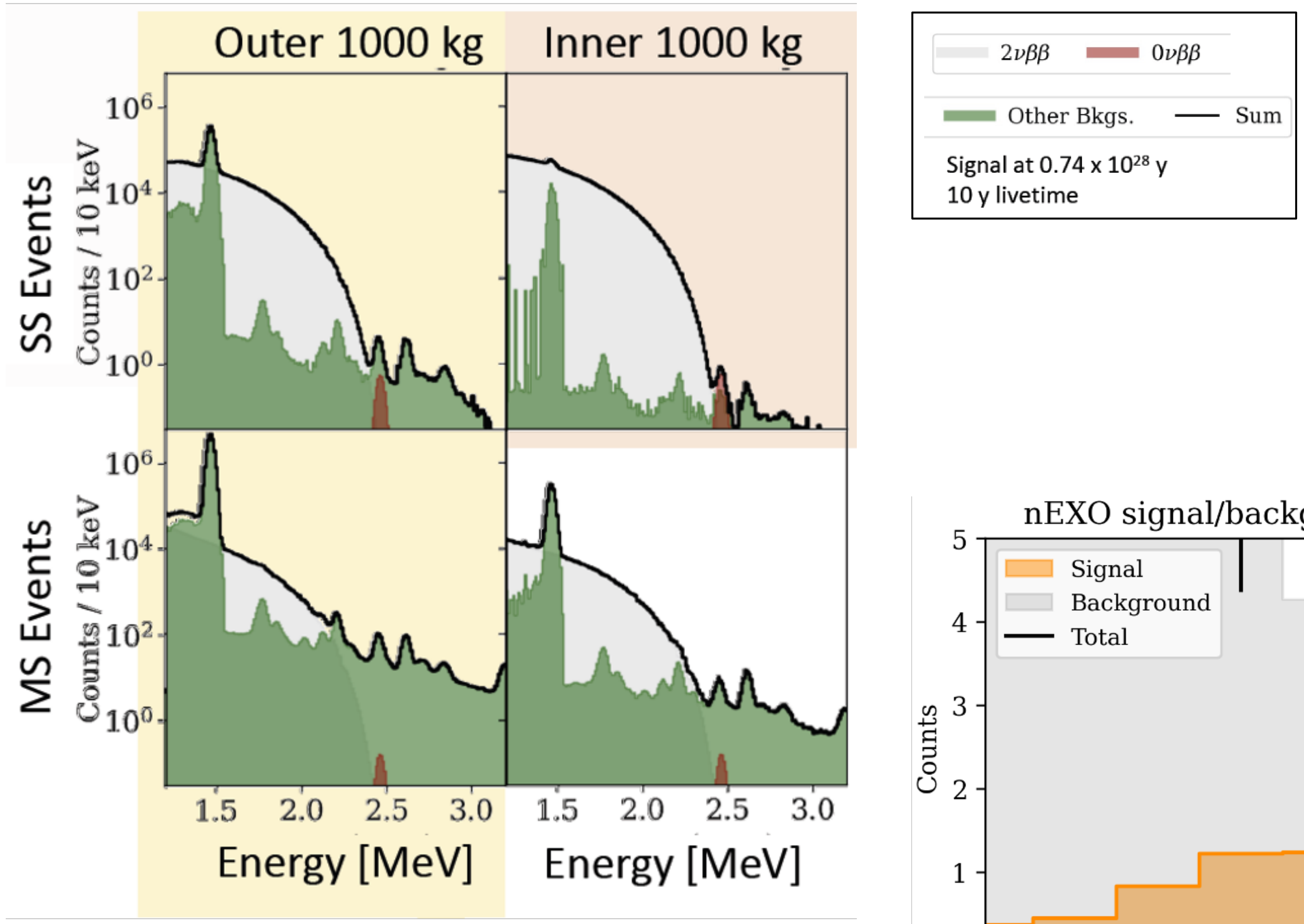


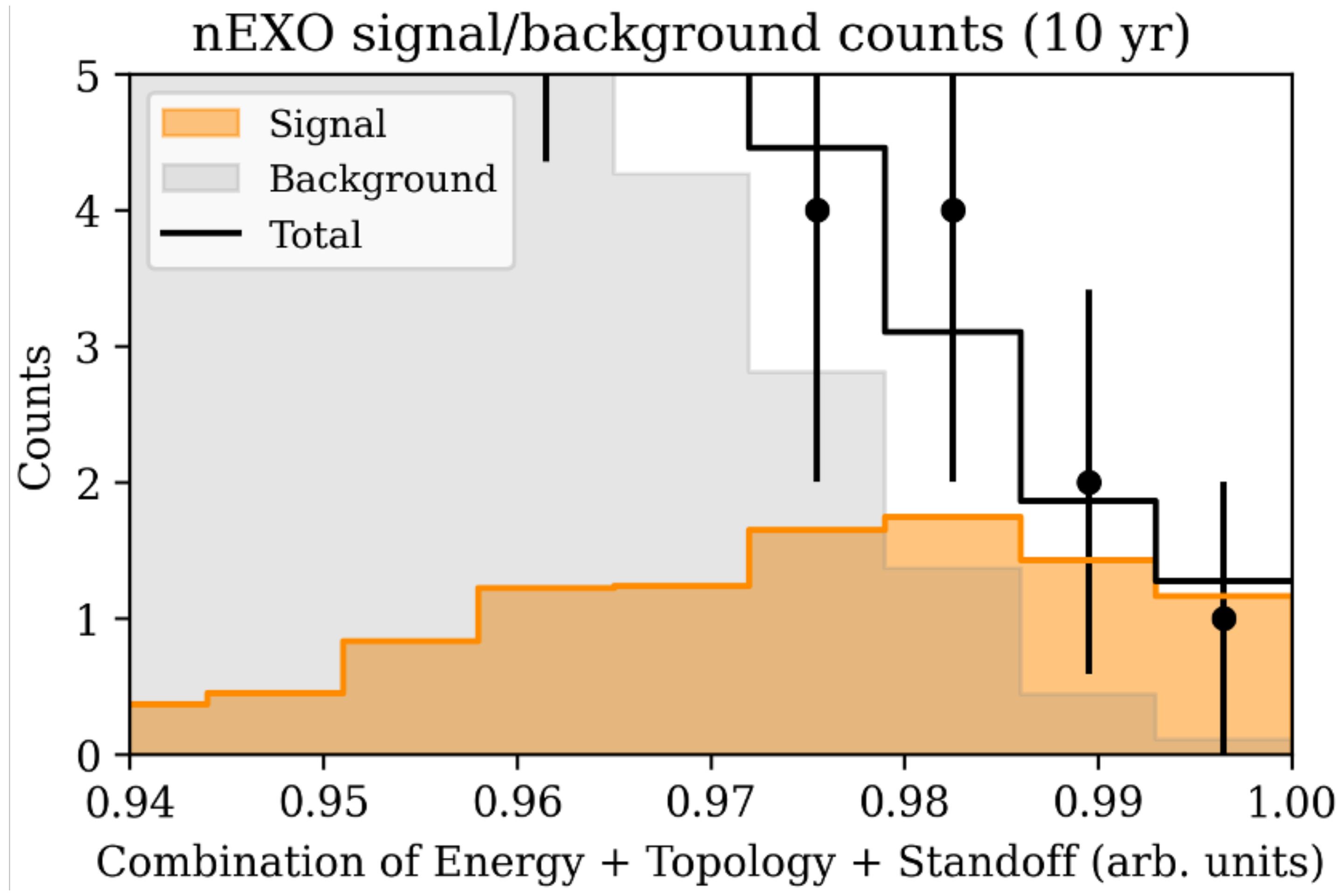




nEXO: What would a discovery look like?

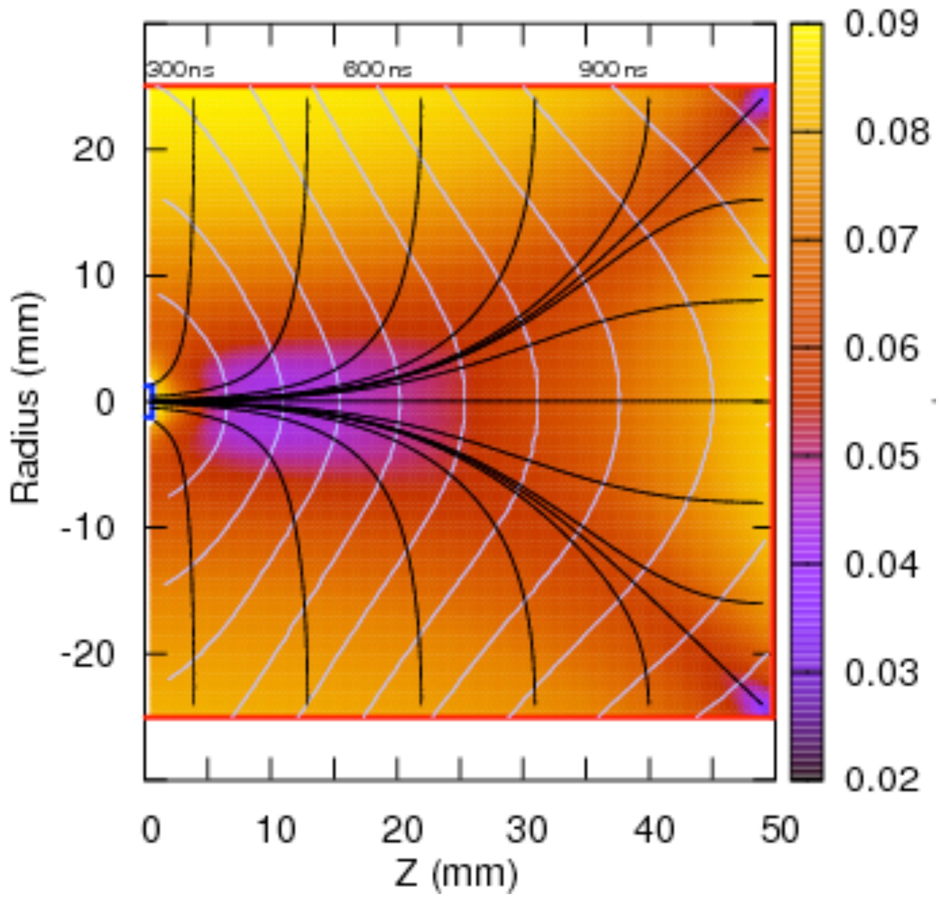
- Simulated 10 year exposure with $T_{1/2}$ = 7.4 x 10^{27} yr
- Inner-SS sample drives sensitivity, other samples pin the backgrounds

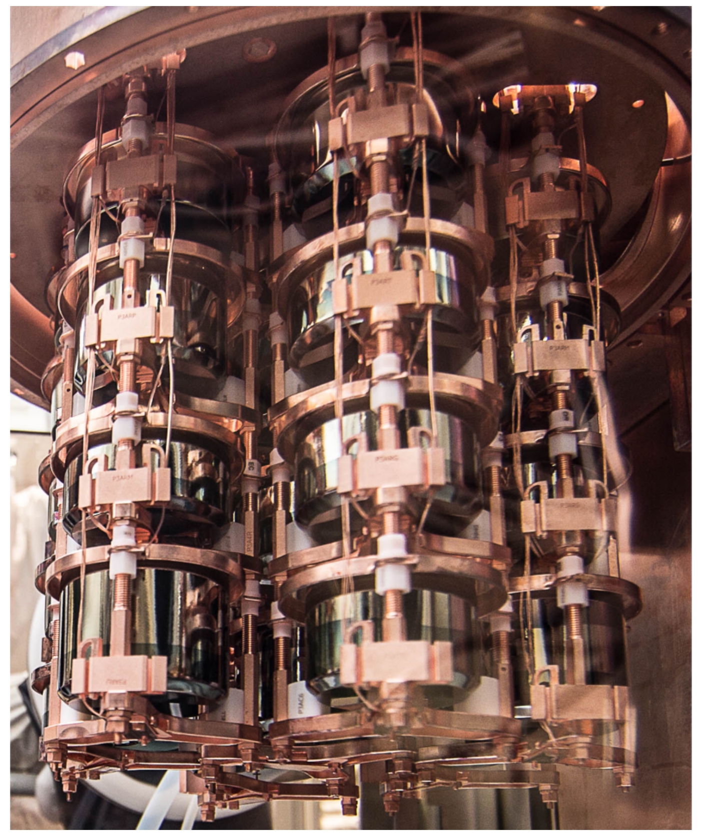


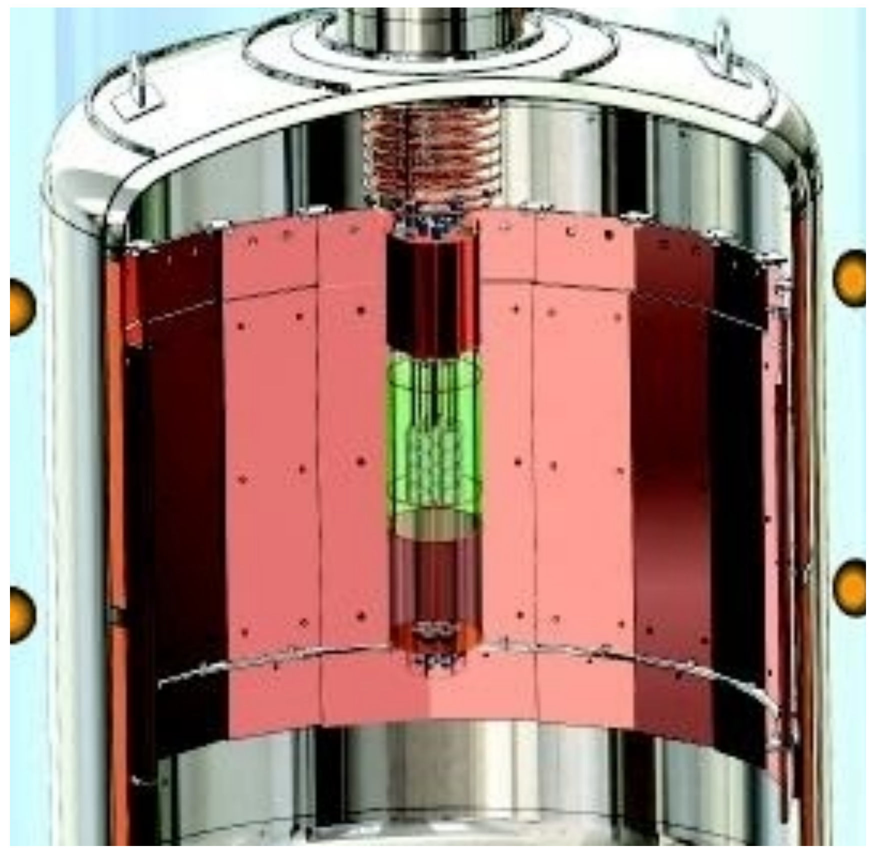


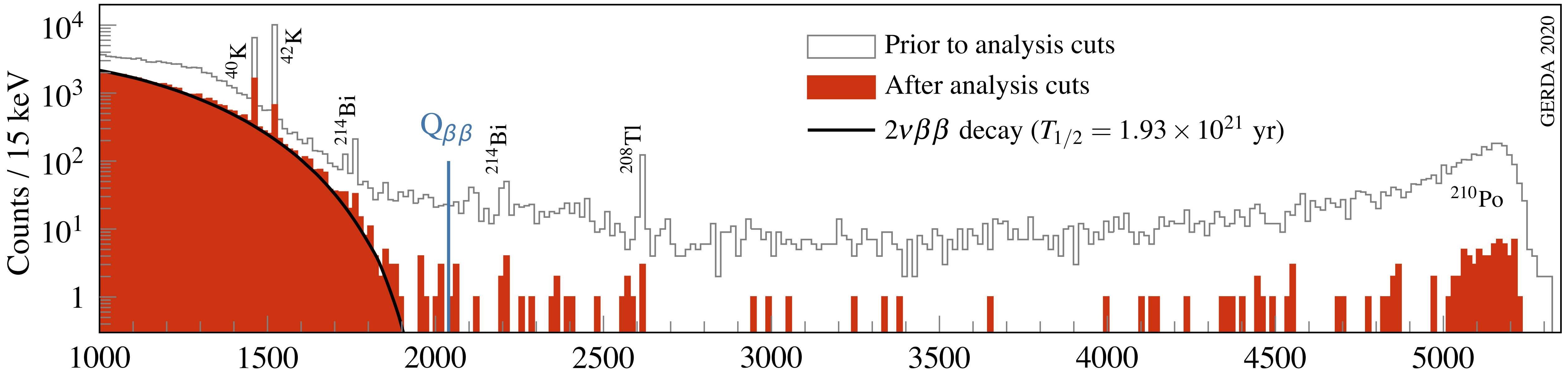
LEGEND Predecessors: MAJORANA and GERDA

- Point-contact HPGe detector arrays
  - Excellent energy resolution + event topology reconstruction
  - MAJORANA focus: material purity (EFCu), low-noise readout
  - GERDA focus: LAr active veto
- Final Results, GERDA (MAJORANA):
  - 40 (24) kg ^{76}Ge deployed, 90 (65) kg yr collected
  - Background dominated by ^{42}Ar, U/Th
  - $T_{1/2}$ > 18 (8.5) x 10^{25} yr, $m_{\beta\beta}$ < 79-180 (113-269) meV





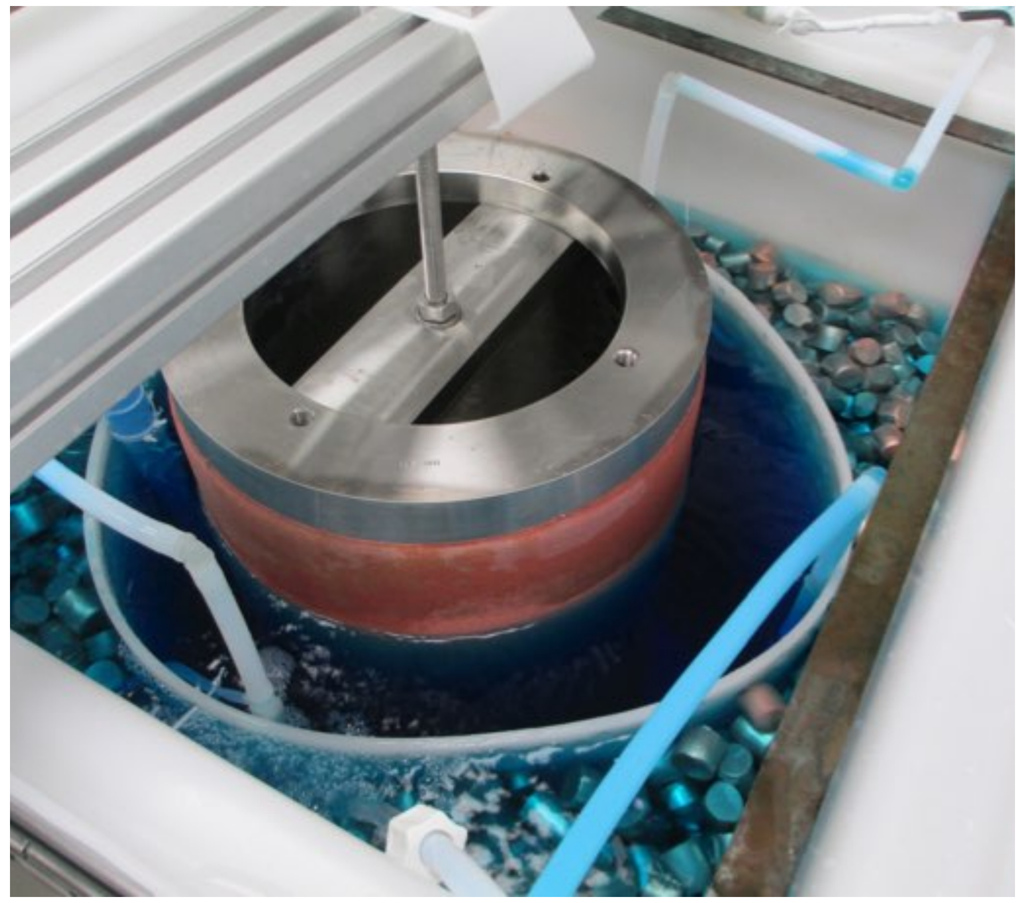


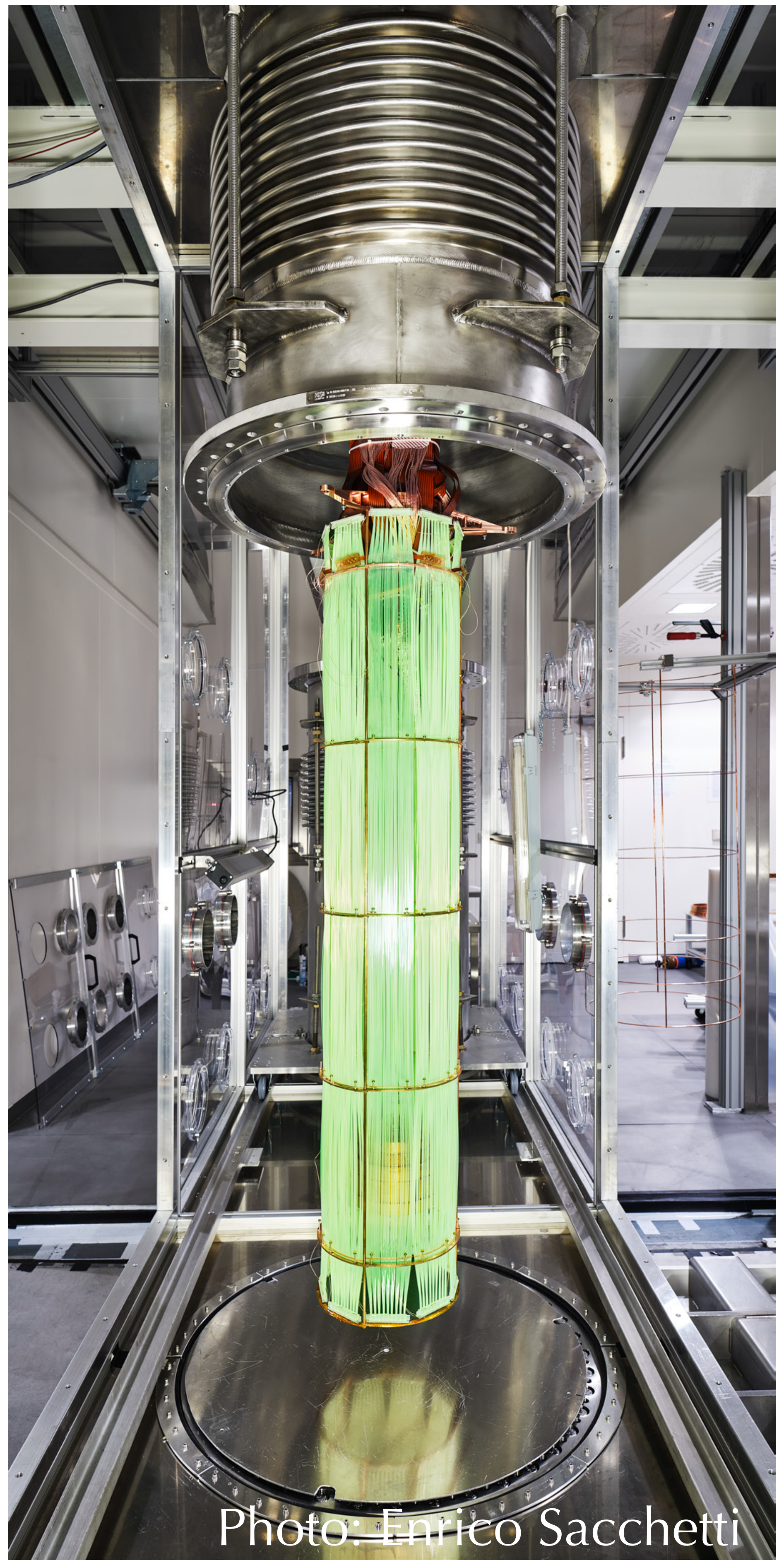


PRL **125**, 252502 (2020); PRL **130**, 062501 (2023)

LEGEND Strategy and Design

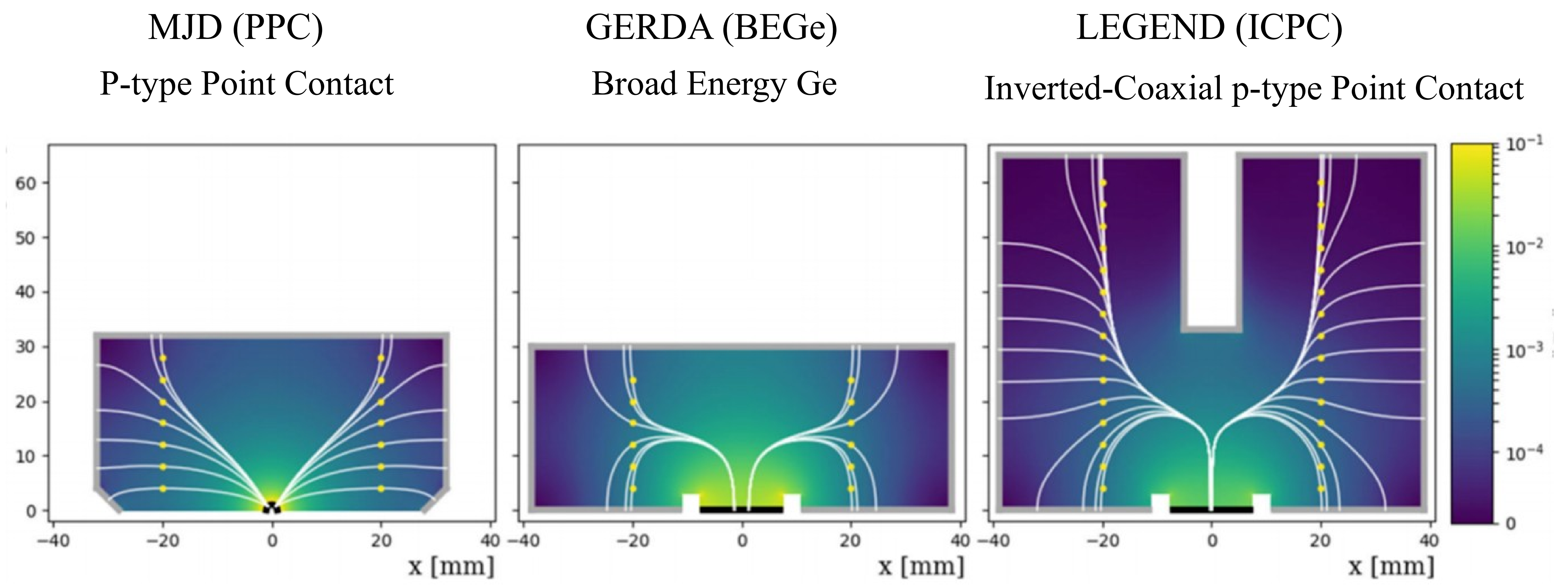
- Combine the best techniques of MAJORANA and GERDA





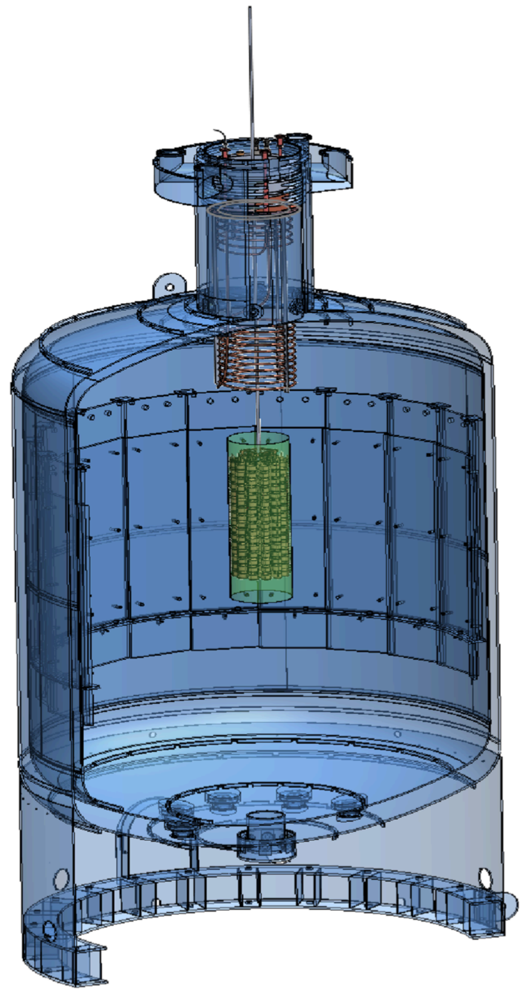
LEGEND Strategy and Design

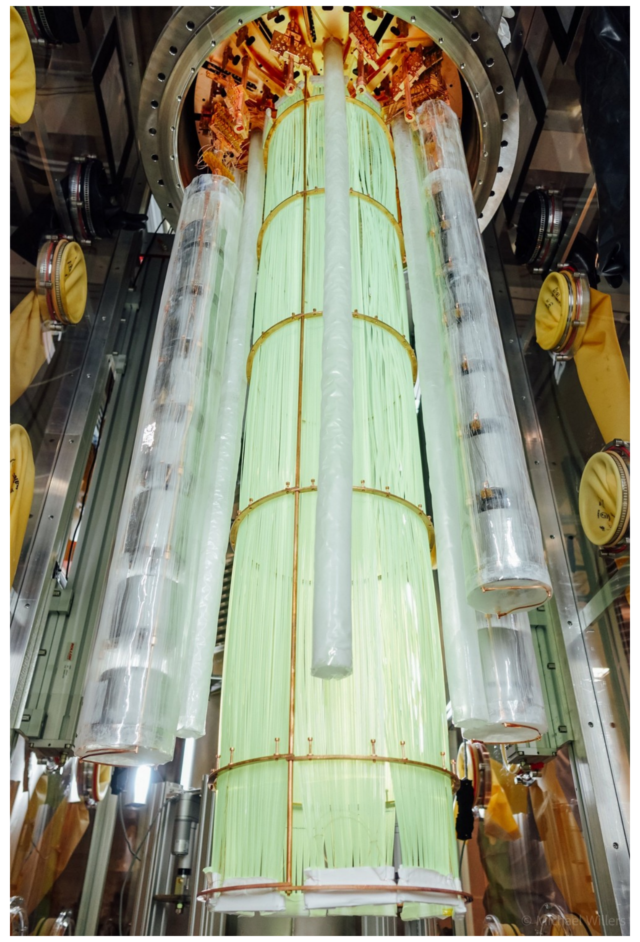
- Combine the best techniques of MAJORANA and GERDA
- Larger crystals ("ICPCs") and use of underground-LAr

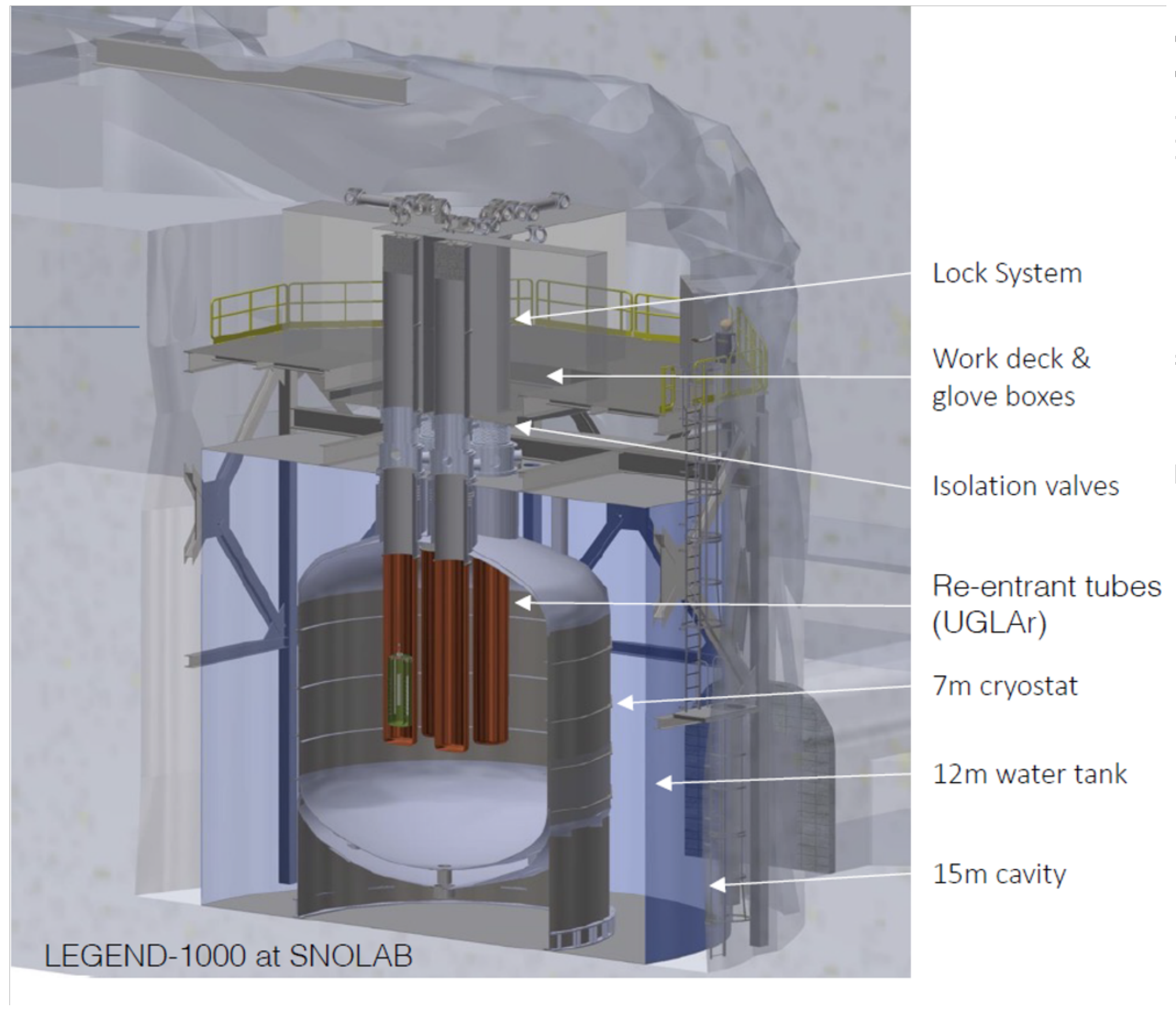


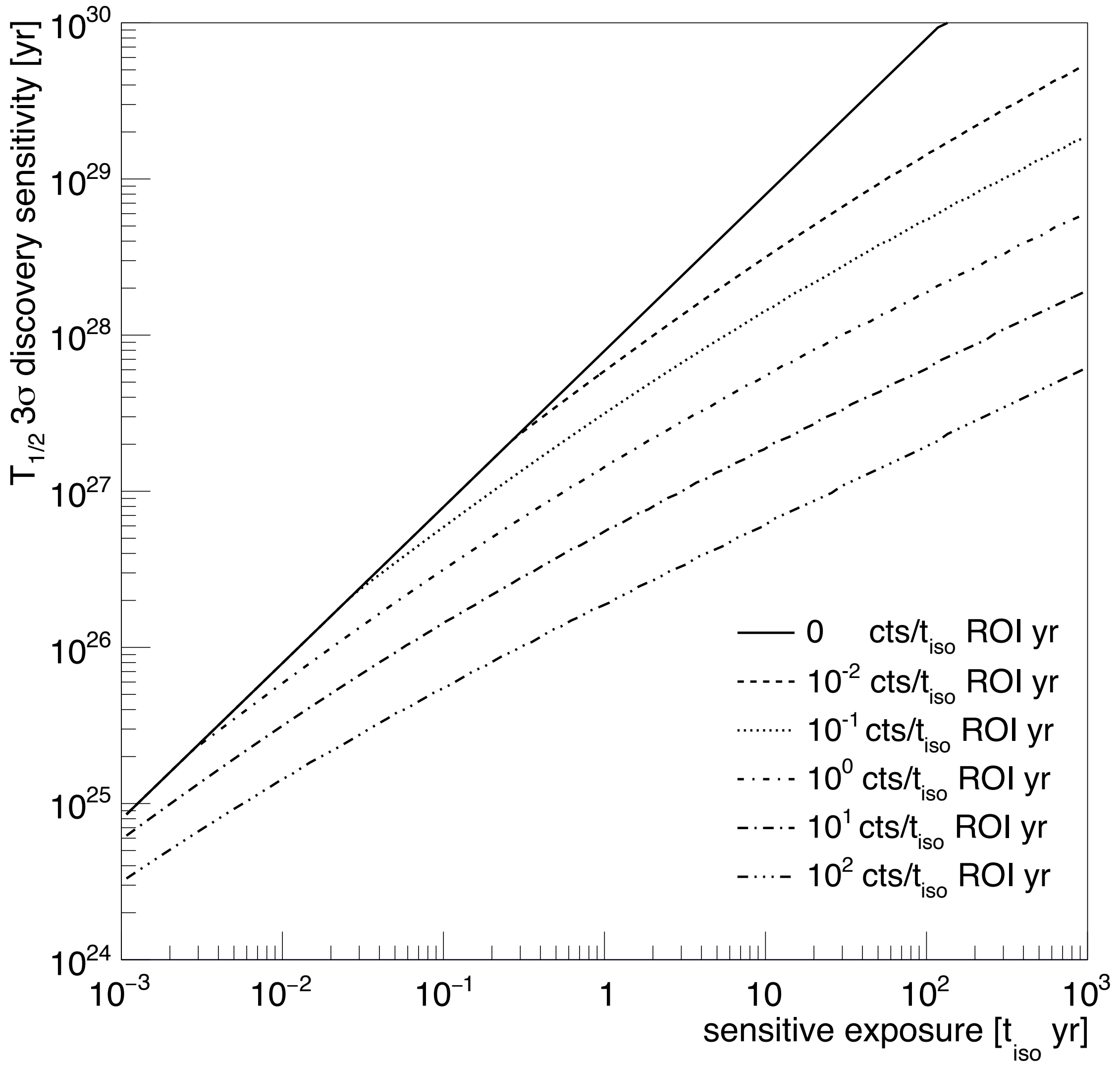
LEGEND Strategy and Design

- Combine the best techniques of MAJORANA and GERDA
- Larger crystals ("ICPCs") and use of underground-LAr
- Scale up while remaining quasi-background-free
  - LEGEND 200 (now running at LNGS):
    - 200 kg of GERDA + MJ crystals + new ICPCs
    - EFCu + MJ electronics + GERDA cryostat
  - LEGEND 1000:
    - 1 ton of large ICPCs deployed in volumes of LAr
    - Site TBD (SNOLAB or LNGS)



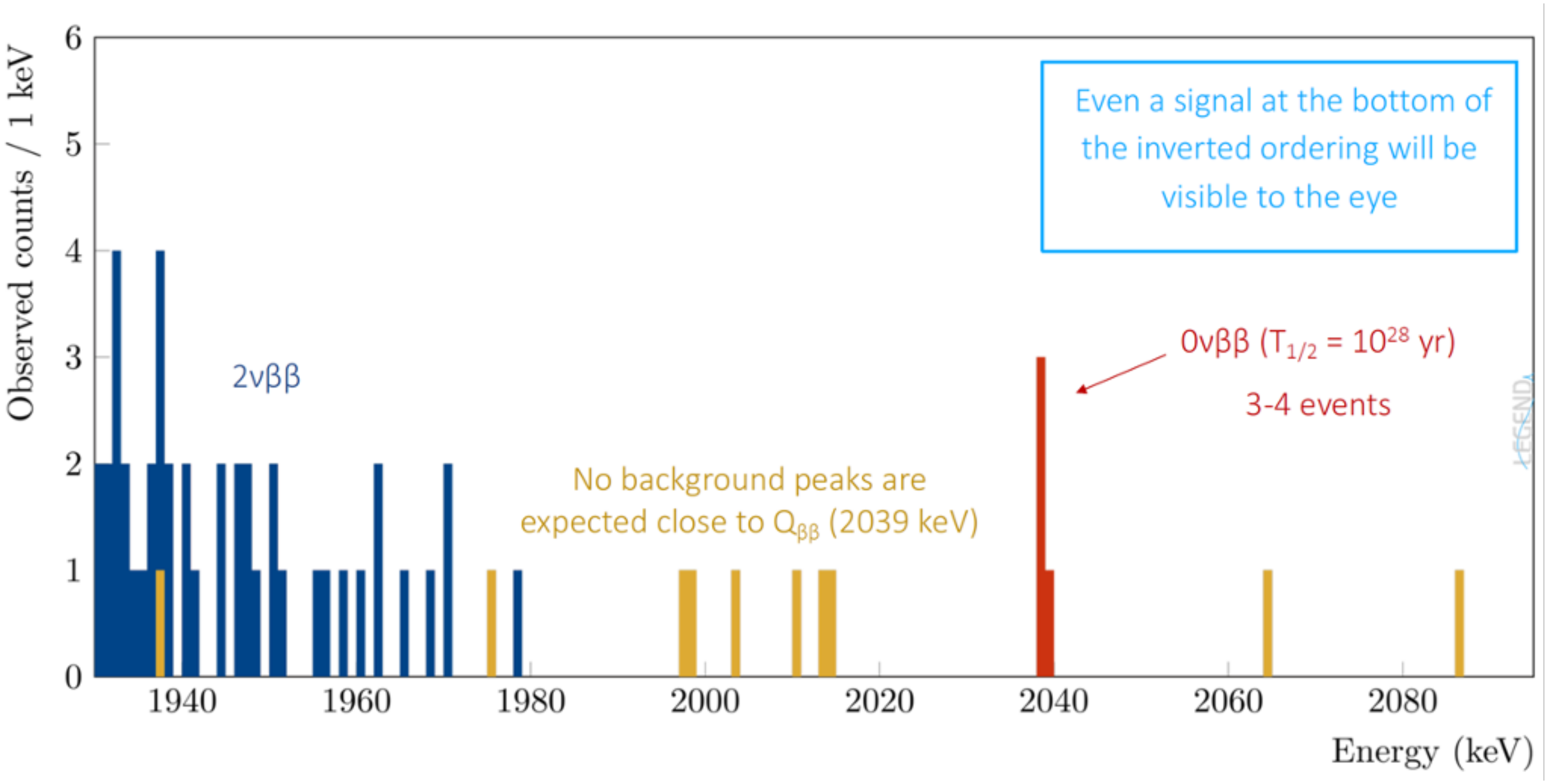






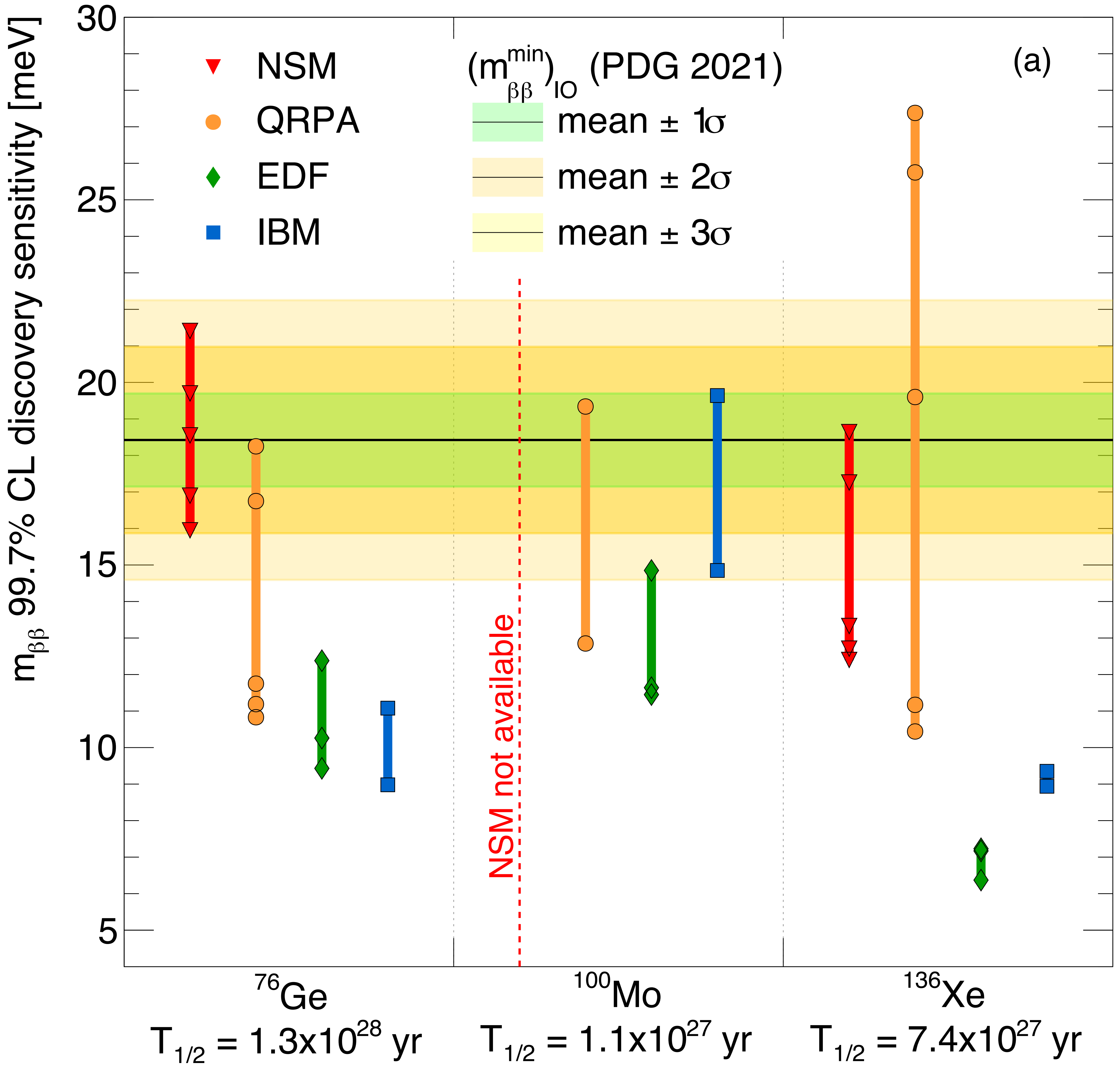
LEGEND: What would a discovery look like?

- Simulated 10 year exposure with $T_{1/2}$ = 7.4 x 10^{27} yr
- Sharp peak over diffuse, flat background



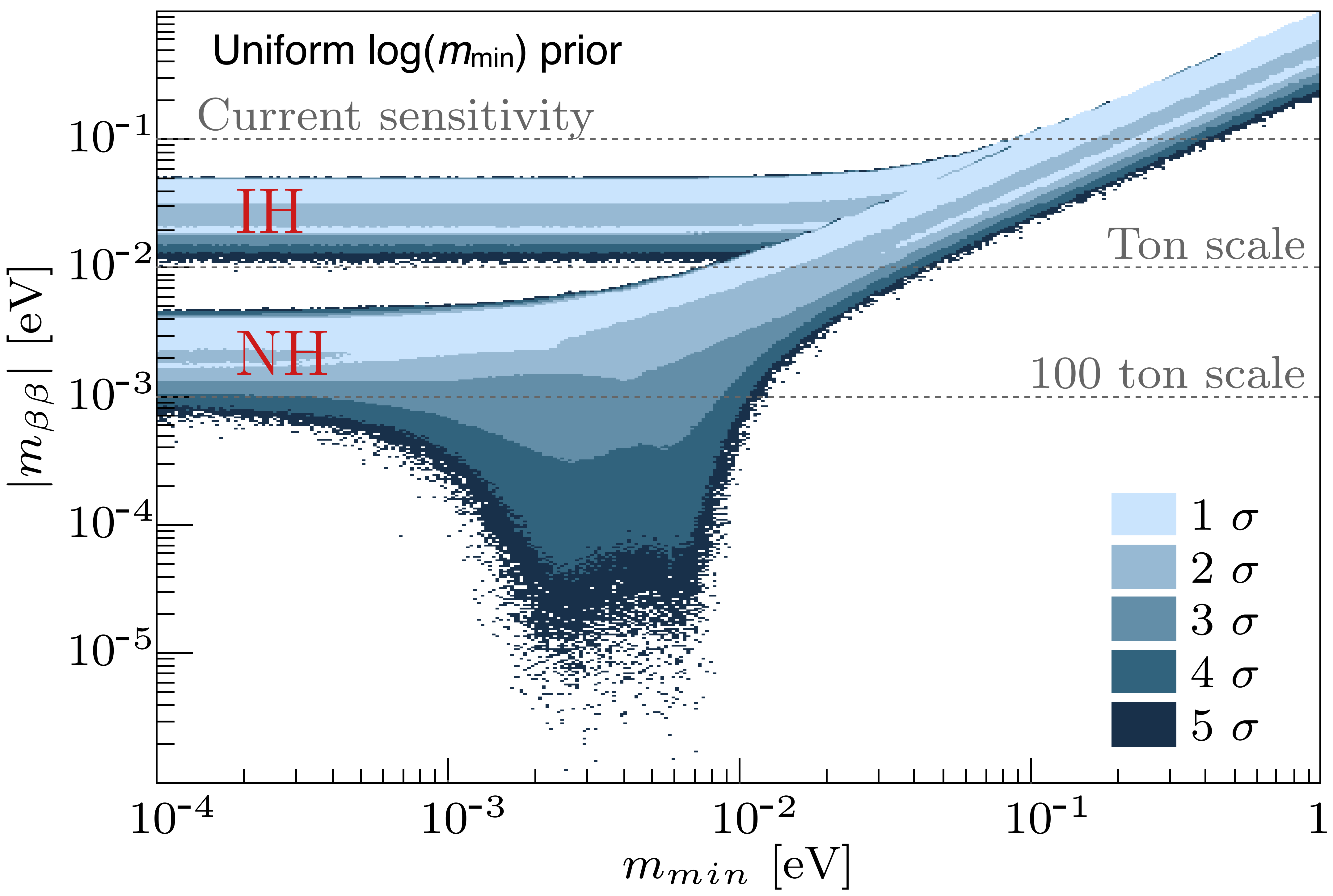
Next-Generation Reach

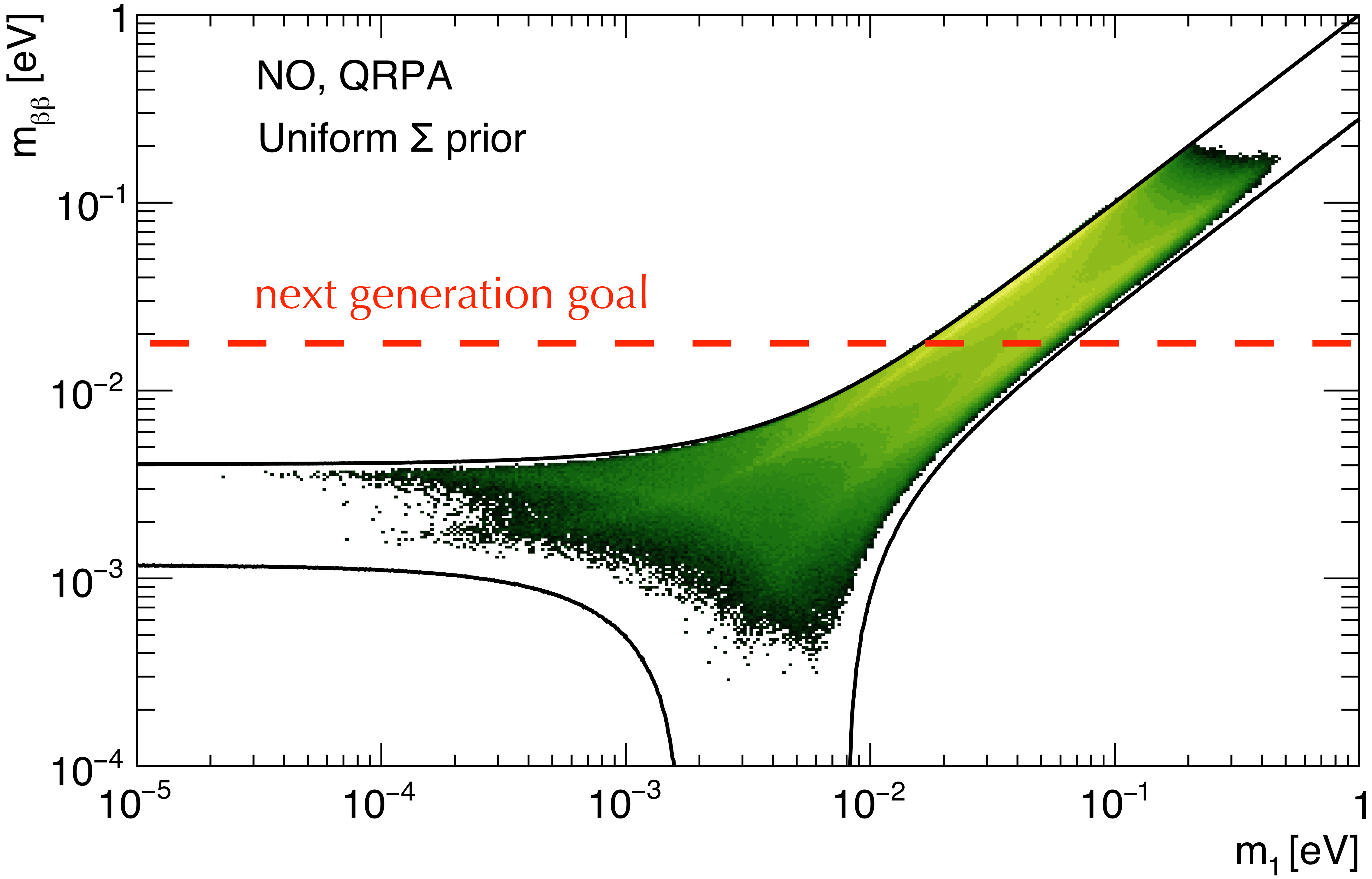
- Next generation experiments are poised to reach the IO minimum:
  - for most NME calculations
  - in multiple isotopes
  - With very different experimental techniques
- Some NME reach well beyond the IO
- Experiments are being designed with upgrade capability to push even further into the NO



Agostini, Benato, Detwiler, Menendez, and Vissani, Phys. Rev. C **104**, L042501 (2021)

Bayesian Treatments





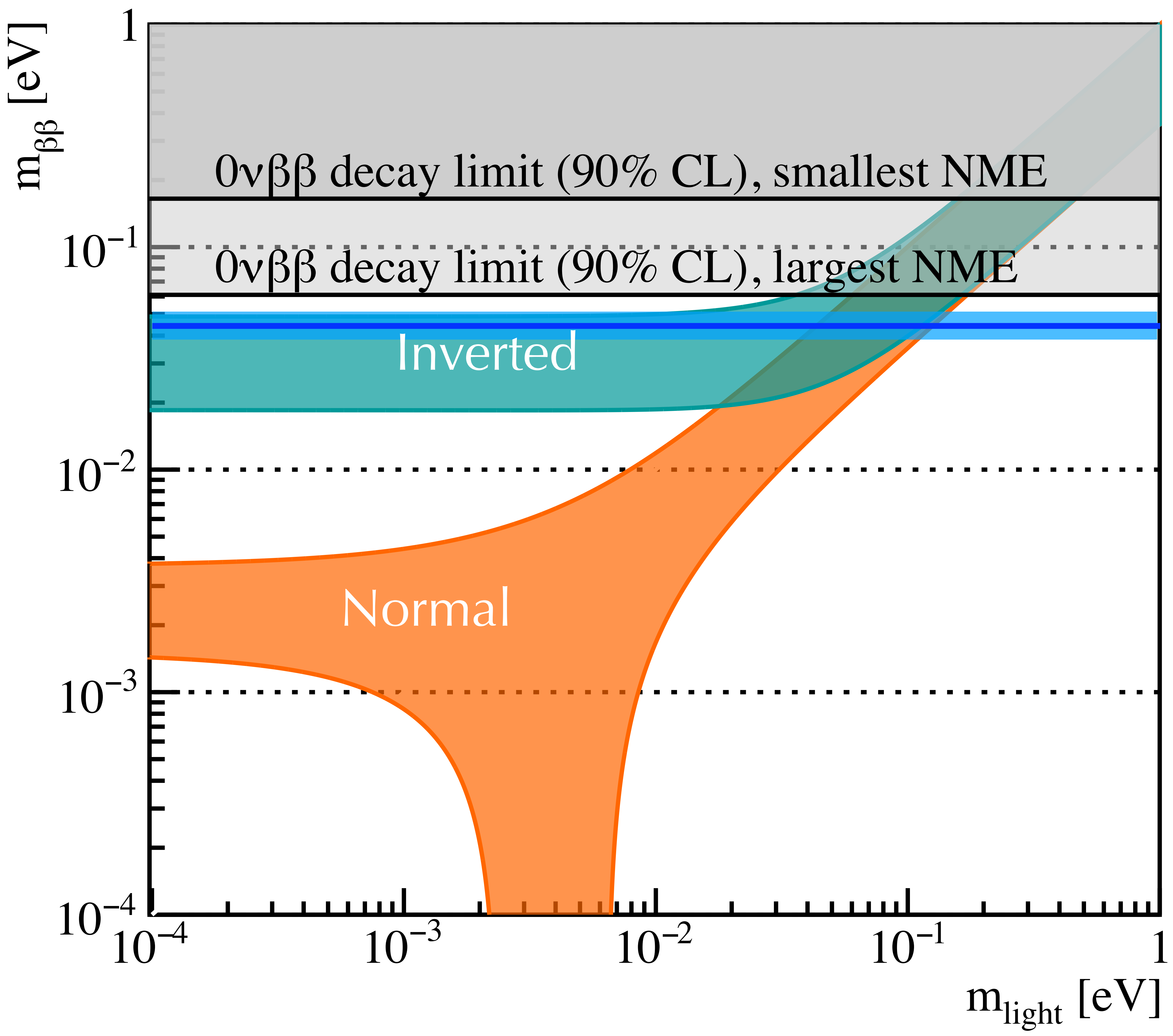
- E.g. m_i ~ NO masses like other leptons, then suppressed
- Natural cutoff for $m_{min} > 10^{-13}$ eV from loop contributions
- Ton-scale experiments will probe ~all of IH, ~very little of NO

- E.g. m_i supressed to some scale, then split about that scale
- Natural cutoff at Σ_{min} leaves little phase space for vanishing m_1
- Ton-scale experiments will probe ~all of IO, up to ~50% of NO

Benato, Eur. Phys. J. C **75**, 563 (2015)
Agostini, Benato, and Detwiler, PRD **96**, 053001 (2017)

Ton-Scale Discovery Scenarios

- $T_{1/2} \ll 10^{28}$ years: 100s of counts
  - O(10%) statistical uncertainty: NME uncertainties dominate
  - Follow up with experiments designed to probe the decay mechanism



Ton-Scale Discovery Scenarios

- $T_{1/2} \ll 10^{28}$ years: 100s of counts
  - O(10%) statistical uncertainty: NME uncertainties dominate
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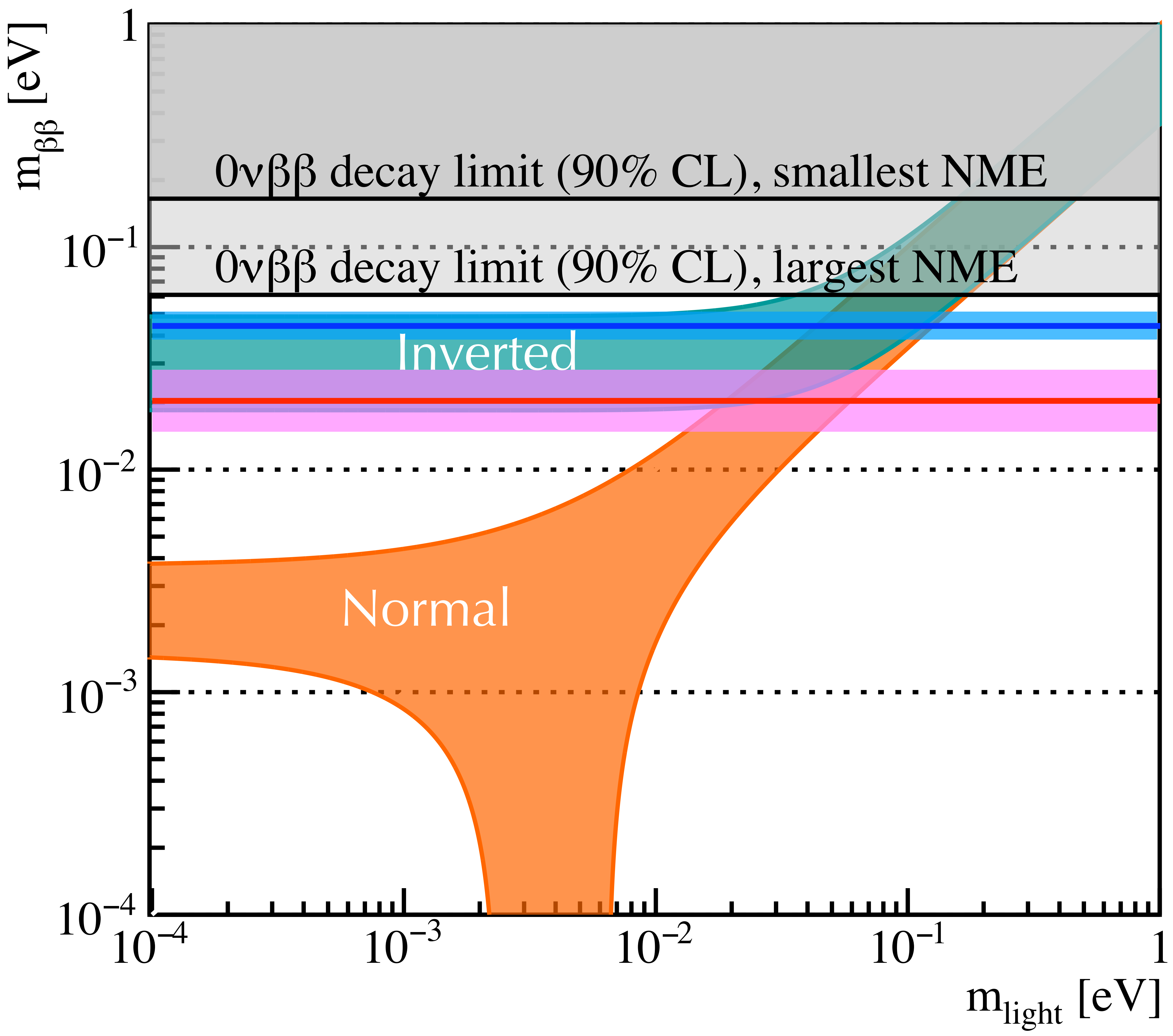
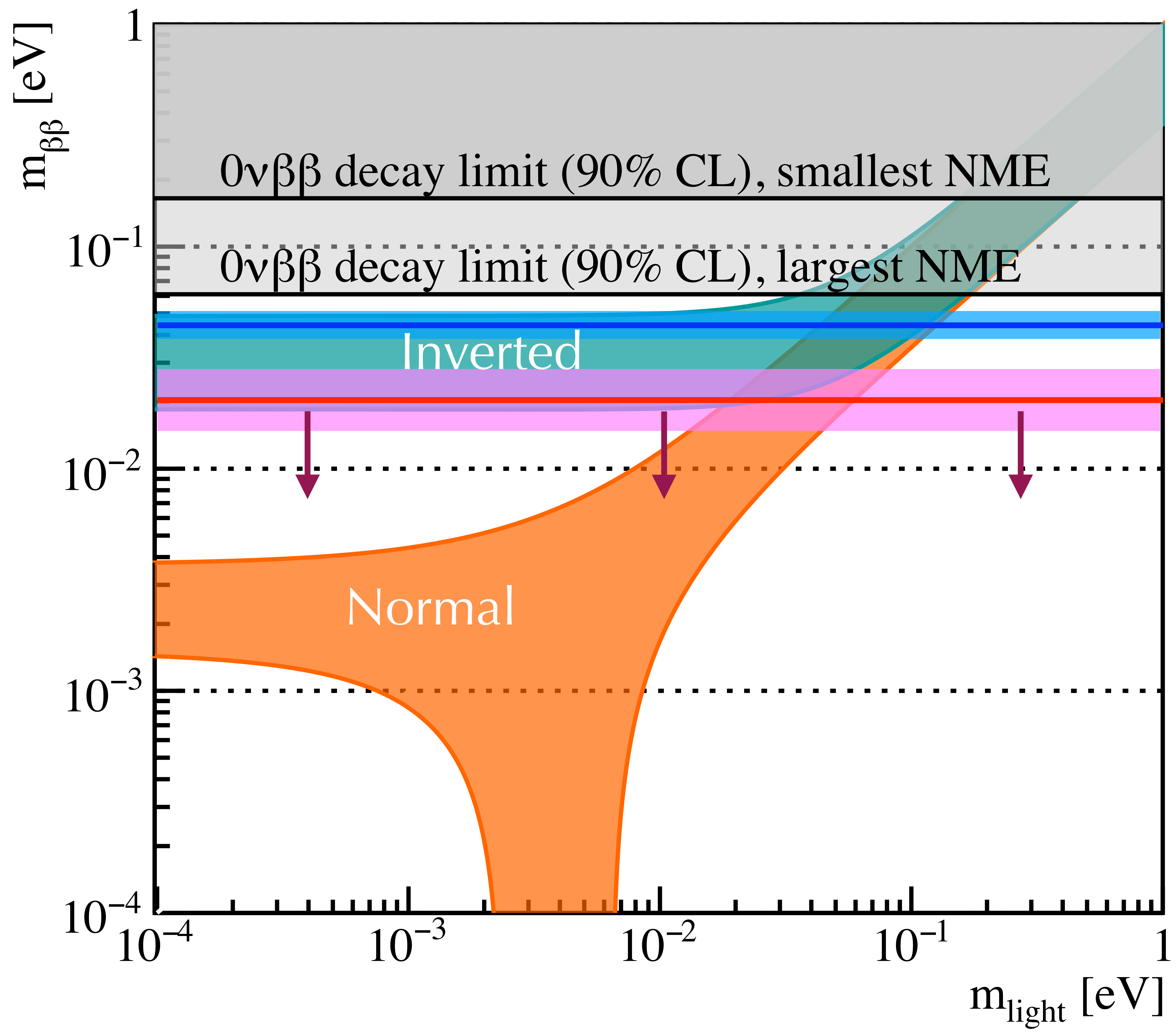
- $T_{1/2} \sim 10^{28}$ years: ~10 counts
  - Statistical uncertainty on same order as NME
  - Follow up with ~ton-scale experiments to confirm the discovery



Ton-Scale Discovery Scenarios

- $T_{1/2} \ll 10^{28}$ years: 100s of counts
  - O(10%) statistical uncertainty: NME uncertainties dominate
  - Follow up with experiments designed to probe the decay mechanism
- $T_{1/2} \sim 10^{28}$ years: ~10 counts
  - Statistical uncertainty on same order as NME
  - Follow up with ~ton-scale experiments to confirm the discovery
- $T_{1/2} \gg 10^{28}$ years: < a few counts
  - R&D required to push into NO bulk, reduce cost



arXiv:2202.01787

Summary

- Discovery of neutrinoless double beta decay would be the first observation of matter creation (without antimatter) by humans, and is deeply important regardless of theoretical motivations.
- The international experimental program in both experiment and theory is robust and aggressive.
- The ton-scale experiments CUPID, nEXO, and LEGEND are poised for discovery!