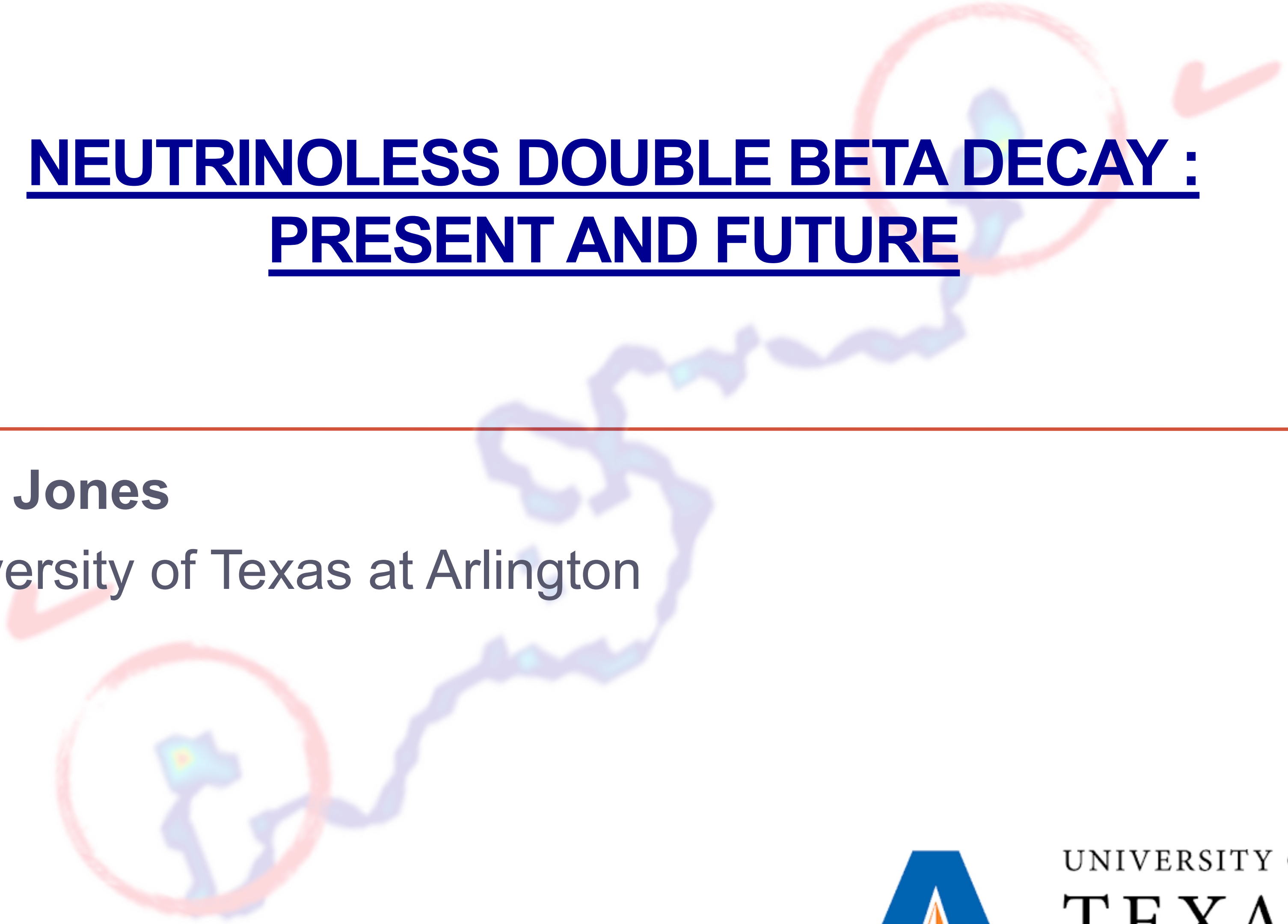

NEUTRINOLESS DOUBLE BETA DECAY : PRESENT AND FUTURE

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Rencontres De Blois 2023

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TEXAS
ARLINGTON

SM as a low energy effective theory:

$$L = L_{SM} + \frac{1}{E_{new}} L_1 + \frac{1}{E_{new}^2} L_2 + \dots$$

SM is a low energy effective theory:

$$L = L_{SM} + \frac{1}{E_{new}} L_1 + \frac{1}{E_{new}^2} L_2 + \ldots$$

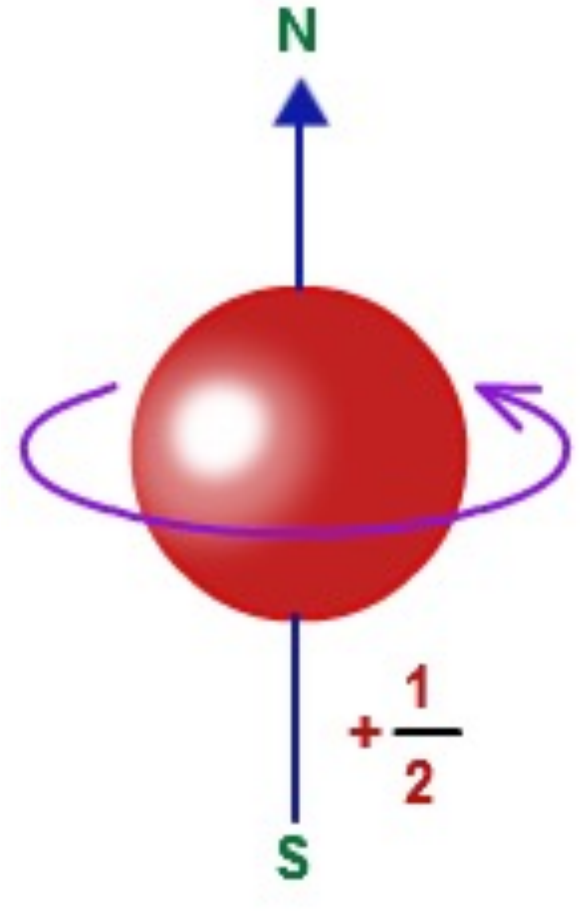
- The only dimension-5 operator one can add obeying SM gauge symmetry:

$$\frac{L_1}{E_{new}} = y_{ij} \frac{\nu^i H \nu^j H}{E_{new}}$$

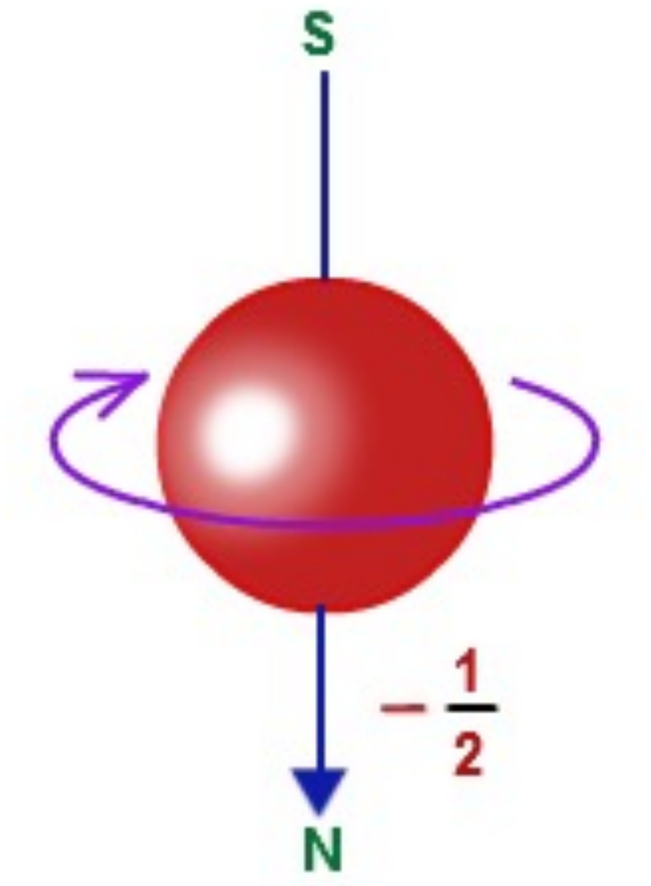
Weinberg 1979.

- This term does ~one observable thing - it makes neutrinos Majorana particles, with mass suppressed by new physics scale.
- And it makes the theory non-renormalizible – implying there must be something else at high scale too (see also: Seasaw)

Majorana Neutrinos in a Nutshell



Behaves like matter



Behaves like antimatter

Robust observation of Majorana neutrinos would tell us 5 things about nature before breakfast:

1) Lepton number conservation is violated.

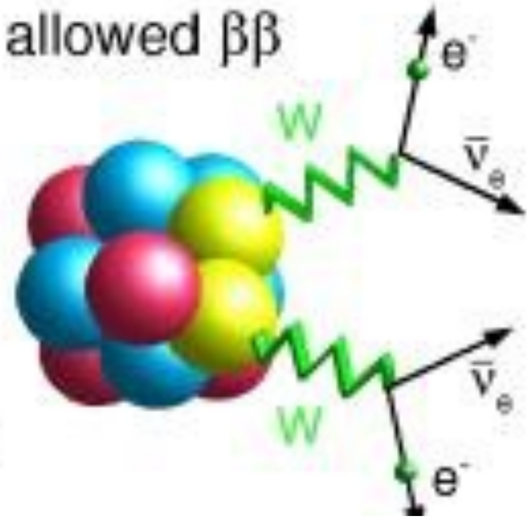
2) Massive fermions exist that are neither matter or antimatter but something else (Majorana fermions)

3) The SM with the Majorana term is non-renormalizible → SM is definitely a low energy effective theory.

4) There are other mass generating mechanisms in nature beyond the Higgs mechanism (though the Higgs may be involved, nonetheless).

5) Majorana neutrinos are a prediction of the theory of Leptogenesis that may generate observed matter/anti-matter asymmetry of the Universe (given leptonic CPV – see also: HyperK / DUNE)

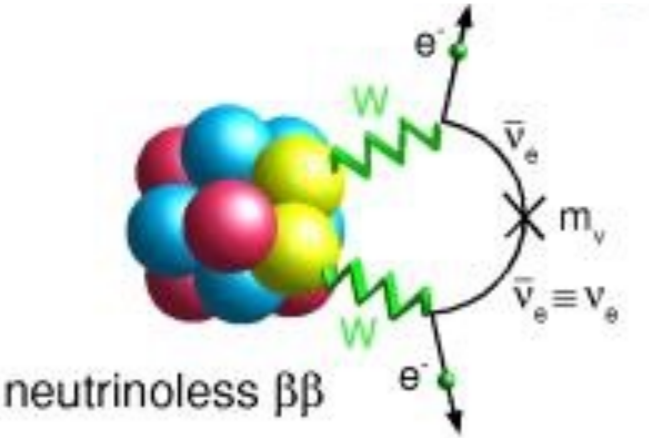
Double beta decay



A known standard model process and an important calibration tool

$$T_{\frac{1}{2}} = 10^{19} - 10^{21}\text{yr}$$

Final state: $e^- e^- \bar{\nu}_e \bar{\nu}_e$



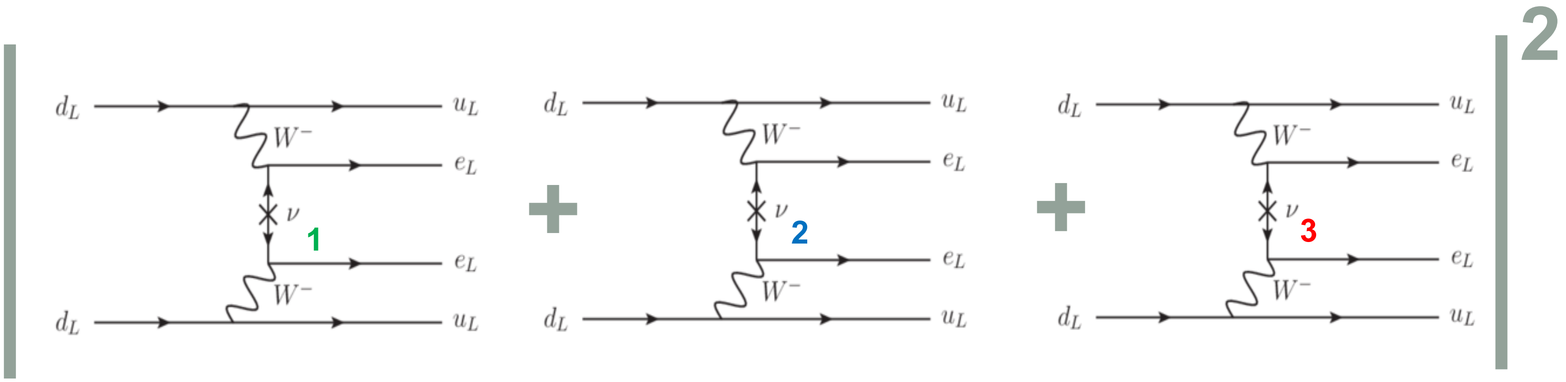
Observation would prove that the neutrino is a Majorana fermion

$$T_{\frac{1}{2}} = \left[G \times |M|^2 \times m_{\beta\beta}^2\right]^{-1}$$

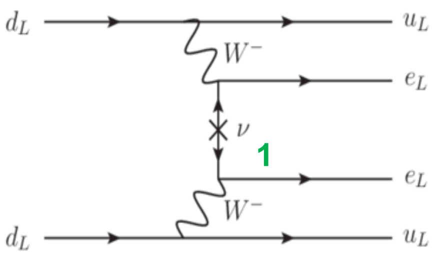
Final state: $e^- e^-$

The "minimal" mechanism:

$\Gamma \alpha$



$\Gamma \, \alpha \, \Big|$



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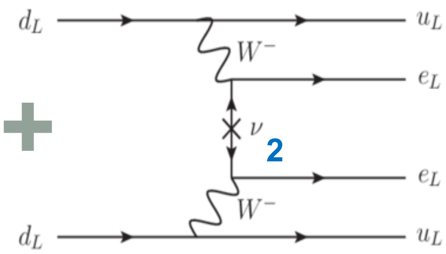

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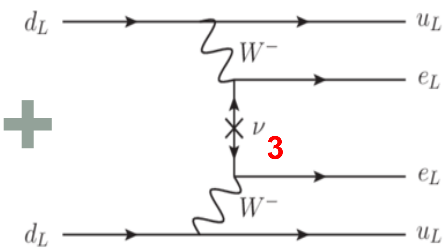
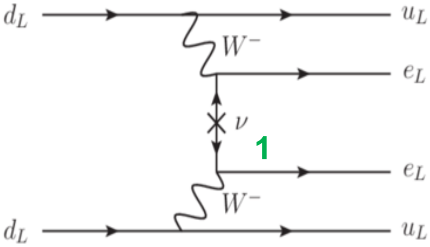


$\Big|^2$

$$= \left| (U_{e1})^2 m_1 + (U_{e2})^2 m_2 + (U_{e3})^2 m_3 \right|^2$$

$\Gamma \propto \Big|$



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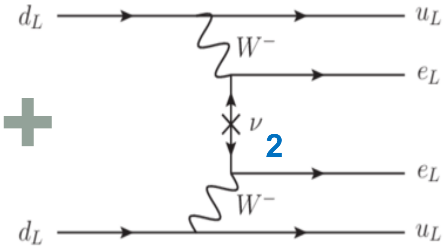

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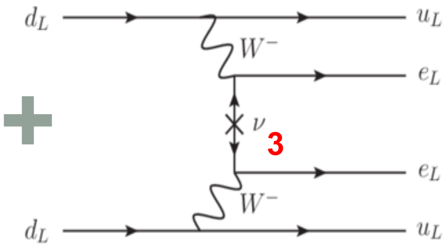
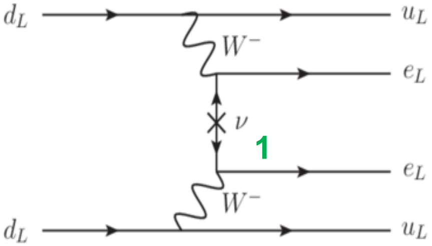


$\Big|^2$

$$= \left| (U_{e1})^2 m_1 + (U_{e2})^2 m_2 + (U_{e3})^2 m_3 \right|^2$$

$$= \left| c_{12}^2 c_{13}^2 e^{2i\alpha}\, m_1 + c_{12}^2 s_{12}^2 e^{2i\beta}\, m_2 + s_{13}^2 m_3 \right|^2$$

$\Gamma \; \alpha \; \Big|$



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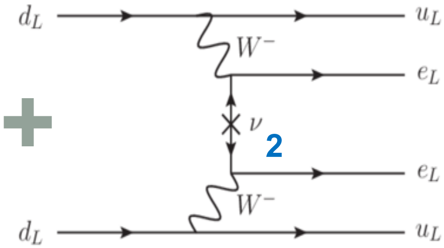

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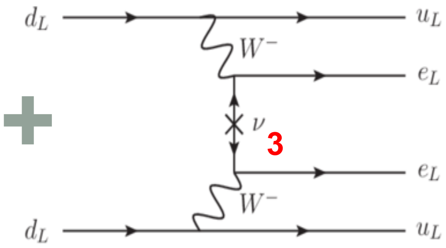


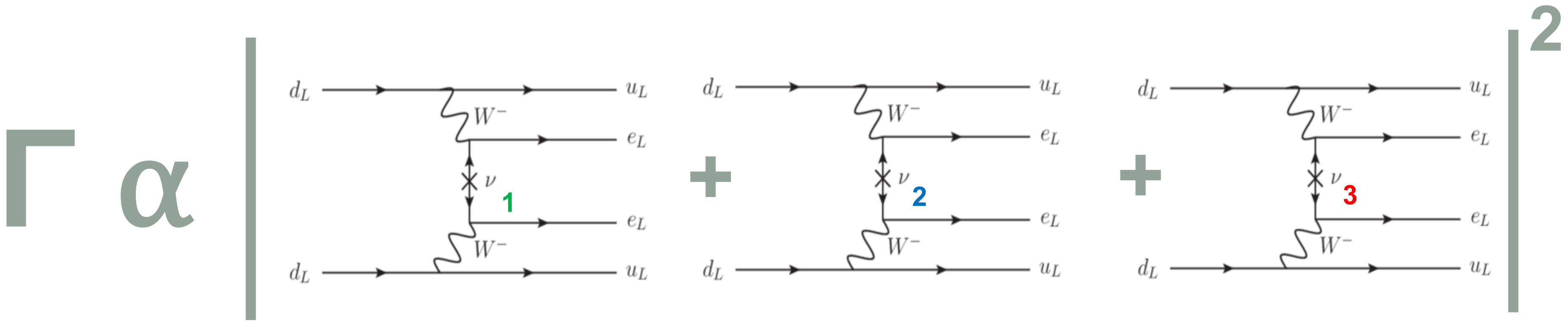
$\Big|^2$

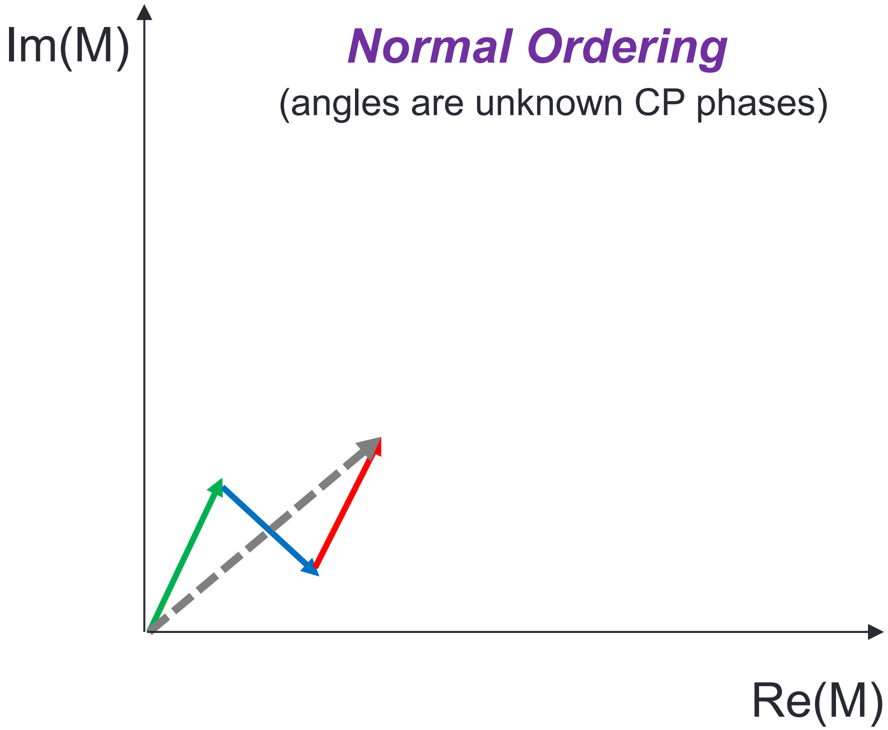
$$= \left| (U_{e1})^2 m_1 + (U_{e2})^2 m_2 + (U_{e3})^2 m_3 \right|^2$$

$$= \left| c_{12}^2 c_{13}^2 e^{2i\alpha} m_1 + c_{12}^2 s_{12}^2 e^{2i\beta} m_2 + s_{13}^2 m_3 \right|^2$$

$$= \left| m_{\beta\beta} \right|^2$$

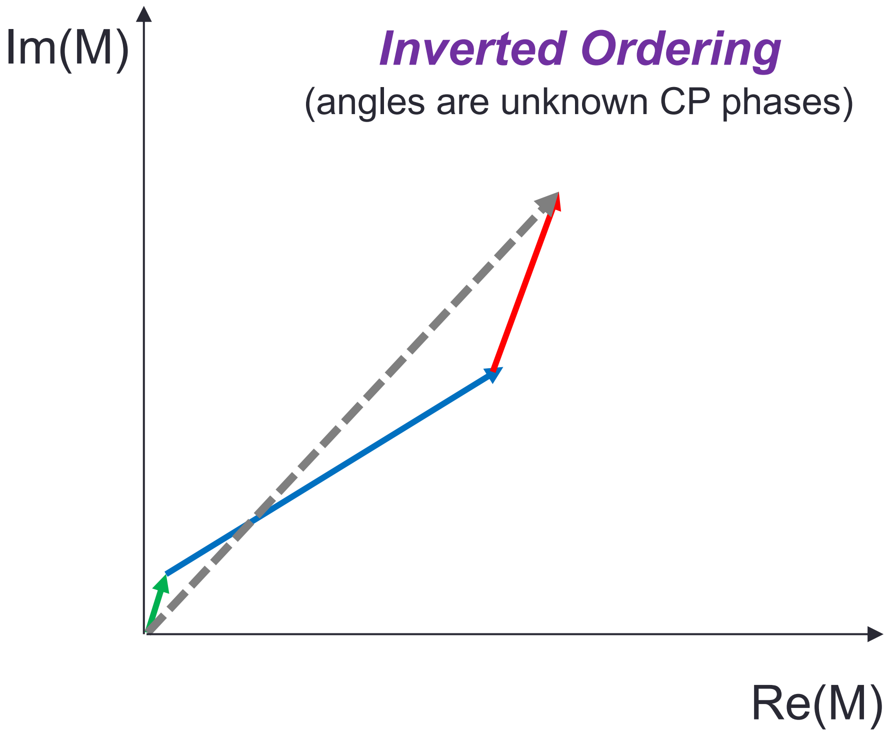
$$\boxed{T_{\frac{1}{2}} = \left[G \times |M|^2 \times m_{\beta\beta}^2 \right]^{-1}}$$





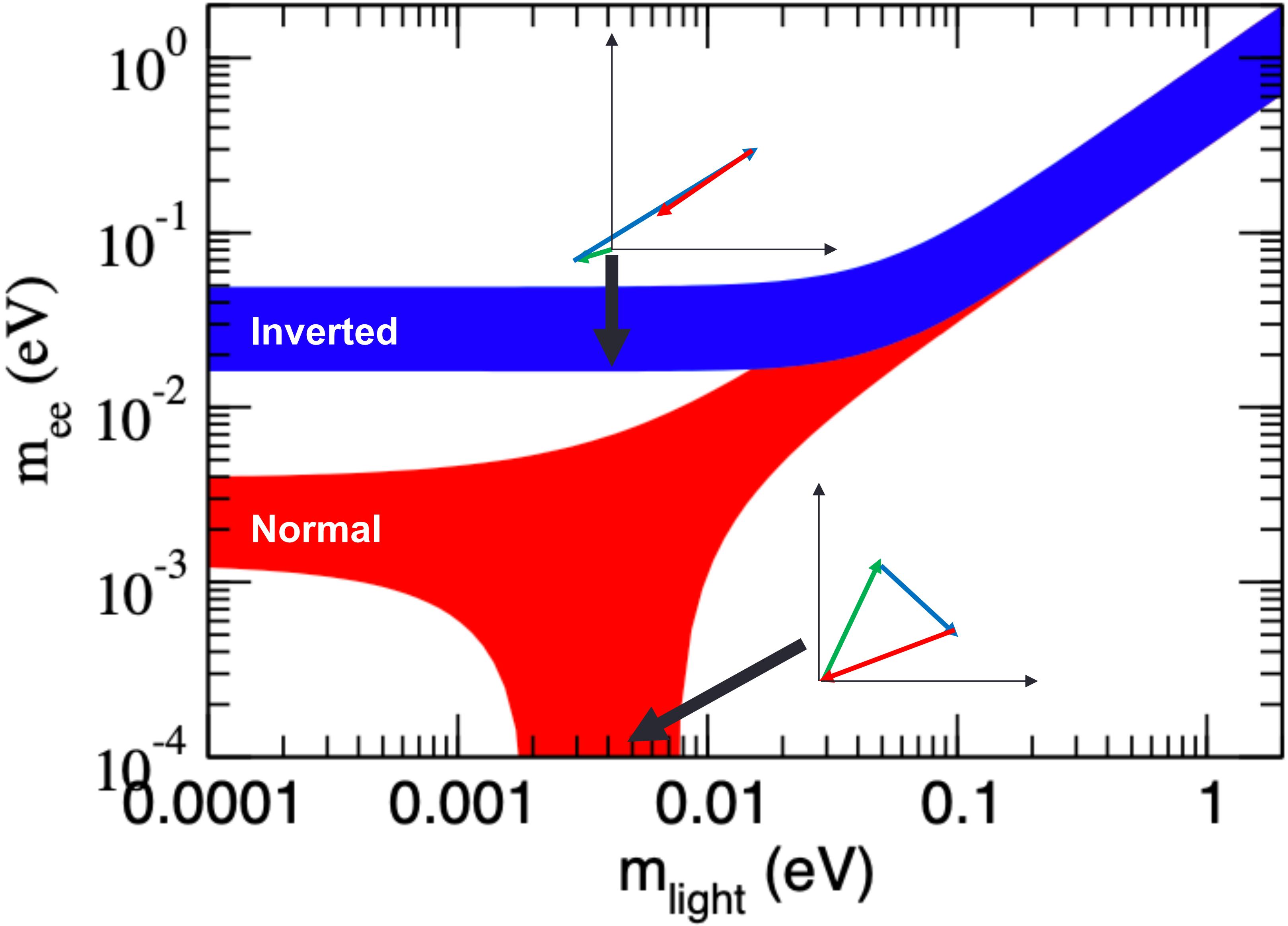
Normal Ordering

(angles are unknown CP phases)



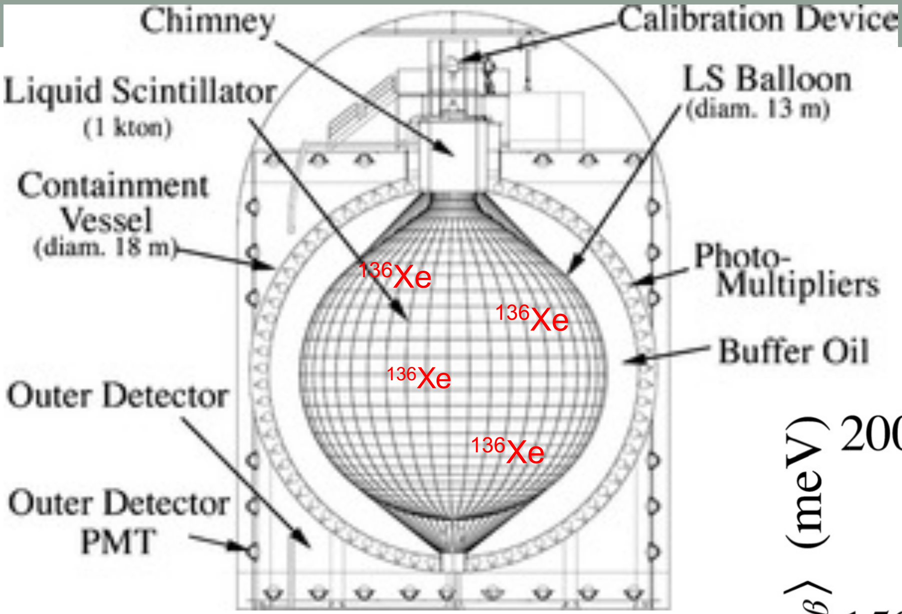
Inverted Ordering

(angles are unknown CP phases)


10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
m_{ee} (eV)
Inverted
Normal
0.0001
0.001
0.01
0.1
1
m_{light} (eV)

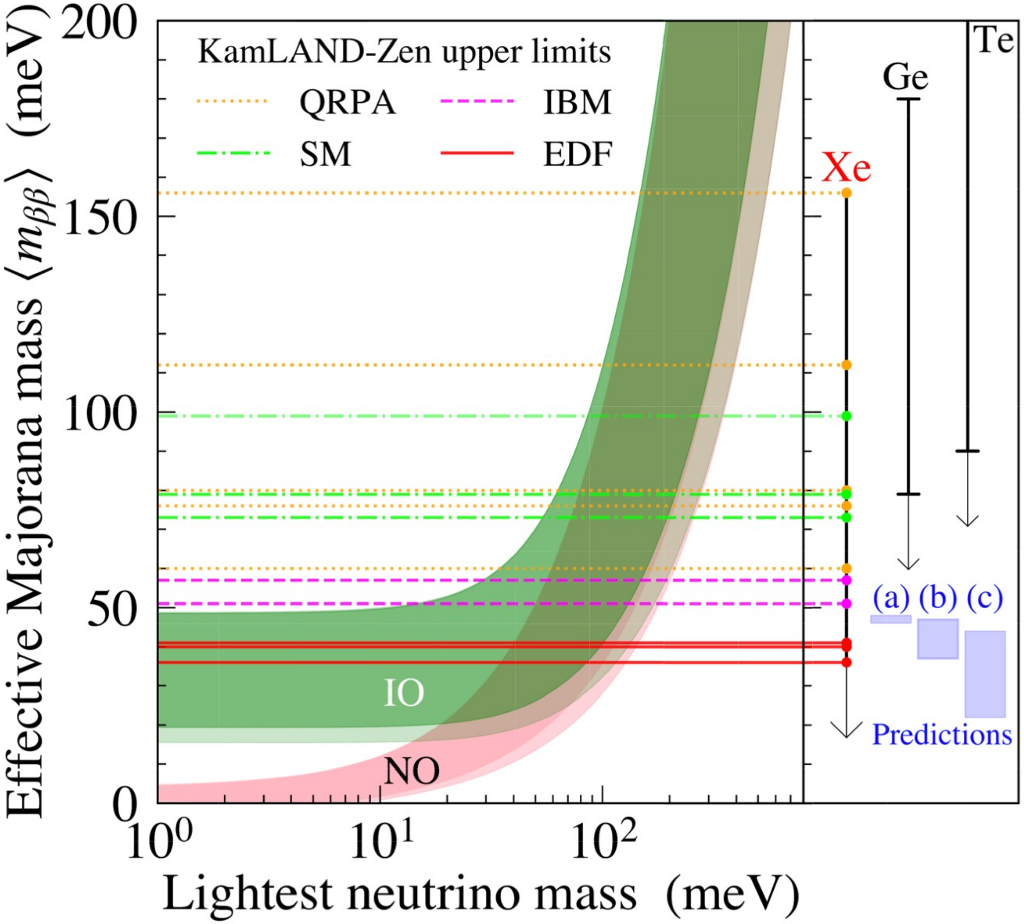
Current limits

KZ leads with:
$T_{1/2}>2.3\text{x}10^{26}$yr

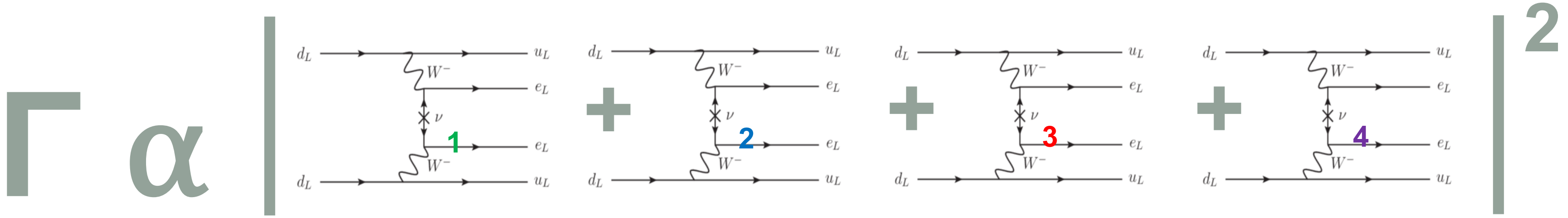


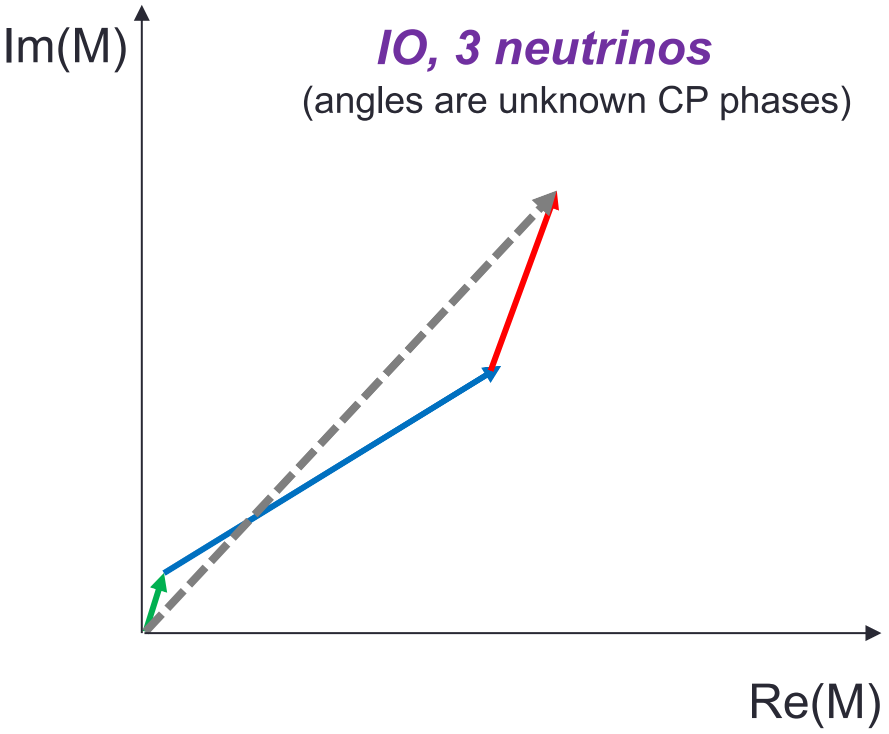
Leading limits in each isotope:

Experiment	Isotope	Exposure [kg yr]	$T^{0\nu}_{1/2}$ [10^{25} yr]	$m_{\beta\beta}$ [meV]
Gerda	^{76}Ge	127.2	18	79-180
Majorana	^{76}Ge	26	2.7	200-433
KamLAND-Zen	^{136}Xe	970	23	36-156
EXO-200	^{136}Xe	234.1	3.5	93-286
CUORE	^{130}Te	1038.4	2.2	90-305



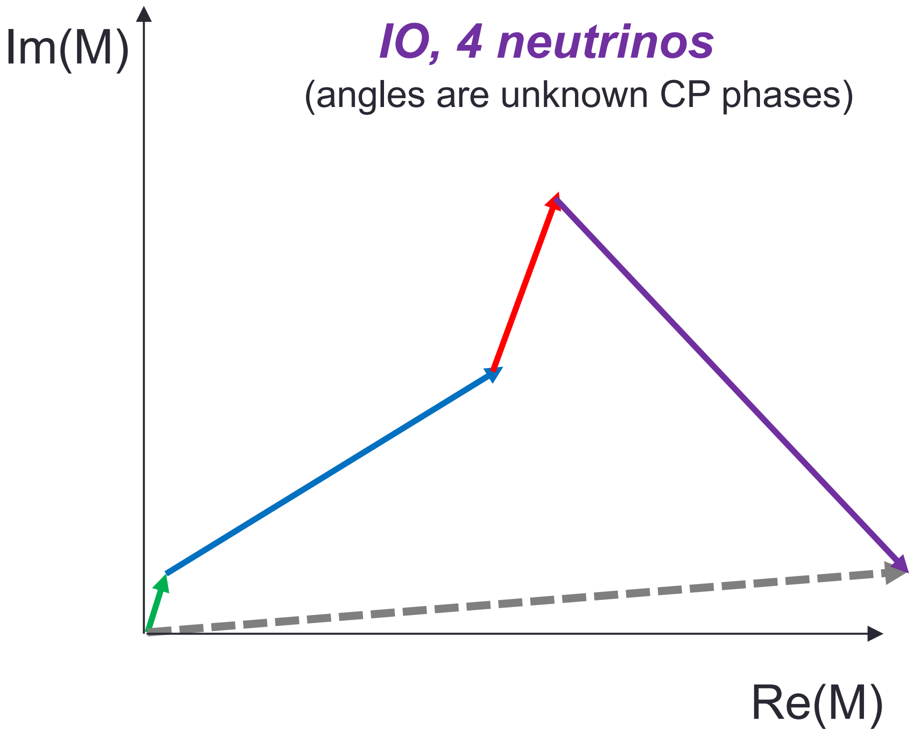
Non-minimal mechanisms:





IO, 3 neutrinos

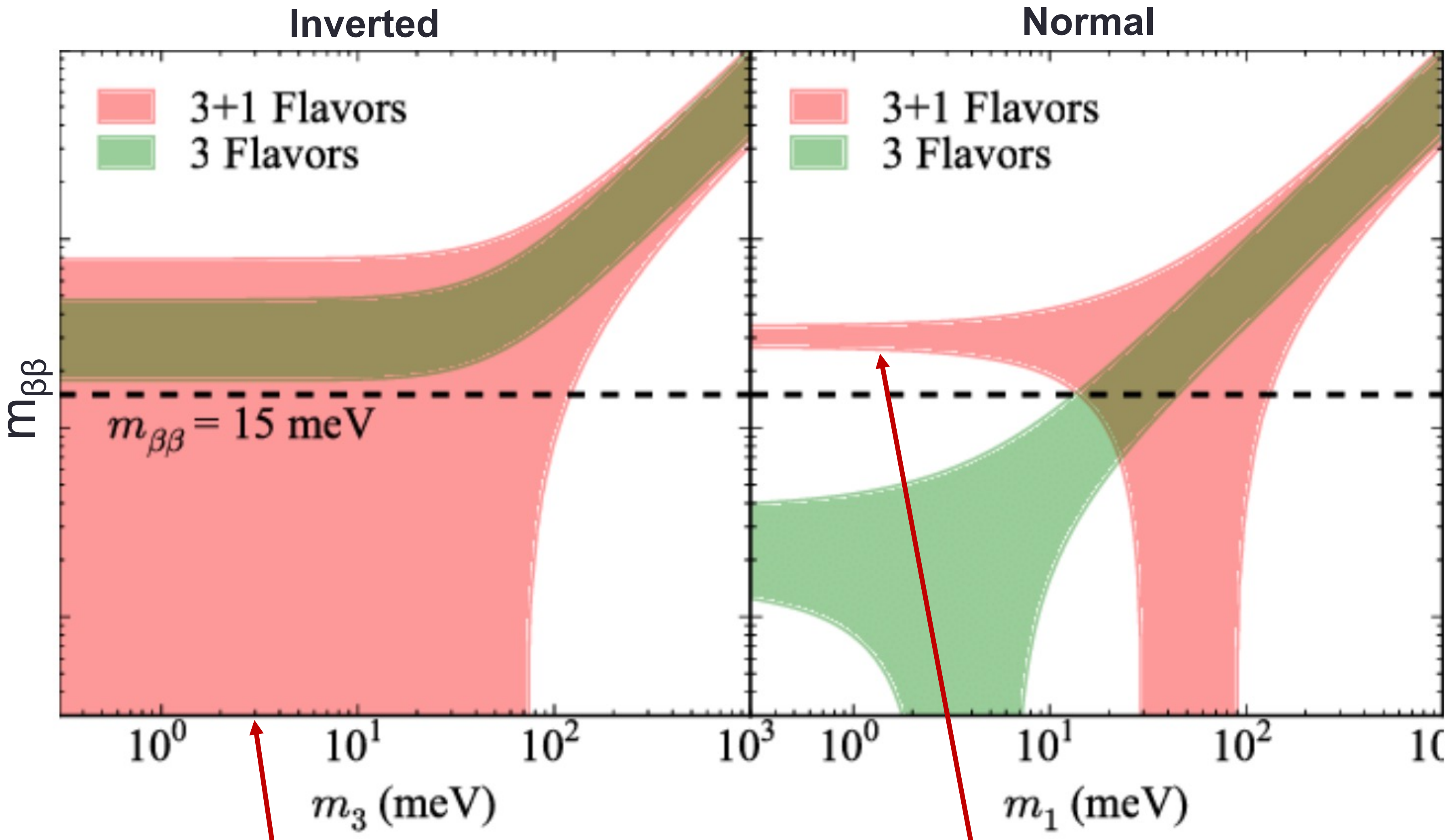
(angles are unknown CP phases)



IO, 4 neutrinos

(angles are unknown CP phases)

With a sterile neutrino:



Now you can close the loop here after all

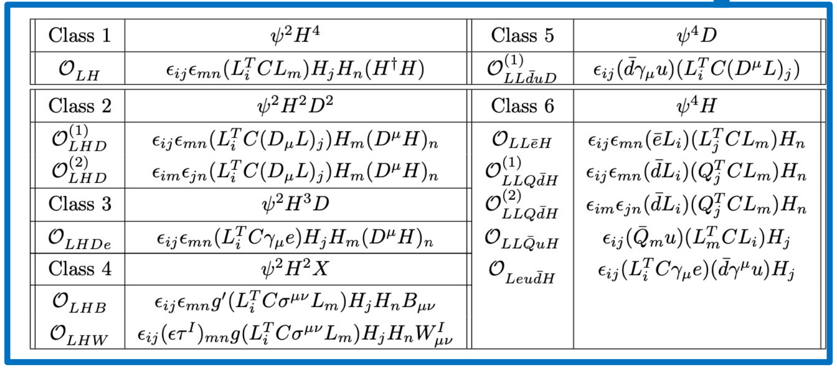
But this gets less difficult!

Higher order operators

NDBD can also come from up here

$$L = L_{SM} + \frac{1}{E_{new}} L_1 + \frac{1}{E_{new}^2} L_2 + \dots$$

Weinberg operator
("minimal" model)



Class 1	$\psi^2 H^4$	Class 5	$\psi^4 D$
$\mathcal{O}_{LH}$	$\epsilon_{ij}\epsilon_{mn}(L_i^T C L_m) H_j H_n (H^\dagger H)$	$\mathcal{O}^{(1)}_{LL\bar{d}uD}$	$\epsilon_{ij}(\bar{d}\gamma_\mu u)(L_i^T C (D^\mu L)_j)$
Class 2	$\psi^2 H^2 D^2$	Class 6	$\psi^4 H$
$\mathcal{O}^{(1)}_{LHD}$	$\epsilon_{ij}\epsilon_{mn}(L_i^T C (D_\mu L)_j) H_m (D^\mu H)_n$	$\mathcal{O}_{LL\bar{e}H}$	$\epsilon_{ij}\epsilon_{mn}(\bar{e}L_i)(L_j^T C L_m) H_n$
$\mathcal{O}^{(2)}_{LHD}$	$\epsilon_{im}\epsilon_{jn}(L_i^T C (D_\mu L)_j) H_m (D^\mu H)_n$	$\mathcal{O}^{(1)}_{LLQ\bar{d}H}$	$\epsilon_{ij}\epsilon_{mn}(\bar{d}L_i)(Q_j^T C L_m) H_n$
Class 3	$\psi^2 H^3 D$	$\mathcal{O}^{(2)}_{LLQ\bar{d}H}$	$\epsilon_{im}\epsilon_{jn}(\bar{d}L_i)(Q_j^T C L_m) H_n$
$\mathcal{O}_{LHDe}$	$\epsilon_{ij}\epsilon_{mn}(L_i^T C \gamma_\mu e) H_j H_m (D^\mu H)_n$	$\mathcal{O}_{LL\bar{Q}uH}$	$\epsilon_{ij}(\bar{Q}_m u)(L_m^T C L_i) H_j$
Class 4	$\psi^2 H^2 X$	$\mathcal{O}_{Leu\bar{d}H}$	$\epsilon_{ij}(L_i^T C \gamma_\mu e)(\bar{d}\gamma^\mu u) H_j$
$\mathcal{O}_{LHB}$	$\epsilon_{ij}\epsilon_{mn} g' (L_i^T C \sigma^{\mu\nu} L_m) H_j H_n B_{\mu\nu}$		
$\mathcal{O}_{LHW}$	$\epsilon_{ij}(\epsilon\tau^I)_{mn} g (L_i^T C \sigma^{\mu\nu} L_m) H_j H_n W^I_{\mu\nu}$		

https://arxiv.org/pdf/1708.09390.pdf

Higher order operators

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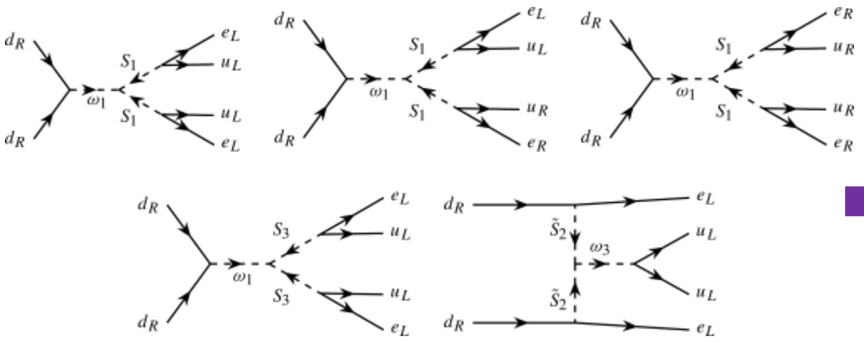
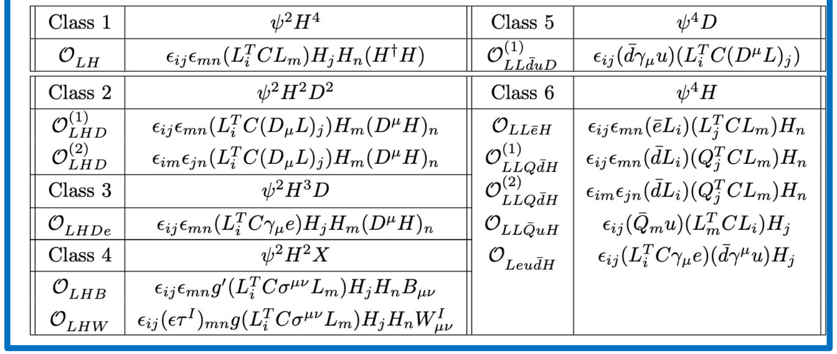
Your favorite LNV theory





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https://arxiv.org/pdf/1708.09390.pdf

Leptoquarks, SUSY, Kaluza Klein, LR symmetric couplings, etc etc

Higher order operators

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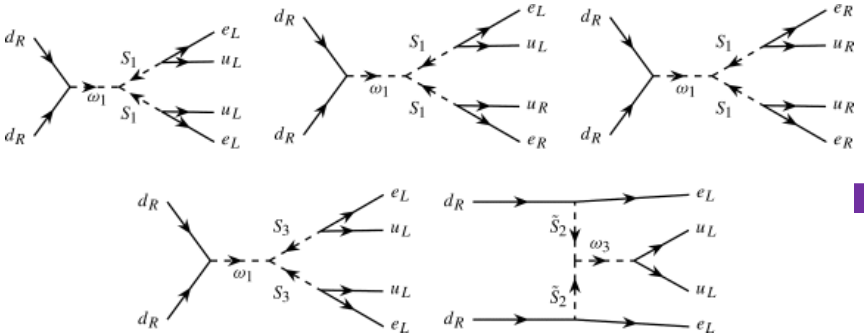
Your favorite LNV theory



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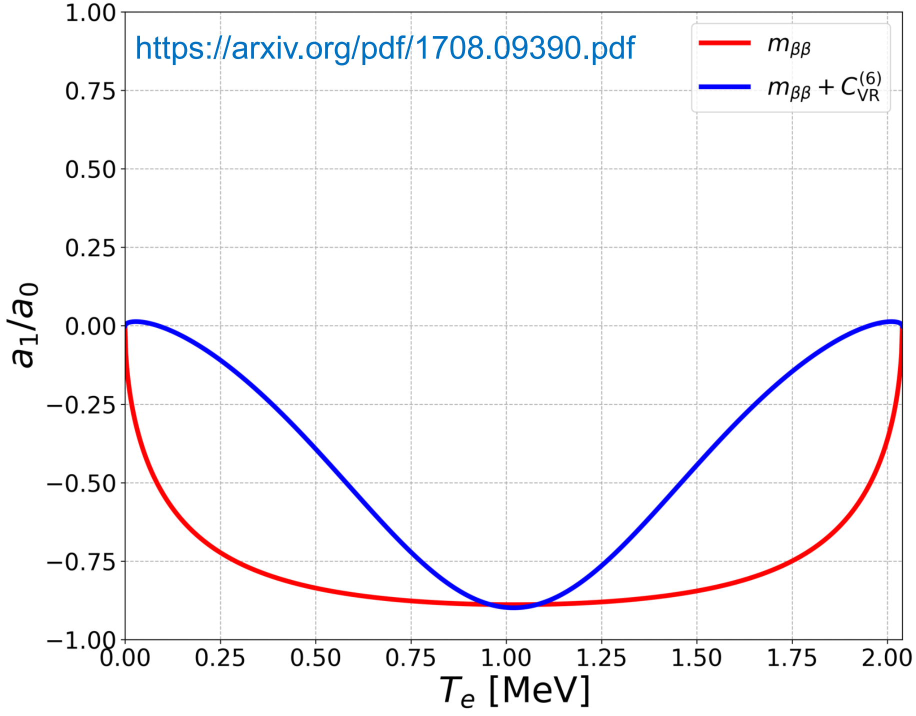
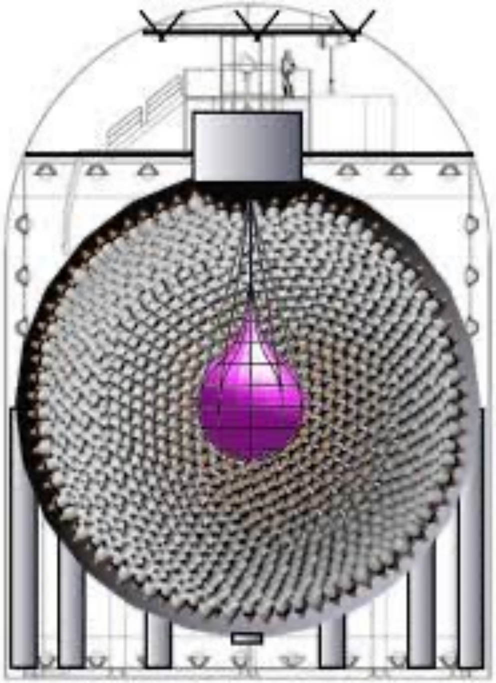


https://arxiv.org/pdf/1708.09390.pdf

If your detector can resolve the electron tracks, you can tell the difference…!

But we need to see it first…



Kamland-Zen backgrounds →

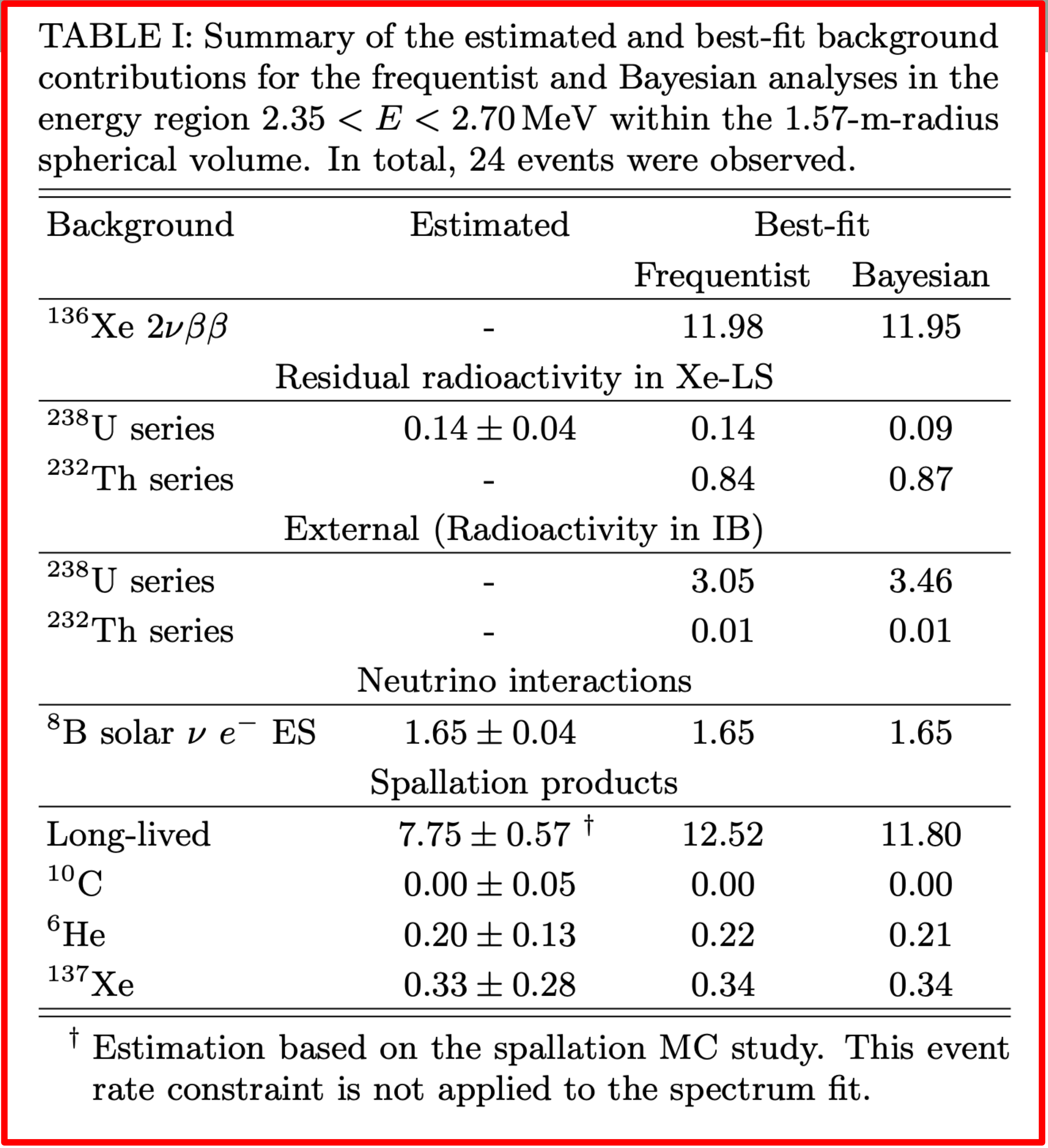
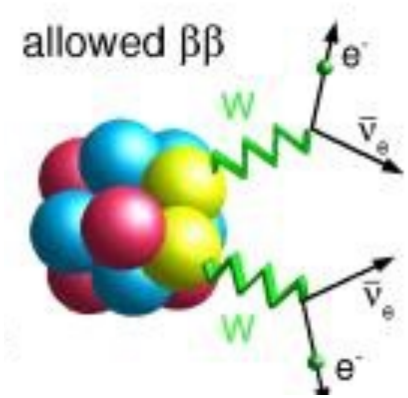
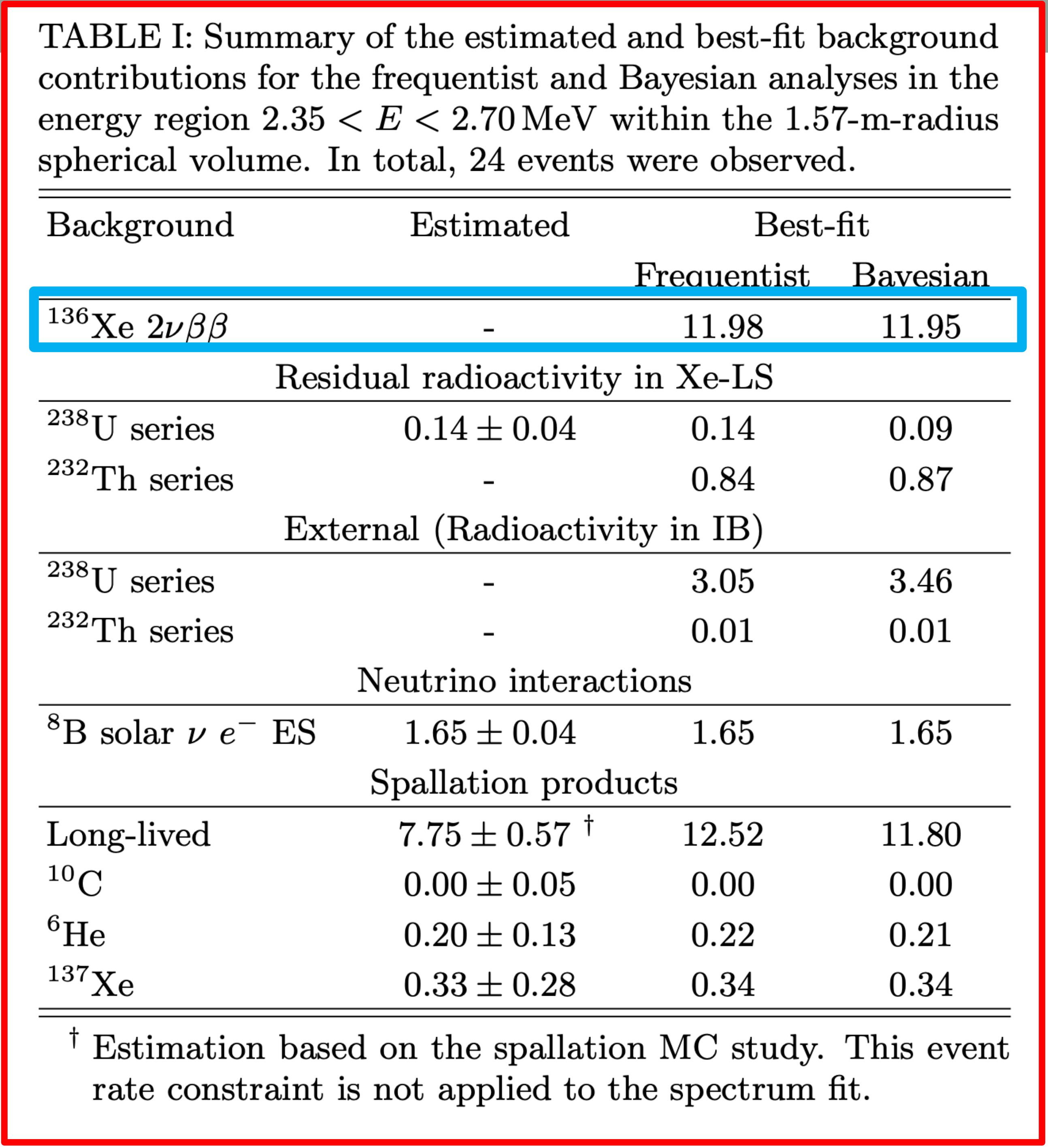


TABLE I: Summary of the estimated and best-fit background contributions for the frequentist and Bayesian analyses in the energy region $2.35 < E < 2.70$ MeV within the 1.57-m-radius spherical volume. In total, 24 events were observed.

Background	Estimated	Best-fit Frequentist	Best-fit Bayesian
^{136}Xe $2\nu\beta\beta$	-	11.98	11.95
Residual radioactivity in Xe-LS			
^{238}U series	0.14 ± 0.04	0.14	0.09
^{232}Th series	-	0.84	0.87
External (Radioactivity in IB)			
^{238}U series	-	3.05	3.46
^{232}Th series	-	0.01	0.01
Neutrino interactions			
^{8}B solar ν e^- ES	1.65 ± 0.04	1.65	1.65
Spallation products			
Long-lived	7.75 ± 0.57 †	12.52	11.80
^{10}C	0.00 ± 0.05	0.00	0.00
^{6}He	0.20 ± 0.13	0.22	0.21
^{137}Xe	0.33 ± 0.28	0.34	0.34

† Estimation based on the spallation MC study. This event rate constraint is not applied to the spectrum fit.





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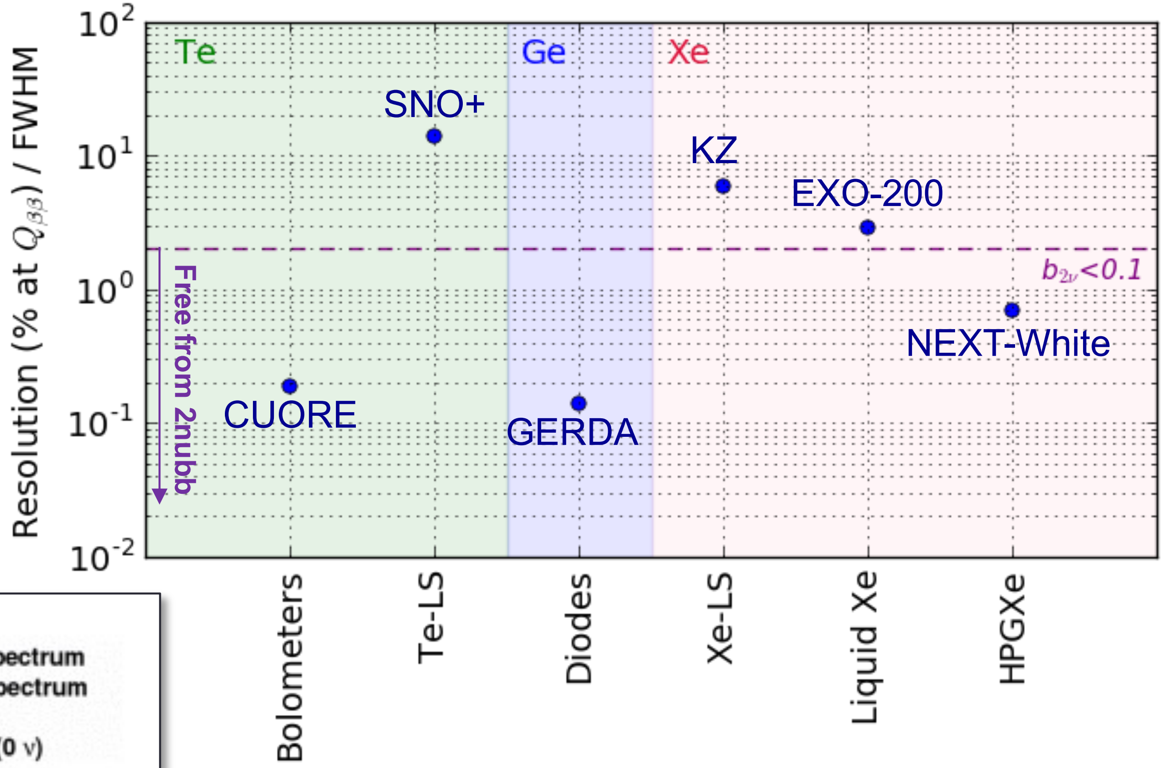
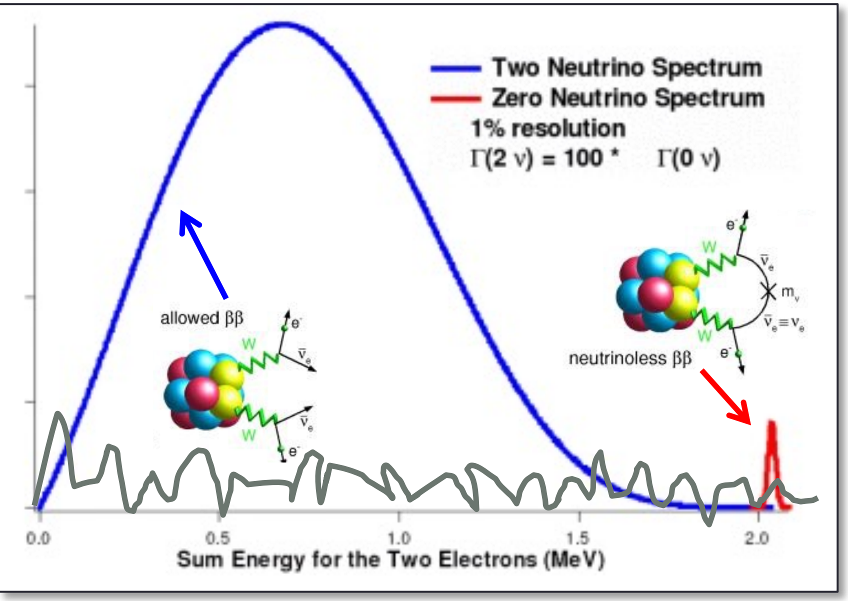
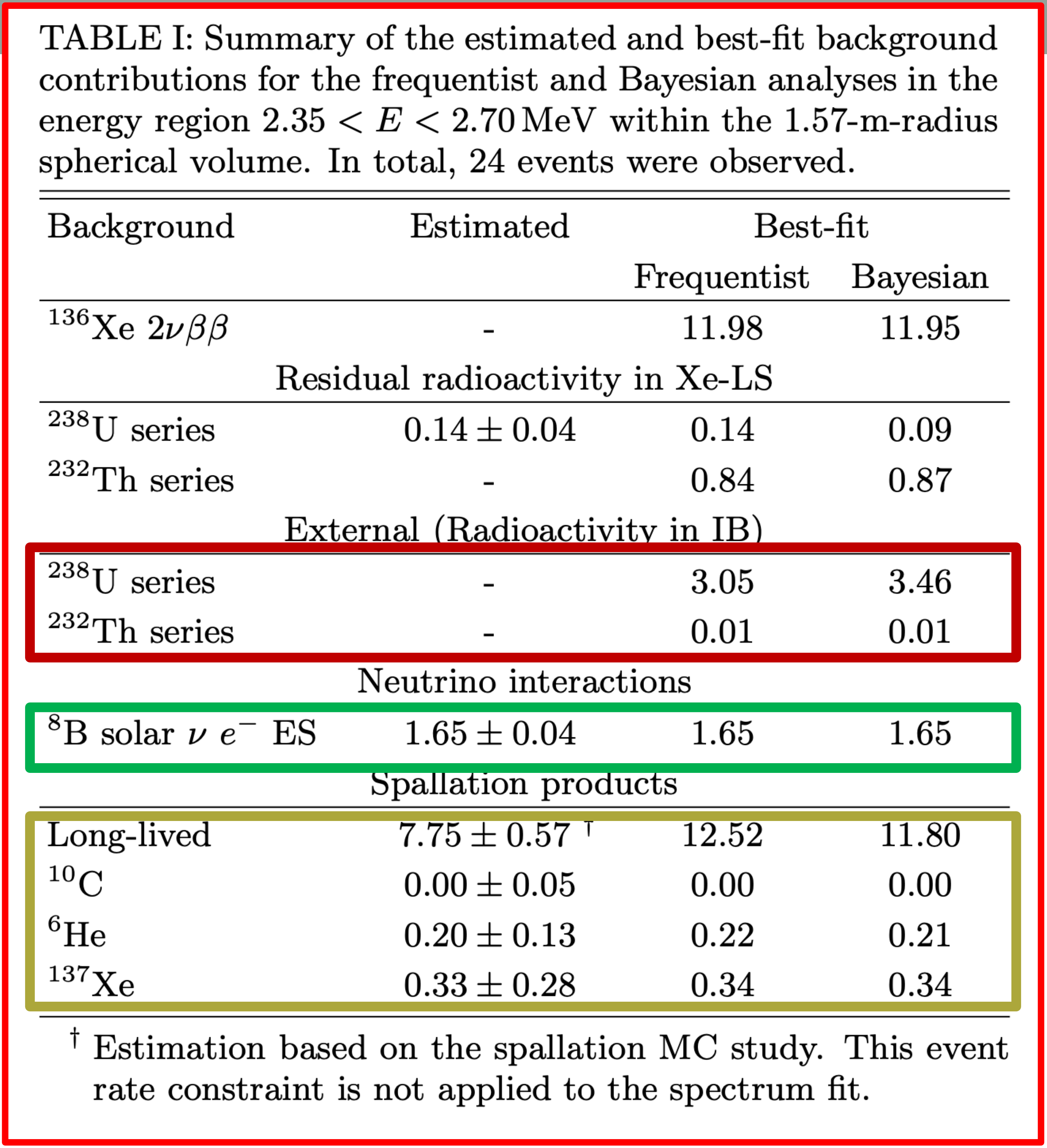
Measuring Energy





2nubb can be efficiently rejected with sufficient energy resolution alone.

Where are the backgrounds from?



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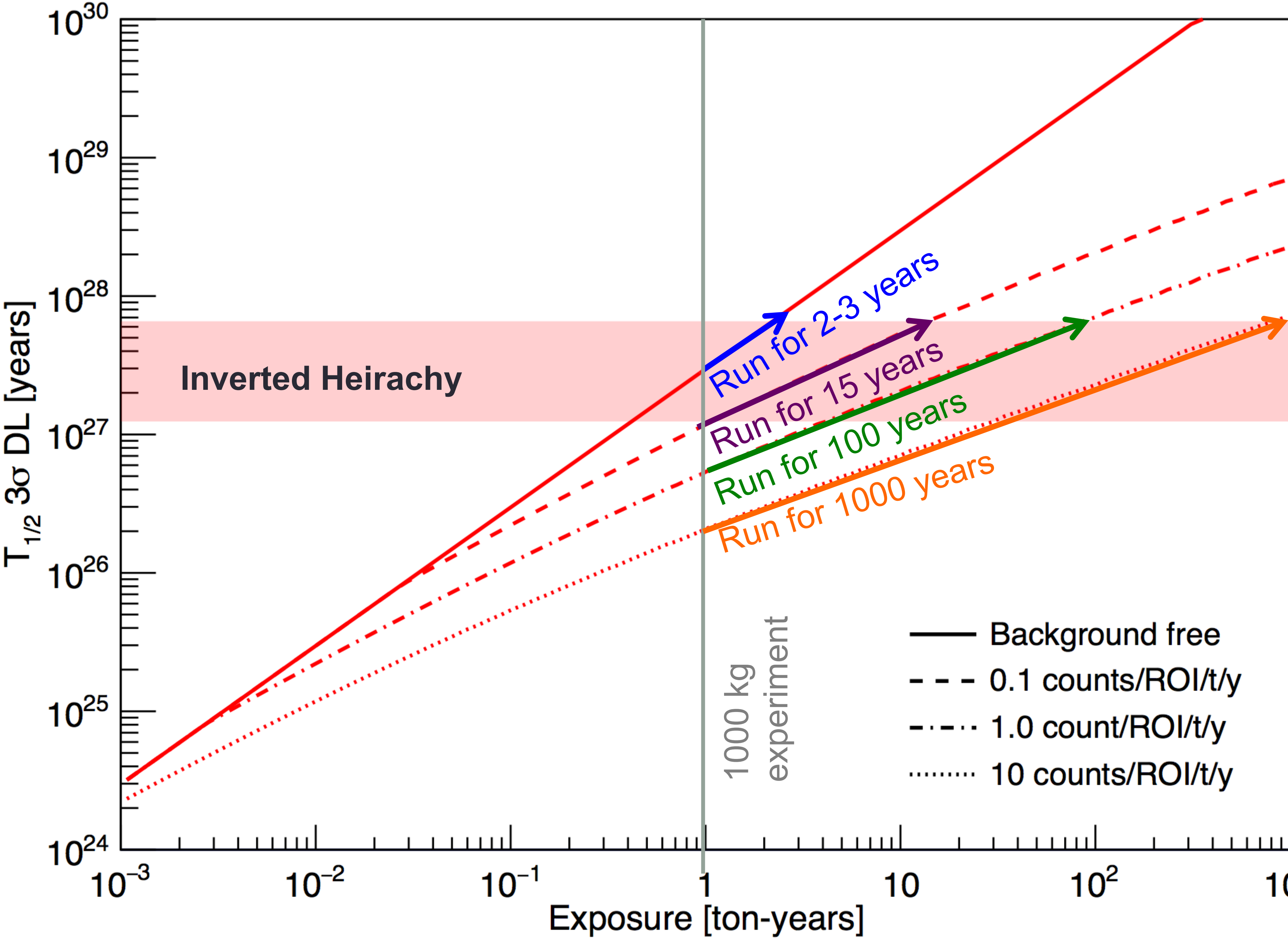
Radiogenics

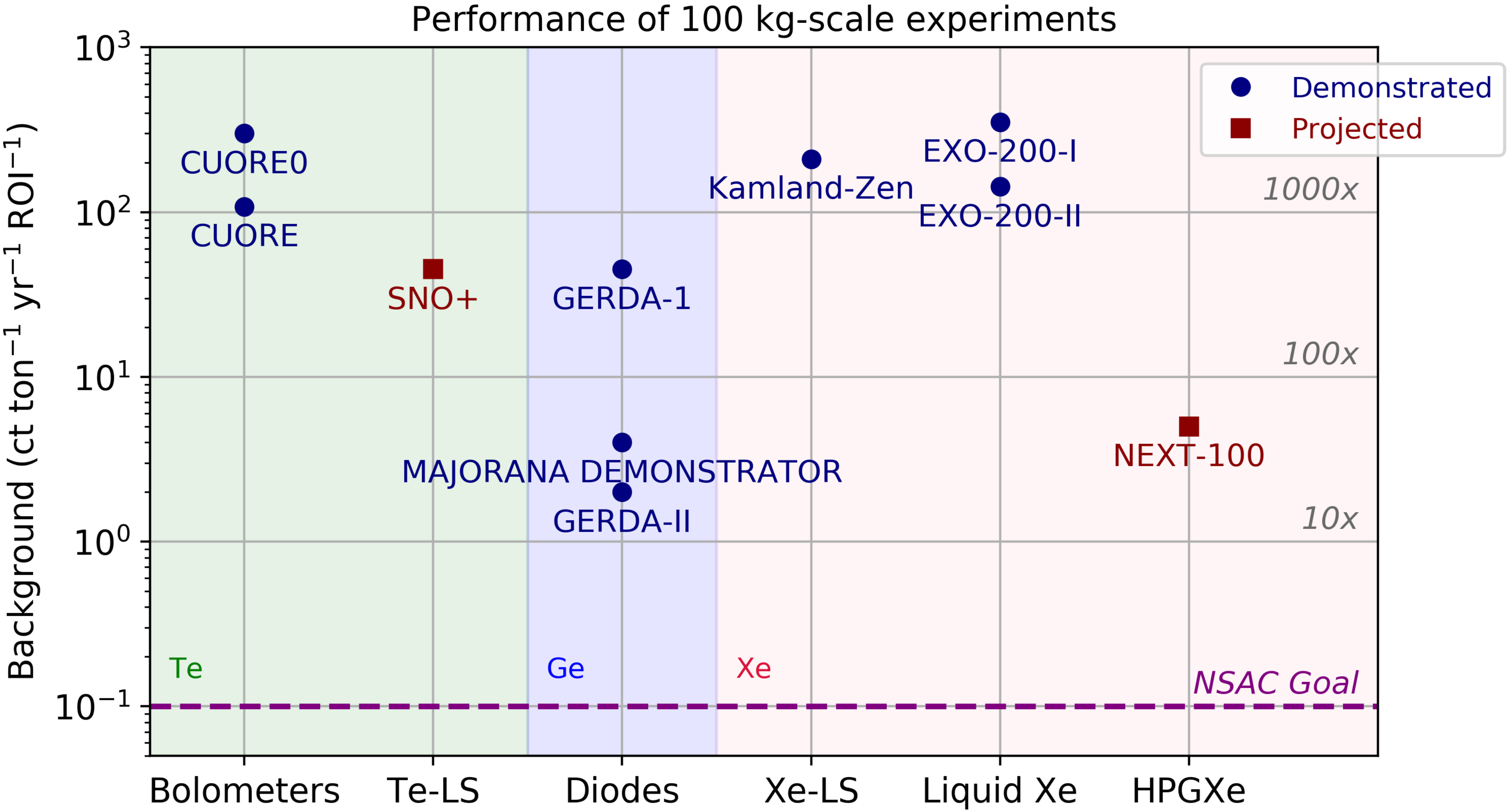
Solar neutrinos(!)

Cosmogenics

These will limit all future experiments.

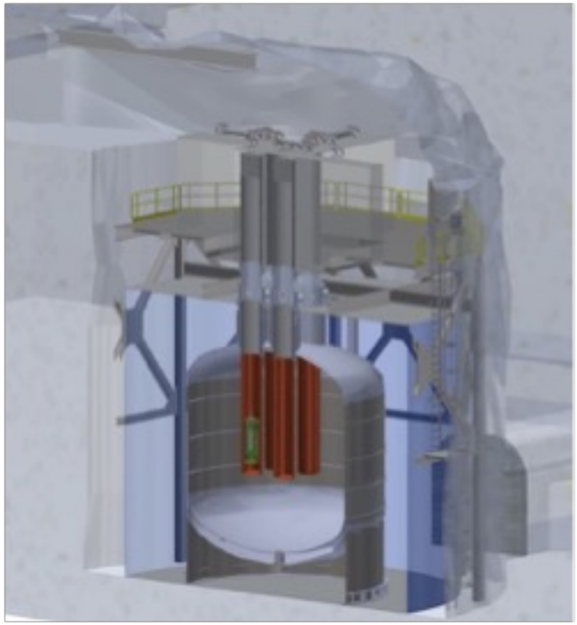

10^{30}
10^{29}
10^{28}
10^{27}
10^{26}
10^{25}
10^{24}
$T_{1/2}$ 3σ DL [years]
Inverted Heirachy
Run for 2-3 years
Run for 15 years
Run for 100 years
Run for 1000 years
1000 kg experiment
Background free
0.1 counts/ROI/t/y
1.0 count/ROI/t/y
10 counts/ROI/t/y
10^{-3}
10^{-2}
10^{-1}
1
10
10^{2}
10
Exposure [ton-years]

“100kg-class” experiments:



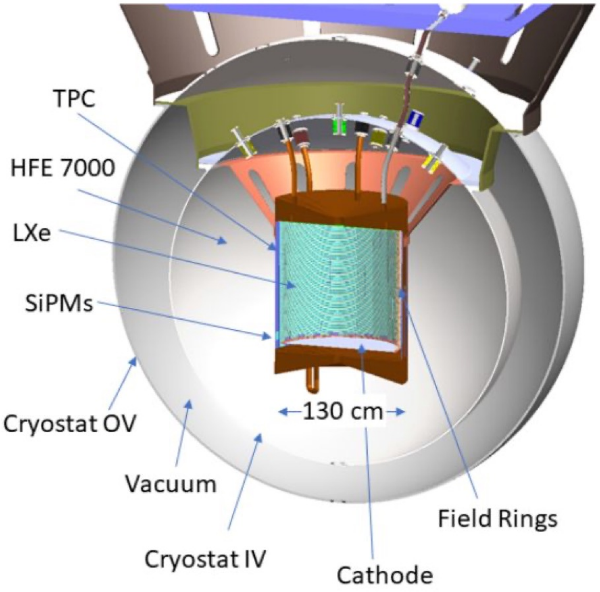
LEGEND

- Germanium diodes immersed in low background liquid argon.
- Lowest demonstrated background from any technology with GERDA and Majorana.
- 200 kg phase in operation, 1 Ton phase proposed.
- Superb energy resolution, ~0.2% FWHM
- Deployable in stages as isotope becomes available.



nEXO

- 5 Ton liquid xenon time projection chamber using enriched ^{136}Xe.
- Several signal-sensitive variables combined in a multivariate manner for final signal metric.
- Demonstrated energy res around 2-3% FWHM, aiming to improve through ongoing R&D.
- Outer tons of ^{136}Xe self-shield the middle ~2 tons to give a clean, very sensitive inner region.



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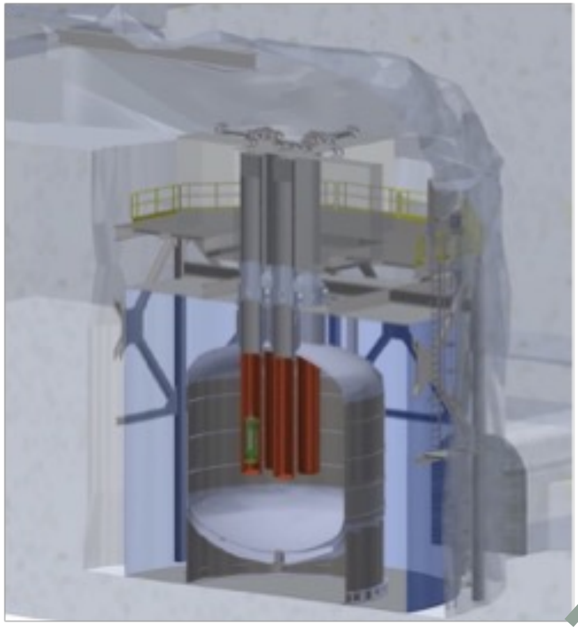
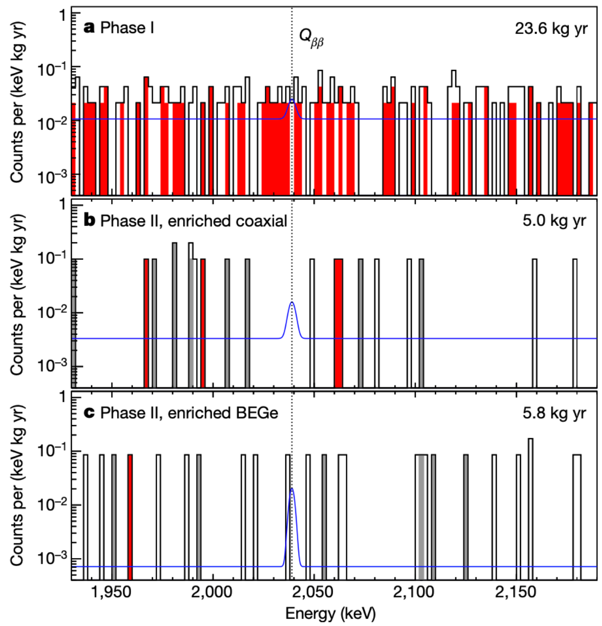
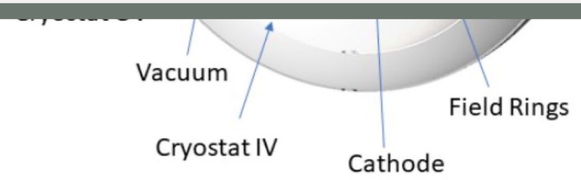


nEXO

Proven essentially background free using energy reconstruction alone by MJD / GERDA



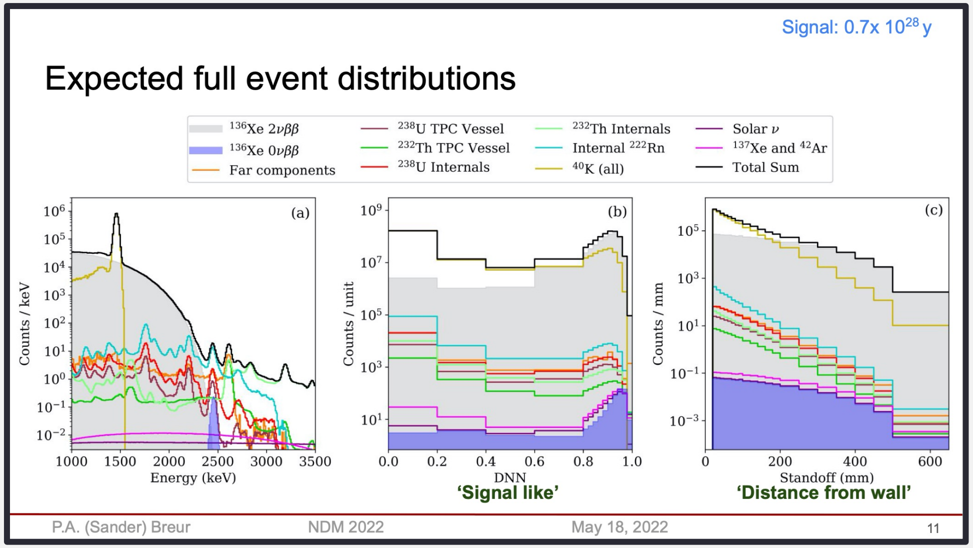
Scaling is mostly a matter of repetition.



LEGEND

- Germanium diodes immersed in low background
-
-
-
-

Background suppression from self shielding emerges at large scale, and power comes from a multivariate analysis of many somewhat-signal-sensitive variables.



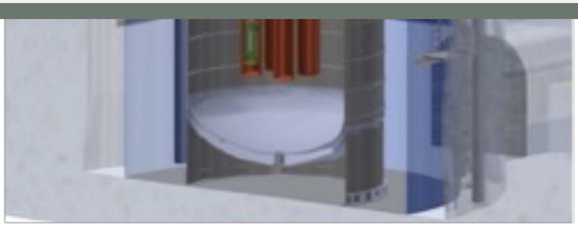
Signal: 0.7x 10^{28} y

Expected full event distributions

'Signal like'

'Distance from wall'

P.A. (Sander) Breur NDM 2022 May 18, 2022 11



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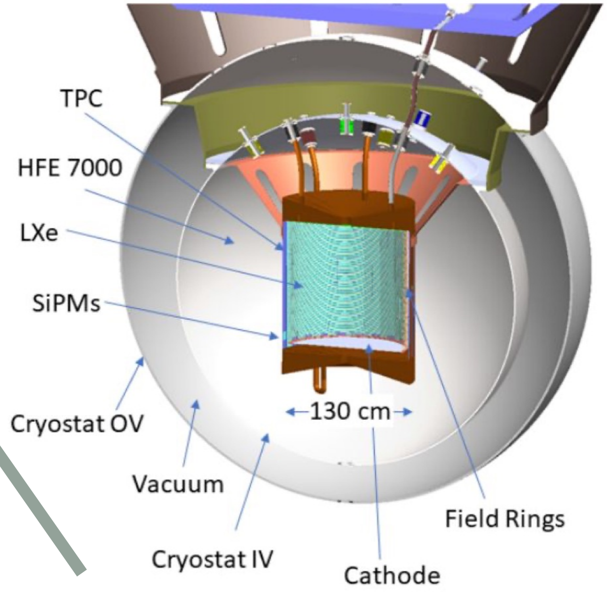
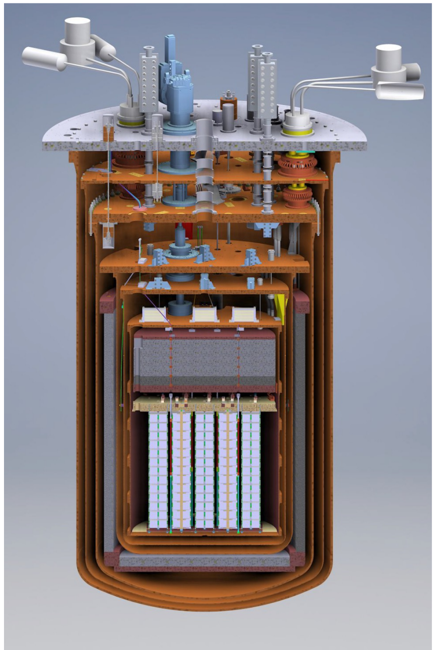


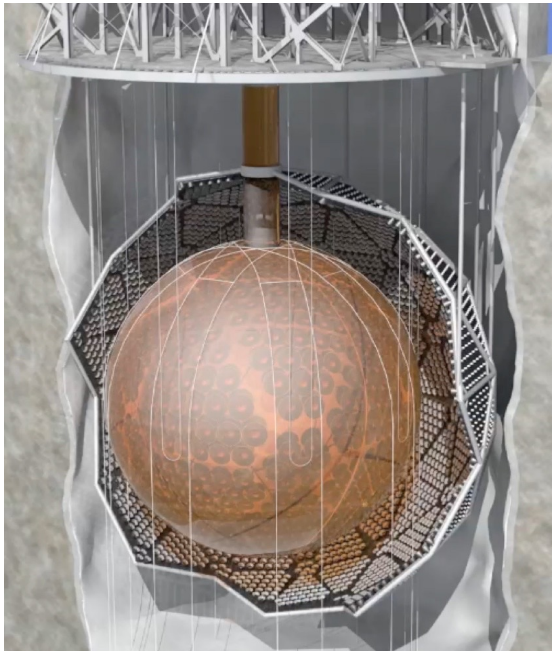
CUPID

- ^{100}Mo enriched scintillating Li_2MoO_4 bolometers read out with transition edge sensors. 280kg of isotope.
- Excellent demonstrated energy resolution of 0.2% FWHM.
- Scintillation allows separation of surface backgrounds from bulk, which ultimately limited CUORE sensitivity.
- New crystals have been operated in CUPID-Mo demonstrator, showing strong performance.

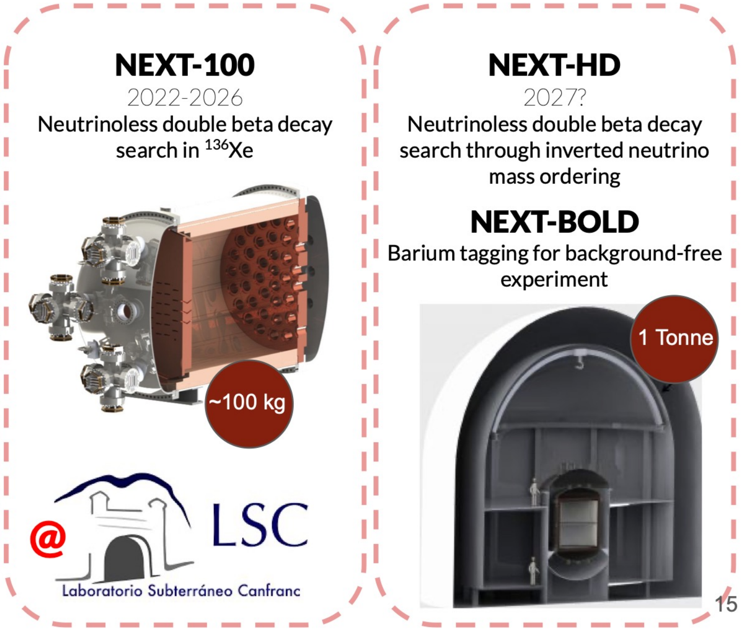


SNO+

- 3.9 tons of tellurium loaded in 780 tons of liquid scintillator in an upgraded SNO detector
- Water-filled phase, scintillator-phase in progress.
- Isotope to be added in stages until maximal loading without detriment to scintillator optical properties.
- Modest energy resolution characteristic of scintillator detectors.
- Large isotope mass enabled by high natural abundance of ^{134}Te - no enrichment needed.



NEXT



NEXT-100
2022-2026
Neutrinoless double beta decay search in ^{136}Xe

~100 kg

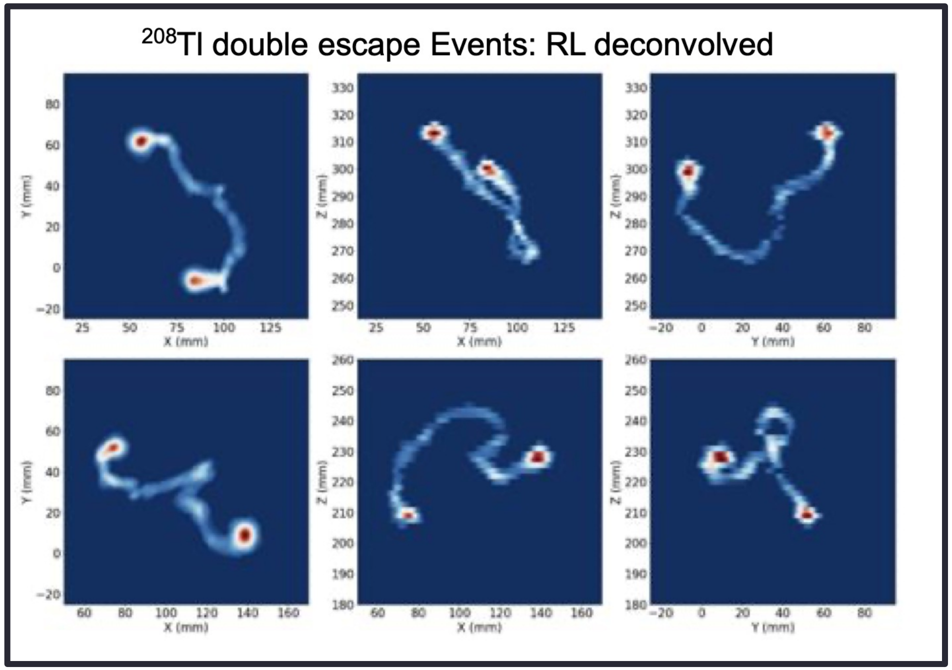
@ LSC
Laboratorio Subterráneo Canfranc

NEXT-HD
2027?
Neutrinoless double beta decay search through inverted neutrino mass ordering

NEXT-BOLD
Barium tagging for background-free experiment

1 Tonne

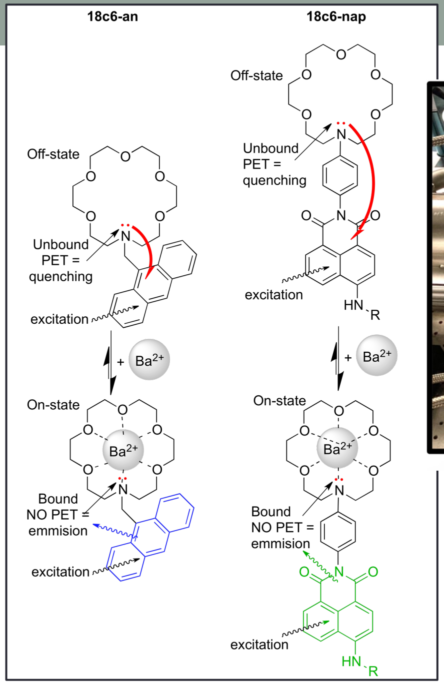
15

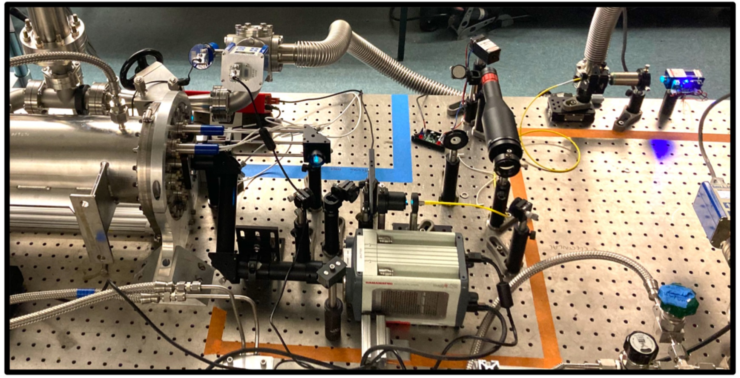

^{208}Tl double escape Events: RL deconvolved

- Xenon gas (10-15 bar) time projection chambers with enriched ^{136}Xe.
- Recombination-less ionization readout in gas gives leading energy resolution in xenon, ~0.9% FWHM.
- Tracks can be imaged topologically to separate signals (2 blobs) from backgrounds (1 blob)
- Full detector volume is active isotope (no self shielding)
- NEXT-100 will run in 2023, followed by ton-scale phases.

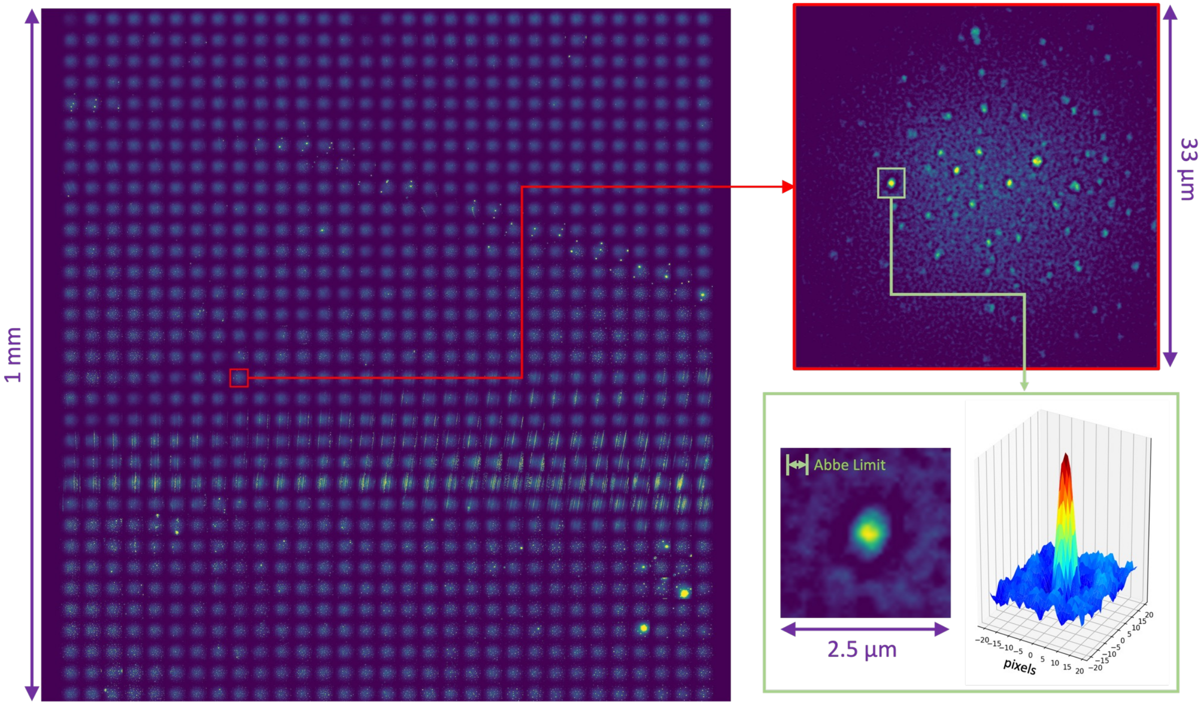
Please indulge me while I talk about my own stuff for 2 slides… 🤓

Barium Tagging





Eg: Single Ba^{2+} ions imaged over mm^2 surfaces in high pressure xenon gas for NEXT.



In the decay:

$$^{136}Xe \rightarrow {}^{136}Ba + 2e$$

Barium does not accompany any of the major cosmogenic or radiogenic backgrounds.

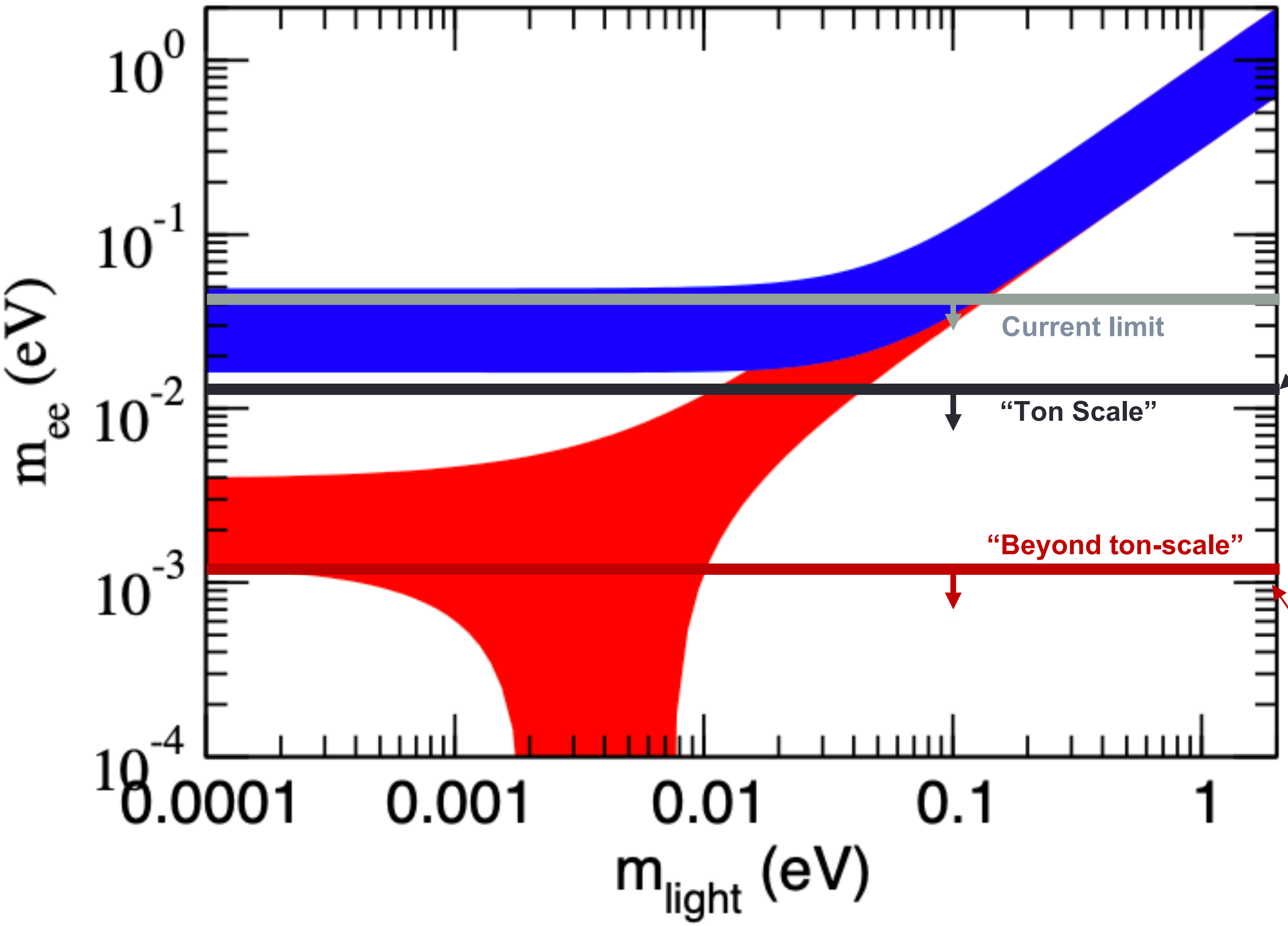
Single ion imaging may enable background-free multi-ton scale techniques.

Efficient identification of one ion in a ton of material is an extreme technological challenge.

Progress on imaging is being made rapidly in both liquid and gaseous xenon.

Collection from detector volume is the next major R&D challenge.

Toward Normal Ordering



Experiments I just showed you

Can we ever hope to do this?

If so, how?

The path to normal ordering is far from clear. Ultra-low background, very large scale detectors, with hundreds of tons of isotope, are needed.

We would need to do it if:

- Neutrino masses are normal ordered
- The same mechanism generates neutrino mass and drives 0nubb
- The absolute mass of the lightest neutrino is <0.05 eV

These may very well all be true statements…

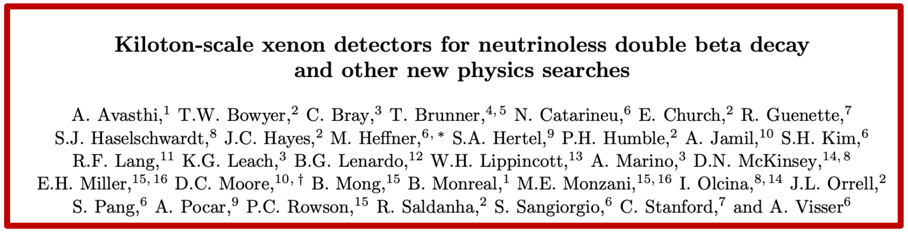
What then?

Isotopes

- Already a challenging problem for ton-scale experiments, but would need hundreds of tons of isotope to go to normal ordering.
- Difficulties are associated with both **acquisition** of raw material and **enrichment**.
- Some notable factoids:
  - **Tellurium:**
    Comes naturally enriched to 34%. So natural tellurium is the most viable for an unenriched experiment.
  - **Molybdenum:**
    New capacity for enrichment of Molybdenum in 100Mo for nuclear medicine is needed. 0nubb may be parasitic?
  - **Germanium:**
    Semiconductor industry enriches germanium already; 76Ge can in principle be extracted as byproduct?
  - **Xenon:**
    Atmospheric carbon capture technology based on metal organic frameworks has plausible extendibility to capture atmospheric Xe. Free from steel industry capacity limit?

R&D and new facilities would be needed to produce isotope at the scale needed for a normal-ordering experiment.

Giant TPCs



Kiloton-scale xenon detectors for neutrinoless double beta decay and other new physics searches

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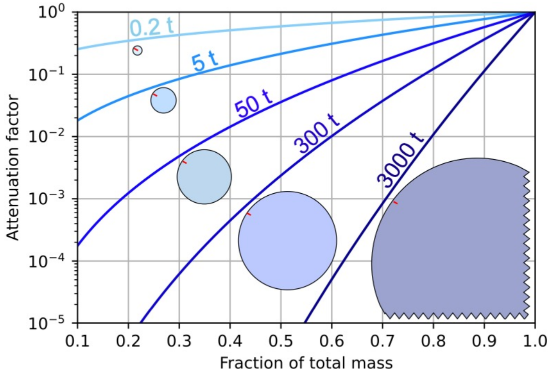
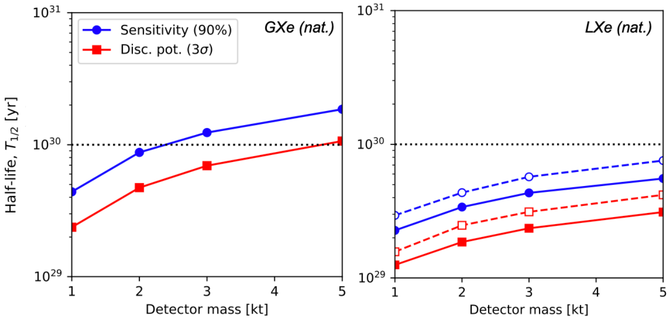


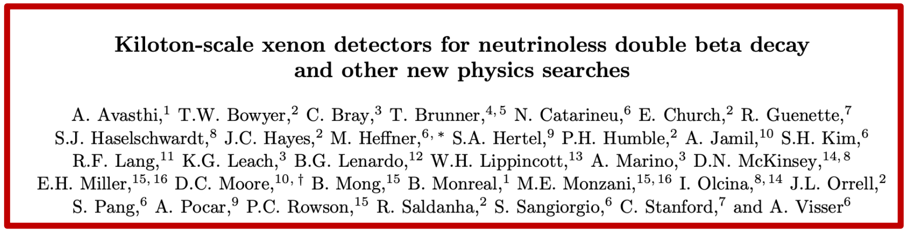
← Radiogenics become totally irrelevant due to self shielding

Cosmogenics and solar neutrinos become a serious concern!

If energy resolution achievable at scale, with kiloton masses, normal ordering parameter space is accessible.



Giant TPCs …in salt caverns?



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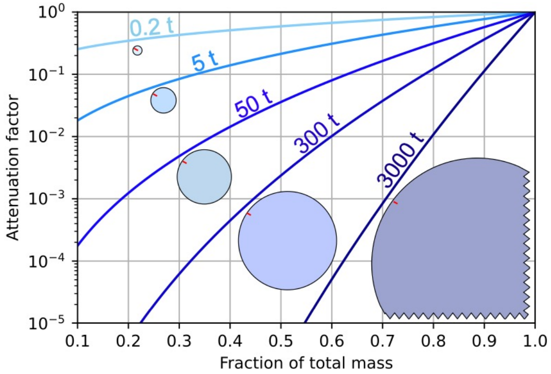

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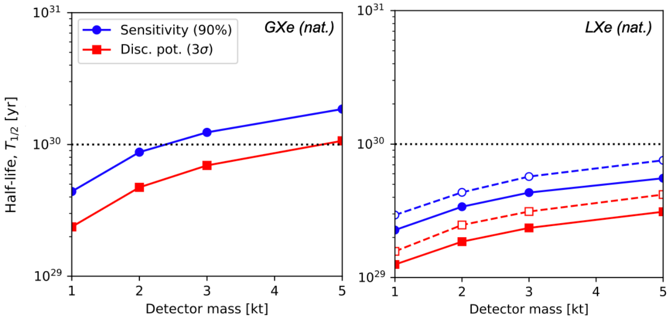
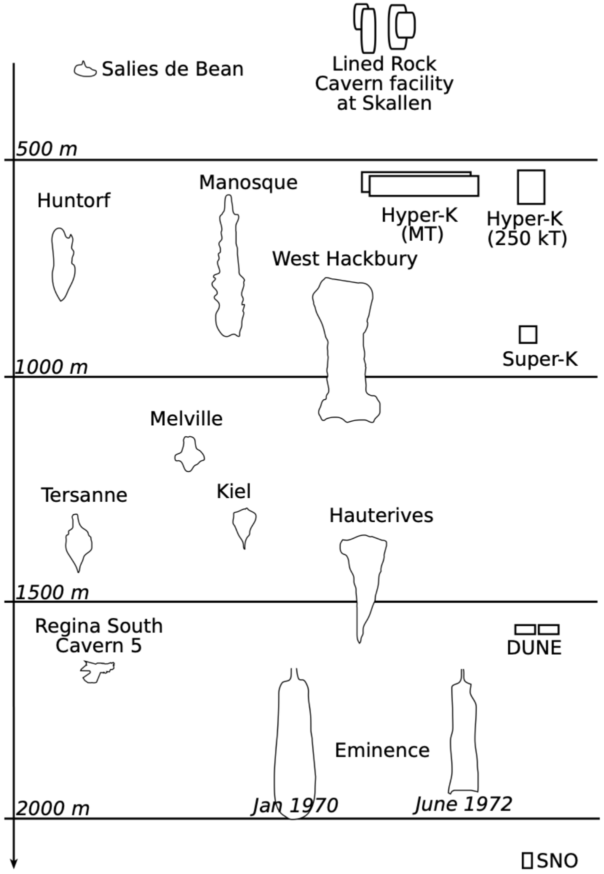
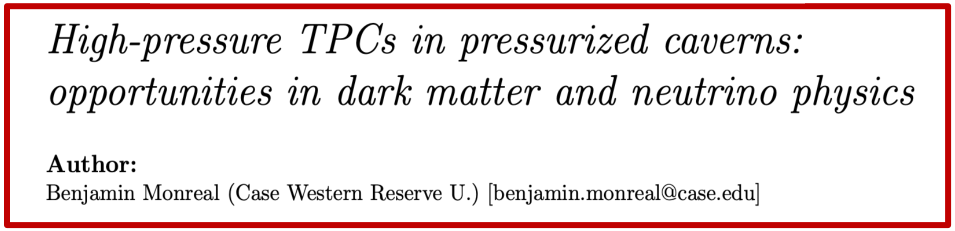




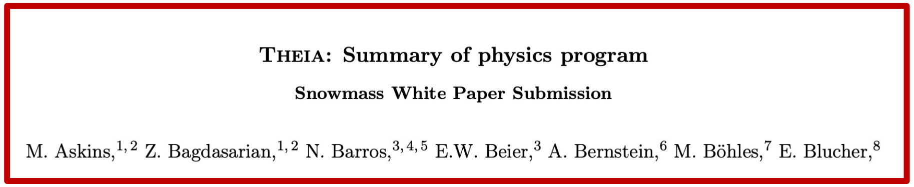


High-pressure TPCs in pressurized caverns: opportunities in dark matter and neutrino physics

Author:

Benjamin Monreal (Case Western Reserve U.) [benjamin.monreal@case.edu]

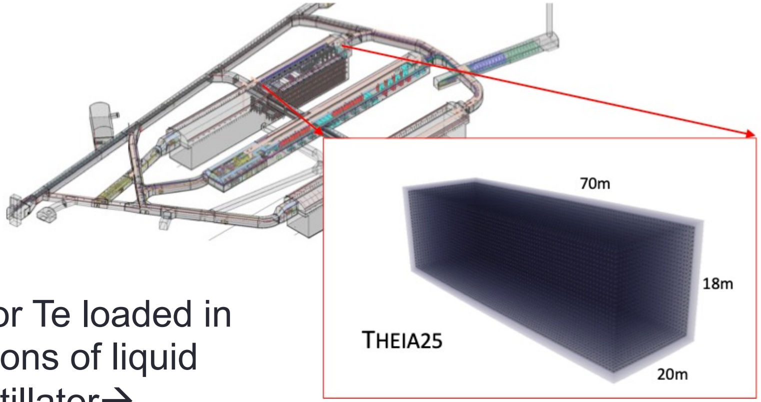
Isotope in kTons of liquid scintillator



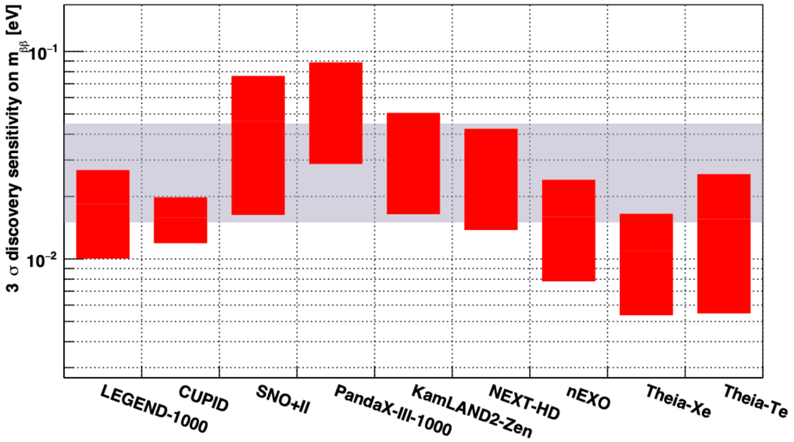
THEIA: Summary of physics program

Snowmass White Paper Submission

M. Askins,[1,2] Z. Bagdasarian,[1,2] N. Barros,[3,4,5] E.W. Beier,[3] A. Bernstein,[6] M. Böhles,[7] E. Blucher,[8]



Xe or Te loaded in kilotons of liquid scintillator→



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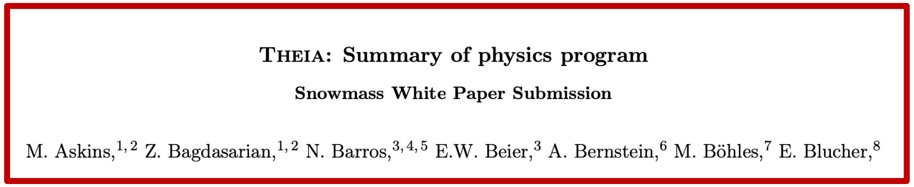

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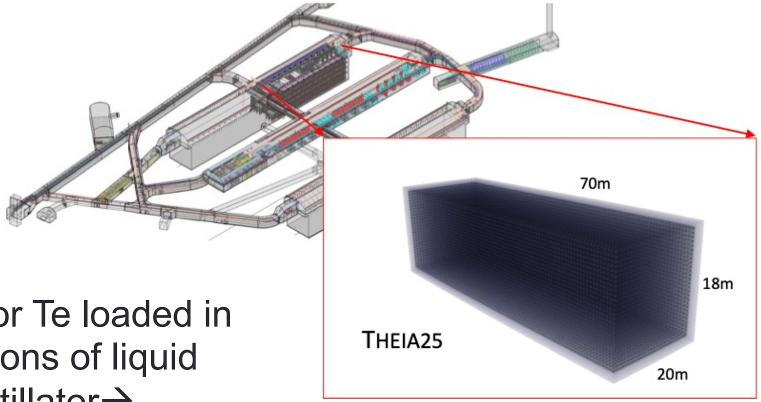

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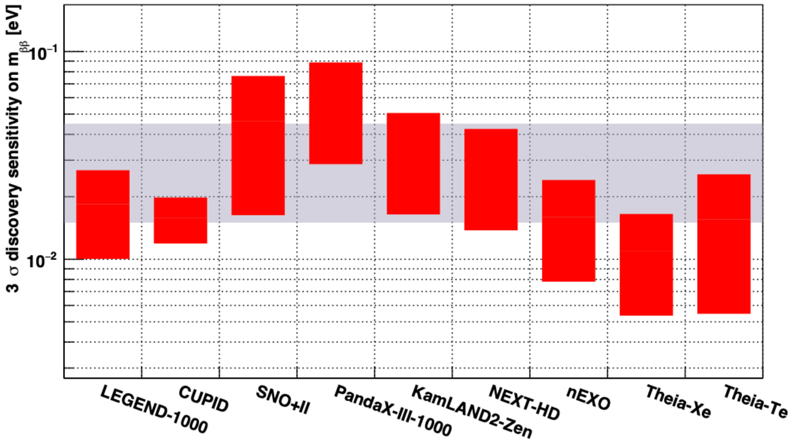
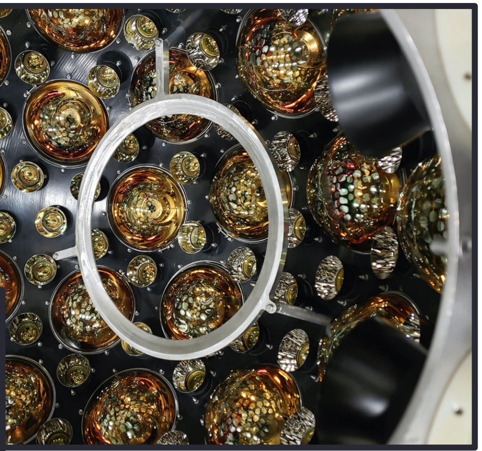
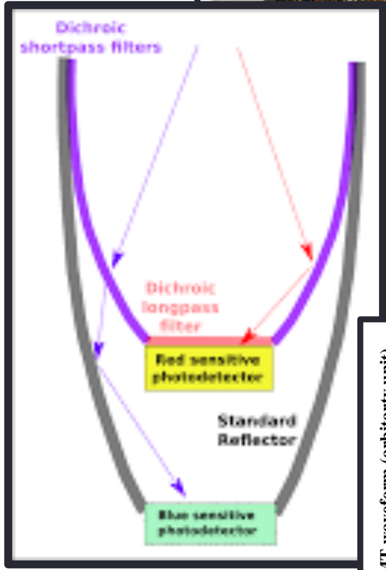


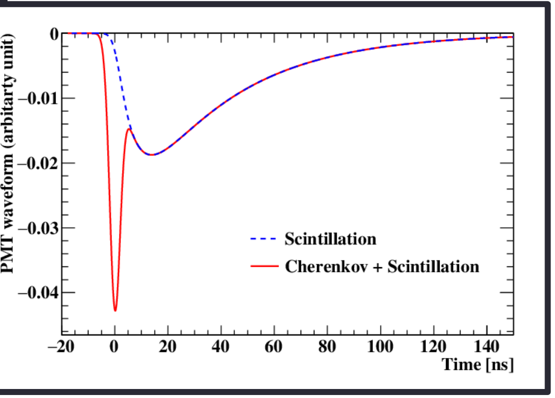
Much ongoing R&D…



Quantum dot doped liquid scintillator @NuDot



Dichroicon



Slow scintillator for Cerenkov separation

Conclusions

- NDBD is the only sensitive known way to probe the Majorana nature of the neutrino.
- Experiments at the 100kg scale have demonstrated background indices in the range 2-200 ct/ton/ky/yr
- Ton-scale experiments plan to reduce backgrounds by 1.5-3 orders of magnitude relative to 100kg phases and probe the inverted mass ordering range of parameter space.
- Beyond-ton-scale will require huge, ultra-low background detectors that we don’t yet know how to build, but need to figure out!

Thank you for your attention