Neutrinoless double-beta decay

UK input to the EU strategy discussion

Simon JM Peeters

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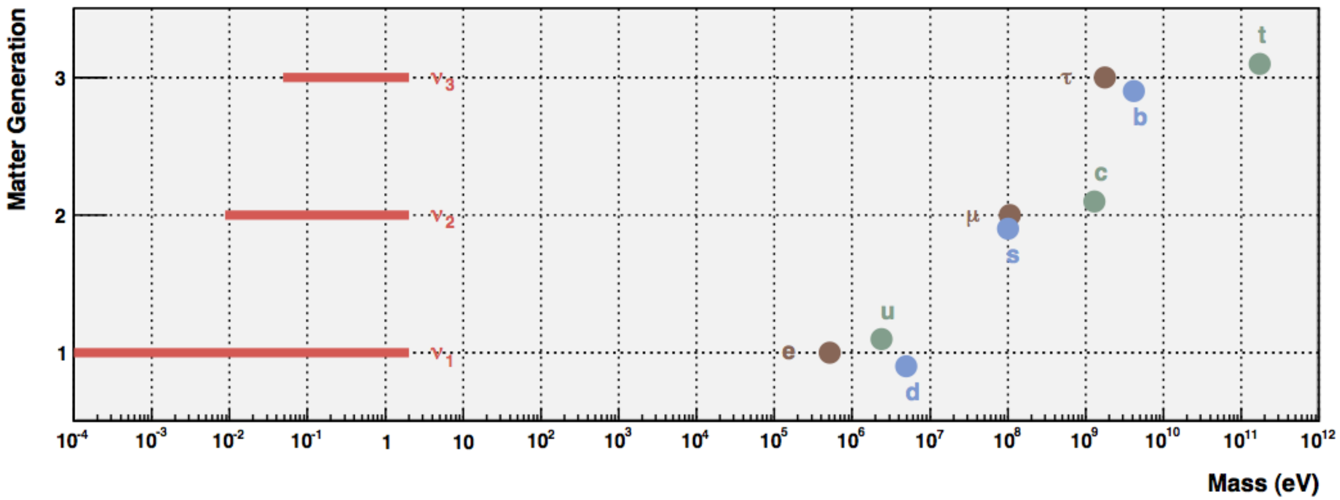
0νββ is important on any current particle physics roadmap

Observation would imply:

- Violation of lepton number (by 2!)
- Neutrinos have Majorana masses (different than quarks and leptons, Schlechter and Valle, 1982)
- Neutrinos are their own anti-particles

It would inform us about:

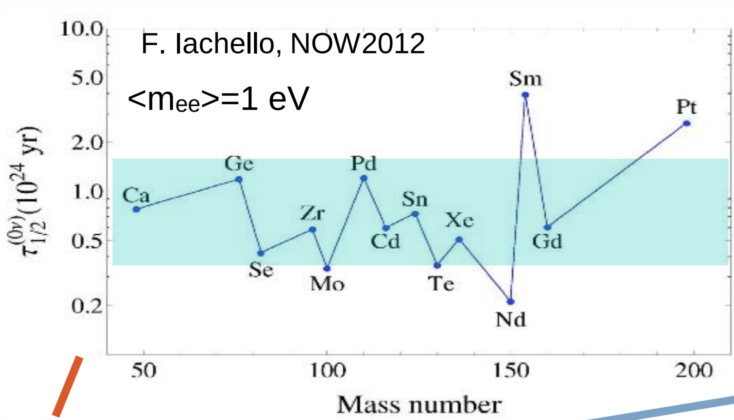
- An explanation why neutrinos are so much lighter than other particles
- Leptogenesis, a possible origin of the baryon-antibaryon asymmetry *if neutrinos violate CP (DUNE/HK)*
- Neutrino absolute mass scale



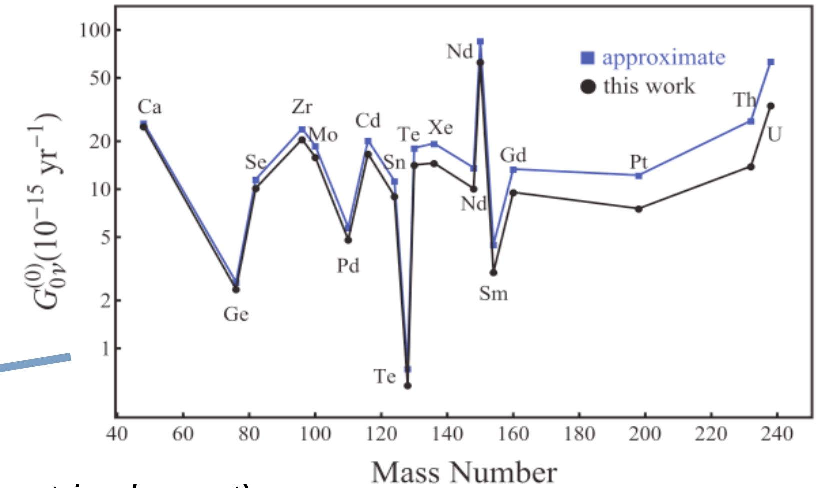
0νββ decay

Observable

Combining NME with PSF we obtain the expected half-lives



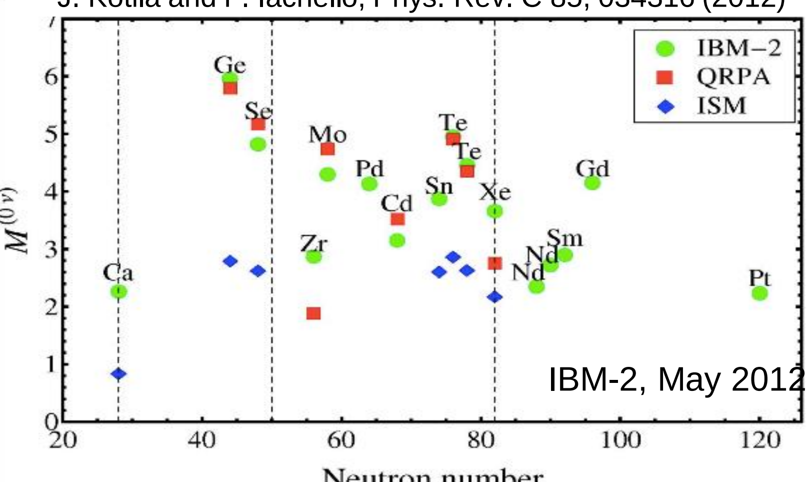
J. Kotila and F. Iachello, Phys. Rev. C 85, 034316 (2012)



$$\tau_{0\nu}^{-1} = G_{0\nu}(Q,Z)\left|M^{0\nu}\right|^2 \langle m_{ee}\rangle^2$$

(g_A in matrix element)

J. Kotila and F. Iachello, Phys. Rev. C 85, 034316 (2012)



$$\langle m_{ee}\rangle = \sum_k U_{ek}^2 m_k$$

$$= \cos^2\theta_{12}\cos^2\theta_{13}m_1 + \sin^2\theta_{12}\cos^2\theta_{13}e^{i\alpha}m_2 + \sin^2\theta_{13}e^{i\beta}m_3$$

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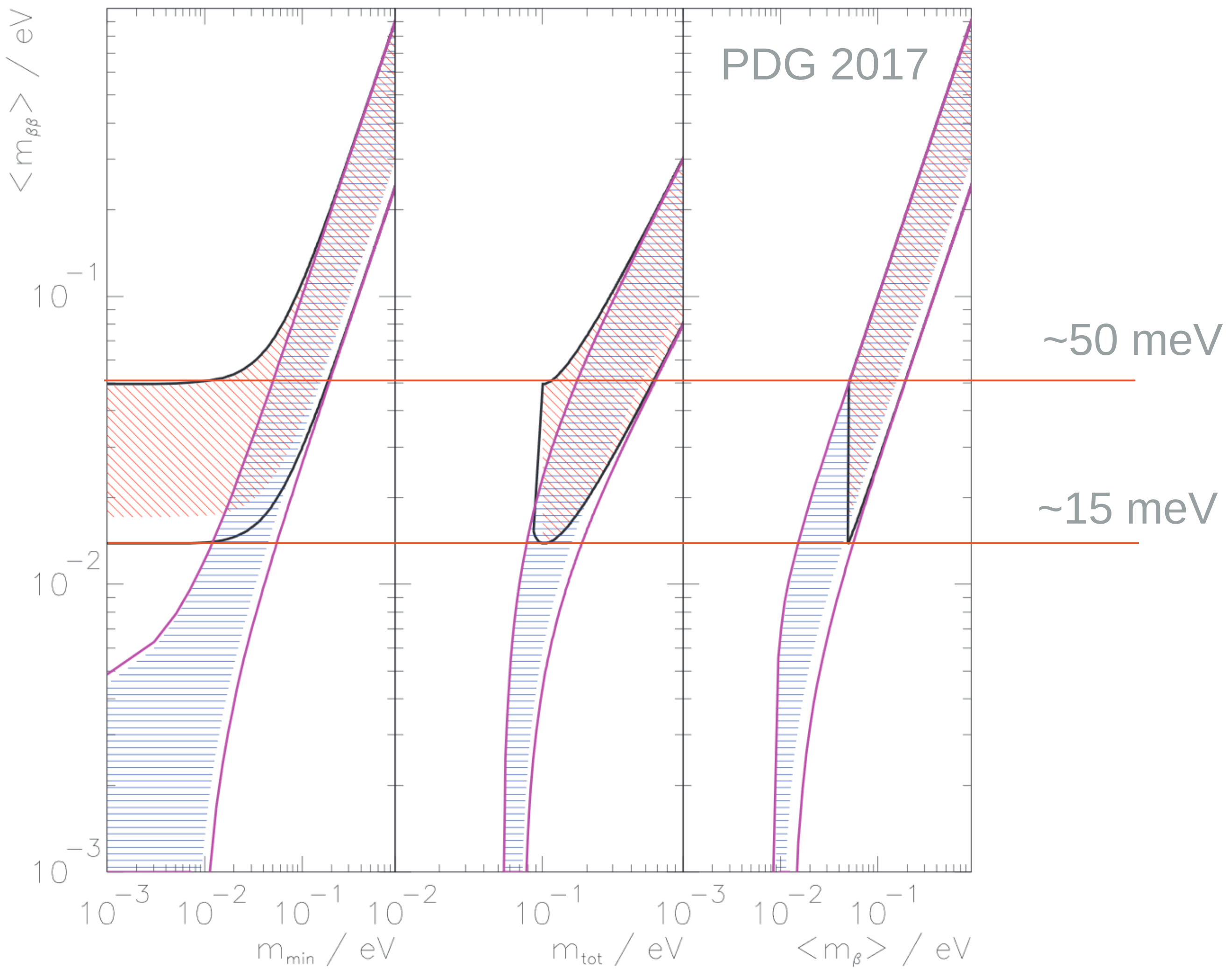
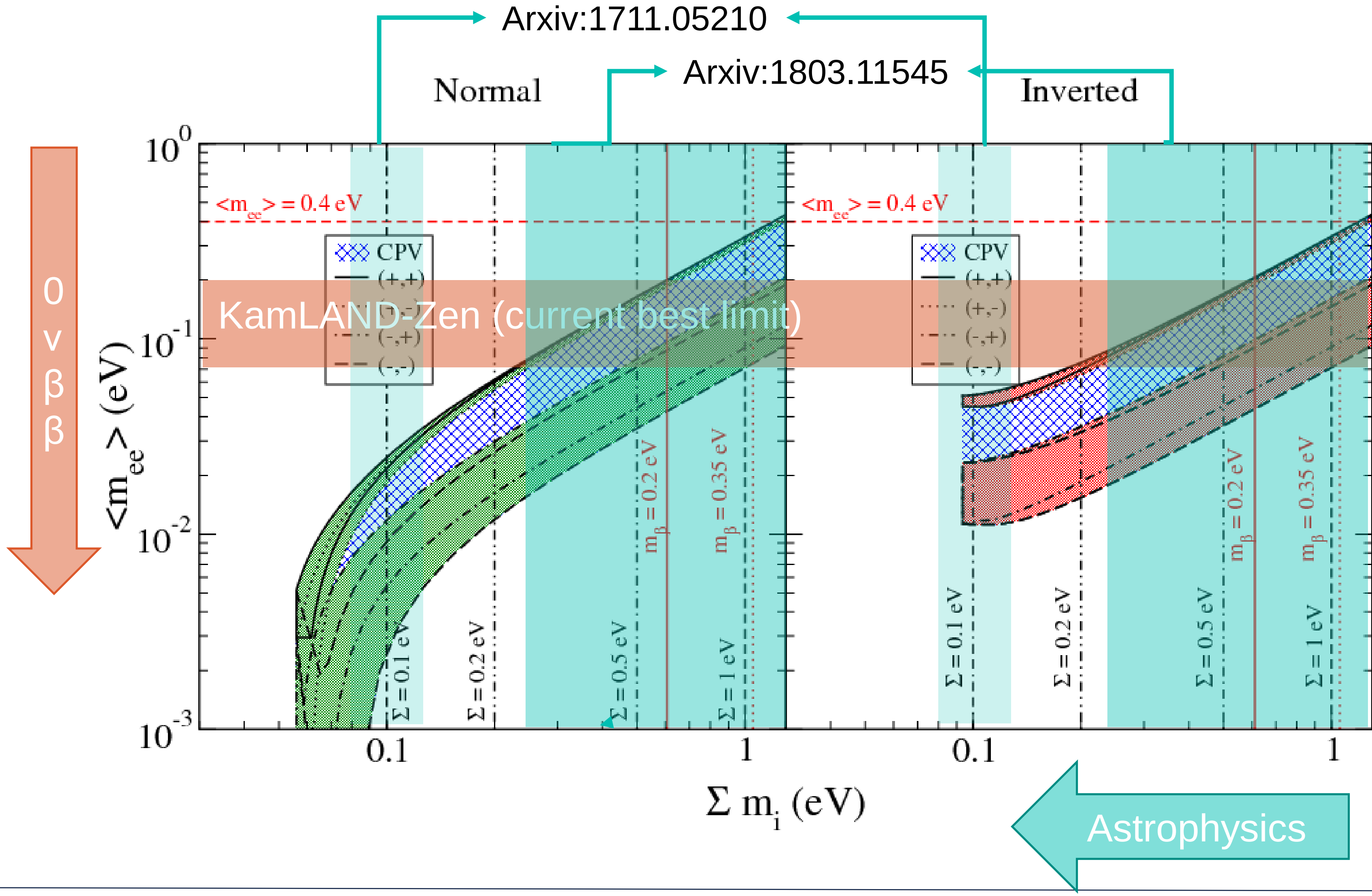
Parameter space



Connection to cosmology



Current status

experiment	isotope	M [kg]	$0\nu\beta\beta$ limit set $T_{1/2}$ [10^{25} yrs]	$m_{\beta\beta}$ [meV]	$0\nu\beta\beta$ sensitivity $T_{1/2}$ [10^{25} yrs] (pred.)	$m_{\beta\beta}$ [meV] (pred.)
Gerda	^{76}Ge	31	5.8	140-300	8.0	120-260
Majorana	^{76}Ge	26	2.1	230-510	1.9	240-530
KamLAND-Zen	^{136}Xe	343	5.6	70-220	10.7	50-160
EXO	^{136}Xe	161	1.9	130-370	1.1	170-490
CUORE	^{130}Te	206	0.7	160-730	1.5	110-500

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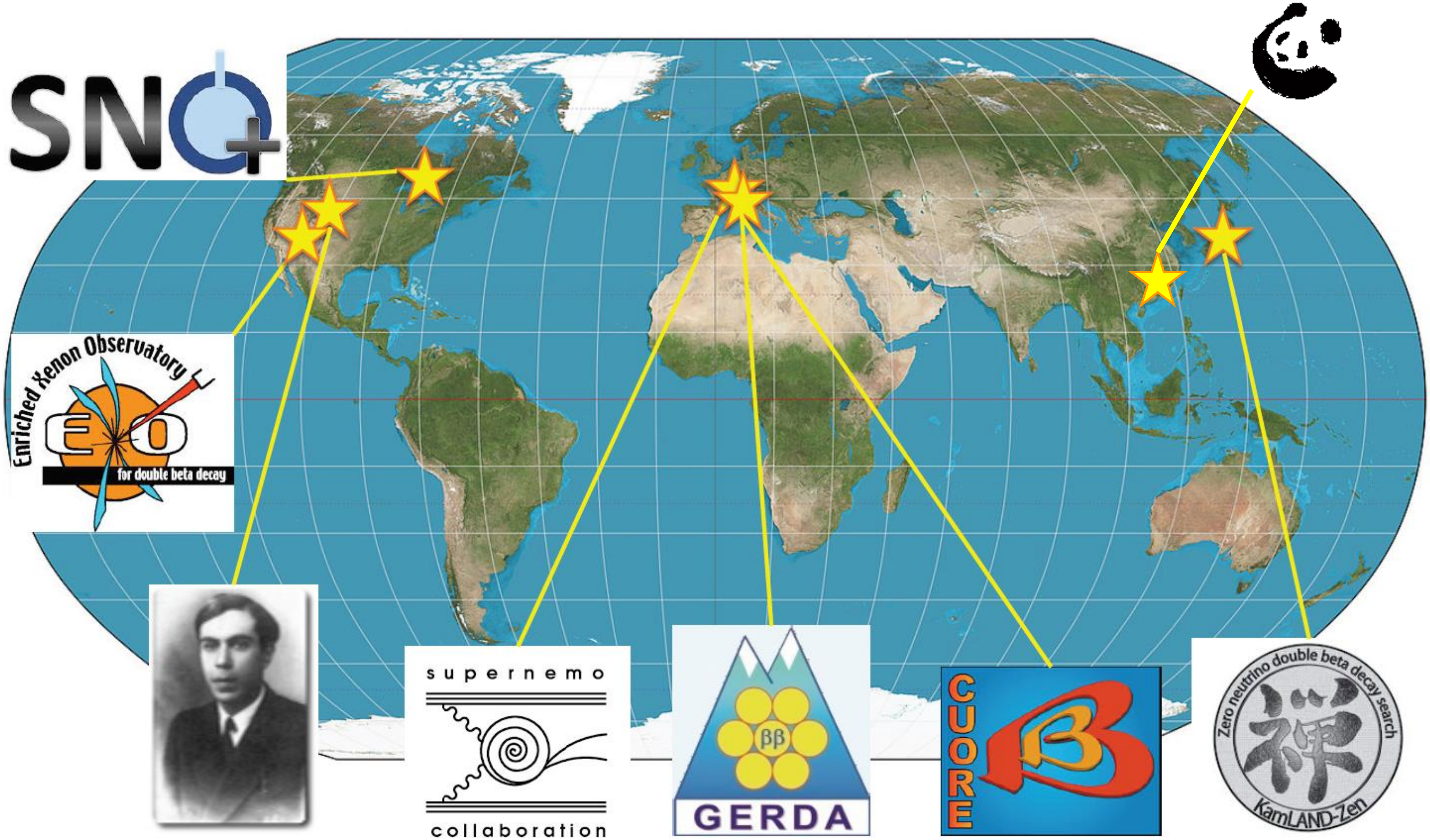
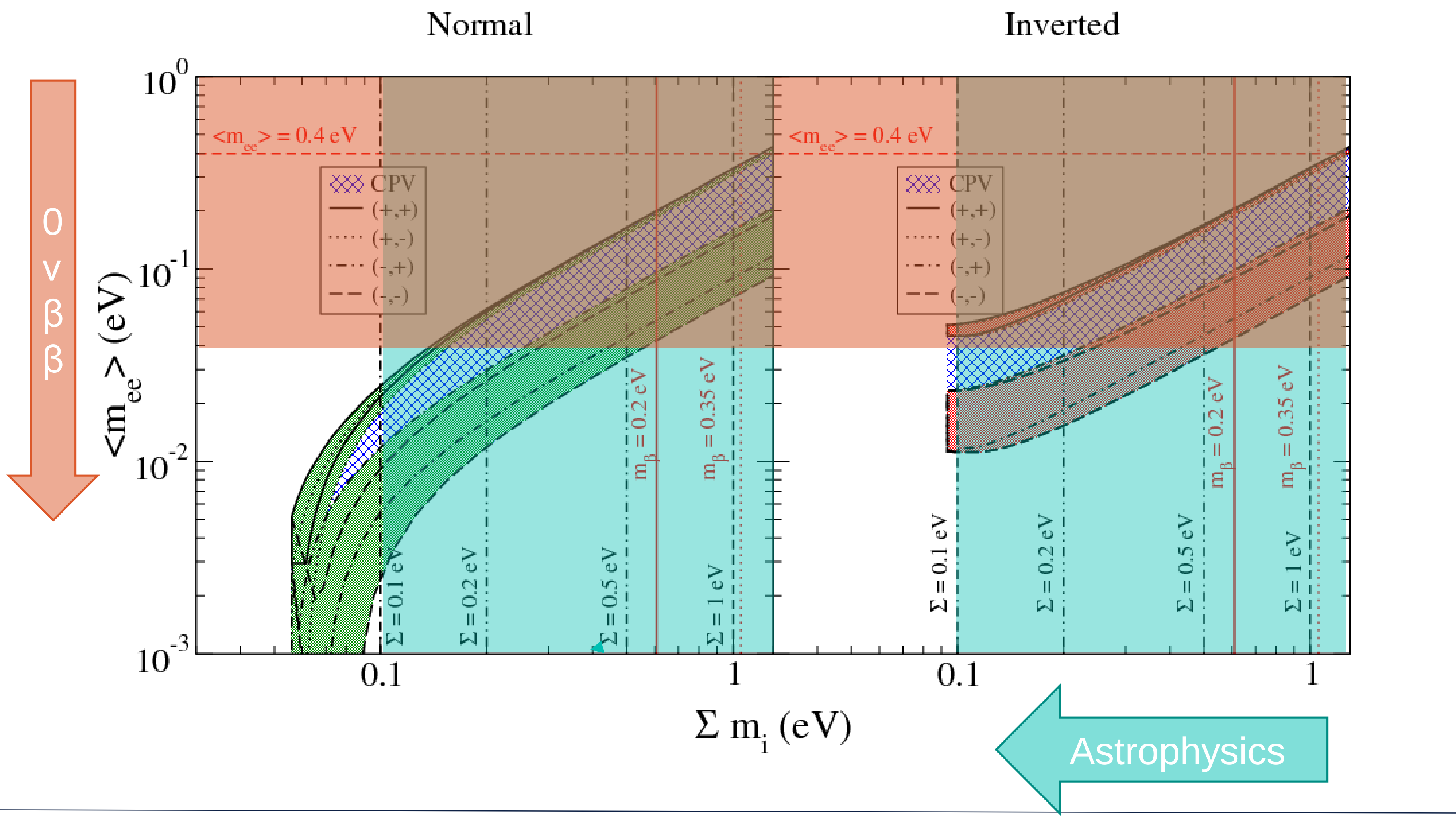
Global perspective



Near-future



0
ν
β
β
Normal
Inverted
<m_ee> = 0.4 eV
CPV
(+,+)
(+,-)
(-,+)
(-,-)
Σ = 0.1 eV
Σ = 0.2 eV
Σ = 0.5 eV
Σ = 1 eV
m_β = 0.2 eV
m_β = 0.35 eV
10^0
10^-1
10^-2
10^-3
0.1
1
<m_ee> (eV)
Σ m_i (eV)
Astrophysics

Future

Experiment	Iso.	Iso. Mass [kg_{iso}]	σ [keV]	ROI [σ]	ϵ_{FV} [%]	ϵ_{sig} [%]	$\mathcal{E}$ $\left[\frac{kg_{iso}\,yr}{yr}\right]$	$\mathcal{B}$ $\left[\frac{cts}{kg_{iso}\,ROI\,yr}\right]$	3σ disc. sens. $\hat{T}_{1/2}$ [yr]	3σ disc. sens. $\hat{m}_{\beta\beta}$ [meV]	Required Improvement: Bkg	Required Improvement: σ	Required Improvement: Iso. Mass
LEGEND 200 [62, 63]	^{76}Ge	175	1.3	[-2, 2]	93	77	119	$1.7 \cdot 10^{-3}$	$8.4 \cdot 10^{26}$	40–73	3	1	5.7
LEGEND 1k [62, 63]	^{76}Ge	873	1.3	[-2, 2]	93	77	593	$2.8 \cdot 10^{-4}$	$4.5 \cdot 10^{27}$	17–31	18	1	29
SuperNEMO [69, 70]	^{82}Se	100	51	[-4, 2]	100	16	16.5	$4.9 \cdot 10^{-2}$	$6.1 \cdot 10^{25}$	82–138	49	2	14
CUPID [59, 60, 71]	^{82}Se	336	2.1	[-2, 2]	100	69	221	$5.2 \cdot 10^{-4}$	$1.8 \cdot 10^{27}$	15–25	n/a	6	n/a
CUORE [53, 54]	^{130}Te	206	2.1	[-1.4, 1.4]	100	81	141	$3.1 \cdot 10^{-1}$	$5.4 \cdot 10^{25}$	66–164	6	1	19
CUPID [59, 60, 71]	^{130}Te	543	2.1	[-2, 2]	100	81	422	$3.0 \cdot 10^{-4}$	$2.1 \cdot 10^{27}$	11–26	3000	1	50
SNO+ Phase I [67, 72]	^{130}Te	1357	82	[-0.5, 1.5]	20	97	164	$8.2 \cdot 10^{-2}$	$1.1 \cdot 10^{26}$	46–115	n/a	n/a	n/a
SNO+ Phase II [68]	^{130}Te	7960	57	[-0.5, 1.5]	28	97	1326	$3.6 \cdot 10^{-2}$	$4.8 \cdot 10^{26}$	22–54	n/a	n/a	n/a
KamLAND-Zen 800 [61]	^{136}Xe	750	114	[0, 1.4]	64	97	194	$3.9 \cdot 10^{-2}$	$1.6 \cdot 10^{26}$	47–108	1.5	1	2.1
KamLAND2-Zen [61]	^{136}Xe	1000	60	[0, 1.4]	80	97	325	$2.1 \cdot 10^{-3}$	$8.0 \cdot 10^{26}$	21–49	15	2	2.9
nEXO [73]	^{136}Xe	4507	25	[-1.2, 1.2]	60	85	1741	$4.4 \cdot 10^{-4}$	$4.1 \cdot 10^{27}$	9–22	400	1.2	30
NEXT 100 [65, 74]	^{136}Xe	91	7.8	[-1.3, 2.4]	88	37	26.5	$4.4 \cdot 10^{-2}$	$5.3 \cdot 10^{25}$	82–189	n/a	1	20
NEXT 1.5k [75]	^{136}Xe	1367	5.2	[-1.3, 2.4]	88	37	398	$2.9 \cdot 10^{-3}$	$7.9 \cdot 10^{26}$	21–49	n/a	1	300
PandaX-III 200 [66]	^{136}Xe	180	31	[-2, 2]	100	35	60.2	$4.2 \cdot 10^{-2}$	$8.3 \cdot 10^{25}$	65–150	n/a	n/a	n/a
PandaX-III 1k [66]	^{136}Xe	901	10	[-2, 2]	100	35	301	$1.4 \cdot 10^{-3}$	$9.0 \cdot 10^{26}$	20–46	n/a	n/a	n/a

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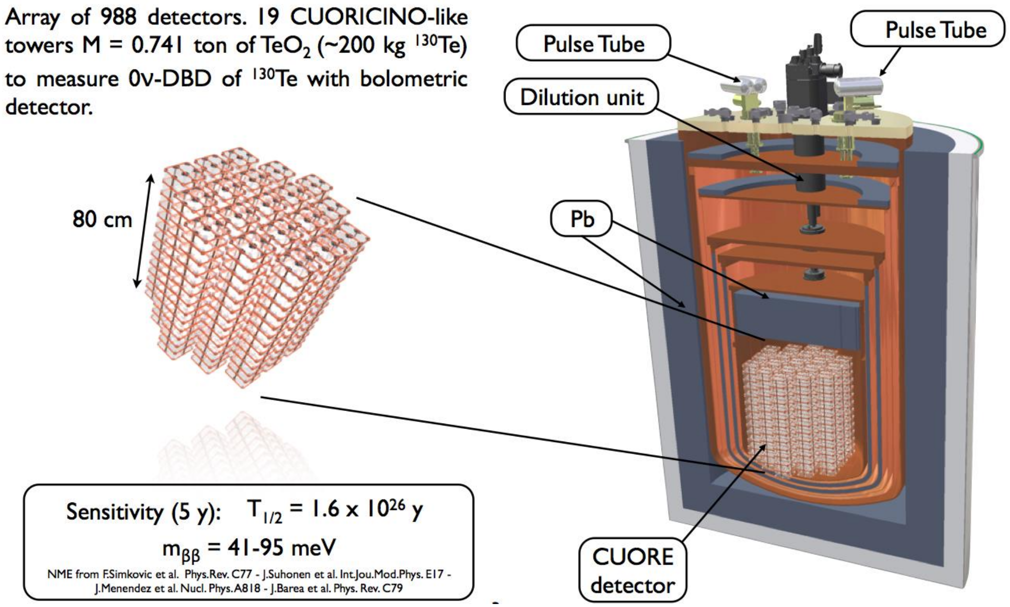
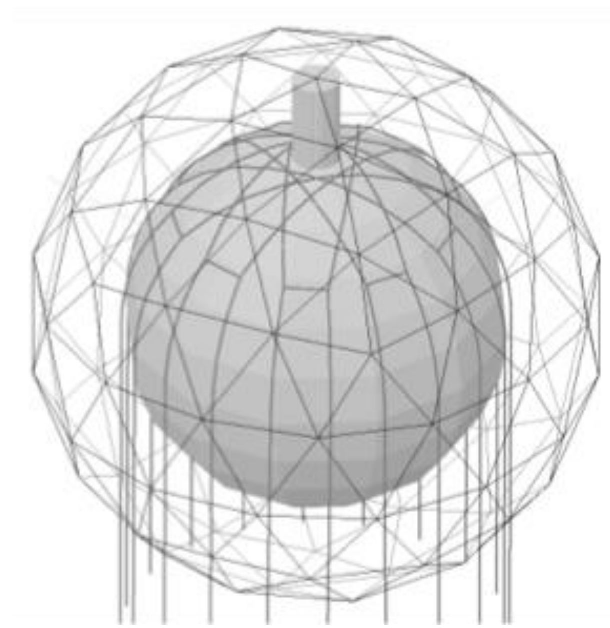
Arxiv:1705.02996

LEGEND: O(264) collaborators

Approaches to the future

Modular (CUORE,LEGEND) Monolithic (SNO+,LXe)





NSAC review (US) Nov 2015:
"The modular and monolithic approaches both offer advantages and disadvantages. However, it is not possible to firmly conclude which approach will be optimal at this point"

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Tracking/PID will become important to suppress backgrounds and for interpretation,
in case of an observation.

European perspective

European Astroparticle Physics Strategy 2017-2026

APPEC **strongly** supports the present range of direct neutrino-mass measurements and searches for neutrinoless double-beta decay. Guided by the results of experiments currently in operation, APPEC intends to converge on a roadmap for the next generation of experiments into neutrino mass and nature by **2020**.

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USA perspective

<u>Reminder of US DoE NSAC guidelines :</u>

- *Favor approaches that have a credible path toward reaching 3σ sensitivity to the effective Majorana neutrino mass parameter $m_{\beta\beta}$=15 meV within 10 years of counting, assuming the lower matrix element values among viable nuclear structure model calculations*

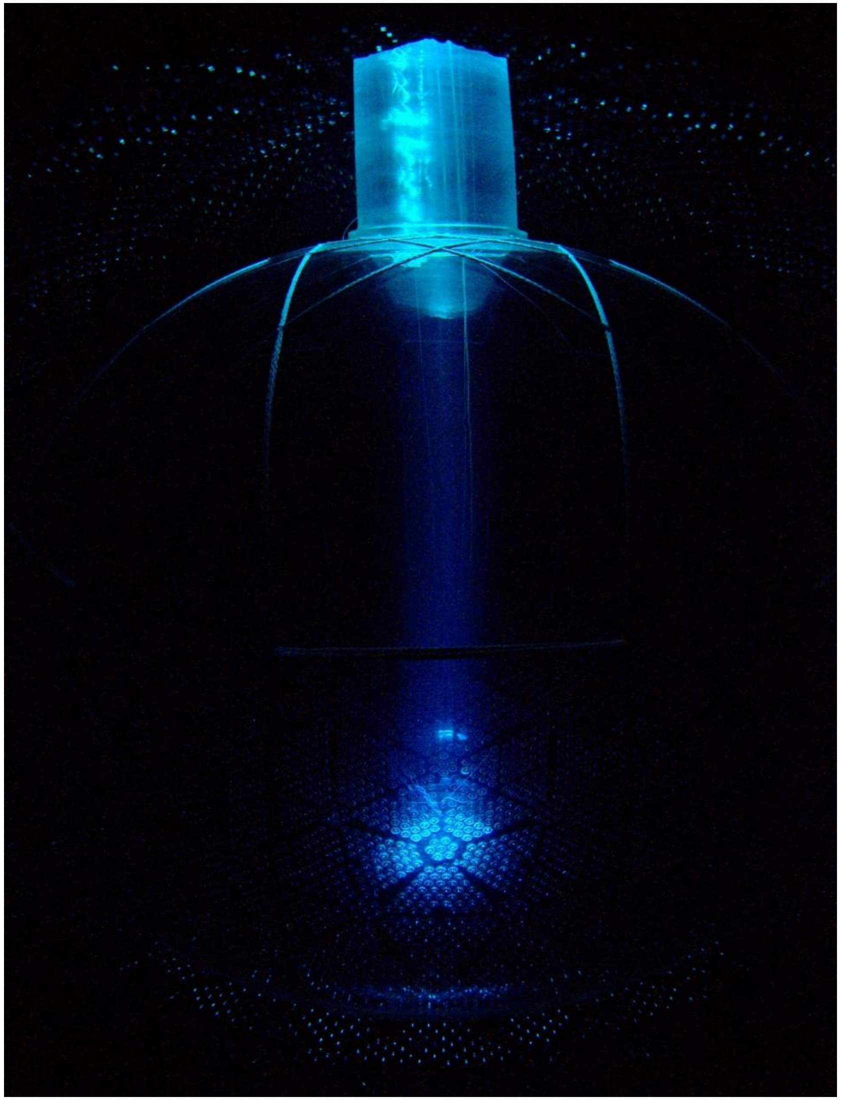
US funding through nuclear part of DoE/NSF (not HEP)

Nr 1 project: 0νββ

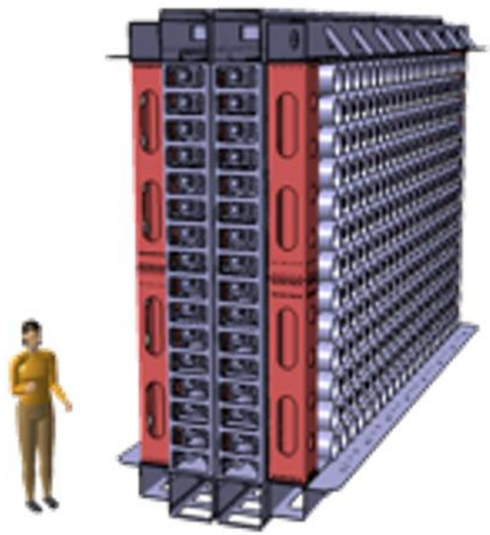
Budget 250-500 M$. Down-select ongoing on basis of :
technologies past the R&D phase
international contributors.

Preparations for next 7-year plan will start in about two years time:
beyond tonne scale

UK perspective



SuperNEMO

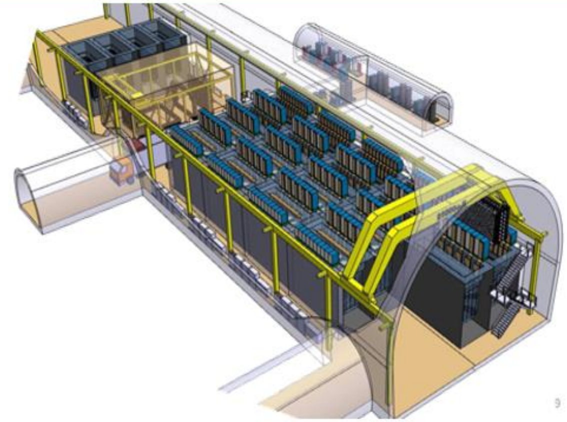


Demonstrator Module (2.5 year run)

17.5 kg × yr initial exposure :

$$T^{0\nu}_{1/2} > 6.5 \times 10^{24}\ \mathrm{yr}$$

$$\langle m_\nu \rangle < 0.20 - 0.40\ \mathrm{eV}$$

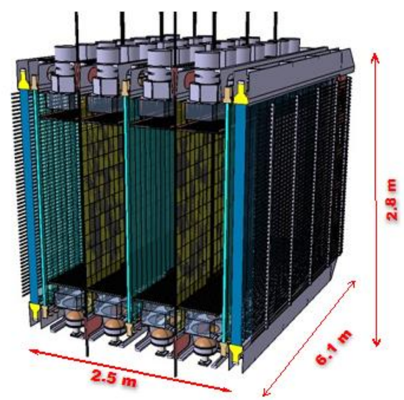


Full SuperNEMO

$T^{0\nu}_{1/2} > 10^{26}$ yr

500 kg × yr :

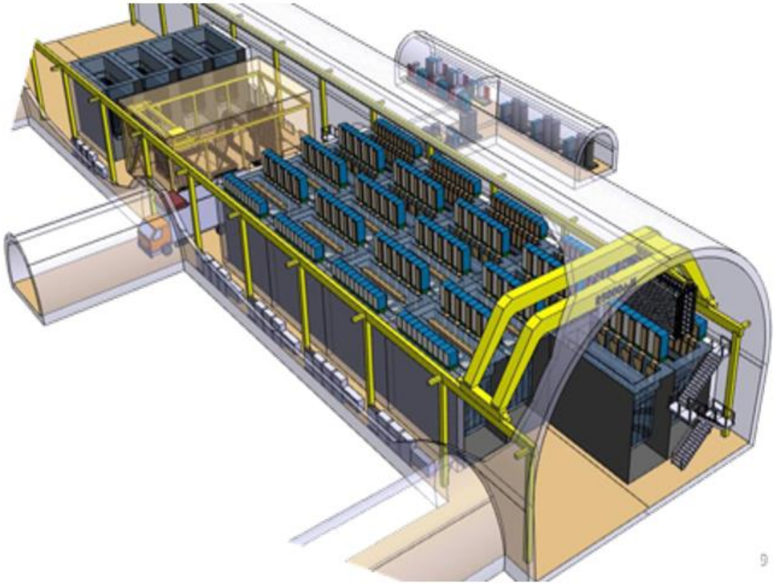
$\langle m_\nu \rangle < 50 - 100$ meV



Alternative Designs

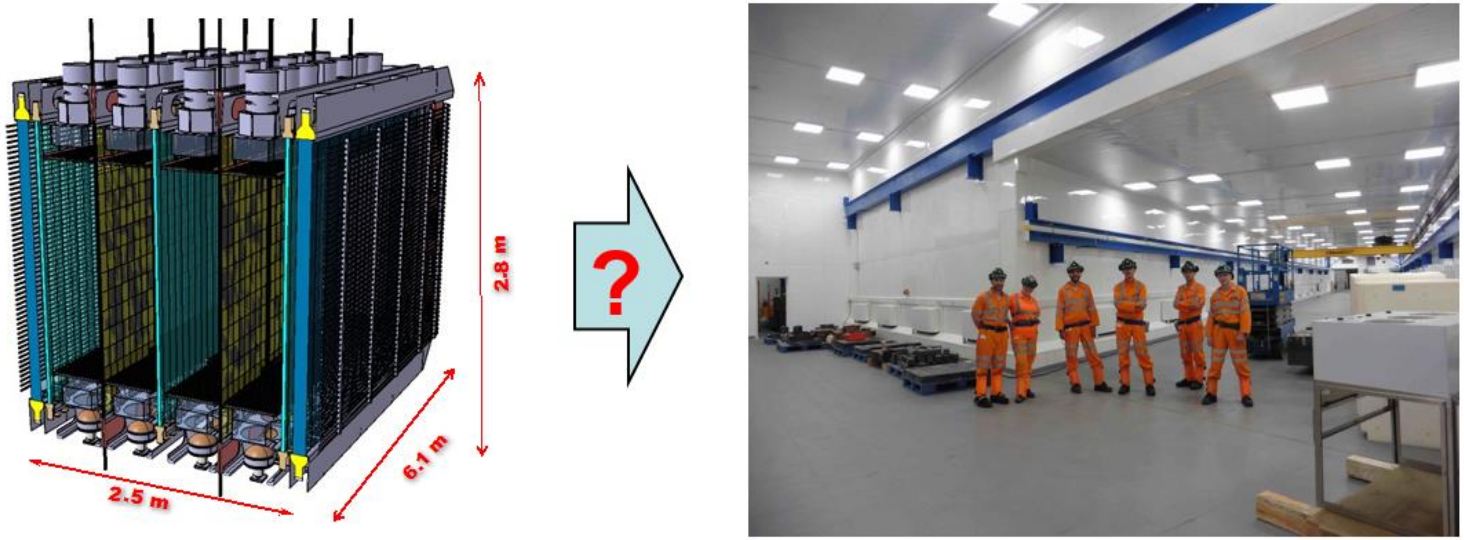
SuperNEMO

- Possible future scenarios for the SuperNEMO technology :
- Build additional Demonstrator-style modules :
  - ✓ We have demonstrated the ability to do this. So far we have met all of the background & performance requirements for SuperNEMO.
  - ✓ Can reach 10^{26} years (~50 meV) with 100 kg × 5 yrs.
  - ✓ Very strongly motivated if there is a discovery "soon" in another $0\nu\beta\beta$ experiment.
  - ✗ Costly.



SuperNEMO

- <u>Consider alternative designs :</u>
  - Cheaper with no significant reduction in performance.
  - Enter the regime cost(detector) ≤ cost(enriched isotope) which is the ultimate requirement for all techniques using enriched isotopes.
  - Look at alternative designs & sites, including Boulby in the UK.



- Can we extend the technique another order of magnitude ?

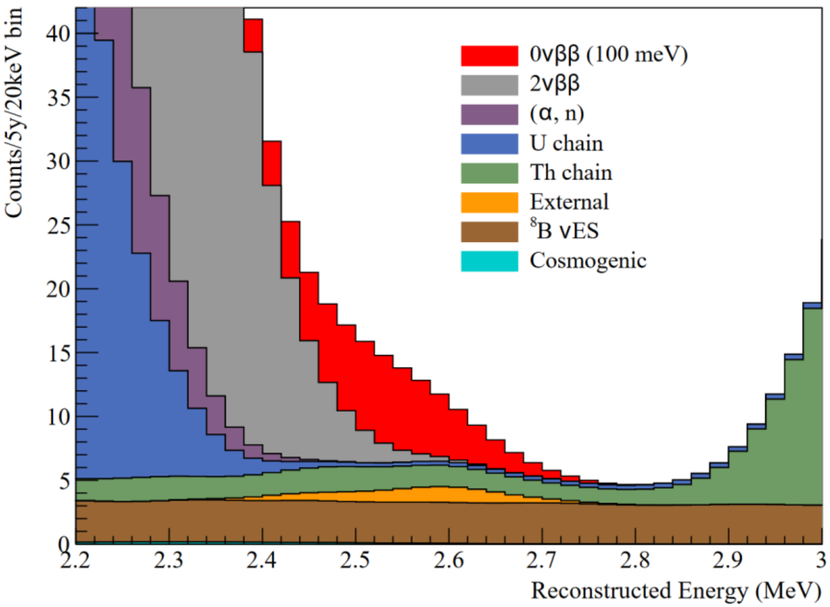
SNO+

Currently taking data with water.

This will be replaced with scintillator in the end of the year, and isotope will be added in April 2019.

Five year counting would enter the inverted hierarchy band region.

Relatively easy to upscale by increasing loading. To go further, more upgrades are needed.

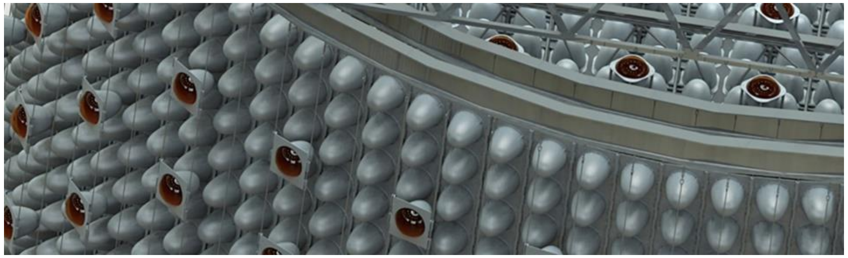


Advanced scintillator detector concept – beyond SNO+

Concept studies underway for large scale scintillator detectors with the possibility of multi-tonne loading, using separation of scintillation and Cherenkov light (removing backgrounds, in particular ^{8}B).

Watchman – a 1 ktonne prototype closely associated with this – will be very likely be constructed in Boulby.

Also under consideration for beyond the first two cavities for DUNE.



THEIA, see Arxiv:1504.08284

Also: Arxiv:1306.5654

<u>Facility</u>

- Geo and reactor anti-neutrinos
- Solar neutrinos
- Supernovae neutrinos
- DSNB
- Nucleon decay
- Sterile neutrinos

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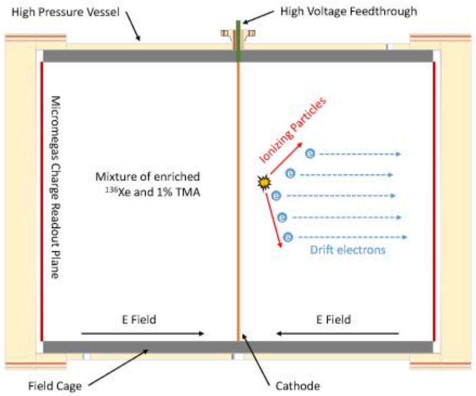
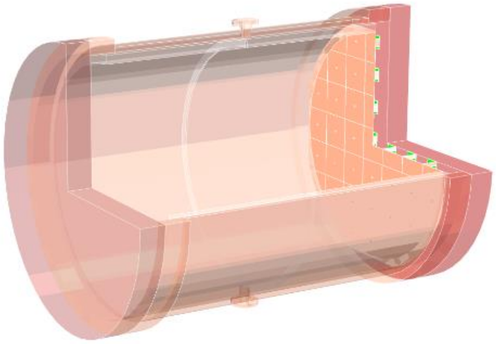
^{136}Xe in DM experiments

PandaX III (and LZ, XENON1T) aiming to compete.





Possible to continue to multi-tonne scale?
(2νββ backgrounds affect DM searches?)

Physics Backgrounds	
136Xe 2νββ	67
Astrophysical ν counts (pp+7Be+13N)	255
Astrophysical ν counts (8B)	0
Astrophysical ν counts (Hep)	0
Astrophysical ν counts (diffuse	0
Astrophysical ν counts (atmospheric)	0
Subtotal (Physics backgrounds)	322

Facility
- WIMP Dark Matter
- Electrophylic WIMPs
- Supernova neutrinos
- Neutrino
- Axion/ALP

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UK perspective

Neutrinoless Double-Beta Decay : UK Strategy

S. Biller[1], J. Evans[2], E. Falk[3], J. Hartnell[3], L. Kormos[4], N. McCauley[5], H. O'Keeffe[4], F. Di Lodovico[6], S. Peeters[3], Y. Ramachers[7], A. Reichold[1], J. Rose[5], R. Saakyan[8], J. Sedgbeer[9], S. Söldner-Rembold[2], J. Tseng[1], D. Waters[8], J. Wilson[6]

[1]*University of Oxford*, [2]*University of Manchester*, [3]*University of Sussex*, [4]*Lancaster University*, [5]*University of Liverpool*, [6]*Queen Mary University of London*, [7]*University of Warwick*, [8]*University College London*, [9]*Imperial College London*

We are convinced of the physics case for neutrinoless double-beta decay.

UK expertise:
Nearing completion of SuperNEMO demonstrator and SNO+ will start loading in spring 2019.

UK community is coming together to form a common R&D programme.

Expertise in:

- Screening & radon assay
- Large scintillator-based detectors

But also:

- Liquid nobel gases (DM)
- HPGe (Nuclear)

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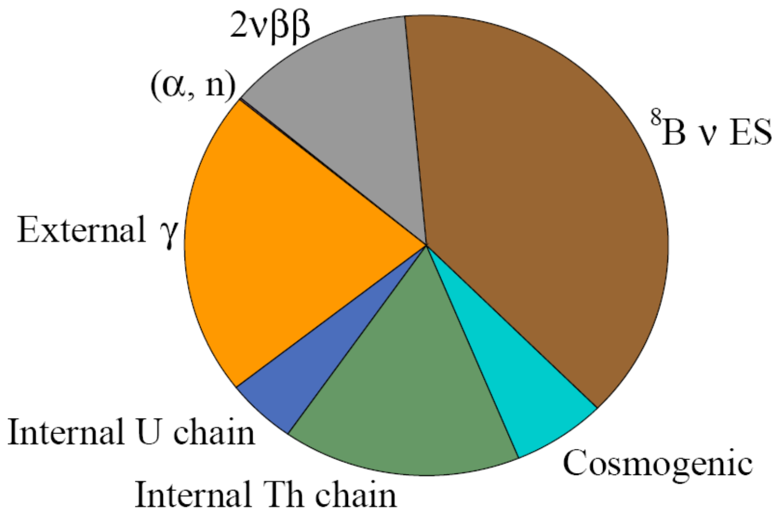
Back up

Why (monolithic) scintillator?

$$\sigma T_{\frac{1}{2}} = \frac{S}{\sqrt{B_{\mathrm{total}}}} = \frac{Mt}{\sqrt{B_i \Delta E t}} \qquad \left(T_{\frac{1}{2}} \propto m_{\beta\beta}^2\right)$$

Background: $$B_i \Delta E = (bM + c)\,\Delta E$$



Background scales with mass *(b dominant)*:

$$m_{\beta\beta} \propto M^{1/4}$$

Background scales with mass *(c dominant)*:

$$m_{\beta\beta} \propto M^{1/2}$$

SNO+
Self-shielding and cleaning

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Question & answer

- What consensus / conflicts (on what should be done in longer term European HEP) are there in this area?
- What are the experimental possibilities? Are different scenarios already envisaged?
- What are the choices for the strategy? What can the UK agree to input?
- What are the potential developments in this field? How do they relate to fundamental physics questions?

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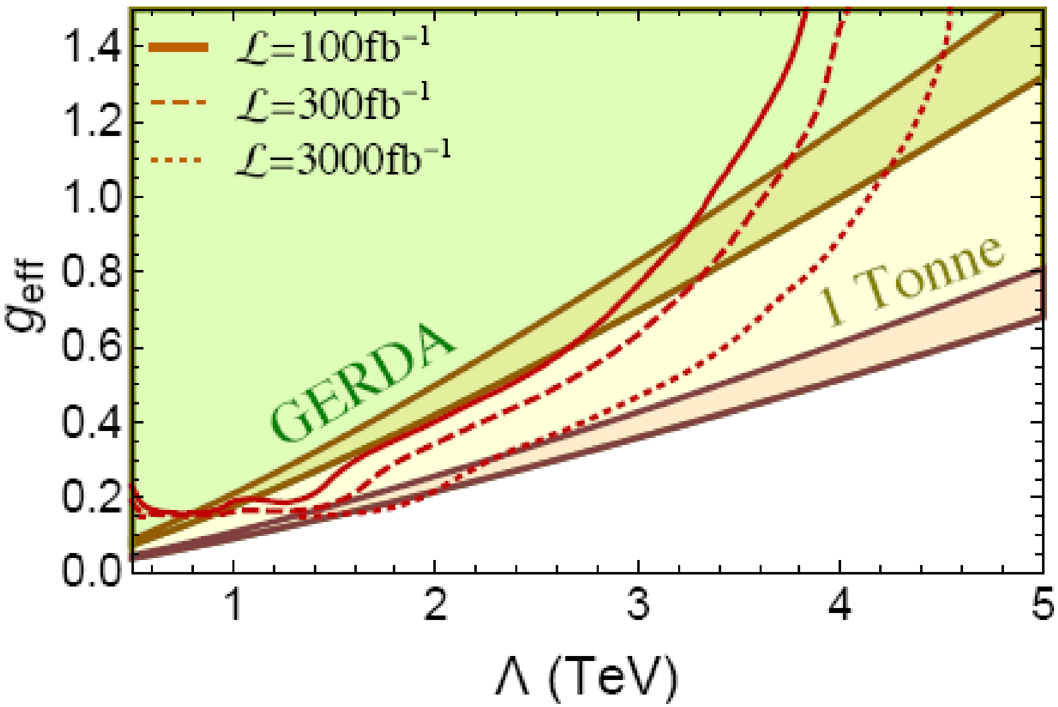
LHC

arXiv:1508.04444



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