Neutrinoless $\beta\beta$ decay and non-accelerator neutrinos

The future (2025-2040)

Matteo Agostini

University College London

PPAP Community Meeting

Birmingham, 25/07/2024

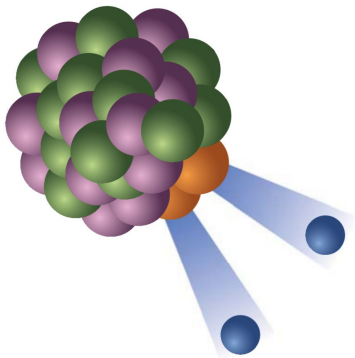
UCL

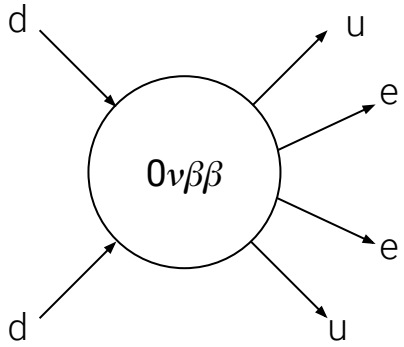
UKRI Science and Technology Facilities Council

Neutrinoless $\beta\beta$ decay

Nuclear decay: (A,Z) -> (A,Z+2) + 2e

- 2 neutrons -> 2 protons ($\Delta B = 0$)
- 2 electrons are emitted ($\Delta L = 2$)





MA, Benato, Detwiler, Menéndez, Vissani
Rev. Mod. Phys. 95, 025002 (2023)

Implication 1: discovery of first matter-creating process

- production of leptons without antileptons
- direct violation of **L** and **B-L**
- matter-antimatter asymmetry in our Universe

Implication 2: neutrinos are their own antiparticles

- nonzero **Majorana mass**
- alternative Higgs mechanism (see-saw)
- breakthrough towards new theory of fermion masses

Implication 3: proof of lepton-number-violating BSM physics

- new energy scale
- interplay with accelerator physics
- leptogenesis and dark-matter

Discovery prospects

A portal to new physics beyond the SM:

$$T_{1/2} \propto \frac{\lambda^n}{\mathcal{M}^2}$$

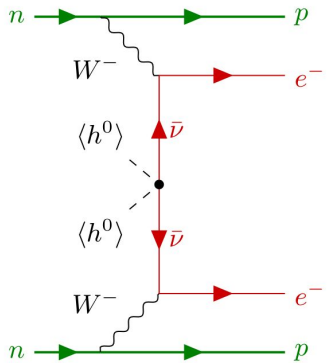
energy scale of new physics

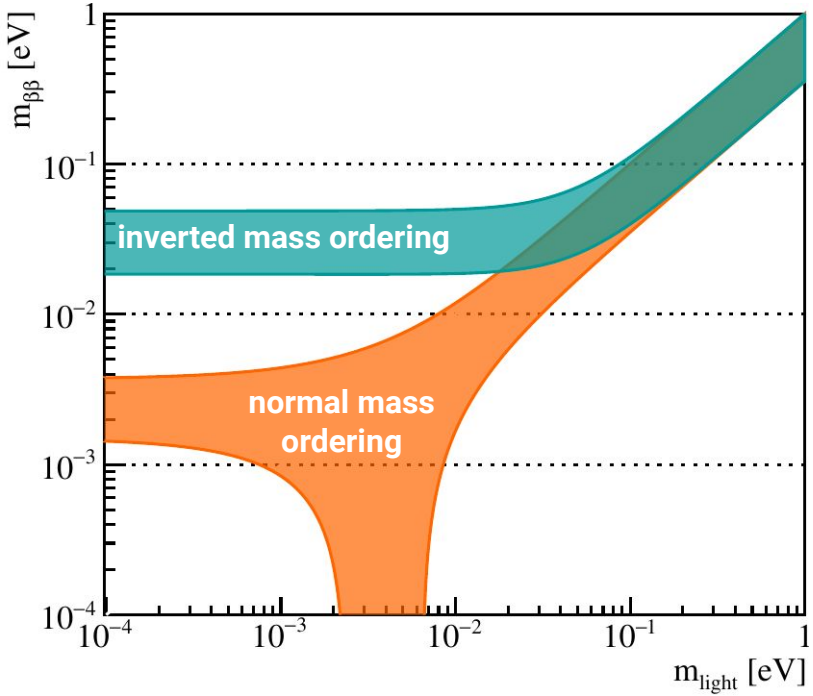
operator dimension

nuclear matrix element (NME)

Exchange of Majorana neutrinos:

- Weinberg operator
- likely the dominant channel
- $\lambda^n \propto m_{\beta\beta}^{-2} = \left|\sum_i U_{ei}^2 m_i\right|^{-2}$





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News since last PPAP meeting

From nuclear physics

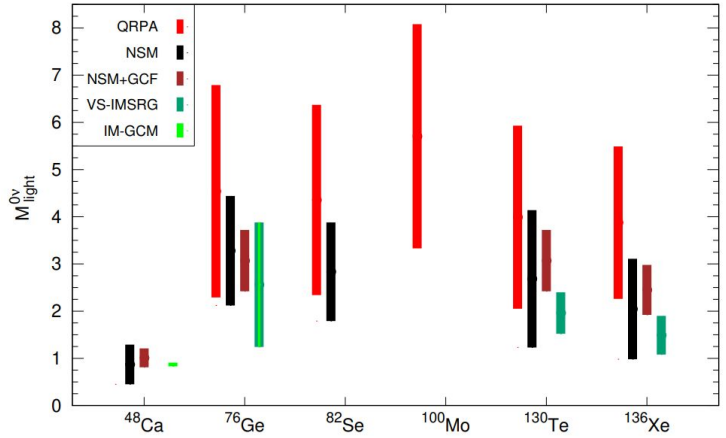
- first **ab initio** calculations with uncertainties
- **short-range** contribution increase NME values
- new estimate: Hamiltonians sampling & 0νββ−2νββ correlation

From cosmology

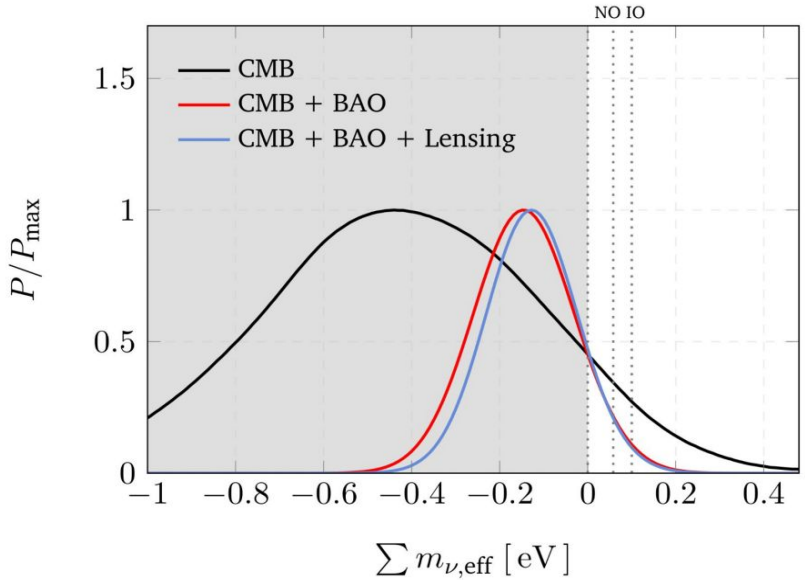
- fit suggest sigma is acting as fudge factor (**missing physics**)
- cosmology might not be able to measure neutrino masses

From neutrino oscillations

- NOvA + T2K pulls towards IO
- SK seems to favor normal ordering, result under scrutiny
- **global fits are inconclusive**

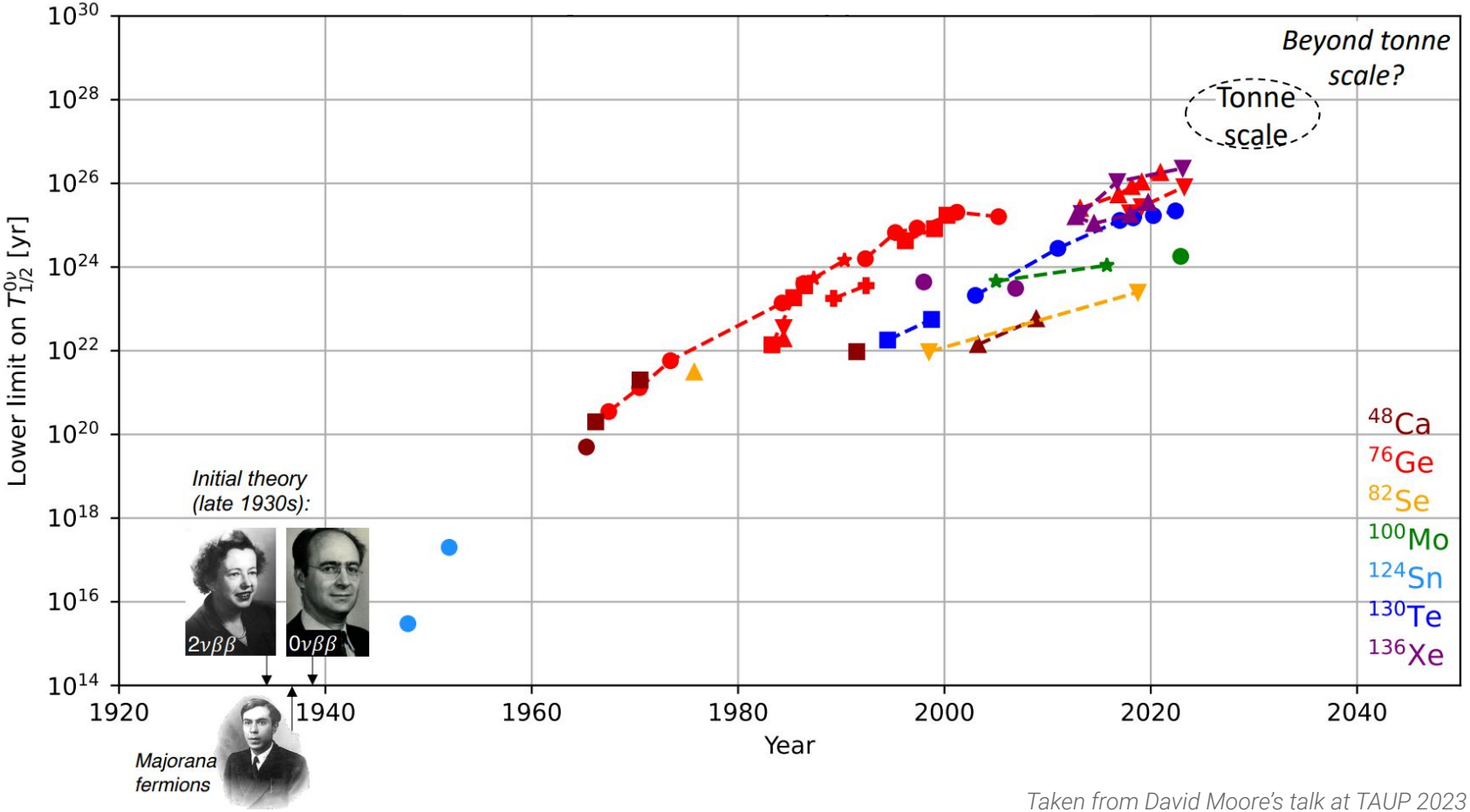


Menéndez @ Neutrino2024



Elbers @ Neutrino2024

The hunt for neutrinoless $\beta\beta$ decay



Taken from David Moore's talk at TAUP 2023

Experimental landscape

Most sensitivity experiments

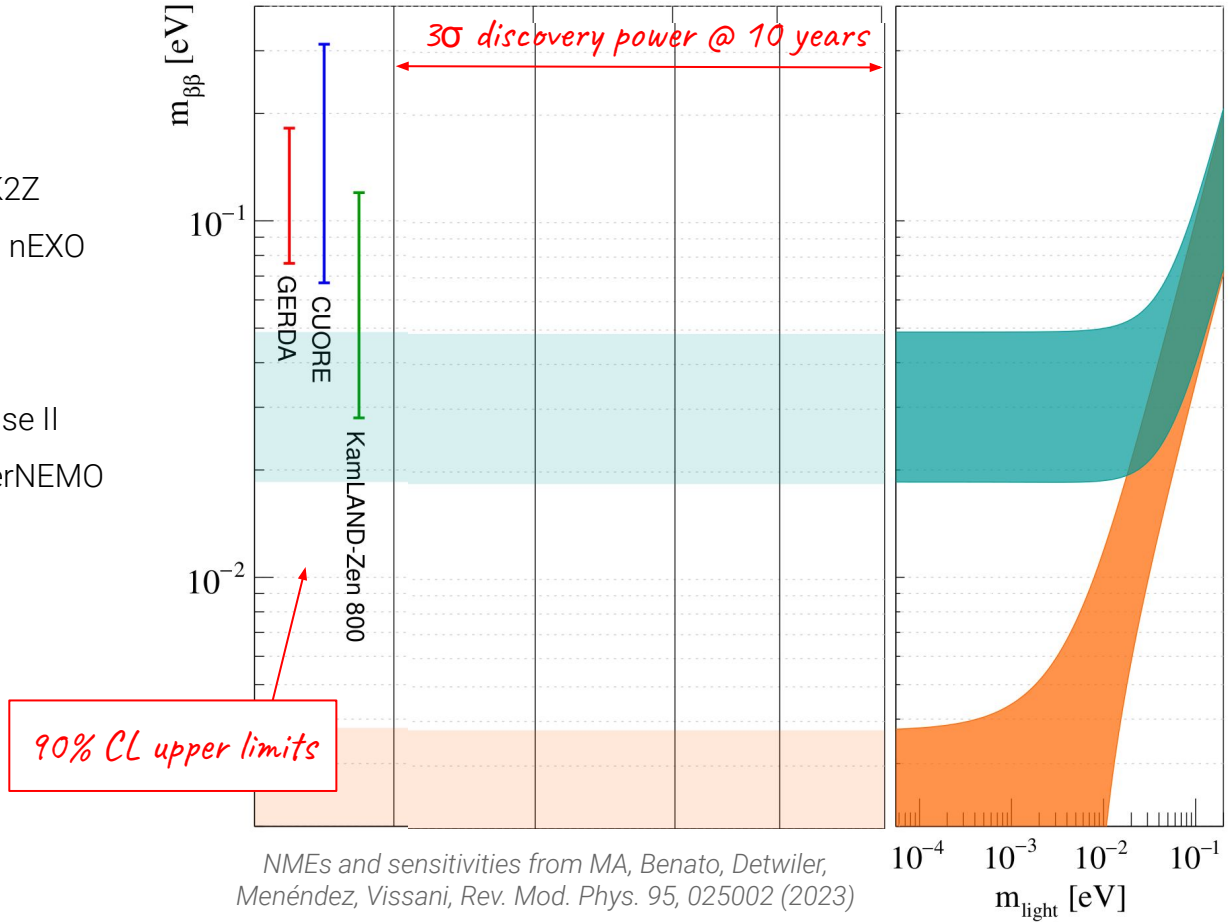
- **past decade:** GERDA, CUORE, KZ
- **next 5 years:** LEGEND-200, SNO+, K2Z
- **next decade:** LEGEND-1000, CUPID, nEXO

Exploring technologies

- **for beyond IO:** NEXT100, SNO+ Phase II
- **for kinematic measurements:** SuperNEMO

Dark-matter detectors:

- DARWIN/XLZD (up to 80 tonne)
- PandaX-xT



NMEs and sensitivities from MA, Benato, Detwiler, Menéndez, Vissani, Rev. Mod. Phys. 95, 025002 (2023)

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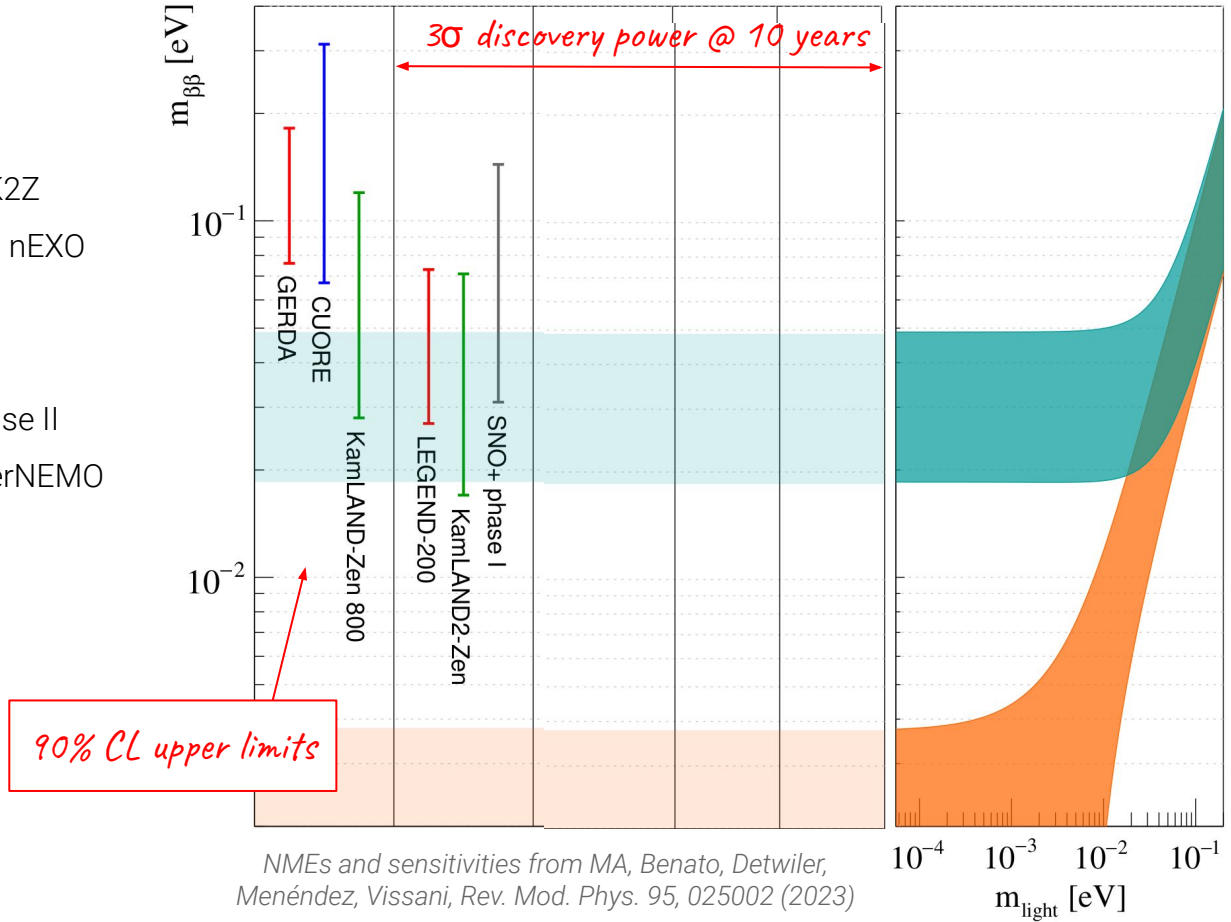

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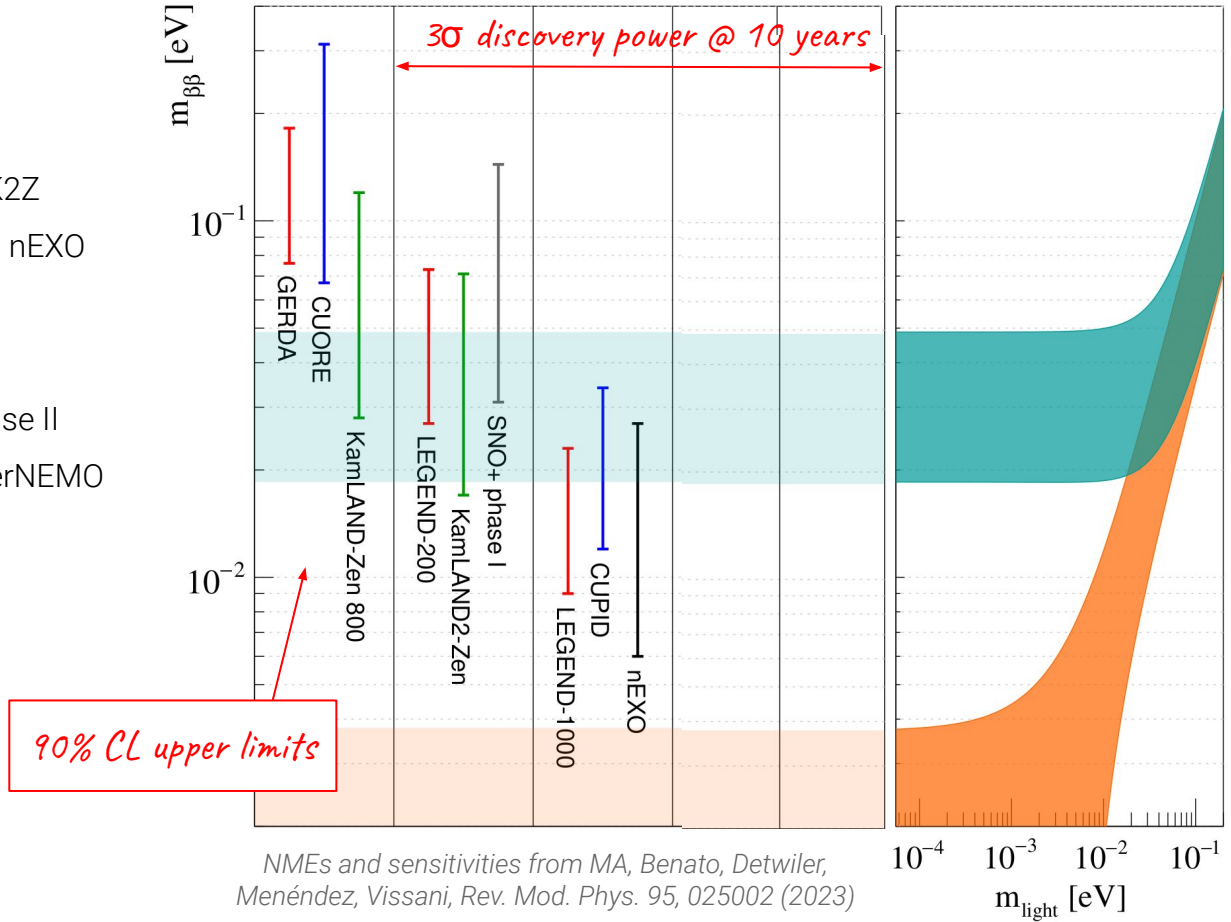

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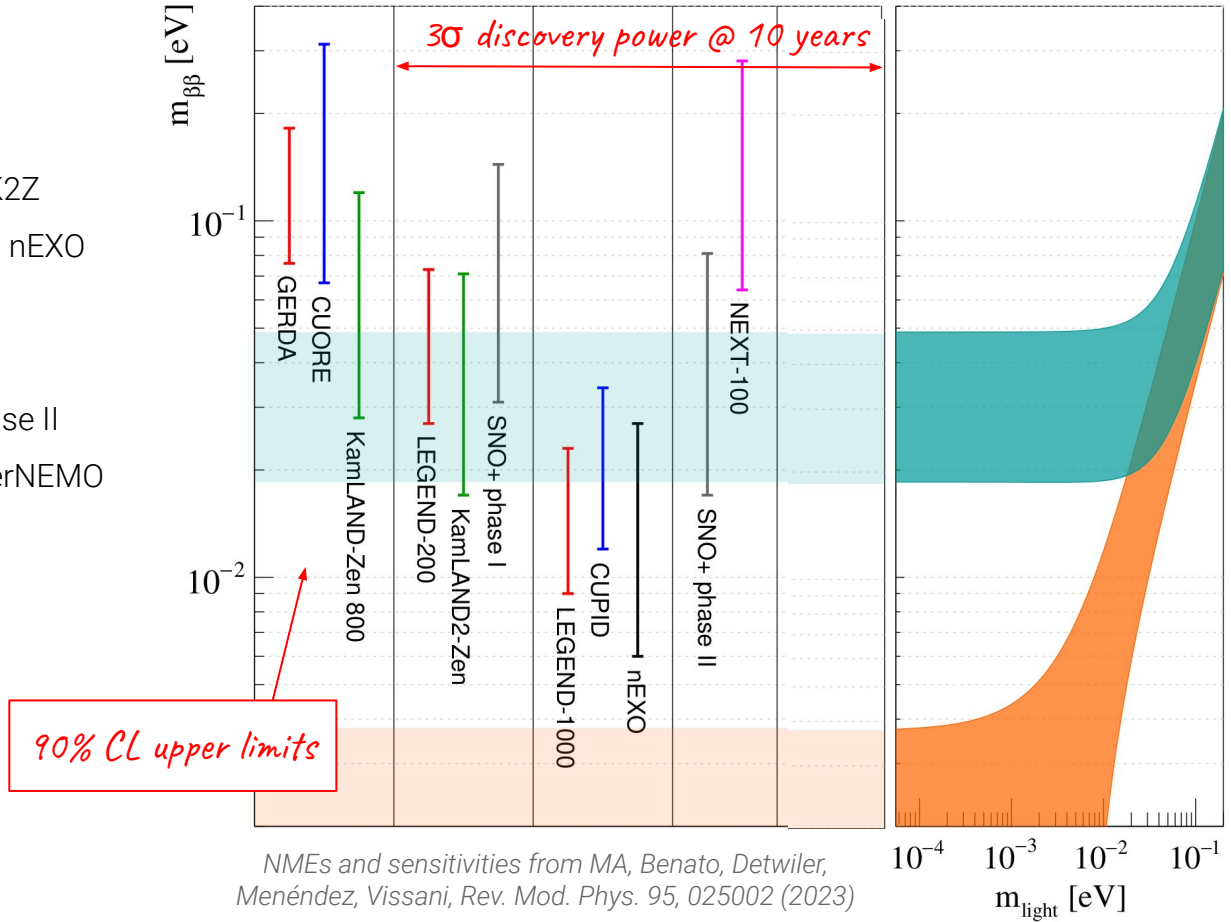

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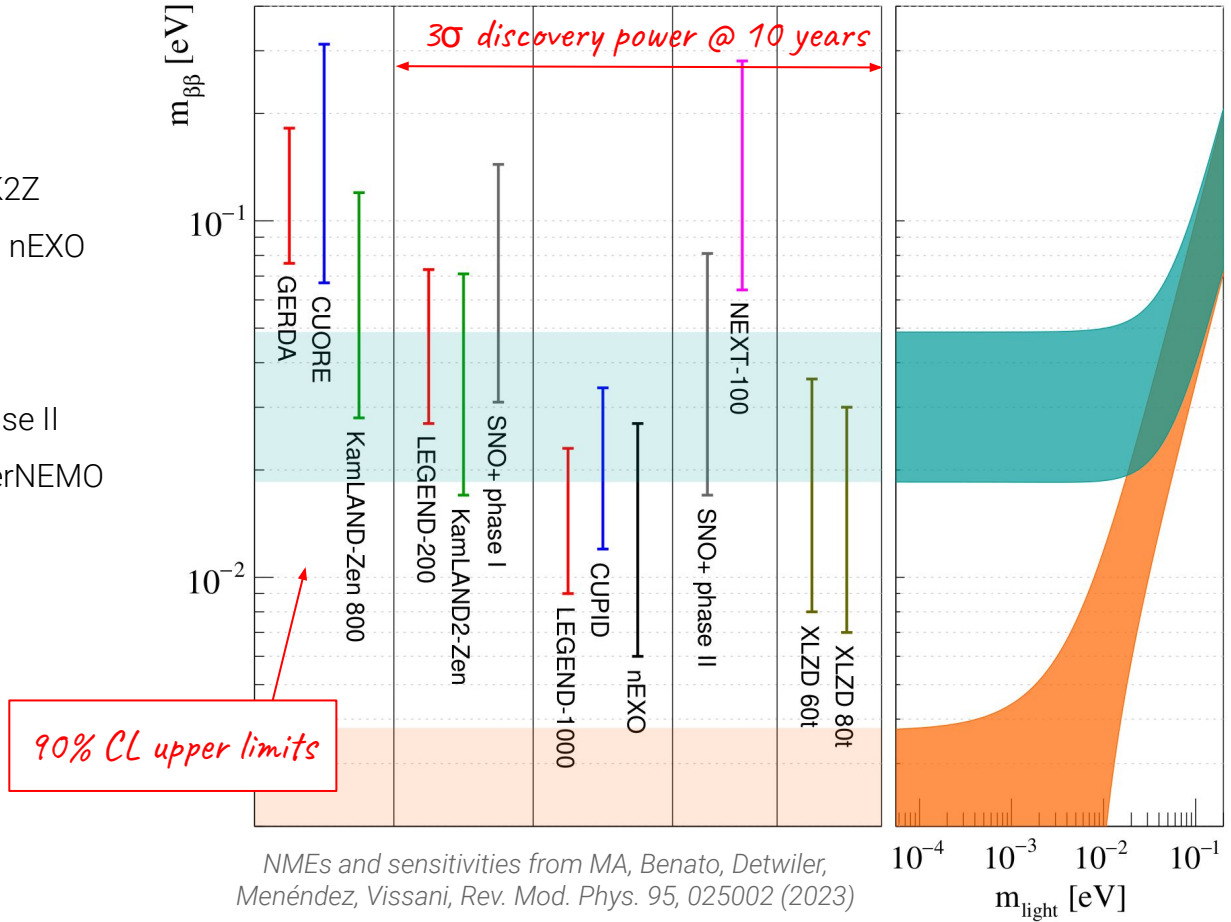
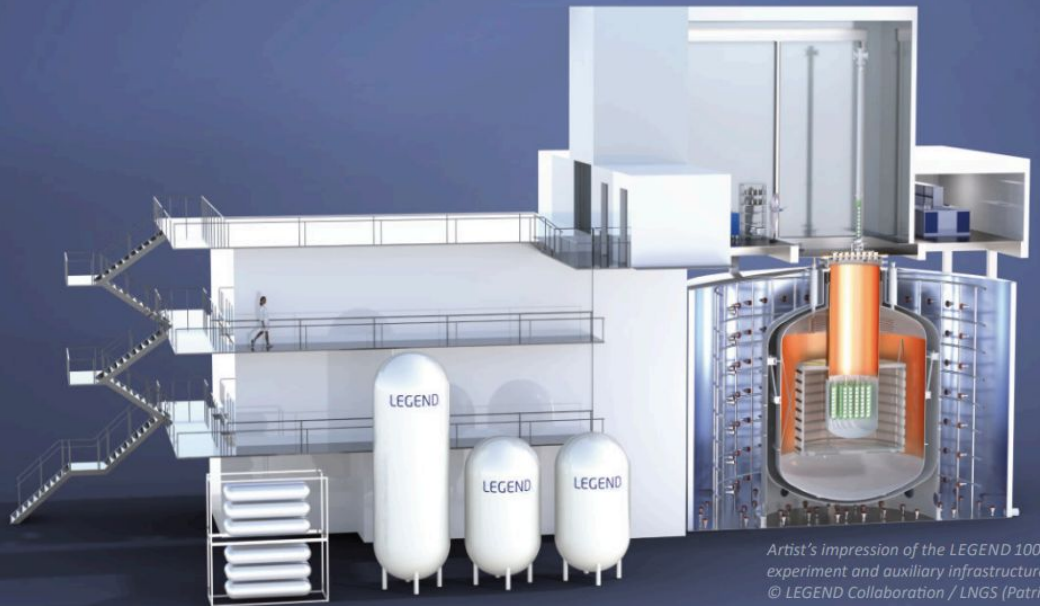


NMEs and sensitivities from MA, Benato, Detwiler, Menéndez, Vissani, Rev. Mod. Phys. 95, 025002 (2023)

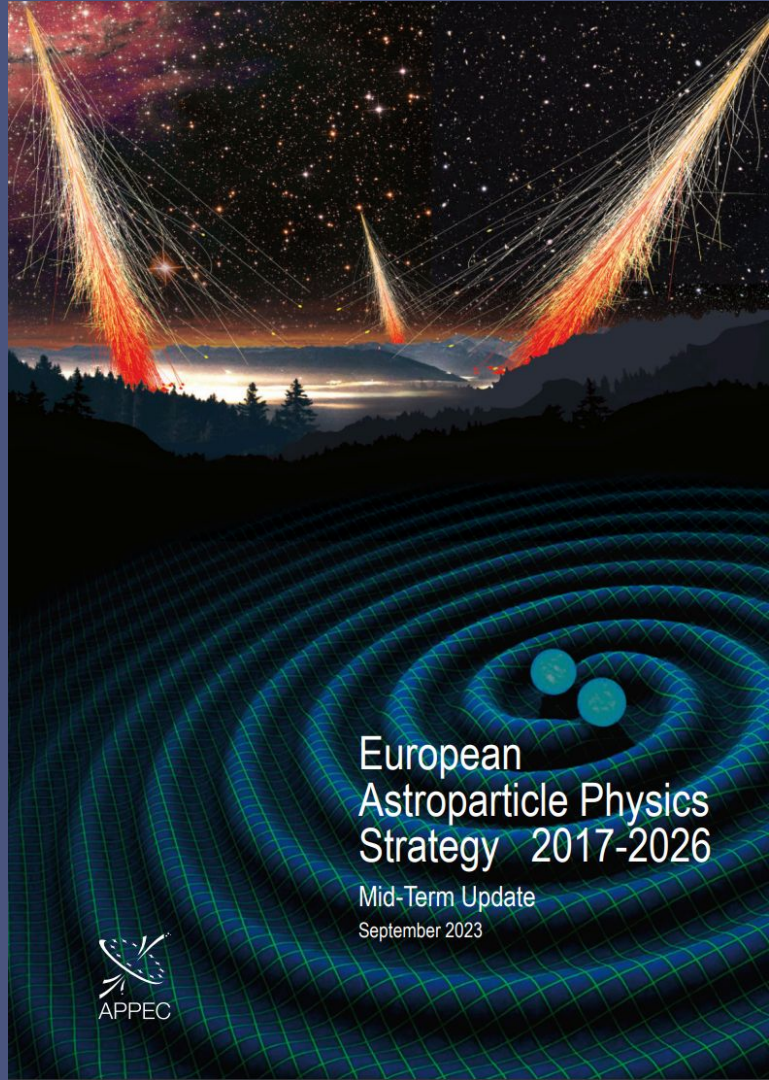
International support (APPEC)

RECOMMENDATIONS:

APPEC strongly supports the CUPID and LEGEND 1000 double-beta decay experiments selected in the US-European process and endorses the development of NEXT. APPEC strongly supports fully exploiting the potential of the KATRIN direct neutrino mass measurement and the development of a new generation of experiments beyond KATRIN.



Artist's impression of the LEGEND 1000 experiment and auxiliary infrastructure
© LEGEND Collaboration / LNGS (Patrick Krause)



International support (DOE/NSF)

The search for neutrinoless double beta decay is a truly international effort, propelled by the compelling and fundamental discovery nature of the science. Three ton-scale projects (CUPID, LEGEND-1000, and nEXO) are all led by distinctly international collaborations with significant US leadership and responsibilities. International cooperation between funding agencies on double beta decay experiments is well organized and strong: two international summits have been held already, and a third is planned for early 2024. These stakeholders formed an International Working Group to coordinate efforts and to advance the field efficiently and cost-effectively.

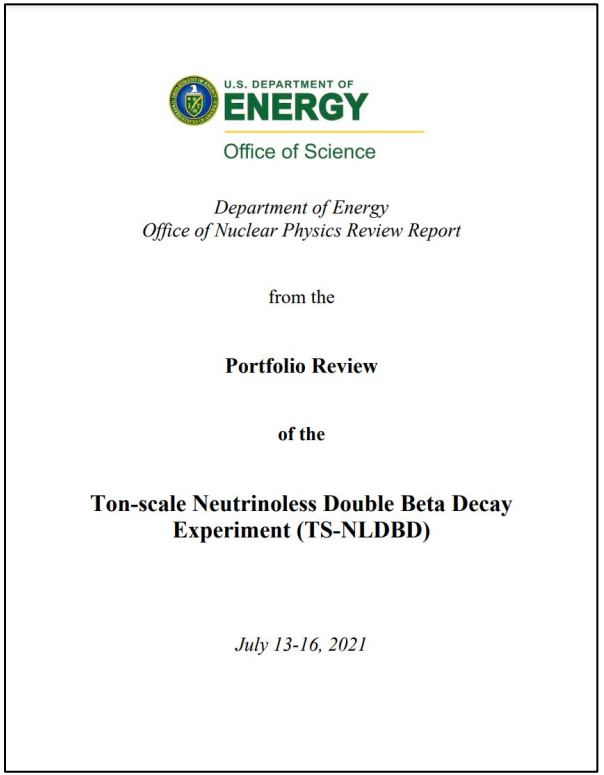
North American-European $0\nu\beta\beta$ Summit (LNGS, Sep 21, APPEC/INFN/DOE)

2nd International Summit on the Future of $0\nu\beta\beta$ Decay (SNOLab, Apr 23)

The big 3: closing up on inverted ordering

DOE's **portfolio review** (Summer 2021)

- review of conceptual designs reports
- panel of 18 experts evaluating against weighted criteria
  1. scientific merit of the proposed experiment
  2. global context
  3. technical maturity
  4. cost competitiveness and timeliness
  5. assurance of successful project delivery
- CUPID, LEGEND, nEXO technical design "ready to go"
- LEGEND top ranked project



U.S. DEPARTMENT OF ENERGY
Office of Science

Department of Energy
Office of Nuclear Physics Review Report

from the

Portfolio Review

of the

Ton-scale Neutrinoless Double Beta Decay Experiment (TS-NLDBD)

July 13-16, 2021

Collaboration	Weighted Score
CUPID	6.4
LEGEND-1000	8.0
nEXO	7.0

NP continues to pursue the possibility, in collaboration with national and international partners, of a multi-experiment campaign capable of providing contemporaneous verification of any apparent observation of $0\nu\beta\beta$. Should it not prove possible to implement multiple projects in the search of $0\nu\beta\beta$, LEGEND-1000 would receive priority based on it receiving the highest ranking from the portfolio review panel.

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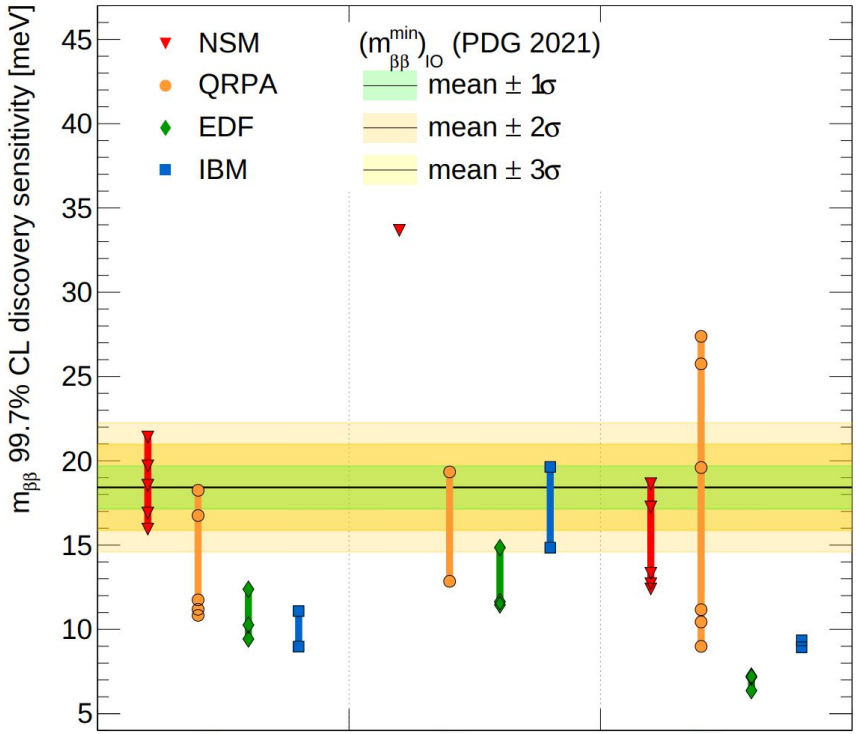
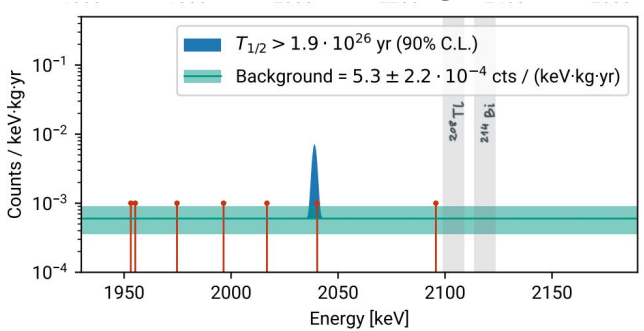
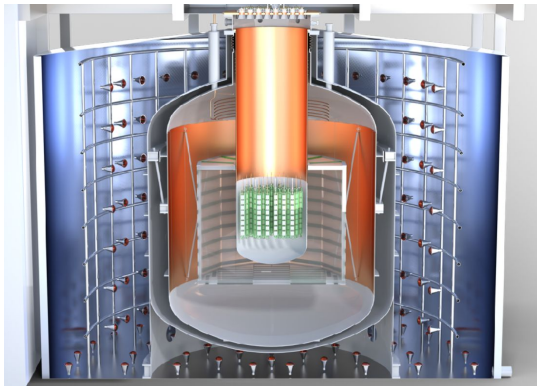
MA, Benato, Detwiler, Menéndez and Vissani, PRC 104, L042501

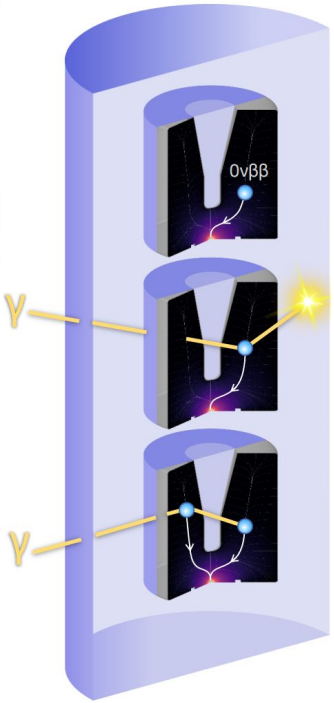


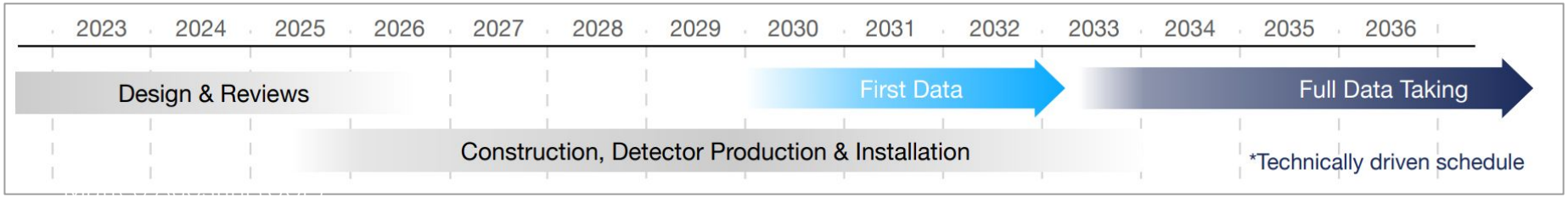
The LEGEND project

- **LEGEND-200** (200 kg) @ LNGS
  - data taking since 2023
  - best background and energy resolution
  - first 0vbb search presented this summer
  - UCL, Liverpool, Warwick, Lancaster, Daresbury
- **LEGEND-1000** (1 tonne) @ LNGS
  - technical design ready, DOE CD1 this year
  - NSF funding under review
  - SoI submitted to STFC (12 institution, 37 academics)



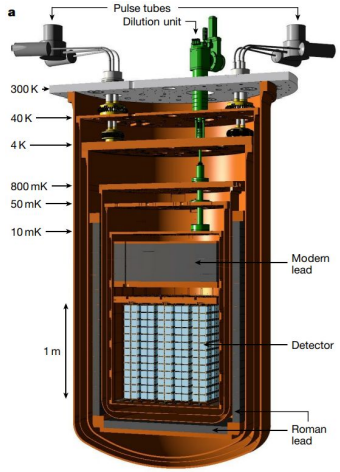


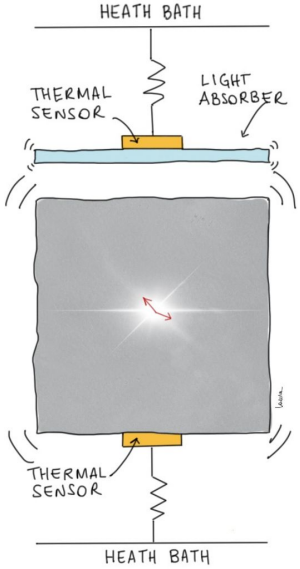


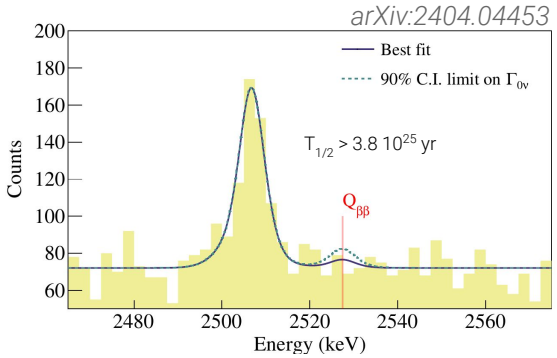


CUPID @ LNGS

- Li_2MoO_4 scintillating bolometers
- cryogenic mK infrastructure of CUORE
- particle identification and good energy resolution

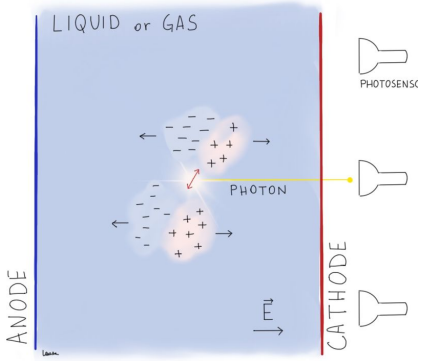


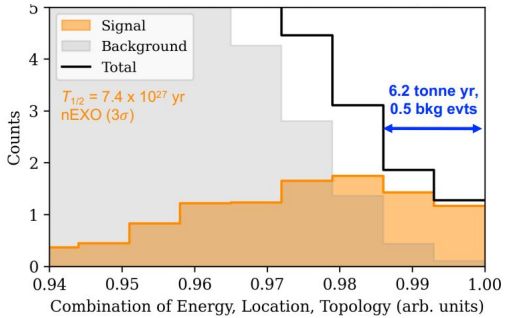




nEXO @ SNOLab

- liquid enrXe TPC with 5 tonne total mass
- ^{136}Xe VUV scintillation light and ionization electron drift -> 3D reconstruction
- background decreasing with distance from surface, ^{214}Bi and ^{222}Rn remain problematic

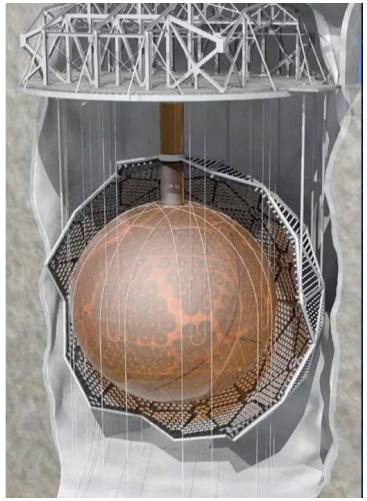




SNO+ @ SNOLab

- isotope systems commissioning
- Te-130 loading in 2025 at 0.5%
- planned phases with 1.5 and 3%
- sensitivity depends on purity during Te loading

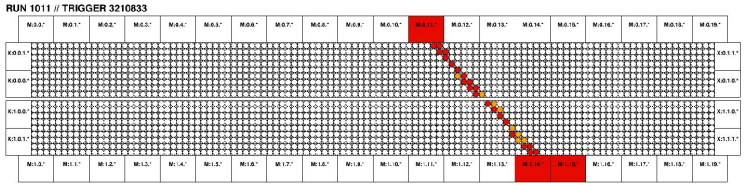
KCL, Lancaster, Liverpool, Oxford, Sussex



SuperNEMO @ Modane

- unique measurement of decay kinematics
- all systems commissioned, installing shielding now
- start data taking by the end of the year

Edinburgh, UCL, Warwick, Manchester, Imperial

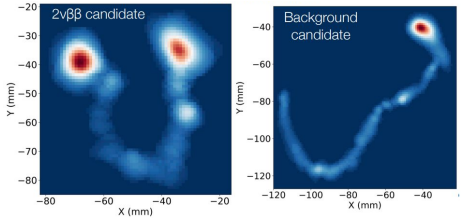


Guenette + posters @ Neutrino 2024

NEXT-100 @ LSC

Manchester

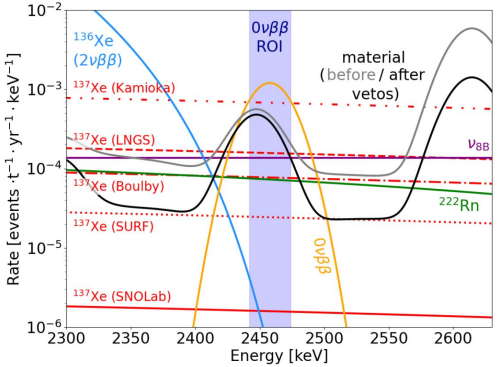
- detector built and under commissioning
- first runs in Ar gas in May 2024
- Xenon runs to start shortly



XLZD

22 institutions

- dark-matter rare-event observatory
- 60-80 tonne of Xe
- 9% ^{136}Xe
- self-shielding
- sensitivity approaching that of nEXO for 80 tonne design



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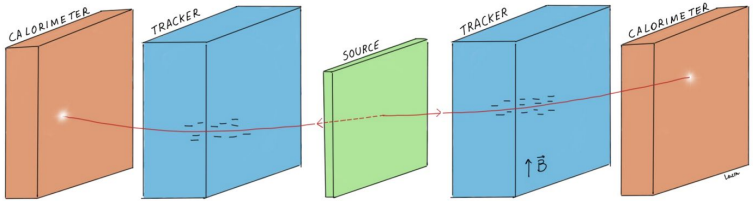
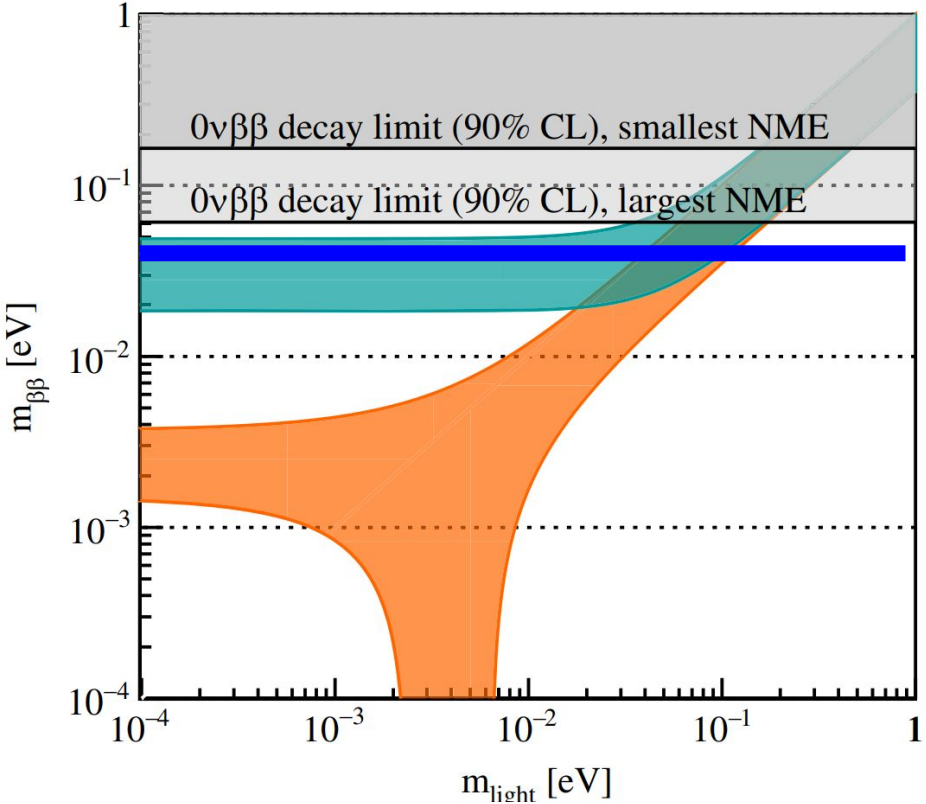
$T_{1/2} < 10^{28}$ years: 100s events in ton-scale experiments

- O(10%) statistical uncertainty
- can probe decay mechanism



supernemo collaboration



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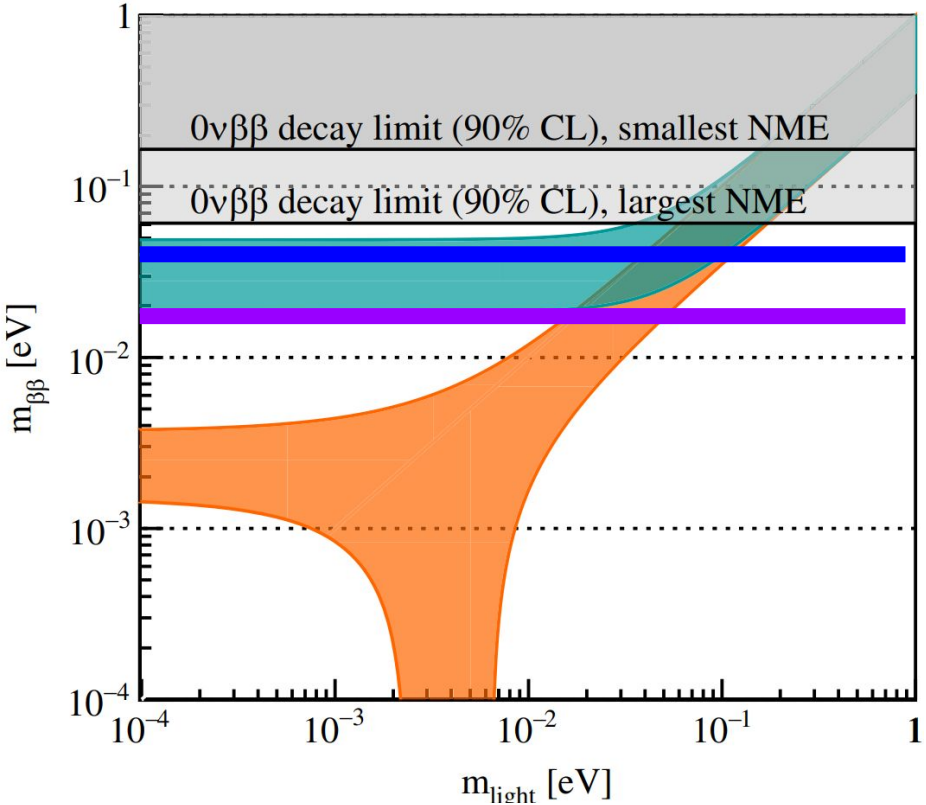
$T_{1/2}$ ~ 10^{28} years: ~10 events in ton-scale experiments

- statistical uncertainty ~ NME uncertainties
- multiple ton-scale experiments to confirm signal



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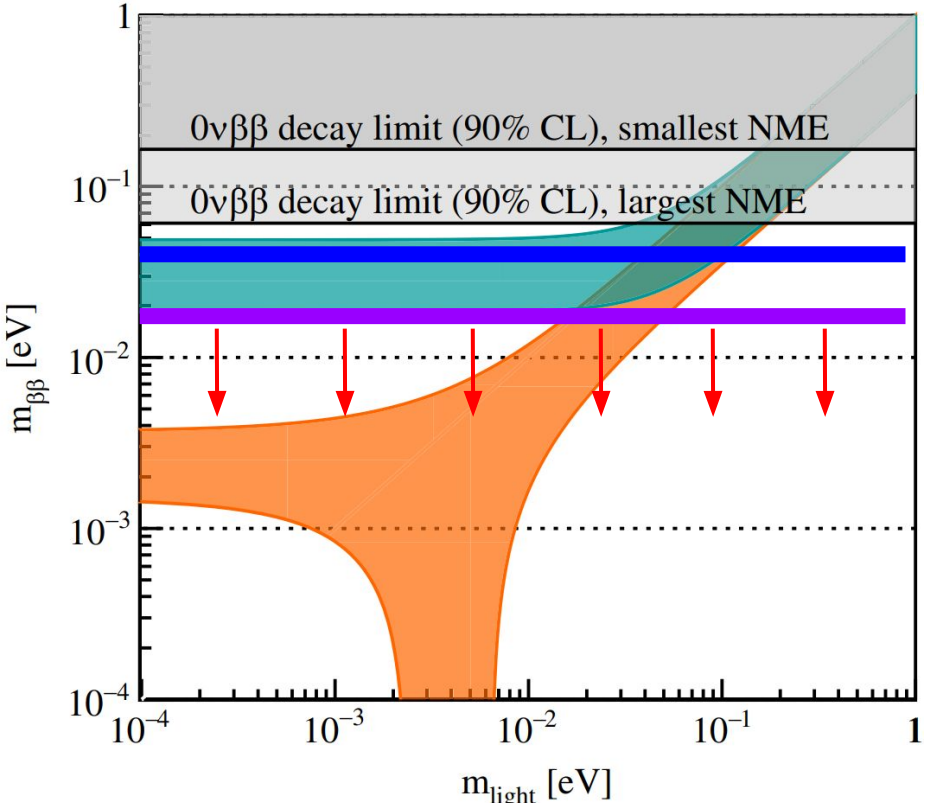
$T_{1/2}$ > 10^{28} years: < few events in ton-scale experiments

- R&D required to push further into NO, reduce cost
- variety of field is a strength



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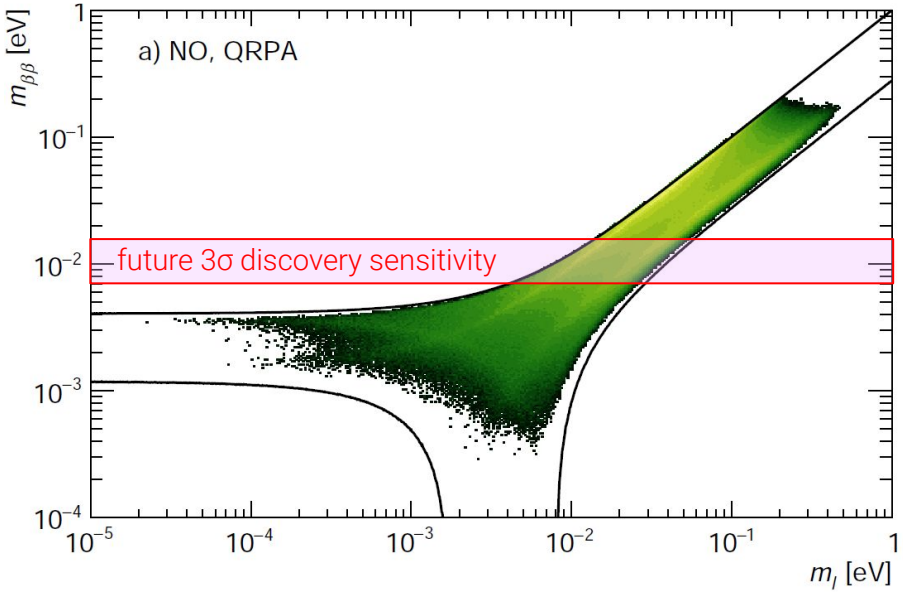
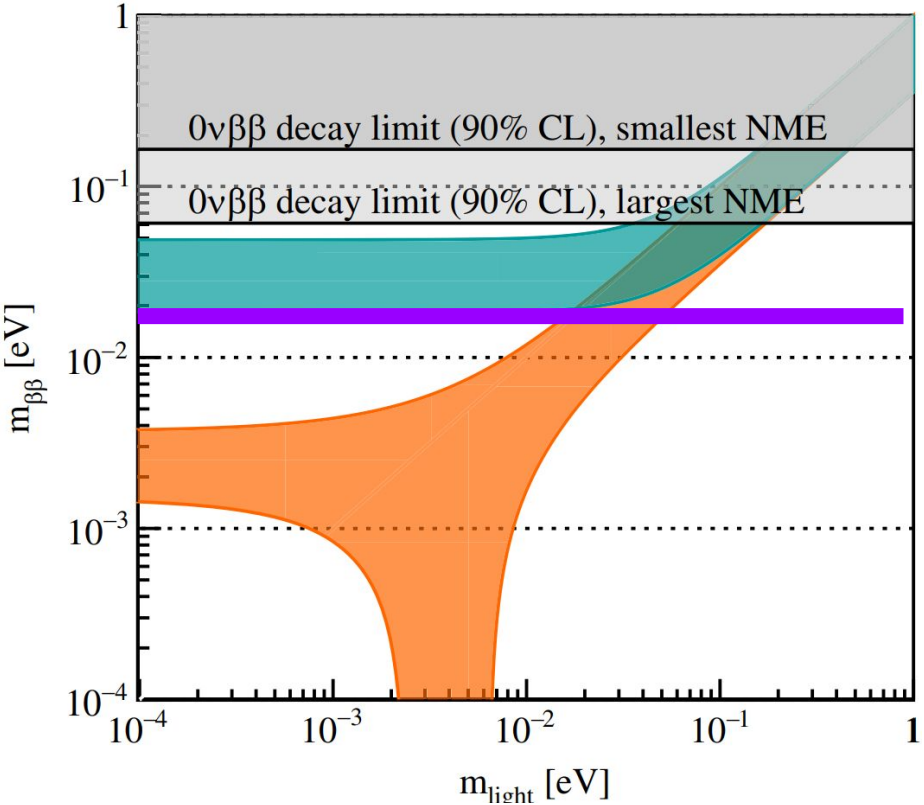


MA, Benato and Detwiler, PRD 96, 053001 (2017)



UK community strategy

- particle, astro-particle and nuclear physics communities
- 64 academics from 20 institutions

near-term:
next 5 years

medium-term:
5 to 15 years

long term:
>15 years

The strategy can be summarised in four points:

1) Continued support for the exploitation of LEGEND-200, SNO+ and the SuperNEMO Demonstrator, recognising the unique near-term physics programmes of each experiment and building on substantial prior UK investment.

2) Support the construction of LEGEND-1000 in the near term as the highest priority project in the USA and Europe, ensuring UK leadership in an experiment that will have $> 3\sigma$ discovery sensitivity for Majorana neutrinos in the inverted neutrino mass ordering range in the medium term.

3) Support the development and implementation of higher loading phases of SNO+, which will provide complementary sensitivity with a different isotope in the medium term and lay foundations for a technique that might be extended to the normal mass ordering in the longer term.

4) Exploit cross-field scientific and technological synergies with the XLZD dark matter community and explore strategic R&D opportunities offered by complementary technologies, such as NEXT, to further strengthen the main programme in the medium term, while continuing to support blue-skies R&D into new technologies able to reach sensitivities beyond the inverted mass ordering in the long term.

Neutrinoless $\beta\beta$ decay and non-accelerator neutrinos

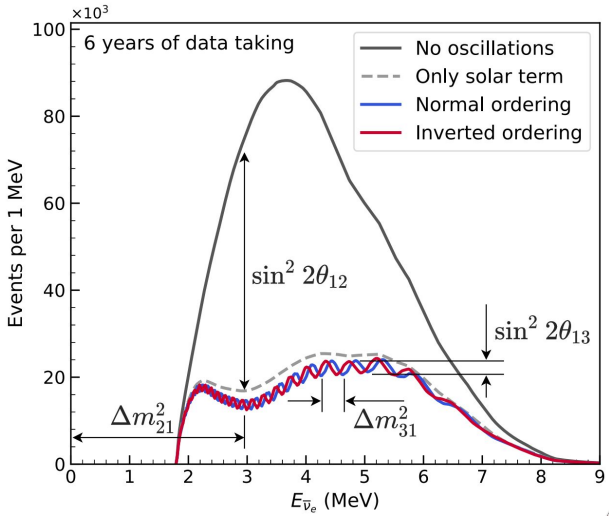
Matteo Agostini
University College London
PPAP Community Meeting
Birmingham, 25/07/2024

- neutrino mass measurements
  - covered by Edward Daw' (QTFP)
- extraterrestrial neutrinos
  - covered by Teppei Katori (UHE neutrinos)
- reactor neutrinos
  - JUNO
  - CLOUD/LIQUIDO

Reactor neutrino experiments with UK participation

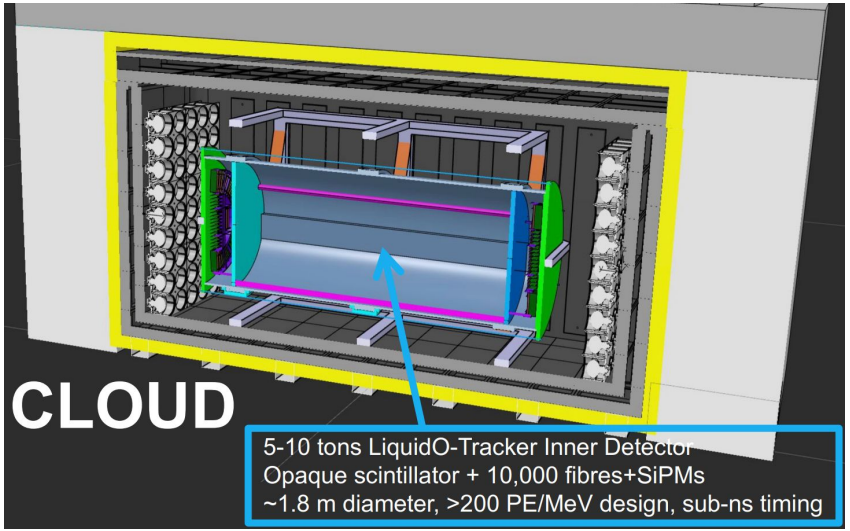
JUNO

- large scintillator reactor-neutrino detector
- 3σ sensitivity to mass ordering in 6 years
- construction close to completion
- world leading broad-program in the next decade



Chooz LiquidO Ultranear Detector

- Phase I: opaque scintillator for U/Pu composition
- Phase II: indium loading for neutrino CC scattering
- Phase II: copper loading to lower threshold inverse beta decay



Warwick Sussex

Conclusions

- observing $0\nu\beta\beta$ decay would be a **ground-breaking discovery** (matter-antimatter asymmetry and theory of fermion masses with Majorana neutrinos)
- vibrant field: **staging** and **innovation** essential for rare-event searches
- current & tonne-scale experiment will explore unprobed parameter space **with high-discovery power**
- the UK has a strong leadership in the field and developed a strategy to maintain and strengthen it
  - exploitation of running experiments (**short term)**
  - construction of a tonne-scale experiment (**short term)** to explore the entire inverted ordering space (**medium term)**
  - forward looking developments strengthening the program (**medium term)** to go beyond the inverted ordering (**long term)**
- some interesting activities on reactor experiments