Neutrinoless $\beta\beta$ Decay - Status & Prospects

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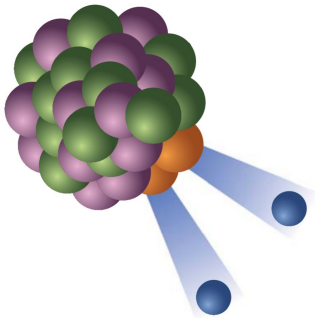
UCL

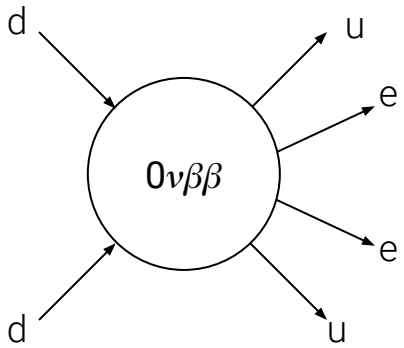
UKRI Science and Technology Facilities Council

Neutrinoless $\beta\beta$ decay

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

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





Discovery of first matter-creating process

- production of leptons without antileptons in the lab
- direct violation of **L** and **B-L**, key to explain the matter-antimatter asymmetry in our Universe

Prove that neutrinos are their own antiparticles

- nonzero **Majorana mass**
- not enough to explain measured neutrino masses, but big step towards a theory of fermion masses

Schechter and Valle, PRD 25, 2951 (1982)

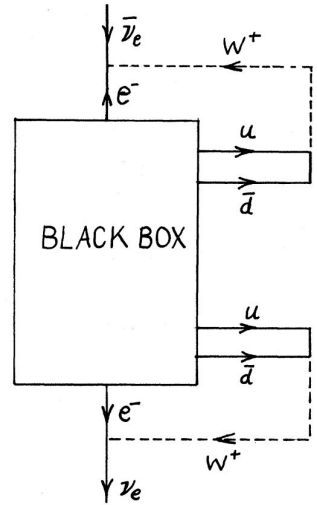


FIG. 2. Diagram showing how any neutrinoless double-β decay process induces a $\bar{\nu}_e$-to-ν_e transition, that is, an effective Majorana mass term.

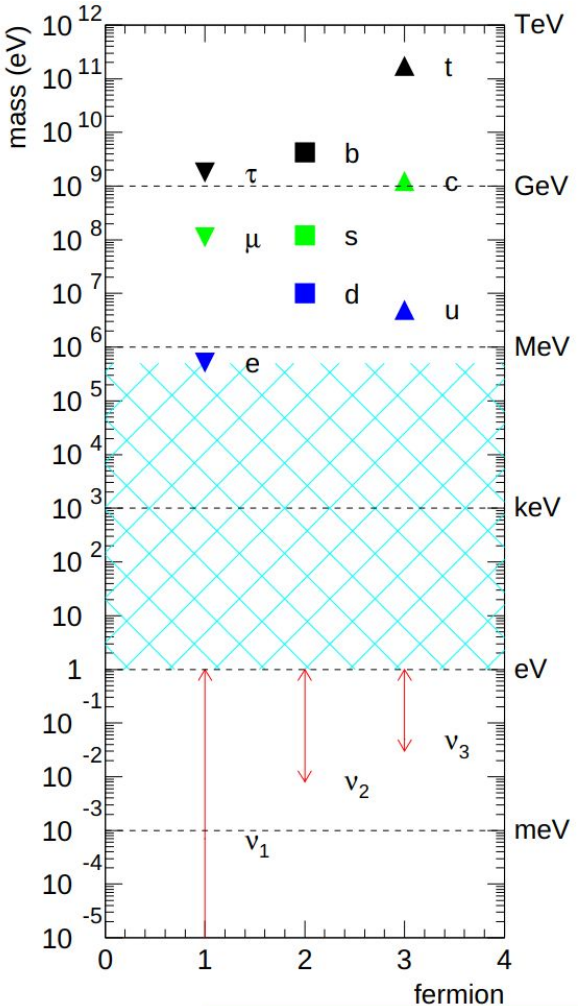
Neutrino masses

- 10 years of LHC have proved minimum Standard Model prescription for electroweak symmetry breaking (at least approximately)

- Still, tiny (but nonzero) neutrino masses imply existence of new physics:

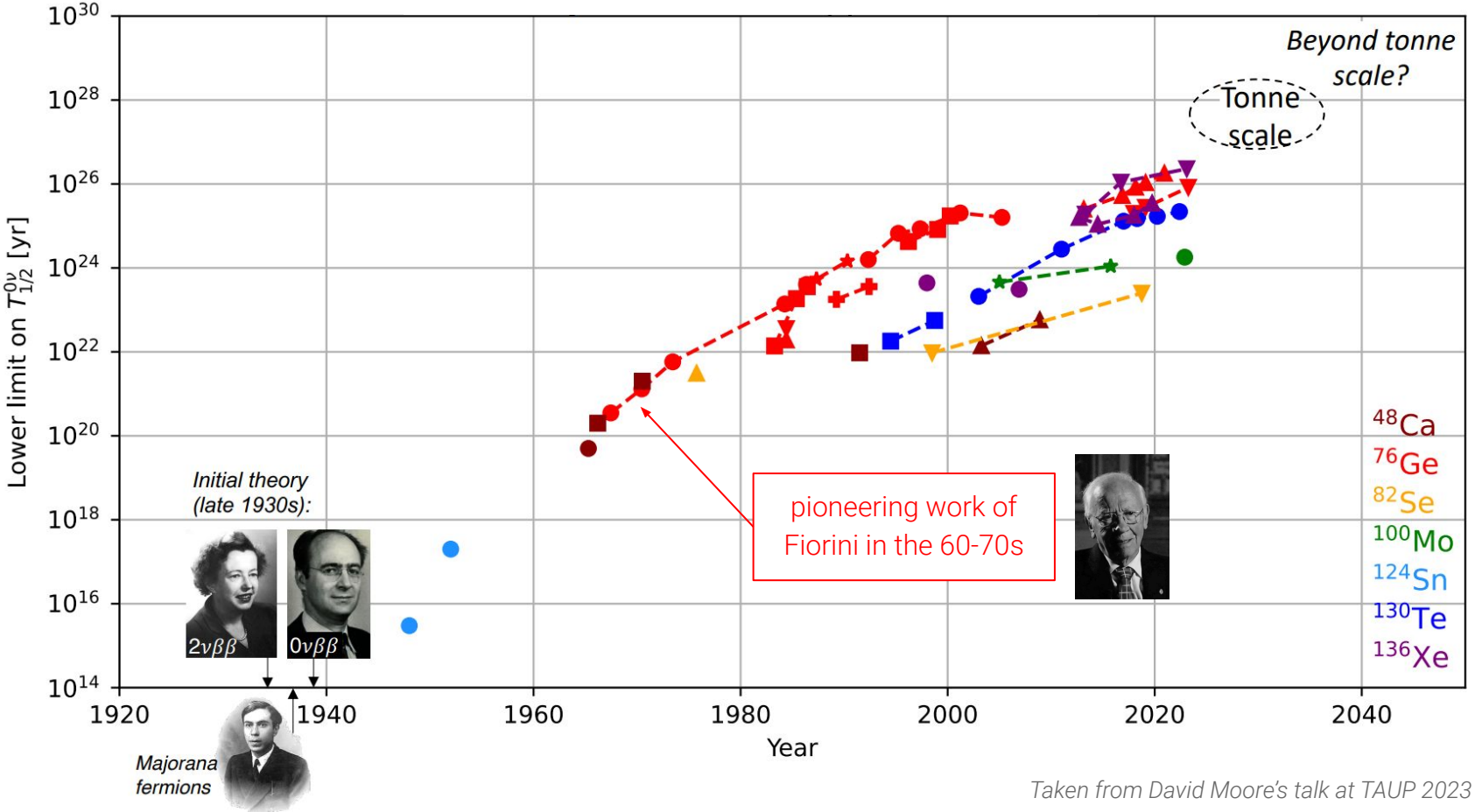
neutrinos talk to the Higgs very weakly	*right-handed neutrinos, tiny Yukawa couplings, L conserved*
neutrinos talk to a different Higgs boson	*new source of electroweak symmetry breaking*
there is another source of mass out there	new energy scale, see-saw mechanism

Majorana neutrinos and $0\nu\beta\beta$ decay!



Taken from Andre de Gouvea's talk at TAUP 2023

The hunt for neutrinoless $\beta\beta$ decay

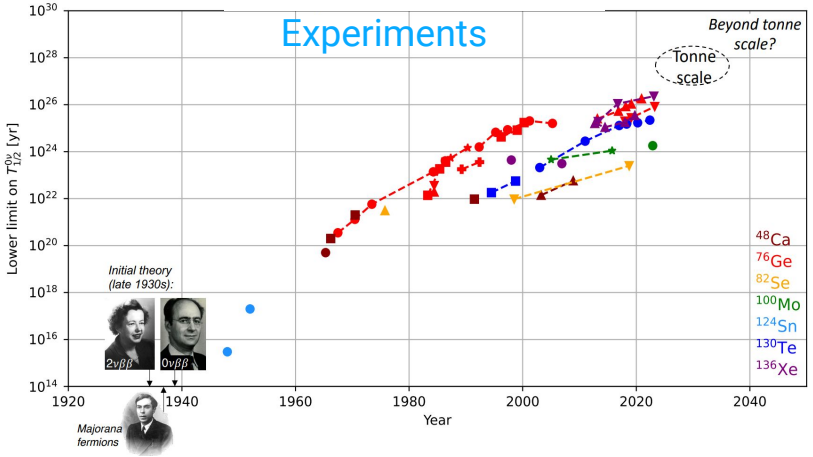


Taken from David Moore's talk at TAUP 2023

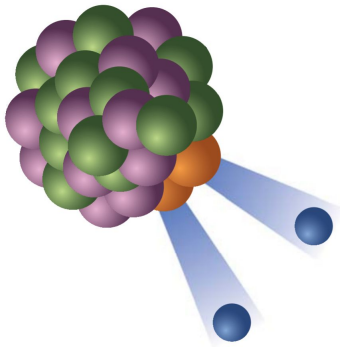
A portal to new physics beyond the SM

$$\frac{1}{T_{1/2}} \propto G\, g^4\, M^2 \left(\frac{\nu}{\Lambda}\right)^n$$

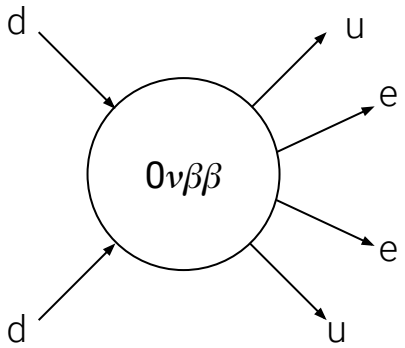
Experiments



Nuclear theory



Particle theory



A portal to new physics beyond the SM

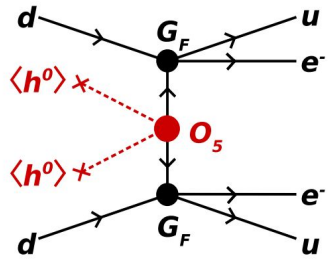
$$\frac{1}{T_{1/2}} \propto G\, g^4\, M^2 \left(\frac{\nu}{\Lambda}\right)^n$$

Higgs vacuum expectation

energy scale of BSM

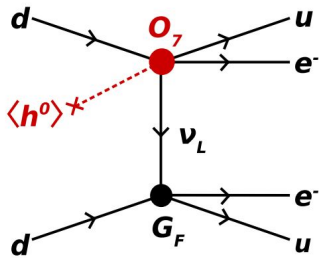
Dim 5: Weinberg Operator

$$\frac{1}{T_{1/2}} \propto \left(\frac{v}{\lambda}\right)^2 \quad \text{with} \quad \frac{\nu}{\Lambda} \propto \frac{m_{\beta\beta}}{m_e}$$



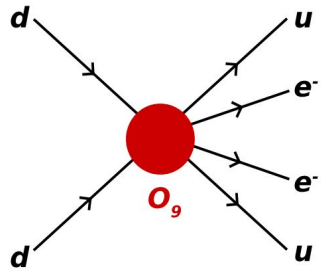
Dim 7

$$\frac{1}{T_{1/2}} \propto \left(\frac{v}{\Lambda}\right)^6$$



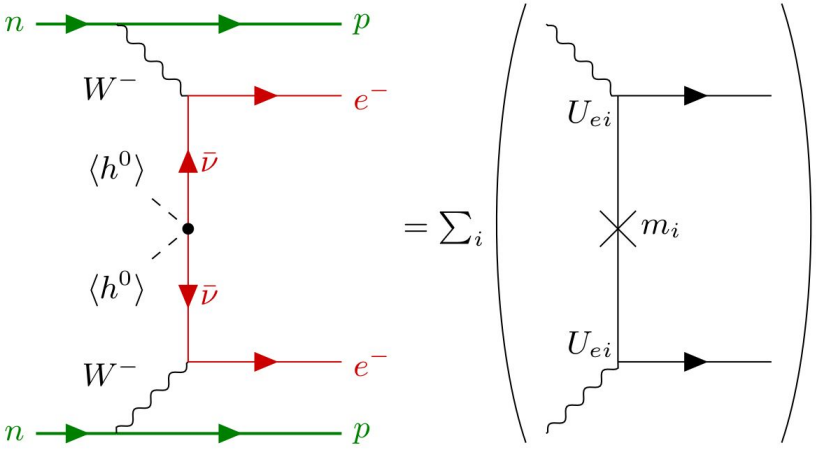
Dim 9

$$\frac{1}{T_{1/2}} \propto \left(\frac{v}{\Lambda}\right)^{10}$$



See for instance Deppisch, Graf, Iachello and Kotila, PRD 102 9, 095016 (2020) and Cirigliano et al., JHEP 12, 097 (2018)

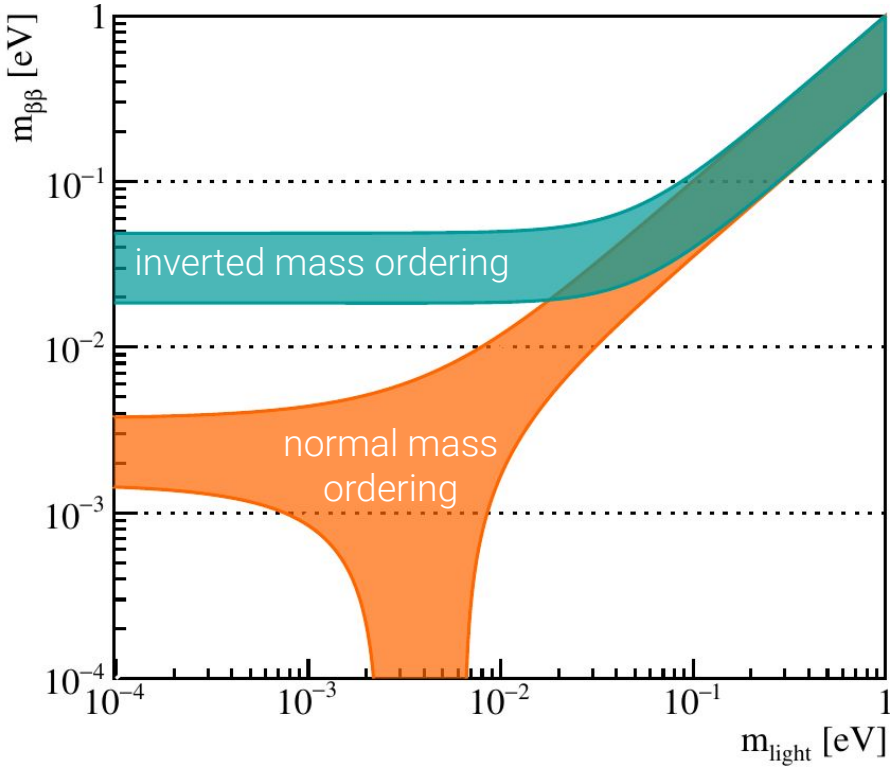
Weinberg operator: light neutrino exchange



$$= \sum_i \left(U_{ei} \times m_i \times U_{ei} \right)$$

$$\frac{1}{T_{1/2}} \propto (m_{\beta\beta})^2 = \left| \sum_i U_{ei}^2 m_i \right|^2$$

Effective Majorana mass



A portal to new physics beyond the SM

$$\frac{1}{T_{1/2}} \propto G\, g^4\, M^2 \left(\frac{\nu}{\Lambda}\right)^n$$

phase space factor

hadronic matrix element

nuclear matrix element (NME)

Can be computed accurately

(even if sometimes ***g*** is used to incorporate biases in NME calculations)

Requires calculations of :

- wavefunction overlap between initial and final states
- lepton-nucleus interaction

Nuclear Matrix Elements (NMEs)

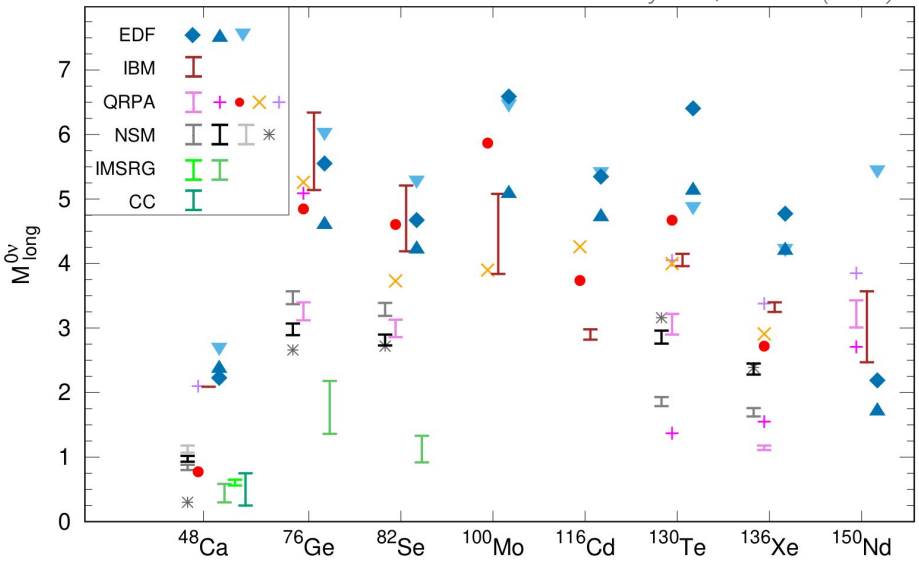
Historically

- large disagreements (factor of ~3)
- limited computation ability
- uncertainties rarely characterized
- concerns about “quenching” (missing contributions)

In the last few years

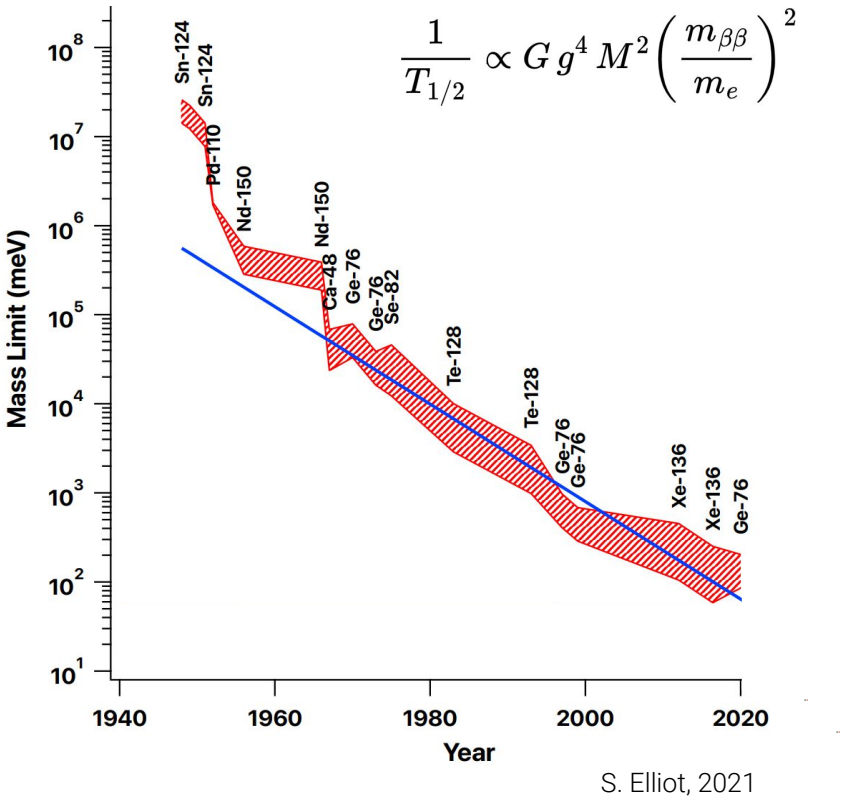
- quenching “solved” for β decay in light nuclei
  - first 0νββ estimates: O(30%) reduction
- identified a new contribution (“contact term”)
  - first estimates: O(30%) increase
- higher fidelity calculations, uncertainty exploration

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

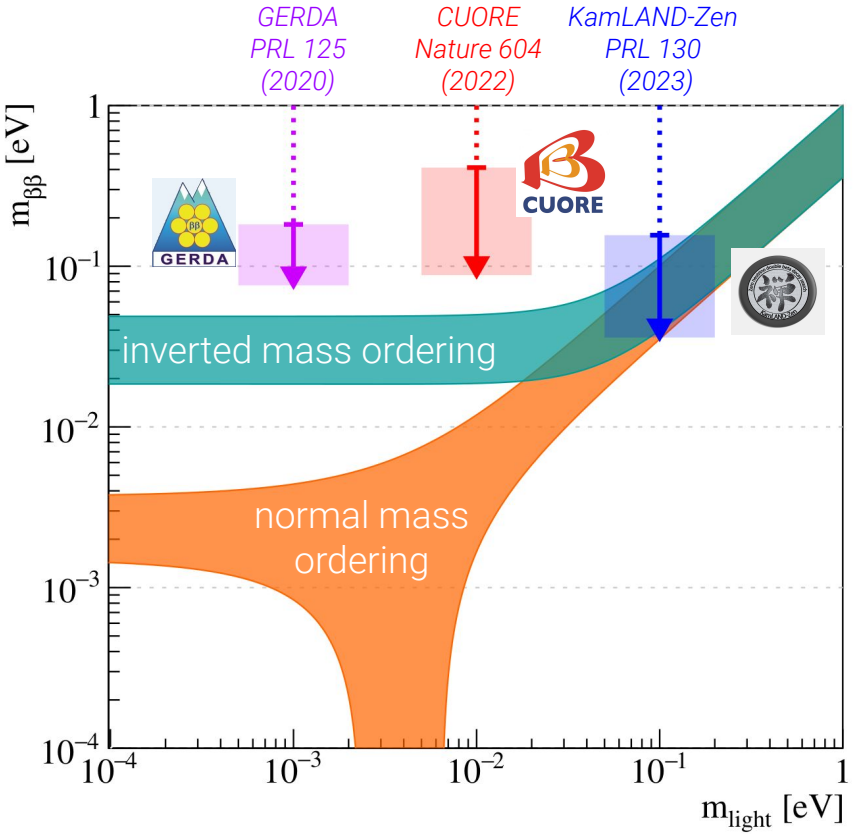


Gysbers et al., Nature Phys. 15 (2019)
Belley et al., PRL 126 (2021)
Cirigliano et al., PRL 120, (2018)
Jokiniemi et al., PLB 823, (2021)
Belley et al., arxiv:2308.15634

Strongest experimental constraints

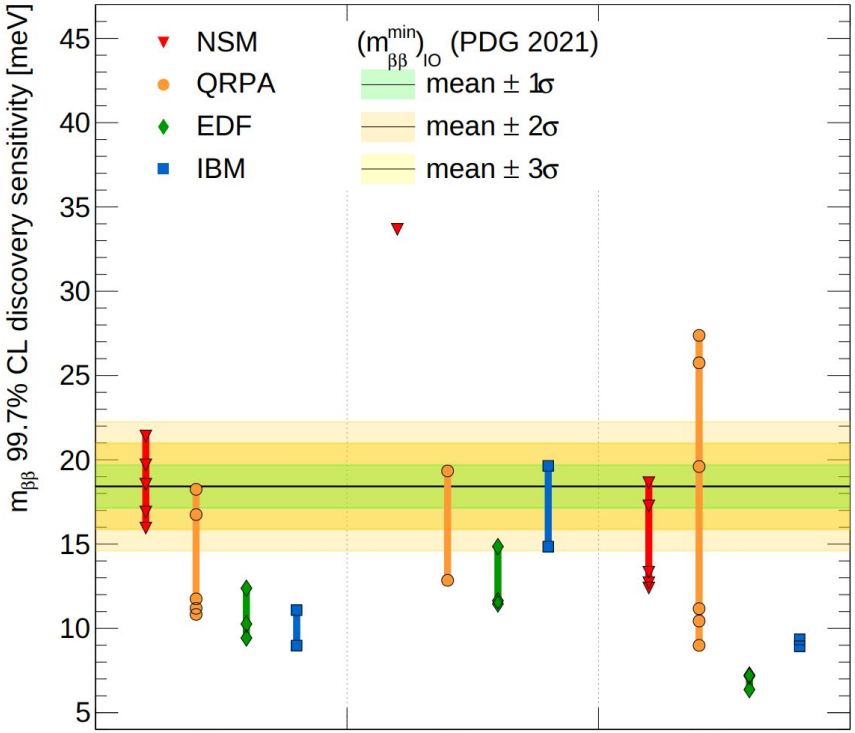


S. Elliot, 2021



Closing up on the inverted ordering

- last decade R&D set ground for “ton-scale” experiments
- DOE’s **portfolio review** finally ran in Summer 2021
  - outcome presented at the FSNN Town Meeting in preparation for NSAC Long Range Plan
  - CUPID, LEGEND, nEXO design “ready to go”
  - strong interest to implement multiple projects (with DOE prioritising LEGEND-1000 if needed)
- international coordination
  - North American-European $0\nu\beta\beta$ Summit (LNGS, Sep 21, organised by APPEC/INFN/DOE)
  - 2nd International Summit on the Future of $0\nu\beta\beta$ Decay (SNOLab, Apr 23)
- established a **funding agency working group** to explore how such an international effort could be coordinated

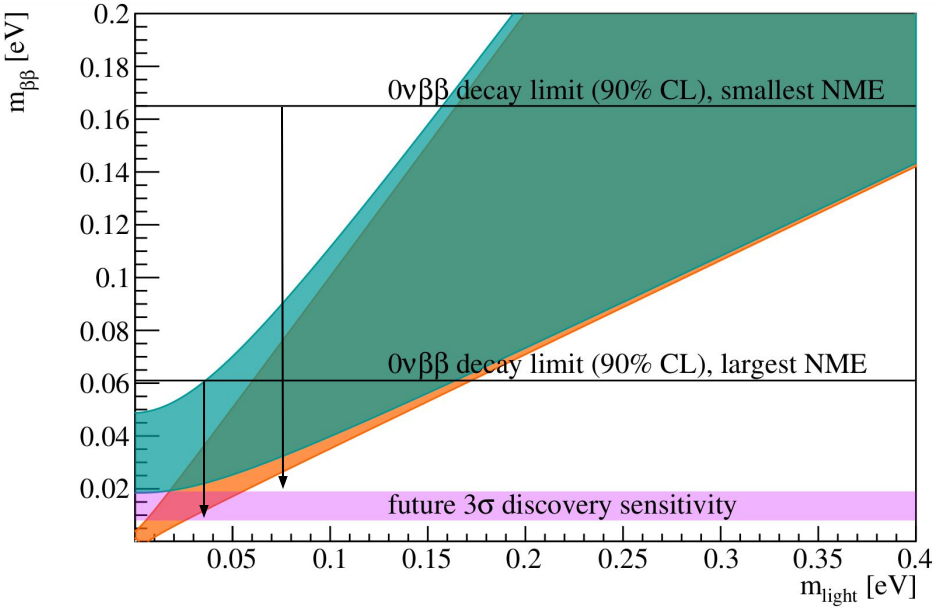


MA, Benato, Detwiler, Menéndez and Vissani, PRC 104, L042501

What about normal ordering?

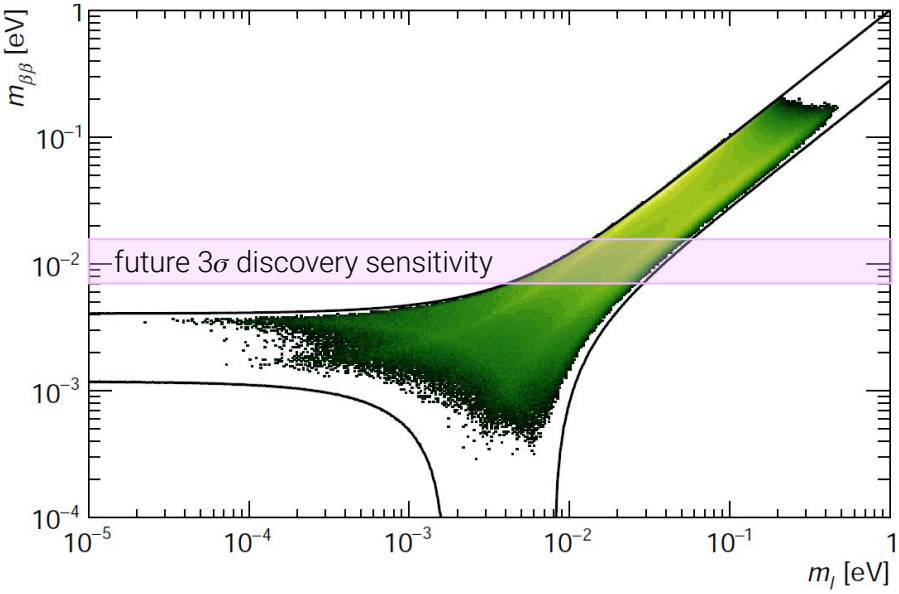
Normal and inverted ordering overlap

Next-gen experiments will also explore normal ordering



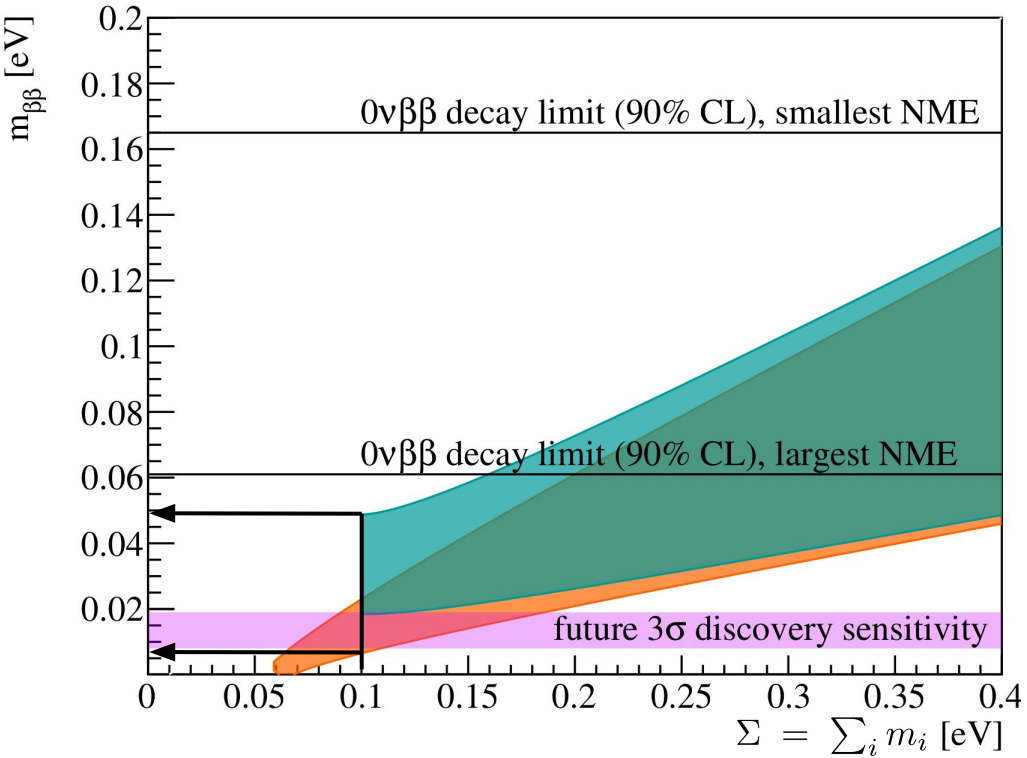
Not equiprobable parameter space

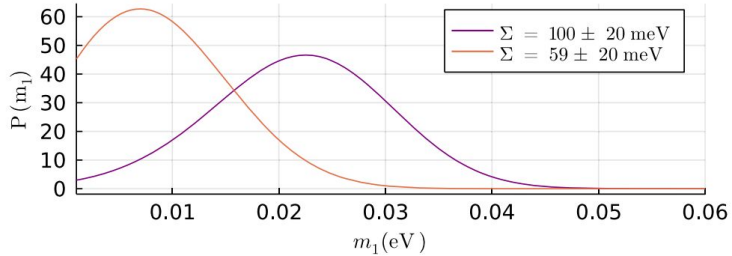
Random phases would naturally favor large $m_{\beta\beta}$ values

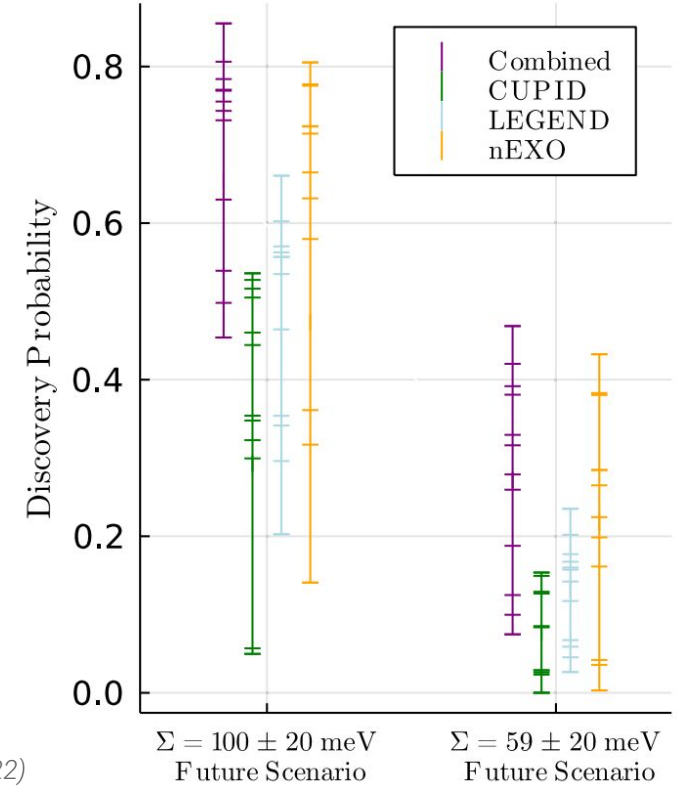


MA, Benato and Detwiler, PRD 96, 053001 (2017)

Interplay with cosmology





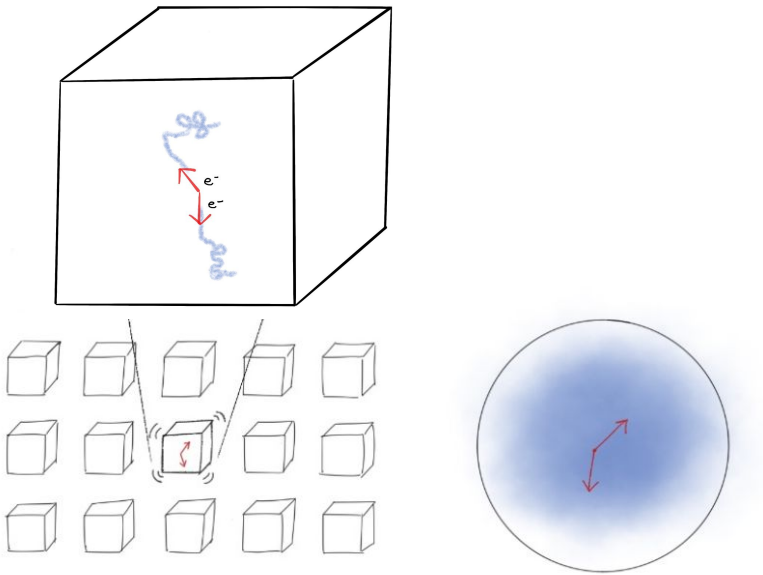


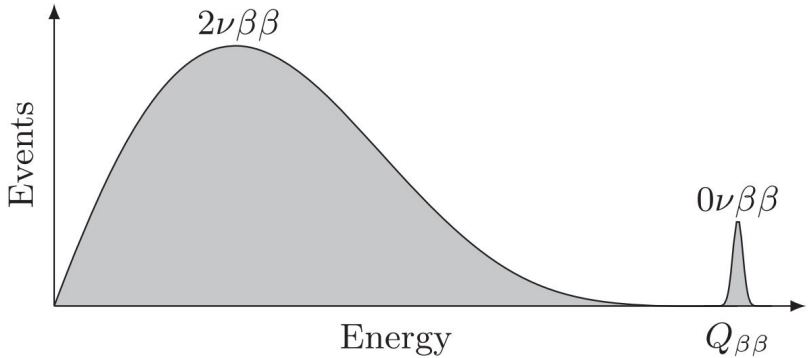
Ettengruber, MA, Caldwell, Eller and Schulz, PRD 106, 073004 (2022)

The experimental landscape

Calorimetric approach: source = detector

- solid state: pixelated detector
- liquid: monolithic self-shielding volume

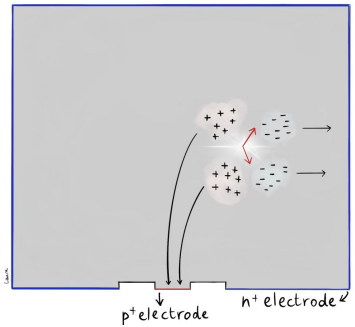




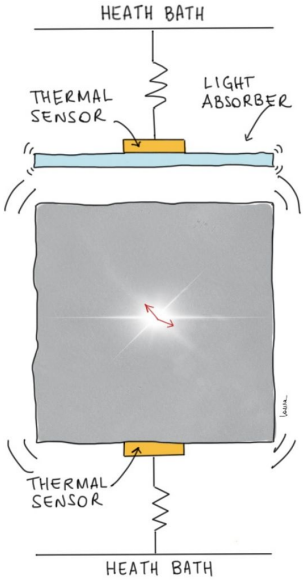
Experimental signature

- 2 electron final state
- **electron summed energy = Q-value**
- (daughter isotope)

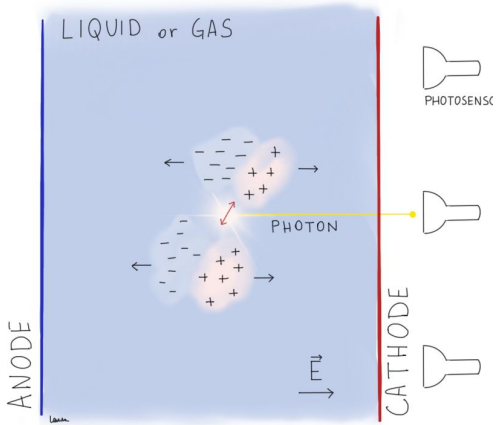
The most sensitive technologies



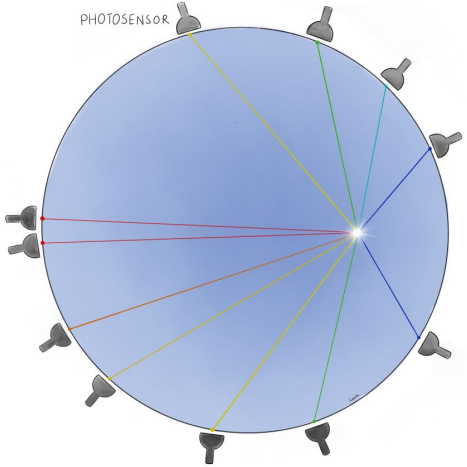
Ge Semiconductor detectors (^{76}Ge)



Cryogenic Calorimeters (^{100}Mo, ^{130}Te)

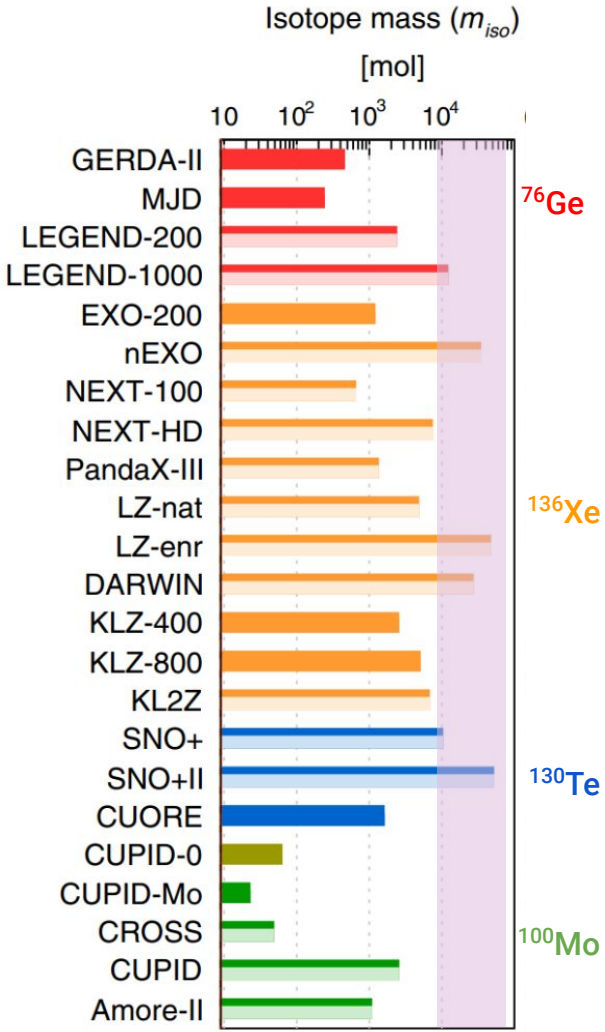


Xe Time Projection Chambers (^{136}Xe)



Large Liquid scintillator detectors (^{130}Te, ^{136}Xe)

MA, Benato, Detwiler, Menéndez, Vissani, RMP 95, 025002 (2023) - Images courtesy of Laura Manenti

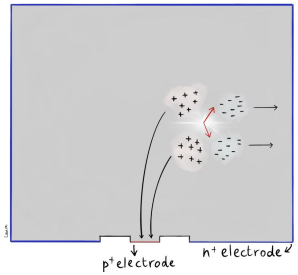


MA, Benato, Detwiler, Menéndez, Vissani, Rev. Mod. Phys. 95, 025002 (2023)

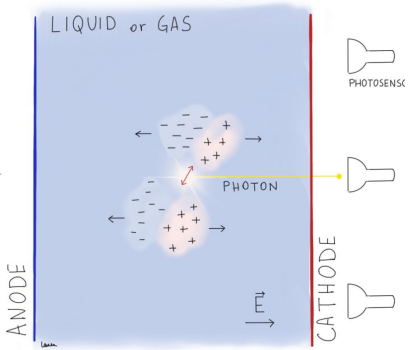
current / recent

in construction / proposed

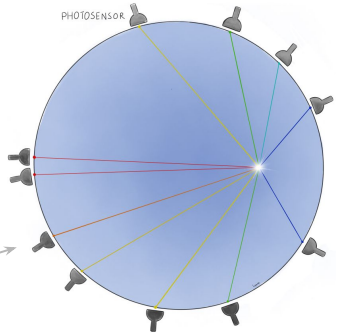
semiconductor detectors



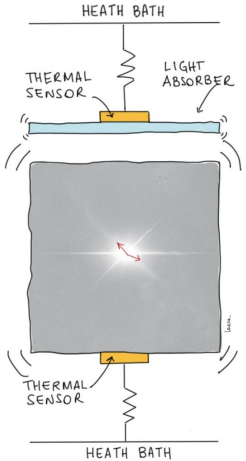
gas/liquid TPCs

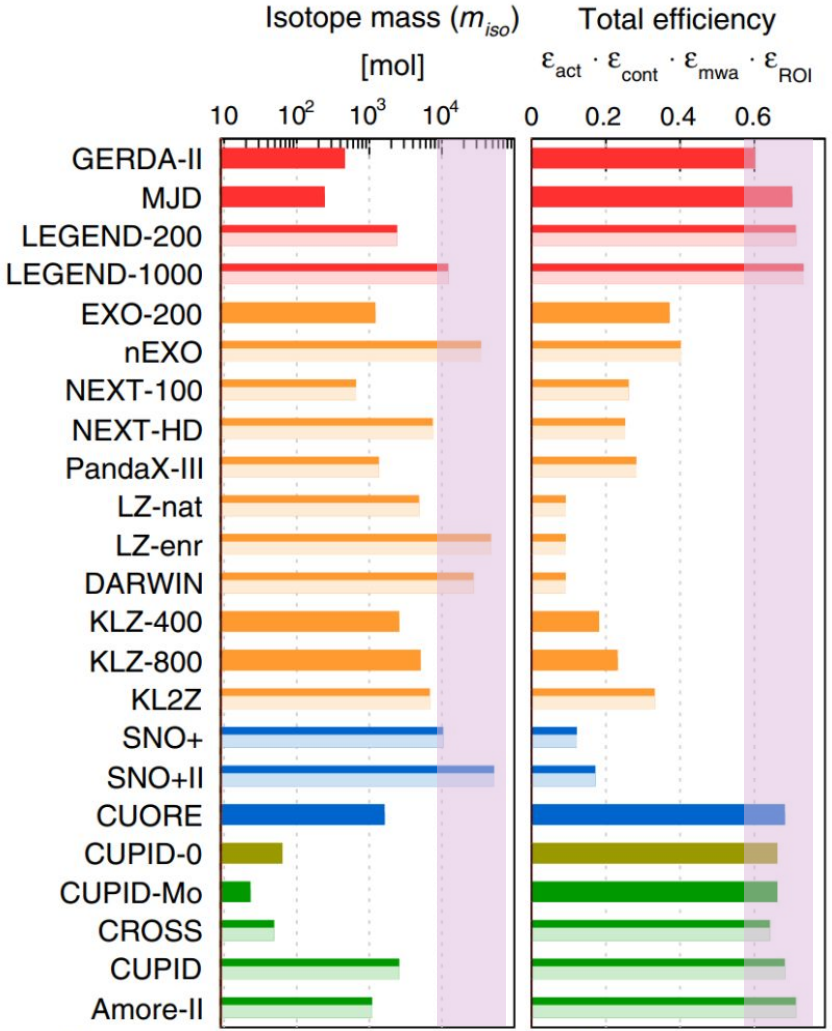


liquid scintillators



cryogenic calorimeters (bolometers)





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

current / recent
in construction / proposed

semiconductor detectors

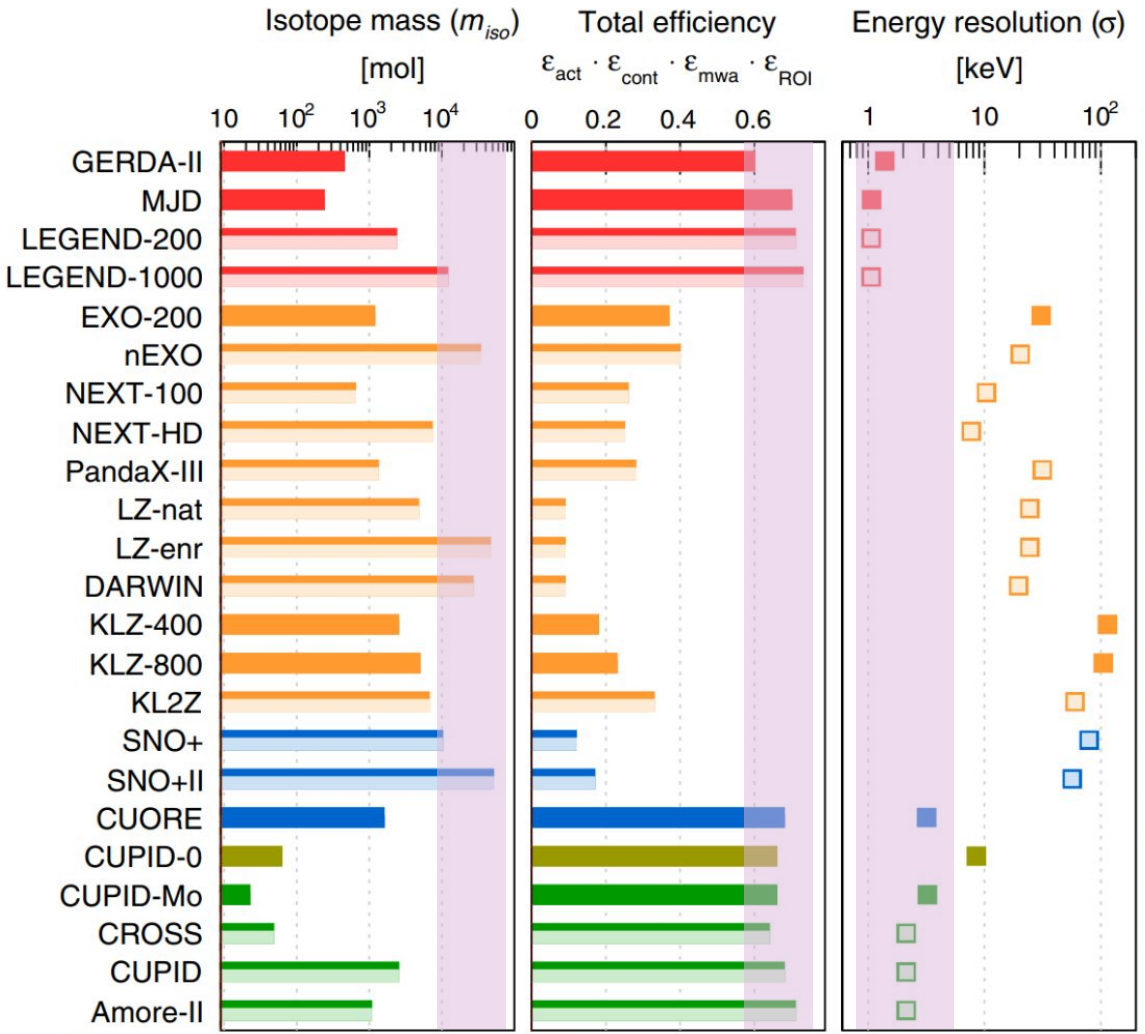
gas/liquid TPCs

liquid scintillators

cryogenic calorimeters (bolometers)

large mass and fidulaciation

less mass and high efficiency



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

current / recent
in construction / proposed

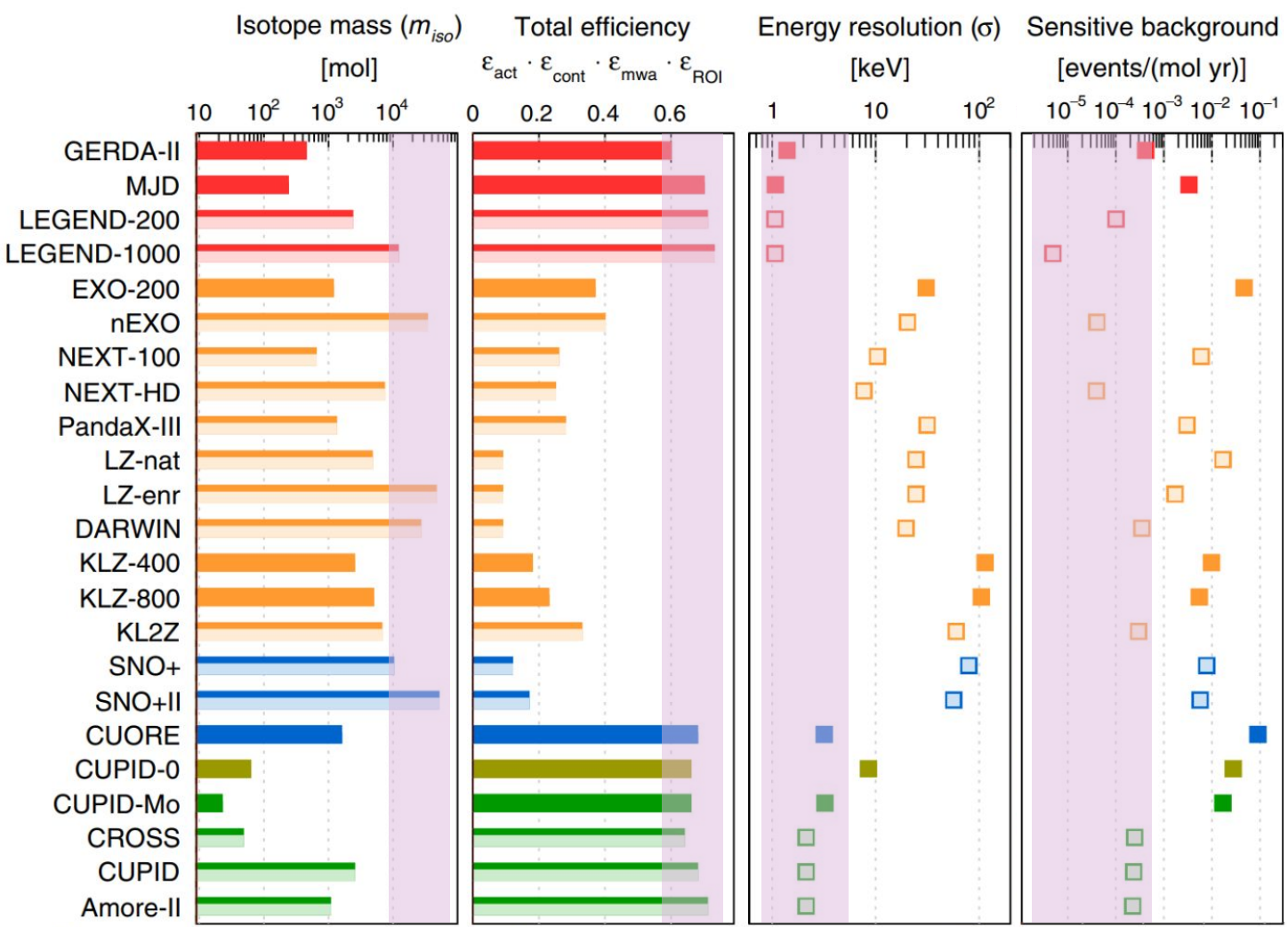
semiconductor detectors

gas/liquid TPCs

liquid scintillators

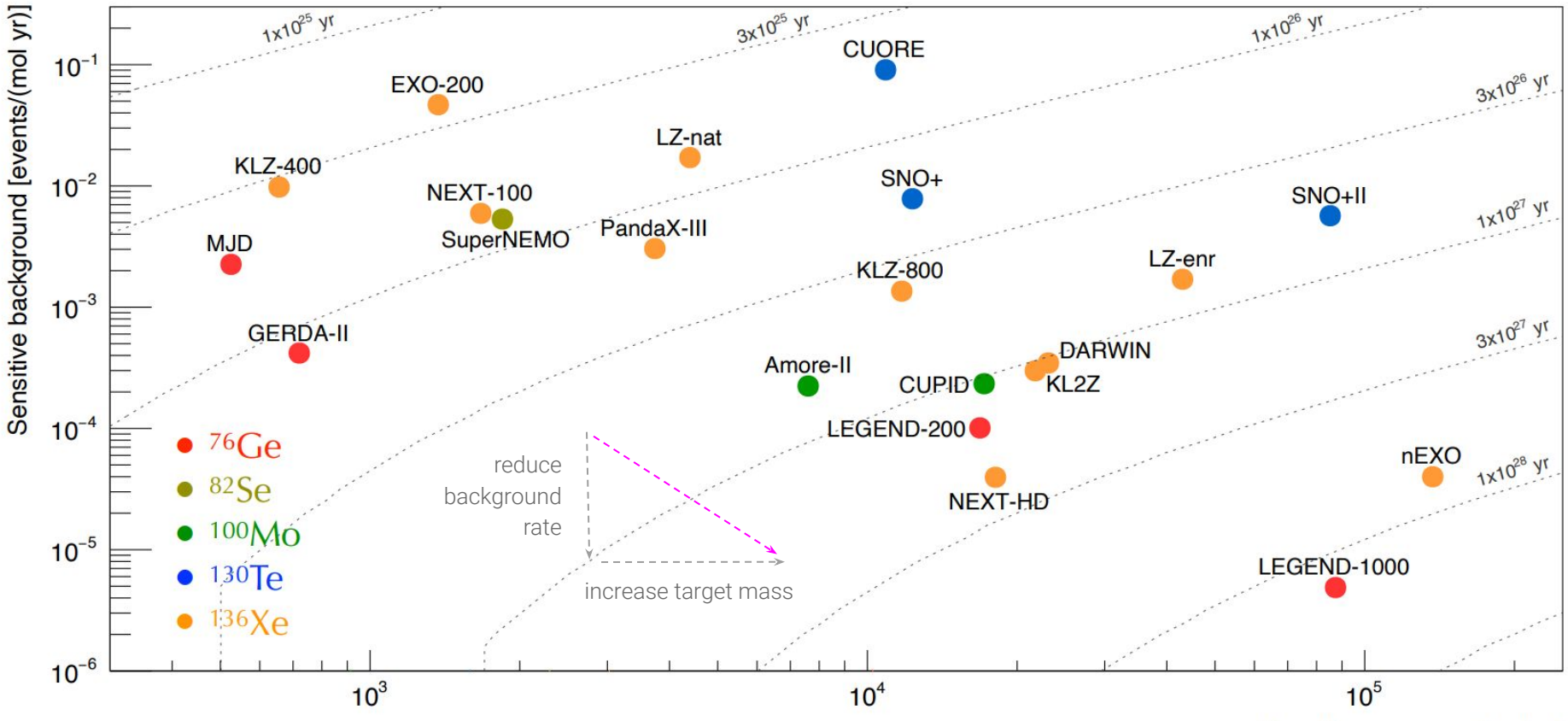
cryogenic calorimeters (bolometers)

solid state high energy resolution



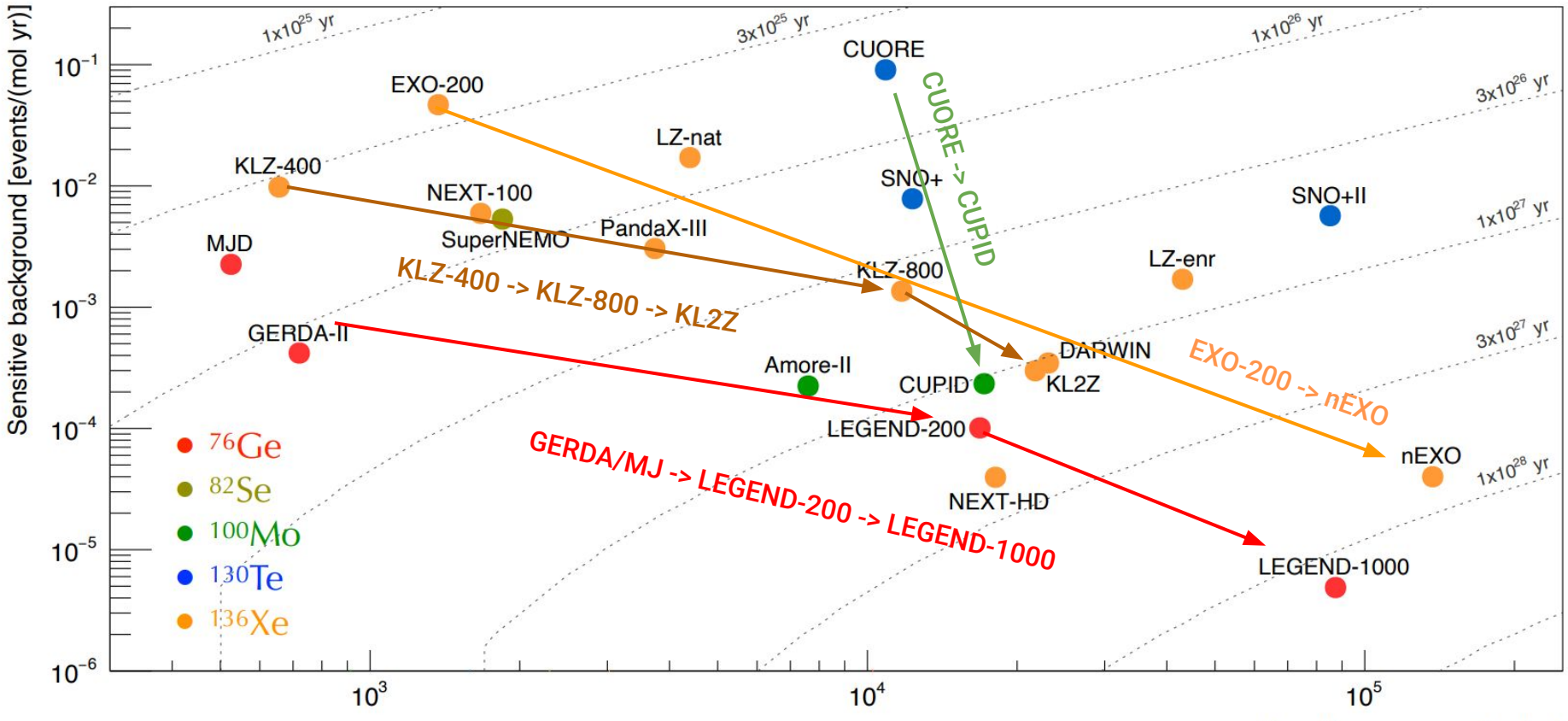
Background reduction essential for all rare-event searches

Discovery Sensitivities



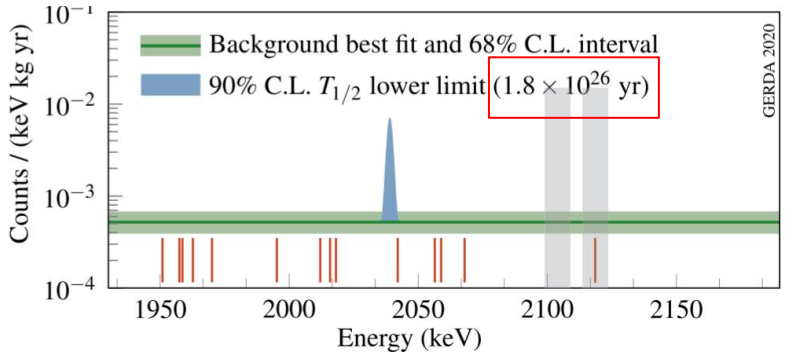
MA, Benato, Detwiler, Menéndez, Vissani, Rev. Mod. Phys. 95, 025002 (2023)

Discovery Sensitivities



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

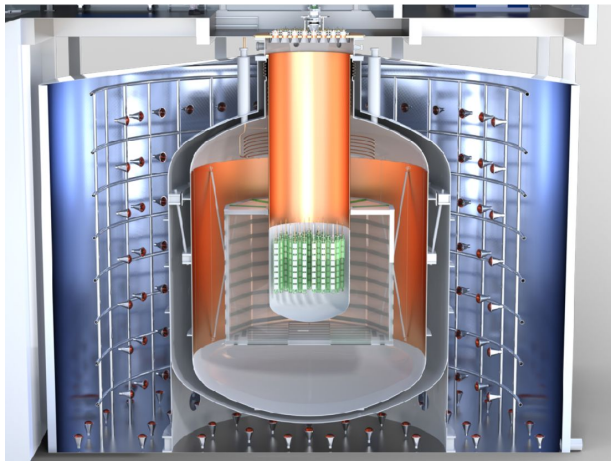
GERDA/MJ -> LEGEND

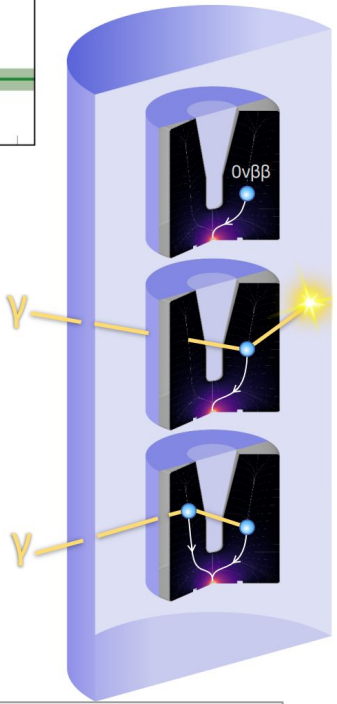


GERDA PRL 125 (2020)

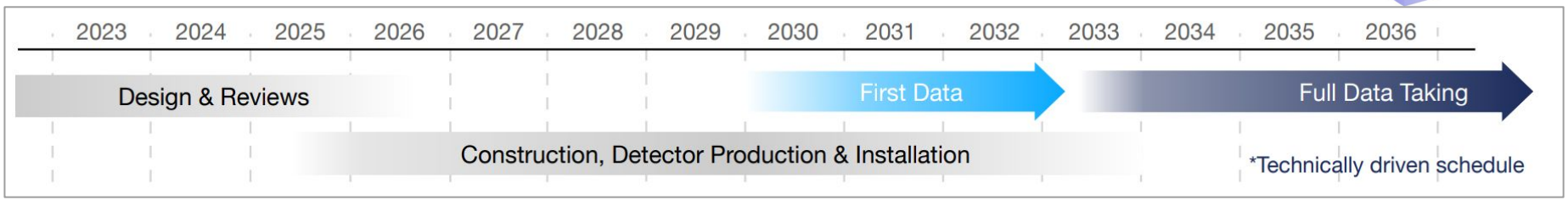
High-purity ^{76}Ge detectors in liquid Ar

- ionization and charge drift
- < 0.1% energy resolution
- Ar shield and scintillation light
- advanced event topology





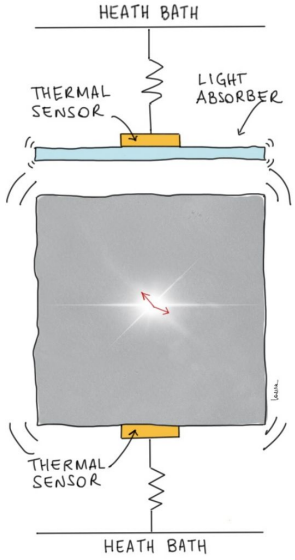
- **GERDA/MAJORANA** (40 kg), lowest background
- **LEGEND-200** (200 kg) in data taking since 2023, good performance and background released at TAUP
- **LEGEND-1000** (1 t) preparing for DOE reviews this and next year, baseline design at LNGS

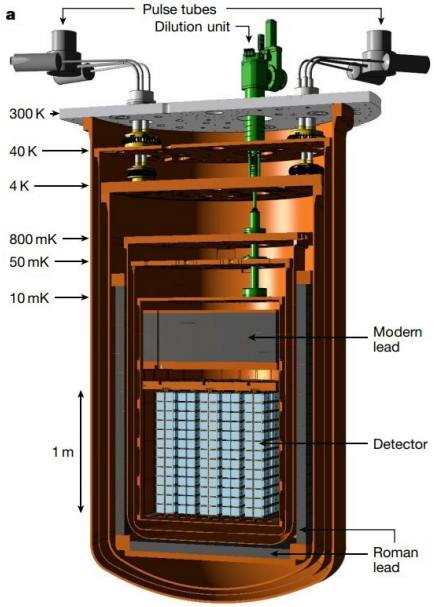


CUORE -> CUPID

Cryogenic calorimeters (bolometers)

- temperature variation and scintillation light
- particle identification and good resolution
- array of enriched crystals operated at ~10 mK



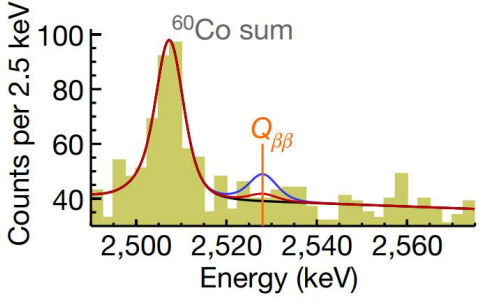


CUORE

- 742 kg TeO_2 (206 kg ^{130}Te), 988 crystals
- 2 tonne years of exposure, still running at LNGS
- new result presented at TAUP

CUORE, Nature 604 (2022)

$$T_{1/2}^{0\nu} > 2.2 \cdot 10^{25} \text{ yr}$$



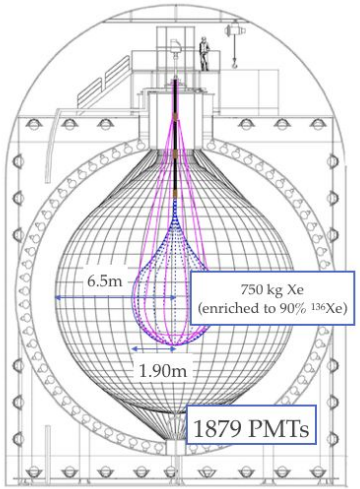
CUPID

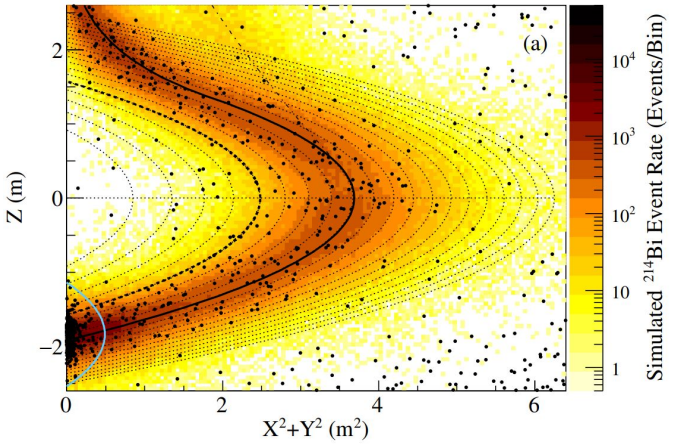
- reusing CUORE existing infrastructure
- scintillating bolometer Li_2MoO_4 technology demonstrated by CUPID-Mo
- particle identification

KamLAND-Zen

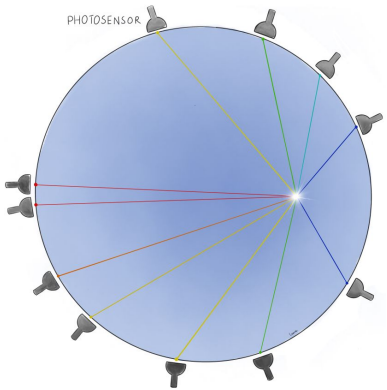
Scintillator loaded with target isotope:

- scintillation photons detected by PMTs
- photon number and arrival time gives event energy and position
- self-shielding and fiducialization





$$T^{0\nu}_{1/2} > 2.3 \times 10^{26}\ \text{yr at 90\% C.L.}$$

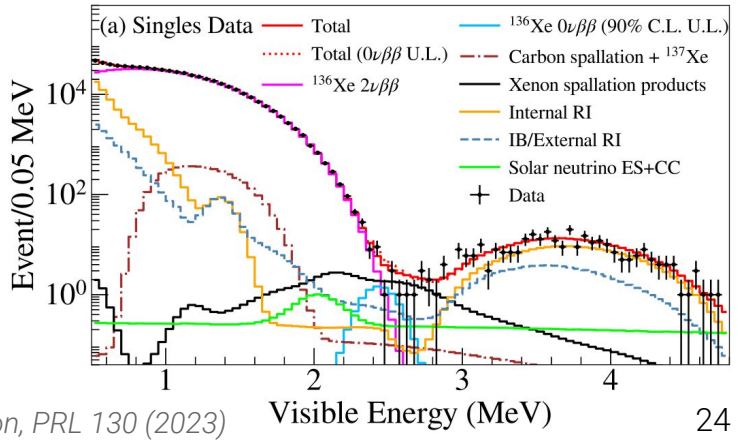


KamLAND-Zen-800

- 750 kg of ^{136}Xe in nylon balloon
- backgrounds: $2\nu\beta\beta$, cosmogenic, solar neutrinos, ^{214}Bi on balloon
- running in Kamioka

KamLAND2-Zen

- new light concentrators and PMTs with higher quantum efficiency
- purer scintillator

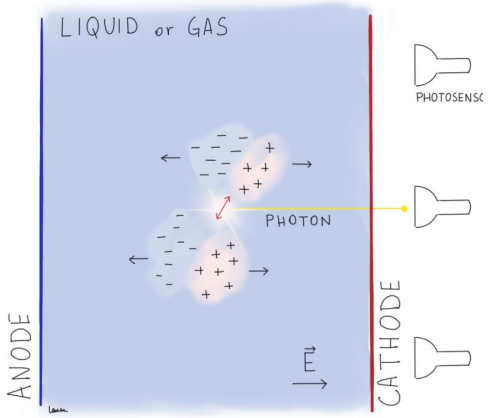


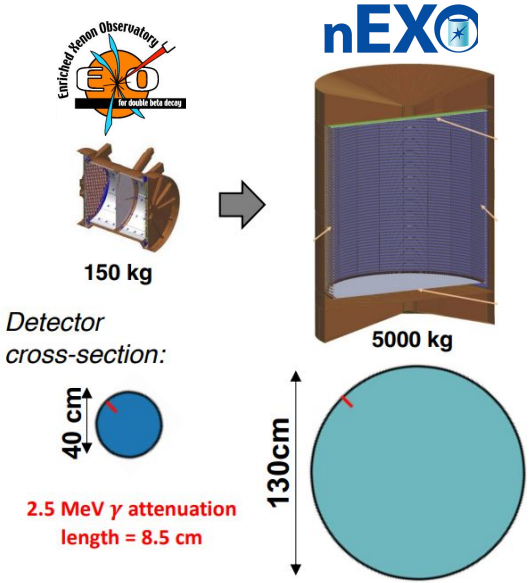
KZ collaboration, PRL 130 (2023)

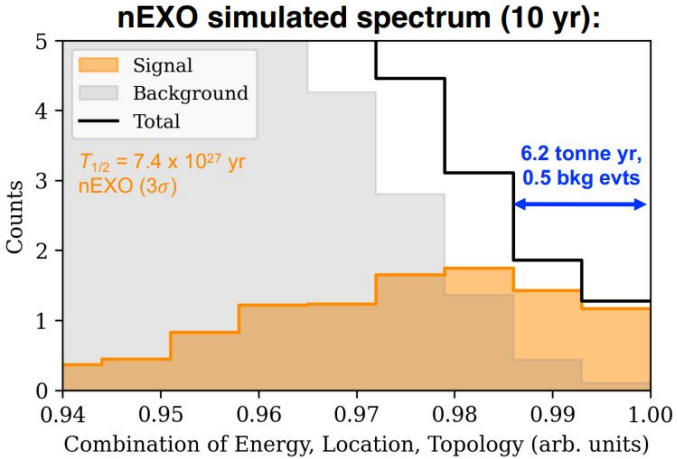
EXO-200 -> nEXO

Time projection chamber

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







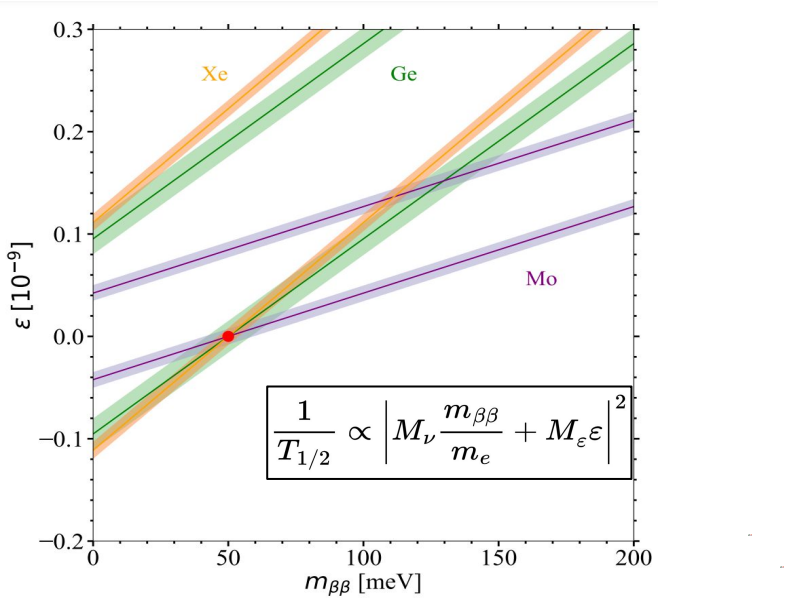
nEXO@SNOLAB

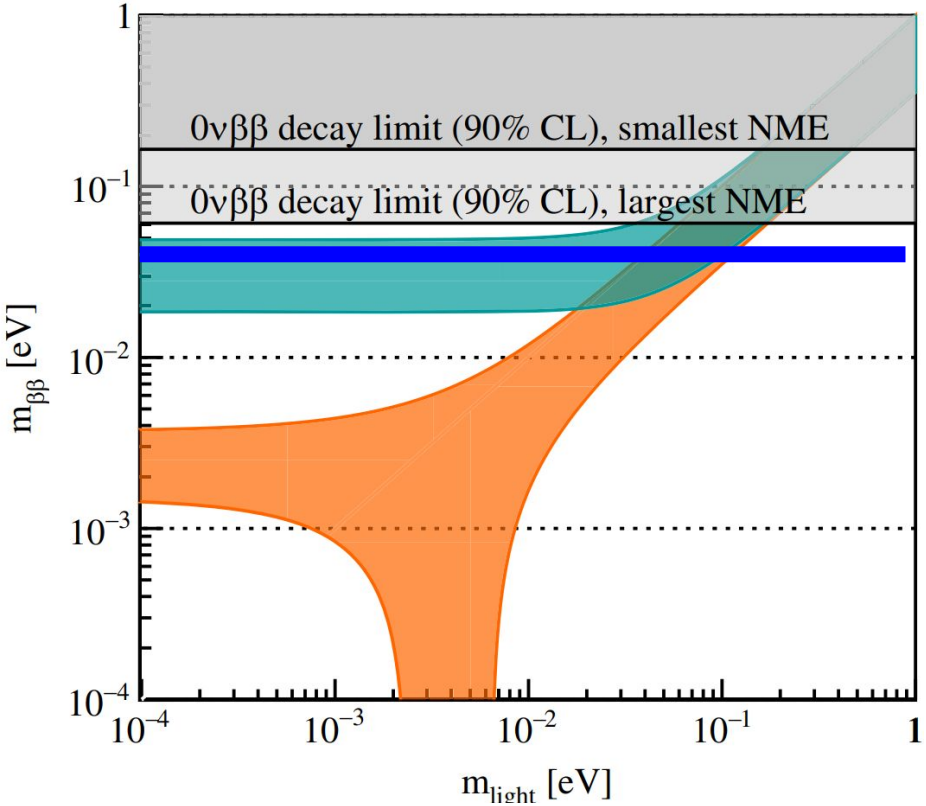
- builds on the EXO-200 experiment (completed in 2019)
- homogeneous, liquid enrXe time projection chamber scaled to 5 tonne total mass
- dominant external backgrounds exponentially attenuated in central region
- preparing for DOE review next year

Where are we heading?

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

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





MA, Deppisch, Van Goffrier, JHEP 02 (2023)
Lisi, Marrone, Nath, PRD 108 (2023)

Where are we heading?

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

- O(10%) statistical uncertainty << NME uncertainties
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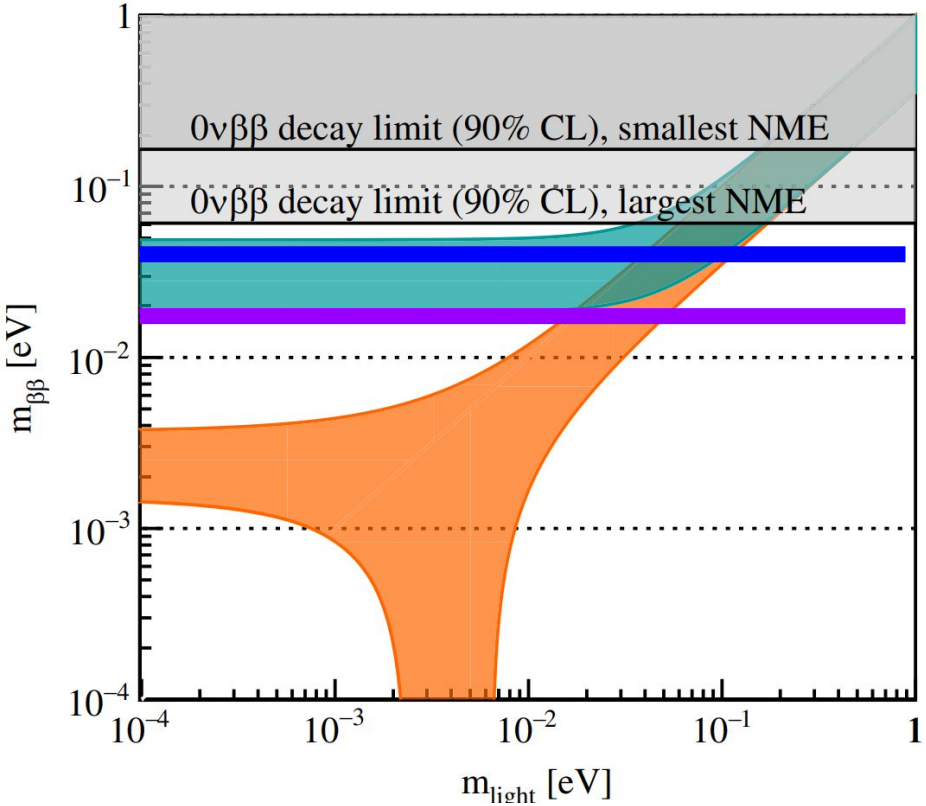
$T_{1/2}$ ~ 10^{28} years: ~10 events in ton-scale experiments

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



Where are we heading?

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

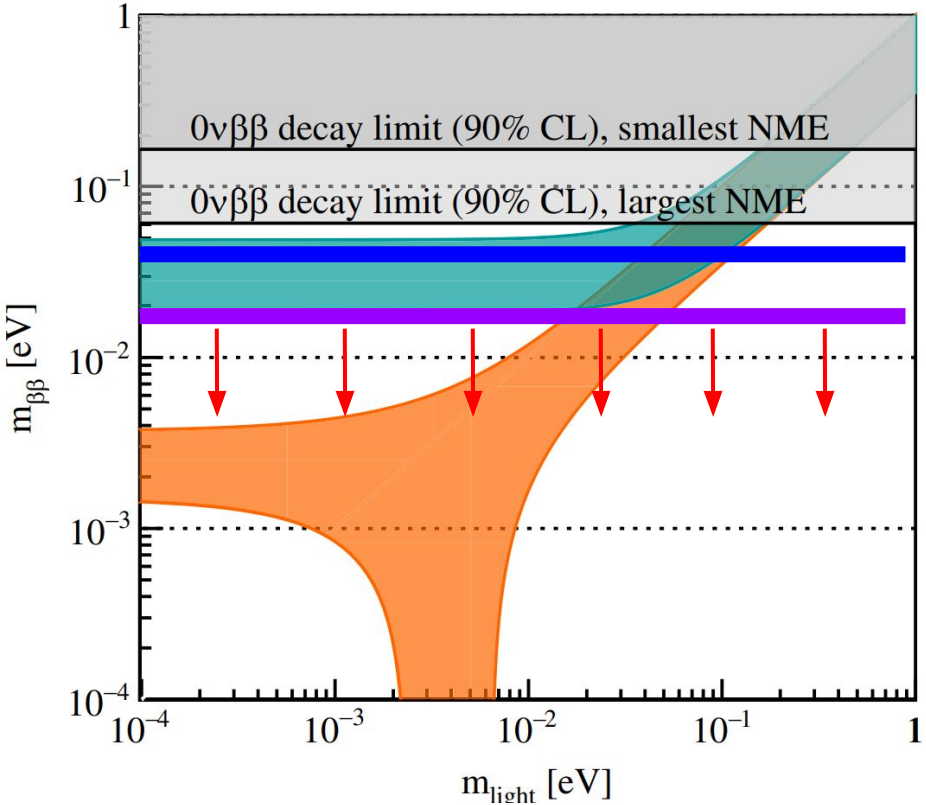
- O(10%) statistical uncertainty << NME uncertainties
- can probe decay mechanism

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

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

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

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



Conclusions

Vibrant field

- decades of R&D set the ground for **ton-scale experiments**
- **staging** and innovation essential for rare-event searches
- significant progress in **nuclear theory for precise NME**

Observing $0\nu\beta\beta$ decay would be a **ground-breaking discovery**

- B-L violation -> **matter-antimatter asymmetry**
- Majorana neutrinos -> **theory of fermion masses**

$0\nu\beta\beta$-decay experiments are **open searches for new physics**

- **inverted-ordered** neutrinos -> discovery guaranteed
- **normal-ordered** neutrinos -> still exciting discovery prospect
- other **L-violating physics** -> discovery could come any time

Wednesday 25th

Latest Results from the CUORE experiment	*Alberto Ressa*
Palazzo Franchetti, Istituto Veneto di Scienze, Lettere e Arti	11:30 - 11:50
The CUPID double beta decay experiment	*Fabio Bellini*
Palazzo Franchetti, Istituto Veneto di Scienze, Lettere e Arti	11:50 - 12:10
SNO+: Current results and 0νββ prospects	*Ana Sofia Inacio*
Palazzo Franchetti, Istituto Veneto di Scienze, Lettere e Arti	12:10 - 12:30
First Results of the LEGEND-200 experiment: Searching for Neutrinoless Double Beta Decay with High-Purity Germanium Detectors	
Valerio D'Andrea	
Probing New Physics Beyond the Neutrinoless Double-Beta Decay of Ge-76	*Ms Sofia Calgaro*
Palazzo Franchetti, Istituto Veneto di Scienze, Lettere e Arti	12:50 - 13:10
Unveiling the mysteries of neutrinoless double beta decay: exploring Nuclear Matrix Elements and their impact on Majorana mass sensitivities.	
Federica Pompa	

Thursday 26th

Cosmological limits on neutrino masses and species	*Olga Mena Requejo*
Palazzo Franchetti, Istituto Veneto di Scienze, Lettere ed Arti	15:30 - 16:00
BINGO proposals for background reduction in 0ν2β bolometric experiments	*Hawraa Khalife*
Palazzo Franchetti, Istituto Veneto di Scienze, Lettere ed Arti	16:55 - 17:15

Friday 27th

Towards a global analysis of absolute neutrino masses	*Eligio Lisi*
Palazzo Franchetti, Istituto Veneto di Scienze, Lettere ed Arti	09:00 - 09:30

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