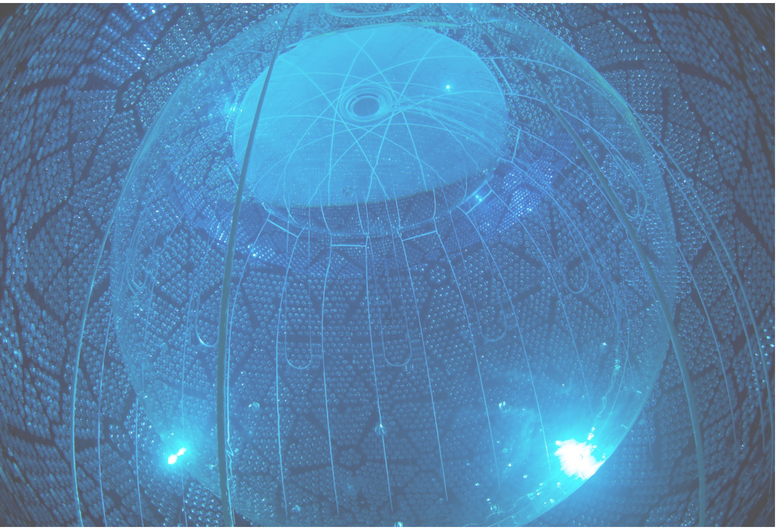


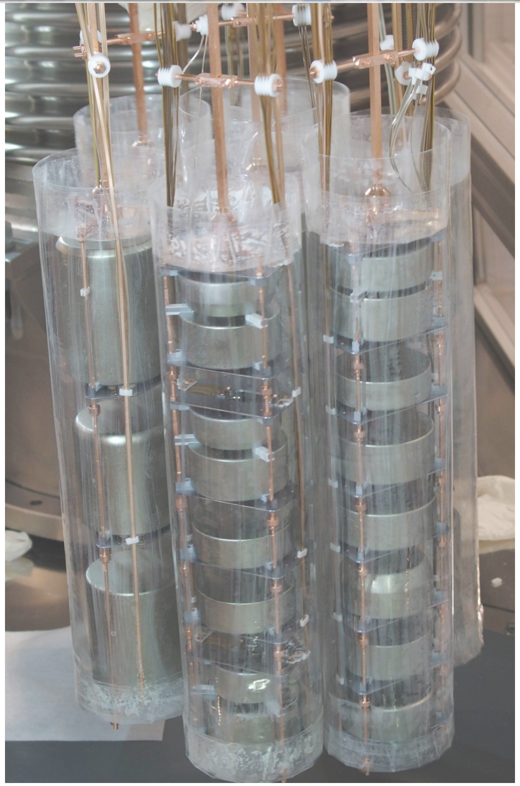
Search for Matter Creation with $0\nu\beta\beta$-decay

(experimental overview)

Ruben Saakyan (UCL)

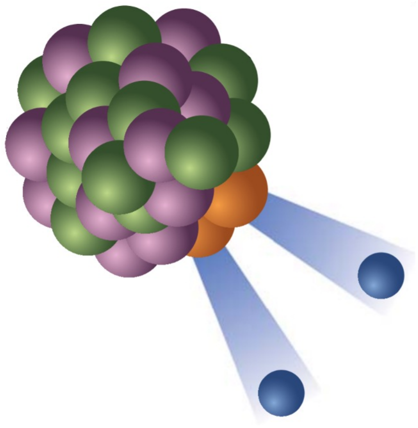
FIPs 2022

20-Oct-2022



Outline

- Introduction and Motivation
- $0\nu\beta\beta$ and neutrino physics, physics reach
- Experimental approaches
- Outlook and international landscape



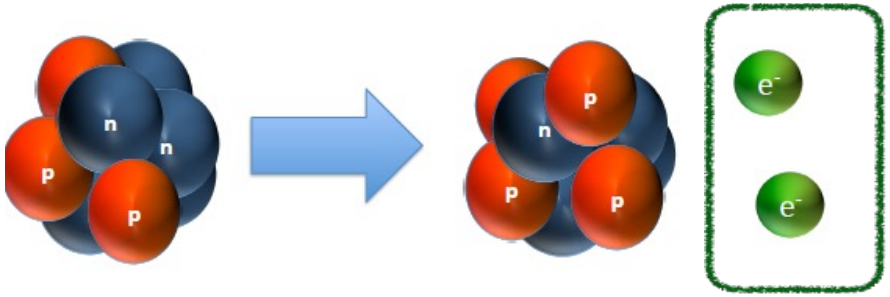
Disclaimer:

- Vibrant field: impossible to do justice to all projects
- Focus on giving an overview of most promising techniques and convey excitement about physics reach, with breakthroughs potentially around the corner

The Big Questions

Proton Decay:
"Disappearance" of nucleons

$B = N_{baryons} - N_{anti\text{-}baryons}$

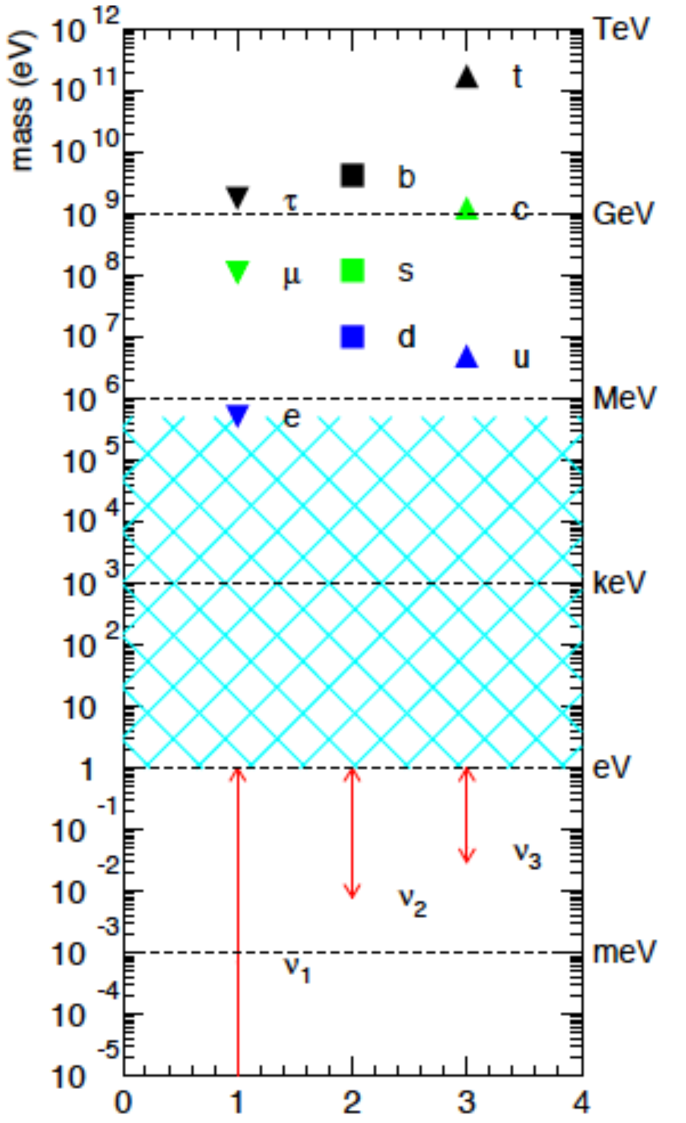


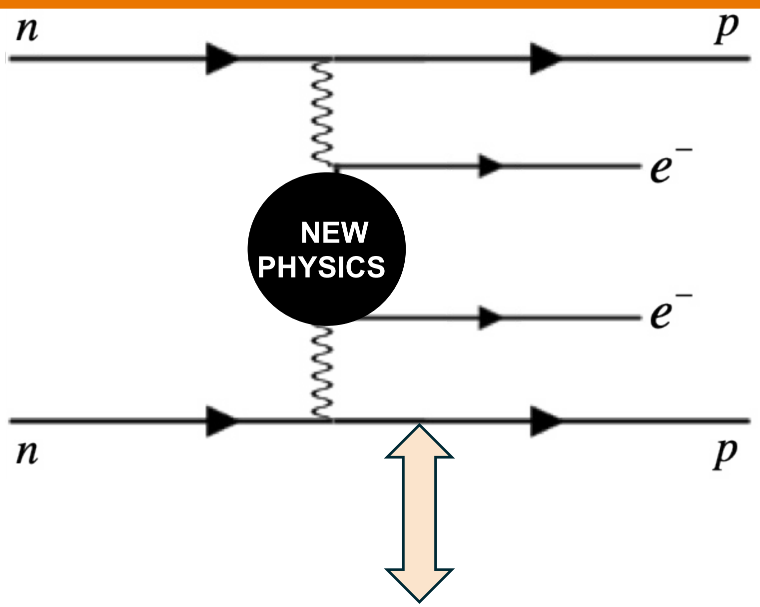
Neutrinoless Double Beta Decay ($0\nu\beta\beta$)
"Creation" of electrons

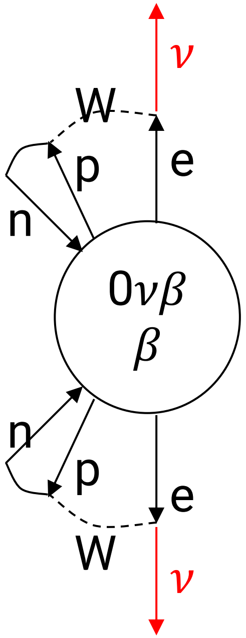
$L = N_{leptons} - N_{anti\text{-}leptons}$

L and B-L non-conservation

- Crucial for understanding ***dominance of matter*** over anti-matter
- Crucial for understanding mechanism behind ***ν-mass*** (***Majorana*** vs **Dirac**)
- 0νββ is the most sensitive way to address **L**epton **N**umber **V**iolation ***regardless*** of underlying mechanism







NME:
~~Nasty~~ Nuclear
Matrix
Element

phase space

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}(Q_{\beta\beta},Z)\left|M^{0\nu}\right|^2 \eta^2$$

LNV parameter

η can be due to $< m_{\beta\beta} >$, $V + A$, Majoron, SUSY, *H*⁻⁻, leptoquarks *<u>or a combination of them</u>*

Schechter and Valle, 1982:

Observation is <u>unambiguous evidence</u> for <u>non-zero Majorana mass</u> (even if it is not dominating mechanism)

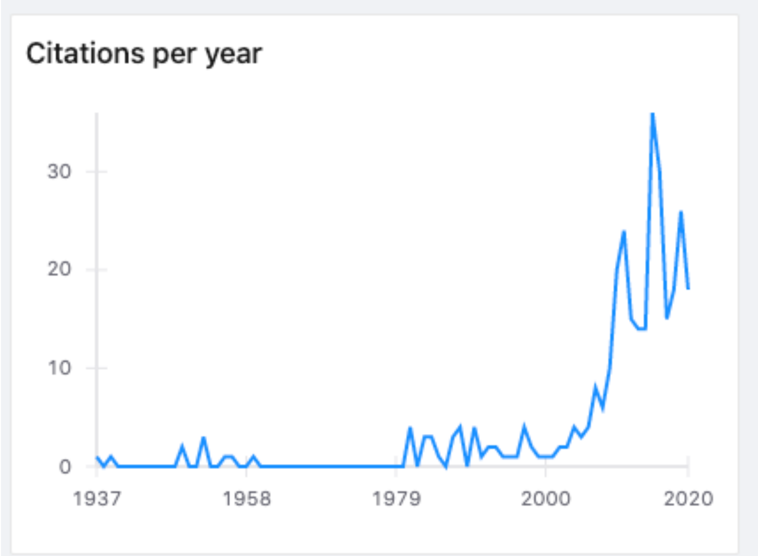
Double Beta Decay

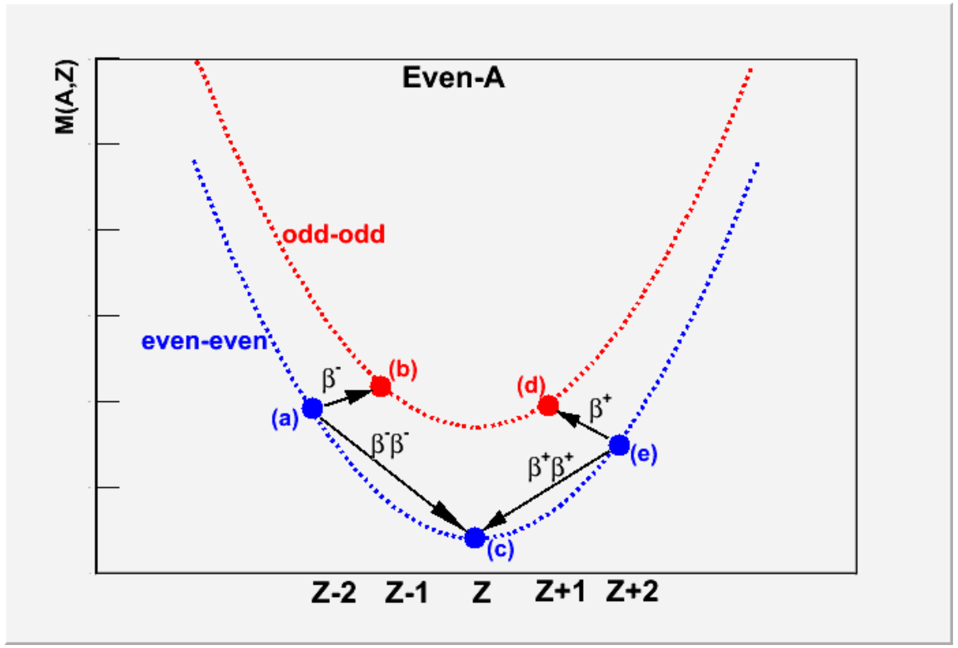
Abstract

From the Fermi theory of β-disintegration the probability of simultaneous emission of two electrons (and two neutrinos) has been calculated. The result is that this process occurs sufficiently rarely to allow a half-life of over 10^{17} years for a nucleus, even if its isobar of atomic number different by 2 were more stable by 20 times the electron mass.

M. Goepert-Mayer

Double beta-Disintegration, Phys.Rev. 48:512-16 (1935)





Over **40 nuclei** can undergo **ββ**-decay (including **β⁺β⁺** and **2K**-capture)

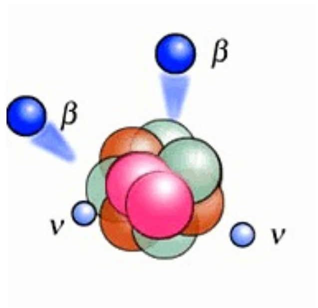
Only ~**9** experimentally **feasible for** $\boldsymbol{0\nu\beta\beta}$

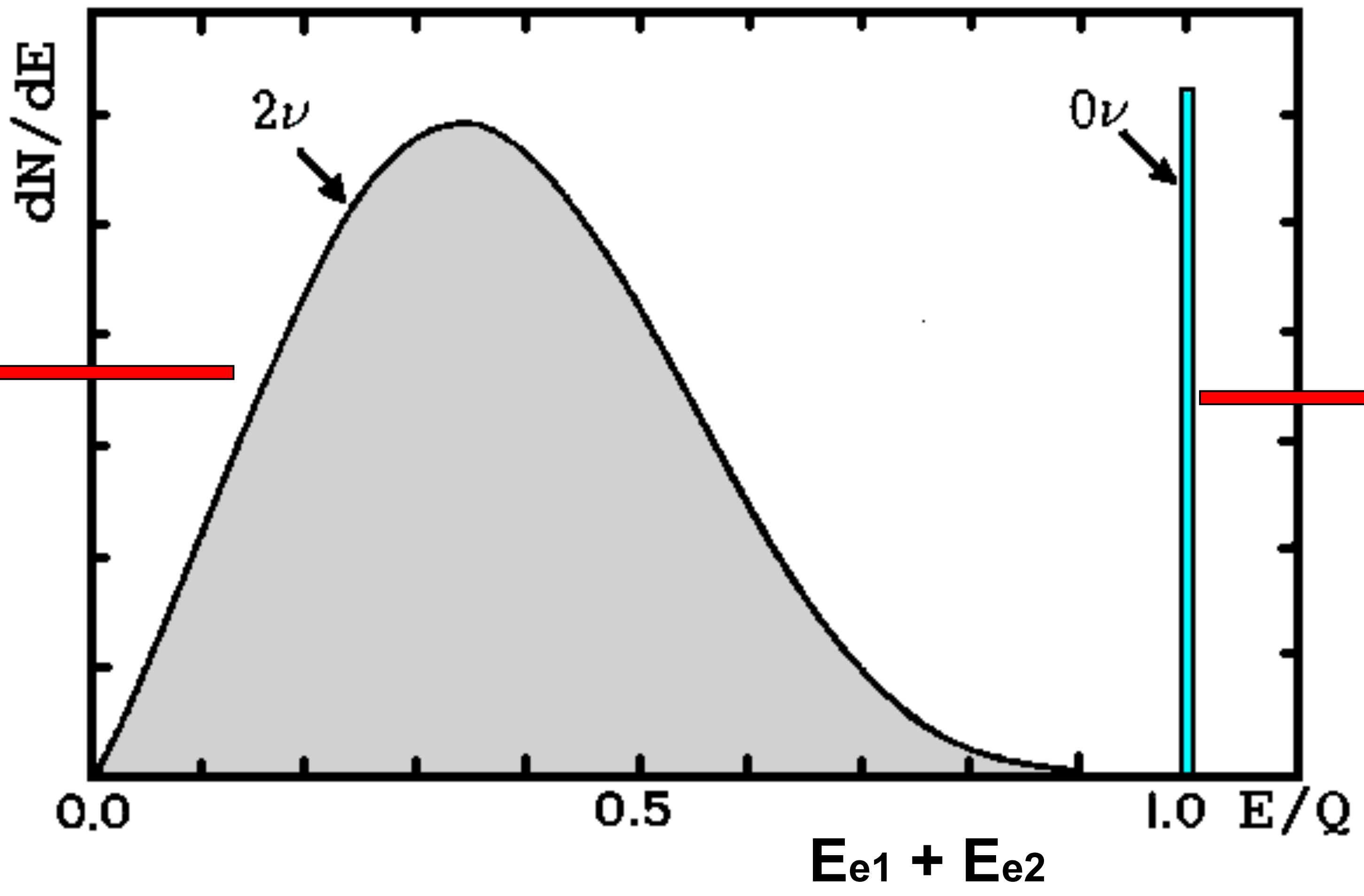
Isotope	Daughter	$Q_{\beta\beta}$ [a] [keV]	f_{nat} [b] [%]	f_{enr} [c] [%]
^{48}Ca	^{48}Ti	4 267.98(32)	0.187(21)	16
^{76}Ge	^{76}Se	2 039.061(7)	7.75(12)	92
^{82}Se	^{82}Kr	2 997.9(3)	8.82(15)	96.3
^{96}Zr	^{96}Mo	3 356.097(86)	2.80(2)	86
^{100}Mo	^{100}Ru	3 034.40(17)	9.744(65)	99.5
^{116}Cd	^{116}Sn	2 813.50(13)	7.512(54)	82
^{130}Te	^{130}Xe	2 527.518(13)	34.08(62)	92
^{136}Xe	^{136}Ba	2 457.83(37)	8.857(72)	90
^{150}Nd	^{150}Sm	3 371.38(20)	5.638(28)	91

Experimental Observables

$\Gamma^{2\nu} \propto G_F^4$

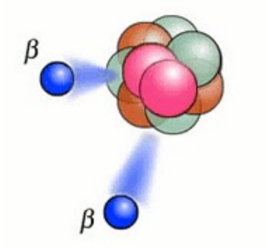
$T_{1/2} \sim 10^{19} - 10^{24}$ yr!





$\Gamma^{0\nu} \propto G_F^4 \cdot \eta_{LNV}^2$

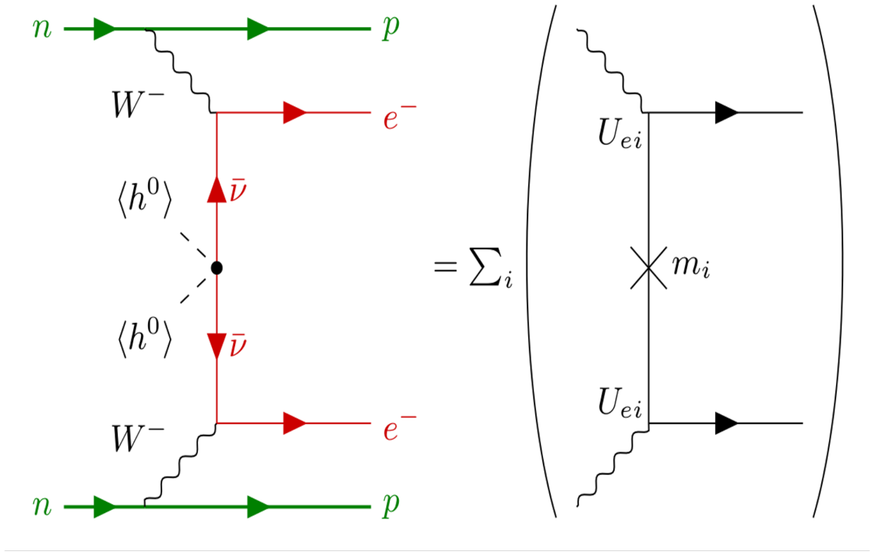
$T_{1/2} > 10^{26}$ yr!



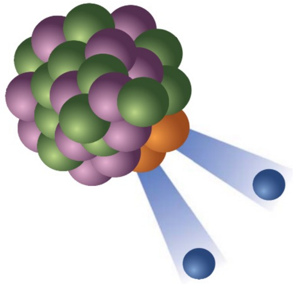
$2\nu\beta\beta(EC/\beta^+)$ has been detected in 13 nuclei!

If possible: individual electron energies, E_{e1}, E_{e2}, and angle θ between them

0νββ: Light Majorana neutrino mass, $m_{\beta\beta}$



$$P \propto \frac{1}{T_{1/2}} \propto G\, g^4\, M^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$



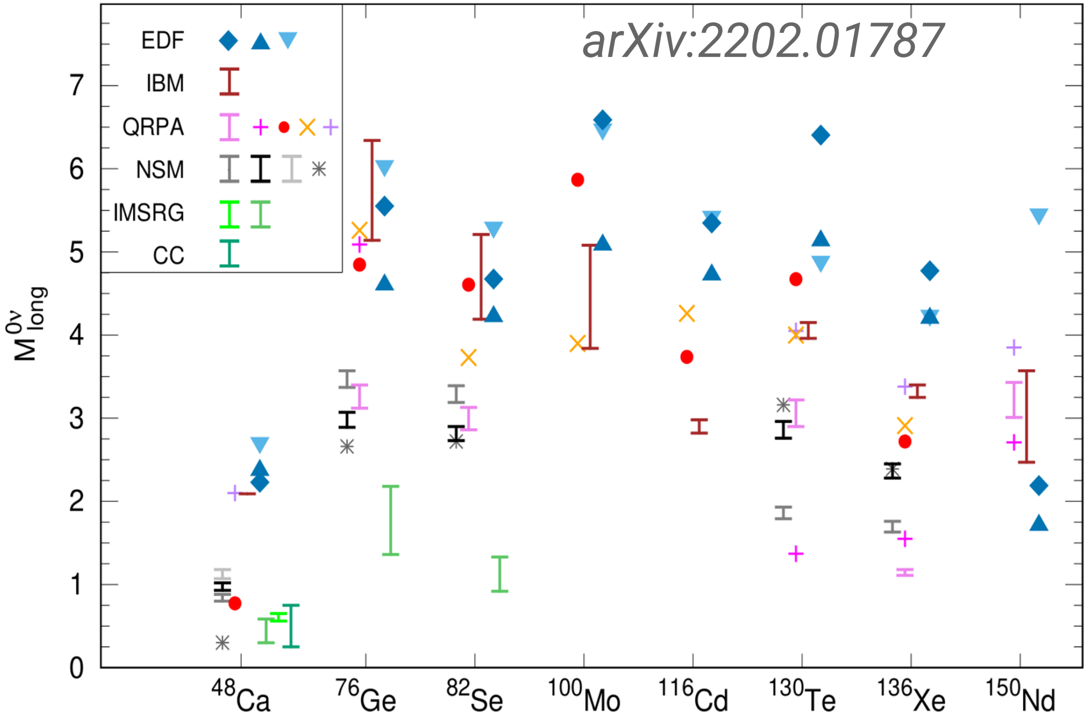
$$m_{\beta\beta} = \left|\sum_i U_{ei}^2 m_i\right| = \left|c_{12}^2\, c_{13}^2\, m_1 + s_{12}^2\, c_{13}^2\, m_2\, e^{i2\alpha} + s_{13}^2\, m_3\, e^{i2\beta}\right|$$

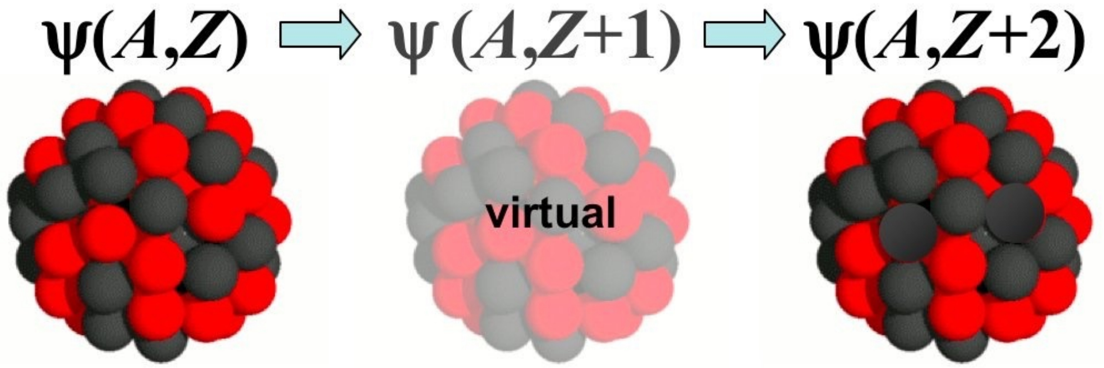
$c_{12} = cos\theta_{12}, c_{13} = cos\theta_{13}, s_{12} = sin\theta_{12}, s_{13} = sin\theta_{13}$

$m_{1,2,3}$ → mass eigenstates α, β → Majorana CP-phases

- Minimal extension of SM
- Access to absolute neutrino mass
- Reach interplay with neutrino oscillations, kinematic measurements (m_β), cosmology (Σ)

0νββ: Connection with Nuclear Physics





$$P \propto \frac{1}{T_{1/2}} \propto G\, g^4 M^2 \left(\frac{m_{\beta\beta}}{m_e}\right)^2$$

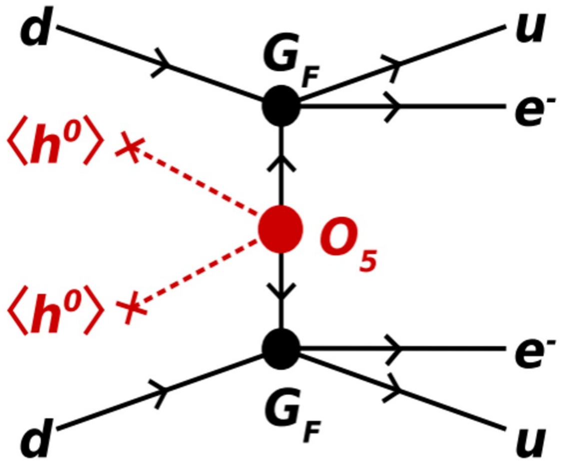
nuclear matrix element (NME)

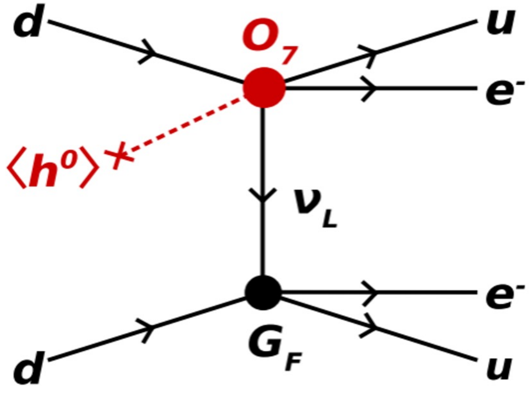
- Significant effort from different groups and different nuclear models
- ***Question of g_A quenching under study***
- No isotope has clear preference. Choice driven by experimental considerations.
- **Multiple isotope confirmation crucial**
- **Experimental input important**
  - » **2νββ decay**
  - » charge exchange reactions
  - » muon capture

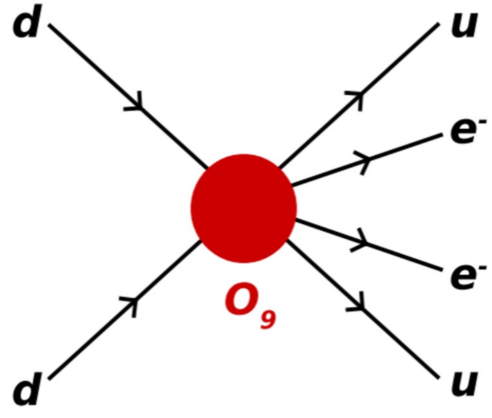
$0\nu\beta\beta$: Generic test for L-violating BSM physics

Cirigliano et al., JHEP 12, 097 (2018)

Deppisch, Graf, Iachello and Kotila
Phys.Rev.D 102 (2020) 9, 095016

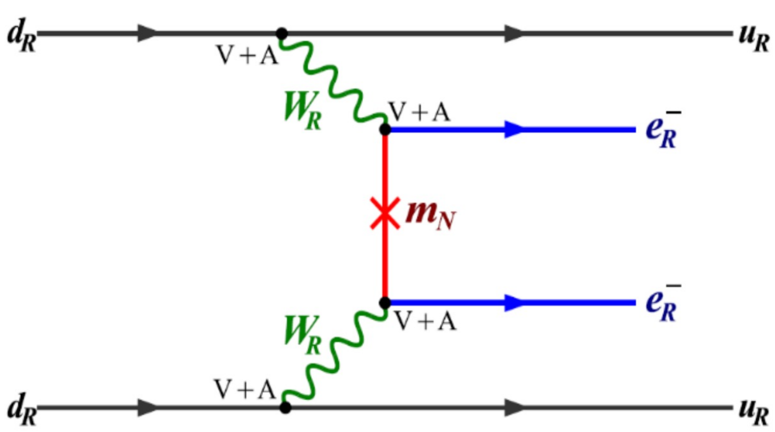




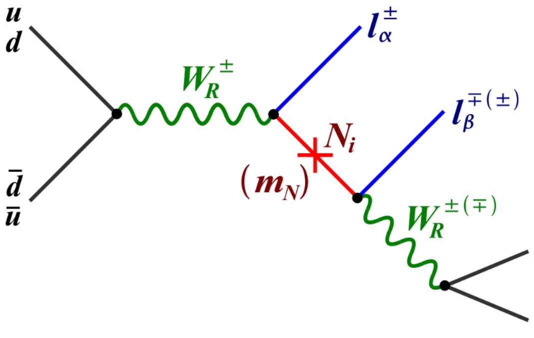


- Any new L-violating physics can result in $0\nu\beta\beta$ (access to ultra-high energy BSM)
- That includes Heavy Neutral Leptons and many other (see F. Deppisch talk)

Example: Left-Right Symmetric models

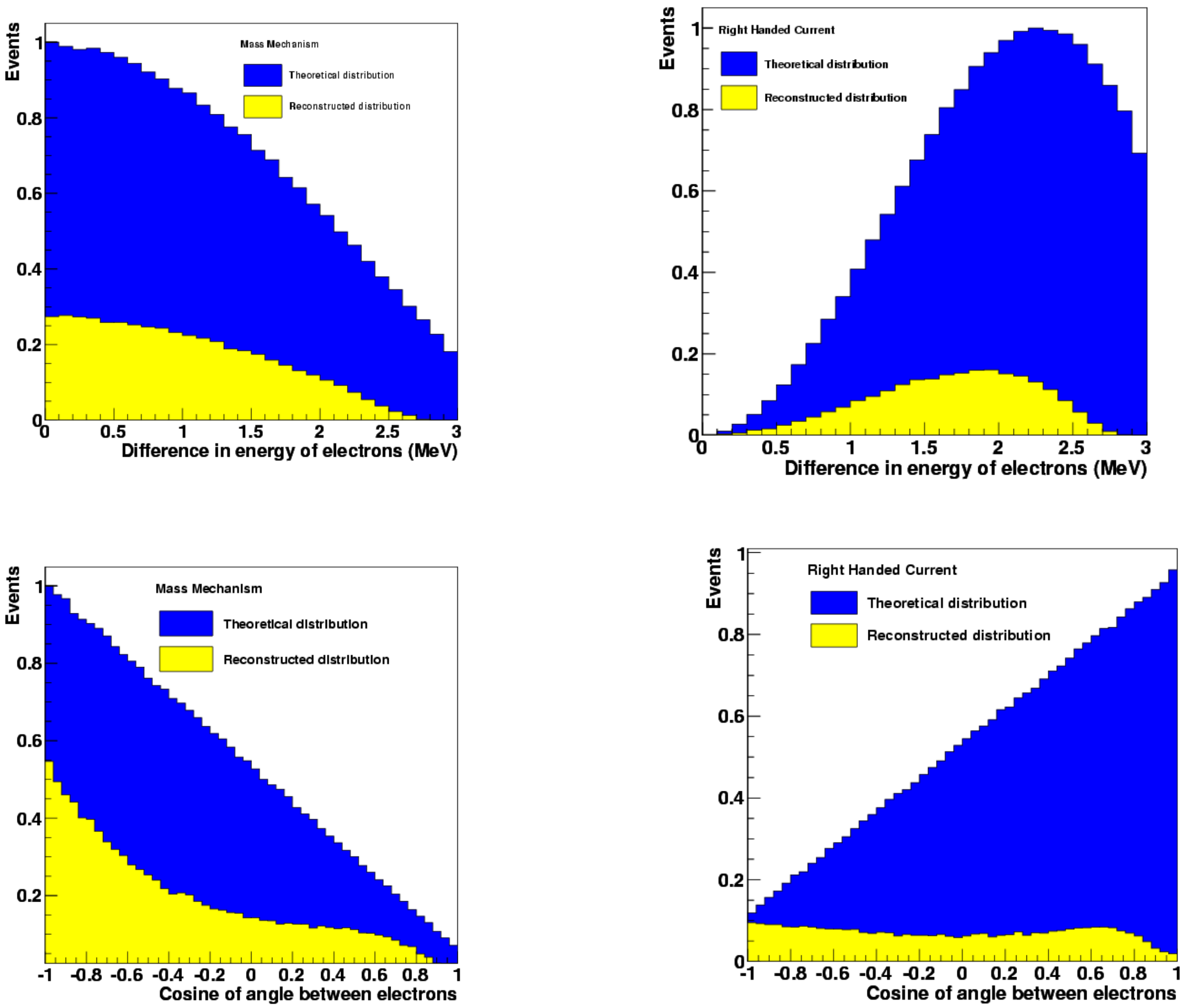


Synergies with LHC searches

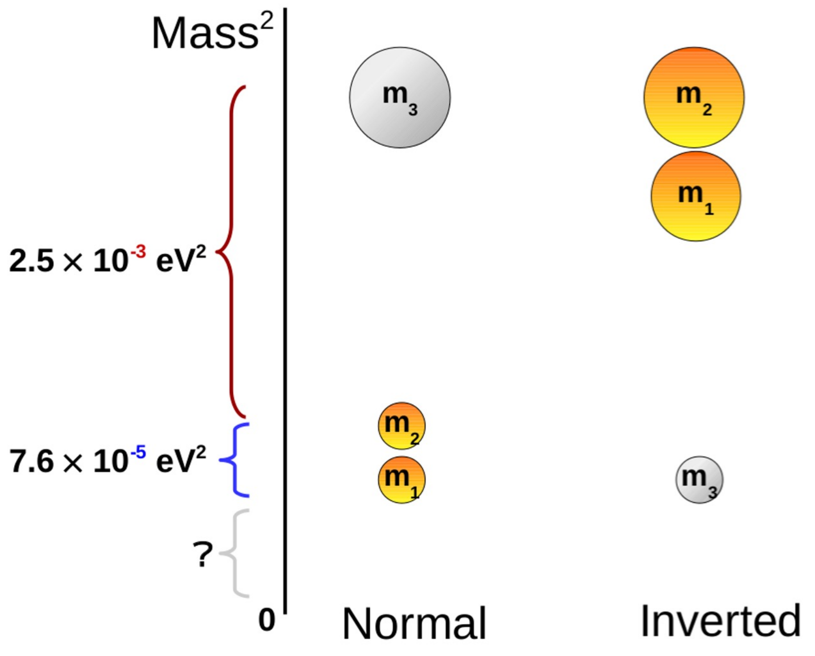


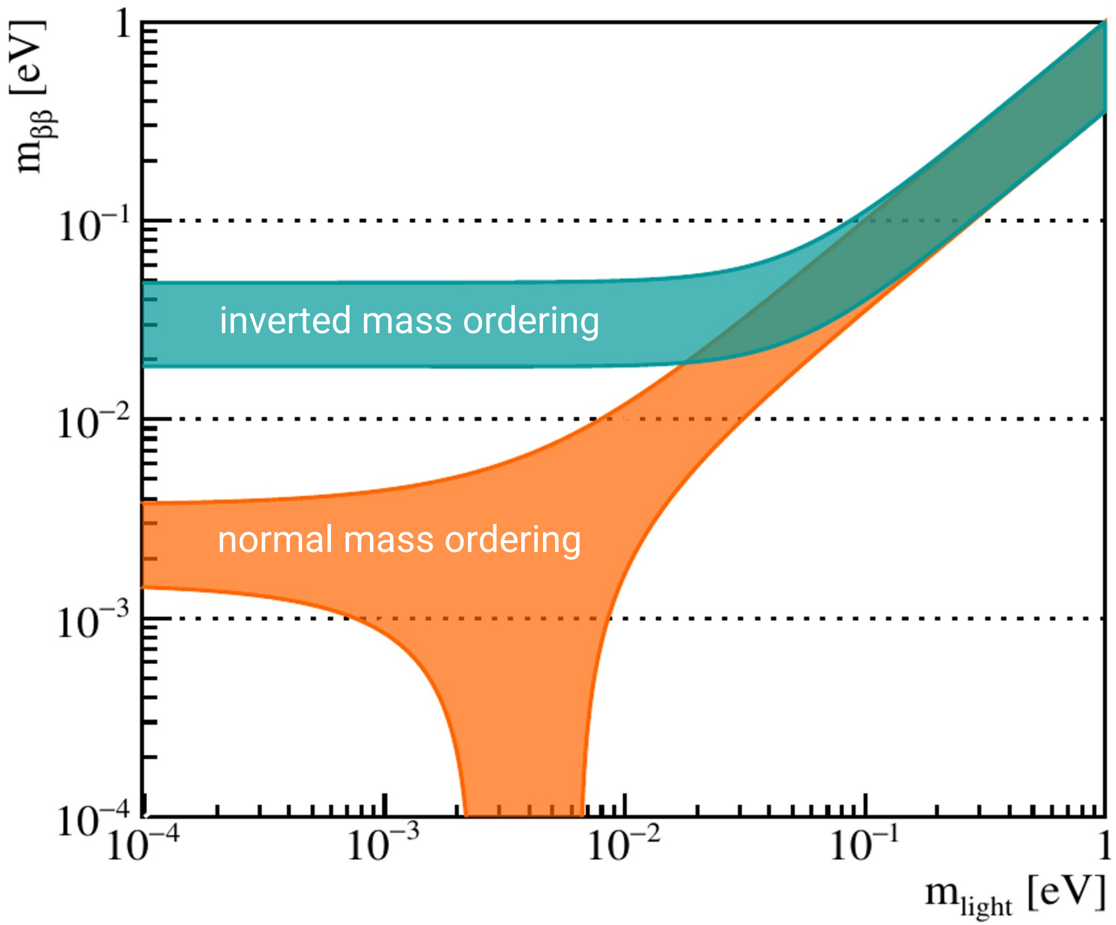
Deppisch, Graf, Iachello and Kotila
Phys.Rev.D 102 (2020) 9, 095016

$\langle m_\nu \rangle$ V+A

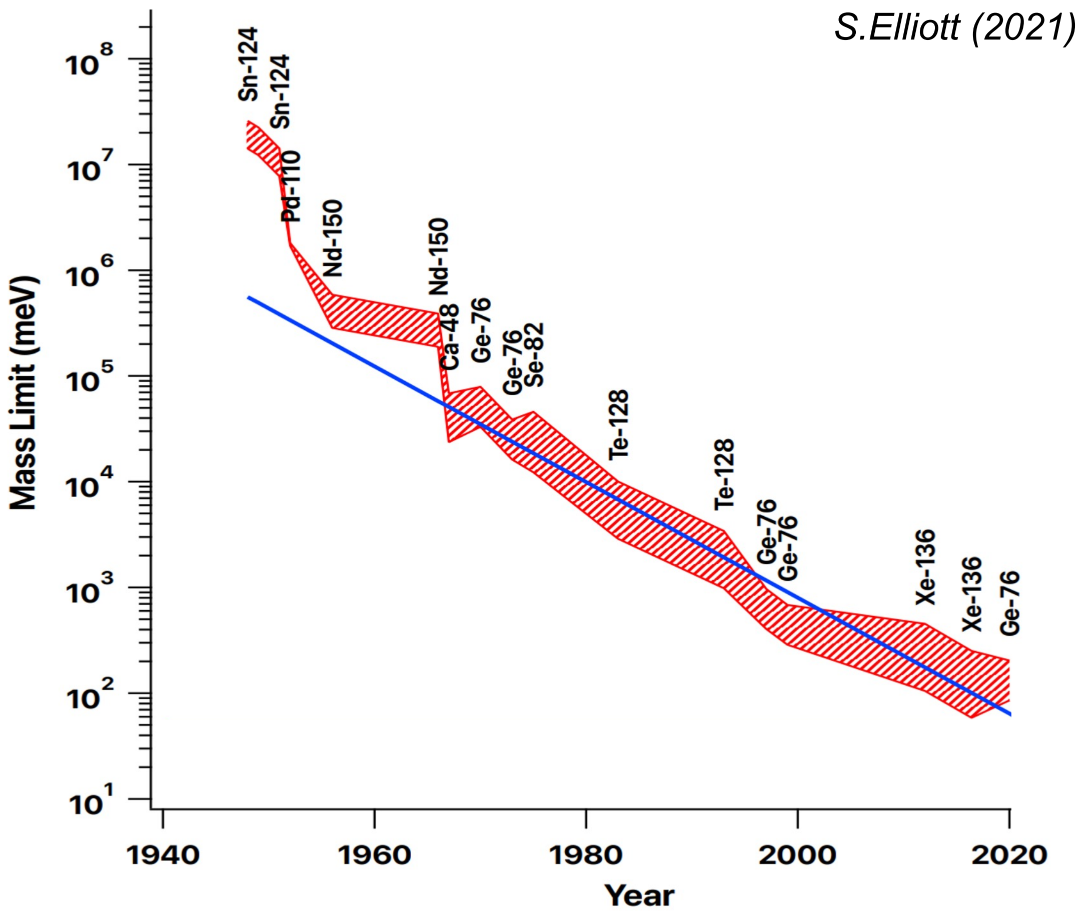


SuperNEMO Collaboration
EPJ C (2010) 70, pp. 972-943.

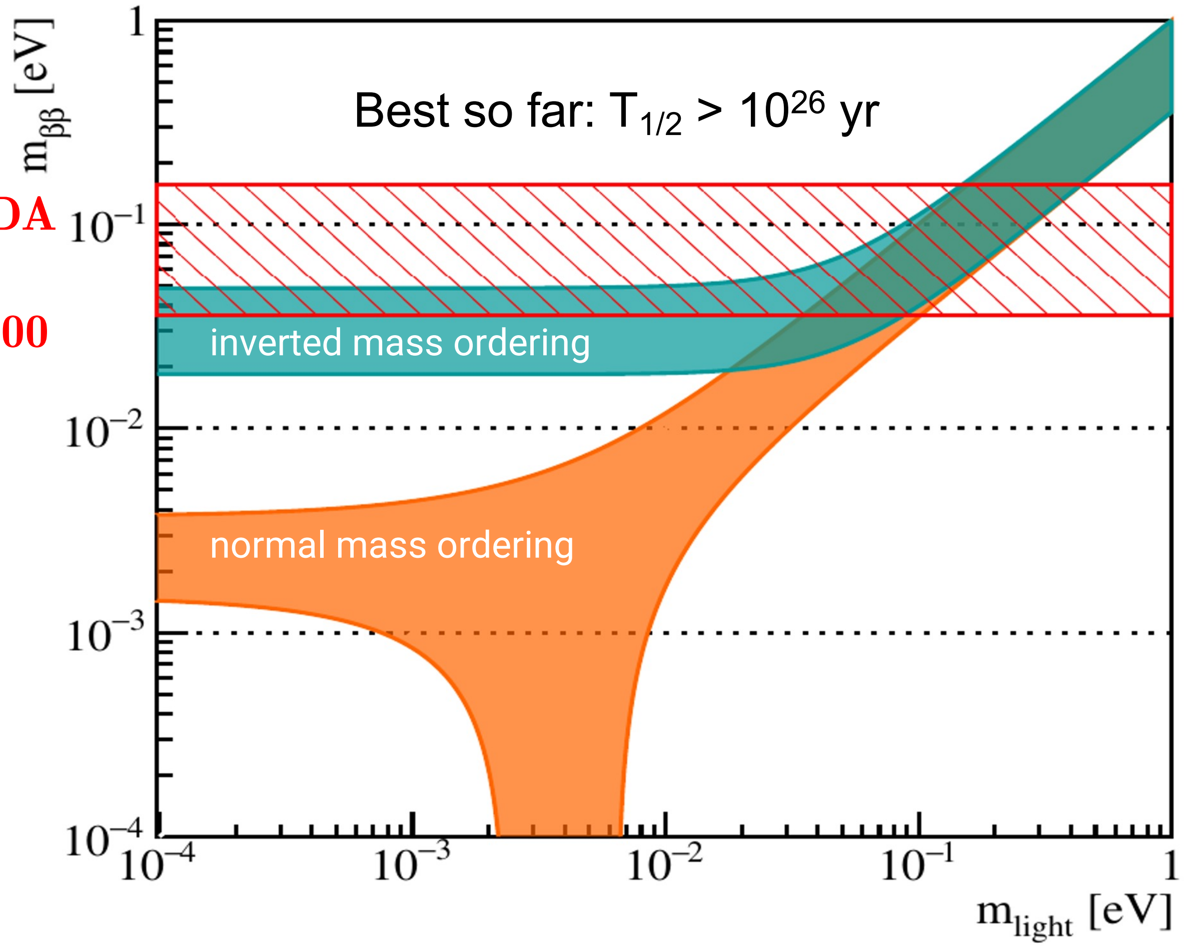




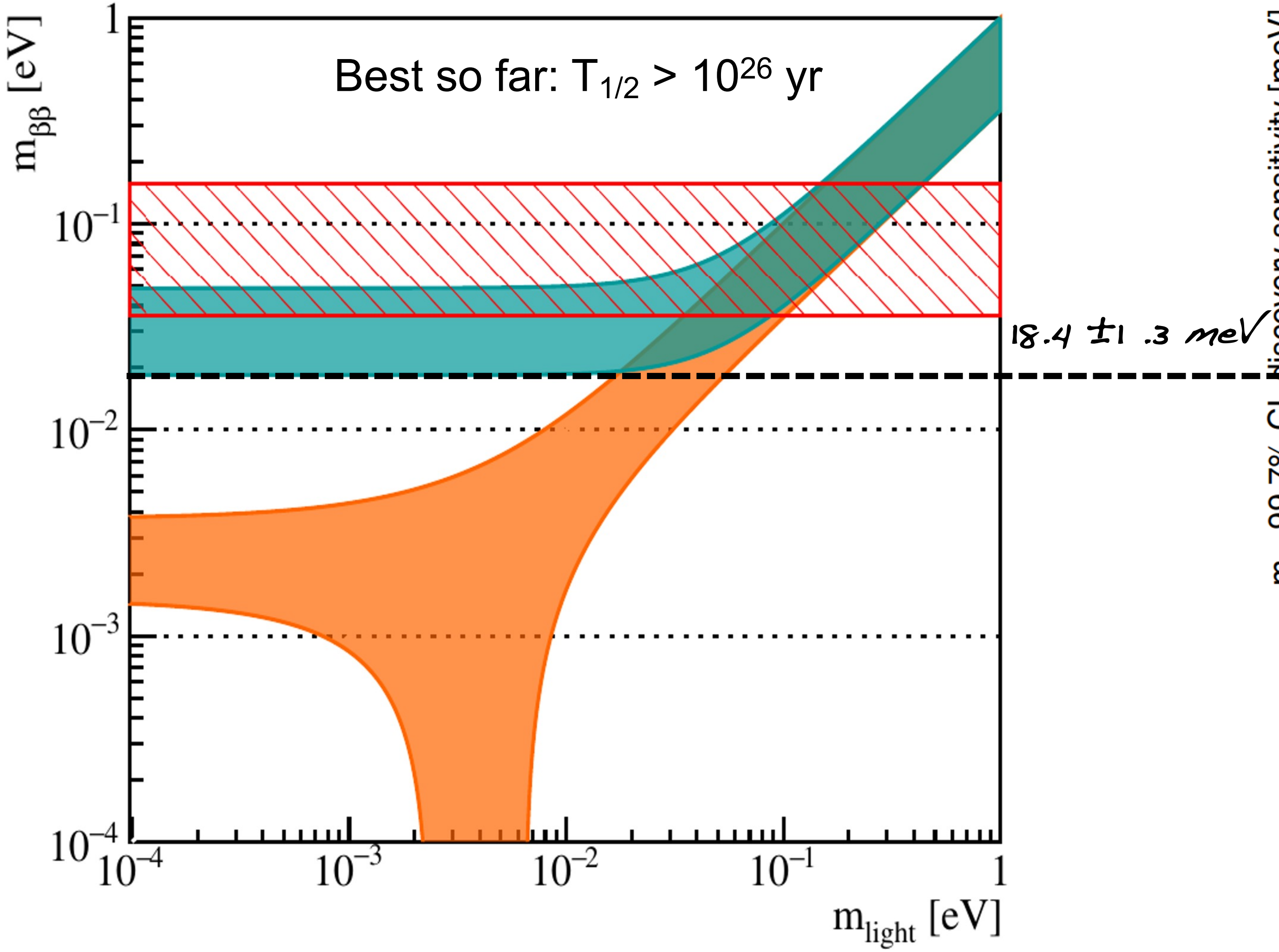
$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 m_i \right|$$



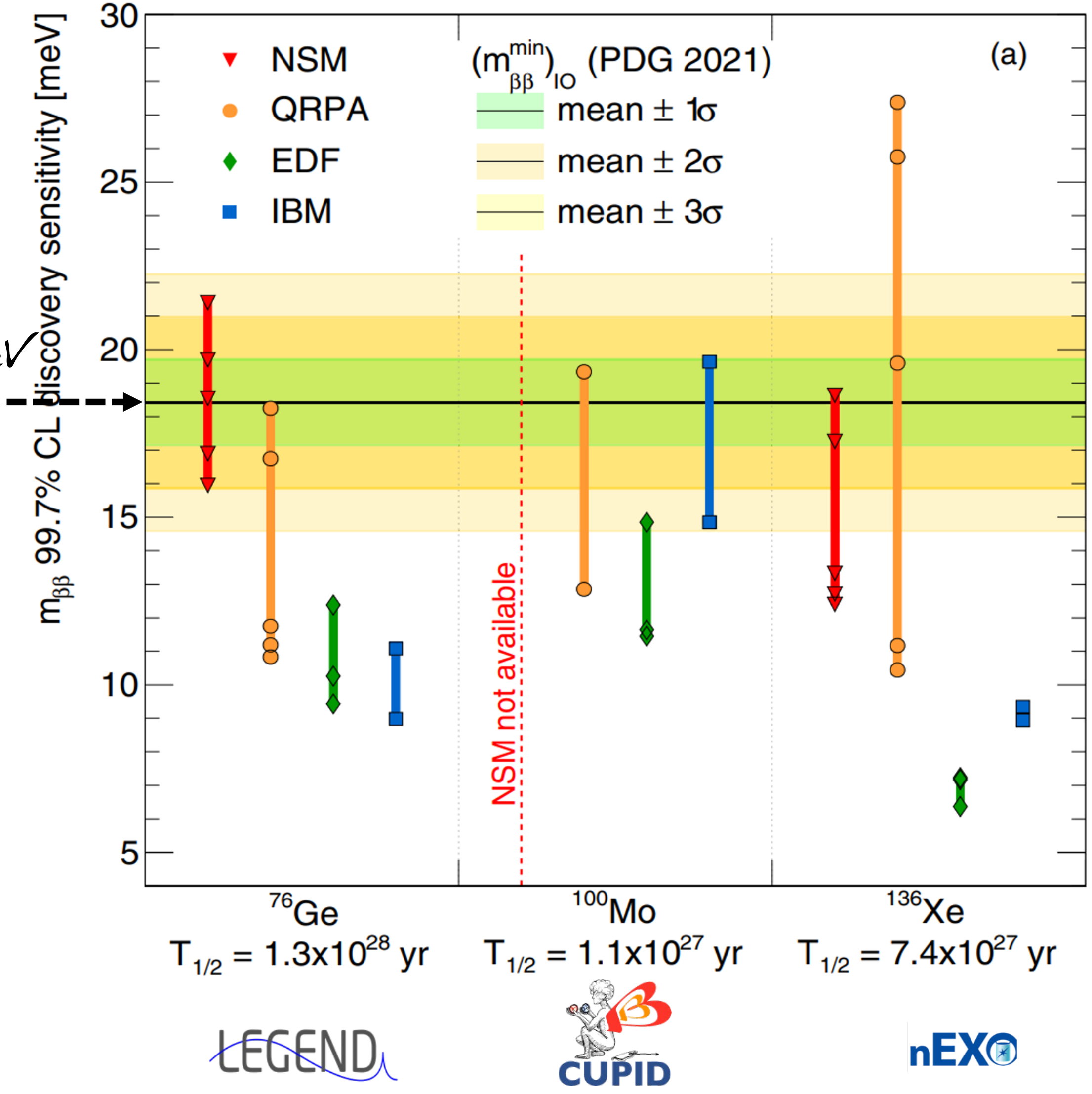
GERDA
KZ
Exo-200



$0\nu\beta\beta$ with $m_{\beta\beta}$ Where are we heading

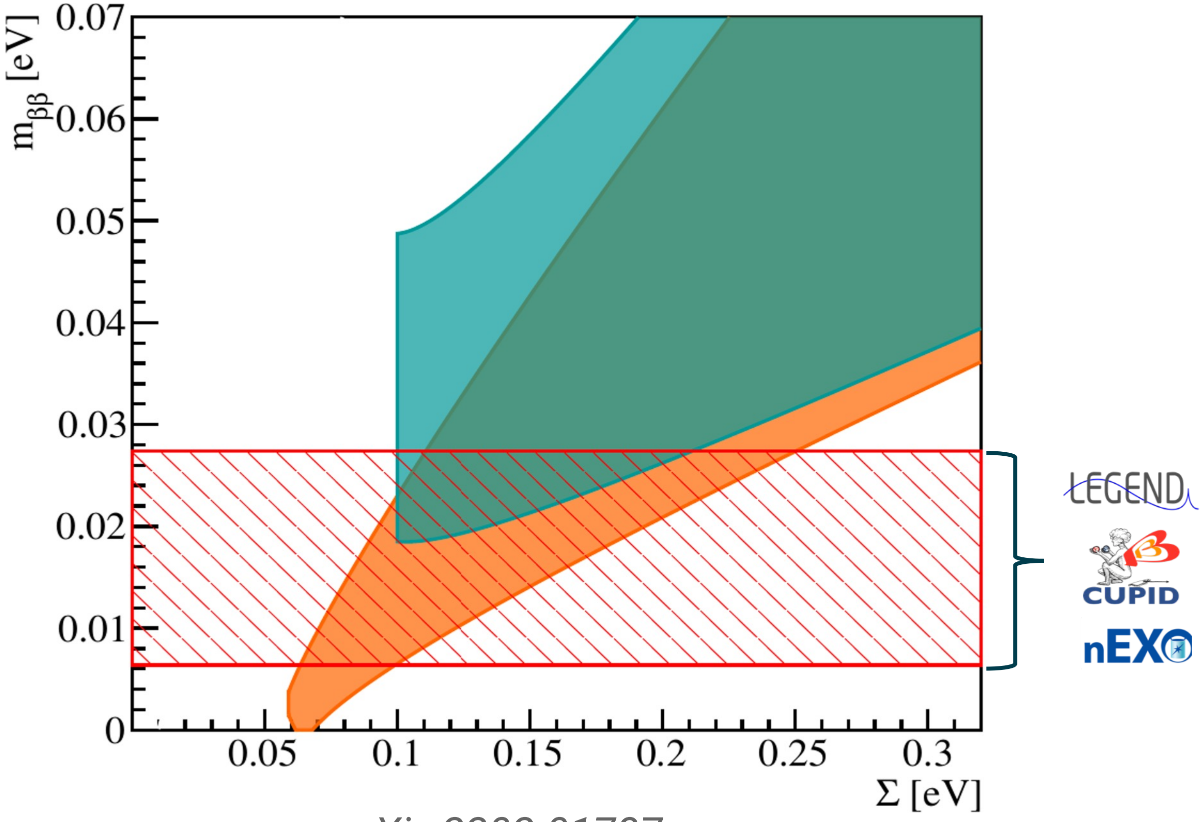


PRC 104, L042501 (2021)

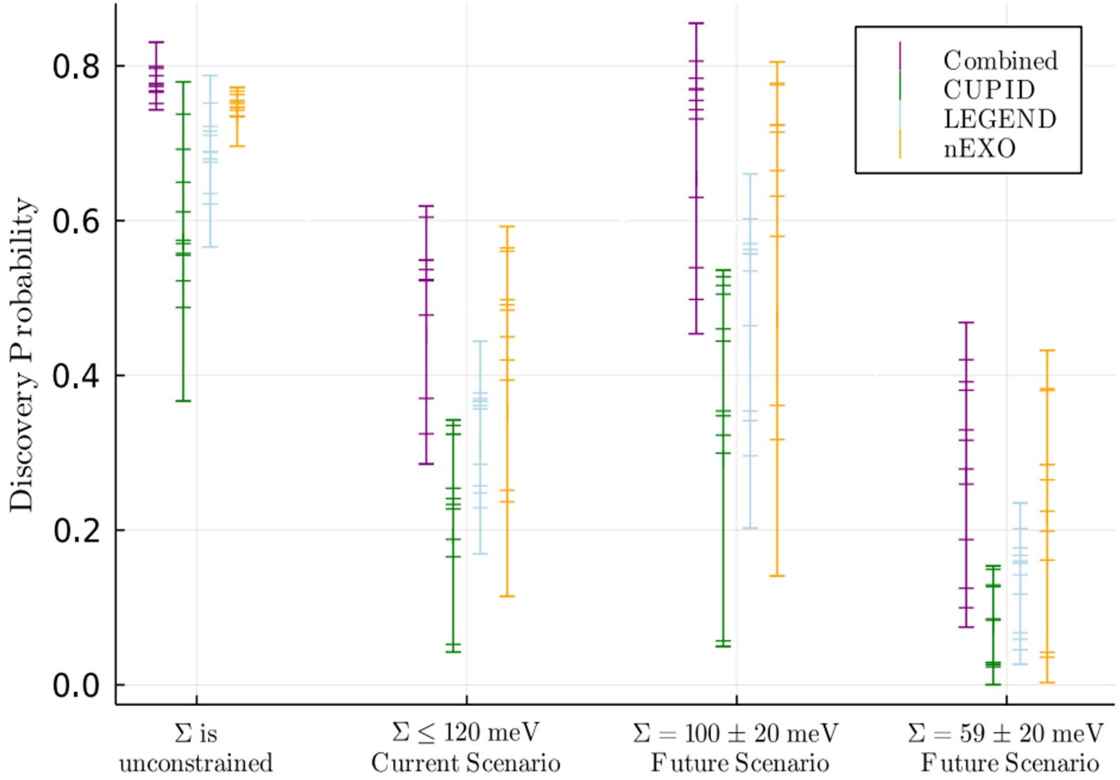


Cosmology surveys (DESI/EUCLID) closing in on positive measurement for Σ

$$\Sigma = \sum_i m_i$$



arXiv:2202.01787



arXiv: 2208.09954

Experimental Approaches

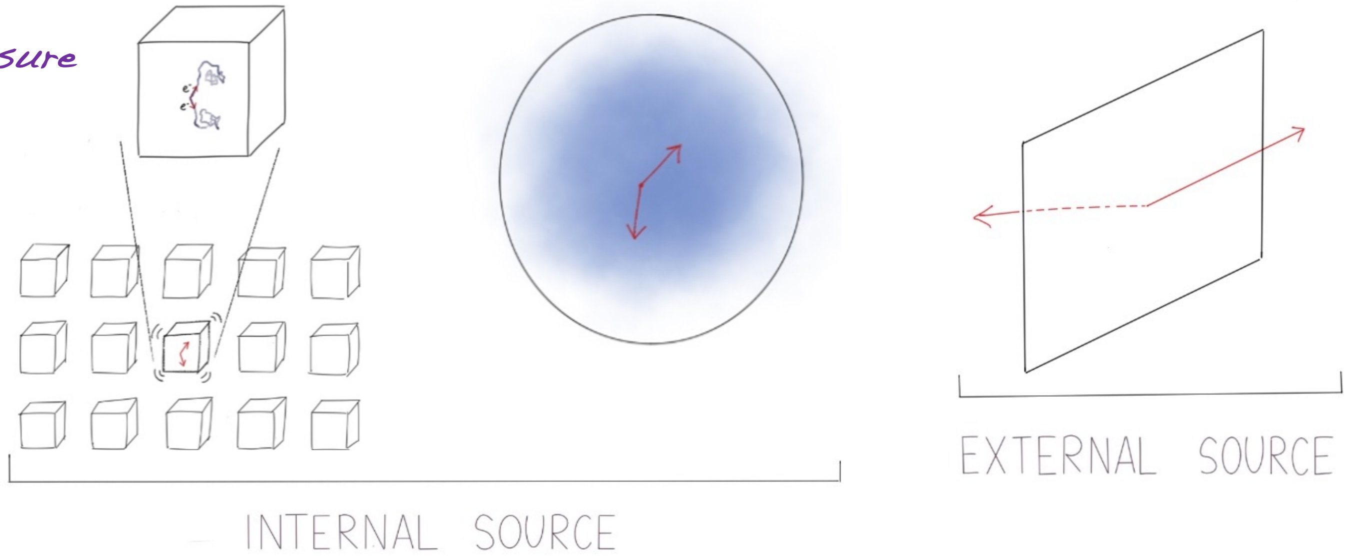
Detection Principles

maximise detection efficiency
and ββ isotope abundance

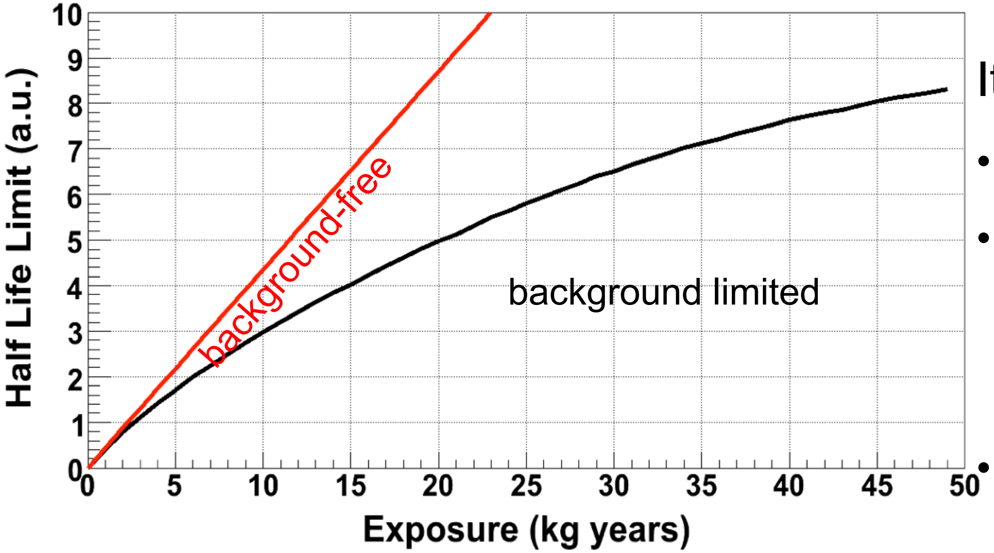
maximise exposure

$$T^{0\nu}_{1/2}(90\%\ \mathrm{C.L.}) = 2.54\times10^{26}\,\mathrm{y}\left(\frac{\varepsilon\times a}{W}\right)\sqrt{\frac{M\times t}{b\times\Delta E}}$$

minimise background

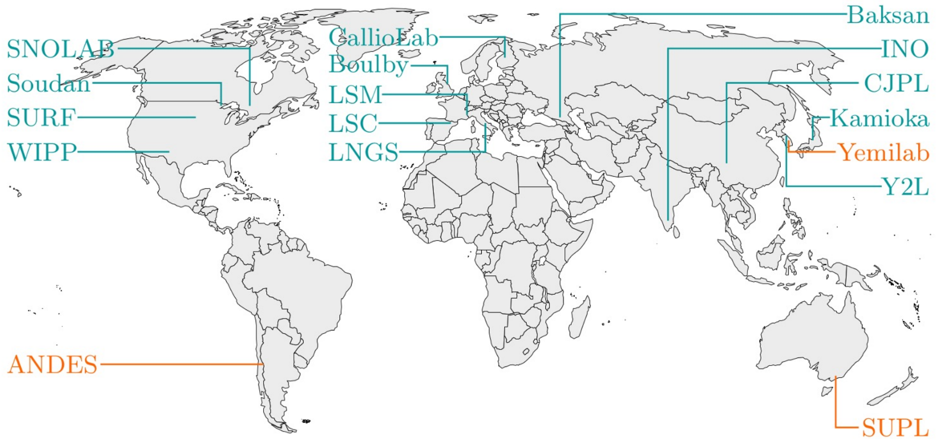


- Drawings courtesy of Laura Manenti



It's all about backgrounds

- Cosmic rays (underground)
- Natural radioactivity (clean materials, particle id and tagging)
- Standard Model $2\nu\beta\beta$ (energy resolution)



Experimental Parameters

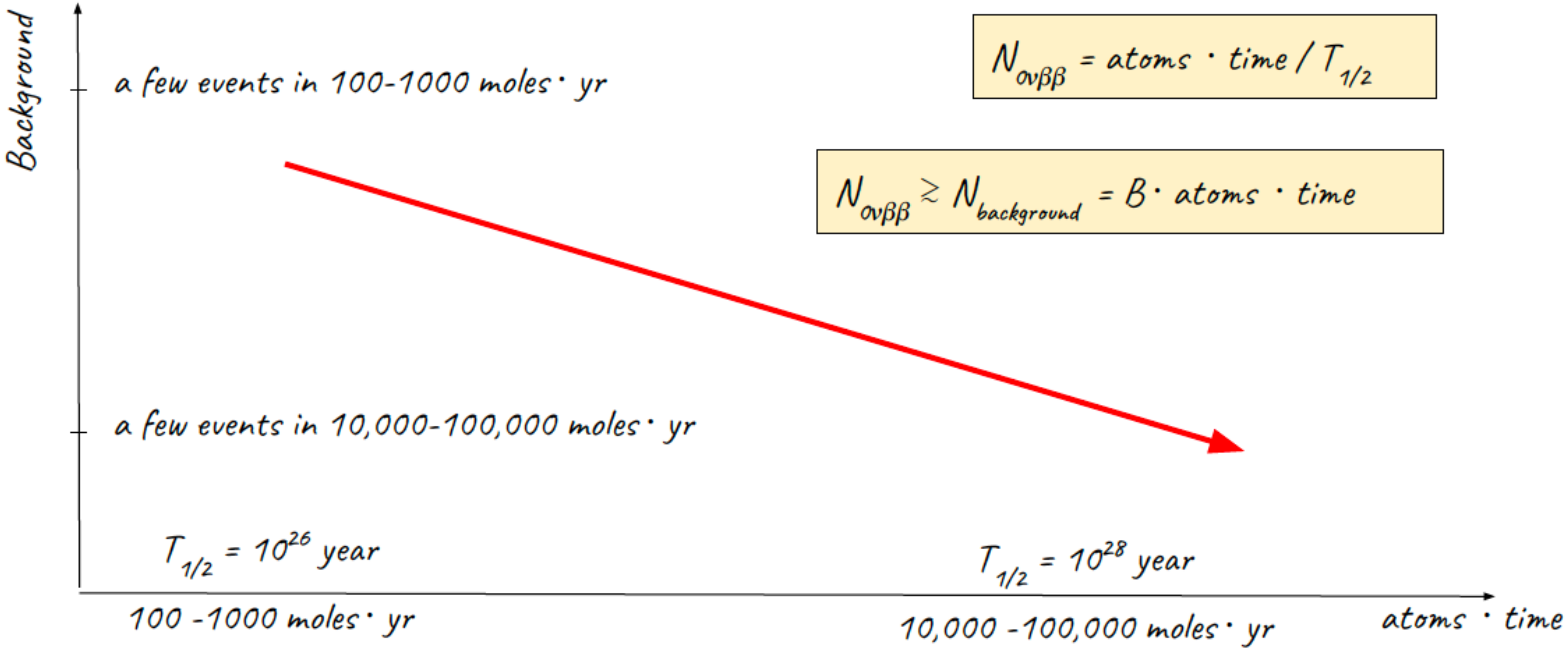
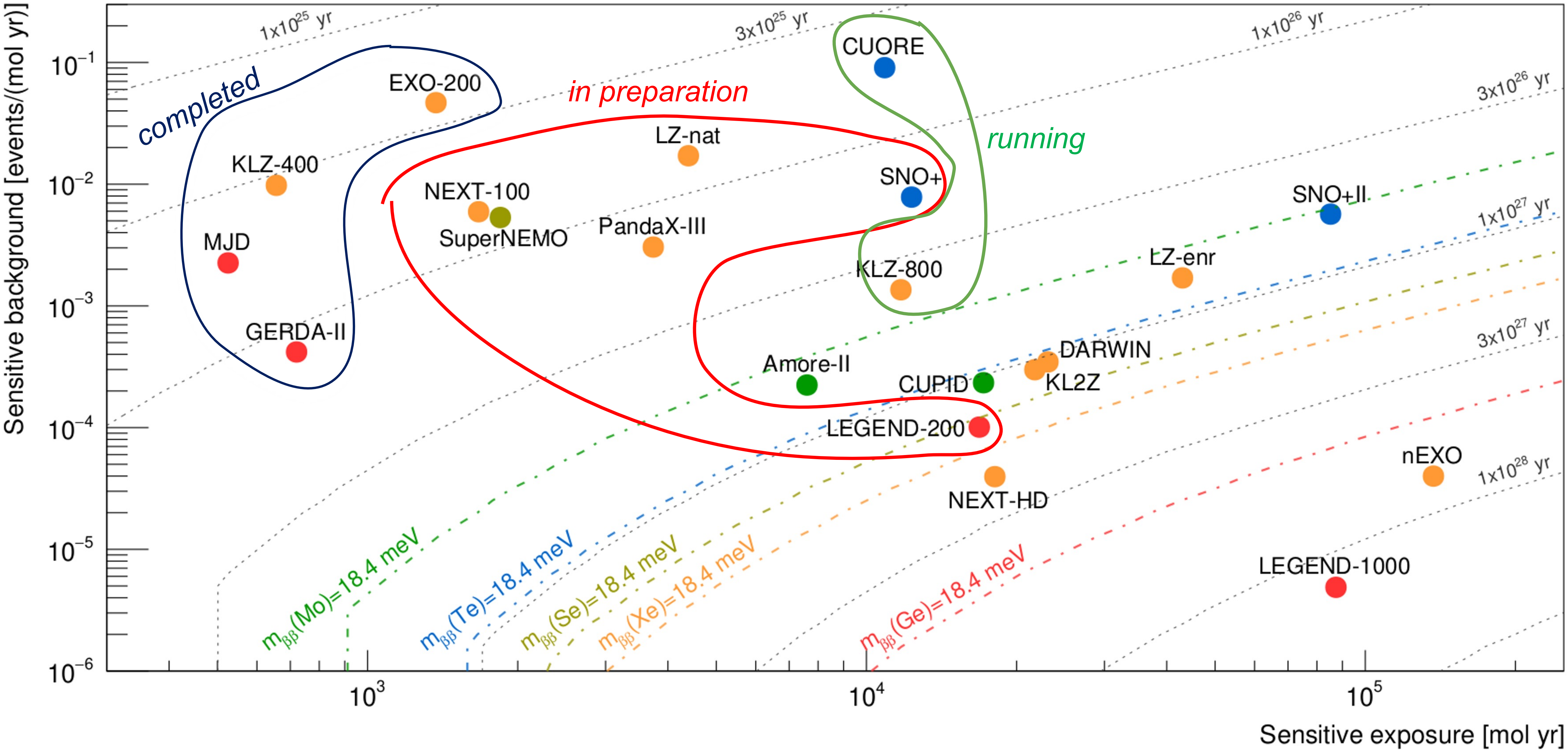
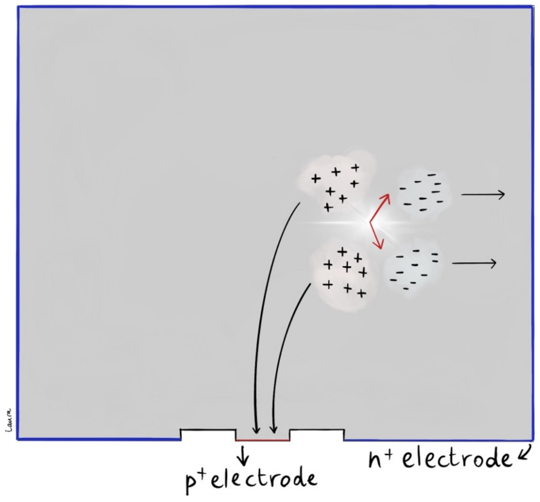


Image courtesy M. Agostini

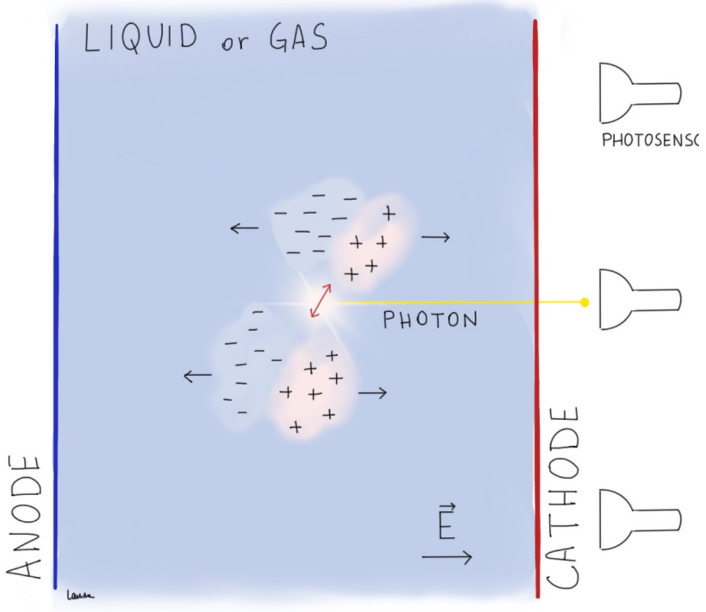
arXiv:2202.01787



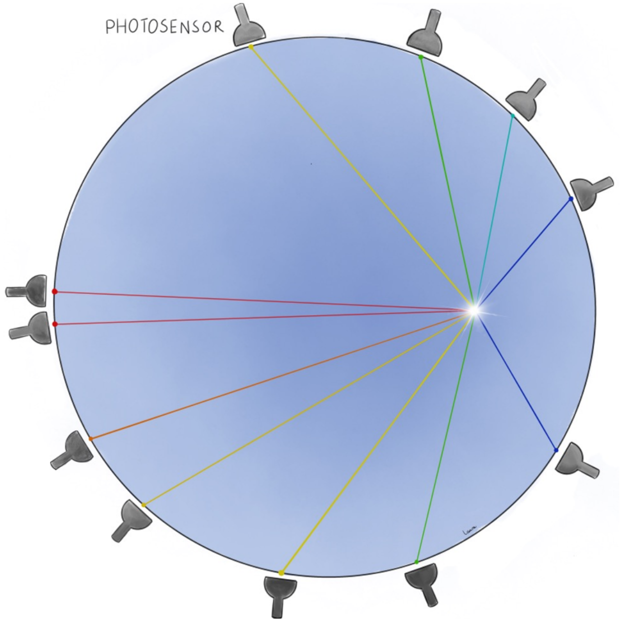
Leading Experimental Techniques



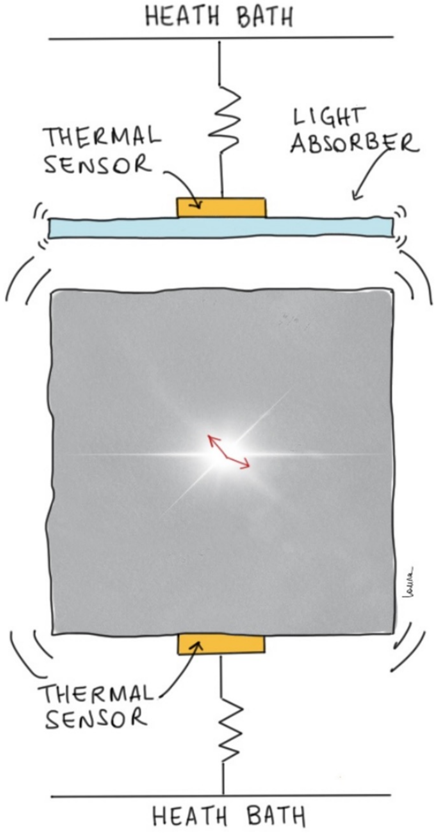
Ge Semiconductor detectors (^{76}Ge)



Xe Time Projection Chambers (^{136}Xe)



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



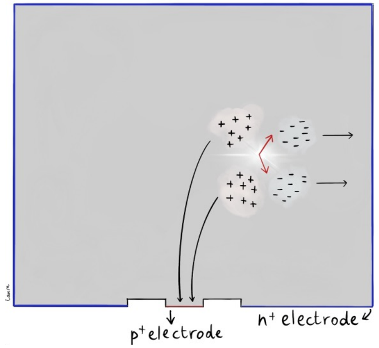
Cryogenic Calorimeters (^{100}Mo, ^{30}Te)

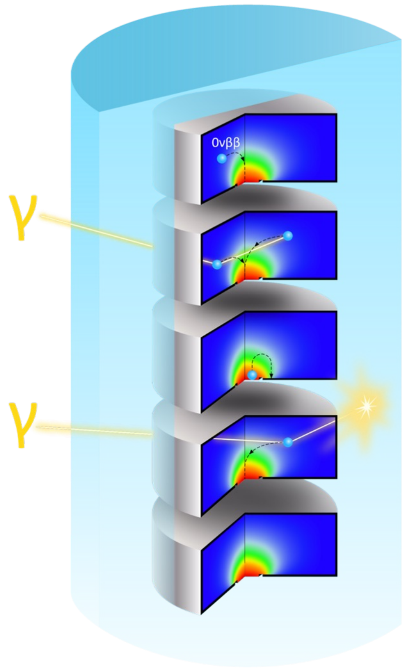
Drawings courtesy of Laura Manenti

Enriched Ge semiconductor detectors

high-purity ^{76}Ge detectors

- ionization and charge drift
- < 0.1% energy resolution
- event topology





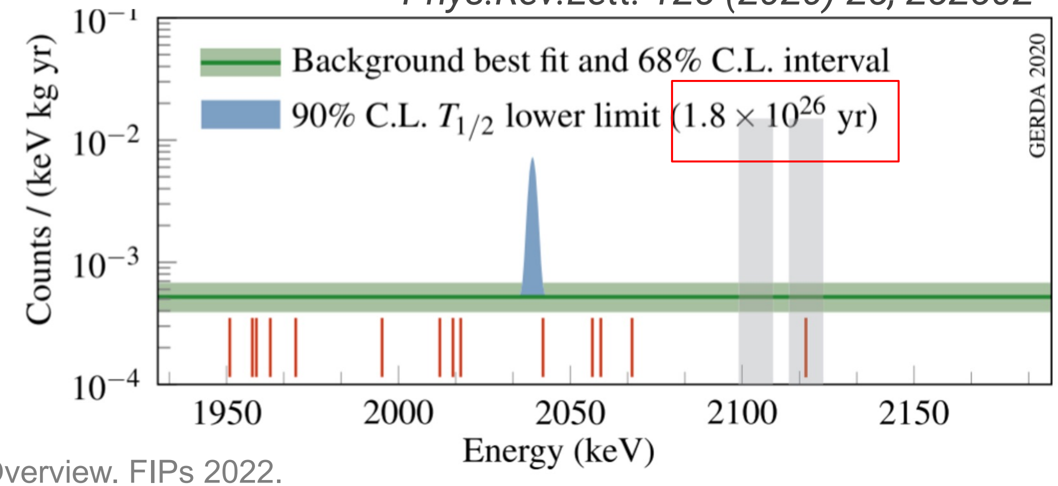
liquid Ar detector

- shield and scintillation light

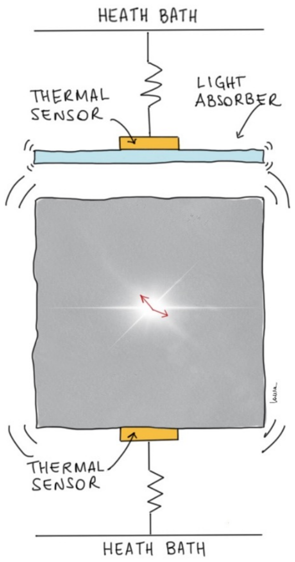
Staged approach:

- **GERDA/MAJORANA** Demonstrator (40 kg)
- **LEGEND-200** under commissioning (200 kg)
- **LEGEND-1000** conceptual design in preparation (1 t)

Phys.Rev.Lett. 125 (2020) 25, 252502

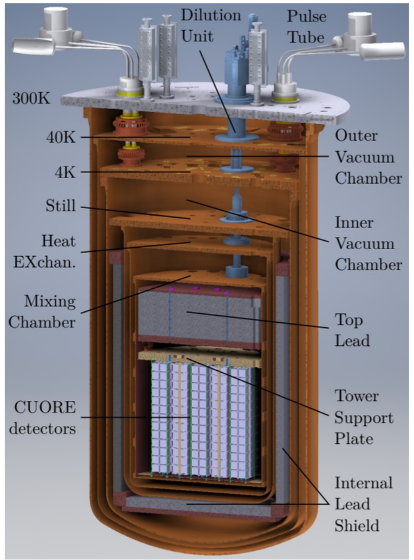


Cryogenic Calorimeters

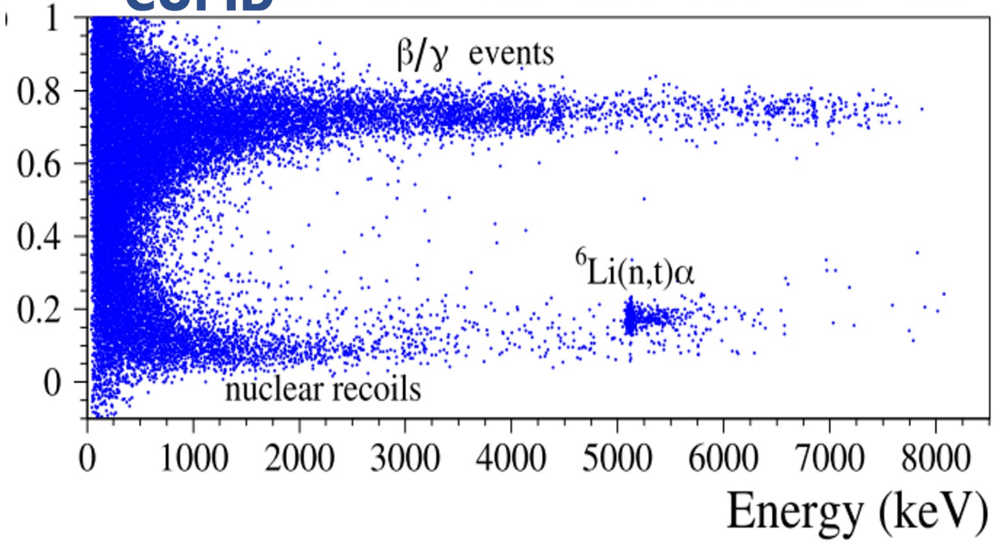


- array of isotopically enriched crystals operated at ~10 mK
- thermal and scintillation signal
- particle ID and good energy resolution
- Leading results for ^{130}Te and ^{82}Se, future focus on ^{100}Mo

Experiment	Crystal	m_{tot} [kg]	f_{enr} [%]
CUORE	$^{nat}TeO_2$	742	34[a]
CUPID-0	$Zn^{enr}Se$	9.65	96
CUPID-Mo	$Li_2{}^{enr}MoO_4$	4.16	97
CROSS	$Li_2{}^{enr}MoO_4$	8.96	98
CUPID	$Li_2{}^{enr}MoO_4$	472	≥95
AMoRE	$Li_2{}^{enr}MoO_4$	200	96

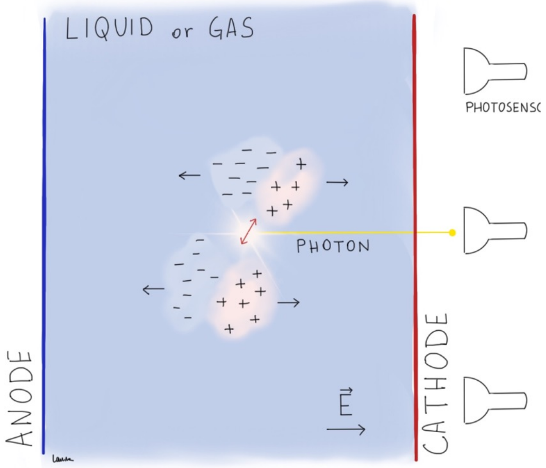


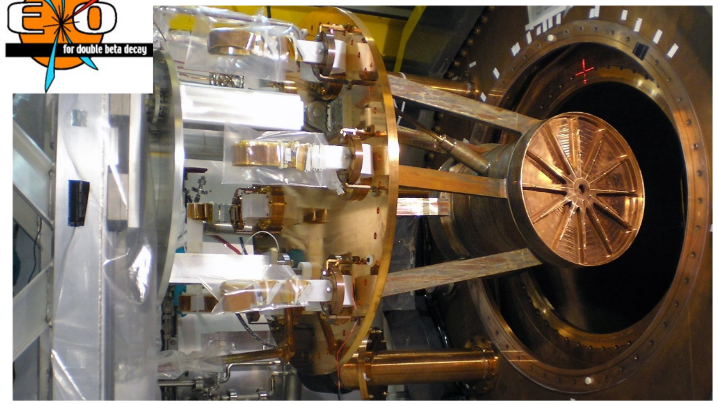
CUPID



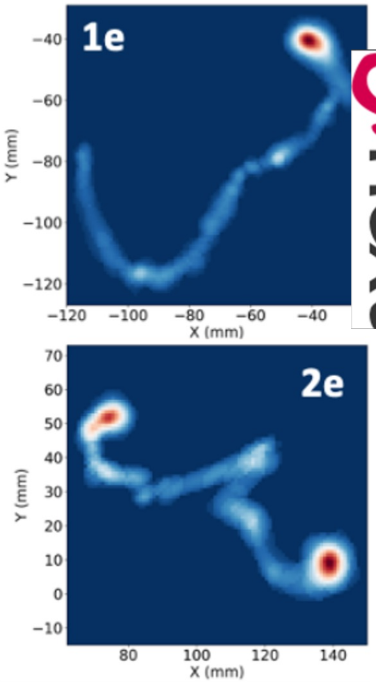
Enriched Xe TPCs

- ^{136}Xe VUV scintillation light and ionization electron drift -> 3D reconstruction
- background decreasing with distance from surface, ^{214}Bi and ^{222}Rn remain problematic
- R&D to tag $0\nu\beta\beta$ decay daughter isotope

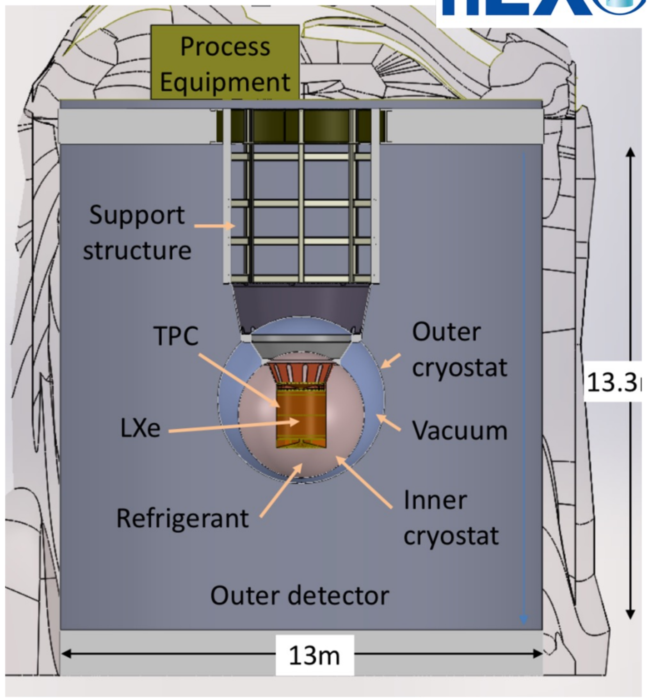




Experiment	m_{tot} [kg]	$f_{enr.}$ [%]	Phase	Readout
EXO-200	161	81	liquid	LAPPDs + wires
nEXO	5109	90	liquid	electrode tiles + SiPM s
NEXT-100	97	90	gas	SiPMs + PMTs
NEXT-HD	1100	90	gas	SiPMs + PMTs
PandaX-III-200	200	90	gas	Micromegas
PandaX-III-1K	1000	90	gas	Micromegas
LZ-nat	7 000	9	dual-phase	PMTs
LZ-enr	7 000	90	dual-phase	PMTs
DARWIN	39 300	9	dual-phase	PMTs

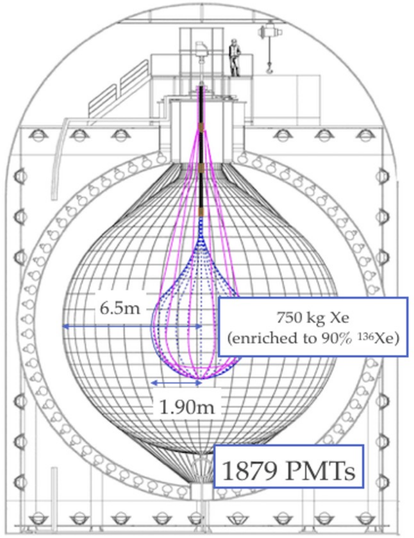


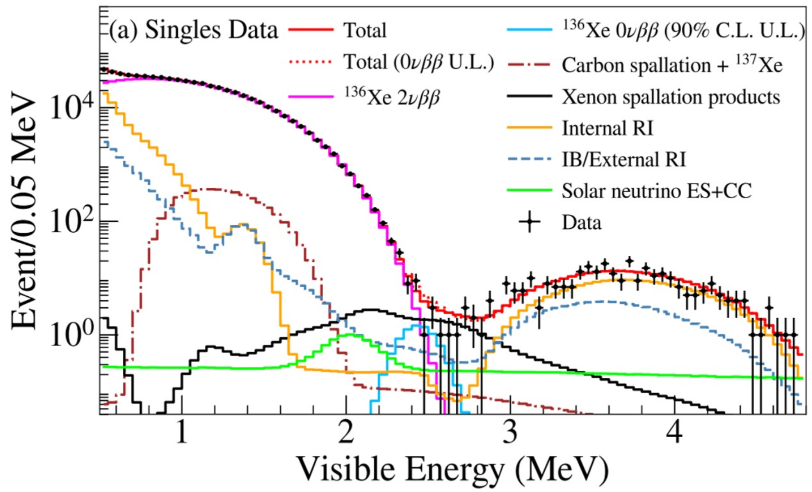
nEXO



Large loaded liquid scintillators

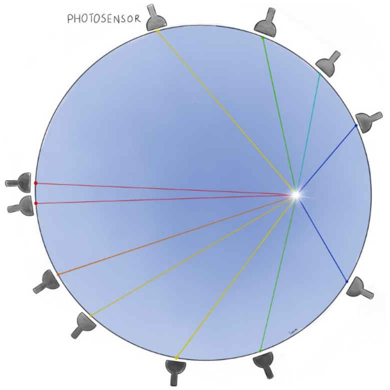
- scintillator loaded with target isotope
- scintillation photons detected by PMTs
- photon number and arrival time gives event energy and position
- self-shielding and fiducialization
- Broad physics program (e.g. solar, reactor, geo-neutrinos)





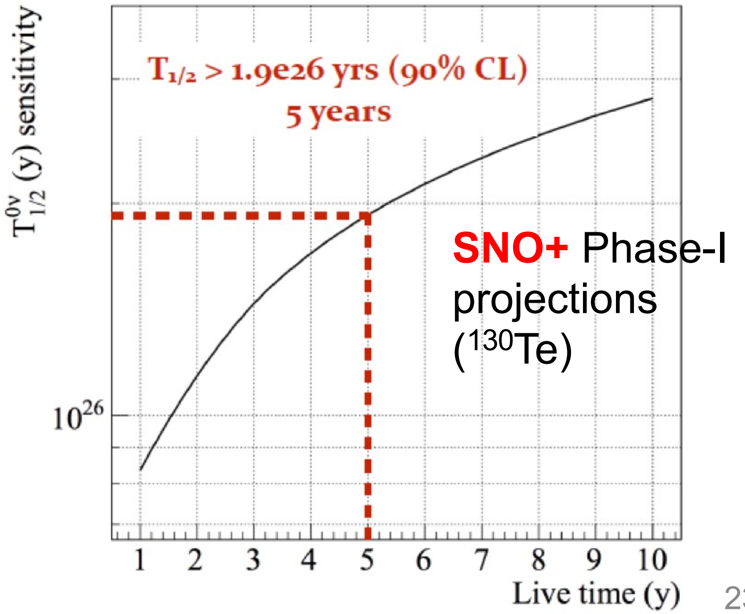
KZ collaboration, 2203.02139

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



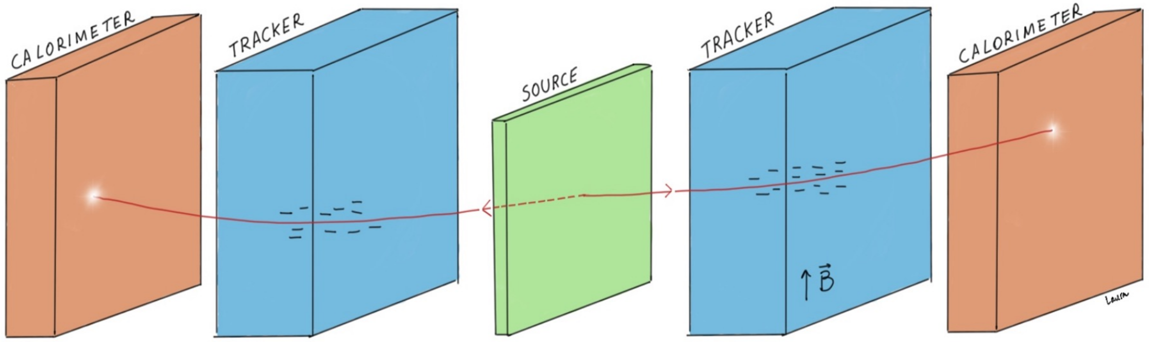
KamLAND-Zen-800 @Kamioka (^{136}Xe)

- 750 kg of enriched Xe in nylon balloon
- **Strongest constraints so far: $m_{\beta\beta}$ < 36-156 meV**
- backgrounds:, cosmogenic, solar neutrinos, ^{214}Bi on balloon
- next phase: improved resolution and purer scintillator

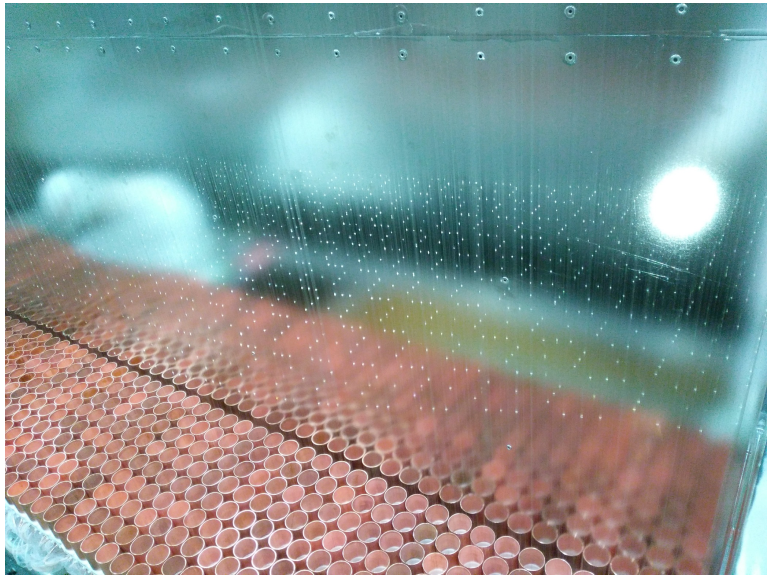


Planning for success ($m_{\beta\beta} \gtrsim 50$ meV)

NEMO-technique: full topology reconstruction of final states

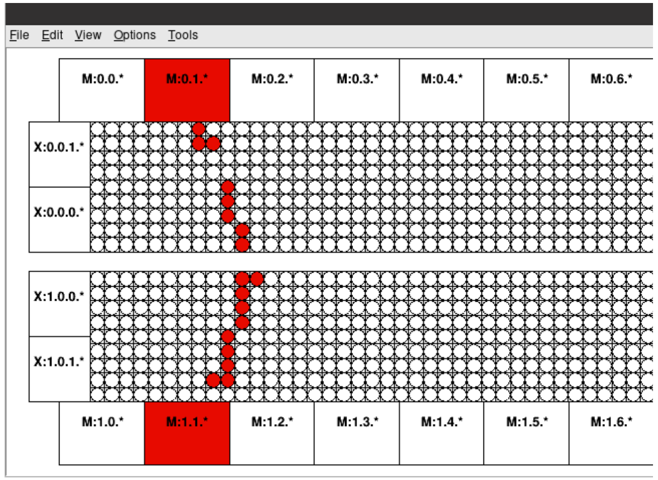


supernemo
collaboration



SuperNEMO-Demonstrator *running* at LSM

- **Multi-isotope** confirmation
- Exploring underlying **physics mechanism**
  - Angular distributions
  - Single electron energies
- Constraining nuclear physics → **NME and g_A** through precision $2\nu\beta\beta$ studies
- **BSM** physics with **$2\nu\beta\beta$** (*Phys.Rev.Lett.125 (2020) 17, 171801*)



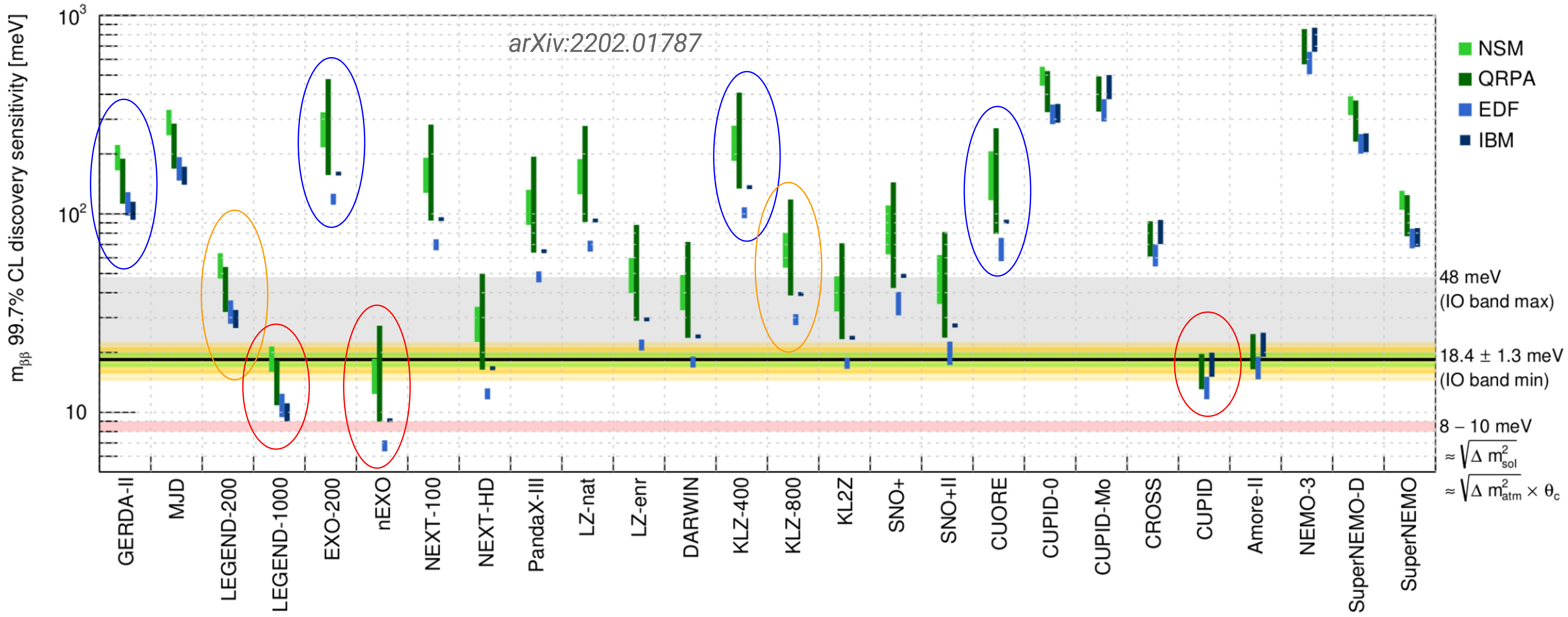
Outlook

UCL

The Big 4 of last decade: **GERDA, EXO-200, KamLAND-Zen-400, CUORE**

The two to watch: **LEGEND-200, KamLAND-Zen-800**

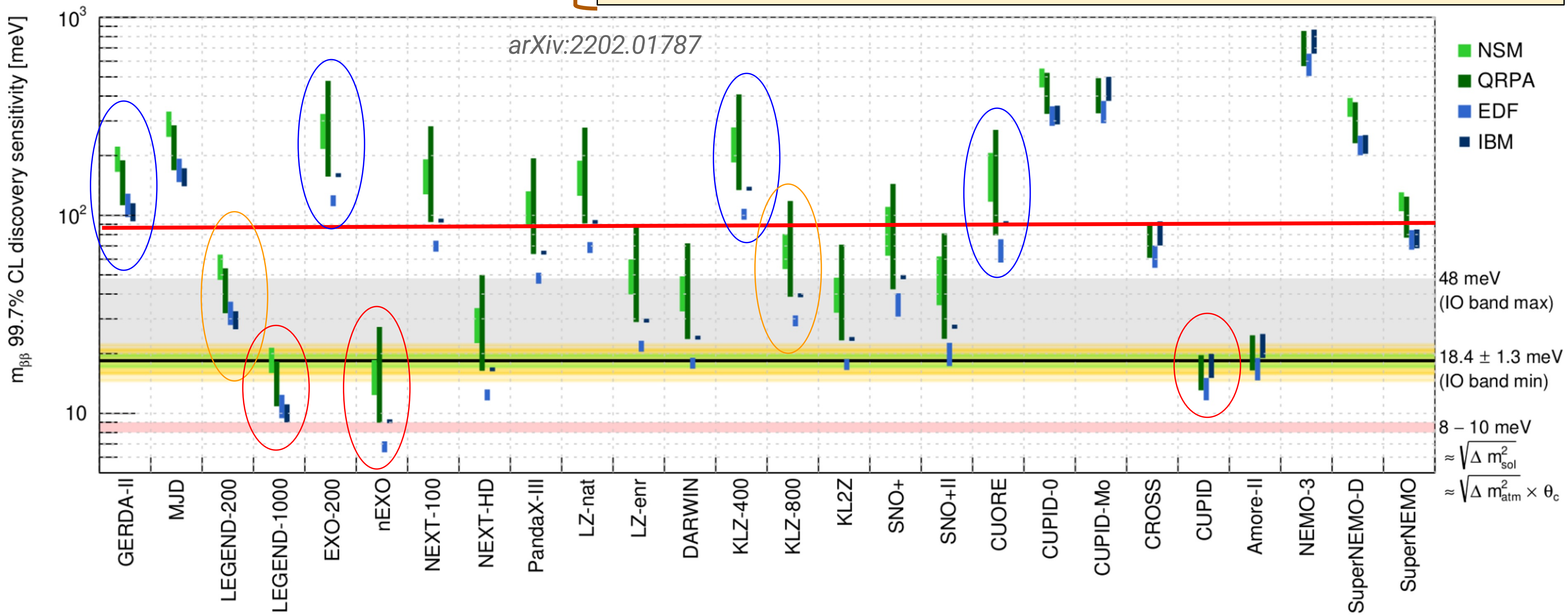
The ultimate I.O. experiments: **LEGEND-1000, CUPID, nEXO**



Outlook

Scenario 1: signal just beyond current limits

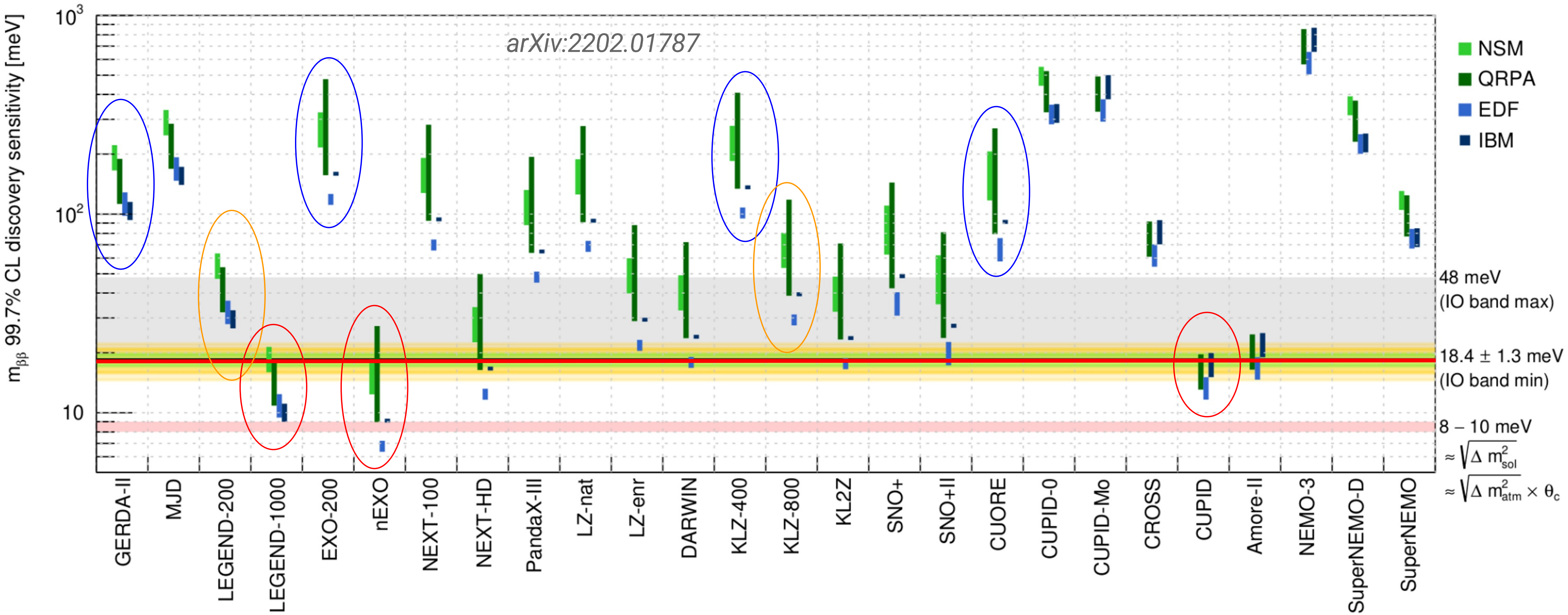
- discovery within few years
- precise rate measurement with next-gen experiments
- Access to underlying mechanism with SNEMO-like technique



Outlook

Scenario 2: signal at bottom of I.O.

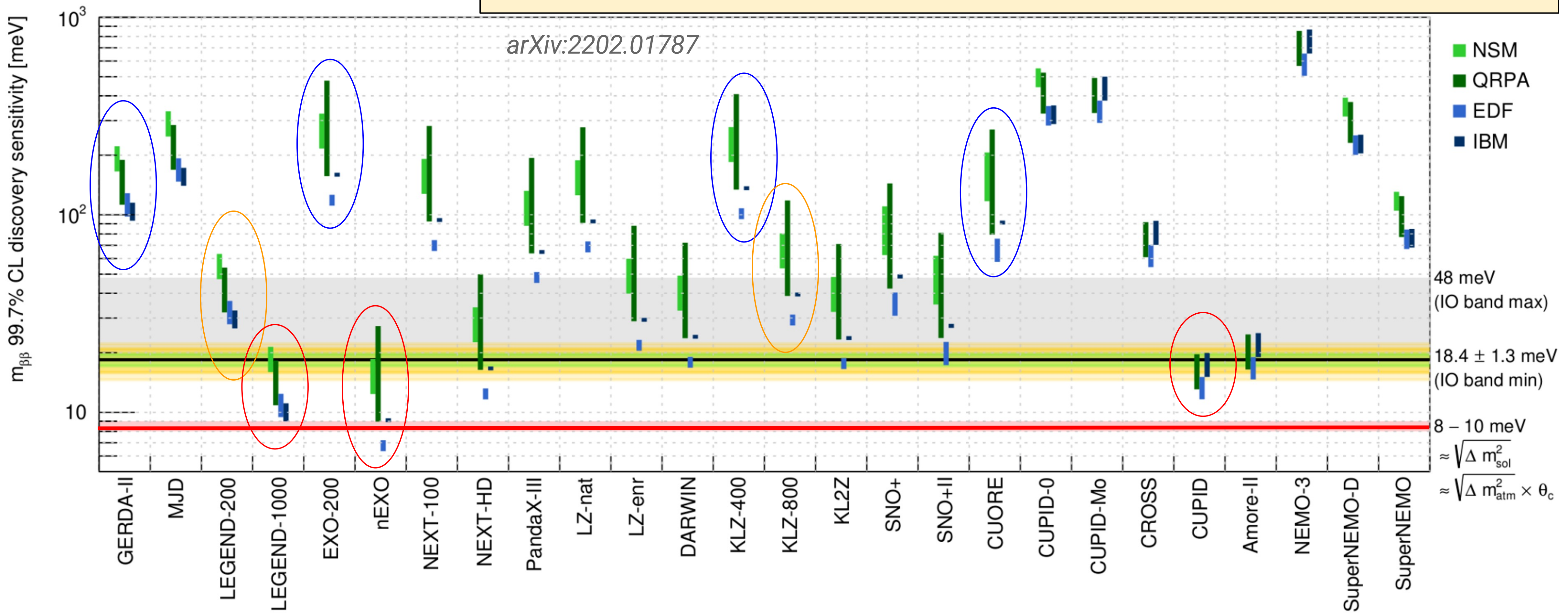
- need to wait next-gen experiments for a discovery
- need R&D to measure decay features



Outlook

Scenario 3: signal in N.O. (or absent)

- R&D and new ideas for convincing discovery
- interplay with oscillation experiments and cosmology can lead to breakthroughs even in absence of signal

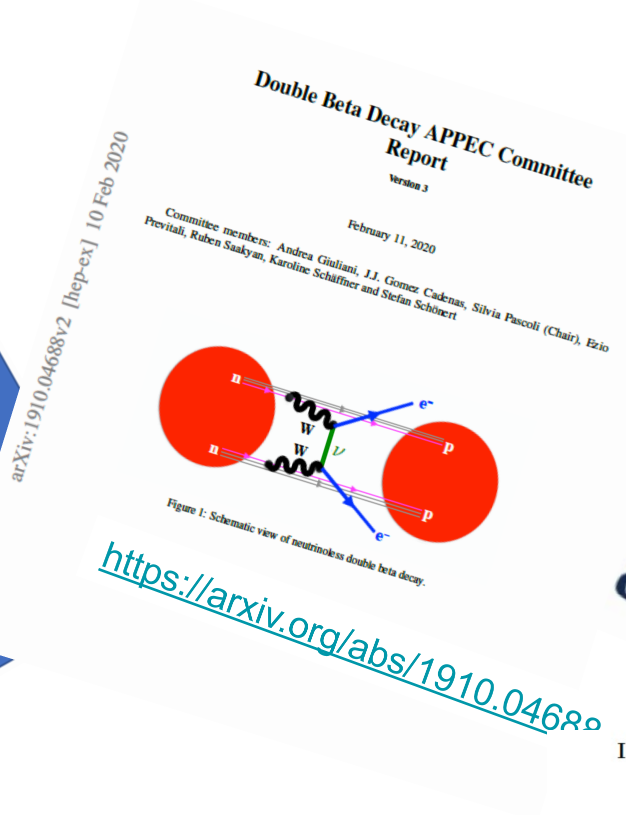


International Landscape

UCL

https://science.osti.gov/np/nsac

DOE NP Portfolio Review
July 2021
CUPID
LEGEND-1000
nEXO



https://arxiv.org/abs/1910.04688

https://agenda.infn.it/event/27143/

IUPAP Neutrino Panel White Paper

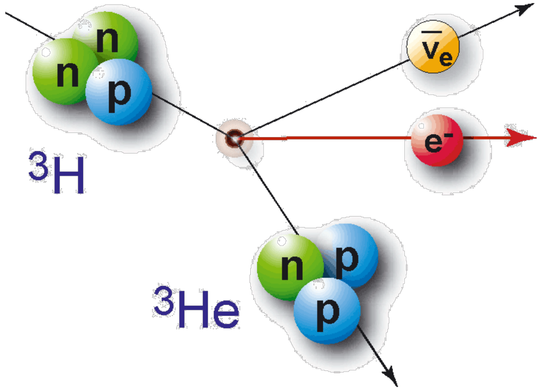
New LRP process started (2023-2032)

Concluding Remarks

- $0\nu\beta\beta$ is the best way to probe **Lepton Number Violation** and its connection to preponderance of **matter** and **neutrino mass** generation mechanism
- Huge progress over past decade has led to a **coordinated international effort**
  - Phased approach, convergence on experiments fully covering I.O. sensitivity
  - Continuing R&D to tackle N.O. and detailed exploration of signal
  - Strong effort in NME modelling, ab initio calculations, experimental input
- Interplay with oscillations, cosmology and β-decay results yields a significant likelihood of **discovery in next 2-15 years**!
- $0\nu\beta\beta$ could be driven by a different LNV mechanism – open minded, **discovery oriented** search

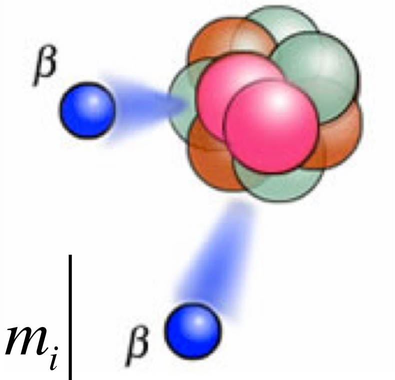
Additional Material

β-decay

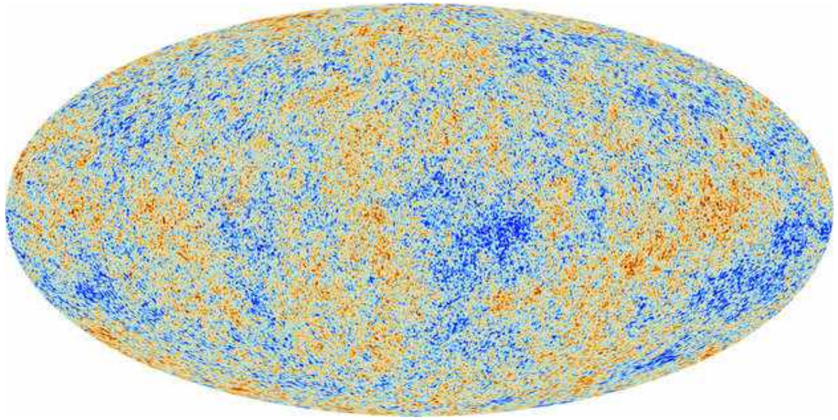


$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 \cdot m_i^2}$$

0νββ-decay



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

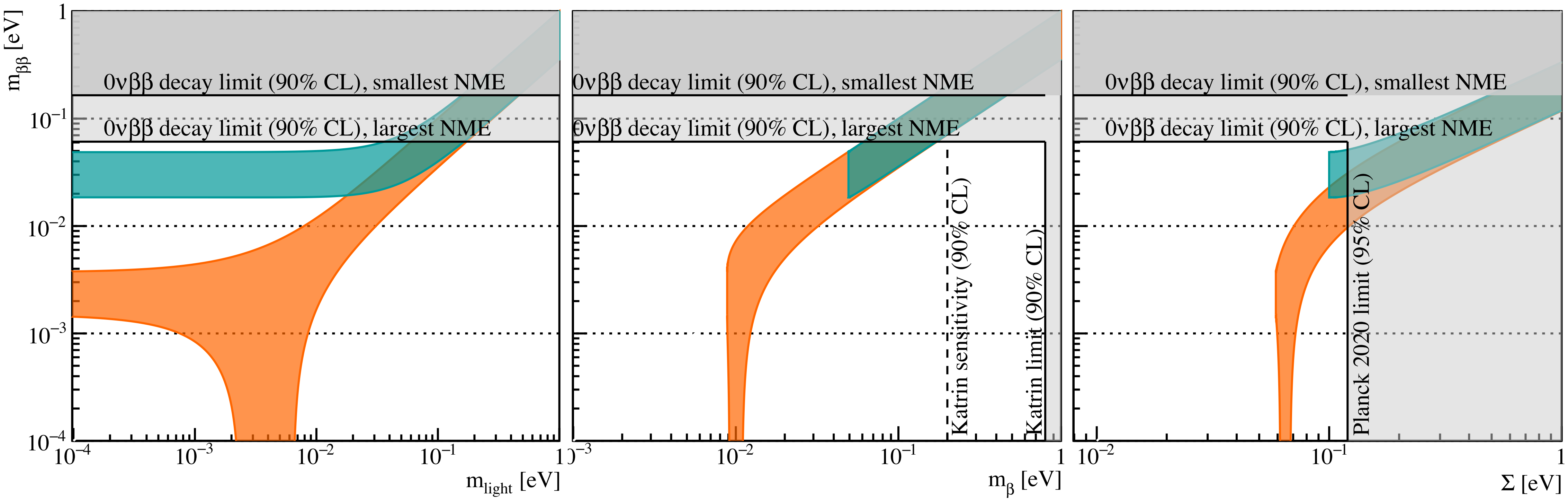


Cosmology

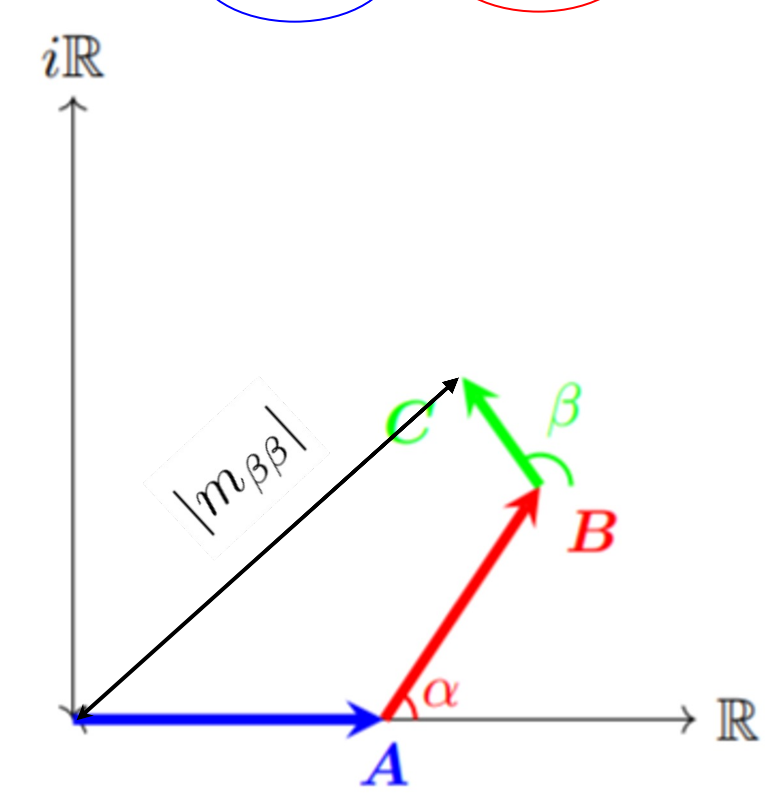
$$\sum_i m_i$$

Interplay between different neutrino mass measurements

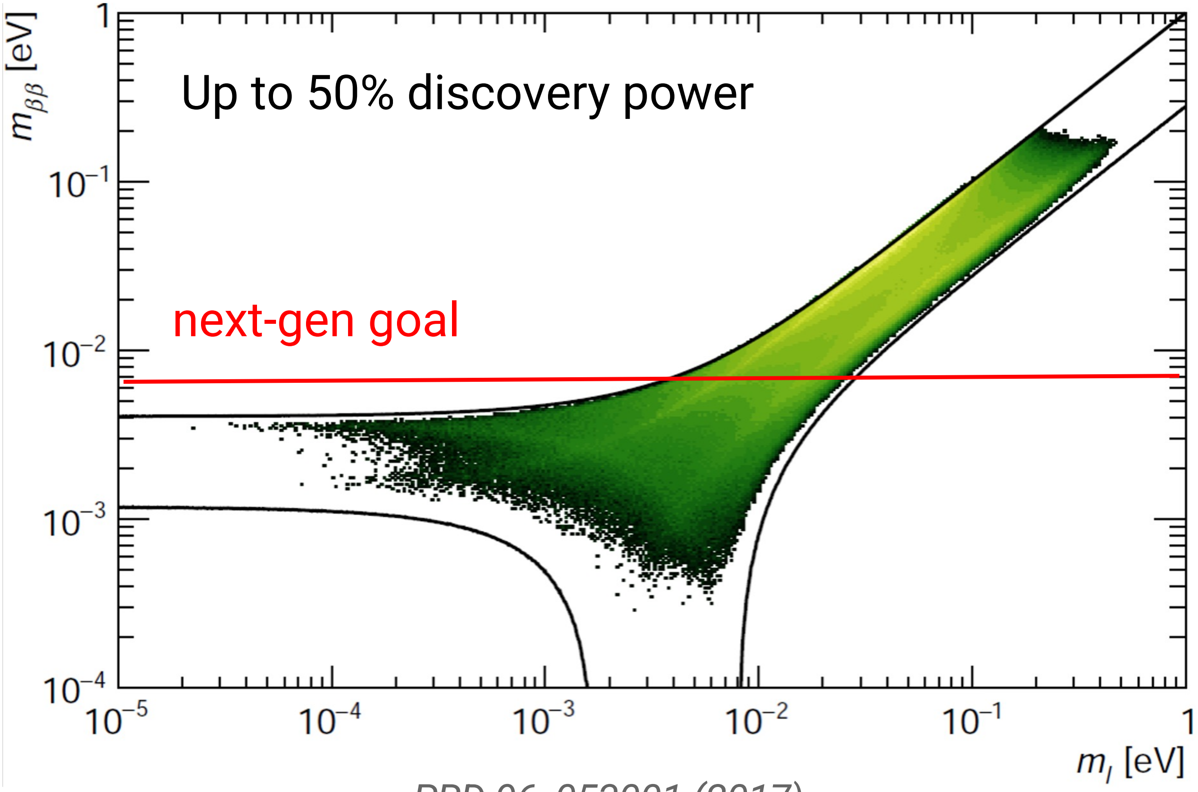
arXiv:2202.01787



$$|m_{\beta\beta}| = |c_{12}^2\, c_{13}^2\, m_1 + s_{12}^2\, c_{13}^2\, m_2\, e^{i2\alpha} + s_{13}^2\, m_3\, e^{i2\beta}|$$

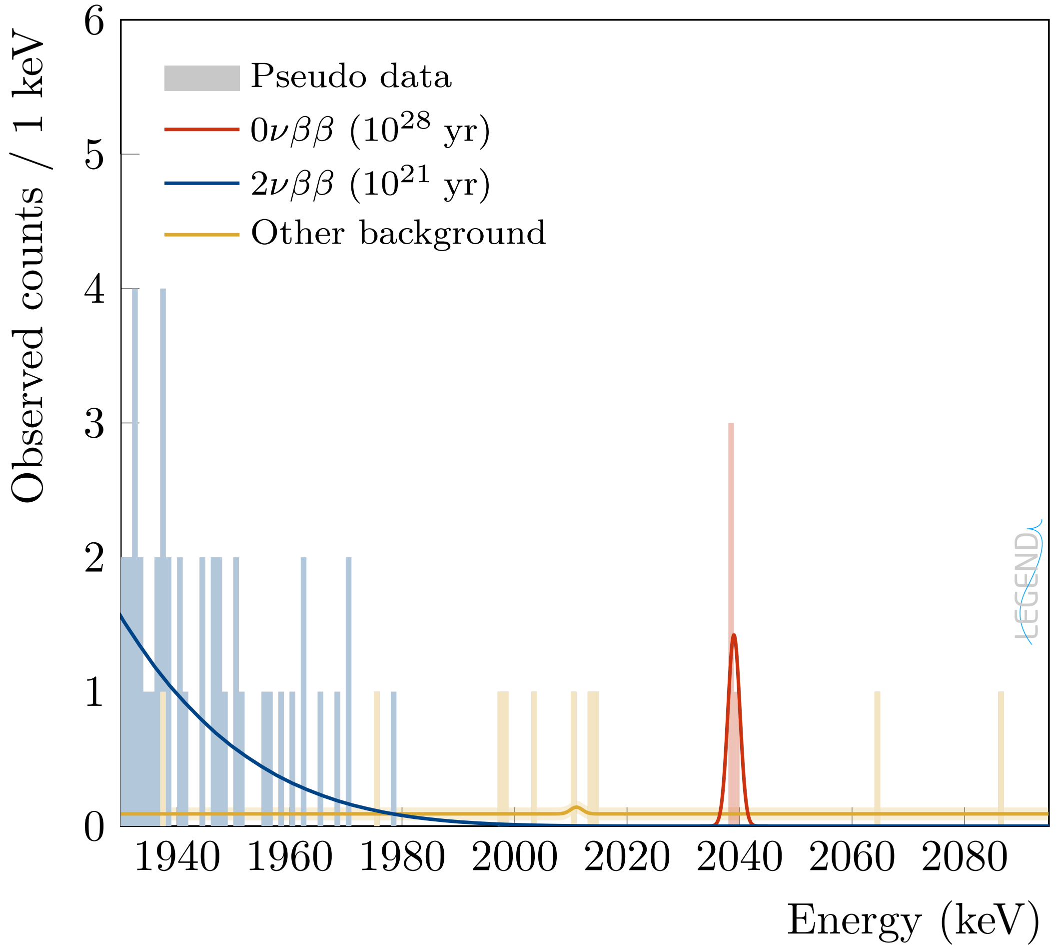


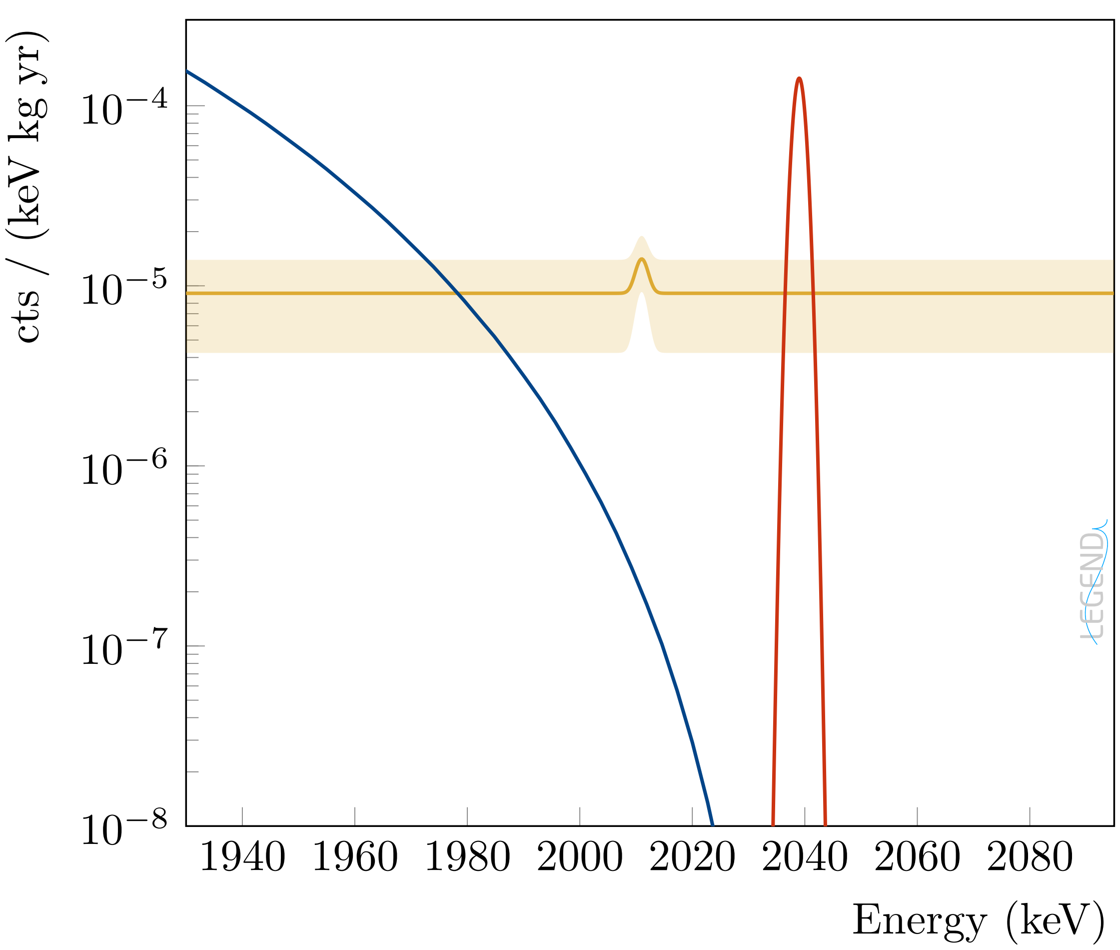
Not equiprobable parameter space: random phases favors large $m_{\beta\beta}$ values.



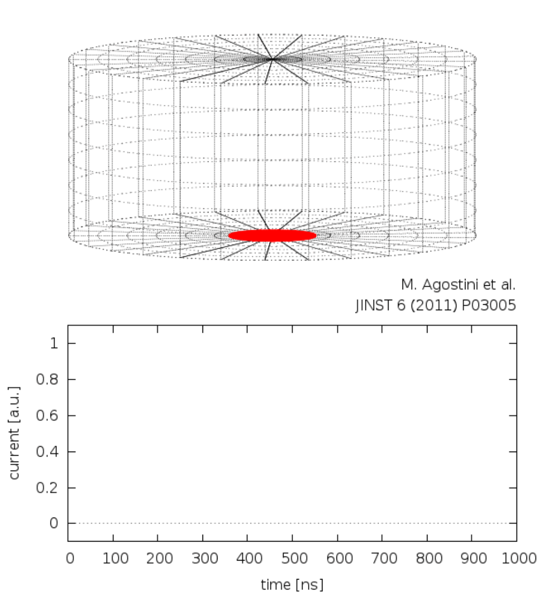
PRD 96, 053001 (2017)

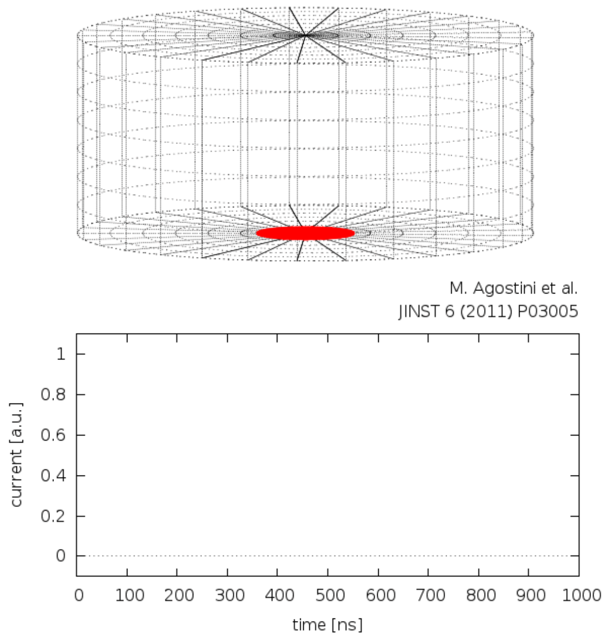
LEGEND 10 t.yr exposure

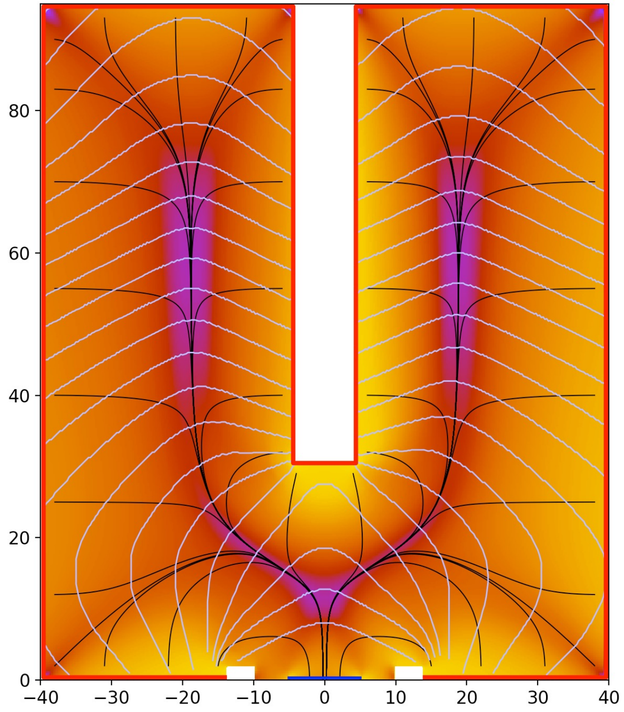




HPGe point-like detectors







Inverted Coaxial Point Contact

- Source = Detector: $HP^{76}Ge$
- Superb energy resolution ~0.1% at Q_{bb} = 2039 keV
- "Solid state TPC" capabilities: particle ID and background rejection
- Feasibility to reach zero BG regime

GERDA
Majorana
→ LEGEND-200 → LEGEND-1000