Neutrinoless $\beta\beta$ Decay and LEGEND

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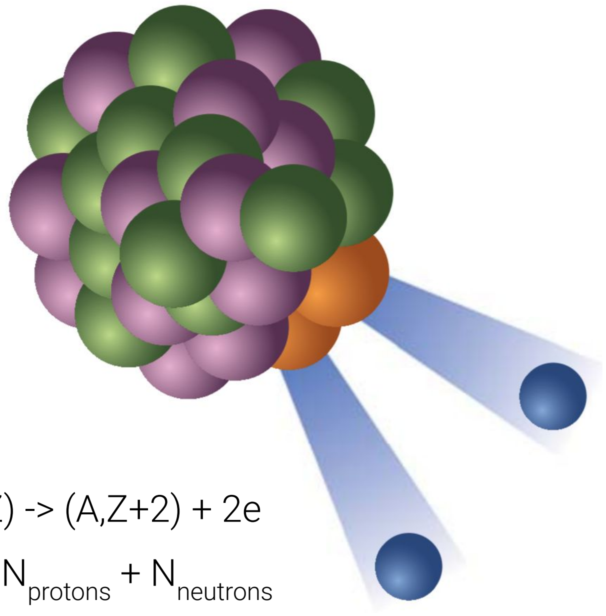
STFC Ernest Rutherford Fellow at UCL
EPAP Seminar - King's College
Feb 24, 2023

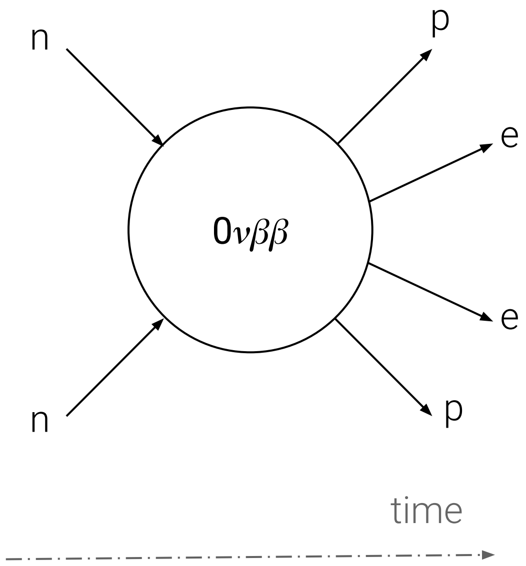
What are we looking for?



(A,Z) -> (A,Z+2) + 2e

$A = N_{protons} + N_{neutrons}$

$Z = N_{protons}$



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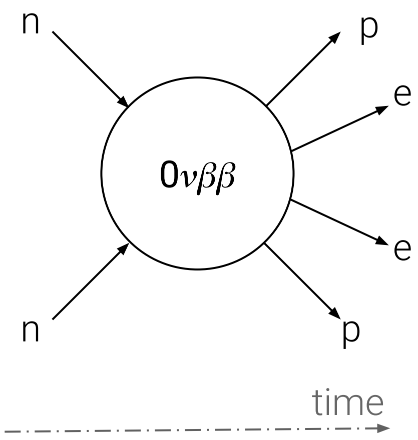
(A,Z) -> (A,Z+2) + 2e

- 2 neutrons -> 2 protons (ΔB = 0)
- 2 electrons are emitted (ΔL = 2)



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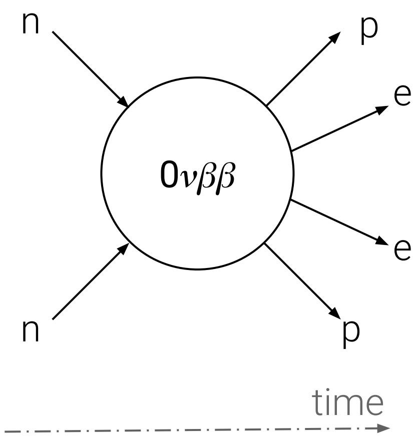

Matter-creation in the laboratory!
Direct violation of **L** and **B-L**

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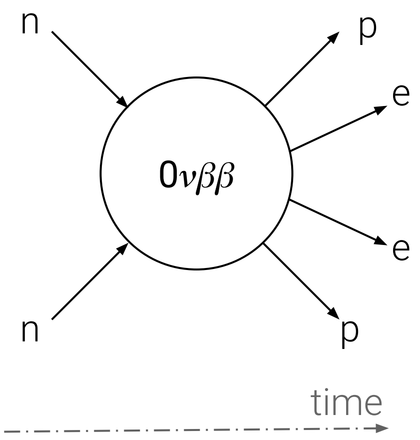

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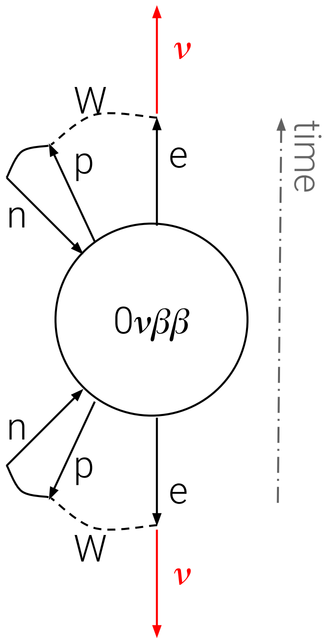
Same diagram

creates $\boldsymbol{\nu}\leftrightarrow\overline{\boldsymbol{\nu}}$

Schechter and Valle

1982



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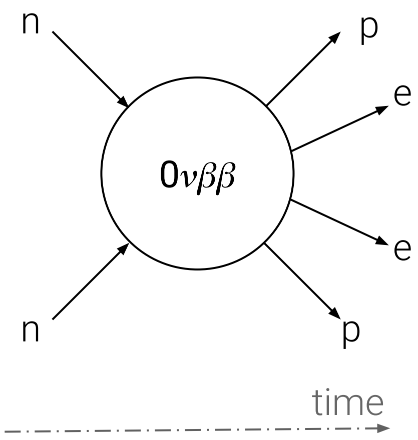

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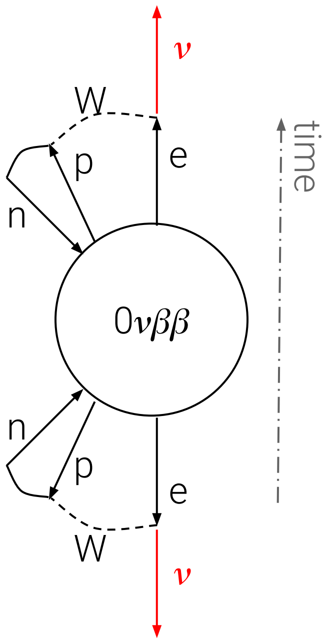
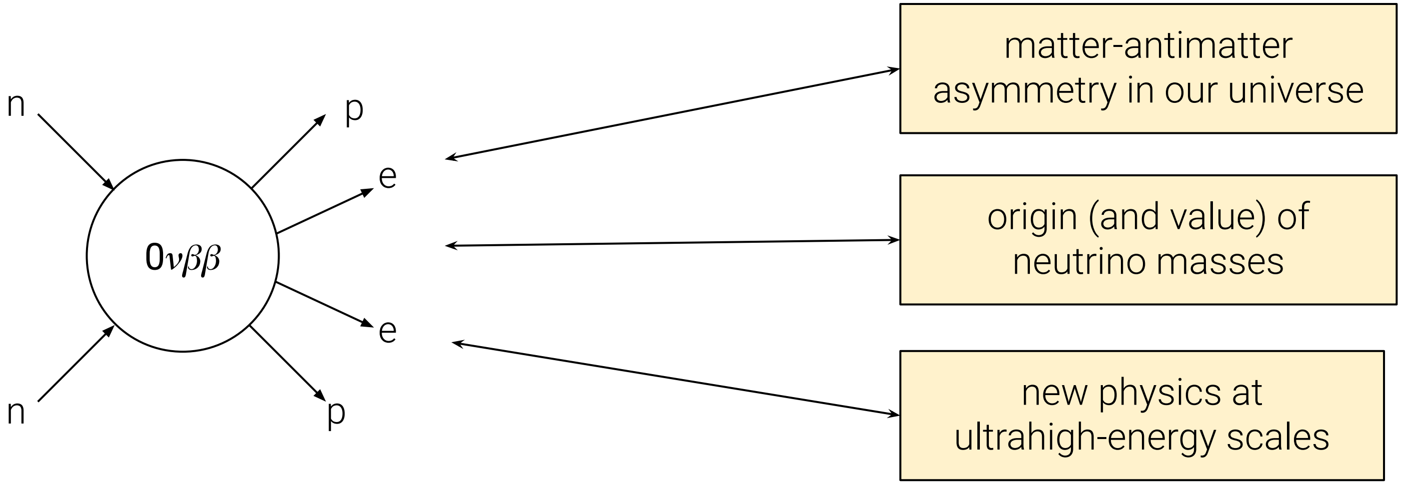


Prove that **neutrinos and antineutrinos** are the **same object**

Addressing the most pressing theory questions



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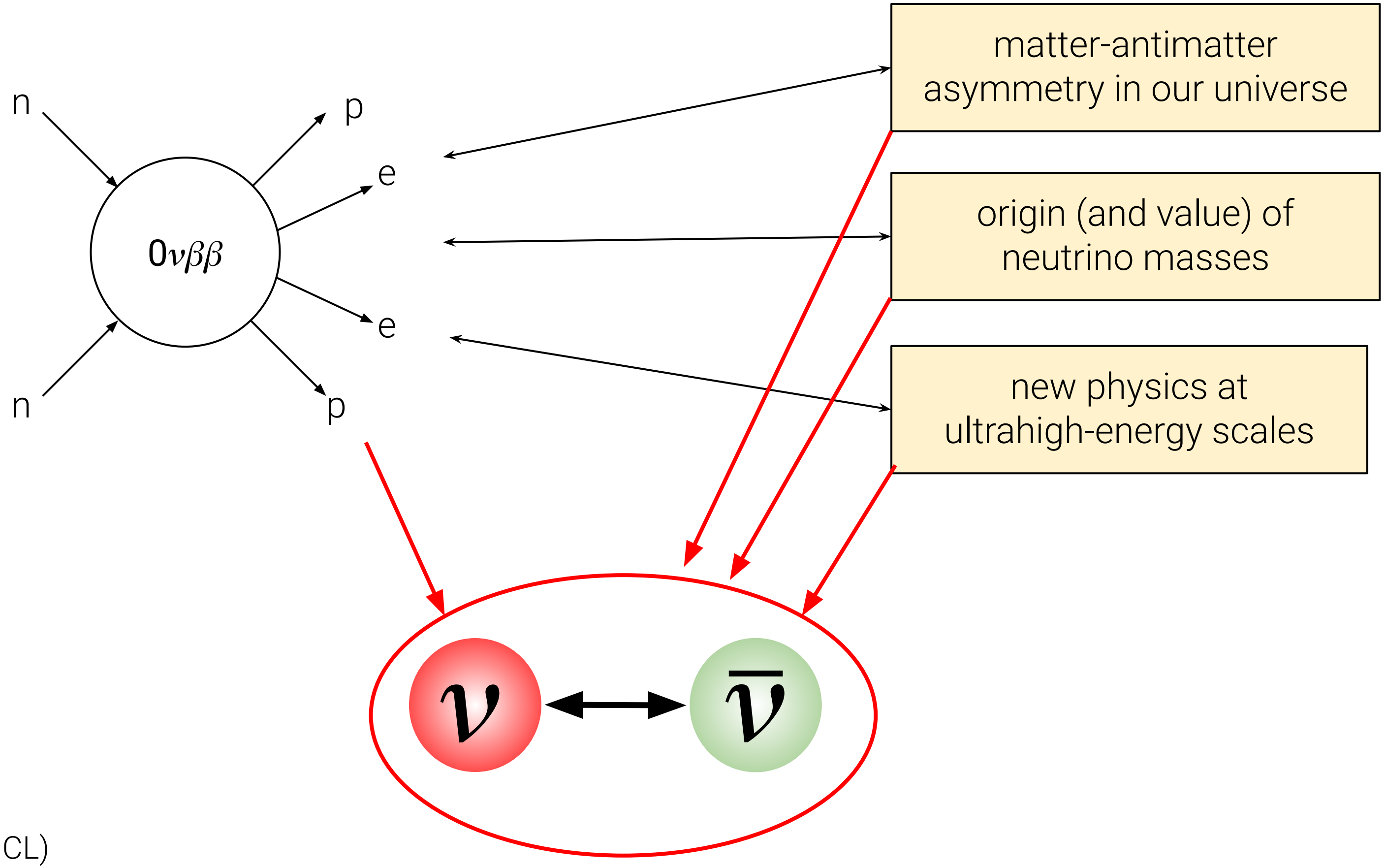
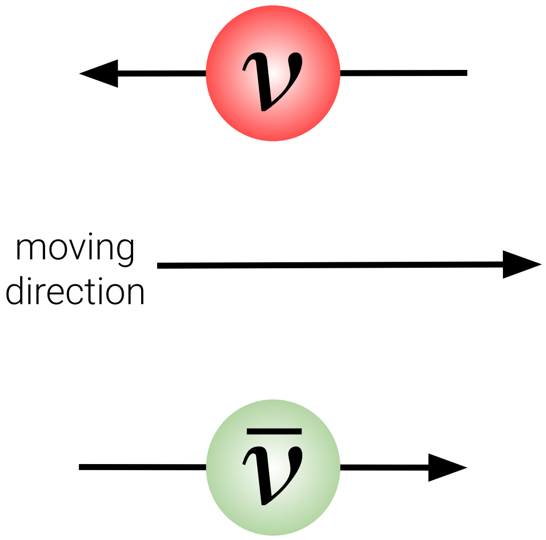


What distinguishes neutrinos from antineutrinos?

If they have no mass…



1) spin/helicity -> intrinsic semi-classical property

2) chirality -> weak force when they are created/destroyed

Dell'Oro, Marcocci, Viel and Vissani, Adv.High Energy Phys. 2016 (2016) 2162659

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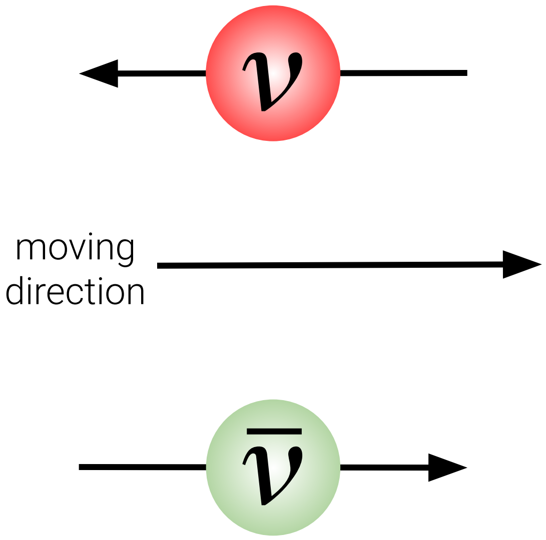
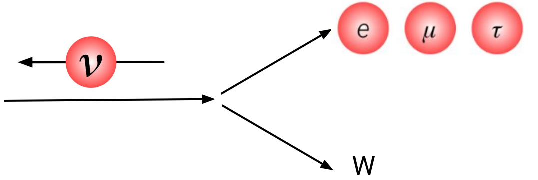
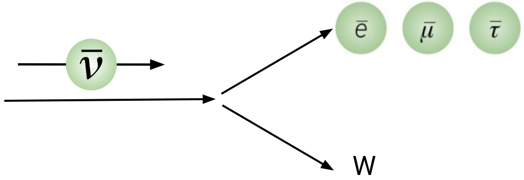




neutrinos move **antiparallel** to their spin

left-handed chirality -> weakly-interact creating **particles**



anti-neutrinos move **parallel** to their spin

right-handed chirality -> weakly-interact creating **antiparticles**

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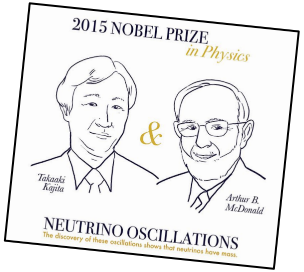
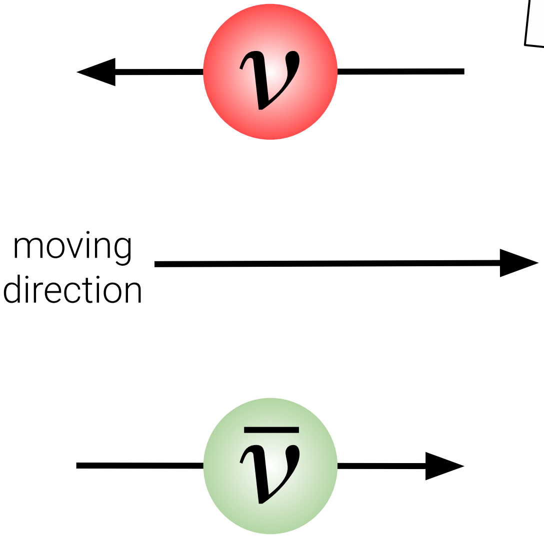
What distinguishes neutrinos from antineutrinos?

But neutrinos are massive!





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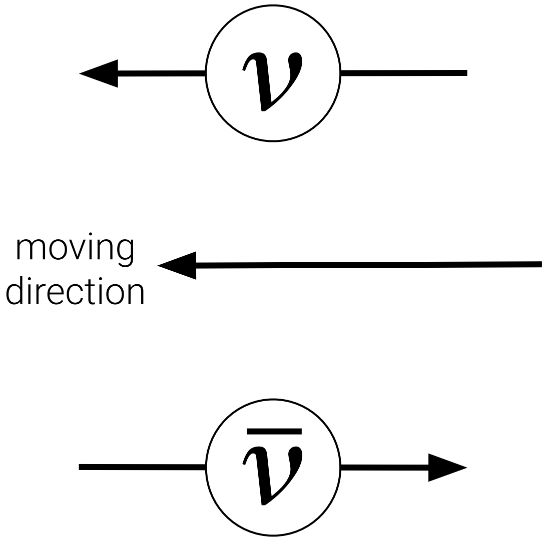
What distinguishes neutrinos from antineutrinos?

We can boost in a frame in which they move in the opposite direction



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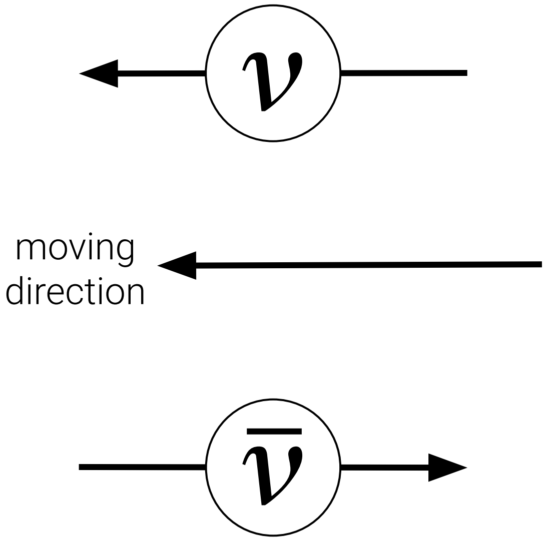
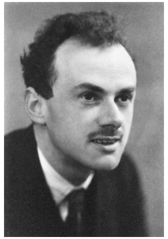
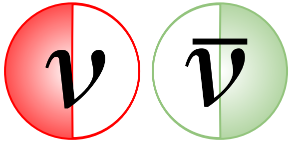
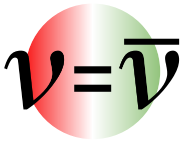




Dirac



Majorana



There are two new non-interacting “sterile” states….

…or the same object has both chiral states

Dell’Oro, Marcocci, Viel and Vissani, Adv.High Energy Phys. 2016 (2016) 2162659

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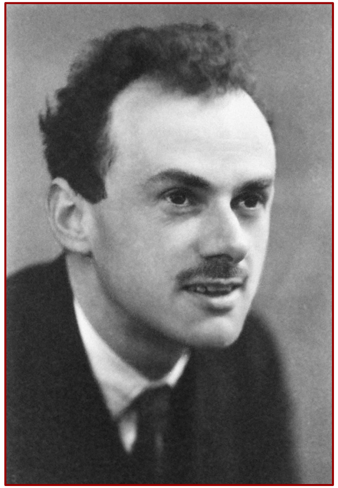
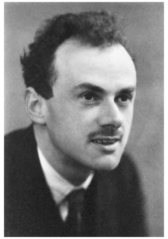


νs

Majorana

Neutrino masses



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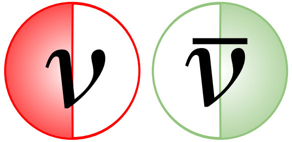
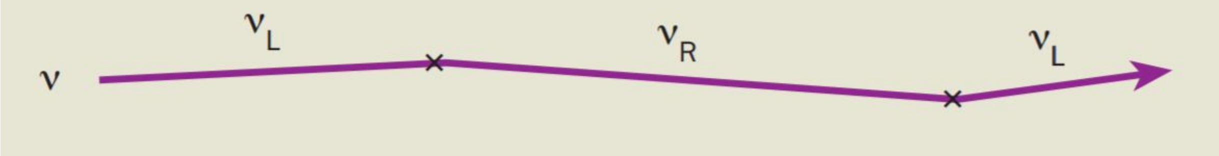
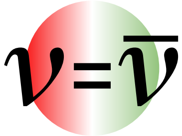
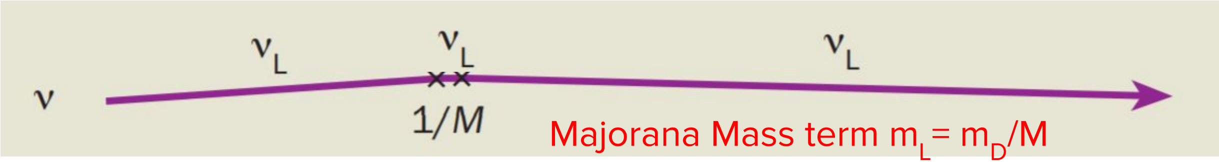




- new right-handed neutrinos
- standard Higgs mechanism
- “unnaturally” small neutrino masses

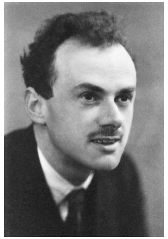
Majorana





- alternative Higgs mass mechanism
- neutrino mass violates L (and thus B-L)
- “naturally” small mass (see-saw mechanism)

Neutrino masses



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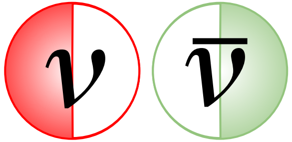

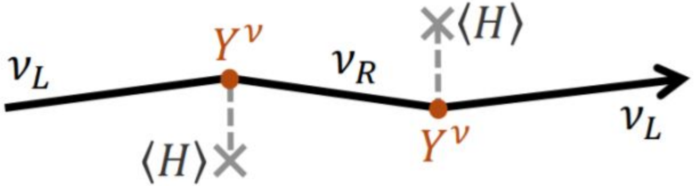

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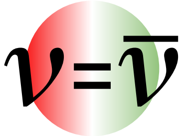

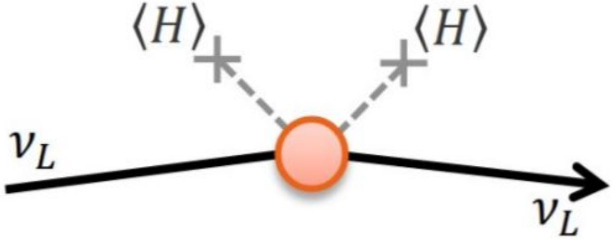

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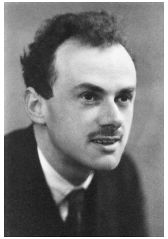

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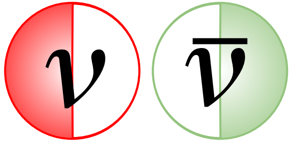

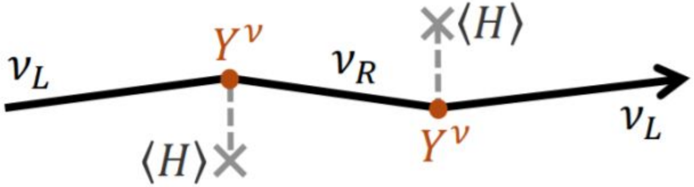

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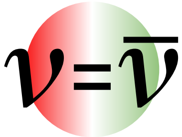

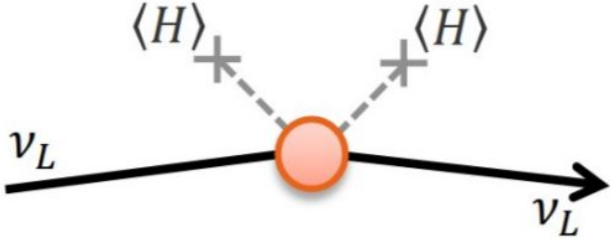

neutrinos desperately want to be an Italian particle

A bit of history

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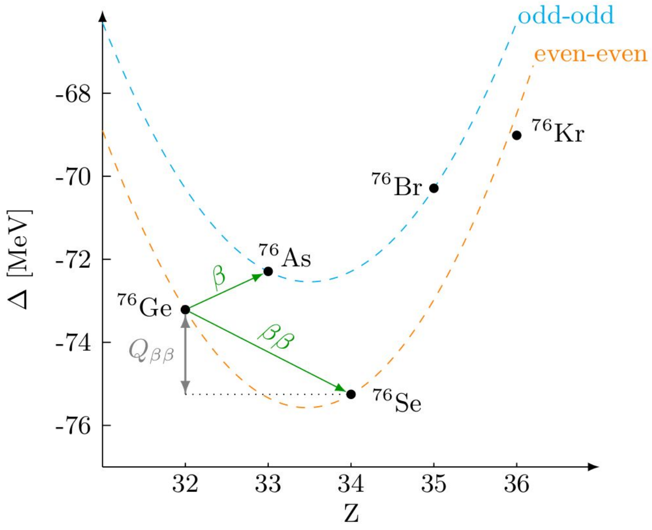
1935: Goeppert-Mayer → $\beta\beta$ decay

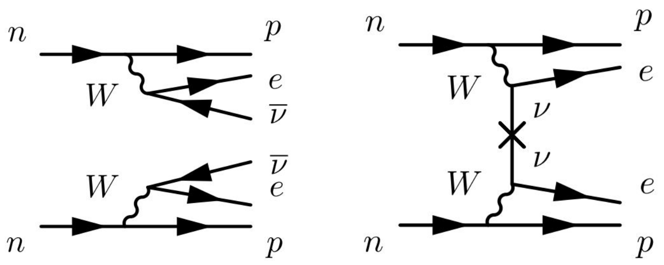
1937: Majorana and Racah → the neutrino is its own antiparticle

1939: Furry → "neutrinoless $\beta\beta$ decay" ($0\nu\beta\beta$)

1987: Moe's → first observation of a $\beta\beta$ decay with neutrinos ($2\nu\beta\beta$)

2000: SNO/SK → discovery that neutrinos oscillate → are massive





MA, Benato, Detwiler, Menéndez and Vissani, RMP 2023 (arXiv:2202.01787)

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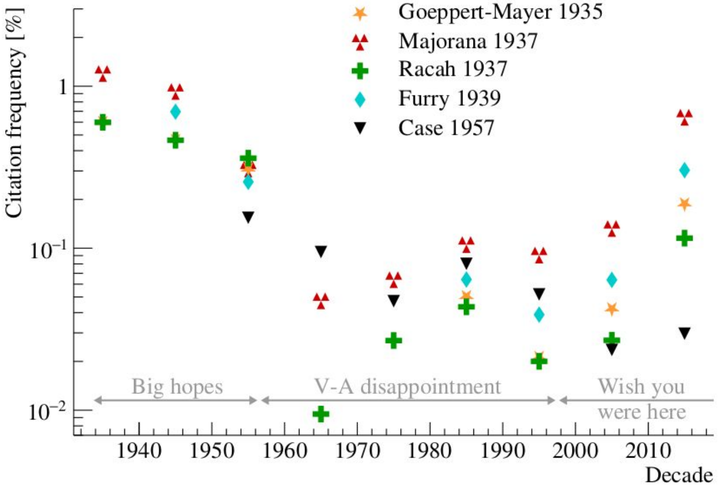

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How did we end up with this name?

OK, it is a nuclear transition

Neutrinoless double-beta decay

beta refers to “beta-rays”, something used when people believed electrons were leaving within the atomic nuclei

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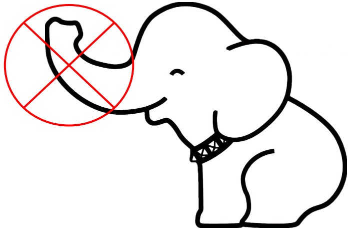
Neutrinoless double-beta decay

Nobody would call hippos
"trunkless elephants"



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What about
lepton-creating nuclear decay?

What can we measure?

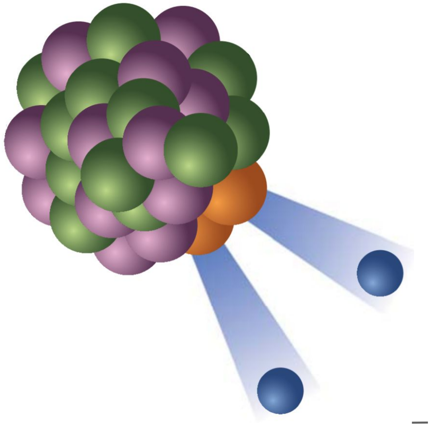
- decay rate
  - electron momentum
    - daughter isotope
      - gamma-rays from excited states

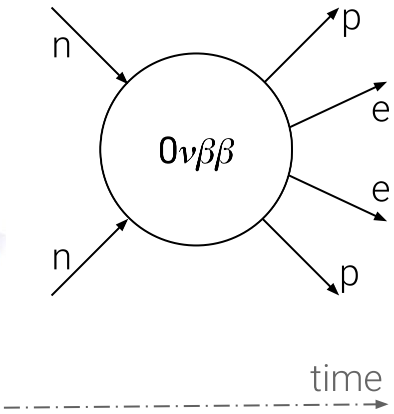
A portal to new physics beyond the SM

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

Particle Physics

Nuclear Physics





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Particle Physics

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

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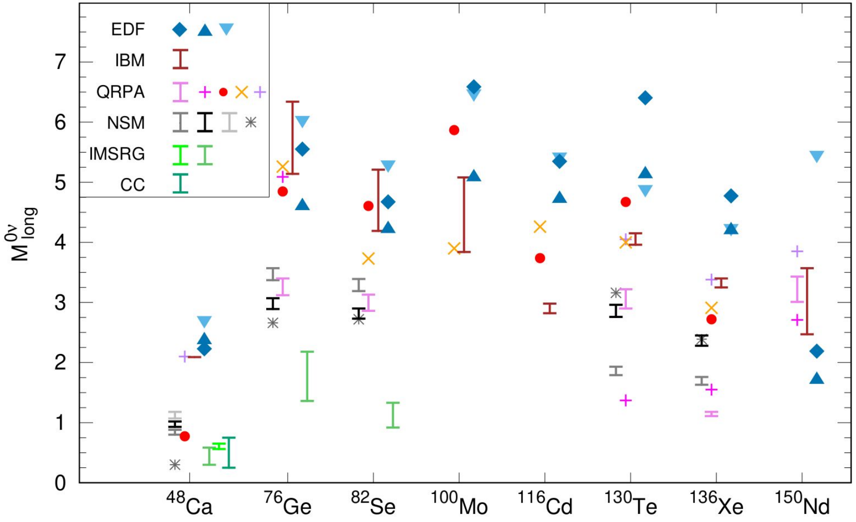

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Deppisch, Graf, Iachello and Kotila
Phys.Rev.D 102 (2020) 9, 095016

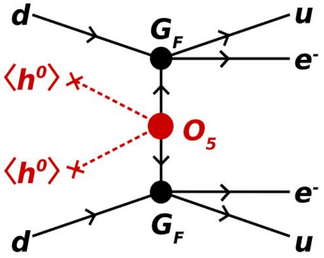
Cirigliano et al., JHEP 12, 097 (2018)

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

- ν → Higgs vacuum expectation
- Λ → energy scale of BSM

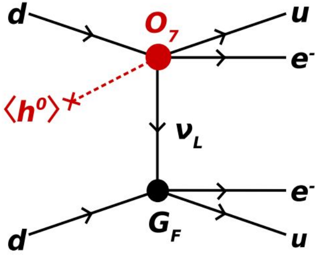
Dim 5: Weinberg Operator

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



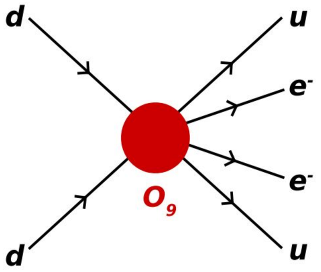
Dim 7

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



Dim 9

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



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Higgs vacuum expectation

ergy scale of BSM

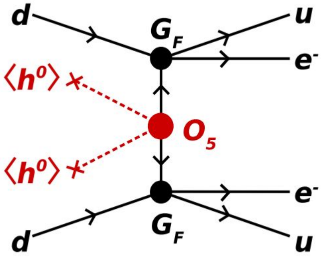
$0\nu\beta\beta$ and collider searches are similar

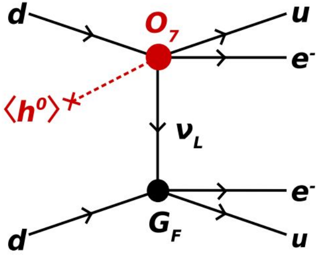
$T_{1/2}$ is proportional to the energy scale

Open search for a signal that can manifest at any time!

Dim 5: Weinb

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





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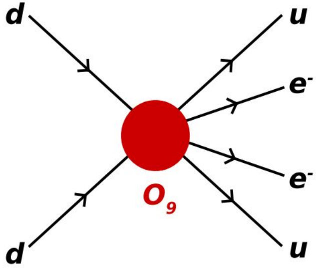
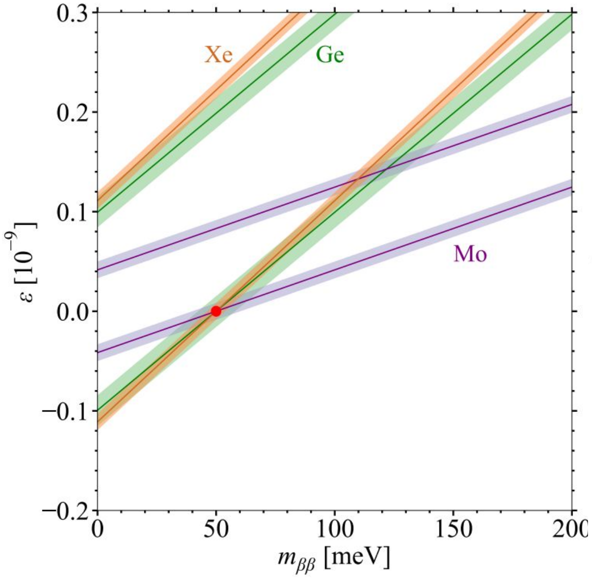


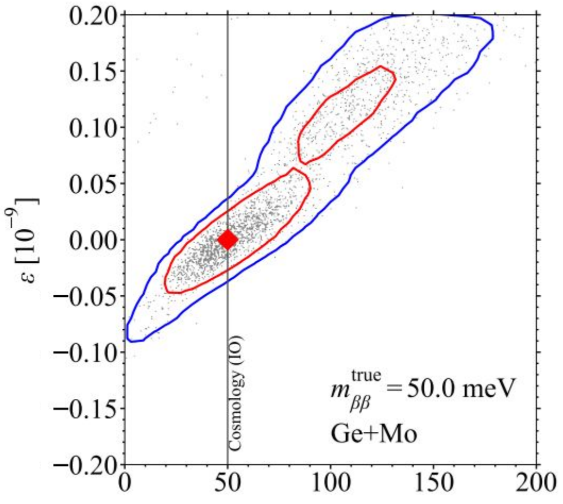
Probing the mechanism

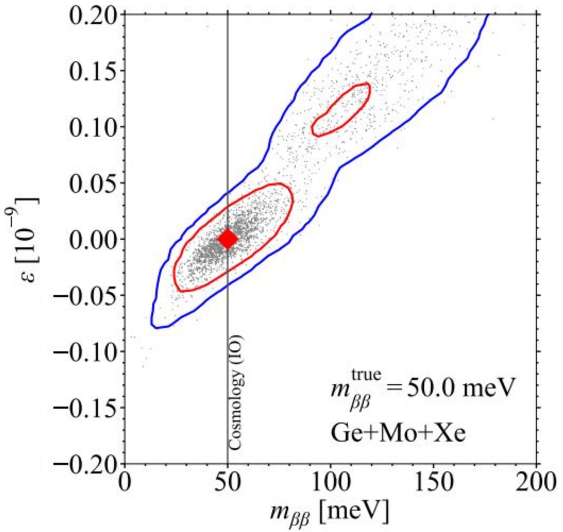
$$T_{1/2}^{-1}(X) = G^{(0)}_{11+}(X)\left[\frac{m_{\beta\beta}}{m_e}M_\nu(X) + \epsilon M_{\mathrm{SR}}(X)\right]^2$$

- Data in multiple isotopes pin down channels
- NME values drive sensitivity
- epsilon: R-parity-violating supersymmetry, similar conclusions for other models

MA, Deppisch, Van Goffrier, JHEP 02 (2023) 172



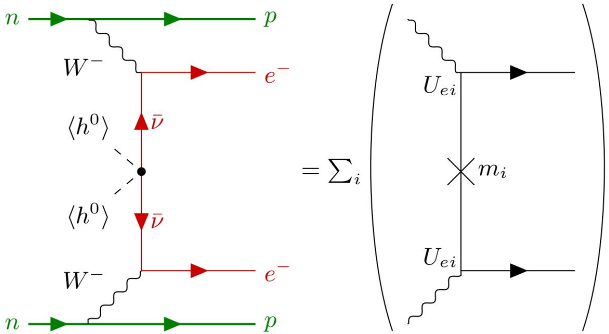




Discovery odds for the vanilla model

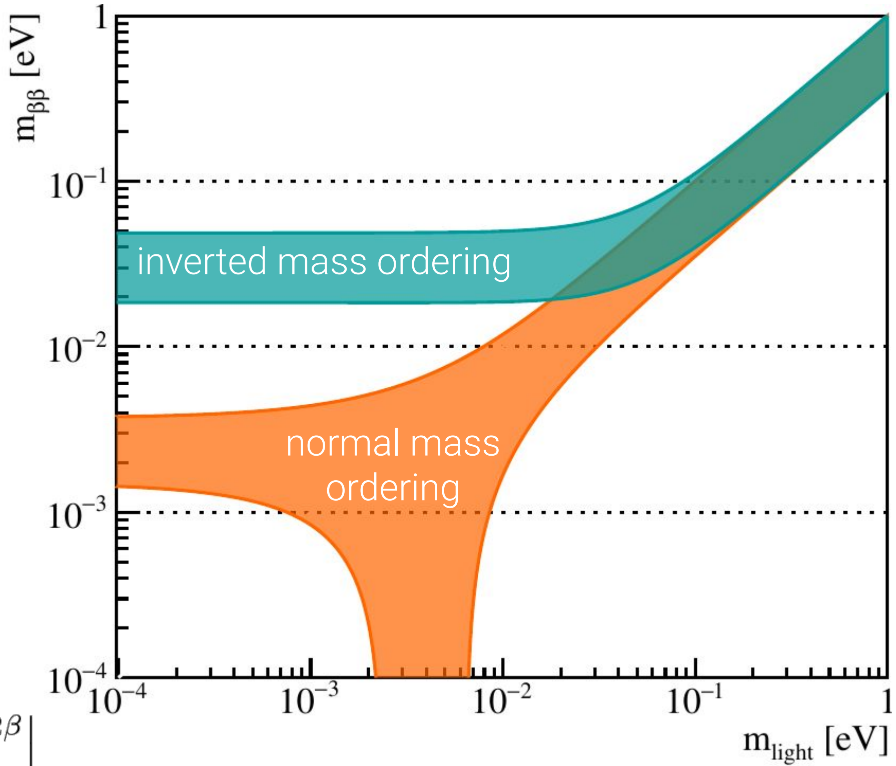
Light Majorana neutrino exchange

$$P \propto \left(\frac{\nu}{\Lambda}\right)^2 \quad \text{with} \quad \frac{\nu}{\Lambda} \propto m_{\beta\beta}$$



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

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

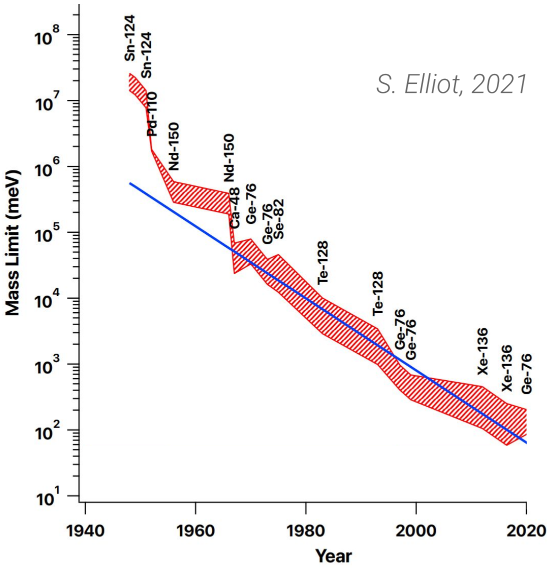


MA, Benato, Detwiler, Menéndez and Vissani, RMP 2023 (arXiv:2202.01787)

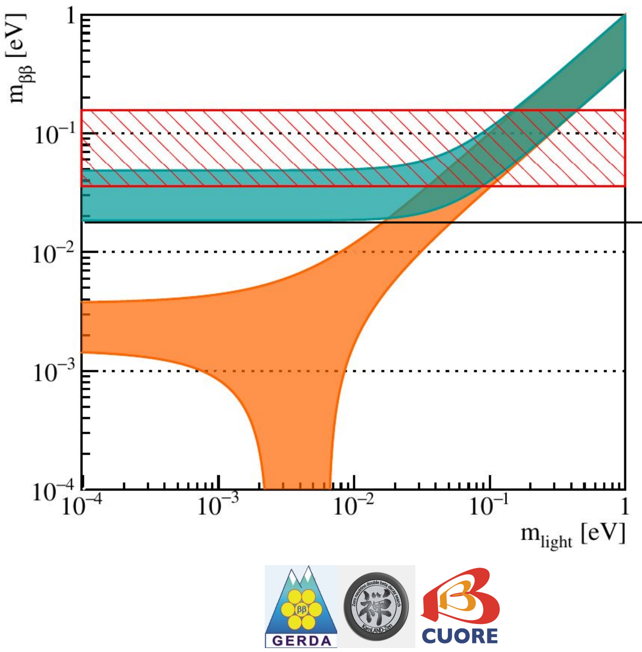
Discovery odds: **inverted** neutrinos

Probability for an atom to decay: << 1 in a million billion times the age of the universe

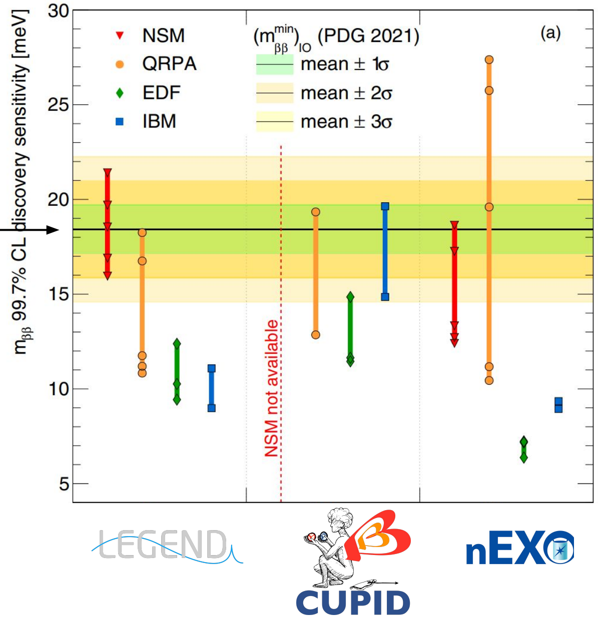
1940-2020



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



Future: $T_{1/2} > 10^{28}$ yr

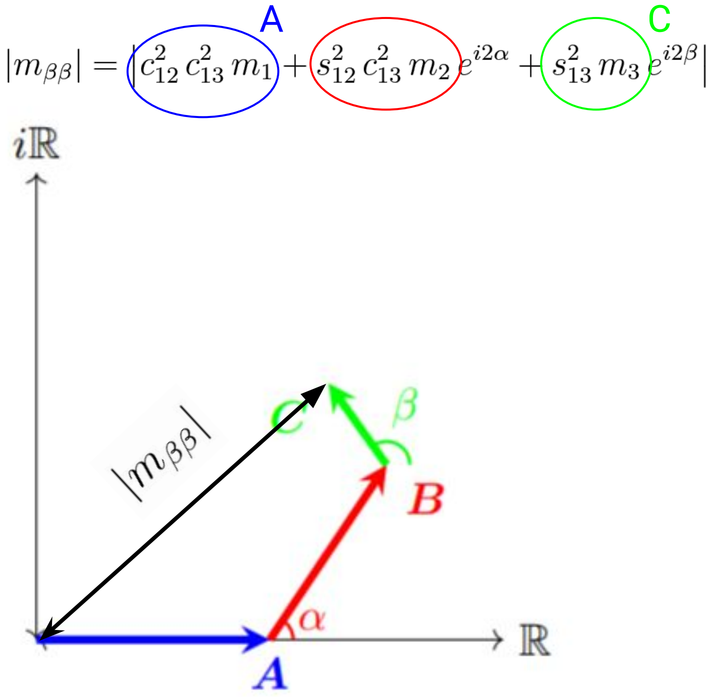


M.A., Benato, Detwiler, Menéndez and Vissani
PRC 104, L042501

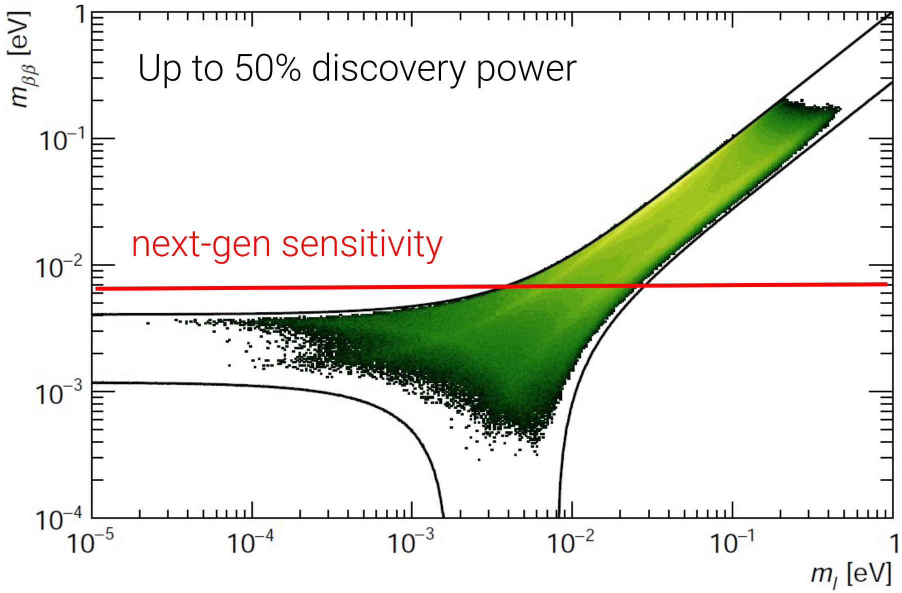
Matteo Agostini (UCL)

Discovery odds: **normal** ordered neutrinos

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



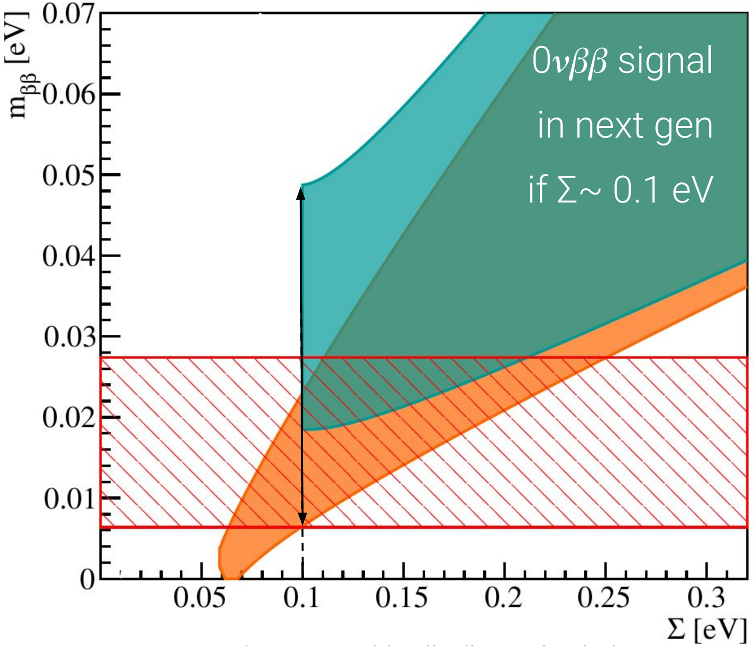
Not equiprobable parameter space: random phases favors large $m_{\beta\beta}$ values.



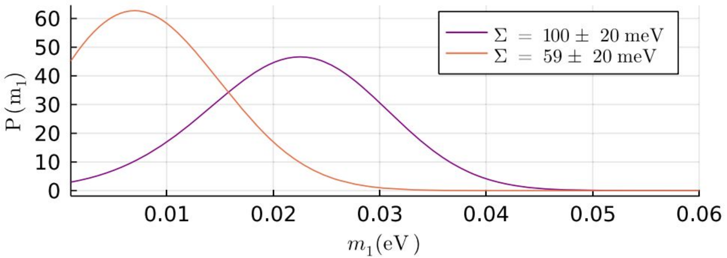
MA, Benato and Detwiler, PRD 96, 053001 (2017)

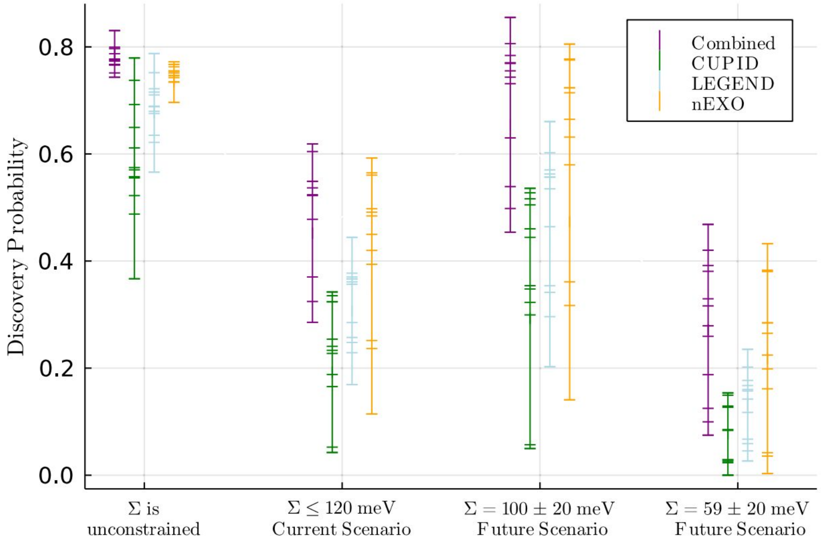
Discovery odds: **normal** ordered neutrinos

Cosmology surveys (DESI/EUCLID) close to measure $\Sigma = \sum_i m_i$



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





LEGEND

The LEGEND Collaboration

2022 Collaboration Meeting @ LNGS

Our mission:

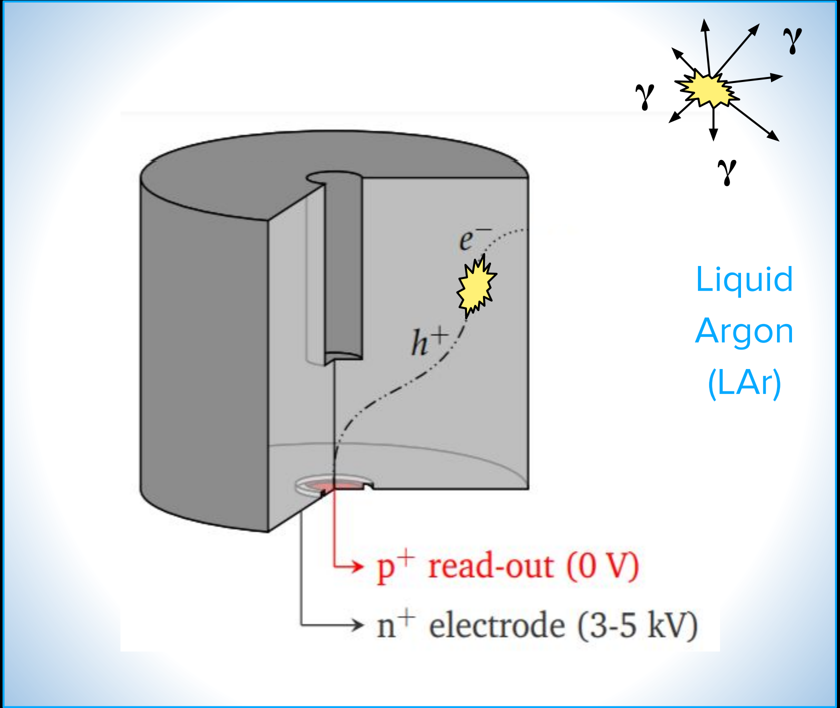
“Develop a **phased**, **^{76}Ge based** double-beta decay experimental program with **discovery potential** at a half-life **beyond 10^{28} years**”

260 members

47 institutions across the world

Two-component detection concept

Semiconductor HPGe Detectors
• 92% of detector material is ^{76}Ge • advanced event reconstruction • high spatial and energy resolution



Liquid Argon Scintillation Detector
• ultraclean and cryogenic liquid • isotropic emission of XUV photons • calorimetric energy measurement

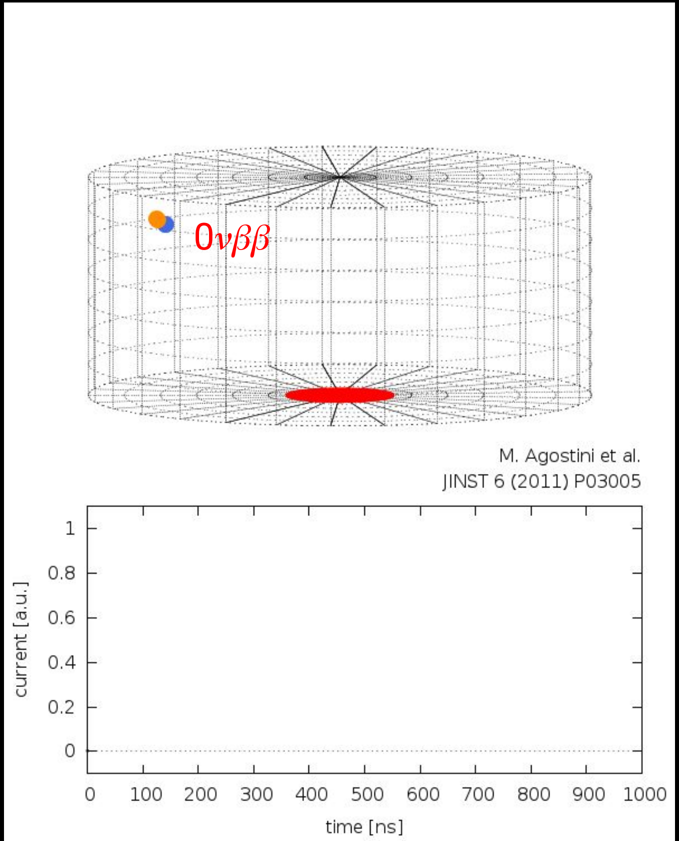
HPGe detectors

Solid state **time projection chambers**

- 200 V/cm minimum E-field
- O(10ns) resolution on the cluster arrival time
- sub-mm-scale cluster separation

Semiconductor detectors

- >10^5 e-h pairs / MeV
- **0.1% energy resolution** at 2 MeV



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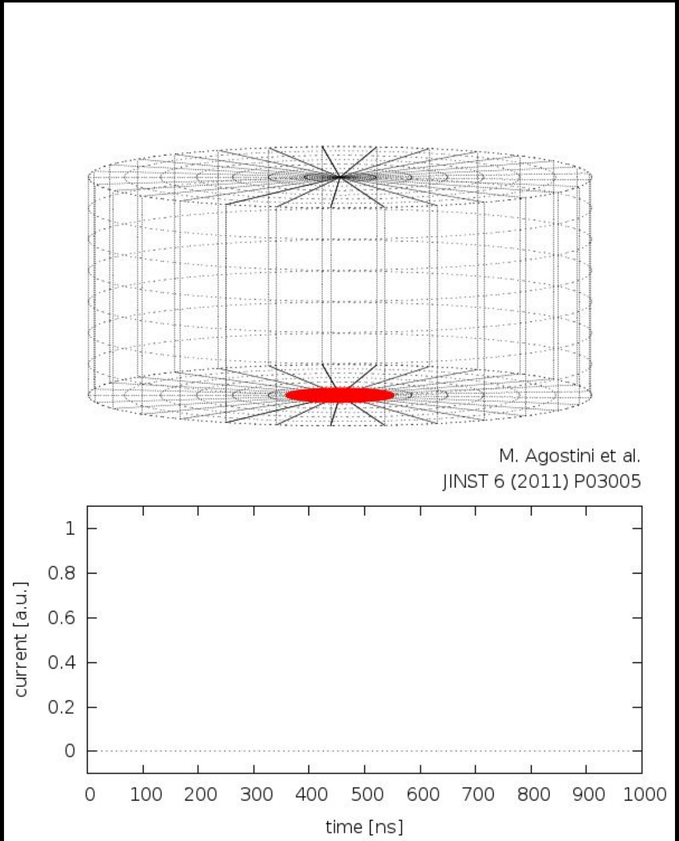

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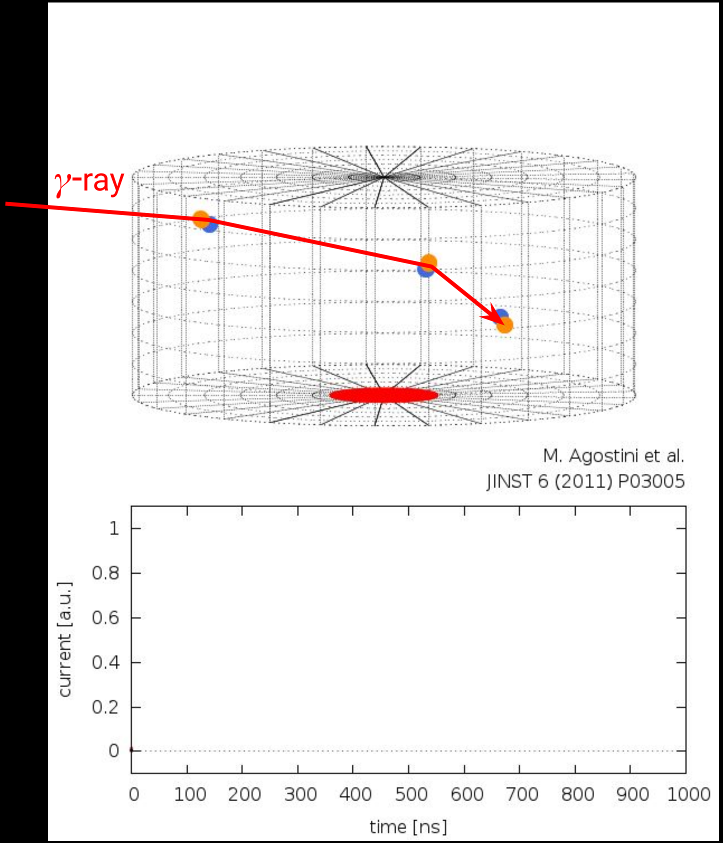

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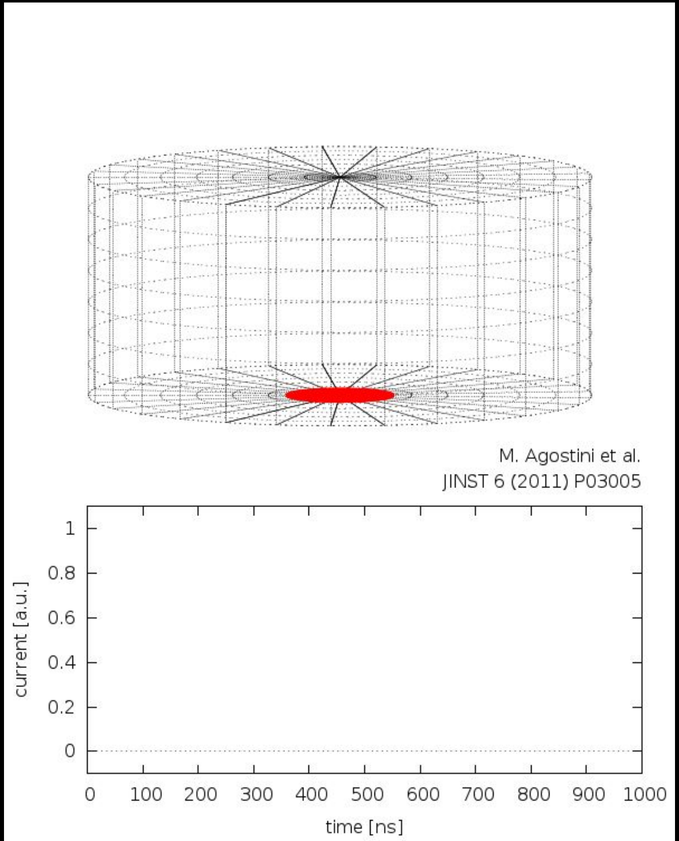

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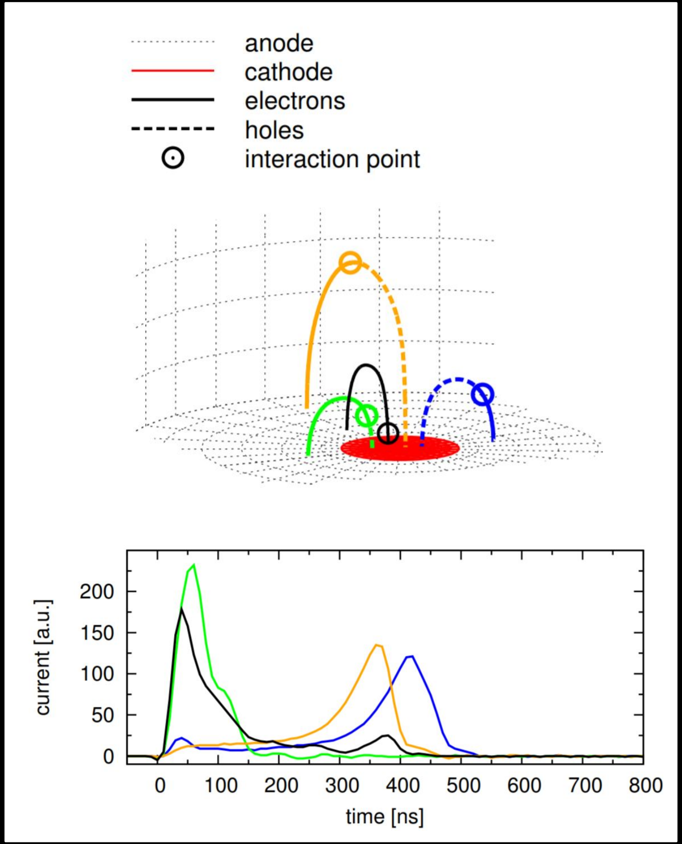

HPGe detectors

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Semiconductor detectors

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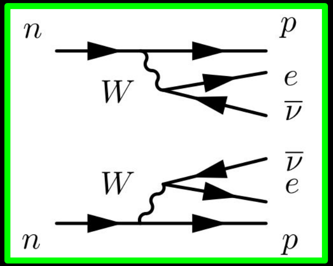

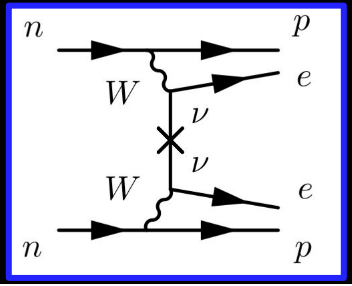

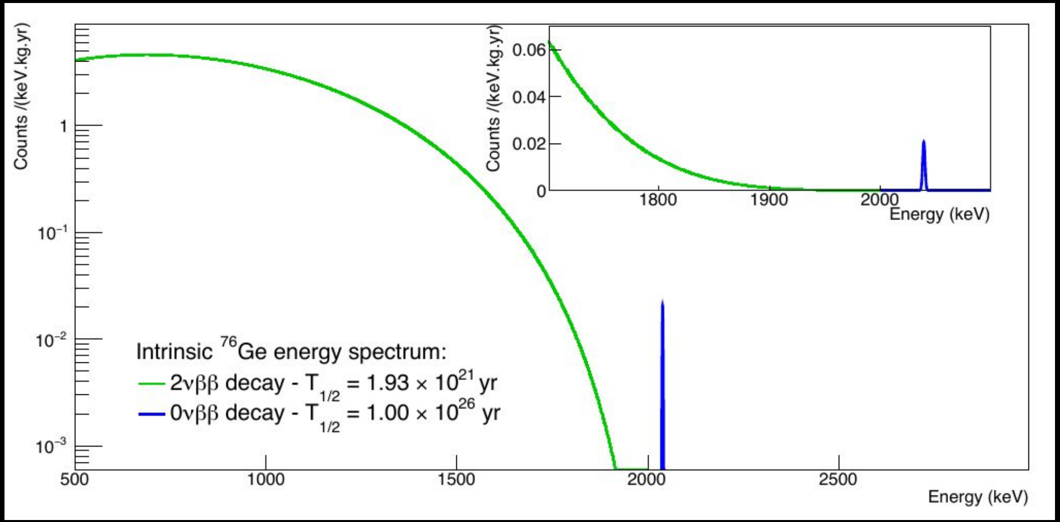

HPGe detectors

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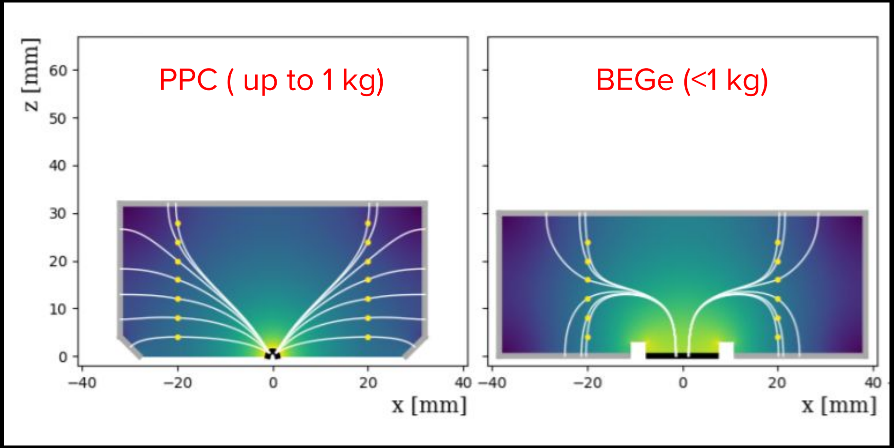
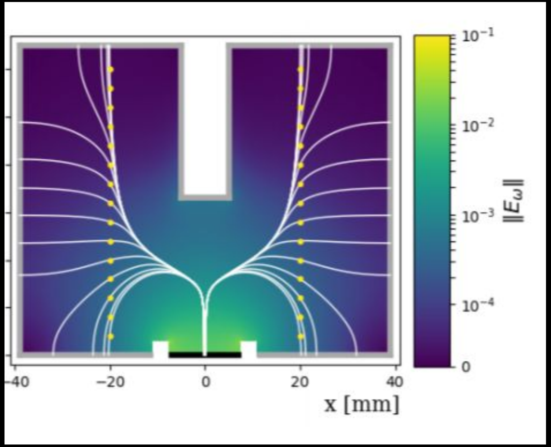


ICPC (LEGEND)
- up to 4 kg
- longer drift times
- optimal PSD

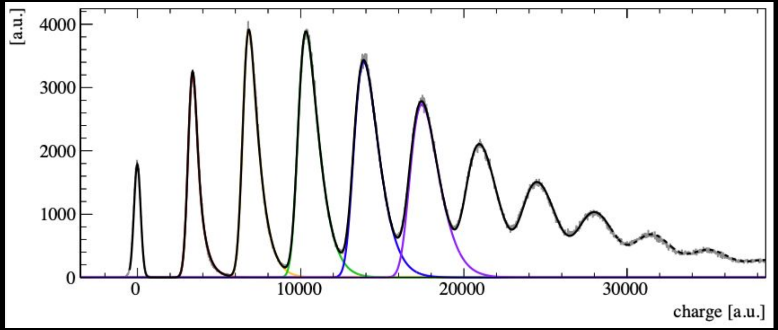


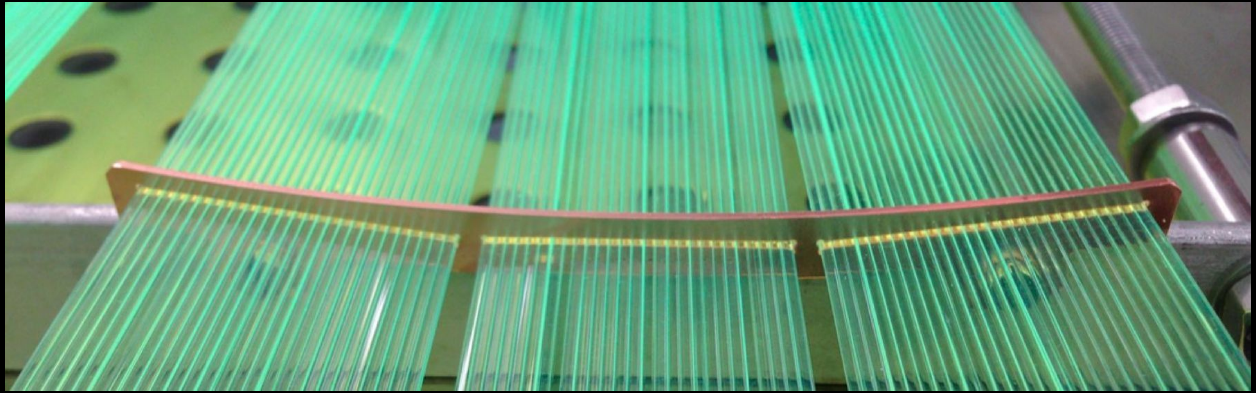
[Eur.Phys.J.C 81 (2021)]

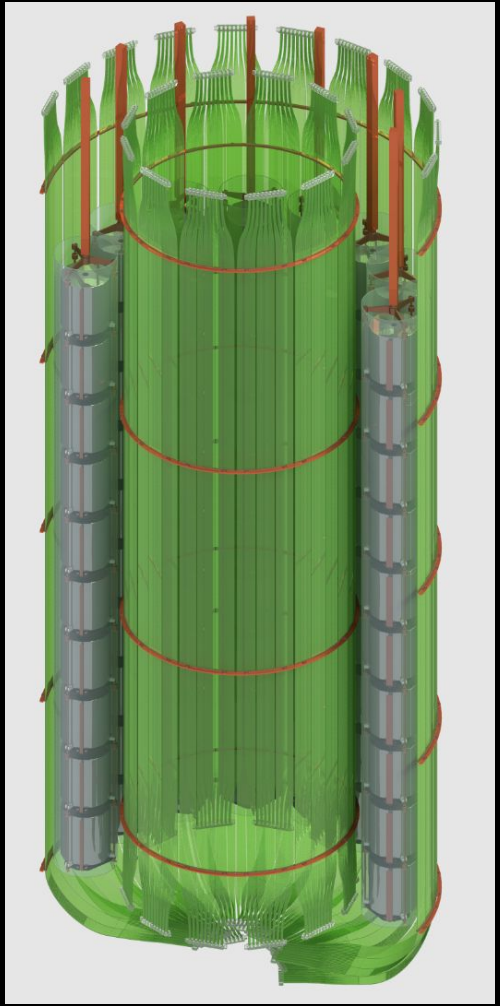
Liquid argon scintillation detector

- $O(10^4)$ XUV photons per MeV
- wavelength shifting surfaces
- fibers and SiPM

LEGEND-200 SiPM characterization







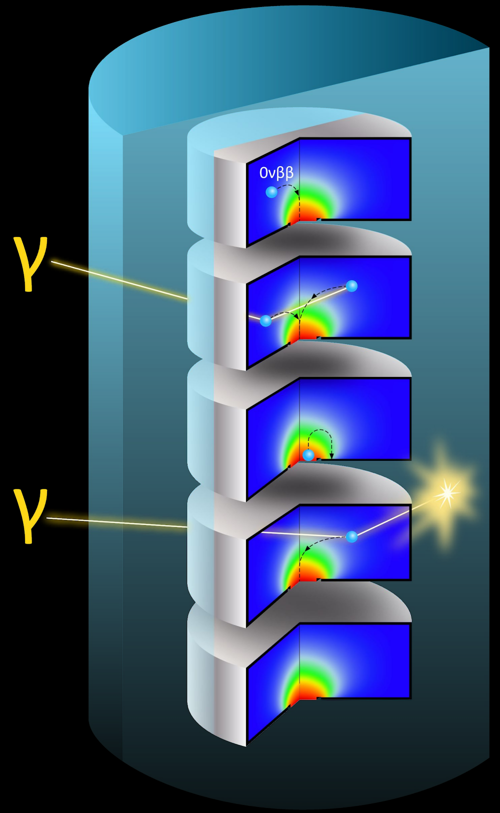
0νββ signal and backgrounds

Multivariate 0νββ tagging

- no energy in LAr
- single Ge-detector hit
- energy = 2039 keV
- single-cluster event in Ge bulk volume (no surface interactions)

Background events can have these features only if:

- Q-value > 2039 keV
- extra energy deposited in dead detector areas



Our design driving principle:

minimize structural material around Ge detectors

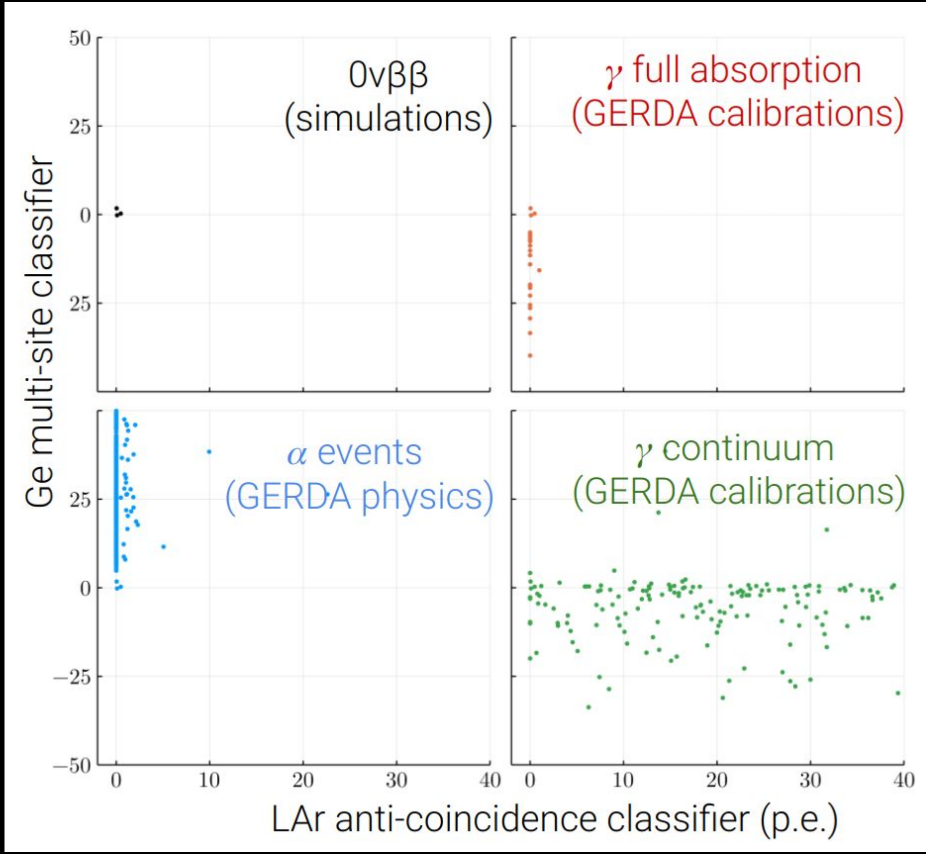
0νββ signal and backgrounds

Multivariate 0νββ tagging

- no energy in LAr
- single Ge-detector hit
- energy = 2039 keV
- single-cluster event in Ge bulk volume (no surface interactions)

Background event populations are well separated in the multivariate space

- very small probability to enter the signal region
- very distinctive features to constrain it



Towards a Ton Scale Experiment

GERDA / Majorana Demonstrator

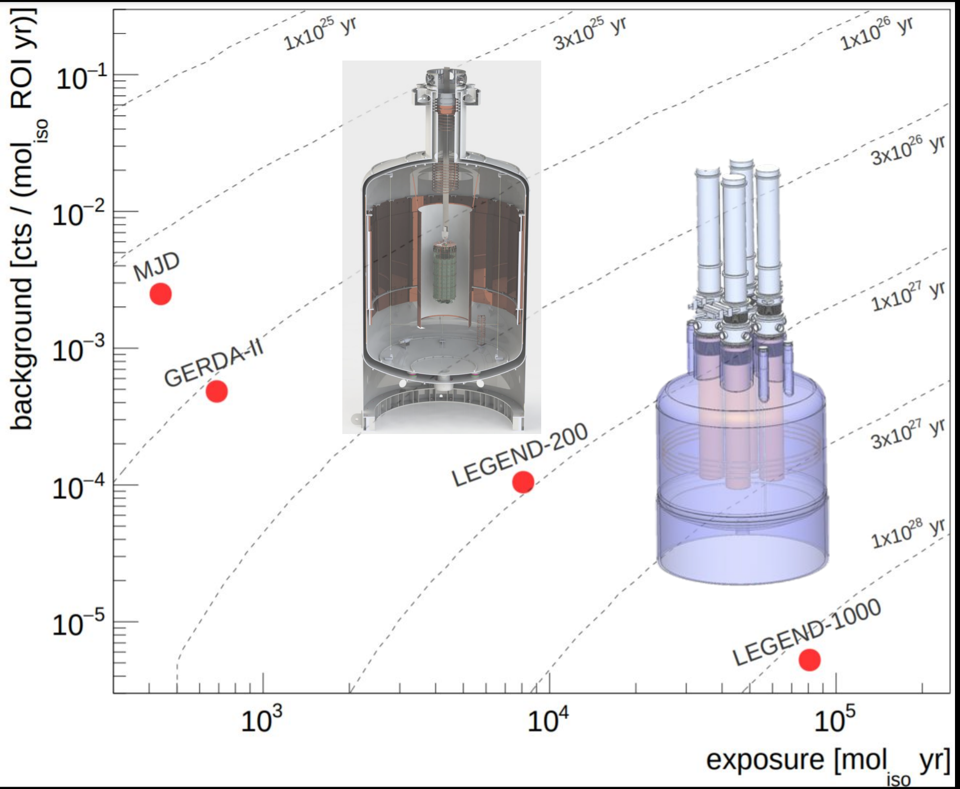
- 36/30 kg
- $T_{1/2} > 10^{26}$ yr

LEGEND - 200

- 200 kg
- background 2.5x lower than current values
- $T_{1/2} > 10^{27}$ yr

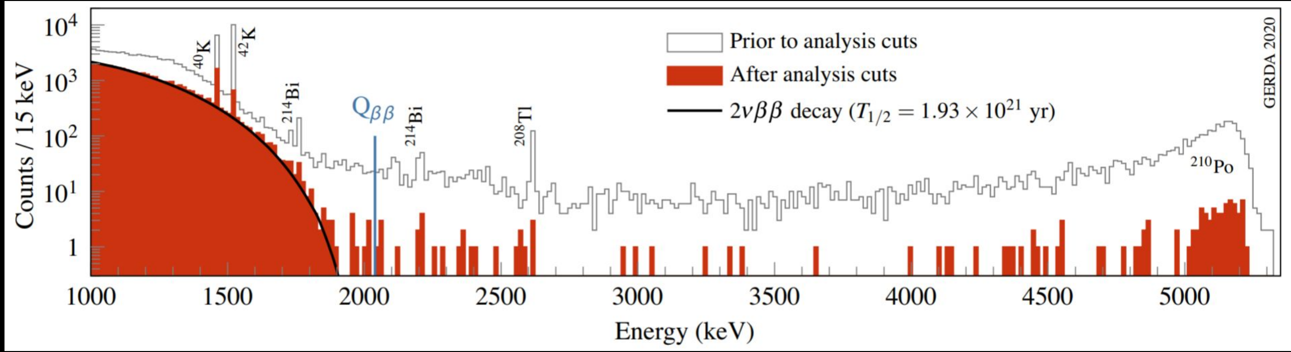
LEGEND - 1000

- 1000 kg
- background 50x lower than current values
- $T_{1/2} > 10^{28}$ yr



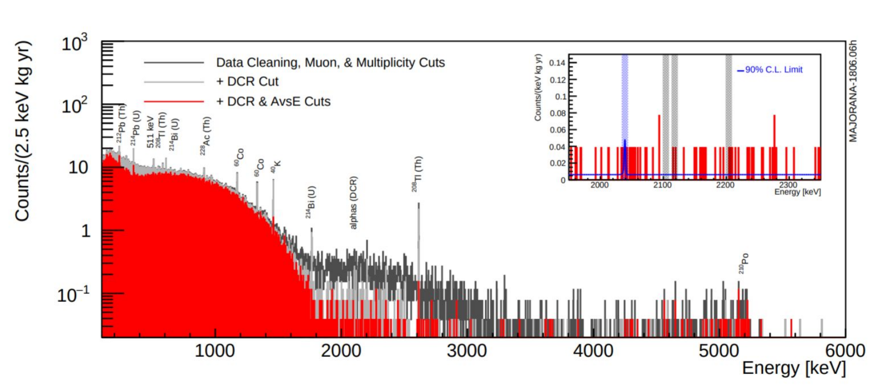
GERDA

- HPGe and LAr detectors
- completed in 2019
- 100 kg y of exposure
- background index: $5.2_{-1.3}^{+1.6}$ 10^{-4} cts/keV/kg/yr
- $T_{1/2}$ > 1.8 10^{26} yr (90% C.L.)
- best half-life sensitivity in the field



Phys.Rev.Lett. 125 (2020) 252502

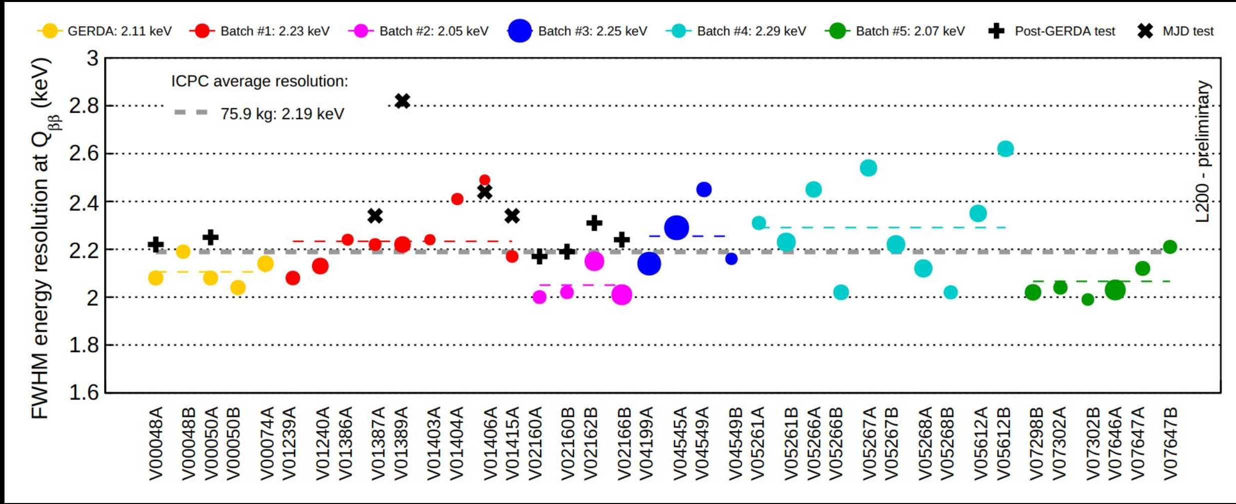
Majorana Demonstrator



- compact Cu shielding
- completed in 2020
- FWHM energy resolution of 2.5 keV

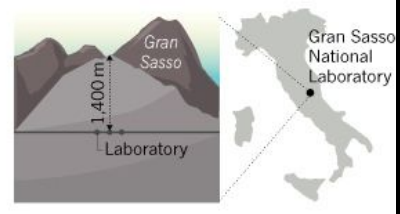
LEGEND-200

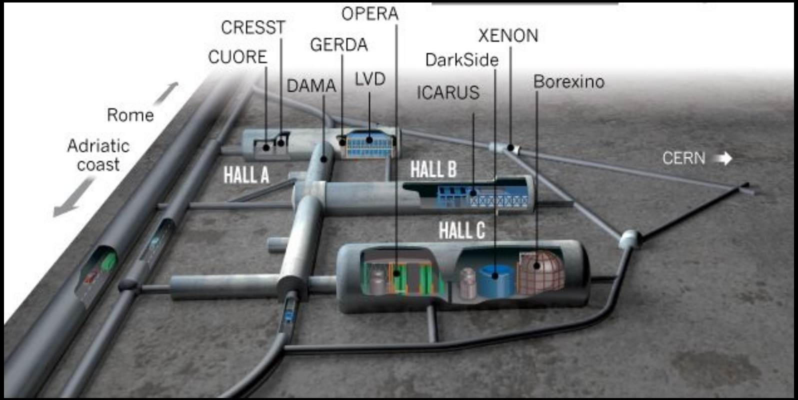
- HPGe detectors
  - 70 kg of GERDA/MAJORANA detectors + 130 kg of new ICPC
- structural materials: electroformed copper + polyester scintillating plastic
- two-stages read-out electronics with JFET next to detectors' electrodes



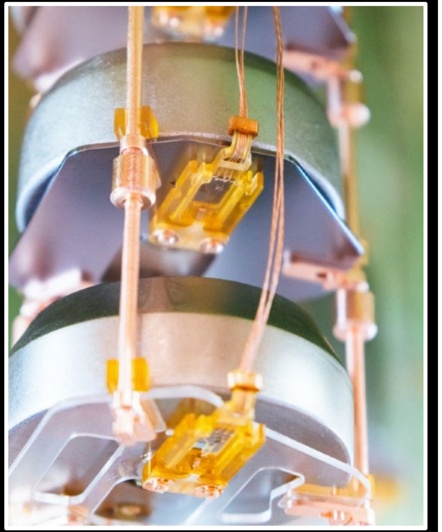
LEGEND-200

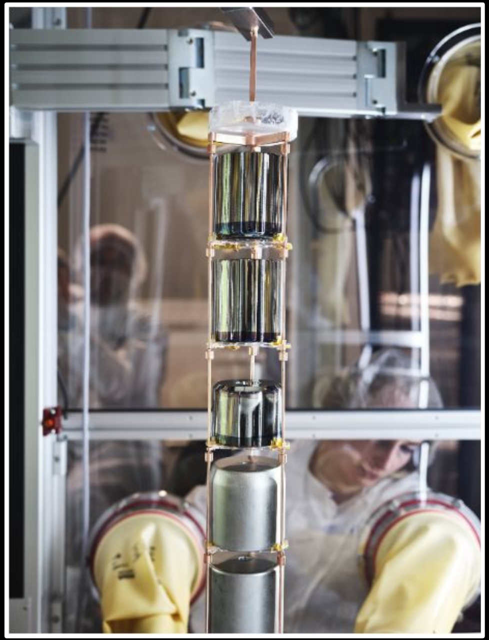
- 3500 m.w.e. underground at LNGS
- water tank instrumented with PMTs
- 64 m^3 LAr cryostat





LEGEND-200 preparation and commissioning





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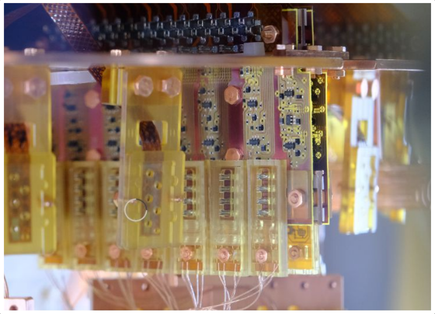
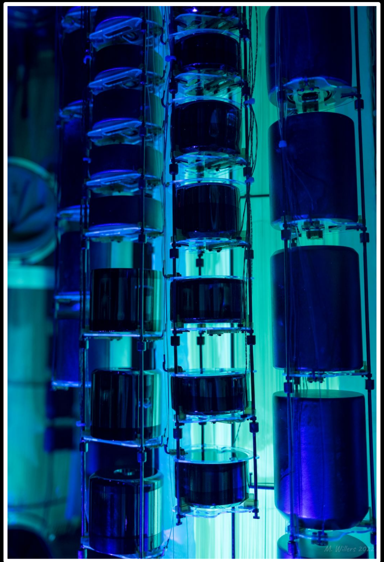
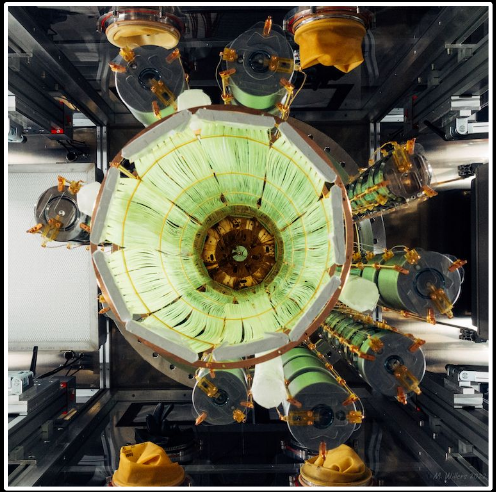
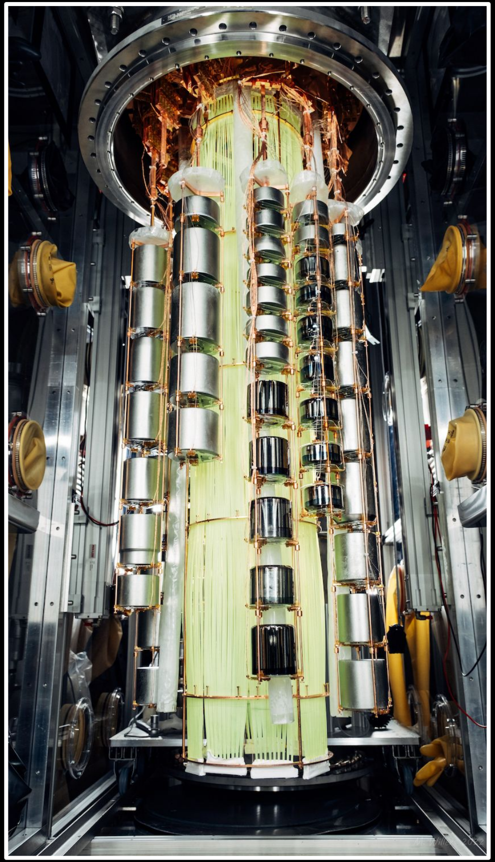


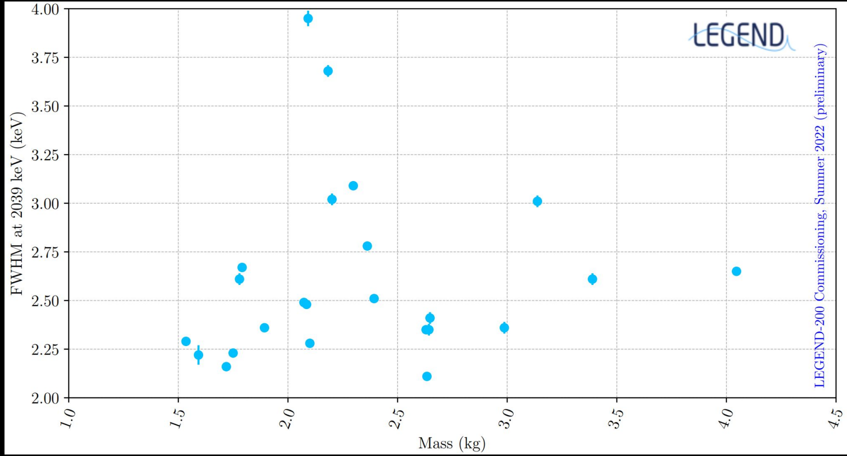


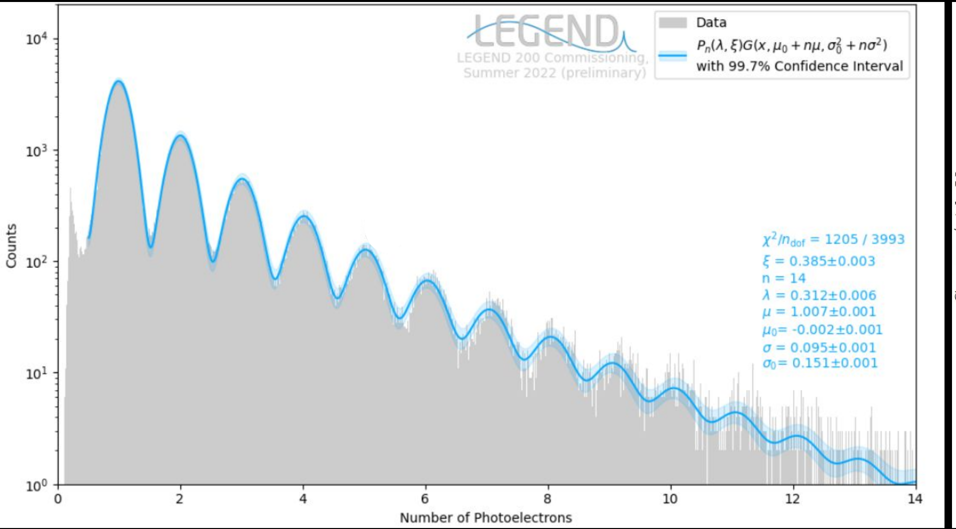


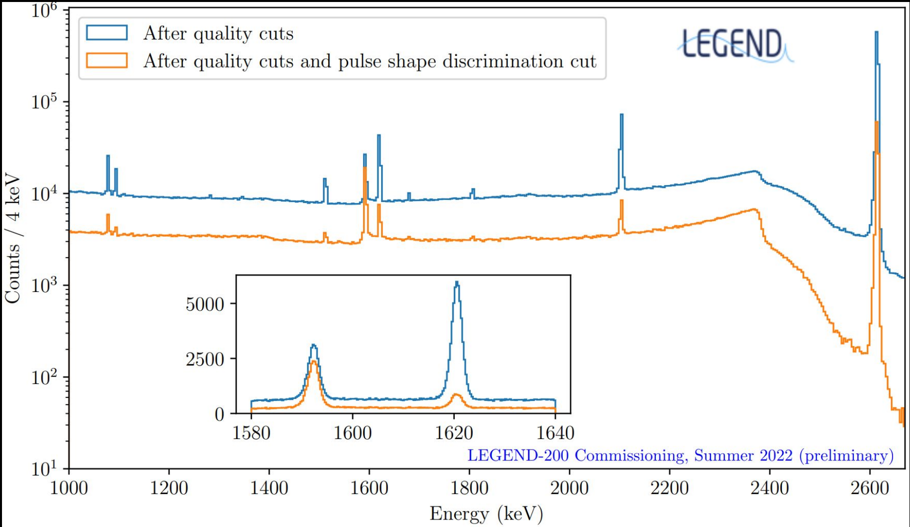


LEGEND-200 commissioning

- Last commissioning phase started in Autumn 2022
- All final systems and more than 100 HPGe dets
- Currently fine-tuning operational parameters
- First physics run starting anytime



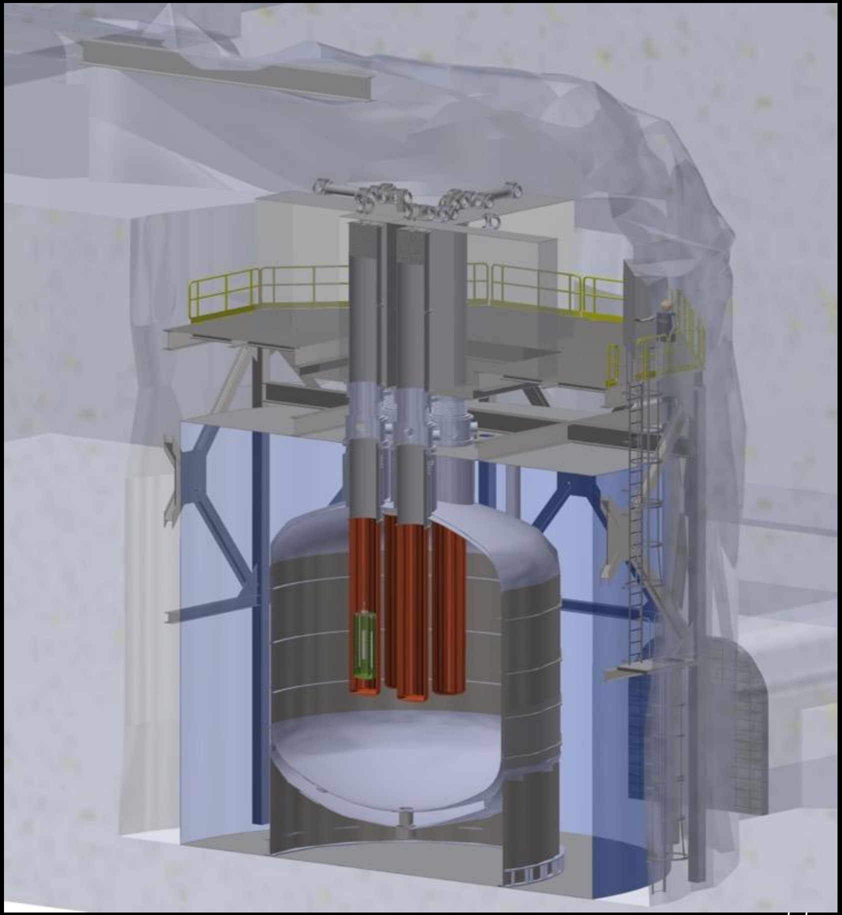




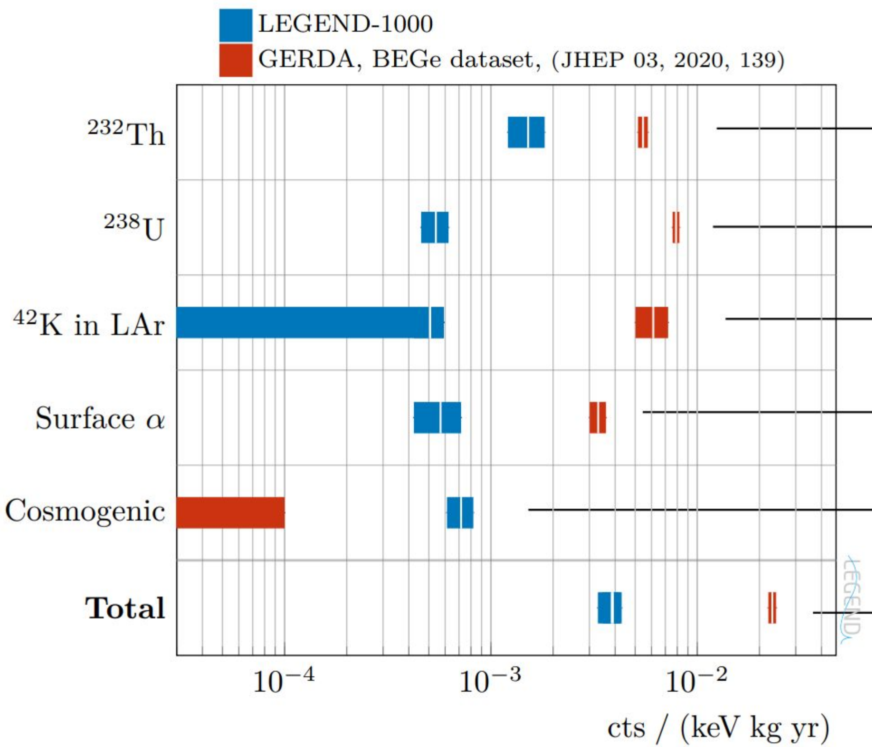
LEGEND-1000

- 4 payloads, each with up to 300 kg detectors
- underground argon in reentrant tubes
- lower-background solutions for electronics and cables
  - ASIC-based read-out
  - copper or Kapton flat flex cables
- candidate host labs: LNGS and SNOLAB

Conceptual design depicted for SNOLAB cryopit



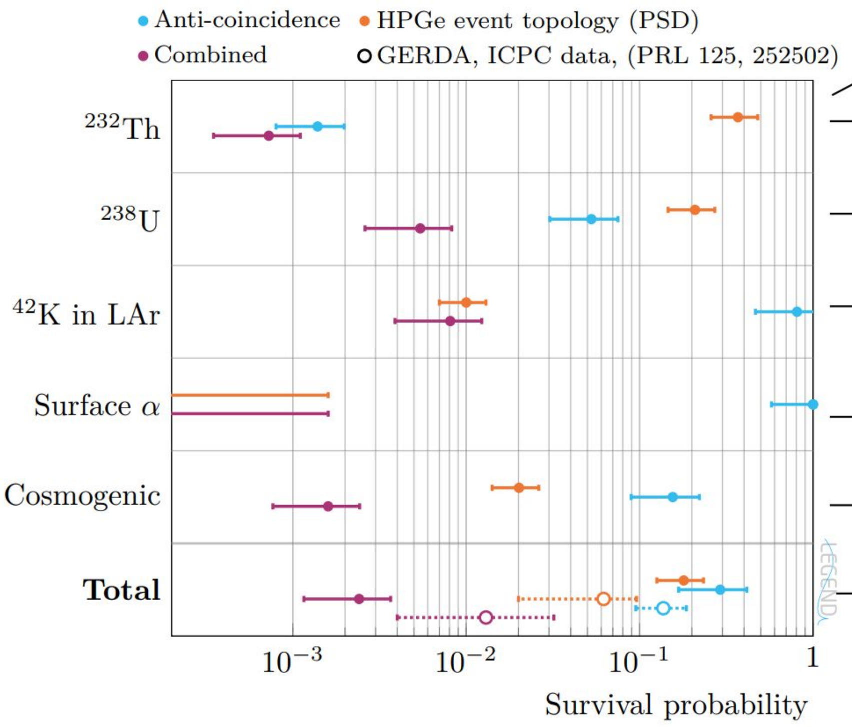
Background Levels Before Analysis Cuts



Background reduction due to:

- larger detectors ⇨ less cables and holders
- new cables & ASIC read-out
- increased detector spacing
- underground Ar
- larger detectors ⇨ larger surface-to-volume ratio
- only ^{210}Pb supported term
- ^{68}Ge decays away, 2 yr less cool down than in GERDA
- Factor 6 reduction, driven by underground Ar

Signal/Background Discrimination

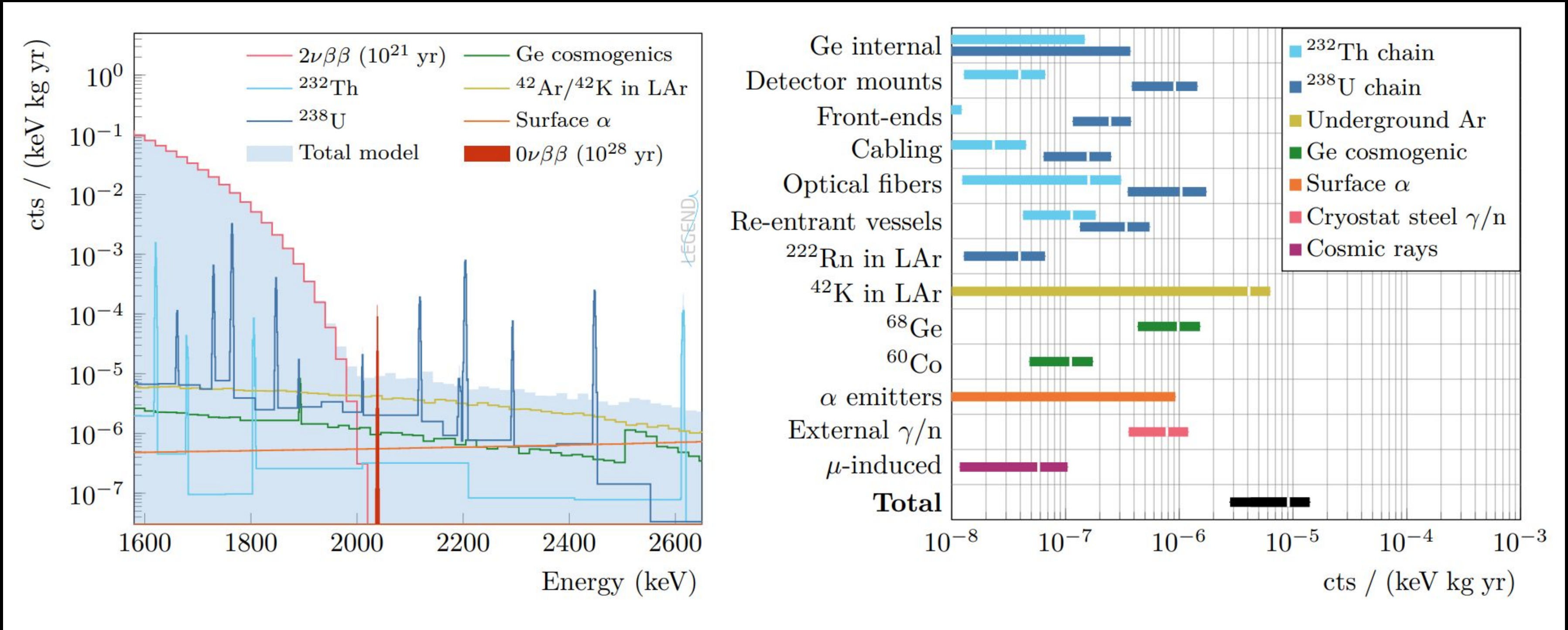


Effective background suppression due to:

- Greater ^{208}Tl γ energy: enhances suppression over ^{238}U chain
- Improved light collection through:
  - Ge detector spacing
  - Fiber coverage
  - SiPM quantum efficiency

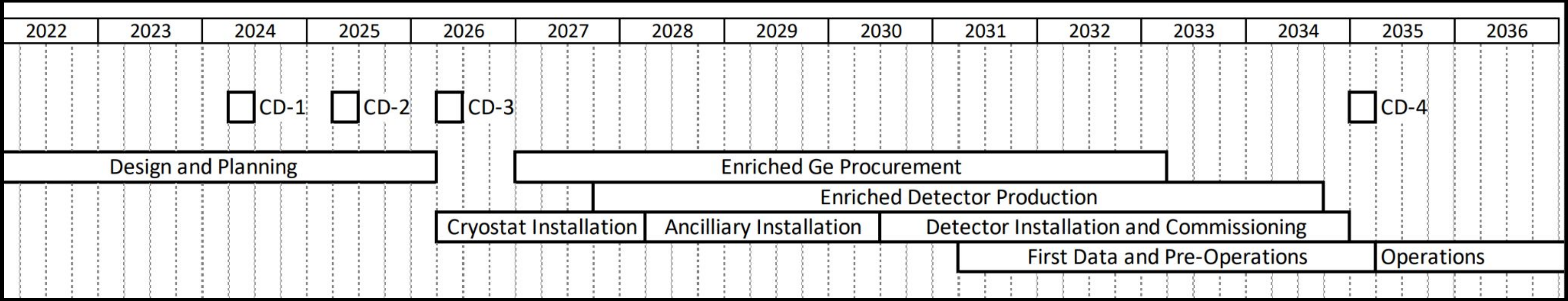
  Minimization of inactive material to suppress γ events
- A PSD suppression demonstrated in GERDA
- Inherently multi-site
- Overall improvement in combined suppression relative to GERDA

Background After Analysis Cuts



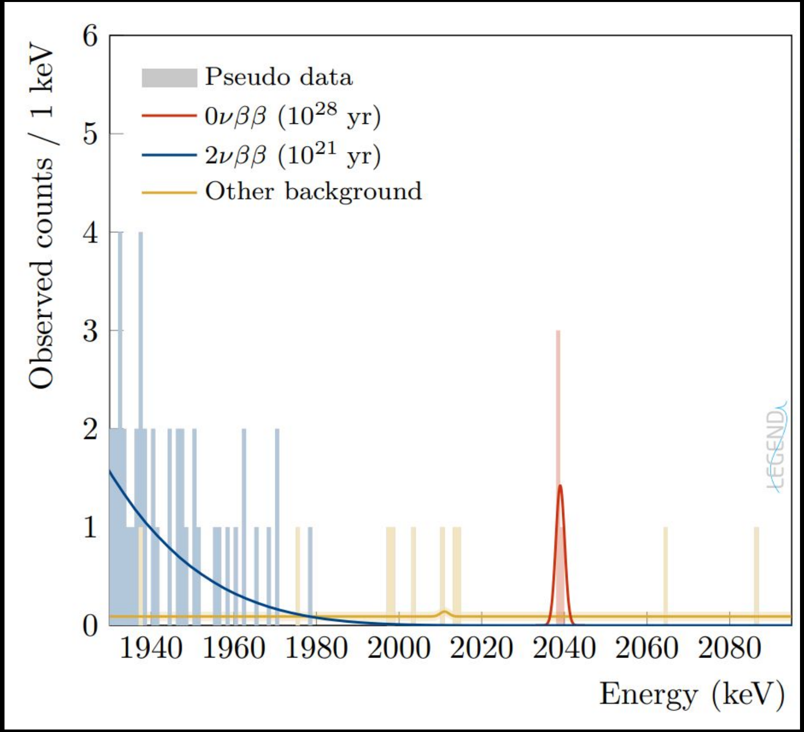
Variable bin width, 1 keV binning for gamma lines

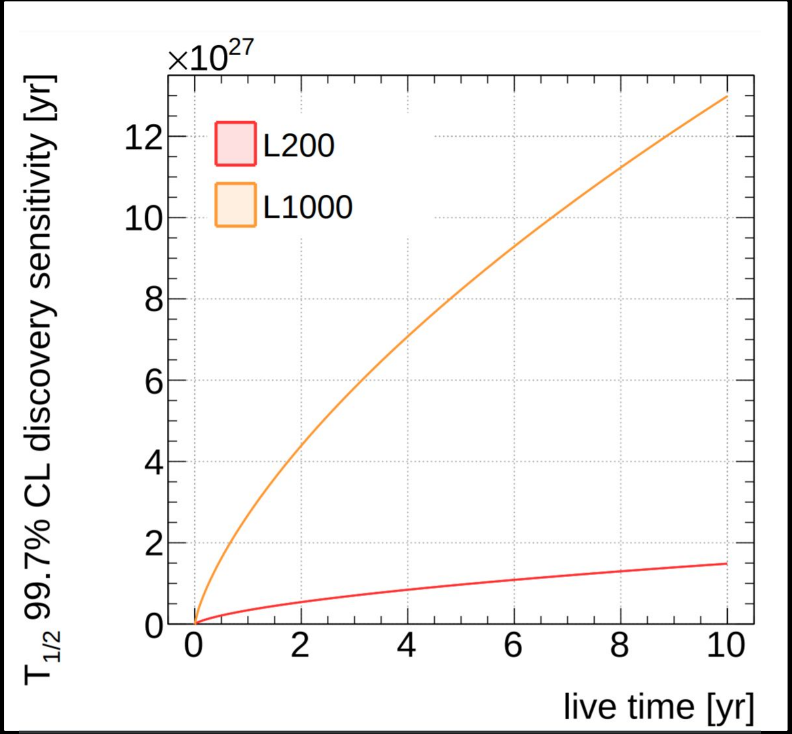
LEGEND-1000 Schedule



High Discovery Power Experiments

Almost linear growth in discovery sensitivity

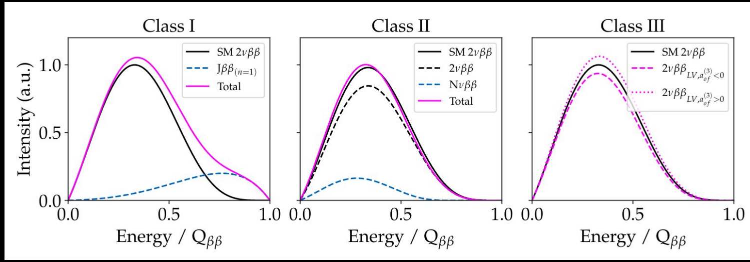


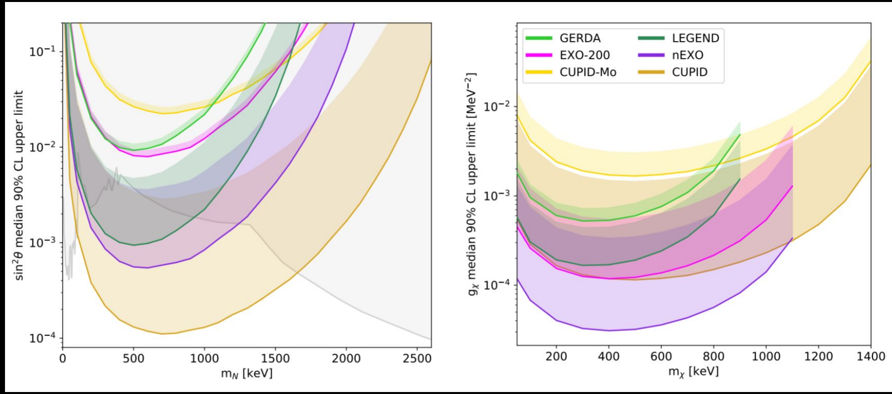


Illustrative Toy Data Set for 10 ton yr

Other physics opportunities beyond $0\nu\beta\beta$ decay

Physics	Signature	Energy Range
Bosonic dark matter	Peak at DM mass	< 1 MeV
Electron decay	Peak at 11.8 keV	~ 10 keV
Pauli exclusion principle violation	Peak at 10.6 keV	~ 10 keV
Solar axions	Peaked spectra, daily modulation	< 10 keV
Majoron emission	$2\nu\beta\beta$ spectral distortion	$< Q_{\beta\beta}$
Exotic fermions	$2\nu\beta\beta$ spectral distortion	$< Q_{\beta\beta}$
Lorentz violation	$2\nu\beta\beta$ spectral distortion	$< Q_{\beta\beta}$
Exotic currents in $2\nu\beta\beta$ decay	$2\nu\beta\beta$ spectral distortion	$< Q_{\beta\beta}$
Time-dependent $2\nu\beta\beta$ decay rate	Modulation of $2\nu\beta\beta$ spectrum	$< Q_{\beta\beta}$
WIMP and related searches	Exponential excess, annual modulation	< 10 keV
Baryon decay	Timing coincidence	> 10 MeV
Fractionally charged cosmic-rays	Straight tracks	few keV
Fermionic dark matter	Nuclear recoil/deexcitation	$<$ few MeV
Inelastic boosted dark matter	Positron production	$<$ few MeV
BSM physics in Ar	Features in Ar veto spectrum	ECEC in ^{36}Ar

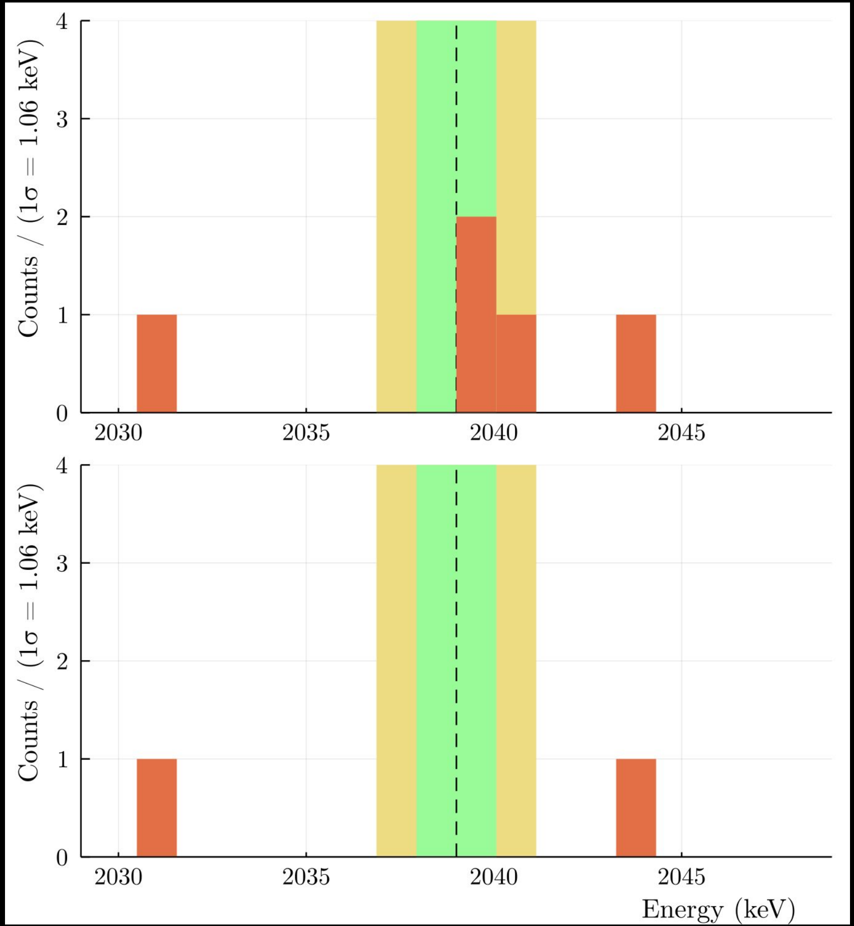




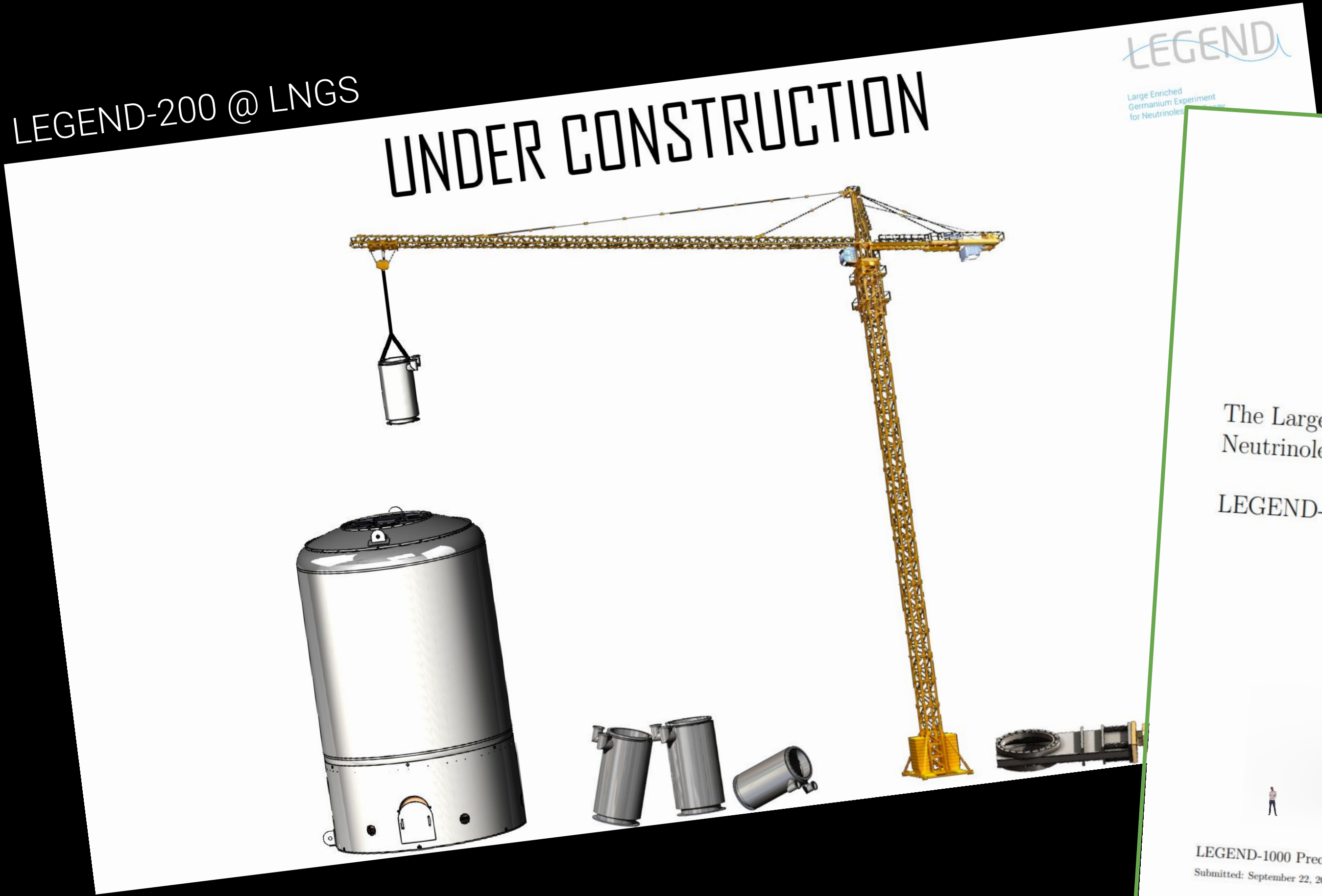
MA and Bossio, Ibarra, Marcano, Phys. Lett. B 815 (2021), 136127

Outlook

- $0\nu\beta\beta$ decay search is a priority
  - direct observation of B-L violation
  - L-violating Majorana neutrinos
  - new physics at ultrahigh energy
- Ge-76 experiments aim at a background-free discovery
- LEGEND-200 is coming online, pioneering exploration of invented-ordered neutrinos
- LEGEND-1000 under preparation, top-ranked by DOE, CD1 in fall, high discovery potential



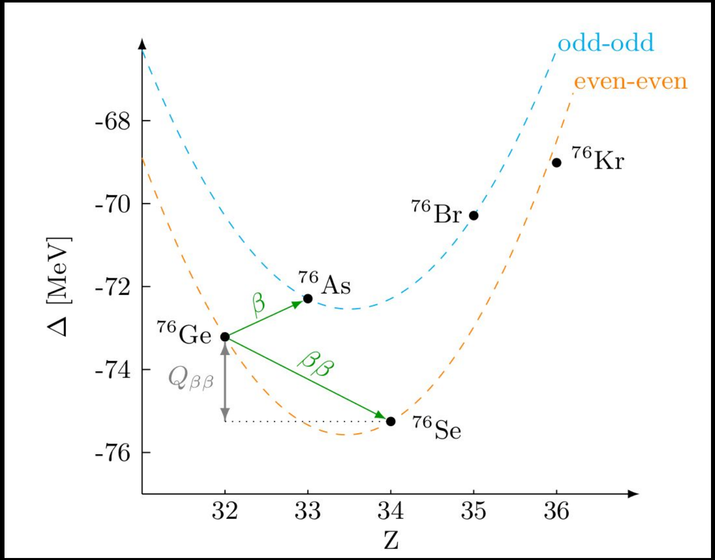
LEGEND-200 @ LNGS



LEGEND-1000 pCDR

How to build a $0\nu\beta\beta$ decay experiment?

Step 1: Choose a $0\nu\beta\beta$-decay candidate isotope



Single β decay forbidden or strongly suppressed

$1/T_{1/2} \propto (Q_{\beta\beta})^5$ makes it cheaper lowers background

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

M.A., Benato, Detwiler, Menéndez and Vissani
arXiv:2202.01787

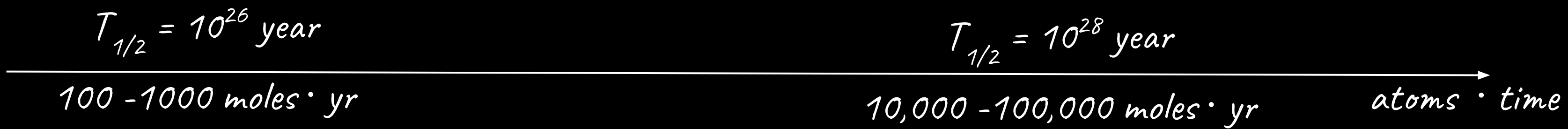
How to build a $0\nu\beta\beta$ decay experiment?

Step 1: Choose a $0\nu\beta\beta$-decay candidate isotope

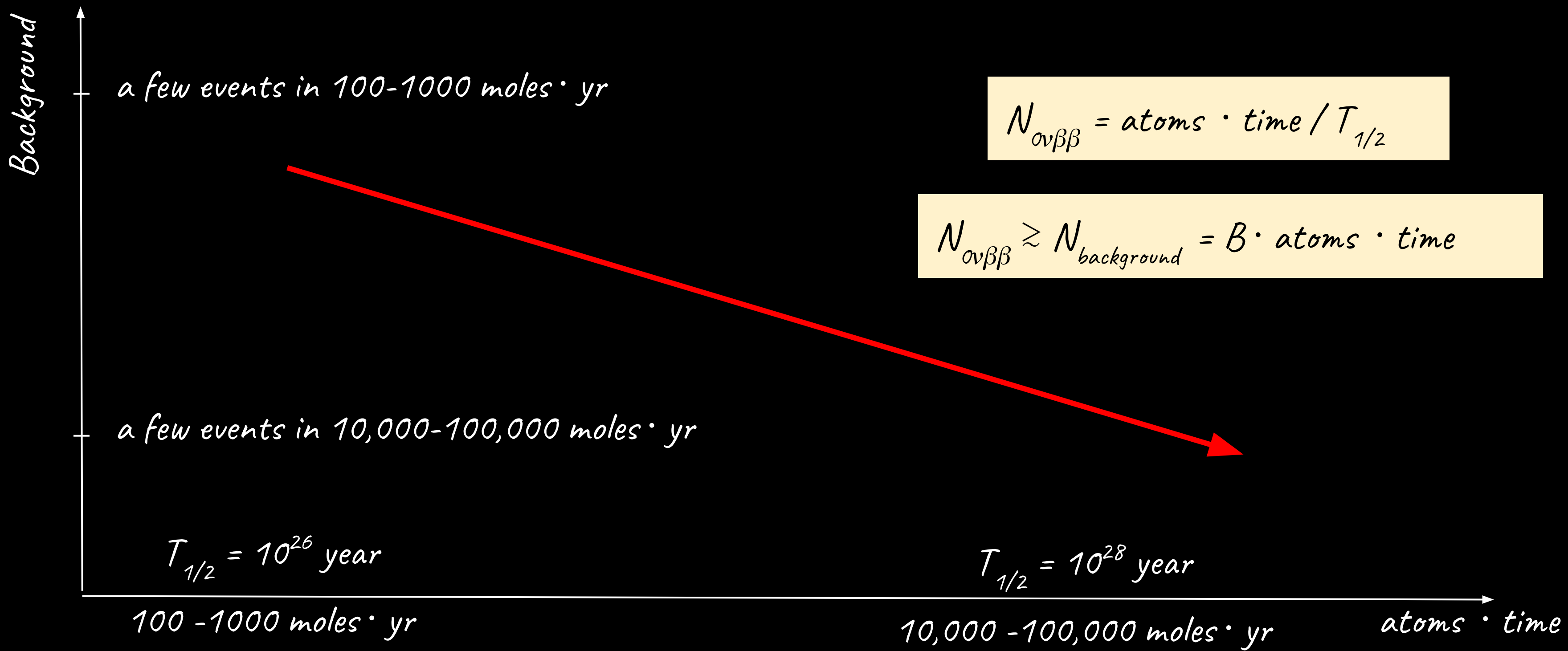
Step 2: Develop a detection concept able to detect each single decay without false positives

$$N_{0\nu\beta\beta} = atoms \cdot time \, / \, T_{1/2}$$

Step 3: Make it big enough



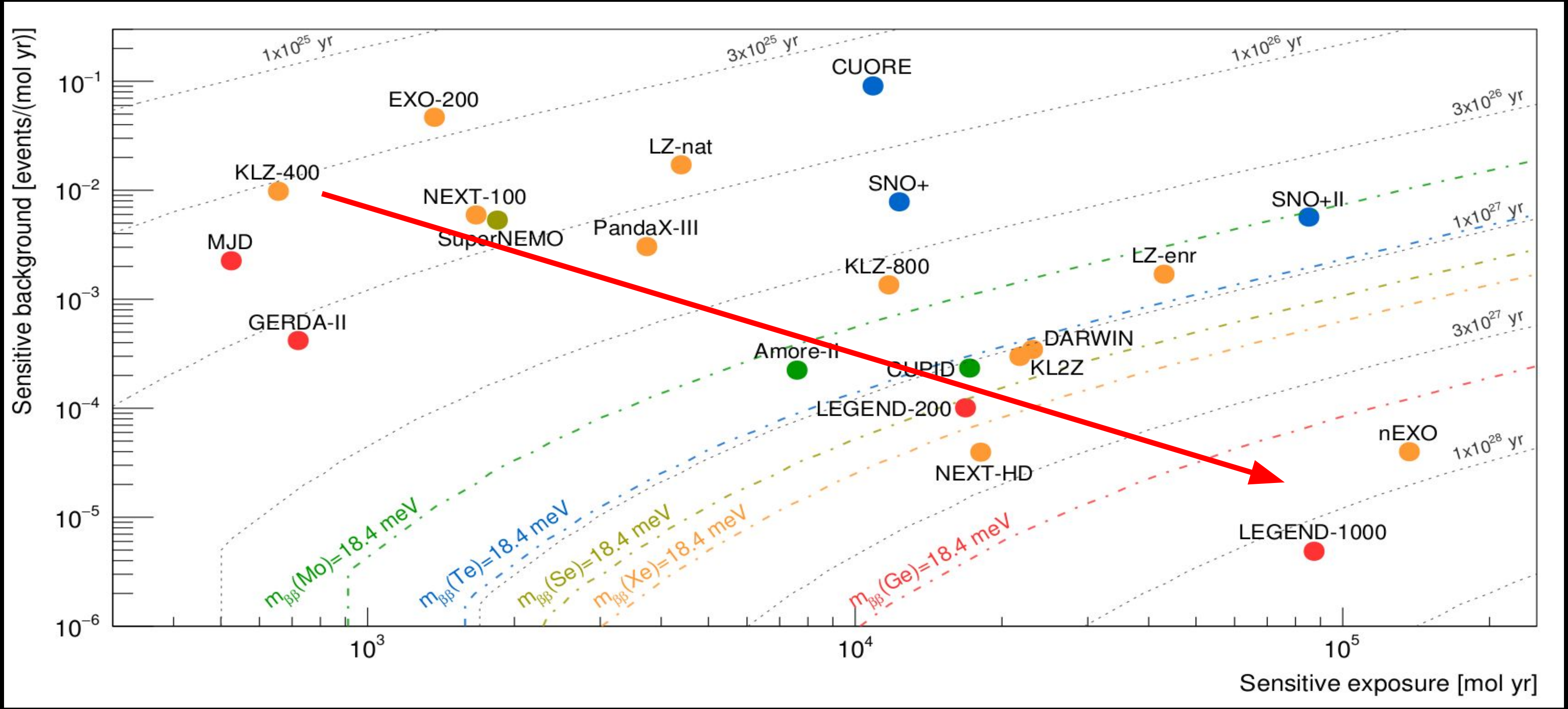
How to build a $0\nu\beta\beta$ decay experiment?



$$N_{0\nu\beta\beta} = \text{atoms} \cdot \text{time} \,/\, T_{1/2}$$

$$N_{0\nu\beta\beta} \gtrsim N_{\text{background}} = B \cdot \text{atoms} \cdot \text{time}$$

Recent and future experiments



M.A., Benato, Detwiler, Menéndez and Vissani
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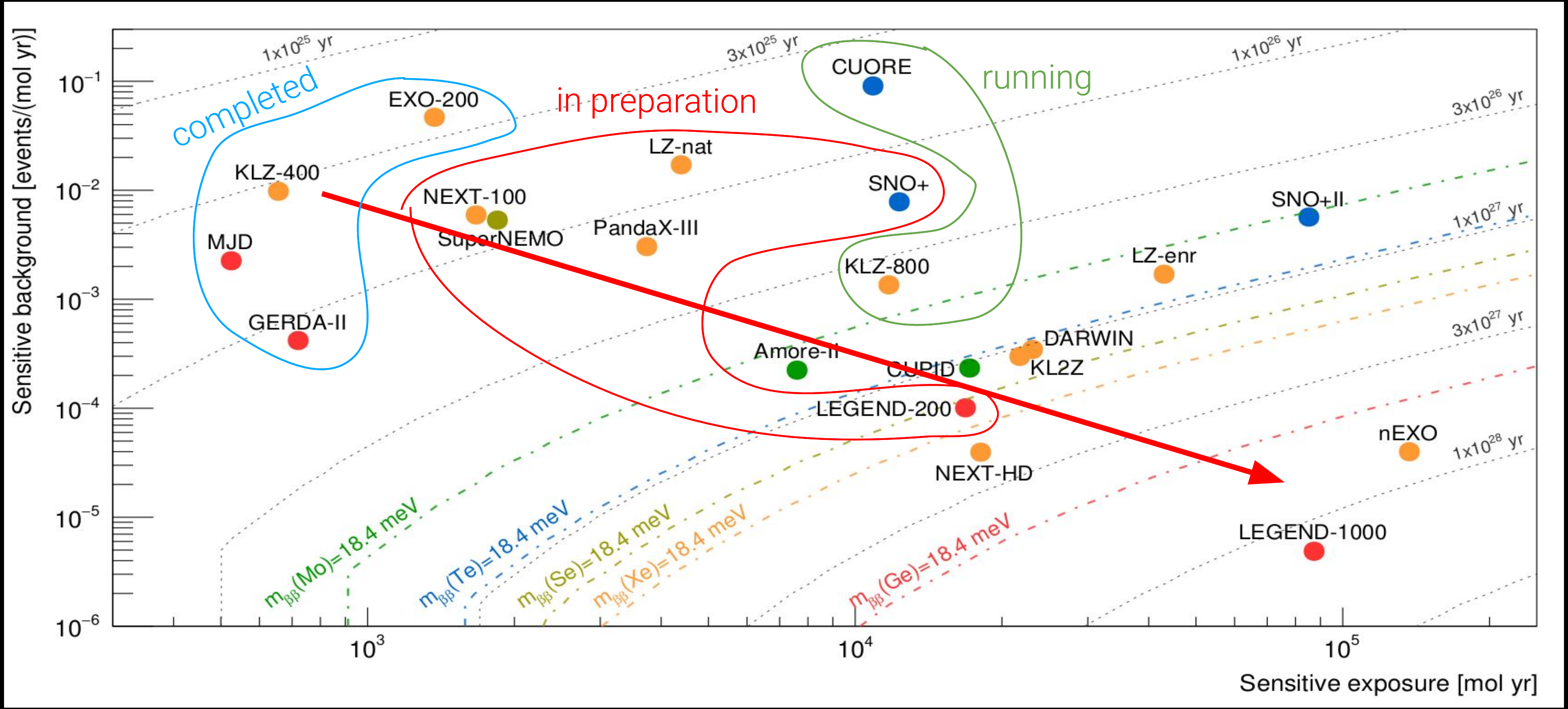
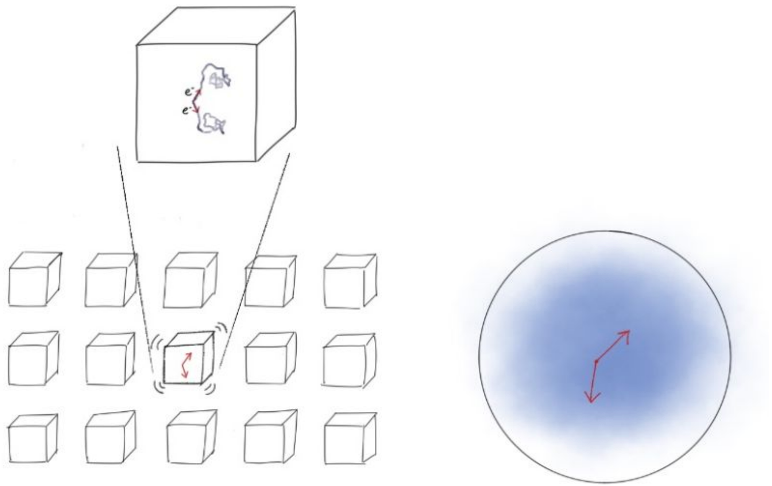
Recent and future experiments



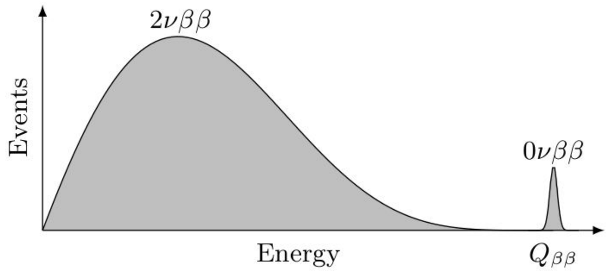
M.A., Benato, Detwiler, Menéndez and Vissani
arXiv:2202.01787

Detection concepts

- calorimetric approach: source = detector
- solid state: pixelated detector
- liquid: monolithic self-shielding volume
- energy: primary and sufficient observable



arXiv:2202.01787 - Image courtesy of Laura Manenti



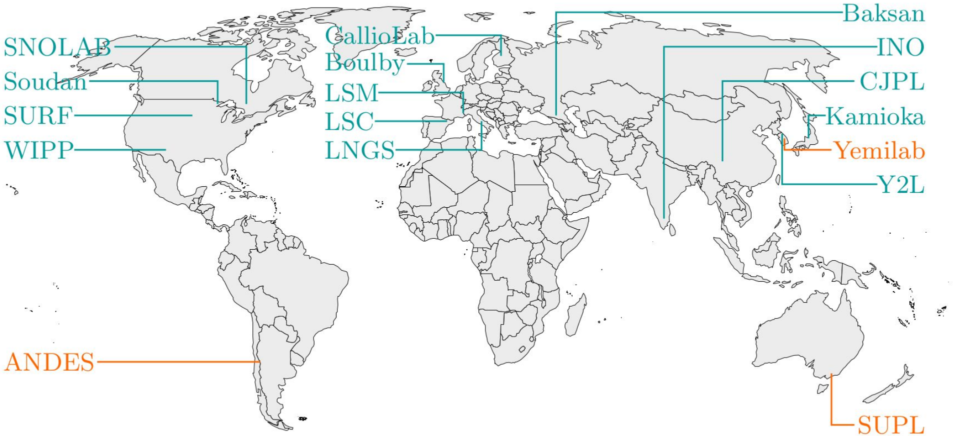
Tagging $0\nu\beta\beta$ decay events:

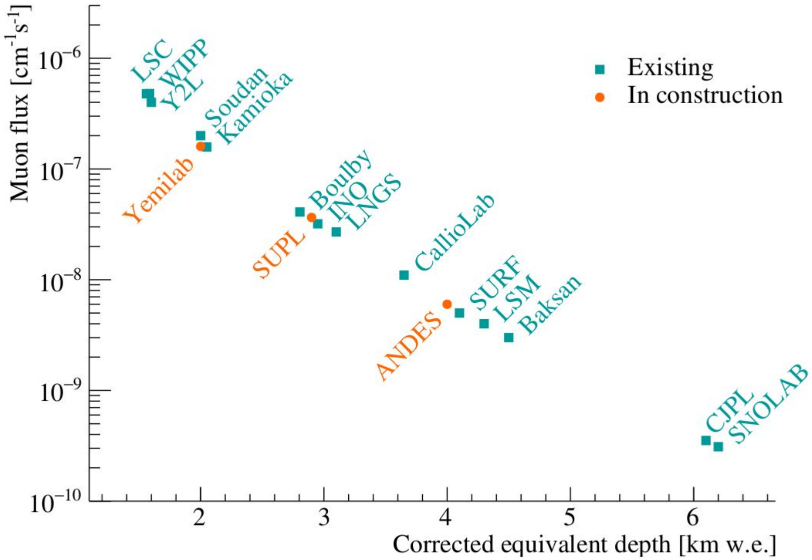
- two-electron summed energy = Q-value
- two-electron event topology
- (excited states/daughter isotope)

Backgrounds:

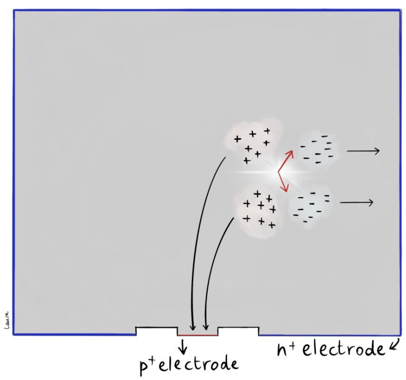
- cosmic-ray induced
- $^{238}U/^{228}Th$ decay chains
- neutrons
- solar neutrinos
- $2\nu\beta\beta$ decay (only irreducible background)

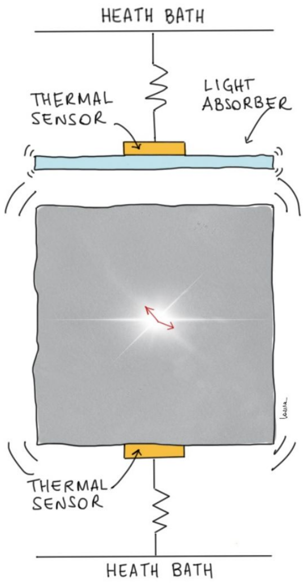
Underground Laboratories

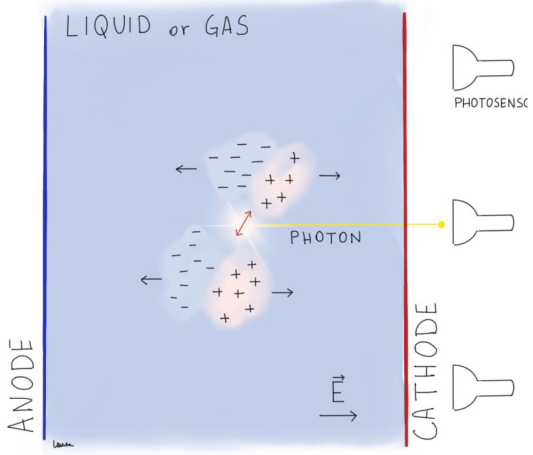


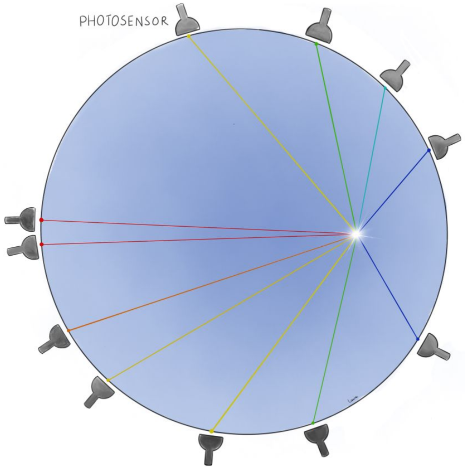


The most sensitive technologies









Ge Semiconductor detectors (^{76}Ge)

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

Xe Time Projection Chambers (^{136}Xe)

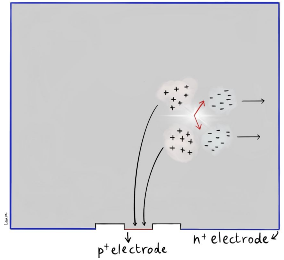
Large Liquid scintillator detectors (^{130}Te, ^{136}Xe)

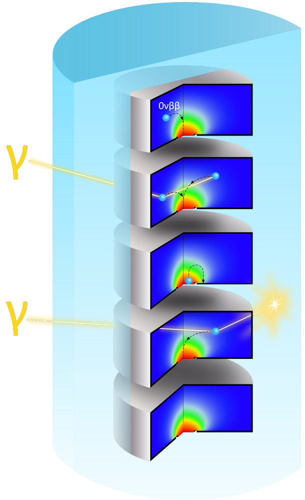
arXiv:2202.01787 - Image courtesy of Laura Manenti

Ge semiconductor detectors

high-purity ^{76}Ge detectors

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





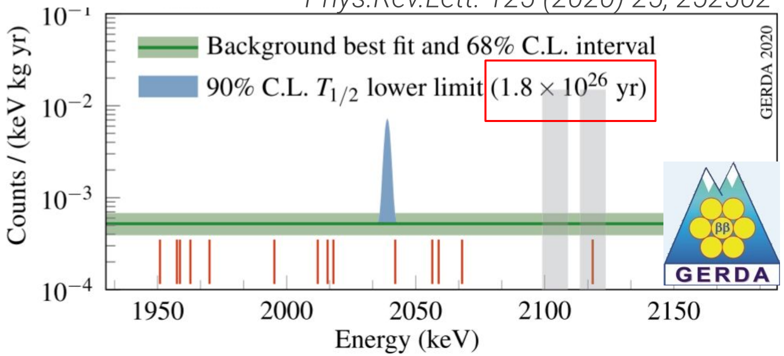
liquid Ar detector

- 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)

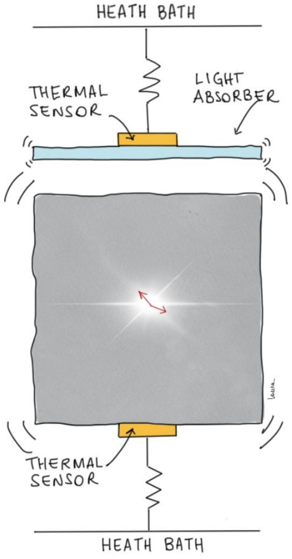
Phys.Rev.Lett. 125 (2020) 25, 252502



Cryogenic calorimeters

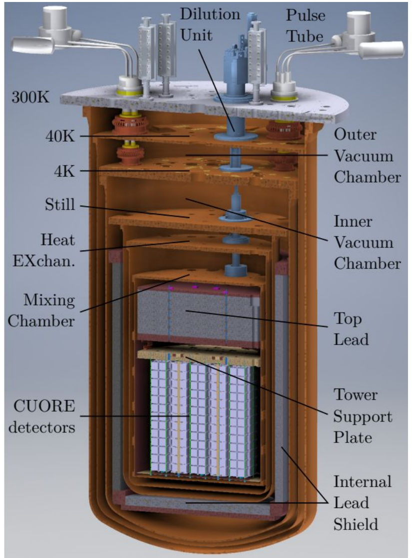
- temperature variation and scintillation light
- particle identification and good resolution
- array of isotopically enriched crystals operated at ~10 mK

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

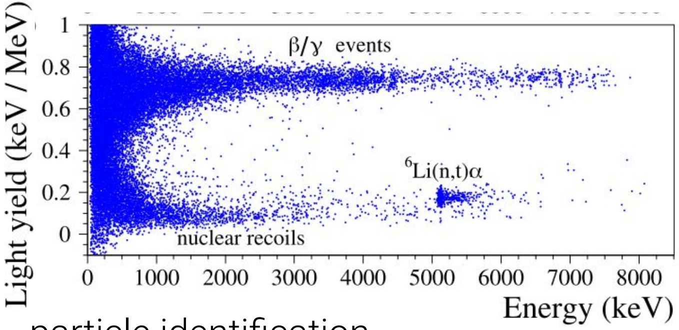


Nature 604 (2022) 7904, 53-58

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



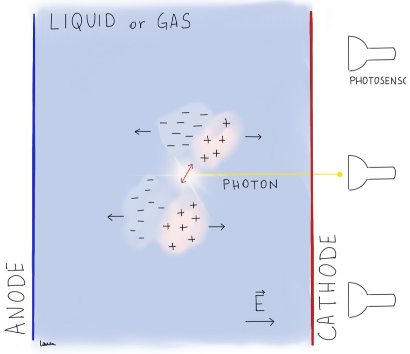
CUPID

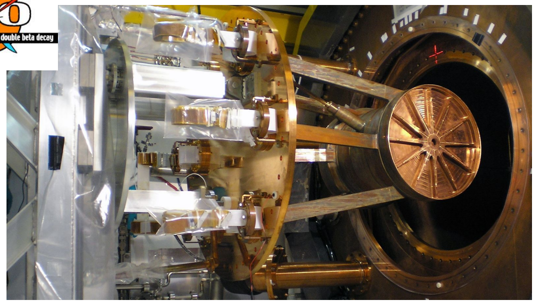


particle identification

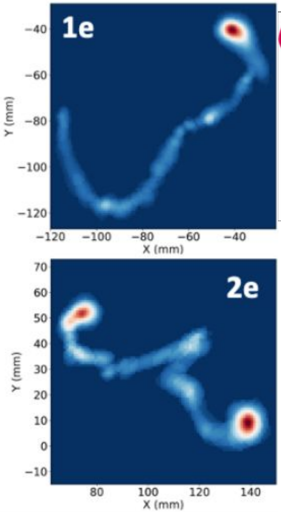
Xe time projection chambers

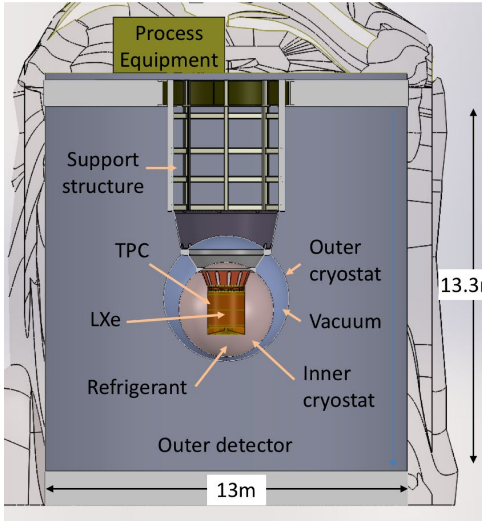
- ^{136}Xe VUV scintillation light and ionization electron drift -> 3D reconstruction
- background decreasing with distance from surface, ^{214}Bi and ^{222}Rn remain problematic
- R&D to tag $0\nu\beta\beta$ decay daughter isotope





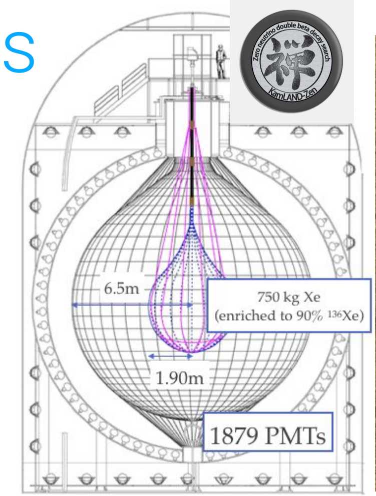
Experiment	m_{tot} [kg]	$f_{enr.}$ [%]	Phase	Readout
EXO-200	161	81	liquid	LAPPDs + wires
nEXO	5109	90	liquid	electrode tiles + SiPM s
NEXT-100	97	90	gas	SiPMs + PMTs
NEXT-HD	1100	90	gas	SiPMs + PMTs
PandaX-III-200	200	90	gas	Micromegas
PandaX-III-1K	1000	90	gas	Micromegas
LZ-nat	7 000	9	dual-phase	PMTs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

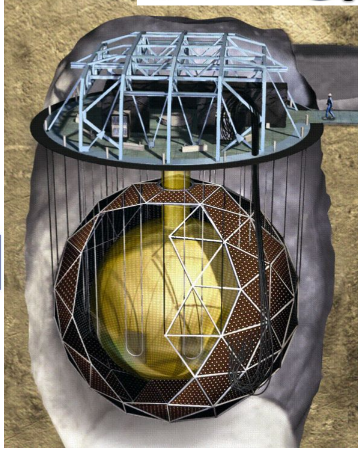




Large liquid scintillators

- scintillator loaded with target isotope
- scintillation photons detected by PMTs
- photon number and arrival time gives event energy and position
- self-shielding and fiducialization

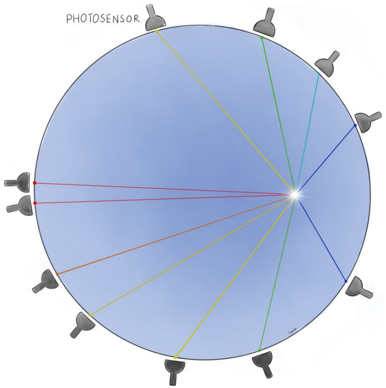




SNO+ @ SNOLab

Currently preparing for loading with 1.3 t of Te (0.5% loading)

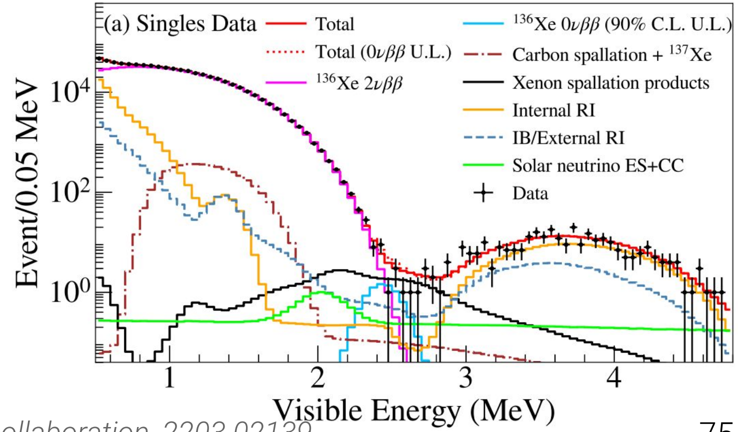
3% loading in future phases



KamLAND-Zen-800 @Kamioka

- 750 kg of enriched Xe in nylon balloon
- backgrounds: $2\nu\beta\beta$, cosmogenic, solar neutrinos, ^{214}Bi on balloon
- next phase: improved resolution and purer scintillator

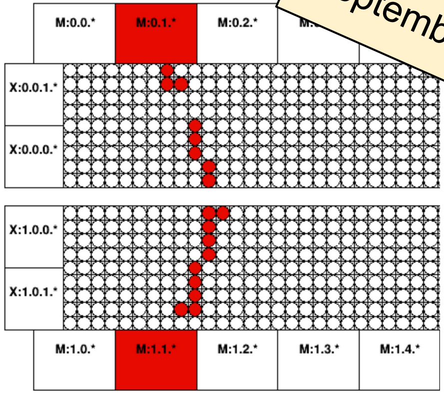
$$T^{0\nu}_{1/2} > 2.3 \times 10^{26} \text{ yr at } 90\% \text{ C.L.}$$



KZ collaboration, 2203.02139

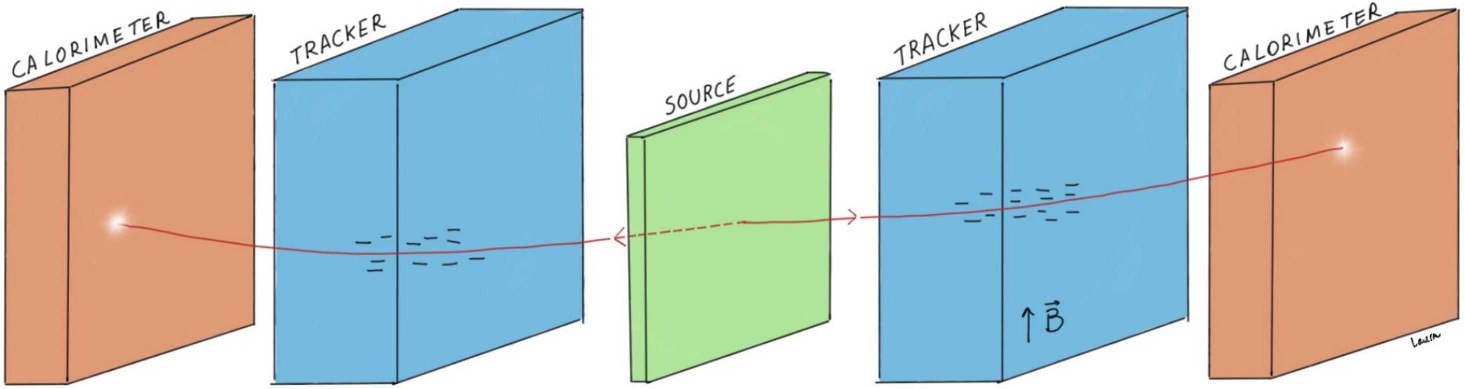
Beyond a simple rate measurement

First light!
September 2021



How to gain insight on the decay channel?

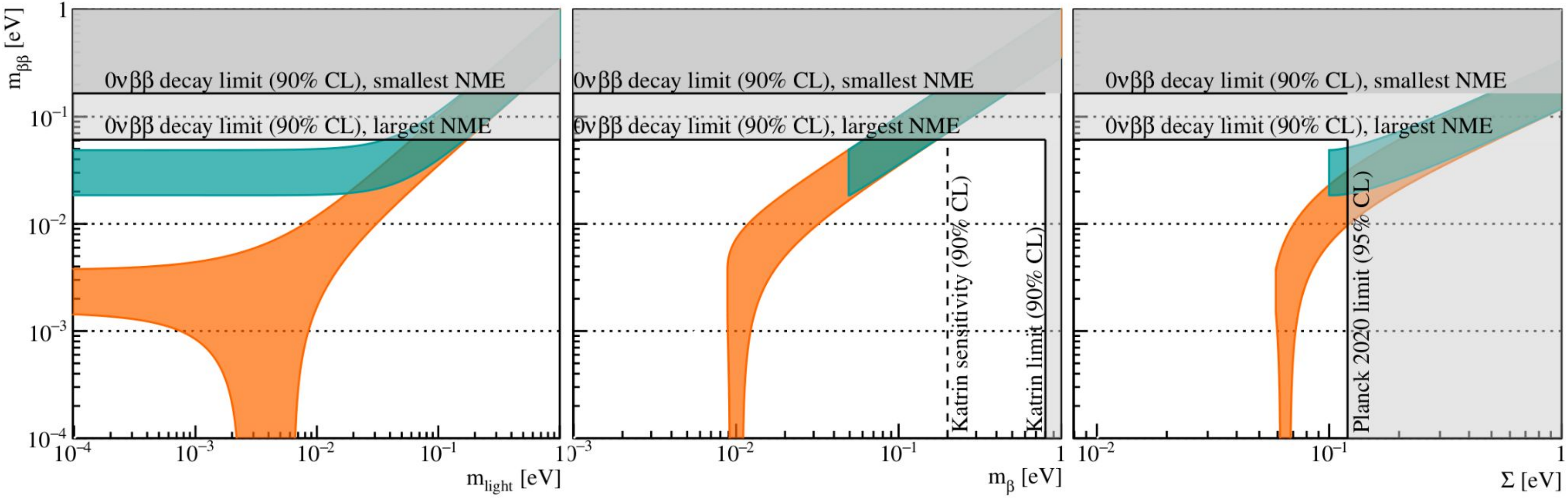
- measure the electron momenta → angular distribution
- compare decay rate in different isotopes
- combined analysis of neutrino physics, including cosmology



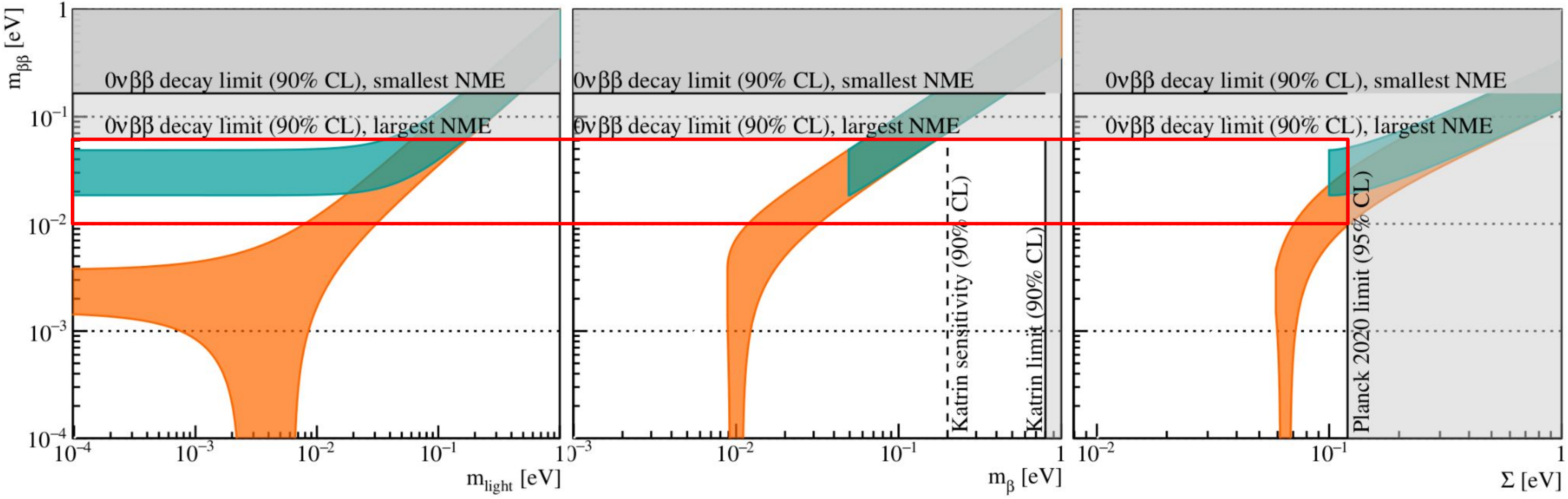
arXiv:2202.01787 - Image courtesy of Laura Manenti

supernemo collaboration

Interplay between mass experiments

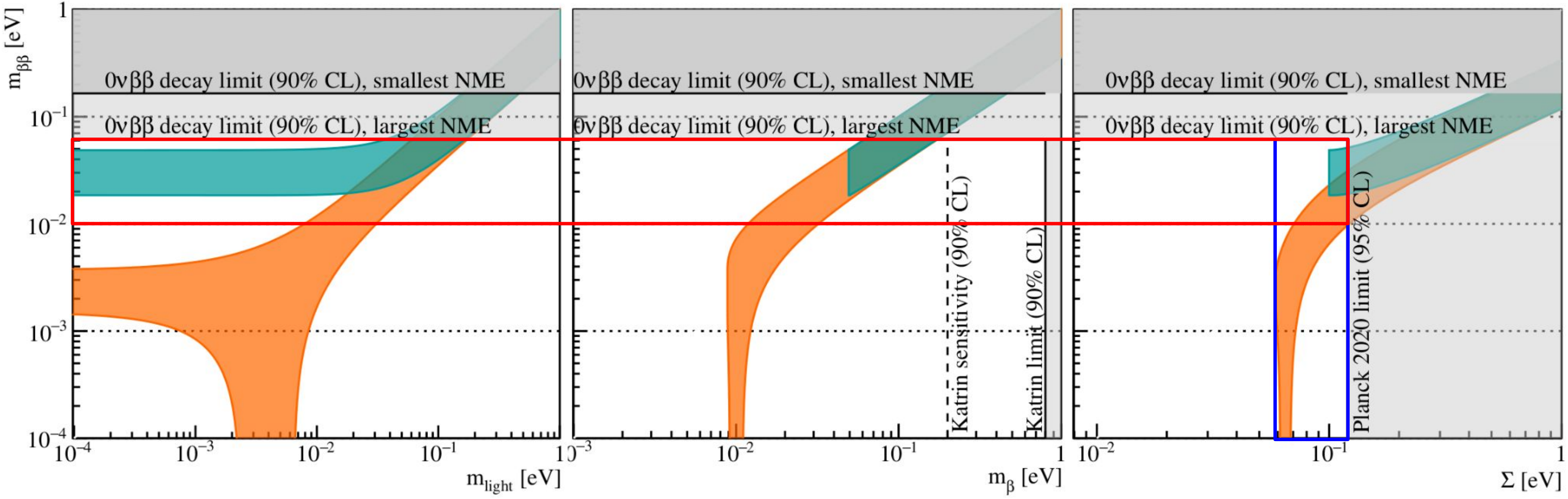


Interplay between mass experiments



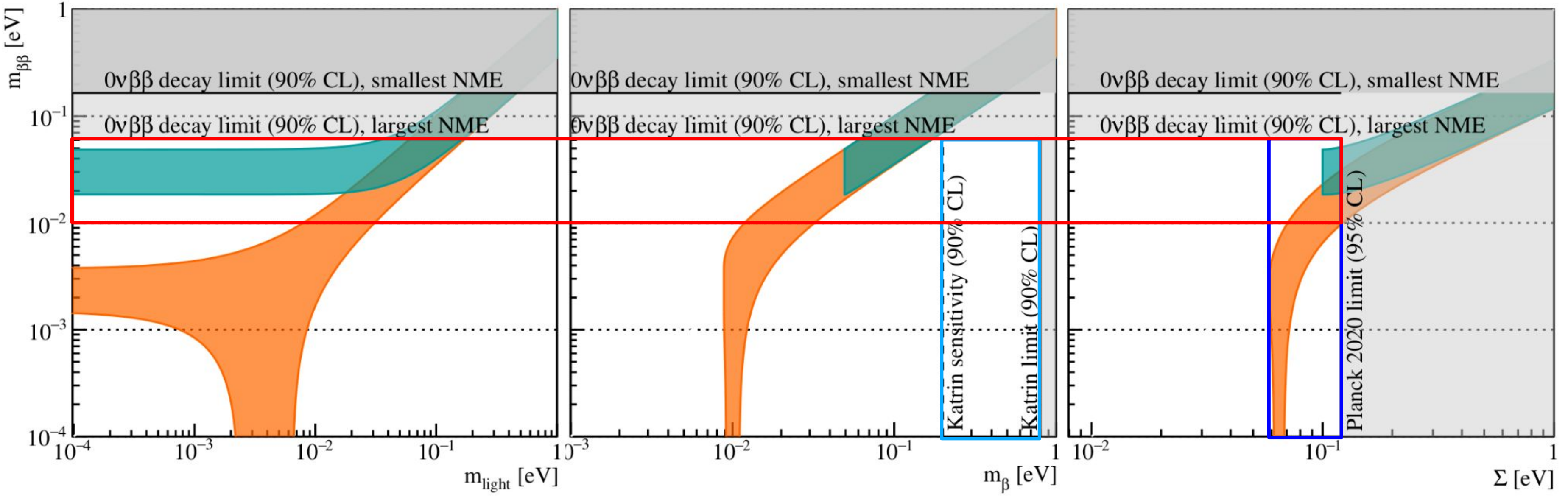
CUPID, LEGEND, nEXO will explore $m_{\beta\beta}$ values till the bottom of the inverted ordering and beyond, with a good chance to discover matter-creation

Interplay between mass experiments



DESI and EUCLID promise to measure Σ. This will define a target for $0\nu\beta\beta$ experiments, with a no observation potentially hinting at Dirac masses or non-standard cosmology

Interplay between mass experiments



KATRIN's parameter space is already excluded by both $0\nu\beta\beta$ decay and cosmology.

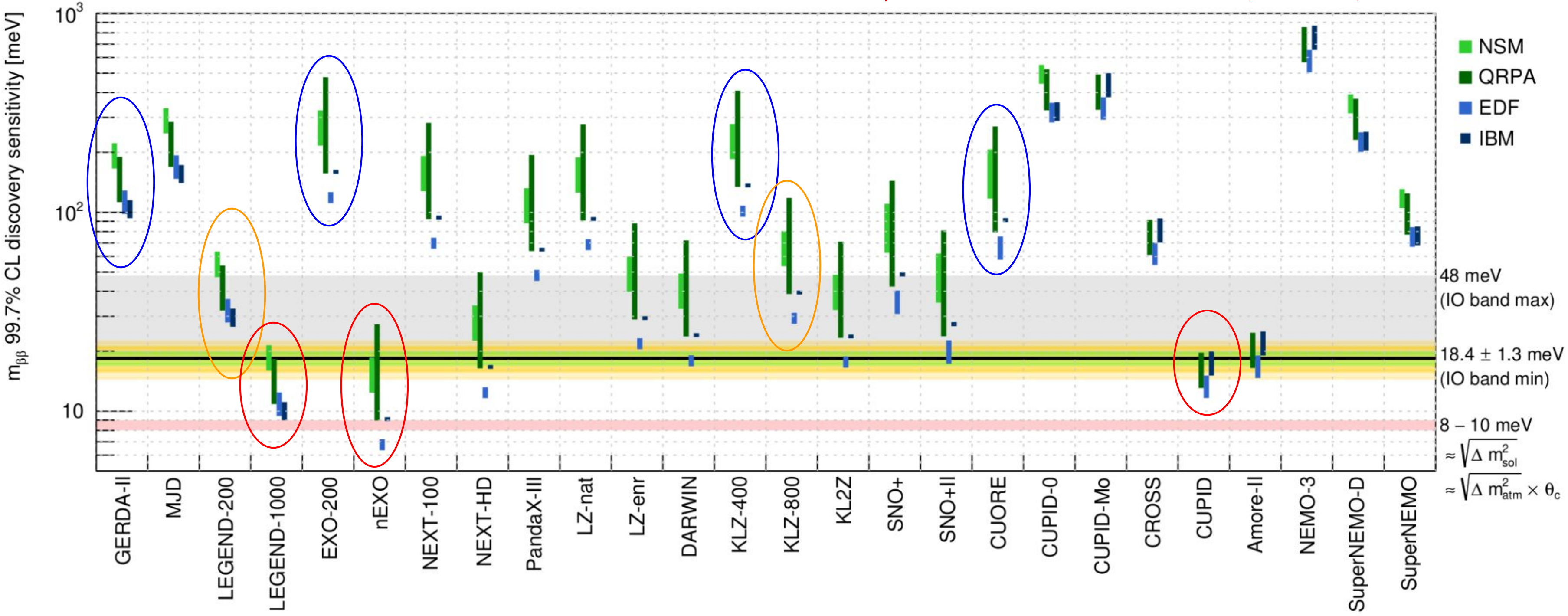
A signal would force to drastically rethink our phenomenology theory framework

Where are we heading?

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

The two that will dominate the next few years: **LEGEND-200, KamLAND-Zen-800**

The ultimate 1-ton experiments: **LEGEND-1000, CUPID, nEXO**

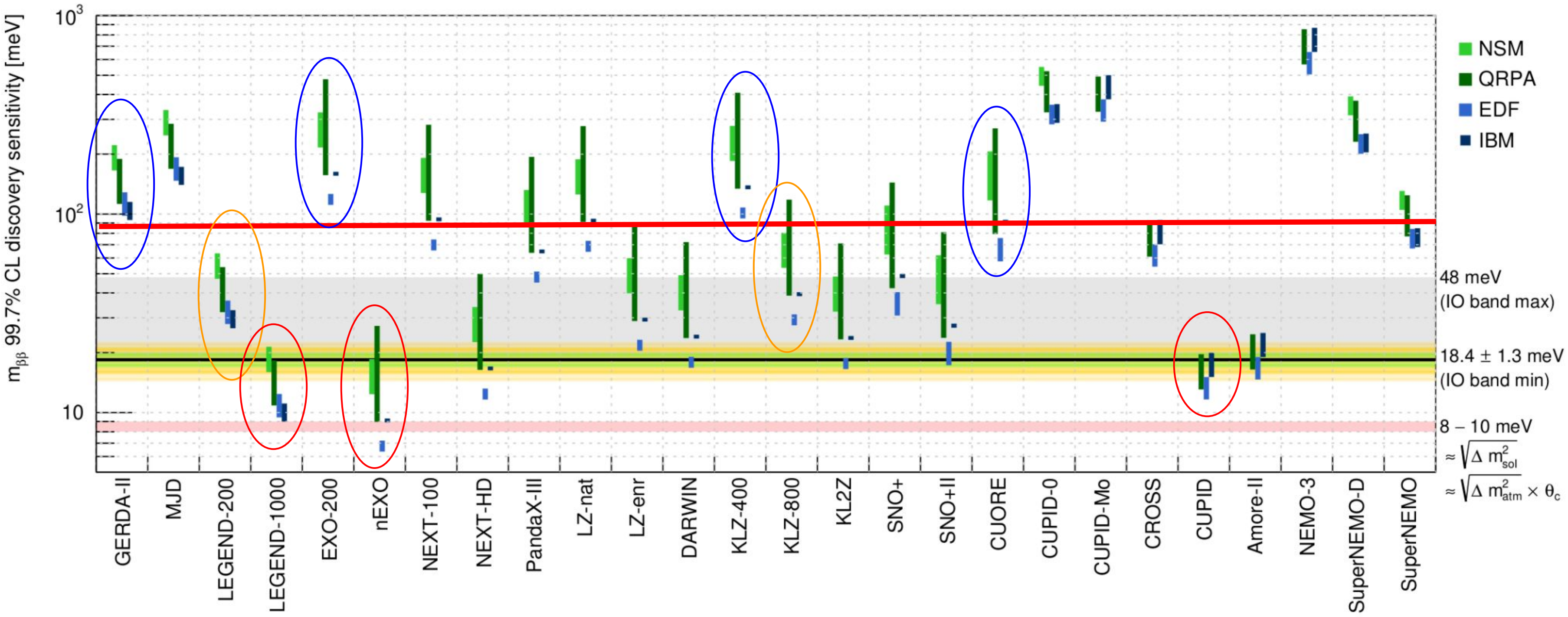


M.A., Benato, Detwiler, Menéndez and Vissani, arXiv:2202.01787

Where are we heading?

Scenario 1: signal just beyond current limits

- experiments will discover it within a few years
- next-gen experiments will measures rate
- follow-up measurements of decay features

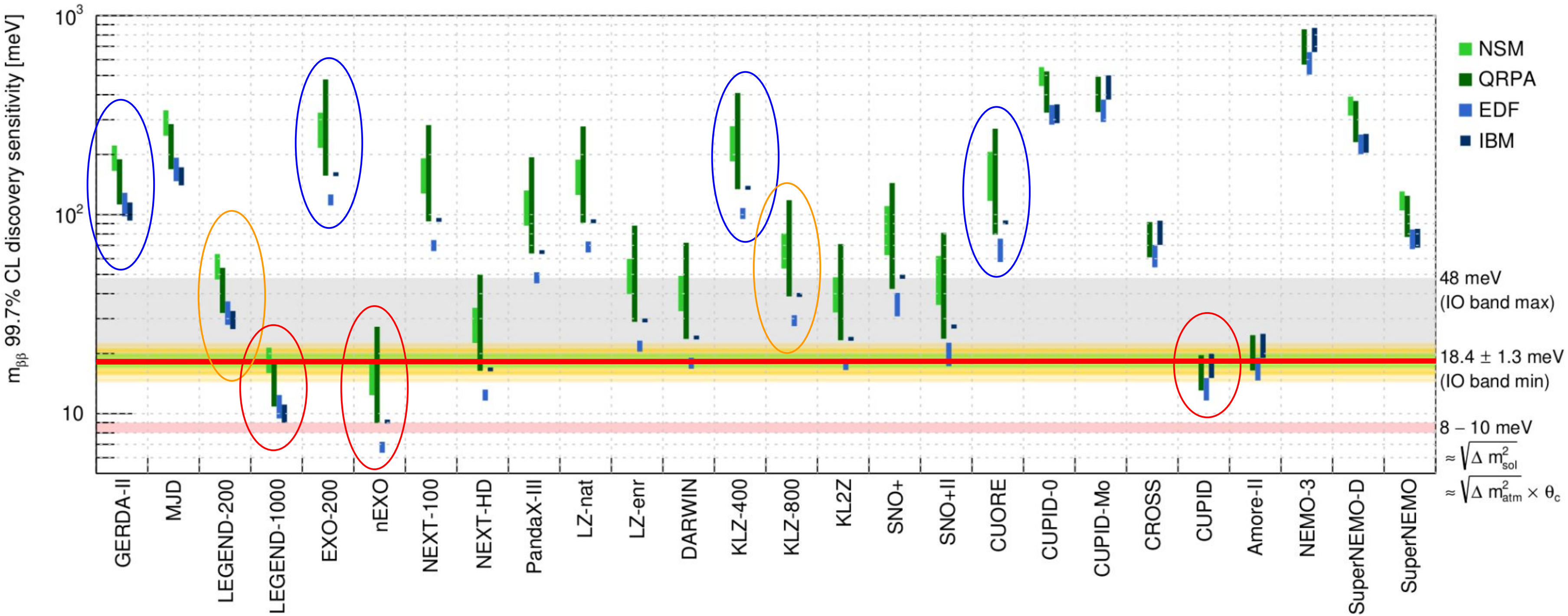


M.A., Benato, Detwiler, Menéndez and Vissani, arXiv:2202.01787

Where are we heading?

Scenario 2: weakest signal for inverted ordered neutrinos

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

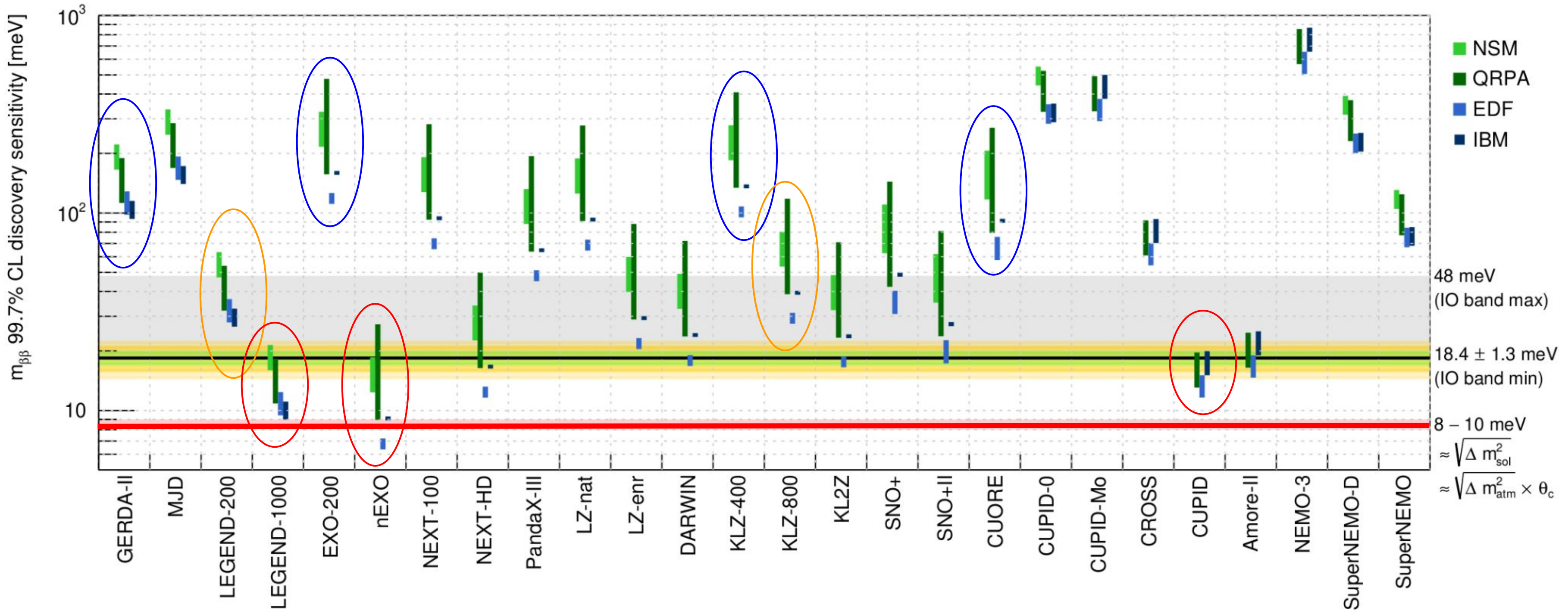


M.A., Benato, Detwiler, Menéndez and Vissani, arXiv:2202.01787

Where are we heading?

Scenario 3: signal even weaker or absent

- need R&D for a convincing discovery
- interplay with oscillation experiments and cosmology can still lead to theory breakthroughs



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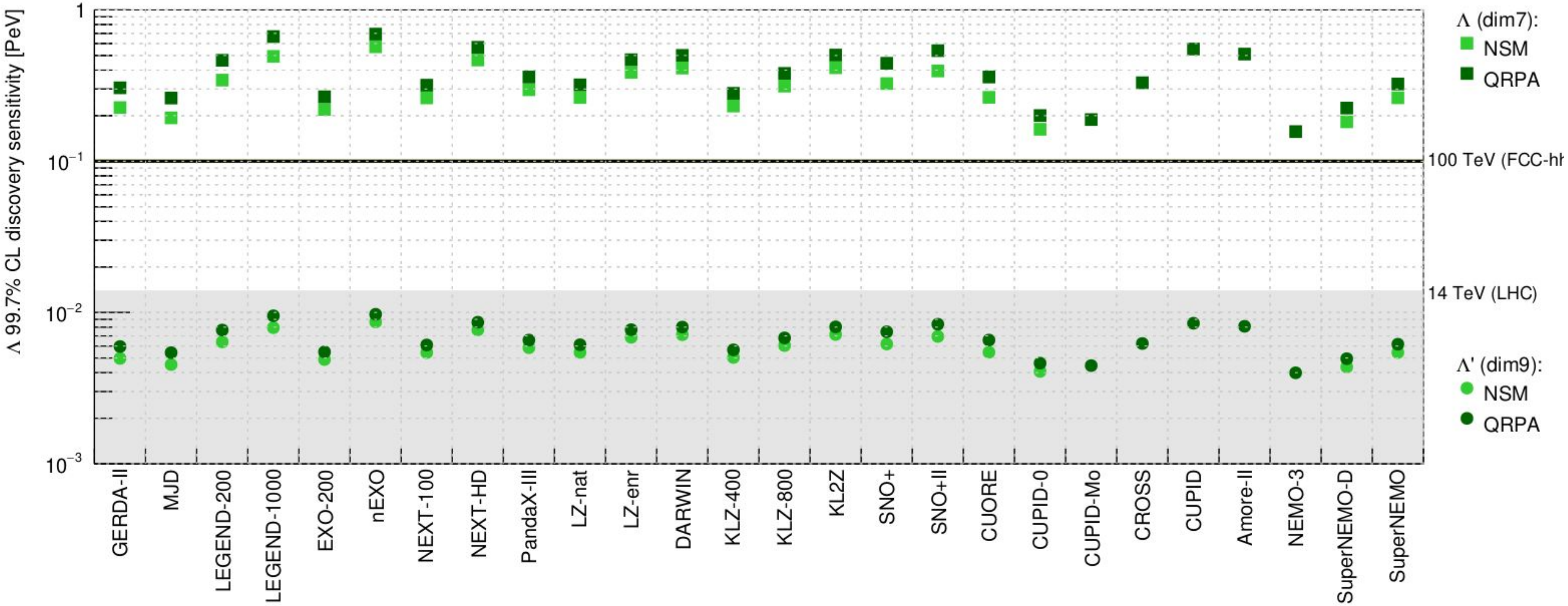
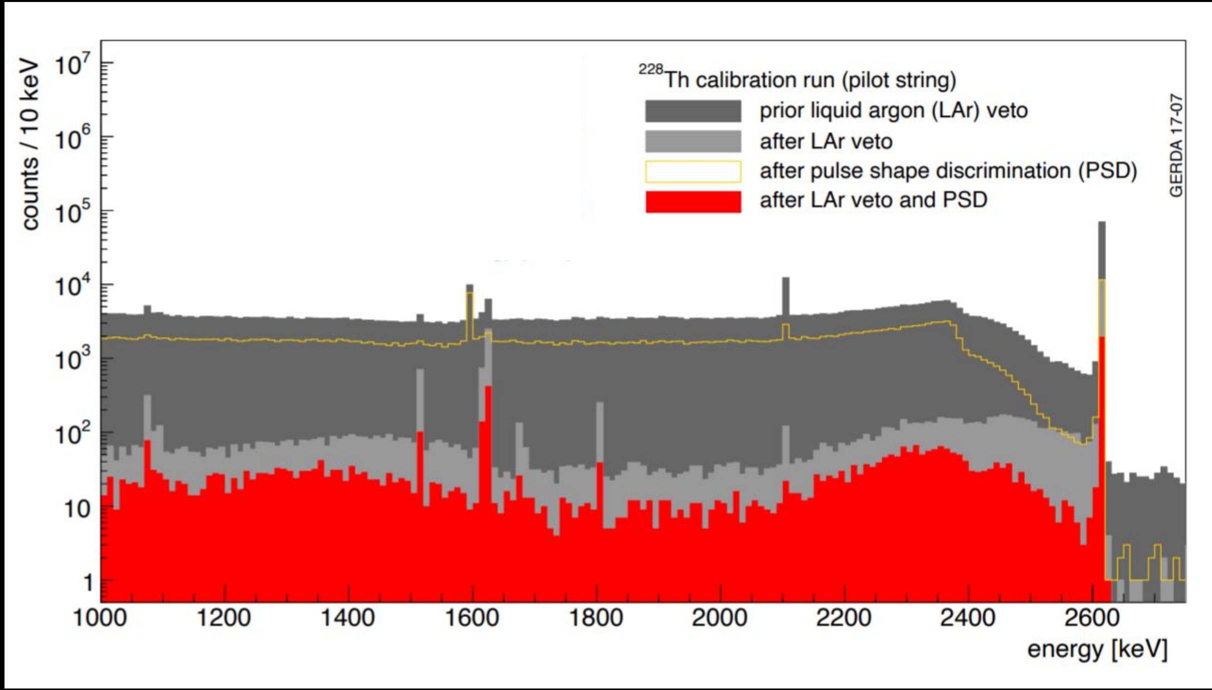
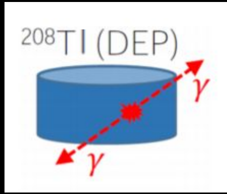
Where are we heading?

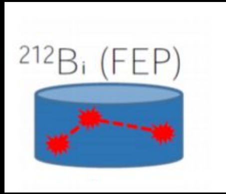


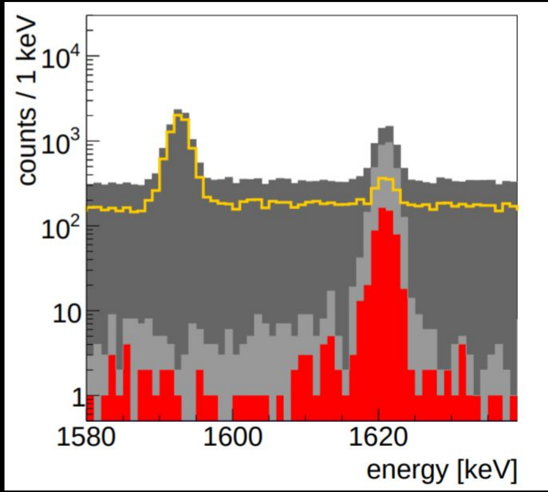
Background Suppression

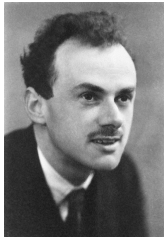
<$1% probability of ^{228}Th events leaking our $0\nu\beta\beta$ multivariate tagging



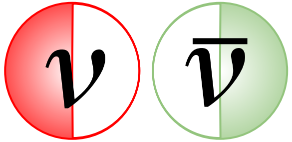






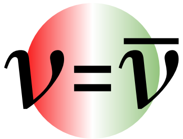


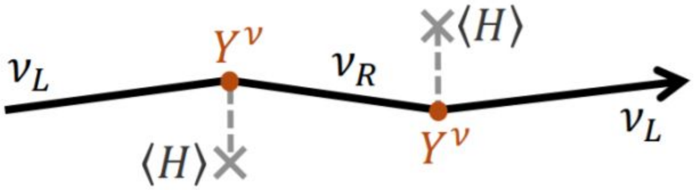
Dirac

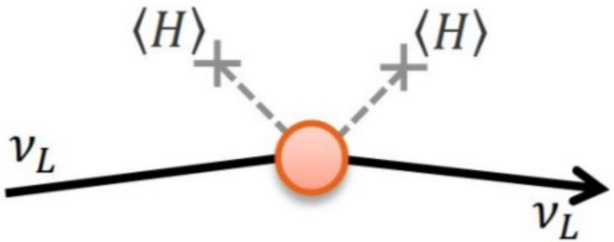


Neutrino masses

Majorana







- new right-handed neutrinos
- standard Higgs mechanism
- “unnaturally” small neutrino masses

- alternative Higgs mass mechanism
- neutrino mass violates L (and thus B-L)
- “naturally” small mass (see-saw mechanism)