Toward the discovery of lepton creation with neutrinoless double-β decay

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Fellini Seminar - November 8th, 2021

Toward the discovery of lepton creation with 0νββ decay

Content:

1. Historical landscape
2. Particle physics theory and motivation → I'm not a theorist, please don't ask tough questions
3. Nuclear physics and implications → I know even less about nuclear theory! 😳
4. Experimental aspects and methods
5. Recent and future experiments
6. Discovery probability and impact

Work developed in collaboration with:

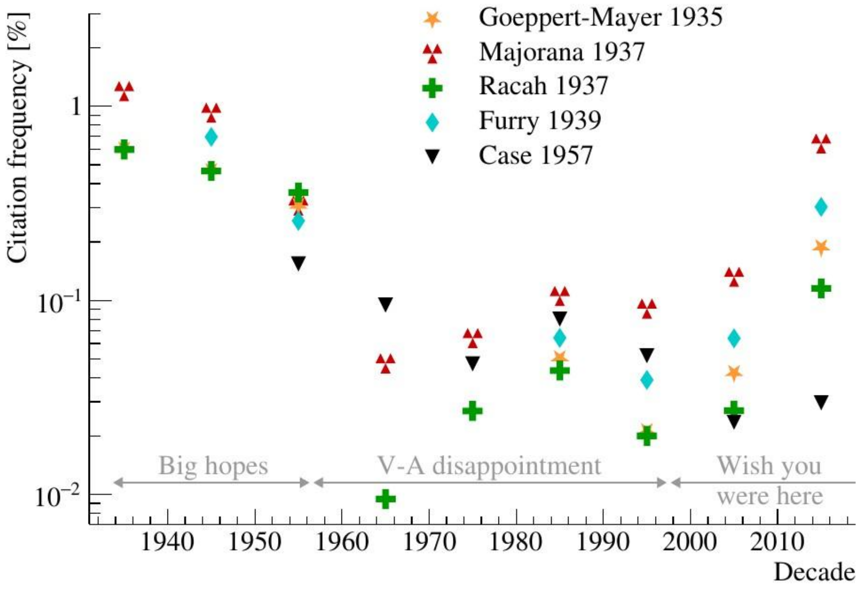
- M. Agostini, University College London
- J. Detwiler, University of Washington
- J. Menéndez, University of Barcelona
- F. Vissani, Laboratori Nazionali del Gran Sasso

Review paper foreseen to come out around mid December → Stay tuned!

Historical landscape: theoretical aspects

1920ies	Nucleus made of A protons and (A-Z) *inner electrons* → Monochromatic β spectrum
1930	Pauli proposes existence of neutrino *inside the nucleus* → Non relativistic model
1934	Fermi theory of β decay → Creation and destruction of matter particles
1935	Goeppert-Mayer applies Fermi theory to ββ decay
1937	Majorana theory: neutral elementary particles can be their own antiparticles
1938	Furry introduces 0νββ decay through emission and re-absorption of virtual Majorana ν
1950ies	(V-A) theory: 0νββ rate depends also on ν mass, not only on its nature → Loss of interest
1960ies	Models for flavor transformation of massive neutrinos
~1980	Seesaw mechanisms
~2000	Definitive evidence of neutrino oscillations → Mass mechanism as "standard" for 0νββ decay

Historical landscape: experimental aspects



~1950	Geochemical and direct experiments
~1970	First searches with Ge(Li) and scintillators
~1990	HPGe, TPCs, tracking detectors
~2000	O(10) kg HPGe sensitivity; KK claim 😲
~2010	O(100) kg HPGe, TPCs, liquid scintillators
now	moving towards the ton-scale!

Which are the fundamental symmetries and conserved quantities?

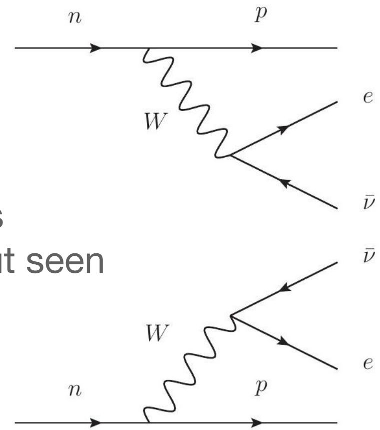
- B, L_e, L_μ, L_τ and $L=L_e+L_\mu+L_\tau$ are accidental symmetries that emerge without being *a priori* required
- Actually, these are anomalous symmetries spoiled by the full quantum theory
- Exact *global* symmetries of the standard model:

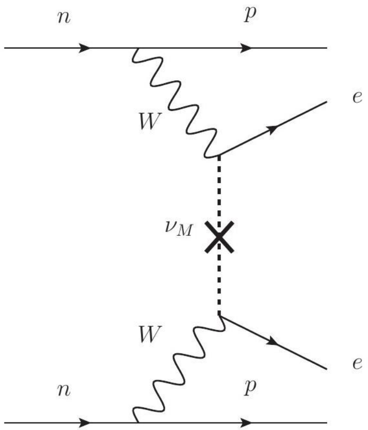
L_e-L_μ → Violation seen in appearance mode by T2K

L_μ-L_τ → Violation seen in appearance mode by OPERA

B-L → We don't know yet

2νββ DECAY
→ SM process
→ Very rare but seen





0νββ DECAY
→ BSM process
→ Violates B-L
→ Creates matter
→ Yet unseen!

What generated the matter-antimatter asymmetry in the Universe?

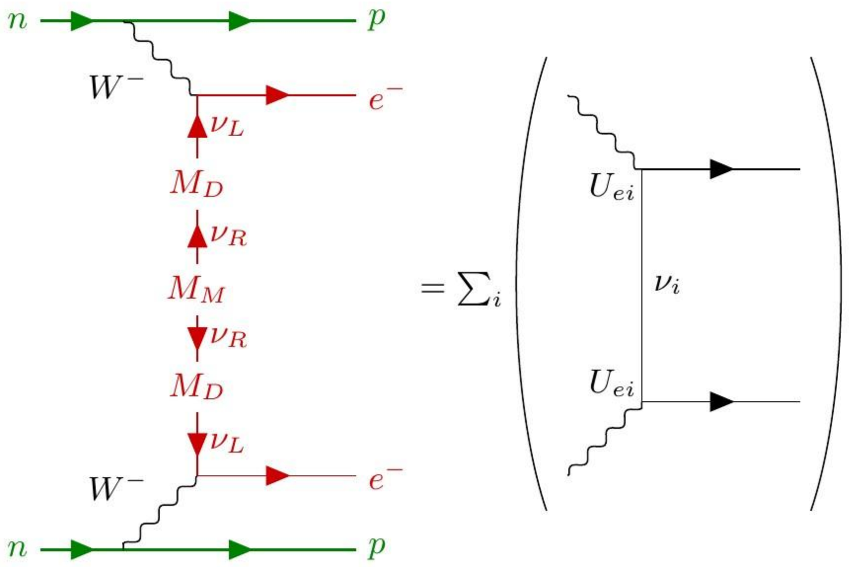
- Non-perturbative effect violate B+L, but can't explain *quantitatively* the asymmetry
  → We need a *dynamical* explanation yielding the asymmetry at some point in history: *baryogenesis*
- Sakharov conditions for baryogenesis:
  a. Violation of B (or B-L)
  b. Violation of C and CP
  c. Interactions out of thermal equilibrium
- Possible solution: baryogenesis through *leptogenesis*
  → Observing the violation of B-L in the lepton sector would give a strong qualitative indication for the correctness of the baryogenesis hypothesis

What are the origin and nature of neutrino mass?

Why are neutrino masses so small?
Maybe, are they Majorana masses?

- Neutrino mass terms generated by odd-dimensional operators with D≥5
- D=5 case *only* implies an additional right-handed Majorana neutrino
  - Light neutrino masses generated through seesaw mechanism from the heavy Majorana one:
    $M_\nu = -M_D \cdot M_M^{-1} \cdot M_D$
    where:
    M_ν = Majorana mass for light neutrino
    M_D = Dirac mass
    M_M = Heavy Majorana neutrino mass
  - In terms of neutrino oscillations:

$$m_{\beta\beta} = \left| \sum_{i=1}^{3} |U_{\mathrm{ei}}^2| \, e^{i\varphi_{\mathrm{i}}} \, m_{\mathrm{i}} \right|$$

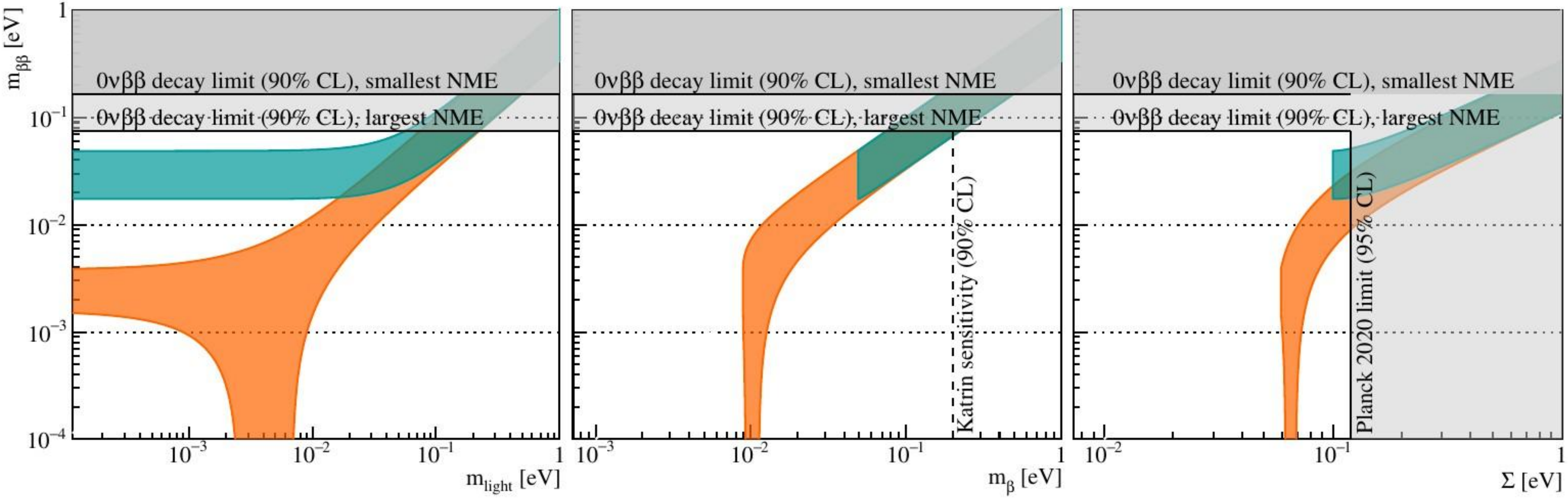


From 0νββ decay to the neutrino mass

- Connection between 0νββ decay rate and new physics terms:

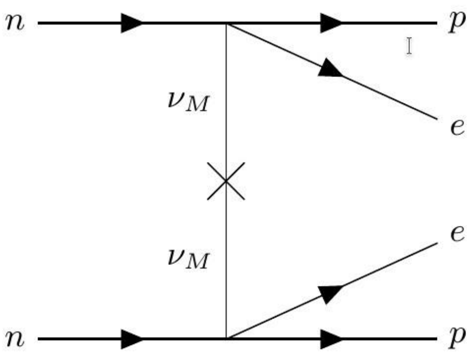
$$\frac{\Gamma_{0\nu}}{\ln 2} = \frac{1}{T^{0\nu}_{1/2}} = \sum_i G_i\, g_i^4\, M_i^2\, f_i(\Lambda) + \text{interference terms},$$

- In the case of D=5 (light neutrino exchange): $\frac{1}{T^{0\nu}_{1/2}} = G_{01}\, g_A^2\, \left(M^{0\nu}_{light}\right)^2 \frac{m^2_{\beta\beta}}{m^2_e}$



Nuclear physics theory and implications

- 0νββ decay triggered by BSM physics, but takes place in a highly correlated many-body system
- Nuclear Matrix Elements computed in two approximations:
  - Light: $m_\nu \ll p \sim 200$ MeV
  - Heavy: $m_\nu \gg p \sim 200$ MeV
- Different nuclear models yield NMEs differing by up to a factor 3
- New approaches worth remarking:
  - Ab-initio calculations
    → Good explanation of β decay
    → Not so good (yet) at predicting energy levels of heavy nuclei
  - Effective Field Theory
    → Compute contribution due to *any* odd-dimensional operator
    → Short-range exchange of high-energy light neutrinos might not be negligible

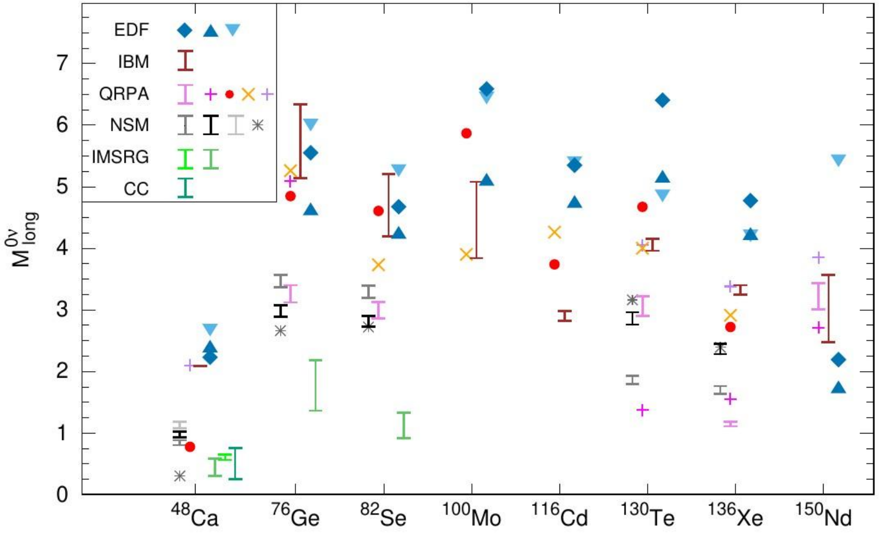


$$T_{1/2}^{-1} = G_{01}\, g_A^4 \,\left(M_{\text{light}}^{0\nu}\right)^2 \frac{m_{\beta\beta}^2}{m_e^2} + \frac{m_N^2}{m_e^2}\tilde{G}\,\tilde{g}^4\,\tilde{M}^2\left(\frac{v}{\tilde{\Lambda}}\right)^6 + \frac{m_N^4}{m_e^2\, v^2}\tilde{G}'\,\tilde{g}'^4\,\tilde{M}'^2\left(\frac{v}{\tilde{\Lambda}'}\right)^{10} + \cdots$$

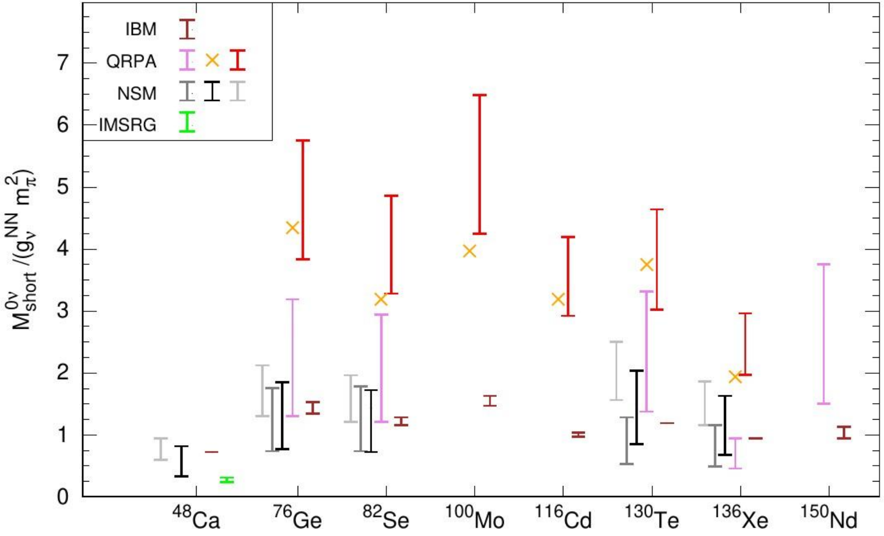
$$T_{1/2}^{-1} = G_{01}\, g_A^4 \left(M_{\text{long}}^{0\nu} + M_{\text{short}}^{0\nu}\right)^2 \frac{m_{\beta\beta}^2}{m_e^2}$$

Nuclear physics theory and implications

Long-range, light neutrino exchange

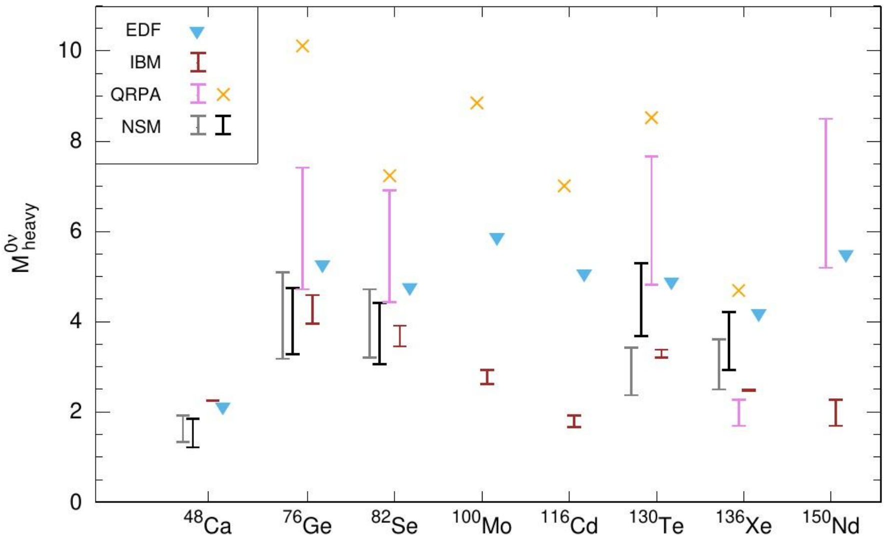


Short range, light neutrino exchange



Nuclear physics theory and implications

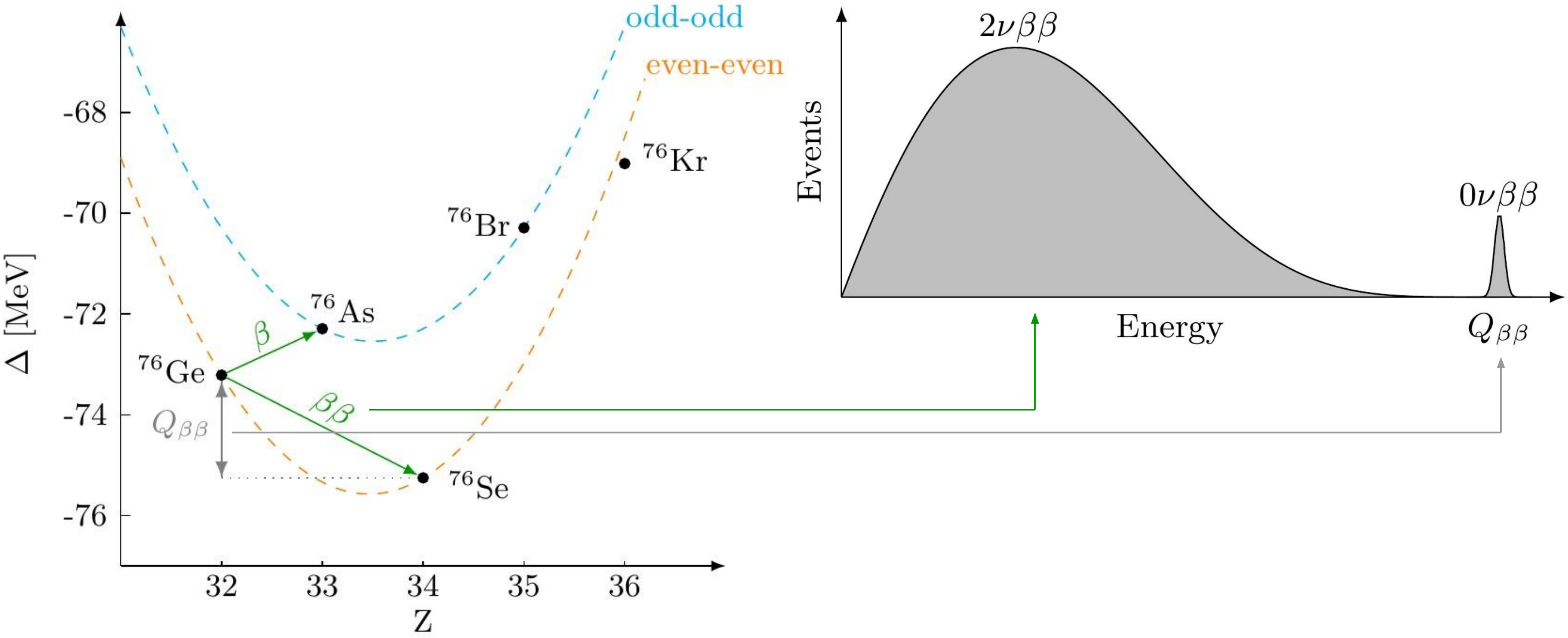
Heavy neutrino exchange



Possible experimental validations

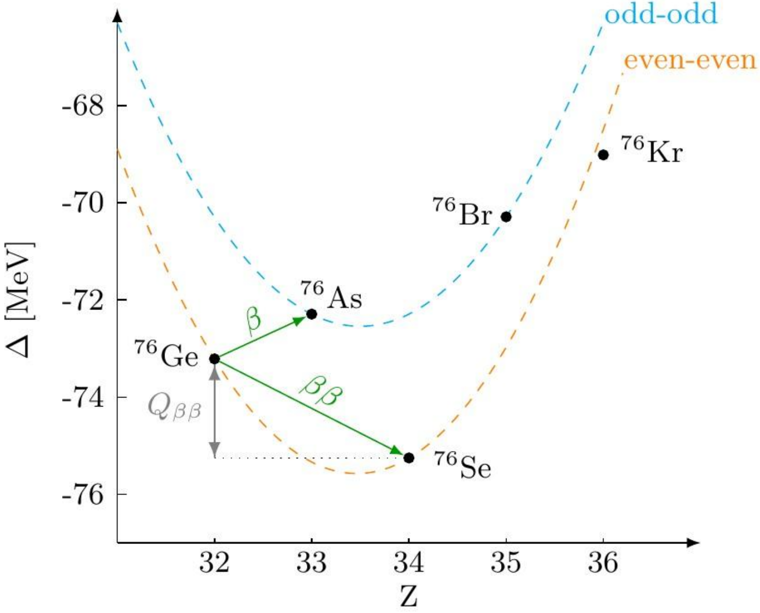
- Validation of NMEs for single β decay and 2νββ decay not enough, because of different exchanged momentum
- Ordinary muon capture: $\mu^- + p \rightarrow n + \nu_\mu$
- Inelastic neutrino-nucleon scattering
- Two-nucleon transfer reactions, e.g. ^{136}Ba (p,t) ^{138}Ba
  → However this is a strong interaction
- Double charge-exchange reaction, e.g. ^{40}Ca(^{18}O,^{18}Ne)^{40}Ar
  → However this is a strong interaction
- NMEs for Double Gamow-Teller transitions and γγ transitions possibly correlated to 0νββ decay NME

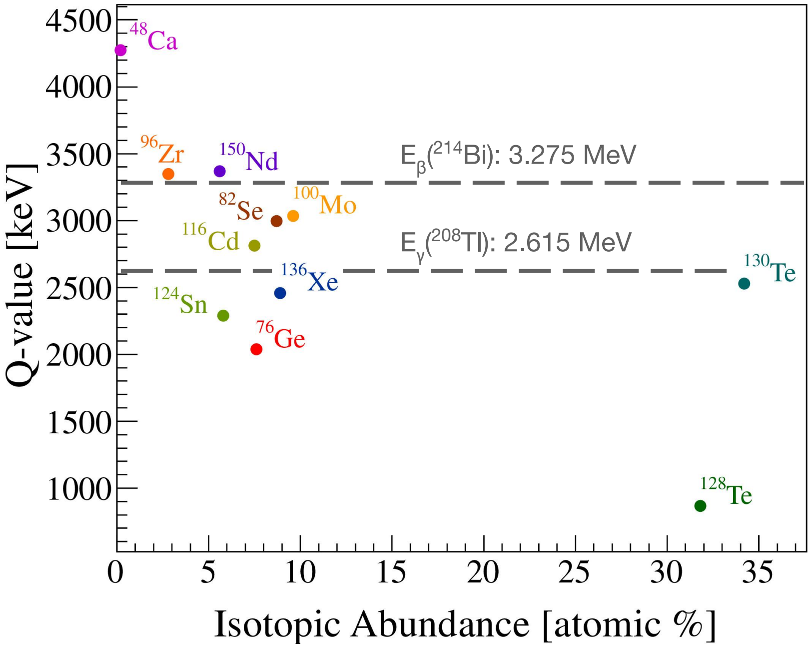
Experimental aspects: 0νββ decay signature



- 0νββ decay can be searched only with isotopes for which the regular β decay is forbidden
- 0νββ decay signature is an excess at the Q-value ($Q_{\beta\beta}$) in the sum electron spectrum
- 2νββ decay yields a continuum up to $Q_{\beta\beta}$

Isotope selection





- High Q-value ($Q_{\beta\beta}$) is highly preferable:
    - Larger phase space
    - Lower background from natural radioactivity
- High isotopic abundance preferable → Easier enrichment

Isotope selection

Isotope	Daughter	$Q_{\beta\beta}$ [a] [keV]	f_{nat} [b] [%]	f_{enr} [c] [%]	$T_{1/2}^{2\nu\beta\beta}$ [d] [yr]	$T_{1/2}^{0\nu\beta\beta}$ [e] [yr]
^{48}Ca	^{48}Ti	4 267.98(32)	0.187(21)	16	$\left(6.4^{+0.7}_{-0.6}(\text{stat})^{+1.2}_{-0.9}(\text{syst})\right) \cdot 10^{19}$	$> 5.8 \cdot 10^{22}$
^{76}Ge	^{76}Se	2 039.061(7)	7.75(12)	92	$(1.926 \pm 94) \cdot 10^{21}$	$> 1.8 \cdot 10^{26}$
^{82}Se	^{82}Kr	2 997.9(3)	8.82(15)	96.3	$\left(8.60 \pm 0.03(\text{stat})^{+0.19}_{-0.13}(\text{syst})\right) \cdot 10^{19}$	$> 3.5 \cdot 10^{24}$
^{96}Zr	^{96}Mo	3 356.097(86)	2.80(2)	86	$(2.35 \pm 0.14(\text{stat}) \pm 0.16(\text{syst})) \cdot 10^{19}$	$> 9.2 \cdot 10^{21}$
^{100}Mo	^{100}Ru	3 034.40(17)	9.744(65)	99.5	$\left(7.12^{+0.18}_{-0.14}(\text{stat}) \pm 0.10(\text{syst})\right) \cdot 10^{18}$	$> 1.5 \cdot 10^{24}$
^{116}Cd	^{116}Sn	2 813.50(13)	7.512(54)	82	$2.63^{+0.11}_{-0.12} \cdot 10^{19}$	$> 2.2 \cdot 10^{23}$
^{130}Te	^{130}Xe	2 527.518(13)	34.08(62)	92	$\left(7.71^{+0.08}_{-0.06}(\text{stat})^{+0.12}_{0.15}(\text{syst})\right) \cdot 10^{20}$	$> 3.2 \cdot 10^{25}$
^{136}Xe	^{136}Ba	2 457.83(37)	8.857(72)	90	$(2.165 \pm 0.016(\text{stat}) \pm 0.059(\text{syst})) \cdot 10^{21}$	$> 1.1 \cdot 10^{26}$
^{150}Nd	^{150}Sm	3 371.38(20)	5.638(28)	91	$\left(9.34 \pm 0.22(\text{stat})^{+0.62}_{-0.60}(\text{syst})\right) \cdot 10^{18}$	$> 2.0 \cdot 10^{22}$

- Highest sensitivities achieved with isotopes that:
  - are easier to enrich
  - can be used in a well-established detector technology
- Detector technology plays primary role through several parameters:
  - energy resolution
  - detector material purity
  - background suppression

Detector technologies

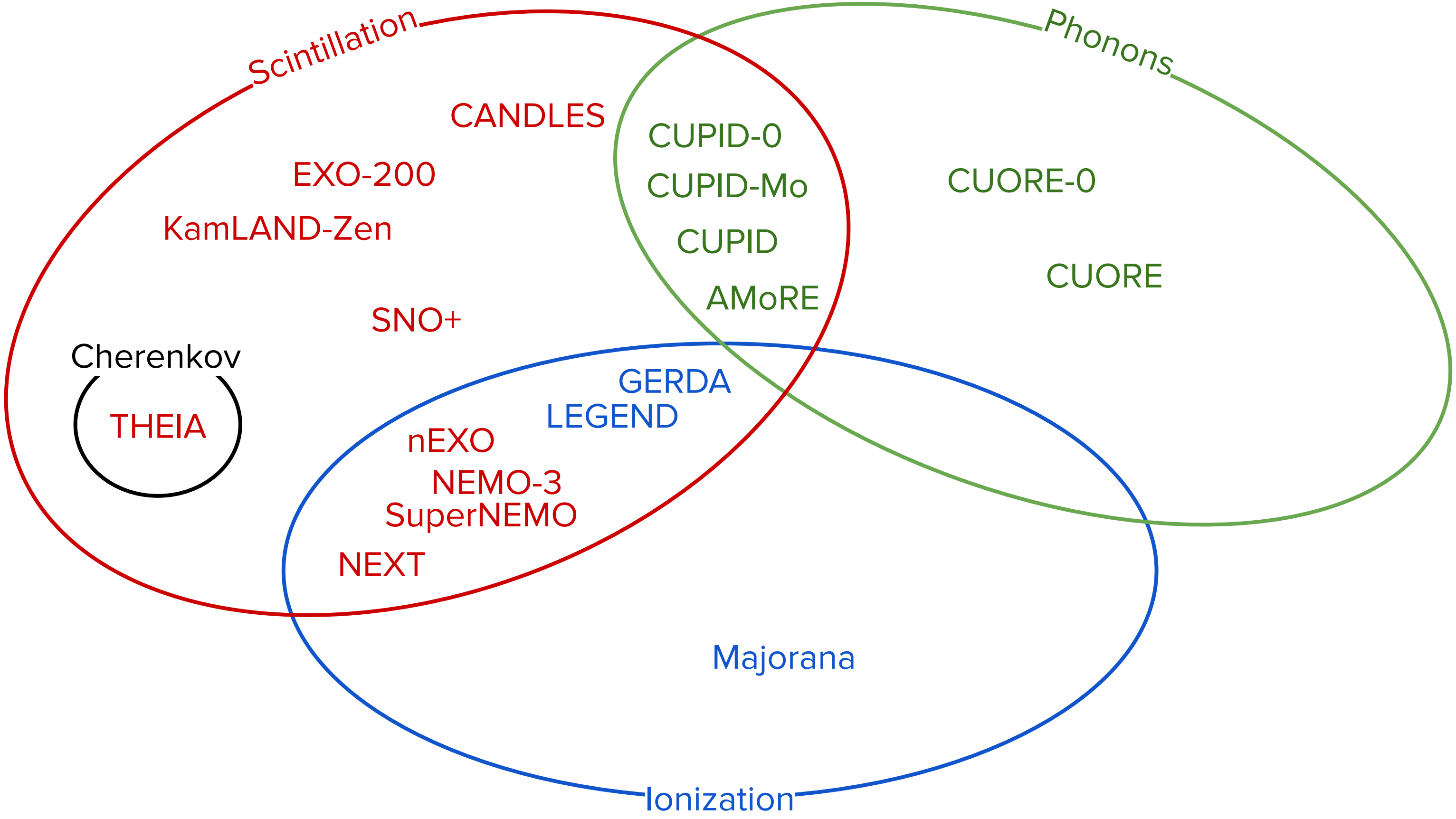
Detector type	Description	Typical isotope mass	Containment efficiency	Pros and cons
Solid state granular	Crystals containing ββ isotope	0.1-1 kg (single crystal)	70-95%	+ Scalable + High resolution - Many crystals required
Monolithic liquid or gaseous	Material = isotope or isotope dissolved in liquid	100-1000 kg	100%	+ Single detector + Self shielding - Poor resolution
Composite	Foil with isotope in low-pressure gas tracker	10 kg	~50%	+ Ultra-low background + Multiple isotopes - Very hard to scale

Detector technologies

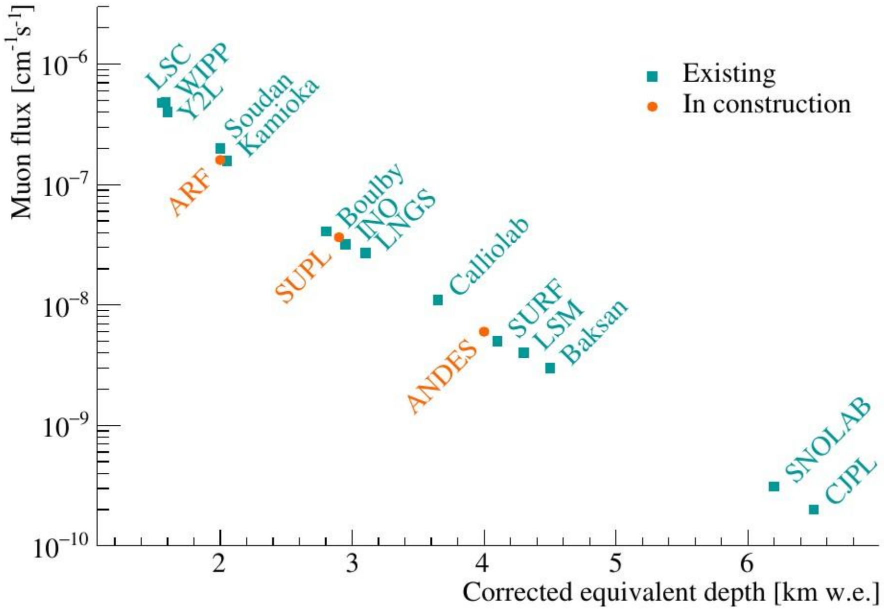
Readout channel	Energy resolution	Particle identification	Sensitivity to position	Applicable to multiple isotopes
Ionization	0.1-1%	Only in gas	Yes	Not really
Phonons	~0.2%	Nope	Nope	Yes
Scintillation	Few %	α vs β	In liquids and gases	Yes
Cherenkov	Forget it!	Visible only for β's	Maybe	Yes

- Take-away messages:
  - The best detector technology doesn't exist
  - Combined readout channels are VERY helpful
    → good resolution with one, background suppression with the other

0νββ decay experimental fauna



Cosmic ray background

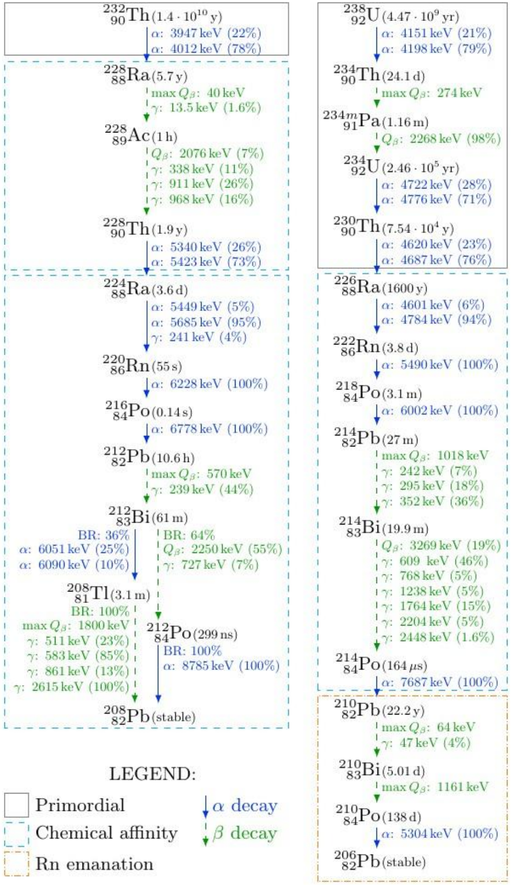


Residual backgrounds from cosmic in underground experiments:

- High energy muons (up to TeV)
  → Reconstruct muon tracks (monolithic)
  → Muon veto around granular detector
- Spallation products
  - Activate isotopes in the detector material prior to the installation underground
  - Activation in situ
    → Relevant for large volume scintillators
    → If the activated isotope decays quickly, search for delayed coincidences
  - High energy spallation neutrons
    → Well, this is a problem!

Background from actinides contamination

- Uranium and thorium contamination present in **many** materials
- Several particle types involved:
  - α between 4 and 9 MeV
  - β up to 3.3 MeV
  - γ up to 2.6 MeV, but summation possible
  - neutrons from (α,n) reactions
- Decay chains not always in equilibrium
  - Material exposure to air
    → ^{222}Rn deposition followed by ^{210}Pb accumulation
  - Surface cleaning
    → Pb removed, ^{210}Po remains
  - Mechanical or chemical processes in material bulk or surface
    → Accumulation of “chemically active” radium
- Possible suppression techniques:
  - Use cleaner materials and surfaces
  - Minimize exposure to radon
  - Particle identification to reject α
  - Event topology
  - Delayed coincidences



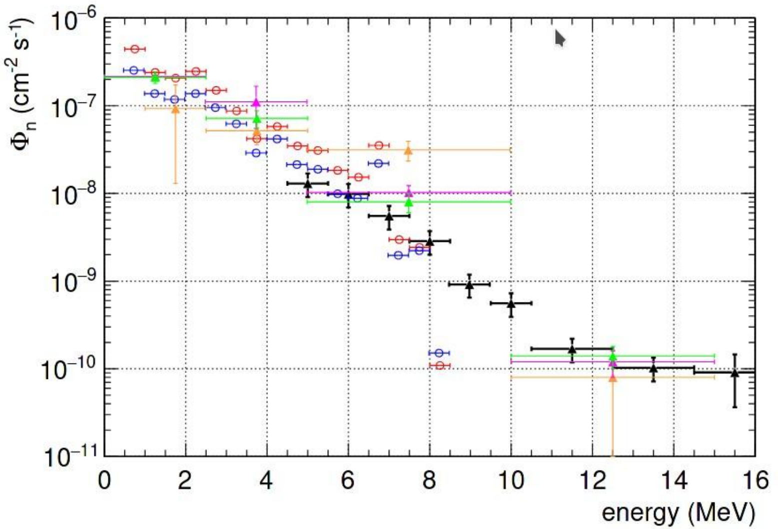
Man-made isotopes

- Several man-made isotopes visible in ultra-low background experiments
- Background only from:
  - Isotopes decaying β with $Q_{\beta}>Q_{\beta\beta}$
  - Isotopes or decay chains with dominant half-life comparable to experiment lifetime
- So far, only ^{110m}Ag has been found

Isotope	Half life	Q_{β} [keV]	Detected	Notes
^{88}Y	107 d	3008	No	Several γ lines
^{90}Sr	28.8 y	546	No	
^{90}Y	64 h	2279	No	Pure β emitter
^{110m}Ag	250 d	3008	Yes	Several γ lines
^{134}Cs	2 y	2059	No	Several γ lines
^{144}Ce	285 d	319	No	
^{144}Pr	17.3 m	2997	No	Pure β emitter

Neutrons

Source	Location	Energy
^{238}U fission	Concrete or internal	<10 MeV
(α,n) reactions	Concrete or internal	<10 MeV
Spallation	Rock, concrete, …	up to GeV



Neutron suppression

- Passive shielding (polyethylene, boron, water) → good for neutrons <10 MeV
- Active shielding in liquid scintillator outer layer
- Add element with high neutron cross section (e.g. ^{6}Li) in active volume

Neutron backgrounds

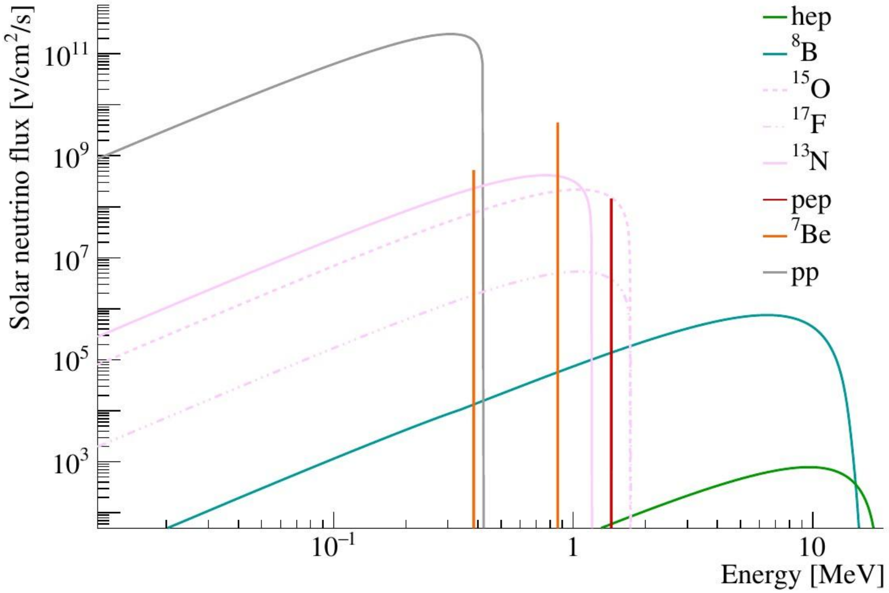
- In-situ isotope activation
- γ's from inelastic scattering or captures

Solar neutrinos

Elastic scattering

$\nu + e^- \rightarrow \nu + e^-$

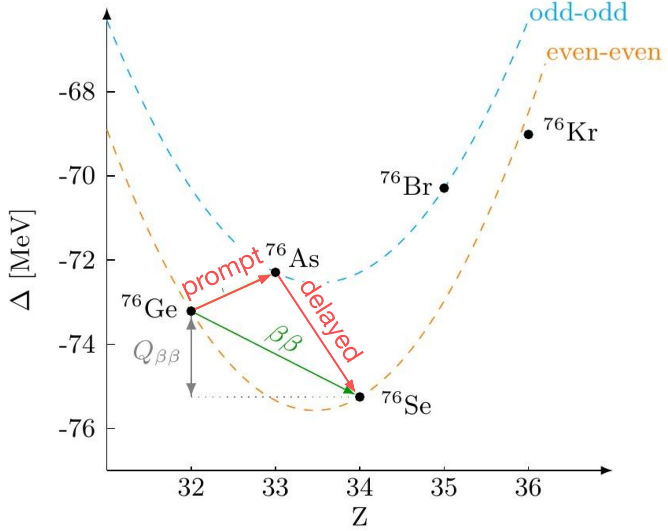
- Only relevant for large scintillators
- Can be suppressed through signal directionality



Charge Current

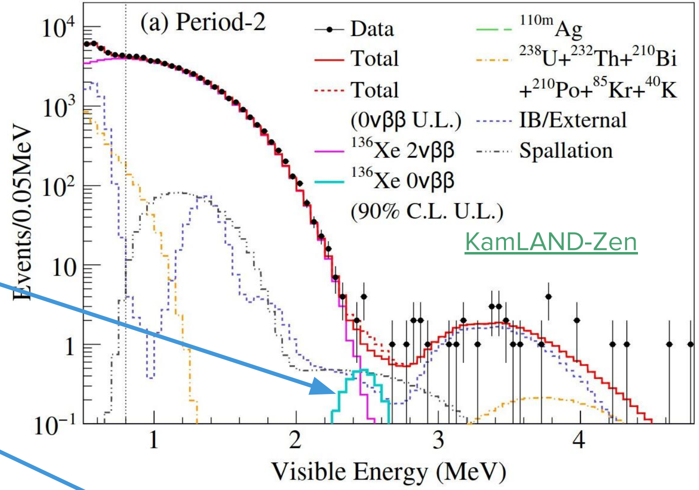
Prompt: $^{Z}A + \nu \rightarrow {}^{Z+1}A + e^- \,[+ \gamma(s)] + Q_\nu$
Delayed: $^{Z+1}A \rightarrow {}^{Z+2}A + \beta^- \,[+ \gamma(s)] + Q_\beta$

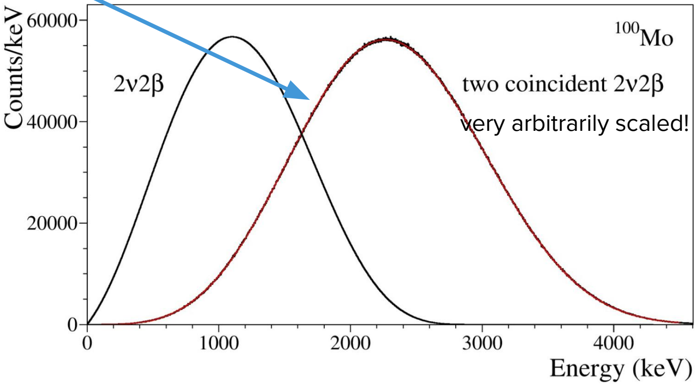
- Can be suppressed via topology and delayed coincidences, depending on isotope
- Not quite relevant, yet



2νββ decay

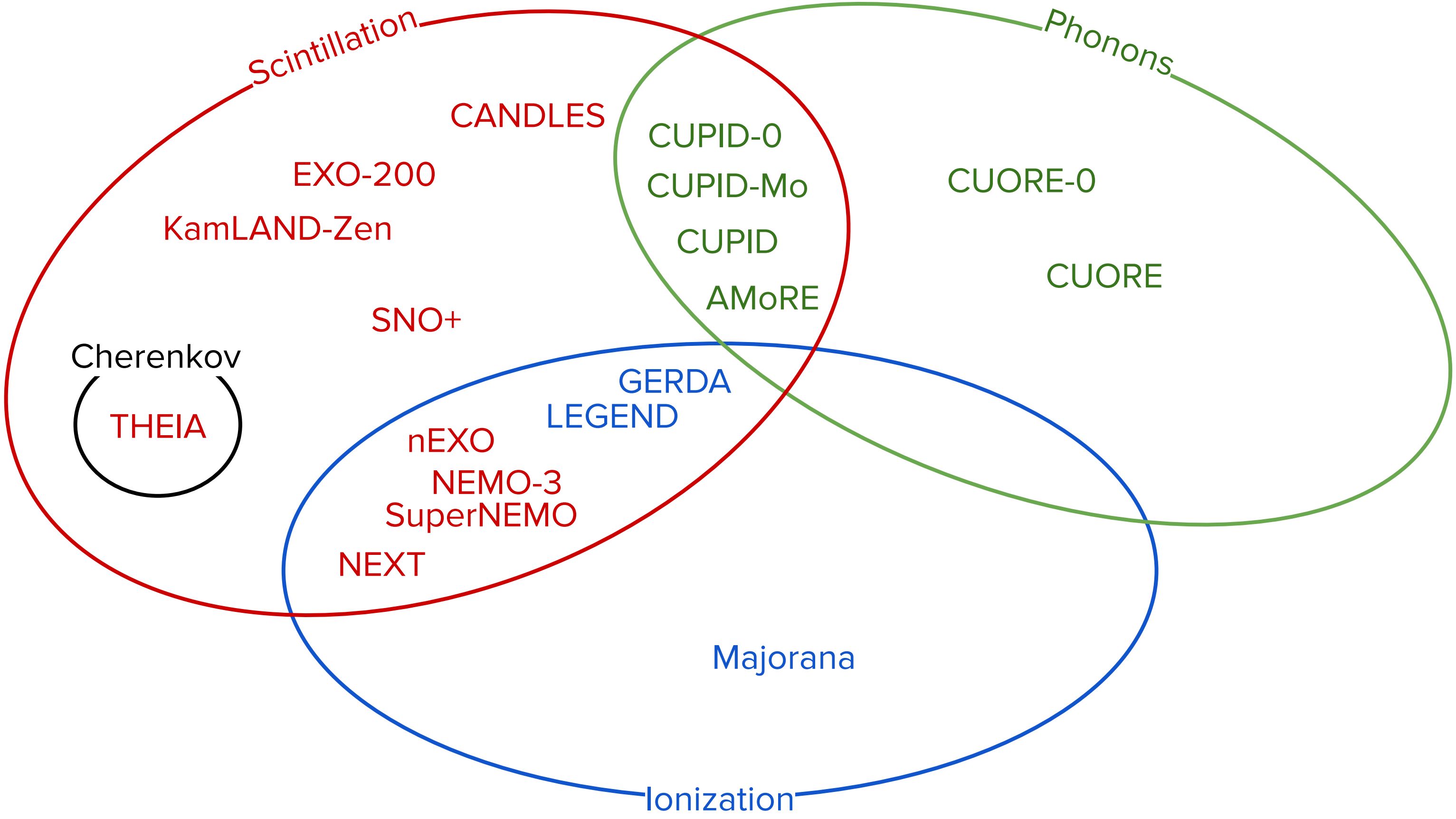
- Irreducible 2νββ background
  - Tail of 2νββ spectrum
    ⟹ Energy resolution
  - Pile-up of 2νββ events
    ⟹ Time resolution



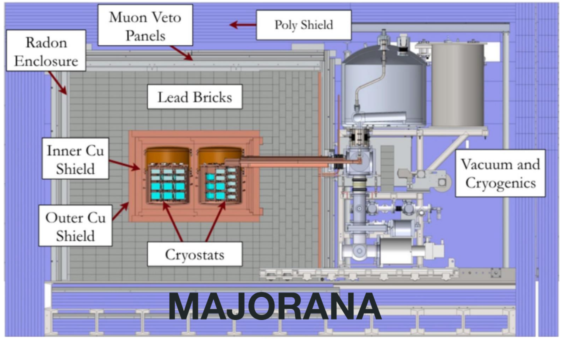


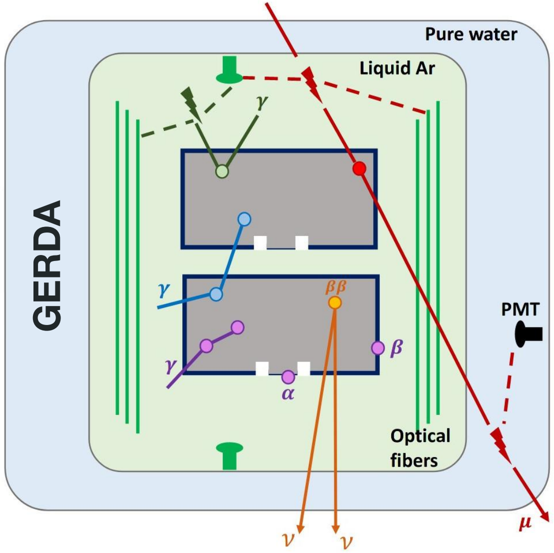
D. M. Cherniak et al., EPJ C72 (2012) 1989

0νββ decay experimental fauna

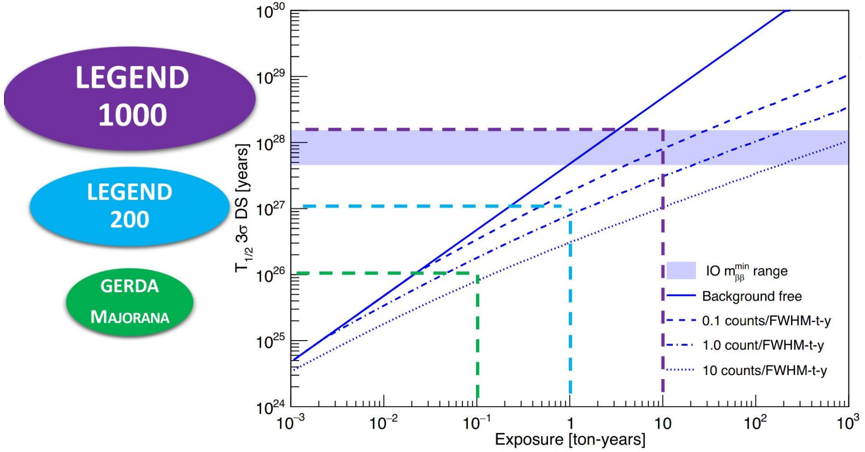


Germanium experiments



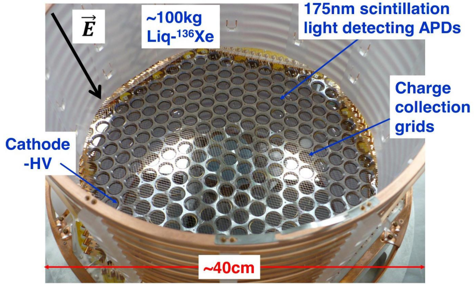


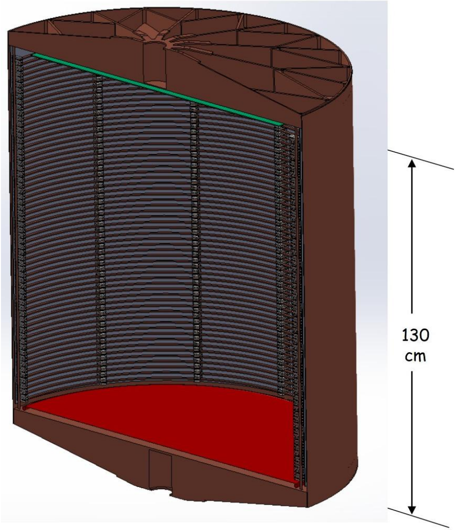
- Low Q-value: 2039 keV
- Highest energy resolution: ~0.1%
- Extremely low bkg: ~5·10^{-4} counts/keV/kg/yr
  → Operating next to linear sensitivity regime
- MAJORANA + GERDA joining for next generation experiment: LEGEND



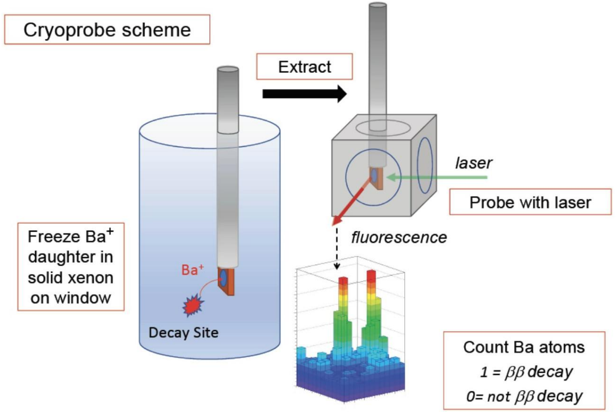
Xenon TPCs

EXO-200 / nEXO





- Liquid TPC
  → Self shielding, easy to scale up
- Gas TPC
  → Energy resolution ~1%
  → Particle tracking
- Double readout: ionization and scintillation
- Daughter tagging possible!



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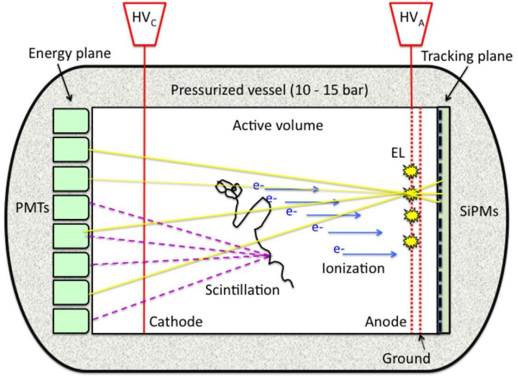
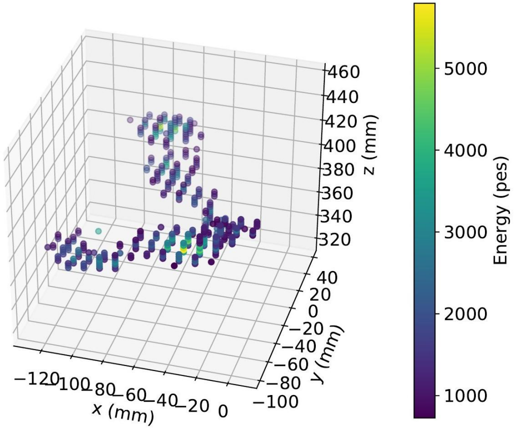


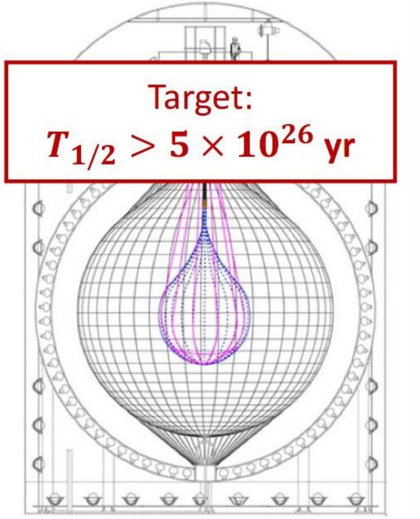


Liquid scintillator experiments

KamLAND-Zen

Current

Target:
$T_{1/2} > 5 \times 10^{26}$ yr



KamLAND-Zen 800

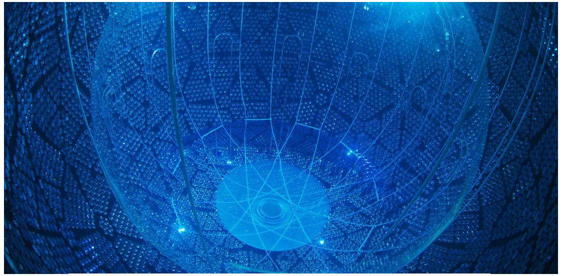
Mini-balloon Radius = 1.90 m

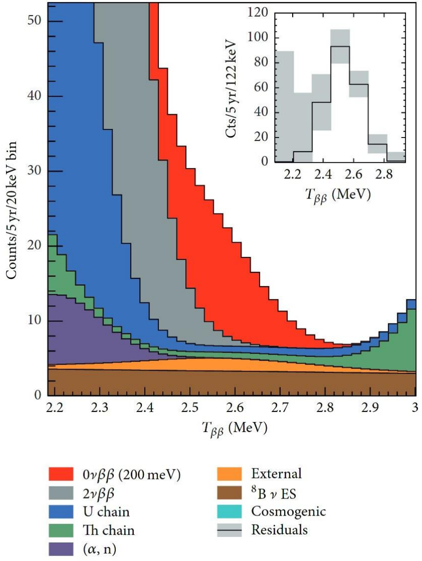
Xenon mass = 745 kg

Started January 2019

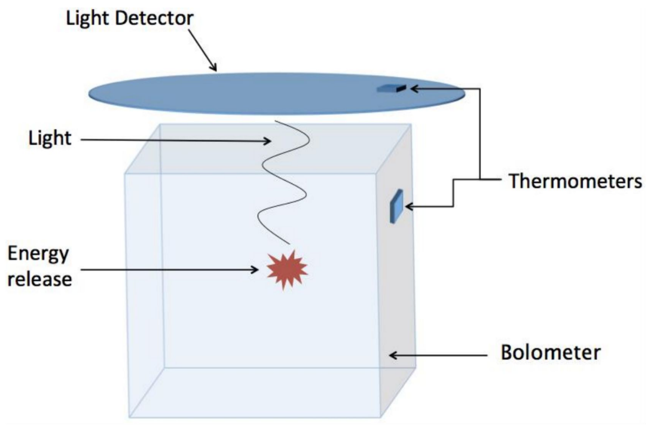
- Readout of scintillation only
  → Energy resolution of few %
  → Particle identification possible
- Very large volume
  → Isotope in central part
  → Highly effective self shielding
- Isotope (^{130}Te or ^{136}Xe) dissolved in liquid scintillator
  → Easily scalable
  → Enrichment not strictly required
- Readout of Cherenkov light possible in future experiments

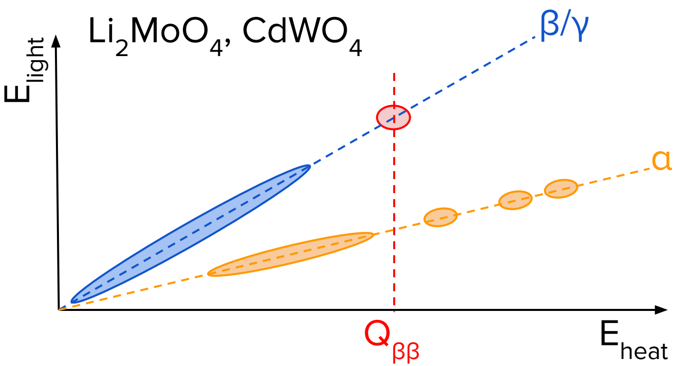
SNO+



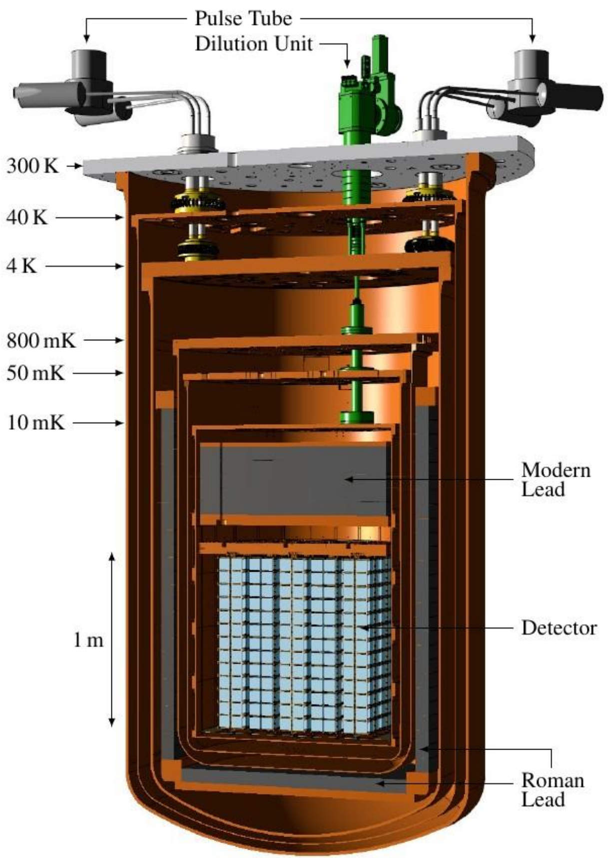


Cryogenic calorimeters



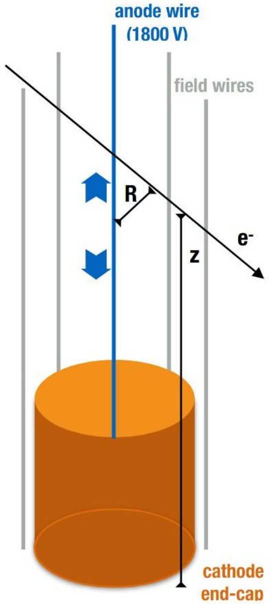


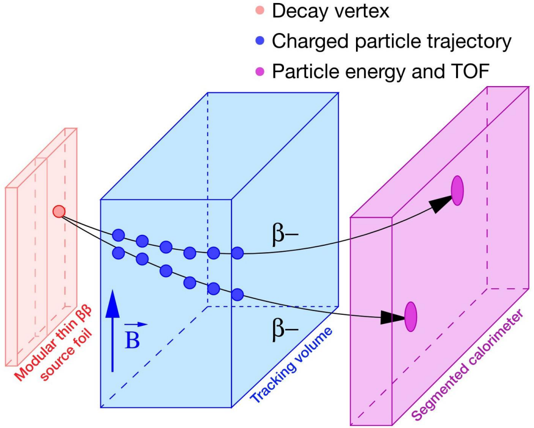
- Array of crystals operated at ~10 mK
- Measure temperature increase following phonon recombination
- Resolution: 5-10 keV
- Main background: α's from support materials
- Scintillating crystal allow particle discrimination!
- CUORE: 200 kg of ^{130}Te
  → Taking data since 2017
  → BI~10^{-2} cts/keV/kg/yr
- CUPID: upgrade of CUORE in preparation
  → 250 kg of ^{100}Mo
  → BI~10^{-4} cts/keV/kg/yr thanks to light readout!

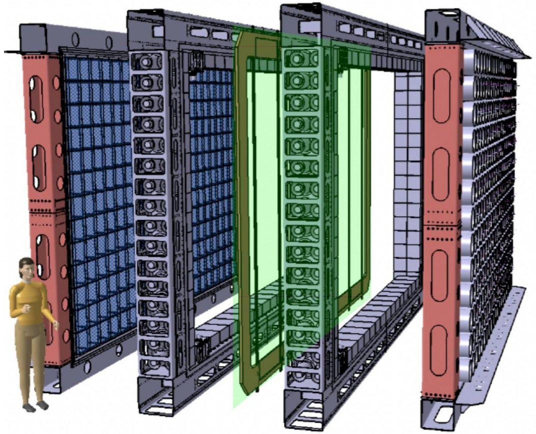


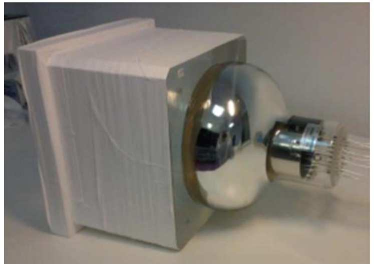
Tracking calorimeters: SuperNEMO

- Measure both energy and momentum
  → Background suppression
  → Single electrons resolved
  → Possible to study $0\nu\beta\beta$ decay mechanism
- Source ≠ detector
  → Limited isotope mass
  → Any isotope is usable
- Perfect technology for precision measurement of $0\nu\beta\beta$ and $2\nu\beta\beta$ decay









Other technologies

Project	Isosope(s)	Description and main features
CANDLES†[a]	^{48}Ca	Scintillator crystal. Possible operation as cryogenic calorimeter.
COBRA†[b]	^{70}Zn, ^{114,116}Cd, ^{128,130}Te	CdZnTe semiconductor detectors. Room temperature; multi-isotope.
Selena[c]	^{82}Se	Amorphous ^{82}Se on high resolution, high-granularity CMOS array with integrated readout. Particle discrimination via space resolution; room temperature; no self-shielding needed.
NνDEx[d]	^{82}Se	High-pressure gaseous $^{82}SeF_6$ ion-imaging TPC. $\lesssim 1\%$ energy resolution; precise signal topology; possible multi-isotope.
R2D2[e]	^{136}Xe	Spherical TPC. Single readout channel; inexpensive infrastructure.
AXEL[f]	^{136}Xe	High-pressure TPC operated in proportional scintillation mode. High energy resolution; possible positive ion detection.
JUNO[g]	n.d.y.	Isotope loaded liquid scintillator. Multi-isotope.
NuDot[h]	n.d.y.	Liquid scintillator loaded with quantum dots or perovskites as wavelength shifter for Cherenkov light. Discriminate directional backgrounds; multi-isotope.
ZICOS[i]	^{96}Zr	Zr-loaded liquid scintillator. Topology and particle discrimination via Cherenkov light readout.
THEIA[j]	n.d.y.	Water-based loaded liquid scintillator with Cherenkov light readout. Topology and particle discrimination; multi-isotope; multi-purpose.
LiquidO[k]	n.d.y.	Opaque isotope-loaded liquid scintillator with wavelength shifting fibers for event topology. Room temperature; multi-isotope; multi-purpose.

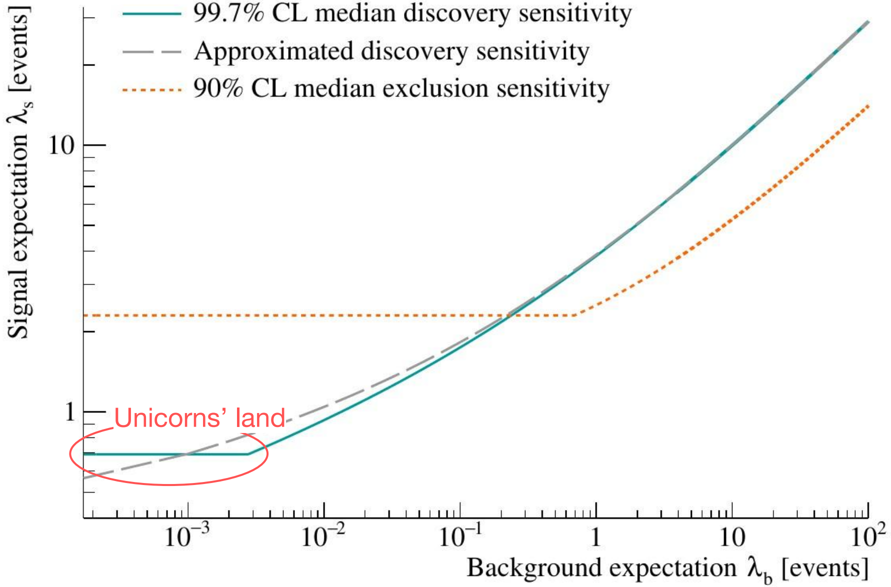
Discovery and exclusion sensitivity

- Events measured in multi-dimensional space: energy, position, topology, particle type, …
- Energy is the only necessary and sufficient quantity for claiming a discovery
- Option 1: multi-dimensional fit
- Option 2: cut on variables with good signal/background separation + energy fit
- Signal is restricted to small region, background dominant everywhere else
  → Counting analysis in ROI possible
  → Signal and background follow Poisson
- Discovery sensitivity:

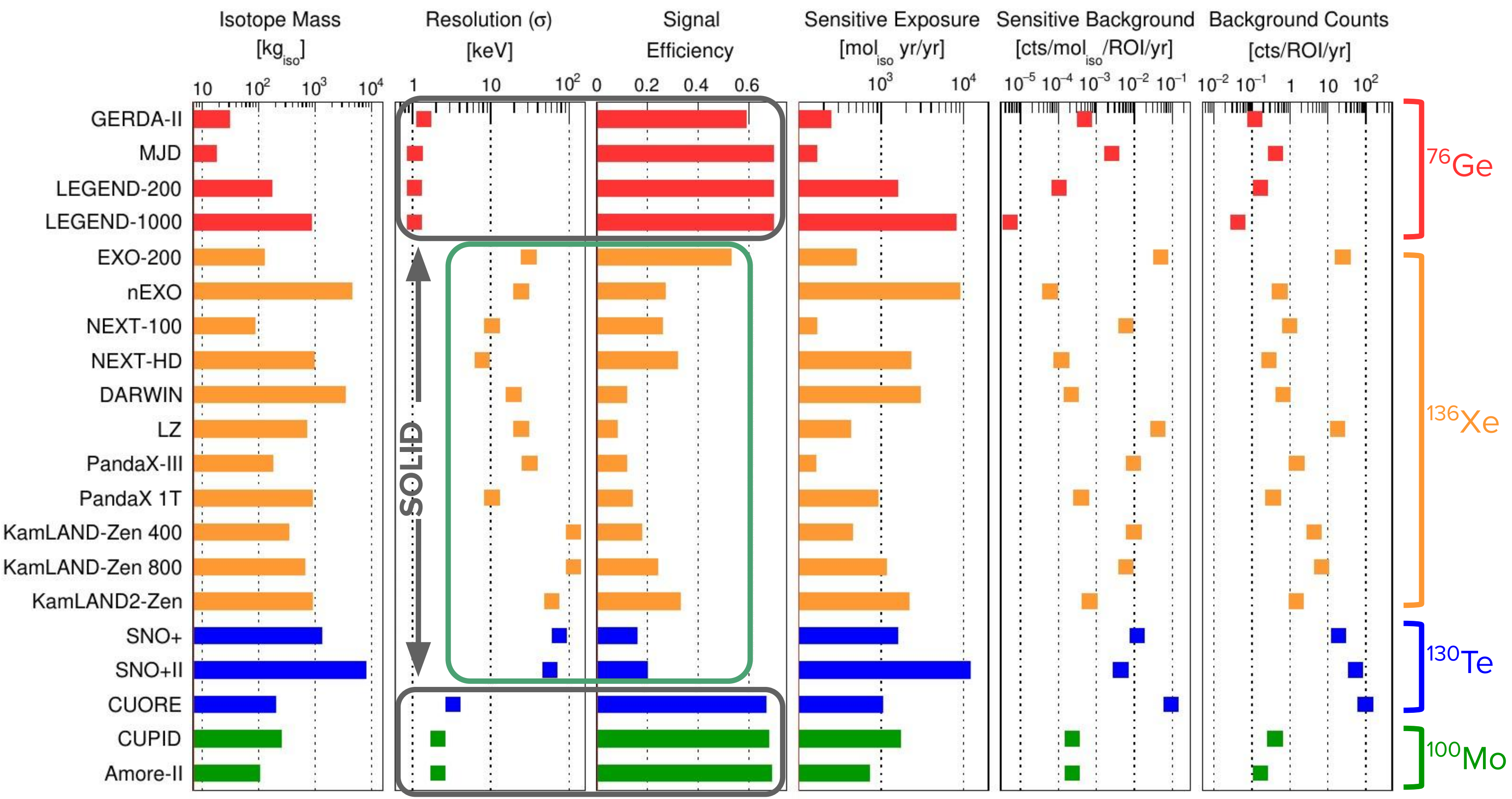
$$\begin{cases} P(X \leq x|\lambda_b) \geq 99.73\% \\ P(X \geq x|\lambda_b + \lambda_s) \geq 50\% \end{cases}$$

- Exclusion sensitivity:

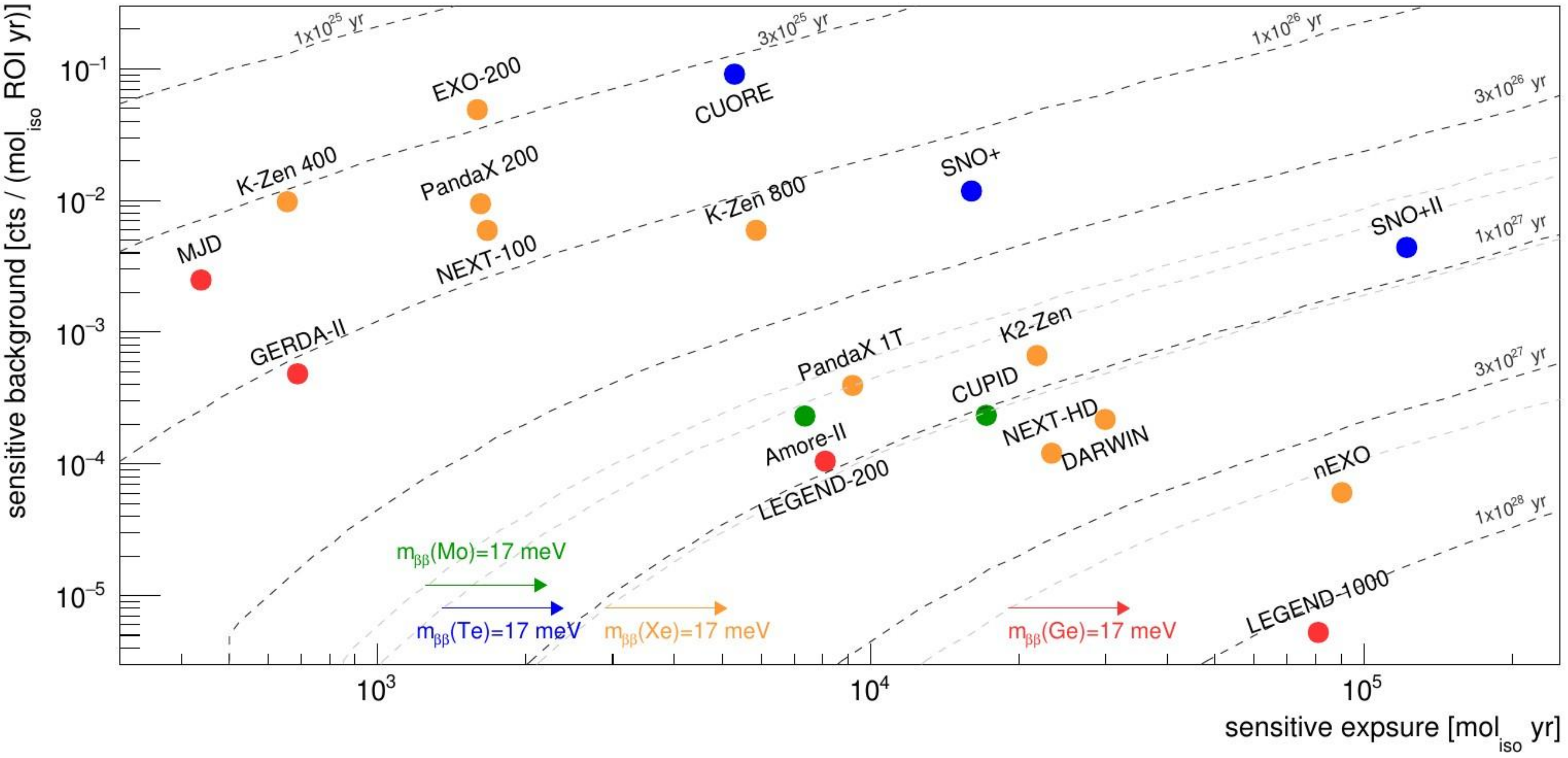
$$\begin{cases} P(X \leq x|\lambda_b) \geq 50\% \\ P(X \geq x|\lambda_b + \lambda_s) \geq 90\% \end{cases}$$



Summary of relevant experiments' parameters

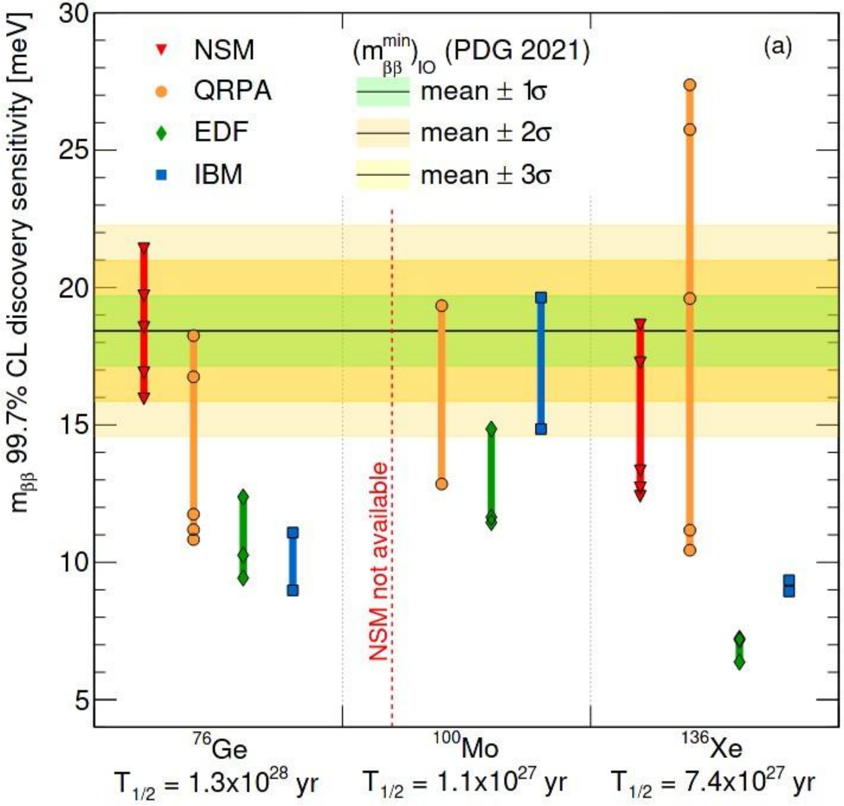


Exposure + background ⟶ sensitivity

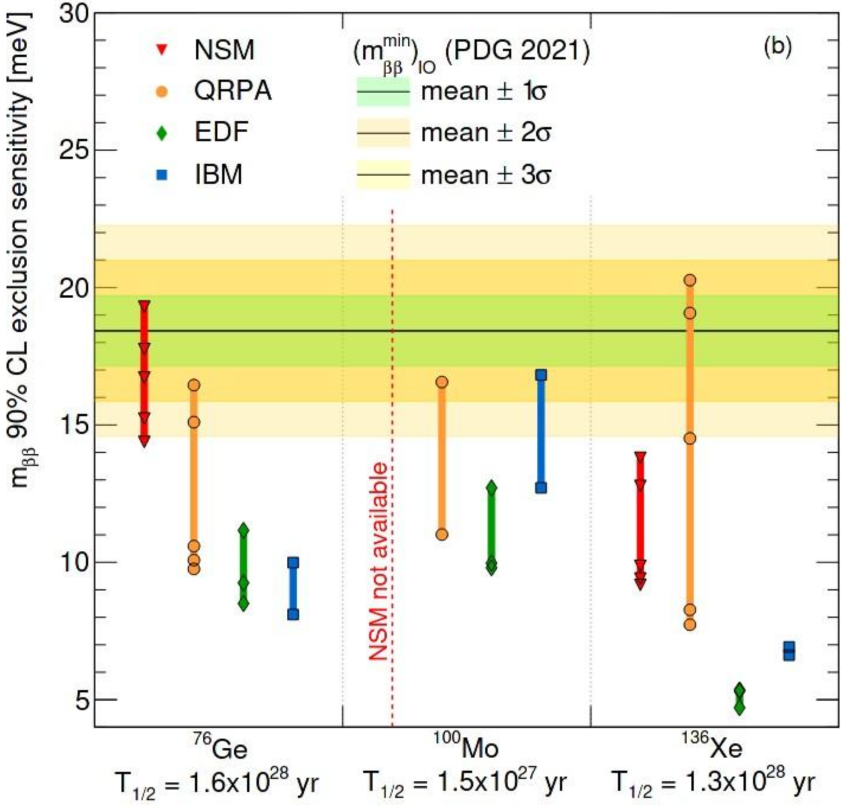


Discovery probability and impact

Discovery sensitivity



Exclusion sensitivity



THANK YOU!