# Majorana neutrinos and rare decays: where we are

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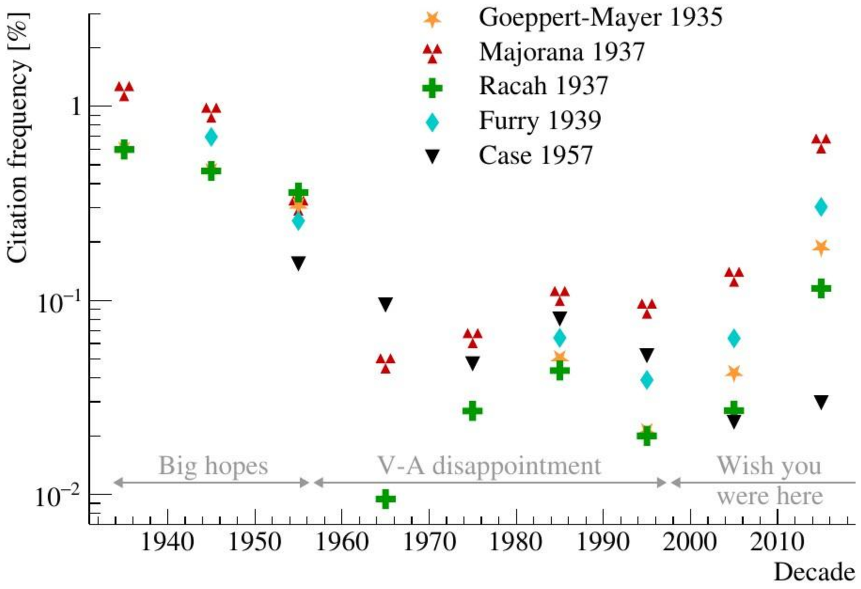
# Majorana neutrinos and rare decays: where we are

**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

A lot of content and plots from arXiv:2202.01787

# Historical landscape




| | |
|---|---|
| ~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! |

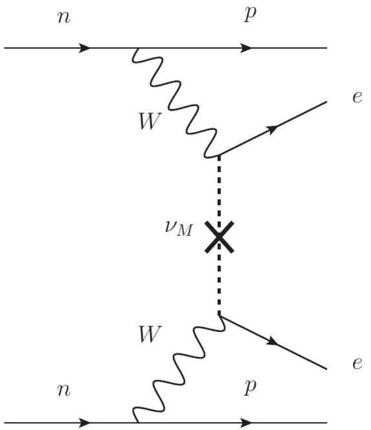
# Which are the fundamental symmetries and conserved quantities?

- B, $L_e$, $L_\mu$, $L_\tau$ 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:

**$L_e$-$L_\mu$** → Violation seen in appearance mode by T2K

**$L_\mu$-$L_\tau$** → Violation seen in appearance mode by OPERA

**B-L** → We don't know yet




→ BSM process
→ Violates B-L
→ Creates matter

# 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*
- 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

# From 0νββ decay to the neutrino mass

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

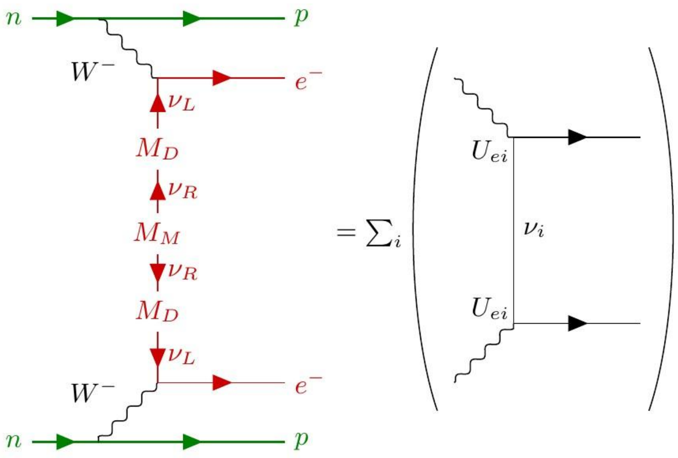
- Connection between 0νββ decay rate and new physics terms:

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

- In the case of D=5 (light neutrino exchange):

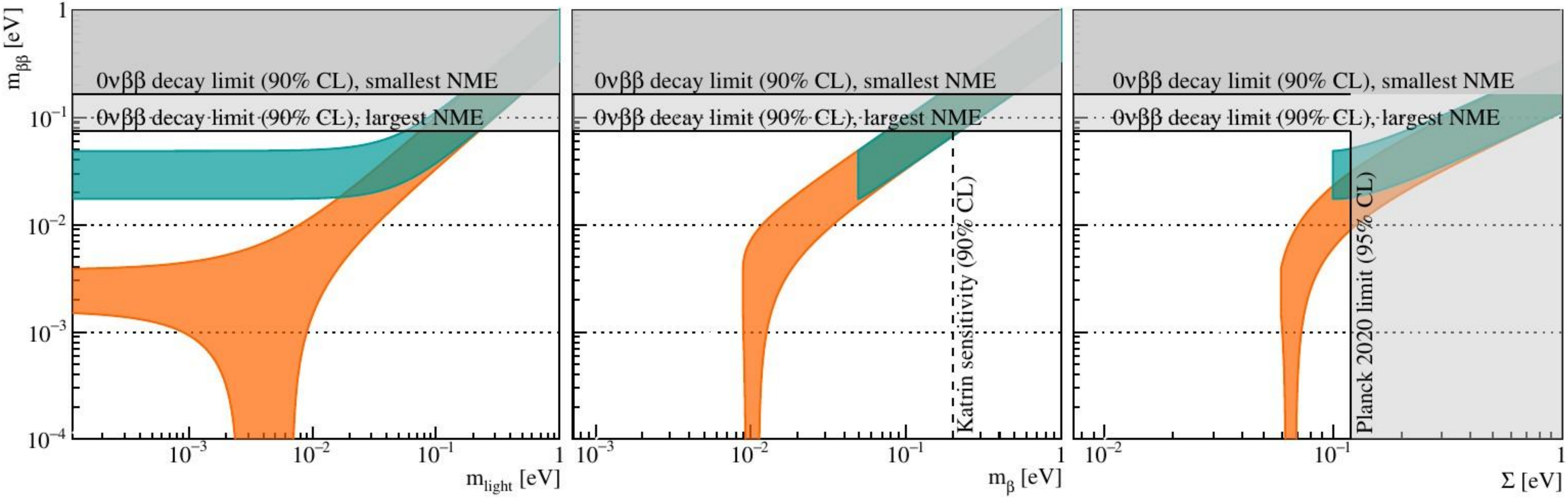
$$\frac{1}{T_{1/2}^{0\nu}} = G_{01}\, g_A^2\, \left(M_{light}^{0\nu}\right)^2 \frac{m_{\beta\beta}^2}{m_e^2}$$

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



# From 0νββ decay to the neutrino mass

$$m_{\beta\beta} \equiv \left| m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{i\alpha_{21}} + m_3 s_{13}^2 e^{i(\alpha_{31}-\delta)} \right|$$

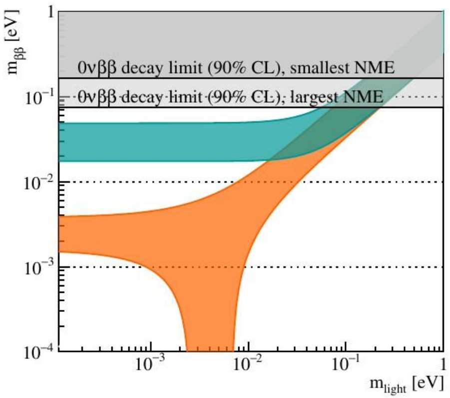


# Majorana phases

$$m_{\beta\beta} \equiv \left| m_1 c_{12}^2 c_{13}^2 + m_2 s_{12}^2 c_{13}^2 e^{i\alpha_{21}} + m_3 s_{13}^2 e^{i(\alpha_{31}-\delta)} \right|$$

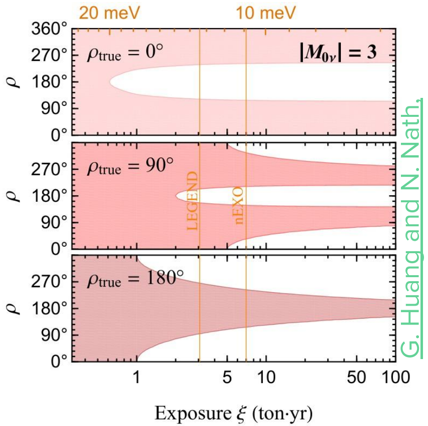
### “Traditional” approach

- Assume worst- and best-case scenario and merge them
- Compute allowed space, no probability distribution!




### Frequentist approach

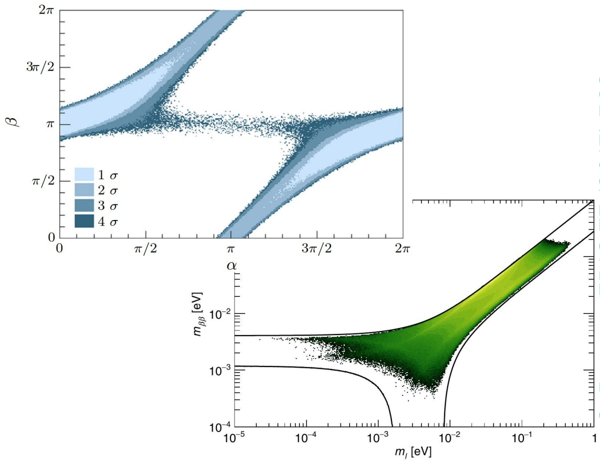
- Maximum likelihood analysis
- Compute allowed space also for Majorana phases




G. Huang and N. Nath, arXiv:2206.06688

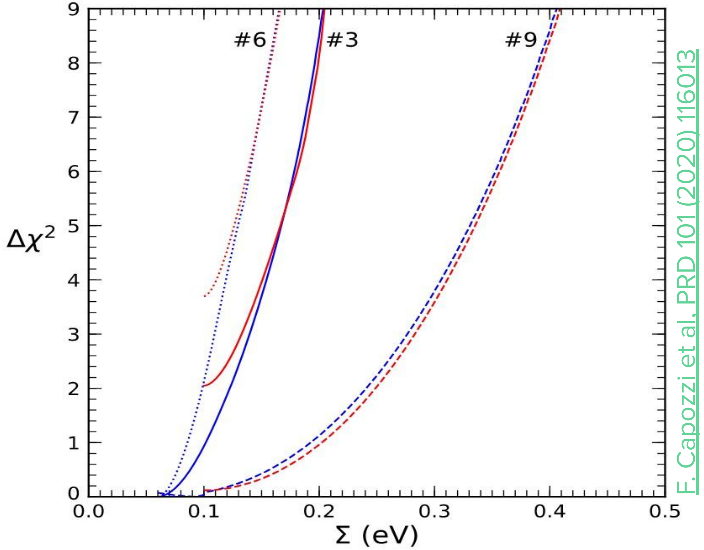
### Bayesian approach

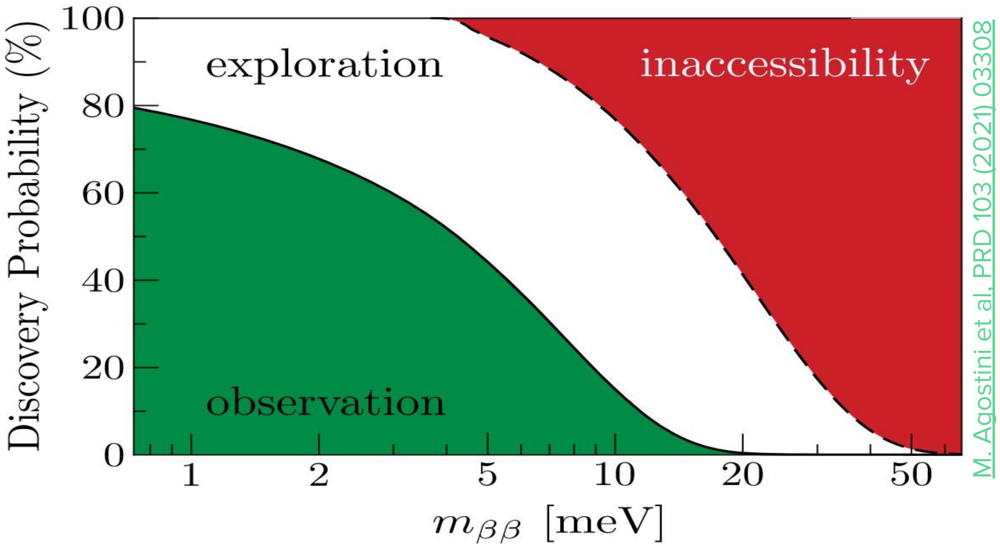
- Assume priors on phases
- Compute probability distribution on all parameters
- Strong dependence on priors!




G. Benato, EPJC 75 (2015) 563
M. Agostini et al., PRD 96 (2017) 053001

# Interplay between 0νββ decay and cosmology

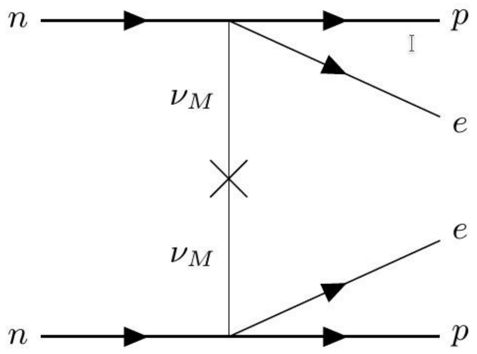



- Robust constraints on Σ from cosmological observations
  → Single results are model dependent, but limit fairly independent from selected dataset/assumption
- Possibility to evaluate discovery probability for $m_{\beta\beta}$ with minimal assumptions

# Nuclear physics theory and implications

- $0\nu\beta\beta$ decay triggered by BSM physics, but takes place in a highly correlated many-body system
  → Nuclear model(s) required to connect experimental sensitivity/results on $0\nu\beta\beta$ decay rate to underlying BSM physics
- Connection to any BSM mechanism possible with just two approximations:
  - Light: $m_\nu << p \sim 200$ MeV
  - Heavy: $m_\nu >> p \sim 200$ MeV



# Effective field theory

- BSM models defined at higher energy than electroweak scale (250 GeV), hadron scale (1 GeV) and nuclei (200 MeV)
  → EFT suitable to study and organize all 0νββ contributions
- Master formula for 0νββ decay rate:

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

→ Compute contribution due to *any* odd-dimensional operator
→ Phase spaces well known (computed)
→ NMEs computed by nuclear theory
→ Can be used to place limits on new physics scale
→ Short-range exchange of high-energy light neutrinos might not be negligible

# Many-body methods

| Name | Method | Performance |
|---|---|---|
| Nuclear Shell Model | Mix nuclear 1- and 2-shell configurations within given space | Good nuclear spectroscopy from O to Pb; effective Hamiltonian tuned on each nucleus |
| Quasiparticle Random-Phase Approximation | Large configuration spaces with several shells; few nuclear correlations | Overestimated NMEs for non-spherical nuclei → fixed recently |
| Interacting Boson Model | Models nucleus as set of bosons and map bosonic operators to nucleon DOF | No p-p correlations → Overestimates NMEs |
| Energy-Density Functional | Mean-field description + correlations | Very good spectroscopy; Expensive inclusion of correlation → Overestimates NMEs |

- Systematic trend: for all nuclei, NSM predicts the smallest NME, EDF the largest
- **Factor ~3 difference** between the methods
- Most predicted NME for single-β decay overpredicts the experiment
  → Caused by missing nuclear correlations or suboptimal transition operator
  → Same effect expected for ββ decay
  → Commonly fixed by **ad-hoc *quenching of $g_A$***

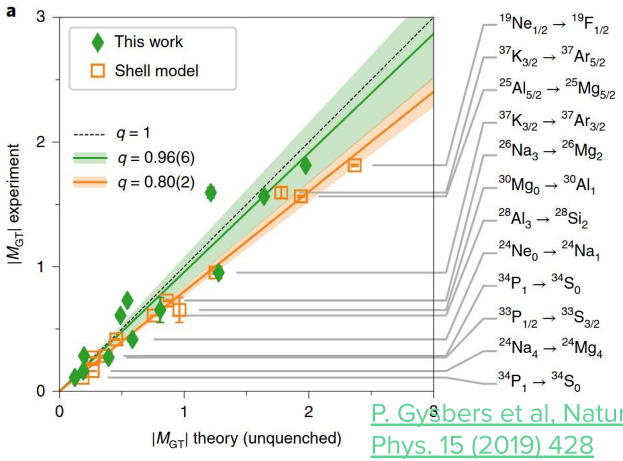
# Ab-initio methods

- Treat explicitly all nucleons in the nucleus interacting with realistic forces
  → Include nucleon-nucleon and three nucleon forces
  → Include 1-body operators and 2-body correlations
- NMEs similar or smaller than from NSM

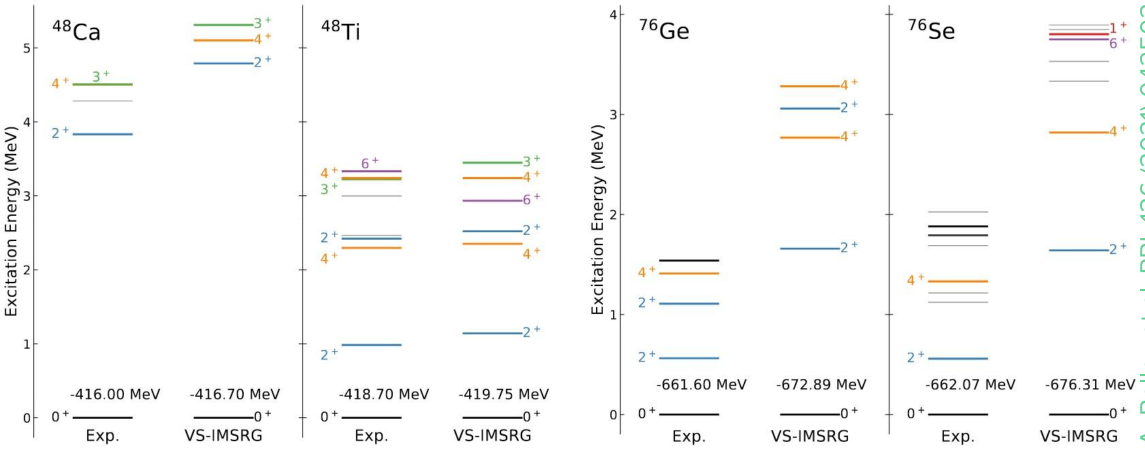
| Name | Method | Performance |
|---|---|---|
| Quantum MC | Time evolution of trial nuclear state (via Hamiltonian) towards lowest-energy configuration | Most accurate for A$\lesssim$12<br>Exponential scaling vs A |
| No-Core Shell Model | Extension of NSM: lowest-energy nucleons treated explicitly + high-energy orbitals | Limited to A$\lesssim$22<br>Exponential scaling vs A |
| In-Medium Similarity Renormalization Group | Based on unitary transformation that simplify the solution of the many-body problem + correlations to reference state | Polinomial scaling vs A |
| In-Medium Generator Coordinate Method | Combination of reference state + GCM to include correlations and proton-proton pairing | Polinomial scaling vs A;<br>smaller $M_{long}$ but enhanced $M_{short}$ |
| Coupled-Cluster | Up to triple correlations to reference state | Polinomial scaling, limited to spherical nuclei near magic ones |

# Ab-initio methods

- QMC and NCSM can reproduce experimental NMEs of single-β decay with few percent precision
- Reliable NME calculation for 0νββ decay not available yet
  → Nuclear spectroscopy not matching data yet
- Seems to confirm that “the quenching of $g_A$ is not a theory” (cit. F. Vissani)



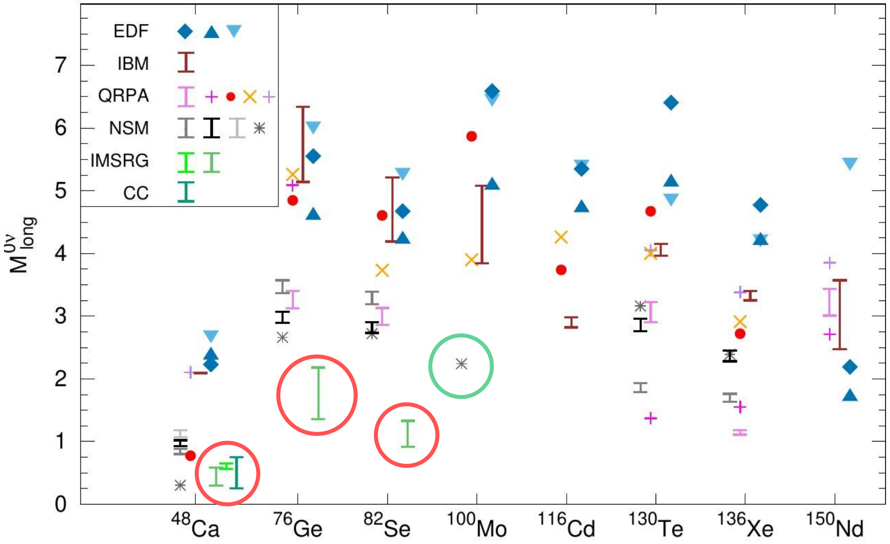

P. Gysbers et al, Nature Phys. 15 (2019) 428



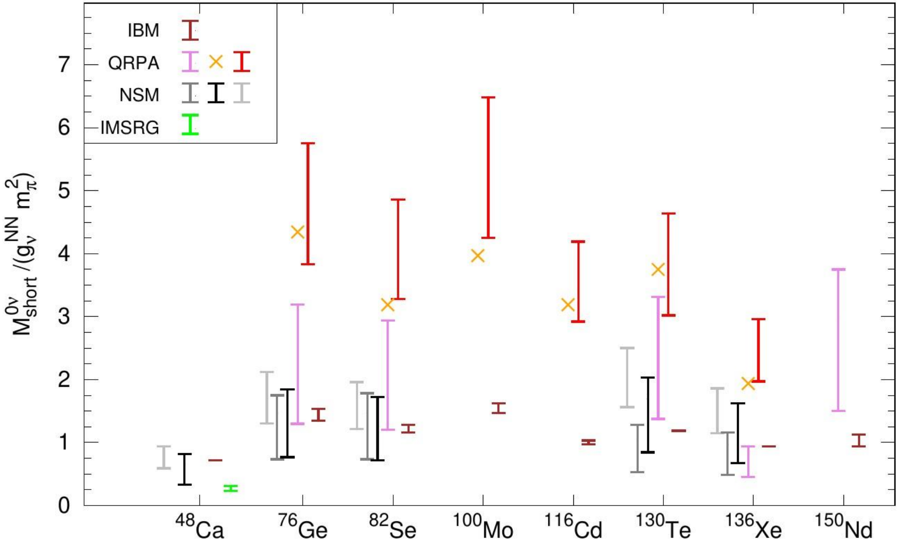

A. Belley et al, PRL 126 (2021) 042502

# Light neutrino exchange

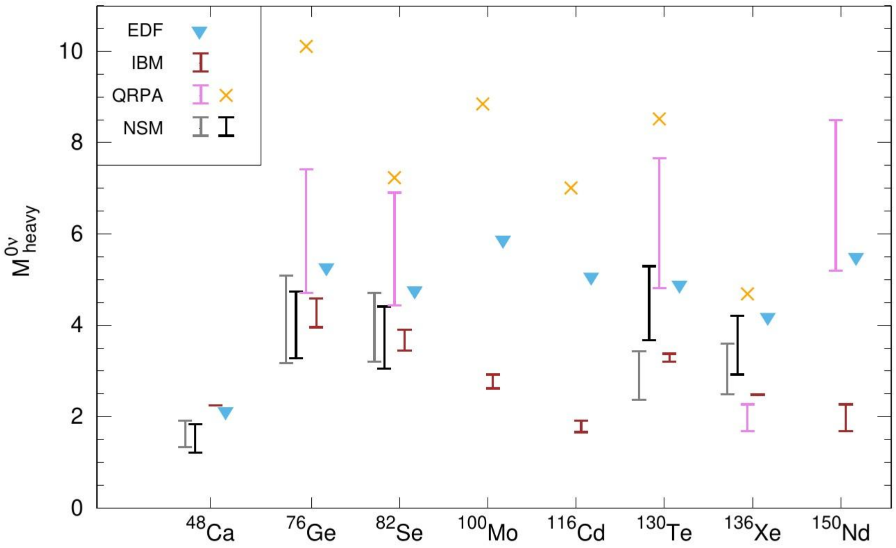
**Long-range NME**




**Short range NME**

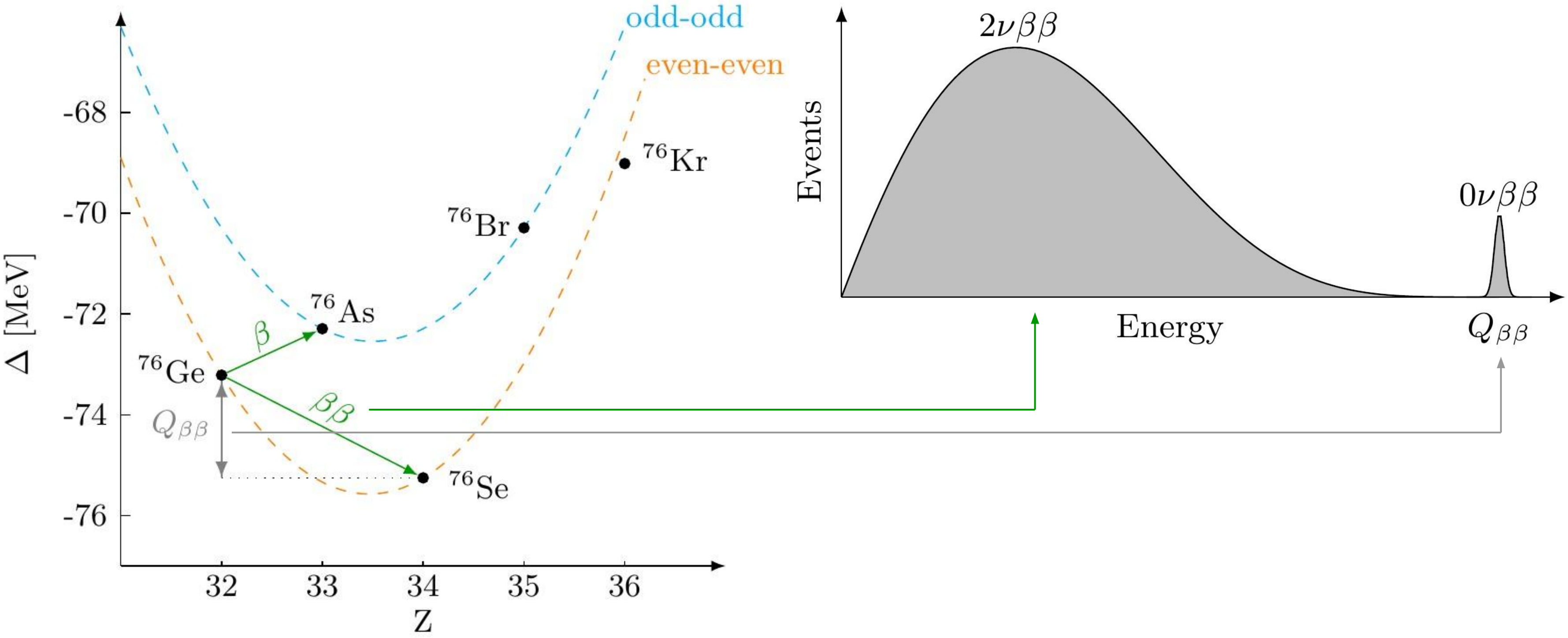


# Heavy neutrino exchange



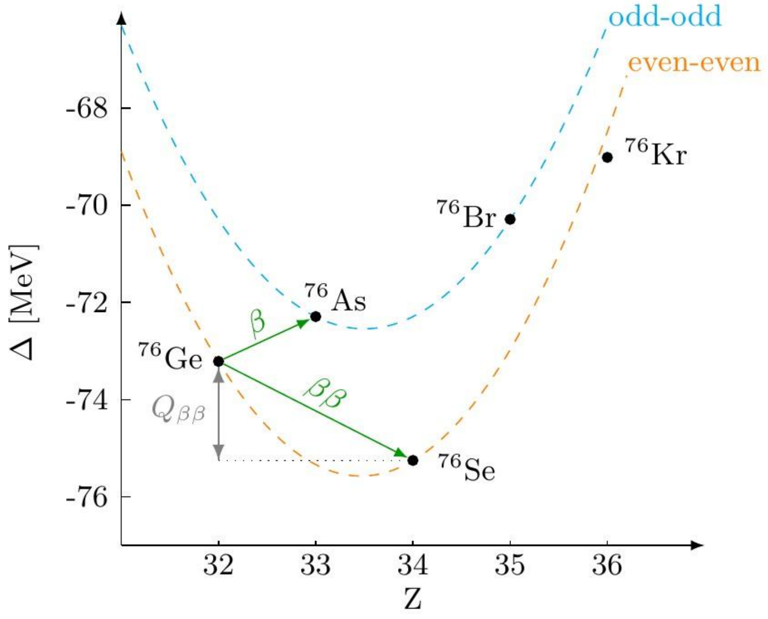

- Better general agreement, except for QRPA
- Large uncertainty due to ignored short-range correlations

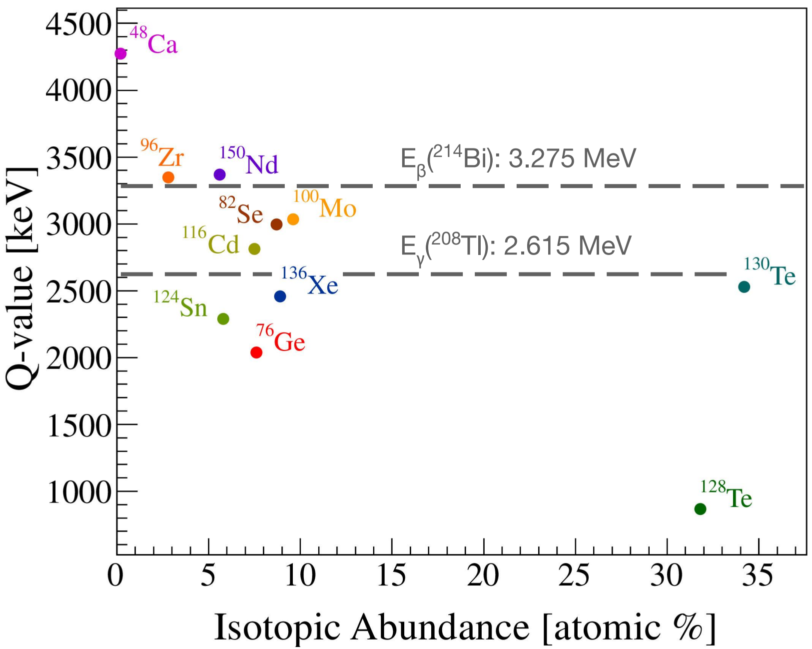
# Experimental aspects: 0νββ decay signature




- 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] | $f_{\text{nat}}$ [b] [%] | $f_{\text{enr}}$ [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 | $\left(2.63^{+0.11}_{-0.12}\right) \cdot 10^{19}$ | $> 2.2 \cdot 10^{23}$ |
| $^{130}$Te | $^{130}$Xe | 2 527.518(13) | 34.08(62) | 92 | $\left(7.71^{+0.08}_{-0.06}(\text{stat})^{+0.12}_{0.15}(\text{syst})\right) \cdot 10^{20}$ | $> 2.2 \cdot 10^{25}$ |
| $^{136}$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 | $\left(9.34 \pm 0.22(\text{stat})^{+0.62}_{-0.60}(\text{syst})\right) \cdot 10^{18}$ | $> 2.0 \cdot 10^{22}$ |

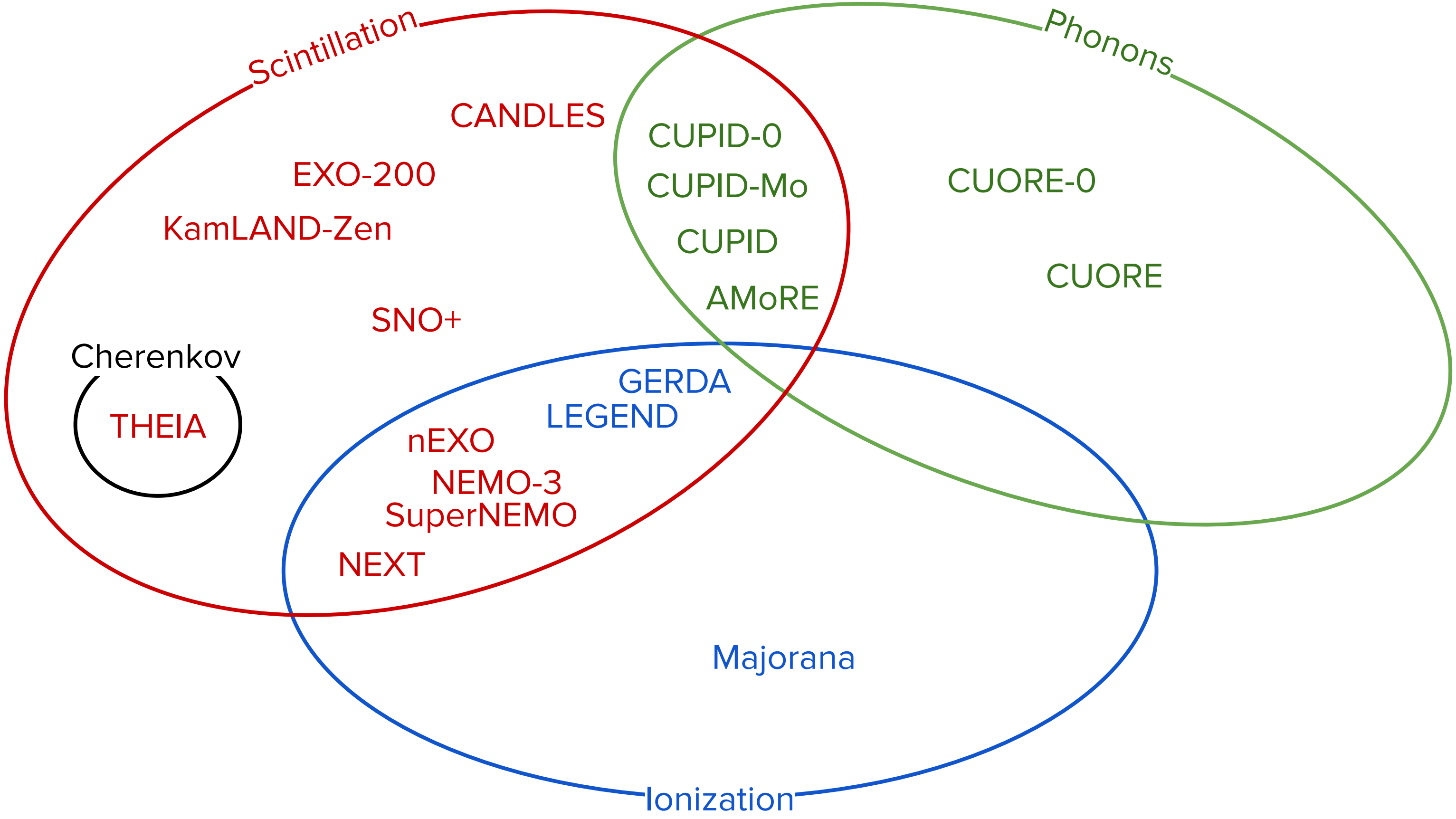
# Detector technologies

| 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<br>+ High resolution<br>- Many crystals required |
| Monolithic liquid or gaseous | Material = isotope or isotope dissolved in liquid | 100-1000 kg | 100% | + Single detector<br>+ Self shielding<br>- Poor resolution |
| Composite | Foil with isotope in low-pressure gas tracker | 10 kg | ~50% | + Ultra-low background<br>+ Multiple isotopes<br>- 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 % | $\alpha$ vs $\beta$ | In liquids and gases | Yes |
| Cherenkov | Forget it! | Visible only for $\beta$’s | Maybe | Yes |

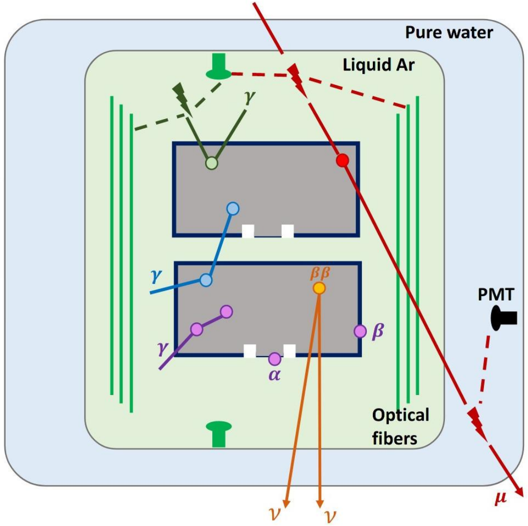
# 0νββ decay experimental fauna

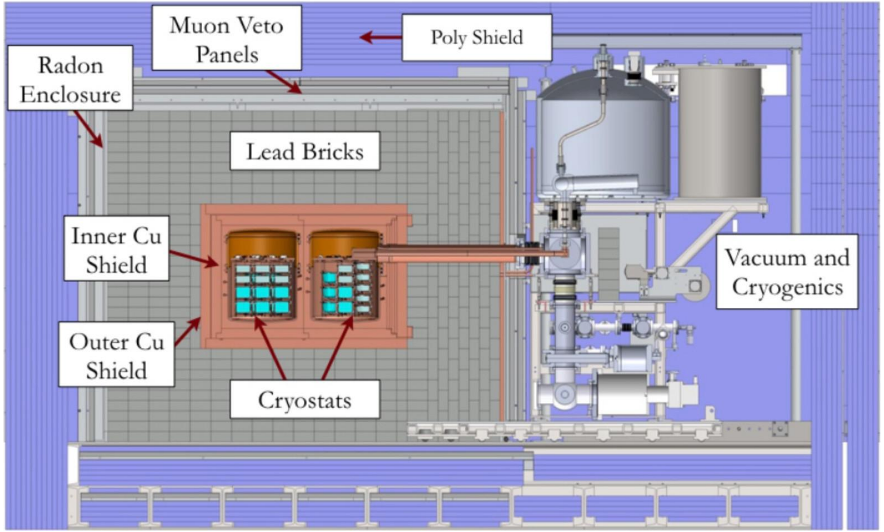


# Germanium experiments

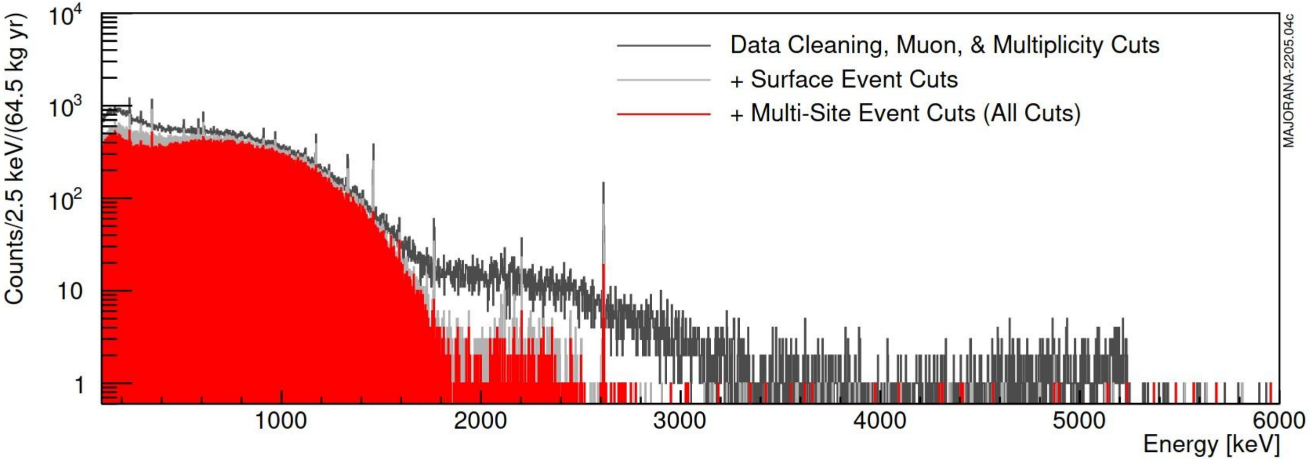

- Low Q-value: 2039 keV
- Highest energy resolution: **~0.1% FWHM**
- **Discrimination of ββ vs α vs γ** + possibility of **active γ veto**
  → Extremely low bkg: ~$5\cdot10^{-4}$ counts/keV/kg/yr reached by GERDA
  → Operating next to linear sensitivity regime
- MAJORANA and GERDA completed, joining for next-gen experiment LEGEND

→ GERDA talk by T. Comellato, LEGEND talk by R. Brugnera

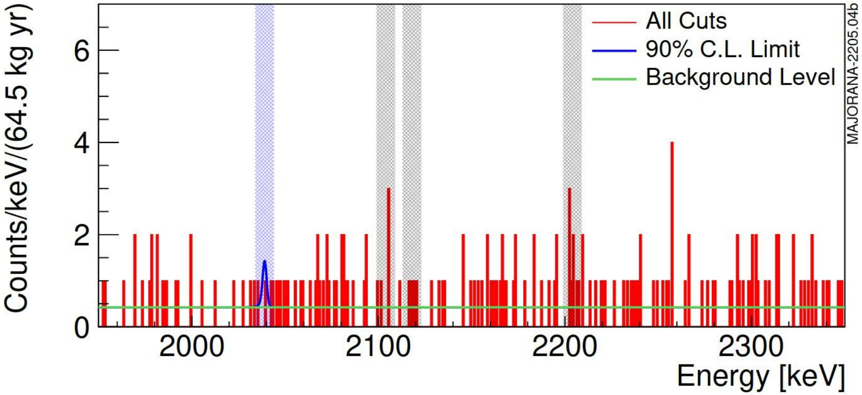


# Majorana demonstrator



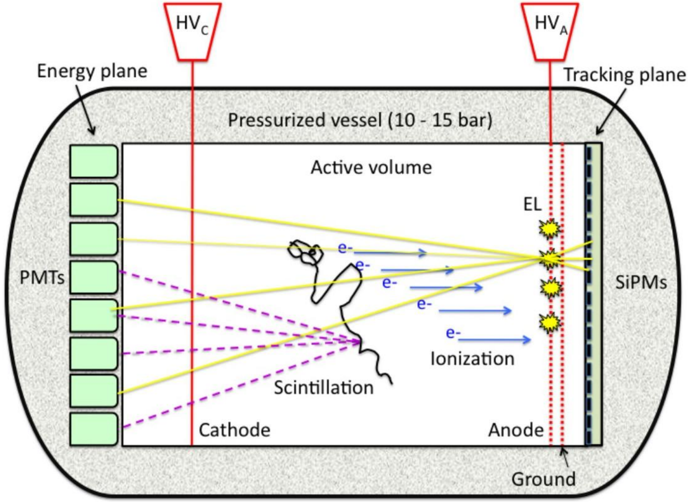

- Pioneers of ultrapure **copper electroforming underground**
- 27.2 kg of 88% $^{enr}$Ge + ~13 kg of $^{nat}$Ge
- **2.52 keV FWHM** @ $Q_{\beta\beta}$
- Final results:
  $T_{1/2} > 8.3 \cdot 10^{25}$ yr, $m_{\beta\beta} < 223\text{-}269$ meV @ 90% CL

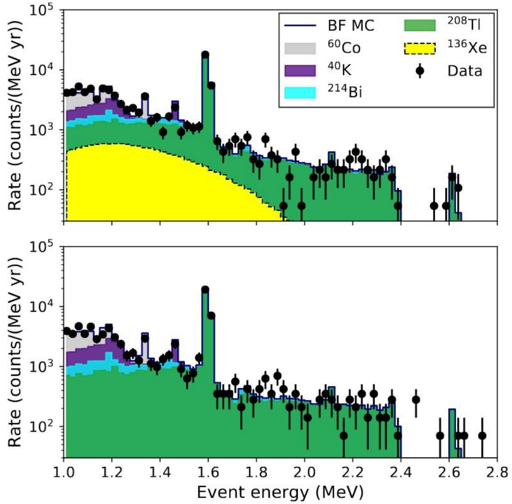


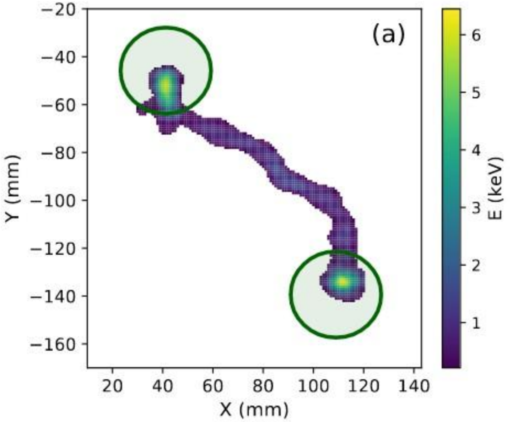

MJD, arXiv:2207.07638

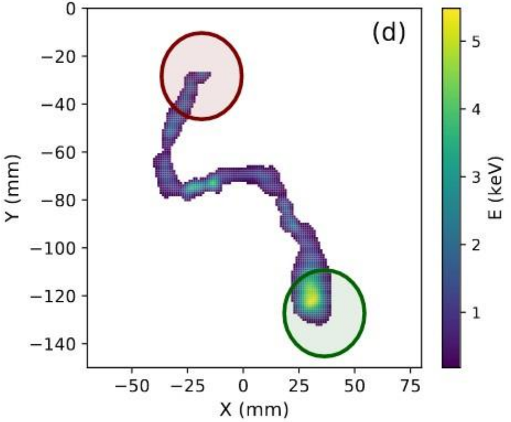
# Gas-Xe TPCs: NEXT

- High-pressure ~10 bar with double readout (ionization + scintillation)
- Energy resolution **~1% FWHM** demonstrated
- Particle tracking
  → Discrimination of **ββ from α and single-β or γ events**
- **2νββ decay measured by NEXT-White** using 3.5 kg of Xe only!
- NEXT-100 under construction @ Canfranc
  → Expected background $5 \cdot 10^{-4}$ counts/keV/kg/yr
  → Expected resolution 0.5-0.7% FWHM



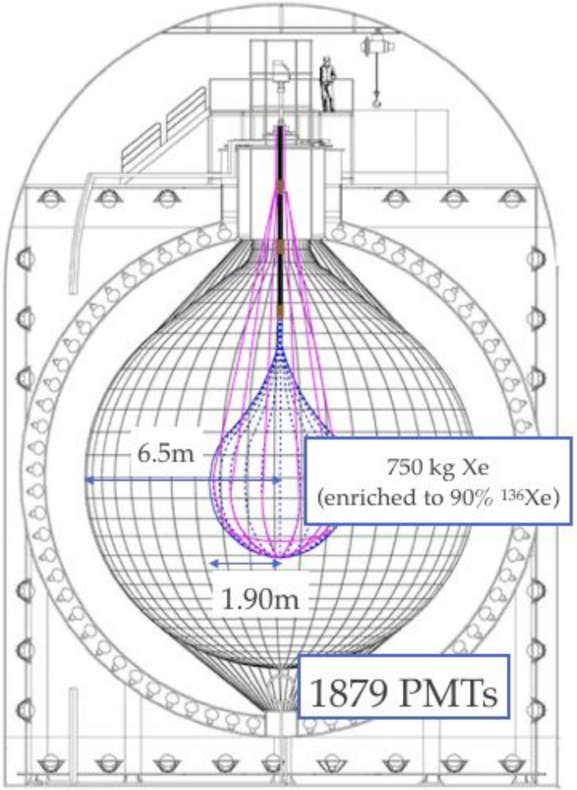



# Liquid scintillator experiments

**KamLAND-Zen**

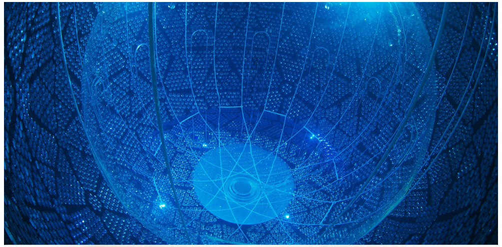


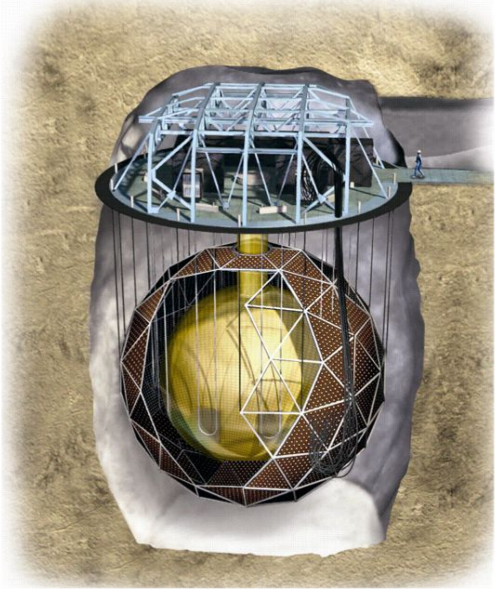

- Very large volume
  → Isotope in central part
  → Highly effective **self shielding**
- Isotope ($^{130}$Te or $^{136}$Xe) dissolved in liquid scintillator
  → Easily **scalable**
  → Enrichment not strictly required
- **High intrinsic backgrounds**
- Readout of scintillation only
  → Particle identification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

Good for limit setting,
not for discovery

→ KamLAND-Zen talk by K. Ichimura

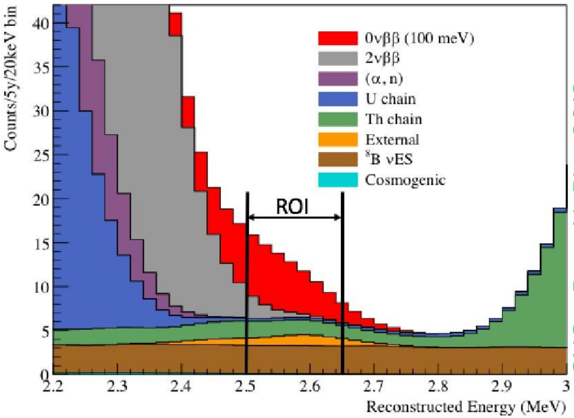
**SNO+**



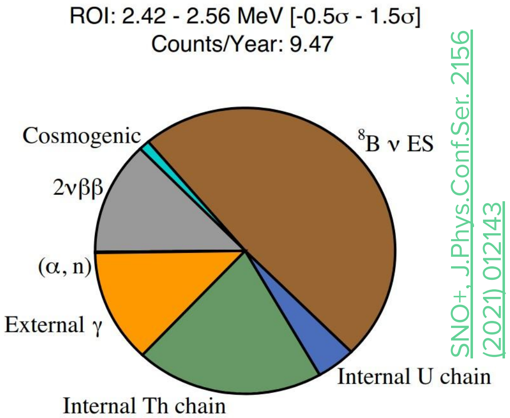


# Liquid scintillator experiments: SNO+

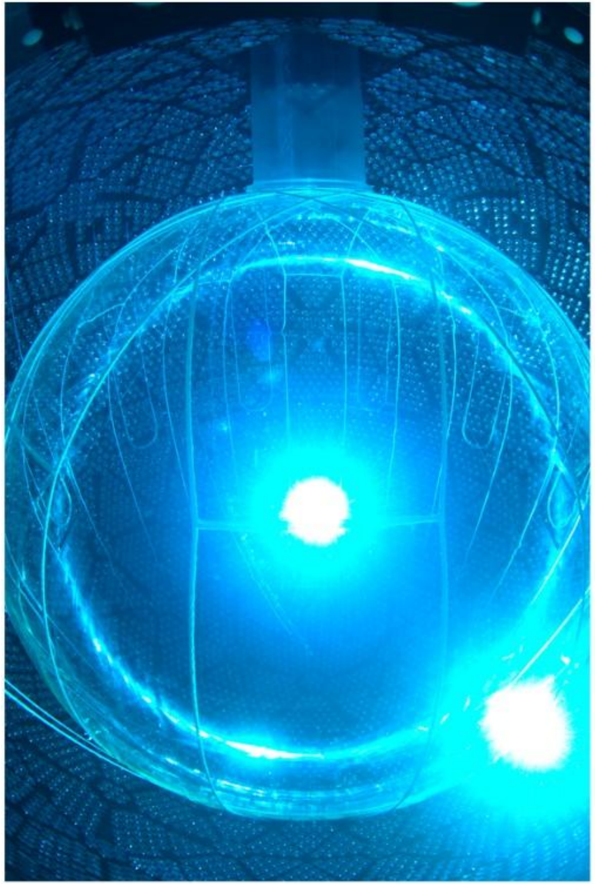
- Repurposed SNO experiment with 0.5% Te-loaded scintillator
- Te-loading not as easy as Xe-loading
- Separate background and signal+background measurements
  - 2017-2019 as pure-water Cherenkov detector
    → Characterization of detector response
  - 2019-now with unloaded LAB scintillator
    → Study scintillator response
    → Study scintillator-related backgrounds
  - Late 2022-20?? with Te-loaded scintillator
    → Looking forward to hear good news!



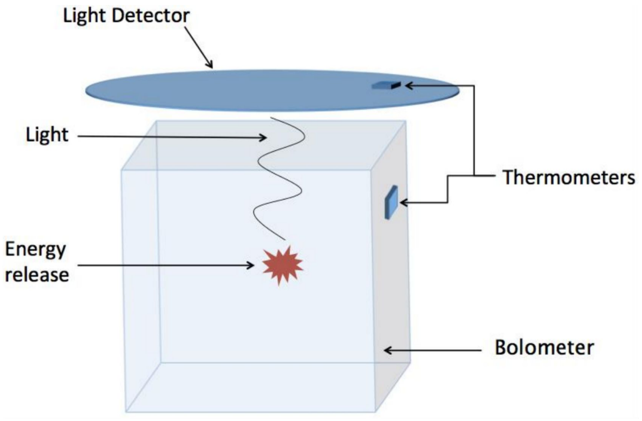

SNO+, Proc. NuPhys2018

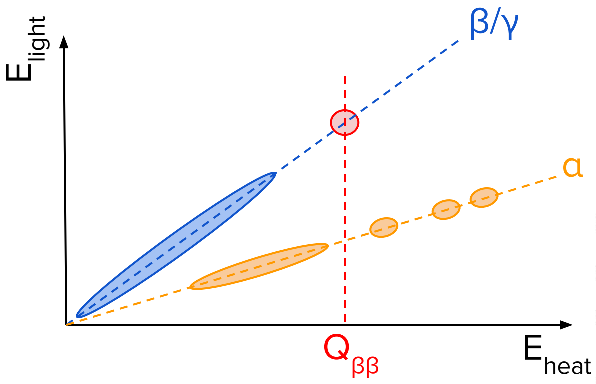


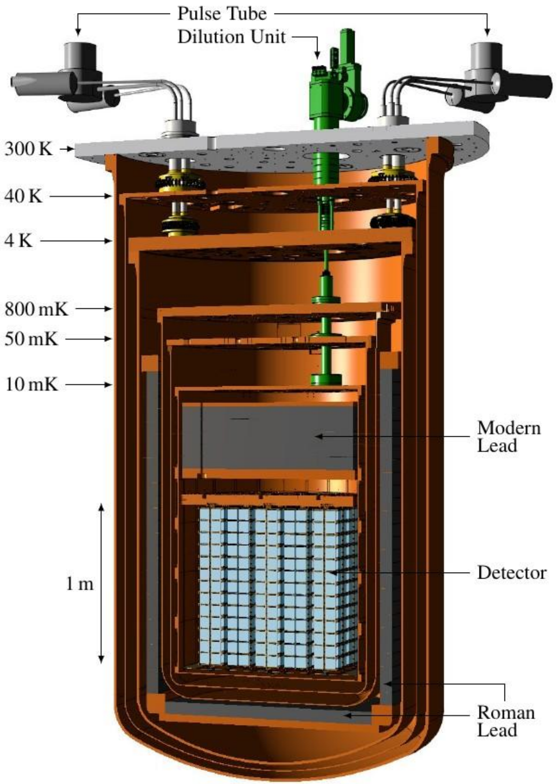

SNO+, J.Phys.Conf.Ser. 2156 (2021) 012143



# Cryogenic calorimeters



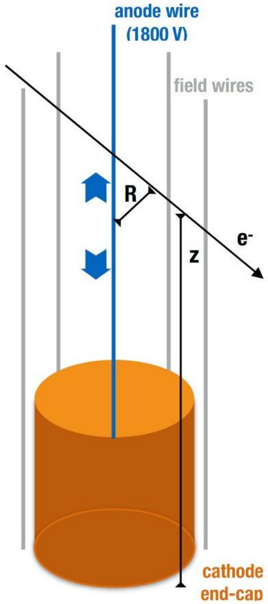



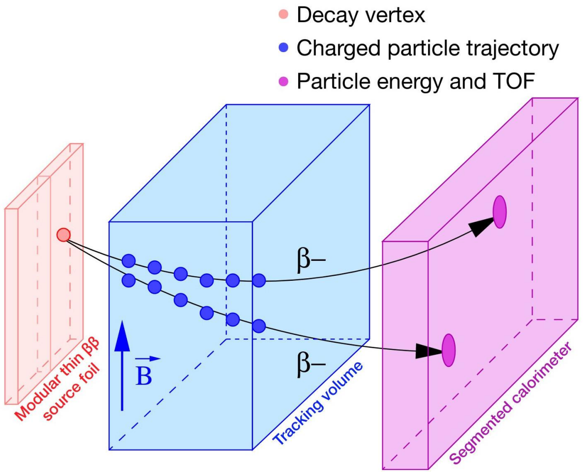

- Resolution: **5-10 keV FWHM**
- Main background: α's
  → Scintillating crystal allow **α vs β/γ discrimination**
- Multi-yr operation of **ton-scale cryogenic detector** demonstrated by CUORE
- Detector decoupled from isotope
  → Multi-isotope possible

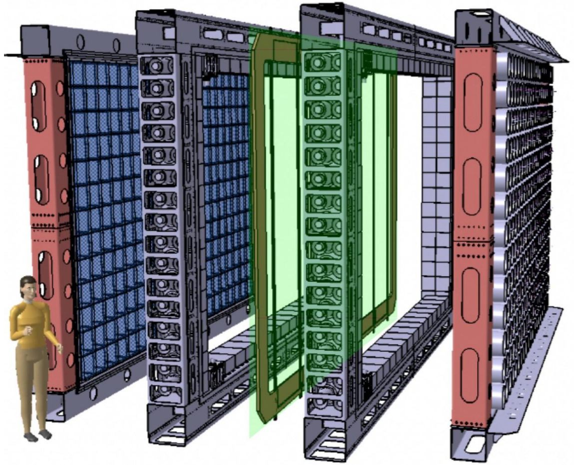
→ Talks by S. Di Lorenzo and A. Giuliani

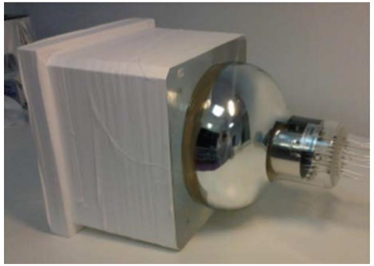
# Tracking calorimeters: SuperNEMO

- Measure both energy and momentum
  → Background suppression
  → Single electrons resolved
  → Possible to study 0νββ decay mechanism
- Source ≠ detector
  → Limited isotope mass
  → Any isotope is usable
- Perfect technology for precision measurement of 0νββ and 2νββ decay
- SuperNEMO demonstrator under commissioning





# THANK YOU!