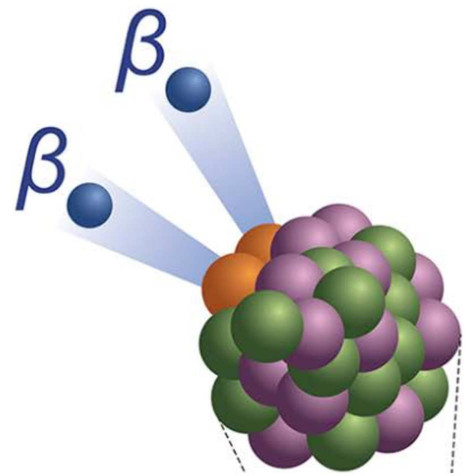
# An experimental view on double beta decay searches





**Yoann KERMAÏDIC**

IJCLab, CNRS/IN2P3 & Université Paris-Saclay, Orsay, France


## International Workshop on the Origin of Matter-Antimatter Asymmetry

École de physique des Houches

13 February 2023

Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis

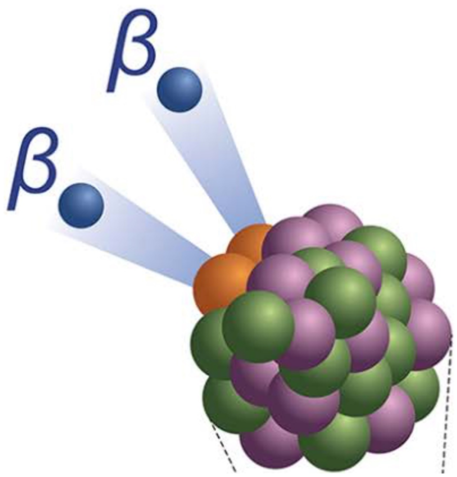
An experimental view on double beta decay searches

What is a proper name for $(A,Z) \rightarrow (A,Z+2) + 2e$? [2202.01787] (Vissani, et al.)

# Experimental search for creation of matter without antimatter


**Yoann KERMAÏDIC**

IJCLab, CNRS/IN2P3 & Université Paris-Saclay, Orsay, France

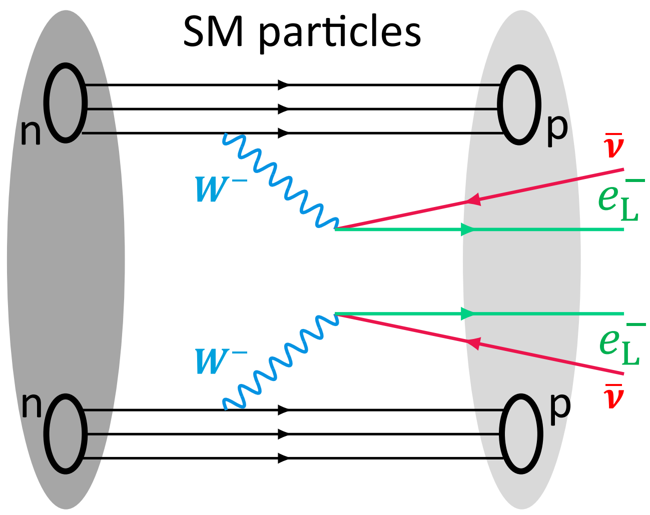




## International Workshop on the Origin of Matter-Antimatter Asymmetry

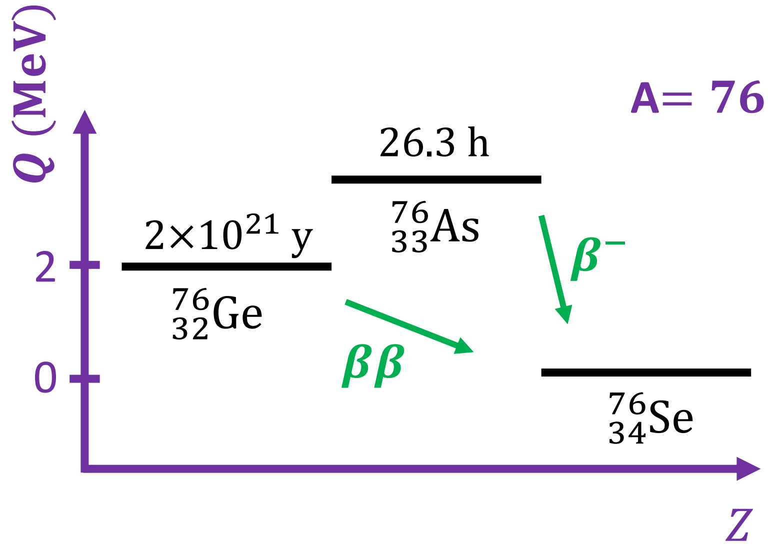
École de physique des Houches

13 February 2023

# Two neutrinos double beta decay - $2\nu\beta\beta$




$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}$




Such process:

- ✓ energetically favored in some isotopes ($^{76}$Ge, $^{100}$Mo, $^{130}$Te, $^{136}$Xe, …)
- ✓ is predicted by the SM [Goppert-Mayer – 1935]
- ✓ is a strongly suppressed 2nd order weak interaction process
- ✓ is measured experimentally if background is extremely low

# Ultra low background experiment opportunities

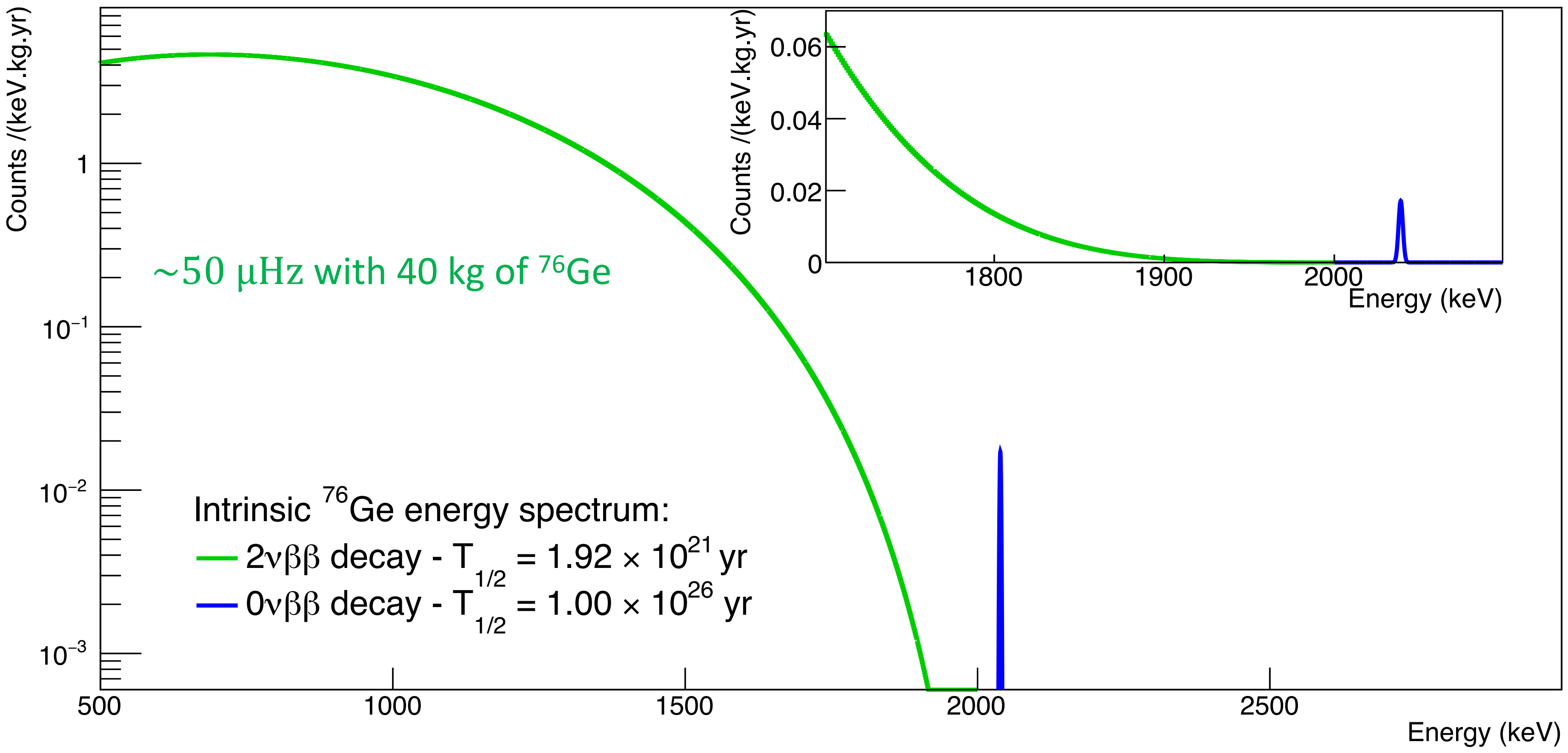
- **Can look for rare events:**
  - any shape distortion of the standard $2\nu\beta\beta$ decay spectrum
  - unknown very low rate gamma lines
  - unexpected time modulation in some rates

- **These can be caused by:**
  - violation of fundamental principles
    (Lorentz invariance, Pauli Exclusion Principle, CPT symmetry, …)
  - new particles (Sterile neutrinos, WIMPs, axions, …)
  - new interactions (B-violating tri-nucleon decay, charge violating electron decay, …)

See recent reference in [2202.01787] review

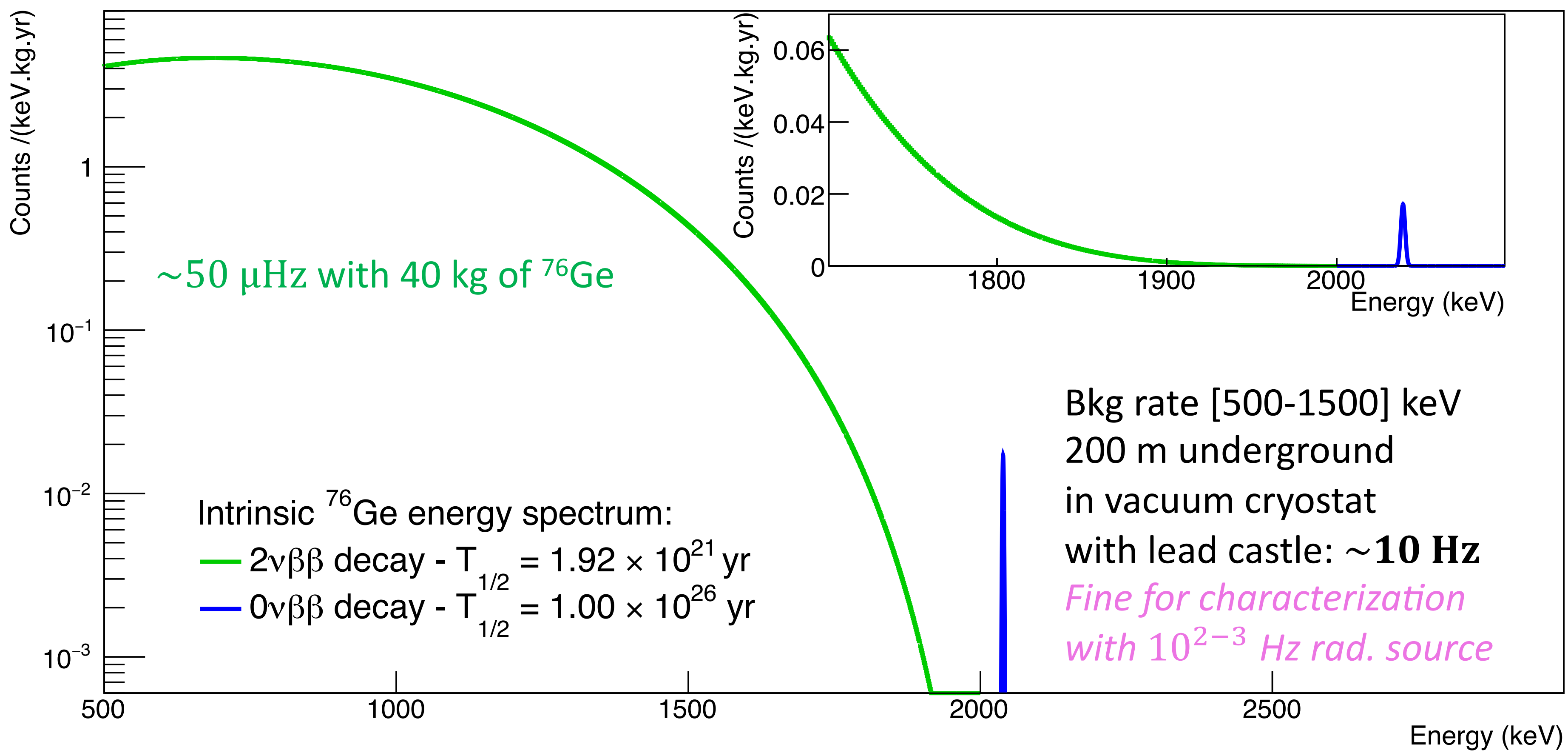
# The « ideal » $^{76}Ge$ energy spectrum

E.g. one can expect about $10^{4-5}$ "$2\nu$" events datasets (e.g. in $^{76}Ge$ or $^{100}Mo$ [1912.07272])



# The « ideal » $^{76}$Ge energy spectrum

E.g. one can expect about $10^{4-5}$ "$2\nu$" events datasets (e.g. in $^{76}$Ge or $^{100}$Mo [1912.07272])

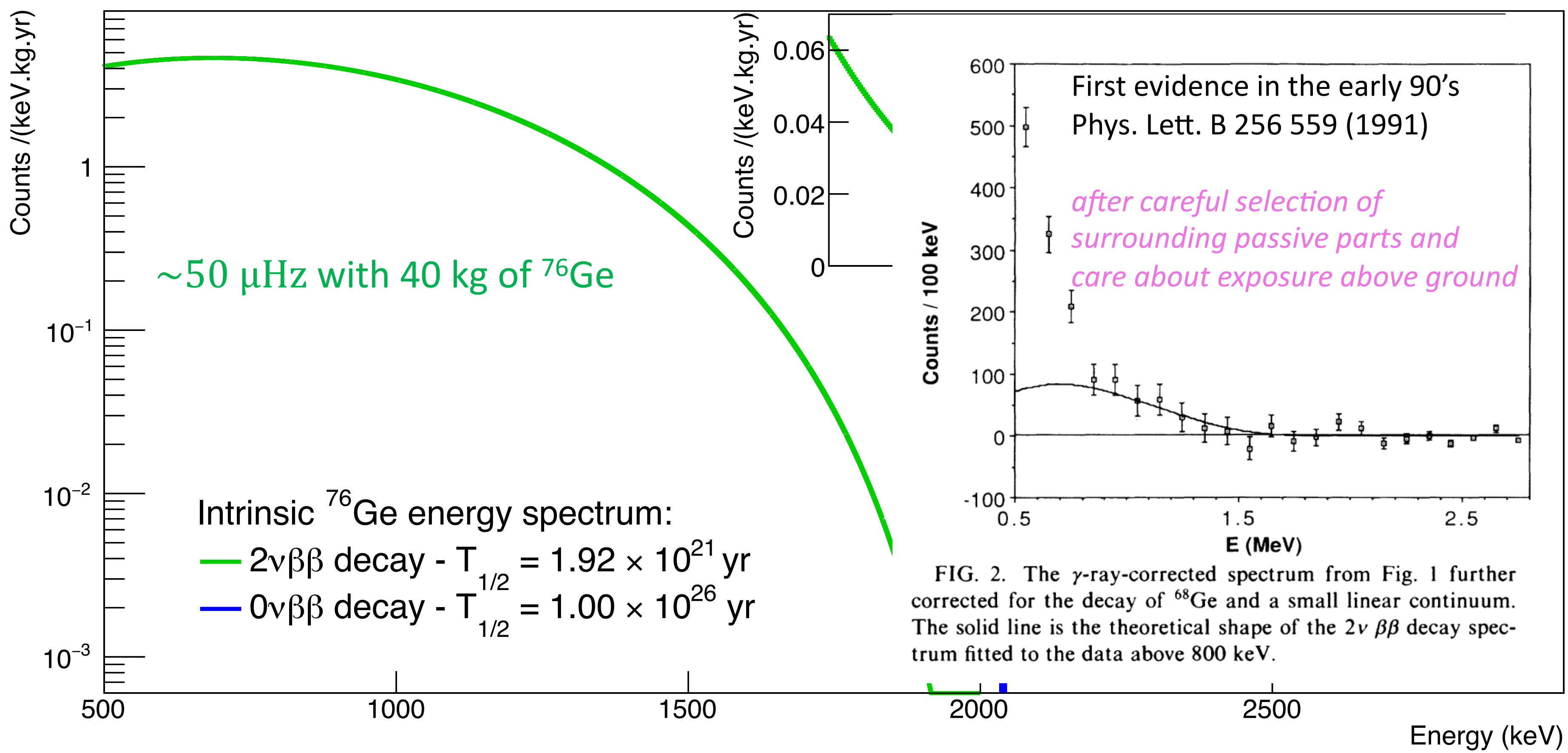



~50 µHz with 40 kg of $^{76}$Ge

Bkg rate [500-1500] keV
200 m underground
in vacuum cryostat
with lead castle: **~10 Hz**
*Fine for characterization*
*with $10^{2-3}$ Hz rad. source*

# The « ideal » $^{76}$Ge energy spectrum

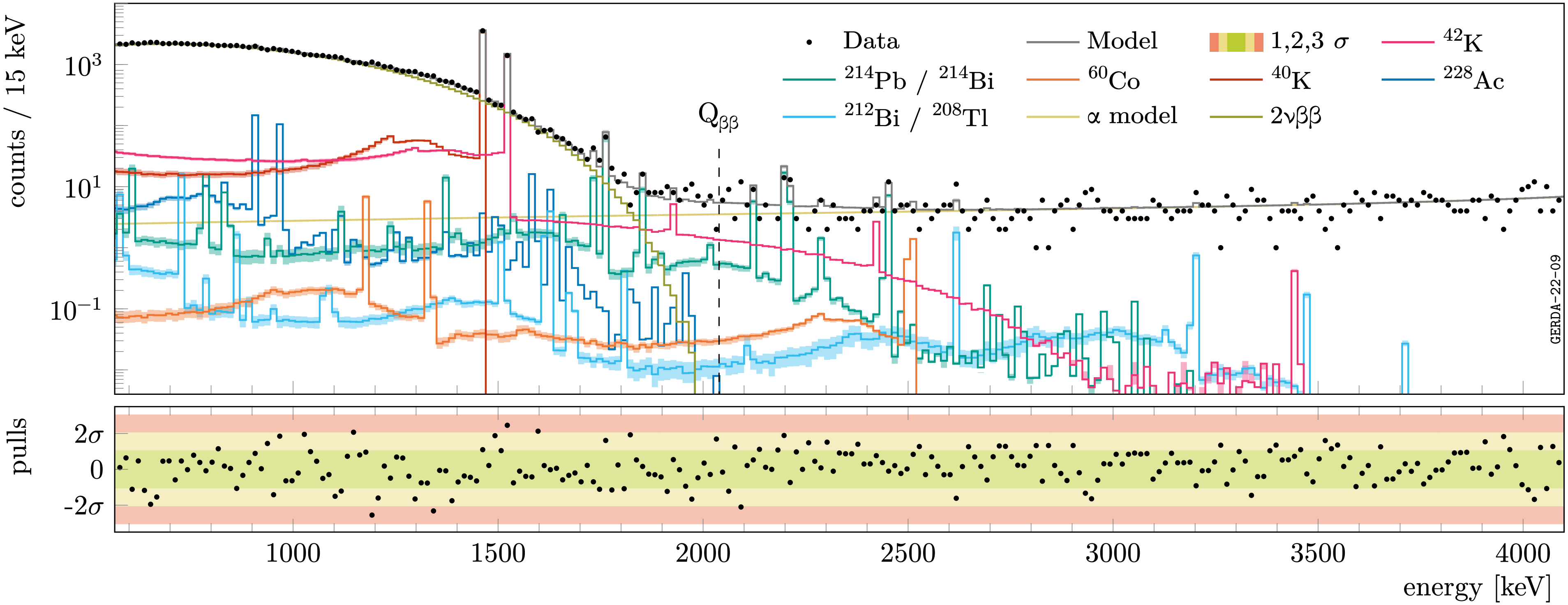
E.g. one can expect about $10^{4-5}$ "$2\nu$" events datasets (e.g. in $^{76}$Ge or $^{100}$Mo [1912.07272])



# The measured and modelled one

- **Single detector GERDA energy spectrum***

Liquid argon light collection and veto modeling in GERDA Phase II [2212.02856]




- **Precision measurement of the $2\nu\beta\beta$ decay spectral shape possible**
- **Unknown gamma lines can pop-up**

*After LAr veto. The LAr veto cuts any event where a Ge triggered event is accompanied with scintillation light emission in the Lar cryostat
500 keV lower limits driven by $^{39}Ar$ end-point at 465 keV

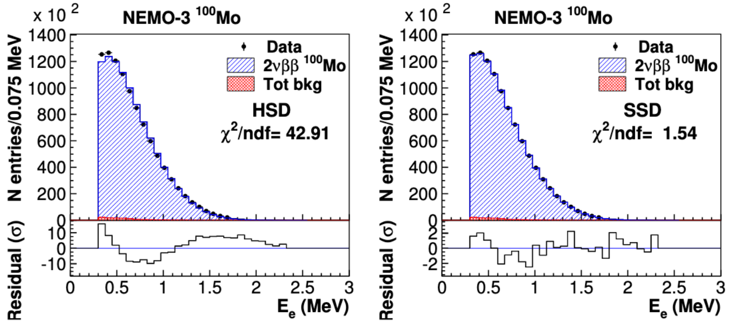
# How $2\nu\beta\beta$ decay informs nuclear calculations?

See review [2009.14451]

$$T_{1/2}^{-1} = G_{2\nu} \cdot g_A^4 \cdot (m_e c^2 \cdot M_{2\nu})^2$$

| | |
|---|---|
| $T_{1/2}^{-1}$ | **experimentally probed half-life** |
| $g_A$ | **axial vector coupling cnst = 1.25(?)** |
| $M^{2\nu}$ | **nuclear matrix element (NME)** |
| $G^{2\nu}$ | phase space factor |
| $m_e$ | electron mass |

- Test nuclear models hypothesis (SSD/HSD)
  E.g. NEMO-3 [1903.08084]




- Unfortunately, many-body nuclear models are unable to predict the experimentally observed half-life better than 10-25 % (quenching by ~0.75)

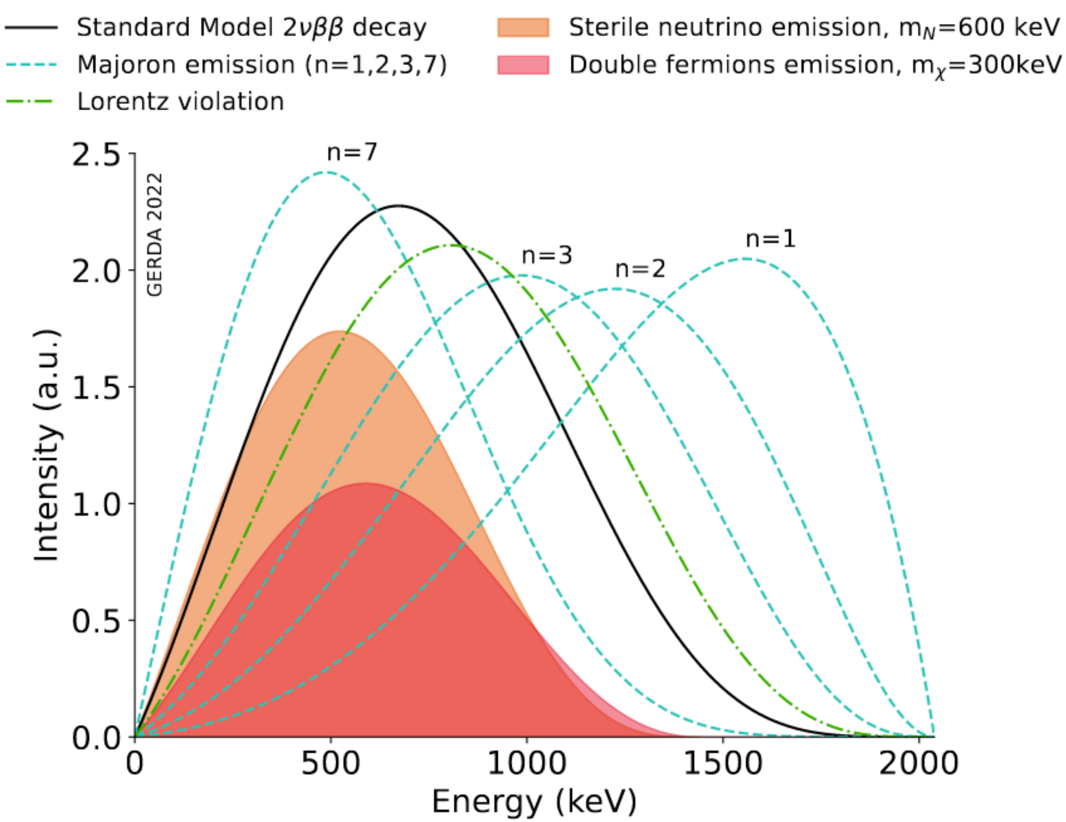
- Promising calculations from first principle 'ab-initio' up to A=76 start to be available

# New physics from spectral shape

**Example: $0\nu\beta\beta J$ decay** [2209.01671]

- $0\nu\beta\beta$ decay accompanied with the emission of a massless boson, called 'Majoron'
- $\beta\beta$ kinematics + NME modified by $J$, depending on the models (various spectral index)

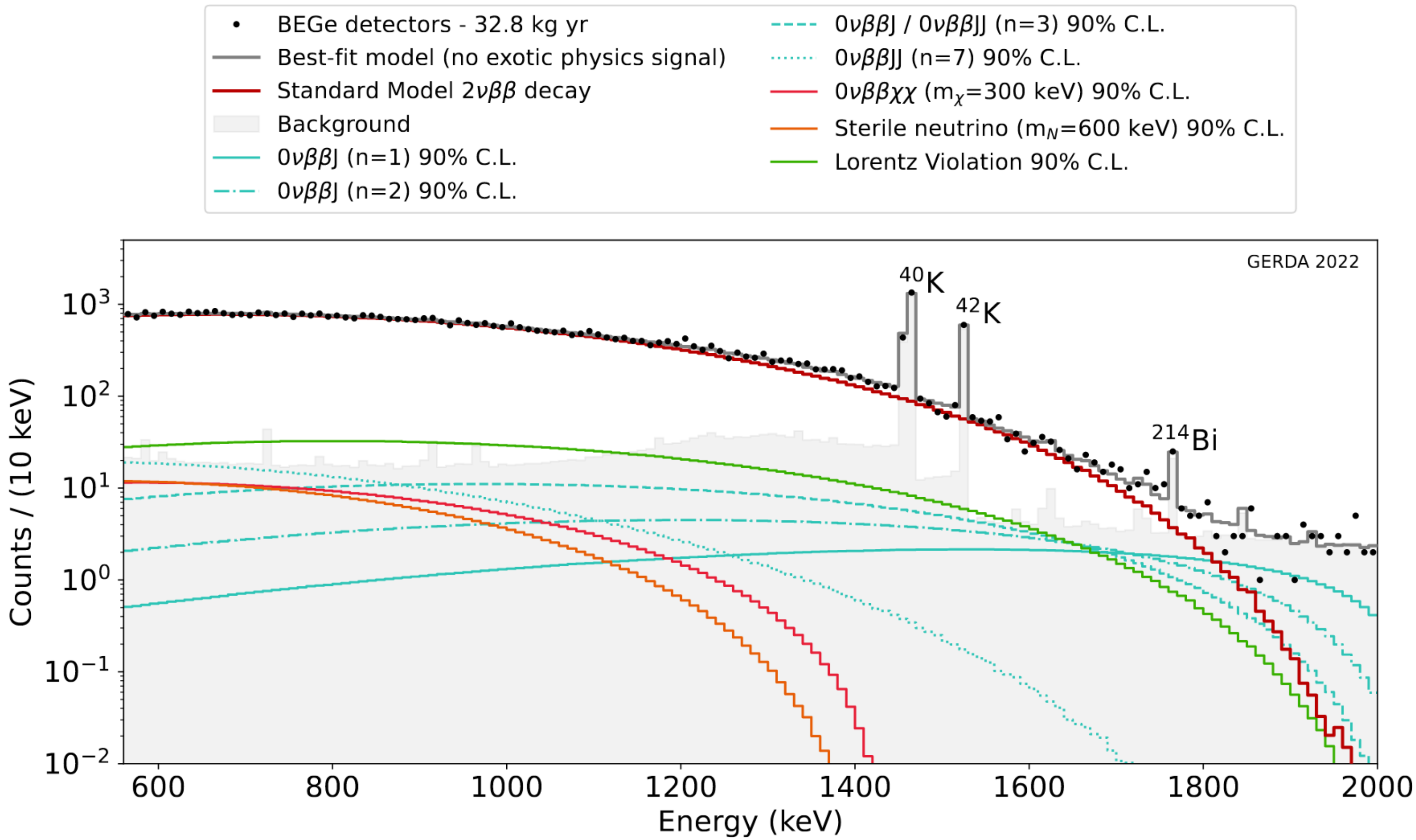
$$[T_{1/2}]^{-1} = g_J^{2m} |g_A^2 \mathcal{M}_\alpha|^2 G^\alpha$$ , $m$ is the number of emitted $J$



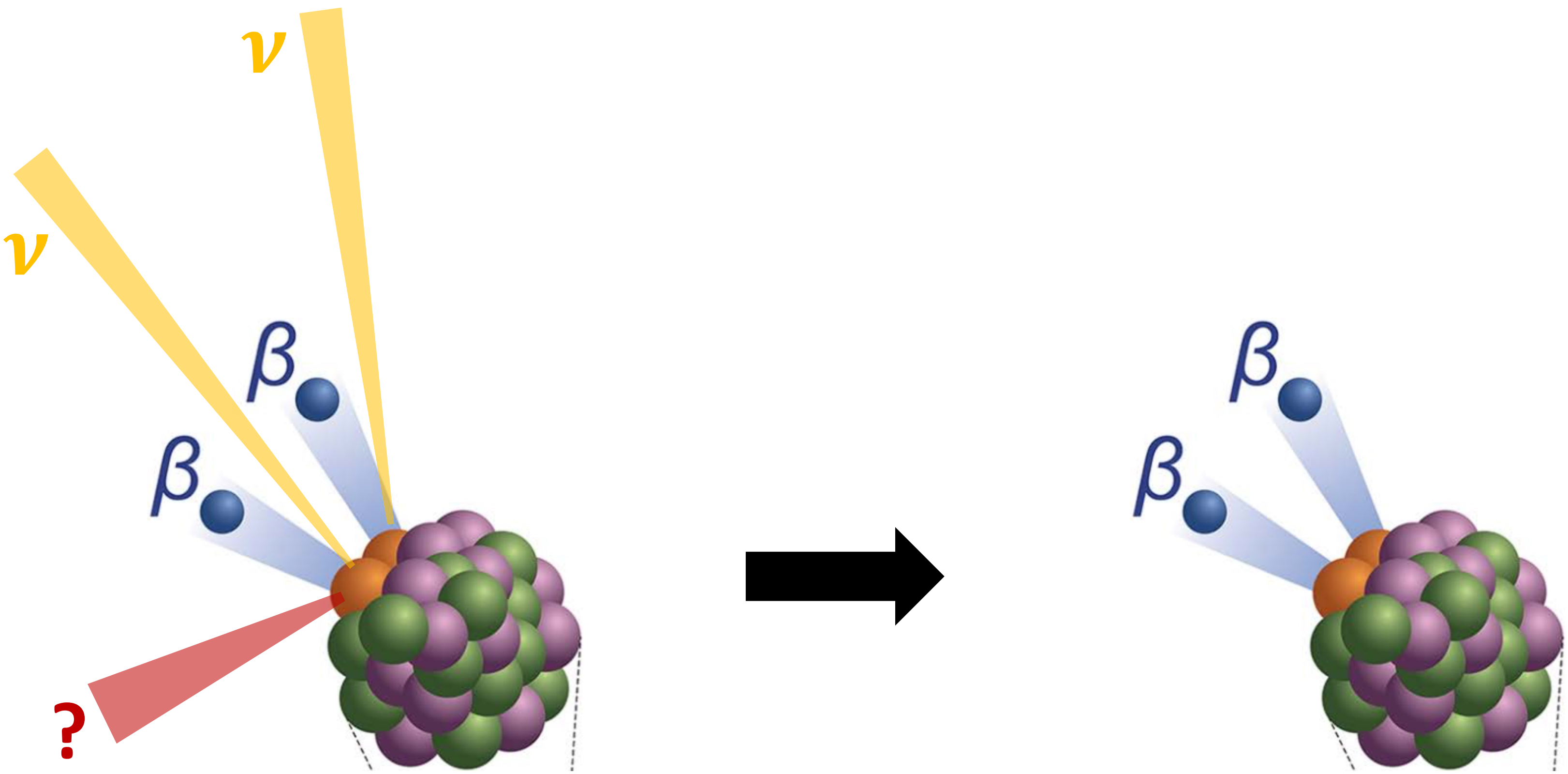
# New physics from spectral shape

**Example: $0\nu\beta\beta J$ decay** [2209.01671]

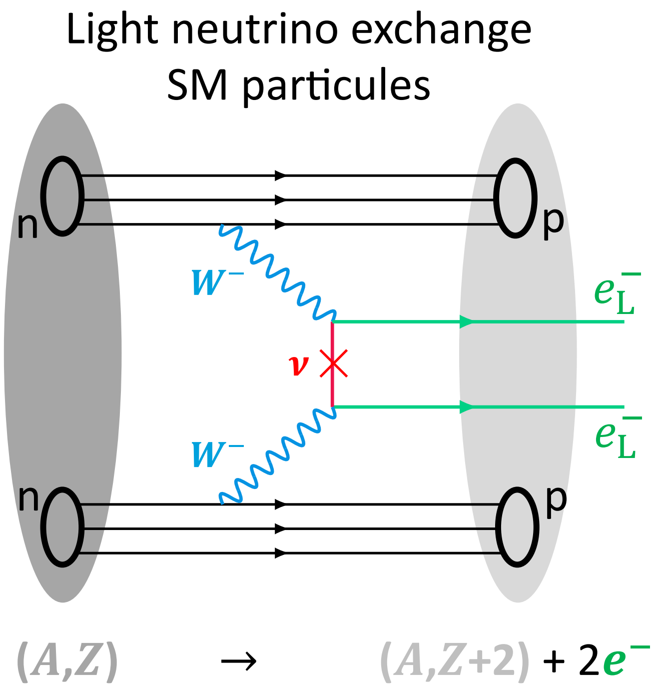
- $0\nu\beta\beta$ decay accompanied with the emission of a massless boson, called 'Majoron'
- $\beta\beta$ kinematics + NME modified by $J$, depending on the models (various spectral index)
- No indication of new physics so far. Competitive isotopes: $^{76}\mathrm{Ge}$, $^{100}\mathrm{Mo}$ , $^{116}\mathrm{Cd}$, $^{136}\mathrm{Xe}$



# Moving to the $0\nu\beta\beta$ decay search



# « Light neutrino exchange »

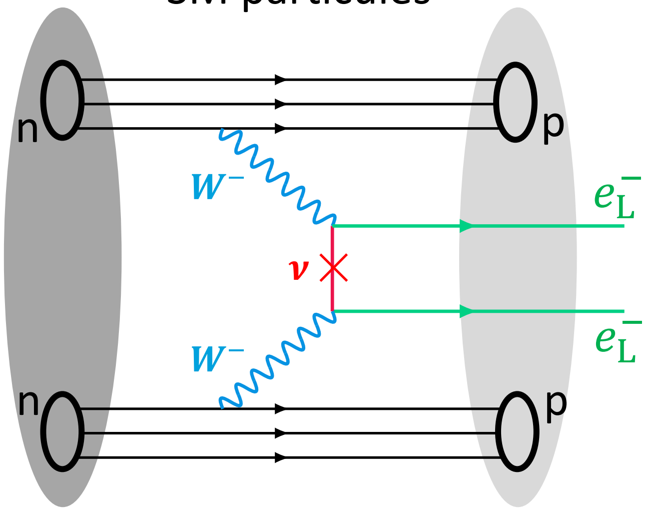



$$\left(T_{1/2}^{0\nu}\right)^{-1} = g_A^4 \, G^{0\nu} \left|M^{0\nu}\right|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

| | |
|---|---|
| $T_{1/2}^{0\nu}$ | **experimentally probed half-life** |
| $g_A$ | **axial vector coupling cnst = 1.25(?)** |
| $M^{0\nu}$ | **nuclear matrix element (NME)** |
| $G^{0\nu}$ | phase space factor |
| $m_e$ | electron mass |

# « Light neutrino exchange »

Light neutrino exchange
SM particles




$(A,Z) \rightarrow (A,Z+2) + 2e^-$

$$T_{1/2}^{0\nu\ -1} = g_A^4\, G^{0\nu}\, \left|M^{0\nu}\right|^2 \frac{\langle m_{\beta\beta}\rangle^2}{m_e^2}$$

| | |
|---|---|
| $T_{1/2}^{0\nu}$ | **experimentally probed half-life** |
| $g_A$ | **axial vector coupling cnst = 1.25(?)** |
| $M^{0\nu}$ | **nuclear matrix element (NME)** |
| $G^{0\nu}$ | phase space factor |
| $m_e$ | electron mass |

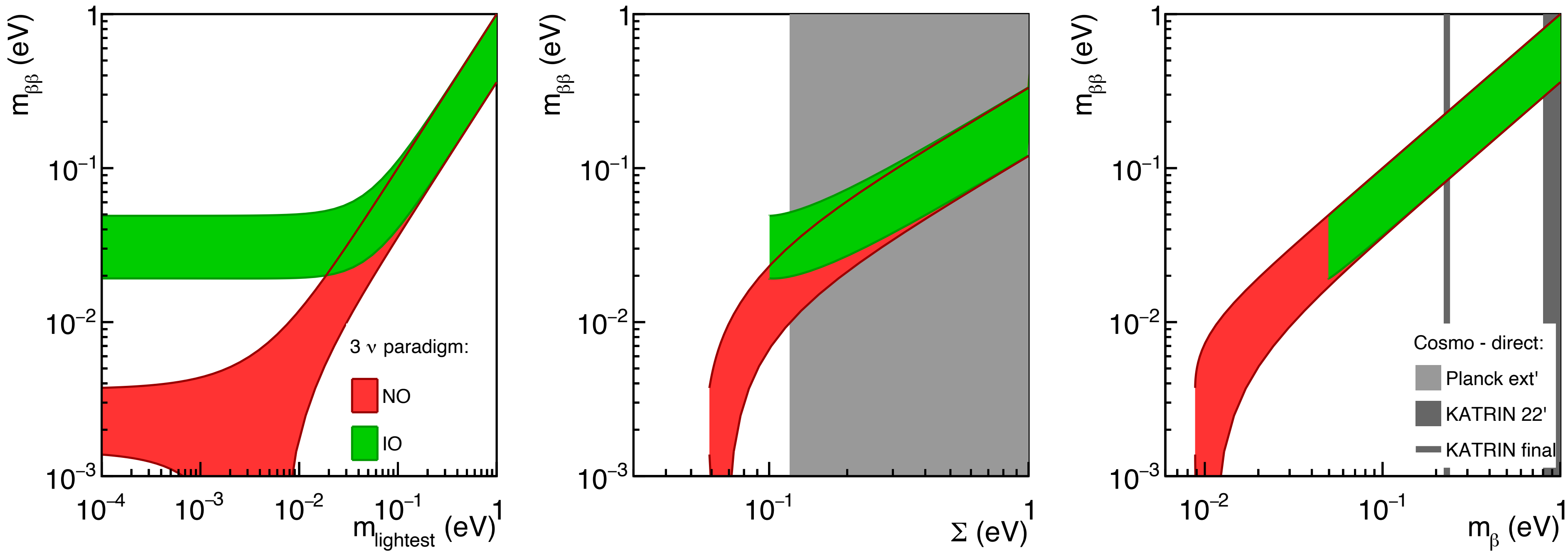
- Attractive: Minimal model without requiring new particles (mediator = active $\nu$ + SM bosons)

$$m_{\beta\beta} = \left|\sum_{i=1}^{3} \left|U_{ei}^2\right| e^{i\varphi_i} m_i\right|$$

$U$ = PMNS matrix [NuFit]

Relation between nuclear calculation and neutrino oscillation parameters

# « Light neutrino exchange »



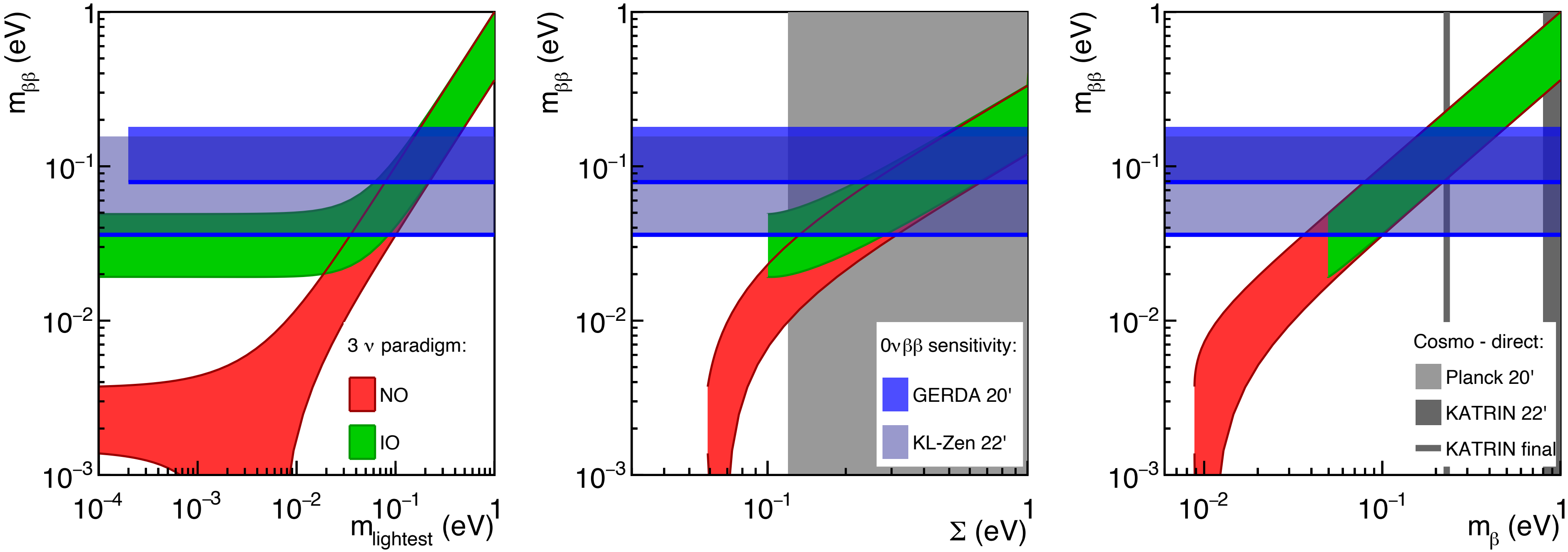

- Attractive: Minimal model without requiring new particles (mediator = active $\nu$ + SM bosons)

$$m_{\beta\beta} = \left|\sum_{i=1}^{3} |U_{ei}^2| e^{i\varphi_i} m_i\right| \qquad \Sigma = \sum_{i=1}^{3} m_i \qquad m_\beta = \sqrt{\sum |U_{ei}^2| m_i^2}$$

$U$ = PMNS matrix [NuFit]

- Direct relationship with the cosmological neutrino mass sum and direct mass measurement
- Rich complementarity in case of non-zero measurement in one of the channel

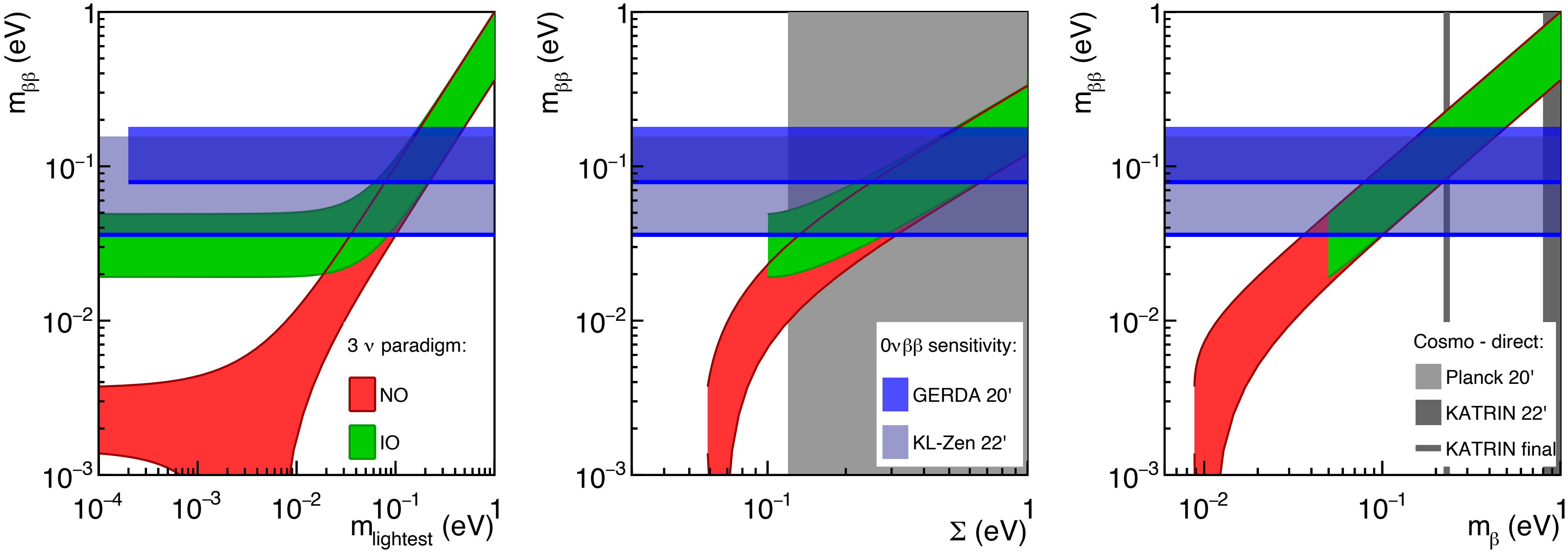
# « Light neutrino exchange »




- The current situation on the $0\nu\beta\beta$ decay side
  - ➢ Start to cover the inverted ordering $m_{\beta\beta}$ band prediction

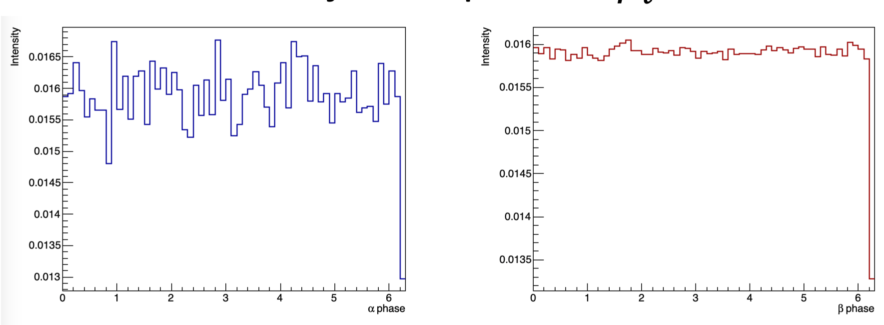
# « Light neutrino exchange »

Side note



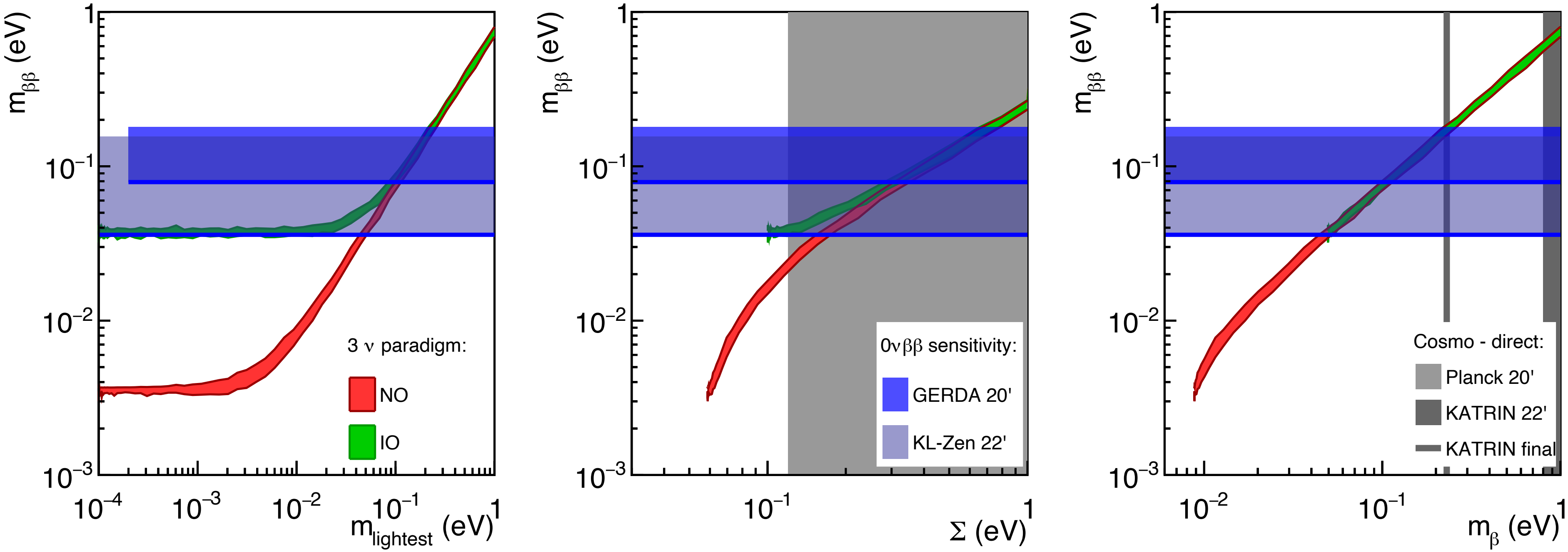

- **Bands width:**
  - ➢ Green and red dominated by unknown Majorana phases (not osc. params. uncertainty)
  - ➢ Blue dominated by NMEs calculations

Majorana phases $\varphi_i$



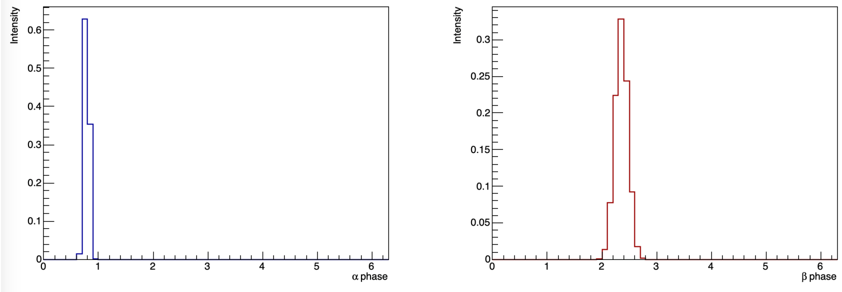
# « Light neutrino exchange »

Side note

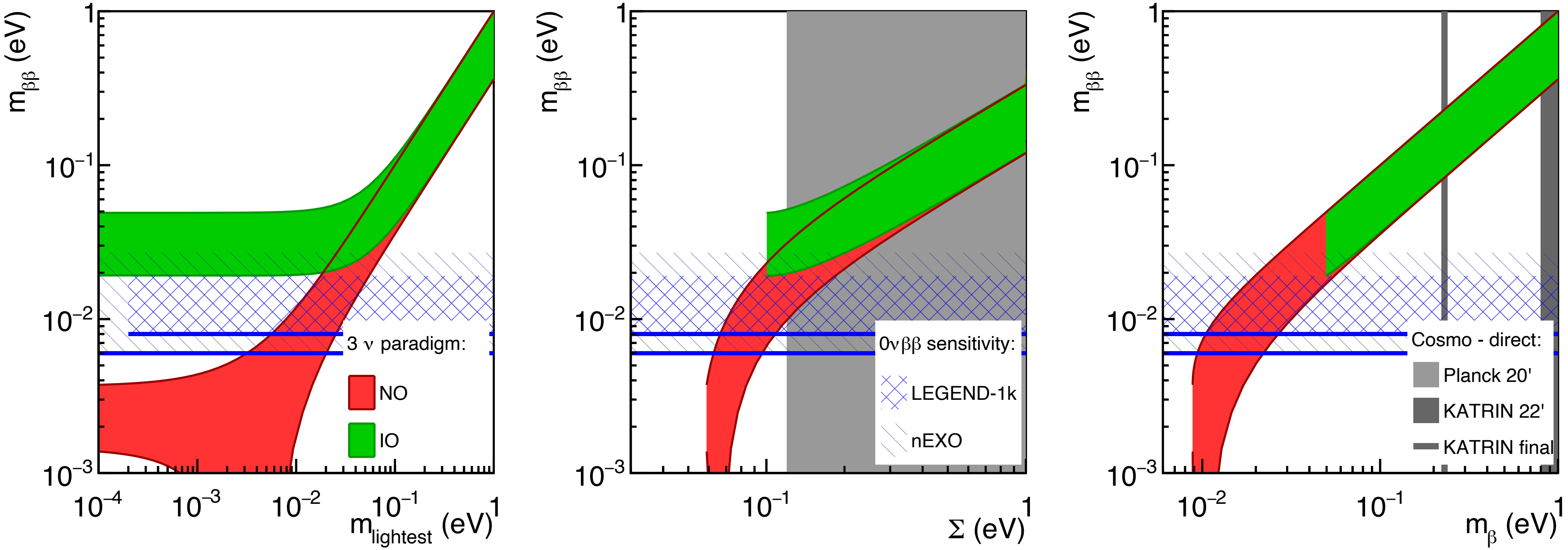



- **Bands width:**
  - ➢ Green and red dominated by unknown Majorana phases (not osc. params. uncertainty)
  - ➢ Blue dominated by NMEs calculations

Majorana phases $\varphi_i$

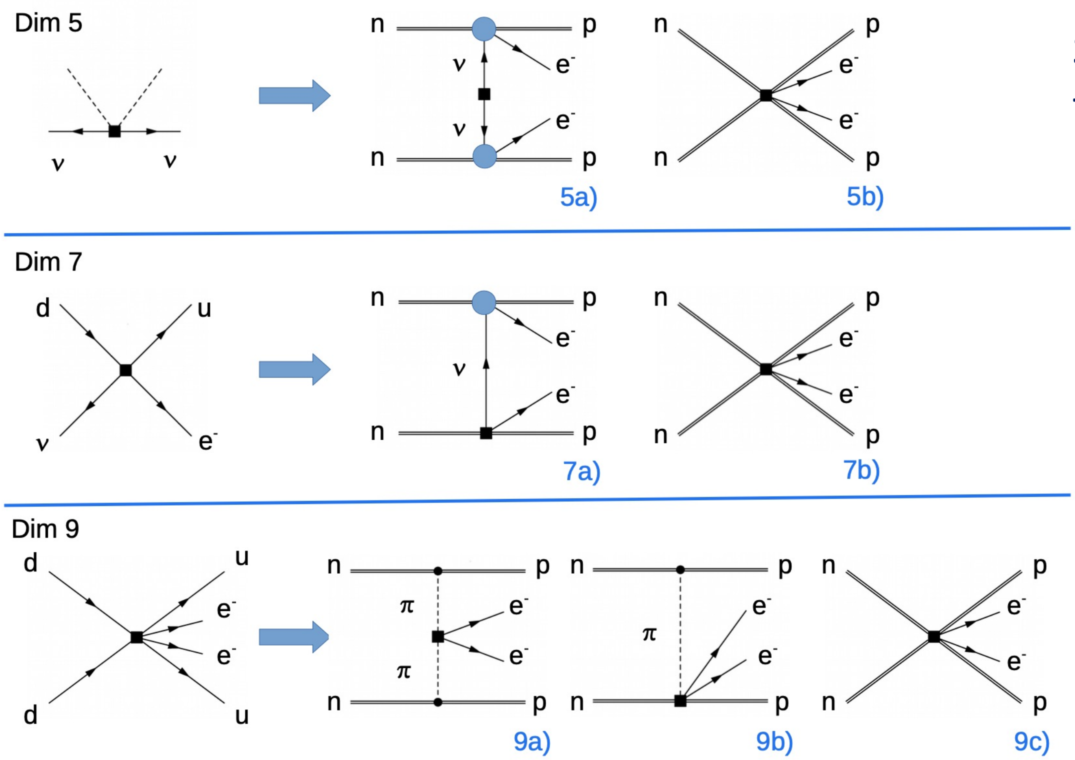


# « Light neutrino exchange »




- Next gen $0\nu\beta\beta$ decay experiment reach
  - ➢ Entirely cover the inverted ordering $m_{\beta\beta}$ band prediction for most NMEs

# Neutrinoless double beta decay - $0\nu\beta\beta$

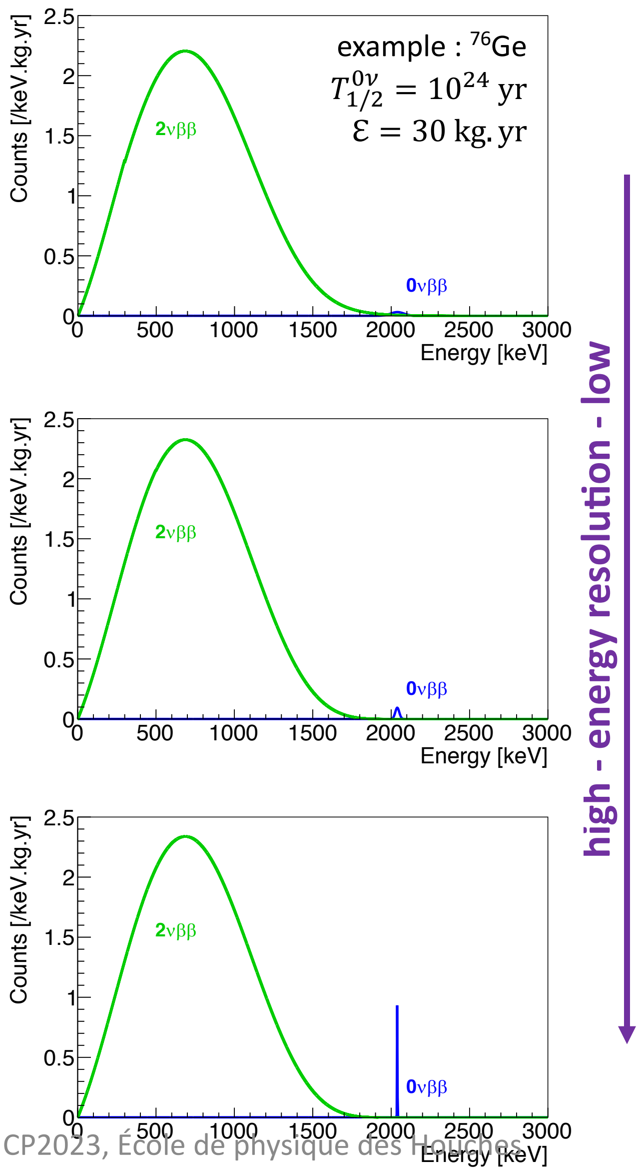



See recent review on theoretical tools [2203.12169]

Such process:

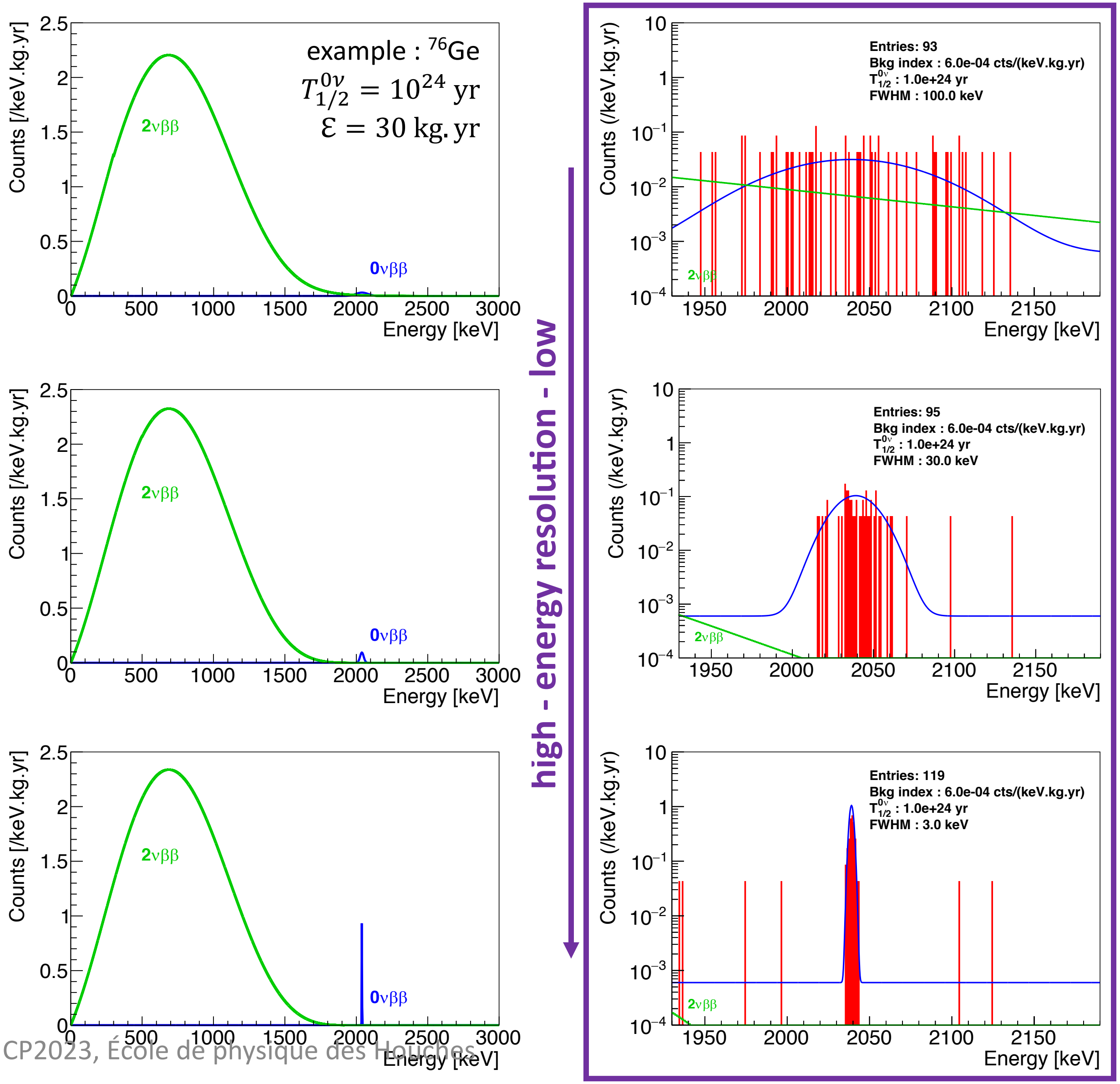
- ✓ **violates the Lepton Number** by 2 units = New Physics! ($\mathcal{O}(5)$, $\mathcal{O}(\ldots)$)
- ✓ determines the nature of neutrinos: **Majorana particle** $\boldsymbol{\nu = \bar{\nu}}$ [Valle – 1982]
- ✓ gives information on the $\nu$ mass via $m_{\beta\beta}$ (light neutrino exchange scenario)
- ✓ has never been observed so far

# $0\nu\beta\beta$ decay experimental signature

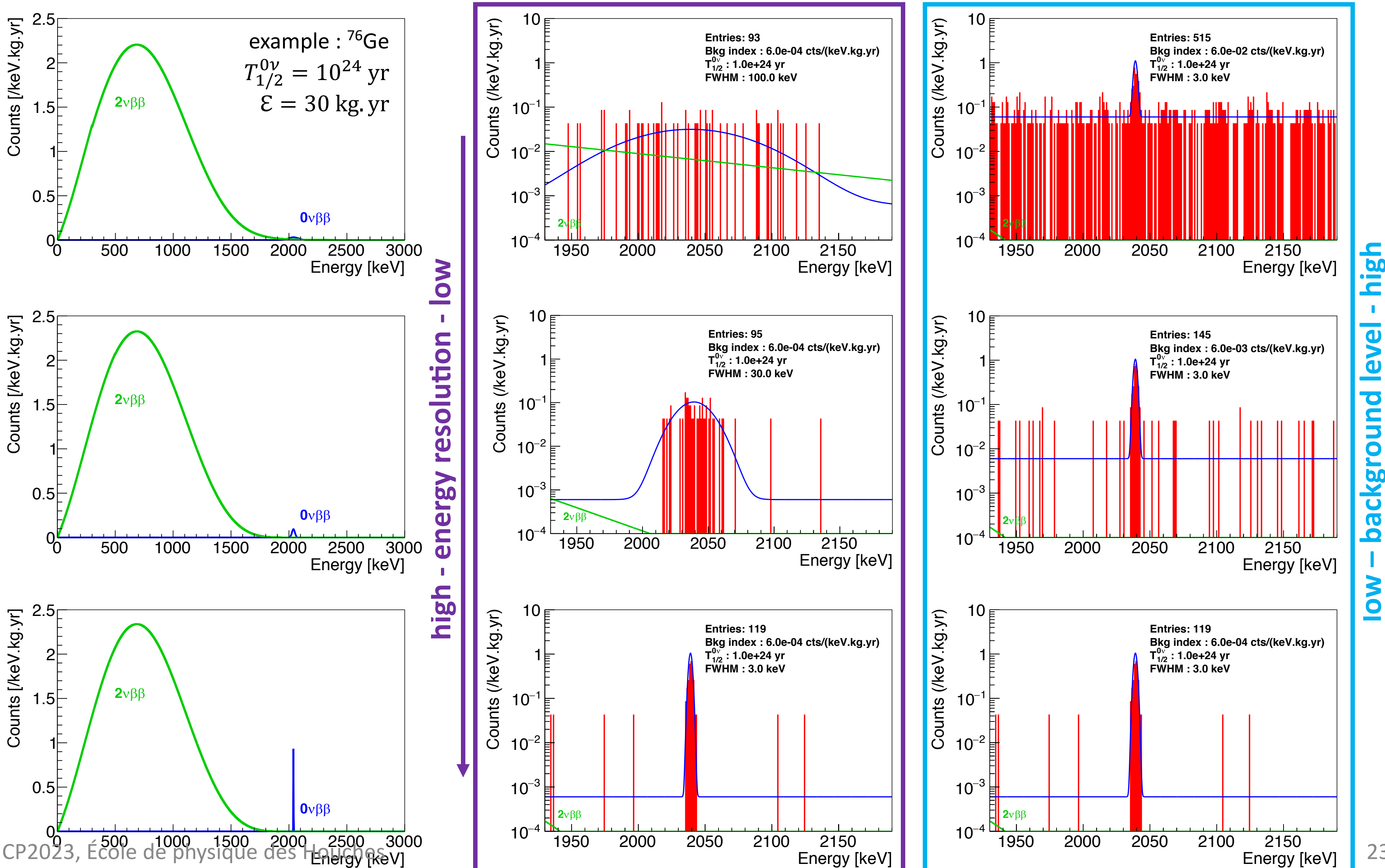



- $2\nu\beta\beta$ continuum + peak at $Q_{\beta\beta}$
- $T^{0\nu}_{1/2} = \ln 2 \,.\, \frac{N_A}{m_A} \,.\, \epsilon \,.\, \mathcal{E} \,.\, \frac{1}{N^S}$
- **Key points:**
  - Avogadro number: $N_A$
  - Efficiency [%] x exposure [kg.yr]: $\epsilon \,.\, \mathcal{E}$
  - Energy resolution [keV]
  - $\mathrm{BI} = \frac{N^B}{\mathcal{E} \,.\, \Delta E}$ [cts/(keV.kg.yr)]
- **Topology :**
  - Signal = *Single-Site Event (SSE)*
  - Background $\gamma$ = *Multi-Site Event (MSE)*
    $\alpha/\beta$ = *Surface Event*

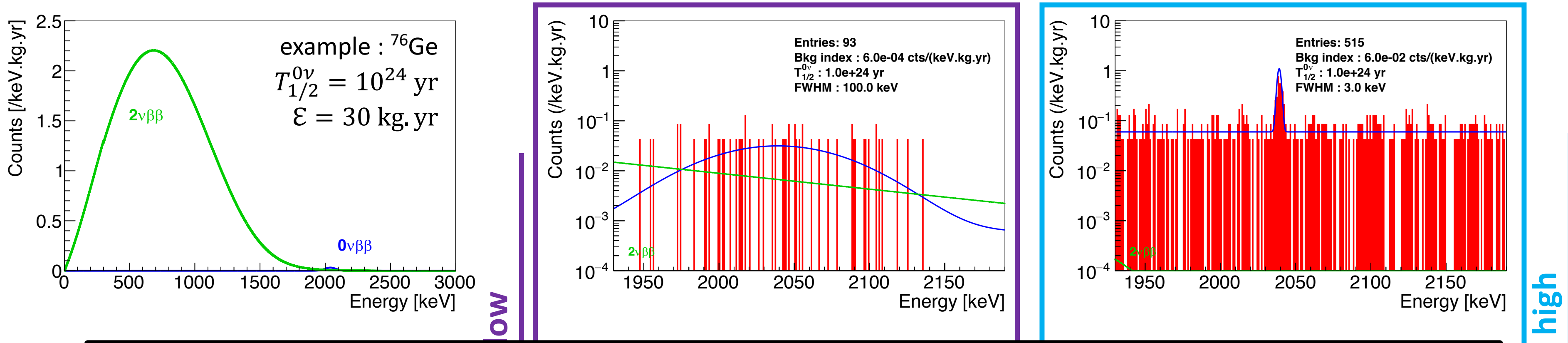
# $0\nu\beta\beta$ decay experimental signature



# $0\nu\beta\beta$ decay experimental signature



# $0\nu\beta\beta$ decay experimental signature

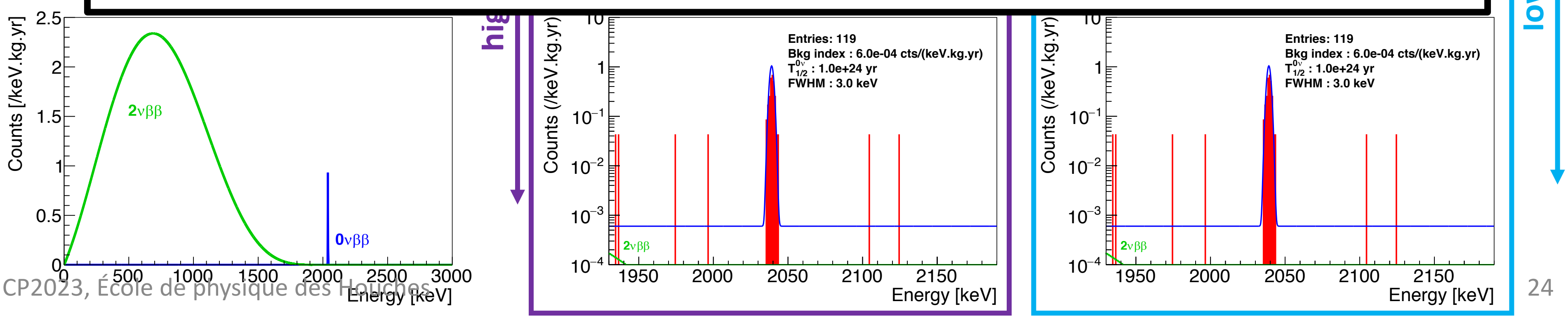



**Two statistical notions scrutinized:**

- sensitivity for limit setting (90% C.L.)
  « *limit on the signal strength assuming no signal* »

- $3\sigma$ discovery potential sensitivity
  « *minimal signal strength for which a discovery is expected with $3\sigma$ C.L.* »

*see detailed discussion in: [1705.02996]*

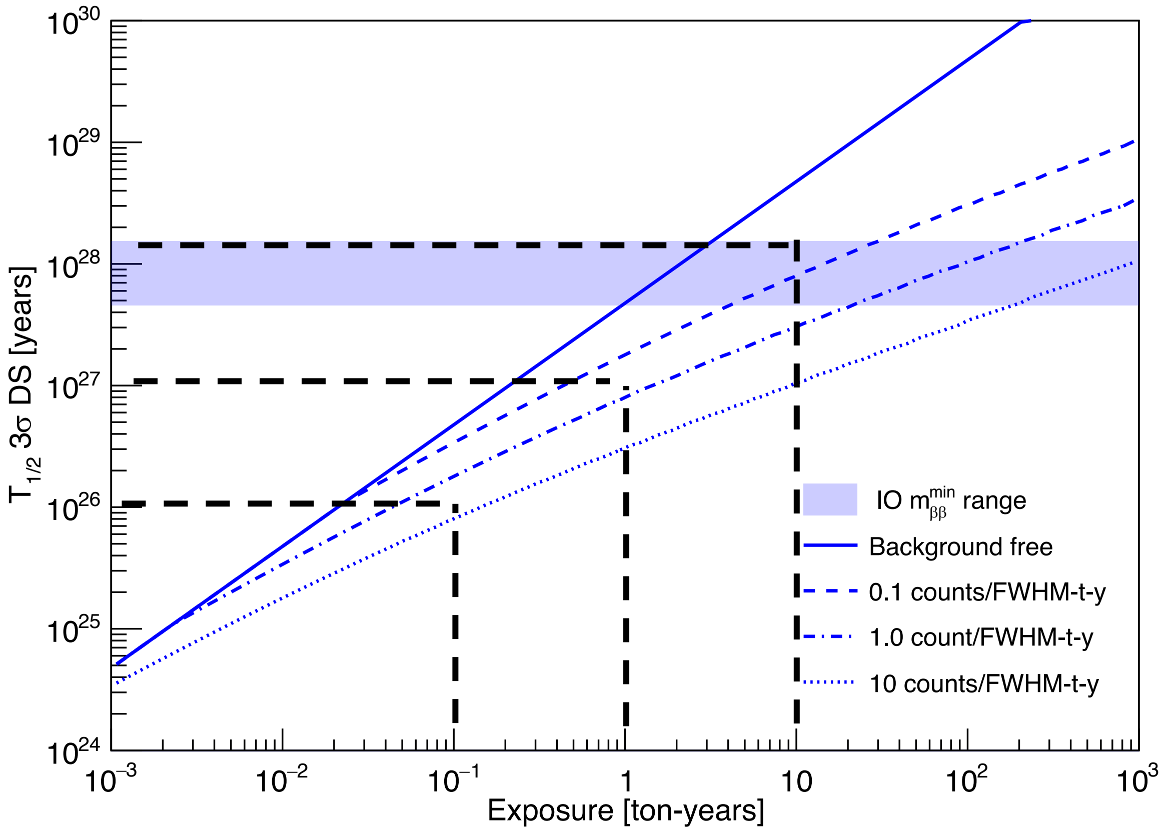


# Figure of merit – discovery potential

« *minimal signal strength for which a discovery is expected with 3σ C.L.* »

*see detailed discussion in: [1705.02996]*

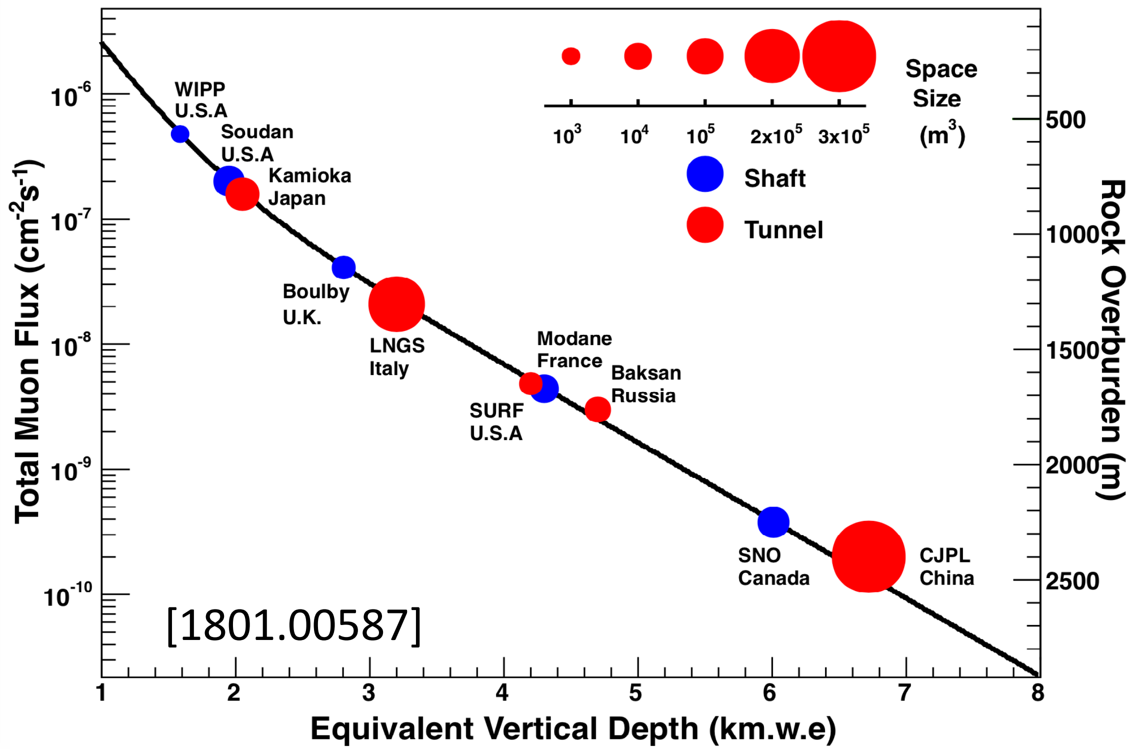
example : $^{76}$Ge (88% enr.)




Defines the experimental design in terms of

- exposure (mass et duration)
- background goal (passive/active veto, detector design, analysis techniques)

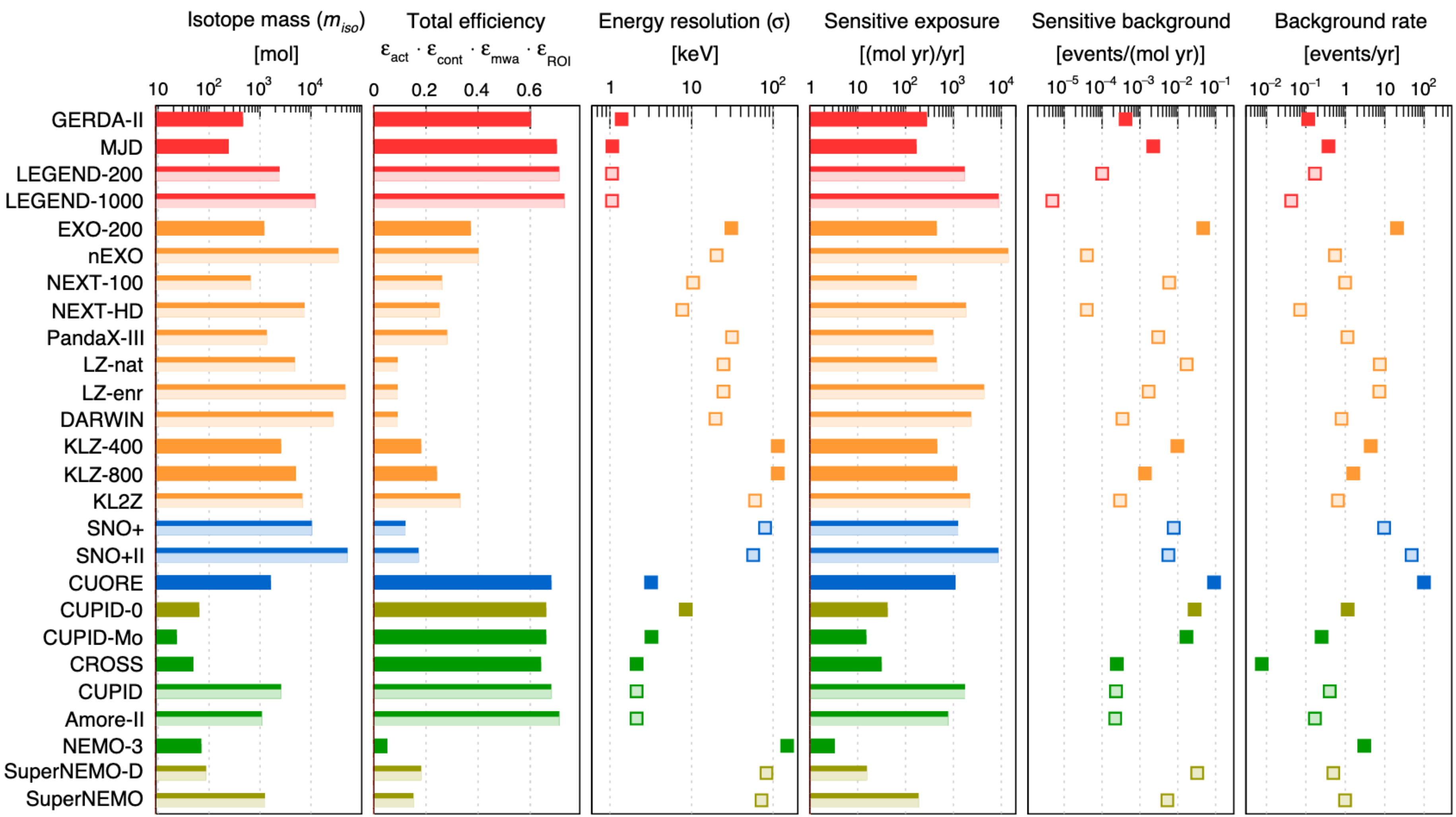
# Underground laboratories worldwide




- Underground = passive background suppression for « free »
- Isotopic activation suppression (neutron capture– e.g. $^{76}\text{Ge} + n \rightarrow {}^{77\text{m}}\text{Ge} \rightarrow {}^{77}\text{As}$ + **2.7 MeV**)
- Large experimental infrastructure required (shielding, cryostat, instrumentation)
- Size/depth/access compromise taken into account by the collaborations

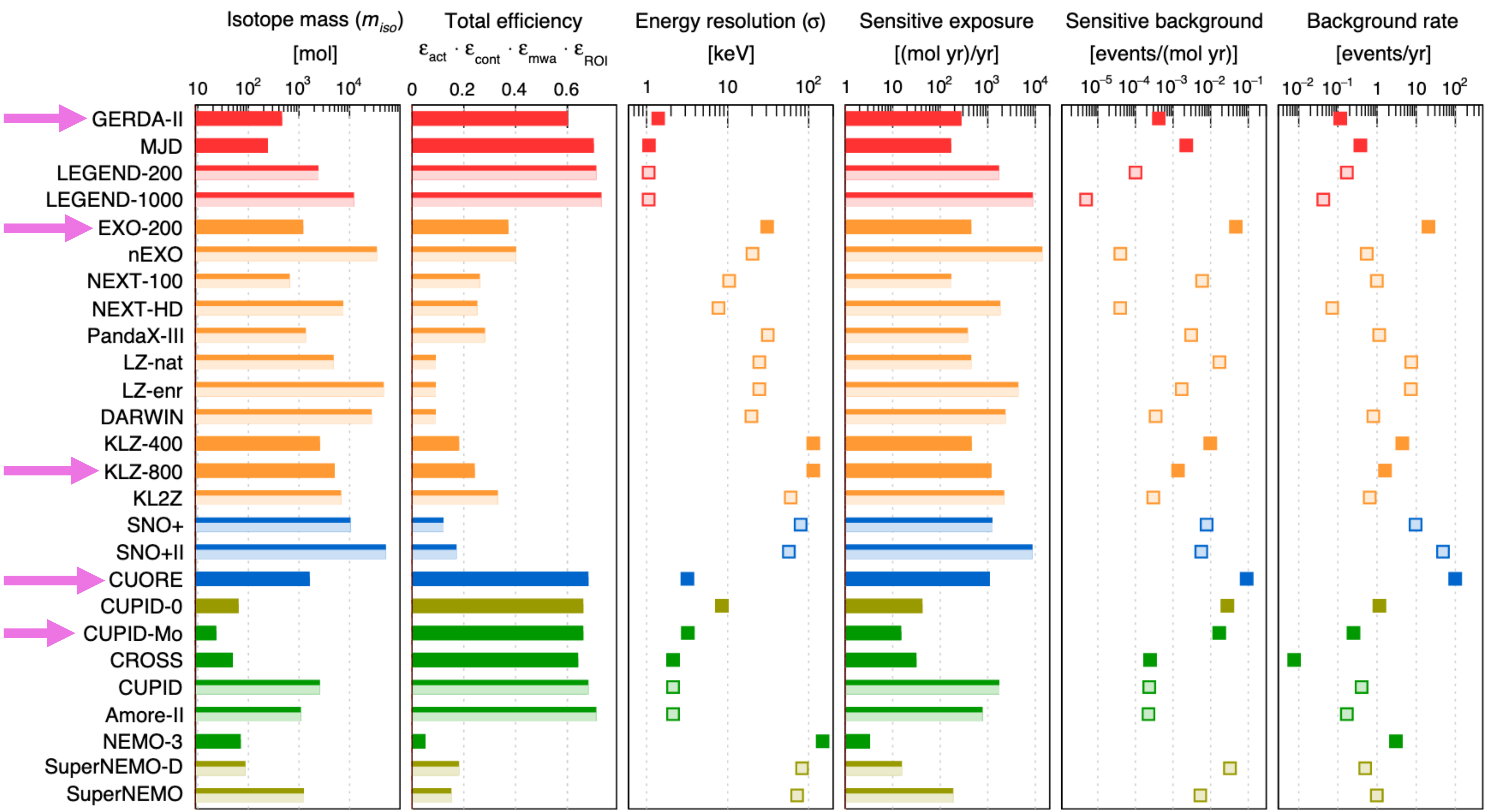
# The experimental landscape

See fresh exhaustive review [2202.01787]



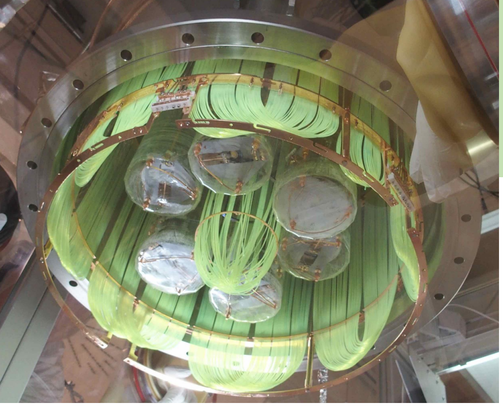
# The experimental landscape

See fresh exhaustive review [2202.01787]

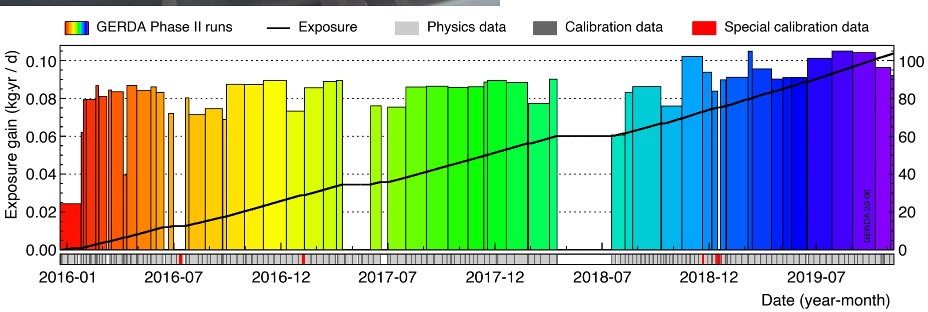


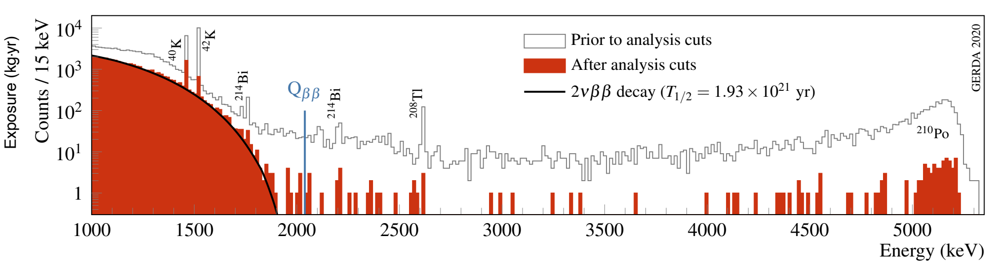
# Détecteur semi-conducteur GERDA @ LNGS

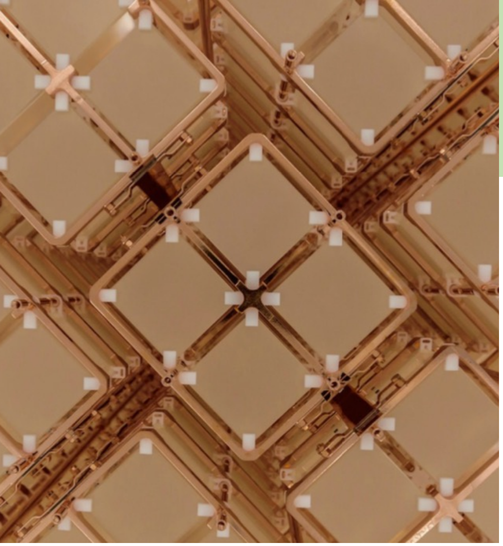
[PRL, 2020]



- **$^{76}$Ge $Q_{\beta\beta} = 2039$ keV** - $T_{1/2}^{2\nu} \sim 2 \times 10^{21}$ yr
- High detection efficiency de (detector = source)
- Enrichment up to 88% - active mass ~ 40 kg
- **New detector technology (0.7 kg → 3 kg /det.)**
- Excellent energy resolution : < 3 keV FWHM @ $Q_{\beta\beta}$
- **"Background-free"** experiment at final exposure (LAr veto + PSD)
- Sensitivity $T_{1/2}^{0\nu} > 10^{26}$ yr for the 1st time!
- Final exposure of 100 kg.yr reached in Nov. 2019
- $\boldsymbol{T_{1/2}^{0\nu} > 1.8 \times 10^{26}}$ **yr** $-$ $\boldsymbol{m_{\beta\beta} < [79 - 180]}$ **meV (90% C.L.)**
- **Successor : LEGEND**



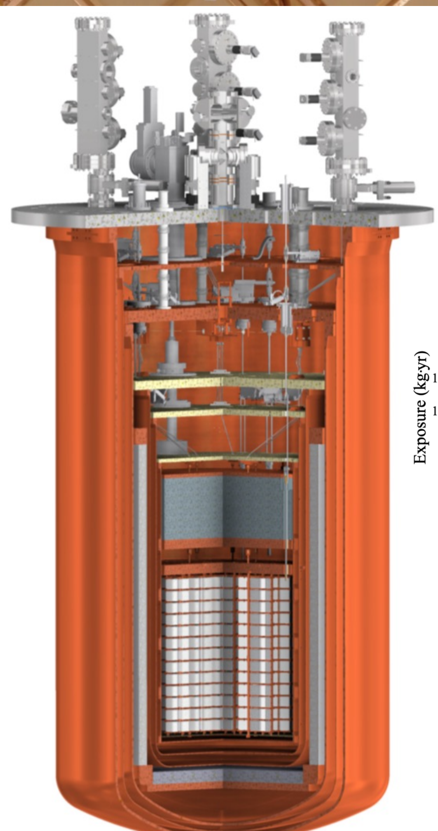



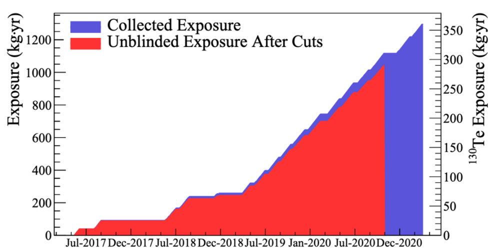


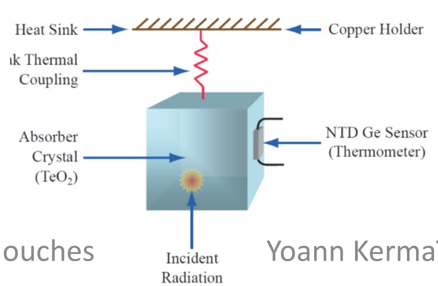
[Nature, 2022]

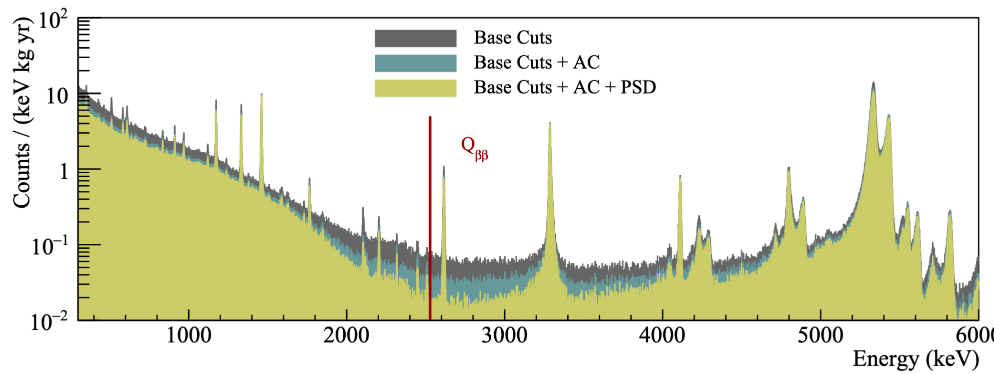
# Bolometric detector CUORE @ LNGS

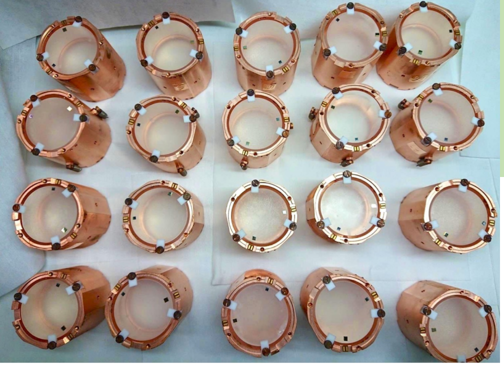
- **$^{130}$Te $Q_{\beta\beta} = 2528$ keV** - $T_{1/2}^{2\nu} \sim 8 \times 10^{20}$ yr
- 988 $TeO_2$ crystals with an active mass of 206 kg
- Natural abondance: 35%  - no enrichment
- **Largest mK cryostat in the world**
- Very good energy resolution : 7.8 keV FWHM @ $Q_{\beta\beta}$
- $\mathbf{T_{1/2}^{0\nu} > 0.2 \times 10^{26}}$ **yr** $-$ $\mathbf{m_{\beta\beta} < [90 - 305]}$ **meV (90% C.L.) with 1038.4 kg.yr**
- **Stable operation of the cryostat demonstrated in 2021** continue the data taking while waiting for CUPID
- Problematic $\alpha/\gamma$ background → active veto needed (CUPID)

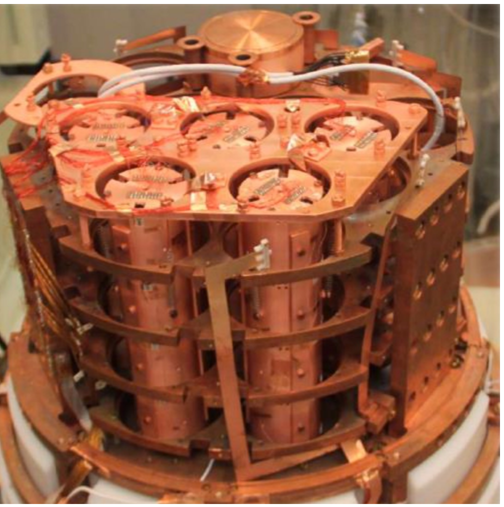




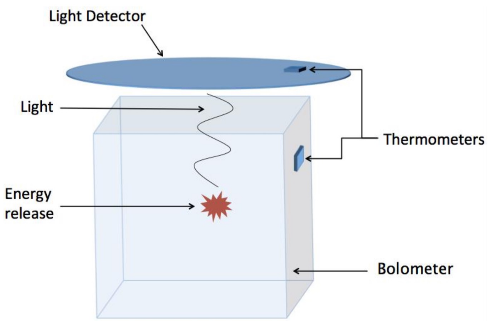


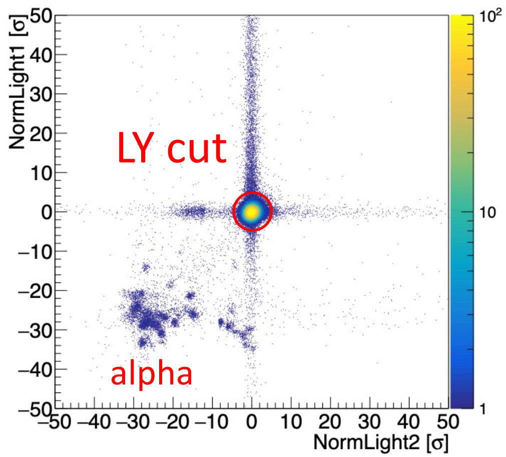


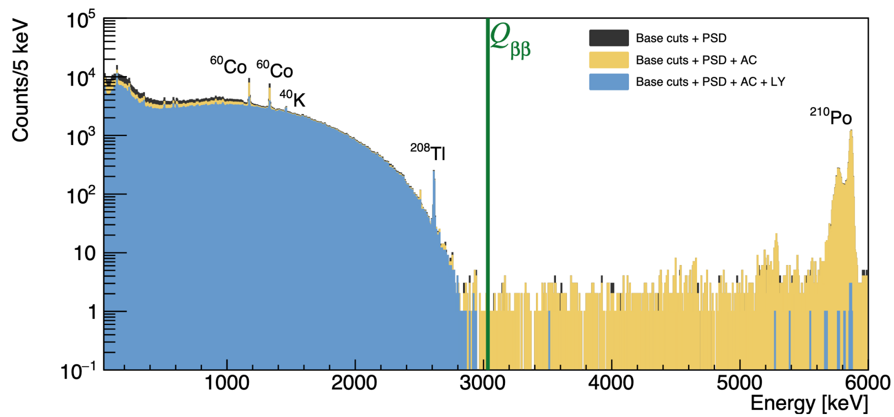
# Bolometric detector CUPID-Mo @ LSM

[EPJC, 2022]

- **$^{100}$Mo $Q_{\beta\beta} = 3035$ keV** - $T^{2\nu}_{1/2} \sim 7 \times 10^{18}$ yr
- **20 $Li_2MoO_4$ bolometers ran at 20 mK with improved radiopurity w.r.t. CUORE**
- Enrichment up to 97% - active mass ∼ 4 kg
- **New veto technology: scintillating photons collection**
- Very good energy resolution: 7.4 keV FWHM @ $Q_{\beta\beta}$
- $\mathbf{T^{0\nu}_{1/2} > 0.02 \times 10^{26}\ yr\ -\ m_{\beta\beta} < [280 - 480]\ meV\ (90\%\ C.L.)}$ with a final 1.5 kg.yr (481 days) exposure
- **Launching pad for CUPID**

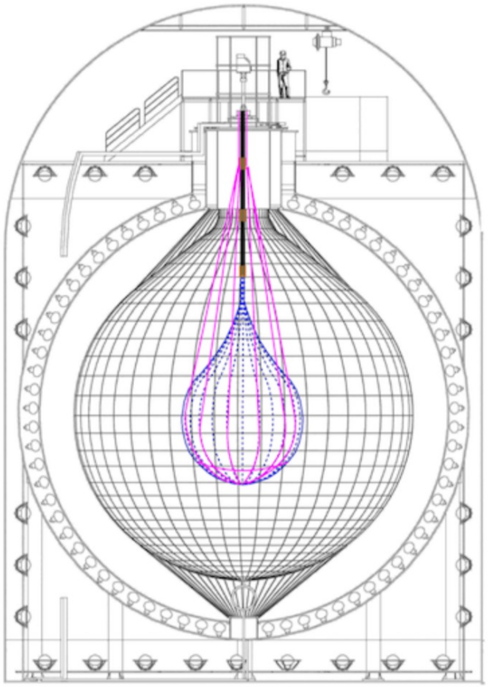


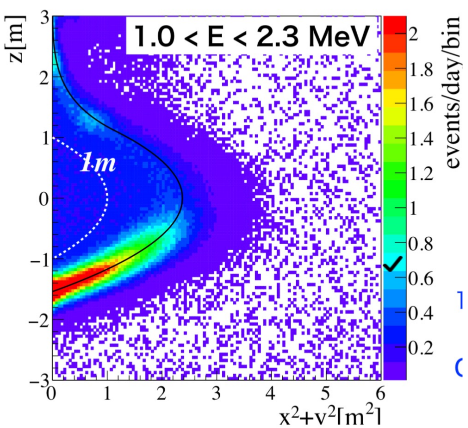
# Liquid scintillator detector KamLAND-Zen @ Kamioka

[PRL, 2023]

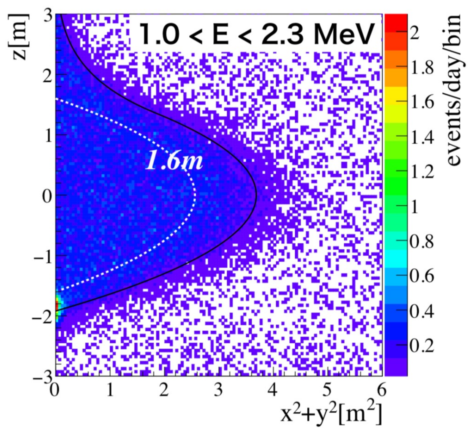


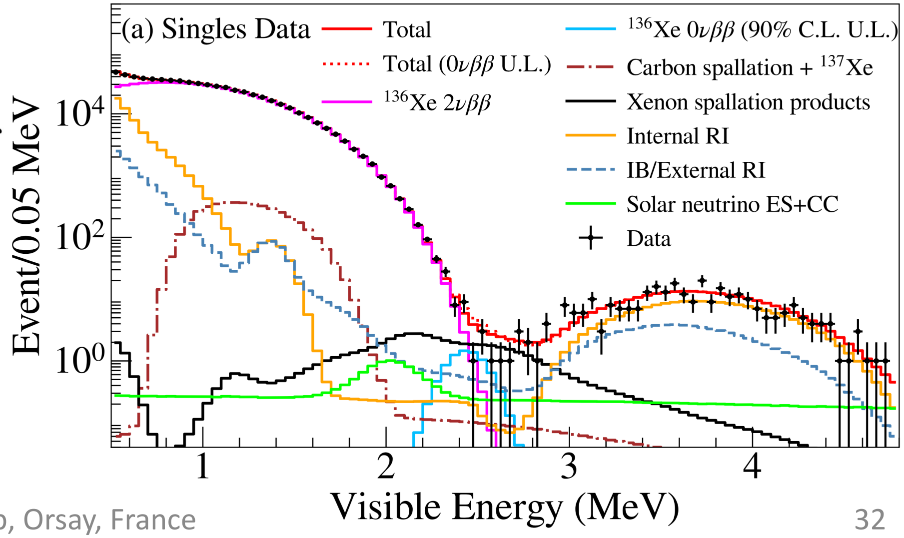
- $^{136}$Xe $\boldsymbol{Q_{\beta\beta} = 2458}$ **keV** - $T^{2\nu}_{1/2} \sim 2 \times 10^{21}$ yr
- **Large LXe volume within a radiopure balloon immersed within a PMT instrumented liquid scintillator volume**
- Enrichment up to 91% - active mass ~ 745 kg
- **Balloon volume and mass increase x2 in 4 ans**
- post-Fukushima $^{110m}$Ag contamination removed + overall bkg ÷10
- Low energy resolution: 250 keV FWHM @ $Q_{\beta\beta}$
- $\boldsymbol{T^{0\nu}_{1/2} > 2.3 \times 10^{26}}$ **yr –** $\boldsymbol{m_{\beta\beta} < [36 - 156]}$ **meV (90% C. L.) with 523.4 days exposure**

KamLAND-Zen 400 phaseII



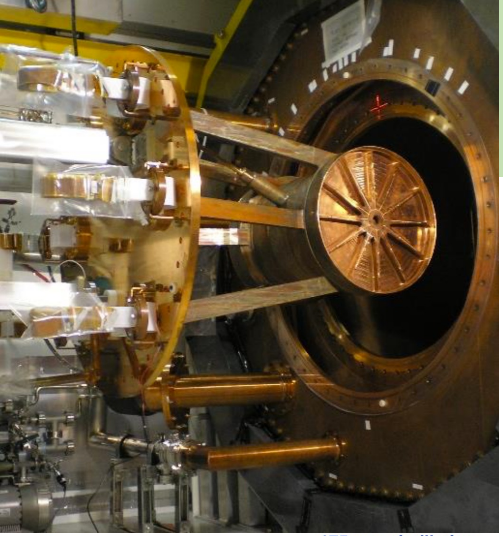

KamLAND-Zen 800

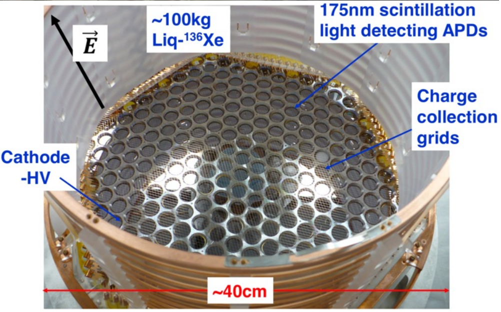


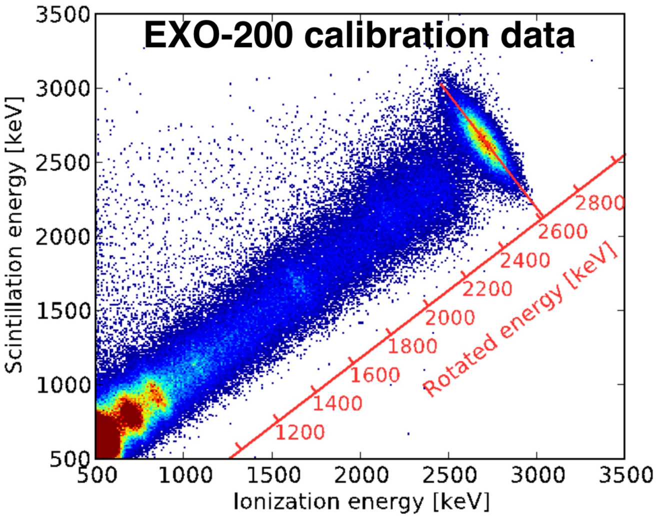
# Liquid Xe TPC detector EXO-200 @ WIPP

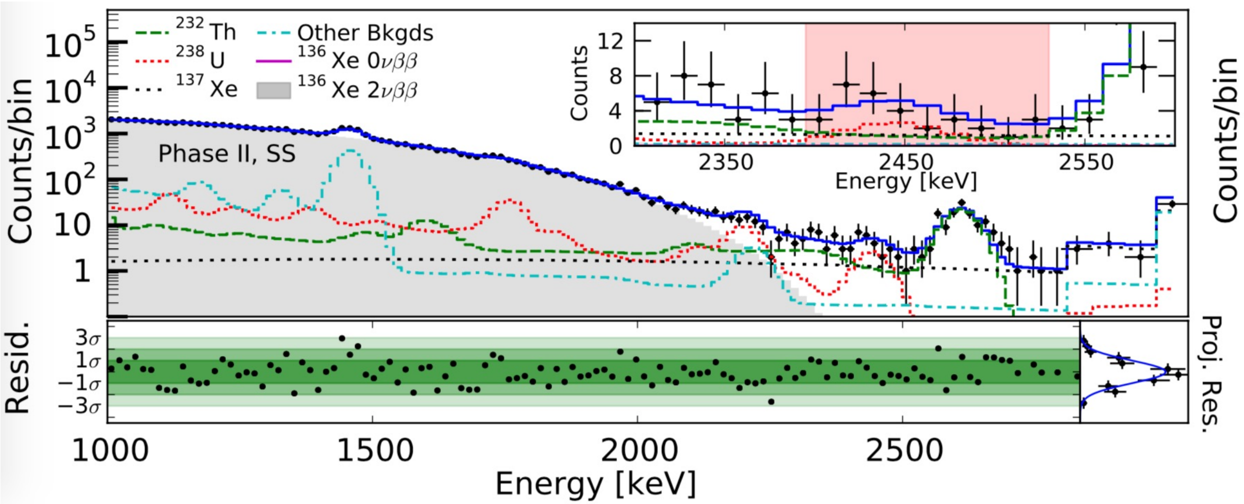
[PRL, 2019]






- **$^{136}$Xe $Q_{\beta\beta} = 2458$ keV** - $T^{2\nu}_{1/2} \sim 2 \times 10^{21}$ yr
- **LXe cylindrical *Time Projection Chamber***
- Enrichment up to 81% - active mass ~ 100 kg
- **Effective scintillation-ionisation correlation**
- Event reconstruction (x-y-z) + fiducialization for SSE vs MSE topology
- Low energy resolution: 60 keV FWHM @ $Q_{\beta\beta}$
- $T^{0\nu}_{1/2} > 0.4 \times 10^{26}$ yr $-$ $m_{\beta\beta} < [78 - 239]$ meV (90% C.L.)



# Experimental state of the art

See fresh exhaustive review [2202.01787]

| Experiment | Isotope | Status | Lab | $m_{\mathrm{iso}}$ [mol] | $\varepsilon_{\mathrm{act}}$ [%] | $\varepsilon_{\mathrm{cont}}$ [%] | $\varepsilon_{\mathrm{mva}}$ [%] | $\sigma$ [keV] | ROI [$\sigma$] | $\varepsilon_{\mathrm{ROI}}$ [%] | $\mathcal{E}$ $\left[\frac{\mathrm{mol\cdot yr}}{yr}\right]$ | $\mathcal{B}$ $\left[\frac{\mathrm{events}}{\mathrm{mol\cdot yr}}\right]$ | $\lambda_b$ $\left[\frac{\mathrm{events}}{\mathrm{yr}}\right]$ | $T_{1/2}$ [yr] | $m_{\beta\beta}$ [meV] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *High-purity Ge detectors (Sec. VI.B)* | | | | | | | | | | | | | | | |
| GERDA-II | $^{76}$Ge | completed | LNGS | $4.5 \cdot 10^{2}$ | 88 | 91 | 79 | 1.4 | -2,2 | 95 | 273 | $4.2 \cdot 10^{-4}$ | $1.1 \cdot 10^{-1}$ | $1.2 \cdot 10^{26}$ | 93-222 |
| MJD | $^{76}$Ge | completed | SURF | $2.4 \cdot 10^{2}$ | 90 | 91 | 89 | 1.1 | -2,2 | 95 | 166 | $2.3 \cdot 10^{-3}$ | $3.7 \cdot 10^{-1}$ | $5.5 \cdot 10^{25}$ | 140-334 |
| LEGEND-200 | $^{76}$Ge | construction | LNGS | $2.4 \cdot 10^{3}$ | 91 | 91 | 90 | 1.1 | -2,2 | 95 | 1 684 | $1.0 \cdot 10^{-4}$ | $1.7 \cdot 10^{-1}$ | $1.5 \cdot 10^{27}$ | 27-63 |
| LEGEND-1000 | $^{76}$Ge | proposed | | $1.2 \cdot 10^{4}$ | 92 | 92 | 90 | 1.1 | -2,2 | 95 | 8 736 | $4.9 \cdot 10^{-6}$ | $4.3 \cdot 10^{-2}$ | $1.3 \cdot 10^{28}$ | 9-21 |
| *Xenon time projection chambers (Sec. VI.C)* | | | | | | | | | | | | | | | |
| EXO-200 | $^{136}$Xe | completed | WIPP | $1.2 \cdot 10^{3}$ | 46 | 100 | 84 | 31 | -2,2 | 95 | 438 | $4.7 \cdot 10^{-2}$ | $2.1 \cdot 10^{+1}$ | $2.4 \cdot 10^{25}$ | 111-477 |
| nEXO | $^{136}$Xe | proposed | SNOLAB | $3.4 \cdot 10^{4}$ | 64 | 100 | 66 | 20 | -2,2 | 95 | 13 700 | $4.0 \cdot 10^{-5}$ | $5.5 \cdot 10^{-1}$ | $7.5 \cdot 10^{27}$ | 6-27 |
| NEXT-100 | $^{136}$Xe | construction | LSC | $6.4 \cdot 10^{2}$ | 88 | 76 | 49 | 10 | -1.0,1.8 | 80 | 167 | $5.9 \cdot 10^{-3}$ | $9.9 \cdot 10^{-1}$ | $7.0 \cdot 10^{25}$ | 66-281 |
| NEXT-HD | $^{136}$Xe | proposed | | $7.4 \cdot 10^{3}$ | 95 | 89 | 44 | 7.7 | -0.5,1.7 | 65 | 1 809 | $4.0 \cdot 10^{-5}$ | $7.2 \cdot 10^{-2}$ | $2.2 \cdot 10^{27}$ | 12-50 |
| PandaX-III-200 | $^{136}$Xe | construction | CJPL | $1.3 \cdot 10^{3}$ | 77 | 74 | 65 | 31 | -1.2,1.2 | 76 | 374 | $3.0 \cdot 10^{-3}$ | $1.1 \cdot 10^{+0}$ | $1.5 \cdot 10^{26}$ | 45-194 |
| LZ-nat | $^{136}$Xe | construction | SURF | $4.7 \cdot 10^{3}$ | 14 | 100 | 80 | 25 | -1.4,1.4 | 84 | 440 | $1.7 \cdot 10^{-2}$ | $7.5 \cdot 10^{+0}$ | $7.2 \cdot 10^{25}$ | 64-277 |
| LZ-enr | $^{136}$Xe | proposed | SURF | $4.6 \cdot 10^{4}$ | 14 | 100 | 80 | 25 | -1.4,1.4 | 84 | 4302 | $1.7 \cdot 10^{-3}$ | $7.3 \cdot 10^{+0}$ | $7.1 \cdot 10^{26}$ | 20-87 |
| Darwin | $^{136}$Xe | proposed | | $2.7 \cdot 10^{4}$ | 13 | 100 | 90 | 20 | -1.2,1.2 | 76 | 2 312 | $3.5 \cdot 10^{-4}$ | $8.0 \cdot 10^{-1}$ | $1.1 \cdot 10^{27}$ | 17-72 |
| *Large liquid scintillators (Sec. VI.D)* | | | | | | | | | | | | | | | |
| KLZ-400 | $^{136}$Xe | completed | Kamioka | $2.5 \cdot 10^{3}$ | 44 | 100 | 97 | 114 | 0,1.4 | 42 | 450 | $9.9 \cdot 10^{-3}$ | $4.4 \cdot 10^{+0}$ | $3.3 \cdot 10^{25}$ | 95-408 |
| KLZ-800 | $^{136}$Xe | taking data | Kamioka | $5.0 \cdot 10^{3}$ | 58 | 100 | 97 | 114 | 0,1.4 | 42 | 1 173 | $1.4 \cdot 10^{-3}$ | $1.6 \cdot 10^{+0}$ | $4.0 \cdot 10^{26}$ | 28-118 |
| KL2Z | $^{136}$Xe | proposed | Kamioka | $6.7 \cdot 10^{3}$ | 80 | 100 | 97 | 60 | 0,1.4 | 42 | 2 176 | $3.0 \cdot 10^{-4}$ | $6.5 \cdot 10^{-1}$ | $1.1 \cdot 10^{27}$ | 17-71 |
| SNO+I | $^{130}$Te | construction | SNOLAB | $1.0 \cdot 10^{4}$ | 20 | 100 | 97 | 80 | -0.5,1.5 | 62 | 1 232 | $7.8 \cdot 10^{-3}$ | $9.7 \cdot 10^{+0}$ | $1.8 \cdot 10^{26}$ | 31-144 |
| SNO+II | $^{130}$Te | proposed | SNOLAB | $5.1 \cdot 10^{4}$ | 27 | 100 | 97 | 57 | -0.5,1.5 | 62 | 8 521 | $5.7 \cdot 10^{-3}$ | $4.8 \cdot 10^{+1}$ | $5.7 \cdot 10^{26}$ | 17-81 |
| *Cryogenic calorimeters (Sec. VI.E)* | | | | | | | | | | | | | | | |
| CUORE | $^{130}$Te | taking data | LNGS | $1.6 \cdot 10^{3}$ | 100 | 88 | 92 | 3.2 | -1.4,1.4 | 84 | 1 088 | $9.1 \cdot 10^{-2}$ | $9.9 \cdot 10^{+1}$ | $5.1 \cdot 10^{25}$ | 58-270 |
| CUPID-0 | $^{82}$Se | completed | LNGS | $6.2 \cdot 10^{1}$ | 100 | 81 | 86 | 8.5 | -2,2 | 95 | 41 | $2.8 \cdot 10^{-2}$ | $1.2 \cdot 10^{+0}$ | $4.4 \cdot 10^{24}$ | 283-551 |
| CUPID-Mo | $^{100}$Mo | completed | LSM | $2.3 \cdot 10^{1}$ | 100 | 76 | 91 | 3.2 | -2,2 | 95 | 15 | $1.7 \cdot 10^{-2}$ | $2.5 \cdot 10^{-1}$ | $1.7 \cdot 10^{24}$ | 293-500 |
| CROSS | $^{100}$Mo | construction | LSC | $4.8 \cdot 10^{1}$ | 100 | 75 | 90 | 2.1 | -2,2 | 95 | 31 | $2.5 \cdot 10^{-2}$ | $7.6 \cdot 10^{-3}$ | $4.9 \cdot 10^{25}$ | 54-93 |
| CUPID | $^{100}$Mo | proposed | LNGS | $2.5 \cdot 10^{3}$ | 100 | 79 | 90 | 2.1 | -2,2 | 95 | 1 717 | $2.3 \cdot 10^{-4}$ | $4.0 \cdot 10^{-1}$ | $1.1 \cdot 10^{27}$ | 12-20 |
| AMORE | $^{100}$Mo | proposed | Yemilab | $1.1 \cdot 10^{3}$ | 100 | 82 | 91 | 2.1 | -2,2 | 95 | 760 | $2.2 \cdot 10^{-4}$ | $1.7 \cdot 10^{-1}$ | $6.7 \cdot 10^{26}$ | 15-25 |
| *Tracking calorimeters (Sec. VI.F)* | | | | | | | | | | | | | | | |
| NEMO-3 | $^{100}$Mo | completed | LSM | $6.9 \cdot 10^{1}$ | 100 | 100 | 11 | 148 | -1.6,1.1 | 42 | 3 | $9.3 \cdot 10^{-1}$ | $3.0 \cdot 10^{+0}$ | $5.6 \cdot 10^{23}$ | 505-866 |
| SuperNEMO-D | $^{82}$Se | construction | LSM | $8.5 \cdot 10^{1}$ | 100 | 100 | 28 | 83 | -4.2,2.4 | 64 | 15 | $2.1 \cdot 10^{-2}$ | $5.0 \cdot 10^{-1}$ | $8.6 \cdot 10^{24}$ | 201-391 |
| SuperNEMO | $^{82}$Se | proposed | LSM | $1.2 \cdot 10^{3}$ | 100 | 100 | 28 | 72 | -4.1,2.8 | 54 | 185 | $5.4 \cdot 10^{-3}$ | $9.8 \cdot 10^{-1}$ | $7.8 \cdot 10^{25}$ | 67-131 |

# Experimental state of the art

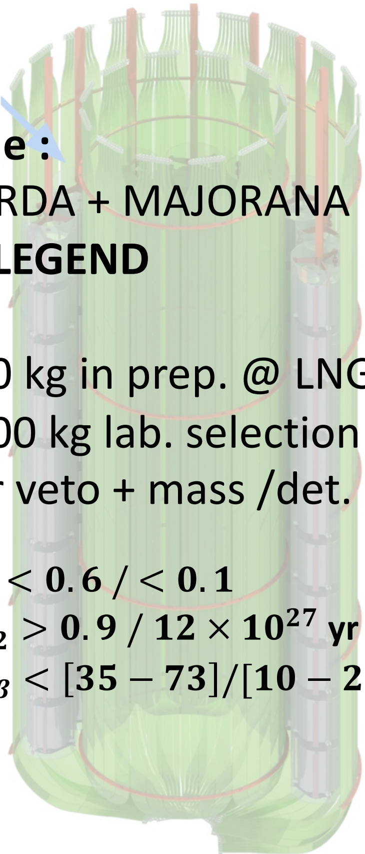
See fresh exhaustive review [2202.01787]

| Experiment | Isotope | Status | Lab | $m_{iso}$ [mol] | $\varepsilon_{act}$ [%] | $\varepsilon_{cont}$ [%] | $\varepsilon_{mva}$ [%] | $\sigma$ [keV] | ROI [$\sigma$] | $\varepsilon_{ROI}$ [%] | $\mathcal{E}$ $\left[\frac{mol\cdot yr}{yr}\right]$ | $\mathcal{B}$ $\left[\frac{events}{mol\cdot yr}\right]$ | $\lambda_b$ $\left[\frac{events}{yr}\right]$ | $T_{1/2}$ [yr] | $m_{\beta\beta}$ [meV] |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *High-purity Ge detectors (Sec. VI.B)* | | | | | | | | | | | | | | | |
| GERDA-II | $^{76}$Ge | completed | LNGS | $4.5\cdot10^{2}$ | 88 | 91 | 79 | 1.4 | -2,2 | 95 | 273 | $4.2\cdot10^{-4}$ | $1.1\cdot10^{-1}$ | $1.2\cdot10^{26}$ | 93-222 |
| MJD | $^{76}$Ge | completed | SURF | $2.4\cdot10^{2}$ | 90 | 91 | 89 | 1.1 | -2,2 | 95 | 166 | $2.3\cdot10^{-3}$ | $3.7\cdot10^{-1}$ | $5.5\cdot10^{25}$ | 140-334 |
| LEGEND-200 | $^{76}$Ge | construction | LNGS | $2.4\cdot10^{3}$ | 91 | 91 | 90 | 1.1 | -2,2 | 95 | 1 684 | $1.0\cdot10^{-4}$ | $1.7\cdot10^{-1}$ | $1.5\cdot10^{27}$ | 27-63 |
| LEGEND-1000 | $^{76}$Ge | proposed | | $1.2\cdot10^{4}$ | 92 | 92 | 90 | 1.1 | -2,2 | 95 | 8 736 | $4.9\cdot10^{-6}$ | $4.3\cdot10^{-2}$ | $1.3\cdot10^{28}$ | 9-21 |
| *Xenon time projection chambers (Sec. VI.C)* | | | | | | | | | | | | | | | |
| EXO-200 | $^{136}$Xe | completed | WIPP | $1.2\cdot10^{3}$ | 46 | 100 | 84 | 31 | -2,2 | 95 | 438 | $4.7\cdot10^{-2}$ | $2.1\cdot10^{+1}$ | $2.4\cdot10^{25}$ | 111-477 |
| nEXO | $^{136}$Xe | proposed | SNOLAB | $3.4\cdot10^{4}$ | 64 | 100 | 66 | 20 | -2,2 | 95 | 13 700 | $4.0\cdot10^{-5}$ | $5.5\cdot10^{-1}$ | $7.5\cdot10^{27}$ | 6-27 |
| NEXT-100 | $^{136}$Xe | construction | LSC | $6.4\cdot10^{2}$ | 88 | 76 | 49 | 10 | -1.0,1.8 | 80 | 167 | $5.9\cdot10^{-3}$ | $9.9\cdot10^{-1}$ | $7.0\cdot10^{25}$ | 66-281 |
| NEXT-HD | $^{136}$Xe | proposed | | $7.4\cdot10^{3}$ | 95 | 89 | 44 | 7.7 | -0.5,1.7 | 65 | 1 809 | $4.0\cdot10^{-5}$ | $7.2\cdot10^{-2}$ | $2.2\cdot10^{27}$ | 12-50 |
| PandaX-III-200 | $^{136}$Xe | construction | CJPL | $1.3\cdot10^{3}$ | 77 | 74 | 65 | 31 | -1.2,1.2 | 76 | 374 | $3.0\cdot10^{-3}$ | $1.1\cdot10^{+0}$ | $1.5\cdot10^{26}$ | 45-194 |
| LZ-nat | $^{136}$Xe | construction | SURF | $4.7\cdot10^{3}$ | 14 | 100 | 80 | 25 | -1.4,1.4 | 84 | 440 | $1.7\cdot10^{-2}$ | $7.5\cdot10^{+0}$ | $7.2\cdot10^{25}$ | 64-277 |
| LZ-enr | $^{136}$Xe | proposed | SURF | $4.6\cdot10^{4}$ | 14 | 100 | 80 | 25 | -1.4,1.4 | 84 | 4302 | $1.7\cdot10^{-3}$ | $7.3\cdot10^{+0}$ | $7.1\cdot10^{26}$ | 20-87 |
| Darwin | $^{136}$Xe | proposed | | $2.7\cdot10^{4}$ | 13 | 100 | 90 | 20 | -1.2,1.2 | 76 | 2 312 | $3.5\cdot10^{-4}$ | $8.0\cdot10^{-1}$ | $1.1\cdot10^{27}$ | 17-72 |
| *Large liquid scintillators (Sec. VI.D)* | | | | | | | | | | | | | | | |
| KLZ-400 | $^{136}$Xe | completed | Kamioka | $2.5\cdot10^{3}$ | 44 | 100 | 97 | 114 | 0,1.4 | 42 | 450 | $9.9\cdot10^{-3}$ | $4.4\cdot10^{+0}$ | $3.3\cdot10^{25}$ | 95-408 |
| KLZ-800 | $^{136}$Xe | taking data | Kamioka | $5.0\cdot10^{3}$ | 58 | 100 | 97 | 114 | 0,1.4 | 42 | 1 173 | $1.4\cdot10^{-3}$ | $1.6\cdot10^{+0}$ | $4.0\cdot10^{26}$ | 28-118 |
| KL2Z | $^{136}$Xe | proposed | Kamioka | $6.7\cdot10^{3}$ | 80 | 100 | 97 | 60 | 0,1.4 | 42 | 2 176 | $3.0\cdot10^{-4}$ | $6.5\cdot10^{-1}$ | $1.1\cdot10^{27}$ | 17-71 |
| SNO+I | $^{130}$Te | construction | SNOLAB | $1.0\cdot10^{4}$ | 20 | 100 | 97 | 80 | -0.5,1.5 | 62 | 1 232 | $7.8\cdot10^{-3}$ | $9.7\cdot10^{+0}$ | $1.8\cdot10^{26}$ | 31-144 |
| SNO+II | $^{130}$Te | proposed | SNOLAB | $5.1\cdot10^{4}$ | 27 | 100 | 97 | 57 | -0.5,1.5 | 62 | 8 521 | $5.7\cdot10^{-3}$ | $4.8\cdot10^{+1}$ | $5.7\cdot10^{26}$ | 17-81 |
| *Cryogenic calorimeters (Sec. VI.E)* | | | | | | | | | | | | | | | |
| CUORE | $^{130}$Te | taking data | LNGS | $1.6\cdot10^{3}$ | 100 | 88 | 92 | 3.2 | -1.4,1.4 | 84 | 1 088 | $9.1\cdot10^{-2}$ | $9.9\cdot10^{+1}$ | $5.1\cdot10^{25}$ | 58-270 |
| CUPID-0 | $^{82}$Se | completed | LNGS | $6.2\cdot10^{1}$ | 100 | 81 | 86 | 8.5 | -2,2 | 95 | 41 | $2.8\cdot10^{-2}$ | $1.2\cdot10^{+0}$ | $4.4\cdot10^{24}$ | 283-551 |
| CUPID-Mo | $^{100}$Mo | completed | LSM | $2.3\cdot10^{1}$ | 100 | 76 | 91 | 3.2 | -2,2 | 95 | 15 | $1.7\cdot10^{-2}$ | $2.5\cdot10^{-1}$ | $1.7\cdot10^{24}$ | 293-500 |
| CROSS | $^{100}$Mo | construction | LSC | $4.8\cdot10^{1}$ | 100 | 75 | 90 | 2.1 | -2,2 | 95 | 31 | $2.5\cdot10^{-2}$ | $7.6\cdot10^{-3}$ | $4.9\cdot10^{25}$ | 54-93 |
| CUPID | $^{100}$Mo | proposed | LNGS | $2.5\cdot10^{3}$ | 100 | 79 | 90 | 2.1 | -2,2 | 95 | 1 717 | $2.3\cdot10^{-4}$ | $4.0\cdot10^{-1}$ | $1.1\cdot10^{27}$ | 12-20 |
| AMORE | $^{100}$Mo | proposed | Yemilab | $1.1\cdot10^{3}$ | 100 | 82 | 91 | 2.1 | -2,2 | 95 | 760 | $2.2\cdot10^{-4}$ | $1.7\cdot10^{-1}$ | $6.7\cdot10^{26}$ | 15-25 |
| *Tracking calorimeters (Sec. VI.F)* | | | | | | | | | | | | | | | |
| NEMO-3 | $^{100}$Mo | completed | LSM | $6.9\cdot10^{1}$ | 100 | 100 | 11 | 148 | -1.6,1.1 | 42 | 3 | $9.3\cdot10^{-1}$ | $3.0\cdot10^{+0}$ | $5.6\cdot10^{23}$ | 505-866 |
| SuperNEMO-D | $^{82}$Se | construction | LSM | $8.5\cdot10^{1}$ | 100 | 100 | 28 | 83 | -4.2,2.4 | 64 | 15 | $2.1\cdot10^{-2}$ | $5.0\cdot10^{-1}$ | $8.6\cdot10^{24}$ | 201-391 |
| SuperNEMO | $^{82}$Se | proposed | LSM | $1.2\cdot10^{3}$ | 100 | 100 | 28 | 72 | -4.1,2.8 | 54 | 185 | $5.4\cdot10^{-3}$ | $9.8\cdot10^{-1}$ | $7.8\cdot10^{25}$ | 67-131 |

# Future of double-beta decay search

- Sensitivity goals: Cover $m_{\beta\beta} \sim 17$ meV (IH)

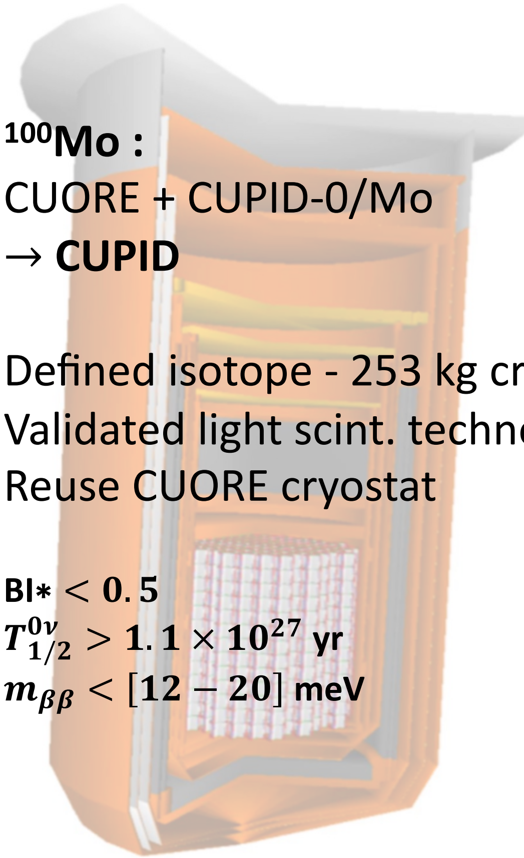
*$[\mathbf{cps/(FWHM.t.yr)}]$
** + KamLAND2-Zen + NEXT-HD



**$^{76}$Ge :**
GERDA + MAJORANA
→ **LEGEND**

200 kg in prep. @ LNGS
1000 kg lab. selection
LAr veto + mass /det.

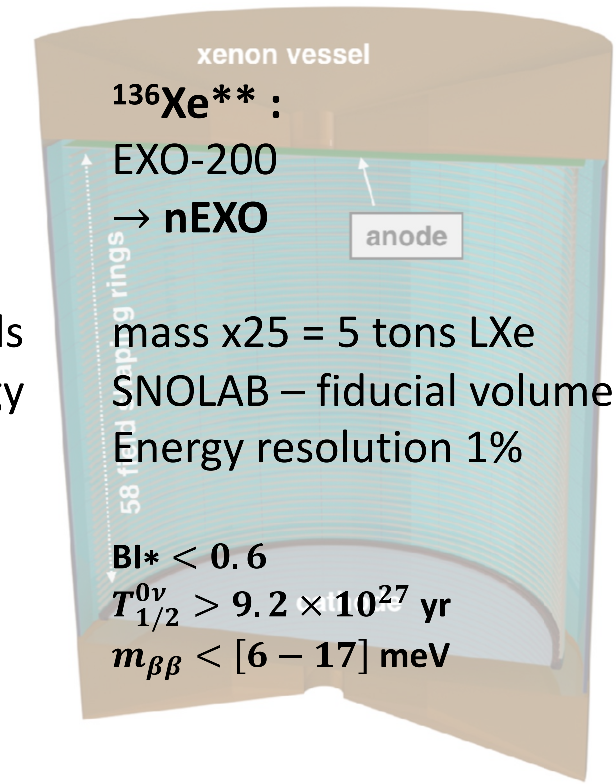
**BI*** $< \mathbf{0.6} / < \mathbf{0.1}$
$T^{0\nu}_{1/2} > \mathbf{0.9} / \mathbf{12} \times \mathbf{10^{27}}$ **yr**
$m_{\beta\beta} < [\mathbf{35-73}]/[\mathbf{10-20}]$ **meV**



**$^{100}$Mo :**
CUORE + CUPID-0/Mo
→ **CUPID**

Defined isotope - 253 kg cristals
Validated light scint. technology
Reuse CUORE cryostat

**BI*** $< \mathbf{0.5}$
$T^{0\nu}_{1/2} > \mathbf{1.1} \times \mathbf{10^{27}}$ **yr**
$m_{\beta\beta} < [\mathbf{12-20}]$ **meV**




**$^{136}$Xe** :**
EXO-200
→ **nEXO**

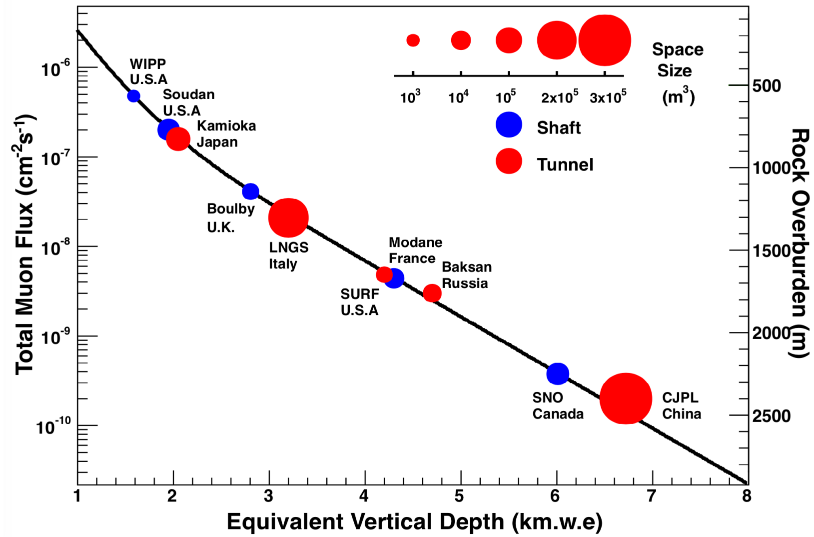
mass x25 = 5 tons LXe
SNOLAB – fiducial volume
Energy resolution 1%

**BI*** $< \mathbf{0.6}$
$T^{0\nu}_{1/2} > \mathbf{9.2} \times \mathbf{10^{27}}$ **yr**
$m_{\beta\beta} < [\mathbf{6-17}]$ **meV**

- Three major experiment in terms of mass/funding
  but many other alternative technology under development

# Candidate underground labs

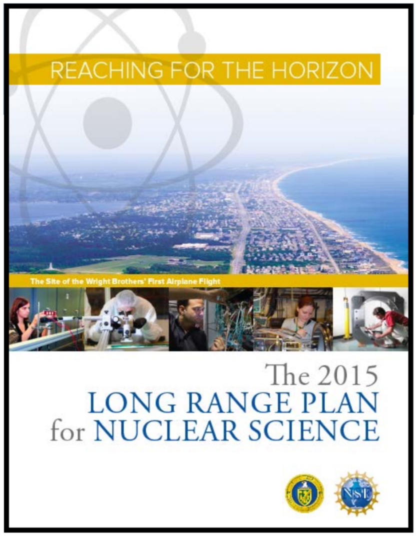
- **Europe:**
  - Feasibility studies of LEGEND-1000 at LNGS
  - LSC not deep enough
  - Not enough space at LSM




- **North America:**
  - Preference for SNOLAB in Canada (SURF not retained)
  - Active mine – new experimental hall dedicated to double-beta decay


- **China:**
  - Large hosting capacity at CJPL experimental hall built for CDEX (dark matter)

# Selection process in the US




"We recommend the timely development and deployment of a U.S.-led ton-scale neutrinoless double beta decay experiment."

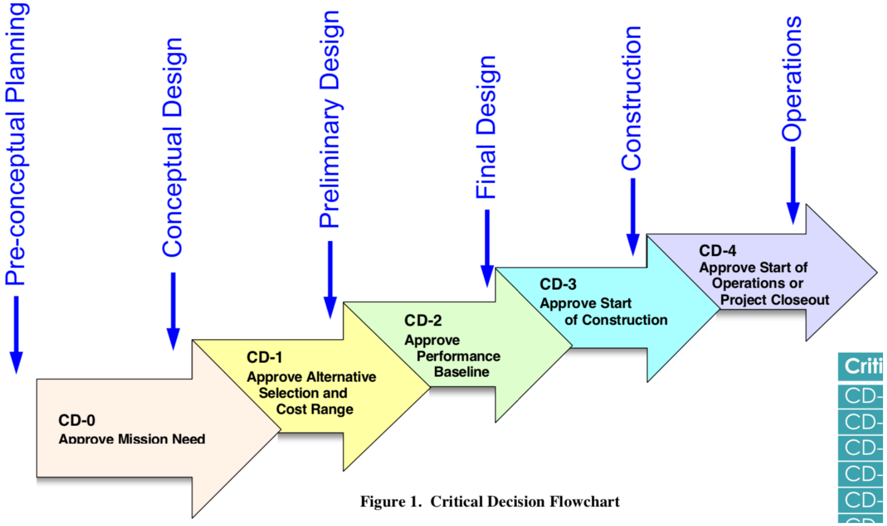
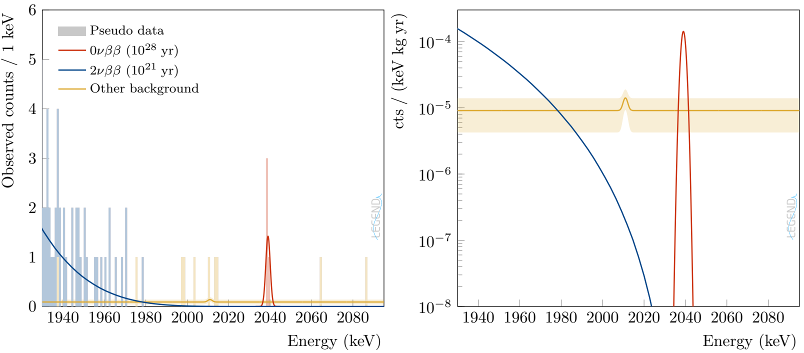



Figure 1. Critical Decision Flowchart

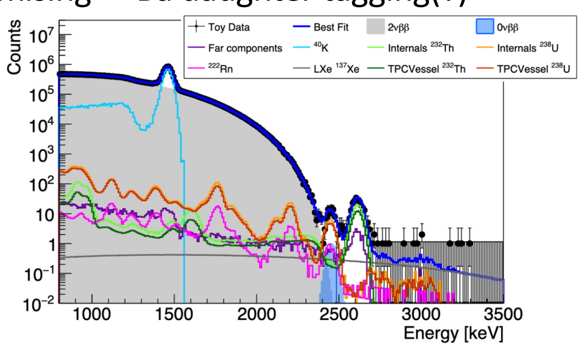
- **Three experiments seriously considered**
  - LEGEND-1k $^{76}$Ge – after LEGEND-200
  - nEXO $^{136}$Xe – after EXO-200
  - CUPID $^{100}$Mo – after CUORE
  - (?)
- **Support document**: « pCDR » (pre Conceptual Design Report)
  - LEGEND-1k : [2107.11462]
  - nEXO : [1805.11142] / [2106.16243]
  - CUPID : [1907.09376] / [2203.08386]
- **Budget**: Order of magnitude is ~[60-400] M$ [see DOE statement]
- **Selection** : unknown date
  **interplay with EU funding strategy**

# Sensitivity comparison with other isotopes

**Strength of the LEGEND-1000 proposal:**
- Quasi-background free at full exposure
- No known peaks near $Q_{\beta\beta}$



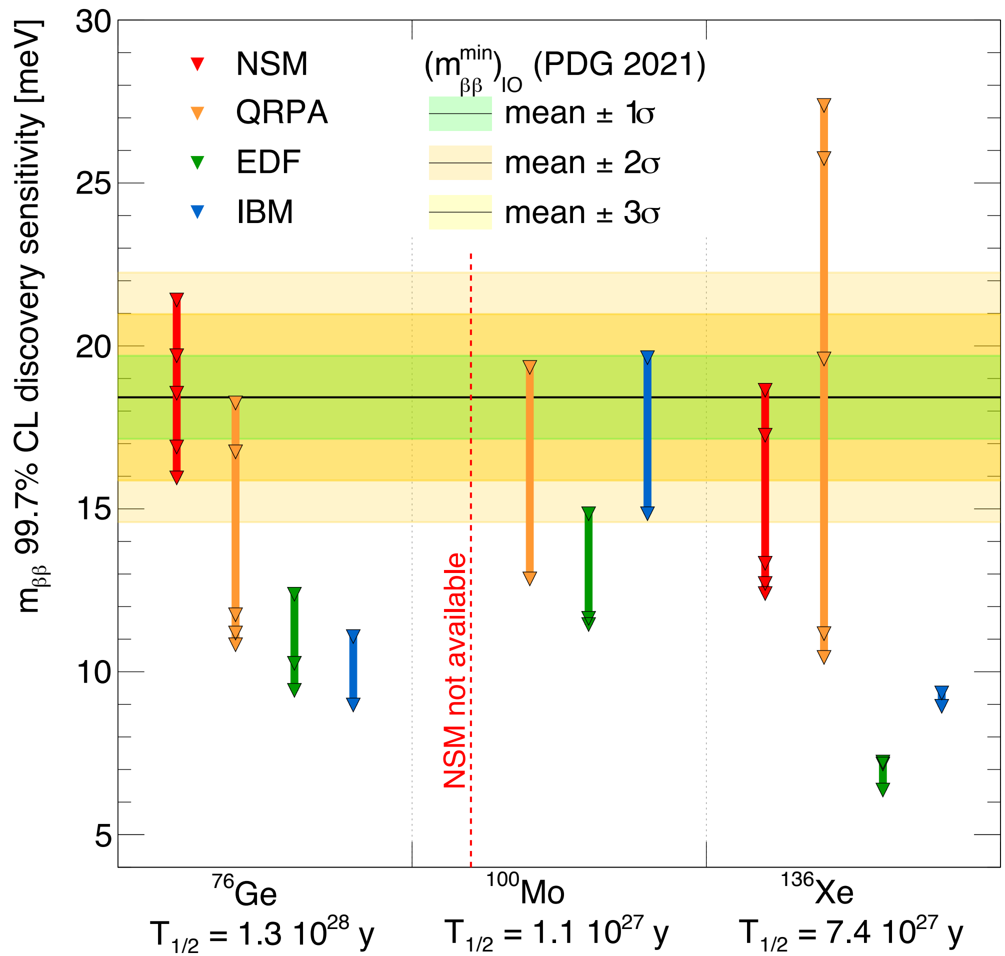

**Strength of the nEXO proposal:**
- Exposure (5 t) + fiducialization
- Promising $^{136}$Ba daughter tagging(?)




**Strength of the CUPID proposal:**
- Existing cryogenic infrastructure
- Demonstrated bkg reduction technique w.r.t. CUORE

**$m_{\beta\beta}$ inverted ordering band**

[2107.11462]



# Conclusions

- **Double beta decay experiments are probing particle physics symmetries with highly sensitive detectors**
  - ➢ We may rather refer them as
    'experiment searching for creation of matter without antimatter'

- **Neutrinoless double beta decay community is in an exciting phase!**
  - ➢ Many highly sensitive experiments have recently delivered results
  - ➢ There is a roadmap to increase sensitivities by two order of magnitude on $T_{1/2}^{0\nu}$
    Future projects rely on different isotopes

- **The community is moving toward ton-scale projects**
  - ➢ with ultra-low background, high energy resolution
  - ➢ offering many possibility to probe rare events connected to new physics

# Can a neutrino be its own antiparticle?

Majorana neutrinos: a bridge between matter and antimatter [2202.01787] (Vissani, et al.)

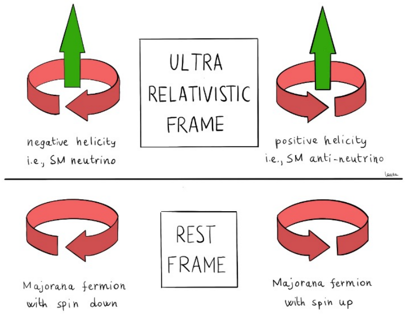



FIG. 2 Artistic illustration of the relation between the neutrino and antineutrino helicity, which is given by the projection of the spin (red arrow) onto the momentum (green arrow). The helicity distinguishes neutrinos from antineutrinos in the ultra-relativistic limit (top panel). However, in the rest frame the neutrino and antineutrino are two spin states of the same particle (lower panel). Image courtesy of Laura Manenti.

### 1. Majorana neutrinos: a bridge between matter and antimatter

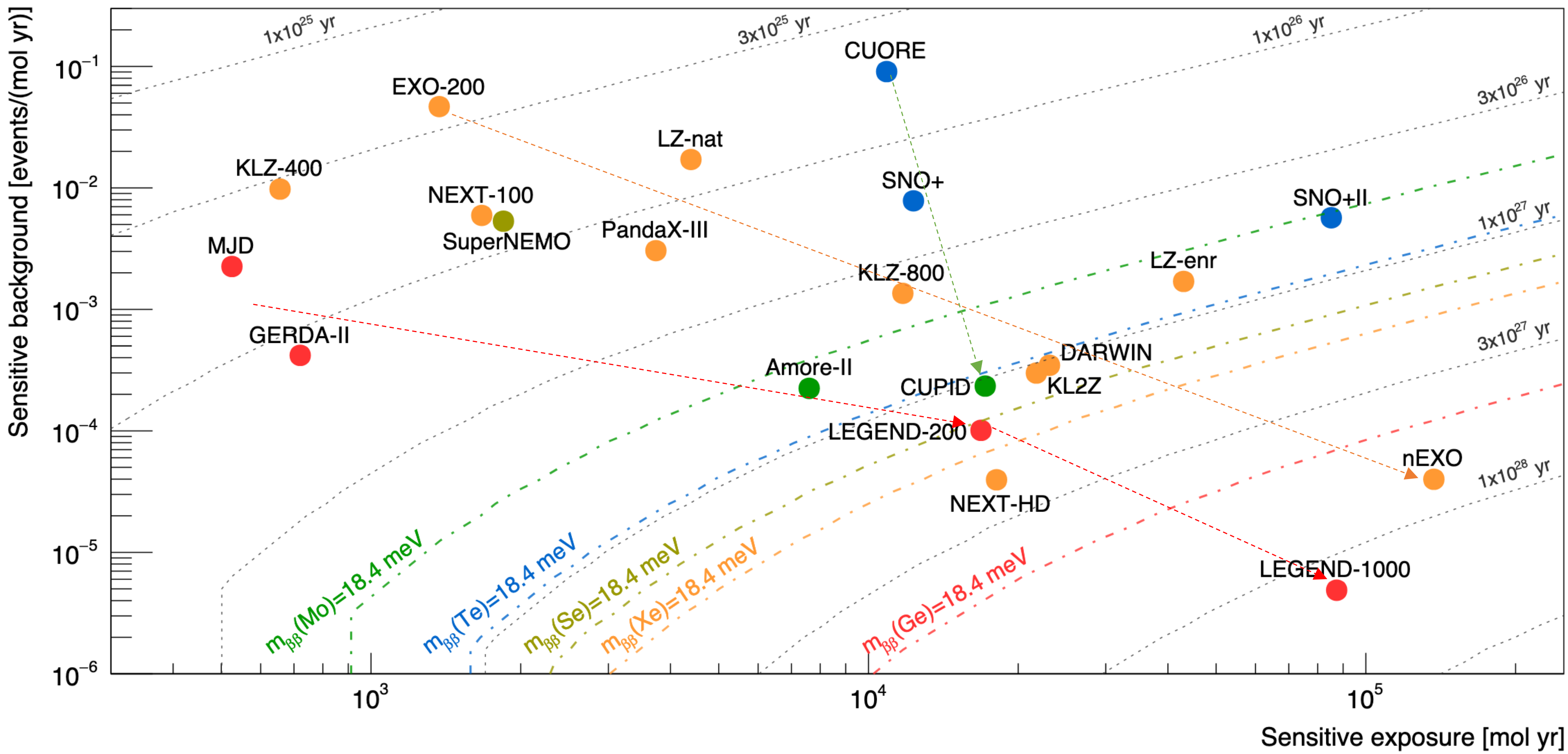
Majorana's neutrinos are both particles and antiparticles. This often-heard statement is far from being trivial. To clarify its meaning, it is useful to remember that neutrinos are particles with spin 1/2, i.e. fermions. Fermions constitute matter (and antimatter), whereas bosons constitute forces. In the context of the Standard Model of Glashow, Weinberg and Salam, neutrinos along with all other particles are distinct from their antiparticles. Such a difference is evident for charged fermions, but what about for neutral ones?

In fact, Standard-Model neutrinos are neutral. They have hypercharge but this is broken spontaneously, leaving only two ways to distinguish neutrinos from antineutrinos. The first way concerns the helicity of the particle: it is negative for the neutrino and positive for the antineutrino. The second way is based on the charged lepton that accompanies charged lepton interactions: for example, in all observed $\beta^{\mp}$-decays, the (anti)neutrino is co-produced with a particle of (negative) positive charge.

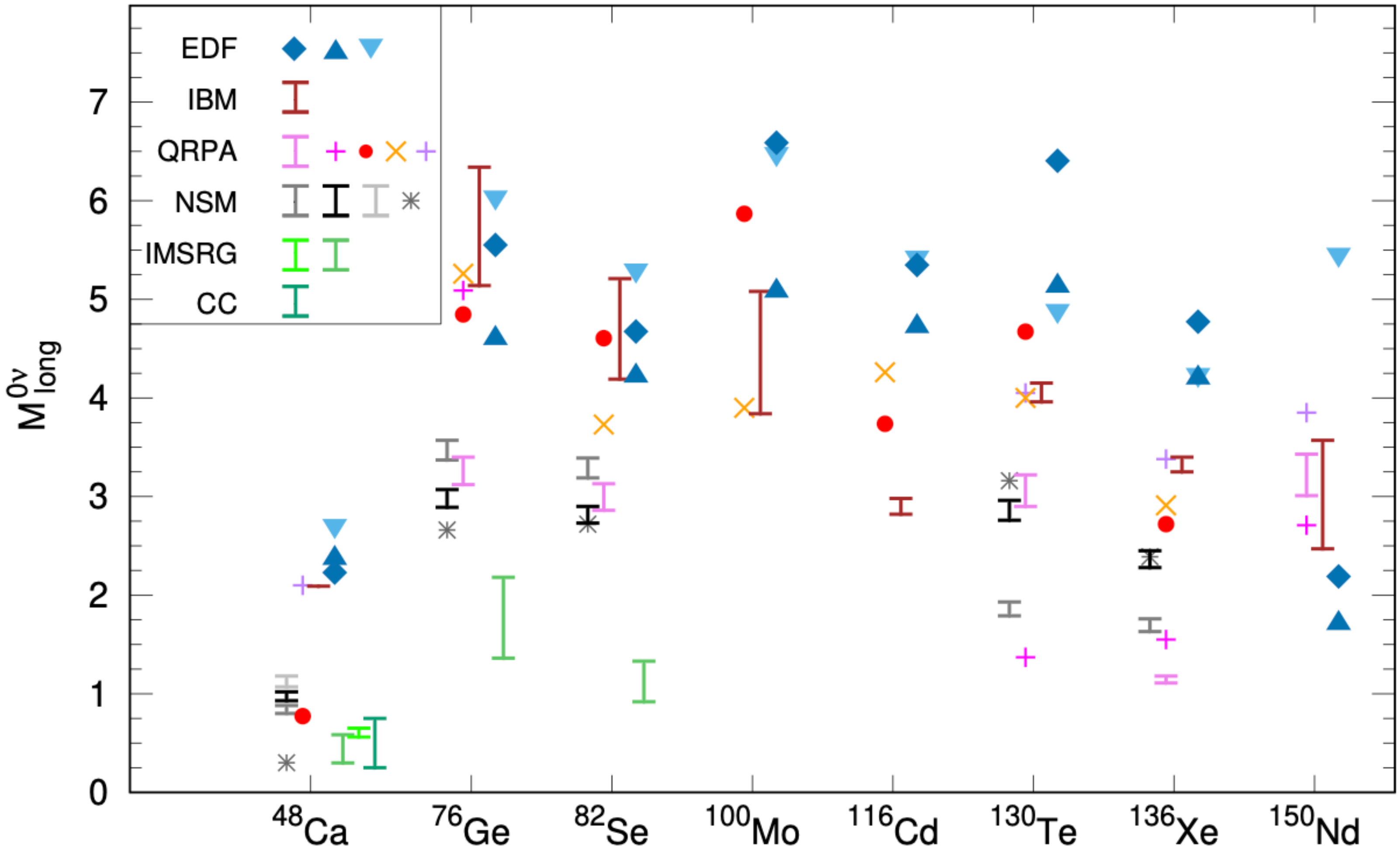
The neutrino's helicity is a consequence of the chiral structure of the weak interactions — formally corresponding to the presence of the $P_L$ projector in the charged interactions — but only provided that the neutrino mass is exactly zero. If neutrinos are massive, helicity coincides with chirality only in the ultra-relativistic limit. All experimental observations related to weak interactions have been made, and can be made, only on ultra-relativistic neutrinos. However, as a thought experiment, we can consider observing a neutrino and an antineutrino in their rest frame, whose existence is guaranteed by their tiny masses measured through oscillation experiments. In this frame, the momentum and helicity of the neutrino and antineutrino are both zero and, in the absence of additional quantum numbers, the two particles can differ only by the orientation of their spin. Therefore, symmetry under rotations implies that the two states must be the same particle. In conclusion, the structure of the Standard Model, together with the hypothesis that neutrinos have mass, suggests that the neutrino and the antineutrino are the very same particle in the rest frame. The point is summarised graphically in Fig. 2 and discussed also by Dell'Oro *et al.* (2016).

# Technological risk evaluation

- **Large gap in exposure (horizontal axis)**
  = potential unknowns on the experiment functioning / long term robustness / …
- **Large gap on the background (vertical axis)**
  = potential unknowns on the radiopurity / ignored background components / …



# Nuclear Matrix Element status




New NSM, IBM and QRPA calculations have been performed in 2020

Ab-initio (first principles) calculations now available for $^{76}$Ge and $^{82}$Se!