# Experimental Searches for Neutrinoless Double-Beta Decays and Prospects

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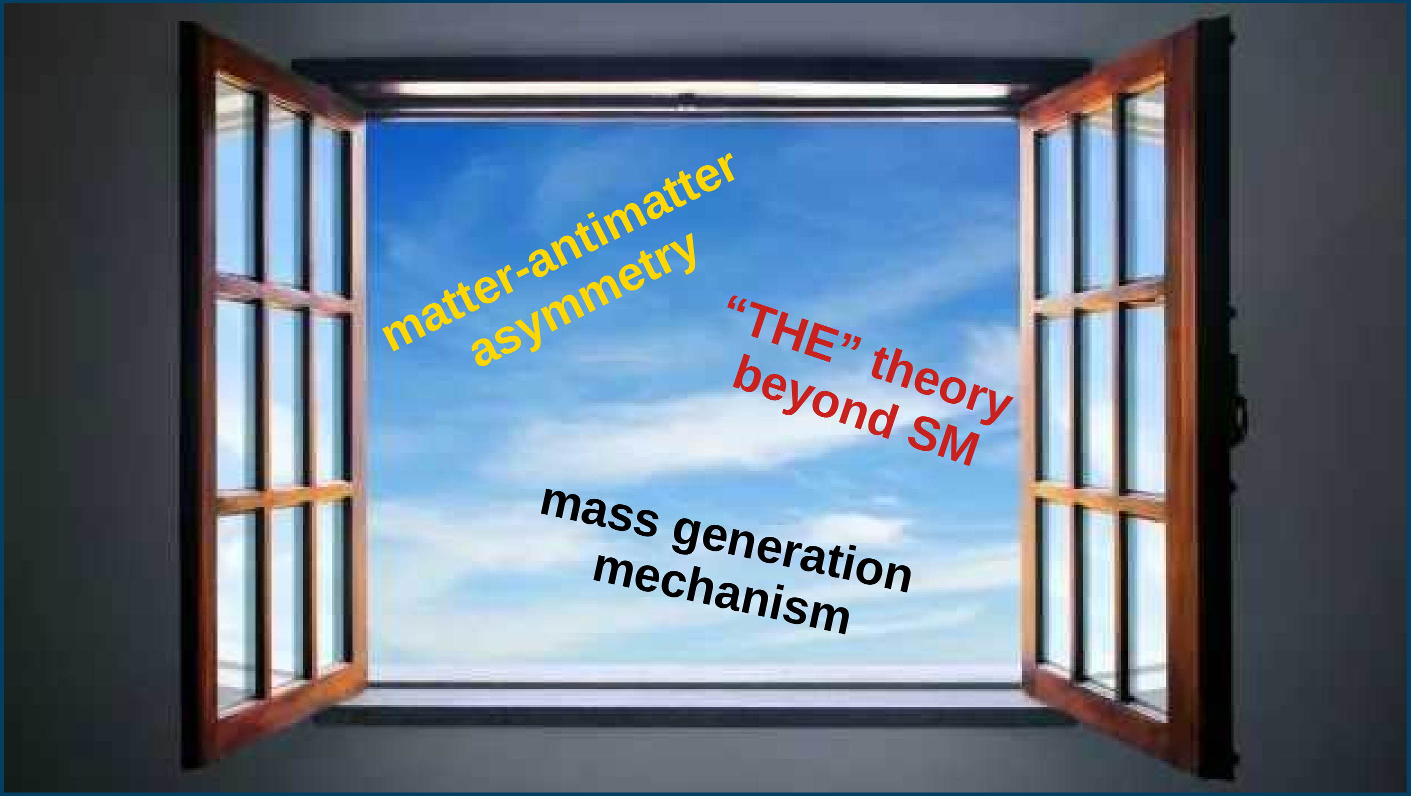
FBCP2021 - Shanghai

# a window opened to the unknown

neutrino oscillations

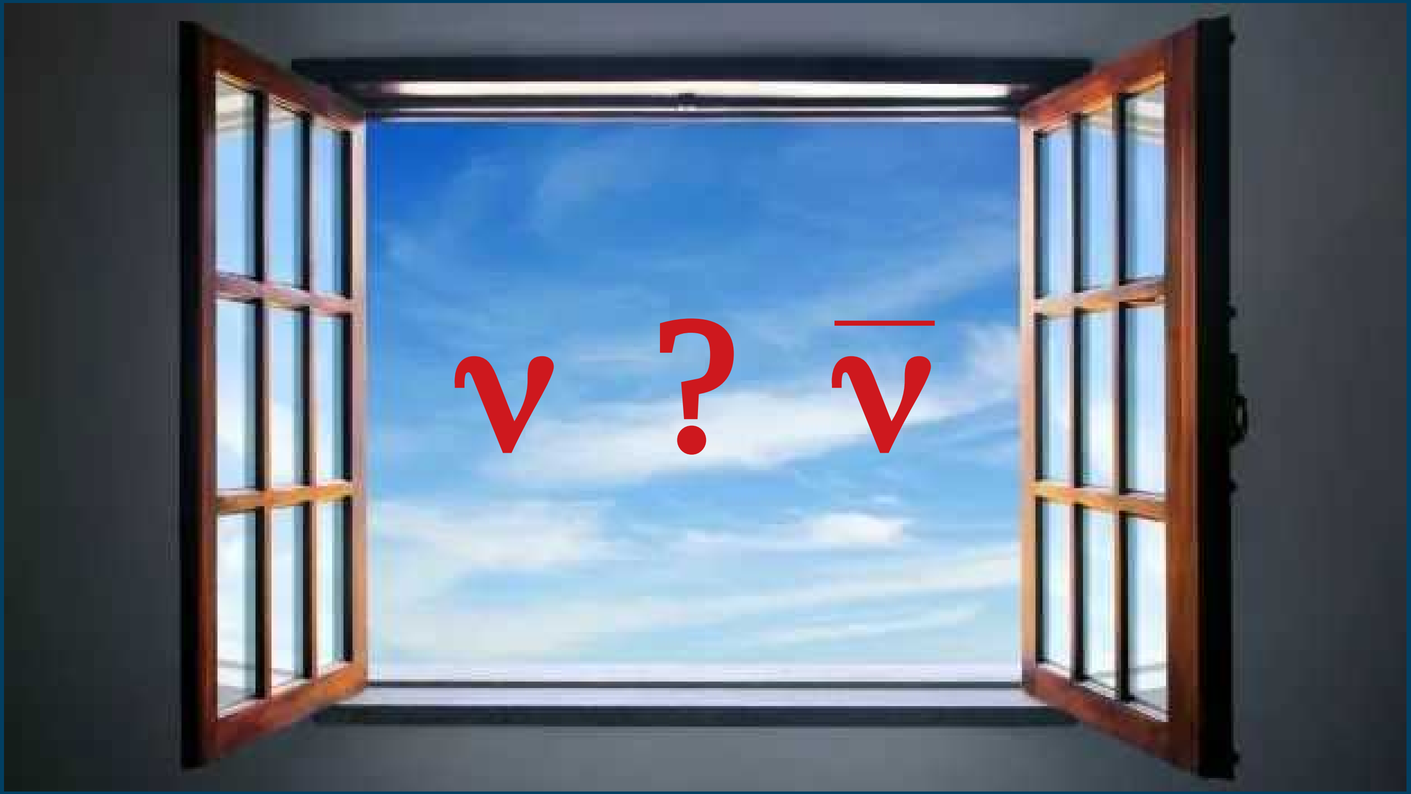
only clear failure of Standard Model

neutrino masses open a new window into Physics



# a window opened to the unknown

neutrino oscillations → only clear failure of Standard Model → neutrino masses open a new window into Physics



# Majorana ν

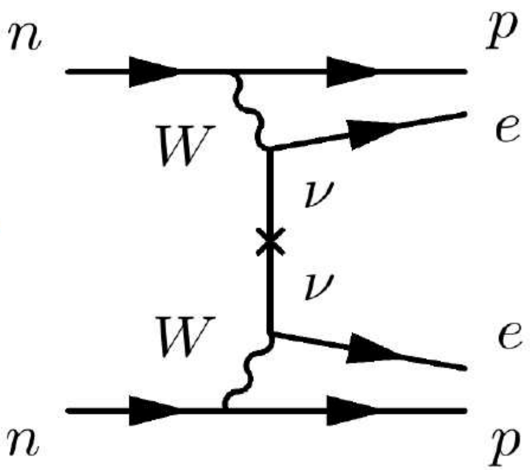
- experimental observations ν ≠ $\bar{\nu}$ → just helicity
- a number of *good* theoretical motivations for a self-conjugated massive **Majorana** ν
- only one experimental viable way to prove it

**Neutrinoless Double Beta Decay**

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

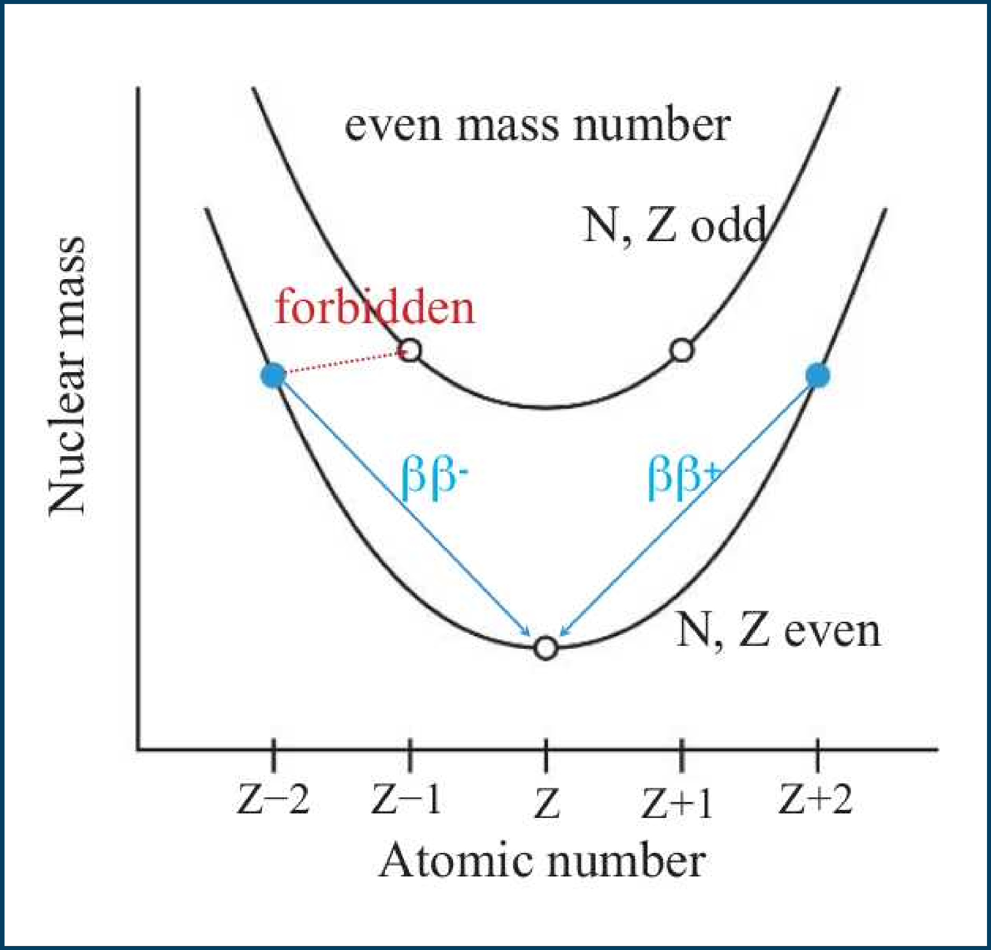
**ΔL = 2**

**Δ(B-L) = -2**



# ββ decay

$$\left(A,Z\right)\rightarrow\left(A,Z+2\right)+something$$




a number of isotopes **A-Z even** reach stability only through ββ decay

these are the **ββ candidates**

a small group of them have high transition energies $Q_{\beta\beta} > 1$ MeV ... and other nice features

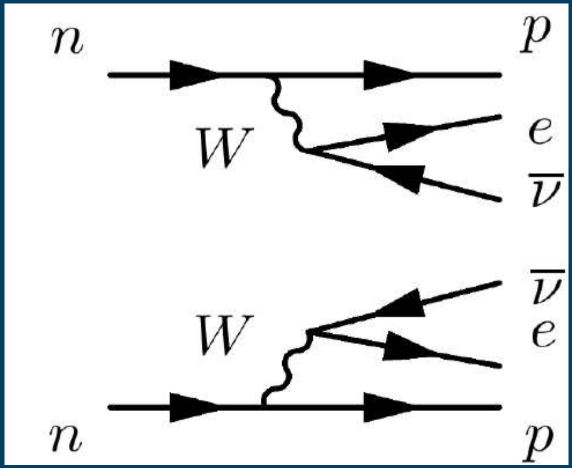
these are the **golden ββ candidates**

$^{76}$Ge $^{100}$Mo $^{130}$Te $^{136}$Xe

# $2\nu2\beta$ - $0\nu2\beta$

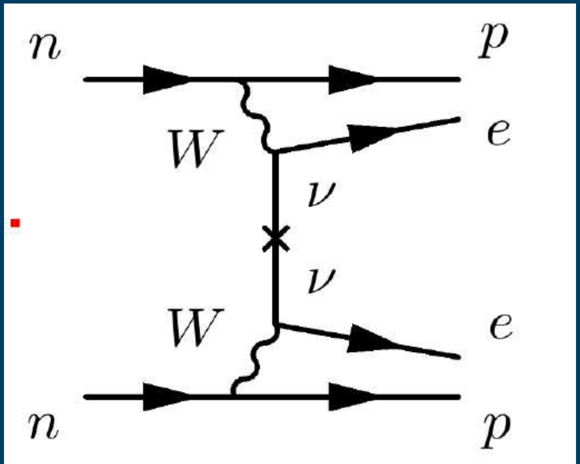
$$(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}$$

- **2νββ decay** - observed, rare decay
- 2nd weak process allowed by SM
- measured $T_{1/2} > 10^{18}$ y




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

- **0νββ decay –** ΔL=2 process
- forbidden in Standard Model
- light mass Majorana ν exchange or other non SM diagrams

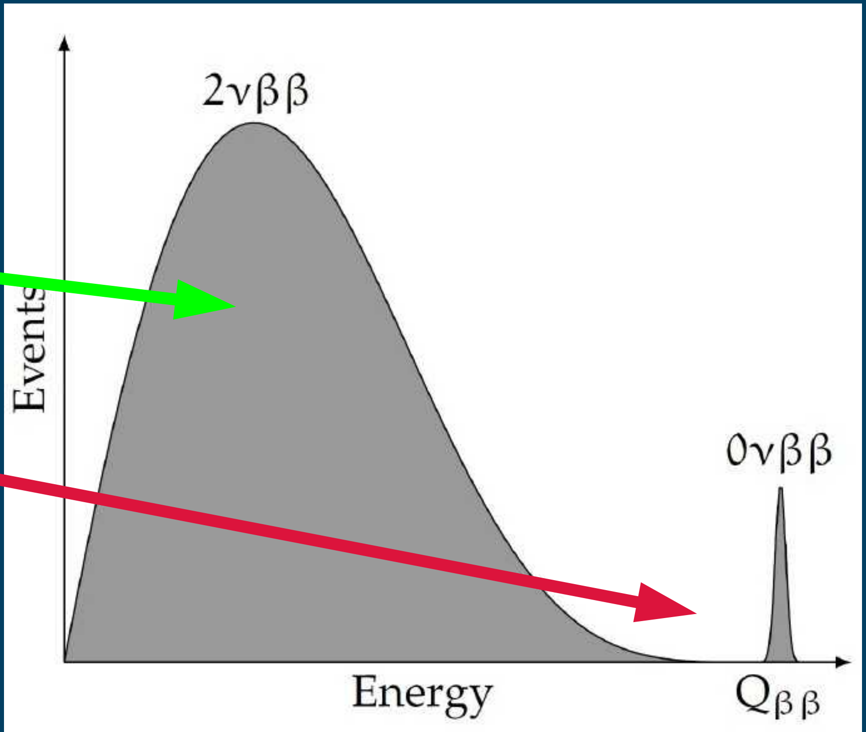



**… + other diagrams**

# $0\nu2\beta$ SIGNATURE

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

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




**main signature → a peak at $Q_{\beta\beta}$**

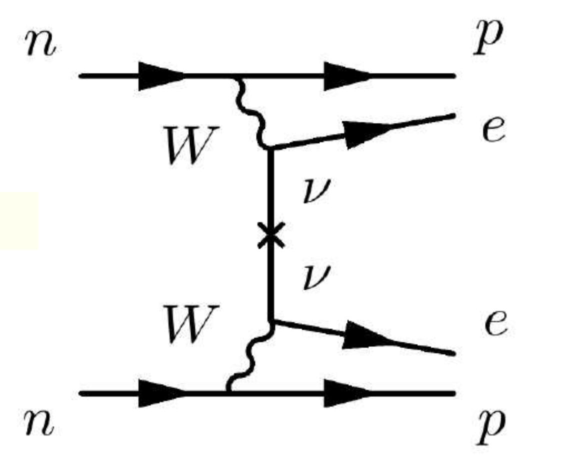
- typically $Q_{\beta\beta}$ ~1-3 MeV (the higher, the lower is the background of spurious events that mimic the signal)
- 2 $e^-$ have a short range → detection of their sum energy

**processes spoiling the signal and their mitigation:**

- $2\nu\beta\beta$ → **energy resolution**
- background → **particle identification** ($\alpha$ rejection, SS vs MS ...)
  → daughter identification ...

# $0\nu 2\beta$ half-life

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}(Q,Z) \cdot g_A^4 \left|M^{0\nu}\right|^2 \cdot m_{ee}^2$$




Standard (dominant) Mechanism:
**exchange of a light Majorana ν**

# $0\nu2\beta$ half-life

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}(Q,Z)\cdot g_A^4\left|M^{0\nu}\right|^2\cdot m_{ee}^2$$

experimental result
(upper limit)

nuclear calculations

new Physics
(mass)

**decay observation implies:**

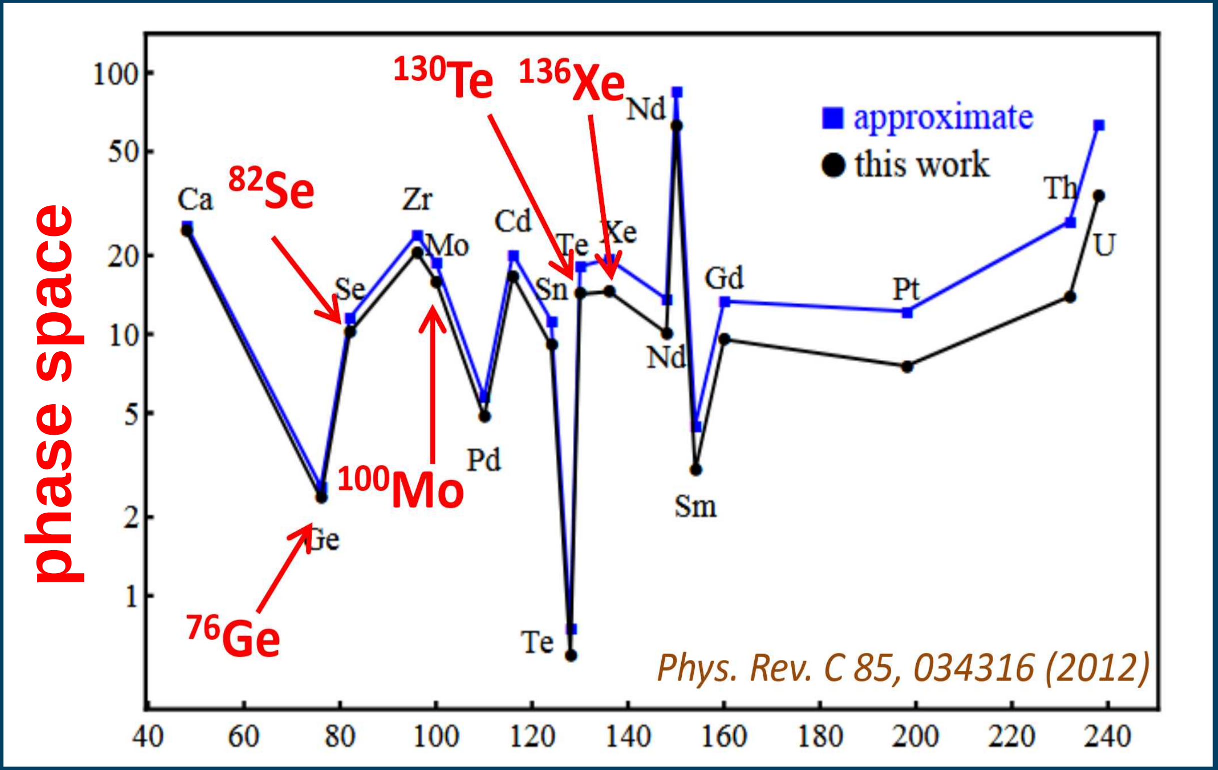
- DISCOVERY
- measurement of the half-life
- $\nu$ in a Majorana particle
- $m_{ee}$ is measured

# $0\nu2\beta$ half-life

$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu}(Q,Z)\cdot g_A^4\left|M^{0\nu}\right|^2\cdot m_{ee}^2$$

**phase space**

- is computed
- favors high $Q_{\beta\beta}$ isotopes



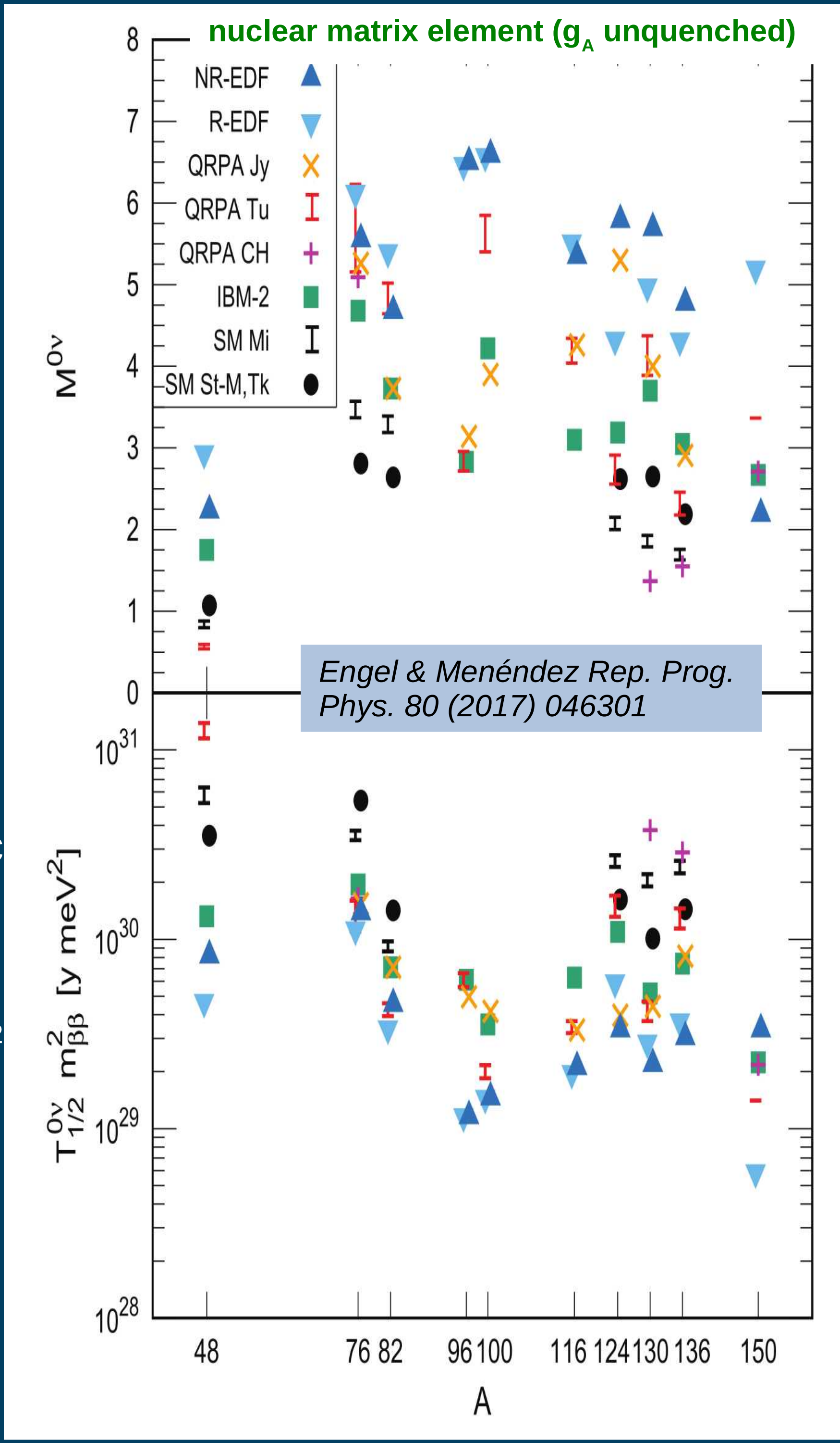

**phase space** is and additional motivation for chosing high $Q_{\beta\beta}$ isotopes (the stronger motivation is background suppression)

# $0\nu2\beta$ half-life

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}(Q,Z)\cdot g_A^4\left|M^{0\nu}\right|^2\cdot m_{ee}^2$$

**nuclear matrix element -** is evaluated on the basis of different nuclear models

- model dependent
- **"quenched $g_A$"** ? used to correct the systematic over-predictions of $\beta$ and $2\nu\beta\beta$ measured rates
- **does it apply also to $0\nu\beta\beta$** ? (if so predicted $T_{1/2}$ underestimated by a factor 2-6)



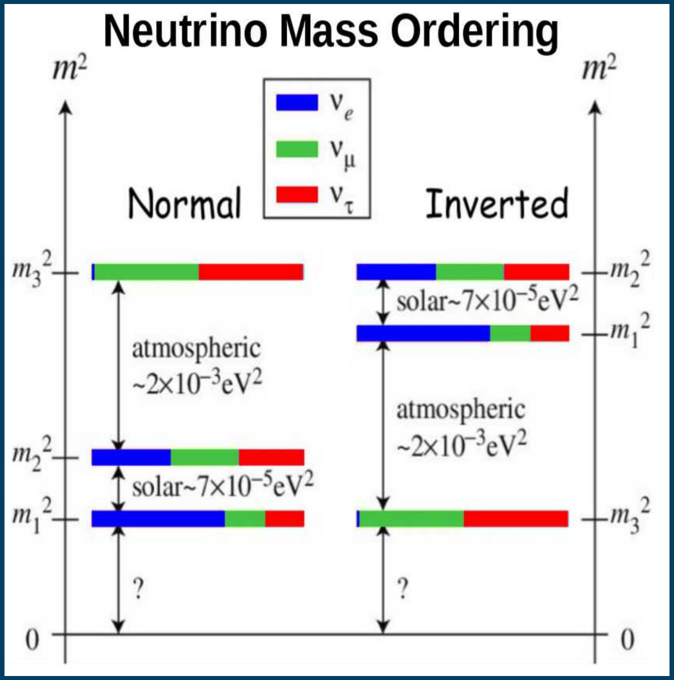
# $0\nu 2\beta$ half-life

$$\left(T^{0\nu}_{1/2}\right)^{-1} = G^{0\nu}(Q,Z)\cdot g_A^4 \left|M^{0\nu}\right|^2 \cdot m_{ee}^2$$

$$m_{ee} = \sum_k U_{ek}^2 m_i = c_{12}^2 c_{23}^2 m_1 + s_{12}^2 c_{13}^2 e^{i\alpha} m_2 + s_{13}^2 e^{i\beta} m_3$$

**3 neutrinos eigenstates + mixing**

- 3 mixing angles → $c_{ij}$ $s_{ji}$
- 2 mass differences → $\Delta m^2_{solar}$ $\Delta m^2_{atm}$
- 2 phases → $\alpha$, $\beta$ (Majorana phases)
- mass ordering → lightest neutrino mass



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**3 neutrinos eigenstates + mixing**

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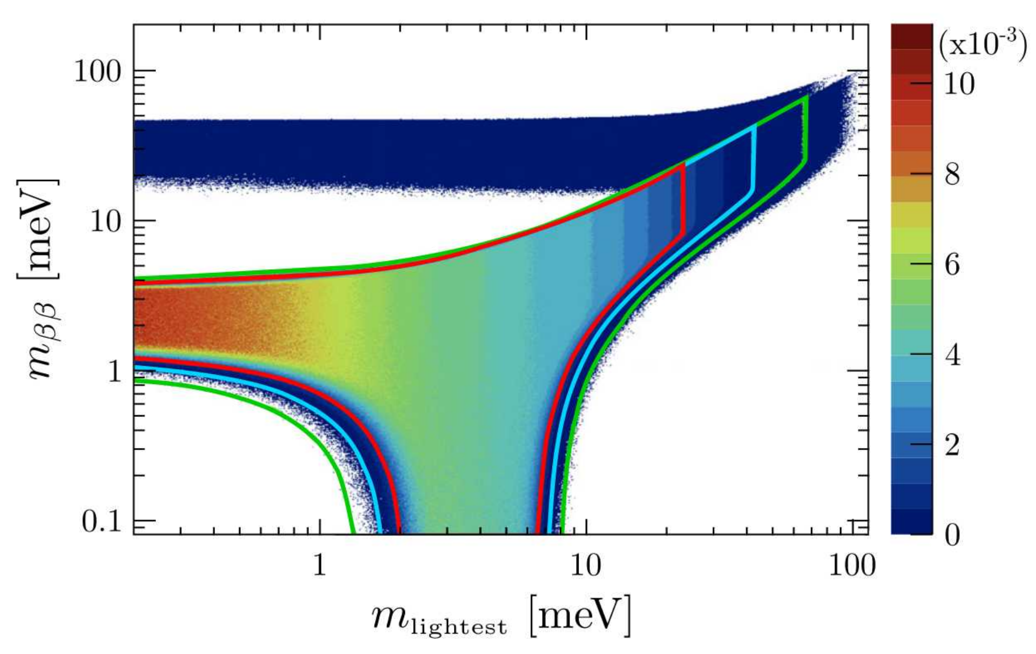



→ $m_{ee} = f(\alpha, \beta, m_{lightest})$

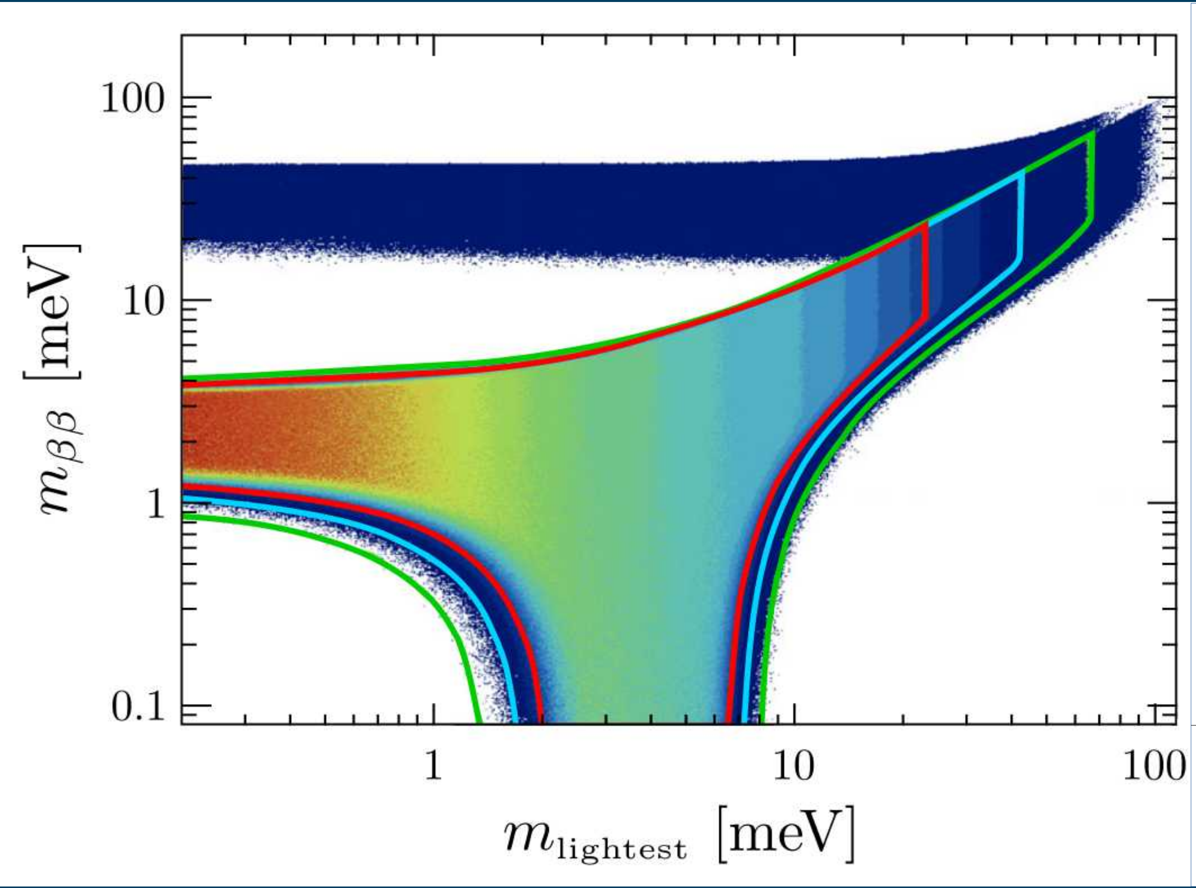
+

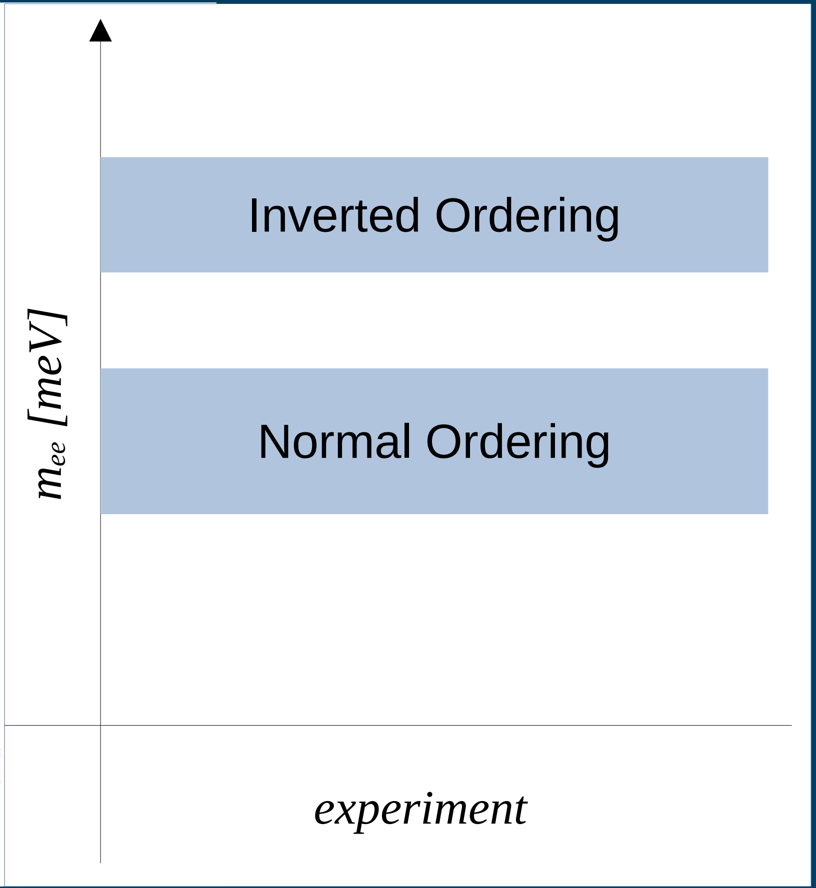
*Vissani et al. Phys Rev D 100, 073003 (2019)*
*probability distribution for $m_{ee}$ obtained using the Likelihood for Σ*

# $0\nu2\beta$ ranking experiments

On result basis:

- **$T_{1/2}$** measurements can't be compared directly, the conversion into **$m_{ee}$** is not trivial because of the uncertainties in NME



# 0ν2β ranking experiments

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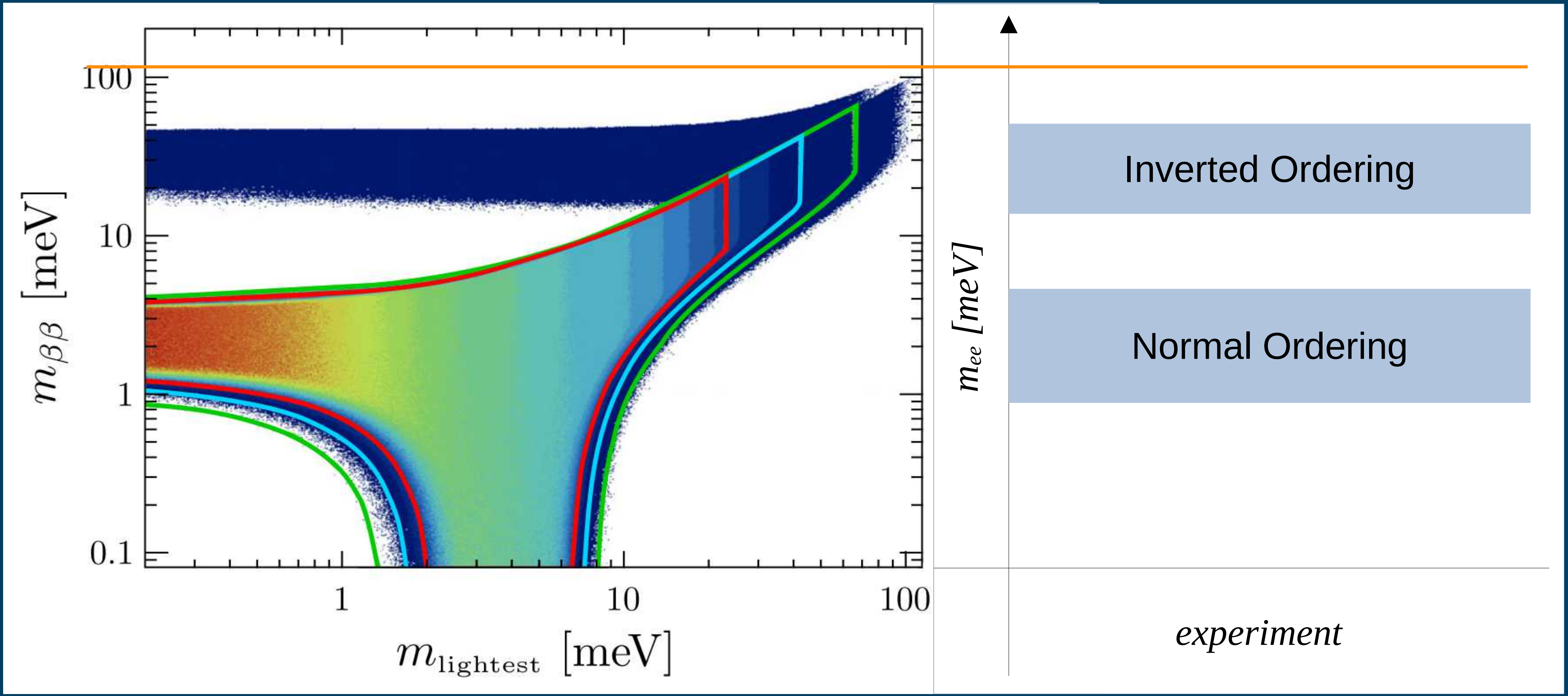
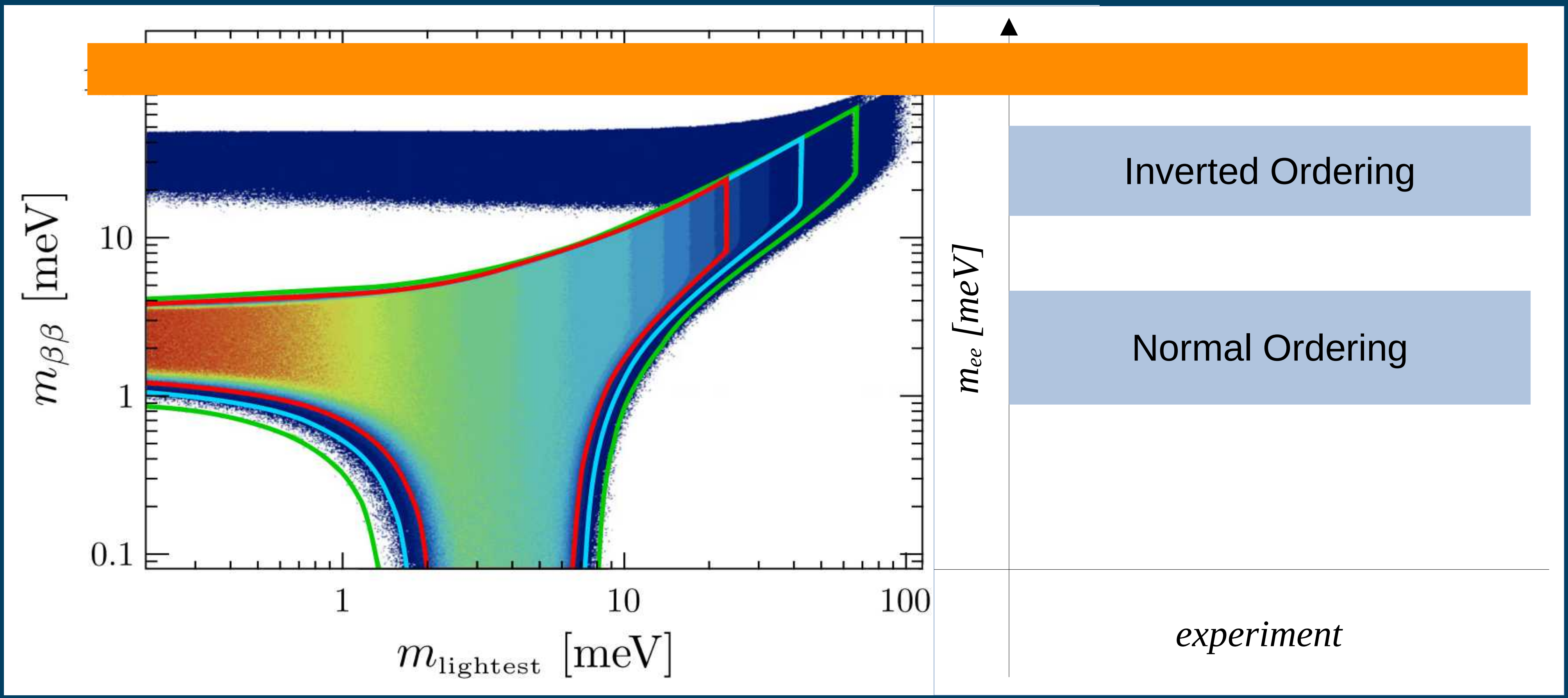


# $0\nu2\beta$ ranking experiments

On result basis:

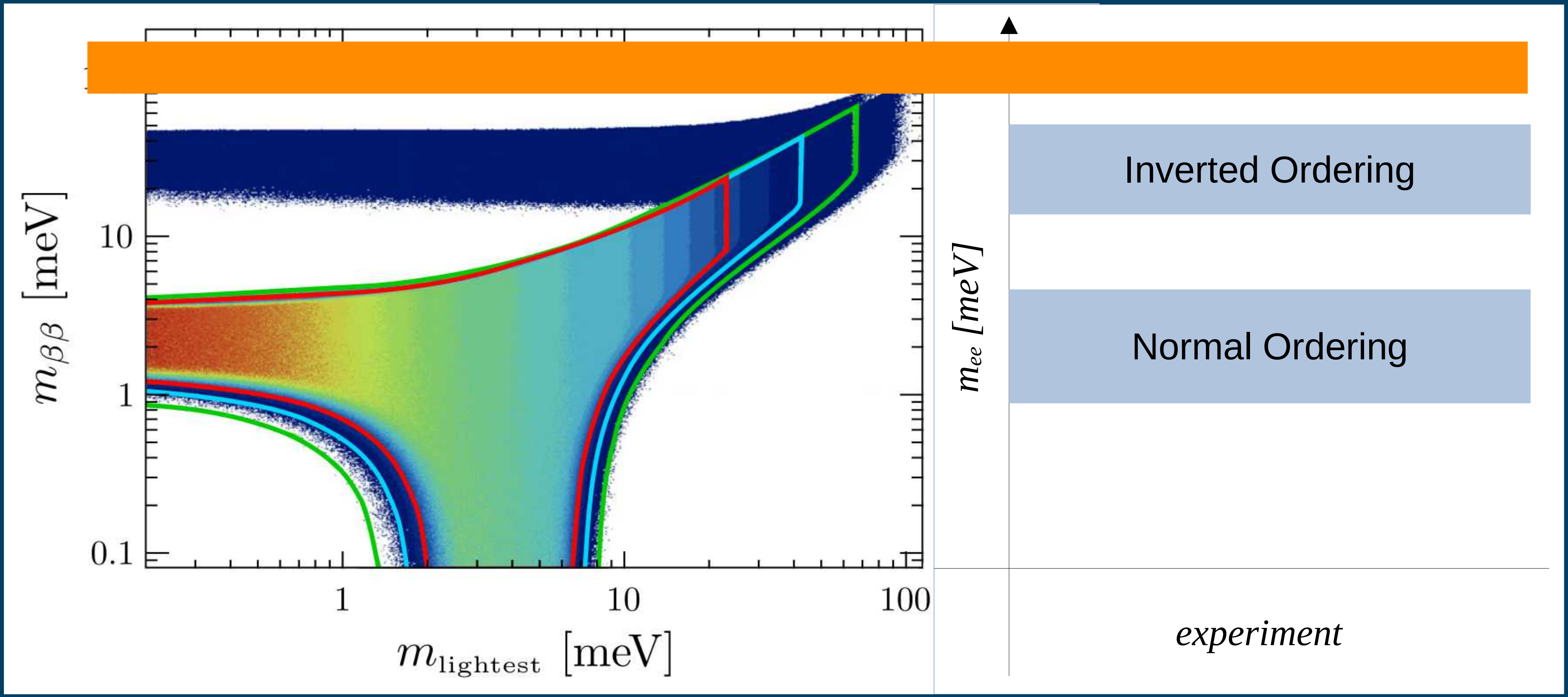
- a pragmatic solution is to convert **$T_{1/2} \rightarrow m_{ee}$** range and compare the range



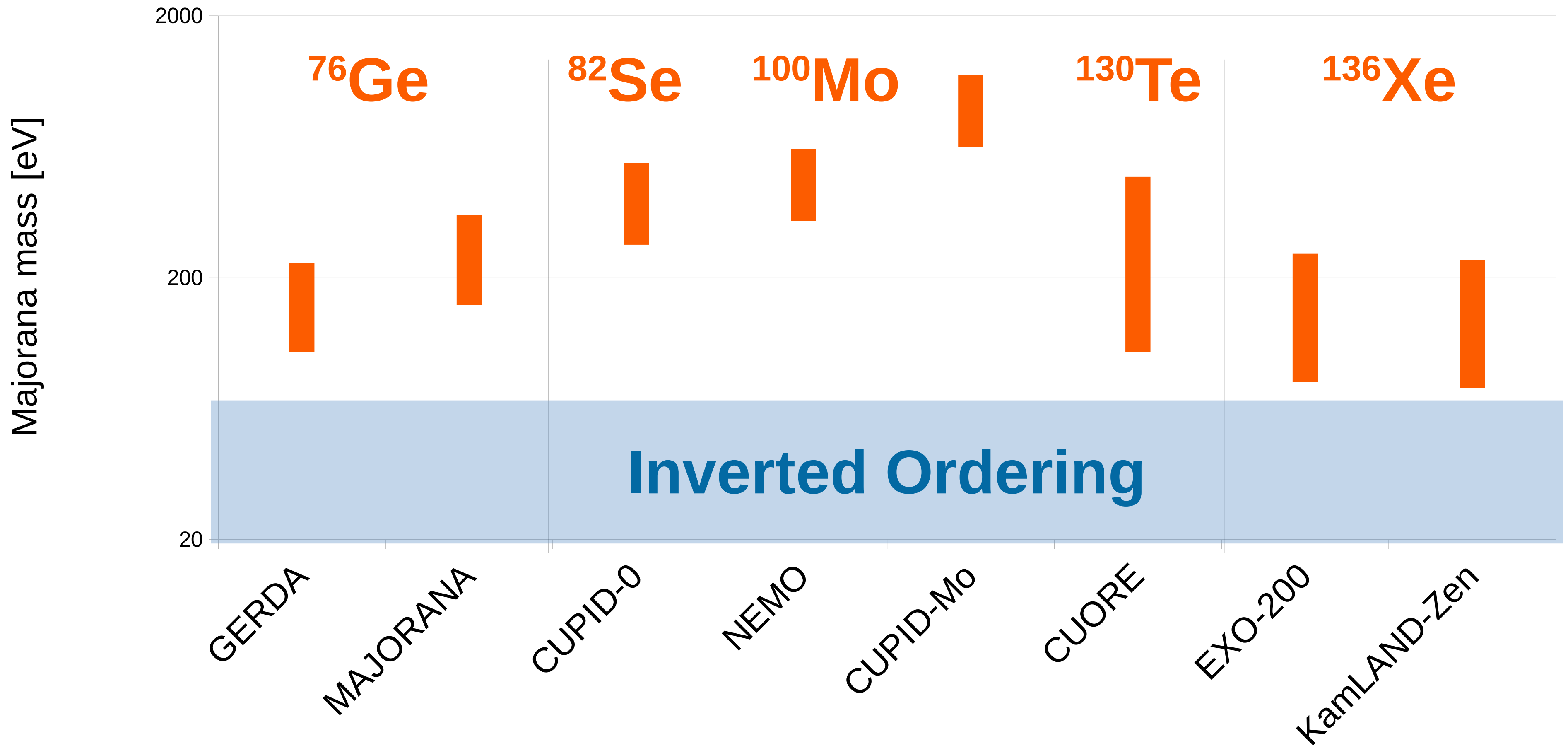
# 0ν2β ranking experiments

On result basis:

- neglect correlations (a by model comparison could be better) forget that sometimes a Nuclear Model works better for one isotope



# $m_{ee}$ intervals from $T_{1/2}$




*this is a personal selection of high sensitivity running or just closed expts.*

# $0\nu2\beta$ ranking experiments

On sensitivity basis (future expts):

- sensitivities or discovery potentials are defined by 3 parameters
    - **Mass Time = Exposure**
    - **Energy Resolution** (often extrapolated ..)
    - **Background** (guessed, desired …)
- extrapolations, guess … can be strongly biased !
- robustness of hypotheses on the achievement of energy resolution and background is hard to judge

  → experiments with a long history of precursors, with clear strategies for background suppression are more reliable (but this is not a number !)

# $0\nu2\beta$ sensitivity $S_{0\nu}$

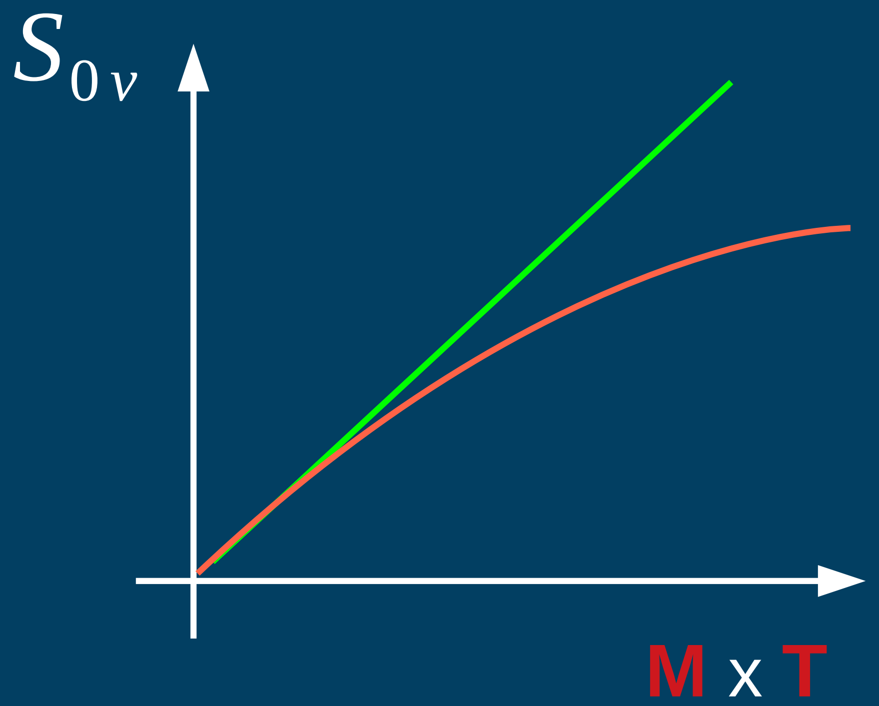
Half-life corresponding to the minimum detectable number of events over background at a given confidence level:

**M** x **T** = exposure
**ΔE** = energy resolution (ROI)
**B** = background rate / keV

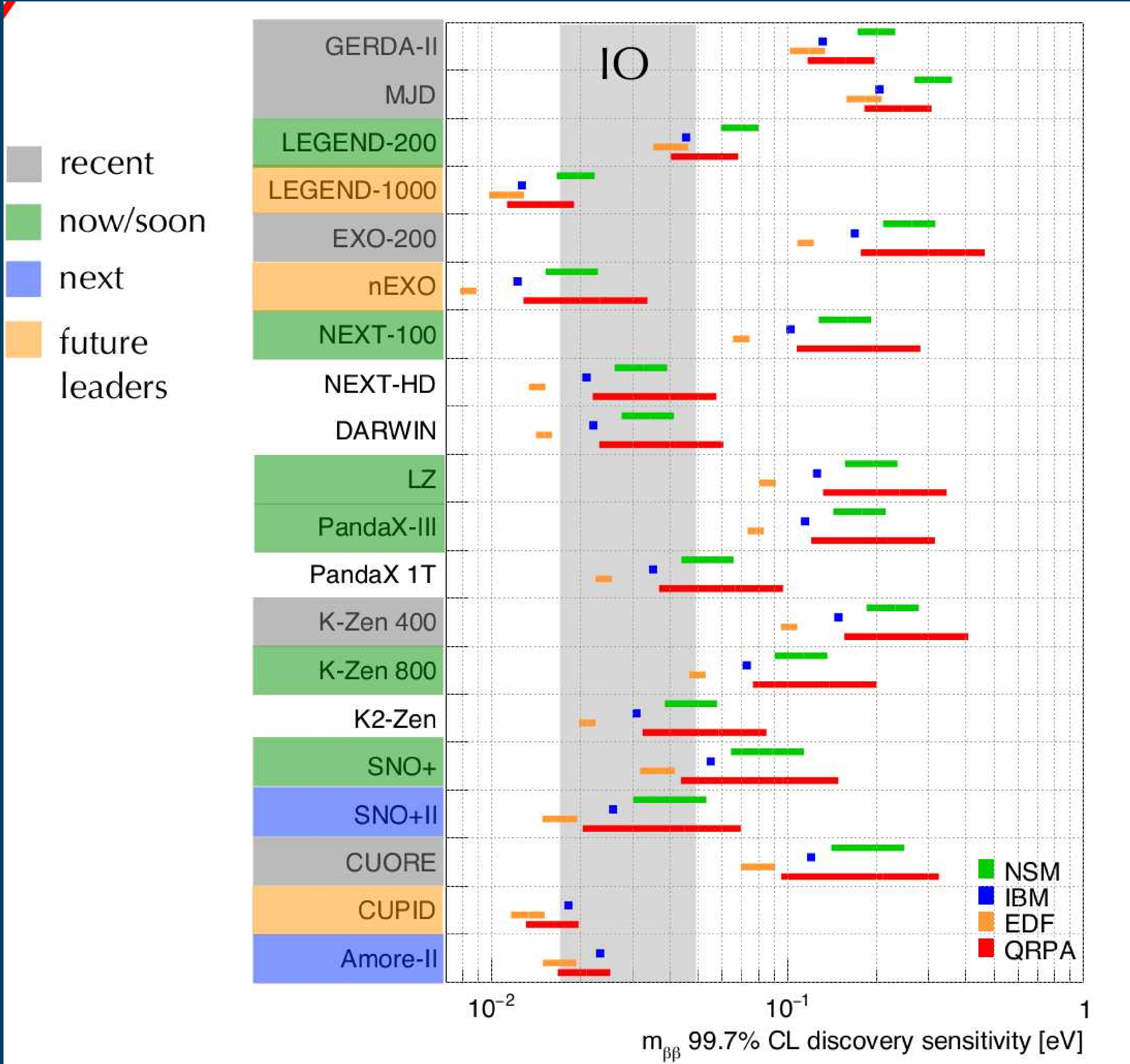
$$S_{0\nu\beta\beta} \propto \sqrt{\frac{M\,x\,T}{B \times \Delta E}}$$

"zero bkg" → **M** x **T** x **B** x **ΔE** < 1

$$S_{0\nu\beta\beta} \propto M\,x\,T$$



Neutrino 2020- Agostini, Benato, Dewiler, Menendez, Vissani



# selected experiments
## (I apologize for those not included)

- running or with a plan for near/far the future
- competitive

# Experiments

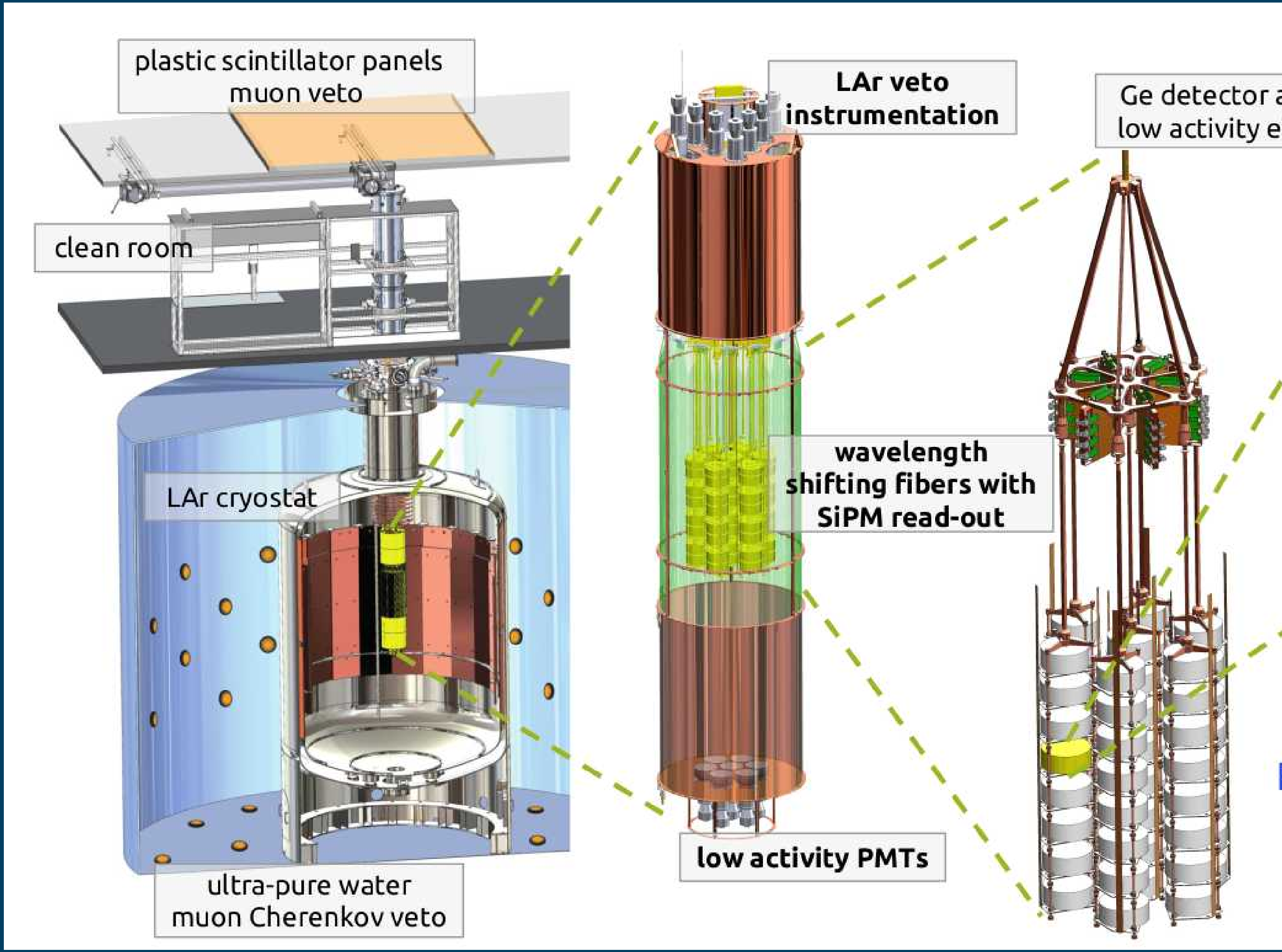
| Collaboration | Isotope | Technique | mass ($0\nu\beta\beta$ isotope) | Status |
|---|---|---|---|---|
| CANDLES-III | $^{48}Ca$ | 305 kg $CaF_2$ crystals in liquid scintillator | 0.3 kg | Operating |
| CANDLES-IV | $^{48}Ca$ | $CaF_2$ scintillating bolometers | TBD | R&D |
| GERDA | $^{76}Ge$ | Point contact Ge in active LAr | 44 kg | Complete |
| MAJORANA DEMONSTRATOR | $^{76}Ge$ | Point contact Ge in Lead | 30 kg | Operating |
| LEGEND 200 | $^{76}Ge$ | Point contact Ge in active LAr | 200 kg | Construction |
| LEGEND 1000 | $^{76}Ge$ | Point contact Ge in active LAr | 1 tonne | R&D |
| SuperNEMO Demonstrator | $^{82}Se$ | Foils with tracking | 7 kg | Construction |
| SELENA | $^{82}Se$ | Se CCDs | <1 kg | R&D |
| NvDEx | $^{82}Se$ | $SeF_6$ high pressure gas TPC | 50 kg | R&D |
| ZICOS | $^{96}Zr$ | 10% $^{nat}Zr$ in liquid scintillator | 45 kg | R&D |
| AMoRE-I | $^{100}Mo$ | $^{40}CaMoO_4$ scintillating bolometers | 6 kg | Construction |
| AMoRE-II | $^{100}Mo$ | $Li_2MoO_4$ scintillating bolometers | 100 kg | Construction |
| CUPID | $^{100}Mo$ | $Li_2MoO_4$ scintillating bolometers | 250 kg | R&D |
| COBRA | $^{116}Cd/^{130}Te$ | CdZnTe detectors | 10 kg | Operating |
| CUORE | $^{130}Te$ | $TeO_2$ Bolometer | 206 kg | Operating |
| SNO+ | $^{130}Te$ | 0.5% $^{nat}Te$ in liquid scintillator | 1300 kg | Construction |
| SNO+ Phase II | $^{130}Te$ | 2.5% $^{nat}Te$ in liquid scintillator | 8 tonnes | R&D |
| Theia-Te | $^{130}Te$ | 5% $^{nat}Te$ in liquid scintillator | 31 tonnes | R&D |
| KamLAND-Zen 400 | $^{136}Xe$ | 2.7% in liquid scintillator | 370 kg | Complete |
| KamLAND-Zen 800 | $^{136}Xe$ | 2.7% in liquid scintillator | 750 kg | Operating |
| KamLAND2-Zen | $^{136}Xe$ | 2.7% in liquid scintillator | ~tonne | R&D |
| EXO-200 | $^{136}Xe$ | Xe liquid TPC | 160 kg | Complete |
| nEXO | $^{136}Xe$ | Xe liquid TPC | 5 tonnes | R&D |
| NEXT-WHITE | $^{136}Xe$ | High pressure GXe TPC | ~5 kg | Operating |
| NEXT-100 | $^{136}Xe$ | High pressure GXe TPC | 100 kg | Construction |
| PandaX | $^{136}Xe$ | High pressure GXe TPC | ~tonne | R&D |
| AXEL | $^{136}Xe$ | High pressure GXe TPC | ~tonne | R&D |
| DARWIN | $^{136}Xe$ | $^{nat}Xe$ liquid TPC | 3.5 tonnes | R&D |
| LZ | $^{136}Xe$ | $^{nat}Xe$ liquid TPC | | R&D |
| Theia-Xe | $^{136}Xe$ | 3% in liquid scintillator | 50 tonnes | R&D |

R&D | Construction | Operating | Complete

Updated from J. Wilkerson

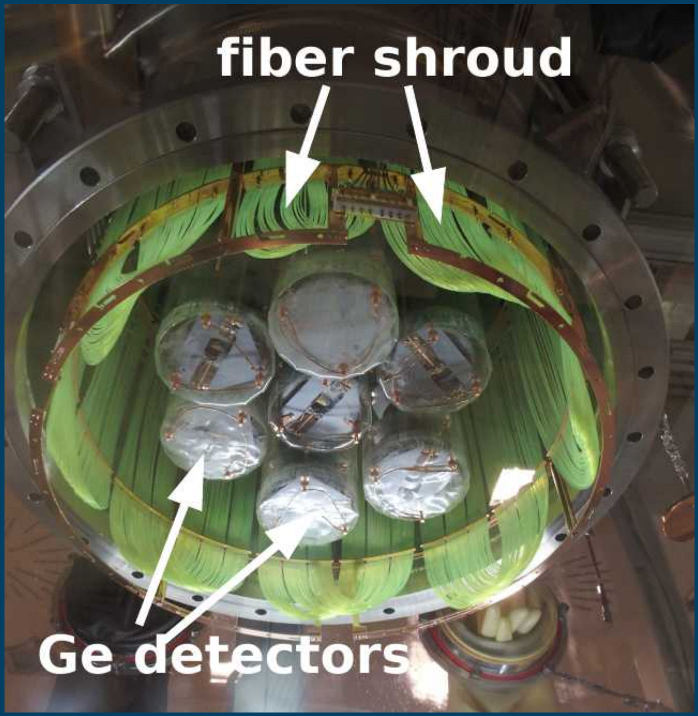
# GERDA

- $^{76}$Ge $Q_{\beta\beta}$ = 2.0 MeV
- enrichement ~ 90%
- 37 $^{enrich}$Ge HPGe in LAr

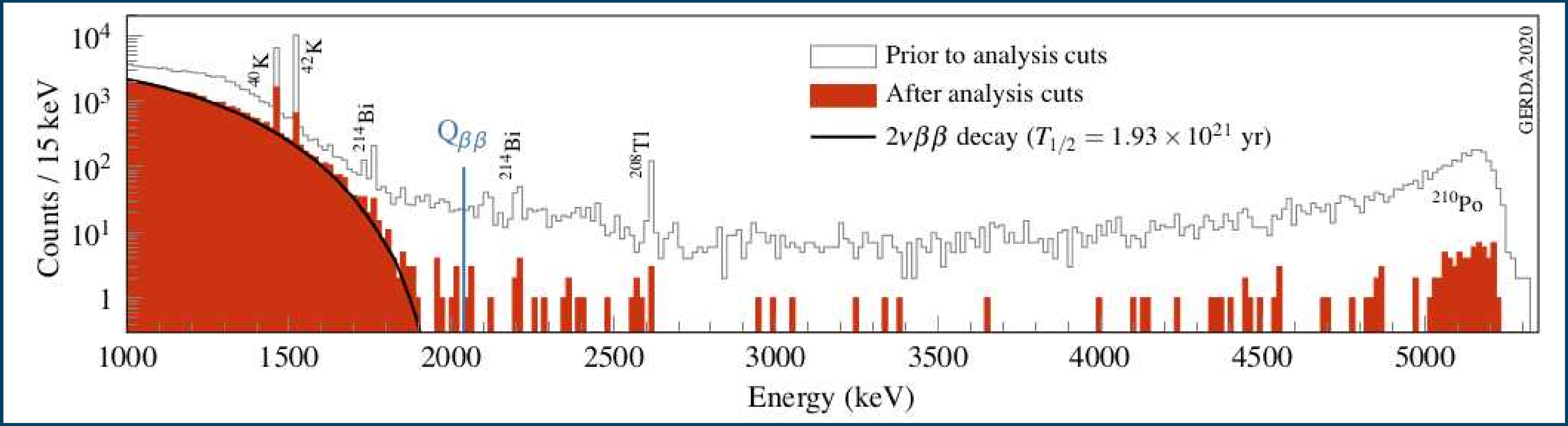




PSA to separate single vs multisite events

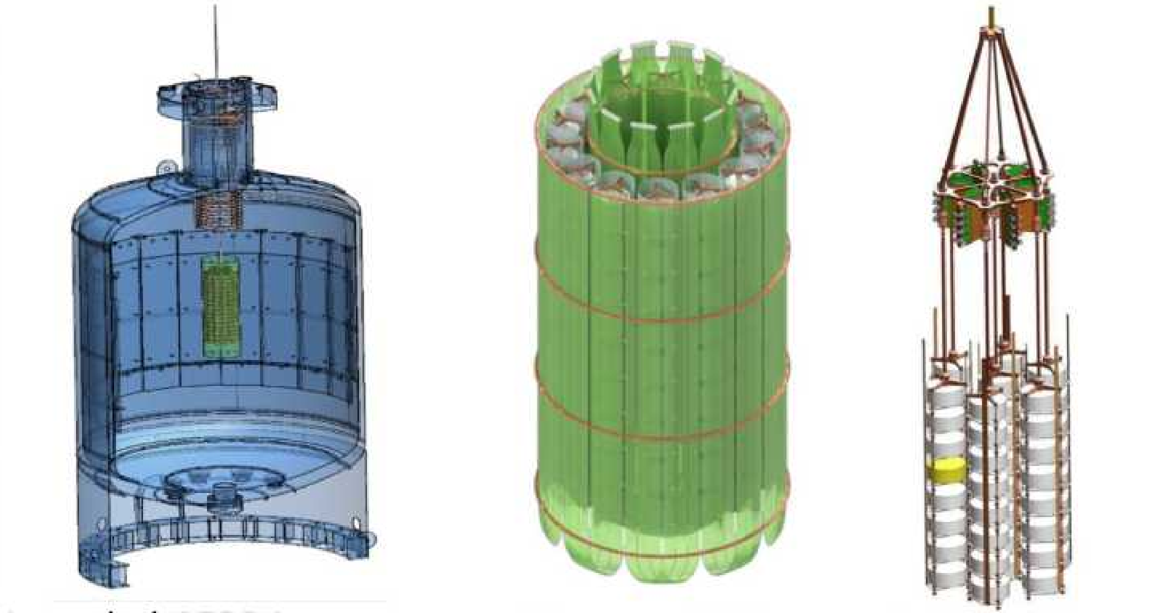
- **resolution** FWHM ~ 3.6 keV at $Q_{\beta\beta}$
- **PSA** used to separate SingleSite from MultiSite
- **status:** CLOSED on Nov 2019
  - **exposure I+II:** 127.2 kg·yr
- **background:** ~ 5.2 $10^{-4}$ counts/(keV kg y)
  - $T_{1/2}^{0\nu\beta\beta}$ **>** 1.8 x $10^{26}$ yr (90% C.L.)
  - $\langle m_{\beta\beta} \rangle$ **<** (79 – 180) meV [NMEs]




**Risultati di fase II** PHYSICAL REVIEW LETTERS **125**, 252502 (2020)



# LEGEND-200

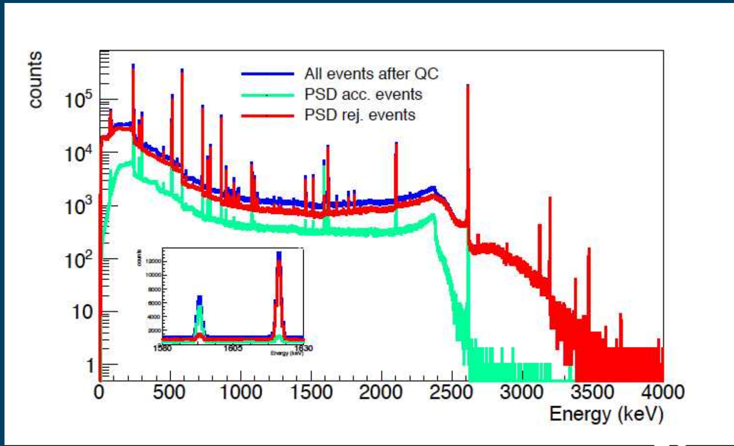



Upgraded GERDA cryostat: new lock, cabling detector suspension

LAr veto, SiPM coupled fibers

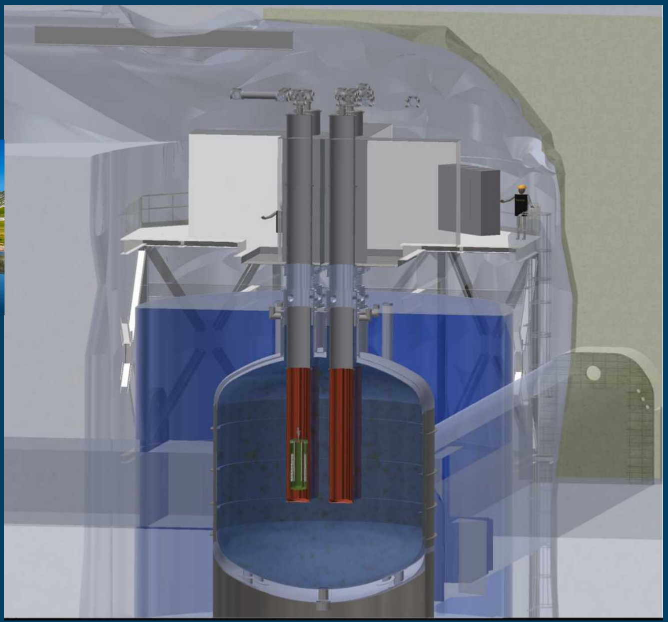
New String layout, front end electronics

- **start** in 2022 (delay due to COVID emergency)
- **200 kg** in upgraded GERDA infrastructure
  - ➔ new dets = inverted coax → large mass

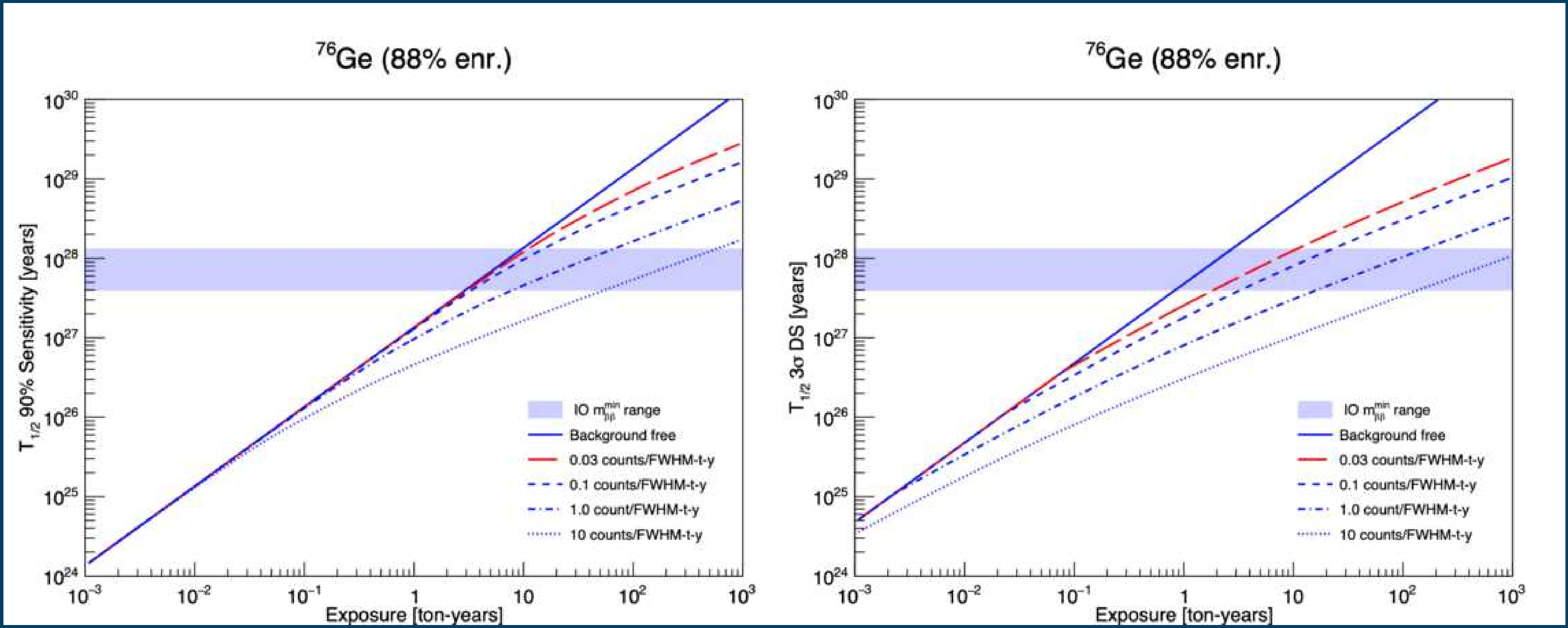



- **background**
  - ➔ 1-2 $10^{-4}$ counts/(keV kg y) (5 times improvement)
  - ➔ dominated by $^{42}$K β-decays & α-surface emitters
- $T_{1/2}^{0\nu\beta\beta}$ ~ $10^{27}$ y or $m_{ee}$ 35-75 meV

# LEGEND-1000



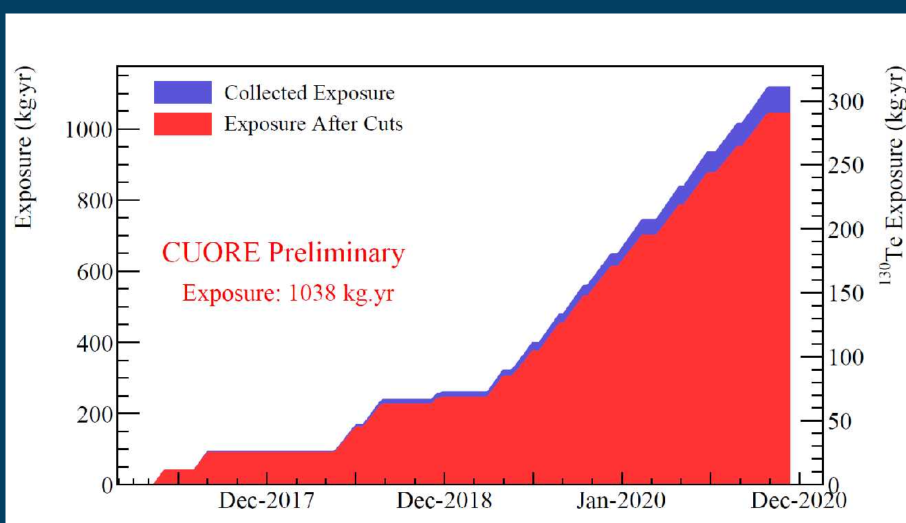
- **@ where ?** LNGS or SNOLAB
- **detectors =** inverted coaxial
- **mass =** 1000 kg
- **bkg =** 0.1 cts/(FWHM ton y) → 30 times better than GERDA-II

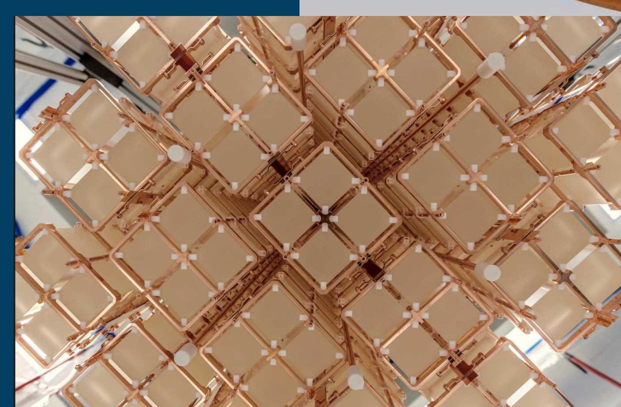


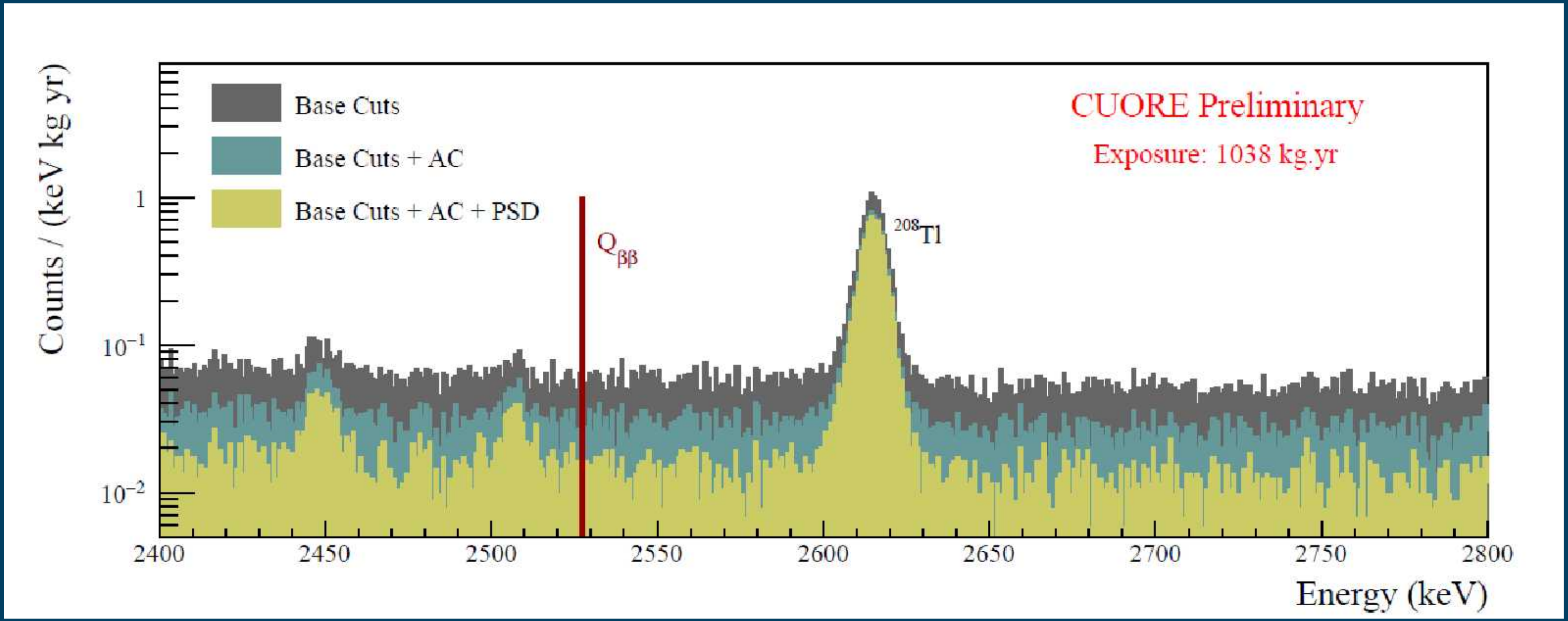
# CUORE


- **$^{130}$Te $Q_{\beta\beta}$ = 2.5 MeV**
- **enrichment NO – i.a.~ 30%**
- **988 $TeO_2$ bolometers @ 10 mK**

- **FWHM** ~ 7 keV at $Q_{\beta\beta}$
- **status** running (> 1344 kg yr of raw exposure acquire

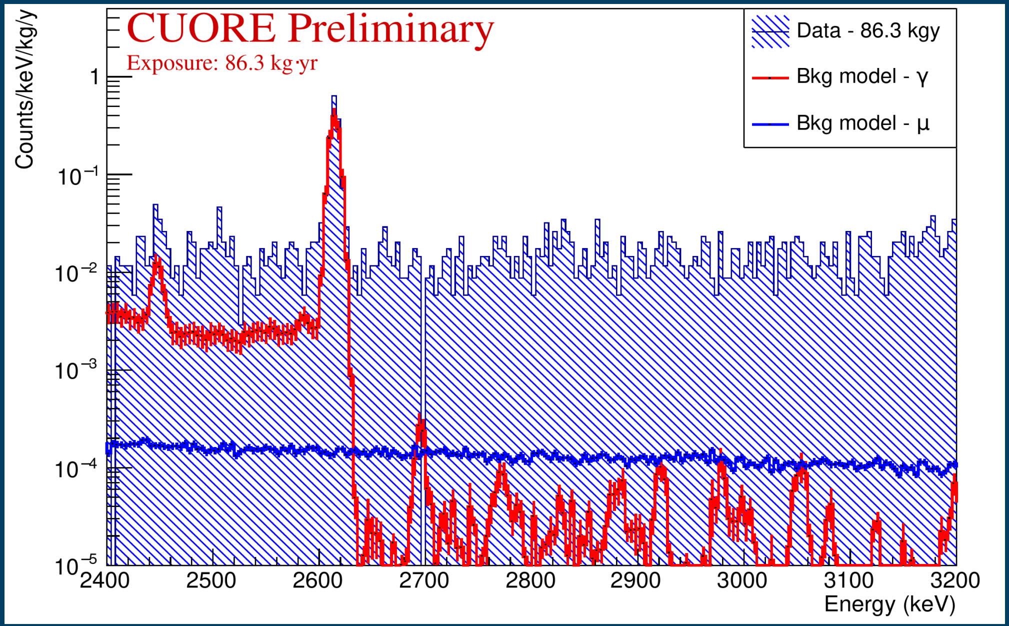




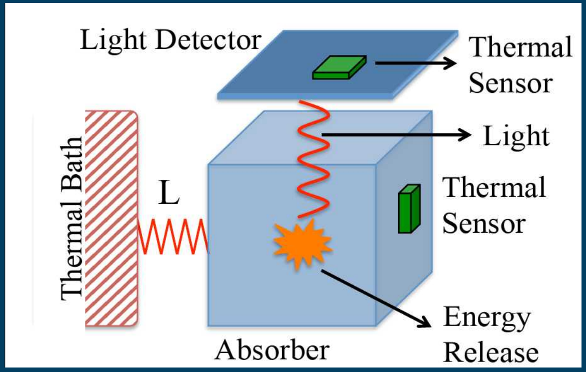

- **exposure:** 1038 kg·yr
- **background:**
  - 1.5 $10^{-2}$ counts/(keV kg y)
  - dominated by $\alpha$ particles

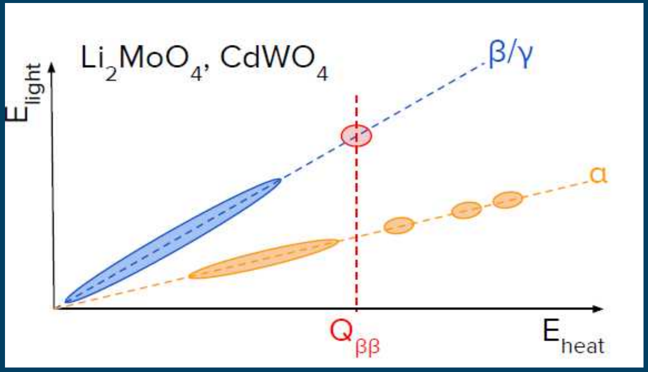
- $T_{1/2}^{0\nu\beta\beta}$ > 2.2 x $10^{25}$ yr (90% C.L.)
- $\langle m_{\beta\beta} \rangle$ < (90 – 305) meV

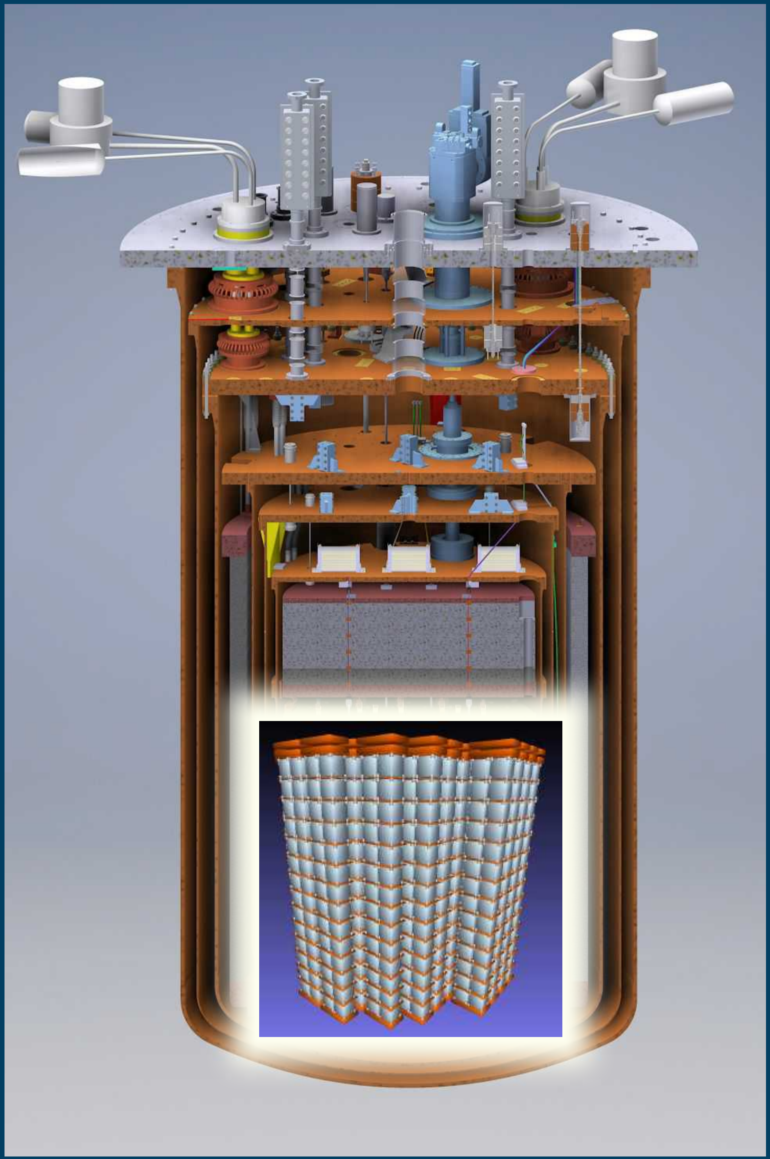


# CUPID

- **@ where ? LNGS in CUORE infrastructure**
- $^{100}$**Mo $Q_{bb}$** = 3.0 MeV
- **enrichment** ~ 90%
- **detectors** ~1500 $Li_2MoO_4$ scintillating bolometers



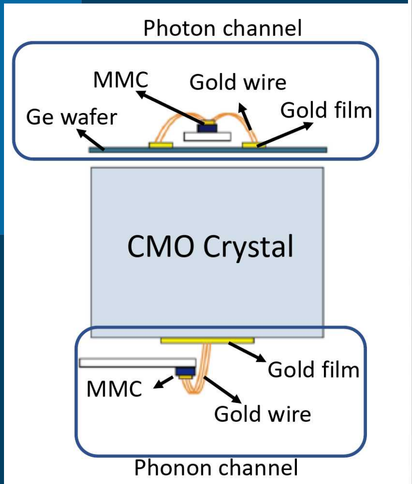



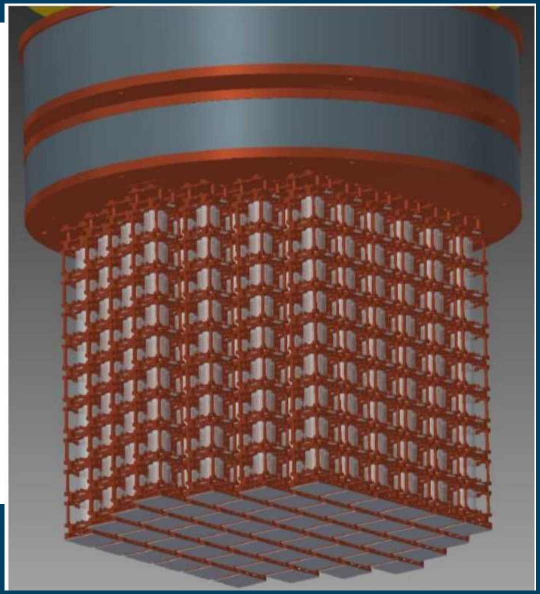
- **mass =** 250 kg of $^{100}$Mo
- **bkg =** $10^{-4}$ ckky
  - CUORE without α induced bkg
  - dominated by $2\nu\beta\beta$ pile-up

$T_{1/2}^{0\nu\beta\beta} > 10^{27}$

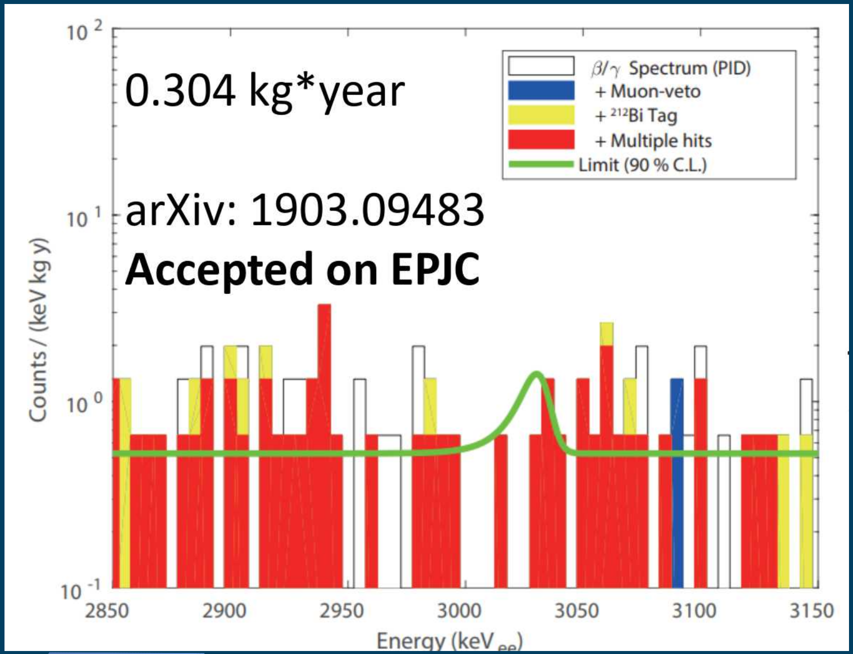
# AMORE

- scintillating $^{100}$Mo crystals
  $^{depl}Ca^{100}MoO_4$ or $Li_2{}^{100}MoO_4$
- MMC sensors fast !! techn. challenging !!
- underground lab under excavation



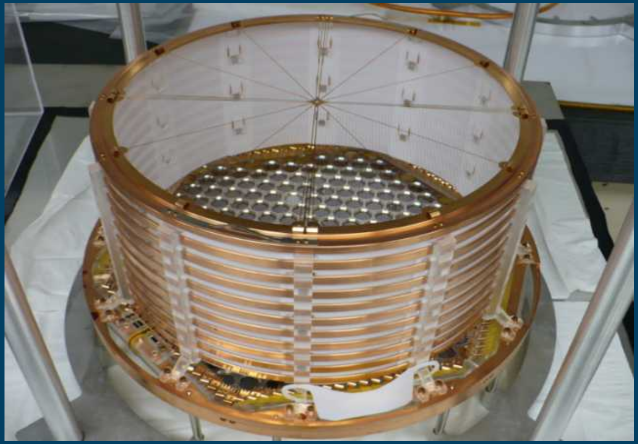



| | AMoRE-Pilot | AMoRE-I | AMoRE-II |
|---|---|---|---|
| Mass [kg] | 1.9 | ~6.1 | ~200 |
| Channels | 12 | 36 | ~1000 |
| BKG goal [ckky] | 0.01 | 0.001 | 0.0001 |
| Sensitivity [year] | $\sim 10^{24}$ | $\sim 10^{25}$ | $\sim 5\times 10^{26}$ |
| Sensitivity [meV] | 380 to 640 | 120 to 200 | 17 to 29 |
| Location | Y2L | Y2L | Yemilab |
| schedule | 2017 to 2018 | 2019~ | 2021~ |



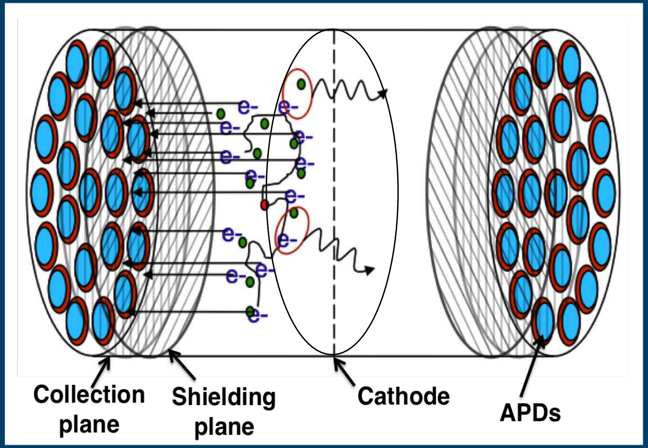
# EXO-200

- $^{136}Xe\ Q_{\beta\beta}$ = 2.54 MeV
- enrichment
- 200 kg LXe

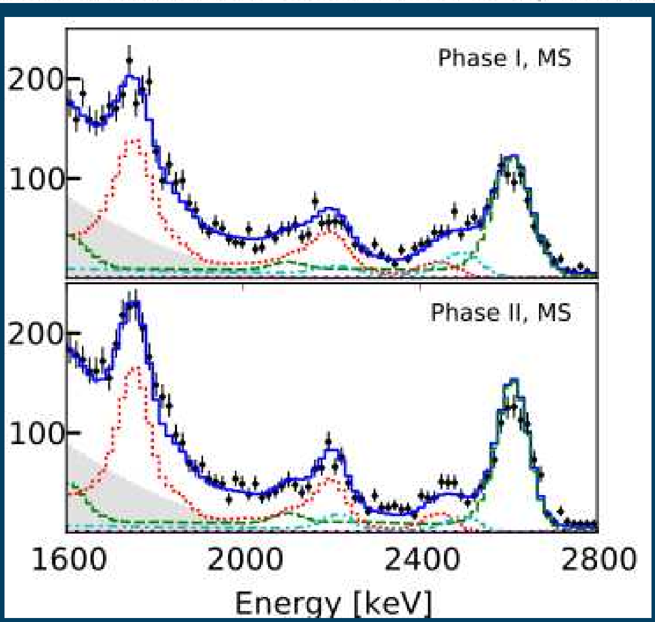


**energy** measured using two signals:
ionization signal drifted to crossed wire planes
scintillation (175nm) collected by APD

**topology** used to separate Signal/Background
separation of SingleSite/MultiSite events

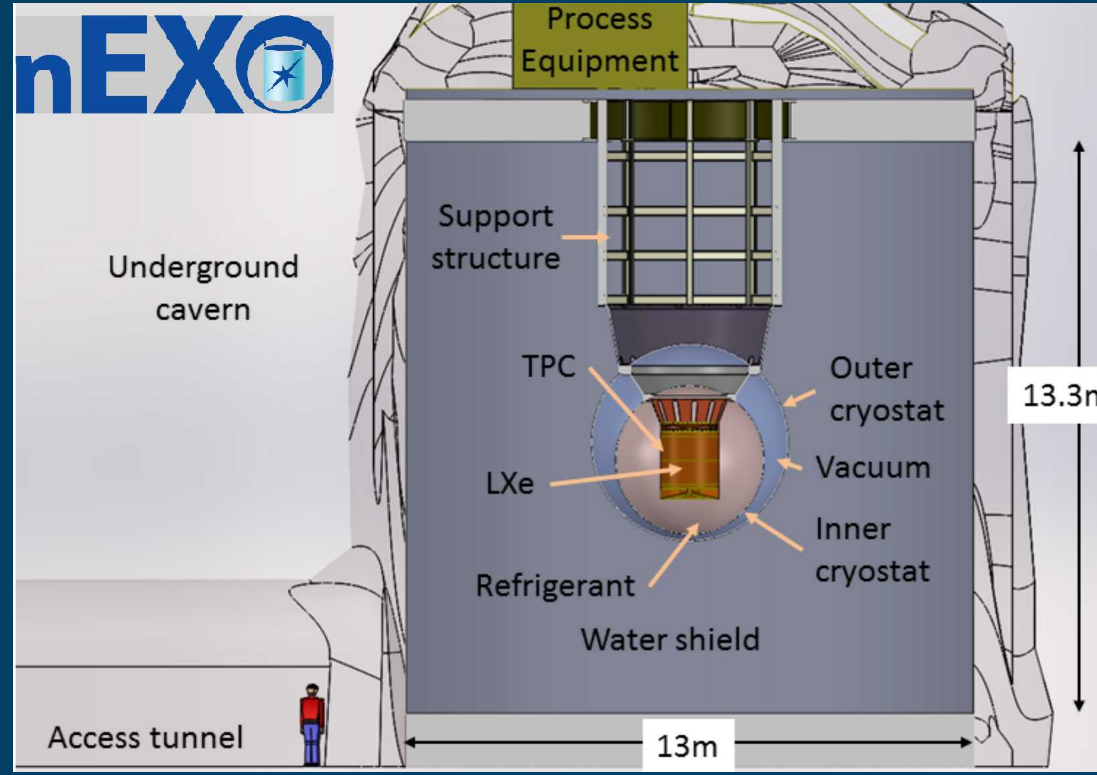



PHYSICAL REVIEW LETTERS **123**, 161802 (2019)

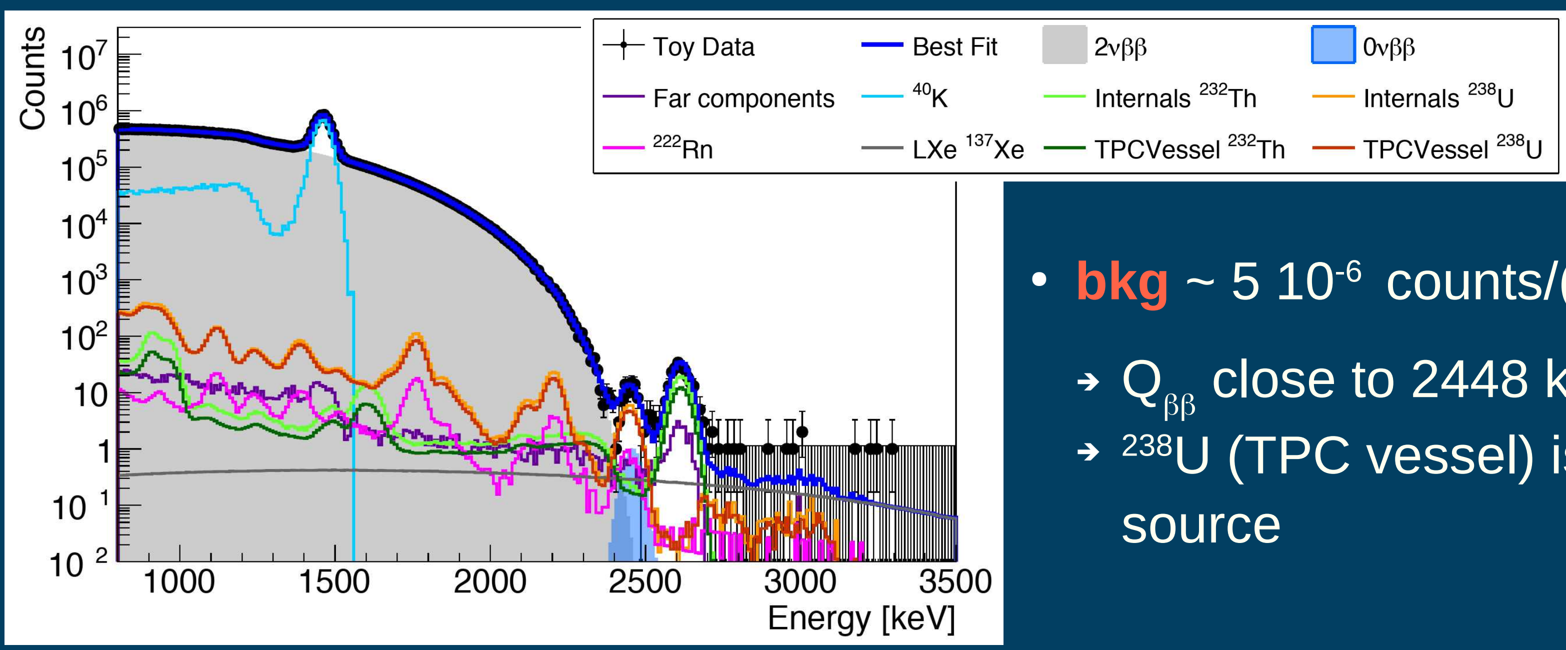



- **FWHM** ~ 65 keV at $Q_{\beta\beta}$
- **status** closed
- **exposure:** 234.1 kg·yr
- $T_{1/2}^{0\nu\beta\beta}$ > $3.5 \times 10^{25}$ yr (90% C.L.)
- $\langle m_{\beta\beta} \rangle$ < (78 – 239) meV

# nEXO

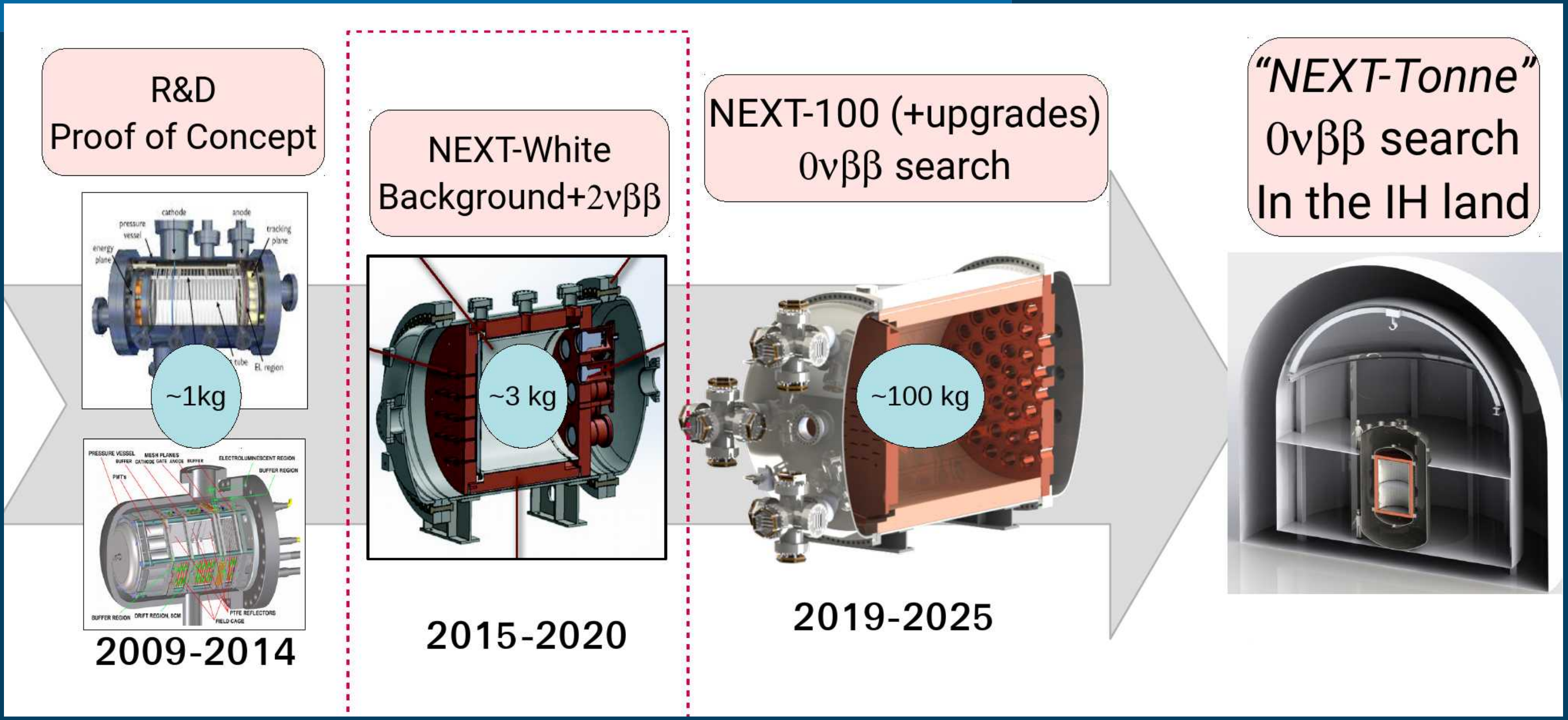



- **5000 kg LXe**
- $T_{1/2}^{0\nu\beta\beta}$ > $9\ 10^{27}$

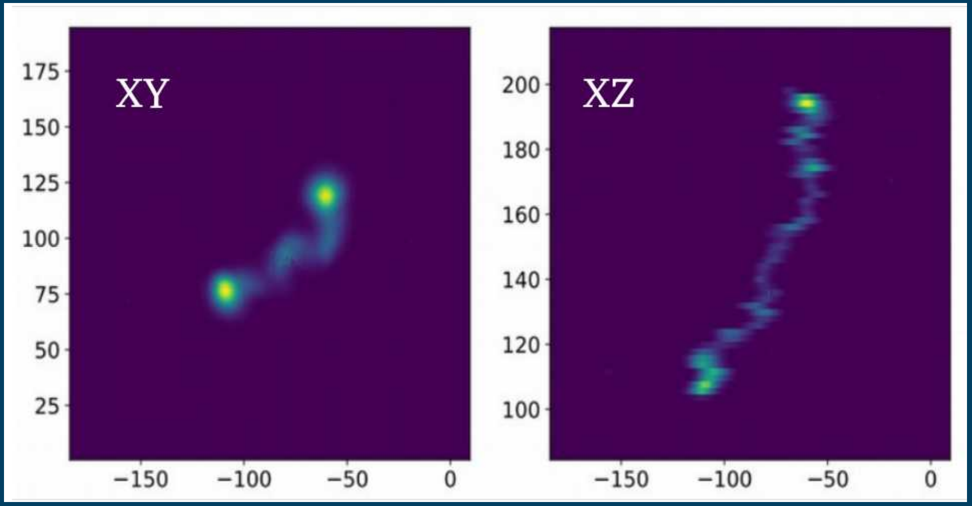



- **bkg** ~ $5\ 10^{-6}$ counts/(keV kg y)
  - $Q_{\beta\beta}$ close to 2448 keV $^{214}$Bi line
  - $^{238}$U (TPC vessel) is the dominant source

# NEXT

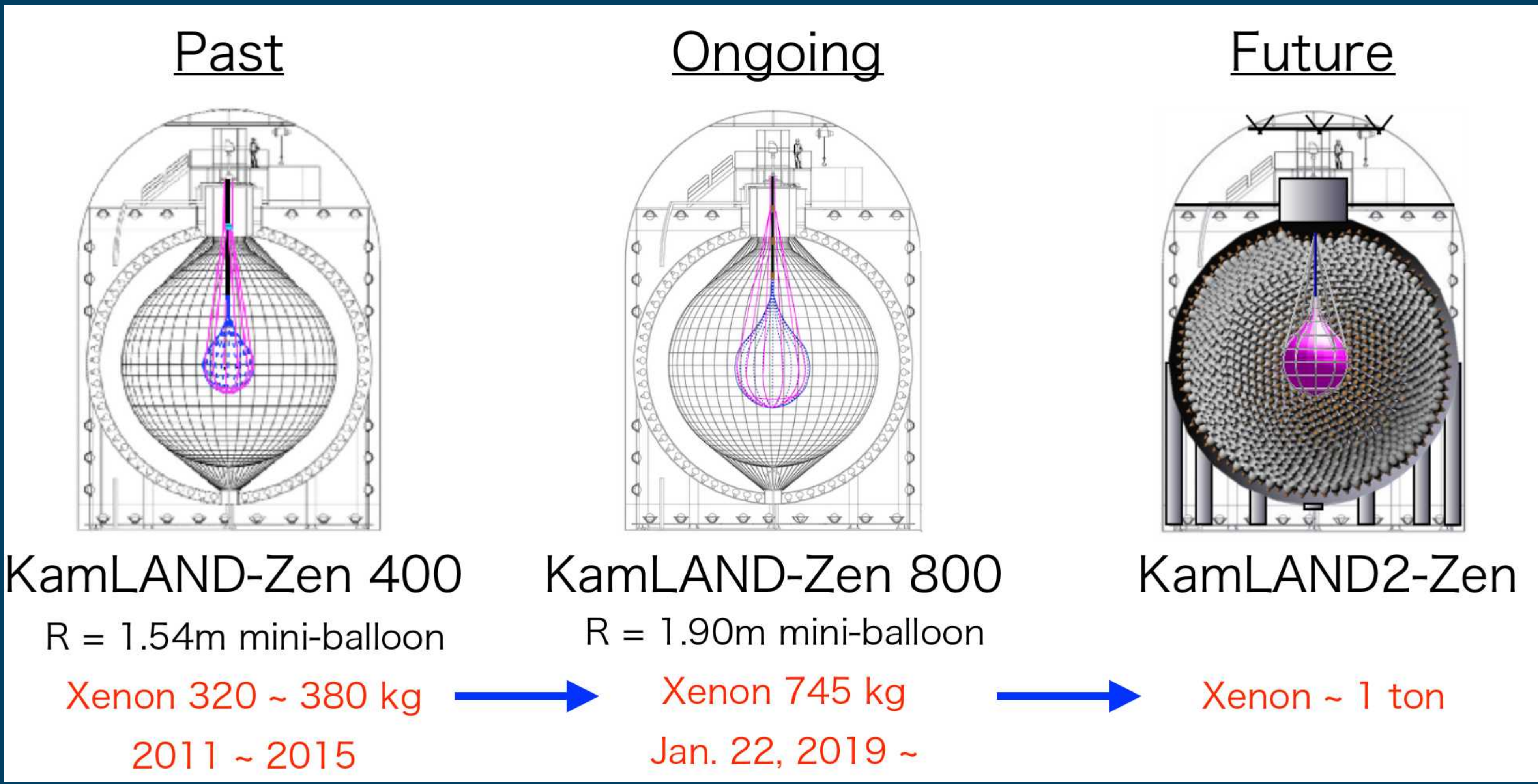



- **gas TPC** with 2 dedicated readout planes
- **event topology**
- **FWHM ~ 25 keV**

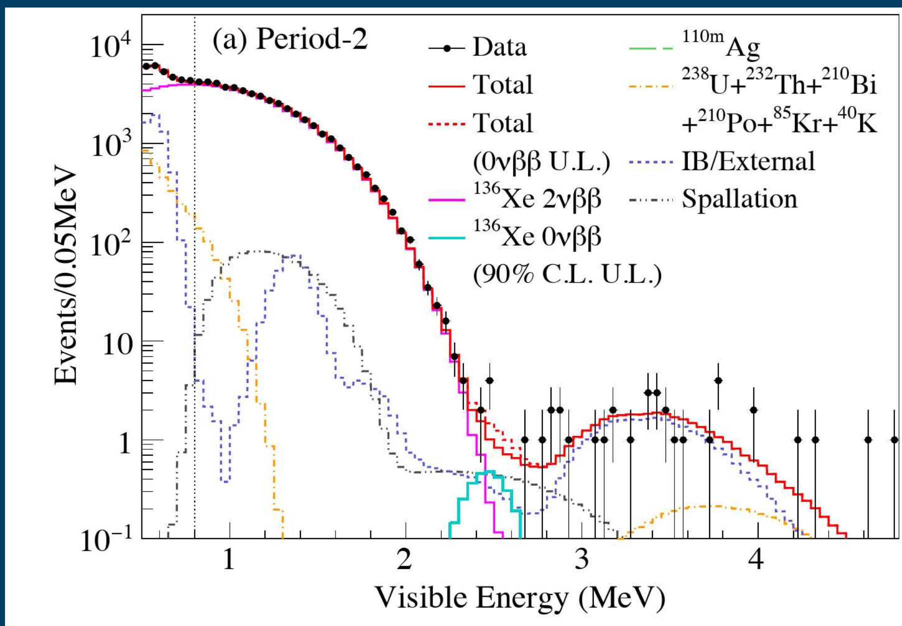


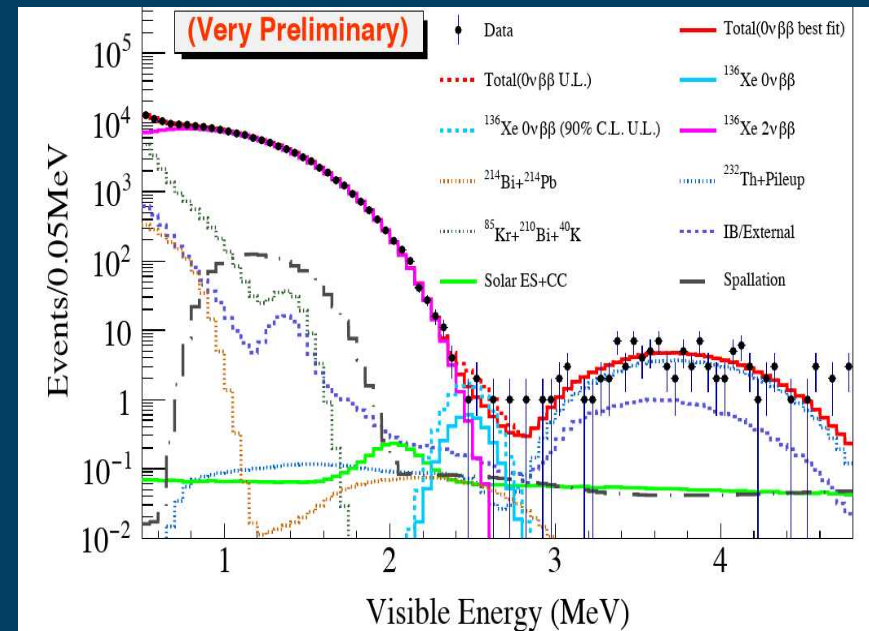
# KamLAND-Zen

LS with $^{136}Xe$ balloon



# KamLAND-Zen




**KamLAND-Zen 400**
- **closed**
- limit 1.1 $10^{26}$ y

**KamLAND-Zen 800**
- running since Jan 2019
- Very preliminary results with 132.7 days data
  $T^{0\nu}_{1/2} > 4 \times 10^{25}$ year (90% C.L.)
  Sensitivity : $8 \times 10^{25}$ year
- target 5 yr sensitivity 5 $10^{26}$

# SNO+

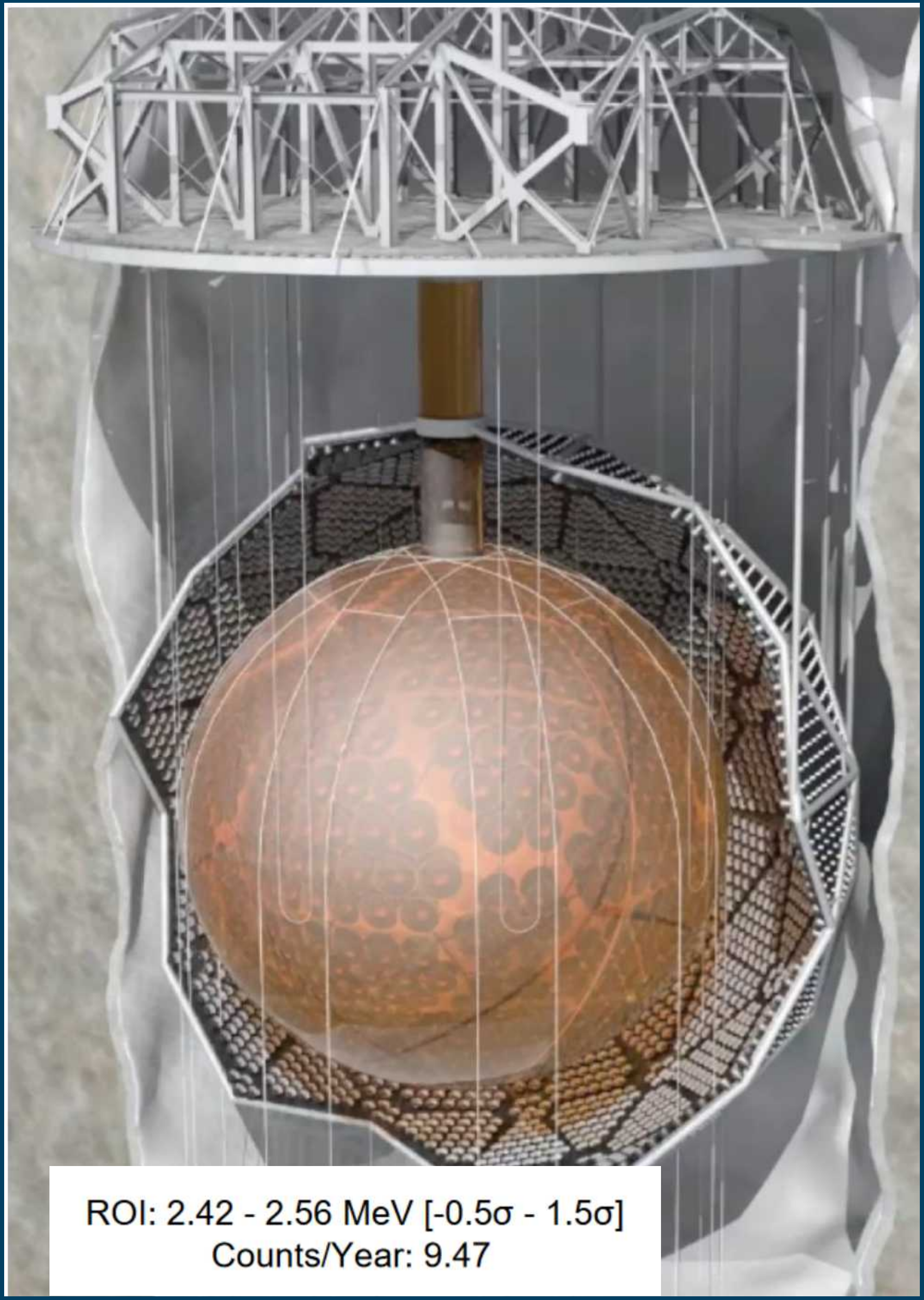
- 780 tonne scintillator
  (47% filled,  COVID stopped)

- loaded with Te(0.5%)-butanediol
  ➔ 1330 kg $^{130}$Te
  ➔ **$^{130}$Te $Q_{\beta\beta}$ = 2.5 MeV**

- predicted 460 p.e./MeV
  → 3%  $\sigma$/E FWHM=180 keV

- challenge: stability
  (for 35 l > 26 months)

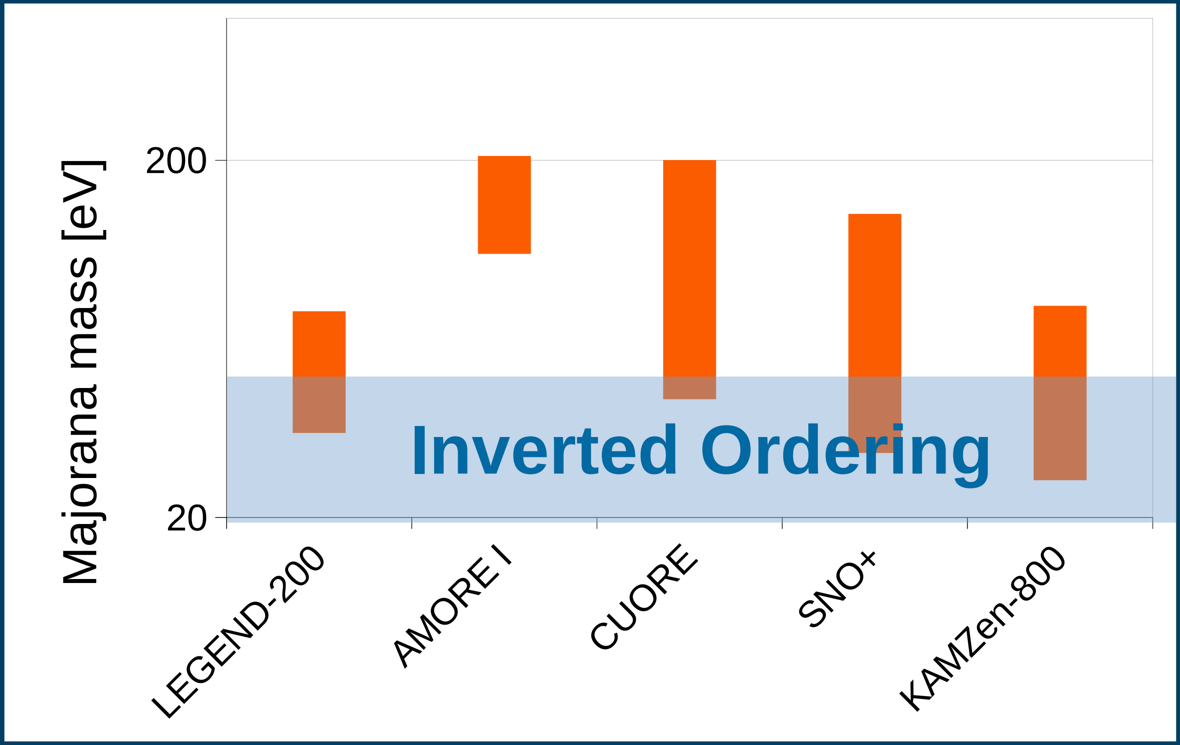
**$T_{1/2}^{0\nu\beta\beta}$ > 2.1 $10^{26}$ y**



# ~ 2026

**we will likely have these experiments approaching their design sensitivity**

| | | |
|---|---|---|
| $^{76}$**Ge** | LEGEND-200 | $10^{27}$ yr |
| $^{100}$**Mo** | AMORE I | $10^{25}$ yr |
| $^{130}$**Te** | CUORE | $9\ 10^{25}$ yr |
| | SNO+ I | $2\ 10^{26}$ yr |
| $^{136}$**Xe** | KamZEN800 | $4.6\ 10^{26}$ yr |




SNO+ and AMORE are still in a very preliminary stage, schedule and sensitivity may be subject to delay ...

# ~ 2030

*future leaders*

$^{76}$Ge **LEGEND-1000** $10^{28}$ yr

---

$^{100}$Mo AMORE II $5\ 10^{26}$ yr

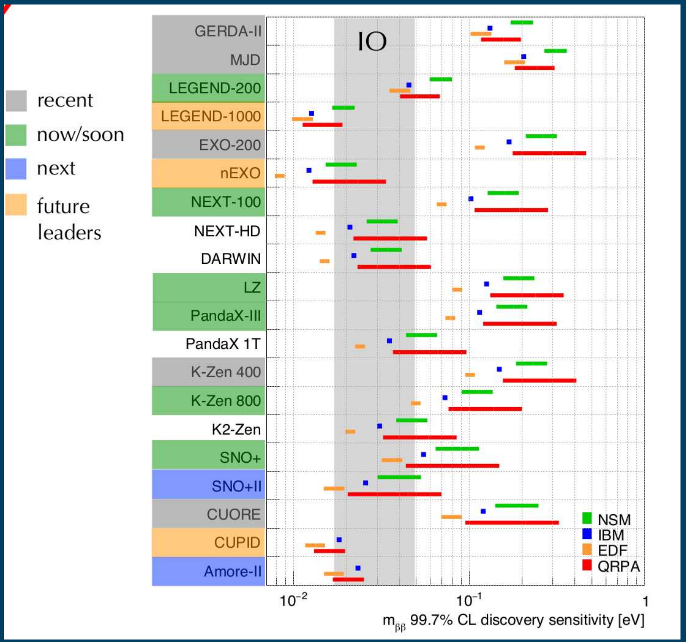
**CUPID** $10^{27}$ yr

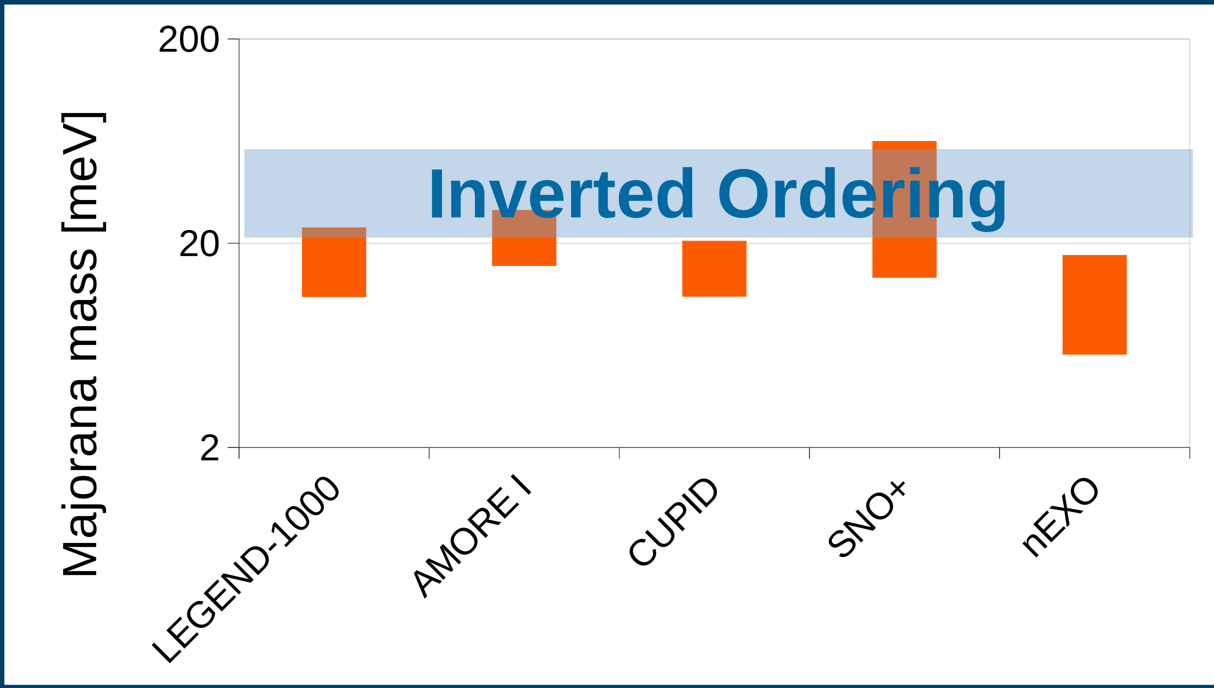
---

$^{130}$Te SNO+ II $10^{27}$ yr

---

$^{136}$Xe **nEXO** $10^{28}$ yr



# Thanks for your attention !

# Majorana D

Latest Release:

First unblinding of data

16 kg-yr exposure

**[PRC 100 025501 (2019)]**

Median $T_{1/2}$ Sensitivity:

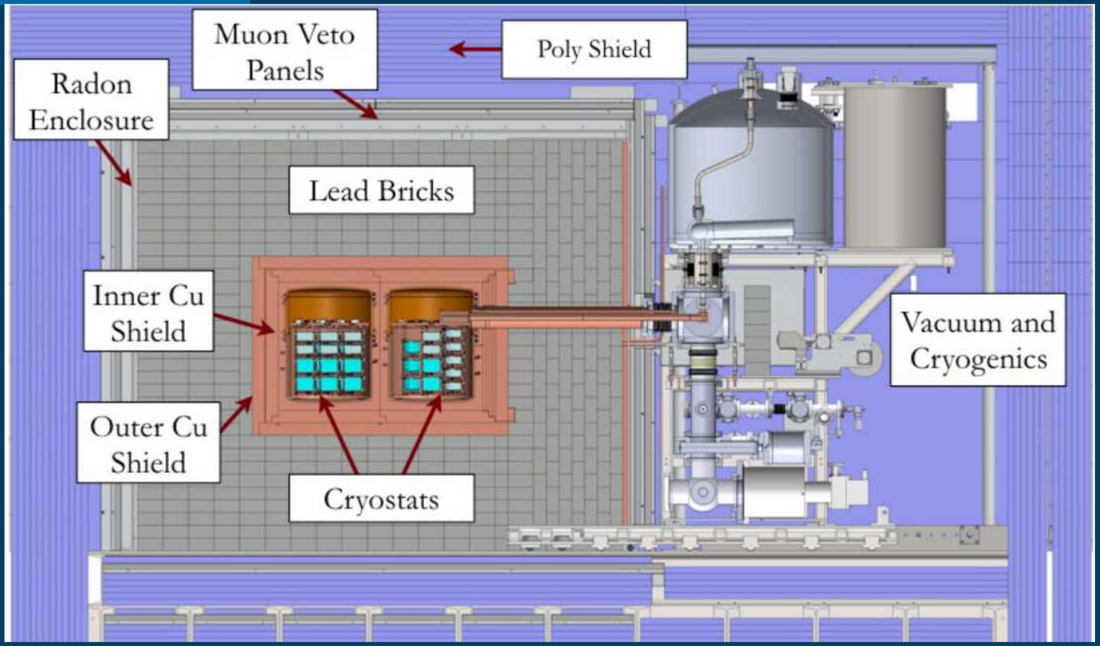
$4.8 \times 10^{25}$ yr

Full Exposure Limit:

$T_{1/2} > 2.7 \times 10^{25}$ yr (90% CL)

Background Index at 2039 keV in lowest background config:

$11.9 \pm 2.0$ cts/(FWHM t yr)



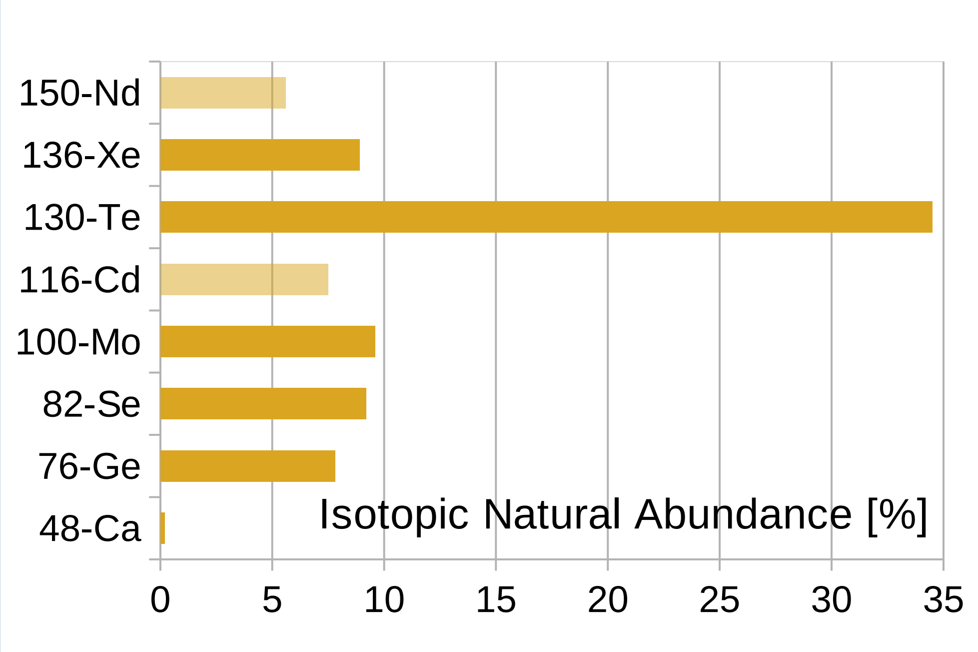

P-type Point-Contact (PPC)

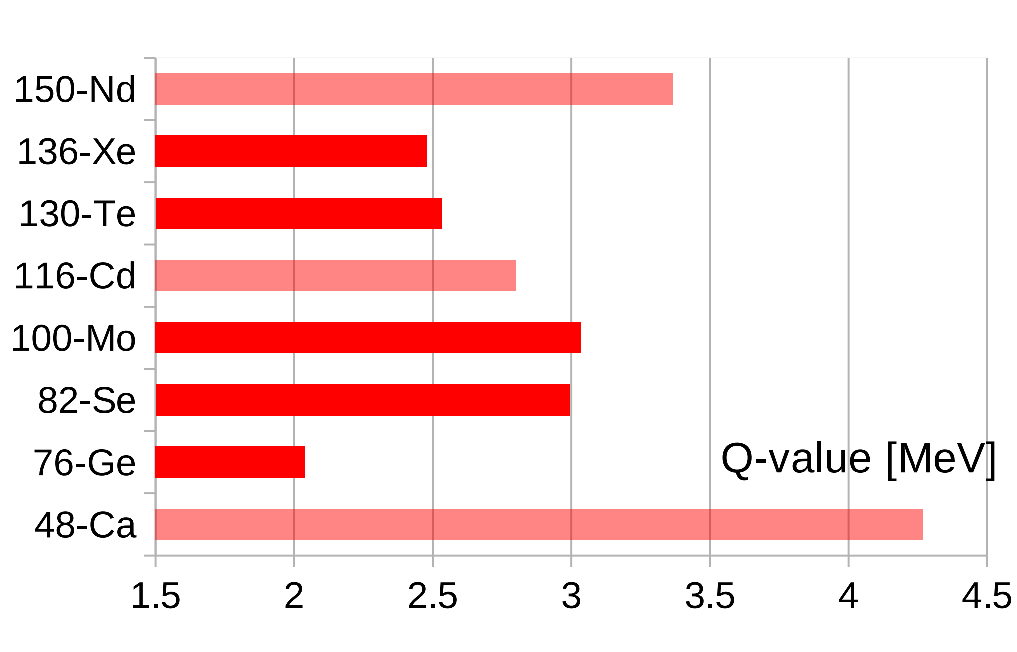
# 0ν2β CANDIDATES

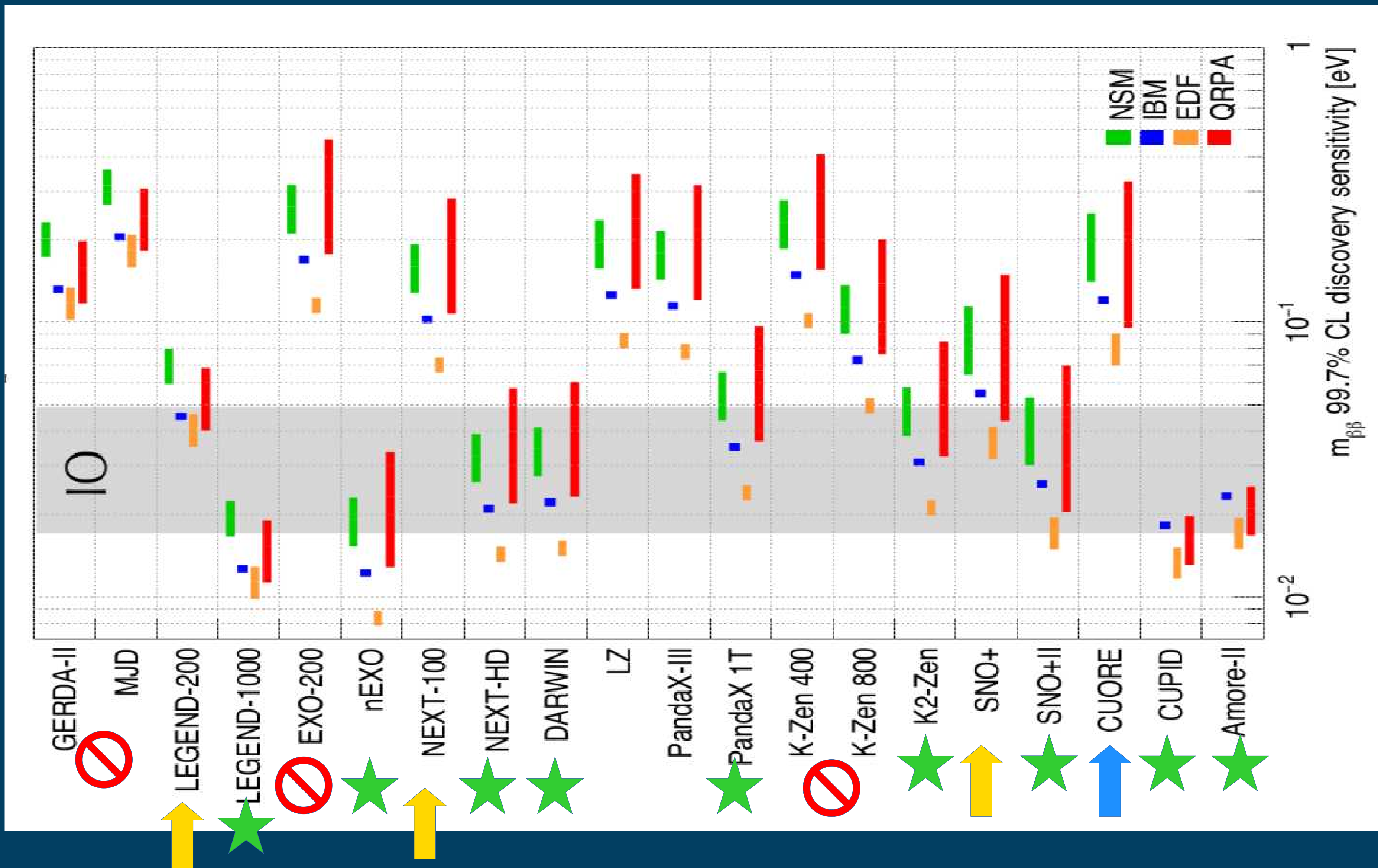
- in most cases driven by **detector characteristic**
  - → $^{76}$Ge with Ge diodes
  - → $^{136}$Xe with TPCs
  - → bolometers and scintillators have multiple choices

- **isotopic abundance as high as possible**
  → (not only) money issue

- **Q-value** as high as possible
  - → phase space
  - → background

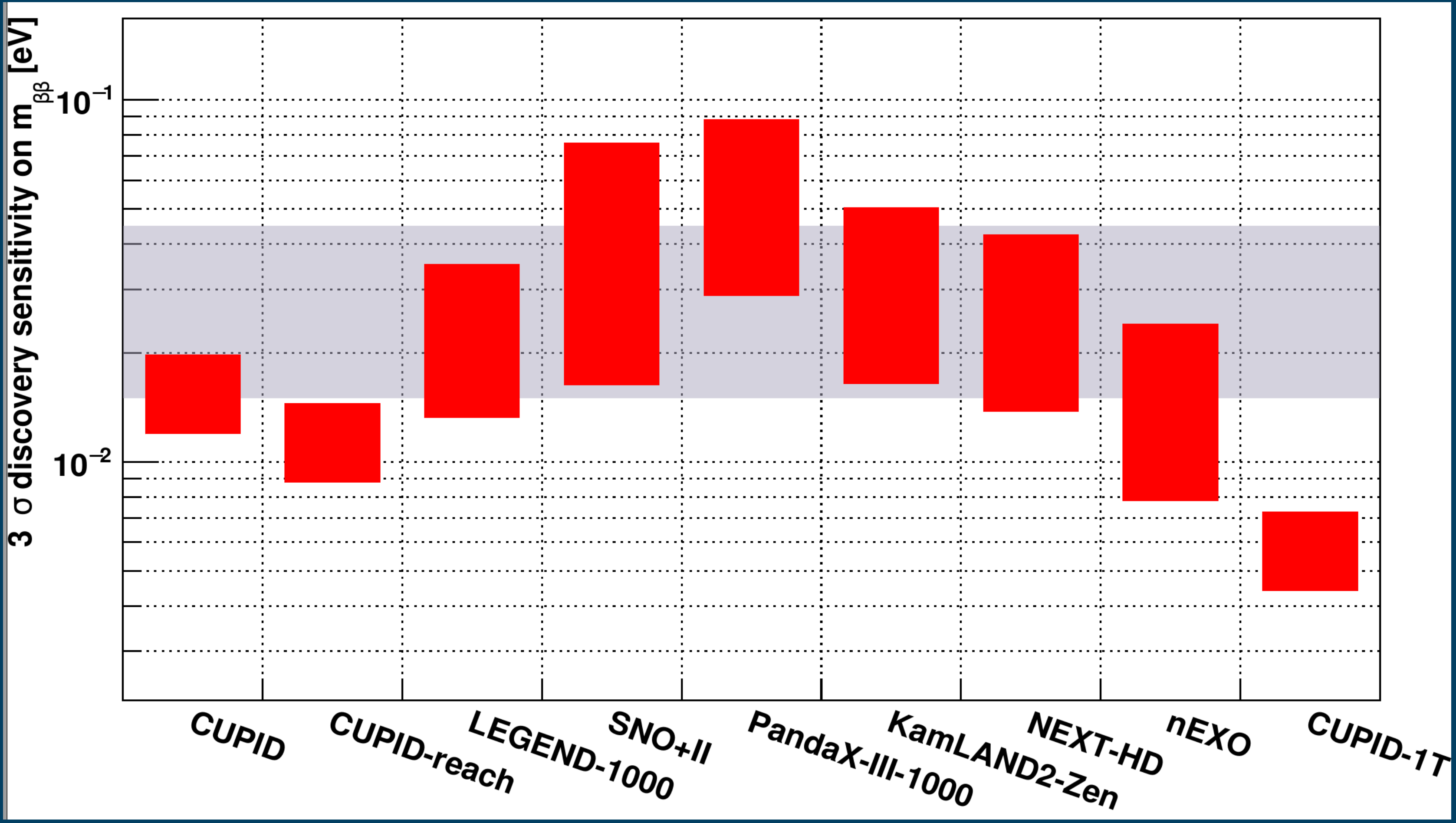





closed running construction next generation

*Snowmass2020- Agostini, Benato, Dewiler, Menendez, Vissani*


3 σ discovery sensitivity on $m_{\beta\beta}$ [eV]
$10^{-1}$
$10^{-2}$
CUPID
CUPID-reach
LEGEND-1000
SNO+II
PandaX-III-1000
KamLAND2-Zen
NEXT-HD
nEXO
CUPID-1T

# $0\nu2\beta$ half-life

the race to the exclusion of IO region started

- increase detector size ($M_{\beta\beta}$ i.e. the source size)
- reduce background with active rejection techniques

**high resolutions detectors**

→ Ge diodes & bolometers

→ localization of the signal in a few keV

→ mass scalability not trivial

**lower resolution detectors**

→ fluids

→ localization of the signal in a >50 keV

→ mass scalability rather simple

*Neutrino 2020- Agostini, Benato, Dewiler, Menendez, Vissani*

# Discovery Sensitivity Comparison