# Neutrinoless Double Beta Decay: where we stand and what lies ahead

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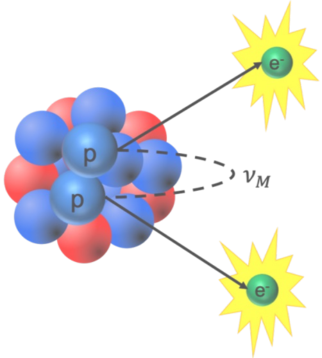
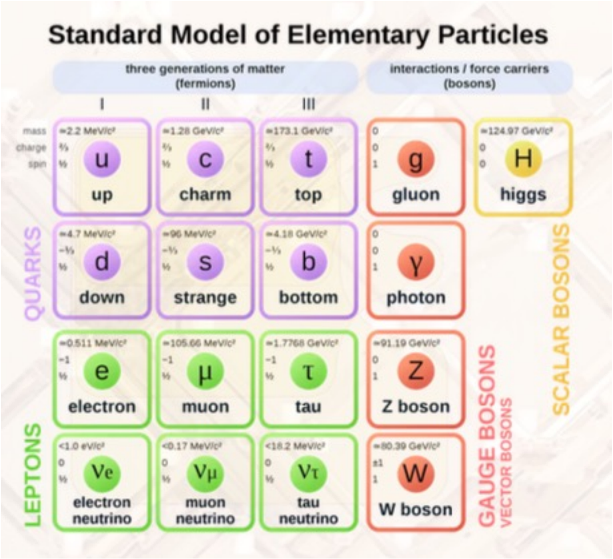



EuNPC2025, September 21-26, 2025

# The context:  ghostly neutrinos

- The most poorly understood particle within the SM
- First postulated by Pauli in 1930 to explain missing energy in beta decay
- Detected by Reines & Cowan in 1956 (nuclear reactor experiment)
- According to SM: electrically neutral, massless, weakly interacting





- Neutrino oscillations: evidence that neutrinos have mass
- **Physics beyond the Standard Model**

# The Majorana Neutrino

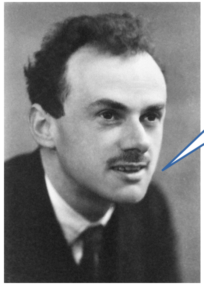
- **In the Standard Model, all the fermions are so-called Dirac particles** and have an anti-fermion partner.
- In 1937 E. Majorana proposed that in the case of a neutral particle, the fermions and the anti-fermions could coincide. **The neutrino could therefore be a « Majorana particle ».**
- **A Majorana neutrino mass term could then be added to the Standard Model's Lagrangian**, and the « See-Saw » mechanism could explain the smallness of the mass eigenstsate by predicting a sterile « right-handed » and heavy neutrino.

**Majorana neutrino**

Violation of the lepton number conservation

With see-saw mechanism the small mass is explained

$\nu=\nu^{C}$



$\nu\neq\nu^{C}$

**Dirac neutrino**

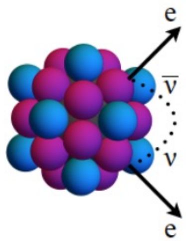
Lepton number conservation

But why the mass is that small ?

**The question is still pending** if the neutrino is a Dirac or a Majorana neutrino

**Answering it is crucial for our understanding of particle physics.**

# Nuclear Double Beta Decay in a nutshell

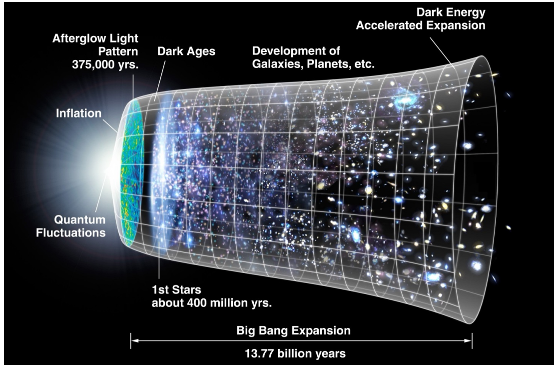



Double Beta Decay is the **rarest nuclear weak process**

It takes place between **two even-even isobars**

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

If only electrons and nothing else:




x $10^{15}$

- Need to find single events in a ton of isotope x year(s) of exposure!
- $3 \times 10^{-14}$ Bq/g
- We go to extreme length to limit ubiquitous radioactivity

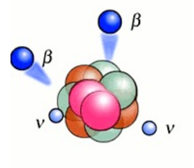
15 Bq / banana

**Half-life larger > $10^{25}$ y - $10^{26}$ y**

# More details on double beta decay

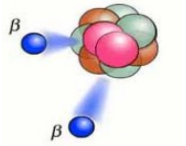
Double beta decay is a nuclear transition involving two even-even isobars

① $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\nu_e$ ⇨ 2ν Double Beta Decay
allowed by the Standard Model
already observed – $\tau \sim 10^{19} - 10^{21}$ y




② $(A,Z) \rightarrow (A,Z+2) + 2e^-$ ⇨ Neutrinoless
Double Beta Decay ($0\nu2\beta$)
never observed $\tau > 10^{24} - 10^{26}$ y

$2n \rightarrow 2p + 2e^-$




⇩

Creation of matter without antimatter partners

**Beyond Standard Model**

**Lepton Number Violation (LNV)**

⇨ The only currently viable experimental approach to probe the Majorana nature of neutrino

# More details on double beta decay

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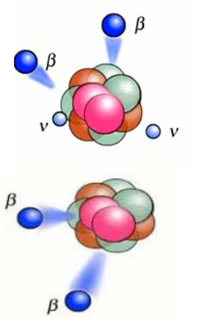
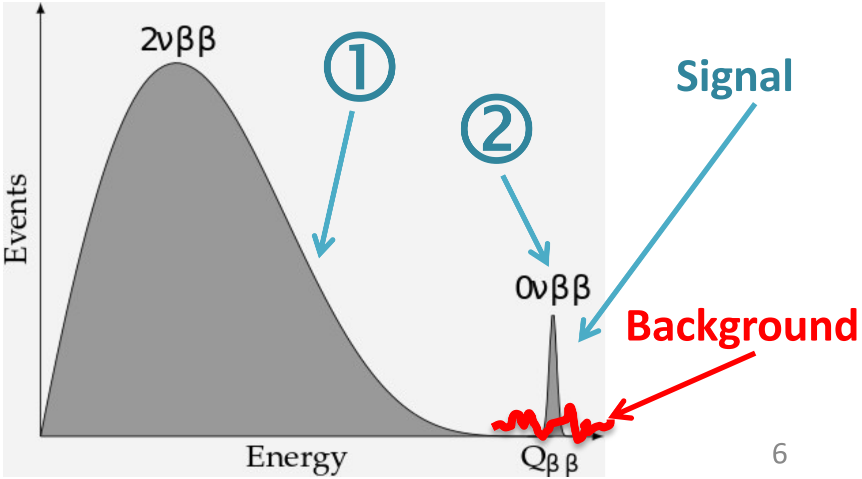



Experimental signatures based on the

**Sum energy spectrum of the two electrons**

$Q_{\beta\beta} \sim$ **2-3 MeV**

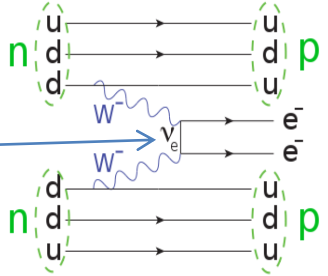
for the most promising candidates



# Why neutrinoless Double Beta Decay is important

- Majorana nature of neutrino (irrespectively of the mechanism)
- See-saw mechanism $\Rightarrow$ naturalness of small neutrino masses
- Leptogenesis and matter-antimatter asymmetry in the Universe
- Neutrino mass scale and hierarchy

**Standard mechanism**: **neutrino physics**
$0\nu2\beta$ is mediated by
**light massive Majorana neutrinos**
(exactly those which oscillate)
Sometimes defined "**mass mechanism**"

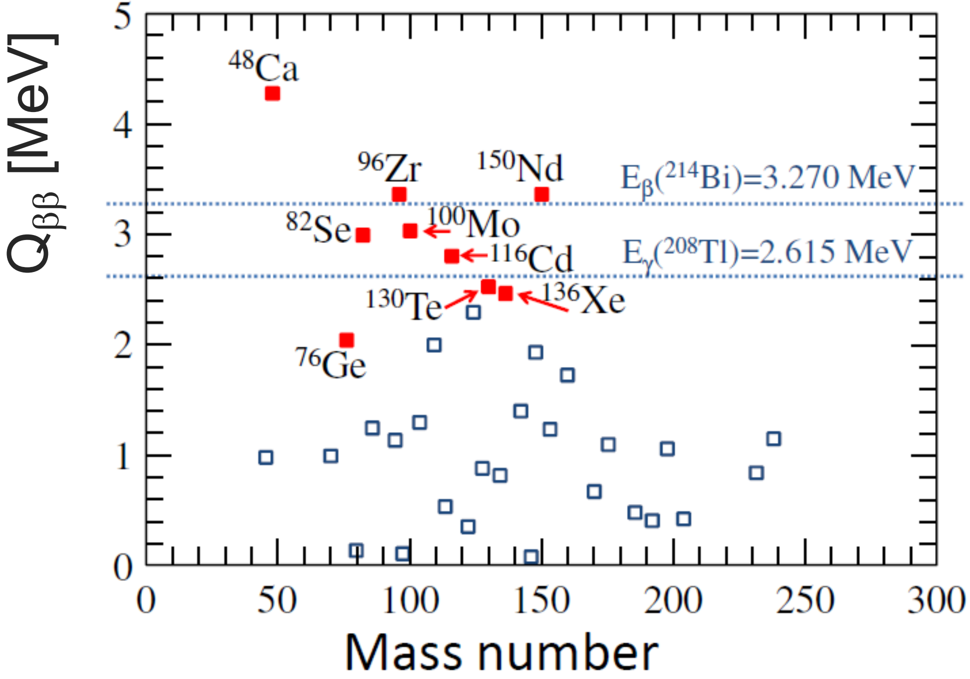



**Non-standard mechanisms**:
**Sterile $\nu$, LNV,...**
Not necessarily neutrino physics

- Minimal straightforward extension of the Standard Model
- Metric to compare experiments and technologies

# Which and how many nuclei?

Double Beta Decay is the main decay channel for 35 nuclei, with a large span of **$Q_{\beta\beta}$** $\rightarrow$ energy available for the decay products




**Most promising candidates**

High $Q_{\beta\beta}$

# Rate in case of mass mechanism

how **0ν-DBD** is connected to **neutrino mixing matrix** and **masses** in case of process induced by light ν exchange (**mass mechanism**)

$$1/\tau = G(Q,Z)\, g_A^4\, |M_{nucl}|^2 \langle m_{\beta\beta} \rangle^2$$

- $1/\tau$: Neutrinoless Double Beta Decay **rate** – what the experimentalists try to measure
- $G(Q,Z)$: **Phase Space** (calculable)
- $g_A$: **Axial vector** coupling constant
- $M_{nucl}$: **Nuclear matrix elements** – what the nuclear theorists try to calculate
- $\langle m_{\beta\beta} \rangle$: Effective **Majorana mass** – parameter containing neutrino physics: **Effective Majorana mass**

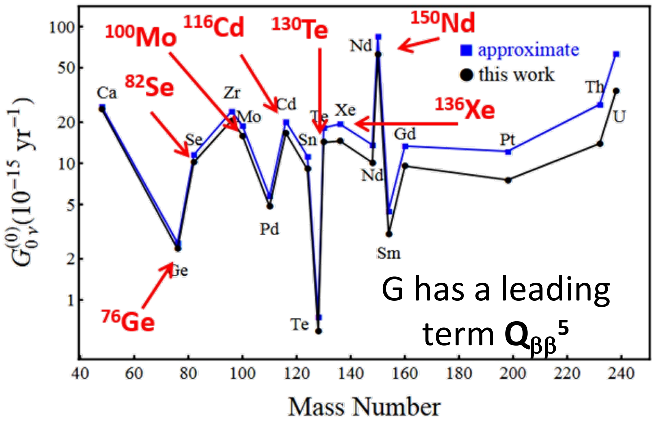
Majorana phases

$$\langle \mathbf{m}_{\beta\beta} \rangle = \left|\, |U_{e1}|^2 m_1 + e^{i\alpha_1} |U_{e2}|^2 m_2 + e^{i\alpha_2} |U_{e3}|^2 m_3 \,\right|$$

# Phase space and nuclear matrix elements


$$1/\tau = G(Q,Z)\, g_A^{\,4}\, |M_{nucl}|^2 \langle m_{\beta\beta}\rangle^2$$

**Phase space**: exactly calculable



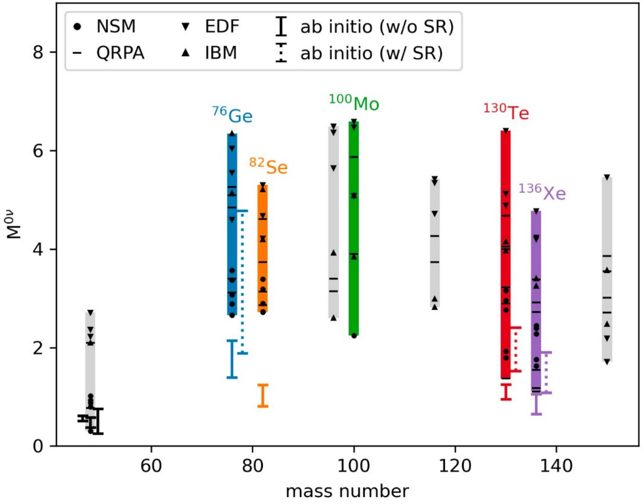

*Phys. Rev. C 85, 034316 (2012)*

$g_A$ = { 1.269 Free nucleon; 1 Quark }

$g_{A,eff}$ ~ **0.6 – 0.8** to be taken (« quenching ») to describe β and 2νββ rates with current nuclear models

- Controversial
- Ab-initio calculation with unquenched $g_A$ are required
- Progress ongoing

- NMEs encode the structure of the parent and daughter nuclides
- Several nuclear models




*Credit Christoph Wiesinger – TAUP 2025*

# Phase space and nuclear matrix elements

$$1/\tau = G(Q,Z)\, g_A^{\,4}\, |M_{nucl}|^2 \langle m_{\beta\beta}\rangle^2$$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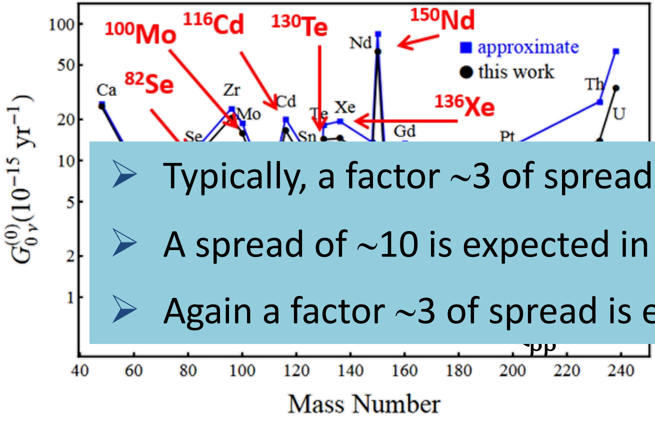


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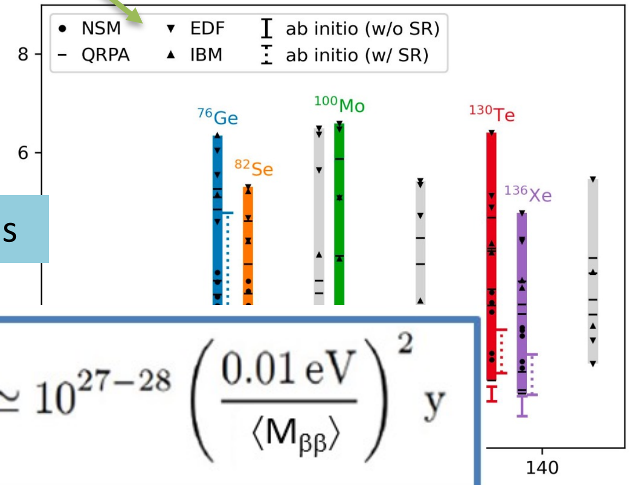
$g_A$ = { 1.269 Free nucleon; 1 Quark }

$g_{A,eff} \sim$ **0.6 – 0.8** to be taken (« quenching ») to describe ... models

- Ab-initio calculation w... unquenched $g_A$ are rec...
- Progress ongoing



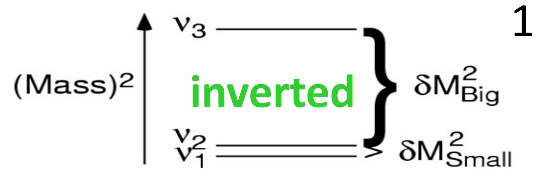

- Typically, a factor ~3 of spread for $|M_{nucl}|$ among the various models
- A spread of ~10 is expected in the half life predictions
- Again a factor ~3 of spread is expected for $\langle M_{\beta\beta}\rangle$

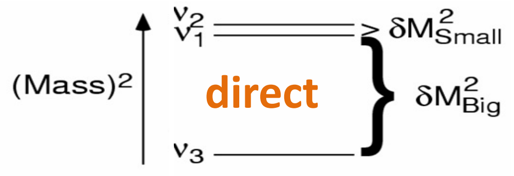
$$T^{0\nu}_{1/2} \simeq 10^{27-28} \left(\frac{0.01\,\mathrm{eV}}{\langle M_{\beta\beta}\rangle}\right)^2 \mathrm{y}$$

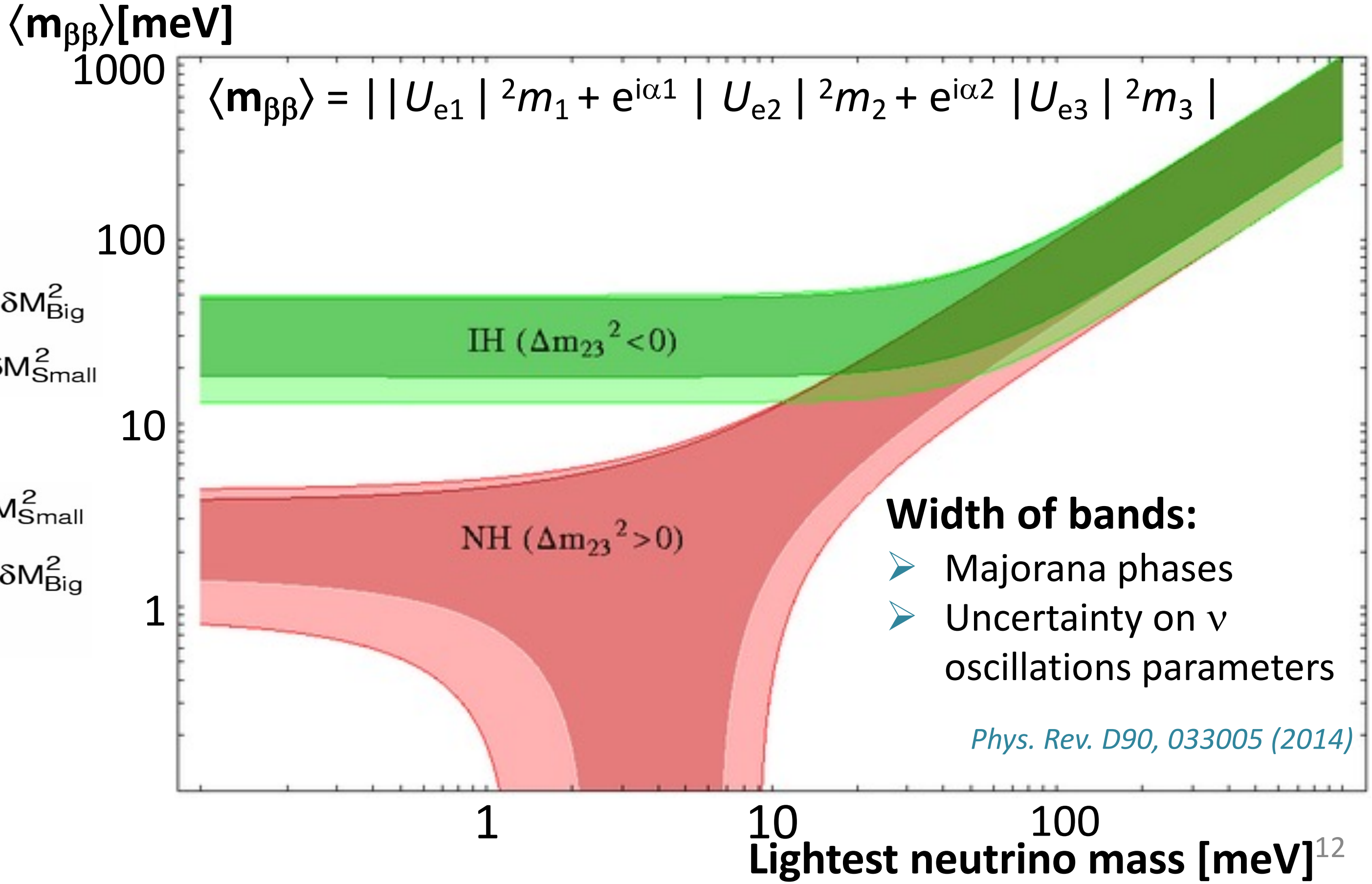
*Credit Christoph Wiesinger – TAUP 2025*

# The effective Majorana mass

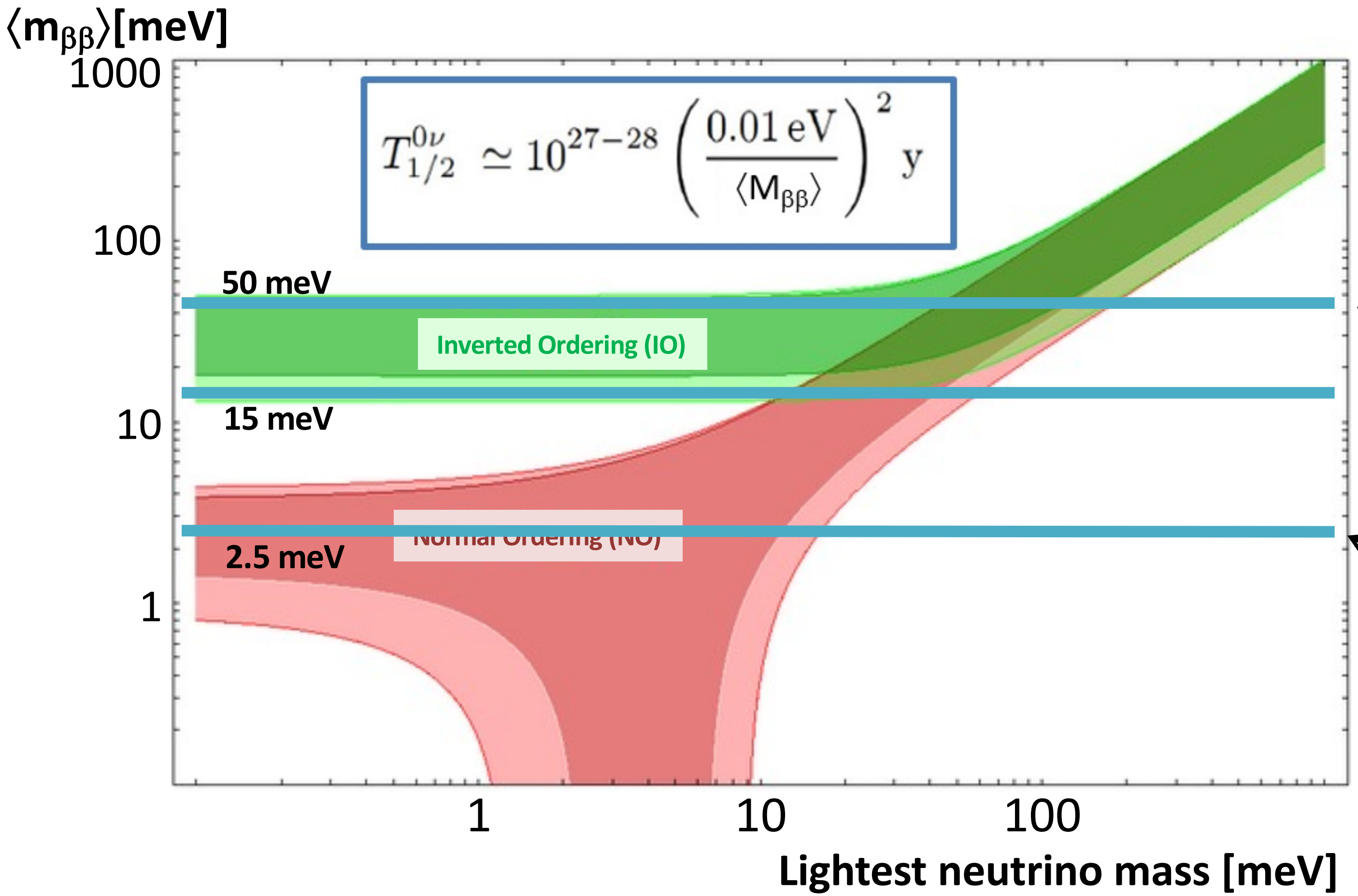
A reference plot



# Experimental challenge

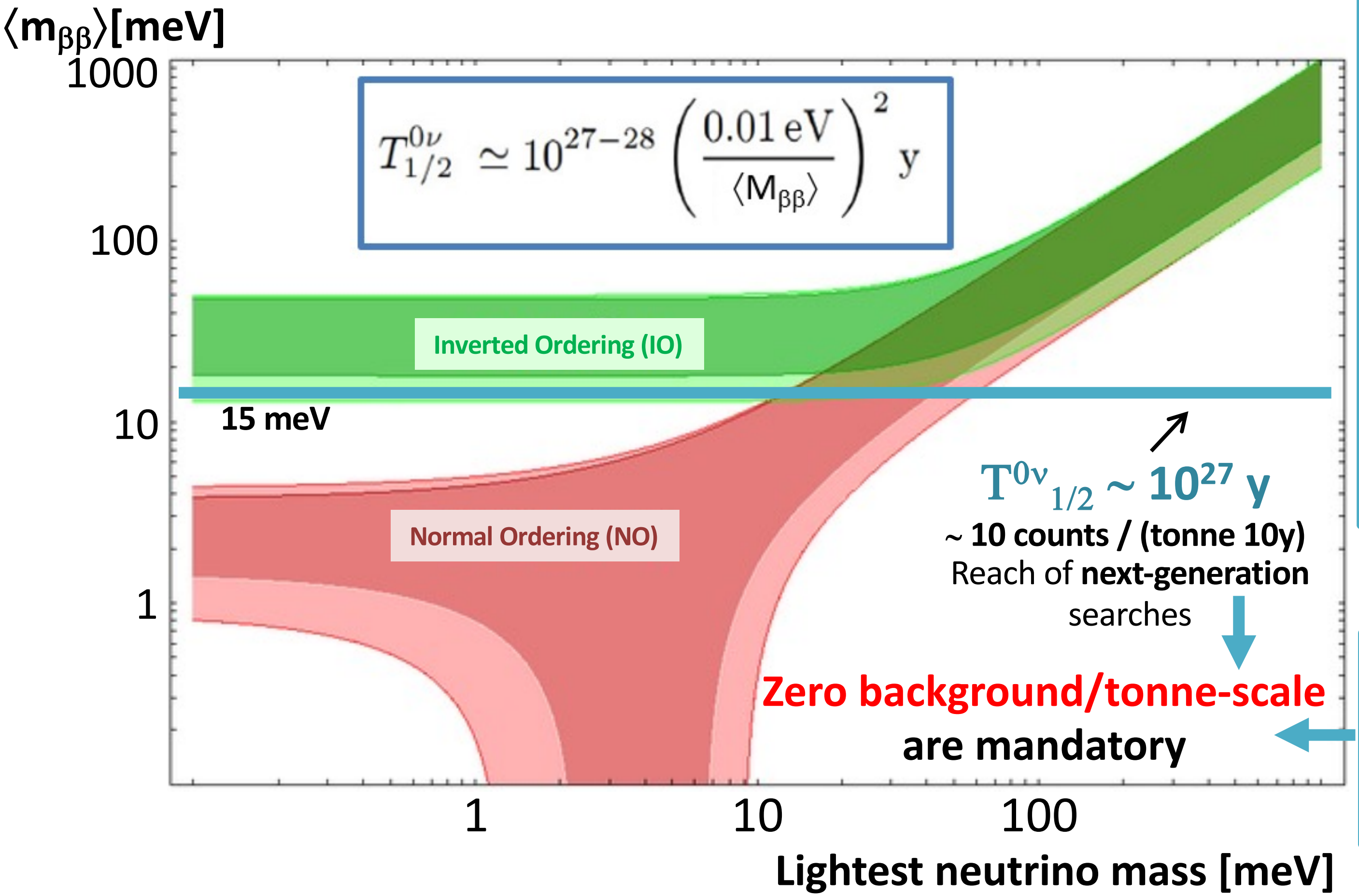



$T^{0\nu}_{1/2} \sim 10^{26}$ y
~ **10 counts / (tonne y)**
Reach of the **current** searches

$T^{0\nu}_{1/2} \sim 10^{27}$ y
~ **10 counts / (tonne 10y)**
Reach of **next-generation** searches

$T^{0\nu}_{1/2} \sim 10^{29}$ y
~ **0.1 counts / (tonne 10y)**
**Next-to-next generation**

# Next generation




**F**: half-life sensitivity

**Poisson limit**

**> 20 background counts**

source mass, live time, energy resolution

$F \propto (MT / b\Delta E)^{1/2}$

background index

$b = \frac{\text{background counts @}Q_{\beta\beta}}{M \times \Delta E \times T}$

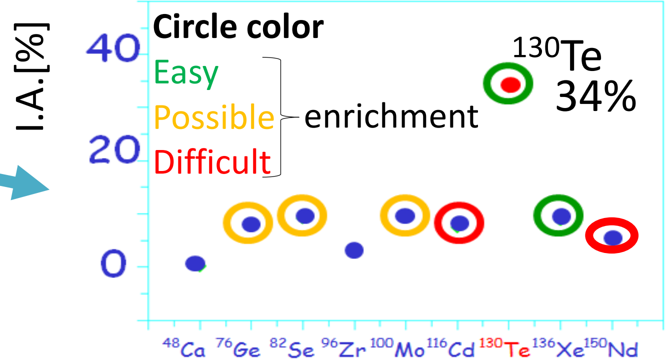
**Zero background**

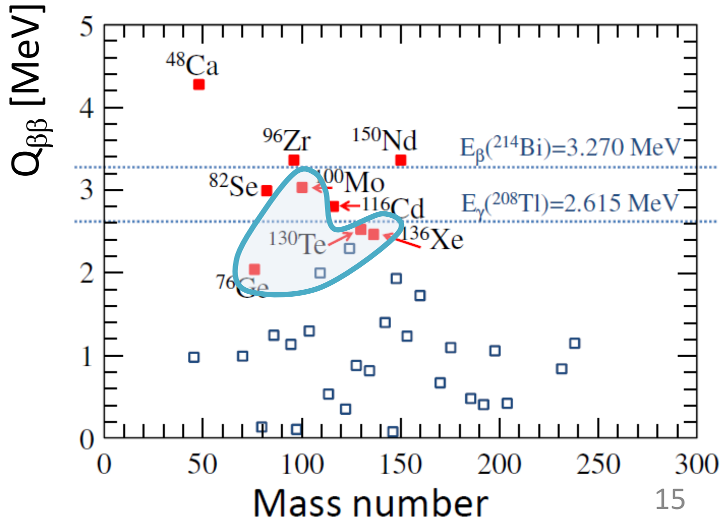
$b \times M \times \Delta E \times T \ll 1$

$F \propto MT$

# Factors guiding isotope selection

- **High isotopic abundance** (I.A.) and/or **easy enrichment**
- **High $Q_{\beta\beta}$**
  - Larger phase space: $G(Q,Z) \propto Q^5$
  - Easier background control
- Compatibility with a beneficial detection technique
  - **High energy resolution**
  - **Background identification**
  - **Efficiency and scalability**



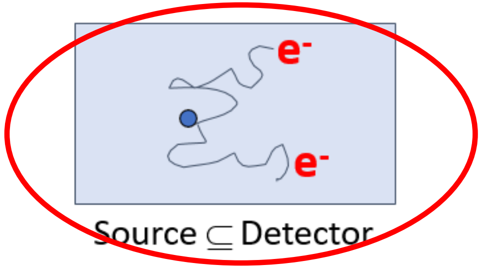
# General features for $0\nu2\beta$ searches

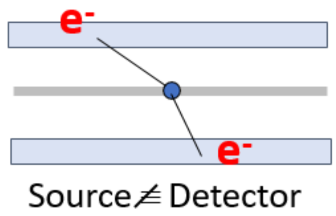
## Requests for the source

① **Large source** → tonne scale → > $10^{27}$ nuclei

② **Maximize efficiency**

→ The option in which the source is separated from the detector is abandoned for next-generation experiments




However, this option may be interesting in case of discovery to investigate the mechanism of $0\nu2\beta$

## Requests for the background

Generic measures as underground operation, shielding (passive and active), radiopurity of materials, vetos are common to $0\nu2\beta$ and other rare event search

### Specific desirable features for $0\nu2\beta$

- High energy resolution
- Particle identification
- Tracking / Event topology
- Multi-site vs. single-site events
- Surface vs. bulk events
- Fiducial volume / Active shielding
- Final-state nucleus identification

# Currently competing technologies (1)

① **Source dilution in a liquid scintillator**

KamLAND-Zen ($^{136}$Xe) – SNO+ ($^{130}$Te)

- Re-use of existing infrastructures
- Large amount of isotopes (multi-ton)
- Isotope dilution (a few %)
- Energy resolution ~ 10 % FWHM
- Rough space resolution

② **TPCs**

EXO-200 – NEXT – nEXO ($^{136}$Xe)

- Large amount of isotopes (multi-ton)
- Full isotope concentration
- Energy resolution ~ 1 % - 2 % FWHM
- Event topology

Liquids and gases

③ **Semiconductor detectors**

GERDA – LEGEND ($^{76}$Ge)

④ **Bolometers**

CUORE ($^{130}$Te) – AMoRE – CUPID ($^{100}$Mo)

- Crystal array (~1 ton scale in total)
- (Almost) full isotope concentration
- Energy resolution ~ 0.1 % - 0.2 % FWHM
- Particle identification
- Pulse shape discrimination

Single crystals

# Currently competing technologies (2)

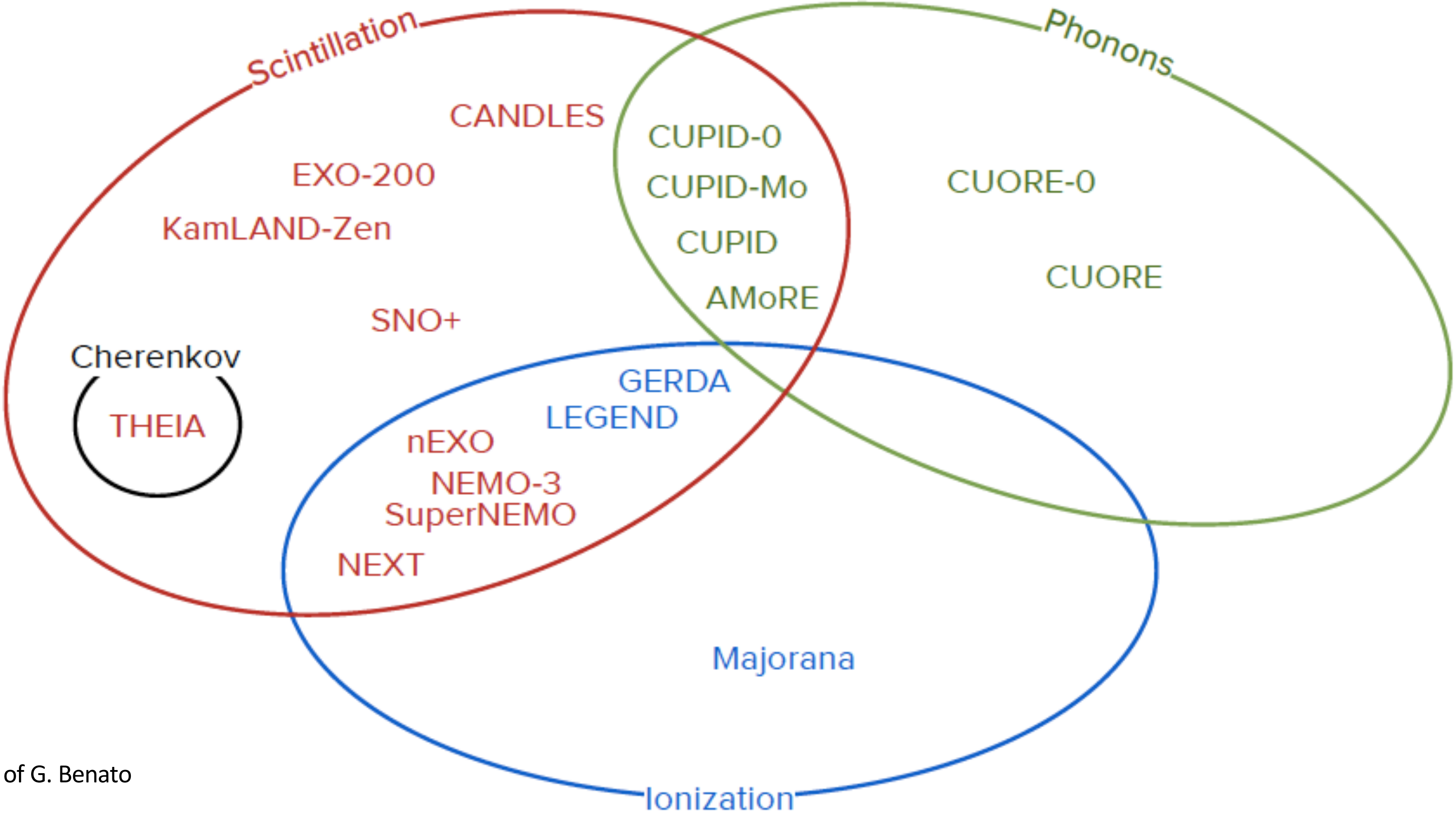
| Readout channel | Energy resolution | Particle identification | Sensitivity to position | Applicable to multiple isotopes |
|---|---|---|---|---|
| Ionization | 0.1-1% | Only in gas | Yes | Not really |
| Phonons | ~0.2% | Nope | Nope | Yes |
| Scintillation | Few % | α vs β | In liquids and gases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

***Take-away messages***:

- The best detector technology does not exist
- The combination of readout channels is very welcome

→Good resolution with one, background rejection with the other

# Currently competing technologies (3)




Courtesy of G. Benato

# Experimental status

**KamLAND-Zen 800** - $T_{1/2} > 3.8\times10^{26}$ y
*arXiv:2406.11438 (2024)*

**GERDA** - $T_{1/2} > 1.8\times10^{26}$ y
*Phys. Rev. Lett. 125, 252502 (2020)*

**EXO-200** - $T_{1/2} > 3.5\times10^{25}$ y
*Phys. Rev. Lett. 123, 161802 (2019)*

**MAJORANA dem.** - $T_{1/2} > 8.3\times10^{25}$ y
*Phys. Rev. Lett. 130, 062501 (2023)*

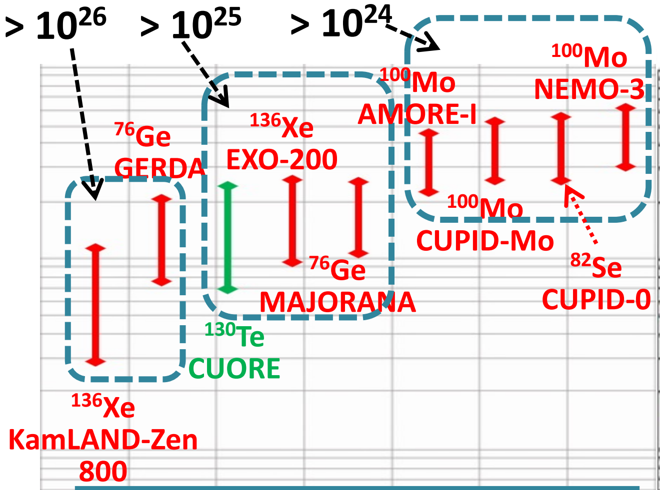
**CUORE** - $T_{1/2} > 3.5\times10^{25}$ y
*TAUP 2025 (2025)*

**CUPID-0** - $T_{1/2} > 4.6\times10^{24}$ y
*Phys. Rev. Lett. 129, 111801 (2022)*

**AMORE-I** - $T_{1/2} > 2.9\times10^{24}$ y
*Phys. Rev. Lett. 134, 082501 (2025)*

**CUPID-Mo** - $T_{1/2} > 1.8\times10^{24}$ y
*Eur. Phys. J. C 82, 1033 (2022)*

**NEMO-3** - $T_{1/2} > 1.1\times10^{24}$ y
*Phys. Rev. D 92, 072011 (2015)*

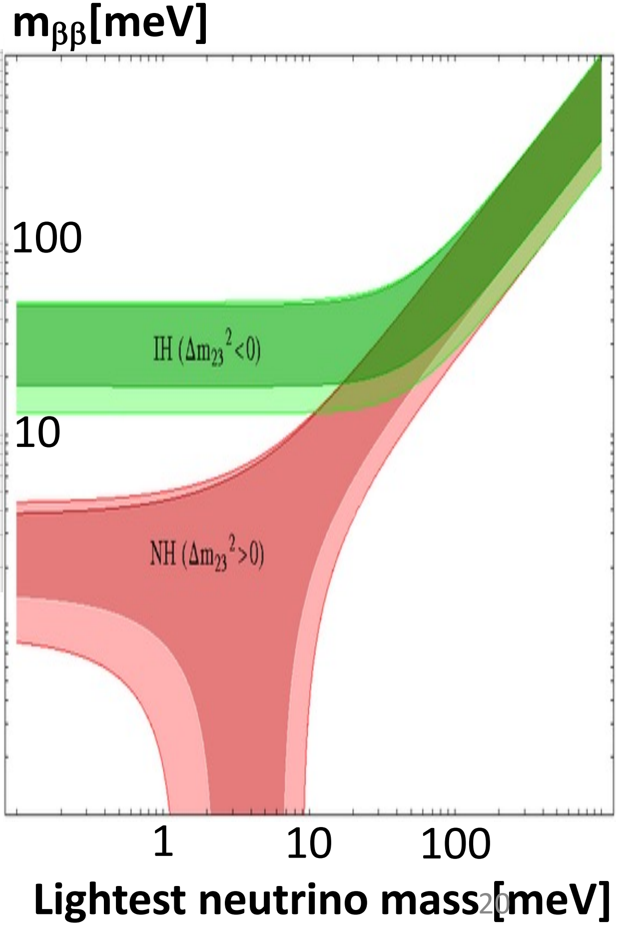



**$T_{1/2} > 10^{24}$ y 90% C.I.**
**restricted club**

All these experiments stopped except **CUORE** (expected end: mid-2026)

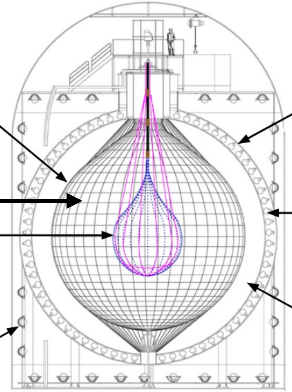
## Waiting for next generation!

**LEGEND200 already in data taking [$1.9\times10^{26}$y]**



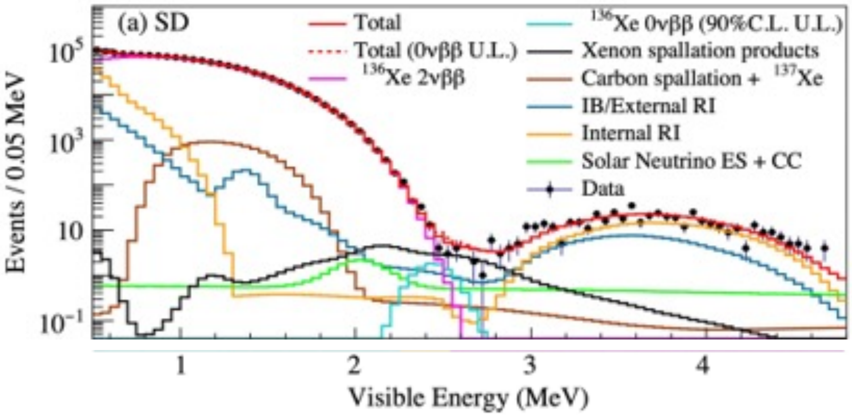
# KamLAND-Zen

- **1000 ton liquid scintillator detector**
- Re-use facility used for ν oscillation experiment




- **Nylon balloon** with **$^{enr}$Xe-loaded** scintillator
- **KamLAND-Zen-800**, 2$^{nd}$ phase
  - **Large isotope mass**, 750 kg of 91% $^{136}$Xe
  - **Poor energy resolution**, 4% at 2.5 MeV
  - ➔ Final result, **world-best constraint**
    $T_{1/2}$($^{136}$Xe) **> 3.8·10$^{26}$ yr** (90% CL)
    → $m_{\beta\beta}$ **< [28, 122] meV** (90% CL)
    **> 2.6·10$^{26}$ yr** (90% CL, sensitivity)

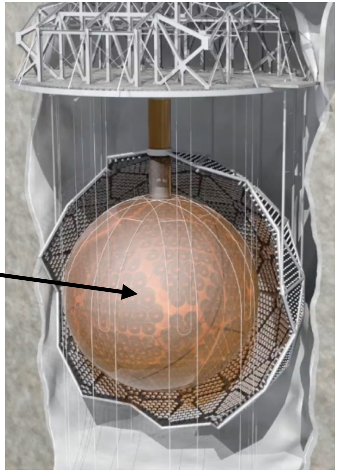
[Abe et al., arXiv:2406.11438]




- **KamLAND2-Zen**, planned detector upgrade ➔ After 5 years: $\mathbf{T_{1/2}^{0\nu}}$ > 2 x 10$^{27}$ yr

# SNO+

- **780 ton liquid scintillator** detector
  Re-use facility used for solar ν experiment
- Staged **$^{nat}$Te loading**
  - **Large isotope mass,**
    e.g. 1.3 ton of $^{130}$Te for 0.5% loading
  - **Poor energy resolution**, 4% at 2.5 MeV

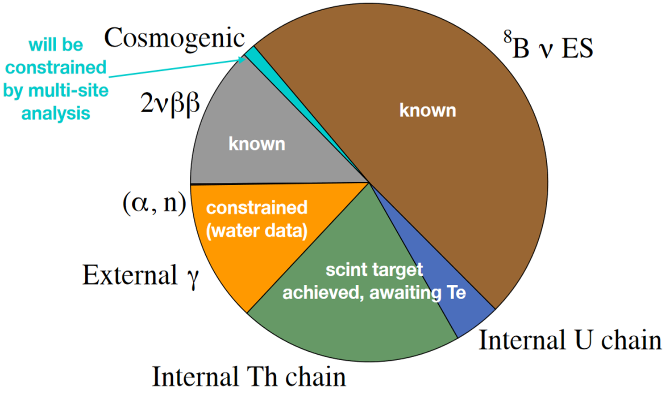


- Water phase completed, scintillator phase ongoing, **0.5% loading in preparation**

  ➔ Projected sensitivity

  $T_{1/2}(^{130}\mathrm{Te})$ **> 2.0·10$^{26}$ yr** (90% CL), 3 yr with 0.5%

  $T_{1/2}(^{130}\mathrm{Te})$ **> 7.4·10$^{26}$ yr** (90% CL), 5 yr with 1.5 %




**Background budget**
(low concentration → dominated by $^8$B solar ν)

# nEXO

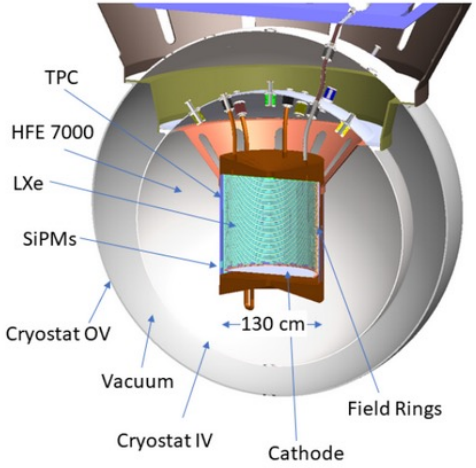
- **Liquid $^{enr}$Xe time projection chamber,**
  - building on EXO-200
  - **Large isotope mass**, 5 ton of 90% $^{136}$Xe
  - **Reasonable energy resolution**, 1% at 2.5 MeV

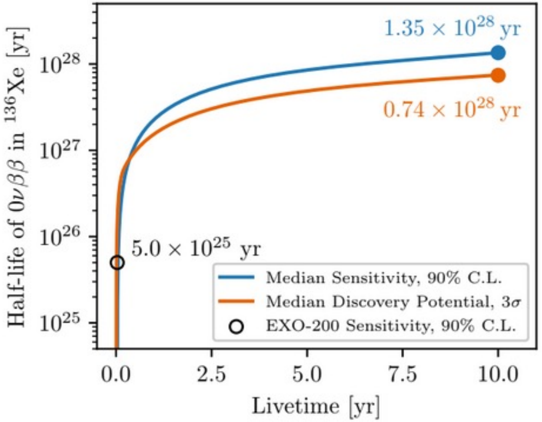
➔ Projected sensitivity, 10 yr
[Adhikari et al., J.Phys.G 49 (2022) 1, 015104]

$T_{1/2}(^{136}\text{Xe})$ **> 1.35·10$^{28}$ yr** (90% CL)

$T_{1/2}(^{136}\text{Xe})$ = **7.4·10$^{27}$ yr** (3σ) Discovery sensitivity

- Development of **Ba tagging**
  [Chambers et al., Nature 569 (2019) 7755, 203-207; Ray et al., Atoms 12 (2024) 12, 71]

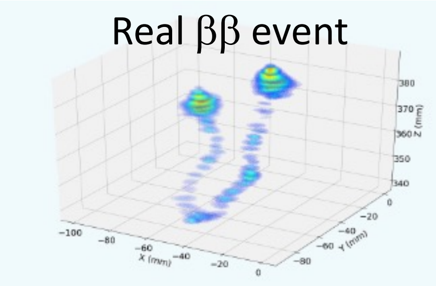



**Background** dominated by Rn outgassing and intrinsic radioactivity

# NEXT

- **High pressure (10-15 bar) gas $^{enr}Xe$ TPC**
  - Primary scintillation ($t_0 \rightarrow$ z coordinate)
  - Electroluminescence for energy resolution and for tracking




**Staged approach**

- **NEXT-White** (2015-2021) – **LSC, Spain**

5 kg prototype

- **NEXT-100** (2023-2029**)** – **LSC, Spain**

**Upscaling of NEXT-White** → 97 kg

  - Currently, operation at 4 bar
  - Operation at 10 bar by 2026
  - Good energy resolution <1%

Projected sensitivity

$T_{1/2}(^{136}Xe)$ **> $4 \cdot 10^{25}$ yr** (90% CL) – 3 year

[JHEP 2016, 159 (2016)]

- **NEXT-HD** (High Definition) – start in 2030

Up to 1 ton enriched Xe gas at 20 bar

**Target sensitivity: $10^{27}$ y** **5 ton×y**

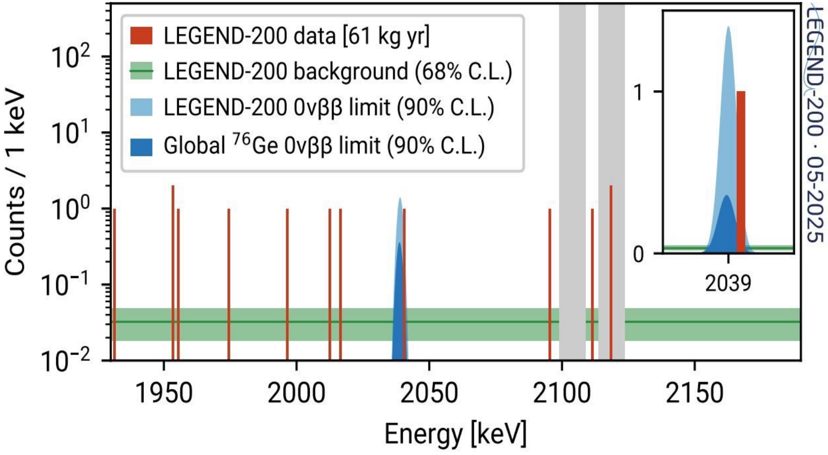
- **NEXT-BOLD** (Barium On Light Detection)
  - Ba tagging by **SMFI** (Single Molecule Fluorescence Imaging) was proved – demonstrator under R&D
  - Background free [JINST 18 P08006 (2023)]

**Target sensitivity: $10^{28}$ y** **10 ton×y**

# LEGEND

*A. Leder at this conference*

- High-purity $^{enr}$Ge detectors in **active liquid argon shield**, building on:
  - GERDA, **lowest background**, background-free [Agostini et al., PRL 125 (2020) 25, 252502]
  - MAJORANA, **best energy resolution**, 2.5 keV (FWHM) at 2.0 MeV [Arnquist et al., PRL 130 (2023) 6, 062501]




- **LEGEND-200**, up to 200 kg of 90% $^{76}$Ge in
  - Upgraded GERDA infrastructure, improved light read-out
  - Data taking

➔ Projected discovery sensitivity, 5 yr [Agostini et al., Rev.Mod.Phys. 95 (2023) 2, 025002]

$T_{1/2}(^{76}\mathrm{Ge}) = \mathbf{1.5 \cdot 10^{27}\ yr}$ (3σ)

- **LEGEND-1000**, new infrastructure in preparation at LNGS
  - **Sizeable isotope mass**, 1 ton of 90% $^{76}$Ge

➔ Projected discovery sensitivity, 10 yr

- [Abgrall et al., arXiv:2107.11462]

$T_{1/2}(^{76}\mathrm{Ge}) > \mathbf{1.6 \cdot 10^{28}\ yr}$ (90% CL)

$T_{1/2}(^{76}\mathrm{Ge}) = \mathbf{1.3 \cdot 10^{28}\ yr}$ (3σ)

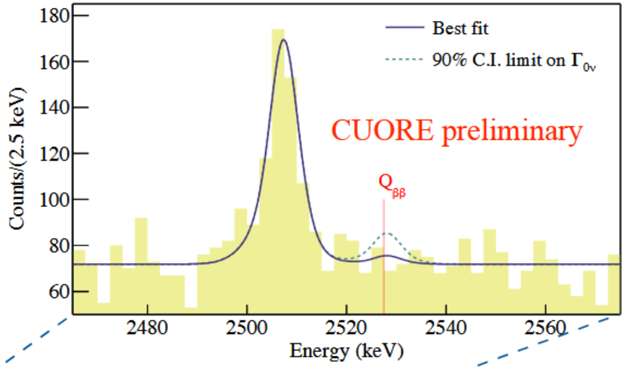
# CUORE

*I. Nutini at this conference*

## CUORE - LNGS, Italy

- **Array of natural $TeO_2$ crystals operated as bolometers at 10 mK**
  - Built on the precursor CUORICINO experiment
  - **988 $TeO_2$ crystals**, arranged in **19 towers – 206 kg of $^{130}Te$**
  - Energy resolution ΔE ~ 7.8 keV FWHM @$Q_{\beta\beta}$

**Results: $T_{1/2}$ > 3.5×$10^{25}$ y (90%) – 2039 kg y**
[TAUP 2025]

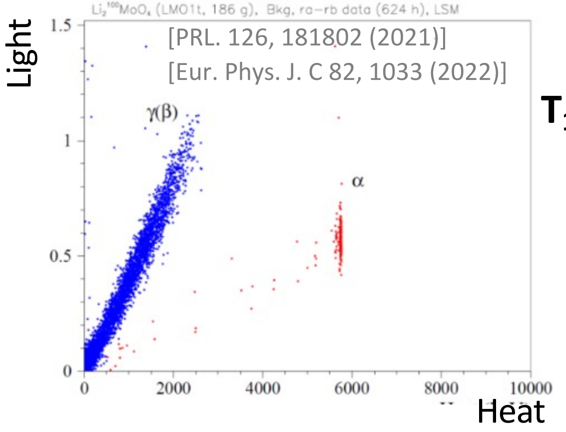



Background dominated by **energy-degraded surface α's**

## CUPID demonstrators

### CUPID-Mo - LSM, France

- **Pure bolometers → Scintillating bolometers**
- **$^{130}Te$ ($TeO_2$) → $^{100}Mo$ (enriched $Li_2MoO_4$)**
  $Q_{\beta\beta}$=3034 keV > 2.6 MeV (**Reject external γ background**)
- **20 $Li_2Mo_4$ crystals – 2.26 kg of $^{100}Mo$**
- Energy resolution ΔE ~ 7.7 keV FWHM @$Q_{\beta\beta}$




**Results:**
**$T_{1/2}$ > 1.8×$10^{24}$ y (90%)**
**2.71 kg y**

**Reject α background**

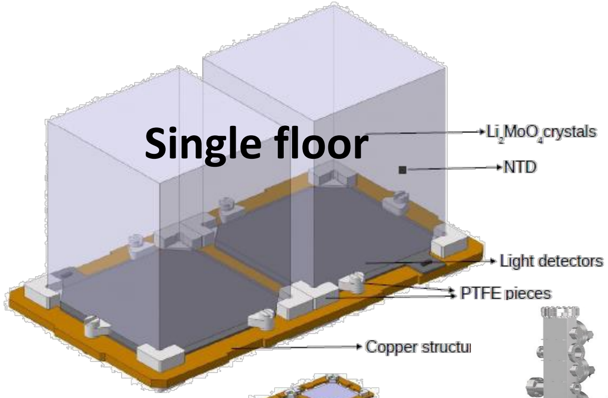
### CUPID-0 - LNGS, Italy $Zn^{82}Se$

**First scintillating bolometer demonstrator**

[PRL, 129, 111801 (2022)]

**$T_{1/2}$ > 4.6×$10^{24}$ y**

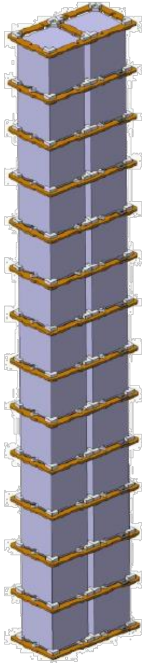
# CUPID

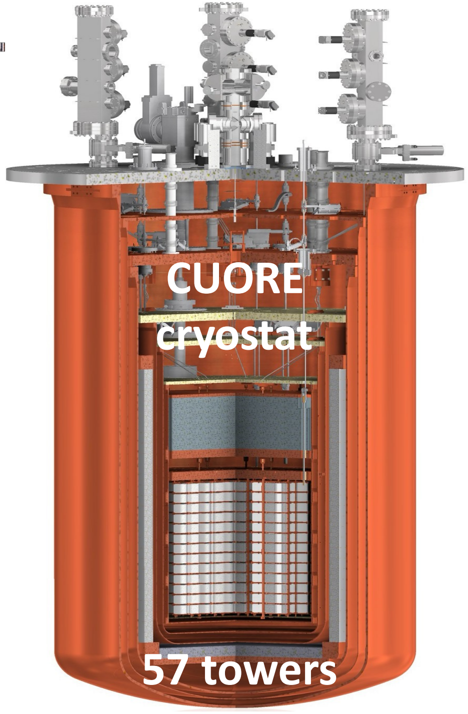



**$^{enr}$Mo-containing scintillating bolometers**

- Heat readout based on **NTD Ge sensors**
- Energy resolution **ΔE ~ 5 keV FWHM @$Q_{\beta\beta}$**

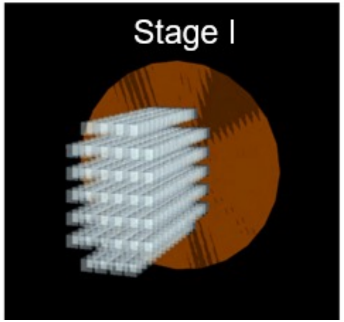
- Exploit CUORE infrastructure changing isotope
- Adopt CUPID-Mo technology
- Single module: $Li_2{}^{100}MoO_4$ **45×45x45 mm – 280 g**
- **1596 crystals**
- **240 kg of $^{100}$Mo** with >95% enrichment
- **Bolometric Ge light detectors** as in CUPID-Mo, CUPID-0 upgraded with **Neganov-Trofimov-Luke mode** to achieve the required rejection of $2\nu2\beta$ random coincidences [**BINGO/CROSS development**]

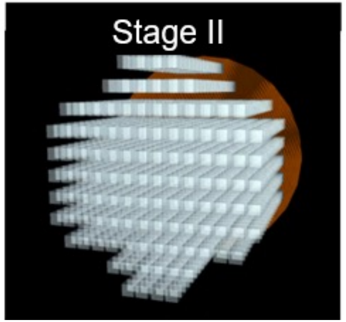


# CUPID – Timeline and sensitivity

- **Staged development**
  - Stage-I $\rightarrow$ 1/3 of crystals (**2030-2033**)
  - Stage-II $\rightarrow$ remaining 2/3 of crystals (**2034**)




## CUPID Stage-I

- **3 σ - discovery sensitivity**
  **$T^{0\nu}_{1/2}$ = 0.2 x $10^{27}$ yr**
  **$m_{\beta\beta}$ < (26-44) meV**

## FULL CUPID

- **Exclusion sensitivity 90% C.I.**
(10 y livetime - 240 kg $^{100}$Mo + 5 keV FWHM)
  **$T^{0\nu}_{1/2}$ > 1.4 x $10^{27}$ yr**
  **$m_{\beta\beta}$ < (10-17) meV**
- **3 σ - discovery sensitivity**
  **$T^{0\nu}_{1/2}$ = 1 x $10^{27}$ yr**
  **$m_{\beta\beta}$ < (12-21) meV**

R&D ongoing to reduce the BI by a further order of magnitude (BINGO and others), making possible

- **CUPID-1T**

10 y livetime - 1000 kg $^{100}$Mo + 5 keV FWHM
  **$T^{0\nu}_{1/2}$ > 9.2 x $10^{27}$ yr**
  **$m_{\beta\beta}$ < (4.0-6.9) meV**

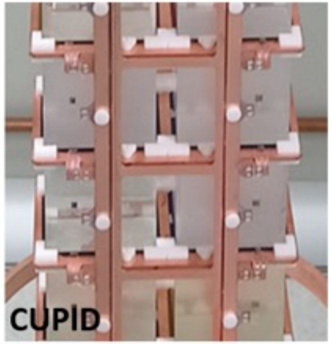
Deep inside the normal ordering region

# Beyond CUORE and CUPID: BINGO

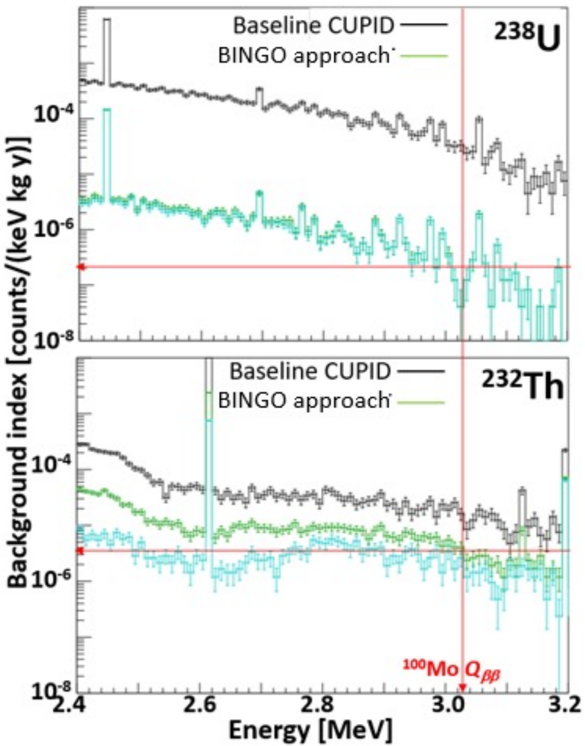
**Techniques for background rejection in future $Li_2MoO_4$ / $TeO_2$ based experiments**
**3 main innovations**

- **Internal active shield** (ultrapure BGO scintillators)
  - mitigate $\gamma$ background in $TeO_2$
- **Revolutionary assembly** to reject surface background
- **Enhanced-sensitivity (Neganov-Trofimov-Luke)** light detectors
  - mitigate pile-up
  - read out the BGO active shields
  - detect Cherenkov light in $TeO_2$

**MINI-BINGO in Modane (demonstrator)**
12 $Li_2MoO_4$ crystals
12 $TeO_2$ crystals from 2026

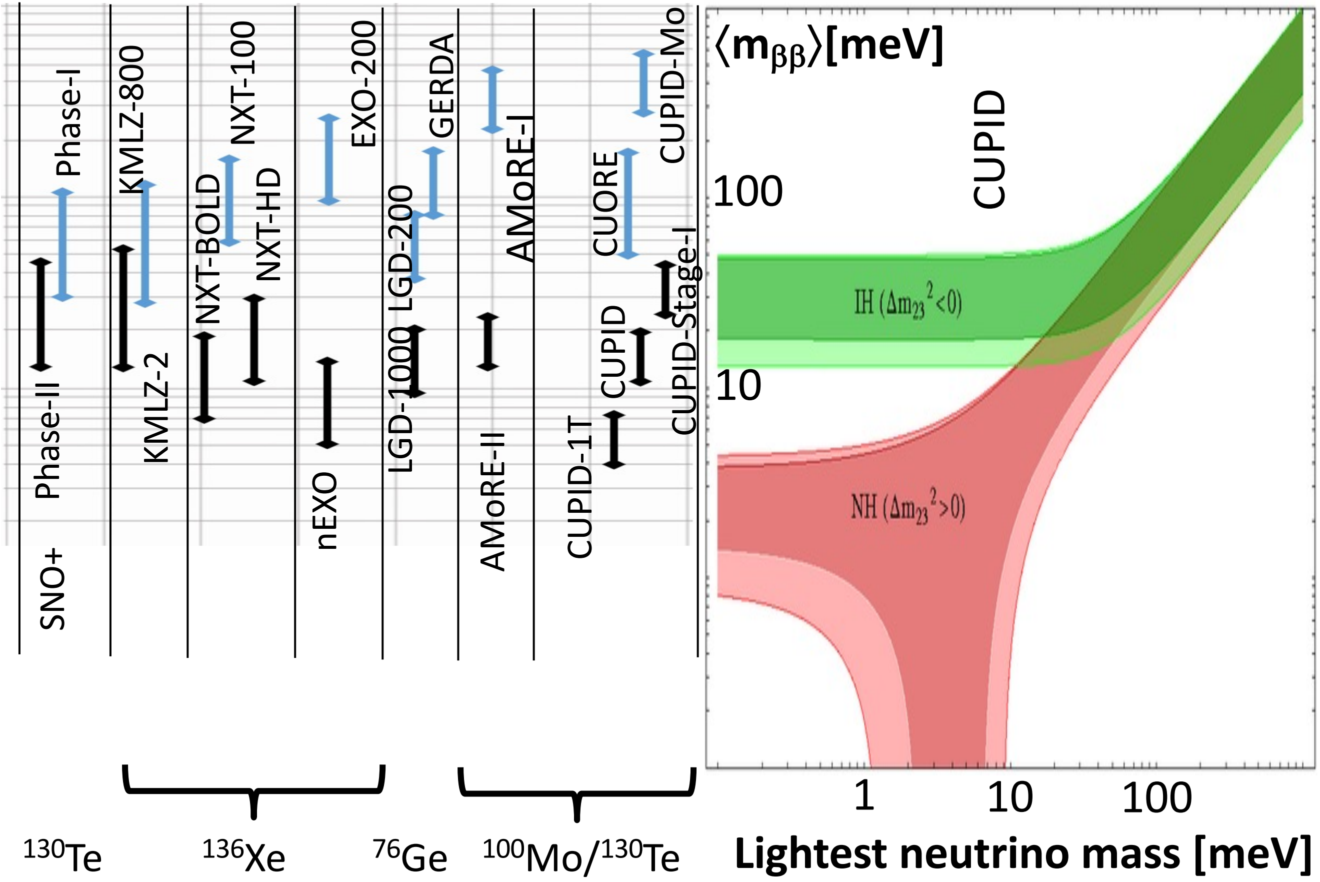

Simulation CUPID vs. BINGO



# How we are moving forward

**Current generation** (final sensitivity for concluded/running projects)

**Next generation** (projects to be started on 5-10 years' time scale)



# Conclusions

- $0\nu\beta\beta$ is a crucial process for particle physics and cosmology
- Several approaches and technologies make this field very active
- Many projects will extend their sensitivity in the next years
- Next-generation experiments have a good discovery potential

# Neutrinoless double beta decay is a high-risk, high-reward pursuit

A hard search, but a discovery would reshape physics:
the Standard Model, mass, and the matter–antimatter asymmetry.

# What lies ahead

## From the current to the next generation

Emphasis on **7 promising research lines**

| | | | |
|---|---|---|---|
| ① | KamLAND-Zen 400 → KamLAND-Zen 800 → KamLAND2-Zen | **$^{136}$Xe** | **Source dilution in a liquid scintillator** |
| ② | SNO+ → SNO+-phase II | **$^{130}$Te** | |
| ③ | EXO-200 → nEXO | **$^{136}$Xe** | **Xe TPCs** |
| ④ | NEXT-White → NEXT-100 → NEXT-HD / NEXT-BOLD | | |
| ⑤ | {GERDA, MAJORANA dem.} → LEGEND-200 → LEGEND-1000 | **$^{76}$Ge** | **Semiconductor detectors – Ge diodes** |
| ⑥ | AMORE-I → AMORE-II | **$^{100}$Mo** | **Bolometers** |
| ⑦ | {CUORE **$^{130}$Te**, CUPID-Mo **$^{100}$Mo**, CUPID-0 **$^{82}$Se**} → CUPID → CUPID 1t | **$^{100}$Mo** | |

# Neutrino mass scale and effective neutrino mass

**Cosmology**, **single** and **double β decay** measure different combinations of the neutrino mass eigenvalues, constraining the neutrino mass scale

$$\Sigma \equiv \sum_{i=1}^{3} m_i$$

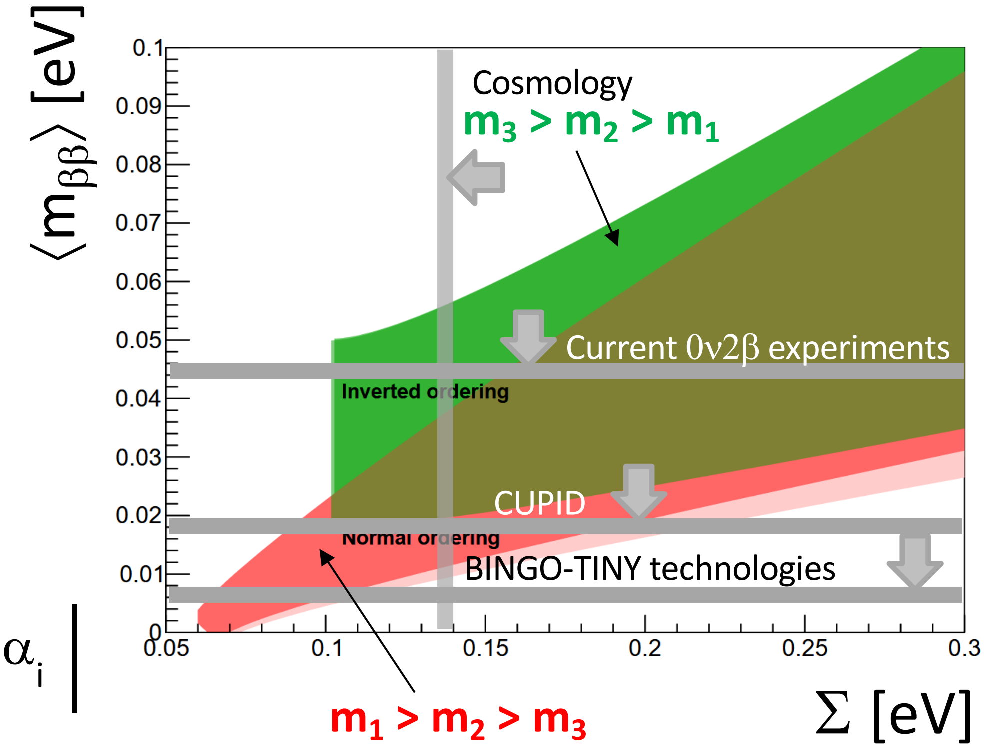
**Cosmology-** simple sum - pure kinematical effect

$$\langle m_\beta \rangle \equiv \left( \sum_{i=1}^{3} m_i^2 \, |U_{ei}|^2 \right)^{1/2}$$

**β Decay – KATRIN -** incoherent sum - **real** neutrino

$$\langle m_{\beta\beta} \rangle \equiv \left| \sum_{i=1}^{3} m_i \, |U_{ei}|^2 e^{i\alpha_i} \right|$$

**double β decay -** coherent sum - **virtual** neutrino - Majorana phases



# Many theoretical models for the nuclear matrix elements

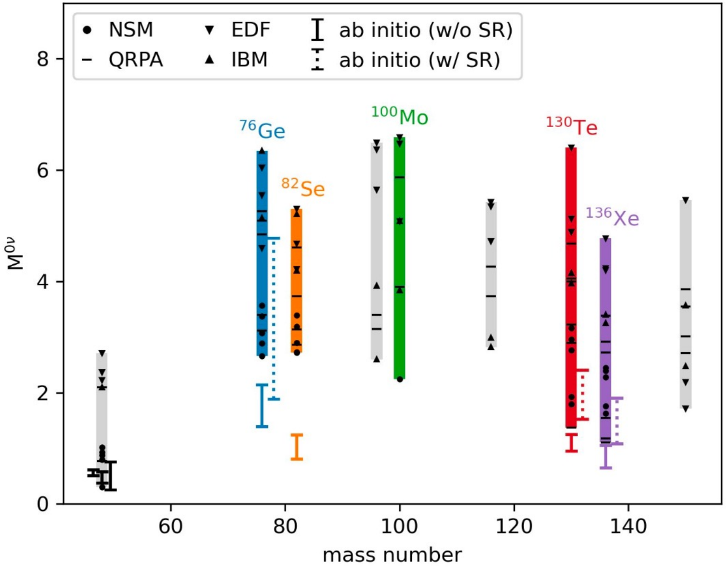

$$1/\tau = G(Q,Z)\, g_A^4\, |M_{nucl}|^2 \langle m_{\beta\beta}\rangle^2$$

The $0\nu\beta\beta$ community in general assumes **$g_A \approx 1.27$** (no quenching)

- Different **phenomenological many-body methods** using different approximations (e.g. limited number of nuclear shells), **significant spread**
  [Agostini et al., Rev.Mod.Phys. 95 (2023) 2, 025002; ..]
- Experiments provide **range of $m_{\beta\beta}$ constraints**

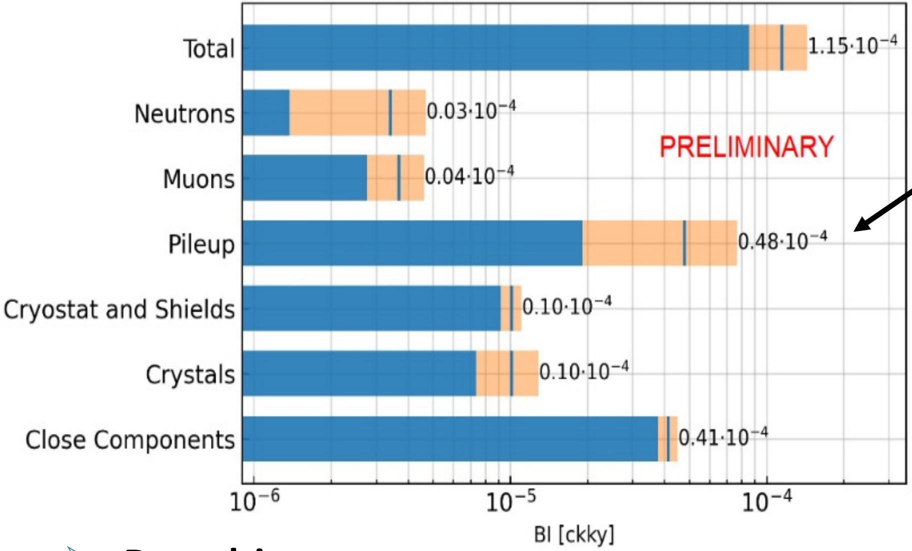
  $$T_{1/2} = .. \rightarrow m_{\beta\beta} = [.., ..]$$

- First **ab initio calculations available**, may resolve quenching issue
  [Yao et al., PRL 124 (2020); Belley et al., PRL 126 (2021); Novario et al., PRL 126 (2021); Cirigliano et al., PRL 120 (2018); Belley et al., arXiv:2307.15156; Belley et al., PRL 132 (2024); ..]
- Effective field theory (EFT) analysis identified additional **short-range contribution**
  [Cirigliano et al., PRL 120 (2018) 20, 202001; ..]

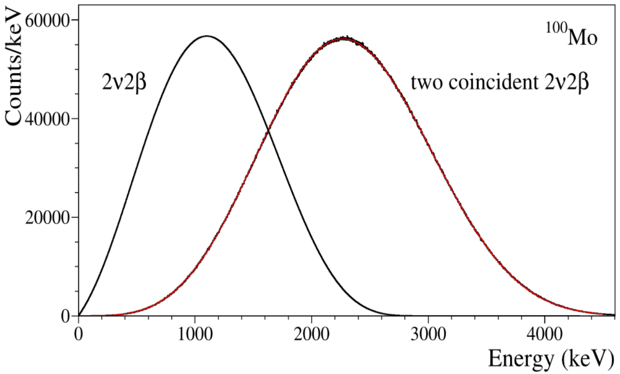



*Credit Christoph Wiesinger – TAUP 2025*

# CUPID - background




Dominant contributions: **pile-up events** (random coincidences of ordinary $2\nu\beta\beta$ events)




- **Fastest $2\nu2\beta$ decay: $T_{1/2} \sim 7.1 \times 10^{18}$ y**
- **Slow response of bolometric signals**

Mitigated by Neganov-Trofimov-Luke light detectors

➢ **Data driven**:
based on CUORE and CUPID-Mo background models

[Phys. Rev. D 110 (2024) 052003] [Eur. Phys. J. C 83 (2023) 675]

**Conservative projections based on current available data: BI = 1.1 x $10^{-4}$ ckky**

**Two orders of magnitude better than in CUORE**

# AMoRE

**$^{enr}$Mo-containing scintillating bolometers**

- Heat readout based on **MMC sensors**
- Energy resolution **ΔE ~ 10-15 keV FWHM @$Q_{\beta\beta}$**

- **AMoRE-I (2020-2022)**
  - 13x $^{48depl}Ca^{100}MoO_4$ (4.6 kg)
  - 5x $Li_2{}^{100}MoO_4$ (1.6 kg)

  **Results: $T_{1/2}$ > 2.9×10$^{24}$ y**
  [Phys. Rev. Lett. 134, 082501 (2025)]

- **AMORE-II** – from 2026 – phased approach
  - Secured **110 kg of $^{100}$Mo** – 596x $Li_2{}^{100}MoO_4$ crystals
  - New cryostat and underground lab – work in progress

**Projected sensitivity: 8×10$^{26}$ y** in 5 years