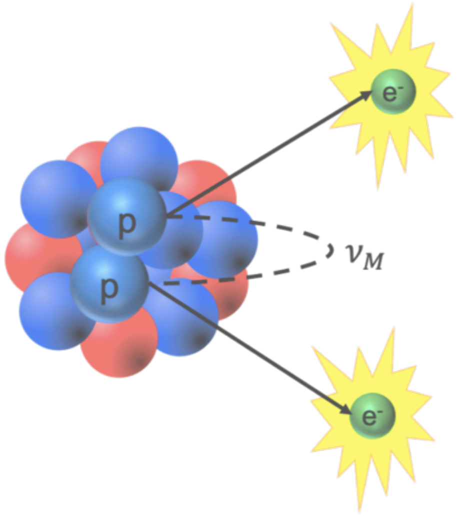
cea irfu



Neutrinoless Double Beta Decay: the creation of matter without antimatter partners

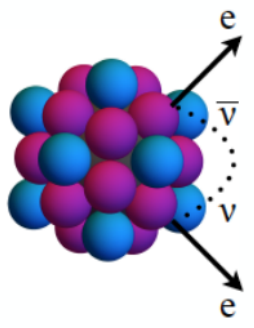
Claudia Nones

IRFU/DPhP

Outline

- What neutrinoless double beta decay is
- Why it is important
- How much it is difficult
- Which isotopes and which techniques
- State of the art
- The future

Nuclear Double Beta Decay

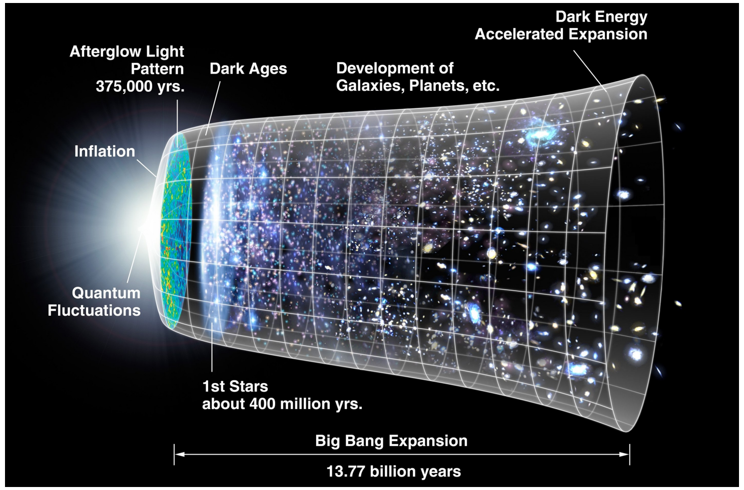


Double Beta Decay is the **rarest nuclear weak process**

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}

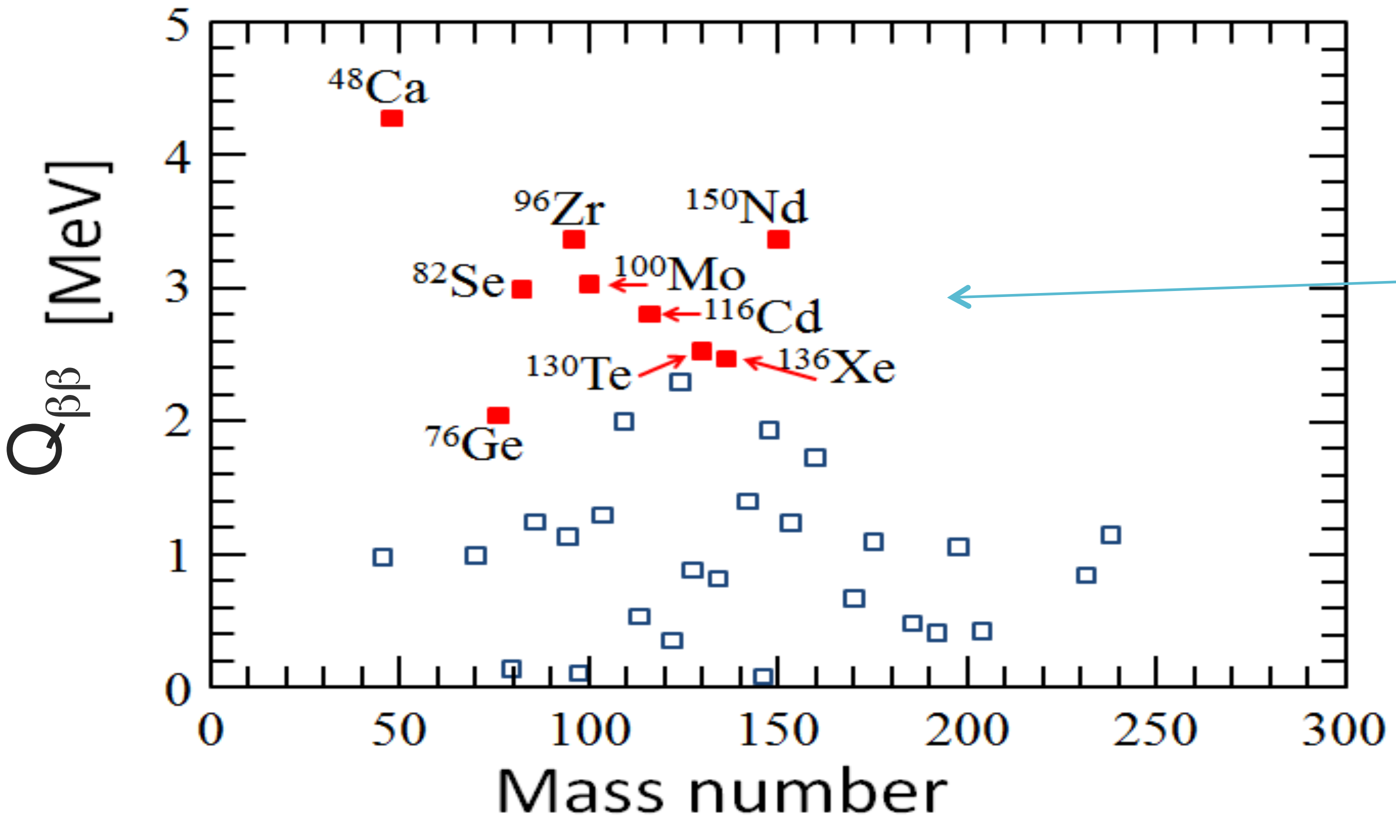
- Need to find single events in a ton of isotope x year(s) of exposure!
- 3 x 10^{-14} Bq/g
- We go to extreme length to limit ubiquitous radioactivity

Half-life larger > 10^{25} yr - 10^{26} yr

15 Bq / banana

Which and how many nuclei?

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



Most promising candidates
High $Q_{\beta\beta}$

Decay channels for Double Beta Decay

① $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$ → 2ν Double Beta Decay
allowed by the Standard Model
already observed – $\tau \sim 10^{18} - 10^{21}$ y

② $(A,Z) \rightarrow (A,Z+2) + 2e^-$ → **Neutrinoless Double Beta Decay**
never observed
$\tau > 10^{25} - 10^{26}$ y

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

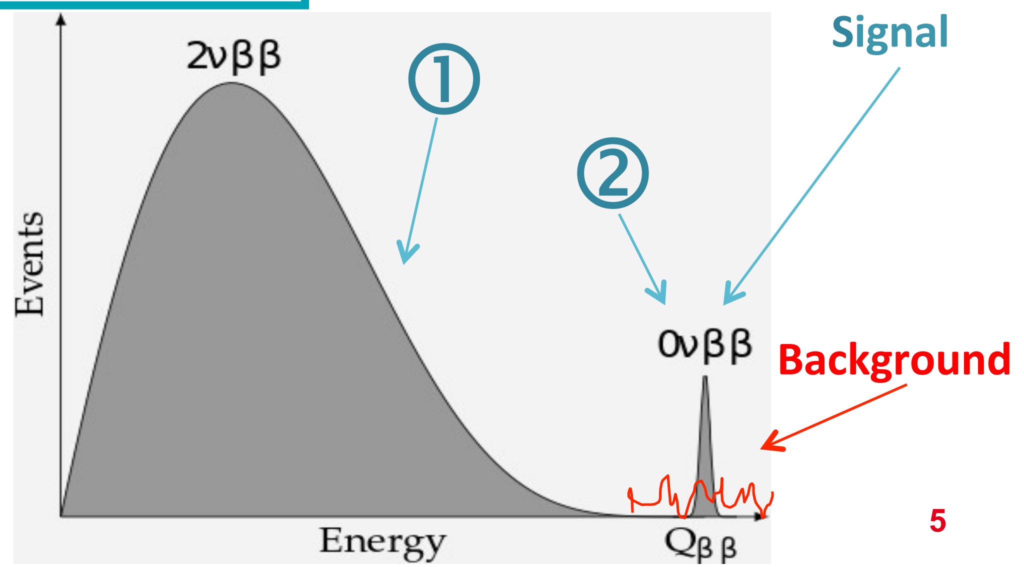
Processes ② would imply new physics beyond the Standard Model

violation of total lepton number conservation

Experimental signatures based on the

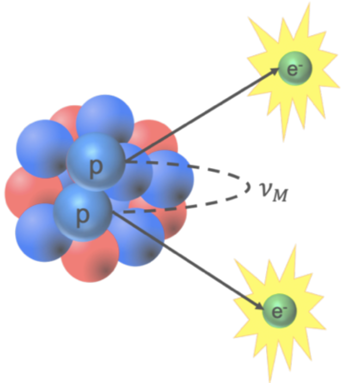
Sum energy spectrum of the two electrons

$Q_{\beta\beta} \sim$ 2-3 MeV
for the most promising candidates

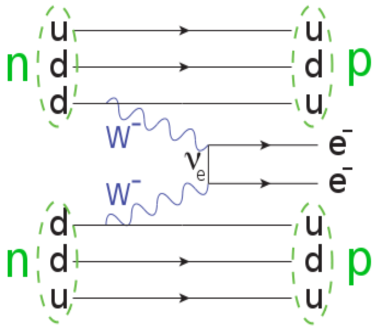


Why Neutrinoless Double Beta Decay is important

- Majorana nature of neutrino (irrespectively of the mechanism)
- See-saw mechanism ⇒ 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 ν, LNV,…
Not necessarily neutrino physics

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

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**)

Neutrinoless Double Beta Decay **rate**

Phase Space (calculable)

Axial vector coupling constant

Nuclear matrix elements

Effective **Majorana mass**

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

what the experimentalists try to measure

what the nuclear theorists try to calculate

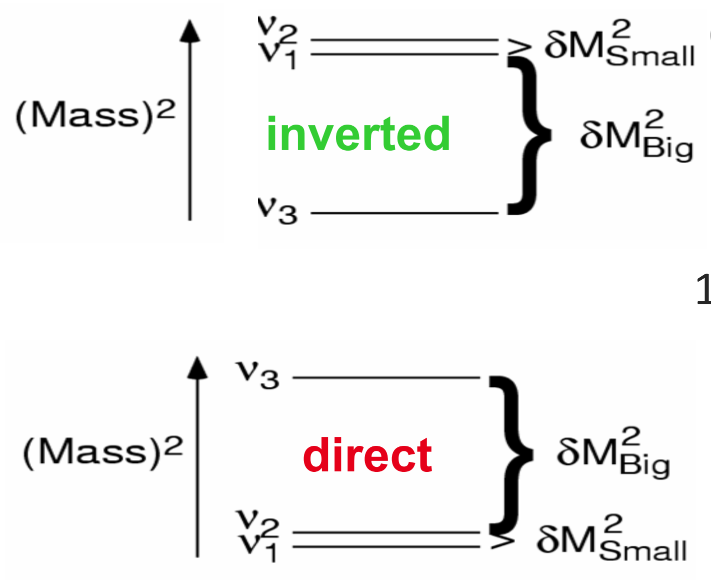
parameter containing neutrino physics: **Effective Majorana mass**

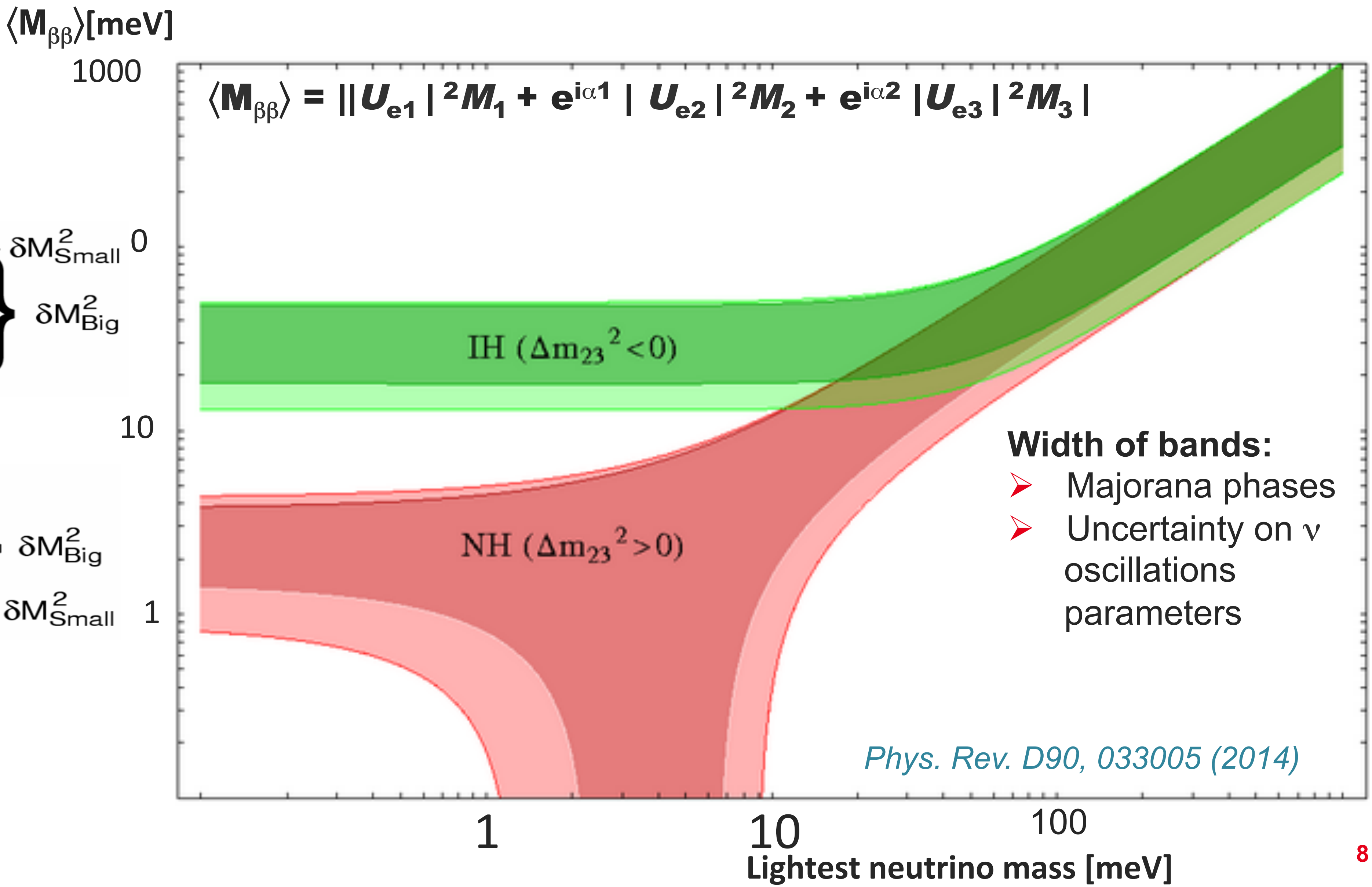
Majorana phases

$$\langle M_{bb} \rangle = \left| |U_{e1}|^2 M_1 + e^{i\alpha_1} |U_{e2}|^2 M_2 + e^{i\alpha_2} |U_{e3}|^2 M_3 \right|$$

The effective Majorana mass

A reference plot



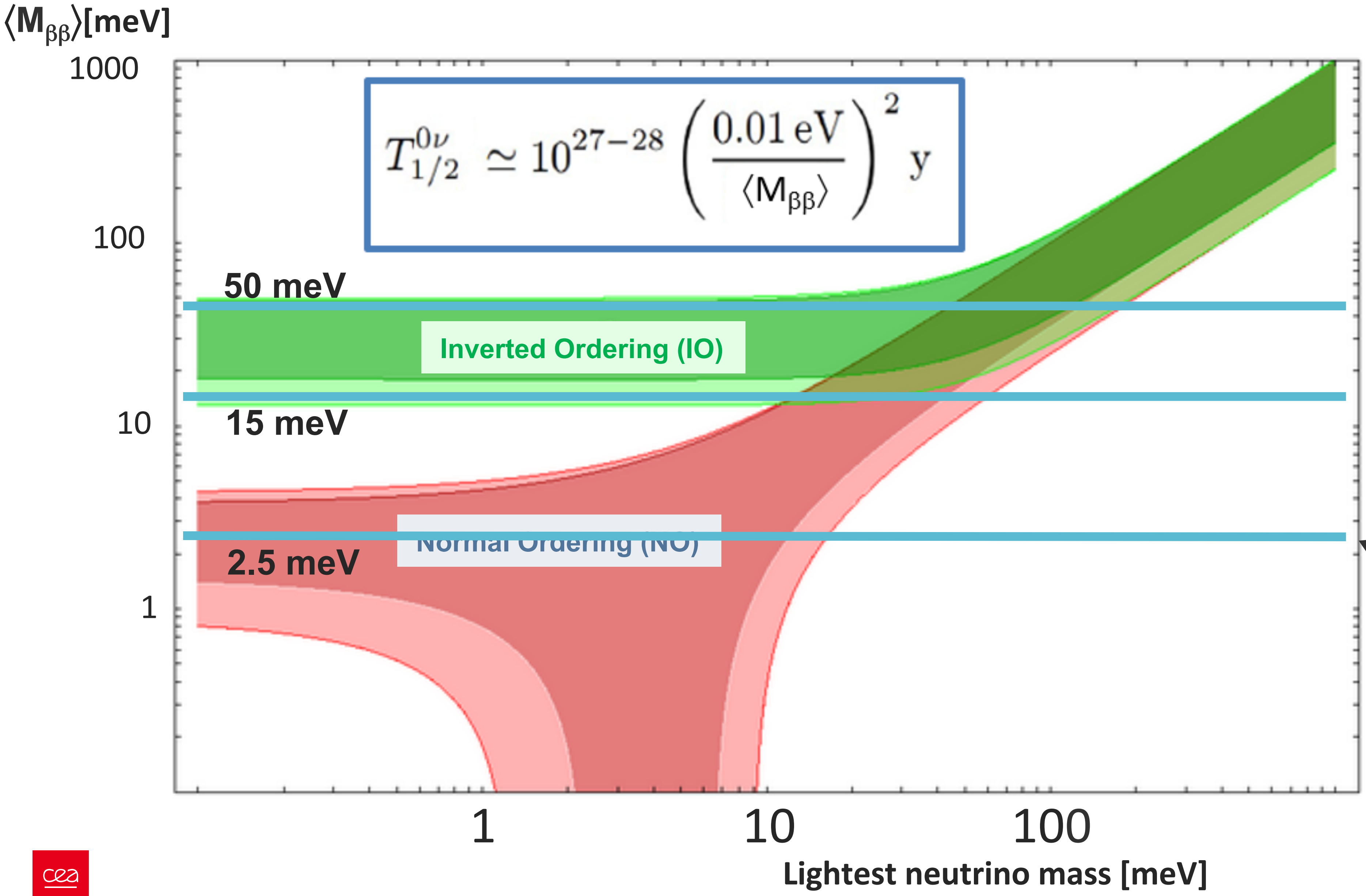


Width of bands:

- Majorana phases
- Uncertainty on ν oscillations parameters

Phys. Rev. D90, 033005 (2014)

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)

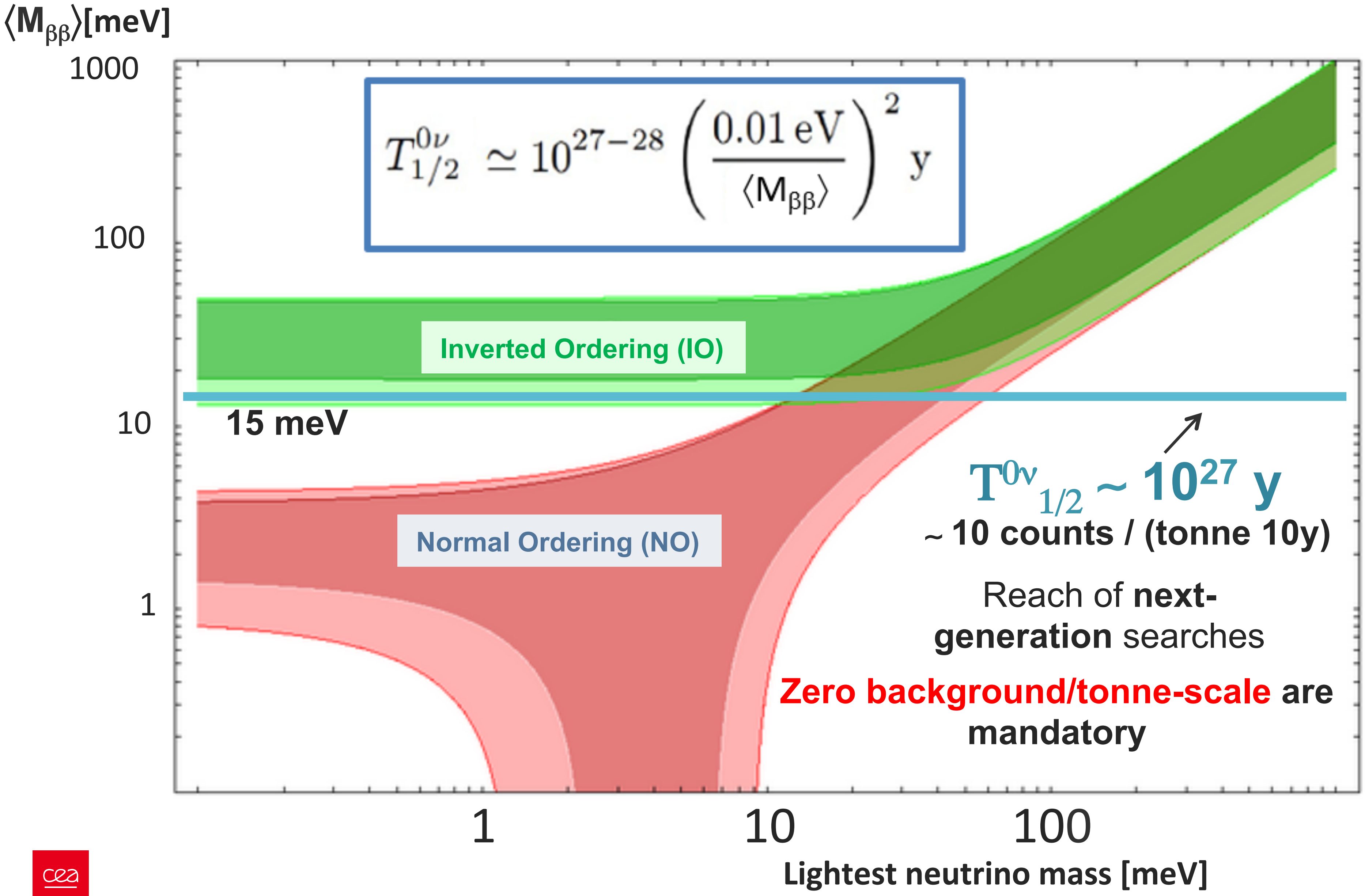
Reach of **next-generation** searches

$T^{0\nu}_{1/2} \sim 10^{29}$ 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

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

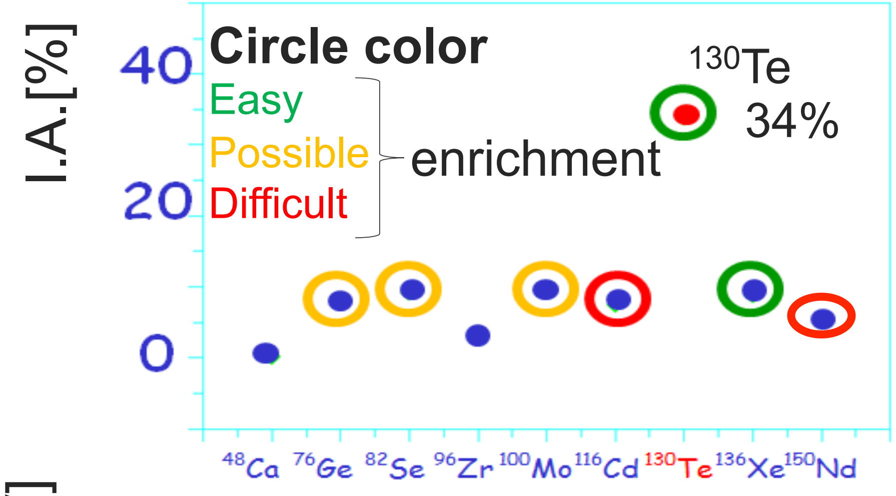
⇕

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

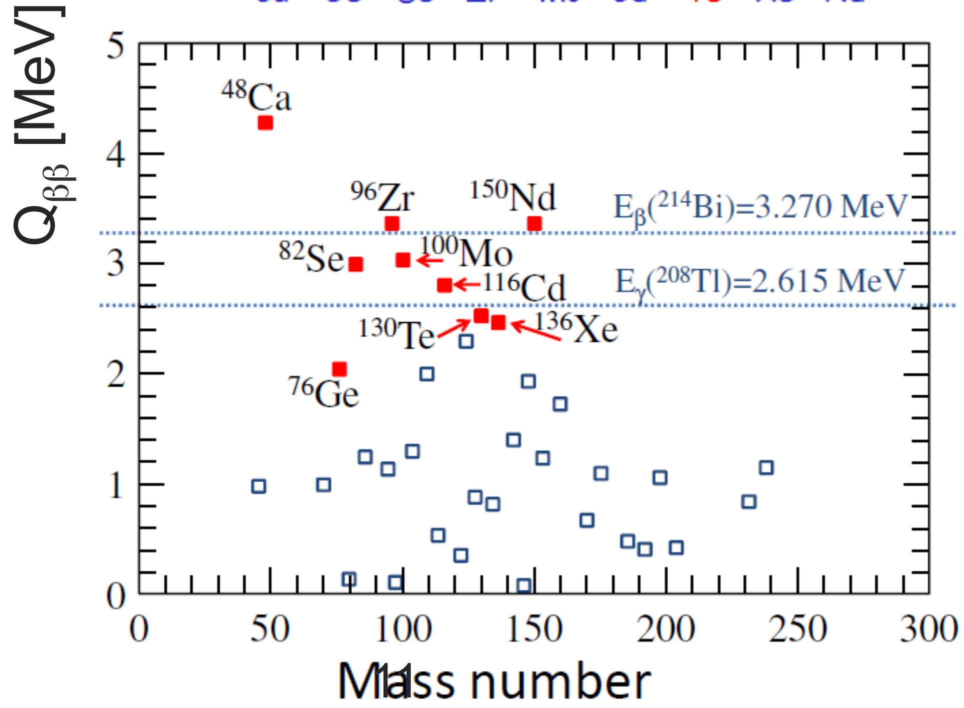
$F \propto MT$

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



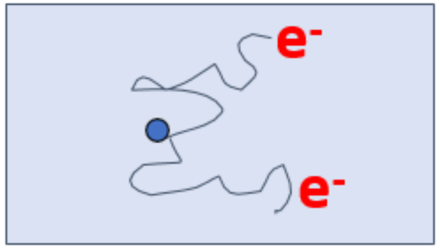
- Compatibility with a beneficial **detection technique**
  - **High energy resolution**
  - **Background identification**
  - **Efficiency and scalability**

General features for 0νββ searches

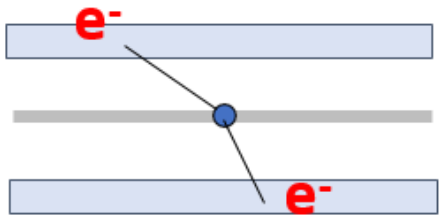
Requests for the source

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



Source $\subseteq$ Detector



Source $\nsubseteq$ Detector

However, this option may be interesting in case of discovery to investigate the mechanism of 0νββ

Requests for the background

Generic measures as underground operation, shielding (passive and active), radiopurity of materials, vetos are common to 0ν2β and other rare event search

Specific desirable features for 0νββ

- 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** →

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

② **TPCs** →

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

③ **Semiconductor detectors**

④ **Bolometers**

→

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

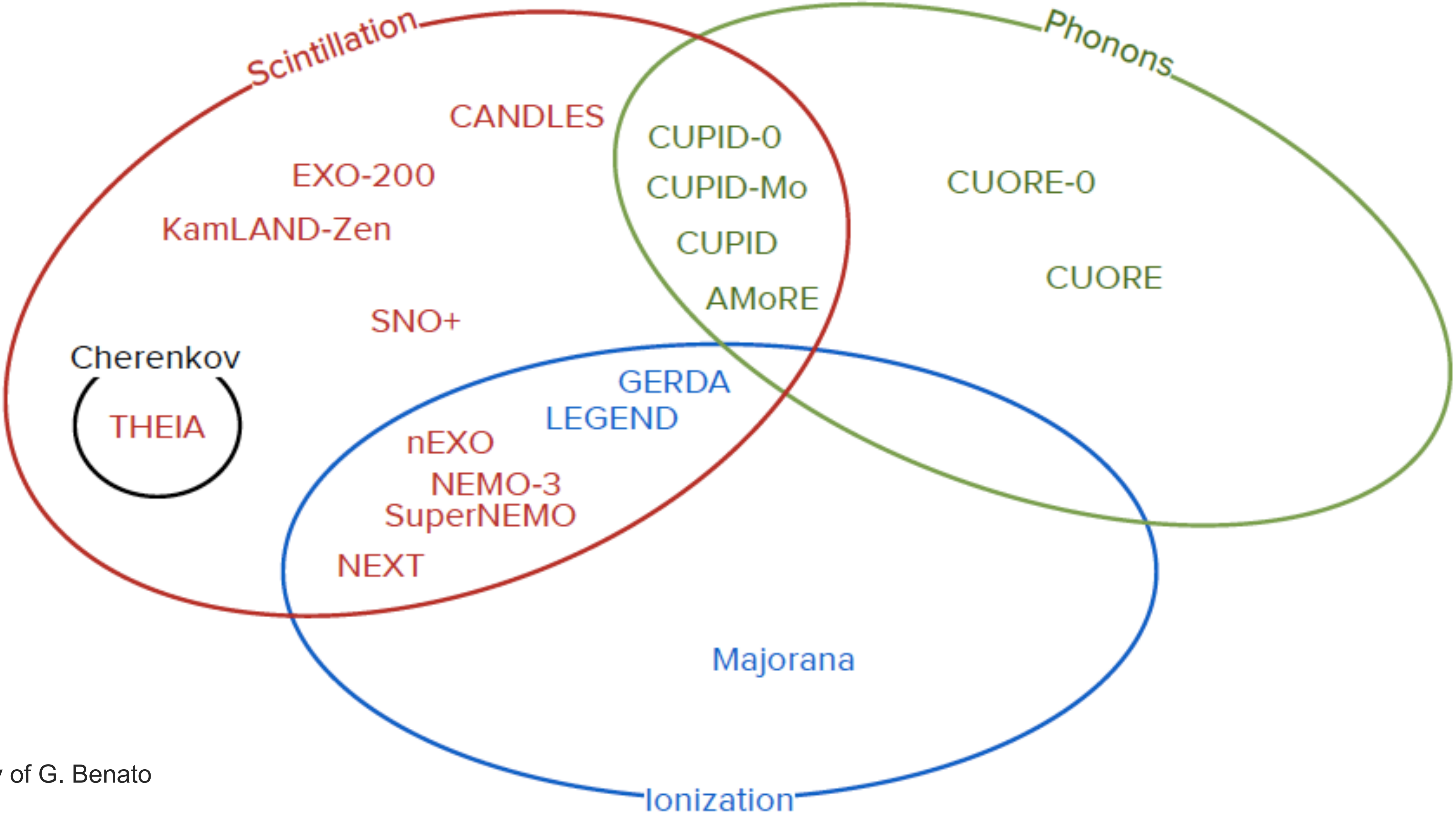
Currently competing technologies (2)

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

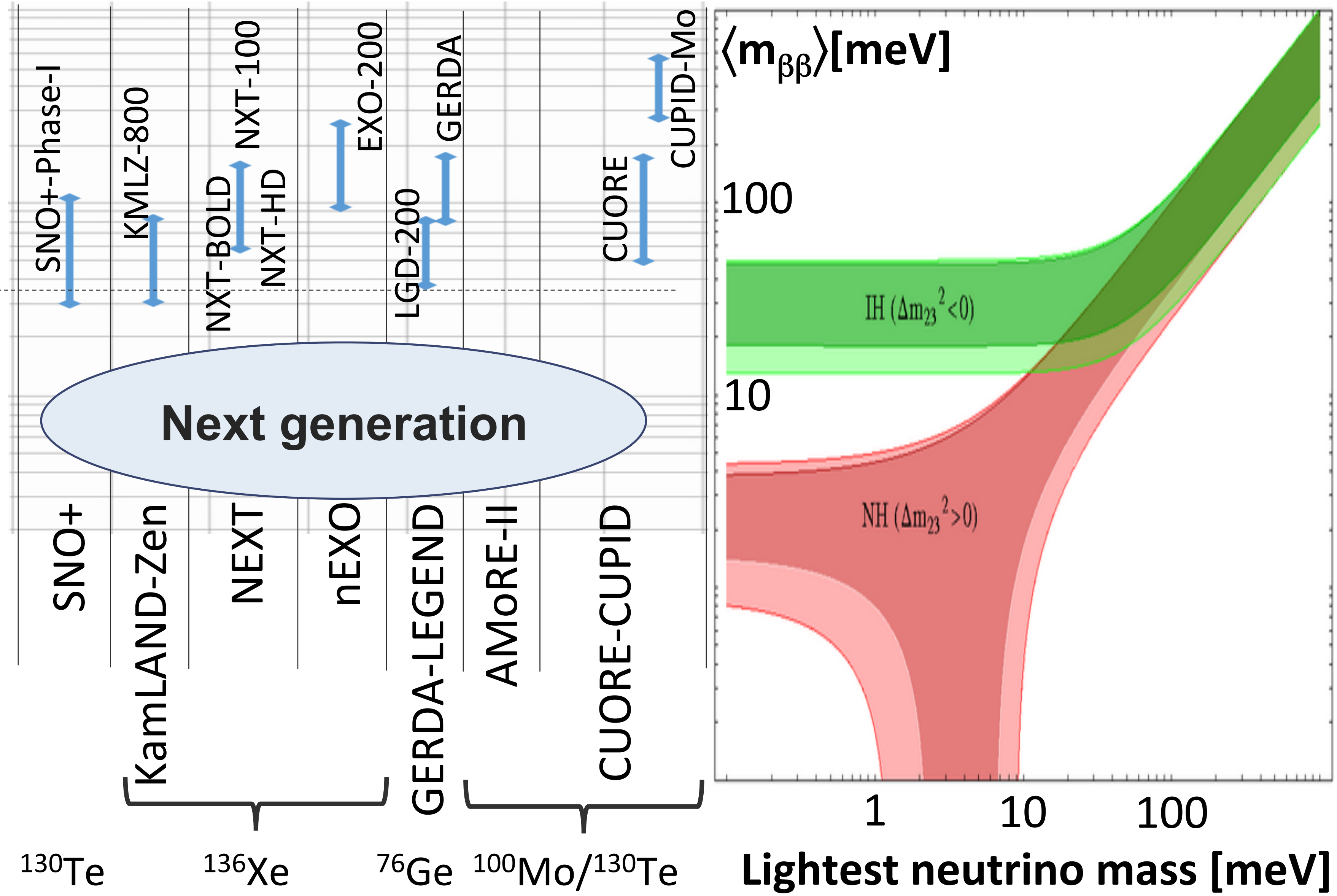
$0\nu\beta\beta$: status and prospects

Current generation

(final sensitivity for recently concluded - running - on- commissioning projects)

- KamLAND-Zen 400/800 - $T_{1/2} > 2.3\times10^{26}$ y
- GERDA - $T_{1/2} > 1.8\times10^{26}$ y
- EXO-200 - $T_{1/2} > 3.5\times10^{25}$ y
- MAJORANA dem. - $T_{1/2} > 2.7\times10^{25}$ y
- CUORE - $T_{1/2} > 2.2\times10^{25}$ y
- CUPID-0 - $T_{1/2} > 4.7\times10^{24}$ y
- CUPID-Mo - $T_{1/2} > 1.8\times10^{24}$ y
- NEMO-3 - $T_{1/2} > 1.1\times10^{24}$ y

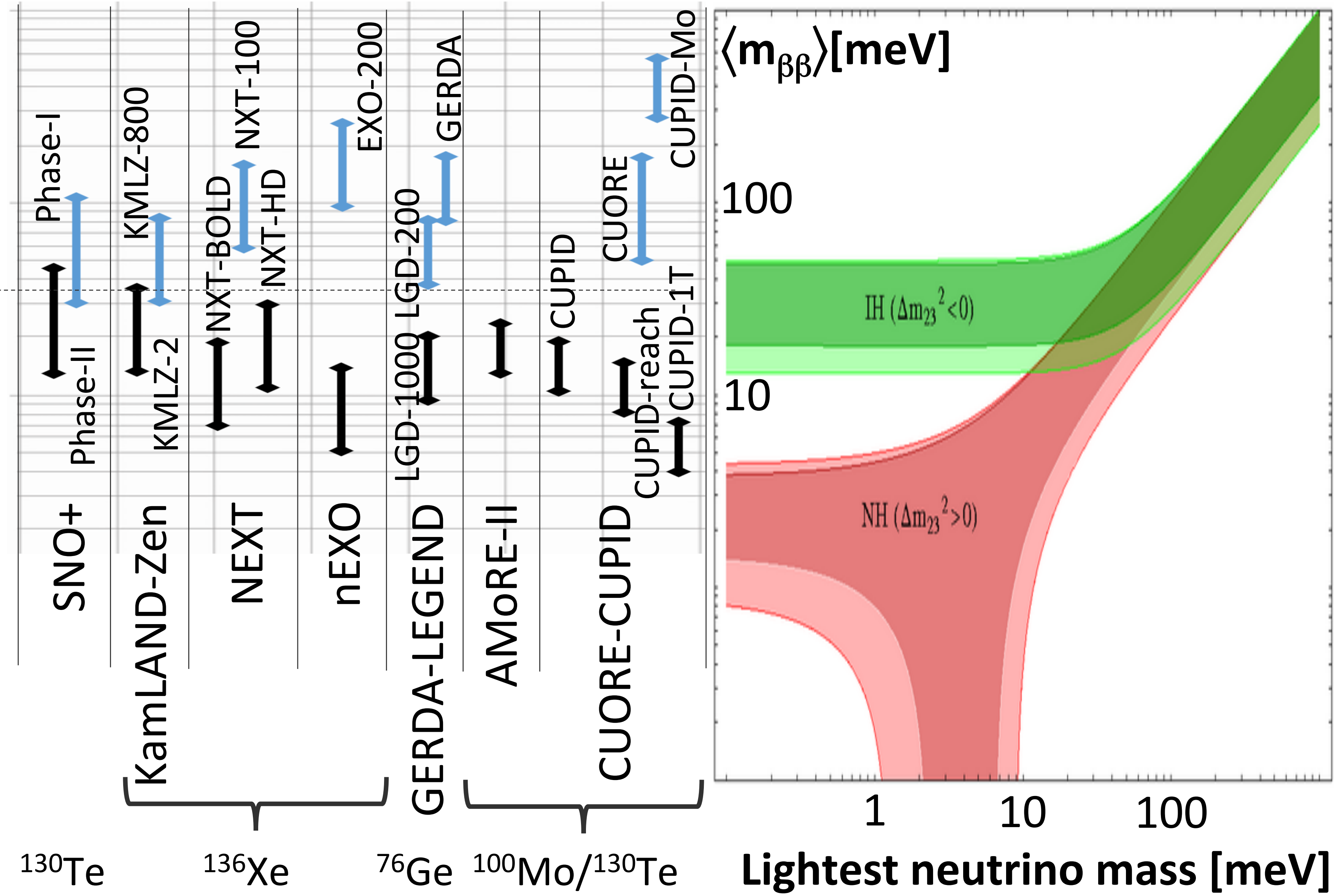
$> 10^{24}$ y club



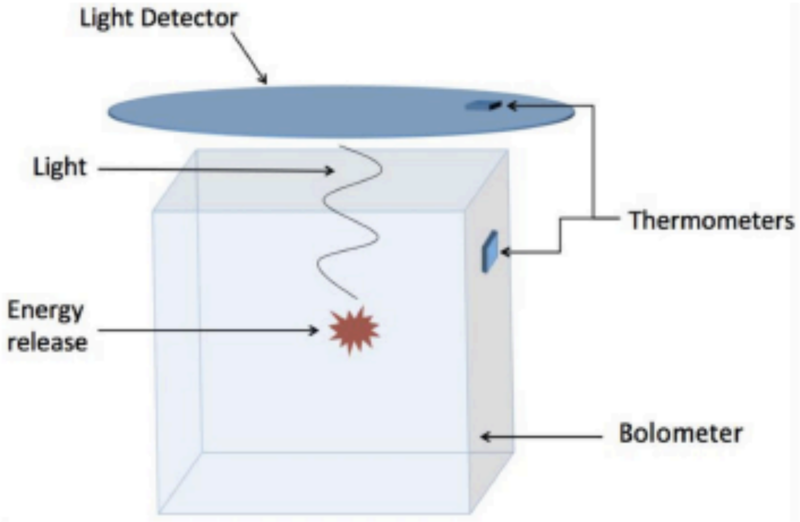
0νββ: status and prospects

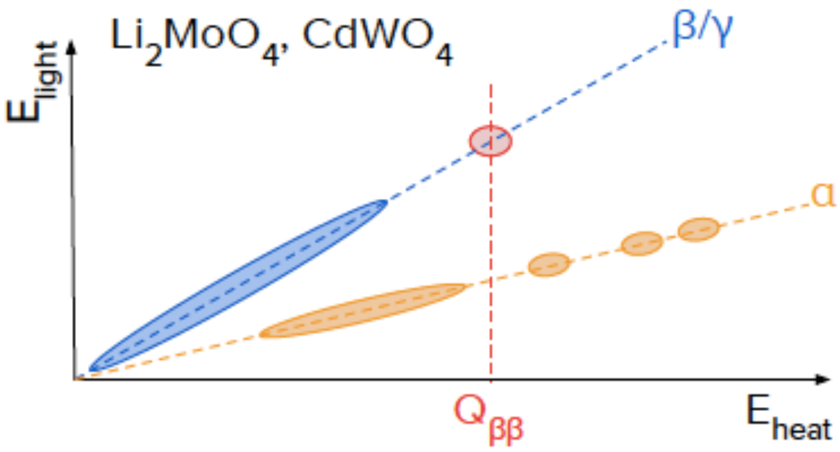
Current generation
(final sensitivity for recently concluded - running - on- commissioning projects)

Next generation
(projects to be started during the next decade)

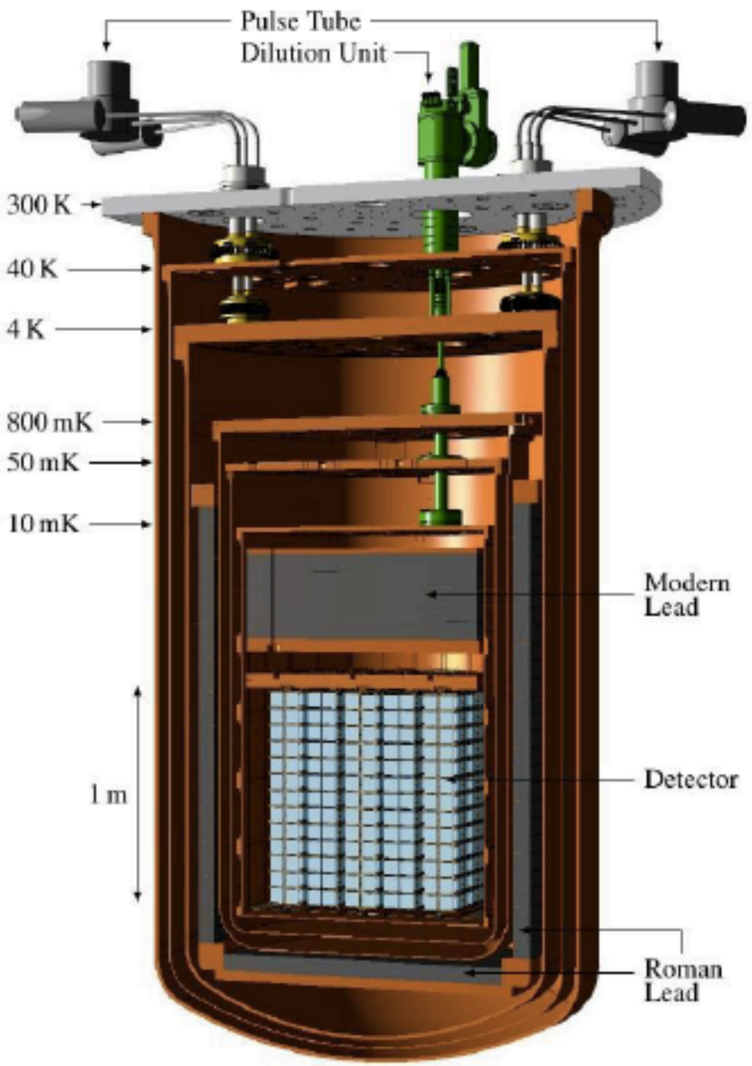


One exemple: cryogenics calorimeters





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



CUORE and CUPID demonstrators

Experimental concept - CUORE

Array of natural TeO_2 bolometers at 10 mK

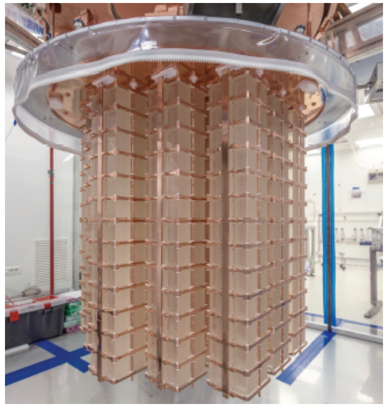
- Built on the precursor CUORICINO experiment
- **988 TeO_2 crystals in 19 towers – 206 kg of ^{130}Te**
- $\Delta E \sim 7.8$ keV FWHM $@Q_{\beta\beta}$ – $Q_{\beta\beta}$=2527 keV
- Background index **1.49×10^{-2} c/(keV·kg·y)**

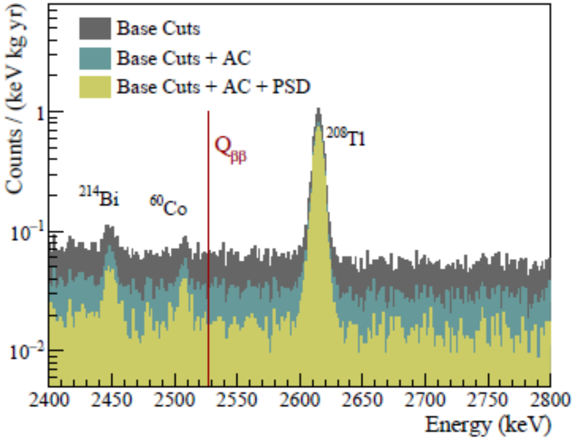
Dominated by **energy-degraded surface α's**

CUORE - LNGS, Italy

Exposure: **1038.4 kg × y – **Record for bolometers

$T_{1/2} > 2.2\times10^{25}$ y – $m_{\beta\beta} < 90 – 305$ meV



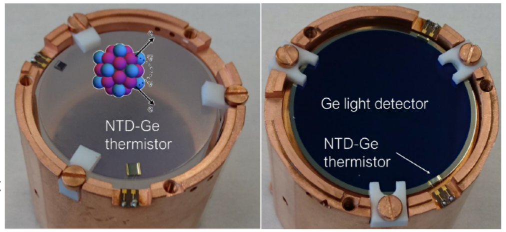


Target sensitivity: **9×10^{25} y – $m_{\beta\beta} < 50 – 130$ meV**

Experimental concept – CUPID-Mo

2 changes wrt CUORE:

① **Pure bolometers → Scintillating bolometers** (**reject α background**)

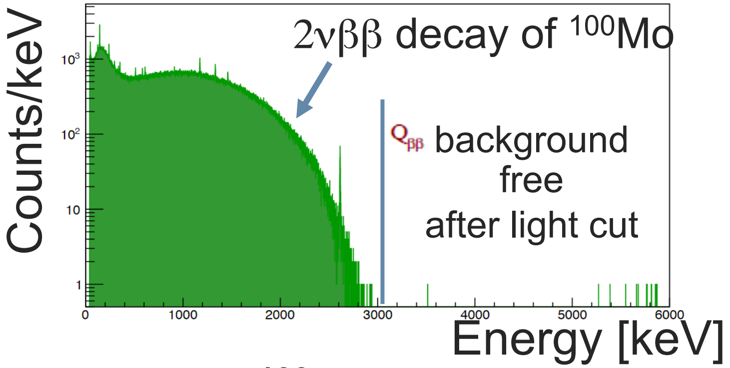


② **^{130}Te (TeO_2) → ^{100}Mo (enriched Li_2MoO_4)**

$Q_{\beta\beta}$=3034 keV > 2.6 MeV (**reject external γ background**)

CUPID-Mo - LSM, France

Exposure: **2.71 kg × y**



- **20 Li_2MoO_4 crystals – 2.26 kg of ^{100}Mo**
- Energy resolution **$\Delta E \sim 7.8$ keV FWHM $@Q_{\beta\beta}$**

$T_{1/2} > 1.8\times10^{24}$ y

$m_{\beta\beta} < 280 – 490$ meV

CUPID

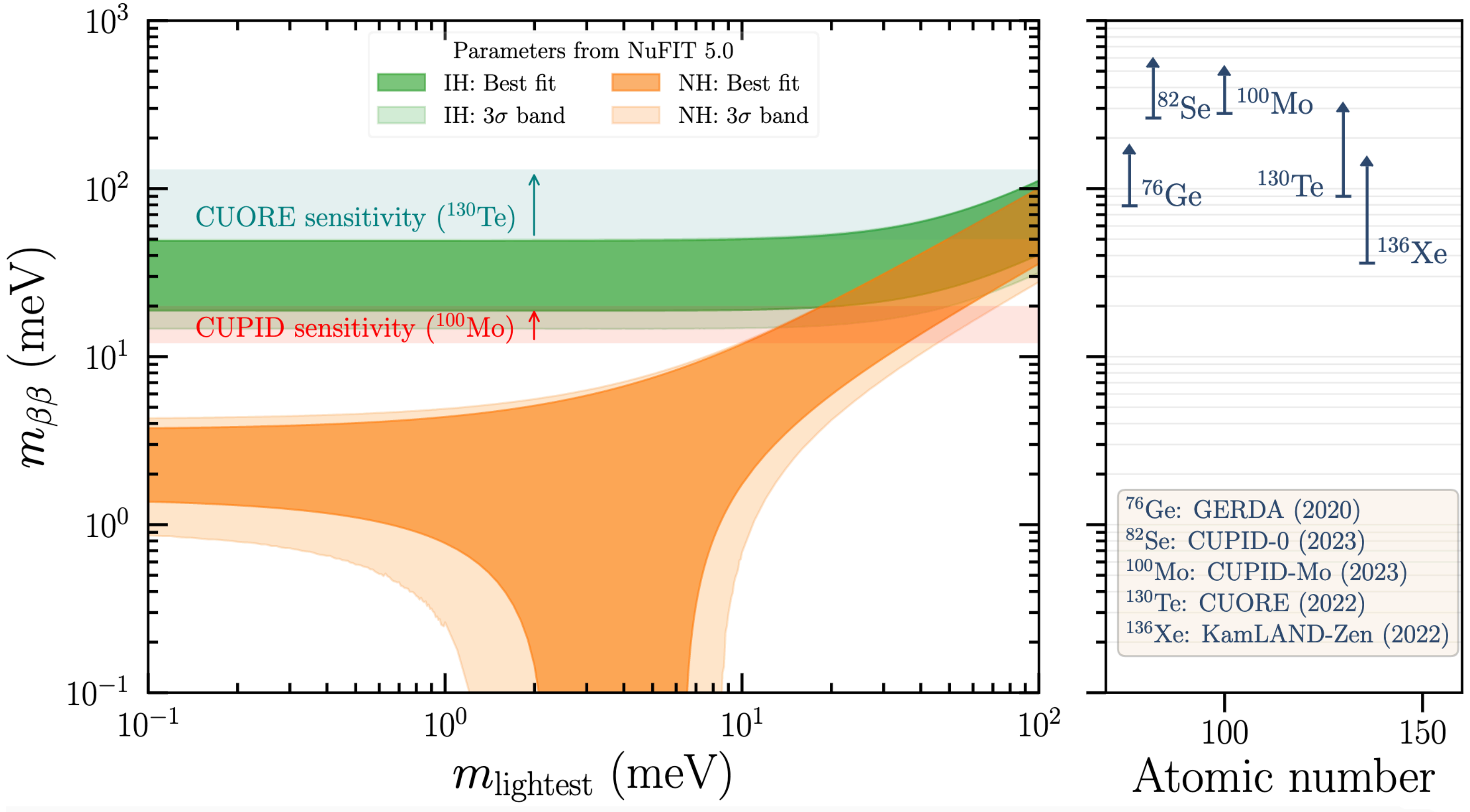
Ton-scale array of high-resolution bolometers for the search for $0\nu\beta\beta$ and other rare events

- Deploy 472 kg $Li_2{}^{100}MoO_4$ crystals (**240 kg of ^{100}Mo**)
- Exploit the **existing CUORE cryogenic facility** at LNGS with some upgrades
- **5 keV FWHM at $Q_{\beta\beta}$**
- Background goal: **10^{-4} c/keV/kg/yr**

- Discovery sensitivity @ 3 sigma
- $T_{1/2}$ > 1.1x10^{27} yr ($m_{\beta\beta}$: 12-20 meV)

- $T_{1/2}$ > 2.2x10^{27} yr ($m_{\beta\beta}$: 8.4-14 meV) [reach]

same parameters but factor 5 improvement on background



Preparing the next-next generation of bolometric experiments

In case of **no discovery** for next generation experiments
the technological bondaries will have to be pushed further

It is crucial to start to prepare now this eventuality:

- **Larger isotope masses (>1-10 ton)**
  → Increase of the cost

- **Further background reduction required ($<10^{-5}$ ckky)**
  → Need of innovative technologies

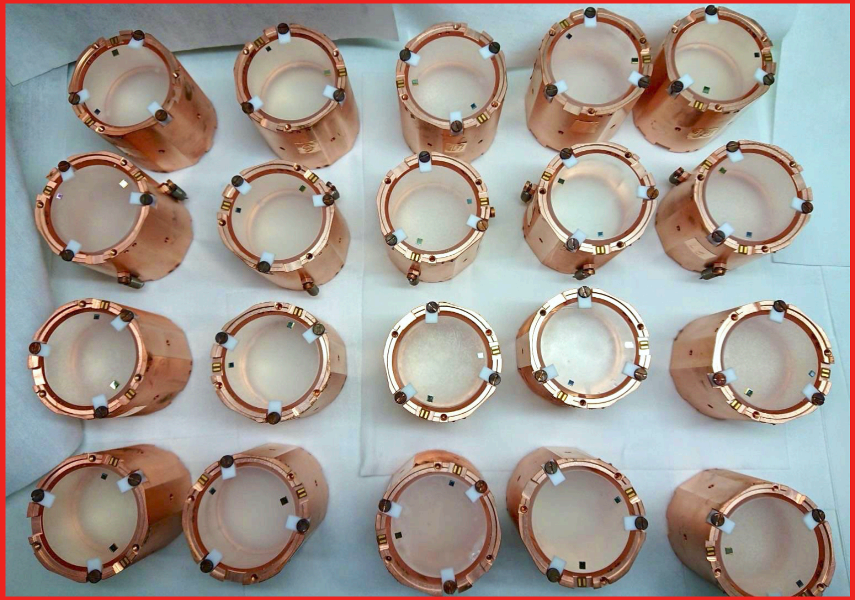
This is the goal of BINGO and TINY !

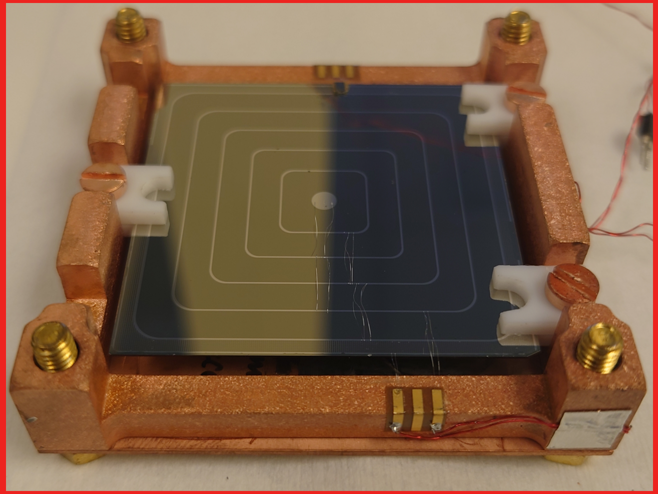
Conclusions

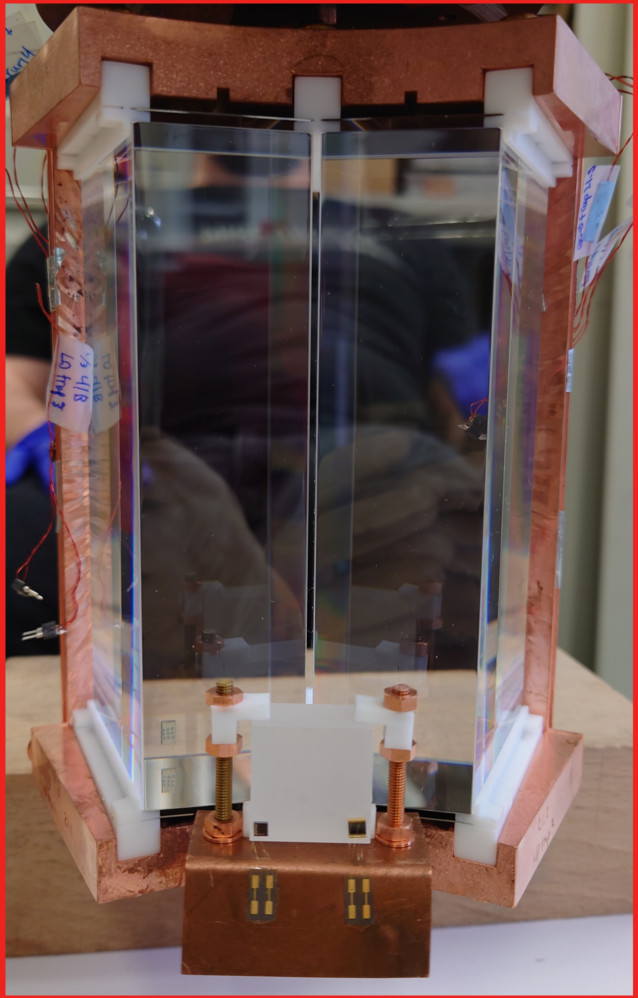
- The discovery of 0νββ decay would dramatically revise our foundational understanding of physics and the cosmos
  - Lepton number is not conserved
  - The neutrino is a fundamental Majorana particle
  - There is a potential path for understanding the matter - antimatter asymmetry in the cosmos, through leptogenesis
  - There is a new mechanism demonstrated for the generation of mass
- The search for 0νββ decay is one of the most compelling and exciting challenges in all of contemporary physics
- There has been tremendous progress in developing and demonstrating the required technologies
- The projects and collaborations are in an advanced state of planning and the field is now ready to proceed
- Next-generation experiments have a good discovery potential

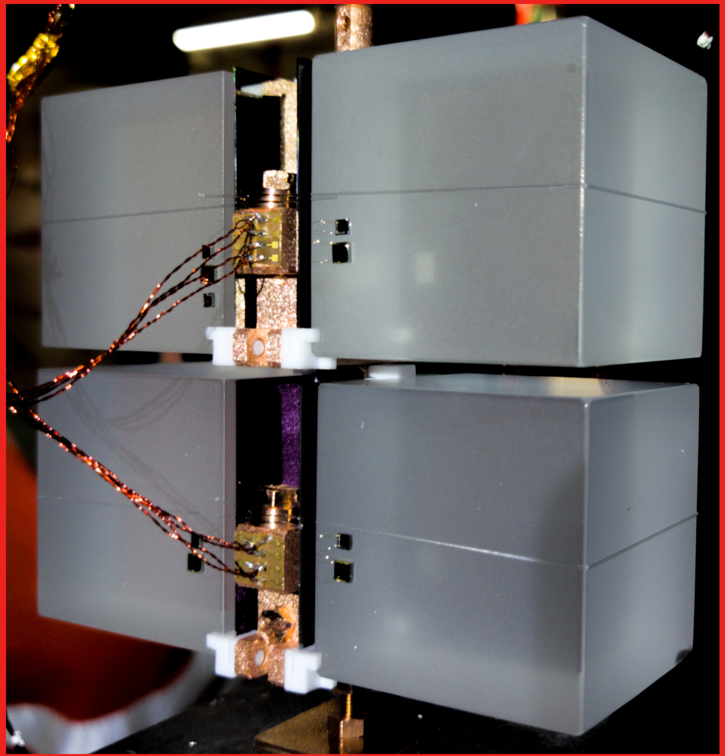
STAY TUNED

Thanks for your attention









BINGO

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TINY EXPERIMENT

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