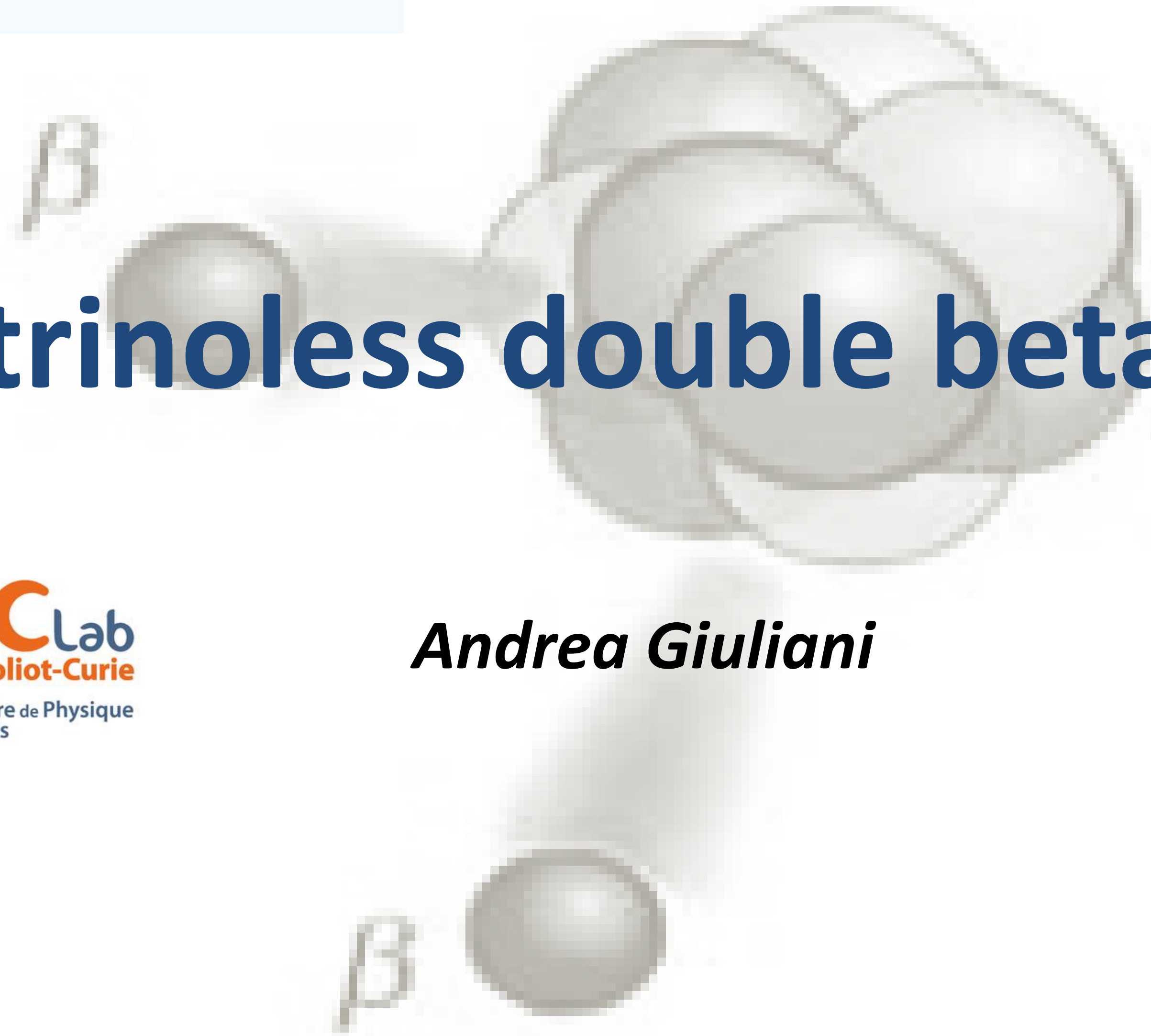
Physique et détecteurs à la frontière

22-24 June 2021
zoom

June 22nd, 2021

Neutrinoless double beta decay



IJCLab
Irène Joliot-Curie
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PARIS-SACLAY

Neutrino: mass and nature

A. Meregaglia's talk

- Les neutrinos sont introduits avec masse nulle dans le modèle standard, mais la découverte des oscillations démontre que leur masse n'est pas zéro. C'est une première indication de **physique au-delà du modèle standard.**

Les oscillation ne donnent pas d'indications sur la masse absolue des neutrinos ni sur son origine (Dirac Vs Majorana). Détails sur ce sujet dans la présentation de A.Giuliani

Since $\mathbf{m_\nu \neq 0}$, and considering that ν is the only massive fermion with **Q=0**, then we can ask the crucial question:

$\nu \neq \bar{\nu}$

DIRAC

Like electrons and all charged fermions

Charge → Lepton Number

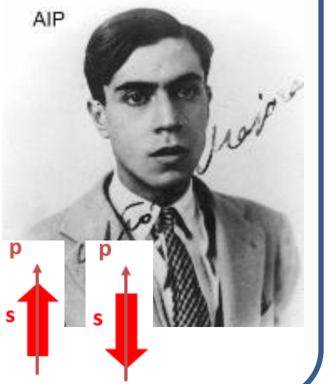
?

$\nu \equiv \bar{\nu}$

MAJORANA

New form of matter

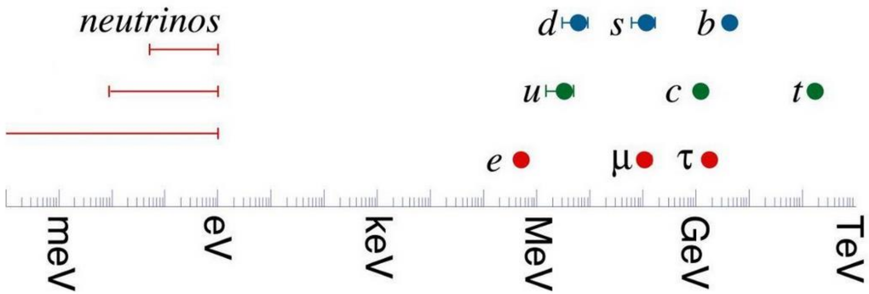
Helicity rules the interactions



If neutrino is a Majorana particle, we can introduce a **new mass term** in the Standard Modern Lagrangian, in addition to the "classical" couplings to the Higgs field

$$\mathscr{L}_M = -\frac{1}{2} M_R (\bar{\nu}_R^C \nu_R + \text{h.c.})$$

- Explain **smallness of neutrino masses**



- Can explain **matter / antimatter asymmetry** in the Universe
- Naturally incorporated in **Grand Unification Theories**

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Since **$m_\nu \neq 0$**, and considering … ive fermion with **Q=0**, then … n:

…ew form of matter

…ber

Detection of Neutrinoless Double Beta Decay is the only viable experimental technique to ascertain the Majorana nature of neutrinos

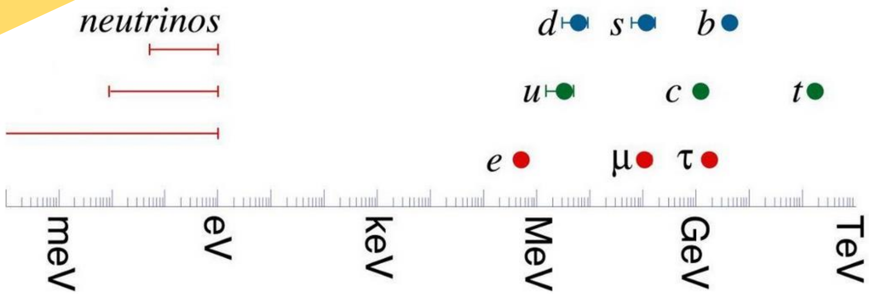
If neutrino is a M…

introduce a…

M…

$\mathscr{L}_M$ … $_R$ + h.c.)

…ness of neutrino masses



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What is double beta decay?

Very rare nuclear transition – 2nd order weak process
Two decay modes are usually discussed:

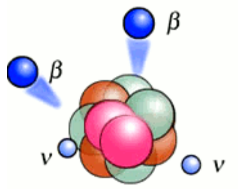
① $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\overline{\nu}_e$

2 X

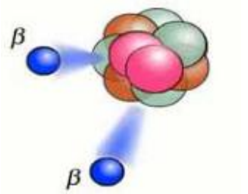
décroissance β- (après 1930)
$n \rightarrow p + e- + \nu$

② $(A,Z) \rightarrow (A,Z+2) + 2e^-$

2neutrino Double Beta Decay (2ν2β)
allowed by the Standard Model
already observed – **$\tau \sim 10^{18} – 10^{24}$ y**



Neutrinoless Double Beta Decay (0ν2β)
never observed – **$\tau > 10^{24} – 10^{26}$ y**



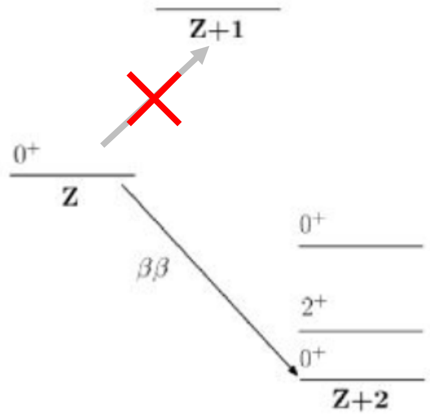
Processes ② would imply new physics beyond the Standard Model

Violation of total lepton number conservation (**LNV**)

It is a very sensitive test to new physics since the phase space term is much larger for process ② than for process ①

Interest for 0ν-DBD lasts for > **80 years** !
Goeppert-Meyer proposed the standard process in 1935
Furry proposed the neutrinoless process in 1939

35 nuclei can undergo double beta decay



Only a few are experimentally relevant
^{100}Mo, ^{136}Xe, ^{76}Ge, ^{130}Te, ^{82}Se

Neutrinoless double beta decay (0ν2β): standard and non-standard mechanisms

$0\nu2\beta$ is a test for « creation of leptons »:

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

This test is implemented in the nuclear matter:

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

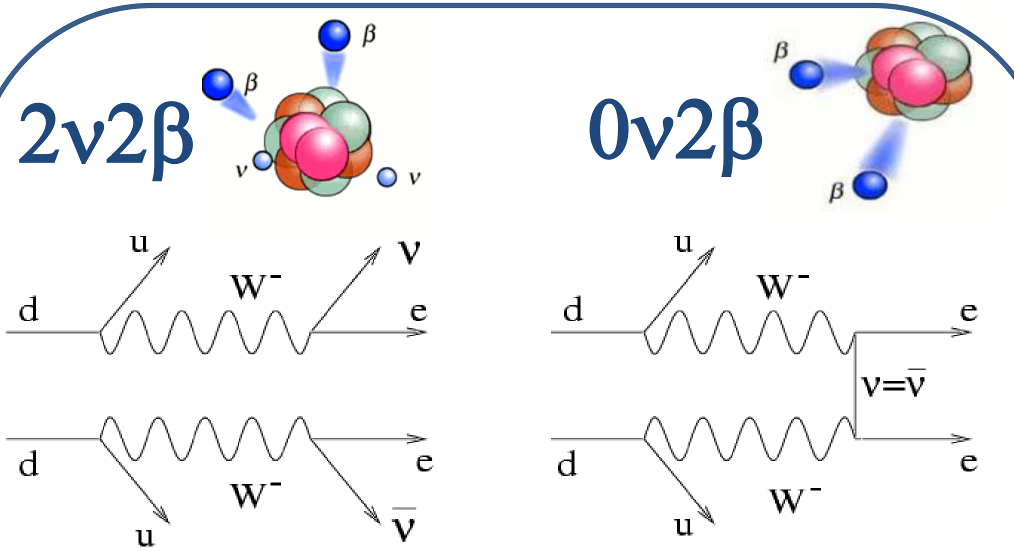
$0\nu2\beta$

Standard mechanism: **neutrino physics**

$0\nu2\beta$ is mediated by **light massive Majorana neutrinos** (exactly those which oscillate)

Non-standard mechanism: **Sterile ν, LNV**

Not necessarily neutrino physics



$\bar{\nu} = \nu$

Neutrinos are massive **MAJORANA** particles, unlike electrons, muons and tau's that are **DIRAC** particles

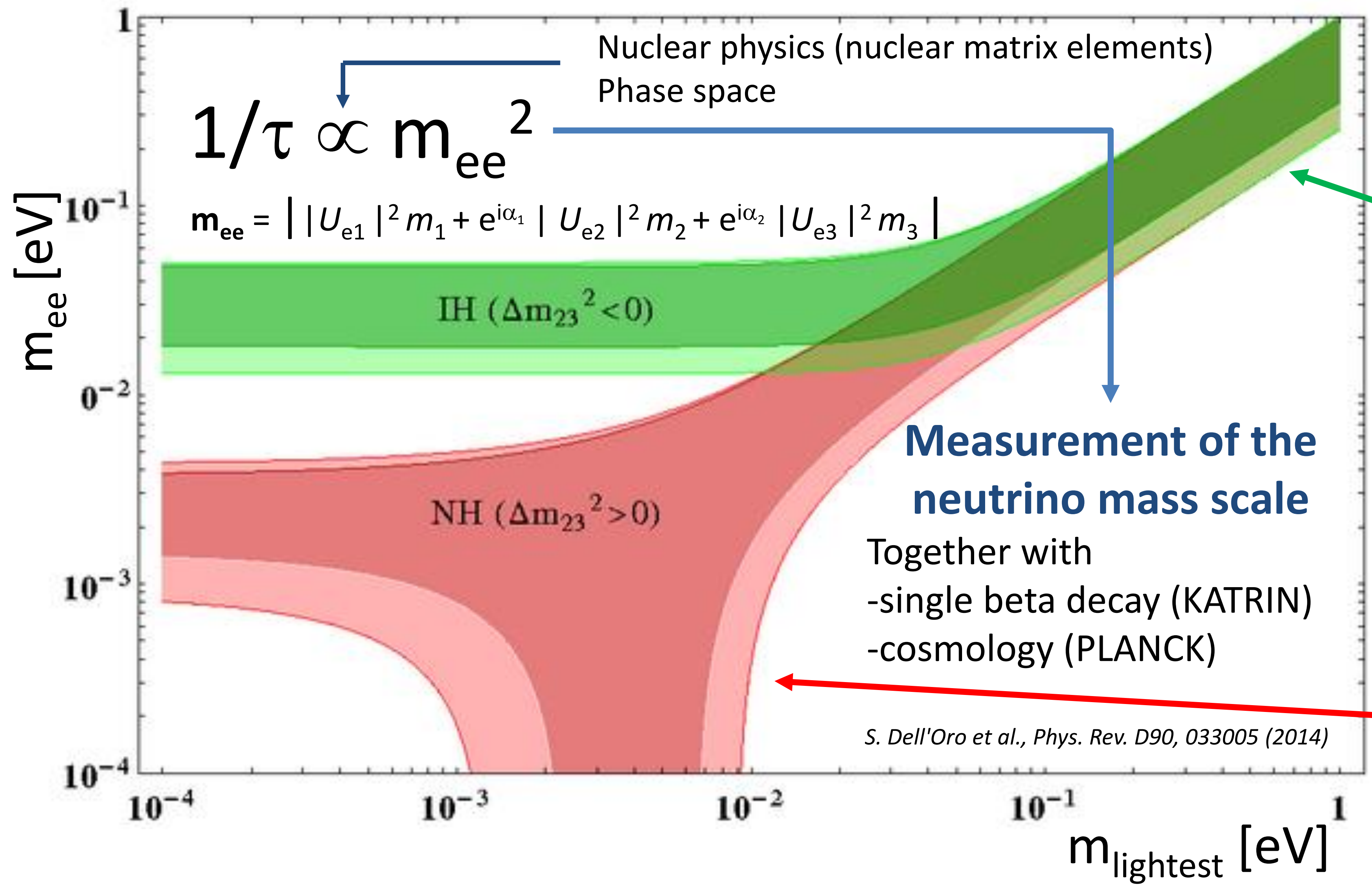
a virtual neutrino is exchanged between the two electroweak lepton vertices

m_{ee} vs. lightest ν mass

Nuclear physics (nuclear matrix elements)
Phase space

$$1/\tau \propto m_{ee}^2$$

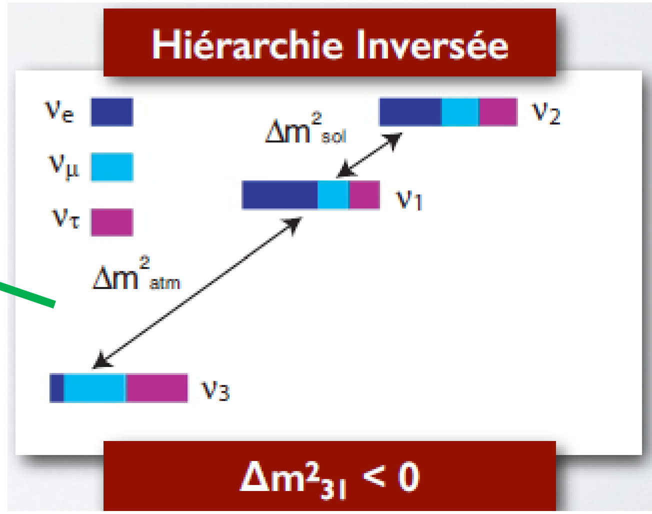
$$m_{ee} = \left|\, |U_{e1}|^2 m_1 + e^{i\alpha_1} |U_{e2}|^2 m_2 + e^{i\alpha_2} |U_{e3}|^2 m_3 \,\right|$$

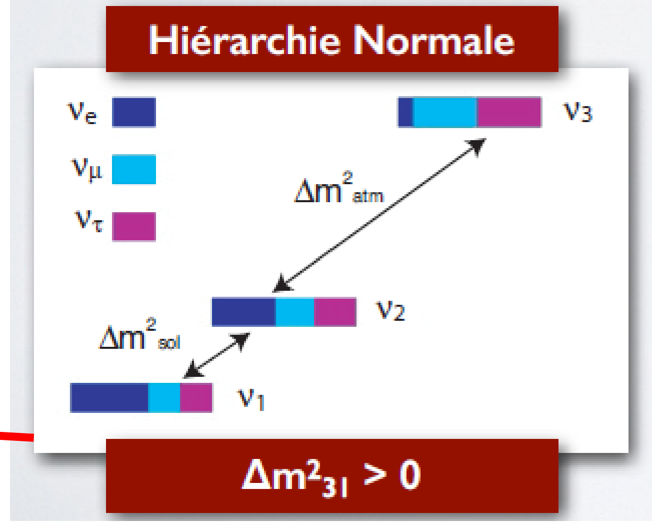


Measurement of the neutrino mass scale

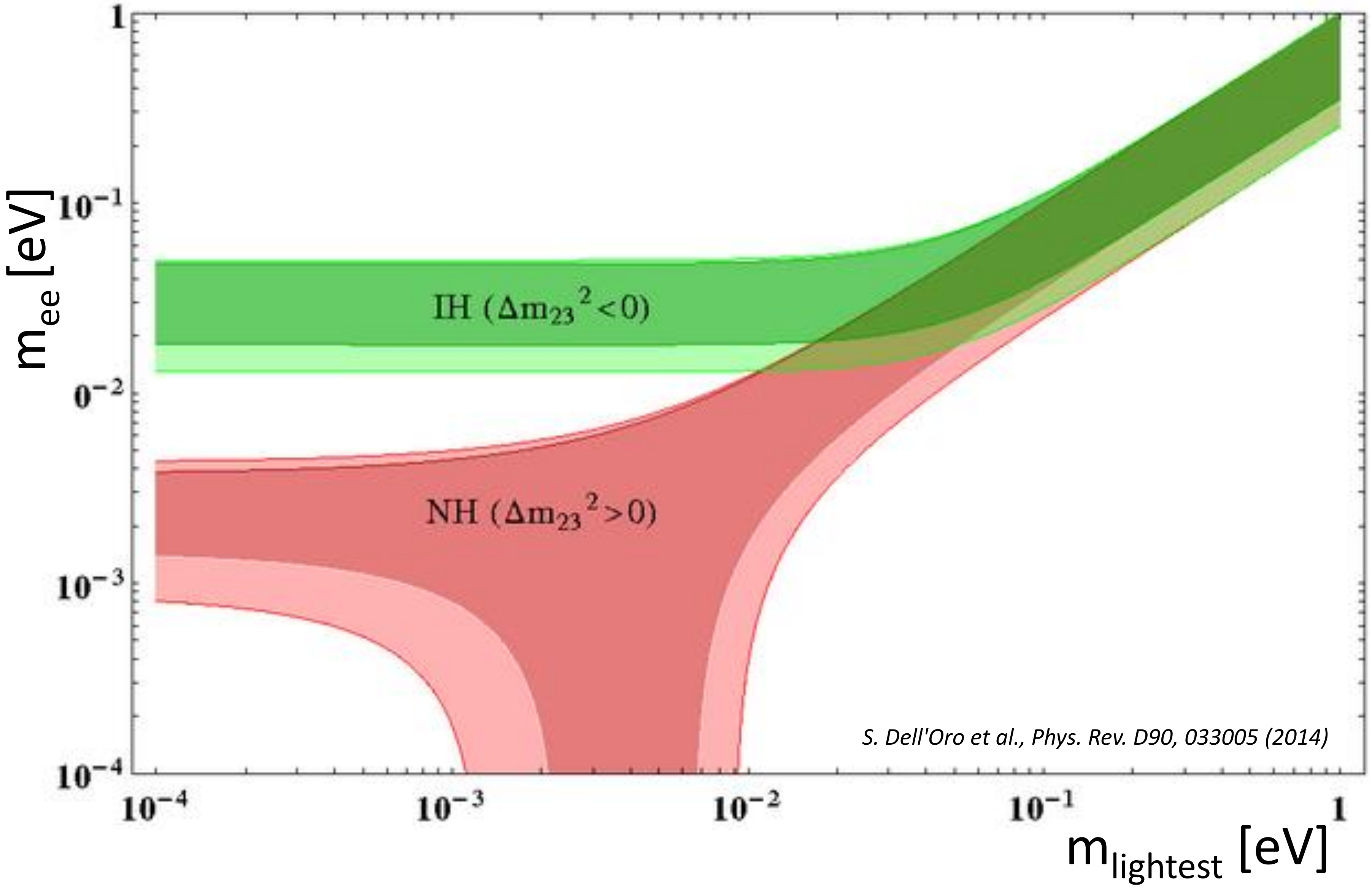
Together with
-single beta decay (KATRIN)
-cosmology (PLANCK)

S. Dell'Oro et al., Phys. Rev. D90, 033005 (2014)





Challenges



1
10−1
0−2
10−3
10−4
10−4
10−3
10−2
10−1
1
mee [eV]
mlightest [eV]
IH (Δm23²<0)
NH (Δm23²>0)
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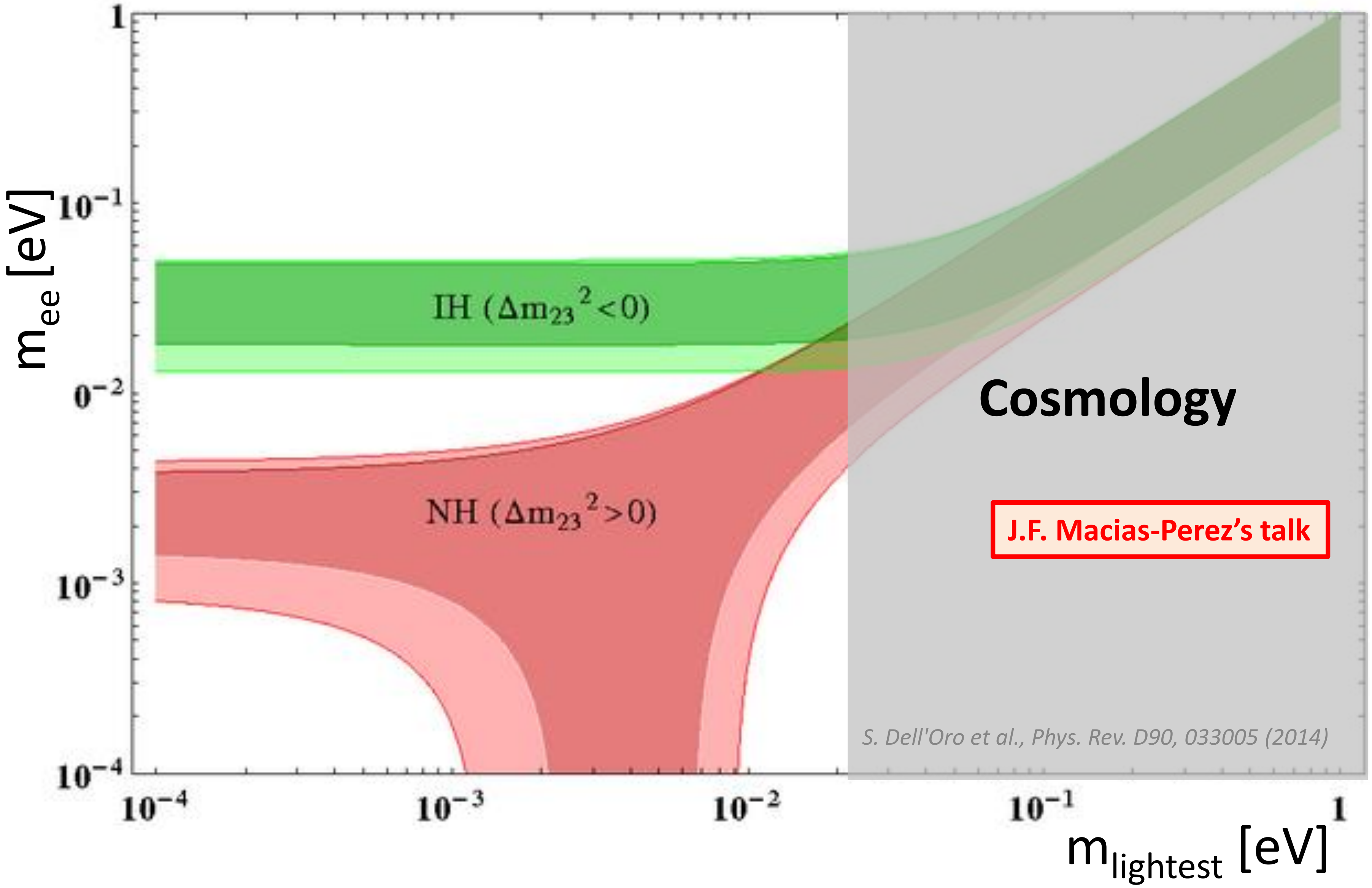
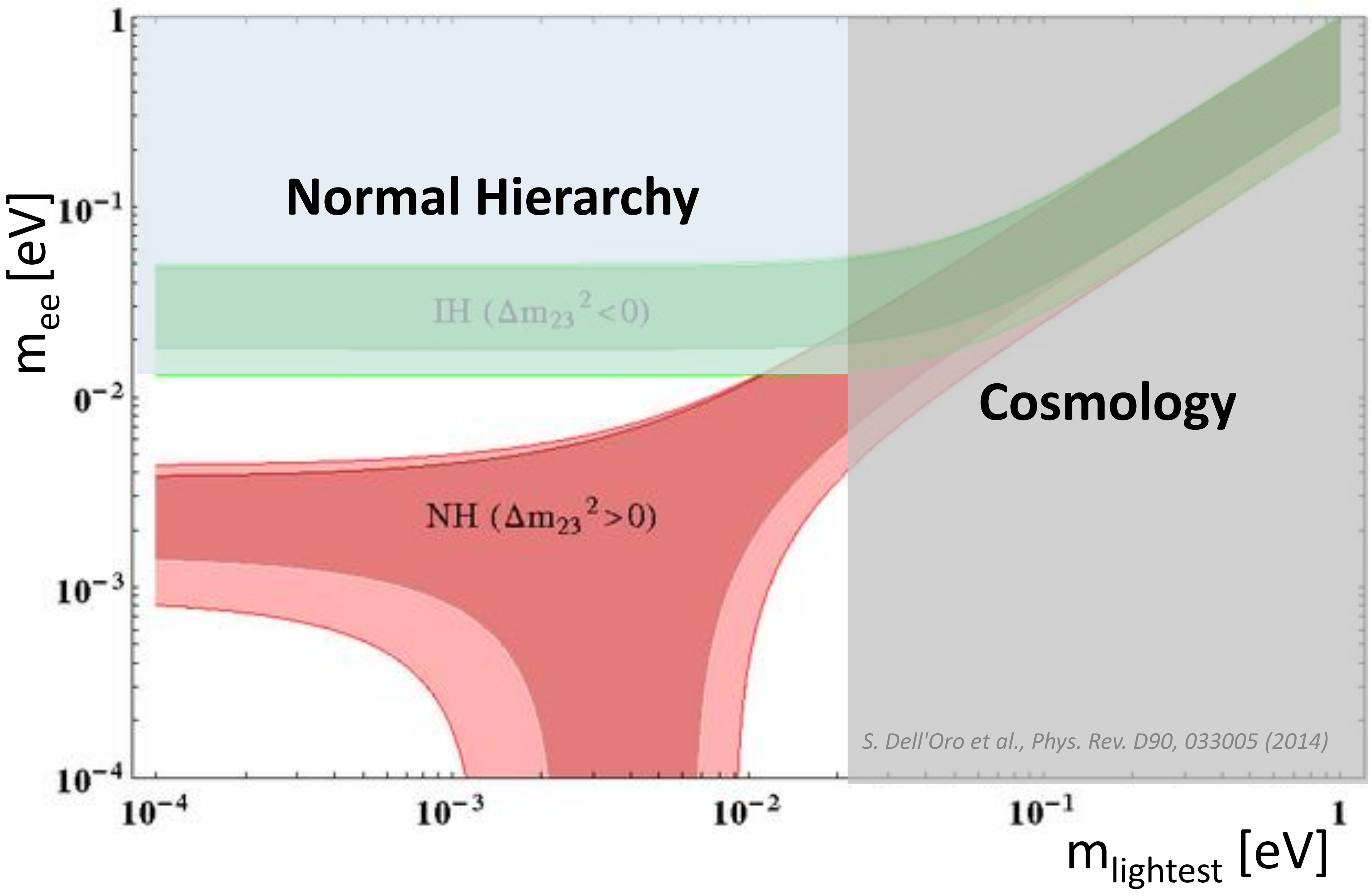
Challenges



1
10⁻¹
0⁻²
10⁻³
10⁻⁴
10⁻⁴
10⁻³
10⁻²
10⁻¹
1
m_ee [eV]
m_lightest [eV]
IH (Δm₂₃²<0)
NH (Δm₂₃²>0)
Cosmology
J.F. Macias-Perez's talk
S. Dell'Oro et al., Phys. Rev. D90, 033005 (2014)

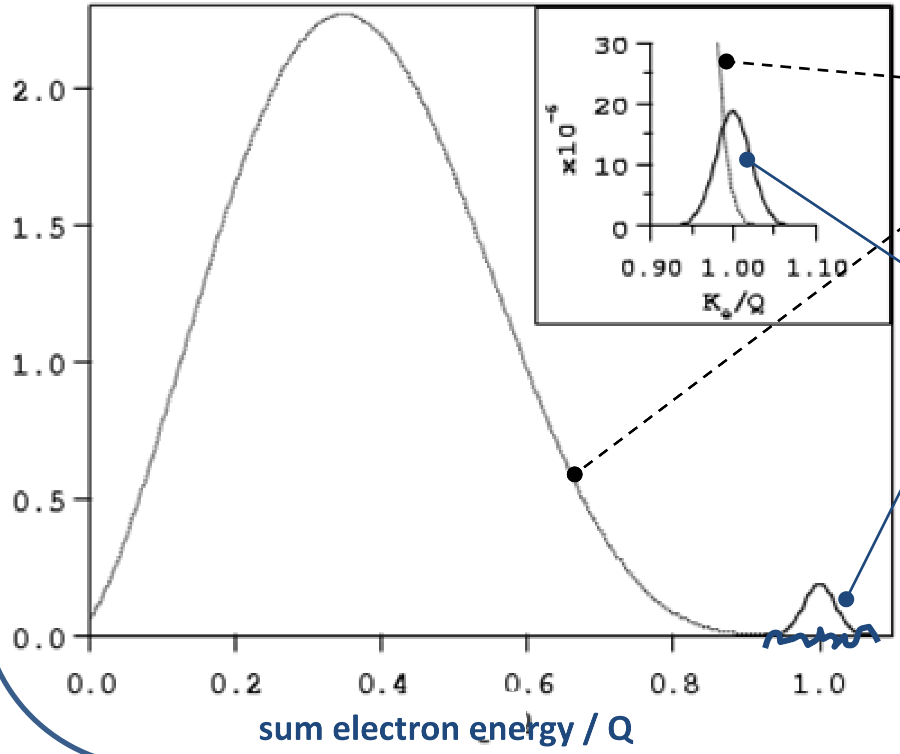
Challenges



1
10^{-1}
0^{-2}
10^{-3}
10^{-4}
m_{ee} [eV]
Normal Hierarchy
IH ($\Delta m_{23}^2<0$)
NH ($\Delta m_{23}^2>0$)
Cosmology
S. Dell'Oro et al., Phys. Rev. D90, 033005 (2014)
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
$m_{lightest}$ [eV]

What we are looking for

The shape of the two-electron sum-energy spectrum enables to distinguish between the **0ν** (new physics) and the **2ν** decay



2ν2β : (A,Z)→(A,Z+2)+2e+2ν
continuum with maximum at ~1/3 Q

0ν2β : (A,Z)→(A,Z+2)+2e
peak enlarged only by
the detector energy resolution

Q-value ~ 2-3 MeV for the most promising candidates

The experimentally relevant candidates

^{100}Mo, ^{136}Xe, ^{76}Ge, ^{130}Te, ^{82}Se

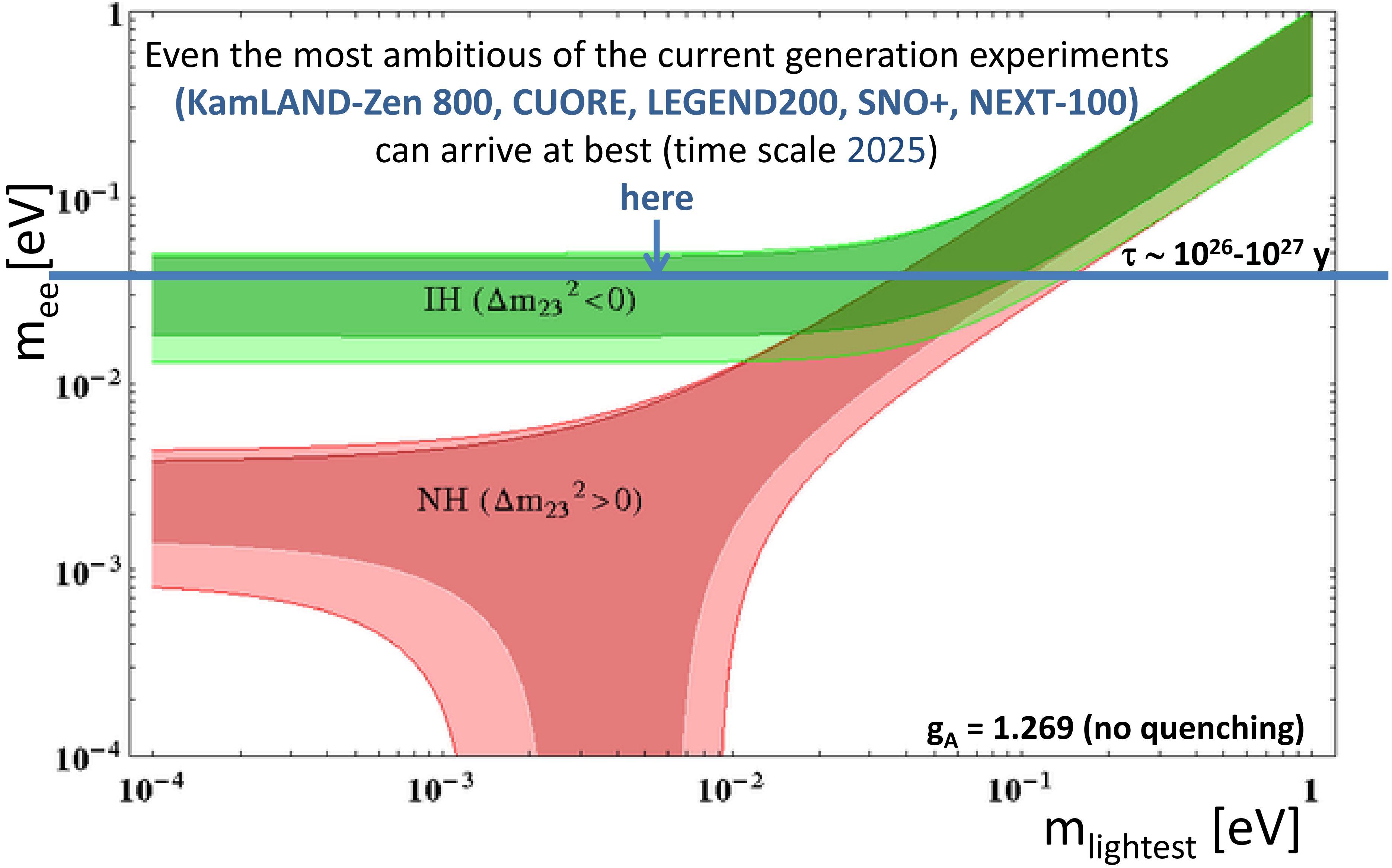
combine

- **High Q-value**
- High isotopic abundance and/or possibility of **isotopic enrichment**
- The lowest predicted half-lives for a given m_{ee}

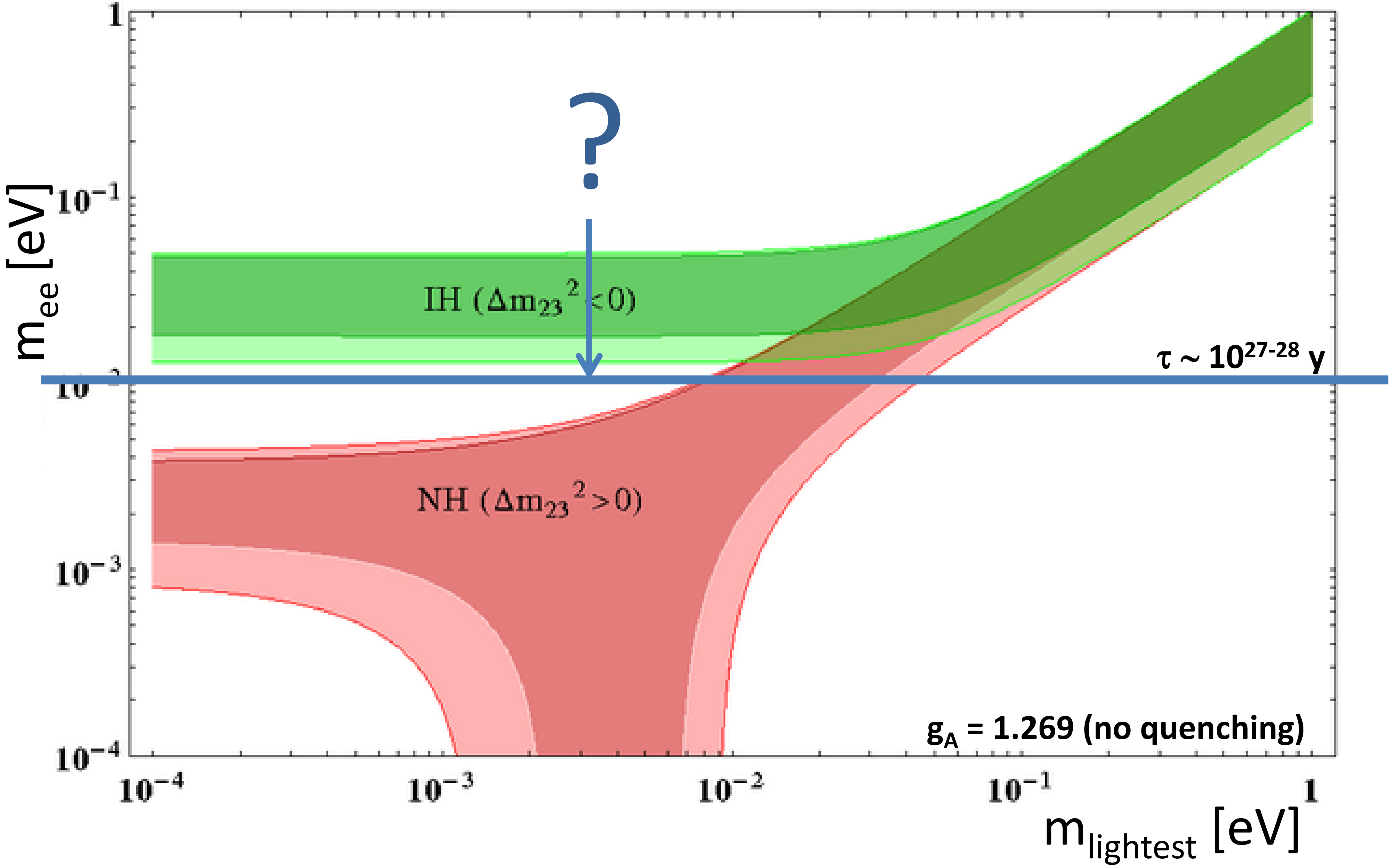
High decay probability
Low background

The signal is an elusive **peak (at the Q-value)** over an almost **flat background**

Current-generation experiments



Strategic milestone



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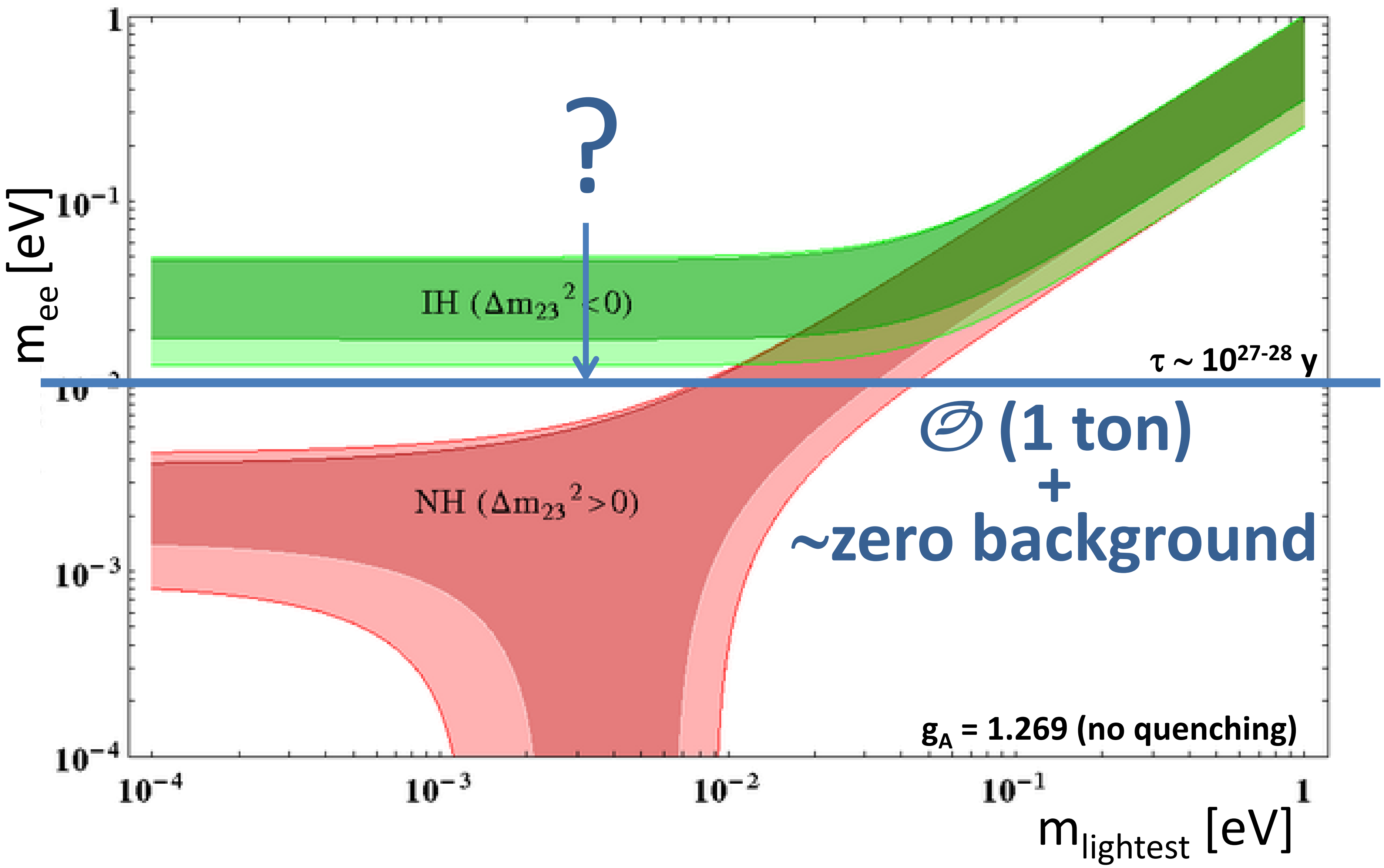
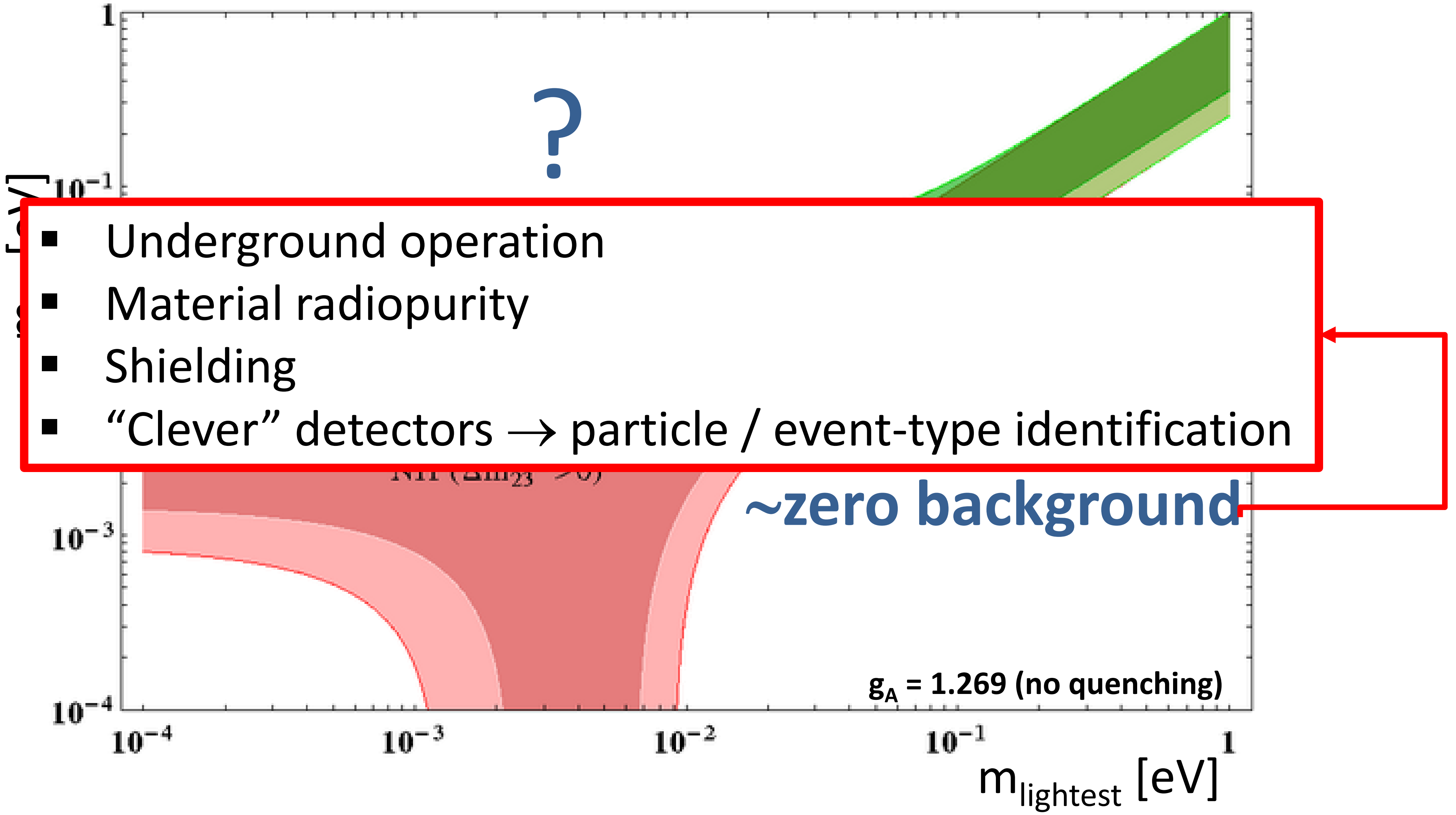


Strategic milestone

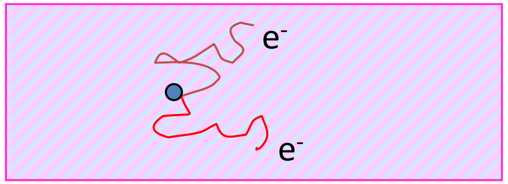


- Underground operation
- Material radiopurity
- Shielding
- “Clever” detectors → particle / event-type identification

How we do it: experimental approaches

Two approaches:

①



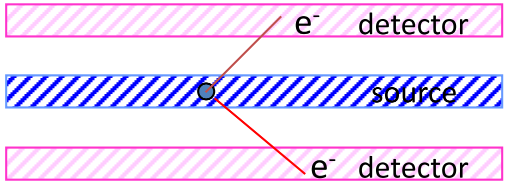
Source = Detector
(calorimetric technique)
High efficiency

- solid-state devices
- bolometers
- gaseous/liquid detectors
- solid scintillators

→

- ☹ constraints on detector materials
- ☺ very large masses are possible
  demonstrated: up to ~ 0.1 - 1 ton
- ☺ with proper choice of the detector, very high energy resolution
  - Ge-diodes
  - bolometers
- ☺ TPC xenon detectors, indication of event topology
- ☺ Source embedded in liquid scintillator large masses are possible

②



Source ≠ Detector

- scintillation
- gaseous detectors
- magnetic field and TOF

→

- ☹ it is difficult to get large source mass
- ☺ neat reconstruction of event topology
- ☺ several candidates can be studied with the same detector

Experiments
(in red, projects leading the field)

GERDA, LEGEND

CUORE, CUPID
AMoRE

EXO-200, nEXO (liquid)
XENON, DARWIN (2 phases)
NEXT, PANDA=X (gas)

KamLAND-ZEN
SNO+

SuperNEMO

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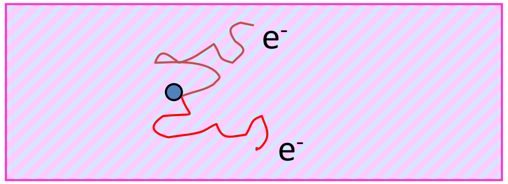

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very high energy resolution

A. Torrento's talk

- Ge-diodes
- bolometers

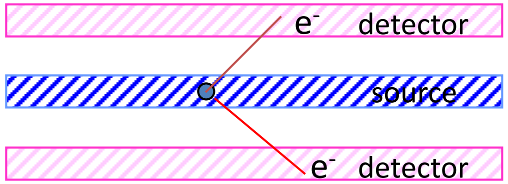
A. Juillard's talk

☺ TPC xenon detectors,
indication of event topology

G. Charles' talk

☺ Source embedded in liquid scintillator
large masses are possible

②



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KamLAND-ZEN
SNO+

SuperNEMO

$0\nu2\beta$ at IN2P3

Mature technology

SuperNEMO
Tehcnically ready
Unique: full event reconstruction
Non-scalable to next-generation

XENON-DARWIN
Technically ready
Multipurpose rare-event experiments
Scalable to next generation

CUPID
Technically ready
Cost-effective and data driven
Scalable to next-generation / beyond

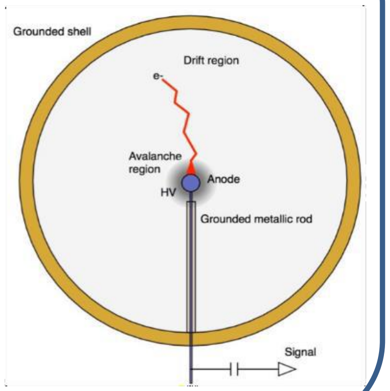
R&D

R2D2
Simple → low radioactivity
Scalable

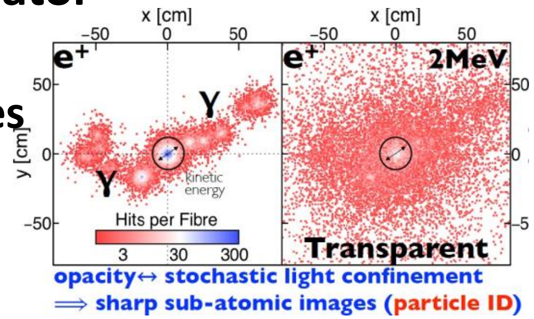
Liquid0
Event ID by revolutionary approach in liquid scintillators
Scalable

R&D program for a
zero background ton scale detector
Spherical Xenon gas TPC at high pressure
(i.e. 40 bars)

→ 1 ton ~1 m radius
(common R&D with **NEWS-G**)



R&D activity based on **liquid scintillator technology**
Opaque scintillator + **tight array of fibres**
- conventional paradigm of transparency is abandoned
- $0\nu2\beta$ candidate is diluted in the scintillator



R&D programs for a CUPID follow-up
Innovative bolometric techniques for background mitigation

Projects **CROSS** and **BINGO**

^{82}Se

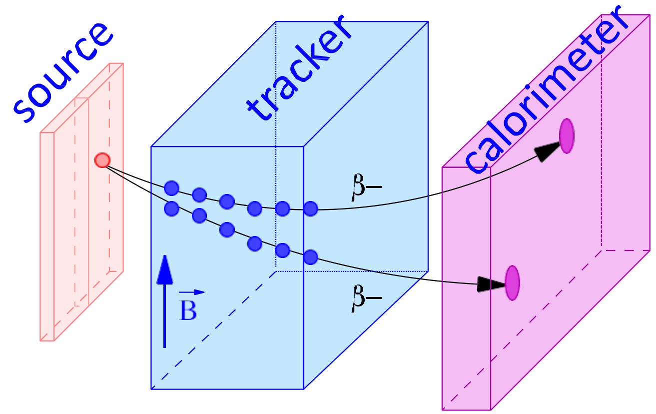
SuperNEMO

source ≠ detector

9 countries
21 Laboratories

Main objectives:

- Build on the experience of the successful **NEMO-3 experiment**
- **Tracking-calorimeter approach**
  → identification and suppression of background.
- **Zero-background experiment** in the **SuperNEMO demonstrator** at LSM
- In case of a discovery by current or future experiments, provide a unique technology to **identify the mechanism inducing 0ν2β decay**

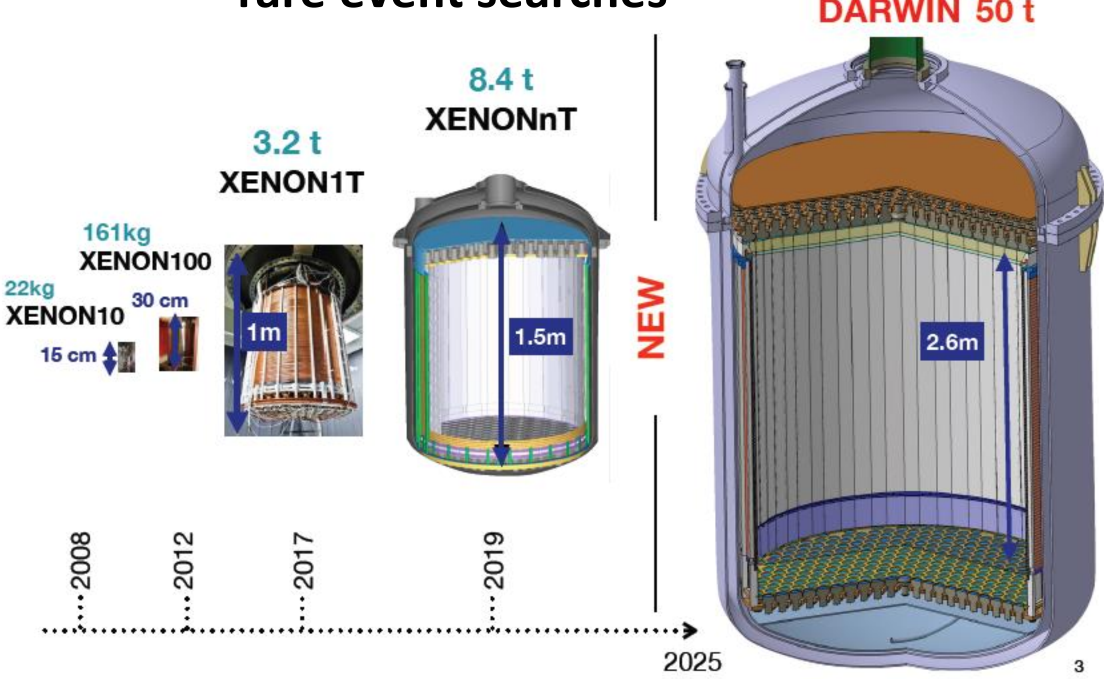


SuperNEMO Demonstrator Module:
final commissioning in progress at LSM

- **6 kg of ^{82}Se**
- Background rate in ROI: **0.043 counts/(kg y)**
- Sensitivity: ~**6.5 × 10^{24} y** in **3 y** → **$m_{\beta\beta}$ < 260 – 500 meV** with exposure of 18 kg × y → 3 y data-taking
- **Full event reconstruction of 2ν2β of ^{82}Se**
  → **unique precision measurements**
  (**limits on right currents, Majoron emission, supersymmetric modes, excited states**)
  → access to nuclear physics: **g_A analysis**

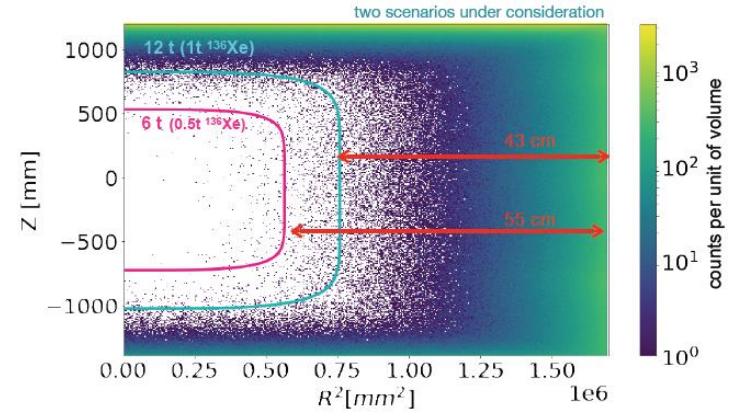
XENON → DARWIN

Dark matter + double beta decay + other rare event searches



Dual-phase Time Projection Chamber (TPC)
50 t total (**40 t active**) of natural liquid xenon (LXe)

DARWIN will have more than **3.5 t** of active ^{136}Xe



Main background sources

- ^{222}Rn in LXe
- ^{137}Xe from μ-induced neutrons
- ^{8}B Solar neutrinos

Factor 10^4 reduction with respect to XENON1T

10 y sensitivity: $T_{1/2} > 2.4 \times 10^{27}$ y
m_{ee} < 18 – 46 meV

$^{130}Te \rightarrow {}^{100}Mo$

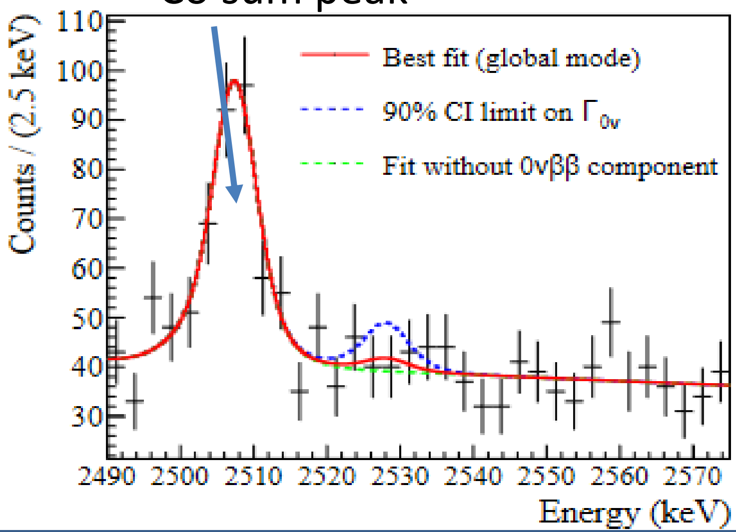
CUORE → CUPID

CUORE is collecting data succesfully

LNGS – Italy

- 988 TeO_2 bolometers → candidate ^{130}Te
- Exposure: 1.038 tonne × y - $T_{1/2}$ **> 2.8×10^{25} y** → m_{ee} **< 90 – 305 meV**
- 5 y projected half-life sensitivity: **~10^{26} y** → m_{ee} **< 50 – 190 meV**
  - Background close to expectations: **b = 1.49 × 10^{-2} c/(keV·kg·yr)** → **dominated by α radioactivity**
  - Energy close to expectations (5 keV) **~7.8 keV FHWM** → margins for improvement

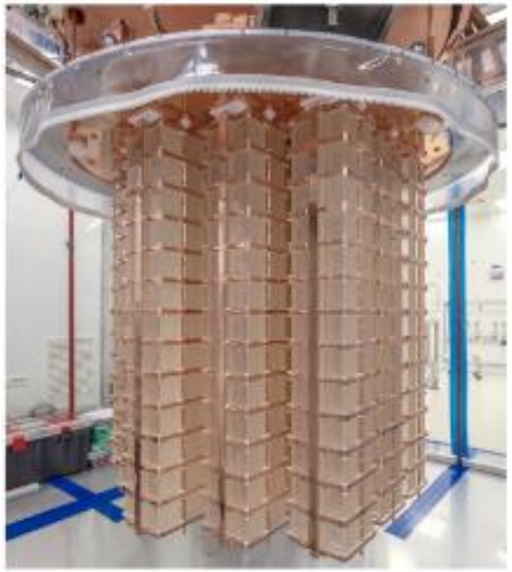
^{60}Co sum peak

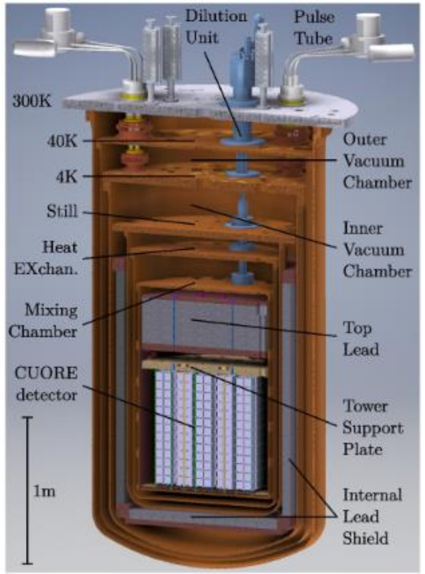


Three important messages from CUORE

1. **A tonne-scale bolometric detector** is feasable
2. Analysis of **~1000 individual bolometers** is handable
3. **An infrastructure** to host a bolometric next-generation 0νββ experiment **is already available**

CUPID is the natural evolution of CUORE





CUPID-Mo as CUPID demonstrator

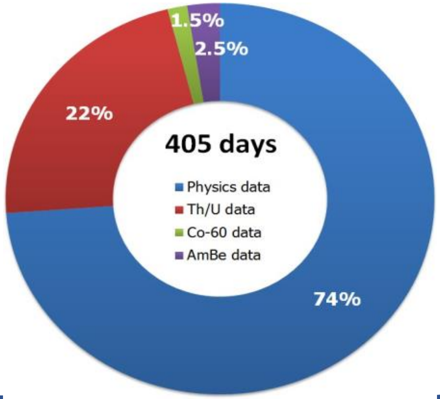
LUMINEU (from 2013) has succesfully developed the scintillating-bolometer **$Li_2{}^{100}MoO_4$ technology** → **reject α radioactivity**

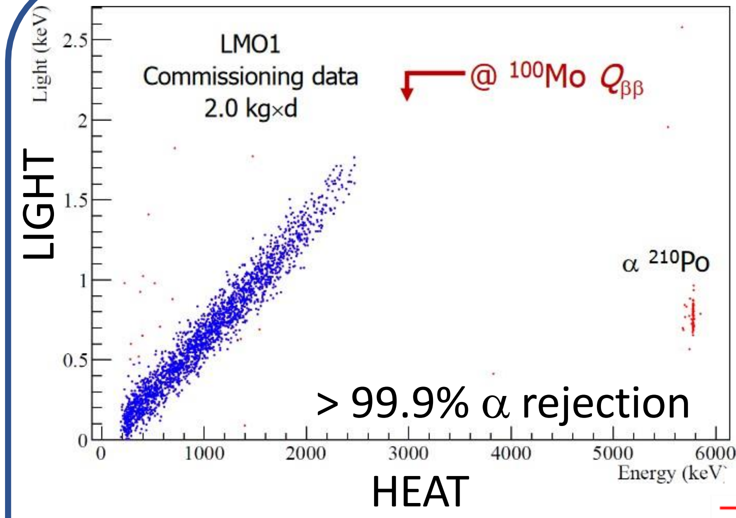
CUPID-Mo

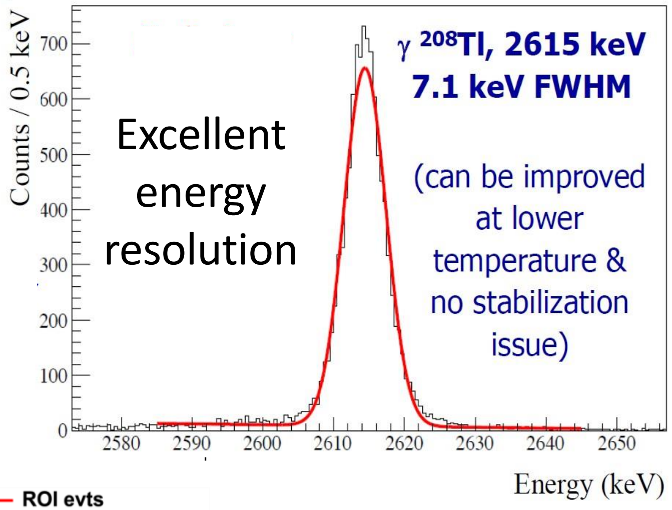
- 20 ^{100}Mo-enriched (97%) Li_2MoO_4 crystals
  ⇒ **~2.3 kg of ^{100}Mo**
- 20 Ge light detectors
- 5 towers with 4 detectors each
- **EDELWEISS set-up @ LSM (France)**

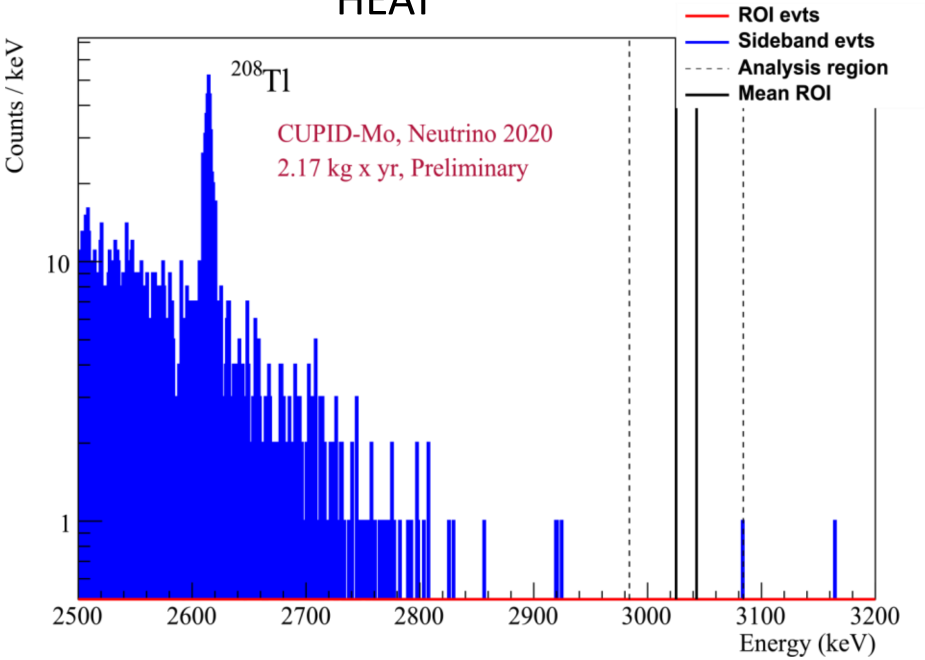
Data taking:
April 2019 – July 2020

Exposure: 2.17 kg × y









$T_{1/2}$ > 1.5 ×10^{24} y at 90% C.I.

New world leading limit on 0ν2β of ^{100}Mo

m_{ee}< (310-540) meV 90% c.i.

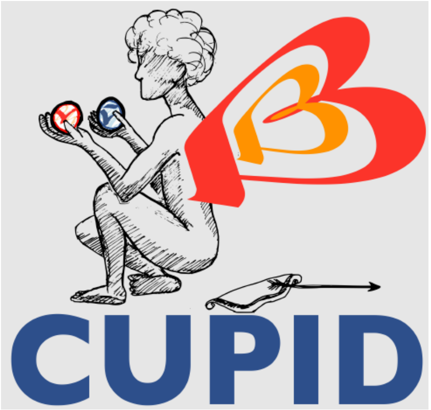
Zero counts in the region of interest

^{100}Mo

CUPID: prospects and sensitivity

The CUORE collaboration has selected the **Li_2MoO_4 technology for CUPID**

Experiment described in CUPID CDR
arXiv:1907.09376



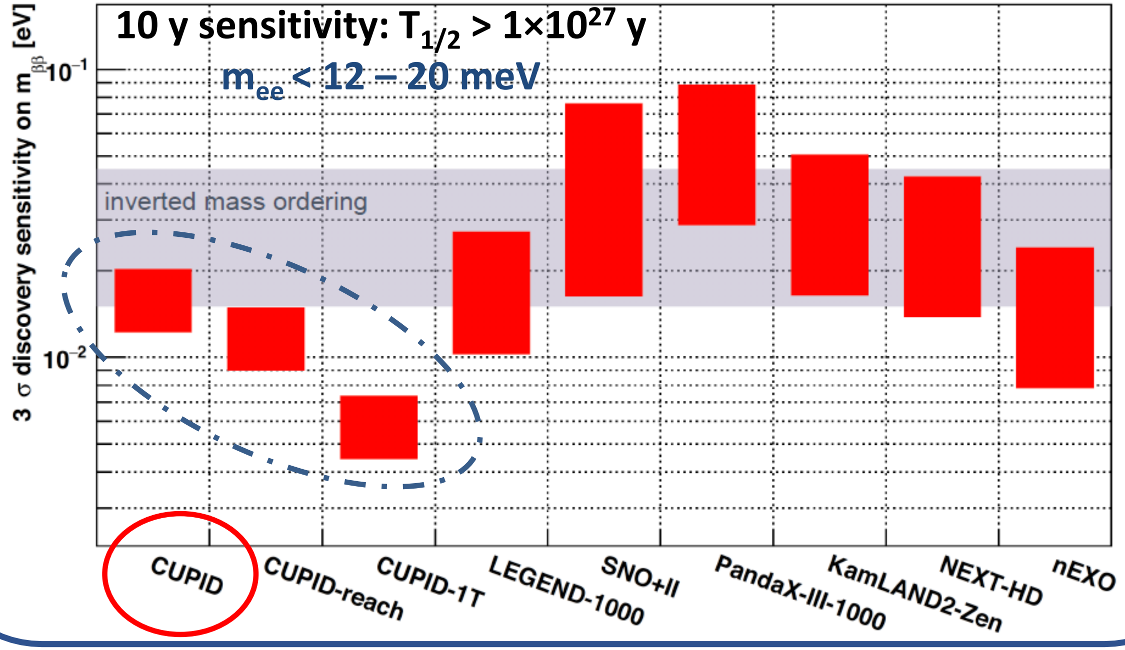
7 countries, 33 institutions, 160 physicists

- Single module: $Li_2{}^{100}MoO_4$ **45x45x45 mm**
- 57 towers / 14 floors / 2 crystals/floor- **1596 crystals**
- **~240 kg of ^{100}Mo** for >95% enrichment
- **1.6×10^{27}** ^{100}Mo atoms
- **Background ~ 10^{-4} counts/(keV kg y)**

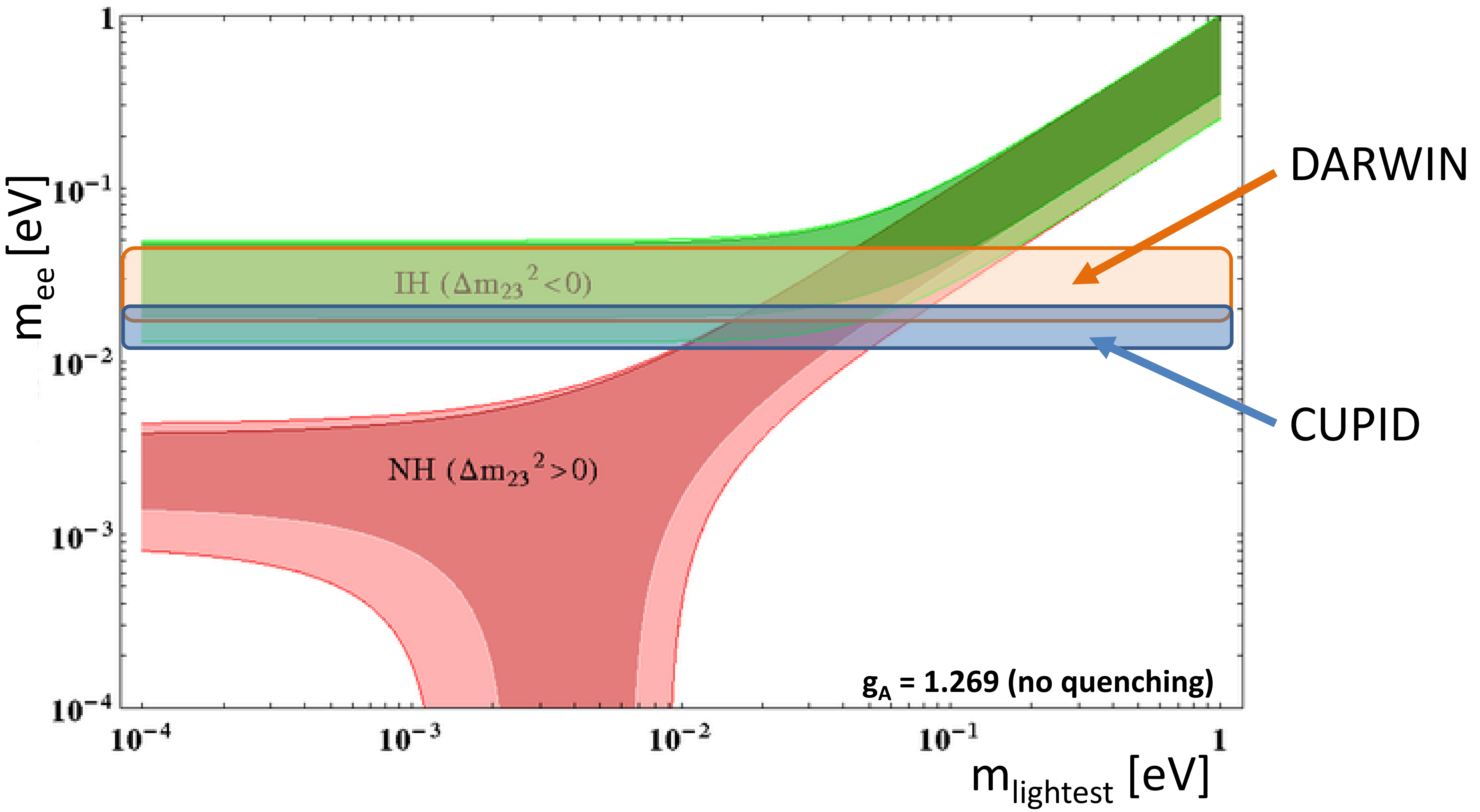
Excellent prospects for funding in Italy and US

CUPID =
CUORE infrastructure (LNGS) + CUPID-Mo approach

- Achieved technology
- Reliable background mode
- Existing infrastructure
- Costs dominated by isotope and crystals
- Commissioning: 2027



Future reach



Conclusions

- $0\nu 2\beta$ is a crucial process for neutrino physics and to test LNV
- Next-generation experiments have a good discovery potential
- Many projects aim at extending the present sensitivity
- Activity in France: CUPID, DARWIN, SuperNEMO