Neutrinoless double beta decay: where we are and where we are going

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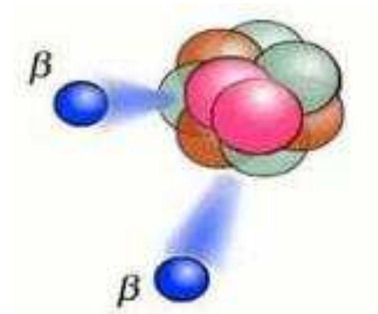
Outline

- $0\nu 2\beta$ decay: theoretical relevance and experimental challenges
- The experimental status: overview of the current experiments
- A selected sample of important experiments
- Towards the next generation: $\mathcal{O}$(1 ton) of candidate mass
- g_A quenching issue
- Conclusions

Neutrinoless double beta decay ($0\nu2\beta$): 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 nuclear matter:
$(A,Z) \rightarrow (A,Z+2) + 2e^-$



Energetically possible for **~40 nuclei**
Only a few are experimentally relevant

$0\nu2\beta$

Standard mechanism: **neutrino physics**

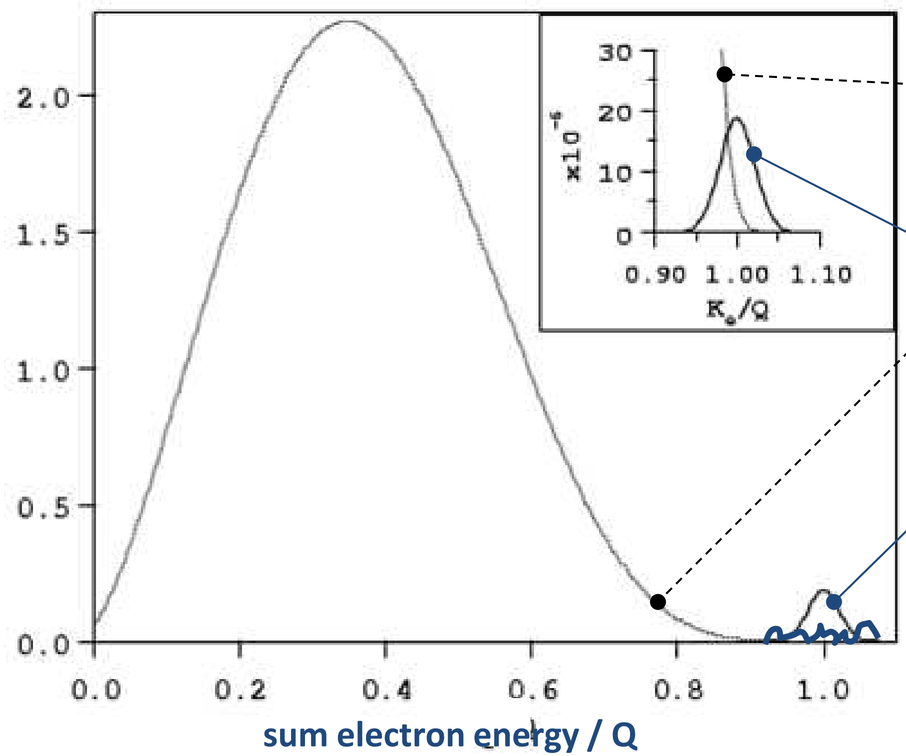
$0\nu2\beta$ is mediated by light massive Majorana neutrinos
(exactly those which oscillate)
$\rightarrow$ **ν Majorana nature**, **ν mass scale** and **hierarchy**, **Majorana phases**

Non-standard mechanism: **BSM, LNV**

Not necessarily neutrino physics

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 modes



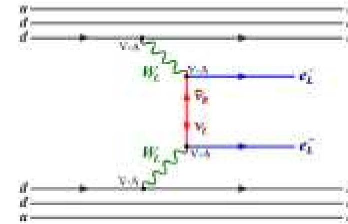
2ν DBD: (A,Z)→(A,Z+2)+2e+2ν
continuum with maximum at ~1/3 Q

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

Q ~ 2-3 MeV for the most promising candidates

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

Standard 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** → $1/\tau$

Phase space → $G(Q,Z)$

Axial vector coupling constant → g_A^4

Nuclear matrix elements → $|M_{nucl}|^2$

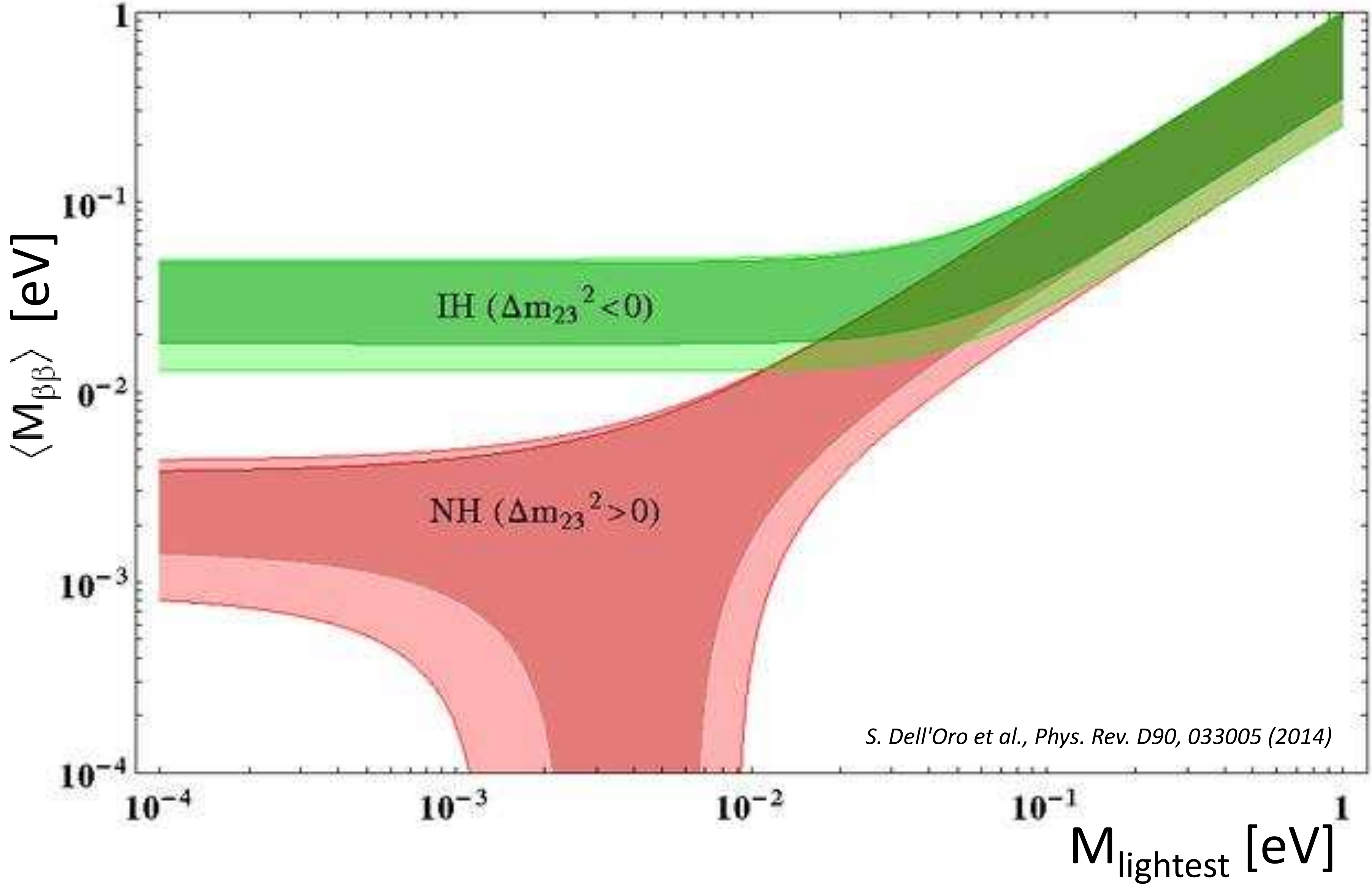
Effective **Majorana mass** → $\langle M_{\beta\beta}\rangle^2$

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

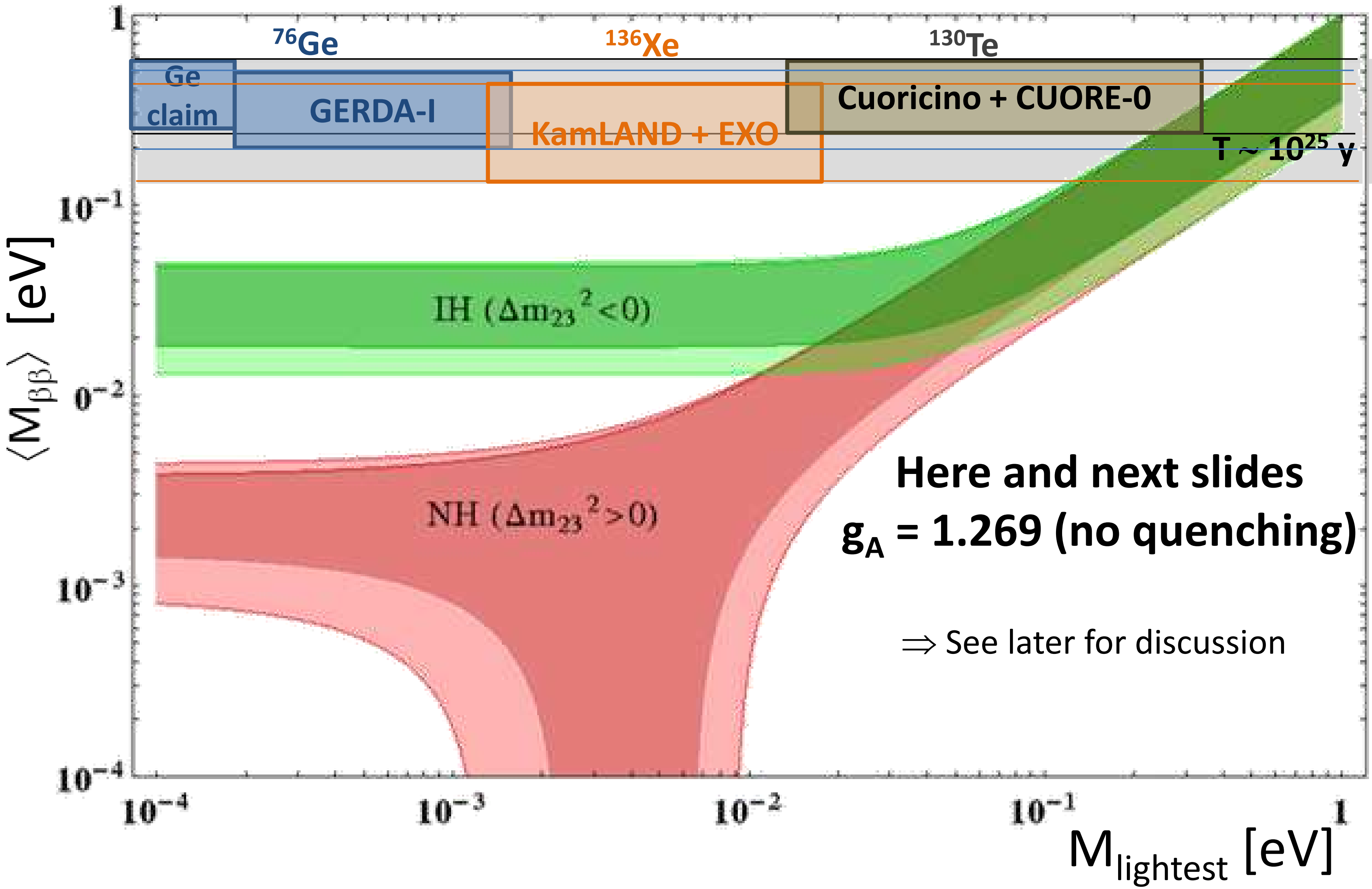
- $1/\tau$: Experiments
- $G(Q,Z)$: Calculable
- g_A^4: Controversial
- $|M_{nucl}|^2$: Nuclear theory
- $\langle M_{\beta\beta}\rangle$: Neutrino physcis

$$\langle \mathbf{M}_{\beta\beta}\rangle = \left|\, |U_{e1}|^2 M_1 + e^{i\alpha_1} |U_{e2}|^2 M_2 + e^{i\alpha_2} |U_{e3}|^2 M_3 \,\right|$$

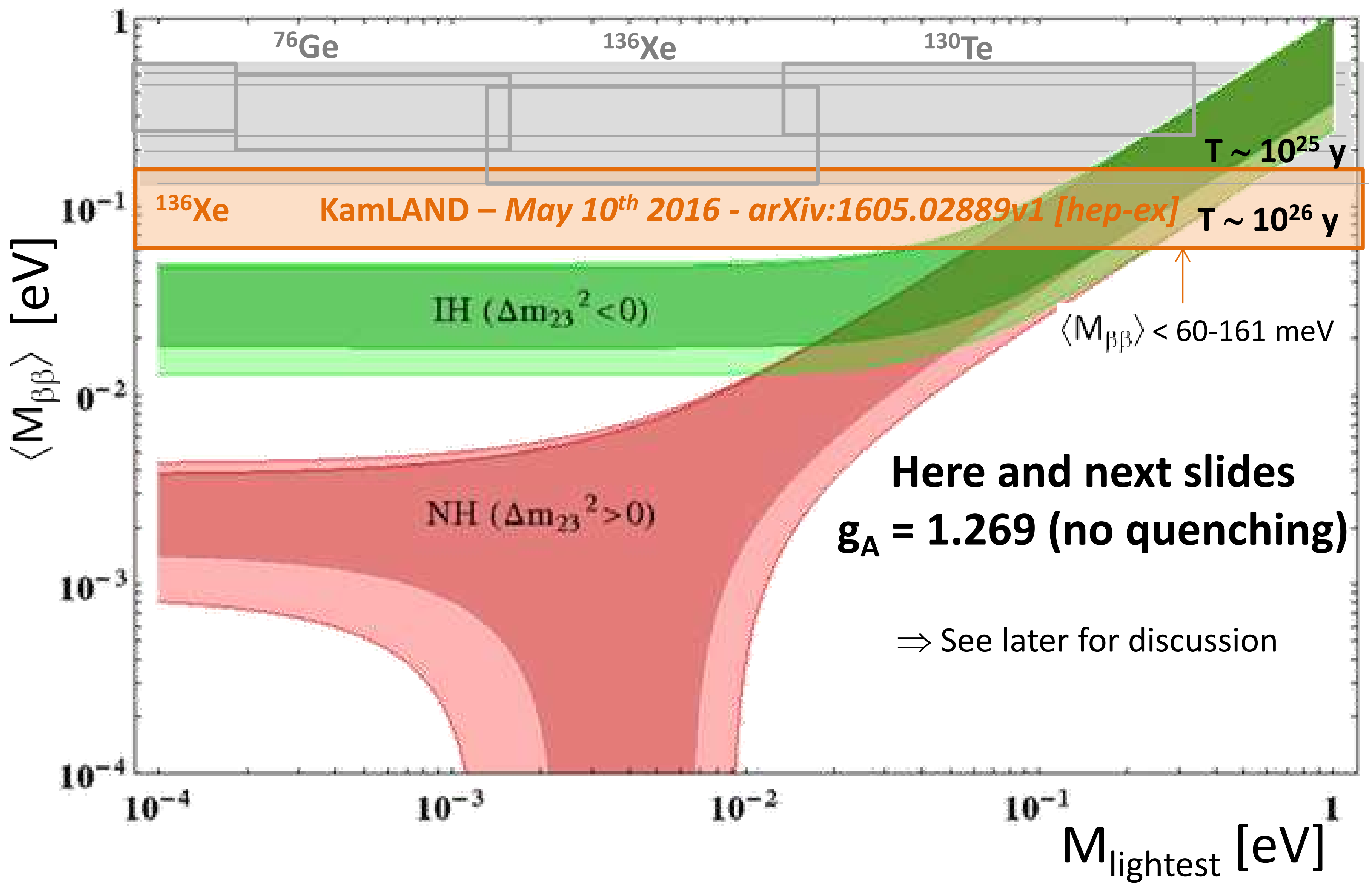
$\langle M_{\beta\beta} \rangle$ vs. lightest ν mass



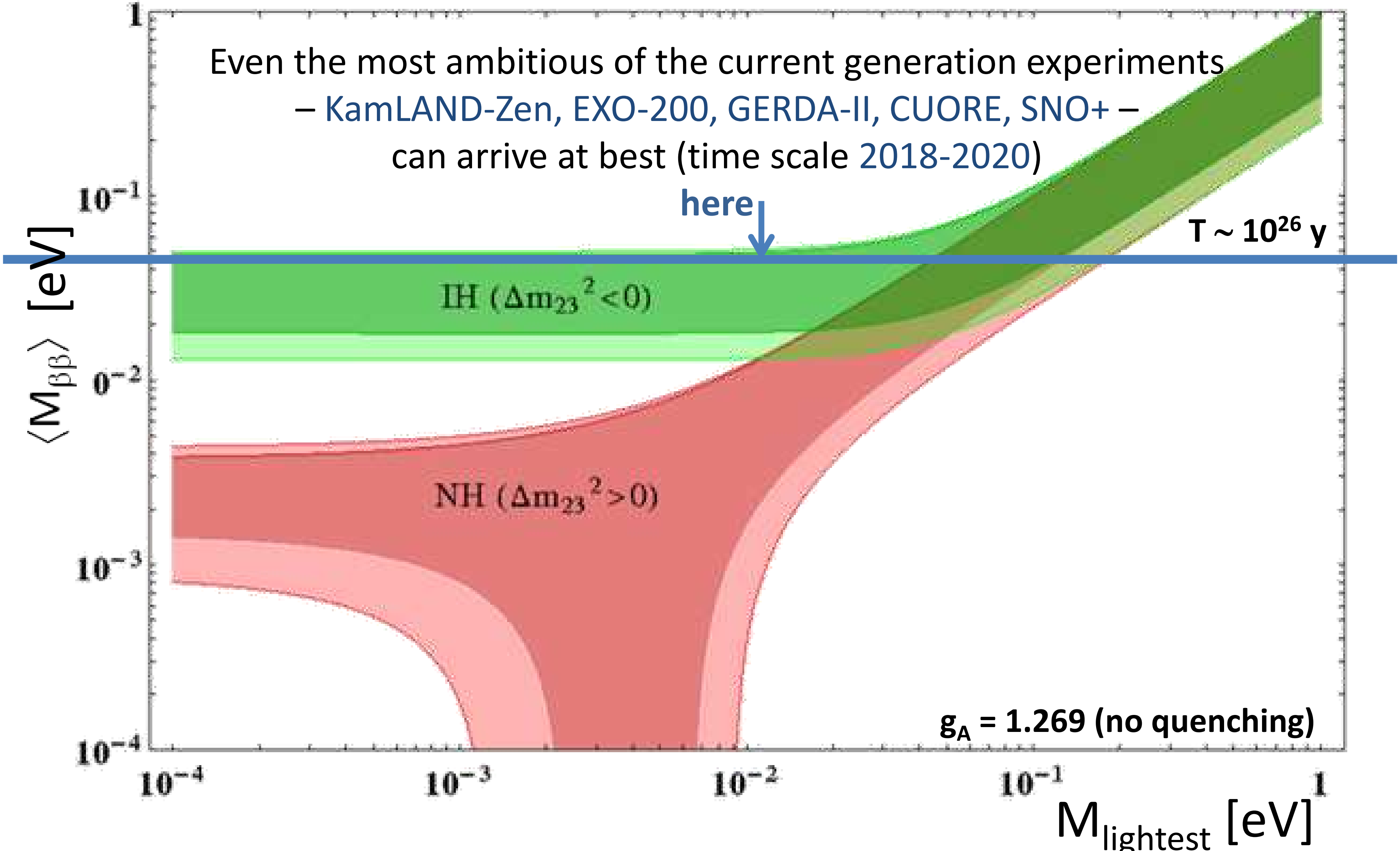
Status (up to two weeks ago…)



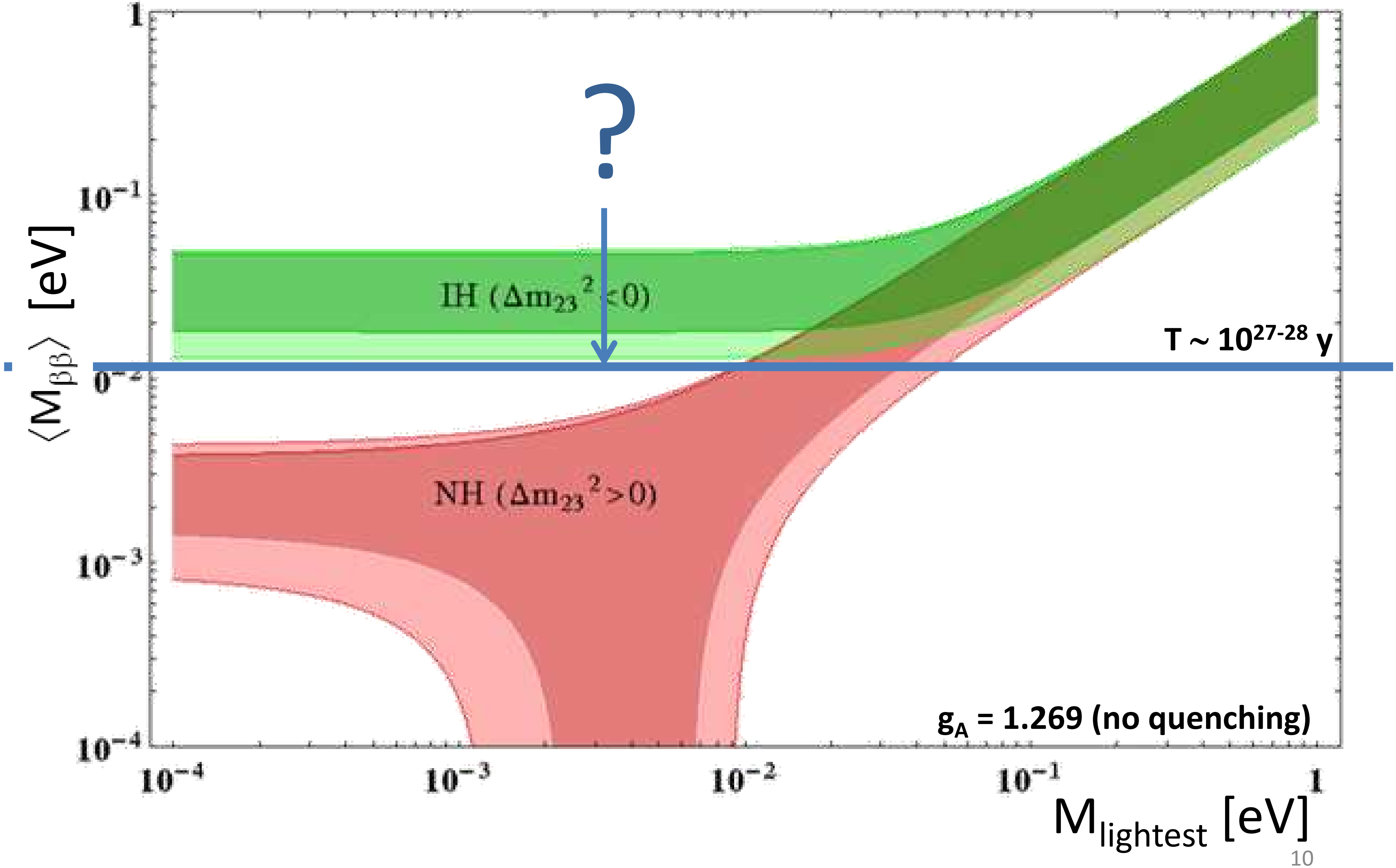
Status (today)



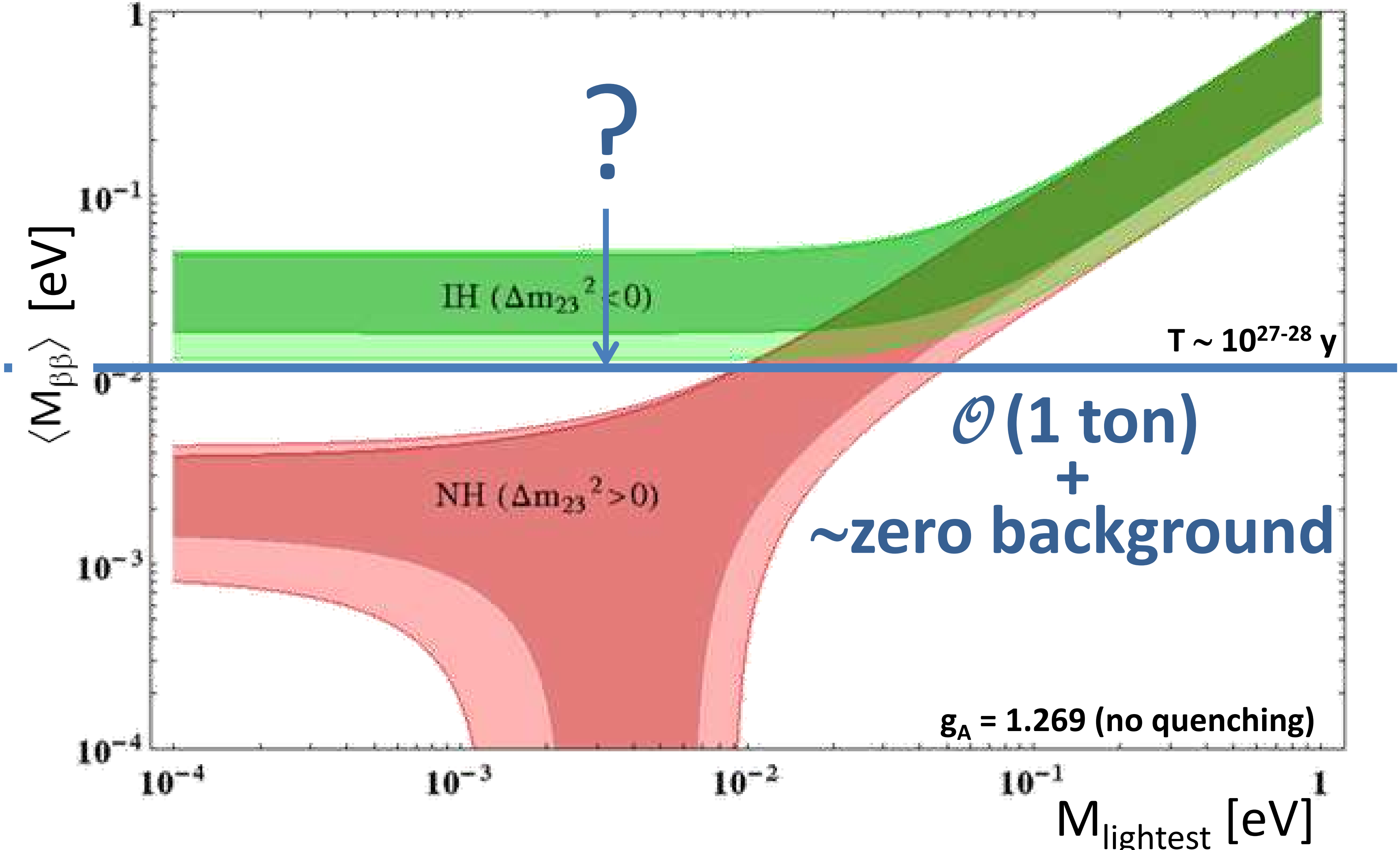
Current-generation experiments



Strategic milestone

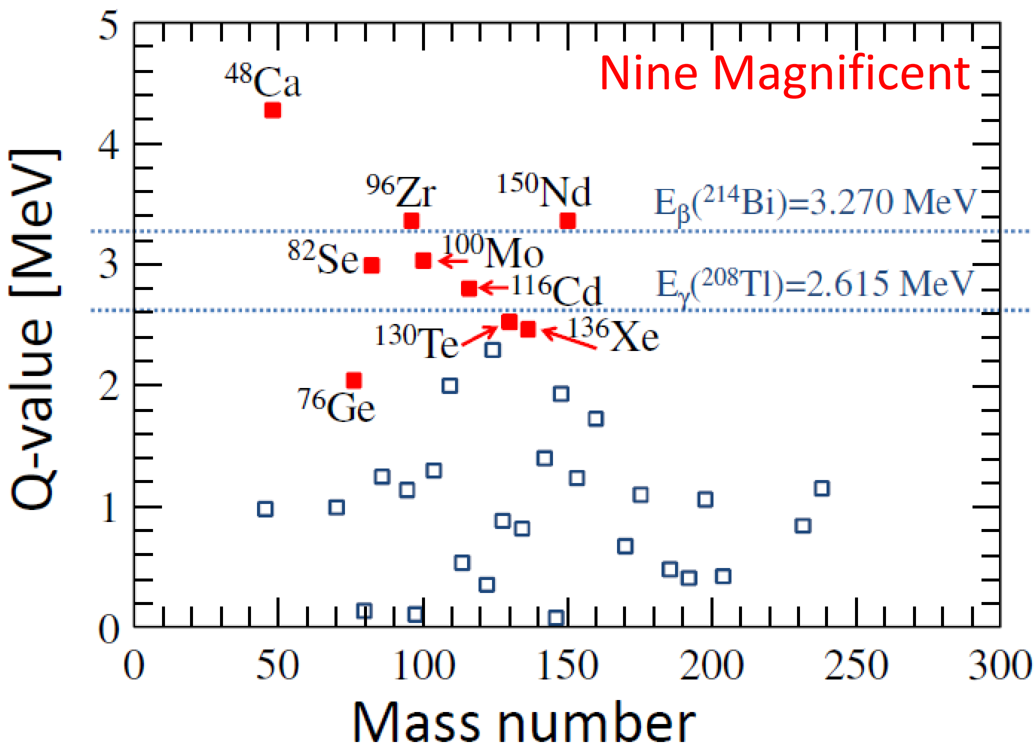


Strategic milestone



Factors guiding isotope selection

Q is the crucial factor → Phase space: $G(Q,Z) \propto Q^5$; Background

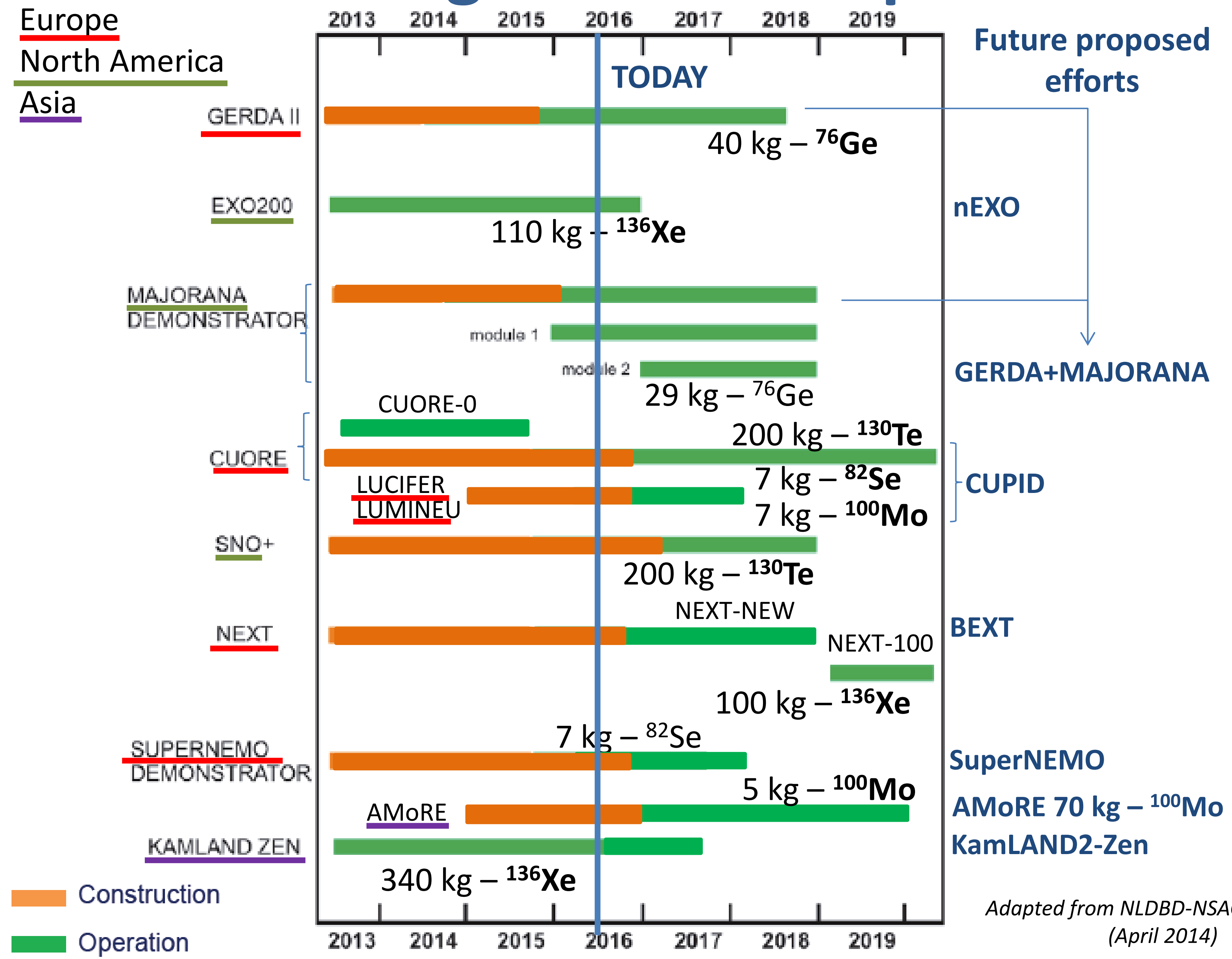


End-point of ^{222}Rn-induced radioactivity

End-point of natural γ radioactivity

Dominant role of **enrichment** / **technology** issues

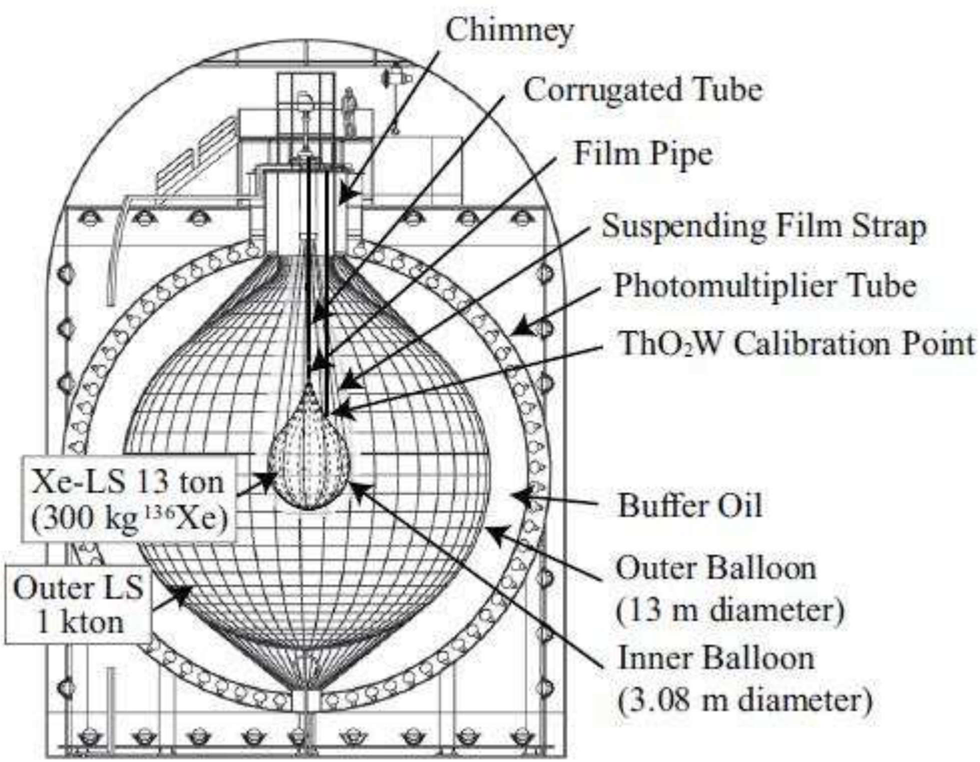
Current-generation experiments



Adapted from NLDBD-NSAC document (April 2014)

KamLAND-Zen

Technique/location: enriched Xenon dissolved in liquid scintillator (KamLAND setup, Kamioka)
Source: ^{136}Xe enriched at 91% - ~340 kg (~100 kg fiducial ⇒ **4.3x10^{26} nuclides**)



- Moderate energy resolution (9% FWHM)
- No tracking/topology but impact point (fiducial volume)
- Coincidence cuts

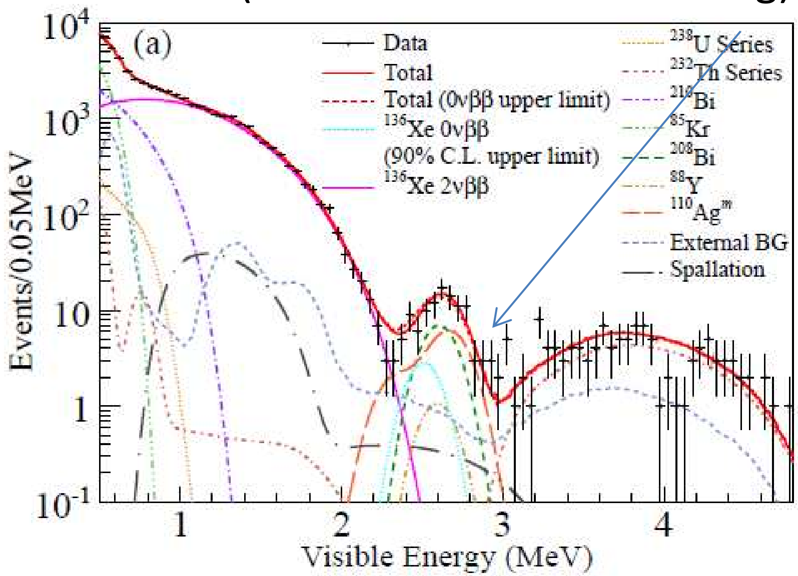
Phase I (contamination from ^{110m}Ag) **Phase II** (after purification campaign)

$T_{1/2}$ > **1.9 x 10^{25} y** ⟶ $T_{1/2}$ > **1.1 x 10^{26} y**

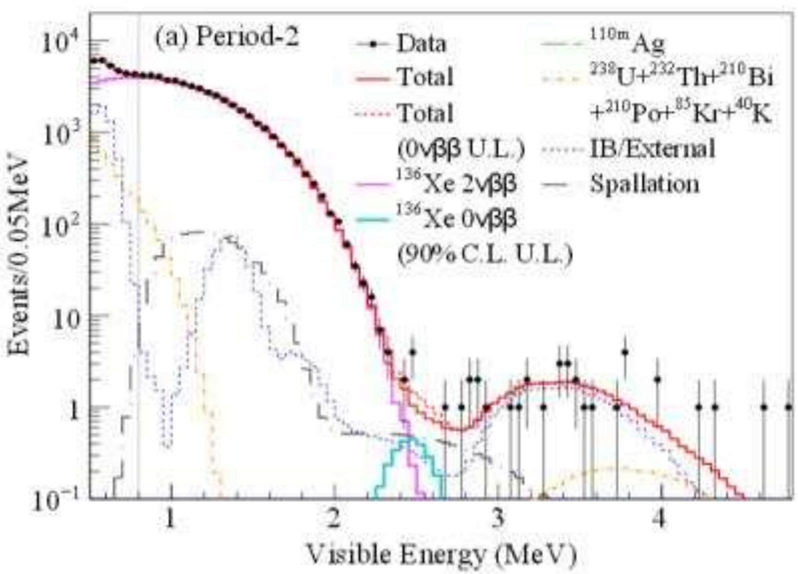
$\langle M_{\beta\beta} \rangle$ < 60-161 meV

KamLAND-Zen

Phase I (contamination from ^{110m}Ag)



Phase II (after purification campaign)



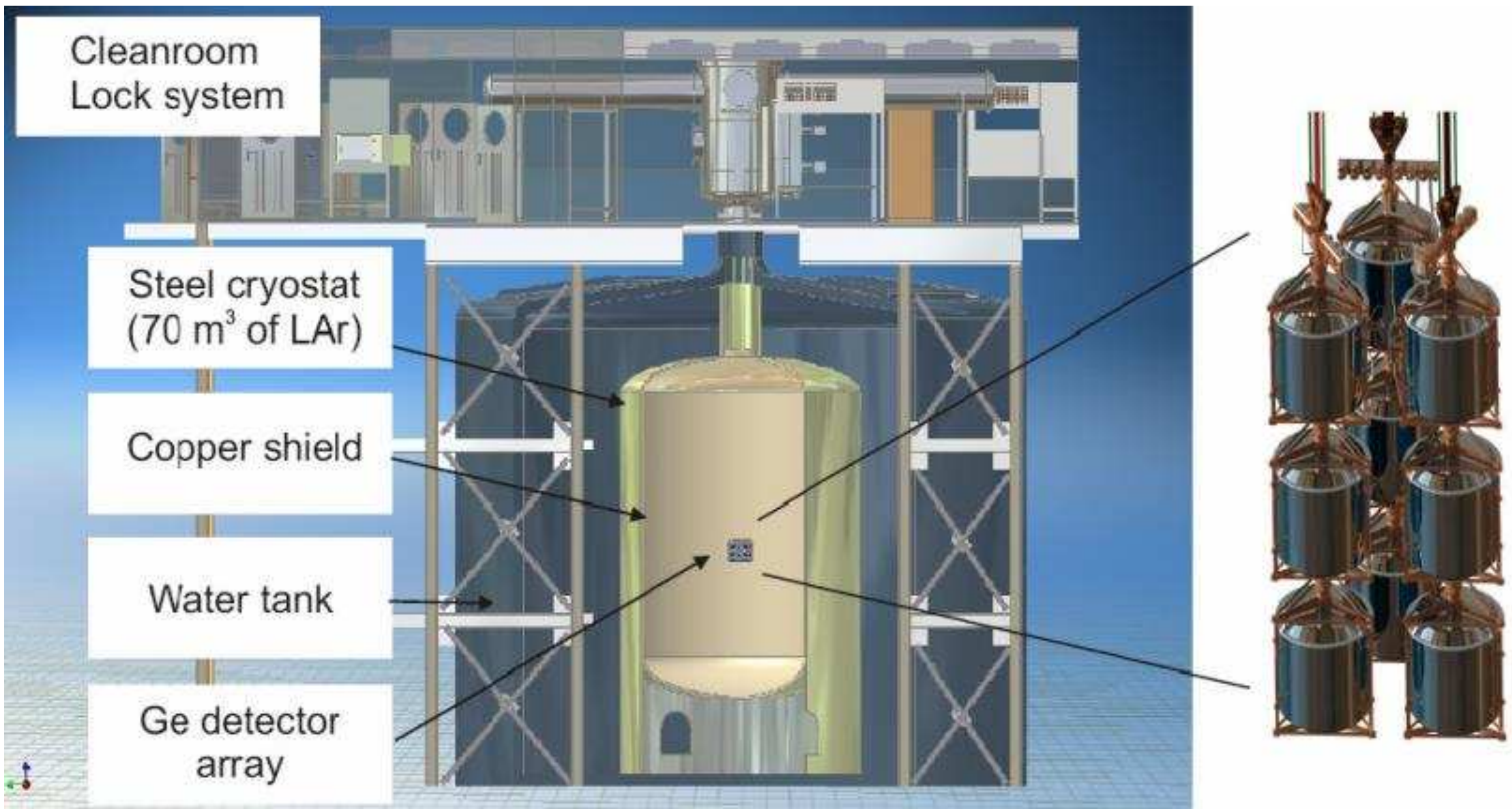
Background budget in ROI

Irreducible background

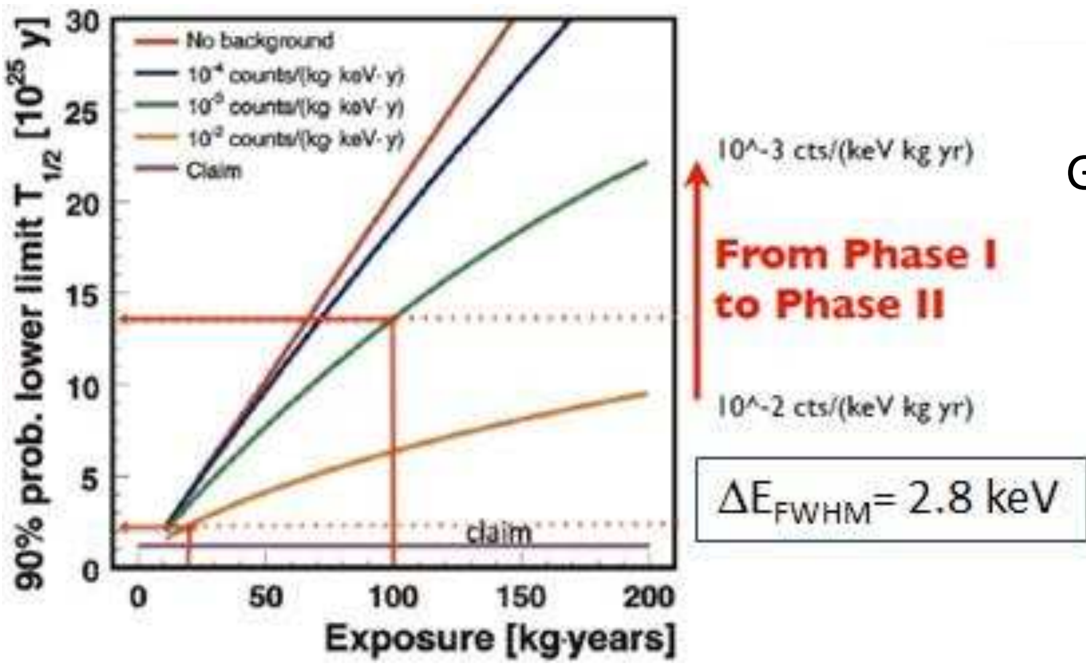
	Period-1 (270.7 days)		Period-2 (263.8 days)	
Observed events	22		11	
Background	Estimated	Best-fit	Estimated	Best-fit
$^{136}Xe\ 2\nu\beta\beta$	-	5.48	-	5.29
Residual radioactivity in Xe-LS				
^{214}Bi (^{238}U series)	0.23 ± 0.04	0.25	0.028 ± 0.005	0.03
^{208}Tl (^{232}Th series)	-	0.001	-	0.001
^{110m}Ag	-	8.0	-	0.002
External (Radioactivity in IB)				
^{214}Bi (^{238}U series)	-	2.55	-	2.45
^{208}Tl (^{232}Th series)	-	0.02	-	0.03
^{110m}Ag	-	0.002	-	0.001
Spallation products				
^{10}C	2.7 ± 0.7	3.2	2.6 ± 0.7	2.7
^{6}He	0.07 ± 0.18	0.08	0.07 ± 0.18	0.08
^{12}B	0.15 ± 0.04	0.16	0.14 ± 0.04	0.15
^{137}Xe	0.9 ± 0.5	1.1	0.9 ± 0.5	0.8

GERDA

Technique/location: bare enriched Ge diodes in liquid argon – LNGS (Italy)
Source: Phase I: Ge - 14.6 kg (coax) + 3 kg (BEGe) – ^{76}Ge enriched at 86% → **1.2×10^{26} nuclides**
Phase II: additional 20 kg → **2.6×10^{26} nuclides**
Sensitivity: Phase I: Klapdor's claim strongly disfavored; Phase II: **80 – 150 meV**
Timeline: GERDA phase I is over; GERDA phase II is taking data from fall 2015



GERDA-II



One of the main purpose of the GERDA-II is to demonstrate that a background index of

10^{-3} c/(keV kg y)

is achievable with the GERDA technology

Stay tuned!

Phase II currently taking data in LNGS

- Additional 30 enriched BEGe detectors (about 20 kg)
- Background reduction through
  - Pulse-shape discrimination (single-site vs. multi-site events)
  - Instrumented scintillating Lar shielding for background identification and rejection

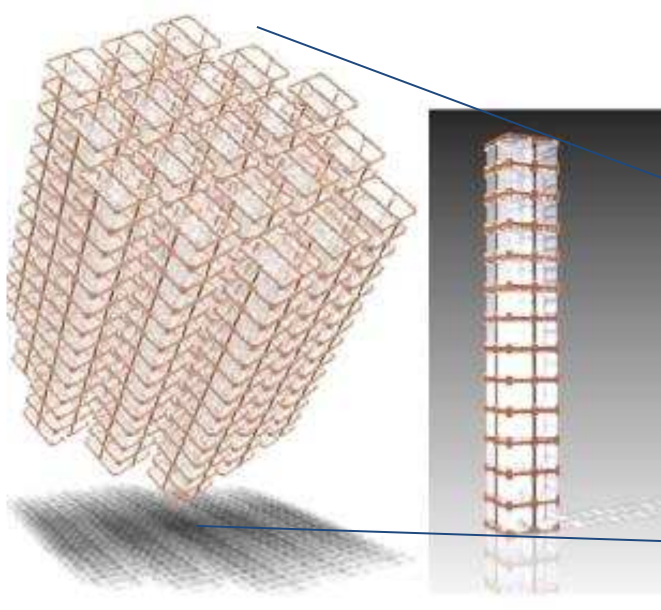
$\rightarrow$ **preliminary results very soon**

Scale-up to 1 ton: **GERDA-MAJORANA common effort**

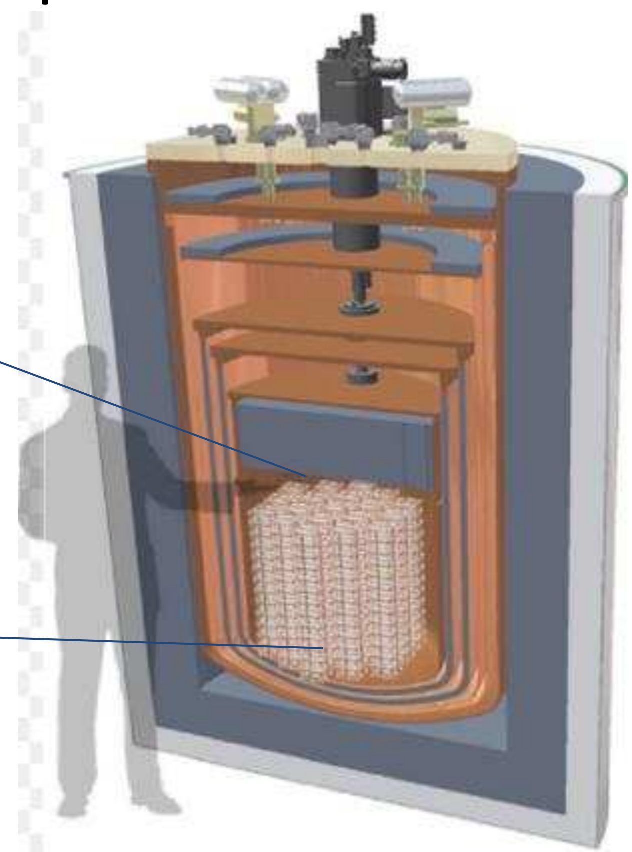
https://www.npl.washington.edu/indico/conferenceTimeTable.py?confId=9#20160425.detailed

CUORE

Technique/location: natural 988 TeO_2 bolometers at 10-15 mK– LNGS (Italy)
evolution of Cuoricino
Source: TeO_2 – 741 kg with natural tellurium - **9.5x10^{26} nuclides of ^{130}Te**
Sensitivity: **51 – 133 meV** (5 years) – approach closely inverted hierarchy region
Timeline: first CUORE tower (CUORE-0) has completed successfully its physics run
Full apparatus operational in 2016 – **all 19 towers completed** – **installation in summer 2016**



Structure of the detector



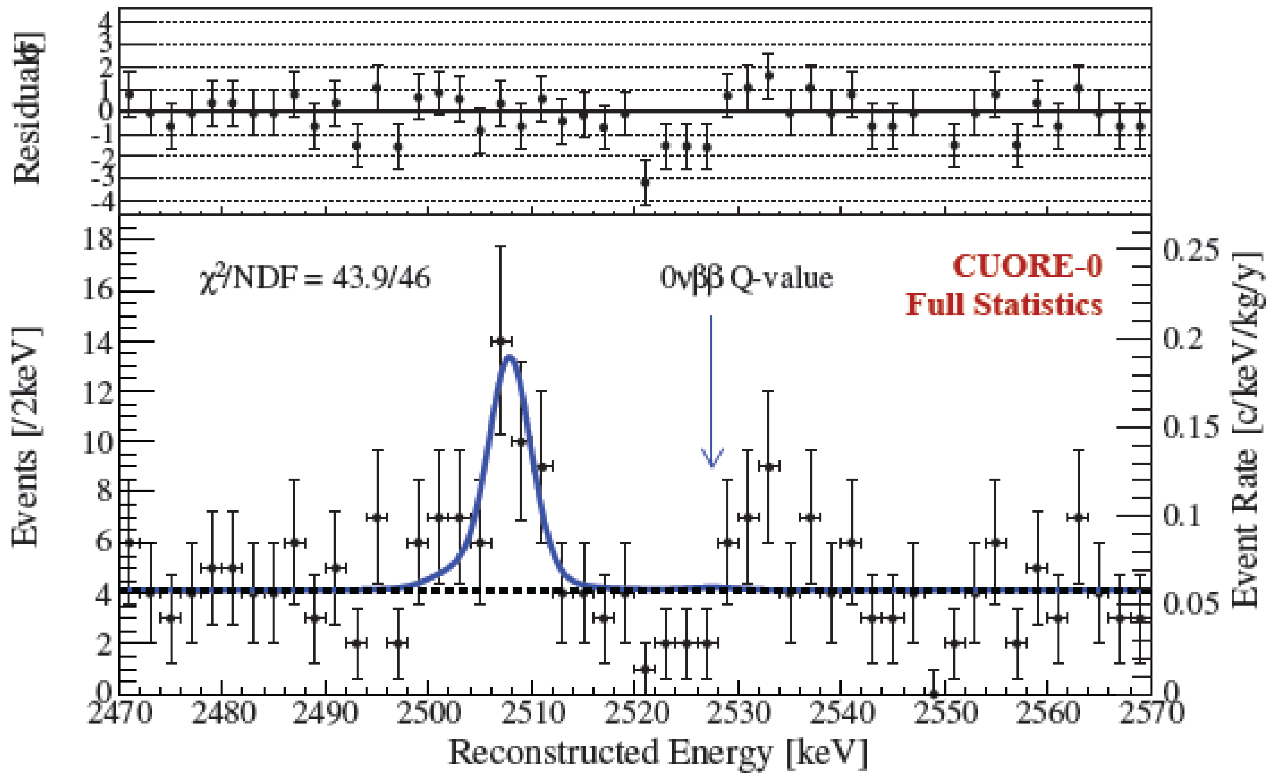
Detector in the custom fridge

CUORE-0

- Excellent energy resolution (5.1 ± 0.2 keV FWHM) – CUORE goal achieved
- Validation of the background reduction protocols for CUORE (goal of 10^{-2} c/(keV kg y) within reach)
- Surpassed Cuoricino sensitivity in less than a half run time
- New limit combining results with Cuoricino (^{130}Te exposure: 9.8 kg·yr CUORE-0 +19.75 kg·yr Cuoricino)

$T_{1/2}$ > 4.0 x 10^{24} y $\langle M_{\beta\beta} \rangle$ < 270-650 meV

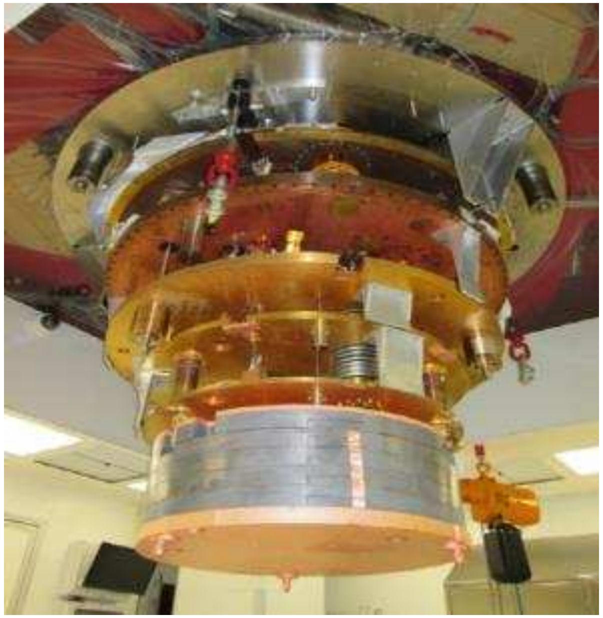
Phys.Rev.Lett. 115 (2015) 10, 102502 (ArXiv:1504.02454)



CUORE status

- Detector (19 towers) ready to be cooled down (2014)
- Cryostat commissioned in 4 runs (2014 – 2016)
  T = 5.9 mK bare cryostat - T=6.3 mK full load
- Detector commissioning from summer 2016

Stay tuned!



CUPID: follow-up to CUORE
(Cuore with Particle Identification)

Basic idea: *arXiv:1504.03612 [physics.ins-det]; arXiv:1504.03599 [physics.ins-det]*

Use CUORE infrastructure (after completion of CUORE programme) with:

- **enriched crystals** (sensitive mass: 210 kg – 550 kg depending on isotope)
- upgraded technology to get **0 background at ton × y scale** (**5-15 meV sensitivity**)

Technology selection + CDR in ~2018/2019

Three R&D areas:

- Reduce / control background from materials and from muon /neutrons
- Optimize the enrichment-purification-crystallization chain
- Improve **detector technology** to get rid of α **/ surface background**

^{130}**Te**O_2 (non scintillating) + advanced light detectors (detection of Cherenkov light)	Scintillating crystals ($Li_2{}^{100}$**Mo**O_4, Zn^{82}**Se**, Zn^{100}**Mo**O_4) + standard light detectors

R&D

LUCIFER – ERC AdG (CE)
LUMINEU in France (ANR)
CUPID-0 in Italy (INFN)

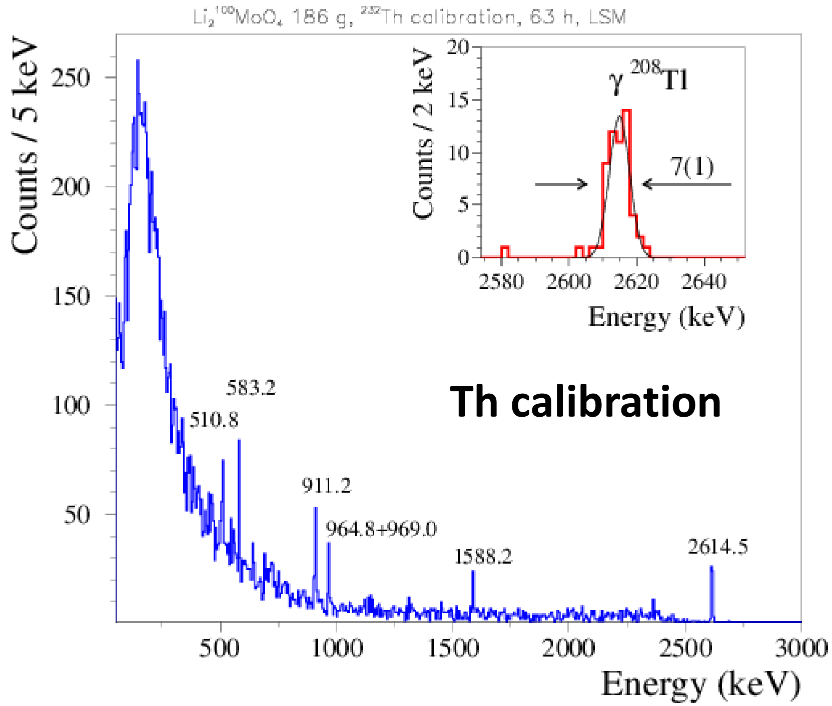
LUMINEU

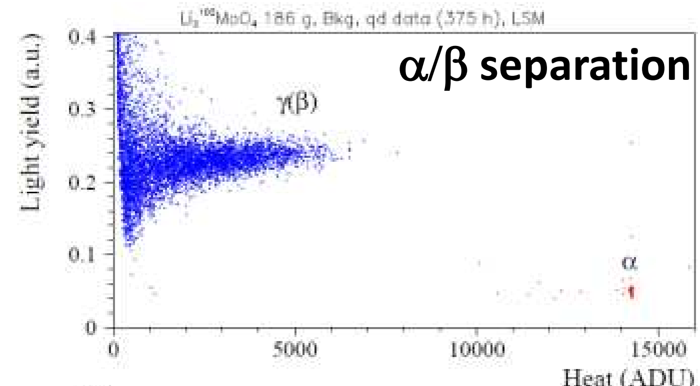
After 3 years' succesfull R&D on $ZnMoO_4$ and Li_2MoO_4 scintillating bolometers,

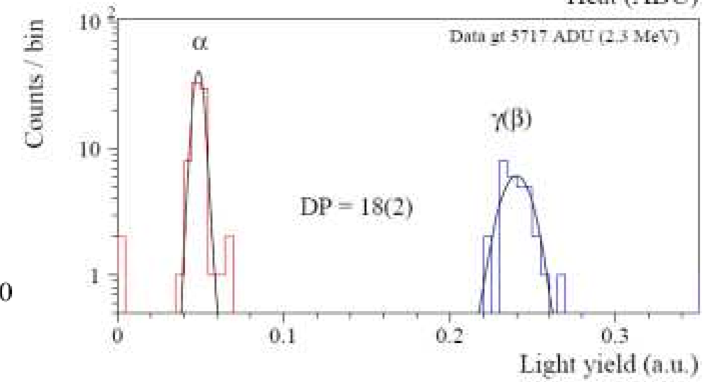
Li_2MoO_4 has been selected for a ~ **^{100}Mo 7 kg technology demonstrator** because of:

- **Excellent energy resolution** (4 – 7 keV FWHM at 2615 keV)
- **Easy crystallization** procedure → extraordinary radiopurity (**< 6 μBq/kg in ^{226}Ra, ^{228}Th**)
- Less critical than $ZnMoO_4$ in terms of **activation**

186 g module installed in Modane







Systematic production of **40 enriched crystals from summer 2016** (**MoU INFN/IN2P3/ITEP**)

→ **20 to be installed in Modane and 20 in LNGS**

Possible routes to $\mathcal{O}(1)$ ton

Collaborations are already working to improve/upgrade their technology in view of 1/multi ton set-up

↓

In order to select the best(s) technology(ies) for 1/multi ton, it is necessary to get the complete scenario of the current generation experiments and demonstrators

↓

Wait 2-3 years for a sensible decision

- in agreement with the down-selection process in the US after report of NSAC about DBD
  http://science.energy.gov/~/media/np/nsac/pdf/docs/2016/NLDBD_Report_2015_Final_Nov18.pdf
- a similar guiding role could be played by ApPEC in Europe

→ global coordination

Possible routes to $\mathcal{O}(1)$ ton

Scalability

1 Fluid-embedded-source way

- **SNO+** (^{130}**Te** 200 kg) → **SNO+** (^{130}**Te** 800 kg)
- **KamLAND-Zen** → **KamLAND2-Zen** (0.8 ton ^{136}**Xe**, higher energy resolution)
- **EXO-200** → **nEXO** (5 ton liquid ^{136}**Xe** TPC)
- **NEXT-100 → BEXT** (1-3 ton high pressure ^{136}**Xe** TPC)

Low energy resolution
250 keV FWHM
80 keV FWHM

- Irreducible $2\nu2\beta$
- ^{214}Bi line not resolved from $0\nu2\beta$ ^{136}Xe signal

High ΔE

2 Crystal-source way

Extreme background demand
(10^{-4} counts/keV/kg/y at 2 MeV)

- **GERDA-II → GERDA+MAJORANA** → 1 ton ^{76}Ge
- **CUORE** → **CUPID** (0.5-0.2 ton ^{130}**Te** or ^{100}**Mo** or ^{82}**Se**)
  LUCIFER, LUMINEU
  AMoRE-I (^{100}**Mo** ~10 kg) → **AMoRE-II** (^{100}**Mo** ~70 kg)

Cryogenics
Crystallization

CAVEATS

It is problematic to reach the 1 ton scale with the **External-source approach** (**SuperNEMO**), but the use of a high promising isotope as ^{150}**Nd** could partially compensate for the lower mass

Impact of enrichment cost

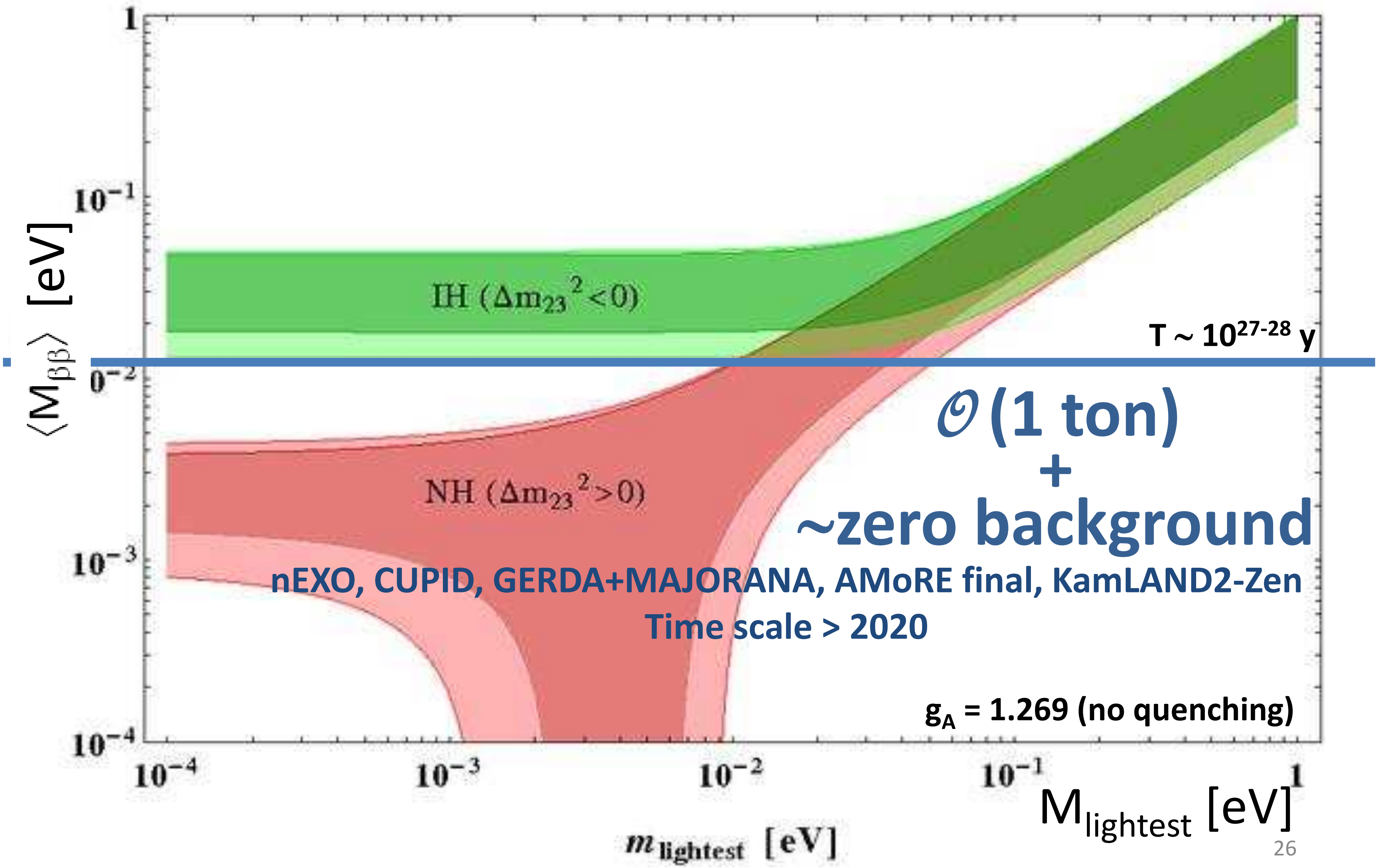
Isotope	Abundance	Price/ton [M$]
^{76}Ge	7.61	~ 80
^{82}Se	8.73	~ 80
^{100}Mo	9.63	~ 80
^{116}Cd	7.49	~ 180
^{130}Te	34.08	~ 20
^{136}Xe	8.87	~ 5-10
^{150}Nd (?)	5.6	> 200

Adapted from A. Barabash J. Phys. G: Nucl. Part. Phys. 39 (2012) 085103

Not always really 1 ton:

- **nEXO** – **5 tons** – sensitivity: **5-16 meV** in 10 y (no barium tagging)
- **CUPID ^{130}Te** – **0.54 tons** – sensitivity: **6-15 meV** in 10 y
- **CUPID ^{100}Mo** – **0.21 tons** – sensitivity: **6-17 meV** in 10 y

Strategic milestone



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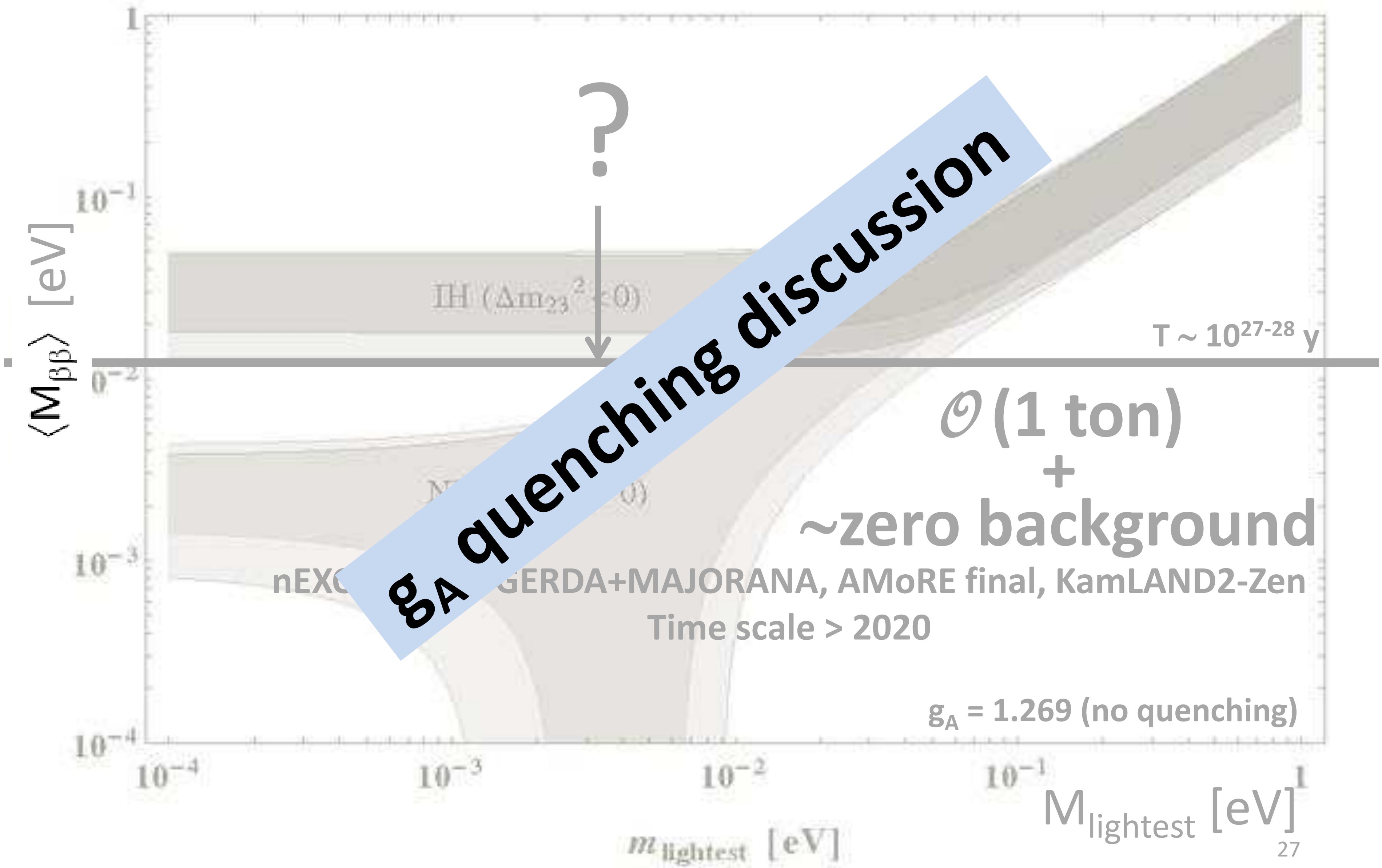


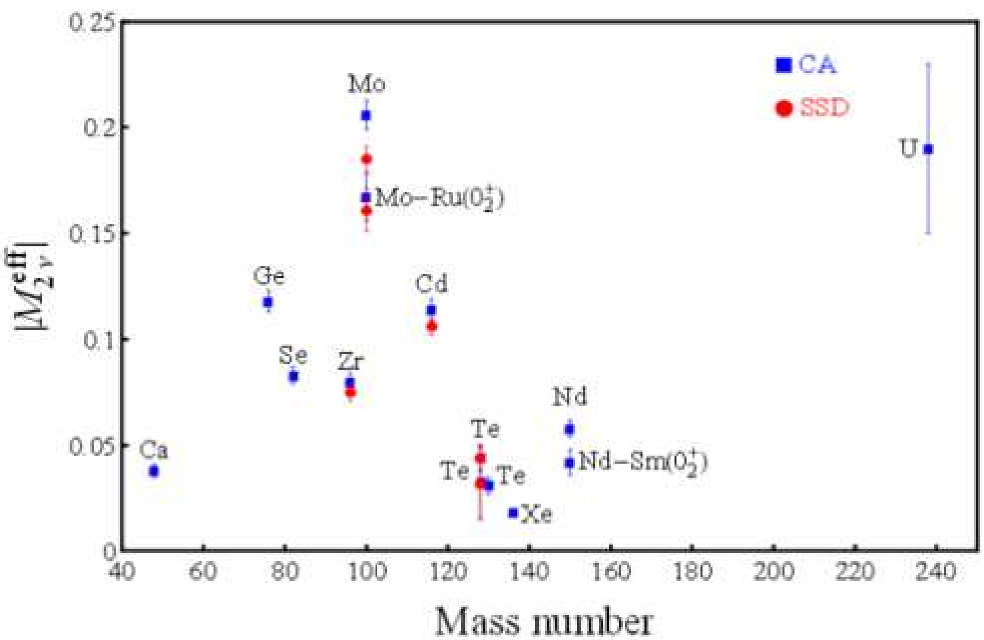
g_A quenching

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

g_A =
- 1.269 Free nucleon
- 1.25 Often taken in the calculations
- 1 Quark

J. Barea et al. and Ejiri et al. realized that **g_A is quenched** in $2\nu2\beta$ decay (confirmed by β-like processes)

J. Barea et al., Phys. Rev. C 87, 014315 (2013)
E. Ejiri et al., Physics Letters B 729 (2014) 27–32
J. Kotila et al., Phys. Rev. C 85, 034316 (2012)



- ✓ Evaluate $M_{2\nu}^{eff}$ from experiments

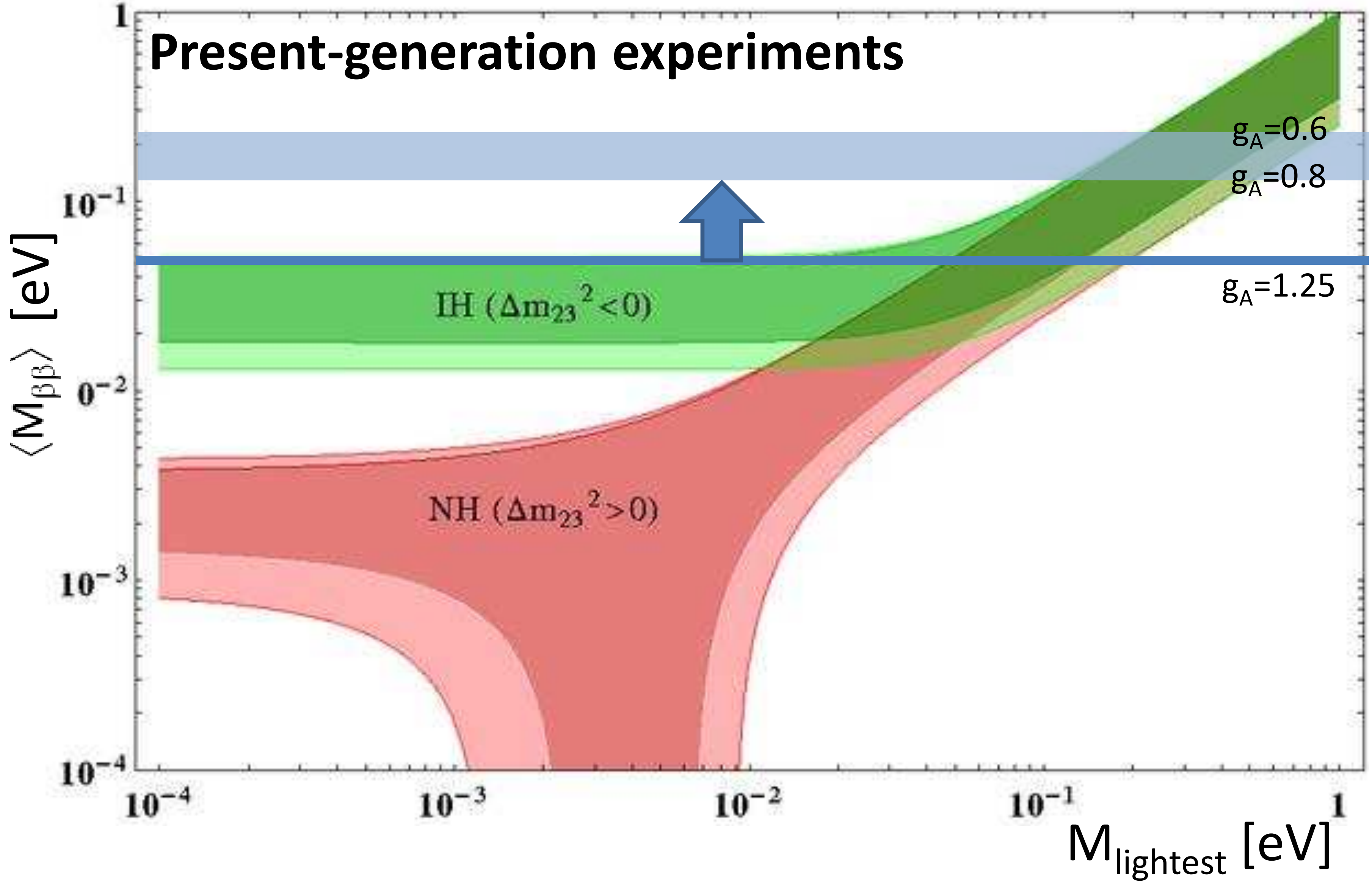
$$\left[T_{1/2}^{2\nu,exp}\right]^{-1} = G_{2\nu}|M_{2\nu}^{eff}|^2$$

- ✓ Compare $M_{2\nu}^{eff}$ (exp) with $M_{2\nu}$(theo)
- ✓ Observe that $M_{2\nu}^{eff}$ (exp) < $M_{2\nu}$(theo)
- ✓ Rescale g_A to explain the difference

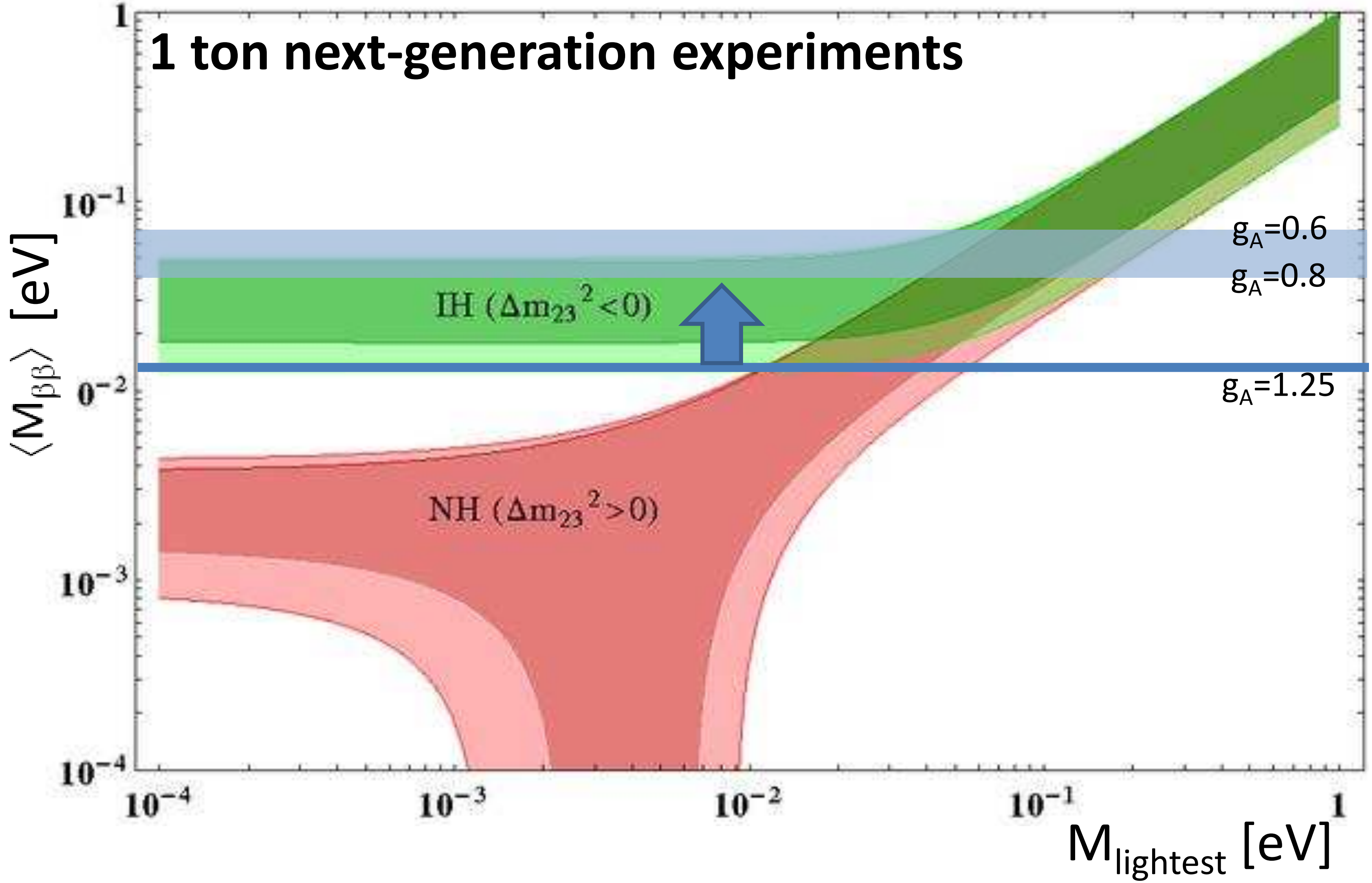
$g_{A,eff}$ ~ 0.6 – 0.8 (depending on model)

$g_{A,eff} = 1.269A^{-\gamma}$
- IBM-2: $\gamma = 0.18$
- QRPA: $\gamma = 0.16$
- ISM: $\gamma = 0.12$

g_A quenching impact



g_A quenching impact



But...

Is g_A renormalization the same for $2\nu2\beta$ decay and $0\nu2\beta$?

It depends on the reason of the quenching, up to now poorly understood.

If the quenching depends on the limited model space in which the calculation is done, it could be common to both. However…

Unlike $2\nu2\beta$, $0\nu2\beta$ is characterized by:

- ✓ All the states of the intermediate nucleus contribute (while only 1+(GT) multipoles contribute to $2\nu2\beta$ decay) → Some could be unquenched or even enhanced
- ✓ Large momentum transfer $p \sim m_\pi$
  $\Rightarrow$ Chiral EFTs seem to show that indeed $g_{A,eff}$ increases as p increases
  J. Menendez et al., Phys. Rev. Lett. 107, 062501 (2011)
  → No quenching is needed to describe μ capture rate on nuclei, where $p \sim m_\mu$ as in $0\nu2\beta$ decay
  N.T. Zinner et al., Phys.Rev. C74 (2006) 024326

Program for g_A issue

- ✓ Study nuclear reactions with **Double Charge Exchange** → NUMEN *F. Cappuzzello et al., J. Phys. Conf. Ser., 012018 (2015)*
- ✓ Further theoretical studies using **chiral EFTs**
- ✓ New proposed method: dependence on g_A of **spectral shape** in forbidden β decays

M. Haaranen et al., Phys. Rev. C 93, 034308 (2016)

But...

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Unlike $2\nu2\beta$, $0\nu2\beta$ is characterized by:

- ✓ All the states of the intermediate nucleus... (while only 1+(GT) multipoles contrib... ...y)
- ✓ Large momentum transfer *p* ~ m...
  - ⇒ Chiral EFTs seem to show th... ...ncreases as *p* increases

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NUMEN

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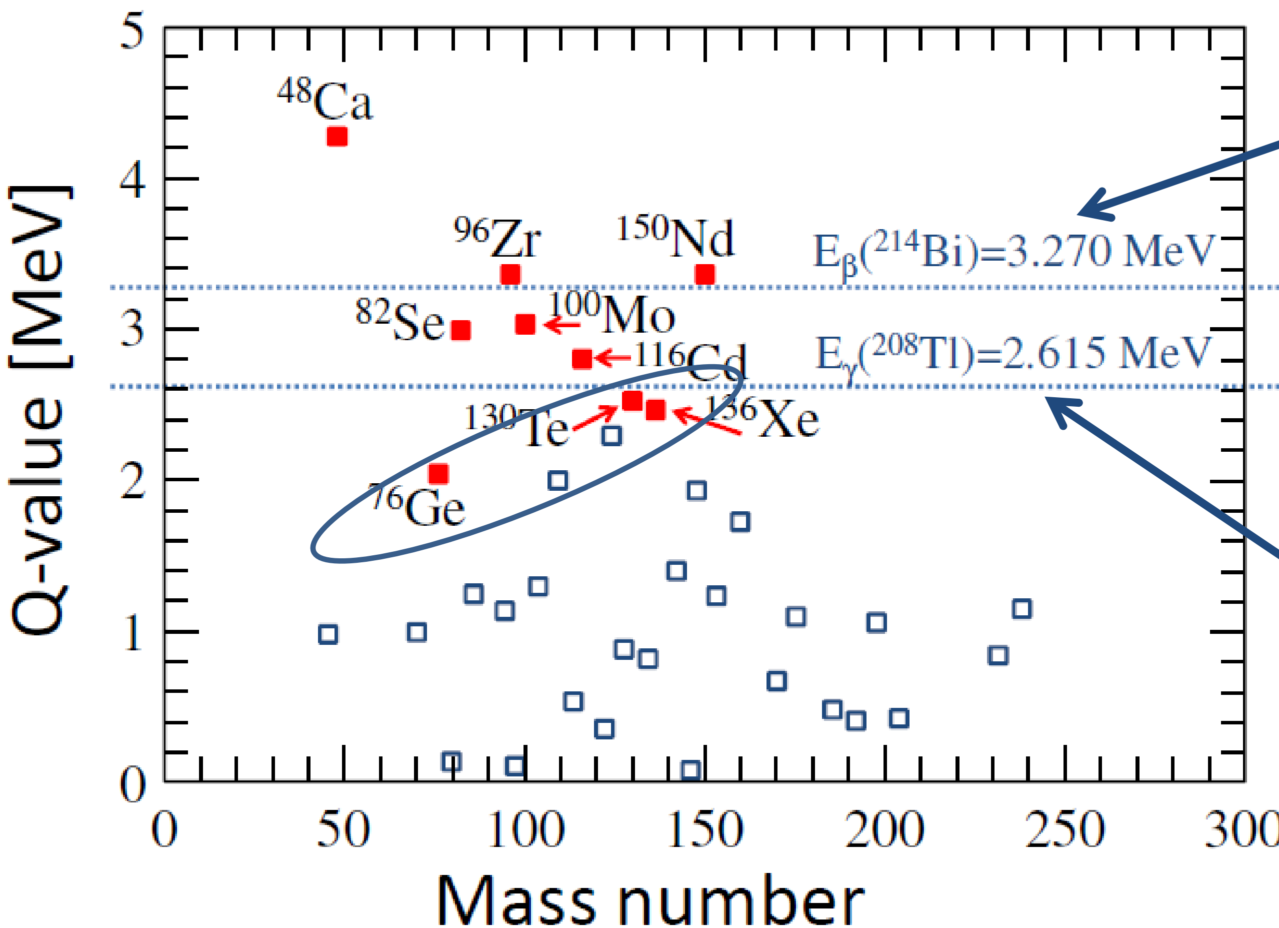
Consider g_A issue more as an additional nuclear uncertainty rather than a safely-established quenching factor

Conclusions

- Klapdor’s claim strongly disfavored by GERDA-I
- Present sensitivity in the 60-400 meV range (lead by KamLAND-Zen): KamLAND-Zen, GERDA-I, EXO-200, CUORE-0
- Sensitivity will approach further the inverted hierarchy region: KamLAND-Zen, GERDA-II, CUORE, EXO-200, SNO+
- ~10 kg demonstrators will aim to validate new/alternative technologies in: CUPID-0/LUMINEU, AMoRE, NEXT-NEW, SuperNEMO demonstrator
- Towards the “1 ton scale”: nEXO, CUPID, GERDA+MAJORANA, KamLAND2-Zen, BEXT
- g_A quenching, impact of cosmology, interplay with LHC are emerging issues

Back-up

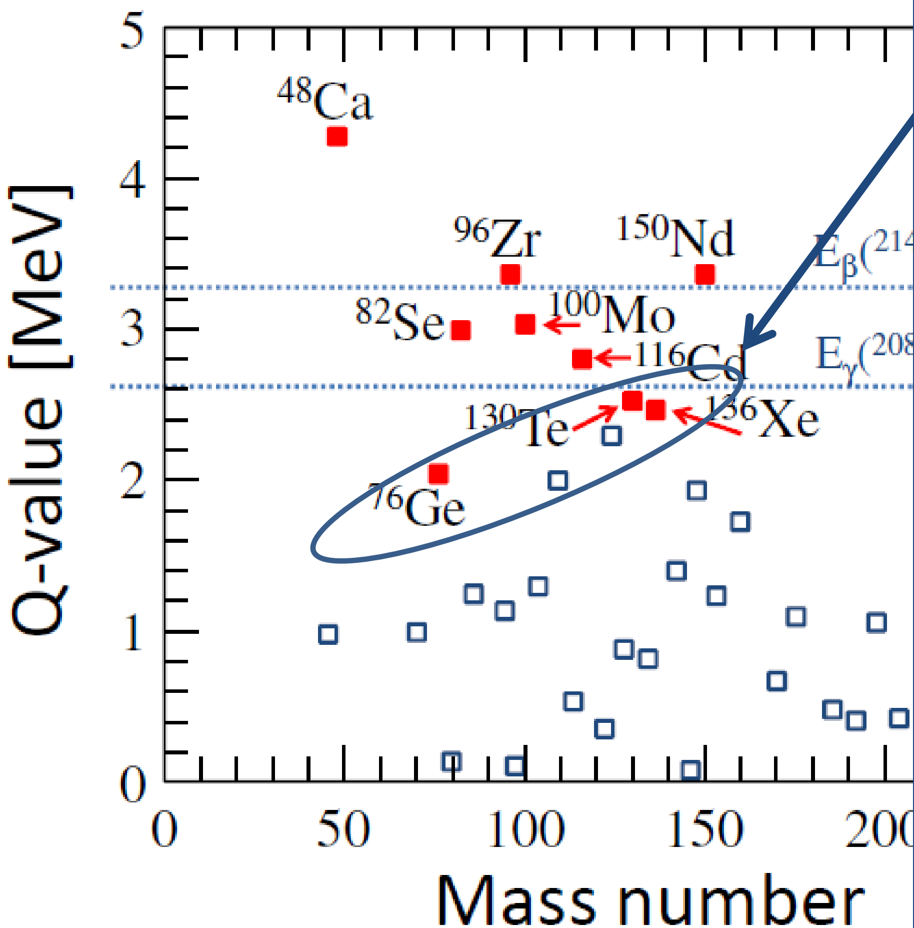
Isotope, enrichment and technique



End-point of ^{222}Rn-induced radioactivity

End-point of natural γ radioactivity

Isotope, enrichment and technique



Excellent technologies are available in the source=detector approach:

- **Ge diodes $\Rightarrow$ ^{76}Ge (GERDA, MAJORANA)** - $\Delta E \ll 1\%$
- **Bolometers $\Rightarrow$ ^{130}Te (TeO_2 crystals) (CUORE)** - $\Delta E \ll 1\%$
- **Dissolving the element** (**Te**) in a large liquid scintillator volume **(SNO+)**
- **TPCs (EXO, NEXT), inclusion in large volume of liquid scintillator (KamLAND-Zen) $\Rightarrow$ ^{136}Xe**

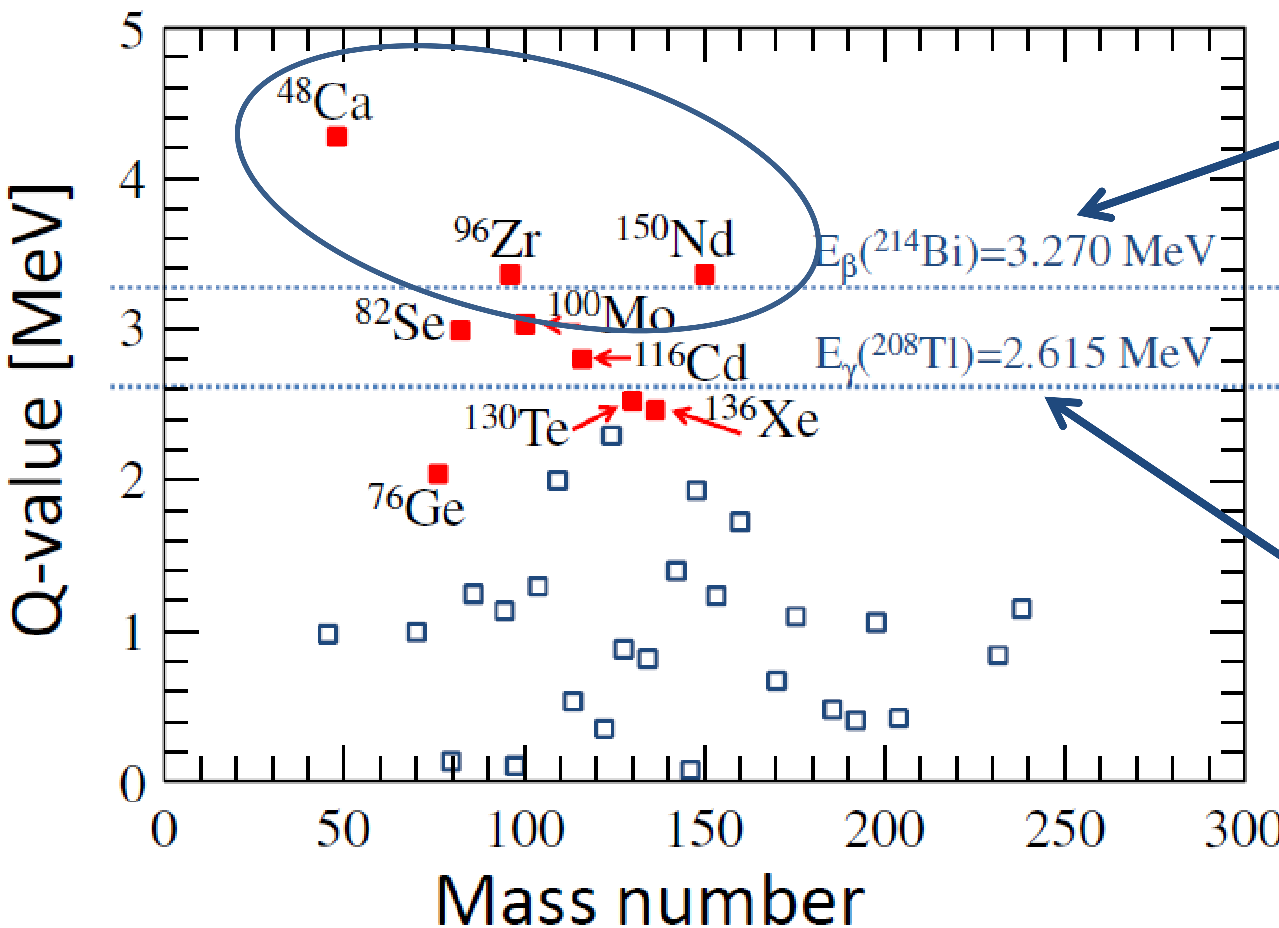
Enrichment is "easy" and for ^{130}Te not necessary at the present level

BUT

Less favorable in terms of background!

In red, projects located in EU

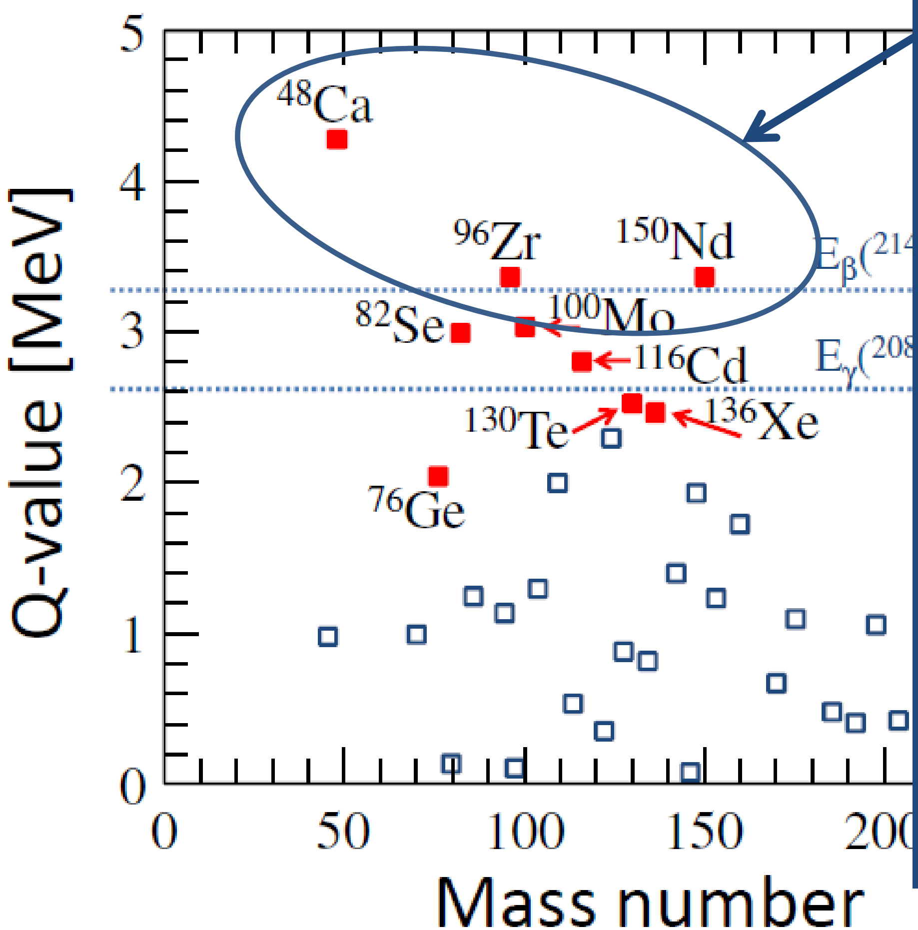
Isotope, enrichment and technique



End-point of ^{222}Rn-induced radioactivity

End-point of natural γ radioactivity

Isotope, enrichment and technique



Almost background free isotopes!

BUT

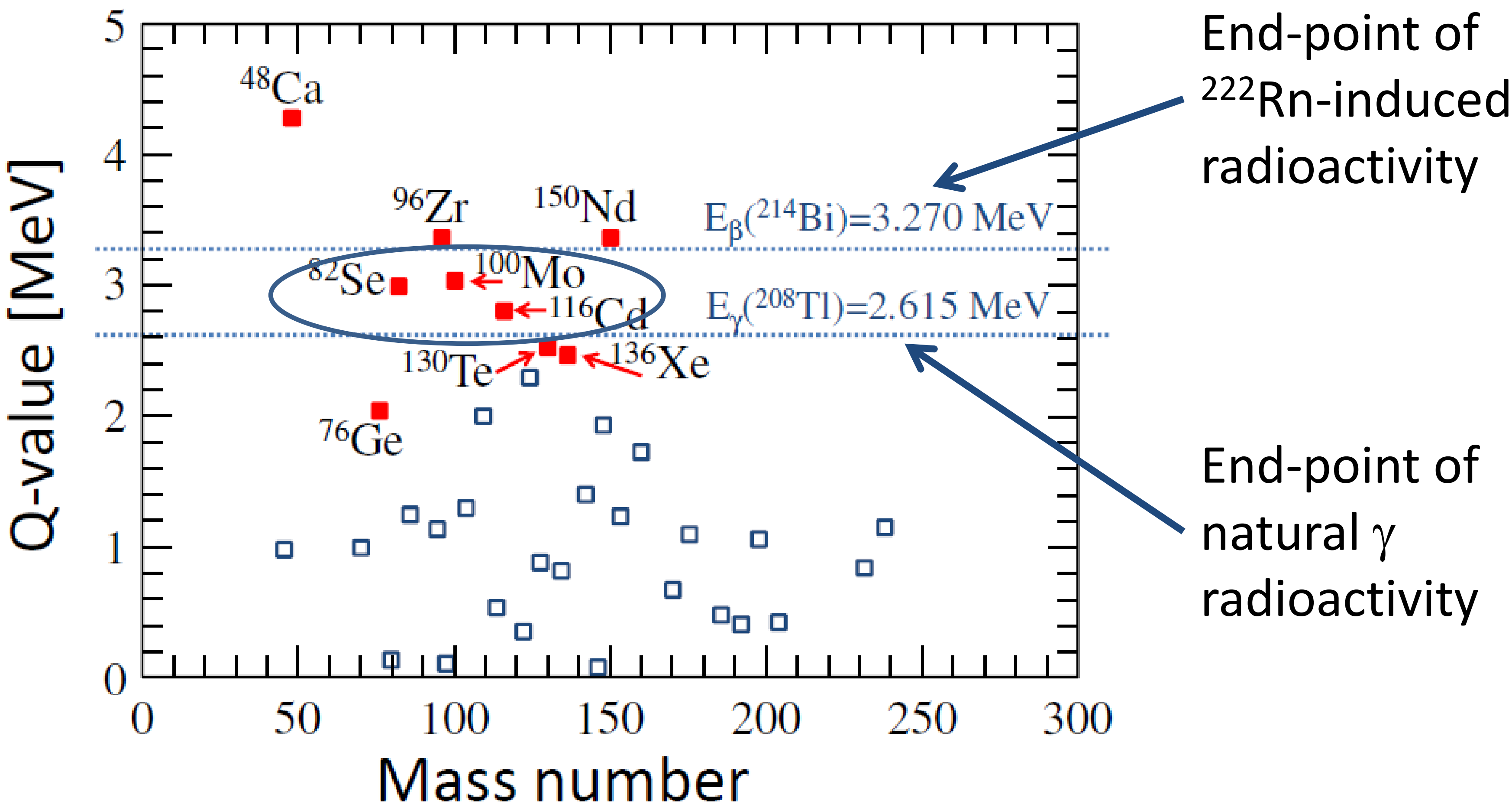
Low isotopic abundance and problematic enrichment (good news about Nd)

Better studied with source≠detector (**tracko-calo approach**) (**SuperNEMO**)

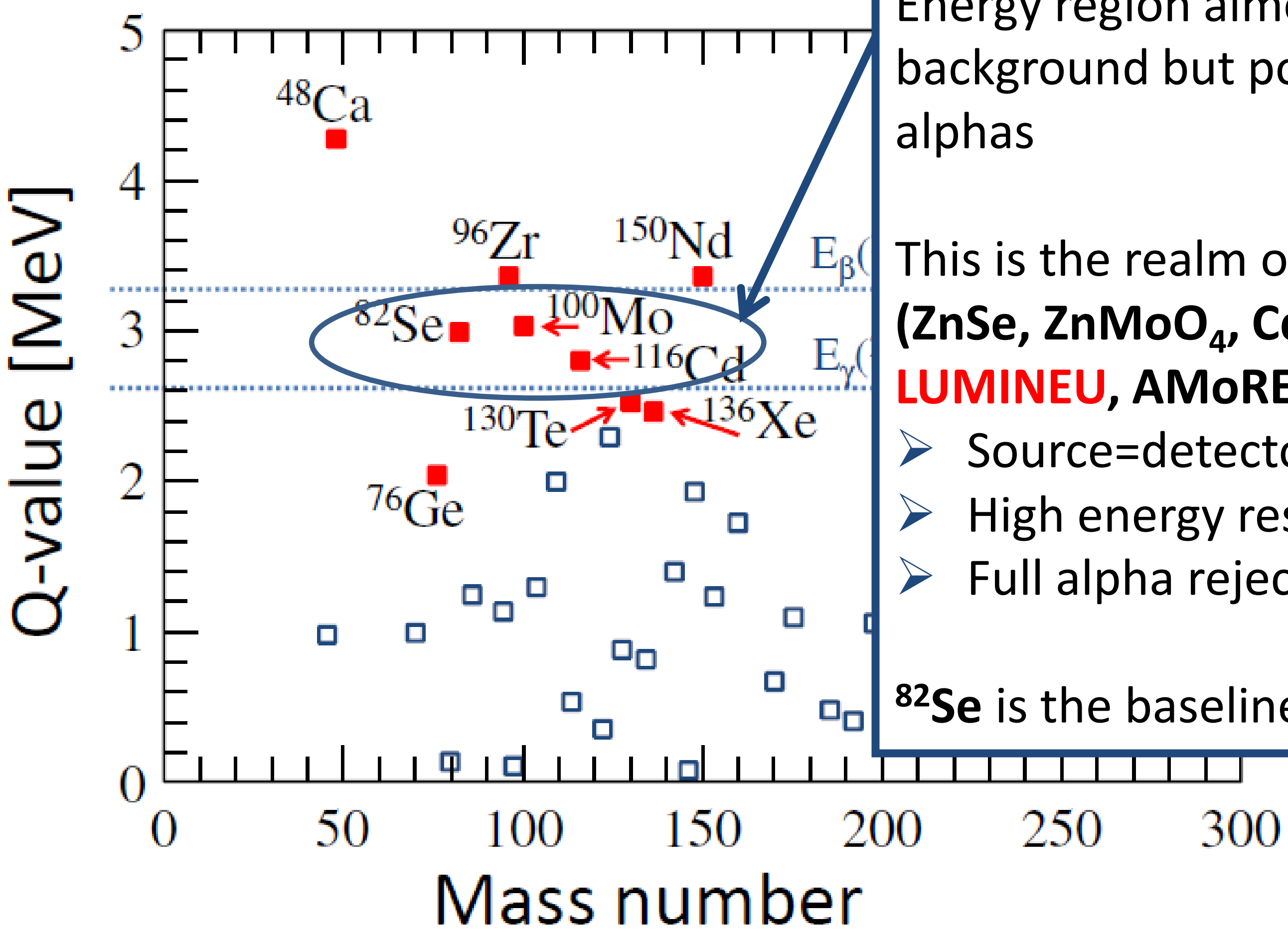
CaF_2 scintillators (and in principle bolometers) are interesting for **^{48}Ca (CANDLES)**

In red, projects located in EU

Isotope, enrichment and technique



Isotope, enrichment and technique



Energy region almost free from natural γ background but populated by degraded alphas

This is the realm of **scintillating bolometers (ZnSe, $ZnMoO_4$, $CdWO_4$) (LUCIFER, LUMINEU, AMoRE)** , which offer:

- Source=detector
- High energy resolution – $\Delta E \ll 1\%$
- Full alpha rejection

^{82}Se is the baseline option for **SuperNEMO**

In red, projects located in EU

Impact of cosmology on $\langle M_\beta \rangle$ and $\langle M_{\beta\beta} \rangle$

Recently, very strong limits have been set on Σ from cosmological observations

Initial Planck result using only CMB data:

$\Sigma < 0.66$ eV (95% C.L.)

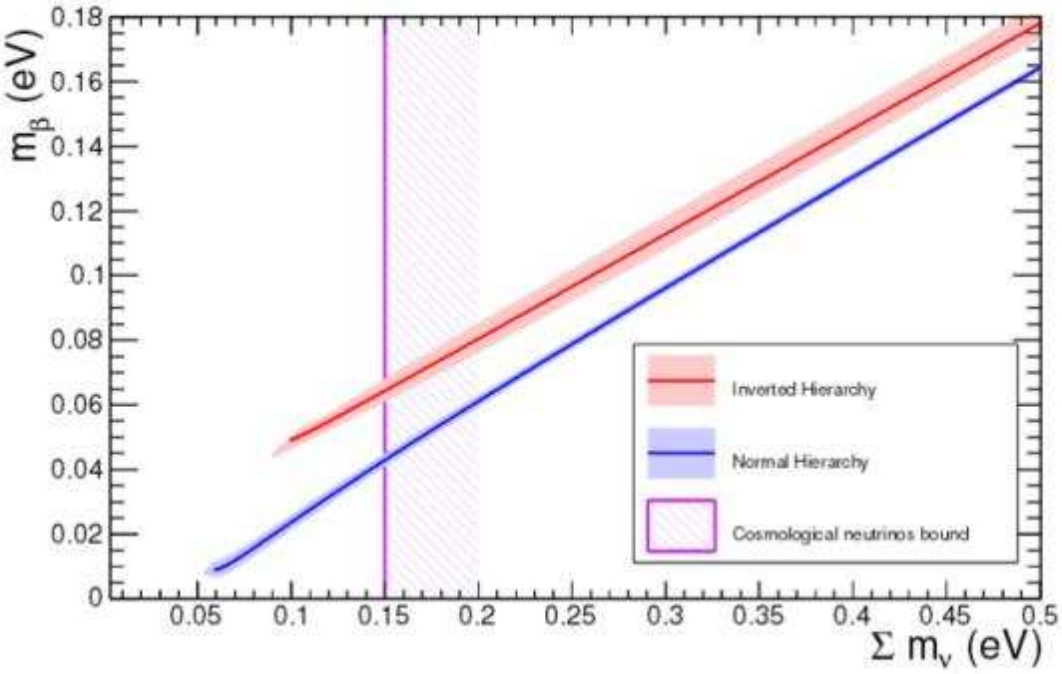
The result improves adding other cosmological probes, i.e. BAO:

$\Sigma < 0.23$ eV (95% C.L.)

Very recently, combining CMB, Lyman α forest, BAO

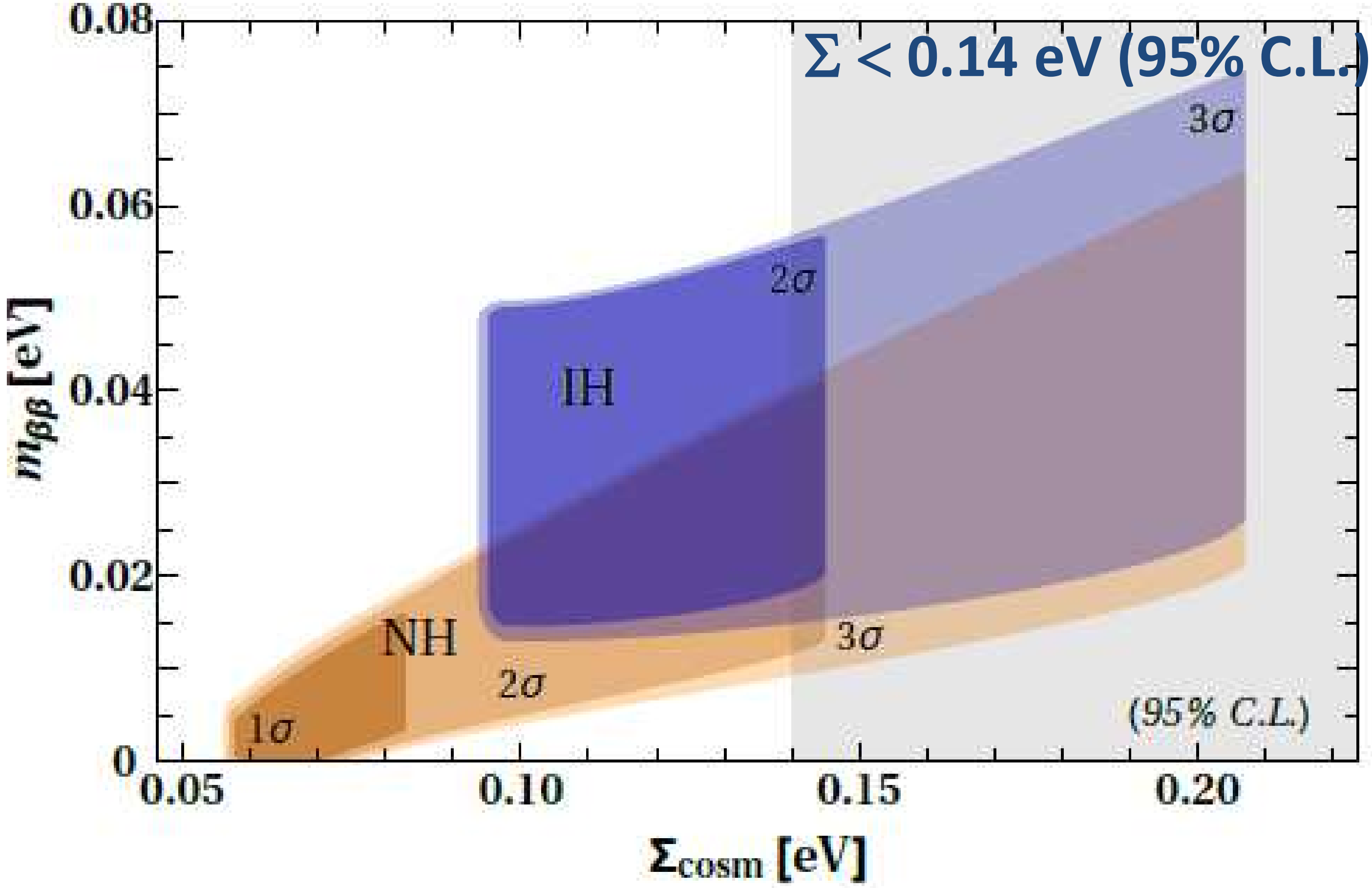
$\Sigma < 0.14$ eV (95% C.L.)

N. Palanque-Delabrouille et al., JCAP 1502, 045 (2015)



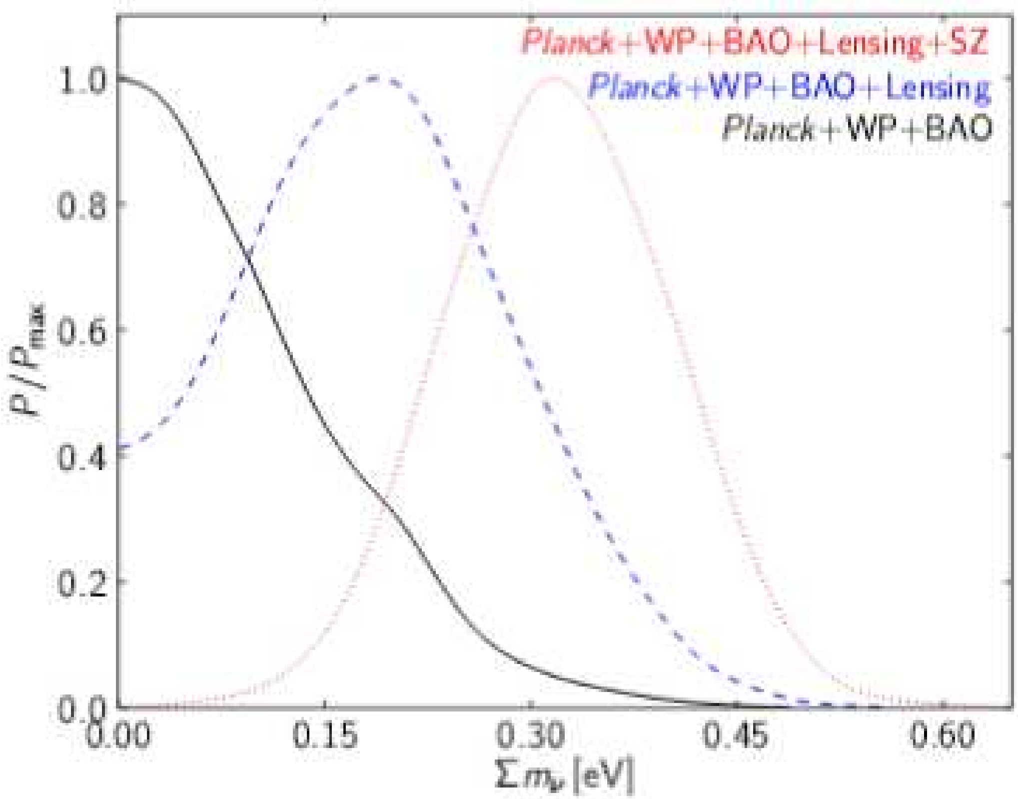
Impact of cosmology on $\langle M_\beta \rangle$ and $\langle M_{\beta\beta} \rangle$

Inverted hierarchy disfavoured at 1 σ level



Impact of cosmology on $\langle M_\beta \rangle$ and $\langle M_{\beta\beta} \rangle$

The situation becomes more controversial when adding results on Large Scale Structure



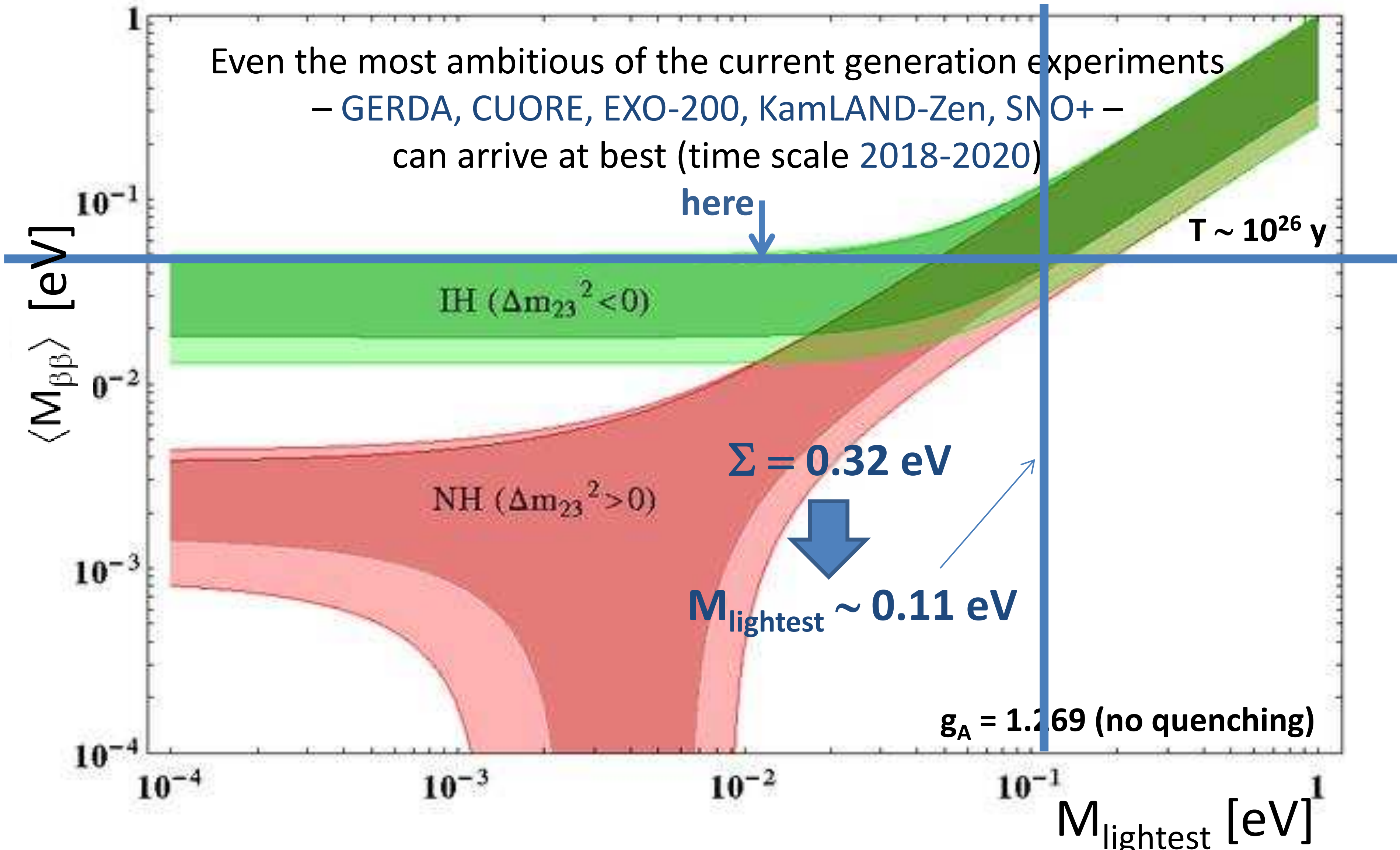
$$\Sigma = 0.32 \text{ eV} \pm 0.081 \text{ eV}$$

R. A. Battye and A. Moss, Phys. Rev. Lett. 112, 051303 (2014)

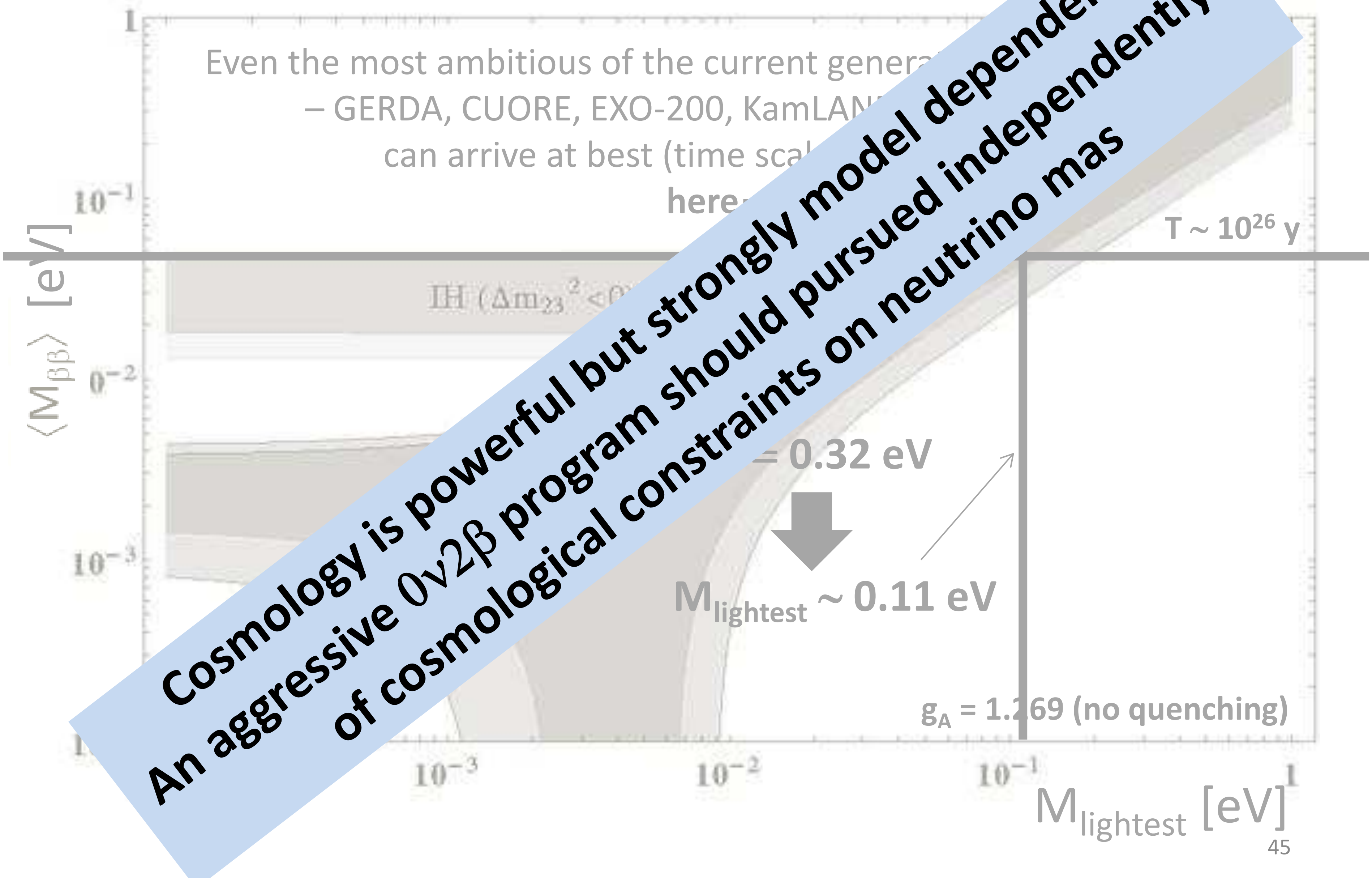
Similar results from an other analysis (BOSS collaboration).

Mon.Not.Roy.Astron.Soc. 444 (2014) 3501

Impact of cosmology on $\langle M_\beta \rangle$ and $\langle M_{\beta\beta} \rangle$



Impact of cosmology on $\langle M_{\beta} \rangle$ and ... $_{\beta}\rangle$



Non standard mechanism

Other mechanisms are however possible Beyond the Standard Model (BSM):

- ✓ heavy neutrinos
- ✓ right-handed currents
- ✓ non standard Higgs
- ✓ SUSY
- ✓ …

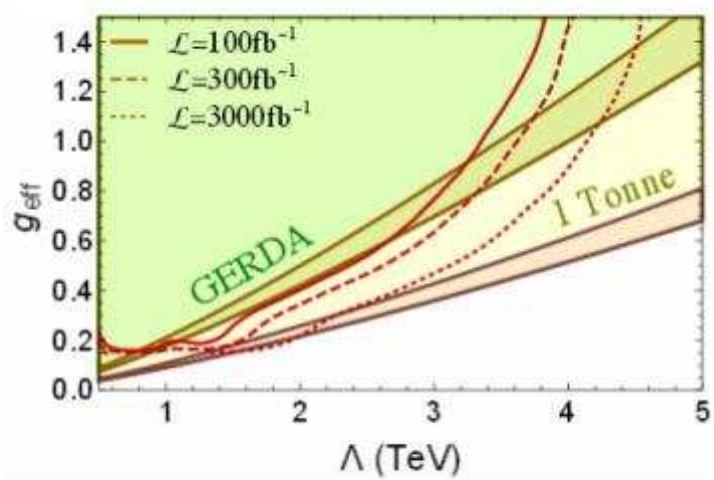
LNV but not necessarily neutrino masses

The famous Scheckter-Valle « theorem » implies Majorana masses of the order 10^{-24} eV

Interplay with search for LNV at **LHC** $\Rightarrow$ **$e^- e^-$ + di-jet signal**

Several works appear recently about $0\nu2\beta \Leftrightarrow$ LHC

- ✓ Right-handed currents
  Shao-Feng Ge et al., arXiv:1508.07286v1
- ✓ TeV Lepton Number Violation
  Tao Peng et al., arXiv:1508.04444v1
- ✓ LHC dijet constraints on $0\nu2\beta$
  J.C. Helo et al., Phys. Rev. D 92, 073017 (2015)



- ✓ **Observed excess at LHC at 2 TeV** interpretable as W_R
  F.F. Deppisch et al., Phys. Rev. D 93, 013011 (2016)

Measurable $0\nu2\beta$ decay (right handed currents)

Non standard mechanism

Other mechanisms are however possible Beyond the Standard Mod…

- ✓ heavy neutrinos
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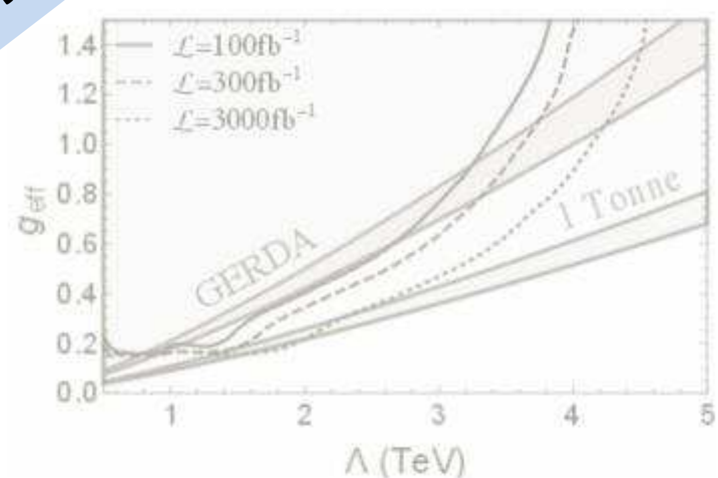
The famous Schec… …orem » implies Majorana … …order 10^{-24} eV

Interplay with search for LNV at **LHC** … **…i-jet signal**

Several works appear recently … …HC

- ✓ Right-handed curre…
  Shao-Feng Ge et a…
- ✓ TeV Lepton … …on
  Tao P… …444v1
- ✓ LHC … …s on $0\nu2\beta$
  … …s. Rev. D 92, 073017 (2015)
- ✓ …d **excess at LHC at 2 TeV** interpretable as W_R
  …F. Deppisch et al., Phys. Rev. D 93, 013011 (2016)

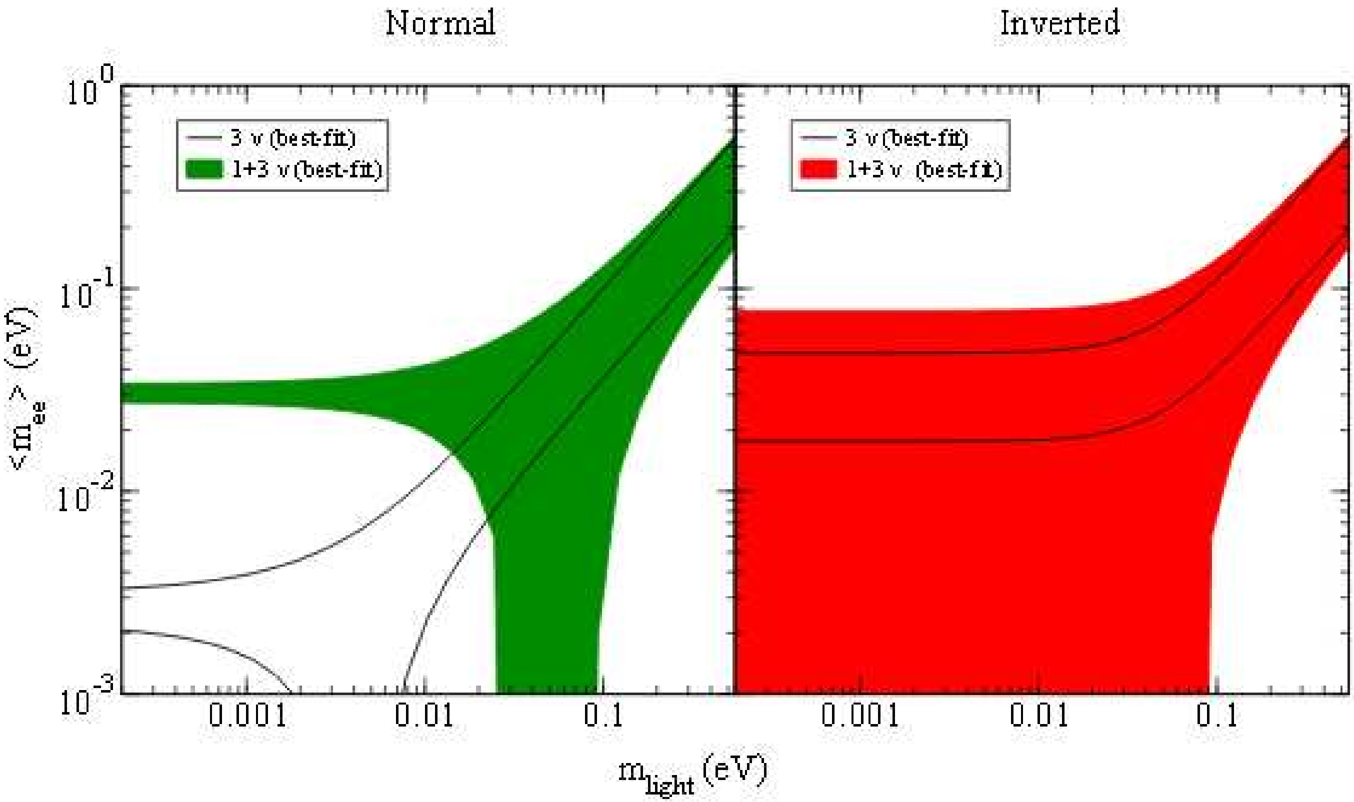


Measurable $0\nu2\beta$ decay (right handed currents)

Interesting and growing interplay between $0\nu2\beta$ and LHC
Fully complementary

Light sterile neutrinos

$$\langle \mathbf{M}_{\beta\beta} \rangle = ||U_{e1}|^2 M_1 + e^{i\alpha 1}\, |U_{e2}|^2 M_2 + e^{i\alpha 2}\, |U_{e3}|^2 M_3 | + e^{ia3}\, |U_{e4}|^2 M_4 ||$$



Muon capture on nuclei: random phase approximation evaluation versus data for $6 \leq Z \leq 94$ nuclei

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We use the random phase approximation to systematically describe the total muon capture rates on all nuclei where they have been measured. We reproduce the experimental values on these nuclei to better than 15% accuracy using the free nucleon weak form factors and residual interactions with a mild A dependency. The isospin dependence and the effects associated with shell closures are fairly well reproduced as well. However, the calculated rates for the same residual interactions would be significantly lower than the data if the in-medium quenching of the axial-vector coupling constant is employed to other than the true Gamow-Teller amplitudes. Our calculation thus suggests that no quenching is needed in the description of semileptonic weak processes involving higher multipole transitions and momentum transfer $\sim m_\mu$, with obvious importance to analogous weak processes.