APPEC Town Meeting 2016

6-7 April, 2016
Amphitheatre Paris-Sorbonne, France

Lepton number violation and basic neutrino properties

Andrea Giuliani

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Outline

- The neutrino mass scale
- Single beta decay and neutrino mass
- Double beta decay: neutrino mass and LNV
- Double beta decay: experimental status and prospects
- Double beta decay: open issues

The absolute neutrino mass scale

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

In a standard three active neutrino scenario:

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

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
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

$$\langle M_\beta \rangle$$

Direct ν mass measurement

use $\mathbf{E^2 = p^2c^2 + m^2c^2}$ $\rightarrow$ $m^2(\nu)$ is the observable

Use low Q-value beta-like processes and study endpoint of electron or γ spectrum

MAC-E-filter
Spectrometers
KATRIN

CRES
PROJECT 8

$^3H \rightarrow {}^3He + e^- + \nu_e$ Q ~ 18.6 keV

Bolometers
NUMECS
HOLMES
ECHO

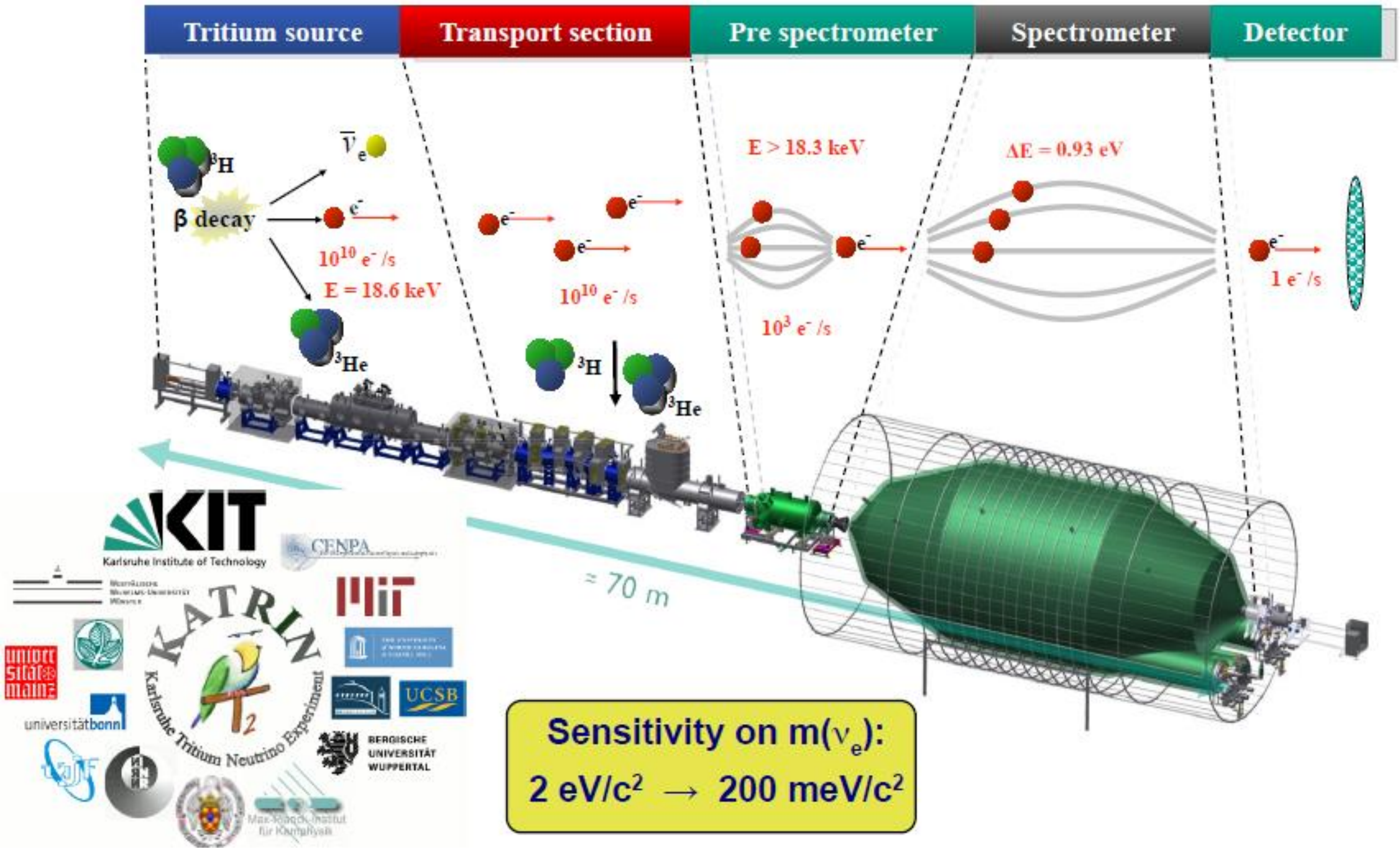
$\cancel{^{187}Re \rightarrow {}^{187}Os + e^- + \nu_e}$ Q ~ 2.5 keV

$^{163}Ho + e^- \rightarrow {}^{163}Dy^* + \nu_e$ Q ~ 2.8 keV

γ

In red, projects located in EU

KATRIN concept



Sensitivity on $m(\nu_e)$:

$2\ eV/c^2 \rightarrow 200\ meV/c^2$

Thanks to Ch. Weinheimer

KATRIN status

- Commissioning of spectrometer & detector SDS IIb finished in August 2015
- Commissioning of tritium source & transport section: up to summer 2016
- Tritium data taking: start in 2016
- sensitivity: 200 meV

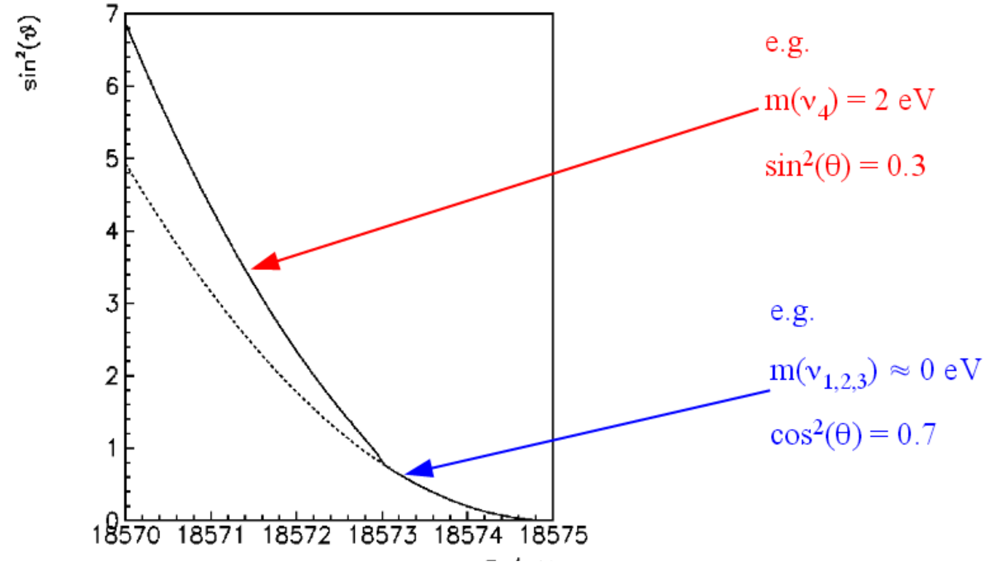
Thanks to Ch. Weinheimer

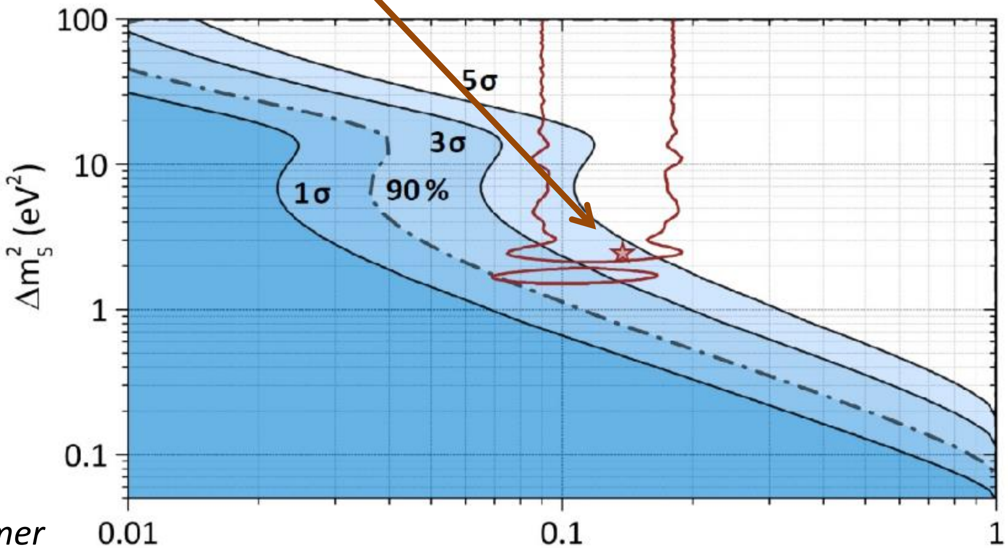
KATRIN and light sterile neutrinos

Reactor neutrino anomaly

large mixing: $\sin^2(2\theta) \approx 0.1$

large masses: $\Delta m^2 > 1\ eV^2$





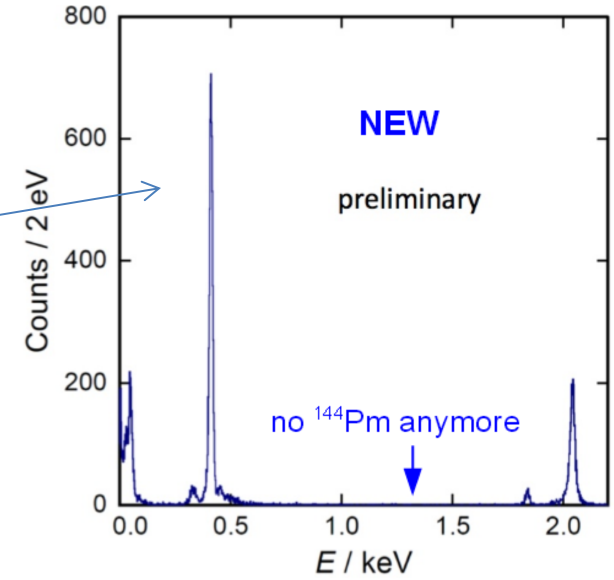
M.Kleesiek, PhD thesis, KIT (2014)

Thanks to Ch. Weinheimer

How to improve KATRIN

Ho-embedding cryogenic bolometers
(ECHO, HOLMES, NUMECS)

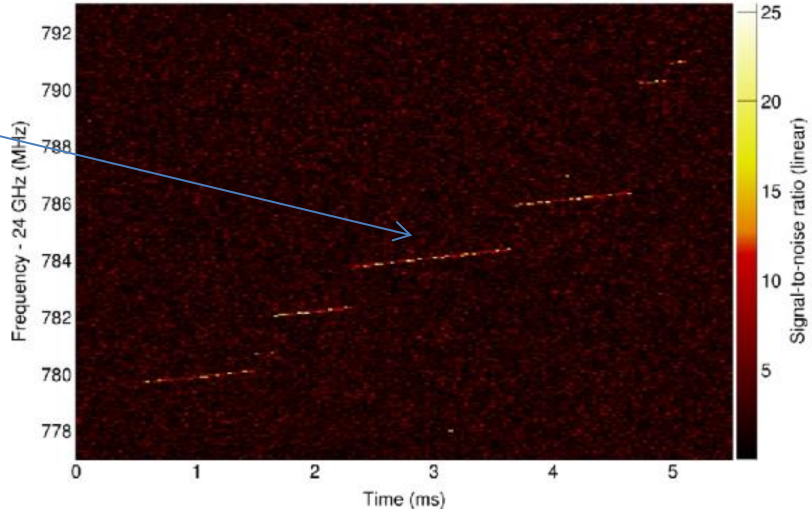
- ✓ Interesting new results from ECHO
- ✓ Technology starts to be scalable
- ✓ **But**: many orders of magnitude to go to achieve required satistics
- ✓ Systematics?



Project 8

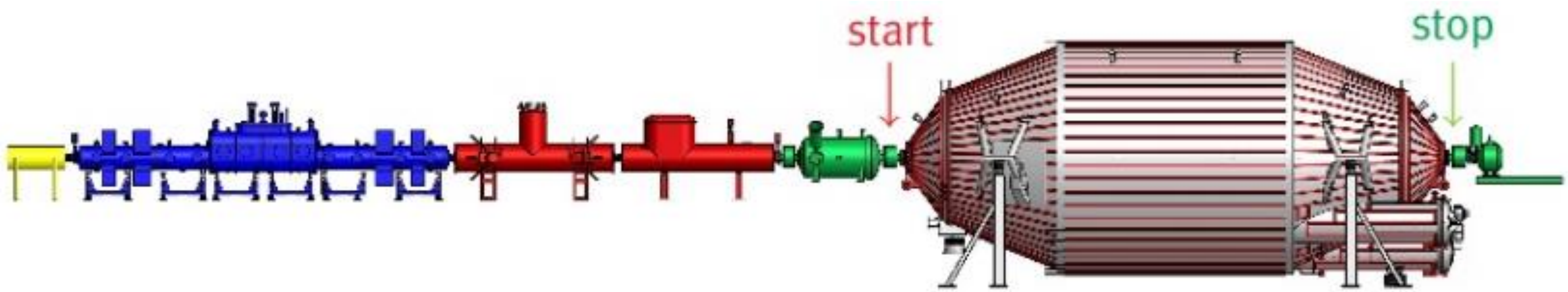
Measure the coherent cyclotron radiation from tritium β electrons

- ✓ Detection of single electron succesfull
- ✓ **But**: is the experiment scalable?
- ✓ Systematics?

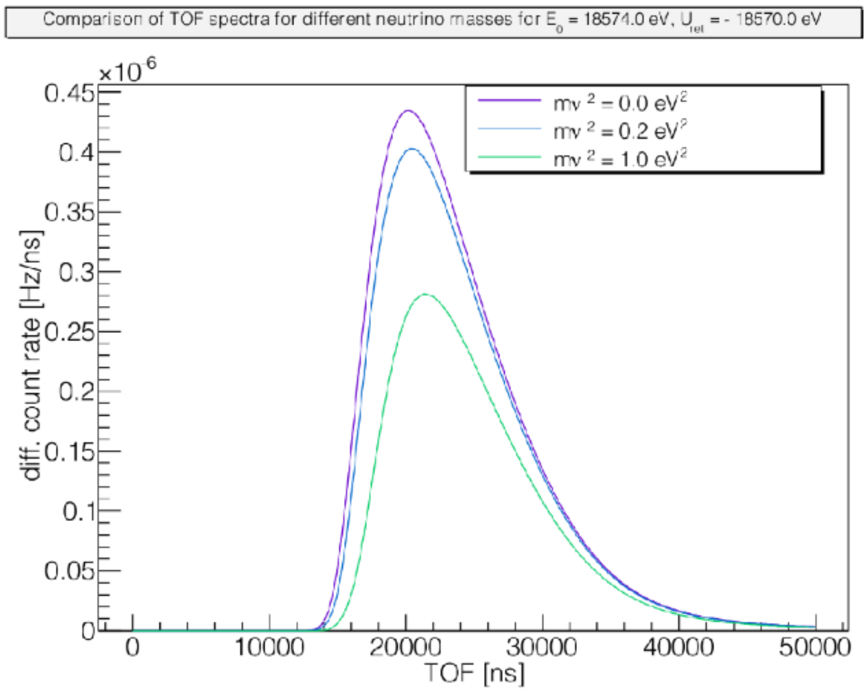


Thanks to Ch. Weinheimer

How to improve KATRIN: time of flight



TOF spectrum is sensitive to neutrino mass



The difficulty is to measure START without disturbing electron energy at the 10 meV level

Interesting possibility: **use Project8 technology** for START measurement

→ factor 5 in $\Delta m(\nu)^2_{stat}$ under ideal cond.

Thanks to Ch. Weinheimer

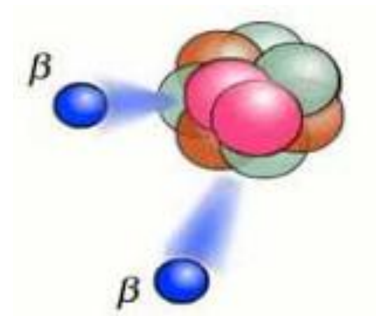
$$\langle M_{\beta\beta} \rangle$$

LNV

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)

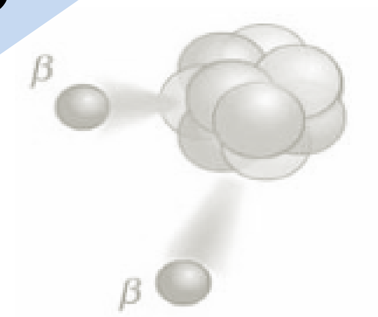
Non-standard mechanism: **BSM, LNV**
Not necessarily neutrino physics

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

0ν2β is a test for « creation of leptons »: **2n → 2** ⇒ **LNV**

This test is implemented in the nuclear m

(A,Z) → (A,Z+2) + 2e$^-$



Energetically possible for **~40**

Only a few are experiment vant

ard mechanism: **neutrino physics**

β is mediated by light massive Majorana neutrinos (those which oscillate)

0ν2

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

Not necessarily neutrino physics

0ν2β is not a mere neutrino physics experiment

Why it is important to test LNV

L and B are **accidentally conserved** in the SM

Effective theory: $\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda}\mathcal{L}_5 + \frac{1}{\Lambda^2}\mathcal{L}_6 + \cdots + \frac{1}{\Lambda^5}\mathcal{L}_9$

dim 4

dim 5

Majorana mass term, LNV

dim 6

Proton decay

dim 9

LNV

Seesaw

Light Majorana ν_L

Heavy Majorana N_R

Baryogenesis (Leptogenesis) $\Rightarrow$ **B (L) violation**

B, L often connected in **GUTs**

GUTs have **Majorana neutrinos** and **seesaw**

Why it is important to test LNV

L and B are **accidentally conserved** in the SM

Effective theory: $\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\mathcal{L} \cdots + \frac{1}{\Lambda^5}\mathcal{L}_9$

dim 4

m,
NV

dim 6
Proton
decay

dim 9
LNV

Seesaw
Light Majorana ν_L
Heavy Majorana N_R

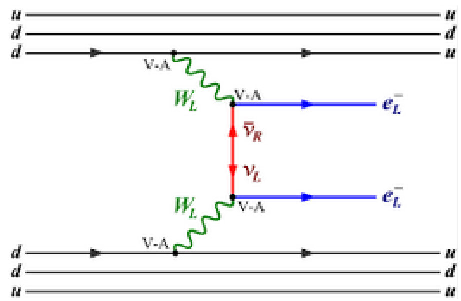
Baryogenesis **B (L) violation**

B, L ofte UTs

GU a neutrinos and **seesaw**

Lepton Number Violation is as important as Baryon Number Violation

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**

Phase space

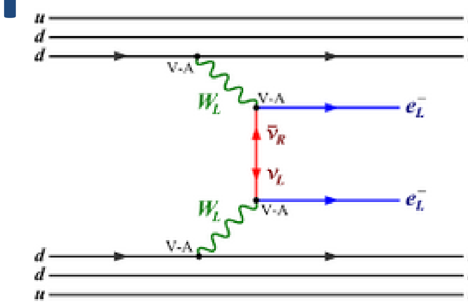
Axial vector coupling constant

Nuclear matrix elements

Effective **Majorana mass**

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

Standard mechanism



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Effective **Majorana mass**

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

Experiments

Calculable

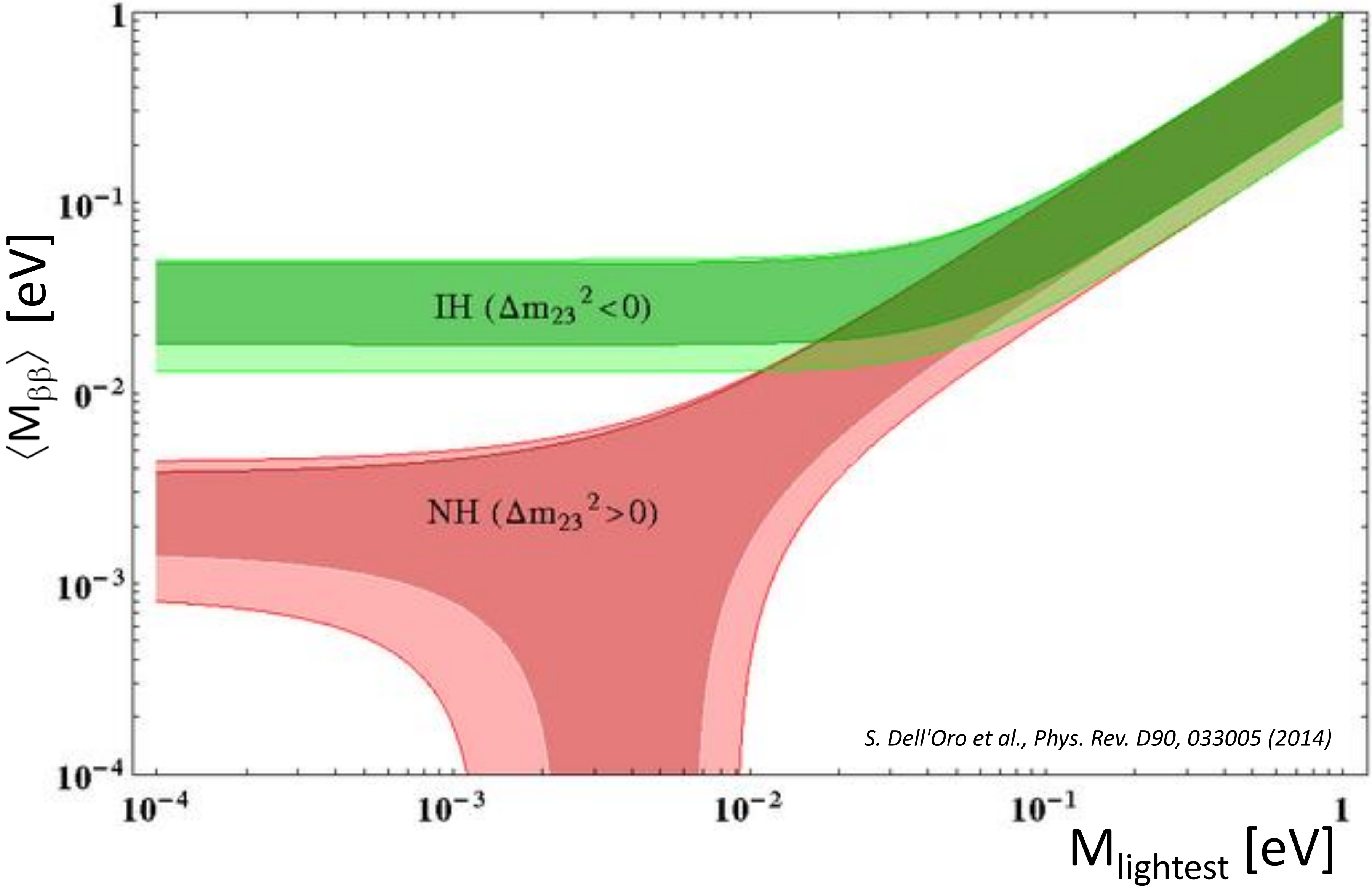
Controversial

Nuclear theory

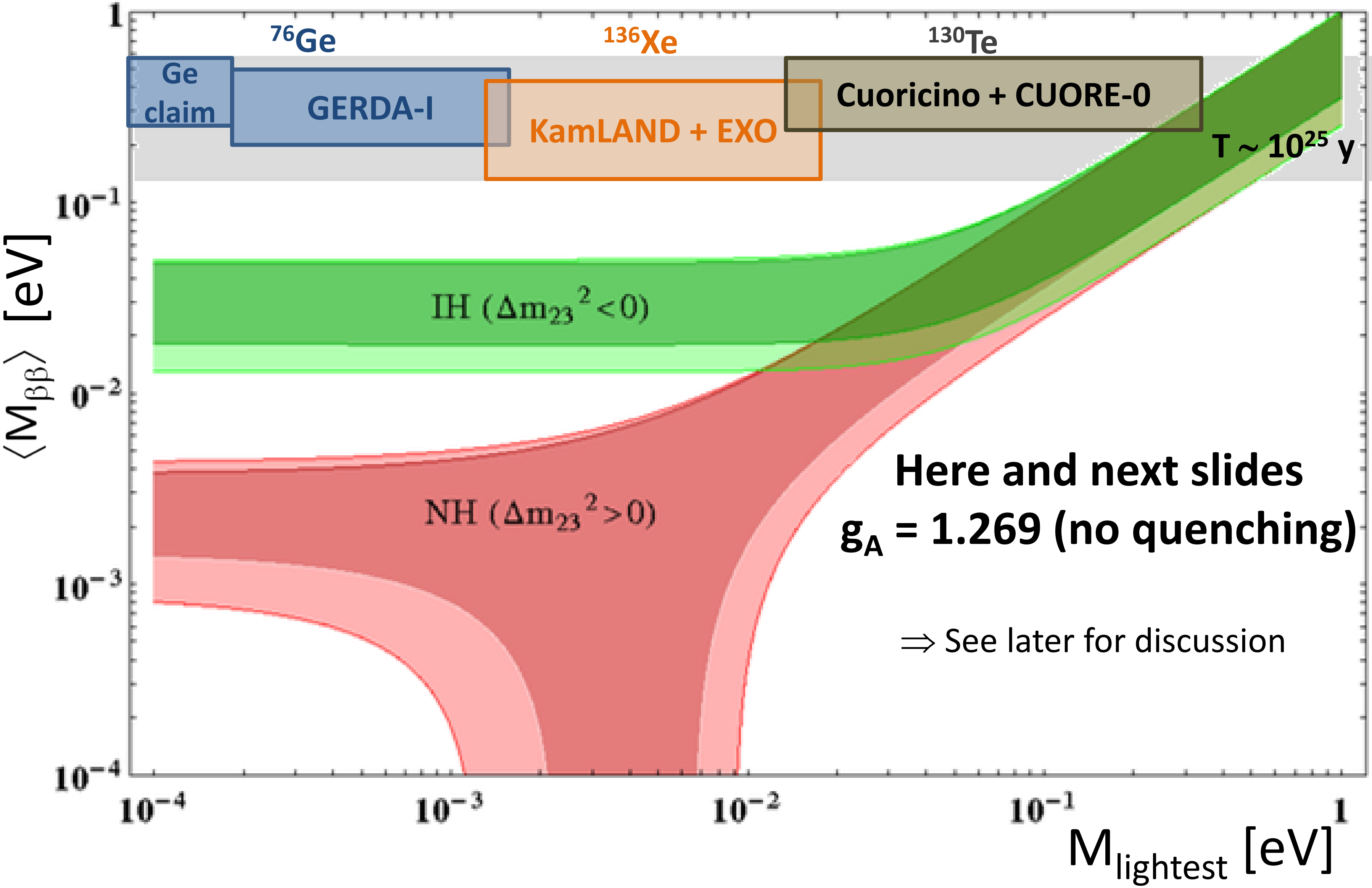
Neutrino physcis

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

⟨$M_{\beta\beta}$⟩ vs. lightest ν mass

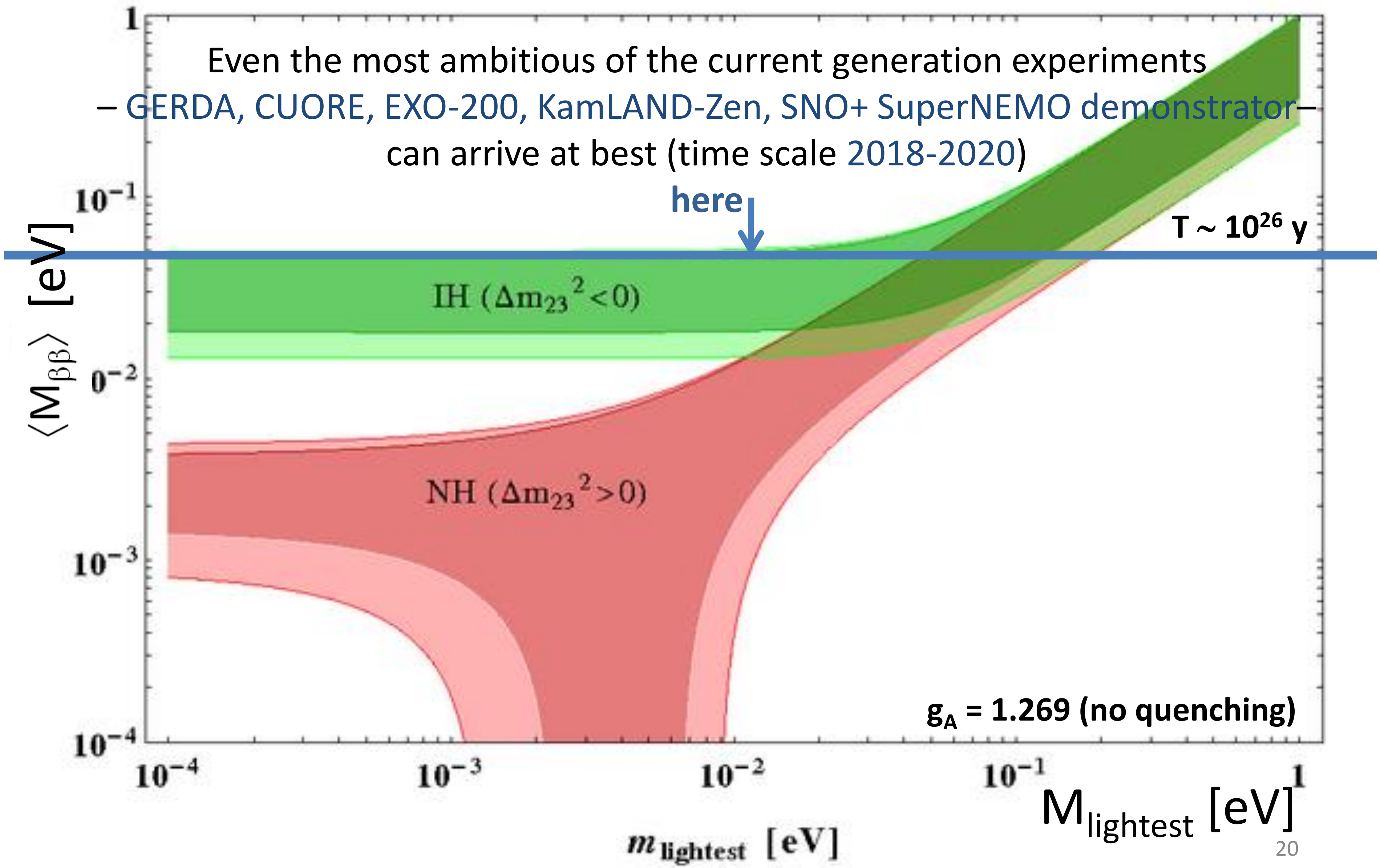


Status

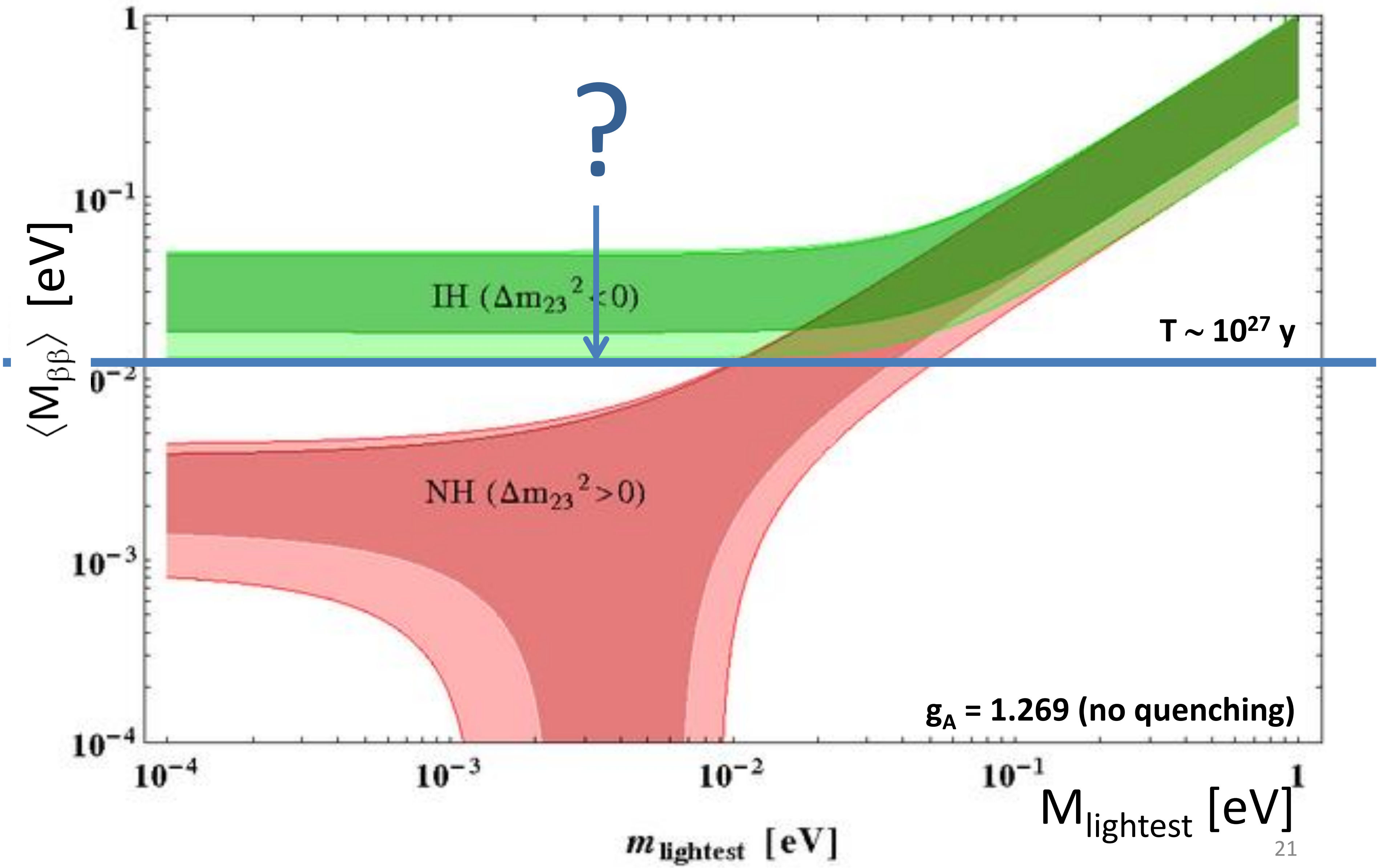


^{76}Ge
^{136}Xe
^{130}Te
Ge claim
GERDA-I
KamLAND + EXO
Cuoricino + CUORE-0
T ~ 10^{25} y
IH ($\Delta m_{23}{}^2 < 0$)
NH ($\Delta m_{23}{}^2 > 0$)
Here and next slides
g_A = 1.269 (no quenching)
⇒ See later for discussion
$\langle M_{\beta\beta} \rangle$ [eV]
$M_{lightest}$ [eV]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}

Current-generation experiments



Strategic milestone



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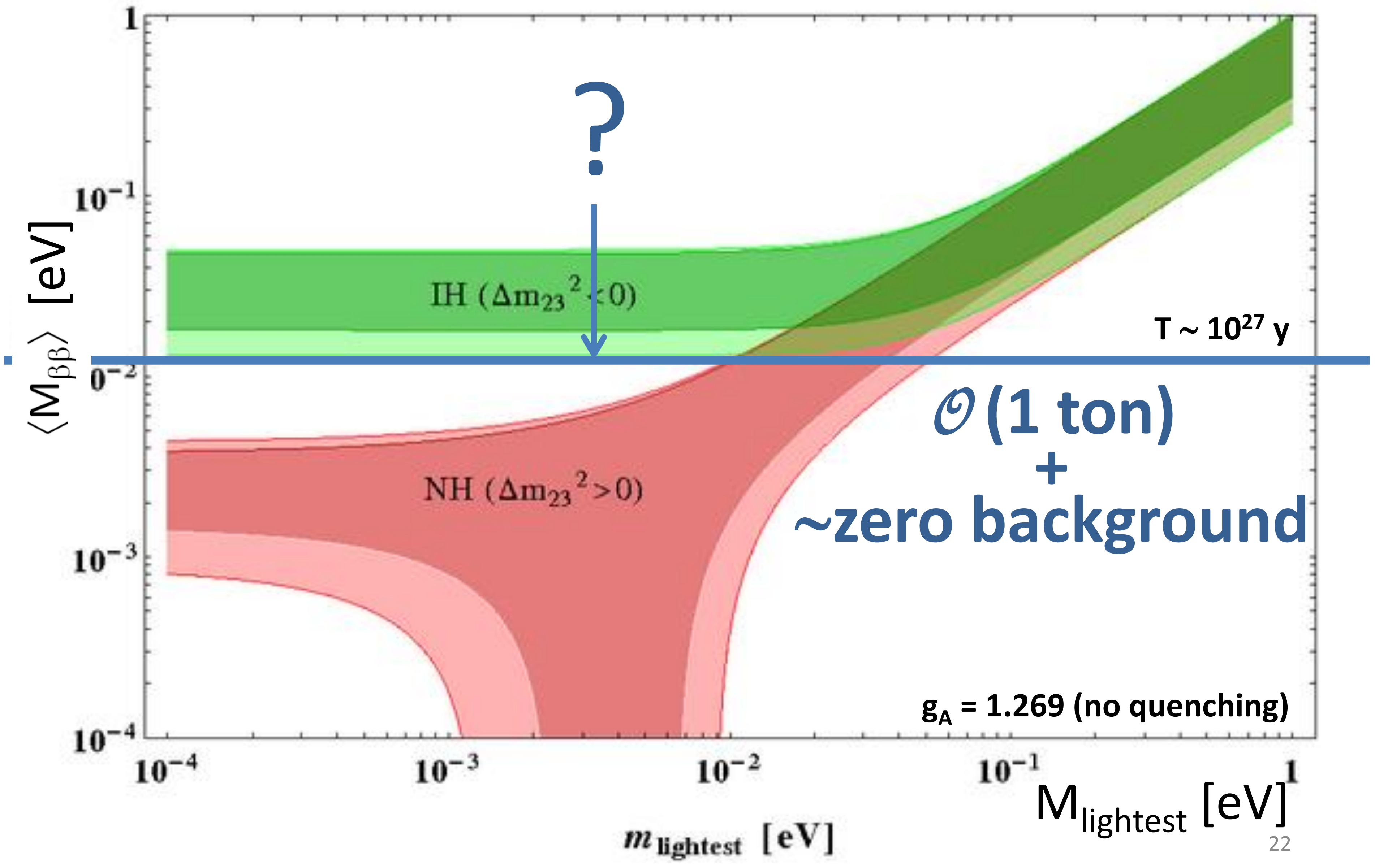
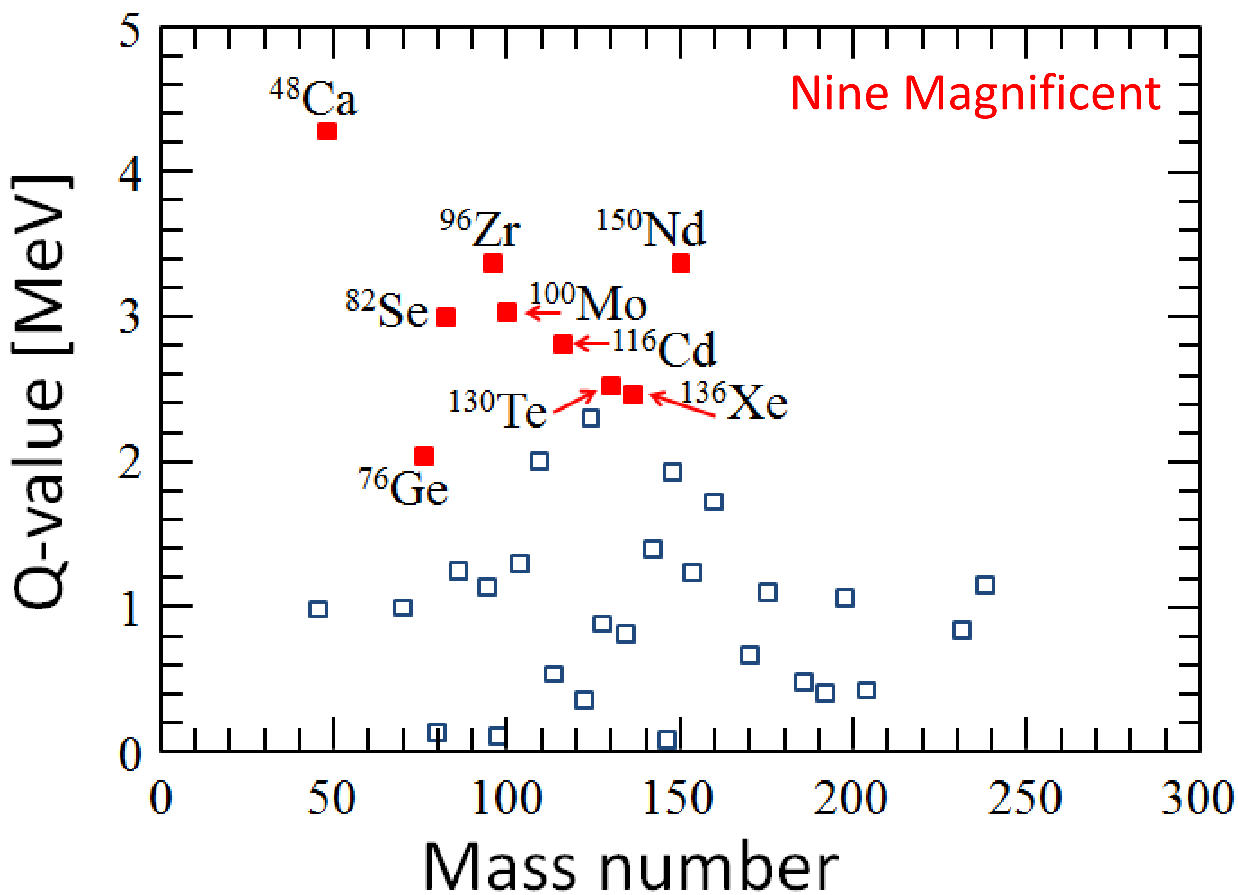


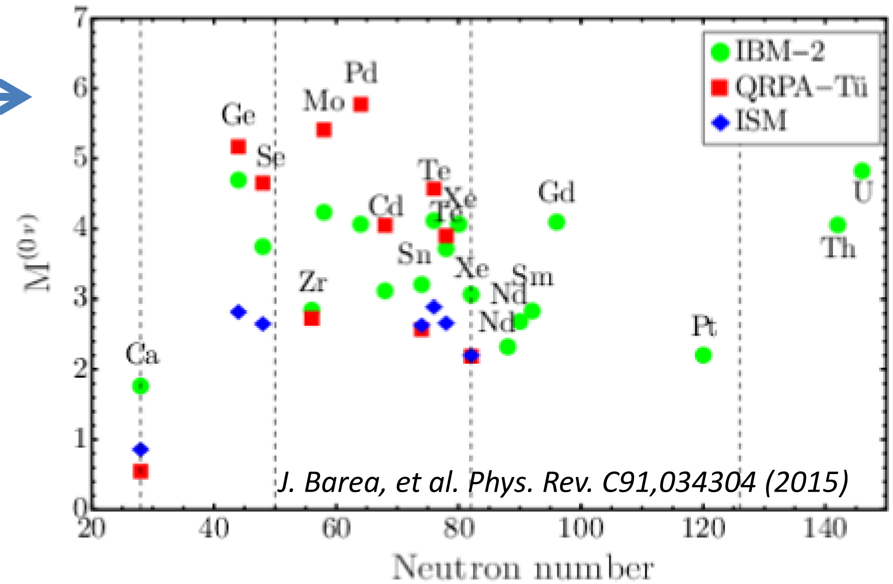
Factors guiding isotope selection

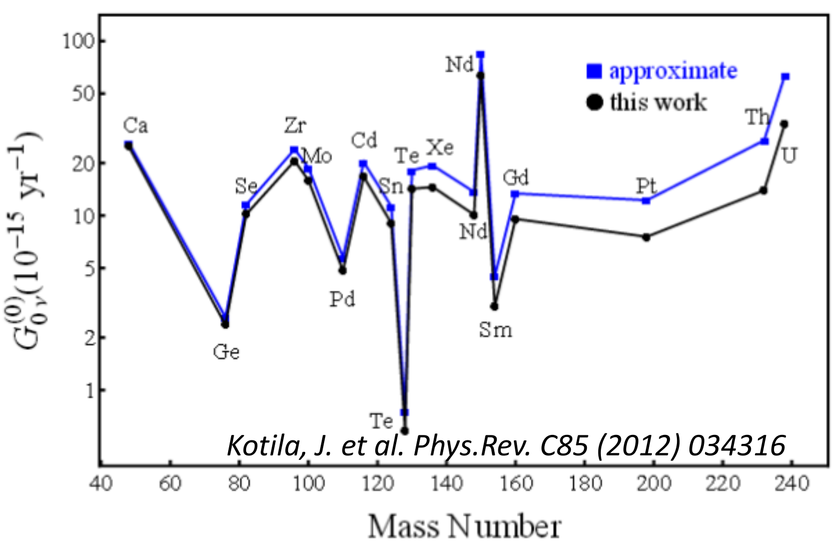
Q is the crucial factor
- Phase space: $G(Q,Z) \propto Q^5$
- Background

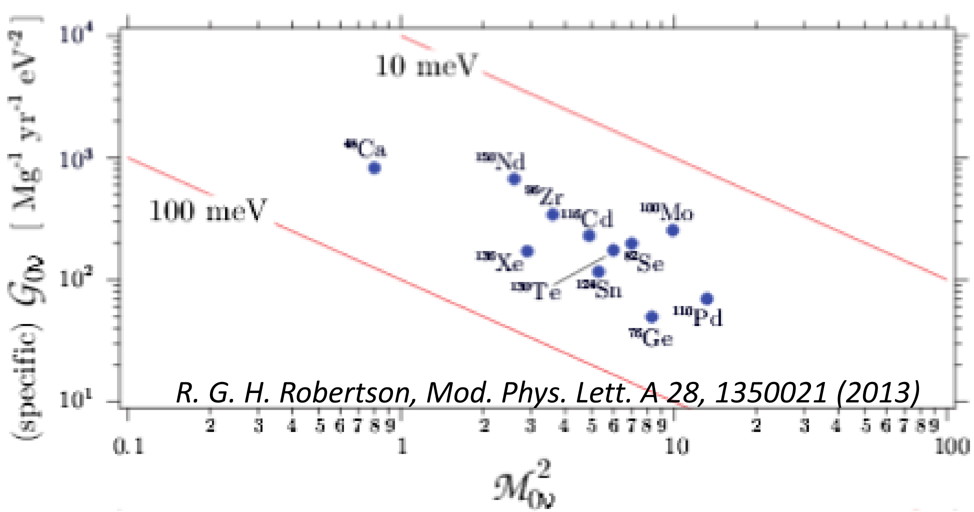


Isotope choice and nuclear matrix elements

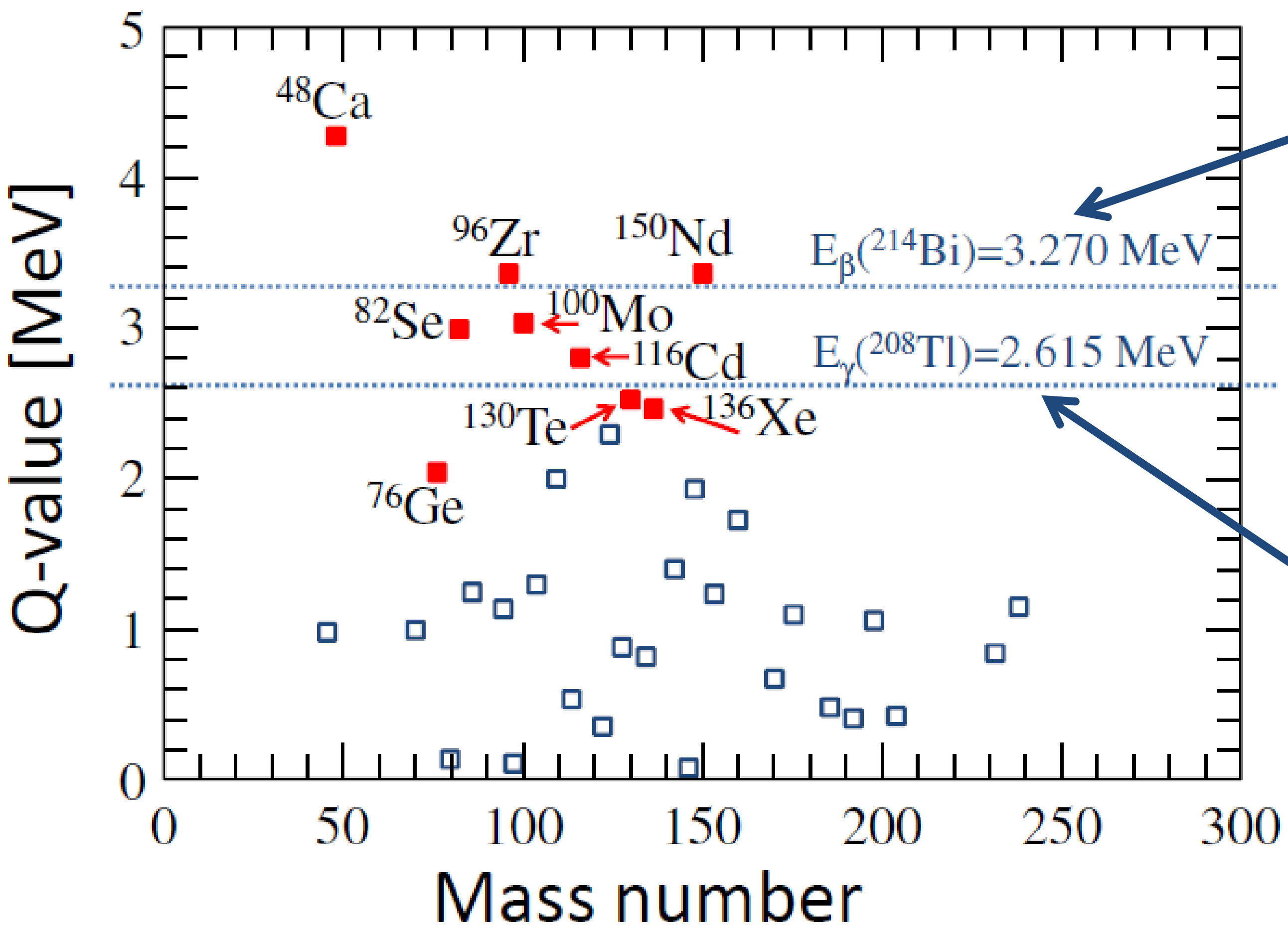
$$1/\tau = G(Q,Z)\, g_A^4\, |M_{nucl}|^2 \langle M_{\beta\beta}\rangle^2$$







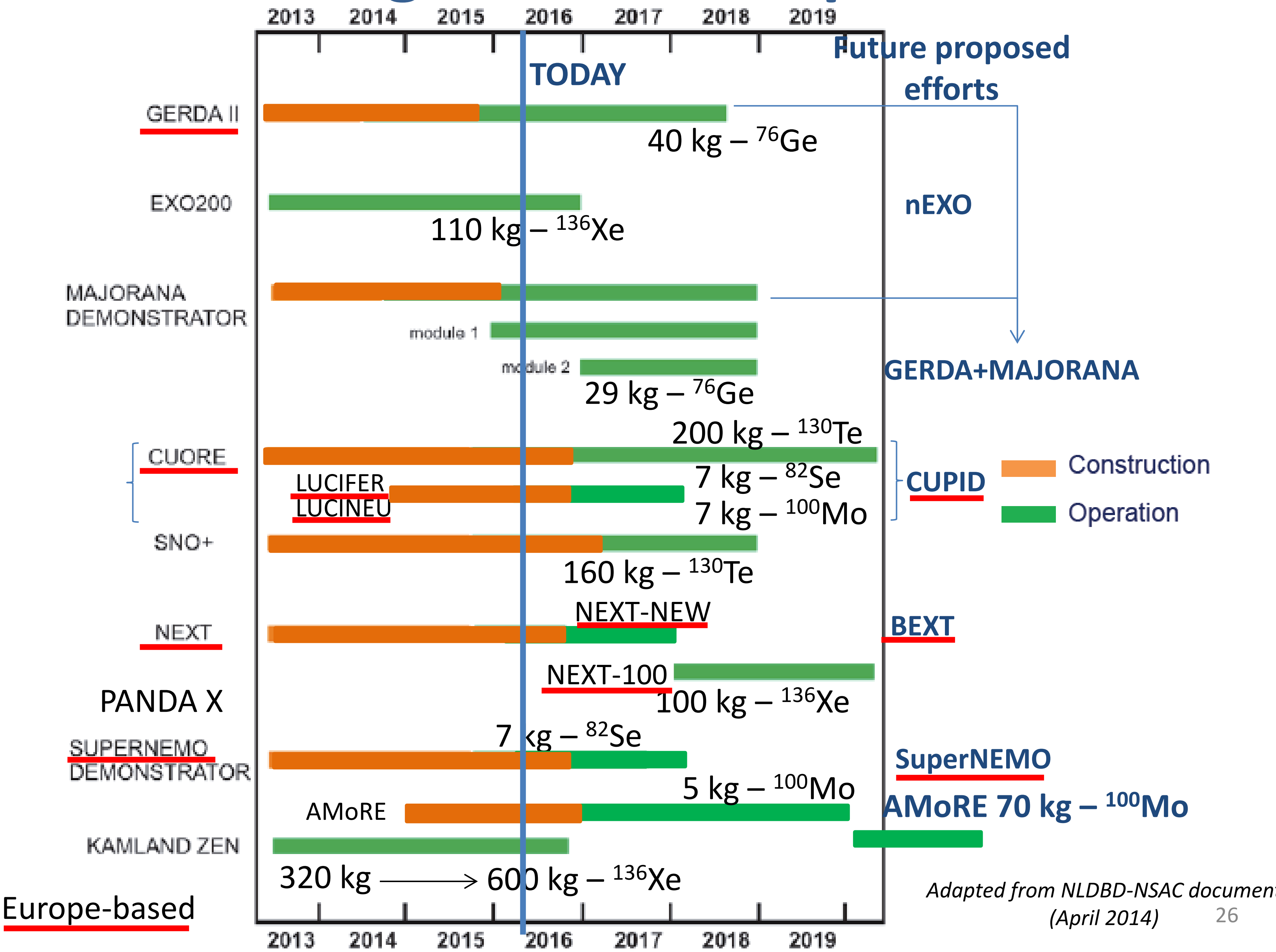
Isotope and background



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

End-point of natural γ radioactivity

Current-generation experiments



Adapted from NLDBD-NSAC document (April 2014)

Possible routes to 1 ton

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

↓

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

↓

Wait 2-3 years for a sensible decision

Possible routes to 1 ton

Scalability

❶ Fluid-embedded source way

- SNO+ (^{130}**Te** 200 kg) – SNO+ (^{130}**Te** 800 kg)
- KamLAND-Zen → KamLAND2-Zen
  (1 ton ^{136}**Xe**, higher energy resolution, pressurized Xe)
- 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

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

High ΔE

❷ Crystal source way

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

- **GERDA 2 → GERDA+MAJORANA** → 1 ton ^{76}Ge (Ge diodes)
- **CUORE** → **CUPID** (1 ton ^{130}**Te** or ^{100}**Mo** or ^{82}**Se**) (bolometers)
  LUCIFER, LUMINEU, LUCINEU
  AMoRE (^{100}**Mo** 10 kg) → AMoRE (^{100}**Mo** 100 kg)

Cryogenics
Crystallization

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

In red, projects located in EU

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	$\sim$ 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

Down-selection process in the US

http://science.energy.gov/~/media/np/nsac/pdf/docs/2016/NLDBD_Report_2015_Final_Nov18.pdf

REPORT TO THE

NUCLEAR SCIENCE ADVISORY COMMITTEE

Neutrinoless Double Beta Decay

NOVEMBER 18, 2015

Therefore the subcommittee strongly recommends that R&D efforts aimed at solving specific technical issues relevant to the downselect decision be supported. 2-3 years time scale

The subcommittee strongly urges continuation of longer term R&D necessary for the future development of the subject in addition to the support of shorter term R&D aimed at a near future downselect.

There is clearly substantial, and growing, international interest in NLDBD. The decision by the US community on its strategy for the next generation experiment will necessarily involve consideration of the international context. Coordination with the international community will clearly be a necessary component in future decisions on technology selection.

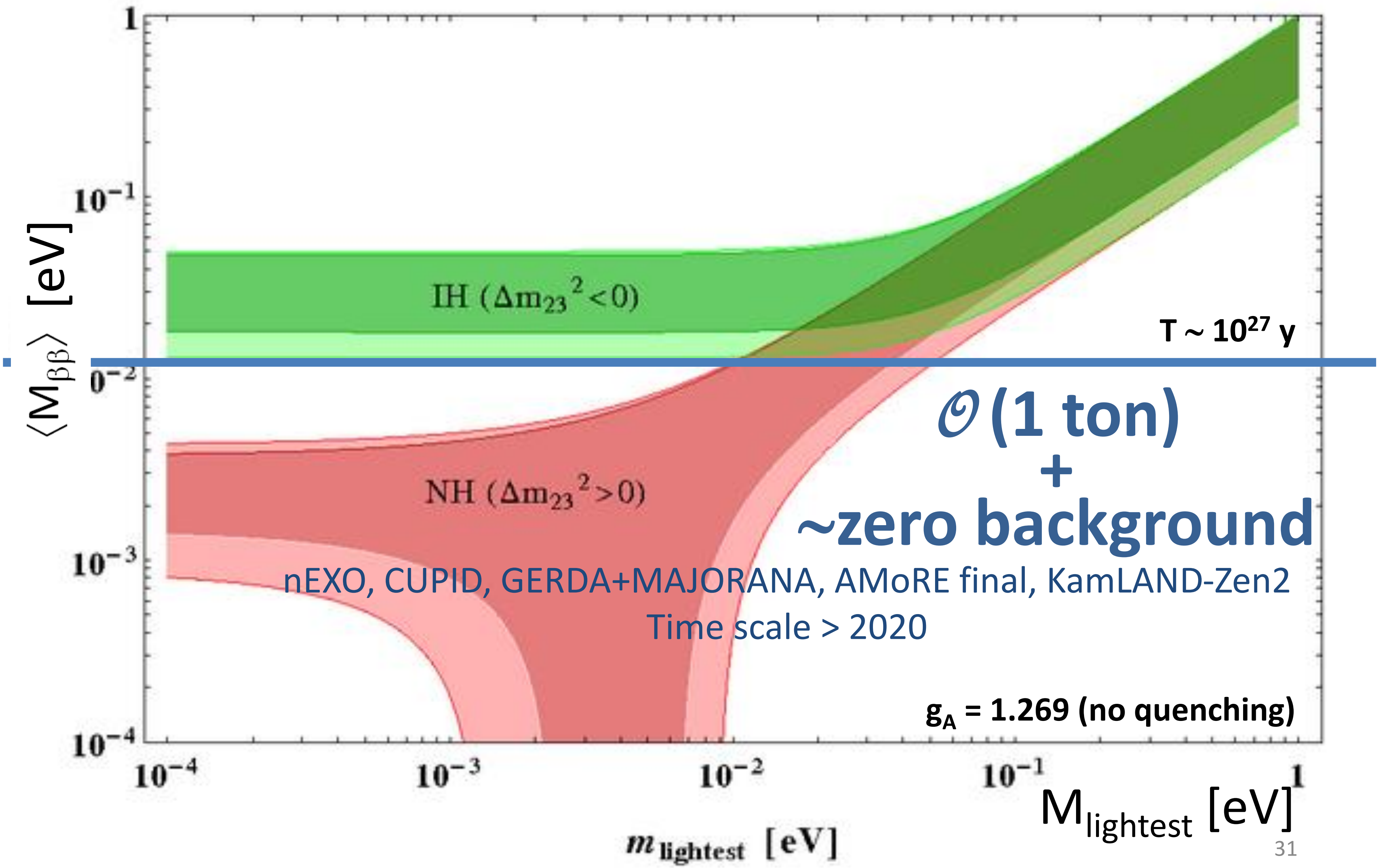
NSAC recommandations:

RECOMMENDATION II

The excess of matter over antimatter in the universe is one of the most compelling mysteries in all of science. The observation of neutrinoless double beta decay in nuclei would immediately demonstrate that neutrinos are their own antiparticles and would have profound implications for our understanding of the matter-antimatter mystery.

We recommend the timely development and deployment of a U.S.-led ton-scale

Strategic milestone



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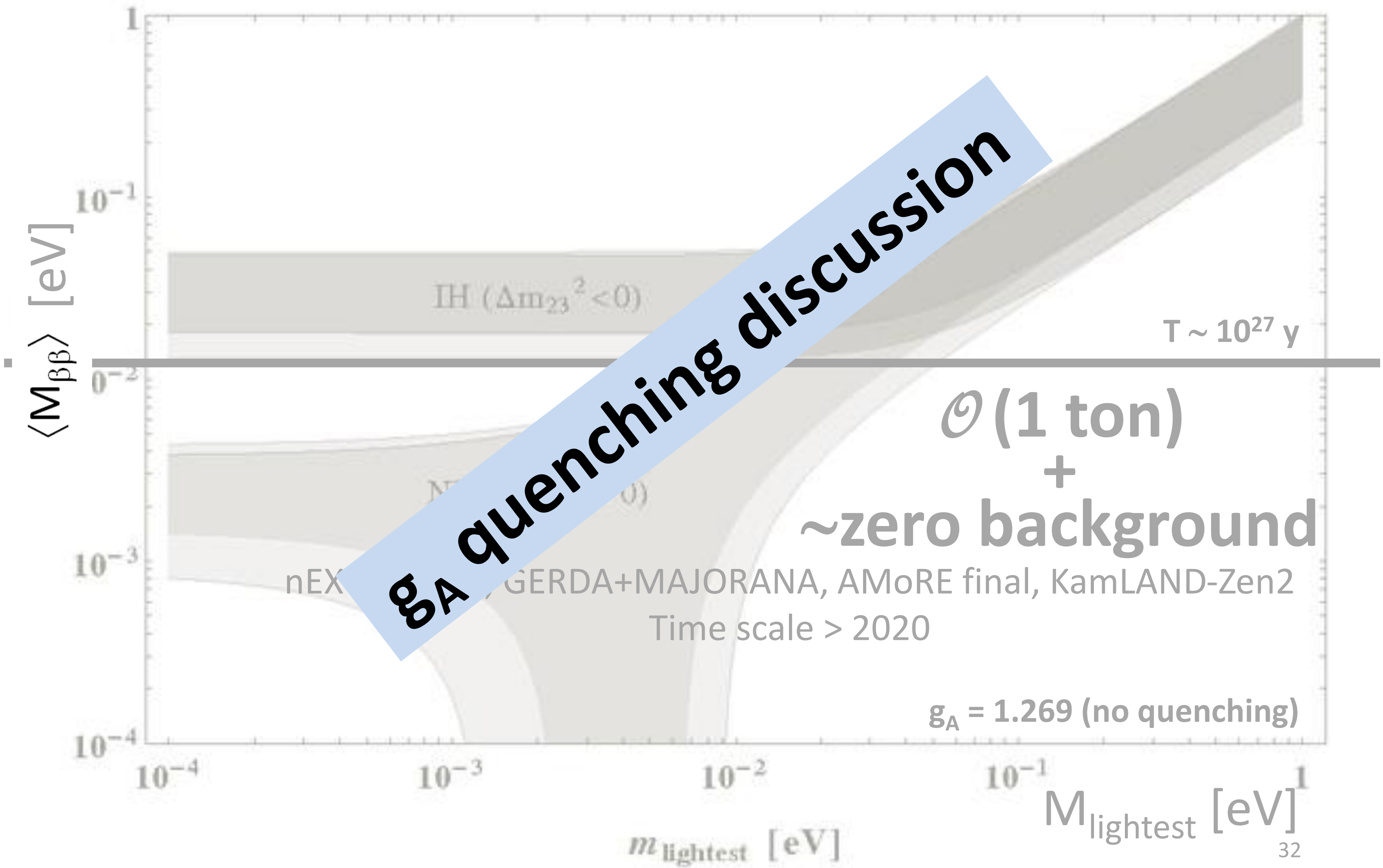


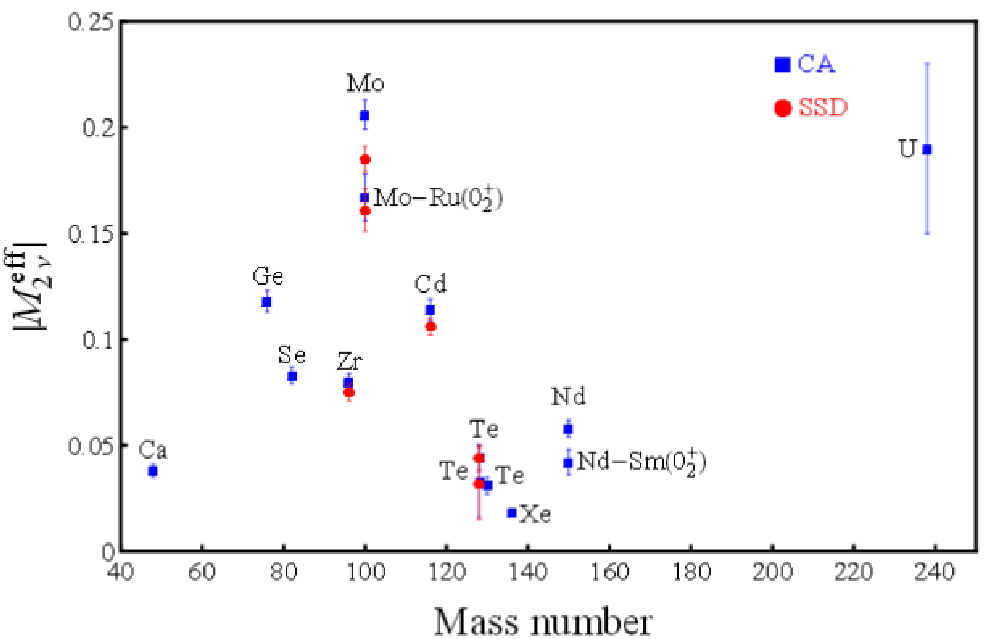
g_A quenching

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

$$g_A = \begin{cases} 1.269 & \text{Free nucleon} \\ 1.25 & \text{Often taken in the calculations} \\ 1 & \text{Quark} \end{cases}$$

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

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

g_A =
- 1.269 Nucleon
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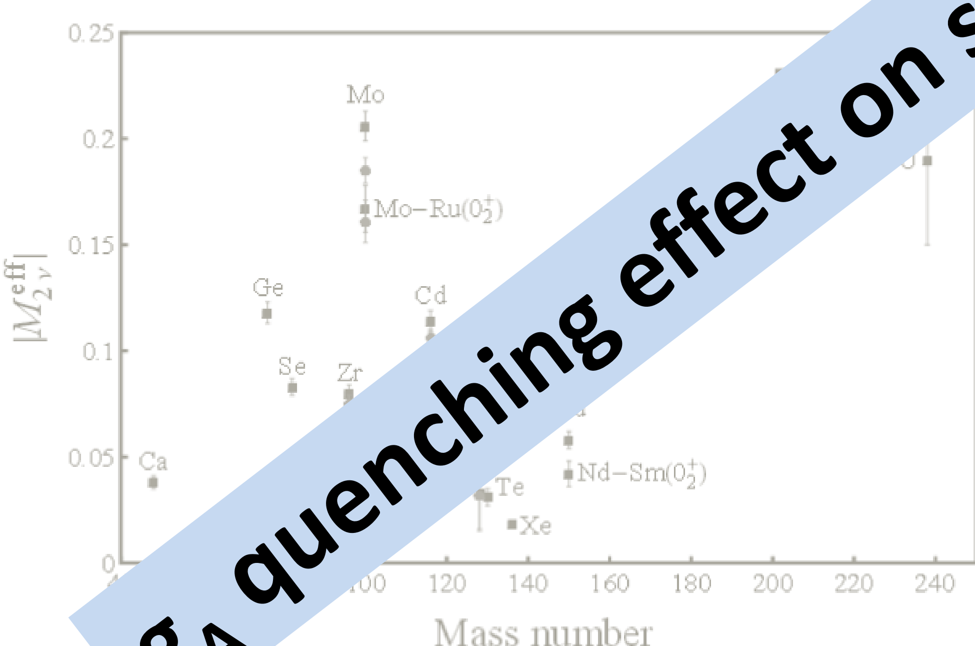

g_A quenching effect on sensitivity is dramatic

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)
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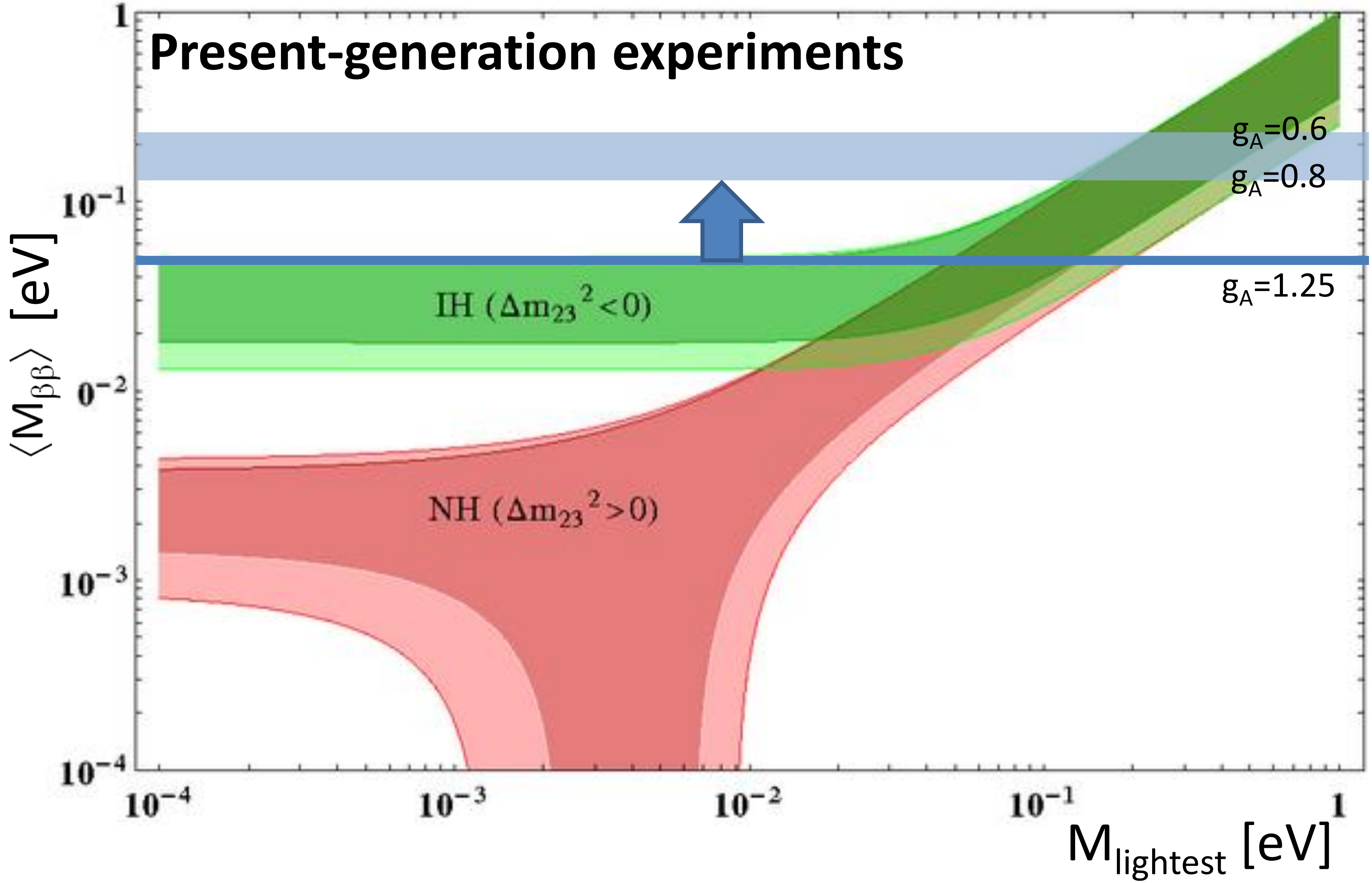
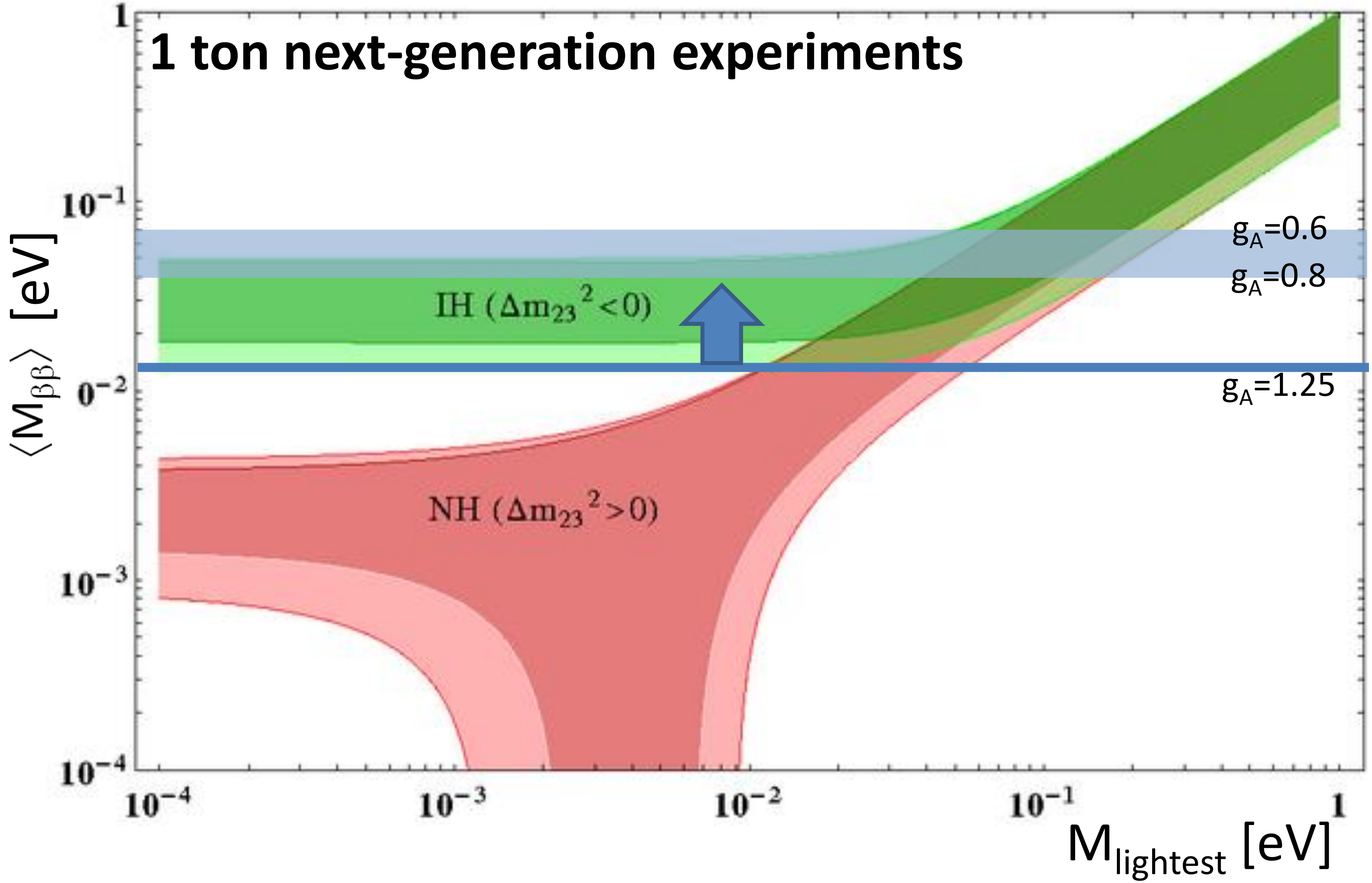
g_A quenching impact



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)
- ✓ Large momentum transfer $p \sim m_\pi$
  $\Rightarrow$ Chiral EFTs seem to show that indeed $g_{A,eff}$ increases as p increases

Some could be unquenched or even enhanced

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

NUMEN

F. Cappuzzello et al., J. Phys. Conf. Ser., 012018 (2015)

Program for g_A issue

- ✓ Study nuclear reactions with **Double Charge Exchange**
- ✓ 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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Program f...

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- ✓ Fu... ...ical studies using **chiral EFTs**
- ✓ New ... ...sed method: dependence on g_A of **spectral shape** in forbidden β decays

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

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

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.)

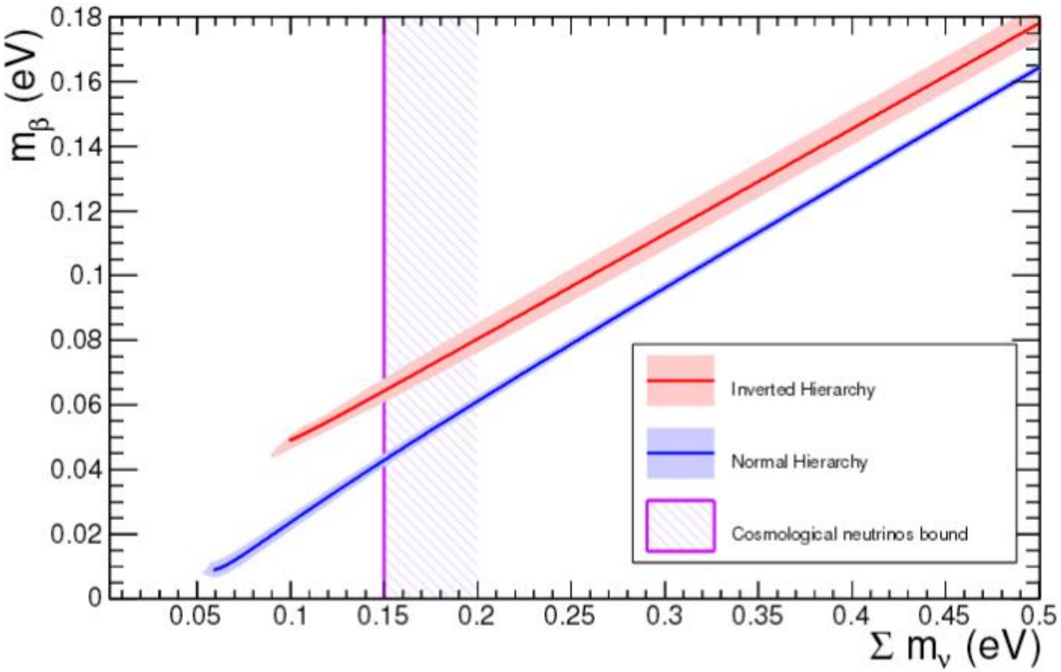
The result improves adding other cosmological probes, i.e. BAO:

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

Very recently, combining CMB, Lyman α forest, BAO

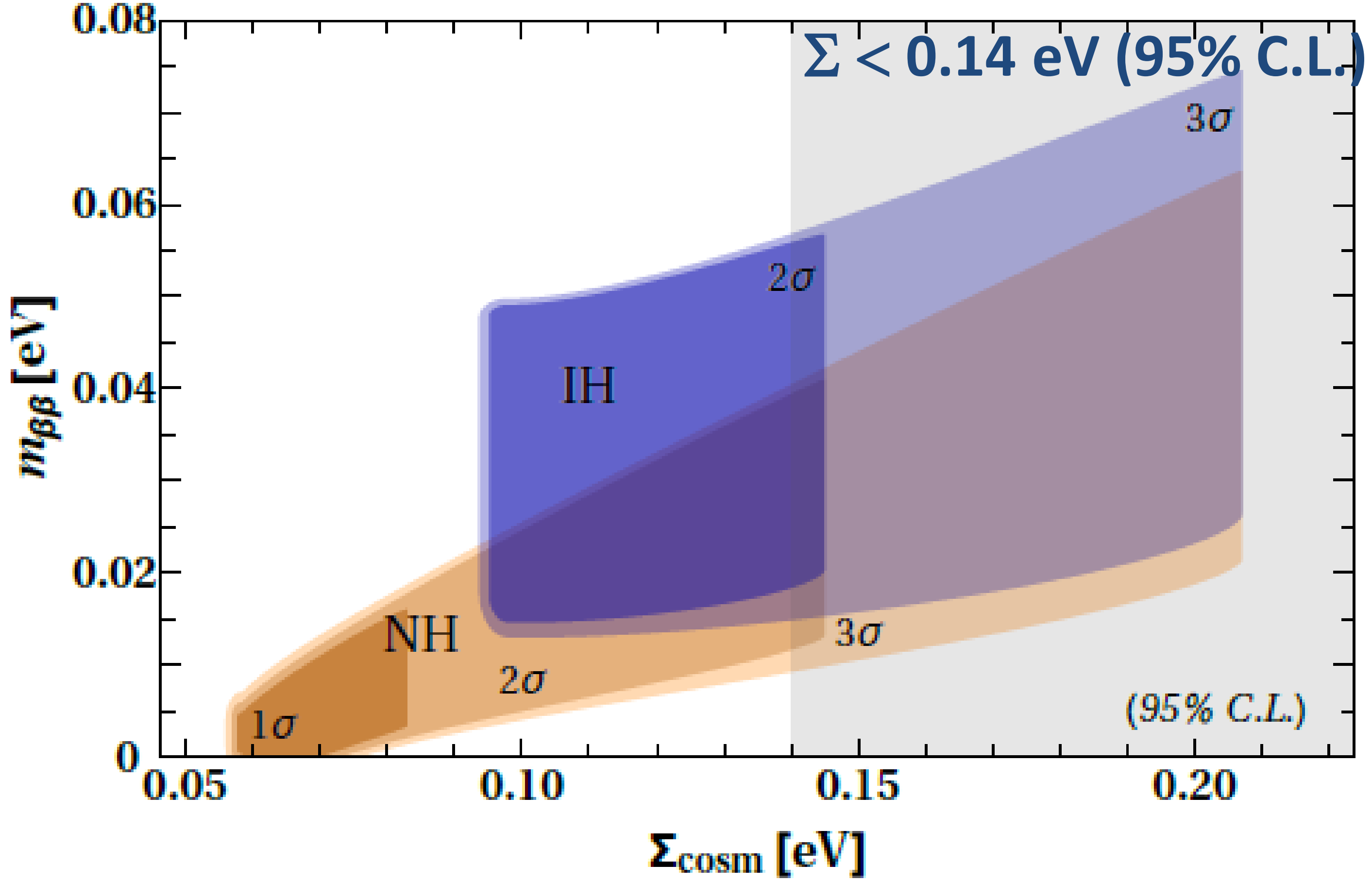
$\Sigma < 0.14$ eV (95% C.L.)

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



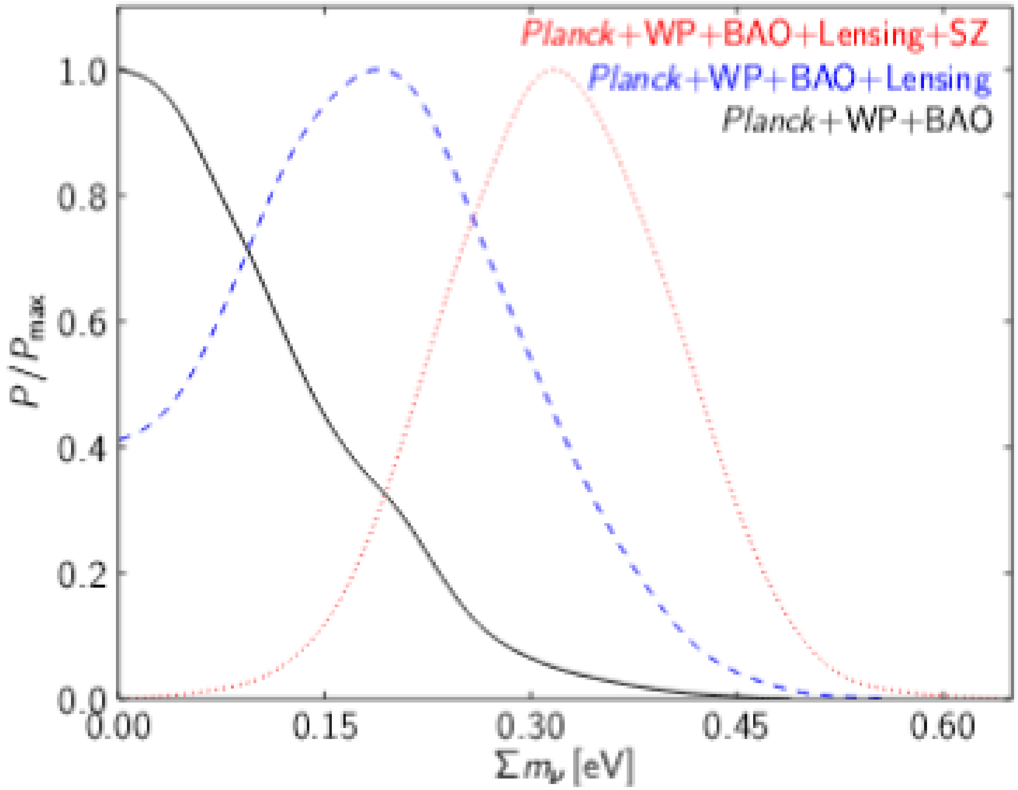
Impact of cosmology on ⟨M_β⟩ and ⟨$M_{\beta\beta}$⟩

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



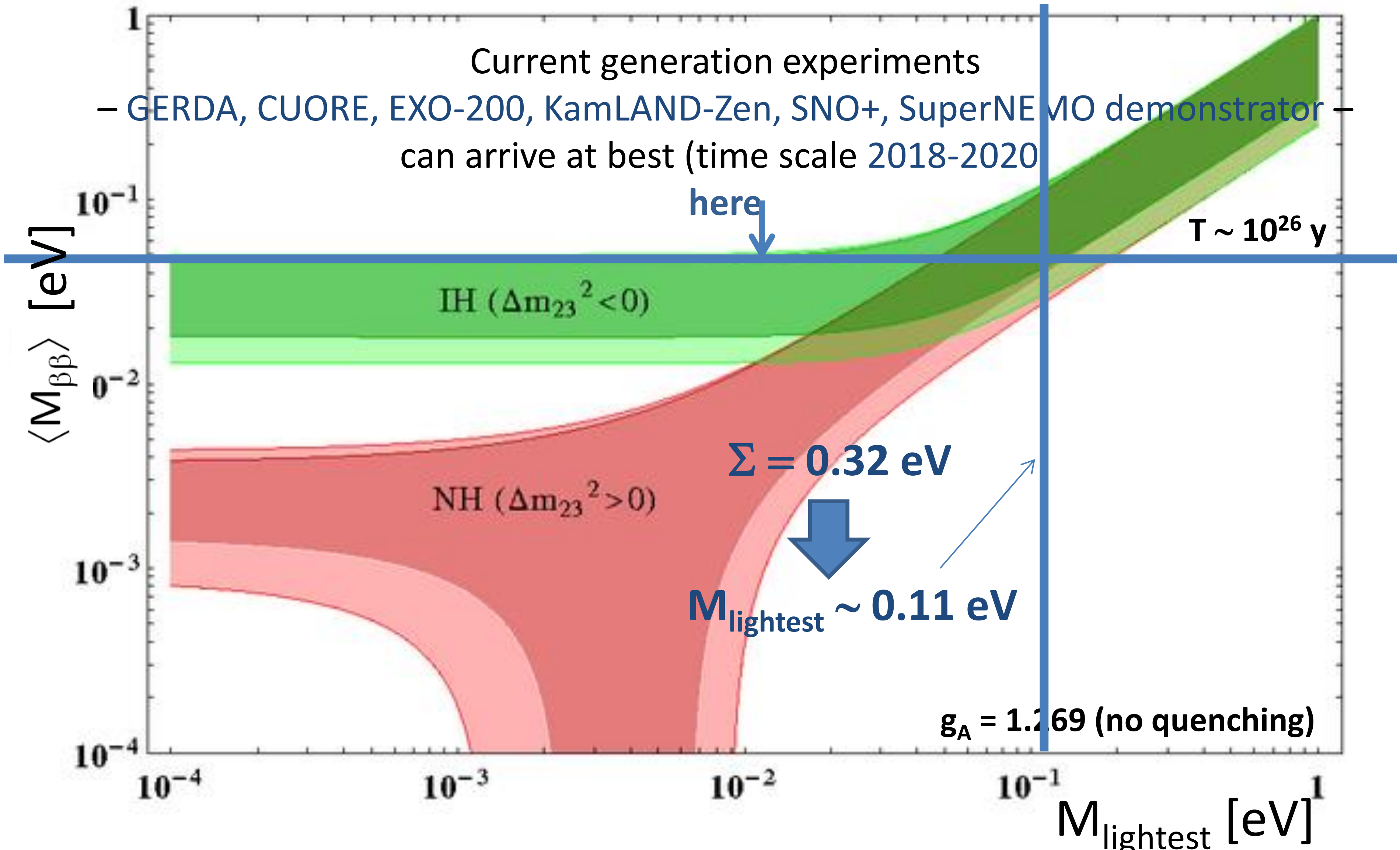
$$\Sigma = 0.32 \text{ eV} \pm 0.081 \text{ eV}$$

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

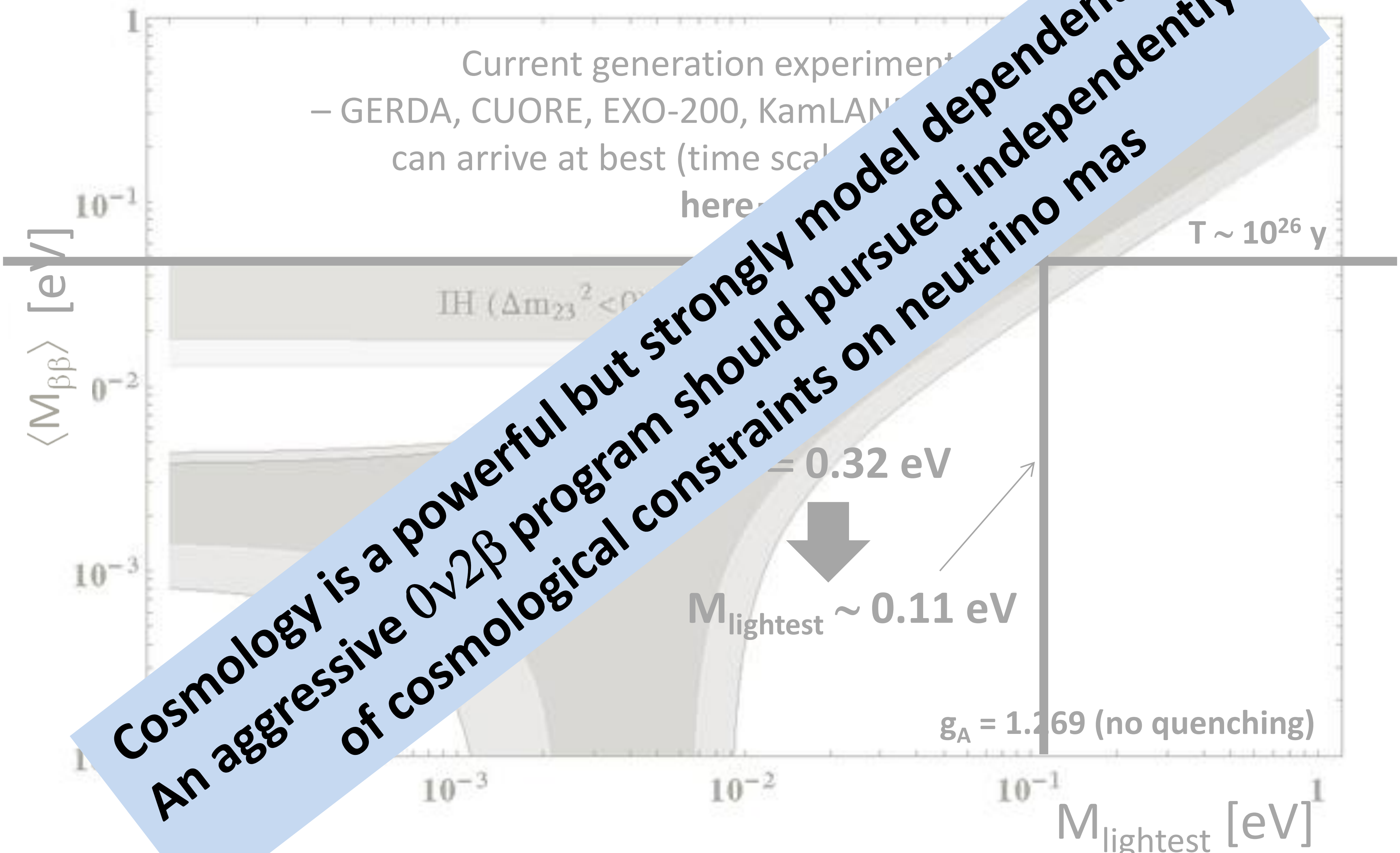
Similar results from an other analysis (BOSS collaboration)

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 … $_\beta\rangle$



Cosmology is a powerful but strongly model dependent tool
An aggressive $0\nu2\beta$ program should pursued independently of cosmological constraints on neutrino mas

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

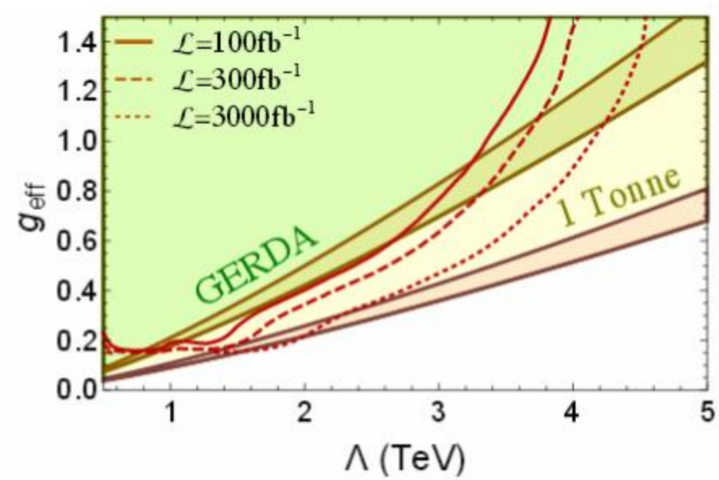
The famous Scheckter-Valle « theorem » implies Majorana masses of the order 10^{-24} eV

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

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

some examples:

- ✓ 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)

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Interplay with search for LNV at **LHC** **di-jet signal**

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  Tao P 44v1
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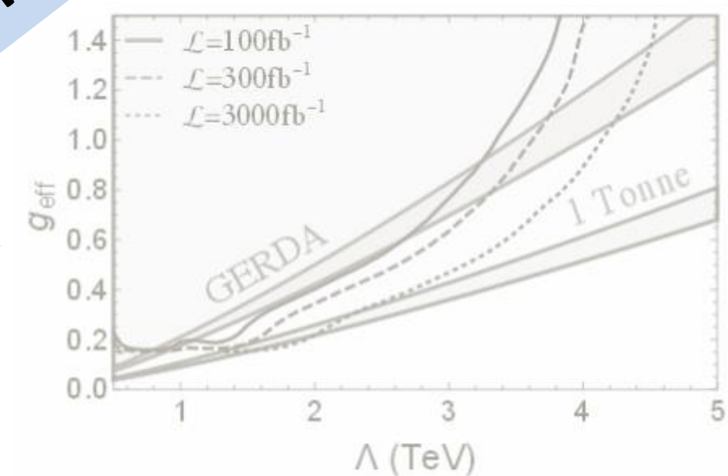

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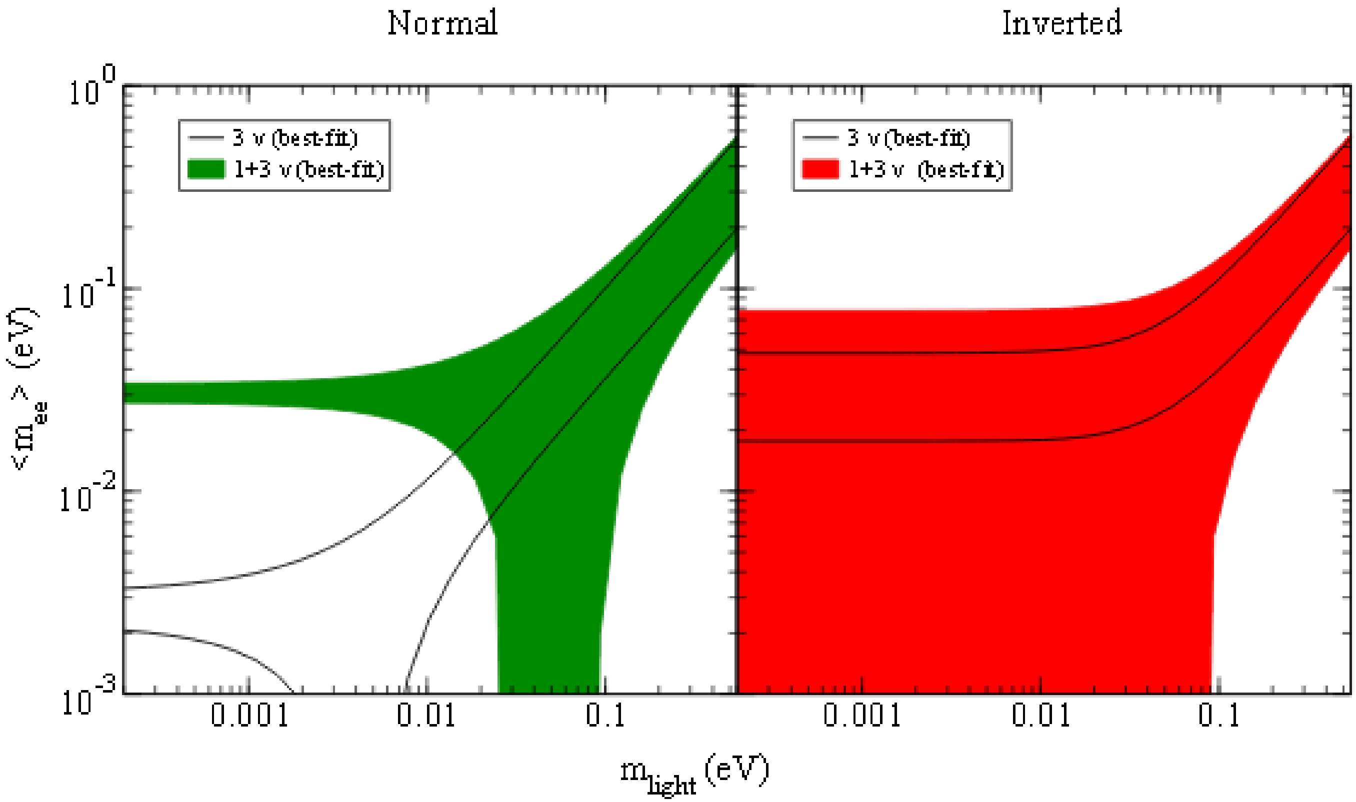
  .F. Deppisch et al., Phys. Rev. D 93, 013011 (2016)

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

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

Light sterile neutrinos

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



Conclusions

$\langle M_\beta \rangle$

- KATRIN will take date in 2016, with sensitivity 0.2 eV
- R&D in progress with low temperature calorimeters and Project8
- Ideas to improve KATRIN

$\langle M_{\beta\beta} \rangle$ - LNV

- Klapdor's claim strongly disfavored by GERDA - 1
- Present sensitivity in the 150-400 meV range:
  GERDA–1, EXO, KamLAND-Zen, CUORE-0
- Current experiments will approach the inverted hierarchy region:
  GERDA–2, CUORE, EXO-200, KamLAND-Zen, SNO+
- ~10 kg demonstrators will aim to validate new technologies in:
  SuperNEMO demonstrator, NEW (NEXT-10), LUCIFER+LUCINEU, AMoRE
- Towards the "1 ton scale": nEXO, CUPID, BEXT, GERDA+MAJORANA, KamLAND-Zen2
- g_A quenching, impact of cosmology, interplay with LHC are emerging issues

Fluid-embedded source

	Helpful	Harmful
Internal Origin	**Strengths**	**Weaknesses**
	➢ Source=Detector ➢ Scalability ➢ Large compatibility with isotope ^{136}Xe ➢ Compatibility with isotope ^{130}Te ➢ Possibility of extreme purification of fluids ➢ Fiducialization, delayed coincidence, tracking, single vs multisite events for background reduction (according to technique)	➢ In most of technologies, low energy resolution ➢ No compatibility with high Q-value (> 2615 keV) isotopes ➢ In "dilution approach" (SNO+, KamLAND) low efficiency (isotope mass much smaller than active mass)
External Origin	**Opportunities**	**Threats**
	➢ Use of existing facilities (SNO+, KamLAND, Borexino) ➢ Use of well-established technologies (liquid scintillators, TPC)	

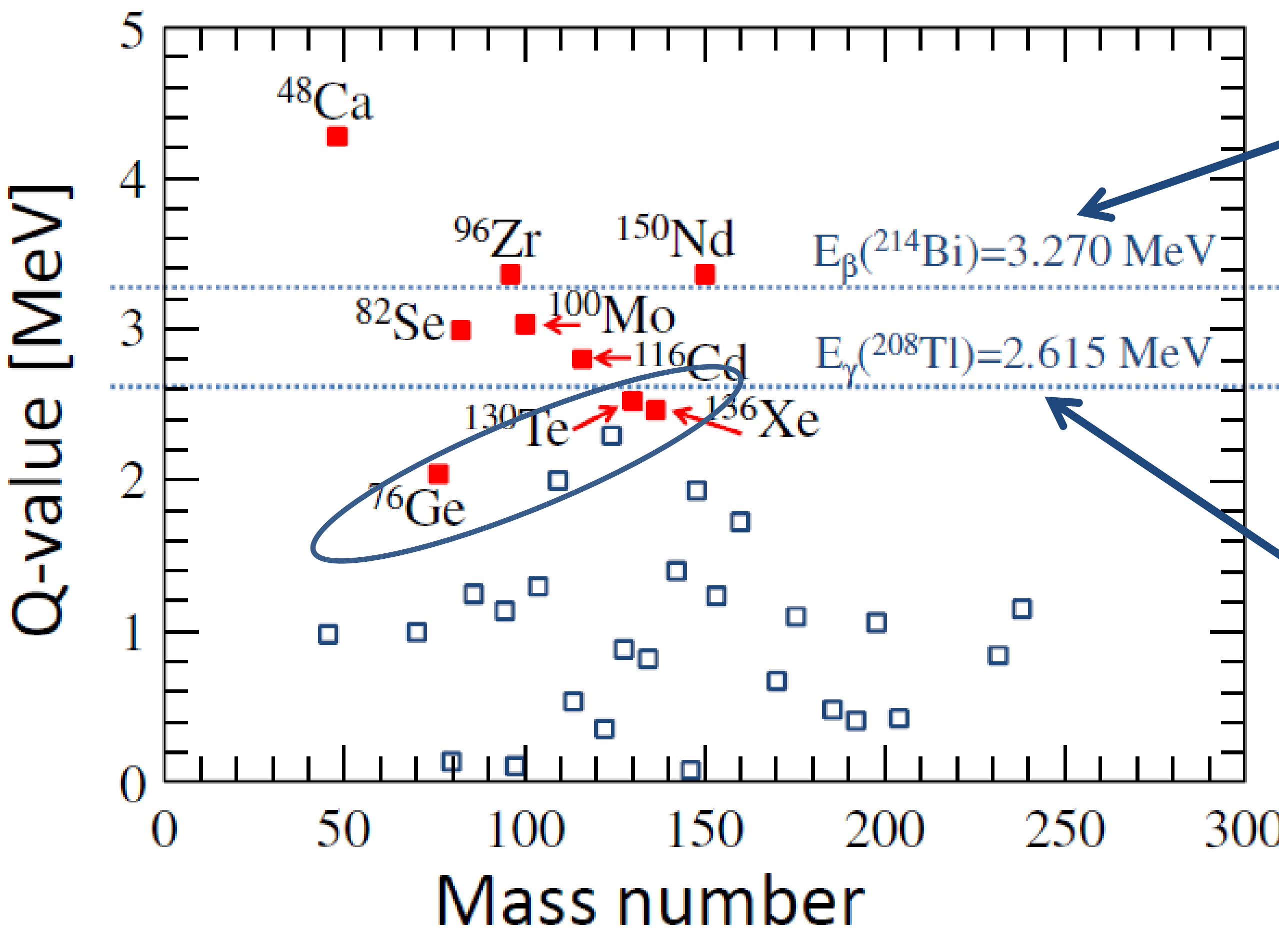
Crystal source

	Helpful	Harmful
Internal Origin	**Strengths** ➢ Source=Detector ➢ Modularity ➢ Compatibility with numerous isotopes (^{76}Ge, ^{100}Mo, ^{82}Se, ^{116}Cd – the last three with Q-values > 2615 keV) ➢ High energy resolution ➢ High efficiency ➢ Particle- or event-type discrimination	**Weaknesses** ➢ No tracking ➢ Scalability possible but costly and complicated ➢ Complicated enrichment-crystallization-purification chain
External Origin	**Opportunities** ➢ Well-studied precursors (Heidelberg Moscow, IGEX, Cuoricino, CUORE-0)	**Threats**

External source

	Helpful	Harmful
Internal Origin	**Strengths** ➢ Modularity ➢ Compatibility with all isotopes in principle ➢ Full event reconstruction ➢ Information on the mechanism ➢ Excellent opportunity to study Majoron mode	**Weaknesses** ➢ Low efficiency ➢ Low energy resolution ➢ Scalability possible but with high cost and space occupation
External Origin	**Opportunities** ➢ Well-studied precursor (NEMO3)	**Threats** ➢ Risk of insufficient underground space (or necessity of use of multiple underground laboratories)

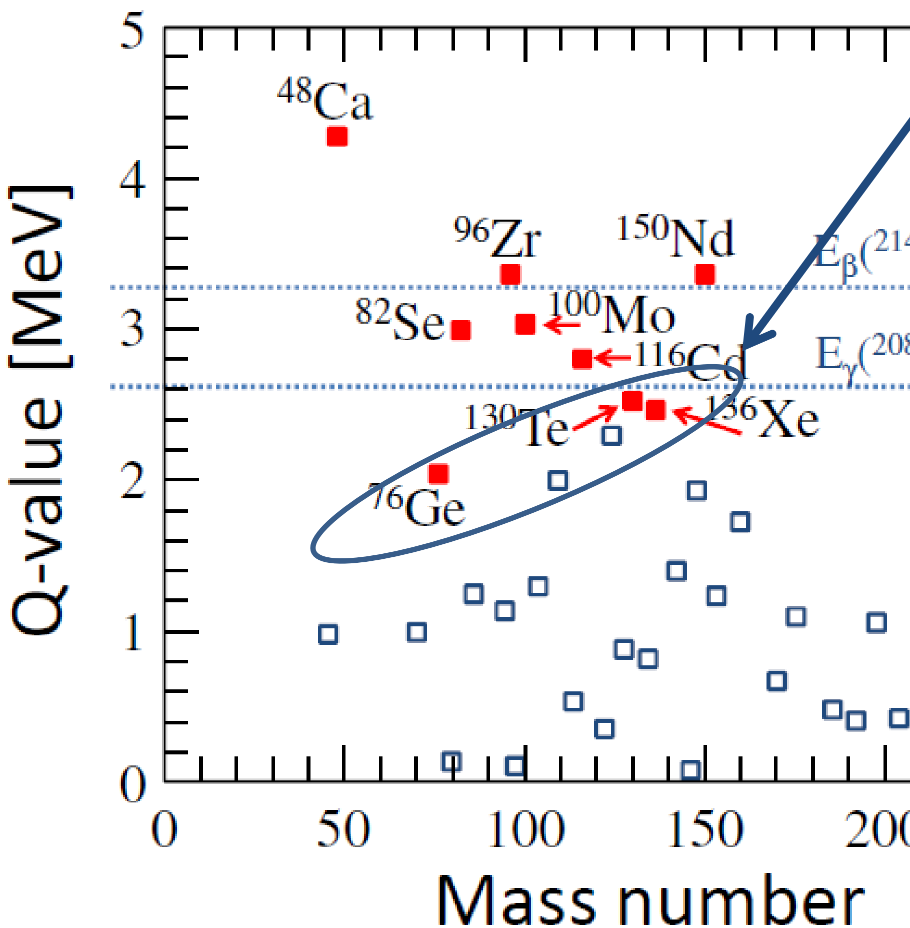
Isotope, enrichment and technique



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

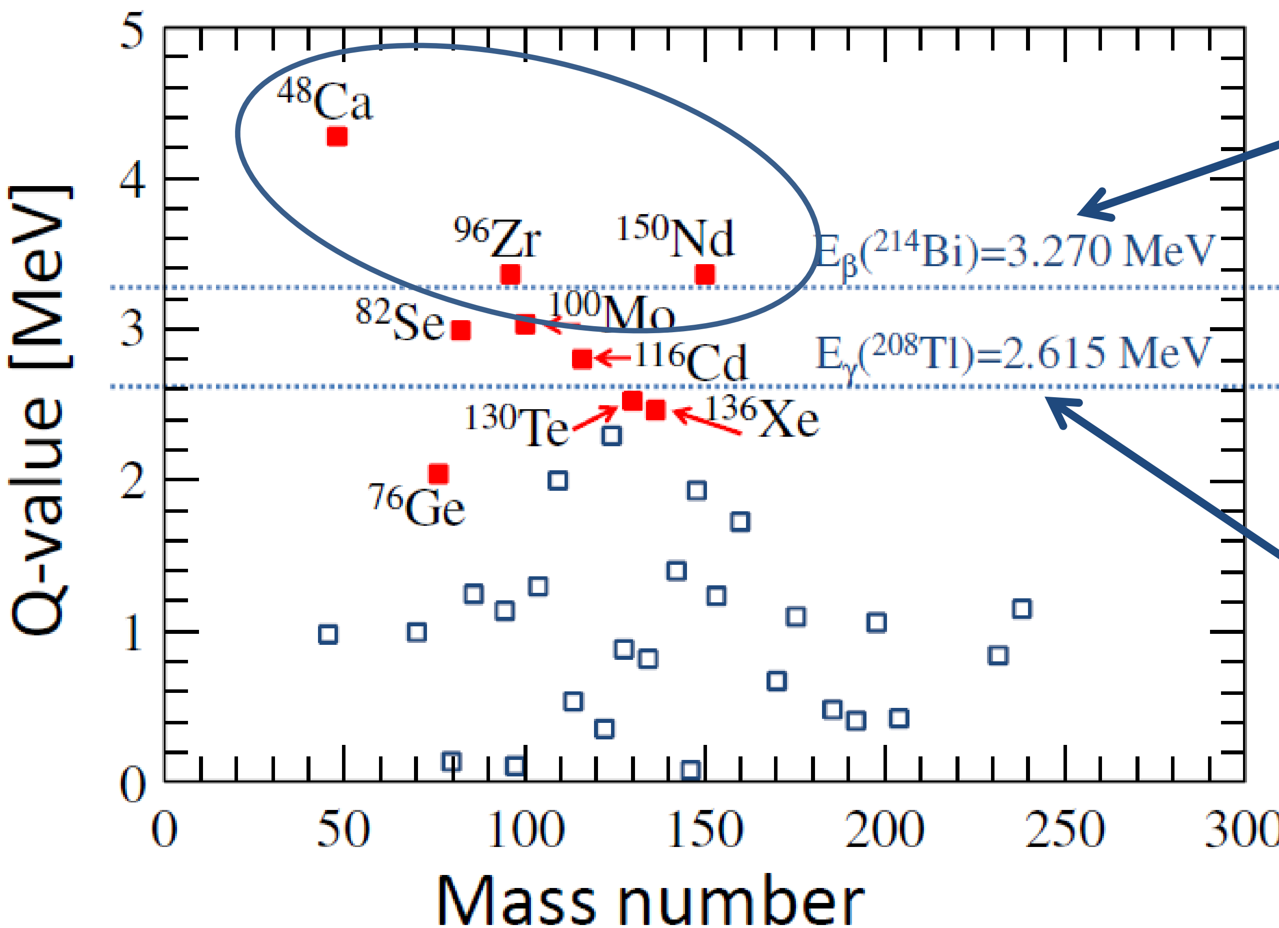
Enrichment is "easy" and for ^{130}Te not necessary at the present level

BUT

Less favorable in terms of background!

In red, projects located in EU

Isotope, enrichment and technique



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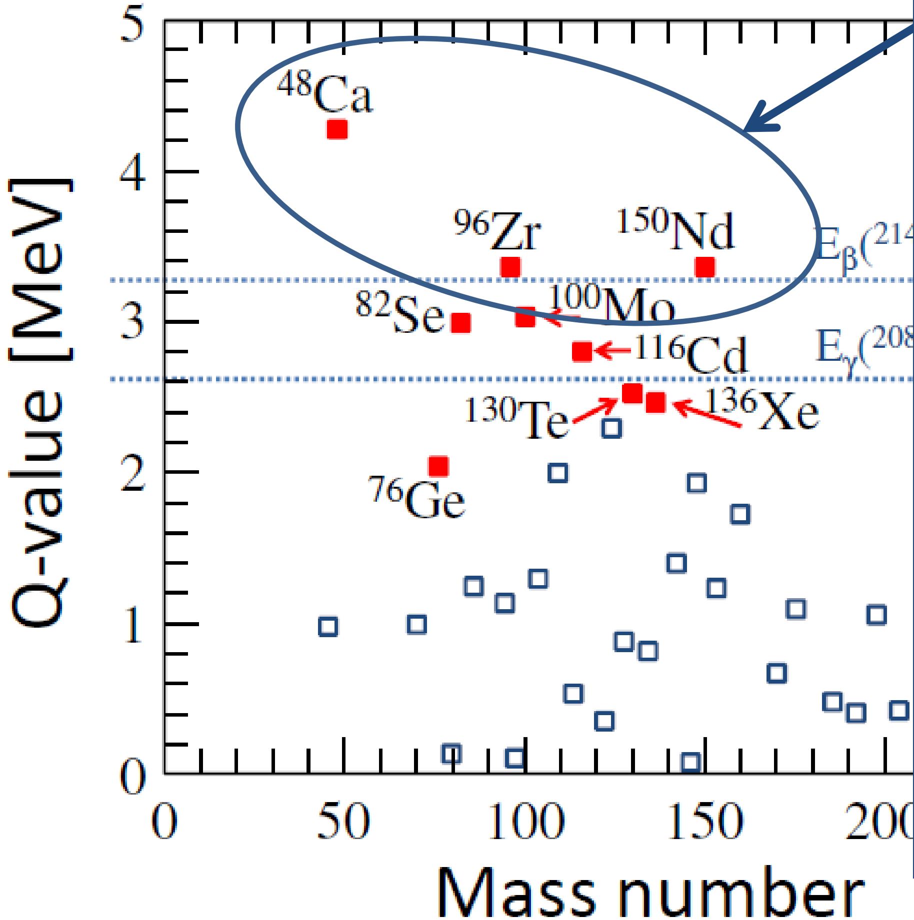
Isotope, enrichment and technique



Almost background free isotopes!

BUT

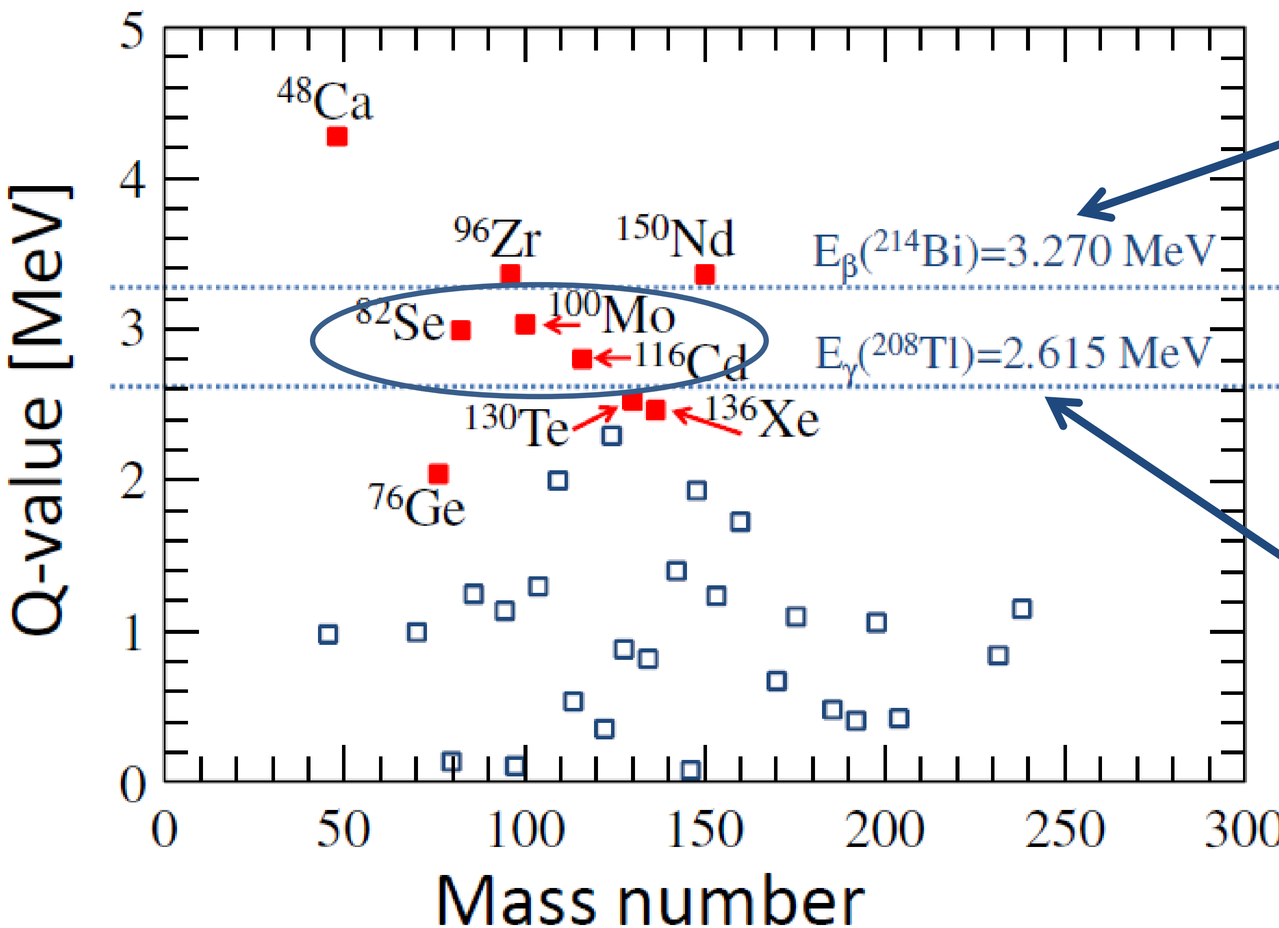
Low isotopic abundance and problematic enrichment (good news about Nd)

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



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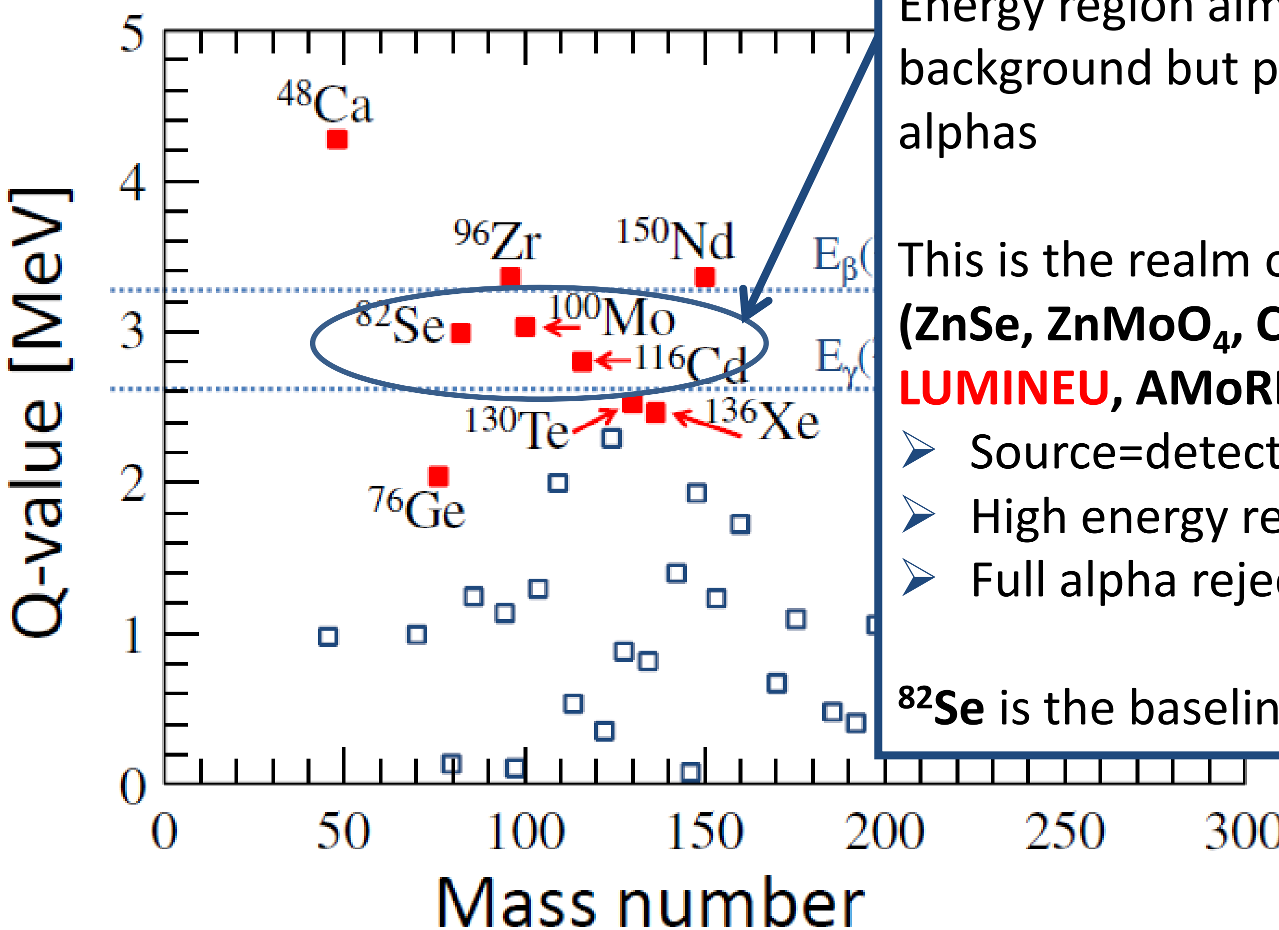
Isotope, enrichment and technique



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