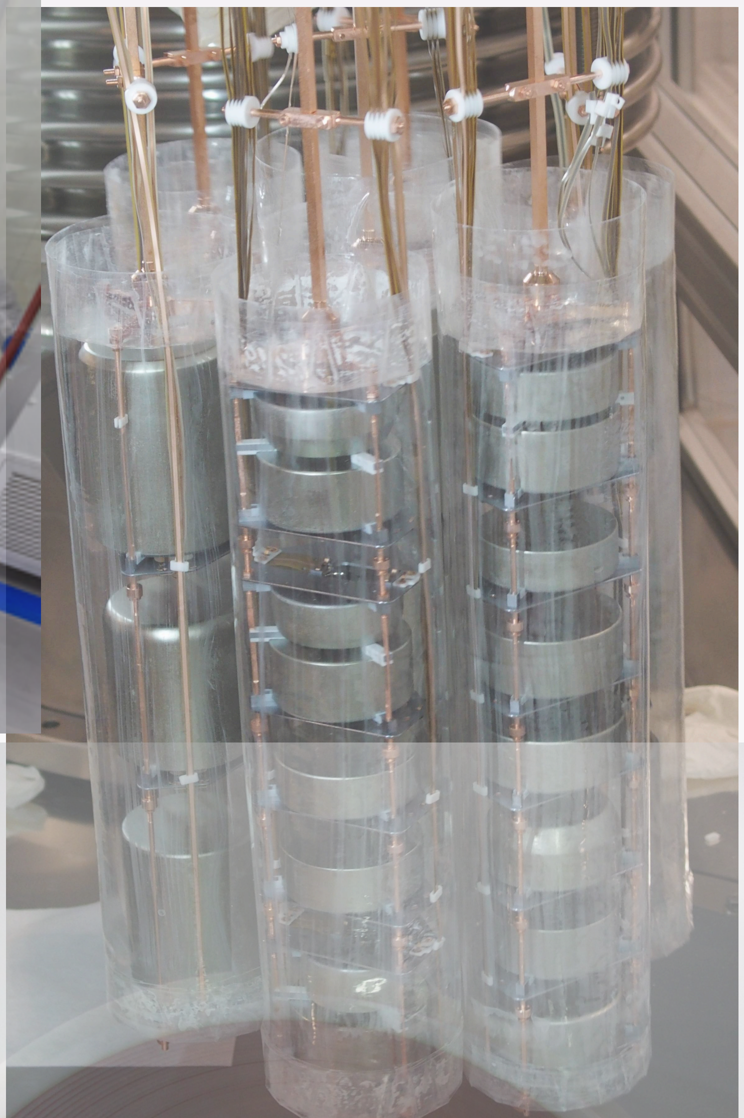
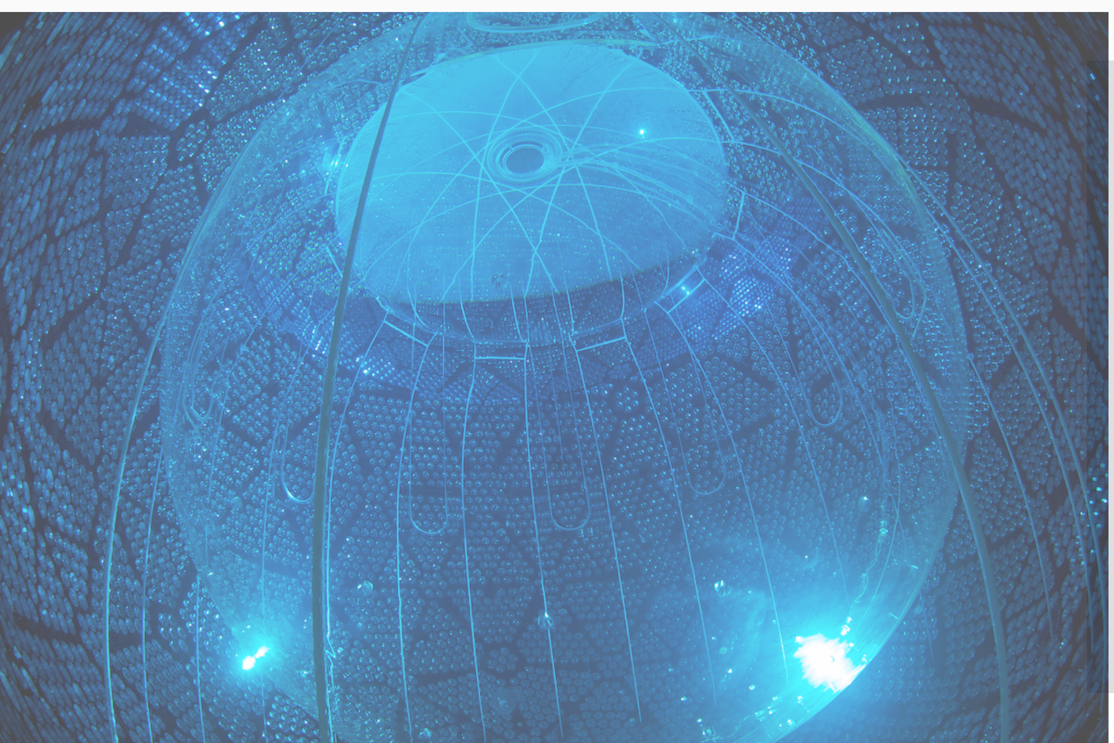


Double Beta Decay Experiments
(opportunities and challenges)



Ruben Saakyan
University College London

Atomic Nuclei for BSM Physics
Trento
17-Apr-2019

- Overview of Double Beta Decay
- Recent Results
- g_A, $2\nu\beta\beta$ decay and all that jazz…
- Next Steps
  - Experiments aimed at exploring inverted ordering of neutrino masses
- Speculations for "ultimate" experiment
  - attacking normal ordering, *O*(1 meV)

Disclaimer: Impossible to do justice to such a vibrant field. Apologies for omitting many brilliant ideas and experiments.

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Only if I have time

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Remaining **Big Questions:**

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- **CP- violation** — Dirac phase

addressed by neutrino oscillations

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- **Majorana vs Dirac — mass mechanism**
- **CP- violation — Majorana phases**
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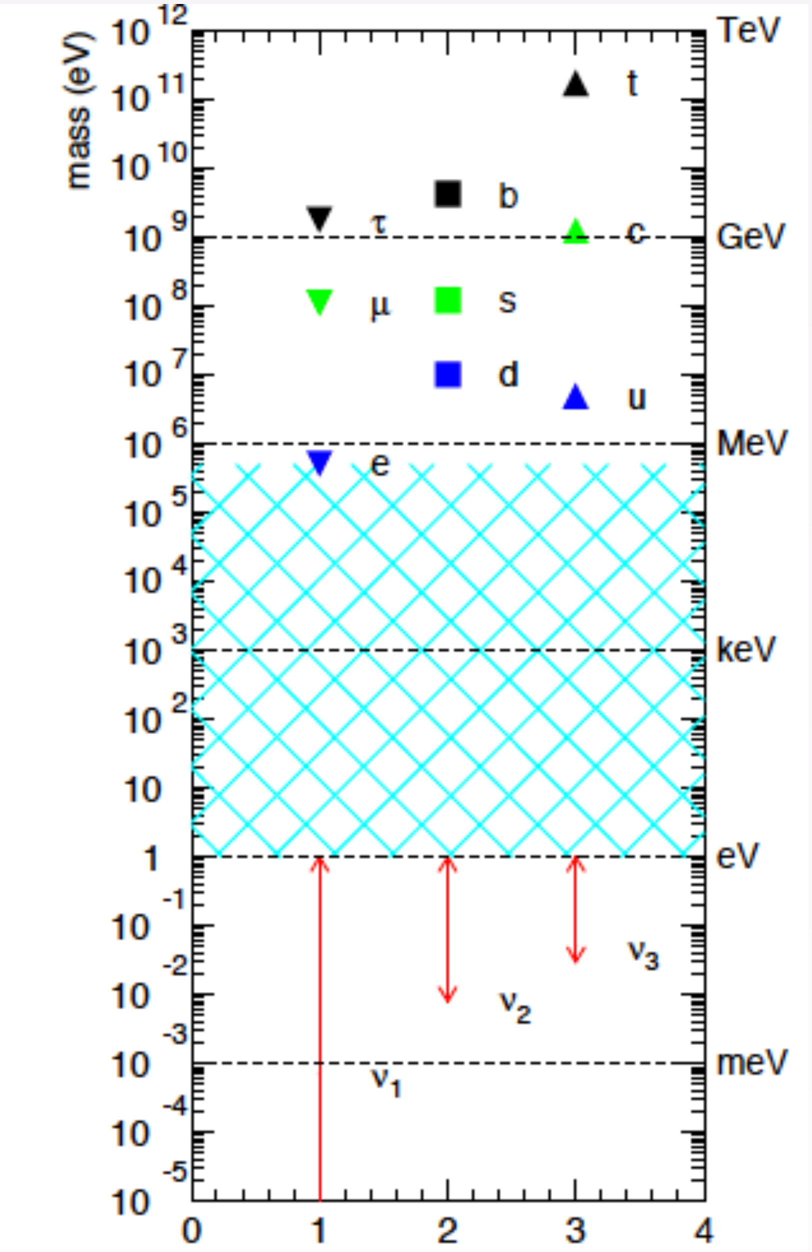
addressed by $0\nu\beta\beta$



The nuclear process of $0\nu\beta\beta$ is the most sensitive way to address LNV

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addressed by 0νββ

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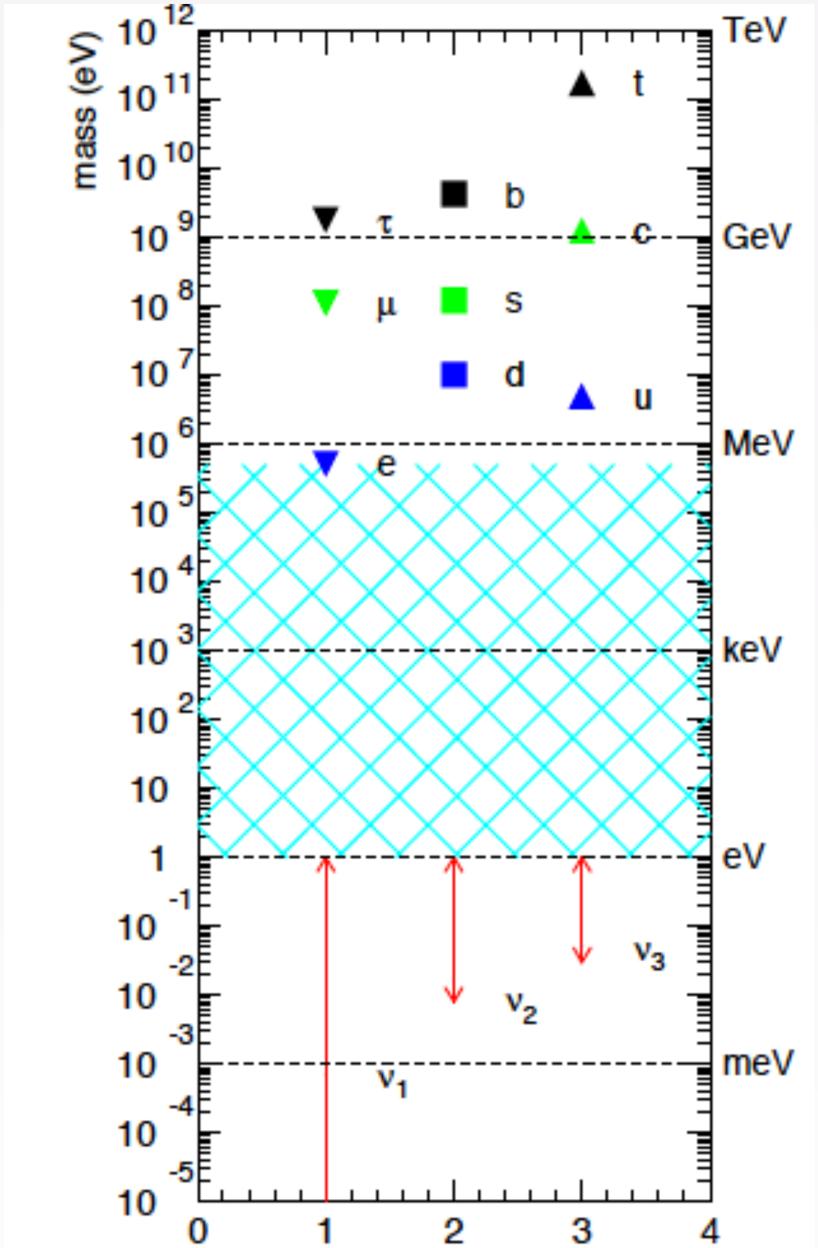
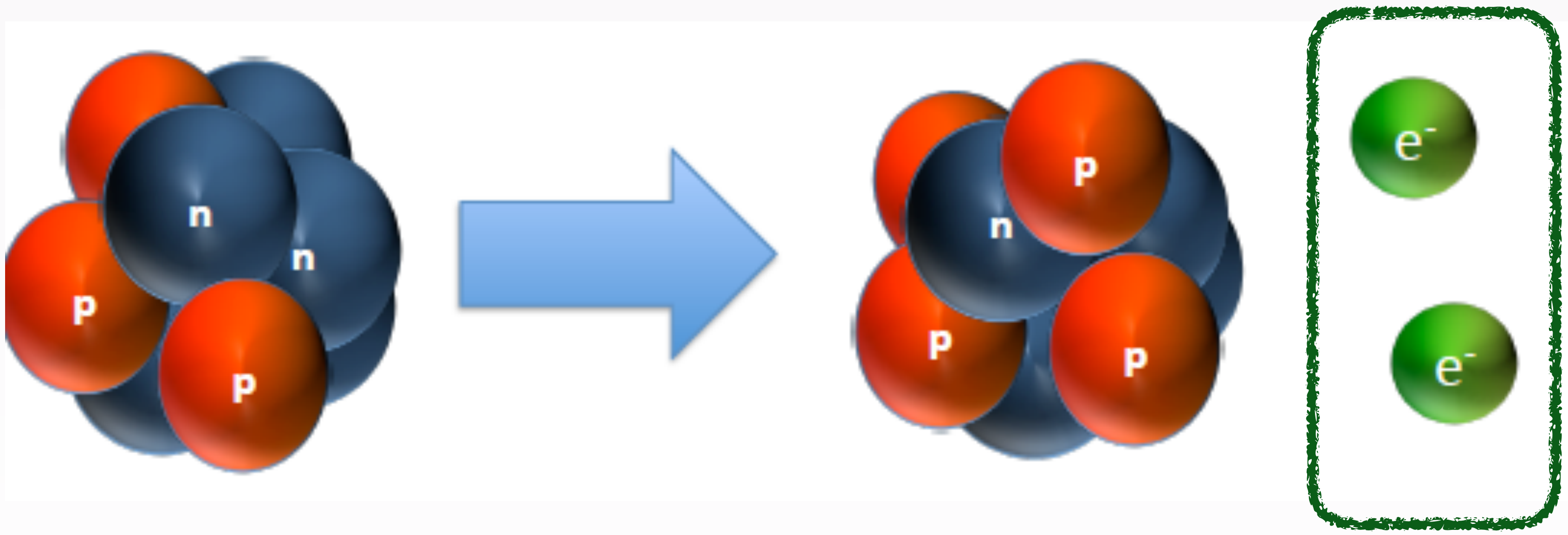


And of course neutrinos are historic dark matter (recall Zeldovich Pancakes!). They are still part of HDM!

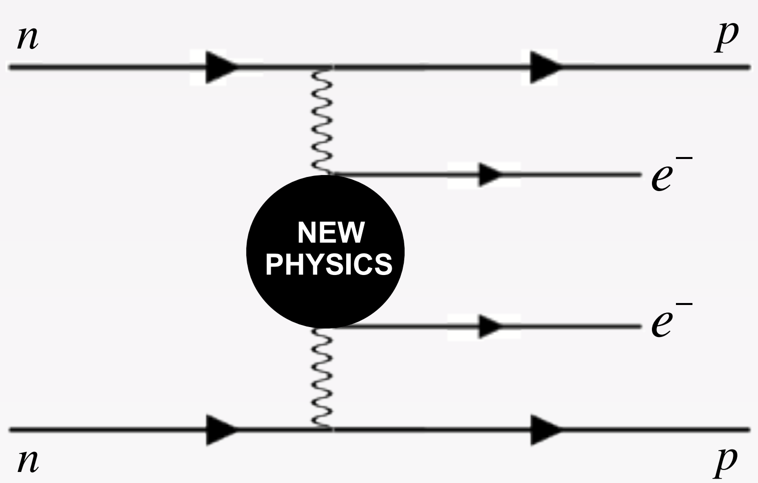
Rebranding 0νββ ⟶ Search for Matter Creation©

Proton Decay: "Disappearance" of nucleons



Neutrinoless Double Beta Decay "Creation" of electrons

© Francesco Vissani



ΔL = 2! (a. k. a. Matter Creation)

phase space

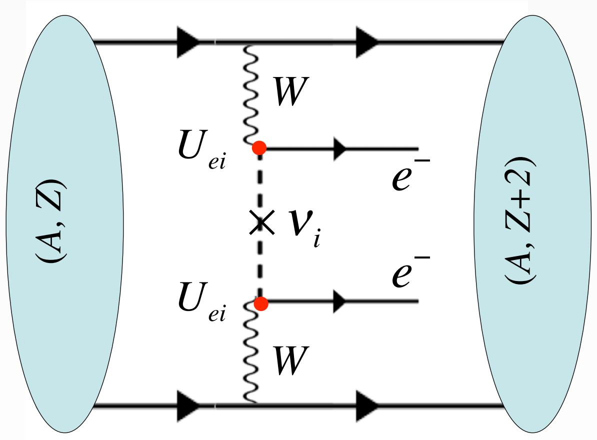
NME: ~~Nasty~~ Nuclear Matrix Element

LNV parameter

$$\frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}(Q_{\beta\beta}, Z)\left|M^{0\nu}\right|^2 \eta^2$$

η can be due to $\langle m_\nu \rangle$, V+A
Majoron, SUSY, H^{--}, leptoquarks,
or a combination of them

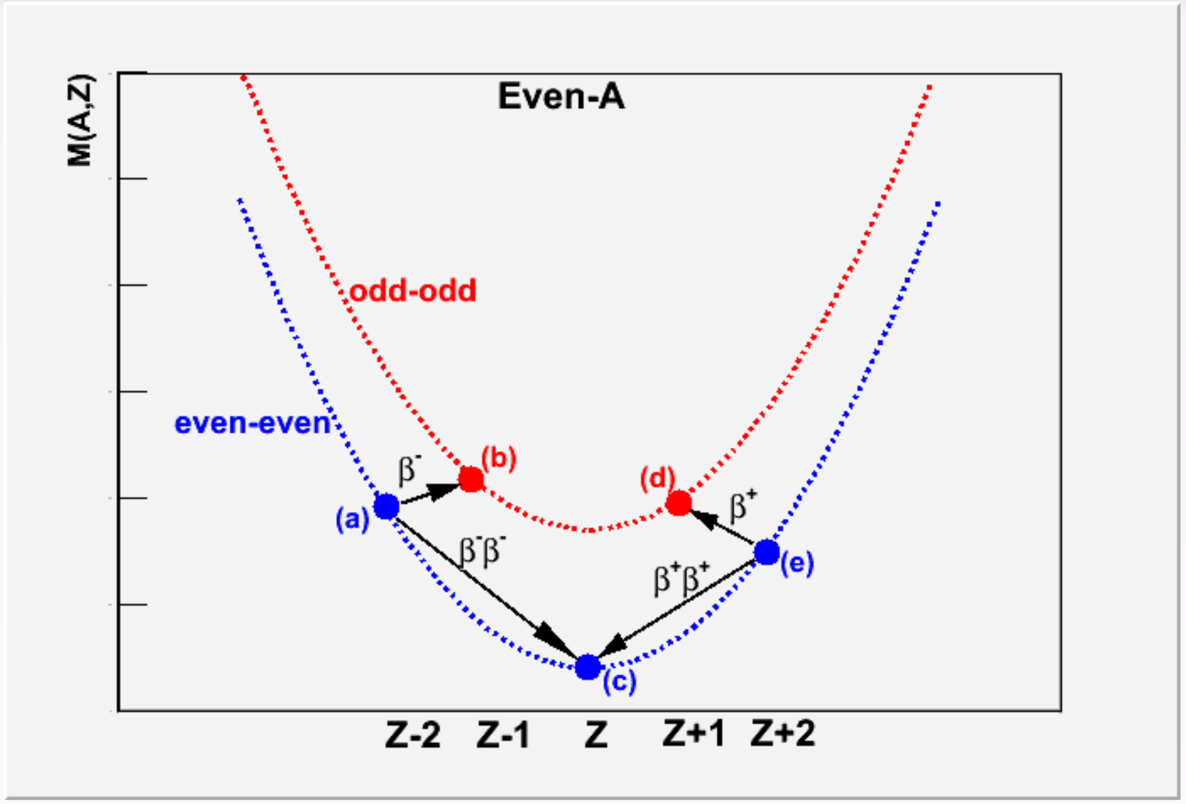
Most discussed mechanism:
Light Majorana neutrino exchange



Coherent sum over neutrino amplitudes

$$\langle m_\nu \rangle = \left|\sum U_{ei}^2 m_i\right| = \left|U_{e1}^2 m_1 + U_{e2}^2 m_2 e^{i\alpha_{21}} + U_{e3}^2 m_3 e^{i\alpha_{31}}\right|$$

Observation of LNV would have profound implications beyond neutrino physics



1935

M. Goeppert-Mayer
Phys. Rev. 48, 512 –

Published 15 September 1935

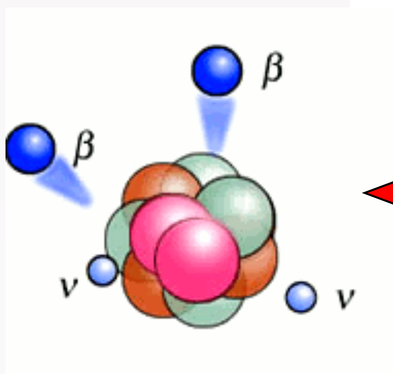
Over **40 nuclei** can undergo **ββ**-decay (including $\beta^+\beta^+$ and 2K-capture)
Only ~**9** experimentally **feasible**

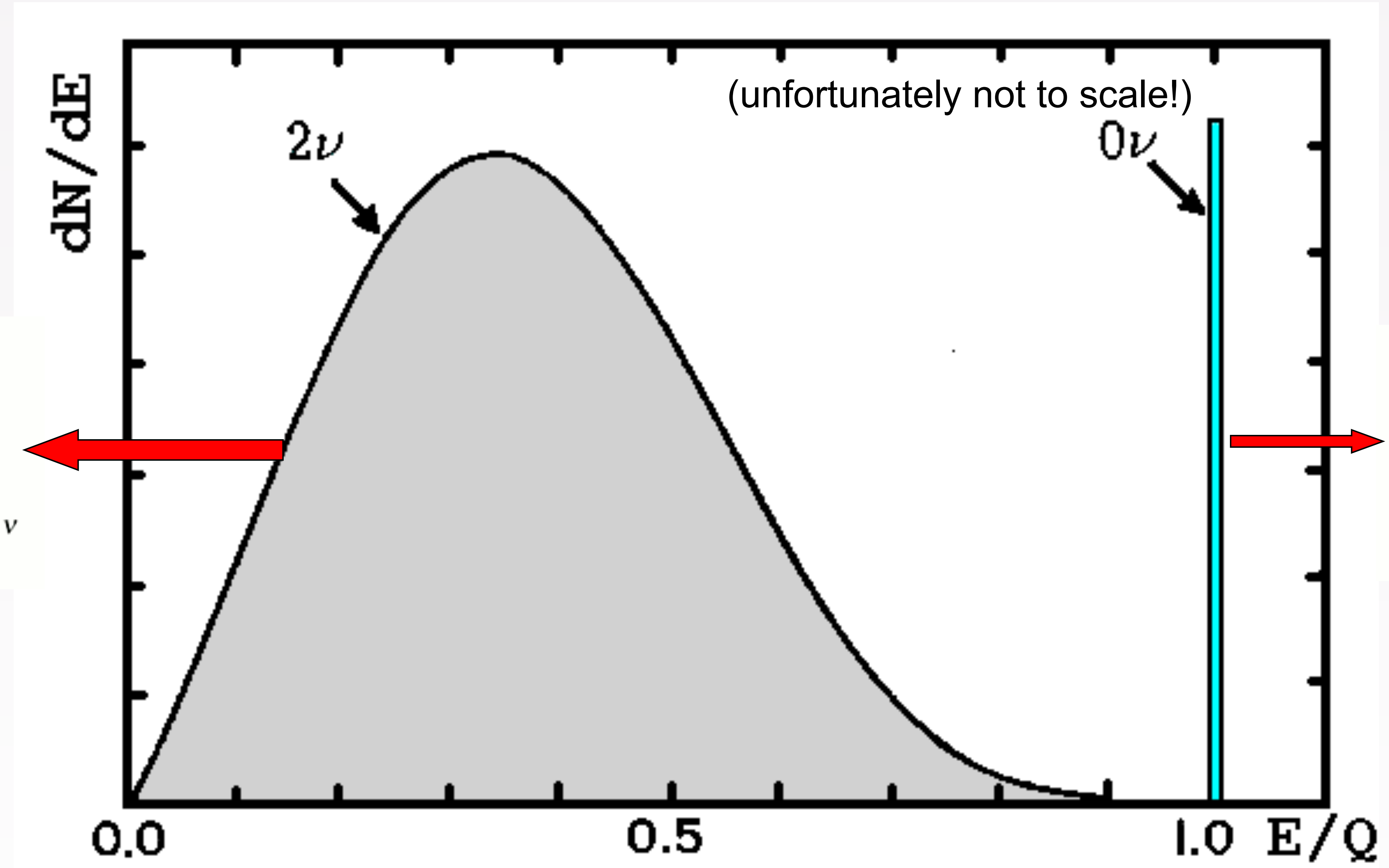
Isotope	Nat. Abundance (%)	$Q_{\beta\beta}$ (MeV)
Ca48	0.187	4.274
Ge76	7.8	2.039
Se82	9.2	2.996
Zr96	2.8	3.348
Mo100	9.6	3.035
Cd116	7.6	2.809
Te130	34.5	2.530
Xe136	8.9	2.462
Nd150	5.6	3.367

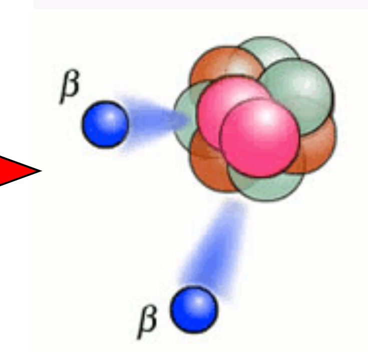
$$\Gamma^{2\nu} = \frac{1}{T_{1/2}^{2\nu}} = G^{2\nu} g_A^4 \left| M^{2\nu} \right|^2$$

- Direct **experimental** access to **NME**
- Possible sensitivity to ***g_A***

Experimental Observables



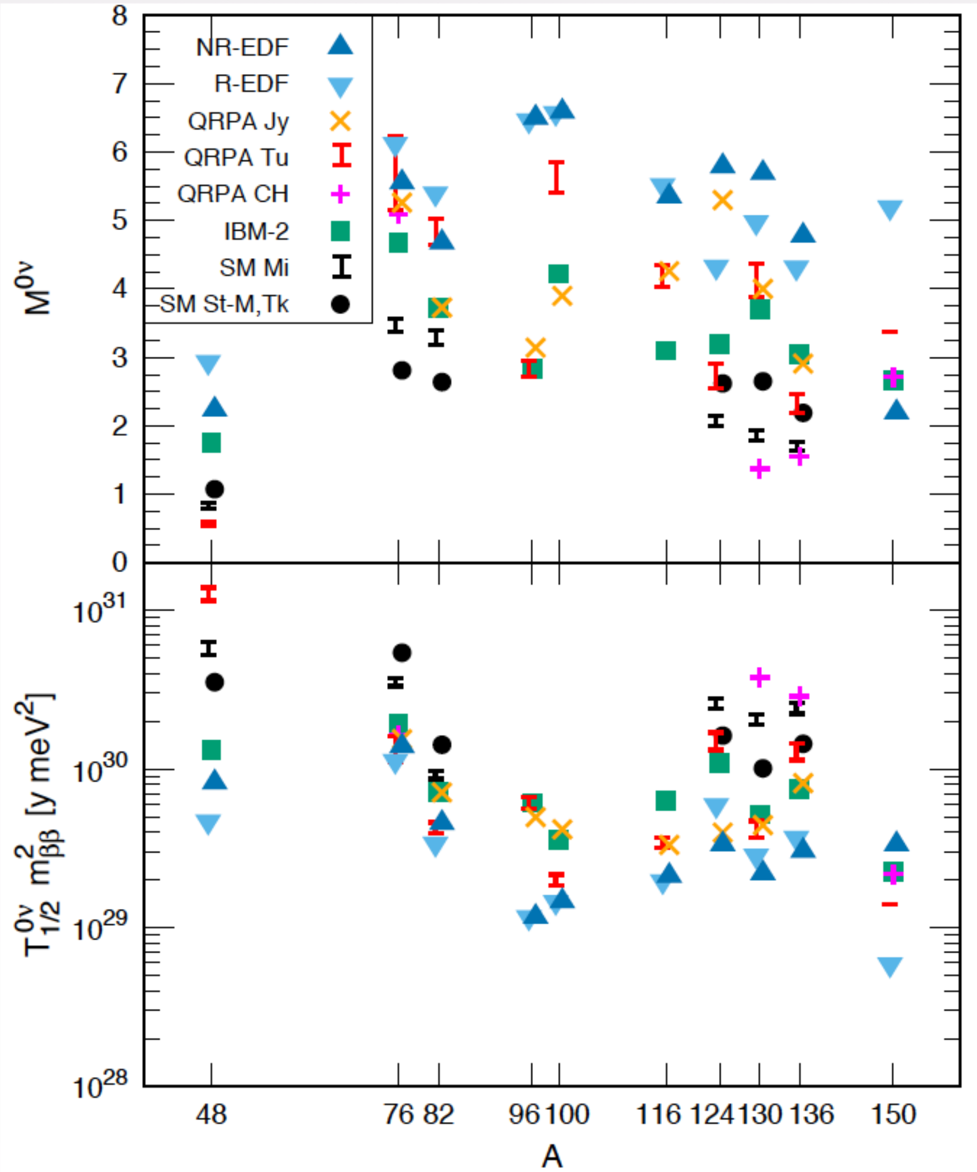


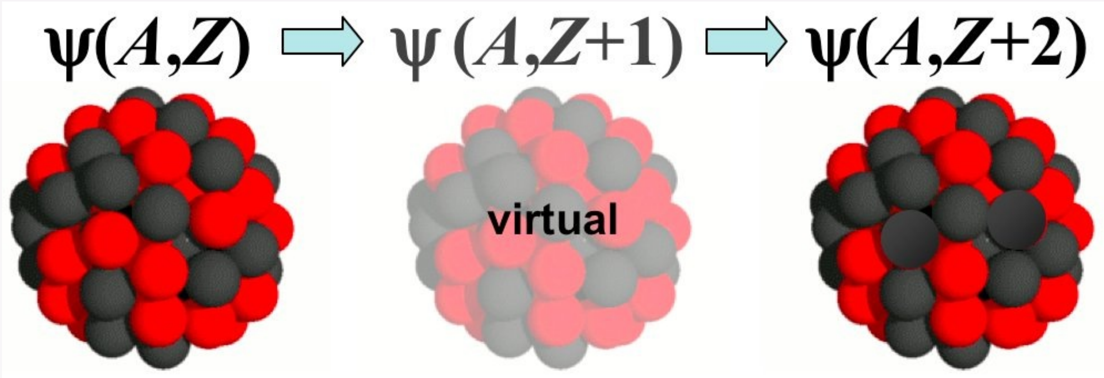


$E_{e1} + E_{e2}$

Also: individual electron energies, Ee1, Ee2, and angle θ between them

(available only from NEMO-3/SuperNEMO)





- Significant effort from different groups and different nuclear models
- ***Question of g_A quenching under study***
- No isotope has clear preference. Choice driven by experimental considerations.
- **Multiple isotope confirmation crucial**
- **Experimental input important**
  - » **2νββ decay**
  - » charge exchange reactions
  - » muon capture

$$\Gamma^{0\nu} = G^{0\nu} g_A^4 \left| M^{0\nu} \right|^2 \langle m \rangle^2$$

g_A could be quenched in nuclear matter

Experimental input from 2νββ (and single-β) possible

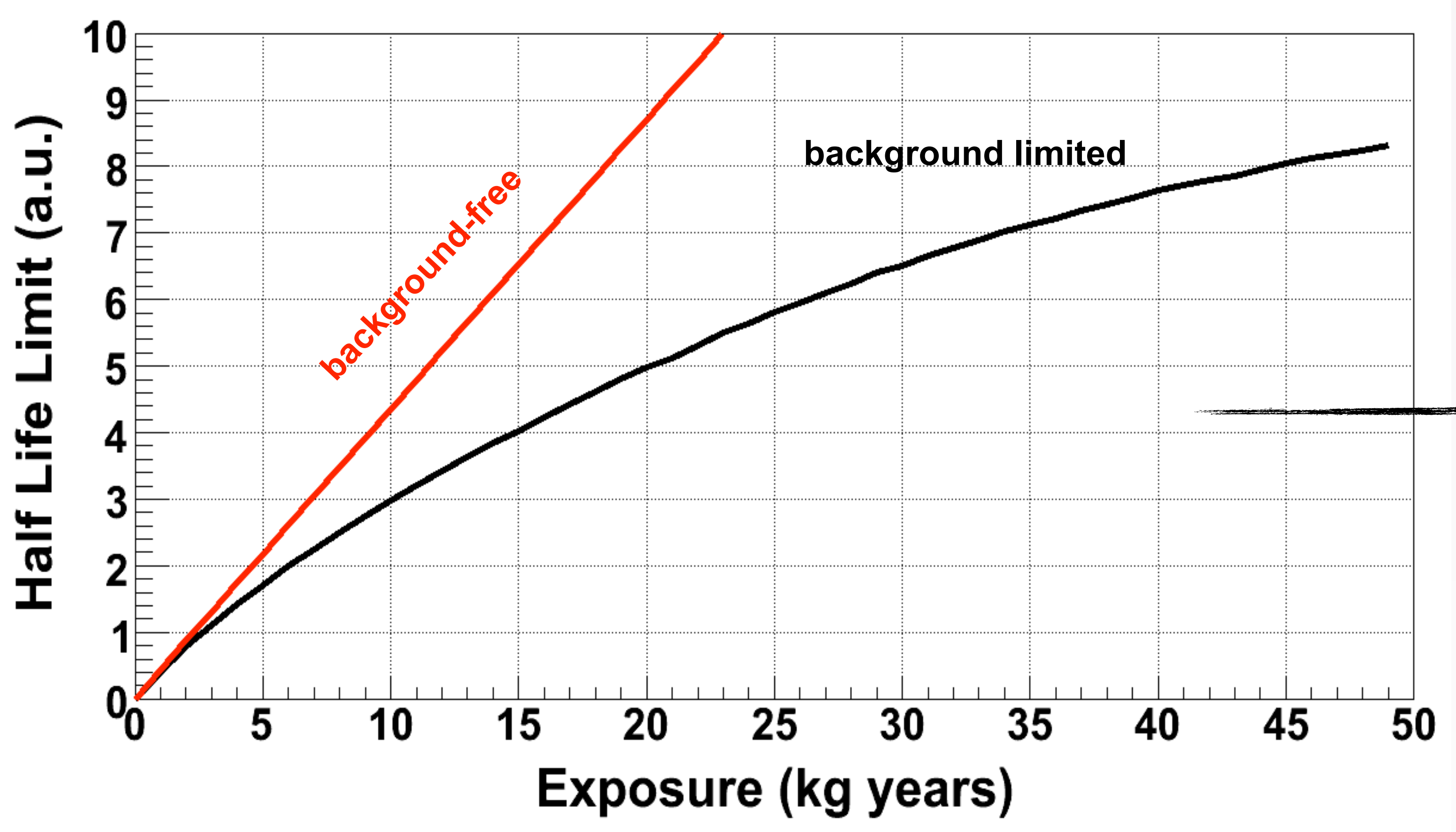
Experimental Sensitivity

maximise efficiency & isotope abundance

maximise exposure = mass (isotope) × time

$$T^{0\nu}_{1/2}(90\%\ \mathrm{C.L.}) = 2.54\times10^{26}\,\mathrm{y}\left(\frac{\varepsilon\times a}{W}\right)\sqrt{\frac{M\times t}{b\times\Delta E}}$$

minimise background & energy resolution



ββ is about **background suppression!**

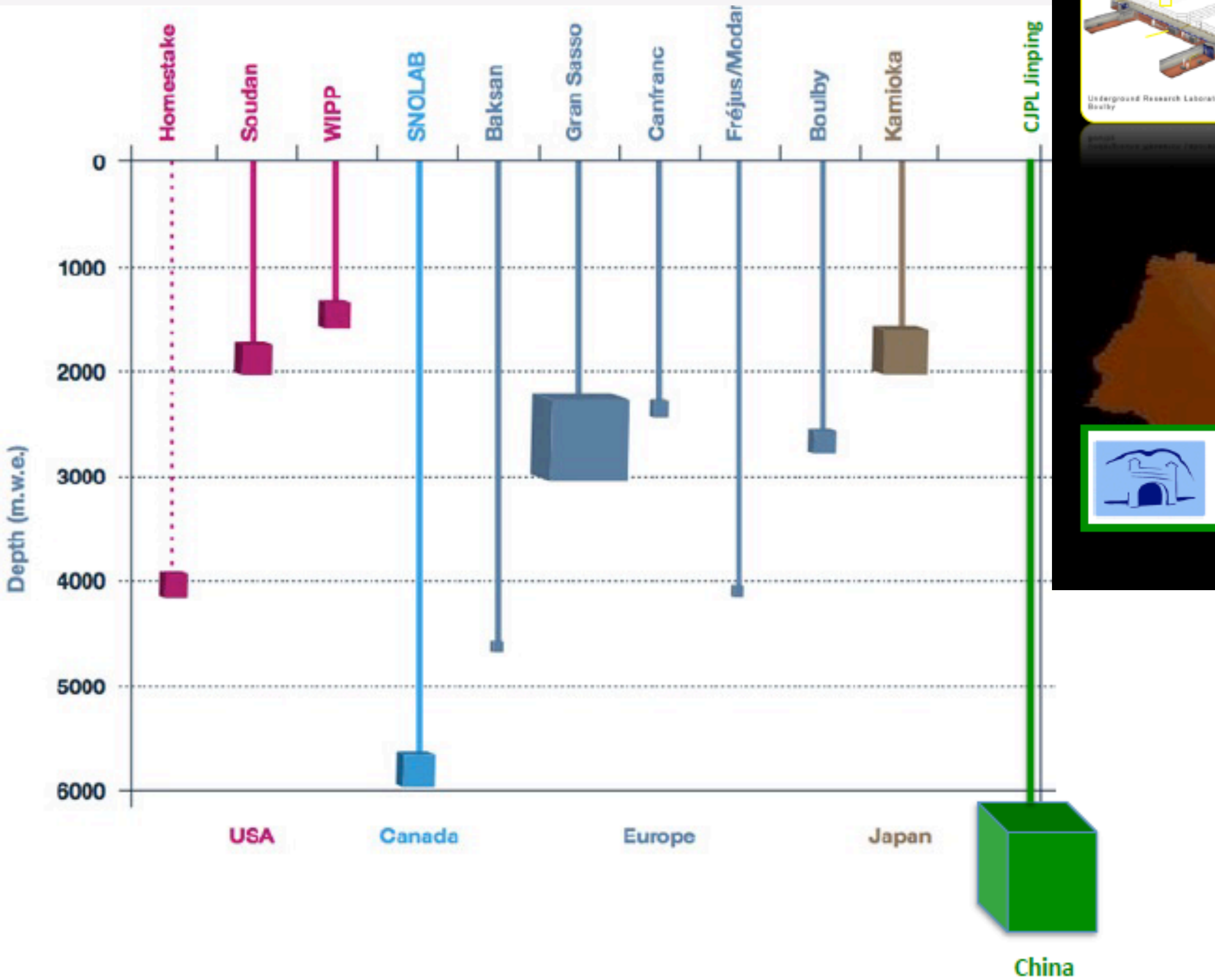
Backgrounds:

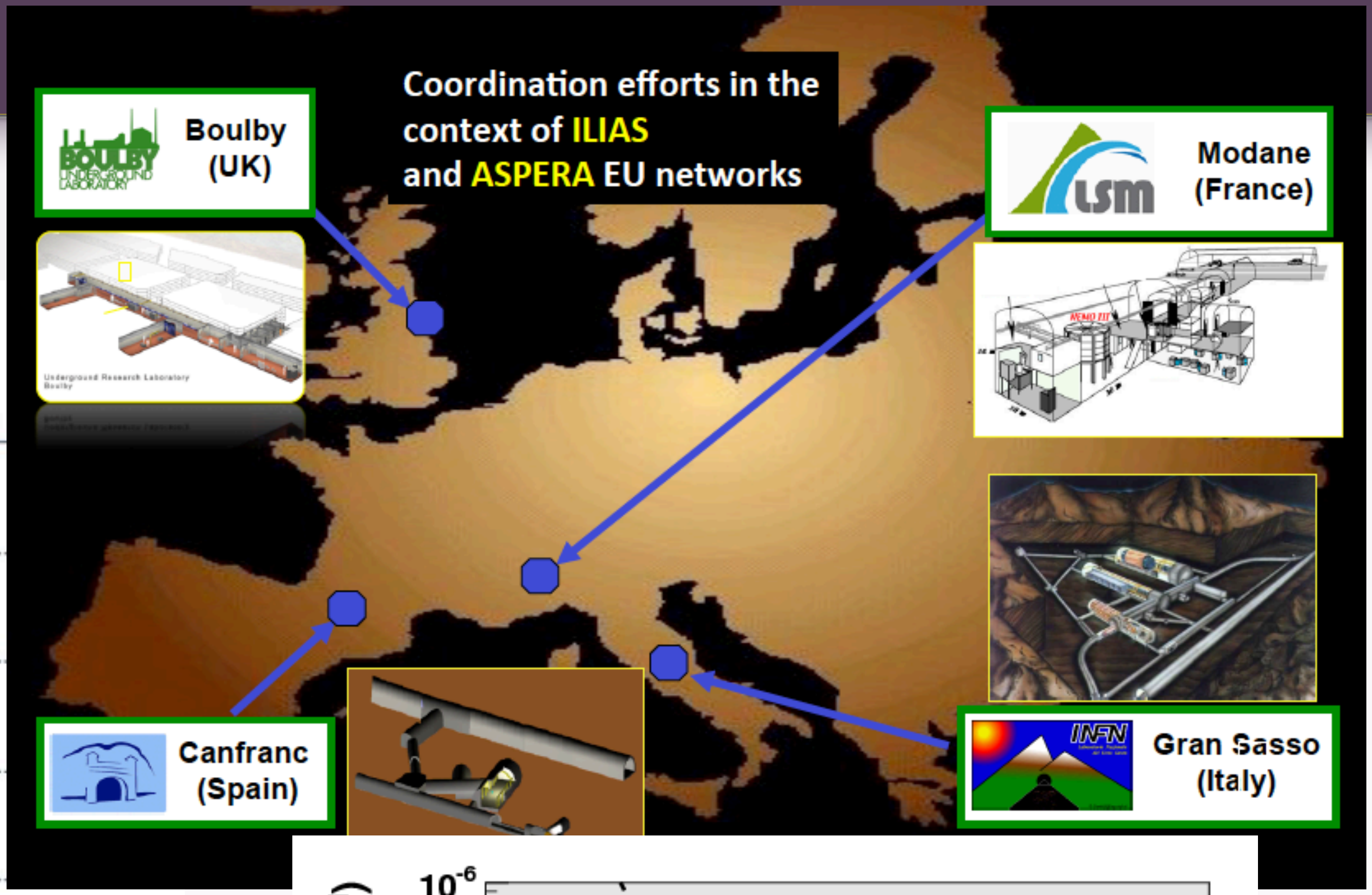
- Cosmic ray muons (**underground lab is a must**)
- **Natural radioactivity** ^{238}U, ^{232}Th, neutrons,…
- **2νββ**

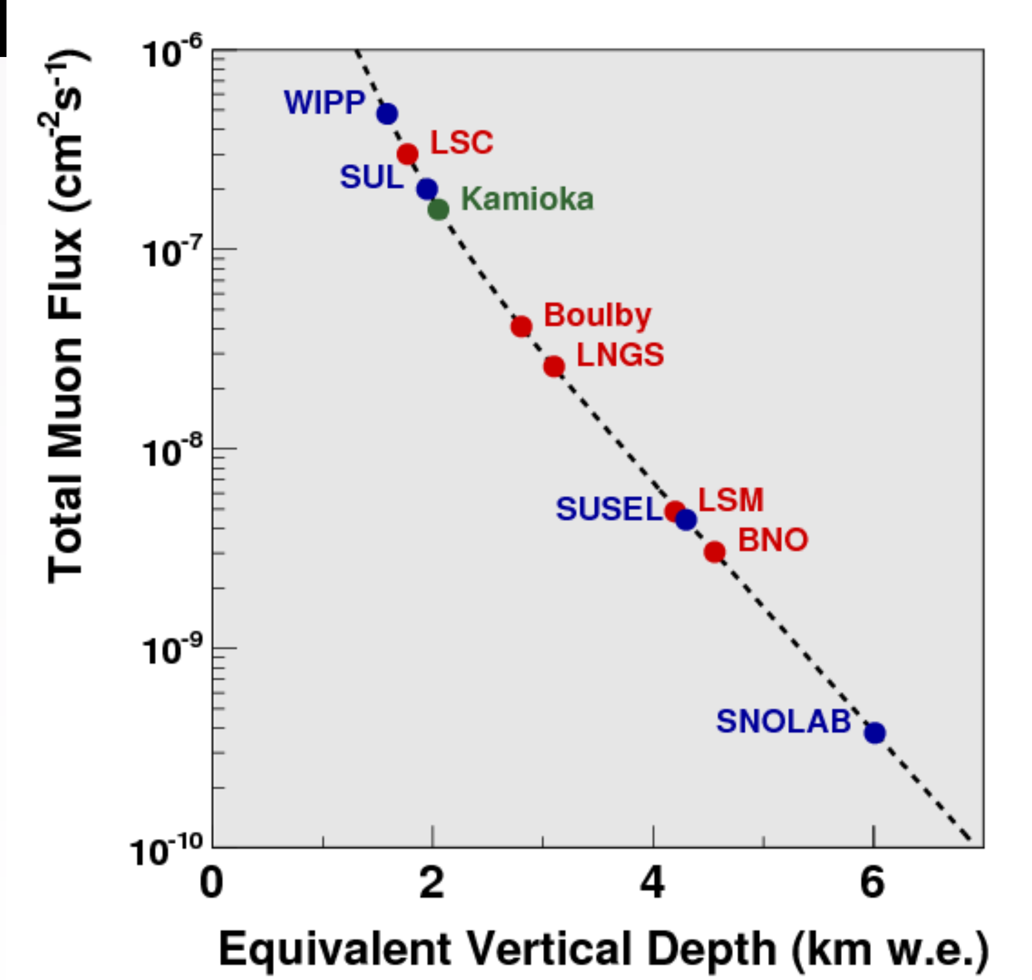
Take Home Message:

$T_{1/2}$~10^{26}yr (<m_ν>~50-100 meV) with 100kg isotope — ~1 event/yr!

- Large isotope mass
- Superior background suppression
- Good energy resolution





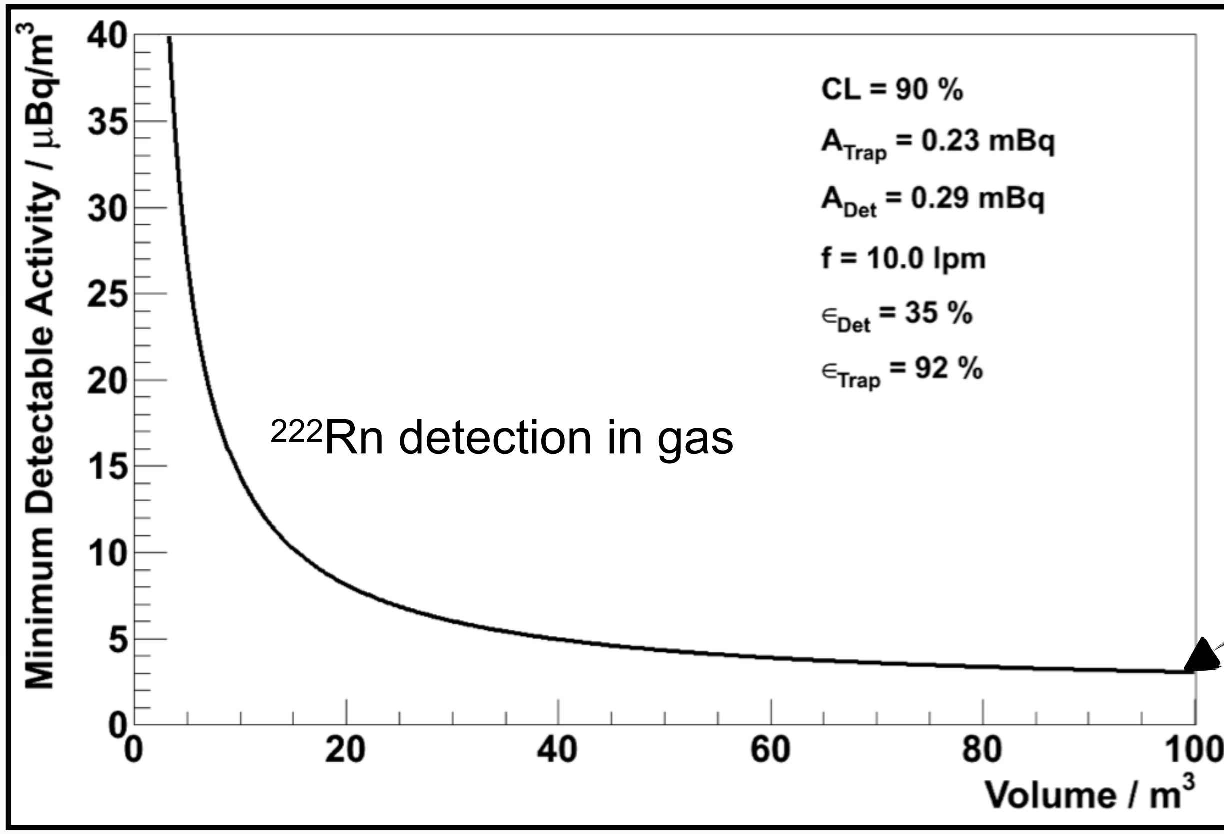


Deep underground lab infrastructure is critically important in planning and running a DBD experiment

Natural Radioactivity Backgrounds

UCL

- Suppress **radioactive backgrounds**, primarily Uranium and Thorium decay chain products which are present in all materials.
  - **$T_{1/2}(^{232}Th, ^{238}U) \sim 10^{10}$ years**
  - **$T_{1/2}(0\nu\beta\beta) > 10^{25}$-$10^{26}$ years**



- Background from $2\nu\beta\beta$: energy **resolution** and **isotope** choice.

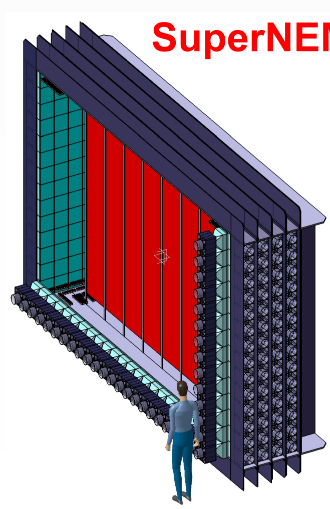
Pushing low-background technology limits

2.4 ^{222}Rn atoms/m^3 of N_2/He/Ar/etc.

or

1 part in 10^{25} !!!

Synergy with Dark Matter experiments



SuperNEMO Demonstrator Module
20 tons

=

1kg of bananas

= $O(100Bq)$

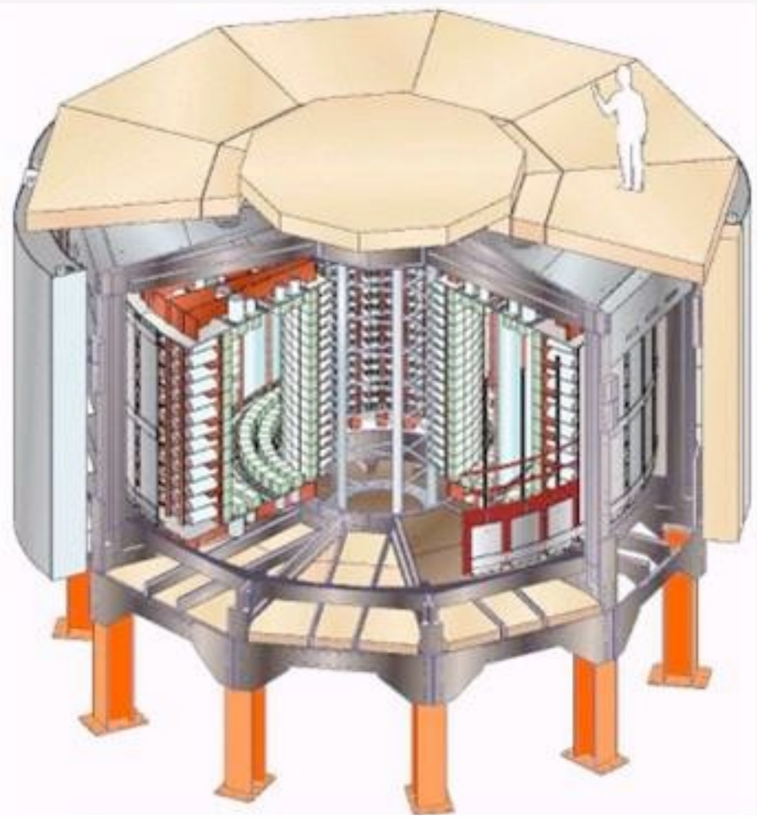
2vbb results, intermediate nuclear states and g_A

Best results from $2\nu\beta\beta$

Isotope	$T_{1/2}$ (10^{19} yrs)	Experiment
^{48}Ca	6.4 ± 1.2	NEMO-3
^{76}Ge	192.6 ± 9.4	GERDA
^{82}Se	9.4 ± 0.6	NEMO-3
^{96}Zr	2.35 ± 0.21	NEMO-3
^{100}Mo	0.68 ± 0.05	NEMO-3
^{116}Cd	2.74 ± 0.18	NEMO-3/Aurora
^{130}Te	79 ± 2	CUORE
^{136}Xe	216.5 ± 6.1	EXO-200
^{150}Nd	0.93 ± 0.06	NEMO-3

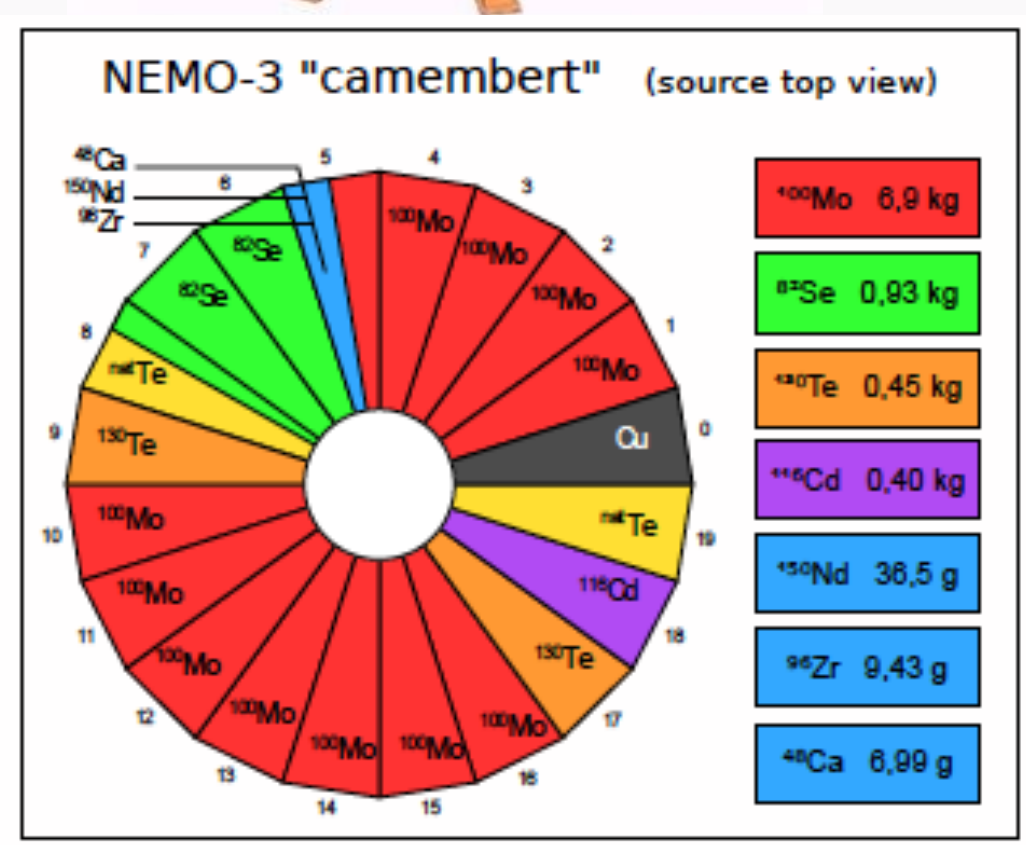
- **Probe nuclear models**
  - **SSD vs HSD**
- **Possible experimental access to g_A**
- Ultimate background characterisation
- Sensitive to exotic new physics
  - (LNV with Majoron, Lorentz violation, boson neutrinos, G_F variation etc)

NEMO-3 - 20 sectors with ~10 kg of isotopes



Data taking 2003-2011
at LSM, Frejus tunnel

25G B-field
Passive shielding
+ anti-radon shielding

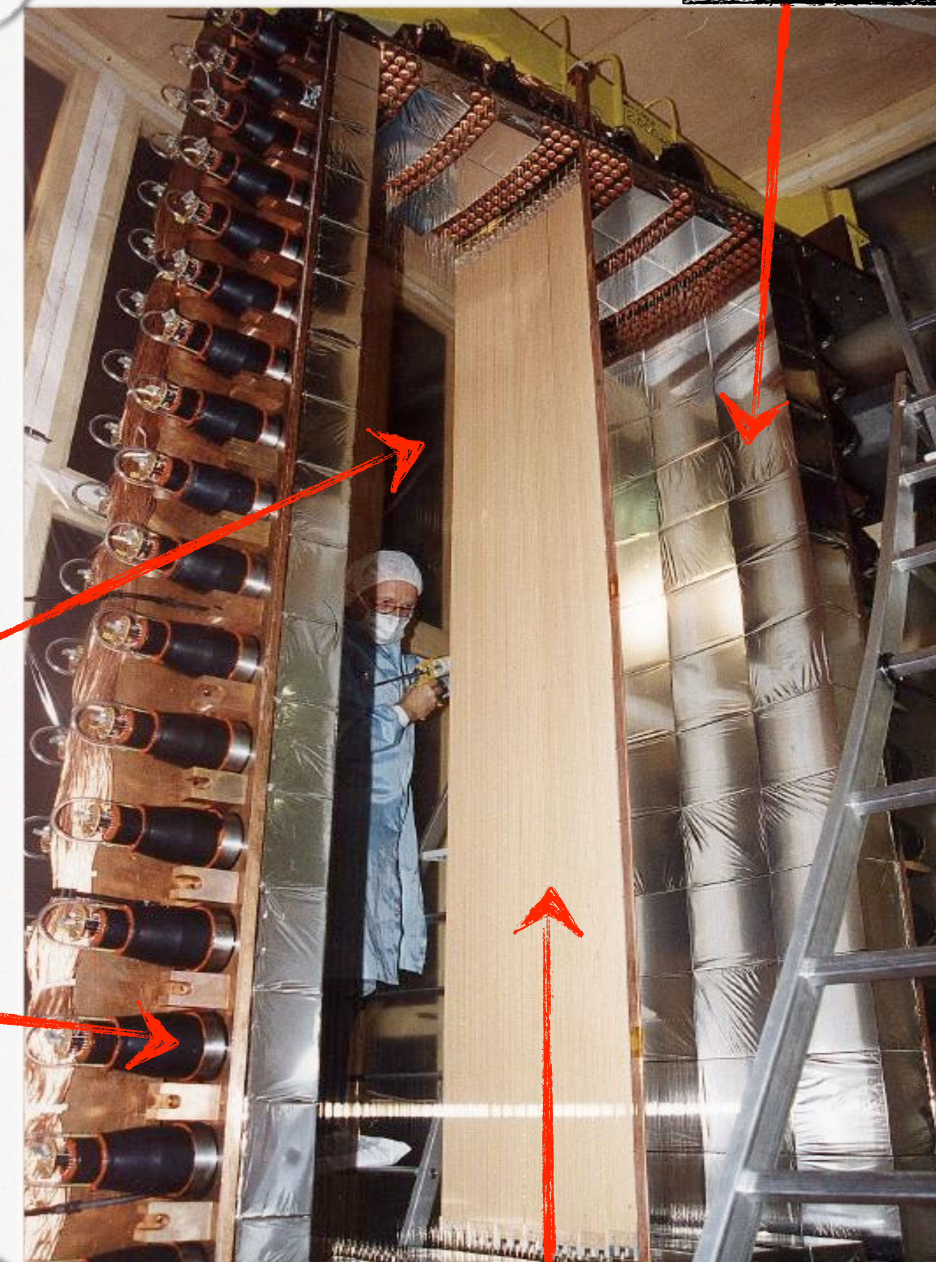


Wire Chamber

95% He + 4% C_2H_6O
+ 1% Ar

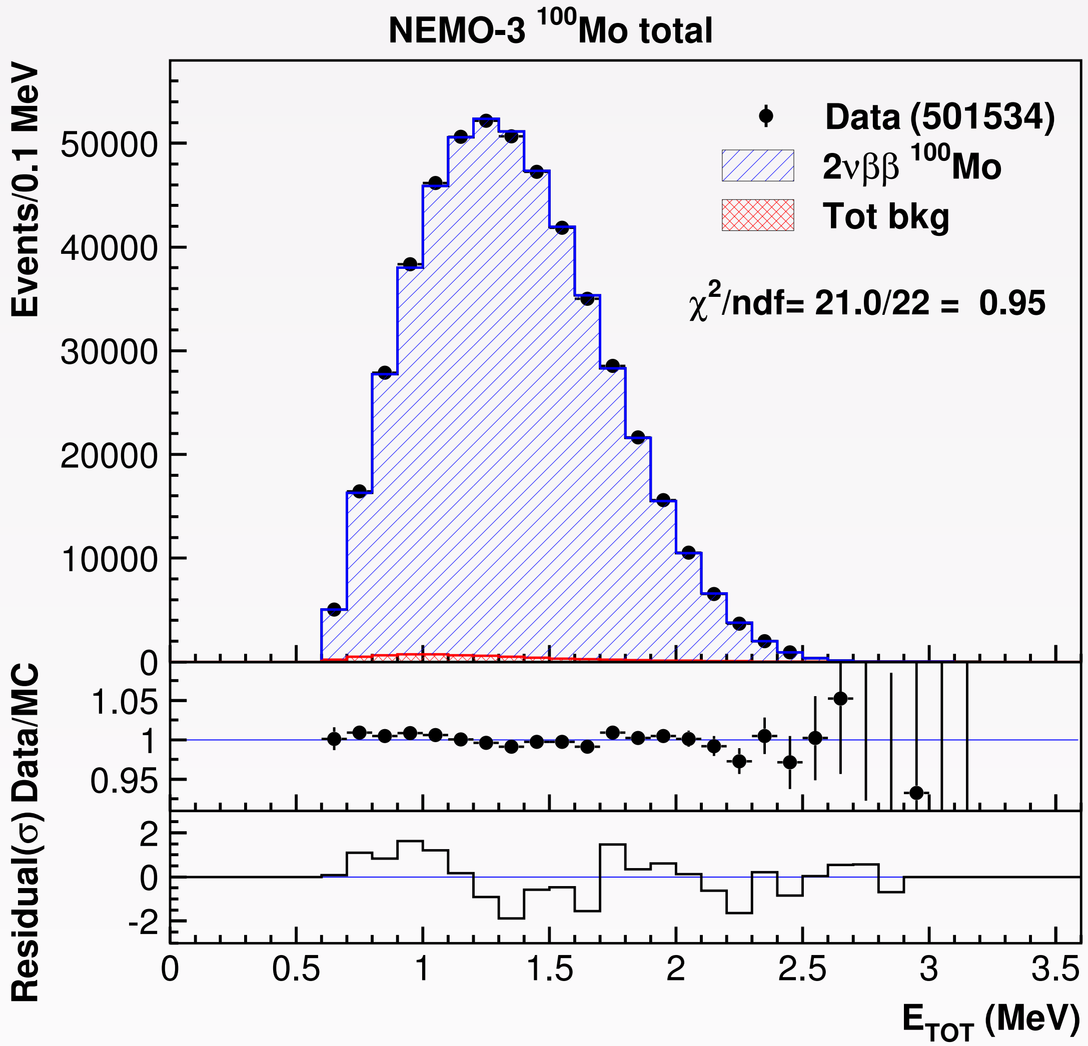
PMTs

Plastic scintillator

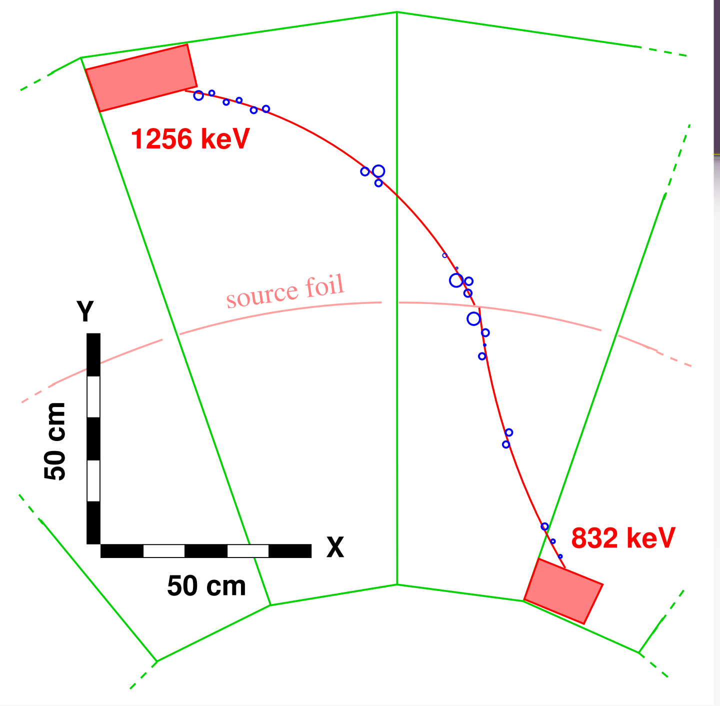


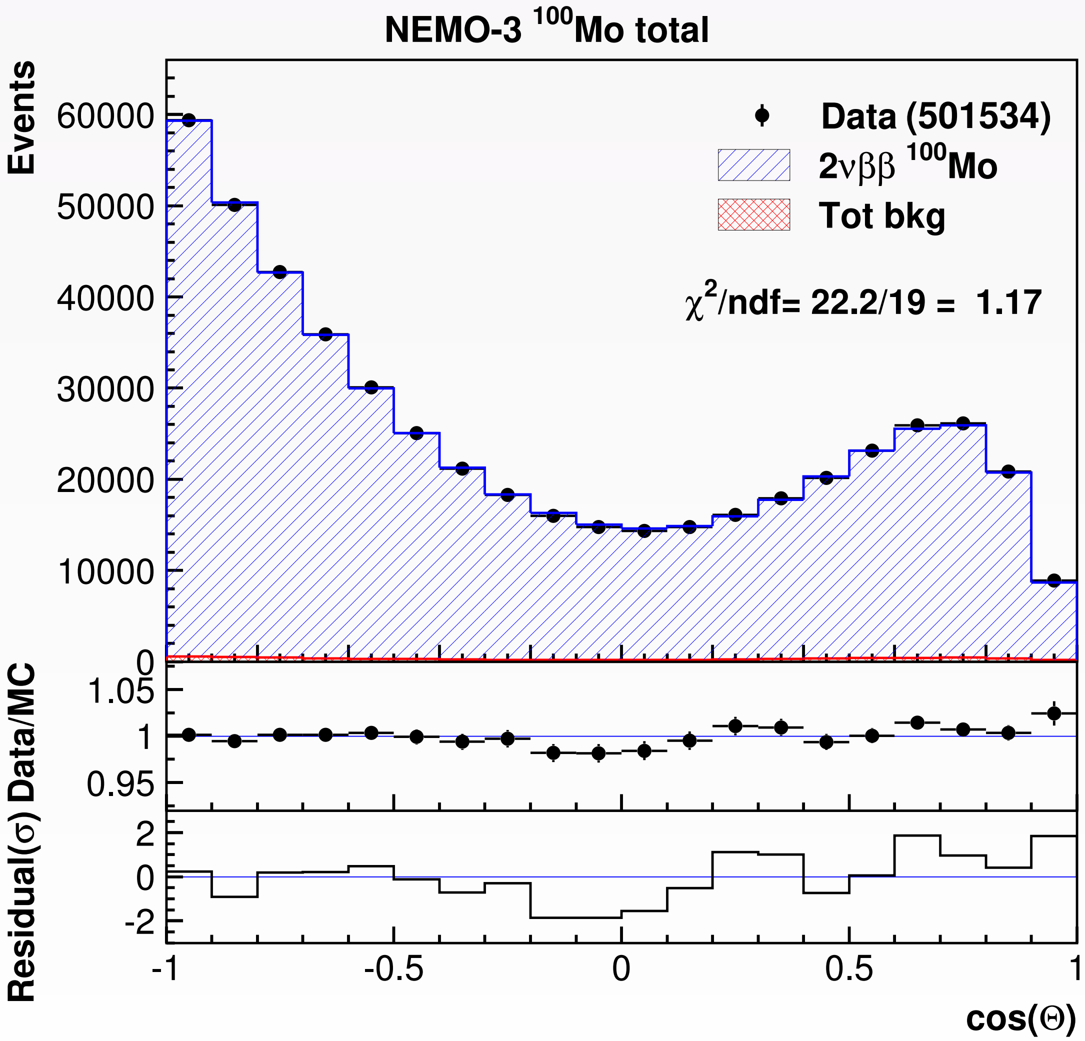
ββ isotope foils

NEMO-3. 2νββ input to NME



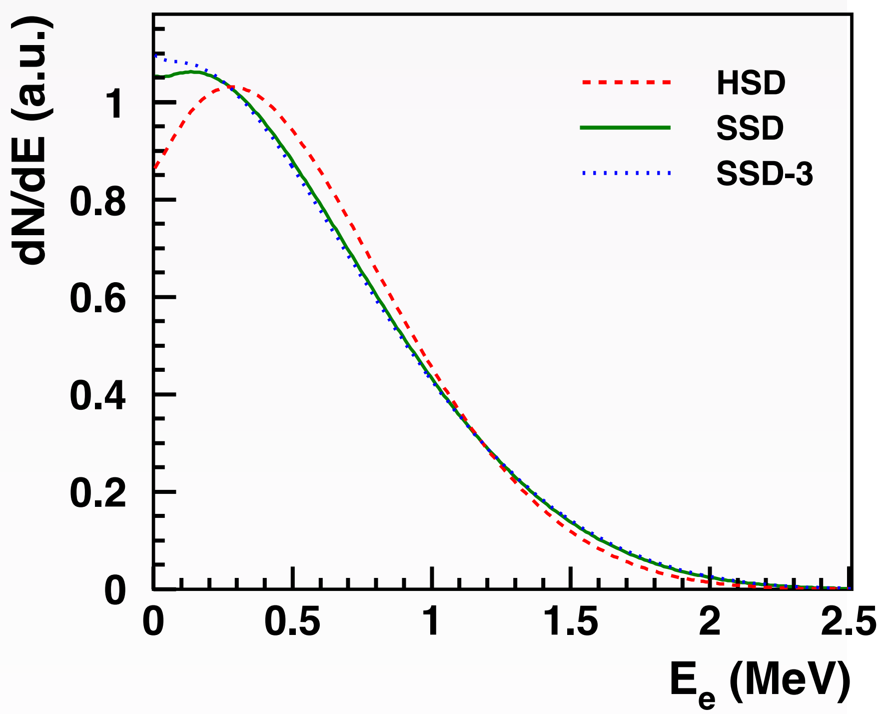
^{100}Mo

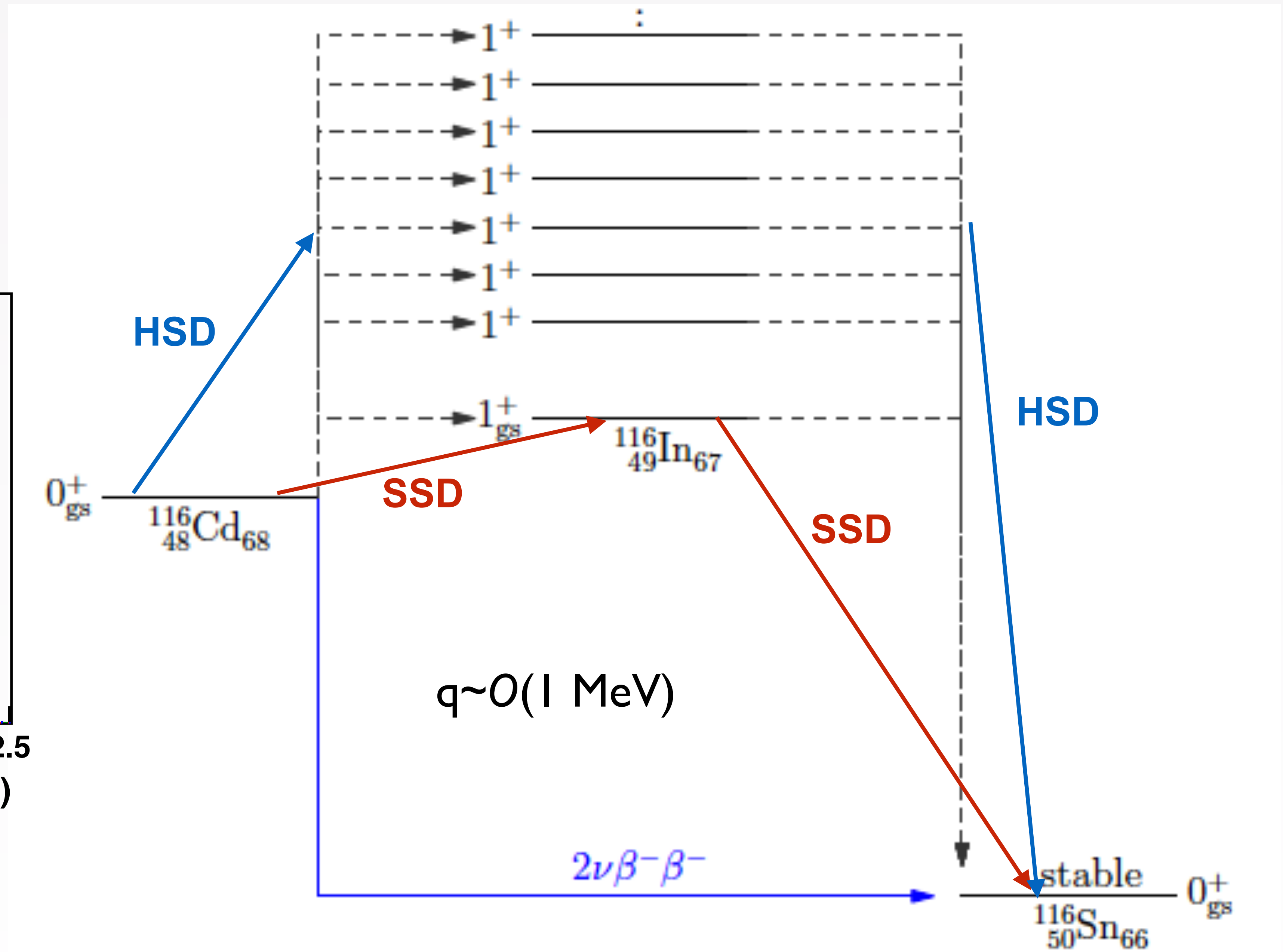




arXiv:1903.08084

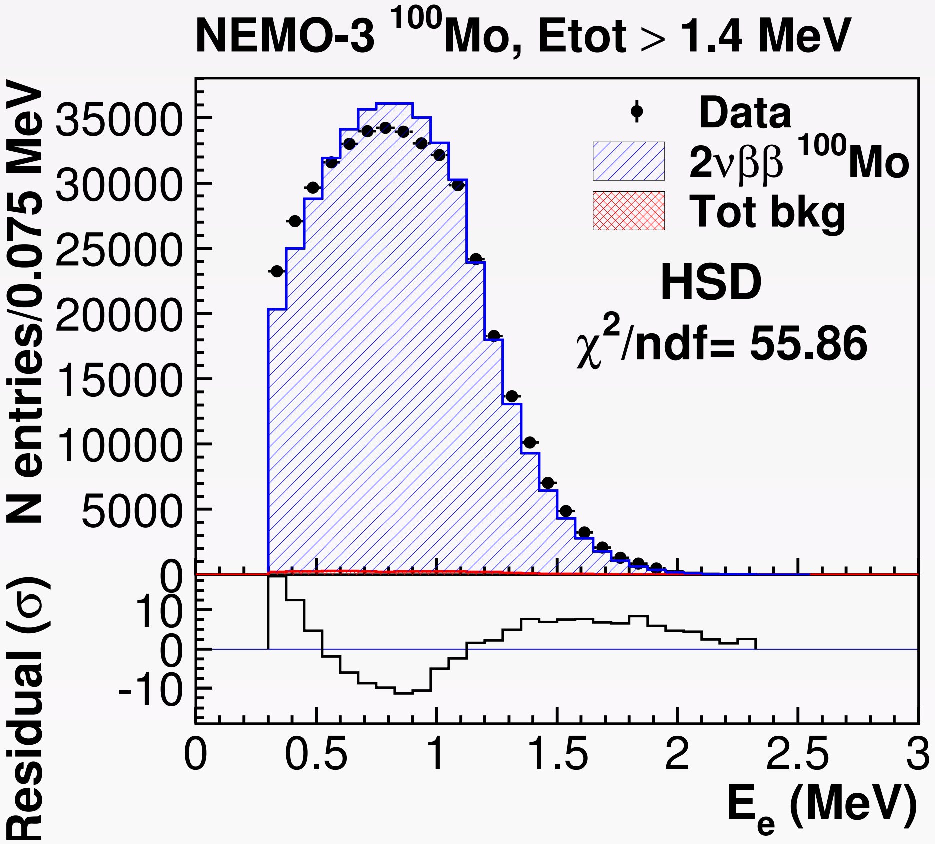
Single State Dominance vs Higher States Dominance

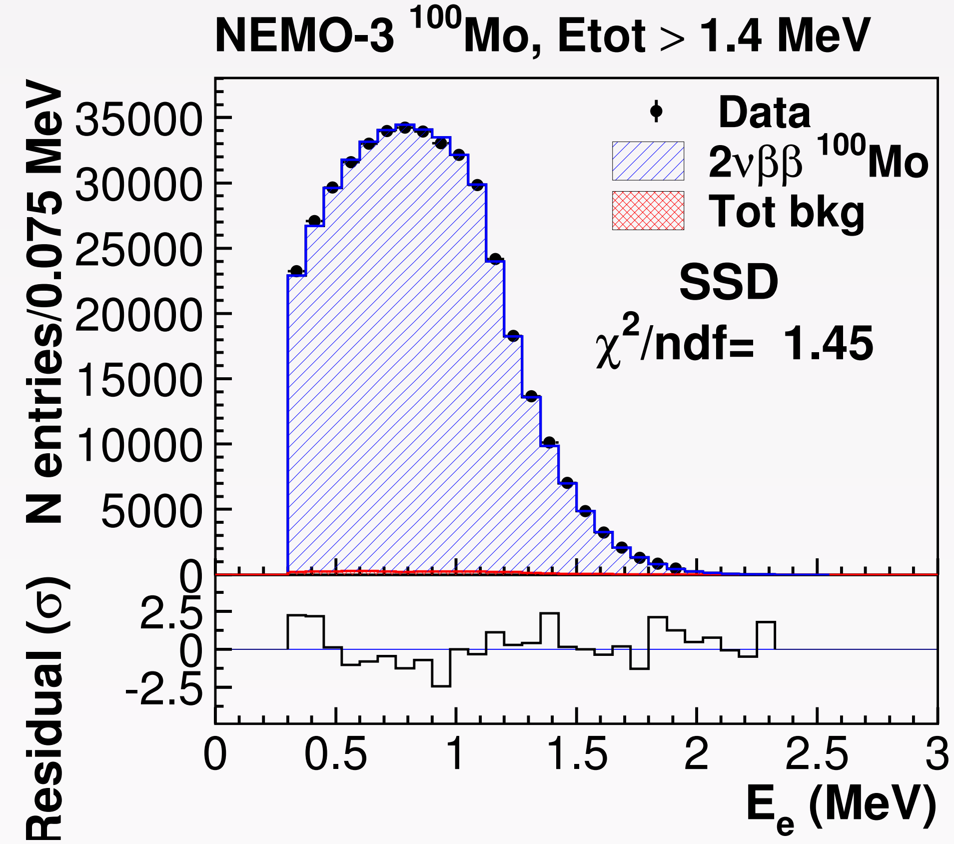


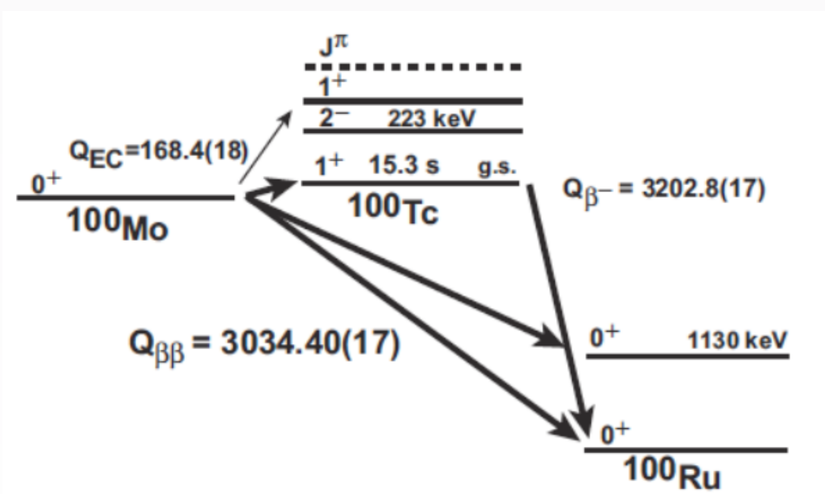


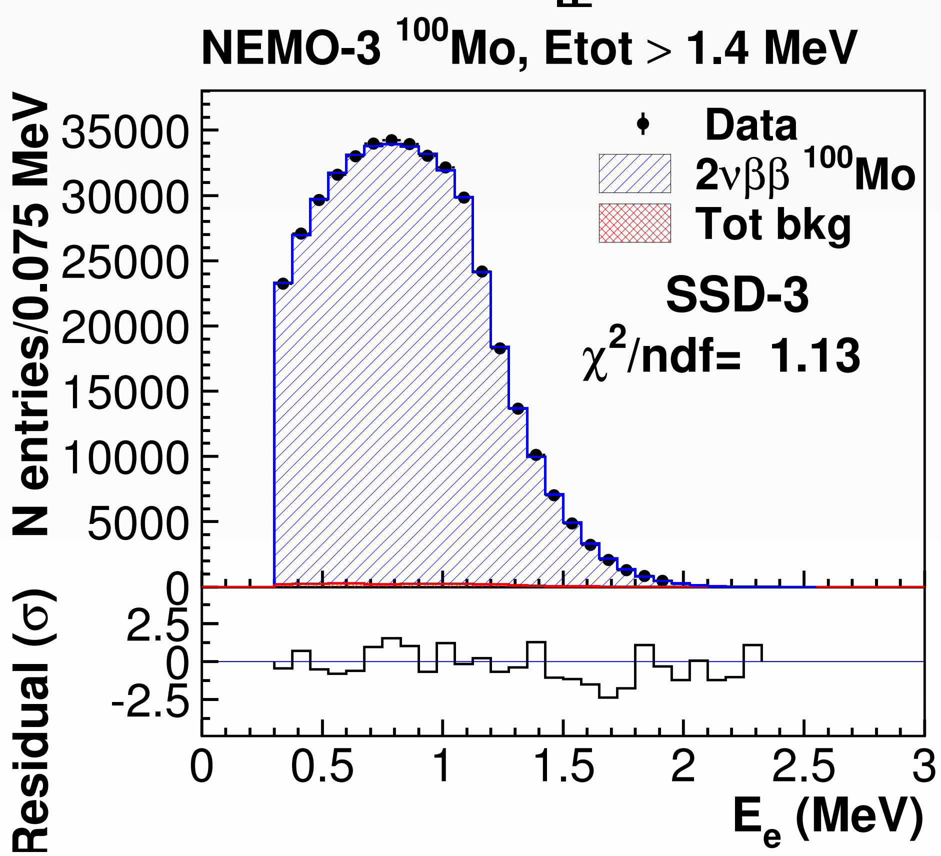
NEMO-3. $2\nu\beta\beta$ input to NME. SSD vs HSD

^{100}Mo









Clear evidence for Single State Dominance

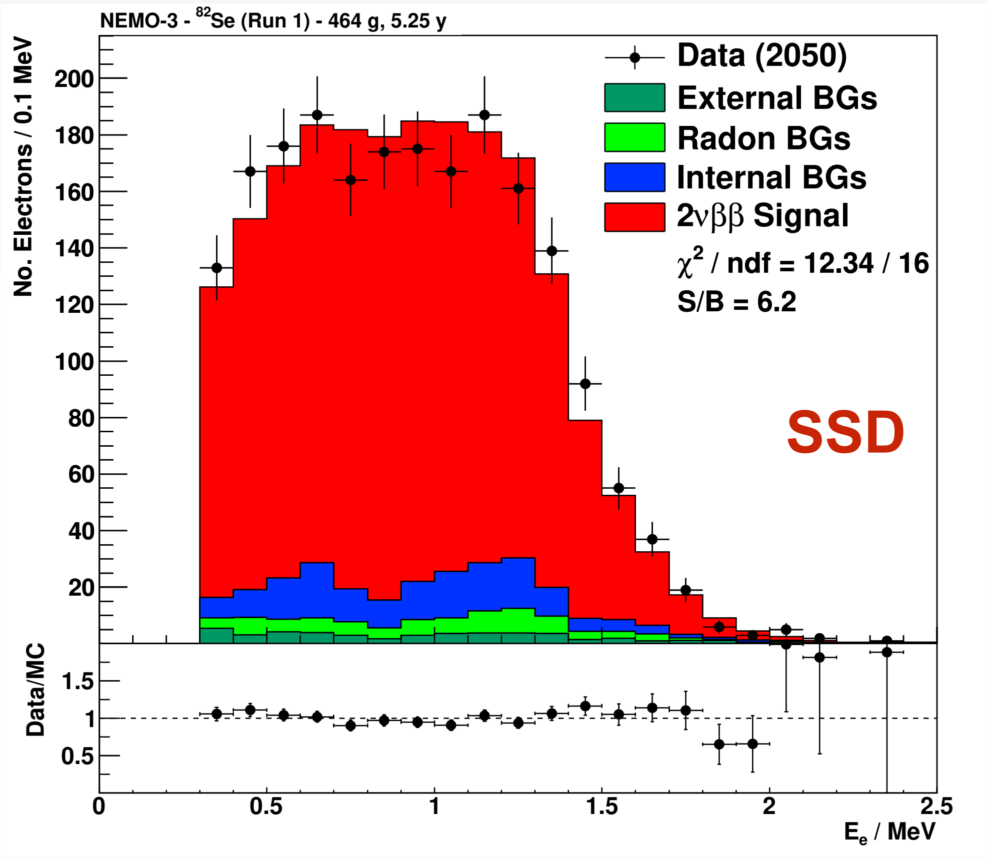
Largest discriminating power in ***single electron energy distributions***

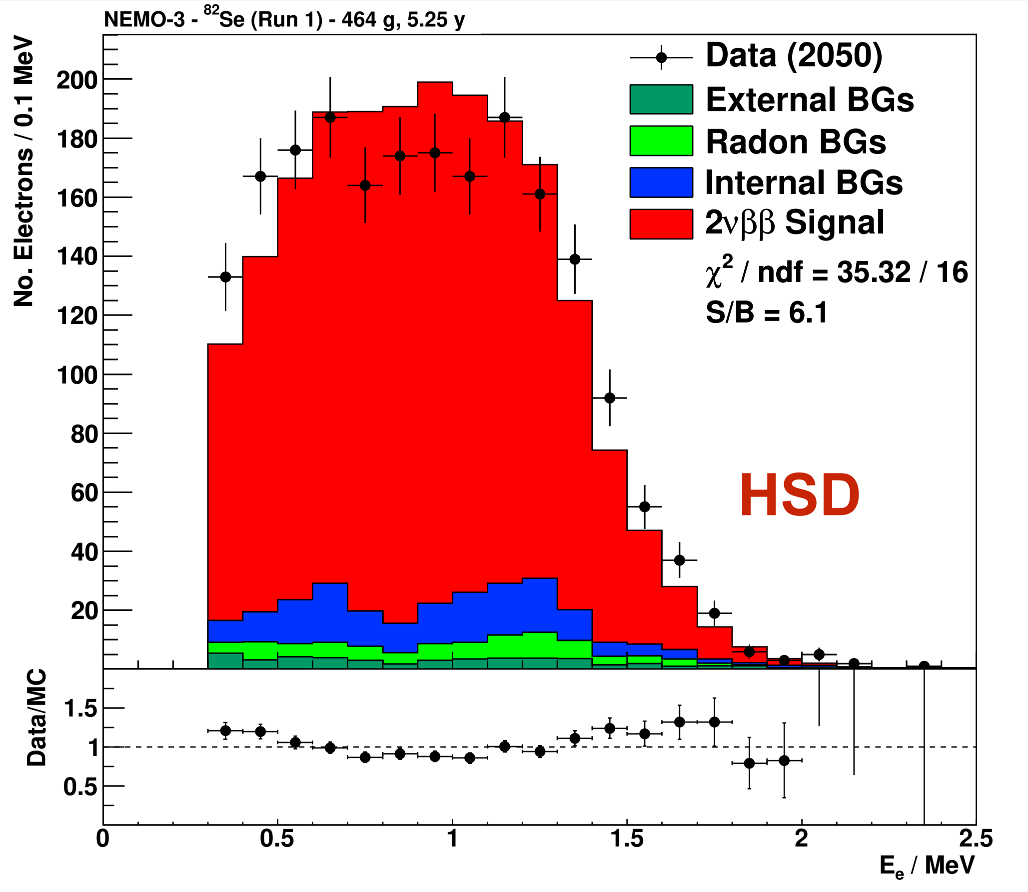
arXiv:1903.08084

NEMO-3. $2\nu\beta\beta$ input to NME. SSD vs HSD

^{82}Se

EPJ C78, 821 (2018)





Unexpectedly, data favour SSD. HSD excluded at 2.1σ

Other indications from charge-exchange reactions : ^{82}Se(^{3}He,^{3}H)^{82}Br
D. Frekers et al., Phys. Rev, C94 014614 (2016)

Largest discriminating power in ***single electron energy distributions***

$$T_{1/2}^{2\nu} = \left[9.39 \pm 0.17(\text{stat}) \pm 0.58(\text{syst})\right] \times 10^{19} \text{ yr}$$ with SSD

c.f. if HSD: $$T_{1/2}^{2\nu} = \left[10.63 \pm 0.19(\text{stat}) \pm 0.66(\text{syst})\right] \times 10^{19} \text{ yr}$$

Reformulate SSD vs HSD in order to extract g_A from $2\nu\beta\beta$?

F.Šimkovic et al. Phys. Rev. C 97, 034315 (2018)

$$\varepsilon_K = (E_{e2} + E_{\nu 2} - E_{e1} - E_{\nu 1})/2$$
$$\varepsilon_L = (E_{e1} + E_{\nu 2} - E_{e2} - E_{\nu 1})/2$$

Usually lepton energies are neglected

$$M_{GT}^{K,L} \simeq M_{GT}^{2\nu} = m_e \sum_n \frac{M_n}{E_n - (E_i + E_f)/2}$$

c.f. full expression

$$M_{GT}^{K,L} = m_e \sum_n M_n \frac{E_n - (E_i + E_f)/2}{[E_n - (E_i + E_f)/2]^2 - \varepsilon_{K,L}^2}$$

$$M_n = \langle 0_f^+ \| \sum_m \tau_m^- \sigma_m \| 1_n^+ \rangle \langle 1_n^+ \| \sum_m \tau_m^- \sigma_m \| 0_i^+ \rangle$$

Include lepton energies by performing Taylor expansion

Then $$[T_{1/2}^{2\nu}]^{-1} = \frac{\Gamma^{2\nu}}{\ln 2} \simeq \frac{\Gamma_0^{2\nu} + \Gamma_2^{2\nu} + \Gamma_4^{2\nu}}{\ln 2}$$

$$\frac{\Gamma_0^{2\nu}}{\ln 2} \simeq (g_A^{eff})^4 M_0 G_0^{2\nu}, \quad \frac{\Gamma_0^{2\nu}}{\ln 2} \simeq (g_A^{eff})^4 M_2 G_2^{2\nu}$$

$$\frac{\Gamma_4^{2\nu}}{\ln 2} \simeq (g_A^{eff})^4 (M_4 G_4^{2\nu} + M_{22} G_{22}^{2\nu})$$

where $M_0 = (M_{GT-1}^{2\nu})^2, \; M_2 = M_{GT-1}^{2\nu} M_{GT-3}^{2\nu}$, etc

$$M_{GT-1}^{2\nu} \equiv M_{GT}^{2\nu}, \quad M_{GT-3}^{2\nu} = \sum_n M_n \frac{4 m_e^3}{[E_n - (E_i + E_f)/2]^3}$$

Keeping only first expansion term

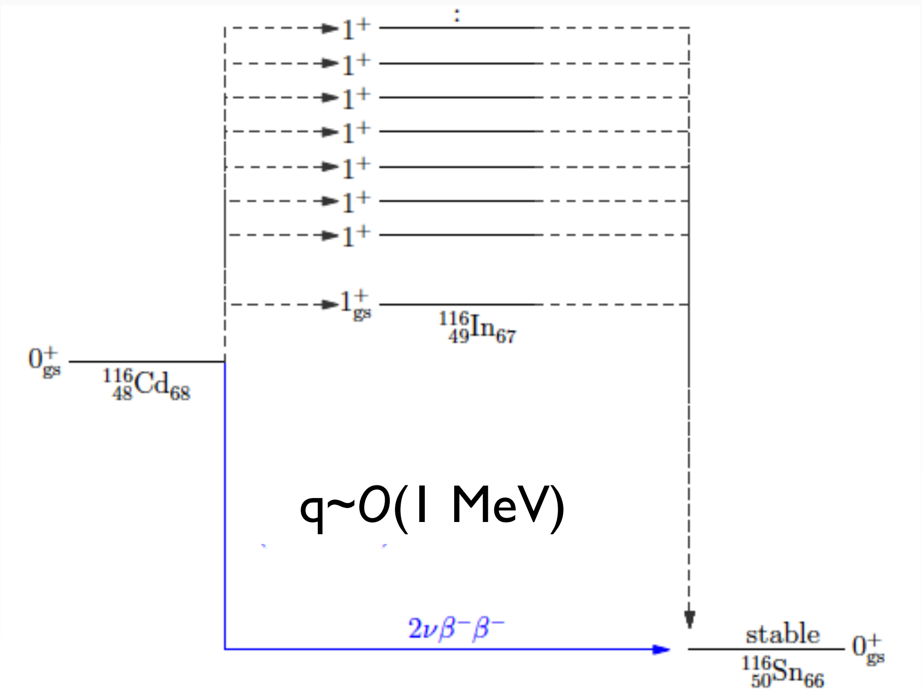
$$[T_{1/2}^{2\nu}]^{-1} \simeq (g_A^{eff})^4 \left(\left| M_{GT-1}^{2\nu} \right|^2 G_0^{2\nu} + M_{GT-1}^{2\nu} M_{GT-3}^{2\nu} G_2^{2\nu} \right)$$

Introducing $\xi_{31}^{2\nu} = \frac{M_{GT-3}^{2\nu}}{M_{GT-1}^{2\nu}}$ the previous

$$[T_{1/2}^{2\nu}]^{-1} \simeq (g_A^{eff})^4 \left(\left| M_{GT-1}^{2\nu} \right|^2 G_0^{2\nu} + M_{GT-1}^{2\nu} M_{GT-3}^{2\nu} G_2^{2\nu} \right)$$

can be rewritten as

$$[T_{1/2}^{2\nu\beta\beta}]^{-1} \simeq (g_A^{eff})^4 \left| M_{GT-3}^{2\nu} \right|^2 \frac{1}{\left| \xi_{31}^{2\nu} \right|^2} \left(G_0^{2\nu} + \xi_{31}^{2\nu} G_2^{2\nu} \right)$$



$\xi_{31}^{2\nu} = \frac{M_{GT-3}^{2\nu}}{M_{GT-1}^{2\nu}}$ is sensitive to contributions from low-lying intermediate states (SSD, SSD+) since

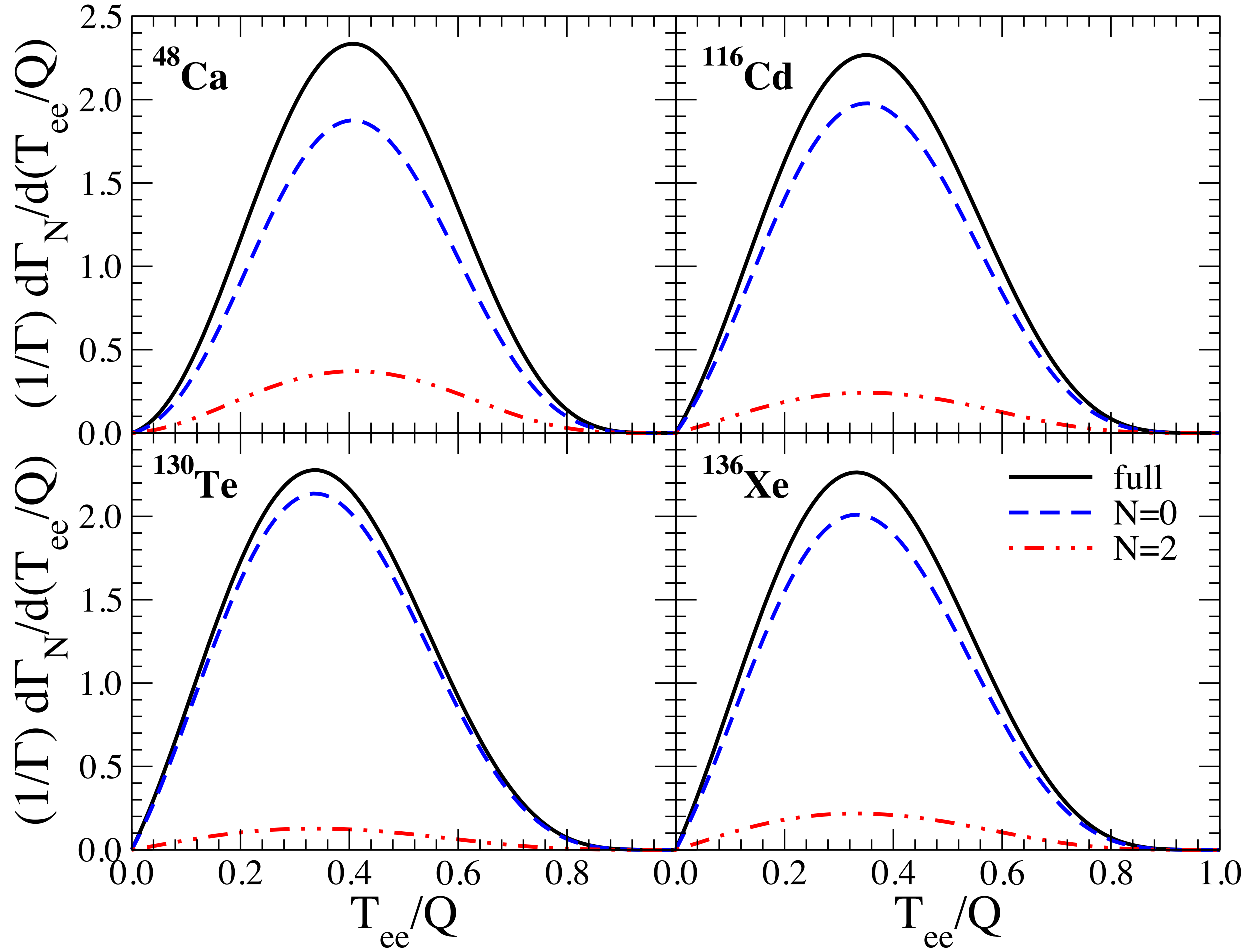
$$M_{GT-3}^{2\nu} = \sum_n M_n \frac{4m_e^3}{[E_n - (E_i + E_f)/2]^3}$$

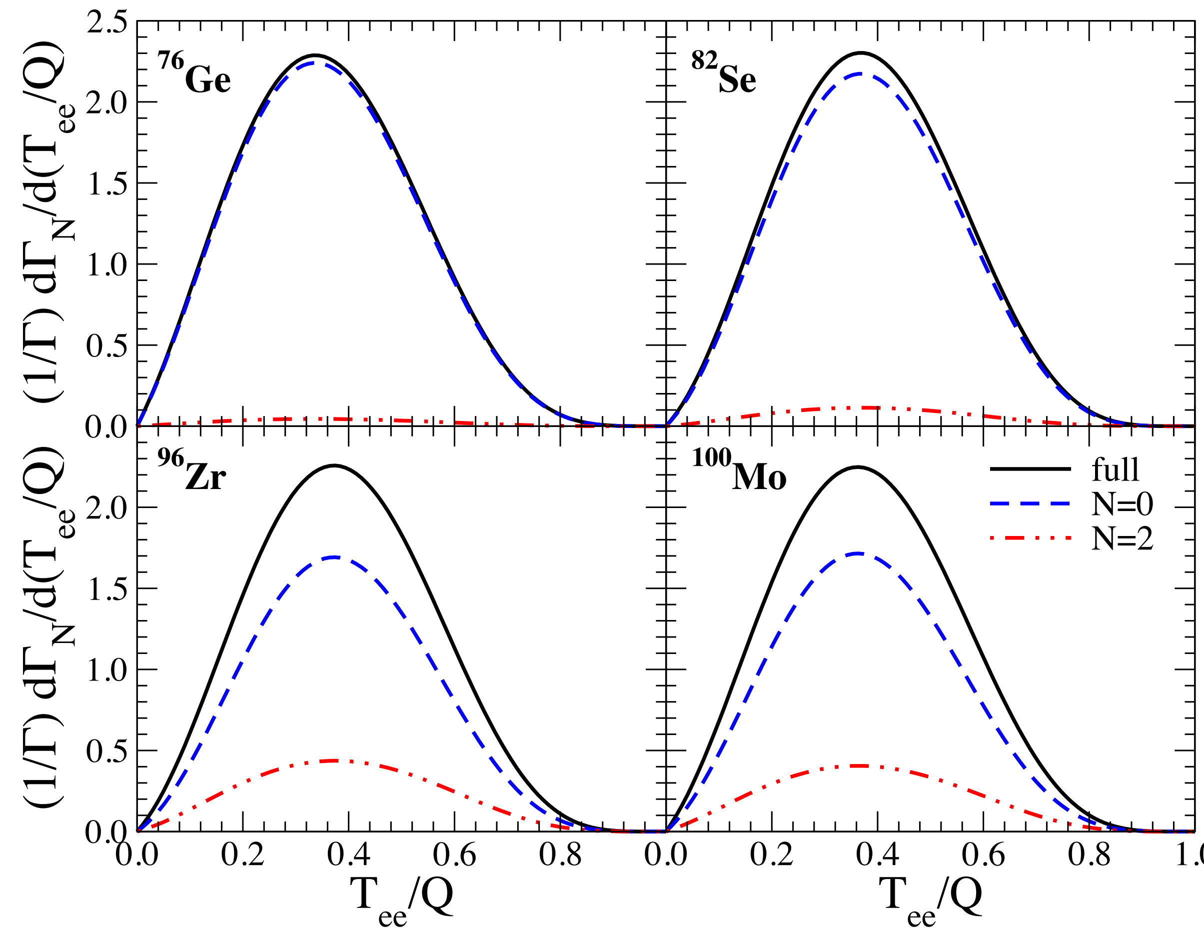
is suppressed for higher states

F.Šimkovic et al. Phys. Rev. C 97, 034315 (2018)

$$\left[T_{1/2}^{2\nu\beta\beta}\right]^{-1} \simeq \left(g_A^{\rm eff}\right)^4 \left|M_{GT-3}^{2\nu}\right|^2 \frac{1}{|\xi_{31}^{2\nu}|^2}\left(G_0^{2\nu} + \xi_{31}^{2\nu} G_2^{2\nu}\right)$$

$$\xi_{31}^{2\nu} = \frac{M_{GT-3}^{2\nu}}{M_{GT-1}^{2\nu}}$$



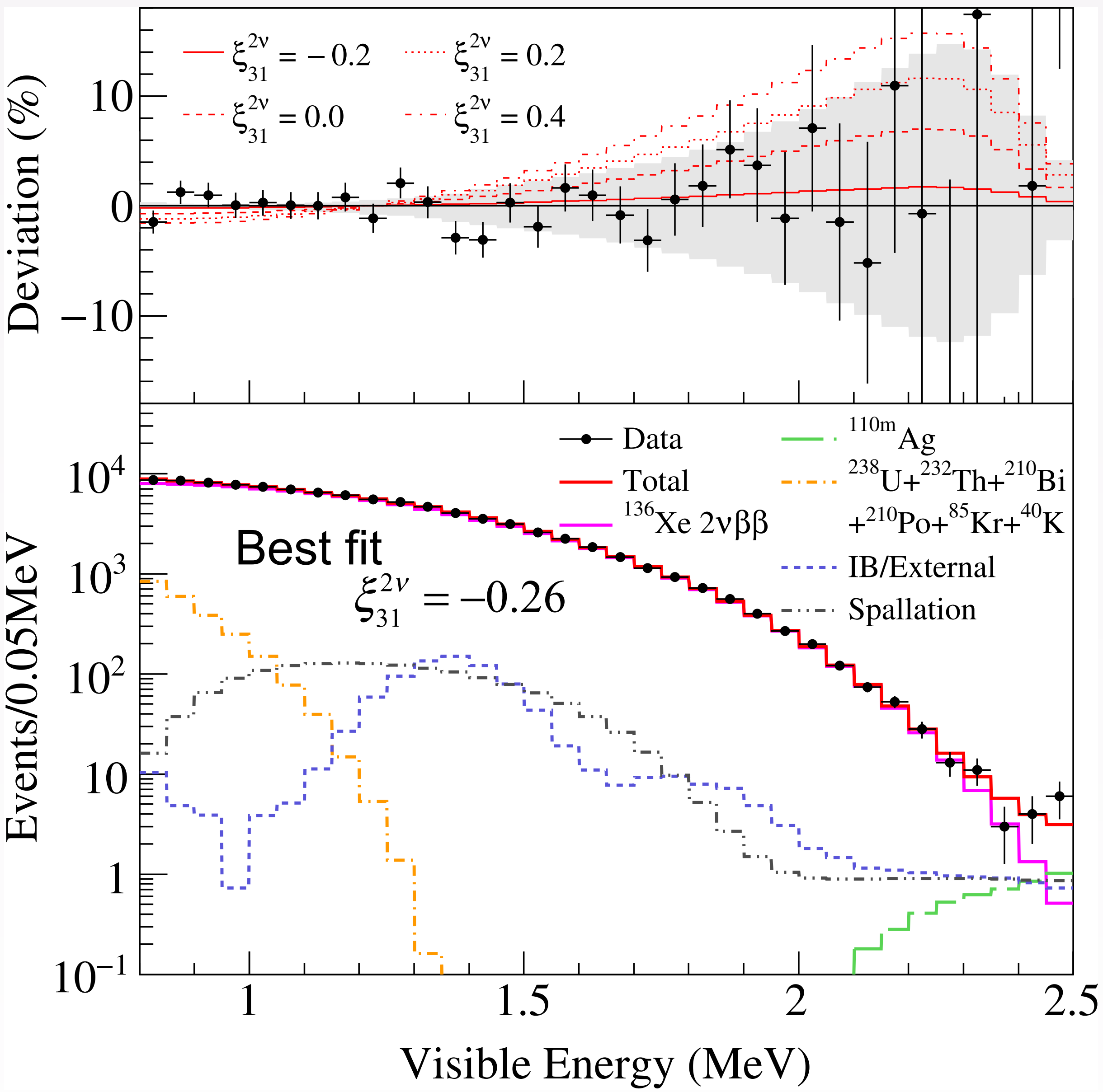


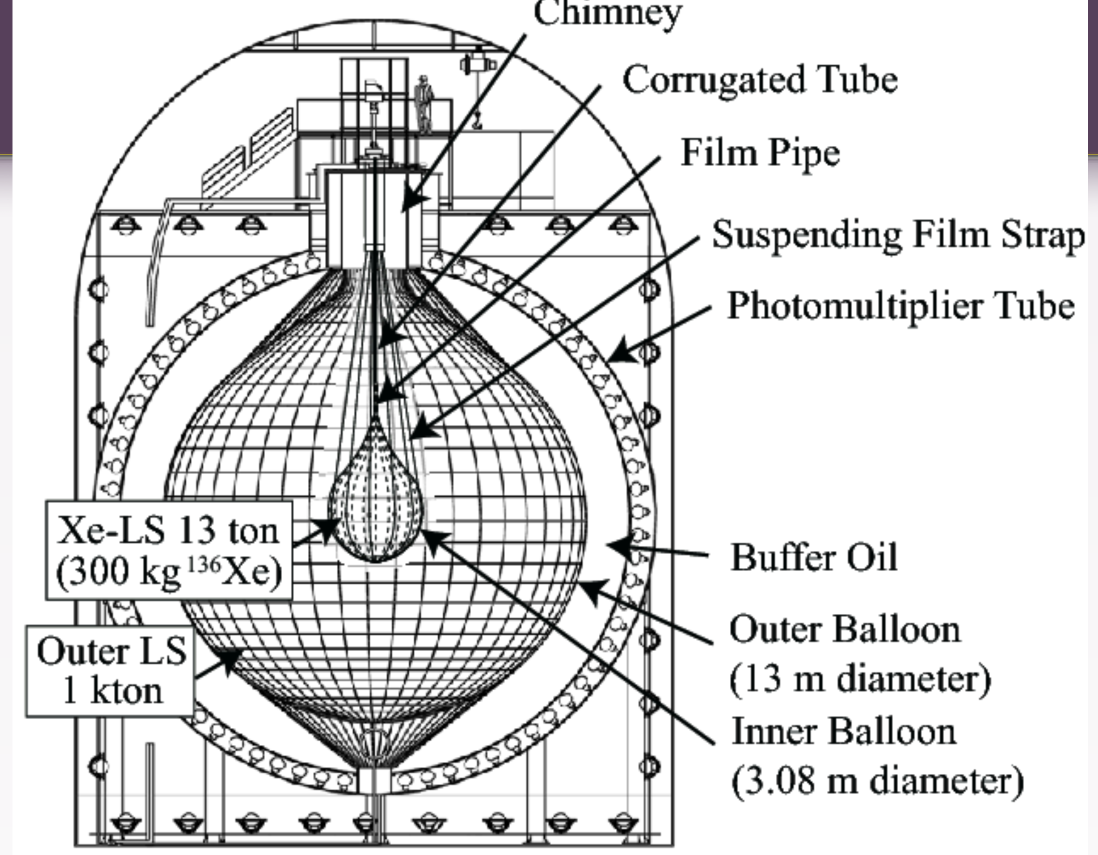
Fit energy spectra of 2νββ electrons to extract $\xi_{31}^{2\nu}$

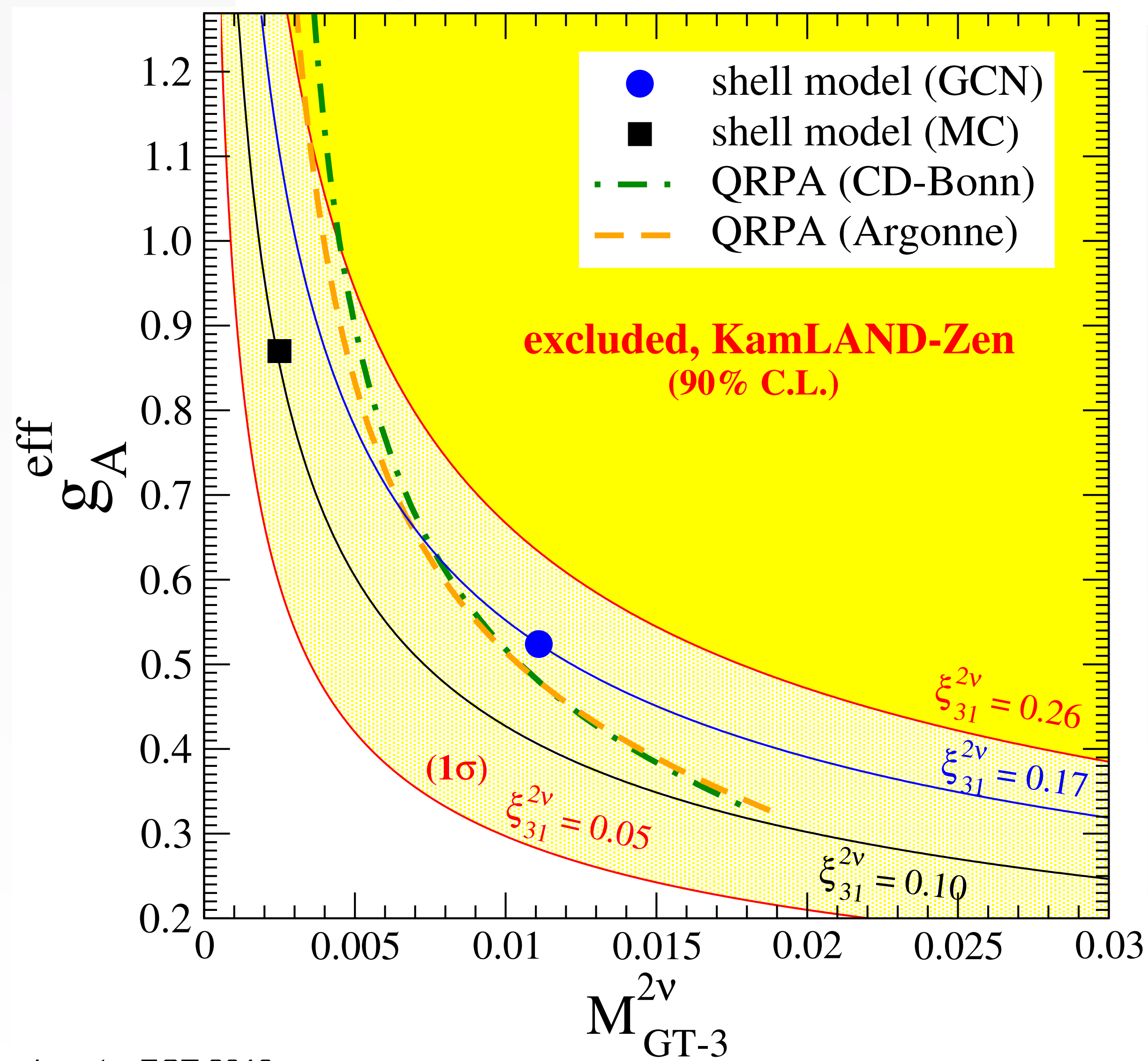
Then use NME calculations and experimental $T_{1/2}(2\nu)$measurement to constraint g_A ($M^{2\nu}$)

KamLAND-Zen

arXiv:1901.03871



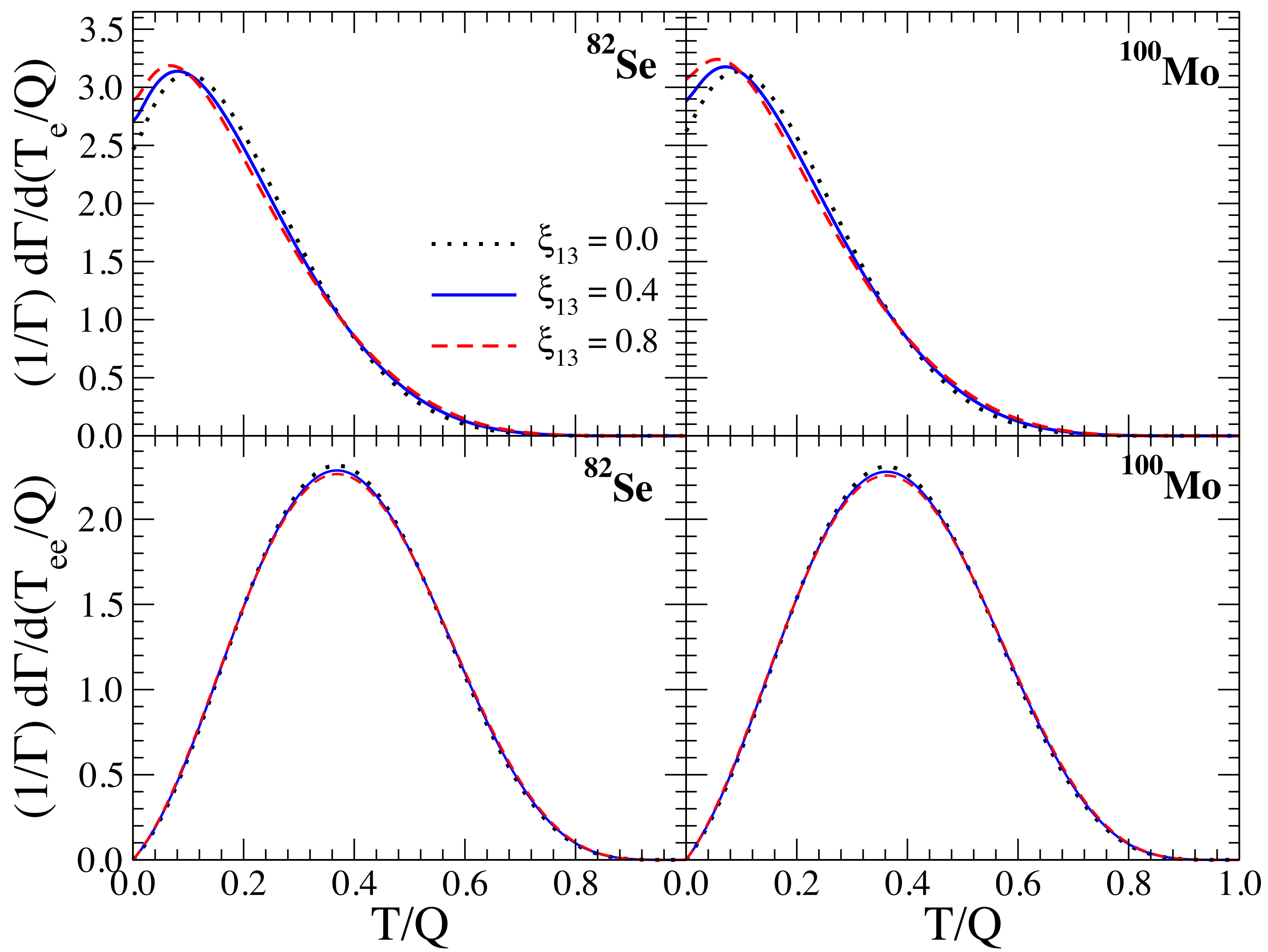




Starts excluding some of NME models

More discriminating power in single electron energy distribution

F.Šimkovic et al. Phys. Rev. C 97, 034315 (2018)



E_1 (or E_2) energy distribution

$E_1 + E_2$ energy distribution

Angular distributions being looked it

NEMO-3/SuperNEMO technique is likely to be most sensitive here

0νββ Results and Next Generation Experiments

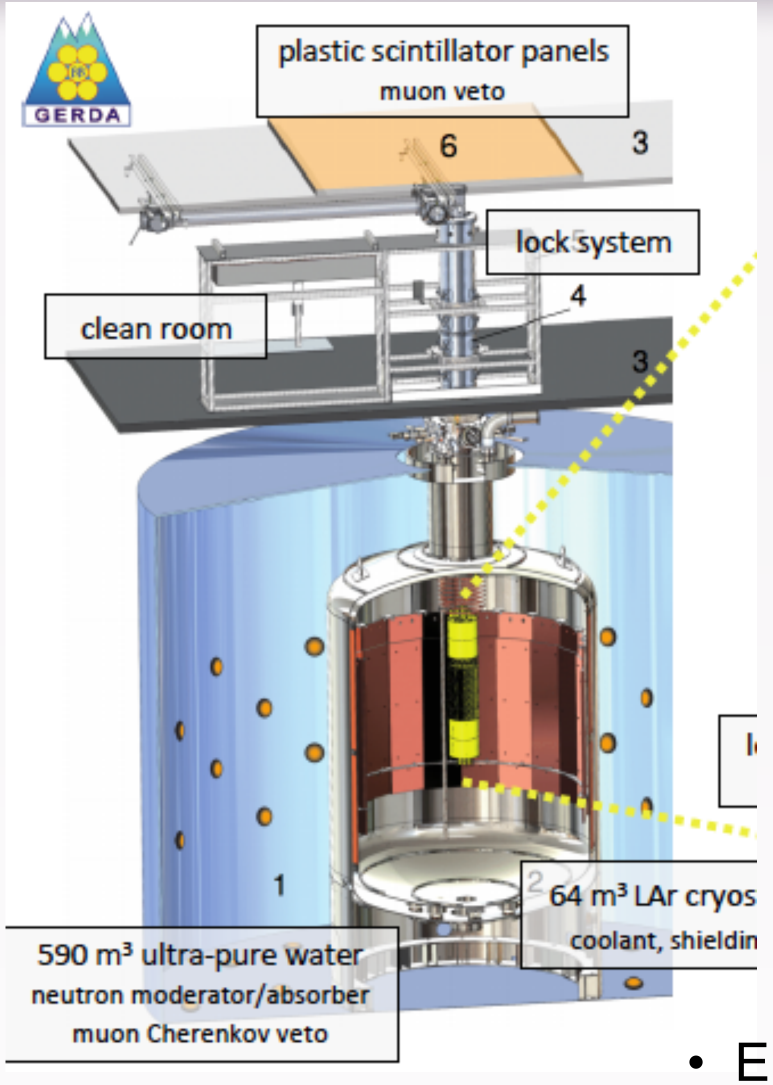
Best results from 0νββ

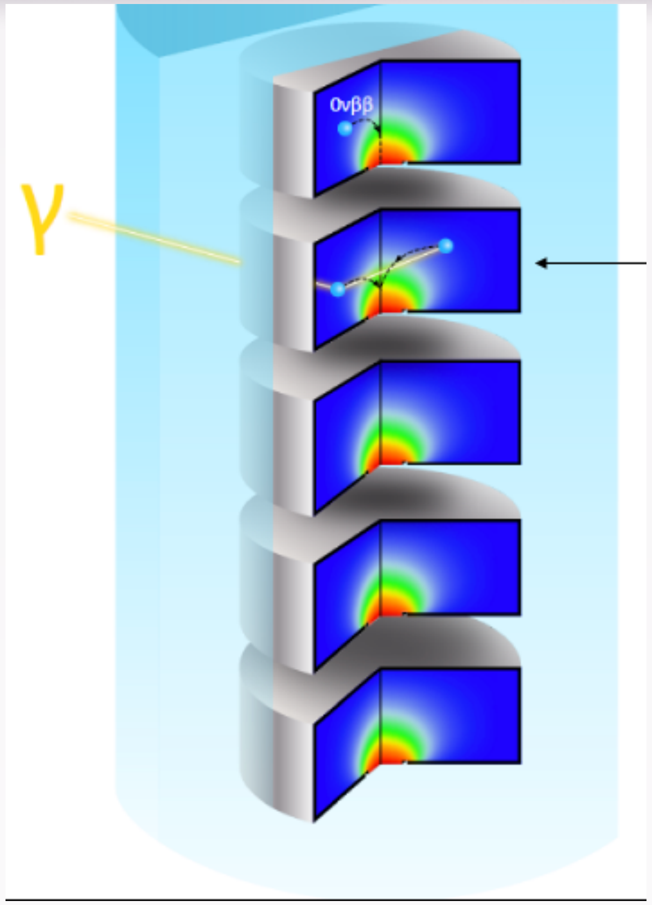
$$T^{0\nu}_{1/2}(90\%\ \text{C.L.}) = 2.54\times10^{26}\,\text{y}\left(\frac{\varepsilon\times a}{W}\right)\sqrt{\frac{M\times t}{b\times\Delta E}}$$

Isotope, mass	$Q_{\beta\beta}$, keV	b x ΔE x M, counts/yr	$T_{1/2}$, yr	<m_ν>, eV	Experiment, technique
^{76}Ge, 40kg	**2039**	**0.07**	**> 0.9 x 10^{26}**	**< 0.11-0.25**	**GERDA, HPGe**
^{82}Se, 5kg	2998	0.4	> 2.4 x 10^{24}	< 0.38-0.77	CUPID-0, scintillating bolometers
^{100}Mo, 7kg	3034	1.5	> 1.1 x 10^{24}	< 0.33-0.62	NEMO-3, tracko-calo
^{130}Te, 200kg	2528	21	> 1.5 x 10^{25}	< 0.13-0.50	CUORE, bolometers
^{136}Xe, 380kg	**2458**	**1**	**> 1.07 x 10^{26}**	**< 0.06-0.16**	**KamLAND-Zen, doped LS**

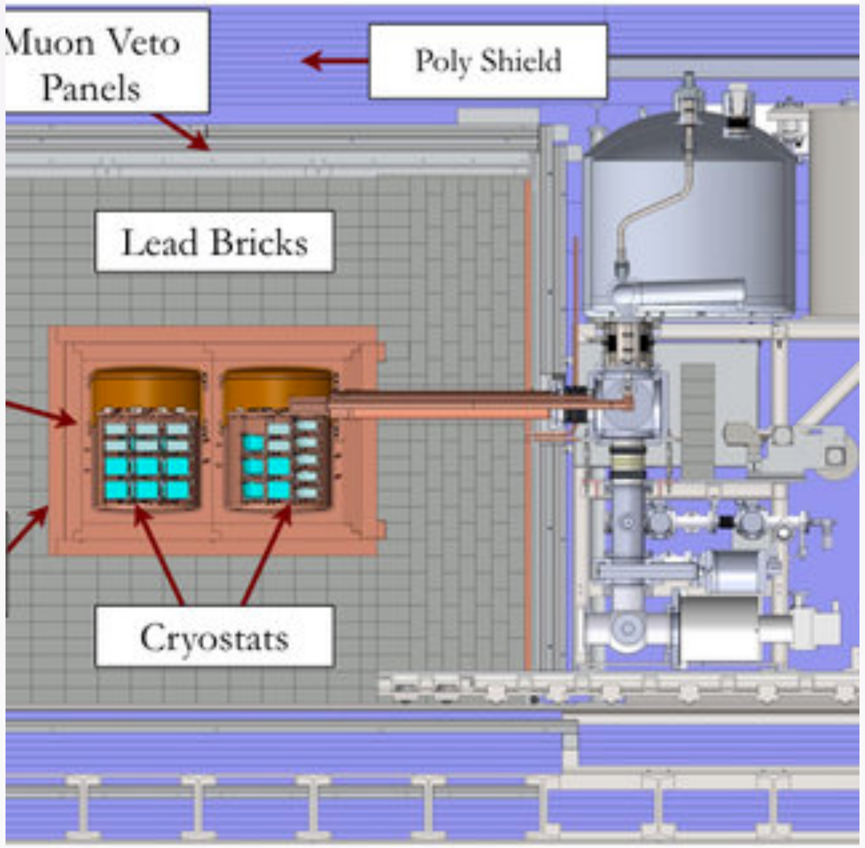
Different techniques reach similar sensitivity with different isotope mass

$HP^{76}Ge$





Majorana



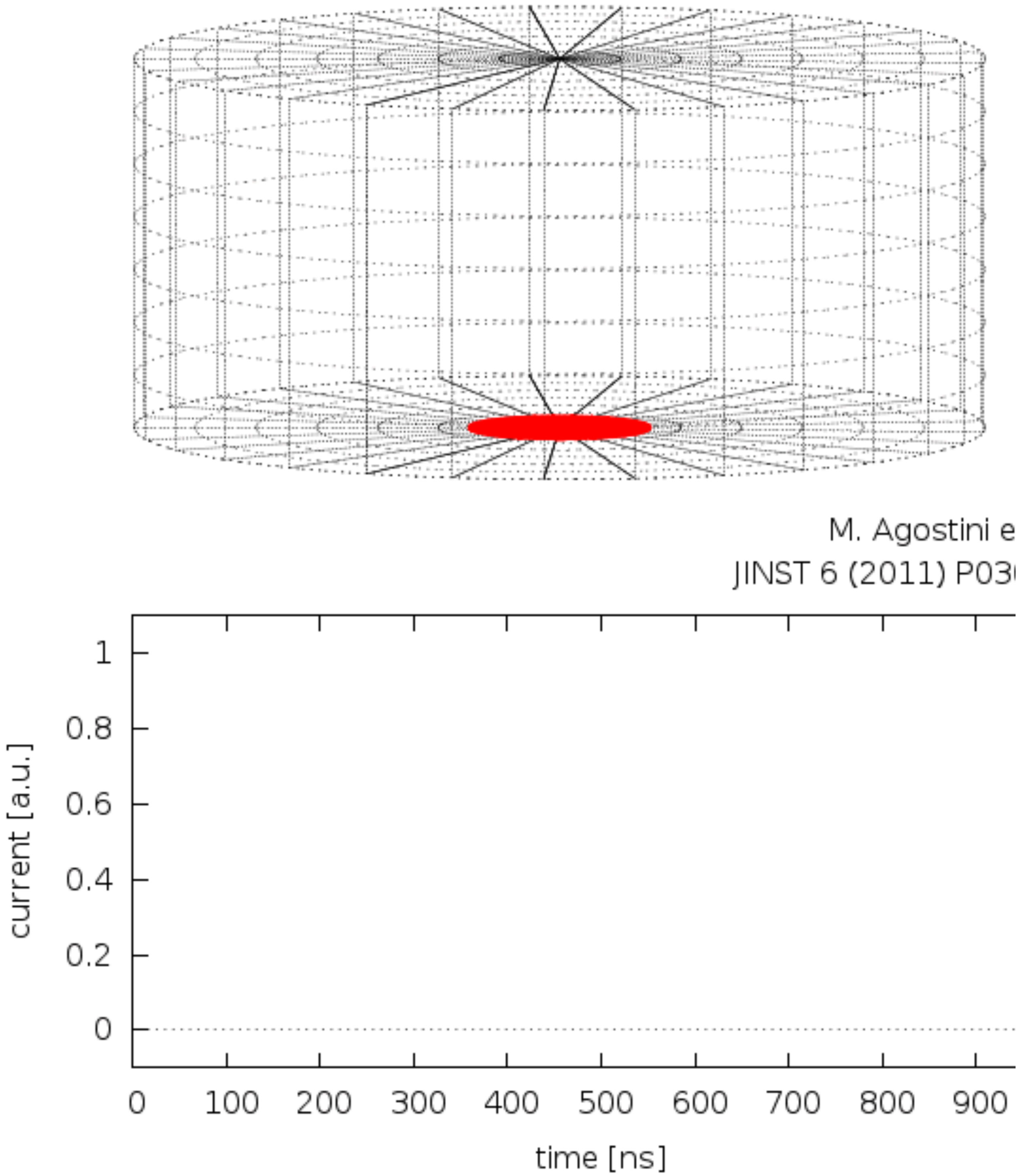
- Enriched ^{76}Ge crystals (in LAr in case of GERDA)
- Particle ID with single-site (ββ) vs multiple-site (γ) events using pulse shape

- Superior ΔE/E ~0.15% at 2039 keV ($Q_{\beta\beta}$)
- High detection efficiency ~ 70-90%

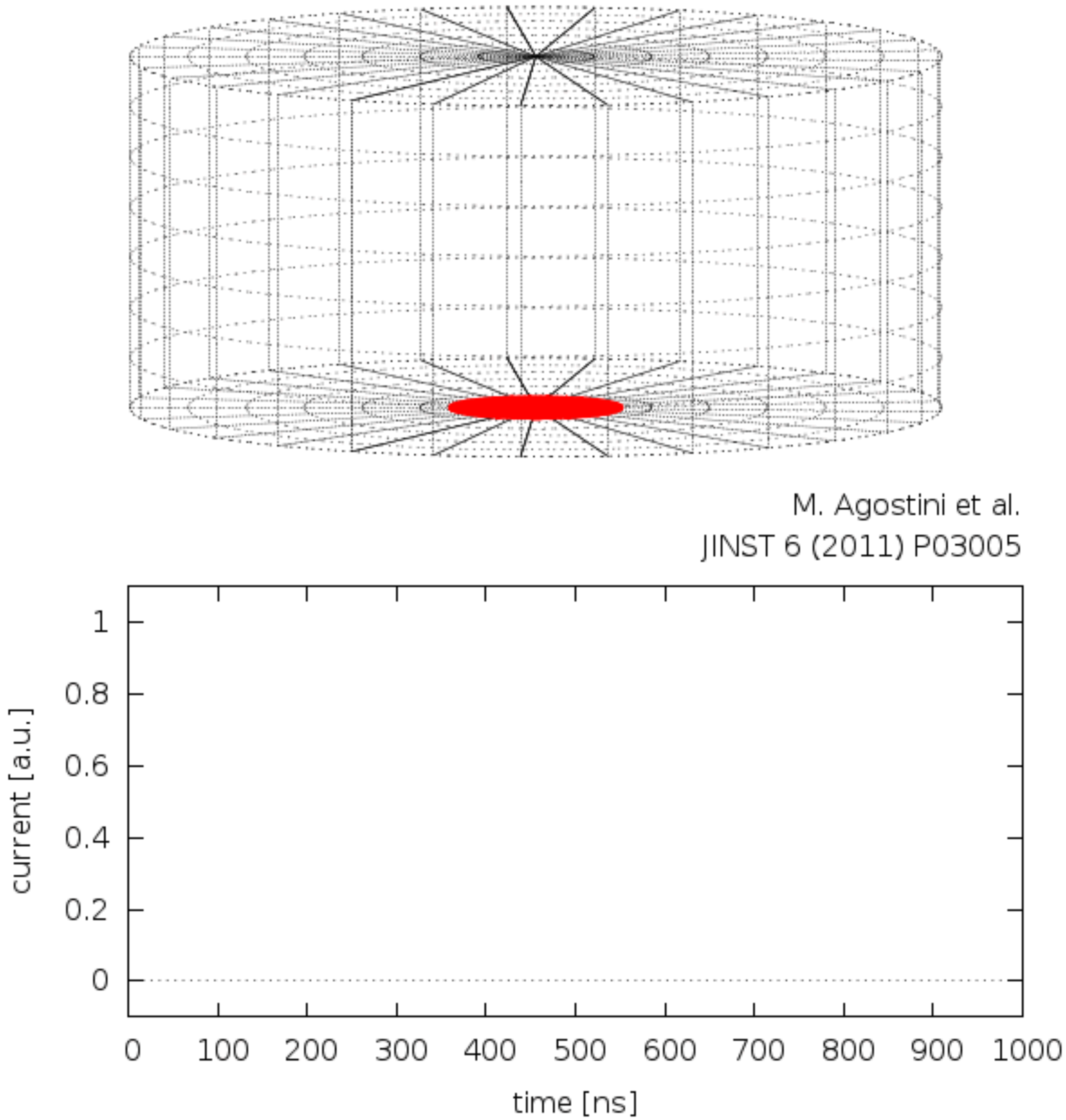
- Low $Q_{\beta\beta}$ = 2039 keV. Need to reach longer $T_{1/2}$ for same $\langle m_\nu \rangle$
- Single isotope

Broad Energy Ge detectors (BEGe) — "solid state TPC"

multi-site events (γ background)



single-site events (ββ signal)



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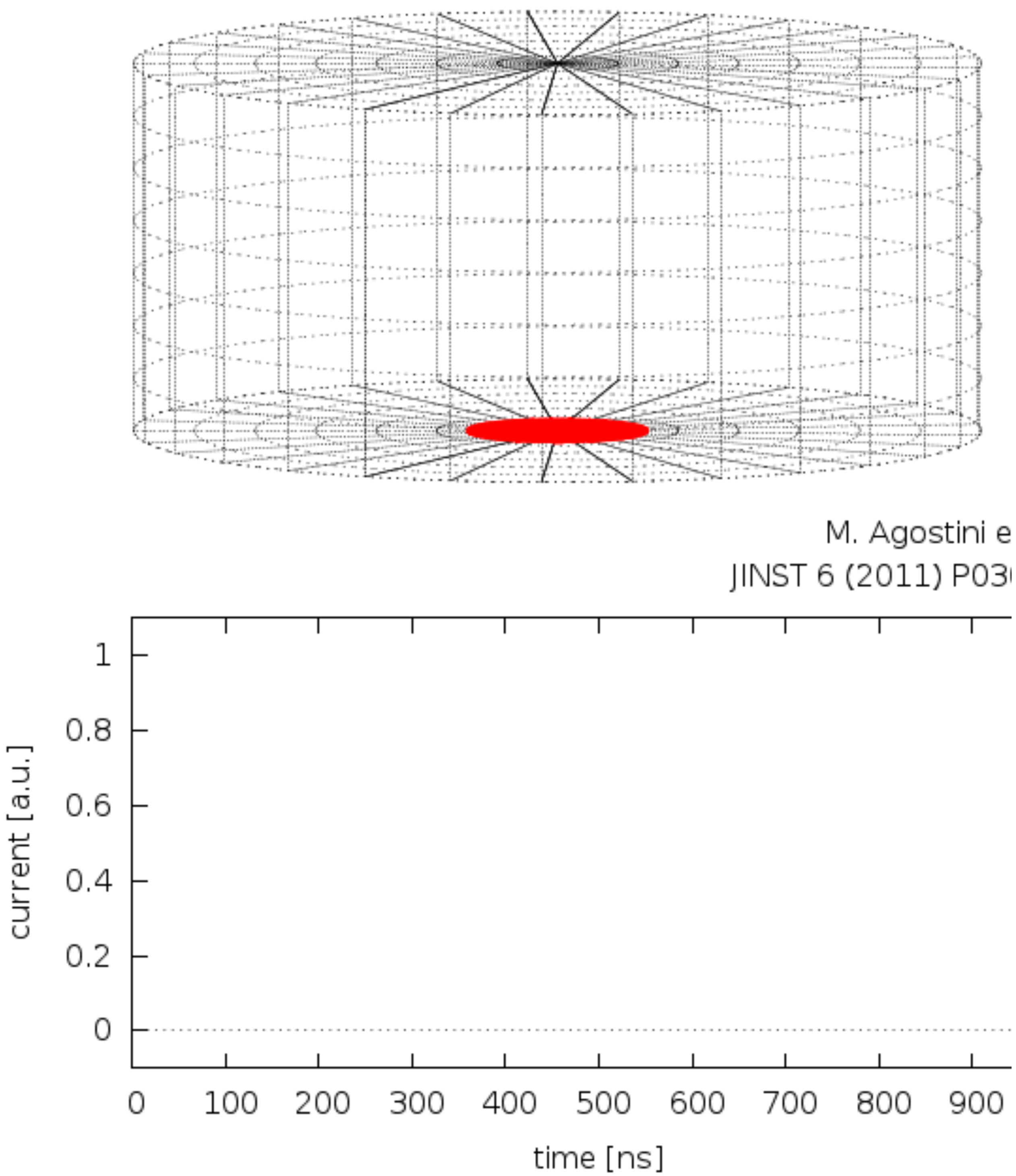
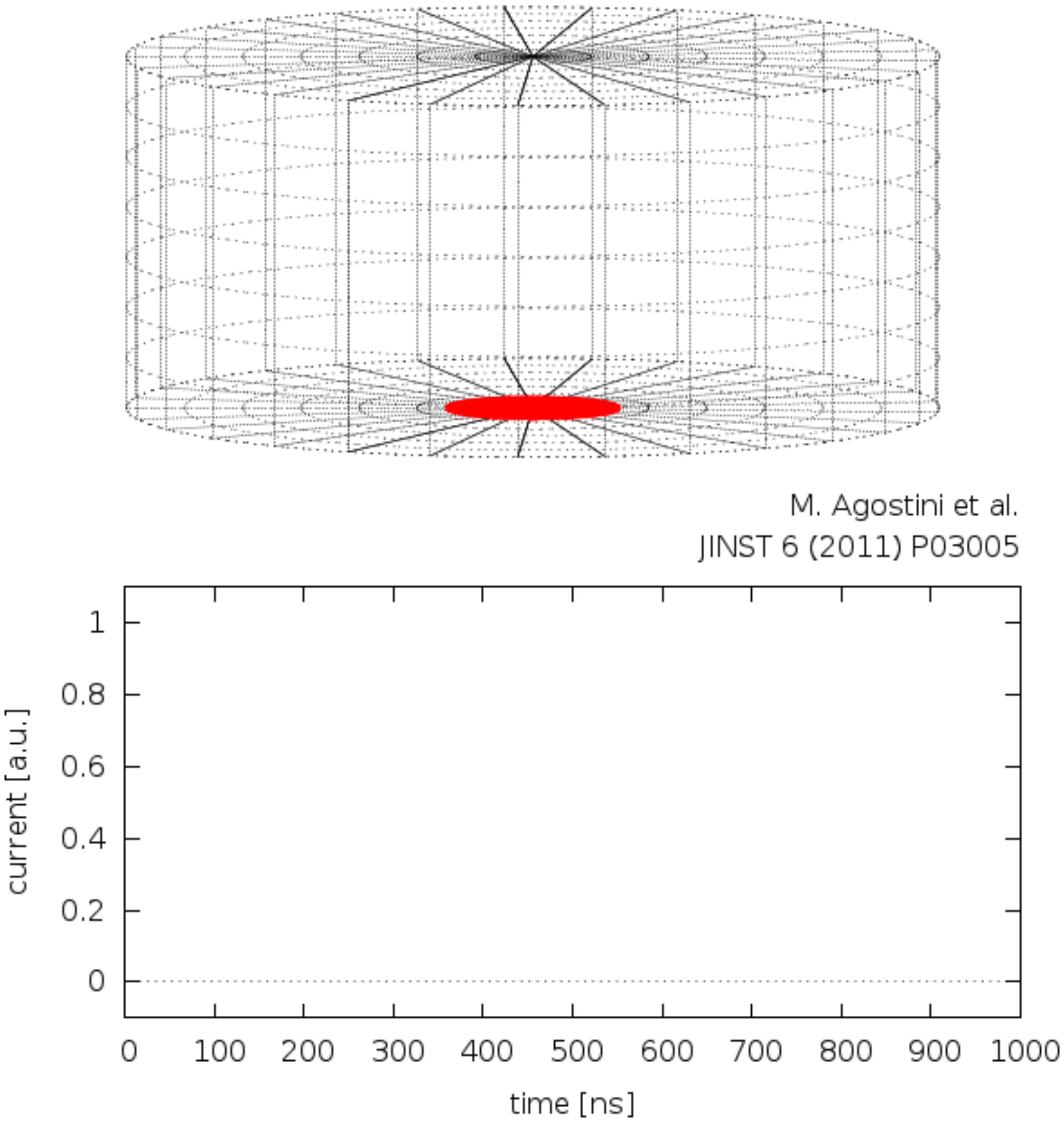


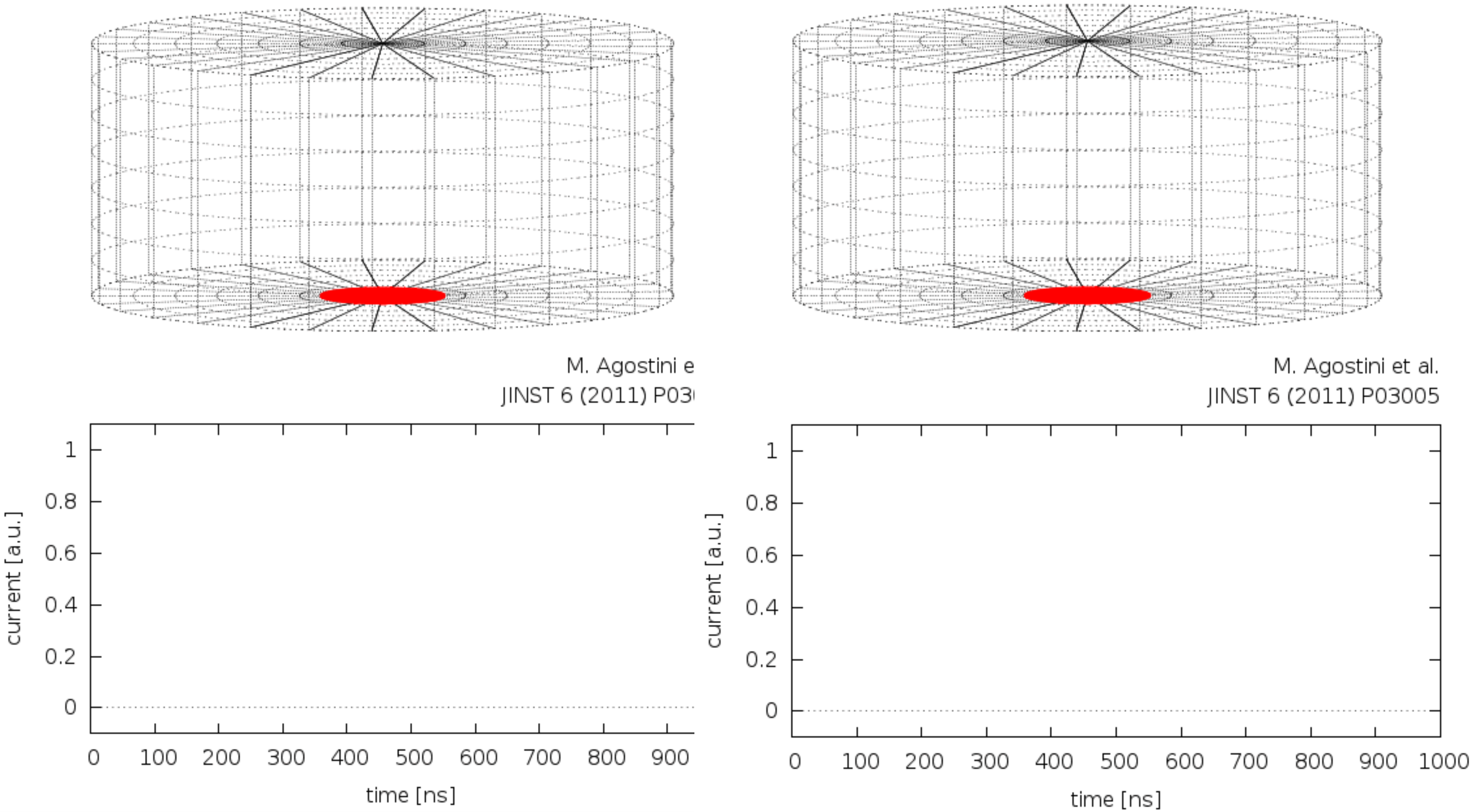
single-site events ($\beta\beta$ signal)



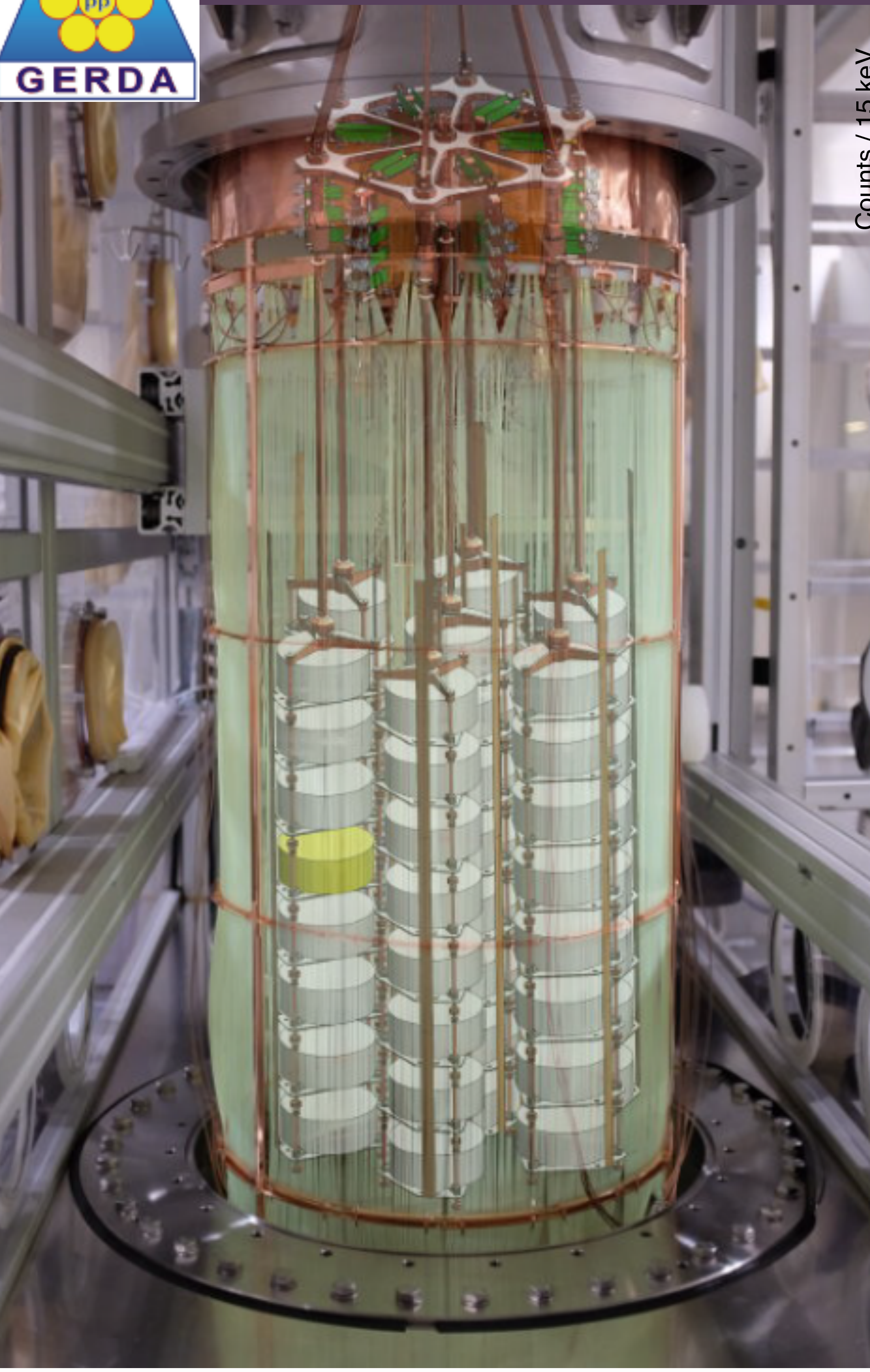
Broad Energy Ge detectors (BEGe) — "solid state TPC"

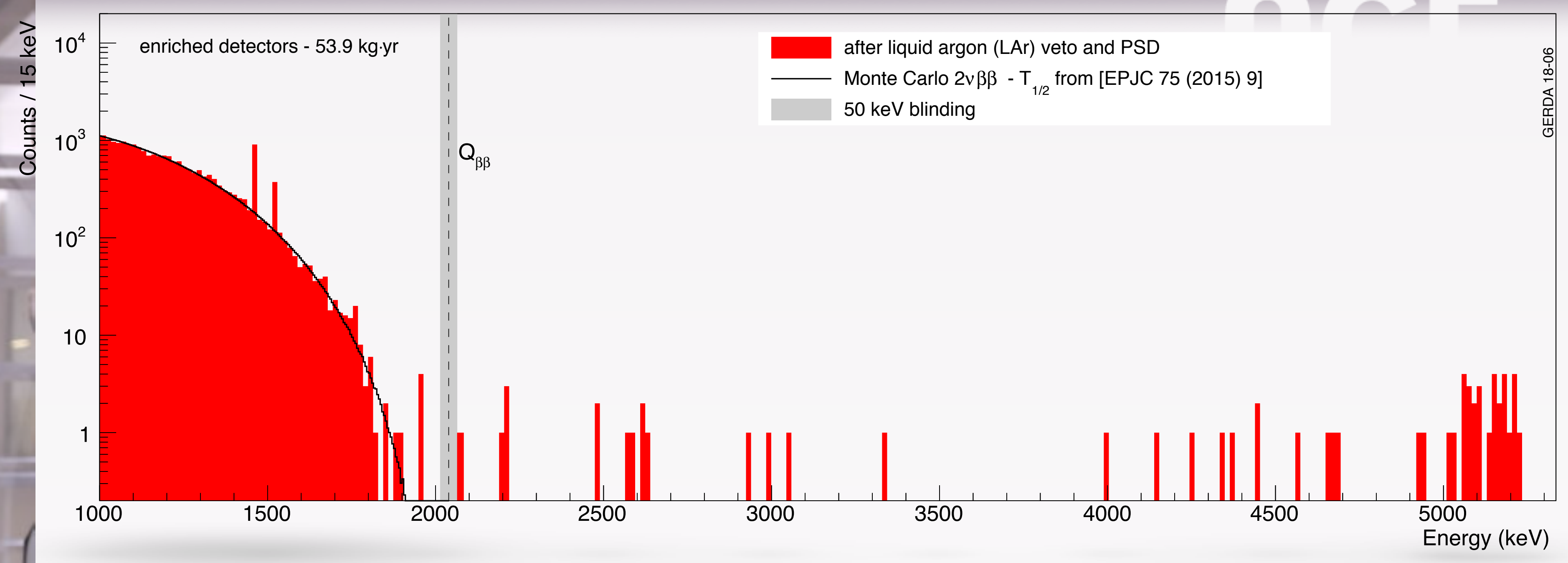
multi-site events (γ background)

single-site events (ββ signal)



GERDA (^{76}Ge)





- Enriched ^{76}Ge crystals in LAr
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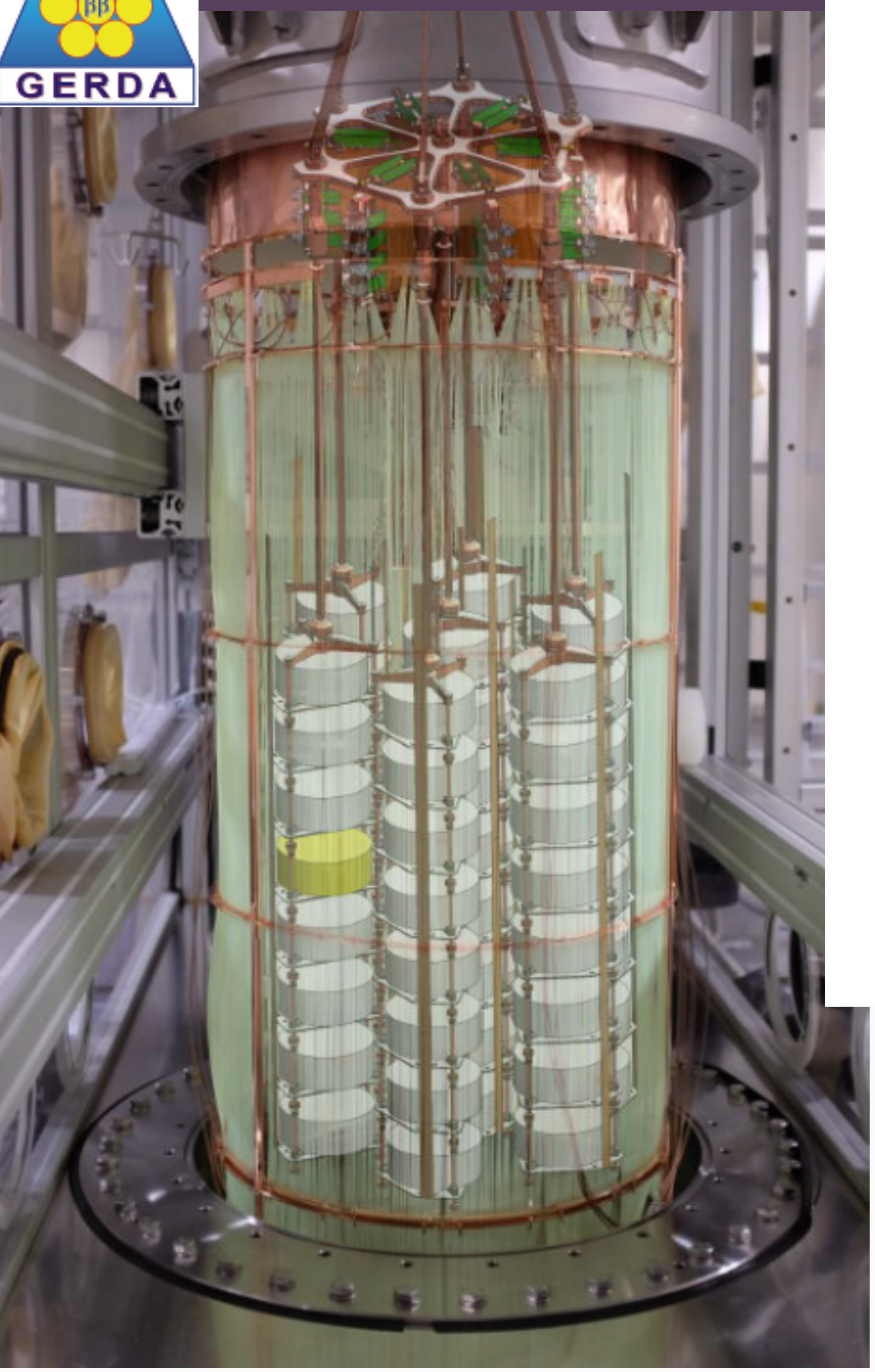
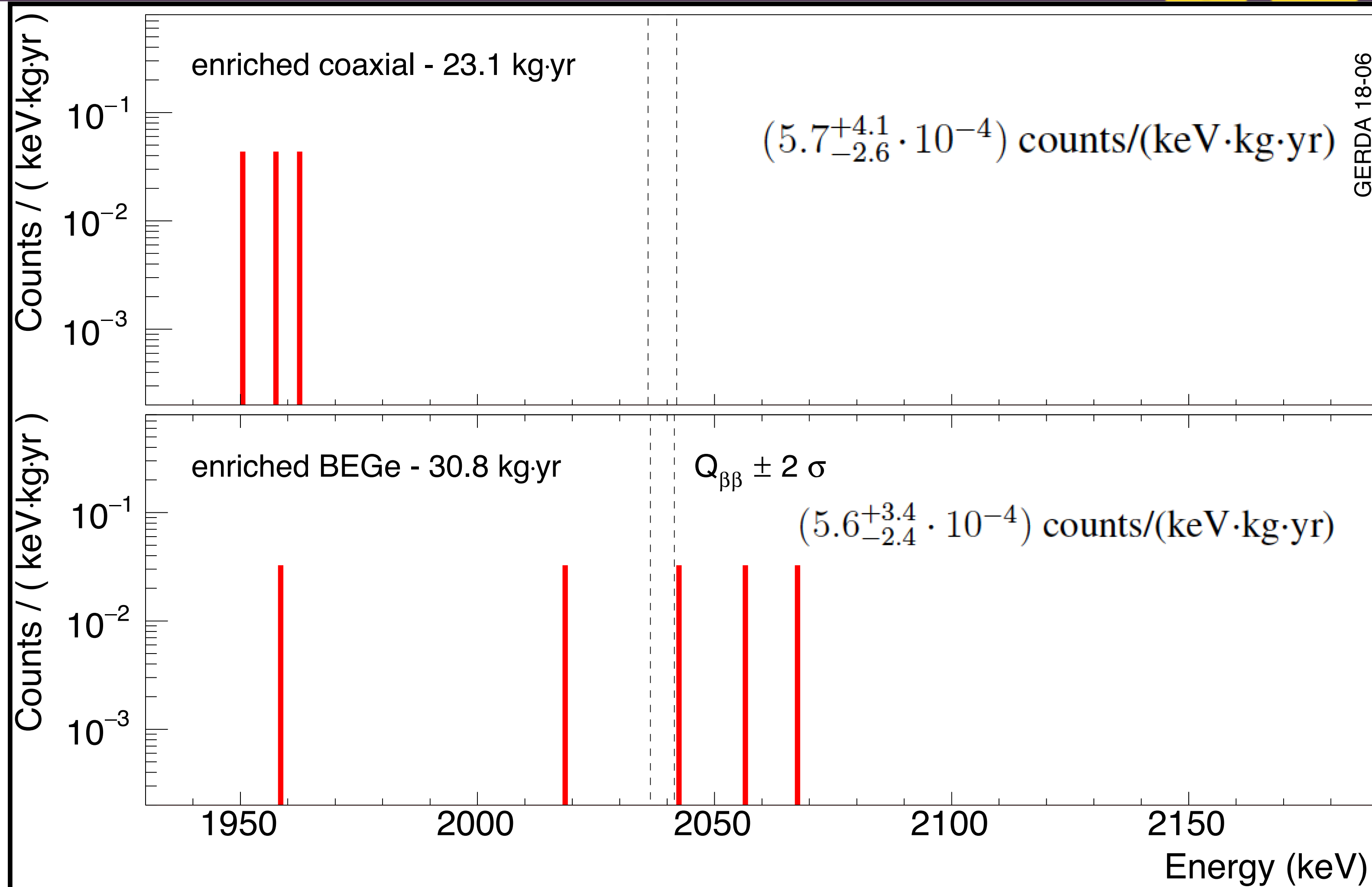
- High detection efficiency ~ 70-90%

Upgrades in summer 2018:

- 5 inverted coax detectors (LEGEND-200 prototypes)
- Improved LAr veto

GERDA (^{76}Ge)





Best fit $N^{0\nu} = 0$
$T^{0\nu}_{1/2} > 0.9 \cdot 10^{26}$ yr (90% C.L.)
Median sensitivity (NO Signal)
$T^{0\nu}_{1/2} > 1.1 \cdot 10^{26}$ yr (90% C.L.)

$m_{\beta\beta} < 0.11 - 0.25$ eV

- Enriched ^{76}Ge crystals in LAr
- Superior ΔE/E ~0.15% at 2039 keV ($Q_{\beta\beta}$)
- High detection efficiency ~ 70-90%

Upgrades in summer 2018:

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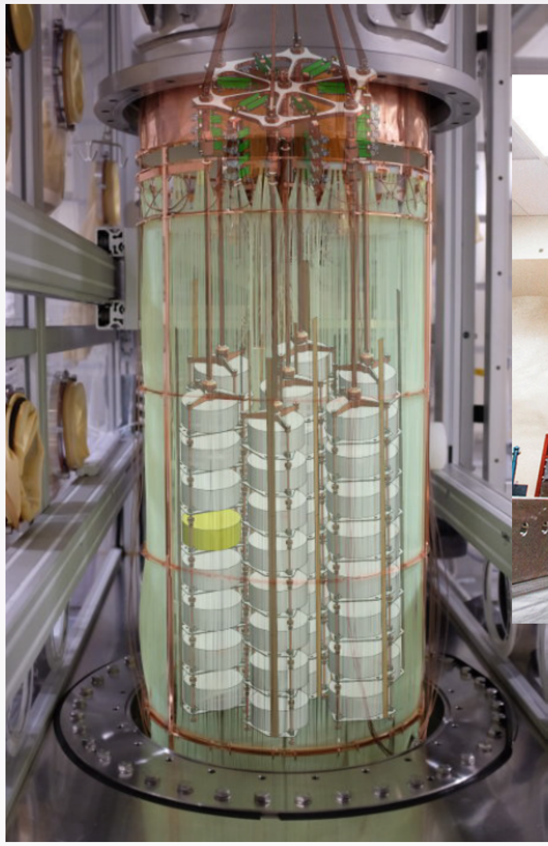
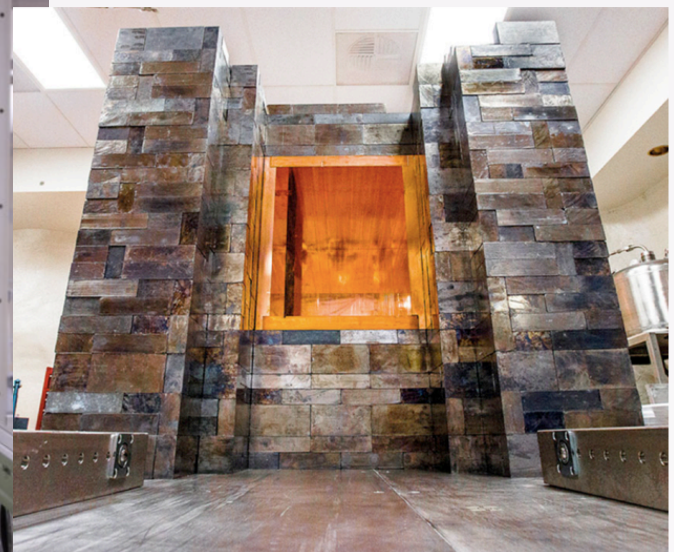
- Improved LAr veto

LEGEND

Large Enriched Germanium Experiment for Neutrinoless ββ Decay





Merging the best of GERDA and Majorana:

E.g. LAr veto of GERDA and ultra-pure copper/electronics of Majorana

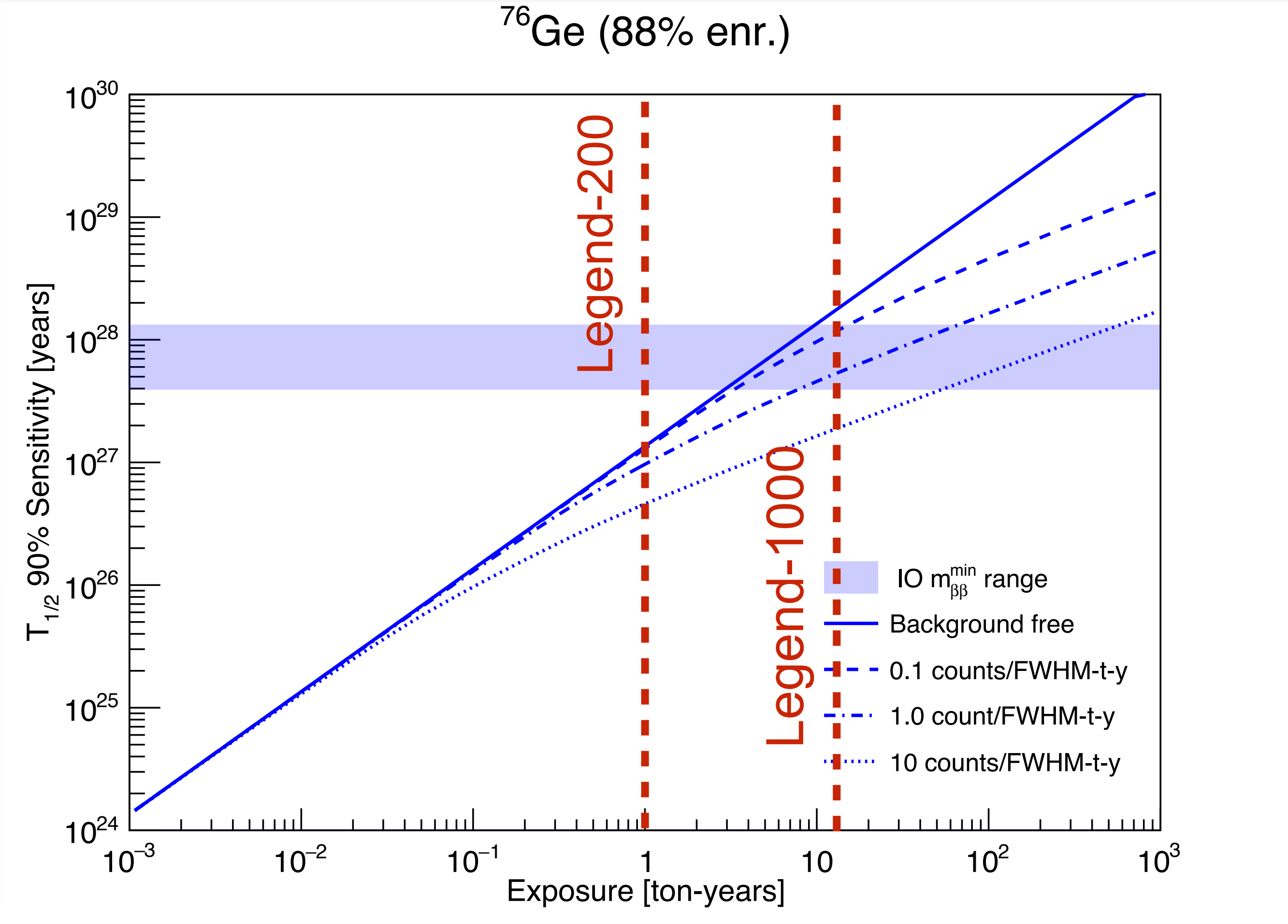
Phased approach

LEGEND-200 (first phase):
- up to 200 kg of detectors
- BI ~0.6 cts/(FWHM t yr)
- use existing GERDA infrastructure at LNGS
- design exposure: 1 t yr
- Sensitivity 10^{27} yr
- Isotope procurement ongoing
- Start in 2021

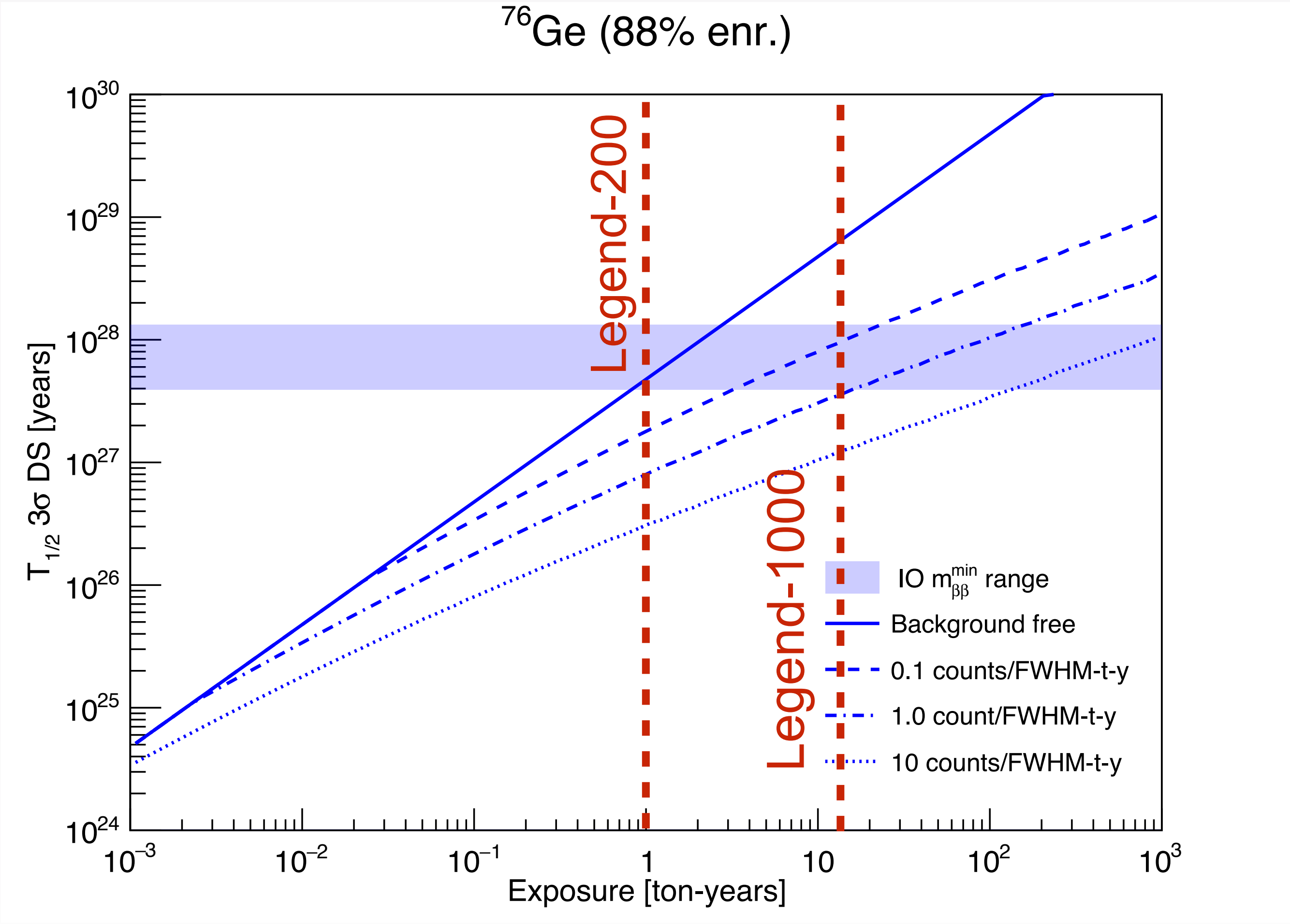
LEGEND-1000 (second phase):
- 1000 kg of detectors (deployed in stages)
- BI <0.1 cts/(FWHM t yr)
- Location tbd
- Design exposure 12 t yr
- 1.2 x10^{28} yr

LEGEND Sensitivity

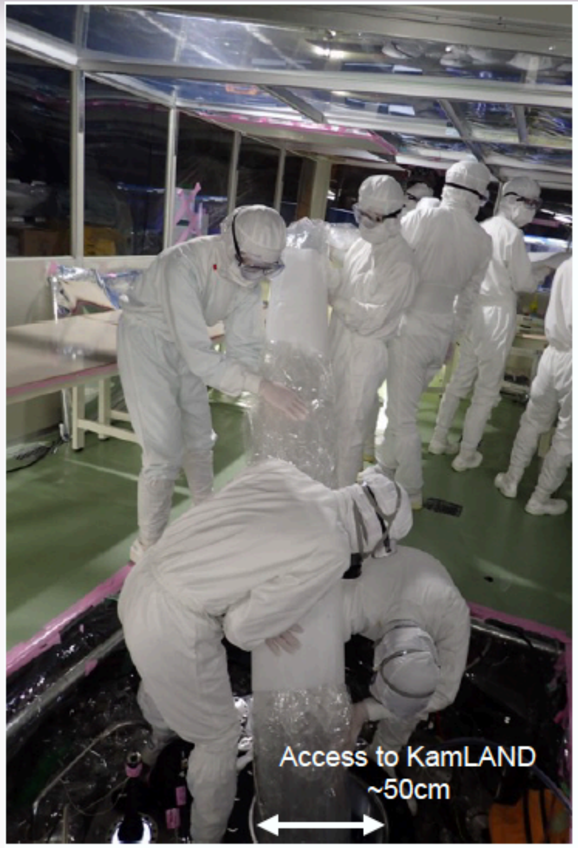
90% CL exclusion

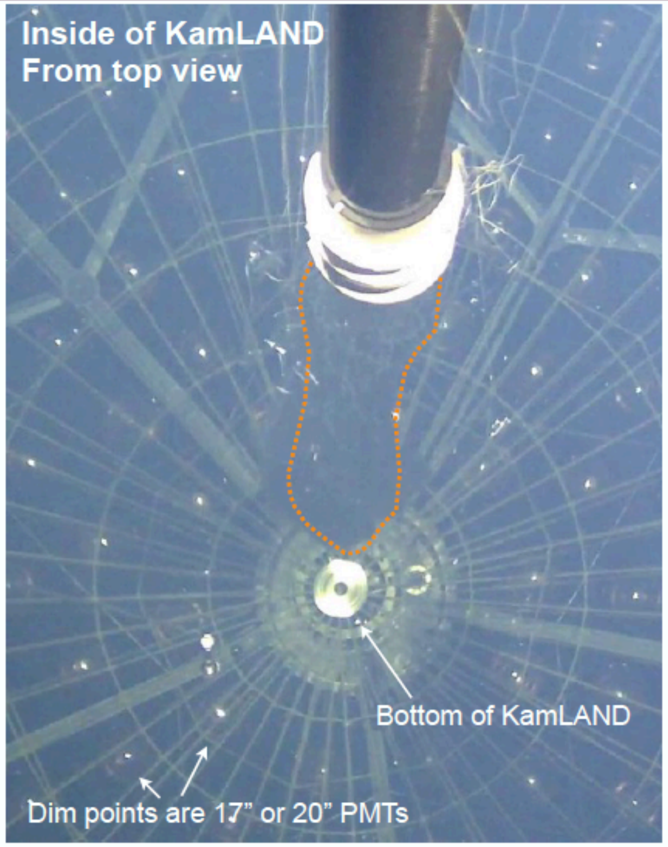


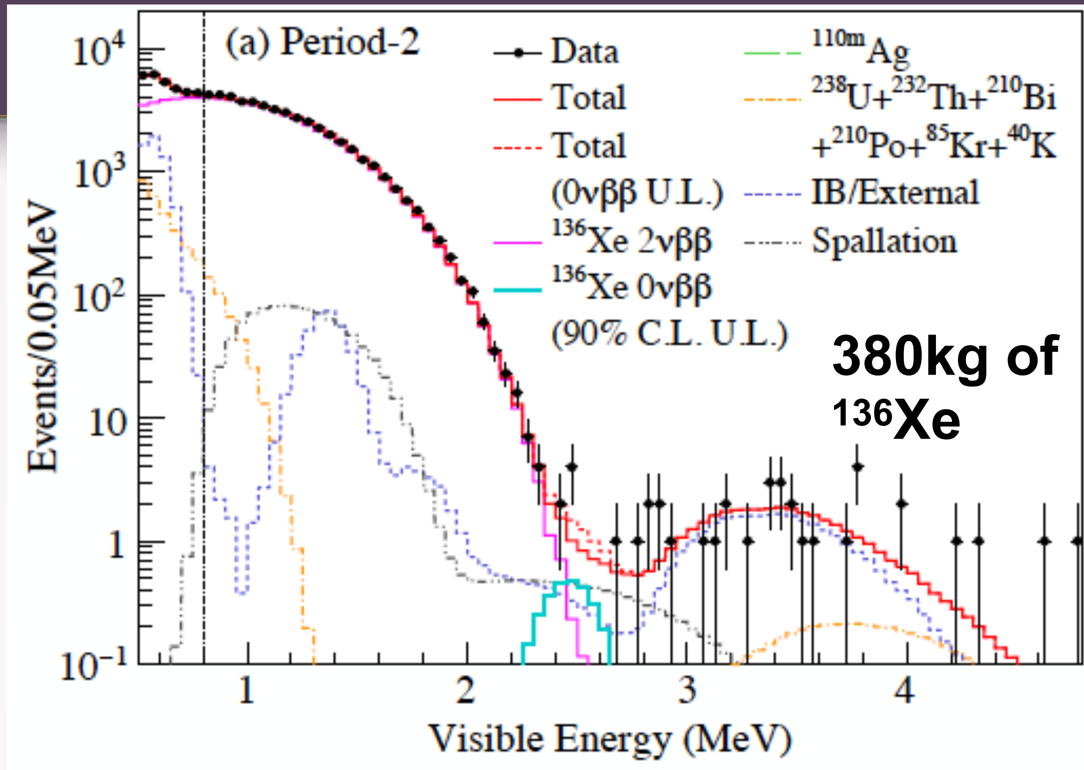
3σ evidence



KamLAND-Zen ^{136}Xe in Liquid Scintillator







380kg of ^{136}Xe

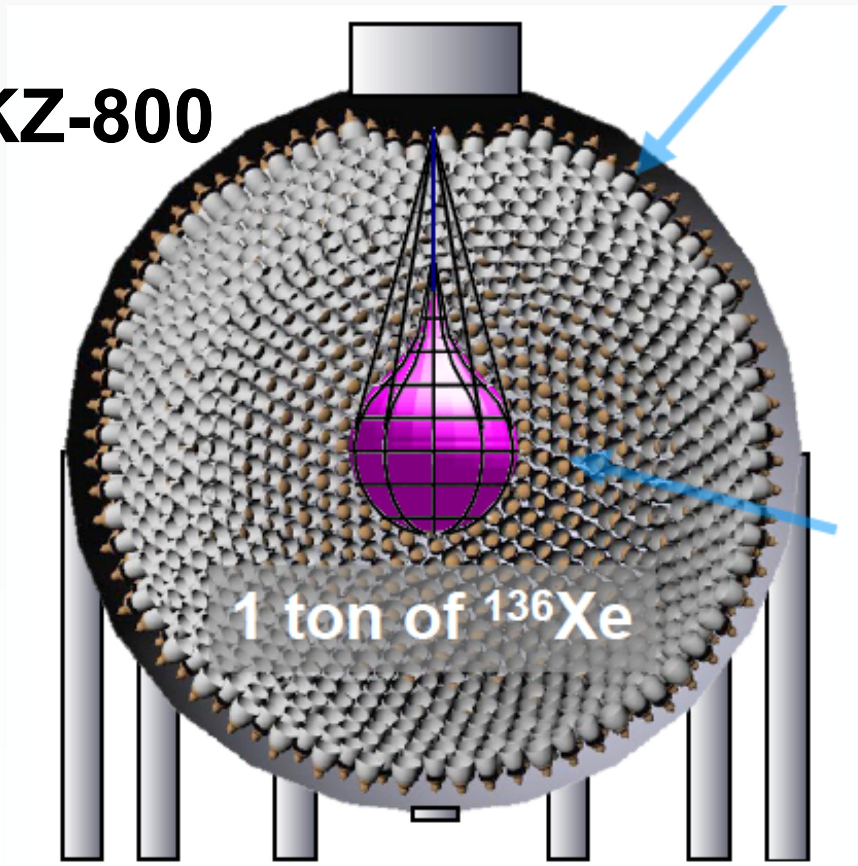
Upcoming: KamLAND-Zen 800

- New inner ballon installation in May'18
- Final preparations to load 800 kg of ^{136}Xe underway
- DAQ expect to start this year
- 50 meV sensitivity

- Improved scintillator and PMT coverage

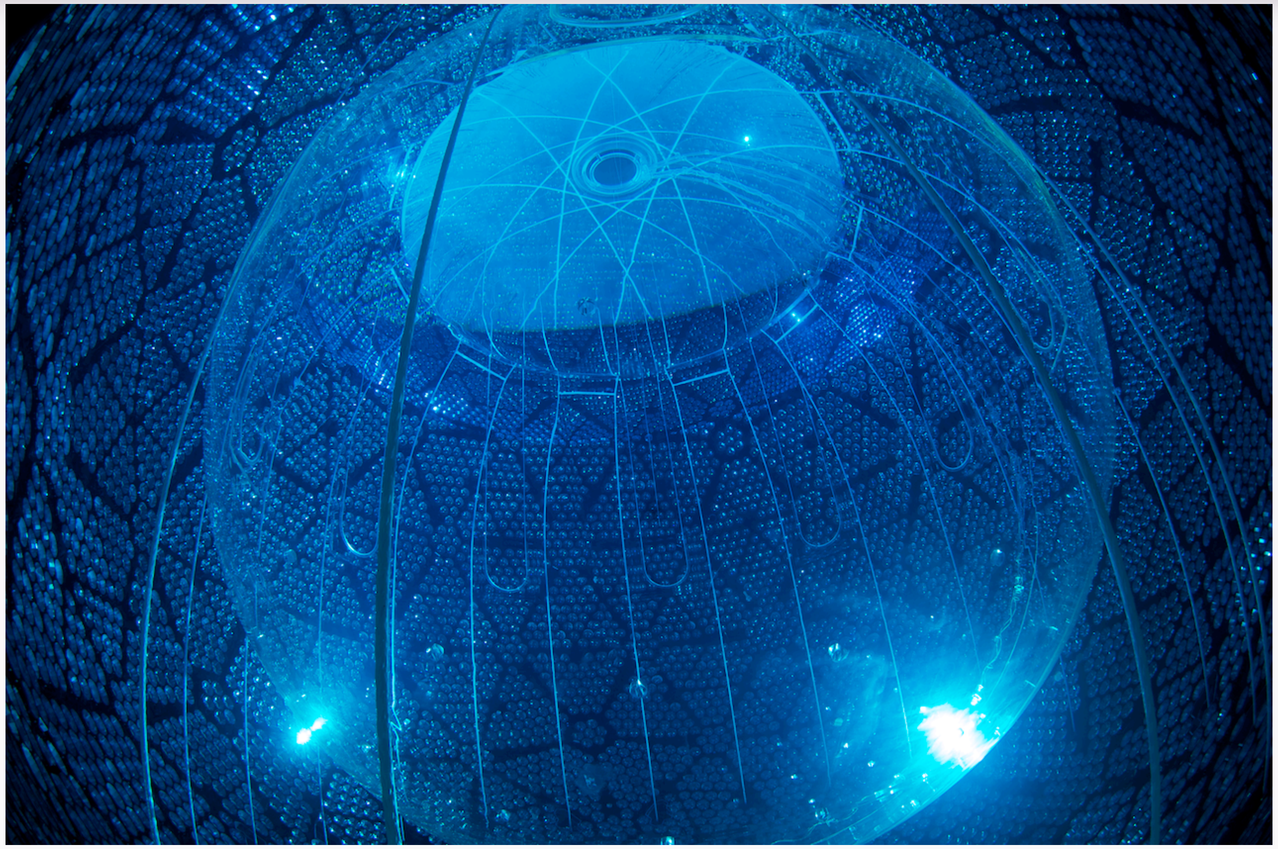
σ(2.6MeV)=4% → < 2.5%
Target ⟨$m_{\beta\beta}$⟩ ~20meV in 5 yrs

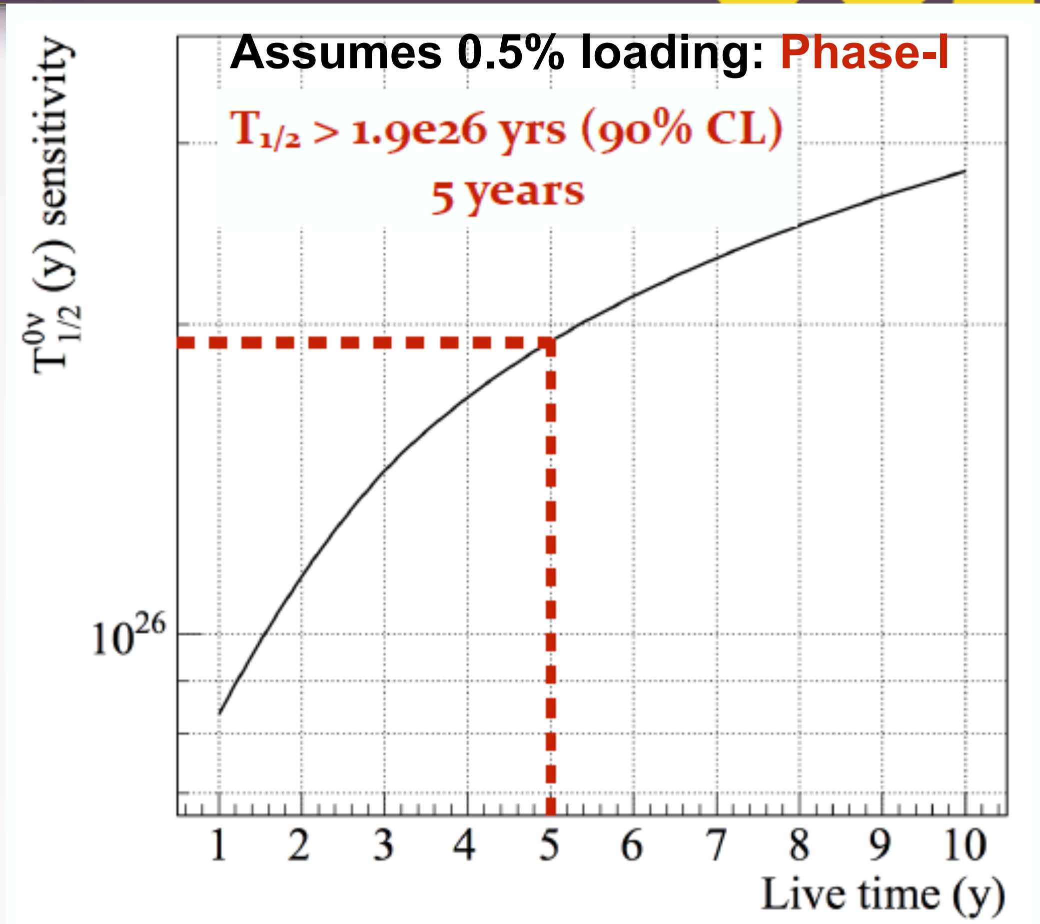
Beyond KZ-800



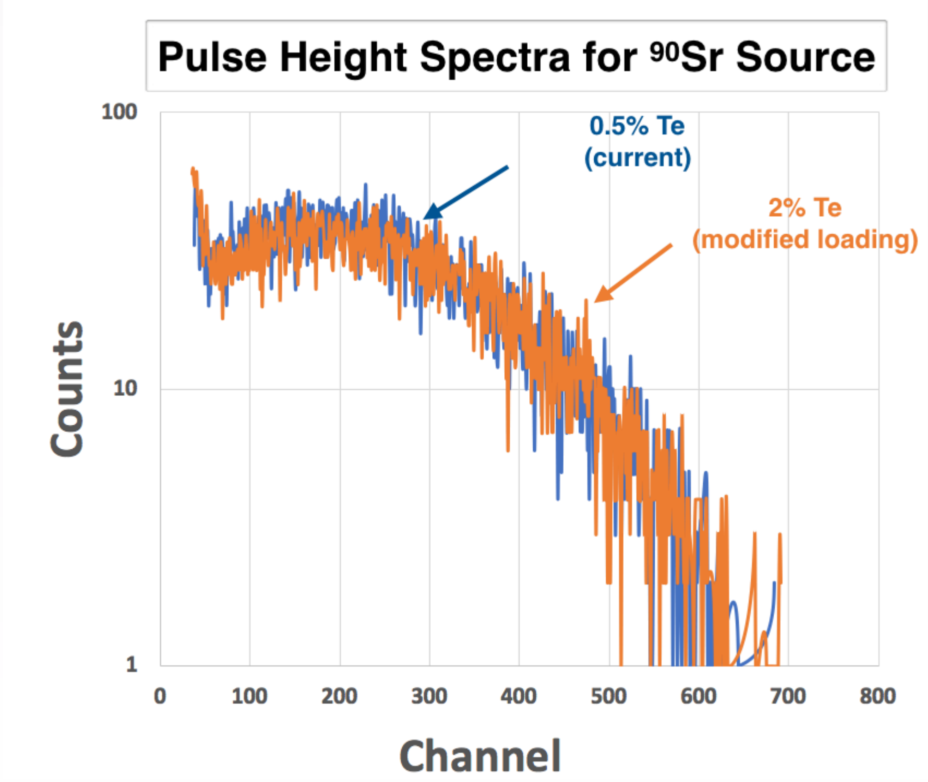
SNO+ ^{130}Te in Liquid Scintillator

UCL



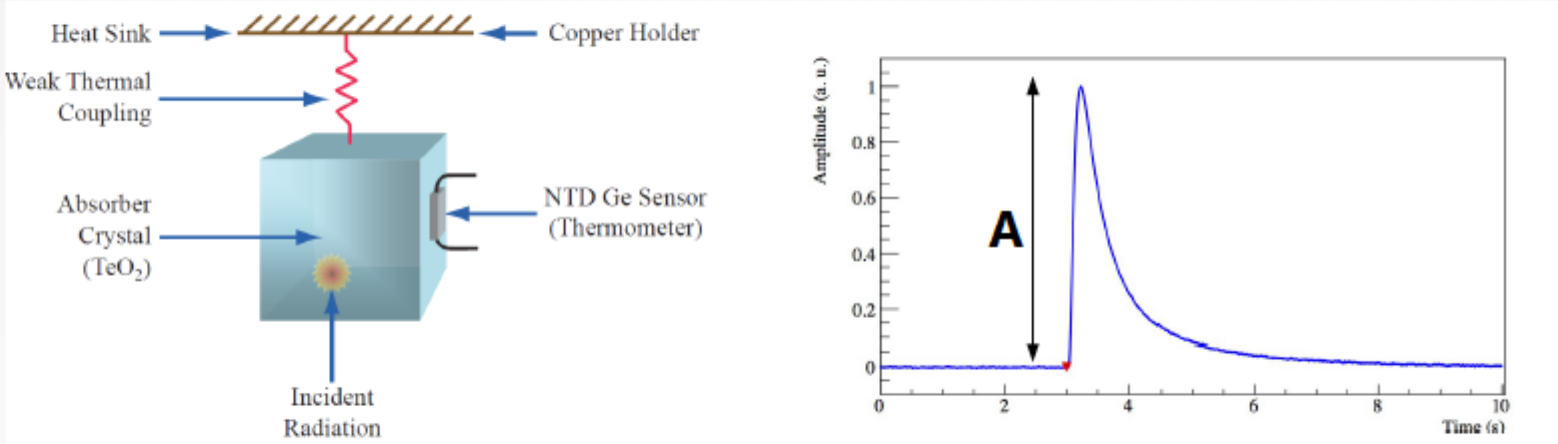


- Has been operating with water since Spring 2017@SNOLAB
- Background model in good agreement with data
- First solar-ν results
- Transition to scintillator later this month
- Te loading envisaged this year
- **Phase-I** result by 2024

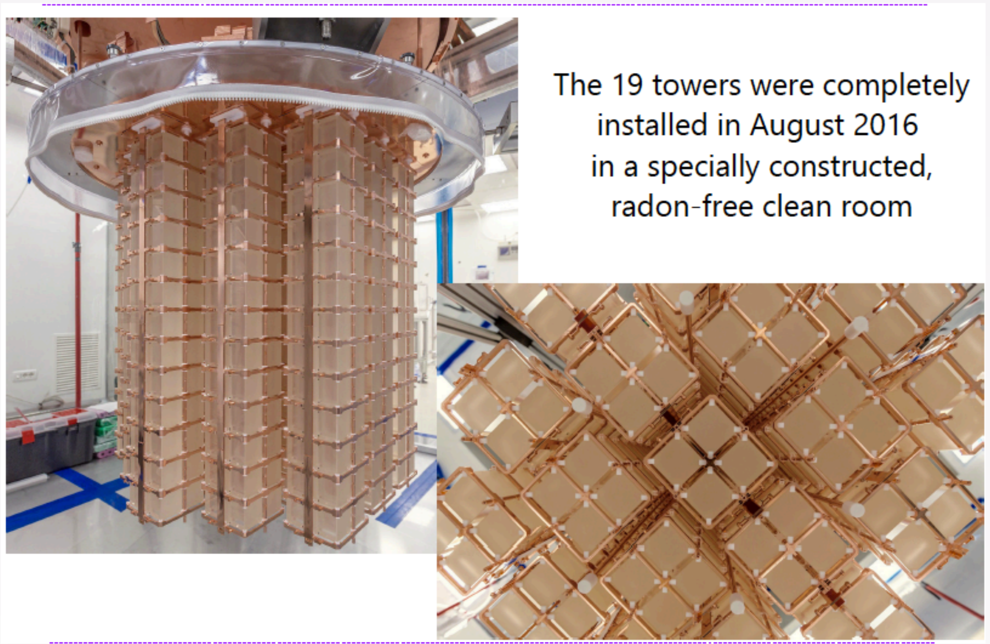


- **R&D on increased loading**
- **If successful 15-50 meV in phase-II**

Bolometers

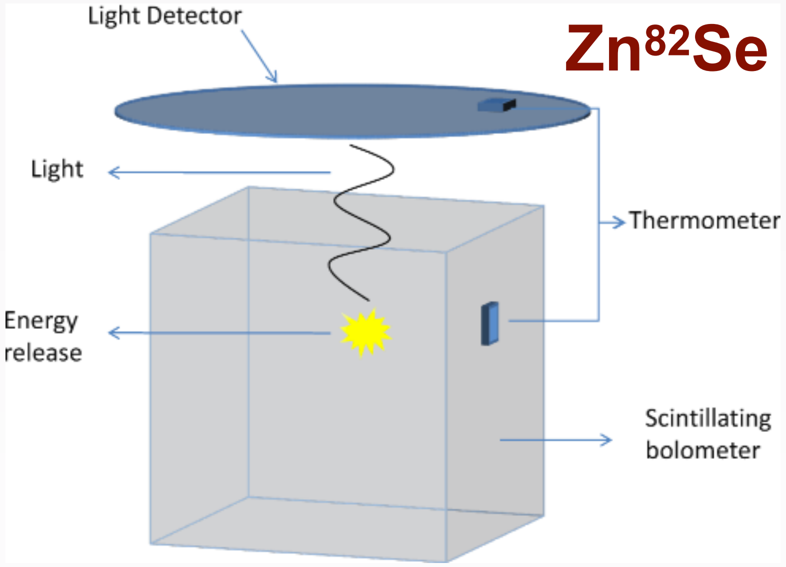


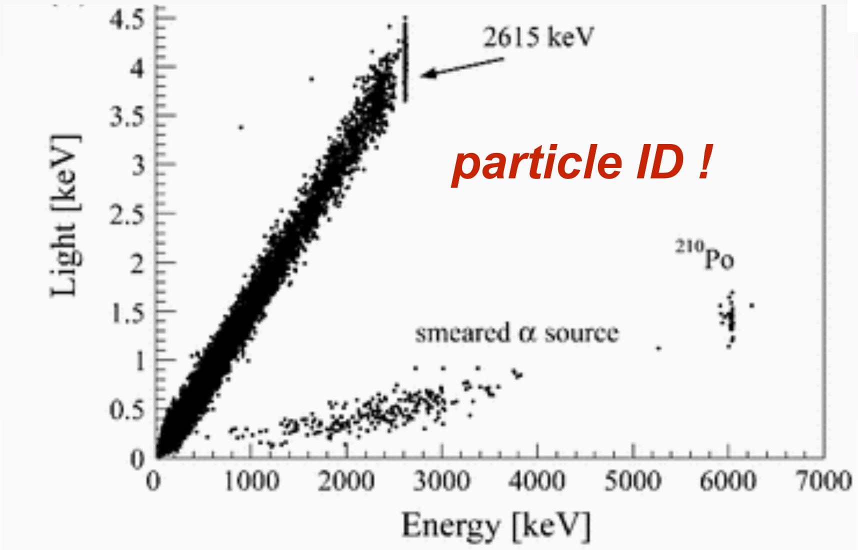
CUORE@LNGS

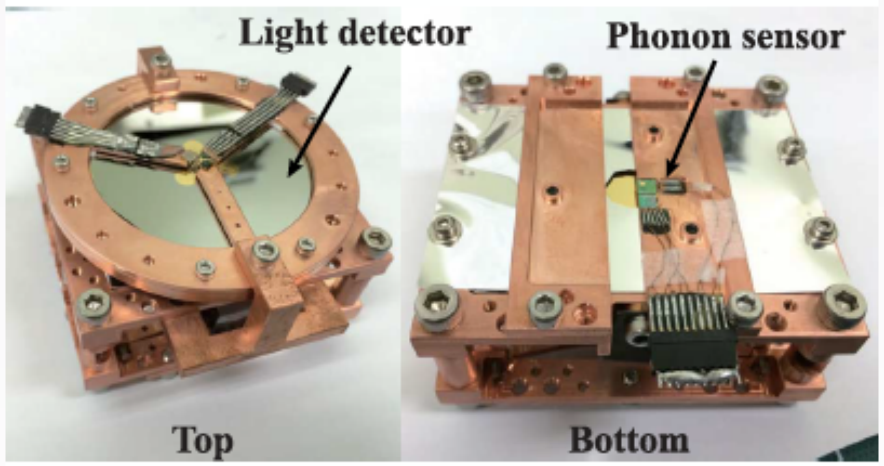


Scintillating bolometers to suppress surface contamination background

CUPID-0, $Zn^{82}Se$ **AMoRE** $Ca^{100}MoO_4$







- Excellent ΔE/E ~0.2-0.3% at $Q_{\beta\beta}$
- Multiple isotopes possible
- Complex ultra-low temperature technology

Significant synergies with direct DM detection technologies

Prospects for CUPID

^{100}Mo, ^{130}Te

Results of the ongoing R&D and demonstrators + CUORE background model

1. $Li_2{}^{100}MoO_4$ scintillating bolometers → promising **baseline option** for CUPID
2. $^{130}TeO_2$ Cherenkov bolometers → mature viable alternative

→ Fast and high-sensitivity light detectors are a common R&D
- Detection of Cherenkov light in TeO_2
- Rejection of $2\nu2\beta$ random coincidences in $Li_2{}^{100}MoO_4$

The purpose of CUPID is to fully explore the IO region

Mission: **half-life sensitivity higher than 10^{27} y**

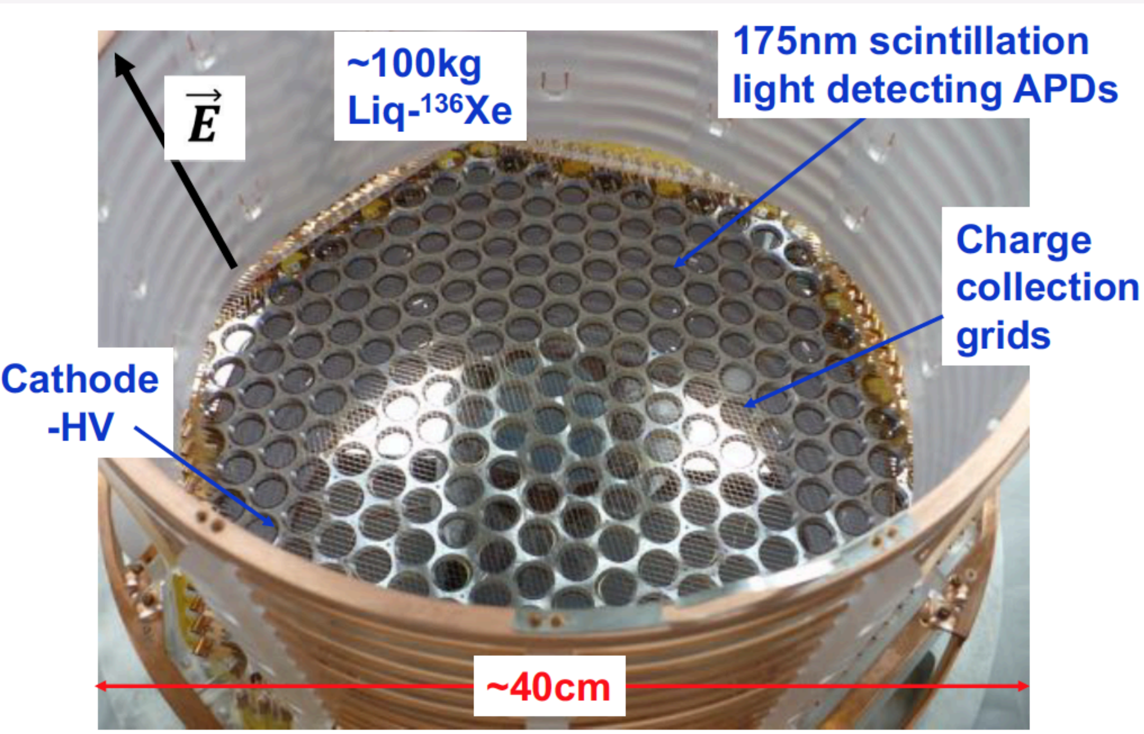
With background < 0.1 counts/(ton y) in the ROI, ^{100}Mo sensitivity is **2.1×10^{27} y**

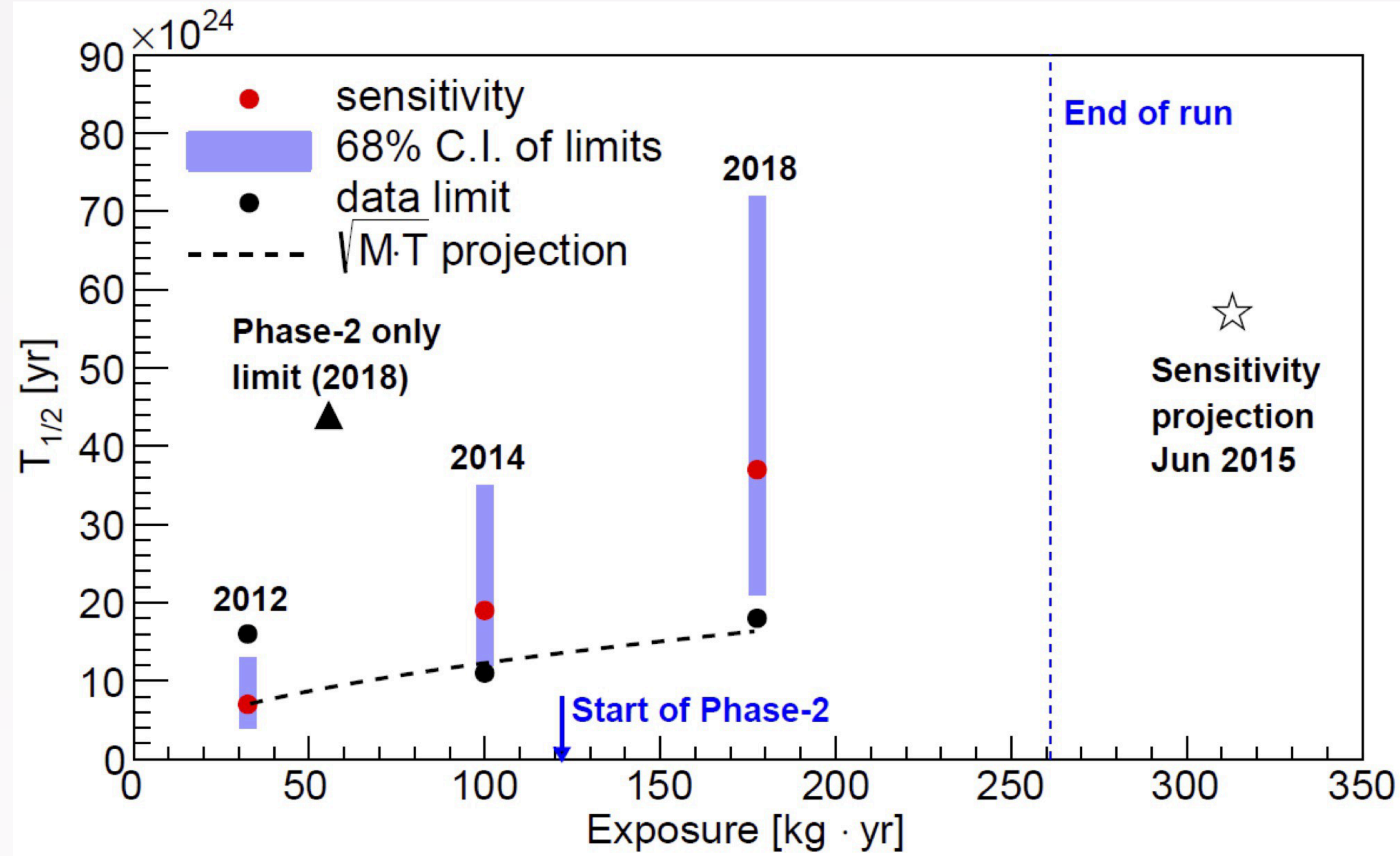
$m_{\beta\beta} < 6 - 17$ meV

- **CUPID collaboration will be formed in the near future**
- **CUPID kick-off meeting is being planned in fall 2018**

by A. Giuliani, Neutrino'2018

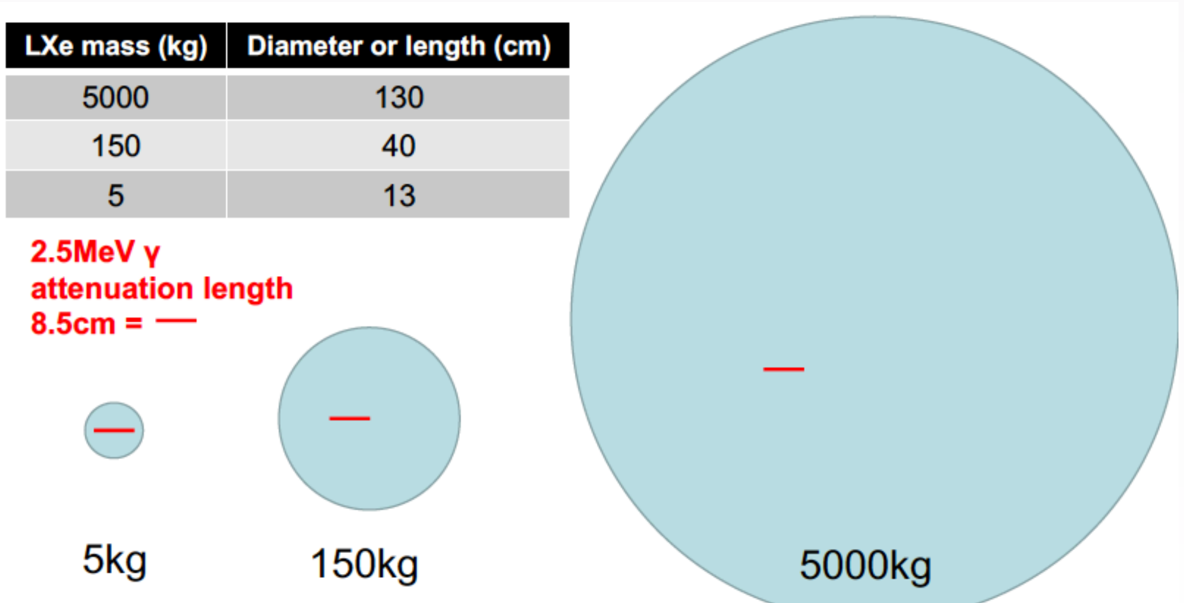
EXO-200 at WIPP. Active $L^{136}Xe$ mass ~110kg



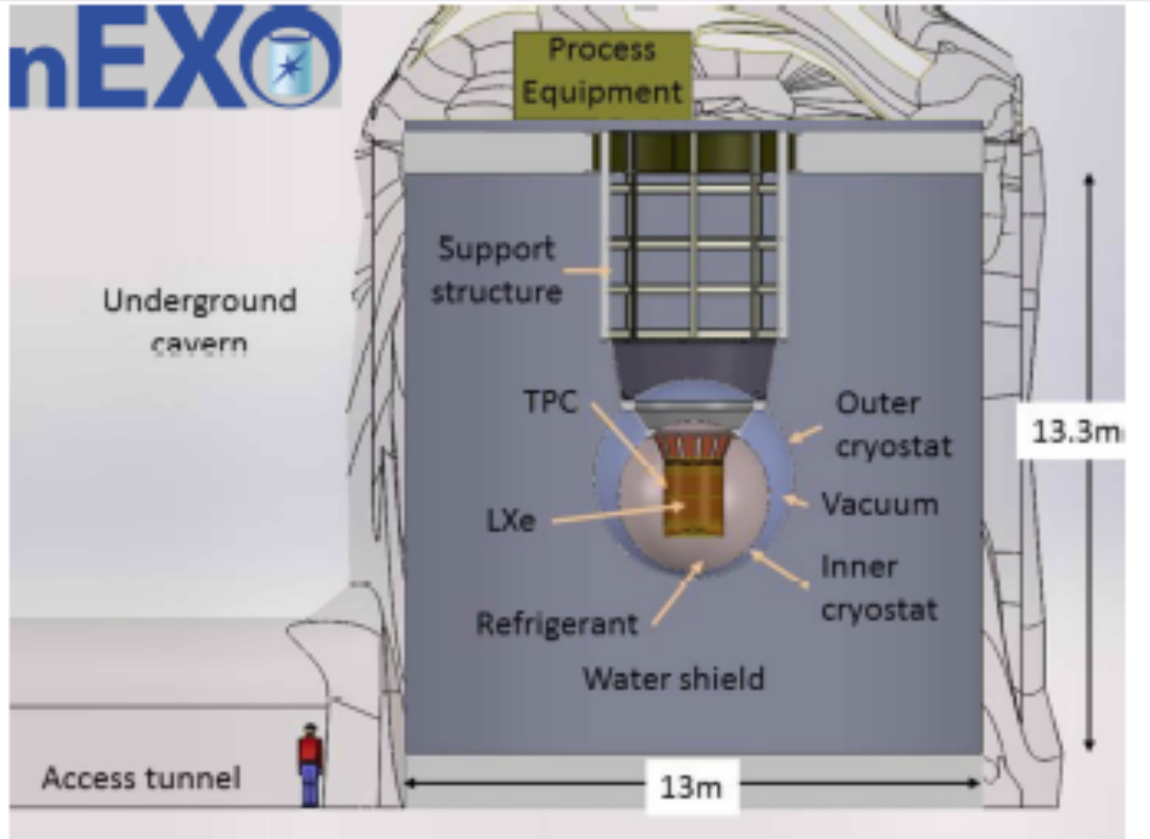


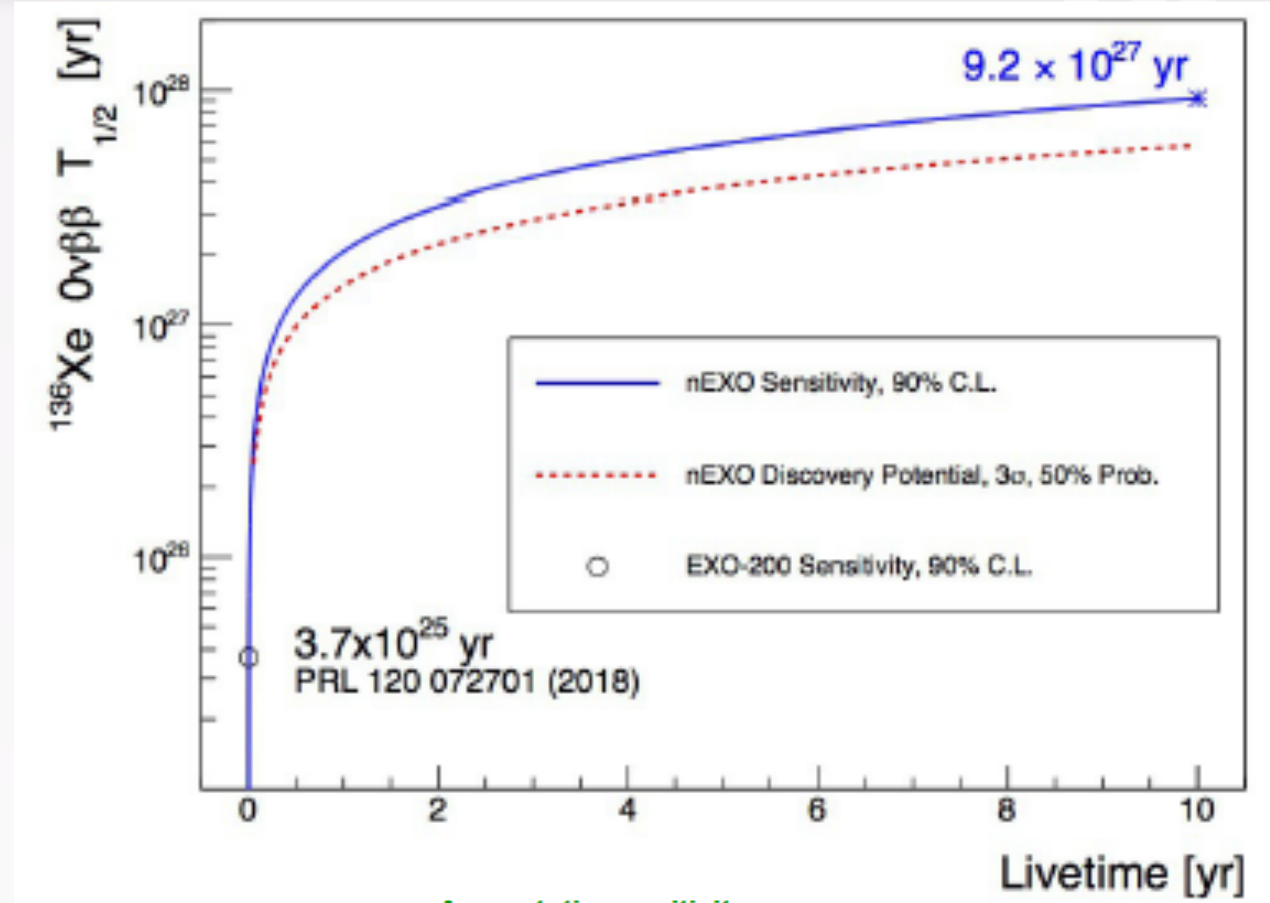
Towards nEXO

LXe mass (kg)	Diameter or length (cm)
5000	130
150	40
5	13

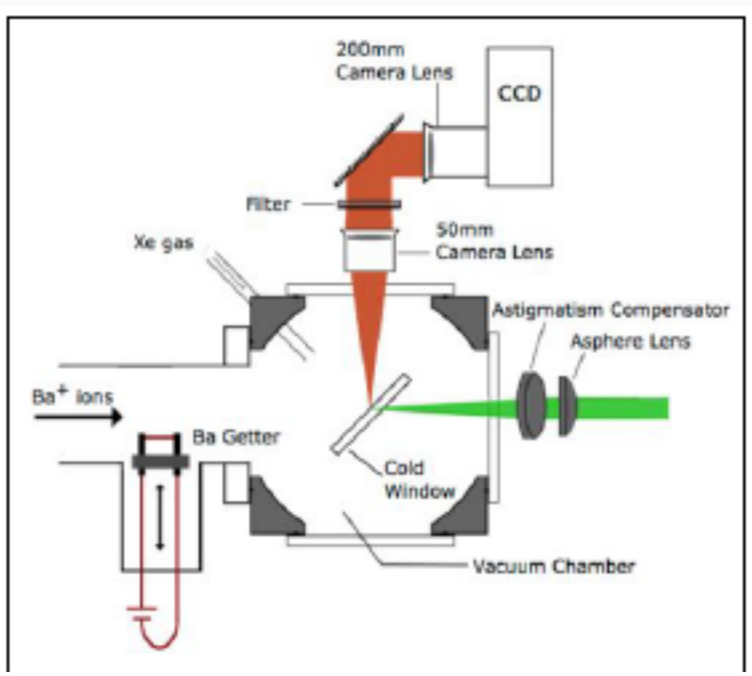


- Self-shielding better for larger detectors!
- Sensitivity estimates rely on ***measured*** materials

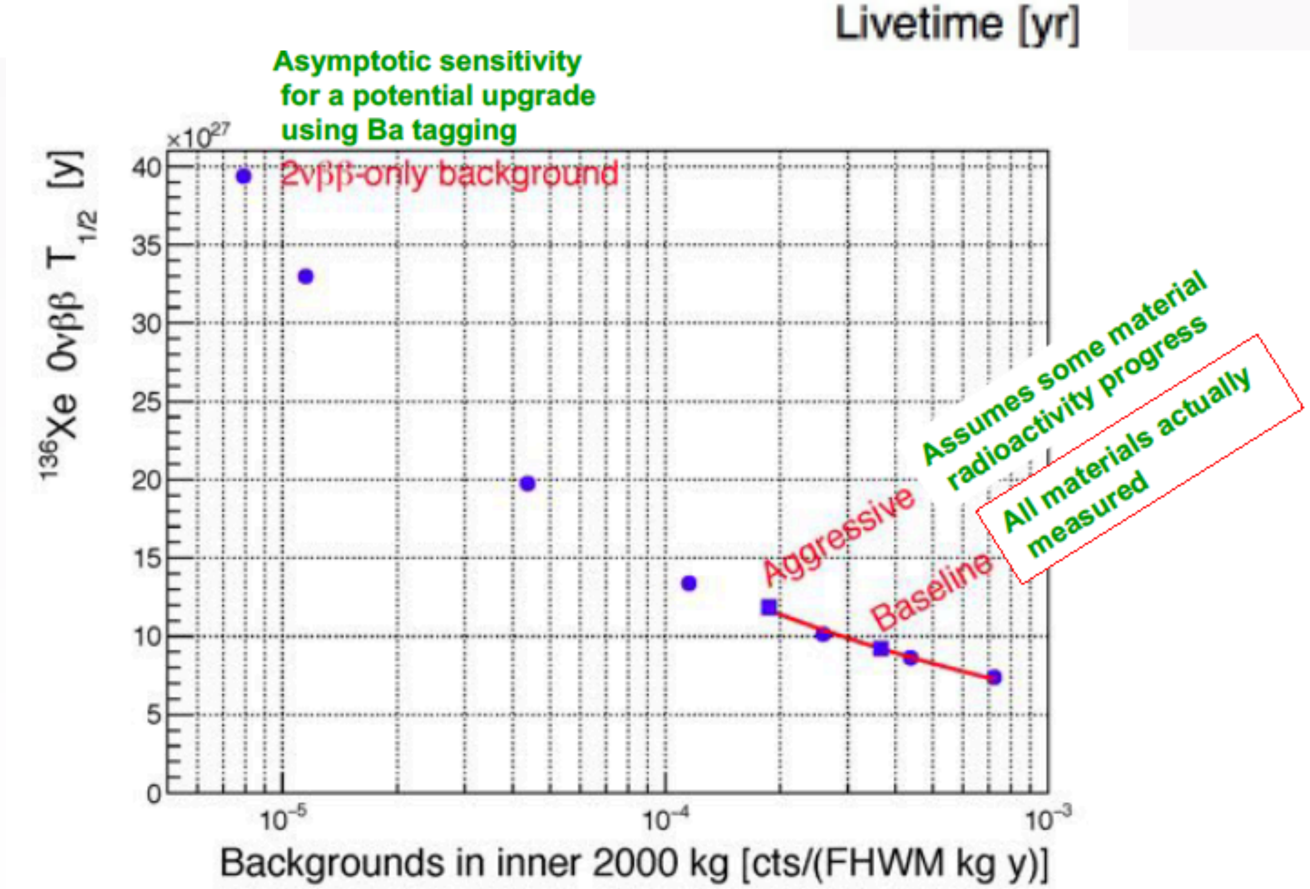




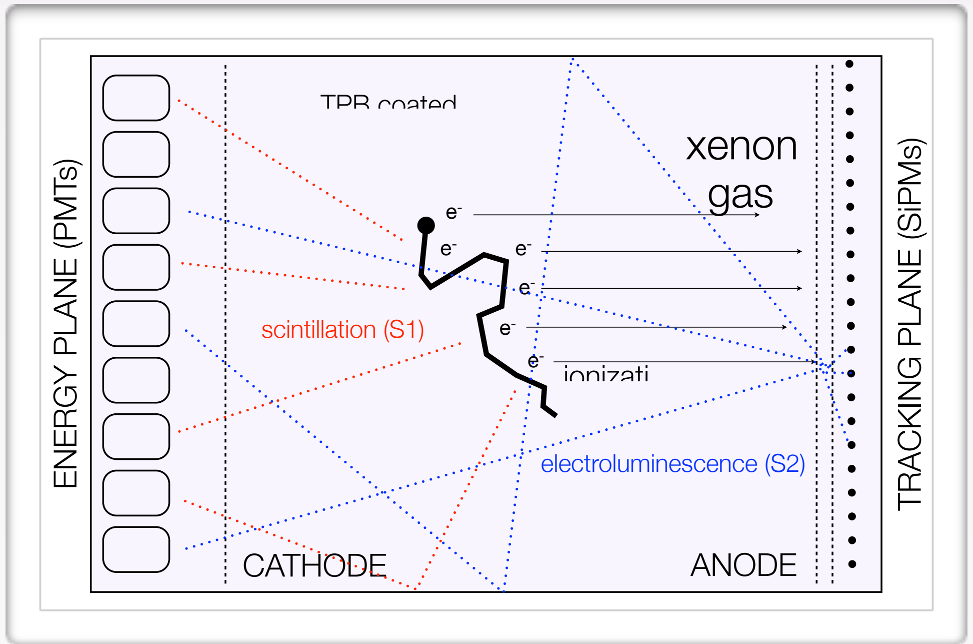
Ba-tagging



Possibility to identify daughter ^{136}Ba to eliminate all backgrounds apart from 2νββ

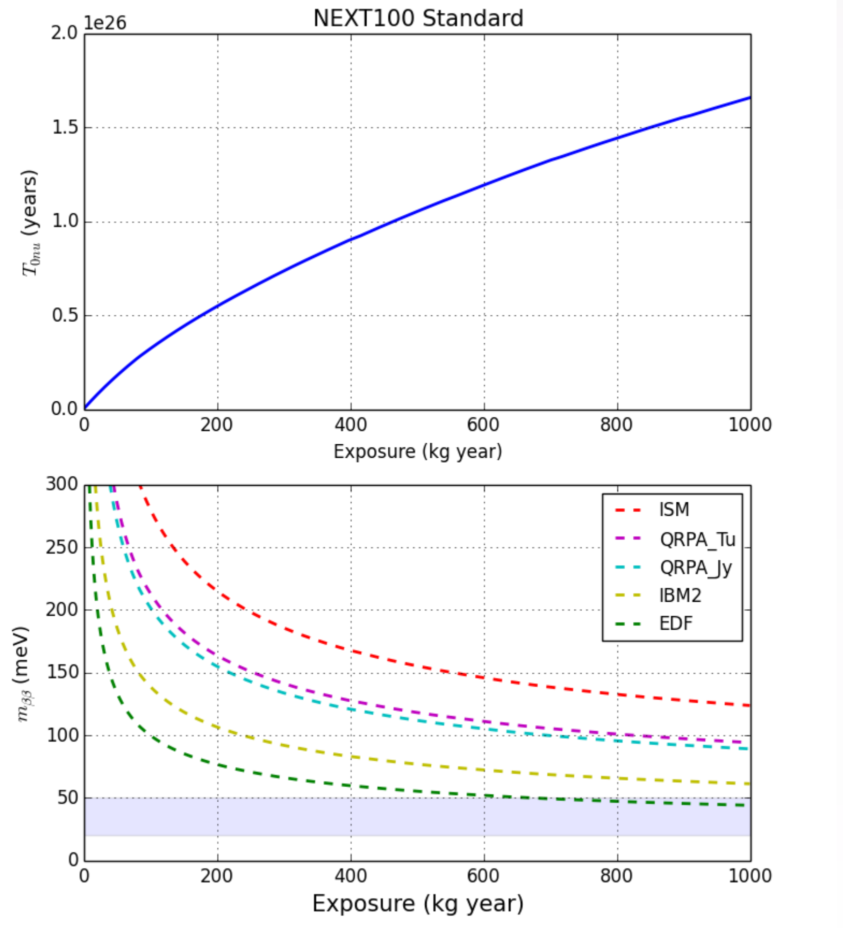


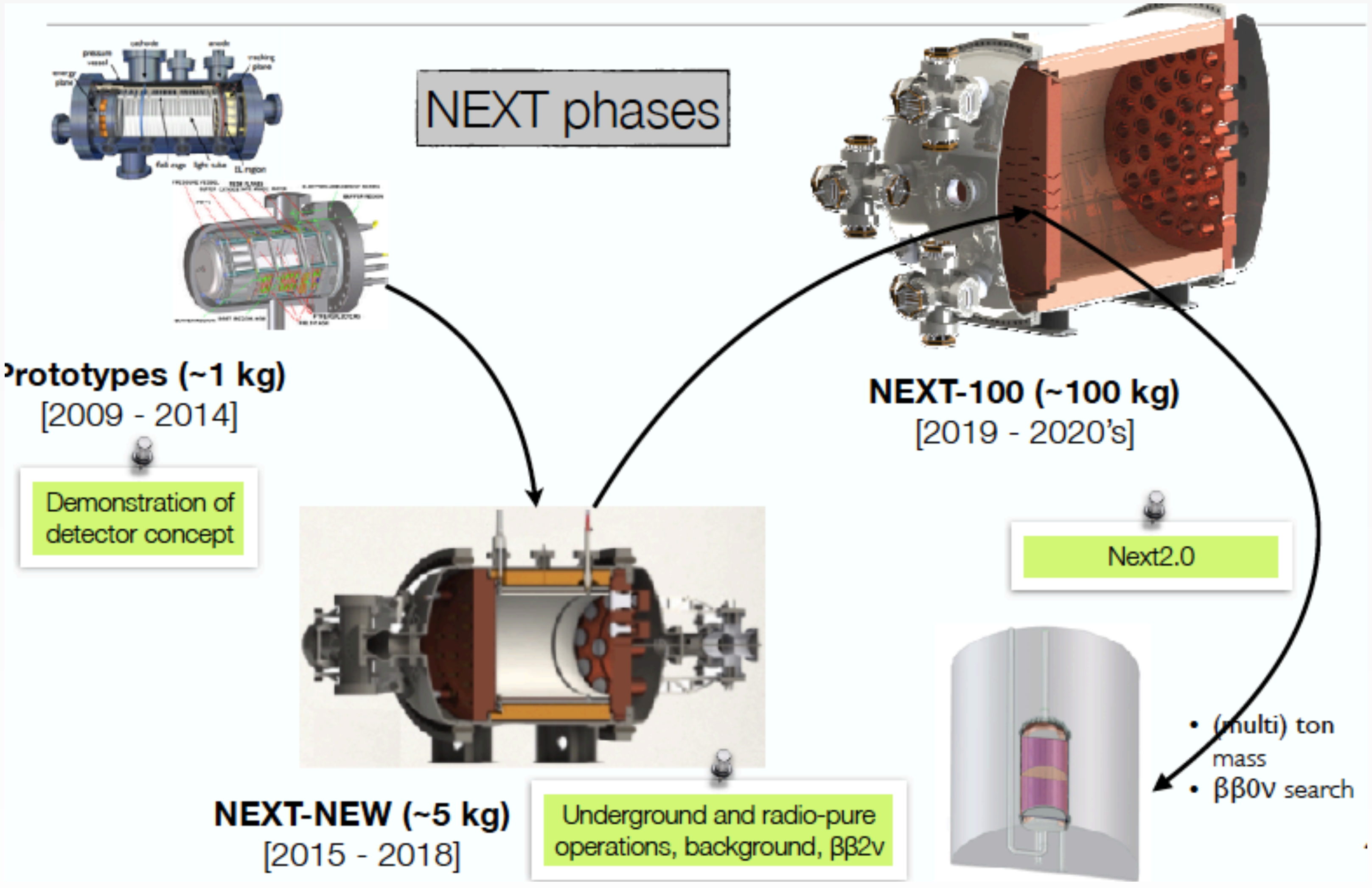
NEXT — High Pressure ^{136}Xe TPC



- High-Pressure ^{136}Xe TPC (10-20 bar)
- **Topological signature** to suppress backgrounds
- EL amplification allows for good **$\Delta E/E$ <1% at $Q_{\beta\beta}$**
- Prototypes operated at LSC (Canfranc, Spain) show reaching resolutions and backgrounds possible

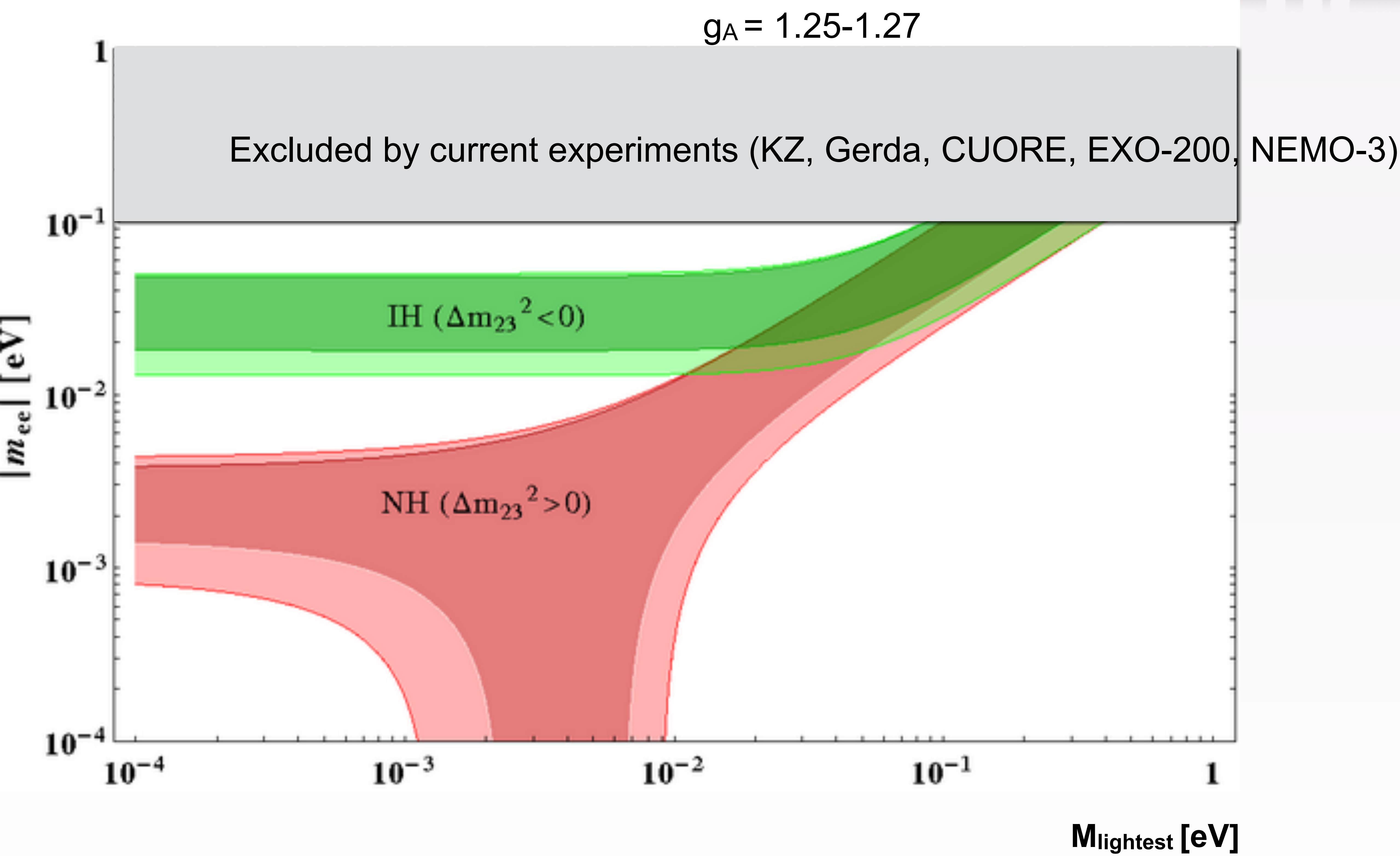
- NEXT-100 aims to start in 2019



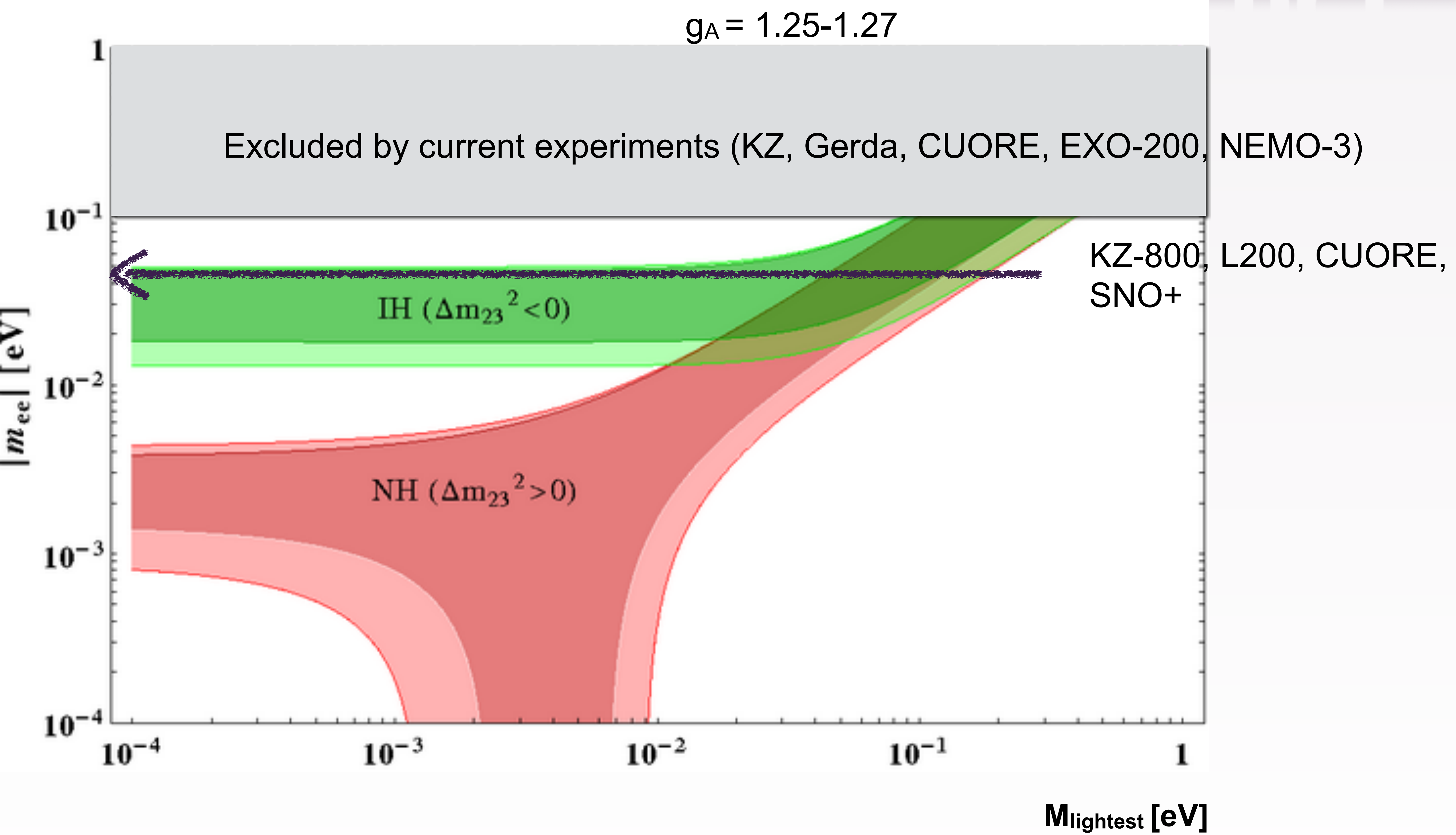


Ba-tagging might be easier in gas

Outlook



g_A = 1.25-1.27
Excluded by current experiments (KZ, Gerda, CUORE, EXO-200, NEMO-3)
IH ($\Delta m_{23}^2 < 0$)
NH ($\Delta m_{23}^2 > 0$)
$|m_{ee}|$ [eV]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
$M_{lightest}$ [eV]


g_A = 1.25-1.27
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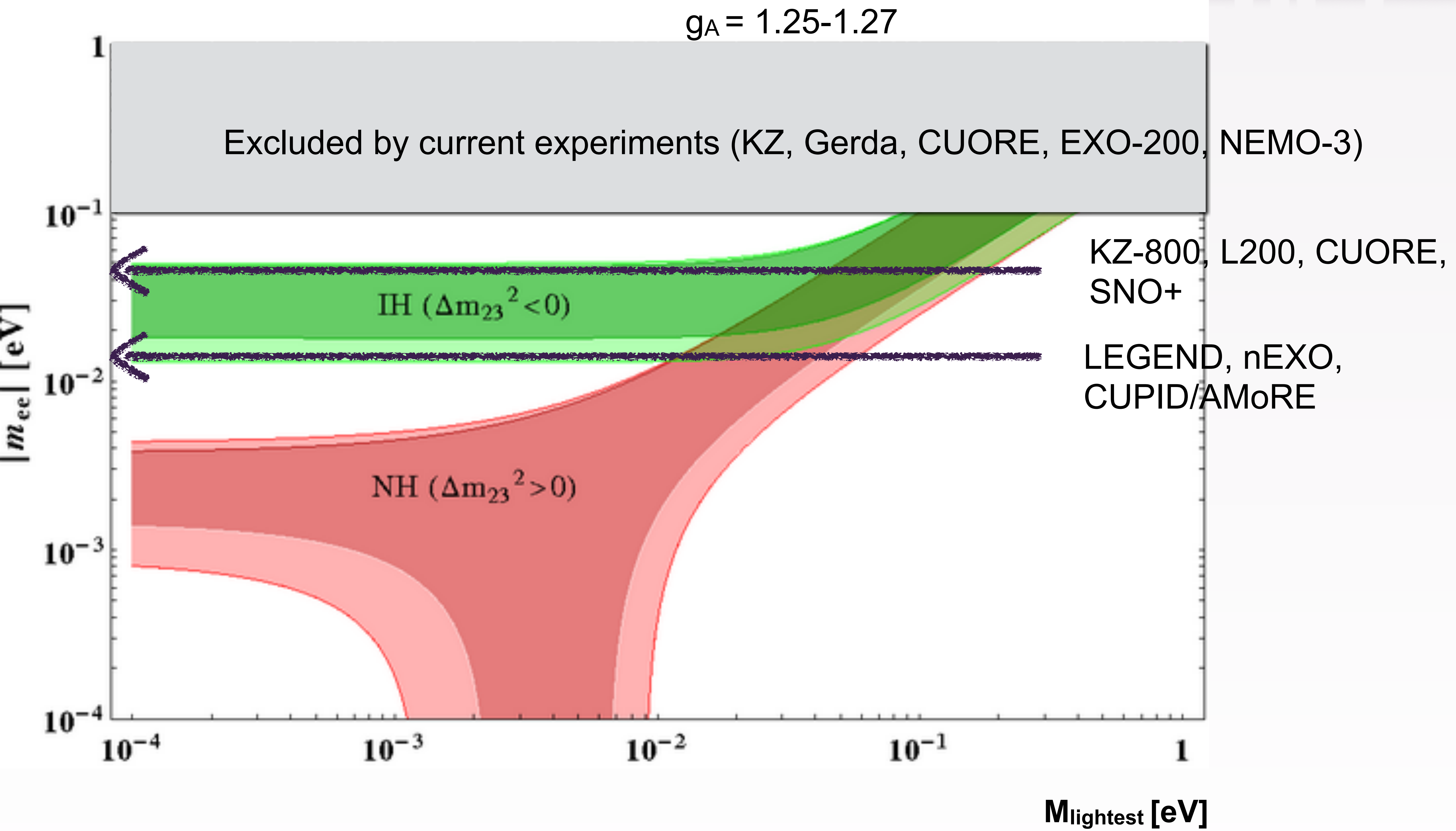
KZ-800, L200, CUORE, SNO+
IH ($\Delta m_{23}^2 < 0$)
NH ($\Delta m_{23}^2 > 0$)
$|m_{ee}|$ [eV]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
$M_{lightest}$ [eV]

Outlook



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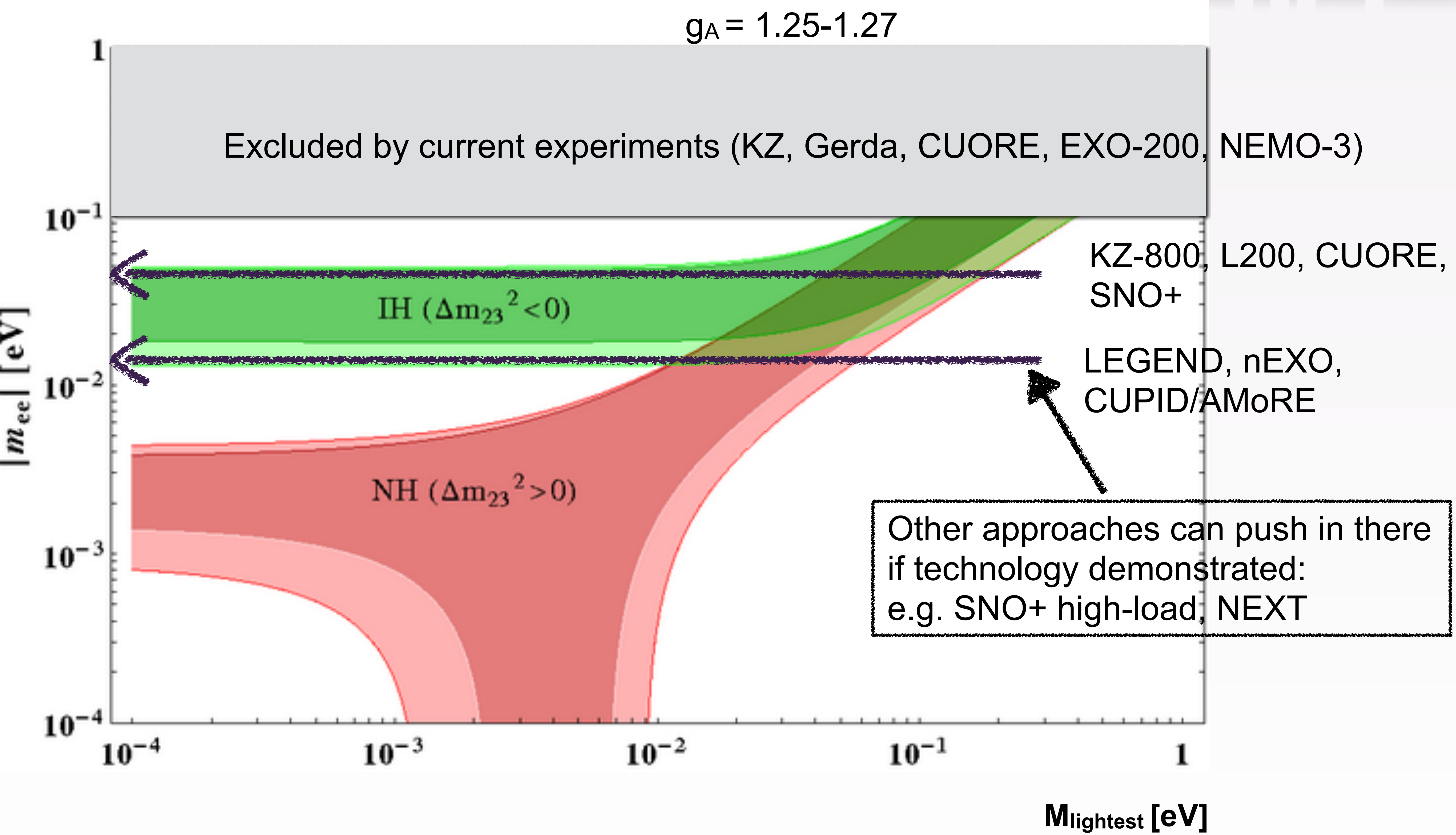
$|m_{ee}|$ [eV]
$M_{lightest}$ [eV]

Outlook

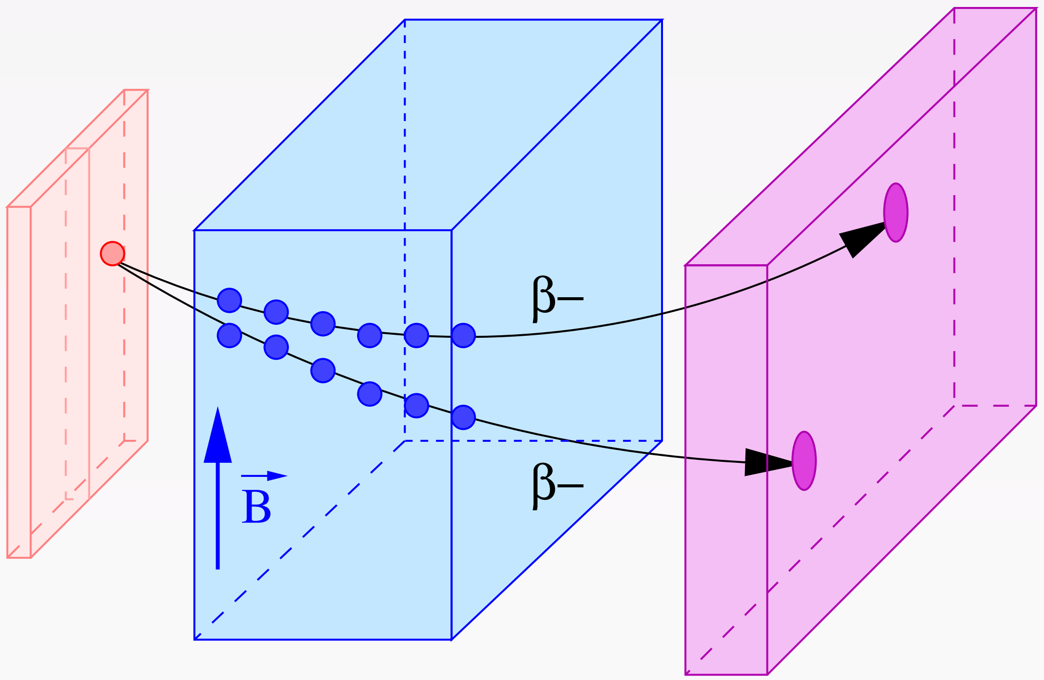


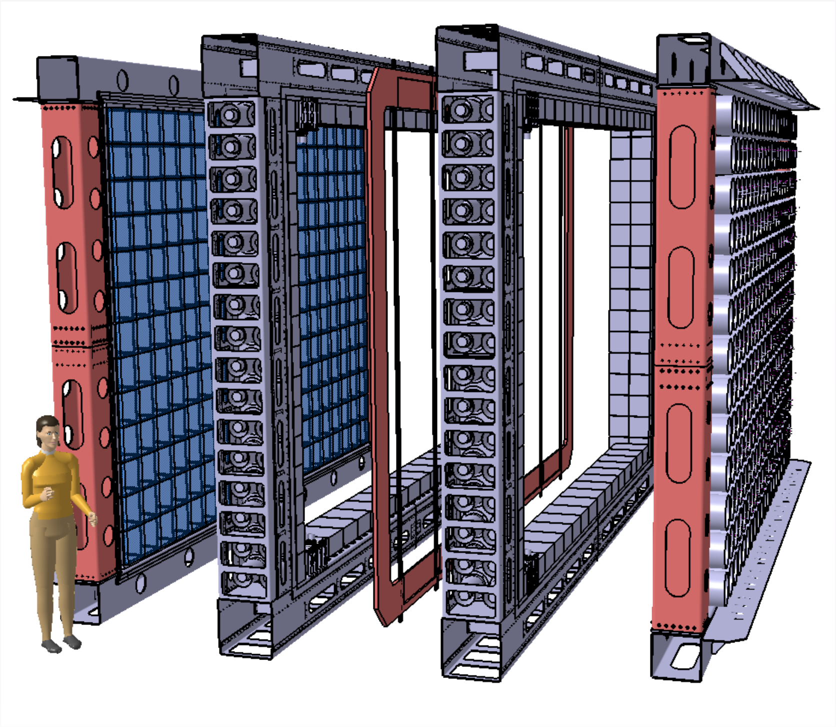
gA = 1.25-1.27
Excluded by current experiments (KZ, Gerda, CUORE, EXO-200, NEMO-3)
KZ-800, L200, CUORE, SNO+
LEGEND, nEXO, CUPID/AMoRE
IH (Δm23 2<0)
NH (Δm23 2>0)
Other approaches can push in there if technology demonstrated: e.g. SNO+ high-load, NEXT
|mee| [eV]
Mlightest [eV]

Planning for success: In the event of a discovery in IH region

Opportunity for:

- **Multi-isotope confirmation**
- **Exploring underlying physics mechanism (need not be <m$_\nu$>)**





- Experience from **SuperNEMO Demonstrator** suggests 10^{26} yr (50 meV) tracking experiment possible
- Can the technique be extended to confirm signal **anywhere in IH** region?
- Under study. There is no "no-go theorem" but requires targeted R&D in parallel with Demonstrator exploitation

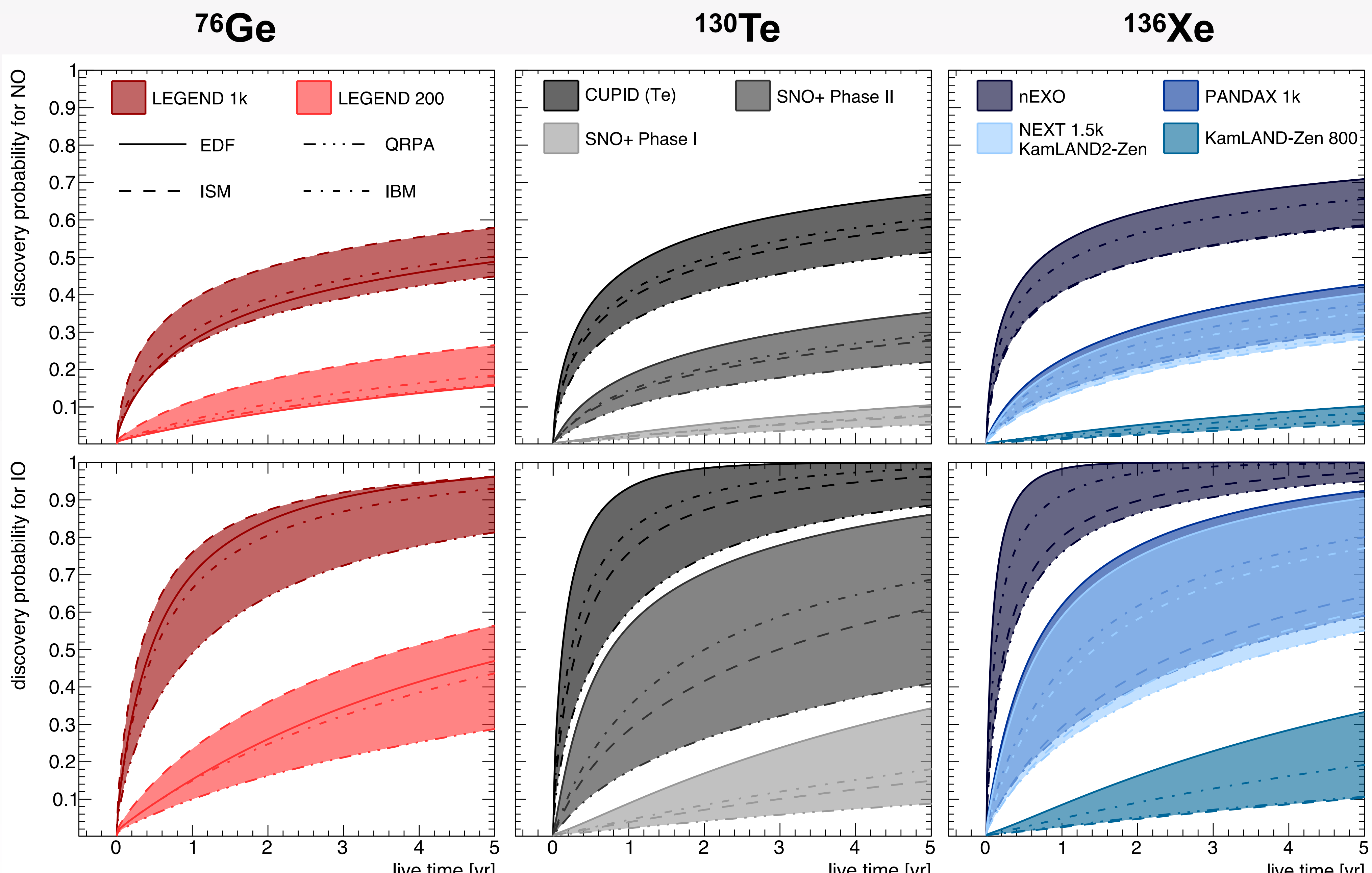
Global Bayesian analysis including neutrino oscillations, ^{3}H β-decay, 0νββ decay, cosmology

Scale-invariant priors: $\Sigma = m_1 + m_2 + m_3;\ \Delta m^2_{ij} \rightarrow$ logarithmic

$\theta_{ij}, \delta, \alpha_{ij} \rightarrow$ flat

3σ Bayesian **discovery probability**

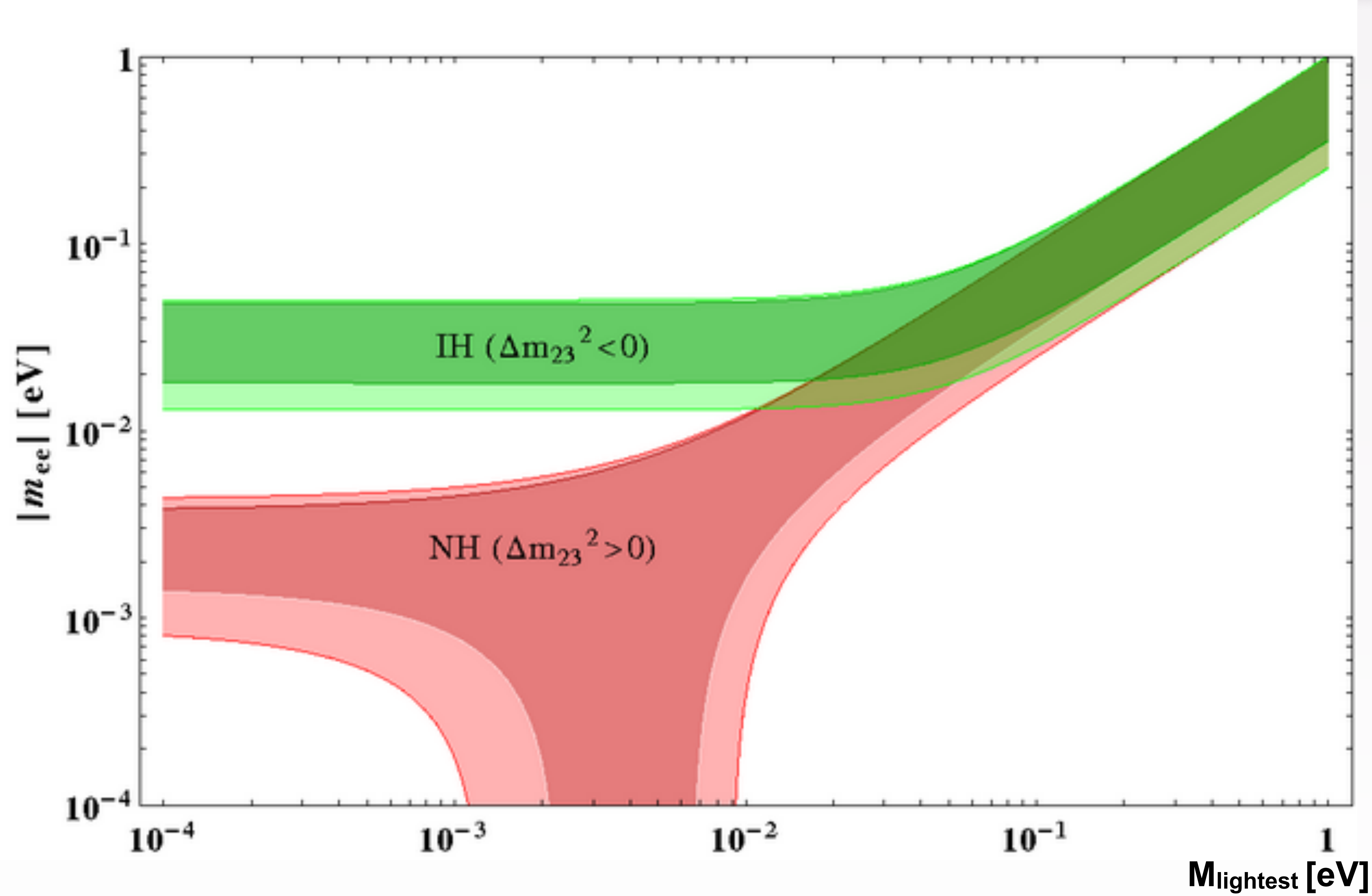
Phys. Rev. D 96, 053001 (2017)



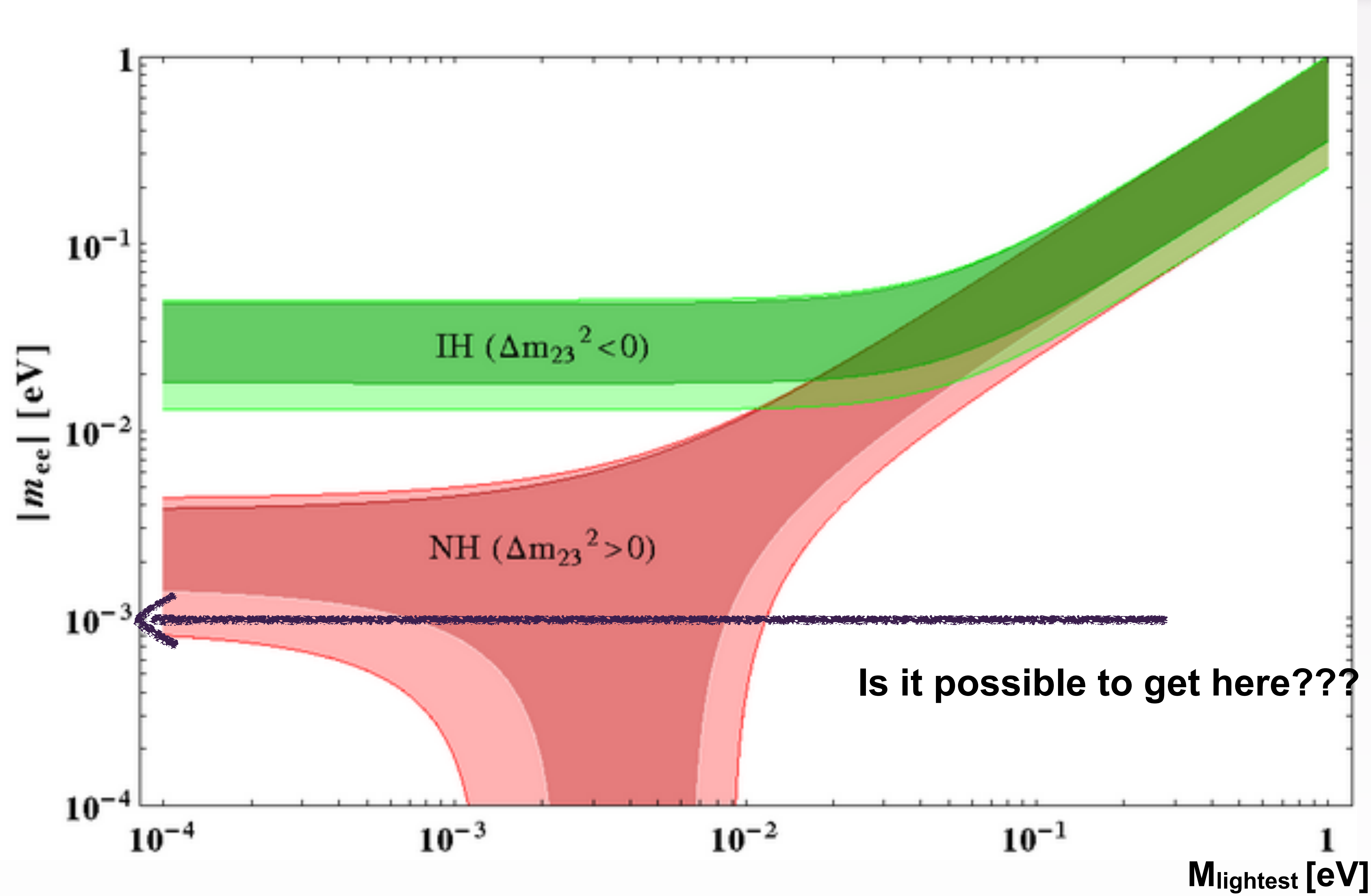
Normal Ordering

Inverted Ordering

Impressive discovery potential of the next generation experiments



IH $(\Delta m_{23}{}^2 < 0)$
NH $(\Delta m_{23}{}^2 > 0)$
$|m_{ee}|$ [eV]
1
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
1
$M_{lightest}$ [eV]



1
10⁻¹
10⁻²
10⁻³
10⁻⁴
|mee| [eV]
IH (Δm23² < 0)
NH (Δm23² > 0)
10⁻⁴
10⁻³
10⁻²
10⁻¹
1
Is it possible to get here???
Mlightest [eV]

Thoughts and speculations on "ultimate"* experiment

*Targeting Normal Ordering of neutrino masses, *O*(meV)

A straightforward extrapolation: **Reaching *O*(meV) requires at least 10t of isotope**

Adopted from arXiv:1803.06894

Isotope	Abundance, %	Cost/kg, k$	Cost/10t, M$
^{76}Ge	7.61	80	640
^{82}Se	8.73	80	640
^{100}Mo	9.63	80	640
^{130}Te	**34.08**	**20**	**160**
^{136}Xe	**8.87**	**5-10**	**40-80**

- Gaseous centrifugation is currently the only feasible isotope enrichment method
  - Current production capacity ~200kg/yr. But x10 increase possible
- ^{130}Te and ^{136}Xe significantly more affordable
- Future breakthrough in enrichment may change this picture

Sensitivity and expected number of 0vbb events after 10t x 10yr =100 t×yr

Range due to NME uncertainties

$\langle m_\nu \rangle$ = 5 meV

Isotope	$T_{1/2}$ (x10^{29} yr)	No of events in ROI
^{48}Ca	0.23-5.6	1.5-37
^{76}Ge	0.48-3.1	1.8-11.5
^{82}Se	**0.14-0.83**	**6-36**
^{96}Zr	**0.05-0.44**	**10-86**
^{100}Mo	**0.05-0.17**	**24-82**
^{130}Te	0.1-1.6	2-32
^{136}Xe	0.16-1.2	2.5-19
^{150}Nd	**0.02-0.23**	**12-140**

$\langle m_\nu \rangle$ = 3 meV

Isotope	$T_{1/2}$ (x10^{29} yr)	No of events in ROI
^{48}Ca	0.64-16	0.5-13.4
^{76}Ge	1.3-8.5	0.7-4.2
^{82}Se	**0.4-2.3**	**2.2-12.5**
^{96}Zr	**0.14-1.2**	**3.6-30.7**
^{100}Mo	**0.13-0.47**	**9-32**
^{130}Te	0.3-4.4	1-11
^{136}Xe	0.4-3.2	1-8
^{150}Nd	**0.06-0.33**	**8.5-47**

For $\langle m_\nu \rangle$ = 1 meV only 100t×yr of ^{150}Nd has any events in RoI: 0.5-5.6

- Assuming an "ideal" detector (good ΔE/E, ε~90-100%, b×ΔE~0) the most promising isotopes appear to be ^{82}Se, ^{96}Zr, ^{100}Mo, ^{150}Nd.
- Only ^{82}Se and ^{100}Mo can be enriched with current technologies but the cost is >0.6B$ only for isotopes (>1B$ for detector)
- ^{130}Te and ^{136}Xe are suitable for a more economical detector (~0.5B$ price tag).
- An "ideal" (see above) detector with ^{130}Te and ^{136}Xe will have some discovery potential in 3-5 meV region.
- A 10t detector with ^{150}Nd could in principle explore a region down to 1 meV. A drastically cheaper technology for ^{150}Nd enrichment will be required.
- Upshot: The "meV" 0νββ experiment will require consolidation of world-wide effort and breakthroughs in a number of technologies

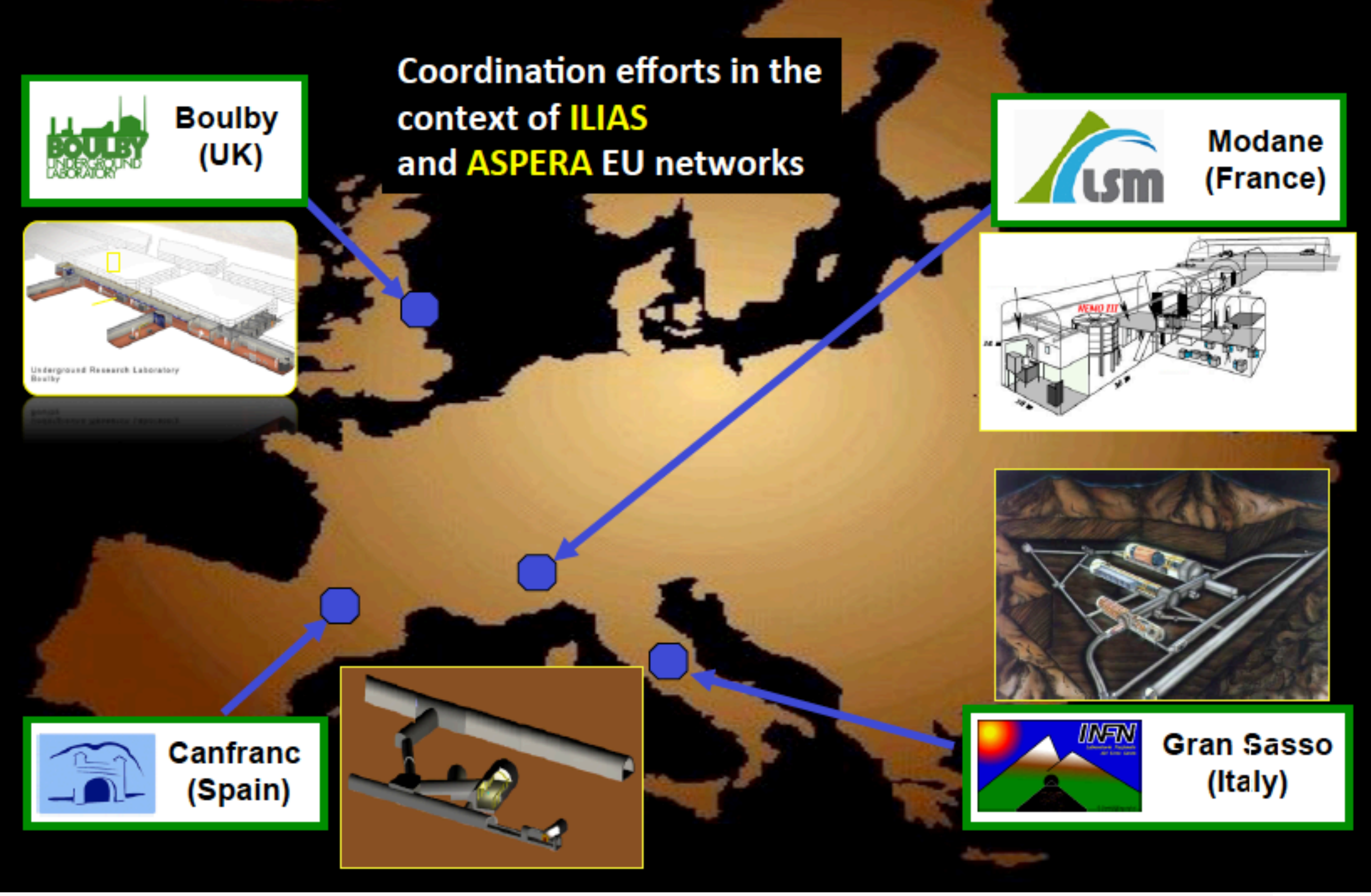
Concluding Remarks I

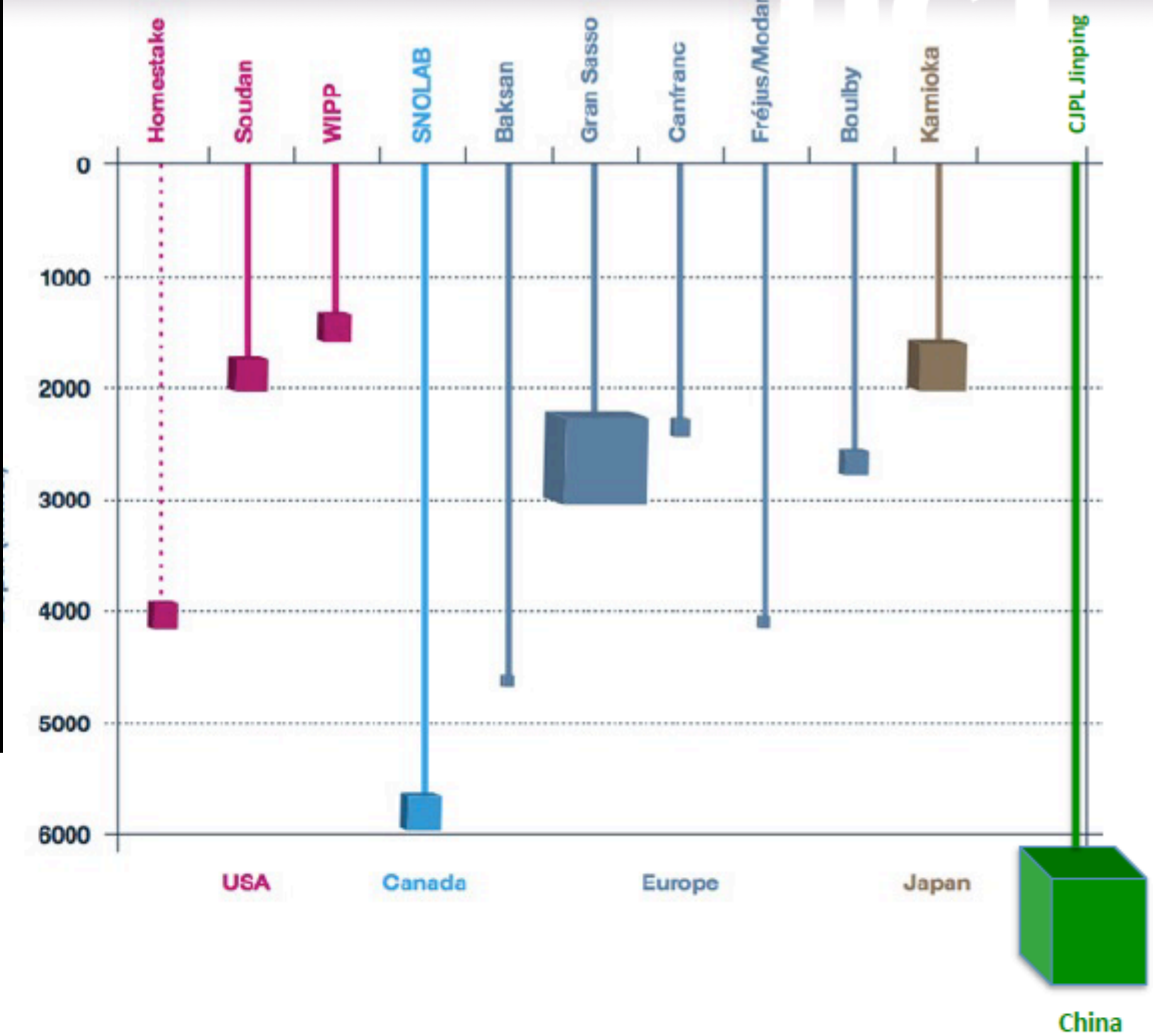
- **0νββ** is the **most sensitive way** to probe **Lepton Number Violation** and its connection to **neutrino mass** mechanism
- The case for **0νββ** is compelling **regardless** of nature's choice for **neutrino mass ordering**
- **0νββ** community is **technologically ready** for experiments exploring **IO** region down to **10-20 meV** — Next Generation NDBD (**NG-NDBD**)
  - **Phased approach** is a must with every stage informing the next phase.
  - Important to be open minded about **mechanism behind LNV** (beyond neutrino mass)

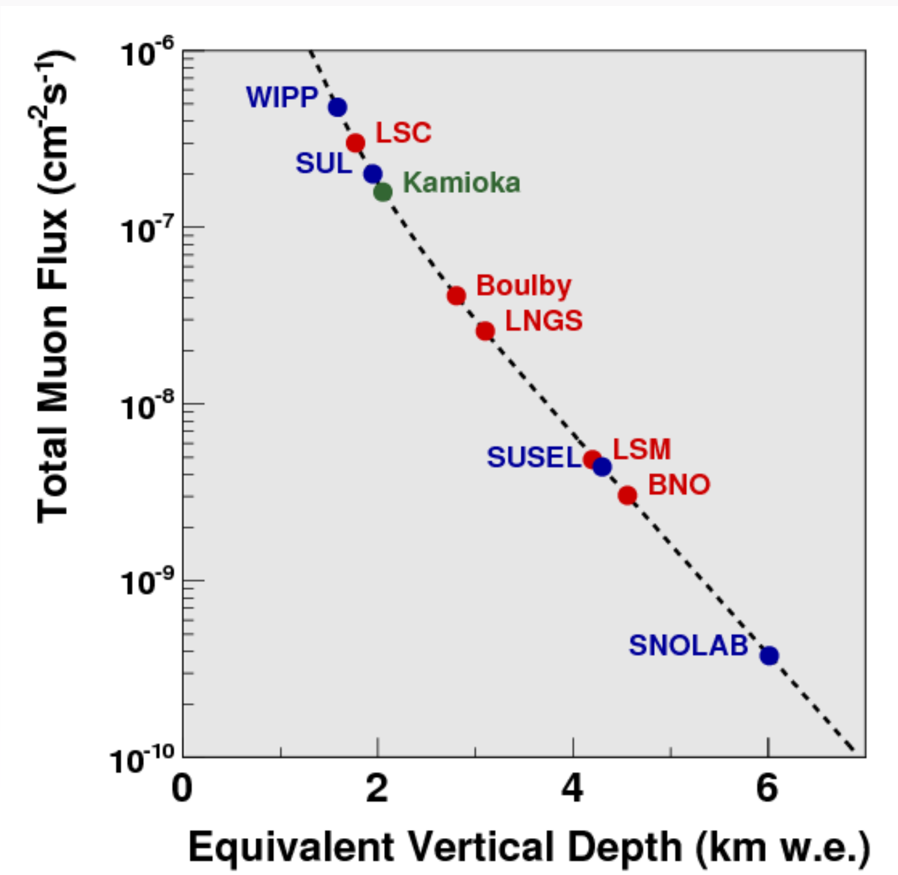
Concluding Remarks II

- **Consolidation of effort** is required as NDBD become *O*($100M) experiments.
  - With experiments operational in mid-2020's. 10 meV target may be reached by mid-late 2030's
  - Does it make sense to push for synergies with DM more aggressively (e.g. combined DM/NDBD LXe experiment)?
- **A major international effort is required for R&D towards "ultimate" experiment aimed at exploring NO region down to *O*(meV)**

BACKUP

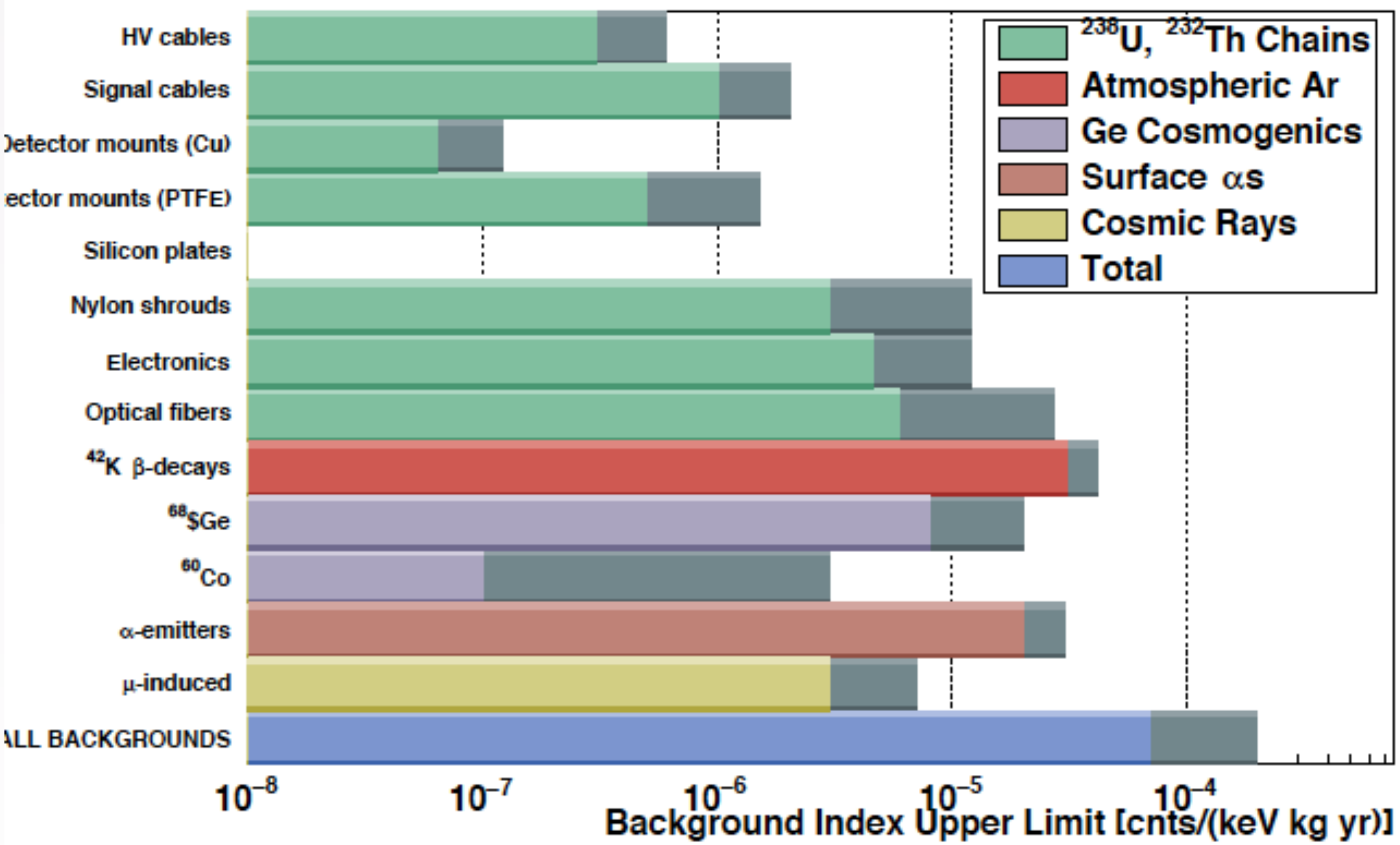






Europe needs to support and enhance its deep underground laboratories to maintain leadership

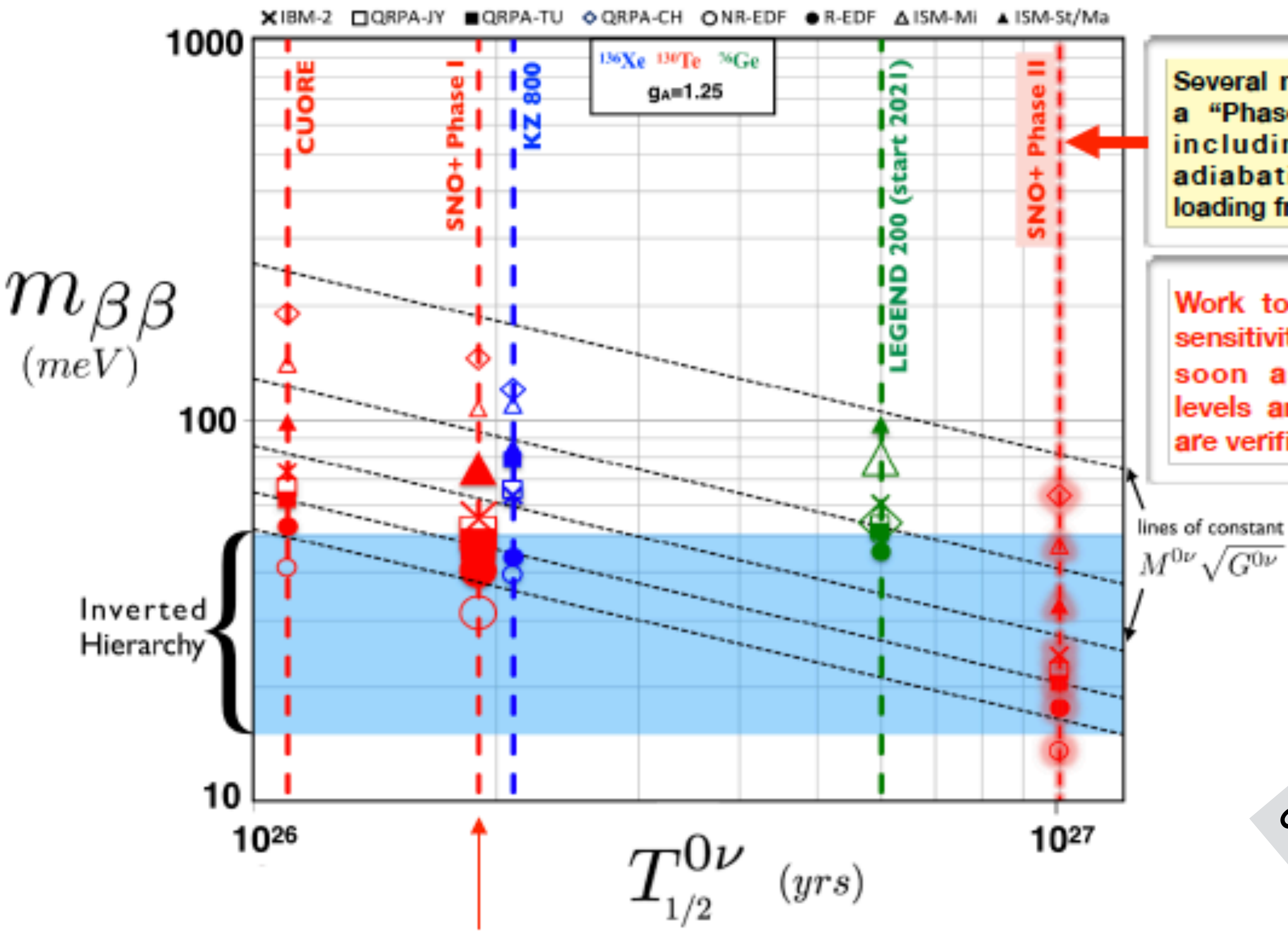
LEGEND-200 background projections



$Q_{\beta\beta}$ BI upper Limit: 7 10^{-5} – 2 10^{-4} cts/(keV kg yr)

- Monte Carlo simulations based on experimental data and material assays.
- Assay limits correspond to the 90% CL upper limit.
- Grey bands indicate uncertainties in overall background rejection efficiency.

Comparison of projected sensitivities after a nominal 5 year SNO+ run (2024) assuming we remain at the nominal 0.5% Te loading level:



Several routes to achieve a "Phase II" sensitivity, including a possible adiabatic increase in loading from Phase I

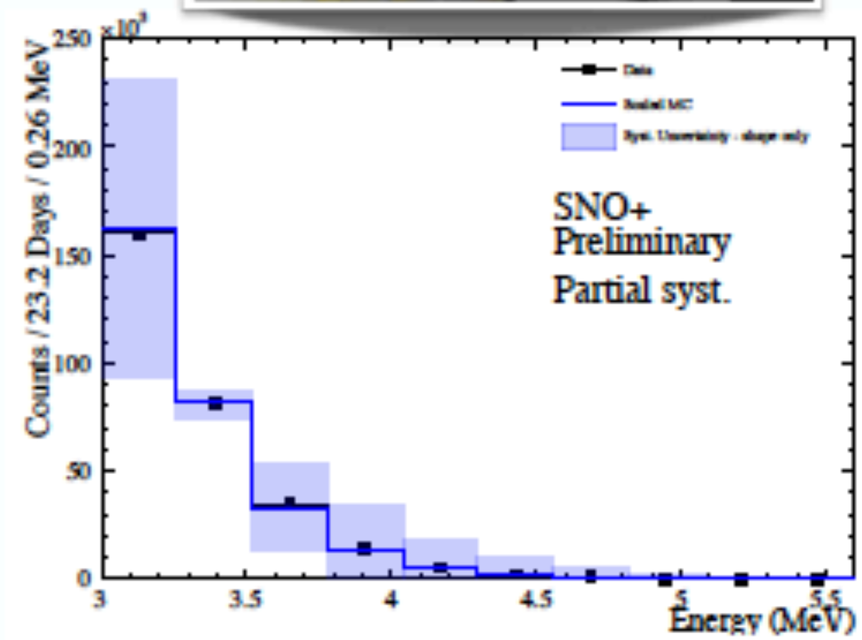
Work towards Phase II sensitivity will begin as soon as background levels and performance are verified for Phase I

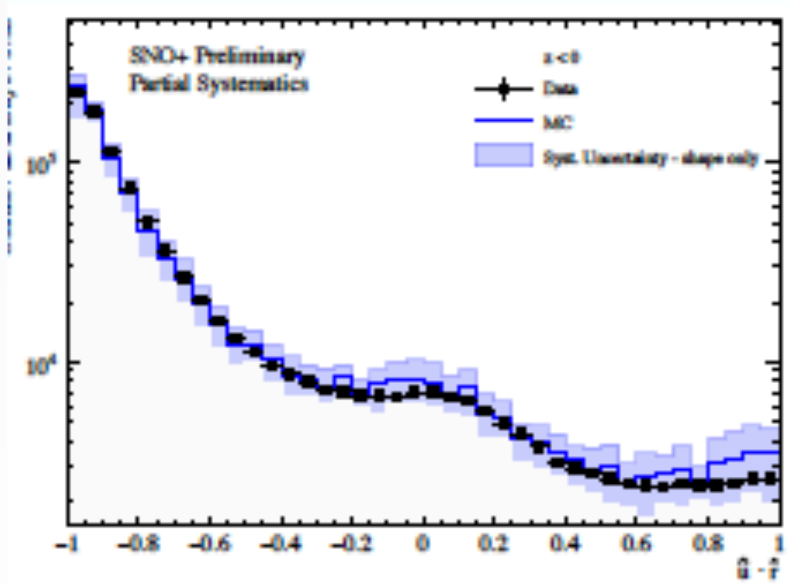
Slide by S. Biller

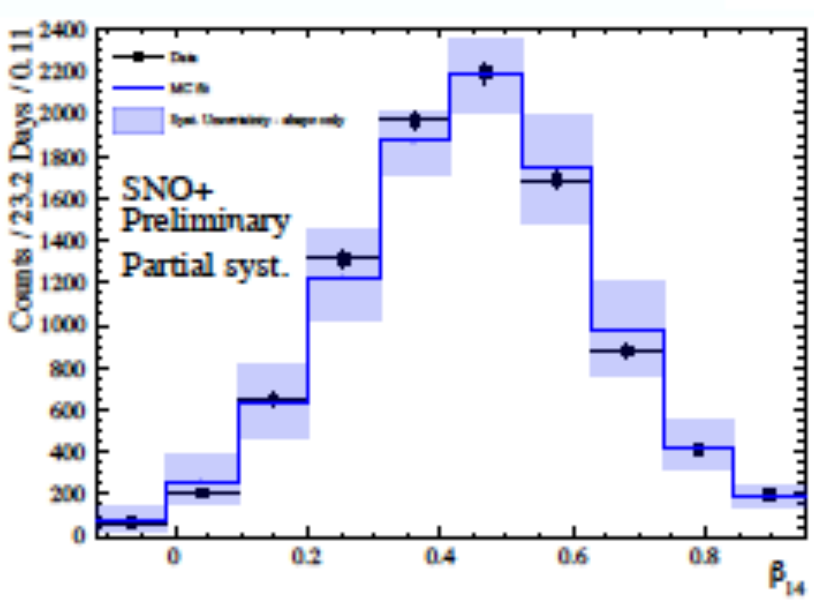
SNO+ Water run background results

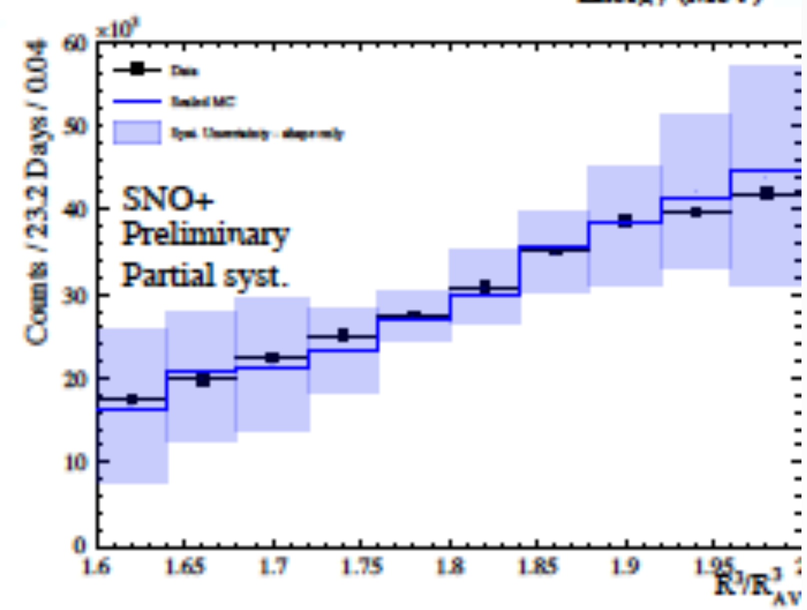
Source	Analysis	Results (measured/expectation)
PMTs	Box	1.07 ± 0.01 (stat) ± 0.66 (syst)
	Fit	1.07 ± 0.002 (stat) $^{+0.76}_{-0.42}$ (syst)
AV + ropes	Box	0.8 ± 0.4 (stat) ± 1.1 (syst)
	Fit	1.35 ± 0.13 (stat) $^{+1.05}_{-0.97}$ (syst)

All results consistent with expectation

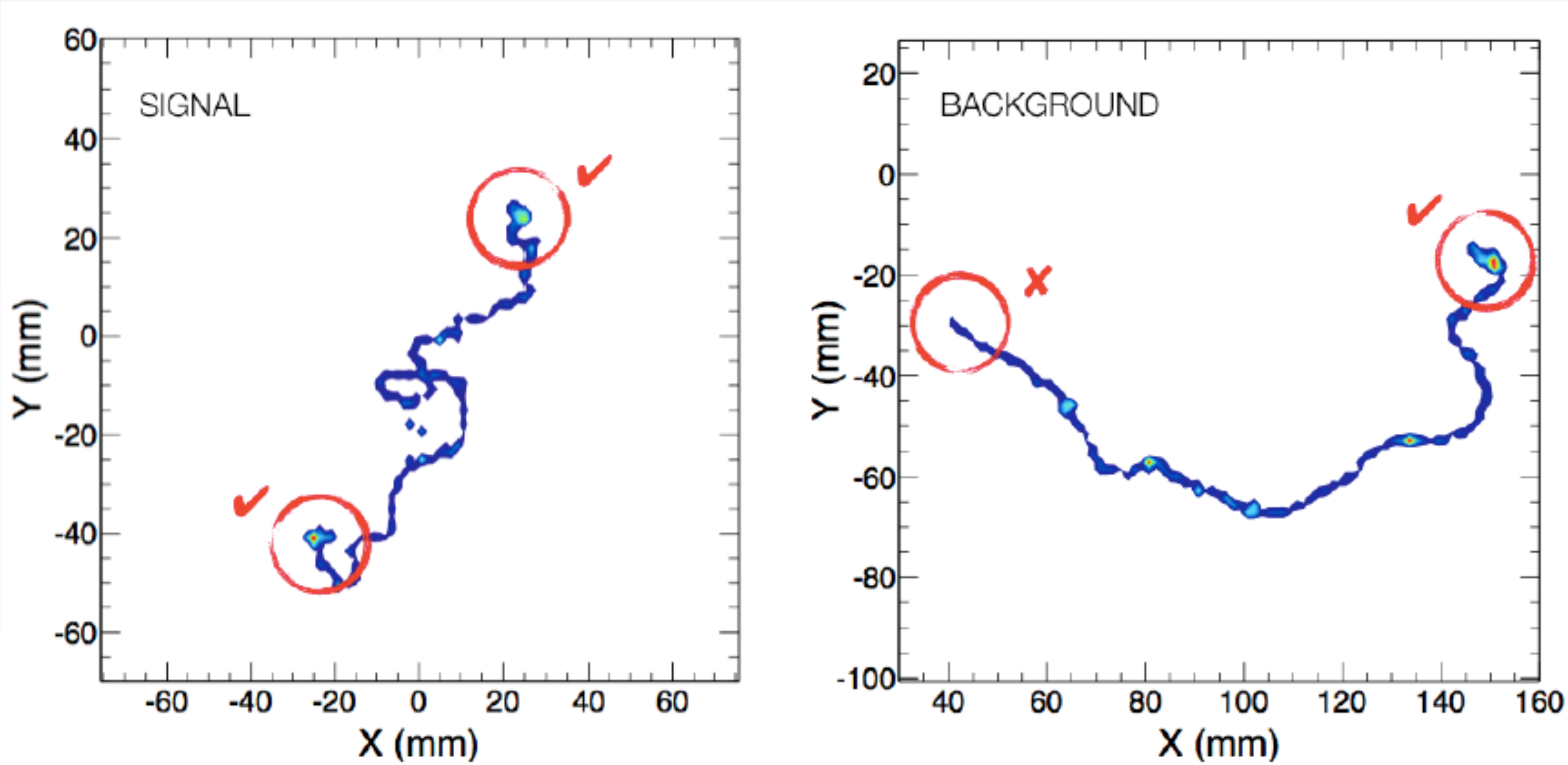








Topological Signature in NEXT



The quenching of g_A

by J. Suhonen

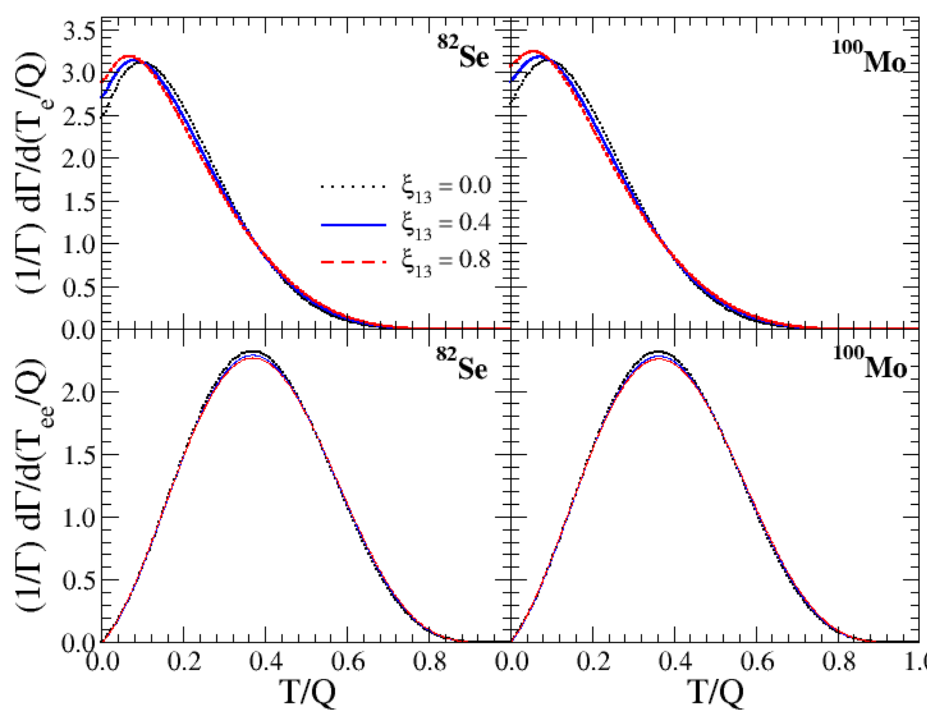
$$0\nu\beta\beta - \text{rate} \sim \left|M^{(0\nu)}_{\text{GTGT}}\right|^2 = (g_{\text{A},0\nu})^4 \left|\sum_{J^\pi}(0_f^+||\mathcal{O}^{(0\nu)}_{\text{GTGT}}(J^\pi)||0_i^+)\right|^2$$

potentially harmful!

Can it be extracted from double-β(2ν) and single-β experimental data?

$$2\nu\beta\beta - \text{rate} \sim \left|M^{(2\nu)}_{\text{GTGT}}\right|^2 = (g_{\text{A}})^4 \left|\sum_{m,n}\frac{M_{\text{L}}(1_m^+)M_{\text{R}}(1_n^+)}{D_m}\right|^2$$

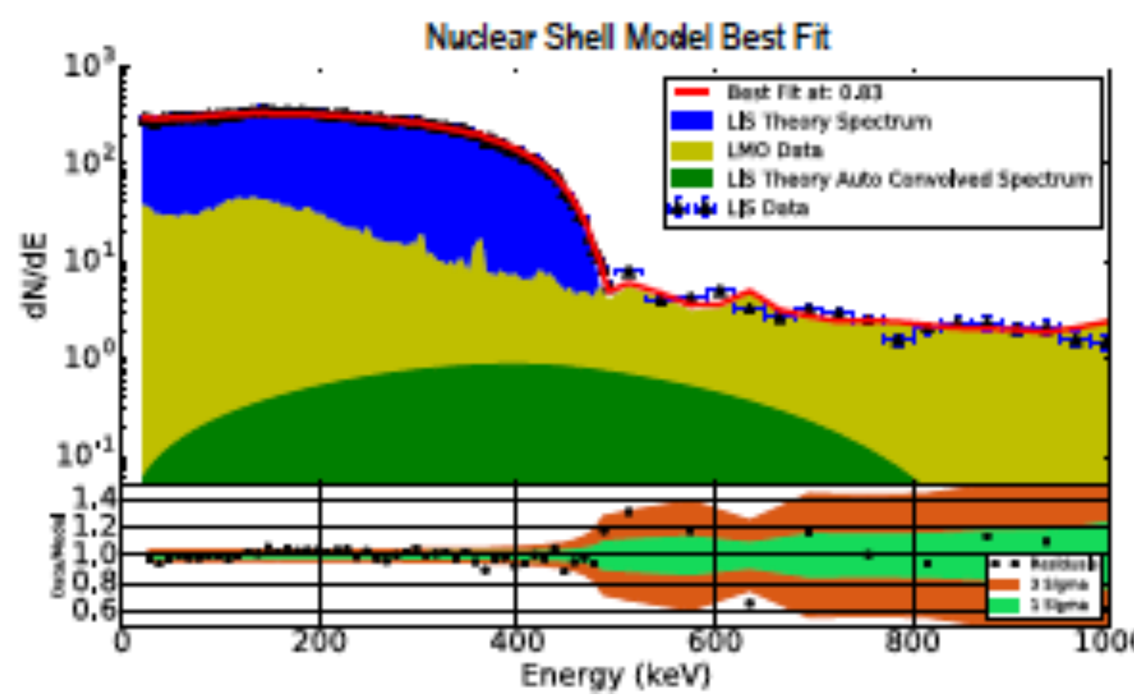
Yes, but still need nuclear physics model



Possible input from SuperNEMO Demonstrator (single electron spectra/angular distribution)
Collaboration with Simkovic and Deppisch

poster by A. Leder

Measuring ^{115}In β-decay shape with $LiInSe_2$ crystal



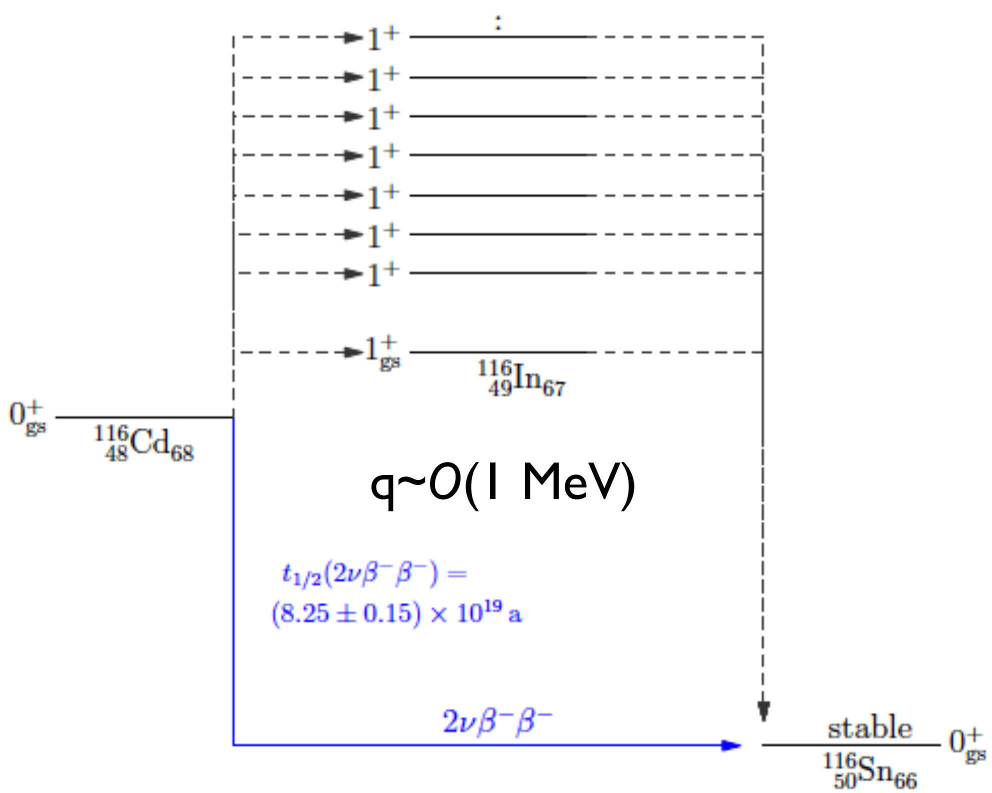
Nuclear Model	g_A Value	Error	Best χ^2
Shell Model	0.83	$\pm$ 0.03	158.2
MQPM Model	0.94	$^{+0.03}_{-0.04}$	170.5
IBM Model	0.880	$\pm$ 0.06	269.0

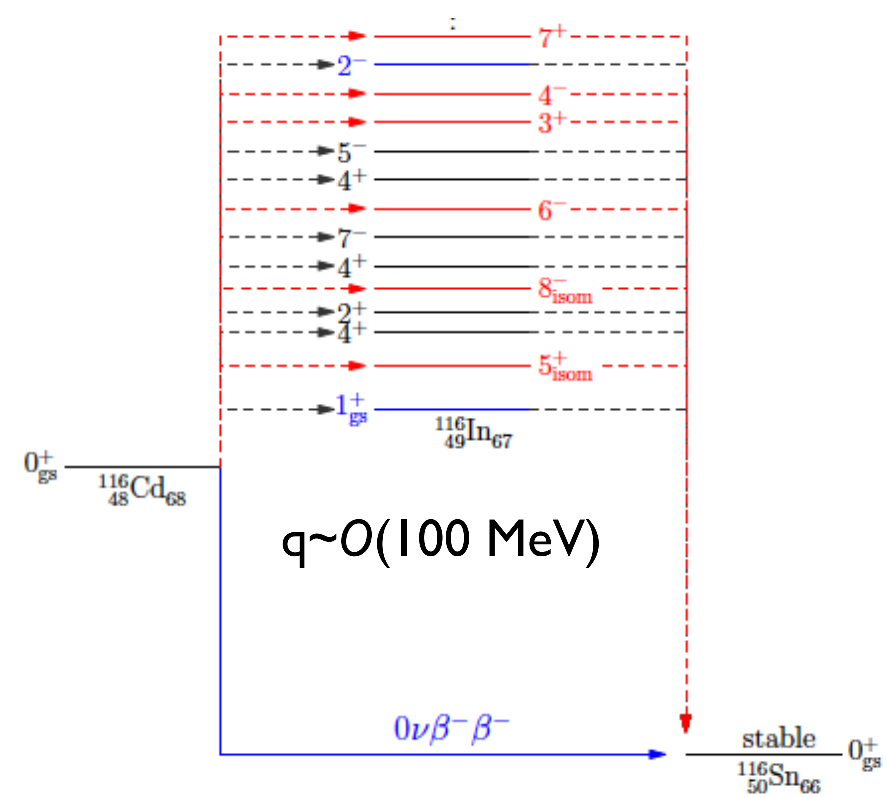
g_A quenching status as of Neutrino'18

Mass range	$A = 76 - 82$	$A = 100 - 116$	$A = 122 - 136$
$g^{\text{eff}}_{\text{A},0\nu}$	$0.7 - 0.9$	0.5	$0.5 - 0.7$

by J. Suhonen

Too early to panic — quenching must depend on momentum transfer





Petcov: Do you mean we do not understand g_A quenching?

Suhonen: Yes. Thank you for summarising my talk .

Reformulate SSD vs HSD in order to extract g_A from $2\nu\beta\beta$?

F.Šimkovic et al. Phys. Rev. C 97, 034315 (2018)

$$\left[T^{2\nu}_{1/2}\right]^{-1} = \frac{m_e}{8\pi^7 \ln 2}(G_\beta m_e^2)^4 \left(g_A^{\rm eff}\right)^4 I^{2\nu},$$

$$I^{2\nu} = \frac{1}{m_e^{11}} \int_{m_e}^{E_i - E_f - m_e} F_0(Z_f, E_{e_1}) p_{e_1} E_{e_1} dE_{e_1} \times \int_{m_e}^{E_i - E_f - E_{e_1}} F_0(Z_f, E_{e_2}) p_{e_2} E_{e_2} dE_{e_2} \times \int_0^{E_i - E_f - E_{e_1} - E_{e_2}} E_{\nu_1}^2 E_{\nu_2}^2 \mathcal{A}^{2\nu} dE_{\nu_1}.$$

$$\mathcal{A}^{2\nu} = \left[\frac{1}{4}|M_{GT}^K + M_{GT}^L|^2 + \frac{1}{12}|M_{GT}^K - M_{GT}^L|^2\right],$$

where

$$M_{GT}^{K,L} = m_e \sum_n M_n \frac{E_n - (E_i + E_f)/2}{[E_n - (E_i + E_f)/2]^2 - \varepsilon_{K,L}^2}$$

with

$$M_n = \langle 0_f^+ \| \sum_m \tau_m^- \sigma_m \| 1_n^+ \rangle \langle 1_n^+ \| \sum_m \tau_m^- \sigma_m \| 0_i^+ \rangle,$$

$$\varepsilon_K = (E_{e_2} + E_{\nu_2} - E_{e_1} - E_{\nu_1})/2,$$
$$\varepsilon_L = (E_{e_1} + E_{\nu_2} - E_{e_2} - E_{\nu_1})/2.$$

Include lepton energies by performing Taylor expansion over the ratio $\varepsilon_{K,L}/(E_n - (E_i + E_f)/2)$

Reformulate SSD vs HSD in order to extract g_A from $2\nu\beta\beta$?

F.Šimkovic et al. Phys. Rev. C 97, 034315 (2018)

Then

$$\left[T_{1/2}^{2\nu}\right]^{-1} \equiv \frac{\Gamma^{2\nu}}{\ln(2)} \simeq \frac{\Gamma_0^{2\nu} + \Gamma_2^{2\nu} + \Gamma_4^{2\nu}}{\ln(2)}$$

$$\frac{\Gamma_0^{2\nu}}{\ln(2)} = \left(g_A^{\rm eff}\right)^4 \mathcal{M}_0 G_0^{2\nu}, \quad \frac{\Gamma_2^{2\nu}}{\ln(2)} = \left(g_A^{\rm eff}\right)^4 \mathcal{M}_2 G_2^{2\nu}$$

$$\frac{\Gamma_4^{2\nu}}{\ln(2)} = \left(g_A^{\rm eff}\right)^4 \left(\mathcal{M}_4 G_4^{2\nu} + \mathcal{M}_{22} G_{22}^{2\nu}\right).$$

Keeping only first expansion term

$$\begin{aligned}(T_{1/2}^{2\nu})^{-1} &\simeq (g_A^{\rm eff})^4 \left|(M_{GT}^{2\nu})^2 G_0^{2\nu} + M_{GT}^{2\nu} M_{GT-3}^{2\nu} G_2^{2\nu}\right| \\ &= (g_A^{\rm eff})^4 |M_{GT-3}^{2\nu}|^2 \frac{1}{|\xi_{31}^{2\nu}|^2} \left|G_0^{2\nu} + \xi_{31}^{2\nu} G_2^{2\nu}\right|,\end{aligned}$$

$$\xi_{31}^{2\nu} = \frac{M_{GT-3}^{2\nu}}{M_{GT-1}^{2\nu}}$$

Reformulate SSD vs HSD in order to extract g_A from $2\nu\beta\beta$?

F.Šimkovic et al. Phys. Rev. C 97, 034315 (2018)

or in full:

$$G_N^{2\nu} = \frac{c_{2\nu}}{m_e^{11}} \int_{m_e}^{E_i - E_f - m_e} F_0(Z_f, E_{e_1}) p_{e_1} E_{e_1} dE_{e_1}$$
$$\times \int_{m_e}^{E_i - E_f - E_{e_1}} F_0(Z_f, E_{e_2}) p_{e_2} E_{e_2} dE_{e_2} \quad (14)$$
$$\times \int_0^{E_i - E_f - E_{e_1} - E_{e_2}} E_{\nu_1}^2 E_{\nu_2}^2 A_N^{2\nu} dE_{\nu_1}, \quad (\text{N}=0,\ 2,\ 4,\ 22)$$

with $c_{2\nu} = m_e (G_\beta m_e^2)^4 / (8\pi^7 \ln 2)$ and

$$A_0^{2\nu} = 1, \quad A_2^{2\nu} = \frac{\varepsilon_K^2 + \varepsilon_L^2}{(2m_e)^2},$$
$$A_{22}^{2\nu} = \frac{\varepsilon_K^2 \varepsilon_L^2}{(2m_e)^4}, \quad A_4^{2\nu} = \frac{\varepsilon_K^4 + \varepsilon_L^4}{(2m_e)^4}.$$

The products of nuclear matrix elements are given by

$$\mathcal{M}_0 = \left(M_{GT-1}^{2\nu}\right)^2,$$
$$\mathcal{M}_2 = M_{GT-1}^{2\nu} M_{GT-3}^{2\nu},$$
$$\mathcal{M}_{22} = \frac{1}{3}\left(M_{GT-3}^{2\nu}\right)^2,$$
$$\mathcal{M}_4 = \frac{1}{3}\left(M_{GT-3}^{2\nu}\right)^2 + M_{GT-1}^{2\nu} M_{GT-5}^{2\nu}, \quad (16)$$

where nuclear matrix elements take the forms

$$M_{GT-1}^{2\nu} \equiv M_{GT}^{2\nu}$$
$$M_{GT-3}^{2\nu} = \sum_n M_n \frac{4\, m_e^3}{(E_n - (E_i + E_f)/2)^3},$$
$$M_{GT-5}^{2\nu} = \sum_n M_n \frac{16\, m_e^5}{(E_n - (E_i + E_f)/2)^5}. \quad (17)$$

By introducing two ratios of nuclear matrix elements,

$$\xi_{31}^{2\nu} = \frac{M_{GT-3}^{2\nu}}{M_{GT-1}^{2\nu}}, \quad \xi_{51}^{2\nu} = \frac{M_{GT-5}^{2\nu}}{M_{GT-1}^{2\nu}}, \quad (18)$$

$$\left[T_{1/2}^{2\nu\beta\beta}\right]^{-1} = \left(g_A^{\text{eff}}\right)^4 \left|M_{GT-1}^{2\nu}\right|^2 \left(G_0^{2\nu} + \xi_{31}^{2\nu} G_2^{2\nu} + \frac{1}{3}\left(\xi_{31}^{2\nu}\right)^2 G_{22}^{2\nu} + \left(\frac{1}{3}\left(\xi_{31}^{2\nu}\right)^2 + \xi_{51}^{2\nu}\right) G_4^{2\nu}\right),$$