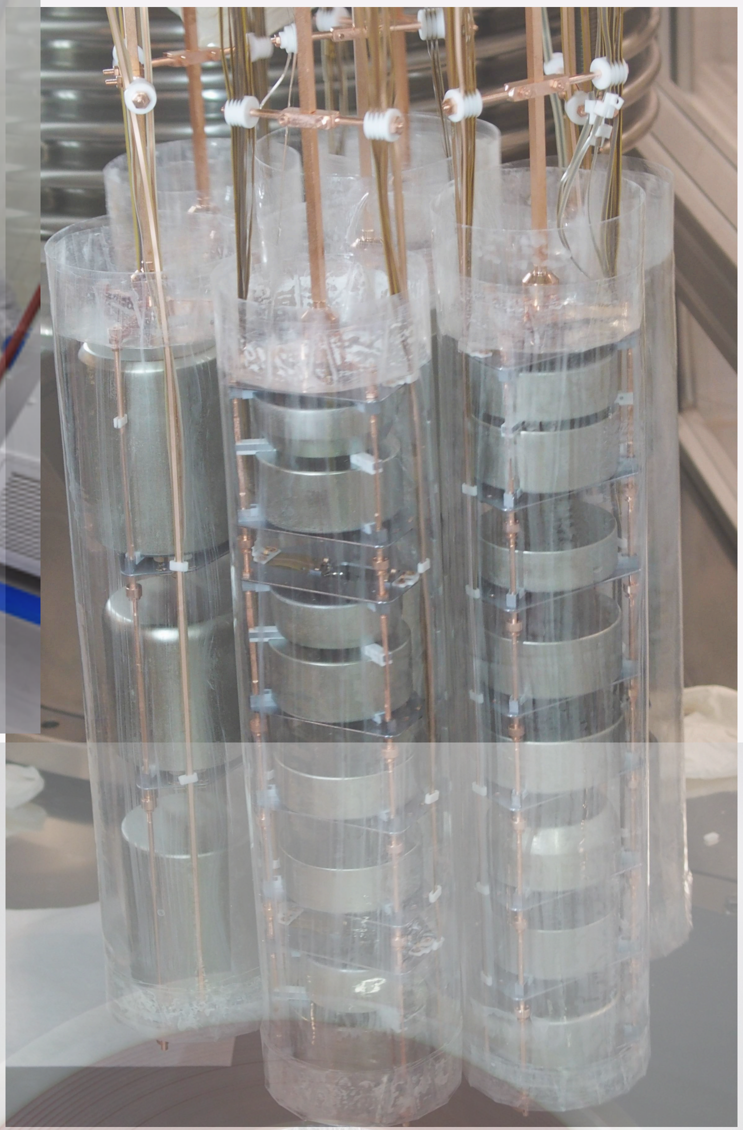
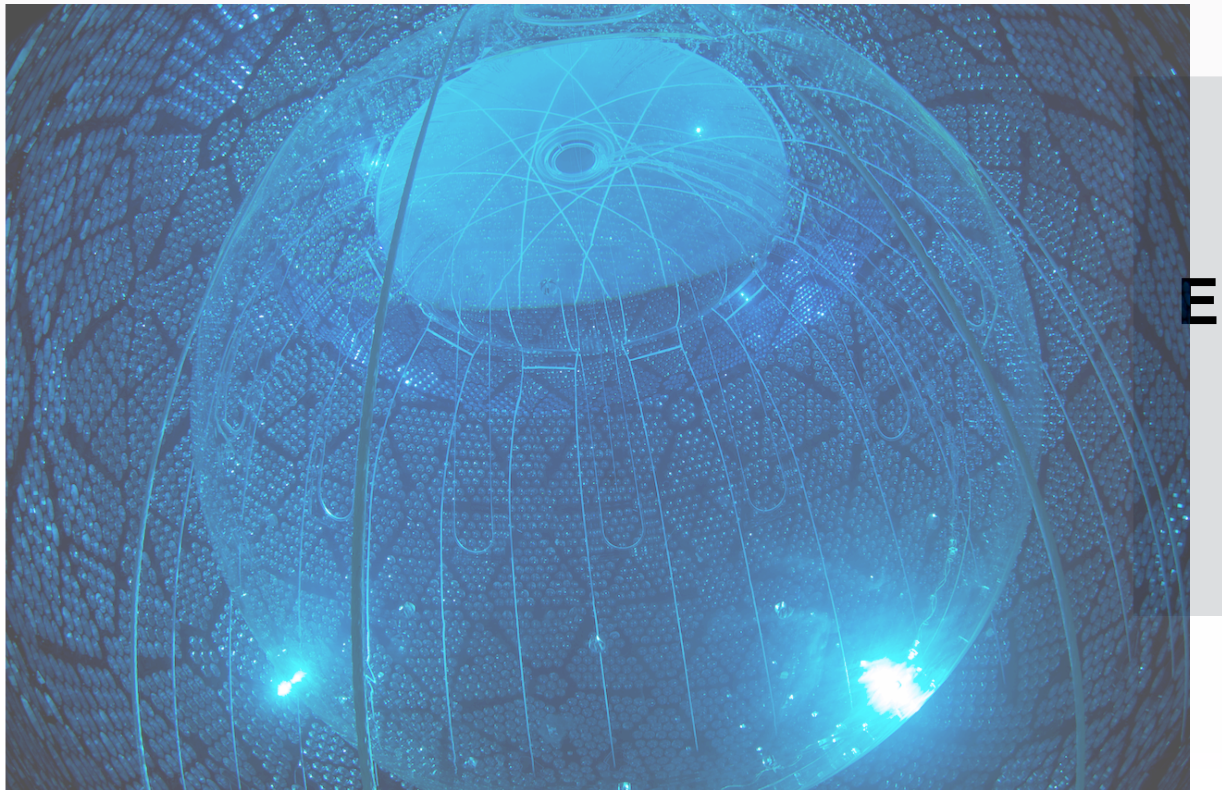




Status and Prospects of Neutrinoless Double Beta Decay



Ruben Saakyan
University College London
European Neutrino Town Meeting
CERN
22-Oct-2018

Outline

- Overview of NDBD
- Recent Results
- Next Steps
  - Experiments aimed at exploring inverted ordering if neutrino masses
- Considerations for "ultimate" experiment
  - aimed at exploring normal ordering, *O*(1 meV)

Disclaimer: Impossible to do justice to such a vibrant field. Focus on projects with significant European leadership/participation. Apologies for omitting many brilliant ideas and experiments.

The Big Picture

- **Neutrinos** provide the only "particle physics evidence" **beyond the SM**

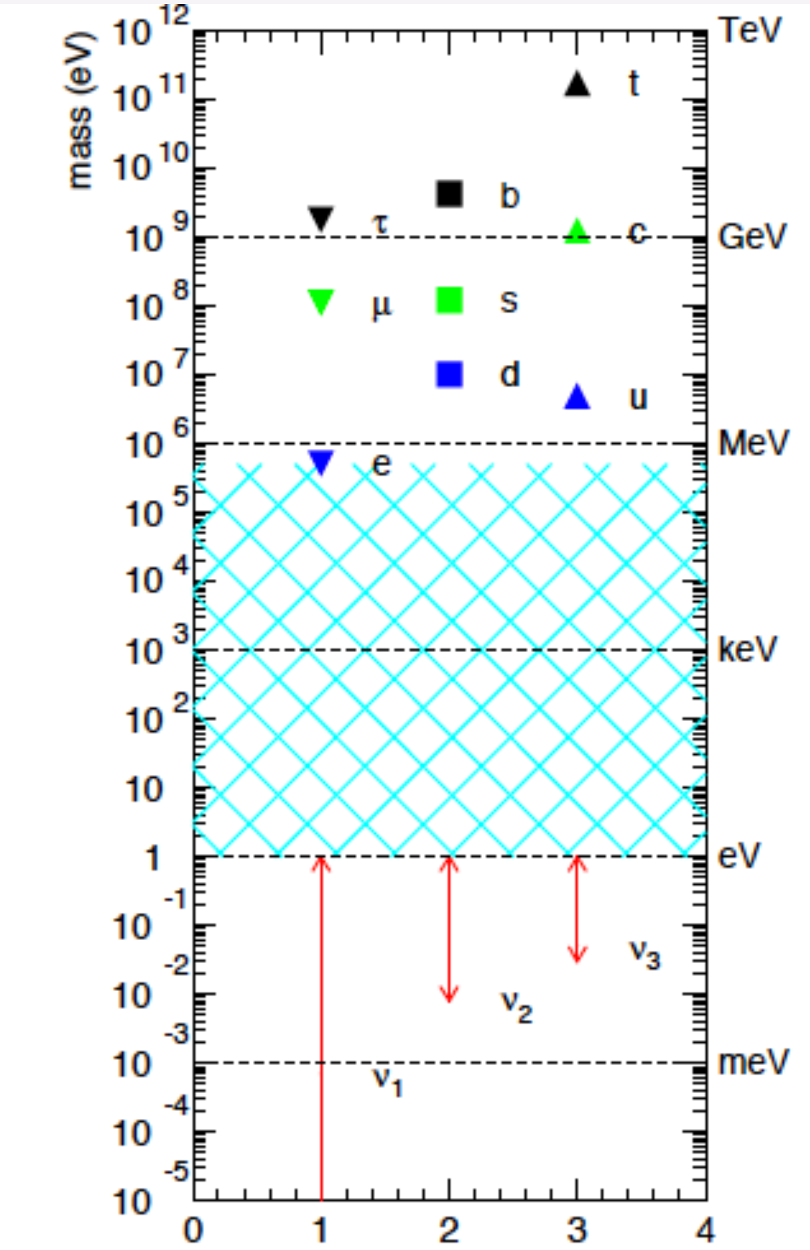
Remaining **Big Questions:**

- Neutrino mass ordering: ***normal*** vs ***inverted***
- **CP- violation** — Dirac phase

addressed by neutrino oscillations

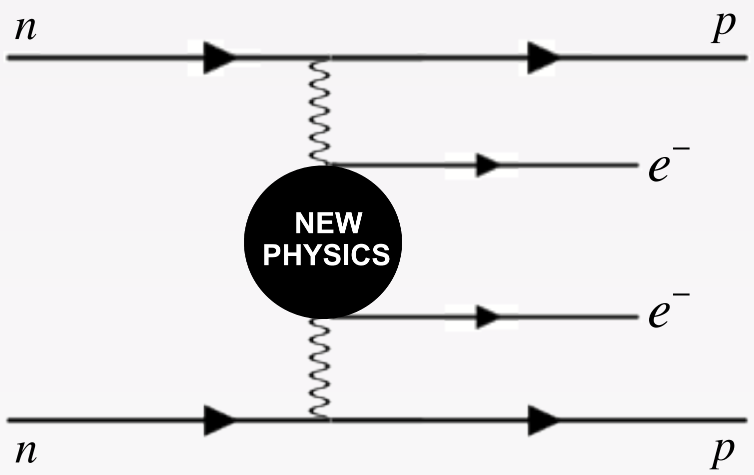
- **Lepton number violation (LNV)**
- **Majorana vs Dirac — mass mechanism**
- **CP- violation — Majorana phases**
- Neutrino mass ordering: ***normal*** vs ***inverted***

addressed by 0νββ



The nuclear process of 0νββ is the only way to address LNV

Overview of 0νββ



ΔL = 2! (a. k. a. Matter Creation)

phase space

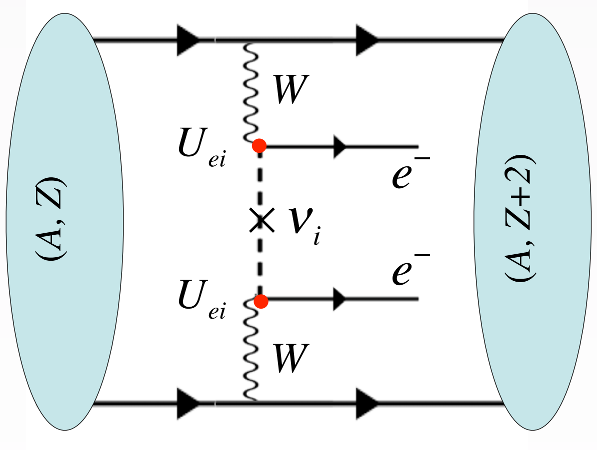
NME: ~~Nasty~~ Nuclear Matrix Element

LNV parameter

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

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

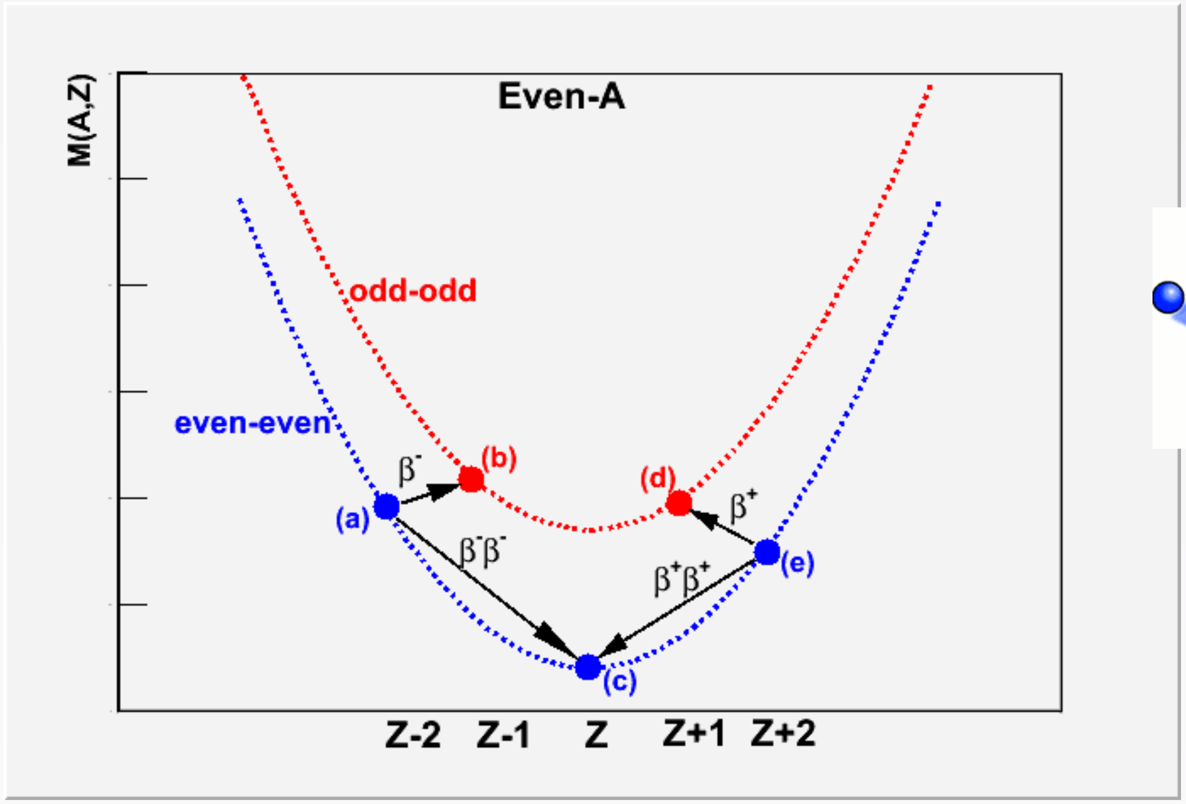


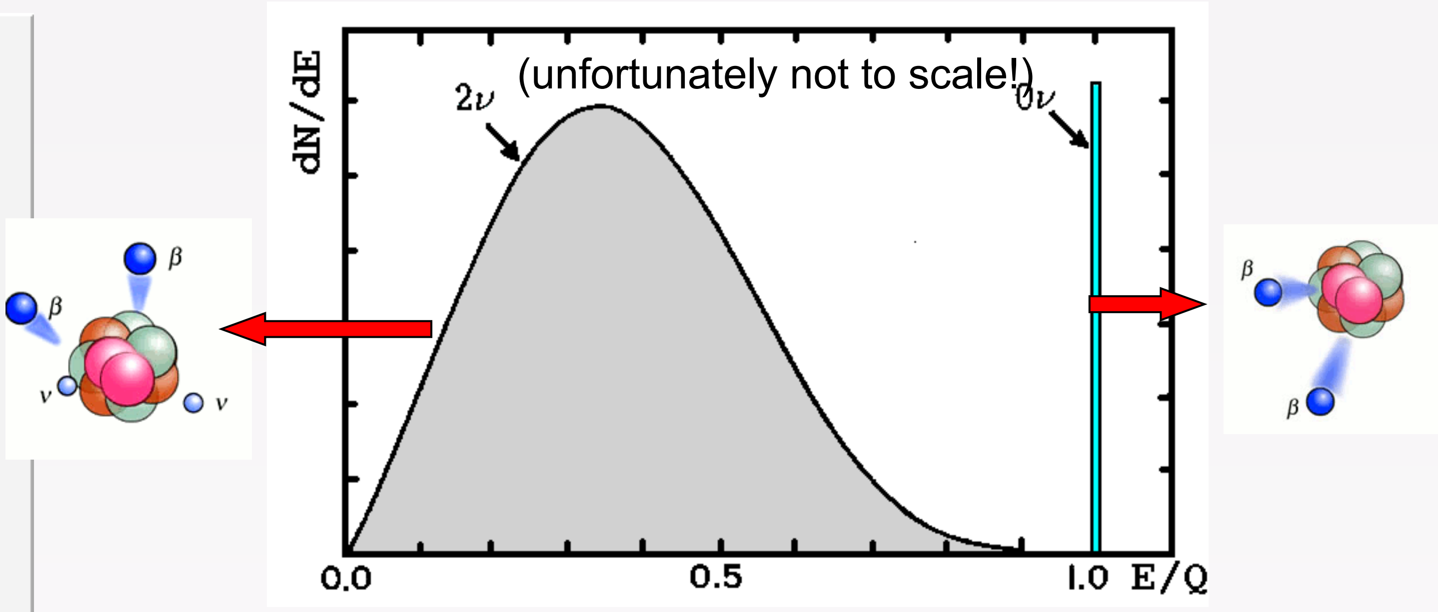
Coherent sum over neutrino amplitudes

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

Observation of LNV would have profound implications beyond neutrino physics

Nuclear Physics and Standard Model 2νββ




(unfortunately not to scale!)

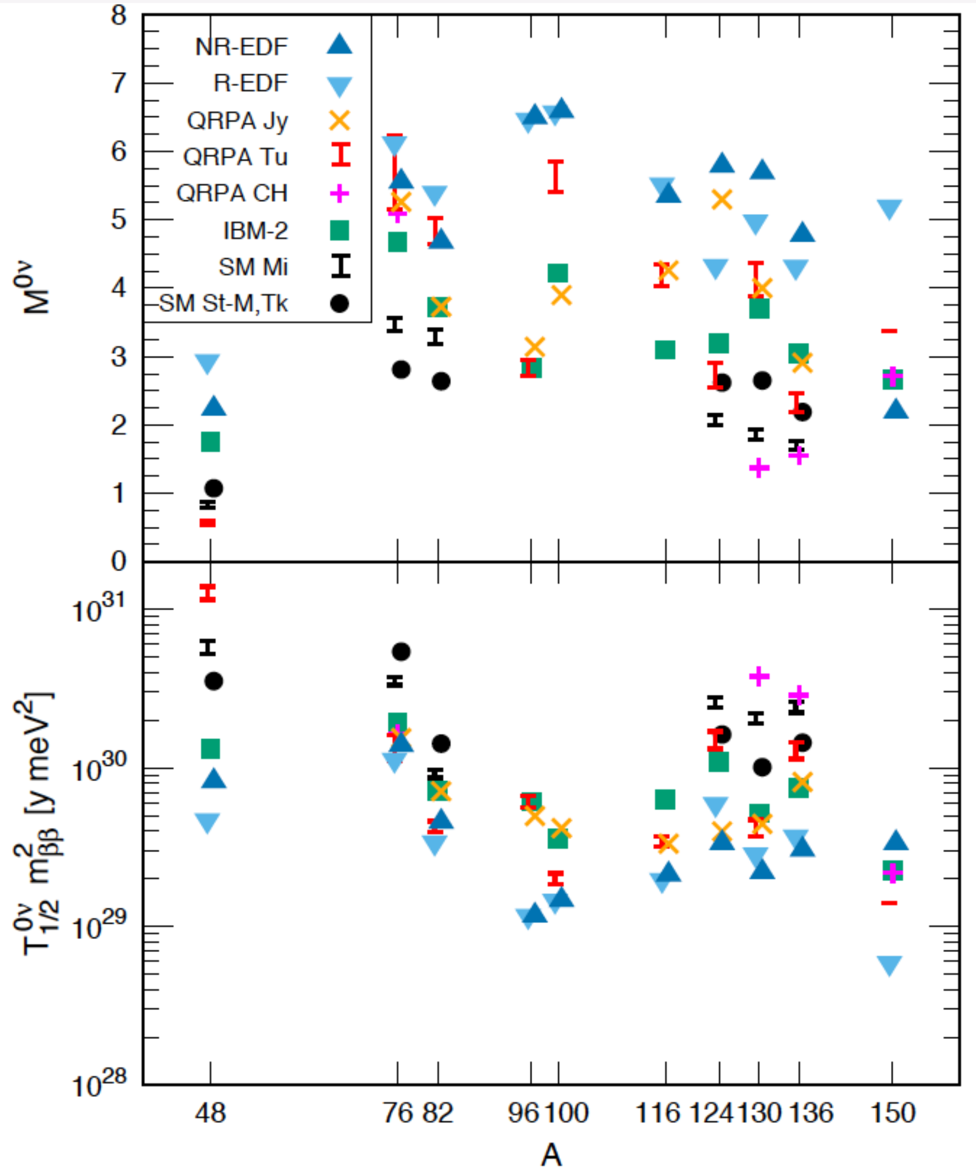
Over **40 nuclei** can undergo **ββ**-decay
(including $\beta^+\beta^+$ and 2K-capture)
Only ~**9** experimentally **feasible**

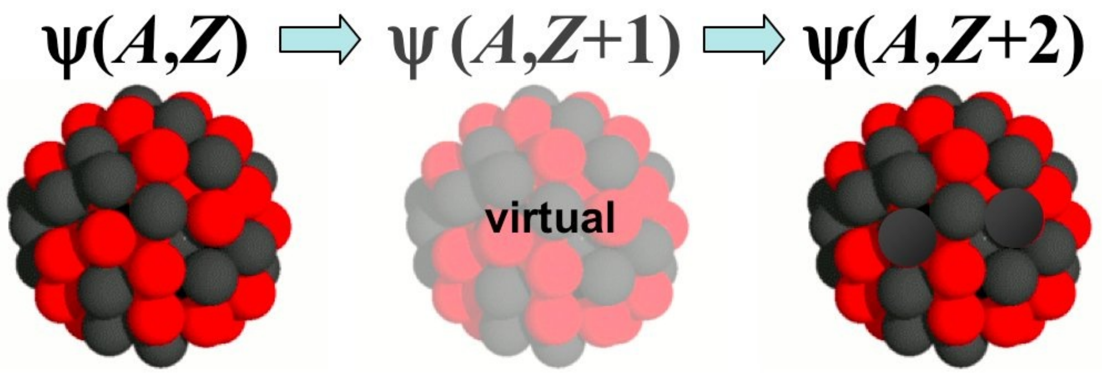
Isotope	Nat. Abundance (%)	$Q_{\beta\beta}$ (MeV)
Ca48	0.187	4.274
Ge76	7.8	2.039
Se82	9.2	2.996
Zr96	2.8	3.348
Mo100	9.6	3.035
Cd116	7.6	2.809
Te130	34.5	2.530
Xe136	8.9	2.462
Nd150	5.6	3.367

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

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

More Nuclear Physics





- 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

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

g_A could be quenched in nuclear matter
Experimental input from 2νββ (and single-β) possible

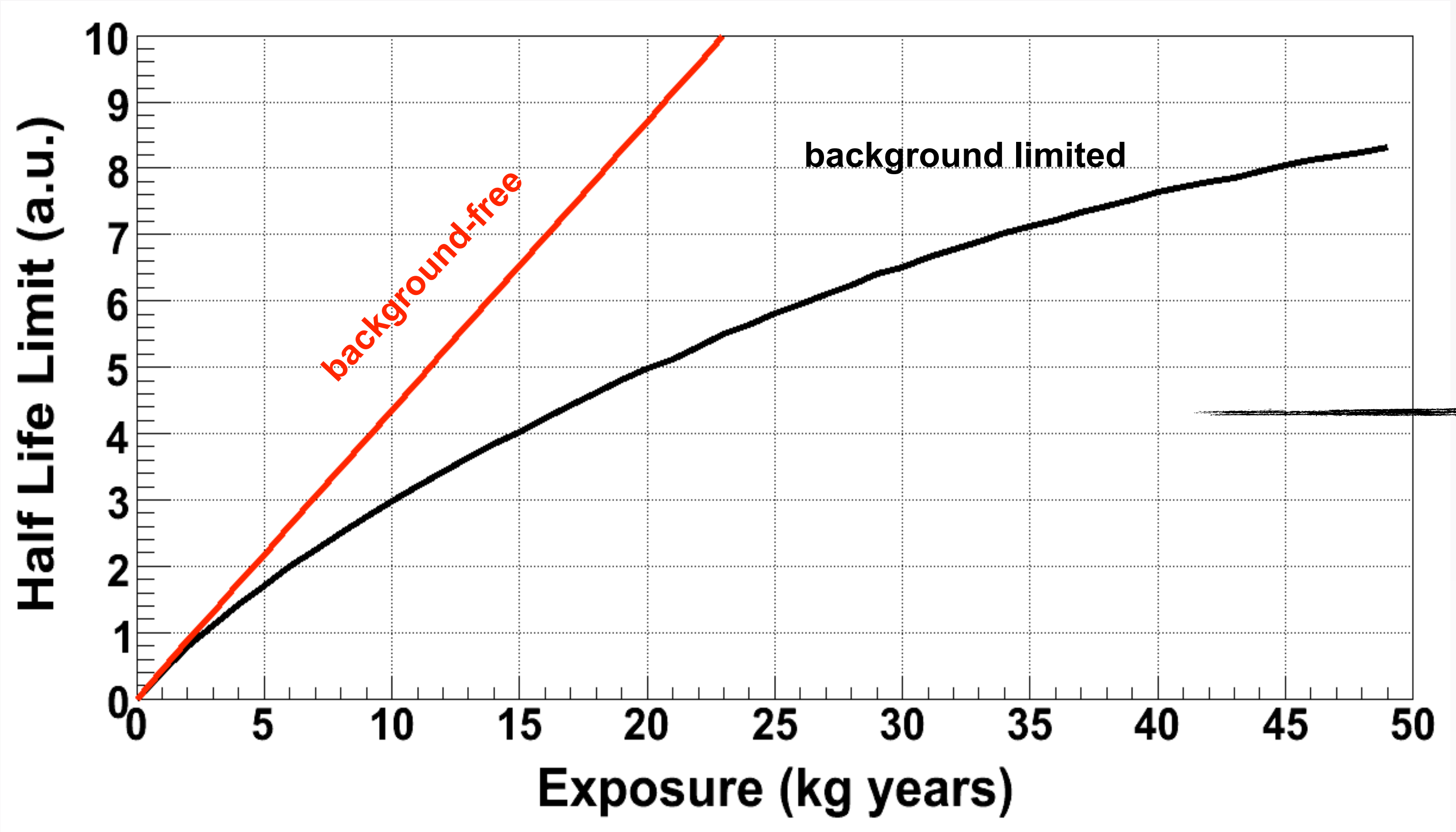
Experimental Sensitivity

maximise efficiency & isotope abundance

maximise exposure = mass (isotope) × time

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

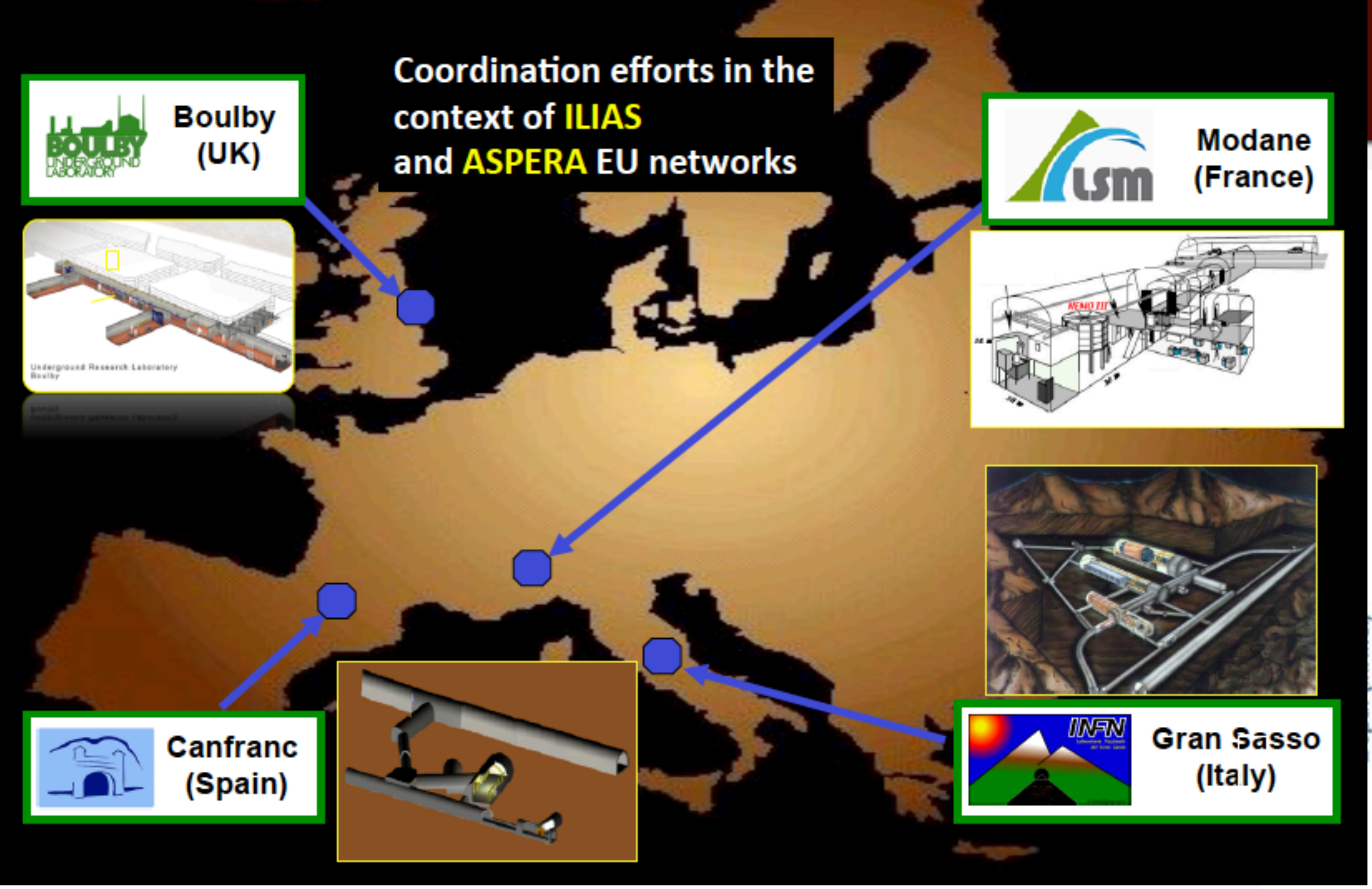
minimise background & energy resolution



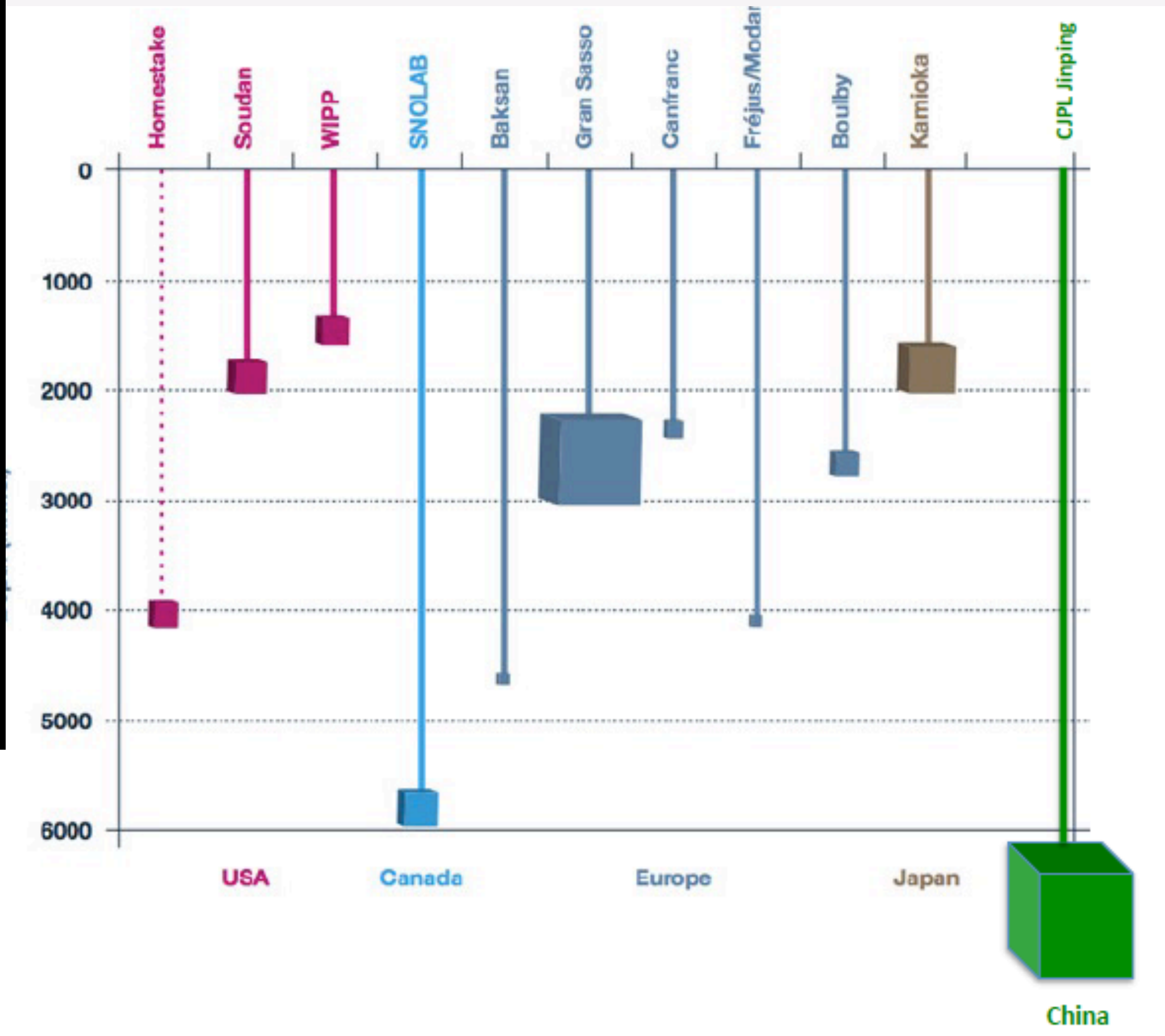
ββ is about **background suppression!**

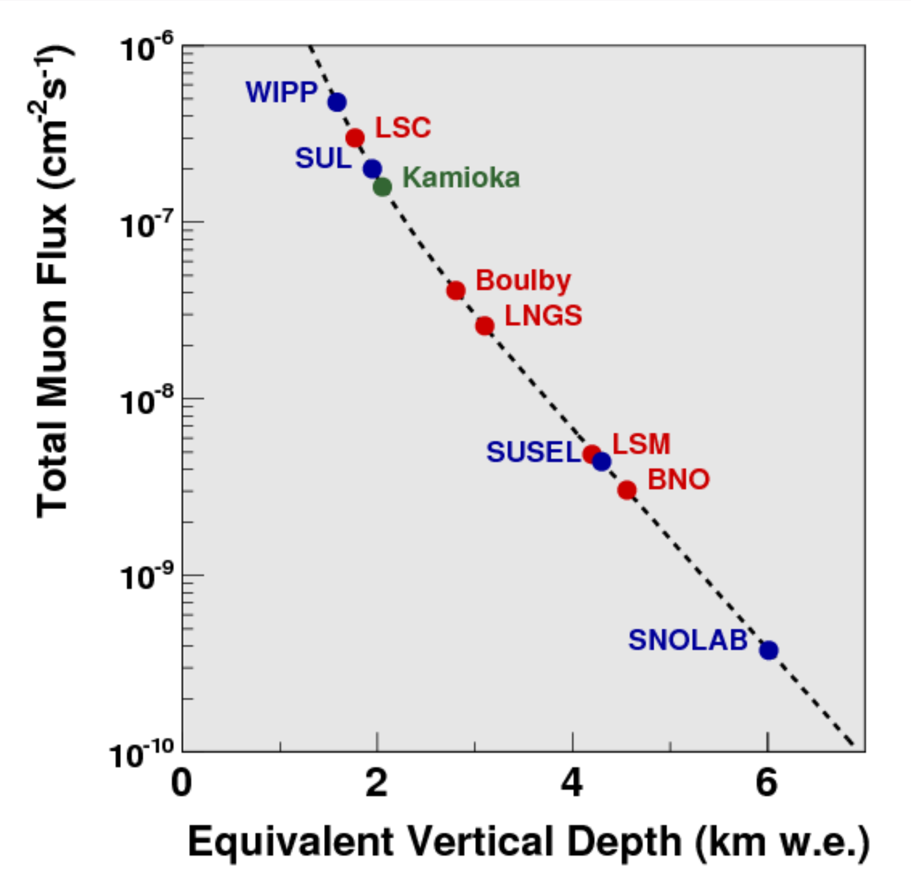
Backgrounds:
- Cosmic ray muons (**underground lab is a must**)
- **Natural radioactivity** ^{238}U, ^{232}Th, neutrons,…
- **2νββ**

Take Home Message:
- Large isotope mass
- Superior background suppression
- Good energy resolution



Coordination efforts in the context of ILIAS and ASPERA EU networks



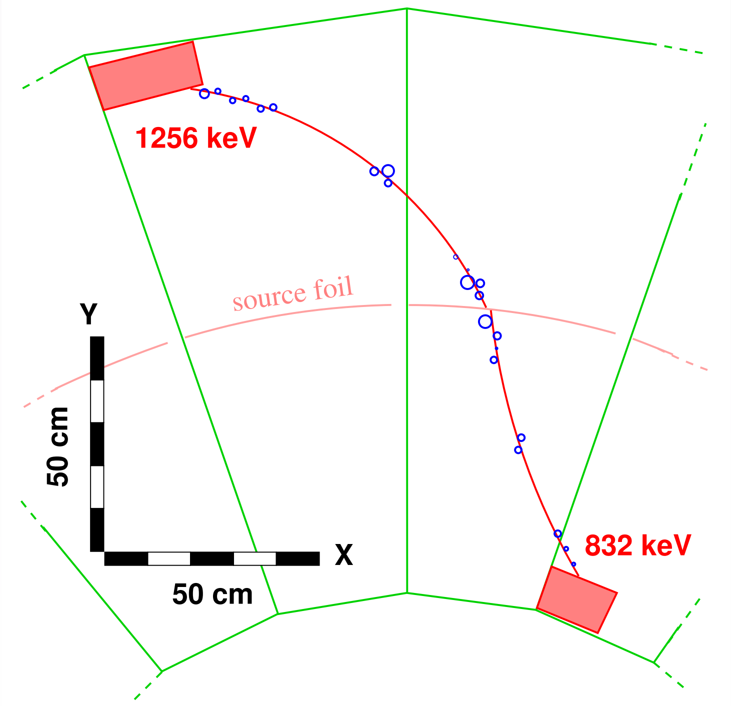


Europe needs to support and enhance its deep underground laboratories to maintain leadership

Best results from 2νββ

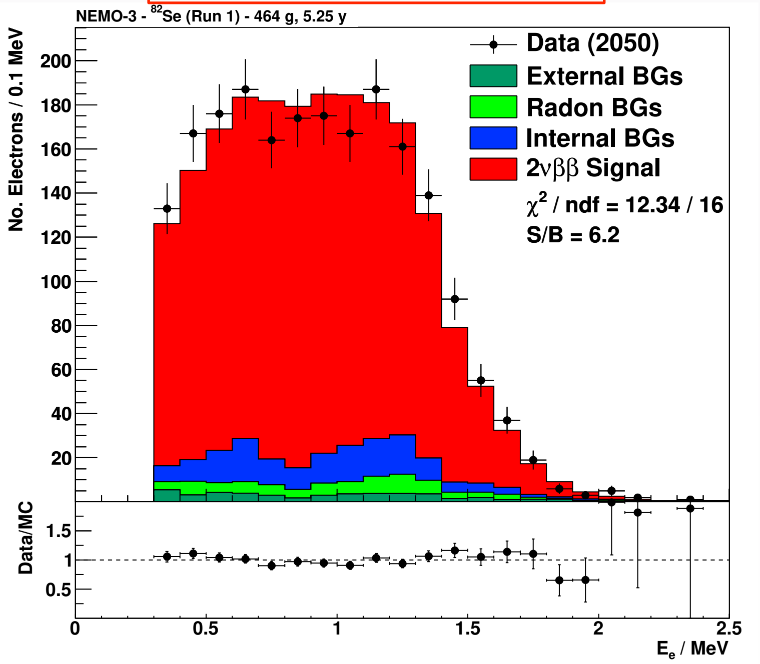
Isotope	$T_{1/2}$ (10^{19} yrs)	Experiment
^{48}Ca	6.4 ± 1.2	NEMO-3
^{76}Ge	192.6 ± 9.4	GERDA
^{82}Se	9.4 ± 0.6	NEMO-3
^{96}Zr	2.35 ± 0.21	NEMO-3
^{100}Mo	0.68 ± 0.05	NEMO-3
^{116}Cd	2.74 ± 0.18	NEMO-3/Aurora
^{130}Te	79 ± 2	CUORE
^{136}Xe	216.5 ± 6.1	EXO-200
^{150}Nd	0.93 ± 0.06	NEMO-3

NEMO-3 candidate ββ event



- 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)

EPJ C78, 821 (2018)



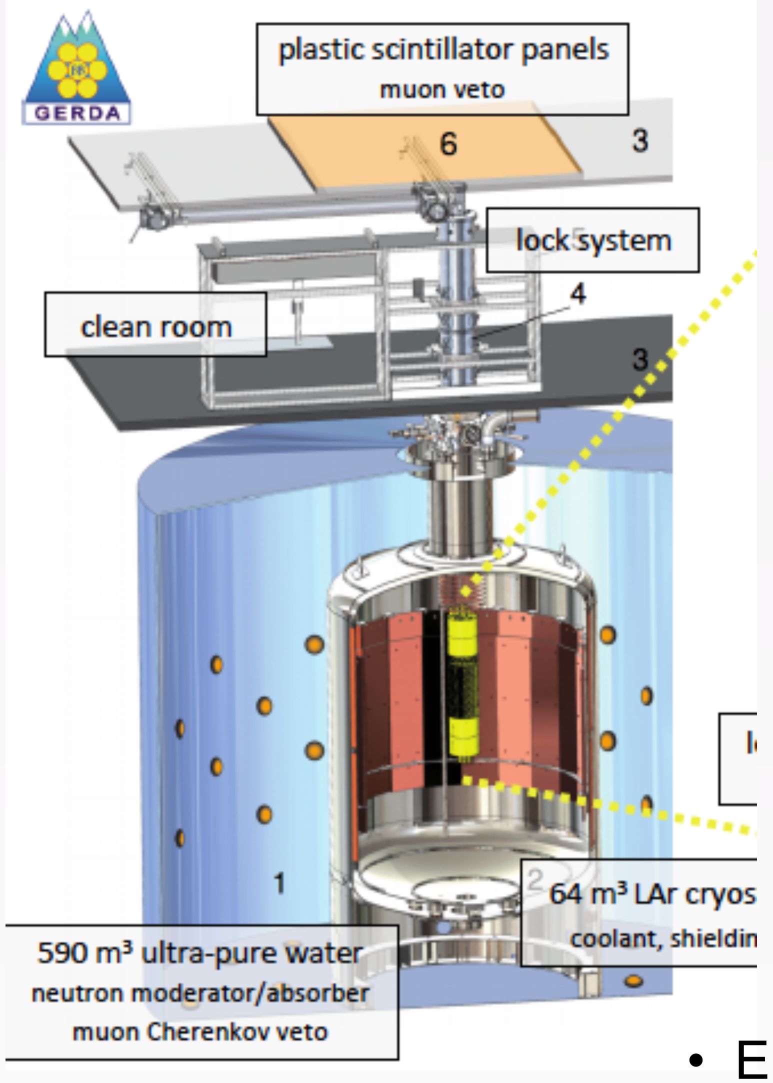
Best results from $0\nu\beta\beta$

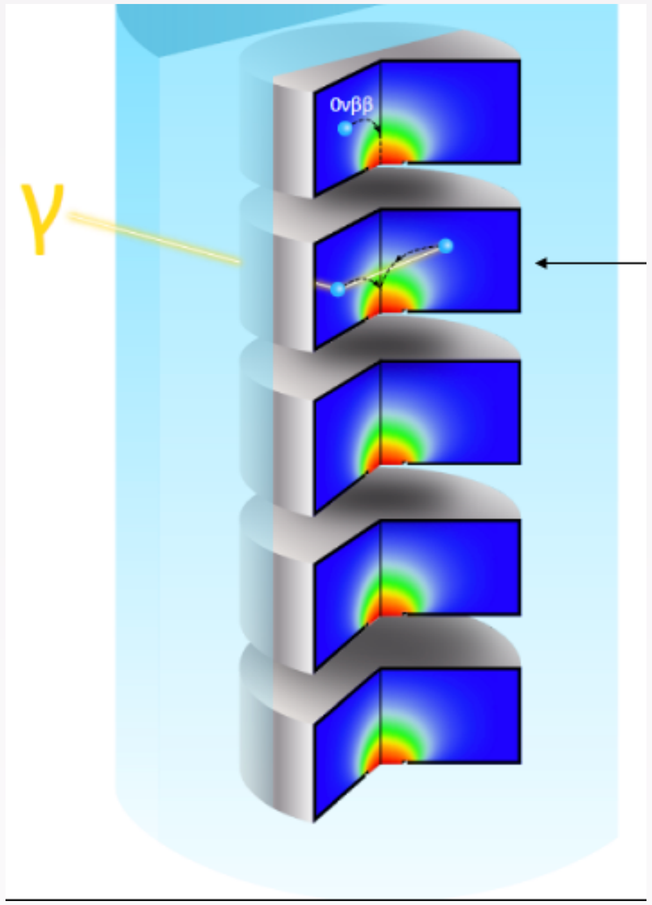
$$T^{0\nu}_{1/2}\,(90\%\ \mathrm{C.L.}) = 2.54\times10^{26}\,\mathrm{y}\left(\frac{\varepsilon\times a}{W}\right)\sqrt{\frac{M\times t}{b\times\Delta E}}$$

Isotope, mass	**$Q_{\beta\beta}$, keV**	**b x ΔE x M, counts/yr**	**$T_{1/2}$, yr**	**$\langle m_\nu \rangle$, eV**	**Experiment, technique**
^{76}Ge, 40kg	**2039**	**0.07**	**$> 0.9\times10^{26}$**	**< 0.11-0.25**	**GERDA, HPGe**
^{82}Se, 5kg	2998	0.4	$> 2.4\times10^{24}$	< 0.38-0.77	CUPID-0, scintillating bolometers
^{100}Mo, 7kg	3034	1.5	$> 1.1\times10^{24}$	< 0.33-0.62	NEMO-3, tracko-calo
^{130}Te, 200kg	2528	21	$> 1.5\times10^{25}$	< 0.13-0.50	CUORE, bolometers
^{136}Xe, 380kg	**2458**	**1**	**$> 1.07\times10^{26}$**	**< 0.06-0.16**	**KamLAND-Zen, doped LS**

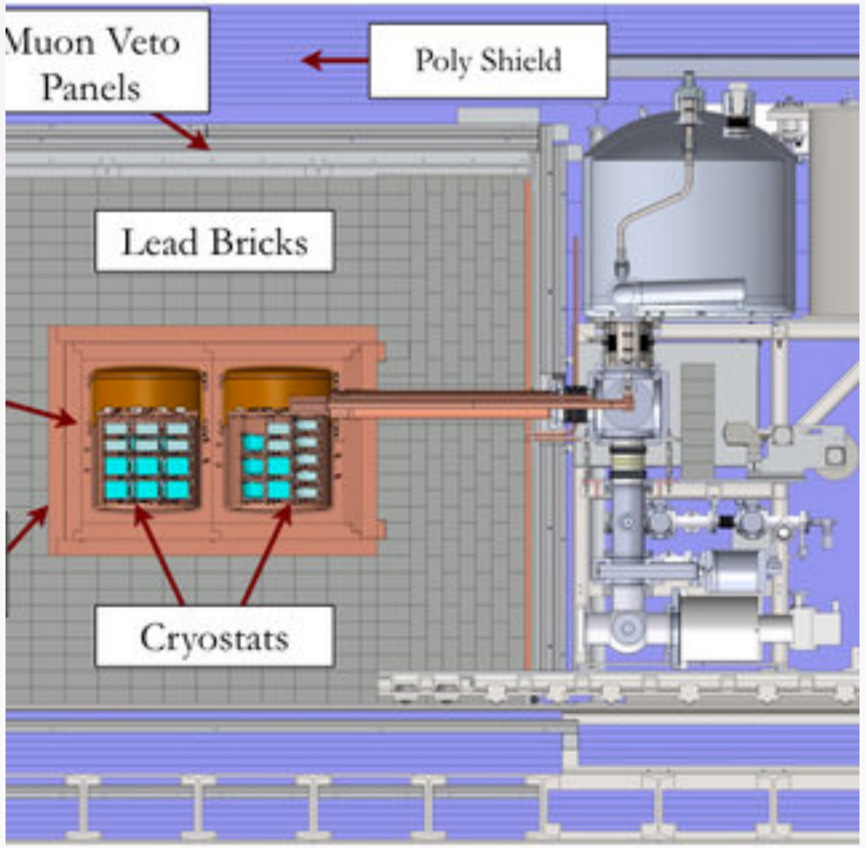
Different techniques reach similar sensitivity with different isotope mass

^{76}Ge semiconductors





Majorana



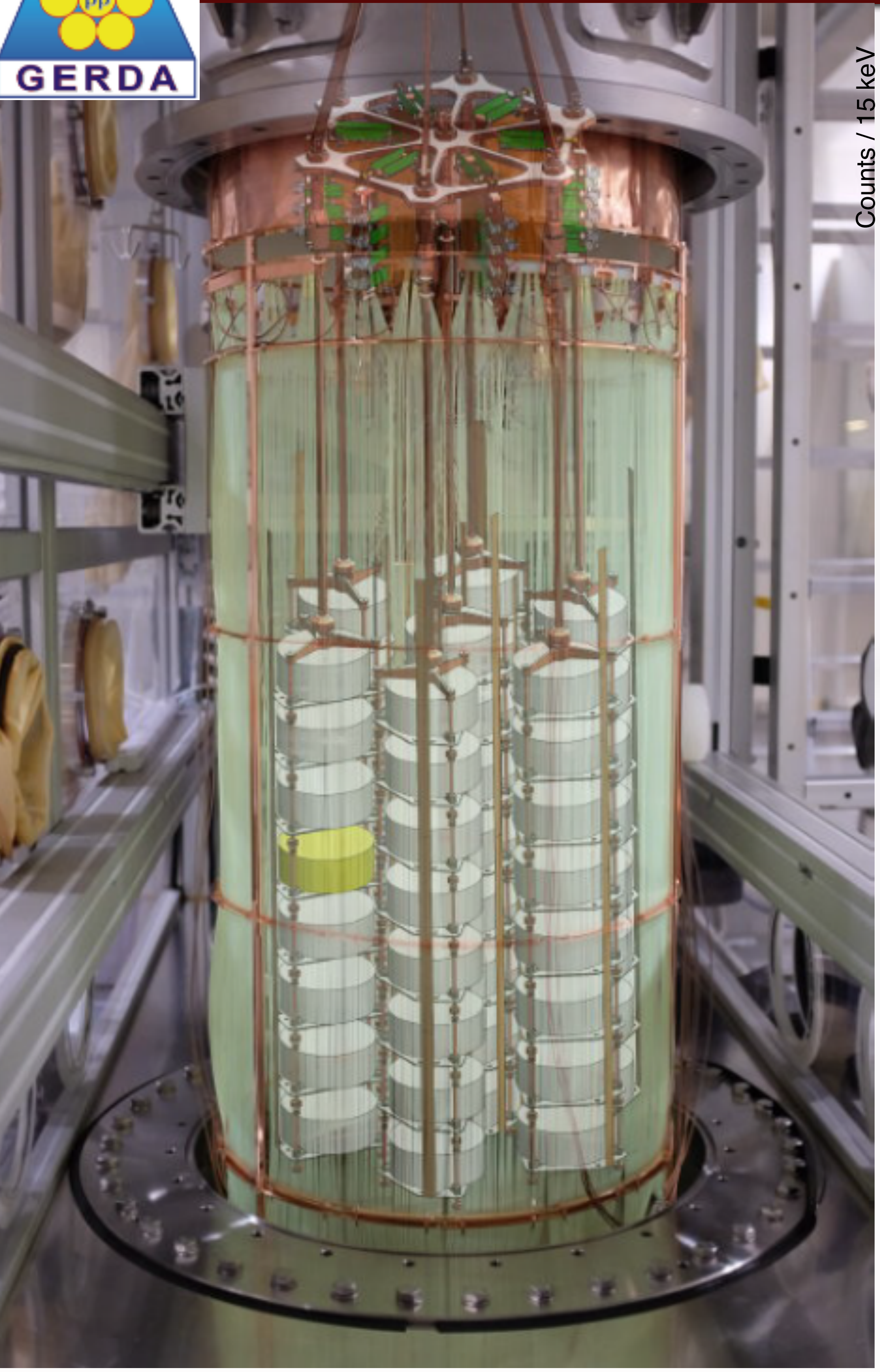
- Enriched ^{76}Ge crystals (in LAr in case of GERDA)

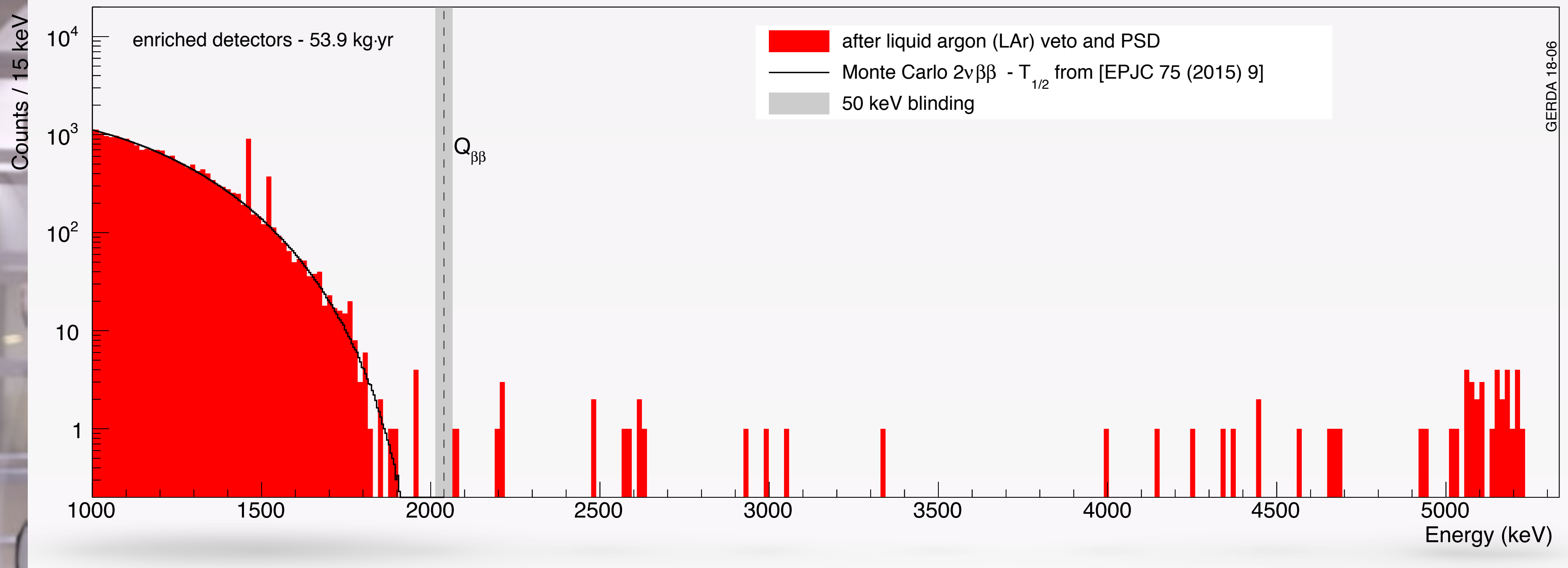
- Particle ID with single-site (ββ) vs multiple-site (γ) events using pulse shape

- 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

GERDA (^{76}Ge)



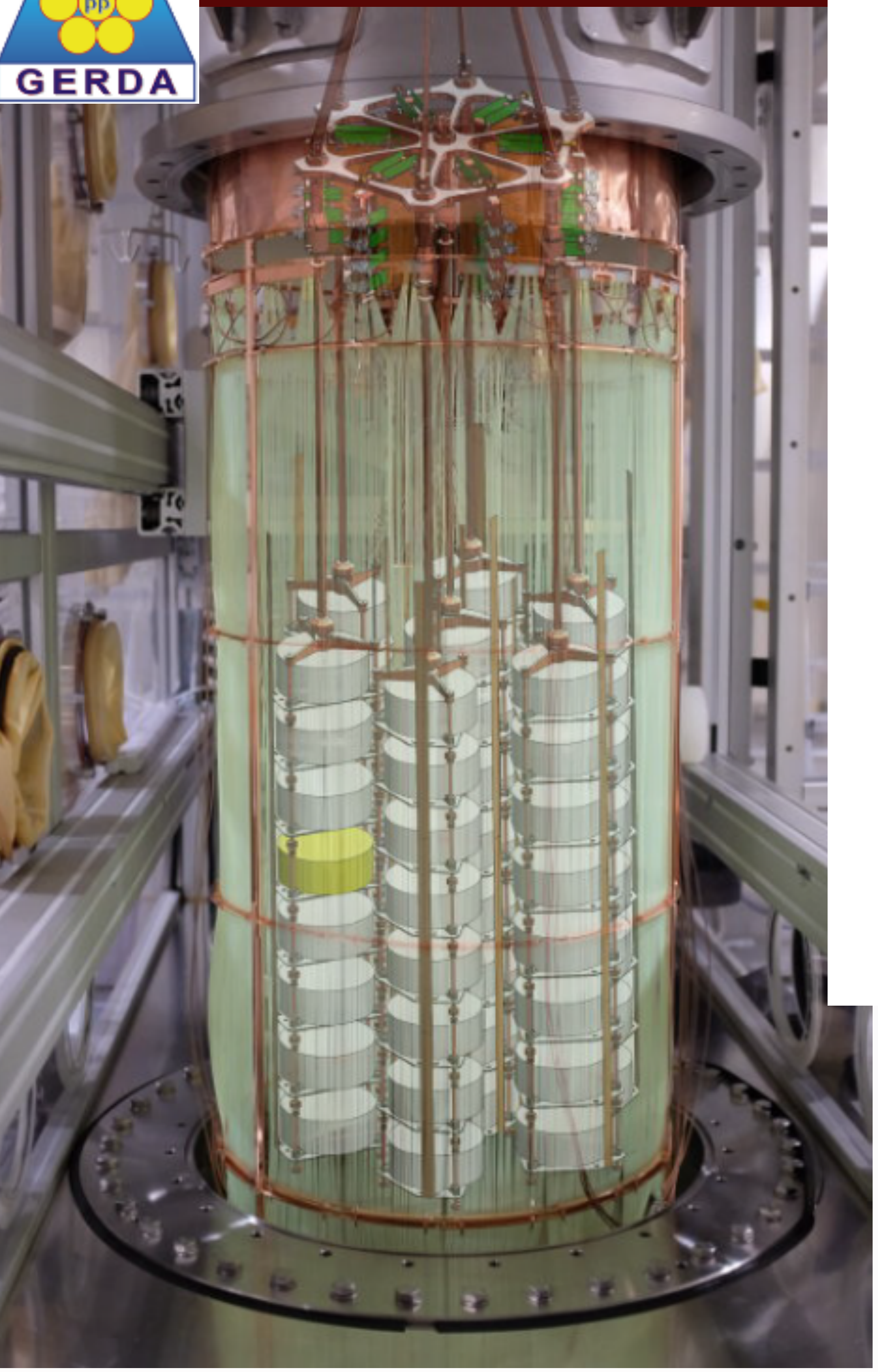


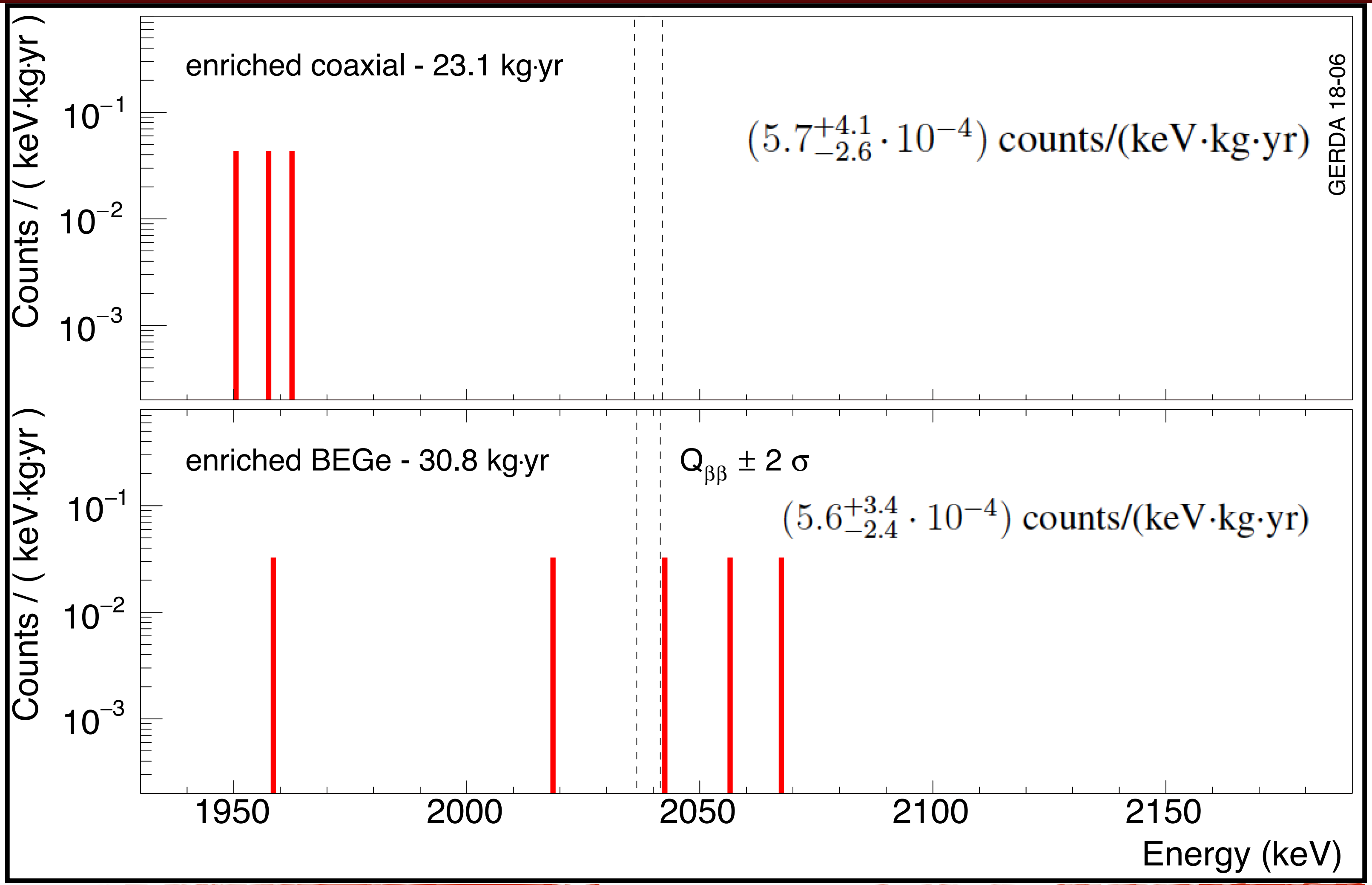
- Enriched ^{76}Ge crystals in LAr
- Superior ΔE/E ~0.15% at 2039 keV ($Q_{\beta\beta}$)
- High detection efficiency ~ 70-90%

Upgrades in summer 2018:

- 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:

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

^{76}Ge next step

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):

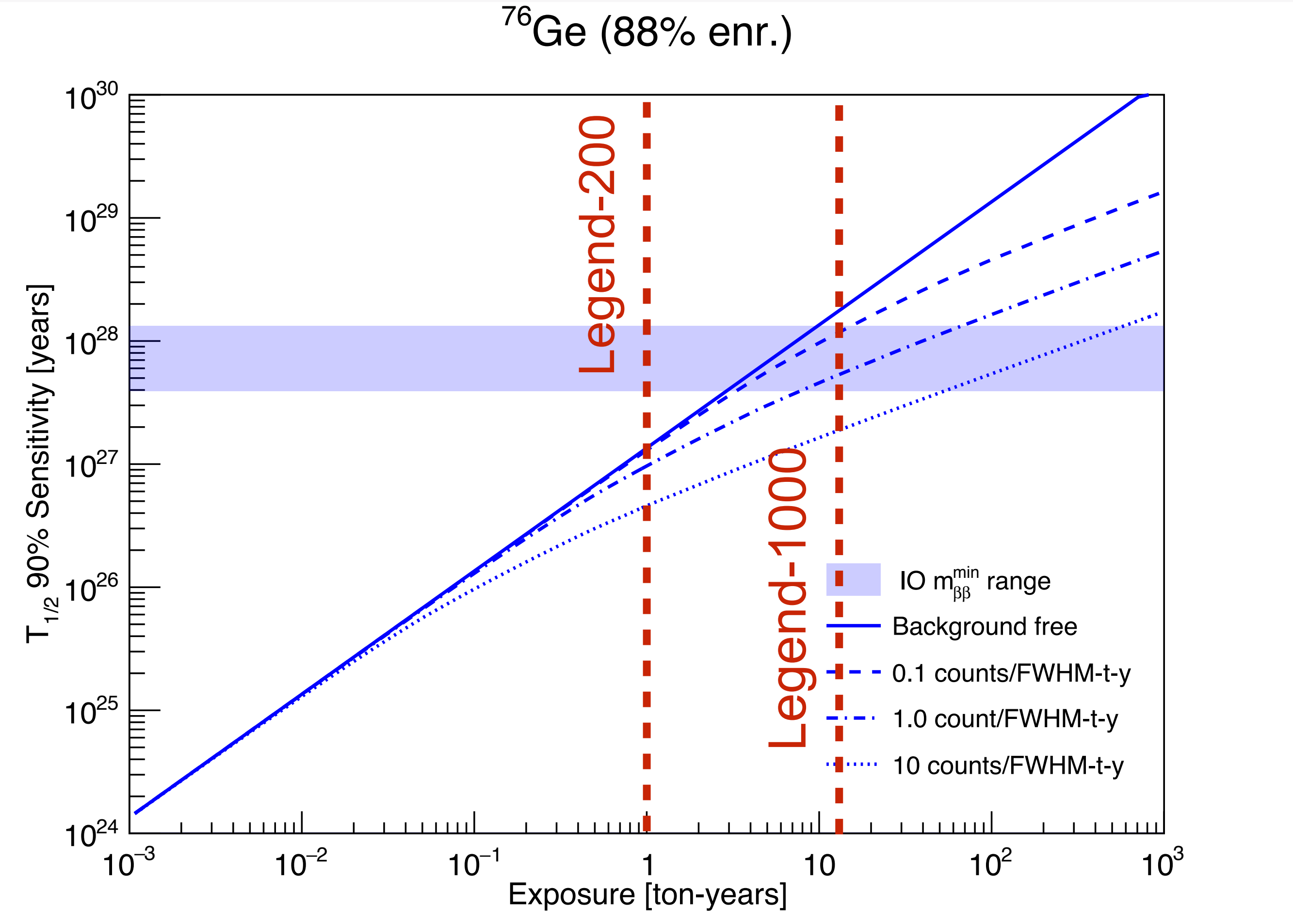
- up to 200 kg of detectors
- BI ~0.6 cts/(FWHM t yr)
- use existing GERDA infrastructure at LNGS
- design exposure: 1 t yr
- Sensitivity 10^{27} yr
- Isotope procurement ongoing
- Start in 2021

LEGEND-1000 (second phase):

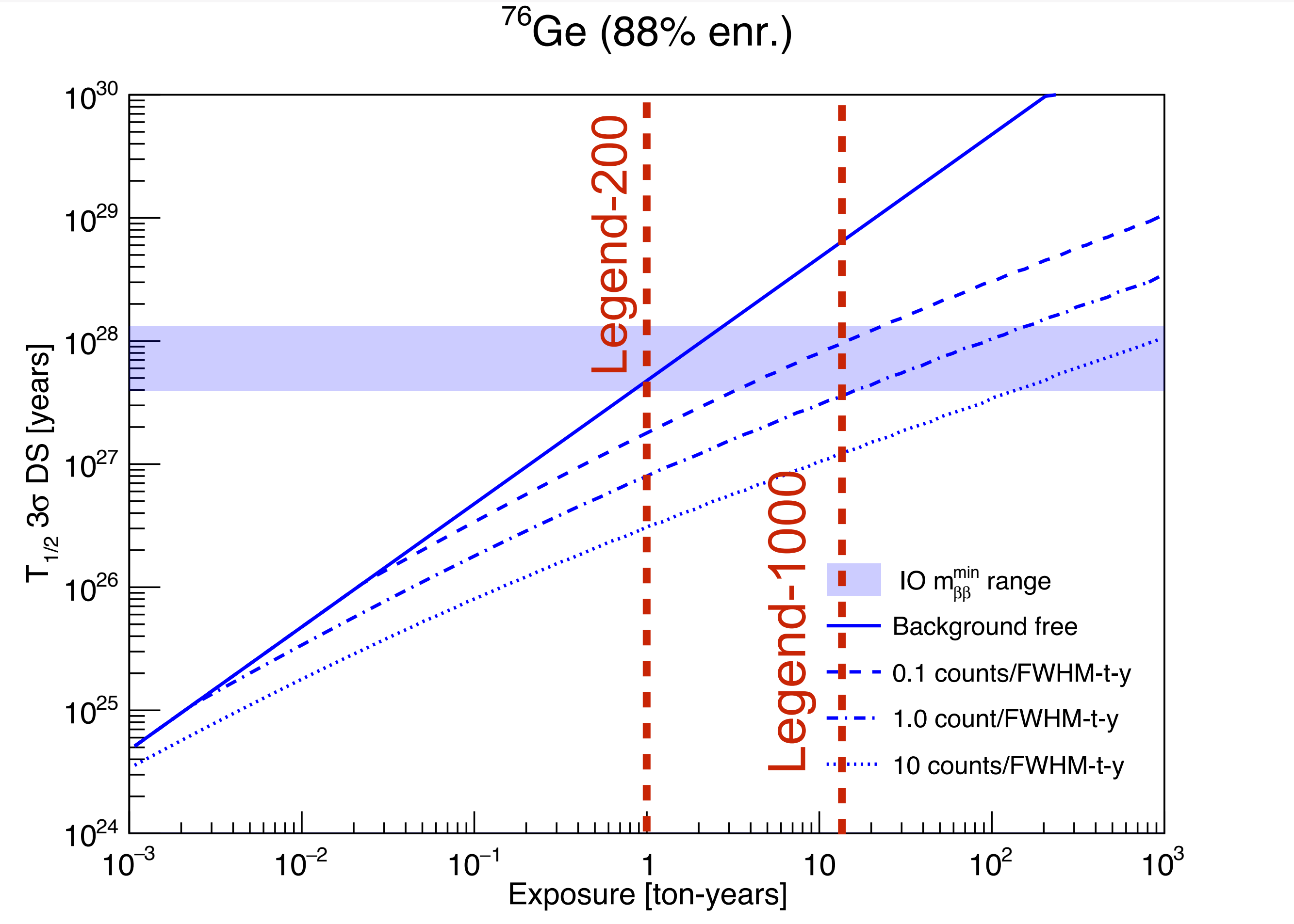
- 1000 kg of detectors (deployed in stages)
- BI <0.1 cts/(FWHM t yr)
- Location tbd
- Design exposure 12 t yr
- 1.2 x10^{28} yr

LEGEND Sensitivity

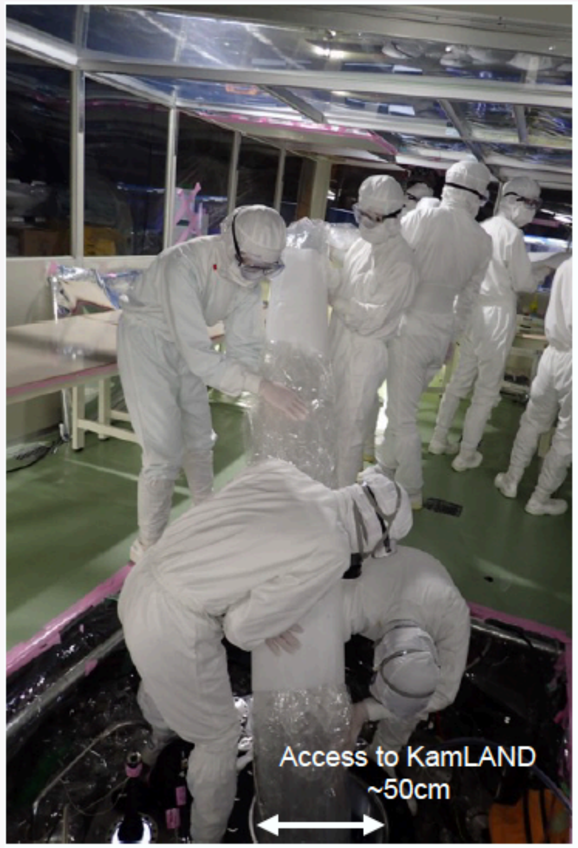
90% CL exclusion

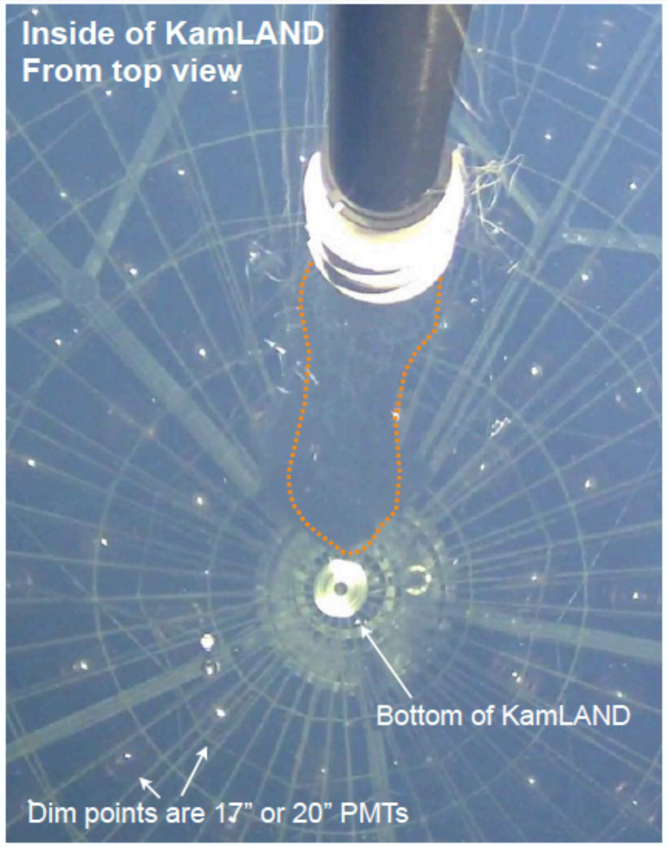


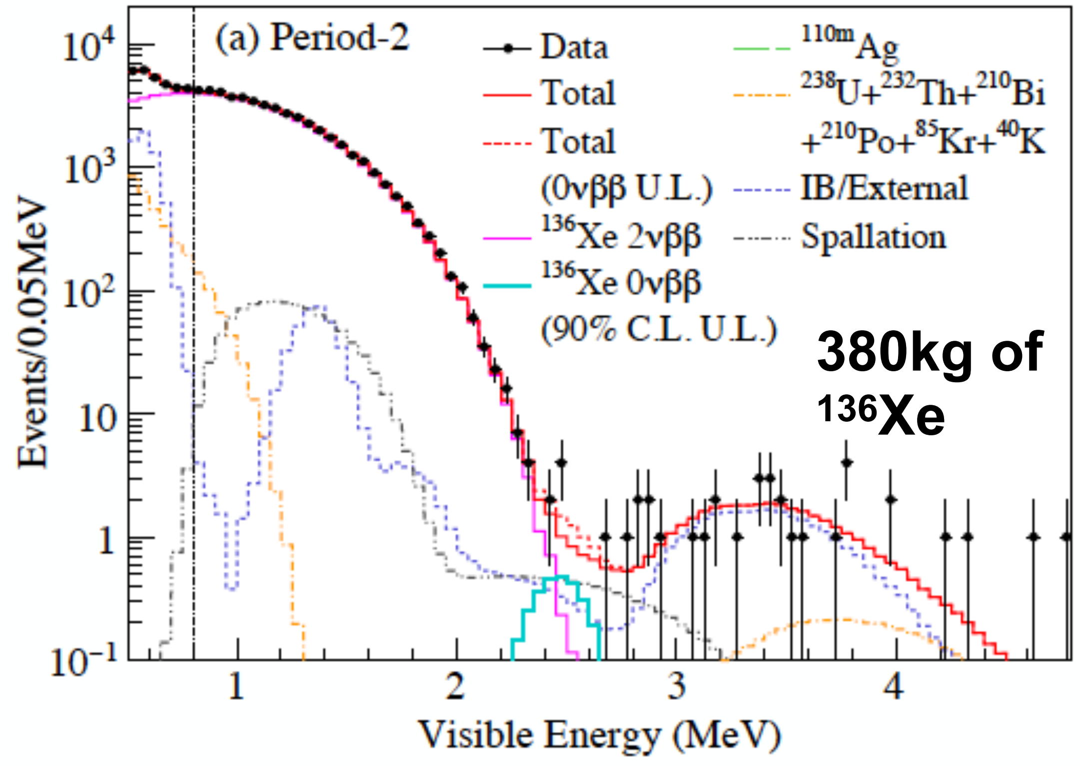
3σ evidence



Doped Liquid Scintillator KamLAND-Zen





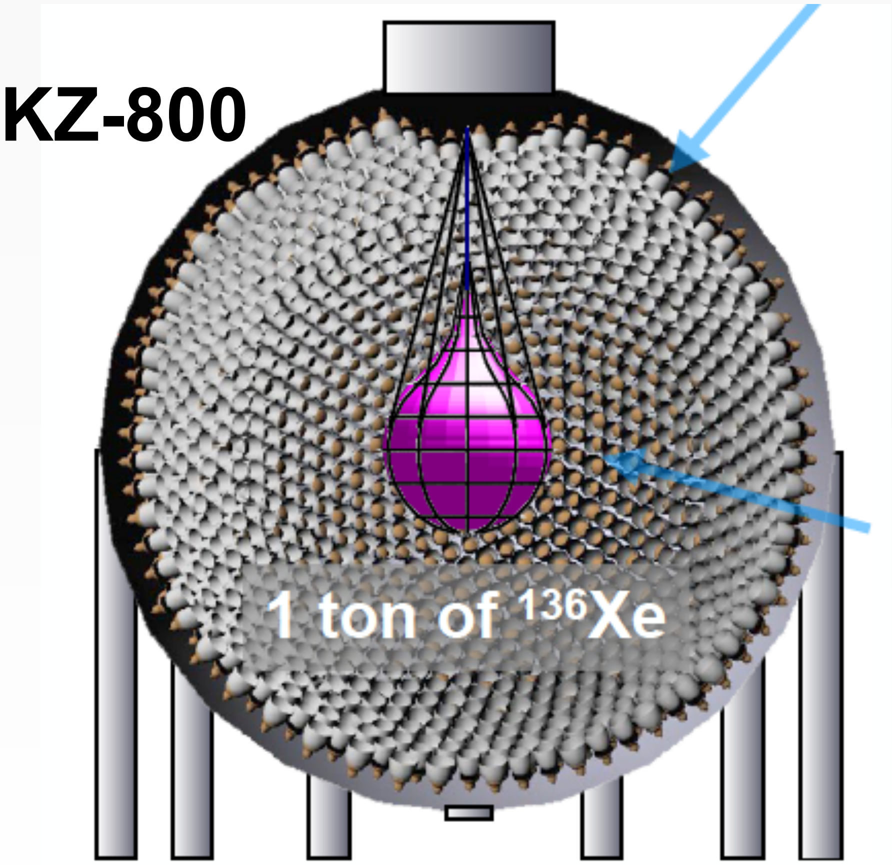


380kg of ^{136}Xe

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

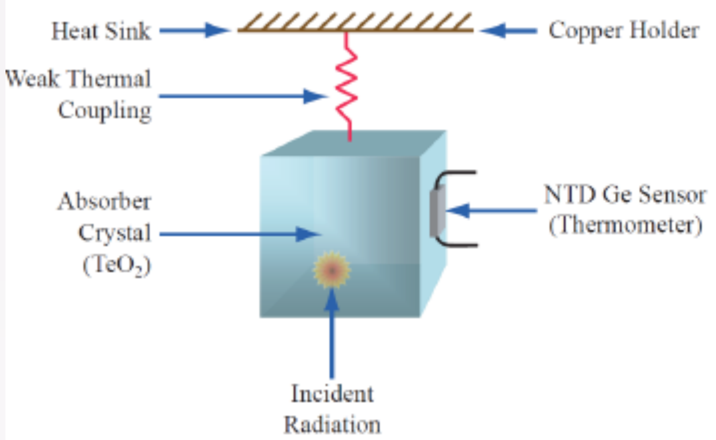
Beyond KZ-800

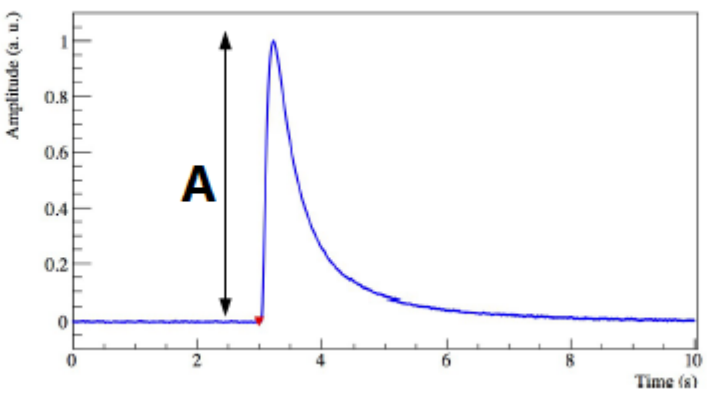


- Improved scintillator and PMT coverage

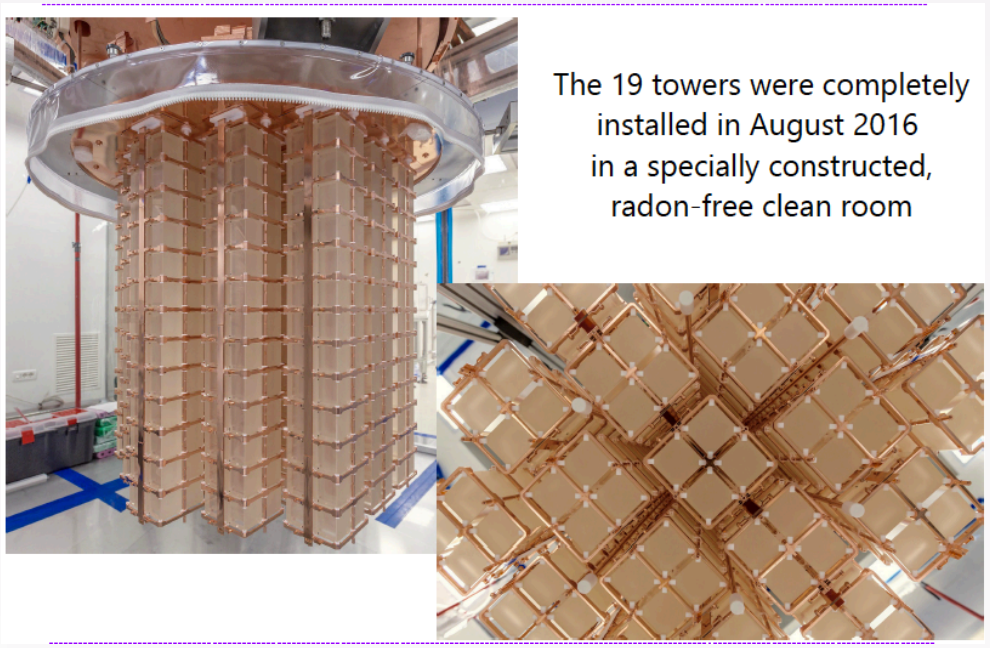
σ(2.6MeV)=4% → < 2.5%
Target ⟨$m_{\beta\beta}$⟩ ~20meV in 5 yrs

Bolometers





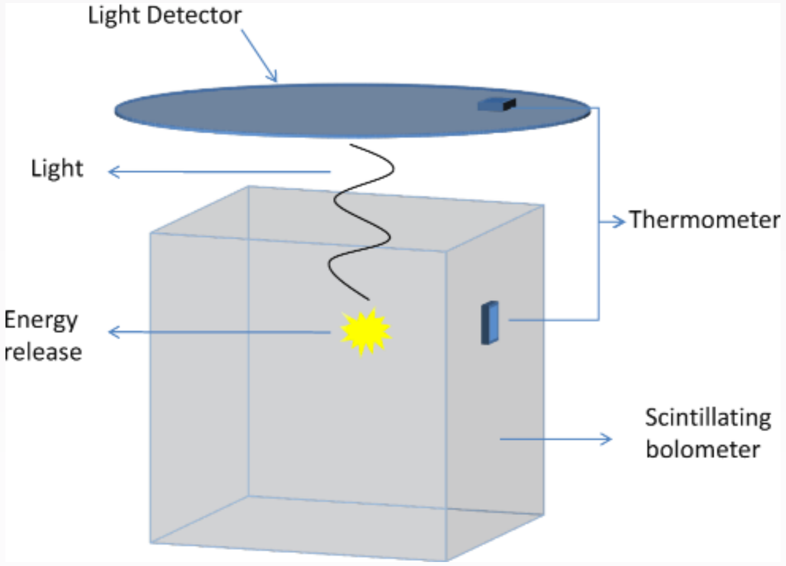
CUORE@LNGS

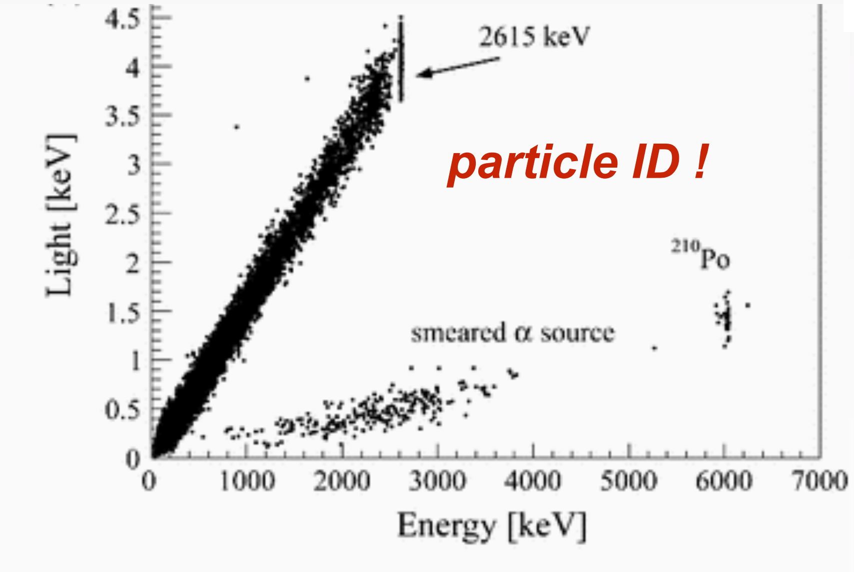


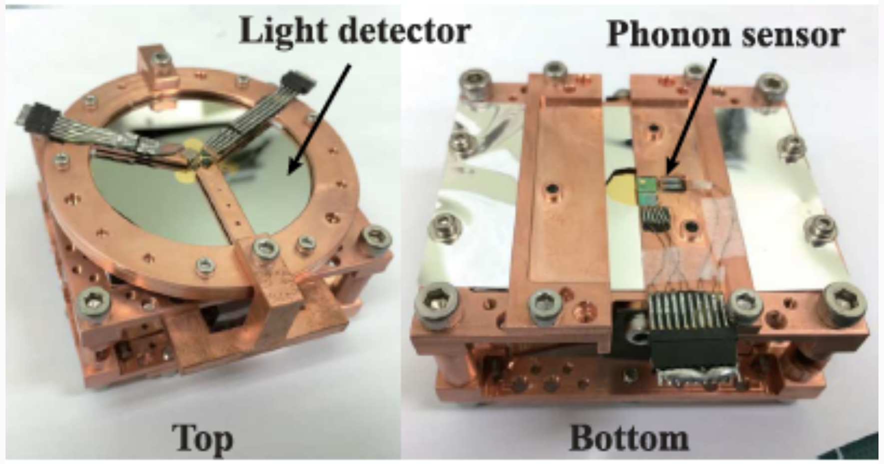
The 19 towers were completely installed in August 2016 in a specially constructed, radon-free clean room

Scintillating bolometers to suppress surface contamination background

CUPID-0, AMoRE

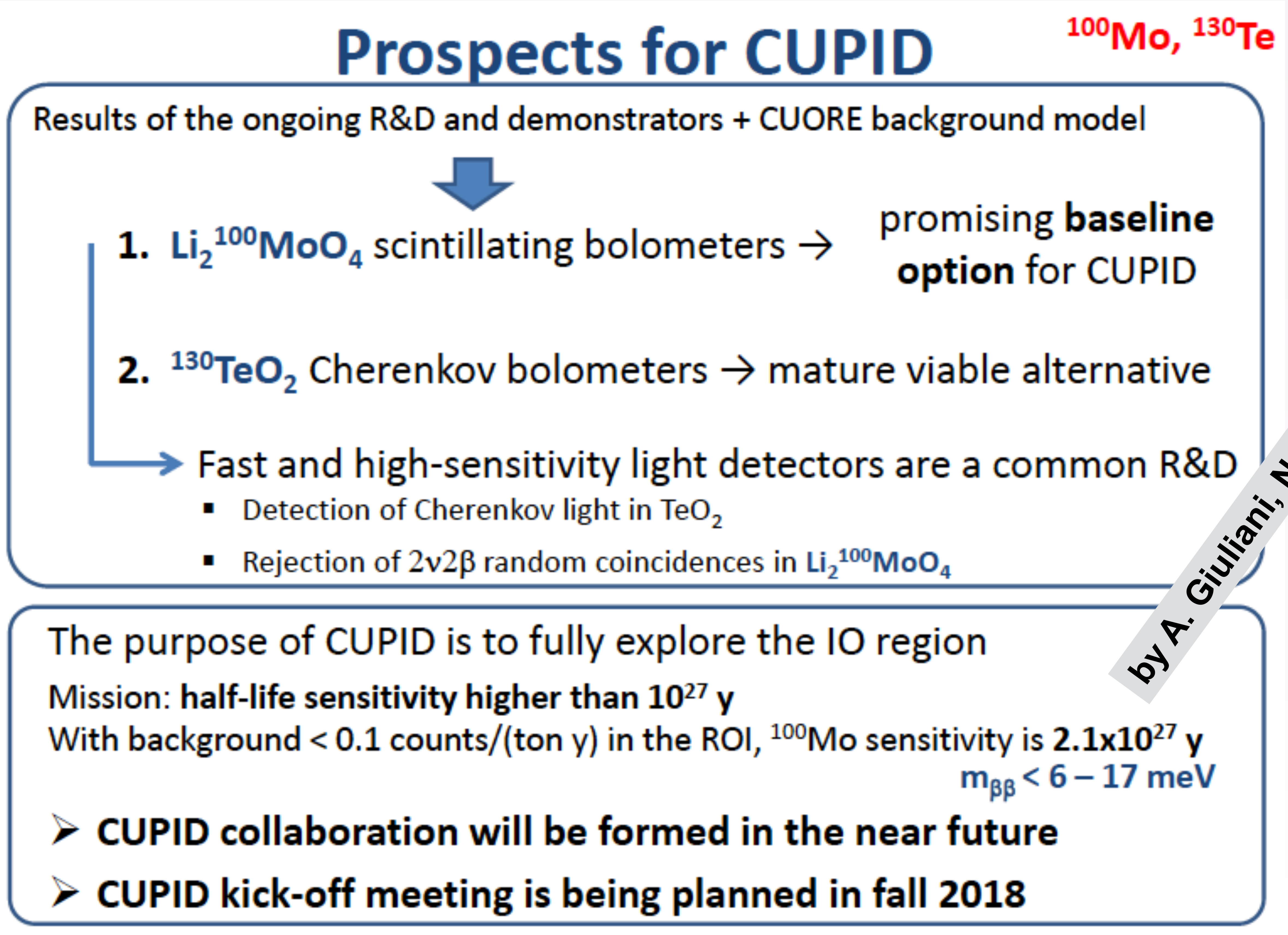






- Excellent ΔE/E ~0.2-0.3% at $Q_{\beta\beta}$
- Multiple isotopes possible
- Complex ultra-low temperature technology

Scintillating Bolometers



Prospects for CUPID

$^{100}\mathrm{Mo}$, $^{130}\mathrm{Te}$

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

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

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

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 **$2.1\mathrm{x}10^{27}$ y**

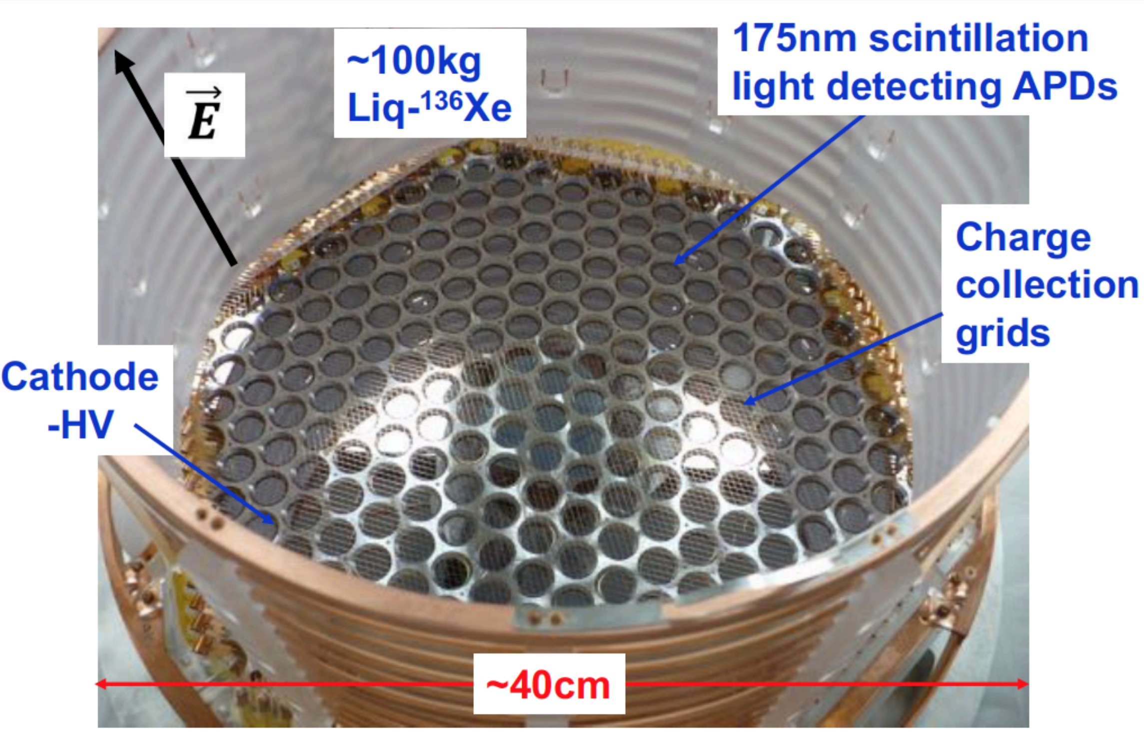
$m_{\beta\beta} < 6 - 17$ meV

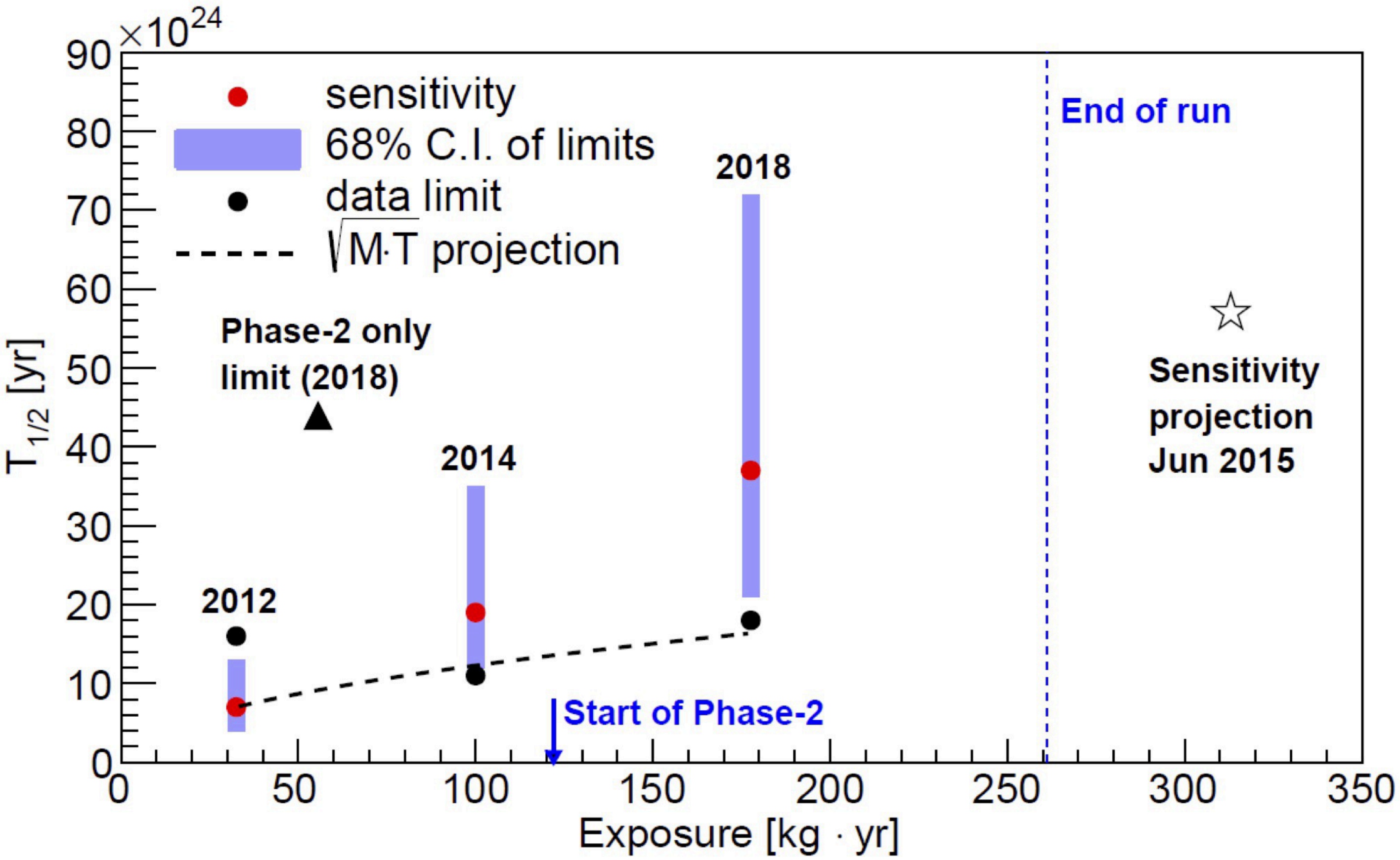
- ➢ **CUPID collaboration will be formed in the near future**
- ➢ **CUPID kick-off meeting is being planned in fall 2018**

by A. Giuliani, Neutrino'2018

LXe-TPC EXO-200 and nEXO

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



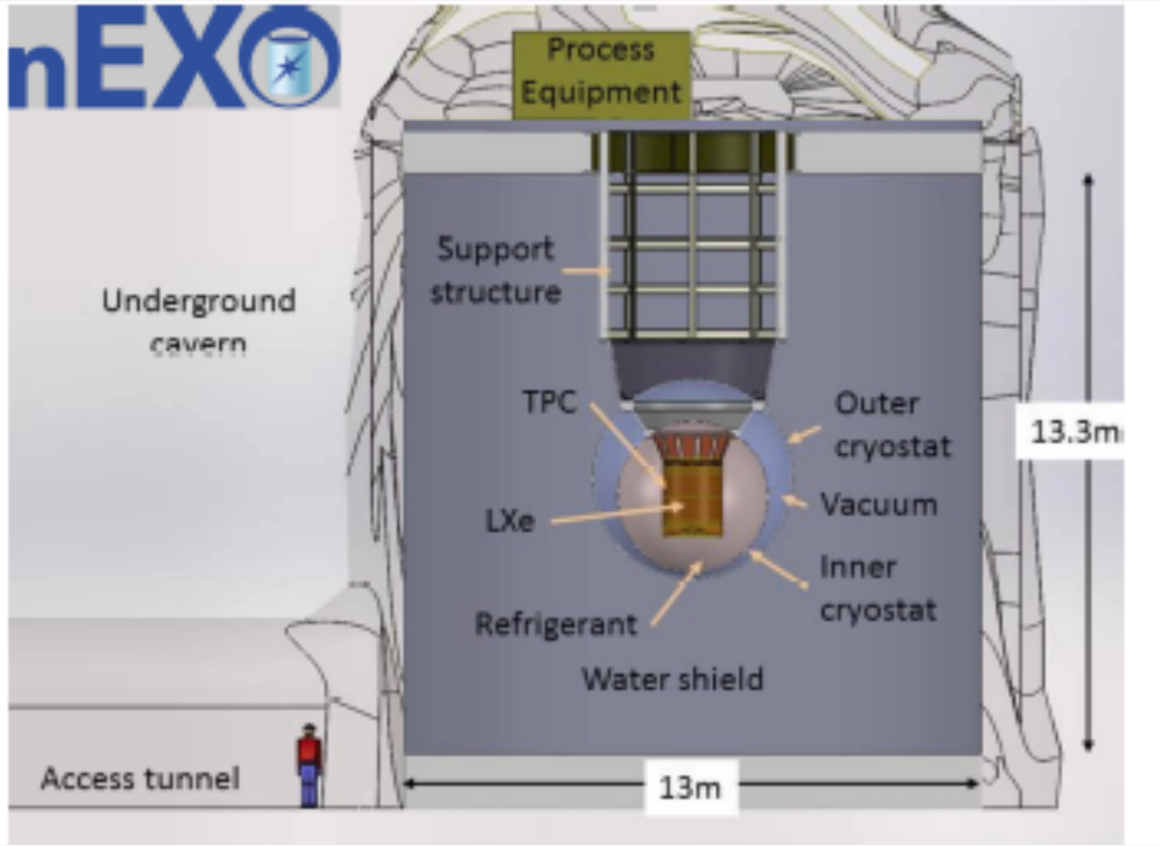


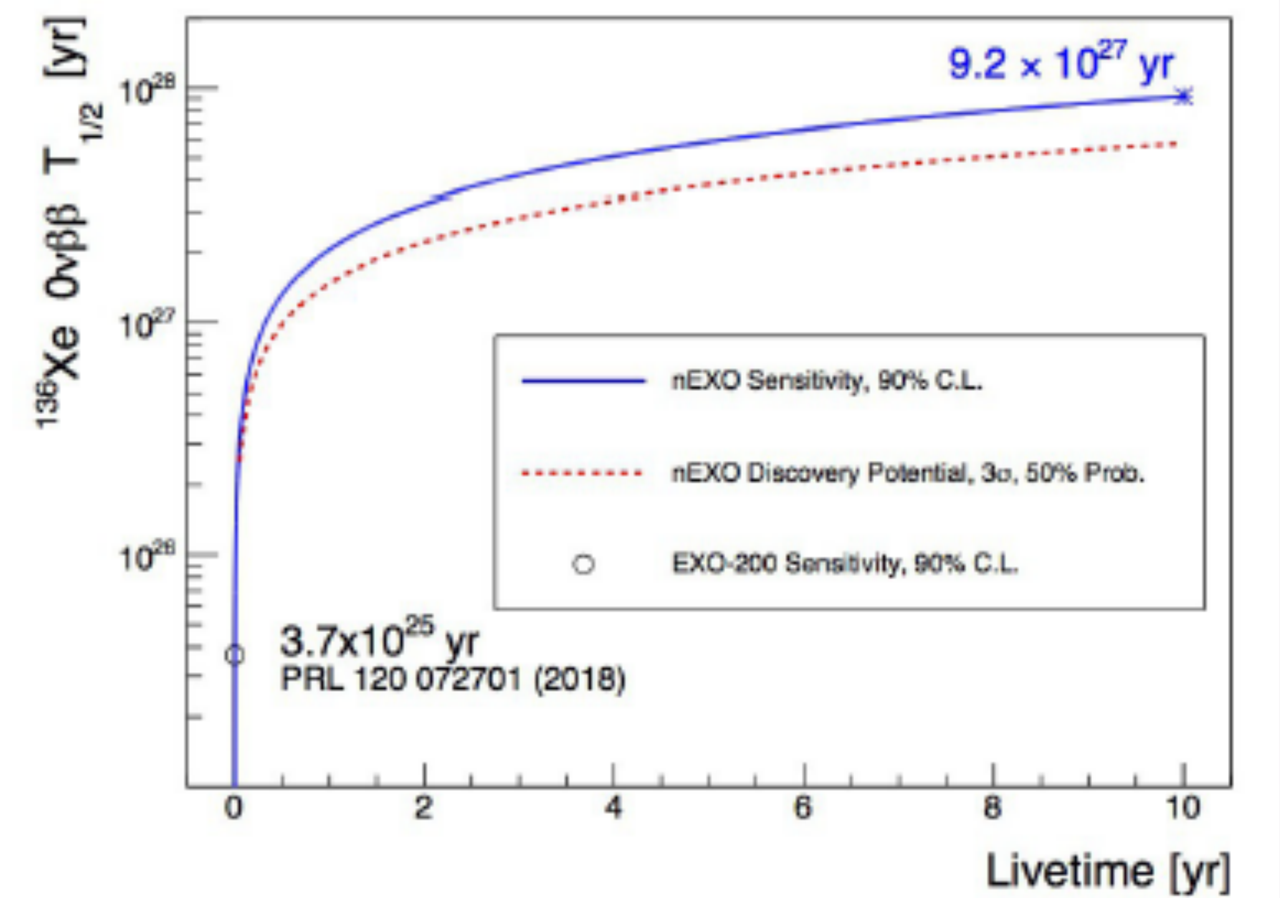
Towards nEXO

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

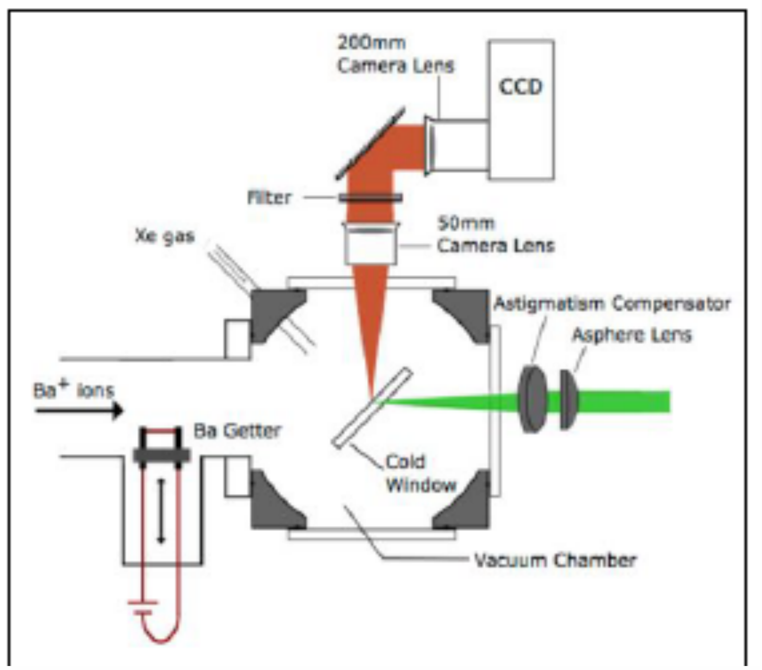
- Self-shielding better for larger detectors!
- Sensitivity estimates rely on *measured* materials

nEXO at SNOLAB

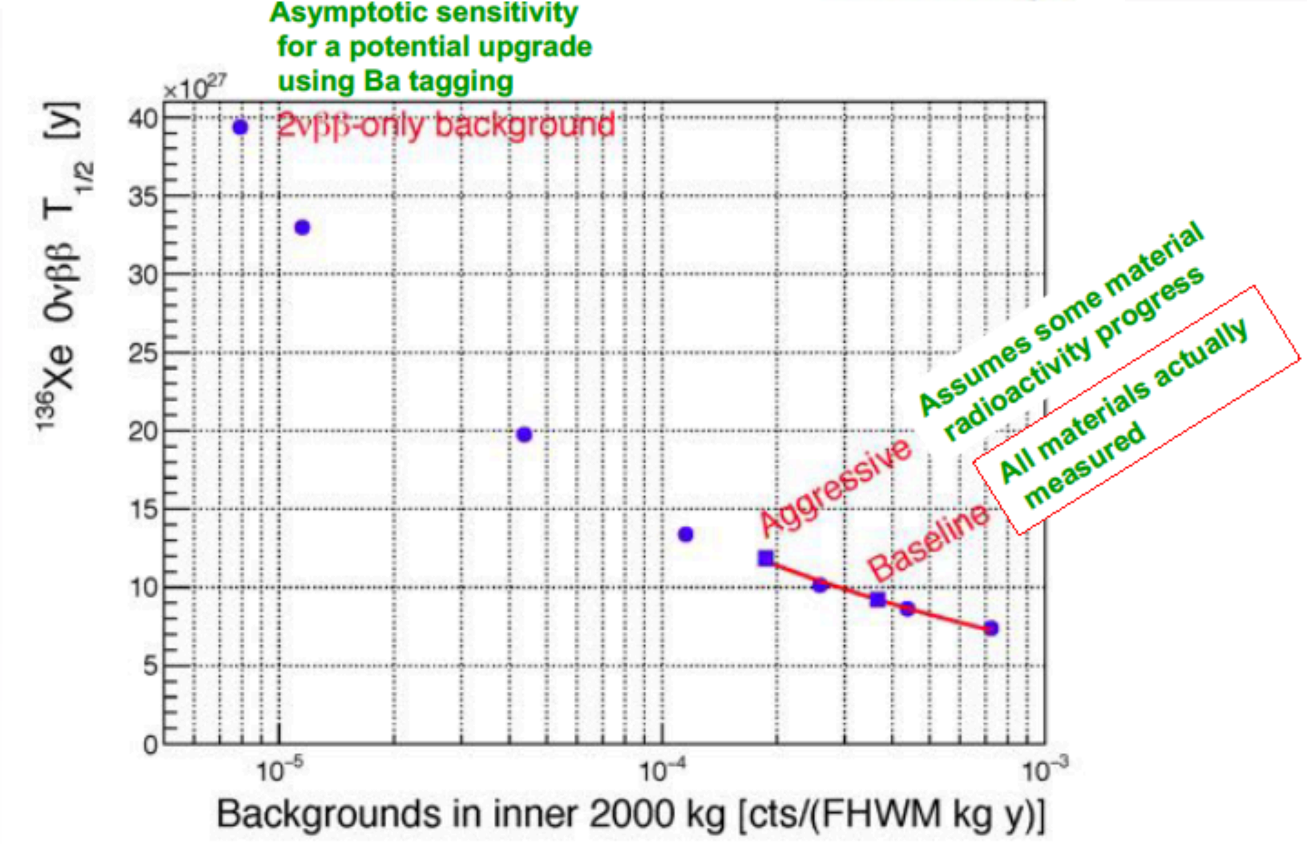




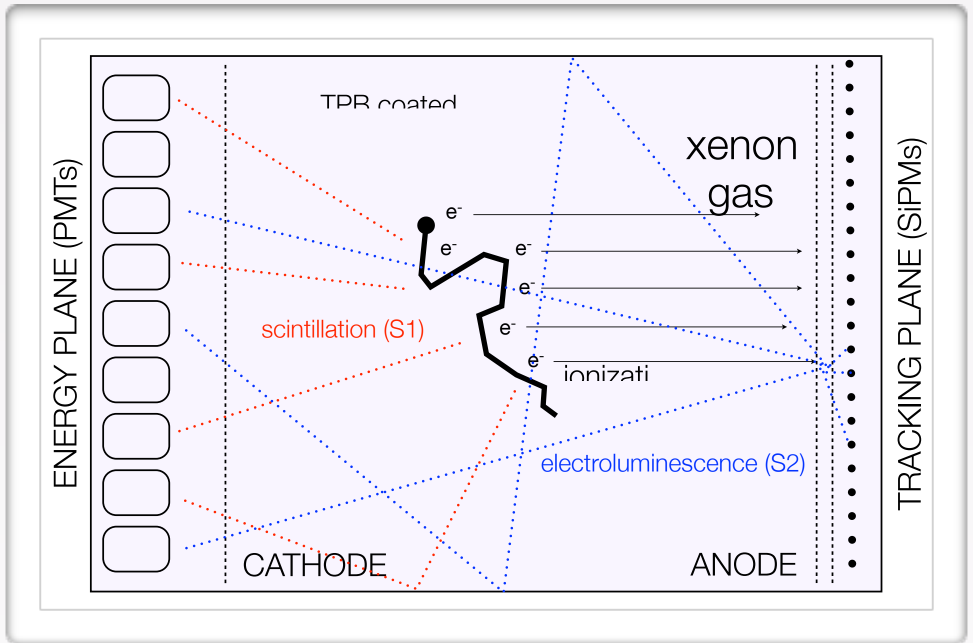
Ba-tagging



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

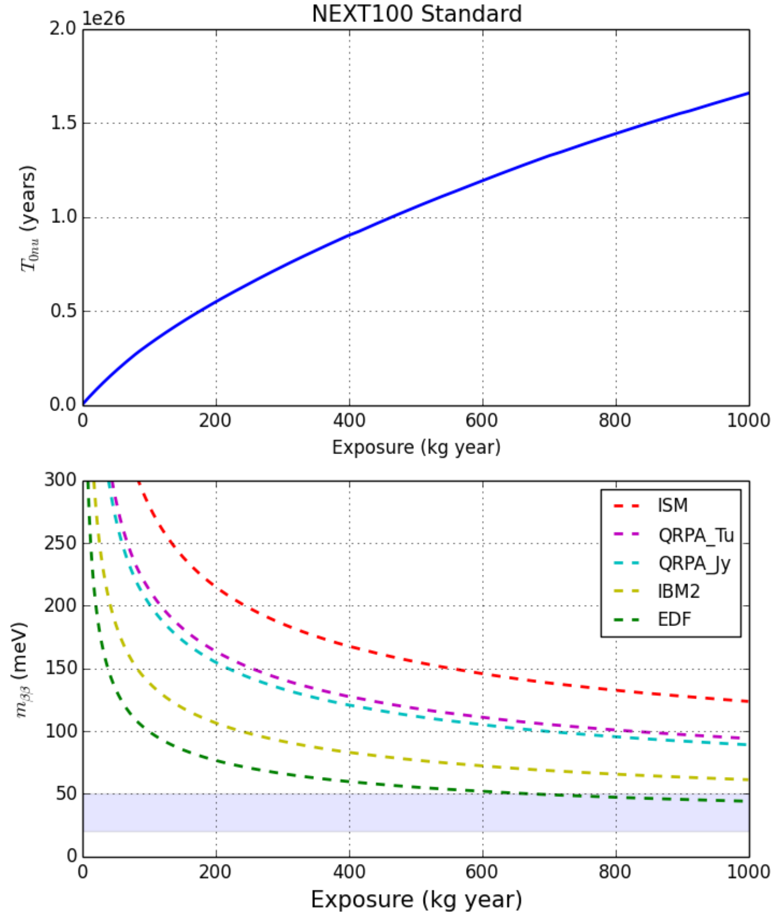


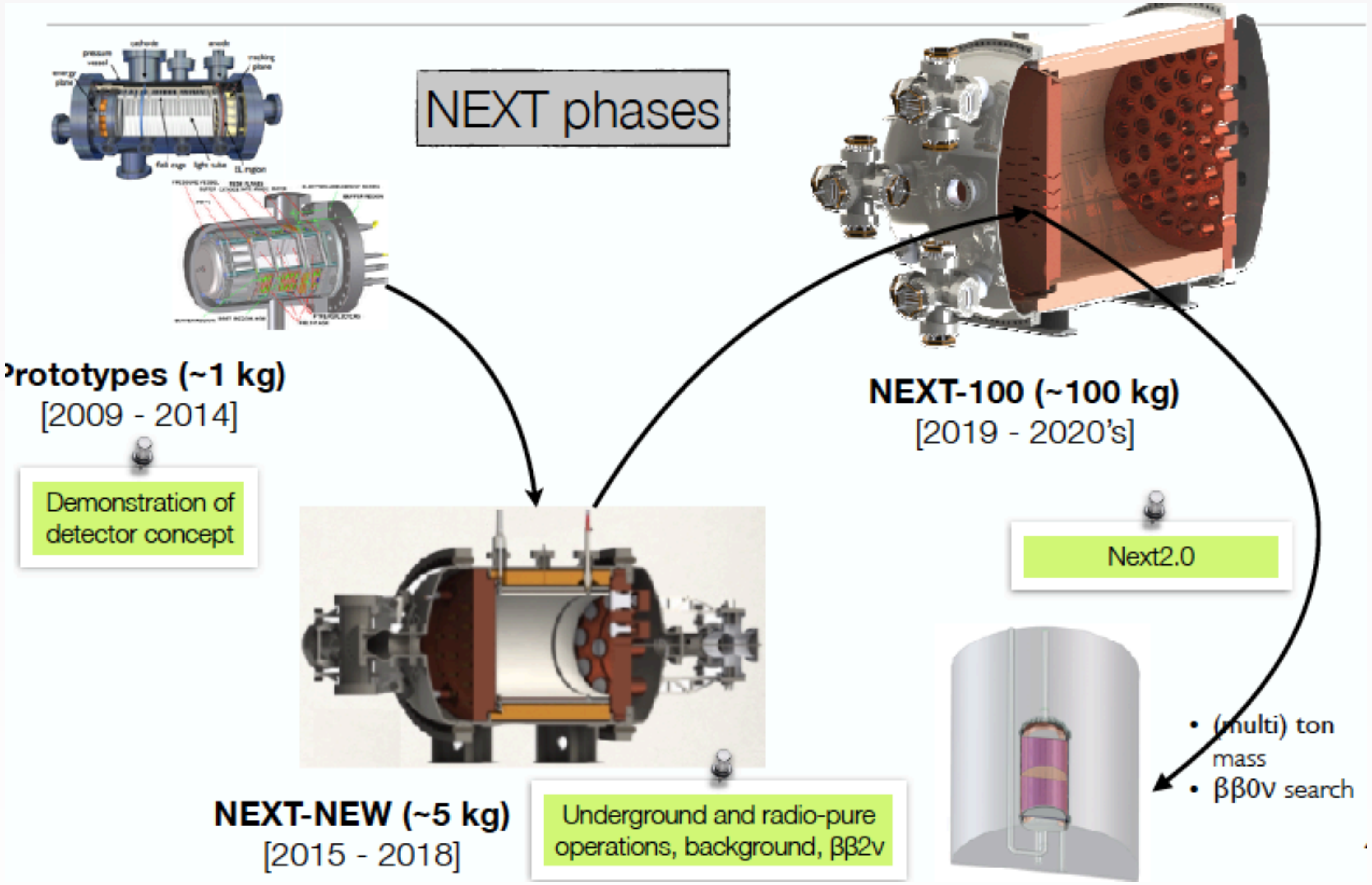
HP-TPC: NEXT



- 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

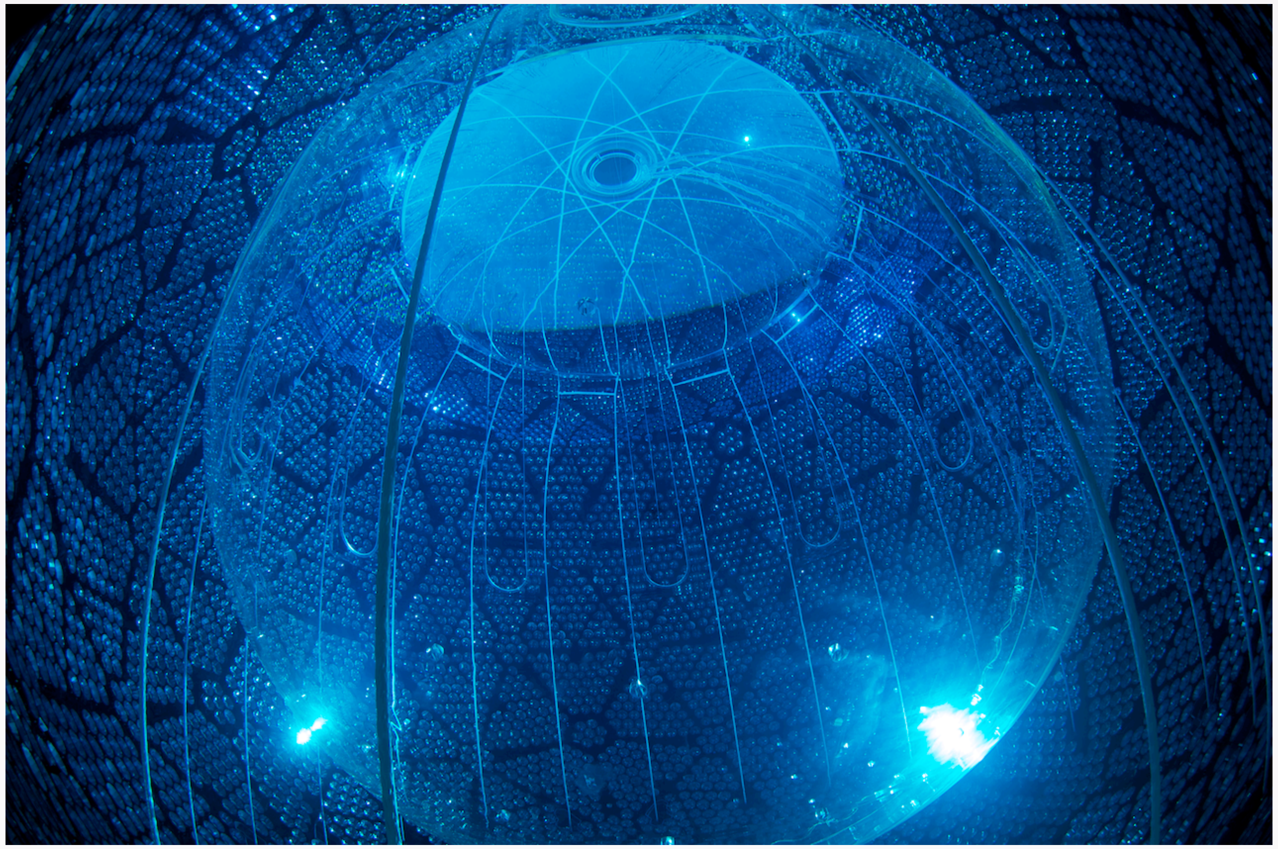
- NEXT-100 aims to start in 2019

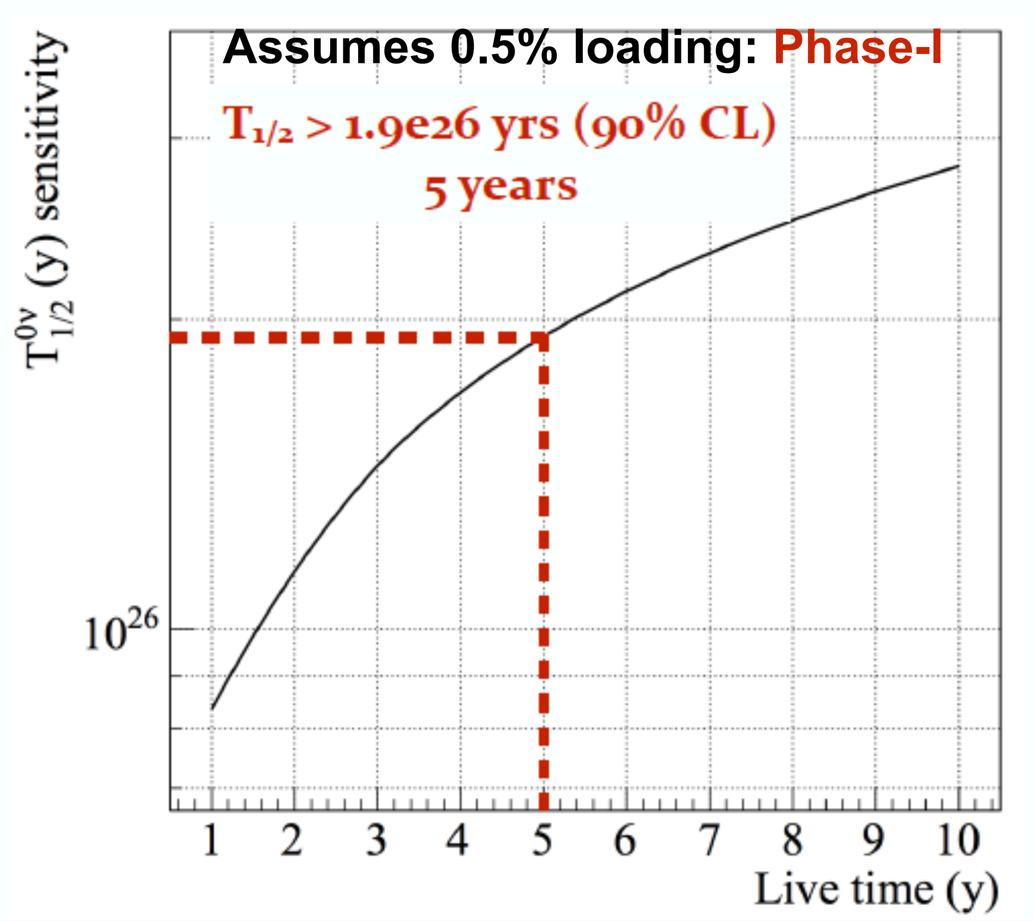




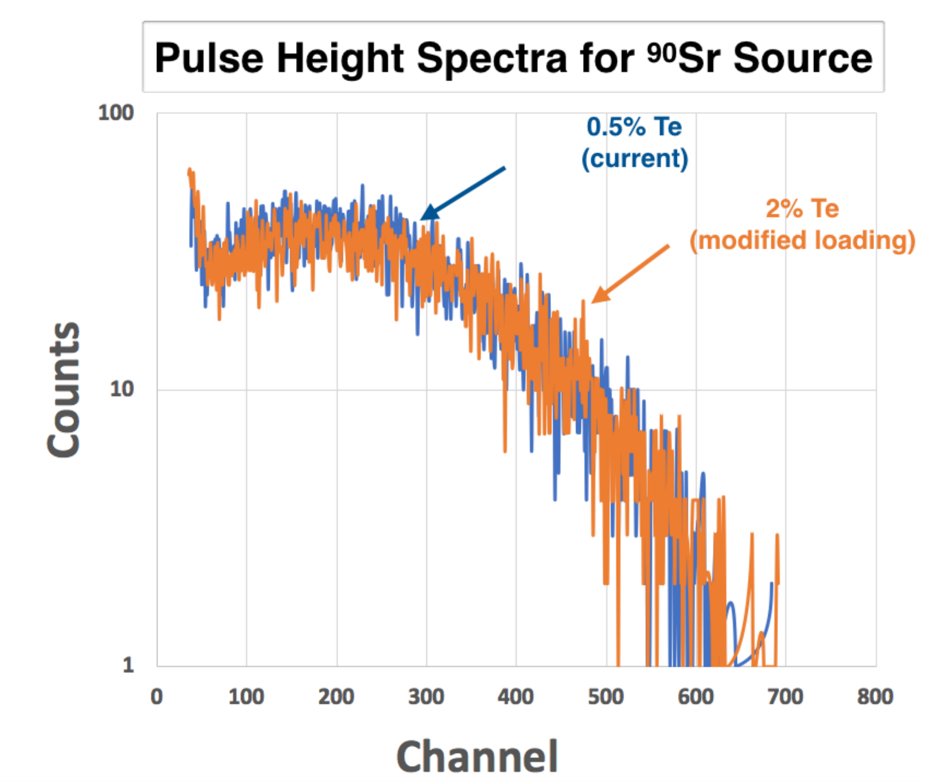
Ba-tagging might be easier in gas

Doped Liquid Scintillator SNO+



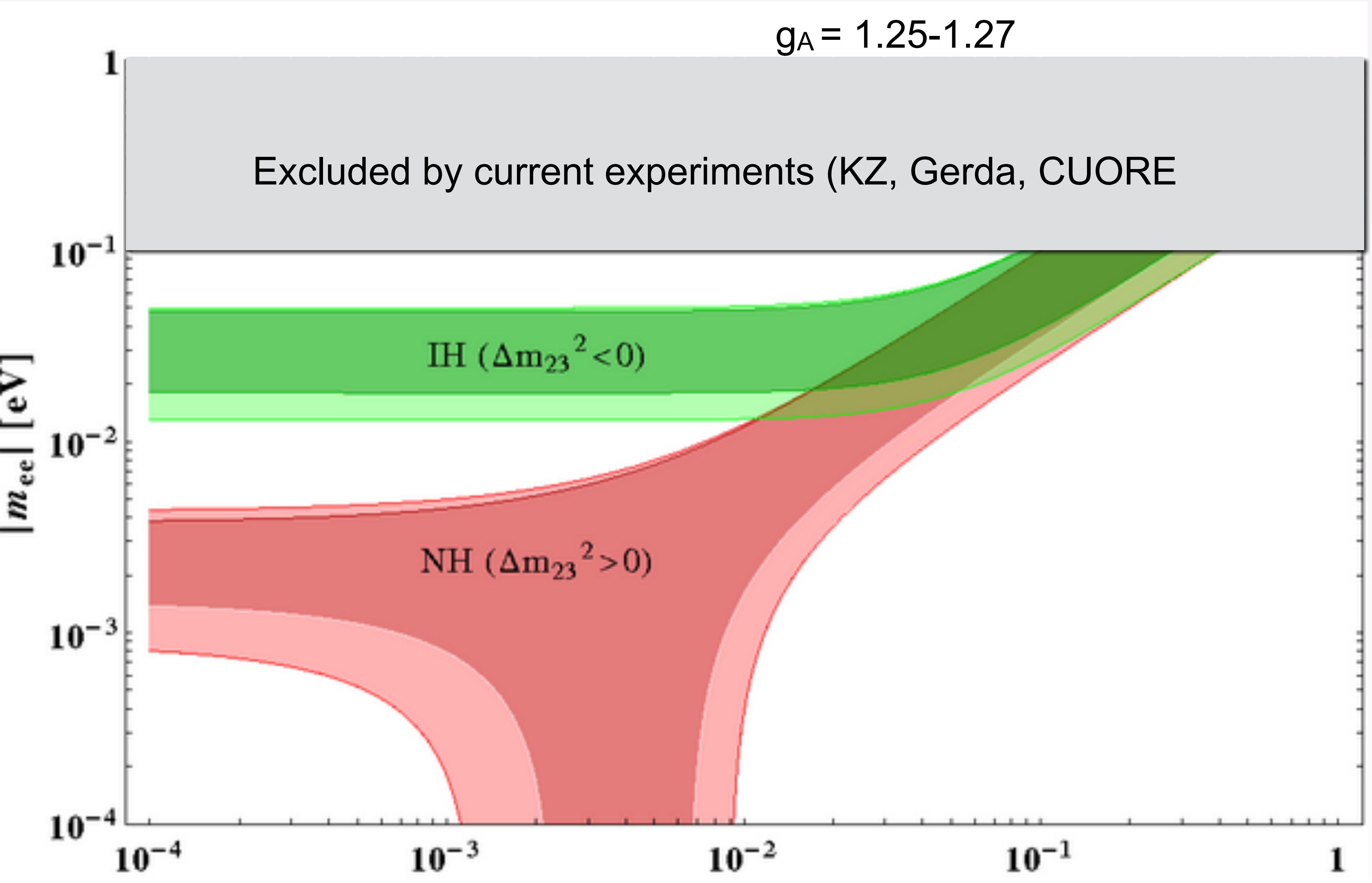


- Has been operating with water since Spring 2017
- Background model in good agreement with data
- First solar-ν results
- Transition to scintillator later this month
- Te loading next year
- **Phase-I** result by 2024



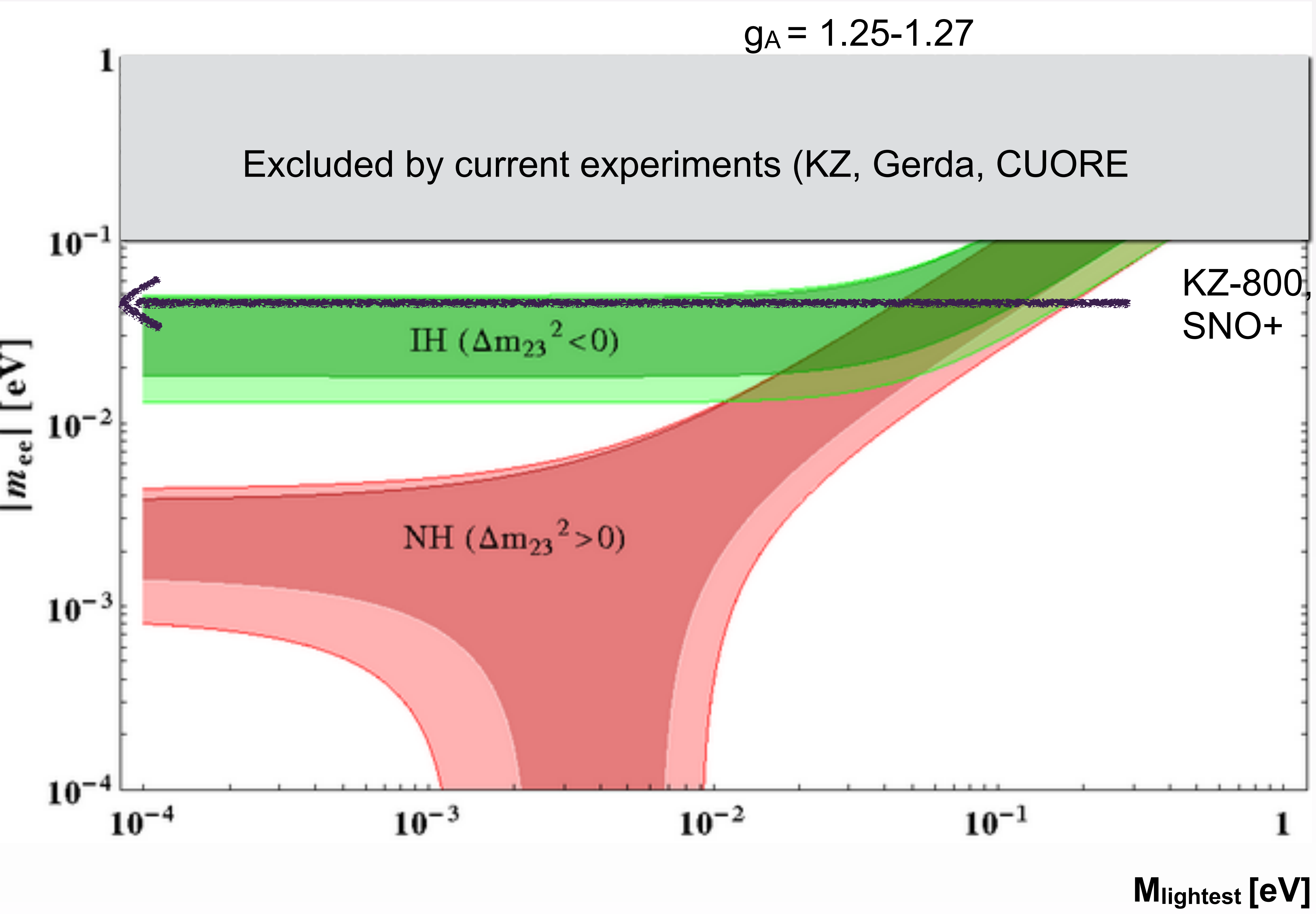
- **R&D on increased loading**
- **If successful 15-50 meV in phase-II**

Current Results and Next Generation prospects



$M_{lightest}$ [eV]

Current Results and Next Generation prospects

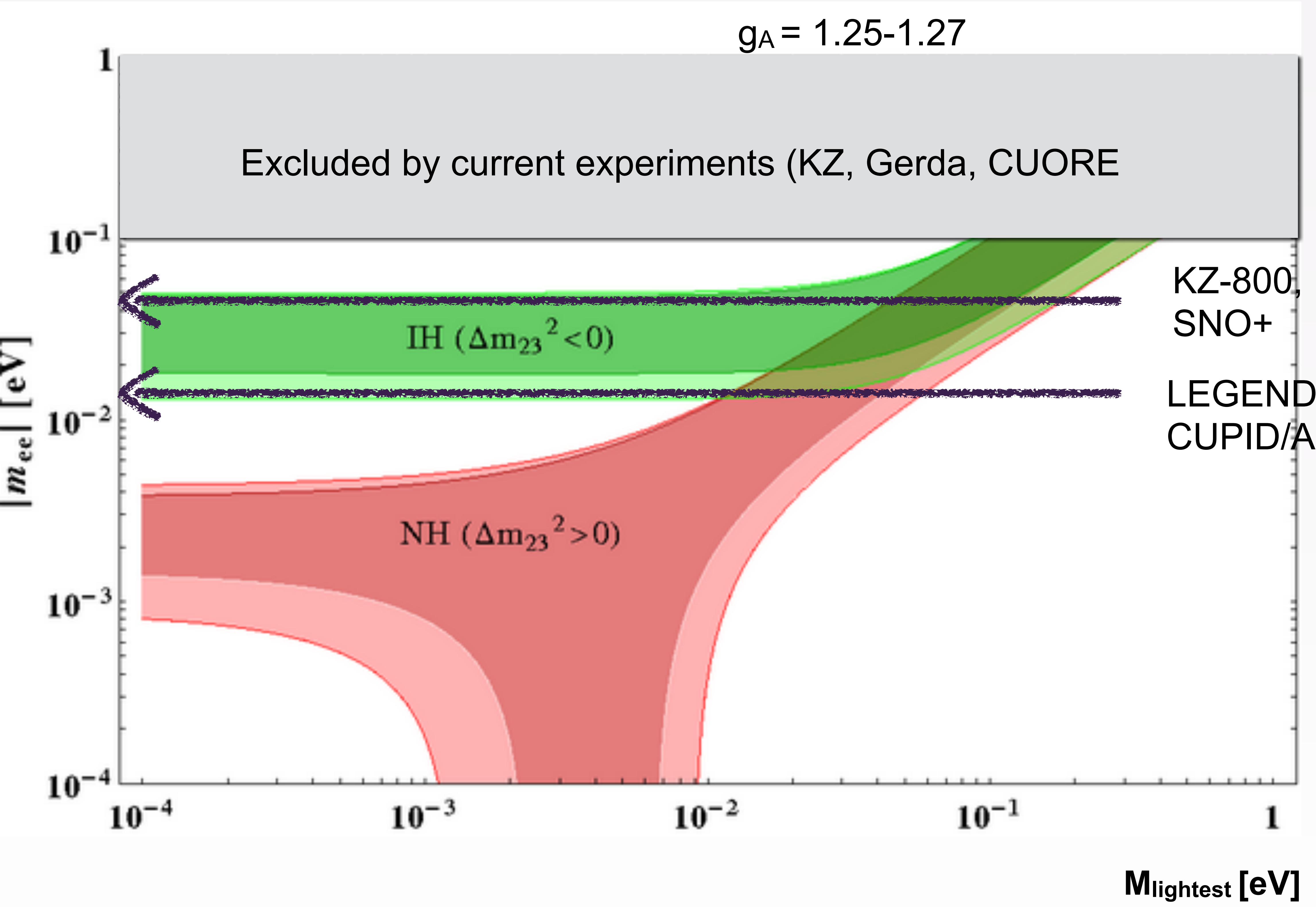


g_A = 1.25-1.27

Excluded by current experiments (KZ, Gerda, CUORE

KZ-800, L200, CUORE, SNO+

Current Results and Next Generation prospects



$g_A = 1.25\text{-}1.27$

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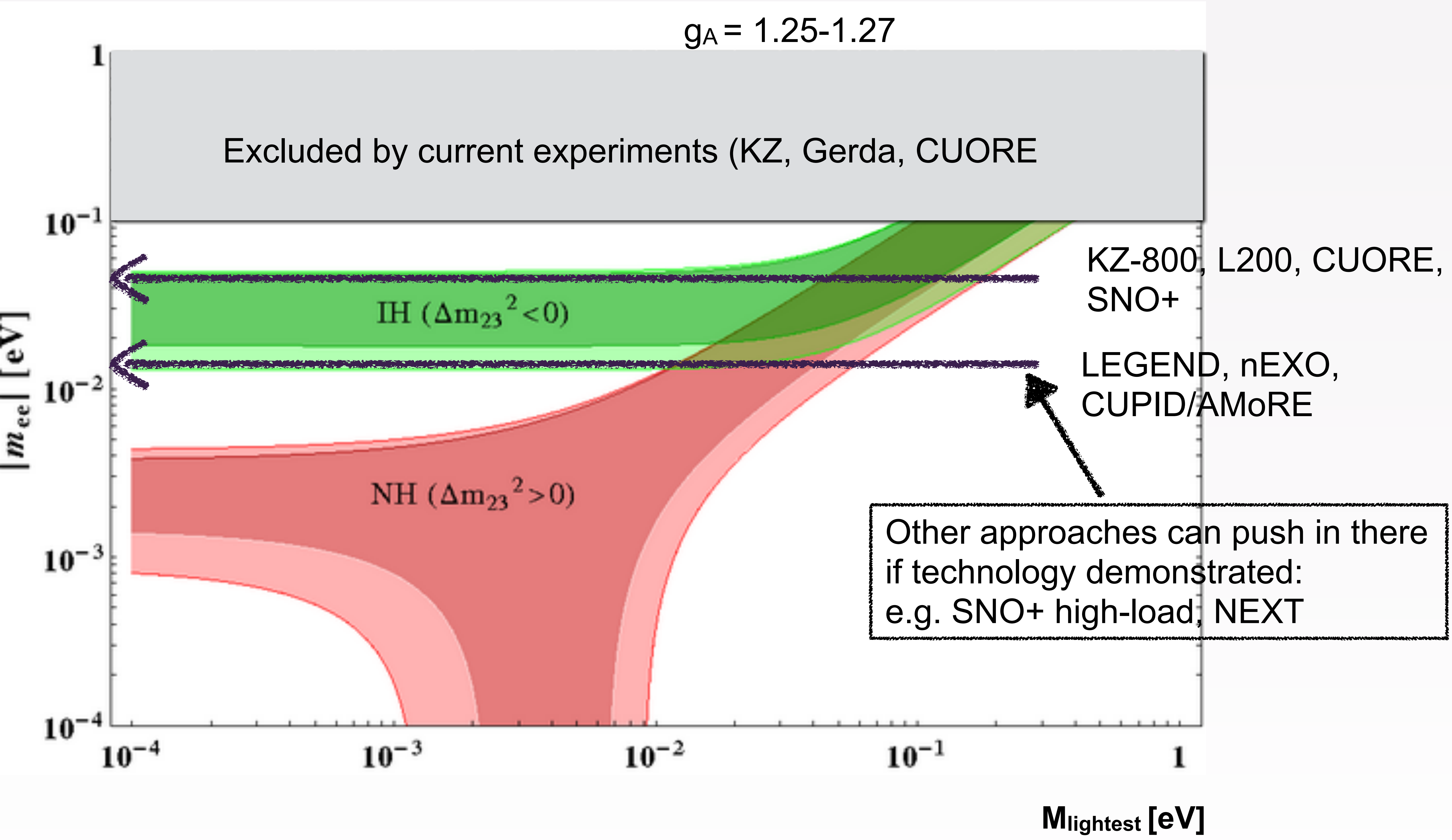
LEGEND, nEXO, CUPID/AMoRE

Current Results and Next Generation prospects



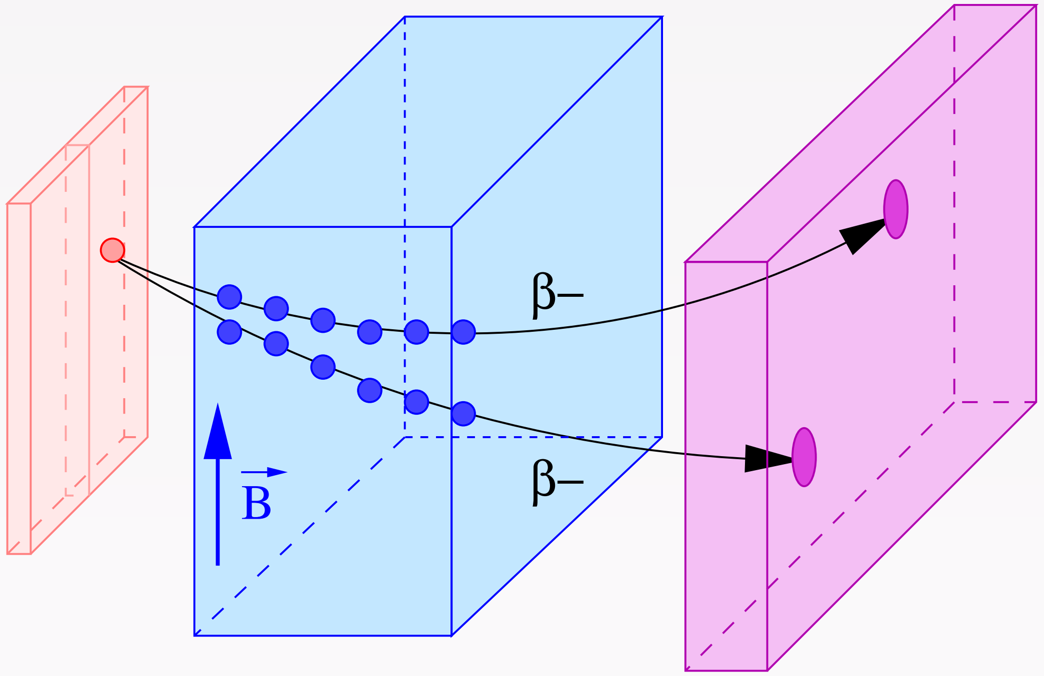
KZ-800, L200, CUORE, SNO+

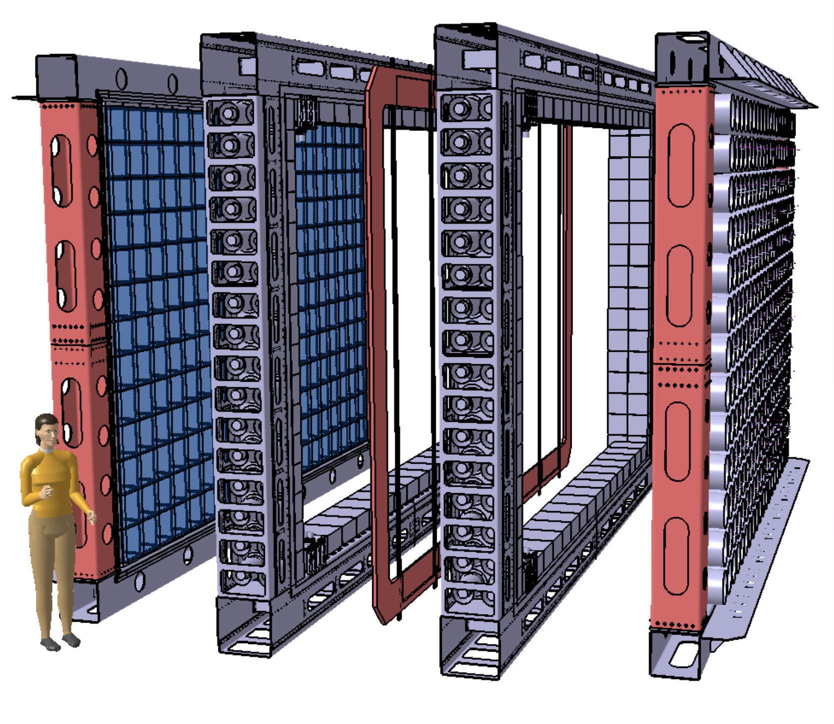
LEGEND, nEXO, CUPID/AMoRE

Other approaches can push in there if technology demonstrated: e.g. SNO+ high-load, NEXT

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

Opportunity for:
- **Multi-isotope confirmation**
- **Exploring underlying physics mechanism (need not be $\langle m_\nu \rangle$)**





- 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

Outlook into Future Sensitivity

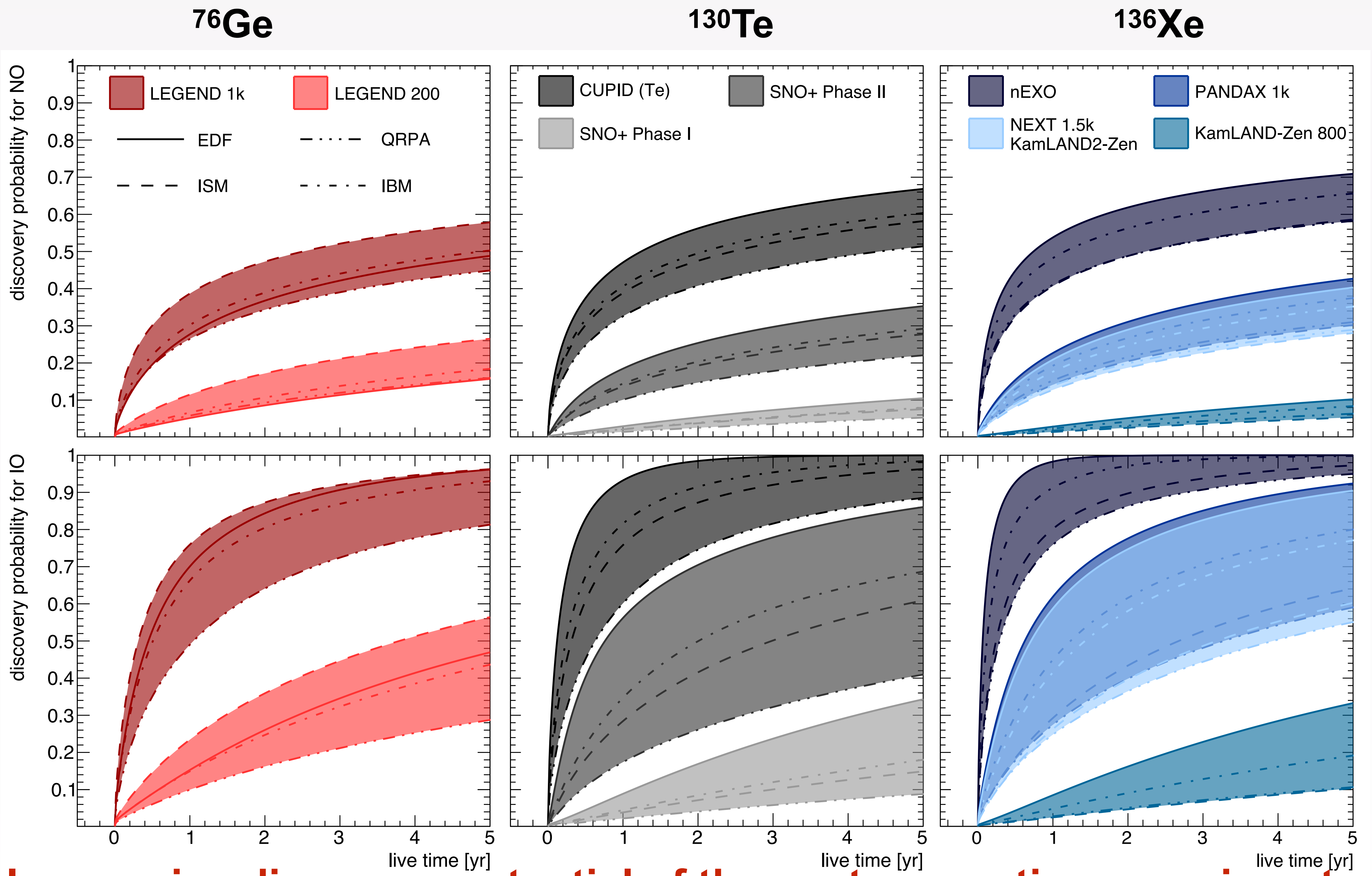
Global Bayesian analysis including neutrino oscillations, ^3H β-decay, 0νββ decay, cosmology

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

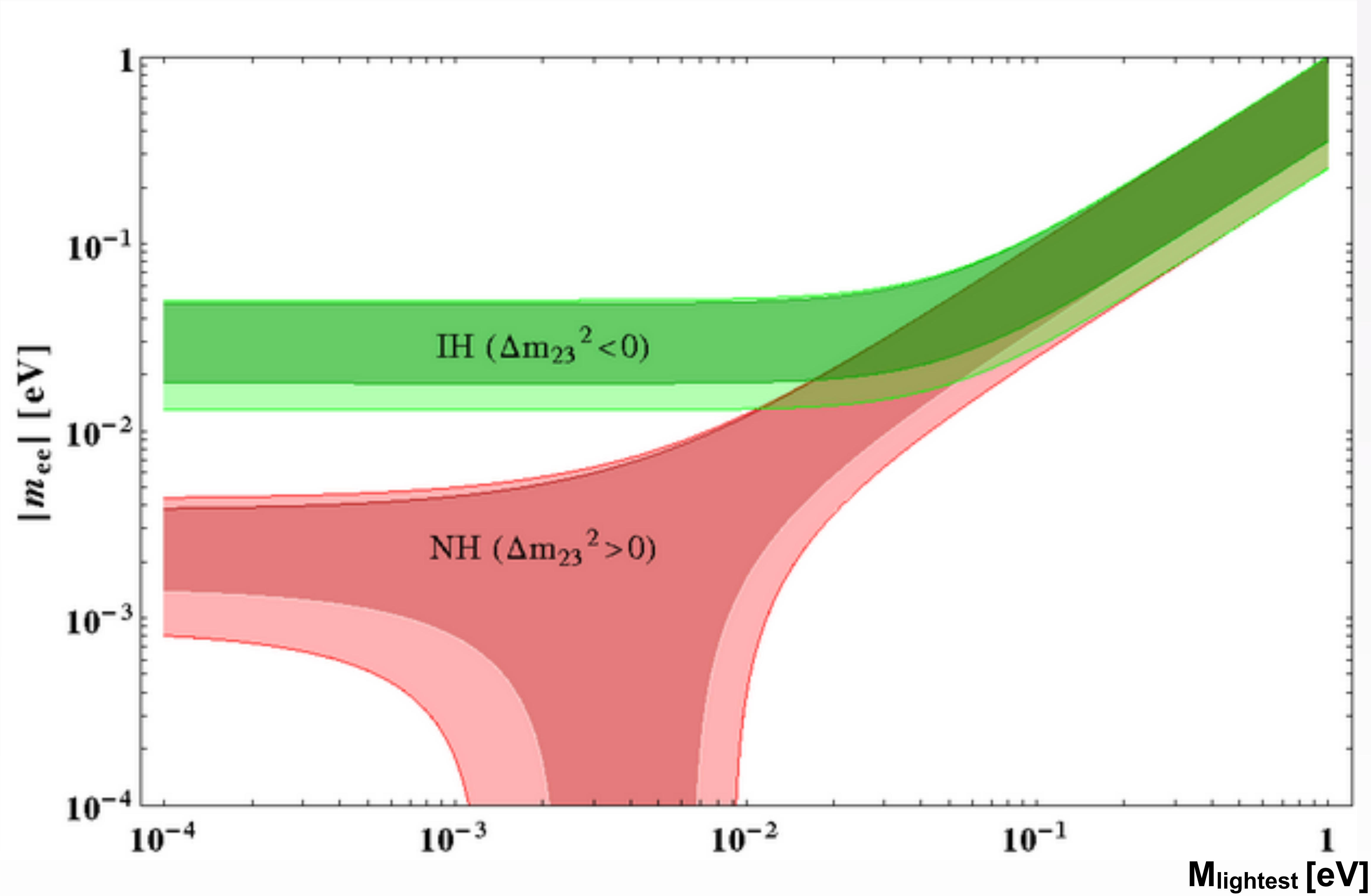
$\theta_{ij}, \delta, \alpha_{ij} \rightarrow \text{ flat}$

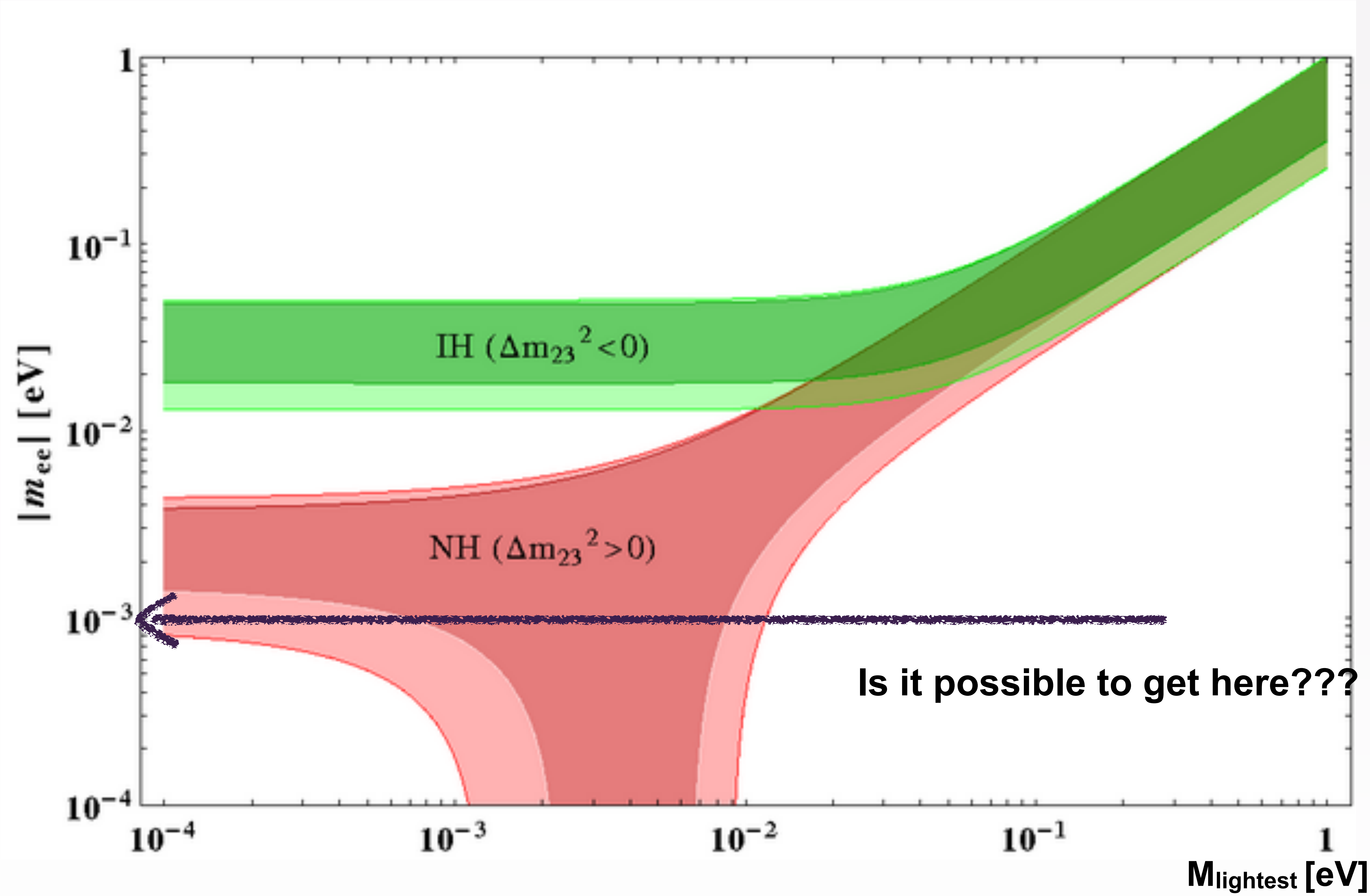
3σ Bayesian **discovery probability**

Phys. Rev. D 96, 053001 (2017)



Impressive discovery potential of the next generation experiments


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



Is it possible to get here???

Thoughts and speculations on “ultimate”* experiment

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

Isotope considerations

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 of “ultimate” experiment

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	$T_{1/2}$ ($\times 10^{29}$ 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	$T_{1/2}$ ($\times 10^{29}$ 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

Summary for “ultimate experiment”

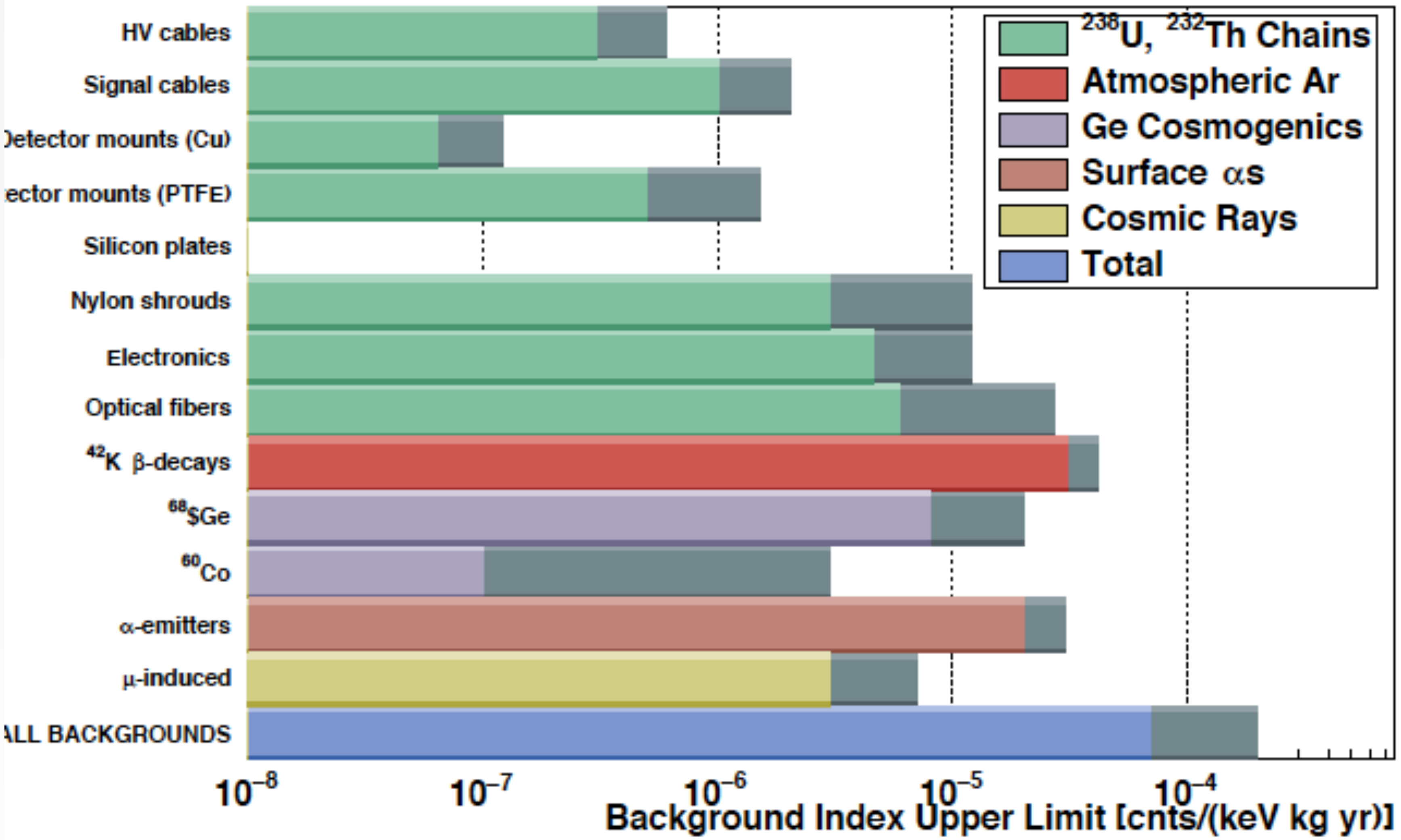
- Assuming an “ideal” detector (good ΔE/E, ε~90-100%, b×ΔE~0) the most promising isotopes appear to be ^{82}Se, ^{96}Zr, ^{100}Mo,^{150}Nd.
- Only ^{82}Se and ^{100}Mo can be enriched with current technologies but the cost is >0.6B$ only for isotopes (>1B$ for detector)
- ^{130}Te and ^{136}Xe are suitable 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

Conclusions

- **0νββ** is the **only 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 IH 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)
- Europe is in a great position to lead **NG-NDBD** with 1-2 experiments hosted in a **European underground laboratory**
  - With experiments operational in mid-2020's. 10 meV target may be reached by mid-late 2030's
- **Europe is well positioned to lead an R&D towards "ultimate" experiment aimed at exploring NH region down to *O*(meV)**

BACKUP

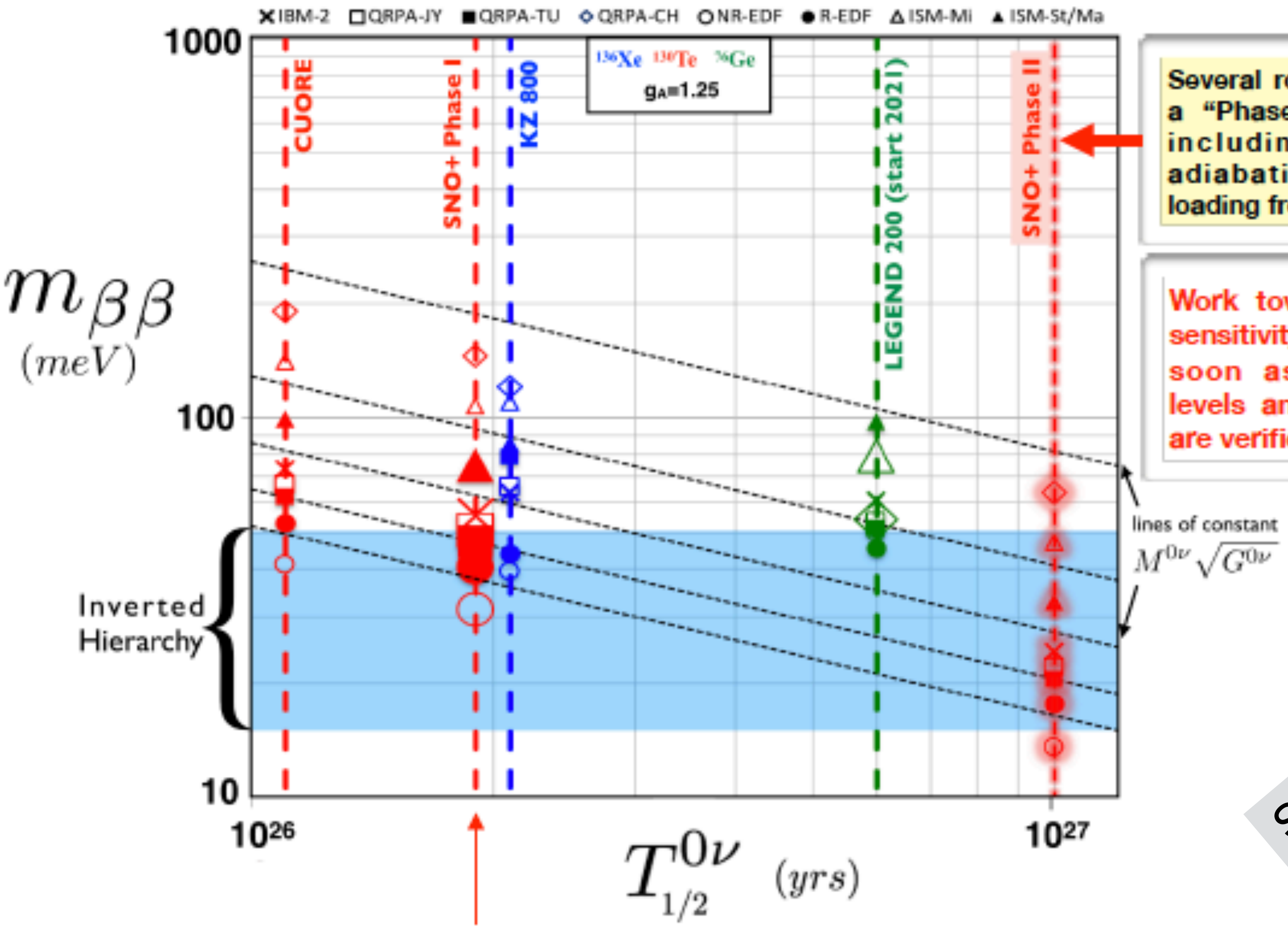
LEGEND-200 background projections



$Q_{\beta\beta}$ 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:

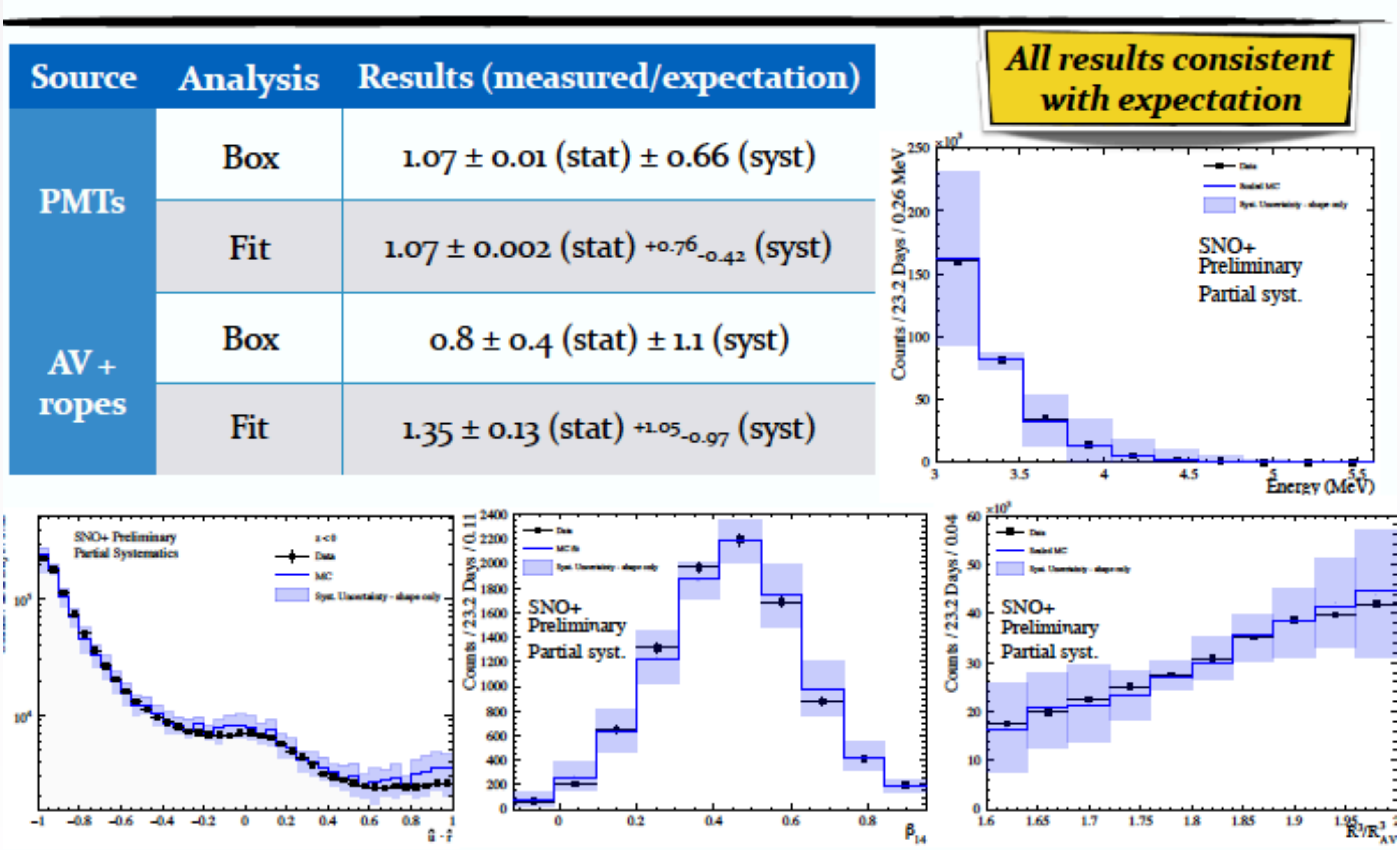


Several routes to achieve a "Phase II" sensitivity, including a possible adiabatic increase in loading from Phase I

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

Slide by S. Biller

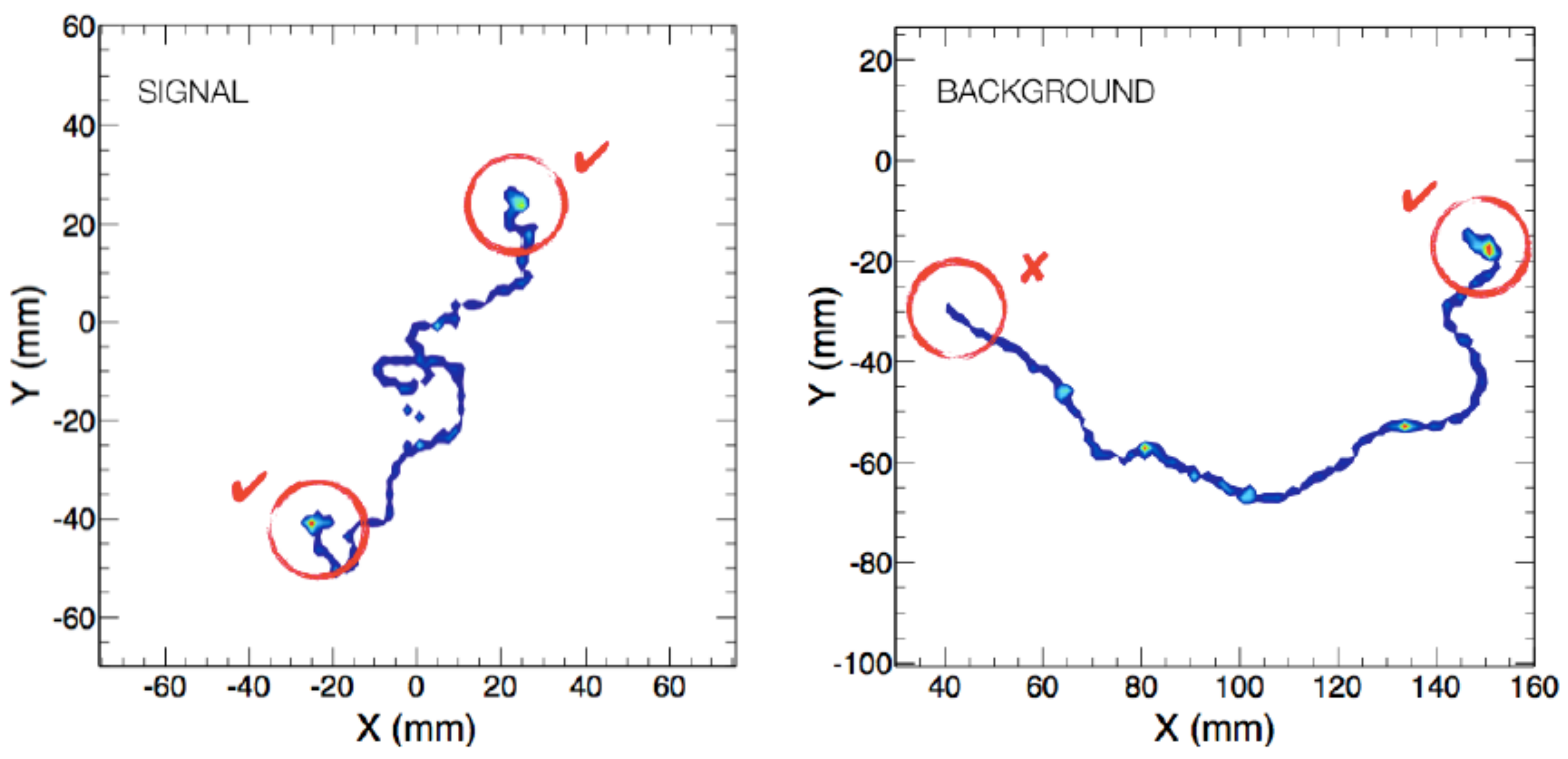
SNO+ Water run background results



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

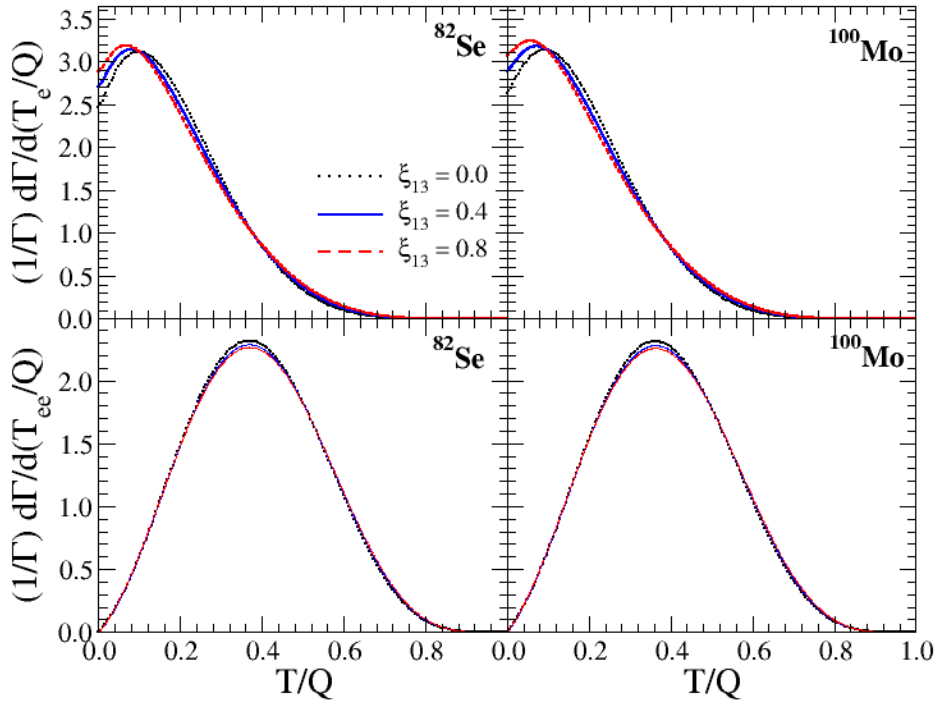
$$0\nu\beta\beta - \text{rate} \sim \left|M^{(0\nu)}_{\text{GTGT}}\right|^2 = (g_{\text{A},0\nu})^4 \left|\sum_{J^\pi} (0_f^+||\mathcal{O}^{(0\nu)}_{\text{GTGT}}(J^\pi)||0_i^+)\right|^2$$

potentially harmful!

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

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

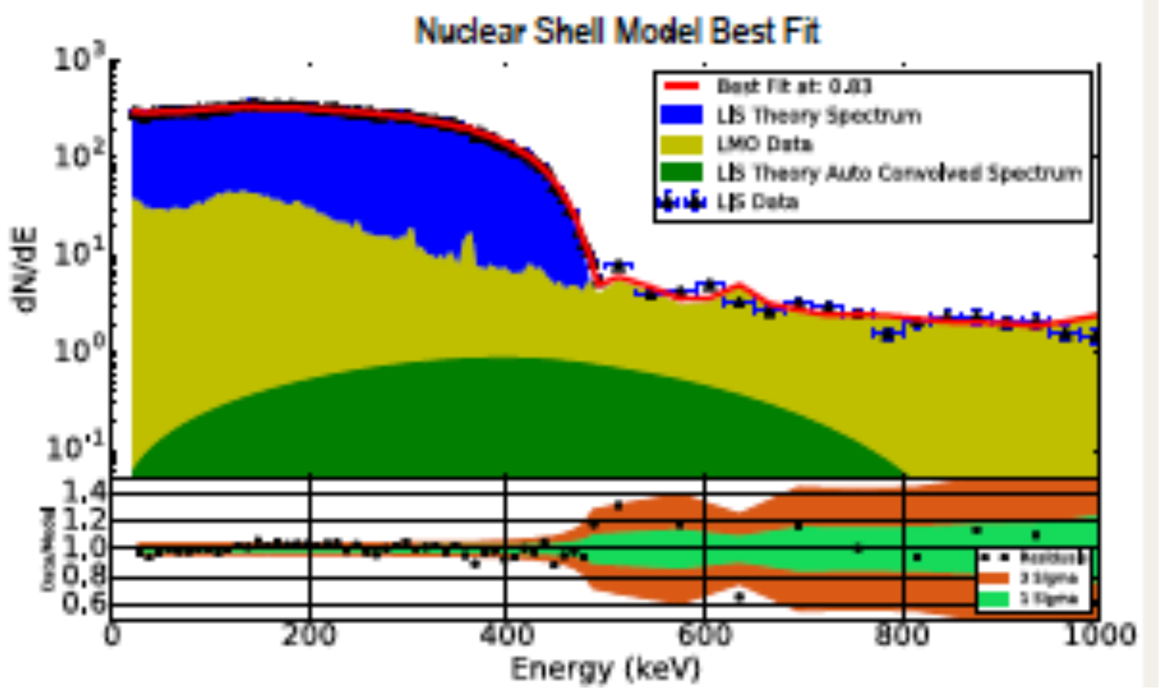
Yes, but still need nuclear physics model



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



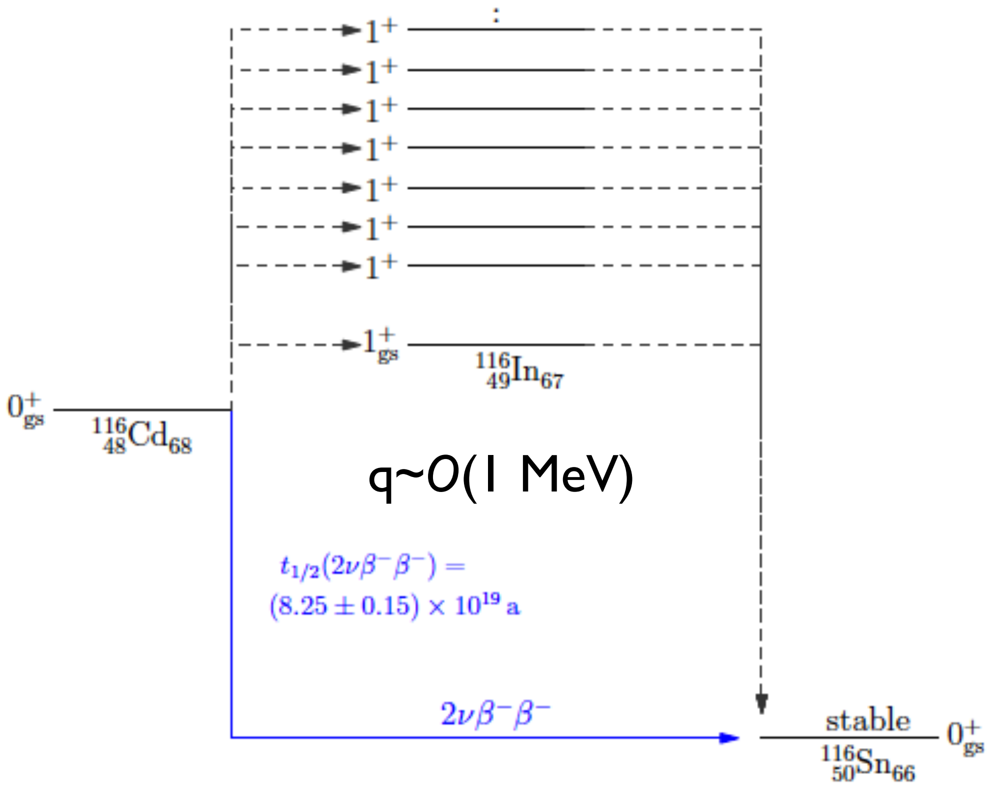
Nuclear Model	g_A Value	Error	Best χ^2
Shell Model	0.83	± 0.03	158.2
MQPM Model	0.94	$^{+0.03}_{-0.04}$	170.5
IBM Model	0.880	± 0.06	269.0

g_A quenching results so far

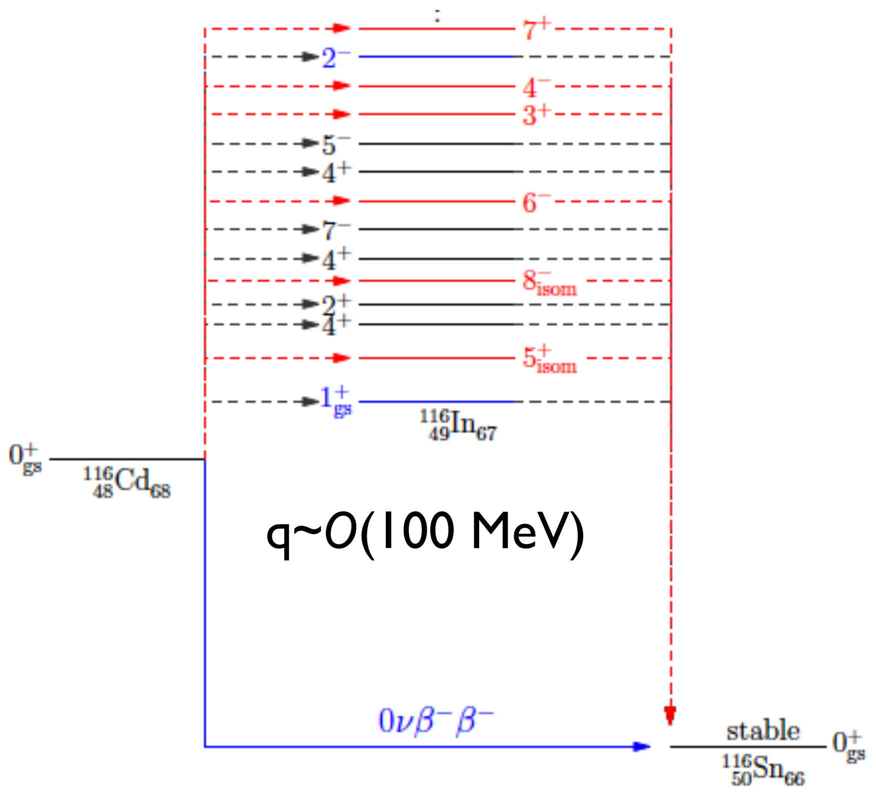
Mass range	$A = 76 - 82$	$A = 100 - 116$	$A = 122 - 136$
$g^{\mathrm{eff}}_{\mathrm{A},0\nu}$	$0.7 - 0.9$	0.5	$0.5 - 0.7$

by J. Suhonen

Too early to panic — quenching must depend on momentum transfer



q~*O*(1 MeV)



q~*O*(100 MeV)

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

Suhonen: Yes. Thank you for summarising my talk .