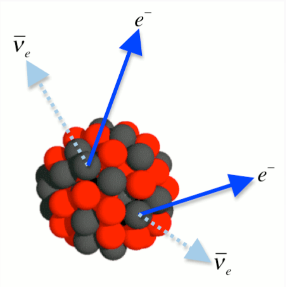
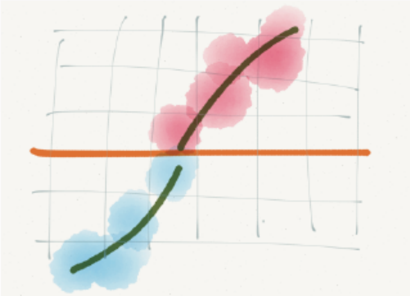
Neutrinoless Double Beta Decay
a.k.a.
Neutrino Physics <u>without</u> Neutrinos

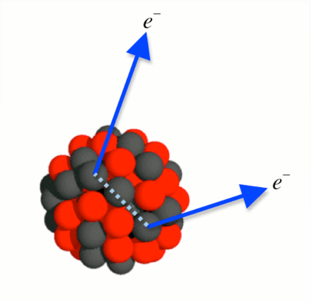


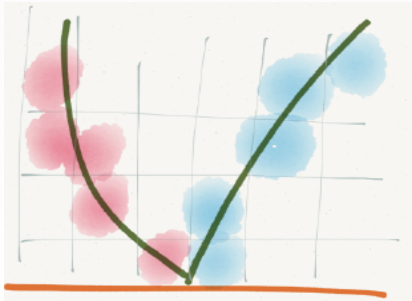
TPC for Rare Events

Paris Diderot University

5-Dec–2016

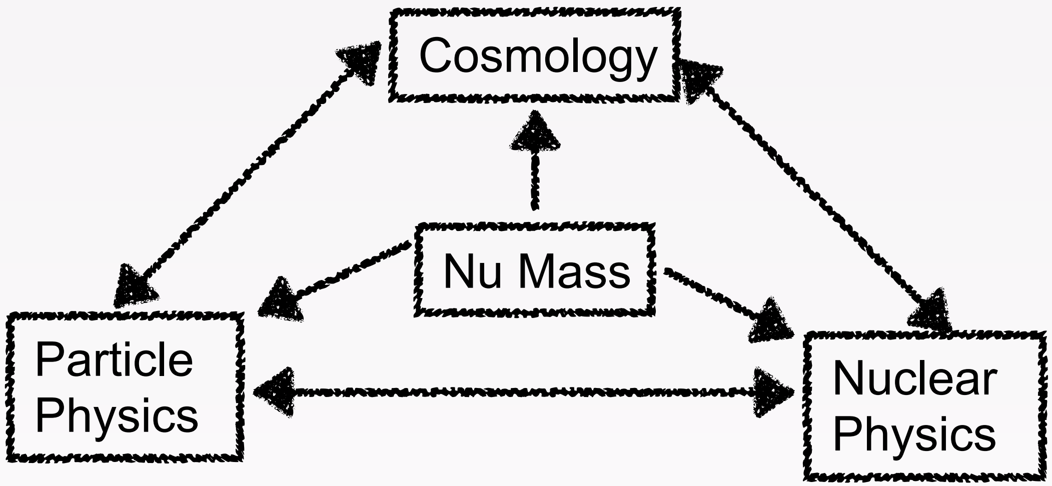


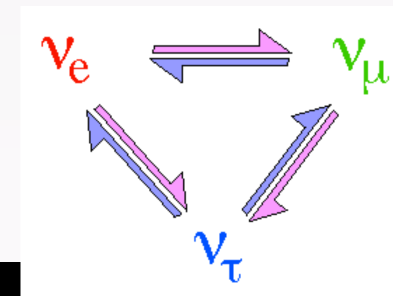




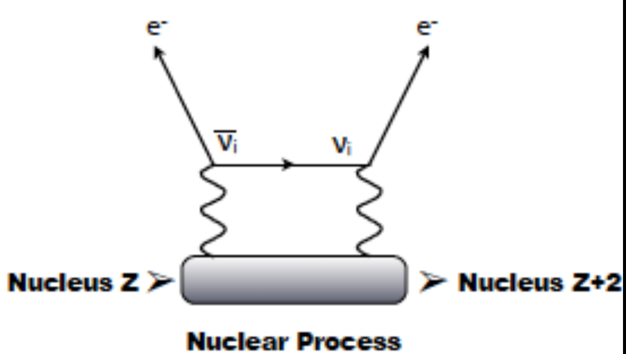
by Ruben Saakyan

Neutrinos is a truly multidisciplinary subject

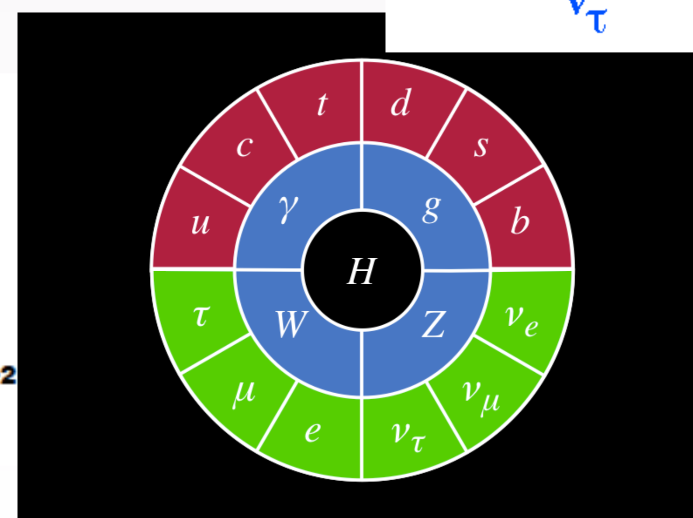




$0\nu\beta\beta$



$\Delta L \neq 0$



The "Big Picture"

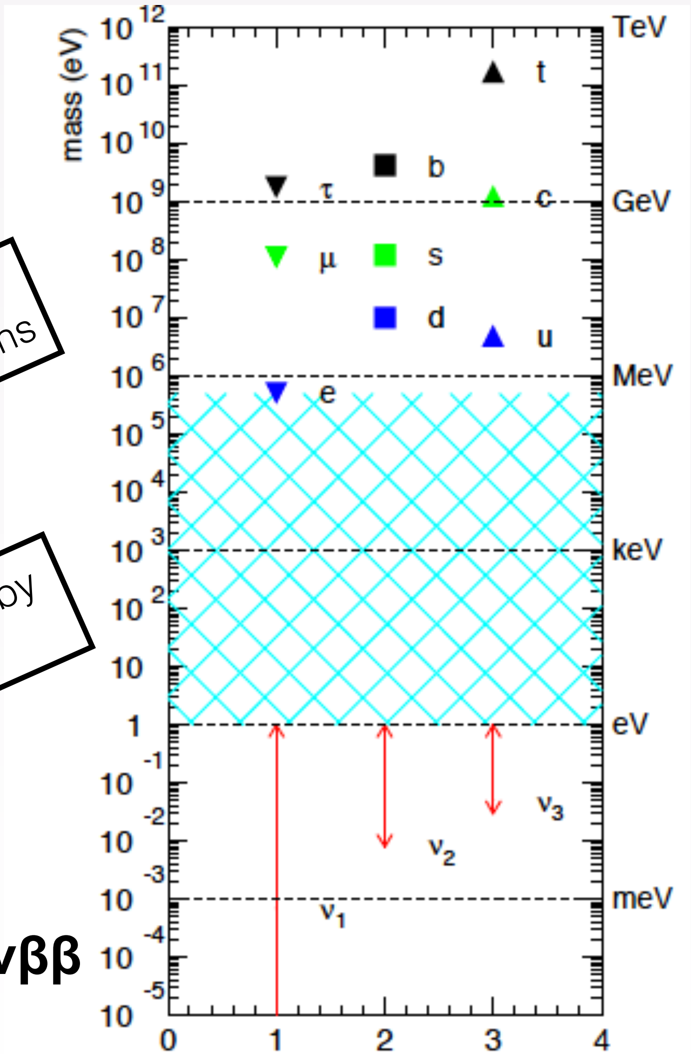
- **Neutrinos** provide the only "particle physics evidence" **beyond the SM**
- Remaining **Big Questions:**

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

addressed by neutrino oscillations

- **Lepton number violation**
- **Majorana vs Dirac — mass mechanism**
- CP- violation — Majorana phase
- Neutrino mass ordering: normal vs inverted

addressed by 0νββ



Impossible to answer key questions without 0νββ

Nature of Neutrinos: Majorana (ν = anti-ν) or Dirac ($\nu \neq$ anti-ν)?

$\Delta L \neq 0$ $\Delta L = 0$

Directly related to fundamental symmetries of particle interactions

Provides important information on origin of neutrino mass

(probably not simple Higgs mechanism as $m_\nu / m_e \sim 10^{-7}$)

SEE-SAW

$$m_\nu \equiv m_M^L = \frac{m_D^2}{M} << m_D$$

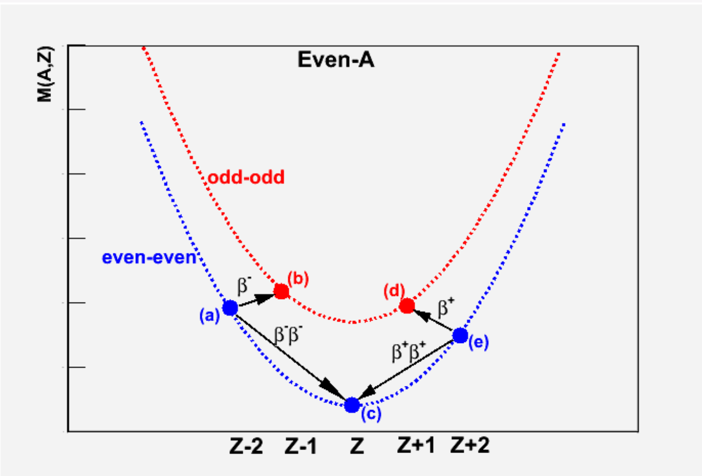
To obtain $m_3 \sim (\Delta m^2_{atm})^{1/2}$, $m_D \sim m_t$, $M_3 \sim 10^{15}$GeV (GUT!)

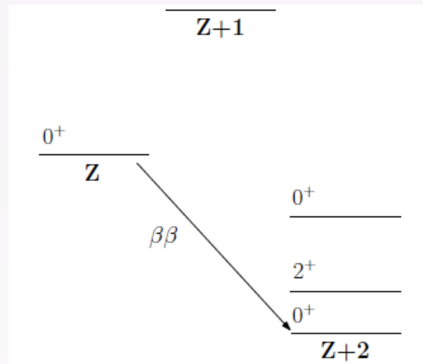
Lepton number violation is one of the key ingredients of **leptogenesis** as the mechanism to generate the baryon asymmetry of the Universe.

More matter than anti-matter!

Double Beta Decay in the Standard Model
(Goeppert-Mayer, 1935)

Recall pairing term in SEMF





M(A,Z) > M(A,Z+2)

$Q_{\beta\beta}$ = M(A,Z) - M(A,Z+2)

phase space

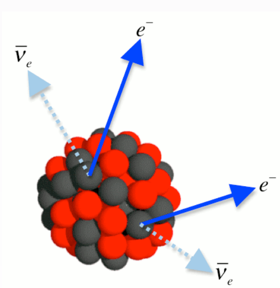
$$\frac{1}{T_{1/2}^{2\nu}} = G^{2\nu}(Q_{\beta\beta},Z)\left|M^{2\nu}\right|^2$$

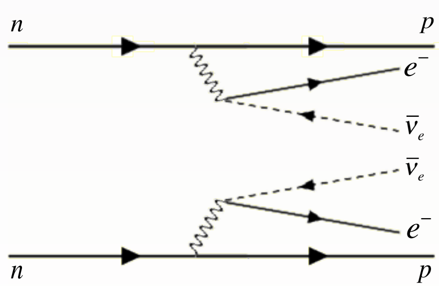
NME:
~~Nasty~~ Nuclear
Matrix
Element

Over **40 nuclei** can undergo **ββ**-decay (including $\beta^+\beta^+$ and 2K-capture)
Only ~**10** experimentally **feasible** (so far!)

NME is **measured** in $2\nu\beta\beta$

- Second order process ⇒ rare (~10^{19}-10^{21} yr)
- Nevertheless **observed for 12 nuclei**
- **Experimental input** for **NME** calculation



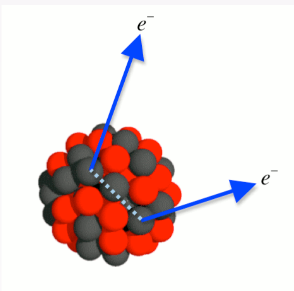


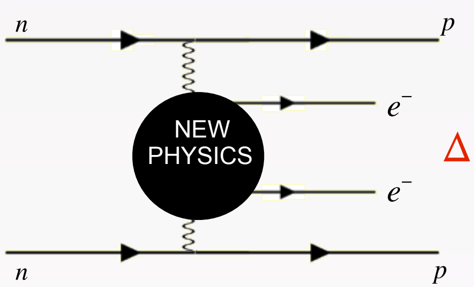
Recent Review:
R.Saakyan, Annu. Rev. Nucl. Part. Sci. 2013.63:503-529

Double Beta Decay Beyond the Standard Model

↓

Neutrinoless Double Beta Decay (Furry, 1939).





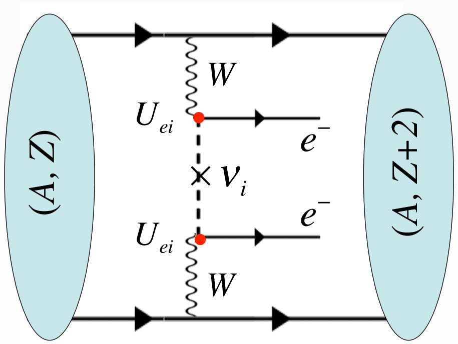
ΔL = 2!

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

Lepton number violating parameter

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

"Popular" scenario - light Majorana mass



Coherent sum over neutrino amplitudes

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

Nuclear Matrix Elements

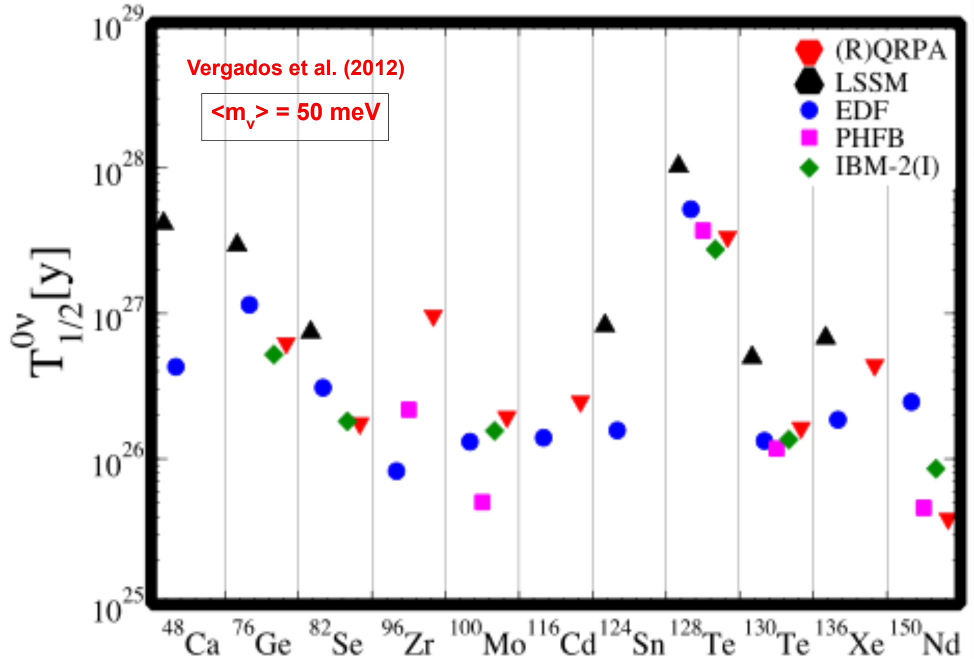
phase-space factor (exactly calculable)

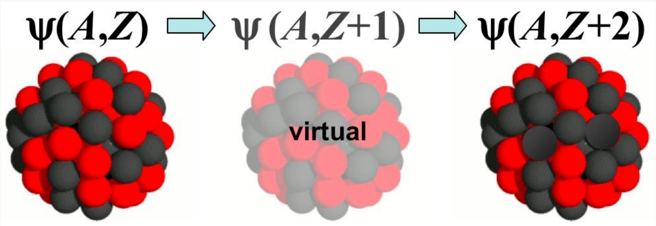
Axial-vector coupling

effective neutrino mass (or your other favourite LNV parameter)

$$0\nu\beta\beta \text{ Rate } \propto \frac{1}{T_{1/2}^{0\nu}} = G^{0\nu}(Q_{\beta\beta},Z)g_A^4\left|M^{0\nu}\right|^2\left\langle m_{\beta\beta}\right\rangle^2$$

<u>N</u>uclear <u>M</u>atrix <u>E</u>lements





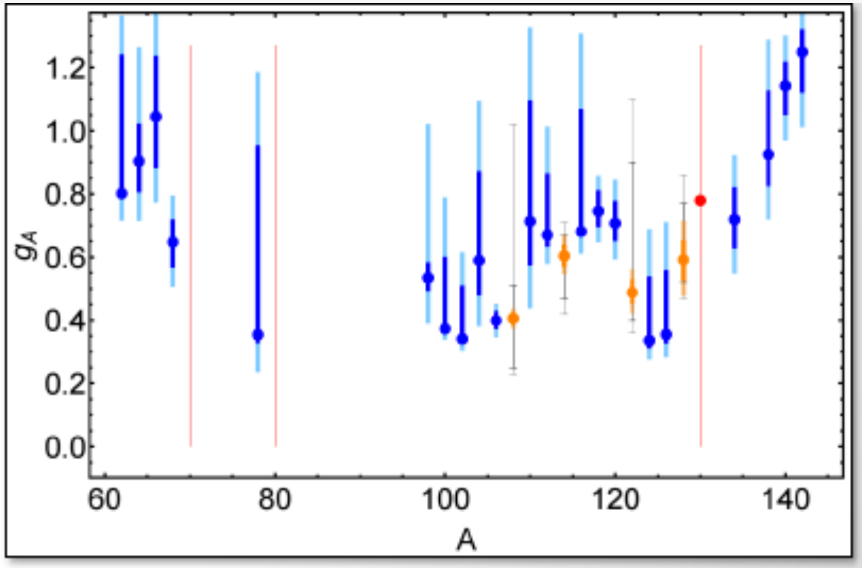
- Does not affect discovery potential
- Correlations between NME's can be exploited to compare experiments.

Quenching of g_A

$$T_{1/2}^{-1} = m_{\beta\beta}^2 G^{0\nu} g_A^4 |M^{0\nu}|^2$$

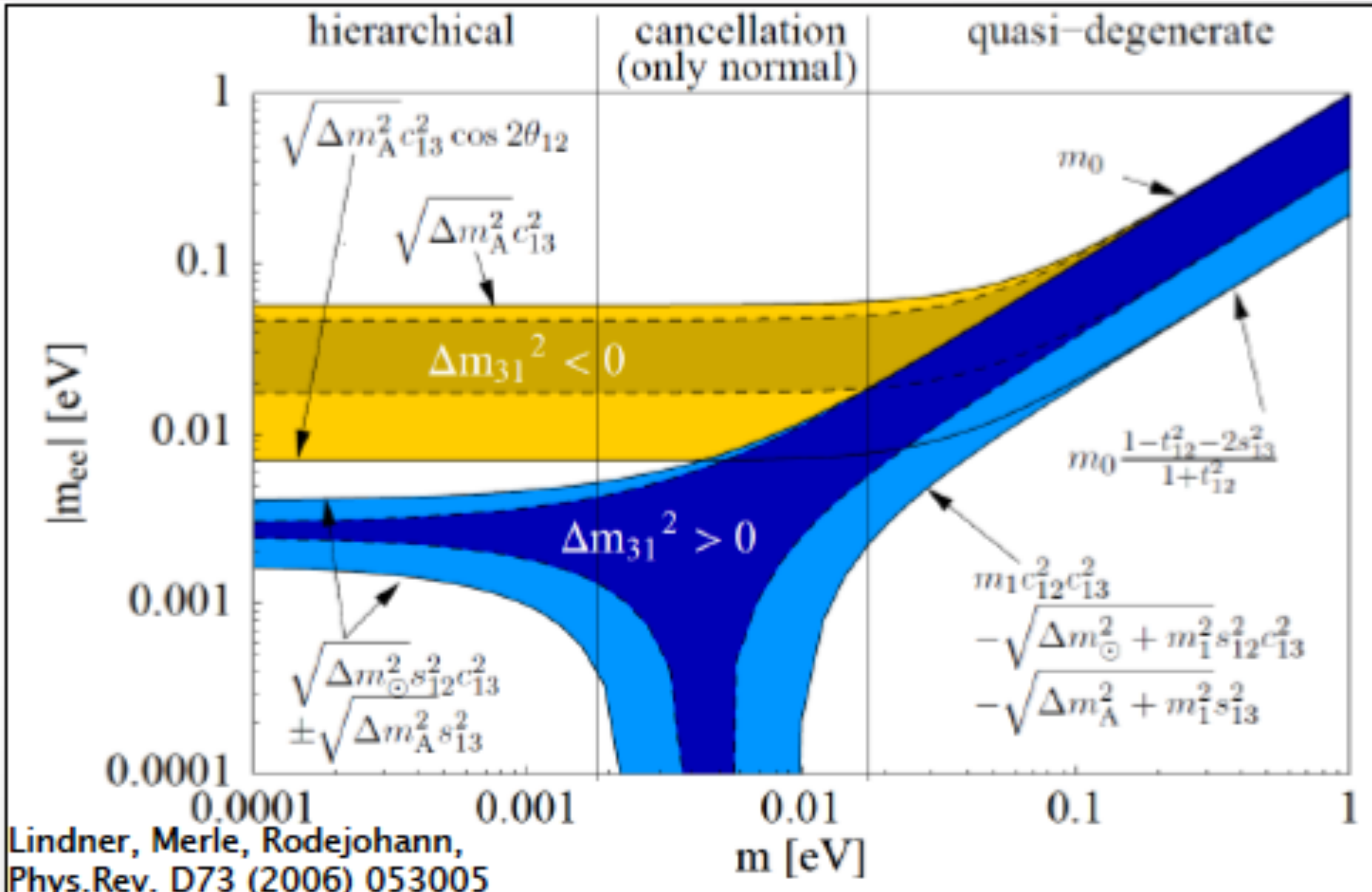
Axial-vector coupling g_A

- $g_A \approx 1.27$ for free nucleon
- Comparing predicted β- and 2vββ decay rates to experiment suggest $g_A \approx 0.6$-0.8
- If applicable to 0vββ, significant reduction in sensitivity to LNV parameter (new physics)
- Real effect or shortcomings of models?
- Need to be addressed by *ab-initio* calculations and experimental data

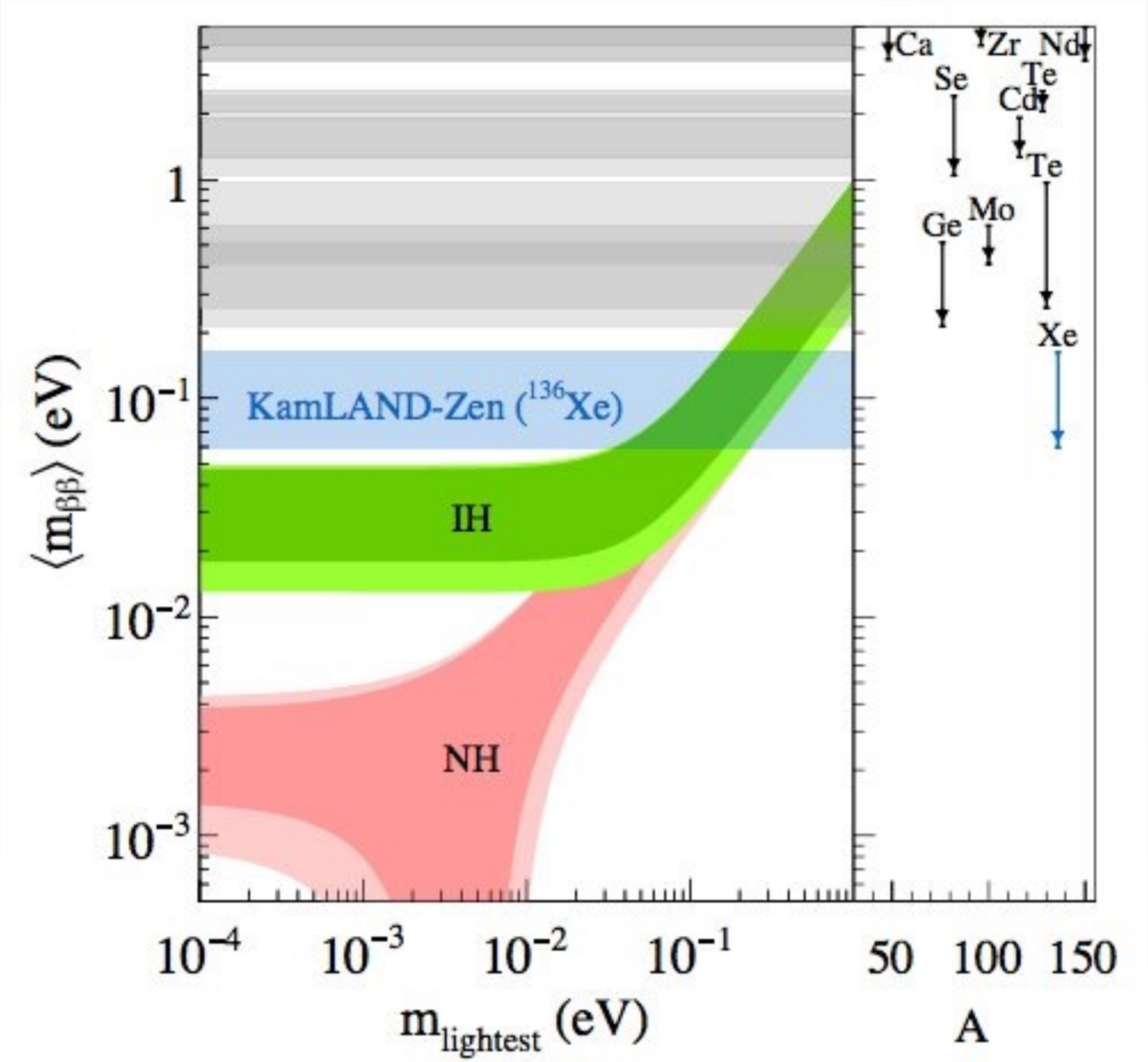


Deppisch, Suhonen, arXiv:1606.02908

$\langle m_\nu \rangle$ and Neutrino Oscillation Parameters



Where we are now

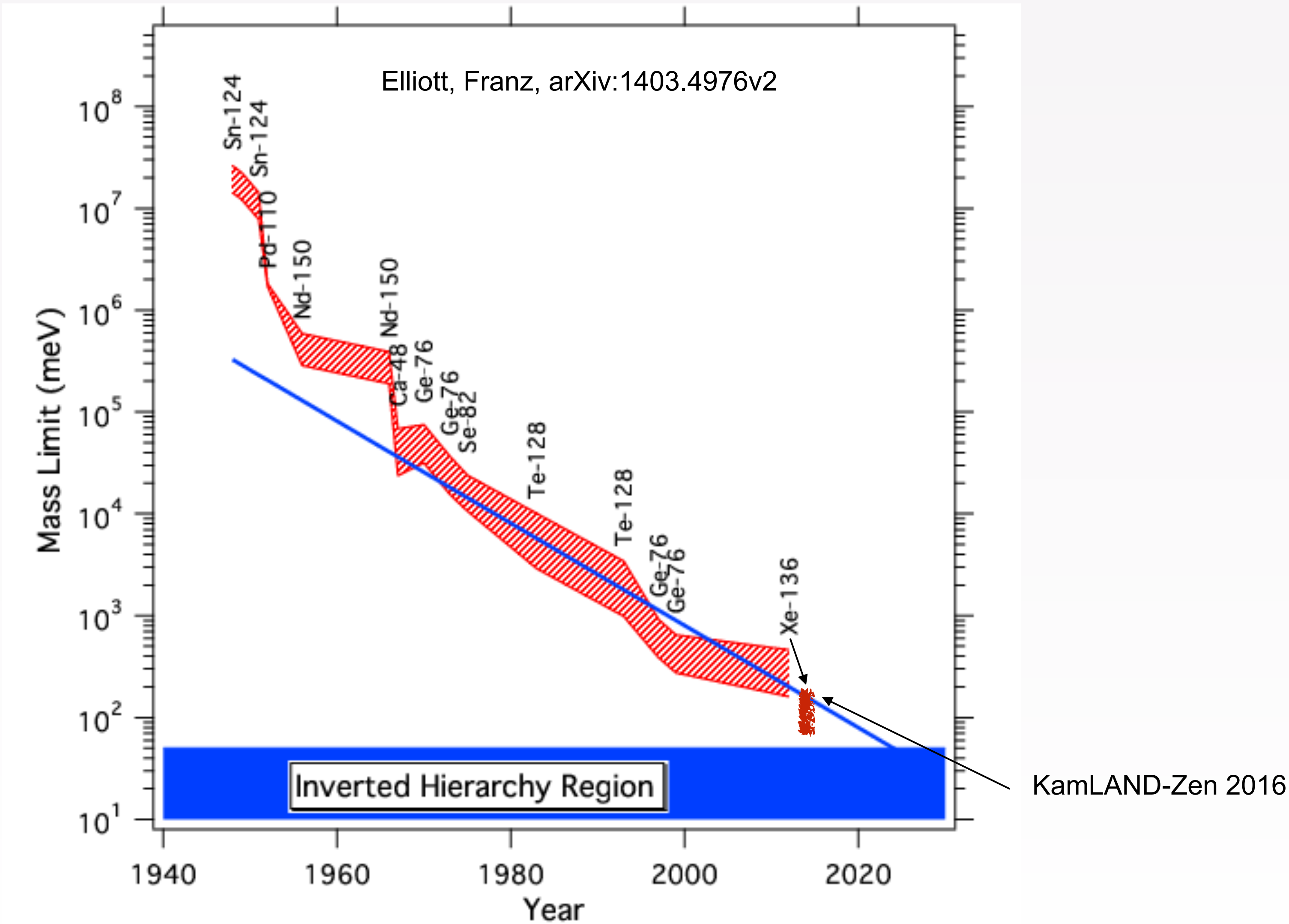


This is $T_{1/2} > 10^{26}$ yr !

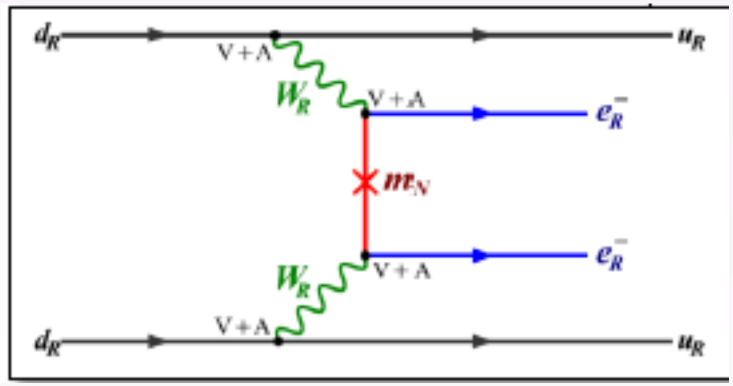
16(!) orders of magnitude

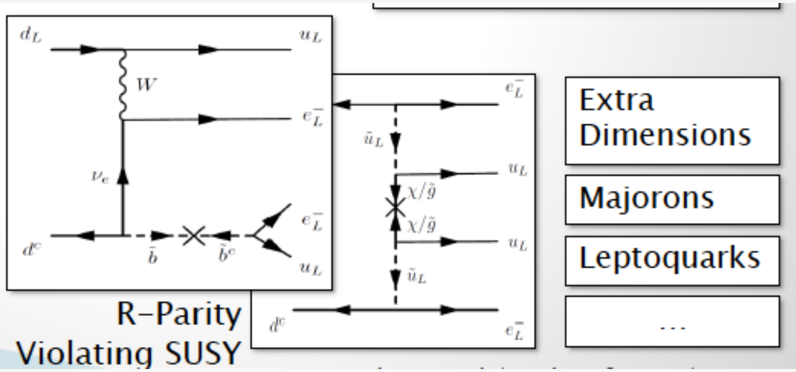
longer than Universe lifetime

History of ββ results



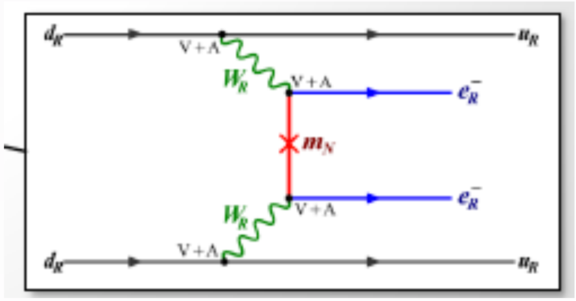
Important to consider other LNV mechanisms

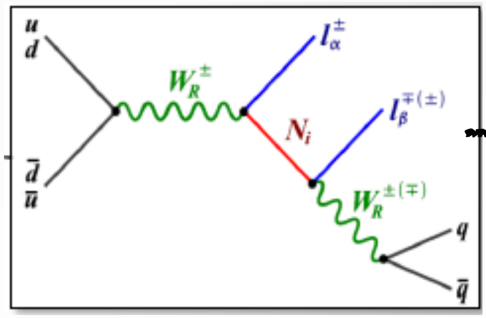


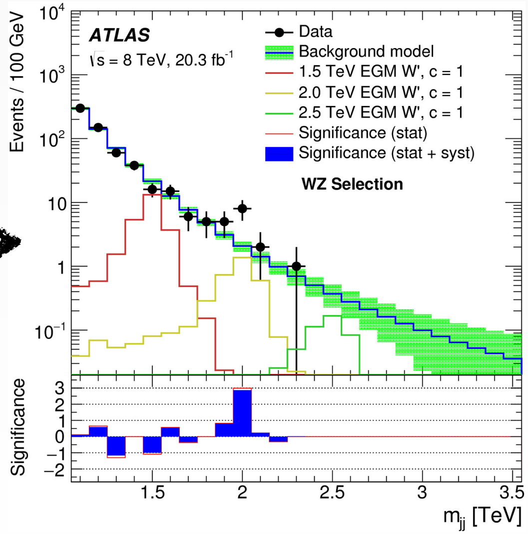


Left-Right symmetry (**V+A**) example

Connection with LHC





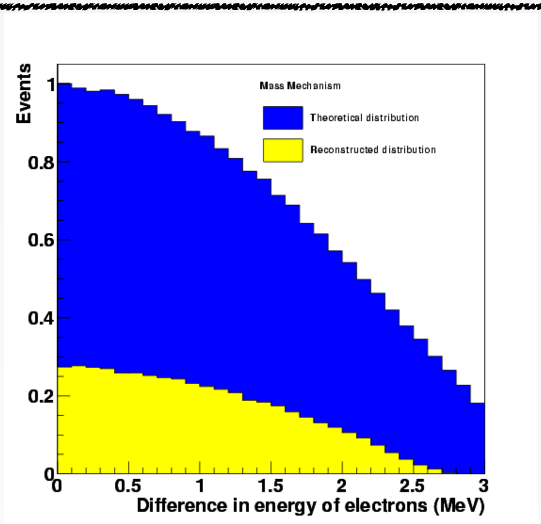


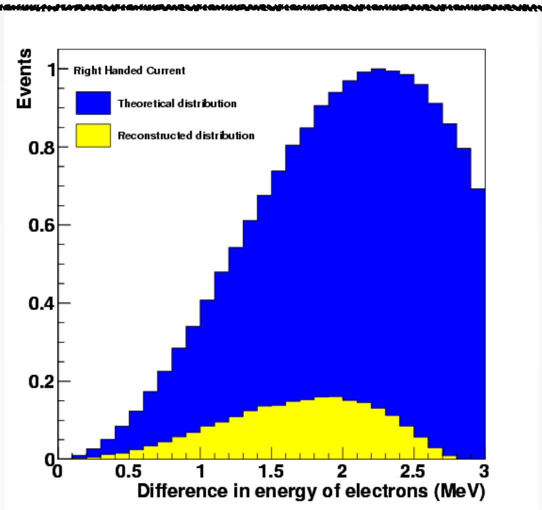
(whatever the mechanism, if observed, ν is still Majorana, Schechter, Valle, Phys. Rev. D25 (1982) 2951)

V+A $0\nu\beta\beta$ mechanisms case

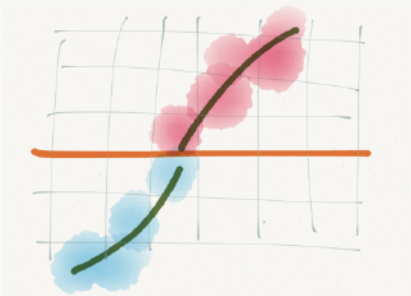
$\langle m_\nu \rangle$ V+A

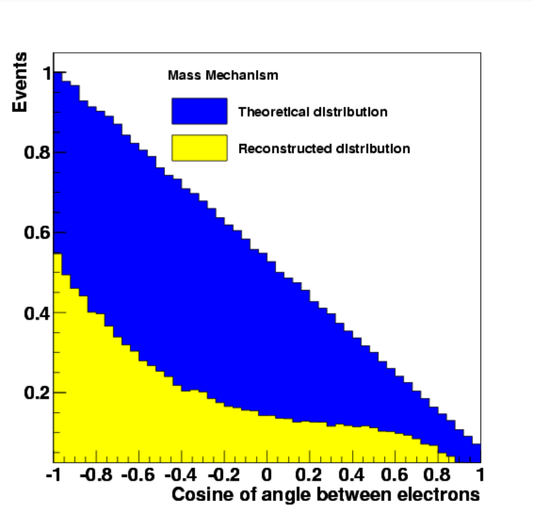
"Probing new physics models of 0νββ with SuperNEMO", EPJ C (2010) 70, pp. 972-943.

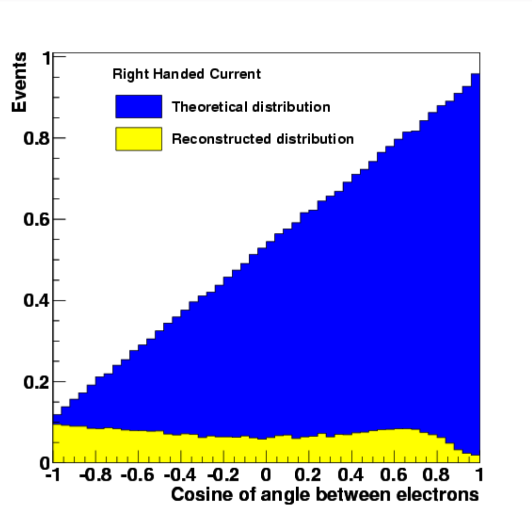


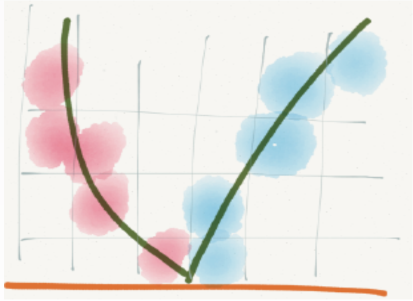


Require the ability to track individual electrons

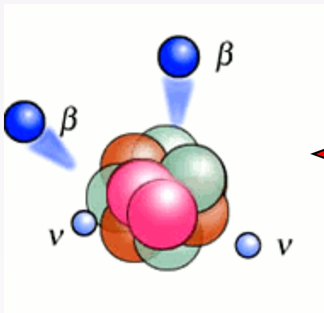




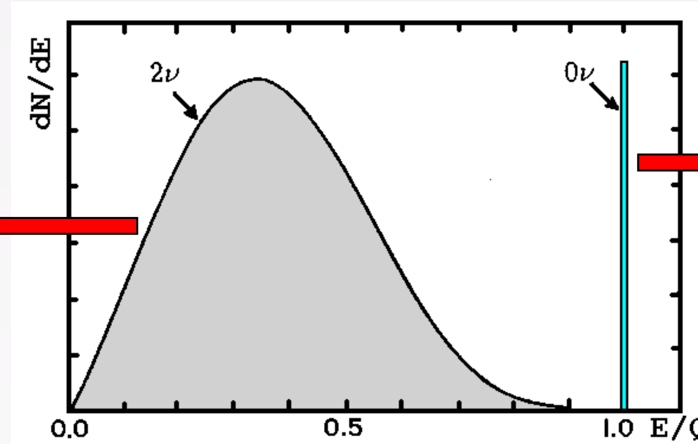




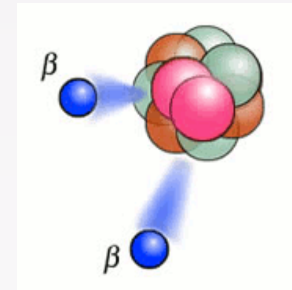
Design of a ββ experiment



$\left(E_1 + E_2\right) \in \left[0, Q_{\beta\beta}\right]$



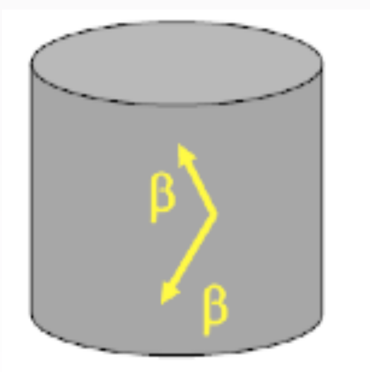
$(E_1+E_2)/Q_{\beta\beta}$ ~MeV



$\left(E_1 + E_2\right)/Q_{\beta\beta} \approx 1$

[⊗ resolution]

Homogenous “source = detector”

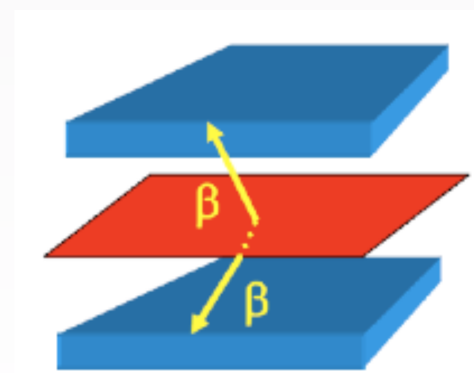


Elements of Both

Gaseous Xe TPC

Pixelated CdZnTe

Heterogenous “source ≠ detector”



(previous slide)

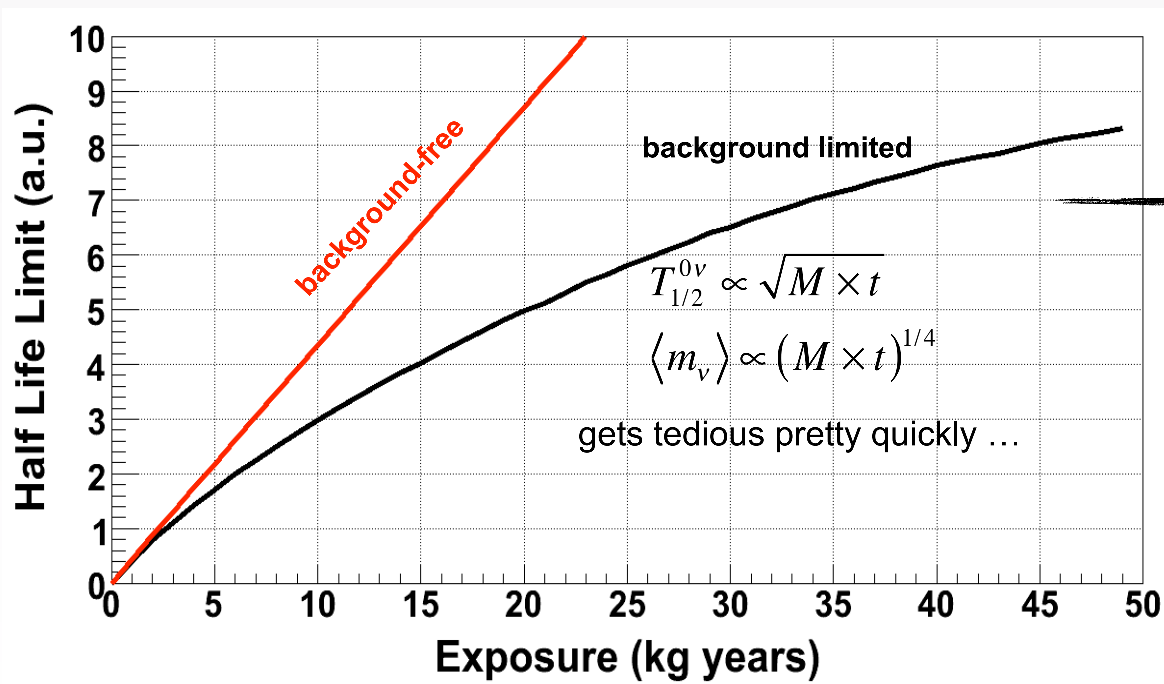
Experimental Sensitivity

maximise efficiency & isotope abundance

maximise exposure = mass × time

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

minimise background & energy resolution



ββ is about **background suppression!**

Double Beta Decay. Isotope Candidates.

Over **40 nuclei** can undergo **ββ**-decay (including $\beta^+\beta^+$ and 2K-capture)
Only ~**10** experimentally **feasible** (so far!)

Isotope choice

- $Q_{\beta\beta}$, Phase space, $G^{0\nu}$, *great if >2.6 MeV due to natural radioactivity, ^{208}Tl (^{232}Th)*
- $T_{1/2}(2\nu)$ (the longer the better)
- Isotope abundance
- Enrichment opportunities
- NME - Input from 2ν measurements is useful

No silver bullet….

*J. Phys. G: Nucl. Part. Phys. 34 667 (2007)

Isotope	Nat. Abundance (%)	$G^{0\nu}$×E-15 yr^{-1}	$Q_{\beta\beta}$ (MeV)
Ca48	0.187	75.8	4.274
Ge76	7.8	7.6	2.039
Se82	9.2	33.5	2.996
Zr96	2.8	69.7	3.348
Mo100	9.6	54.5	3.035
Cd116	7.6	58.9	2.809
Te130	34.5	52.8	2.530
Xe136	8.9	56.3	2.462
Nd150	5.6	249	3.367

more energetic decay : easier to separate from background

centrifugation etc…

enrichment often possible, always expensive !
≥ 50€/gram (apart from ^{136}Xe), *O*(100kg) in current experiments

The Background Problem

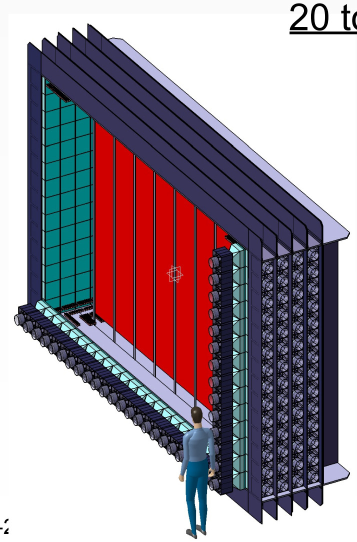
- Suppress **radioactive backgrounds**, primarily Uranium and Thorium decay chain products which are present in all materials.
  - **$T_{1/2}(^{232}Th, ^{238}U) \sim 10^{10}$ years**
  - **$T_{1/2}(0\nu\beta\beta) > 10^{25} - 10^{26}$ years**
- Go **underground** (at least a few thousand meters of water equivalent) to reduce cosmic background by x$O(10^6)$
- Background from $2\nu\beta\beta$: energy **resolution** and **isotope** choice.

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

Background reduction and <u>**rejection**</u>

SuperNEMO Demonstrator Module

20 tons



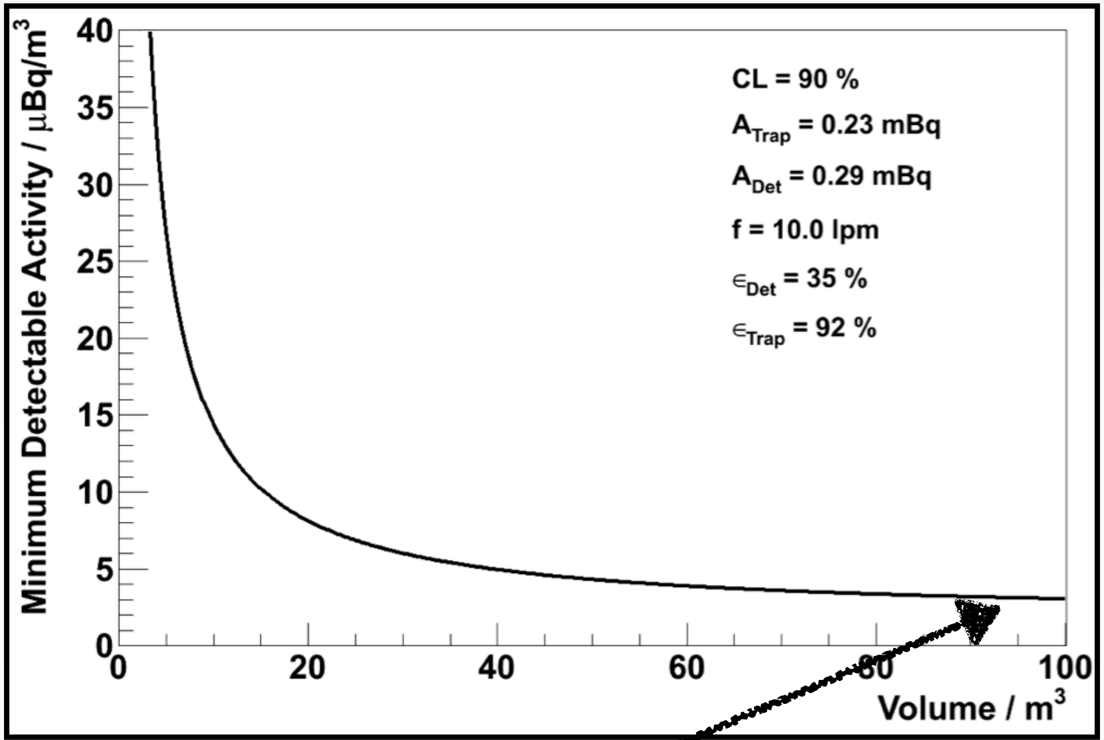
=

1kg of bananas

= 100 Bq

Pushing low background technology boundaries

Based on SuperNEMO radon reduction programme



Rn removal from gas with cold charcoal trap:

- **He**: 10^{10}(!) suppression, complete removal
- **N_2**: ~x20 suppression

  purification down to **$20\mu B/m^3$ (measured!)**

Directly applicable to 0vbb, dark matter and other ultra-low-background experiments

2.4 ^{222}Rn atoms/m³ of N_2/He/Ar/etc.

or

1 part in 10^{25} !!!

A take-home message

- We need to measure different isotopes with different experimental approaches
  - NME uncertainties
  - Tiny signal - Huge Background. Will you ever trust a single positive measurement?
  - Disentangle underlying physics mechanism

We need Diversity

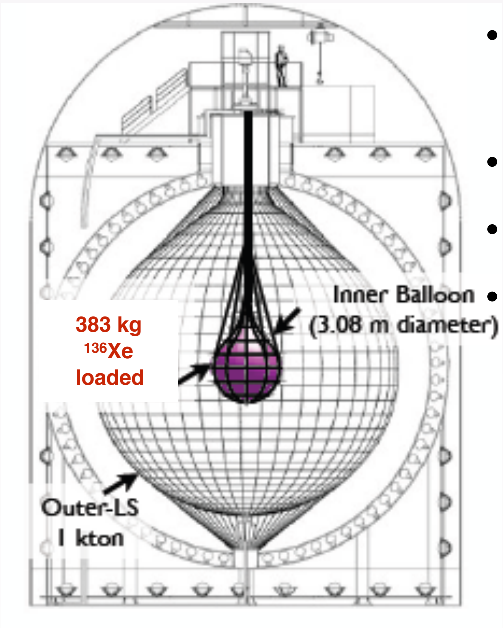
...and we have it!*

Experiment	Isotope(s)	Technique	Main characteristics
NEMO-3	Mo100+6other	Tracking + calorimeter	Bckg rejection, isotope choice,
SuperNEMO	Se82, Nd150,	Tracking + calorimeter	Bckg rejection, isotope choice,
CUORE	Te130	Bolometers	Energy resolution, efficiency
LUCIFER	Se82	Scintillating bolometers	Energy resolution, efficiency
AMoRE	Mo100	Scintillating bolometers	Energy resolution, efficiency
GERDA	Ge76	Ge diodes	Energy resolution, eficiency
Majorana	Ge76	Ge diodes	Energy resolution, efficiency
COBRA	Te130, Cd116	CdZnTe semi-conductors	Efficiency, particle ID
EXO	Xe136	TPC ionisation + scintil.	Mass, efficiency, particle ID
MOON	Mo100	Tracking + calorimeter	Compactness, Bckg rejection
CANDLES	Ca48	CaF_2 scintillating crystals	Efficiency, Active background
SNO+	Te130	Te loaded liquid scintillator	Mass, efficiency
XMASS	Xe136	Liquid Xe	Mass, efficiency
CARVEL	Ca48	CaWO4 scintillating	Mass, efficiency
Yangyang	Sn124	Sn loaded liquid scintillator	Mass, efficiency
DCBA	Nd150	Gaseous TPC	Bckg rejection
KamLAND-Zen	Xe136	Xenon balloon	Mass, efficiency
NEXT	Xe136	Gaseous TPC	Bckg rejection, efficiency

*Apologies to experiments not mentioned in this talk (most from this table)

Liquid Scintillator based

KamLAND-Zen



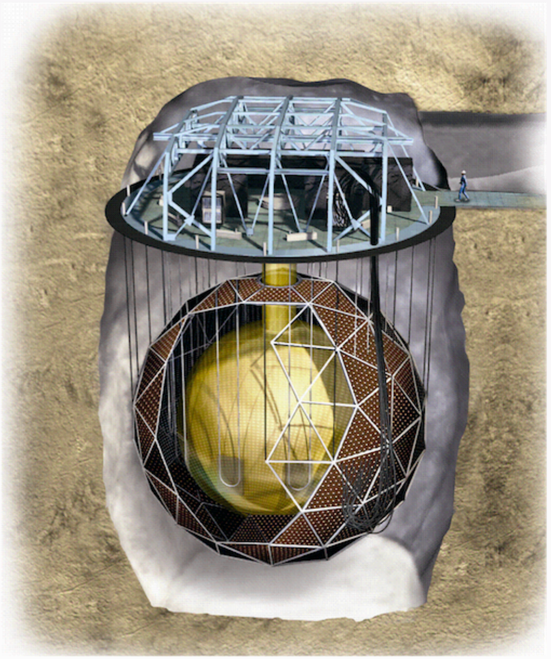
pros

- Large and very radiopure
  - Borexino pioneered ultra-low background LS
- Can use existing infrastructure
- Large isotope mass can be accommodated
- Some isotope flexibility (need to be able to load isotope in scintillator)

cons

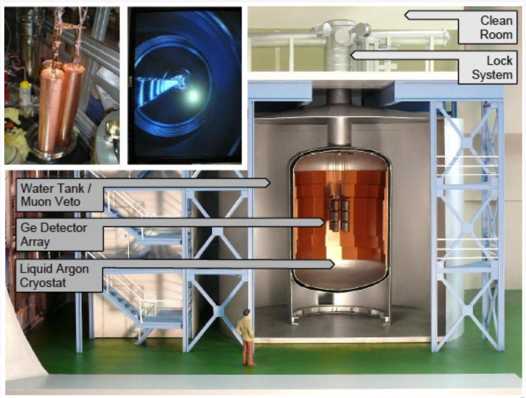
- Relatively poor energy resolution
- Fiducialization
- Particle ID challenging

SNO+



Semiconductors/Bolometers

HP^{76}Ge



GERDA, Majorana

Also, warm semi-conductors, **COBRA**

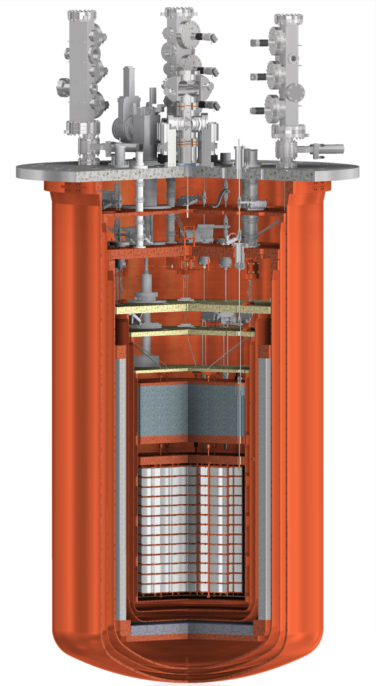
pros

- Excellent energy resolution
- Very radiopure crystals
- Pulse shape analysis for particle ID
- Good ββ track record

cons

- Surface background
- Cosmogenic activation
- Scaling expensive

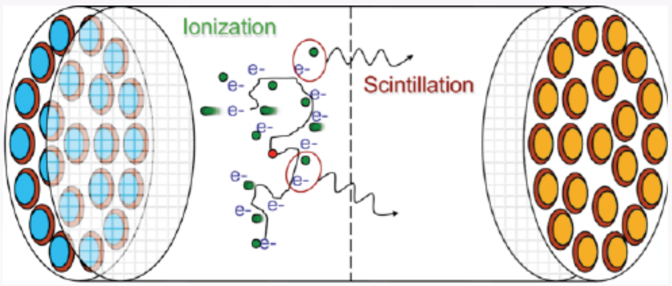
^{130}Te, ^{82}Se, ^{100}Mo



CUORE, AMoRE, LUCIFER

TPC/Tracking

EXO (L^{136}Xe), NEXT (G^{136}Xe)



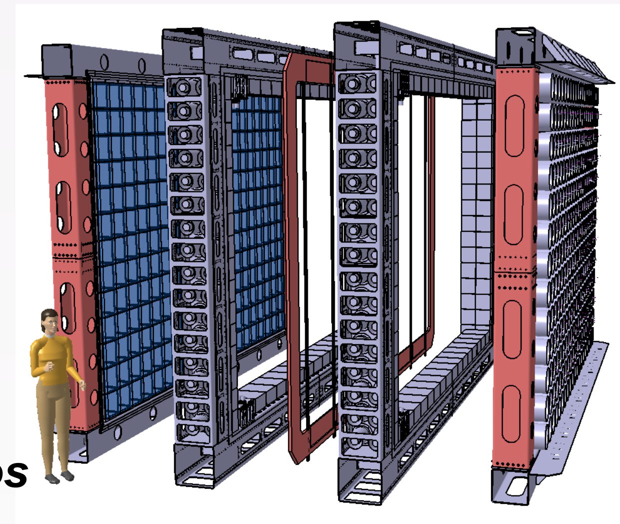
pros

- ^{136}Xe — easiest/cheapest to enrich
- particle ID, some tracking
- prospects of daughter ^{136}Ba tagging

cons

- Fiducialization
- Energy resolution (should be better with GXe)

SuperNEMO



pros

- Complete Isotope flexibility
- Excellent particle ID, full 3D tracking
- Smoking gun signature, can probe different mechanisms

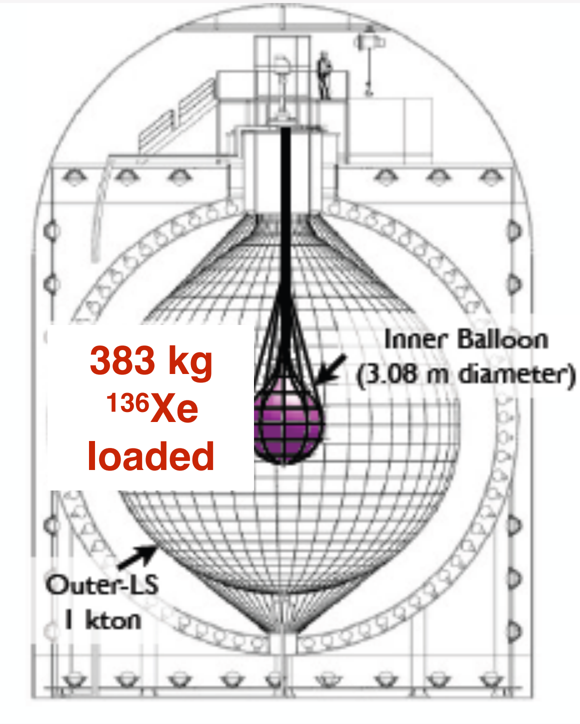
cons

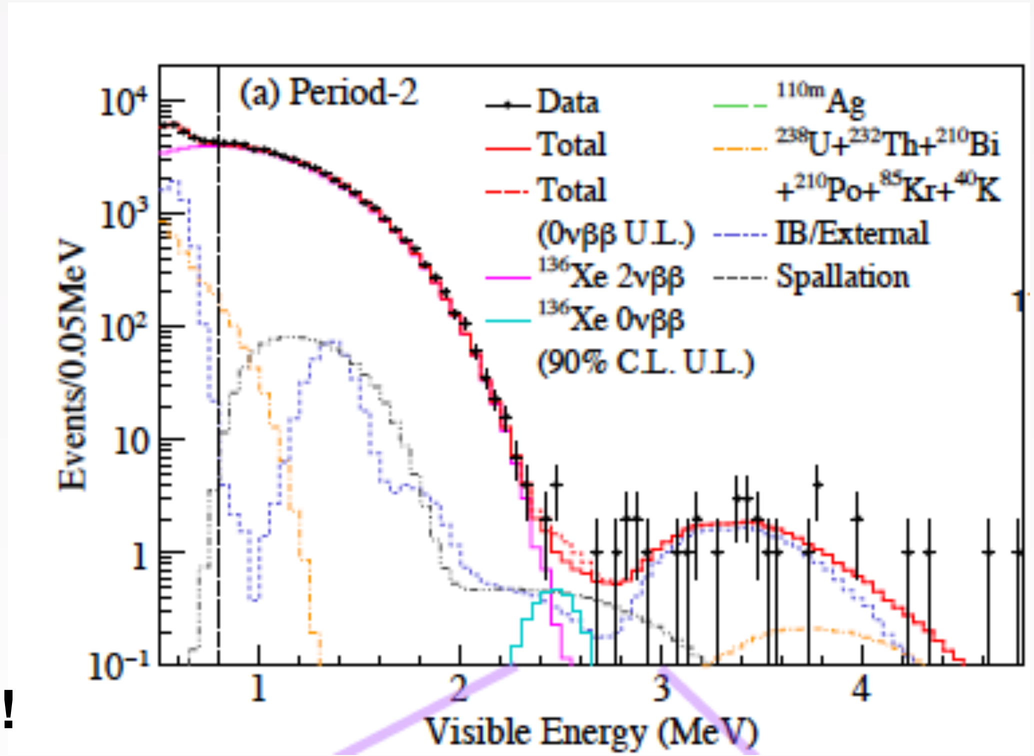
- Energy resolution (~ similar to LXe)
- Scaling costs

Location: Kamioka (Japan) - 2700 m w.e.

KamLAND-Zen ^{136}Xe

(Plots from J. Shirai, Neutrino 2016)



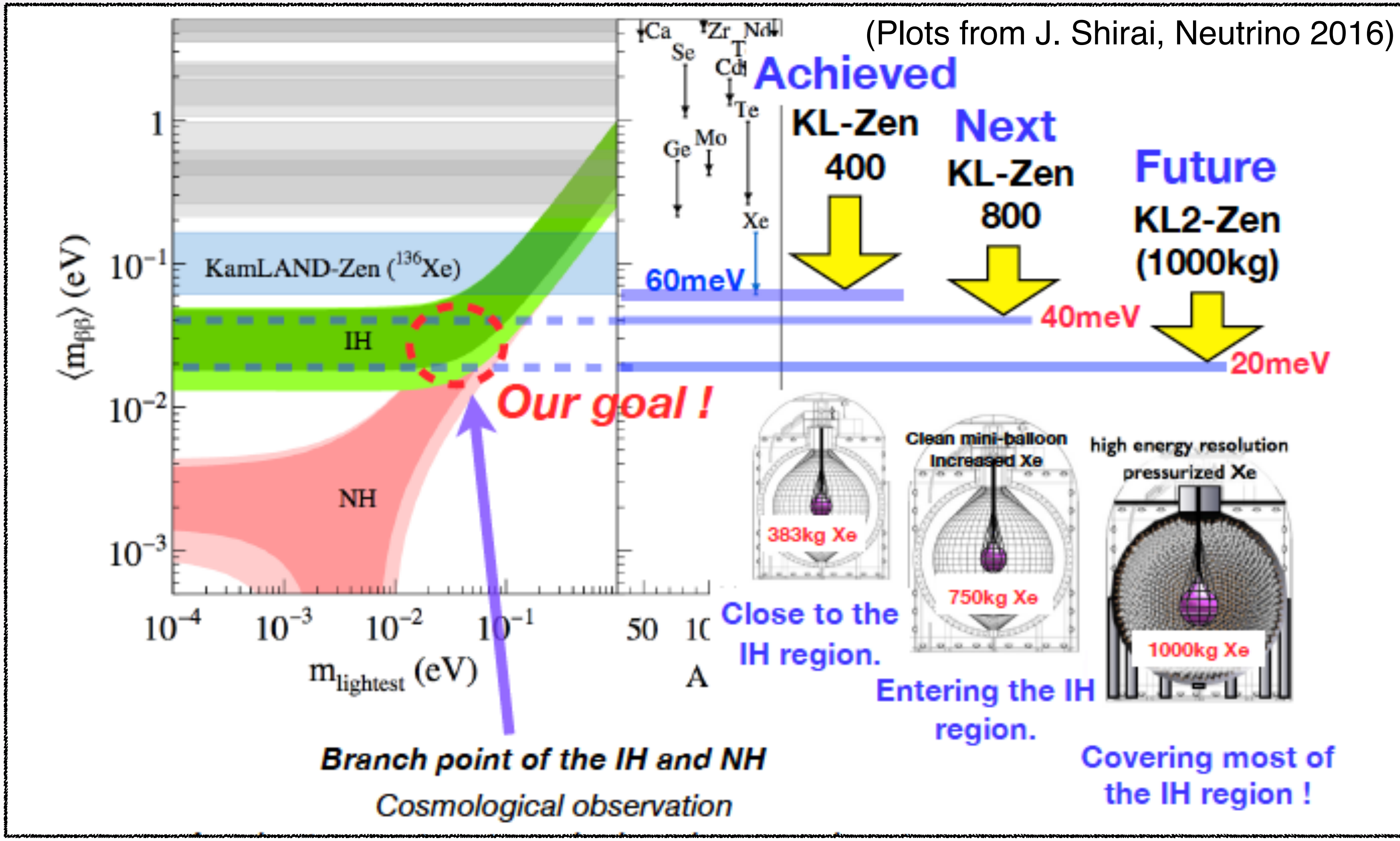


Successful ^{110m}Ag removal

504 kg-yr exposure!

$$T_{1/2}^{0\nu} > 1.07 \times 10^{26}\ \text{yr}$$
$$\langle m_{\beta\beta} \rangle < (61 - 165)\ \text{meV}$$

Limits at 90%CL

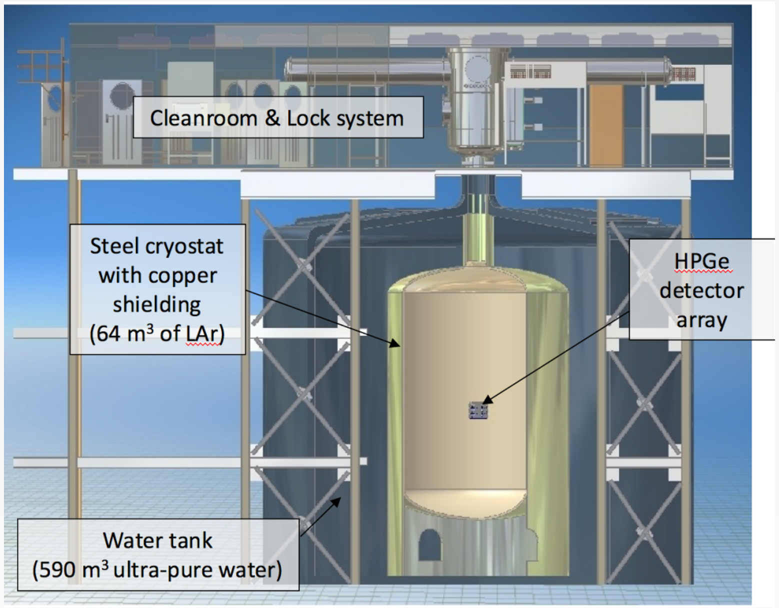


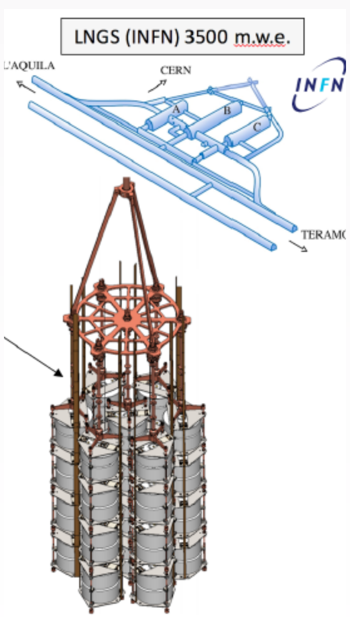
Requires

- Suppression of ^{214}Bi — balloon replacement for KLZ-800
- Dramatic increase in light output, from 250p.e. to 1000 p.e at 1 MeV for KLZ-1000

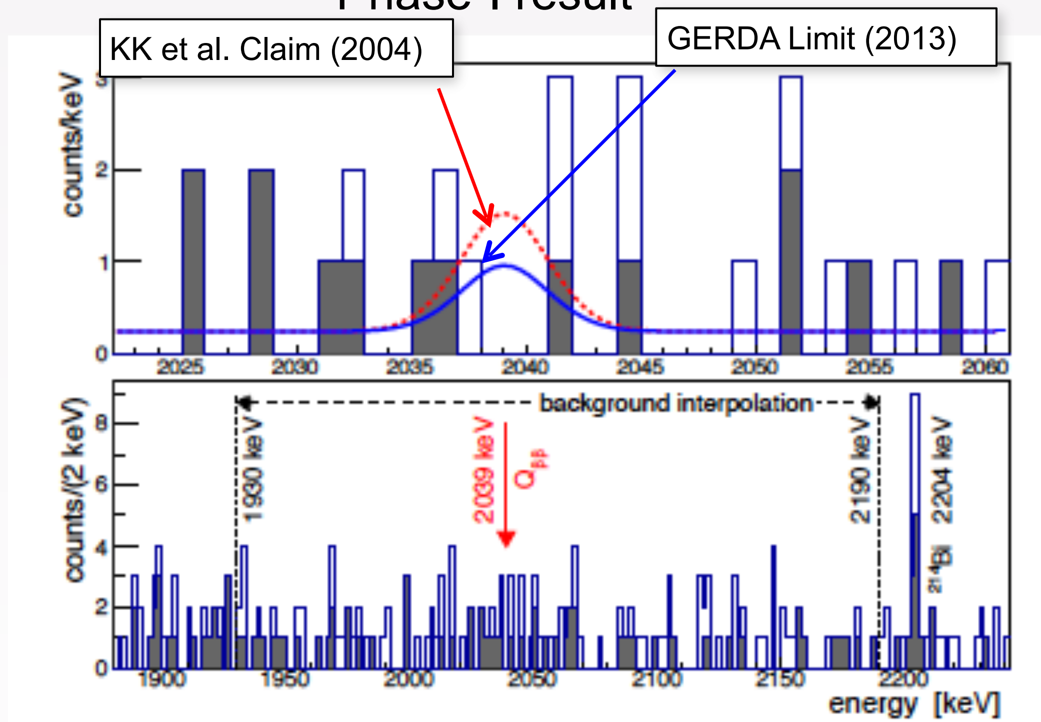
GERDA (^{76}Ge)

ΔE/E(2 MeV) = 0.2%(!)





Phase-I result



21.6 kg.yr

$$T_{1/2}^{0\nu\beta\beta} > 2.1\times10^{25}\ \text{yr @ 90\% C.L.}$$

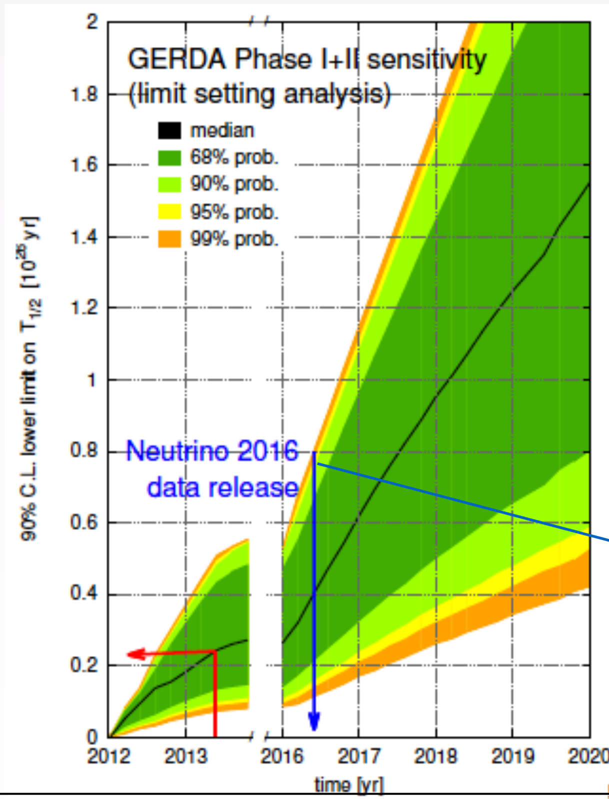
$$\langle m_\nu \rangle < 200 - 400\ \text{meV}$$

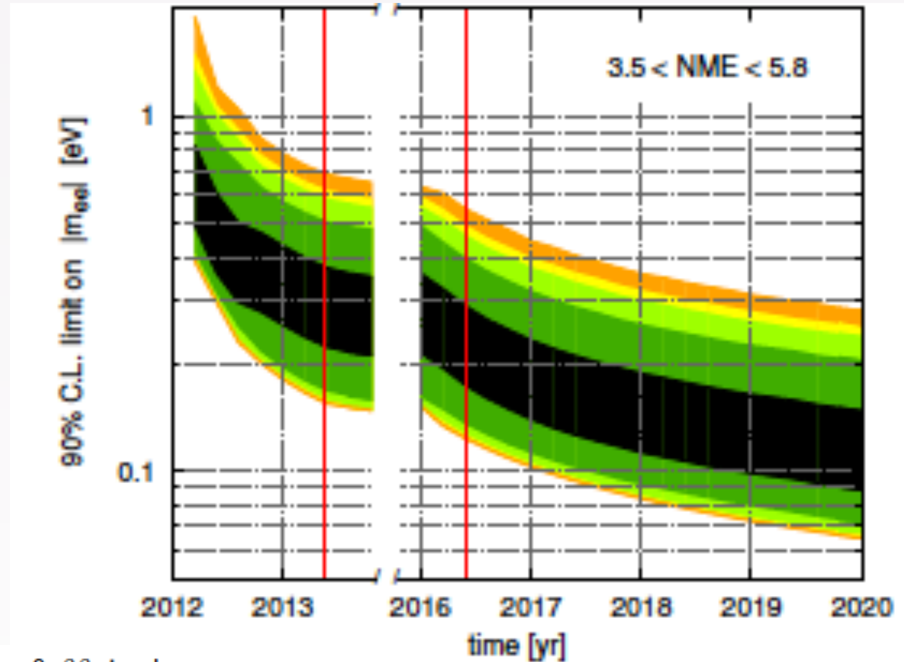
Background index (with PSA):

B~1-2×10^{-2} cts/keV/kg/yr

GERDA Phase-II

- Increase target mass (+20kg = **40kg** Ge detectors in total)
- **Liquid Argon** instrumentation
- **B.I. ~ 10^{-3} cts/keV/kg/yr — achieved!**





- blind analysis, no $0\nu\beta\beta$ signal:

  $T_{1/2}^{0\nu} > 5.2 \cdot 10^{25}$ yr (90% C.L.)*

  $|m_{ee}| <$ [160,260] meV (90% C.L.)*

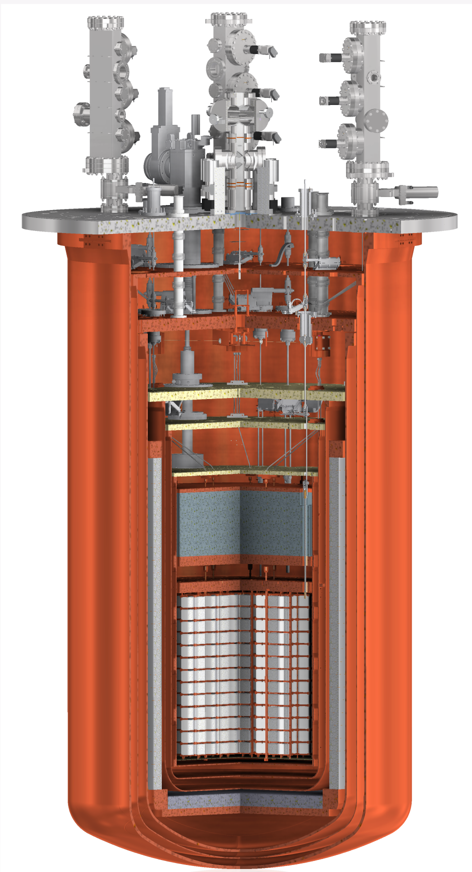
  (* preliminary, ϵ_{coax}^{PSD} to be finalized)

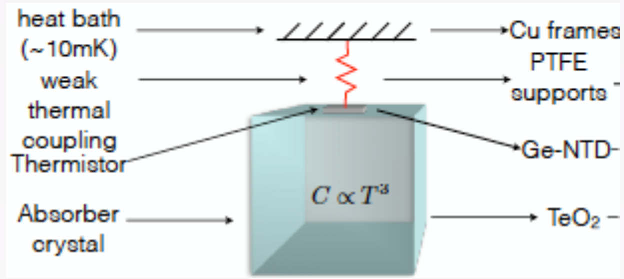
- Sensitivity in 10^{26} yr range (~70-200 meV)

Future single tonne-scale ^{76}Ge detector — collaboration with Majorana

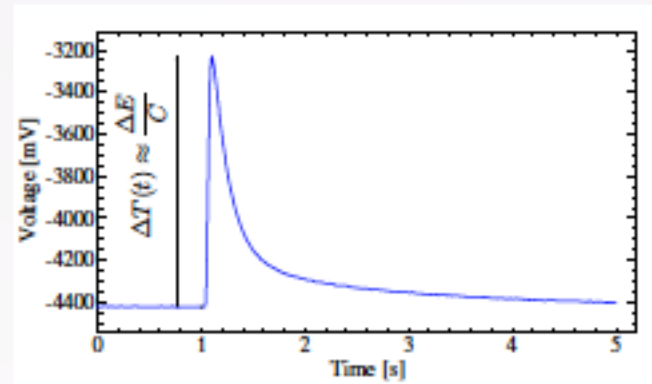
Bolometers

CUORE (^{130}Te)





10mK



Coldest 1m^3 in universe !

- CUORE, 19 towers x 13 floors = 988 $^{nat}TeO_2$ = 209kg ^{130}Te
  - Built on CUORE0 (1 tower)
  - Aim: B.I. = 0.01 cts/keV/kg/yr
  - $\Delta E/E$ = 0.2% @ 2.5 MeV
  - Sensitivity (5y, 90%CL): $T_{1/2}$: 9.5×10^{25}y, <m_ν>: 50-130 meV
  - Start planned: end 2016

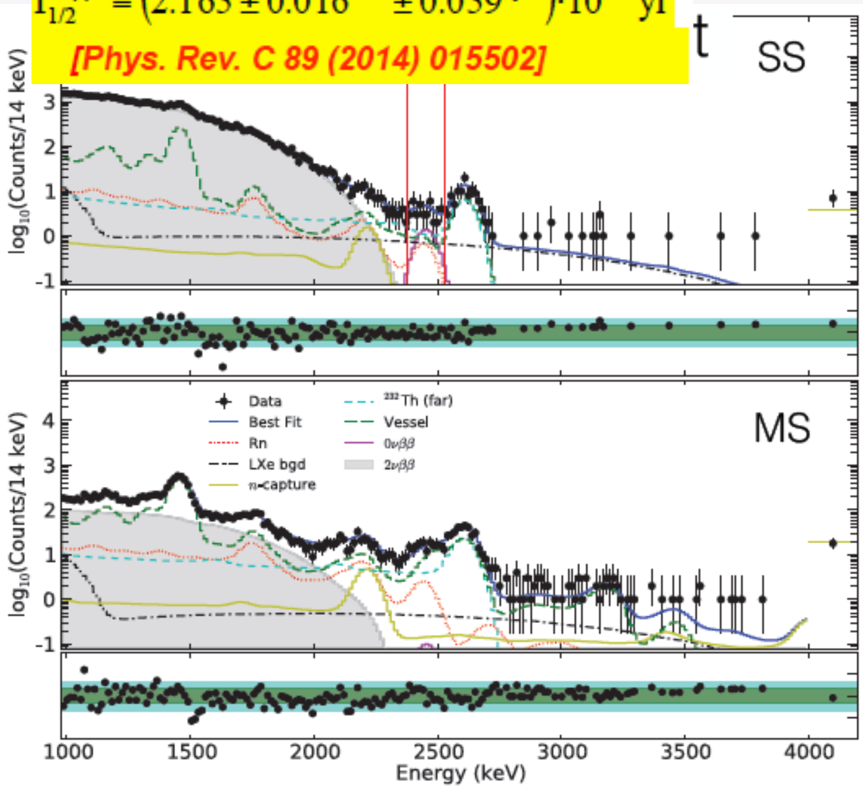
Scintillating bolometer projects:

- LUCIFER - Zn^{82}Se
- LUMINEU - Zn$^{100}MoO_4$
- AMoRE - Ca$^{100}MoO_4$ (also ^{48}Ca)

EXO-200 (^{136}Xe)

$T_{1/2}^{2\nu\beta\beta} = (2.165 \pm 0.016^{stat} \pm 0.059^{syst}) \cdot 10^{21}$ yr

[Phys. Rev. C 89 (2014) 015502]



99.8 kg.yr **B.I. = 0.0017 cts/keV/kg/yr**

$T_{1/2}^{0\nu\beta\beta} > 1.1 \times 10^{25}$ yr @ 90% C.L.

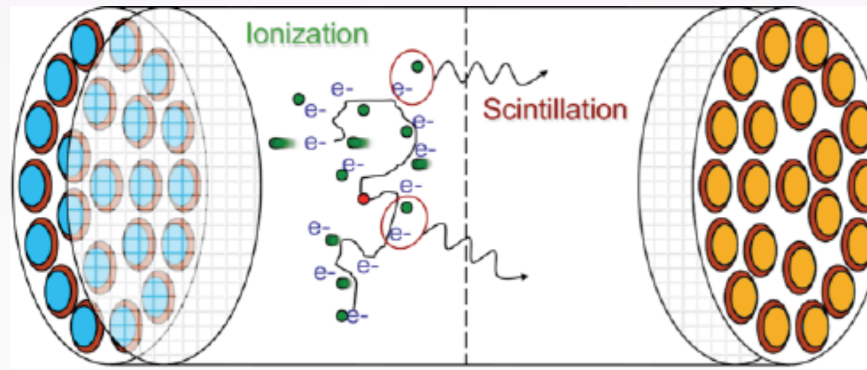
$\langle m_\nu \rangle < 190 - 450$ meV

Nature (2014)

Location: WIPP (NM, USA) - 1585 m w.e.

FWHM(2.5 MeV) = 3.5%

LXe

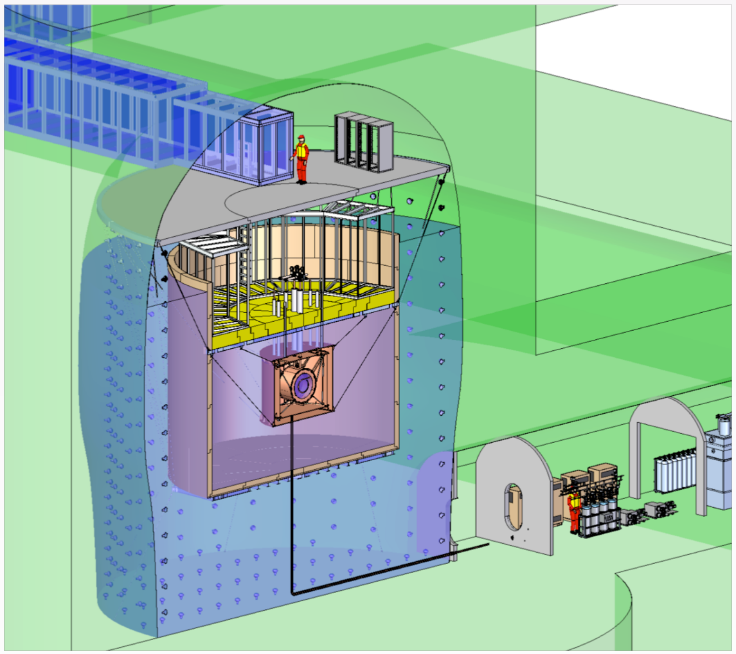


DOE Accident Inv. Rep., Mar 2014

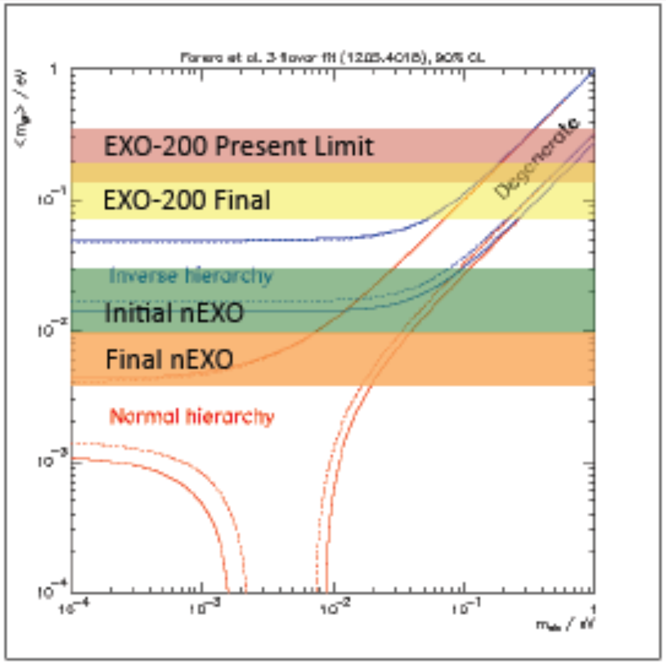
Full recovery, Phase II restart Apr'16

Future EXO - nEXO

nEXO in SNOLAB's Cryopit (~6000 m.w.e.)



- 5 tonne of ^{enr}LXe
- 10 yr running
- $T_{1/2}$(90%CL) > 4.1x10^{27} yr
  - **with Ba-tagging** >2.1x10^{28} yr



2014 2015 2016 2017 2018 2019 2020 2021 2022 2023

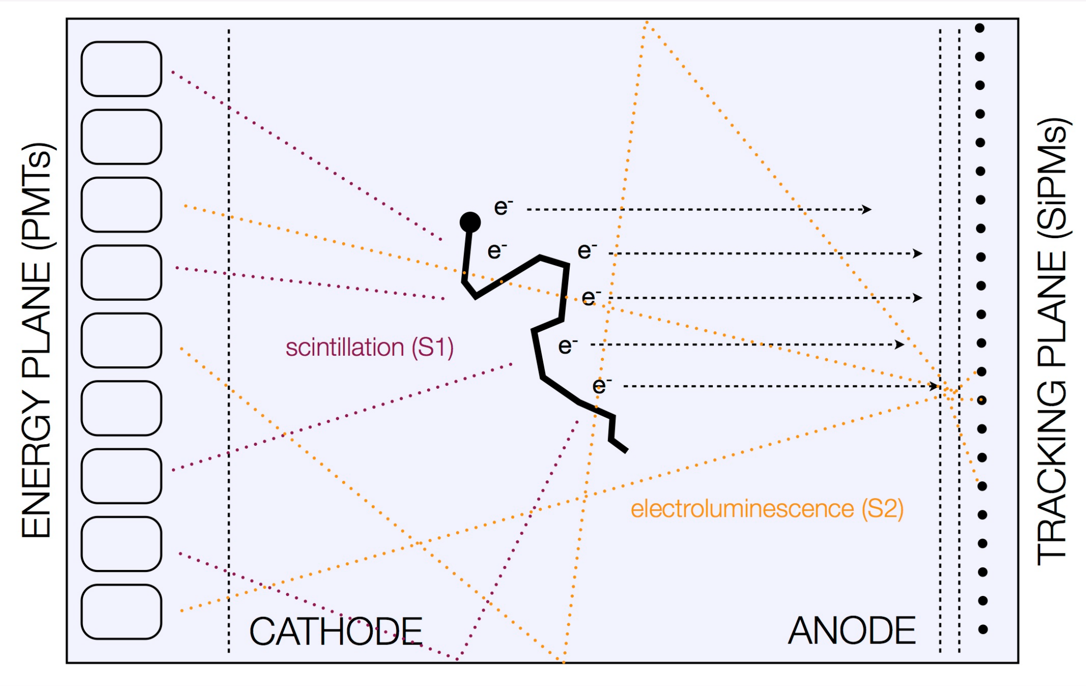
R&D

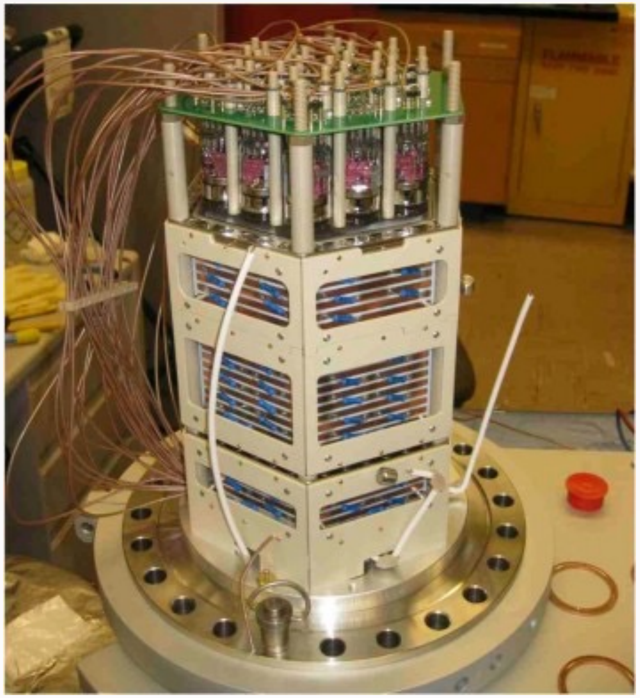
Design

Procurement, Construction and Installation

Start

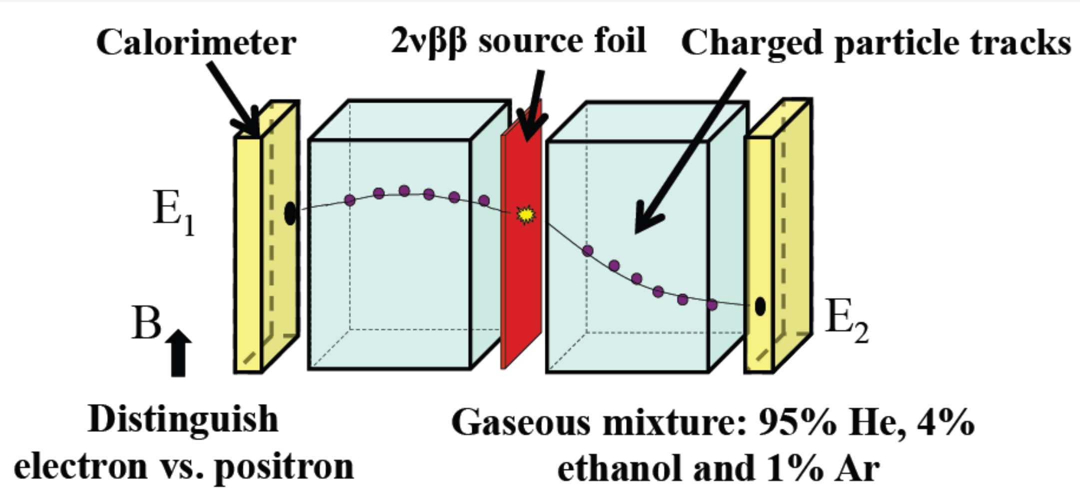
NEXT (^{136}Xe)

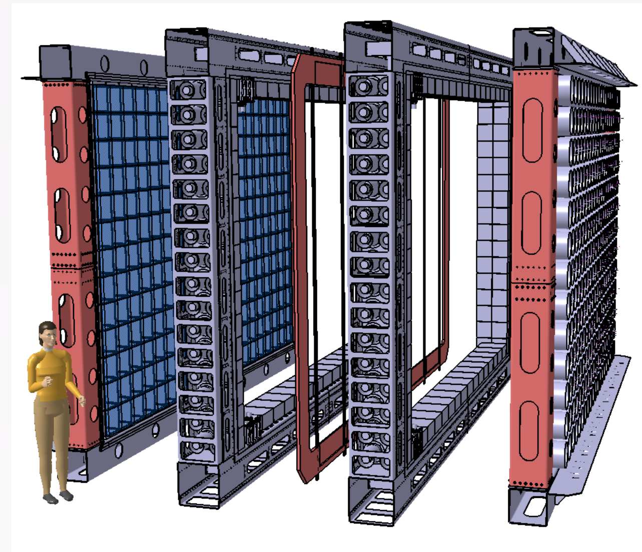




See talk by F. Monrabal

SuperNEMO





- *Full* ***3D topology reconstruction*** *of final states*
- ***Isotope flexibility*** *(^{82}Se in first instance*

SuperNEMO = Demonstrator x 20

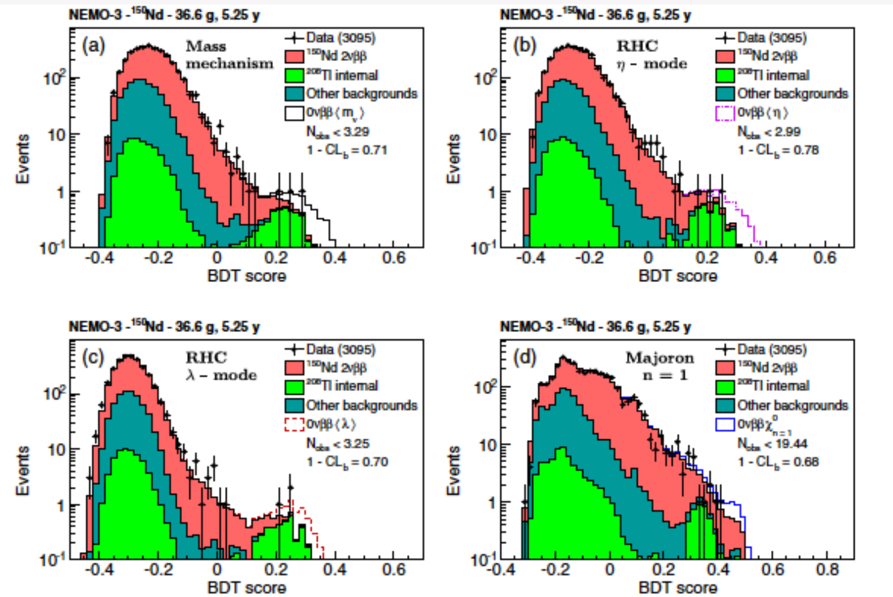
The goals of SuperNEMO :

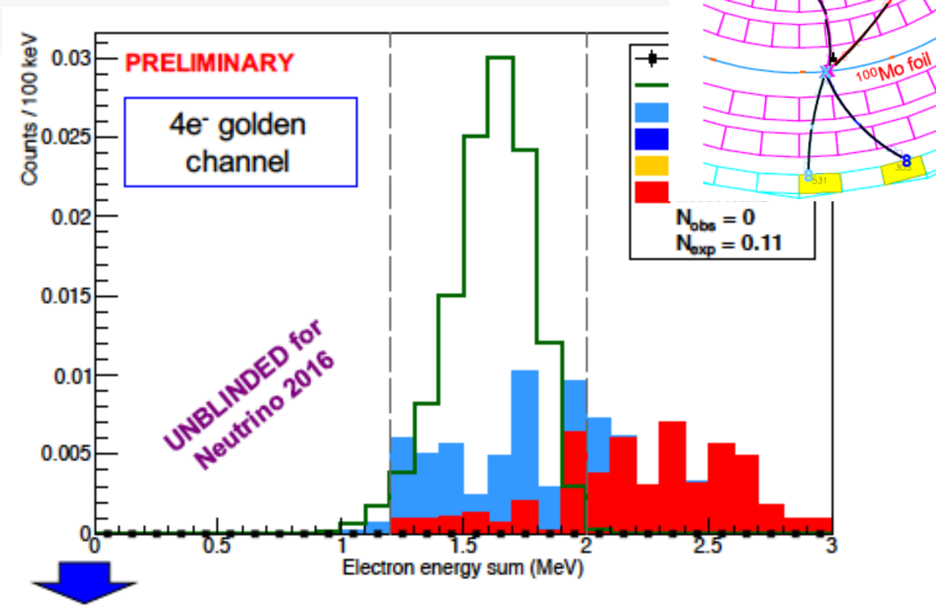
1. Use the power of the tracking-calorimeter approach to identify and suppress backgrounds. This will yield a zero-background experiment in the first (**Demonstrator** Module) phase.
2. Prove that a 100 kg scale experiment can reach the inverted mass hierarchy (~50 meV) domain.
3. In the event of a discovery by any of the next-generation experiments, demonstrate that the tracking-calorimeter approach is by far the best one for **characterising** the **mechanism** of 0νββ decay.

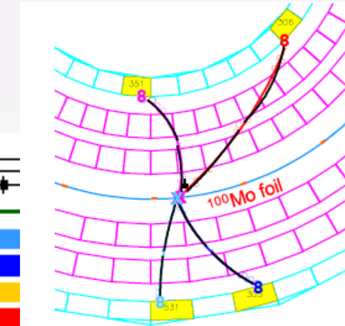
Built on success of NEMO-3

$\langle m_\nu \rangle$ < 0.3-0.6 eV with only 7kg of ^{100}Mo

0ν Quadruple Beta Decay of ^{150}Nd







$$T_{1/2}^{0\nu 4\beta} > 2.6 \times 10^{21} \text{ yr } (90\% \text{ C.L.})$$

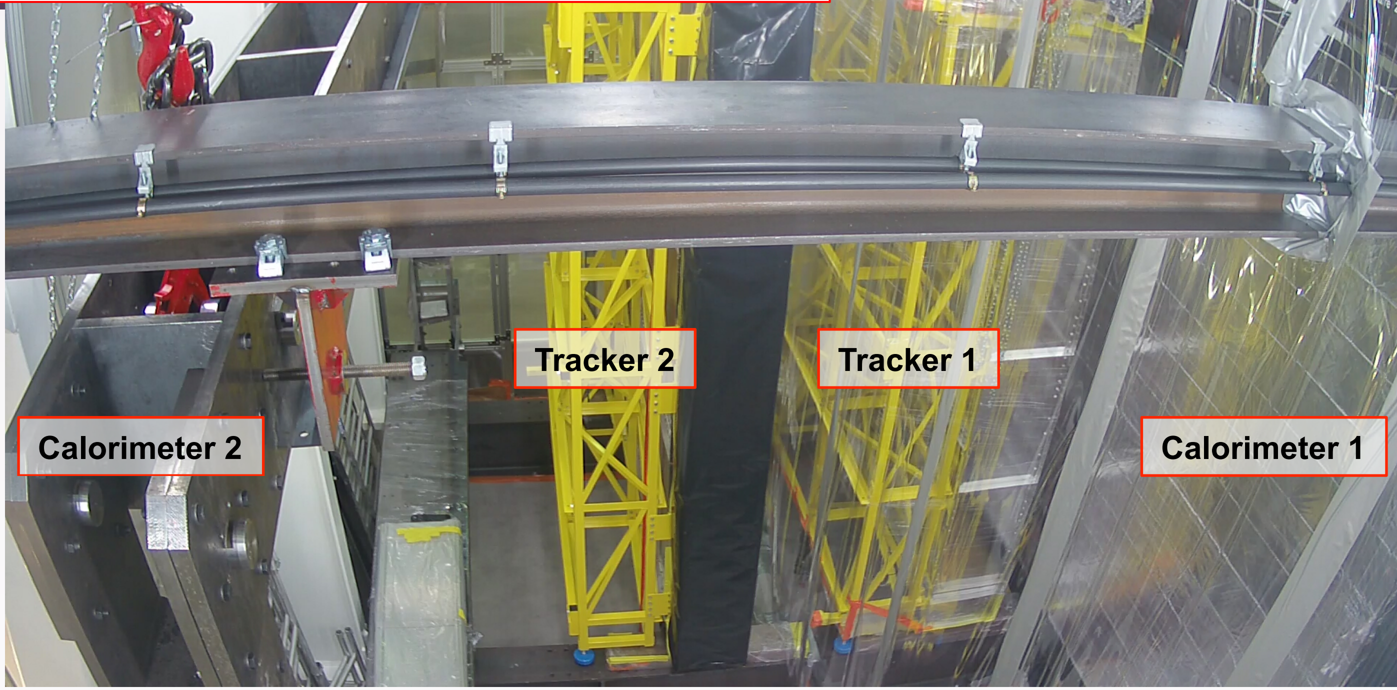
- *World's first limit on this process.*

Different 0vbb mechanisms
Multivariate analysis

2v results of 7(!) isotopes

Isotope	Mass (g)	Qββ(keV)	T(2v) (1E19yrs)	S/B	Comment	Reference
^{82}Se	932	2996	9.6 ± 1.0	4	World's best	Phys.Rev.Lett. 95(2005) 483
^{116}Cd	405	2809	2.7 ± 0.2	10	World's best	*arXiv:1610.03226, submi. to PRD*
Nd150	37	3367	0.93± 0.06	2.7	World's best	Phys.Rev. D 94, 072003 (2016)
Zr96	9.4	3350	2.35 ± 0.21	1	World's best	Nucl.Phys.A 847(2010) 168
Ca48	7	4271	6.4 ± 1.4	6.8 (h.e.)	World's best	Phys.Rev. D 93, 112008 (2016)
Mo100	6914	3034	0.71 ± 0.05	80	World's best	Phys.Rev.Lett. 95(2005) 483
Te130	454	2533	70 ± 14	0.5	First direct detection	Phys. Rev. Lett. 107, 062504 (2011)

SuperNEMO Demonstrator Status

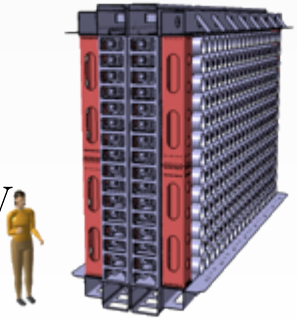


- **All tracker and calorimeter modules delivered to LSM underground (last module delivered 2-Dec-2016)**
- **Commissioning early 2017 followed by physics run**

Demonstrator Module
17.5 kg.yr :

$$T^{0\nu}_{1/2} > 6.5 \times 10^{24}\ \text{yr}$$

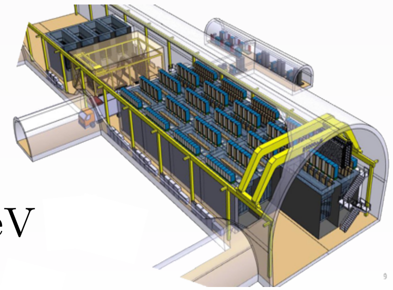
$$\langle m_\nu \rangle < 0.20 - 0.40\ \text{eV}$$



Full SuperNEMO
500 kg.yr :

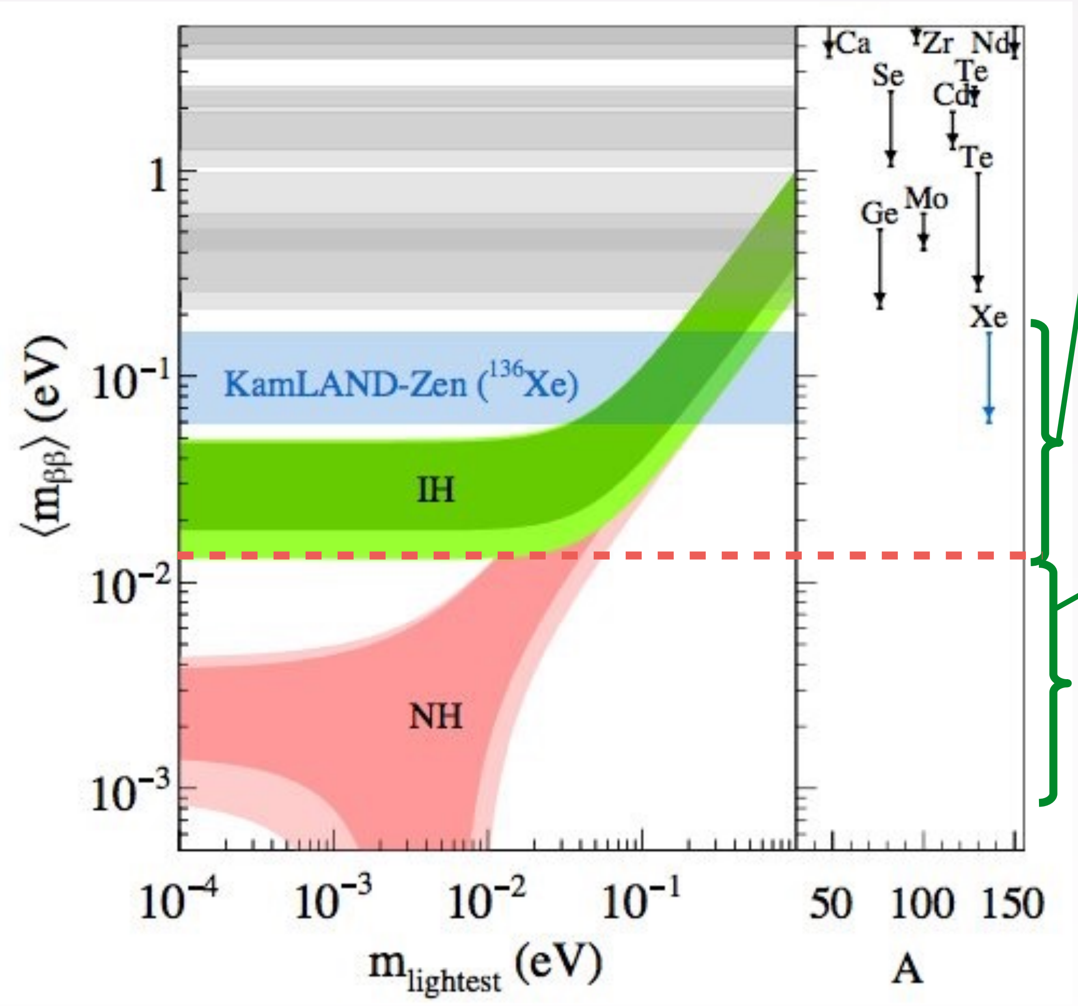
$$T^{0\nu}_{1/2} > 10^{26}\ \text{yr}$$

$$\langle m_\nu \rangle < 50 - 100\ \text{meV}$$



Ideas of cheaper/ compact SuperNEMO being discussed

Outlook

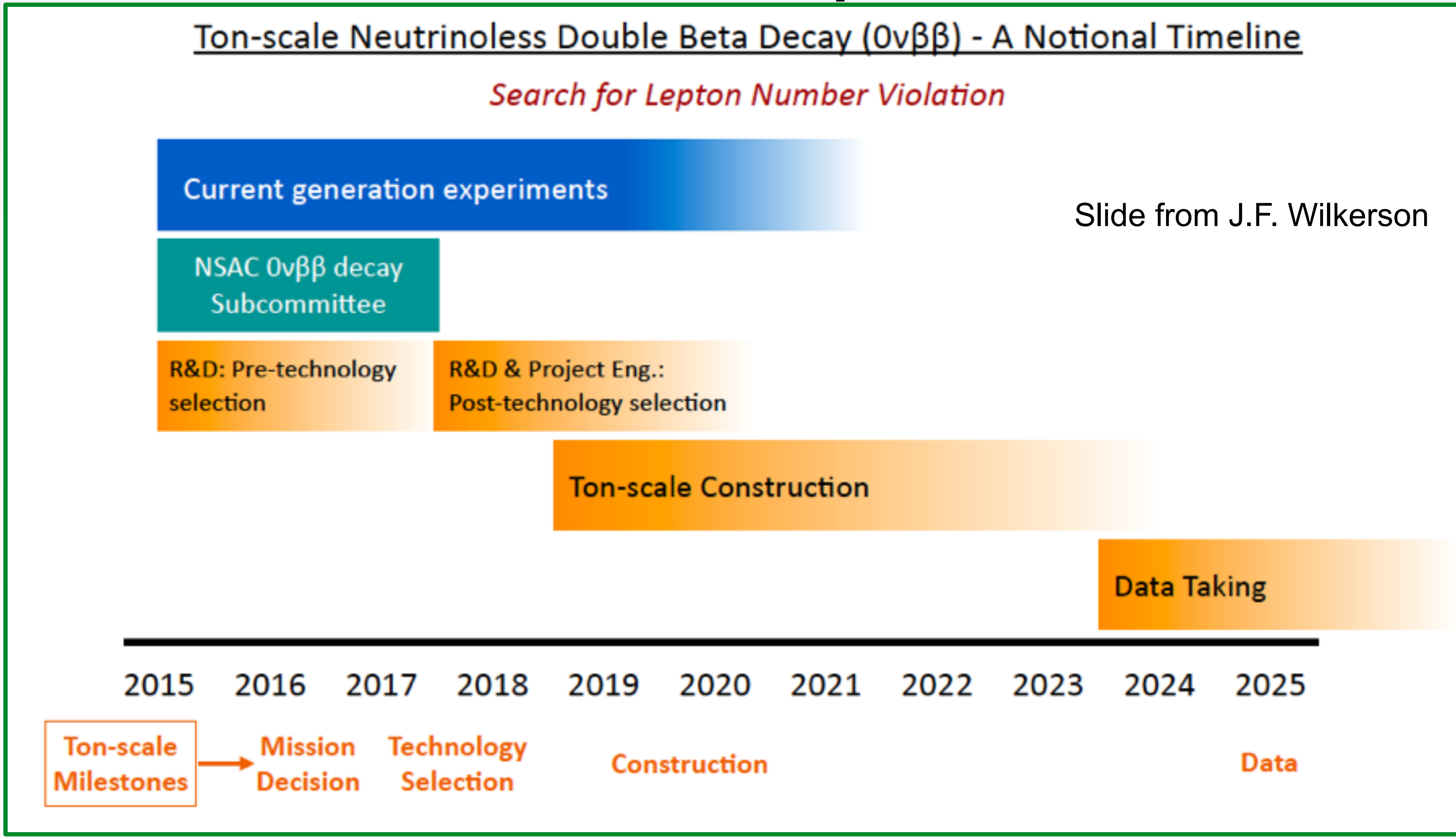


Future target: Inverted Hierarchy: ~1t — **SNO+ Phase 2/3 (?) nEXO (?), Super-KLZ (?), compact SNemo (?)**

Far Future target: Normal Hierarchy: >1t — **Enormous LS, bolometers, monster HPXe ???** **Or radical new ideas…**

However, the plot on the left is not the full story…
(see Concluding Remarks)

US Down-select process



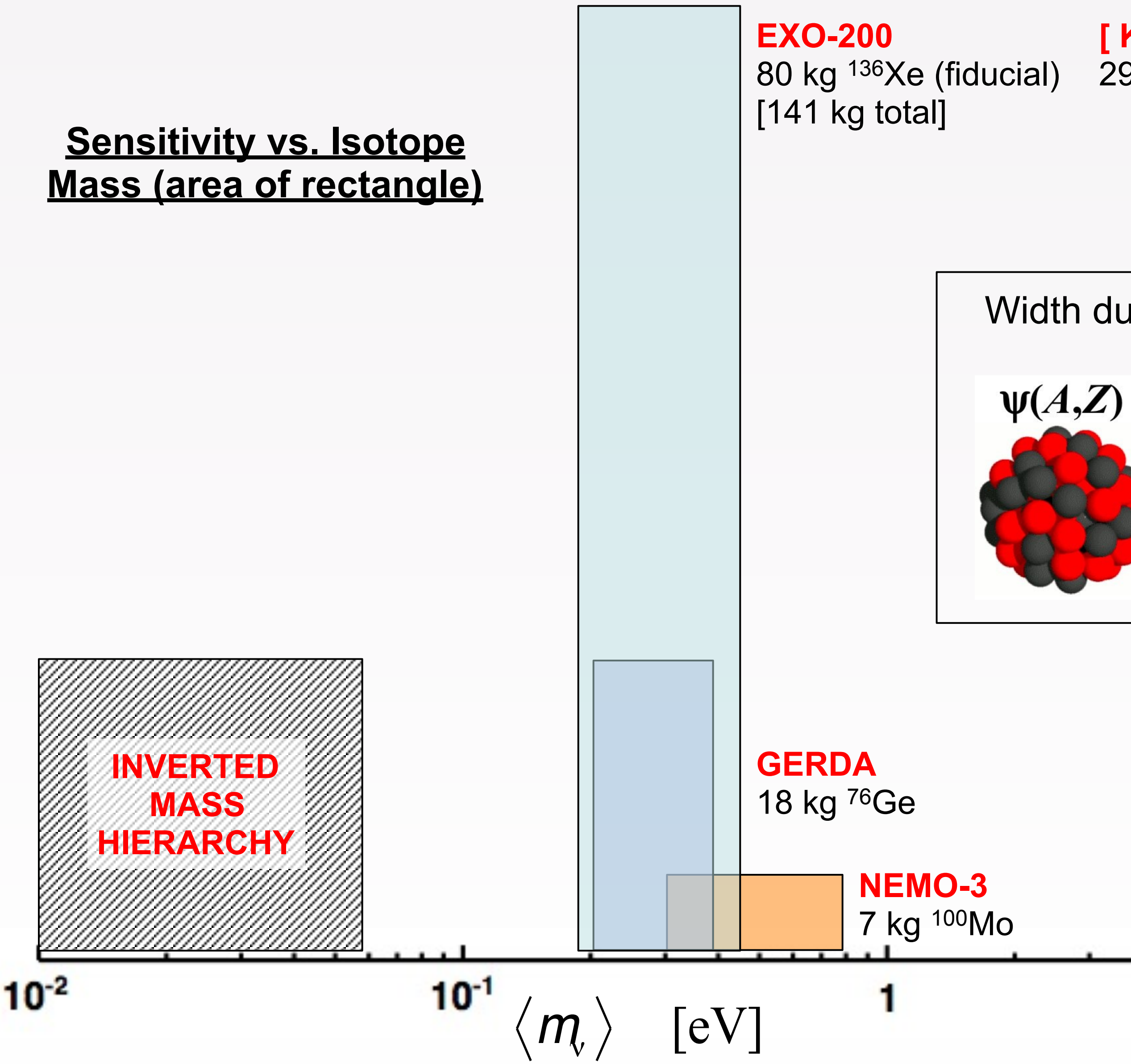
- down-select two technologies by ~2018
- 1 with leading US participation, 1 with significant contribution
- Significant funds “earmarked”

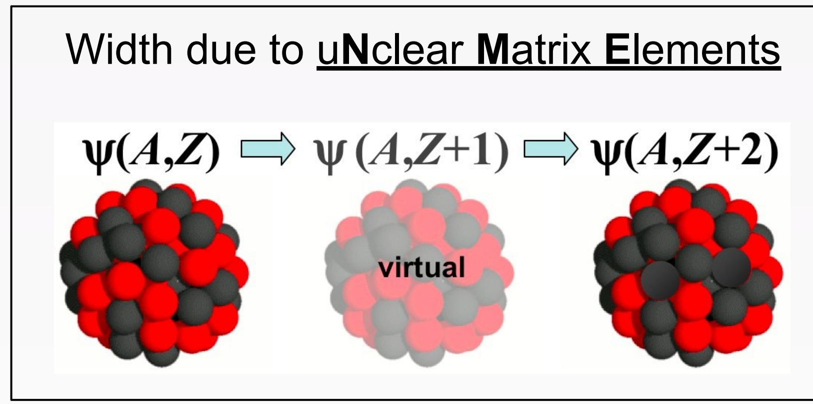
Concluding remarks

- **0νββ** is the **only** way to test **LNV** and nature and mechanism behind **neutrino mass**
- Rich **interplay** with other areas
  - Neutrino Oscillations
  - Neutrino mass from β-decay
  - Cosmology
- **Important**: Must be **open minded** about NP mechanism behind 0νββ.
  - *Normal hierarchy observed in neutrino oscillations (**IF!**) is **not** the reason to stop NDBD programme!*
- Getting to **10 meV** and below will require **novel ideas** and **consolidation** of worldwide experimental effort.

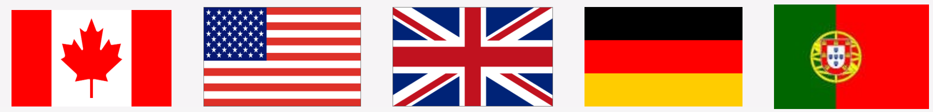
BACKUP

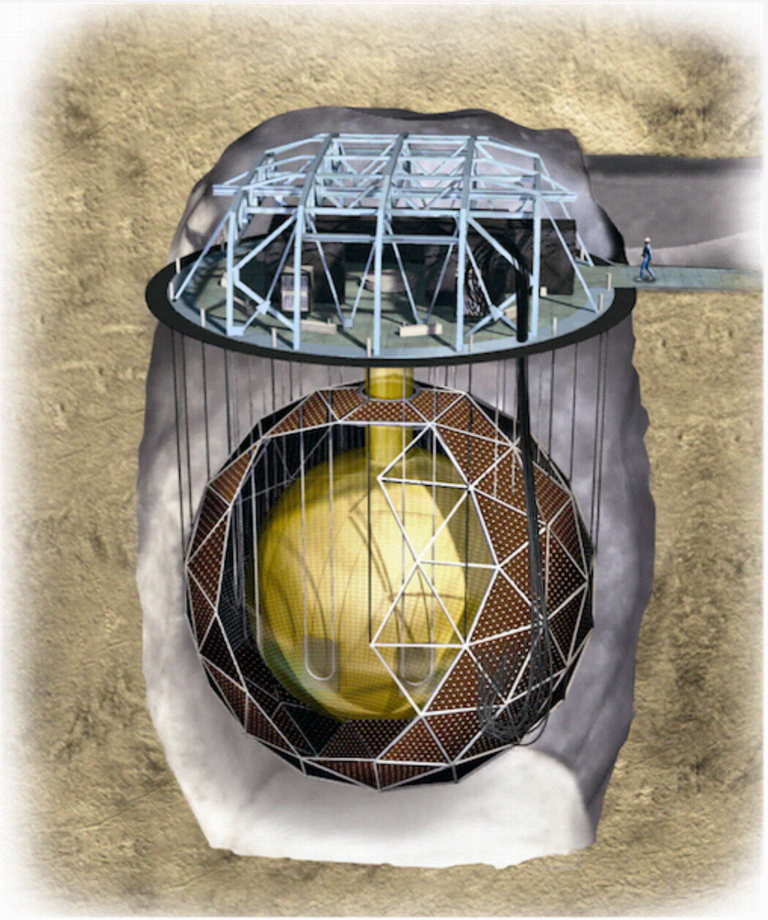
Sensitivity vs. Isotope Mass (area of rectangle)



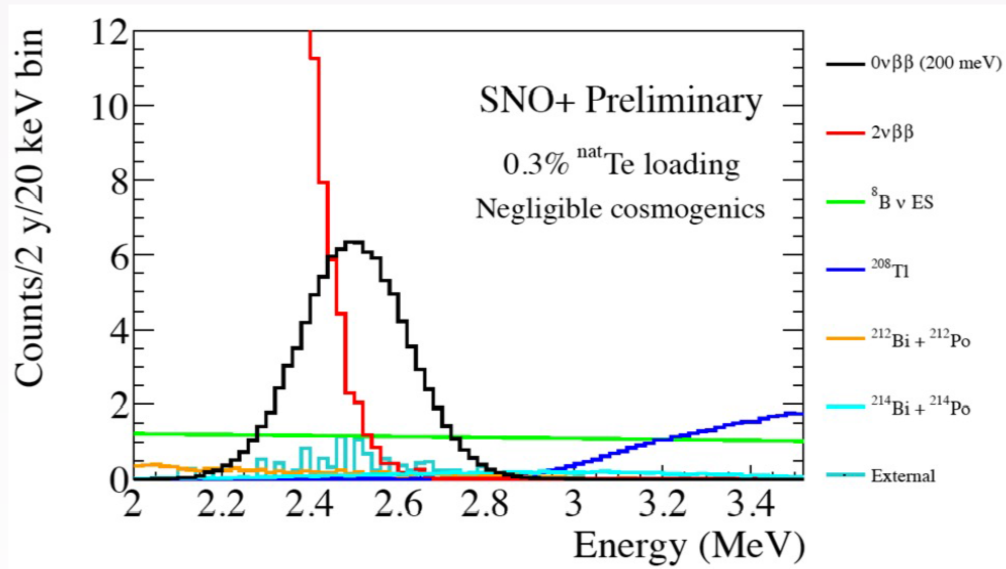


SNO+





- 780 tonnes of LAB LS
- H_2O inner and out shielding
- ~9500 PMTs
- Isotope loading into scintillator — ^{130}Te (high natural abundance)



Advantages: very pure scintillator, isotope flexibility, large isotope mass possible
Disadvantages: ΔE/E(2.5 MeV) = 9% fiducialisation, background id

- Compensate modest resolution with large isotope mass.
- Increase loading fraction to reduce background index.