Experimental Overview of ββ:
Reaching the inverted hierarchy scale

Steve Elliott

The Required Experiment Size

The Present Status of the Experimental program

The Path Forward

What is ββ?

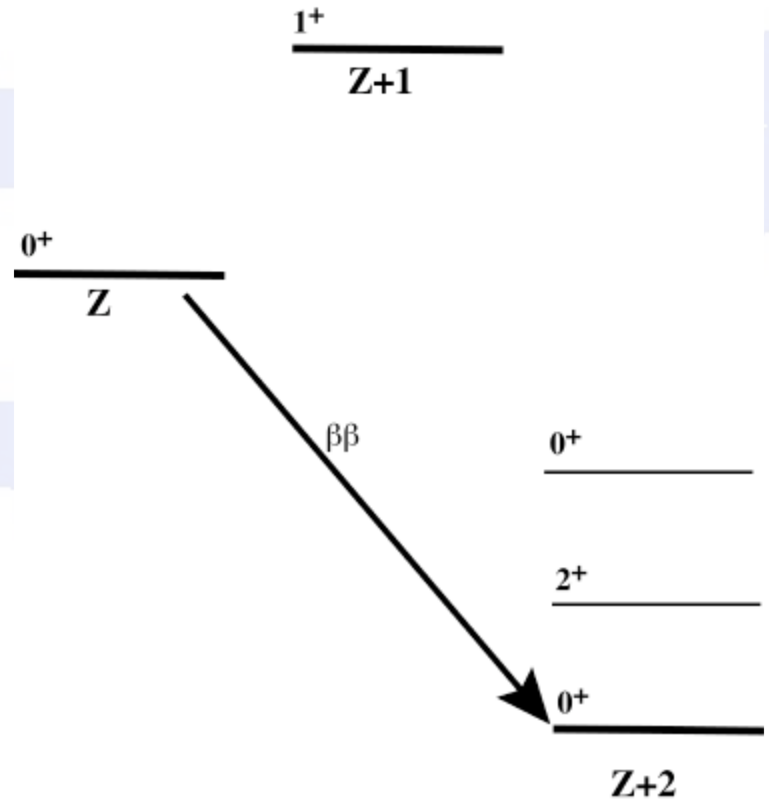


Fig. from arXiv:0708.1033

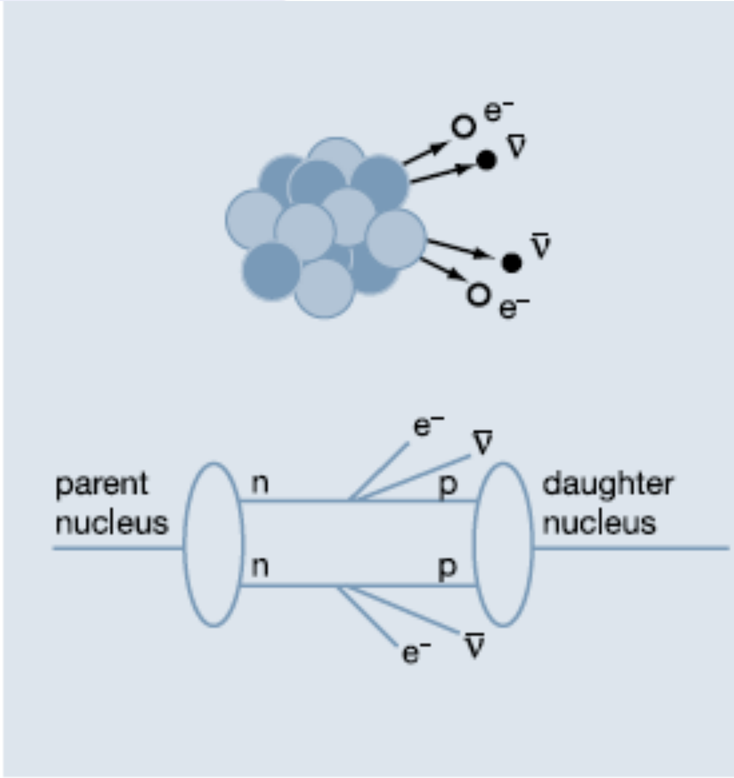


Fig. from Deep Science

What is ββ?

$n \Rightarrow p + e^- + \bar{\nu}_e$ $\nu_e + n \Rightarrow p + e^-$

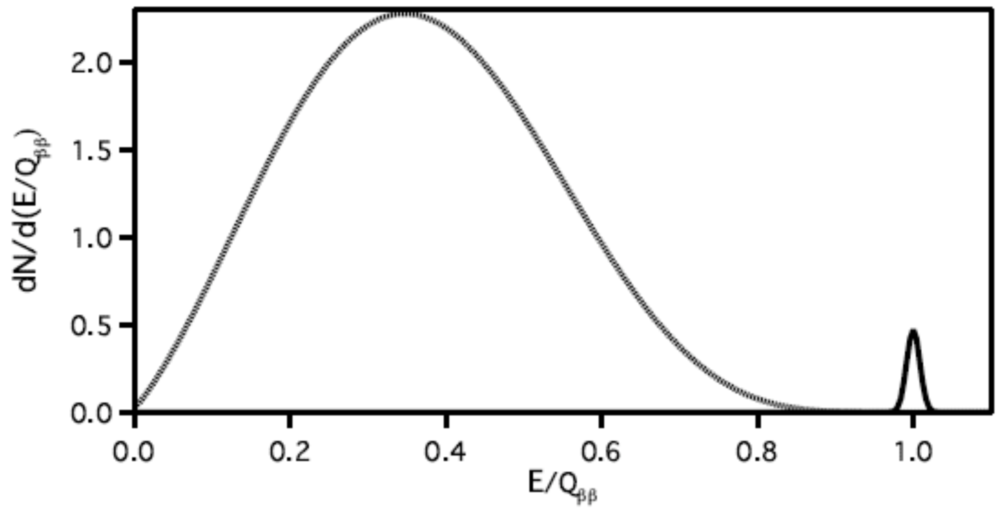


Fig. from arXiv:0708.1033

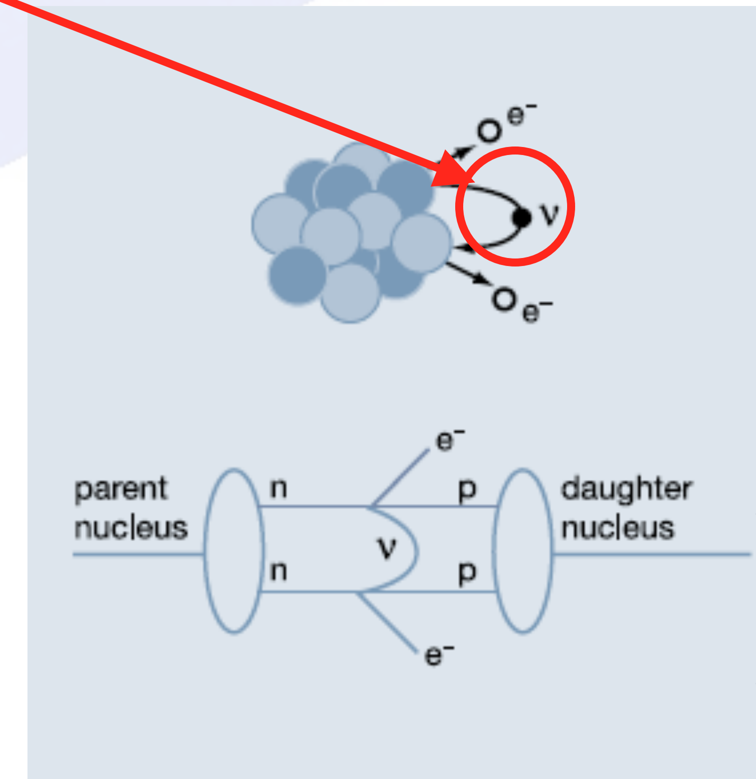
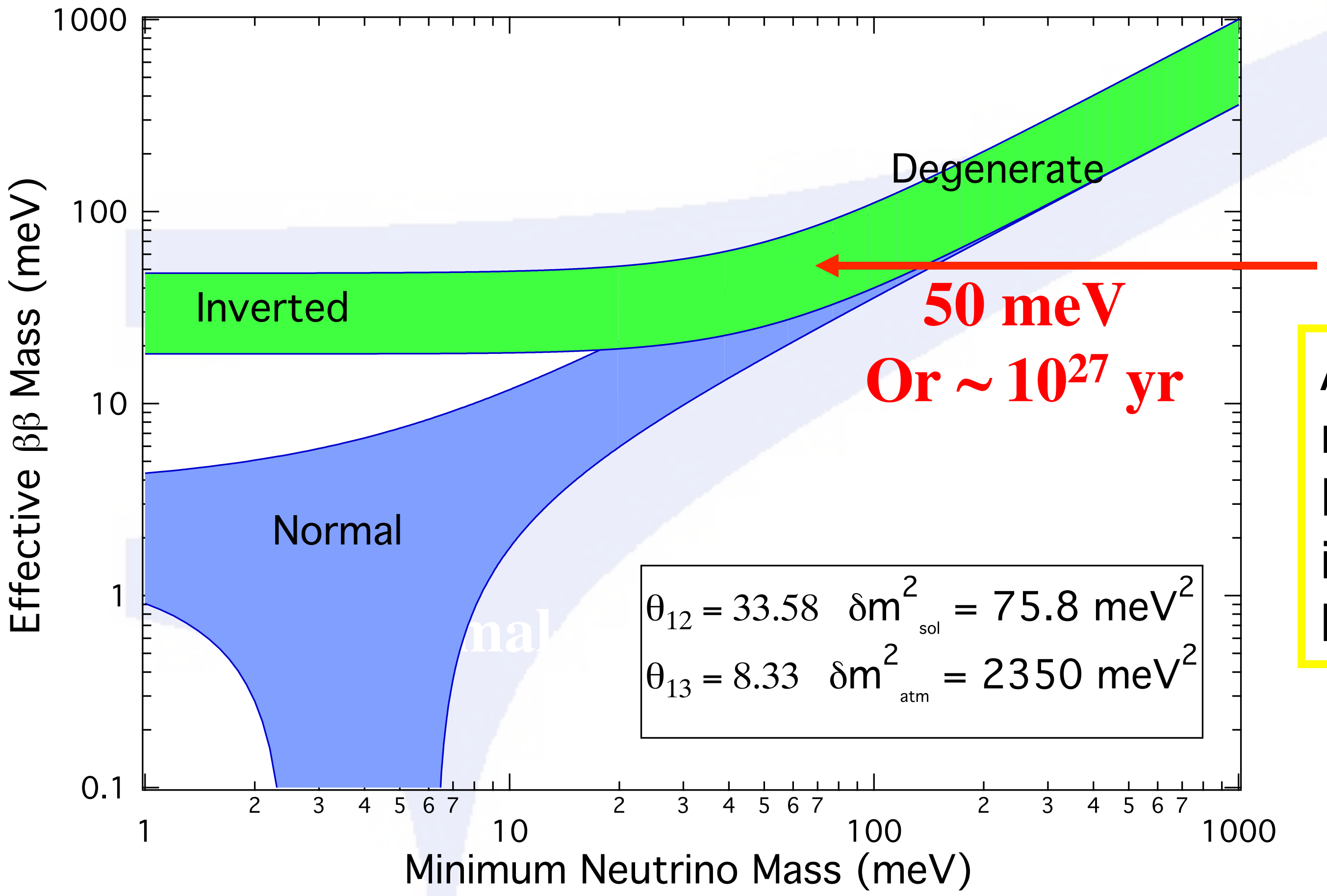


Fig. from Deep Science

ββ Sensitivity

(mixing parameters from arXiv:1106.6028)



50 meV

Or ~ 10^{27} yr

Even a null result will constrain the possible mass spectrum possibilities!

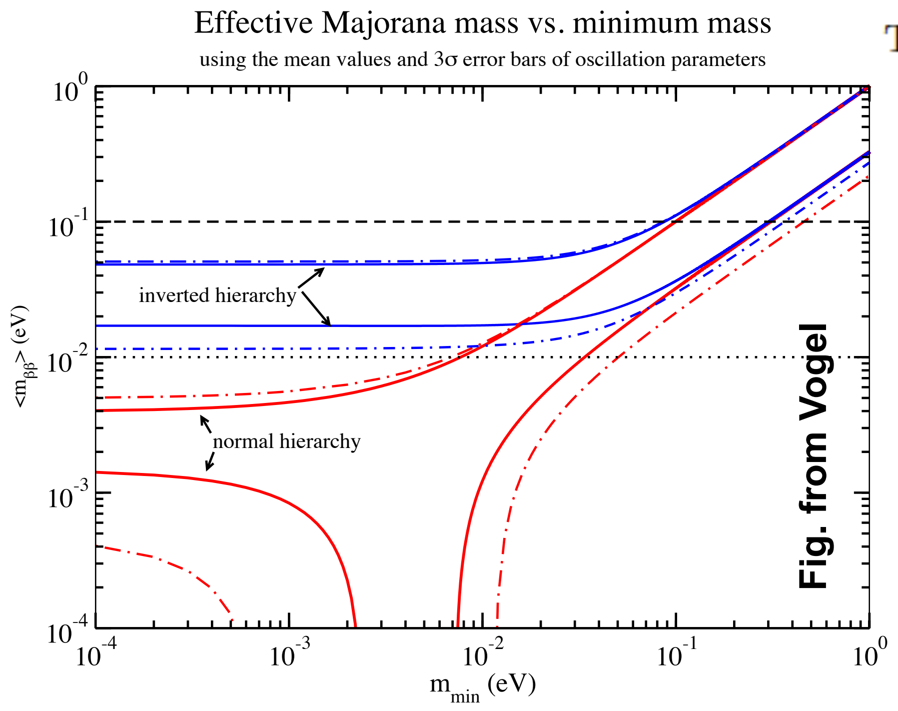
A $m_{\beta\beta}$ limit of ~15 meV would disfavor Majorana neutrinos in an inverted hierarchy.

Signal:Background ~ 1:1

Its all about the background

Half life (years)	~Signal (cnts/ton-year)	~Neutrino mass scale (meV)	
10^{25}	530	400	Degenerate
$5x10^{26}$	10	100	
$5x10^{27}$	**To reach atmospheric scale need BG on order 1/t-y.**	40	Atmospheric
$>10^{29}$	<0.05	<10	Solar

Neutrino Mixing Parameters


Effective Majorana mass vs. minimum mass

using the mean values and 3σ error bars of oscillation parameters

Fig. from Vogel

TABLE I: Neutrino mixing parameters from Ref. [3]

Parameter	Best Fit	2σ Range
δm^2_{sol}	75.4 meV ^{2}	71.5-80.0 meV^2
δm^2_{atm}	2420 meV^2	2260-2530 meV^2
$sin^2\theta_{13}$	0.307	0.275-0.342
θ_{13}	33.65°	31.63-35.79°
$sin^2\theta_{12}$	0.0244	0.0194-0.0291
θ_{12}	8.99°	8.01-9.82°

To cover inverted hierarchy, must reach about 14.9 meV for $m_{\beta\beta}$.

Matrix Elements

Isotope	NSM	QRPA	IBM-2	PHFB	EDF	$G_{0\nu}$ $10^{-15}/\mathrm{y}$
^{48}Ca	0.82-0.90		1.98		2.37	24.81
^{76}Ge	2.81	4.07-6.64	5.42		4.60	2.363
^{82}Se	2.64-3.56	3.53-5.92	4.37		4.22	10.16
^{94}Zr*				2.03		0.680
^{96}Zr		1.43-2.12	2.53	1.45	5.65	20.58
^{98}Mo*				3.37		0.00072
^{100}Mo		2.91-5.56	3.73	3.25	5.08	15.92
^{104}Ru*				2.35		1.286
^{110}Pd			3.62	3.85		4.815
^{116}Cd		2.30-4.14	2.78		4.72	16.70
^{124}Sn	2.62		3.50		4.81	9.040
^{128}Te	2.88	3.21-5.65	4.48	1.62	4.11	0.5878
^{130}Te	2.65	2.92-5.04	4.03	2.21	5.13	14.22
^{136}Xe	1.46-2.19	1.57-3.24	3.33		4.20	14.58
^{148}Nd			1.98			10.10
^{150}Nd		3.34	2.32	1.62	1.71	63.03
^{154}Sm			2.50			3.015
^{160}Gd		3.76	3.62			9.559
^{198}Pt			1.88			7.556
^{232}Th						13.93
^{238}U						33.61

Factors of ~2 variation for each isotope – factor of 4 in required exposure.

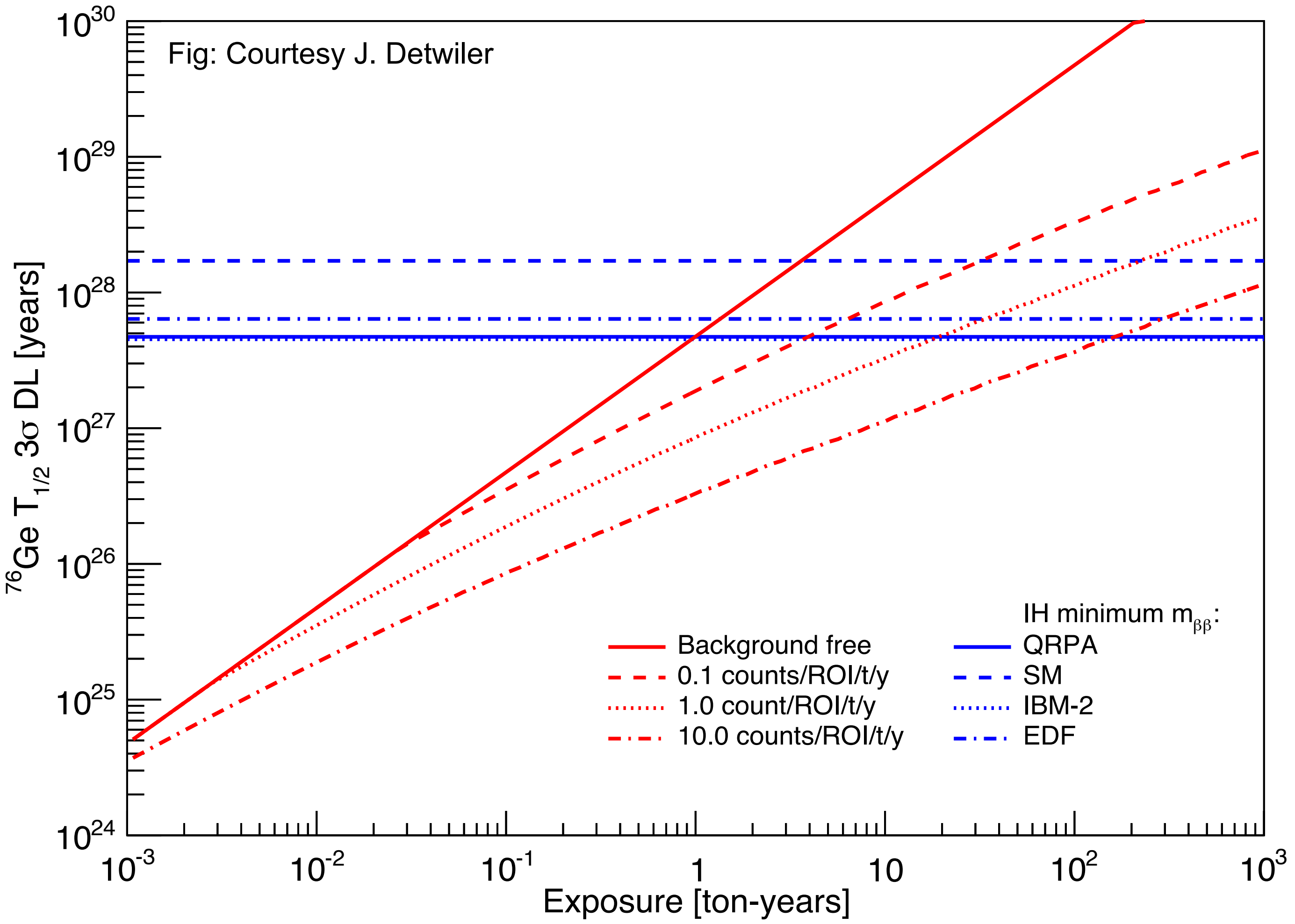
Axial Vector coupling constant appears as 4th power – big effect

- **In β-decay, the theoretical matrix elements are larger than the experimental ones. The ratio is nearly constant, so to account for this, the value of g_A is "quenched" by a factor of about 0.8.**
- **The level of quenching will depend on the number single particle states included in the shell.**
- **In 2νββ, quenching is also observed and how much is required depends on the configurations used in the calculation. Calculations tend to find a g_A near 1.0, instead of 1.27 works best. Some calculations find something near g_A ~0.6. This is a factor of 2^4=16 in the required exposure.**
- **Is quenching required in 0νββ?**
- **2νββ only connects 1+ states in intermediate nucleus, whereas 0νββ a large number of states.**
- **Other processes, such as mu-capture, that involve all such states don't require quenching. If quenching is present, it is unlikely to be as large as in the 2νββ case.**

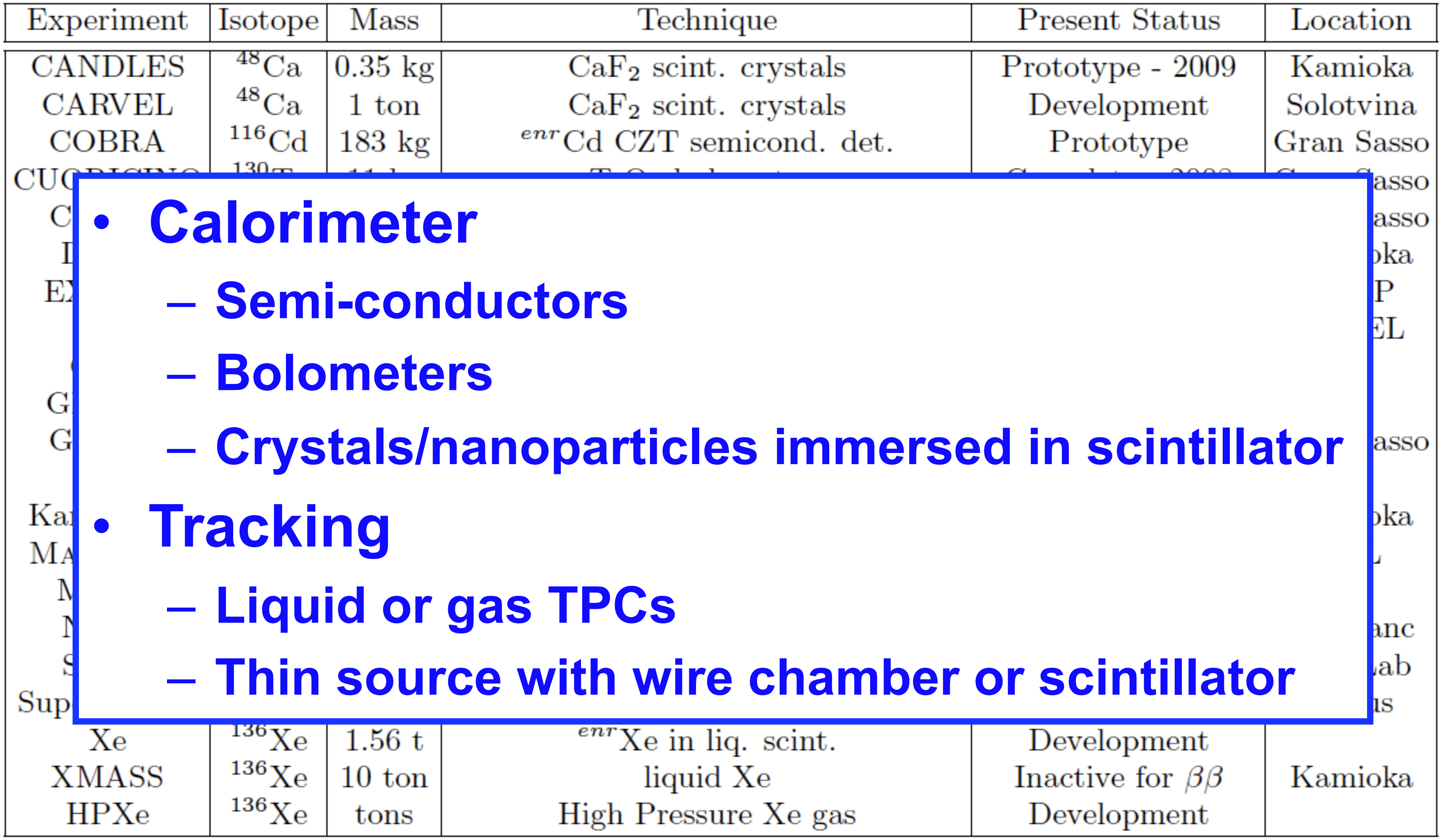
Phase Space Factors, Other $\beta\beta$ Mechanisms

- **$G_{0\nu}$ is known to about 7%, where the uncertainty comes from the uncertainty in the input parameters.** (Katila/Iachello, PRC 85, 034316 (2012)) **Calculations differ depending on isotope by about 1-2%** (Stoica/Mirea arXiv:1307.0290).
- **We know that light neutrinos exist, so it seems plausible to focus on that mechanism.**
  - **However it is, in principle, possible that more than one mechanism exists and contribute at a comparable level and interference might be present.**
  - **Such an interference seems a bit unnatural and it seems likely that one mechanism will dominate.**

Sensitivity, Background and Exposure



Great Number of Proposed Experiments



Experiment	Isotope	Mass	Technique	Present Status	Location
CANDLES	^{48}Ca	0.35 kg	CaF$_2$ scint. crystals	Prototype - 2009	Kamioka
CARVEL	^{48}Ca	1 ton	CaF$_2$ scint. crystals	Development	Solotvina
COBRA	^{116}Cd	183 kg	^{enr}Cd CZT semicond. det.	Prototype	Gran Sasso
CU					asso
C					asso
I					oka
E					P
					EL
G					
G					asso
Ka					oka
MA					L
M					
N					anc
S					ab
Sup					us
Xe	^{136}Xe	1.56 t	^{enr}Xe in liq. scint.	Development	
XMASS	^{136}Xe	10 ton	liquid Xe	Inactive for $\beta\beta$	Kamioka
HPXe	^{136}Xe	tons	High Pressure Xe gas	Development	

- **Calorimeter**
  - **Semi-conductors**
  - **Bolometers**
  - **Crystals/nanoparticles immersed in scintillator**
- **Tracking**
  - **Liquid or gas TPCs**
  - **Thin source with wire chamber or scintillator**

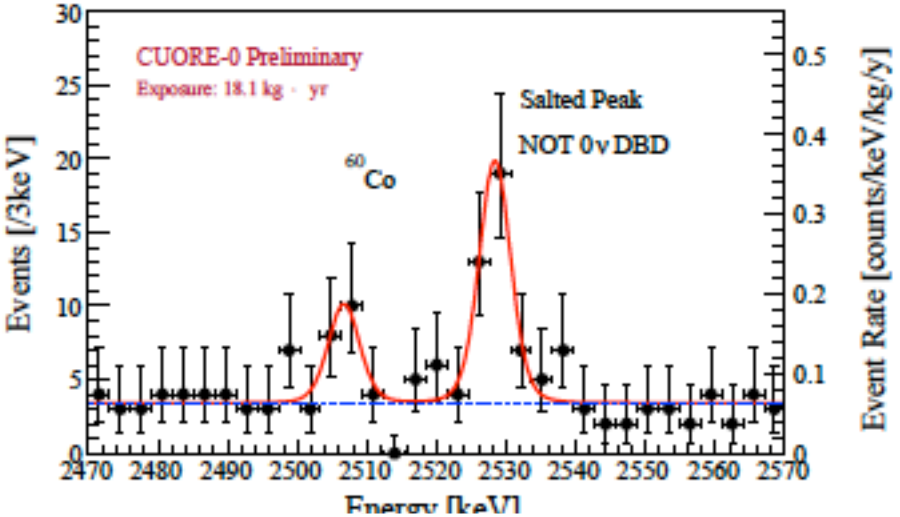
Experiments that will test claim in coming few years.

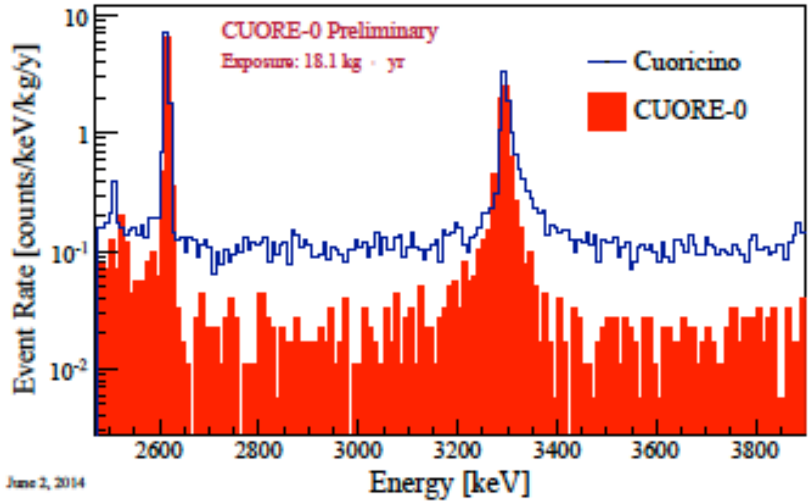
	Mass	Run Plan
CUORE	~200 kg	2014
EXO-200	~100 kg	2011
GERDA I/II	~34 kg	2011/2015
KamLAND-Zen	~300 kg	2012
MAJORANA	~30 kg	2015
NEXT	~10 kg	2016
SNO+	~120 kg	2016
SuperNEMO Dem.	~7 kg	2015

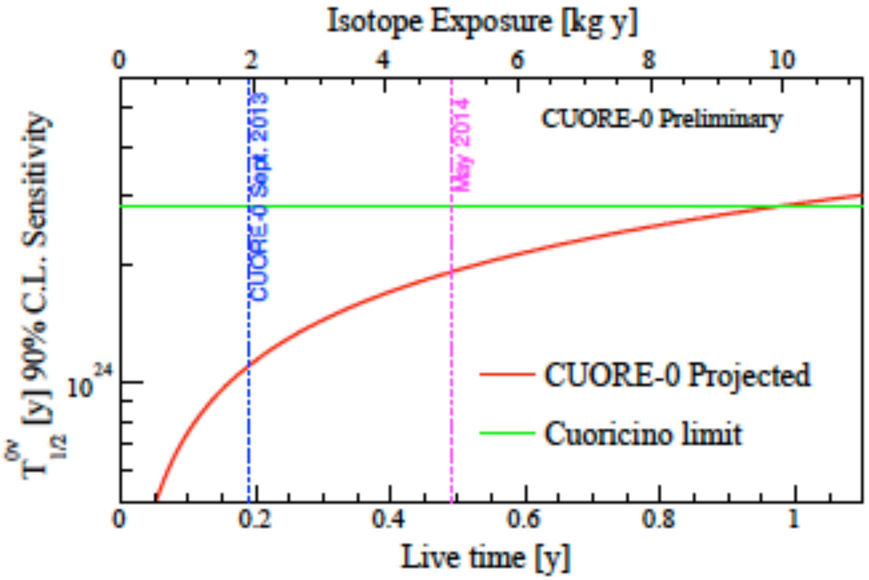
Good guess that we'll reach about 100 meV in the 2016 time frame.

Ton-scale projects might be starting by 2020.

CUORE – See next talk





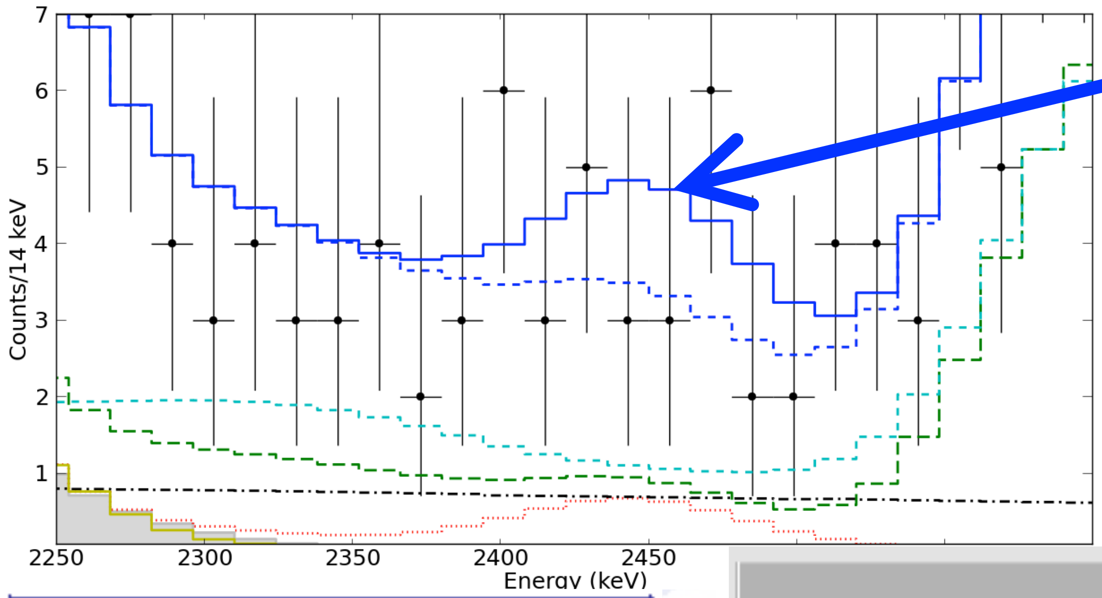


CUORE 90% sensitivity
$T_{0\nu} > 9.5\text{x}10^{25}$ y

EXO result

$T_{0\nu} > 1.1 \text{ x } 10^{25}$ y

$m_{\beta\beta} < 190\text{-}450$ meV

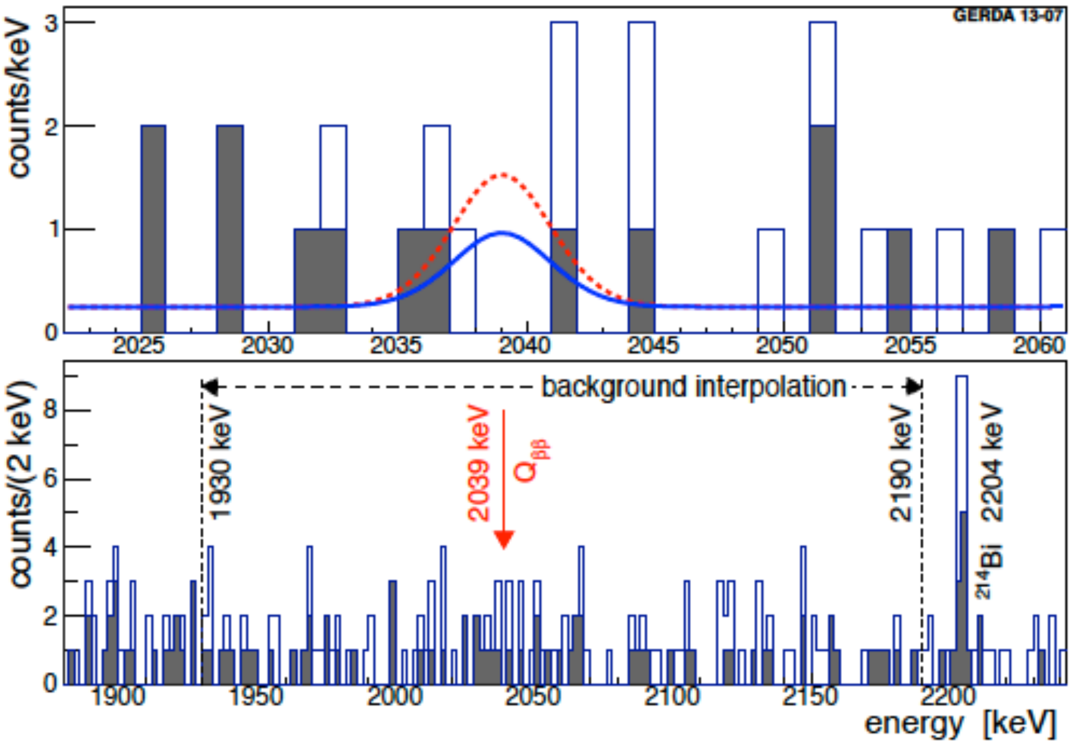


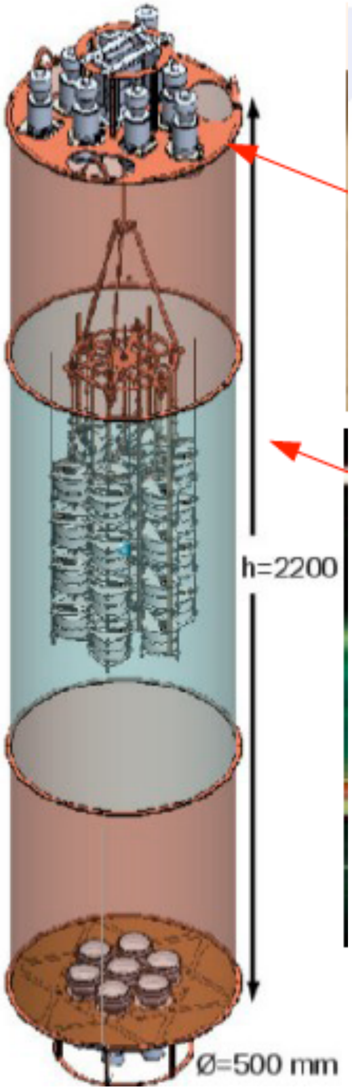
Fit with $0\nu\beta\beta$, but consistent with no signal.

Fit components	
Backgrounds	31.1
$0\nu\beta\beta$ decay	9.9
Total	41.0

	EXO-200	nEXO (5 yr)
fiducial mass [kg]	100	4780
enrichment	80%	90%
FWHM [keV]	88	58
background in [evt/(mol yr ROI)]	0.022	$6\ 10^{-4}$
$T_{1/2}$ limit sens. (90% CL) [yr]	$6\ 10^{25}$	$6\ 10^{27}$

GERDA: $T_{0\nu} > 2.1\times10^{25}$ y





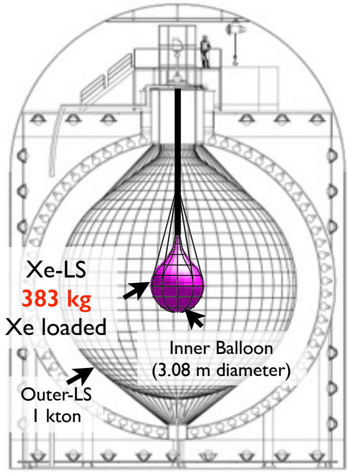
Phase II: 2015 start

2x detector mass

0.1x background

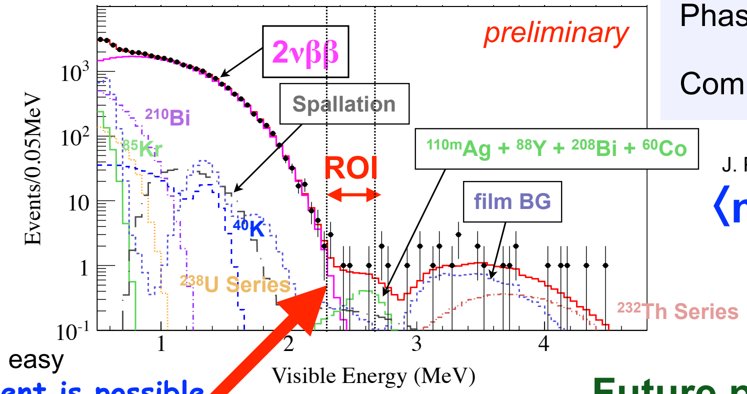
KamLAND-Zen

KamLAND-Zen
Phase 2



Data after purification

Internal (first 114.8 days, R < 1.0 m)



Half-life limit at 90% C.L.

Phase 1	$T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr
Phase 2	$T^{0\nu}_{1/2} > 1.3 \times 10^{25}$ yr
Combined	$T^{0\nu}_{1/2} > 2.6 \times 10^{25}$ yr

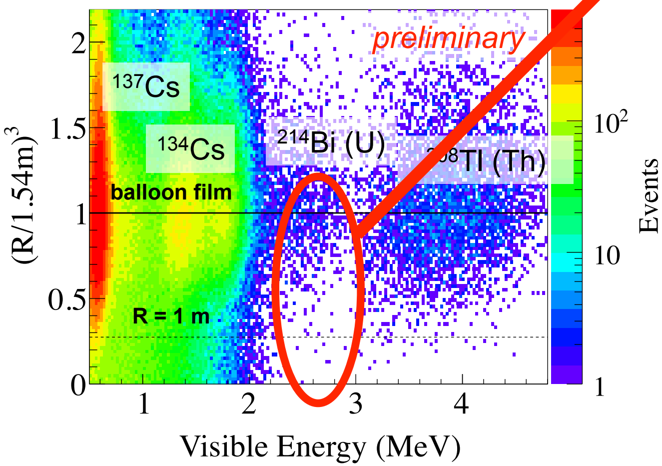
QRPA NME model
J. Phys. G 39 124006 (2012)

$\langle m_{\beta\beta} \rangle < 0.14\text{-}0.28$ eV

future target
$\langle m_{\beta\beta} \rangle \sim 20$ meV

Xe extraction and purification are easy

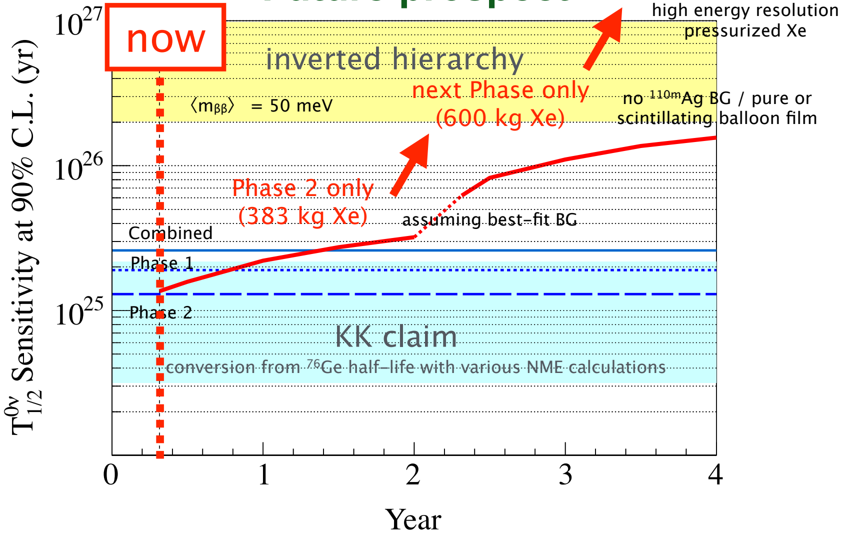
→ *Xe On-Off measurement is possible*



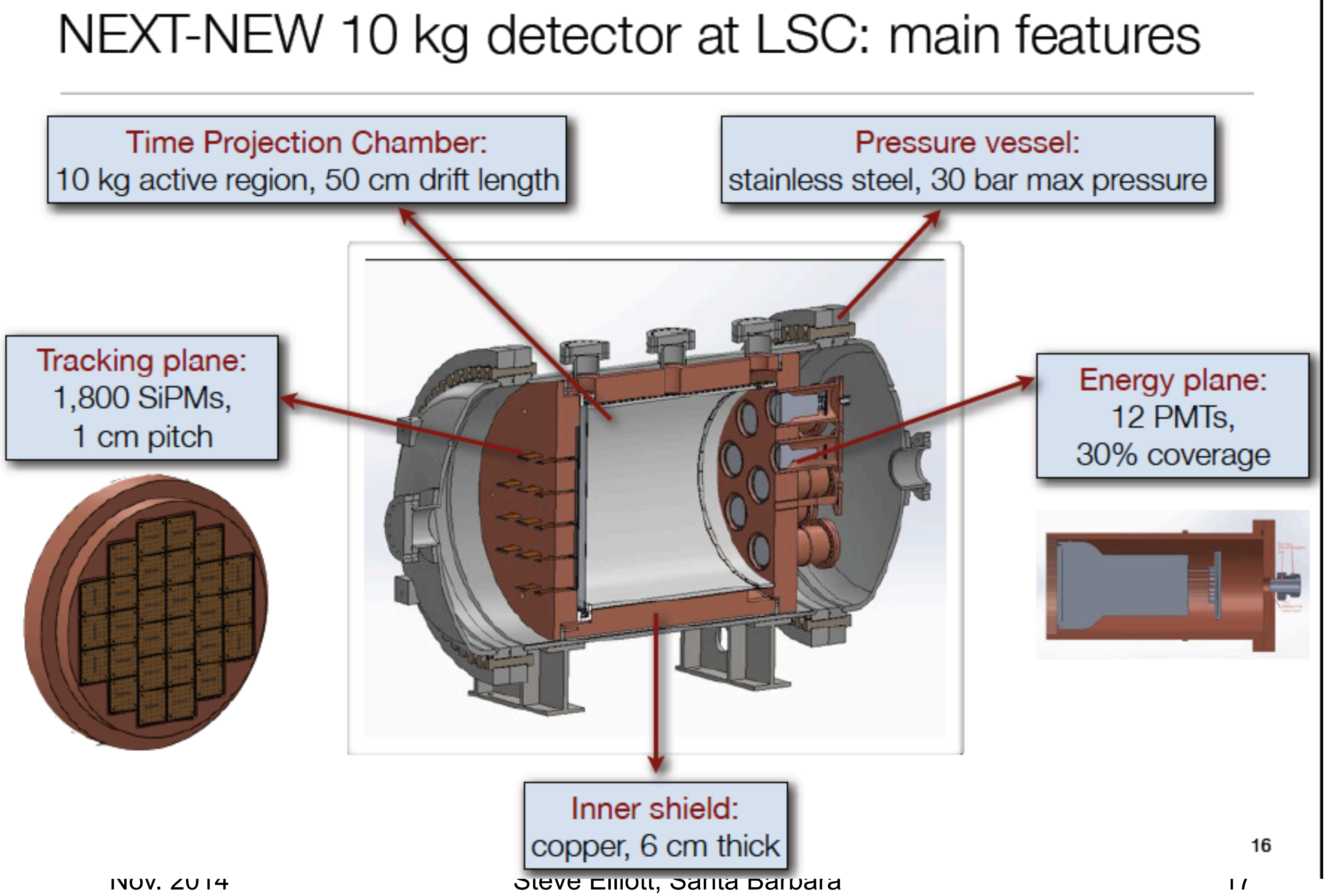
^{110m}Ag background reduction to < 1/10

Future prospect

KamLAND2-Zen
(1,000 kg Xe)



Funded, under construction, 2016



NEXT-NEW 10 kg detector at LSC: main features

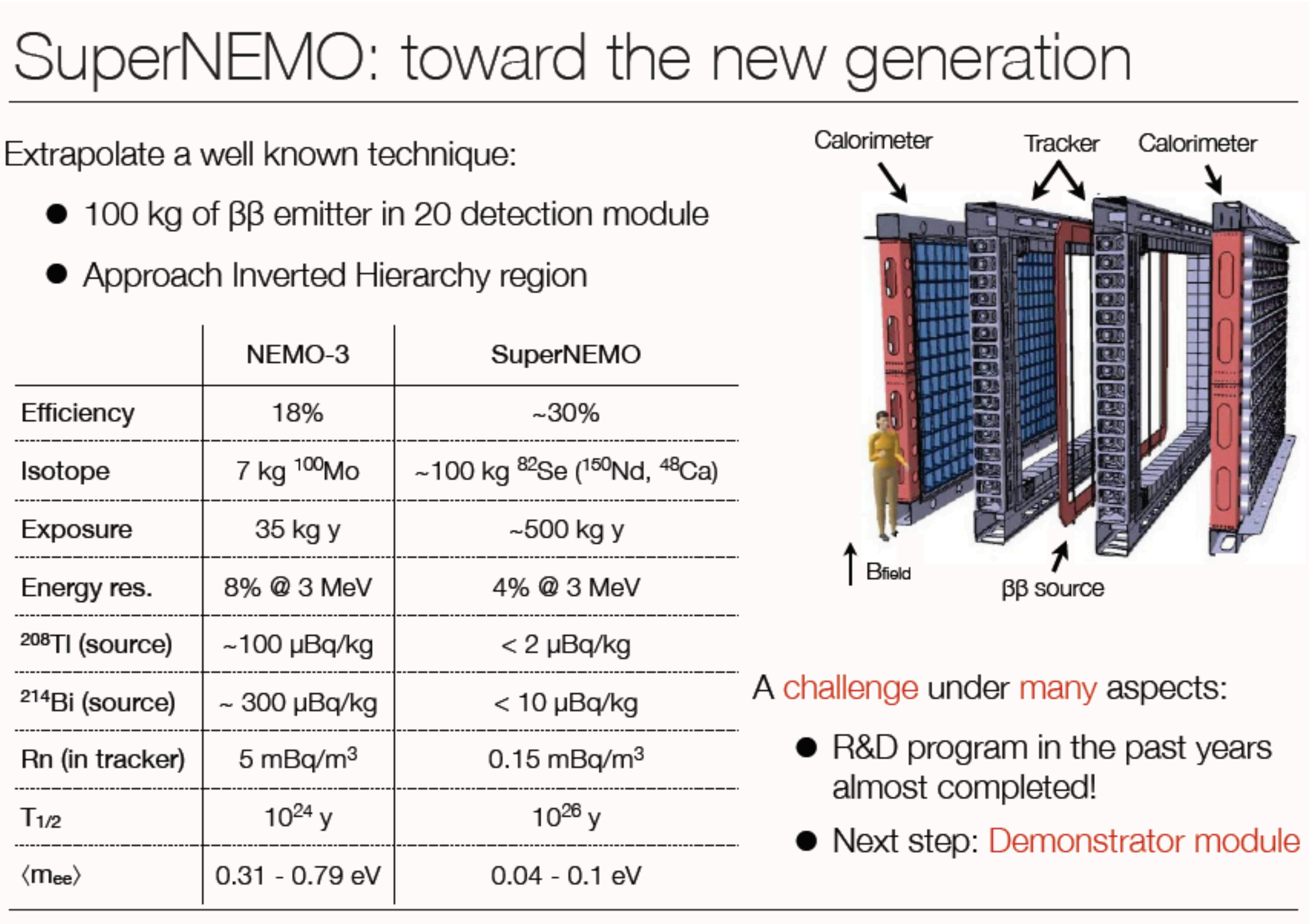
Time Projection Chamber:
10 kg active region, 50 cm drift length

Pressure vessel:
stainless steel, 30 bar max pressure

Tracking plane:
1,800 SiPMs,
1 cm pitch

Energy plane:
12 PMTs,
30% coverage

Inner shield:
copper, 6 cm thick



SuperNEMO: toward the new generation

Extrapolate a well known technique:

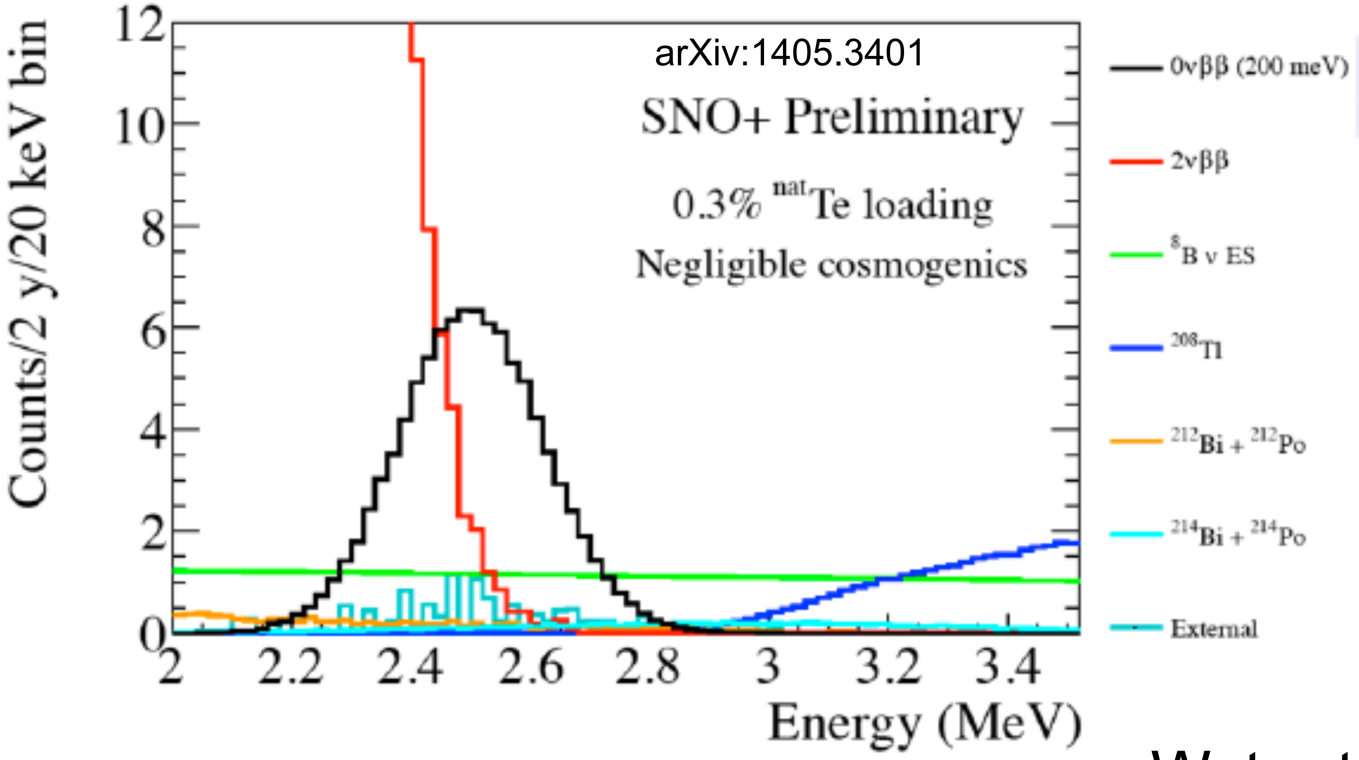
- 100 kg of ββ emitter in 20 detection module
- Approach Inverted Hierarchy region

	NEMO-3	SuperNEMO
Efficiency	18%	~30%
Isotope	7 kg ^{100}Mo	~100 kg ^{82}Se (^{150}Nd, ^{48}Ca)
Exposure	35 kg y	~500 kg y
Energy res.	8% @ 3 MeV	4% @ 3 MeV
^{208}Tl (source)	~100 μBq/kg	< 2 μBq/kg
^{214}Bi (source)	~ 300 μBq/kg	< 10 μBq/kg
Rn (in tracker)	5 mBq/m^3	0.15 mBq/m^3
$T_{1/2}$	10^{24} y	10^{26} y
$\langle m_{ee} \rangle$	0.31 - 0.79 eV	0.04 - 0.1 eV

A challenge under many aspects:

- R&D program in the past years almost completed!
- Next step: Demonstrator module

SNO+

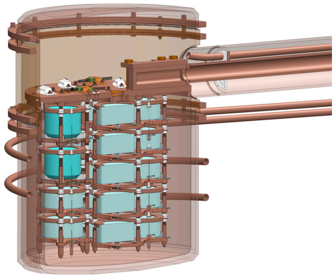


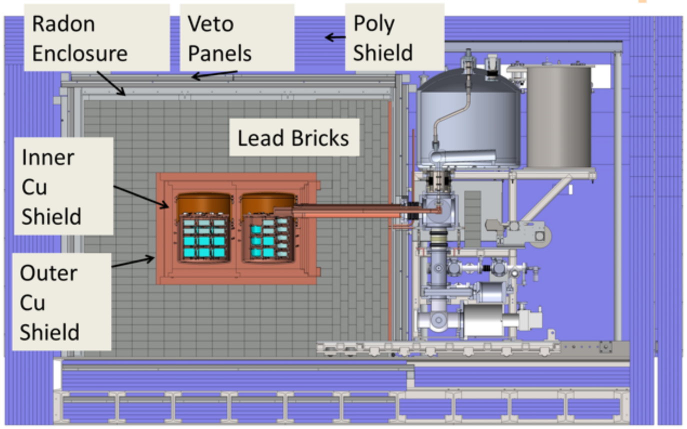
Water test: 2014-15
Scint test: 2015
Telluric acid: 2016

The MAJORANA DEMONSTRATOR Module

^{76}Ge offers an excellent combination of capabilities & sensitivities.

(Excellent energy resolution, intrinsically clean detectors, commercial technologies)

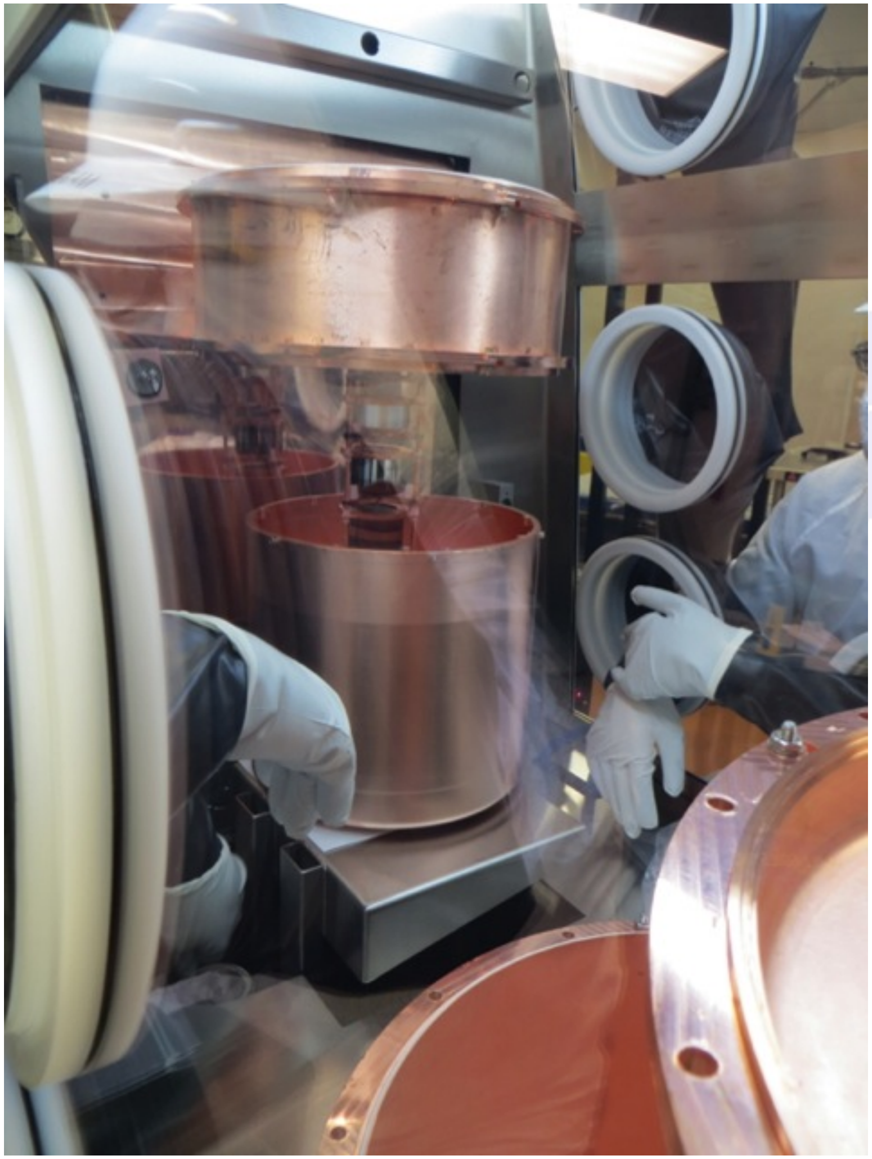




- **40-kg of Ge detectors**
  - **30-kg of 87% enriched ^{76}Ge crystals required for science and background goals**
  - **Point-contact detectors for DEMONSTRATOR**
- **Low-background Cryostats & Shield**
  - **ultra-clean, electroformed Cu**
  - **naturally scalable**
  - **Compact low-background passive Cu and Pb shield with active muon veto**
- **Located at 4850' level at Sanford Lab**
- **Background Goal in the 0νββ peak ROI(4 keV at 2039 keV)**

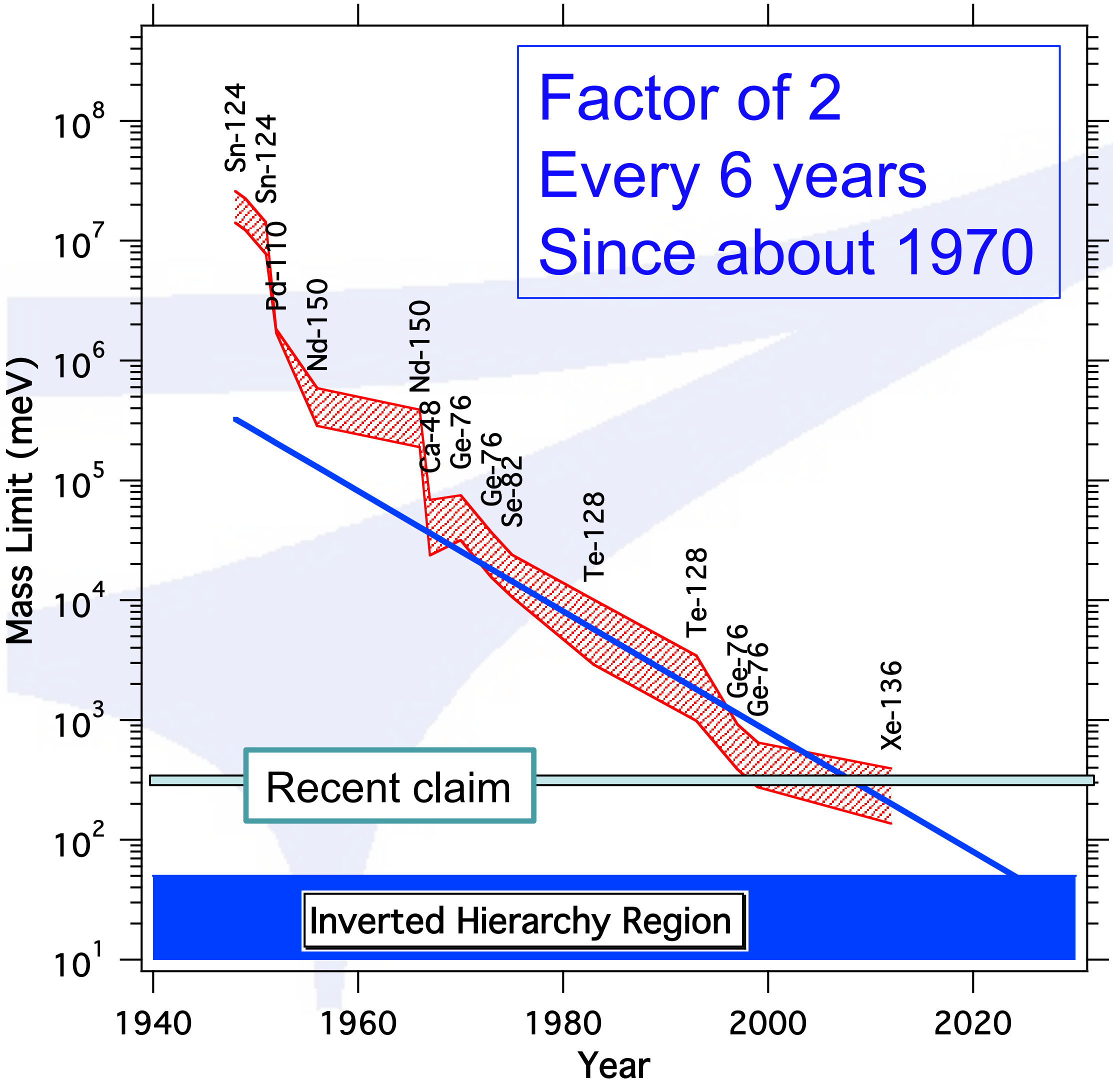
~ 3 count/ROI/t-y (after analysis cuts) (scales to 1 count/ROI/t-y for tonne expt.)

Modules



- **String of enriched detectors being installed into EFCu Cryostat.**

ββ trends



Factor of 2
Every 6 years
Since about 1970

Historically, there are > 100 experimental limits on $T_{1/2}$ of the 0νββ decay. Here are the records expressed as limits on $<m_{\beta\beta}>$ using a range of nuclear matrix elements. Note the approximate linear slope vs time on such semilog plot.

Although Xe has a lead in the mass limit, Ge does a better job excluding the claim.

An Ideal Experiment

Maximize Rate/Minimize Background

$$\langle m_{\beta\beta} \rangle \propto \left(\frac{b\Delta E}{MT_{live}} \right)^{\frac{1}{4}}$$

Large Exposure(~ 10 t-y)
Low Background (< 1count/t-y)
Large Q value, fast ββ(0ν)
Good source radiopurity
Demonstrated technology
Ease of operation
Source = detector
Good energy resolution
Slow ββ(2ν) rate
Identify daughter in real time
Event reconstruction

Experimental Parameters

$$\langle m_{\beta\beta}\rangle \leq \left(2.50x10^{-5}\,meV\right)\sqrt{\frac{W}{fx\varepsilon G_{0\nu}\left|M_{0\nu}\right|^{2}}}\left[\frac{b\Delta E}{MT}\right]^{\frac{1}{4}}$$

- **W – molecular weight of source**
- **f – isotopic abundance**
- **x – number of bb isotopes per molecule**
- **ε – detector efficiency**
- **$G_{0\nu}$ – decay phase space**
- **$|M_{0\nu}|$ - matrix element**
- **b – background in counts/keV-kg-y**
- **ΔE – energy window in keV**
- **M – mass of source in kg**
- **T – counting time in years**

- When comparing isotopes, don't forget W, favors low A. $G_{0\nu}$ favors high A.
- QRPA has more A dependence than SM.

Isotope	$\sqrt{(W/(G_{0\nu}|M_{0\nu}|^2))}$ x10^7
Ge	2.4(QRPA) 4.7(SM)
TeO_2	1.9(QRPA) 3.1(SM)
Xe	2.4(QRPA) 3.3(SM)

Isotope Choice

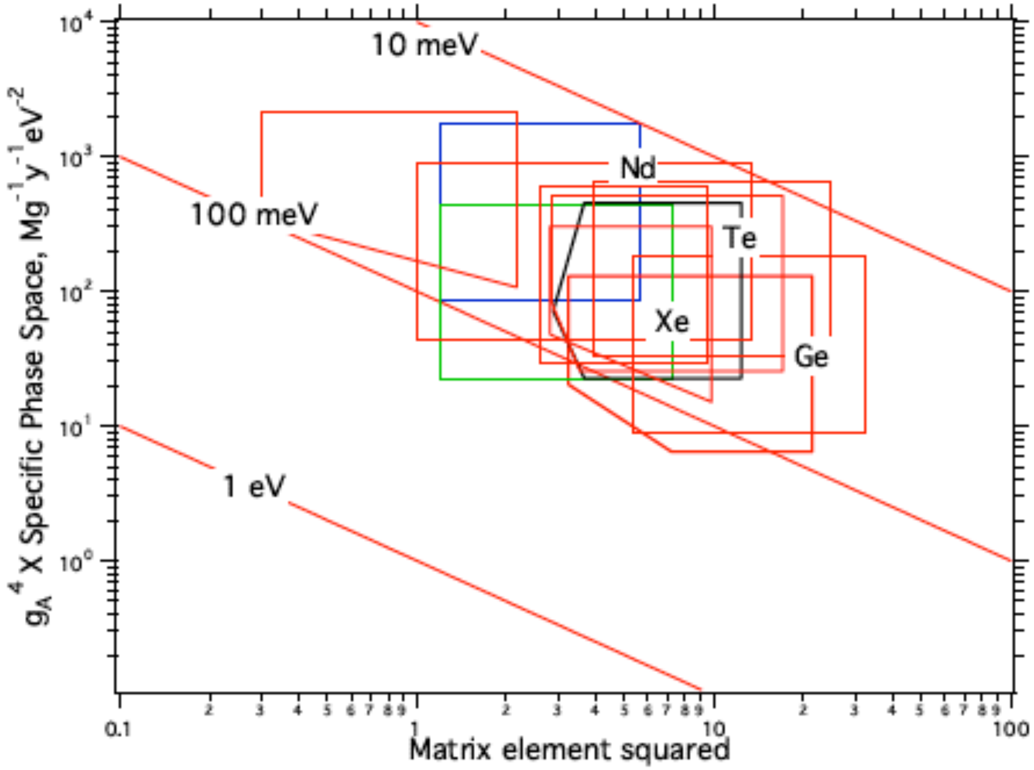
$$MT = (2.50 \times 10^{-5} meV)^2 \frac{NW}{fx\epsilon G_{0\nu}} \left(\frac{1}{\langle m_{\beta\beta} \rangle M_{0\nu} g_A{}^2} \right)^2$$

$$N \; = \; \sqrt{B} = \sqrt{b \Delta E M T} \text{ background limited}$$

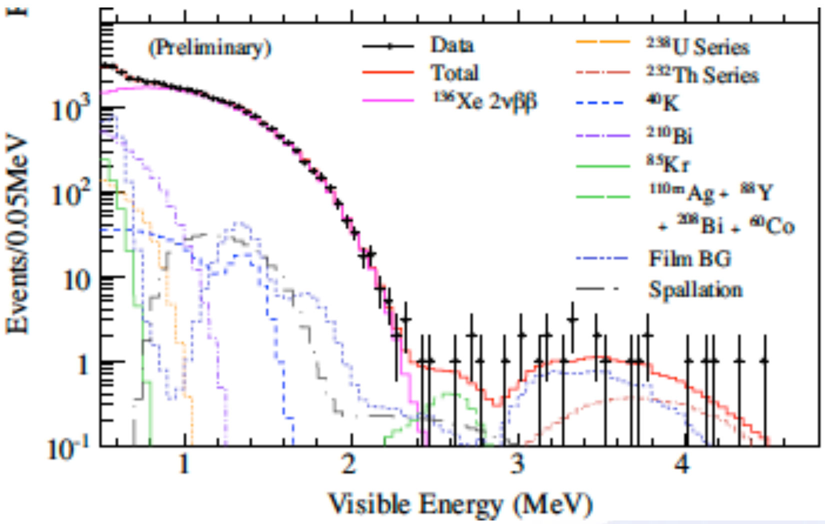
Many authors ignore:
f, x, ε, W
when comparing isotopes

All isotopes are roughly comparable.

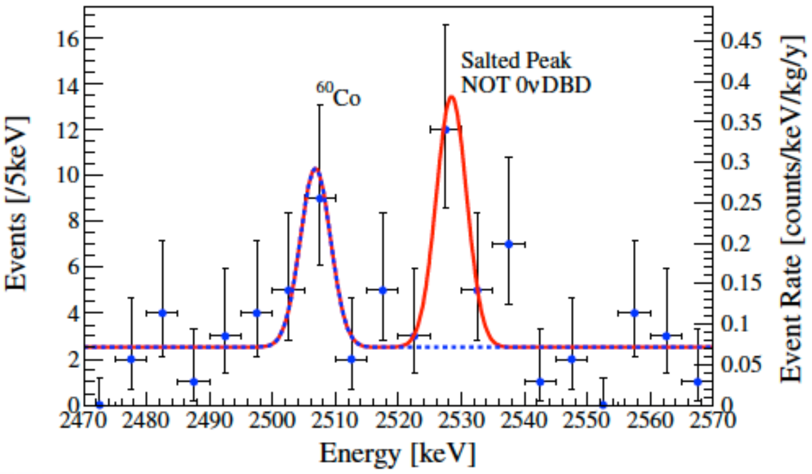
Robertson Mod. Phys. Lett. A, **28** (2013) 1350021



Background in 2014 Experiments



arXiv:1409.0077



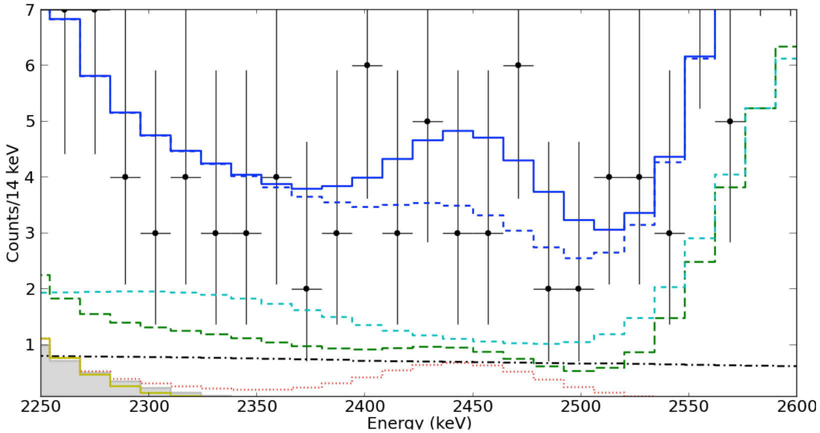
arXiv:1402.6072

KamLAND-Zen: 145 c/ROI/t(Xe)/y

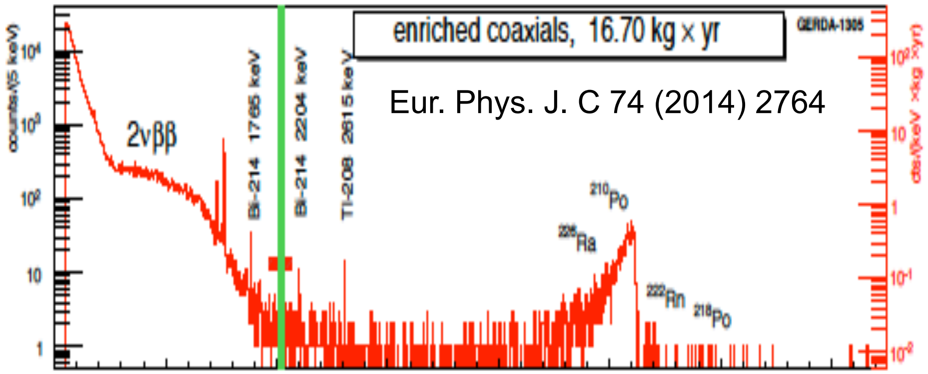
EXO-200: 120 c/ROI/t/y

CUORE-0: 400 c/ROI/t/y

GERDA: 80 c/ROI/t/y



Nature 510, 229-234



Eur. Phys. J. C 74 (2014) 2764

Background State-of-the-Art Summary

Experiment	Background (cnts/ ROI-t-y)	Width (1 FWHM)
IGEX	960 (400 with PSD)	4 keV ROI
Heid-Moscow	440 (50 with PSD)	4 keV ROI
CUORE-0	400	6 keV ROI
GERDA	80	4 keV ROI
EXO-200	120	88 keV ROI
KamLAND-Zen	~4(~145 per t(Xe))	Width not explicitly given

Background is per tonne of material – big difference for KamLAND-Zen.
The arithmetic is mine. Errors are my fault.

Need Several Experiments to Fully Deduce Underlying Physics

If $\Gamma^{0\nu}$ is non-zero, ν's are massive Majorana particles, but…

$$\Gamma^{0\nu} = G^{0\nu}\left|M_{0\nu}\eta\right|^2 \quad \text{or} \quad G^{0\nu}\left|M_{0\nu}\right|^2\left\langle m_{\beta\beta}\right\rangle^2$$

- **There are many physics models that lead to Lepton Number Violation (η), |M| can change with the model**
  - **Light neutrino exchange**
  - **Heavy neutrino exchange**
  - **R-parity violating supersymmetry**
  - **RHC**
  - **etc.**

Observation of ββ(0ν) implies massive Majorana neutrinos, but:

- **Relative rates between isotopes might discern light neutrino exchange and heavy particle exchange as the ββ mechanism.**
- **Relative rates between the ground and excited states might discern light neutrino exchange and right handed current mechanisms.**

Effective comparisons require experimental uncertainties to be small wrt theoretical uncertainties. Correlations between |M| calculations are important.

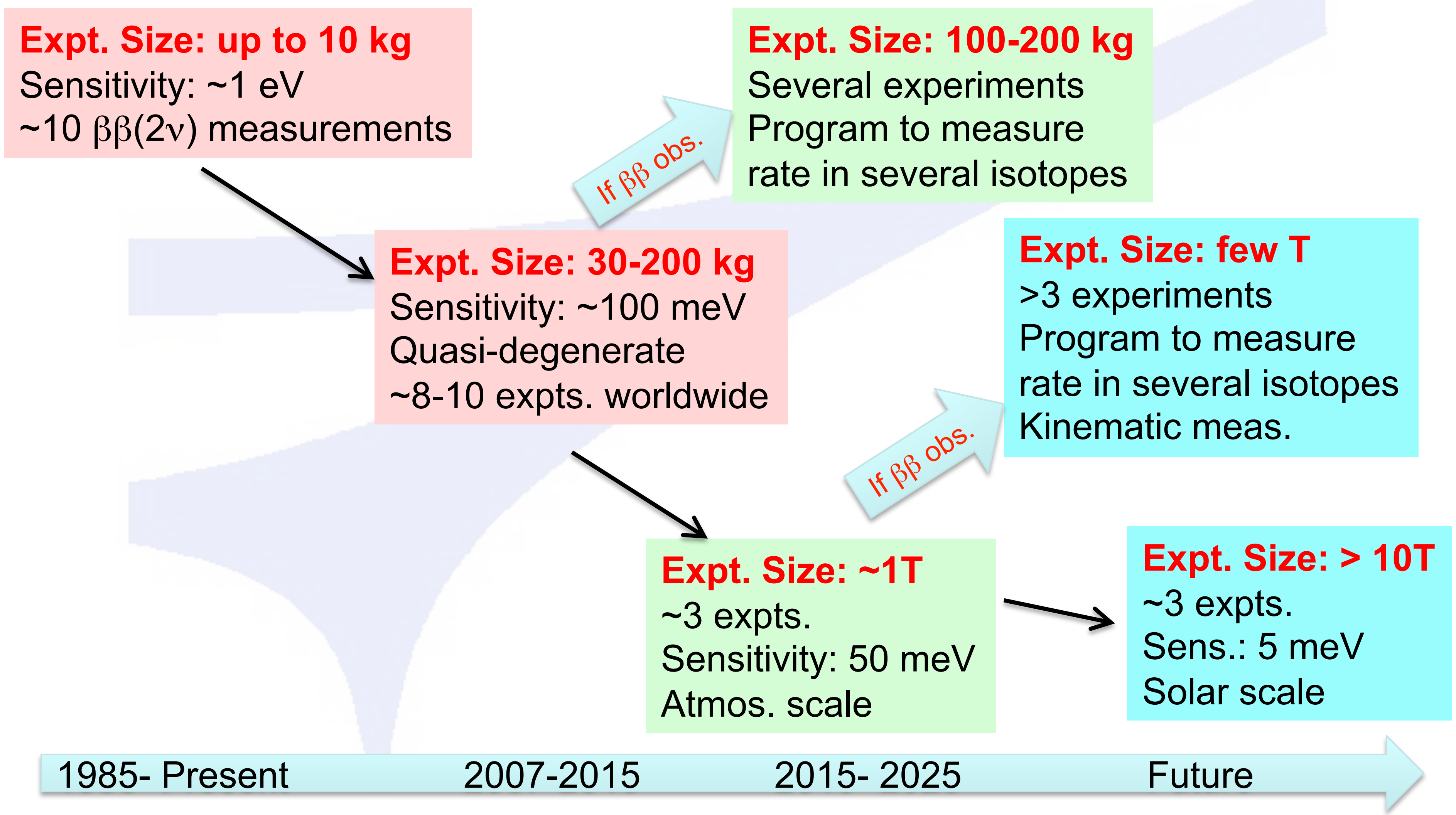
Deppish/Pas Phys. Rev. Lett. 98, 232501 (2007)
Gehman/Elliott J. Phys. G 34, 667 (2007) [Erratum G35, 029701 (2008)
Fogli/Lisi/Rotunno Phys. Rev. D 80, 015024 (2009)

Various Levels of Confidence in a Result

- **Preponderance of the evidence**: a combination of
  - Correct peak energy
  - Single-site energy deposit
  - Proper detector distributions (spatial, temporal)
  - Rate scales with isotope fraction
- **Beyond a reasonable doubt**: include the following
  - Observe the two-electron nature of the event
  - Measure kinematic dist. (energy sharing, opening angle)
  - Observe the daughter
  - Observe the excited state decay
- **Smoking Gun**
  - See the process in several isotopes

Discovery vs. Measurement

a future decision point



Expt. Size: up to 10 kg
Sensitivity: ~1 eV
~10 ββ(2ν) measurements

Expt. Size: 30-200 kg
Sensitivity: ~100 meV
Quasi-degenerate
~8-10 expts. worldwide

If ββ obs.

Expt. Size: 100-200 kg
Several experiments
Program to measure
rate in several isotopes

Expt. Size: ~1T
~3 expts.
Sensitivity: 50 meV
Atmos. scale

If ββ obs.

Expt. Size: few T
>3 experiments
Program to measure
rate in several isotopes
Kinematic meas.

Expt. Size: > 10T
~3 expts.
Sens.: 5 meV
Solar scale

1985- Present
2007-2015
2015- 2025
Future

Solar Scale: Showstoppers?

- Need 100 tons of isotope
  - Enrichment costs and production rates are not sufficient yet
  - Requires R&D to improve capability
- Need excellent energy resolution
  - Better than 1% FWHM
  - An experiment with 10^6 solid state is possible
    - Cost/detector will need to be greatly reduced
    - Large multi-element detector electronics are improving
  - Metal loaded liquid scintillator or Xe techniques
    - Scales more easily and cost effectively
    - Resolution requires R&D
- Need extremely low background
  - Requires improved assay capability, below 0.1 μBq/kg
  - Cables, e.g. x100 lower background, but already approaching edge of sensitivity
  - Usually experiment is only device sensitive enough

Input Needed from Auxiliary Measurements

See nucl-ex/0511009

- **Atomic masses (Cd, Te & radiative EC-EC candidates - better Q values)**
- **Precise $\beta\beta(2\nu)$ data; β^-, β^+ data on intermediate-state isotopes - g_{pp}**
- **Charge exchange reactions on parent & daughter (p,n), (n,p), (^{3}He,t), (d,^{2}He), etc. - charge-changing weak currents**
- **Muon capture - all multipoles populated**
- **Pair correlation studies and nucleon configuration studies using transfer reactions on parent & daughter (p,t), (d,p), (p,d), (α,3He), and (3He, α)**
- **Pion double-charge exchange**
- **Neutrino cross sections**
- **Electromagnetic transitions to isobaric analogue states**

Conclusions

- ββ technology is close to ready for inverted scale sensitivity and we can at least discuss it for the solar scale.
  - To go beyond the inverted scale requires key R&D.
  - Even null results will be interesting.
- Background is still the primary technical issue. If you can't get down below 1 count/ROI-ton-year, you don't have a good motivation for a large scale experiment.
  - GERDA is presently the best at about 40
- Will require about 10 t-y of exposure to cover inverted hierarchy scale, and that's if g_A has an optimistic value.
- The question of g_A needs to be solved and we need continued progress on the matrix elements.
  - The required mass depends significantly on both. Maybe x20.
- Resolution will have a big impact on discovery potential along with background reduction.
- Supporting measurements are important and have an impact.
- If a half-life is measured, we will need several results with a total uncertainty (experiment & theory) of ~50% or less to fully explore the underlying physics.

If we see ββ, the qualitative physics results are profound, but next we'll want to quantify the underlying physics.