Neutrino Mass Measurement Prospects

International Coordination Meeting of Large Neutrino Infrastructures
Paris, June 23-24, 2014

Art McDonald
Queen's University, Kingston, Canada

We know neutrino mass differences but not yet the hierarchy or the absolute mass scale.

For direct Neutrino Mass Measurement, there are two approaches being used:

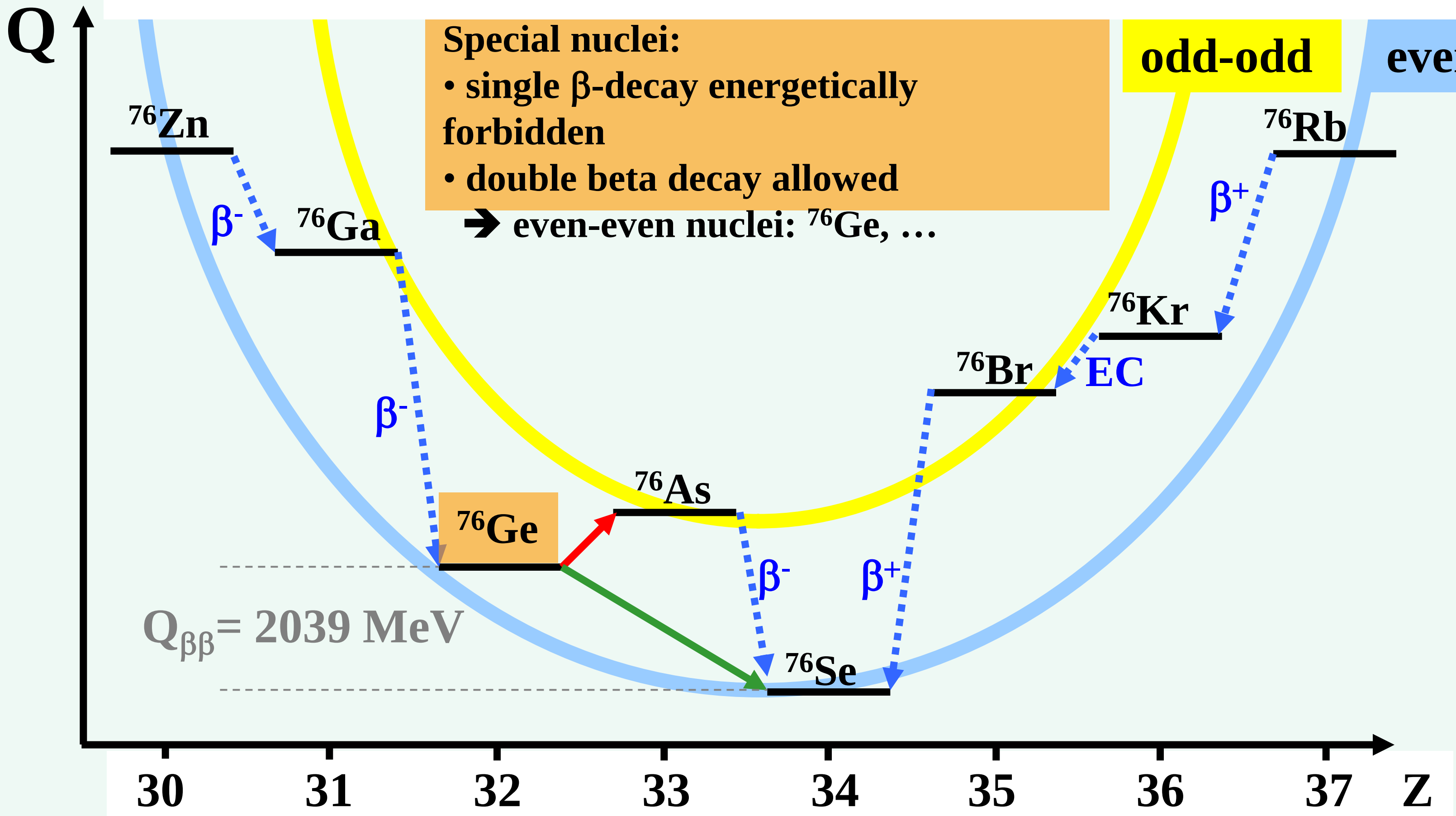
1. **Neutrino-less Double Beta Decay** (in addition to absolute mass information an observation provides substantial additional information including physics beyond the Standard Model)

   - An observation involves:
     - Lepton Flavor Violation
     - Majorana neutrinos (Neutrino = Anti Neutrino)
     - A measure of the absolute mass of neutrinos
     - Majorana CP violating phases.

   The mixing information obtained from oscillations implies that we are within reach of the inverted hierarchy in the next generation experiments.

2. **Distortion of the endpoint of the electron spectrum for beta decay** (a kinematic measurement using physics within the Standard Model)

Double Beta Decay & Mass Parabolas



Double beta decay:

Standard Model: 2 weak decays $X=2e^- + 2\nu_e$ ➔ 2ν beta decay

Beyond the SM: $X=2e^-$ ➔ 0ν (neutrino-less) beta decay

Requires Majorana neutrinos and finite neutrino mass, can involve other physics beyond the SM.

As of today: Oscillation of 3 massive active neutrinos is clearly the dominant effect:

If neutrinos have mass: $|\nu_l\rangle = \sum U_{li} |\nu_i\rangle$

For 3 Active neutrinos.

$$U_{li} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

Pontecorvo-Maki-Nakagawa-Sakata matrix

(Double β decay only)

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & e^{-i\delta} \end{pmatrix} \cdot \begin{pmatrix} c_{13} & 0 & s_{13} \\ 0 & 1 & 0 \\ -s_{13} & 0 & c_{13} \end{pmatrix} \cdot \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot \begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{-i\alpha_2/2} & 0 \\ 0 & 0 & e^{-i\alpha_3/2+i\delta} \end{pmatrix}$$

Atmospheric, Accel. ✓	CP Violating Phase ?	Reactor, Accel. ✓	Solar,Reactor ✓	Majorana CP Phases ?

where $c_{ij} = \cos\theta_{ij}$, and $s_{ij} = \sin\theta_{ij}$

Range defined for Δm_{12}, Δm_{23} ✓

For two neutrino oscillation in a vacuum: (a valid approximation in many cases)

$$P(\nu_\mu \rightarrow \nu_e) = \sin^2 2\theta \sin^2 (1.27 \frac{\Delta m^2 L}{E})$$

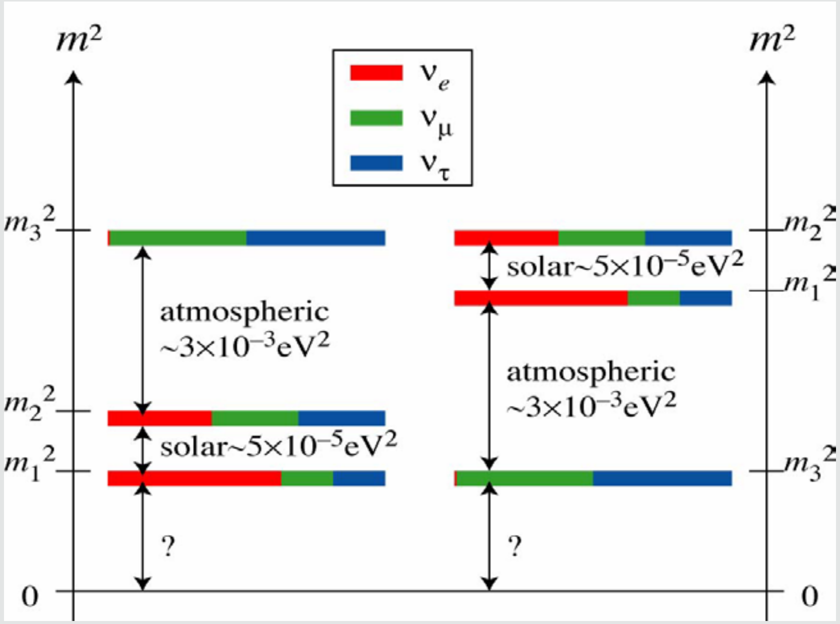
CP Violating Phases: implication for Antimatter/Matter asymmetry via Leptogenesis?

SUMMARY OF RESULTS FOR THREE ACTIVE ν TYPES

Δm~0.05 eV

Parameter	best-fit ($\pm 1\sigma$)
$\Delta m^2_\odot$ [10^{-5} eV ^{2}]	$7.58^{+0.22}_{-0.26}$
$\lvert\Delta m^2_A\rvert$ [10^{-3} eV ^{2}]	$2.35^{+0.12}_{-0.09}$
$\sin^2\theta_{12}$	$0.306\ (0.312)^{+0.018}_{-0.015}$
$\sin^2\theta_{23}$	$0.42^{+0.08}_{-0.03}$
$\sin^2\theta_{13}$ [140]	$0.021\ (0.025)^{+0.007}_{-0.008}$
$\sin^2\theta_{13}$ [142]	0.0251 ± 0.0034

Mass Hierarchies



Normal Inverted

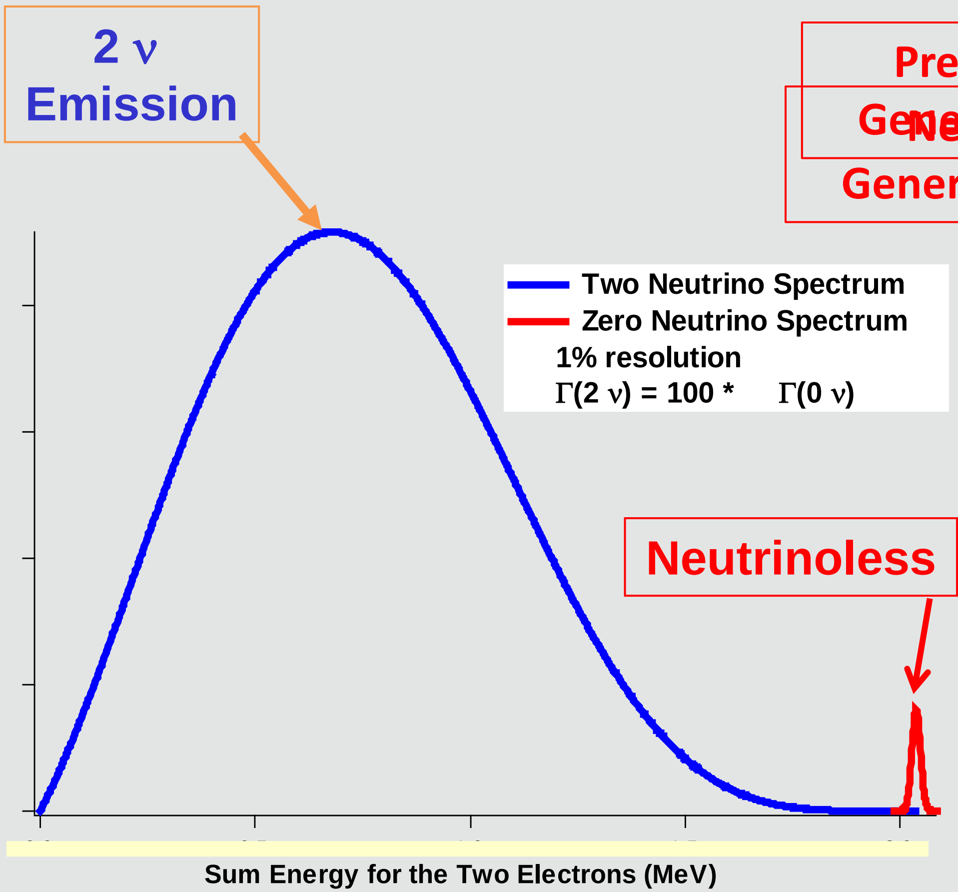
No strong theoretical motivation for choosing between these hierarchies

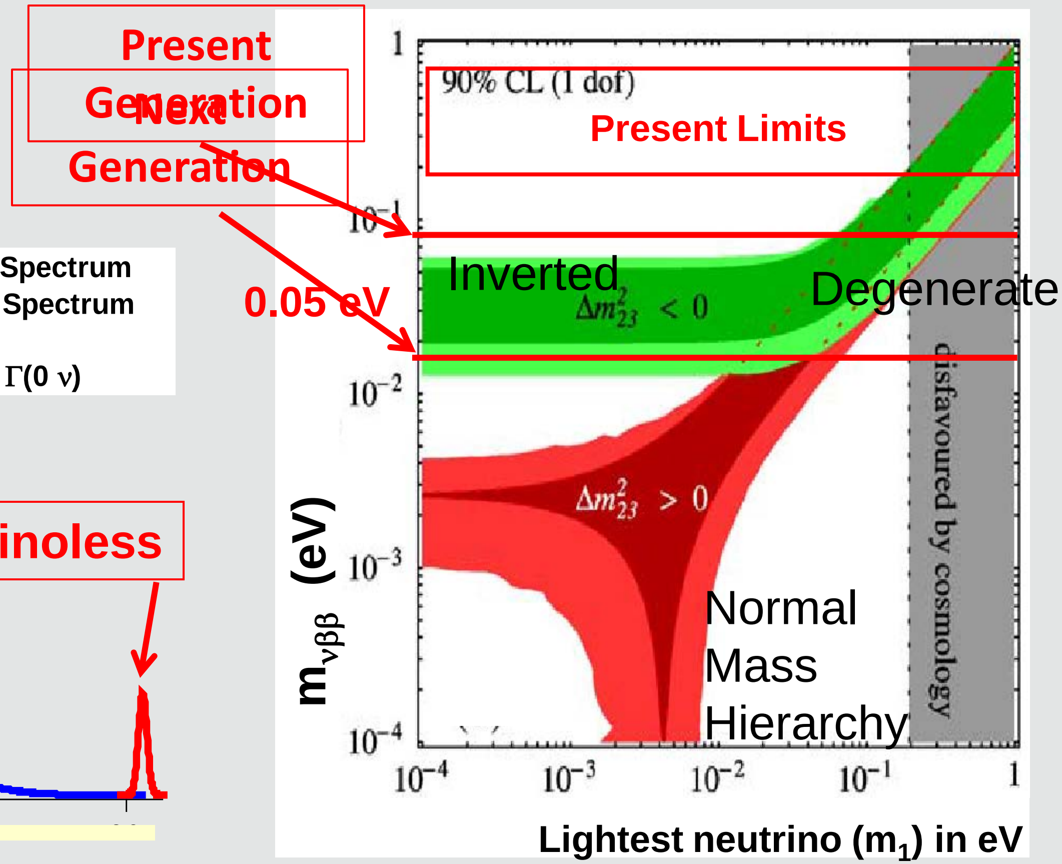
ν-less Double Beta Decay: Measuring Effective ν Mass

$$T_{1/2} = F(Q_{\beta\beta},Z)\ |M^{0\nu}|^2\ \langle m_{\nu\beta\beta}\rangle^2$$

Majorana phases

$$m_{\nu\beta\beta} = |m_1 \cos^2\theta_{13}\cos^2\theta_{12} + m_2\ e^{2i\alpha} \cos^2\theta_{13}\sin^2\theta_{12} + m_3\ e^{2i\beta} \sin^2\theta_{13}|$$



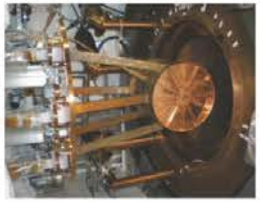


Requires: Neutrino wave function = Anti-neutrino w.f. (Majorana particles)

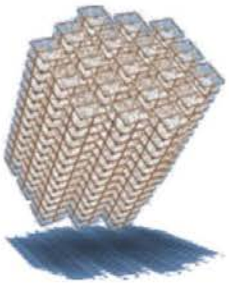
- **Finite ν mass: Lifetimes > ~10^{26} years imply ν mass < 0.1 eV**

0νββ decay Experiments - Efforts Underway

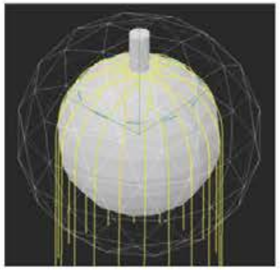
EXO200



CUORE



SNO+

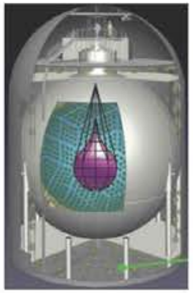


Collaboration	Isotope	Technique	mass (0νββ isotope)	Status
CANDLES	Ca-48	305 kg CaF_2 crystals - liq. scint	0.3 kg	Construction
CARVEL	Ca-48	$^{48}CaWO_4$ crystal scint.	16 kg	R&D
GERDA I	Ge-76	Ge diodes in LAr	15 kg	Operating
GERDA II	Ge-76	Point contact Ge in LAr or LN	30-35 kg	Construction
MAJORANA DEMONSTRATOR	Ge-76	Point contact Ge	26 kg	Construction
1TGe (GERDA & MAJORANA)	Ge-76	Best technology from GERDA and MAJORANA	~ tonne	R&D
NEMO3	Mo-100 Se-82	Foils with tracking	6.9 kg 0.9 kg	Complete
SuperNEMO Demonstrator	Se-82	Foils with tracking	7 kg	R&D
MOON	Mo-100	Mo sheets	200 kg	R&D
CAMEO	Cd-116	$CdWO_4$ crystals	21 kg	R&D
COBRA	Cd-116, Te-130	CdZnTe detectors	10 kg	R&D
CUORICINO	Te-130	TeO_2 Bolometer	11 kg	Complete
CUORE-0	Te-130	TeO_2 Bolometer	11 kg	Operating
CUORE	Te-130	TeO_2 Bolometer	206 kg	Construction
SNO+	Te-130	0.3% ^{nat}Te in liquid scint.	800 kg	Construction
KamLAND-ZEN	Xe-136	2.7% in liquid scint.	370 kg	Operating
NEXT-100	Xe-136	High pressure Xe TPC	80 kg	R&D
EXO-200	Xe-136	Xe liquid TPC	160 kg	Operating
nEXO	Xe-136	Xe liquid TPC	5 tonnes	R&D
DCBA	Nd-150	Nd foils & tracking chambers	32 kg	R&D

GERDA

MAJORANA

KamLAND ZEN

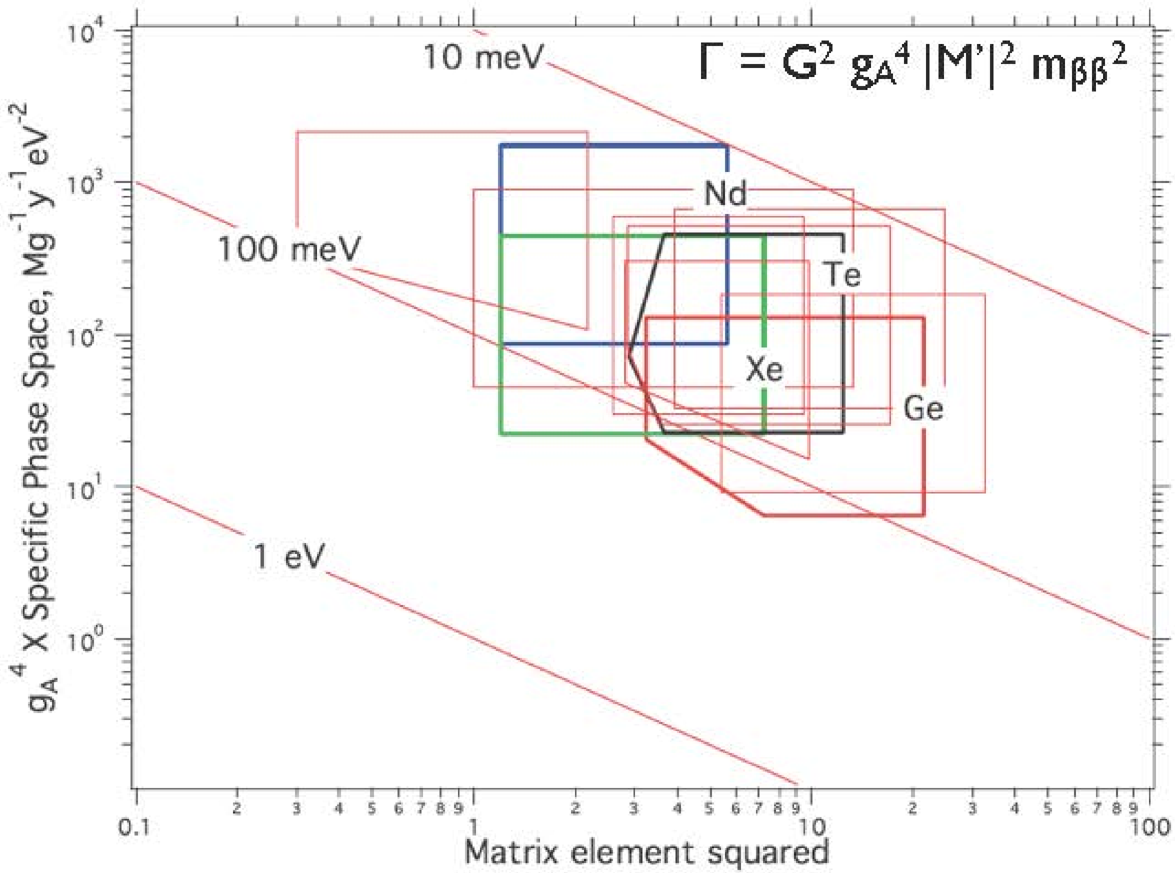


Next Generation: >~$100 M

Complete | Construction | Operating

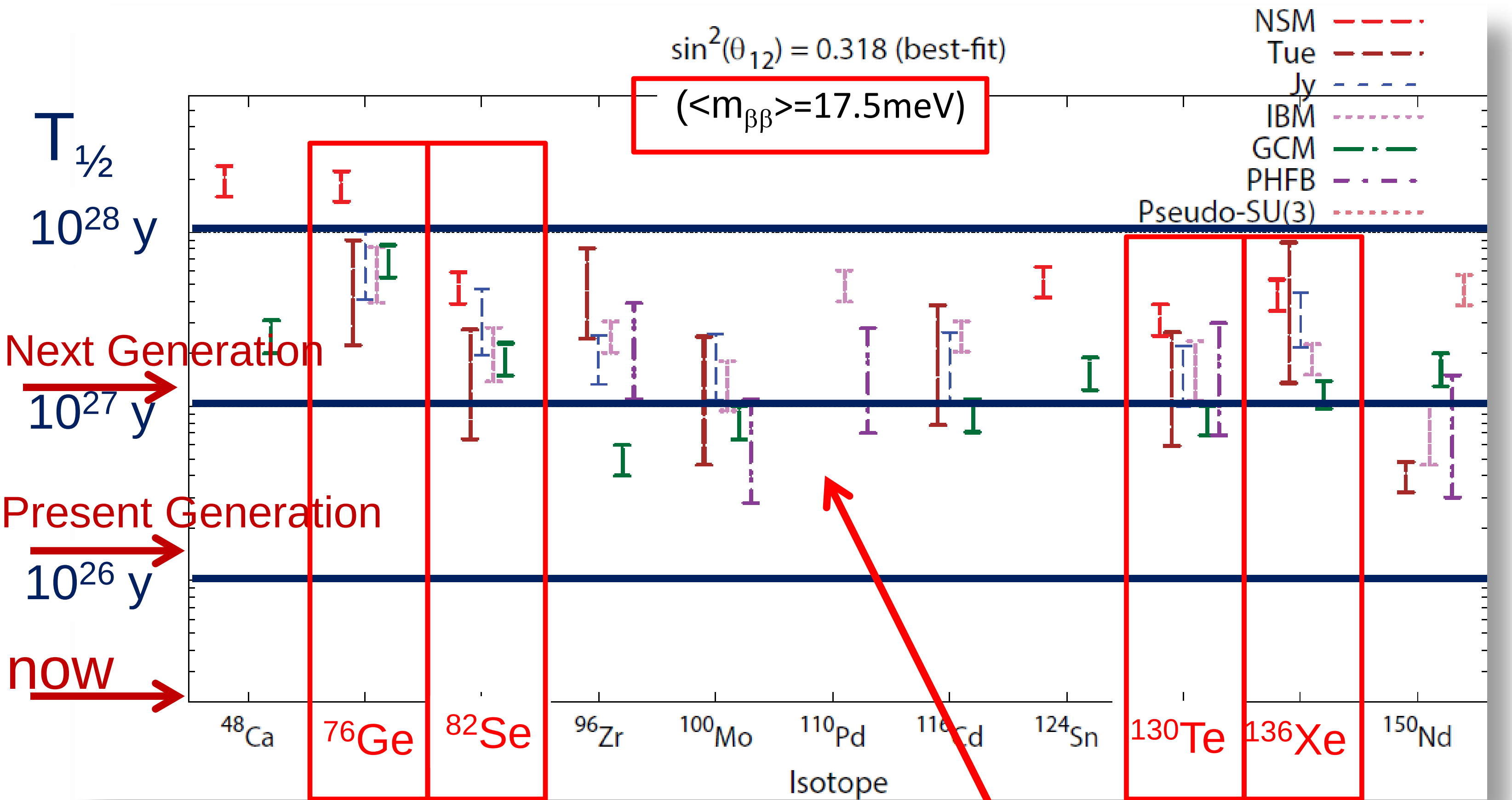
From J. Wilkerson

Isotopes have similar sensitivity per unit mass.
Variations in our knowledge of Nuclear Matrix Elements and effective phase space are shown below.



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

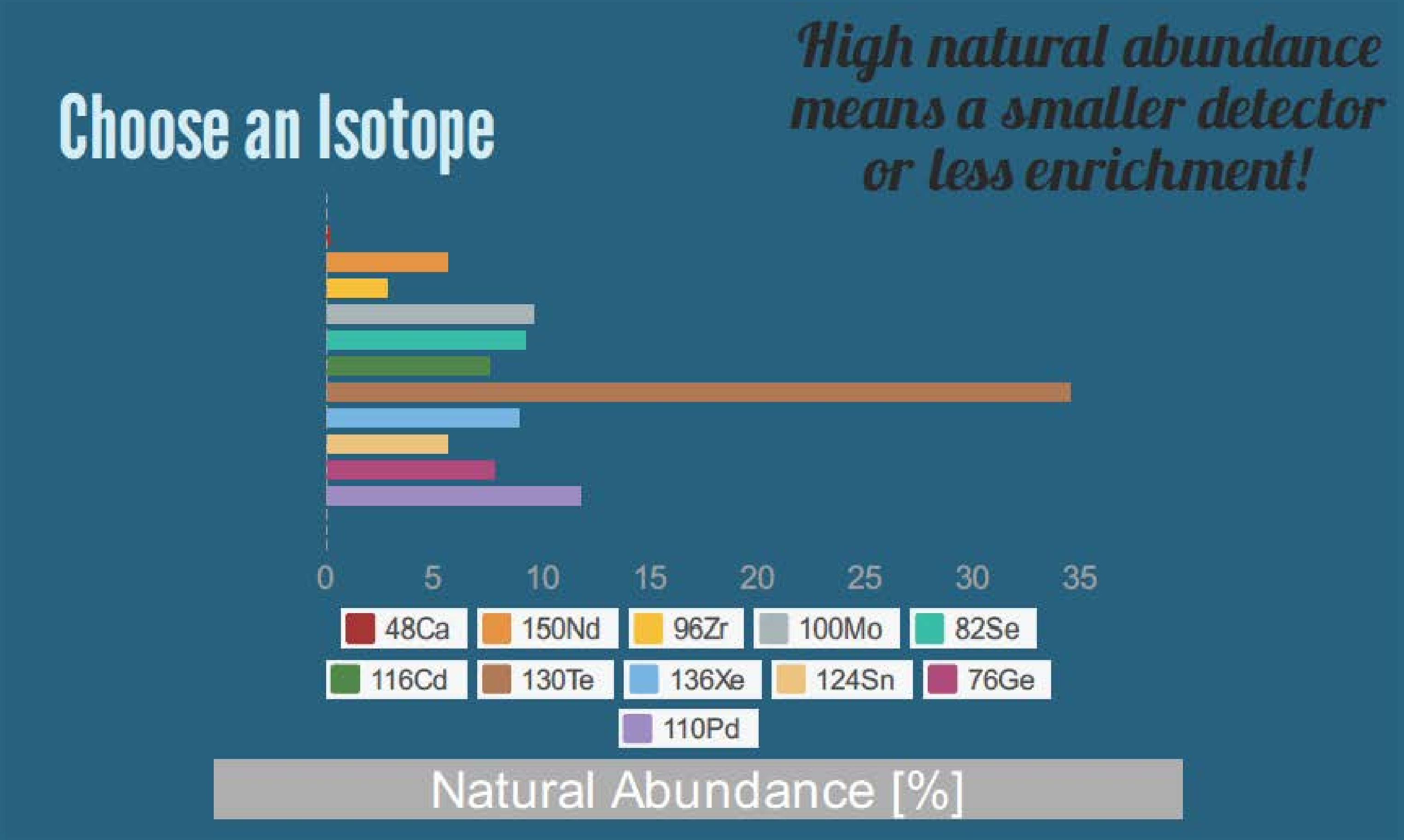
Inverted Hierarchy Coverage



$$\left(T_{1/2}^{0\nu}\right)^{-1} = G^{0\nu} \cdot |M^{0\nu}|^2 \cdot \langle m_{\beta\beta}\rangle^2$$

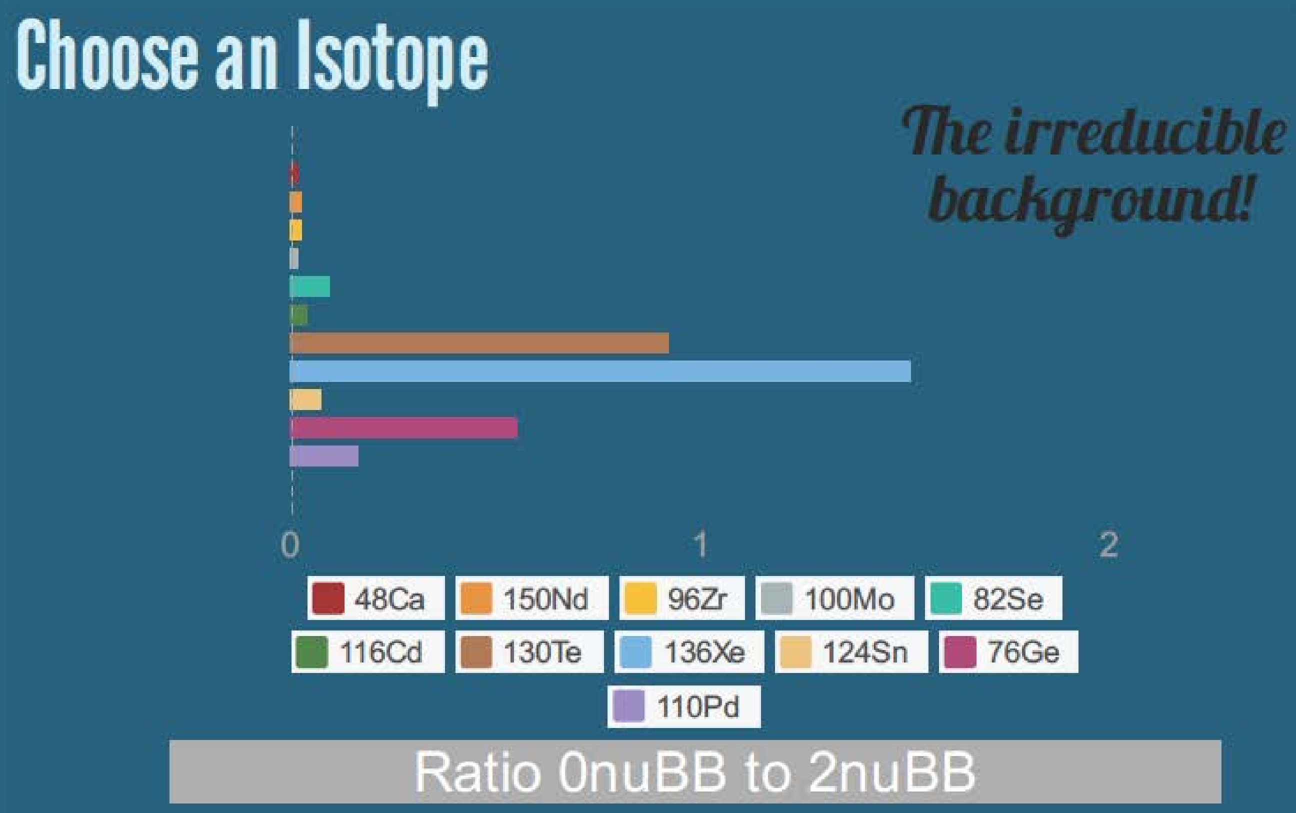
Figure source: A. Dueck, W. Rodejohann, and K. Zuber, Phys. Rev. D83 (2011) 113010.

- **Further work on nuclear theory will be very valuable**



Most isotopes are below 10% abundance, so availability and cost of isotope enrichment is an important question for the future.

PHYSICAL REVIEW D 87, 071301(R) (2013)



Detector Resolution is another major factor affecting sensitivity, as is the amount of other background contained in the region of interest.

PHYSICAL REVIEW D 87, 071301(R) (2013)

Signals and Background for neutrino-less double beta decay

Half life (years)	~Signal (cnts/tonne-year)
10^{25}	500
5×10^{26}	10
5×10^{27}	1
$>10^{29}$	<0.05

From J. Wilkerson

$$\left[T_{1/2}^{0\nu}\right]^{-1} \propto \varepsilon ff \cdot I_{abundance} \cdot Source\ Mass \cdot Time$$

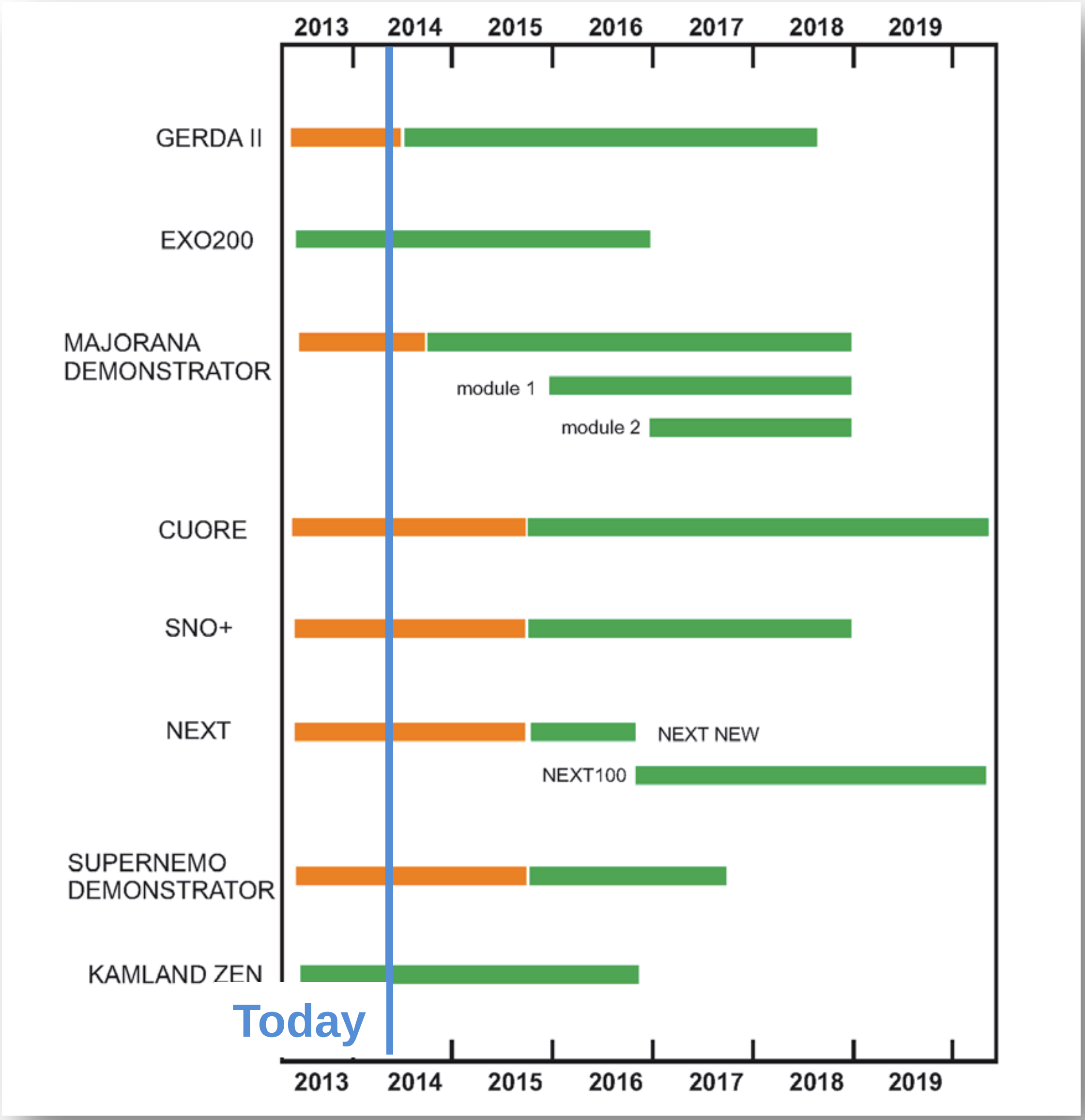
Background free

$$\left[T_{1/2}^{0\nu}\right]^{-1} \propto \varepsilon ff \cdot I_{abundance} \cdot \sqrt{\frac{Source\ Mass \cdot Time}{Bkg \cdot \Delta E}}$$

Background limited

Limiting cosmic ray background is important. Depth is the most effective way to do this, but local shielding can compensate somewhat at shallower depths.

Notional Timeline



Construction

Operation

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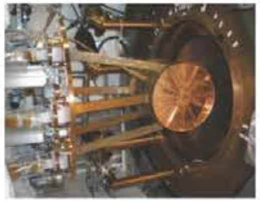
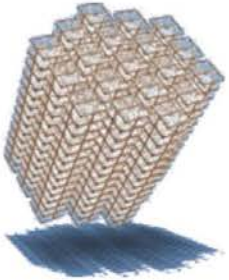


CUORE



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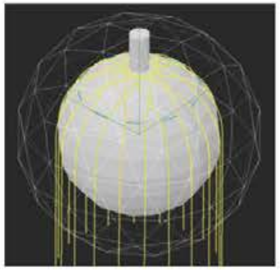

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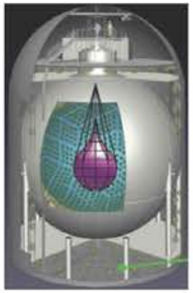


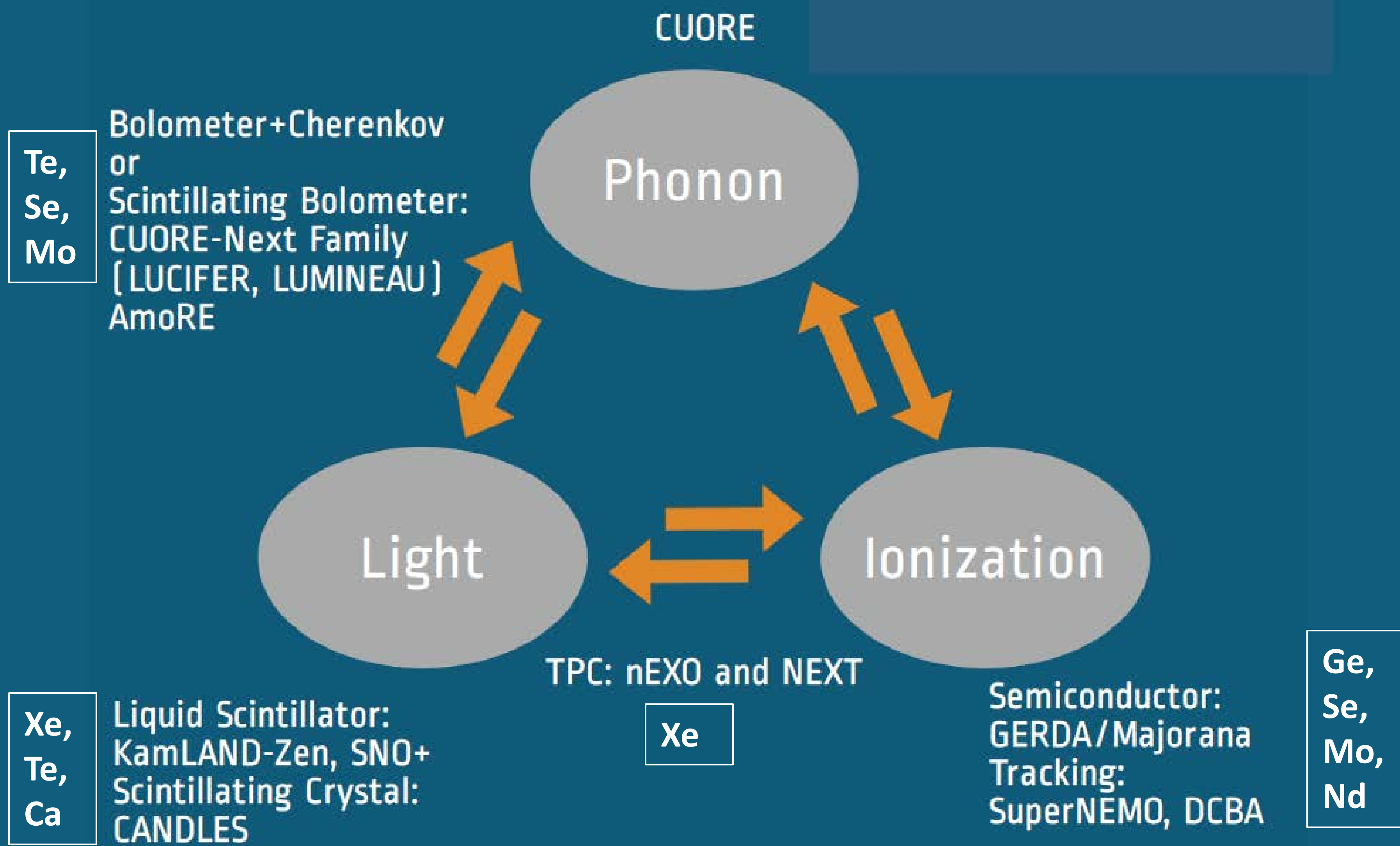
From J. Wilkerson

Report to the Nuclear Science Advisory Committee

http://science.energy.gov/~/media/np/nsac/pdf/docs/2014/NLDBD_Report_2014_Final.pdf

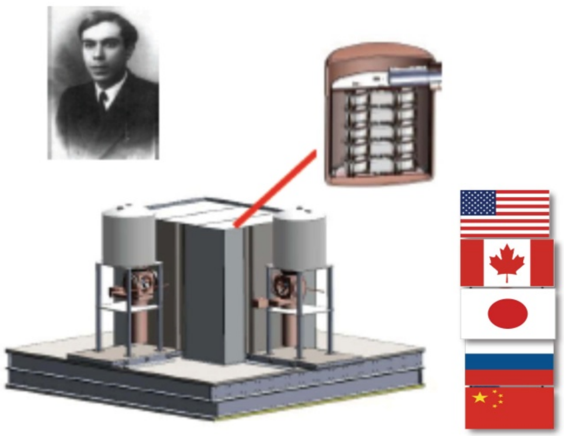
Each of the current approaches has technical advantages and each has significant remaining challenges to demonstrate sensitivity at a level suitable for covering the inverted neutrino mass hierarchy region. Based on the information provided to us, we judge that in a period of 2-3 years there will be much more information available from the results of these experiments. At that point one could assess the future prospects with much higher reliability than today.

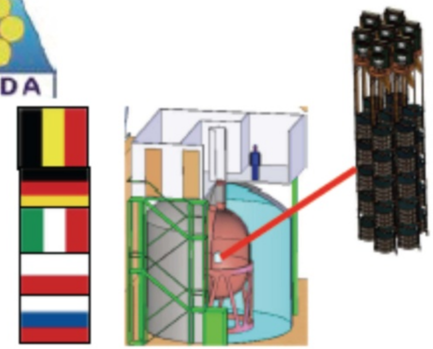
Next Generation Experiments



L. Winslow

MAJORANA DEMONSTRATOR and GERDA





- ^{76}Ge modules in electroformed Cu cryostat, Cu / Pb passive shield
- 4π plastic scintillator μ veto
- DEMONSTRATOR: 30 kg ^{76}Ge and 10 kg ^{nat}Ge PPC detectors

- ^{76}Ge array submersed in LAr
- Water Cherenkov μ veto
- Phase I: 18 kg (H-M/IGEX xtals)
- Phase II: +20 kg PPC detectors

Joint Cooperative Agreement:

Open exchange of knowledge & technologies (e.g. MaGe, R&D)

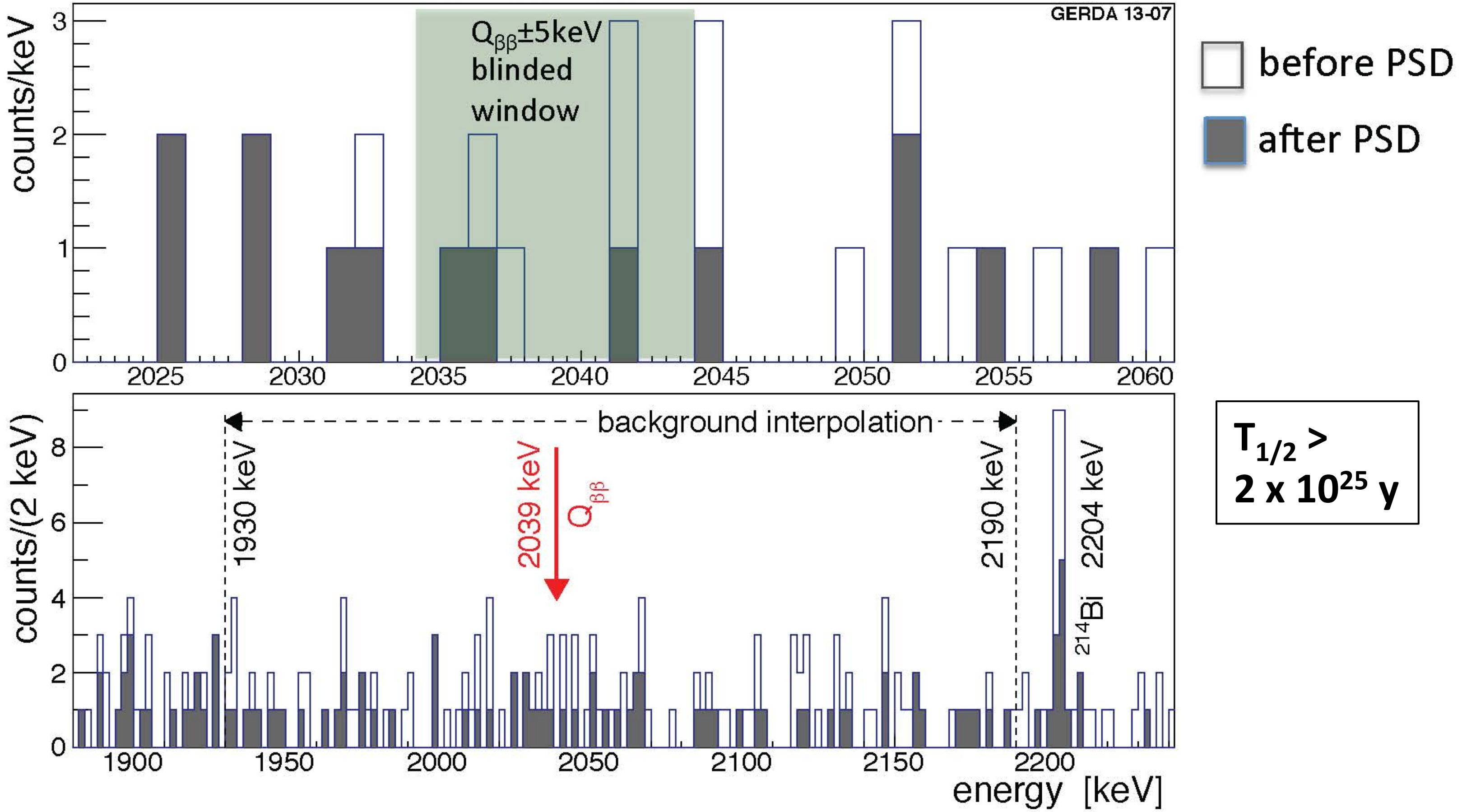
Intention to merge for larger scale experiment

Select best techniques developed and tested in GERDA and MAJORANA

Unblinding: full data set (21.6 kg yr)

PRL 111 (2013) 122503

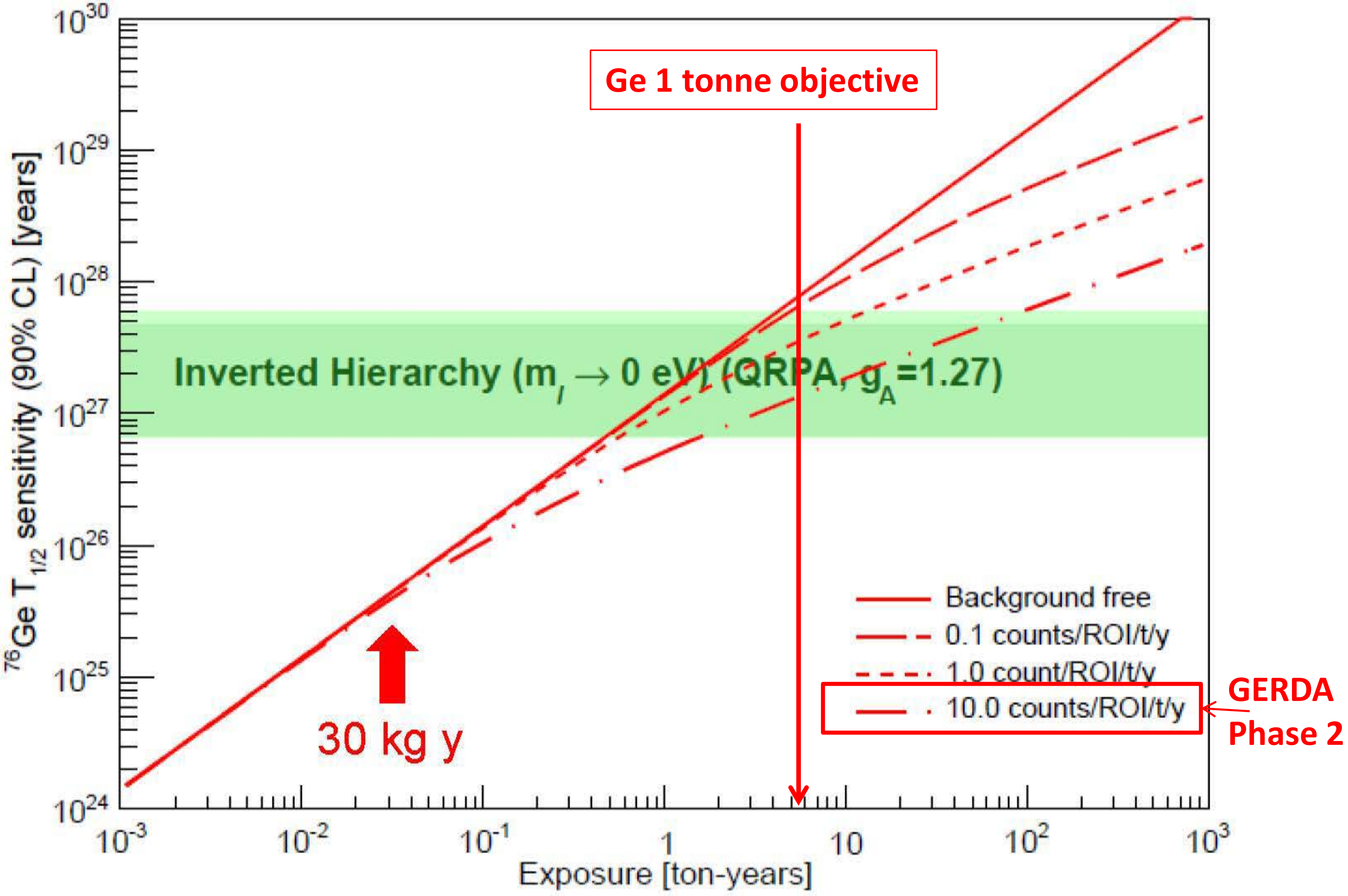
gold-coax: 17.9 kg yr; silver-coax: 1.3 kg yr; bege: 2.4 kg yr



$T_{1/2}$ > 2×10^{25} y

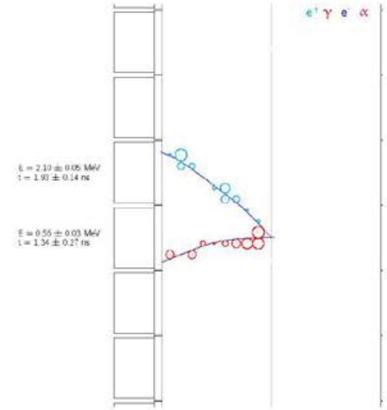
Full data set:	7 events obs. in blinded window	vs. 5.1 expected for bgd only
	3 events survive PSD cut	vs. 2.5 expected for bgd only

Ge Sensitivity

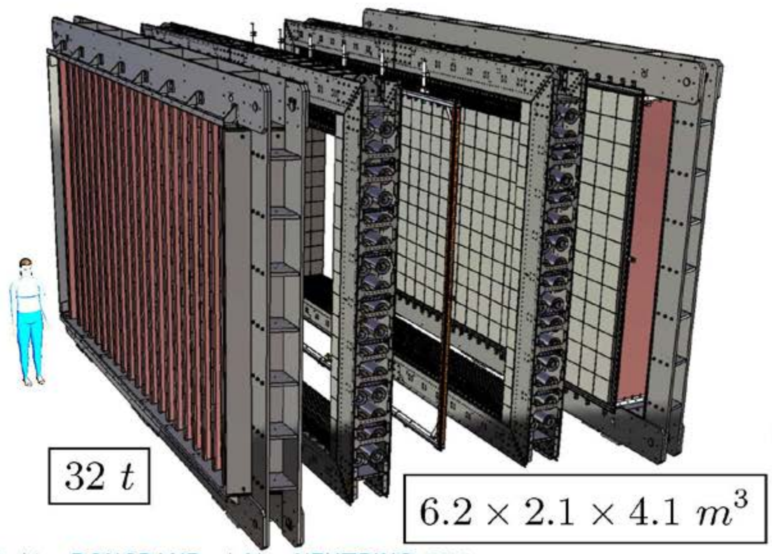


SuperNEMO Demonstrator Goals

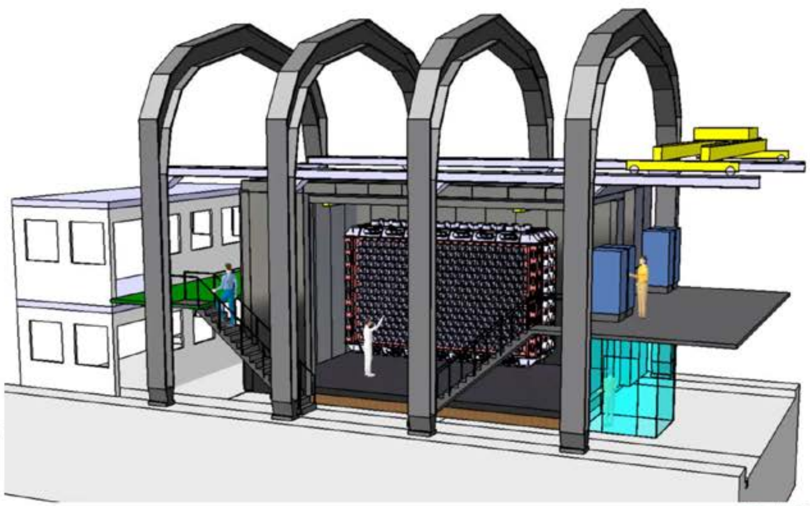
- SuperNEMO demonstrator module construction started in 2012
  - NEMO-3 sensitivity in only 5 months (90 % CL):
    $\mathcal{T}^{0\nu}_{1/2} > 1.1 \times 10^{24}$ y $\rightarrow \langle m_\nu \rangle < 0.33 - 0.87$ eV
  - No background in the $0\nu2\beta$ region in 2.5 years for 7 kg of ^{82}Se
  - Sensitivity after 17.5 kg·y exposure (90 % CL):
    $\mathcal{T}^{0\nu}_{1/2} > 6.5 \times 10^{24}$ y $\rightarrow \langle m_\nu \rangle < 0.20 - 0.40$ eV



- Commissioning and physics data taking expected in Summer 2015



Replacing NEMO-3 in the actual LSM



Tracking reduces background and will enable tests of underlying physics mechanisms once detection takes place.

CUORE @ LNGS

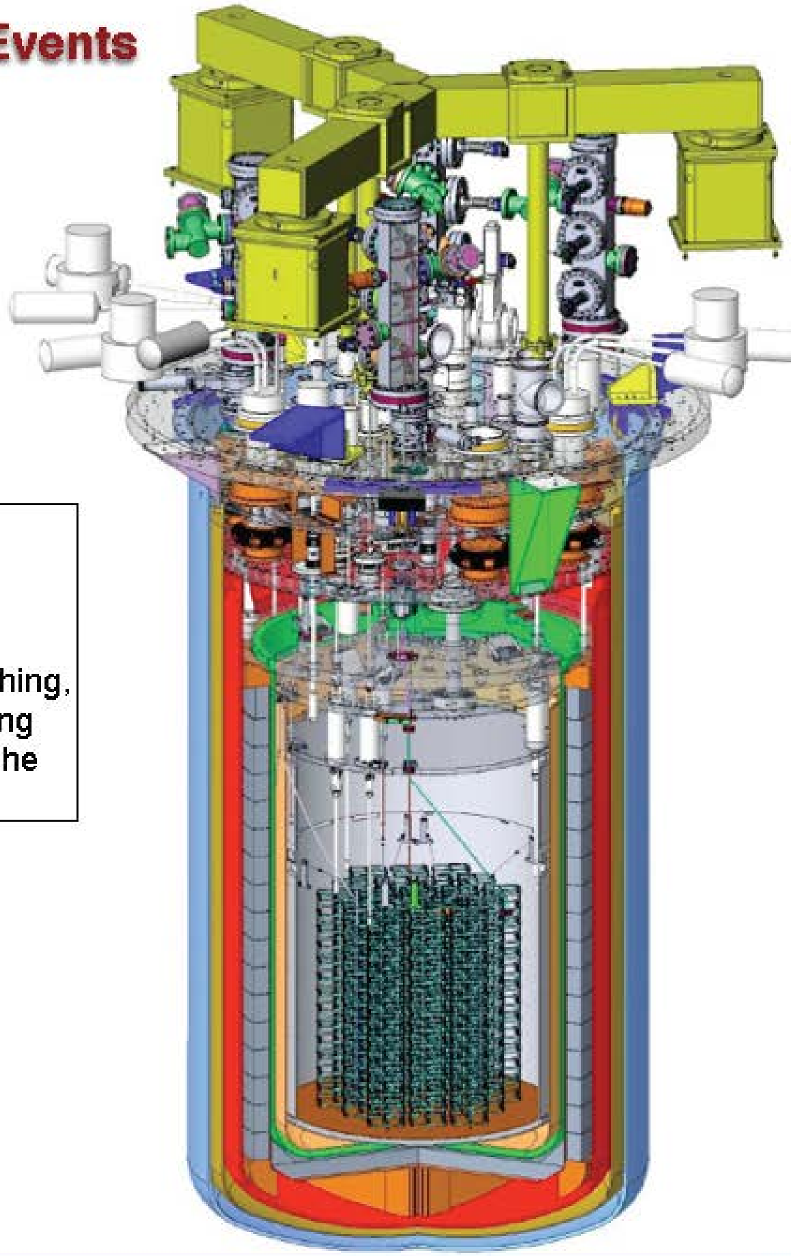
Cryogenic Underground Observatory for Rare Events

CUORE detector

- 988 TeO_2 crystals run as a bolometer array
  - 5x5x5 cm^3 crystal, 750 g each
- 19 Towers; 13 floors; 4 modules per floor
  - 741 kg total - 206 kg ^{130}Te
  - 10^{27} ^{130}Te nuclei
- Excellent energy resolution of bolometers
- Radio-pure material and clean assembly to achieve low background at ROI
  - strict radiopurity control protocol to limit bulk and surface contaminations in crystal production
  - transportation at sea level to LNGS
  - bolometric test to check performances and radio-purity
  - TECM protocol (Tumbling, Electropolishing, Chemical etching, and Magnetron plasma etching) for copper surface cleaning
  - limited exposure to cosmic rays: underground storage of the copper parts in between production and cleaning

Complex cryogenic set-up

- Fully cryogen-free system:
  - custom cryostat
  - 5 pulse tubes
  - a powerful dilution refrigerator and
- ~10 mK operating temperature
- Independent suspension of the detector array
- An embedded detector calibration system
- Radio-pure materials
- Heavy low temperature shield



Beyond CUORE

Primary goal: complete the effort to make CUORE fully operative

Start in 2016: CUORE Objective: $T_{1/2} > 10^{26}$ years

However many new ideas have already been proposed/developed to improve CUORE sensitivity.

R&D's programs recently gathered under a common aegis for a future CUORE upgrade

- common program to gather/share all possible informations
- aim at exploring the IH region with ton-size bolometric detector

CUORE operation is an indispensable step

- to demonstrate viability of a well performing ton-size detector in stable conditions
- to guarantee the needed infrastructure and experience
- to provide unique (high statistics) informations on background at 10^{-2} c/(keV kg y) scale

but it's important to profit of the large amount of new developments to prepare a future project

All existing R&D's are focused on background reduction

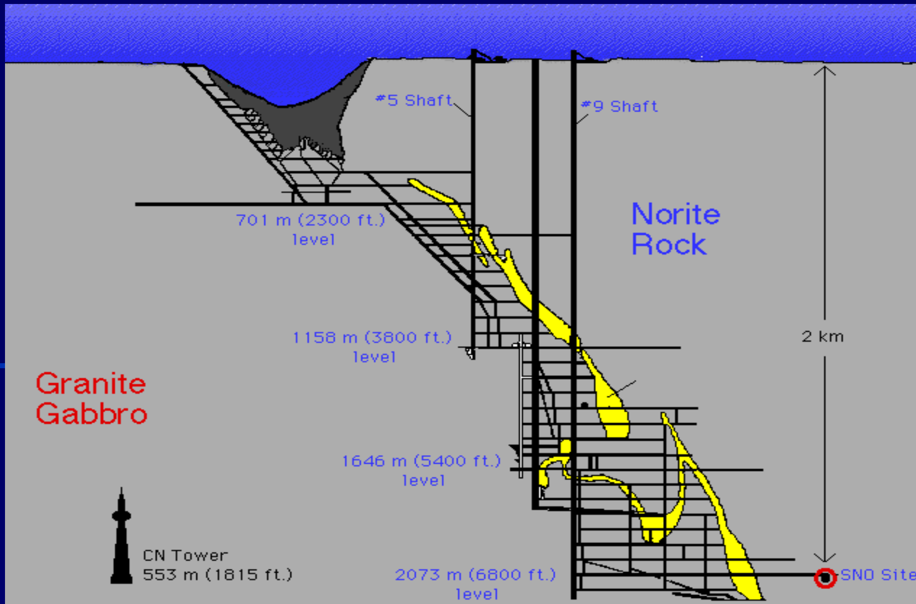
According to Cuoricino (and CUORE-0) background model α surface contributions are the most dangerous source:

- discriminate surface α/β interactions
- discriminate surface/bulk events

CUORE ~ 100 counts/ROI/Tonne/year

Relevant results already obtained at the single detector level (e.g. LUCIFER, LUMINEU, Cherenkov detection, etc.)

Future Prospects using Light from ZnSe, $ZnMoO_4$ to discriminate against surface alphas



~~1000 tonnes D_2O~~ → **780 tonnes liquid scintillator**

12 m diameter Acrylic Vessel

18 m diameter support structure; 9500 PMTs (~54% photocathode coverage)

1700 tonnes inner shielding H_2O

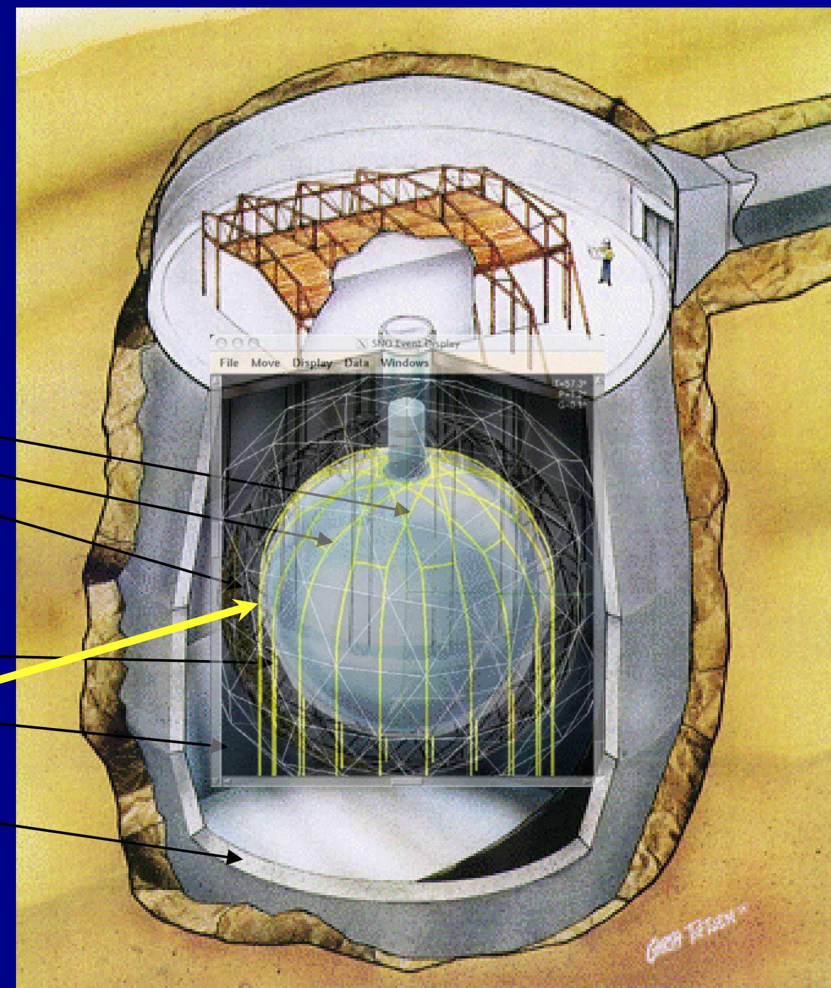
5700 tonnes outer shielding H_2O

Urylon liner radon seal

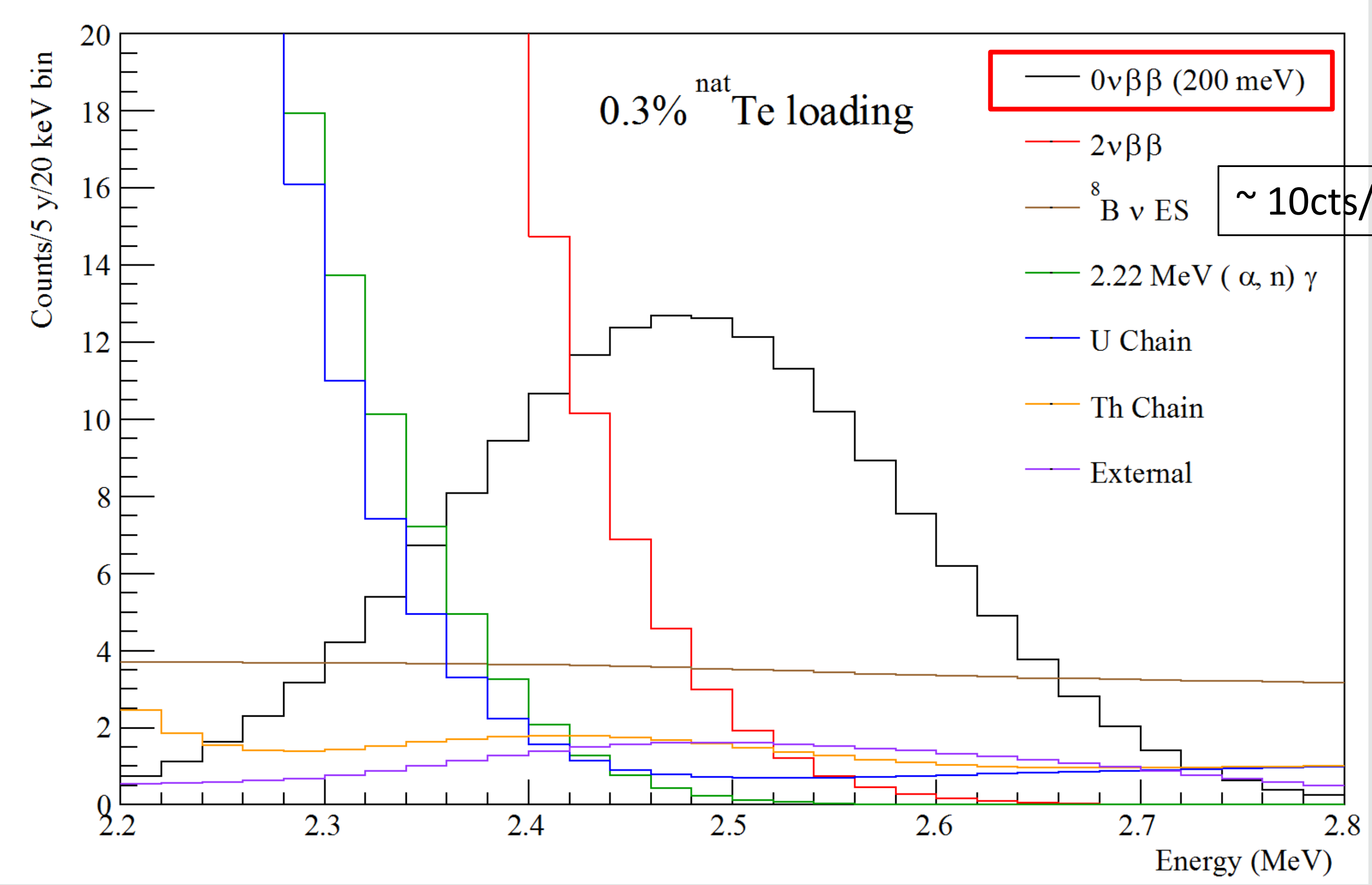
hold-down rope net

depth: 2092 m (~6010 m.w.e.) ~70 muons/day

Start in 2015



SNO+ Double Beta Decay (5-yr Data Simulated)

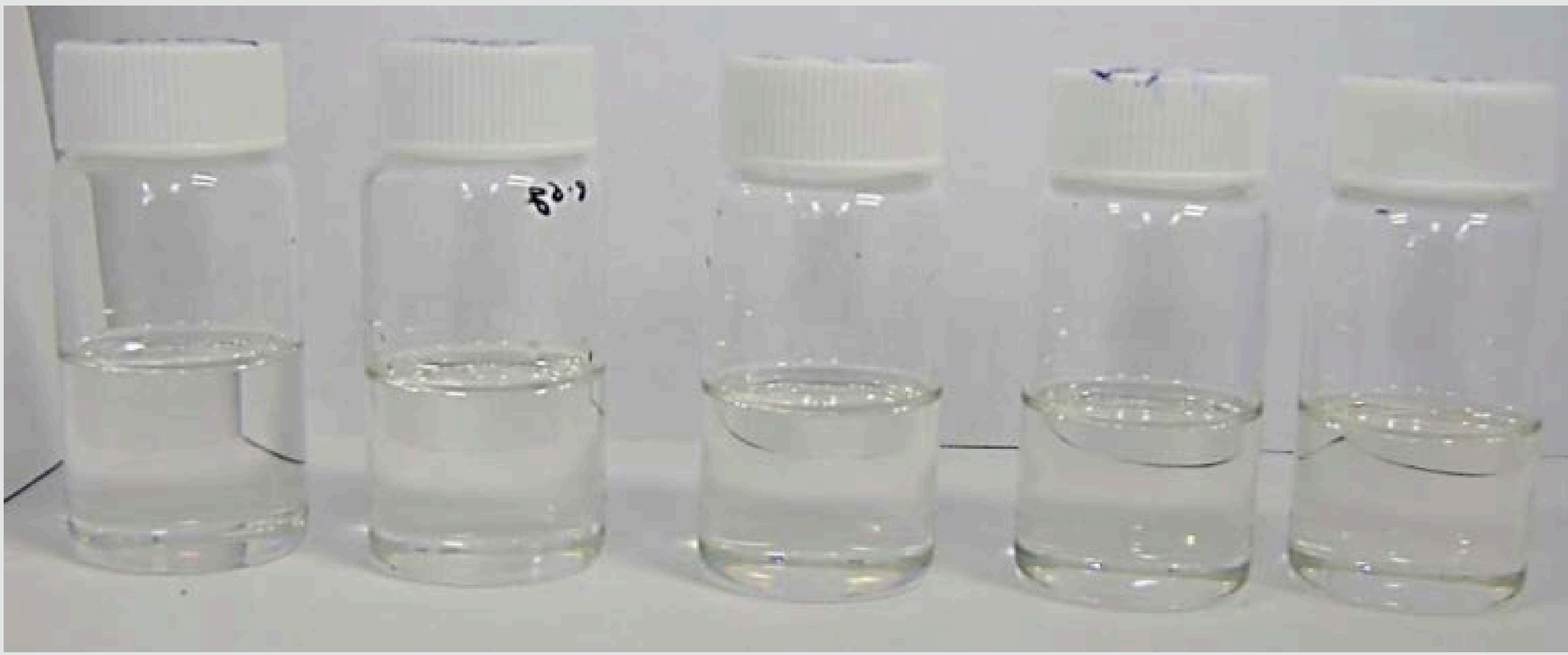


~ 10cts/ROI/T/Yr

For the Future

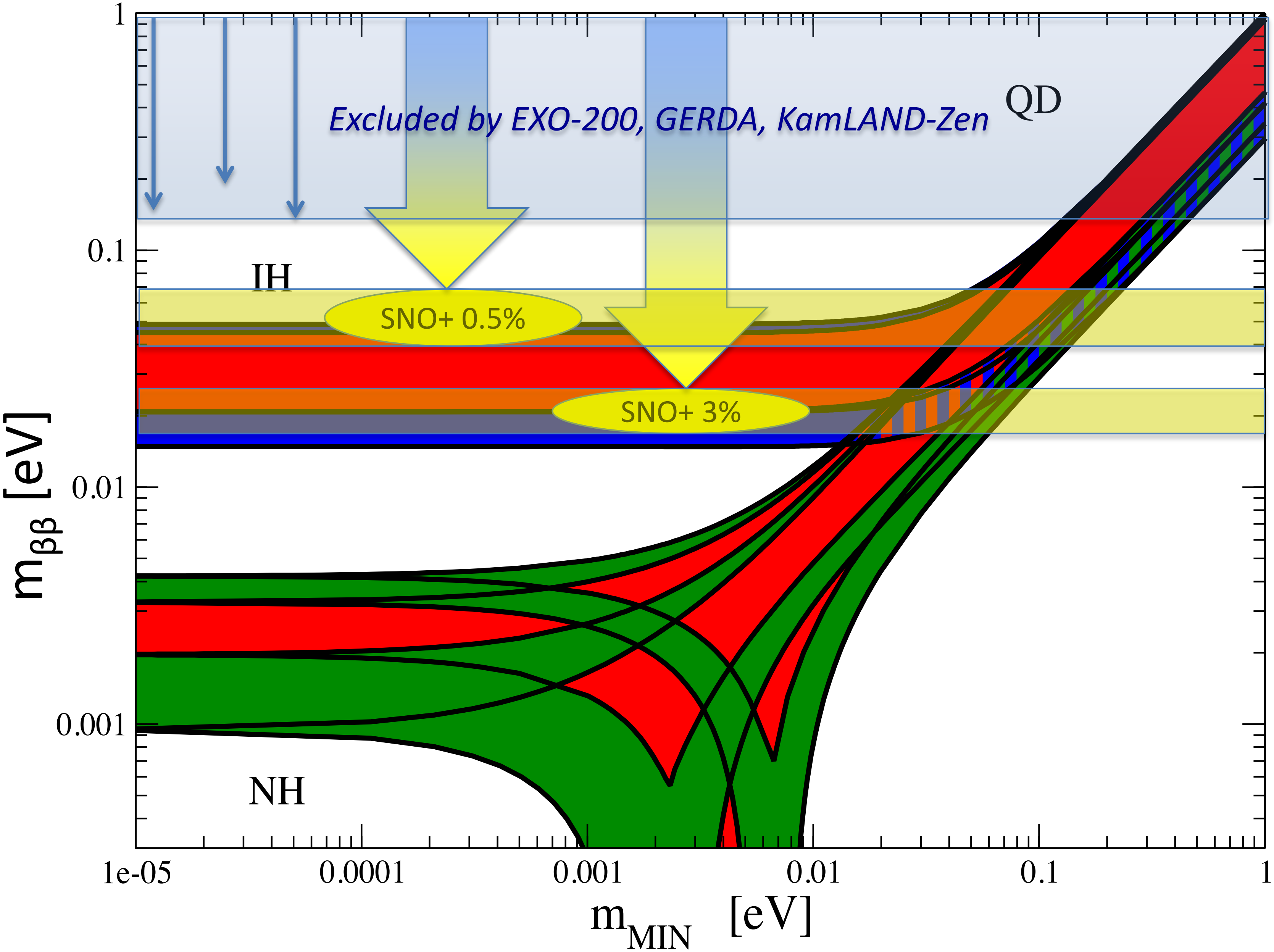
Percent Loading of Tellurium

- 0.3%, 0.5%, 1%, 3%, 5% (from left to right)



800 kg ^{130}Te in SNO+

8000 kg ^{130}Te in SNO+

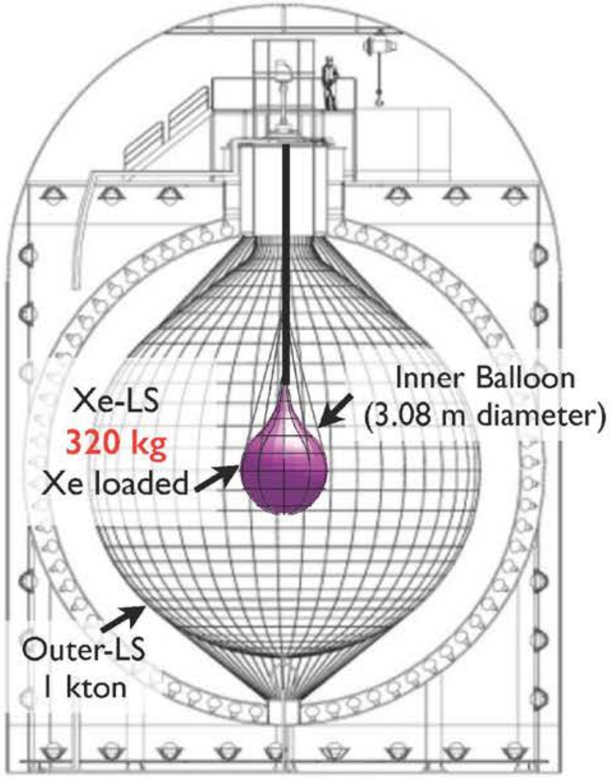


Excluded by EXO-200, GERDA, KamLAND-Zen
QD
IH
SNO+ 0.5%
SNO+ 3%
NH
1
0.1
0.01
0.001
1e-05
0.0001
0.001
0.01
0.1
1
$m_{\beta\beta}$ [eV]
m_{MIN} [eV]

KamLAND-Zen

Kamioka Liquid Scintillator Anti-Neutrino Detector
Zero Neutrino Double Beta

KamLAND-Zen Phase I



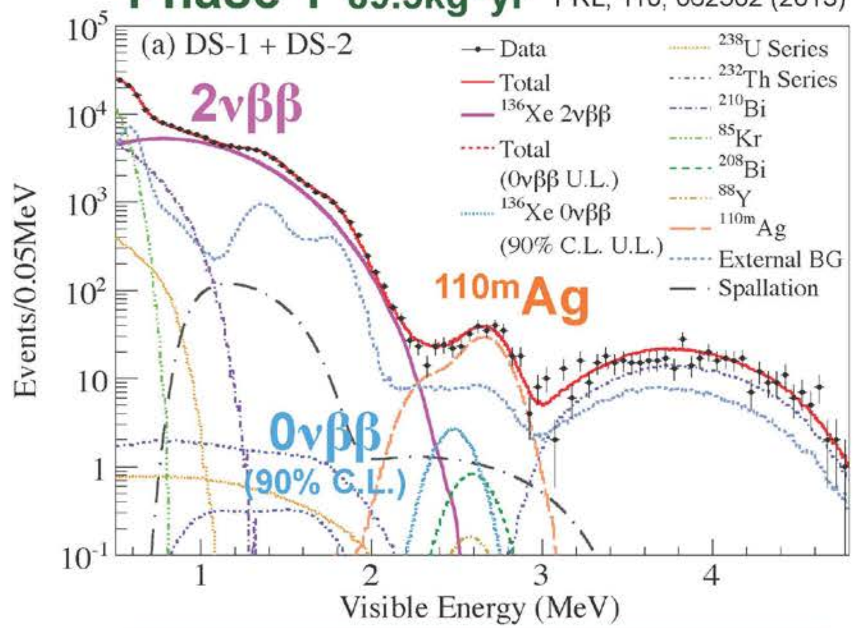
Advantage of KamLAND

- running detector : start quickly with relatively low cost
- big and pure : no BG from external gamma-rays
- purification of LS, replacement of mini-balloon are possible

⟶ **high scalability** (a few ton of Xe)

realize double beta-decay search with **low background**

Phase 1 89.5kg·yr PRL, 110, 062502 (2013)



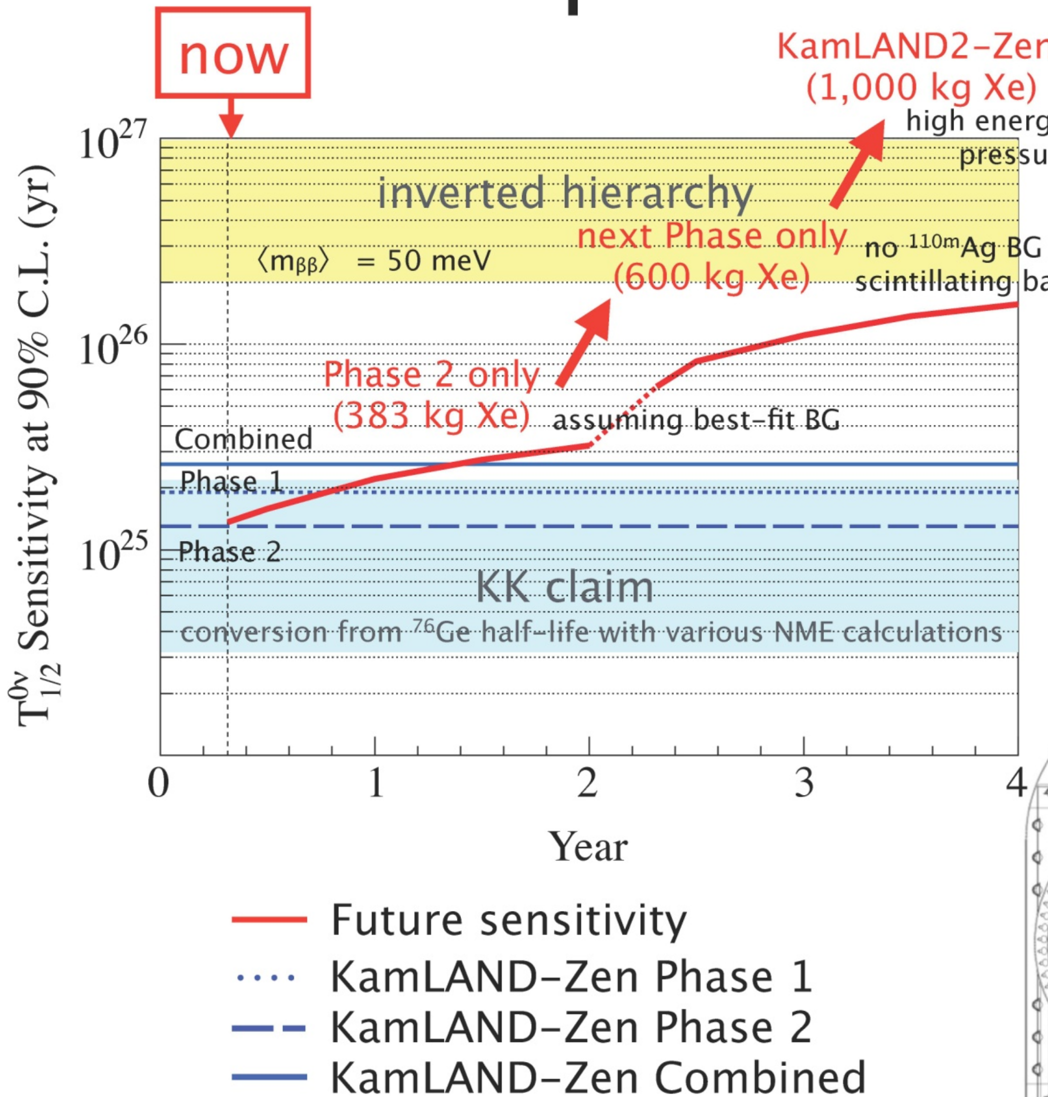
Xenon loaded LS (Xe-LS)	
decane	82%
pseudo-cumene	18%
PPO	2.7 g/liter
xenon	2.44 wt%

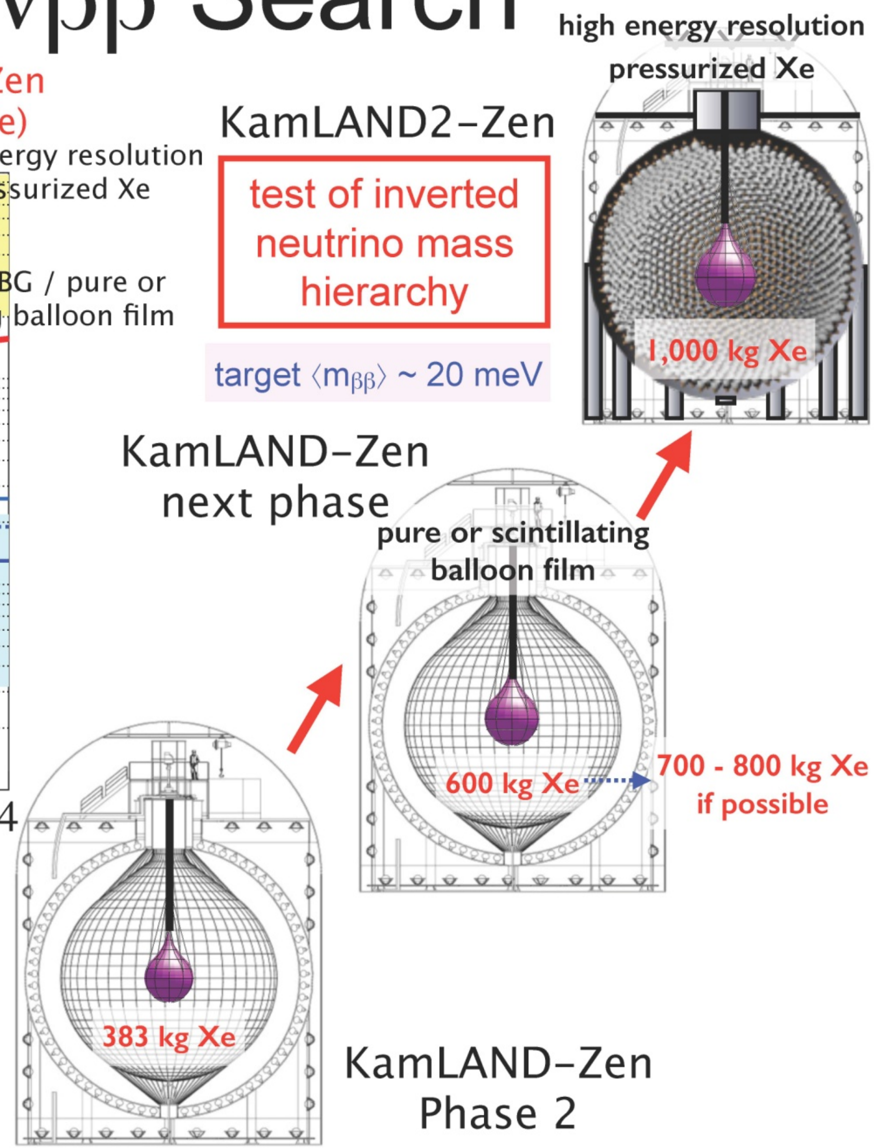
$\sigma_E(2.5\text{MeV}) = 4\%$

$T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr (90% C.L.)

Shimizu Nu2014

Prospect for 0νββ Search

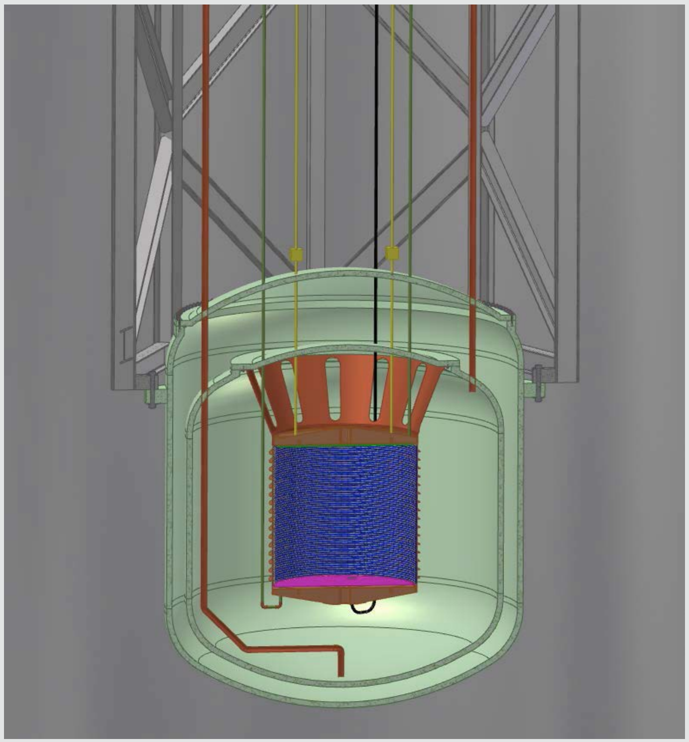




Detector improvements are planned in the near future

Xe TPC

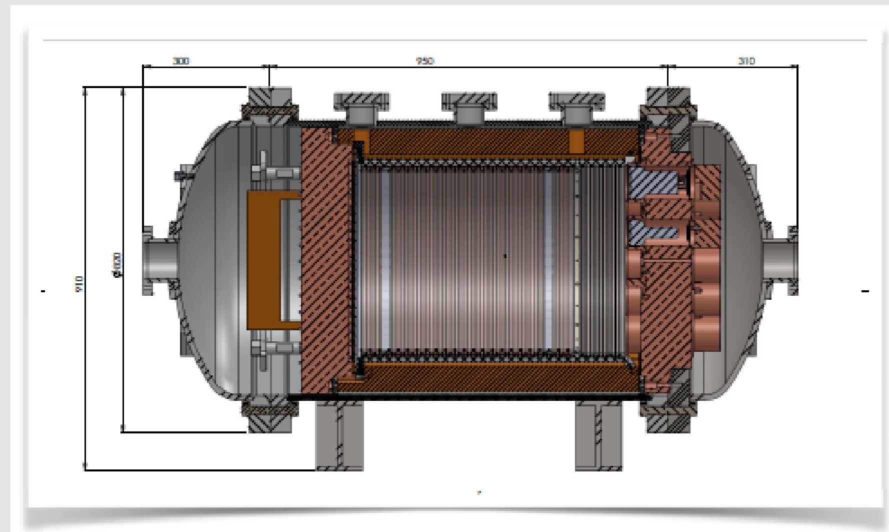
Liquid



EXO -> nEXO

200 kg 84% ^{136}Xe -> ~ 5 tonnes

High Pressure Gas



NEXT -> MAGIX

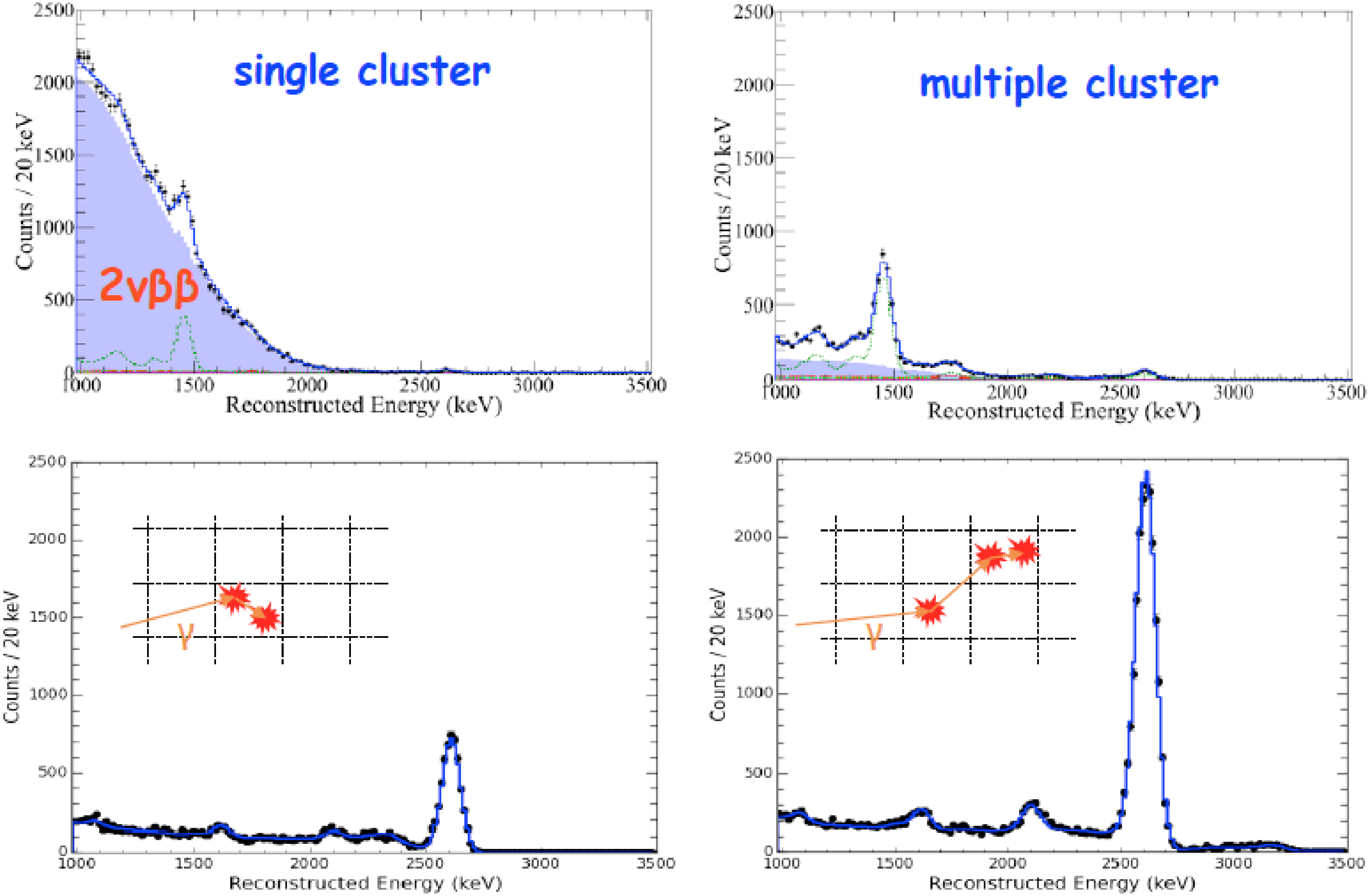
10, 100kg -> 1000 kg 84% ^{136}Xe

Tracking: Shown for EXO, even clearer for NEXT

an essential tool to identify and suppress backgrounds

Low background data

^{228}Th calibration source

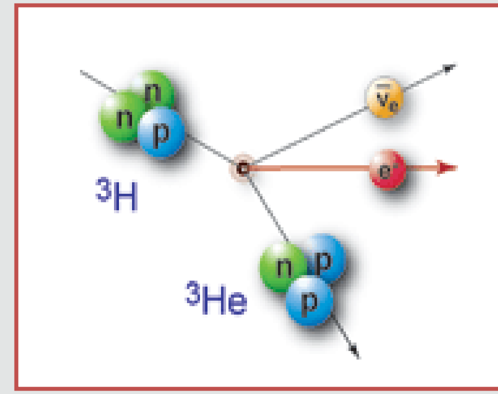


An experiment with 1 to 5 tonnes is capable of reaching below the Inverted hierarchy with adequate control of background. Identifying the Ba daughter may be possible.

Summary of Neutrino-less double beta decay

- A discovery would involve very important physics:
  - Lepton Flavor Violation
  - Majorana neutrinos (Neutrino = Anti Neutrino)
  - A measure of the absolute mass of neutrinos
  - Majorana CP violating phases.
- More than one isotope /technique will be required for clear discovery.
- More work on nuclear theory would be valuable.
- Many experiments are pushing the sensitivity into inverted hierarchy region.
- Next generation experiments will reach the bottom of the inverted hierarchy region (also needed for decay details if discovery made in present generation): Implies several future experiments each > $100 M.
- Isotope separation will be very important for most of the experiments. For example: 1 Tonne of Ge enrichment is estimated to cost ~ $90 M.
- **International cooperation is essential for present generation and particularly for future generation experiments.**

Neutrino mass from Beta Spectra



With flavor mixing:

$$\frac{dN}{dT} = \frac{G_F \cos\theta_C}{2\pi^3} |M_{\rm nuc}|^2 F(Z,T)(T+m)(T^2+2mT)^{1/2}(T_0-T)\sum_i |U_{ei}|^2 \left[(T_0-T)^2 - m_i^2\right]^{1/2}$$

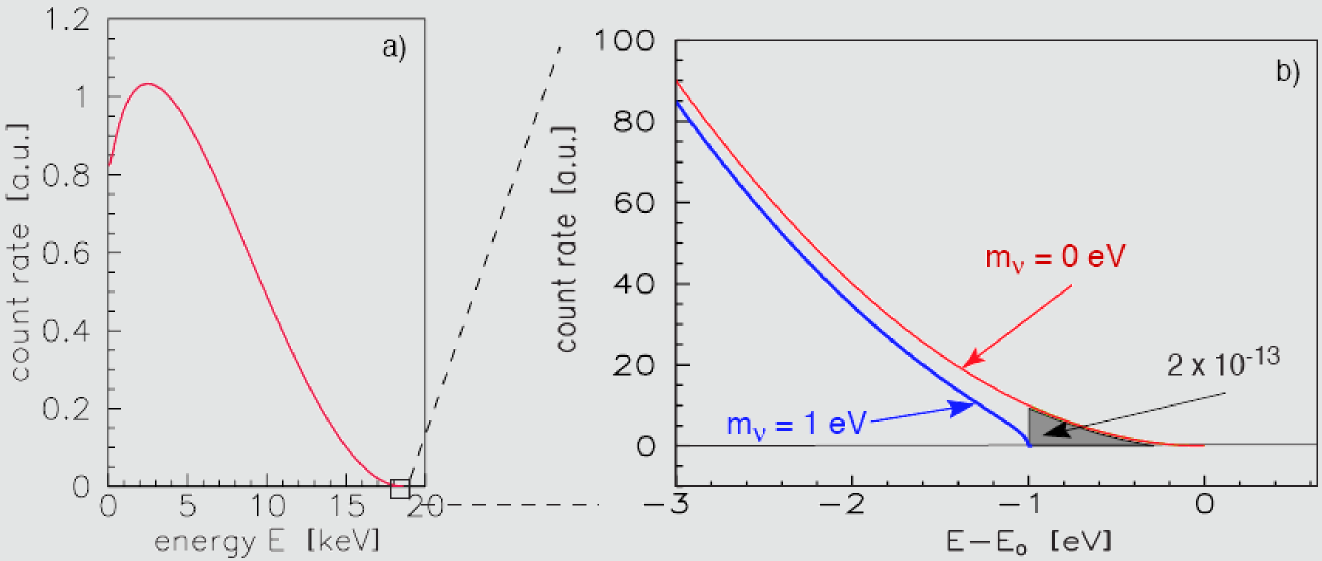
mixing

neutrino masses

$$m_i^2 = \Delta m_{i0}^2 + m_0^2$$

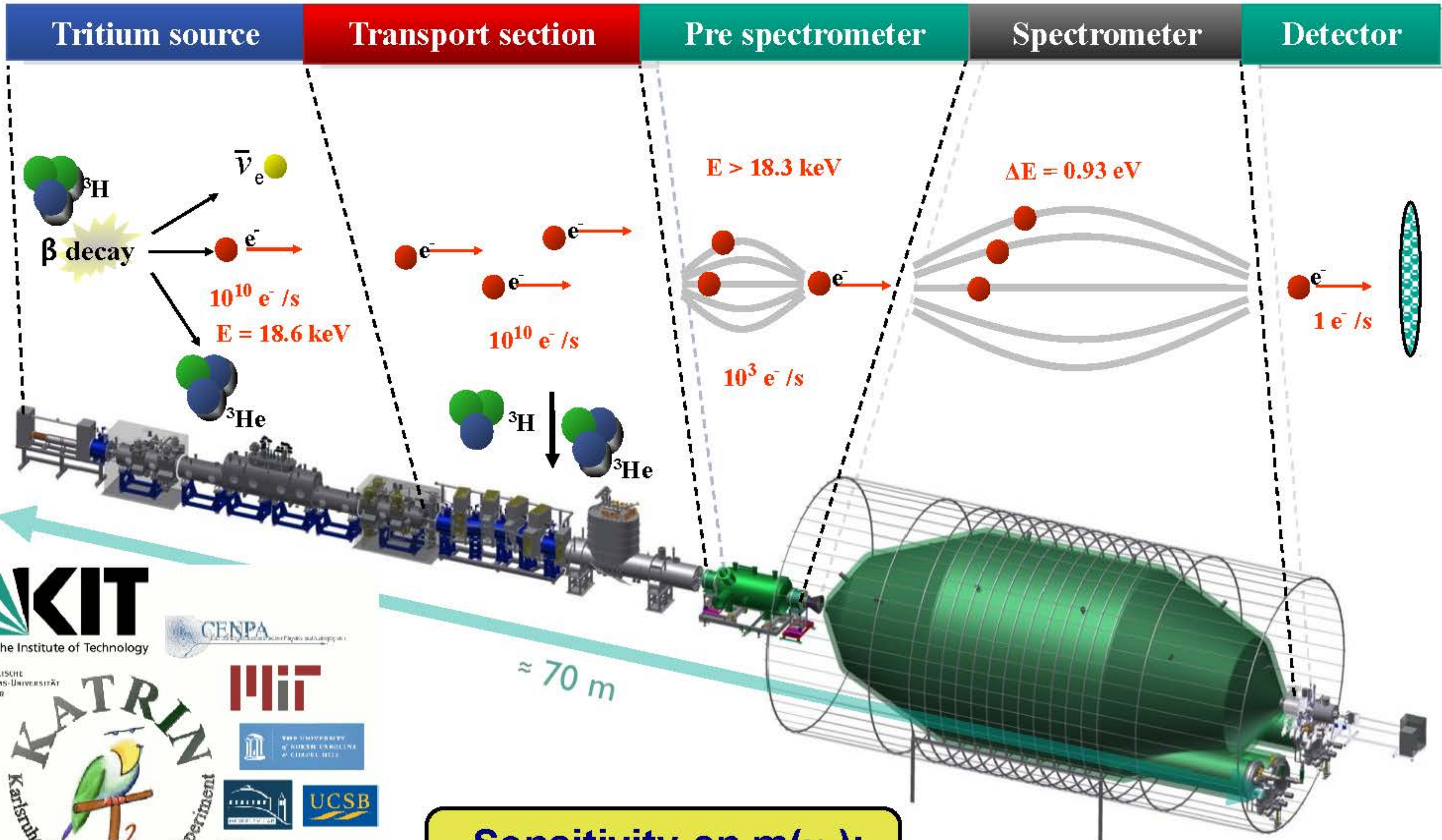
from oscillations

mass scale



From H. Robertson

The Karlsruhe Tritium Neutrino Experiment
KATRIN - overview



Sensitivity on $m(\nu_e)$:

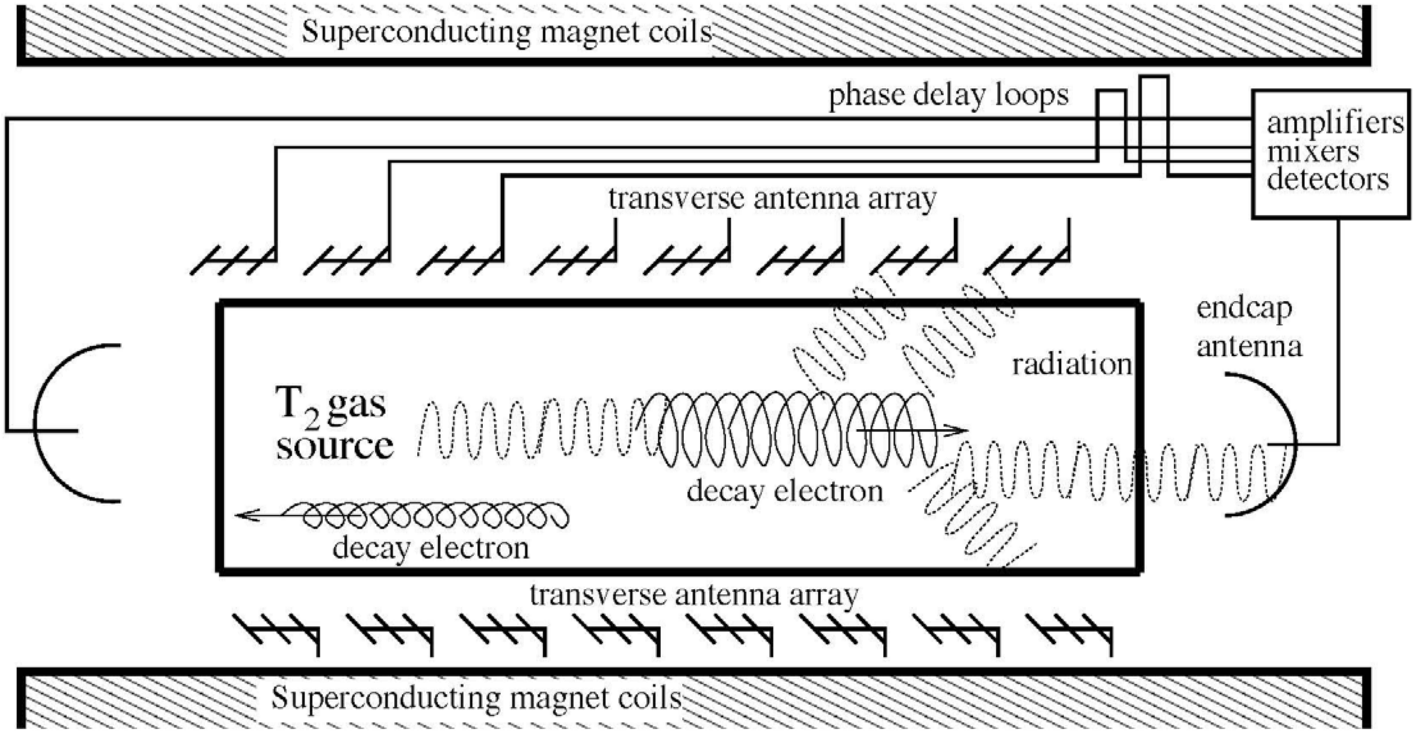
$2\ eV/c^2 \rightarrow 200\ meV/c^2$

Start 2016

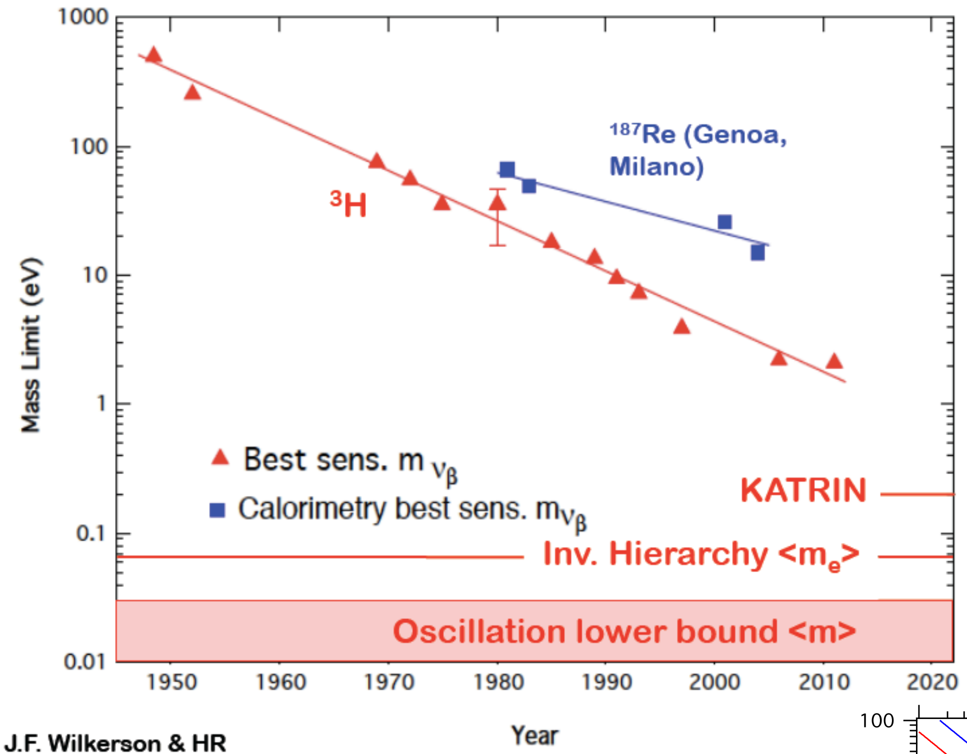
Project 8

The experiment

Detect cyclotron radiation from the decay electrons



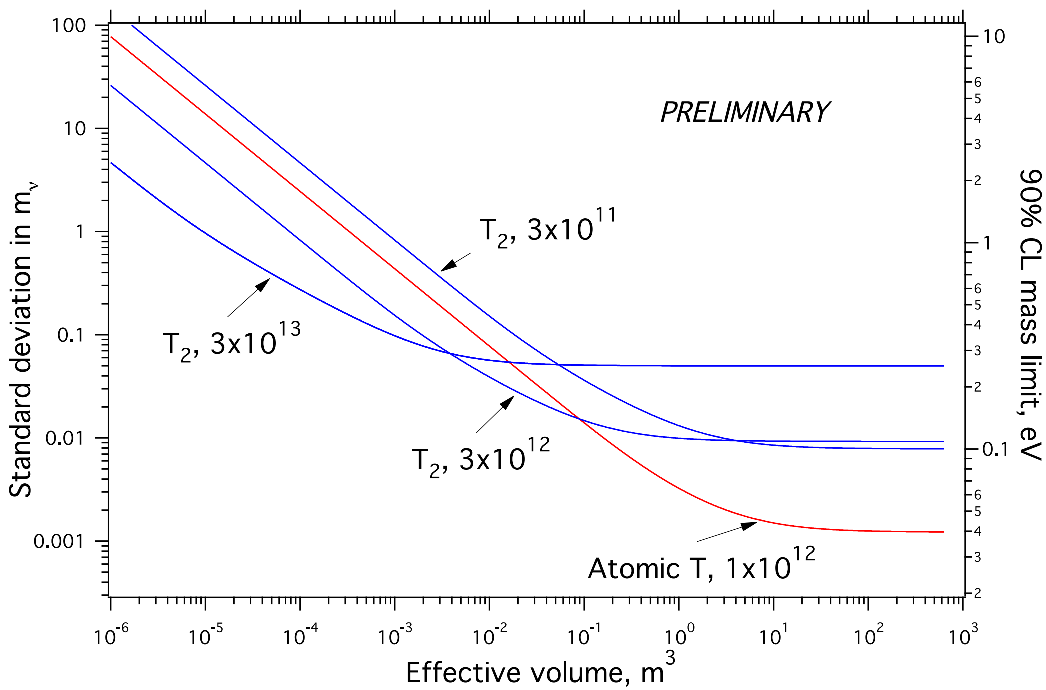
Now testing with ^{83}Kr source at U. Washington. Work with tritium will follow successful testing.



J.F. Wilkerson & HR

Present and Future Neutrino Mass sensitivity, including KATRIN (start 2016)

Potential Project 8 Sensitivity for various Molecular and Atomic Tritium densities



CONCLUSIONS

• Neutrino-less Double Beta Decay and Tritium end-point measurements address very important and fundamental physics

• The scale of the double beta decay experiments is reaching the stage where international cooperation is essential for future success.

• Funding support for present generation experiments and sharing of scientific and technological information is important for future progress.

• Collaboration building and international cooperation on isotope separation & low radioactivity materials and techniques during the next several years will enable the successful selection of the best isotopes, technologies and sites for several Next Generation Neutrino-less Double Beta Decay Experiments.

• This should be done primarily on the basis of accomplishing the best possible science, generating a coalescence of international scientists around the best Next Generation Experiments.

• These topics should be included in the list for the communique from this meeting and the Underground Lab Directors should be encouraged to sponsor meetings over the next 2-3 years to reach a consensus on Next Generation Double Beta Decay Expts.

THANK YOU