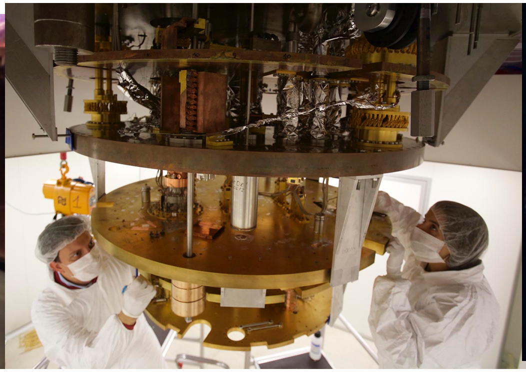
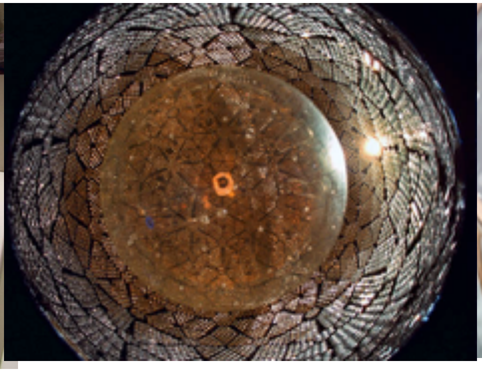
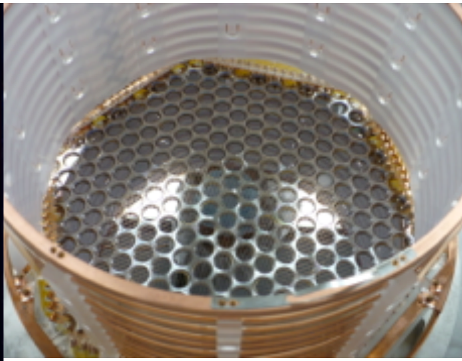
Search for Neutrinoless Double Beta Decay: Recent Results and Future Prospects

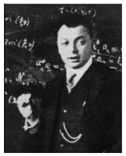


Karsten M. Heeger
Yale University

CIPANP, May 19, 2015

Yale Wright Laboratory

Neutrinos - The First 85 Years



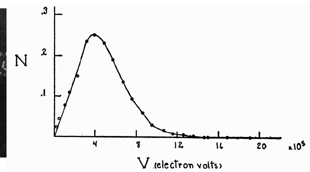
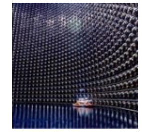


Fig. 5. Energy distribution curve of the beta-rays.

1930 Pauli postulates neutrinos

1933 Fermi names neutrinos, formulates weak interactions theory

1987 SN 1987A



1998 SuperK reports evidence for oscillation of atmospheric neutrinos.

2001/2002 SNO finds evidence for solar ν_e flavor change.

2003 KamLAND discovers disappearance of reactor ν_e

1968 Ray Davis detects solar neutrinos.

2002

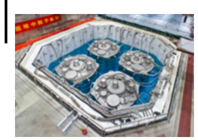
1962 Steinberger, Lederman, Schwartz, et al demonstrate ν_e & ν_μ

1987

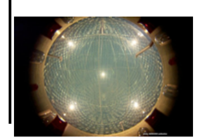
1958 Goldhaber, Grodzins, & Sunyar at BNL demonstrate left-handed helicity

1957 Pontecorvo: Neutrinos may oscillate

1956 Reines & Cowan report the first evidence of neutrinos

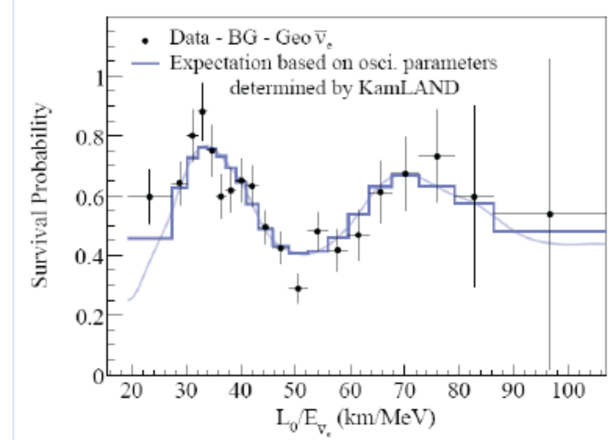


2012 Daya Bay, RENO, Double Chooz measure θ_{13}



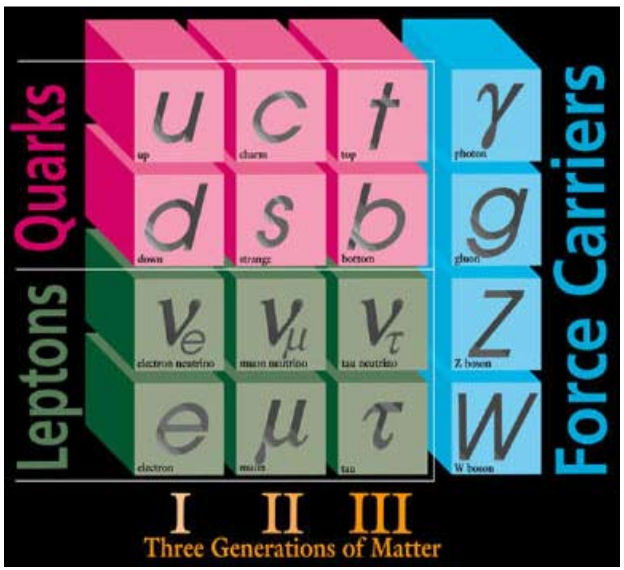
2007 Borexino detection of ^{7}Be solar neutrinos

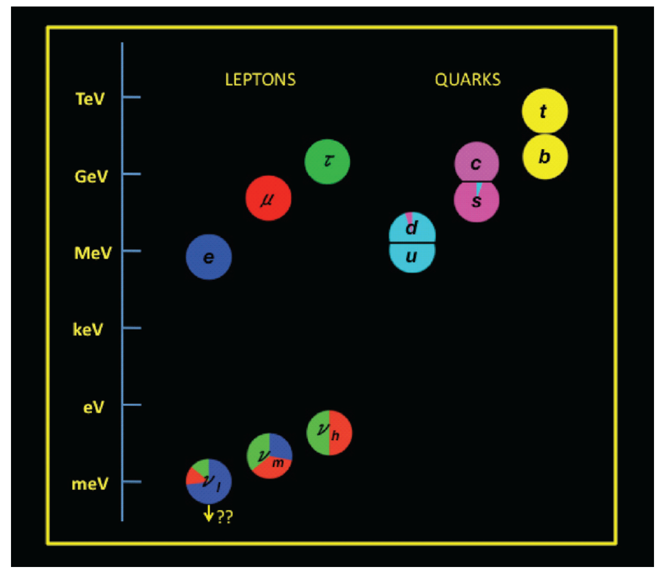
Neutrinos Oscillate and Have Mass



Neutrino Oscillation experiments

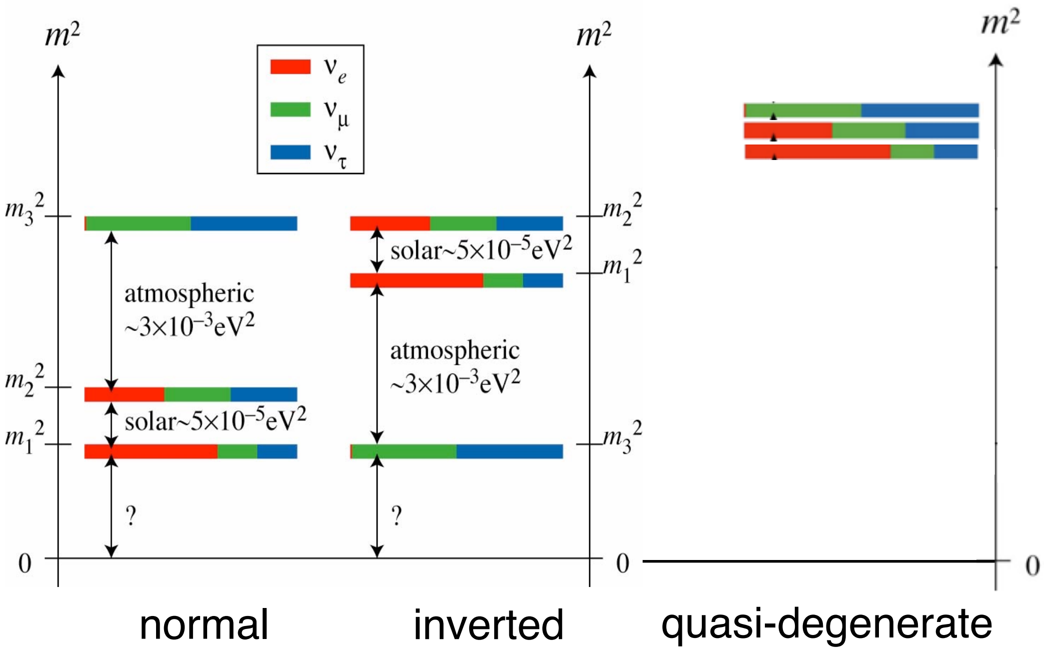
- Neutrinos undergo flavor-changing oscillations
- Neutrinos have mass





Why is neutrino mass so small?
How small is it?
What is the mass generating mechanism?

Neutrino Mass and Hierarchy



We know

- mass splitting
- mixing angles
- minimum mass

Δm_{atm}^2 → $m_\nu > 0.045$ eV

We don't know

- mass ordering
- absolute scale
- CP phases
- nature of neutrino mass

Early Days of Double Beta Decay

1930, Pauli

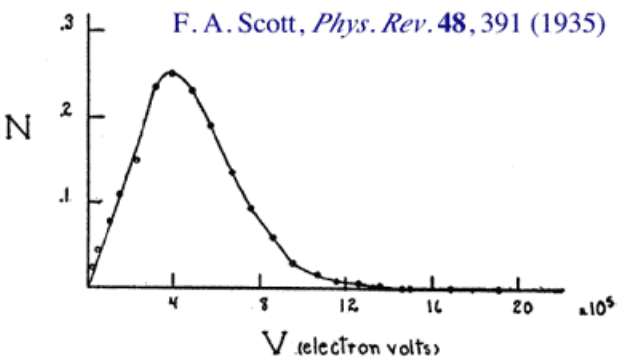
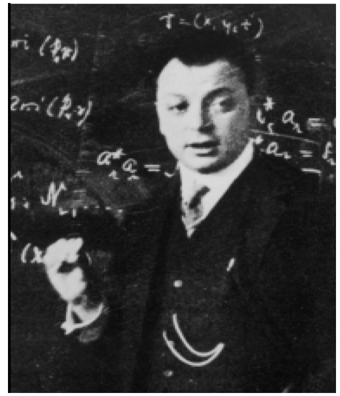
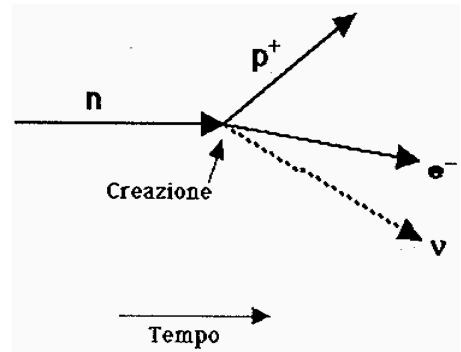


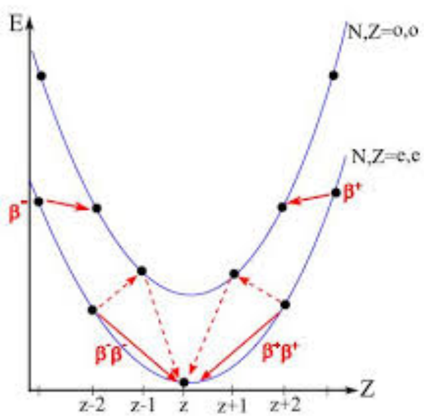
FIG. 5. Energy distribution curve of the beta-rays.



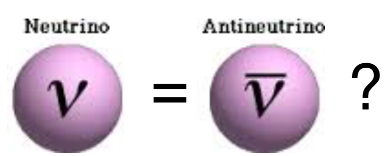
1932, Fermi

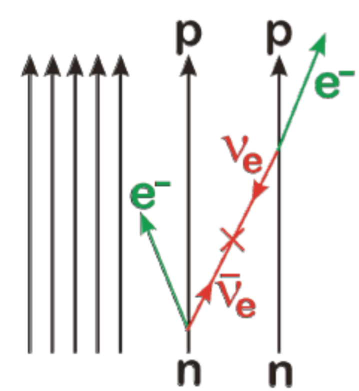


1935, Goeppert Mayer



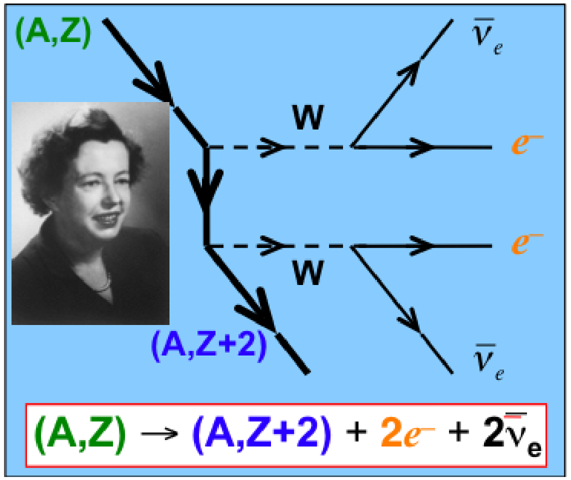
1937, Majorana





Double Beta Decay

$2\nu\beta\beta$

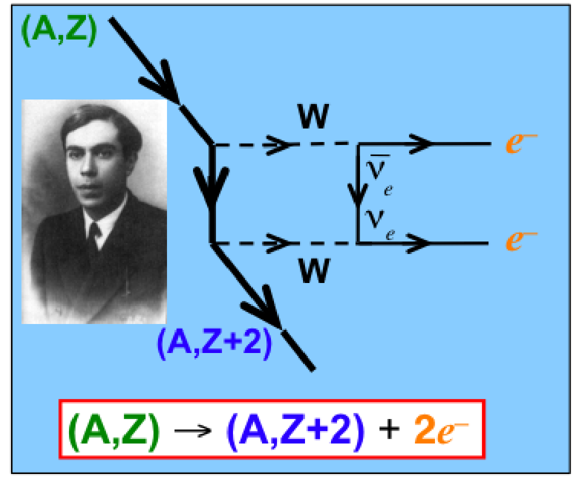


Proposed in 1935 by Maria Goeppert-Mayer

Observed in several nuclei

$T_{1/2} \sim 10^{19} - 10^{21}$ yrs

$0\nu\beta\beta$



Proposed in 1937 by Ettore Majorana

Not observed yet

$T_{1/2} \geq 10^{25}$ y

$$(N,Z) \rightarrow (N-2, Z+2) + e^- + e^-$$

$\Delta L=2$: total lepton number violation (LNV)

nuclei are a laboratory to study lepton number violation at nuclear energies

Physics of Neutrinoless Double Beta Decay

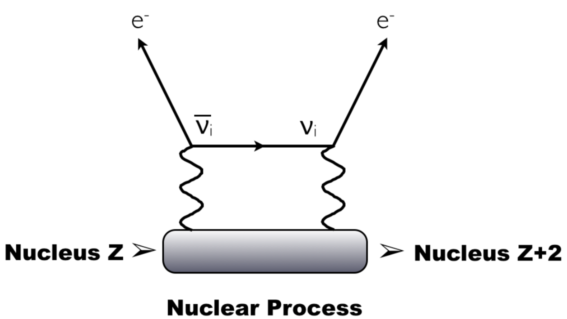
B-L conserved in Standard Model

$0\nu\beta\beta$ is the most powerful and comprehensive probe of Lepton Number Violation, sensitive to new physics over a vast range of scales, with far reaching implications

Observation of $0\nu\beta\beta$ would be direct evidence for new physics

Demonstrate that **neutrinos are Majorana fermions**

Probe **new mechanism of neutrino mass generation,** reaching up to GUT scale



Probe key **ingredient needed to generate cosmic baryon asymmetry** via leptogenesis. Sakharov conditions.

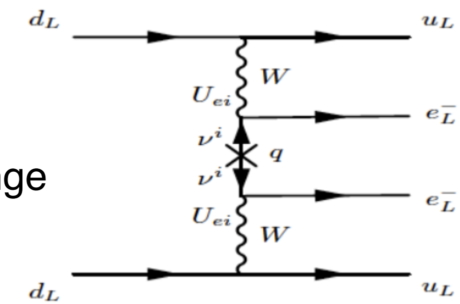
1. *Baryon number violation*
2. *Out of thermal equilibrium*
3. *CP violation*

Proposed experiments have discovery potential in a variety of mechanisms

Double Beta Decay Mechanism

Standard

Light Majorana neutrino exchange



$$\frac{1}{T_{1/2}^{0\nu}} = G_{0\nu} g_A^4 \left| M^{(0\nu)} \right|^2 \langle m_{\beta\beta} \rangle^2$$

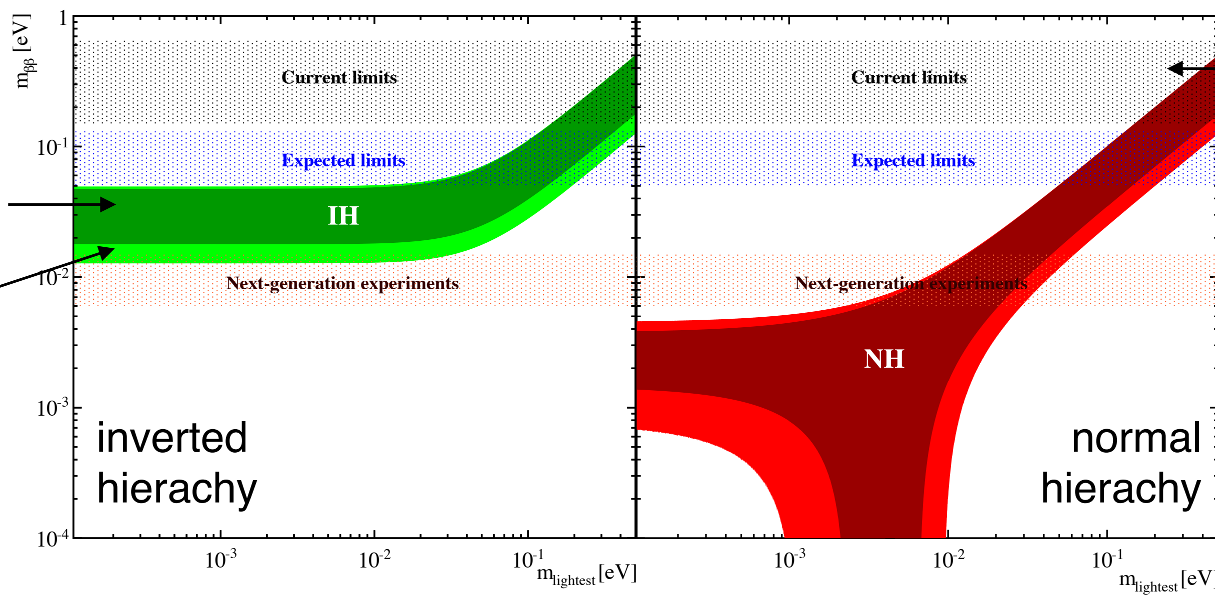
$$\langle m_{\beta\beta} \rangle^2 = |\sum_i U_{ei}^2 m_{\nu i}|^2$$

$$\langle m_{\beta\beta} \rangle^2 = |\cos^2\theta_{12}\cos^2\theta_{13} m_1 + \exp^{2i\lambda_2}\sin^2\theta_{12}\cos^2\theta_{13} m_2 + \exp^{2i(\lambda_3-\delta_{CP})}\sin^2\theta_{13} m_3|^2$$

Effective Majorana Mass

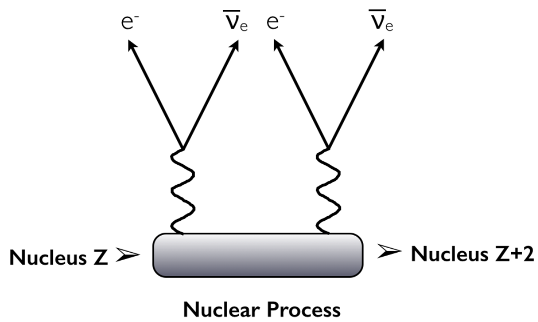
unknown phases

uncertainty form oscillation parameters (90% CL)



nuclear matrix elements

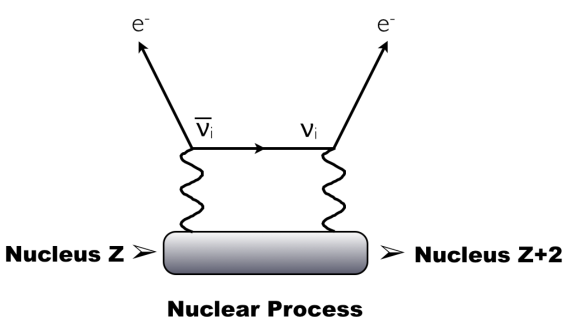
Neutrinoless Double Beta Decay ($0\nu\beta\beta$)



2ν mode: conventional 2nd order process in nuclear physics

$$\Gamma_{2\nu} = G_{2\nu} \mid M_{2\nu} \mid^2$$

G are phase space factors



0ν mode: hypothetical process only if
$M_\nu \neq 0$ AND $\nu = \bar{\nu}$

$$\Gamma_{0\nu} = G_{0\nu} \mid M_{0\nu} \mid^2 \left\langle m_{\beta\beta} \right\rangle^2$$

$G_{0\nu} \sim Q^5$

Observable Half Life of $0\nu\beta\beta$

$$(T^{0\nu}_{1/2})^{-1} = G^{0\nu}(Q,Z)|M^{0\nu}|^2 \frac{|\langle m_{\beta\beta}\rangle|^2}{{m_e}^2}$$

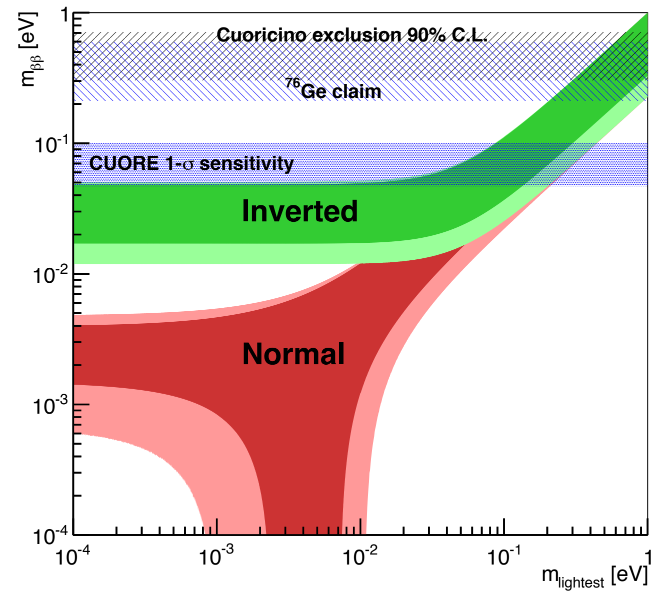
$T^{0\nu}_{1/2}$ = $0\nu\beta\beta$ half-life

$G^{0\nu}(Q,Z)$ = phase space factor ($\propto Q^5$)

$M^{0\nu}$ = nuclear matrix element

$\langle m_{\beta\beta}\rangle$ = effective $\beta\beta$ neutrino mass

m_e = electron mass



Half lives are determined by

- phase space factor (high-Q value desirable)
- nuclear matrix elements

Nuclear matrix elements are calculated theoretically with different models

Effective neutrino mass can be inferred from half-live measurement

Experimental Sensitivity

$$T_{1/2}^{0\nu} \text{ sensitivity} \propto a \cdot \epsilon \sqrt{\frac{M \cdot t}{b \cdot \delta E}}$$

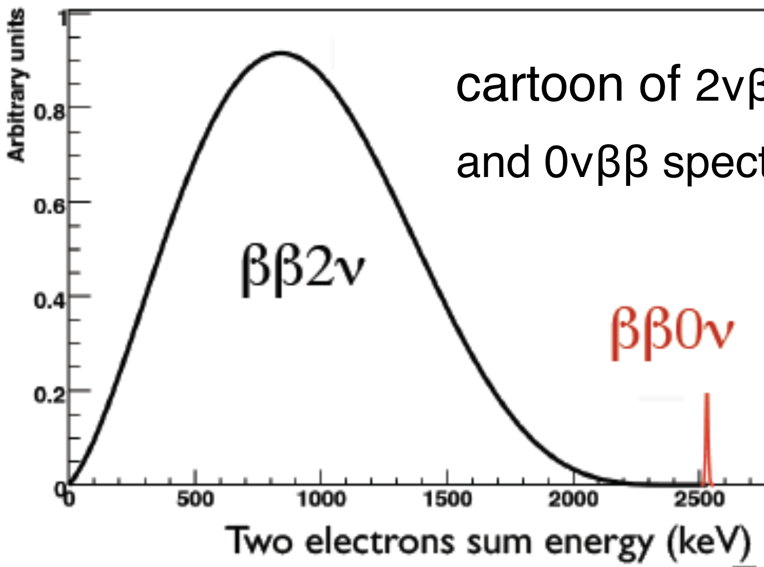
a = source isotopic abundance
ϵ = detection efficiency
M = total mass
t = exposure time
b = background rate at $0\nu\beta\beta$ energy
δE = energy resolution

0νββ source with
- **high isotopic abundance**

Detector with
- **high detection efficiency**
- **good energy resolution**
- **low-background**

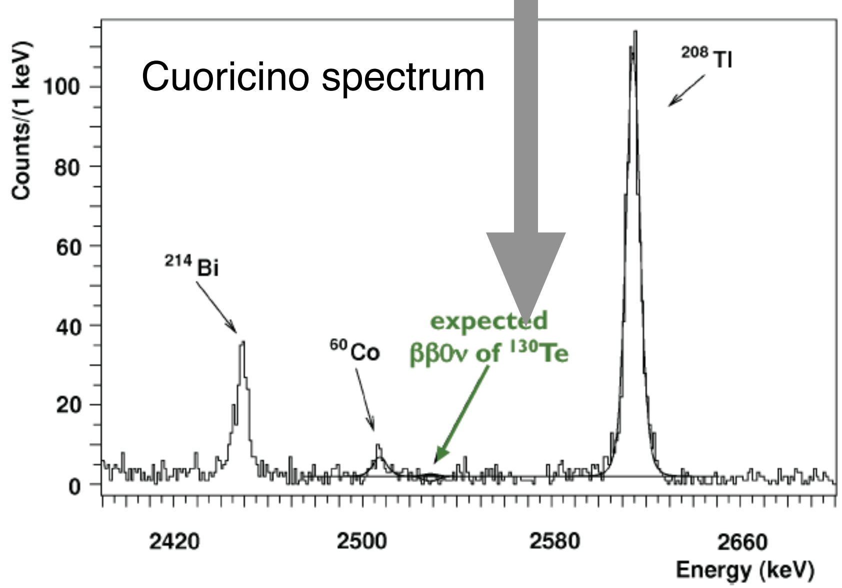
Experiment
- **long exposure time**
- **large total mass of isotope**

Search for 0νββ - Observable Signature



Experimental Signature of 0νββ

- peak at the transition Q-value
- enlarged by detector resolution
- over unavoidable 2νββ background



Example: ^{130}Te

Q(^{130}Te)=2527 keV

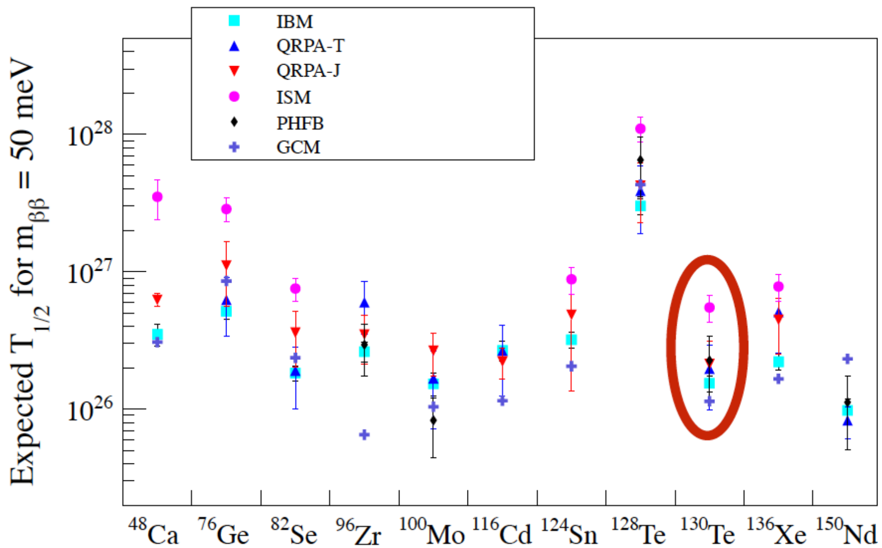
energy
= key event signature

Nuclear Structure in Double Beta Decay

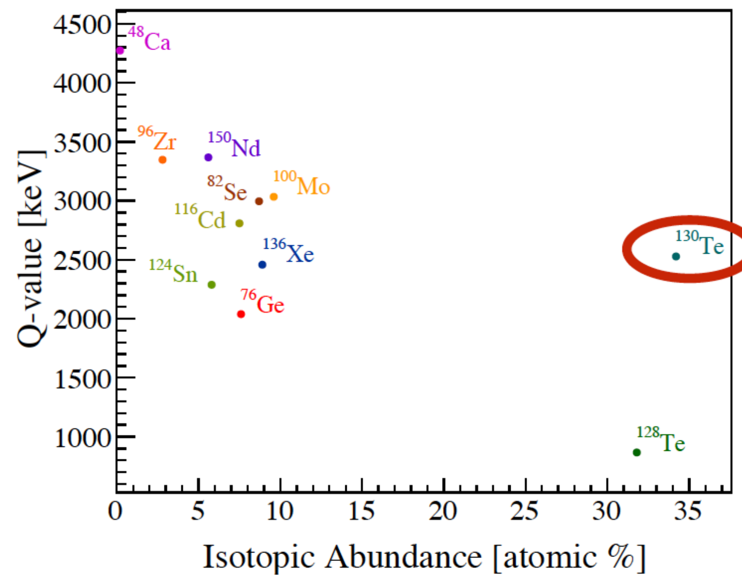
Nuclear structure connects experimental rates to parameters of interaction, requires mechanism dependent nuclear matrix elements.

$T_{1/2}$

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu} g_A^4 \left|M_{0\nu}\right|^2 \left|\frac{\langle m_{\beta\beta}\rangle}{m_e}\right|^2$$



Q-value



range of $T_{1/2}$ depending on nuclear matrix element

Example: ^{130}Te

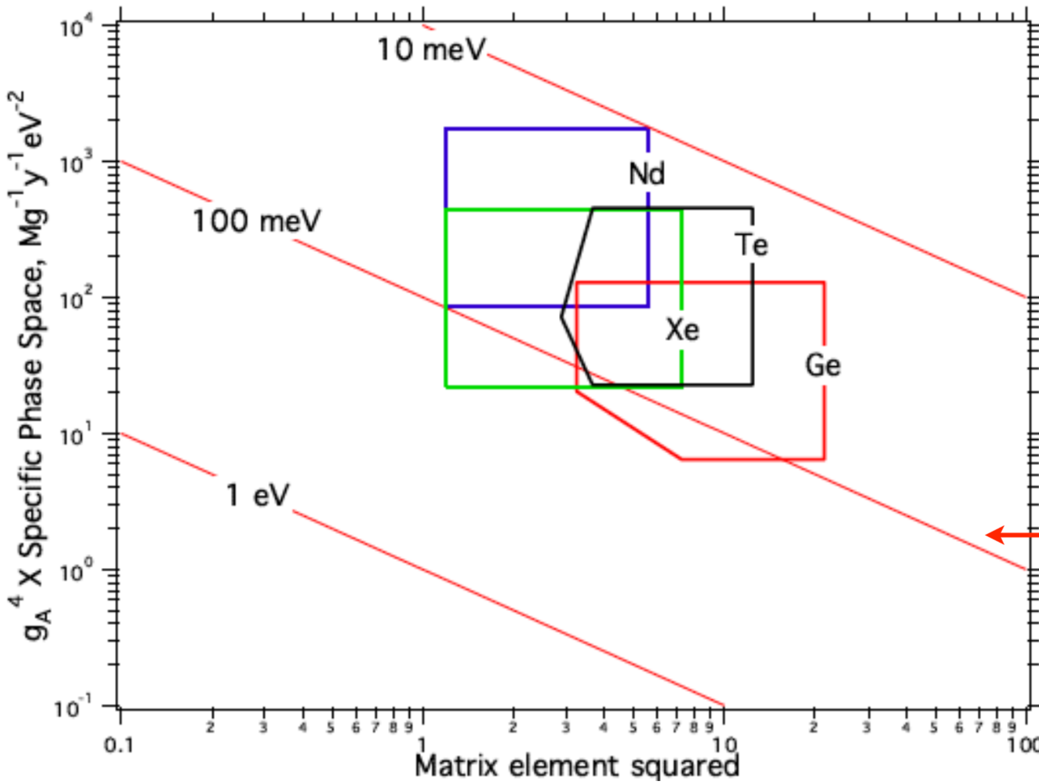
Q(^{130}Te)=2527 keV, good Q-value above Compton edge of 2615 keV line
High natural abundance

Isotopes and Sensitivity to $<m_{\nu\beta\beta}>$

For Ge, Te, Xe, Nd

uncertainty on NME^2

$$\left[T_{1/2}^{0\nu}\right]^{-1} = G_{0\nu} g_A^4 \left|M_{0\nu}\right|^2 \left|\frac{\langle m_{\beta\beta}\rangle}{m_e}\right|^2$$



uncertainty on value of g_A^4

Signal of 1 cnt/t-y for corresponding values of NME and g_A

$$g_A^4 H_{0\nu} = g_A^4 \ln(2) \frac{N_A}{A m_e^2} G_{0\nu}^{(0)}$$

Isotopes have comparable sensitivities in terms of rate per unit mass

Ref: Robertson
MPL A28, 2013, 1350021
arXiv:1301.1323

0vbb Signals and Backgrounds

An experimental challenge of rare events

Most measured half lives of 2vββ are O(10^{21}) years

- Compare to lifetime of Universe: 10^{10} years
- Compare to Avogadro's number 6 x 10^{23}
- Mole of isotope will produce ~ 1 decay/day

If it exists, half lives of 0vββ would be longer
(^{130}Te limits is > 10^{24} years)

Half life (years)	Signal (cts/tonne-year)
10^{25}	500
5x10^{26}	10
10^{27}	1
10^{28}	0.1

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

background free

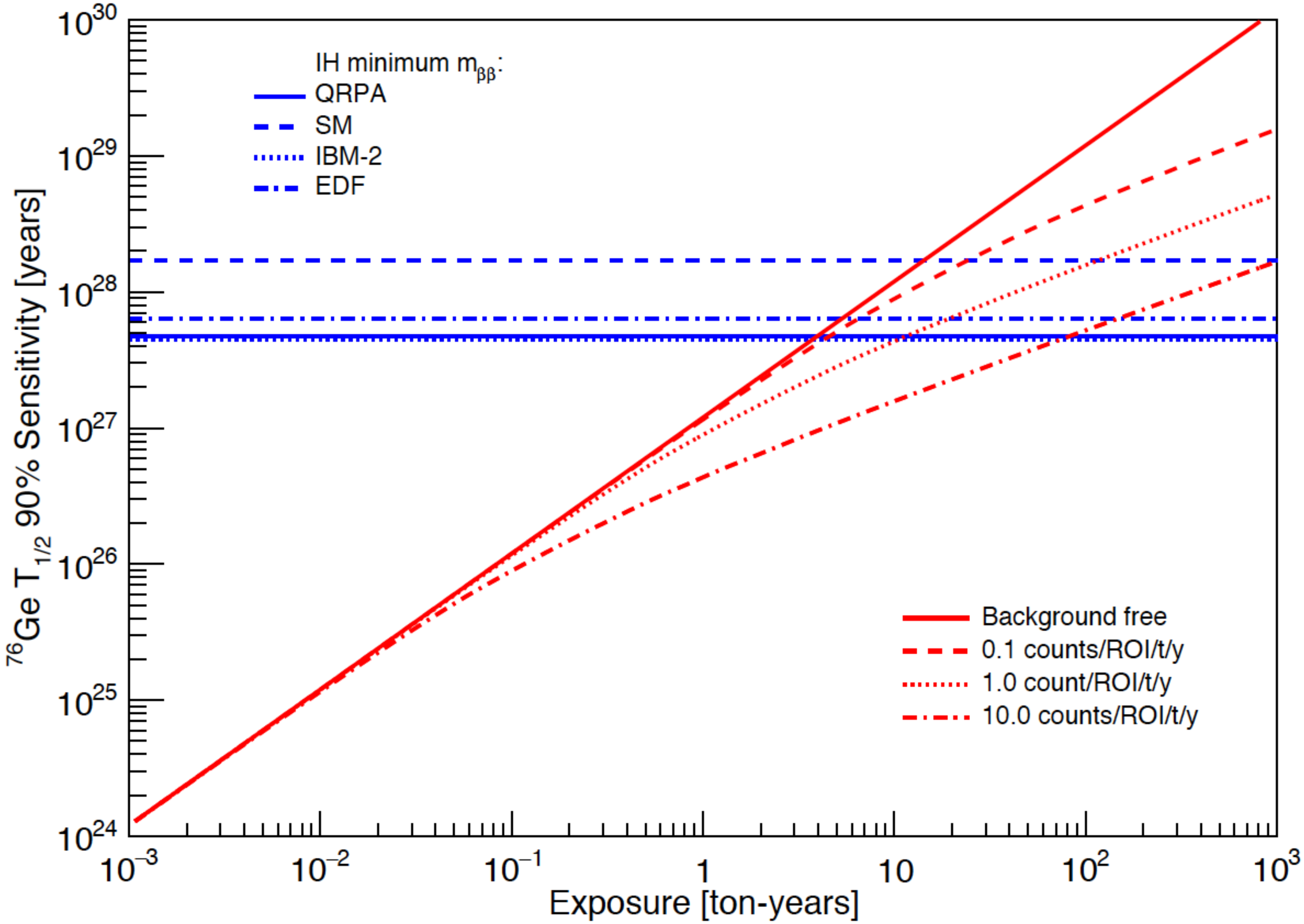
$$\left[T_{1/2}^{0\nu}\right] \propto \varepsilon ff \cdot I_{abundance} \cdot \sqrt{\frac{Source\ Mass \cdot Time}{Bkg \cdot \Delta E}}$$

background limited

backgrounds do not always scale with detector mass

Sensitivity vs Background

Example: ^{76}Ge, similar sensitivities for other isotopes



ROI: Region of interest can be single or multidimensional (E, spatial, …)

J. Detwiler
J. Wilkerson

Background control and reduction are key

0νββ Backgrounds and Mitigation

Potential Backgrounds

- Primordial, **natural radioactivity** in detector components: U, Th, K
- Backgrounds from **cosmogenic activation** while material is above ground (ββ-isotope or shield specific, ^{60}Co, ^{3}H...)
- Backgrounds from the **surrounding environment**:
  external γ, (α,n), (n,α), Rn plate-out, etc.
- **μ-induced backgrounds** generated at depth:
  Cu,Pb(n,n' γ), ββ-decay specific(n,n),(n,γ), direct μ
- **2 neutrino double beta decay** (irreducible, E resolution dependent)

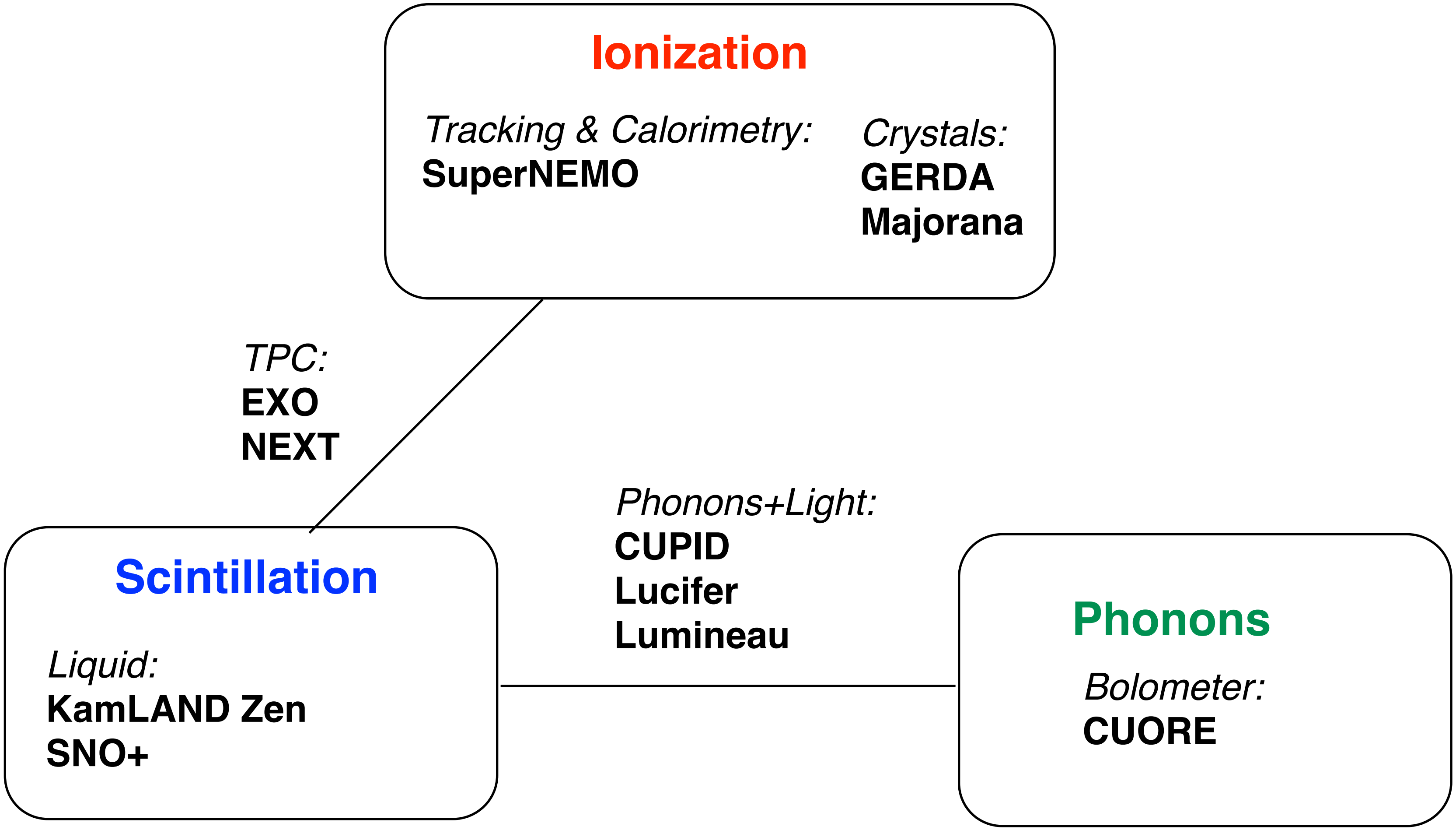
Reduce Backgrounds

- ultra-pure materials
- shielding
- deep underground
- …

Discriminate Backgrounds

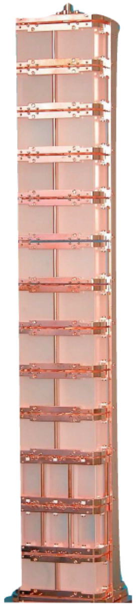
- energy resolution
- tracking (even topology)
- fiducial fits
- pulse shape discrimination (PSD)
- particle ID
- …

0νββ Detection Techniques



Combining detection techniques for improved event identification and background rejection

$0\nu\beta\beta$ Efforts Worldwide

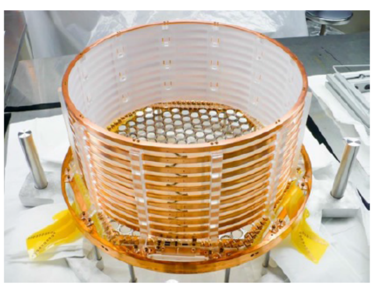


^{130}Te

- Bolometer-based searches
- $T_{1/2} > 2.8 \times 10^{24}$ y
- Cuoricino / CUORE-0 / CUORE

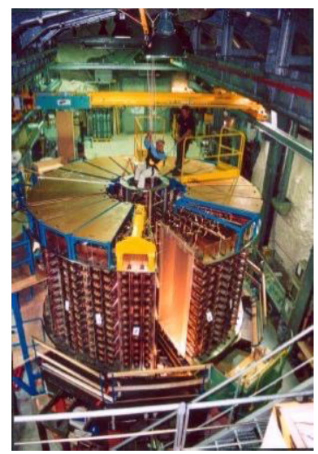
^{76}Ge

- High-purity germanium detectors
- $T_{1/2} > 2.1 \times 10^{25}$ y
- GERDA / MAJORANA



^{136}Xe

- Liquid Xe scintillation / TPC
- $T_{1/2} > 2.6 \times 10^{25}$ y
- Kamland-Zen, EXO-200, nEXO



NEMO-3 / SuperNEMO

- Source foils with tracking and calorimetry
- Half-lives on ^{48}Ca, ^{82}Se, ^{96}Zr, …

Pushing experimental techniques to an extreme:

coldest space in Universe, cleanest radiation detector, deepest laboratory, cleanest tracking chamber, etc…

$0\nu\beta\beta$ Efforts Worldwide

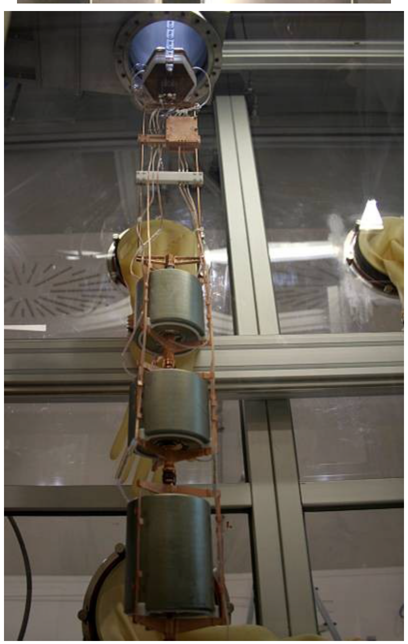
Experiment	Isotope	Isotopic Mass	Start of Operations
CUORE0 CUORE	130	~11 Kg ~210 Kg	2013 (Running) 2015
EXO-200	136	~200 Kg	2011
GERDA I/II	76	~34 Kg	2011/15
KamLAND-Zen	136	~300 Kg	2012 (Running)
MAJORANA	76	~30 Kg	2015
NEXT	136	~100 Kg	2016
SNO+	130	~800 Kg	2016 ?
SuperNEMO	82	~7 Kg	2016

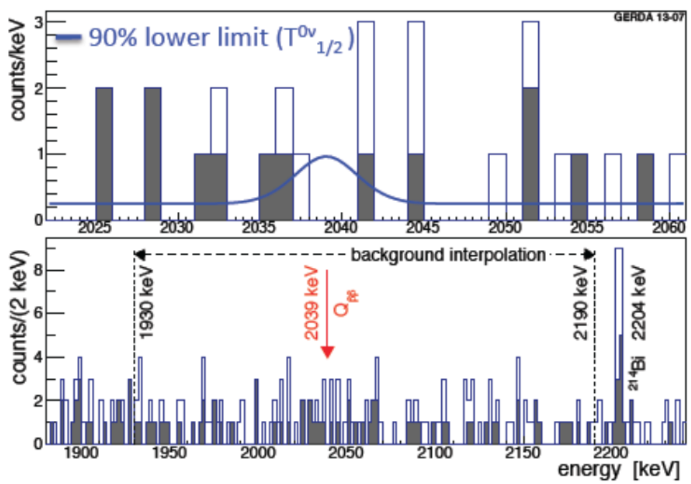
selection of most prominent efforts

Recent Results - Gerda Phase 1 (^{76}Ge)

Ionization

- 87% enriched ^{76}Ge detectors in LAr
- $Q_{\beta\beta}$ = 2039 keV
- 14.6 kg of 86% enriched Ge detectors from H-M, IGEX (4.8 keV FWHM @ $Q_{\beta\beta}$
- 3 kg of 87% enriched BEGe enriched detectors (3.2 keV FWHM @ $Q_{\beta\beta}$)
- Single-site, multi-site pulse shape discrimination





- 21.6 kg-year exposure
- Frequentist
  $T_{1/2}$ > 2.1 x 10^{25} y (90% CL)
- Bayesian
  $T_{1/2}$ > 1.9 x 10^{25} y (90% CL)

GERDA Collaboration, PRL 111 (2013) 122503
Eur. Phys. J. C (2014) 74:2764

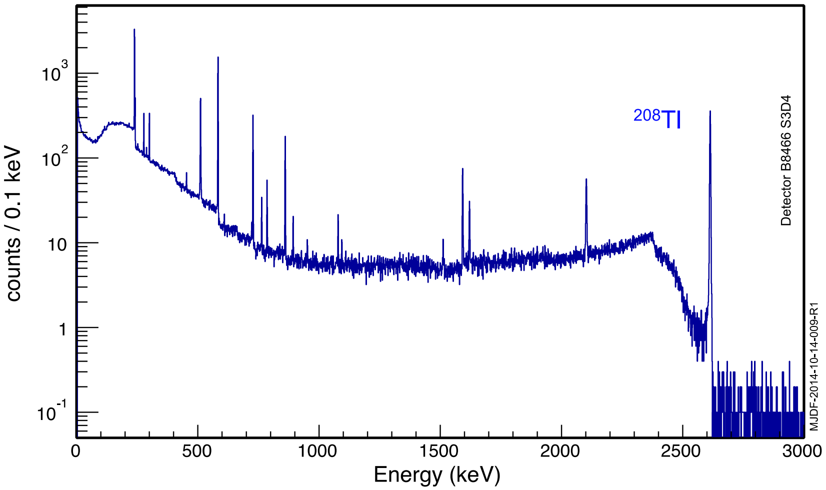
→G. Benato

Recent Progress - Majorana Dem. (^{76}Ge)

Ionization

- MJD Prototype module installed and taking data in shield since July 2014. Simulations and analysis of data are underway .

One detector spectrum within a string mounted in the prototype cryostat and inside shield. FWHM 3.2 keV at 2.6 MeV



- Module 1 with more than half of all enriched detectors will go in-shield in a few days and start operation soon.
- Assembly of strings for Module 2 is underway. Anticipate completion by end of 2015.
- **Expecting data from the completed Demonstrator in 2016.**

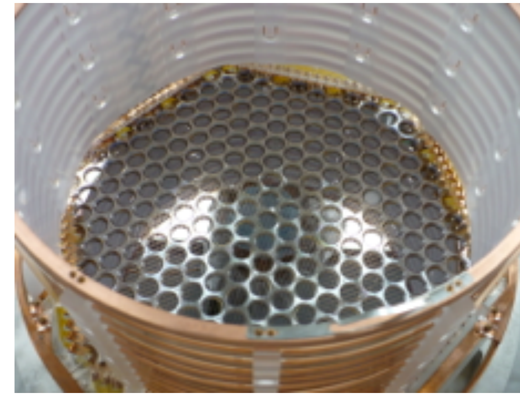
→Wenqin Xu

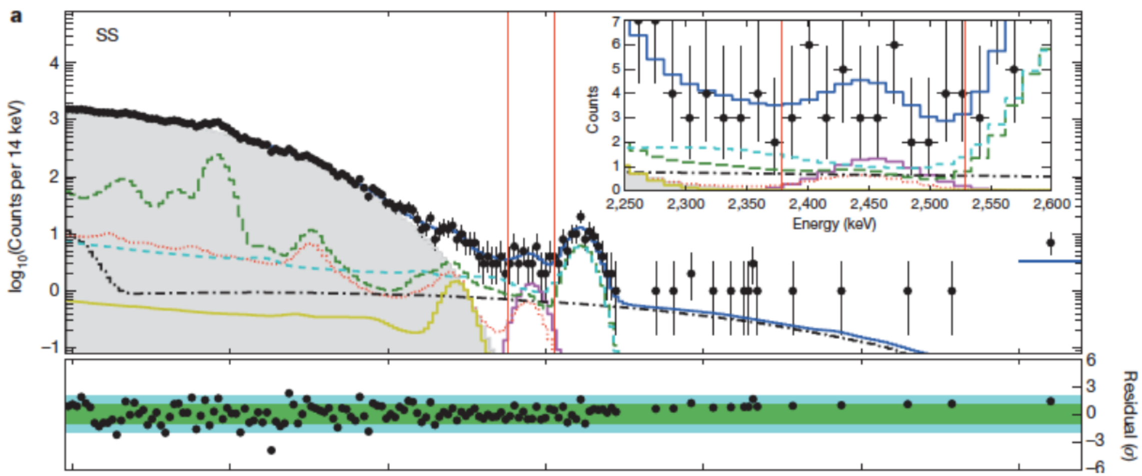
Recent Results - EXO-200 (^{136}Xe)

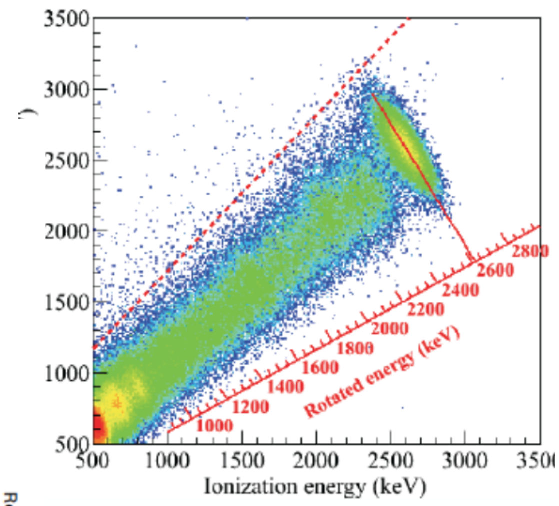
Ionization
Scintillation

- Enriched Liquid Xe in TPC
  - $Q_{\beta\beta}$=2457.8 keV
  - 200 kg of 80.6 % enriched ^{136}Xe
  - 75.6 kg fiducial mass,
  - 100 kg years exposure
  - Combine Scintillation-Ionization signal for improved resolution (88 keV FWHM @ $Q_{\beta\beta}$)
  - Single site - Multisite discrimination

$T_{1/2}$ > 1.1 x 10^{25} y (90% CL)







EXO-200 Collaboration, Nature **510** 229 (2014)

→M. Tarka

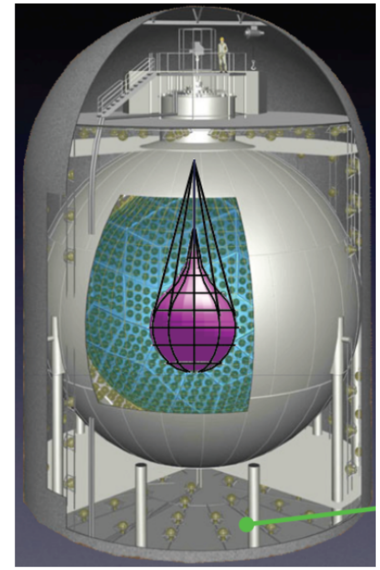
Recent Results - KamLAND-Zen

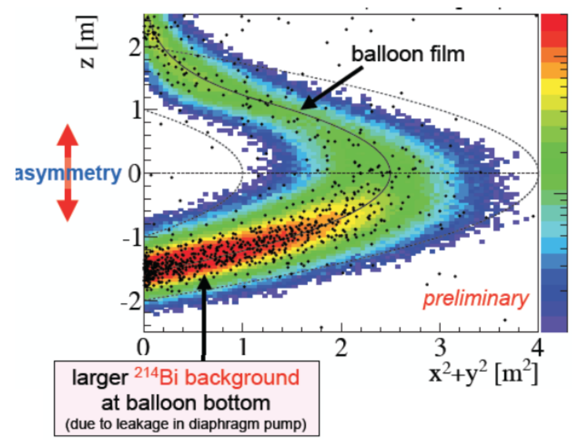
- ^{enr}Xe in liquid scintillator, balloon of R=1.5 m
- $Q_{\beta\beta}$=2457.8 keV
- Phase 1
  - 179 kg (2.44% by Xe wt.) 91.7% enriched ^{136}Xe
  - R=1.35 m fiducial cut
  - 213.4 days, with 89.5 kg years exposure
  - 400 keV FWHM @ $Q_{\beta\beta}$
  - evidence for ^{110m}Ag contamination

  $T_{1/2} > 1.9 \times 10^{25}$ y (90% CL)
- Phase 2
  - 383 kg (2.96% by Xe wt.)
  - R=1 m fiducial cut
  - 114.8 days, with 27.6 kg years exposure
  - ^{110m}Ag contamination reduced by x10

  $T_{1/2} > 1.3 \times 10^{25}$ y (90% CL)

Combined (1&2) $T_{1/2} > 2.6 \times 10^{25}$ y (90% CL)



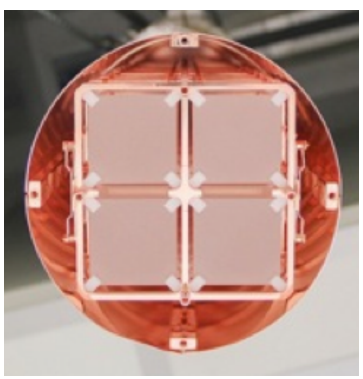


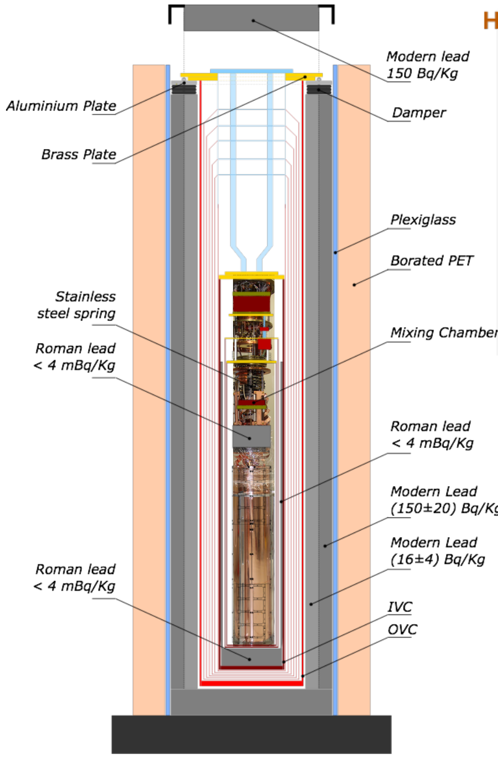
KamLAND ZEN Collaboration, Shimizu, Neutrino 2014

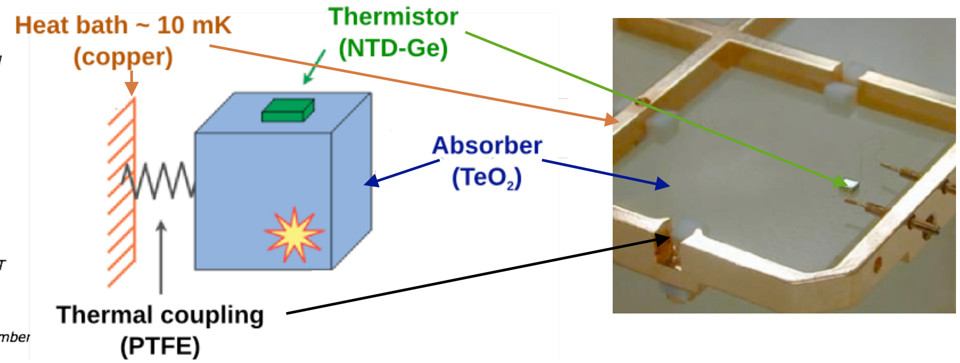
→B. Berger

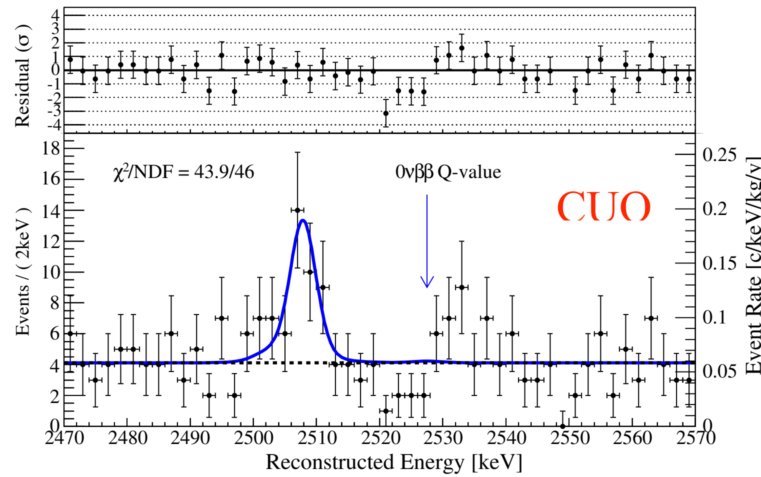
Recent Results - CUORE-0 (^{130}Te)

Phonons









- 11kg ^{130}Te (34% nat.) bolometer (10 m
- $Q_{\beta\beta}$=2527.5 keV
- Array of 52 5x5x5 cm^3 TeO_2 crystals
- 9.8 kg - years exposure
- FWHM of 5.1 keV

$T_{1/2}$ > 2.7 x 10^{24} y (90% CL) CUORE-0

$T_{1/2}$ > 4.0 x 10^{24} y (90% CL) CUORE-0 & Cuoricino

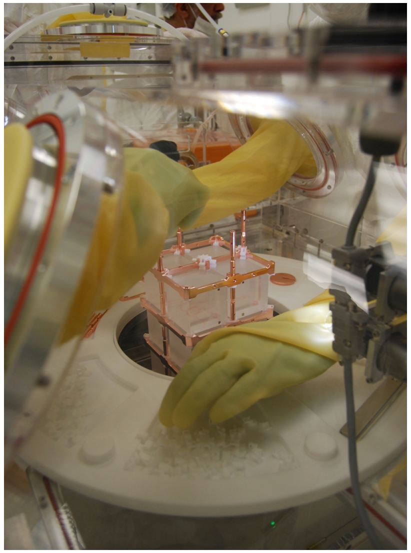
arXiv: 1504.2454

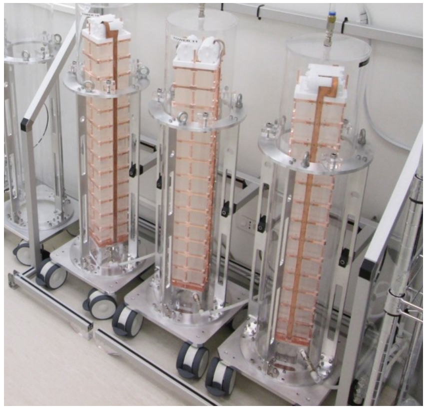
→T. O'Donnell

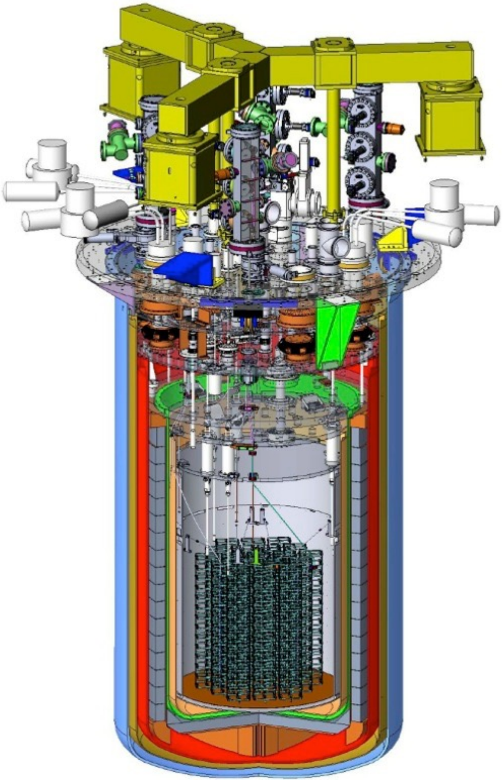
Recent Progress - CUORE (^{130}Te)

Phonons

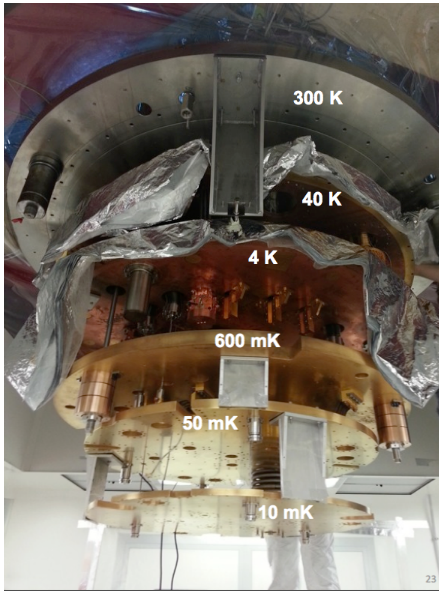
All 988 bolometers (206 kg of ^{130}Te) built and assembled into towers







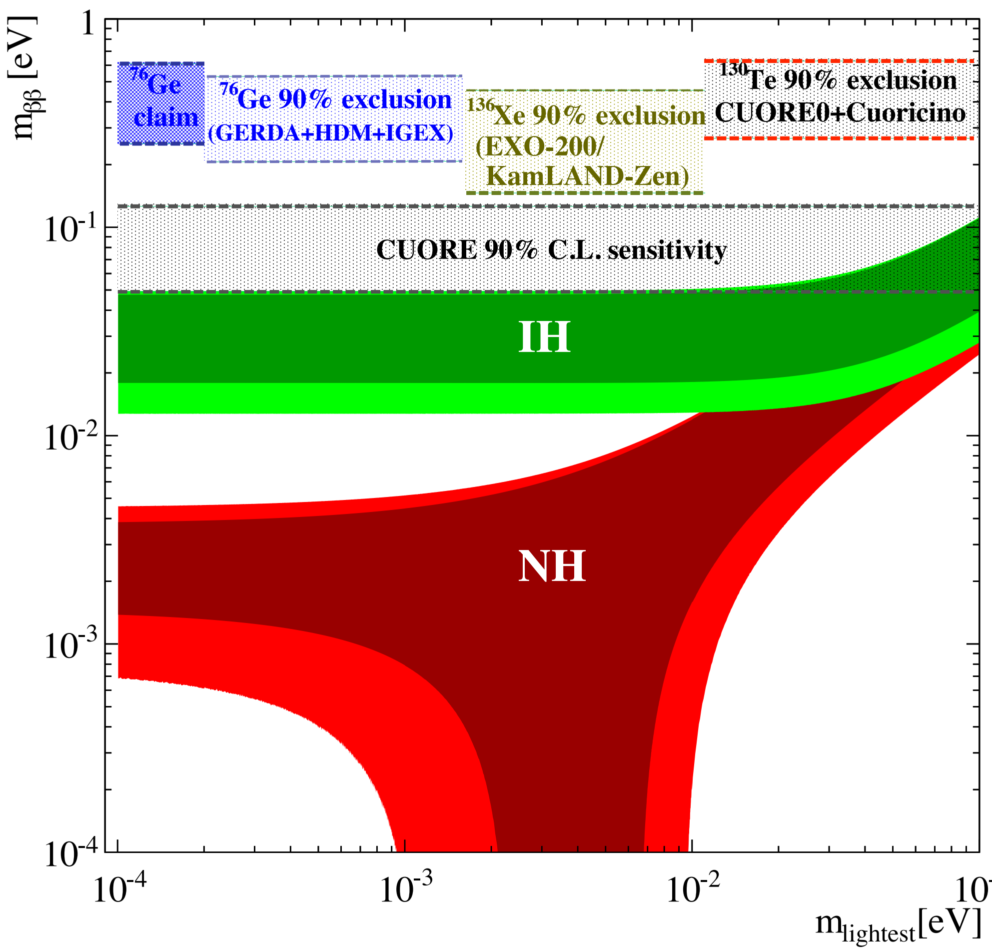
Cryostat Commissioning Underway



Detector installation expected in 2015

No 0νββ Signal Yet!

Limits on Effective Neutrino Mass



CUORE-0 Results

$\langle m_{\beta\beta}\rangle < 270 - 650$ meV

1) IBM-2 (PRC 91, 034304 (2015))
2) QRPA (PRC 87, 045501 (2013))
3) pnQRPA (PRC 024613 (2015)
4) ISM (NPA 818, 139 (2009))
5) EDF (PRL 105, 252503 (2010))

Including additional Shell-Model NME

$\langle m_{\beta\beta}\rangle < 270 - 760$ meV

1) IBM-2 (PRC 91, 034304 (2015))
2) QRPA (PRC 87, 045501 (2013))
3) pnQRPA (PRC 024613 (2015)
4) Shell Model (PRC 91, 024309 (2015))
5) ISM (NPA 818, 139 (2009))
6) EDF (PRL 105, 252503 (2010))

➔J. Engel

Towards a Next-Generation Experiment

Goals/Requirements

- Expect signals of **1 count/tonne-year for half-lives of 10^{27} years,** or **$<m_{\beta\beta}>\sim$ 15 meV.**
- For discovery aim for S:B of better than 1:1 in region of interest
- Region of interest can be single dimension (e.g. energy) or multi-dimensional (e.g. energy+fiducial)

Next Steps

International collaborations are building on current efforts using multiple isotopes:

- **^{76}Ge**: large Ge experiment, HPGE crystals, ton-scale
- **^{82}Se:** SuperNEMO, tracking and calorimeter, 100kg scale
- **^{136}Xe:**
    - nEXO, liquid TPC, 5 tonnes
    - NEXT/BEXT, high pressure gas TPC, tonne-scale
    - KamLAND-Zen, scintillator
- **^{130}Te:**
    - CUPID, bolometers+scintillation/Cherenkov light
    - SNO+ phase II, scintillator
- other efforts worldwide
- staged approach possible, some experiments pursue isotopic enrichment

Next Steps - SuperNEMO (^{82}Se)

Ionization Calorimetry

- Thin foil with tracking and calorimeter, based on successful NEMO3 detector.
- Planar and modular design: ~ 100 kg of enriched isotopes (20 modules × ~5-7 kg)
- Starting with single Demonstrator module, (7 kg of ^{82}Se) to show scalability
- $T_{0\nu 1/2} > 6.5 \times 10^{24}$ y → $\langle m\nu \rangle < 0.20 - 0.40$ eV @ (90 % C.L.)
- SuperNEMO
  - 100 kg of ^{82}Se running for 5 years
  - $T_{0\nu 1/2} > 1 \times 10^{26}$ y (90 % C.L.) $\langle m\nu \rangle <$ 40-100 meV
  - $T_{0\nu 1/2} = 2 \times 10^{25}$ y (5σ)

Demonstrator (1 module):

Source (40 mg/cm²) 4 x 3 m²

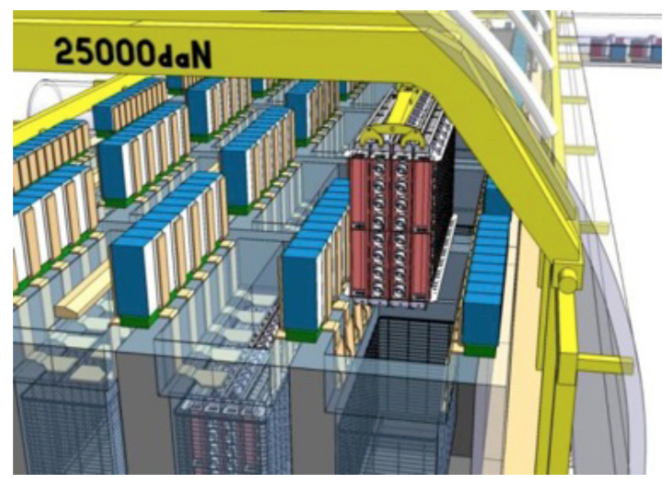
Tracking : drift chamber ~2000 cells in Geiger mode

Calorimeter: scintillators + PMTs

~550 PMTs+scint. blocks

Passive water shield

20 Modules 100 kg



LBR Resolution Meeting

Next Steps - Ge Experiment (^{76}Ge)

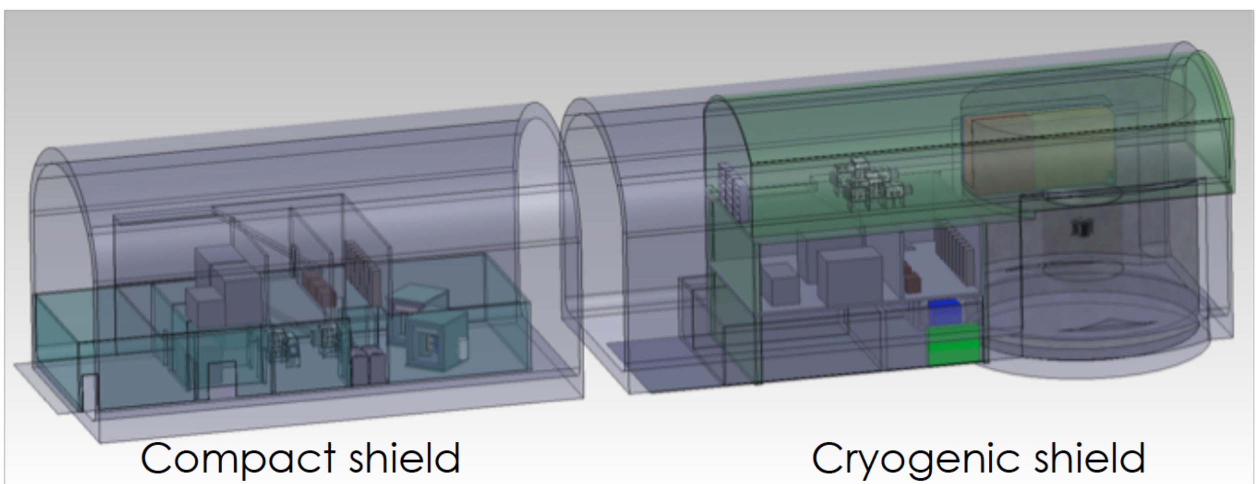
Ionization

- MAJORANA and GERDA are working towards the establishment of a single international ^{76}Ge $0\nu\beta\beta$ collaboration. (Name not set: Ge1T, LSGe, …)
- Envision a phased, stepwise implementation;

  e.g. 250 → 500 → 1000 kg

  5 yr 90% CL sensitivity: $T_{1/2} > 3.2 \cdot 10^{27}$ yr

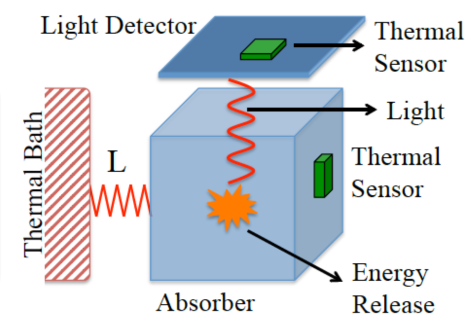
  10 yr 3σ discovery: $T_{1/2} \sim 3 \cdot 10^{27}$ yr
- Moving forward predicated on *demonstration* of projected backgrounds by MJD and/or GERDA
- Anticipate down-select of best technologies, based on results of the two experiments

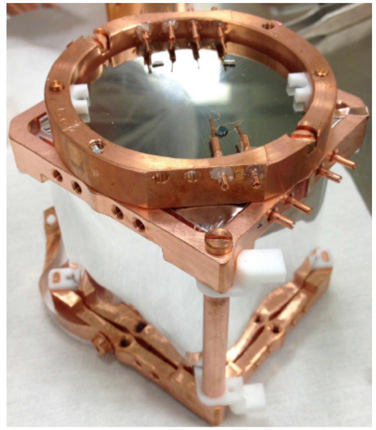


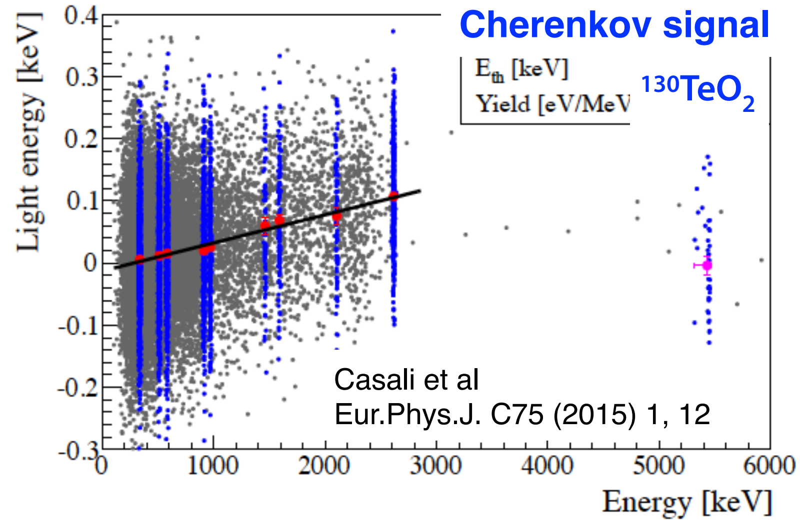
Next Steps - CUPID

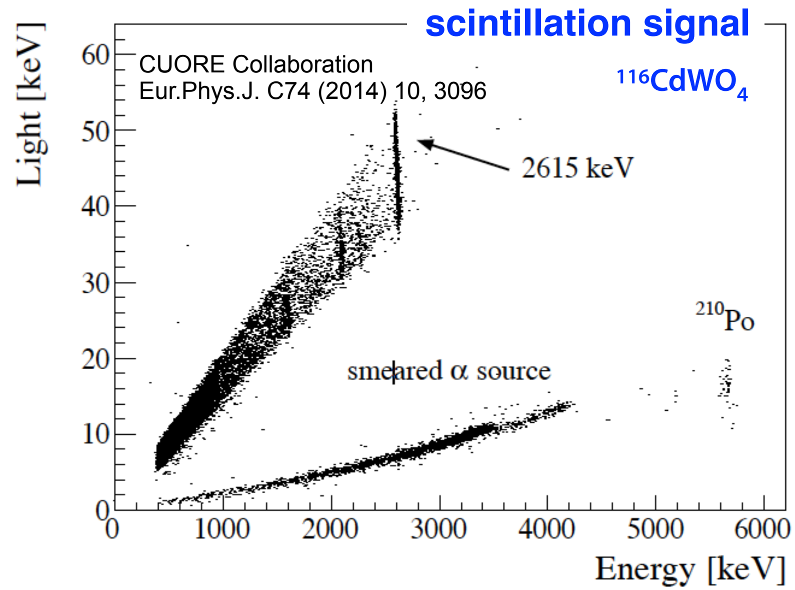
Phonons
Light

phonon+photon









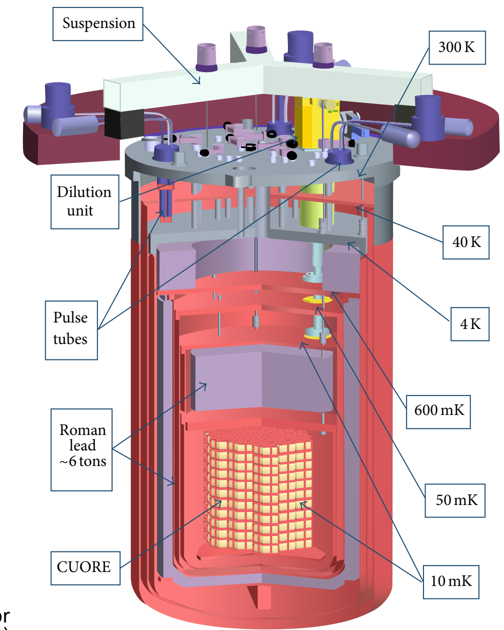
- Cherenkov light or scintillation to distinguish α from β/γ ($^{130}TeO_2$, $Zn^{82}Se$, $^{116}CdWO_4$, and $Zn^{100}MoO_4$)
- More rejection power needed: 99.9% α background suppression. Light detector R&D for better resolution.
- Background free search.

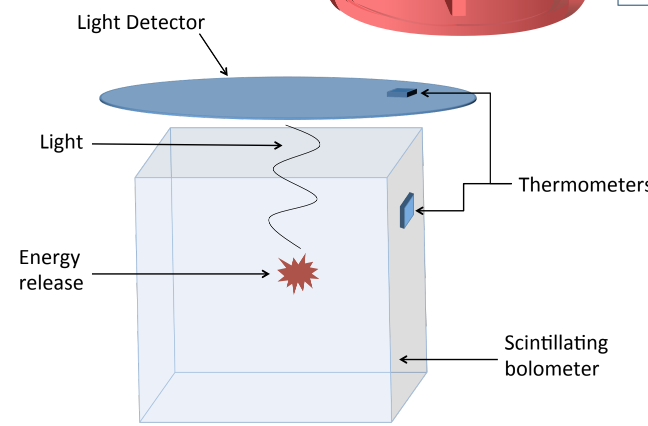
$$m_{\beta\beta} \sim (M \cdot t)^{-1/2}, \text{not } (M \cdot t)^{-1/4}$$

Next Steps - CUPID

Phonons
Light

- Next-generation bolometric tonne-scale experiment. Based on the CUORE design, CUORE cryogenics
  - Largest cryostat and DU built; mature technology
- 988 enriched (90%) crystals, PID with light detection
  - TeO_2 : phonons + Cherenkov detector
  - Options: ZnSe, $ZnMoO_4$, $CdWO_4$ (phonons +scintillation)
- Aim for zero-background measurement
- Sensitivity to inverted hierarchy region
  - CUORE geometry and background model
  - 99.9% α rejection @ >90% signal efficiency (5σ separation of α and β)
  - 5 keV FWHM resolution
  - Aim for nearly zero background measurement: background goal <0.02 events / (ton-year)
  - Half-life sensitivity (2-5)×10^{27} years in 10 years (3σ)
  - $m_{\beta\beta}$ sensitivity 6-20 meV (3σ)





R. Artusa et al., Eur.Phys.J. **C74**, 3096 (2014)
White papers: arXiv:1504.03599, arXiv:1504.03612

Next Steps - SNO+ (^{130}Te)

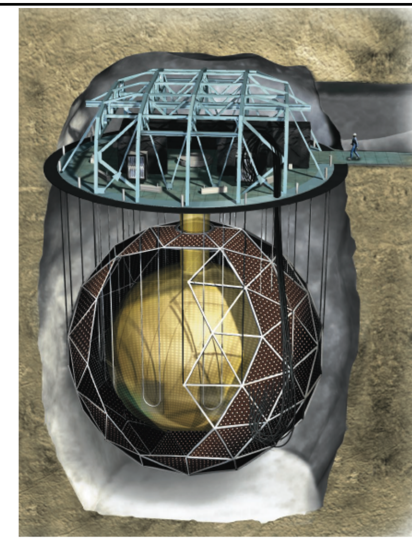
Scintillation

- 3% loading of Te already demonstrated
- Detector response model from Phase I predicts Phase II response

  Plug-in replacement of SNO+ PMTs with R5912-HQEs more than doubles light yield for Phase II

  Additional wavelength-shifter R&D could further improve this
- Containment bag R&D necessary to achieve cleanliness

  Can leverage KamLAND-Zen and BOREXINO knowledge



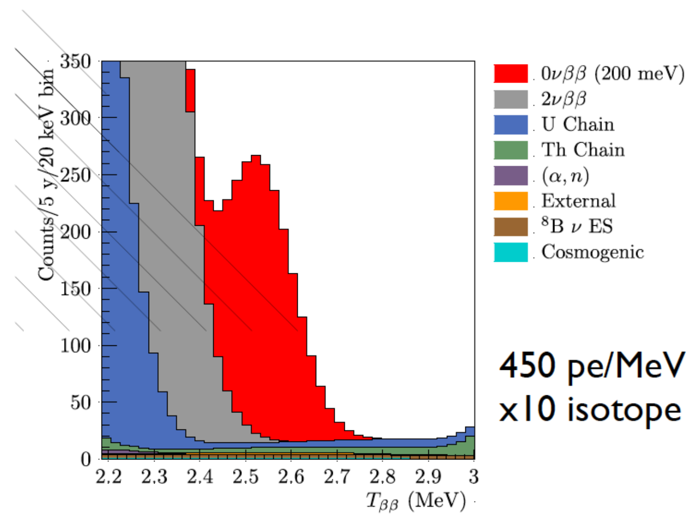
Phase II: $T_{1/2} > 7 \times 10^{26}$ y (90% CL, natural)

$T_{1/2} > 10^{27}$ y (90% CL, enriched)

$T_{1/2} > 4 \times 10^{26}$ y (3σ, natural)

External γ and ^{8}B backgrounds are fixed

(but fewer in ROI because of increased light yield)

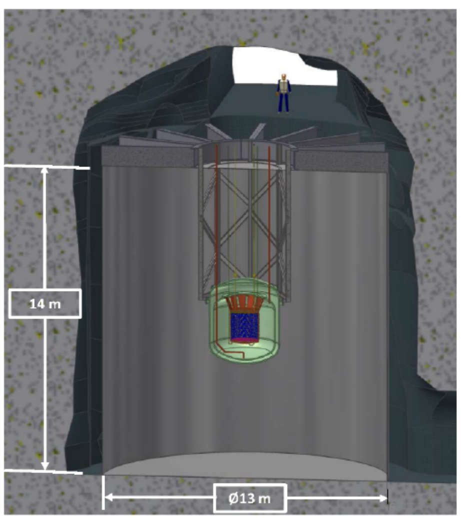


→N. Barros

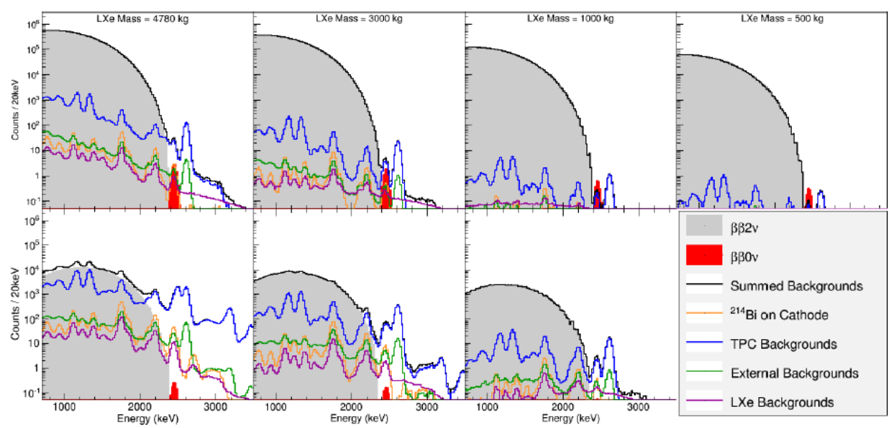
Next Steps - nEXO (^{136}Xe)

Ionization
Scintillation

- 5 tonnes of ^{enr}Xe
- nEXO 5 yr 90% CL sensitivity: $T_{1/2} > 6.6 \cdot 10^{27}$ yr
- LXe homogeneous imaging TPC similar to EXO-200:
  - baseline: install at SNOLAB (cosmogenic background reduced wrt EXO-200)
  - simultaneous measurement: energy, spatial extent, location, particle ID
  - Multi-parameter approach improves sensitivity: strengthens proof in case of discovery
  -inverted hierarchy covered with a well proven detector concept
  -possible later upgrade for Ba retrieval/tagging: start accessing normal hierarchy



Deeper into fiducial volume →

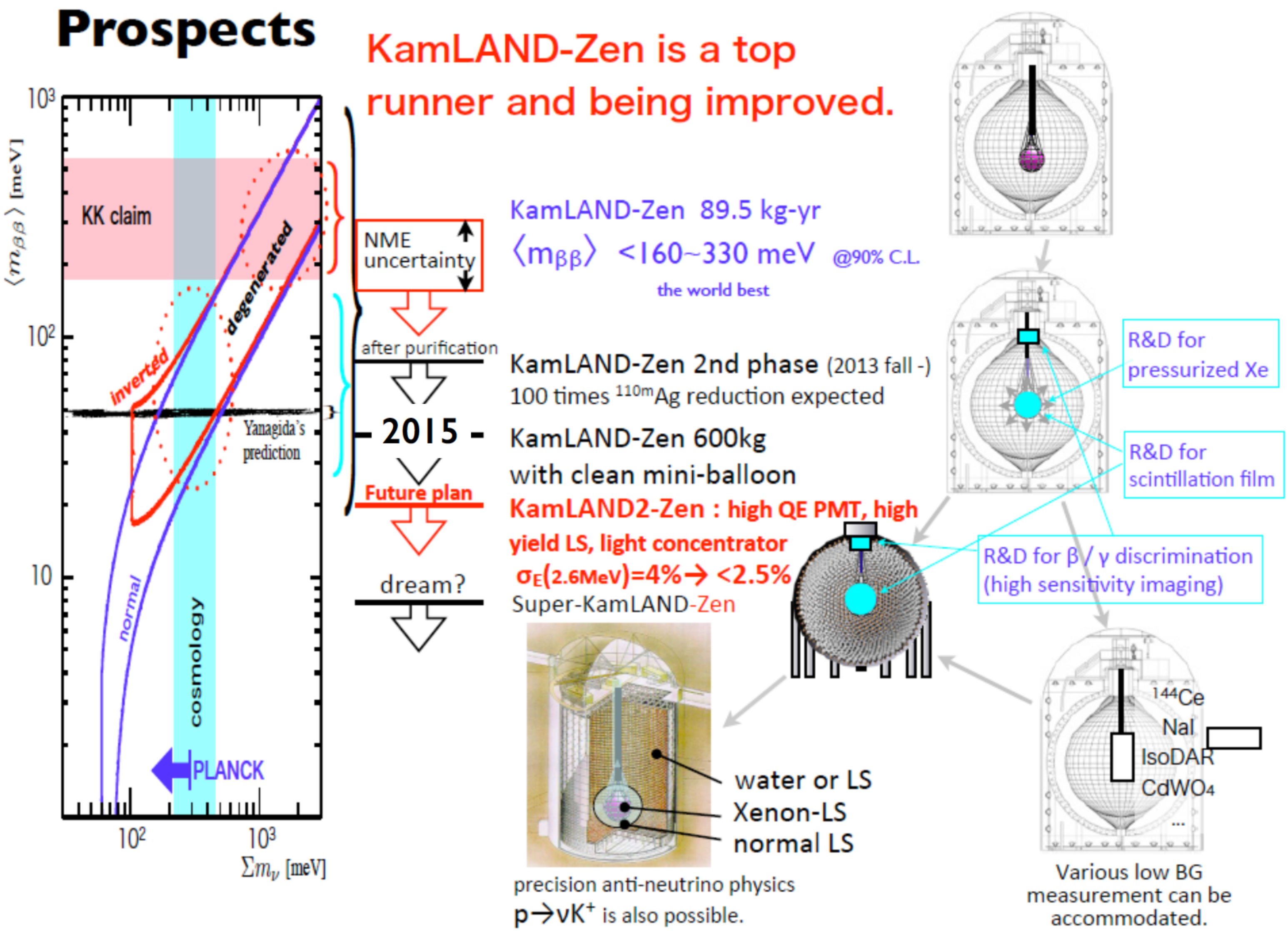


Single-site,
Mainly signal,
2ν and 0ν

Multi-site,
Mainly
background

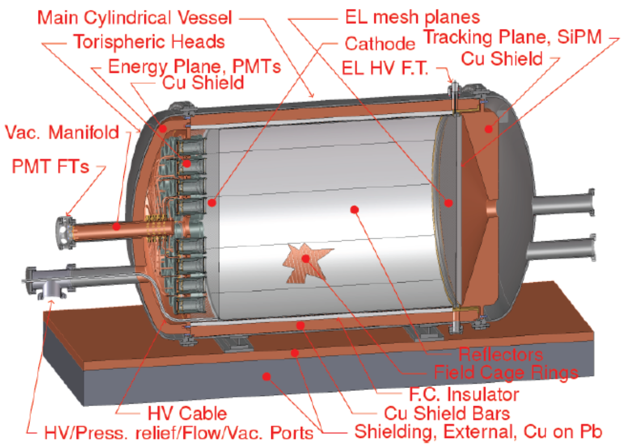
Next Steps - KamLAND Zen (^{130}Xe)

Scintillation



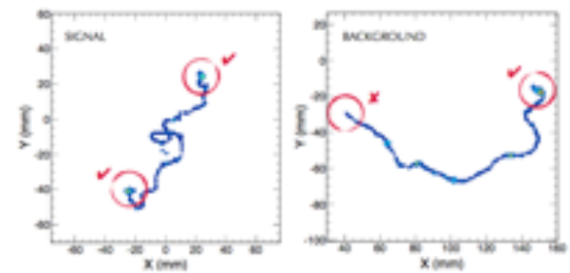
Next Steps - BEXT (^{136}Xe)

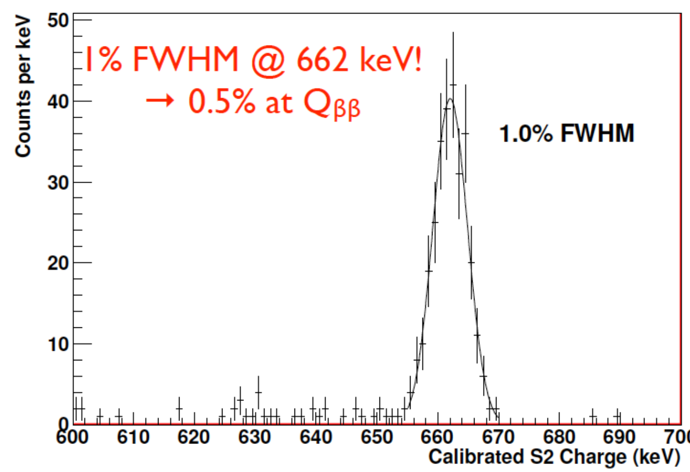
- NEXT with a Magnetic field



NEW - 10 kg prototype at the LSC

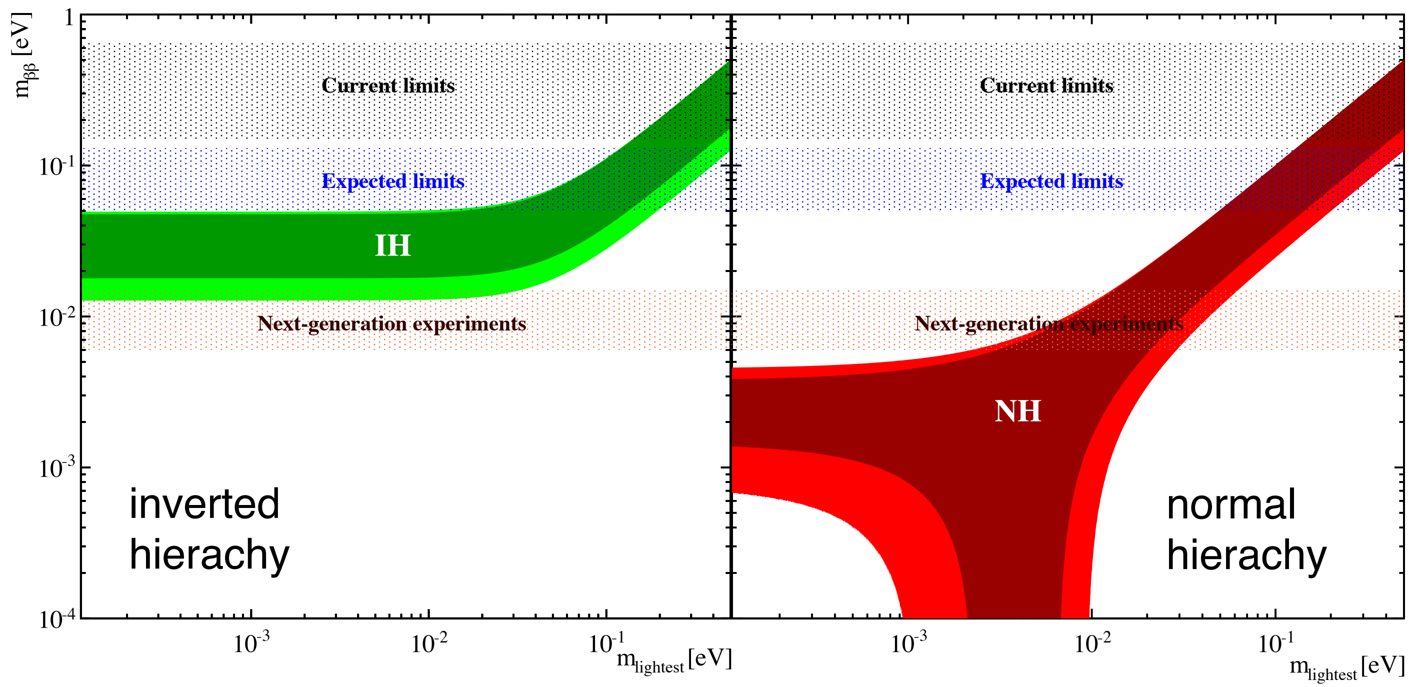
- HP^{136}Xe TPC + EL for high E- resolution + tracking capability
- Tonne-scale sensitivity: $m_{\beta\beta}$ < 15 meV in 10 t-y





Next Frontier - Future Searches for 0νββ

Towards Exploring the Inverted Hierarchy



$T_{1/2}$ ~ 10^{24} yrs
~1 eV
kg scale

$T_{1/2}$ ~ 10^{25} -10^{26} yrs
~100 meV
30-200kg scale

$T_{1/2}$ ~ 10^{27} -10^{28} yrs
~15 meV
ton scale (phased)

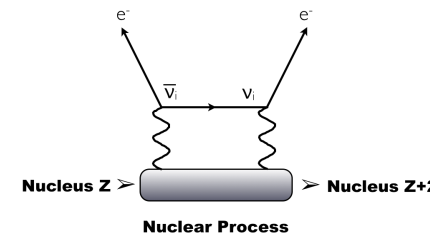
Ton scale experiments will make discovery if
- spectrum has inverted ordering
- $m_{lightest}$ > 50 meV (irrespective of ordering)

improvement of x100 over current results

significant discovery potential

Summary

Neutrinoless double beta (0vββ) is the most powerful and comprehensive probe of lepton number violation (ΔL=2).



Observation would establish lepton number violation, demonstrate that neutrinos are Majorana, and indicate physics beyond Standard Model.

Current experiments probe half lives of 10^{25}-10^{26} years and are demonstrating background reduction and scalability of experimental techniques. Expect new results in next 2-3 years.

Tonne-scale experiments have significant discovery potential, reaching half lives of 10^{27}-10^{28} years.

Ready for a world-wide program of 0vββ searches with different techniques and isotopes, underground locations are available.

We are poised to look for 0vββ down to $\langle m_{bb} \rangle$ ~15 meV, covering the inverted hierarchy.

Exciting years ahead!

Many thanks to all colleagues who contributed with slides to this talk