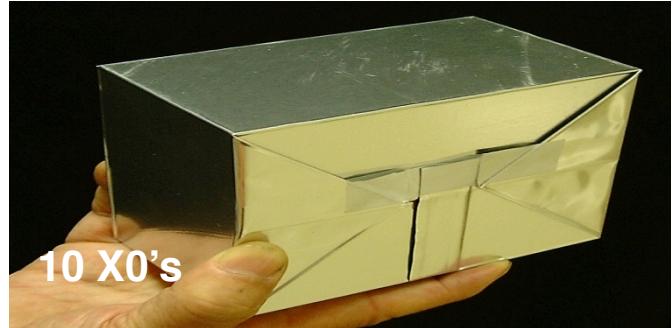
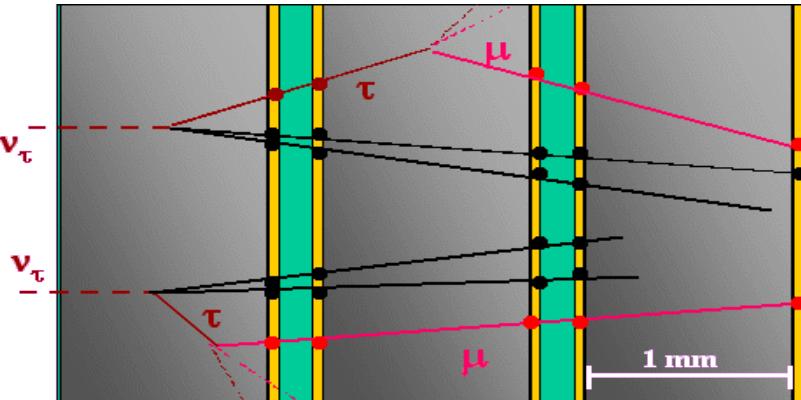
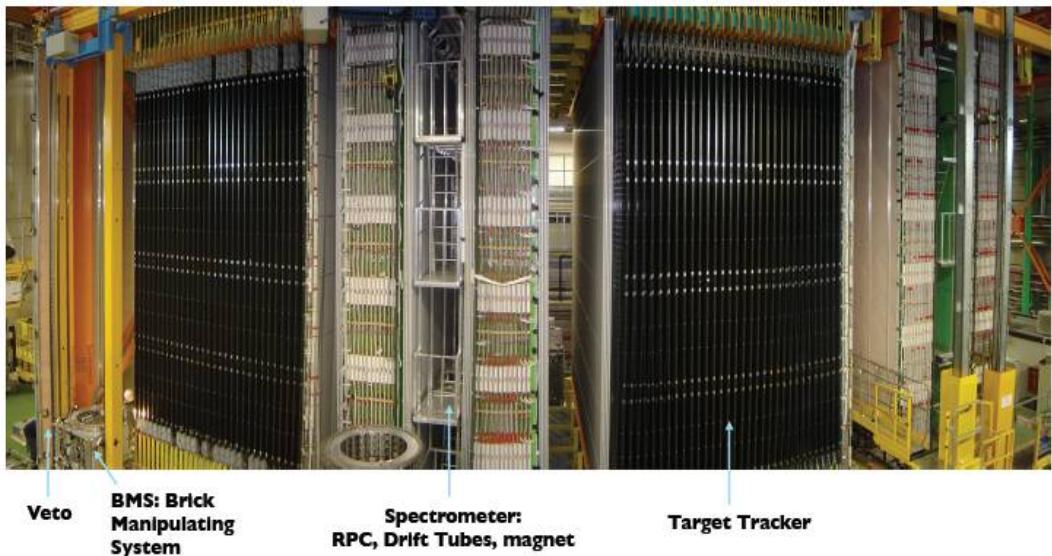


Lead-Emulsion Detector (OPERA)

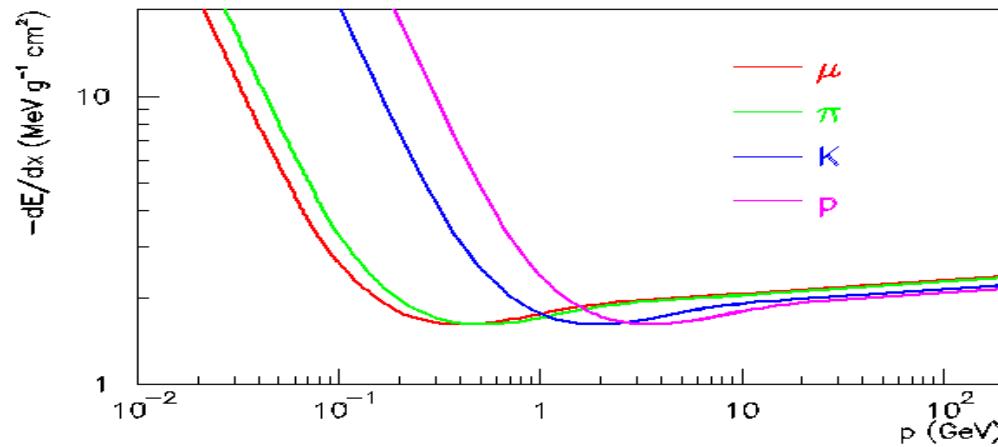


- 1.2kT emulsion detector
 - 146621 bricks, each 8.3kg
 - 56 (1mm) Pb sheets
 - 57 (300mm) FUJI emulsion layers
 - 2 (300mm) changeable sheets (CS)



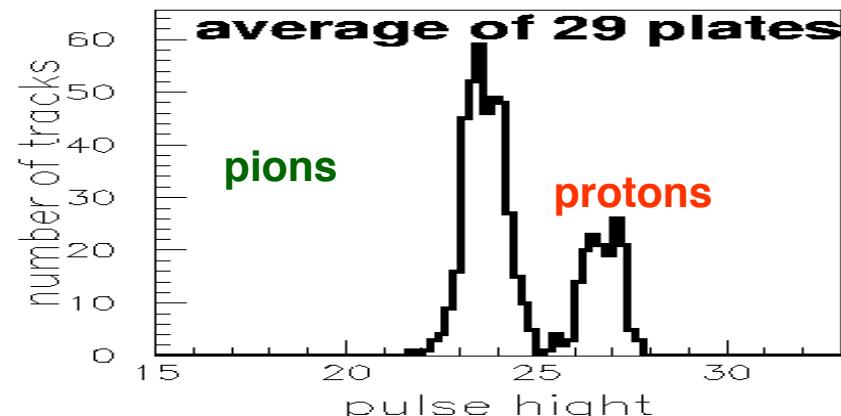
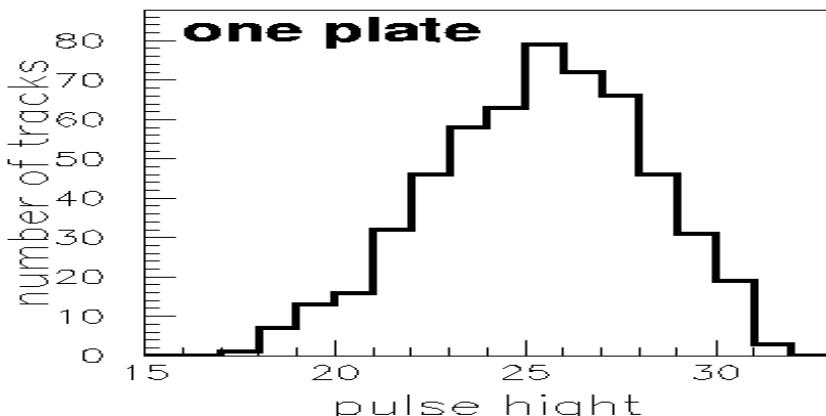
Particle ID in Emulsion

Grain density in emulsion is proportional to dE/dx

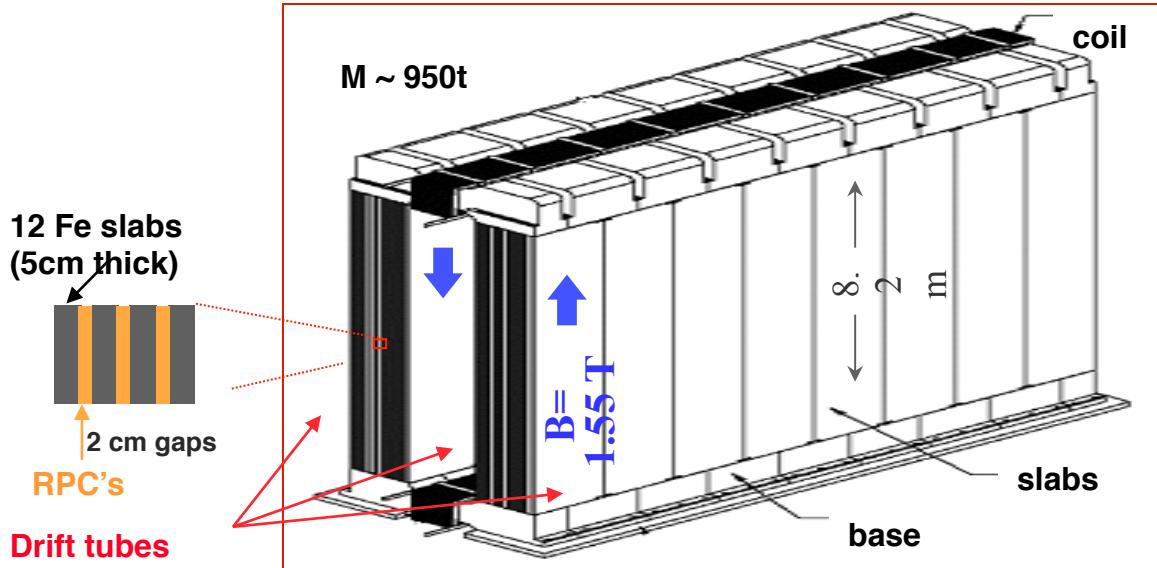


By measuring grain density as a function of the distance from the stopping point, particle identification can be performed.

Test exposure (KEK) : 1.2 GeV/c pions and protons, 29 plates



Muon Spectrometer w/ RPC



$\Delta p/p < 20\%$,
 $p < 50 \text{ GeV}/c$

μ charge
Mis-id prob.
 $\approx 0.1 \div 0.3\%$

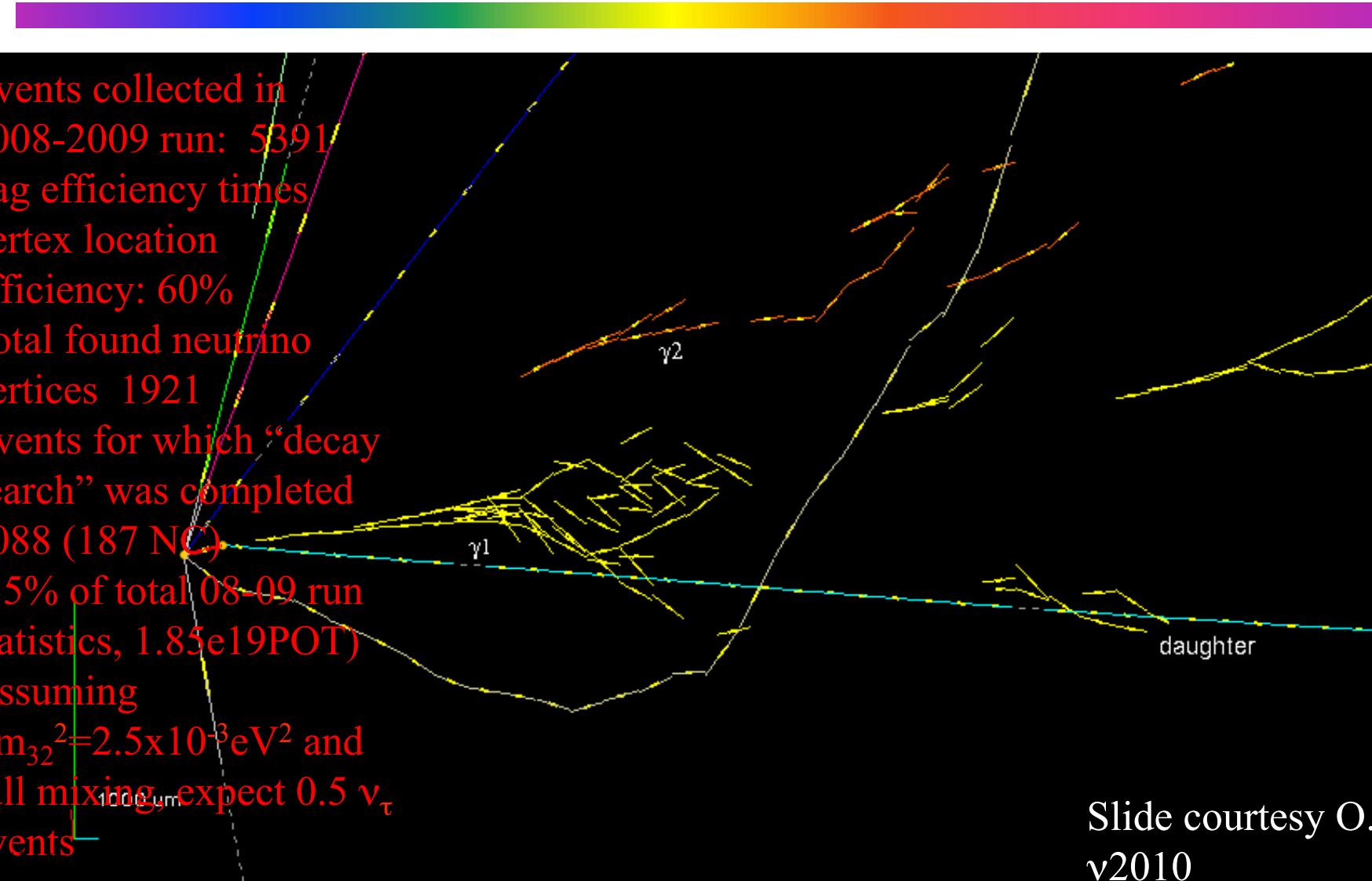
μ identification:
 $\mu\varepsilon > 95\%$ (TT)

Precision tracker:
6 planes of drift tubes
diameter 38mm, length 8m
efficiency: ~99%
space resolution: ~300 μm

Inner Tracker:
11 planes of RPC's
21 bakelite RPC's ($2.9 \times 1.1 \text{ m}^2$) / plane
(~1,500 m^2 / spectrometer)
pickup strips, pitch:
3.5cm (horizontal), 2.6cm (vertical)

RPC: gives digital information about track: has been suggested for use in several “huge mass steel detectors” (Monolith)

First Tau Neutrino Detected



Outstanding Issues



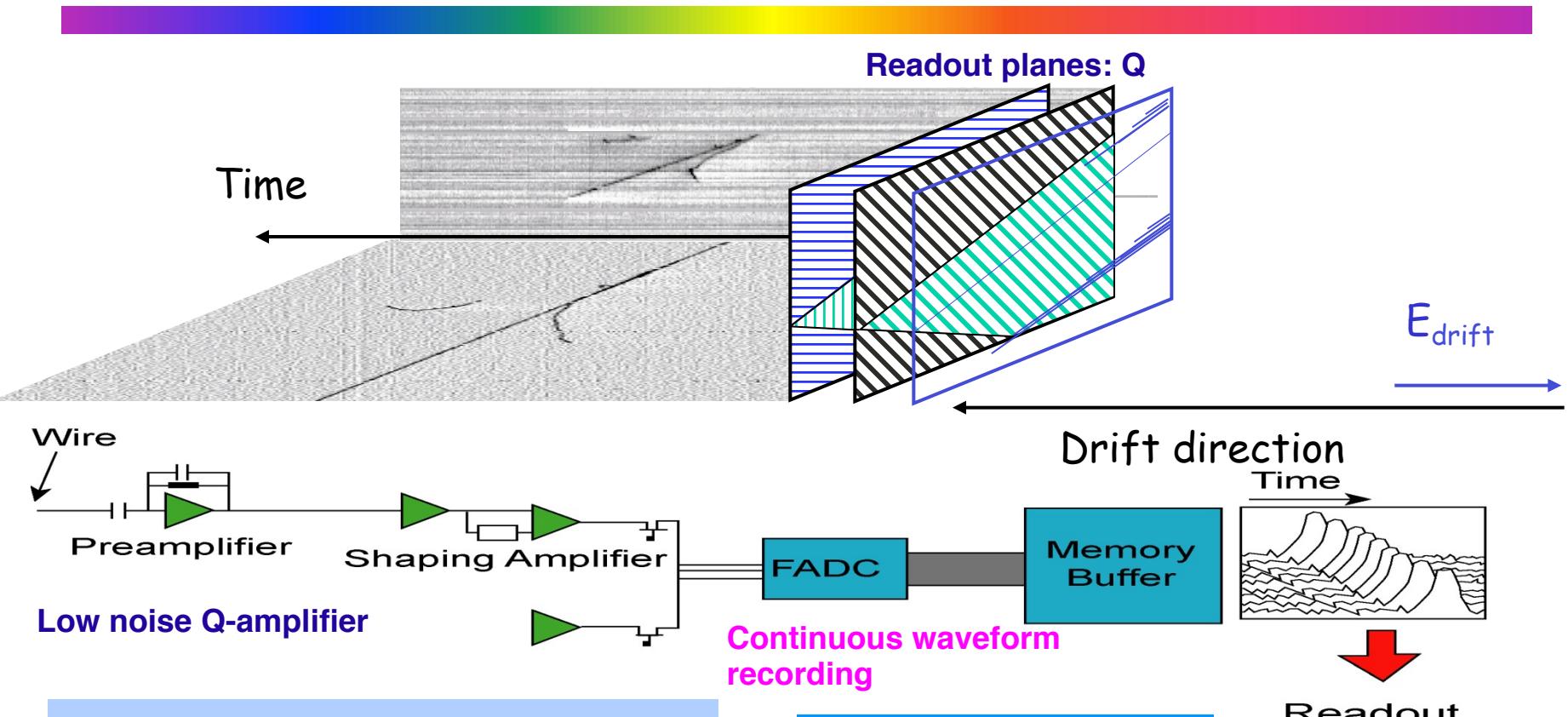
Sampling Detectors

- Any way to make these detectors cheaper?
 - Cheaper absorber
 - Cheaper readout
 - Less segmentation

LIQUID ARGON TPC



Liquid Argon Time Projection Chamber



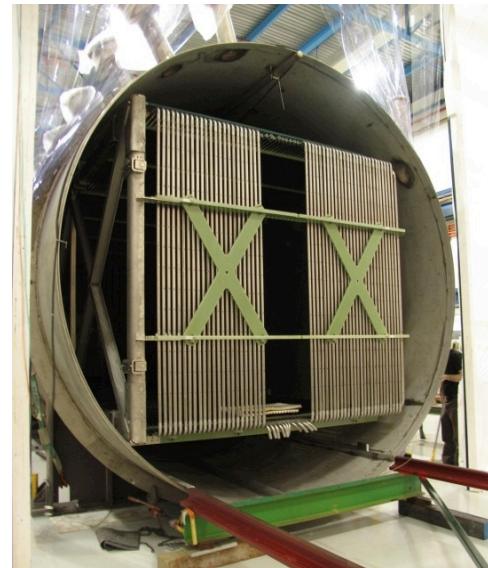
•INGREDIENTS

- VERY PURE ARGON
- STRONG ELECTRIC FIELD
- SEVERAL PLANES OF WIRES

$dE/dx(mip) = 2.1 \text{ MeV/cm}$
 $T=88K @ 1 \text{ bar}$
Density: 1.4 g/cm^3
 $X_0=14\text{cm}$
 $l_{INT}=83\text{cm}$

ICARUS/MicroBooNE

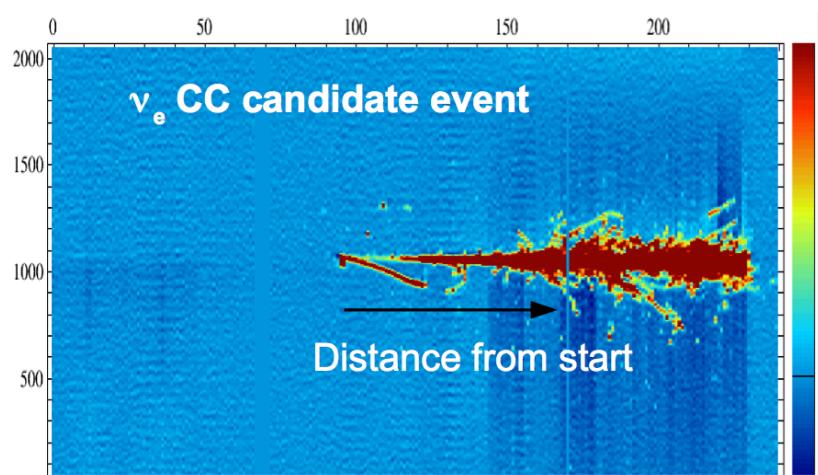
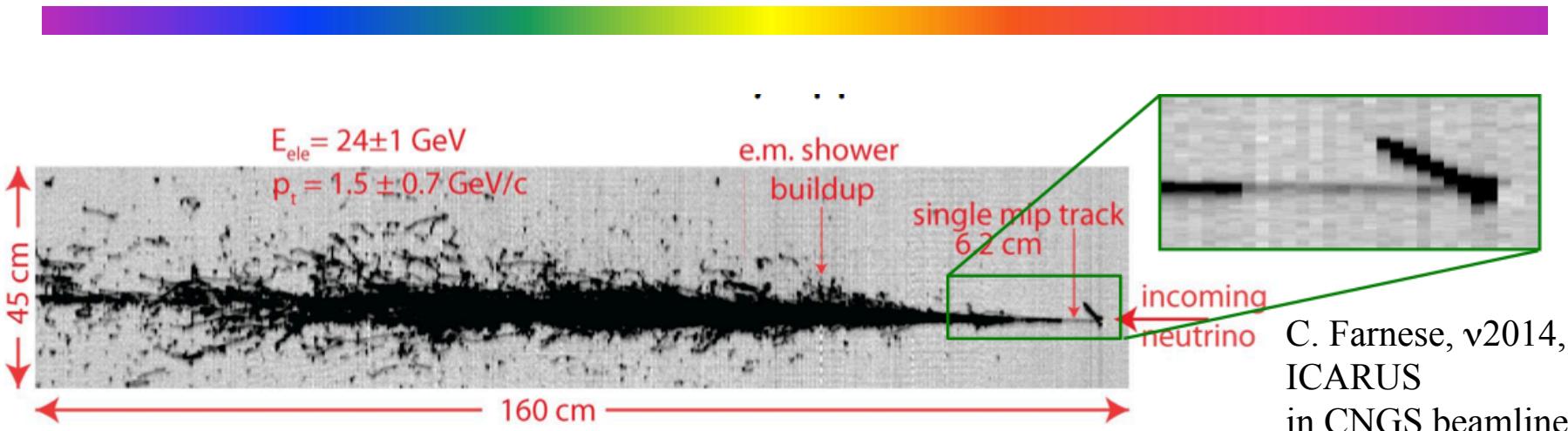
- Active mass: 476 tons / 87 tons
- Wire spacing: 3mm (both)
- Electron drift distance: 1.5m/2.5m
- 54000 wires/10000 wires
- 74 PMT's/ 30 PMT's for scintillation light from pure Argon (timing)
- ICARUS: $\langle E_\nu \rangle \sim 20\text{GeV}$, L=730km
 - Took data in CNGS beamline
- MicroBooNE: $\langle E_\nu \rangle \sim 0.8\text{GeV}$, L=1km
 - About to take data in MiniBooNE beamline (BNB)



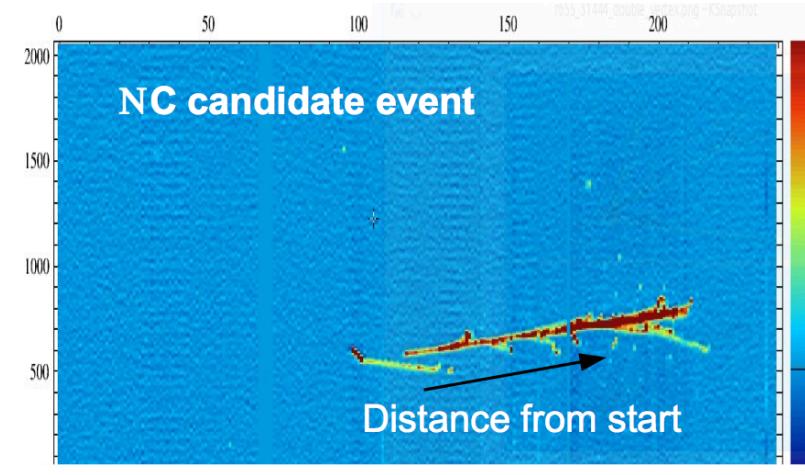
A. Guglielmi, v2010/ A. Szelc, v2014

Examples of Liquid Argon Events

- Lots of information for every event...



A. Szelc,
v2014,
Argoneut
in NuMI
beamline



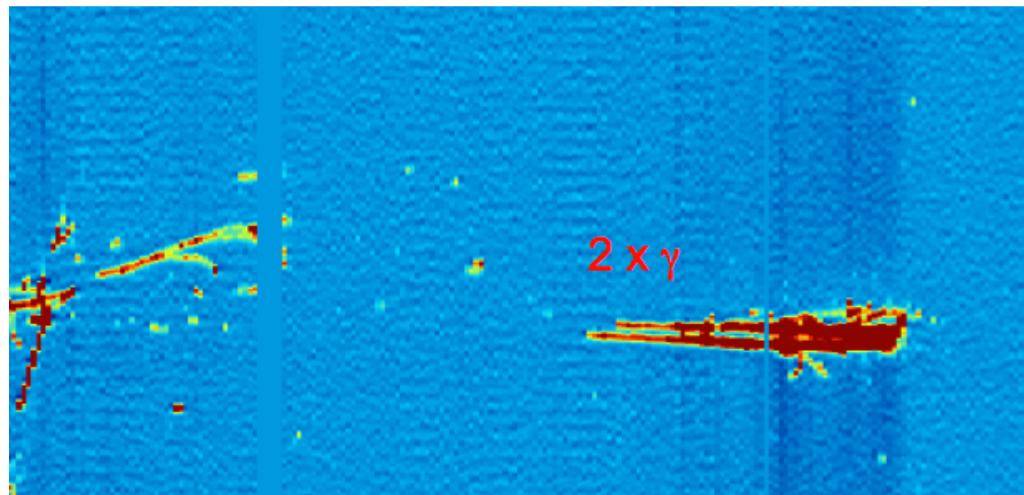
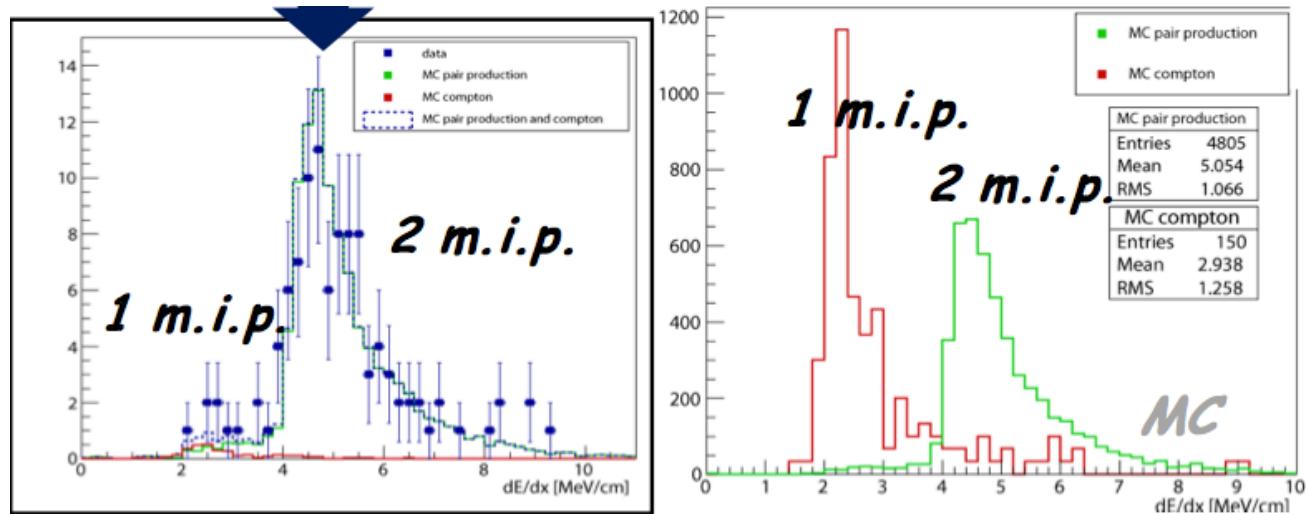
π^0 identification in Liquid Argon

One photon converts to 2 electrons before showering, so dE/dx for photons is higher...

Questions:

What do you expect for the efficiency of this cut for electrons?

What about the rejection factor for π^0 's?



A. Szelc,
v2014,
Argoneut
in NuMI
beamline

Oustanding Issues

Liquid Argon Time Projection Chamber

- Can a magnetic field be applied
- How well can neutral currents be rejected in practice?
- Can the electronics be put inside the cryostat?
- How does the cost scale with size?
 - How large can one module be made?
 - What is largest possible wire plane spacing?



Several R&D Efforts world-wide working to get >10kton detectors “on the mass shell”

Detector Summary



Detector Technology	Largest Mass to Date (kton)	Event by Event Identification			+/-?	Neutrino Energy Measurement
		ν_e	ν_μ	ν_τ		
LAR TPC	0.6	✓	✓		Not yet	Visible Energy
Water Cerenkov	50	✓	✓			CCQE hypothesis
Emulsion/Pb/Fe	0.27	✓	✓	✓		Particle ID (energy)+ μ spectrometer
Scintillator++	14	✓	✓			Visible Energy
Steel/Scint.	5.4		✓		✓	Visible energy + μ spectrometer

Absolute Mass Measurements

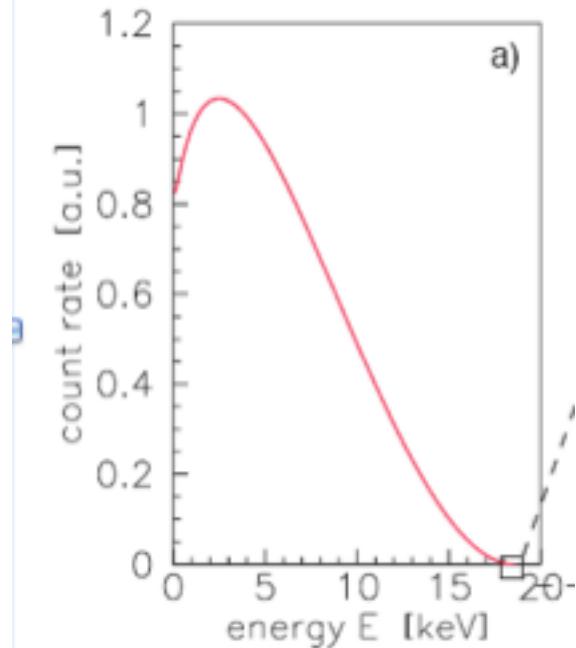


- Experimental considerations
- Current State of the art: KATRIN
- Possible next step: Project 8

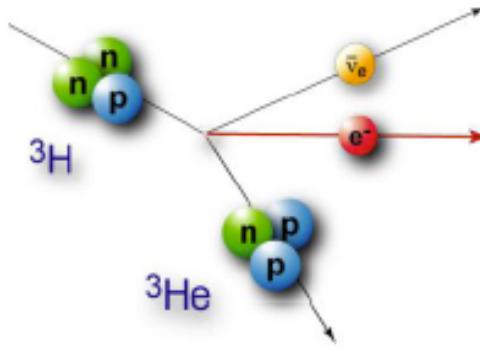
For much more detail, see lectures by L. Yang, INSS 2013

[http://indico.ihep.ac.cn/getFile.py/access?
contribId=28&resId=0&materialId=slides&confId=2999](http://indico.ihep.ac.cn/getFile.py/access?contribId=28&resId=0&materialId=slides&confId=2999)

Measuring Weak Decay Kinematics



β decay: $(A, Z) \rightarrow (A, Z+1)^+ + e^- + \bar{\nu}_e$



$$m_e \sim 0.5 \text{ MeV}, \quad m_{n,p} \sim 1 \text{ GeV}$$

Nuclear recoil is small, but not too small for tritium decay, $\sim 3 \text{ eV}$, is this a problem?

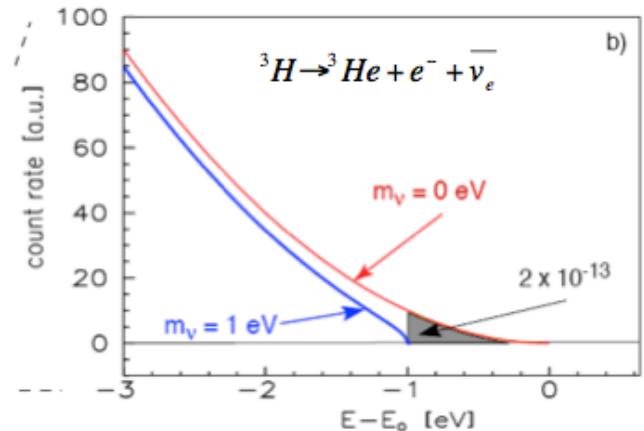
Goal: measure spectral shape near the end point precisely,

- Choose a system to study (several isotopes available, ${}^3\text{H}$ discussed)
- Choose a detection method
- Background and systematics , etc (not discussed here)

-For much more information, see Liang, INSS 2013

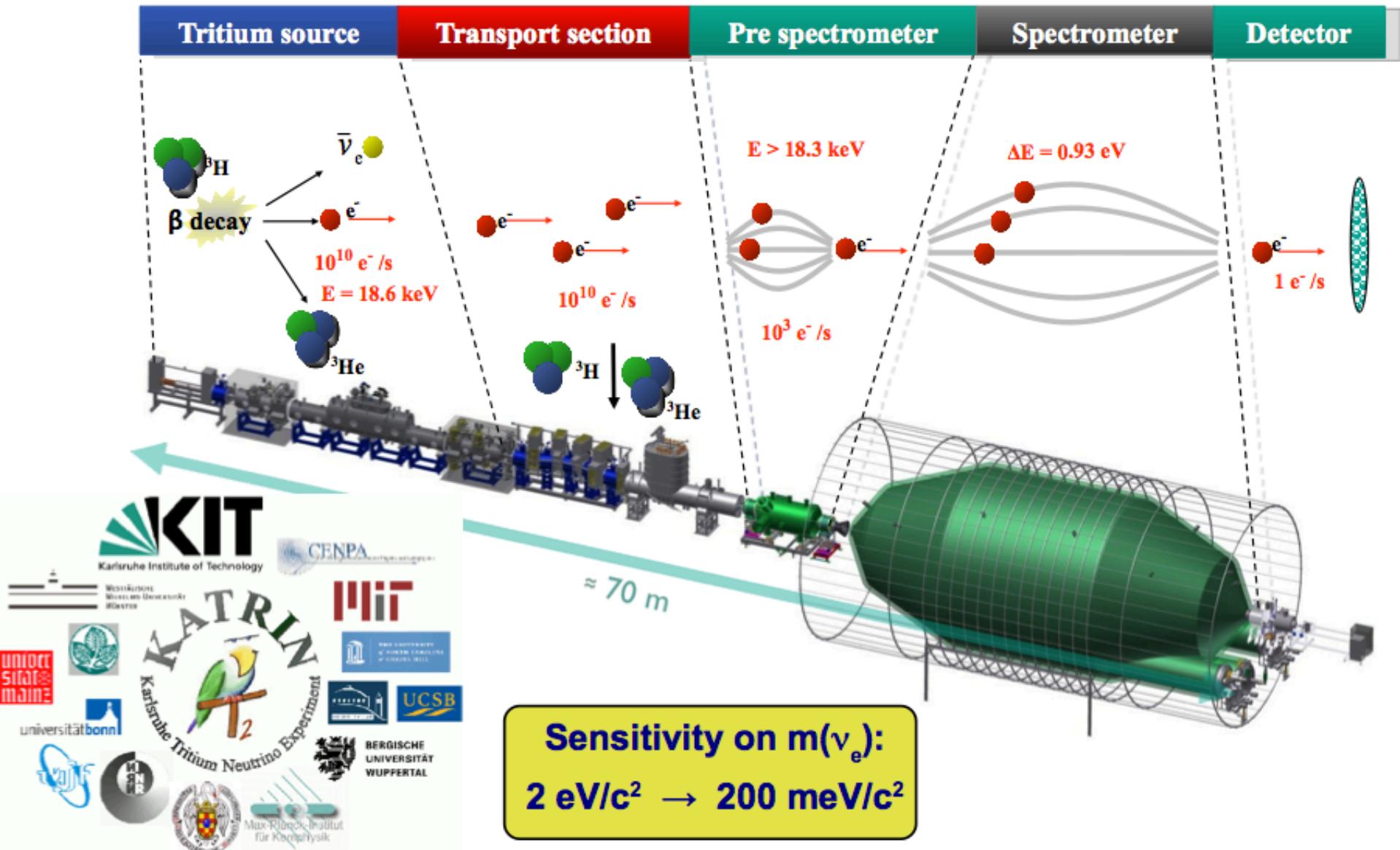
Choosing a Weak Decay to Study

- Low Q values
- High decay rate
- Simple final states
- Isotope availability
- Well understood spectral shape



$$\frac{n(\Delta E)}{n} \propto \left(\frac{\Delta E}{E_0} \right)^3$$

Overview of Katrin Experiment



Principle of MAC-E-Filter

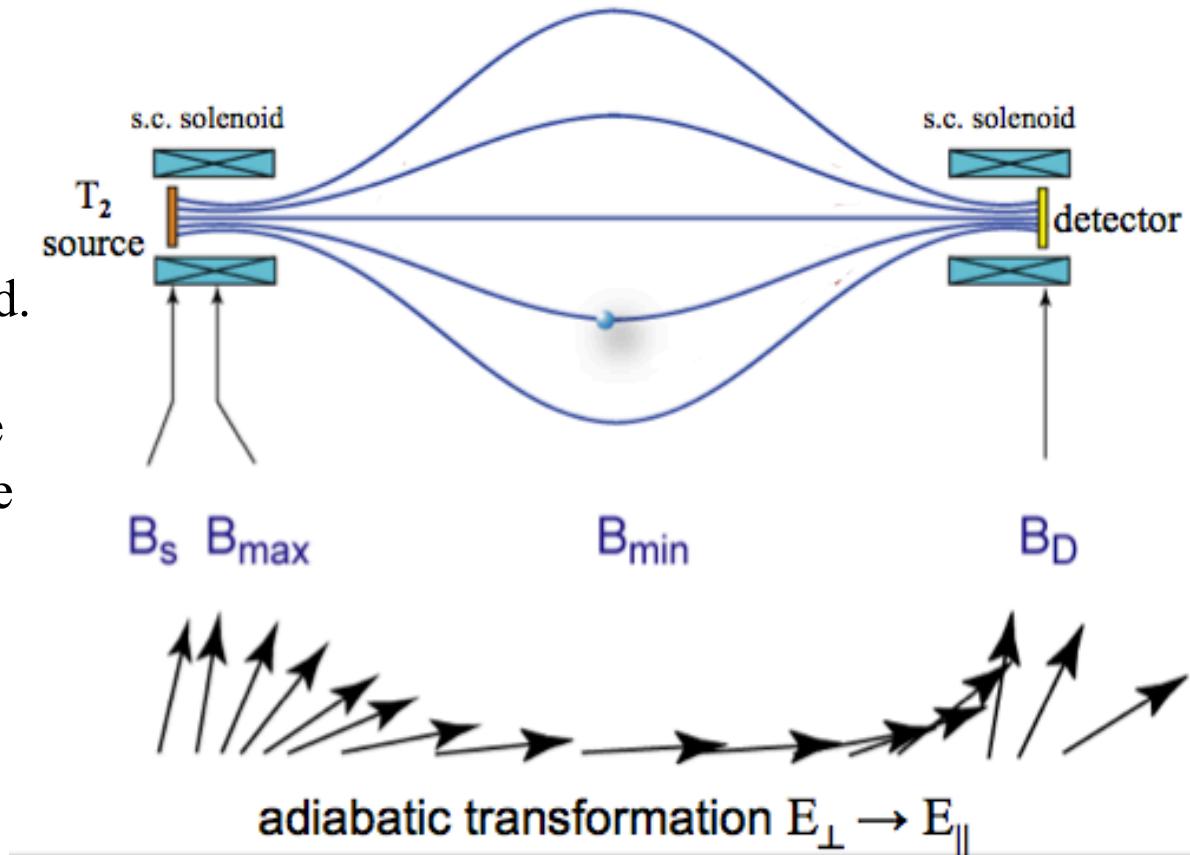
Magnetic Adiabatic Collimation + Electrostatic Filter

A. Picard et. al., Nucl. Instr. Meth. B 63, 345 (1992)

- Two superconducting solenoids with $B_{\max} = 3\text{-}6 \text{ T}$, and $B_{\min} < 1 \text{ mT}$ produce the magnetic guiding field.
- T_2 source in the left solenoid.
- Forward going electrons are adiabatically guided along the magnetic field lines

$$\vec{F} = (\vec{\mu} \cdot \vec{\nabla}) \vec{B} + q \cdot \vec{E}$$

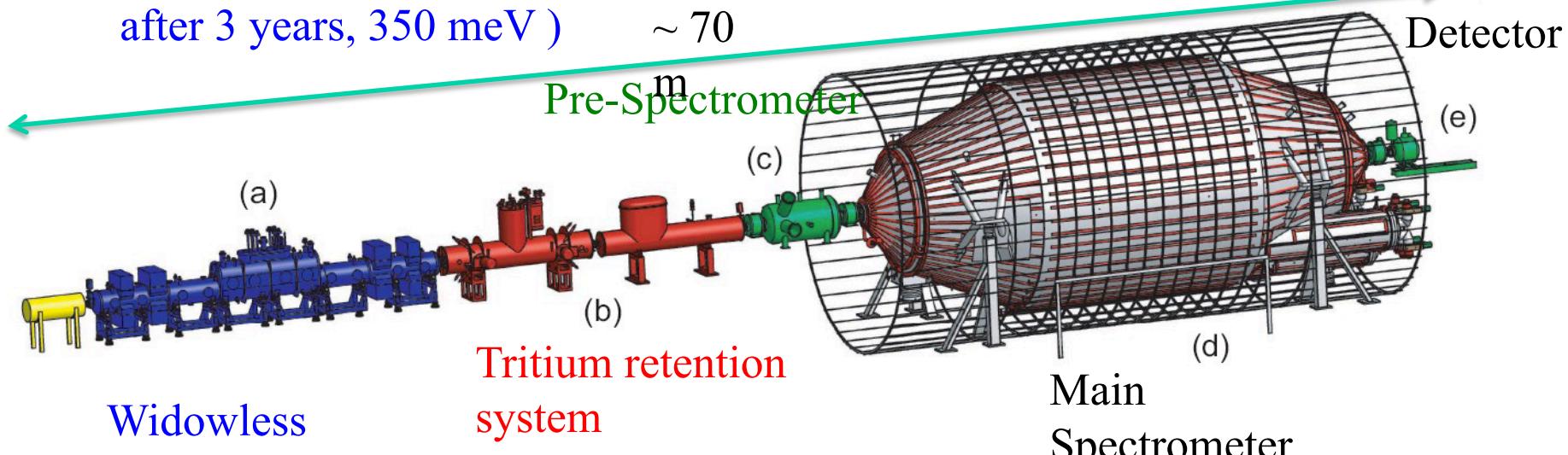
$$\mu = E_{\perp}/B = \text{const.}$$



KATRIN Goals

(Karlsruhe TRItrium Neutrino Experiment)

Goal: Improve the current tritium neutrino mass limit around 2 eV by an order of magnitude to 200 meV. (Need to improve β spectroscopy by 2 orders of magnitude, discovery potential (5σ) after 3 years, 350 meV) ~ 70



Widowless
gaseous T_2
source (WGTS)

Tritium retention
system

- Increase source strength by x 100, measurement time x 10
- Improve energy resolution by x 4
- Background rate $< 10^{-2}$ cps

KATRIN design report

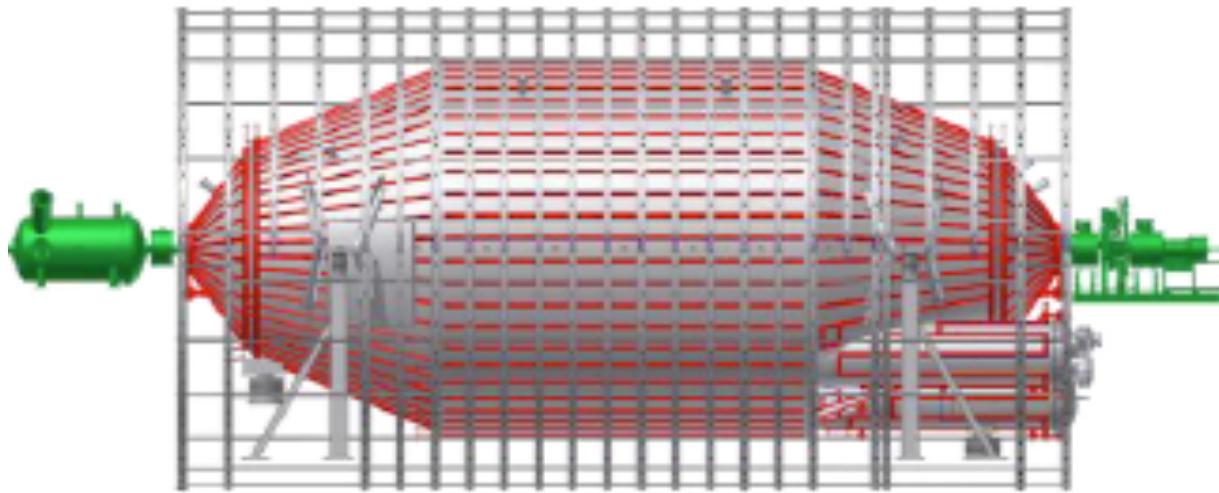
KATRIN: Main Spectrometer – a long way home



- Main spectrometer, 24 m long, 10 m in diameter, 200 ton
- Too large to be shipped on roads, water comes to rescue.
- 400 km journey turned into an 8000 km odyssey.

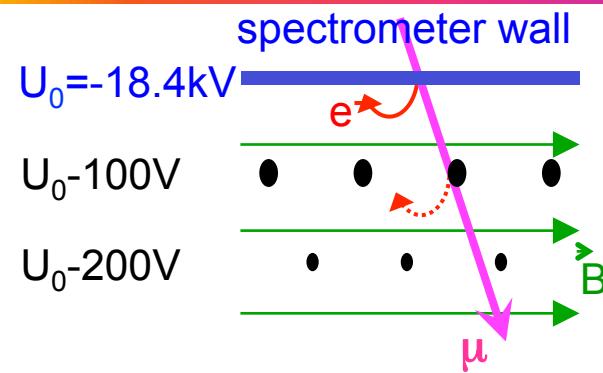
http://www.youtube.com/watch?feature=player_embedded&v=dmmVb779NP4

KATRIN: Main Spectrometer



- Superb analyzer power, $\Delta E = 0.93$ eV. Scanning voltage varies in 0.5 – 1 V steps.
- Air coil to compensate for earth magnetic field, central field 3 Gauss.
- HV stability monitored by another spectrometer, using ^{83m}Kr source
- Huge UHV vessel, (1240 m^3), $< 10^{-11}$ mbar, vacuum baking at 300 C.
- Large surface area, $A \sim 650 \text{ m}^2$, source of background electrons?

KATRIN: Wire Grid System

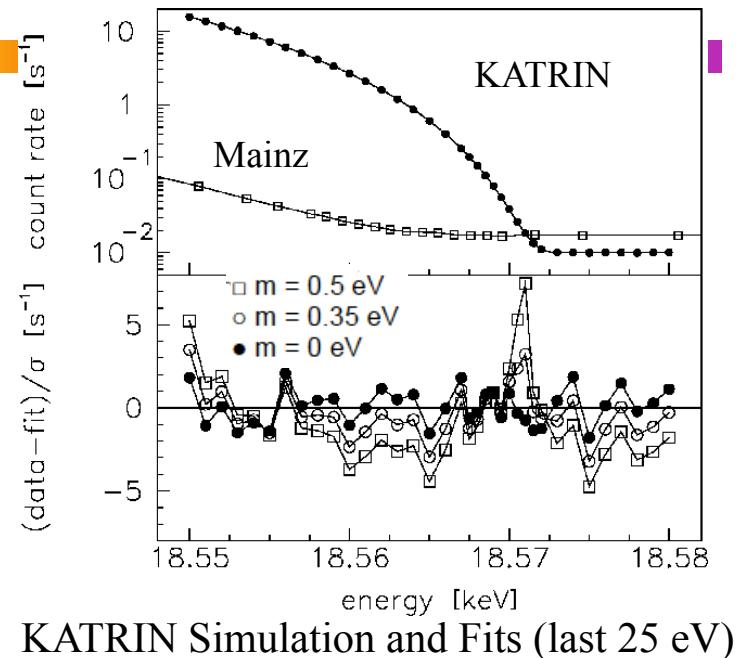
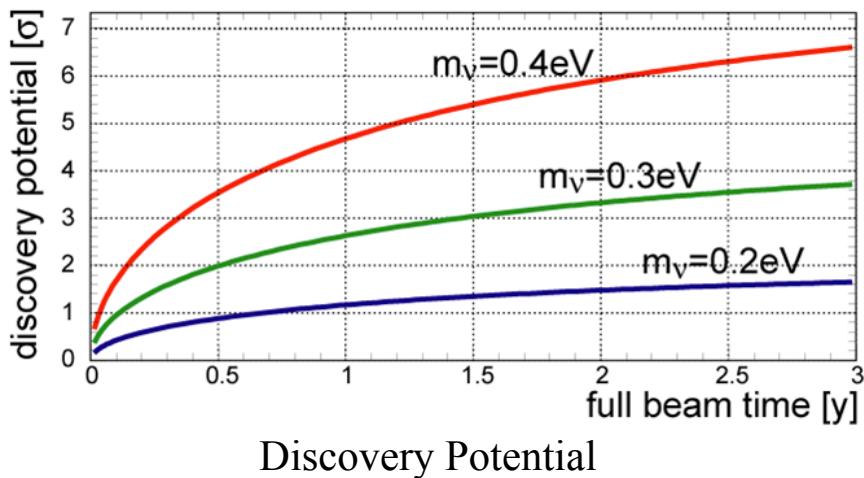


- >23000 wires in 250 frames
- stringent mechanical requirements
- Suppressing background electrons from the chamber wall.
- Fine shaping of the retarding potential
- reduce electrical field fluctuation and active filtering of stored electrons

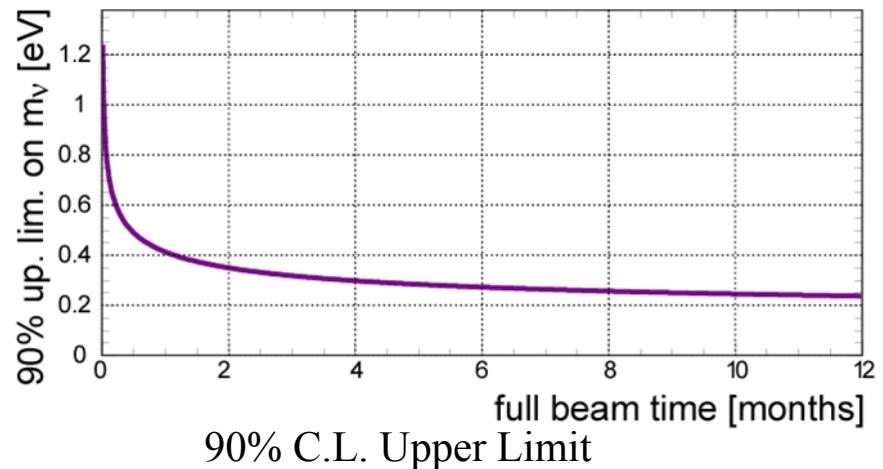
KATRIN: Status and Sensitivity

Weinhermer, NuMass 2013

- All major systems under testing or commissioning, data taking expected to take place in the first half of 2015
- Three years or running to reach $\sigma_{\text{sys}} \sim \sigma_{\text{stat}}$
- Sensitivity $m_\nu < 0.2 \text{ eV}$ (90% C.L.)
- Discovery potential:
 - $m_\nu = 0.3 \text{ eV}$ (3σ)
 - $m_\nu = 0.35 \text{ eV}$ (5σ)



KATRIN Simulation and Fits (last 25 eV)

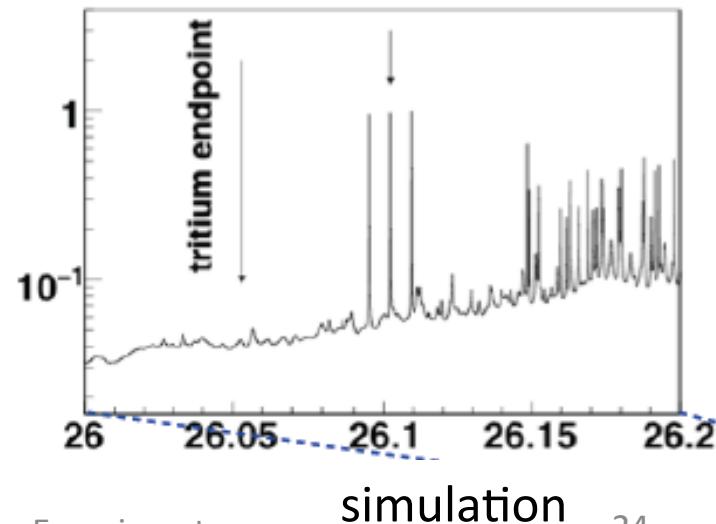
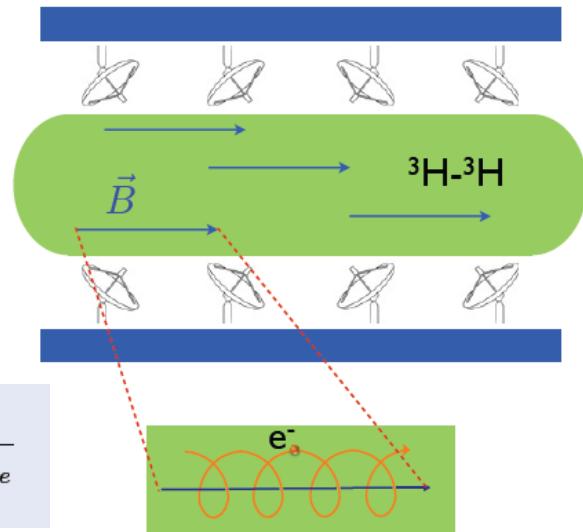


Measuring Mass with Tritium in new way

- Project 8 Concept:
 - trap a volume of tritium (atomic)
 - watch decay electrons process around constant magnetic field
 - measure the cyclotron frequency to get e- Energy
 - Highest Energy electrons give lowest frequency signals
- Working to prove the principle:
 - Start with ^{83m}Kr volume
 - Look for 18 and 30keV conversion electrons
 - Added bonus: see e- lose energy as it processes in field
 - 7TB of data taken in Jan. 2012, must improve data-taking technique



$$\omega(\gamma) = \frac{\omega_0}{\gamma} = \frac{eB}{K + m_e}$$



Absolute Mass Measurement Summary



- Direct neutrino mass measurement using weak decay kinematics is the most sensitive model independent method for neutrino mass determination.
- β spectrometer techniques have been successfully used to measure the tritium decay, culminating in KATRIN, which will probe $m_\nu \sim 200$ meV region.
- Given the technical challenges, it will be difficult to scale up KATRIN type spectrometer further.
- New ideas needed: can we use cyclotron radiation as Project 8? Or full kinematic reconstruction with atomic traps? What about calorimeters? These new ideas will need time to develop and mature.

Outline for $0\nu\beta\beta$ Experiments



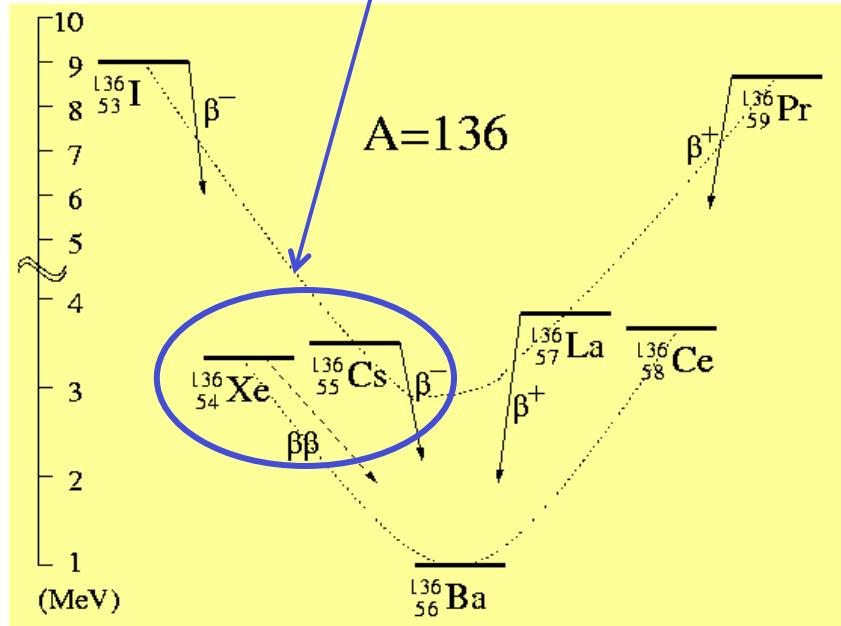
- Brief review of neutrinoless double beta decay
- Experimental choices
- Background reduction techniques
- Review of experimental techniques
- Recent results from NEMO, Cuore, Gerda, Kamland-Zen and EXO

[http://indico.ihep.ac.cn/getFile.py/access?
contribId=31&resId=0&materialId=slides&confId=2999](http://indico.ihep.ac.cn/getFile.py/access?contribId=31&resId=0&materialId=slides&confId=2999)

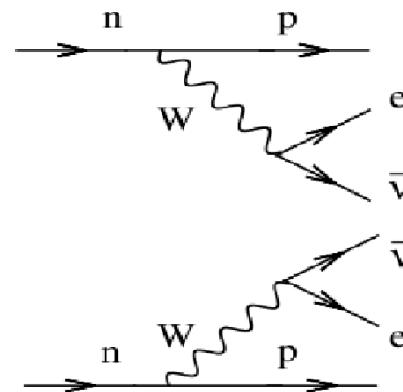
Most slides shamelessly stolen from L. Yang, INSS 2013 unless otherwise noted

Double Beta Decay

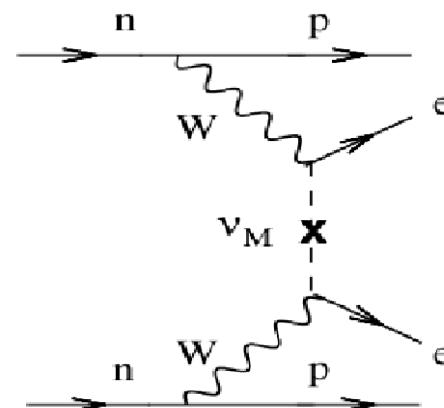
Observable if single beta decay is forbidden



Two neutrino double beta decay



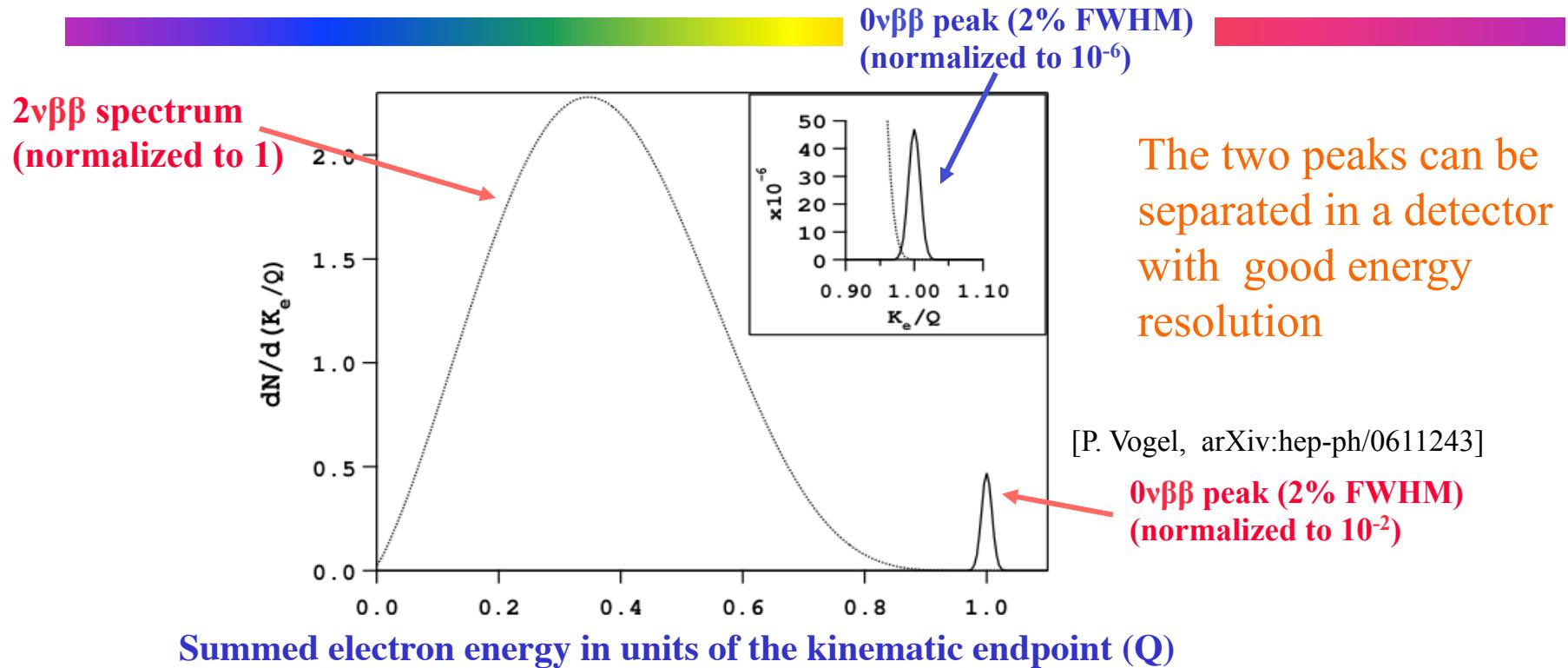
Neutrinoless double beta decay



Observation of $0\nu\beta\beta$:

- Majorana neutrino
- Neutrino mass scale
- Lepton number violation

Double Beta Decay Energy Spectrum



If 0 $\nu\beta\beta$ is due to light ν Majorana masses

$$\langle m_\nu \rangle^2 = \left(T_{1/2}^{0\nu\beta\beta} G_{0\nu\beta\beta}(E_0, Z) |M_{0\nu\beta\beta}|^2 \right)^{-1}$$

$$\langle m_\nu \rangle = \left| \sum_i U_{ei}^2 m_i \varepsilon_i \right|$$

effective Majorana ν mass
($\varepsilon_i = \pm 1$ if CP is conserved)

$M_{0\nu\beta\beta}$ Nuclear matrix element

$G_{0\nu\beta\beta}$ Phase space factor

$T_{1/2}^{0\nu\beta\beta}$ Measured half-life

Experimental Sensitivity

The sensitivity of $T_{1/2}^{0\nu}$ is determined by the number of $0\nu\beta\beta$ events ($N_{0\nu}$) and the number of background (N_{bg}) events in the region of interest (ROI).

$$N_{0\nu} \propto \varepsilon \frac{a}{A} \frac{MT}{T_{1/2}^{0\nu}}$$

$$N_{bg} \propto MTB\Gamma$$

ε is efficiency
 a is isotope abundance
 A is atomic mass
 M is source mass
 T is live time
 B is background index
 Γ is resolution

For background free experiments,

$$N_{0\nu} > 1 \rightarrow S_{1/2}^{0\nu} \propto \varepsilon \frac{a}{A} MT$$

For experiments with background,

$$N_{0\nu} > \sqrt{N_{bg}} \rightarrow S_{1/2}^{0\nu} \propto \varepsilon \frac{a}{A} \sqrt{\frac{MT}{B\Gamma}}$$

Note: for small number of N_{bg} ($< \sim 6$), full statistical treatment is more complicated and will often require Monte Carlo simulations.

Experimental Design Considerations

$$S_{1/2}^{0\nu} \propto \varepsilon \frac{a}{A} \left[\frac{MT}{B\Gamma} \right]^{1/2}$$

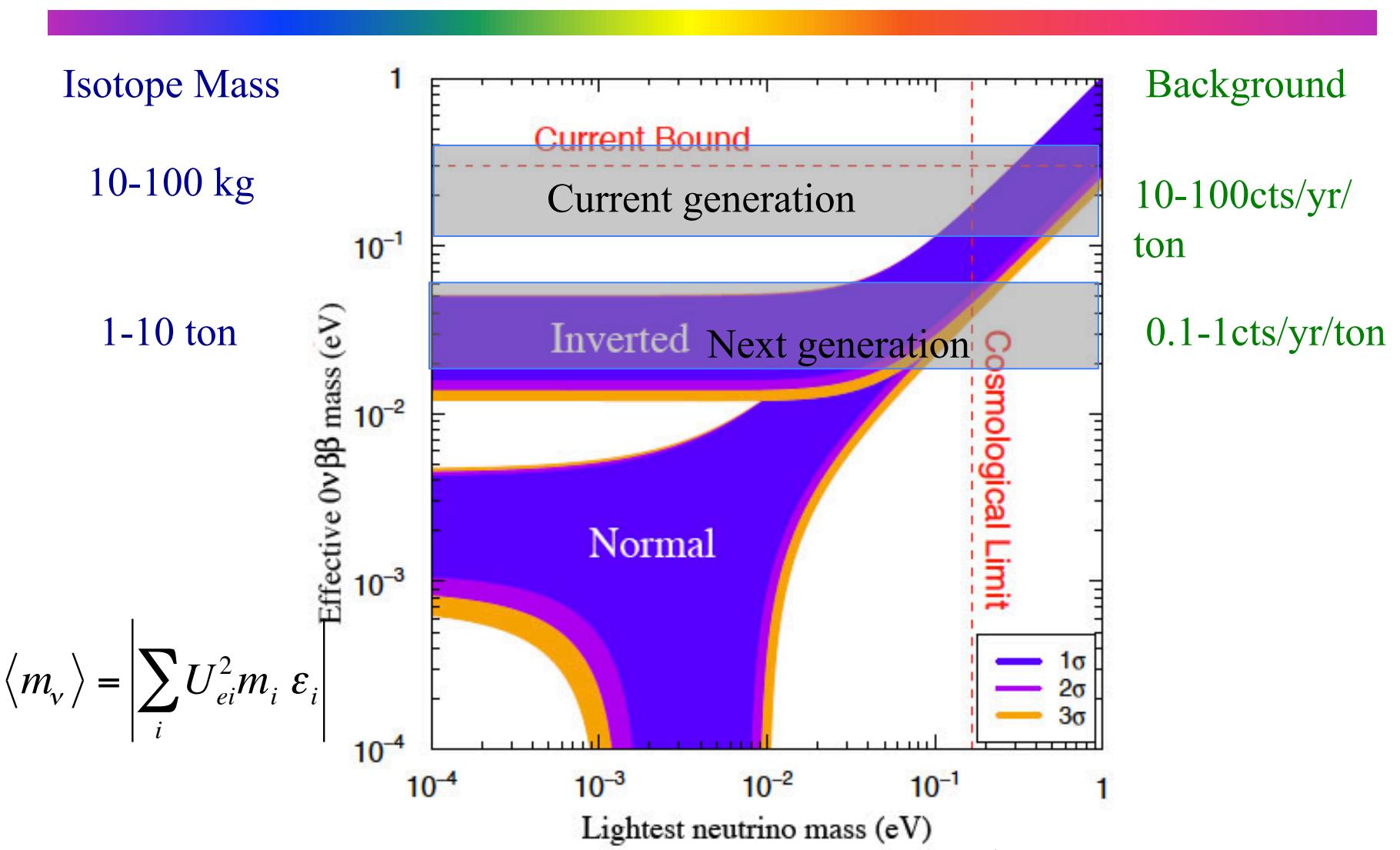
$$S_{m_{\nu ee}}^{0\nu} \propto \frac{1}{\sqrt{G^{0\nu}} |M^{0\nu}|} \left[\frac{A}{\varepsilon} \right]^{1/2} \left[\frac{B\Gamma}{MT} \right]^{1/4}$$

ε is efficiency, a is isotope abundance, A is atomic mass, M is source mass, T is live time
 B is background index, Γ is resolution, $G^{0\nu}$ is phase space, $M^{0\nu}$ is matrix element

To maximize sensitivity:

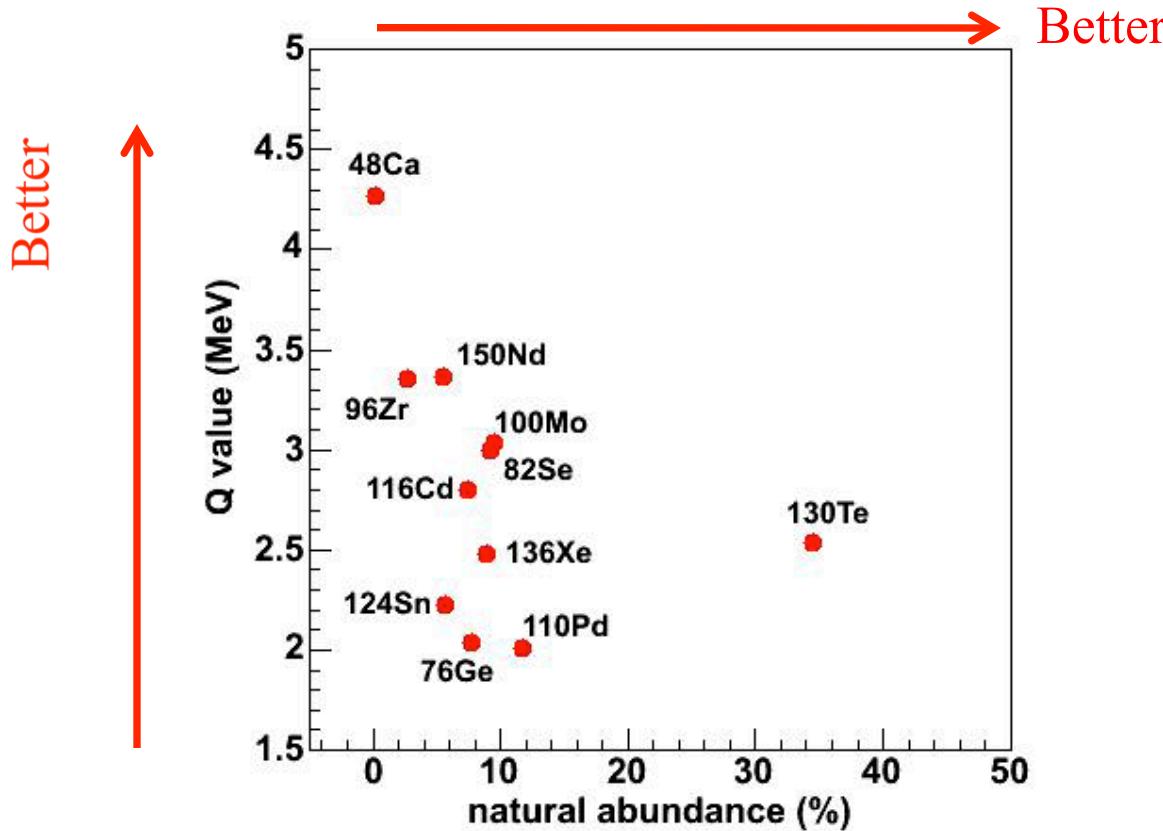
- Large isotope mass (10 – 100 kg now → 1-10 ton)
- High detection efficiency (~ 100 %) source = detector?
- Good energy resolution
 - reduce flat background and resolve nearby background peaks
 - reduce $2\nu\beta\beta$ background
- Low background (10 – 100 cnts/yr/ton → 0.1 – 1 cnts/yr/ton)
 - underground detector to shield cosmic rays
 - clean material, passive and active shielding, good background discrimination

Experimental Sensitivity to Neutrino Mass



arXiv:1203.5250v1

Choice of Isotope



- High natural abundance means lower cost of enrichment
- Large Q value means lower background from natural radioactivity
- No golden element: detector technology and background reduction techniques are crucial considerations in isotope selection.

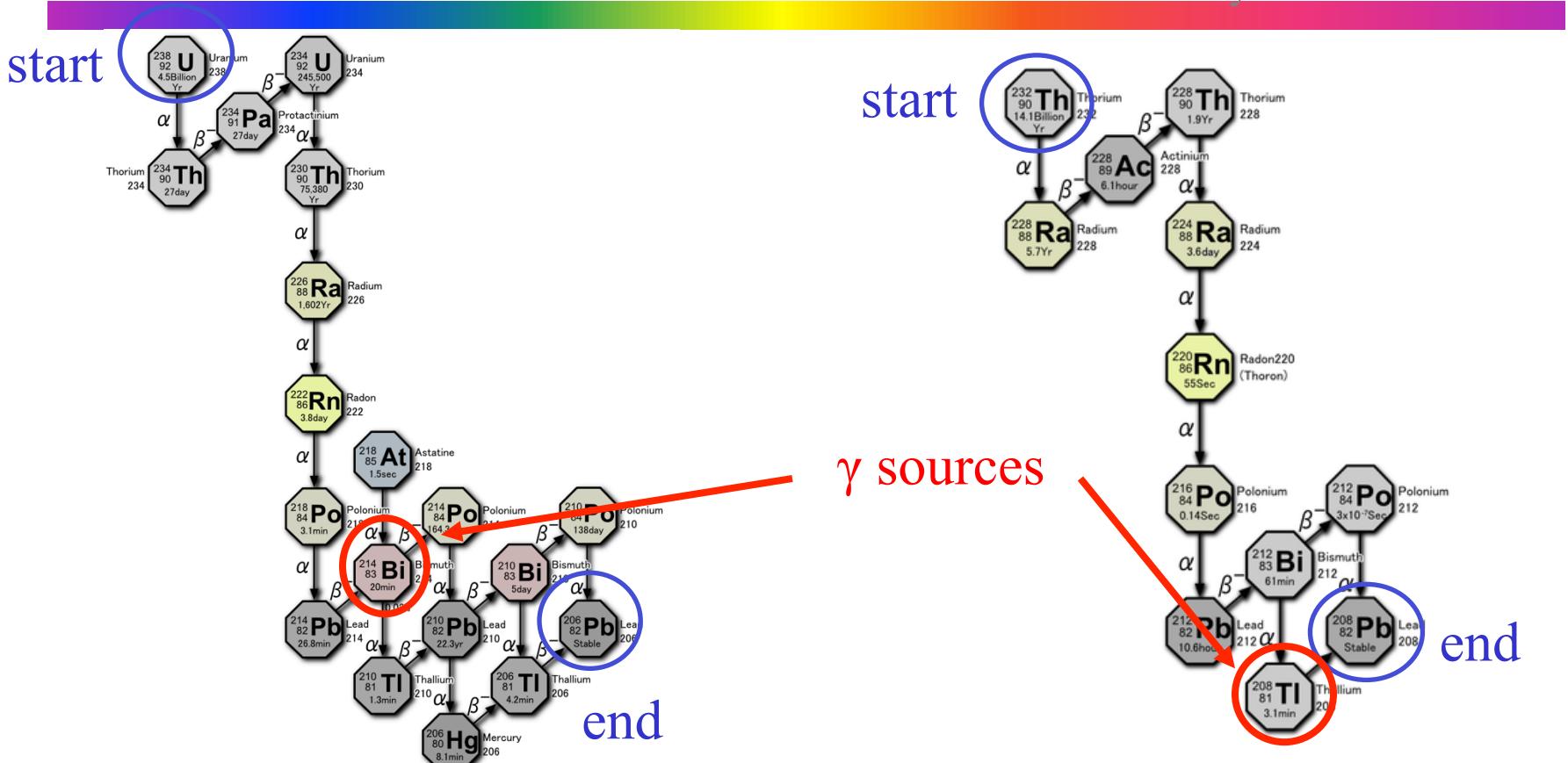
Isotope Choices

Isotope	Experiment
^{48}Ca	ELEGANT-VI
^{76}Ge	Heidelberg-Moscow
^{76}Ge	GERDA [†]
^{82}Se	NEMO-3
^{100}Mo	NEMO-3
^{116}Cd	Solotvino
^{130}Te	Cuoricino
^{136}Xe	KamLAND-Zen ^{††}
^{136}Xe	EXO-200 ^{†††}
^{136}Xe	<i>SNO</i> ++
^{150}Nd	NEMO-3

D. Harris, Fermilab: Neutrino Experiments

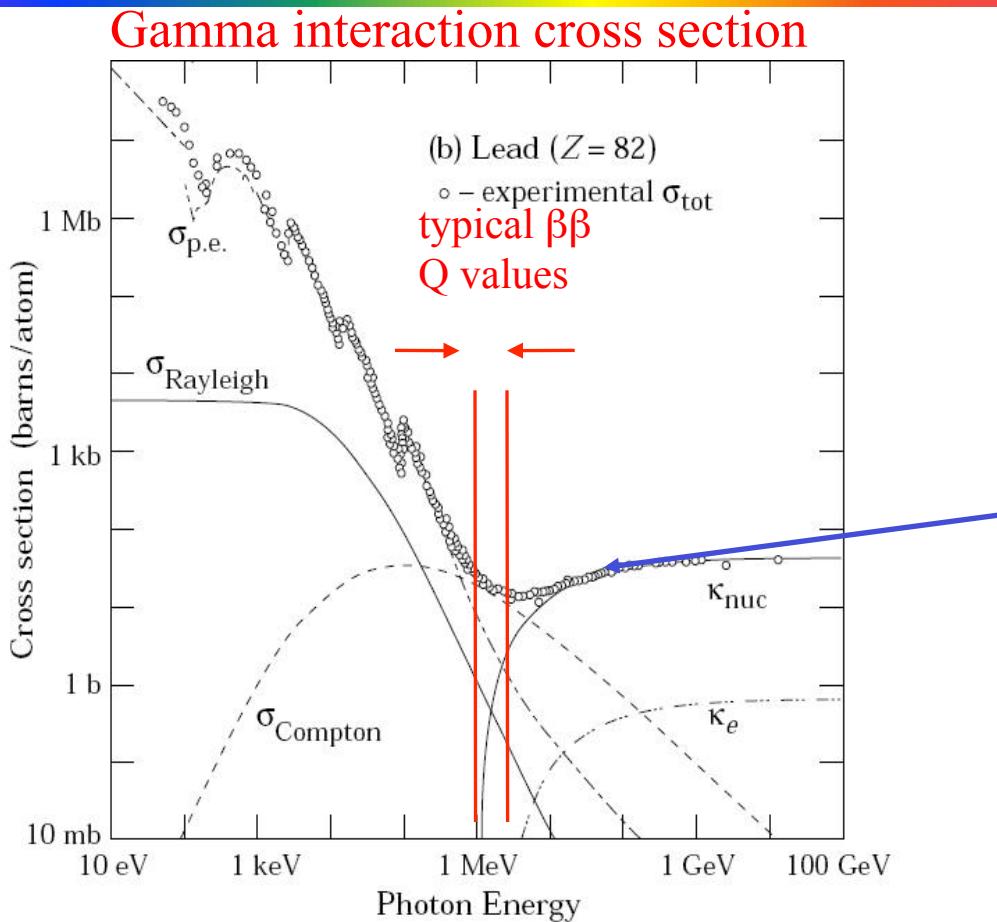
Background from Natural Radioactivity

Uranium-238 decay chain



- Natural radioactivities on earth come from U, Th, ^{40}K (long decay lifetime $\sim 10^9$ yr), or cosmogenic activation, or human related activities.
- U and Th decay via a series α and β decays.
- Most troublesome background comes from high energy ($\sim 2\text{MeV}$) γ rays.

Shielding Difficulties

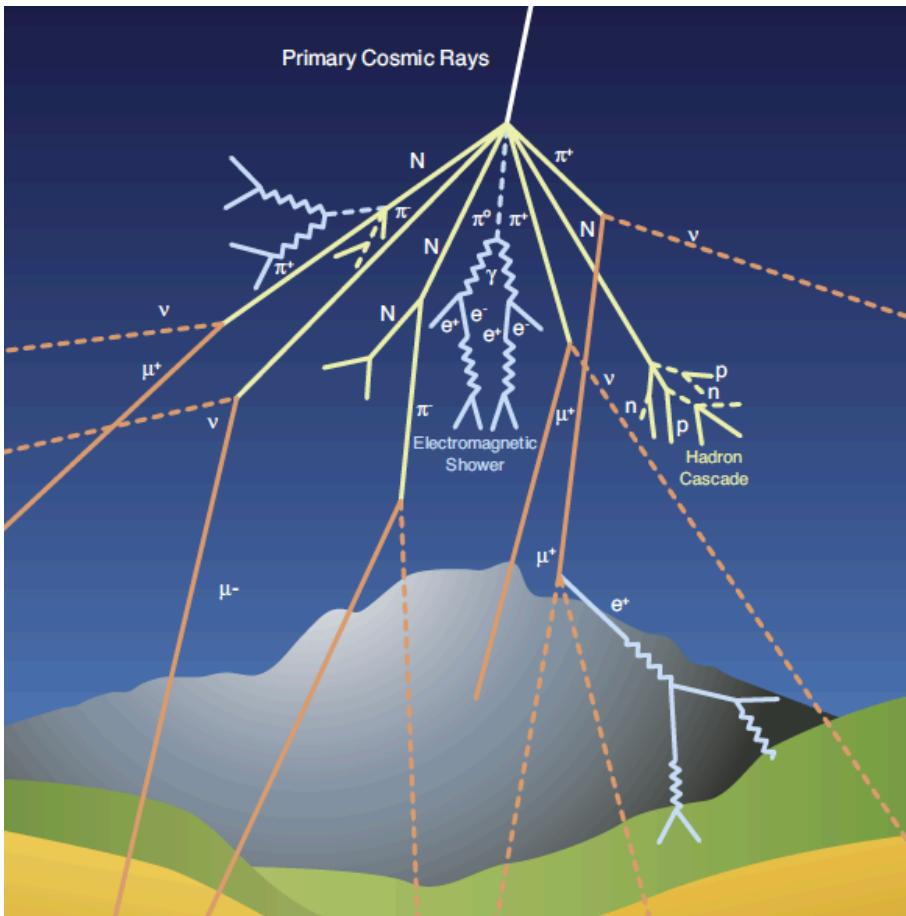


Gammas travel about 2 cm before scattering in lead

C. Hall, SnowMass premeting, 2013

- 1-3 MeV gamma rays are difficult to shield, so passive or self shielding not very effective.
- It is critical to remove background from detector construction materials

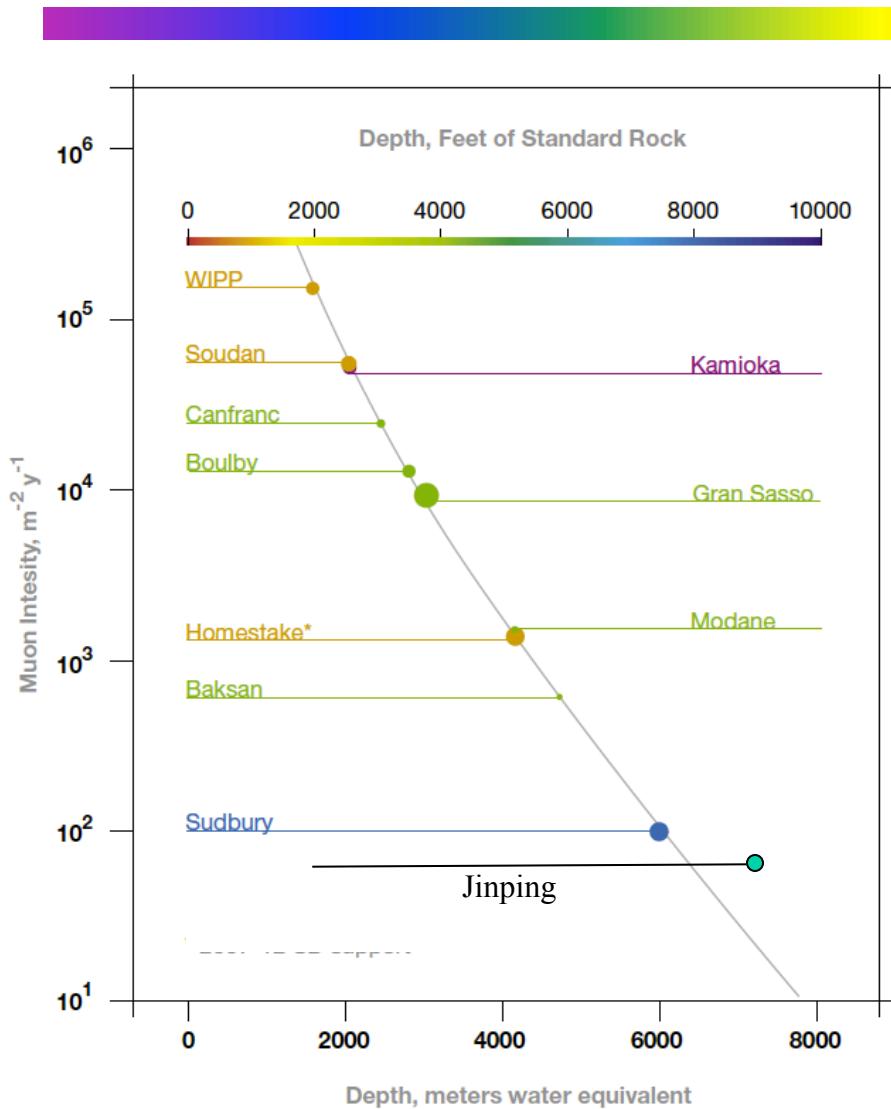
Cosmic Ray Background



Source: CERN

- Cosmic rays striking the upper atmosphere will create a shower of subatomic particles, including energetic muons,
- Cosmic muons can create radioactive isotopes via spallation, neutron activation and other nuclear processes.
- When muon goes through a detector, it can produce radioactive isotopes directly inside the detector.
- Muon can also produce secondary particles in material outside the detector such as fast neutrons, which later interact with the detector material.

Going Underground....



- By going to deeper underground lab, one can effectively shield against cosmic muons.
- At 6600 m.w.e., Jinping lab in Sichuan, China is the deepest underground lab, with a muon flux of $\sim 50/\text{m}^2/\text{yr}$, 9 order of magnitude reduction compared to sea level
- The muon angular and energy distribution depends on the depth, so Monte Carlo simulation is needed to understand the full background from the cosmic ray.

Experimental Methods*



Tracking Detectors:

- Use tracking information of two decay electrons to reject background.
- Often in Source \neq Detector configuration, hard to scale to large mass
- The same detector can be used to study multiple isotopes (NEMO).

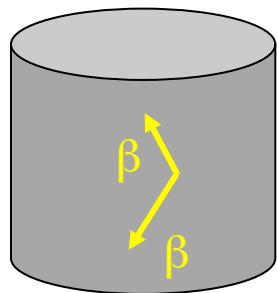
Calorimeter Detectors:

- Concentrate on measuring the sum electron energy accurately.
- Often in Source = Detector configuration
- Diverse detector techniques based on properties of the isotope under study
 - Bolometric detector (Te) (CUORE)
 - Semiconductor crystalline detector (Ge) (GERDA, MAJORANA)
 - Gas and liquid TPC (Xe) (EXO, NEXT)
 - Scintillation detector (Xe, Te, Nd ...) (Kamland-Zen, SNO+)
- Cannot measure angular correlation, single electron energy, etc

* Some experiments use both tracking and calorimetric techniques, such as NEXT.

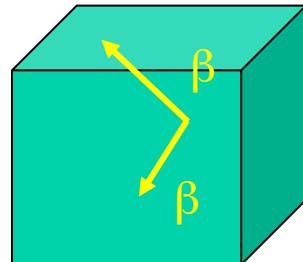
Detector Technology Choices

Calorimeter
Semi-conductors
Scintillators
Source = detector



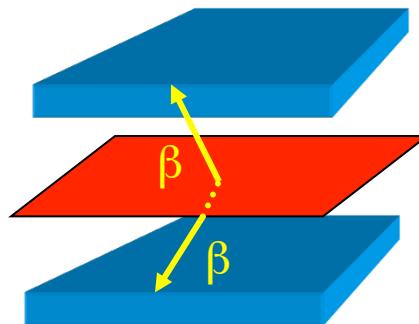
GERDA, Majorana,
CANDRES,
Kamland-Zen,
SNO++,..

Bolometer
Source = detector



Cuoricino,
CUORE, ...

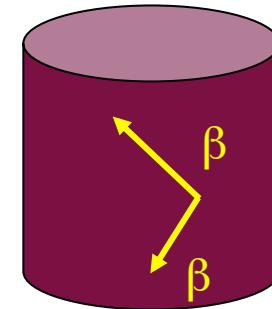
Tracking-calorimeter
Source \neq detector



NEMO3, MOON,
Super-NEMO, ...

$$S_{1/2}^{0\nu} \propto \varepsilon \frac{a}{A} \left[\frac{MT}{B\Gamma} \right]^{1/2}$$

Xe (TPC)
Source = detector



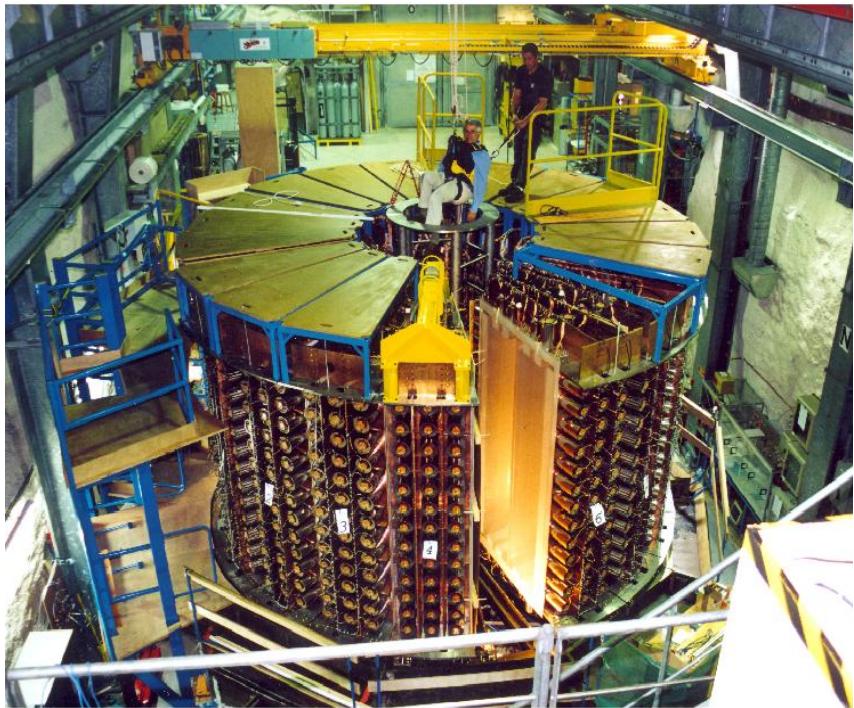
EXO,
NEXT

T. Kajita, INSS 2013

Detector Choices

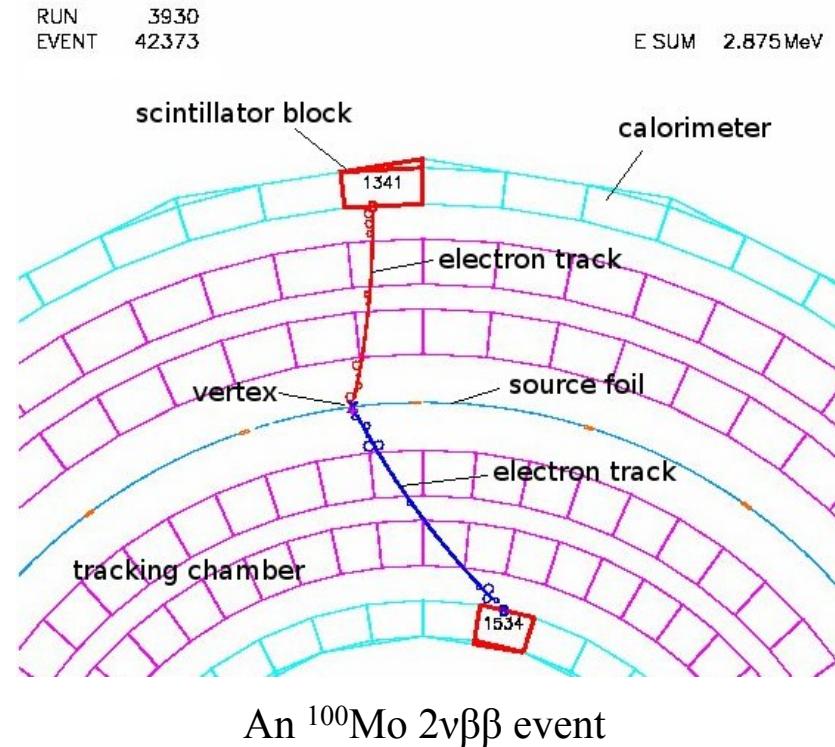
Isotope	Experiment	$\langle m \rangle$ eV
^{48}Ca	ELEGANT-VI	Tracking Calorimeter
^{76}Ge	Heidelberg-Moscow	Calorimeter
^{76}Ge	Subset of HM coll.	Calorimeter
^{76}Ge	GERDA [†]	Calorimeter
^{82}Se	NEMO-3	Tracking Calorimeter
^{100}Mo	NEMO-3	Tracking Calorimeter
^{116}Cd	Solotvino	Tracking Calorimeter
^{130}Te	Cuoricino	Bolometer
^{136}Xe	KamLAND-Zen ^{††}	Scintillator
^{136}Xe	EXO-200 ^{†††}	Xe TPC
^{150}Nd	NEMO-3	Tracking Calorimeter

Tracking Detector: NEMO-3



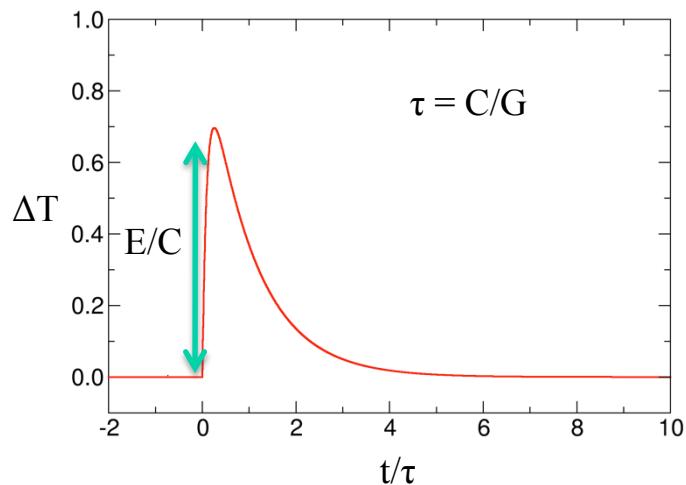
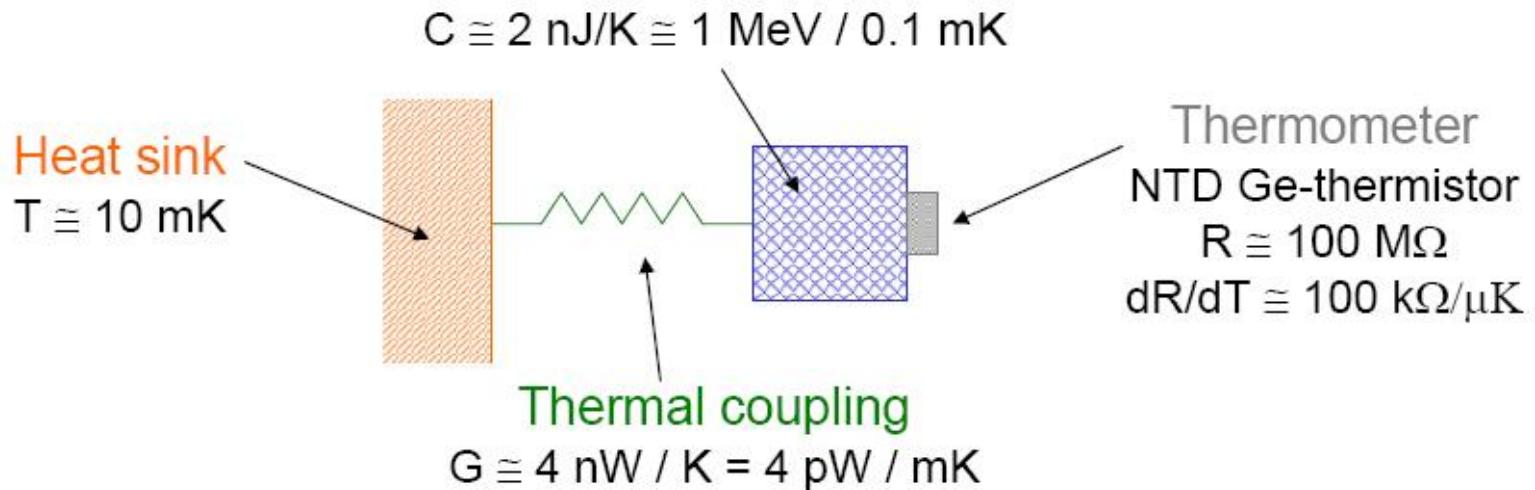
NEMO-3 detector

- Double beta decay isotopes are in the form of thin foils $\sim 60\text{mg/cm}^2$.
- Decay electrons are tracked with Geiger mode drift tubes in modest magnetic field.
- The energy of the electrons are measured by plastic scintillators coupled to PMTs.



An ${}^{100}\text{Mo}$ $2\nu\beta\beta$ event

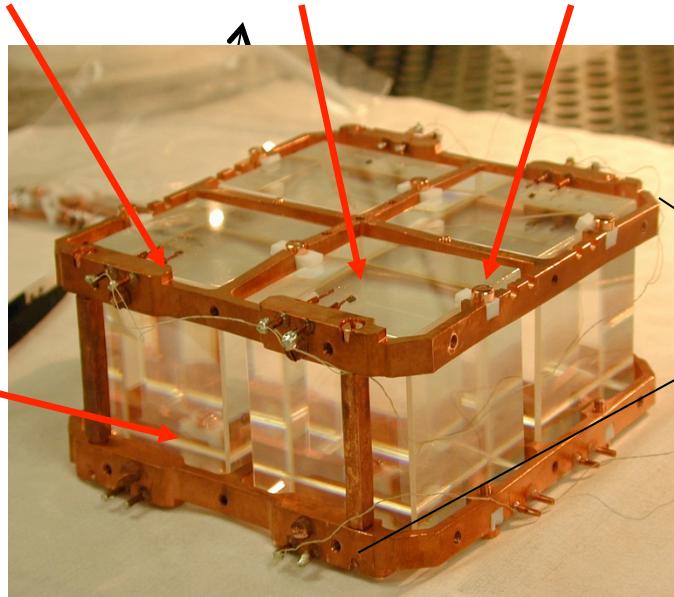
Cryogenic Bolometer: ^{130}Te



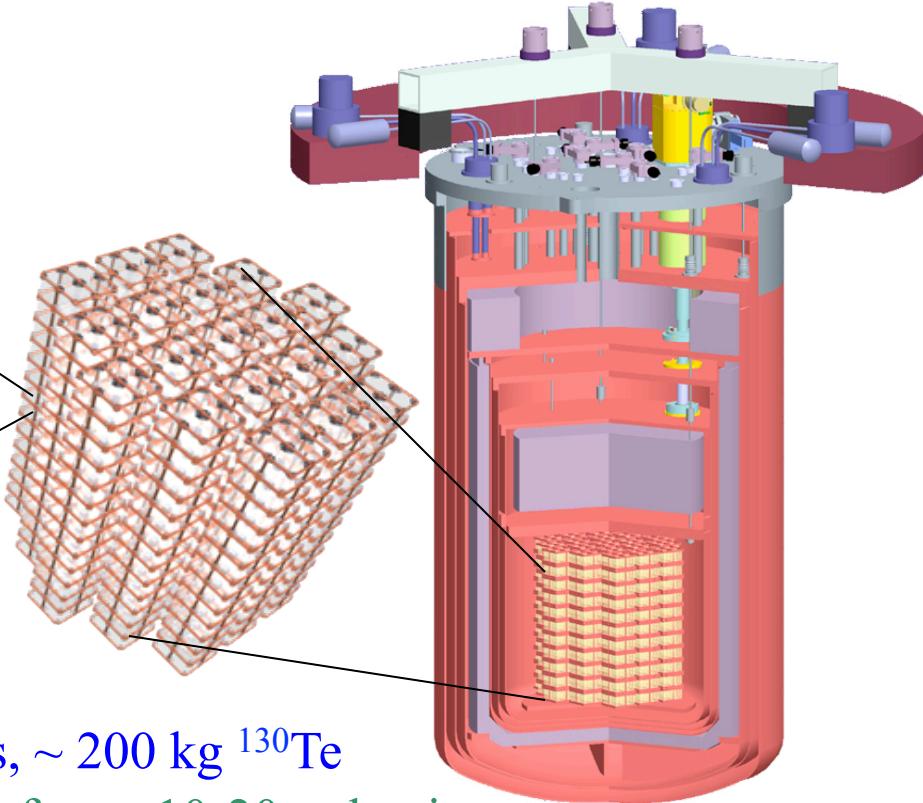
- Measure total energy deposited in the crystal.
- Techniques applicable to many isotopes. Te has the highest natural abundance.
- High energy resolution, 7-9 keV @ 2530keV.
- No information about the particle ID, external γ and surface degraded α are major background concerns.

CUORE: Cryogenic Underground Observatory for Rare Events

heat sink thermometer thermal link

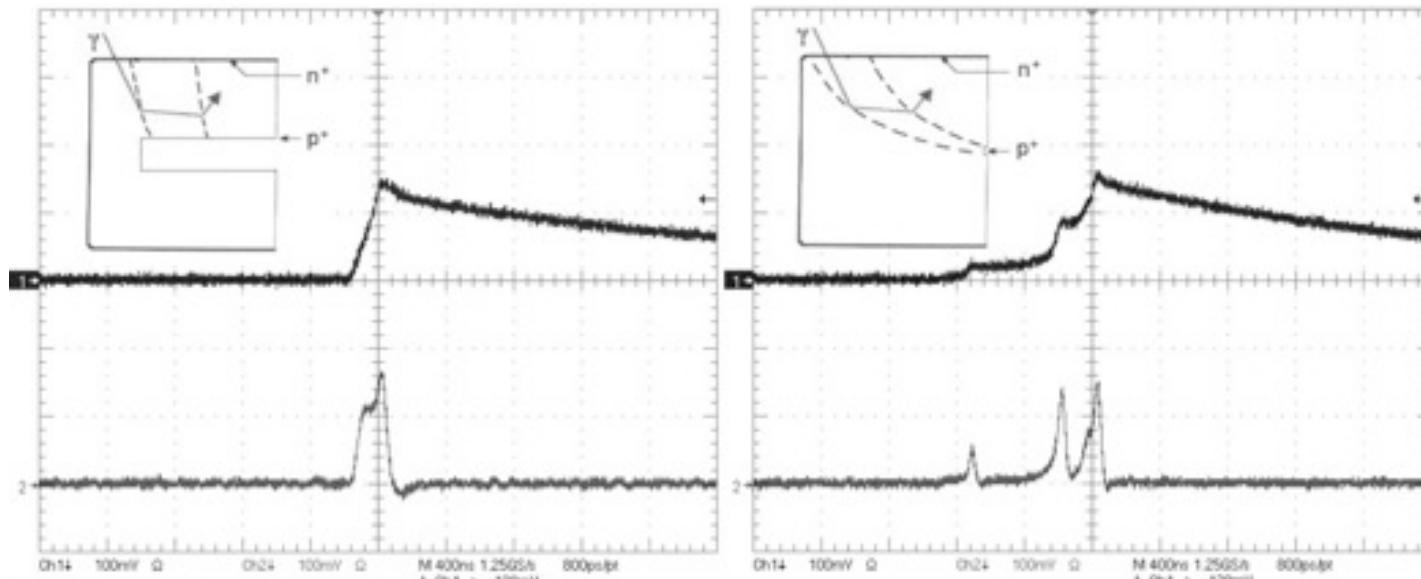


TeO_2
crystal



- 19 Cuoricino-like tower, 988 bolometers, $\sim 200 \text{ kg } ^{130}\text{Te}$
- Background goal $0.01 \text{ cnt}/(\text{keV kg yr})$, a factor 10-20 reduction
- Energy resolution 4.6 keV
- Operation temperature: 8mK
- 5 year sensitivity, $T_{1/2}^{0\nu\beta\beta} > 1.6 \times 10^{26} \text{ yrs}$, $m_{\beta\beta} < 41 - 95 \text{ meV}$

Semiconductor Detector: ^{76}Ge



P-type semi-coaxial Detector

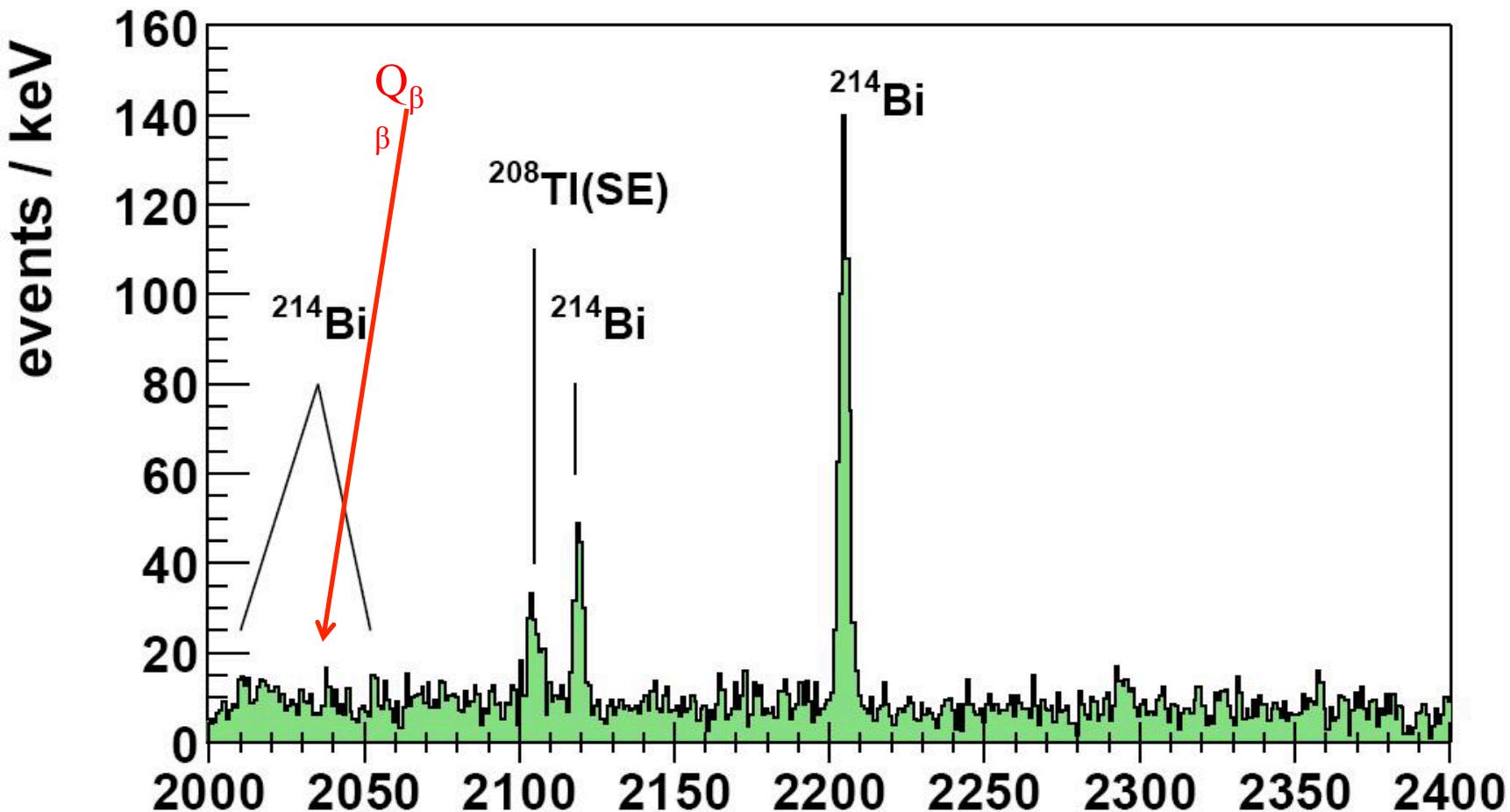
P-type point contact Detector*

Barbeau et al., JACP 09 (2007) 009; Luke et al., IEEE trans. Nucl. Sci. 36, 926 (1989).

- Excellent energy resolution (4keV FWHM at Q value)
- Pulse shape analysis rejects multiple site events within a single crystal.
- P-type point contact crystal has superior single vs. multi-site rejection capability.
- Modest Q value (2039 keV), cosmogenic activation of Ge and Cu cryostat

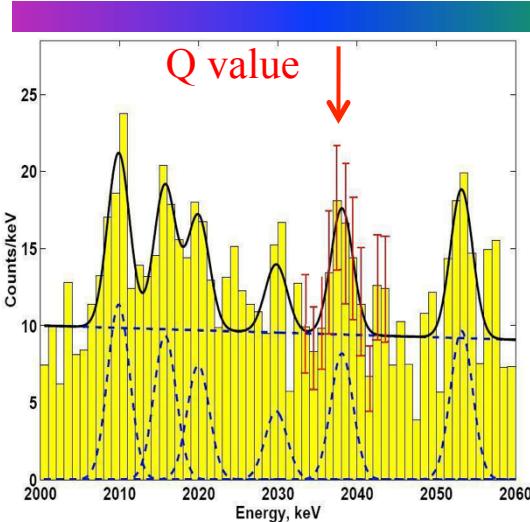
*Also called Broad Energy Ge (BEGe) Detector.

$0\nu\beta\beta$ Discovery Claim



Publication by part of the Heidelberg-Moscow Collaboration,
often referred to as the Klapdor's (or KKDC) claim.

0νββ Discovery Claims 2004, 2006 (PSA)

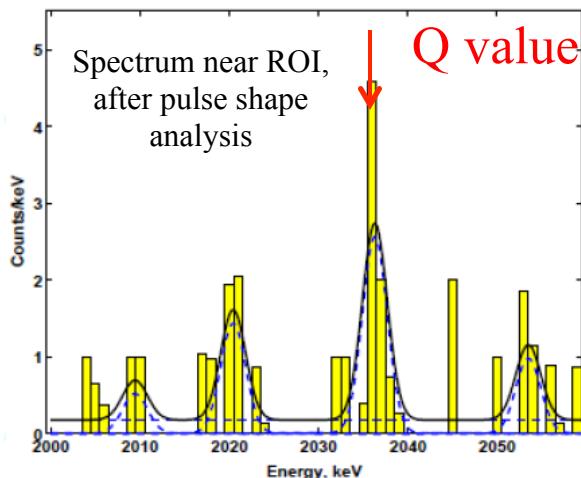


Fit model: 6 Gaussian + linear background
Four lines at 2010, 2016, 2022 and 2053 are consistent with γ from ^{214}Bi

An unknown line at 2030, e- conversion of ^{214}Bi ?
Total exposure: $71.7 \text{ kg}\cdot\text{yr}^{-1} \text{ Ge}^{76}$

Fit intensity @ $Q_{\beta\beta} = 28.75 \pm 6.86 (4.2 \sigma)$

$T_{1/2}^{0\nu} = 1.19_{-0.23}^{+0.37} \times 10^{25} \text{ yr}$ HV. Klapdor-Kleingrothaus, et. al,
Nucl. Instrum, and Meth, A 522 (2004) 371-406



A special pulse shape analysis (PSA) is applied to select only $\beta\beta$ like events.

Background in ROI dropped from 0.17 cnts/(keV kg yr) to 0.015 cnts/(keV kg yr)

PSA efficiency of 100% is used.

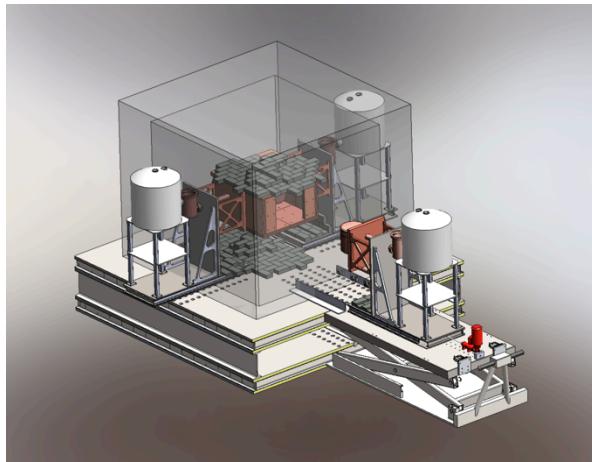
Fit intensity @ $Q_{\beta\beta} = 11.32 \pm 1.75 (6.5 \sigma)$

$T_{1/2}^{0\nu} = 2.23_{-0.31}^{+0.44} \times 10^{25} \text{ yr}$.

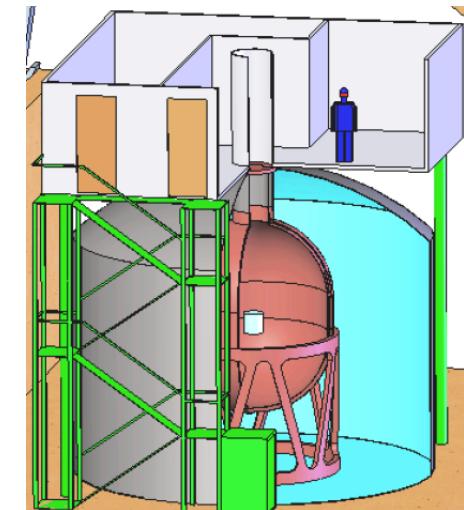
Modern Ge Exps: MAJORANA and GERDA

- ^{76}Ge experiments can check the Klapdor claim in a model independent way.
- More than ten times lower background.
- Superior detector technology, enriched Ge, (MAJORANA and GERDA Phase II)

MAJORANA



GERDA

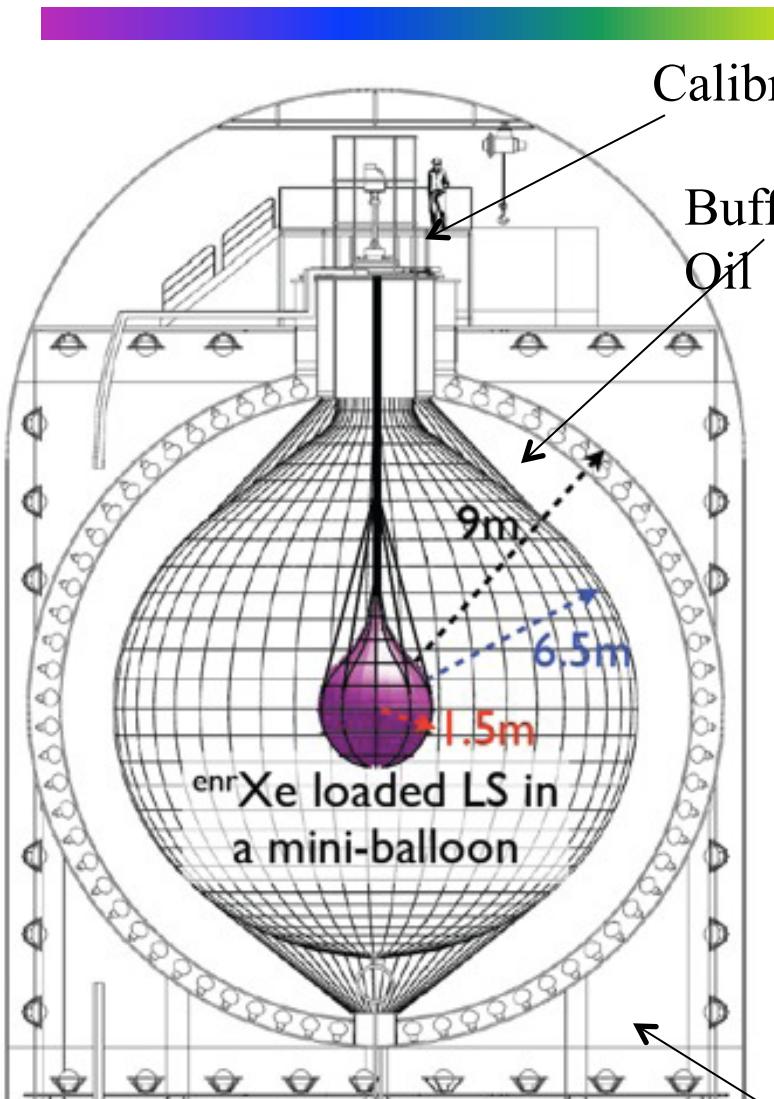


- Use high purity Co as shielding,
Cu/Pd passive outer shielding
- 4π plastic scintillator veto.
- DEMONSTRATOR: 30 kg $^{\text{enr}}\text{Ge}$, 10 kg $^{\text{nat}}\text{Ge}$

- Operate ‘bare’ Ge crystal in liquid Ar
- Liquid Ar can be used as active veto
- Water Cherenkov μ veto
- Phase I: ~ 18 kg, Phase II: + 20kg

Very different background reduction strategy. Intention to merge
for tonne scale experiment with the best techniques.

Scintillation Detector: Kamland-Zen



Calibration access

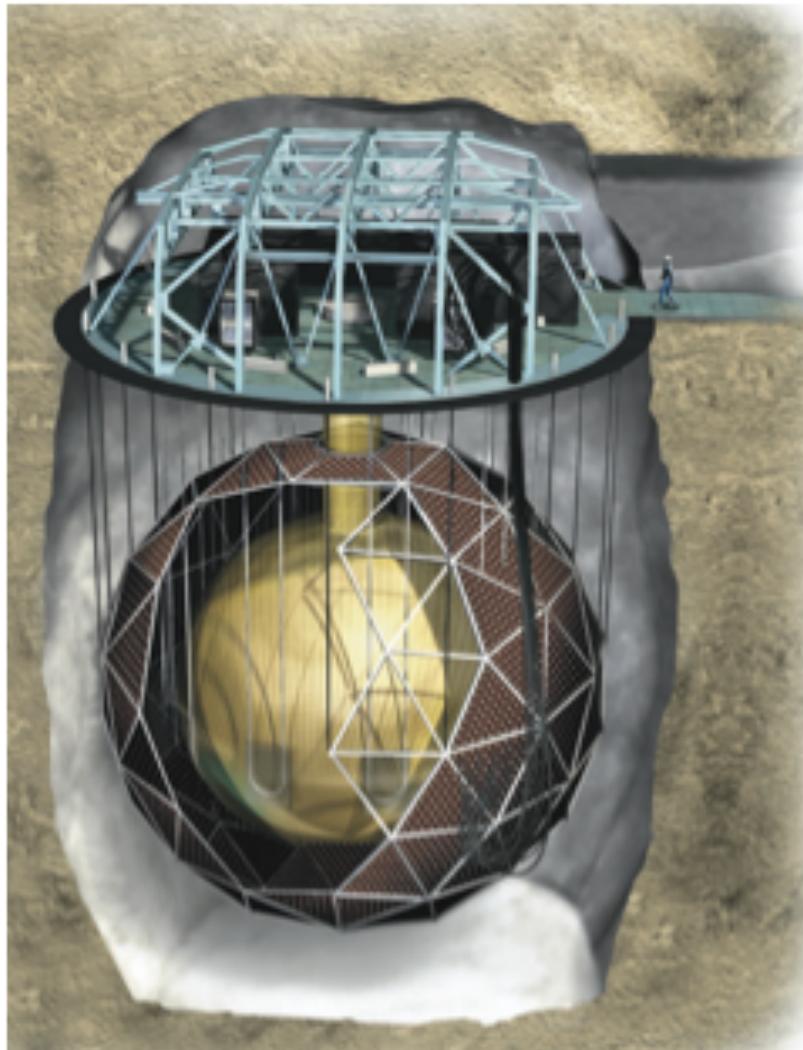
Buffer
Oil

^{enr}Xe loaded LS in
a mini-balloon

Water Cherenkov
Detector

- Experience with large liquid scintillator detectors show that LS can be made extremely pure.
- Radioactivity from PMTs and vessel can be shielded by LS and confining double beta decay isotopes inside a central volume.
- Pro: can be scaled to large mass fairly easily. Most detector background well understood. Can use several different isotopes.
- Con: low energy resolution, background from $2\nu\beta\beta$ and balloon materials. No single site and multisite rejection.

SNO+

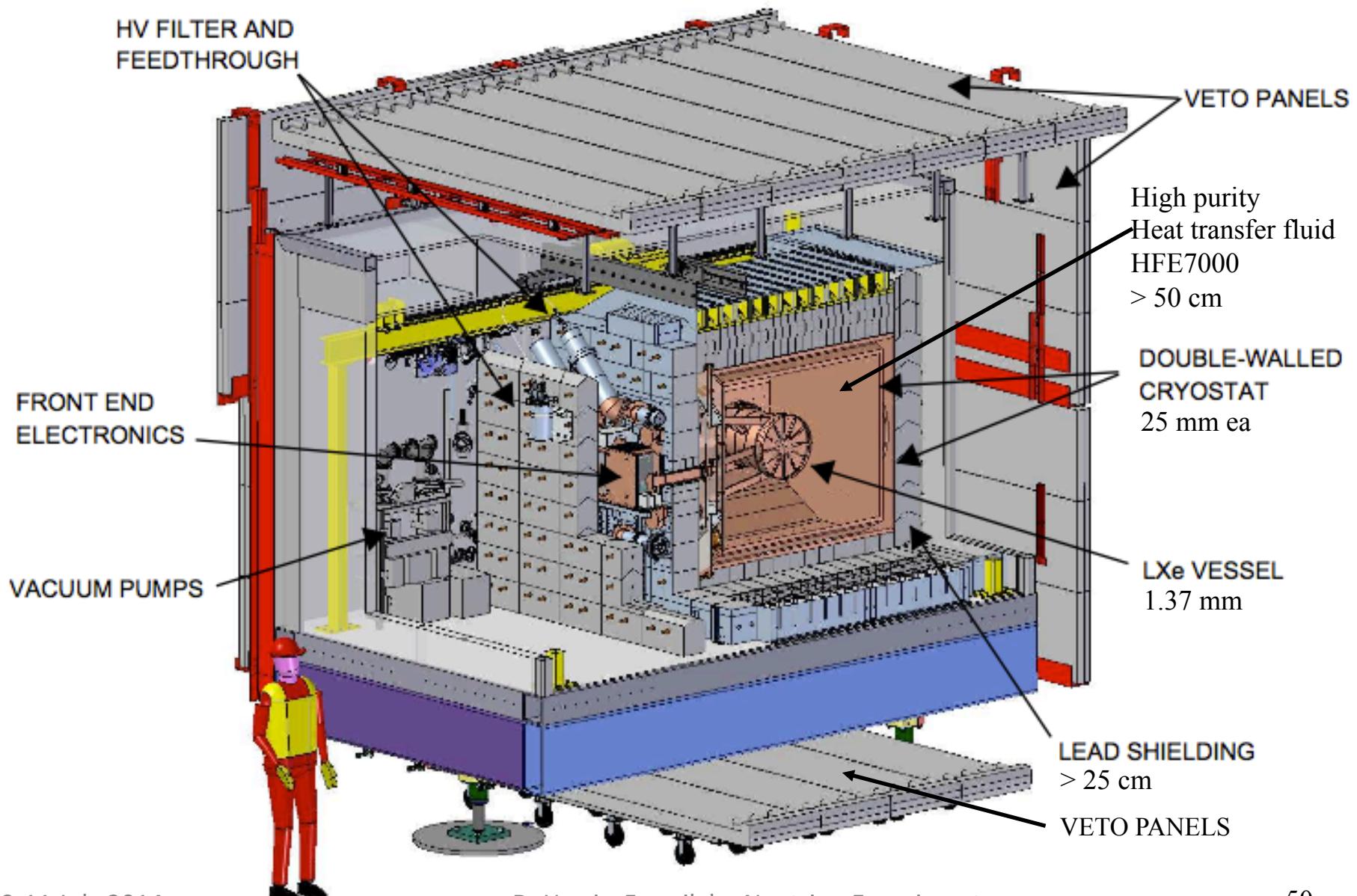


Reuse the SNO detector,
replace D_2O with liquid
scintillator doped with double
beta decay isotope.

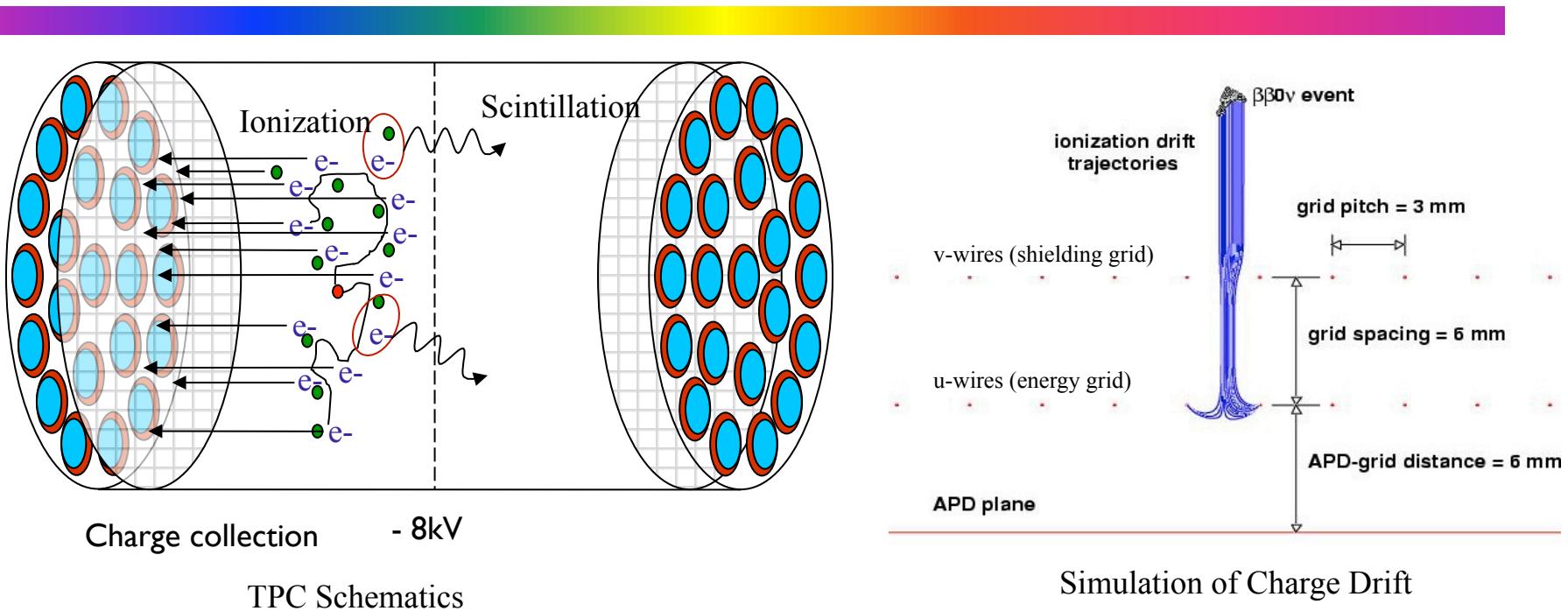
Isotope of choice has changed
from Nd to Te

Scintillator data expected in 2014

The EXO-200 Detector: Liquid Xenon TPC



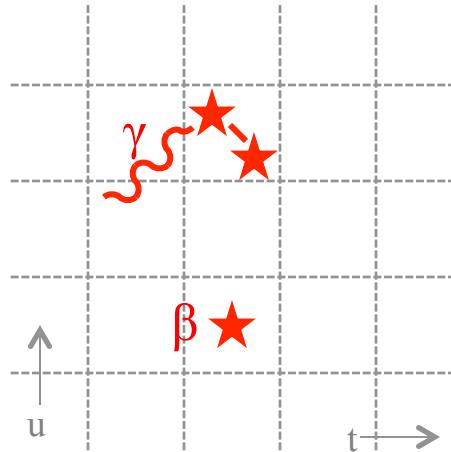
EXO-200 Time Projection Chamber (TPC)



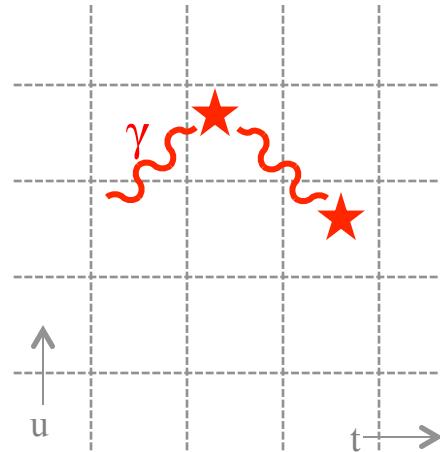
- Two TPC modules with common cathode in the middle.
- APD array observes prompt scintillation for drift time measurement.
- V-position given by induction signal on shielding grid.
- U-position and energy given by charge collection grid.

Topological Event Information

Single Site Events (SS)

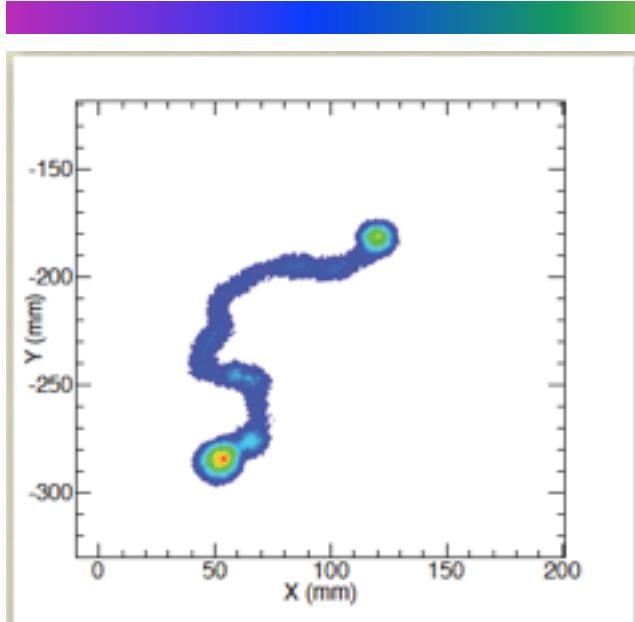


Multiple Site Events (MS)

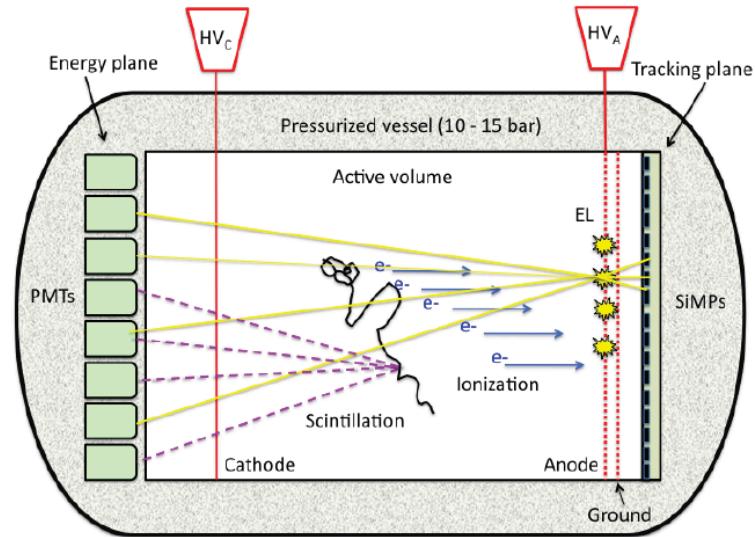


- The time projection chamber allows the rejection of some gamma backgrounds because Compton scattering results in multiple energy deposits.
- We can distinguish multiple charge deposits with resolution 18 mm in u, and 6 mm in z.
- SS/MS discrimination is powerful tool not only for background rejection, but also for signal discovery

Time Projection Chamber (TPC): NEXT



Simulated $0\nu\beta\beta$ track



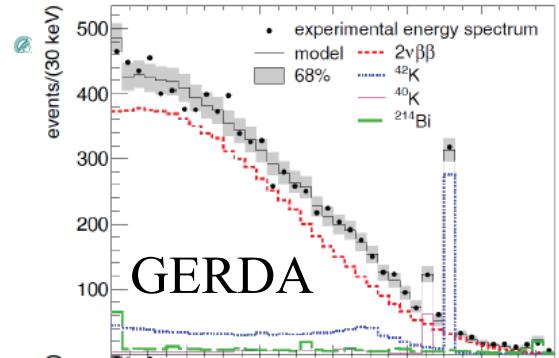
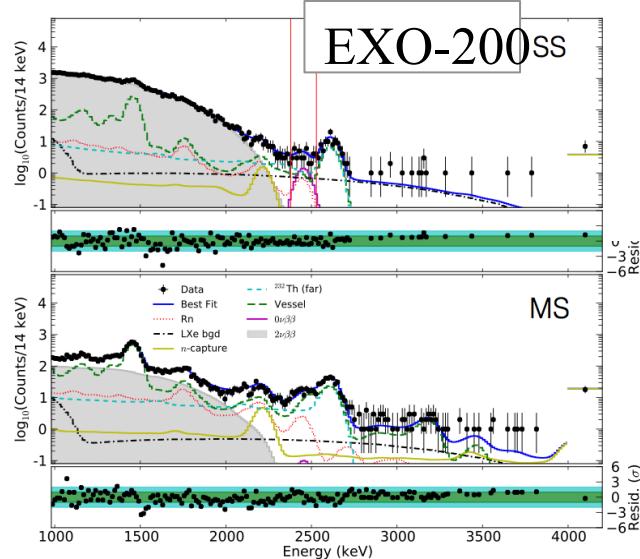
Detector design

NEXT technical design report, arXiv:1202:0721

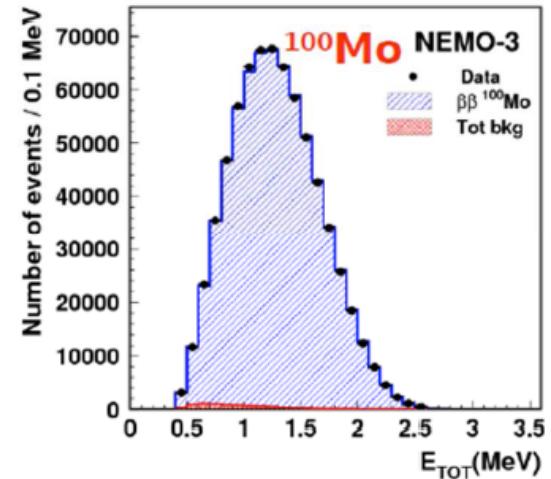
- Neutrino Experiment with a Xenon TPC (NEXT) is a high pressure (10 bar) gas ^{136}Xe experiment
- Energy resolution < 1%, background index 10^{-4} counts/(keV kg y)
- High gamma background rejection ($\sim 10^6$) using event topology.
- Commissioning of the NEXT-100 detector planned in 2014.

$2\nu\beta\beta$ Spectra

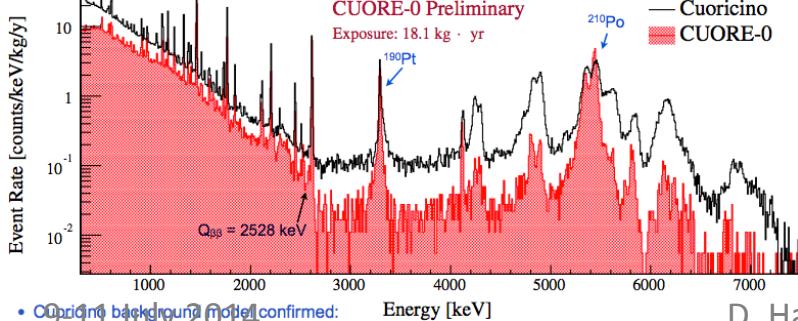
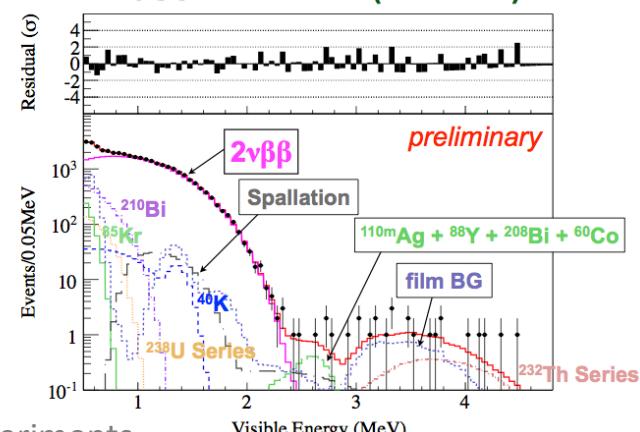
- This is a good way to show the detector works
 - Background predictions and Energy resolution



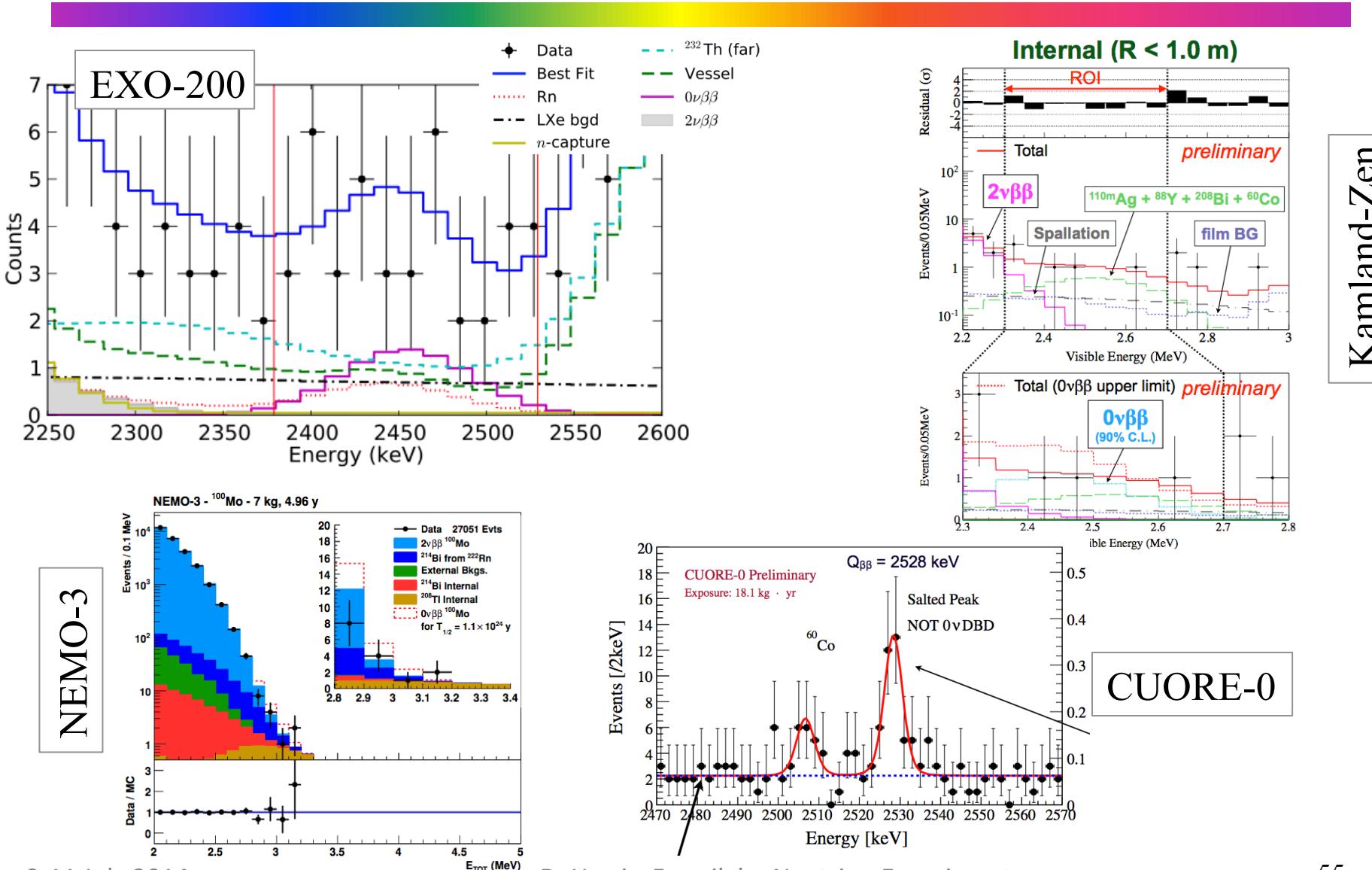
Measurement of ^{76}Ge $2\nu\beta\beta$ with 5.04 kg yr exposure



KamLAND-Zen (2014) Xe loaded liquid scintillator
Phase 2 Internal ($R < 1.0$ m)

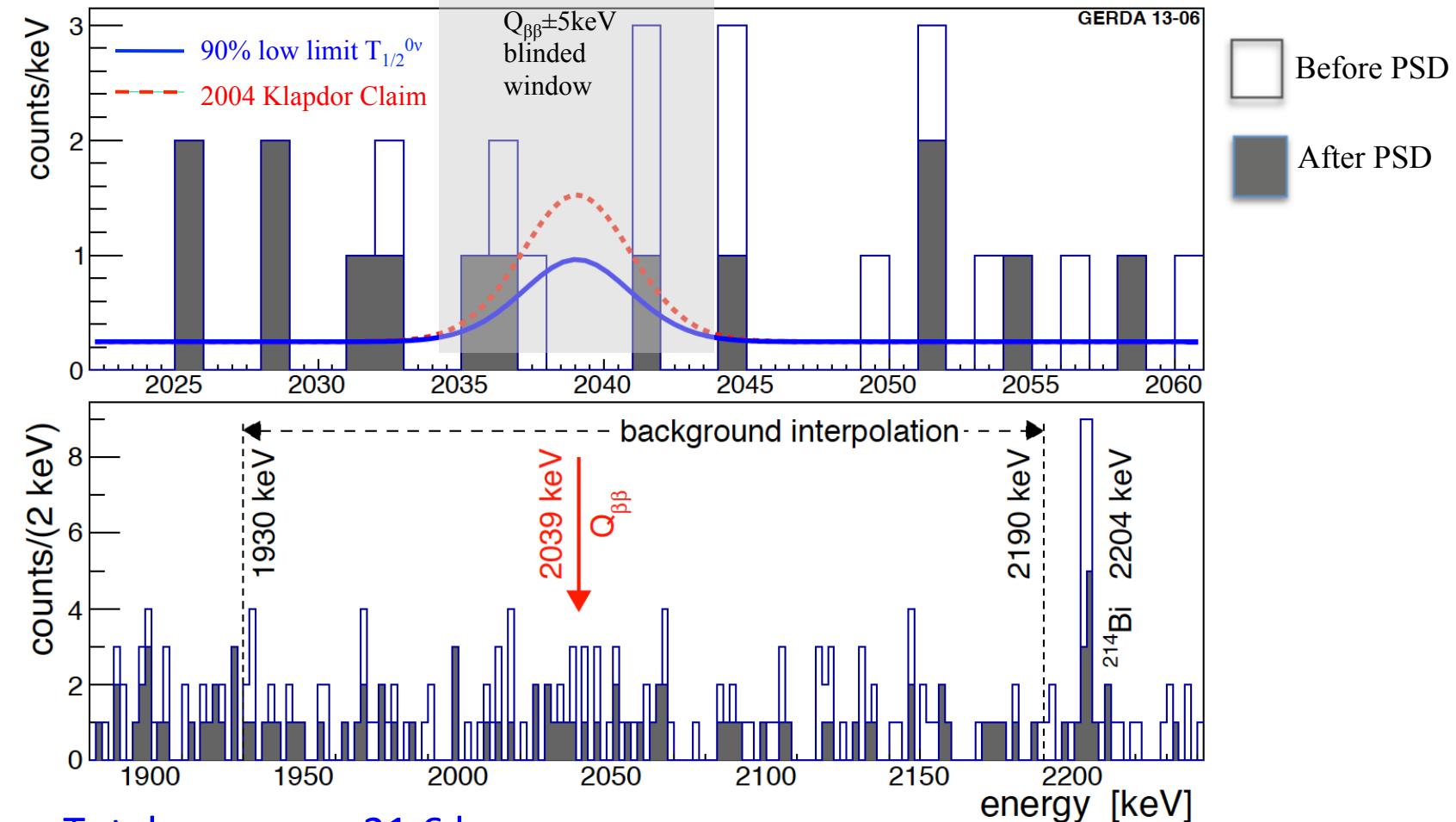


Region of Interest Spectra



GERDA Phase I Result

[GERDA Collaboration], arXiv, 1307.4720 (2013)



Total exposure: 21.6 kg yr

Bg index after PSD: 0.01 cnts/(keV kg yr)

$T_{1/2}^{{}^{0\nu}} > 2.1 \times 10^{25} \text{ yr}$ (90% C.L.)

2004 claim strongly disfavored!

Experimental Limits



Isotope	$0\nu\beta\beta$ half life (90%CL)	Experiment	$\langle m \rangle$ eV
^{48}Ca	$>1.4*10^{22}$	ELEGANT-VI	$< 7 - 44$
^{76}Ge	$>1.9*10^{25}$	Heidelberg-Moscow	< 0.35
^{76}Ge	$1.19_{-0.23}^{+0.37} \times 10^{25} \text{ yr}$	Subset of HM coll.	$0.32 +/- 0.03$
^{76}Ge	$> 2.1*10^{25}$	GERDA [†]	$< 0.2 - 0.4$
^{82}Se	$>2.1*10^{23}$	NEMO-3	$< 1.2 - 3.2$
^{100}Mo	$>5.8*10^{23}$	NEMO-3	$< 0.6 - 2.7$
^{116}Cd	$> 1.7*10^{23}$	Solotvino	< 1.7
^{130}Te	$>2.8*10^{24}$	Cuoricino	$< 0.41 - 0.98$
^{136}Xe	$>2.6*10^{25}$	KamLAND-Zen ^{††}	$< 0.14 - 0.28$
^{136}Xe	$>1.1 \times 10^{25}$	EXO-200 ^{†††}	$< 0.19 - 0.45$
^{150}Nd	$>1.8*10^{22}$	NEMO-3	

[F. Avignone, S. Elliott, J. Engel, arXiv:0708:1033v2 (2007)]

[GERDA Collaboration, arXiv:1307.4720 (2013)]

[Shimizu for KamLAND-Zen Collaboration, Neutrino 2014]

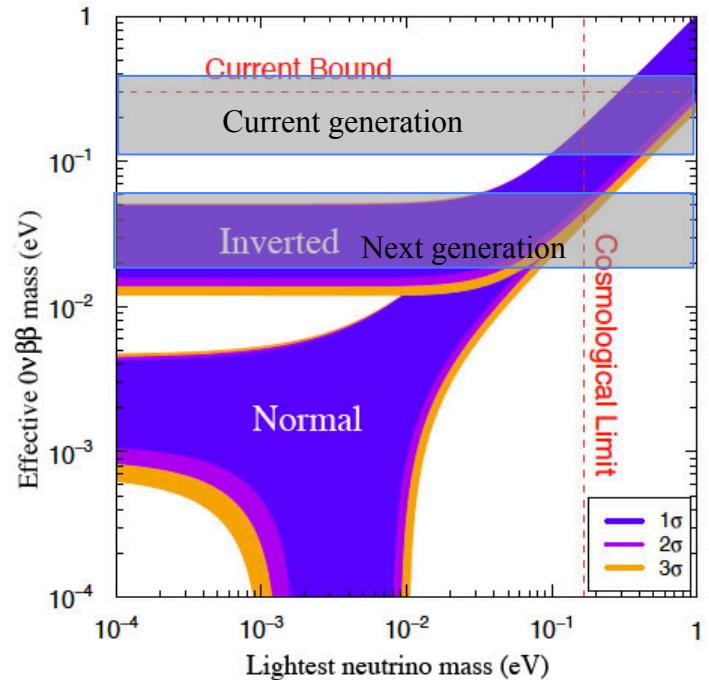
[†]

^{††}

^{†††}

$0\nu\beta\beta$ Summary

- Neutrinoless double beta search is one of the most sensitive probes for the Majorana/Dirac nature of neutrinos.
- Recent results from EXO-200, Kamland-Zen and GERDA are in tension with the claimed discovery in ^{76}Ge .
- Next generation tonne scale experiments are poised to probe the inverted hierarchy.



arXiv:1203.5250v1

New technique and ideas are need to probe the normal hierarchy!