The Search for Neutrinoless Double Beta Decay in CUORE

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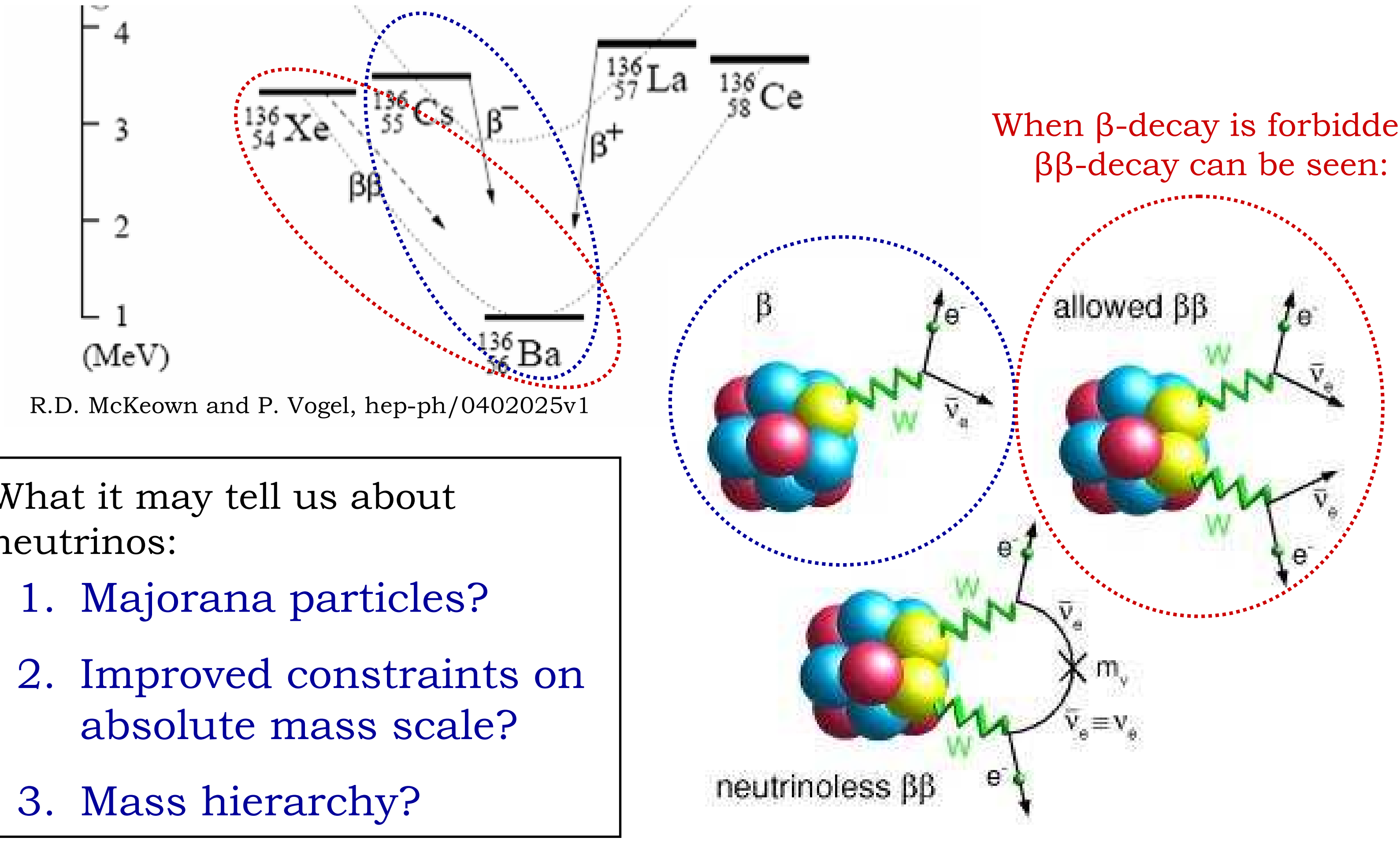
University of Wisconsin-Madison
July 31, 2009

THE UNIVERSITY
of
WISCONSIN
MADISON

CUORE

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



R.D. McKeown and P. Vogel, hep-ph/0402025v1

When β-decay is forbidden, ββ-decay can be seen:

What it may tell us about neutrinos:

1. Majorana particles?
2. Improved constraints on absolute mass scale?
3. Mass hierarchy?

What We Measure & What It Tells Us

What we are looking for is an energy signal:

Q-value for 0νββ in ^{130}Te

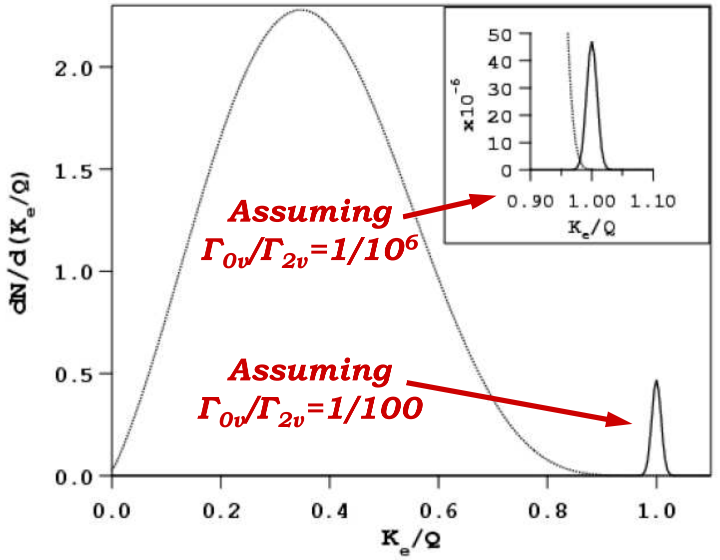
~~2530.3 ± 2.0 keV~~

2527.01 ± 0.32 keV*

2527.518 ± 0.013 keV**

*N. D. Scielzo et al., arXiv:nucl-ex/0902.2376 (2009)

**Matthew Redshaw, Brianna J. Mount, Edmund G. Myers, and Frank T. Avignone III, Masses of ^{130}Te and ^{130}Xe and Double-beta-Decay Q Value of ^{130}Te, Physical Review Letters 102 (2009), no. 21, 212502



Assuming $\Gamma_{0\nu}/\Gamma_{2\nu}=1/10^6$

Assuming $\Gamma_{0\nu}/\Gamma_{2\nu}=1/100$

P. Vogel, arXiv:hep-ph/0807.2457 (2008)

Decay rate

$$\Gamma_{0\nu} = G^{0\nu}\,|M_{\mathrm{nucl}}|^2\,\langle m_\nu\rangle^2$$

Effective 0νββ neutrino mass

$$\langle m_\nu\rangle = \left|\sum_j |U_{ej}|^2 e^{i\varphi_j} m_j\right|$$

Phase space integral
(accurately calculable)

Nuclear matrix elements
(source of theoretical uncertainty)

Neutrino mixing matrix elements
(experimental uncertainty)

Possible Majorana phases
(completely unknown)

Physical mass eigenvalues

Hierarchy & Experimental Sensitivity

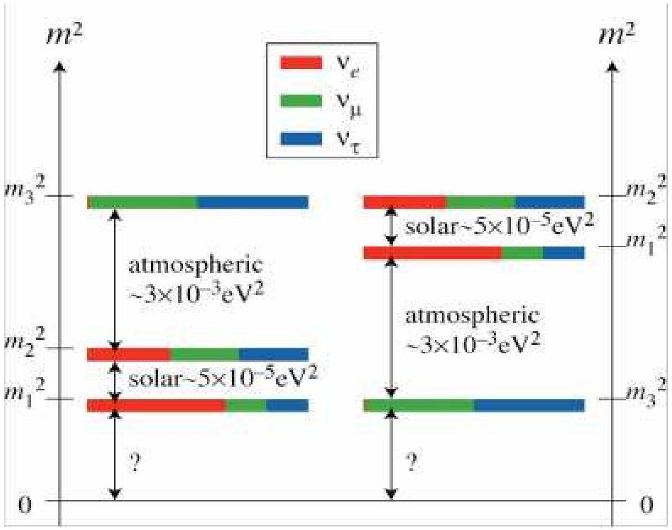
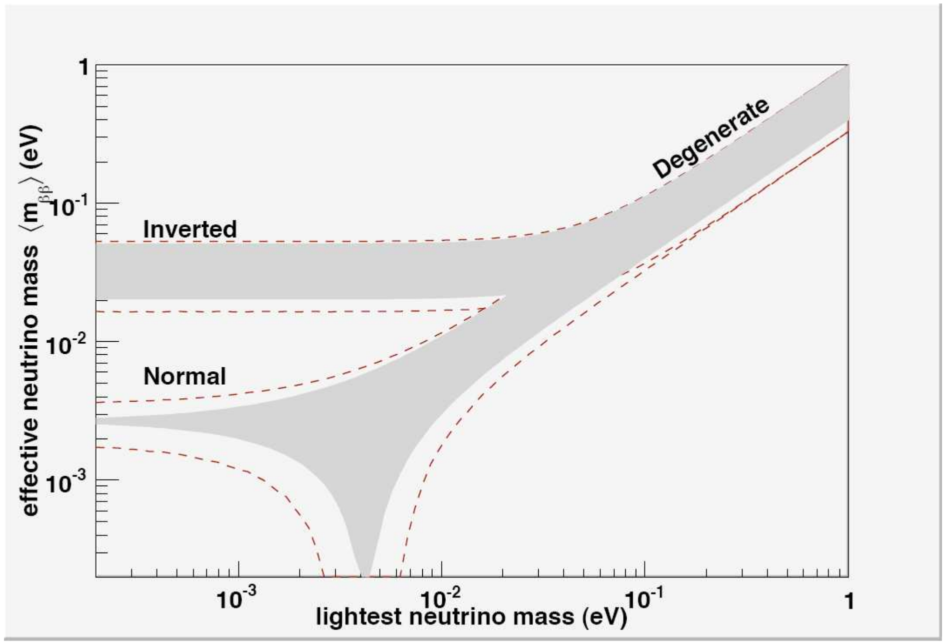


Figure from B. Kayser

Normal hierarchy

Inverted hierarchy

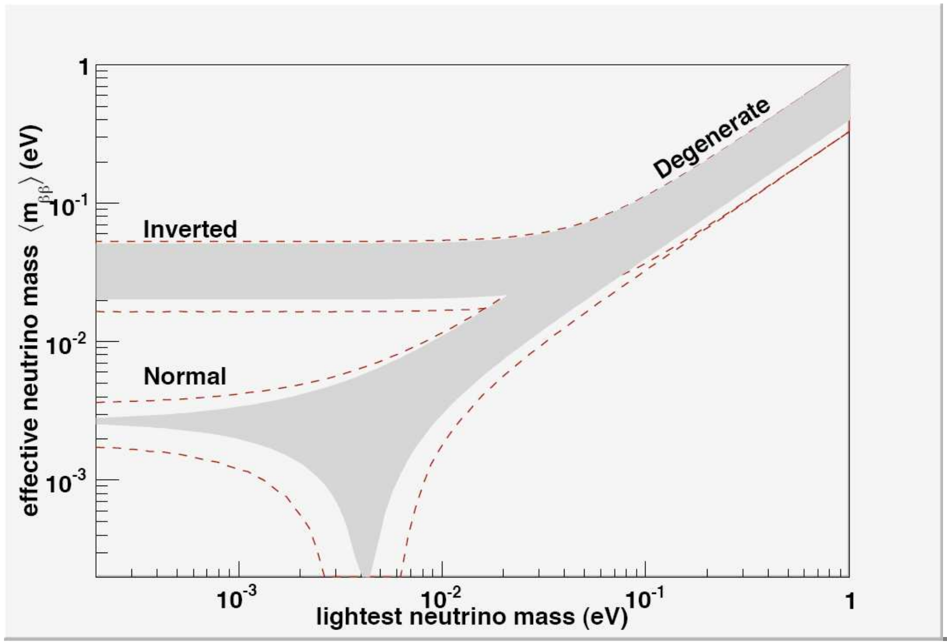


Hierarchy & Experimental Sensitivity

Figure-of-merit for sensitivity:

ratio of signal to background fluctuation

$$F = \frac{N_s}{\sqrt{N_b}} = \underset{0\nu\beta\beta\text{ decay rate}}{\Gamma_{0\nu}} \cdot \overset{\text{isotopic fraction}}{f} \cdot \underset{\text{detector efficiency}}{\epsilon} \cdot \sqrt{\frac{\overset{\text{\# of nuclei (detector mass)}}{N} \cdot \overset{\text{live time}}{\mathcal{T}}}{\Delta E \cdot b}}$$



Hierarchy & Experimental Sensitivity

Figure-of-merit for sensitivity:

ratio of signal to background fluctuation

$$F = \frac{N_s}{\sqrt{N_b}} = \Gamma_{0\nu} \cdot f \cdot \epsilon \cdot \sqrt{\frac{N \cdot \mathcal{T}}{\Delta E \cdot b}}$$

# of nuclei (detector mass)

isotopic fraction

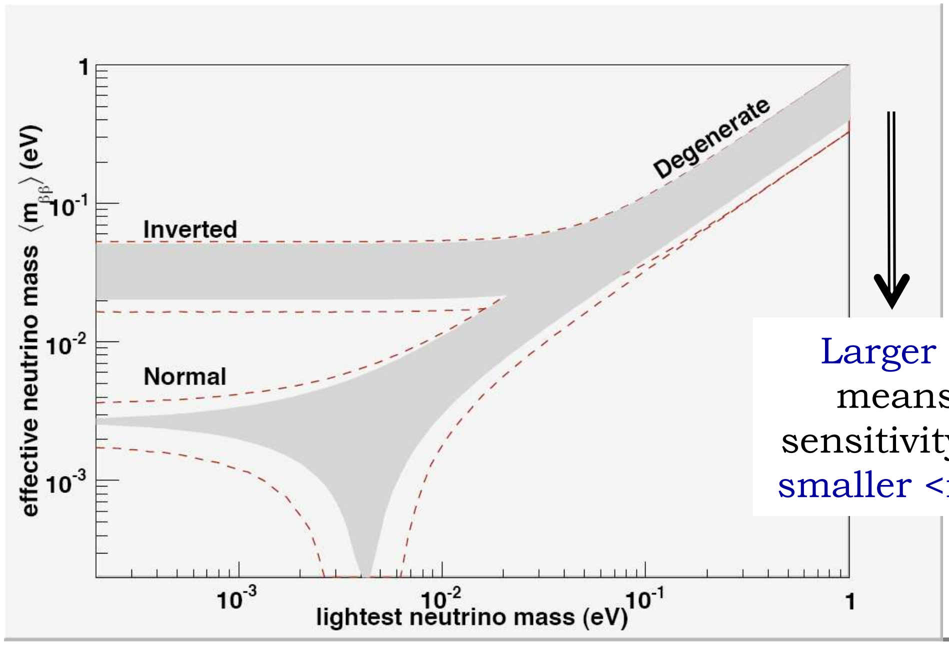
live time

0νββ decay rate

detector efficiency

detector resolution

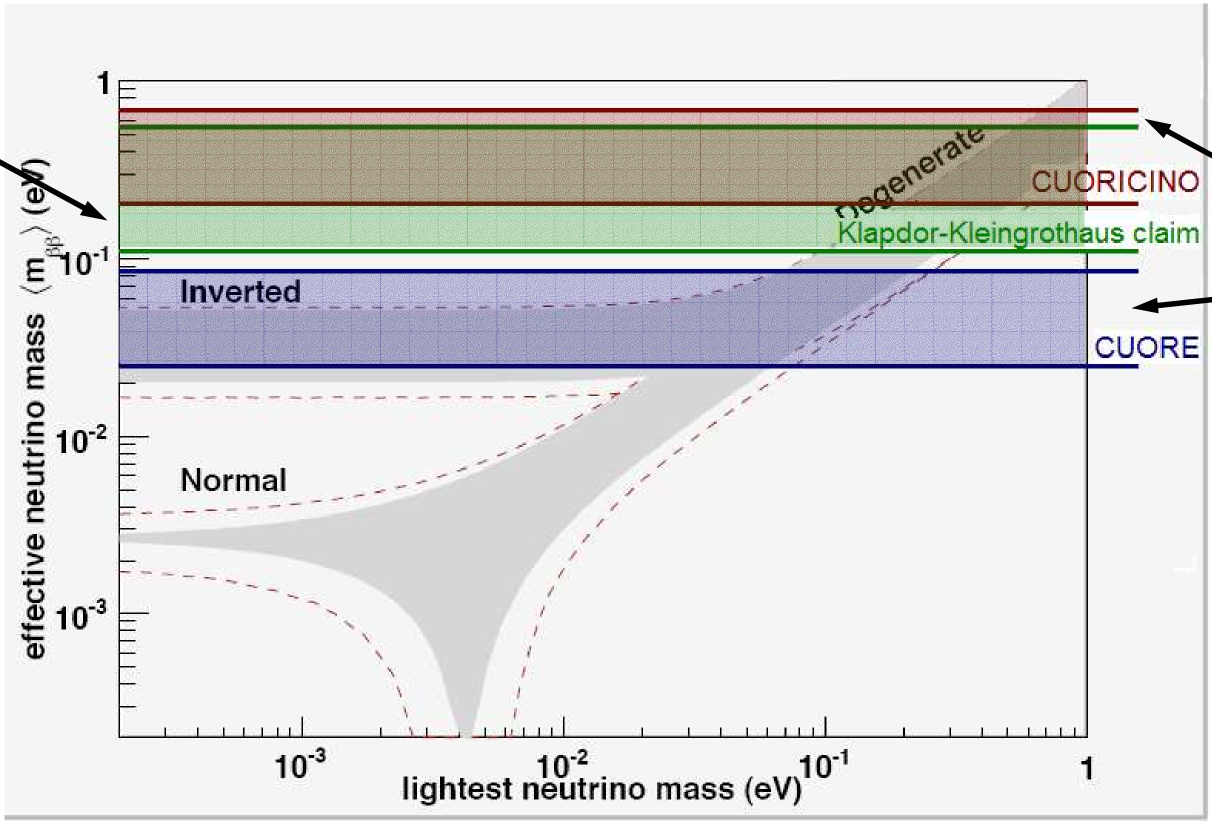
background rate



Larger F means sensitivity to smaller $<m_\nu>$

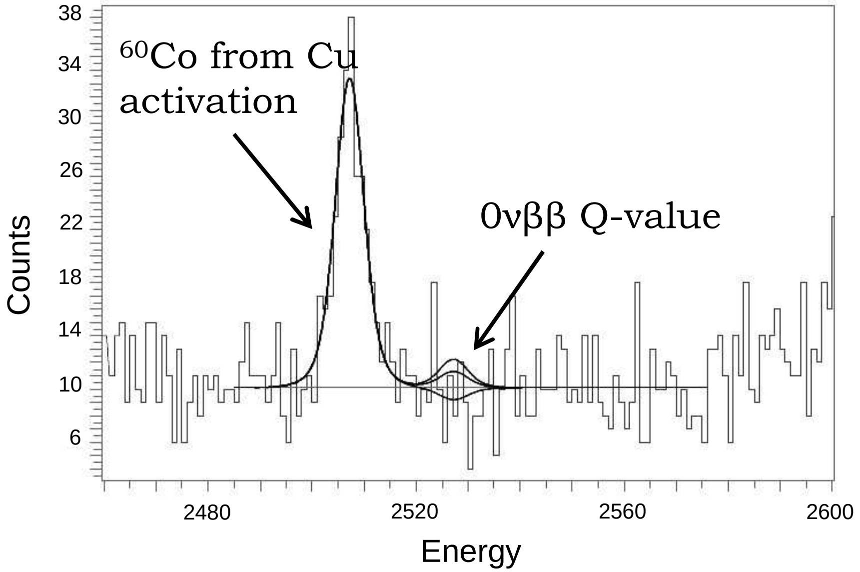
How Cuoricino & CUORE Measure Up

mass range corresponding to claim of discovery in Ge



limits on mass to within theoretical uncertainty

Cuoricino to CUORE



^{60}Co from Cu activation

0νββ Q-value

CUORICINO Performance and Results (PRELIMINARY)

- *Average FWHM resolution (at 2615 keV):* ~8 keV
- *Average background (near Q-value):* 0.18 counts*keV^{-1}*kg^{-1}*yr^{-1}
- *Statistics March 2003 – June 2008 (total exposure 18 yr*kg ^{130}Te):*

$T_{1/2}(90\%\ \text{C.L.}) \geq 2.94\text{x}10^{24}$ yr

$\rightarrow \langle m_\nu \rangle \leq (0.21 - 0.70)$ eV *

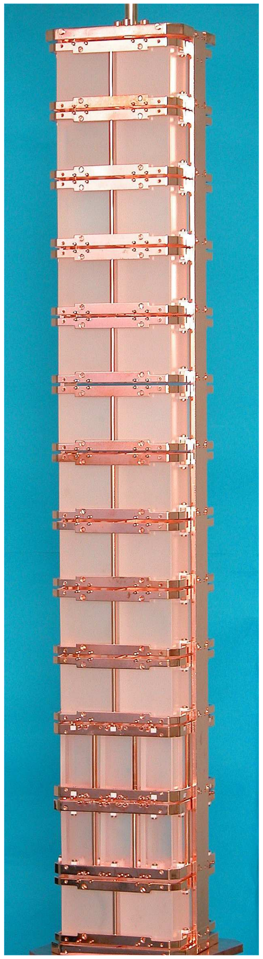
CUORE Goals

- *Average FWHM resolution:* 5 keV
- *Average background:* 0.01 counts*keV^{-1}*kg^{-1}*yr^{-1}
- *Predicted limit after ~5 years of running:*

$T_{1/2} \sim 2.1\text{x}10^{26}$ yr $\rightarrow$ $\langle m_\nu \rangle \leq (24 - 83)$ meV *

**NME from review table of QRPA calculations in Rodin et al Nucl. Phys. A 766,107 (2006) + Erratum nucl-th:0706.4304v1*

Cuoricino to CUORE: Scaling Up

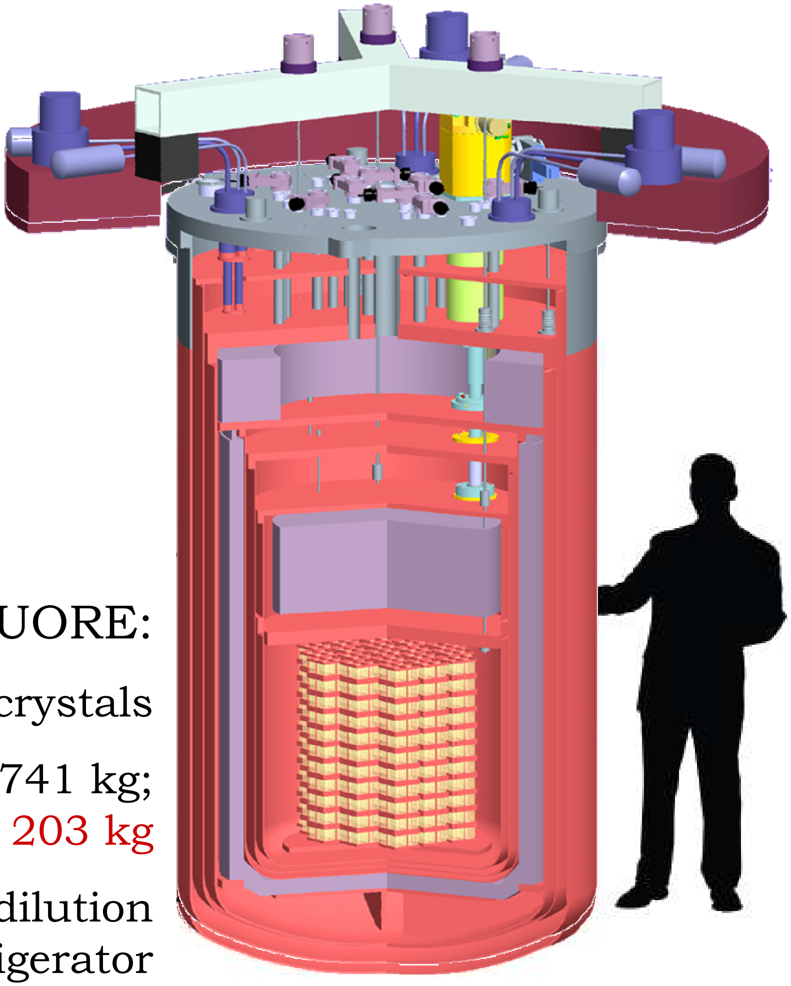


Cuoricino:

44 5x5x5 cm^3
and 18 3x3x6 cm^3
TeO_2 crystals

detector mass 40.7 kg;
^{130}Te mass 11.34 kg

standard dilution
refrigerator



CUORE:

988 5x5x5 cm^3 TeO_2 crystals

detector mass 741 kg;
^{130}Te mass 203 kg

cryogen-free dilution
refrigerator

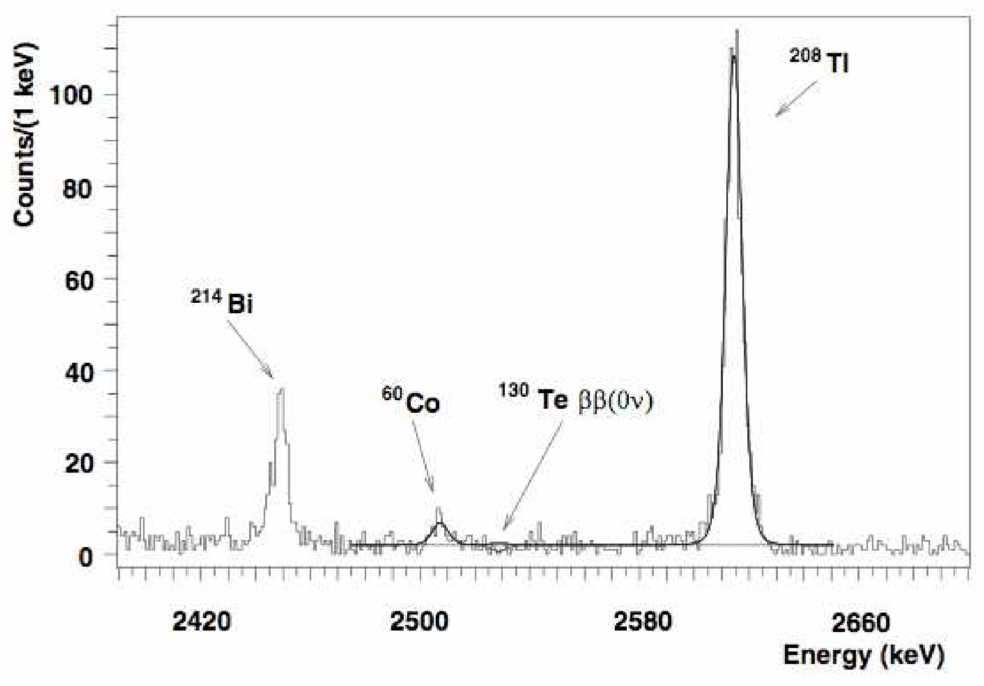
What We See in Cuoricino

Most relevant backgrounds – U and Th contamination

- Flat α background
  - Copper surfaces (50 ± 20 %)
  - Crystal surfaces (10 ± 5 %)
- 2615 keV γ line (30 ± 10 %)
  - Decay chain of Th in cryostat shields

…And additional concerns for CUORE

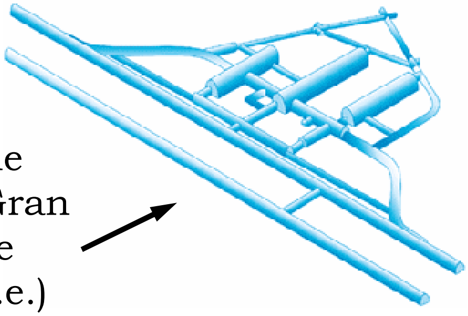
- ^{60}Co from cosmogenic activation of copper supports?
- 2νββ tail?



CUORICINO spectrum in region-of-interest

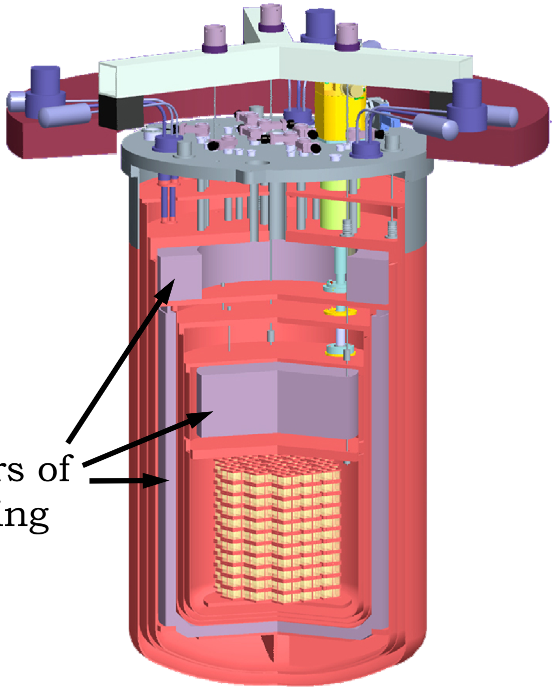
Avg. background in region-of-interest:
0.18 ± 0.01 counts*keV^{-1}*kg^{-1}*yr^{-1}

Cuoricino to CUORE: Backgrounds



Run underground in the Laboratori Nazionali del Gran Sasso in Italy to reduce cosmic rays (~3500 m.w.e.)

☆More stringent material selection, production, cleaning, handling, and storage procedures for all detector components for CUORE☆



Several layers of lead shielding

So far demonstrated:

within a factor of 2 – 4 of goal

GOAL FOR CUORE

Avg. background in region-of-interest:

0.01 counts*keV^{-1}*kg^{-1}*yr^{-1}

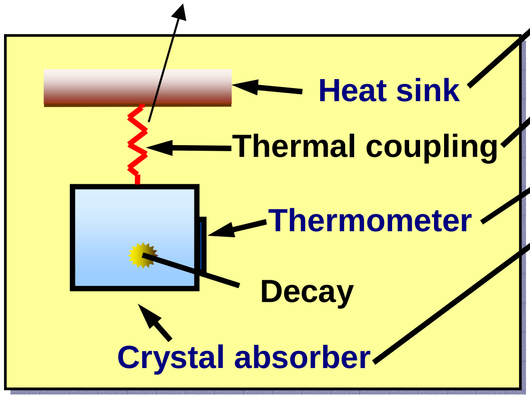
Detector Technology: Bolometers & Thermistors

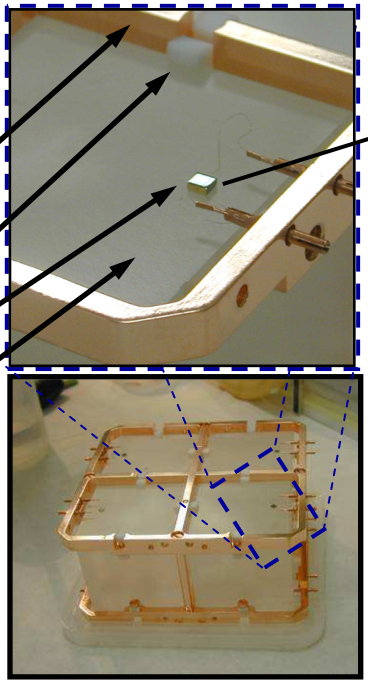
The basic detector unit is a TeO_2 crystal (^{130}Te natural abundance 33.87%).
A decay deposits energy in the crystal, causing a temperature rise:

$$\Delta T(t) = \frac{\Delta E}{C} e^{\left(-\frac{t}{\tau}\right)}, \qquad \tau = \frac{C}{G}$$

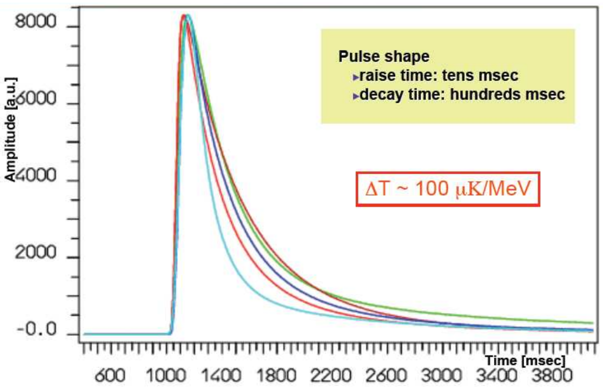
crystals' heat capacity $C \propto T^3$ ⟹ keep array in a cryostat at 8-10 mK

thermal conductivity G





$$R(T) = R_0 e^{\sqrt{\frac{T_0}{T}}}$$



Voltage signal → needs to be calibrated!

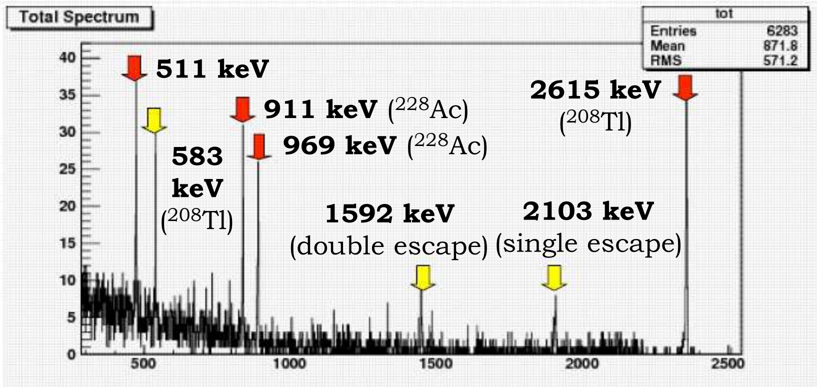
Calibration Approach

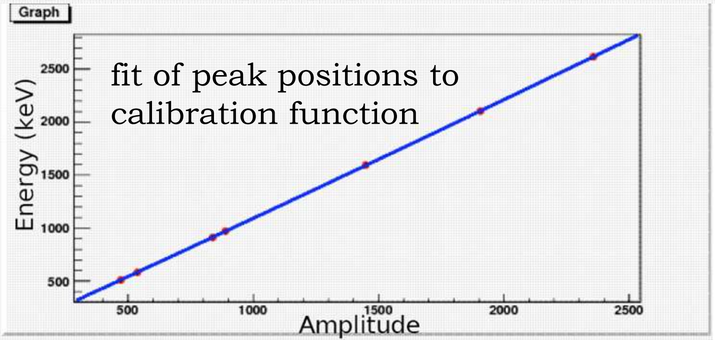
Bolometers provide only energy information.

The response of each is different, so they must be calibrated individually.

We calibrate against γ sources of known energies ~monthly.

Between calibrations we stabilize the response with a heater + pulser system, and stabilize the base temperature with a DC feedback loop.




fit of peak positions to calibration function

- ^{232}Th: used in Cuoricino
  - Several peaks throughout spectrum
  - Strong peak near Q-value
- Option of using different sources
- Non-linear energy response
  - Currently re-optimizing analysis using all Cuoricino data
- Calibration uncertainty affects resolution, and is a systematic error in determining $T^{0\nu}_{1/2}$
  - *Cuoricino:* ±0.4 keV (negligible with respect to ±2 keV Q-value uncertainty)
  - *Goal for CUORE:* ±0.05 keV or better (similar to improvement on Q-value measurement)

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Bolometers provide only energy information.

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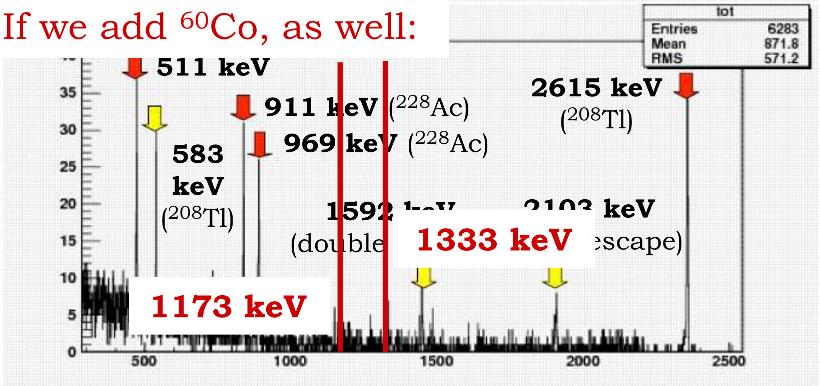
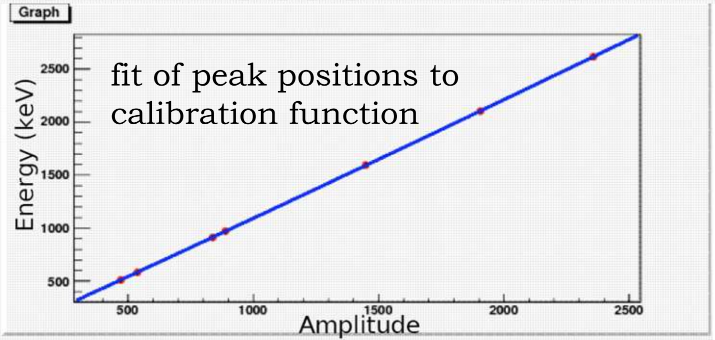
If we add ^{60}Co, as well:





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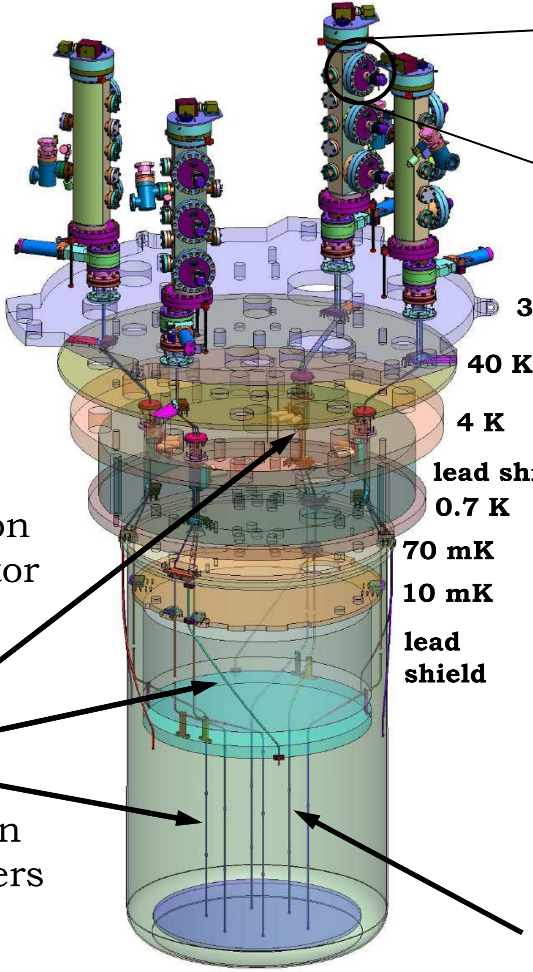
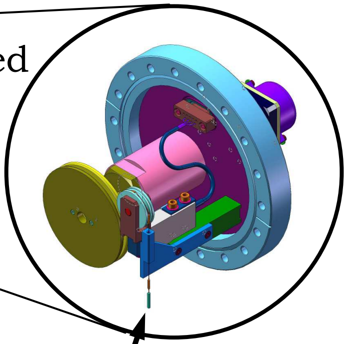
Detector Calibration System (DCS)

Requirements

- Isotope: ^{232}Th (plus ^{60}Co?)
- Source carrier moves between 300 K and detector region
  - Static heat loads
  - Thermalization
  - Friction
- Low-background
  - Materials
  - Source parking position
  - Failsafe against detector contamination



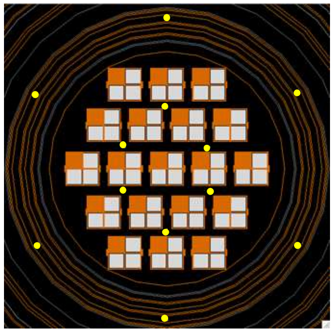


Computer-controlled motion boxes with spools

Guide tubes:

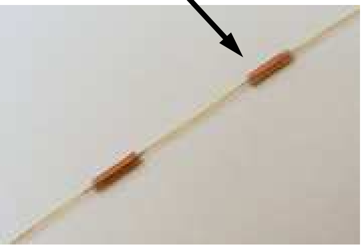
to get calibration sources in BETWEEN the detector towers for even illumination

TOP VIEW



Detector area

Chains of individual sources: 12 strings of ~30 sources each, with a *total* activity ~50 Bq (~1.3 nCi)



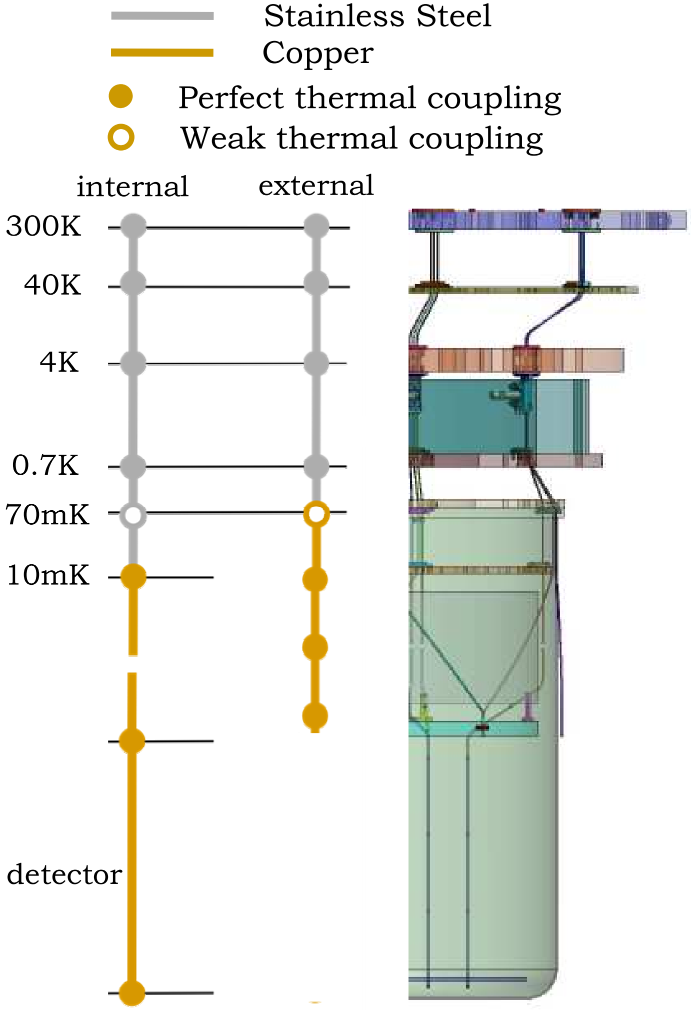
Thermal Considerations

Stage	T [K]	Calibration static cooling power budget [W]	Static heat load from guide tubes [W]	Radiation from source string at 4 K [W]
40K	40 – 50	**~ 1**	~ 1	--
IVC	4 – 5	**0.3**	~0.09	--
STILL	0.6 – 0.9	**0.55m**	0.13m	0.08μ
HEX	0.05 – 0.1	**1.1μ**	negligible	0.3μ
MC	0.01	**1.2μ**	1.07μ	0.08μ
TSP	0.01	**< 1μ**	~1.2n	0.25μ

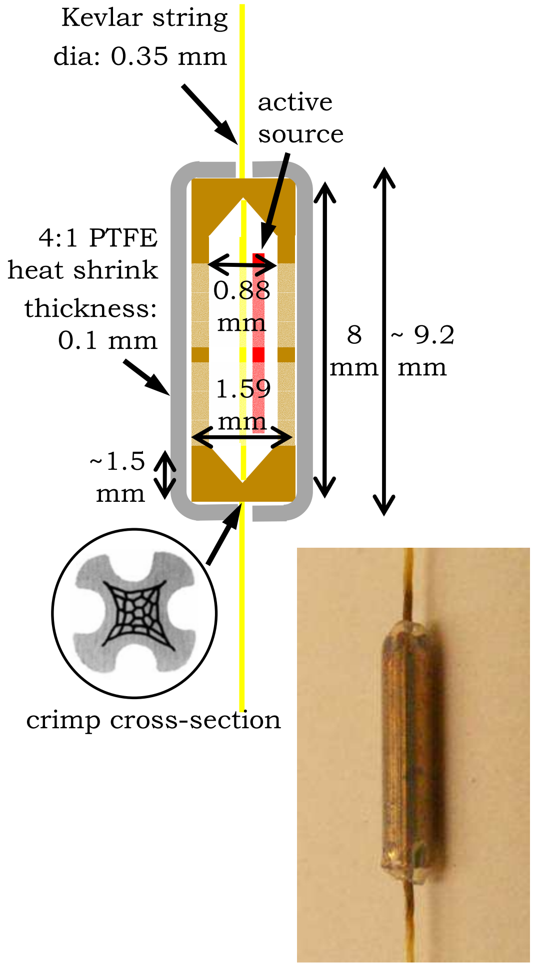
- Conductance of guide tubes
- Radiation funneled from 300 K

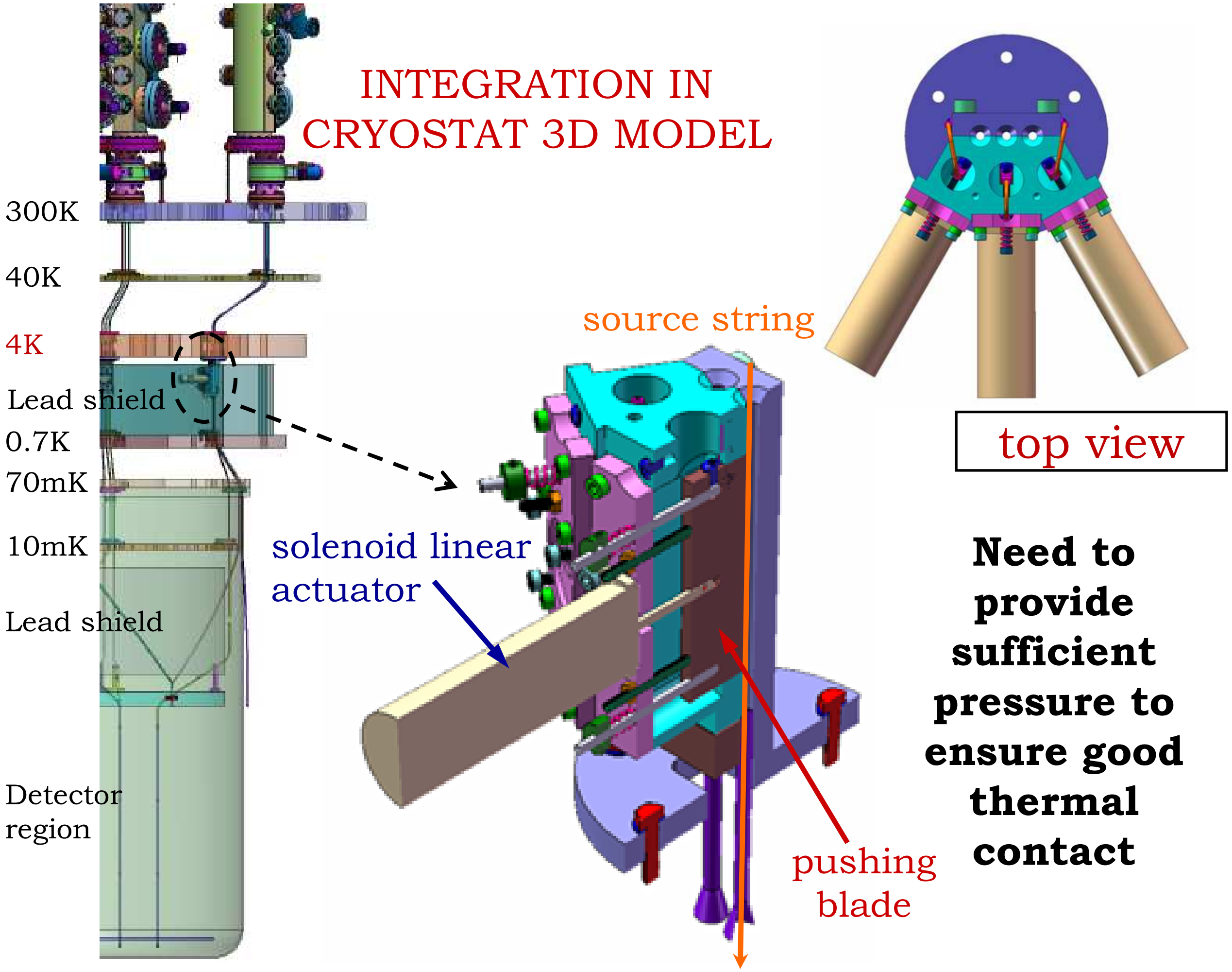
- String must be at 4 K or below for safe insertion

- Minimize friction from source motion through tubes



Source Carriers & Thermalization

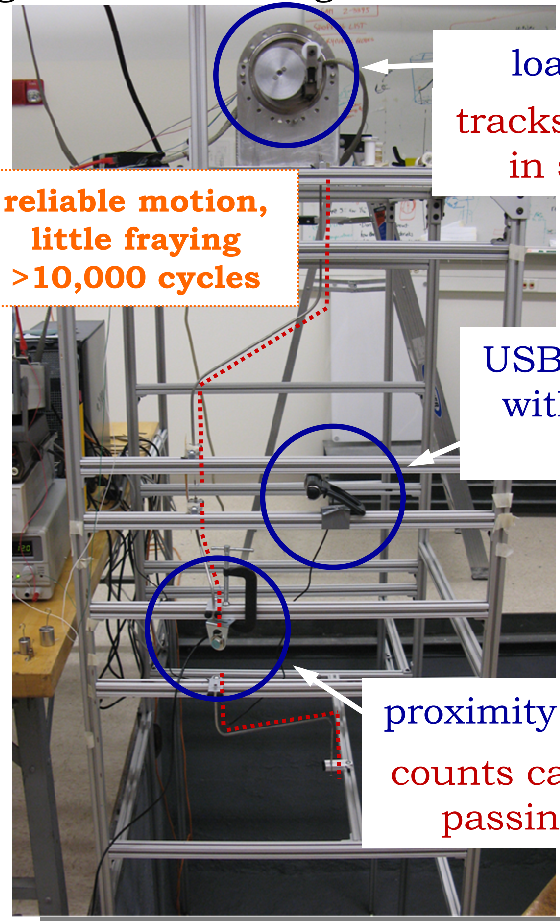




Need to provide sufficient pressure to ensure good thermal contact

Motion & Friction Tests

Lab mock up of a representative guide tube routing



load cell

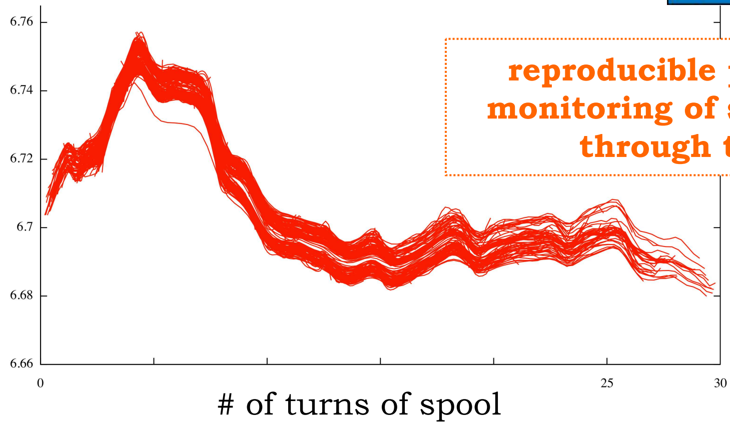
tracks tension in string

reliable motion, little fraying >10,000 cycles

USB camera integrated with LabView control software

proximity sensor

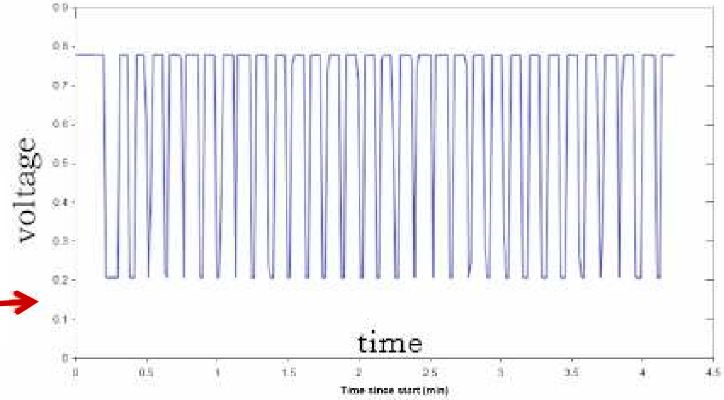
counts capsules passing by



reproducible profile allows monitoring of source's travel through the tubes

takes snapshot of source after given number of turns of the spool

positioning accuracy of ~0.5 mm



CUORE Status & Schedule

Summer 2009 (now)	Crystal production ongoing since 2008 (~30 per month) Cryostat ordered, will be assembled as parts come in Hut construction is almost complete
Winter 2009-2010	Installation of 1st tower in Cuoricino cryostat (CUORE-0) Delivery of dilution unit for cryostat Cryostat hardware tests (room temperature and cold)
2010-2011	Assembly of detector, Faraday cage, and electronics
2012	Start of data taking

Summary

- CUORE is now in the construction phase
- CUORE will be one of the first $0\nu\beta\beta$ experiments to probe the inverse hierarchy mass region
- CUORE plans to start taking data in 2012

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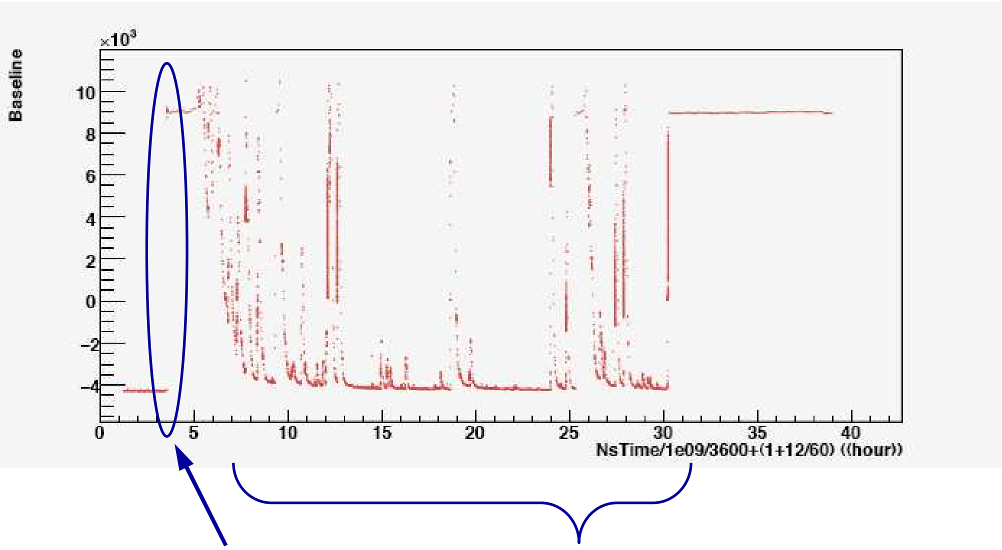
[3] also LLNL
[4] also UC Berkeley

[5] also Sezione di Milano dell'INFN
[6] also Universita' di Genova

Backup Slides

A Major Interruption…

On April 6th, an earthquake destroyed L'Aquila, the nearest major city to the Gran Sasso lab.

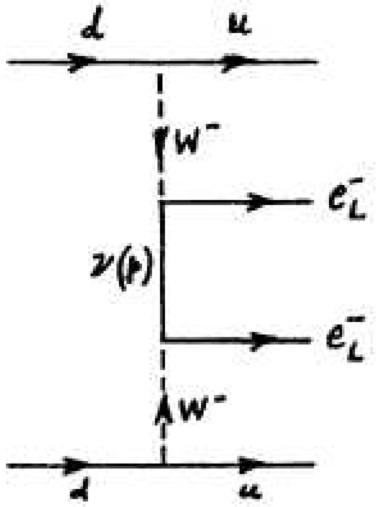


the main shake and aftershocks as seen by the large-scale R&D detector running in the Cuoricino cryostat (the final test of copper cleaning procedures)

Estimated delay of up to 6 months

How Can 0νββ Tell if Neutrinos are Majorana?

Diagrams from J. Schechter and J. Valle, Phys. Rev. D **25**, 2951 (1982)



Standard diagram for 0νββ:

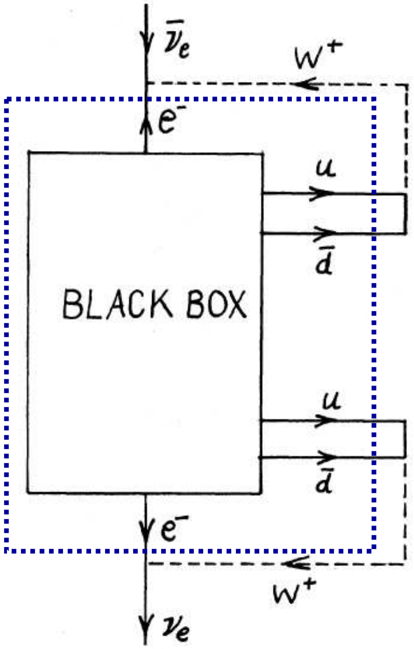
$n\,n \rightarrow p\,p\,e^-\,e^-$

or

$d\,d \rightarrow u\,u\,e^-\,e^-$

BUT

0νββ could also be mediated by some other mechanism, e.g. SUSY particles



Crossing-symmetry diagram:

$0 \rightarrow \bar{d}\,\bar{d}\,u\,u\,e^-\,e^-$

Thus *any* observation of 0νββ implies that neutrinos are Majorana.

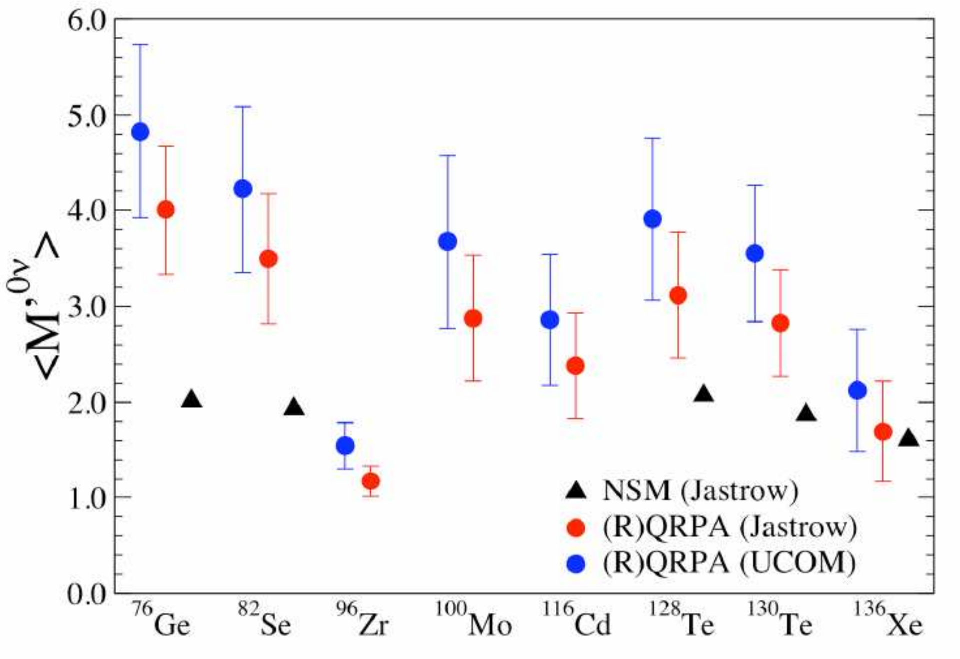
Calculation of Nuclear Matrix Elements

Nuclear Shell Model (NSM)

- Defines a 'valence space' to work with – restricts number of nucleons considered
- Uses effective Hamiltonian obtained from empirical data
- Can be used to describe nuclear deformation

Quasiparticle Random Phase Approximation (QRPA)

- Treats a large fraction of nucleons
- Considers a limited number of correlations; useful only for (nearly)-spherical nuclei
- Dependent on the value of the particle-particle interaction

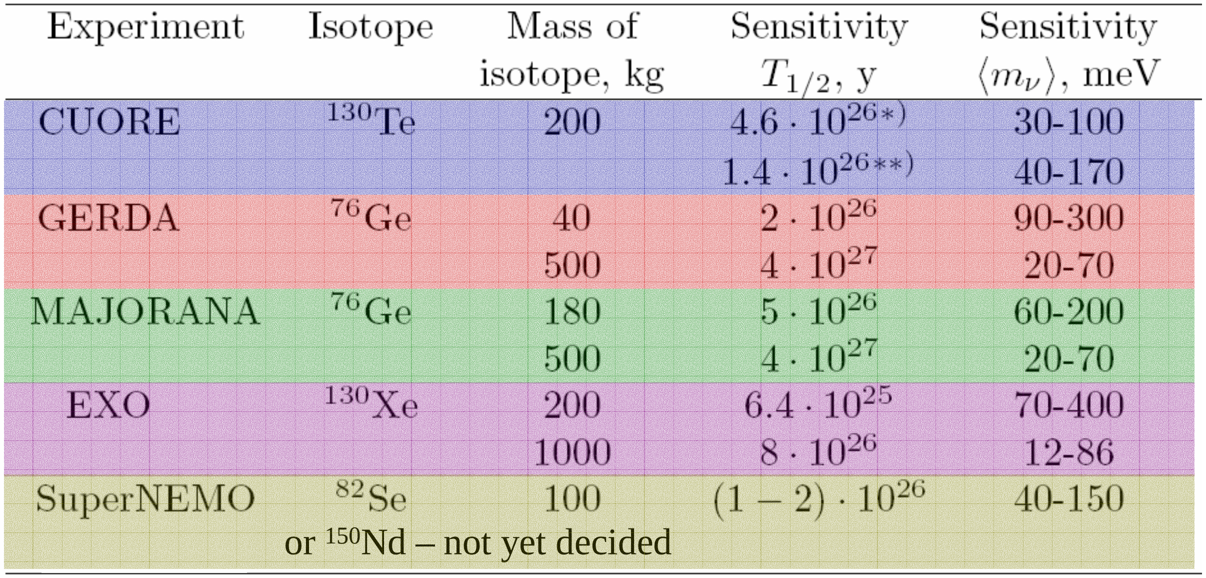


P. Vogel, arXiv:hep-ph/0807.2457 (2008)

Upcoming Experiments & Projected Sensitivities

tellurium dioxide crystal bolometers

germanium diodes surrounded by heavy shielding



Experiment	Isotope	Mass of isotope, kg	Sensitivity $T_{1/2}$, y	Sensitivity $\langle m_\nu \rangle$, meV
CUORE	^{130}Te	200	$4.6 \cdot 10^{26*)}$	30-100
			$1.4 \cdot 10^{26**)}$	40-170
GERDA	^{76}Ge	40	$2 \cdot 10^{26}$	90-300
		500	$4 \cdot 10^{27}$	20-70
MAJORANA	^{76}Ge	180	$5 \cdot 10^{26}$	60-200
		500	$4 \cdot 10^{27}$	20-70
EXO	^{130}Xe	200	$6.4 \cdot 10^{25}$	70-400
		1000	$8 \cdot 10^{26}$	12-86
SuperNEMO	^{82}Se	100	$(1-2) \cdot 10^{26}$	40-150
	or ^{150}Nd – not yet decided			

A.S. Barabash, arXiv:hep-ex/0602037v1 (2006)

germanium diodes immersed in liquid argon

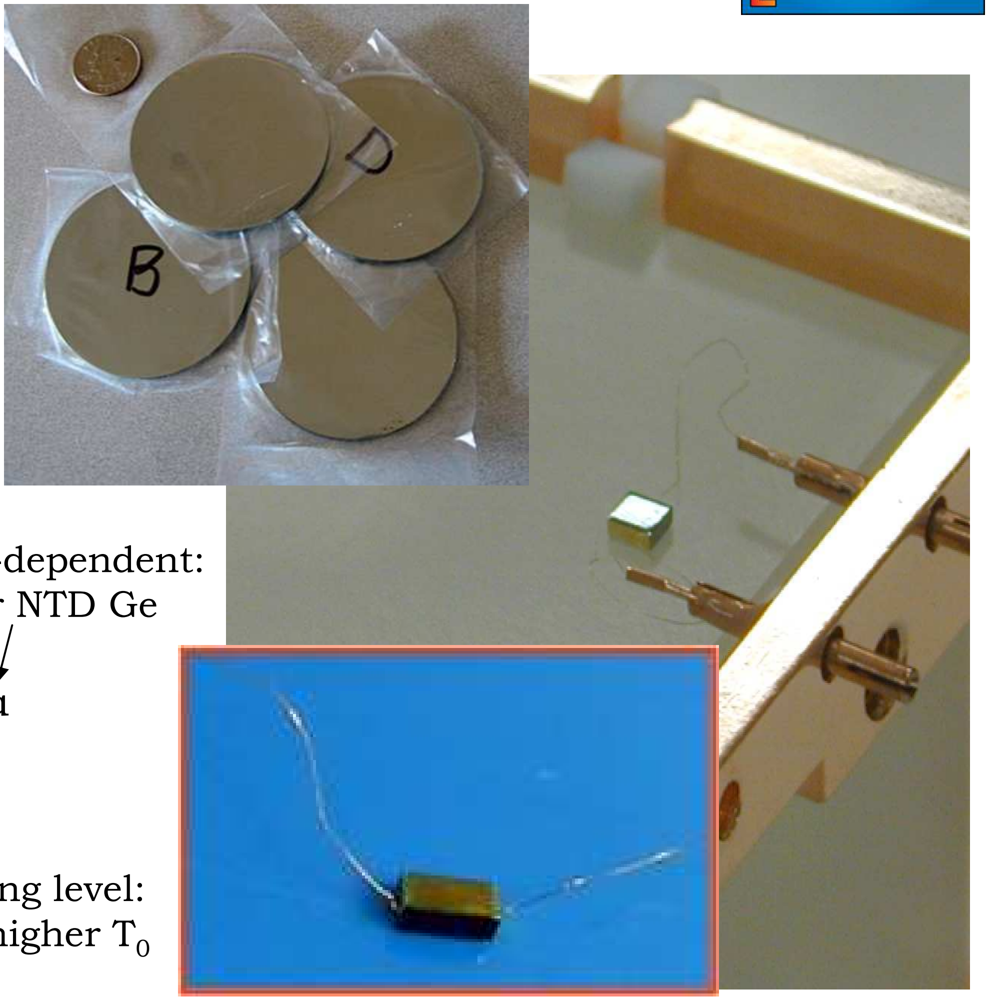
liquid xenon time projection chamber

source foils surrounded by gaseous tracking chamber and calorimeter

NTD Thermistors

Prepared from Neutron Transmutation Doped germanium wafers:

neutron irradiation activates Ge, which then decays to As, Se, and Ga → p-type doping



material-dependent: 0.5 for NTD Ge

$$\rho(T) = \rho_0 \exp (T_0/T)^{\alpha}$$

independent of doping level

depends on doping level: lower doping → higher T_0

ββ-decay Candidates & the Selection of ^{130}Te

a different way to express $\Gamma_{0\nu}$:
$F_N = G^{0\nu}\,|M_{\mathrm{nucl}}|^2\, m_e^2$

Parent Isotope	$F_N(y^{-1})$	$Q_{\beta\beta}$ (KeV)	Ab(%)
^{48}Ca	$(5.4^{+3.0}_{-1.4})\cdot 10^{-14}$	4271	0.187
^{76}Ge	$(7.3 \pm 0.6)\cdot 10^{-14}$	2039	7.8
^{82}Se	$(1.7^{+0.4}_{-0.3})\cdot 10^{-13}$	2995	9
^{100}Mo	$(5.0 \pm 0.15)\cdot 10^{-13}$	3034	9.6
^{116}Cd	$(1.3^{+0.7}_{-0.3})\cdot 10^{-13}$	2902	7.5
^{130}Te	$(4.2 \pm 0.5)\cdot 10^{-13}$	2530	33.9
^{136}Xe	$(2.8 \pm 0.4)\cdot 10^{-14}$	2479	8.9
^{150}Nd	$(5.7^{+1.0}_{-0.7})\cdot 10^{-12}$	3367	5.6

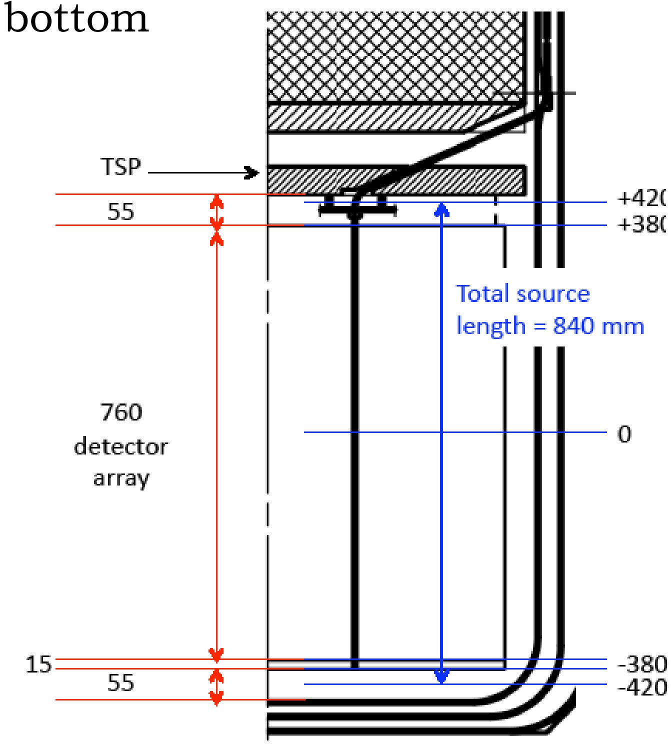
no enrichment necessary

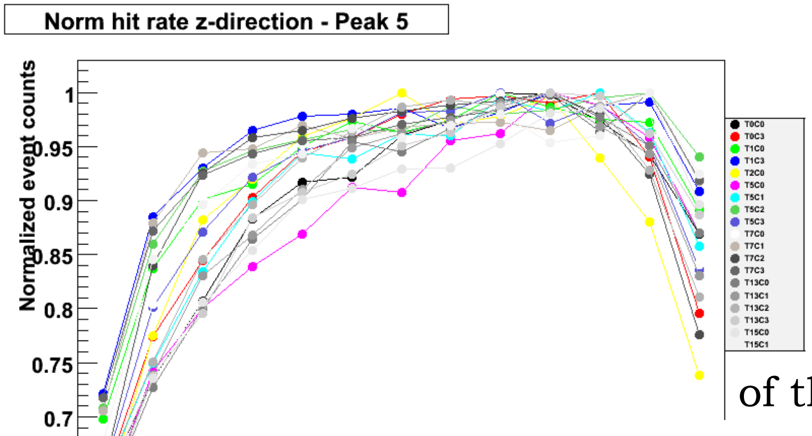
relatively favorable

lies above all natural gammas except 2615 keV (^{208}Tl);
in clean window between peak and Compton edge

Solid-Angle Effect

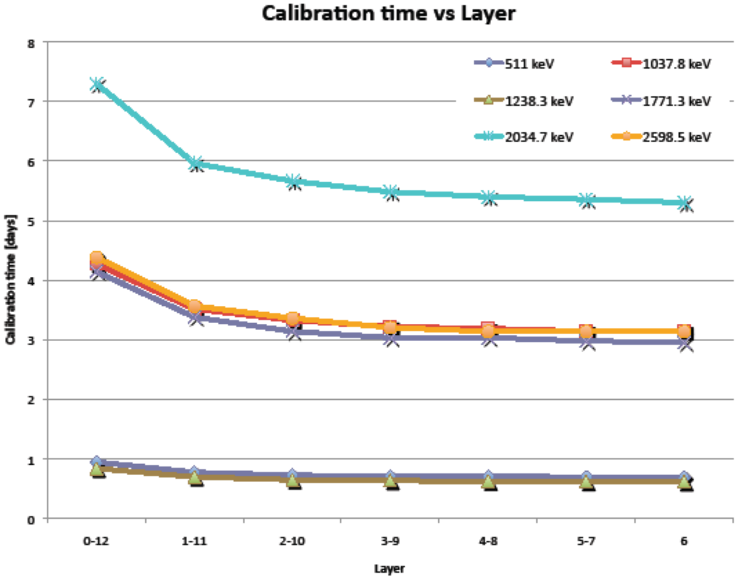
Since the sources extend only slightly above and below the detectors, the middle layers see more activity than the top and bottom





We can compensate somewhat by increasing the activity at the top and bottom of the source string

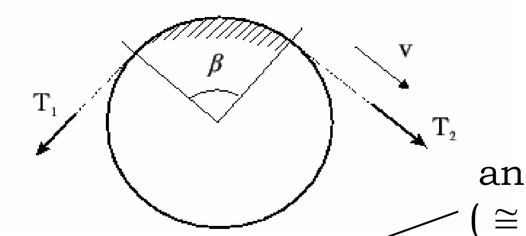
Note: so far this analysis only done for ^{56}*Co*



Distance between bottom of the source and bottom of the MC vessel is 30 mm

Open Questions: Friction

Major factor is the motion of the source carriers over the bends in the guide tubes:

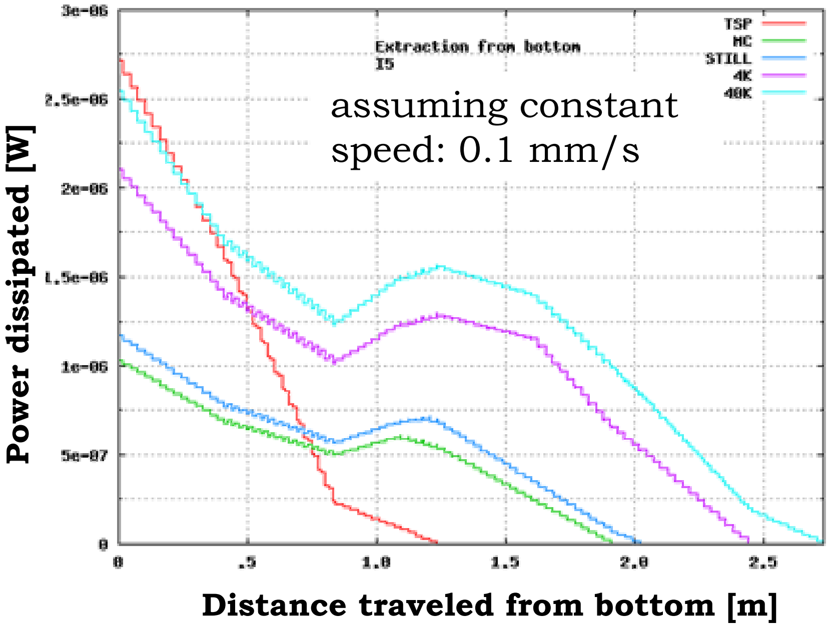


$$\frac{T_2}{T_1}=e^{\mu_k\beta}$$

angle of contact
(≅ bending angle
in our case)

kinetic friction
coefficient

Extraction of a single source string

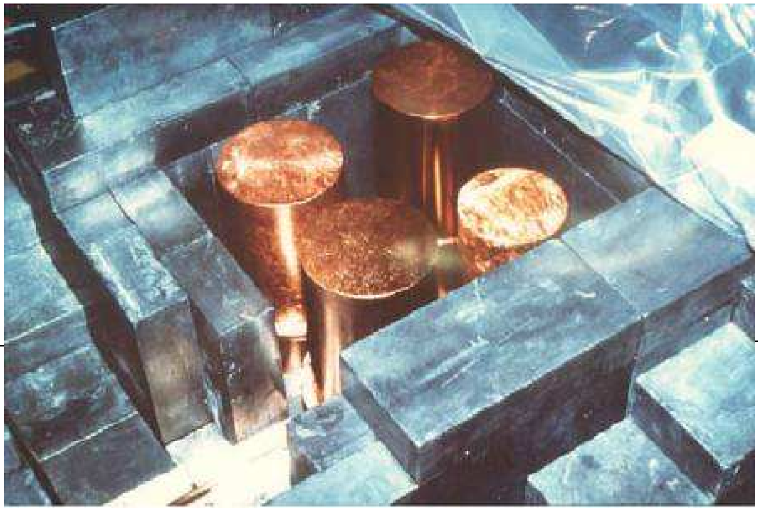


assuming constant speed: 0.1 mm/s

→ Optimization of this model gives ~49 hours for extraction of all 12 strings

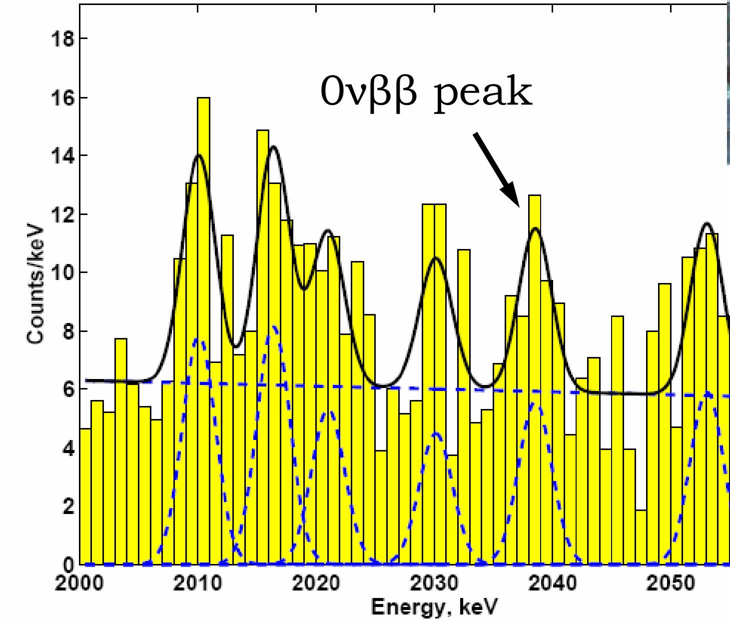
A Controversial Claim in ^{76}Ge

Heidelberg-Moscow experiment: ~11 kg of enriched germanium

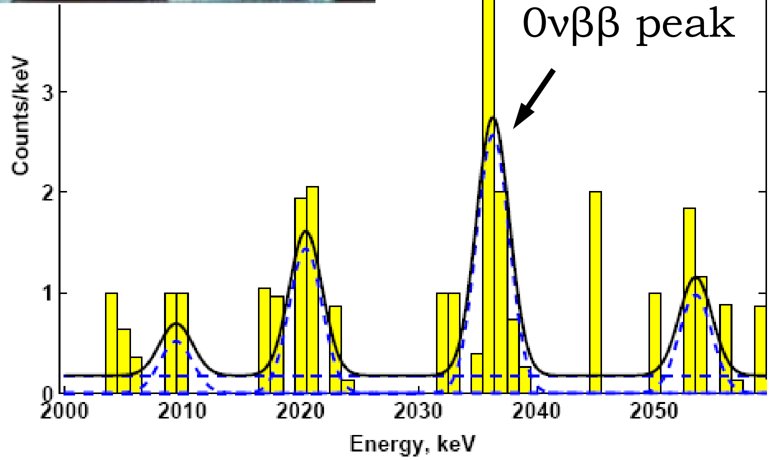


$<m_\nu> \approx 0.4$ eV

H.V. Klapdor-Kleingrothaus et al., Nucl. Inst. And Meth. A **522**, 371 (2004)

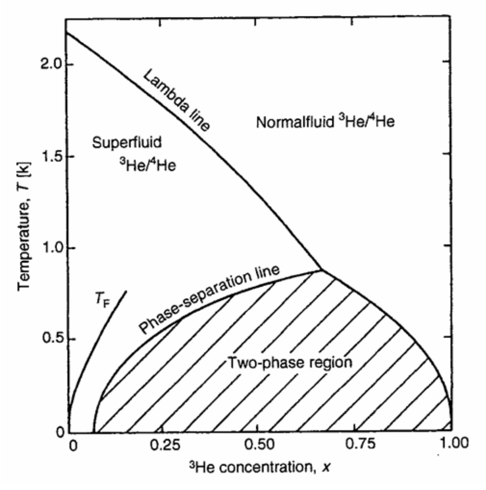


pulse shape selection



Cryogenics

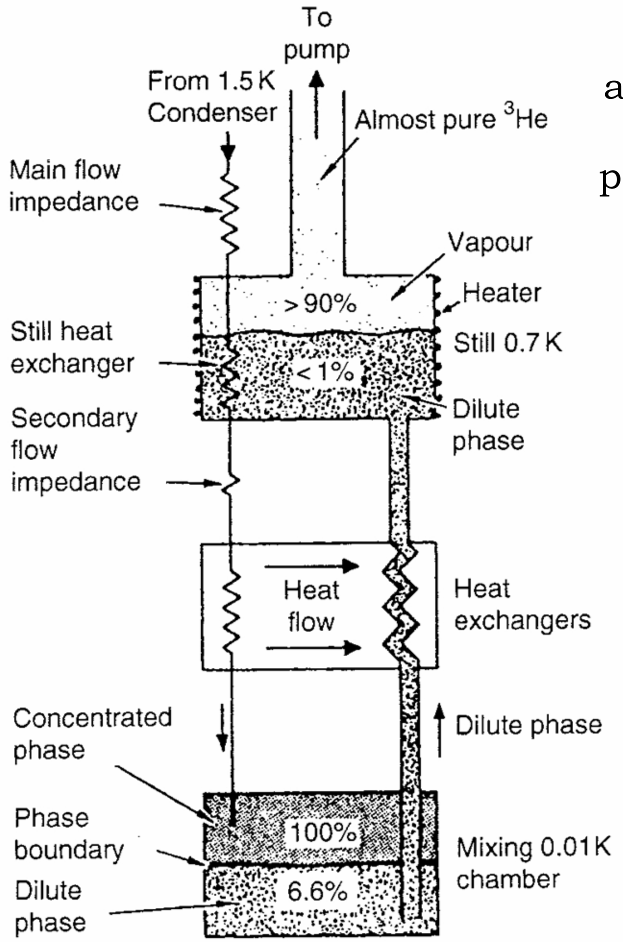
All figures from Pobell, *Matter and Methods at Low Temperatures Third Edition*



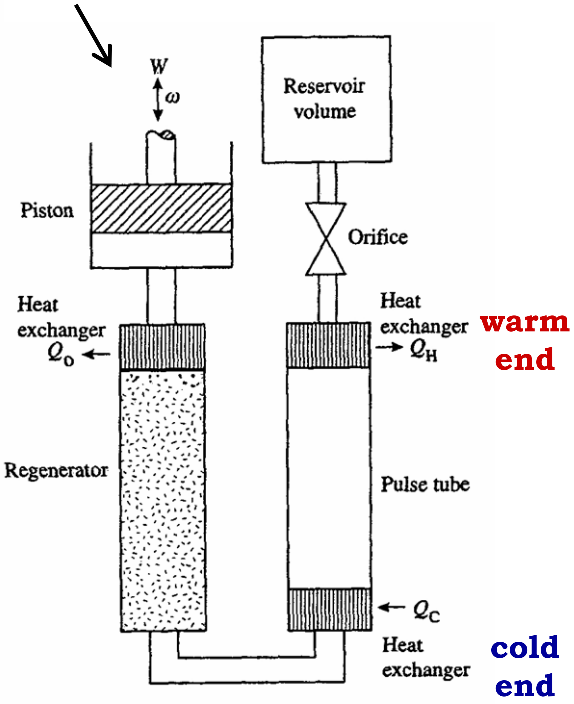
At low enough temperatures, a ^{3}He/^{4}He mixture separates into a 'concentrated ^{3}He' phase and a 'dilute ^{3}He' phase

$C_{3,d} > C_{3,c}$

When ^{3}He moves from concentrated phase to dilute phase, cooling occurs

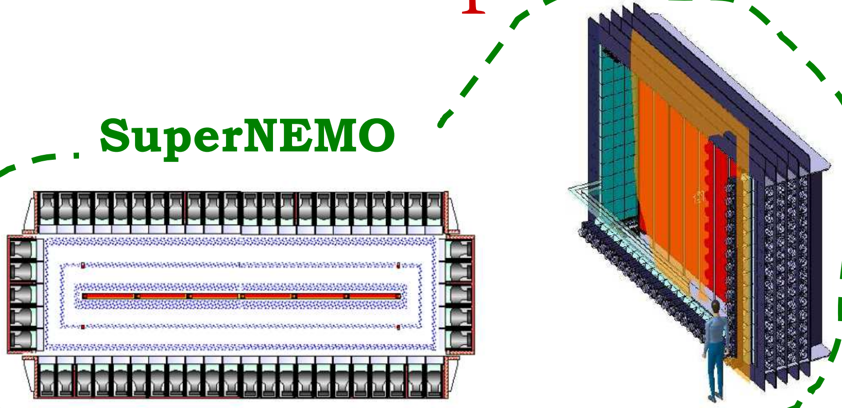


Traditionally precooling is accomplished by immersion in a ~4K ^{4}He bath; pulse tubes provide a mechanical means to reach that temperature

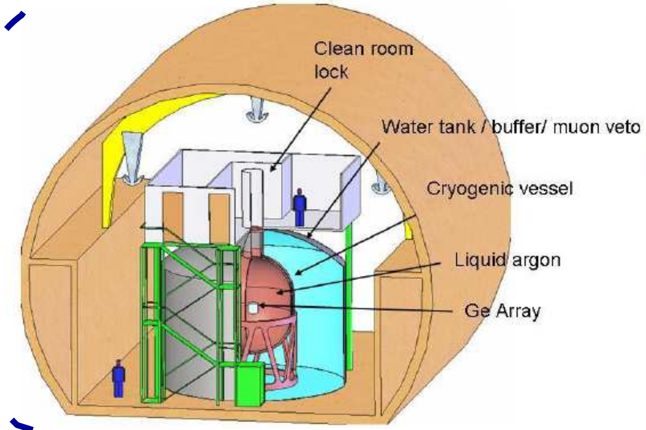


Some Other Upcoming Experiments

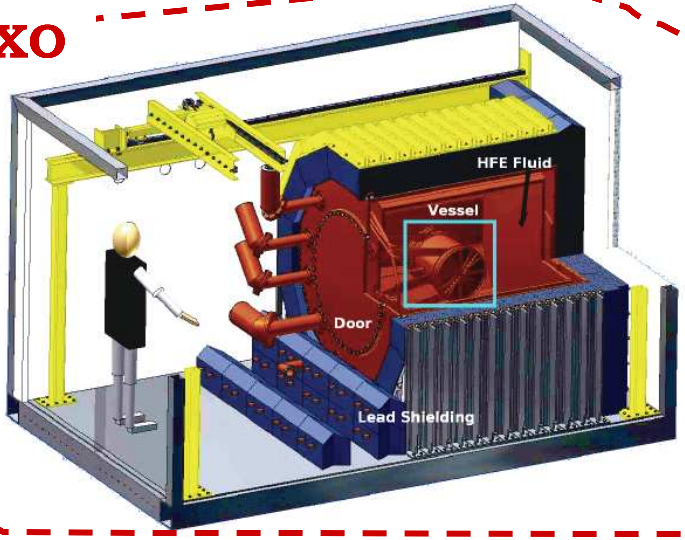
SuperNEMO

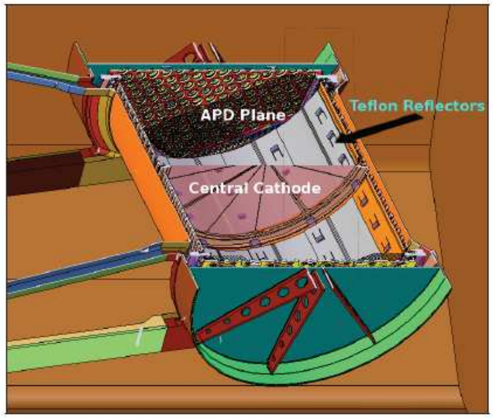


GERDA



EXO



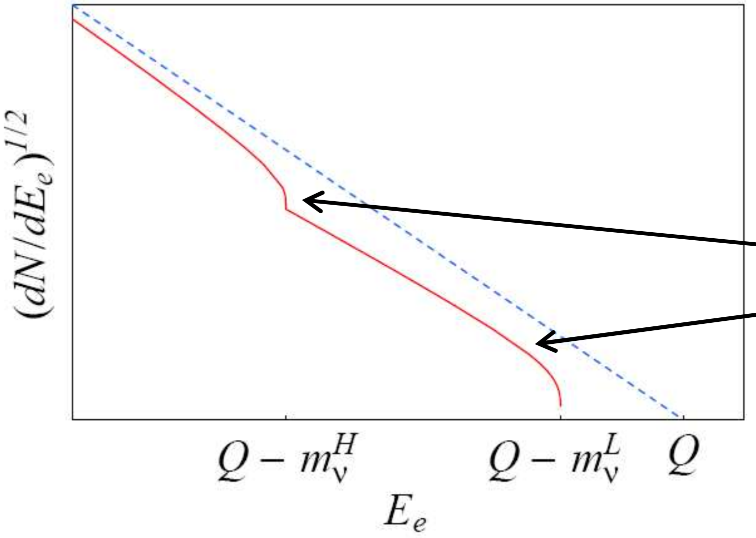


Direct Mass Measurements: Tritium

$^3H \rightarrow {}^3He\ e\ \bar{\nu}_e$

If CPT is not respected (ν and $\bar{\nu}$ can have different masses), bound relaxes from 2.1 eV to ~200 eV

A. Strumia and F. Vissani, arXiv:hep-ph/0606054v2

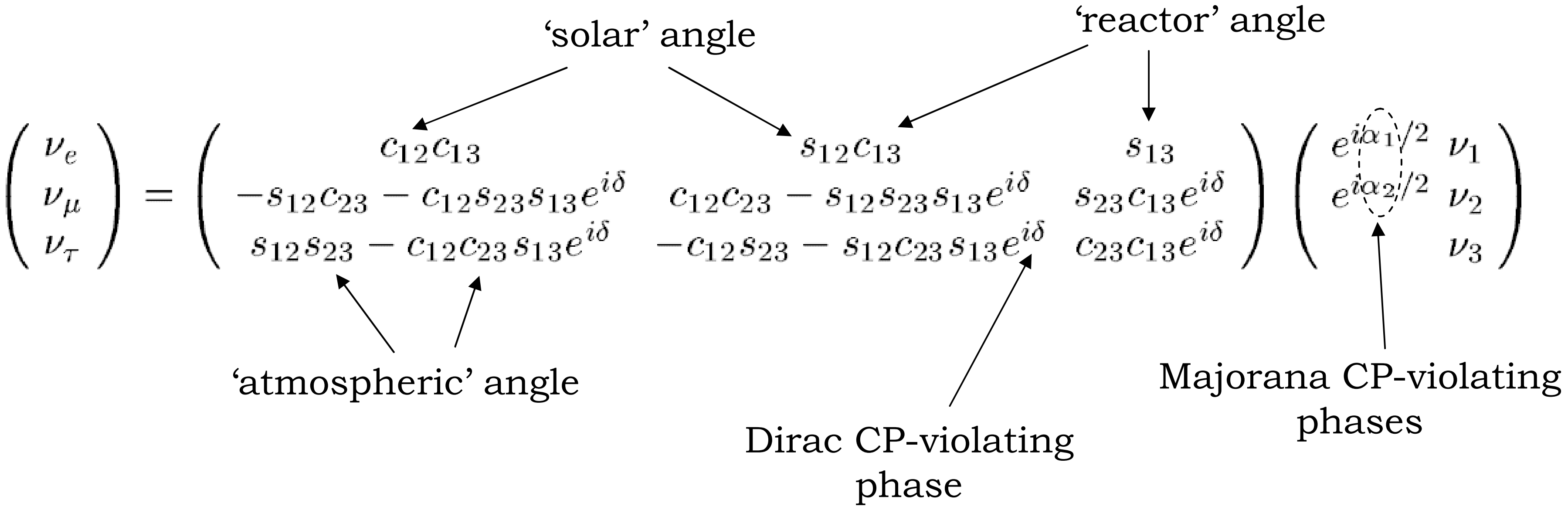


So far, can't resolve these features that would result from different mass states with νe components; can only measure an effective mass:

$$m_{\nu_e}^2 \equiv \sum_i |V_{ei}^2| m_i^2 = \cos^2\theta_{13}(m_1^2\cos^2\theta_{12} + m_2^2\sin^2\theta_{12}) + m_3^2\sin^2\theta_{13}$$

Neutrino Mixing Matrix: Standard Parametrization

c_{ij} and s_{ij} are short for $\cos\theta_{ij}$ and $\sin\theta_{ij}$ respectively



'solar' angle

'reactor' angle

$$\begin{pmatrix}\nu_e\\ \nu_\mu\\ \nu_\tau\end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13} \\ -s_{12}c_{23}-c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23}-s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13}e^{i\delta} \\ s_{12}s_{23}-c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23}-s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13}e^{i\delta}\end{pmatrix}\begin{pmatrix} e^{i\alpha_1/2}\,\nu_1 \\ e^{i\alpha_2/2}\,\nu_2 \\ \nu_3\end{pmatrix}$$

'atmospheric' angle

Dirac CP-violating phase

Majorana CP-violating phases