National Nuclear Physics Summer School

Neutrino Physics
Lecture III
July 18, 2007

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Berkeley

Note

In the simplest three-neutrino model there are only two Δm^2's

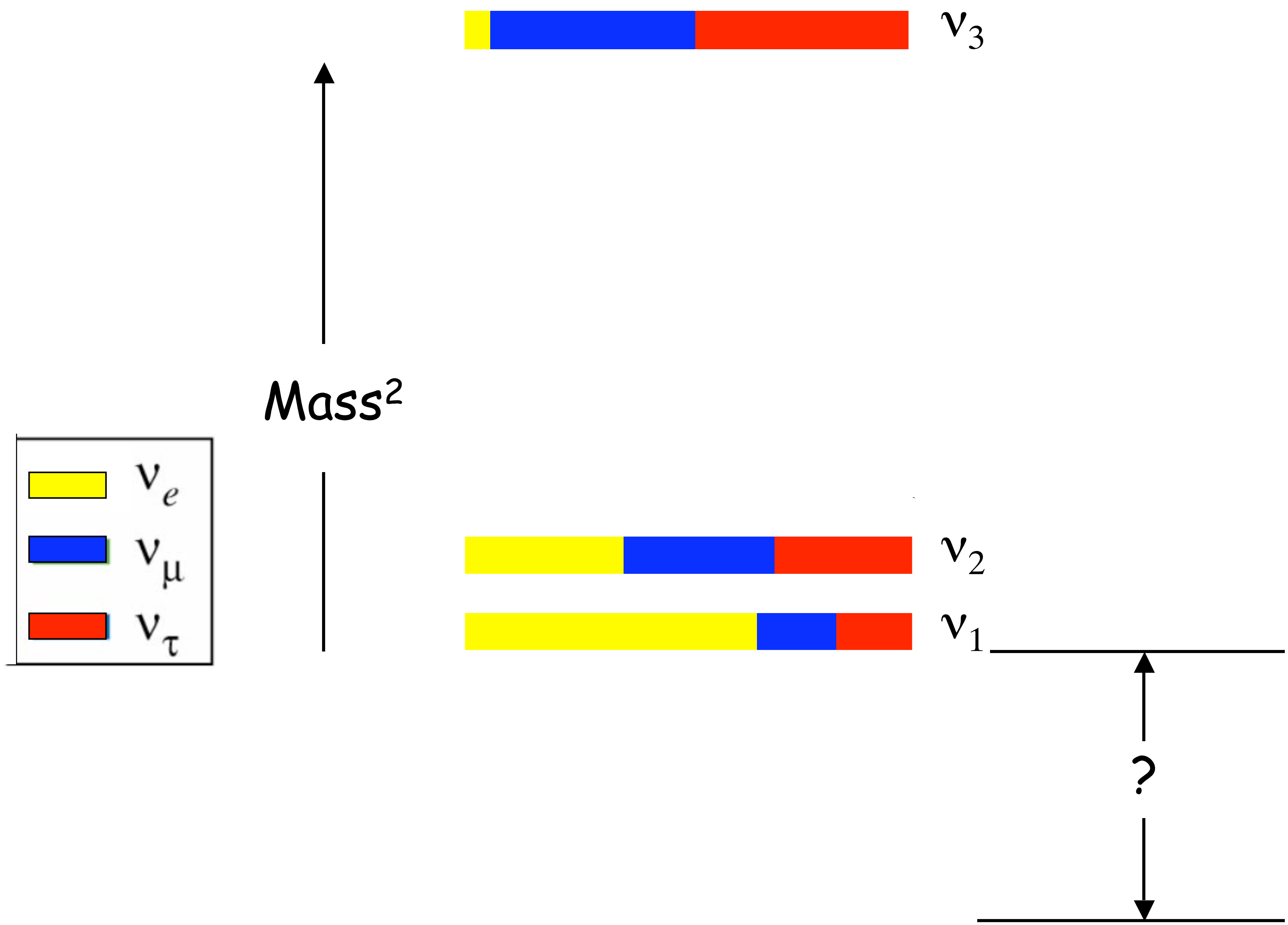
$$\Delta m_{12}^{\ 2} = m_1^2 - m_2^2$$

$$\Delta m_{23}^{\ 2} = m_2^2 - m_3^2$$

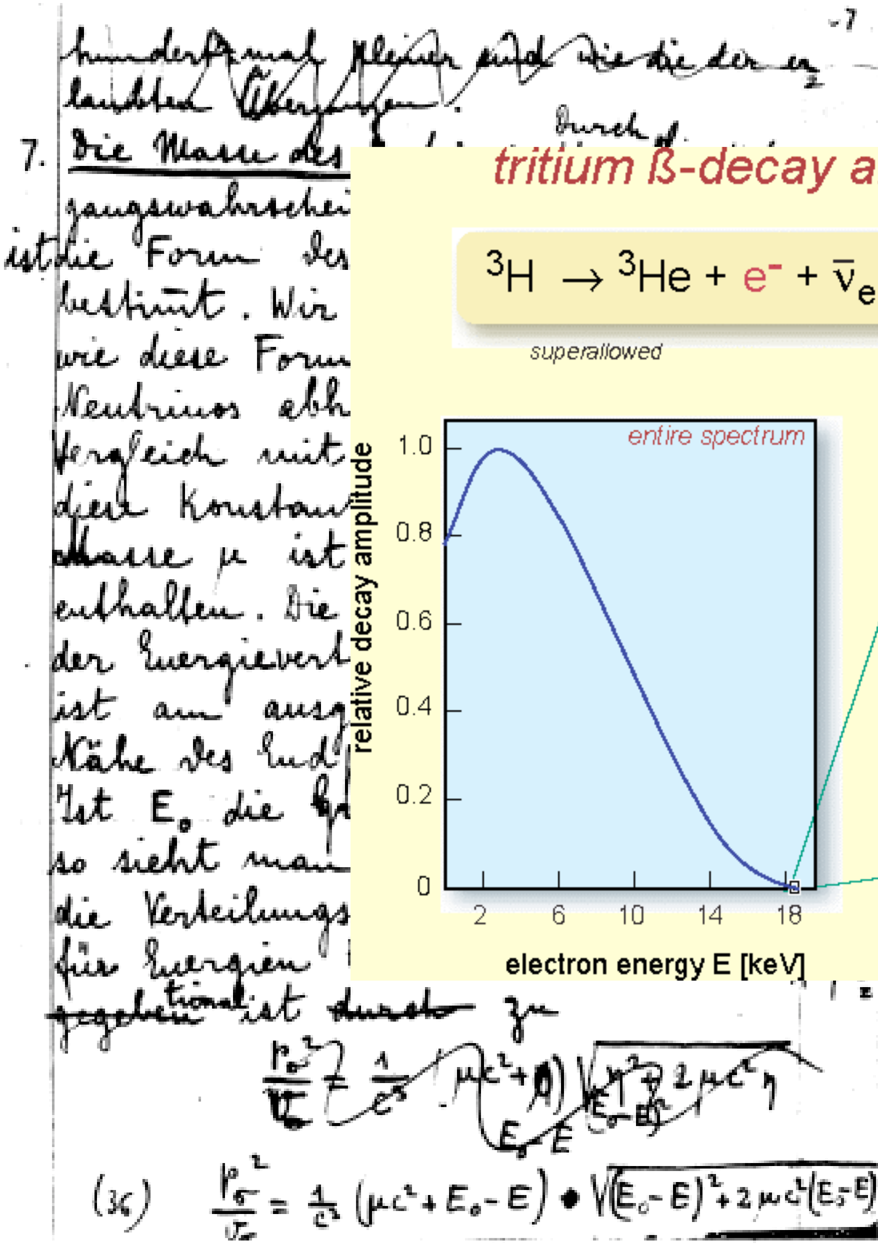
$$\Delta m_{13}^{\ 2} = \Delta m_{12}^{\ 2} + \Delta m_{23}^{\ 2} = m_1^2 - m_3^2$$

Two are already measured (in experiments with solar/reactor and atmospheric/accelerator neutrinos)--so the unmeasured $\Delta m_{13}^{\ 2}$ is determined.
This is why LSND was a problem! Perhaps now resolved by MiniBooNE. No room for ~1 eV ^{2}.

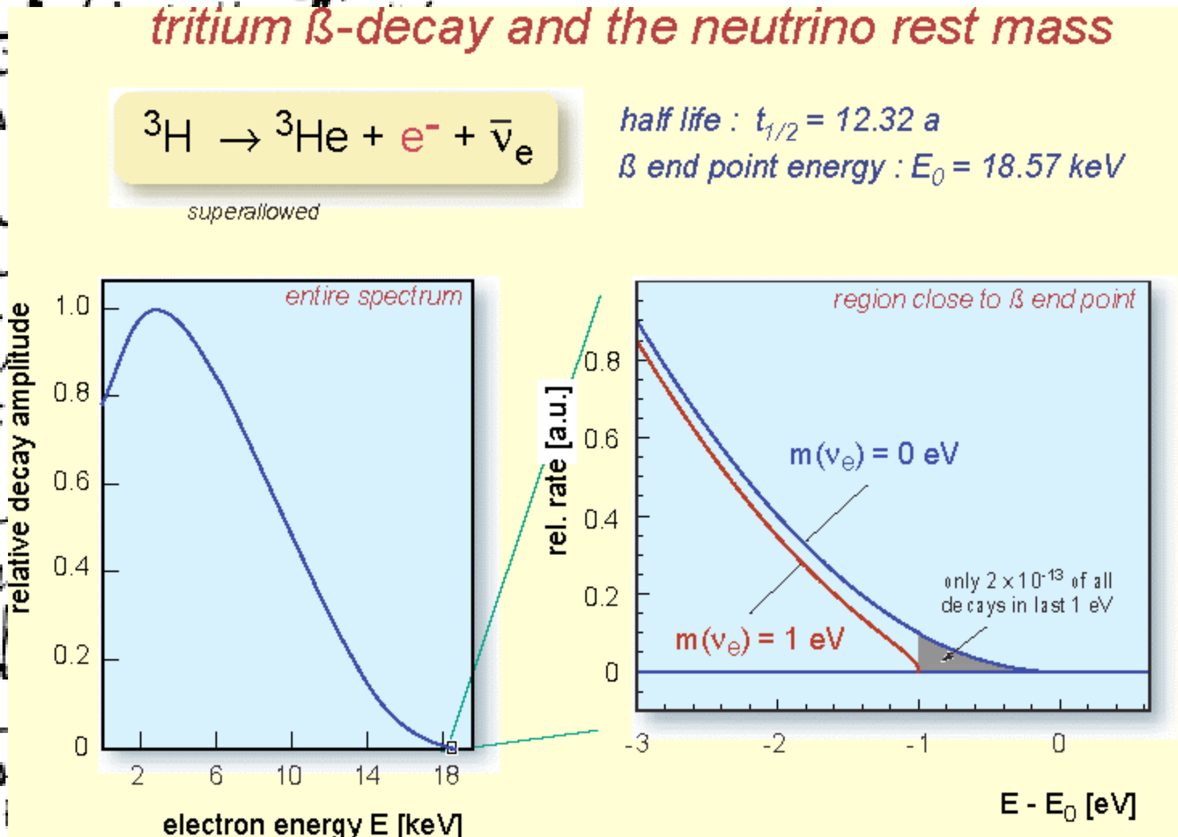
What is the absolute mass scale?



Direct Mass Measurements from Ordinary Beta Decay


~~hundertmal kleiner sind als die der er-~~
laubten Übergängen.
7. Die Masse des ...
gangswahrschei...
ist die Form des ...
bestimmt. Wir ...
wie diese Form ...
Neutrinos abh...
Vergleich mit ...
diese Konstan...
Masse μ ist ...
enthalten. Die ...
der Energievert...
ist am ausg...
Nähe des End...
Ist E_0 die ...
so sieht man ...
die Verteilungs...
für Energien ...
~~gegeben~~ ist ~~durch~~ zu

$$(36) \quad \frac{p_\sigma^2}{v_\sigma} = \frac{1}{c^3}\left(\mu c^2 + E_0 - E\right) \cdot \sqrt{(E_0 - E)^2 + 2\mu c^2 (E_0 - E)}$$



... — E).

... sentata per μ = o, ... somiglianza con le ...

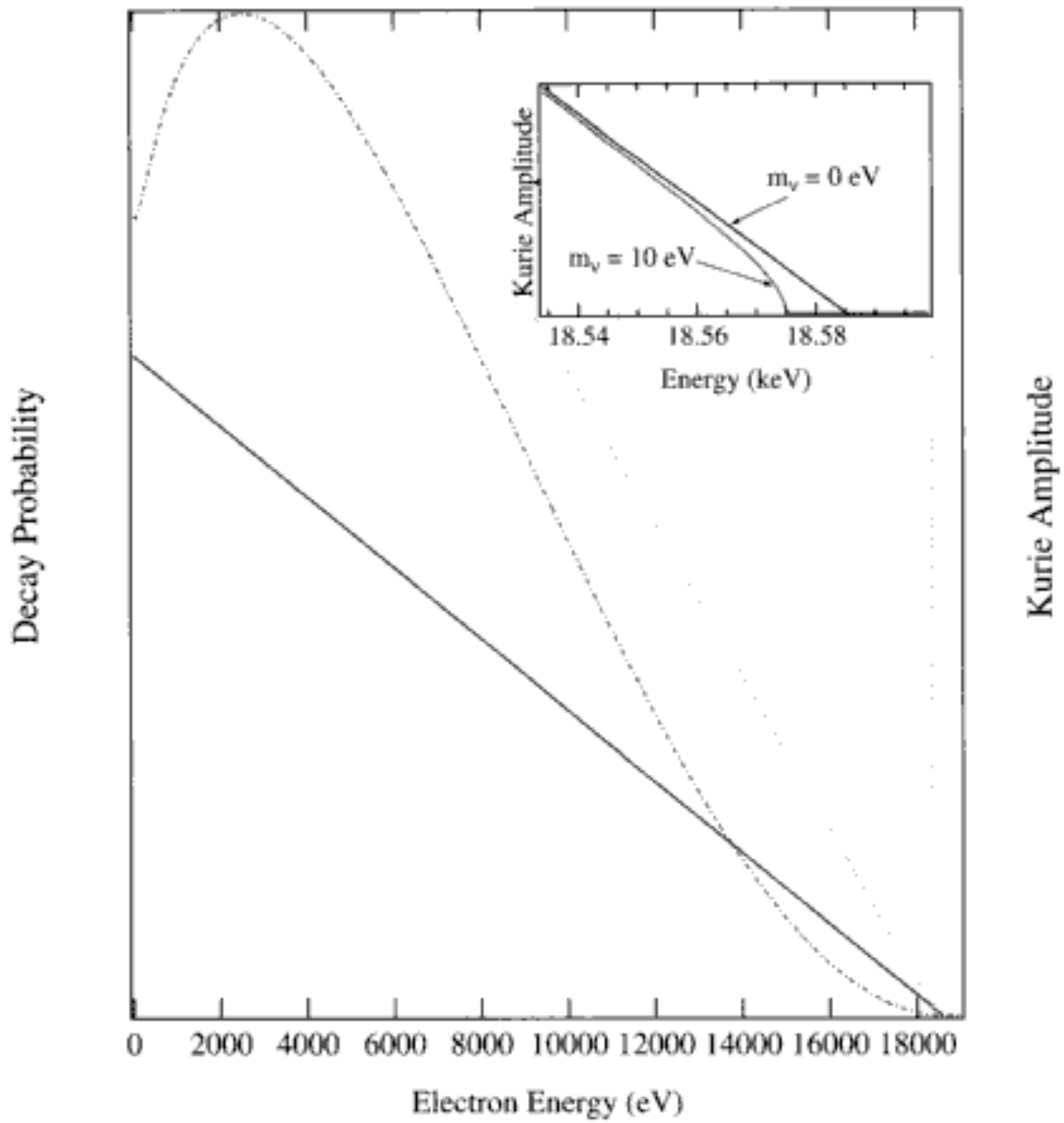
... nte a μ = o. Arriviamo così a concludere che la massa del neutrino è uguale a zero o, in ogni caso, piccola in confronto della massa dell'elettrone (9). Nei calcoli che seguono porremo per semplicità μ = o.


Secret Stories
Experiments We No Longer Believe
Dirty Laundry

Discovery of a 35 eV neutrino

Top 10 reasons to believe that neutrinos have mass

6. Neutrino mass would account for the missing mass of the universe.



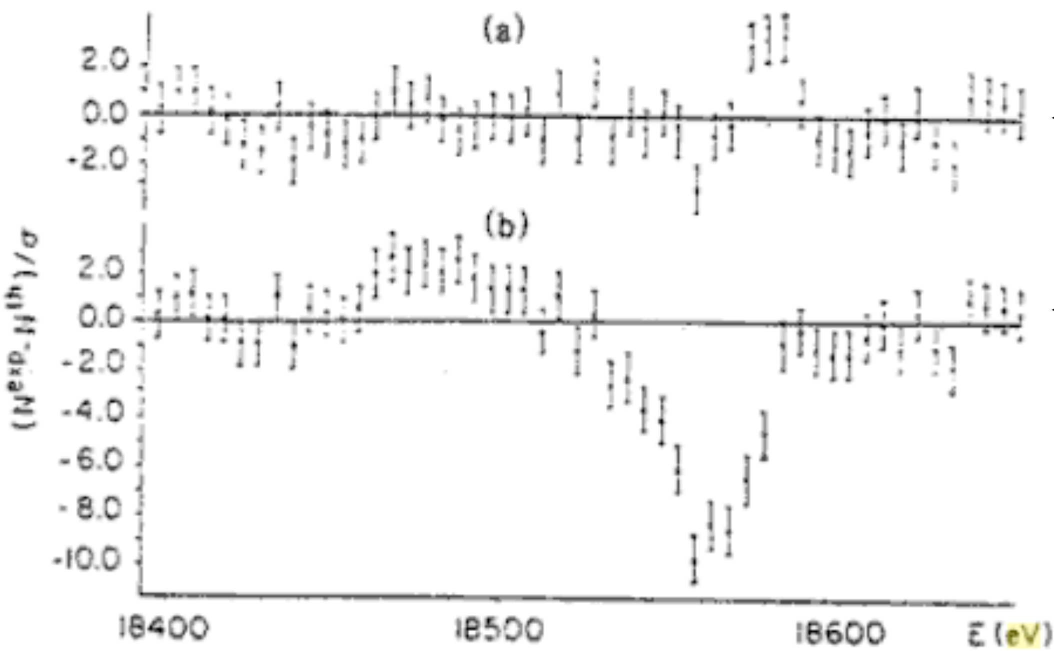
Decay Probability
Kurie Amplitude
0
2000
4000
6000
8000
10000
12000
14000
16000
18000
Electron Energy (eV)
Kurie Amplitude
m_ν = 0 eV
m_ν = 10 eV
18.54
18.56
18.58
Energy (keV)

Mid 1980's

Evidence for a 35 eV neutrino

Used Tretyakov's unique toroidal spectrometer

Rusults of Lubimov et al



← *Fit with $m_\nu \approx 35$ eV*

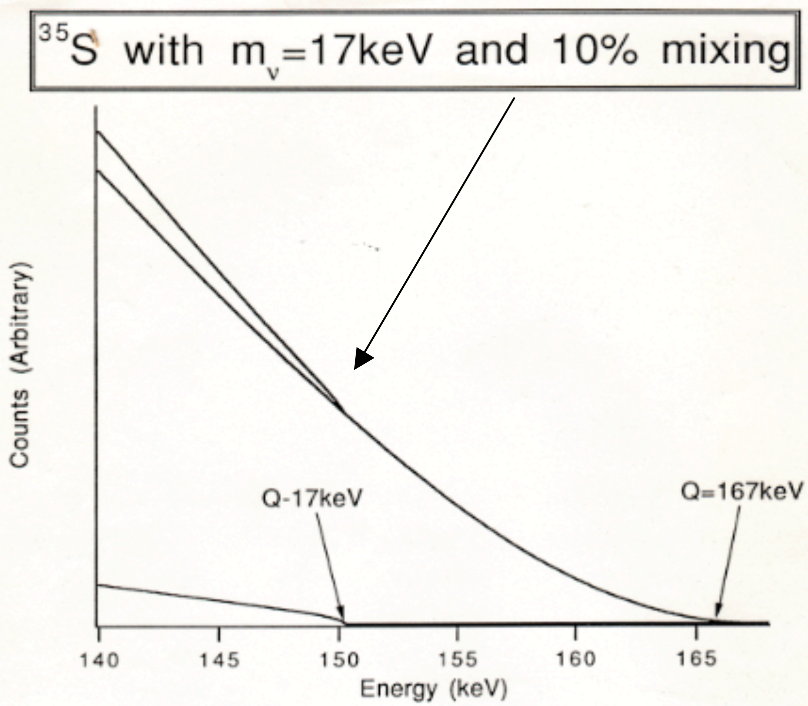
← *Fit with $m_\nu \approx 0$ eV*

FIGURE 6.11 The difference between the experimental data and the theoretical fit for the end-point region of the tritium spectrum for two different values of $M_\nu^{\ 2}$. (a) $M_\nu^{\ 2} = 966$ eV^2 and (b) $M_\nu^{\ 2} = 0$. (Boris et al., 1987).

Residuals for fits

Mid to Late 1980's

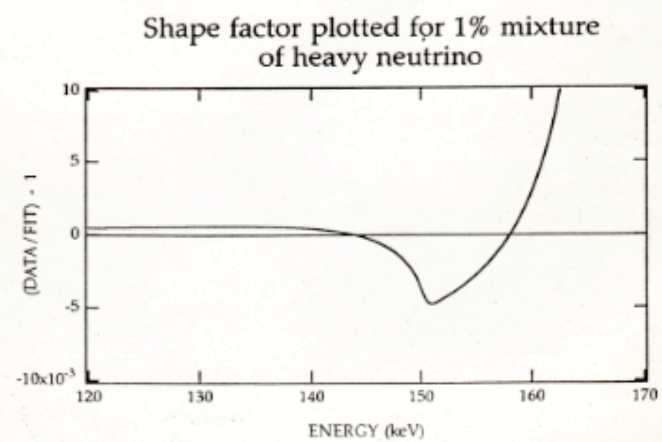
Discovery of a 17 keV neutrino



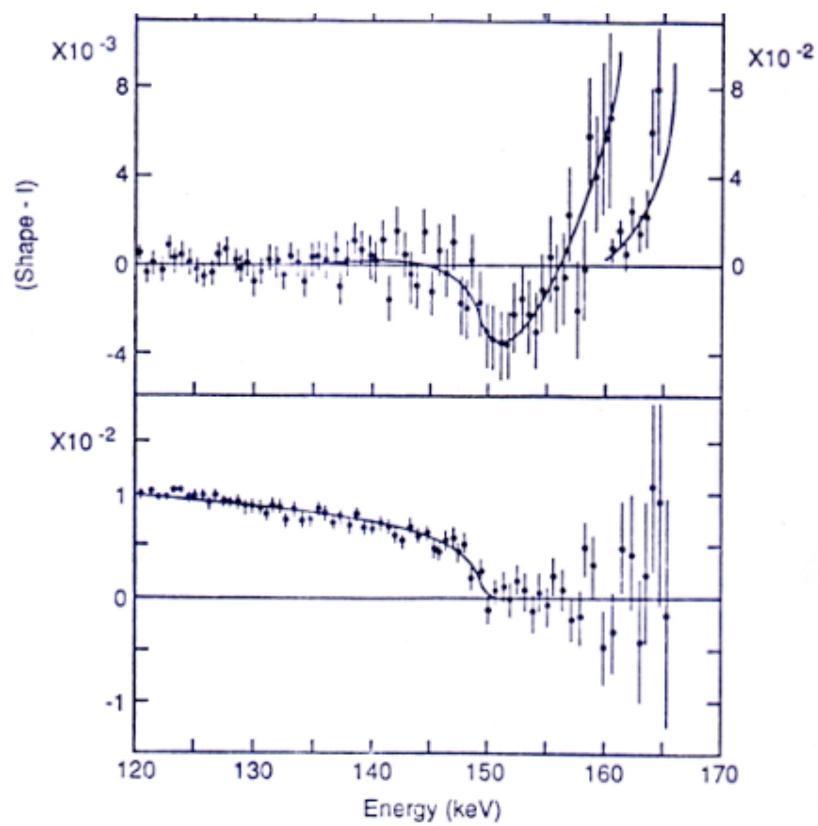
Two neutrino mass states

$m_1 = 0$
$m_2 = 17\ keV/c^2$
$|U_{e2}|^2 \sim 1\%$

Data fit to a "$m_\nu = 0$" shape



Evidence for a 17 keV neutrino in the beta decay of ^{35}S



Residuals from the fit to the beta spectrum

SUMMARY OF POSITIVE RESULTS

SOURCE	$SIN^2\Theta$	M_ν	EXPERIMENT TYPE
^3H	1.10 +/- 0.30	17.07 +/- 0.09	Implanted source
^3H	1.11 +/- 0.14	16.93 +/- 0.07	Implanted source
^{14}C	1.40 +/- 0.45	17.00 +/- 2.00	Implanted source
^{71}Ge	1.60 +/- 0.74	17.20 +/- 1.30	IBEC
^{55}Fe	0.85 +/- 0.45	21.00 +/- 2.00	IBEC
^{35}S	0.73 +/- 0.11	16.90 +/- 0.40	External source
^{35}S	0.84 +/- 0.08	17.00 +/- 0.40	External source
^{63}Ni	0.99 +/- 0.12	16.75 +/- 0.35	External source

$$|U_{e2}|^2 = SIN^2\Theta$$

<u>Eight consistent experiments!</u>

Results widely reported!

The massive neutrino would "violate every theoretical prejudice we have in particle physics, astrophysics, and cosmology," says Michael Turner, a University of Chicago expert on cosmology.

"It's a true surprise. If it's true, then it's pointing us in a different direction than previous physics suggests." adds John Bahcall of the Institute for Advanced Study at Princeton.

Is There a Massive Neutrino?

Three far-flung labs say yes, triggering an avalanche of speculation about how theories from the Standard Model to the Big Bang might need to be revised

EVEN BY THE STANDARDS OF PARTICLE physics, the subatomic particle called the neutrino is a shadowy commodity. It can pass through the entire Earth without leaving a trace, and it's immune to many of the forces that bind matter together, including the electromagnetic force. Until recently, it was even thought to be without mass—or at least without much. But now, dramatic evidence has begun to emerge from laboratories in Oxford, Czechoslovakia, and Berkeley that the neutrino does have mass—and lots of it, thousands of times more than predicted by current theories. Sheldon Glashow, Nobel Prize–winning physicist at Harvard, who's seen the recent results (which are speeding around the physics community in preprint form) calls them "quite spectacular." In fact, he says "it's the kind of thing Nobel Prizes are awarded for."

If the results hold up, and there is a Nobel Prize for the "massive neutrino," the award would likely go to John Simpson, a physicist not in one of the three labs that have claimed recent successes but at the University of Guelph in Ontario. It was Simpson who, in 1985, first presented evidence for a neutrino with a mass as heavy as 17,000 electron-volts (keV, the units of energy that are interchangeable with mass). If Simpson is correct, his discovery will send shock waves through not merely the high-energy physics community but through astrophysics and cosmology as well—indeed it would fundamentally alter physicists' views of the universe.

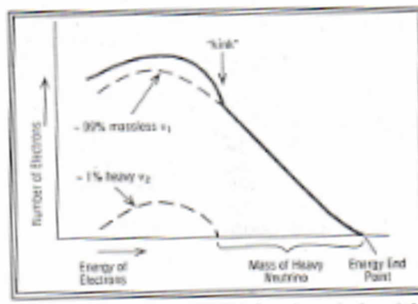
A massive neutrino would "violate every theoretical prejudice we have in particle physics, astrophysics, and cosmology," says Michael Turner, a University of Chicago expert on cosmology. Adds astrophysicist John Bahcall of the Institute for Advanced Study at Princeton: "It's a true surprise. If it's true, then it's pointing us in a different direction than previous physics suggested."

That new direction would actually include a number of major course corrections. Elegant theories purporting to explain why neutrinos are so light would crumble. Overarching conceptions, like the "Standard Model" of particle physics—which unifies the so-called weak force and the electromagnetic force and for which Glashow received his Nobel Prize—would need embellishing. (Glashow has already rushed into print with what he calls "various crazy models" in an attempt to patch his notions up.) And there might be a profound impact even on the Big Bang theory.

All this assumes that the latest discovery isn't just an experimental artifact—something difficult to be sure of in an area where experimental results can be deceptive and prey to perturbations. Although the recent work from the far-flung labs is suggestive, many feel it won't hold up. "My attitude toward this 17keV neutrino," says Bahcall, "is, if you're thinking of skating on a lake which you're not sure is frozen and you see a sign posted on the lake [reading] 'There is suggestive evidence that the ice is safely thick,' I wouldn't skate on that ice, and I wouldn't invest much of my reputation on the likelihood that this 17keV neutrino is real."

Felix Boehm, a respected experimentalist at the California Institute of Technology who has tried and failed to find evidence for a massive neutrino, acknowledges being "a little biased." But Boehm, who has seen the new results, argues that "there is nothing"—the massive neutrino doesn't exist. Even he admits, however, that the case isn't closed: He's still looking for conclusive evidence one way or the other.

The reason for the current excitement is that it is the first time results confirming Simpson's hypothesis have come from outside his own laboratory. In 1985, Simpson, already a world-renowned neutrino physicist, began table-top experiments aimed at measuring the energy of electrons emitted from tritium (heavy hydrogen) in the radioactive process called beta-decay. Although Simpson's interest was in the nearly invisible neutrino (which is spit out alongside the electron), he couldn't observe the neutrino directly. Instead, he measured the effect of the neutrino on the electron.



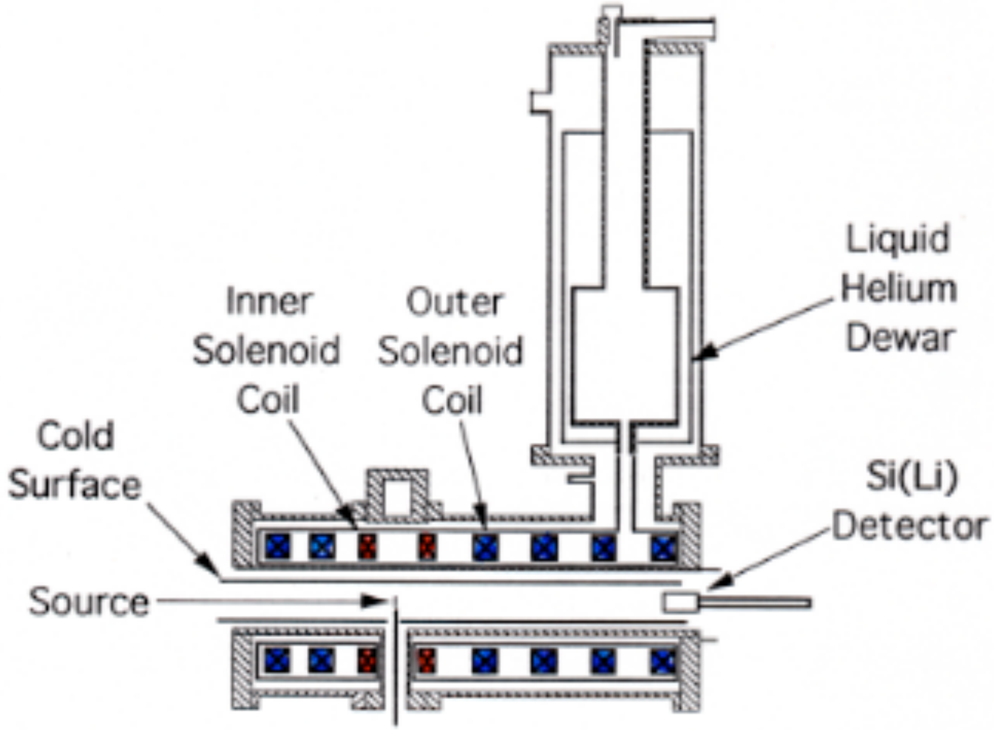
Source: Eric Norman, LBL

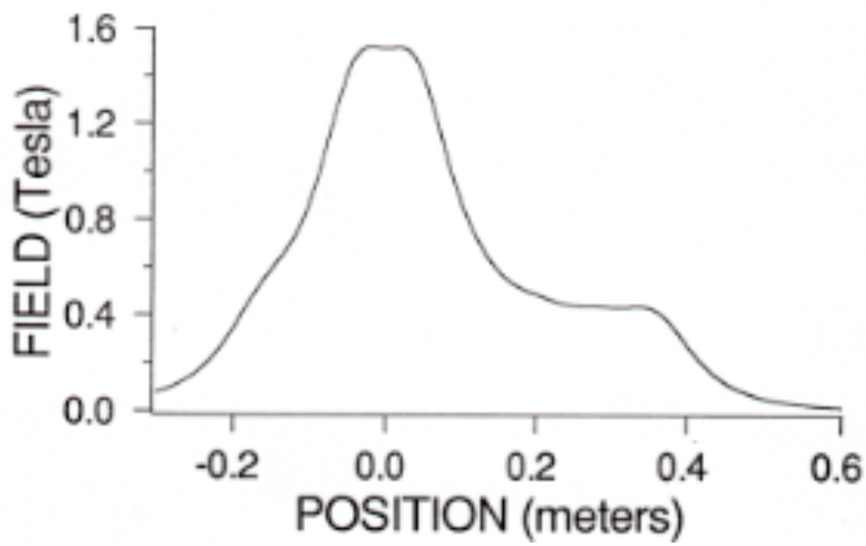
Kinky stuff. *A "kink" 17KeV below the endpoint of the emitted electron's energy spectrum in beta-decay was the first clue to a possible massive neutrino.*

Ordinarily in beta-decay the electron and the neutrino share the energy of the reaction. Under those conditions, the energy of the emitted electrons appears as a spectrum varying smoothly from zero to a maximum called the "endpoint" energy. But in Simpson's mid-'80s work, he observed a small "kink," or disturbance, of the smooth spectrum corresponding to an energy 17keV below the endpoint.

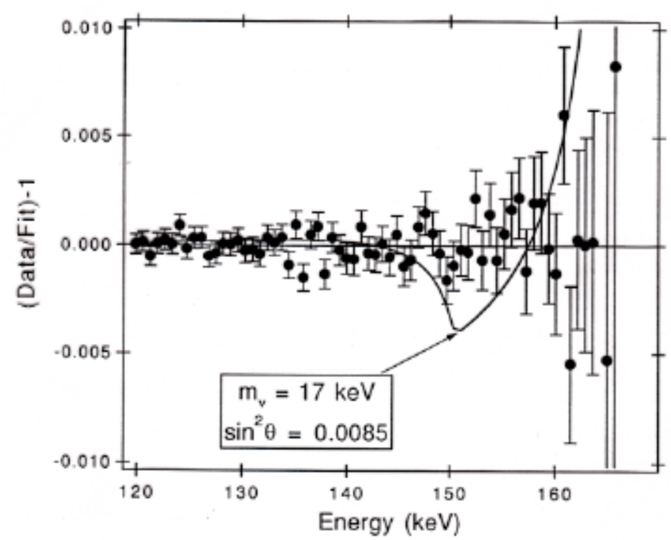
Published in *Physical Review Letters*, this result startled physicists, who have studied beta-decay for decades without seeing the 17keV anomaly. The kink, Simpson argued, came from the occasional emission of a massive neutrino, which was "stealing" energy from the electron and changing its energetic spectrum. But the kink was small: 97% of the time, the electron associated with the ordinary, massless neutrino was found, and only 3% of the time did the electron paired with the massive newcomer show up.

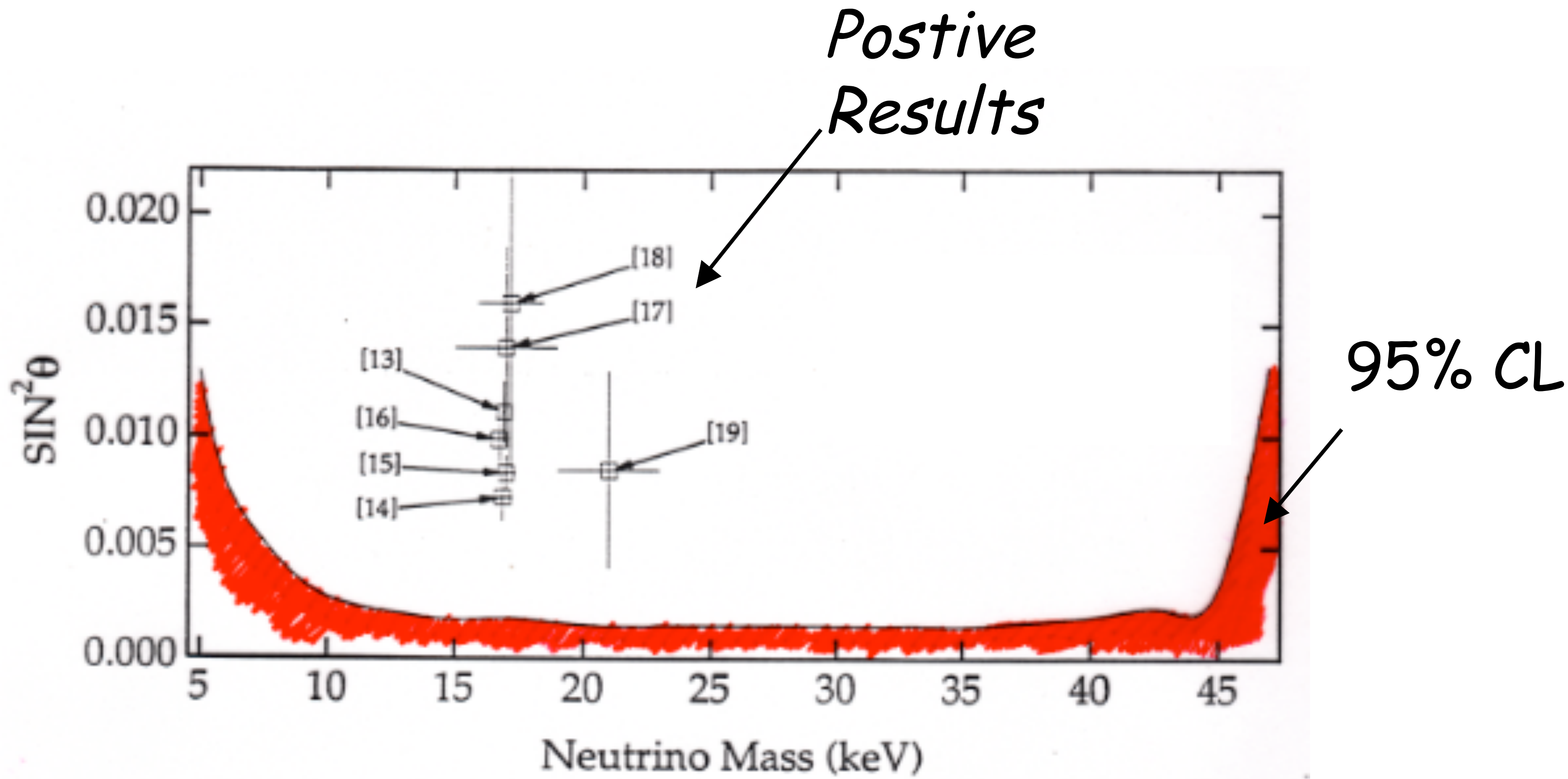
Those early results triggered a feverish hunt aimed at confirming them—or proving that they weren't valid. If the kink was real and was caused by a massive neutrino, experimentalists reasoned, it should appear not just in tritium but also in other nuclei that undergo beta-decay. Moreover, although the endpoint of the electron's spectrum varies from nucleus to nucleus, if there is indeed a 17keV neutrino, the kink should appear 17keV below the endpoint in each case. Eight different groups, including two led by such notables as Caltech's Boehm and Princeton's Frank Calaprice, attempted to find that kink


Liquid Helium Dewar
Inner Solenoid Coil
Outer Solenoid Coil
Cold Surface
Si(Li) Detector
Source


1.6
1.2
0.8
0.4
0.0
FIELD (Tesla)
-0.2
0.0
0.2
0.4
0.6
POSITION (meters)

^{35}S Data


0.010
0.005
0.000
-0.005
-0.010
(Data/Fit)-1
m_ν = 17 keV
$\sin^2\theta$ = 0.0085
120
130
140
150
160
Energy (keV)

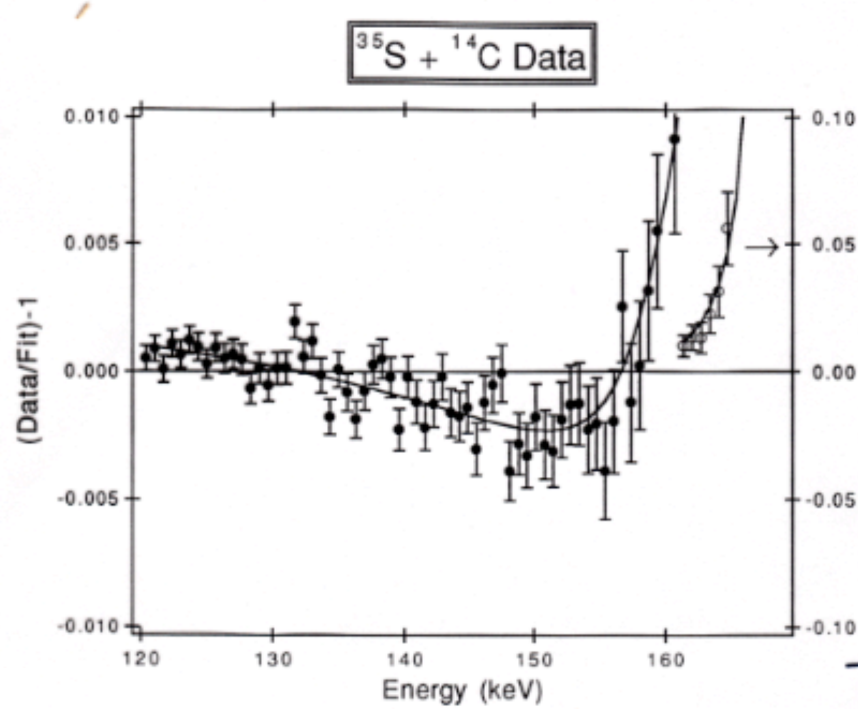


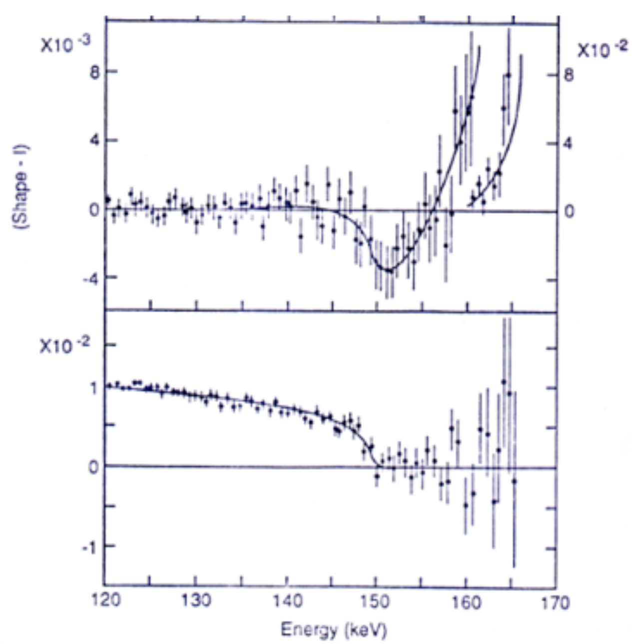
For $m_\nu c^2 = 17$ keV

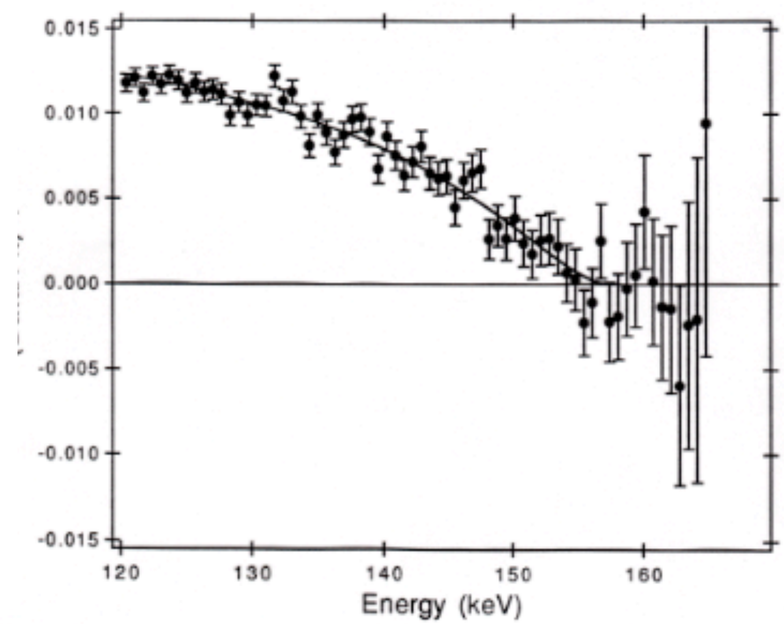
$\sin^2\theta = -0.0004 \pm 0.0008 \pm 0.0008$

Source made with ~1% ^{14}C

^{35}S: E_o ~ 165 keV
^{14}C: E_o ~ 156 keV







1.34%
"^{14}C"
put in,
1.4±0.1%
measured

How should we analyze Ordinary Nuclear beta decay?

$$\frac{\mathrm{d}\Gamma_i}{\mathrm{d}E} = C\, p\,(E + m_e)\,(E_0 - E)\,\sqrt{(E_0 - E)^2 - m_i^2}\, F(E)\,\theta(E_0 - E - m_i)$$

$$C = G_F^2 \frac{m_e^5}{2\,\pi^3}\, \cos^2\theta_C\, |M|^2$$

Incoherent:

$$\frac{d\Gamma}{dE} = \sum_i |U_{ei}|^2 \frac{d\Gamma_i}{dE}$$

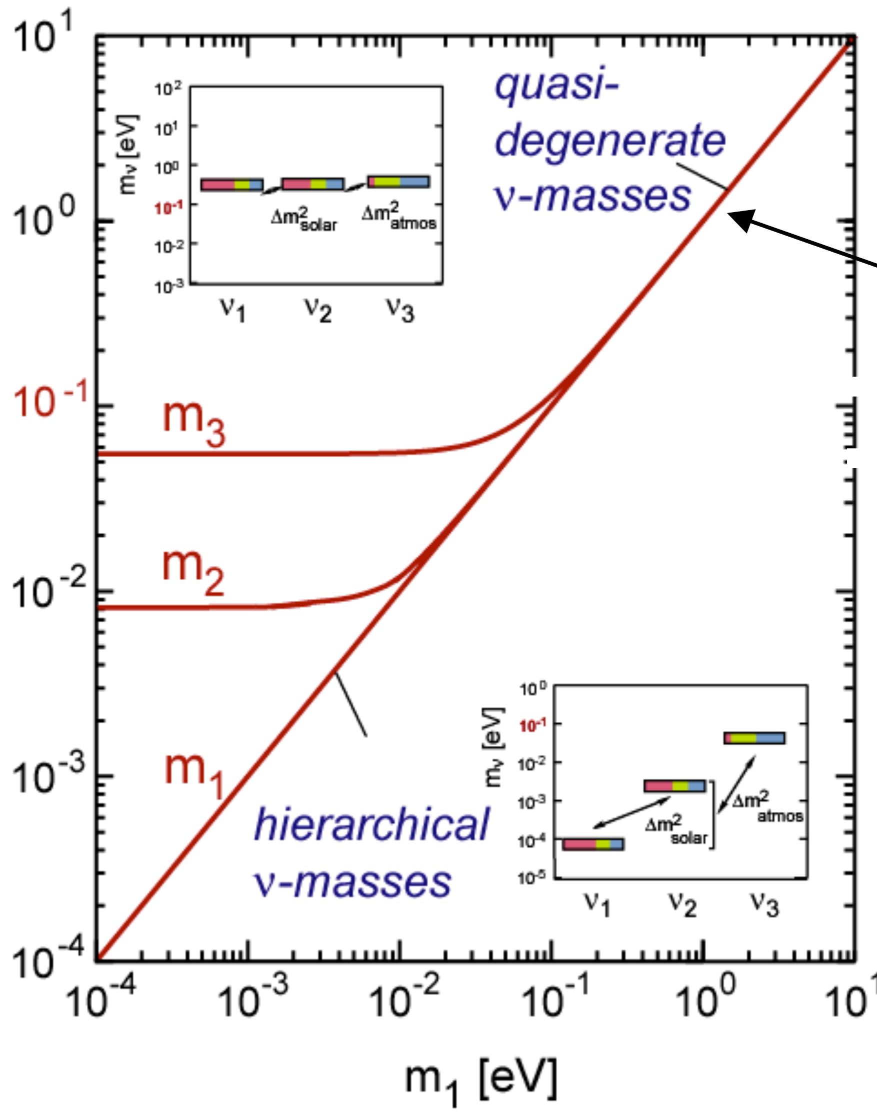
Coherent:

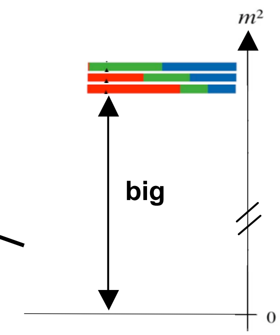
$$m_{\nu_e} = \langle \nu_e | m | \nu_e \rangle = \sum_i |U_{ei}|^2\, m_i$$

$$m_{\nu_e} = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$$

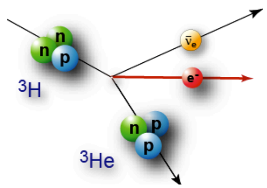
Used in Practice

$$m_{\nu_e} = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 m_i^2}$$





degenerate



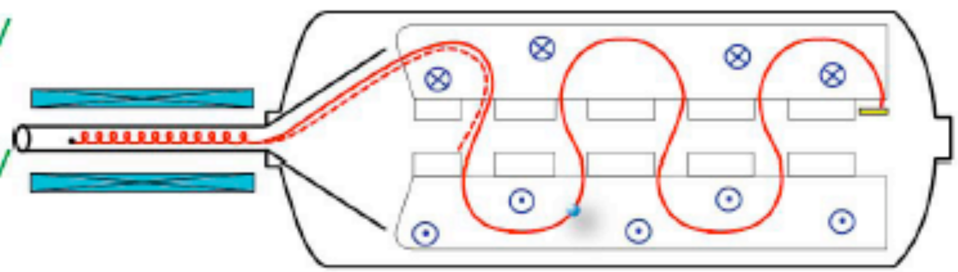
Last generation of tritium experiments

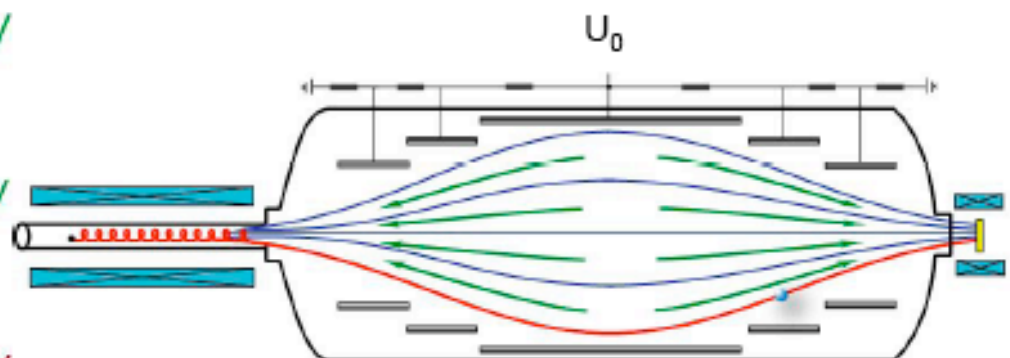
Experiment	m_ν
ITEP *T_2 in complex molecule* *magn. spectrometer (Tret'yakov)*	17-40 eV
Los Alamos *gaseous T_2 - source* *magn. spectrometer (Tret'yakov)*	< 9.3 eV
Tokio *T - source* *magn. spectrometer (Tret'yakov)*	< 13.1 eV
Livermore *gaseous T_2 - source* *magn. spectrometer (Tret'yakov)*	< 7.0 eV
Zürich *T_2 - source impl. on carrier* *magn. spectrometer (Tret'yakov)*	< 11.7 eV
Troitsk (1994-today) *gaseous T_2 - source* *electrostat. spectrometer*	< 2.05 eV
Mainz (1994-today) *frozen T_2 - source* *electrostat. spectrometer*	< 2.3 eV

Tret´yakov

$\Delta p/p = 7 \times 10^{-4}$
$d\Omega = 10^{-3}$

magnetic guiding field: analysis of momentum





MAC-E

$\Delta E/E = 1 \times 10^{-5}$
$d\Omega \approx 2\pi$

magnetic guiding & electric retarding field

Limits on neutrino mass from tritium experiments

	m_ν
ITEP *T_2 in complex molecule* *magn. spectrometer (Tret'yakov)*	17-40 eV
Los Alamos *gaseous T_2 - source* *magn. spectrometer (Tret'yakov)*	< 9.3 eV
Tokio *T - source* *magn. spectrometer (Tret'yakov)*	< 13.1 eV
Livermore *gaseous T_2 - source* *magn. spectrometer (Tret'yakov)*	< 7.0 eV
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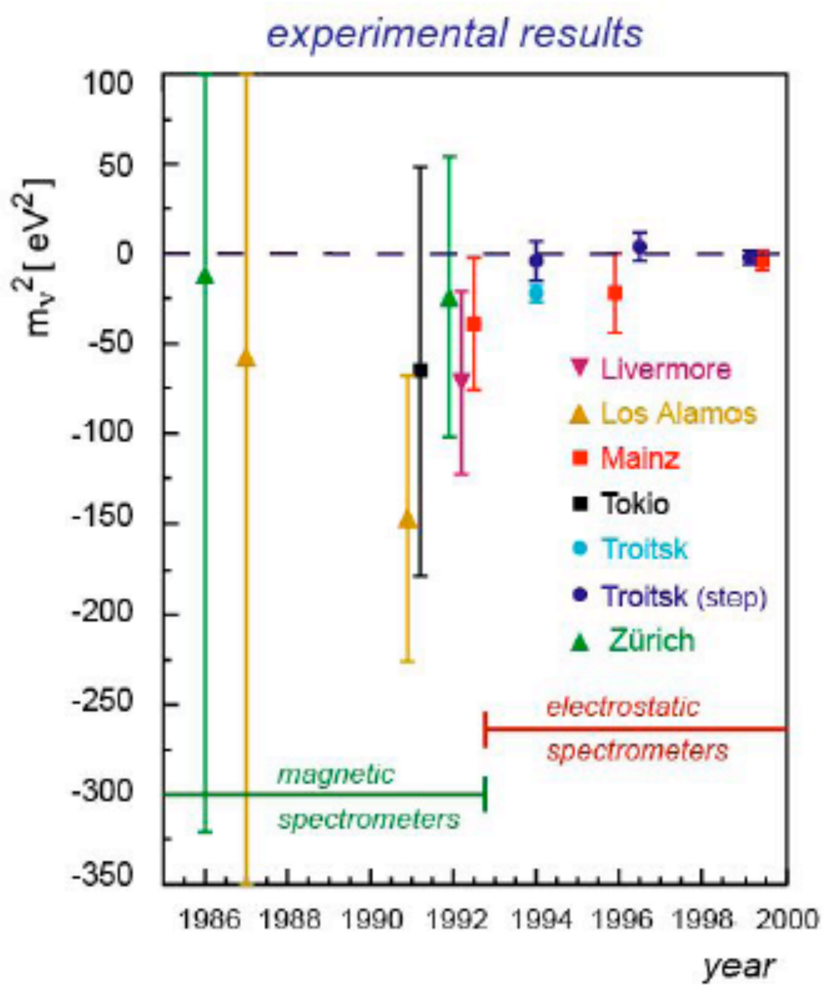
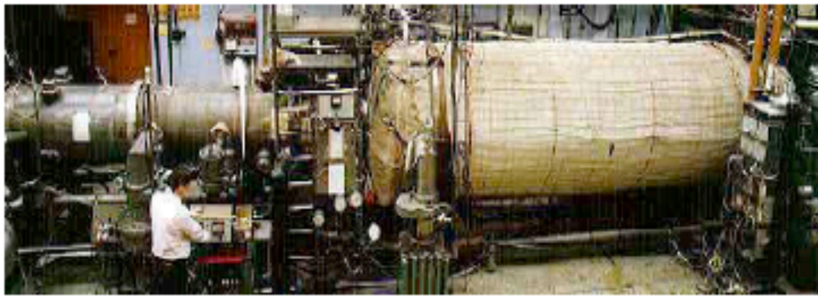
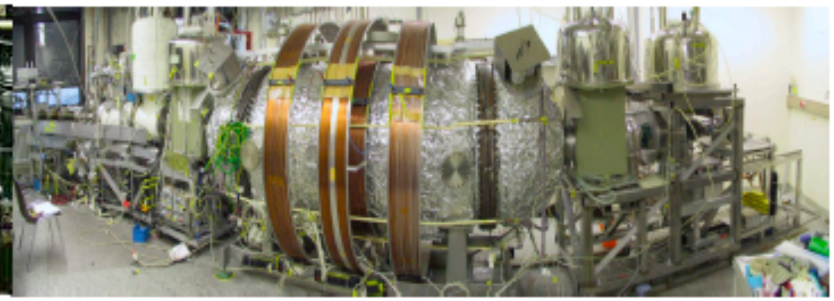
Troitsk (1994-today) *gaseous T_2 - source* *electrostat. spectrometer*	< 2.05 eV
Mainz (1994-today) *frozen T_2 - source* *electrostat. spectrometer*	< 2.3 eV



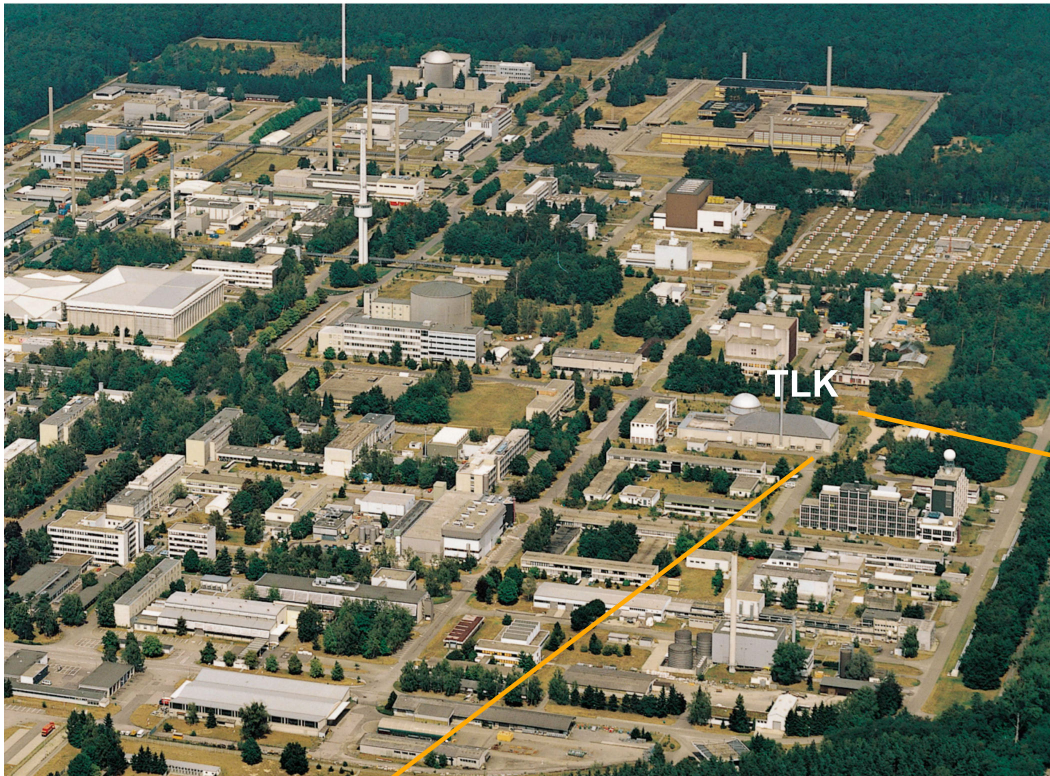
Most recent tritium decay experiments





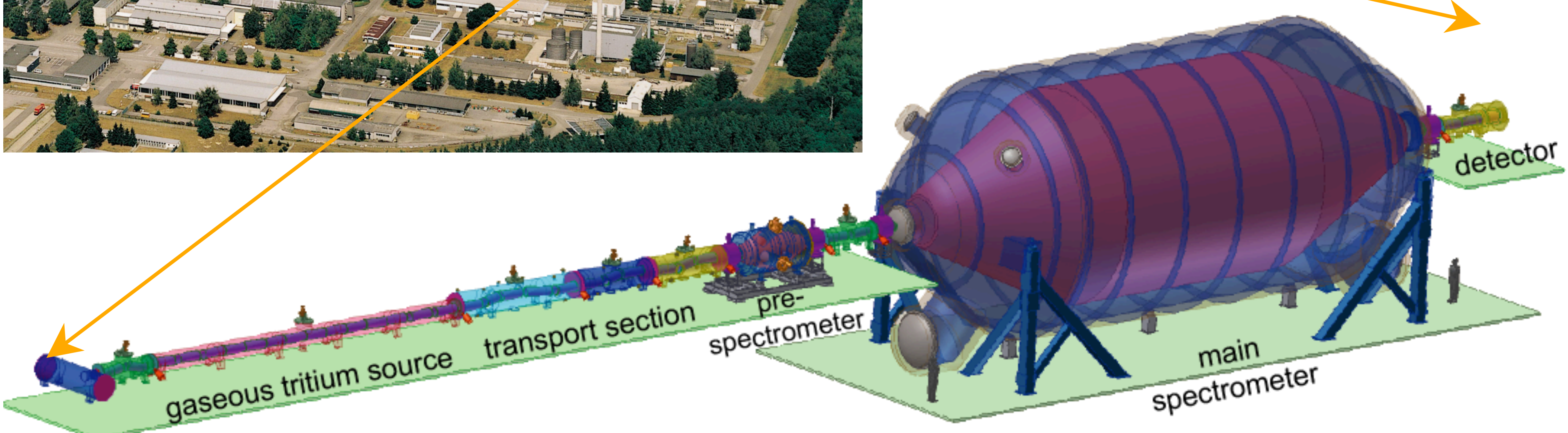
Troitsk	Mainz
windowless gaseous T_2 source	quench condensed solid T_2 source
analysis 1994 to 1999, 2001	analysis 1998/99, 2001/02
$m_\nu^2 = -2.3 \pm 2.5 \pm 2.0\ eV^2$	$m_\nu^2 = -1.2 \pm 2.2 \pm 2.1\ eV^2$
$m_\nu \leq$ 2.2 eV (95% CL.)	$m_\nu \leq$ 2.2 eV (95% CL.)

KATRIN Experiment



Karlsruhe **Tri**tium **N**eutrino Experiment

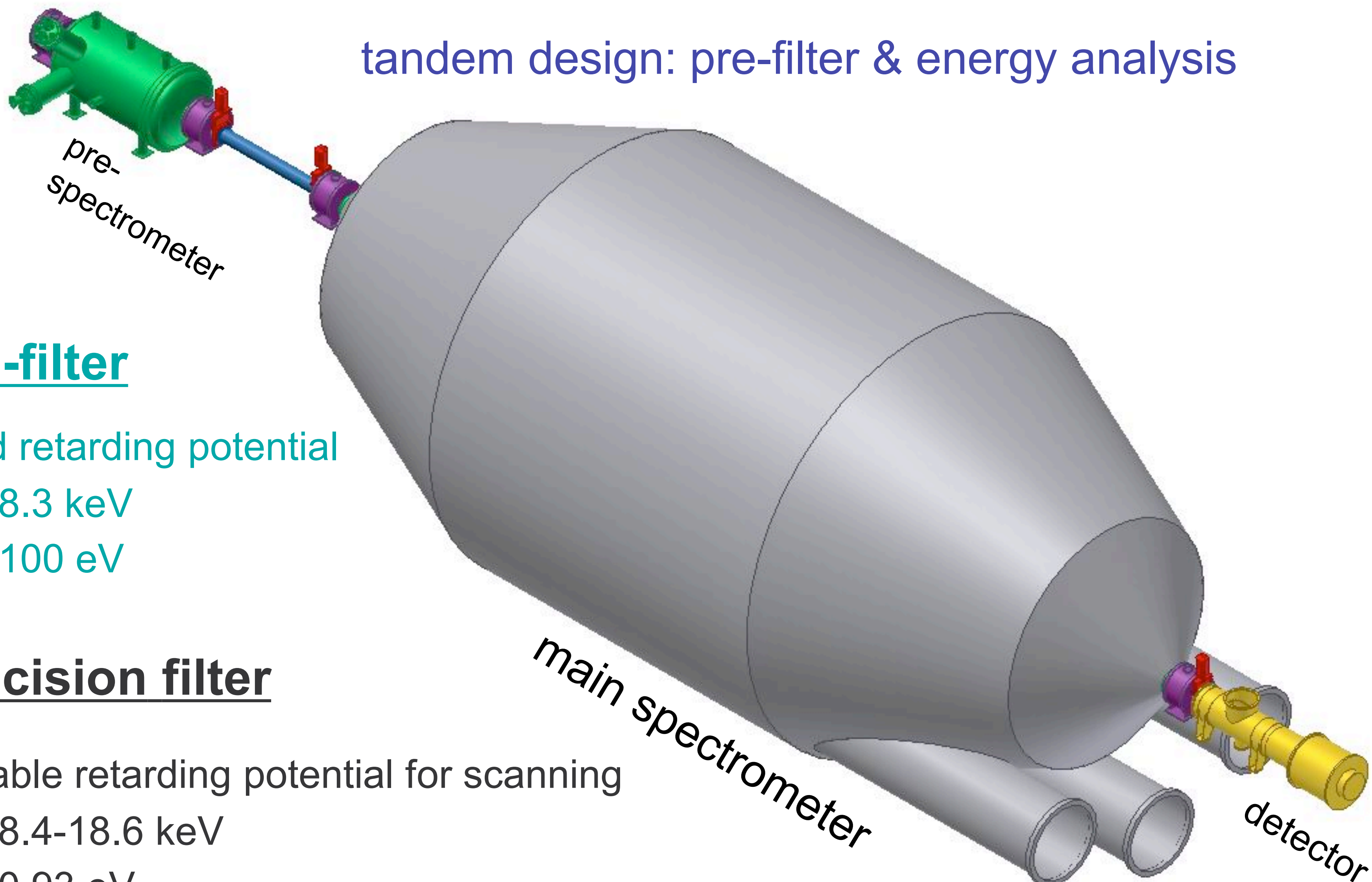
at Forschungszentrum Karlsruhe
unique facility for closed T_2 cycle:
Tritium Laboratory Karlsruhe



~ 75 m linear setup with 40 s.c. solenoids

electrostatic spectrometers

tandem design: pre-filter & energy analysis



pre-filter

fixed retarding potential
U=18.3 keV
ΔE~100 eV

precision filter

variable retarding potential for scanning
U=18.4-18.6 keV
ΔE=0.93 eV

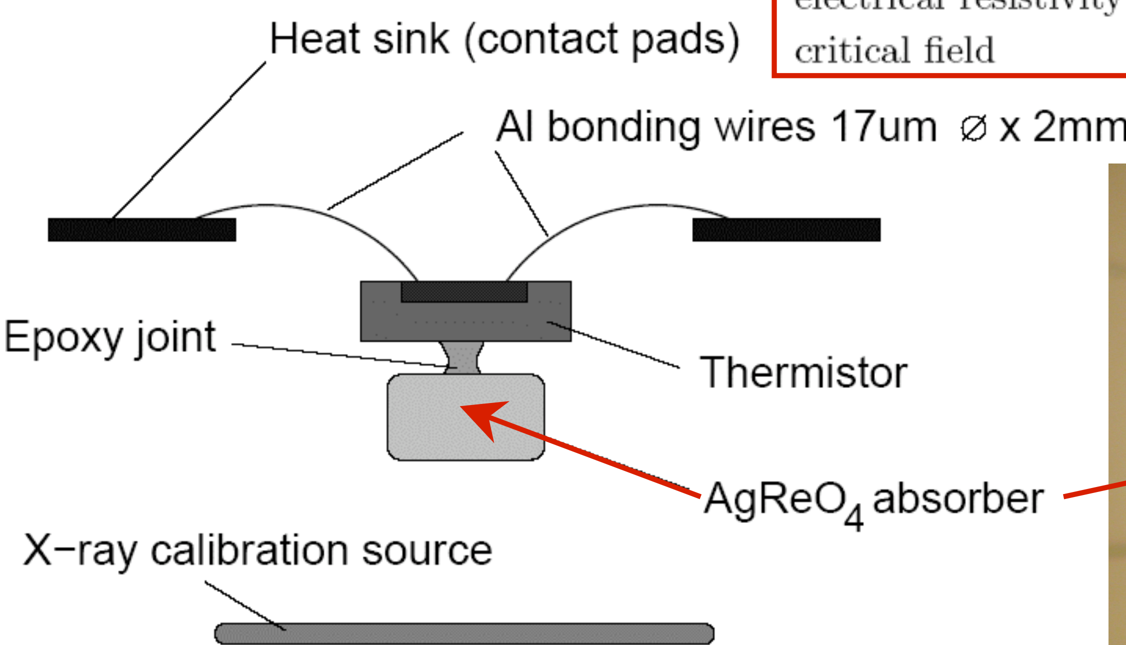
μ-calorimeters for ^{187}Re ß-decay

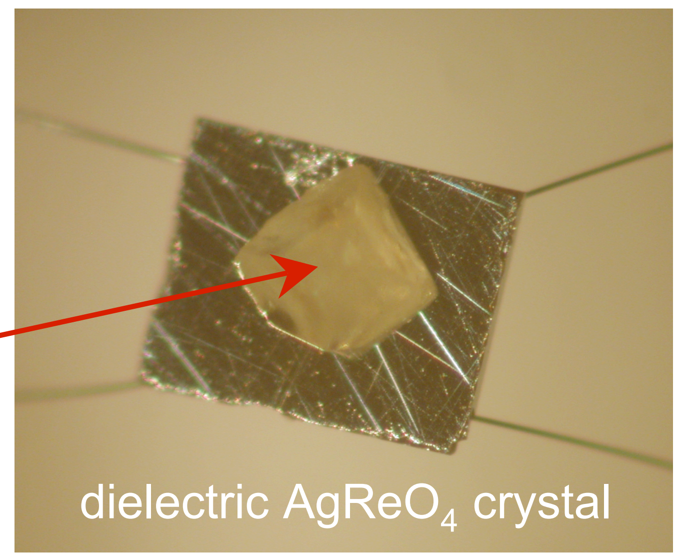
$$^{187}_{85}\mathrm{Re} \rightarrow {}^{187}_{86}\mathrm{Os} + e^- + \bar{\nu}_e$$

Genoa: metallic Re (MANU)
Milano: $AgReO_4$ (MIBETA)

Z	75
isotopes	^{185}Re (37.4%) ^{187}Re (62.6%)
A	186 g/mol
molar volume	11.3 cm^3
electronic. configuration	[Xe] $4f_{14}5d_56s_2$
crystal structure	hcp
density	21.02 g/cm^3
Debye temperature	417 K
transition temperature	1.69 K
electrical resistivity (300 K)	18.4×10^{-6} Ωcm
critical field	20 mT

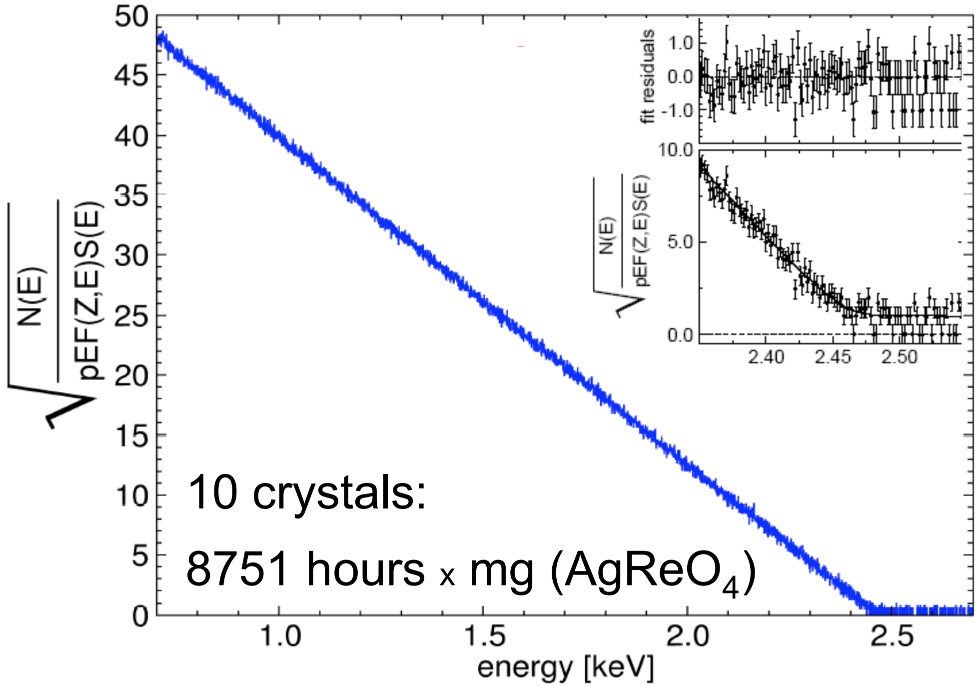
bolometer configuration





μ-calorimeters for ^{187}Re ß-decay

MIBETA: Kurie plot of 6.2×10^6 ^{187}Re ß-decay events (E > 700 eV)



$E_0 = (2465.3 \pm 0.5_{stat} \pm 1.6_{syst})$ eV

$m_\nu^2 = (-112 \pm 207 \pm 90)\ eV^2$

MANU2 (Genoa)
metallic Rhenium
m(ν) < 26 eV

Nucl. Phys. B (Proc.Suppl.) 91 (2001) 293

MIBETA (Milano)
$AgReO_4$
m(ν) < 15 eV

Nucl. Instr. Meth. 125 (2004) 125

MARE (Milano, Como, Genoa, Trento, US, D)
Phase I : m(ν) < 2.5 eV

hep-ex/0509038

calorimeter ⟺ spectrometer

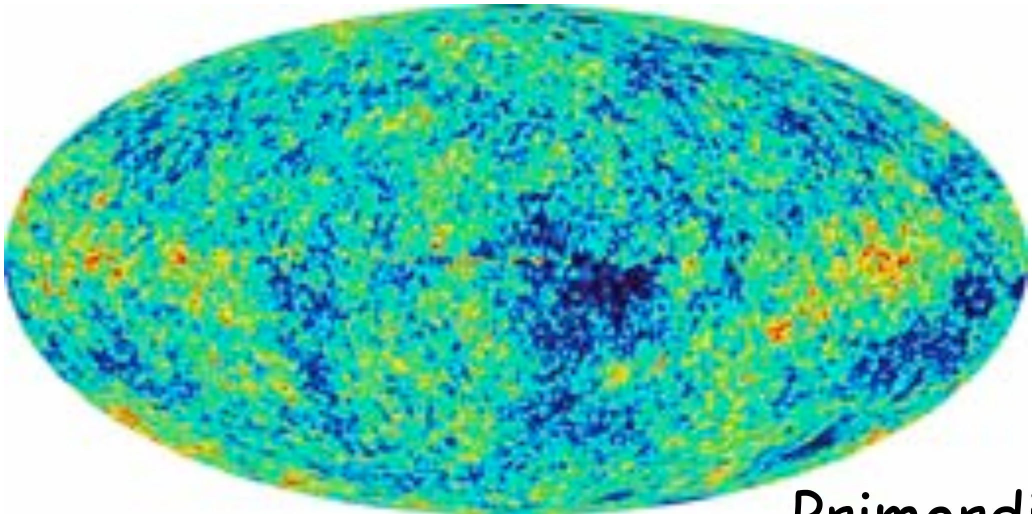
ß-source = detector (^{187}Re)

- metallic Re / diel. $AgReO_4$
- low activity (< 10^5 ß/s)
  ~ 1 Bq/mg Re [x 350 as ~E_0^3]
- energy: single crystal bolometer
- measure *entire* decay energy
- measure entire spectrum
- *differential* ß-energy spectrum
- modular size, expandable (>10^5)
- $\Delta E_{expected}$ ~ 5 eV (FWHM)

external ß-source (^{3}H)

- condensed / gaseous T_2
- high activity ~10^{11} ß/s
  ~ 2 Ci/s injection of T_2
- energy: elstat. spectrometer
- measure *kinetic* energy of ß
- narrow interval close to E_0
- *integrated* ß-energy spectrum
- integral design, size limits
- $\Delta E_{expected}$ = 0.93 eV (100%)

Cosmological connection to neutrinos

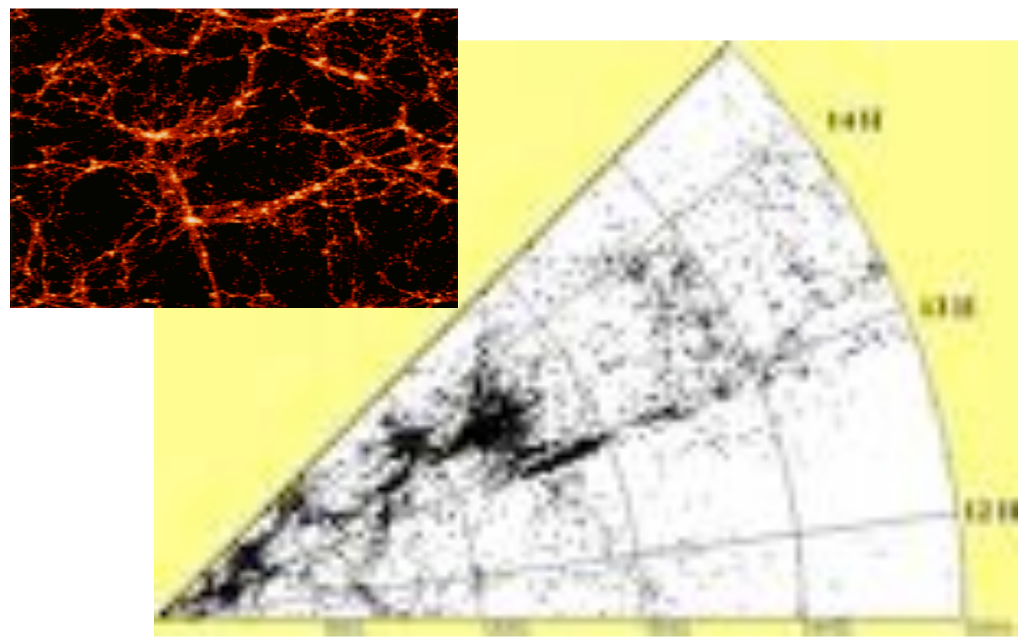


Primordial microwave background

Limit on neutrino mass

$$\sum_i m_i < 0.7 eV$$

From three years of WMAP



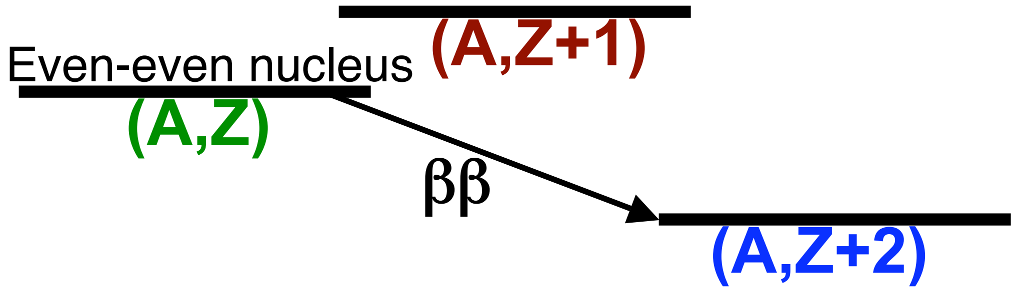
Large scale structure

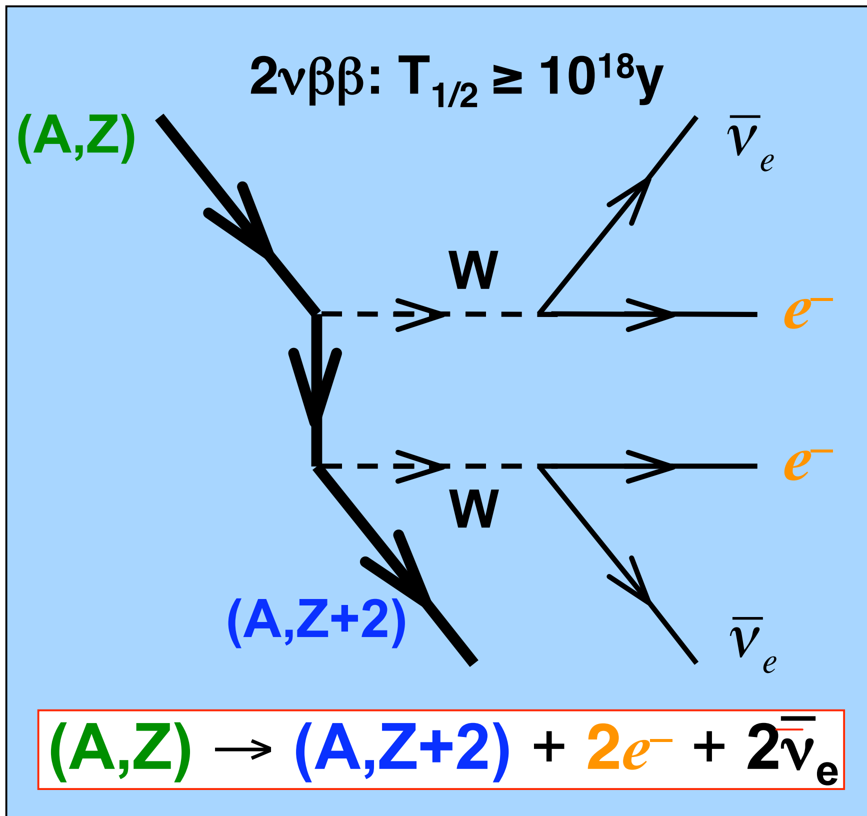
Double Beta Decay and Majorana Neutrinos

Double Beta Decay

2νββ

1935



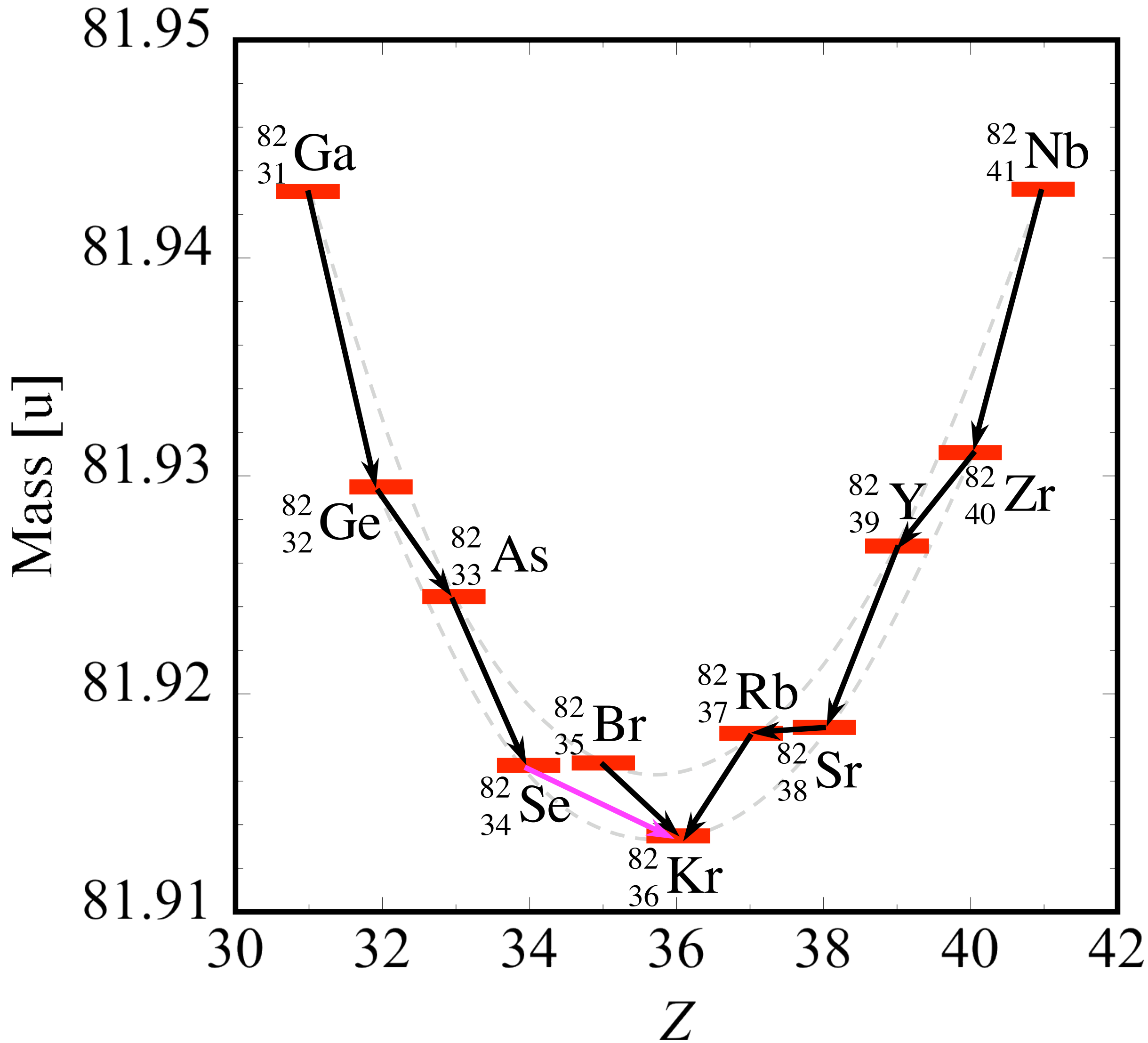


Bethe-Von Weizsacker semi-empirical mass relation

$$M(A,Z) = Zm_p + (A-Z)m_n - a_v A + a_s A^{2/3} + a_c Z^2 A^{-1/3} + a_a (A-2Z)^2 A^{-1} + \delta$$

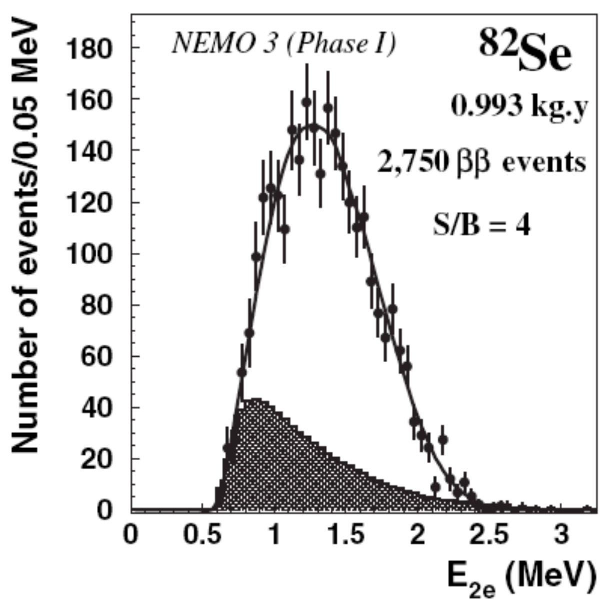
$\delta = -a_p A^{-3/4}$ (even,even) or $+a_p A^{-3/4}$ (odd,odd) or 0 (even,odd)

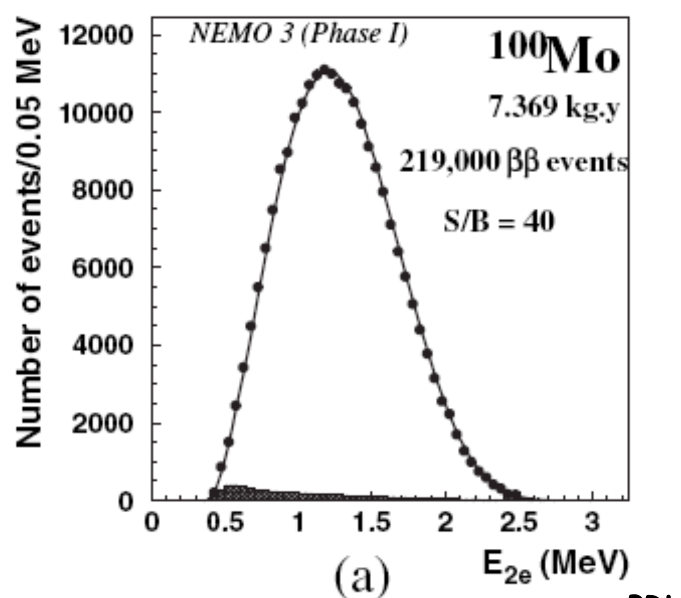
a_p -> 33.5 MeV



^{82}Se first directly observed by Moe and Elliot

Recent $2\nu\beta\beta$ spectra from NEMO



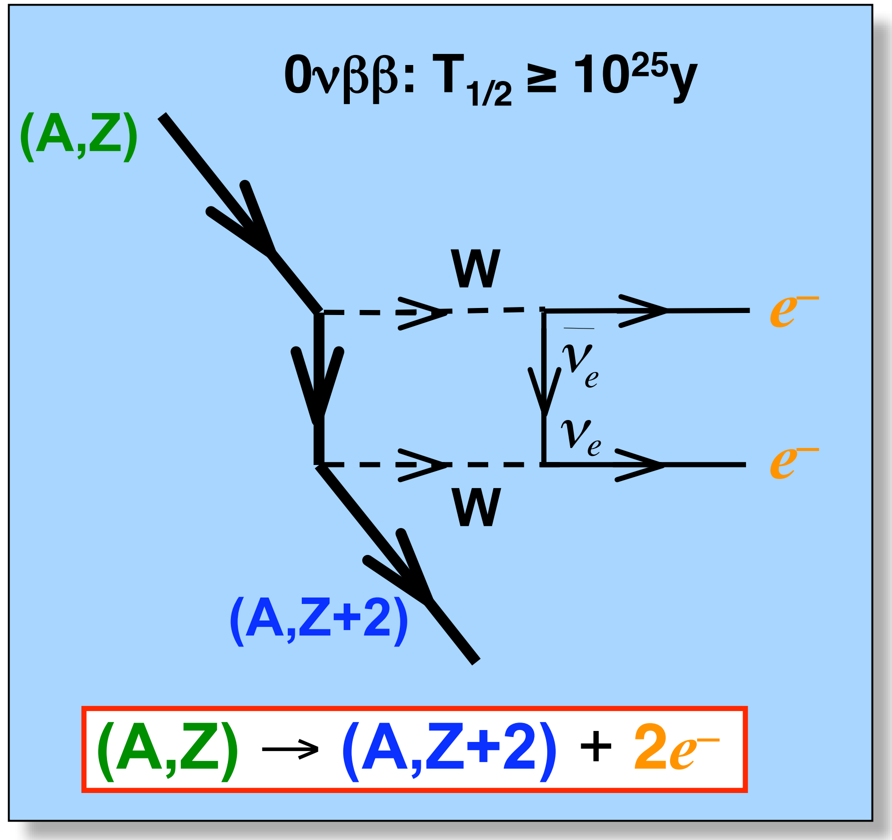


PRL95,182302(2005)

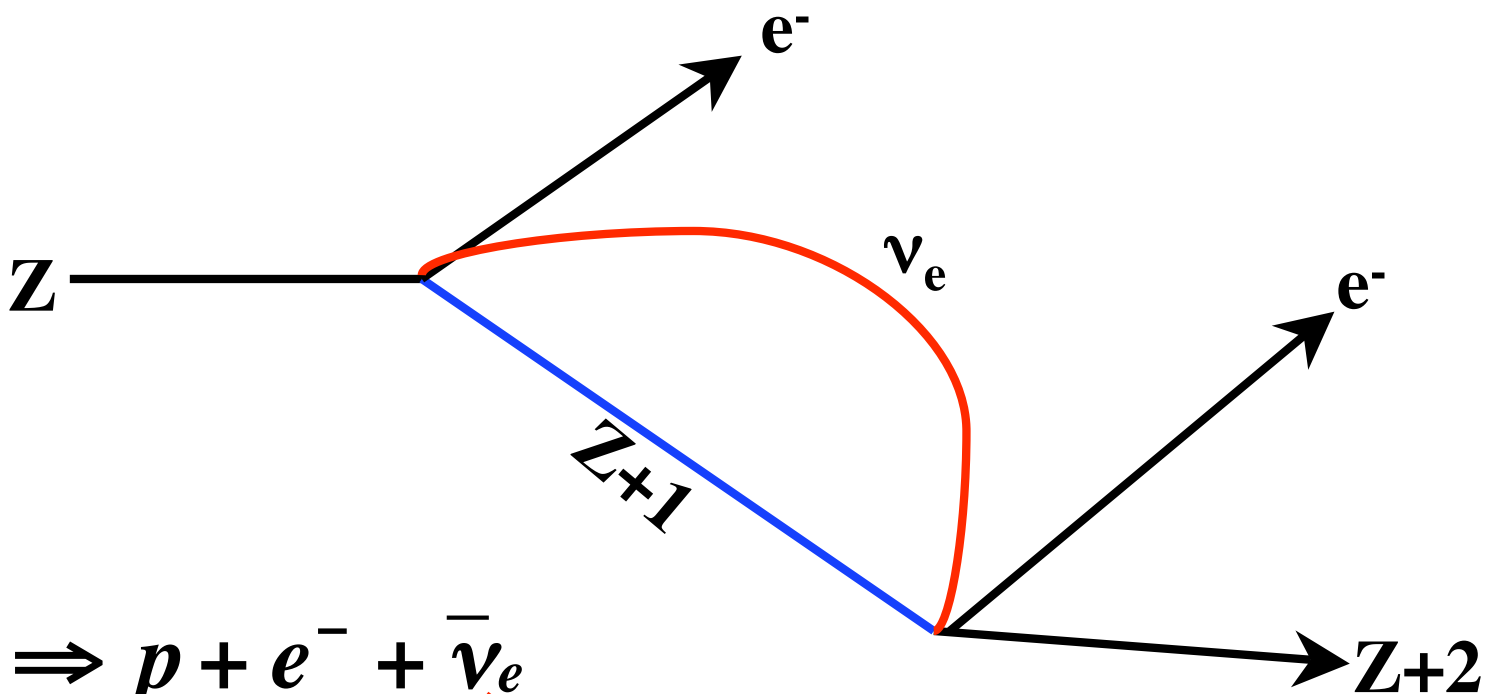
Neutrino-less Double Beta Decay

$0\nu\beta\beta$ *First suggested by Furry*

1937



$0\nu\beta\beta$: requires massive Majorana ν

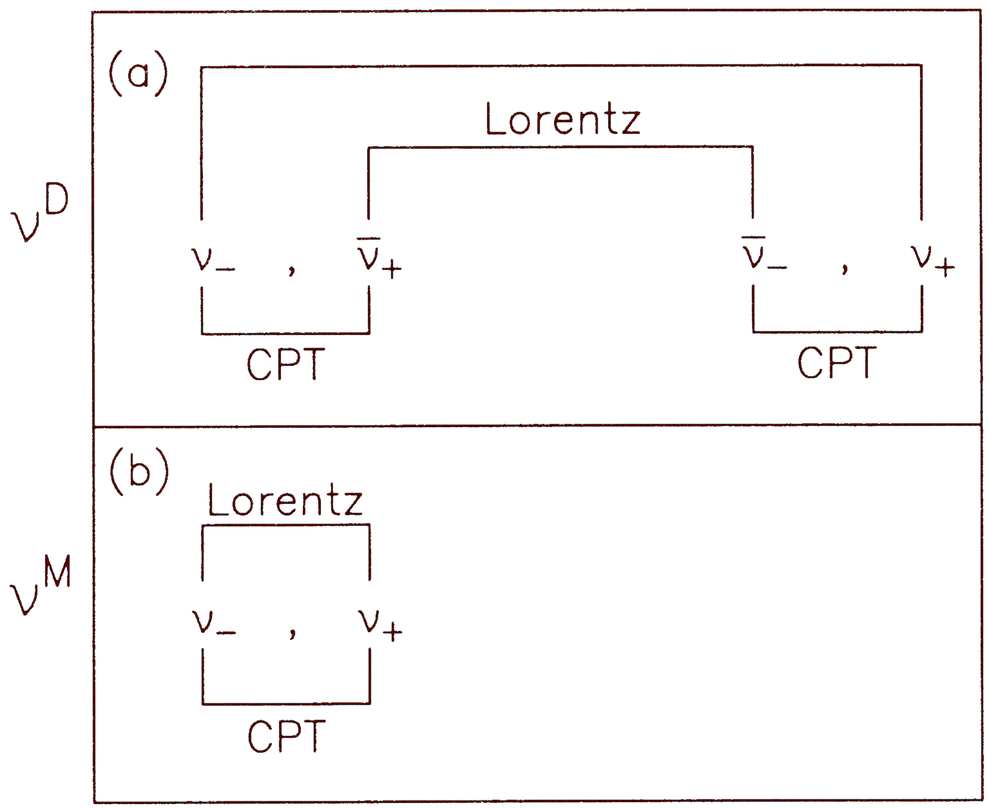


$$n \Rightarrow p + e^- + \overline{\nu}_e$$

(RH $\overline{\nu_e}$) (LH ν_e)

$$\nu_e + n \Rightarrow p + e^-$$

Elliot



Dirac neutrino:

4 states

Lepton number is conservation

$\Delta L=0$

Majorana neutrino:

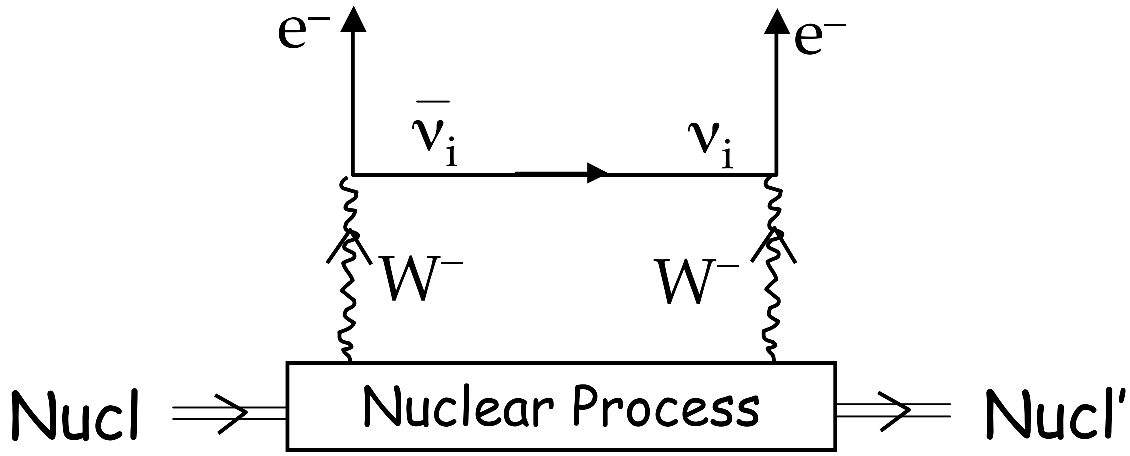
2 states

Lepton number is not conserved

$\Delta L=2$

ν_D and ν_M only different if $m_\nu \neq 0$

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



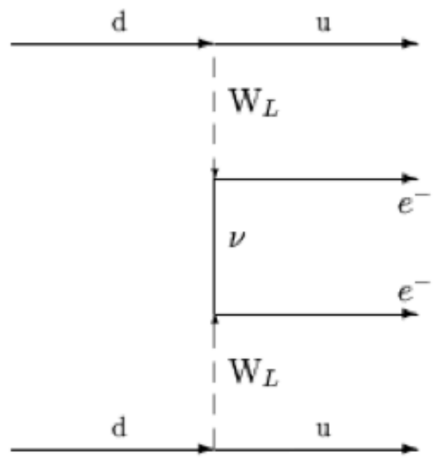
Suppose you see it!

Simple interpretation:

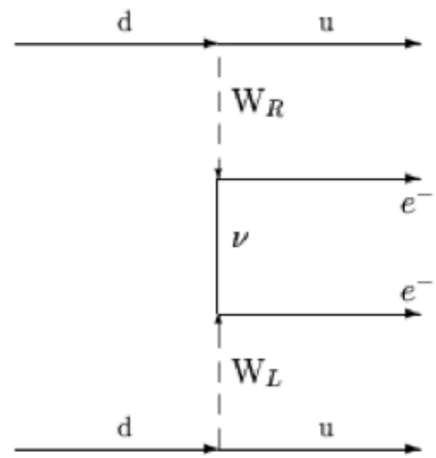
- Lepton number is not conserved
- Neutrinos are Majorana ($\nu = \bar{\nu}$)
- Neutrino mass is different!

EXCEPT

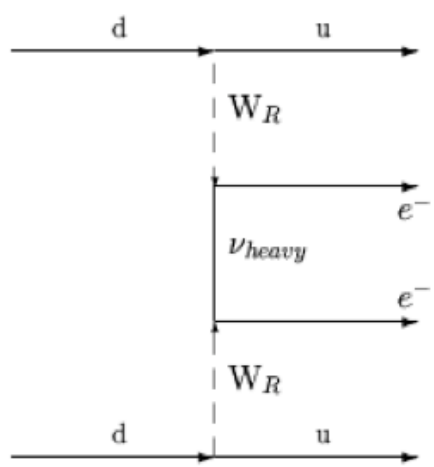
Exchange of a **light** neutrino, only left-handed currents



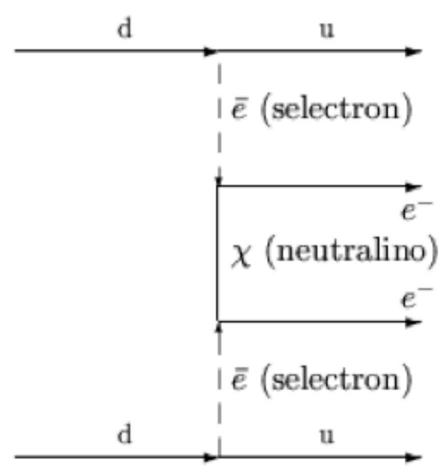
Exchange of a light or heavy neutrino and one **right-handed W_R**



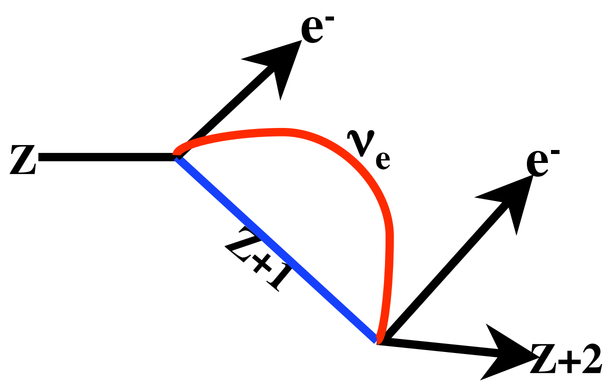
Exchange of a **heavy** neutrino, short range hadron physics at play

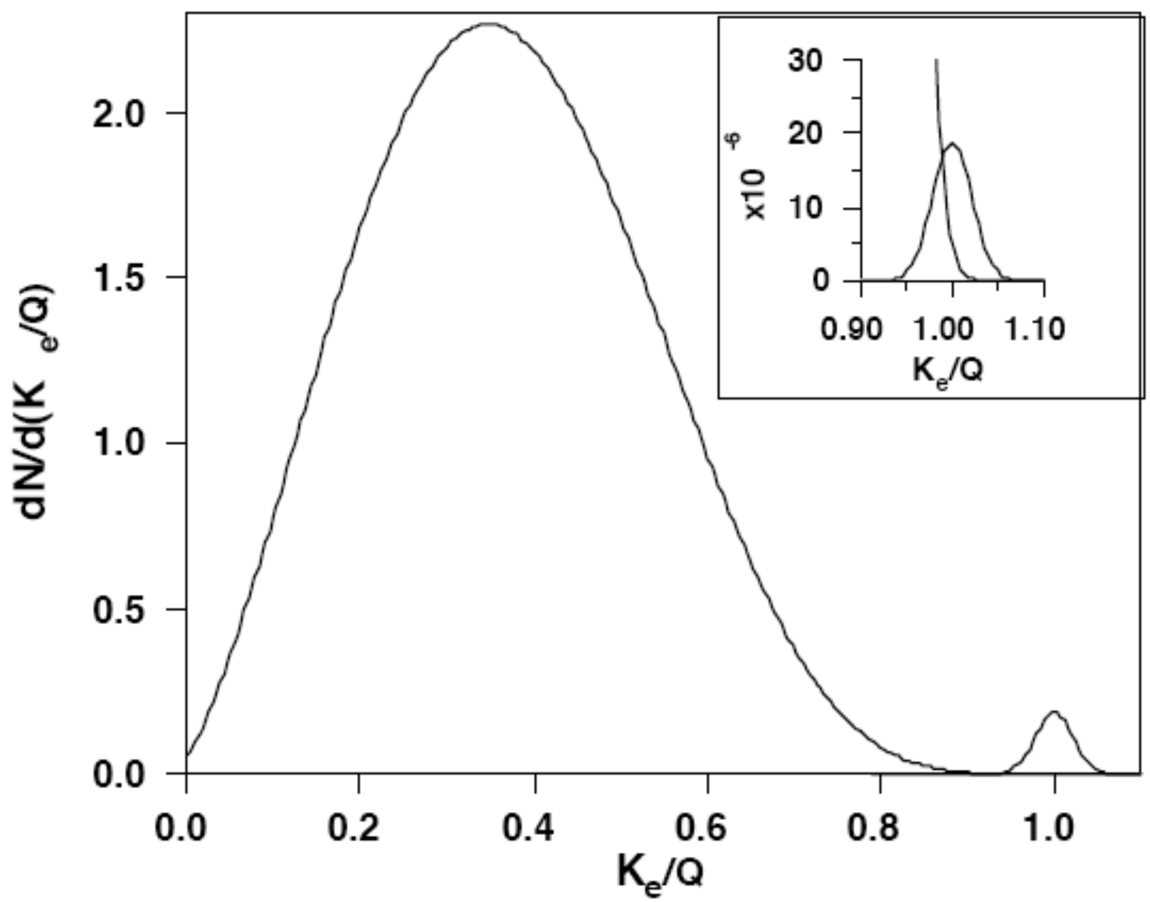


Exchange of **supersymmetric** particles, R-symmetry violated



Experimental Signal of Neutrinoless Double Beta Decay





$$\Gamma_{0\nu} = G_{0\nu}(Q,Z)\ |M_{nucl}|^2 <m_{\beta\beta}>^2$$

0νßß and effective Majorana mass

$$\langle m \rangle = |\sum U_{ei}^2 m_i| = |m_{ee}^{(1)}| + e^{i\phi_2}|m_{ee}^{(2)}| + e^{i\phi_3}|m_{ee}^{(3)}|$$

$$|m_{ee}^{(1)}| = |U_{e1}|^2 m_1,$$

$$|m_{ee}^{(2)}| = |U_{e2}|^2 \sqrt{\Delta m_{21}^2 + m_1^2},$$

$$|m_{ee}^{(3)}| = |U_{e3}|^2 \sqrt{\Delta m_{32}^2 + \Delta m_{21}^2 + m_1^2}$$

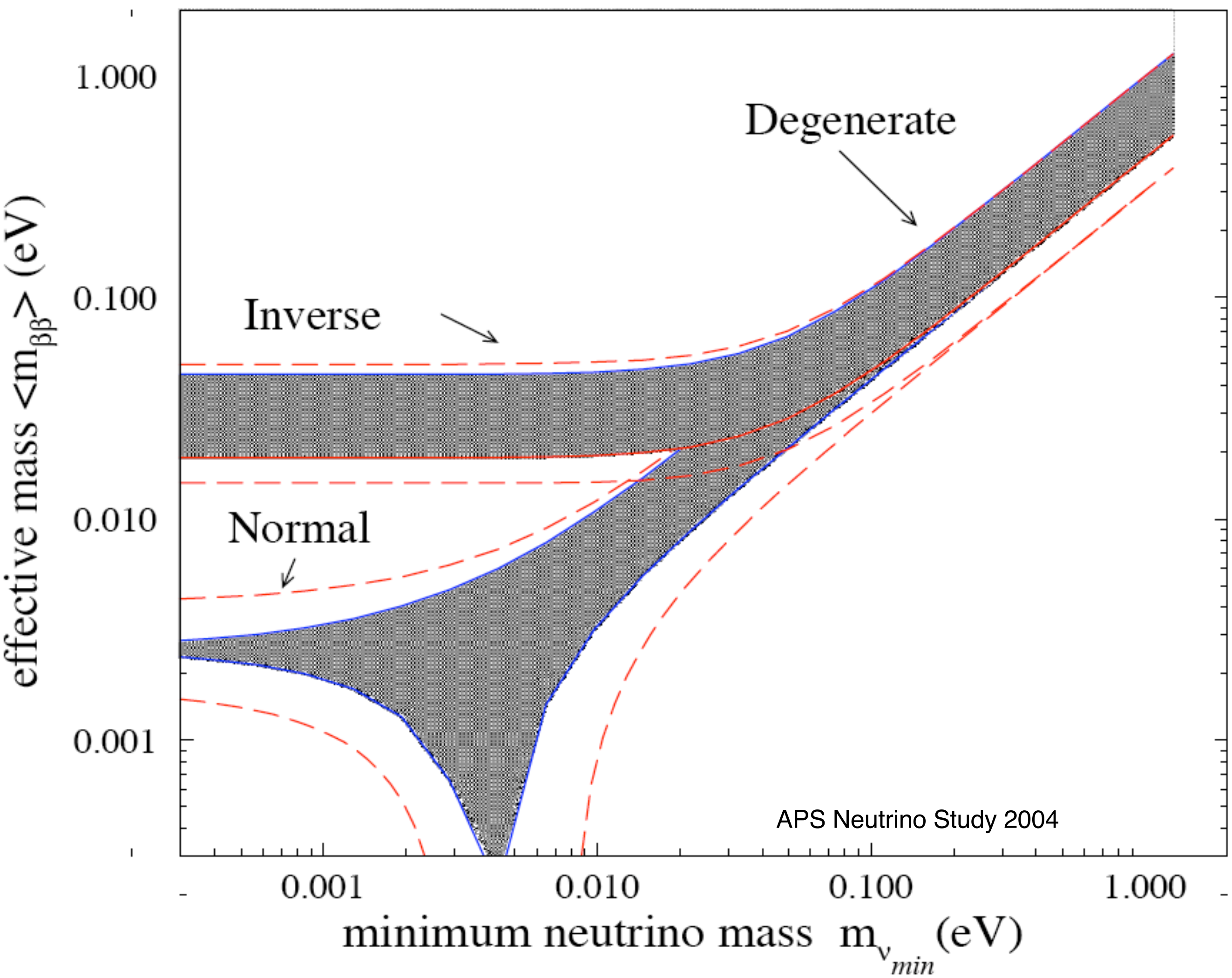
Majorana CP Phases
ϕ = *-1 ….+1*
Cancellations possible

simplified relation if U_{e3} negligible and $\phi = \pm 1$ (CP conservation)

$$\langle m_{\beta\beta} \rangle \sim |U_{e1}|^2 m_1 \pm |U_{e2}|^2 \sqrt{m_1^2 + \delta m_{12}^2}$$

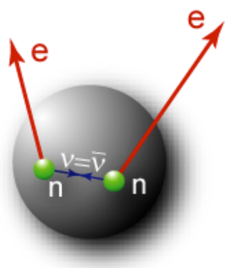
~0.75 ~0.25 from solar and atmospheric ν´s

m_1 scale unknown: quasi-degenerate, hierarchy, inverted hierarchy

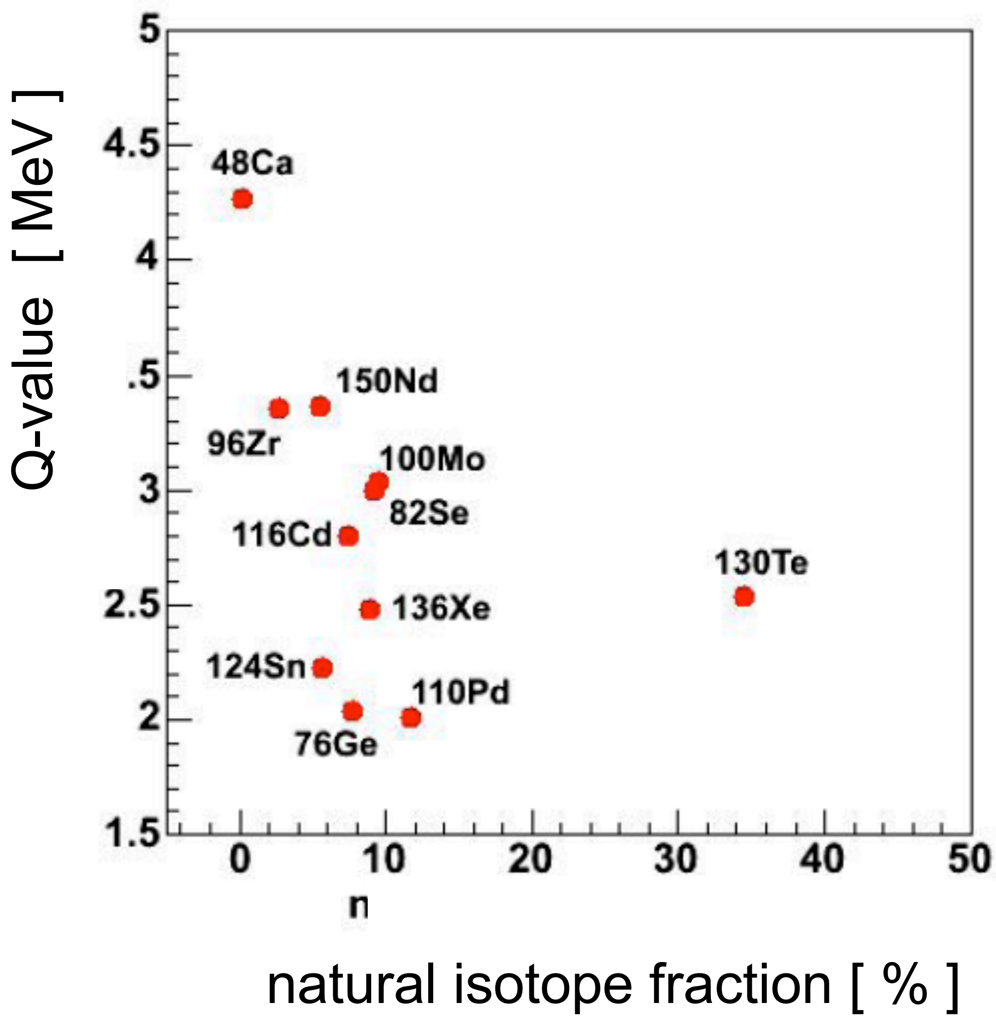


$$\Gamma_{0\nu} = G_{0\nu}(Q,Z)\ |M_{nucl}|^2 <m_{\beta\beta}>^2$$

$$\langle m_{\beta\beta} \rangle = \sum_{i=1}^{3} |U_{ei}|^2 m_i \varepsilon_i$$



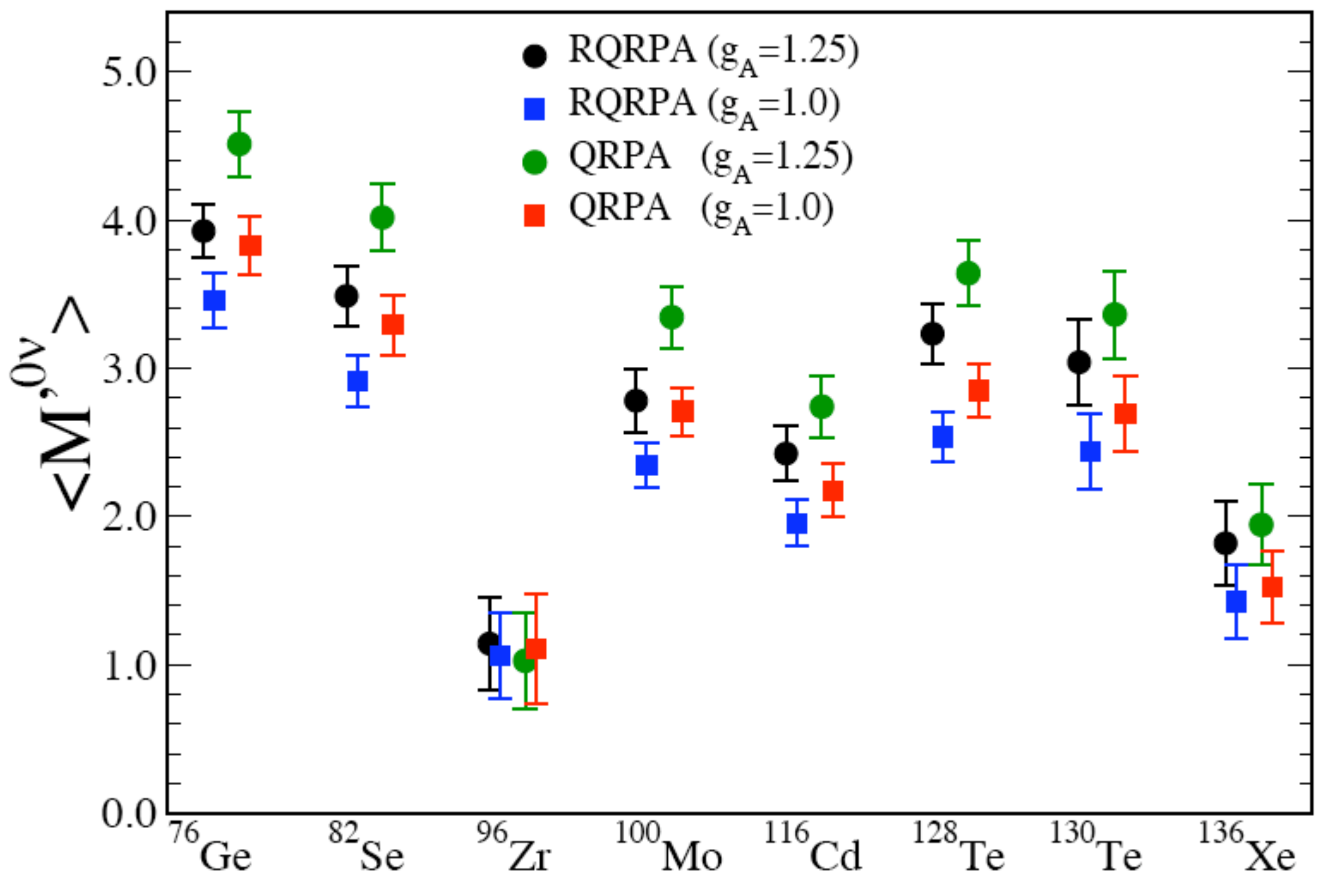
double beta decay isotopes



	E	%
$^{48}Ca \rightarrow ^{48}Ti$	4.271	0.187
$^{76}Ge \rightarrow ^{76}Se$	2.040	7.8
$^{82}Se \rightarrow ^{82}Kr$	2.995	9.2
$^{96}Zr \rightarrow ^{96}Mo$	3.350	2.8
$^{100}Mo \rightarrow ^{100}Ru$	3.034	9.6
$^{110}Pd \rightarrow ^{110}Cd$	2.013	11.8
$^{116}Cd \rightarrow ^{116}Sn$	2.802	7.5
$^{124}Sn \rightarrow ^{124}Te$	2.228	5.64
$^{130}Te \rightarrow ^{130}Xe$	2.533	34.5
$^{136}Xe \rightarrow ^{136}Ba$	2.479	8.9
$^{150}Nd \rightarrow ^{150}Sm$	3.367	5.6

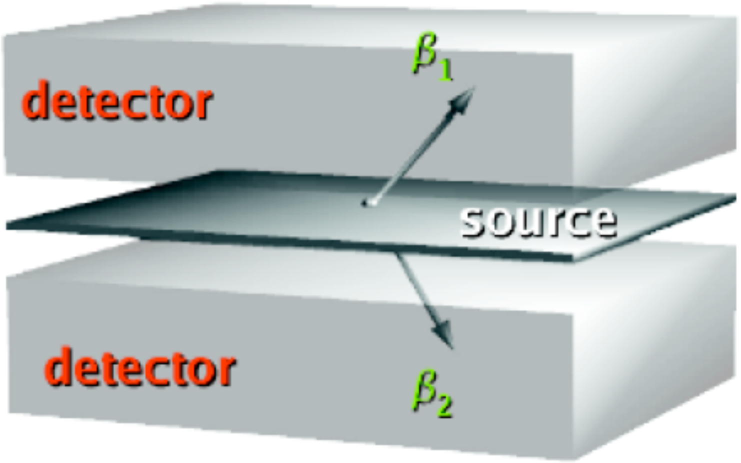
	Authors/Ref.	Method	$T_{1/2}(^{130}Te)$ (10^{23} y)	$F_N(^{130}Te)$ (10^{-13} y^{-1})	$F_N(^{76}Ge)$ (10^{-13} y^{-1})
QRPA	Staudt et al., 1992 [3]	pairing (Paris)	0.77-0.88	29-34	5.9-10
		pairing (Bonn)	0.9-1.1	24-29	4.5-8.9
QRPA	Staudt et al., 1990 [4]		5	5.22	1.12
	Pantis et al., 1996 [5]	no p-n pairing	8.64	3.0	0.73
		p-n pairing	21.1	1.24	0.14
	Vogel et al., 1986 [6]		6.6	3.96	0.19
	Tomoda et al., 1987 [7]		5.2	5.0	1.2
	Civitarese et al., 2003[8]		5.2	5.0	0.7
	Barbero et al., 1999 [9]		3.36	7.77	0.84
	Simkovic et al, 1997 [10]	Full RQRPA	4.66	5.6	0.27
	Simkovic, 1999 [11]	pn-RQRPA	14.5	1.79	0.62
	Suhonen et al., 1992 [12]		8.34	3.13	0.72
	Muto et al., 1989 [13]		4.89	5.34	1.1
	Stoica et al., 2001 [14]	large basis	10.7	2.44	0.65
		short basis	9.83	2.66	0.9
	Faessler et al., 1998 [15]		9.4	2.78	0.83
	Engel et al., 1989 [16]	generalized			
		seniority	2.4	10.9	1.14
	Aunola et al., 1998 [17]	WS	4.56	5.72	0.9
		AWS	5.16	5.06	1.33
	Rodin et al., 2003 [18]	QRPA	34.6	0.75	0.45
		RQRPA	37.9	0.69	0.36
SM	Haxton et al., 1984 [19]	weak coupling	1.6	16.3	1.54
	Caurier et al., 1996 [20]	large basis	58	0.45	0.15
OEM	Hirsh et al., 1995 [21]		7.3	3.6	0.95

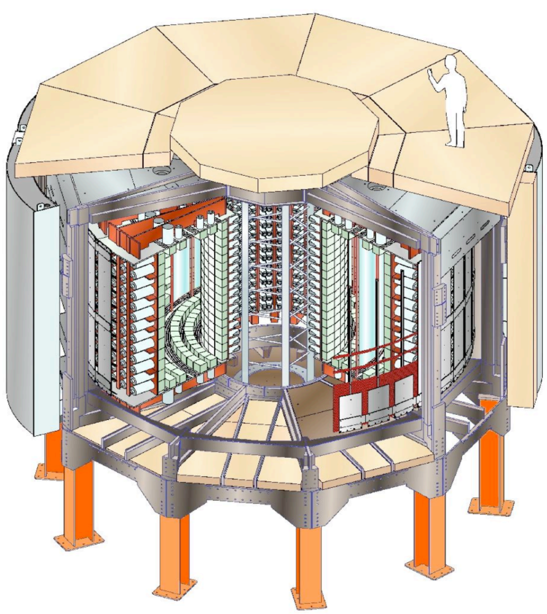
Experimental Sensitivity depends on Nuclear Structure



ßß0ν: experimental techniques

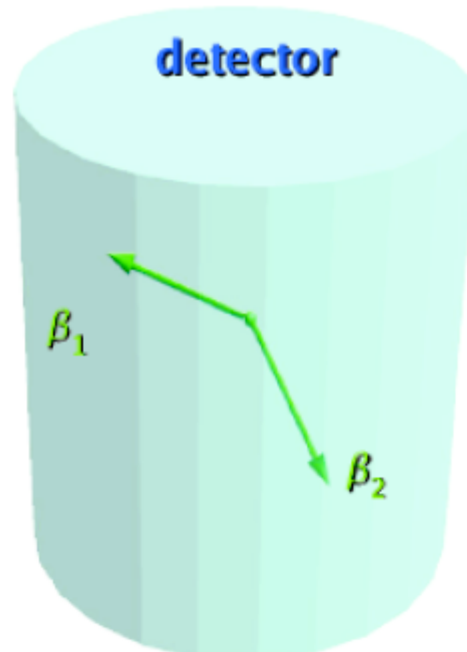
passive: source ≠ detector

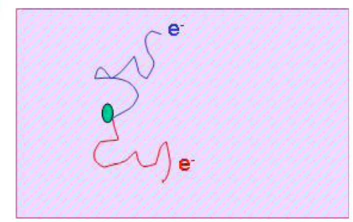


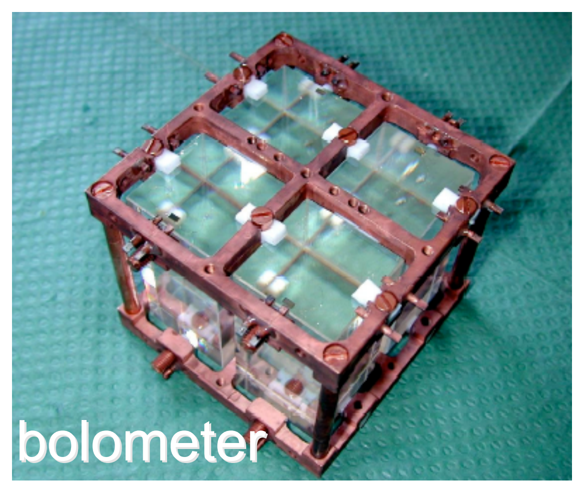


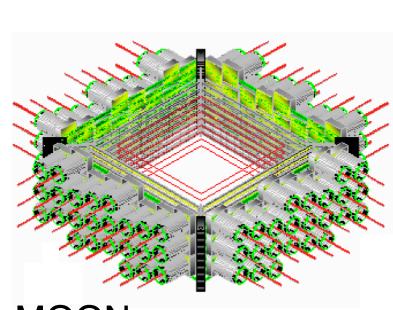
ßß foils

active: source = detector

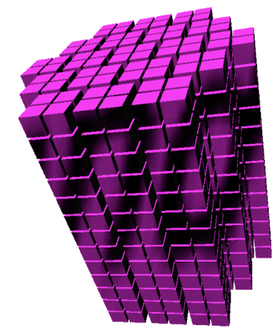








MOON



CUORE

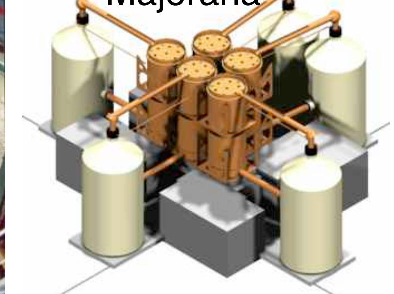
Candidate Experiments

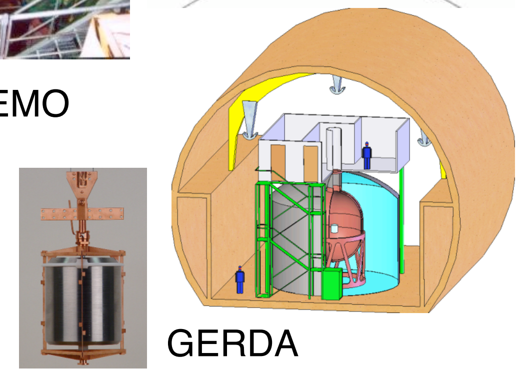
$\sin^2 2\theta_{13}$

Experiment	Nucleus	Detector
NEMO III	^{100}Mo et al	10 kg of enrich. Isotopes -tracking
Cuoricino	^{130}Te + etc.	40 kg of TeO_2 bolometers (nat)
CUORE	^{130}Te + etc.	750 kg of TeO_2 bolometers (nat)
EXO	^{136}Xe	200kg - 1 t Xe TPC
GERDA	^{76}Ge	30 – 40 kg – 1t Ge diodes in LN
Majorana	^{76}Ge	180 kg - 1t Ge diodes
MOON	^{100}Mo	nat.Mo sheets in plastic sc.
DCBA	^{150}Nd	20 kg Nd-tracking
CAMEO	^{116}Cd	1 t $CdWO_4$ in liquid scintillator
COBRA	^{116}Cd , ^{130}Te	10 kg of CdTe semiconductors
Candles	^{48}Ca	Tons of CaF_2 in liquid scintillators
GSO	^{116}Cd	2 t Gd_2SiO_5:Ce scintill.in liquid sc.
Xe	^{136}Xe	1.56 Xenon in liquid scintillator.
Xmass	^{136}Xe	1 t of liquid Xe

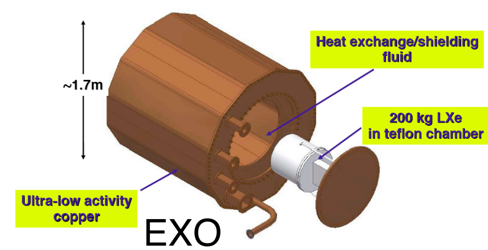
NEMO

Majorana





GERDA



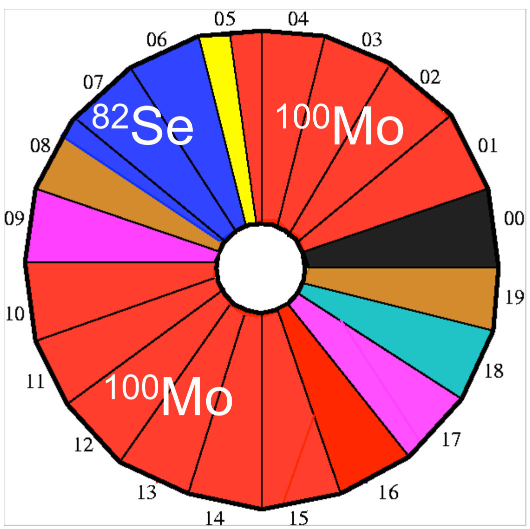
EXO

NEMO3 Experiment at Modane

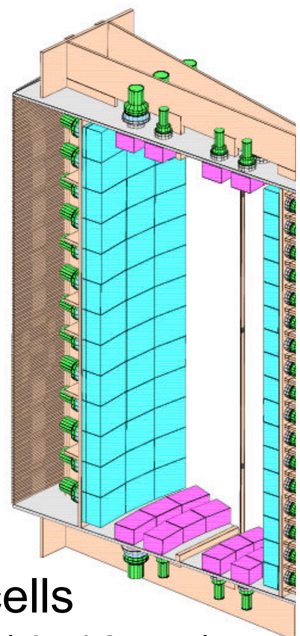
passive foils (6.9 kg ^{100}Mo) & electron track in Geiger cells (B=25 G)

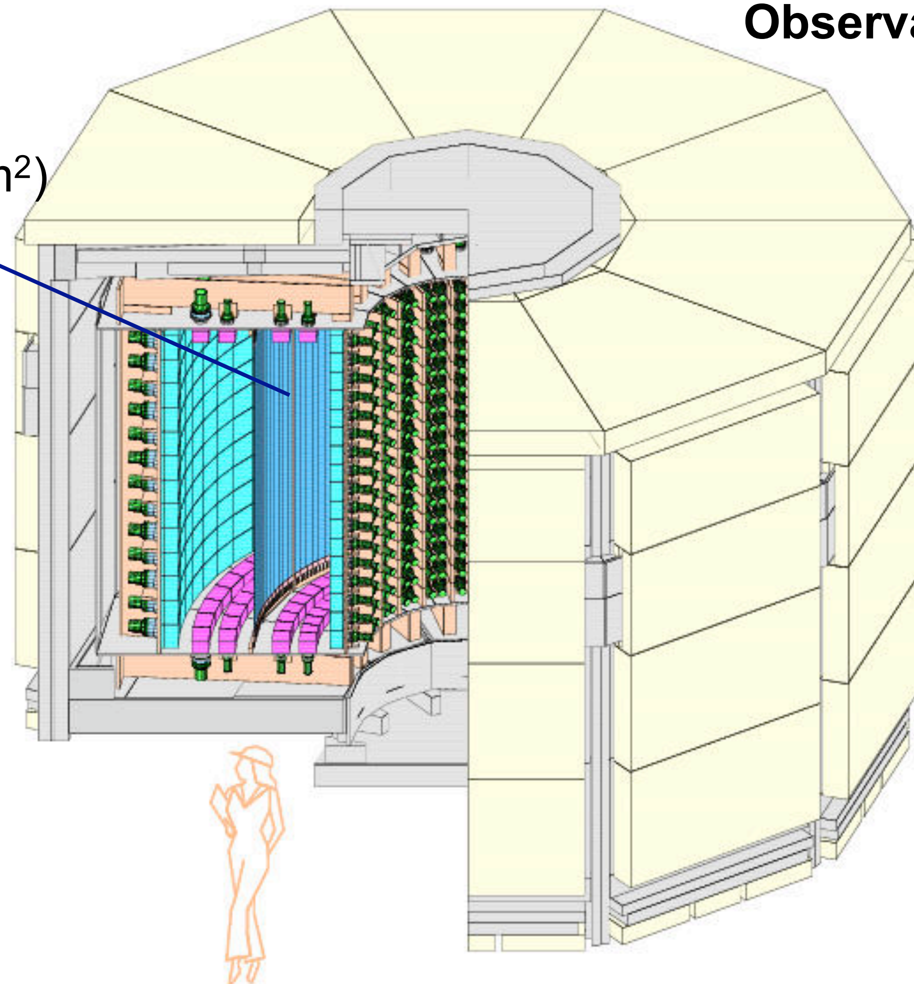
expected sensitivity m_ν = few x 10^2 meV

Neutrino Ettore Majorana Observatory



source-foils
(d=50 μm A=20 m^2)





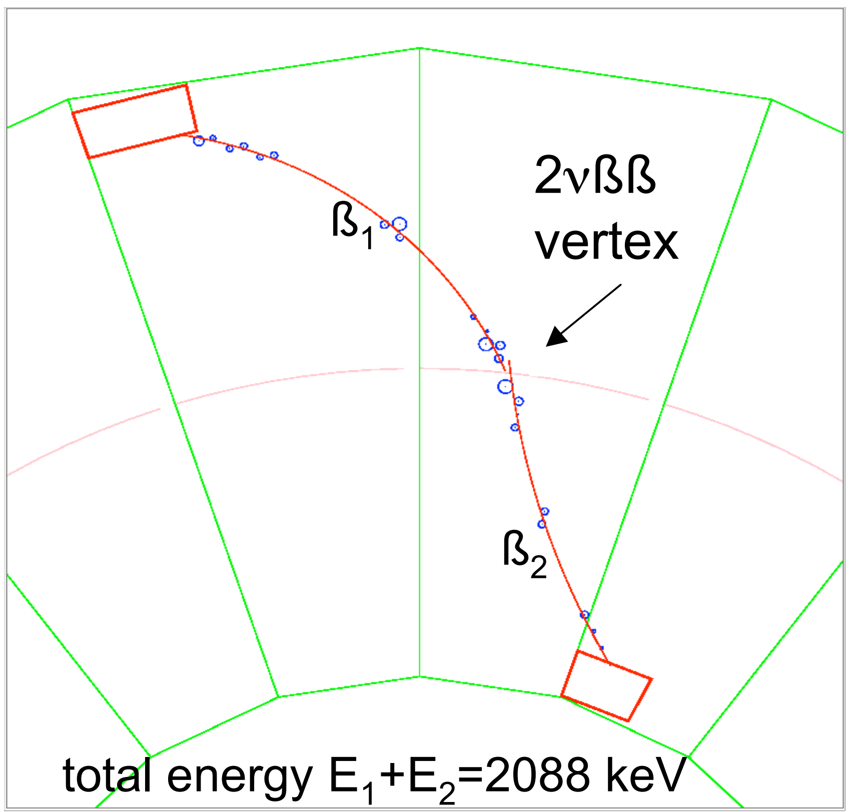
6180 octogonal Geiger cells
1940 plastic scintillators (d=10 cm)
PMTs (low activity)

NEMO3 experiment at Modane

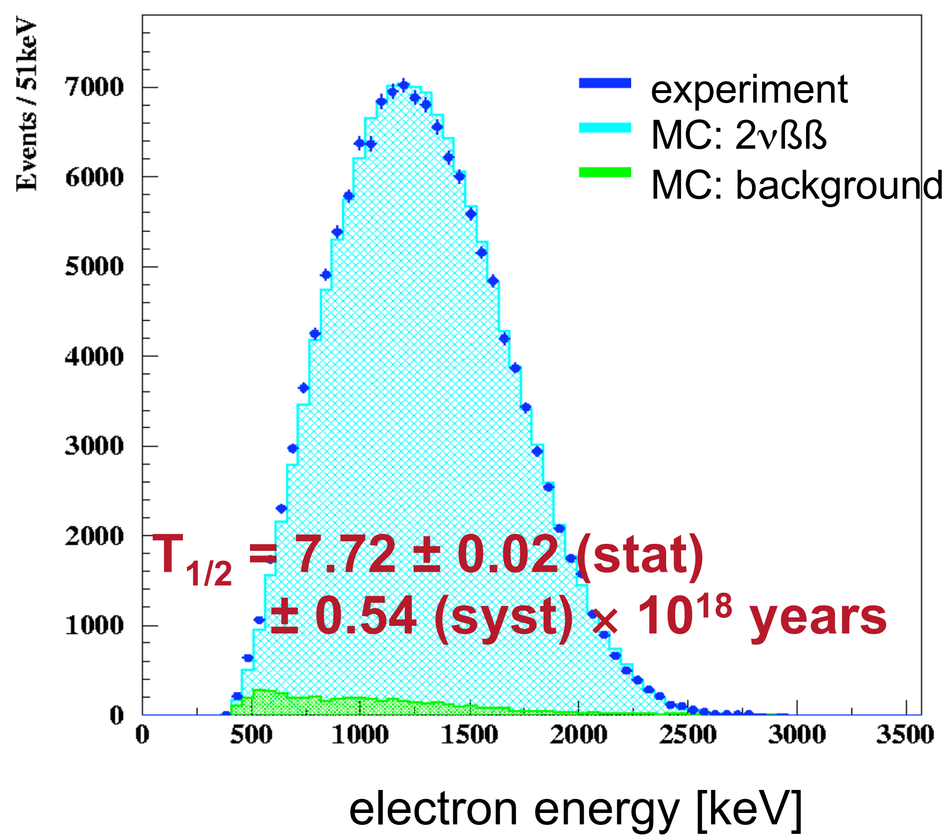
passive foils (6.9 kg ^{100}Mo) & electron track in Geiger cells (B=25 G)

expected sensitivity m_ν = few x 10^2 meV

2 ß-tracks from 2νßß (transv.)



2νßß spectrum for ^{100}Mo



SuperNEMO preliminary design

Plane and modular geometry: ~5 kg of enriched isotope per module

1 module: Source (40 mg/cm2) 4 x 3 m^2

Tracking volume: drift wire chamber in Geiger mode, ~ 3000 cells

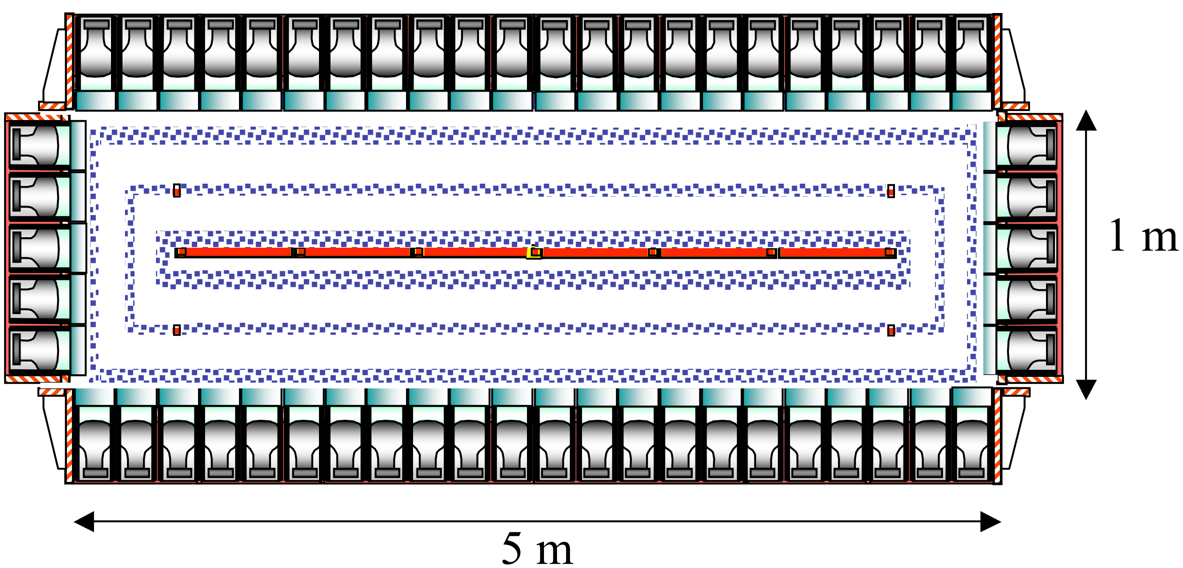
Calorimeter: scintillators + PMTs

20 modules: 100 kg of enriched isotope

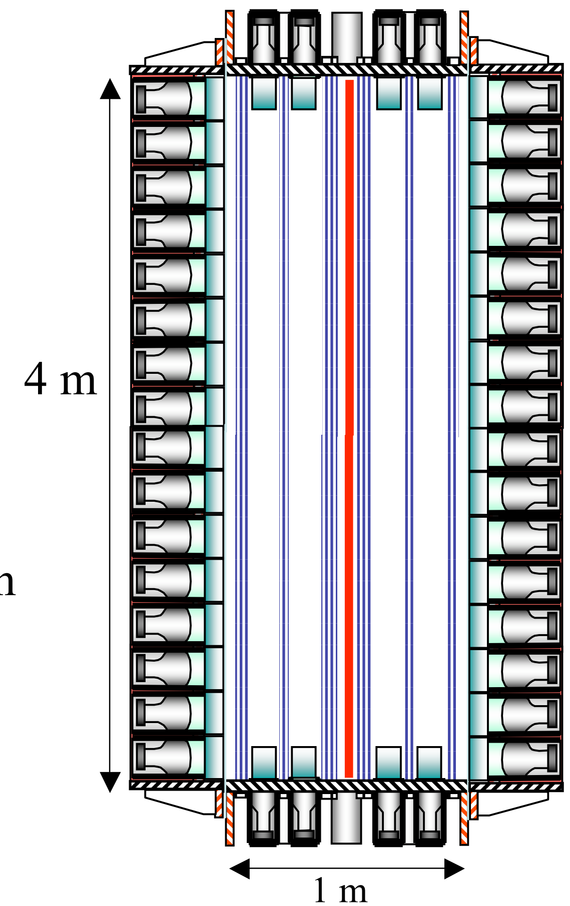
~ 60 000 channels for drift chamber

~ 20 000 PMT if scint. block

~ 2 000 PMT if scint. bars



Top view



Side view

Claimed Observation of $0\nu\beta\beta$ in ^{76}Ge

5 detectors of overall 10.96 kg enriched to 86%.
Most sensitive to date.

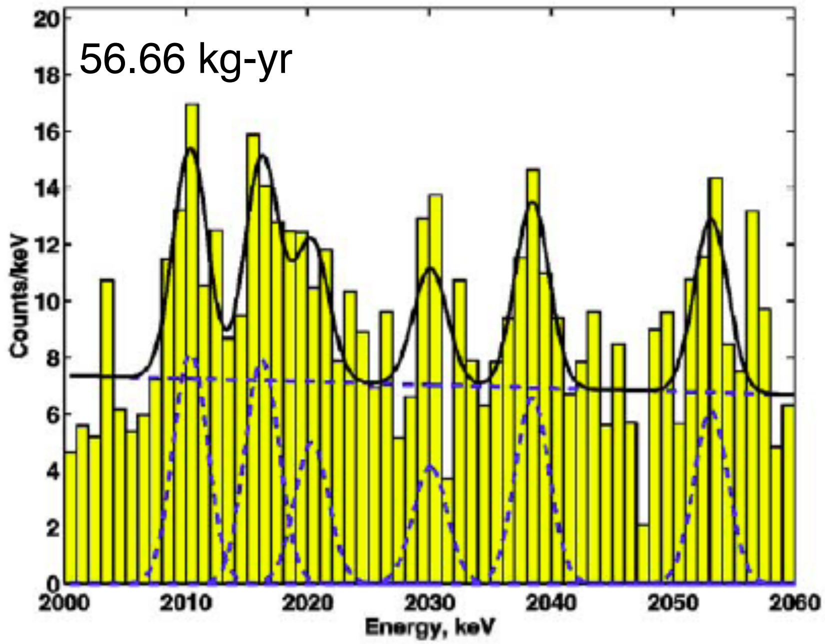
$T_{1/2}$ = (0.67 - 4.45) x 10^{25} *years* (99.73% *C.L.)*

Majorana ν Mass

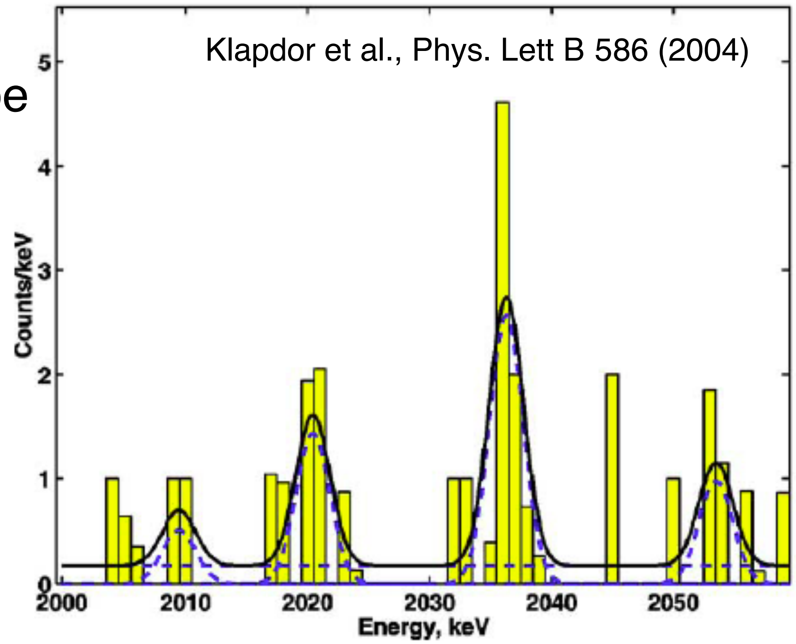
$$<m_{\beta\beta}> = (0.1 - 0.9)\ \text{eV}\ (99.73\%\ C.L.)$$

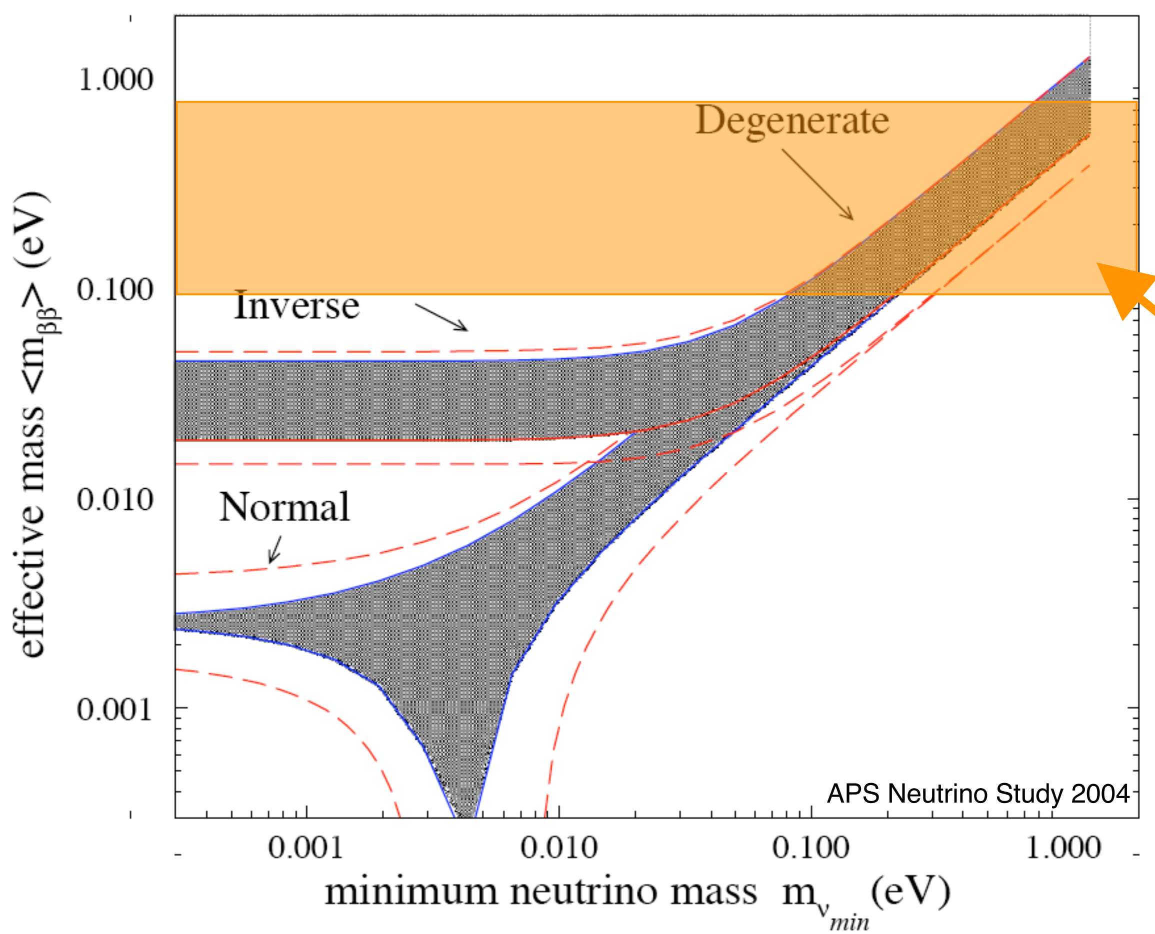
$$<m_{\beta\beta}>_{\text{best}} = 0.45\ eV$$

Backgrounds from ^{214}Bi



Pulse-shape selection





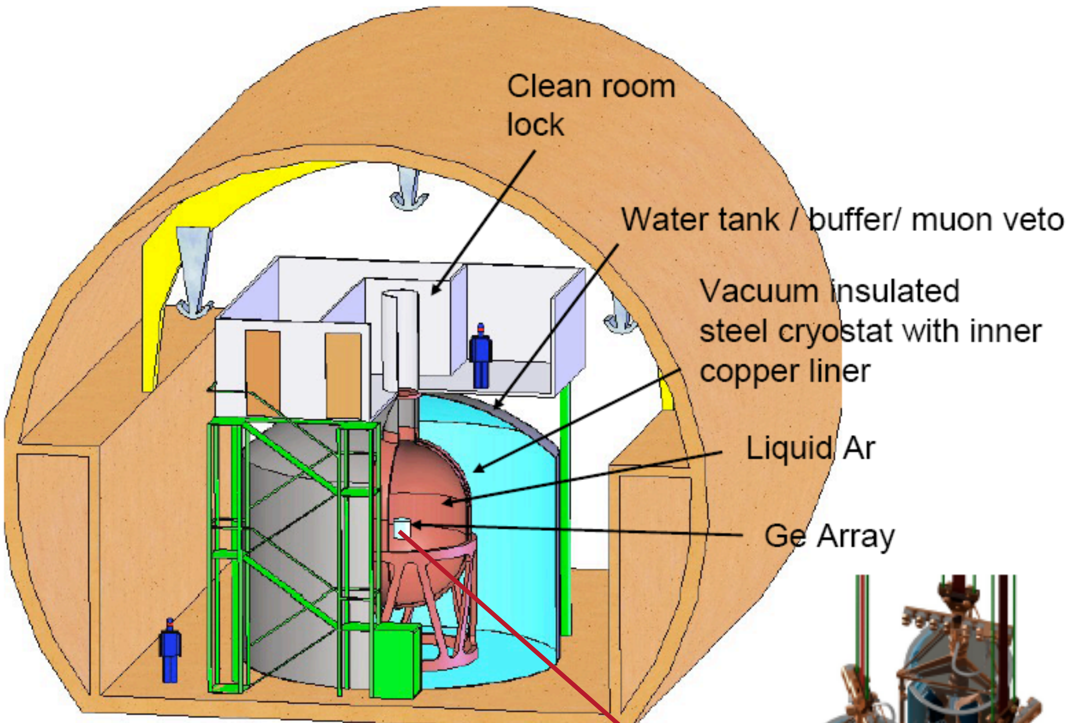
Possible evidence

Klapdor et al., Phys. Lett B 586 (2004) 198

$\langle m_{\beta\beta} \rangle$ ►(0.1 – 0.9) *eV*

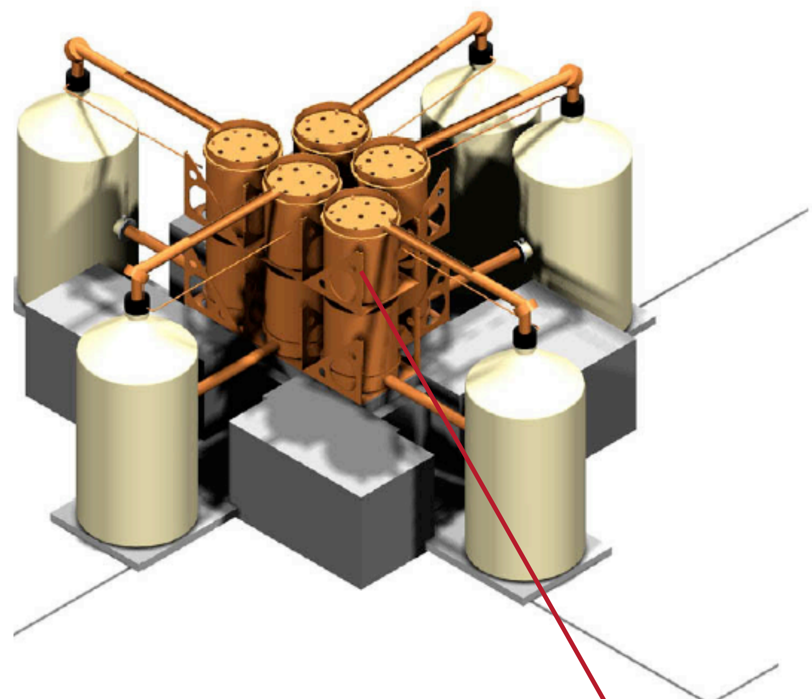
Future Ge-76 Experiments

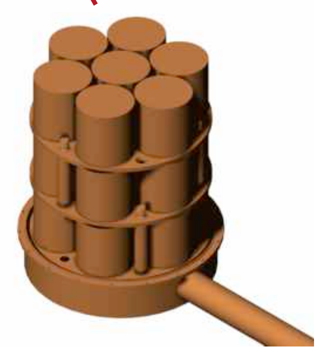
GERDA



- bare ^{enr}Ge array in high purity LAr shield

Majorana

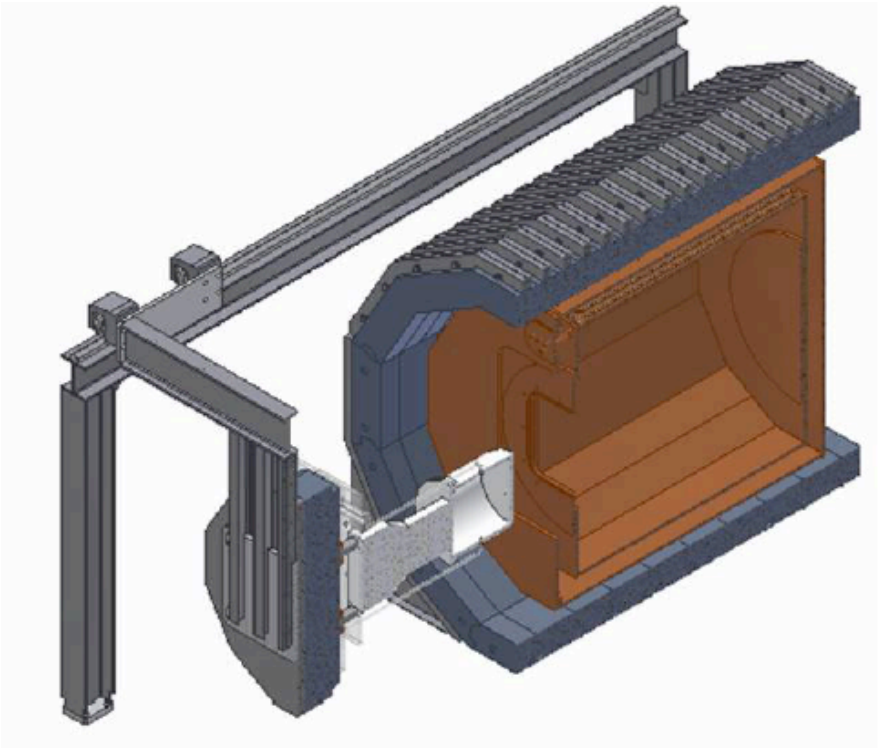




- ^{enr}Ge arrays in high purity shielding electroformed Cu

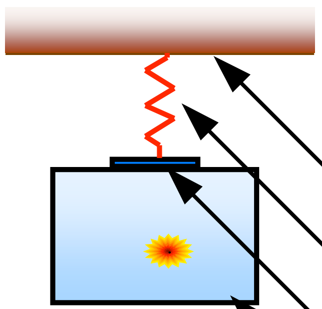
EXO- Enriched Xenon Observatory

$^{136}Xe \rightarrow {}^{136}Ba^{++} + 2\,e^{-}$ (Q = 2.4 MeV)

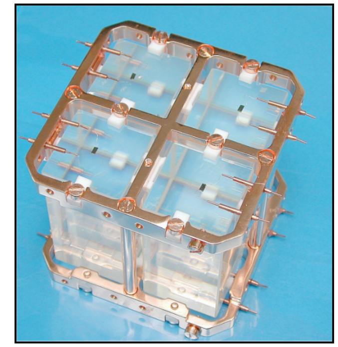


LXe time projection chamber (TPC) with liquid ^{136}Xe

mass [to.]	grade ^{136}Xe [%]	efficiency [%]	time [years]	background [events]	$T_{1/2}$ $0\nu\beta\beta$ [years]	$m_{\beta\beta}$ T1 [meV]	$m_{\beta\beta}$ T2 [meV]
1	90	70	5	1.8	8.3×10^{26}	51	14
10	90	70	10	5.5	1.3×10^{28}	13	3.7

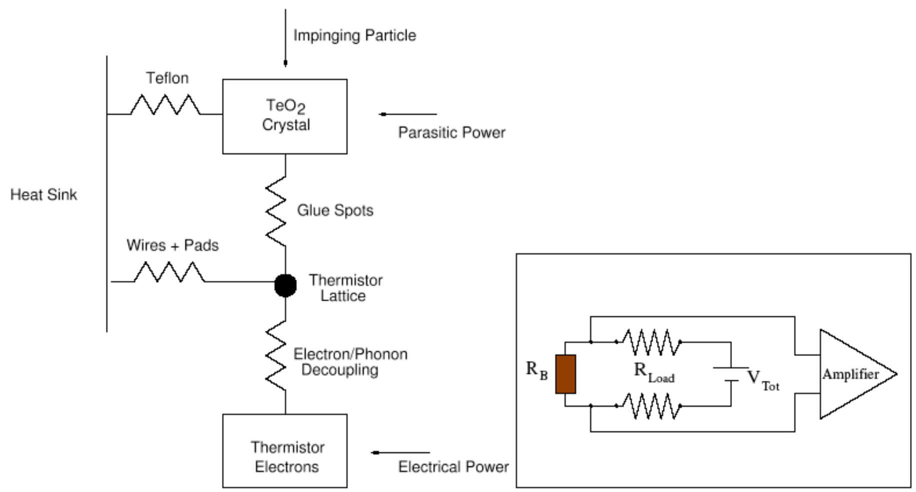


Bolometer



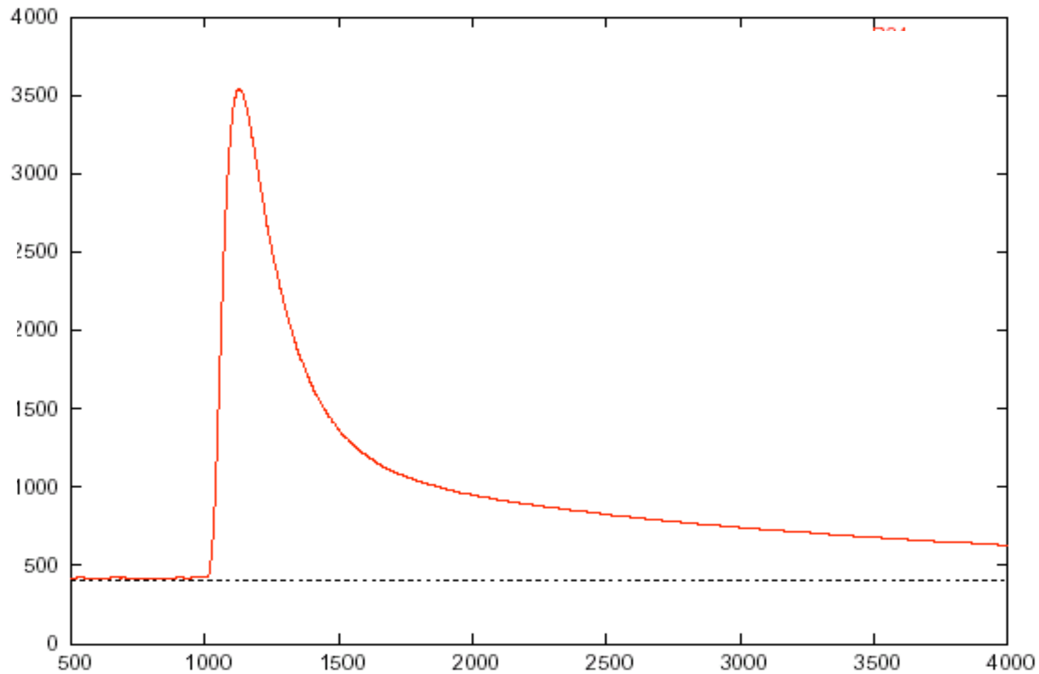
TeO_2 Bolometer: Source = Detector

Heat sink: ~8 mK
Thermal coupling: Teflon
Thermometer: NTD Ge thermistor
Absorber: TeO_2 crystal



Output Signal

Voltage
(Channel
Number)

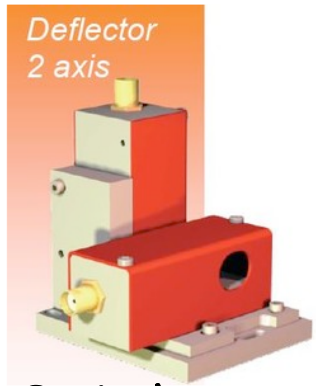


Time
(msec)

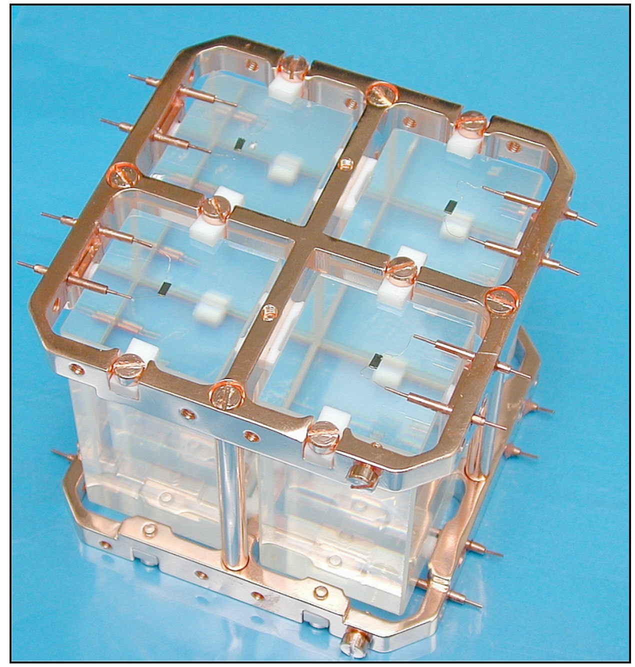
Why ^{130}Te is a good choice for CUORE

TeO_2 Crystals Used in Electro-Optical Components

High-end Laser Printers



Optical Modulators



Natural isotope abundance: **33.8%**

- No enrichment required

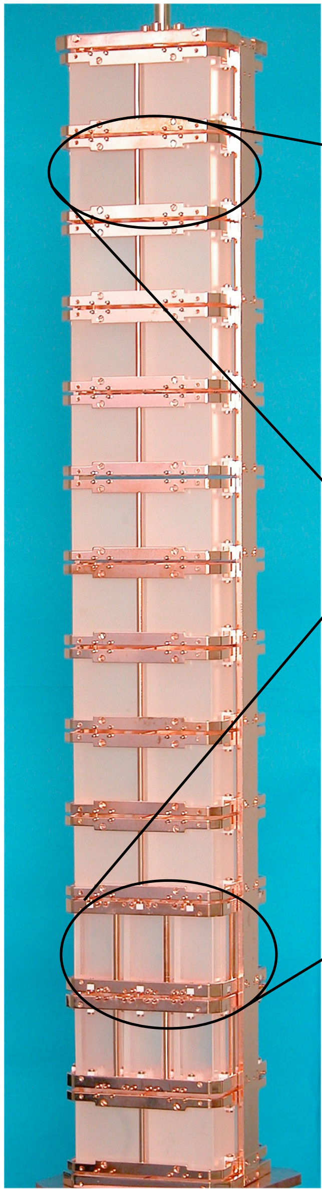
Q = 2530.0 ± 2.0 *keV*

- Large phase space, above most γ's from U and Th
- ^{232}Th Compton edge (2360 *keV*); Total absorption (2615 *keV*)

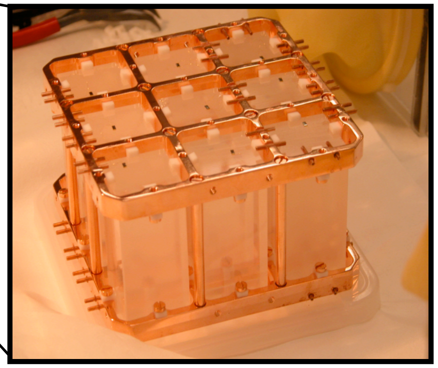
Extensive Developments with TeO_2 Bolometers

Geo-chemical measurements: $T^{2\nu\beta\beta}_{1/2} = (0.7 - 2.7) \times 10^{21}\ y$

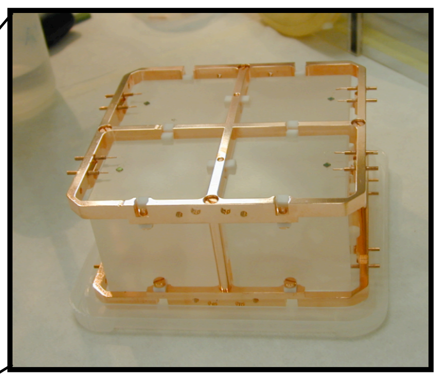
Cuoricino



Total detector mass: 40.7 *Kg* ⇒ **11.64 *Kg*** ^{130}**Te**

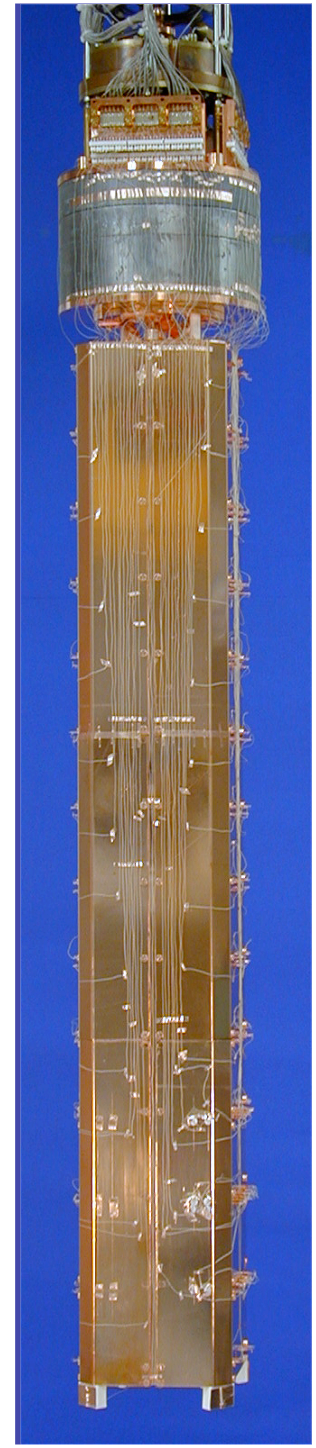


11 modules, 4 detector each
crystal dimension: **5x5x5 cm^3**
crystal mass: **790 *g***
44 x 0.79 = **34.76 *Kg* of TeO_2**



2 modules x 9 crystals each
crystal dimension: **3x3x6 *cm*^{3}**
crystal mass: **330 *g***
9 x 2 x 0.33 = **5.94 *Kg* of TeO_2**
(2 enriched in ^{128}Te @82.3%)
(2 enriched in ^{130}Te @75%)

Running since 2003



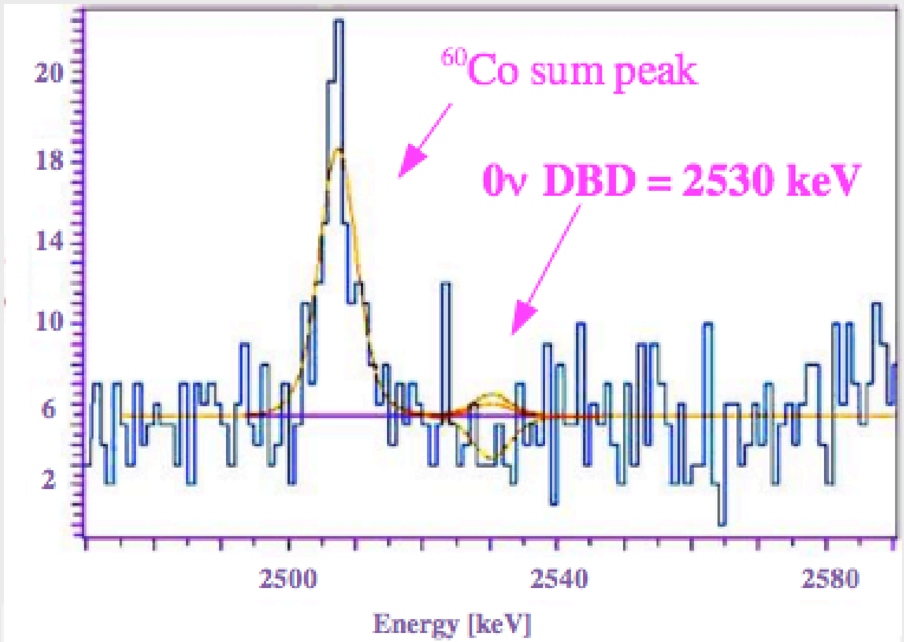
COURICINO Results

Total Exposure: **8.38 kg-y of ^{130}Te**
BKG: **0.18 ± 0.01 cnts/(keV-kg-y)**
FWHM at 2615 keV: **~ 8 keV**

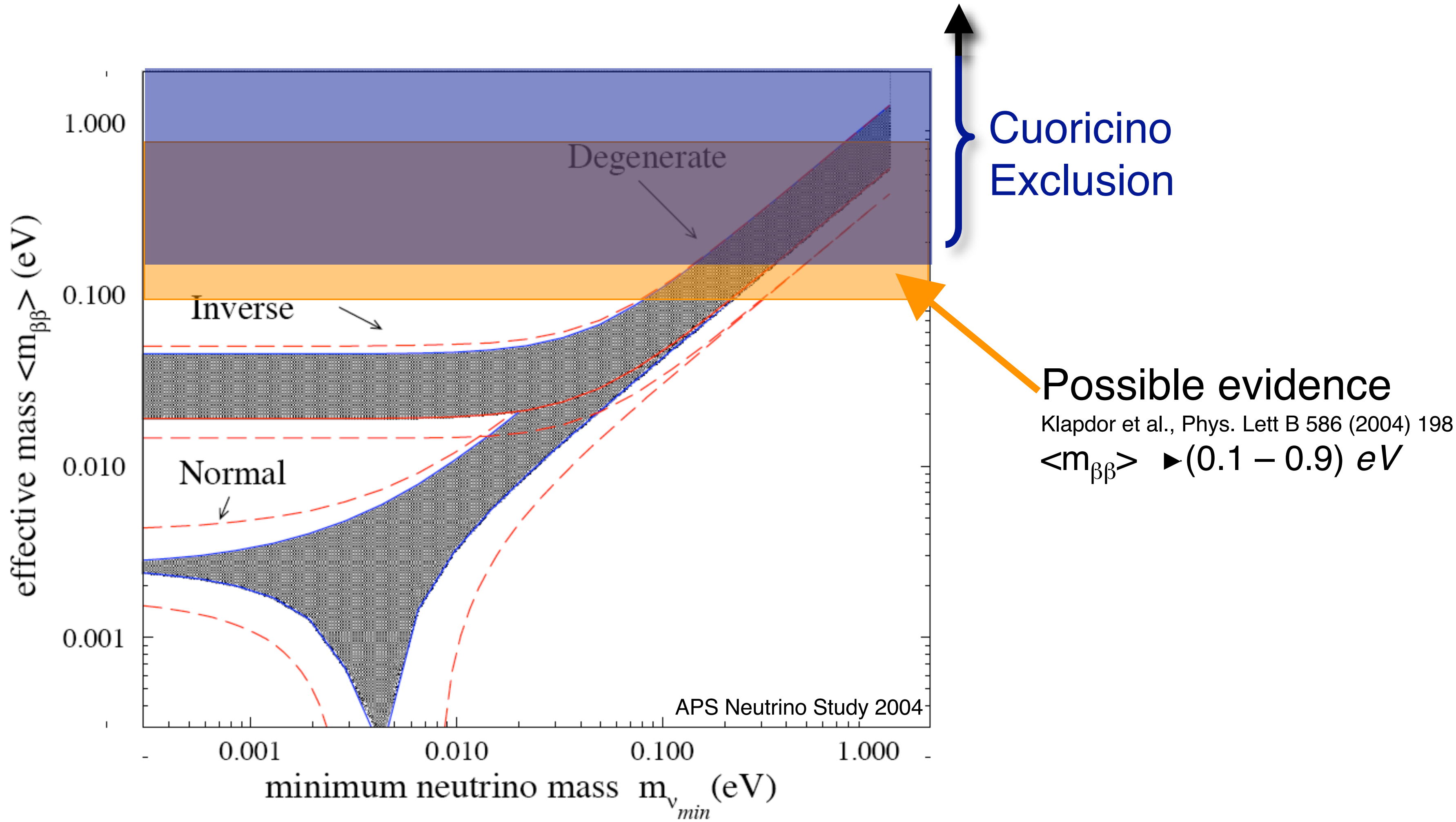
0ν –DBD result

$\tau_{1/2} > 2.4\ 10^{24}$ [y]
@ 90% C.L.

April 2003 - May 2006



Status of 0νββ



Scaling to higher sensitivity

Figure of Merit

$$\left[T_{1/2}^{0\nu}\right]^{-1} = \frac{\left|\langle m_\nu \rangle\right|^2}{m_e^2} F_N$$

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

Isotopic fraction

Detector efficiency

Detector Mass

Running time

Atomic mass

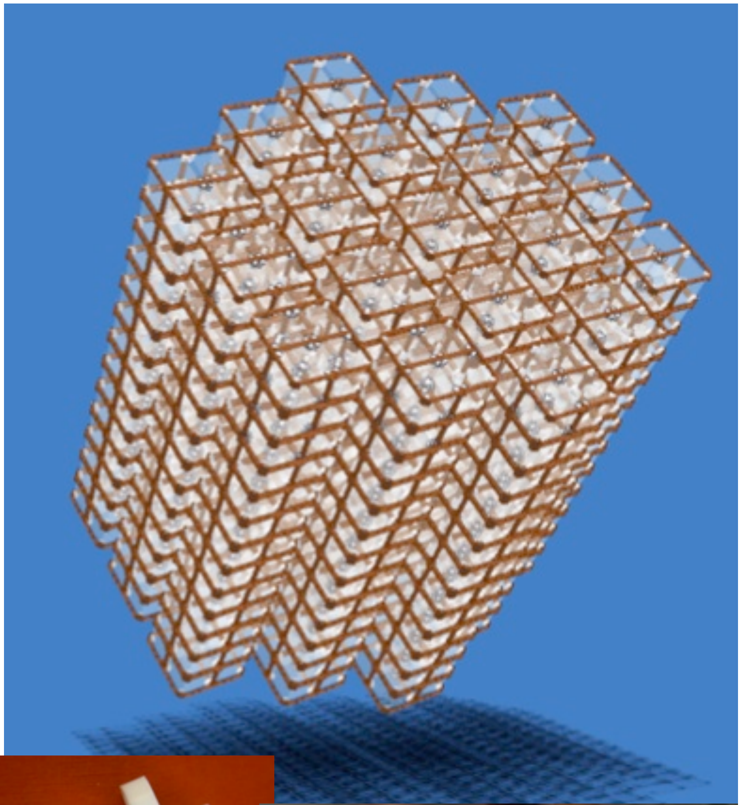
Background

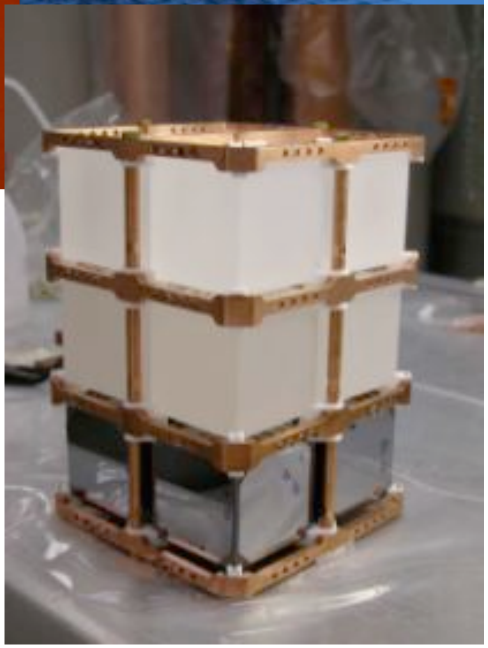
Detector resolution

CUORE

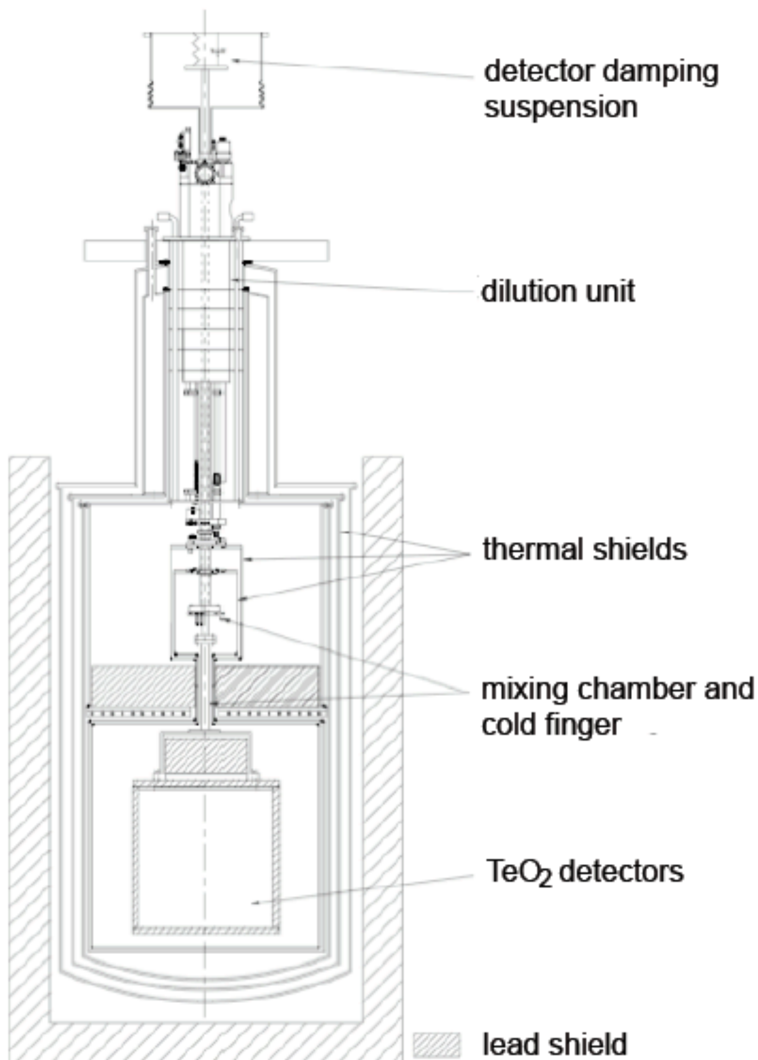
Array of 988 TeO_2 crystals

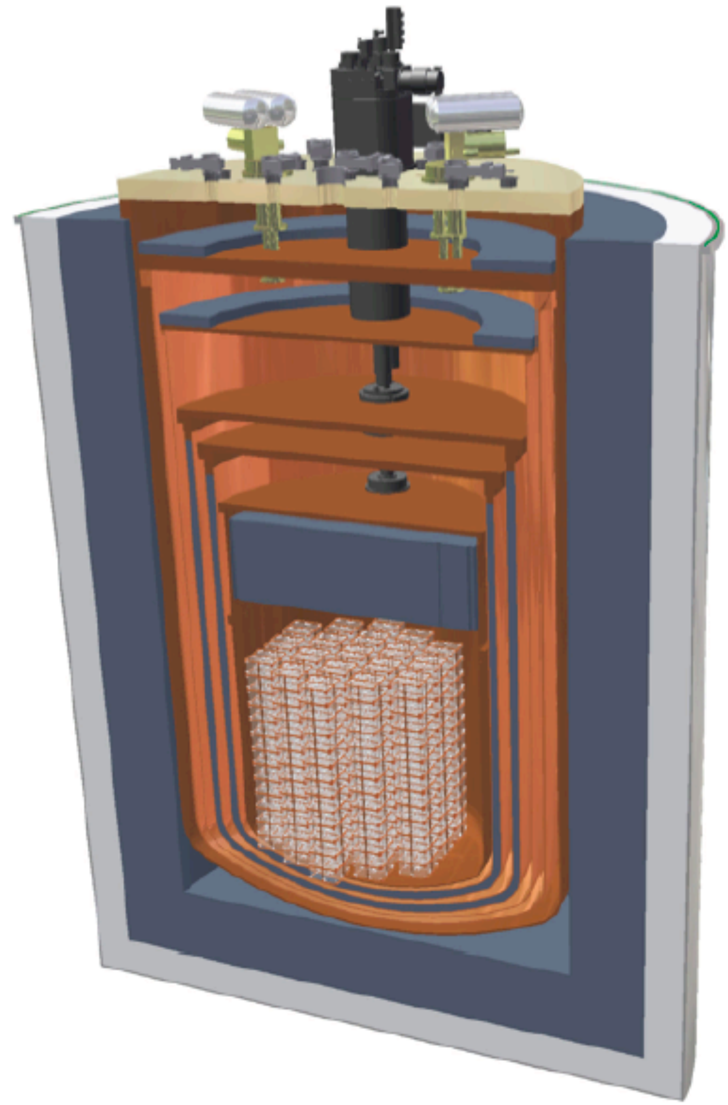
- **19** Cuoricino-like "towers"
- **13** levels, **4** crystals each
- $5x5x5\ cm^3$ (750 *g* each)
- Low conductance Teflon insulators
- OFHC Cu structure
- Crystals equipped with NTDs
- Suspended from cold stage
- Mechanically isolated





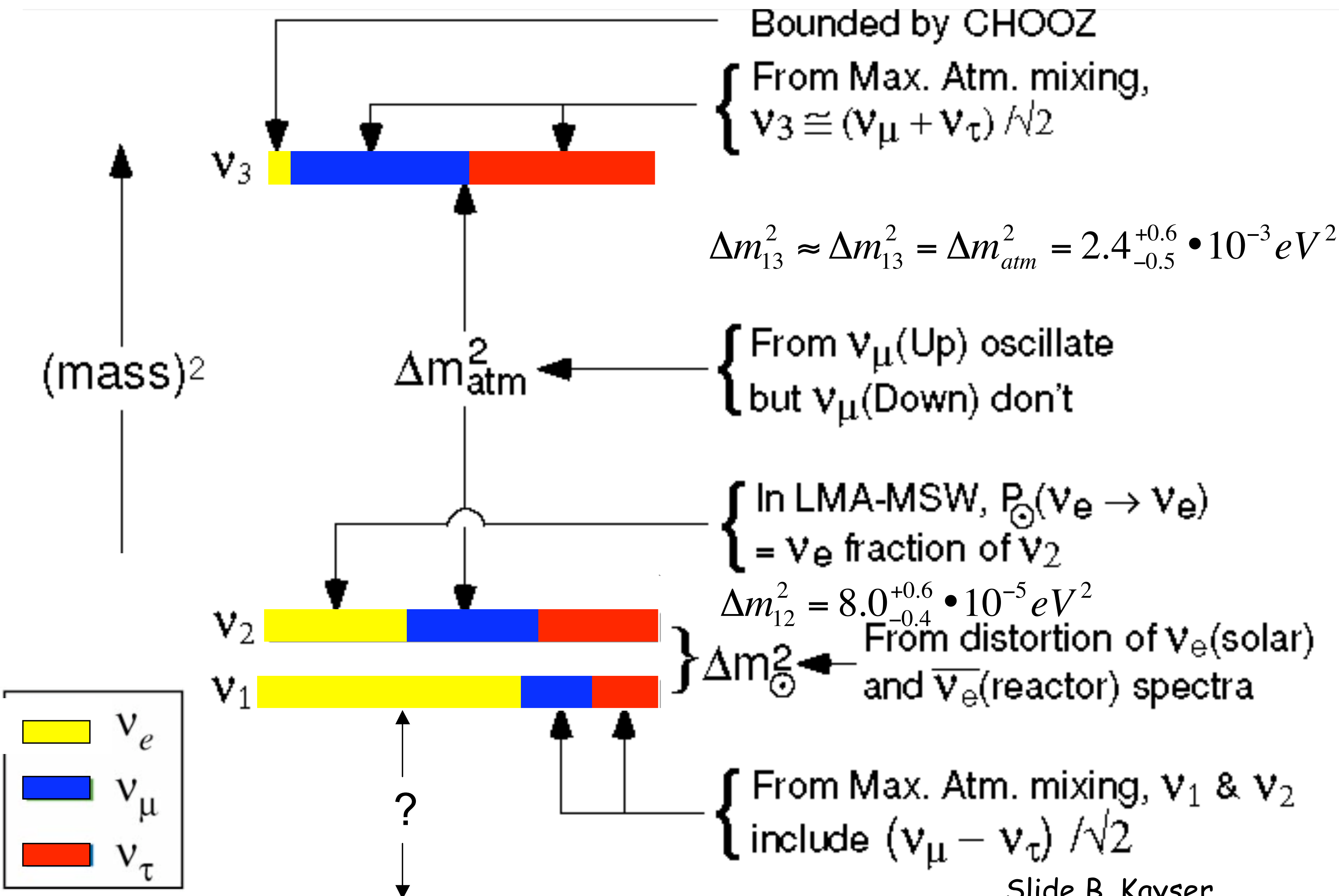
Cuore Cryogenics



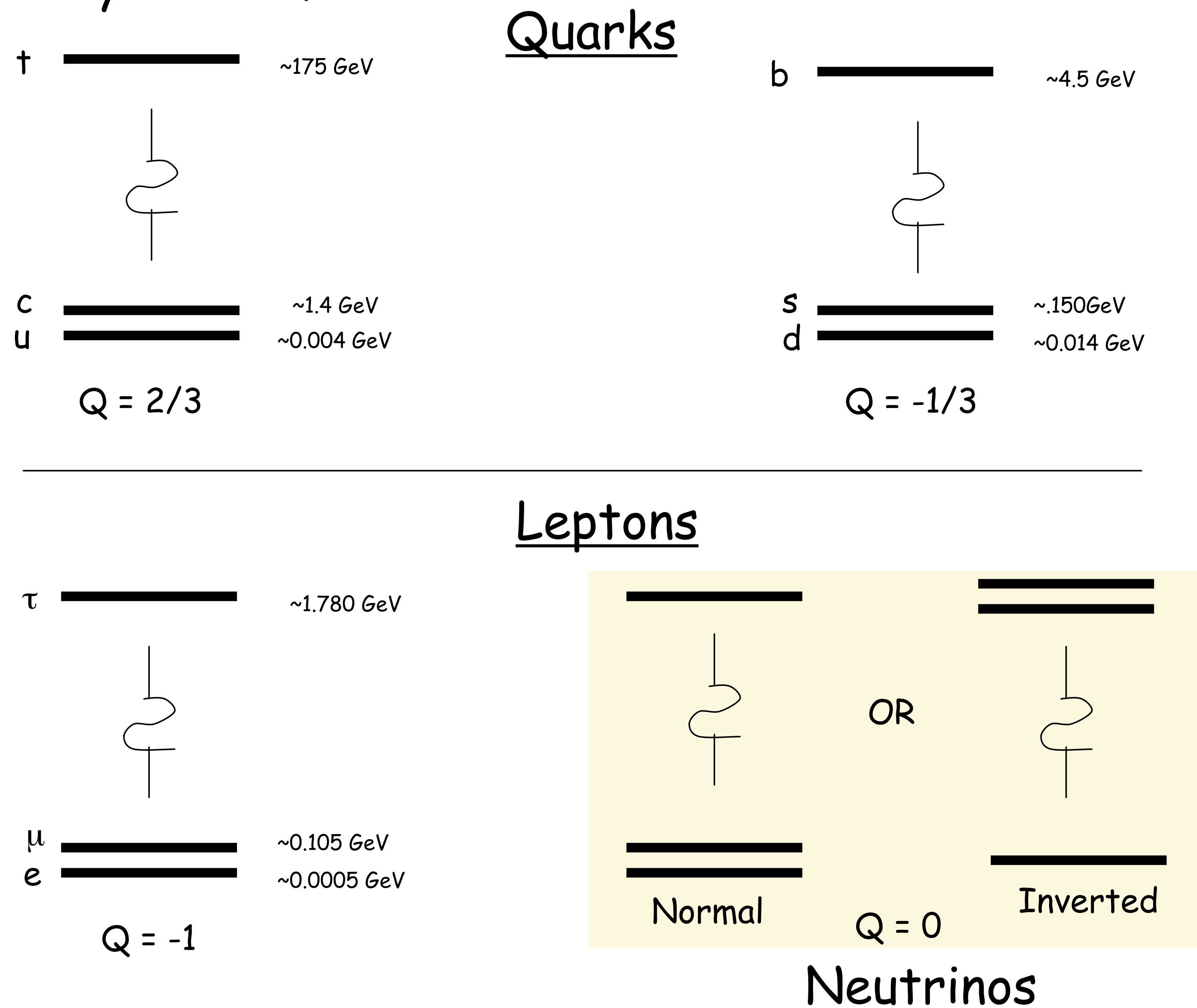


Leiden 3.0 mW at 120 m°K

Summary


Bounded by CHOOZ
From Max. Atm. mixing,
$\nu_3 \cong (\nu_\mu + \nu_\tau)/\sqrt{2}$
ν_3
$\Delta m^2_{13} \approx \Delta m^2_{13} = \Delta m^2_{atm} = 2.4^{+0.6}_{-0.5} \bullet 10^{-3} eV^2$
(mass)^2
Δm^2_{atm}
From ν_μ(Up) oscillate
but ν_μ(Down) don't
In LMA-MSW, $P_\odot(\nu_e \to \nu_e)$
$= \nu_e$ fraction of ν_2
$\Delta m^2_{12} = 8.0^{+0.6}_{-0.4} \bullet 10^{-5} eV^2$
ν_2
ν_1
$\Delta m^2_\odot$
From distortion of ν_e(solar)
and $\overline{\nu_e}$(reactor) spectra
ν_e
ν_μ
ν_τ
?
From Max. Atm. mixing, ν_1 & ν_2
include $(\nu_\mu - \nu_\tau)/\sqrt{2}$
Slide B. Kayser

Hierarchy Problem:



Neutrino mixing matrix

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

$$= \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}} \times \underbrace{\begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta_{CP}} \sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\delta_{CP}} \sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix}} \times \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}} \times \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & e^{i\alpha/2} & 0 \\ 0 & 0 & e^{i\alpha/2+i\beta} \end{pmatrix}}$$

$\theta_{23} = (45 \pm 7)°$

$\theta_{13} < 13°$

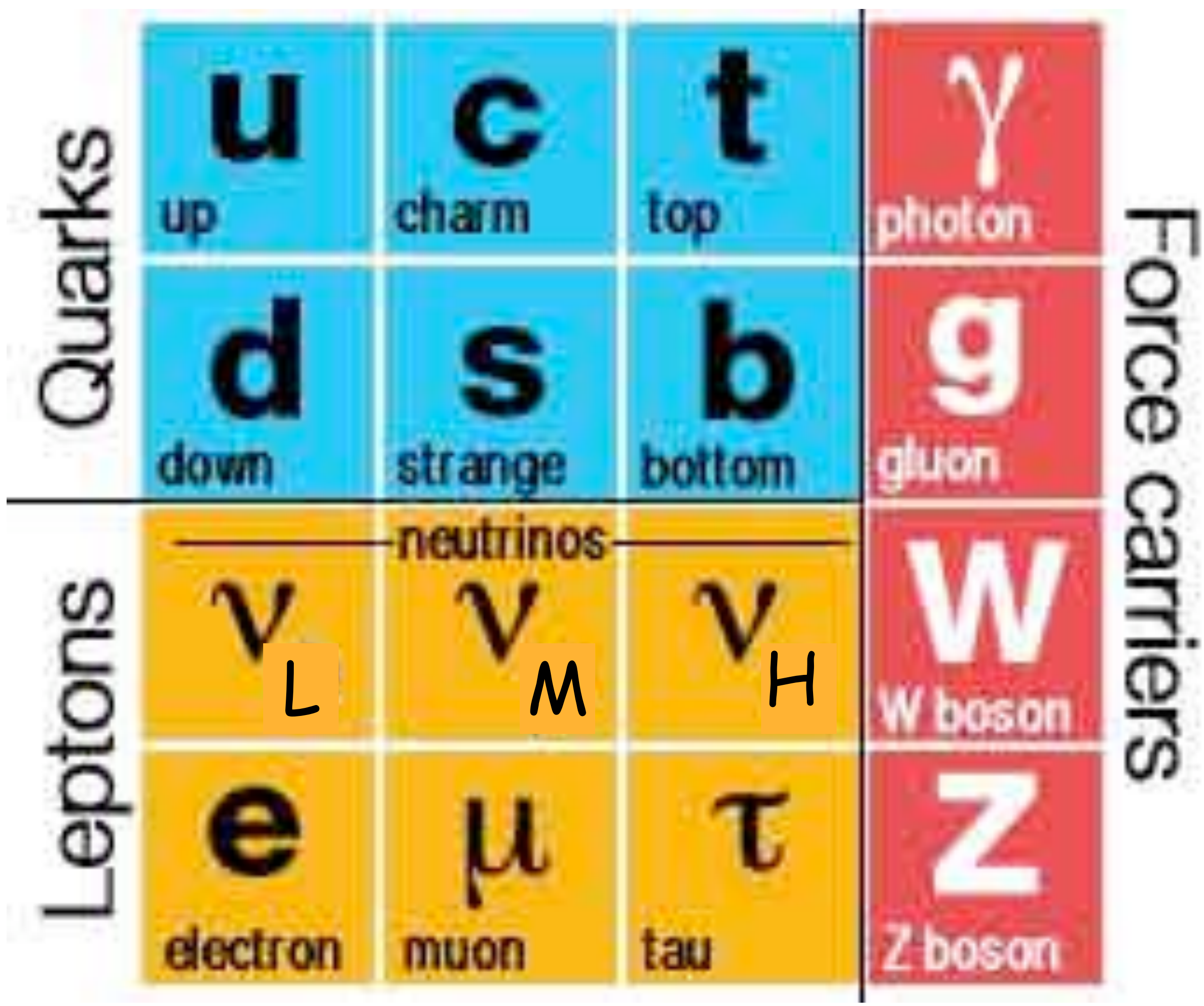
$\delta = ?$

$\theta_{12} = (33.9^{+2.4}_{-2.2})°$

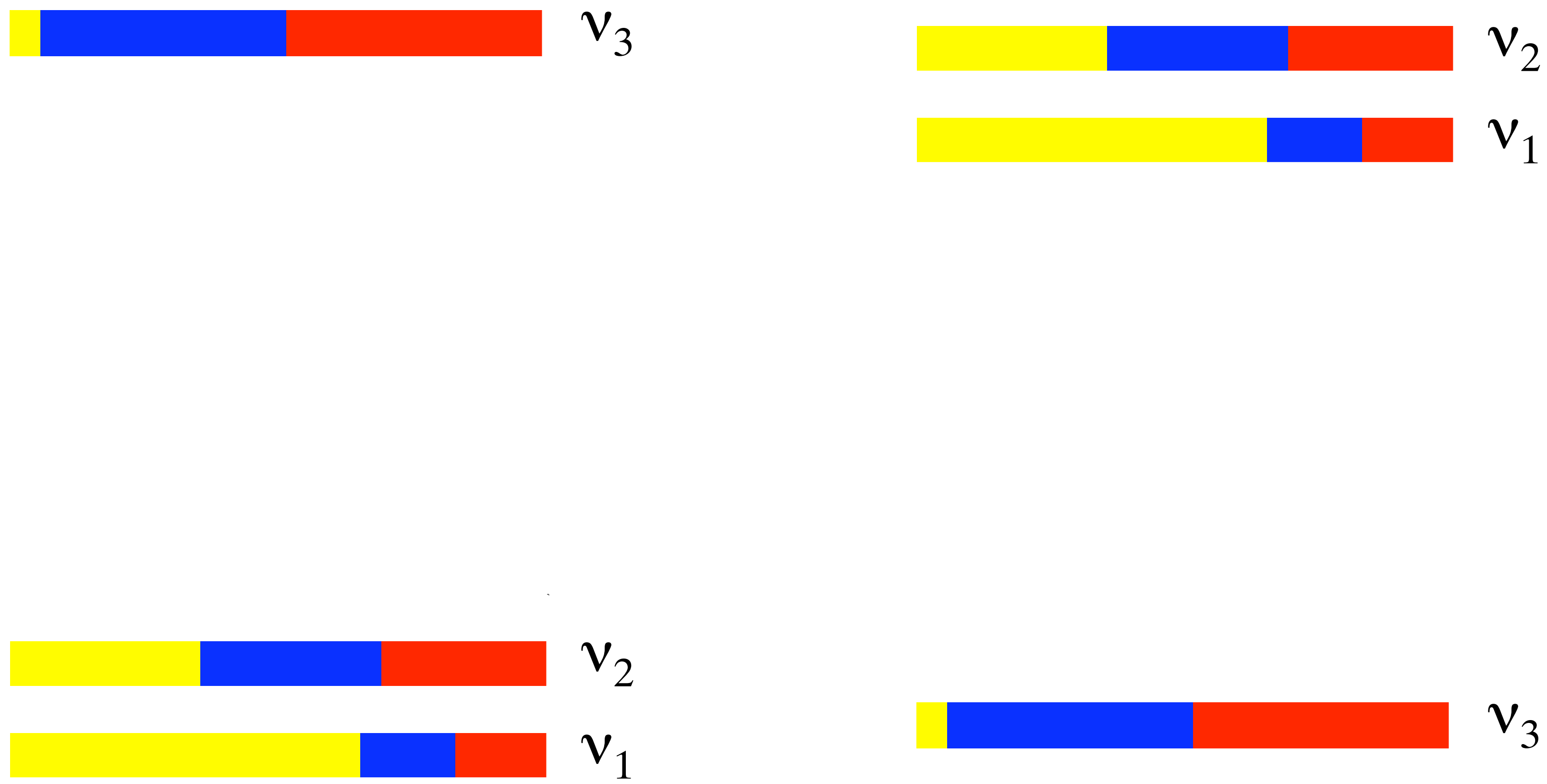
$\alpha = ?$

$\beta = ?$

The Standard Model of Quarks and Leptons



Normal *Inverted*



$\nu_1 = \nu_L$

ν_L has little to do with ν_e !

Long baseline:

~~Normal~~

~~Inverted~~