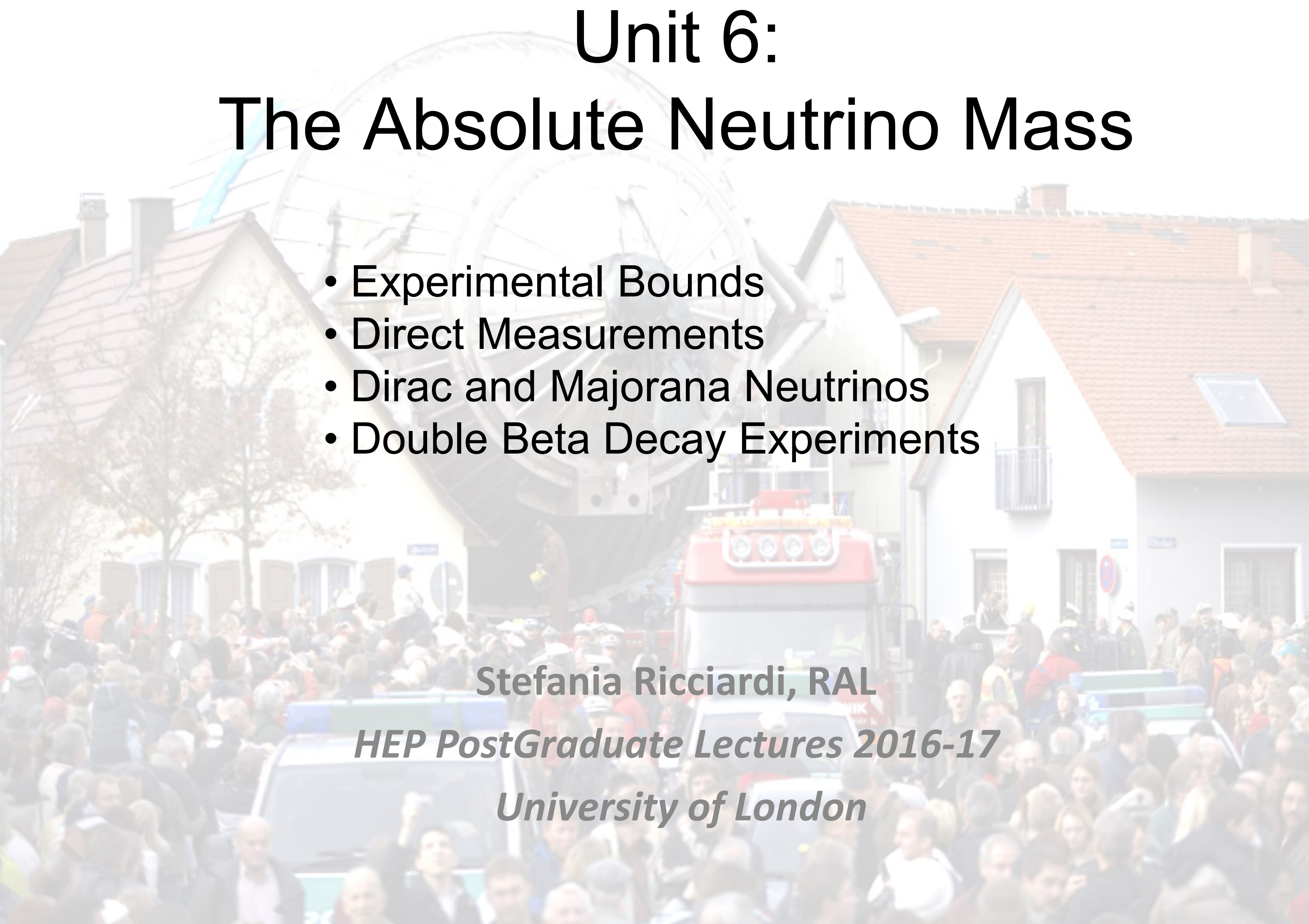


Unit 6:
The Absolute Neutrino Mass

- Experimental Bounds
- Direct Measurements
- Dirac and Majorana Neutrinos
- Double Beta Decay Experiments

Stefania Ricciardi, RAL

HEP PostGraduate Lectures 2016-17

University of London

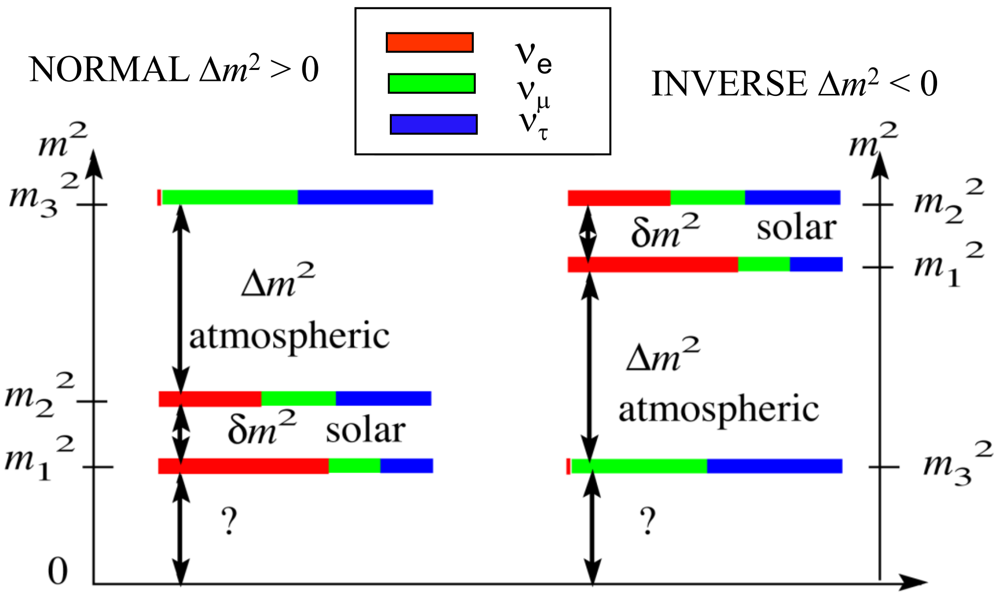
What we have learnt from mixing: neutrino mass lower bound

- Weak eigenstates ν_e, ν_μ, ν_τ superposition of mass eigenstates ν_1, ν_2, ν_3 numbered in increasing order of ν_e content, given by $|U_{ei}|^2$ (shown in red in figure)

$\nu_1 \sim 70\%\ \nu_e$, $\nu_2 \sim 30\%\ \nu_e$, $\nu_3 \sim 2.5\%\ \nu_e$

  - What is the absolute value of neutrino masses?

Neutrino oscillation experiments can measure only mass differences.
However note that $\Delta m^2_{atm} \sim 2.5\ 10^{-3}\ eV^2$
$\Rightarrow$ at least one neutrino with mass > $\sqrt{\Delta m^2_{23}} \sim 50$ meV
Is it m_2 or m_3? Depends on the mass hierarchy!



$\Delta m^2_{sol} = 8 \times 10^{-5}\ eV^2$
$\Delta m^2_{sol} \sim \Delta m_{12}^2 = m_2^2 - m_1^2 > 0$

$\Delta m^2_{atm} = 2.5 \times 10^{-3} eV^2$
$\Delta m^2_{atm} \sim |m_3^2 - m_2^2| \sim |m_3^2 - m_1^2|$

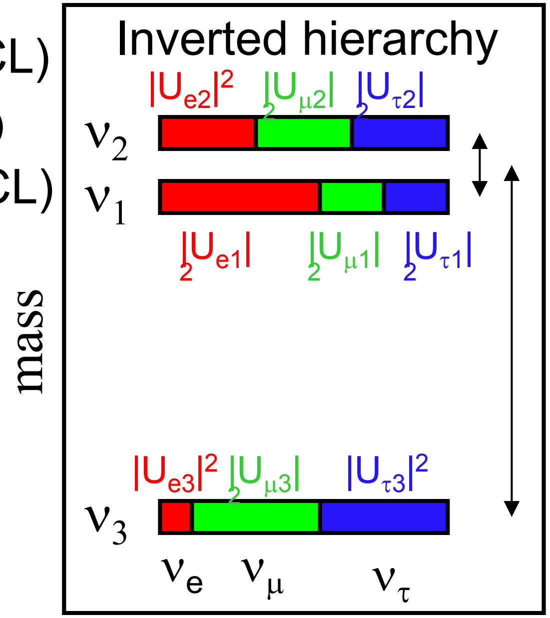
Understanding the mass “hierarchy”

Direct **upper bounds** on neutrino mass:

$m_{\nu e} < 2$ eV from β-decay (95%CL)

$m_{\nu\mu} < 0.19$ MeV from $\pi \to \mu\, \nu$ (90% CL)

$m_{\nu\tau} < 18.2$ MeV from τ decays (95%CL)

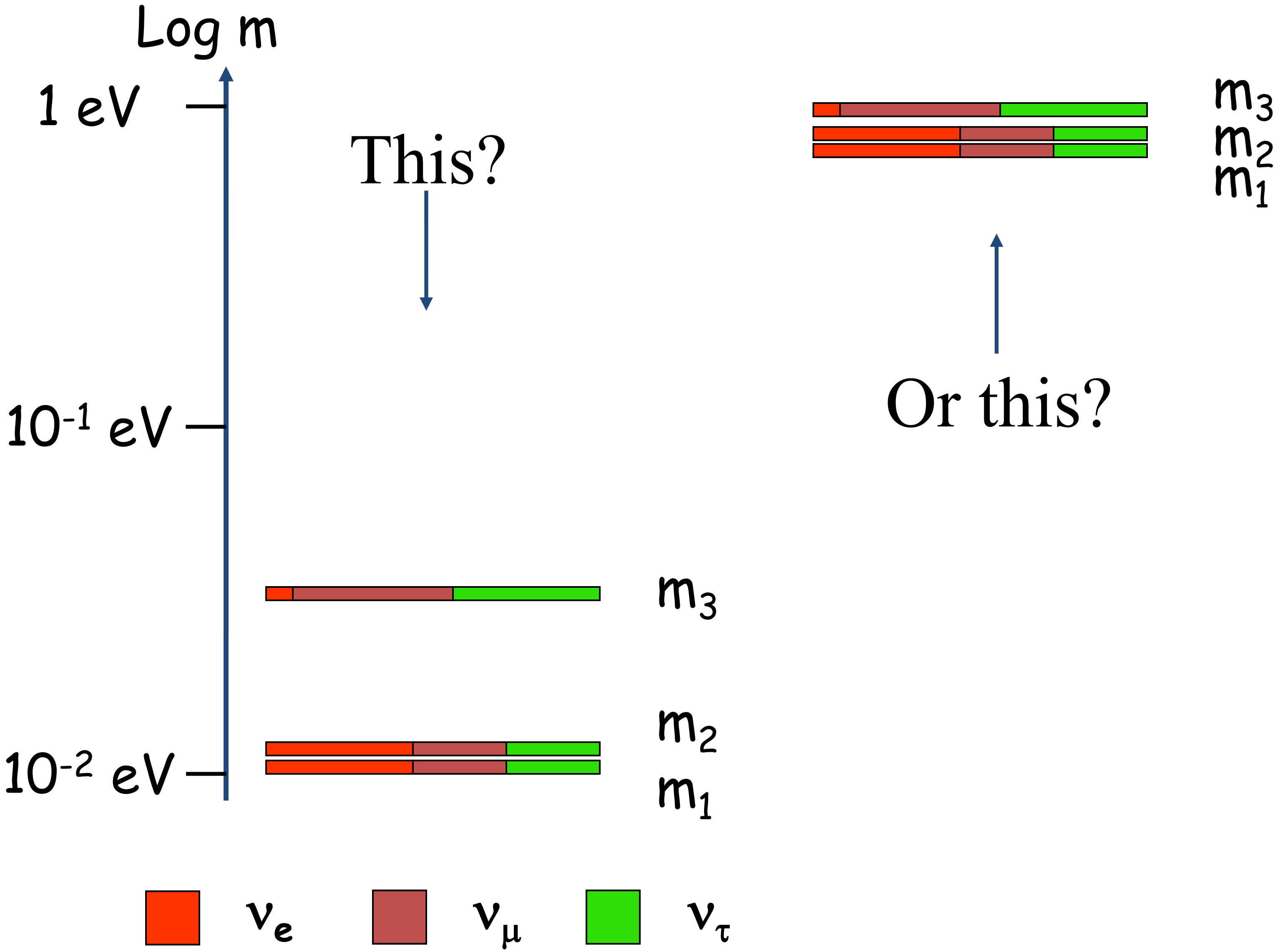


We know now that flavor eigenstates do not coincide with mass eigenstates, so these are bounds on the “effective” mass:

$$m^2_{\text{eff}}(\nu_\alpha) = \Sigma_{\,i=1,3}\, |\, U_{\alpha i}|^2\, m^2(\nu_i)$$

If the mass hierarchy is “inverted” ν_e is effectively heavier than ν_μ and ν_τ !

Even more significant is the absolute scale.


This?

Or this?

Cosmological upper bound on mass

Cosmology Data (Cosmic Microwave Background, Planck)

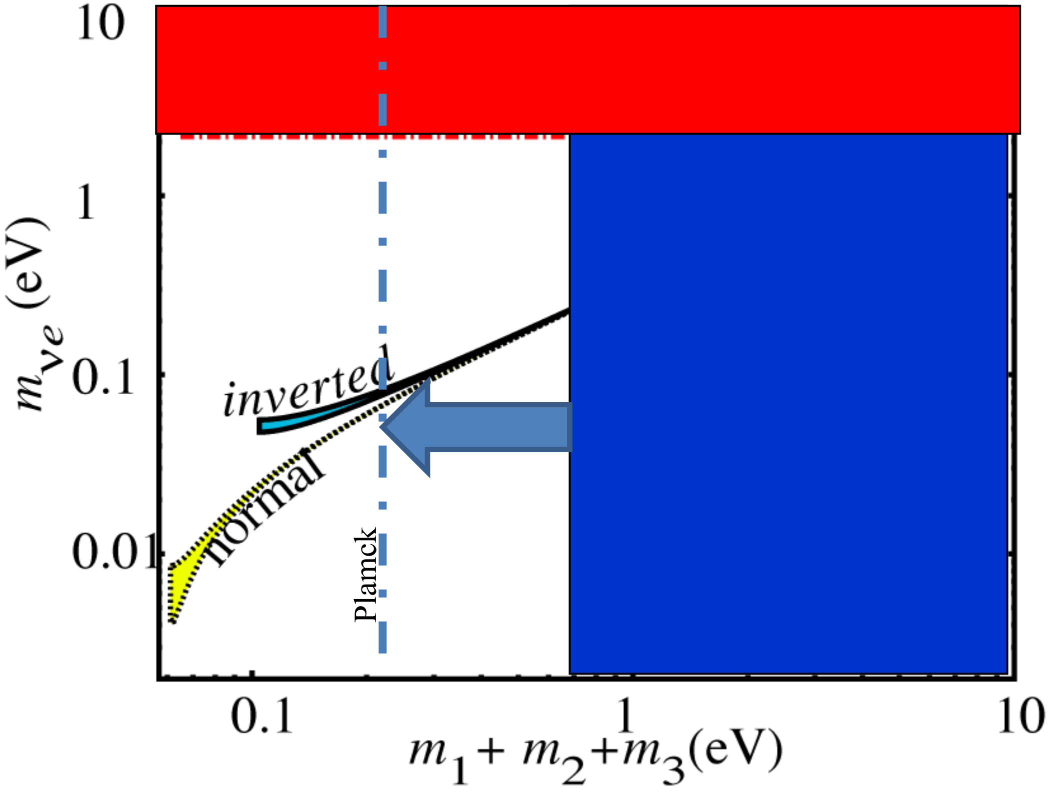
$\Sigma\, m_i < 0.23$ eV @ 95% CL (the bound applies to "light" neutrinos only)

Massive neutrinos affect both the evolution of Universe and the growth of structures on small scales

In general: cosmological constraint much tighter than direct constraints but rely on theoretical models and important assumptions.
Systematic uncertainties hard to quantify.

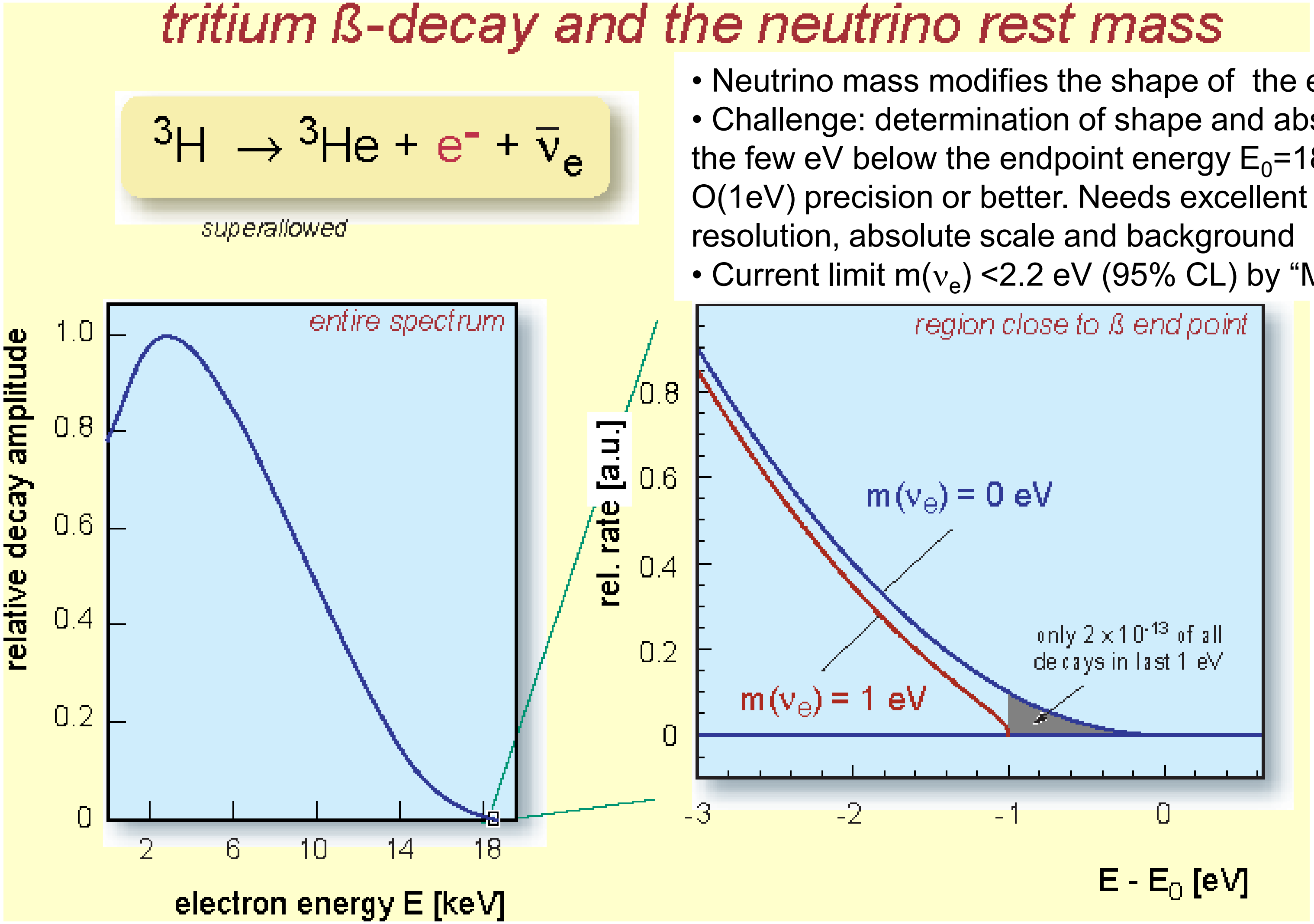
The upper bound would be somewhat worse if you also allowed, for example, the curvature of the universe to vary, and/or the dark energy equation of state, and/or including e.g. an axion component. Perhaps with current data that error would go up by around a factor 2.
[Jo Dunkley, private communication]

For a recent discussion see
PhysRevD.90.063516



Direct Mass Measurement in β decay

- Neutrino mass modifies the shape of the electron spectrum.
- Challenge: determination of shape and absolute energy in the few eV below the endpoint energy E_0=18.57 keV with O(1eV) precision or better. Needs excellent control of resolution, absolute scale and background
- Current limit $m(\nu_e)$ <2.2 eV (95% CL) by “Mainz” experiment

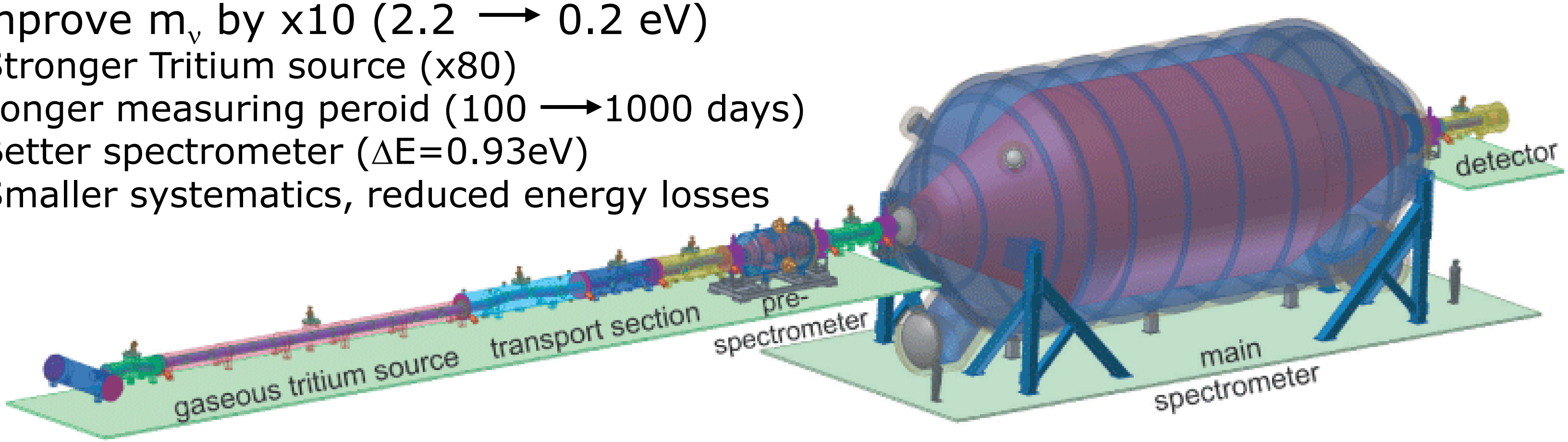


The KATRIN Experiment

(**KA**rlsruhe **TRI**tium **N**eutrino experiment, location: Forschungszentrum Karlsruhe)

Improve m_ν by x10 (2.2 $\longrightarrow$ 0.2 eV)

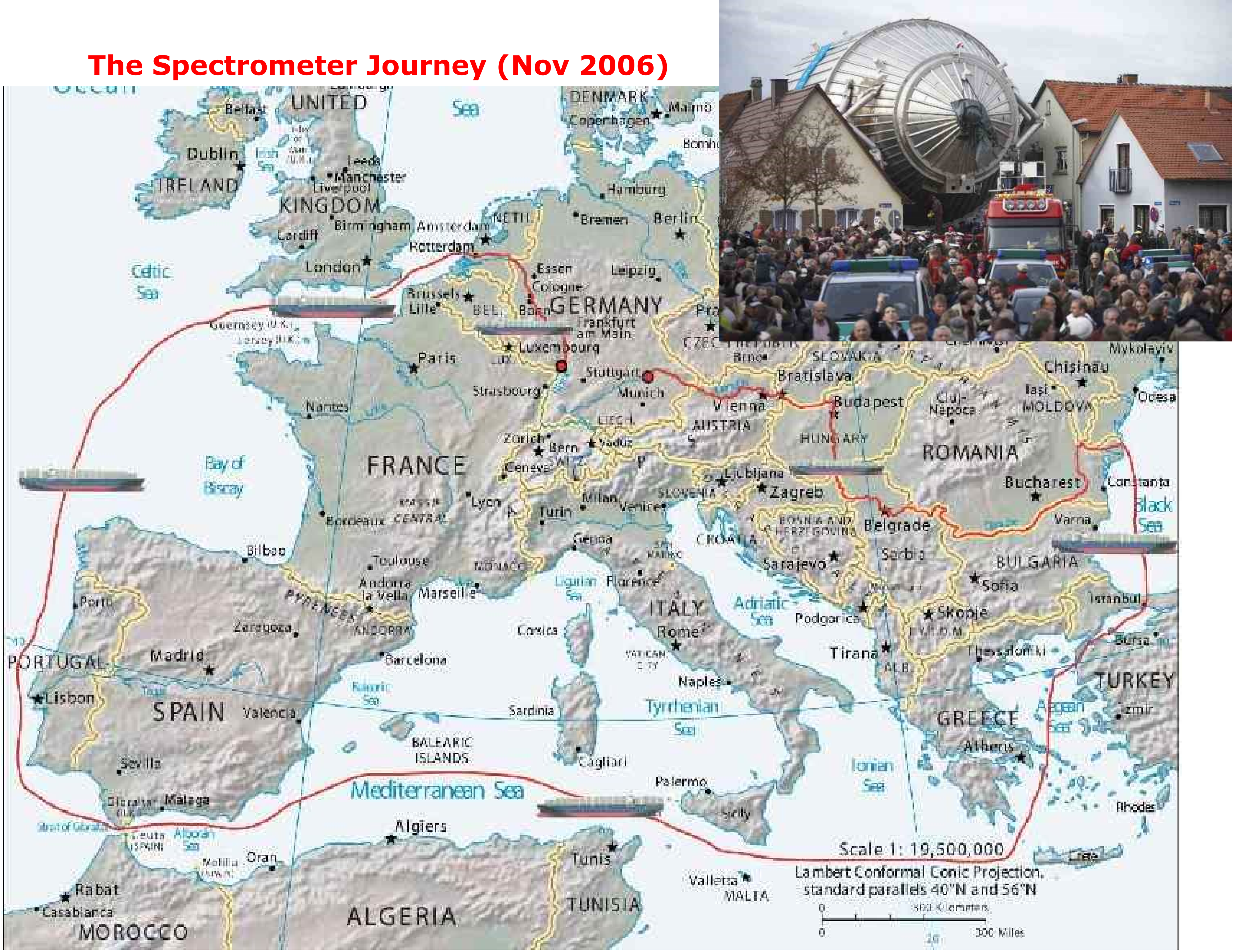
- Stronger Tritium source (x80)
- Longer measuring peroid (100 $\longrightarrow$ 1000 days)
- Better spectrometer ($\Delta E = 0.93$eV)
- Smaller systematics, reduced energy losses



- Katrin aim to improve upper bound by an order of magnitude (0.2 eV)
- Based on special type of spectrometer: MAC-E-Filters (Magnetic Adiabatic Collimation combined with an Electrostatic Filter)
- A pre-spectrometer is required to remove all electrons but a fraction of 10^{-7} at the highest energies (to minimize the background due to trapped electrons)
- The detector at the end counts electrons. High energy and position resolution to suppress the background. Semiconductor technology employed.

First tritium data in 2017

The Spectrometer Journey (Nov 2006)

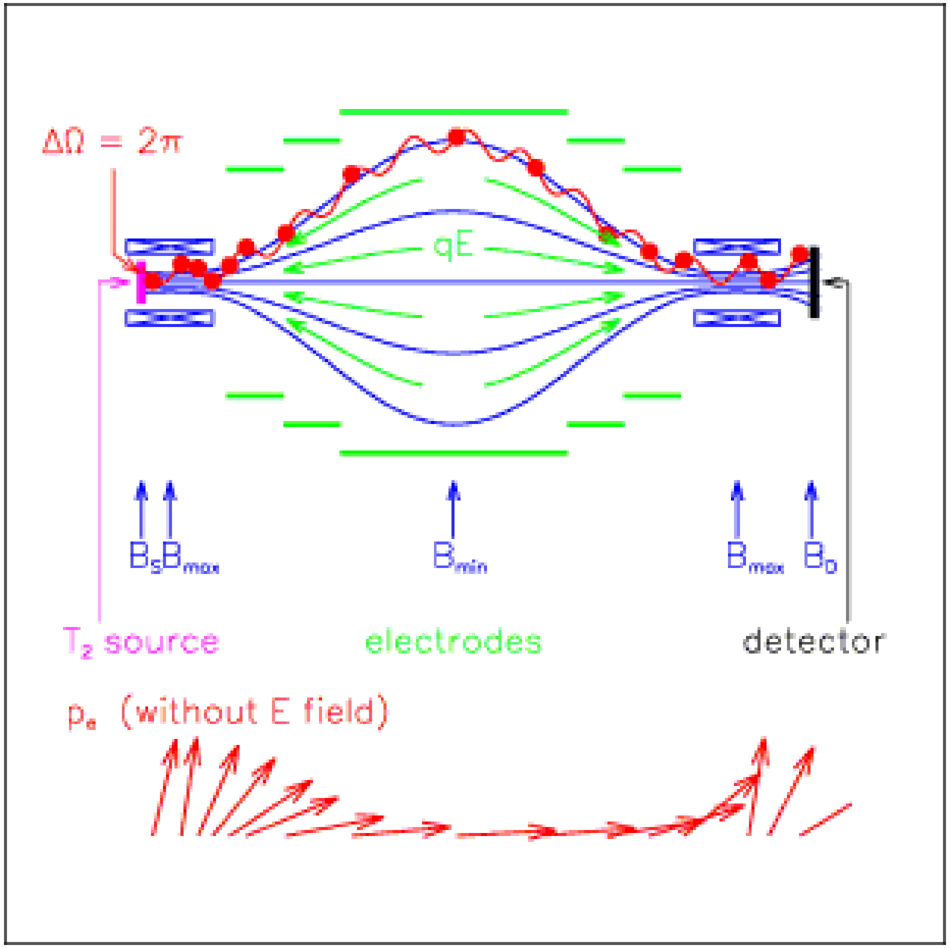


MAC-E Filter

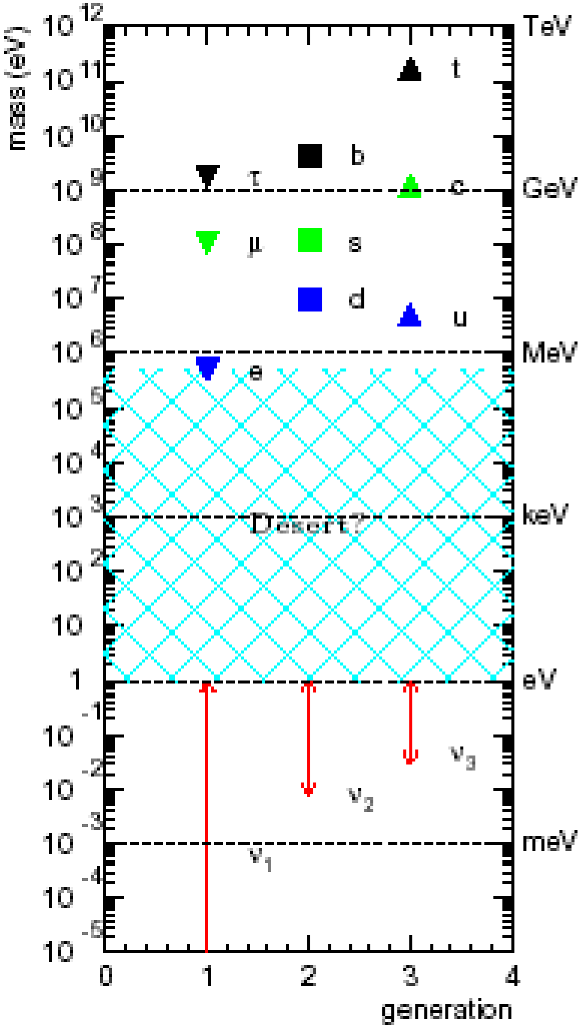
- The spectrometer acts as an integrating high-energy pass filter with a resolution $\Delta E/E = B_{min}/B_{max}$

Principle:

- Two superconducting solenoids
- Electrons guided magnetically on a cyclotron motion around the magnetic field lines into the spectrometer
- In the center the magnetic field drops. Cyclotron motion transformed adiabatically into longitudinal motion.
- Electrons isotropically emitted at the source transformed in a broad beam of electrons flying almost parallel to field lines and run against an electrostatic potential formed by a system of cylindrical electrods
- Only electrons with enough energy to pass the electrostatic barrier are reaccelerated and collimated onto a detector.
- Varying the electrostatic retarding potential allows to measure the beta spectrum in an integrating mode.



Neutrino mass:
physics beyond the SM



- The Big Question: Why are neutrinos so much lighter than other fermions?
- Majorana neutrinos and See-Saw Mechanism introduced in extensions of the Standard Model provide an answer

Dirac and Majorana neutrino

Is the neutrino its own antiparticle? If so, neutrinos are Majorana particles (from Ettore Majorana who first introduced the idea in 1937)

- Charged particles cannot coincide with anti-particle (ex electron different from positron). Different electric charge (which is conserved)
- Neutron is different from anti-neutron (different baryonic number)
- π^0 is a boson and is its own antiparticle!

Lesson: particle/anti particle distinction corresponds to a symmetry of the theory or, in other words, some conserved quantum number

If neutrinos (L = -1) are Dirac particles they are distinct from their anti-particle (L = 1) and leptonic number is conserved

If neutrinos are Majorana particles

$$\nu = \nu^C$$

and leptonic number is violated.

In experimental terms: if, for a given momentum and helicity, neutrinos and anti-neutrinos have identical interactions with matter, neutrinos are Majorana particles.

Why we do not know if $\nu=\bar{\nu}$

- Available neutrinos are always polarised: we observe only left-handed neutrinos and right-handed anti-neutrinos, as a result we are not able to compare the interaction with matter of neutrinos and antineutrinos of the same helicity. Is the different interaction due to different polarisation or real distinction between neutrinos and anti-neutrinos?
- Ex: $\pi^+ \rightarrow \mu^+ \nu_\mu$ produces a left-handed neutral particle

$\nu_\mu N \rightarrow \mu^- X$ Observed

$\nu_\mu N \rightarrow \mu^+ X$ NOT Observed

$\pi^- \rightarrow \mu^- \bar{\nu}_\mu$ produces a right-handed neutral particle

$\bar{\nu}_\mu N \rightarrow \mu^- X$ NOT Observed

$\bar{\nu}_\mu N \rightarrow \mu^+ X$ Observed

is ν_μ different from $\bar{\nu}_\mu$ or is the different charge of the lepton produced in the two cases due to the different polarization?

To distinguish the two cases we should reverse the helicity (how? For example boost to a frame which moves faster than neutrino), which is not possible if neutrino is massless $\Rightarrow$ For massless neutrinos the distinction between Majorana and Dirac disappears

Dirac neutrino mass

General mass term in the Lagrangian for field ψ

$m\psi\overline{\psi}$ where $\overline{\psi} = \psi^{+}\gamma^{0}$

given $\psi_{L,R} = \frac{1}{2}(1 \mp \gamma^{5})\,\psi$

$\overline{\psi}_{L,R} = \frac{1}{2}\,\overline{\psi}\,(1 \pm \gamma^{5})$

$\overline{\psi}\psi = \overline{\psi}_{L}\,\psi_{R} + \overline{\psi}_{R}\,\psi_{L}$

$\Rightarrow$ In order to introduce a DIRAC mass term we need right-handed neutrinos and left-handed antineutrinos (which in the Standard Model are absent) . So if neutrinos are massive DIRAC particles there must be 4 different states (2 X HELICITY)

Within the simplest extension of the SM (no changes in the Higgs sector) neutrino mass would be given by $m_{\nu} = g_{\nu}\, v / \sqrt{2}$

in analogy with electron mass, $m_{e} = g_{e}\, v / \sqrt{2}$ where $\langle h^{0} \rangle = v / \sqrt{2}$

Small mass $g_{e} > 5 \times 10^{5}\, g_{\nu}$

Why would the relative couplings be so different?

Majorana mass terms

- If ν and $\bar{\nu}$ are different helicity states of the same particle

the most generic mass term in the Lagrangian can contain lepton number violating combinations

$$\begin{pmatrix} \bar{\phi} & \bar{\Phi} \end{pmatrix} \begin{pmatrix} M_L & m \\ m & M_R \end{pmatrix} \begin{pmatrix} \phi \\ \Phi \end{pmatrix}$$

with Majorana fields

$\phi \ =(\psi^c_L + \psi_L)/\sqrt{2}$

$\Phi =(\psi^c_R + \psi_R)/\sqrt{2}$

The off-diagonal elements *m* give rise to lepton-number conserving Dirac mass terms and the $M_{L,R}$ terms on the diagonal to lepton-number violating Majorana mass terms

In general for Majorana neutrino we will have both Dirac and Majorana mass terms in the Lagrangian

See-saw mechanism

- To enforce the gauge symmetry of the SM, it is required that $M_L=0$ (hep-ph/0310238). This is called Type I see-saw, where also M_R is very large and $m \approx$ mass charge lepton

$$\begin{pmatrix} 0 & m_\nu \\ m_\nu & M \end{pmatrix}$$

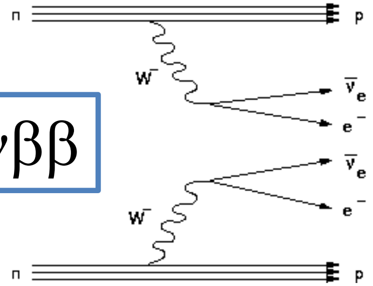
The diagonalization of this matrix gives rise to the mass eigenstates (2 for each neutrino flavour) :

$m_{light} \approx m_\nu^2 / M$ mostly LH

$m_{heavy} \approx M$ mostly RH and not observed because too massive

Double β Decay

2νββ

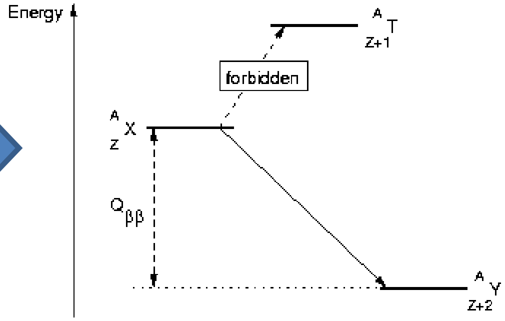


- **Double β decay**

  $(A,Z) \rightarrow (A,Z+2) + 2e^- + 2\bar{\nu}_e$

  Allowed in the SM

  observed for nuclei which do not undergo β decay (energetically forbidden)

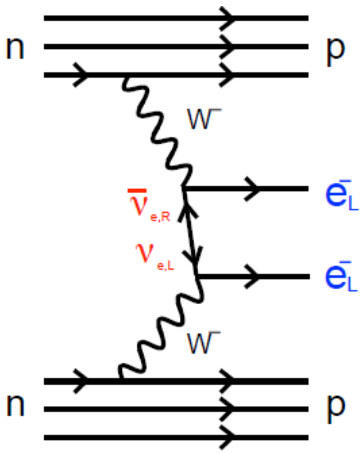


- **Neutrino-less double β decay**

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

  Hypothetical L violating process not allowed in the SM

0νββ



0νββ (in the hypothesis of neutrino exchange)

The emitted antineutrino does not have neither the correct helicity nor the correct leptonic number to be absorbed at the second vertex
Unless neutrinos are Majorana particles

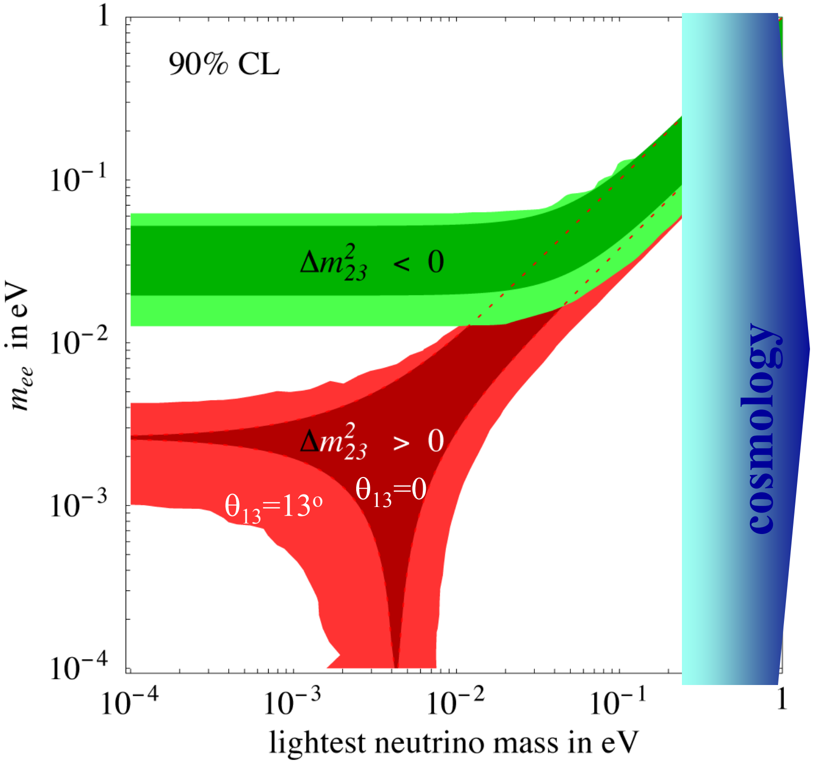
$$\begin{cases} m(\nu) \neq 0 \\ \nu = \bar{\nu} \end{cases}$$

since helicity has to flip

Decay rate and mass

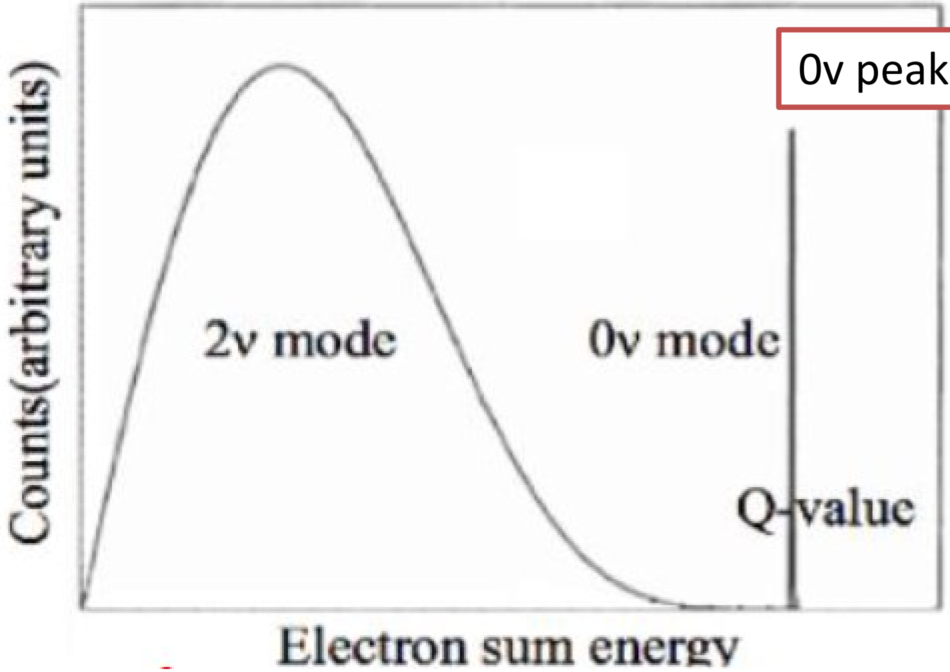
Decay rates are given by: $1/\tau = G(Q_{\beta\beta,Z})\ |M^{0\nu}|^2 <m_\nu>^2$

- $G(Q_{\beta\beta,Z})$ is the phase space integral
- $|M^{0\nu}|$ is the nuclear matrix element (known to factor 2 or 3, source of large uncertainties)
- $<m_\nu>^2 = |\Sigma\, U_{ei}^2\, m_i|^2$
  Note that the effective mass measured in 0ν decay (noted as m_{ee} in the y axis of the plot) is different from the effective mass measured in β decay
  $<m_\nu>^2 = \Sigma |U_{ei}|^2\, m_i^2$



Energy spectrum for 2β decays

- Sum of 2 electron energy allow to separate 0νββ and 2νββ
- Excellent energy resolution required (few keV at 1-2 MeV)
- Very Low background:
  - Underground lab
  - High radio-purity of all materials
  - background rejection in the signal reconstruction (shape analysis)
- Big source (O(100 Kg) now ; 1t in the future)



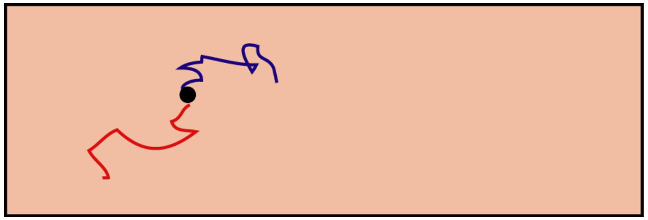
0ν peak width depends on detector resolution

2νββ is ultimate,
irreducible background

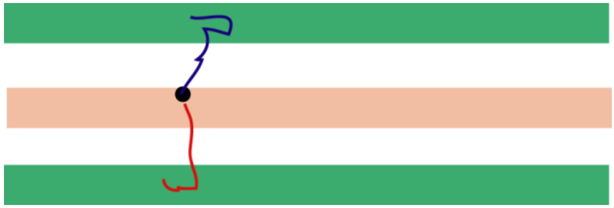
Double-β decay experiments

2 experimental approaches:

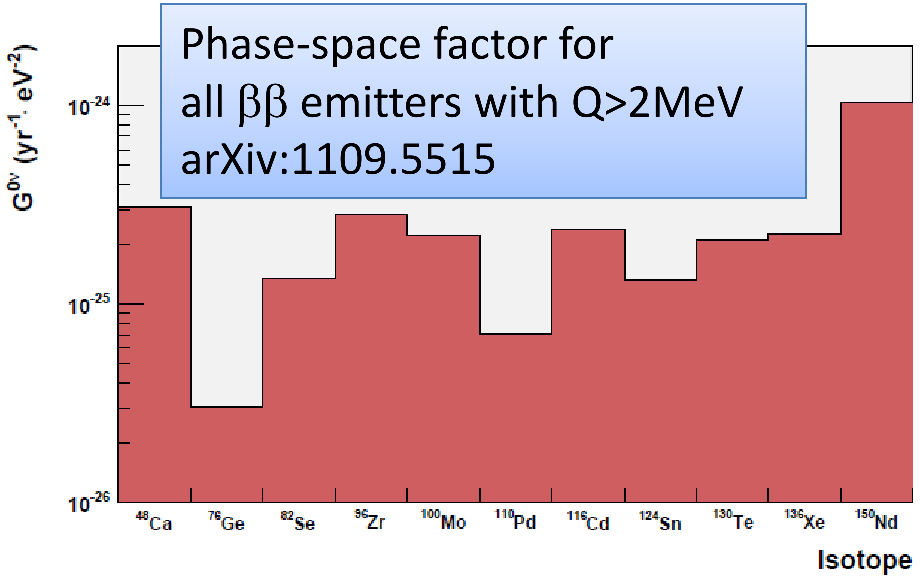
- Source = detector
  Bolometry and calorimetry
  - ✓ good energy resolution
  - ✓ large detector mass



- Source ≠ detector
  Tracking
  - ✓ good topological reconstruction
  - ✓ different isotopes as source allow to circumvent theoretical errors in nuclear matrix calculations



Choice of ββ isotope



Phase-space factor for
all ββ emitters with Q>2MeV
arXiv:1109.5515

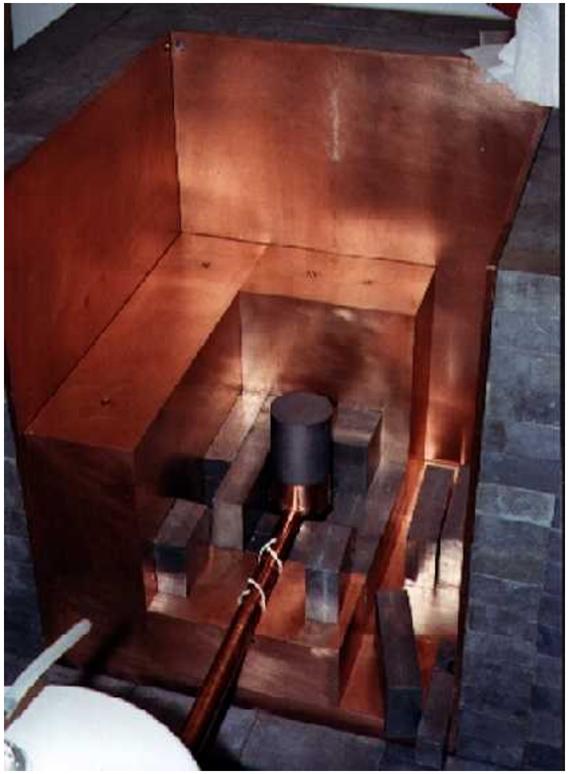
Phase-space $G^{0\nu} \propto Q^5$

⇒Considered only isotopes with Q>2MeV:
⇒Only 11

Other important considerations:
- background control (better above ~3MeV)
- ββ2ν decay rate (preferred slow decaying isotopes, intrinsic bkg)
- Well-understood nuclear physics

Germanium Experiments

- Why Germanium?
  - ^{76}Ge $2\nu2\beta$ decay
  - Excellent energy resolution of Ge semiconductor diodes
  - well-proven technology
- Longest running exp: Heidelberg-Moscow 13 years at Gran Sasso (1990-2003) used about 10 Kg (86% enriched) ^{76}Ge diodes



No $0\nu2\beta$ signal observed

$T_{1/2} > 1.9 \times 10^{25}$ yr (90% CL)

$\Rightarrow m_\nu < 0.4$ eV

H.V. Klapdor-Kleingrothaus et al,
Europ. Phys. J. A 12, 147 (2001)

eidelberg
oscow
Collabøration
at Gran Sasso

A double-β decay evidence?

Analysis of the ^{76}Ge data by a sub-group of the HM Collaboration

(Klapdor-Kleingrothaus et al, PLB 586,198,2004)

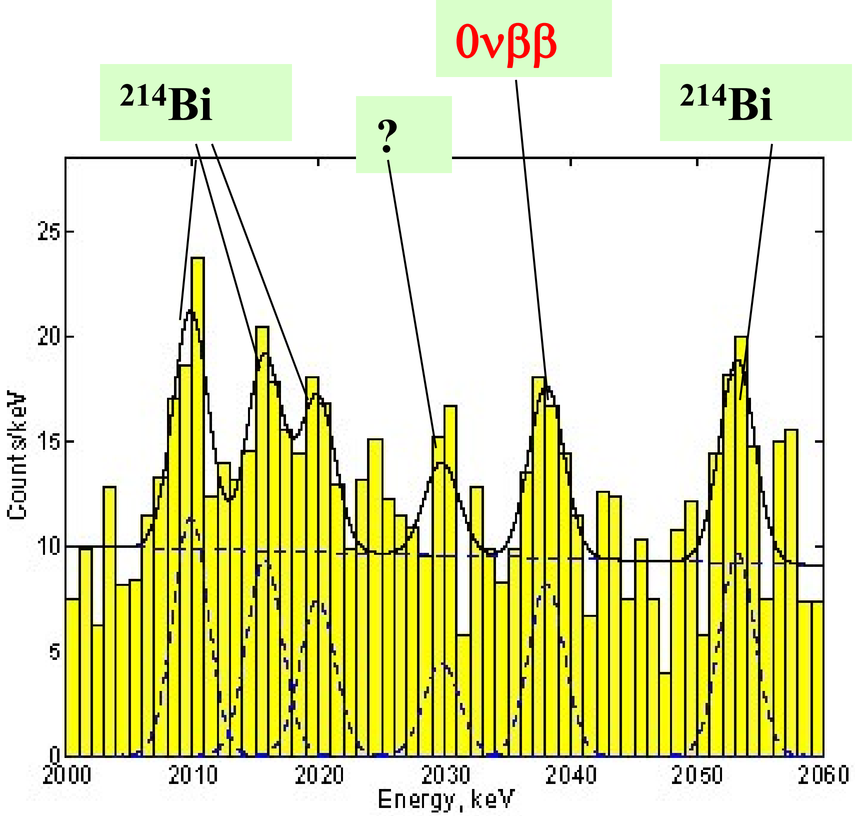
4σ effect claimed

$T^{0\nu}_{1/2}$ = (0.69 – 4.18) 10^{25} y

$\langle m_\nu \rangle$ = (0.17 – 0.63) eV

Critics:

- low statistical significance of signal
- Unknown extra-peak at 2030 keV with similar significance
- Larger energy window checks?



Re-analysis of same data (2006)

1995-2003 data new re-analysis:

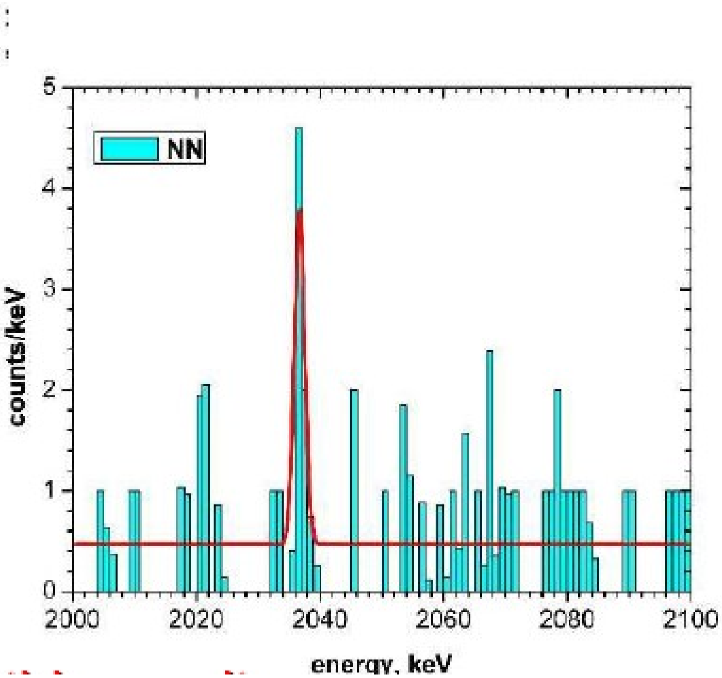
SSE selection by MC & ANN

6.4σ signal

7.05 ± 1.11 events

$2.23^{+0.44}_{-0.31}\ 10^{25}$ years / 0.32 ± 0.03 eV

H.V.Klapdor-Kleingrothaus *et al.*, Phys. Scr. T127 (2006) 40–42



Not confirmed and essentially ruled out by current more sensitive experiments

NEMO (Neutrino Ettore Majorana Observatory) 2003-2011

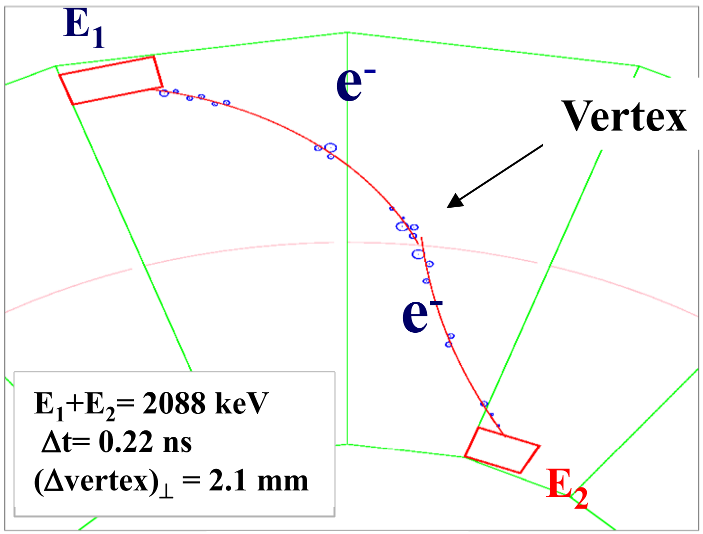
In Frejus @ 4800 meters water equivalent

Magnetic + tracking detector + calorimeter

- tracking for background rejection (drift cells)
- calorimetry for energy resolution (plastic scintillators+PMT)
- multiple isotopes for systematics (^{100}Mo, ^{82}Se, ^{130}Te, ^{116}Cd,..)

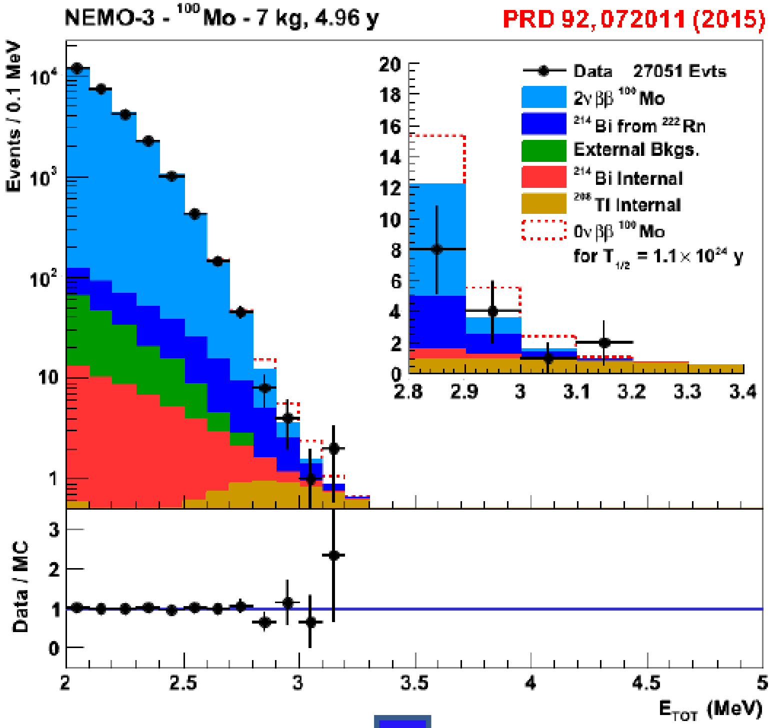
10 Kg distributed in thin source foils

Tag and measures all components of backgrounds: α, γ, e^-, e^+



ββ events

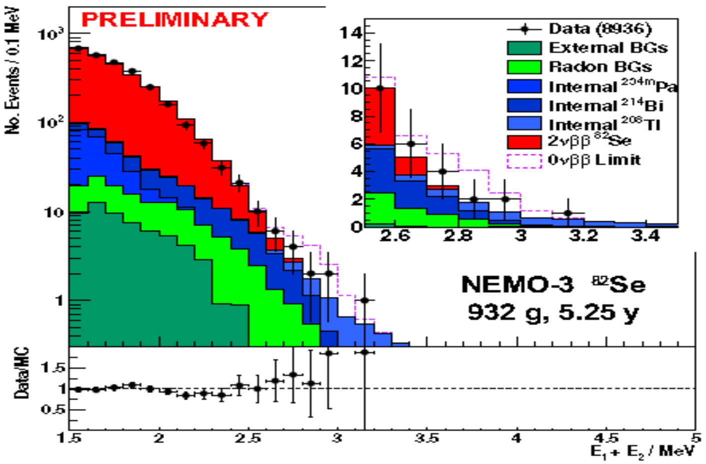
0νββ decay: Nemo3 latest results [Waters, Nu2016]



$$T_{1/2}^{0\nu\beta\beta} > 1.1\times10^{24}\ \mathrm{yr}\ (90\%\ \mathrm{C.L.})$$

$$\langle m_\nu \rangle < 0.3 - 0.6\ \mathrm{eV}$$

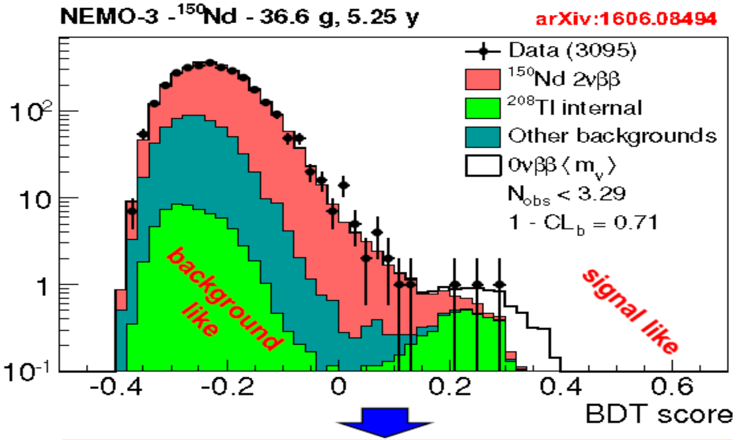
- Close to the best limits from other experiments, with only 7kg of isotope.



$$T_{1/2}^{0\nu\beta\beta} > 2.5 \times 10^{23}\ \mathrm{yr}\ (90\%\ \mathrm{C.L.})$$

$$\langle m_\nu \rangle < 1.2 - 3.0\ \mathrm{eV}$$

- 4 times worse than ^{100}Mo but with less than 15% of the mass.

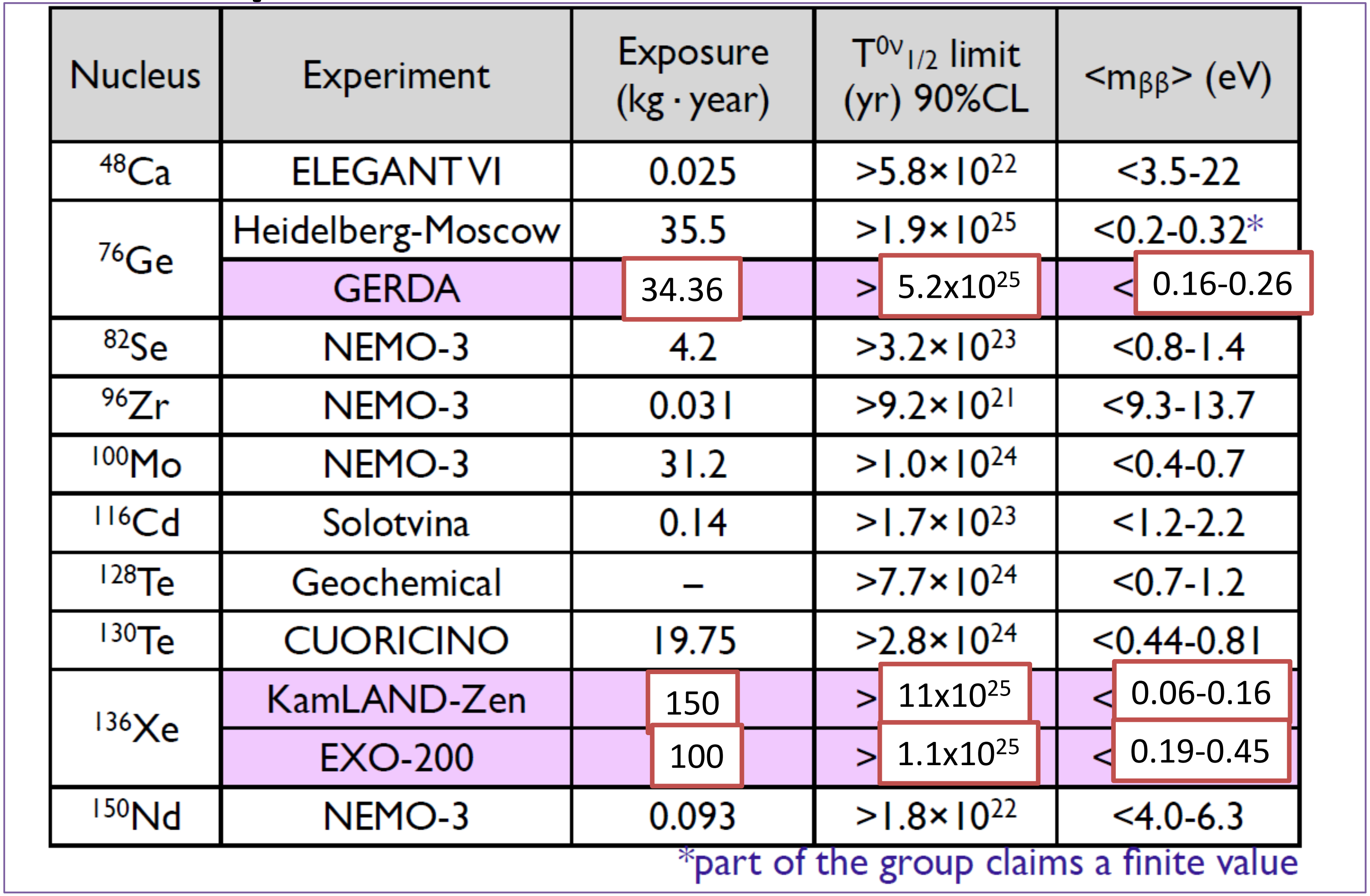


$$T_{1/2}^{0\nu\beta\beta} > 2.0 \times 10^{22}\ \mathrm{yr}\ (90\%\ \mathrm{C.L.})$$

$$\langle m_\nu \rangle < 1.6 - 5.3\ \mathrm{eV}$$

- Expected (observed) half-life limit is 11% (34%) better than using E_{TOT} alone.

Compilation of current results



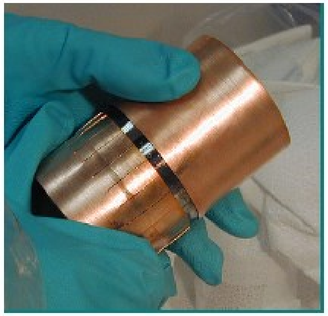
Nucleus	Experiment	Exposure (kg · year)	$T^{0\nu}_{1/2}$ limit (yr) 90%CL	$<m_{\beta\beta}>$ (eV)
^{48}Ca	ELEGANT VI	0.025	$>5.8\times10^{22}$	<3.5-22
^{76}Ge	Heidelberg-Moscow	35.5	$>1.9\times10^{25}$	<0.2-0.32*
	GERDA	34.36	$> 5.2\text{x}10^{25}$	< 0.16-0.26
^{82}Se	NEMO-3	4.2	$>3.2\times10^{23}$	<0.8-1.4
^{96}Zr	NEMO-3	0.031	$>9.2\times10^{21}$	<9.3-13.7
^{100}Mo	NEMO-3	31.2	$>1.0\times10^{24}$	<0.4-0.7
^{116}Cd	Solotvina	0.14	$>1.7\times10^{23}$	<1.2-2.2
^{128}Te	Geochemical	–	$>7.7\times10^{24}$	<0.7-1.2
^{130}Te	CUORICINO	19.75	$>2.8\times10^{24}$	<0.44-0.81
^{136}Xe	KamLAND-Zen	150	$> 11\text{x}10^{25}$	< 0.06-0.16
	EXO-200	100	$> 1.1\text{x}10^{25}$	< 0.19-0.45
^{150}Nd	NEMO-3	0.093	$>1.8\times10^{22}$	<4.0-6.3

*part of the group claims a finite value

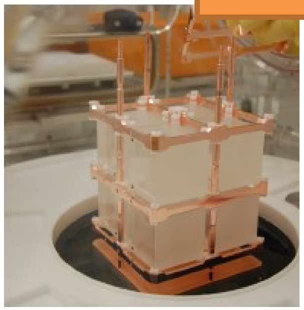
"Klapdor's claim" strongly disfavoured

ββ-decay New Experiments (a selection)

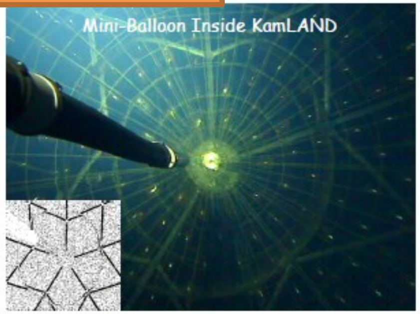
Calorimeters



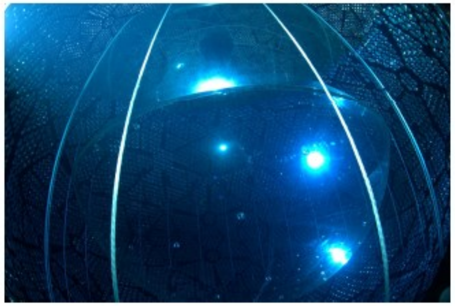
GERDA (GE-76)



CUORE (TeO2)



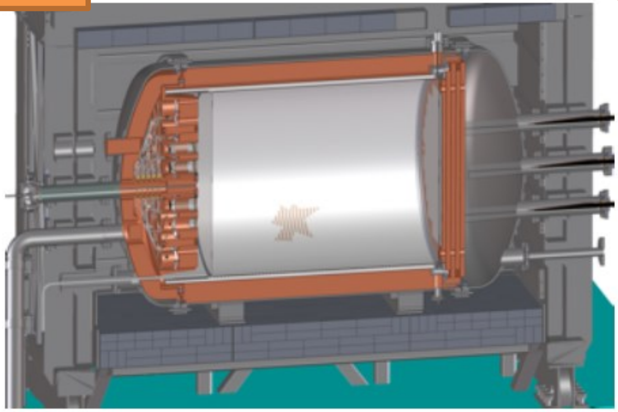
KamLAND-ZEN (Xe-136+LS)



SNO+ (Te + LS)

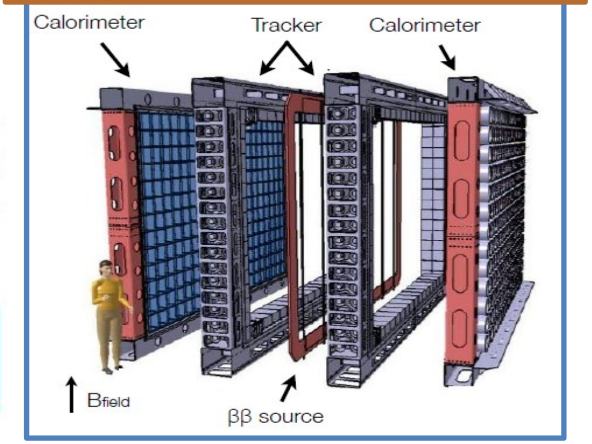
Xe-TPC's

EXO (Xe-136)LXe



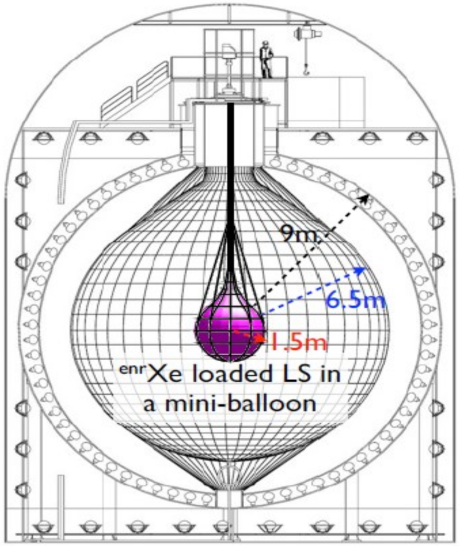
NEXT (Xe-136)HPXe
Also PandaX

Tracking Calorimeter



SuperNEMO (^{82}Se)

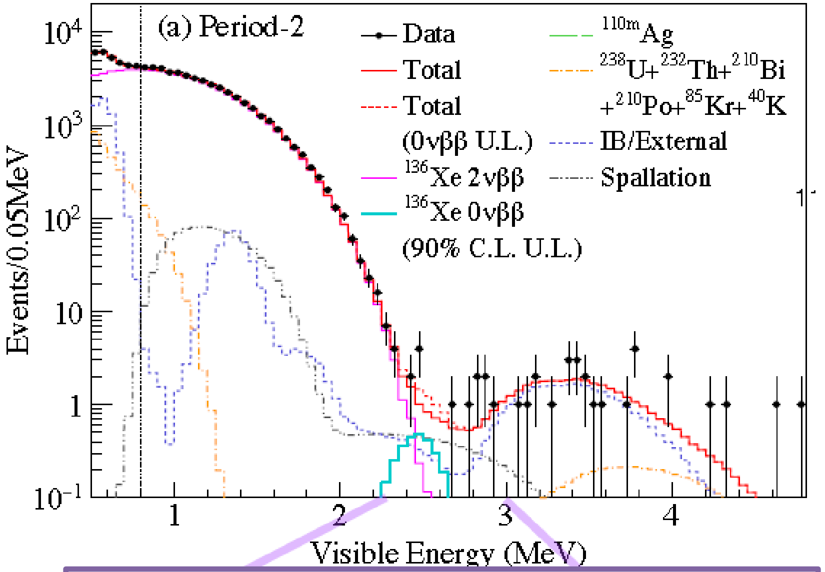
Kamland-ZEN



~400 Kg ^{136}Xe loaded liquid scintillator in a mini-balloo
inside ultra-low background KAMLAND detector

Kamland2-Zen with 1000kg enriched Xe in preparation
Better energy resolution and background rejection
Aiming at full coverage of IH

Phase-2 data (Neutrino 2016)



No excess over background

KamLAND-Zen
Half-life limit (@90%C.L.)

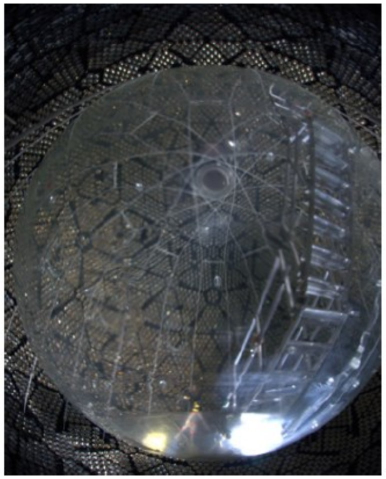
Phase1 $T^{0\nu}_{1/2} > 1.9 \times 10^{25}$ yr

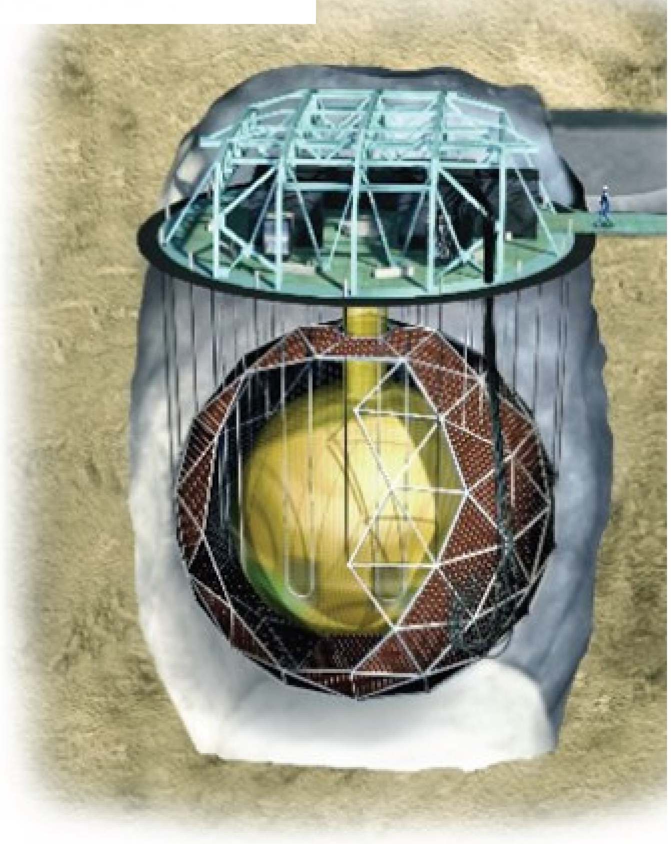
Phase2 $T^{0\nu}_{1/2} > 9.2 \times 10^{25}$ yr

×6!

Combined $T^{0\nu}_{1/2} > 1.07\times10^{26}$ yr

year

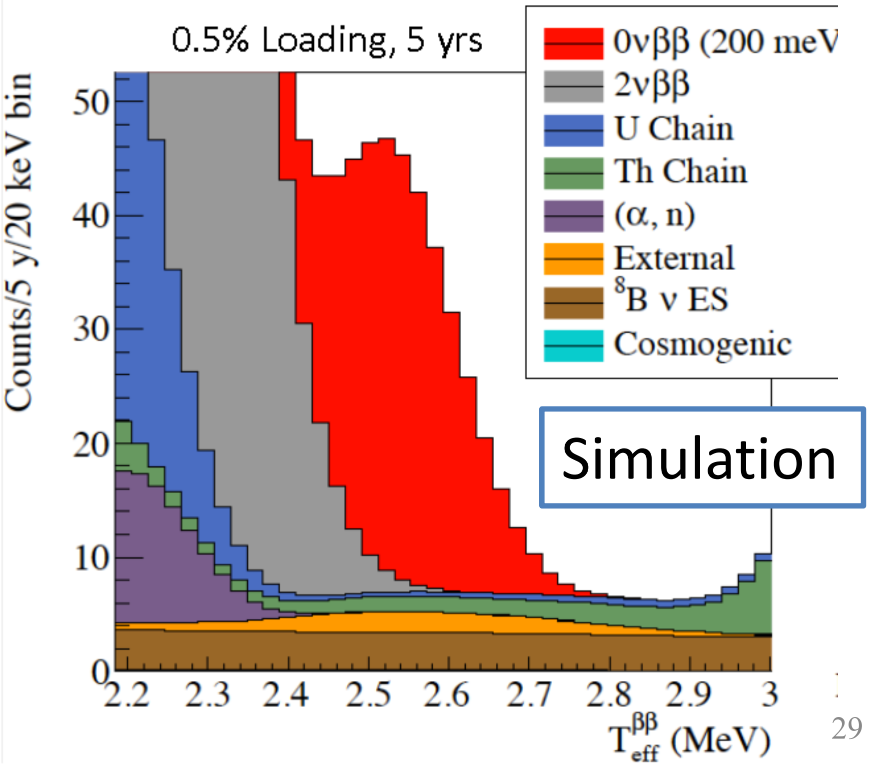




SNO+

Plan to fill SNO vessel with 780t of liquid scintillator loaded with Tellurium

- 34% natural abundance of ^{130}Te
  - Can load high amount of natural isotope (~4tons)
  - Relatively inexpensive compared to enriched isotopes
- Low $2\nu\beta\beta$ decay (100 times smaller than ^{150}Nd)



Simulation

From NEMO to SuperNemo

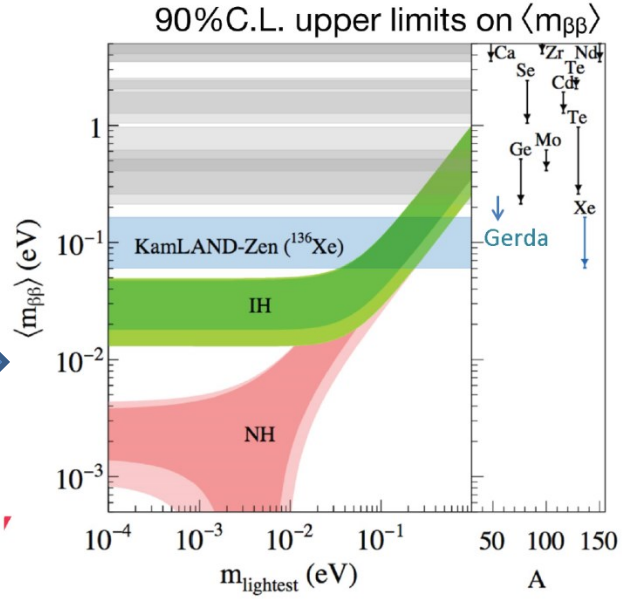
	NEMO-3	SuperNEMO
Mass	7 kg	100 kg
Isotopes	^{100}Mo	^{82}Se
	7 isotopes	^{150}Nd, ^{48}Ca
Foil density	60 mg/cm^2	40 mg/cm^2
Energy resolution (σ | FWHM)		
@ 1 MeV	6.3 | 15 %	3.0 | 7 %
@ 3 MeV	3.4 | 8 %	1.7 | 4 %
Radon in tracker		
$\mathcal{A}(^{222}\mathrm{Rn})$	~ 5.0 mBq/m^3	~ 0.15 mBq/m^3
Sources contaminations		
$\mathcal{A}(^{208}\mathrm{Tl})$	~ 100 μBq/kg	< 2 μBq/kg
$\mathcal{A}(^{214}\mathrm{Bi})$	60 - 300 μBq/kg	< 10 μBq/kg
Detector		
tracking cells	6180	20×2034
calo blocks	1940	20×712
Sensitivity (90 % CL)		
$\mathcal{T}^{0\nu}_{1/2}$	$> 1.1\ 10^{24}$ y	$> 1\ 10^{26}$ y
$\lvert m_{\beta\beta} \rvert$	< 0.3 - 0.8 eV	< 40 - 100 meV

SuperNEMO demonstrator module with 7 kg of ^{82}Se (53 mg/cm^2) is under construction

Near completion

Future sensitivity of 0ν2β experiments

- AIM: 10-20 meV sensitivity
  - ➢ DISCOVERY if mass HIERARCHY is inverted
- What is it required?
  - ✓ Different experiments with different isotopes
  - ✓ Reduce nuclear matrix elements uncertainties
  - ✓ Improve all parameters determining sensitivity



increase isotopic abundance by enrichment

$$\sum(\tau^{0\nu}_{1/2}) \propto \epsilon \cdot \frac{a.i.}{A}\sqrt{\frac{M\,t_{meas}}{\Delta E \cdot bkg}}$$

increase experimental mass

reduce background by:
material selection and proper handling
choosing proper technique
using signatures
improving energy resolution

10 meV are very challenging:

factor *10* in neutrino mass => factor *10*^{4} in M x t/(Bkg x ΔE)!

Need new ideas to reach < 10 meV

Summary

Single beta decay

$$m_\nu = \sqrt{\sum |U_{ei}|^2 m_i^2}$$

KATRIN $m_\nu < 2.3$ eV → $m_\nu < 0.2$ eV

Double beta decay

$$|\langle m_\nu \rangle| = |\sum U_{ei}^2 m_i|$$

Unique tool to study neutrino nature (DIRAC/Majorana)

Experiments have reached a sensitivity at the top of the inverted hierarchy region

Future generation aims to improve the limit by factor 10 and probe the inverted mass-hierarchy region

New ideas needed to go below 10 meV and probe normal hierarchy region