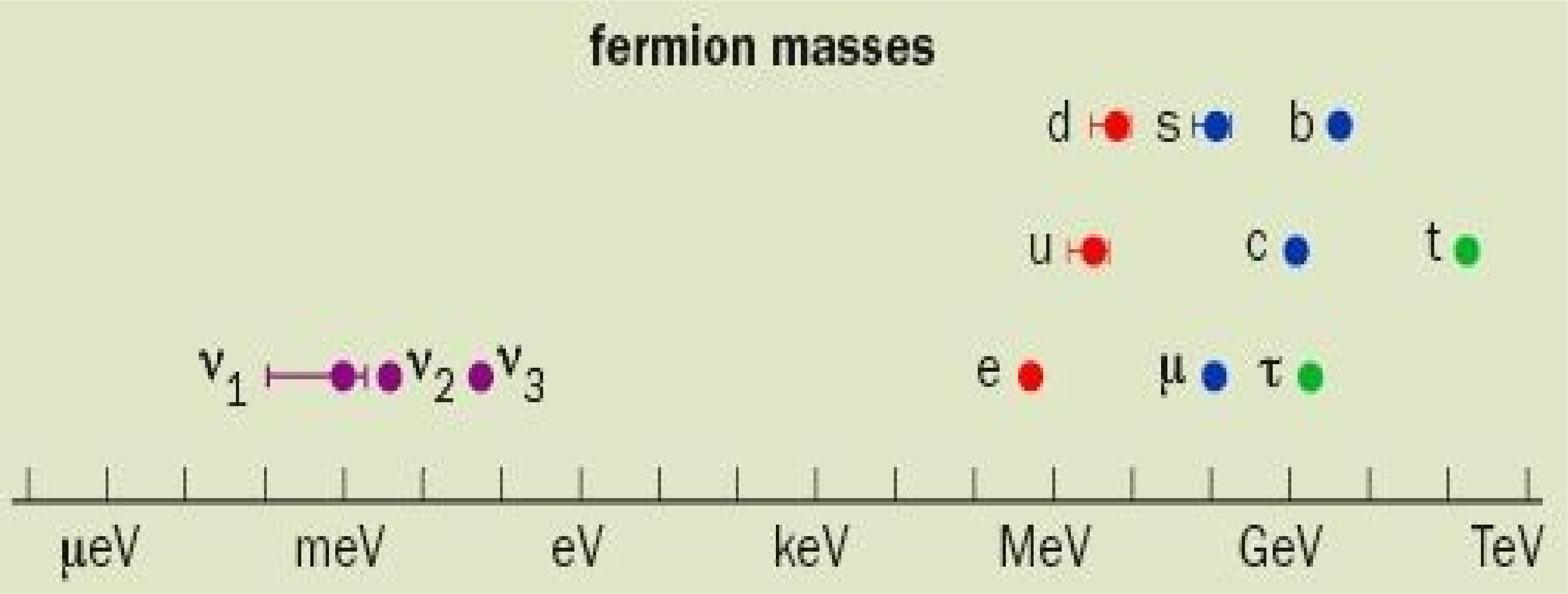
Lecture 2

I*n which the origin of mass is considered and unsuccessfully measured*

The mystery of neutrino mass



Why are neutrino masses so small?

n Mass in the Standard Model

Dirac Lagrangian mass term for fermions contains a Dirac mass term with a Dirac mass, m_D

$$L_\nu = \overline{\psi}\left(i\gamma_\mu \partial^\mu - m_D\right)\psi \;\Rightarrow\; L_{mass} = m_D \overline{\psi}\psi$$

Can rewrite mass term in terms of chiral states

$$L_{mass} = m_D \overline{\psi}\psi = m_D\left(\overline{\psi_L} + \overline{\psi_R}\right)\left(\psi_L + \psi_R\right) = m_D\left(\overline{\psi_L}\psi_R + \overline{\psi_R}\psi_L\right)$$

Mass term is the only place that the L- and R- chiral sectors of the SM meet.

Fermion Mass in the SM

Unfortunately, a Dirac mass term like this cannot preserve gauge invariance

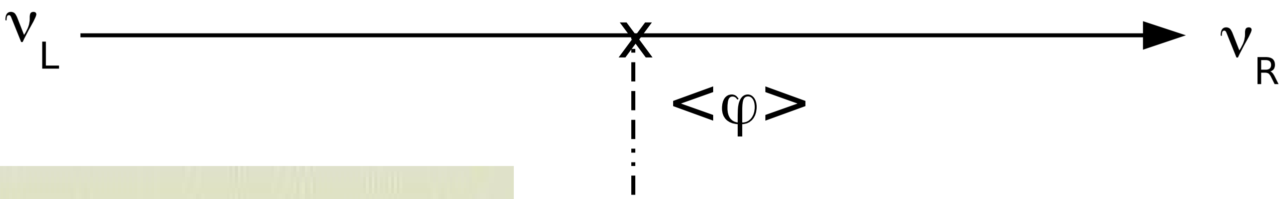
$$L_{mass} = m_D \left(\overline{\psi_L} \psi_R + \overline{\psi_R} \psi_L \right)$$

Left-handed fermion fields transform as $SU(2)_L$ doublets
Right-handed fermion fields transform as $U(1)_Y$ singlets

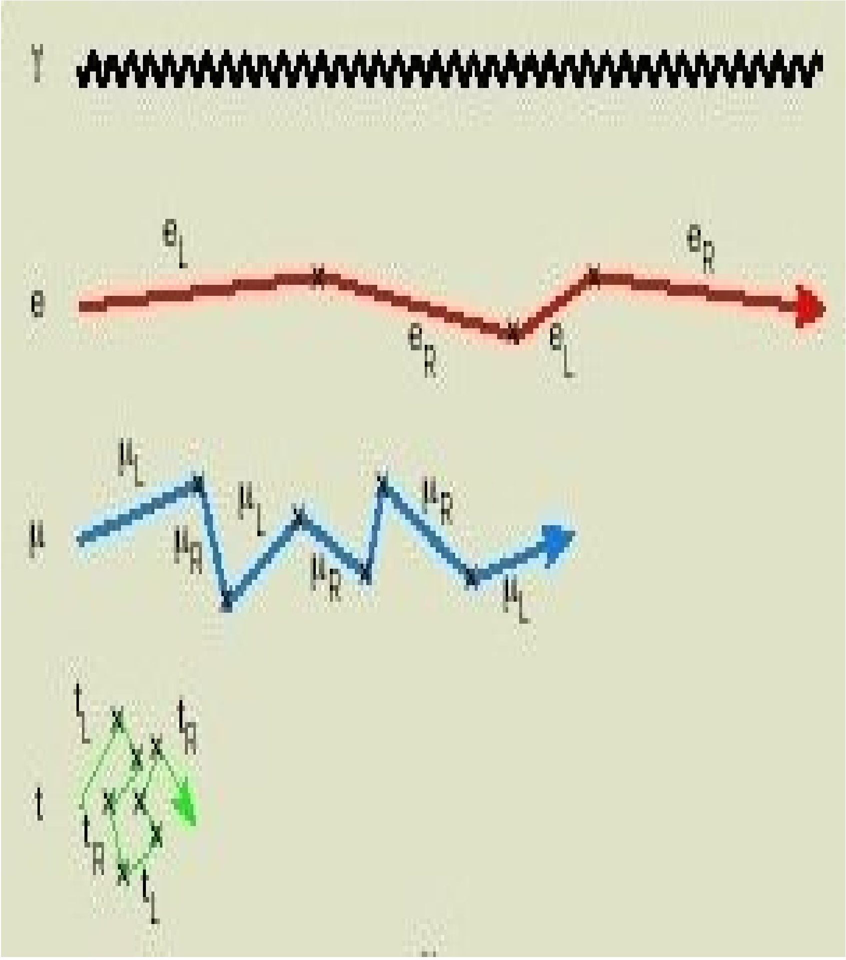
Different gauge groups ⇒ mass term is left with non-zero charges

Mass term is not gauge invariant – another field transforming under SU(2) is needed – the Higgs field

ν Dirac Mass



Dirac Mass



Higgs mechanism : $m_D = G_\nu \frac{\langle \phi \rangle}{\sqrt{2}}$

$<\phi> \sim 246\, GeV$ Higgs VEV

Hang on, but...

- Small m_ν → smaller G_ν ($< 10^{-13}$)
- Need to add a sterile ν_R that is, in principle, undetectable

Majorana Neutrinos

Can one build a R-chiral field only from the L-chiral field?

Yes : Ettore Majorana showed $\nu_L^C = C\,\overline{\nu_L}^T$ is right-handed

C = charge conjugation matrix

Can form a *Majorana* neutrino : $\nu = \nu_L + \nu_L^C$

This is self-conjugate - $\nu = \nu^C$: particle is identical to the antiparticle

The neutrino is the only fundamental fermion with potential to be Majorana.

We can also now write down a mass term for Majorana neutrinos

$$L_{Maj} = \frac{1}{2} m_L \left(\overline{\nu^C} \nu + \overline{\nu} \nu^C \right) = \frac{1}{2} m_L \left(\overline{\nu_L^C} \nu_L + \overline{\nu_L} \nu_L^C \right)$$

We are now coupling neutrinos and antineutrinos, leading to a process which violates lepton number by 2

Damn

The left-handed Majorana mass term also violates gauge invariance.

ν_L $T_3 = 1/2$, $Y = -1$

$\overline{\nu_L^C}\,\nu_L$ $T_3 = 1$, $Y = -2$

To maintain gauge invariance this has to couple to a Higgs-y thing with $Y = +2$ and $T_3 = -1$ - that is a Higgs weak triplet with hypercharge +2.

No such field exists in the Standard Model (although you do get them if you expand the Higgs sector to include both a scalar doublet and triplet)

We are forced then to consider the existence of an independent right-handed U(1) singlet Majorana neutrino field : $N = N_R^C + N_R$

The existence of neutrino mass implies physics beyond the Standard Model, either from a right-handed state needed for the standard mass mechanism, or a Higgs triplet, or a new mass mechanism.

The general mass term

Suppose at the beginning there were 2 Majorana neutrino fields.
An almost massless one, and a very heavy one.The mass term looks like

$$L_{mass}=m\,\overline{\nu_m}\,\nu_m+M\,\overline{N}_m N_m=\begin{pmatrix}\overline{\nu_m} & \overline{N_m}\end{pmatrix}\begin{pmatrix}m & 0\\ 0 & M\end{pmatrix}\begin{pmatrix}\nu_m\\ N_m\end{pmatrix}$$

States of definite mass

Can write the mass eigenstates in terms of the Majorana fields

Mass Eigenstates (Physical particles)

$$\nu=\nu_L+\nu_L^C \qquad N=N_R^C+N_R$$

$$U=\begin{pmatrix}\cos\theta & \sin\theta\\ -\sin\theta & \cos\theta\end{pmatrix}$$

$$\nu_m=\cos\theta\,\nu+\sin\theta\,N \quad ; \quad N_m=-\sin\theta\,\nu+\cos\theta\,N \;\rightarrow\; \begin{pmatrix}\nu_m\\ N_m\end{pmatrix}=U\begin{pmatrix}\nu_L+\nu_L^C\\ N_R+N_R^C\end{pmatrix}$$

Majorana field

$$L_{mass}=\frac{1}{2}\begin{pmatrix}\overline{\nu_L^C} & \overline{N_R}\end{pmatrix}\underbrace{\begin{pmatrix}c & -s\\ s & c\end{pmatrix}^{-1}\begin{pmatrix}m & 0\\ 0 & M\end{pmatrix}\begin{pmatrix}c & -s\\ s & c\end{pmatrix}}_{\text{off-diagonal mass matrix}}\begin{pmatrix}\nu_L\\ N_R^C\end{pmatrix}$$

Written in the Chiral basis

The general mass term

The most general mass term combines Dirac and Majorana masses

From Dirac mass terms using Higgs mechanism

$$L_{mass} = \begin{pmatrix} \overline{\nu_L^C} & \overline{N_R} \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R^C \end{pmatrix}$$

From Majorana mass terms

These states couple to the Weak interaction but are not the “*particle*”

Physical masses are the eigenvalues of the diagonalised mass matrix (m_1,m_2).

$$\tilde{M} = Z^{-1} M Z = \begin{pmatrix} \tilde{m}_1 & 0 \\ 0 & \tilde{m}_2 \end{pmatrix} \qquad \tilde{m}_{1,2} = \frac{1}{2}\left[m_R \pm \sqrt{m_R^2 + 4 m_D^2} \right]$$

Seesaw Mechanism

Suppose there are two Majorana neutrinos – a light one and a heavy one and that *they are not chiral eigenstates .*

Then the mass states are a super-position of the chiral states.

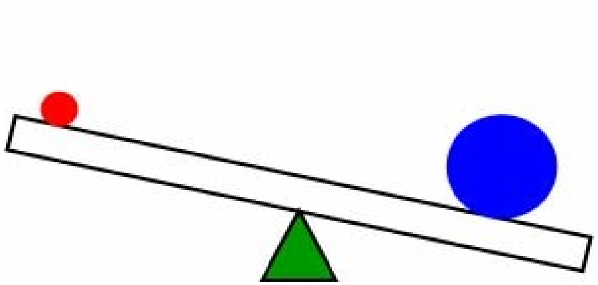
on the order of an MeV or so – Dirac masses like other charged leptons

very large – at the GUT scale - 10^{15} GeV

$$\tilde{m}_1 = \frac{m_D^2}{m_R} = m_\nu$$

$$\tilde{m}_2 = m_R\left(1 + \frac{m_D^2}{m_R^2}\right) \approx m_R = m_N$$

the physical field m_n now naturally has a very small mass ("our" neutrino)



Leptogenesis

Seesaw mechanism requires a GUT scale heavy Majorana neutrino partner.

In GUT theories, B-L is a global U(1) symmetry and is absolutely conserved
(baryon number - lepton number)

Suppose there is direct CP violation in the heavy neutrino decay? This generates a violation of L.

$$\Gamma\left(N_i \to l_i + \overline{H^0}\right) \neq \Gamma\left(N_i \to \bar{l}_i + H^0\right)$$

Produces an asymmetry in the number of leptons, violating lepton number conservation

Leptogenesis

If L is violated then, to keep B-L conserved, one needs to violate B as well.

Generation of baryon asymmetry from lepton asymmetry
(via non perturbative *sphaleron* transitions 🤷)

Could neutrino mass help explain CP violation in the baryons? In other words, could neutrinos help explain why there is more matter than antimatter in the universe?

This idea requires

- the neutrino to be massive
- the neutrino must be Majorana
- a GUT scale heavy neutral lepton must exist

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- the neutrino must be Majorana ? ☜
- a GUT scale heavy neutral lepton must exist ?

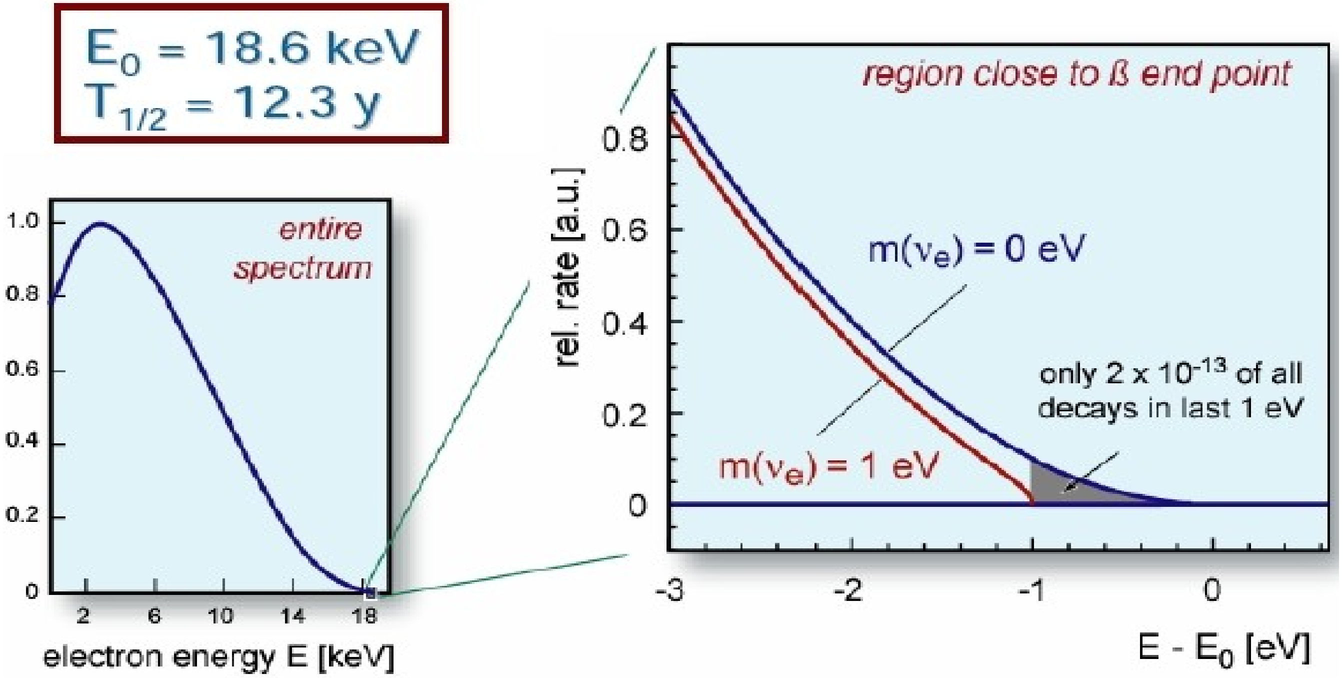
(Attempts at) mass measurements

β decay

Measurement of ν mass from kinematics of β decay.

$$\frac{d\Gamma_i}{dE} = C\, p\,(E+m_e)(E_0-E)\sqrt{(E_0-E)^2-\boxed{m_\nu^2}}\,F(E)\,\theta(E_0-E-m_\nu)$$

Observable is m_ν^2



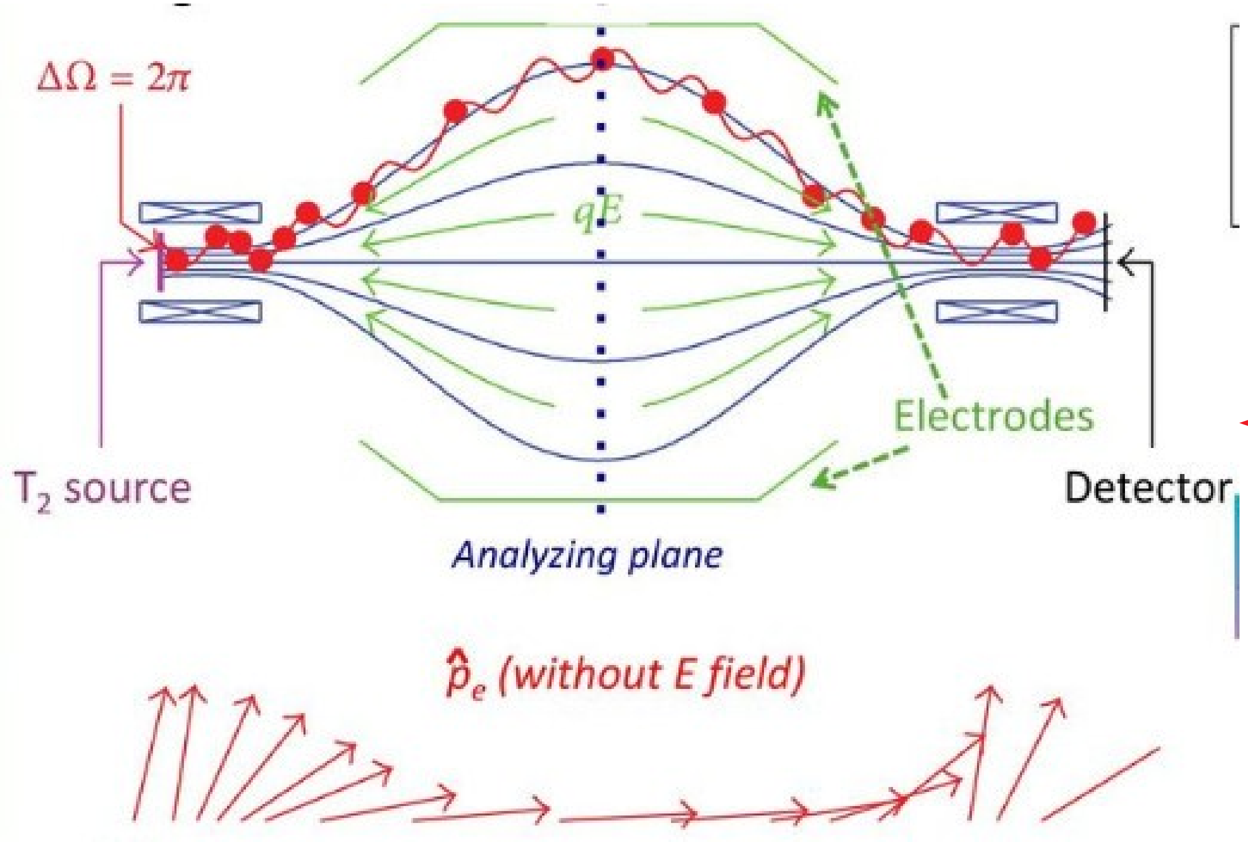
Requirements

- The number of electrons close to the endpoint should be large
- Good (and well-understood) electron energy resolution
- No (or minimal) electron energy loss within the source
- Minimal atomic and nuclear final state effects, of excited transitions

$$Gaseous\,Tritium: {}^{3}H \rightarrow {}^{3}He^{+} + e^{-} + \overline{\nu}_{e}$$

Endpoint is at 18574 eV
No molecular excitation above 18547 eV
Still only 10^{-9} electrons in this region
Gaseous so you can have a very large source

Tritium β-decay experiments

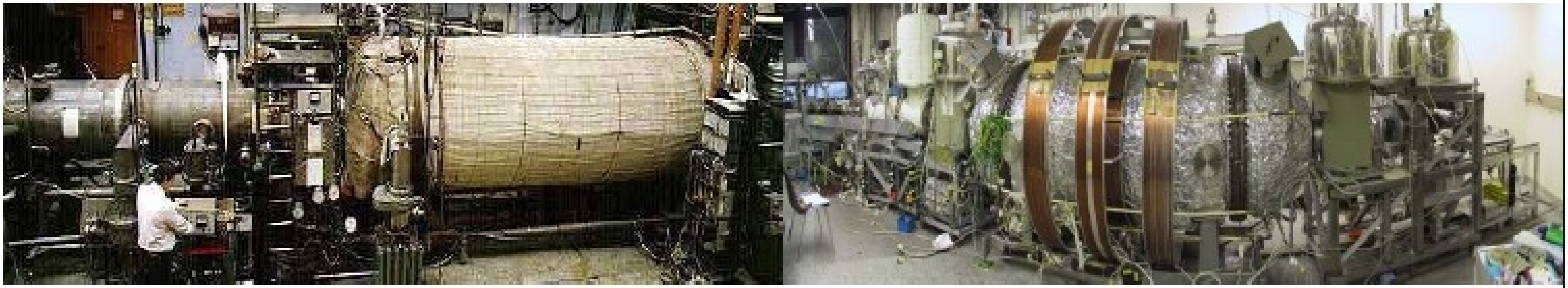


$$\frac{\Delta E}{E} \sim 0.03\,\%$$

Electrostatic MAC-E Filter

- 2 π acceptance
- Precision electron energy measurement

Troitsk/Mainz



Troitsk

windowless gaseous T_2 source

analysis 1994 to 1999, 2001

$m_\nu^2 = -2.3 \pm 2.5 \pm 2.0\ \mathrm{eV}^2$

$m_\nu \leq \quad 2.2\ \mathrm{eV}$ (95% CL.)

Mainz

quench condensed solid T_2 source

analysis 1998/99, 2001/02

$m_\nu^2 = -1.2 \pm 2.2 \pm 2.1\ \mathrm{eV}^2$

$m_\nu \leq \quad 2.2\ \mathrm{eV}$ (95% CL.)

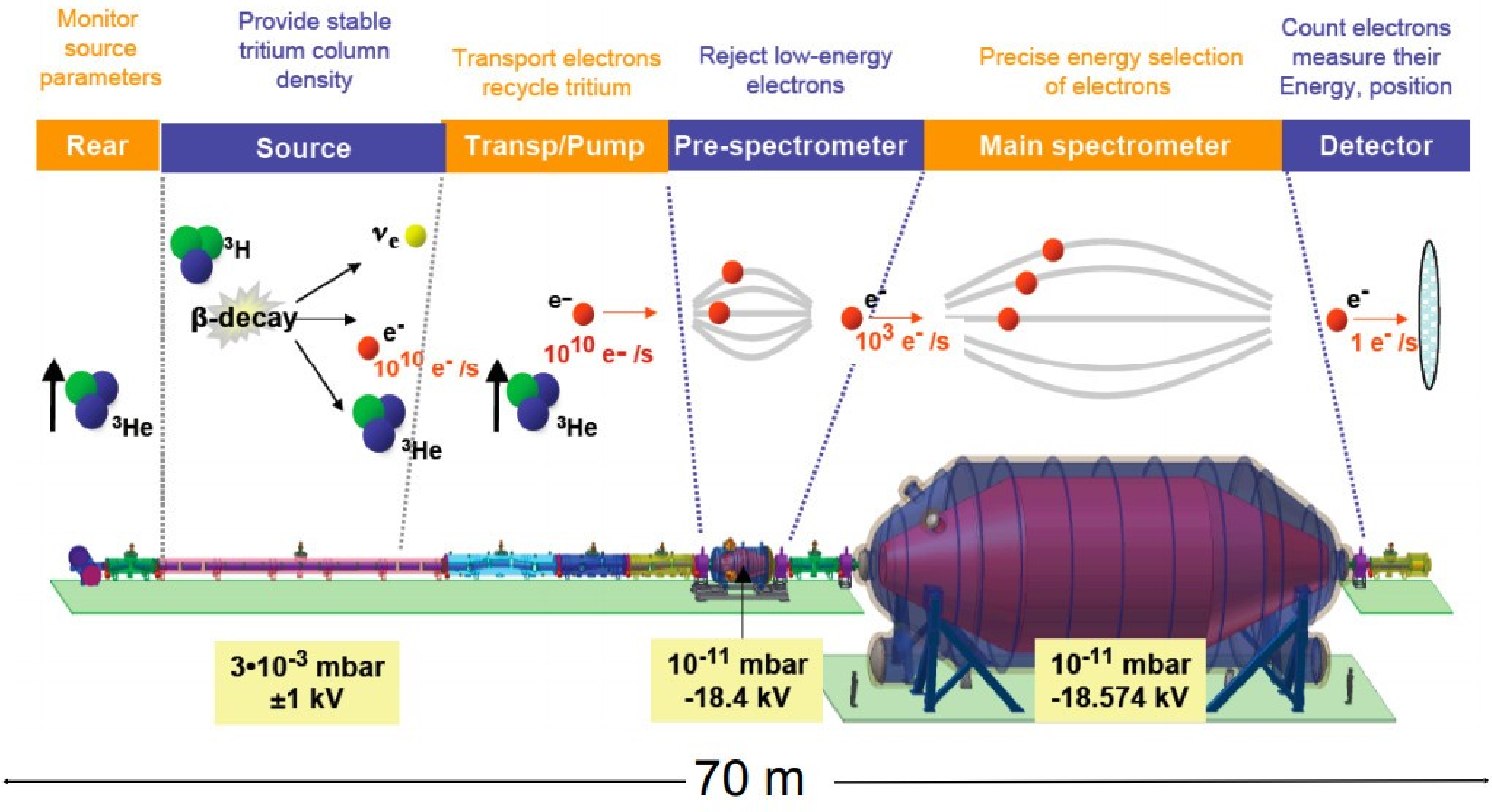
Both experiments reached the intrinsic limit of their sensitivity.

KATRIN

Expected limit : $m\nu_e < 0.2$ eV (90% CL)

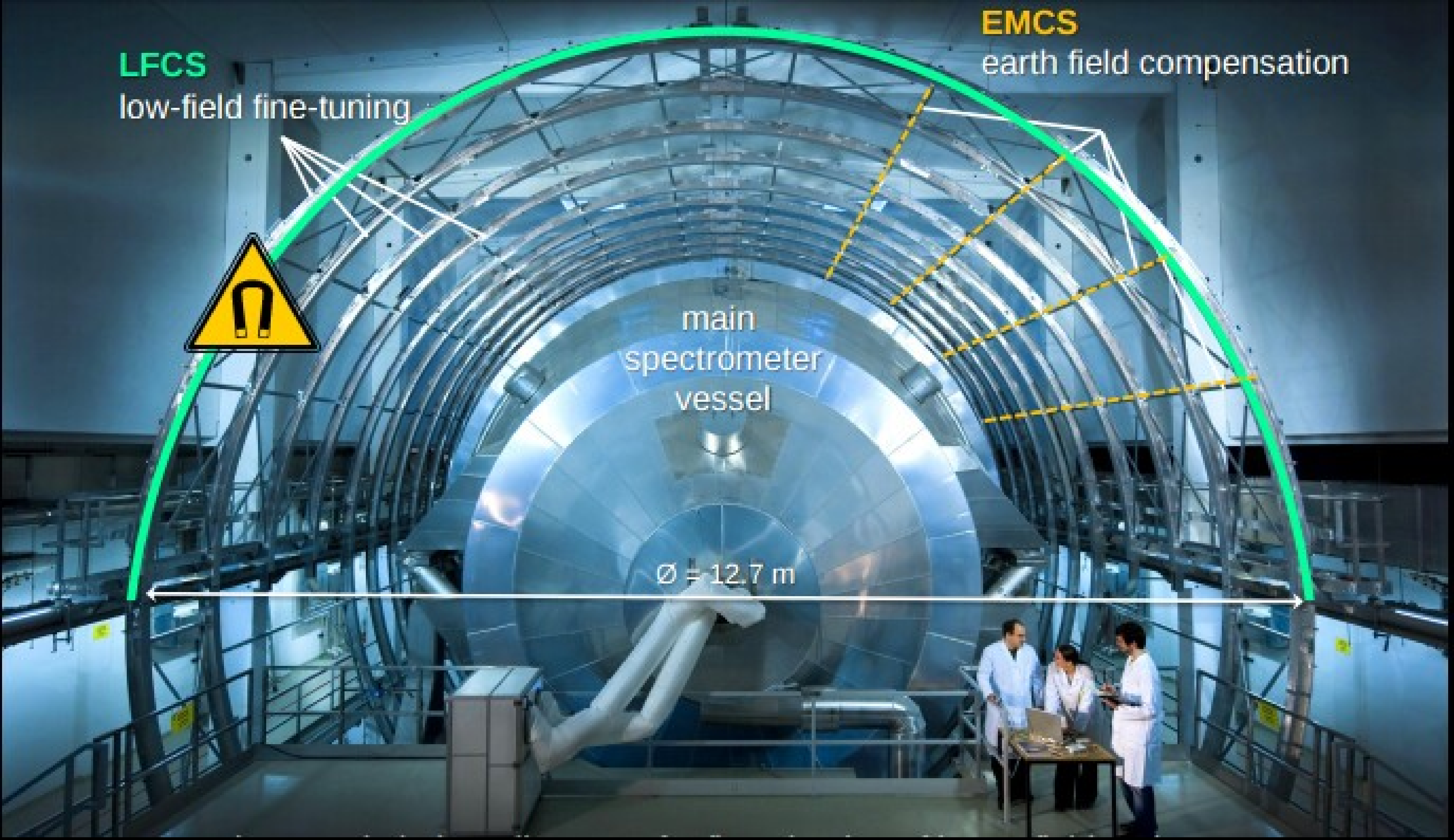
Discovery potential : $m\nu_e = 0.35$ eV at 5 σ

Taking data now!

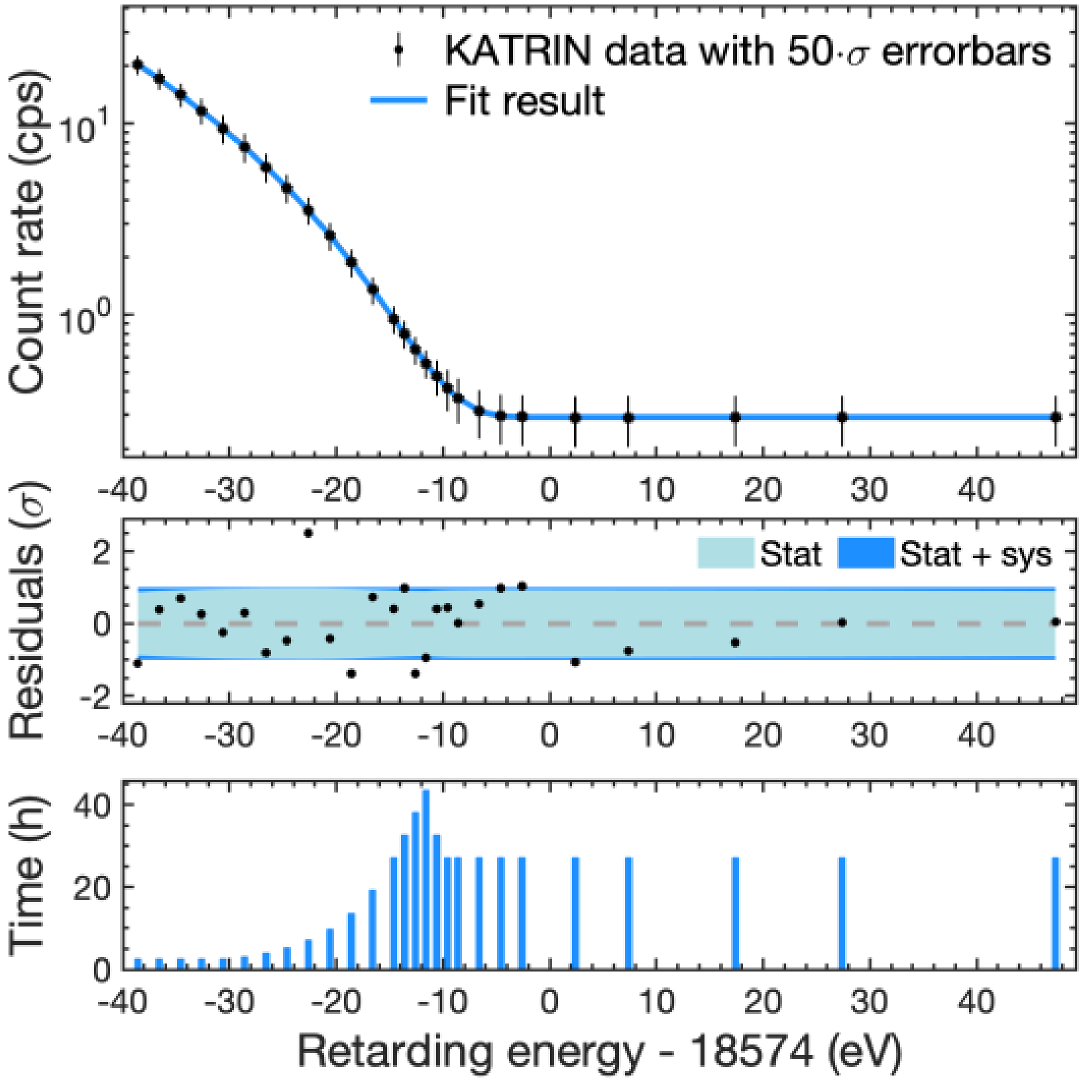


Katrin on the move

KATRIN on the move


LFCS
low-field fine-tuning
EMCS
earth field compensation
main spectrometer vessel
Ø = 12.7 m

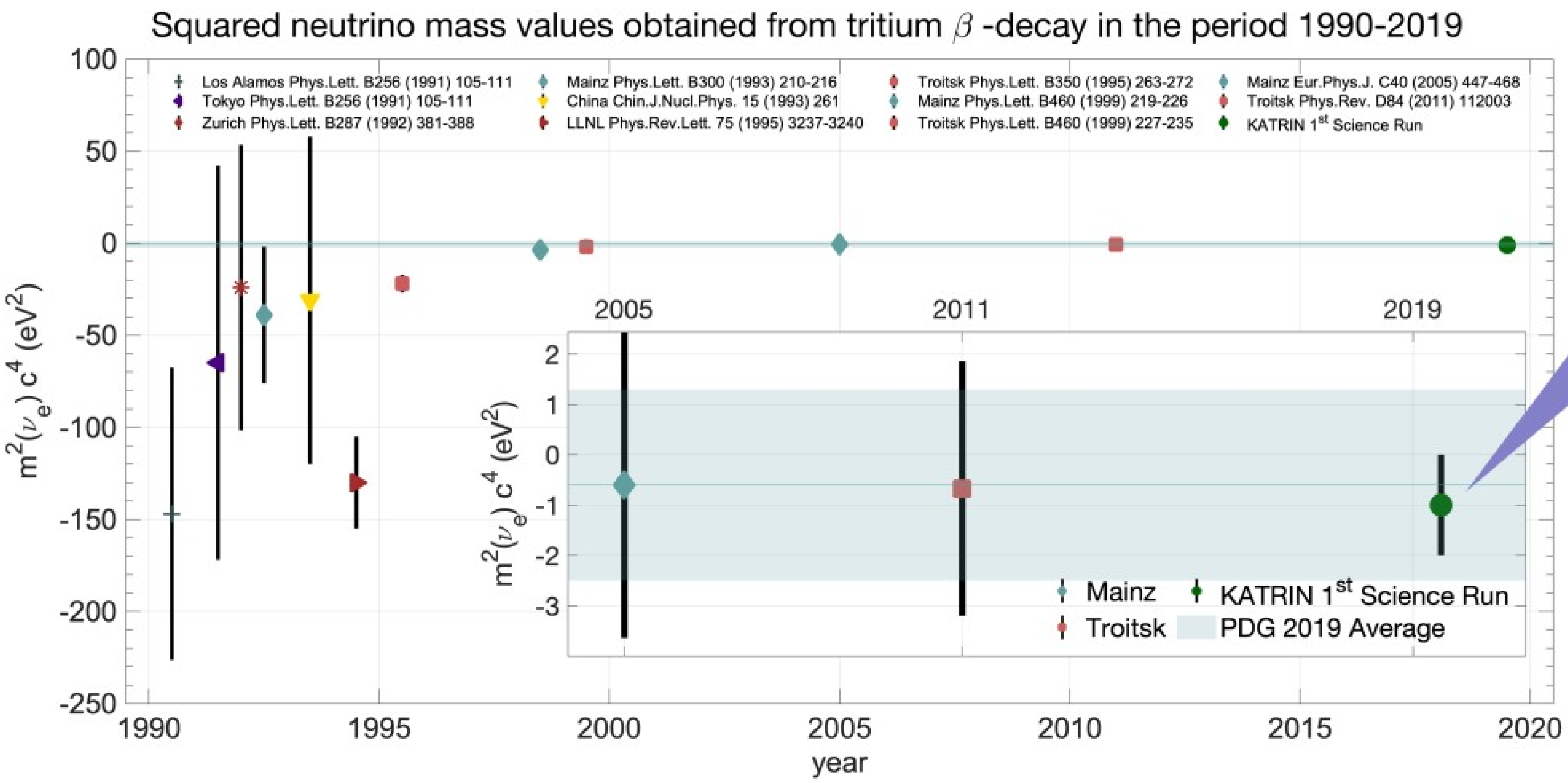
KATRIN



- 2 million events
- Error bars increased by a factor of 50 for visibility
- $m_\nu^2 = (-1.0 \pm 1.0)\ \text{eV}^2$
- $m_\nu < 0.8\text{-}1.0$ eV @ 90% CL

From S. Merten’s talk at Neutrino 2020

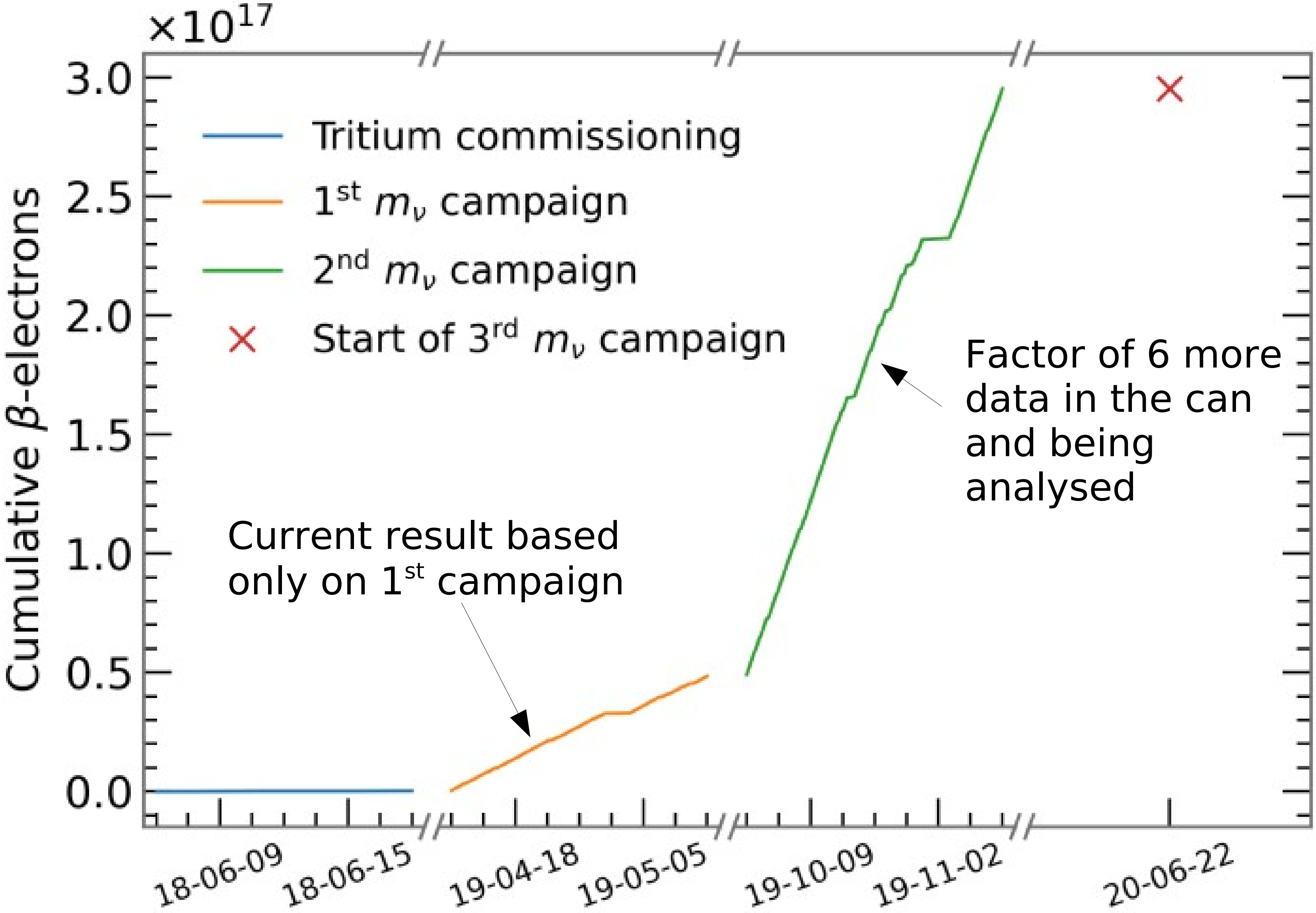
In context



Effective 5 days of data

- Stat. error: ÷ 2
- Syst. error: ÷ 6

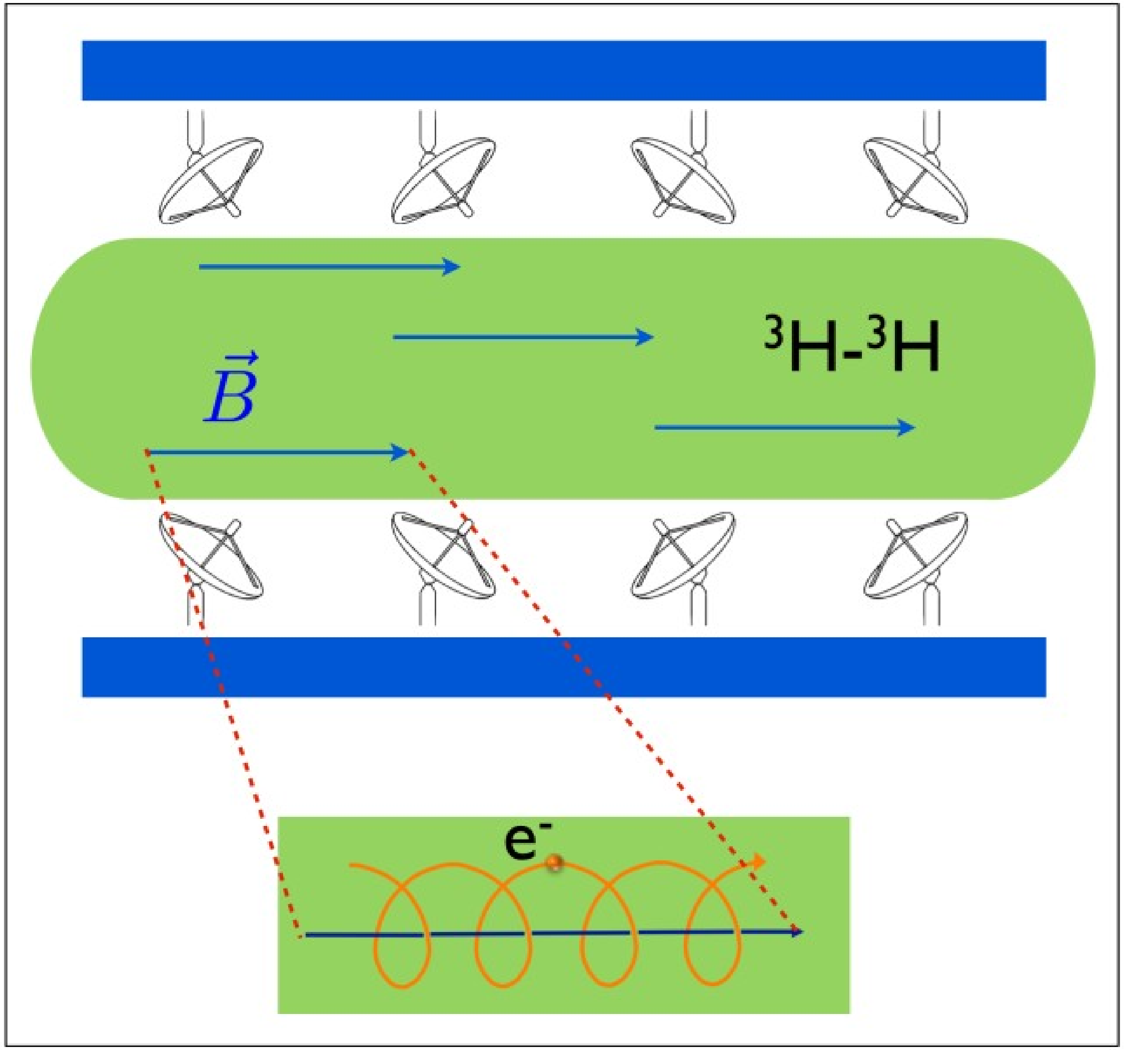
Future Data



Factor of 6 more data in the can and being analysed

Current result based only on 1st campaign

Project 8



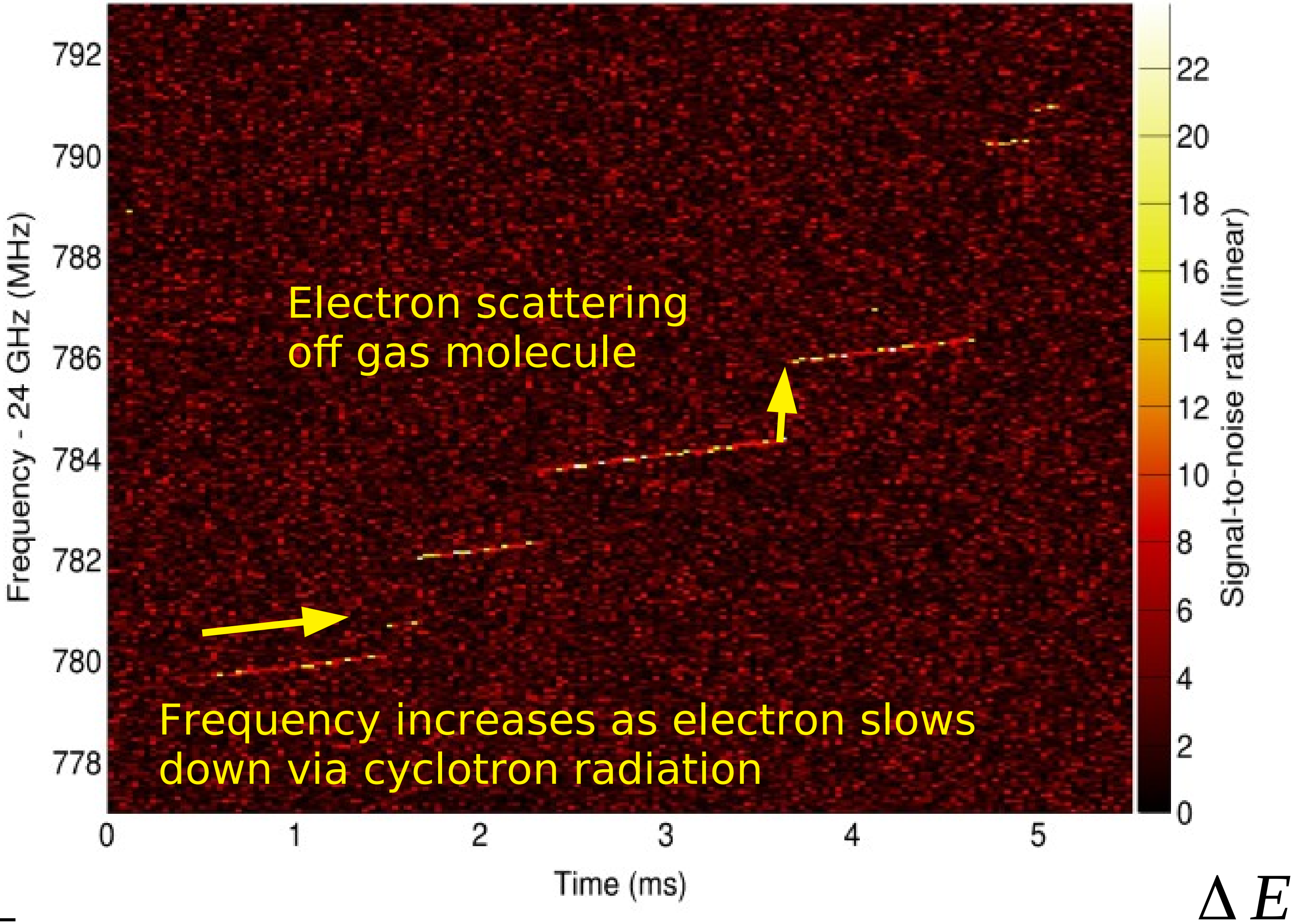
B. Monreal and J. Formaggio, Phys. Rev. D80 051301 (2009)

- electrons emitted by β-decay of tritium
- they spiral around an externally applied magnetic field lines
- as they do, they radiate cyclotron radiation

$$\omega = \frac{eB}{E + m_e}$$

- Frequency depends on electron energy
- Use antennas to measure frequency

Project 8



Electron scattering off gas molecule

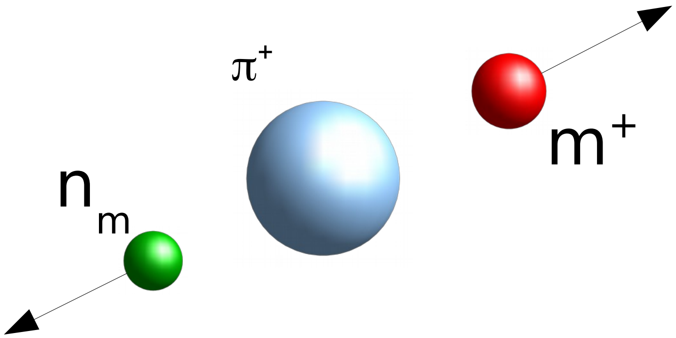
Frequency increases as electron slows down via cyclotron radiation

$$\omega = \frac{eB}{E + m_e}$$

$$\frac{\Delta E}{E} \sim 0.01\%$$

ν_μ mass

Easiest way is to use pion decay at rest



$$m_{\nu_\mu}^2 = m_\pi^2 + m_\mu^2 - 2\, m_\pi \sqrt{p_\mu^2 + m_\mu^2}$$

$$m_\pi = 139.56995 \pm 0.00035\, MeV$$

$$m_\mu = 105.658358 \pm 0.000005\, MeV$$

$$p_\mu = 29.792 \pm 0.00011\, MeV$$

$$m_\nu^2 = (-0.016 \pm 0.023)\, MeV^2$$

$$\boxed{m_\nu < 170\, keV \left(90\,\%\, CL\right)}$$

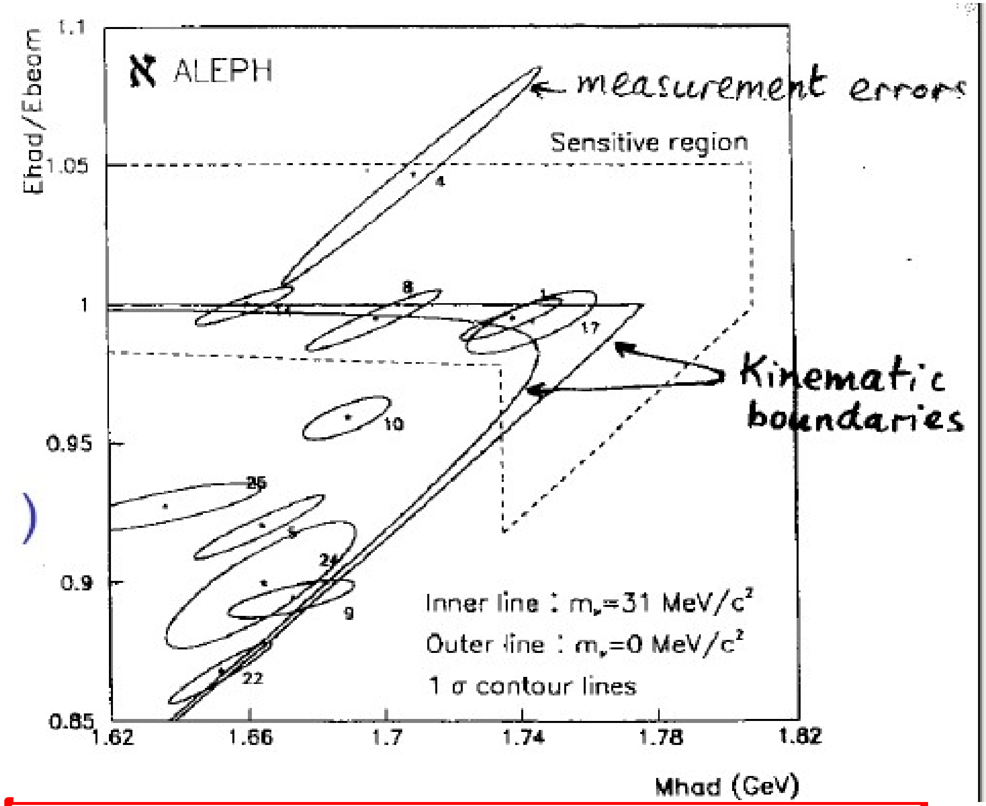
K. Assamagan et al. Phys. Rev. D 53 (1996) 6065

ν_τ mass

$$e^+ e^- \to \tau^+ \tau^-$$

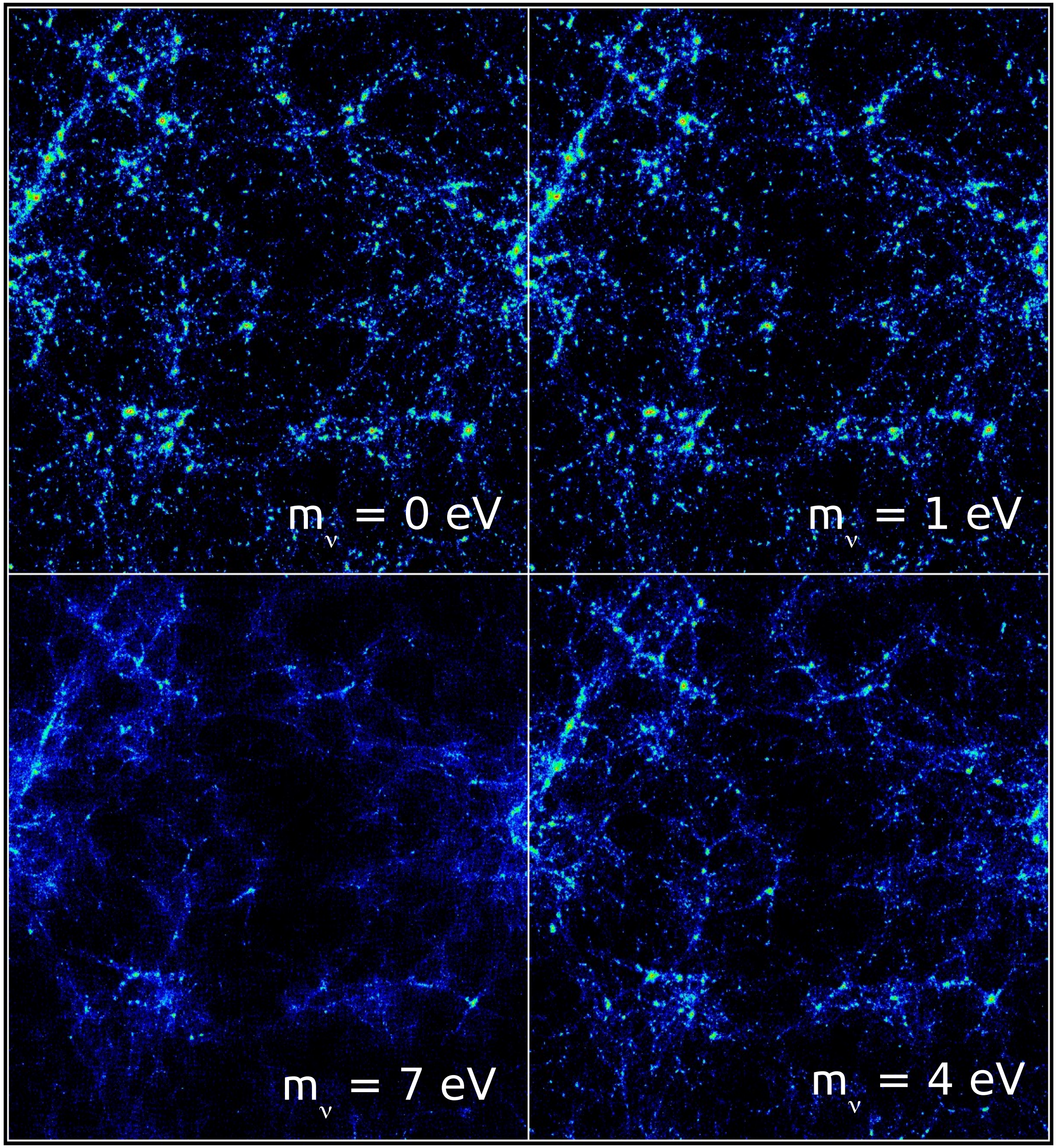
$$\hookrightarrow \ \tau \to \nu_\tau + 5\pi^{+-}(\pi^0)$$

$$E_\tau = \frac{\sqrt{s}}{2}$$



$$\boxed{m_\tau < 15.5\,MeV\,(95\%\,CL)}$$

Cosmology



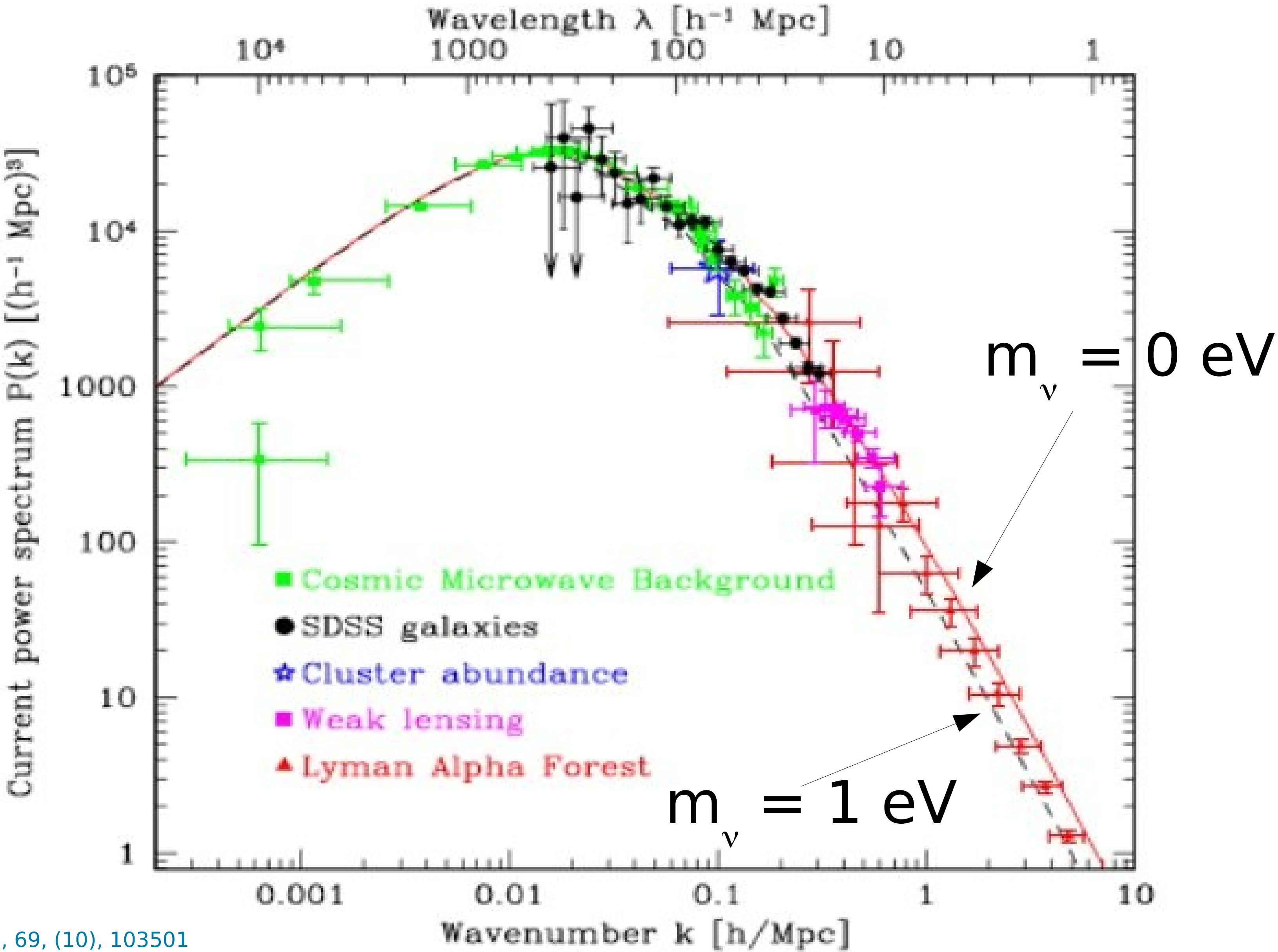
- Density fluctuations are affected by neutrino mass in the early universe
- Highly model dependent
- WMAP,2dF,ACBAR, CBI,PLANCK, BOSS, BAO, SDSS

$$\boxed{\sum m_{\nu_i} < (0.14 - 0.33)\, eV}$$

(rather model dependent)

Power spectra

“1/Wavelength” of density fluctuation



Tegmark, M. et al. 2004. PhRvD, 69, (10), 103501

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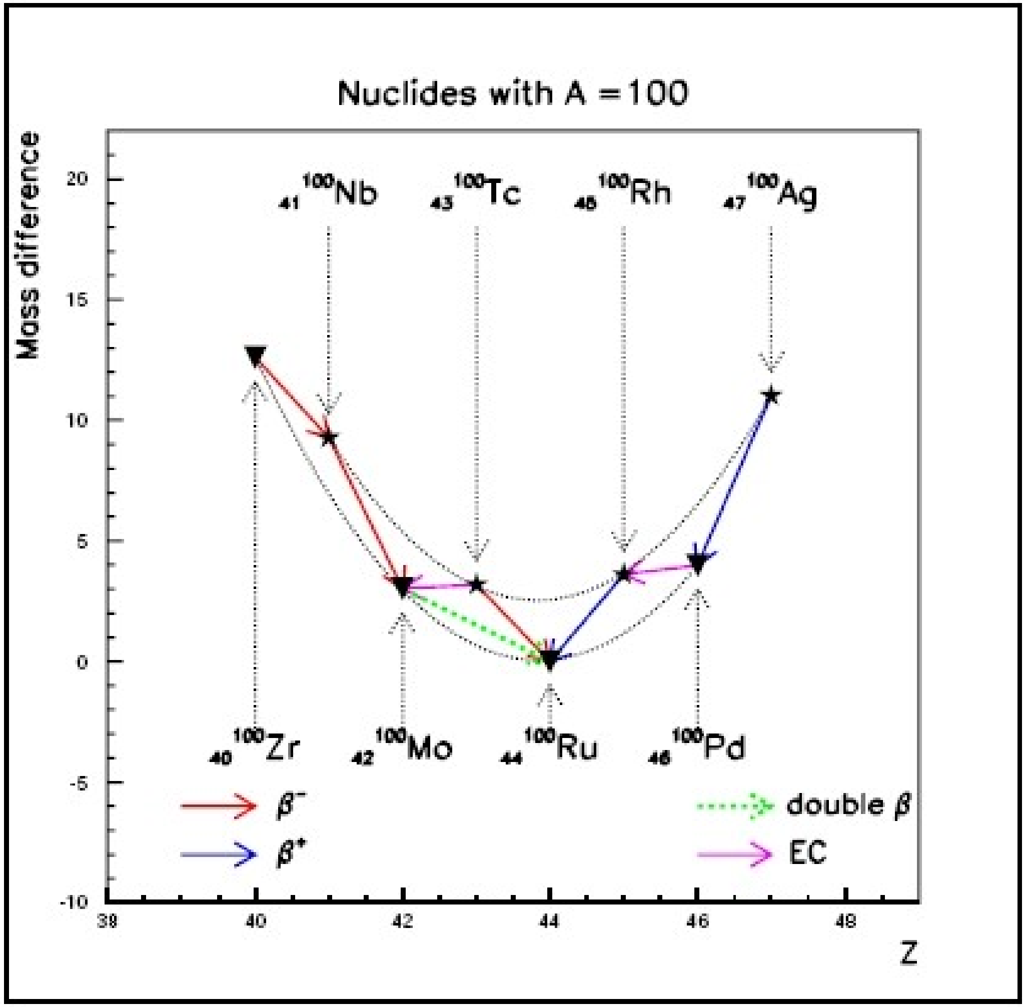
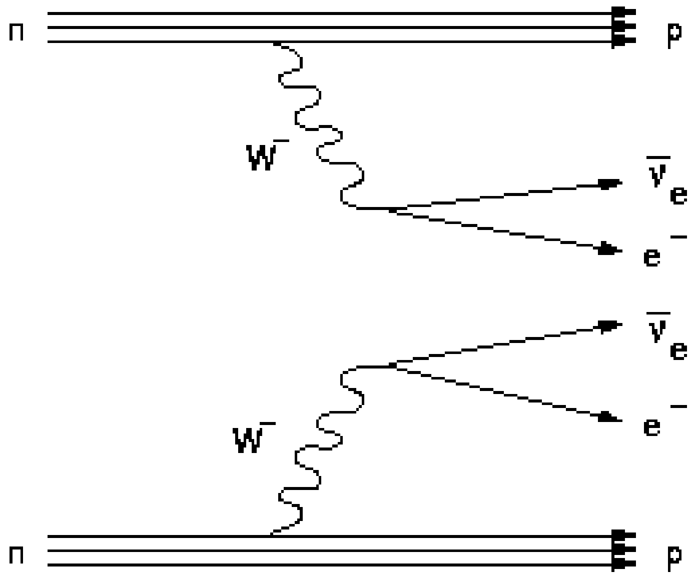
2ν-Double-β Decay

In some nuclei β decay is forbidden but double beta decay is not

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



2nbb Decay



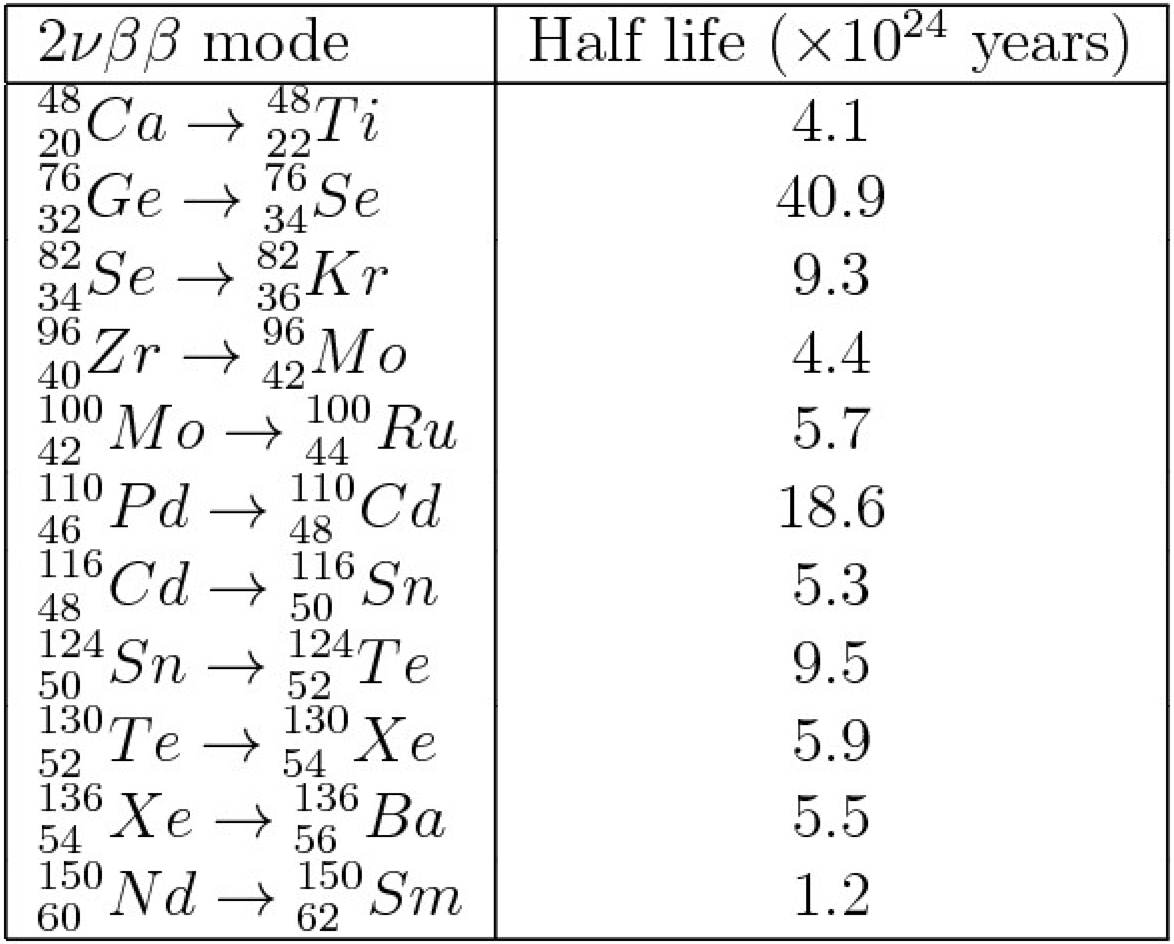
$$\left[T^{2\nu}_{1/2}\right]^{-1} = G^{2\nu}(Q,Z)\left|M^{2\nu}\right|^2$$

Calculable phase space

Nuclear matrix element

- Second order process in perturbation theory
- Severe test for nuclear matrix element calculation
- Nuclear structure effects cause variations in the nuclear matrix elements of factors of 10

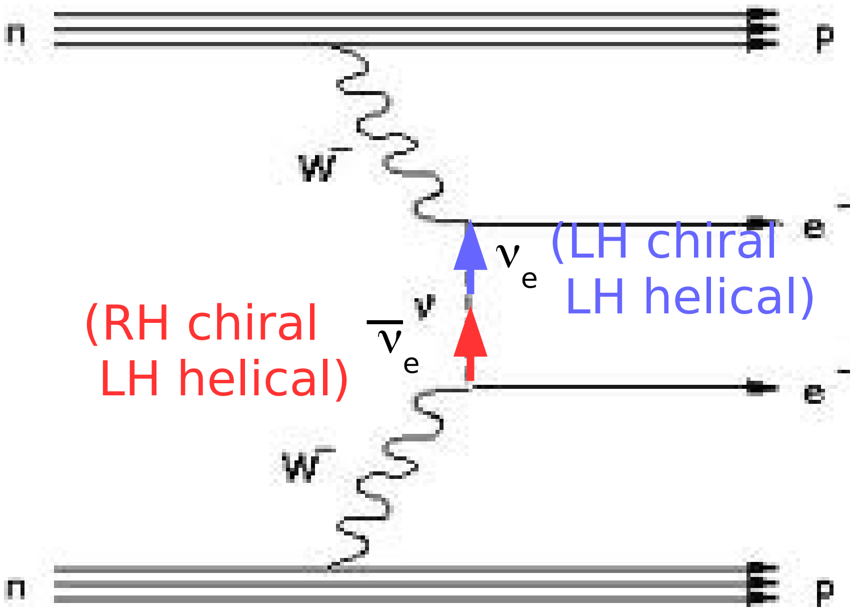
2nbb Decay



$2\nu\beta\beta$ mode	Half life ($\times 10^{24}$ years)
${}^{48}_{20}Ca \rightarrow {}^{48}_{22}Ti$	4.1
${}^{76}_{32}Ge \rightarrow {}^{76}_{34}Se$	40.9
${}^{82}_{34}Se \rightarrow {}^{82}_{36}Kr$	9.3
${}^{96}_{40}Zr \rightarrow {}^{96}_{42}Mo$	4.4
${}^{100}_{42}Mo \rightarrow {}^{100}_{44}Ru$	5.7
${}^{110}_{46}Pd \rightarrow {}^{110}_{48}Cd$	18.6
${}^{116}_{48}Cd \rightarrow {}^{116}_{50}Sn$	5.3
${}^{124}_{50}Sn \rightarrow {}^{124}_{52}Te$	9.5
${}^{130}_{52}Te \rightarrow {}^{130}_{54}Xe$	5.9
${}^{136}_{54}Xe \rightarrow {}^{136}_{56}Ba$	5.5
${}^{150}_{60}Nd \rightarrow {}^{150}_{62}Sm$	1.2

- Only occur in 36 known sources
- Rarest natural radioactive decay
- extremely long half-lives

Neutrinoless Double-β Decay



(LH chiral
LH helical)

(RH chiral
LH helical)

Requirements

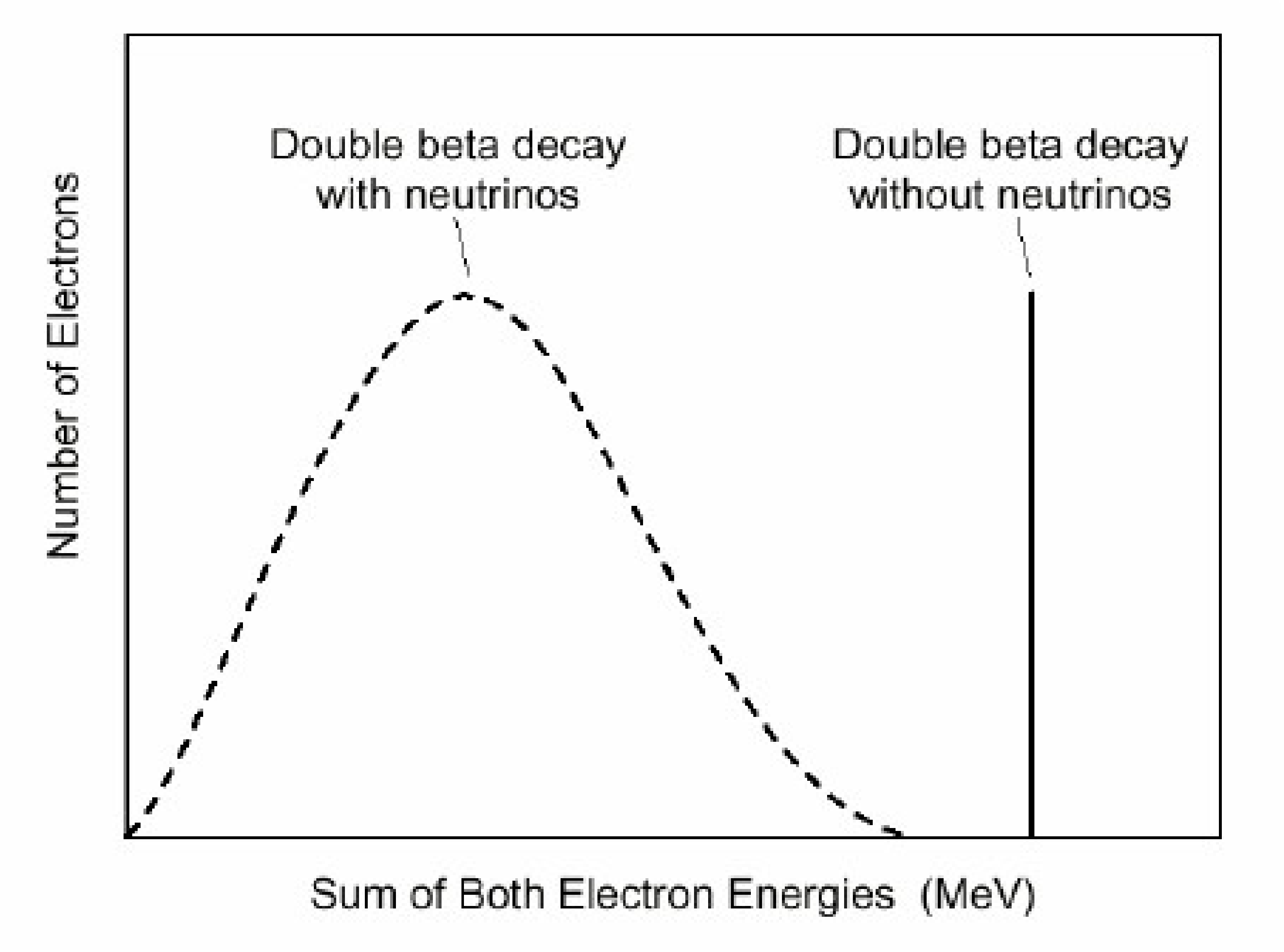
- Neutrino must have mass
- Neutrino is Majorana
- Violation of lepton number conservation

$$|\nu_L> = |\nu_{h=-1}> + \frac{m}{E}|\nu_{h=+1}>$$

helicity states

$$\boxed{\Gamma_{0\nu} = G_{0\nu}\left|M_{0\nu}\right|^2 <m_\nu>^2 \Rightarrow T_{1/2} \sim 10^{27}\ years}$$

0νββ signal


Double beta decay with neutrinos
Double beta decay without neutrinos
Number of Electrons
Sum of Both Electron Energies (MeV)

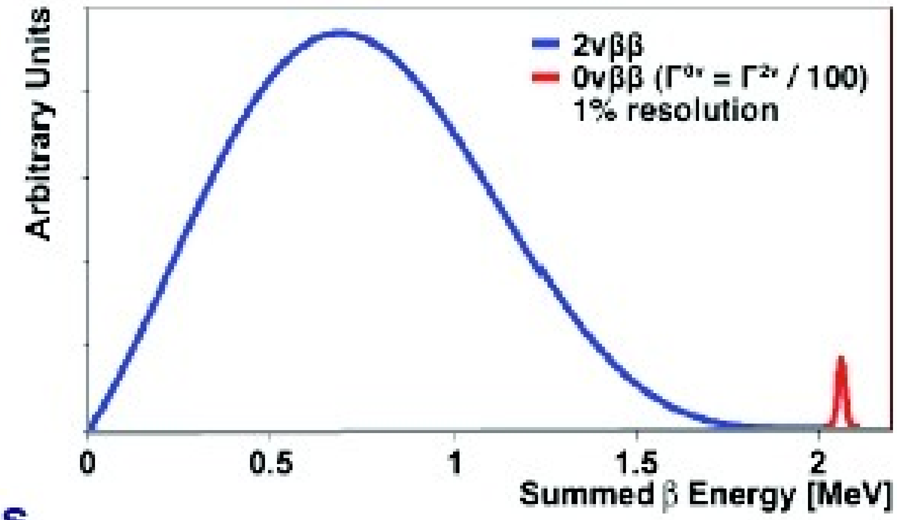
Experimental Requirements

Extremely slow decay rates

($0\nu\beta\beta$ $T_{1/2} \sim 10^{26} - 10^{27}$ years)

Best case,
0 background !

$\propto$ Source Mass • time$_{exp}$



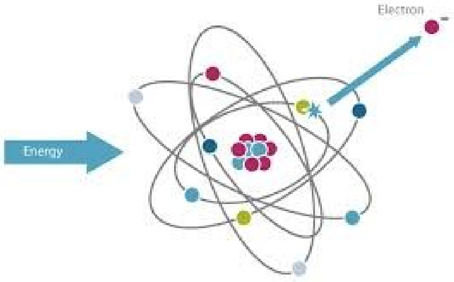
Requires

- Large, highly efficient source mass
  - detector as source
- Best possible energy resolution
  - minimize $0\nu\beta\beta$ peak ROI to maximize S/B
  - separate from $0\nu\beta\beta$ from irreducible $2\nu\beta\beta$ (~ $T_{1/2} \sim 10^{19} - 10^{21}$ years)
- Extremely low (near-zero) backgrounds in the $0\nu\beta\beta$ peak region
  - requires ultra-clean radiopure materials
  - the ability to discriminate signal from background

$0\nu\beta\beta$ detection

- Basic strategy : Measure energy of two outgoing electrons

Ionisation



Tracking Calorimeters

SuperNEMO

Semiconductor crystals

GERDA, Majorana

Gas TPCs:
EXO, NEXT

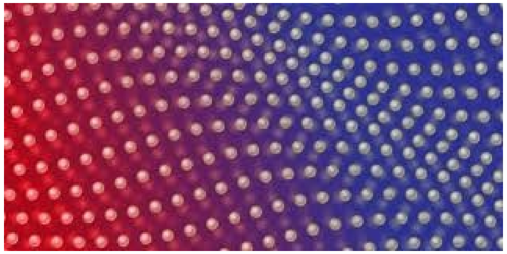
Scintillation

Liquid

KamLAND ZEN
SNO+

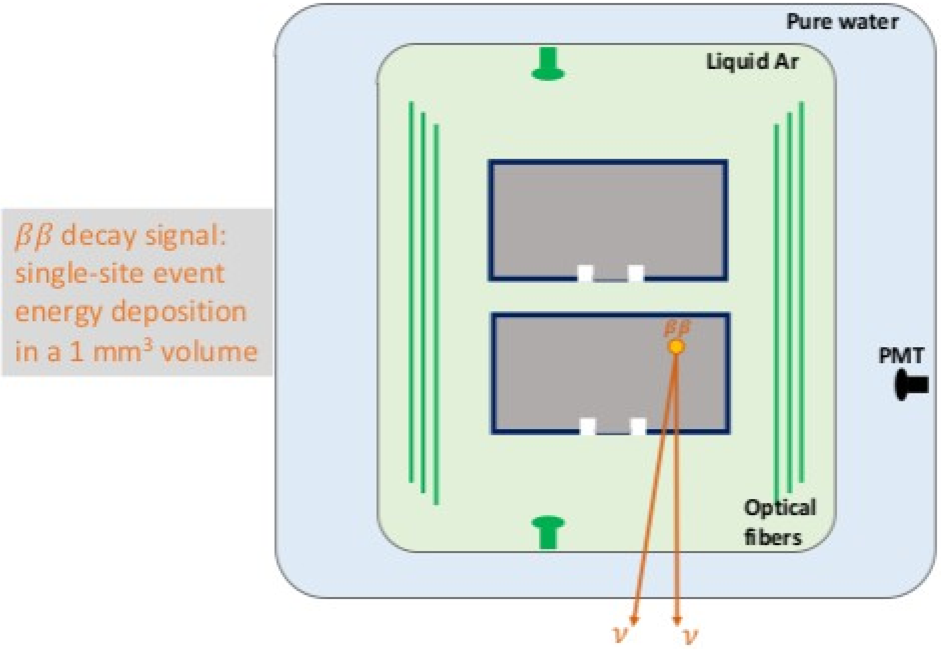
CUPID

Phonons



Bolometers : Cuore

Ionisation : GERDA



$\beta\beta$ decay signal:
single-site event
energy deposition
in a 1 mm^3 volume

- 44kg Ge-76 semiconductor
- inside a Lar cryostat
- surrounded by passive and active background mitigation

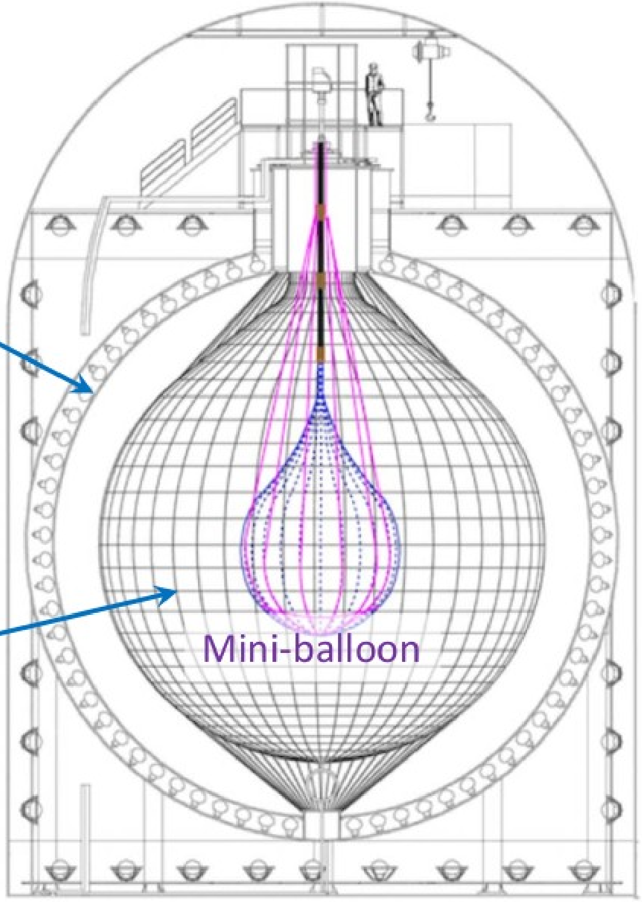
Strings assembly

Inverted Coaxial det. ~1.8 kg

Scintillation : KamLAND Zen

- Balloon containing 785 kg of enriched Xe-136 loaded into liquid scintillator
- Surrounded by buffer LS for detection and background mitigation
- Everything must be ultra-pure

Located in Kamioka Mine at 2700 m.w.e.

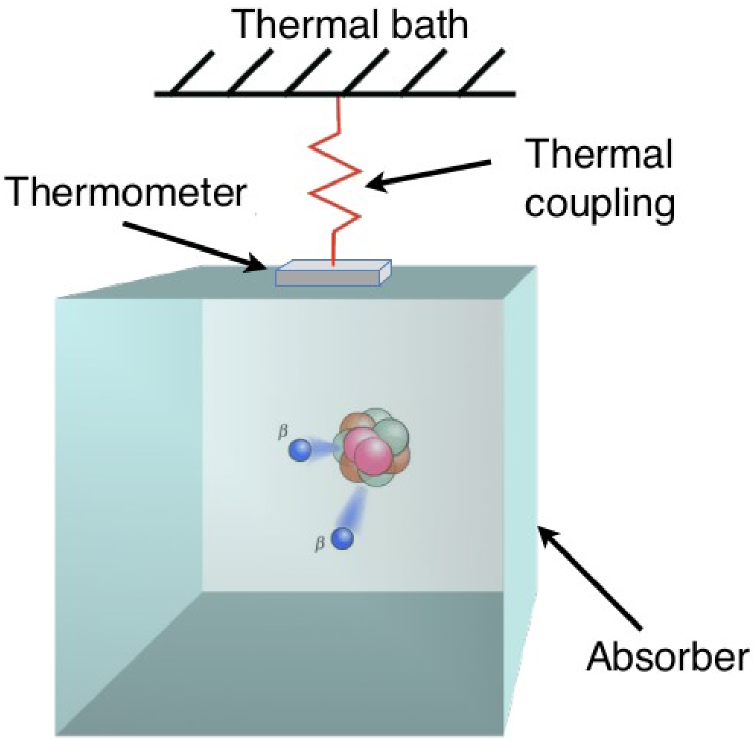


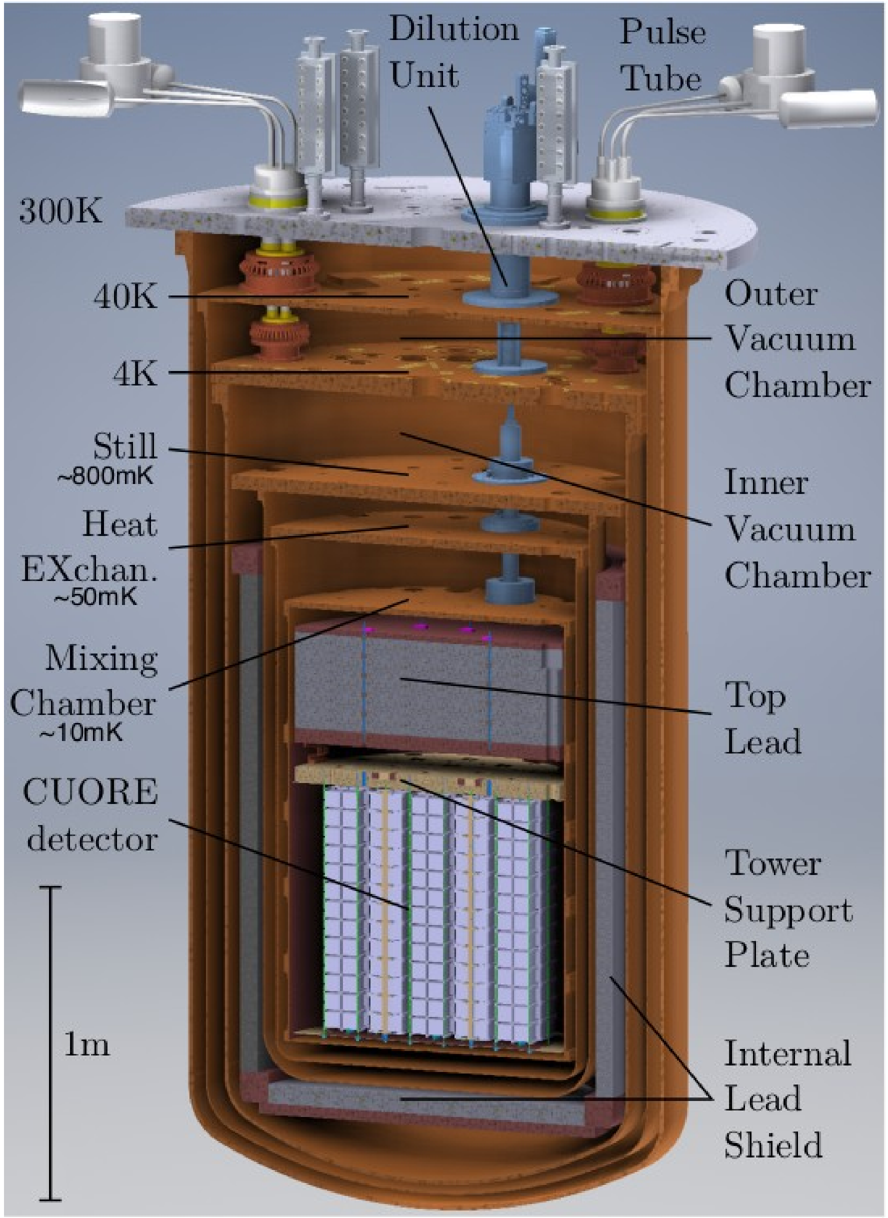
~34% photocoverage

~1 kiloton LS
- 20% PC
- 80% n-dodecane
- 1.36 g/L PPO

91% enriched ^{136}Xe loaded in LS inside mini-balloon (Q value = 2.4578 MeV)

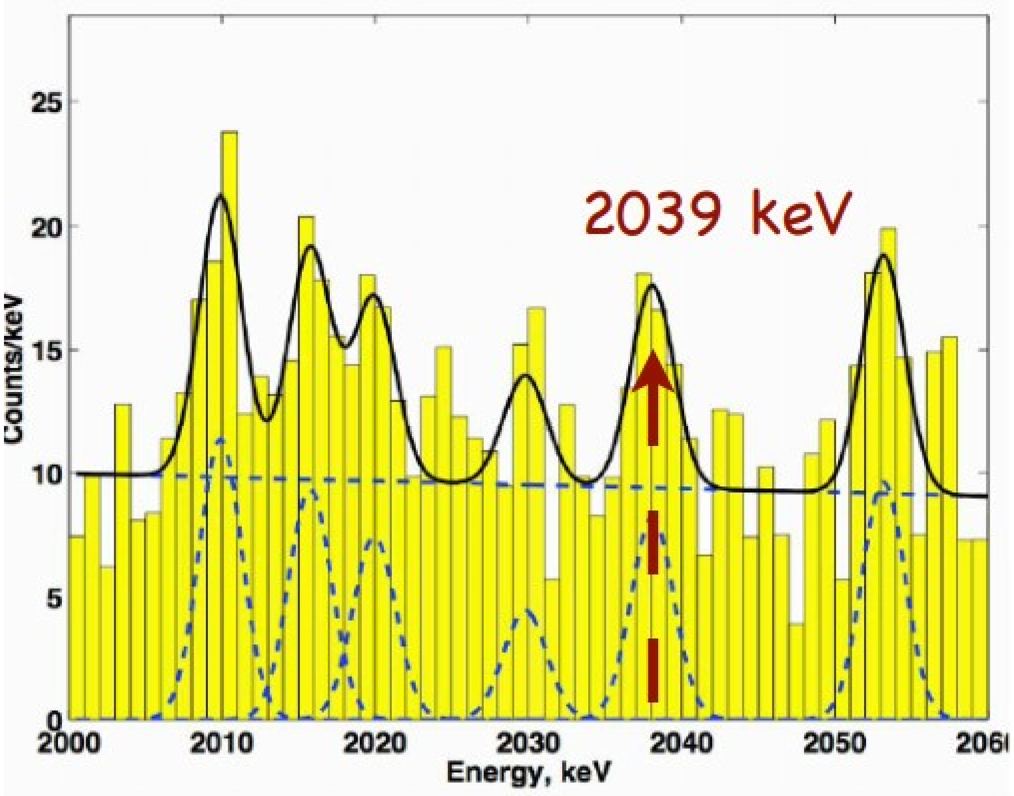
Phonons : CUORE





- 206 kg of Te-130
- Cooled to 10 mK
- Signal is an 80 μK temperature rise from electron energy deposition

A signal?

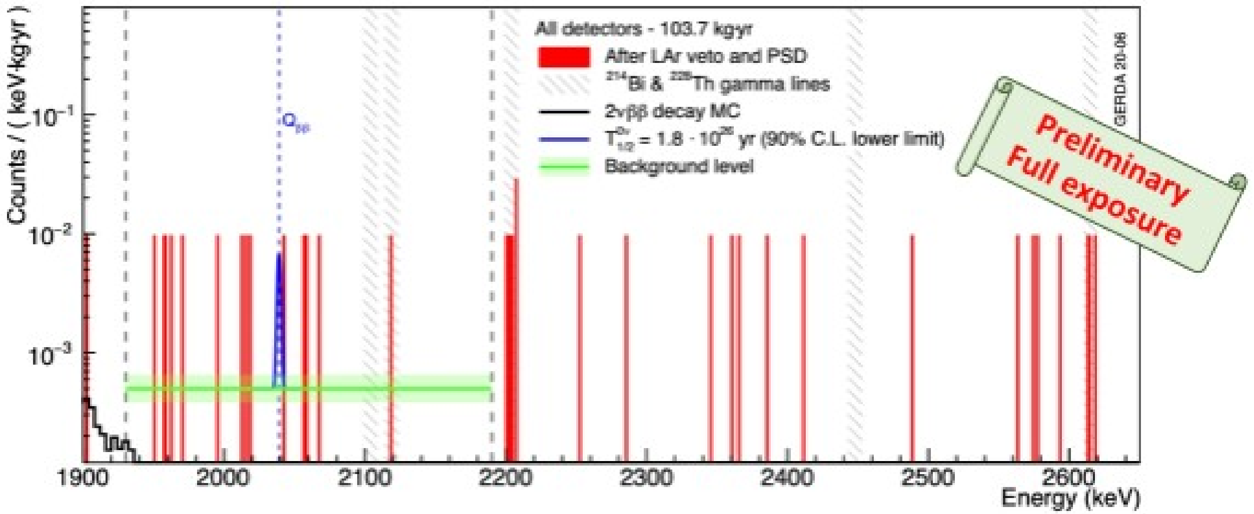


Klapdor-Kleingrothaus H V, Krivosheina I V, Dietz A and Chkvorets O, *Phys. Lett.* B **586** 198 (2004).

- Possible 4.2 σ signal claimed by the Heidelberg-Moscow Germanium experiment
- Highly controversial
    - Unknown lines in the spectrum
    - Rejected by part of the collaboration
    - No verification

If correct: $0.24\ eV < m_{\nu} < 0.58\ eV$

Results so far



GERDA : Ge-76

$$T_{1/2}^{0\nu} > 1.8\times10^{26}\ yr$$

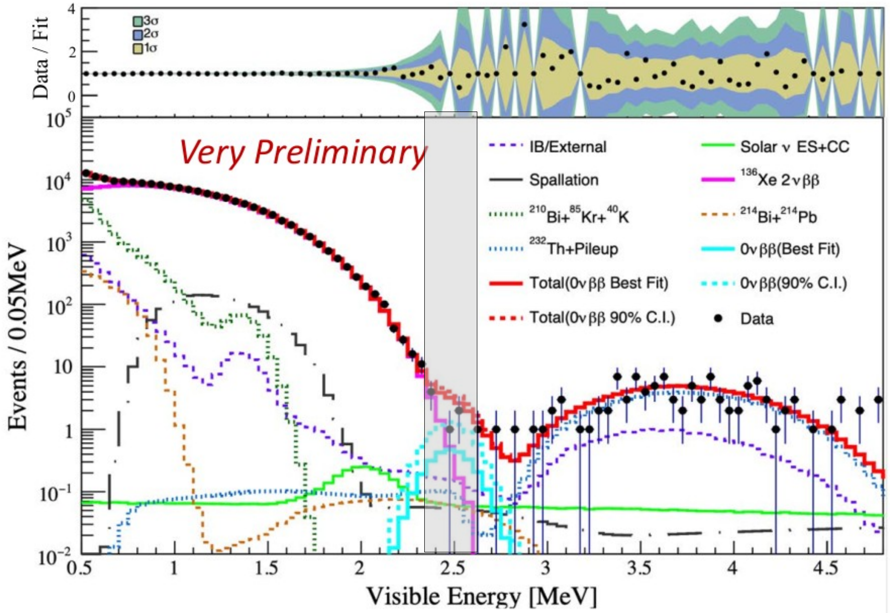
Y. Kermaidic, Neutrino 2020

KamLAND-Zen : Xe-136

8 events in ROI
Estimated BG : 7.9 events

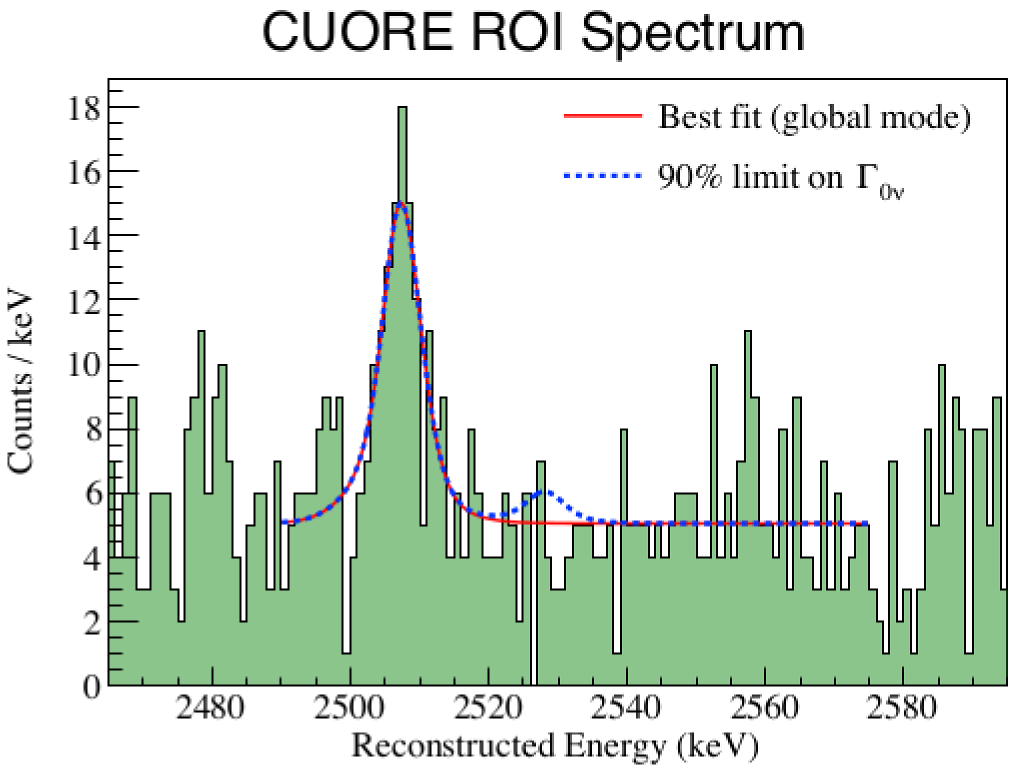
$$T_{1/2}^{0\nu} > 4\times10^{25}\ yr$$

C. Grant, Neutrino 2020



*Data shown for r < 1.57 m

Results so far



$$T^{0\nu}_{1/2} > 3.2\times10^{25}\,yr$$

$$1/T^{0\nu}_{1/2} = G_{0\nu}\left|M_{0\nu}\right|^2 < m_\nu >^2$$

Experiment	**Neutrino Mass Limit**
GERDA	< 8 – 182 meV
KamLAND-Zen	< 61 – 165 meV
CUORE	< 75 – 350 meV

The Future

Collaboration	Isotope	Technique	mass ($0\nu\beta\beta$ isotope)	Status
CANDLES-III	^{48}Ca	305 kg CaF_2 crystals in liquid scintillator	0.3 kg	Operating
CANDLES-IV	^{48}Ca	CaF_2 scintillating bolometers	TBD	R&D
GERDA	^{76}Ge	Point contact Ge in active LAr	44 kg	Complete
Majorana Demonstrator	^{76}Ge	Point contact Ge in Lead	30 kg	Operating
LEGEND 200	^{76}Ge	Point contact Ge in active LAr	200 kg	Construction
LEGEND 1000	^{76}Ge	Point contact Ge in active LAr	1 tonne	R&D
SuperNEMO Demonstrator	^{82}Se	Foils with tracking	7 kg	Construction
SELENA	^{82}Se	Se CCDs	<1 kg	R&D
NvDEx	^{82}Se	SeF_6 high pressure gas TPC	50 kg	R&D
ZICOS	^{96}Zr	10% ^{nat}Zr in liquid scintillator	45 kg	R&D
AMoRE-I	^{100}Mo	$^{40}CaMoO_4$ scintillating bolometers	6 kg	Construction
AMoRE-II	^{100}Mo	Li_2MoO_4 scintillating bolometers	100 kg	Construction
CUPID	^{100}Mo	Li_2MoO_4 scintillating bolometers	250 kg	R&D
COBRA	^{116}Cd/^{130}Te	CdZnTe detectors	10 kg	Operating
CUORE	^{130}Te	TeO_2 Bolometer	206 kg	Operating
SNO+	^{130}Te	0.5% ^{nat}Te in liquid scintillator	1300 kg	Construction
SNO+ Phase II	^{130}Te	2.5% ^{nat}Te in liquid scintillator	8 tonnes	R&D
Theia-Te	^{130}Te	5% ^{nat}Te in liquid scintillator	31 tonnes	R&D
KamLAND-Zen 400	^{136}Xe	2.7% in liquid scintillator	370 kg	Complete
KamLAND-Zen 800	^{136}Xe	2.7% in liquid scintillator	750 kg	Operating
KamLAND2-Zen	^{136}Xe	2.7% in liquid scintillator	~tonne	R&D
EXO-200	^{136}Xe	Xe liquid TPC	160 kg	Complete
nEXO	^{136}Xe	Xe liquid TPC	5 tonnes	R&D
NEXT-WHITE	^{136}Xe	High pressure GXe TPC	~5 kg	Operating
NEXT-100	^{136}Xe	High pressure GXe TPC	100 kg	Construction
PandaX	^{136}Xe	High pressure GXe TPC	~tonne	R&D
AXEL	^{136}Xe	High pressure GXe TPC	~tonne	R&D
DARWIN	^{136}Xe	^{nat}Xe liquid TPC	3.5 tonnes	R&D
LZ	^{136}Xe	^{nat}Xe liquid TPC		R&D
Theia-Xe	^{136}Xe	3% in liquid scintillator	50 tonnes	R&D

R&D Construction Operating Complete

Direct mass measurements

Tritium β decay	$\left(\sum_i \left\|U_{ei}{}^{2}\right\| m_i^2\right)^{\frac{1}{2}}$	< 2.3 eV Katrin extends sensitivity to 0.2 eV
0ν2β decay	$\left\|\sum_i U_{ei}^2 m_i\right\|$	<0.08-0.35 eV
Cosmology	$\sum_i m_i < 0.33\, eV$	Model dependent
Pion decay	$m_{\nu\mu} < 170\, keV$	Fairly pointless
Tau decay	$m_{\nu\tau} < 18.2\, MeV$	Entirely pointless

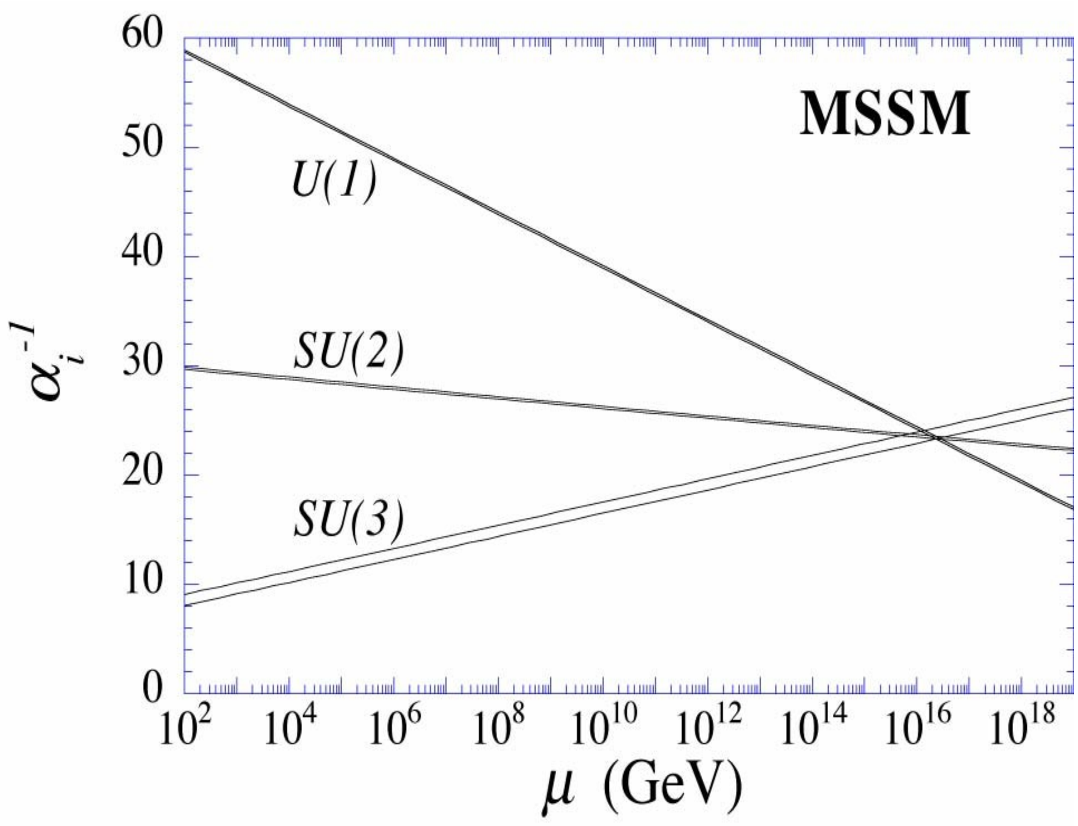
Seesaw and GUTs

- Electromagnetic, strong and weak forces have very different strengths

- If supersymmetry is valid their strengths are the same at around 10^{16} GeV

- To explain light neutrino masses through the see-saw mechanics, we need a heavy neutrino partner with mass 10^{16} GeV

- Probing of GUT scale physics using light neutrinos!

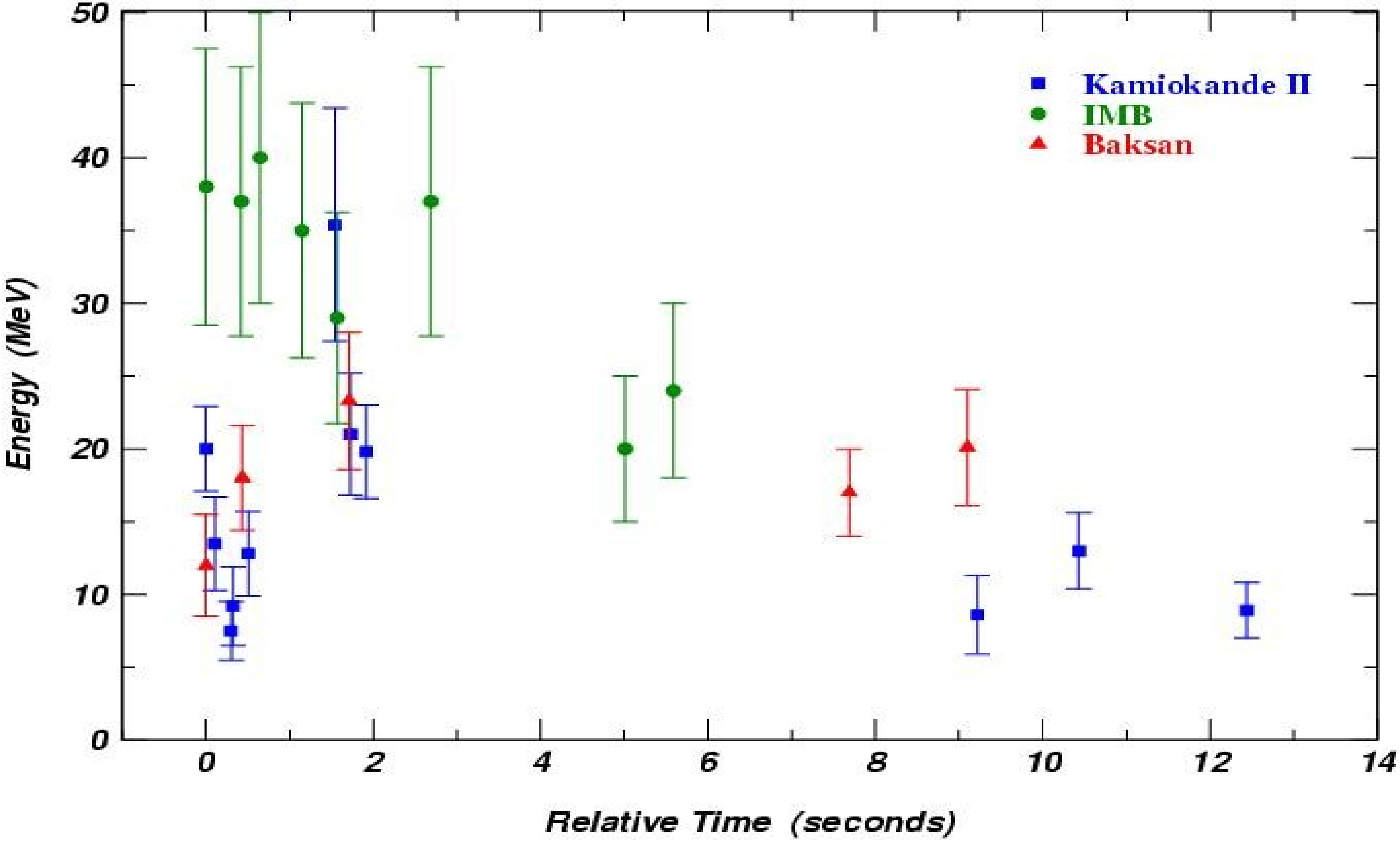


SN1987A

© Anglo-Australian Observatory

Neutrinos detected

Four neutrino detectors operating at the time
Kamiokande II, IMB, BST, Mont Blanc



Mass from Velocity

The neutrinos had travelled 150,000 light years – enough for small mass differences to show up as a difference in arrival times

$$t_F = t - t_0 = \frac{L}{v} = \frac{L}{c}\frac{E_\nu}{p_\nu}c \sim \frac{L}{c}\left(1 + m_\nu^2 \frac{c^4}{2} E^2\right)$$

$$\delta t = t_j - t_i = \delta t_0 + \frac{L m_\nu^2}{2c}\left(\frac{1}{E_j^2} - \frac{1}{E_i^2}\right)$$

Estimate dependent on models of supernova process (emission intervals, size of the neutrino shell etc)

$$m_{\overline{\nu}_e} < 5.7\, eV\, (95\ CL)$$

The General Mass Term

If we are resigned to the existence of a sterile right-handed state, then we can construct a general mass term with Dirac and Majorana masses

$$L_{mass} = \begin{pmatrix} \overline{n_L^C} & \overline{n_R^C} \end{pmatrix} \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix} \begin{pmatrix} n_L \\ n_R^C \end{pmatrix}$$

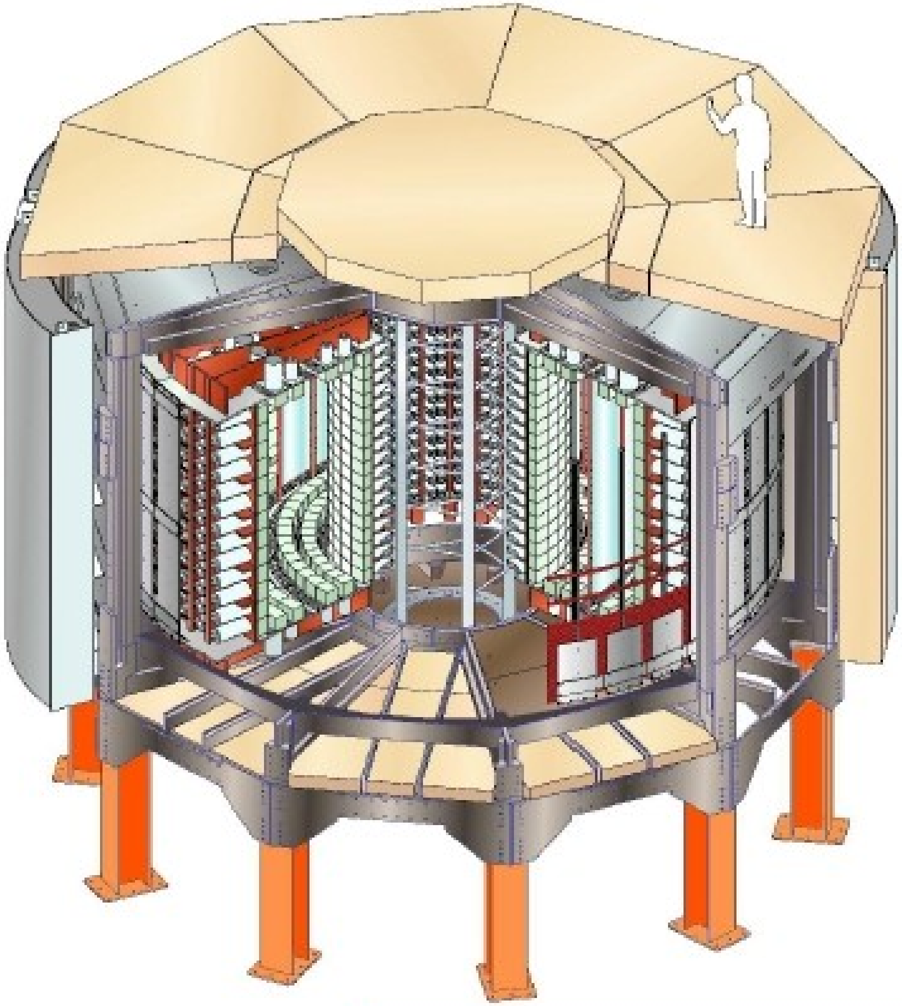
$$n \equiv \begin{pmatrix} n_L \\ n_R^C \end{pmatrix} \rightarrow L_{mass} = -\frac{1}{2}\left[\overline{n^C} M n + \bar{n} M n^C\right] \quad with \quad M = \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix}$$

Observable masses are the eigenvalues of the diagonalised mass matrix (m_1,m_2)

$$\tilde{M} = Z^{-1} M Z = \begin{pmatrix} \tilde{m}_1 & 0 \\ 0 & \tilde{m}_2 \end{pmatrix} \qquad \tilde{m}_{1,2} = \frac{1}{2}\left[(m_L + m_R) \pm \sqrt{(m_L - m_R)^2 + 4 m_D^2}\right]$$

Mixing matrix

Passive Source - NEMO3



Source: 10 kg of ββ isotopes
cylindrical, S = 20 m^2, 60 mg/cm^2

Tracking detector:
drift wire chamber operating
in Geiger mode (6180 cells)
Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H_2O

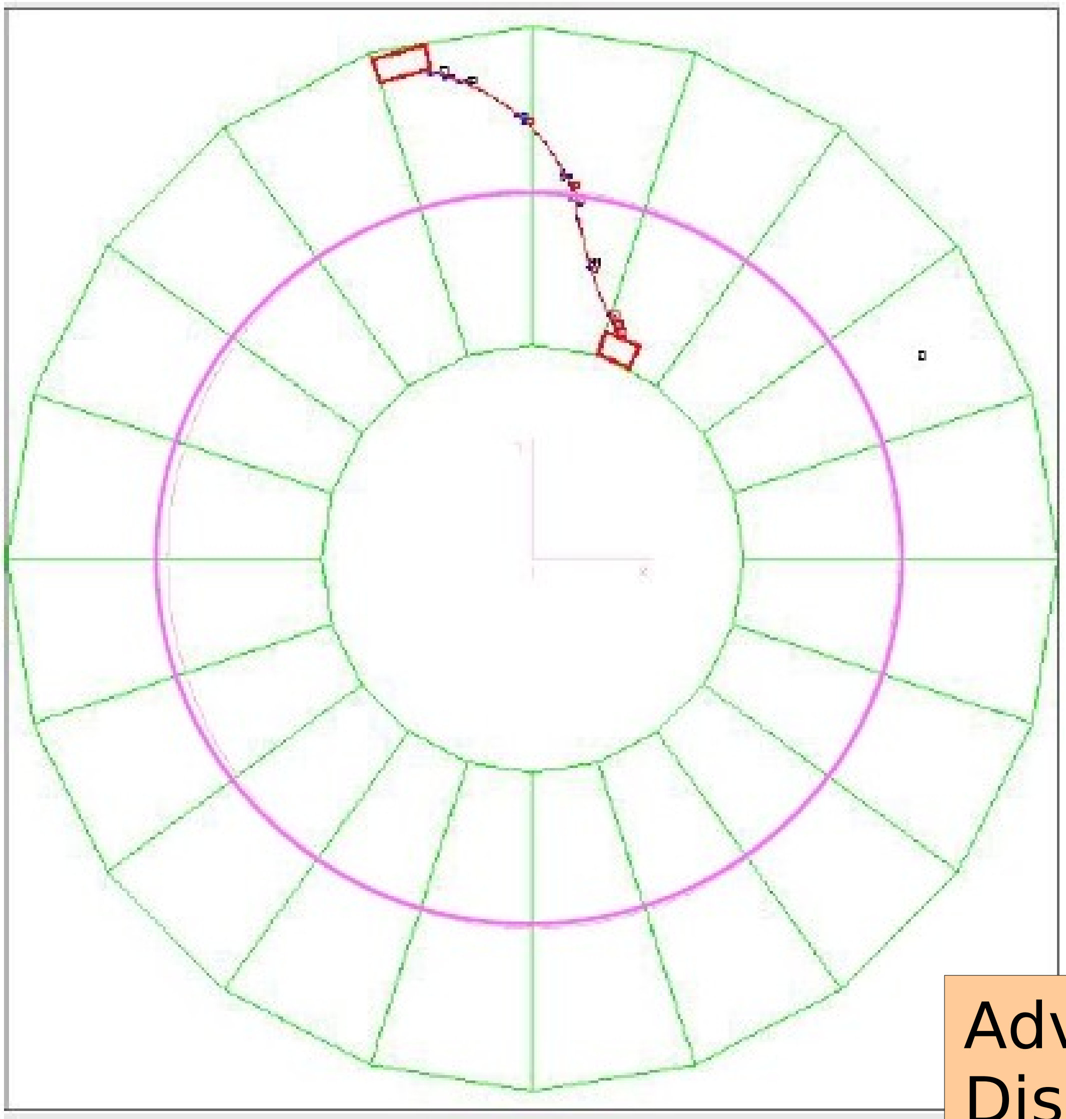
Calorimeter:
1940 plastic scintillators
coupled to low radioactivity PMTs

Magnetic field: 25 Gauss
Gamma shield: Pure Iron (18 cm)
Neutron shield: borated water
+ Wood

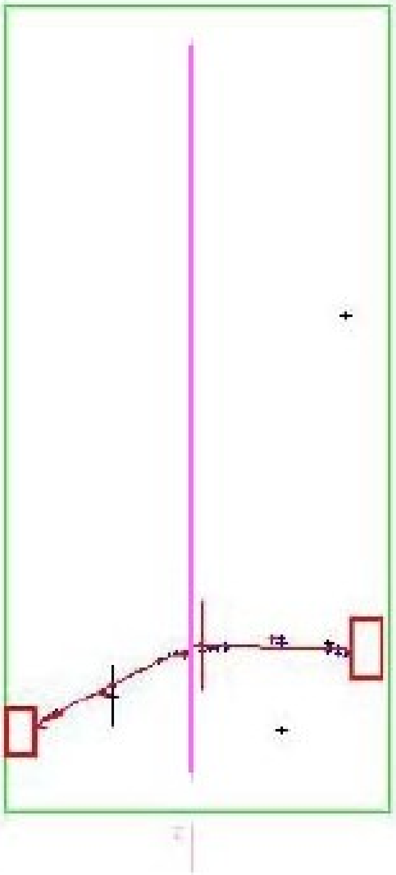
Background: n [illegible] 2.6 MeV)

Able to identify e^-, e^+, γ and α

Typical $\beta\beta 2\nu$ event observed from ^{100}Mo



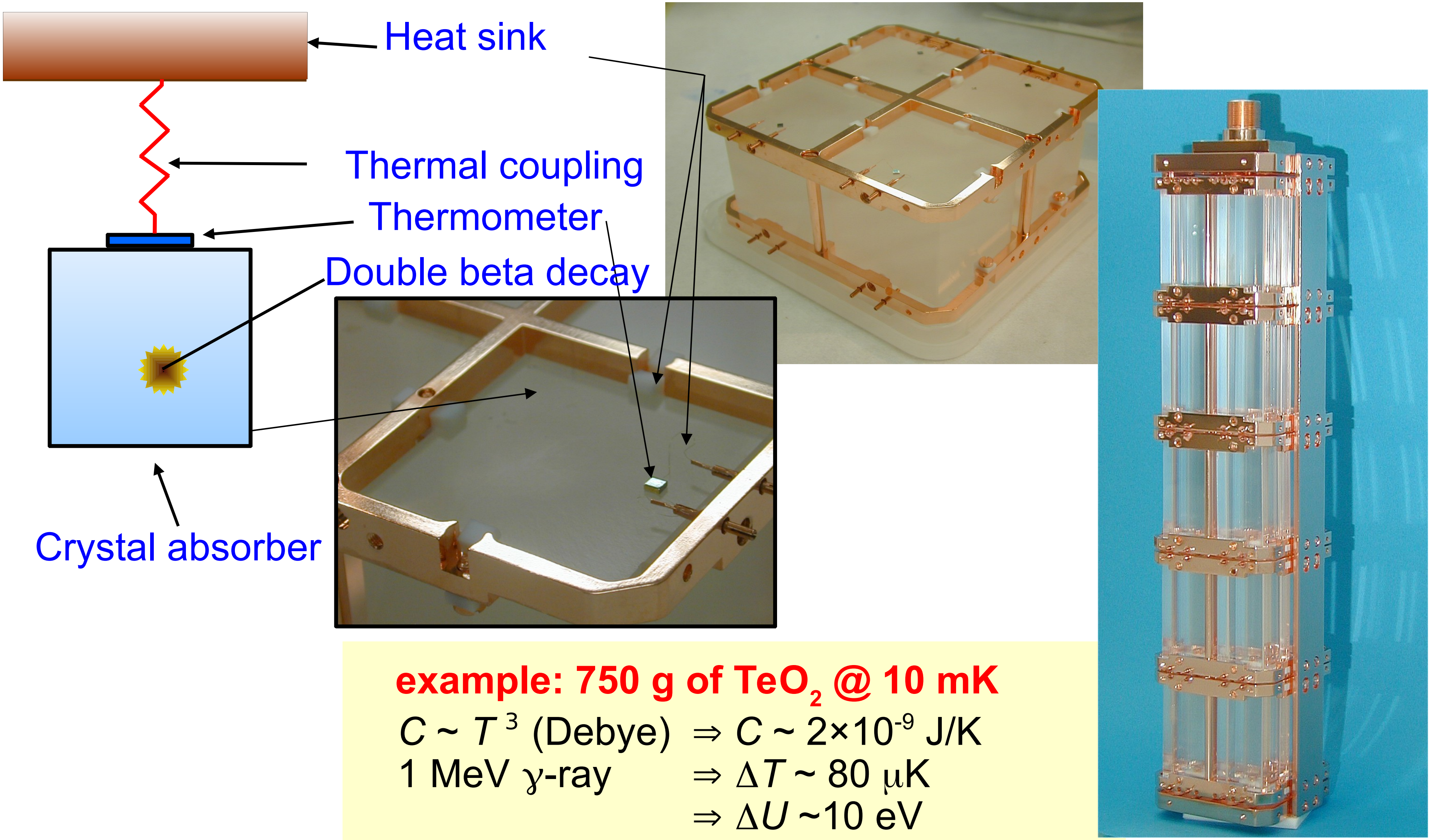
Top view



Side view

Advantage : electron tracking
Disadvantage : less source material and worse energy resolution

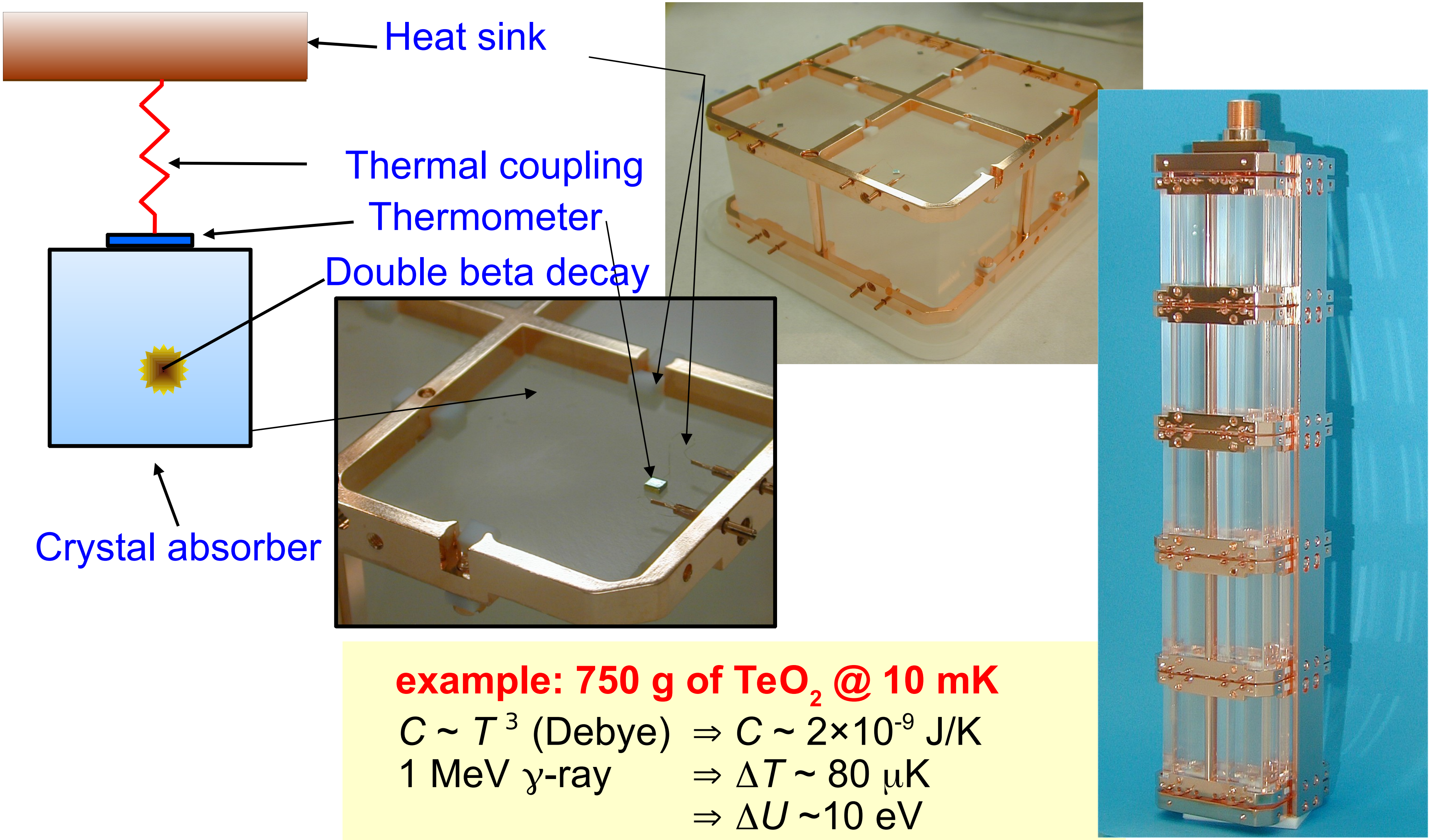
Cuoricino/Cuore



example: 750 g of TeO_2 @ 10 mK

$C \sim T^3$ (Debye) $\Rightarrow C \sim 2\times10^{-9}$ J/K
1 MeV γ-ray $\Rightarrow \Delta T \sim 80\ \mu$K
$\Rightarrow \Delta U \sim 10$ eV

Cuoricino/Cuore



Heat sink

Thermal coupling

Thermometer

Double beta decay

Crystal absorber

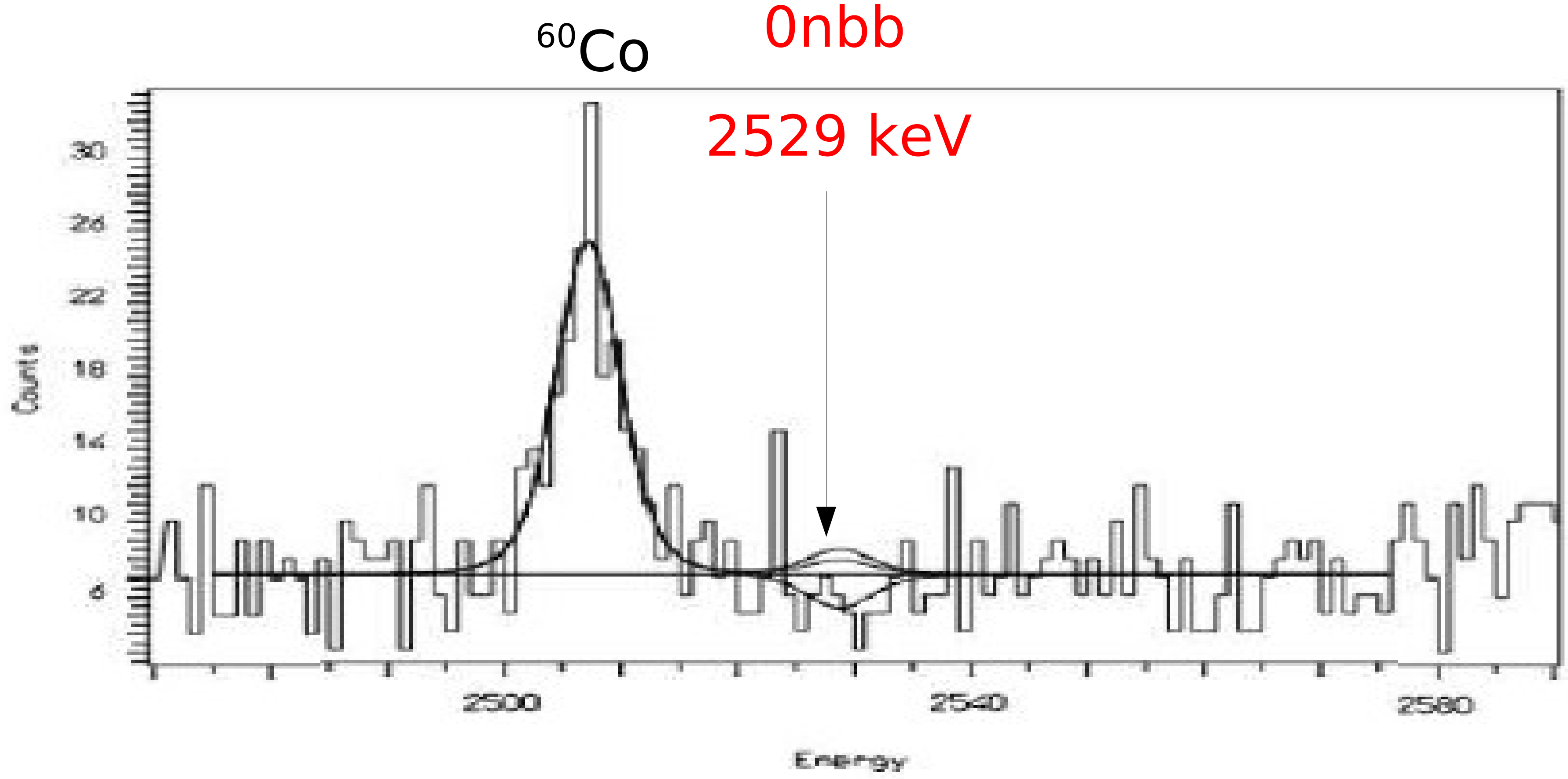
example: 750 g of TeO_2 @ 10 mK

$C \sim T^3$ (Debye) ⇒ $C \sim 2\times10^{-9}$ J/K

1 MeV γ-ray ⇒ $\Delta T \sim 80\ \mu K$

⇒ $\Delta U \sim 10$ eV

Cuoricino Results

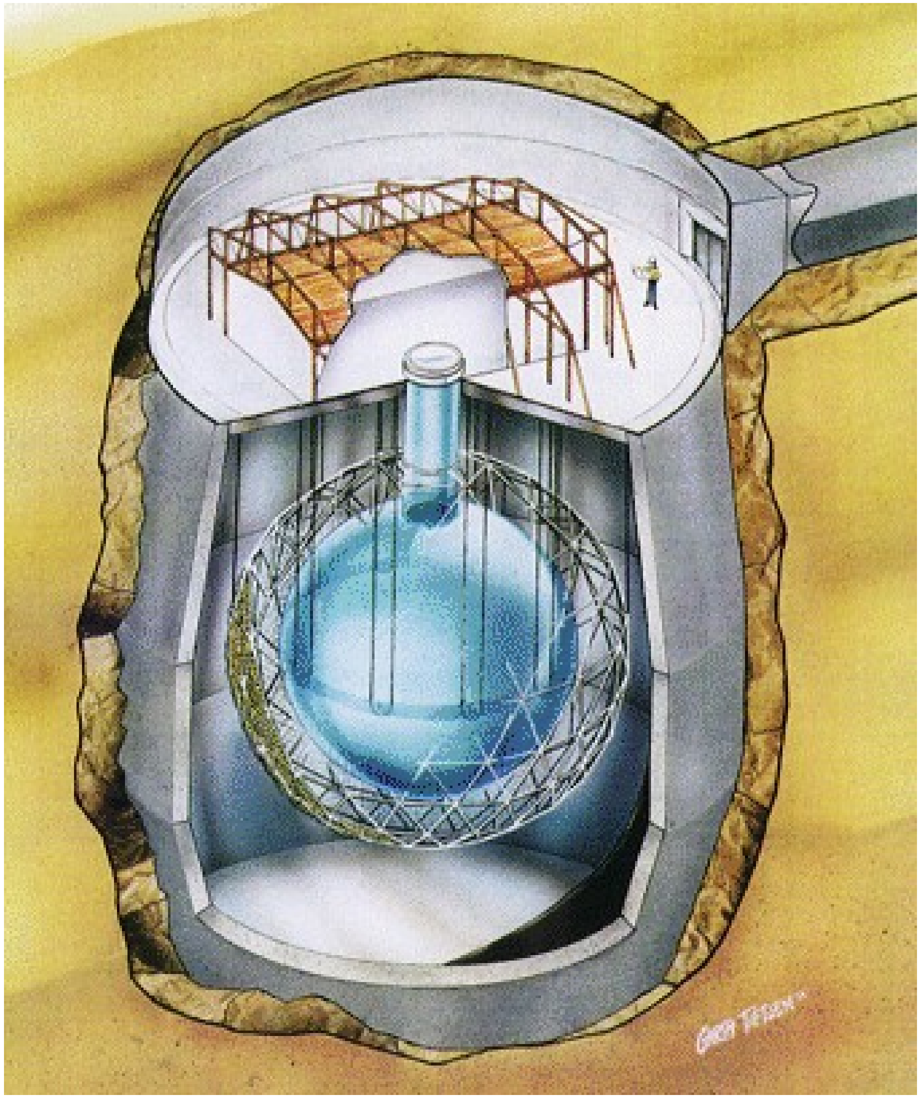

^{60}Co

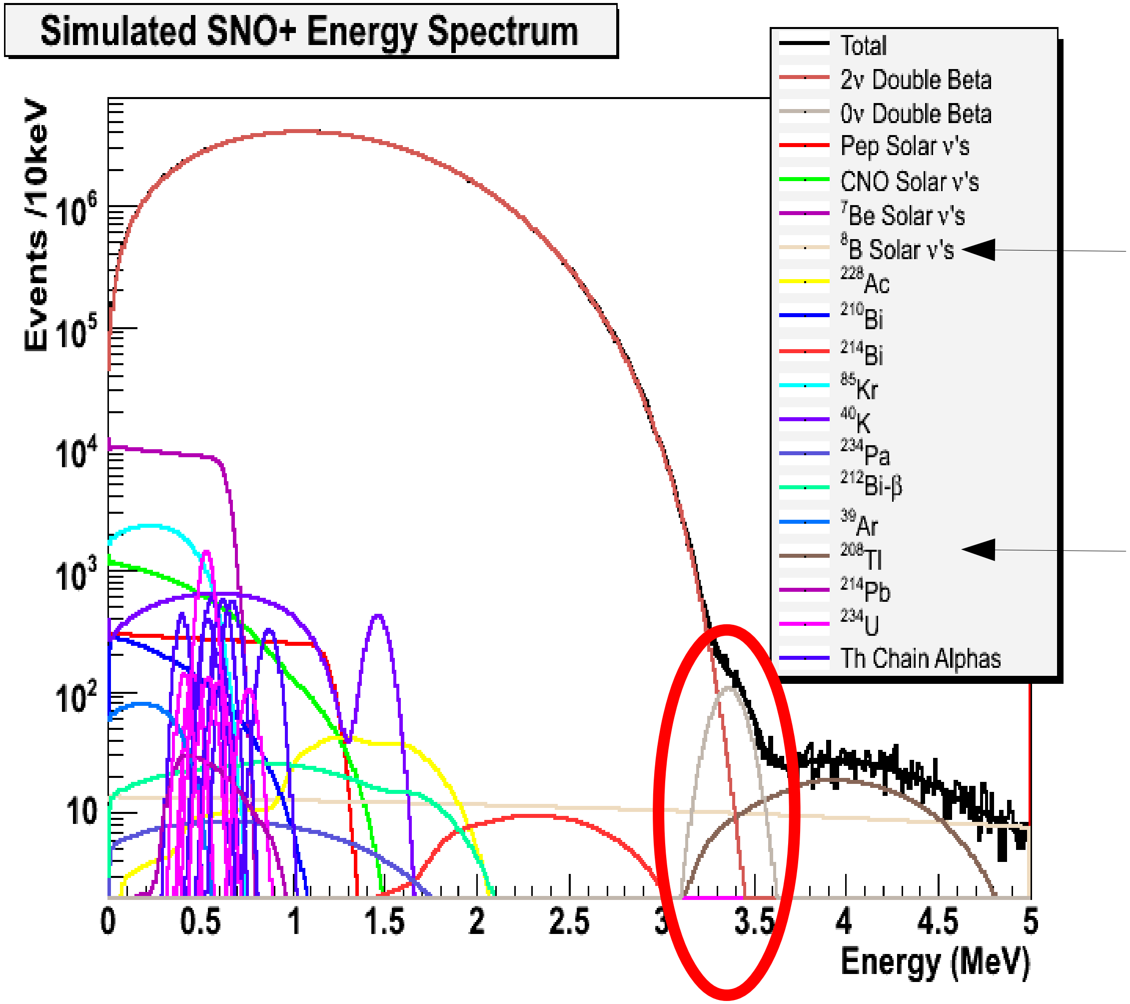
0nbb

2529 keV

$$T^{0\nu}_{1/2} > 3.0\times 10^{24}\, years \;\Rightarrow\; \langle m_\nu \rangle < 0.68\, eV$$

SNO+





^{150}Nd loaded - $m_n < 80$ meV

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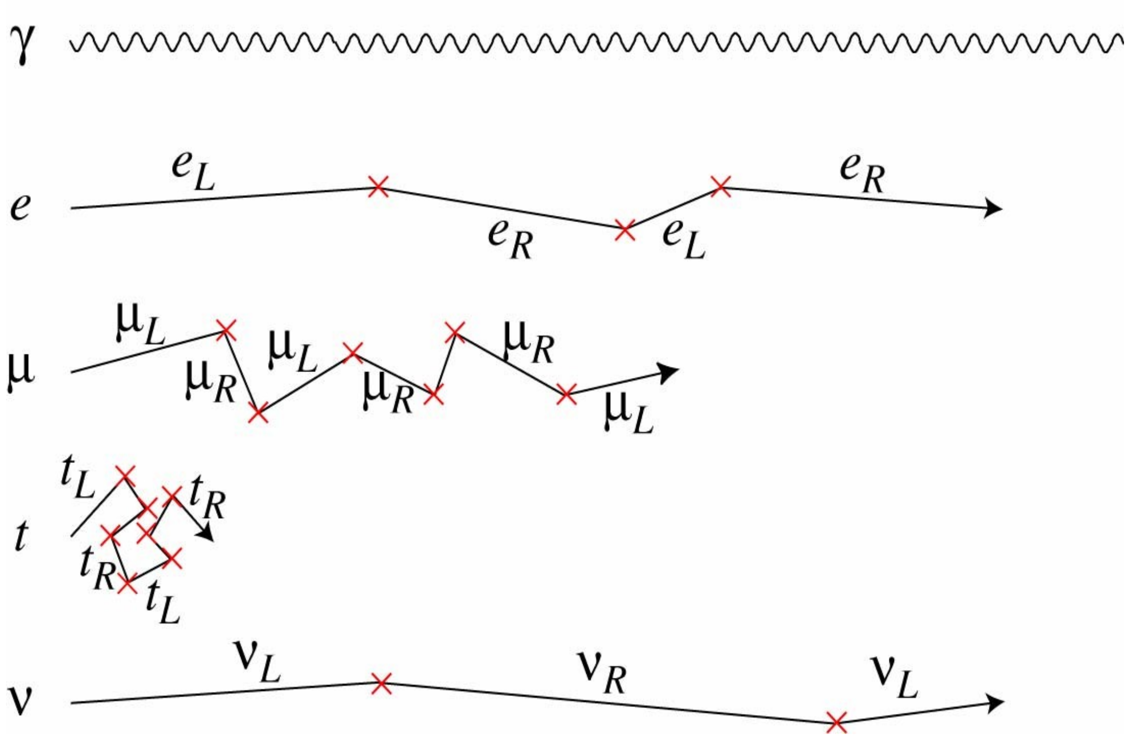
Mixing matrix

Two ways to go

Dirac neutrinos

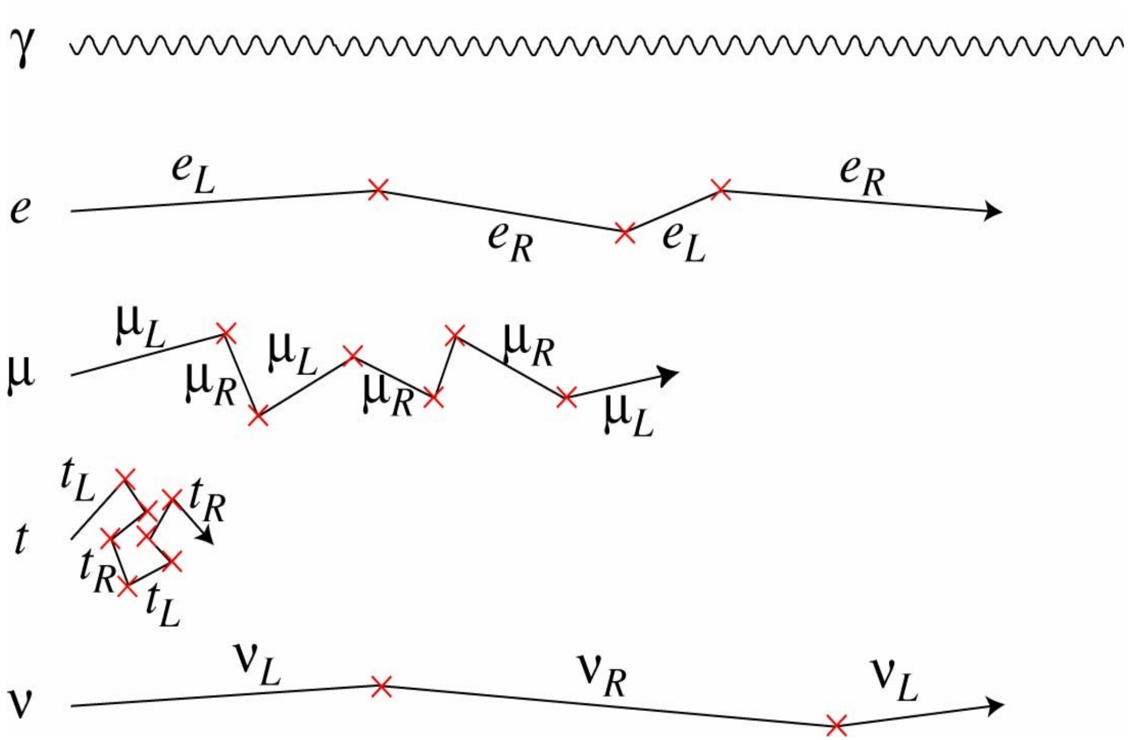
- There are new particles (right handed neutrinos) after all
- Why haven't we seen them?
- They must only exist to give neutrinos mass
- Still have to solve the question of their very very weak coupling



Two ways to go

Majorana neutrinos

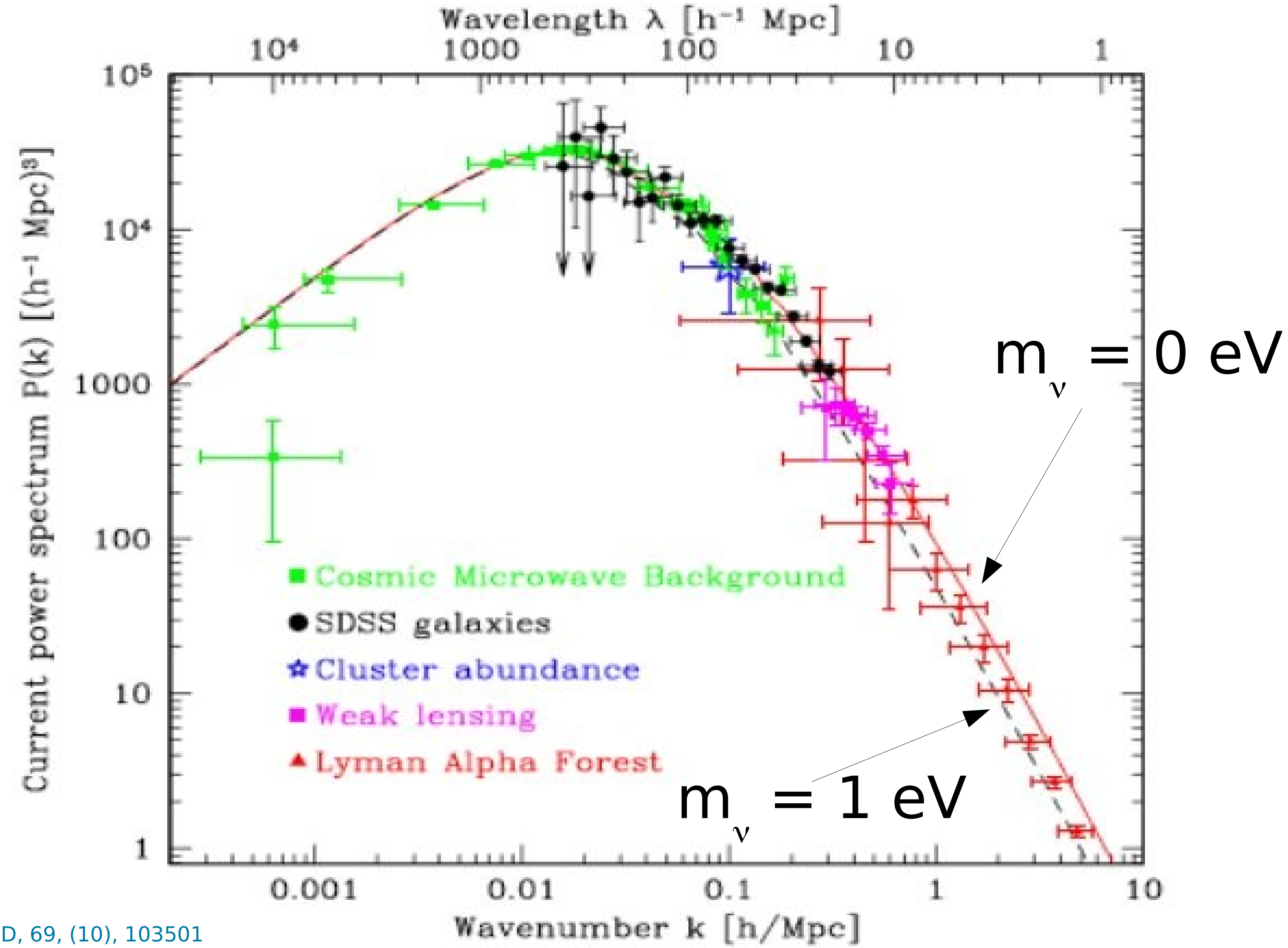
- There are new particles (right handed neutrinos) after all
- If I pass a neutrino and look back I will see a right-handed thing
- Must be a right-handed anti-neutrino
- No fundamental difference between neutrinos and anti-neutrinos



(Theorists Favourite!)

Power spectra

“1/Wavelength” of density fluctuation



$m_\nu = 0$ eV

$m_\nu = 1$ eV

Tegmark, M. et al. 2004. PhRvD, 69, (10), 103501

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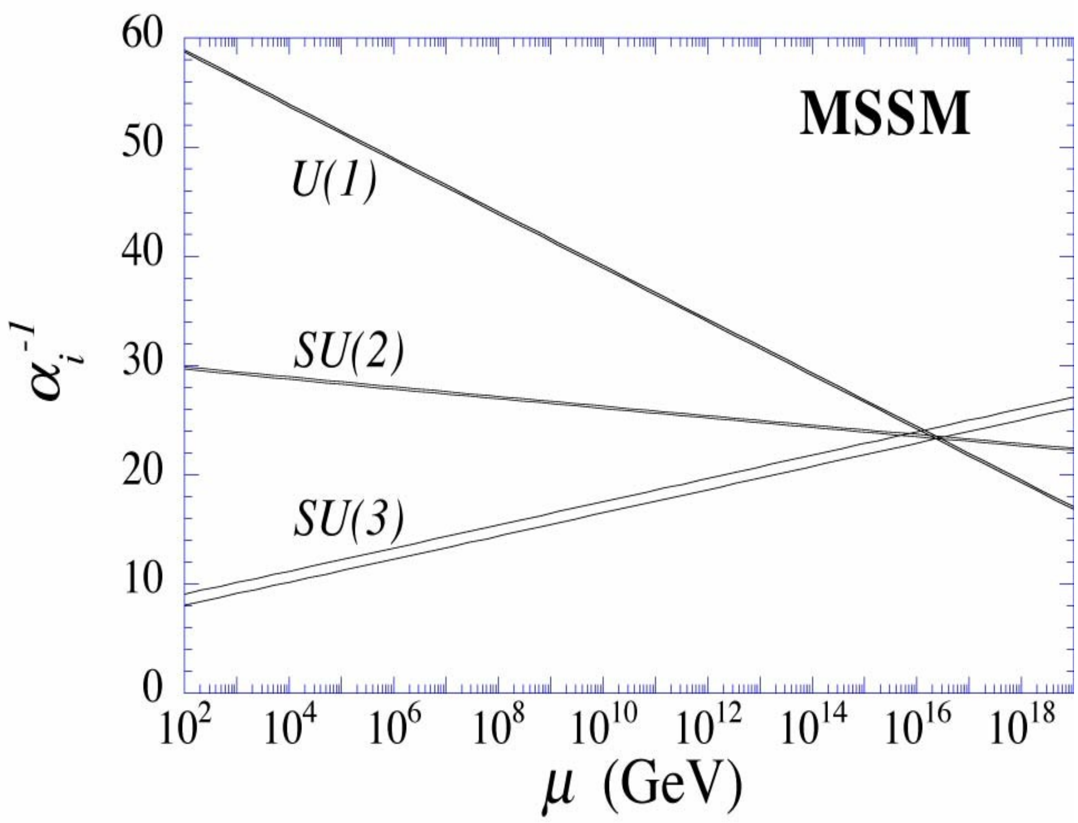
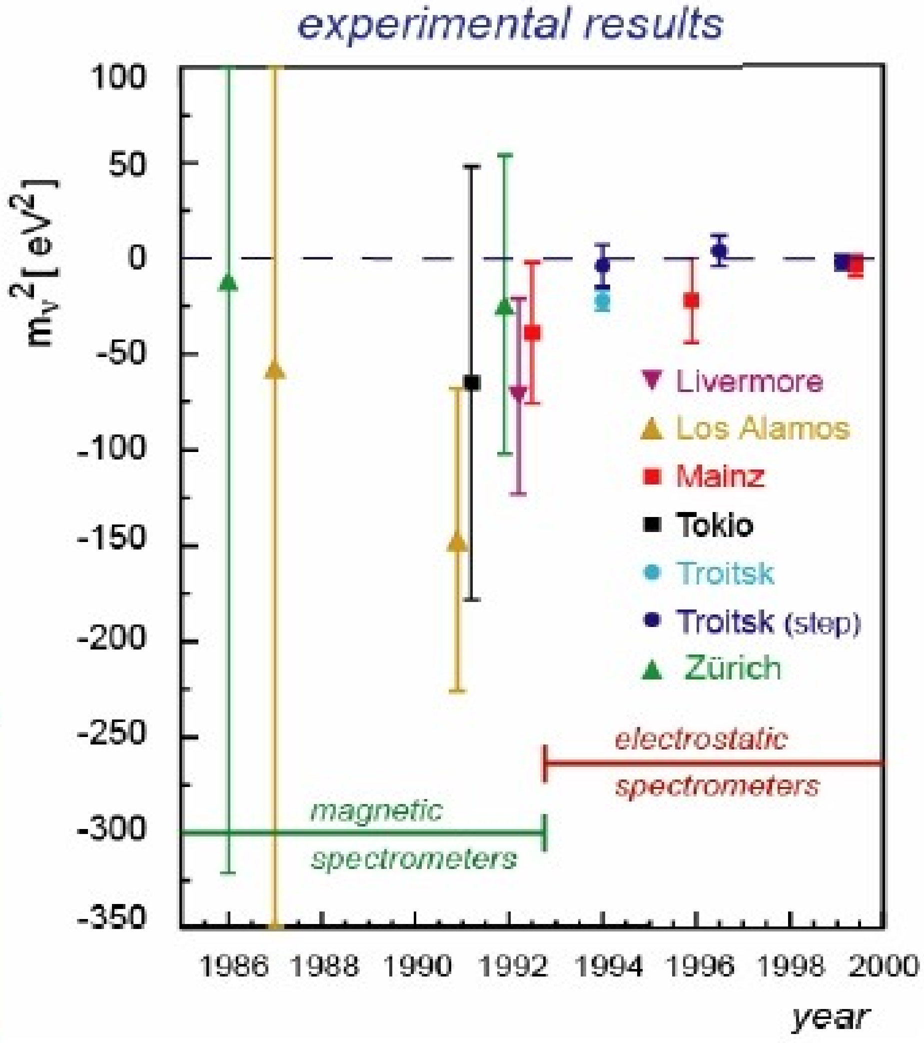
- Probing of GUT scale physics using light neutrinos!



(NB: In the context of a particular supersymmetric model....)

History of Tritium-b decay

	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



Present Status

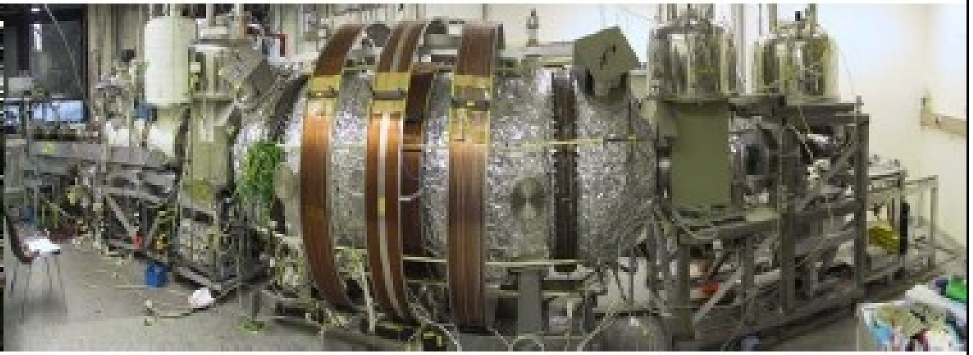
Troitsk

windowless gaseous T_2 source

analysis 1994 to 1999, 2001

$m_\nu^2 = -2.3 \pm 2.5 \pm 2.0\ \mathrm{eV}^2$

$m_\nu \leq$ 2.2 eV (95% CL.)



Mainz

quench condensed solid T_2 source

analysis 1998/99, 2001/02

$m_\nu^2 = -1.2 \pm 2.2 \pm 2.1\ \mathrm{eV}^2$

$m_\nu \leq$ 2.2 eV (95% CL.)

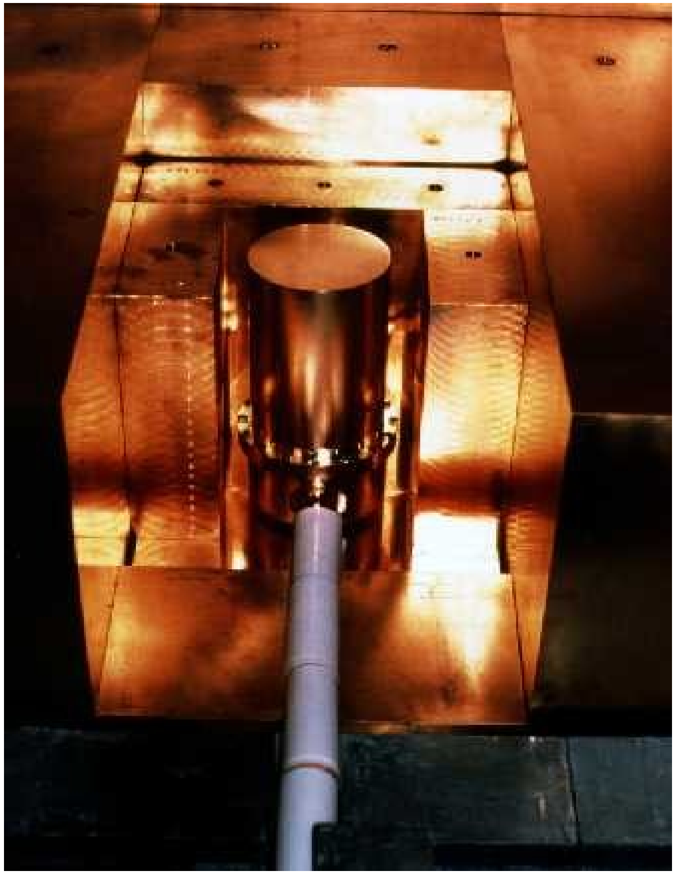
Both experiments have reached the intrinsic limit of their sensitivity.

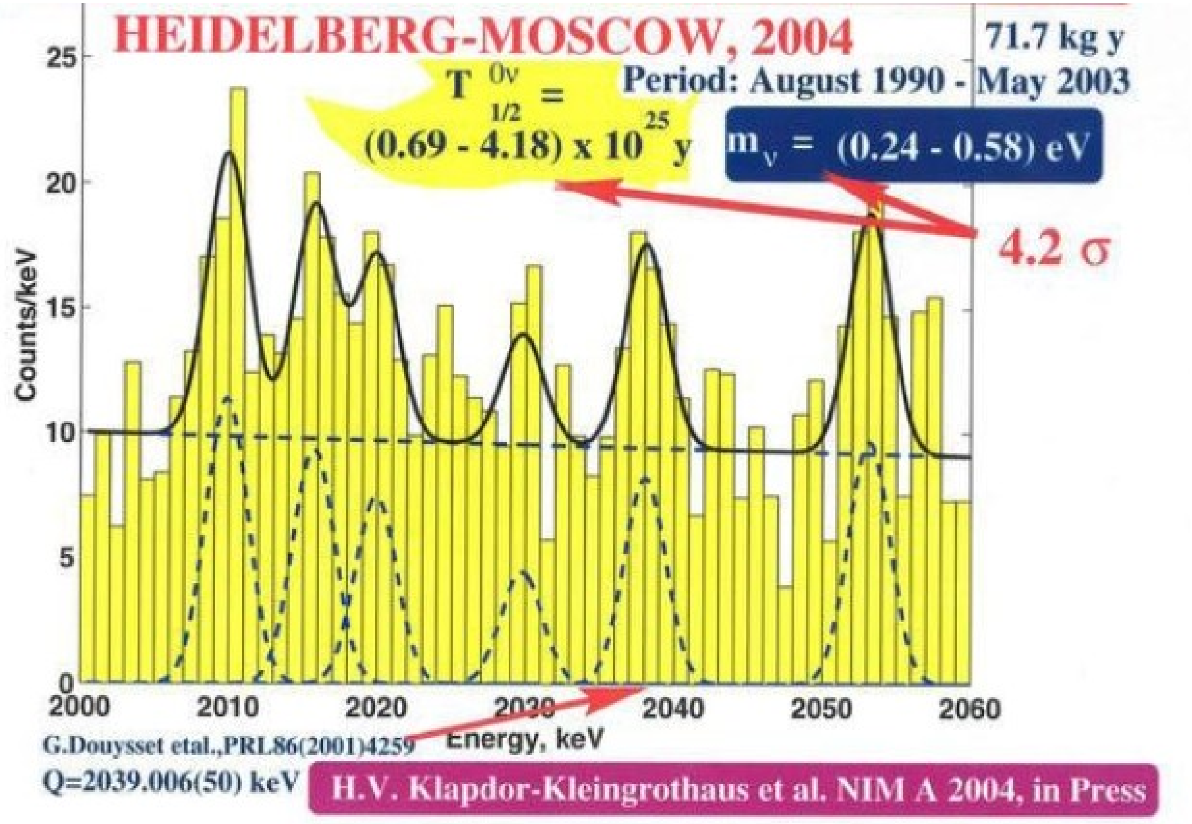
Heidelberg-Moscow (HdM)

11 kg of Ge enriched to 86% of ^{76}Ge in the form of 5 Ge diodes surrounded by Cu,Pb,Bn shielding

0nbb electrons detected by Ge detectors themselves

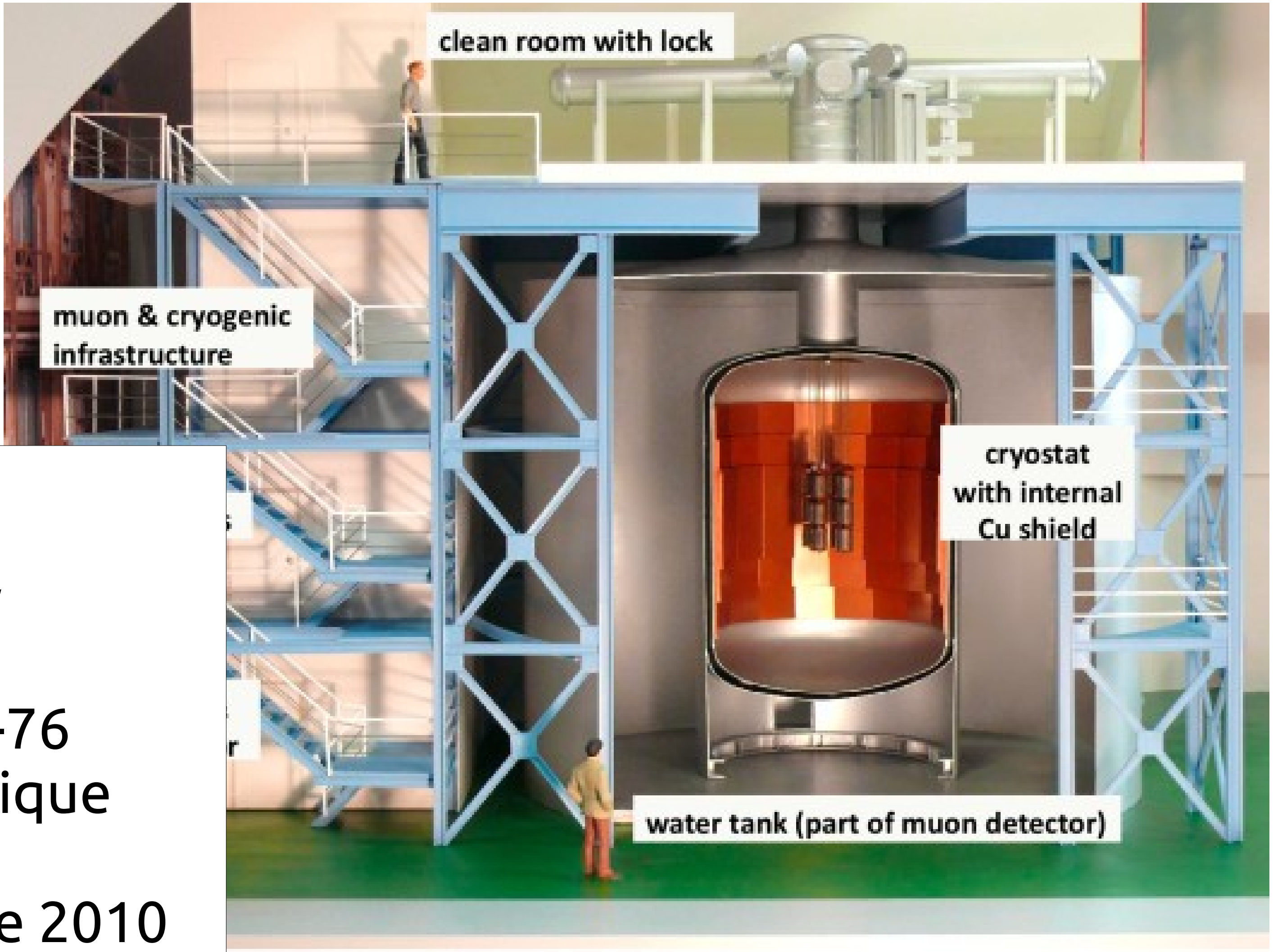
Only sum of electron energy measured



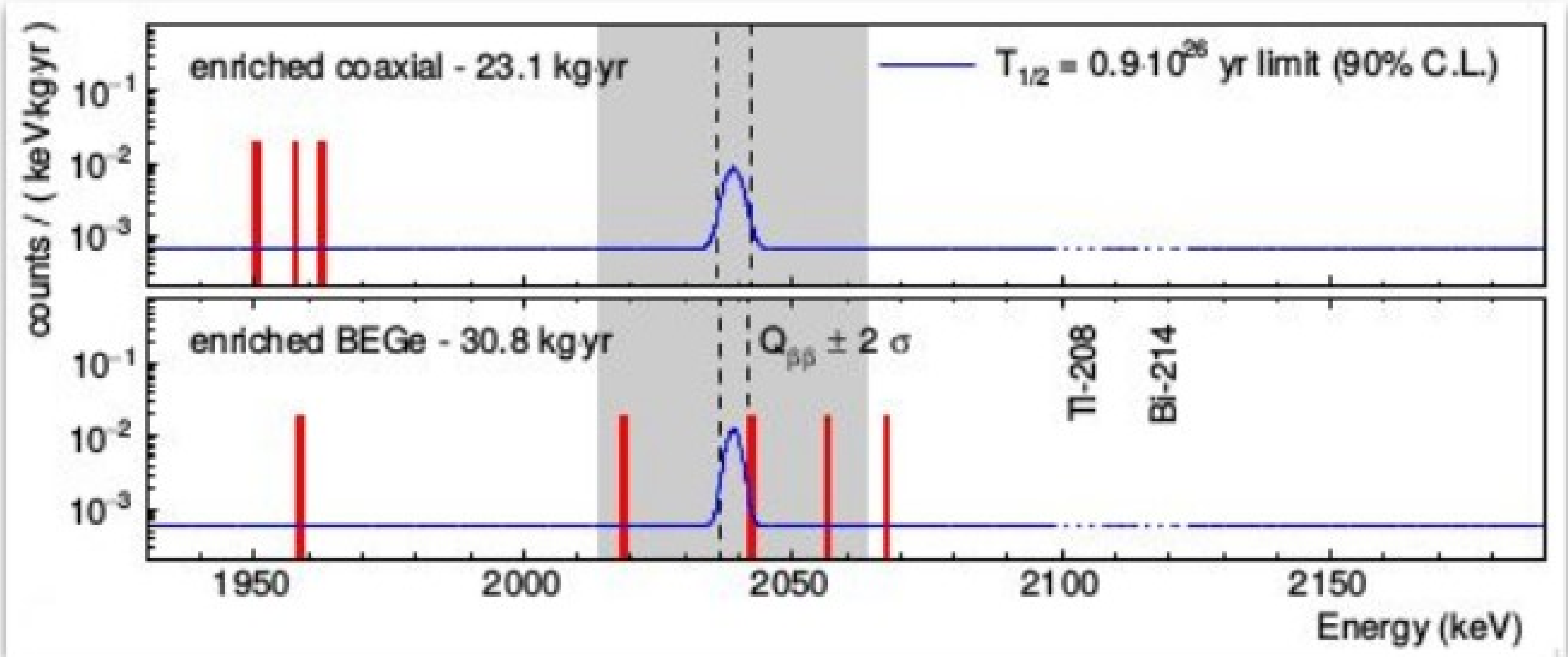


GERDA

- Designed to test Heidelberg-Moscow
- Uses the same Ge-76 isotope and technique
- Been running since 2010



GERDA

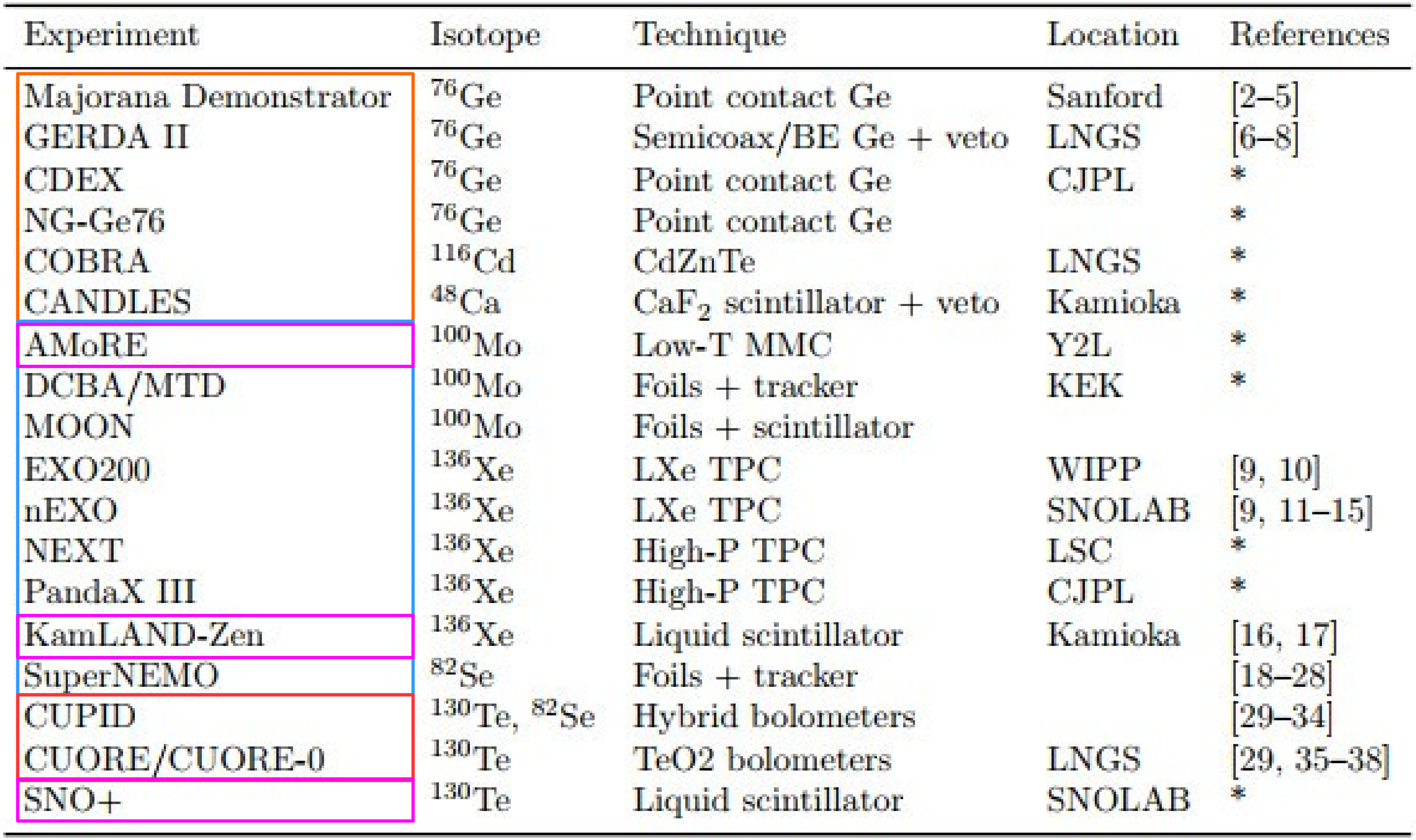


$t_{1/2} > 0.9 \times 10^{26}$ yr @ 90% CL

$m(\nu_e) < 260$ meV

Inconsistent with HdM, but not definitive (yet)

Future Program



Experiment	Isotope	Technique	Location	References
Majorana Demonstrator	^{76}Ge	Point contact Ge	Sanford	[2–5]
GERDA II	^{76}Ge	Semicoax/BE Ge + veto	LNGS	[6–8]
CDEX	^{76}Ge	Point contact Ge	CJPL	*
NG-Ge76	^{76}Ge	Point contact Ge		*
COBRA	^{116}Cd	CdZnTe	LNGS	*
CANDLES	^{48}Ca	CaF_2 scintillator + veto	Kamioka	*
AMoRE	^{100}Mo	Low-T MMC	Y2L	*
DCBA/MTD	^{100}Mo	Foils + tracker	KEK	*
MOON	^{100}Mo	Foils + scintillator		
EXO200	^{136}Xe	LXe TPC	WIPP	[9, 10]
nEXO	^{136}Xe	LXe TPC	SNOLAB	[9, 11–15]
NEXT	^{136}Xe	High-P TPC	LSC	*
PandaX III	^{136}Xe	High-P TPC	CJPL	*
KamLAND-Zen	^{136}Xe	Liquid scintillator	Kamioka	[16, 17]
SuperNEMO	^{82}Se	Foils + tracker		[18–28]
CUPID	^{130}Te, ^{82}Se	Hybrid bolometers		[29–34]
CUORE/CUORE-0	^{130}Te	TeO2 bolometers	LNGS	[29, 35–38]
SNO+	^{130}Te	Liquid scintillator	SNOLAB	*

— Semiconductor	— Tracking
— Scintillator	— Calorimeters