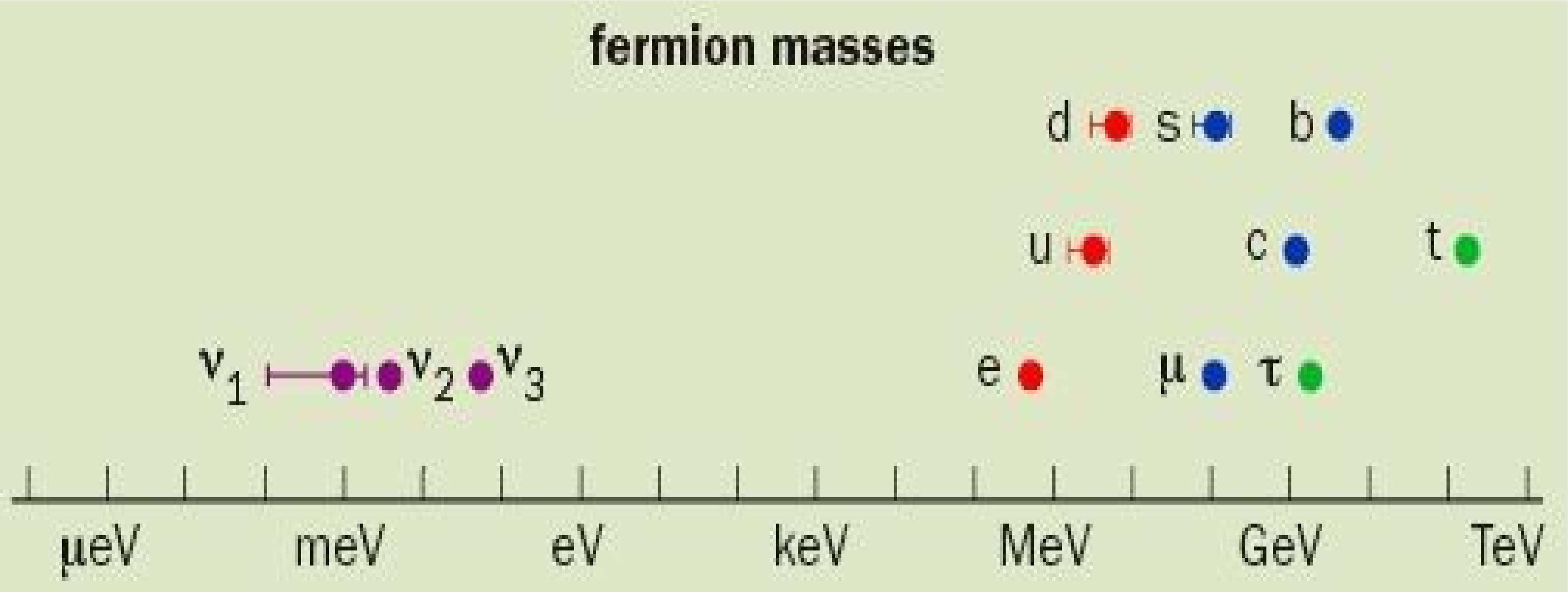
Lecture 2

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

The mystery of neutrino mass



Why are neutrino masses so small?

ν Mass in the Standard Model

Dirac Lagrangian mass term for fermions contains a 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

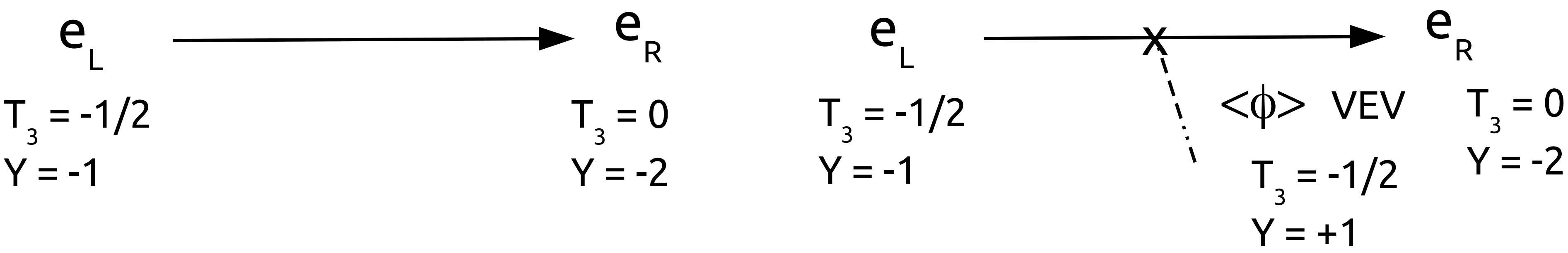
$$L_{mass} = m_D \overline{\psi}\psi = m_D\left(\overline{\psi_L} + \overline{\psi_R}\right)\left(\psi_L + \psi_R\right) = m_D\left(\overline{\psi_L}\psi_R + \overline{\psi_R}\psi_L\right)$$

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

Unfortunately, as it stands, such a term does *not* preserve gauge invariance. You need the Higgs mechanism to fix this.

Higgs mechanism

$$L_{mass}=m_D\left(\overline{\psi_L}\,\psi_R+\overline{\psi_R}\,\psi_L\right)\rightarrow Y_\psi\langle\phi\rangle\left(\overline{\psi_L}\,\psi_R+\overline{\psi_R}\,\psi_L\right)$$



e_L

$T_3 = -1/2$

$Y = -1$

e_R

$T_3 = 0$

$Y = -2$

e_L

$T_3 = -1/2$

$Y = -1$

x

$<\phi>$ VEV

$T_3 = -1/2$

$Y = +1$

e_R

$T_3 = 0$

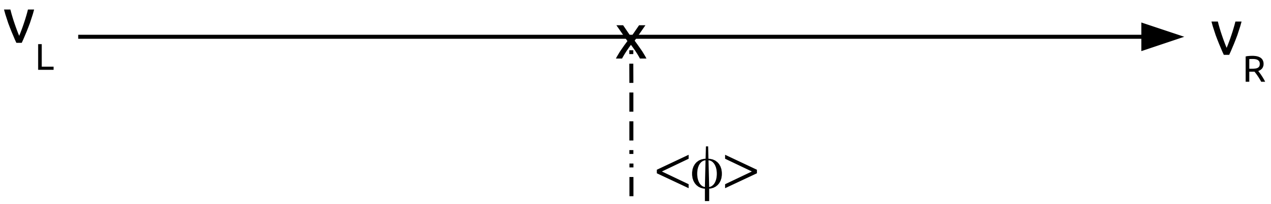
$Y = -2$

Dirac mass : $m_D = Y_\psi\langle\phi\rangle \quad \langle\phi\rangle = 246\ GeV$

- Higgs mechanism provides a means to give mass to fermions
- Preserves gauge invariance of the mass term
- Does not predict the mass, however. Still need to measure the Yukawa coupling.

Neutrino Dirac Mass

$$L_{mass} = Y_{\nu} \langle \phi \rangle \left(\overline{\nu_L} \nu_R + \overline{\nu_R} \nu_L \right)$$



- Addition of a sterile right-handed neutrino state to the SM which is, in principle, undetectable (apart from flavour oscillations)

- Tiny m_ν implies tiny Yukawa coupling : $Y_\nu < 10^{-13}$
  - Smallness of neutrino mass is not addressed by this mechanism

Majorana Neutrinos

Mass terms need a R-chiral field. Neutrinos only have L-chiral field.

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 operator

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

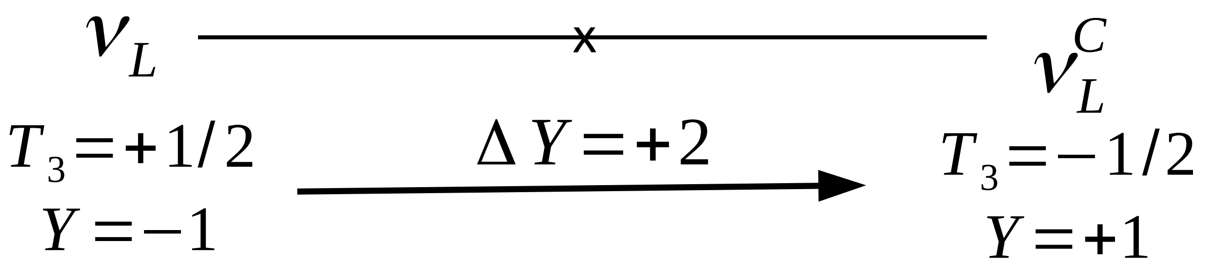
$$L_{Maj} = \frac{1}{2} m_L \left(\overline{\nu^C}\,\nu + \overline{\nu}\,\nu^C \right) = \frac{1}{2} m_L \left(\overline{\nu_L^C}\,\nu_L + \overline{\nu_L}\,\nu_L^C \right)$$

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.

$$\overline{\nu_L^C}\,\nu_L$$



ν_L $T_3=+1/2$ $Y=-1$

$\Delta Y=+2$

ν_L^C $T_3=-1/2$ $Y=+1$

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 Dirac mass mechanism, or a Higgs triplet, or a new mass mechanism.

The general mass term

Suppose : once upon a time there were 2 Majorana neutrinos.
An almost massless one, and a very heavy one. The mass term looks like

$$L_{mass} = m\,\overline{\nu_m}\,\nu_m + M\,\overline{N_m}\,N_m = \left(\overline{\nu_m}\;\overline{N_m}\right)\begin{pmatrix} m & 0 \\ 0 & M \end{pmatrix}\begin{pmatrix} \nu_m \\ N_m \end{pmatrix}$$

Written in the mass basis
States of definite mass

We have, potentially, 4 separate chiral fields to play with :

$$\nu_L \;,\; \nu_L^C \;,\; N_R ,\; N_R^C$$

If we're resigned to having right-handed fields anyway we can write down
4 different mass terms

$$\left.\begin{aligned} L_L^M &= m_L\,\overline{\nu_L^C}\,\nu_L \\ L_R^M &= m_R\,\overline{N_R^C}\,N_R \end{aligned}\right\}$$

Two Majorana mass terms

$$\left.\begin{aligned} L_L^D &= m_D\,\overline{N_R^C}\,\nu_L \\ L_R^D &= m_D\,\overline{\nu_L^C}\,N_R^C \end{aligned}\right\}$$

Two Dirac mass terms

The general mass term

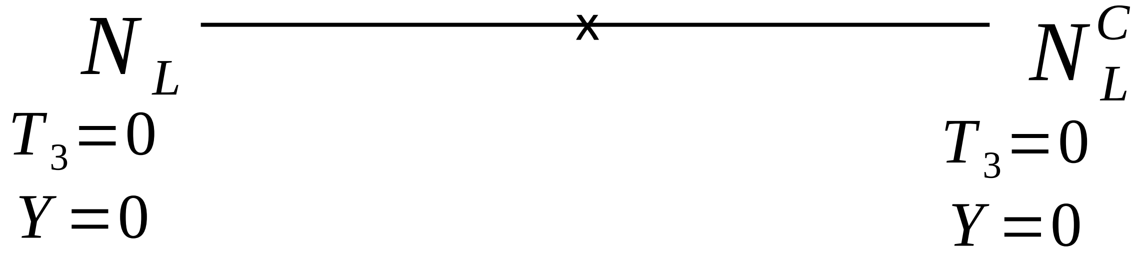
The most general mass term combines all of these

$$L_{mass} = L_L^D + L_R^D + L_L^M + L_R^M$$

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

I've set $m_L = 0$ because of the gauge issue.

$$\overline{N_R^C} N_L$$



N_L

$T_3 = 0$

$Y = 0$

N_L^C

$T_3 = 0$

$Y = 0$

Since right-handed fields are singlets, there is no problem with gauge invariance for the right-handed Majorana term

The general mass term

The most general mass term combines all of these

$$L_{mass} = L_L^D + L_R^D + L_L^M + L_R^M$$

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

I've set $m_L = 0$ because of the gauge issue.

Mass eigenstates are mixes of the chiral eigenstates

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

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

See-Saw mechanism

$$m, M = \frac{1}{2}\left[m_R \pm \sqrt{m_R^2 + 4m_D^2}\right]$$

- M is the mass of a right-handed (singlet) neutral fermion
- Suppose that this is around the GUT scale : Λ

$$M \sim m_R \sim \Lambda \qquad\qquad m \sim \frac{m_D^2}{m_R} \sim \frac{\langle VEV \rangle^2}{\Lambda}$$

right-handed
heavy neutral lepton

“our” neutrino

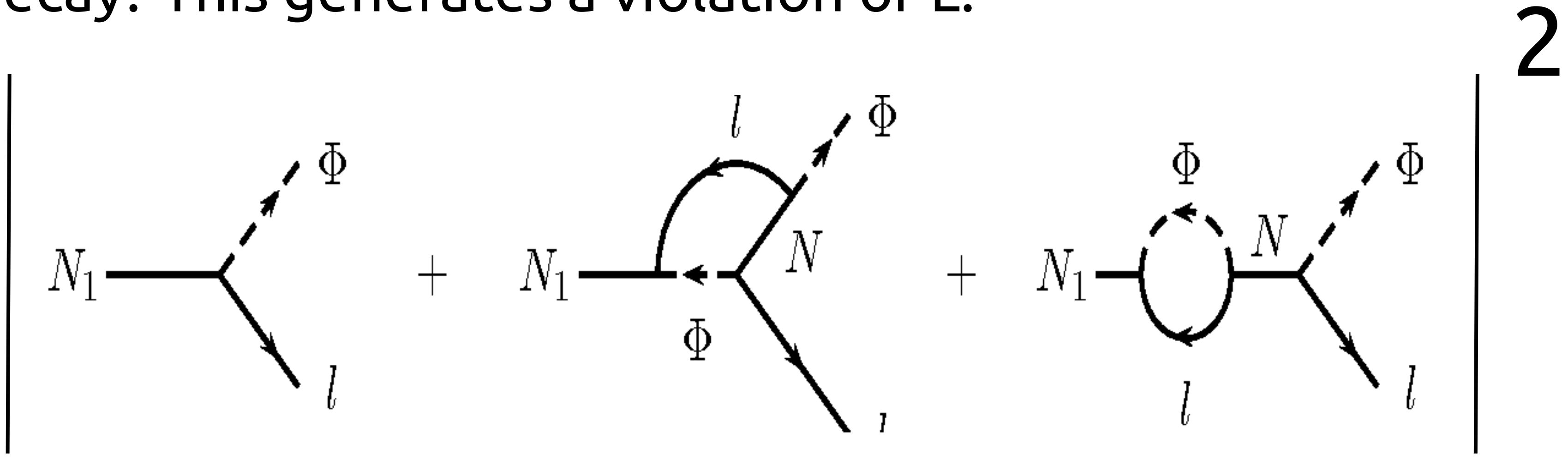
- Mass of “our” neutrino suppressed by the GUT scale
- $\Lambda \approx 10^{16}$ GeV → m $\approx (250)^2/10^{16} \approx$ 10 meV
- Currently our only “natural” way to explain why the neutrino mass is so much smaller than other Dirac particles

Leptogenesis

Seesaw mechanism requires a GUT scale heavy Majorana neutrino partner.

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

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



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

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

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

Leptogenesis

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Generation of baryon asymmetry from lepton asymmetry

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

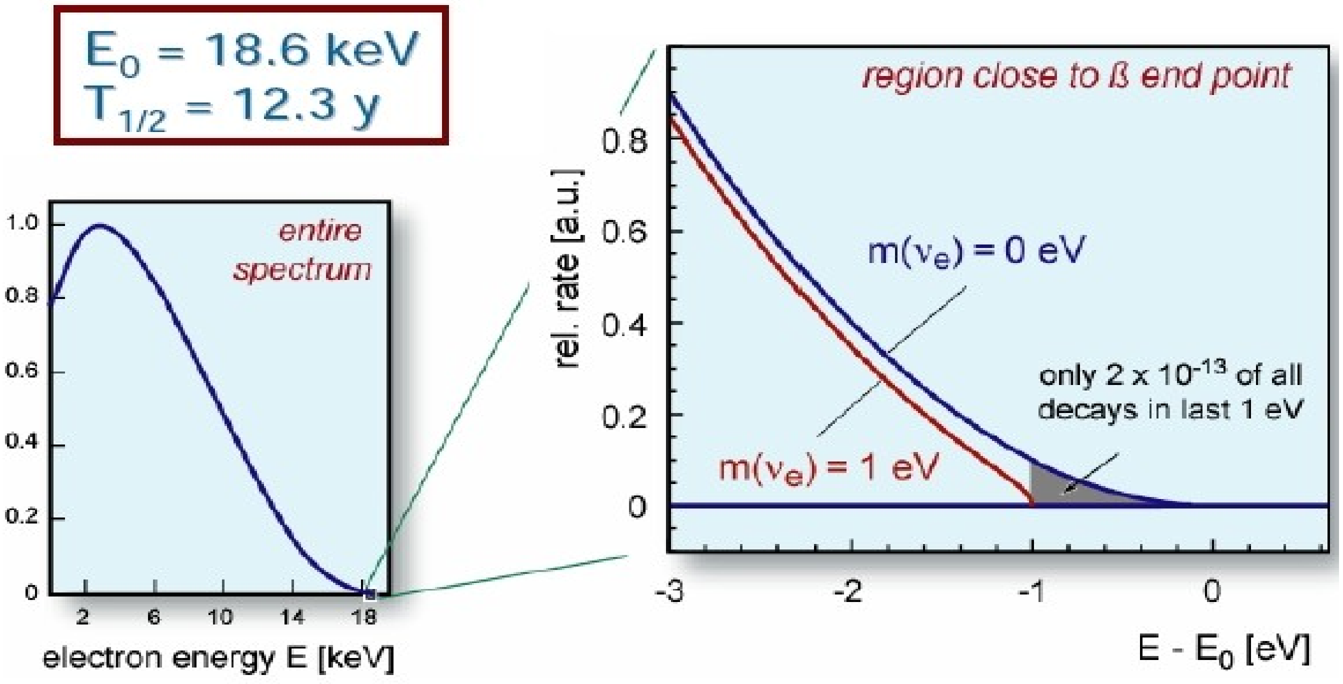
(Attempts at) mass measurements

ν_e mass

Measurement of ν_e mass from kinematics of β decay.

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

Observable is m_ν^2



Requirements

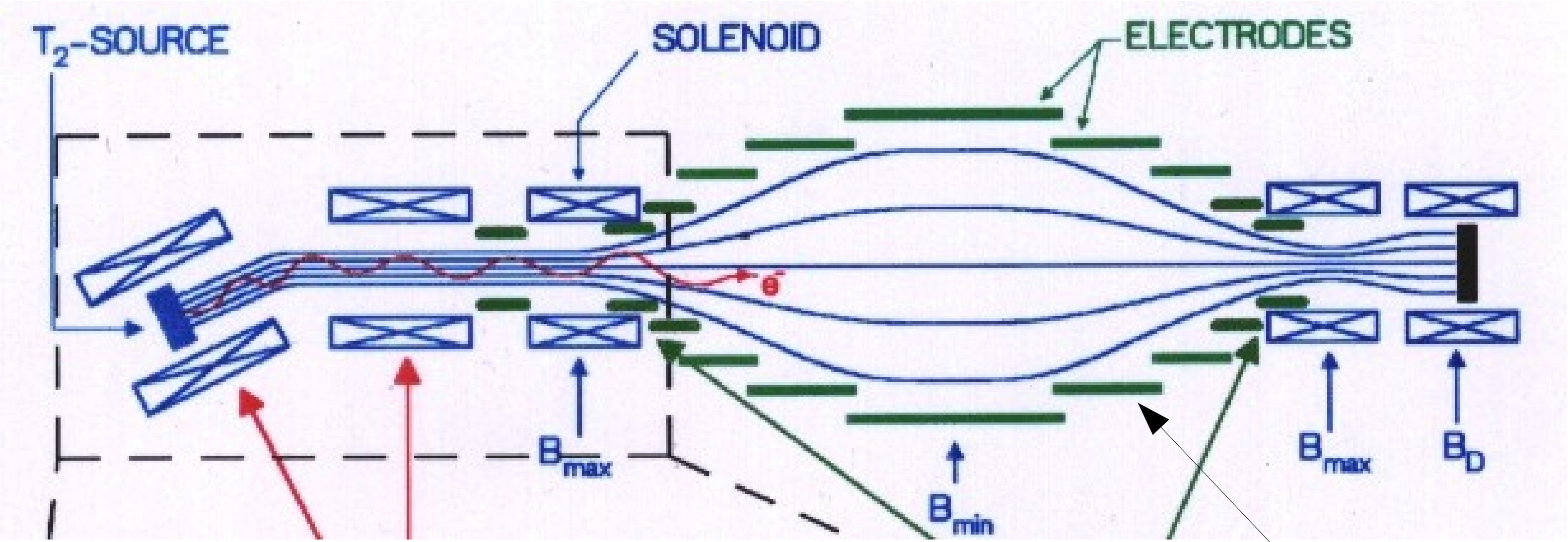
- # electrons close to the endpoint should be large
- Good (and well-understood) electron energy resolution
- No (or minimal) electron energy loss within the source
- Minimal atomic and nuclear final state effects, of excited transitions

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

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

Mainz Experiment

The current standard for tritium beta decay experiments



- 2π acceptance
- High energy resolution

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

Electrostatic MAC-E Filter

Present Status

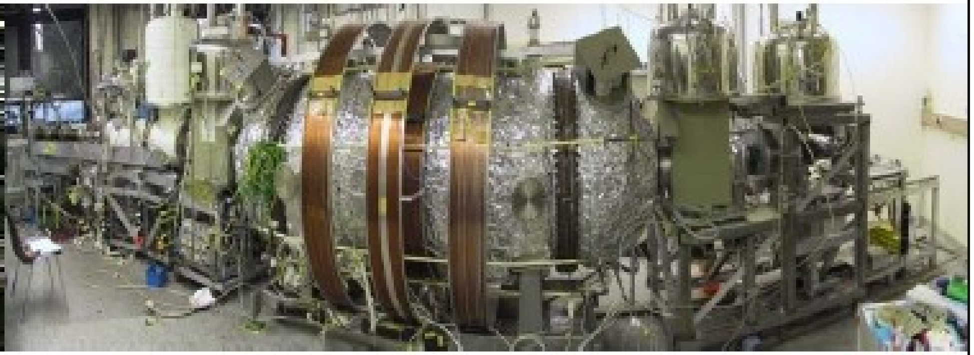
Troitsk

windowless gaseous T_2 source

analysis 1994 to 1999, 2001

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

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



Mainz

quench condensed solid T_2 source

analysis 1998/99, 2001/02

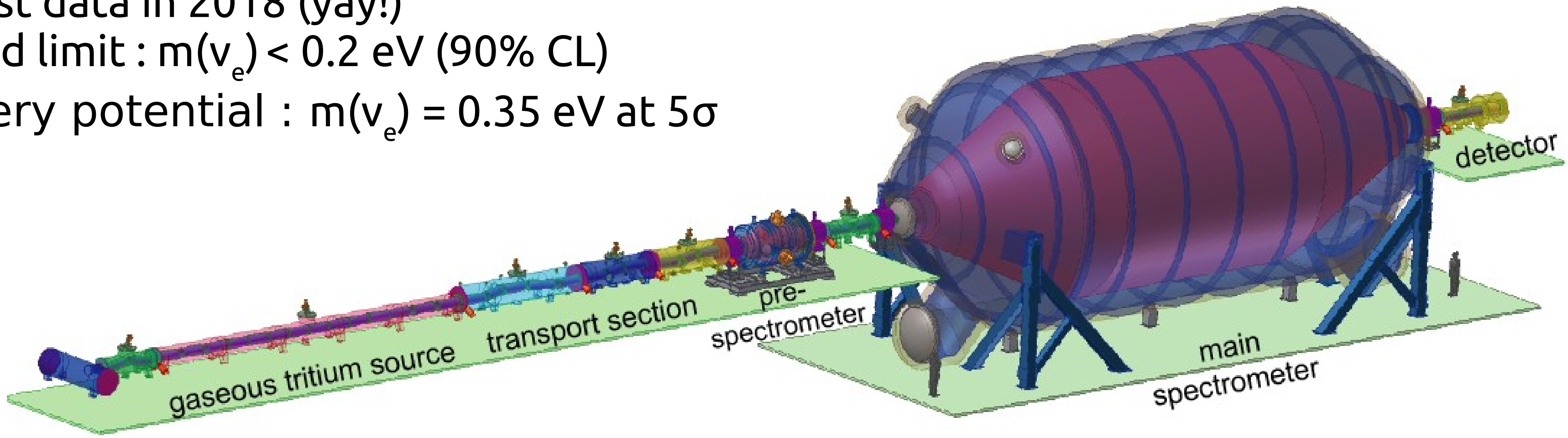
$m_\nu^2 = -1.2 \pm 2.2 \pm 2.1\ \mathrm{eV}^2$

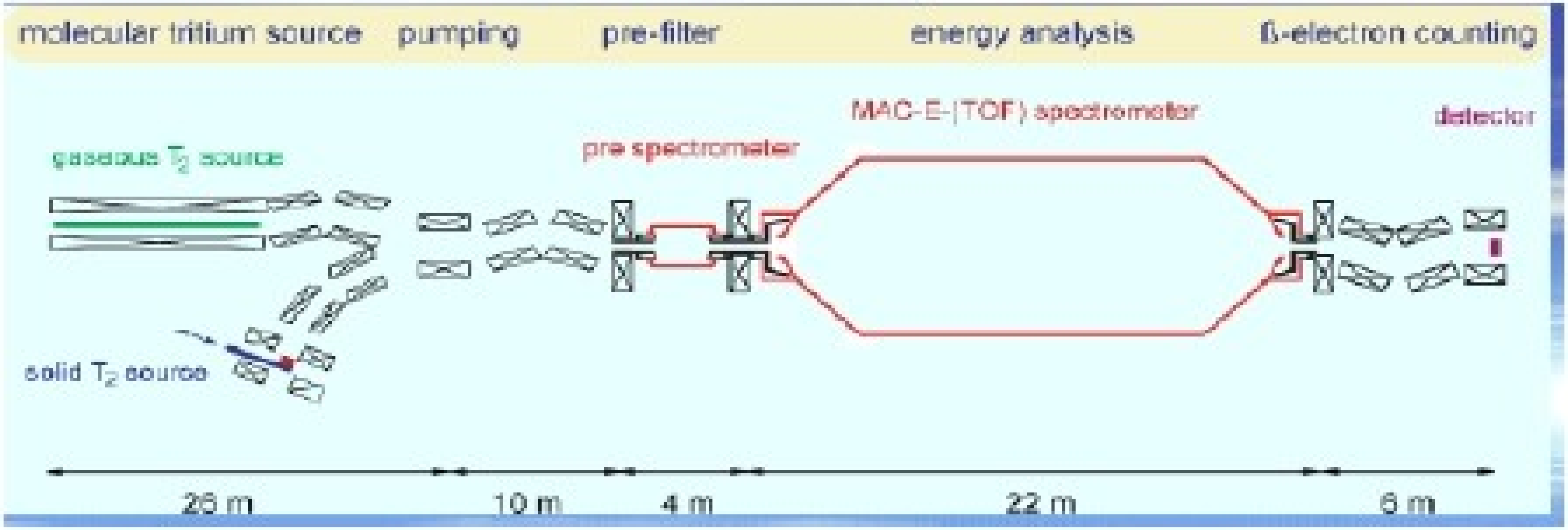
$m_\nu \leq 2.2\ \mathrm{eV}$ (95% CL.)

Both experiments have reached the intrinsic limit of their sensitivity.

KATRIN

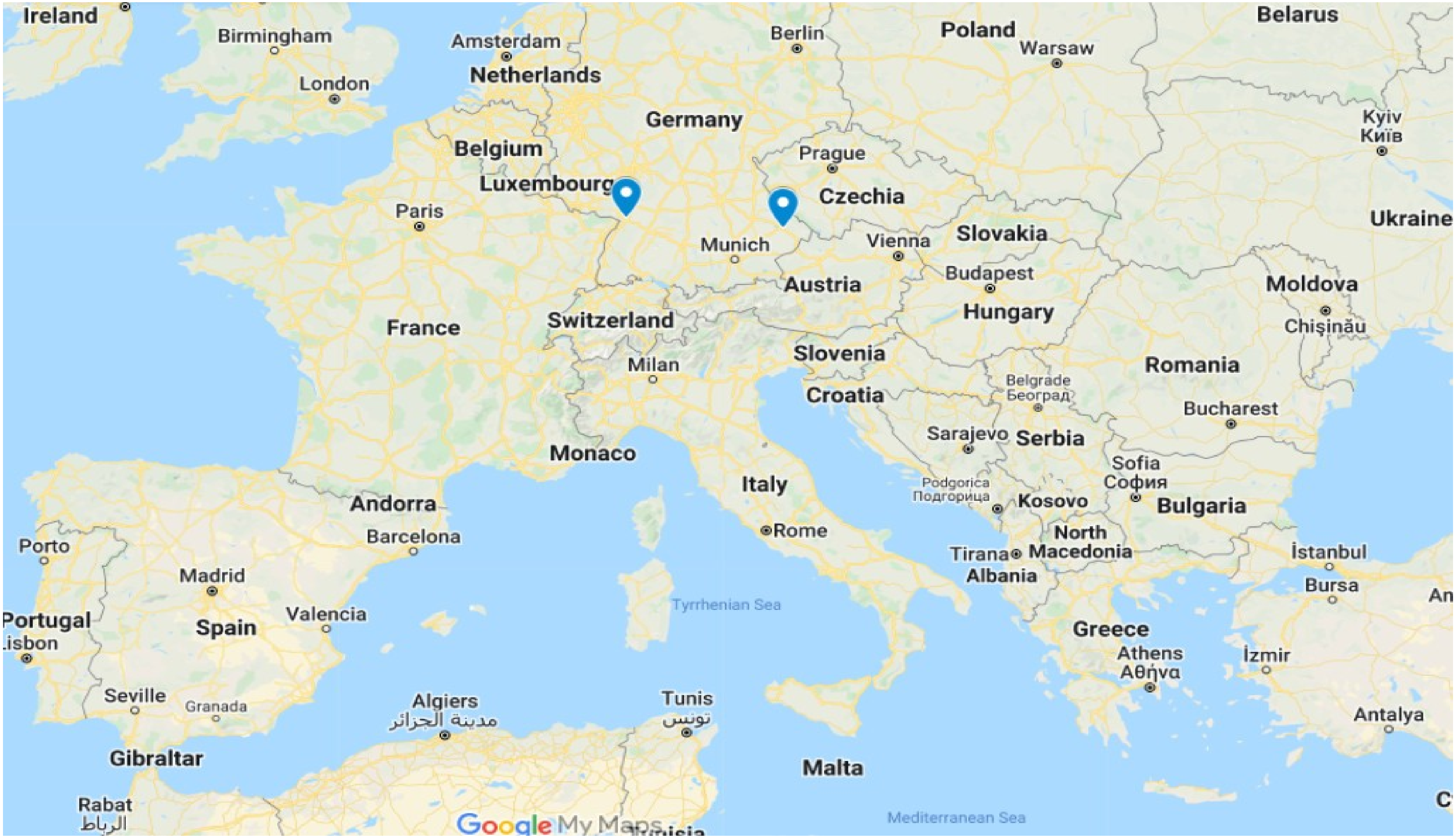
Took first data in 2018 (yay!)
Expected limit : $m(\nu_e) < 0.2$ eV (90% CL)
Discovery potential : $m(\nu_e) = 0.35$ eV at 5σ



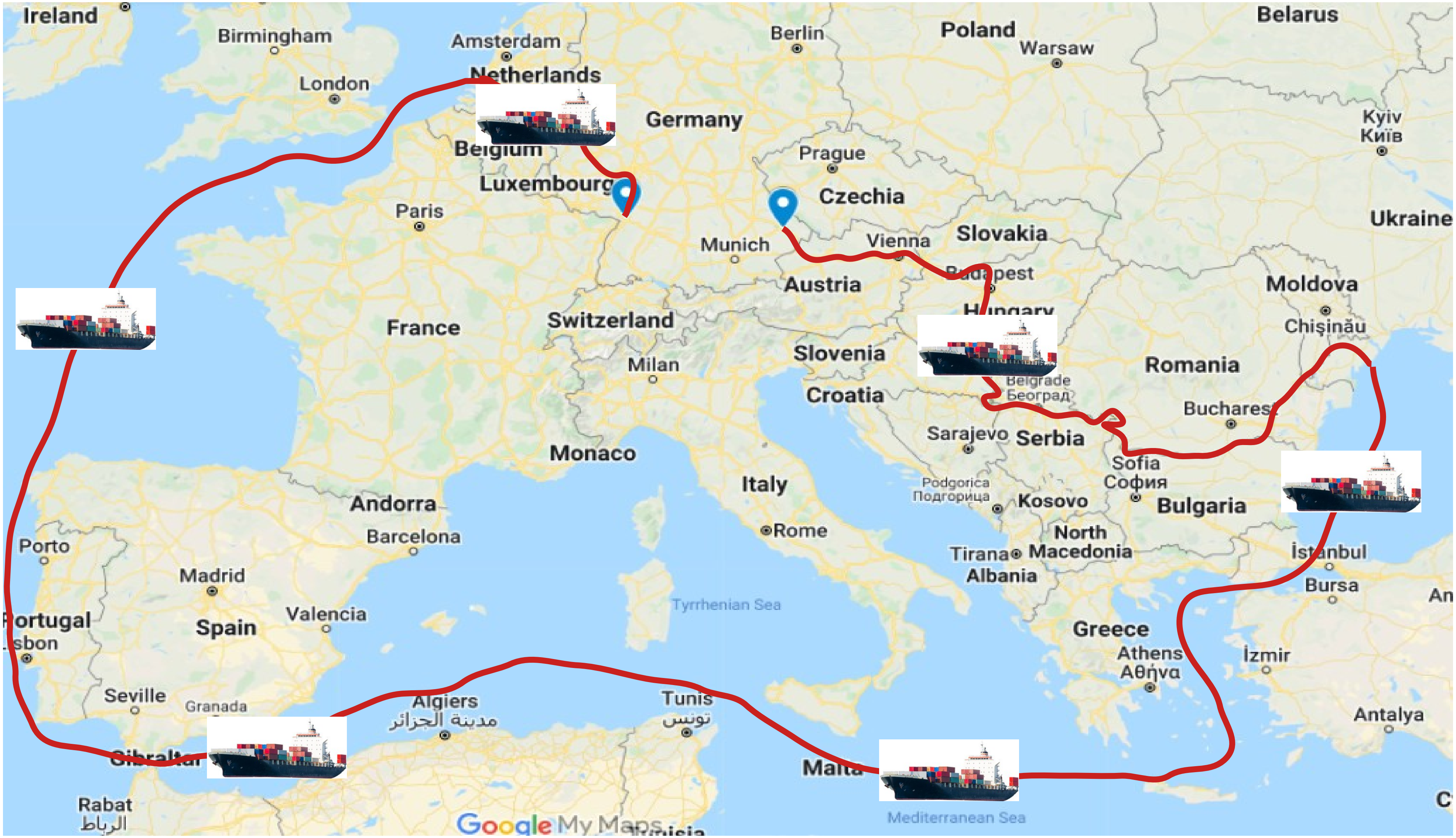


KATRIN on the move

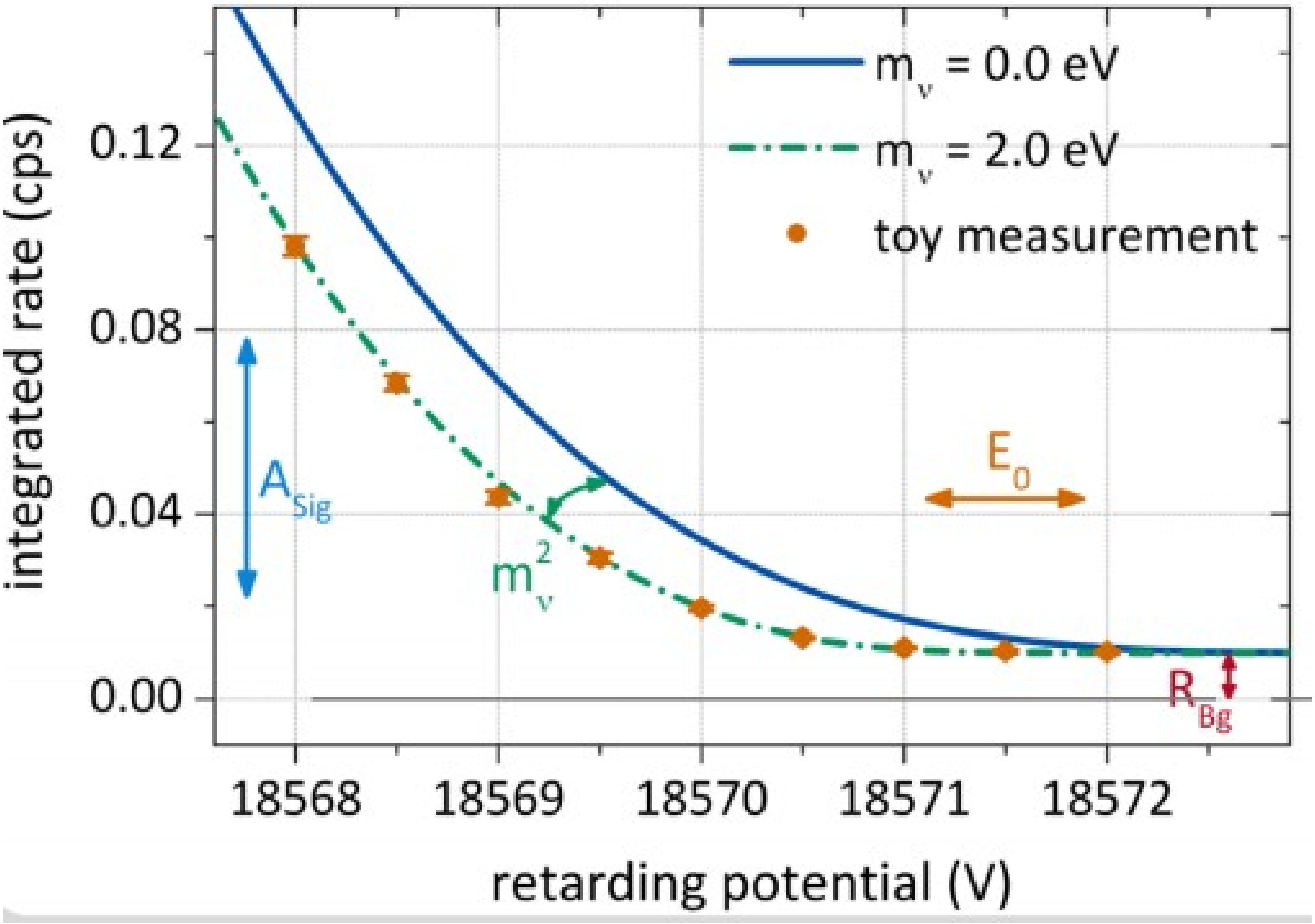
Katrin on the move



Katrin on the move

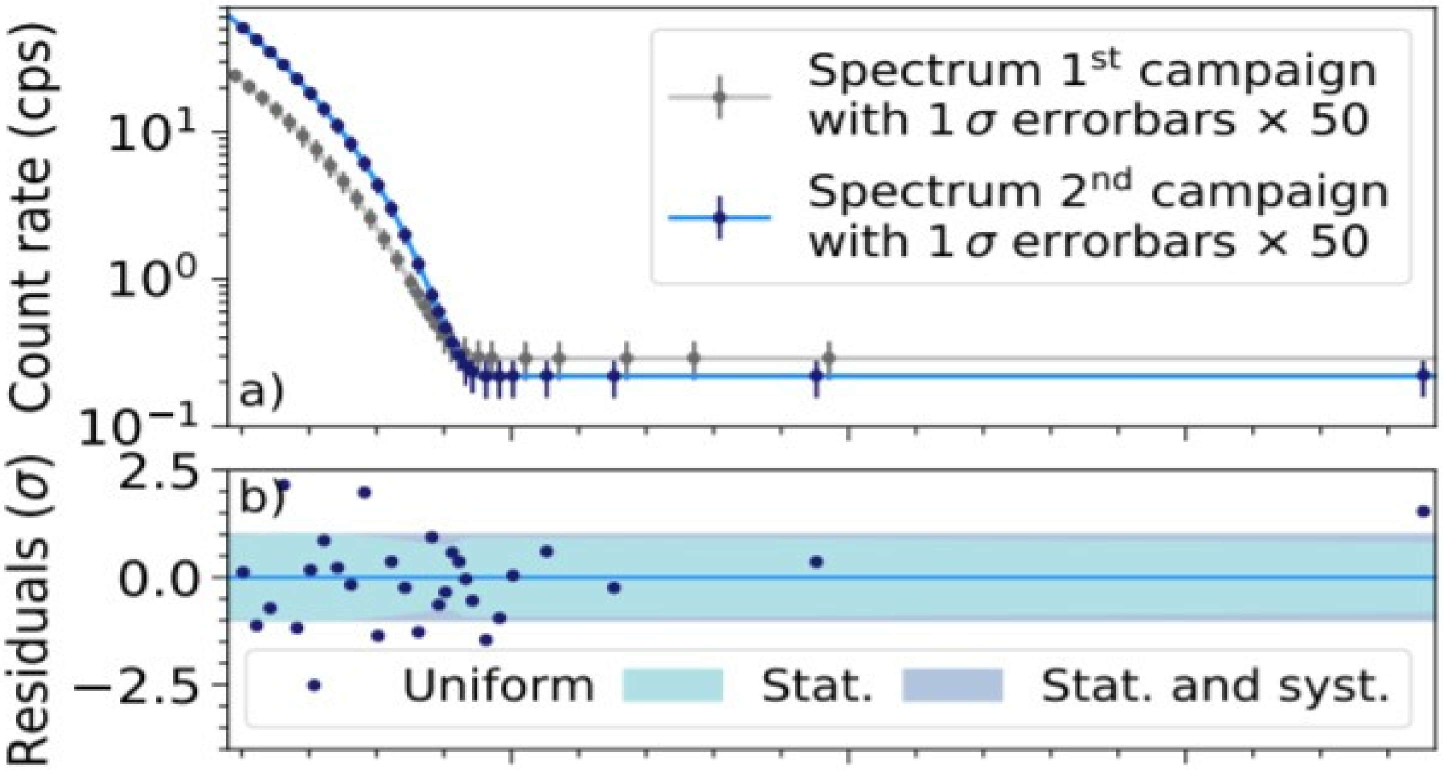


Katrin data



integrated rate (cps)
0.12
0.08
0.04
0.00
18568
18569
18570
18571
18572
retarding potential (V)
m_ν = 0.0 eV
m_ν = 2.0 eV
toy measurement
A_{Sig}
m_ν^2
E_0
R_{Bg}

Latest KATRIN result



5.2 million β-electrons

Statistics limited

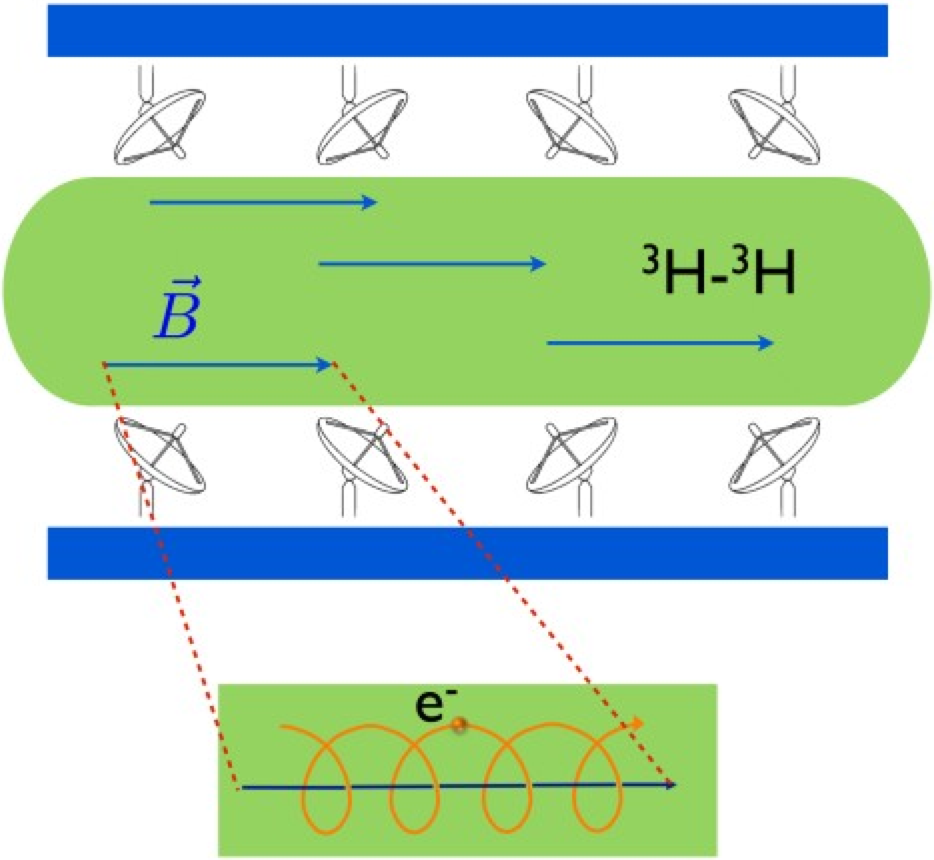
$$m_\nu^2 = (0.1 \pm 0.3)\ eV^2$$

$$m_\nu\ <\ 0.8\ eV\,@\,90\%\,CL$$

Nature Phys. 18 (2022) 2, 160-166

Project 8

Project 8



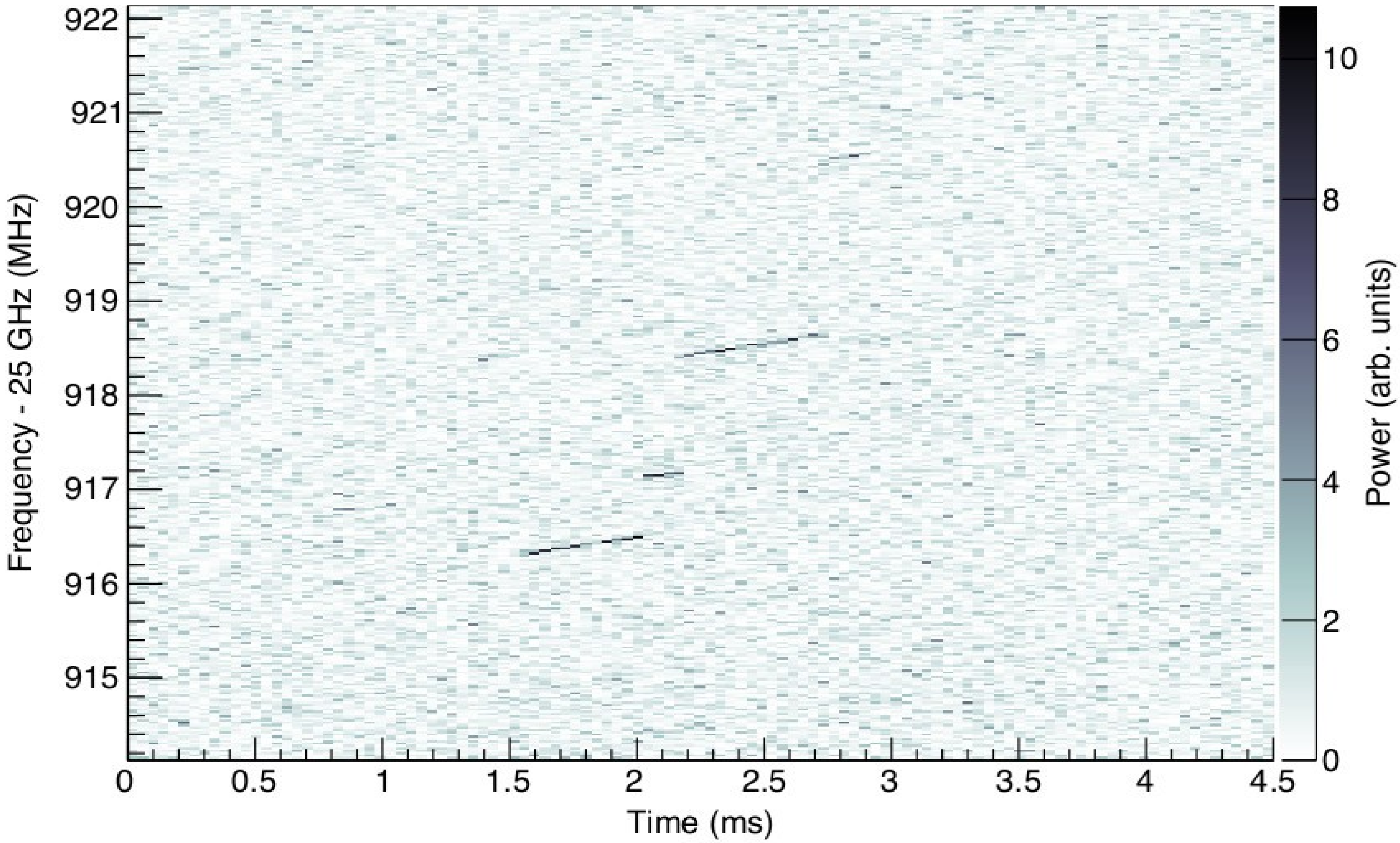
- Tritium beta decay in a magnetic field.
- Electron from beta decay spirals around the field lines
- Emits cyclotron radiation at a particular frequency

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

- Measures electron energy from the frequency of the cyclotron radiation!

Project 8

Project 8 Demonstrator – Decay in tritium



Project 8

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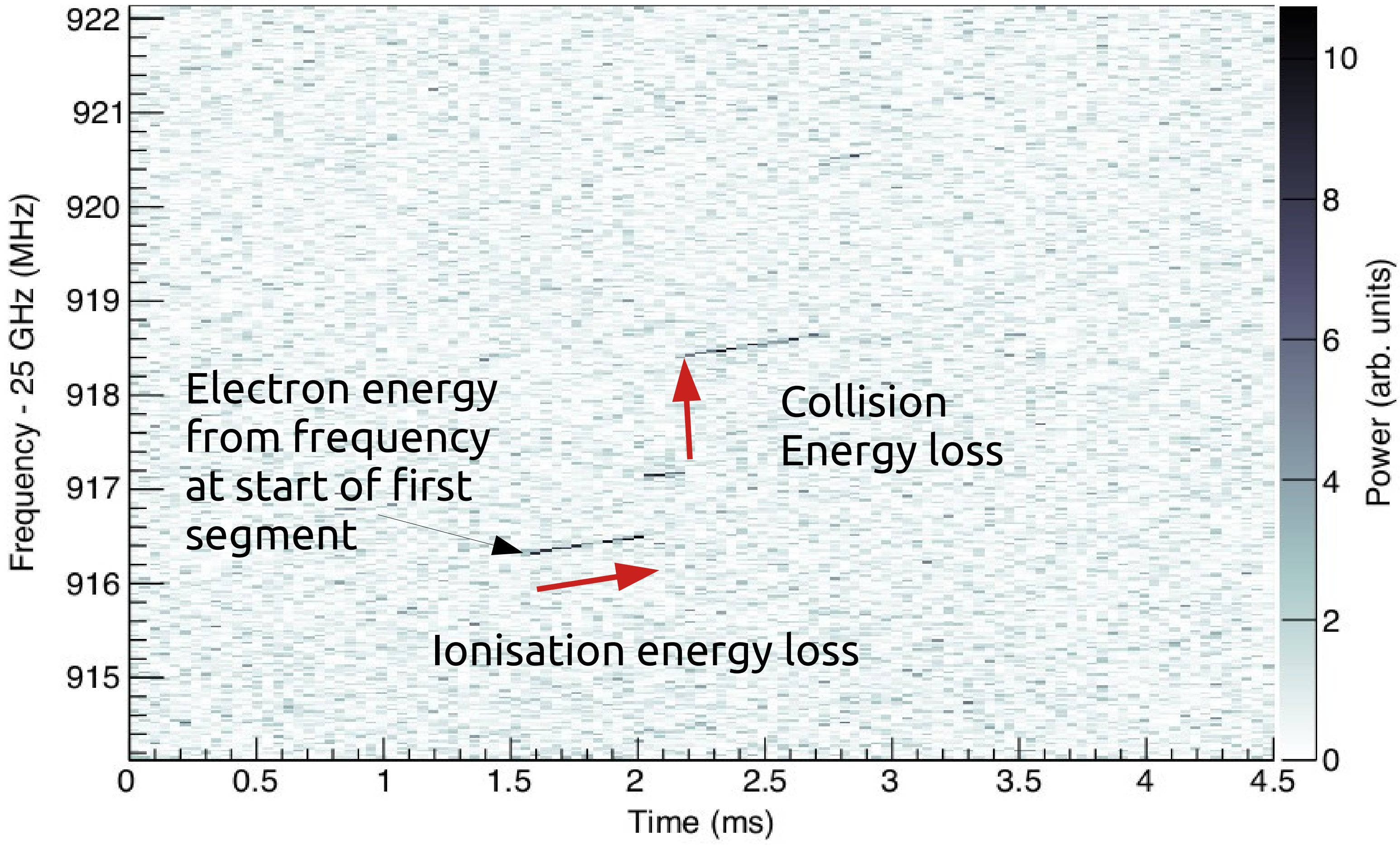


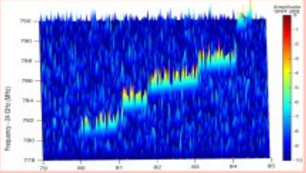
Electron energy from frequency at start of first segment

Collision Energy loss

Ionisation energy loss

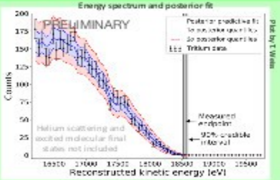
Project 8

Phase I:
Demonstrate CRES technique on 83mKr mono-energetic electrons.
Status: Complete! Technique demonstrated.



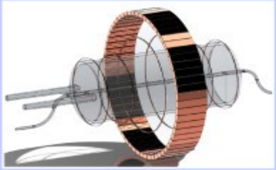
✓

Phase II:
First T2 spectrum. Extract endpoint. Study systematics and backgrounds.
Status: Nearing completion

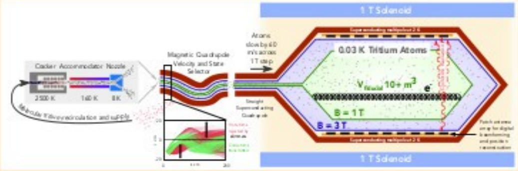


✓

Phase III:
(a) Free-Space CRES Demonstrator (200 cm³ volume, <10 eV mass sensitivity)
(b) Atomic T Demonstrator (trap atomic tritium at high densities)



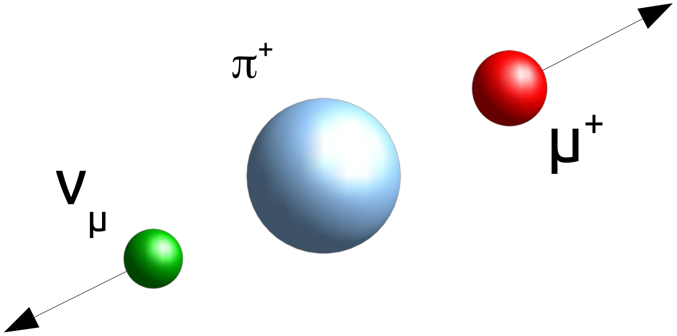
Phase IV:
Atomic tritium source. Inverted ordering reach (40 meV)



Target sensitivity by 2024 : $m \sim 40\,meV$

ν_μ mass

Easiest way is to use pion decay at rest



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

$$m_\pi = 139.57037 \pm 0.00021\,MeV$$

$$m_\mu = 105.658389 \pm 0.000034\,MeV$$

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

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

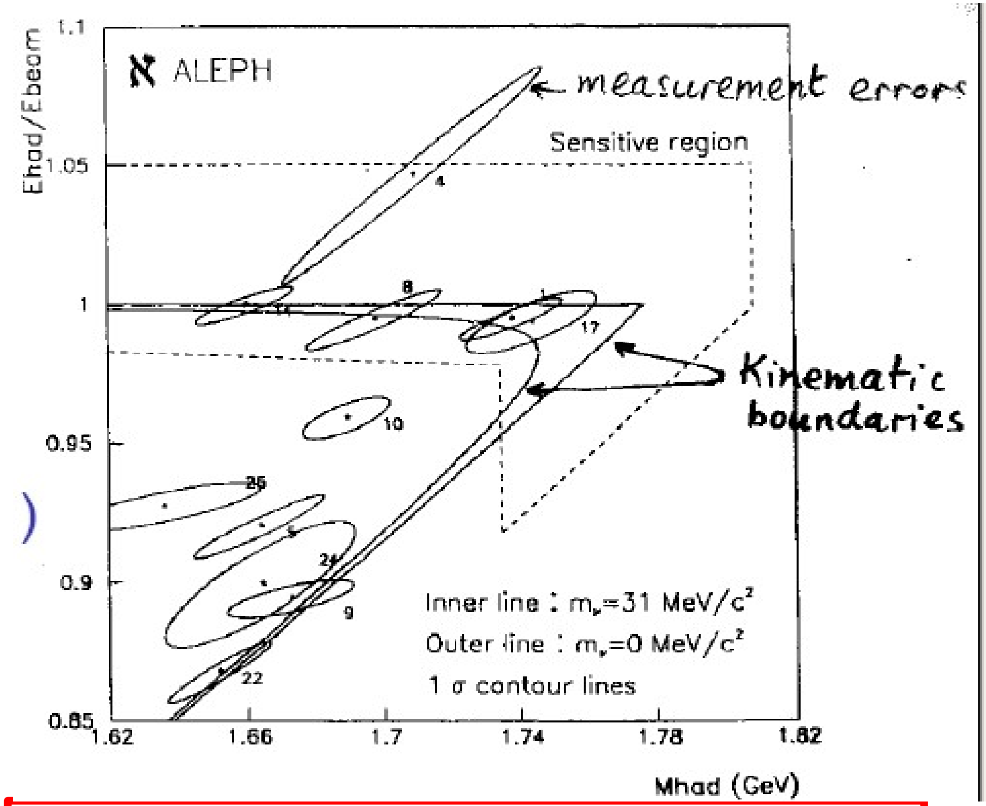
$$\boxed{m_\nu < 190\,keV\,(90\,\%\,CL)}$$

ν_τ mass

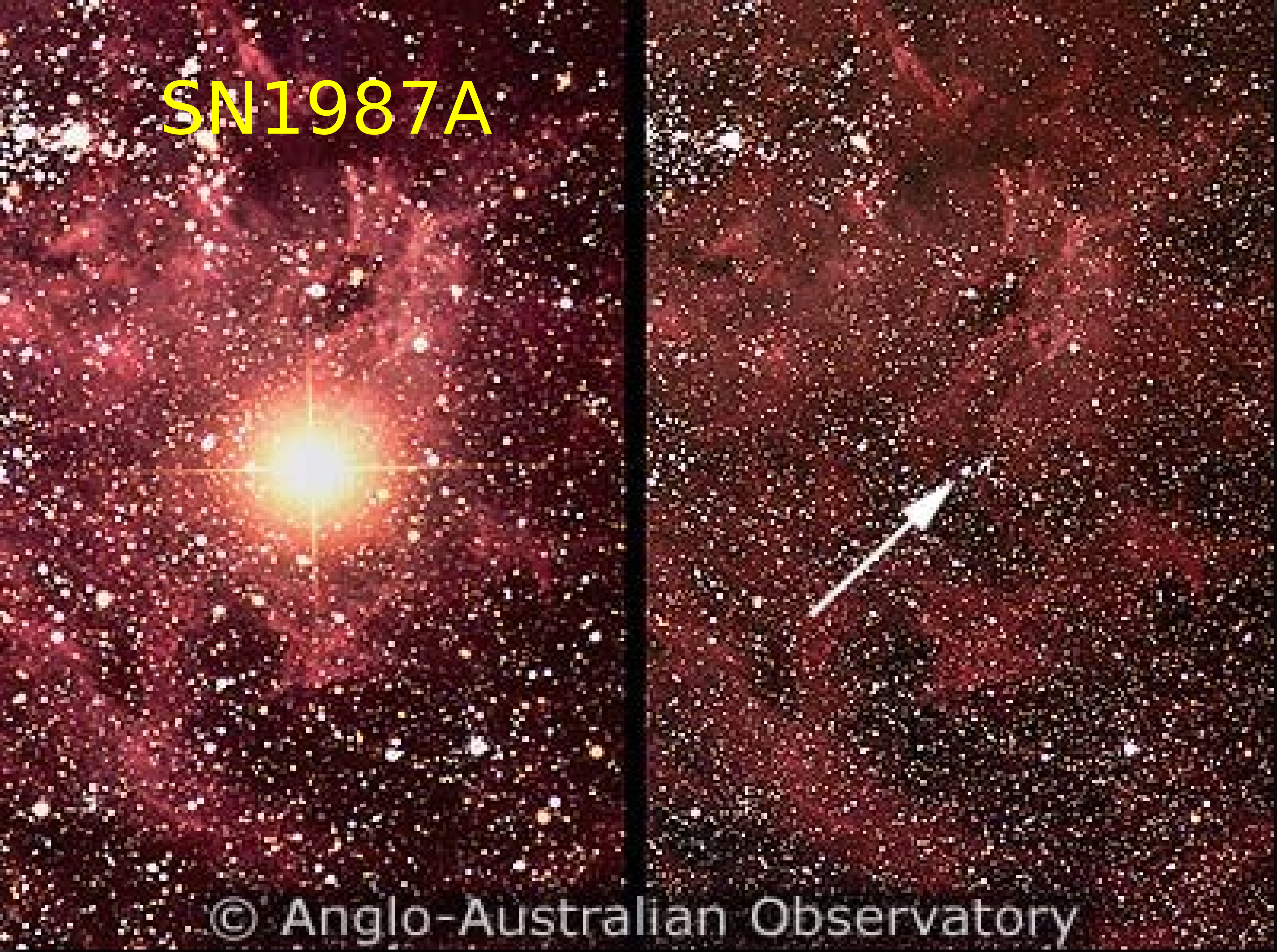
$$e^+e^- \to \tau^+\tau^-$$

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

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



$$\boxed{m_\tau < 19.2\,MeV\,(95\,\%\,CL)}$$



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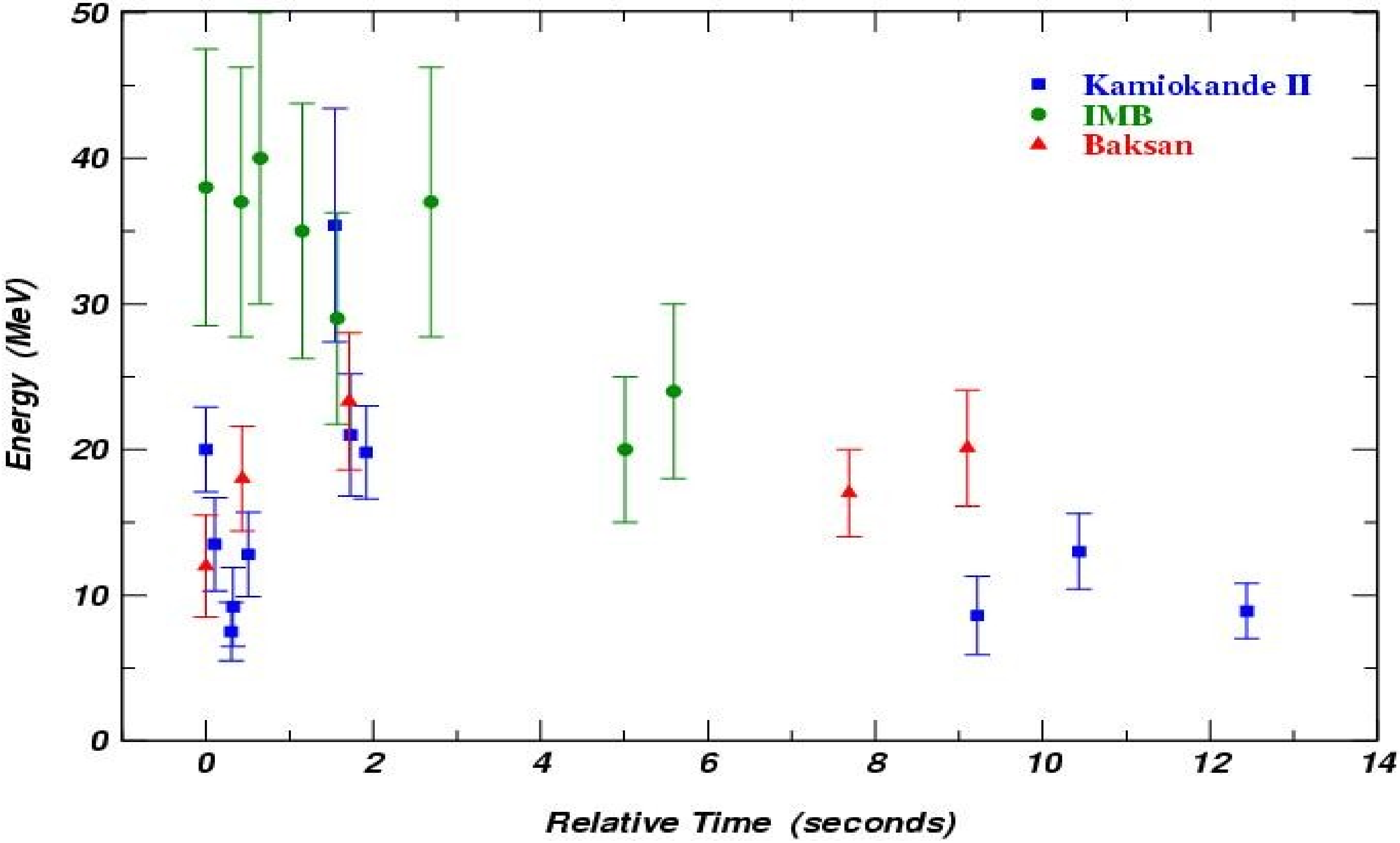
Neutrinos detected

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

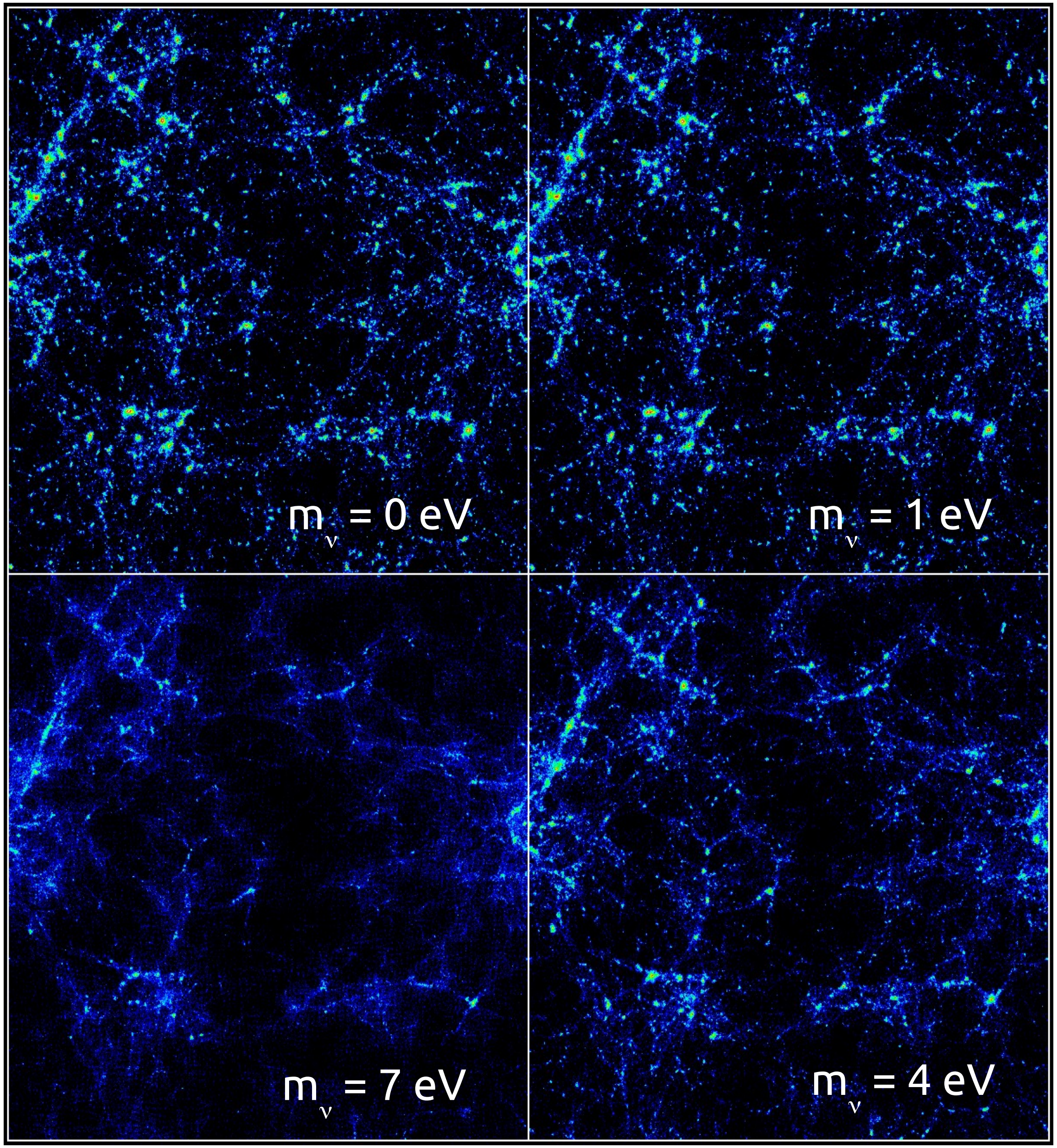
$$t_F = t - t_0 = \frac{L}{v} = \frac{L}{c}\frac{E_\nu}{p_\nu} c \sim \frac{L}{c}\left(1 + m_\nu^2 \frac{c^4}{2} E^2\right)$$

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

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

$$m_{\overline{\nu_e}} < 5.7 \quad eV \left(95\,\%\,CL\right)$$

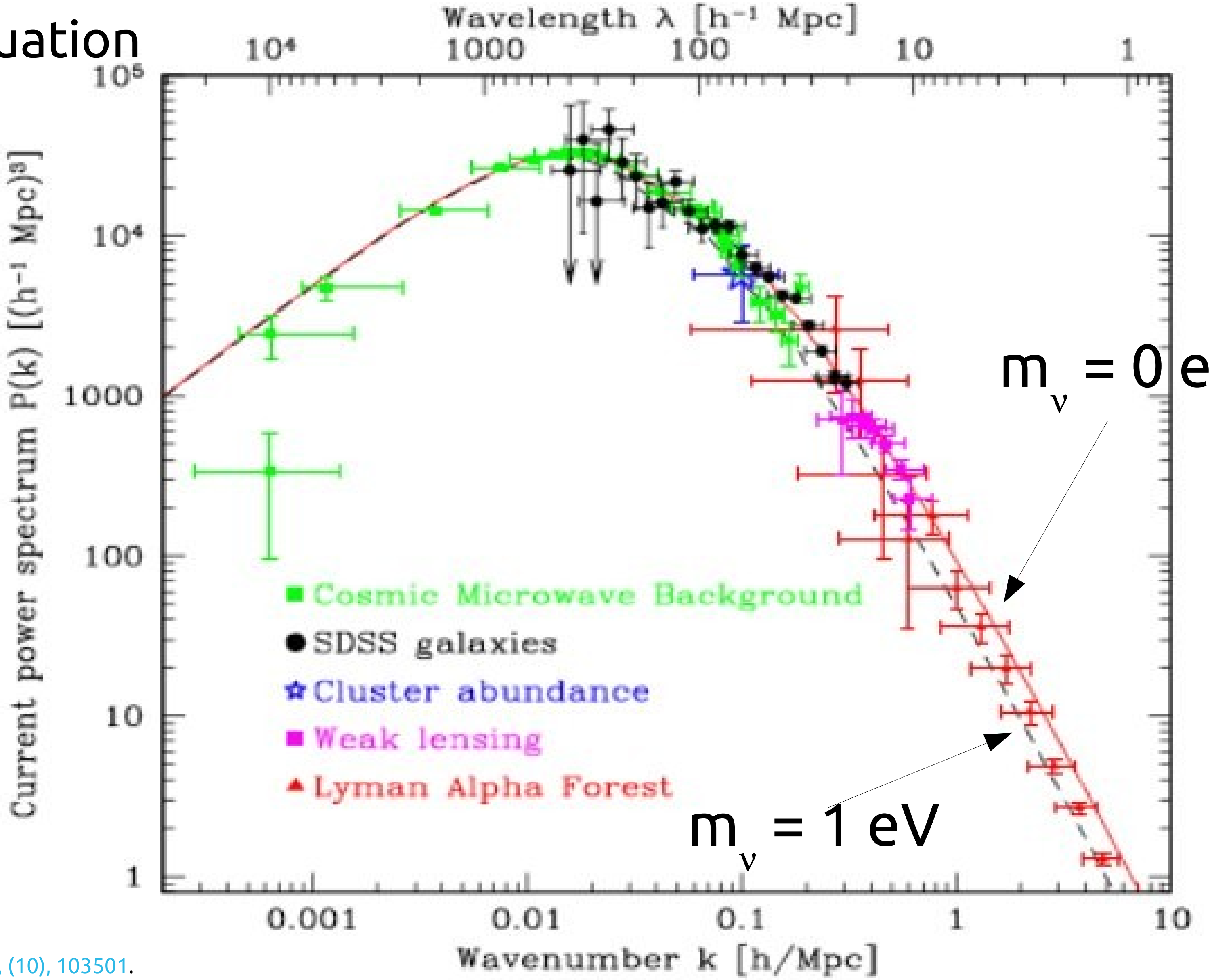
Cosmology



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

Power spectra

"Wavelength" of density fluctuation

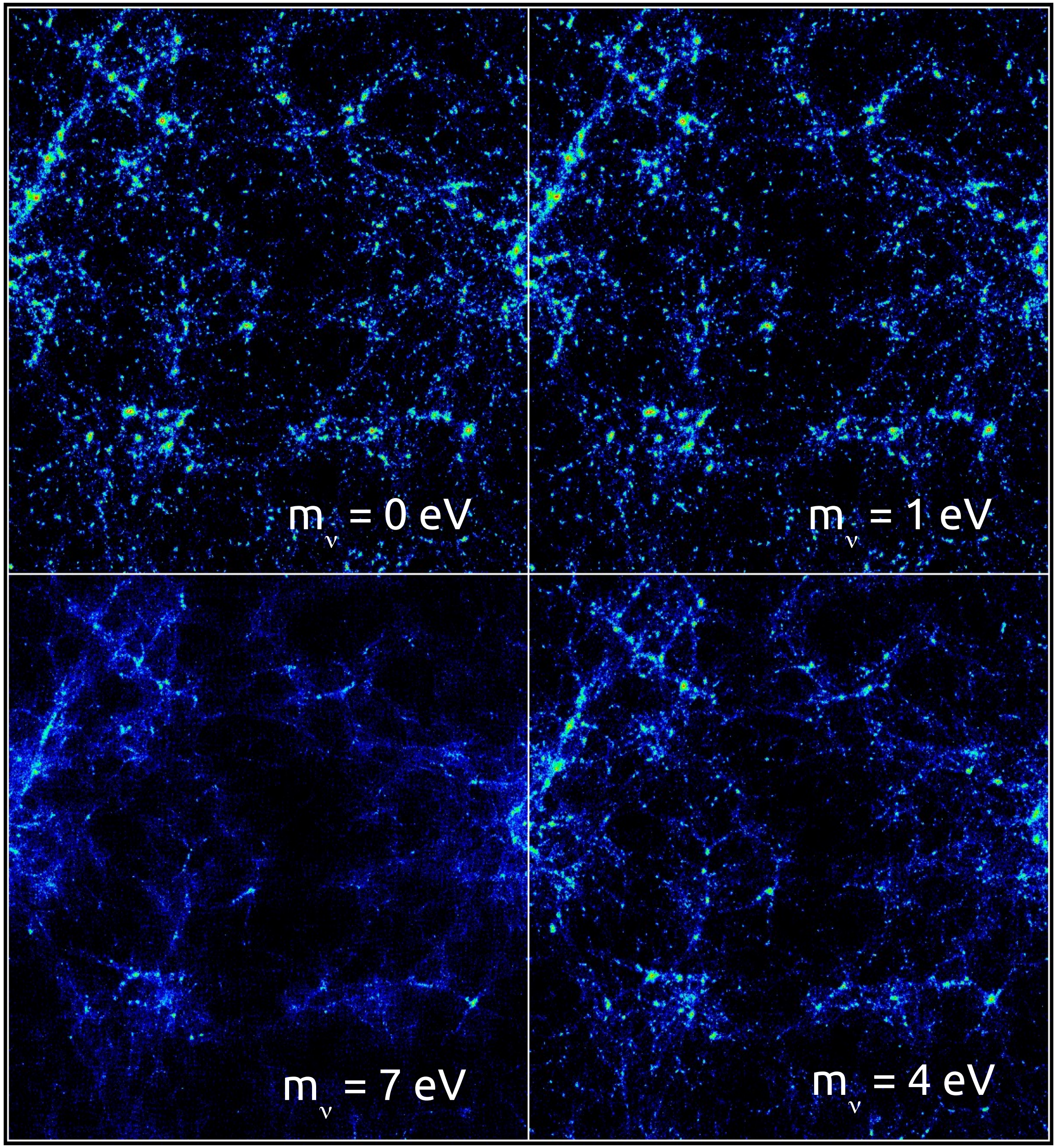


$m_\nu = 0$ eV

$m_\nu = 1$ eV

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

Cosmology



- Density fluctuations are affected by neutrino mass in the early universe
- Highly model dependent
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$$\boxed{\sum m_{\nu_i} \leq (0.14 - 0.60)\, eV}$$

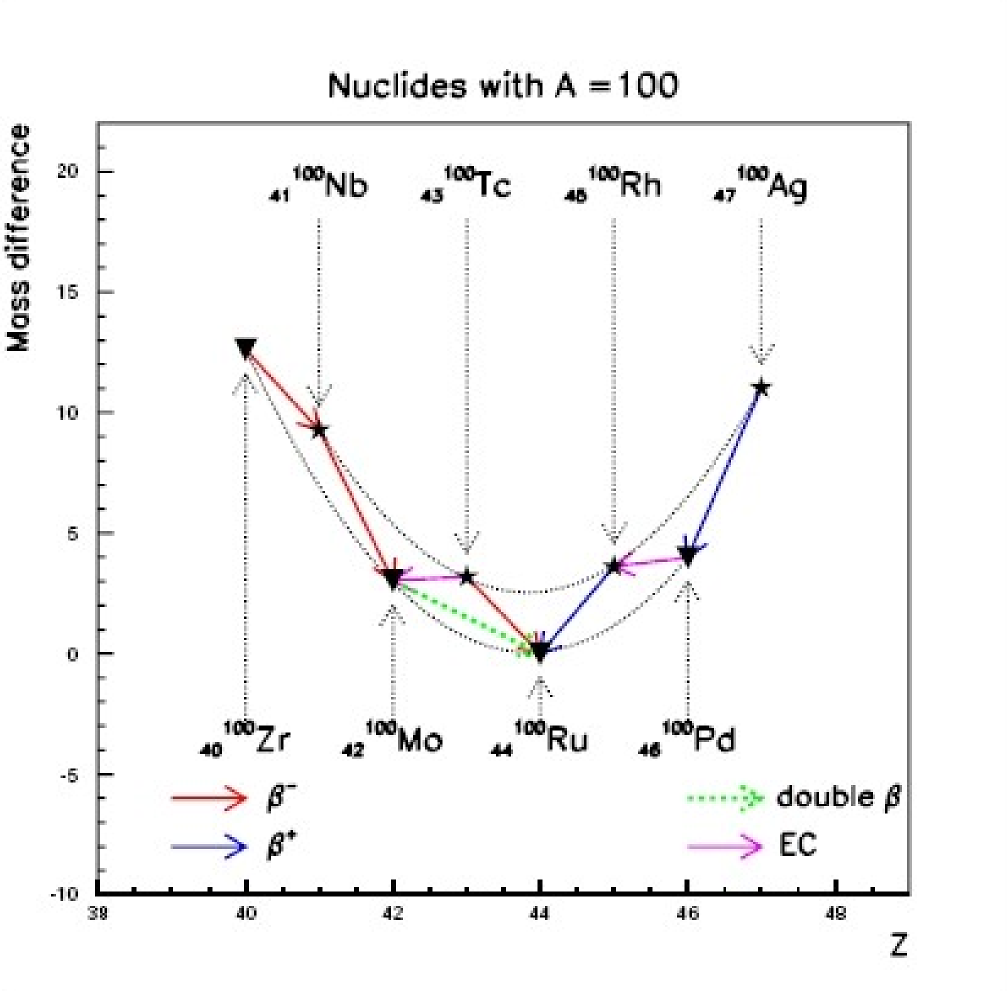
(rather model dependent)

2νββ Decay

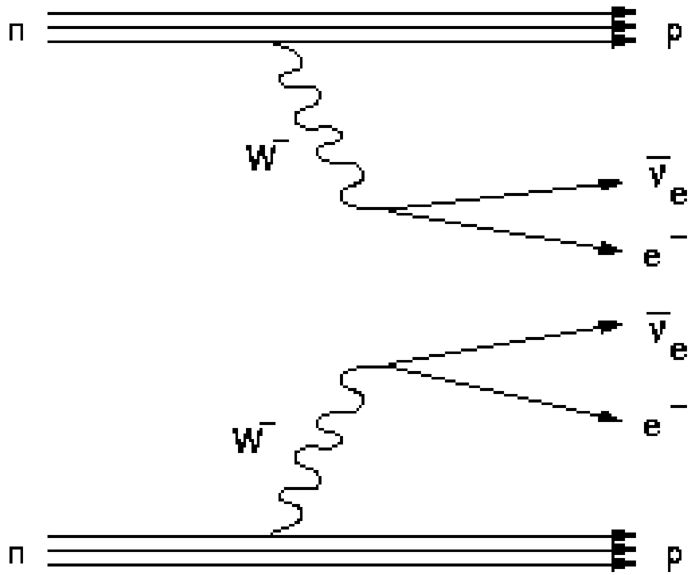
Neutrinoless double beta decay is considered a golden channel for the measurement of neutrino mass.

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

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



2νββ 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

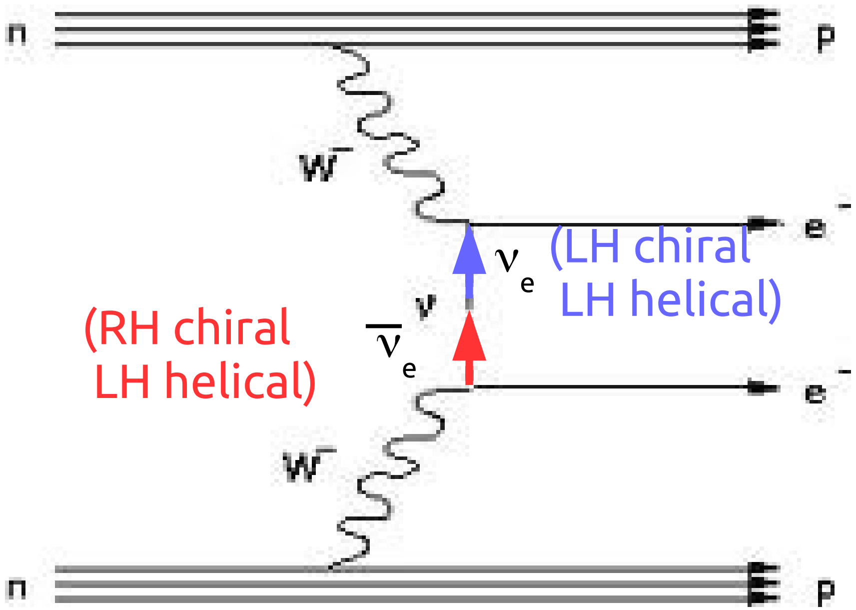
- Second order process in perturbation theory
- Severe test for nuclear matrix element calculation
- Nuclear structure effects cause variations in the nuclear matrix elements of factors of 10

2νββ 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 ββ Decay



Requirements

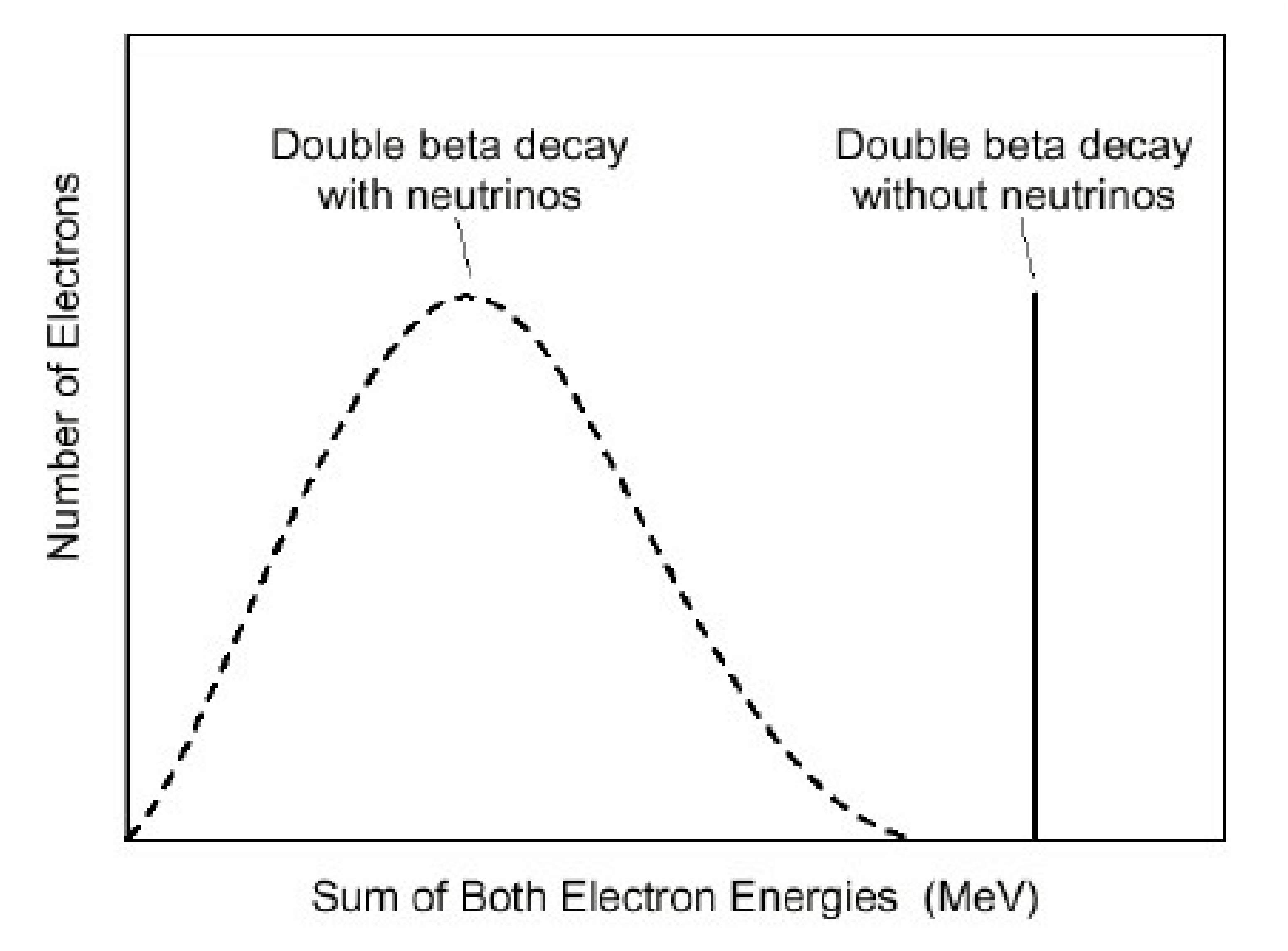
- Neutrino must have mass
- Neutrino is Majorana
- Violation of lepton number conservation

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

helicity states

$$\boxed{\Gamma_{0\nu}=G_{0\nu}\left|M_{0\nu}\right|^2\left|\sum_i\left|U_{ei}\right|^2 m_i\right|^2\Rightarrow T_{1/2}\sim10^{27}\,years}$$

0vββ signal

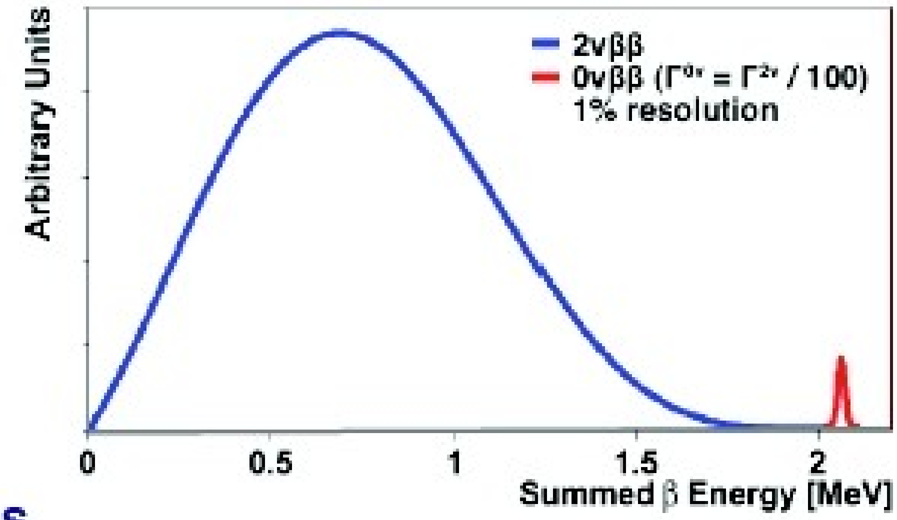

Double beta decay
with neutrinos
Double beta decay
without neutrinos
Number of Electrons
Sum of Both Electron Energies (MeV)

Experimental Requirements

Extremely slow decay rates

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

Best case, **0 background !**	∝ Source Mass • time_{exp}

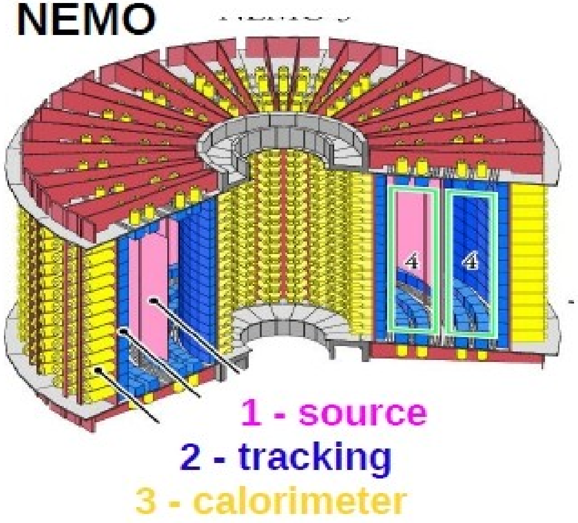


Requires

- 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 $2\nu\beta\beta$ (~ $T_{1/2}$ ~ 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

Types of experiments

NEMO



1. the source is inserted as thin foil inside a tracking detector

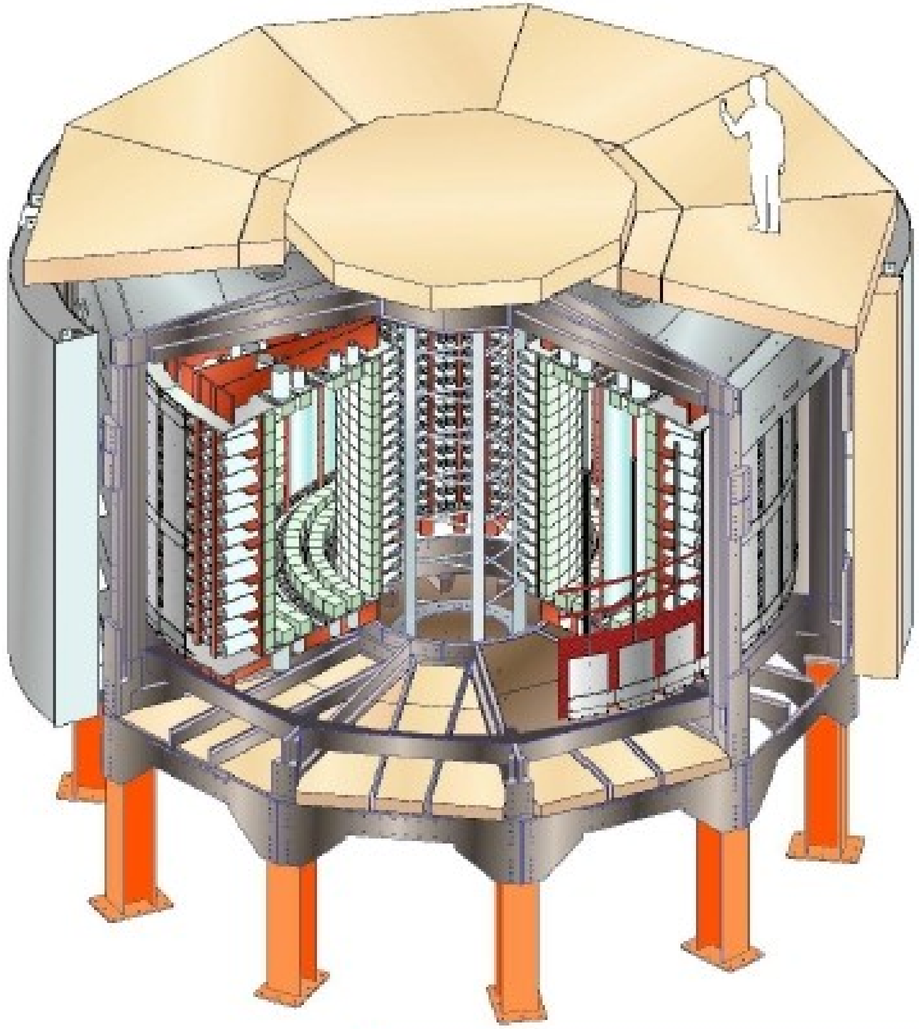
- **$2e^-$ are detected separately**
  → different channels of 0νDBD can be distinguished
- **particle identification**
  → background suppression
- **poor energy resolution**
  → important 2νDBD background
  (limitation on isotope choice)

2. the detector is itself the source

- **solid state detectors**
  → several candidates, high resolution
  no info on kinematic
  techniques for background suppression

- **gaseous detectors for Xe**

Passive Source - NEMO3



Source: 10 kg of ββ isotopes
cylindrical, S = 20 m², 60 mg/cm²

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

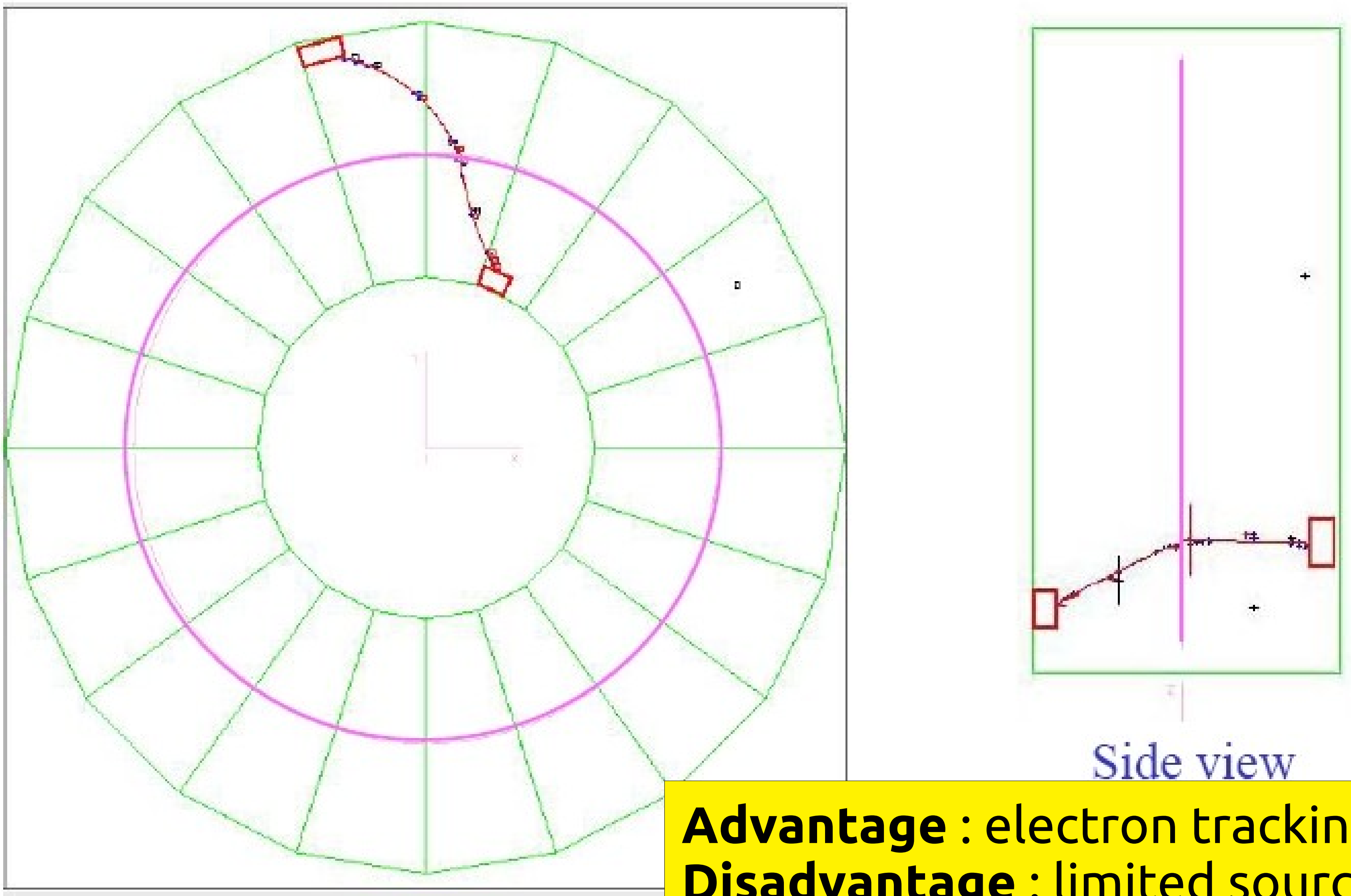
Calorimeter:
1940 plastic scintillators
coupled to low radioactivity PMTs

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

Background: natural radioactivity mainly ^{214}Bi et ^{208}Tl (~ 2.6 MeV)
⇒ [illegible]

Able to identify e^-, e^+, γ and α

Typical ββ2ν event observed from ^{100}Mo

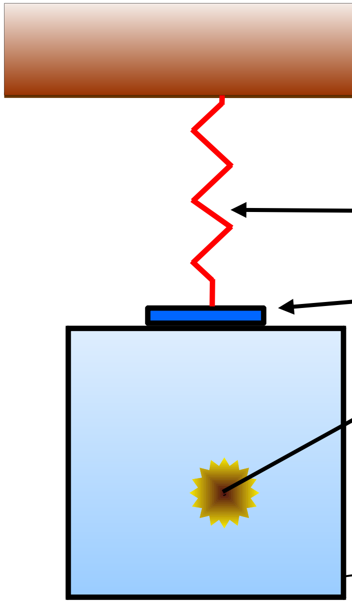


Top view

Side view

Advantage : electron tracking
Disadvantage : limited source material and relatively poor energy resolution

Bolometry : Cuore



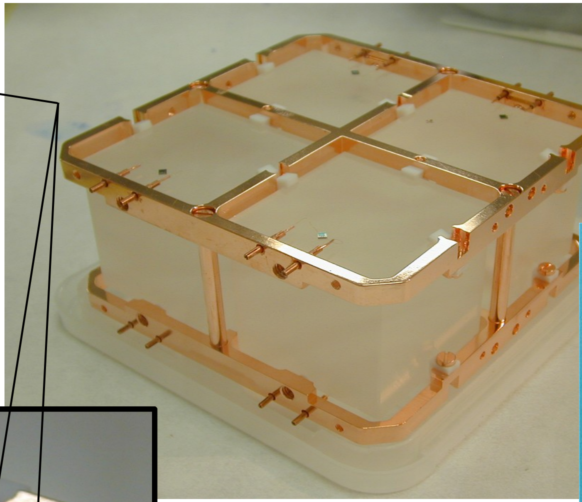
Heat sink

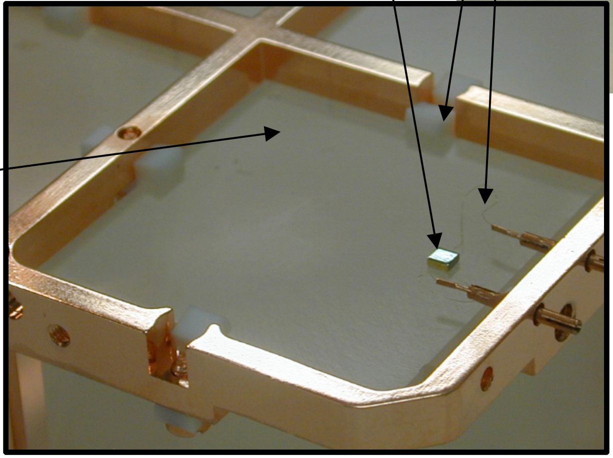
Thermal coupling

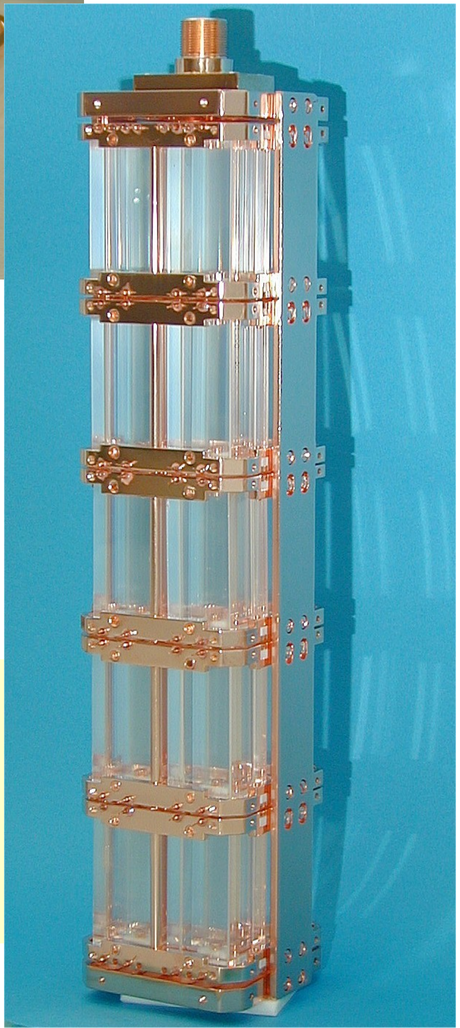
Thermometer

Double beta decay

Crystal absorber







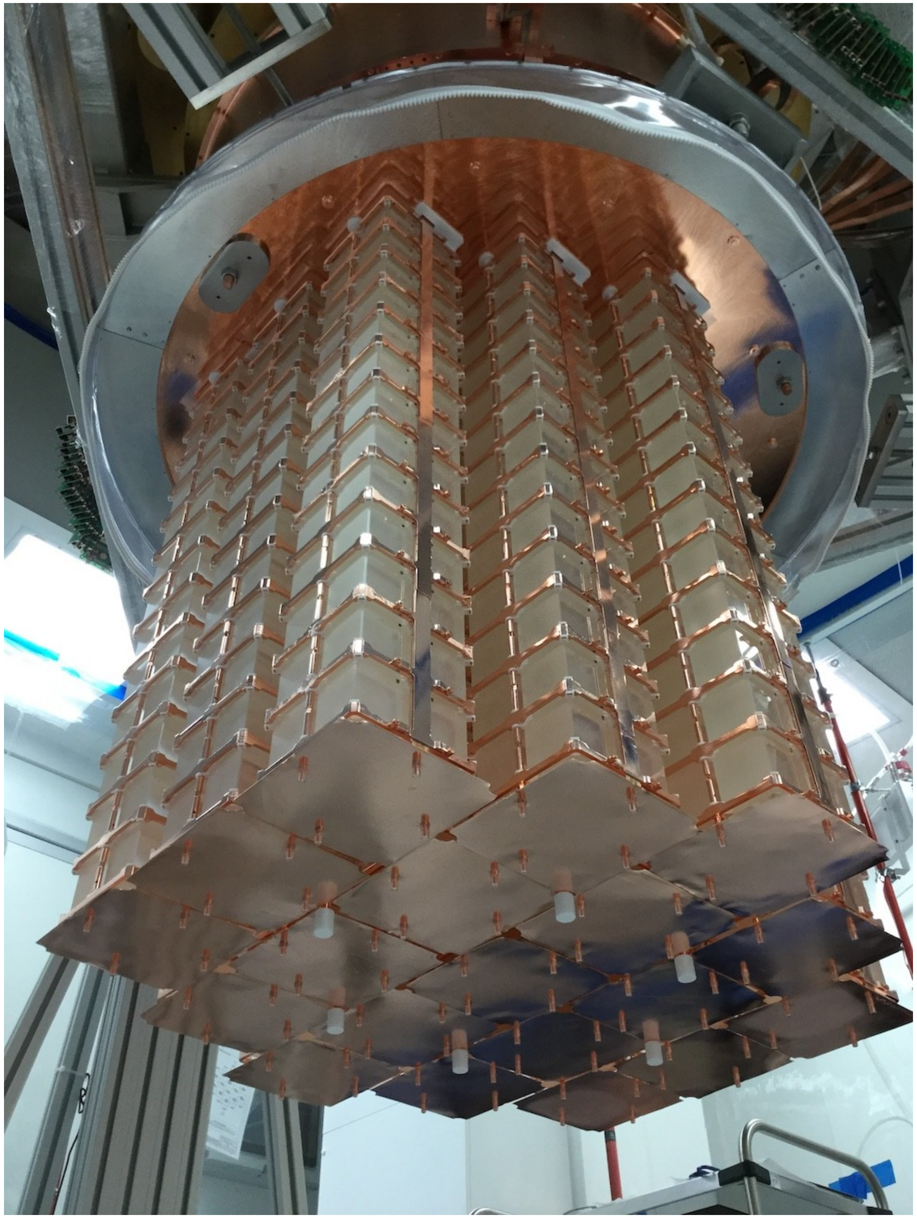
example: 750 g of TeO_2 @ 10 mK

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

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

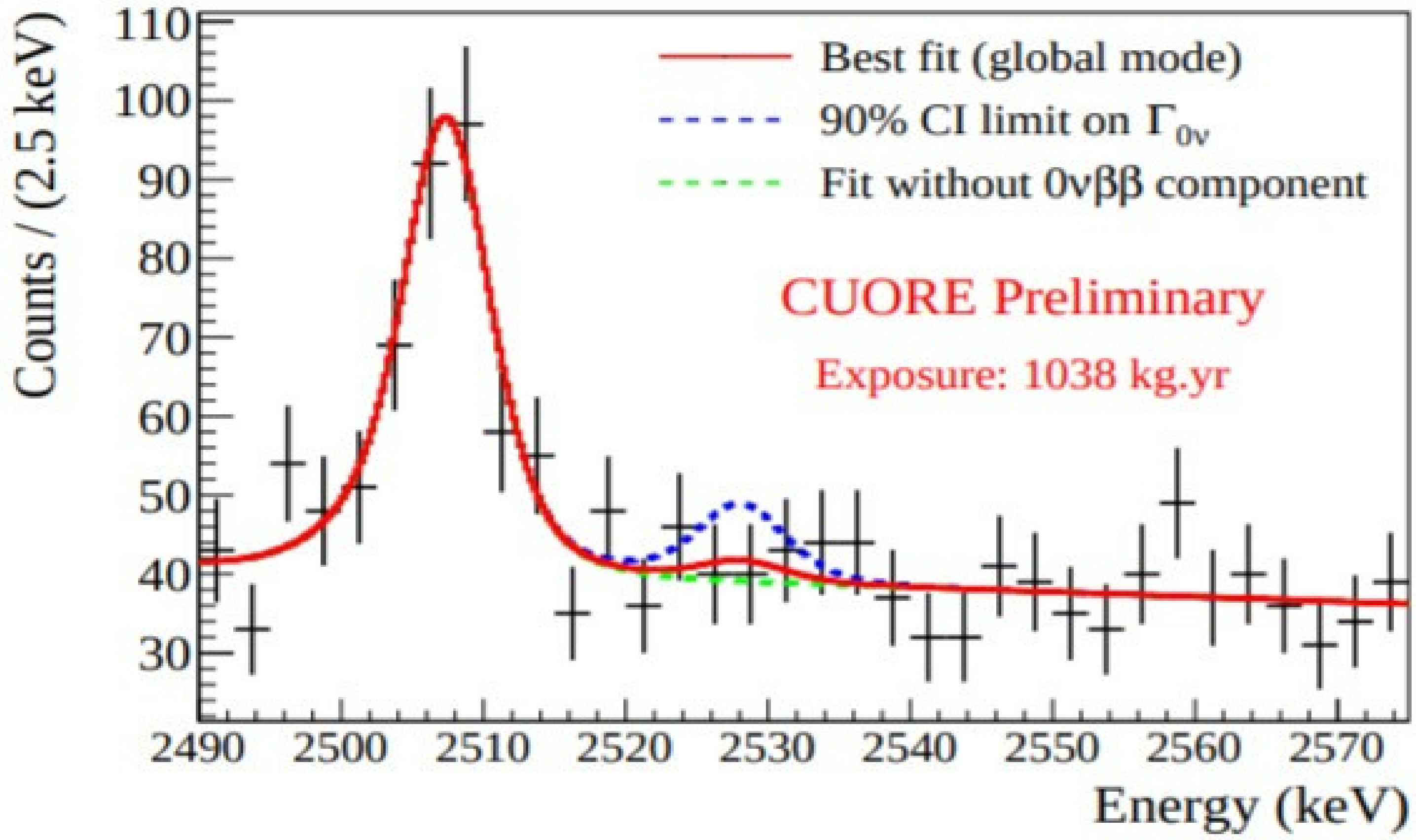
$\Rightarrow \Delta U \sim 10$ eV

Cuore



- 19 towers of 52 5x5x5 cm^3 TeO_2 crystals
- Total mass of 742 kg of TeO_2
- 0.5 kg of 0νββ isotope ^{120}Te
- Crystals held at 10 mK

Cuore Results



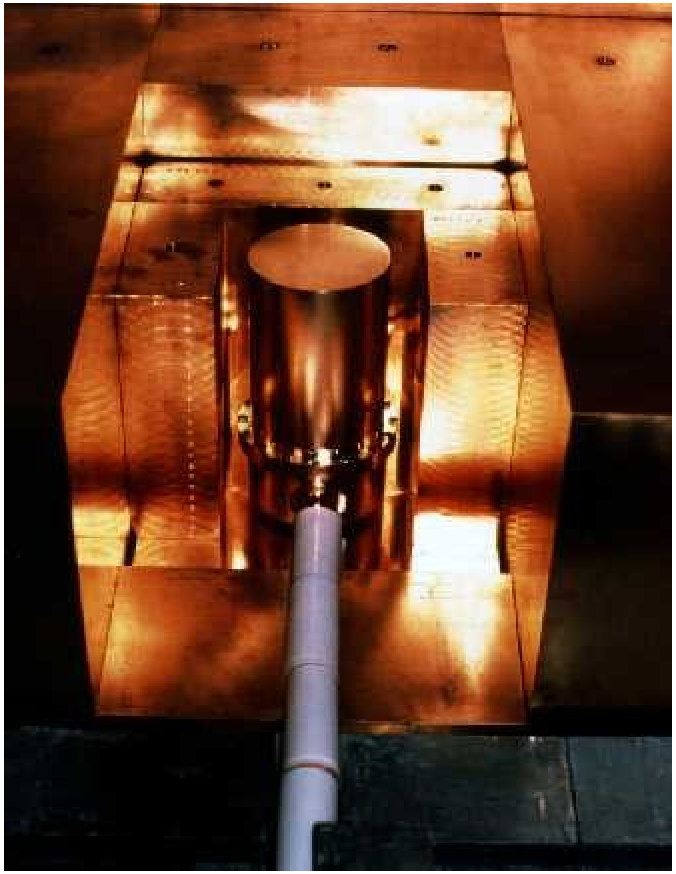
$$T_{1/2}^{0\nu} > 2.2 \times 10^{25}\, years \;\Rightarrow\; \langle m_\nu \rangle < 0.76 - 3.5\, eV$$

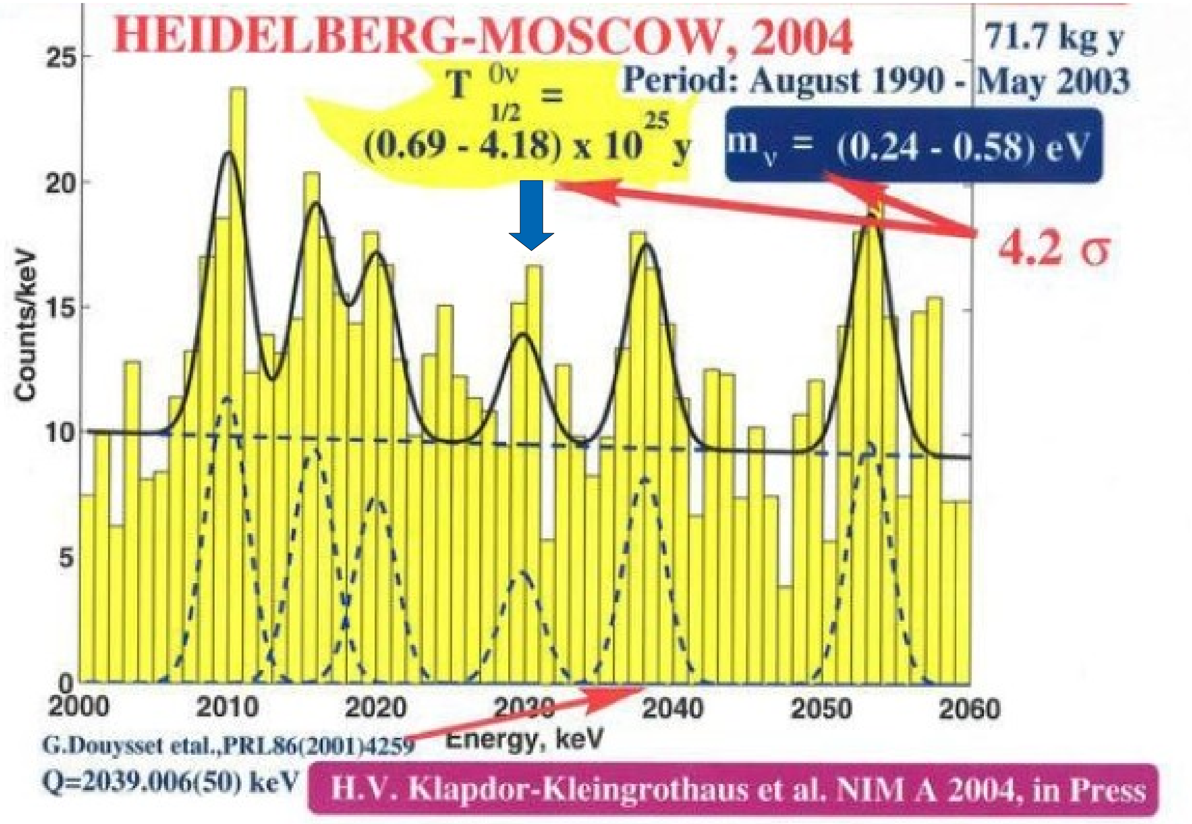
Heidelberg-Moscow (HdM)

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

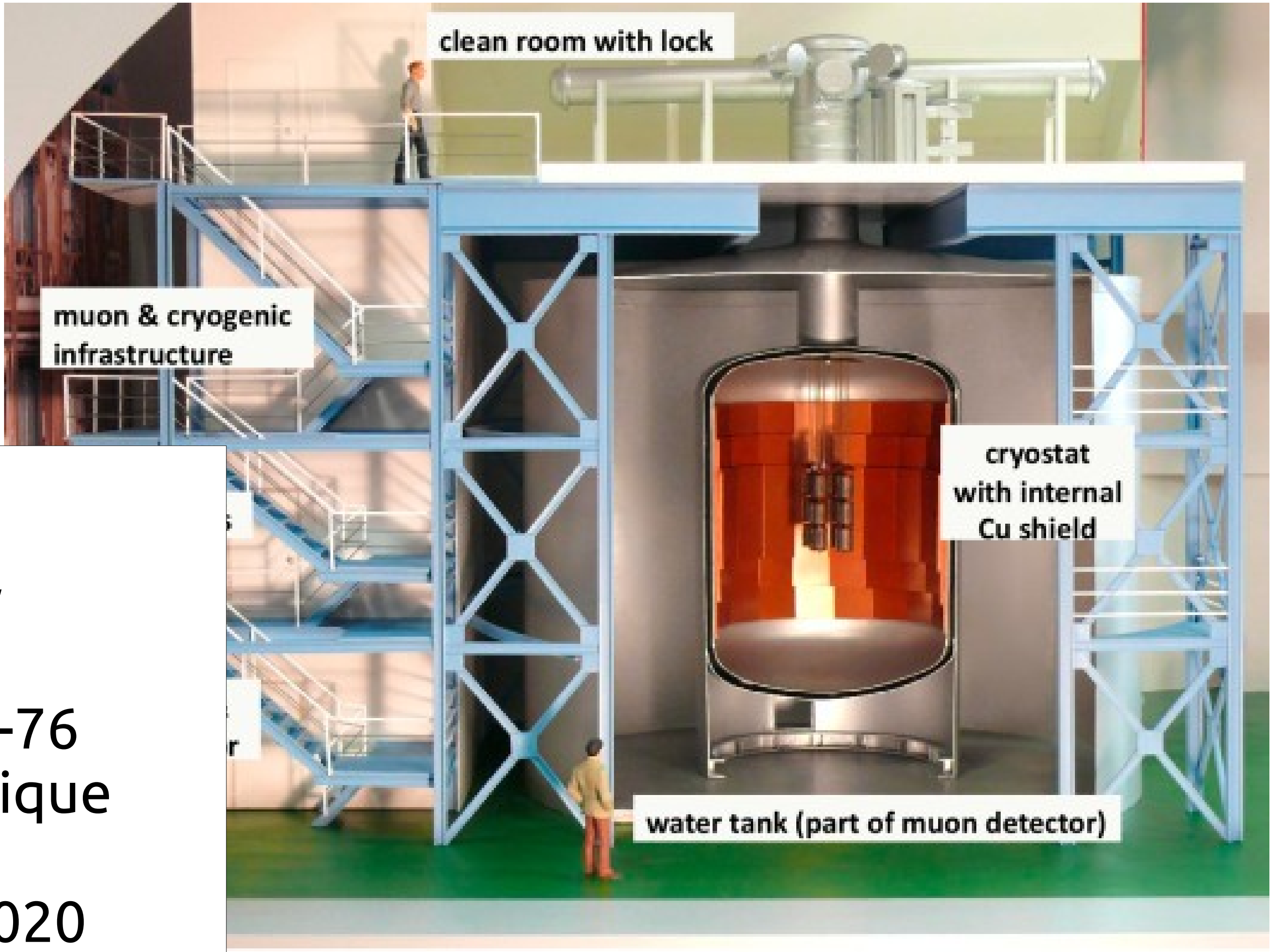
0vββ electrons detected by Ge detectors themselves

Sum of electron energy is measured



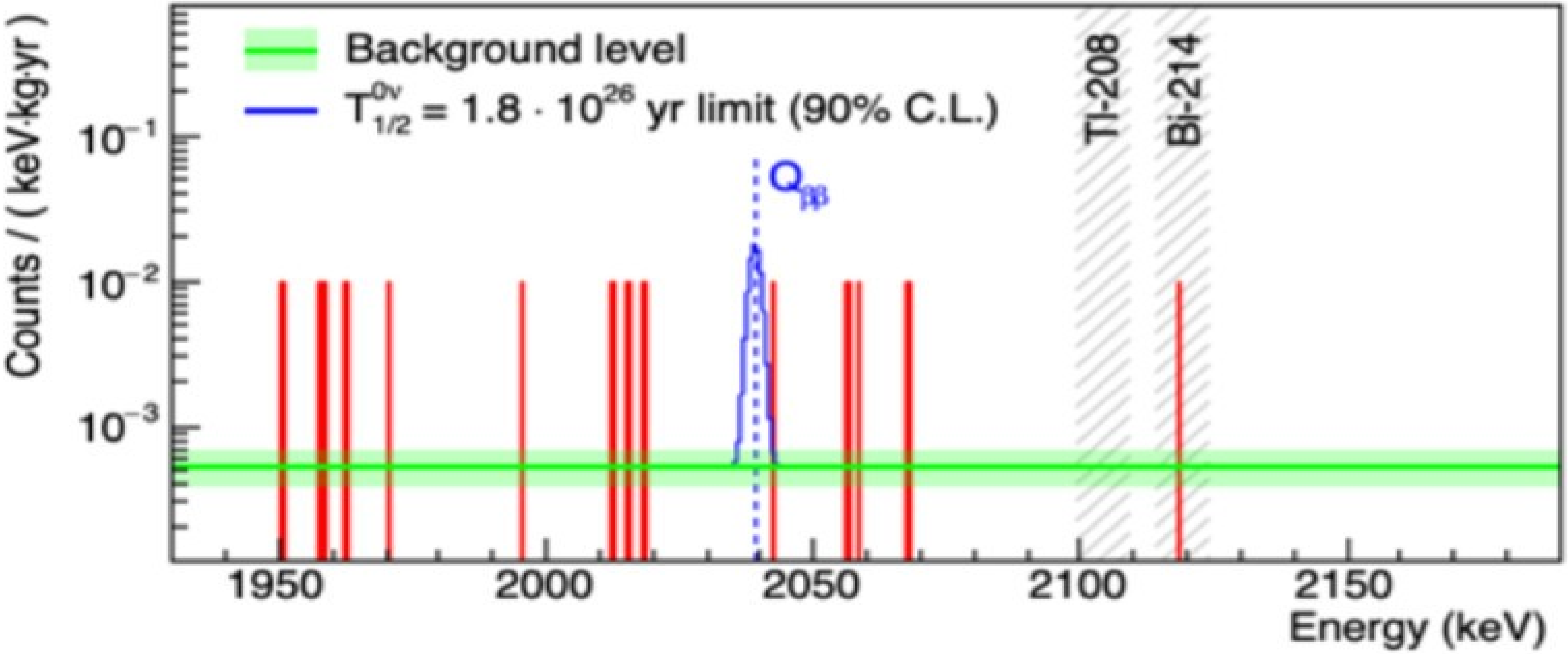


GERDA



- Designed to test Heidelberg-Moscow
- Used the same Ge-76 isotope and technique
- Ran from 2011 - 2020

GERDA



$T_{1/2} > 1.4 \times 10^{26}$ yr @ 90% CL

$m(\nu_e) <$ 79-180 meV @ 90% CL

Inconsistent with HdM, but not definitive (yet)

$$m(\nu_e)(HM) = 240 - 580\, meV$$

Future Program

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	$\left(\sum_i \left\|U_{ei}{}^2\right\| m_i^2\right)^{\frac{1}{2}}$	< 0.8 eV
0v2β decay	$\left\|\sum_i U_{ei}^2 m_i\right\|$	<0.2 eV $<m_{\beta\beta}>$=440 meV from HM
Cosmology	$\sum_i m_i < 0.15\, eV$	Model dependent
Pion decay	$m_{\nu\mu} < 190\, keV$	Fairly pointless
Tau decay	$m_{\nu\tau} < 18.2\, MeV$	Entirely pointless

Question

Is there an experimental way of directly showing that the neutrino is a Dirac particle? What about an indirect approach?

SN1987A

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