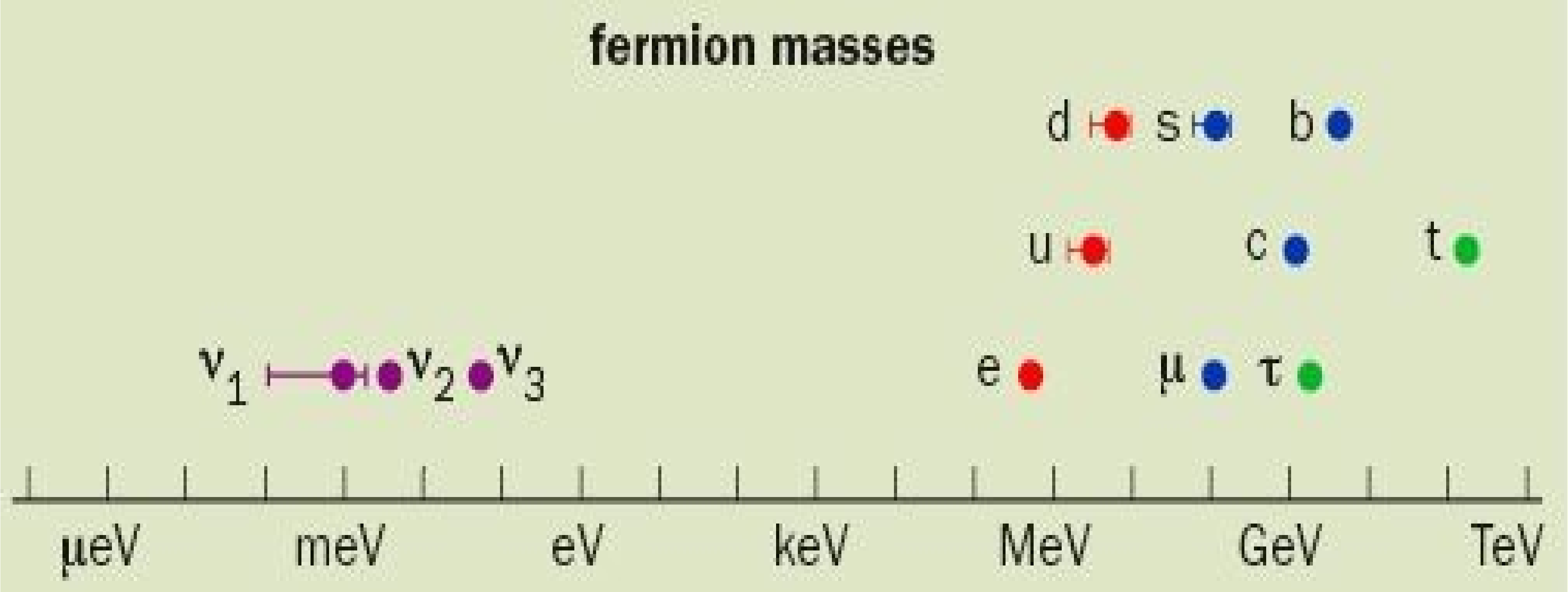
# Lecture 2

*In 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, $m_D$

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

Can rewrite mass term in terms of chiral states

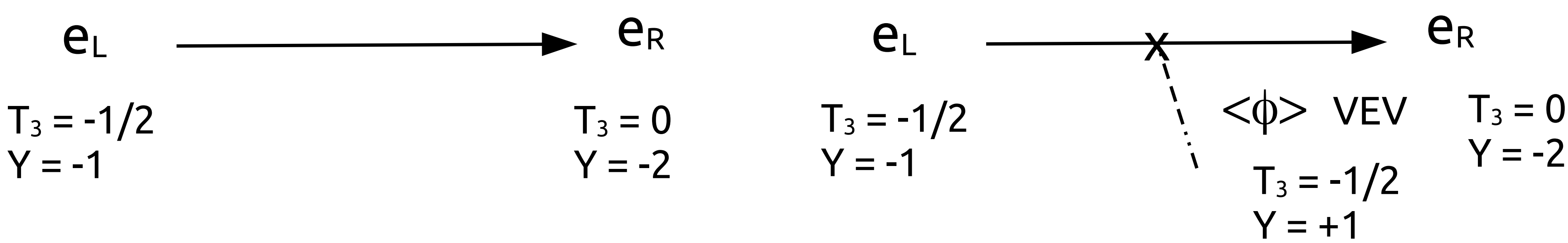
$$L_{mass} = m_D \overline{\psi}\psi = m_D(\overline{\psi_L} + \overline{\psi_R})(\psi_L + \psi_R) = m_D(\overline{\psi_L}\psi_R + \overline{\psi_R}\psi_L)$$

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

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



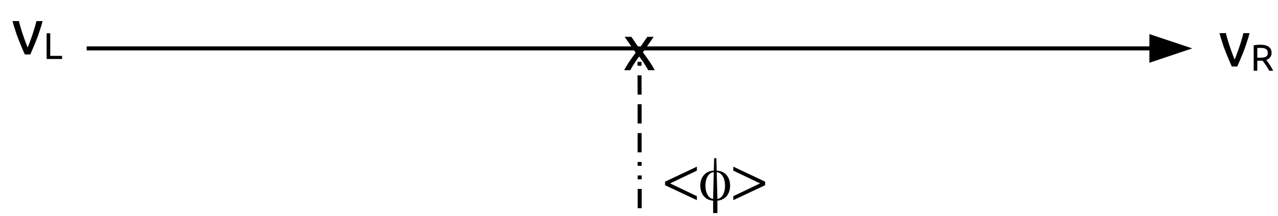

**Dirac mass** : $m_D = Y_\psi\langle\phi\rangle \quad \langle\phi\rangle = 246\ GeV$

- 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 $m_\nu$ 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

# Dirac vs Majorana

|  | helicity | Conserved L | $l^-$ prod. | $l^+$ prod. |
|---|---|---|---|---|
|  | -1/2 | +1 | 1 | 0 |
|  | -1/2 | -1 | 0 | $(m/E)^2 \ll 1$ |
|  | +1/2 | +1 | $(m/E)^2 \ll 1$ | 0 |
|  | +1/2 | -1 | 0 | 1 |

|  | helicity | $l^-$ prod. | $l^+$ prod. |
|---|---|---|---|
|  | -1/2 | 1 | 0 |
|  | +1/2 | 0 | 1 |

# Damn it!

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

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

$$\nu_L \longrightarrow \times \longrightarrow \nu_L^C$$

$$T_3 = +1/2 \qquad \Delta Y = +2 \qquad T_3 = -1/2$$

$$Y = -1 \qquad \longrightarrow \qquad Y = +1$$

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

$$L_L^M=m_L\,\overline{\nu_L^C}\,\nu_L$$
$$L_R^M=m_R\,\overline{N_R^C}\,N_R$$

Two Majorana mass terms

$$L_L^D=m_D\,\overline{N_R^C}\,\nu_L$$
$$L_R^D=m_D\,\overline{\nu_L^C}\,N_R^C$$

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.

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

$N_R$ —×— $N_R^C$

$N_R$: $T_3 = 0$, $Y = 0$

$N_R^C$: $T_3 = 0$, $Y = 0$

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 : $\Lambda$

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

right-handed
heavy neutral lepton

"our" neutrino

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

# Leptogenesis

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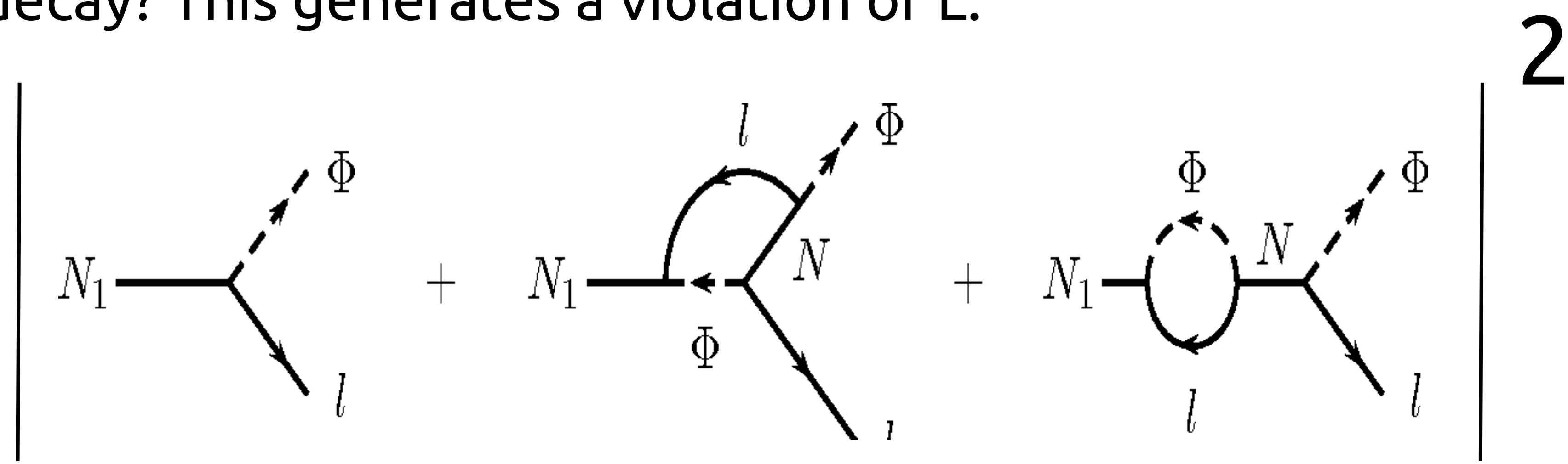
Seesaw mechanism requires a GUT scale heavy Majorana neutrino partner.

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

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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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- a GUT scale heavy neutral lepton must exist ?

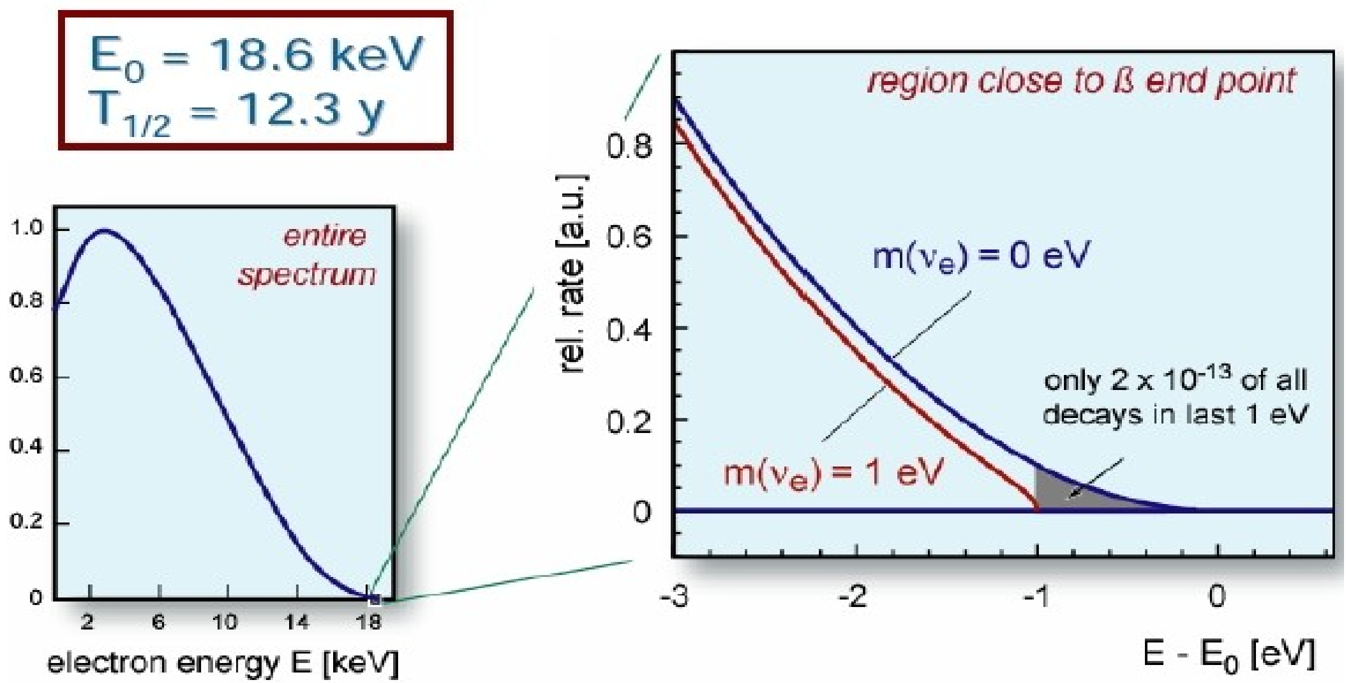
*(Attempts at) mass measurements*

# $\nu_e$ mass

Measurement of $\nu_e$ 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 $m_\nu^2$



# Requirements

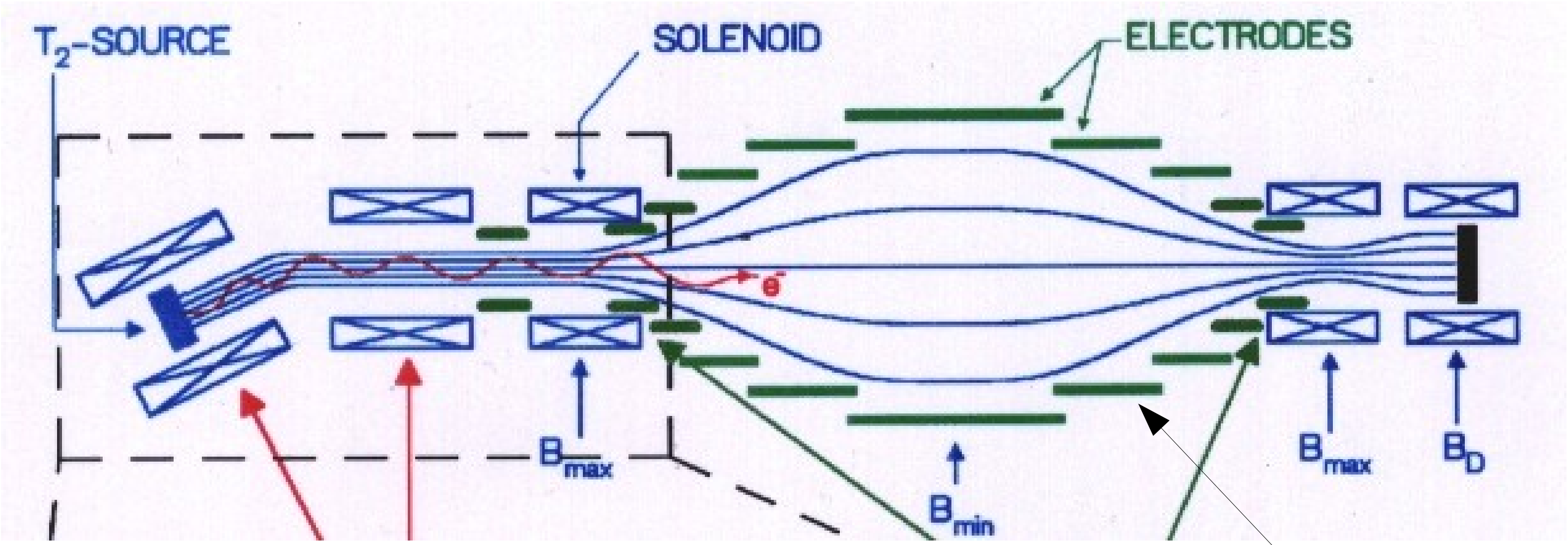
- # electrons close to the endpoint should be large
- Good (and well-understood) electron energy resolution
- No (or minimal) electron energy loss within the source
- Minimal atomic and nuclear final state effects, of excited transitions

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

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

# Early experiments

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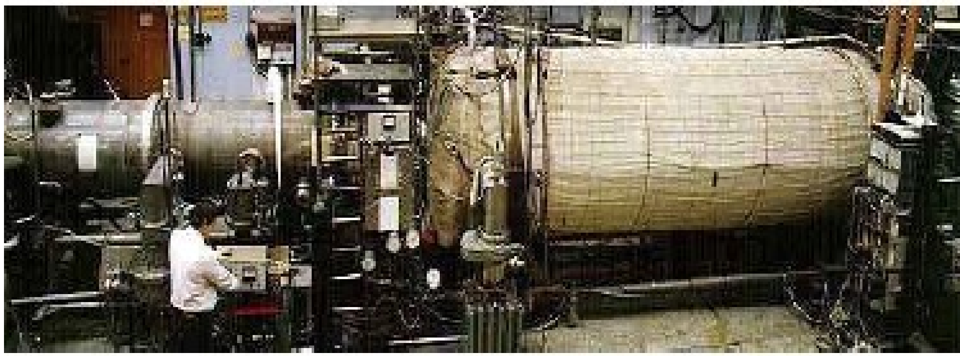
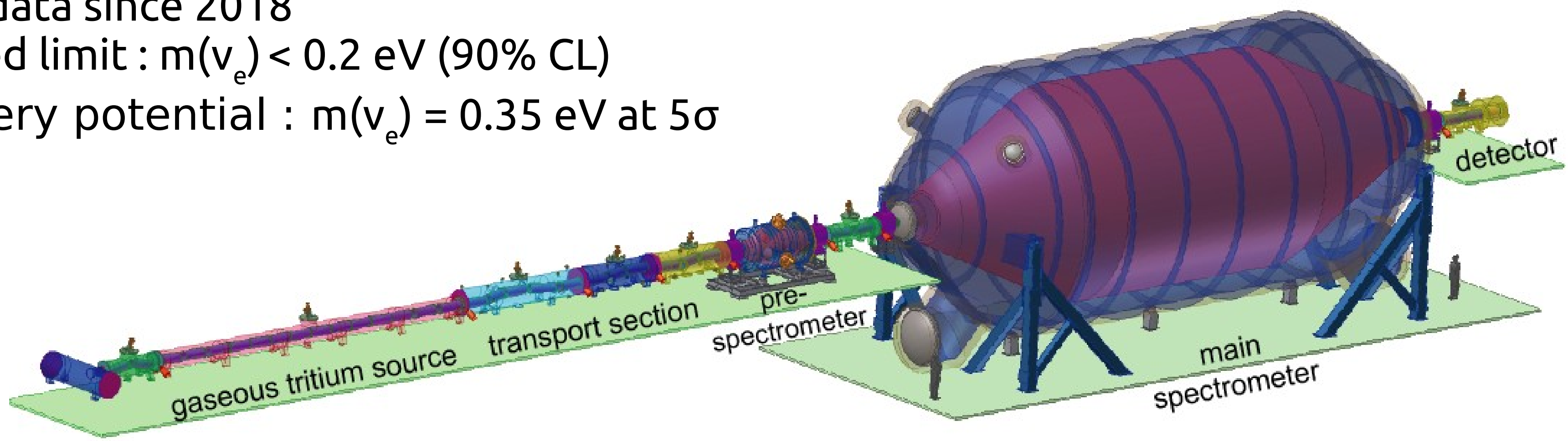


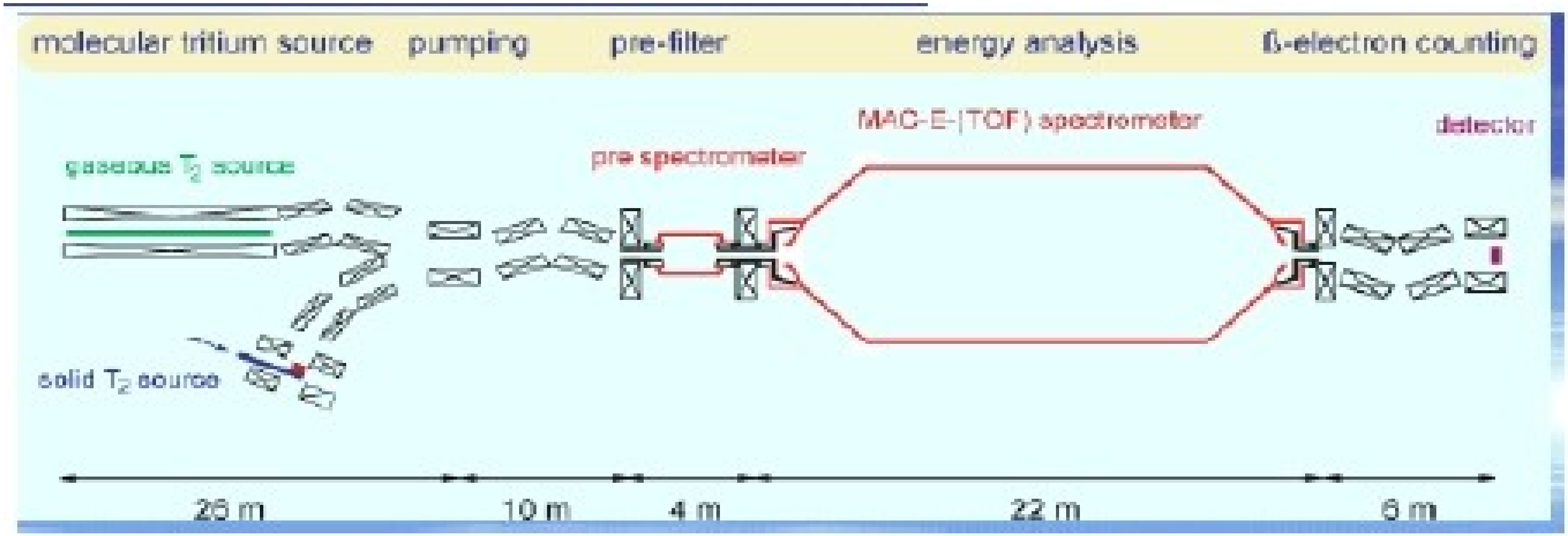
| Troitsk | Mainz |
|---|---|
| windowless gaseous $T_2$ source | quench condensed solid $T_2$ source |
| analysis 1994 to 1999, 2001 | analysis 1998/99, 2001/02 |
| $m_\nu^2 = -2.3 \pm 2.5 \pm 2.0\ eV^2$ | $m_\nu^2 = -1.2 \pm 2.2 \pm 2.1\ eV^2$ |
| $m_\nu \leq$ 2.2 eV (95% CL.) | $m_\nu \leq$ 2.2 eV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

Both experiments have reached the intrinsic limit of their sensitivity.

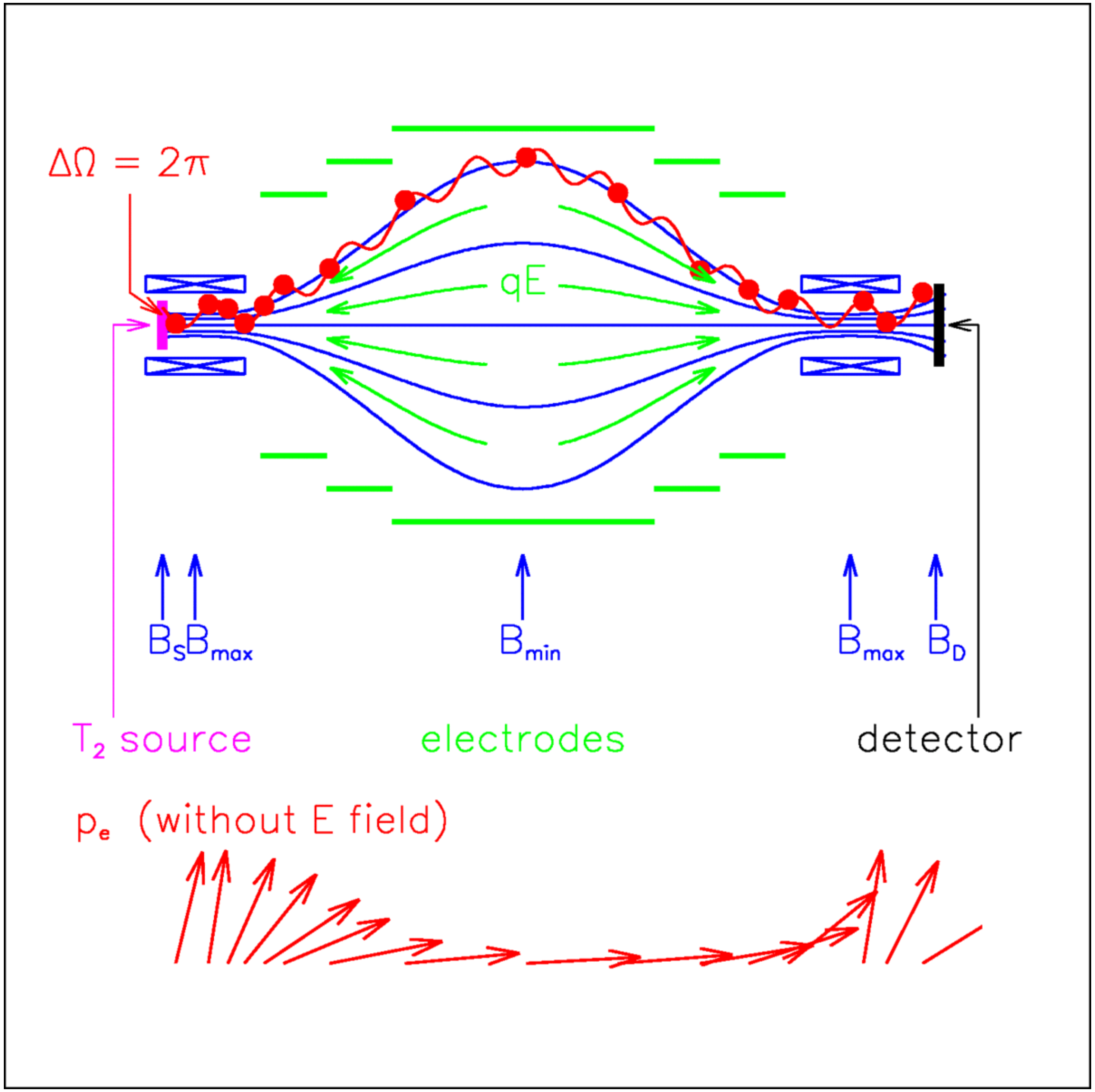
# KATRIN

Taking data since 2018
Expected limit : $m(\nu_e) < 0.2$ eV (90% CL)
Discovery potential : $m(\nu_e) = 0.35$ eV at $5\sigma$



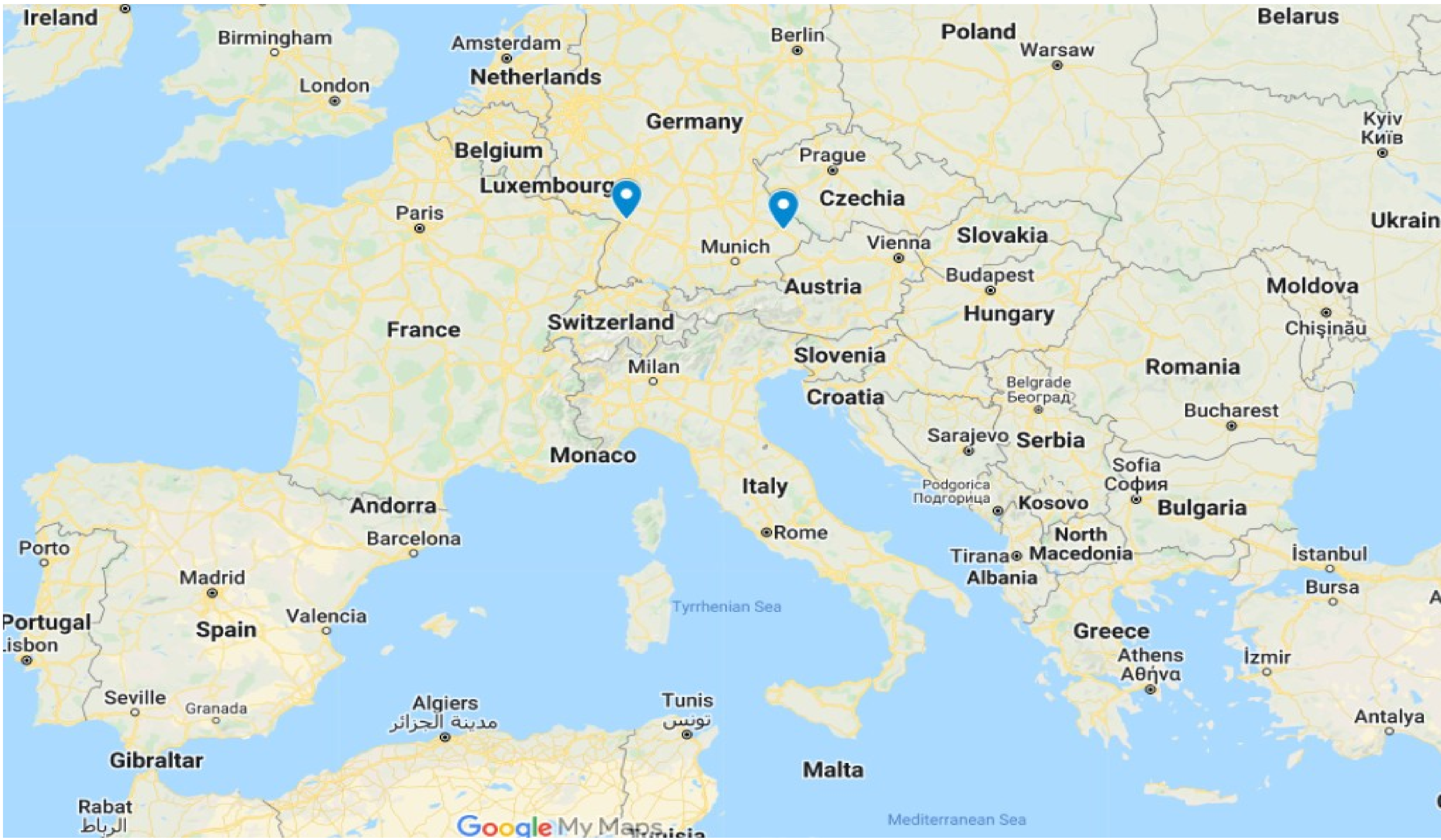



# Principle of operation



# KATRIN on the move

# Katrin on the move



# Katrin on the move

# Latest KATRIN result

**1st campaign (spring 2019)**

- total statistics: 2 million events
- best fit result: $m_\nu^2 = -1.0^{+0.9}_{-1.1}\ \mathrm{eV}^2$
- mass limit: $m_\nu < 1.1\ \mathrm{eV}\ (90\,\%\,CL)$

**2nd campaign (autumn 2019)**

- total statistics: 4.3 million events
- best fit result: $m_\nu^2 = 0.26^{+0.34}_{-0.34}\ \mathrm{eV}^2$
- mass limit: $m_\nu < 0.9\ \mathrm{eV}\ (90\,\%\,CL)$

**Combine 1st and 2nd campaign:**

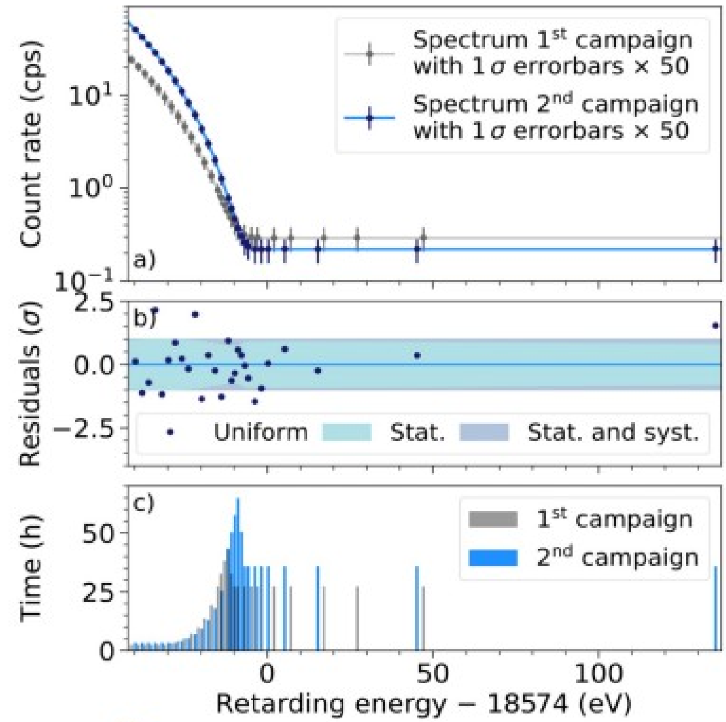
- mass limit: $m_\nu < 0.8\ \mathrm{eV}\ (90\,\%\,CL)$

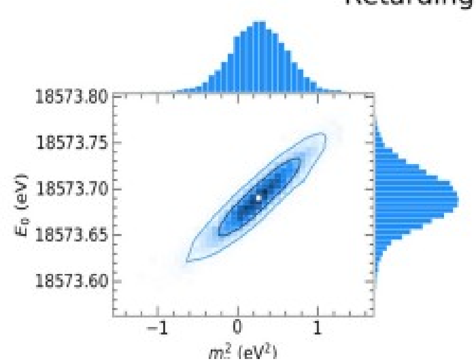
**Cross-check: endpoint energy**

$E_0$ = 18573.69 ± 0.03 eV → Q-value: 18575.2 ± 0.5 eV

→ good agreement with Penning trap experiments:

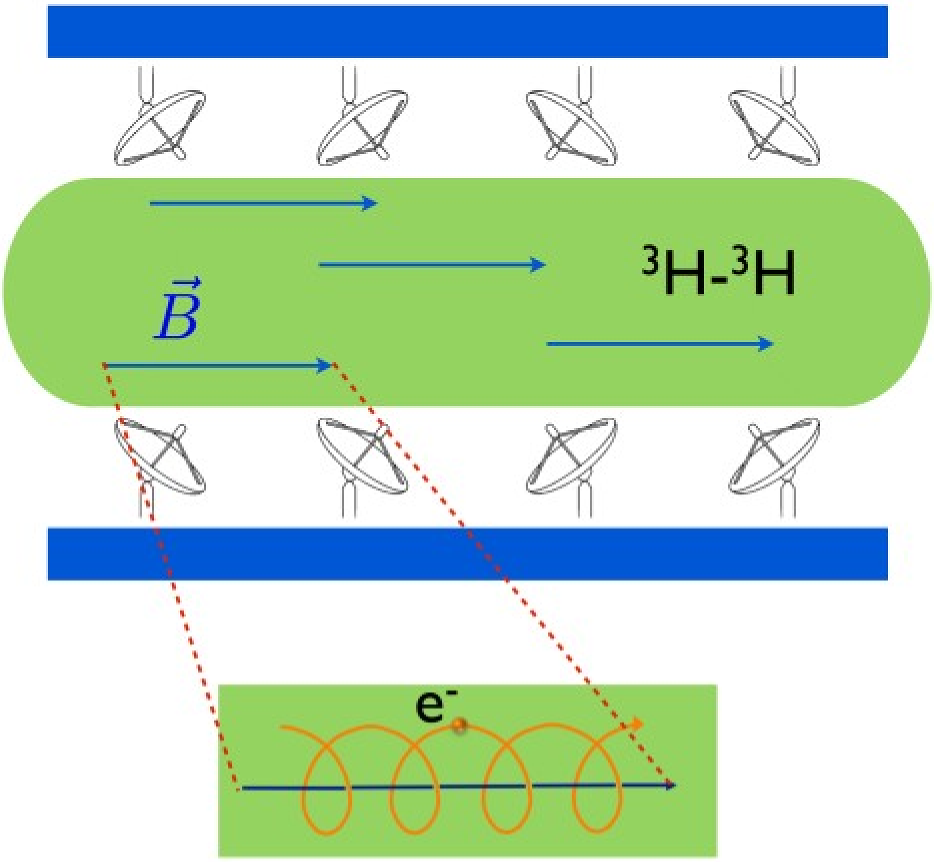
Q = 18575.72 ± 0.07 eV PRL 114 (2015) 013003




Nature Physics 18 (2022) 160

# Cyclotron Radiation Emission Spectroscopy




- 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!

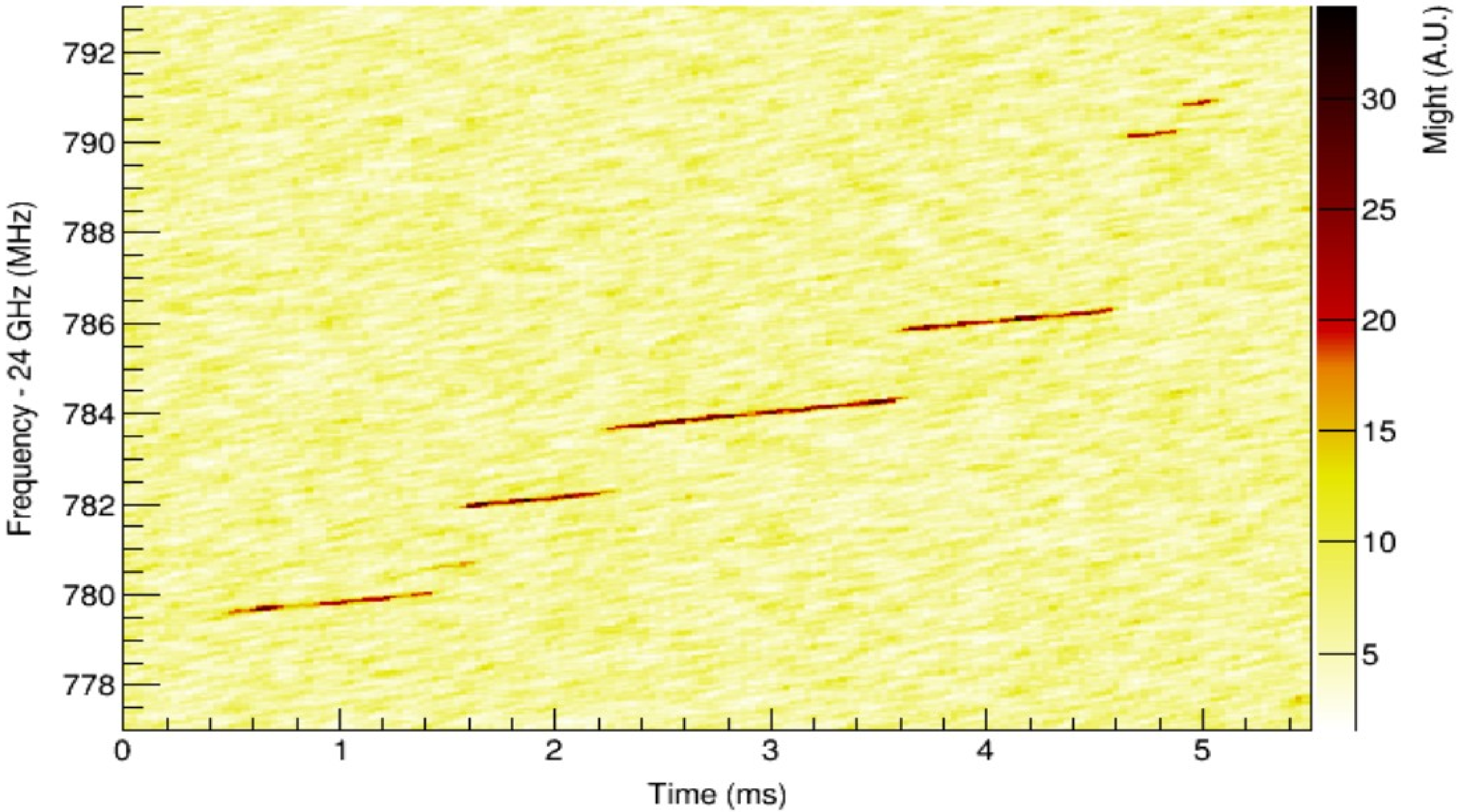
- Push the limit to an order of magnitude lower than KATRIN

- $M_\nu$ < 40 meV

# Project 8



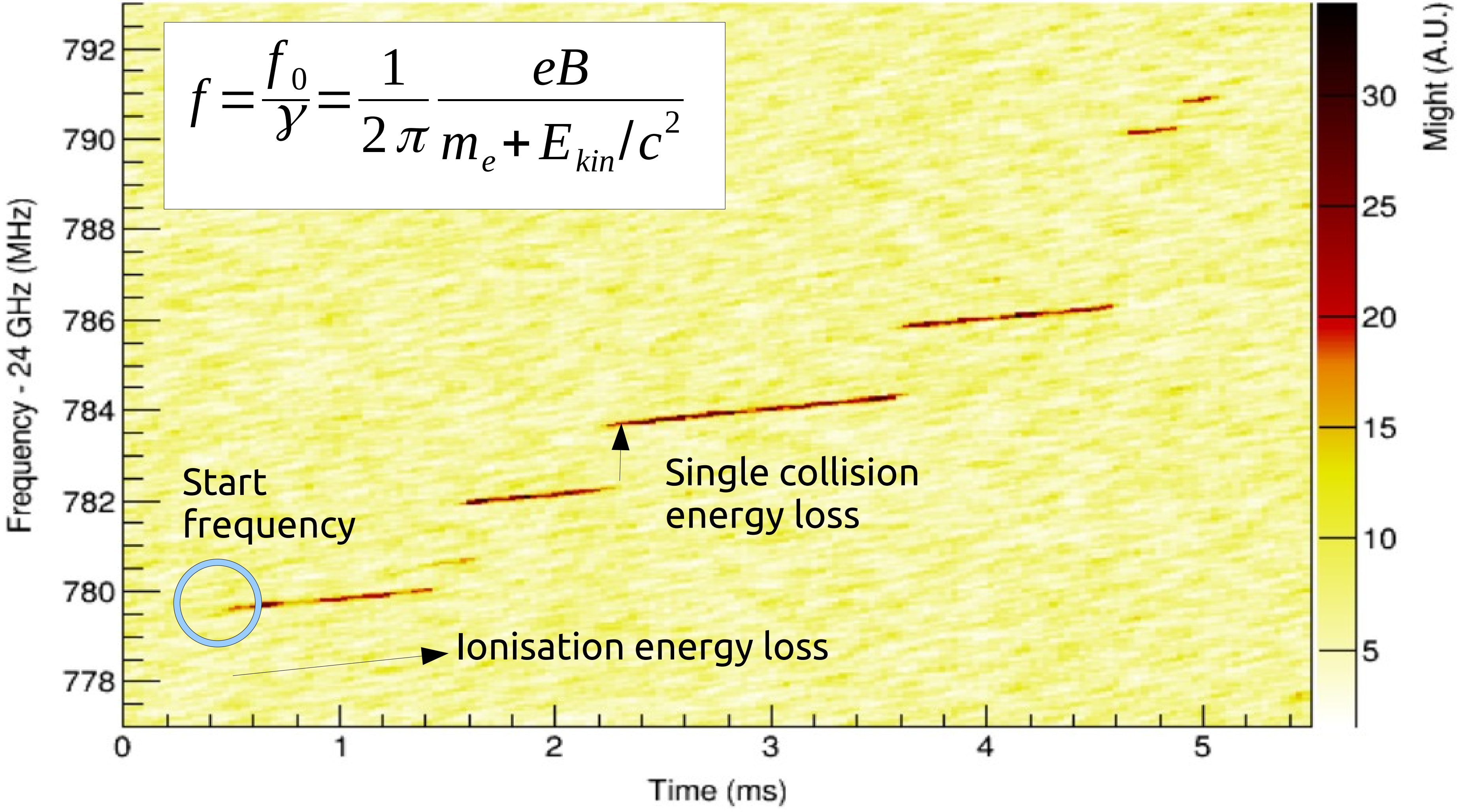
Project 8 Demonstrator – Decay in tritium



# Project 8

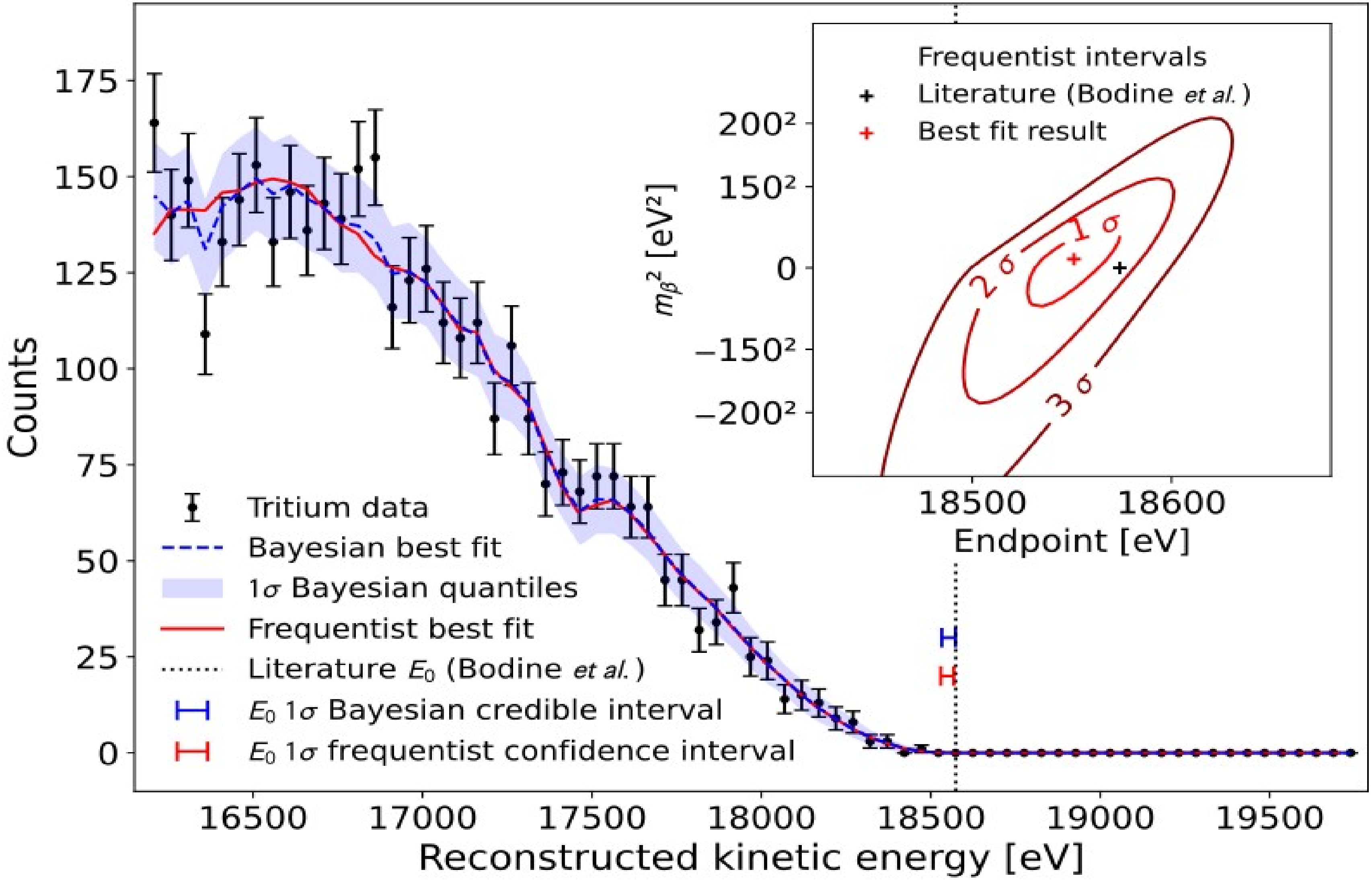
<u>Project 8 Demonstrator – Decay in tritium</u>

$$f = \frac{f_0}{\gamma} = \frac{1}{2\pi} \frac{eB}{m_e + E_{kin}/c^2}$$



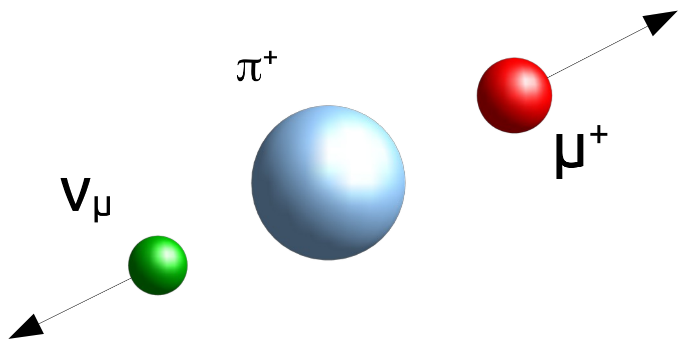
# β-decay from CRES

**prototype proof-of-principle**



# $\nu_\mu$ mass

Easiest way is to use pion decay at rest




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

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

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

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

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

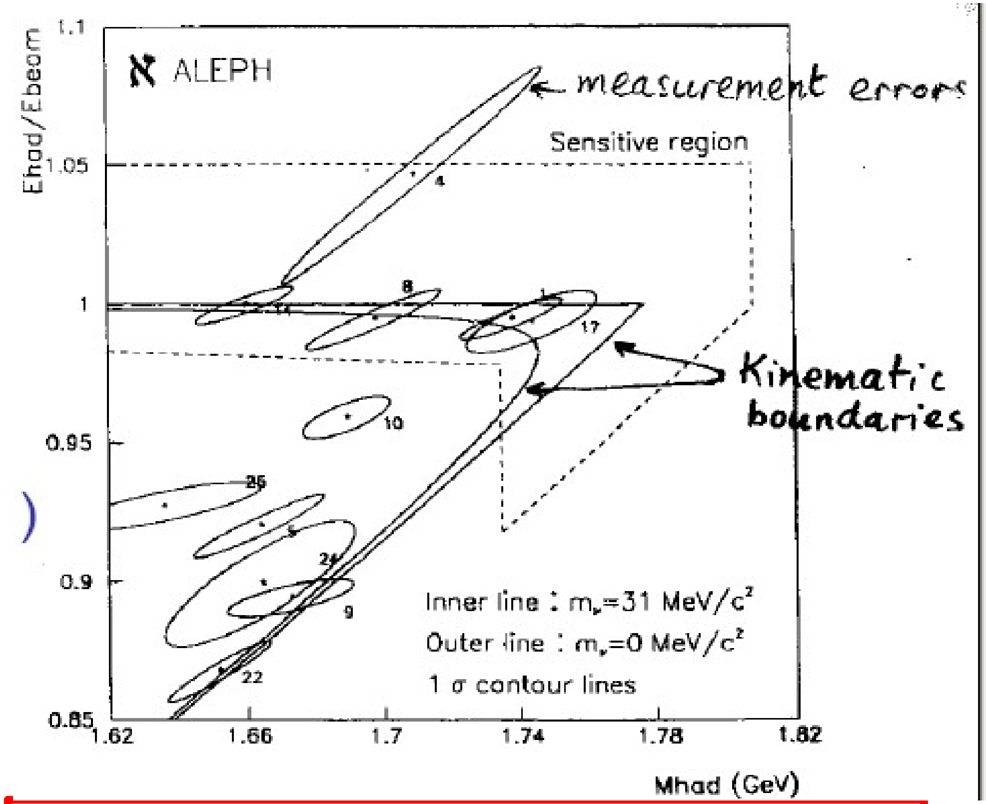
$$m_\nu < 190\, keV\, (90\,\%\, CL)$$

# $\nu_\tau$ mass

$$e^+ e^- \rightarrow \tau^+ \tau^-$$

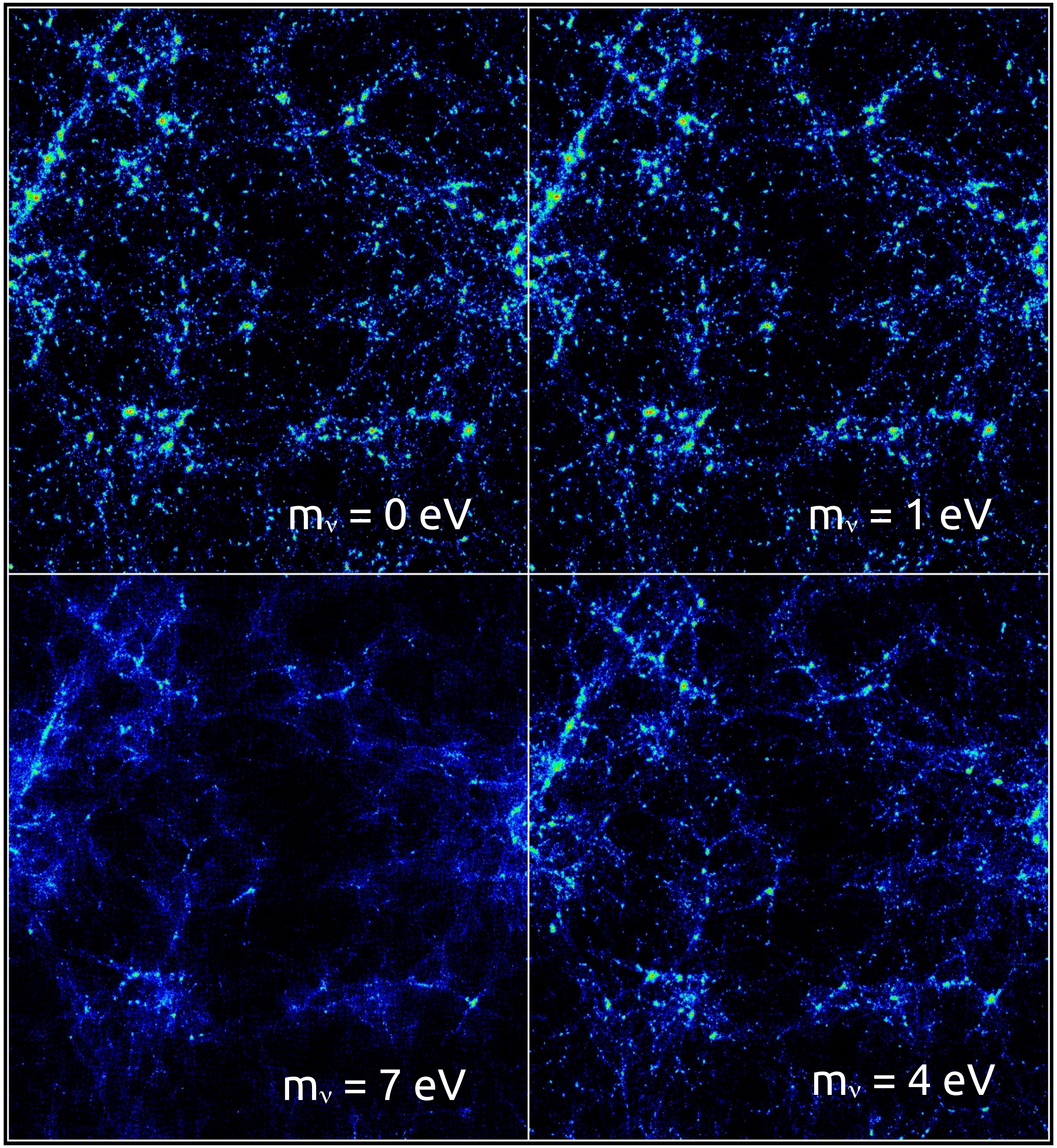
$$\hookrightarrow \ \tau \rightarrow \nu_\tau + 5\pi^{+-}(\pi^0)$$

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




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

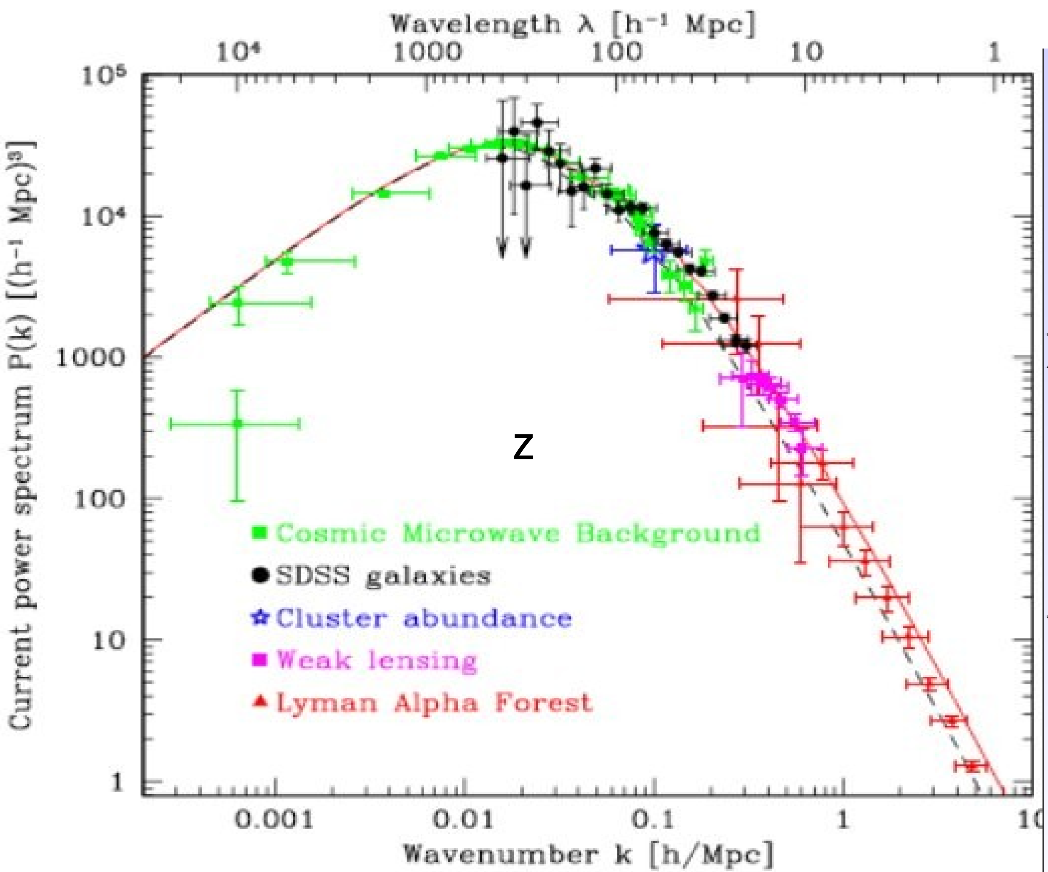
# Cosmology

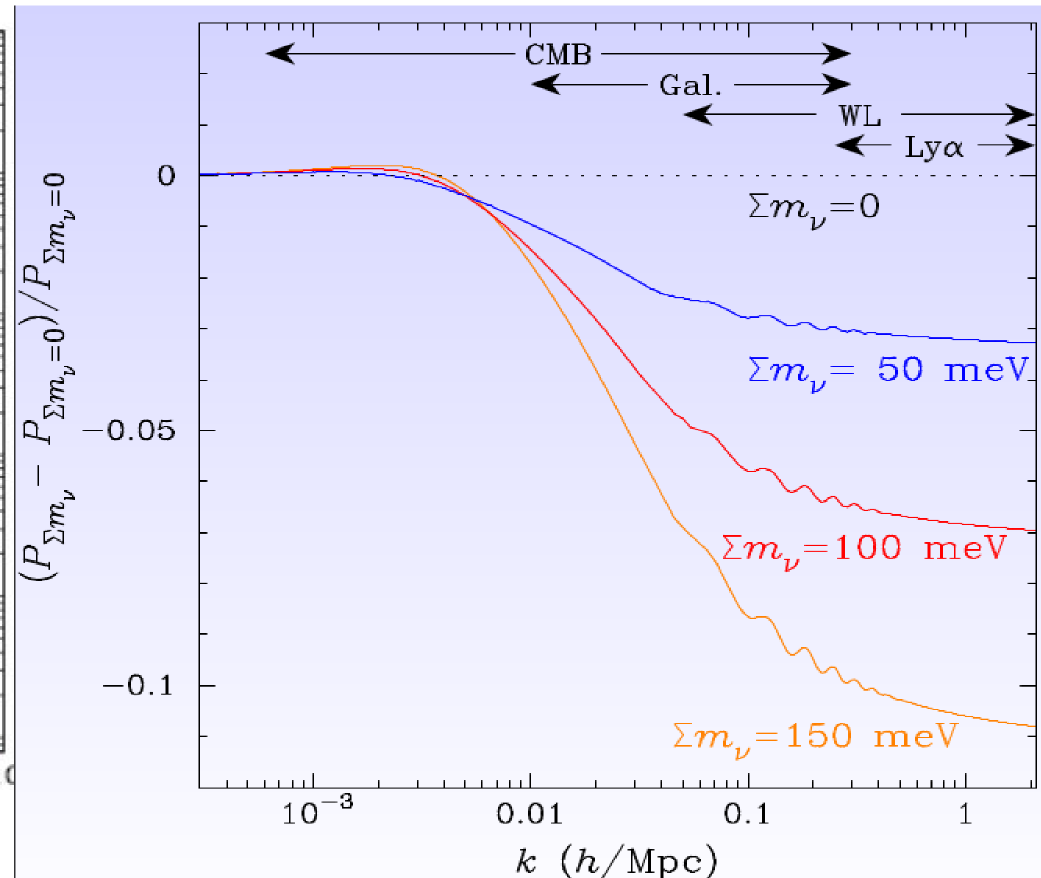



- Density fluctuations are affected by neutrino mass in the early universe
- model dependent
- WMAP,2dF,ACBAR, CBI,PLANCK, BOSS, BAO, SDSS

# Power spectra

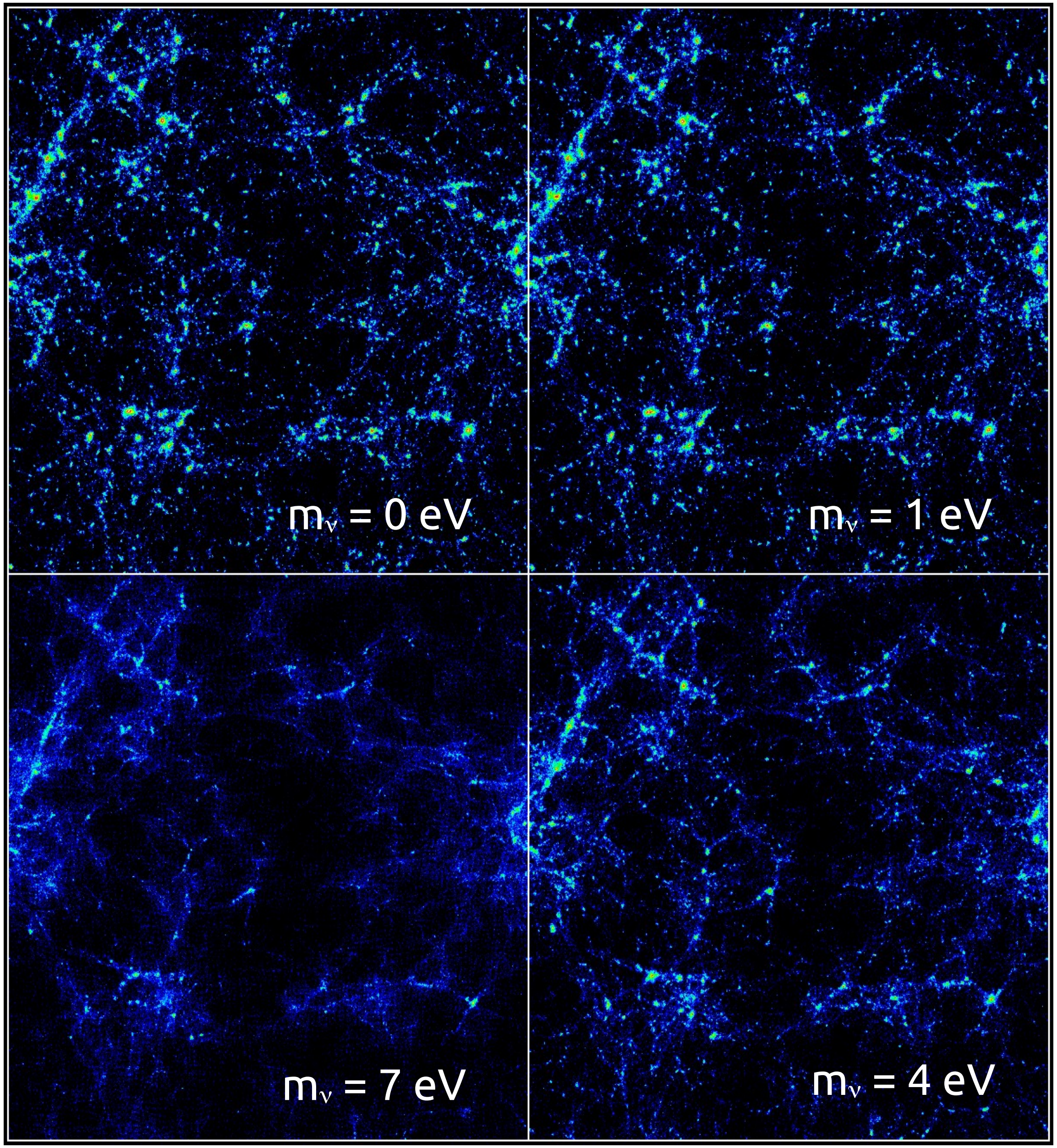
"Wavelength" of density fluctuation
Mass suppresses high wavenumber → small scale structure




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

# Cosmology




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

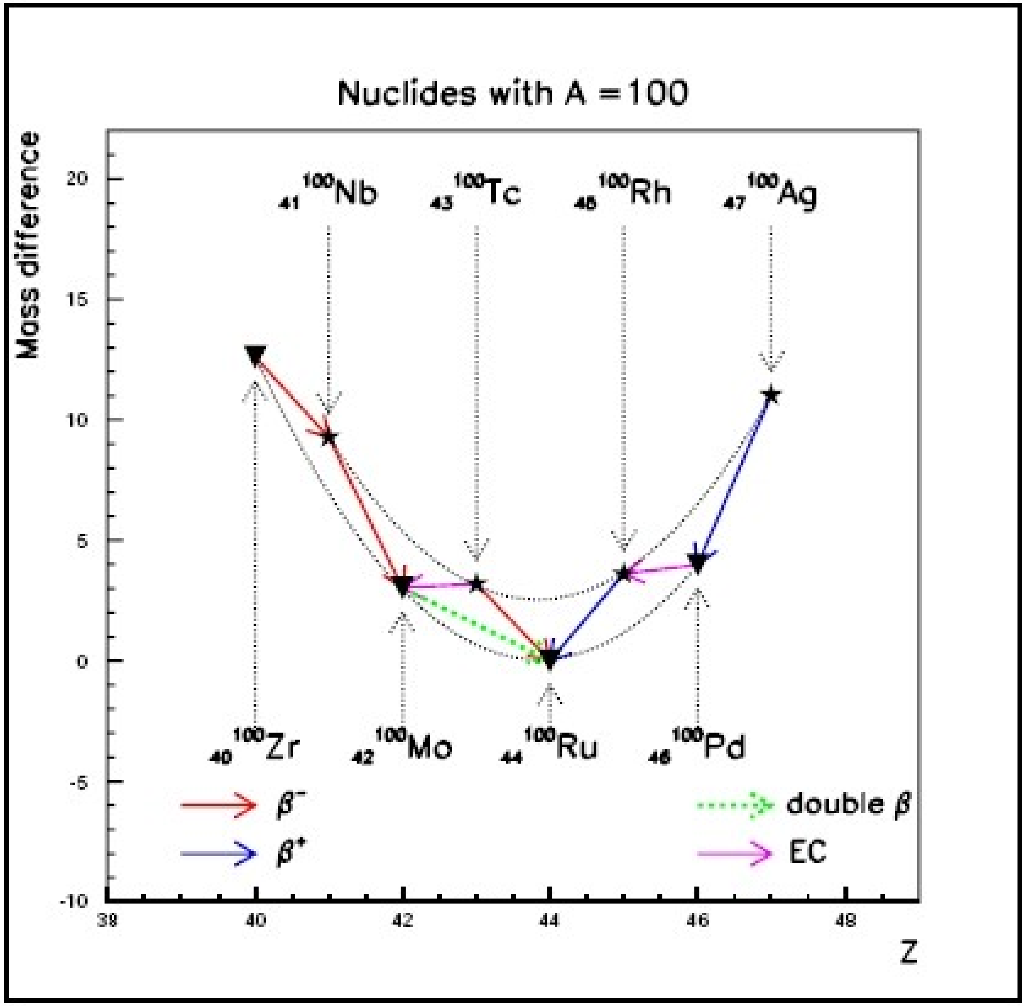
$$\sum m_{\nu_i} \leq 0.3\, eV$$

# 2vββ Decay

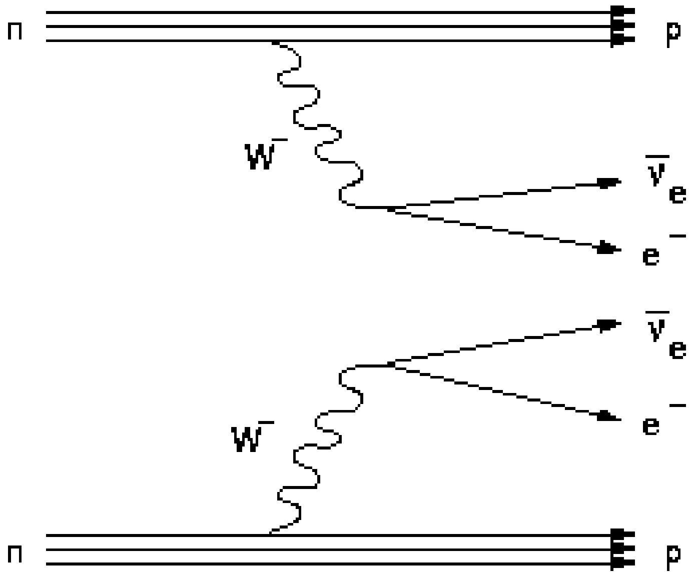
*Neutrinoless double beta decay* is considered a golden channel for the measurement of neutrino mass.

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




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

Calculable phase space

Nuclear matrix element

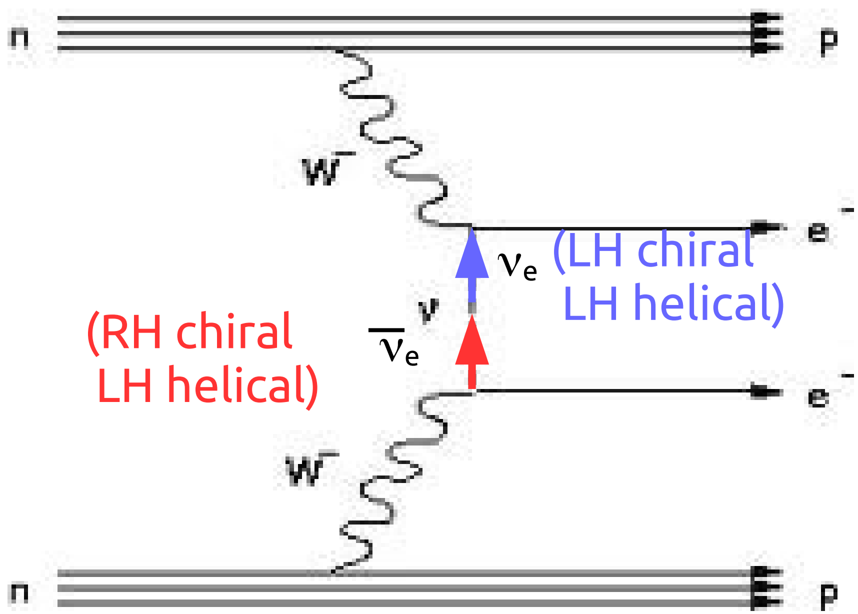
- Second order process in perturbation theory
- Severe test for nuclear matrix element calculation
- Nuclear structure effects cause variations in the nuclear matrix elements of factors of 10

# 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




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

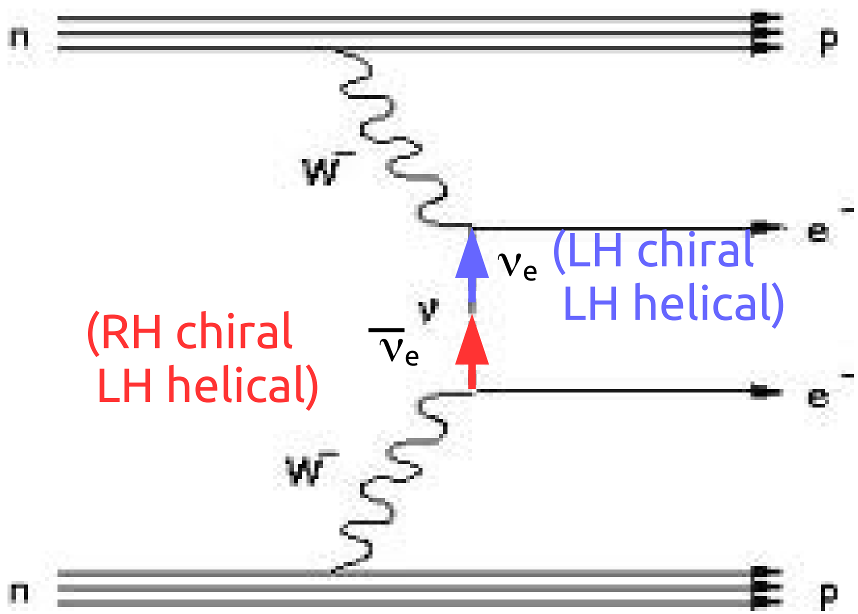
helicity states

$$\Gamma_{0\nu} = G_{0\nu}|M_{0\nu}|^2 \left|\sum_i |U_{ei}|^2 m_i\right|^2 \Rightarrow T_{1/2} \sim 10^{27} \, years$$

Requirements

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

# Neutrinoless ββ Decay




## Requirements

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# Experimental Requirements

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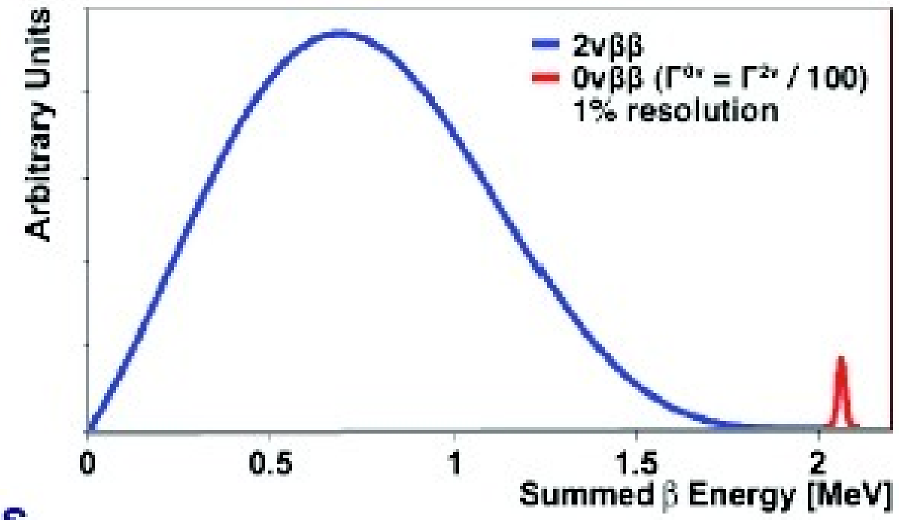
*Extremely* slow decay rates

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

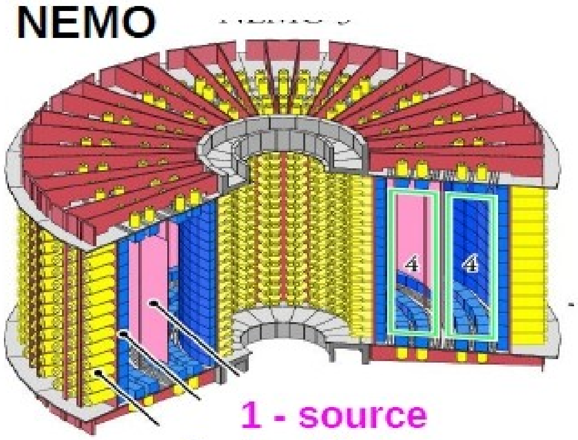
| Best case, 0 background ! | $\propto$ Source Mass • $time_{exp}$ |
|---|---|




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

# Types of experiments




**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)

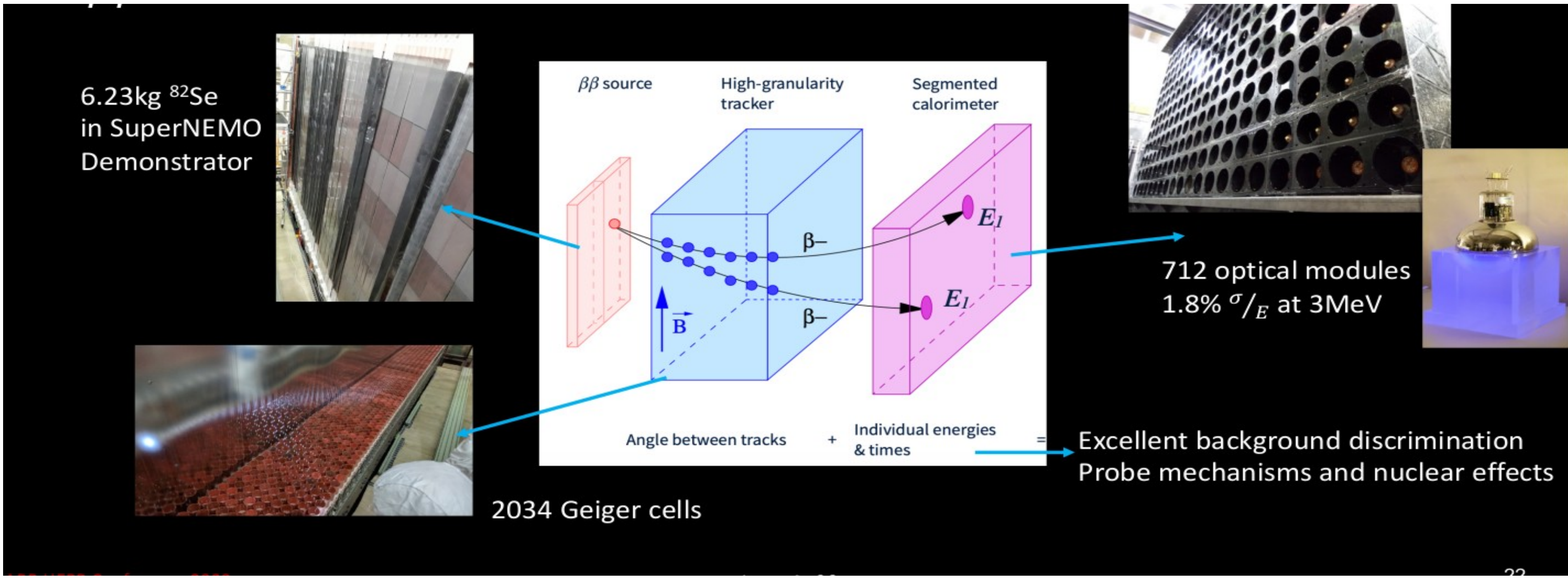
---

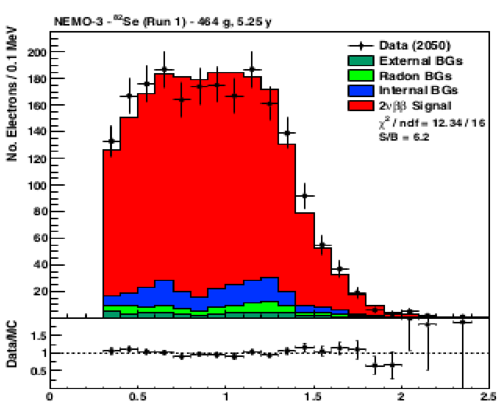
**2. the detector is itself the source**

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

- **gaseous detectors for Xe**

# SuperNEMO

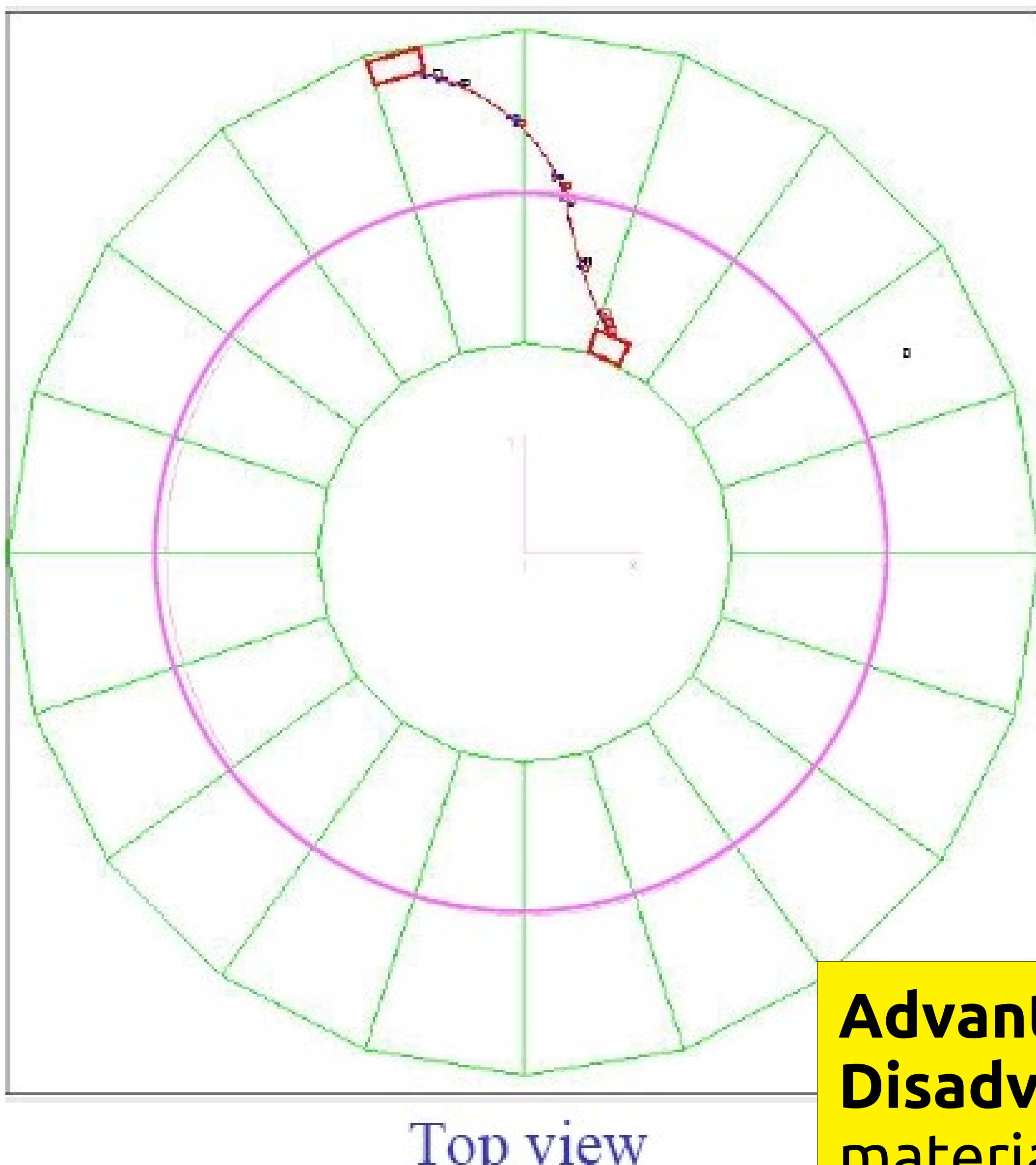


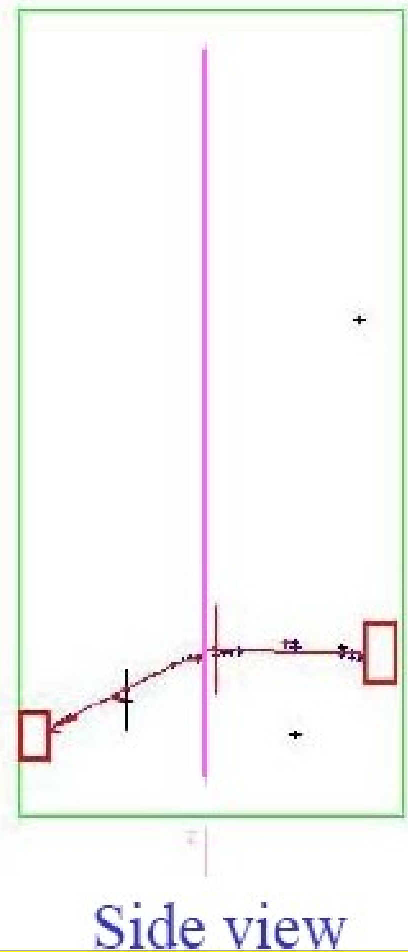




**(b)** Single-state Dominated (SSD)

single electron energy distribution from 2bb decay using $^{82}$Se

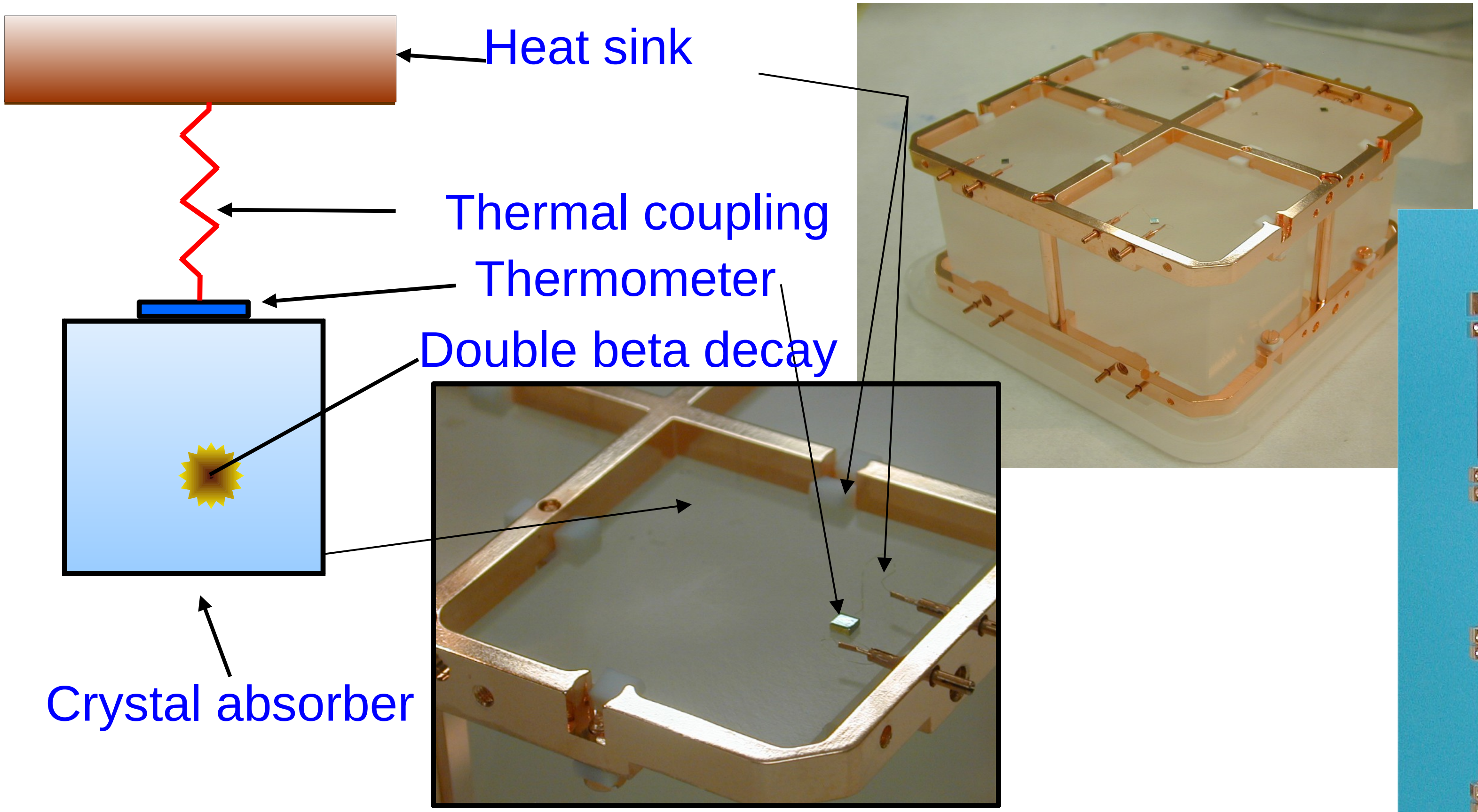
Typical ββ2ν event observed from $^{100}Mo$

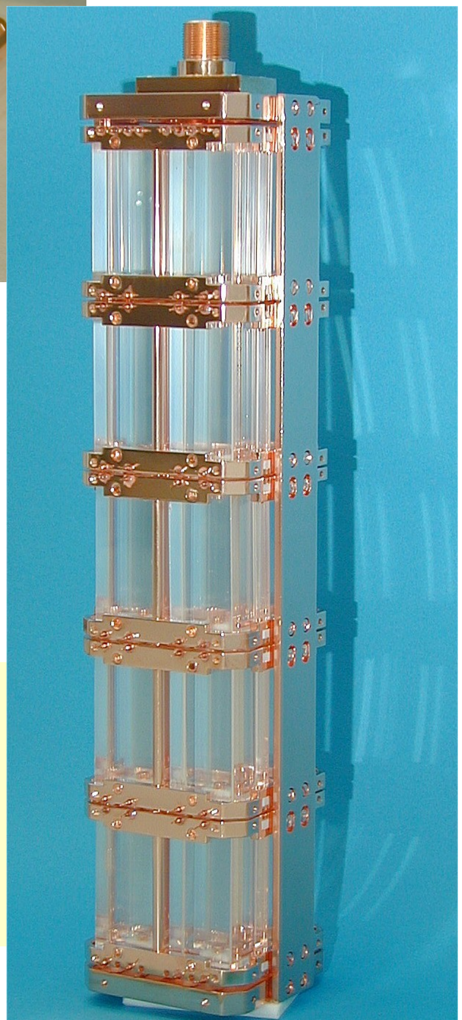



**Advantage** : electron tracking
**Disadvantage** : limited source material and relatively poor energy resolution

# Bolometry : Cuore



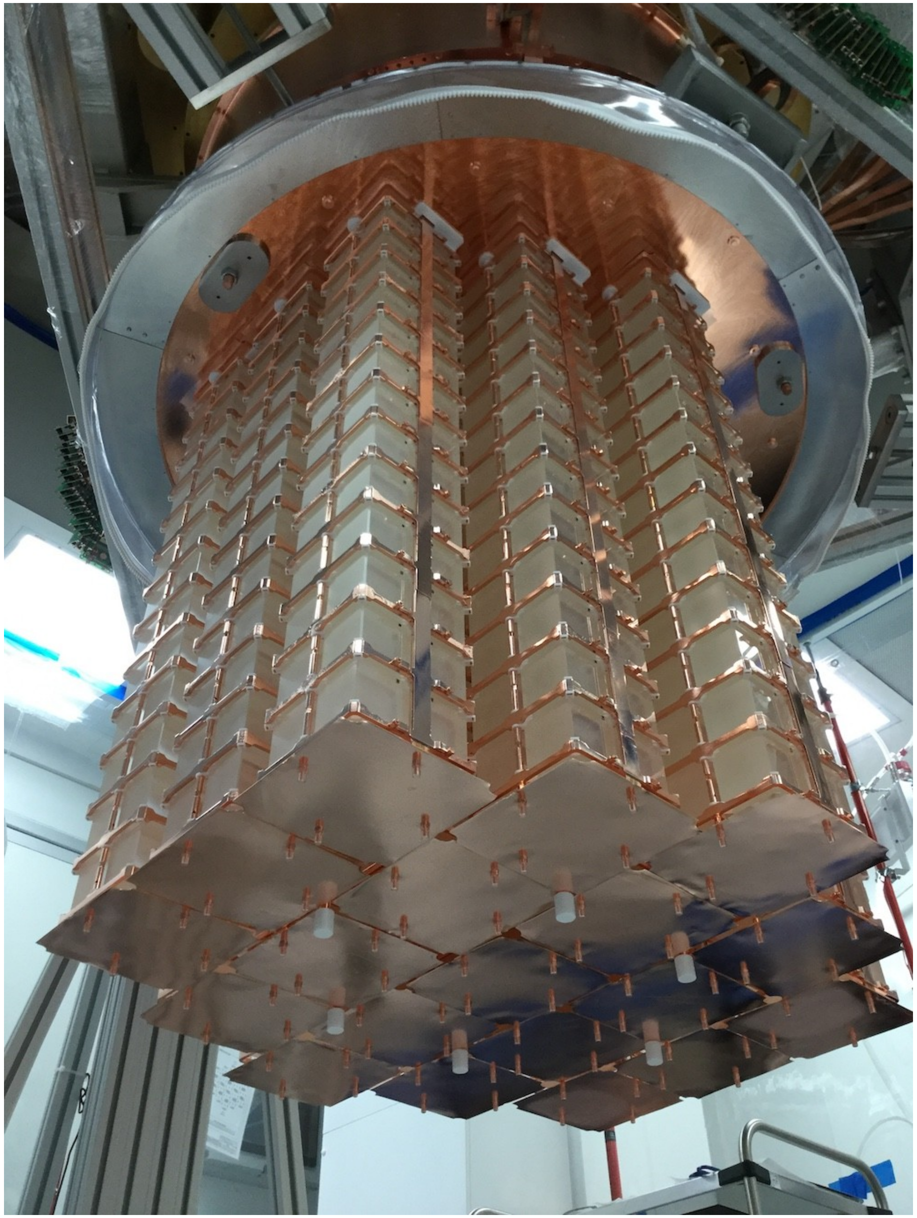
**example: 750 g of $TeO_2$ @ 10 mK**

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

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

$\Rightarrow \Delta U \sim 10$ eV

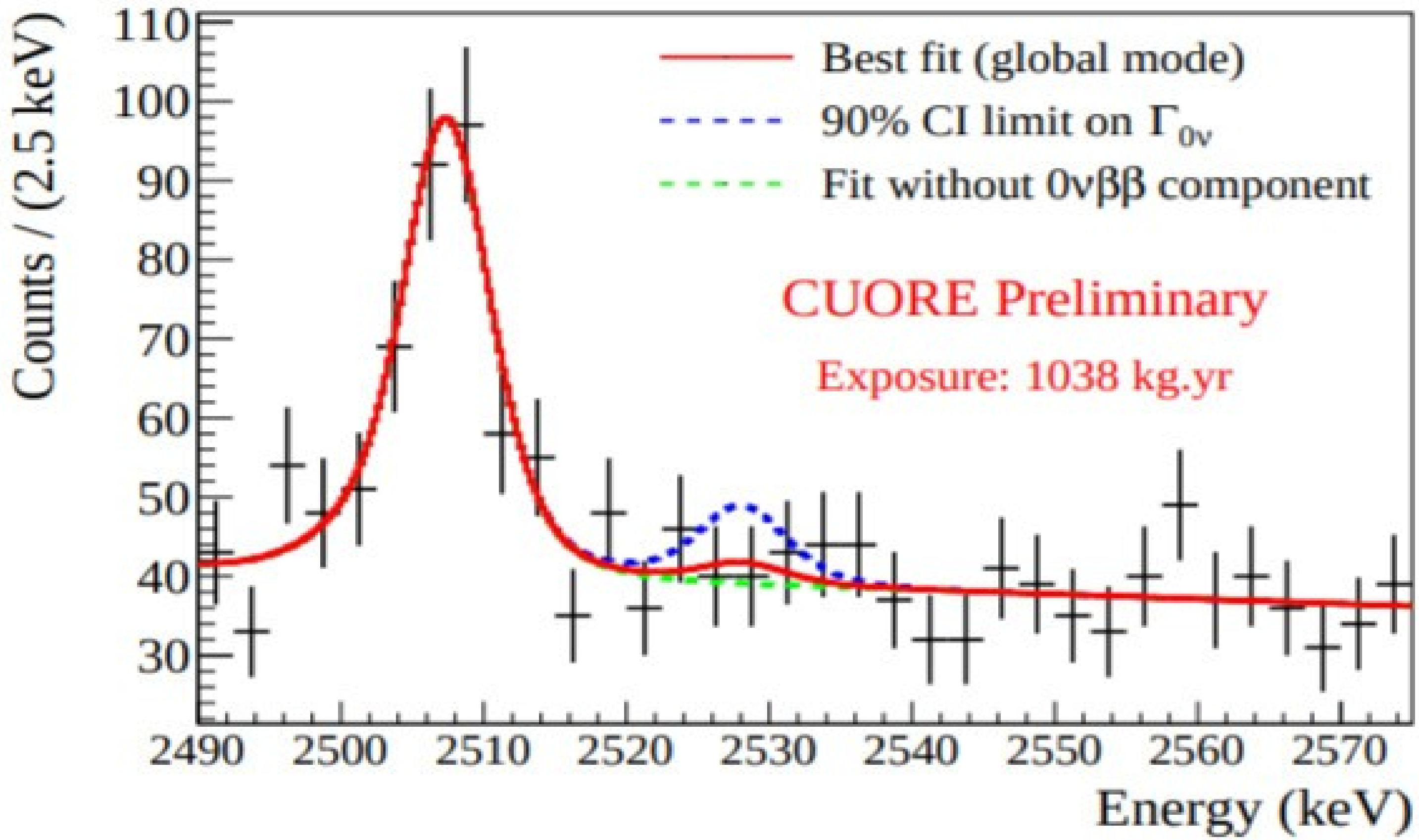
# Cuore



- 19 towers of 52 5x5x5 $cm^3$ $TeO_2$ crystals
- Total mass of 742 kg of $TeO_2$
- 0.5 kg of $0\nu\beta\beta$ isotope $^{120}Te$

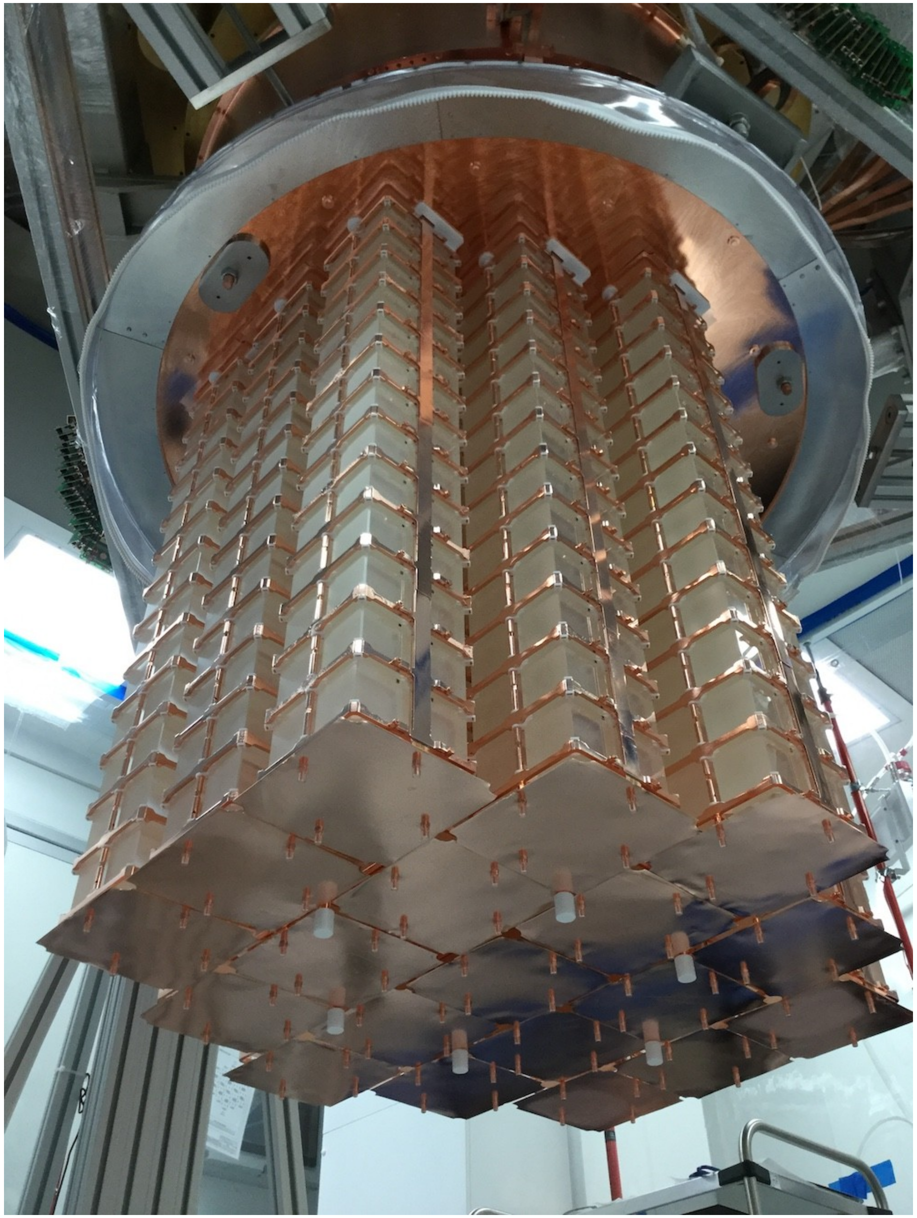
- Crystals held at 10 mK

# Cuore Results




$$T_{1/2}^{0\nu} > 2.2\times10^{25}\,years \;\Rightarrow\; \langle m_{\beta\beta}\rangle < 75-255\,meV$$

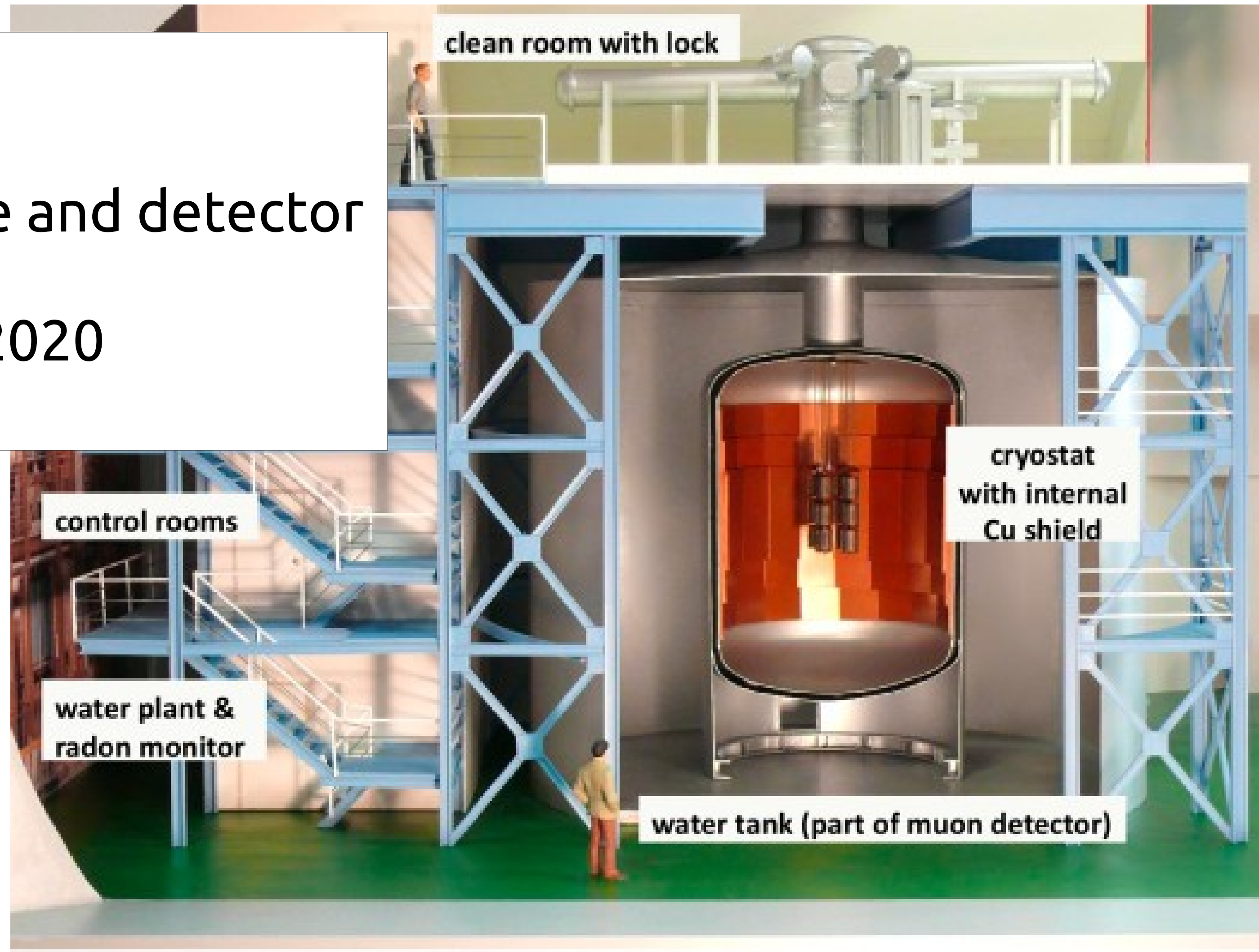
# Cuore



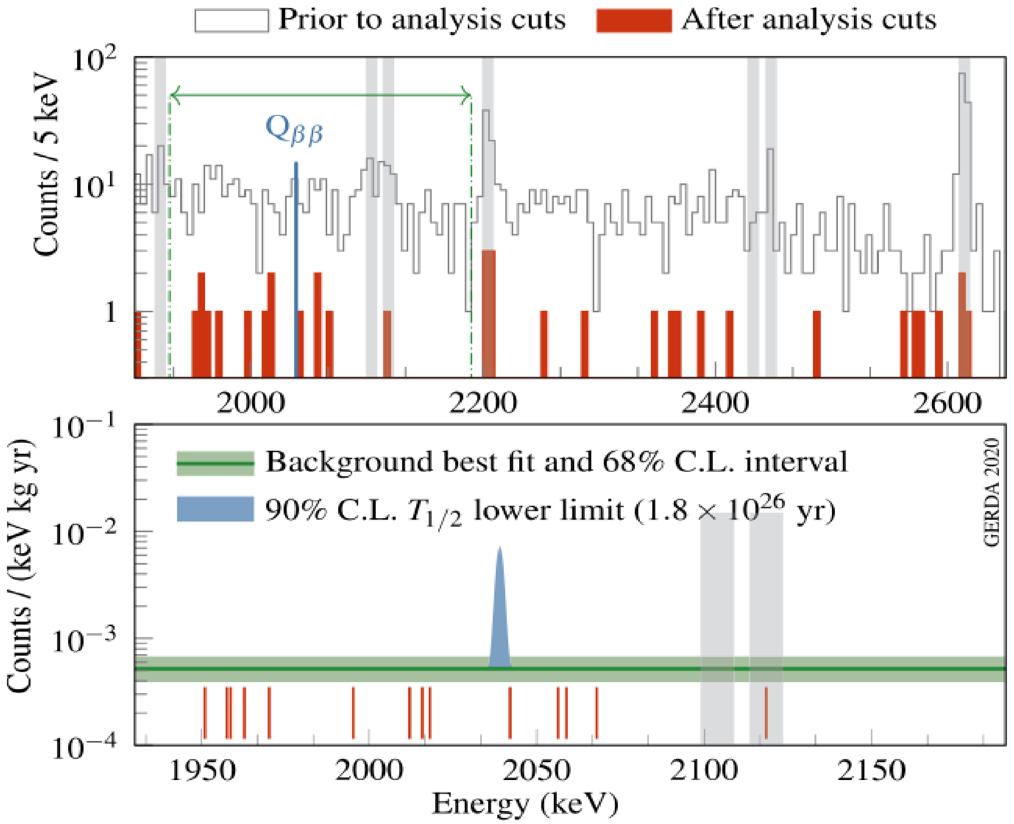
- Infrastructure now being developed for use in
- CUPID
- Will use 4 kg 95% enriched $Li_2{}^{100}MoO$

# GERDA

- 44 kg of Ge-76
- Integrated source and detector
- Ran from 2011 - 2020



# GERDA



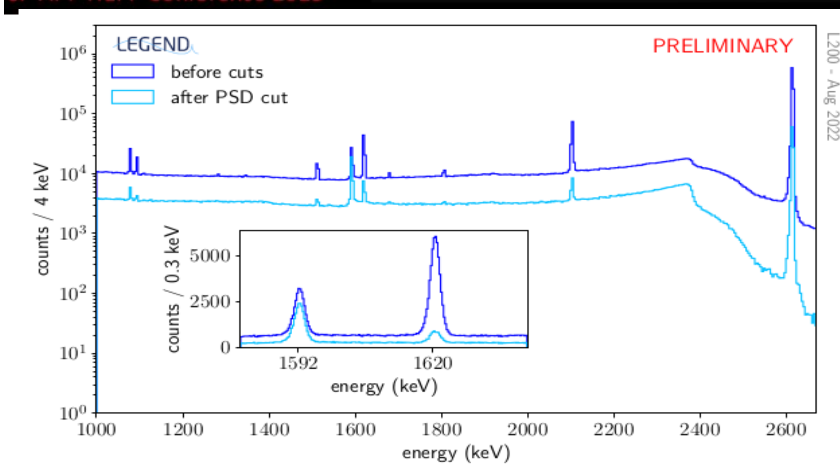

$T_{1/2} > 1.8 \times 10^{26}$ yr @ 90% CL

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

# LEGEND 200 - 1000

A phased $^{76}$Ge $0\nu\beta\beta$ decay program

Sensitivity increased by two orders of magnitude : $t_{1/2} > 10^{28}$ years


- LEGEND-200 has started running
- LEGEND-1000 – first data in 2028
- 11 institutes in UK involved

# Future Program

| Experiment | Isotope | Mass | Technique | Present Status | Location |
|---|---|---|---|---|---|
| CANDLES-III [124] | $^{48}$Ca | 305 kg | $^{nat}CaF_2$ scint. crystals | Operating | Kamioka |
| CDEX-1 [125] | $^{76}$Ge | 1 kg | $^{enr}$Ge semicond. det. | Prototype | CJPL |
| CDEX-300ν [125] | $^{76}$Ge | 225 kg | $^{enr}$Ge semicond. det. | Construction | CJPL |
| LEGEND-200 [16] | $^{76}$Ge | 200 kg | $^{enr}$Ge semicond. det. | Commissioning | LNGS |
| LEGEND-1000 [16] | $^{76}$Ge | 1 ton | $^{enr}$Ge semicond. det. | Proposal | |
| CUPID-0 [19] | $^{82}$Se | 10 kg | Zn$^{enr}$Se scint. bolometers | Prototype | LNGS |
| SuperNEMO-Dem [126] | $^{82}$Se | 7 kg | $^{enr}$Se foils/tracking | Operation | Modane |
| SuperNEMO [126] | $^{82}$Se | 100 kg | $^{enr}$Se foils/tracking | Proposal | Modane |
| Selena [127] | $^{82}$Se | | $^{enr}$Se, CMOS | Development | |
| IFC [128] | $^{82}$Se | | ion drift $SeF_6$ TPC | Development | |
| CUPID-Mo [17] | $^{100}$Mo | 4 kg | $Li^{enr}MoO_4$,scint. bolom. | Prototype | LNGS |
| AMoRE-I [129] | $^{100}$Mo | 6 kg | $^{40}Ca^{100}MoO_4$ bolometers | Operation | YangYang |
| AMoRE-II [129] | $^{100}$Mo | 200 kg | $^{40}Ca^{100}MoO_4$ bolometers | Construction | Yemilab |
| CROSS [130] | $^{100}$Mo | 5 kg | $Li_2{}^{100}MoO_4$, surf. coat bolom. | Prototype | Canfranc |
| BINGO [131] | $^{100}$Mo | | $Li^{enr}MoO_4$ | Development | LNGS |
| CUPID [28] | $^{100}$Mo | 450 kg | $Li^{enr}MoO_4$,scint. bolom. | Proposal | LNGS |
| China-Europe [132] | $^{116}$Cd | | $^{enr}CdWO_4$ scint. crystals | Development | CJPL |
| COBRA-XDEM [133] | $^{116}$Cd | 0.32 kg | $^{nat}$Cd CZT semicond. det. | Operation | LNGS |
| Nano-Tracking [134] | $^{116}$Cd | | $^{nat}$CdTe. det. | Development | |
| *TIN.TIN* [135] | $^{124}$Sn | | Tin bolometers | Development | INO |
| CUORE [10] | $^{130}$Te | 1 ton | $TeO_2$ bolometers | Operating | LNGS |
| SNO+ [136] | $^{130}$Te | 3.9 t | 0.5-3% $^{nat}$Te loaded liq. scint. | Commissioning | SNOLab |
| nEXO [29] | $^{136}$Xe | 5 t | Liq. $^{enr}$Xe TPC/scint. | Proposal | |
| NEXT-100 [137] | $^{136}$Xe | 100 kg | gas TPC | Construction | Canfranc |
| NEXT-HD [137] | $^{136}$Xe | 1 ton | gas TPC | Proposal | Canfranc |
| AXEL [138] | $^{136}$Xe | | gas TPC | Prototype | |
| KamLAND-Zen-800 [13] | $^{136}$Xe | 745 kg | $^{enr}$Xe disolved in liq. scint. | Operating | Kamioka |
| KamLAND2-Zen [41] | $^{136}$Xe | | $^{enr}$Xe disolved in liq. scint. | Development | Kamioka |
| LZ [139] | $^{136}$Xe | 600 kg | Dual phase Xe TPC, nat./enr. Xe | Operation | SURF |
| PandaX-4T [119] | $^{136}$Xe | 3.7 ton | Dual phase nat. Xe TPC | Operation | CJPL |
| XENONnT [140] | $^{136}$Xe | 5.9 ton | Dual phase Xe TPC | Operating | LNGS |
| DARWIN [141] | $^{136}$Xe | 50 ton | Dual phase Xe TPC | Proposal | LNGS |
| R2D2 [142] | $^{136}$Xe | | Spherical Xe TPC | Development | |
| LAr TPC [143] | $^{136}$Xe | kton | Xe-doped LR TPC | Development | |
| NuDot [144] | Various | | Cherenkov and scint. in liq. scint. | Development | |
| THEIA [145] | Xe or Te | | Cherenkov and scint. in liq. scint. | Development | |
| JUNO [146] | Xe or Te | | Doped liq. scint. | Development | |
| Slow-Fluor [147] | Xe or Te | | Slow Fluor Scint. | Development | |

# Direct mass measurements

| | | |
|---|---|---|
| Tritium β decay | $\left(\sum_i \lvert U_{ei}{}^2 \rvert m_i^2\right)^{\frac{1}{2}}$ | < 0.8 eV<br>CRES < 0.04 eV? |
| 0v2β decay | $\left\lvert \sum_i U_{ei}^2 m_i \right\rvert$ | <0.18 eV |
| Cosmology | $\sum_i m_i < 0.3\, eV$ | Model dependent |
| Pion decay | $m_{\nu\mu} < 190\, keV$ | Fairly pointless |
| Tau decay | $m_{\nu\tau} < 18.2\, MeV$ | Entirely pointless |

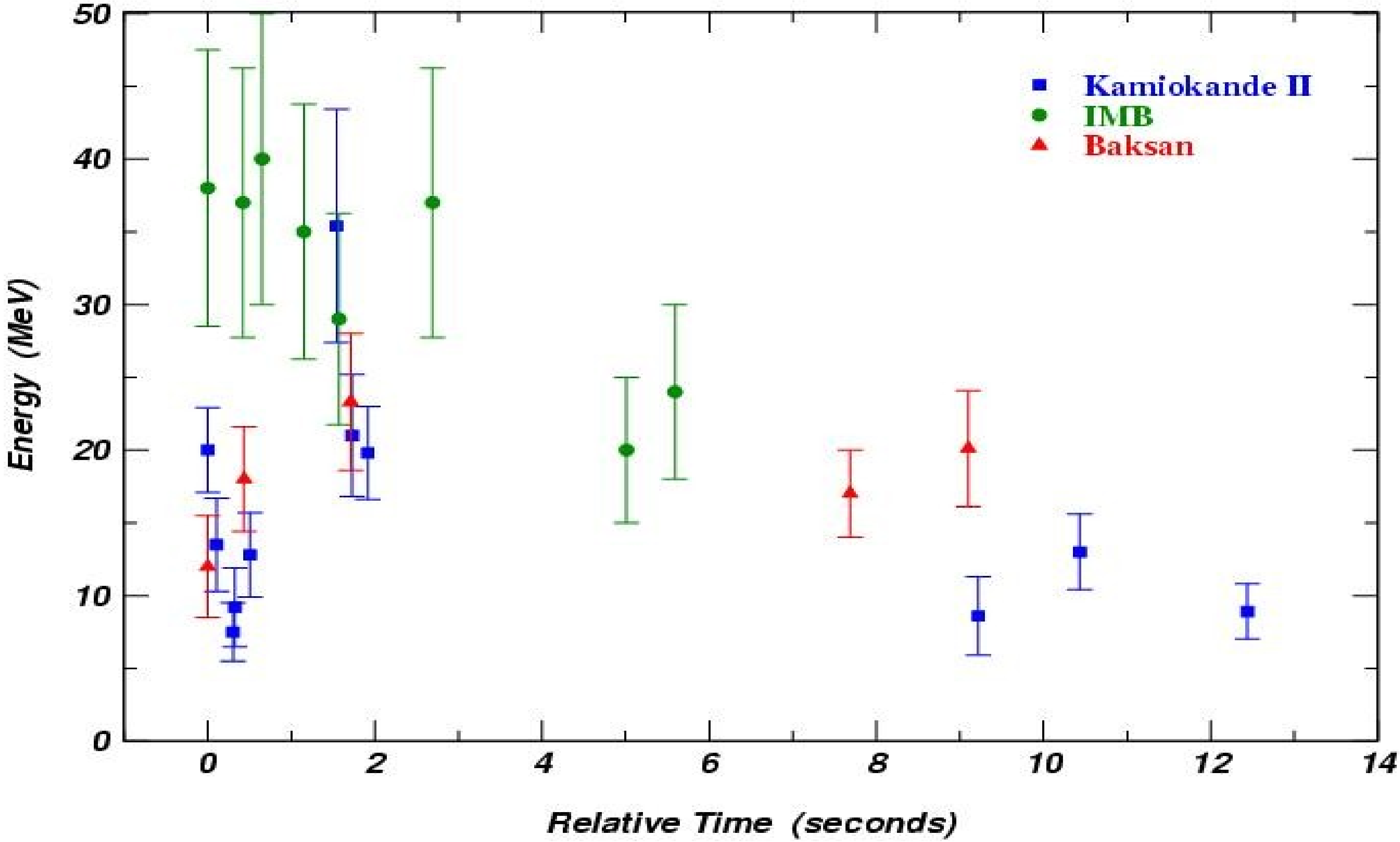
# Question

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


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

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

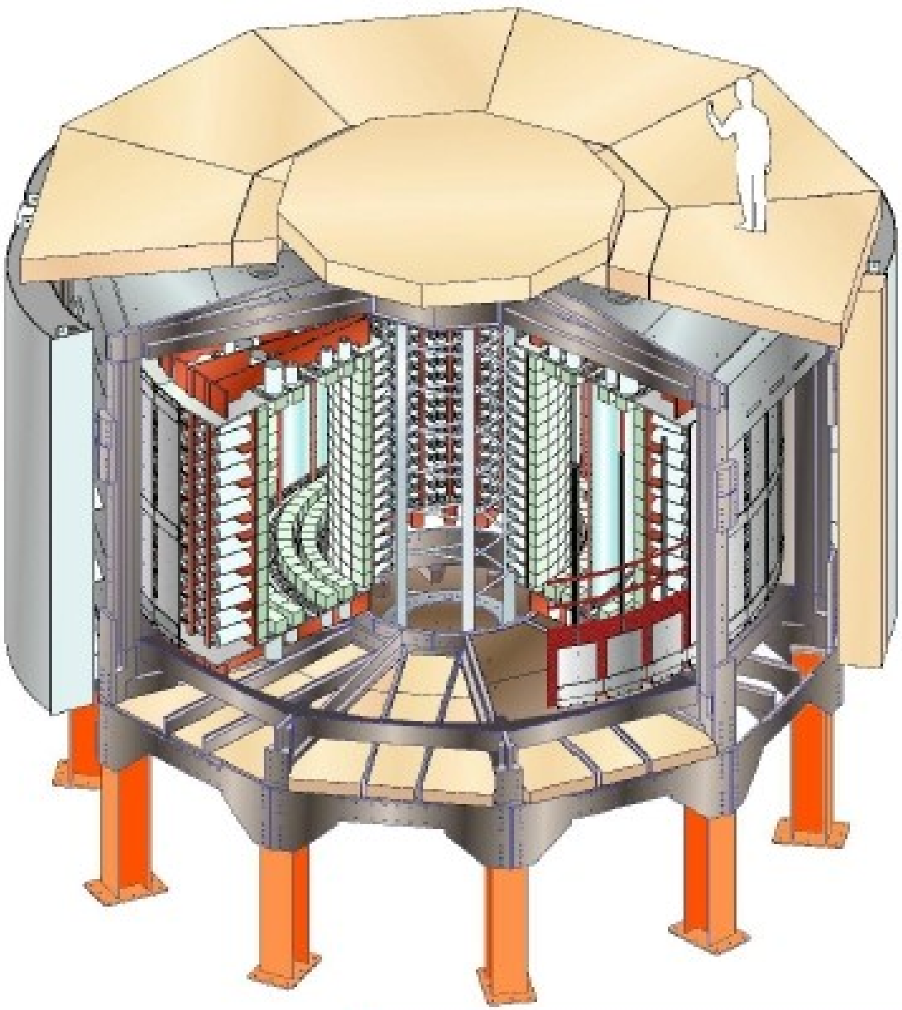
$$n \equiv \begin{pmatrix} n_L \\ n_R^C \end{pmatrix} \rightarrow L_{mass} = -\frac{1}{2}\left[\overline{n^C} M n + \overline{n} M n^C\right] \quad with \quad M = \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix}$$

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% $H_2O$

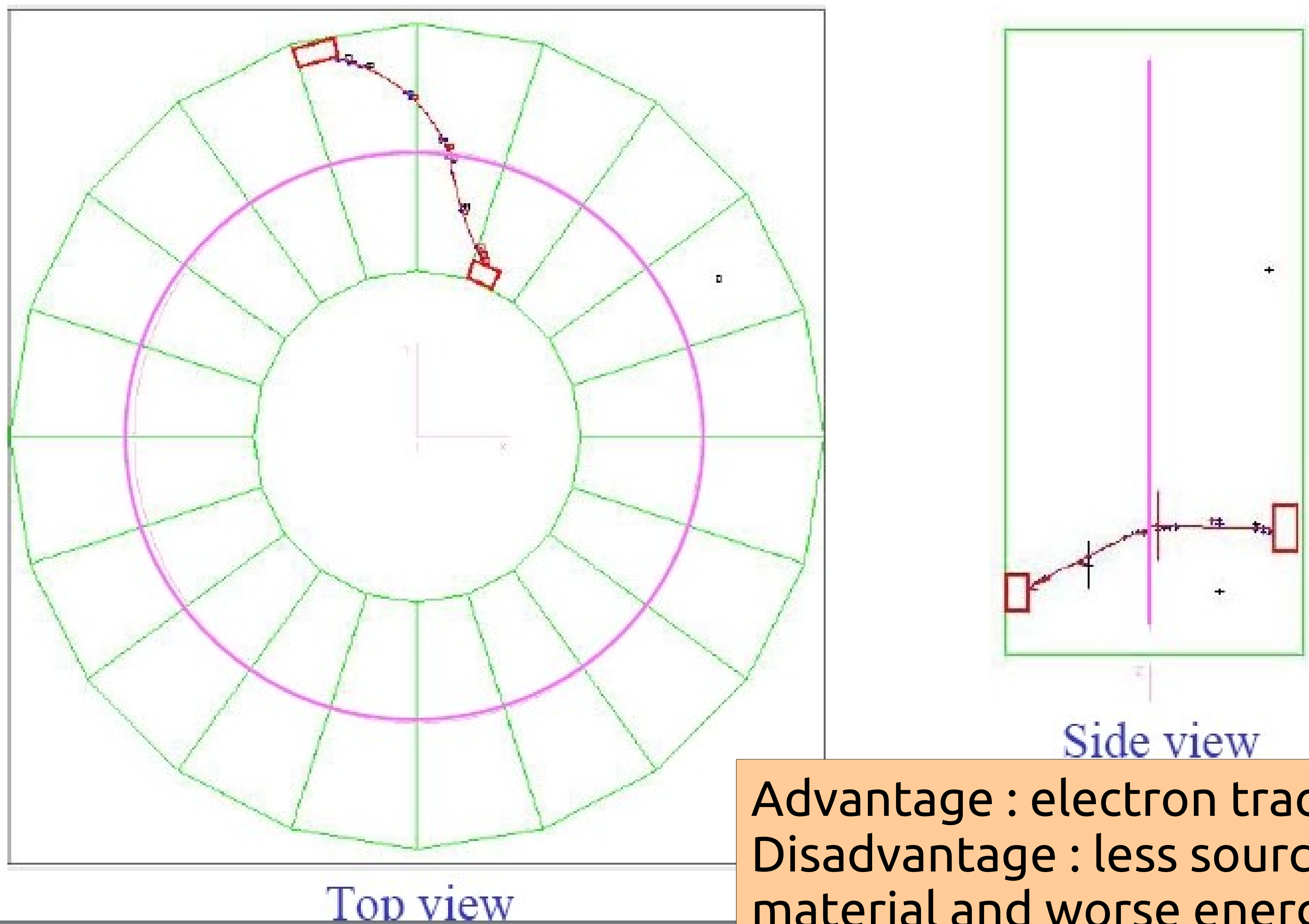
**Calorimeter**:
1940 plastic scintillators
coupled to low radioactivity PMTs

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

Background: n… 2.6 MeV)

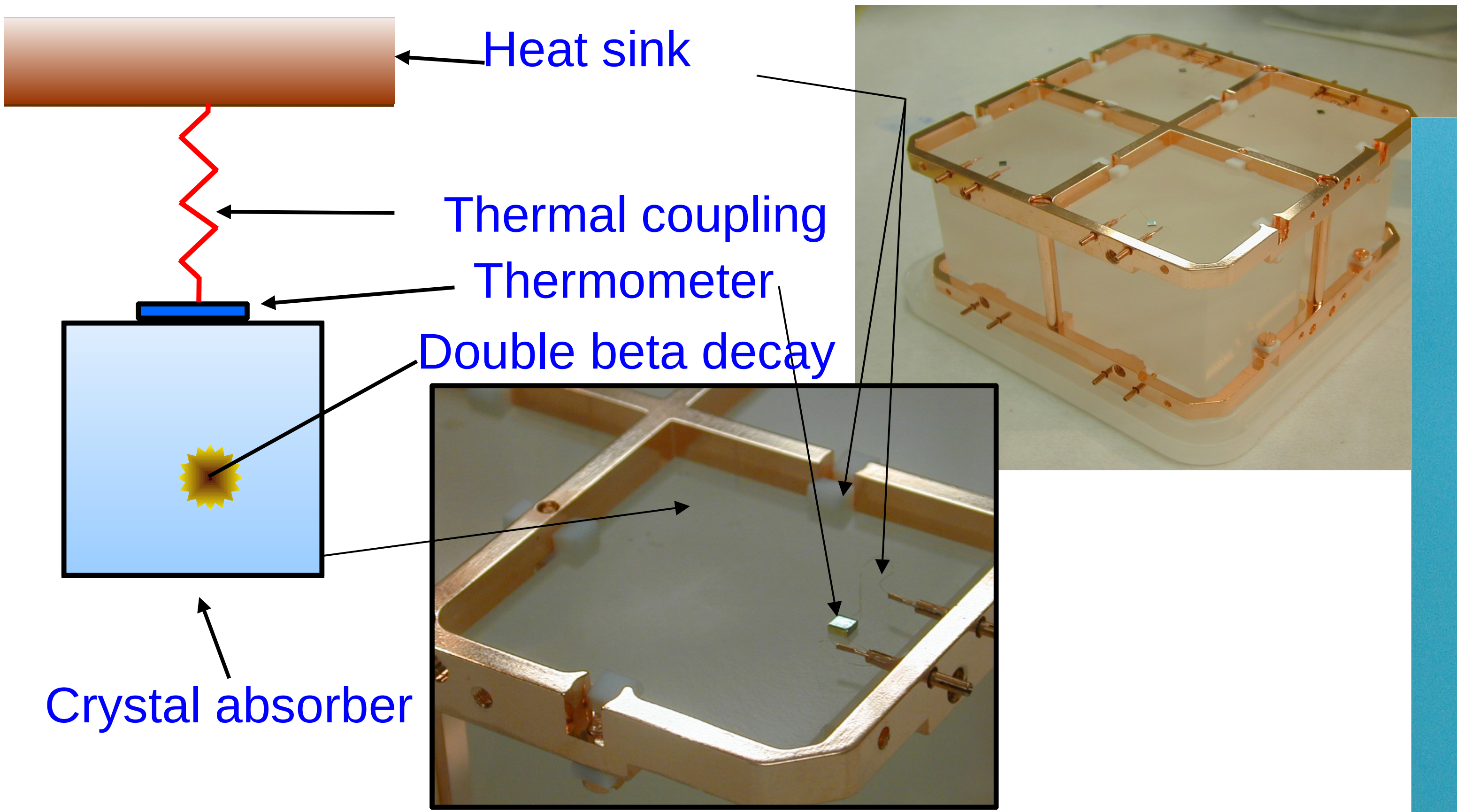
**Able to identify $e^-$, $e^+$, $\gamma$ and $\alpha$**

## Typical ββ2ν event observed from $^{100}Mo$




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

# Cuoricino/Cuore




**example: 750 g of $TeO_2$ @ 10 mK**

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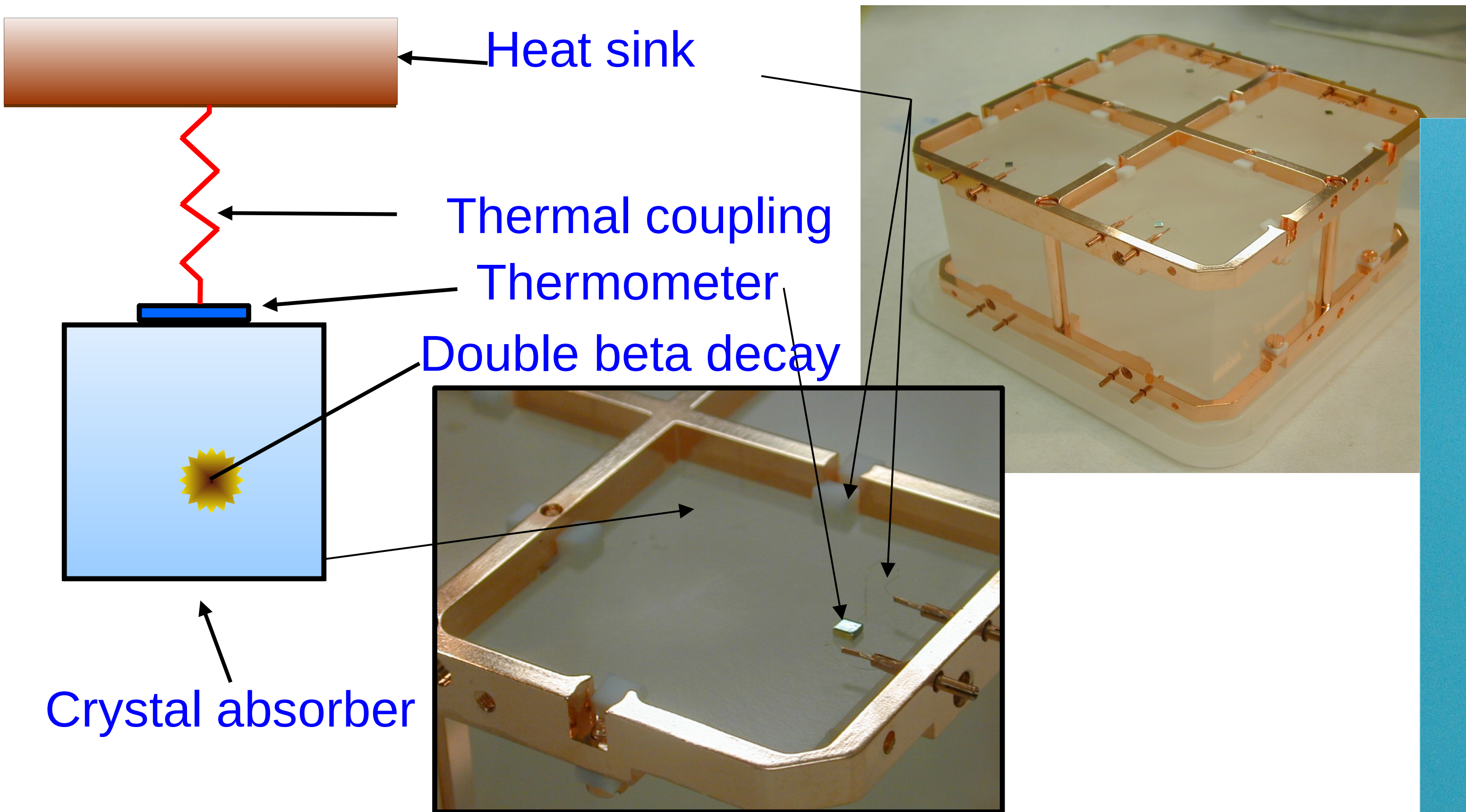
1 MeV $\gamma$-ray $\Rightarrow \Delta T \sim 80\ \mu$K

$\Rightarrow \Delta U \sim 10$ eV

# Cuoricino/Cuore

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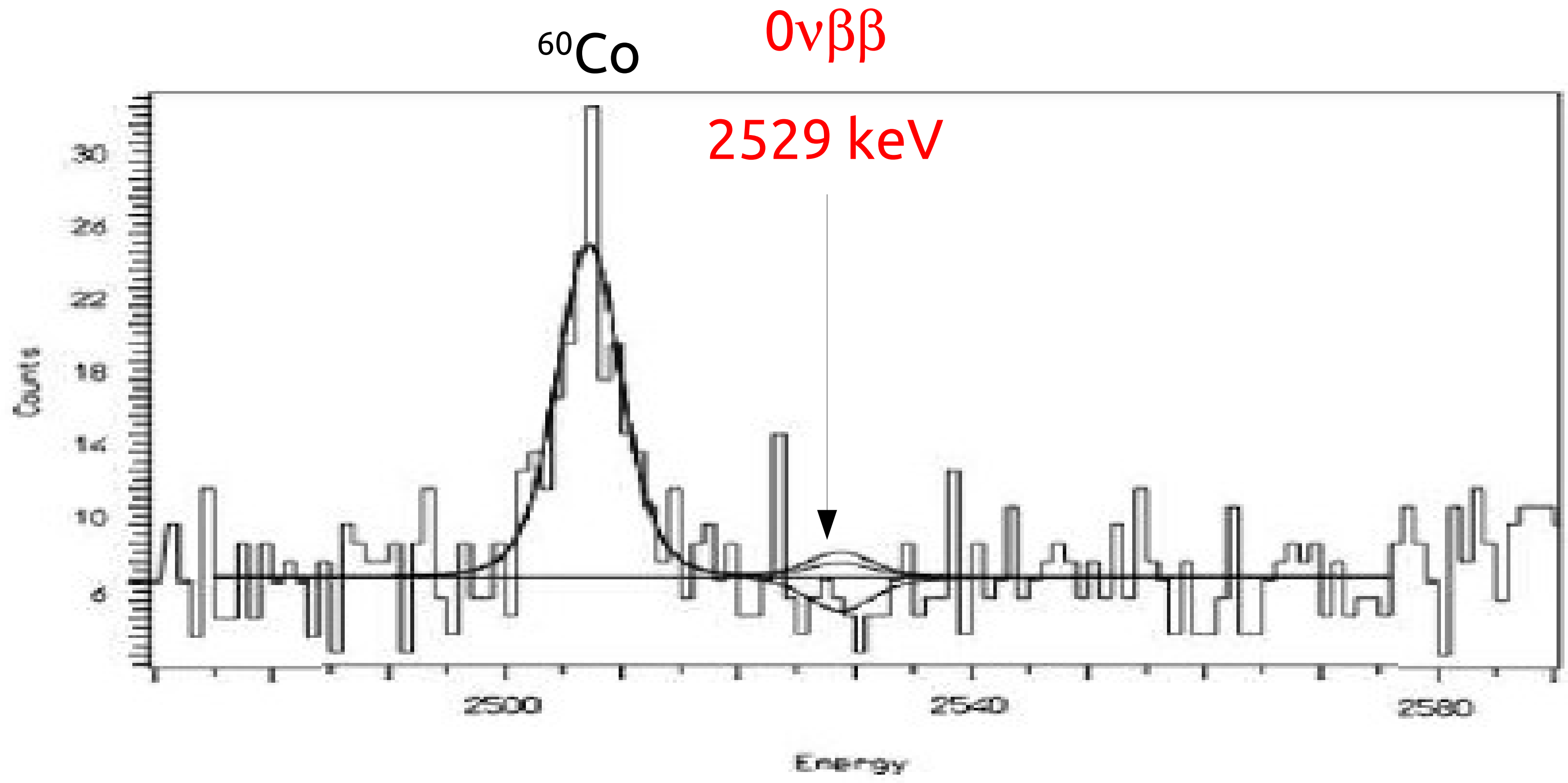
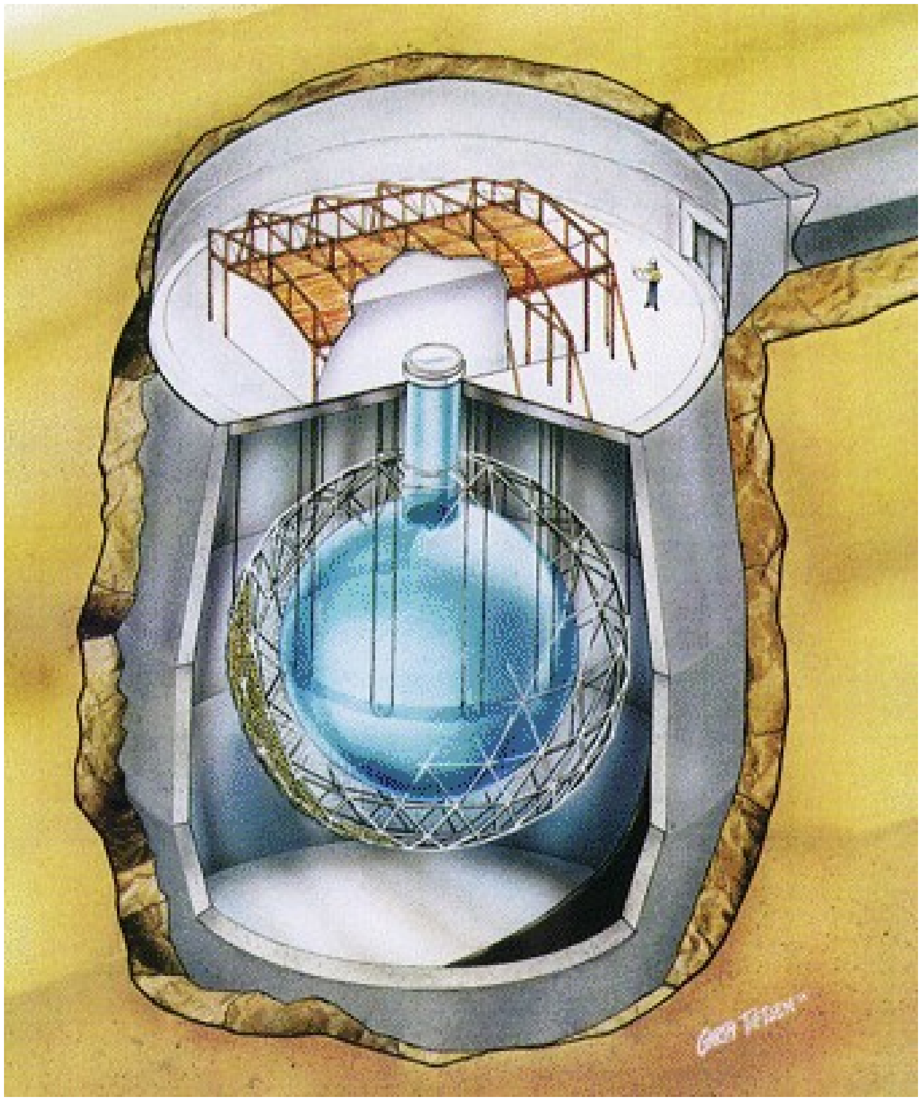
# Cuoricino Results

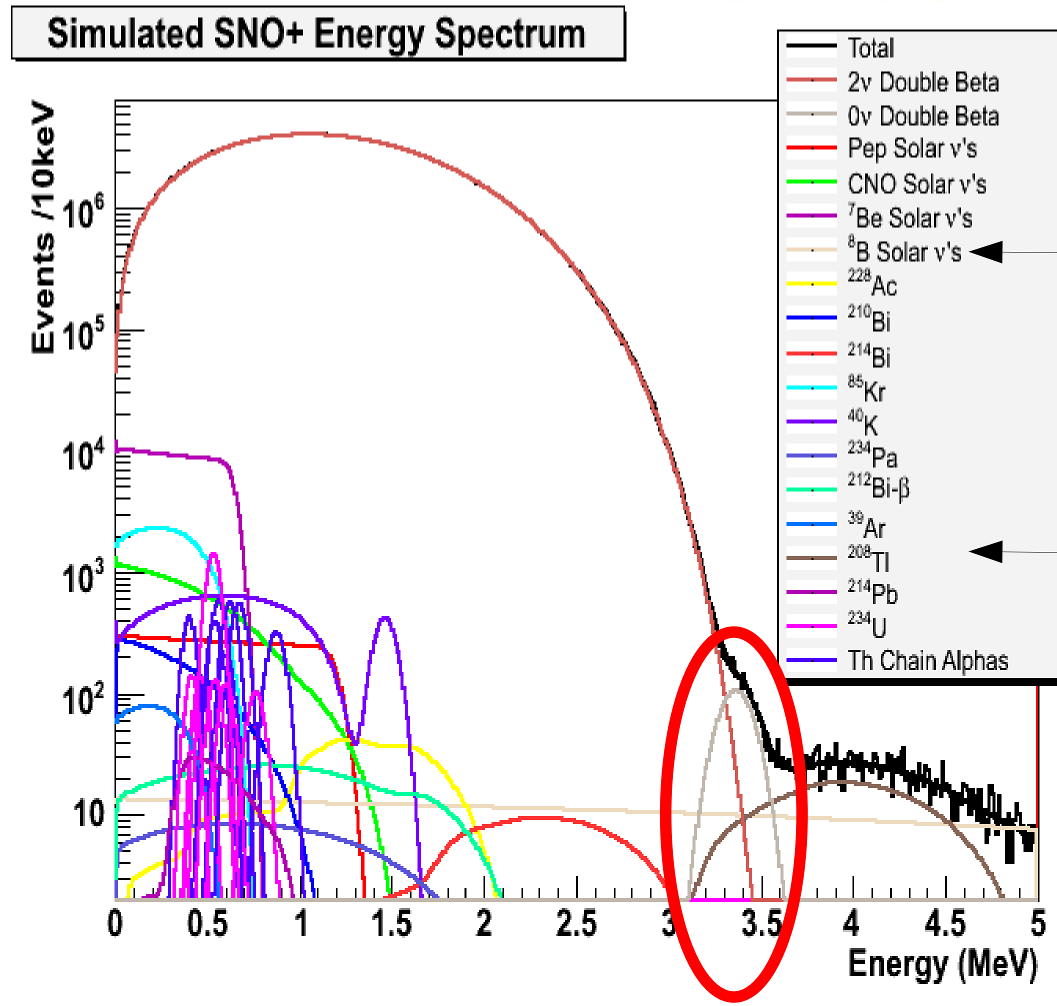



$$T_{1/2}^{0\nu} > 3.0 \times 10^{24} \, years \;\Rightarrow\; \langle m_\nu \rangle < 0.68 \, eV$$

# SNO+








$^{150}$Nd loaded - $m_\nu < 80$ meV

# The General Mass Term

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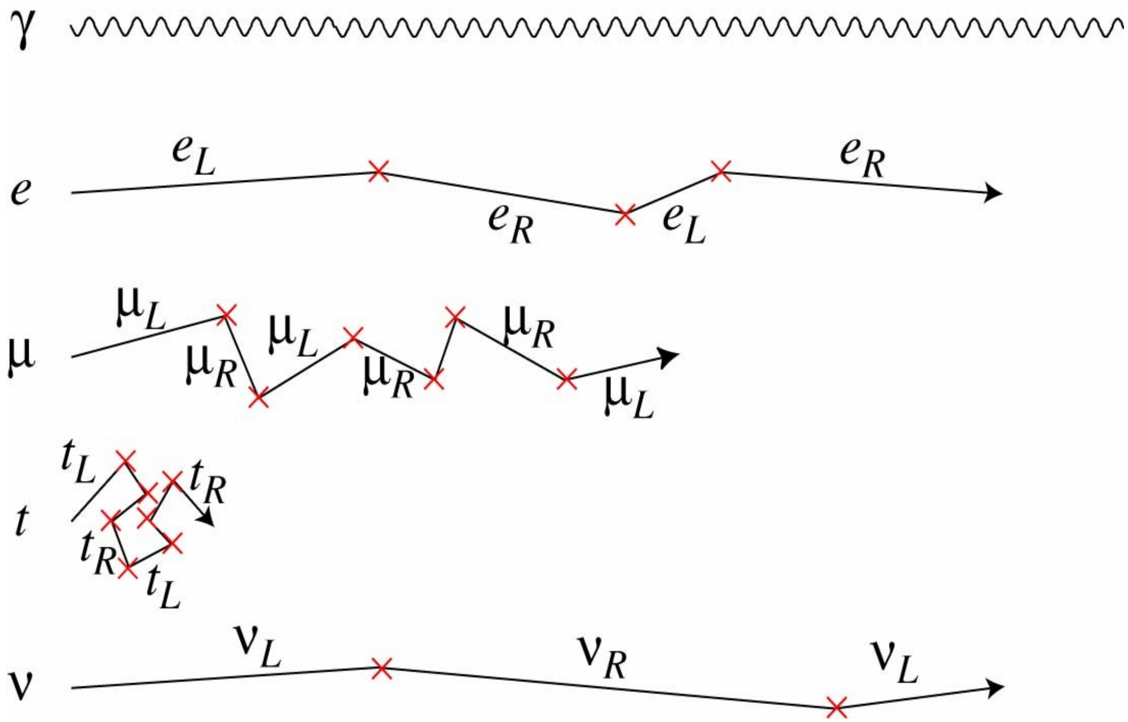
Mixing matrix

# Two ways to go

## Dirac neutrinos

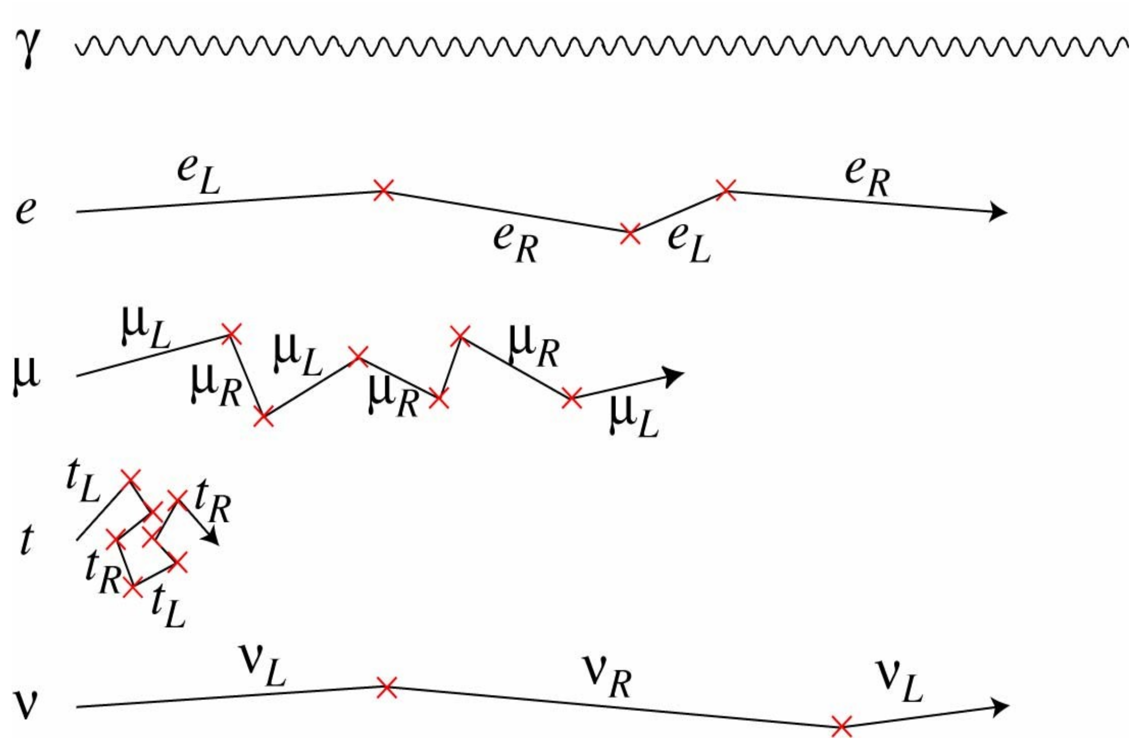
- There are new particles (right handed neutrinos) after all
- Why haven't we seen them?
- They must only exist to give neutrinos mass
- Still have to solve the question of their very very weak coupling



# Two ways to go

## Majorana neutrinos

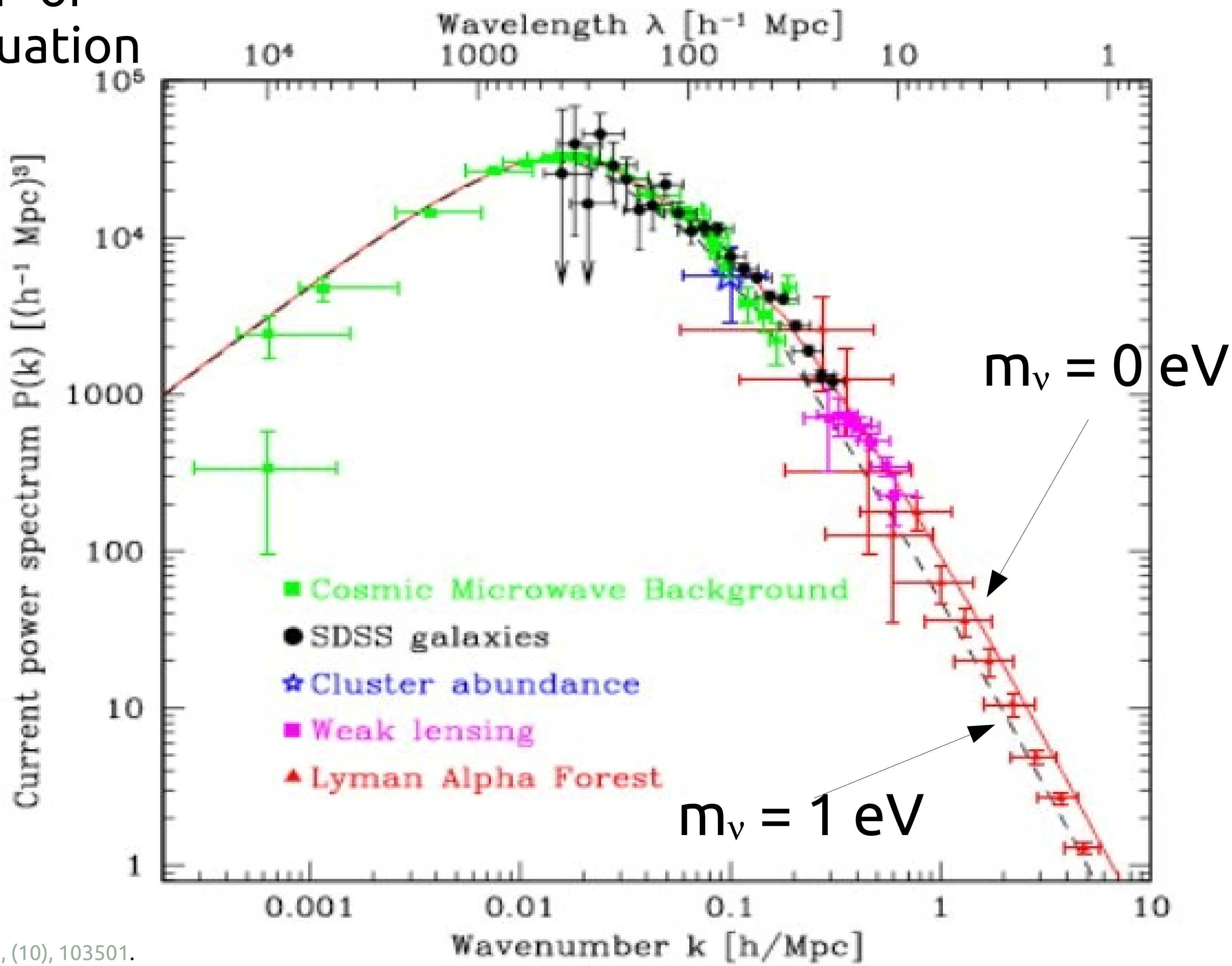
- There are new particles (right handed neutrinos) after all
- If I pass a neutrino and look back I will see a right-handed thing
- Must be a right-handed anti-neutrino
- No fundamental difference between neutrinos and anti-neutrinos




(Theorists Favourite!)

# Power spectra

"Wavelength" of density fluctuation




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

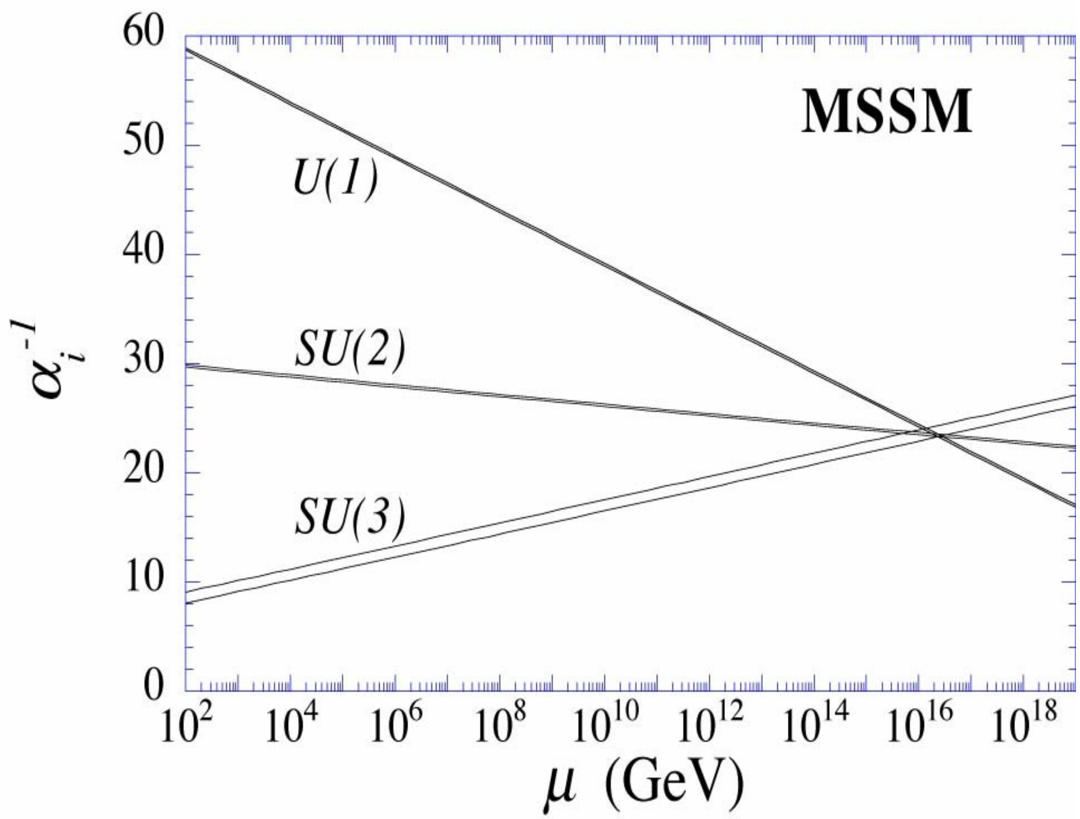
# Seesaw and GUTs

- 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!

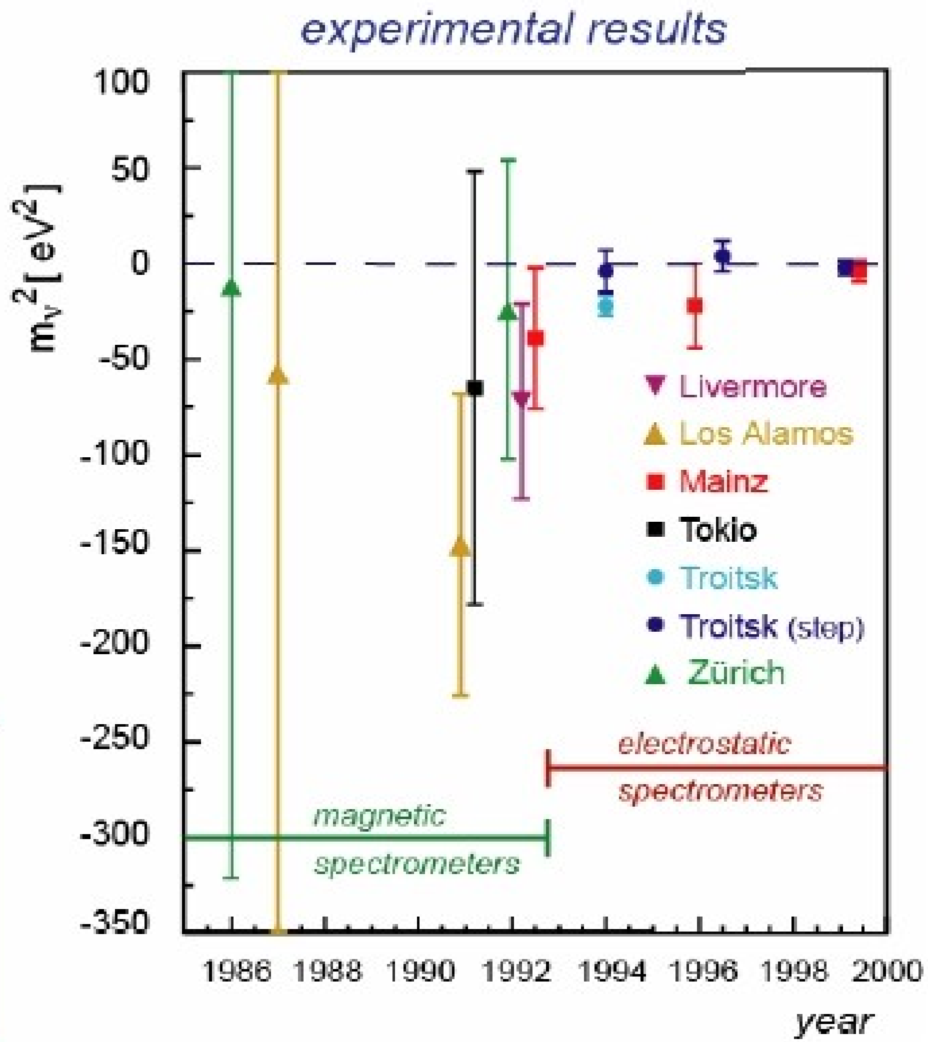



*(NB: In the context of a particular supersymmetric model....)*

# History of Tritium-β decay

WARWICK
THE UNIVERSITY OF WARWICK

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



# 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

Can write the mass eigenstates in terms of the Majorana fields

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

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

**Mass Eigenstates (Physical particles)**

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

**Majorana field**

$$L_{mass} = \frac{1}{2}\left(\overline{\nu_L^C}\quad \overline{N_R}\right)\begin{pmatrix} c & -s \\ s & c \end{pmatrix}^{-1}\begin{pmatrix} m & 0 \\ 0 & M \end{pmatrix}\begin{pmatrix} c & -s \\ s & c \end{pmatrix}\begin{pmatrix} \nu_L \\ N_R^C \end{pmatrix}$$

Written in the Chiral basis

off-diagonal mass matrix

# Katrin on the move