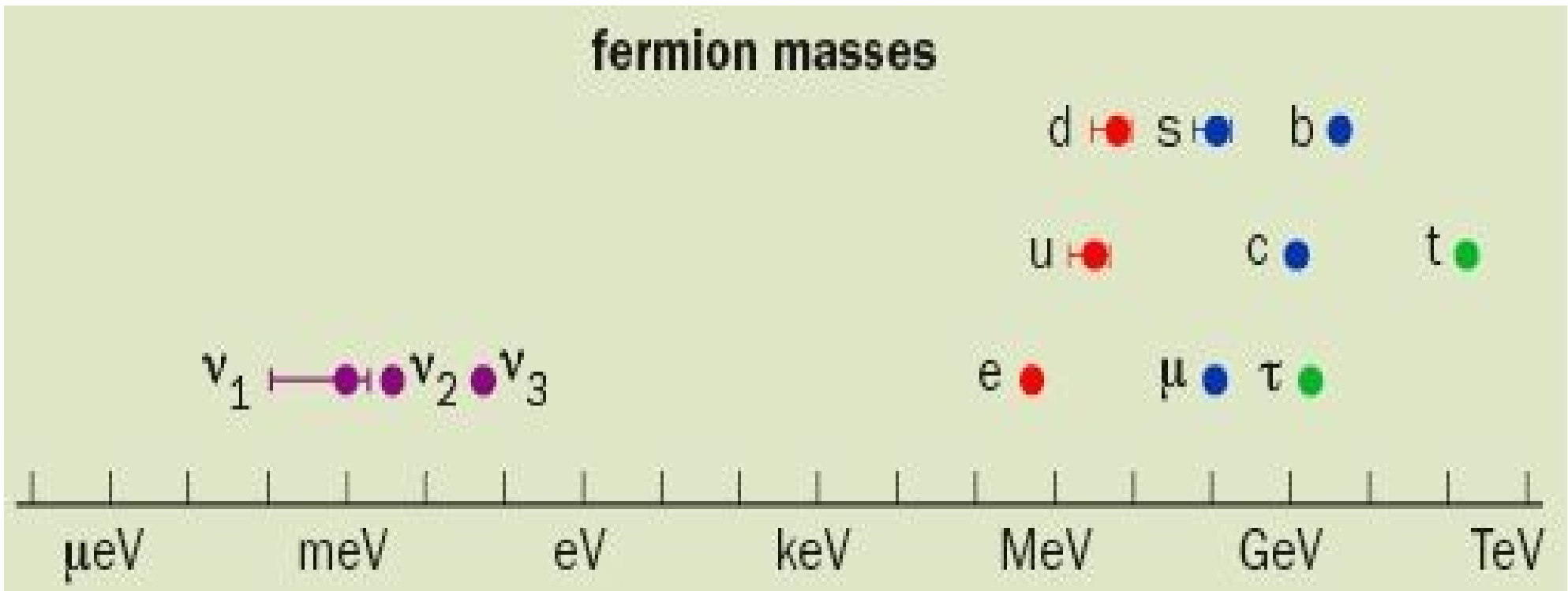


# Lecture 2

*In which the origin of mass is considered and  
unsuccessfully measured*

# The mystery of neutrino mass

## fermion masses



Why are neutrino masses so small?

# $\nu$ Mass in the Standard Model

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

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

Can rewrite mass term in terms of chiral states

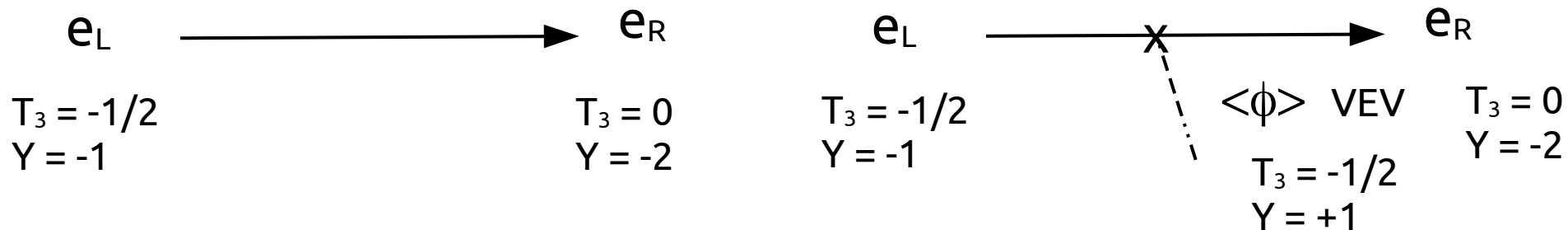
$$L_{mass} = m_D \bar{\psi} \psi = m_D (\bar{\psi}_L + \bar{\psi}_R) (\psi_L + \psi_R) = m_D (\bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L)$$

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

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

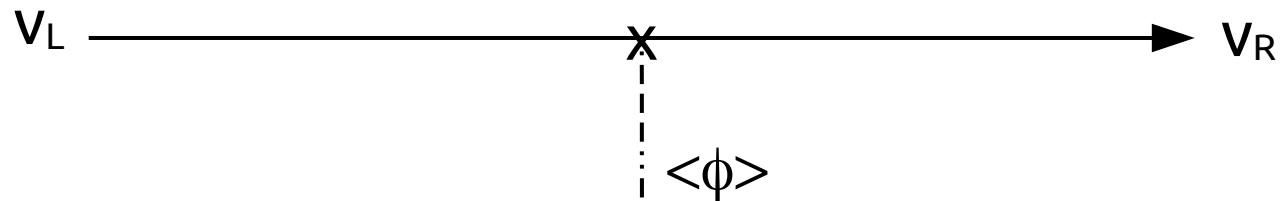


$$\text{Dirac mass: } m_D = Y_\psi \langle \phi \rangle \quad \langle \phi \rangle = 246 \text{ GeV}$$

- ▶ 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

$$L_{mass} = Y_\nu \langle \phi \rangle (\bar{\nu}_L \nu_R + \bar{\nu}_R \nu_L)$$



- ▶ 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  $\nu_L^C = C \bar{\nu}_L^T$  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

$$L_{Maj} = \frac{1}{2} m_L (\bar{\nu}^C \nu + \bar{\nu} \nu^C) = \frac{1}{2} m_L (\bar{\nu}_L^C \nu_L + \bar{\nu}_L \nu_L^C)$$

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

# Damn it!

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

$$\begin{array}{ccc}
 \overline{\nu}_L^C \nu_L & \xrightarrow{\quad \times \quad} & \nu_L^C \\
 \begin{array}{c} T_3 = +1/2 \\ Y = -1 \end{array} & \xrightarrow{\Delta Y = +2} & \begin{array}{c} T_3 = -1/2 \\ Y = +1 \end{array}
 \end{array}$$

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

$$L_{mass} = m \overline{\nu}_m \nu_m + M \overline{N}_m N_m = \left( \overline{\nu}_m \overline{N}_m \right) \begin{pmatrix} m & 0 \\ 0 & M \end{pmatrix} \begin{pmatrix} \nu_m \\ N_m \end{pmatrix} \quad \text{Written in the mass basis}$$

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

$$\nu_L, \quad \nu_L^C, \quad N_R, \quad N_R^C$$

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

$$\left. \begin{aligned} L_L^M &= m_L \overline{\nu}_L^C \nu_L \\ L_R^M &= m_R \overline{N}_R^C N_R \\ L_L^D &= m_D \overline{N}_R^C \nu_L \\ L_R^D &= m_D \overline{\nu}_L^C N_R^C \end{aligned} \right\} \begin{array}{l} \text{Two Majorana mass terms} \\ \text{Two Dirac mass terms} \end{array}$$

# The general mass term

The most general Lagrangian combines all of these

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

$$L_{chiral} = \begin{pmatrix} \overline{\nu}_L^C & \overline{N}_R \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R^C \end{pmatrix}$$

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

$$\overline{N}_R^C N_R \quad N_R \xrightarrow{\quad \times \quad} N_R^C$$

$T_3 = 0$   $T_3 = 0$   
 $Y = 0$   $Y = 0$

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

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

$$L_{chiral} = \begin{pmatrix} \overline{\nu}_L^C & \overline{N}_R \end{pmatrix} \begin{pmatrix} 0 & m_D \\ m_D & m_R \end{pmatrix} \begin{pmatrix} \nu_L \\ N_R^C \end{pmatrix}$$

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  $(m_1, m_2)$ .

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

# See-Saw mechanism

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

- ▶ 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

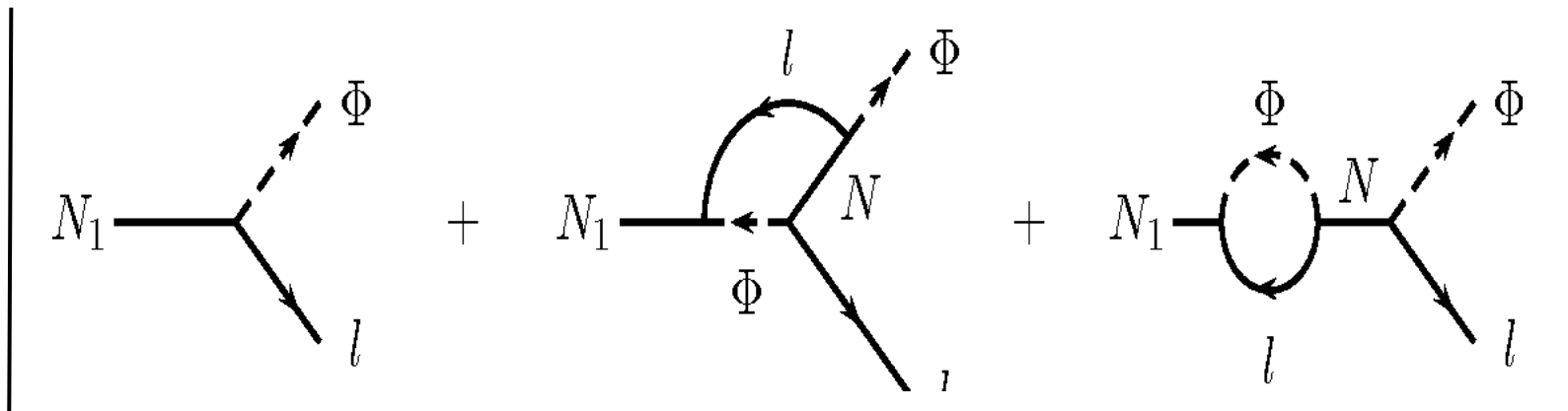
- ▶ Mass of "our" neutrino suppressed by the GUT scale
- ▶  $\Lambda \approx 10^{16} \text{ GeV} \rightarrow m \approx (250)^2 / 10^{16} \approx 10 \text{ meV}$
- ▶ Currently our only "natural" way to explain why the neutrino mass is so much smaller than other Dirac particles

# 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.



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

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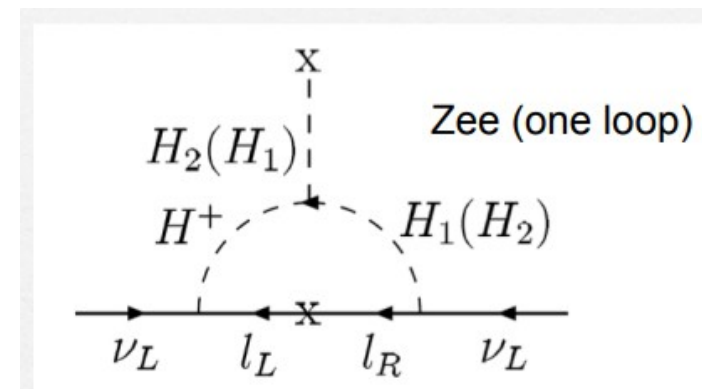
- ⦿ the neutrino to be massive
- ⦿ the neutrino must be Majorana
- ⦿ a GUT scale heavy neutral lepton must exist



# Other mass models

Model	New Physics
Dirac neutrino	U(1) gauge singlet neutral lepton triplet
Type 1 Seesaw	U(1) gauge singlet heavy neutral lepton
Type 2 Seesaw	Heavy Higgs triplet
Type 3 Seesaw	New SU(2) <sub>L</sub> fermion triplet (e.g. supersymmetry)
Loop models	Extra Higgs; new scalar fields
R-parity violating SUSY	SUSY
Extra dimensions (snap)	

Every neutrino mass model  
requires new physics.



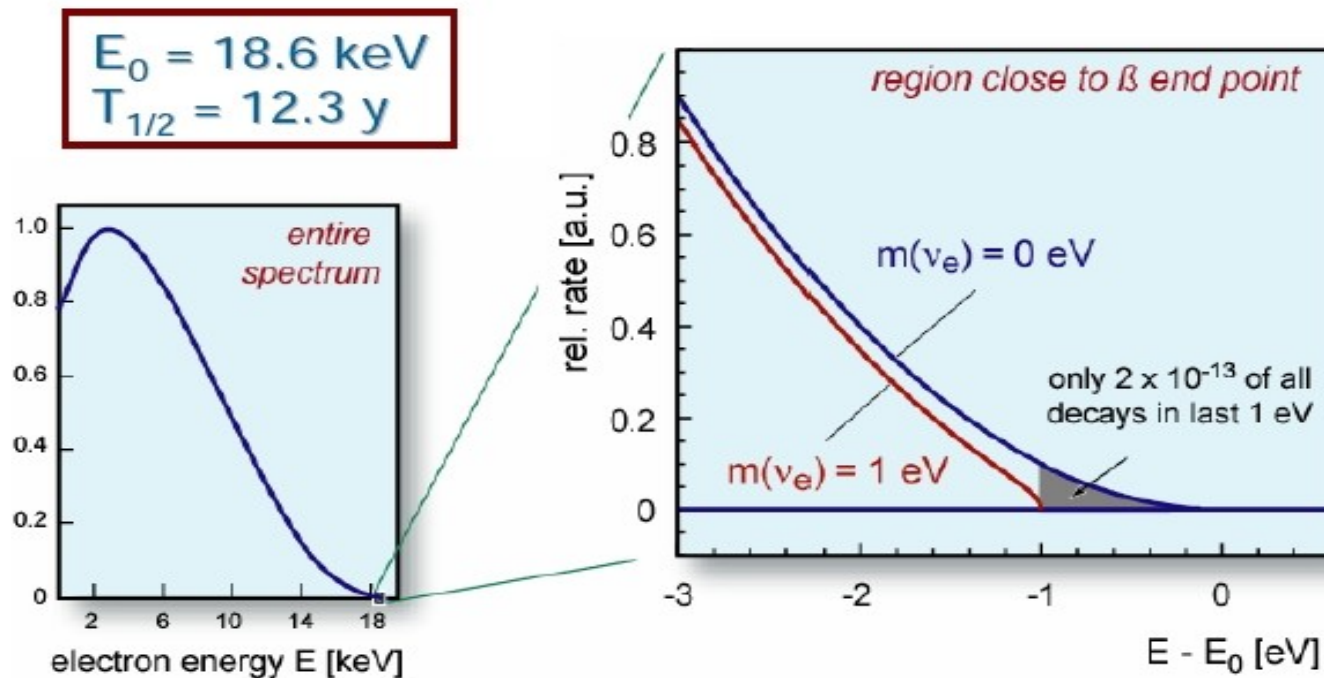
*(Attempts at) mass measurements*

# $\nu_e$ mass

Measurement of  $\nu_e$  mass from kinematics of  $\beta$  decay.

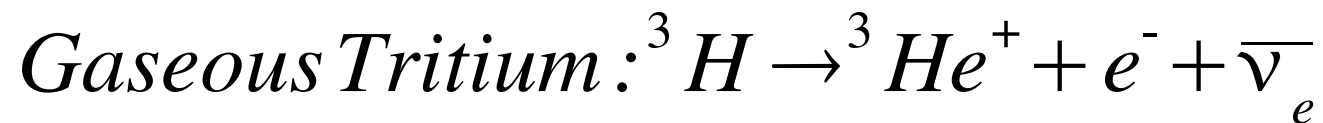
$$\frac{d\Gamma_i}{dE} = C p(E + m_e)(E_0 - E) \sqrt{(E_0 - E)^2 - m_\nu^2} F(E) \theta(E_0 - E - m_\nu)$$

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



Endpoint is at 18574 eV

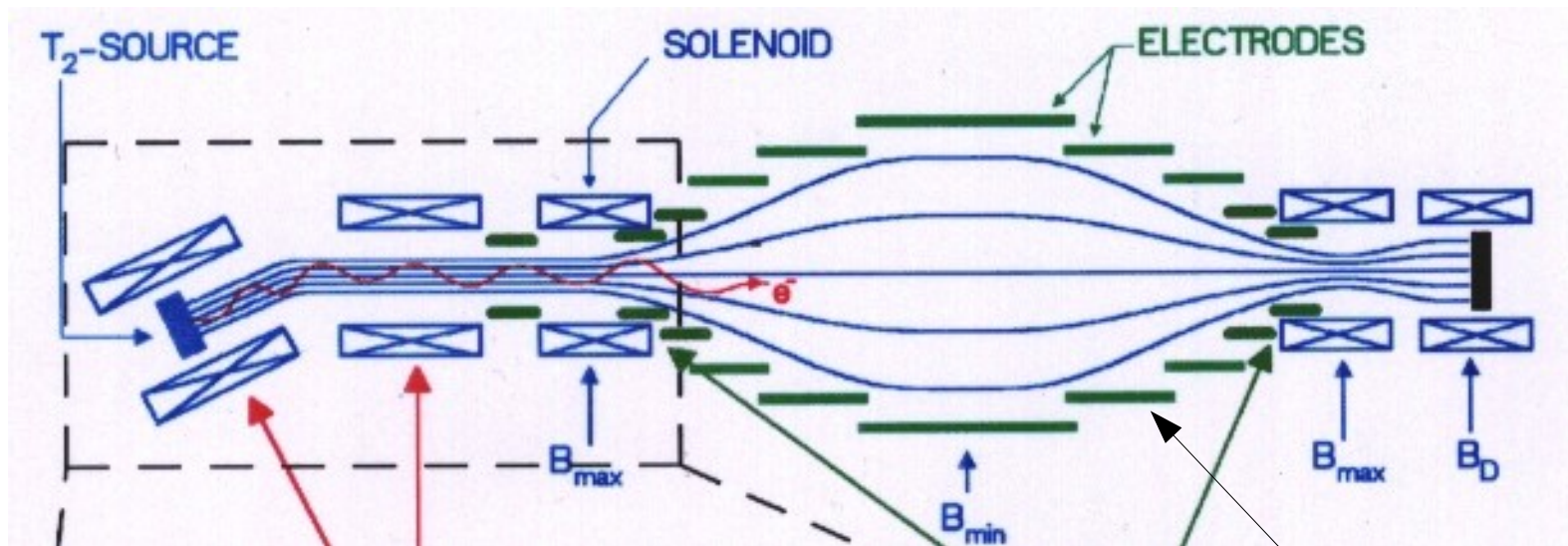
No molecular excitation above 18547 eV

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



- $2\pi$  acceptance
- High energy resolution

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

Electrostatic  
MAC-E Filter

# Early experiments



Troitsk

windowless gaseous  $T_2$  source

analysis 1994 to 1999, 2001

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

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

Mainz

quench condensed solid  $T_2$  source

analysis 1998/99, 2001/02

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

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

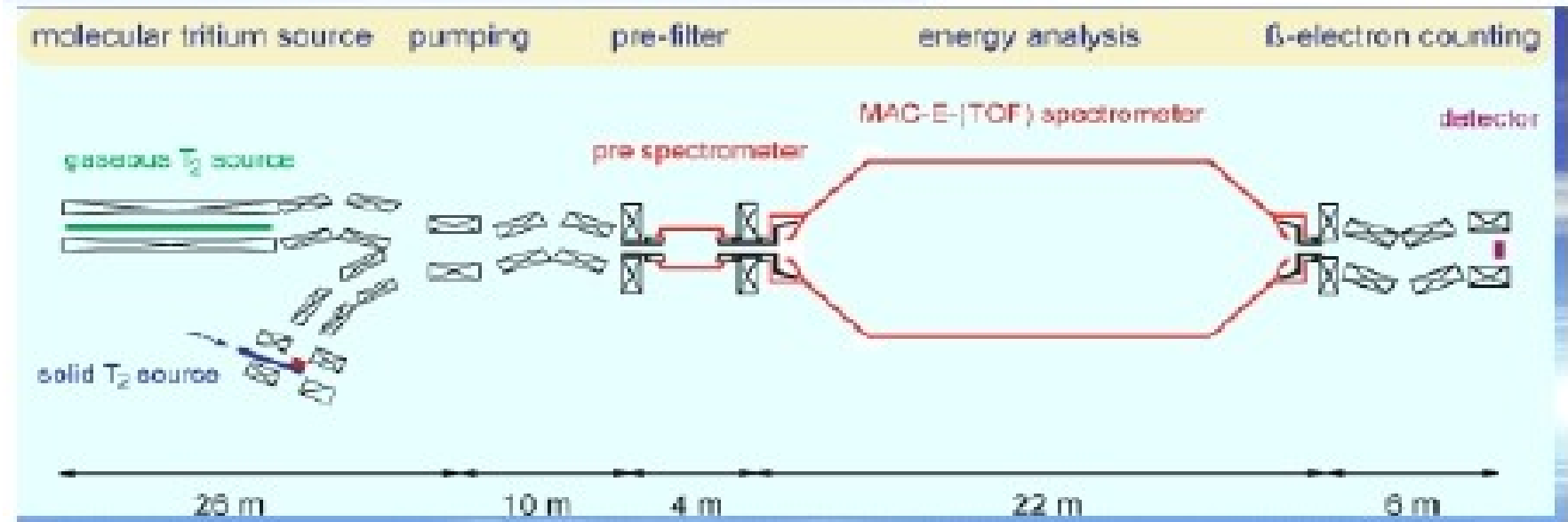
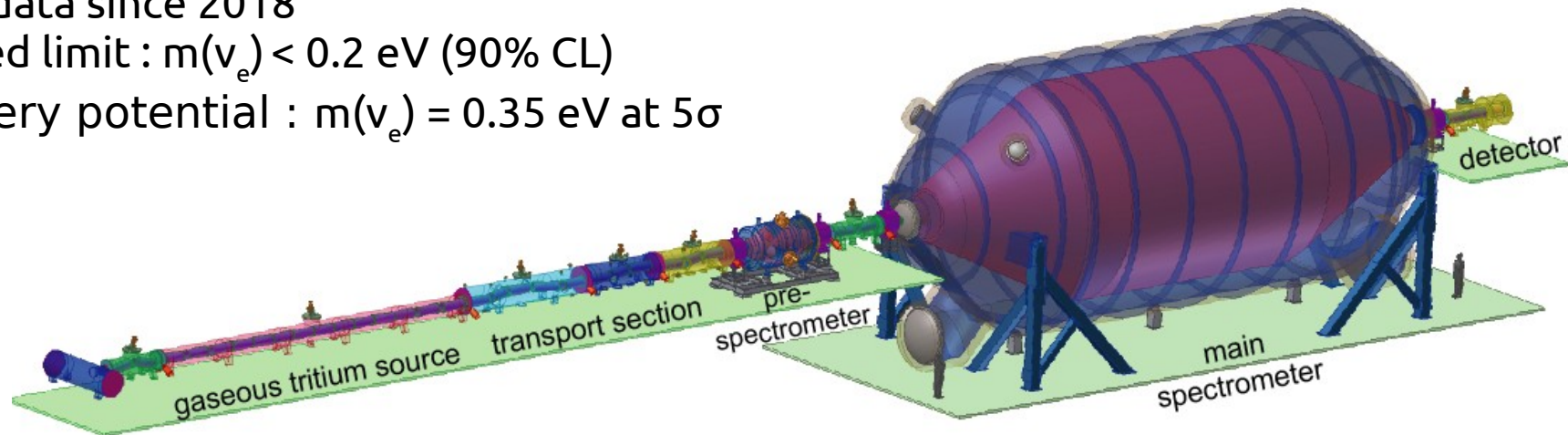
Both experiments have reached the intrinsic limit of their sensitivity.

# KATRIN

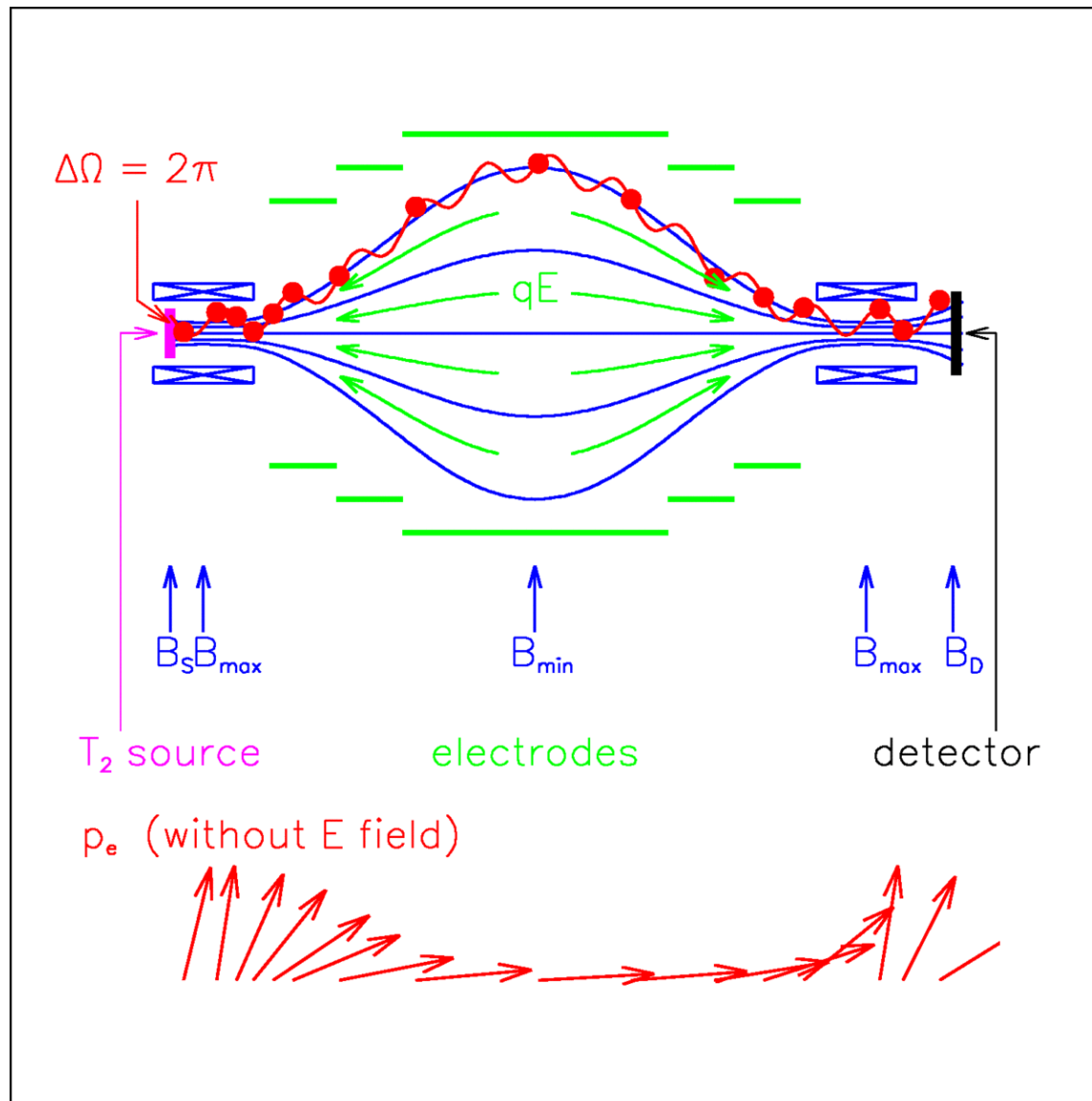
Taking data since 2018

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

Discovery potential :  $m(\nu_e) = 0.35 \text{ eV}$  at  $5\sigma$



# Principle of operation



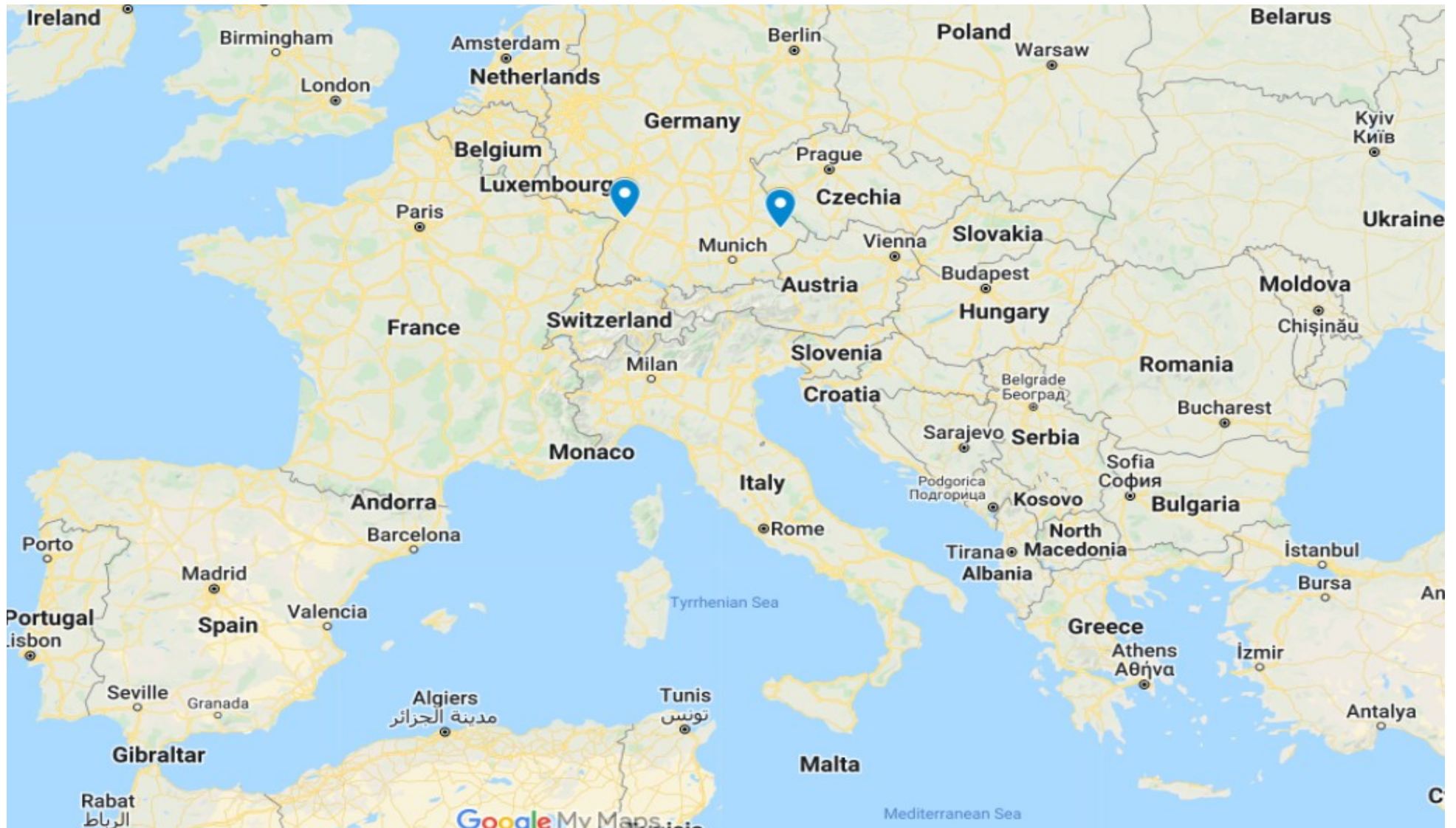




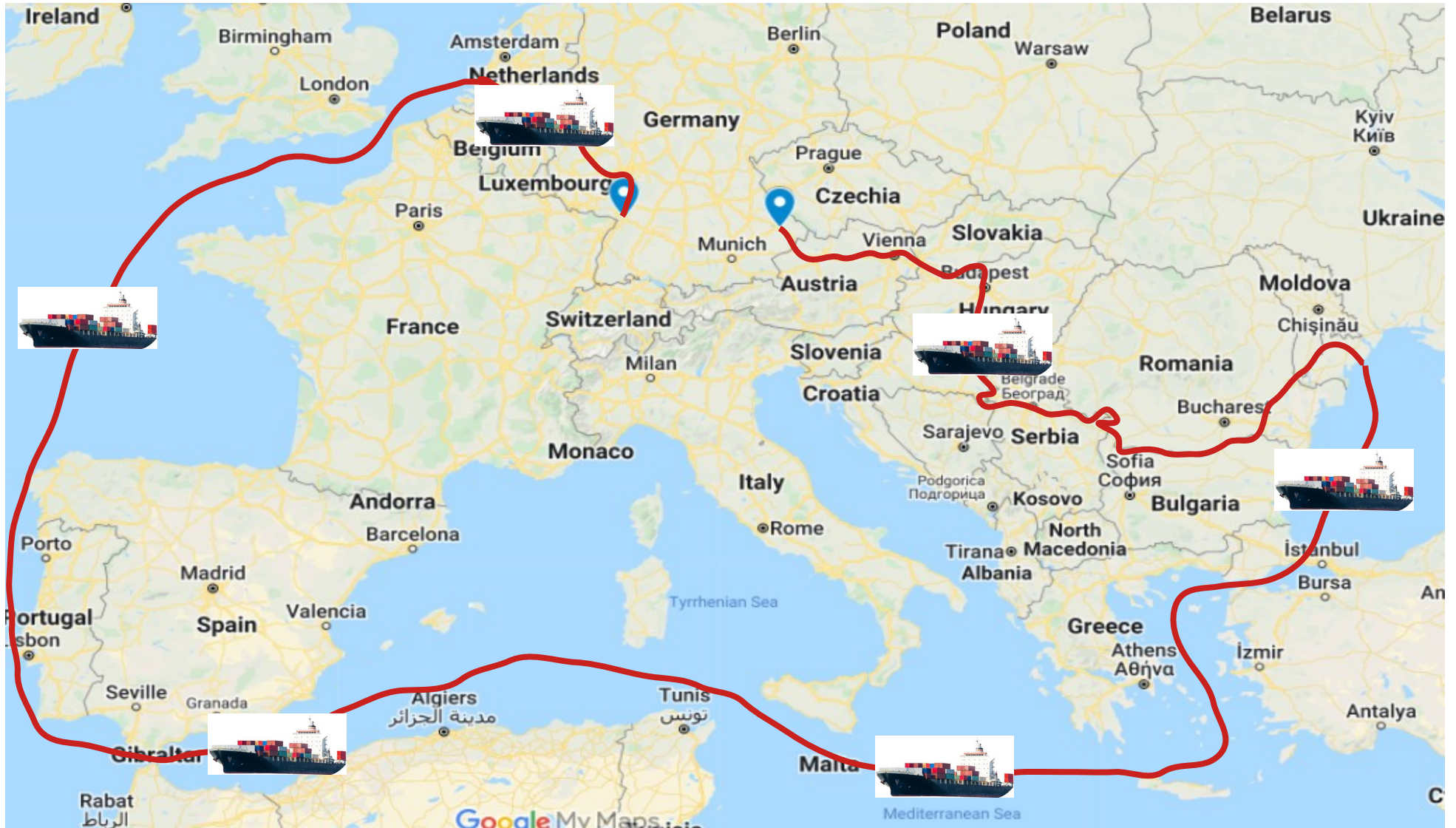
# KATRIN on the move



# Katrin on the move



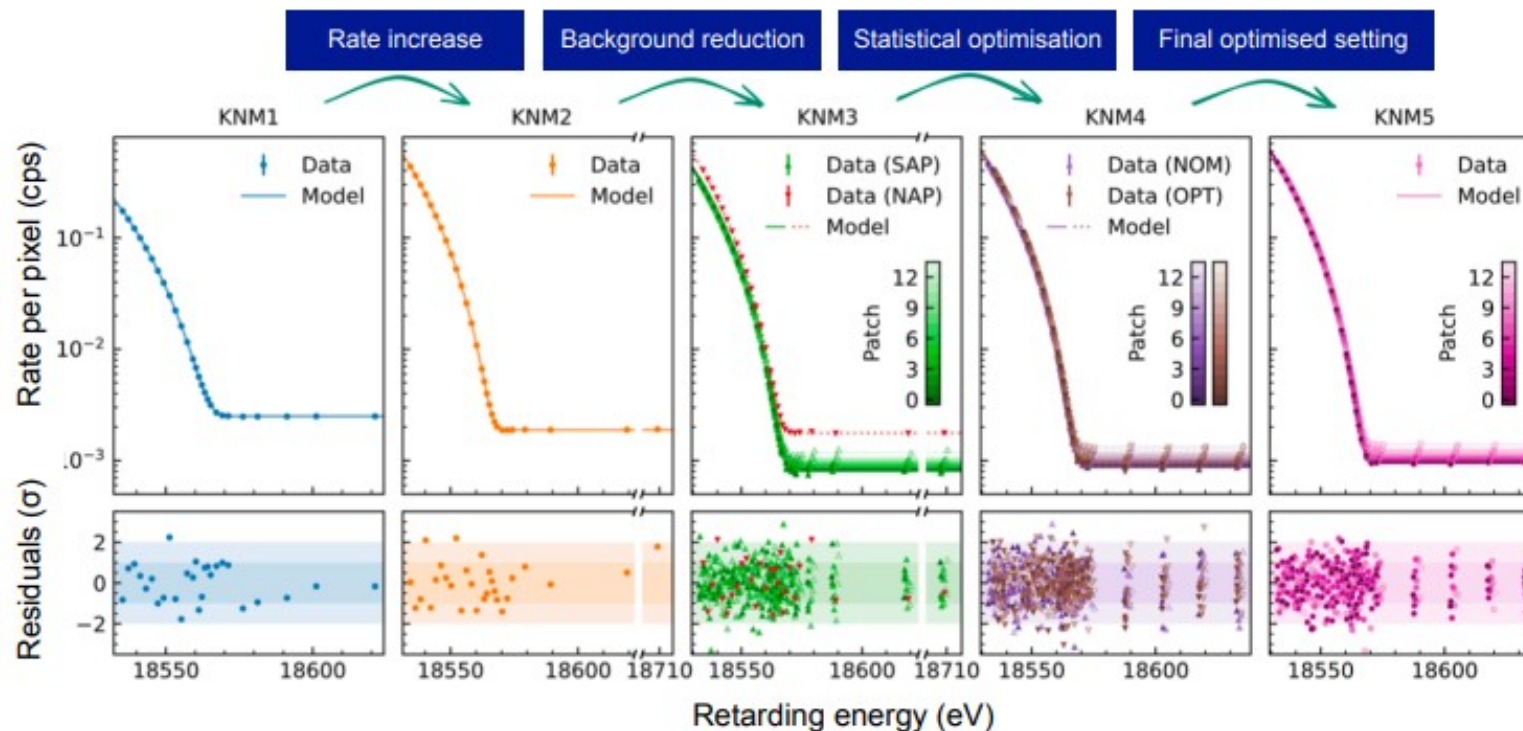
# Katrin on the move



# Latest KATRIN result

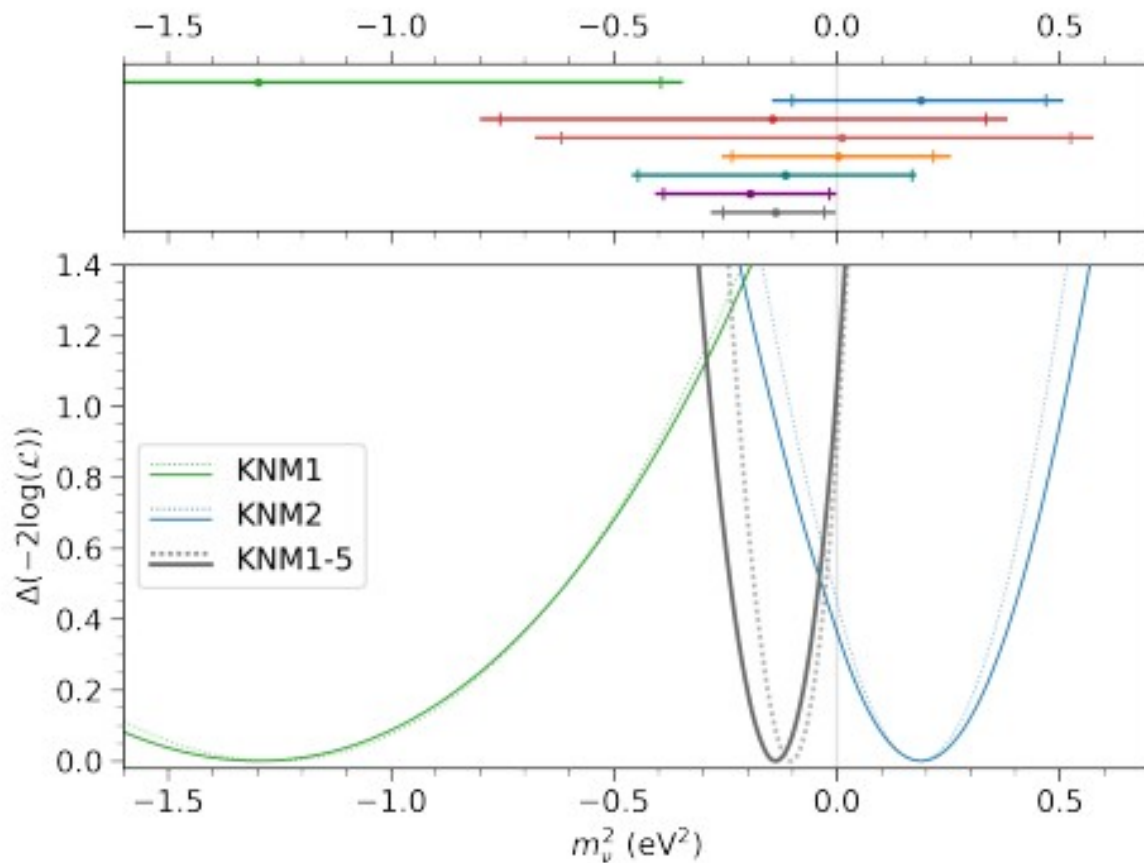
Data from KNM1-5 science runs

KATRIN Coll.,  
Science 388 (2025)  
180-185



- ▶ Maximum likelihood fit with common  $m_\nu^2$  parameter in **59 data sets** (1609 data points)

# Latest KATRIN result



Best fit from fit to combined datasets

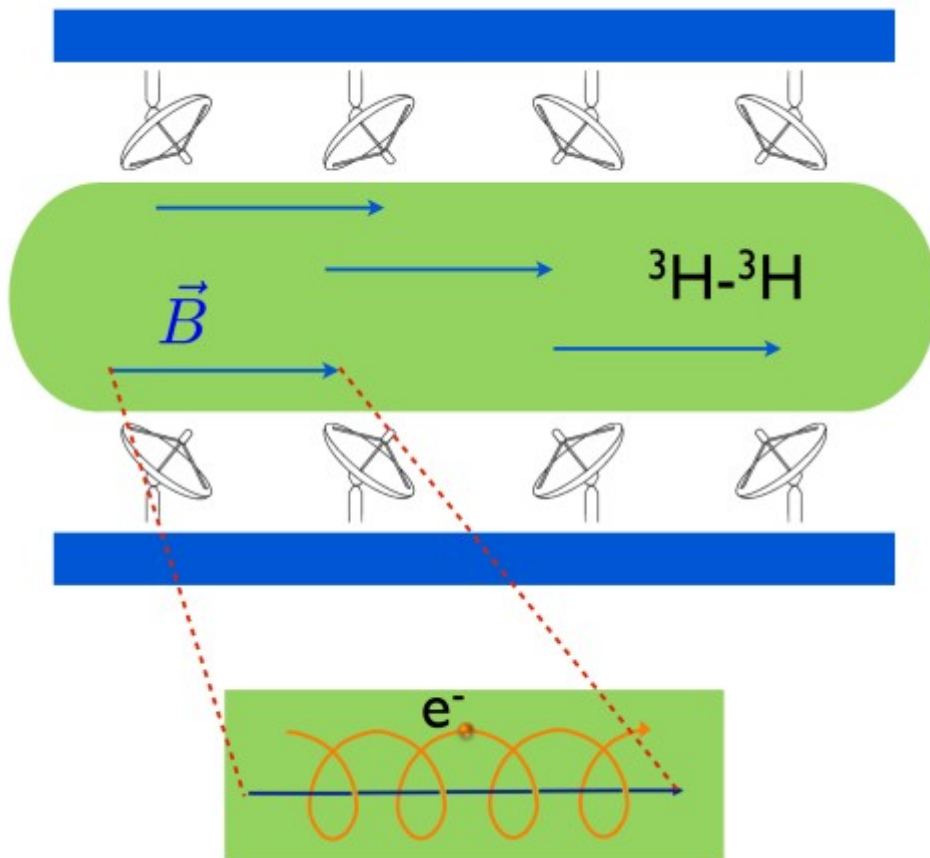
$$m_\nu^2 = -0.14 \pm 0.14 \text{ eV}^2$$

Upper limit  
(depends on statistical treatment)

$$m_\nu < 0.31 - 0.45 \text{ eV} \text{ (90\% CL)}$$

Work beginning on an improved KATRIN++ experiment. Expected to be sensitive  $m_\nu < 0.4$  eV. Could take data in mid-2030's

# 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

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

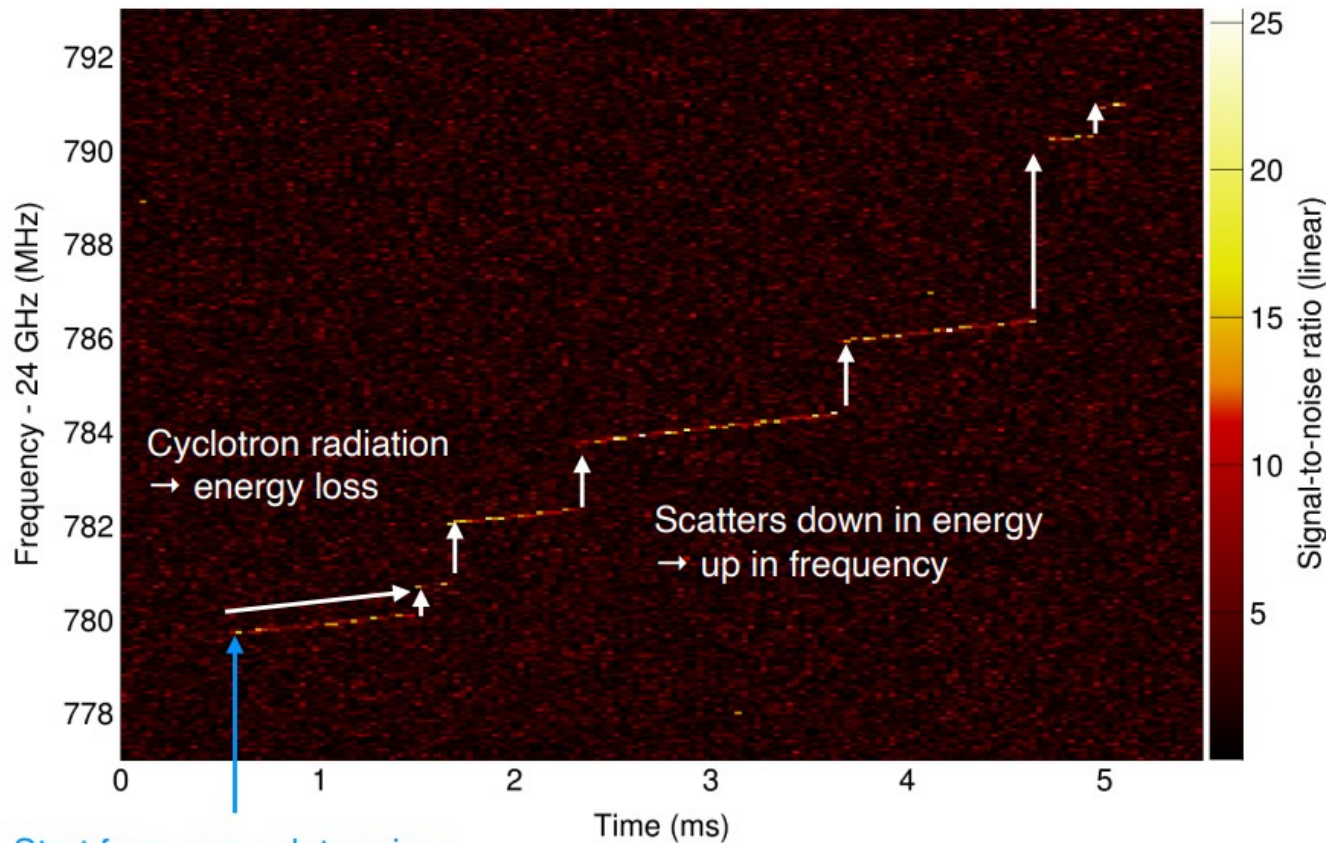
- ▶ Measures electron energy from the frequency of the cyclotron radiation!
- ▶ Push the limit to an order of magnitude lower than KATRIN

▶  $M_\nu < 40 \text{ meV}$

# Project 8

PROJECT 8

## A Typical\* CRES Event



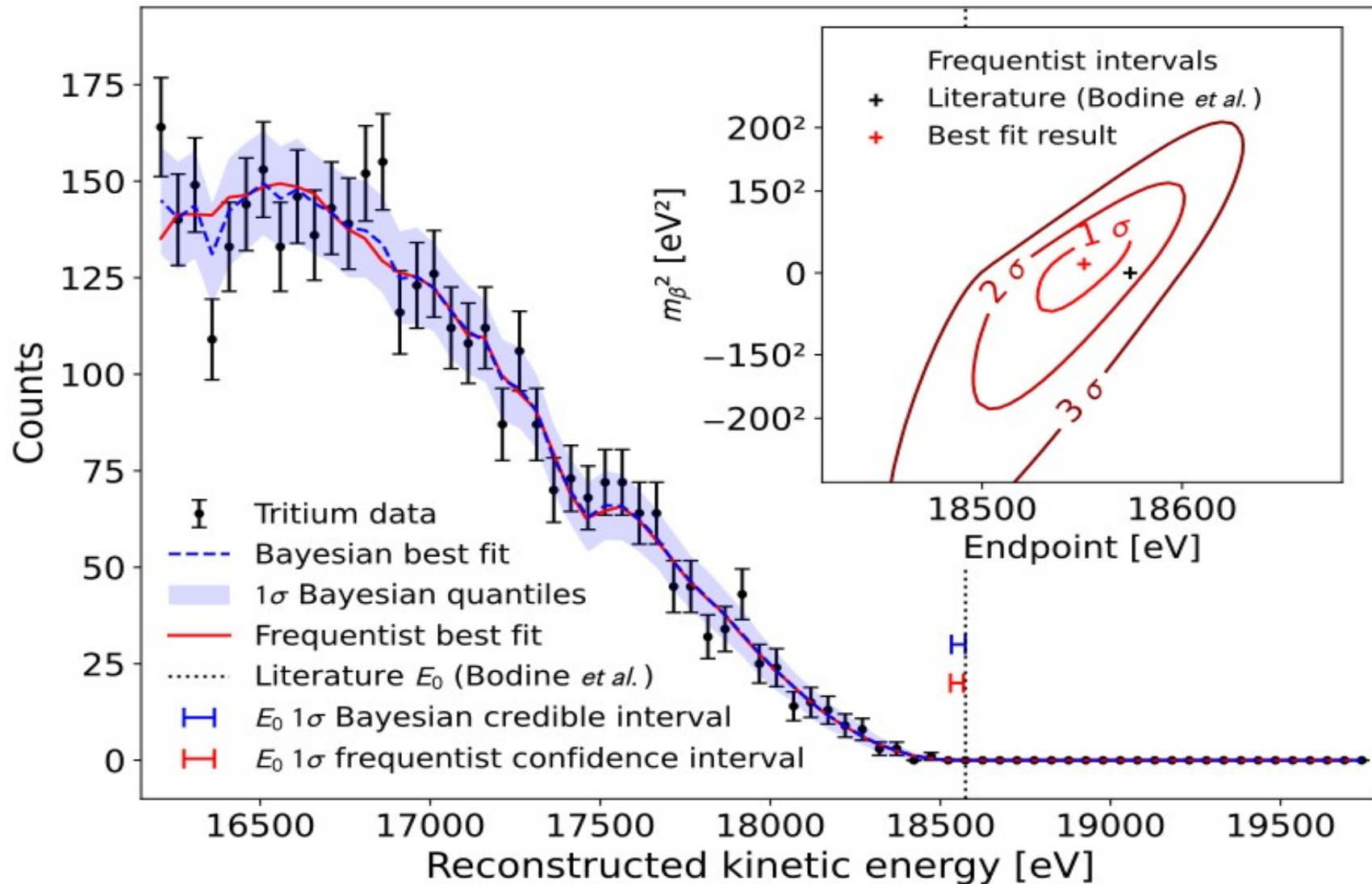
Start frequency: determines  
electron energy before losses

\* so far

$$2\pi f = \frac{e\langle B \rangle}{m_e + K_e/c^2}$$

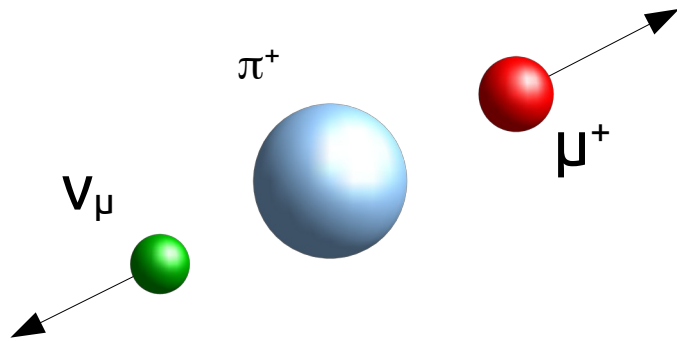
# $\beta$ -decay from CRES

prototype proof-of-principle



# $\nu_\mu$ mass

Easiest way is to use pion decay at rest



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

$$m_\pi = 139.57037 \pm 0.00021 \text{ MeV}$$

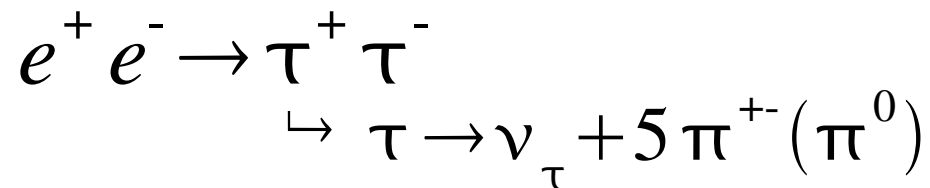
$$m_\mu = 105.658389 \pm 0.000034 \text{ MeV}$$

$$p_\mu = 29.792 \pm 0.00011 \text{ MeV}$$

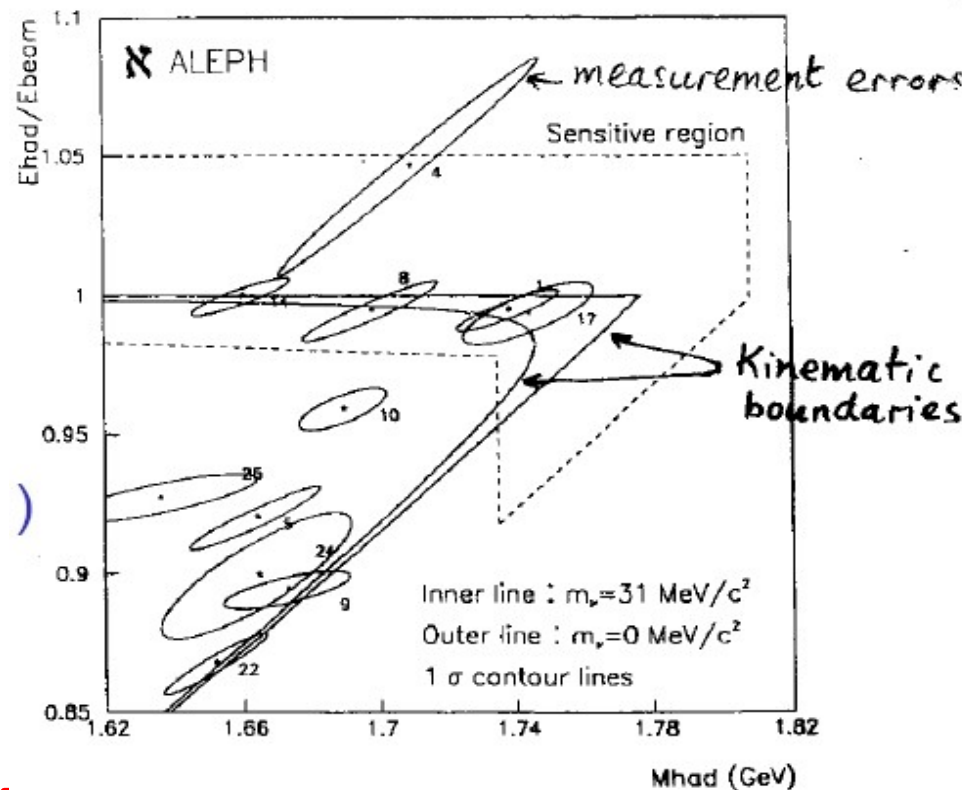
$$m_\nu^2 = (-0.016 \pm 0.023) \text{ MeV}^2$$

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

# $\nu_\tau$ mass



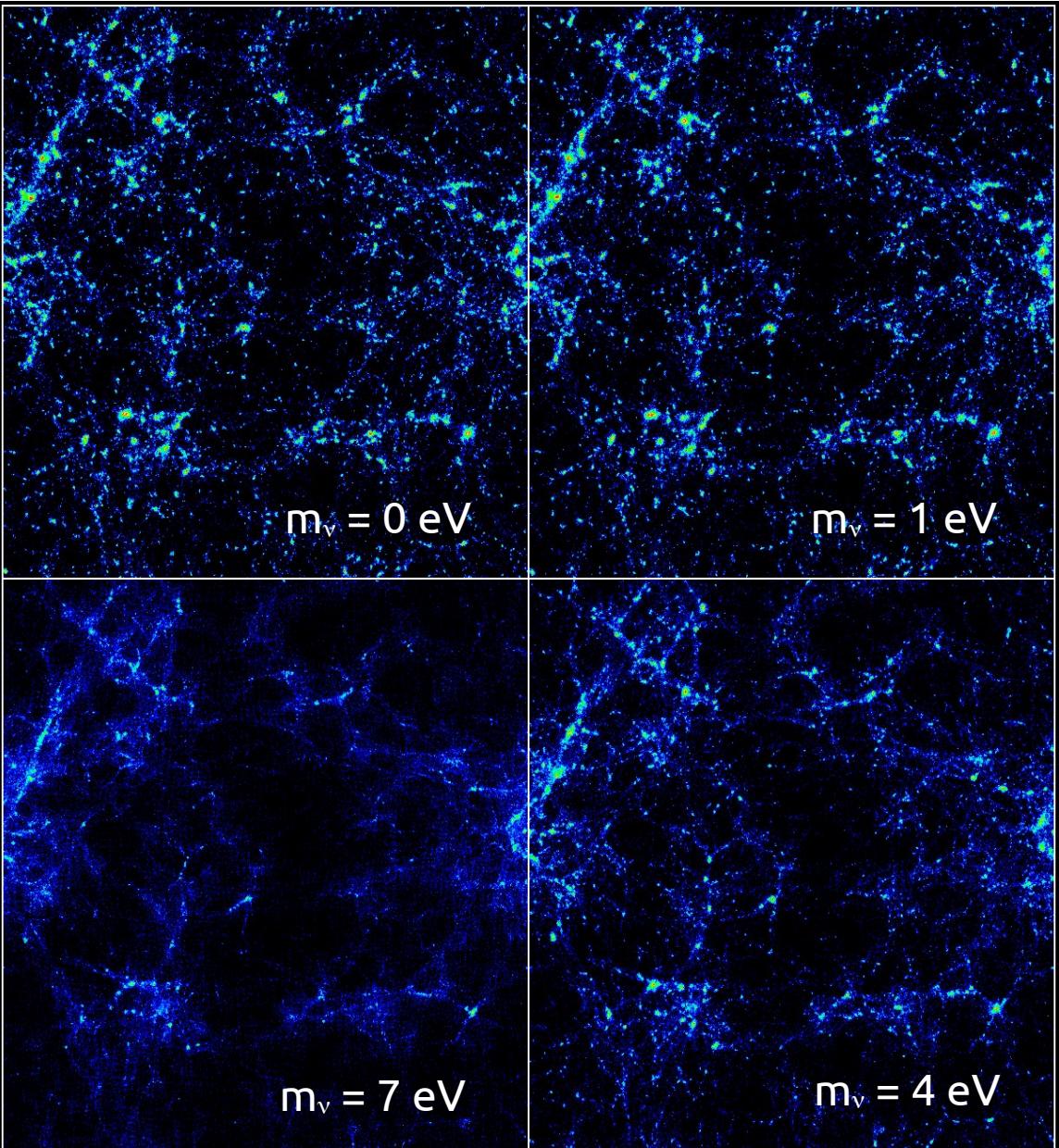
$$E_\tau = \frac{\sqrt{s}}{2}$$



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

# Cosmology

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



$m_\nu = 0 \text{ eV}$

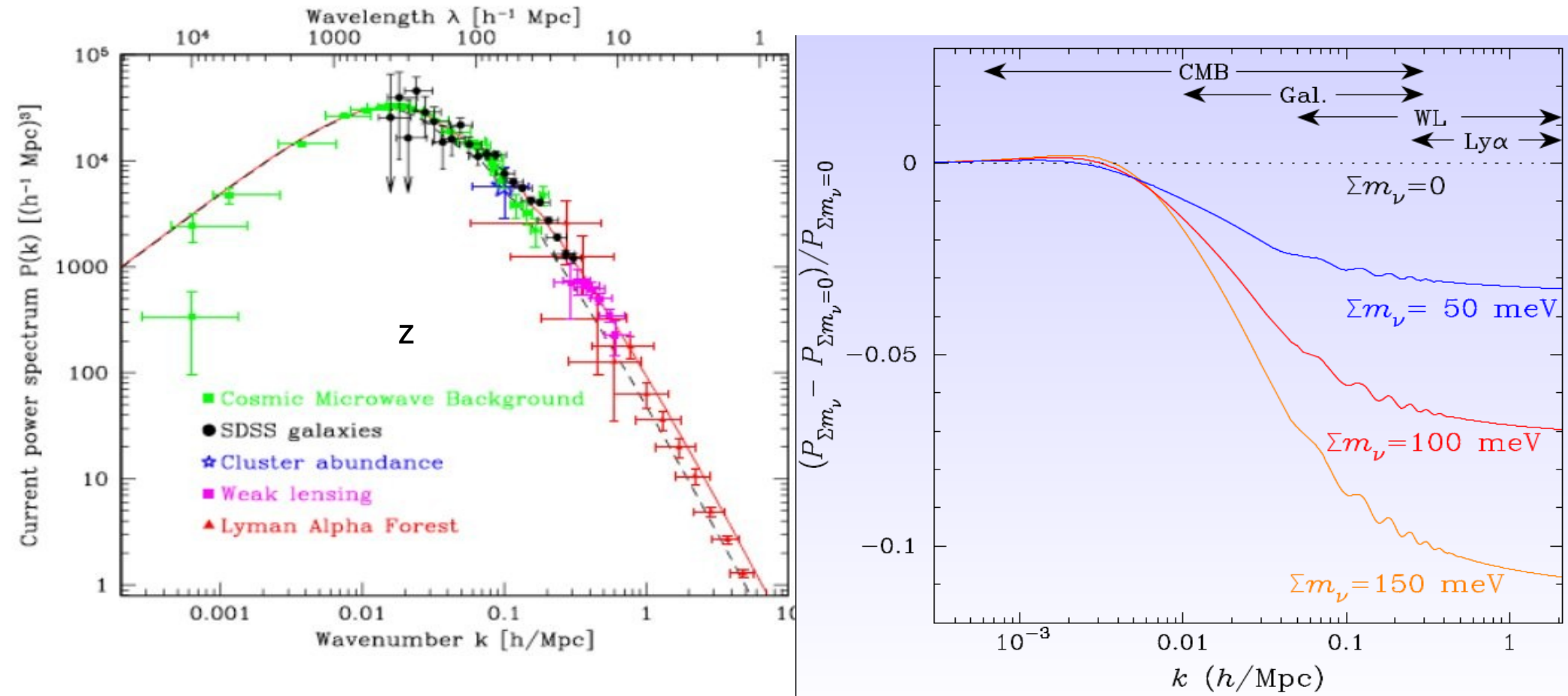
$m_\nu = 1 \text{ eV}$

$m_\nu = 7 \text{ eV}$

$m_\nu = 4 \text{ eV}$

# Power spectra

“Wavelength” of density fluctuation  
Mass suppresses high wavenumber  $\rightarrow$  small scale structure



# Cosmology

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

$$\sum m_{\nu_i} \leq 0.14 - 0.17 \text{ eV}$$

$m_{\nu} = 0 \text{ eV}$

$m_{\nu} = 1 \text{ eV}$

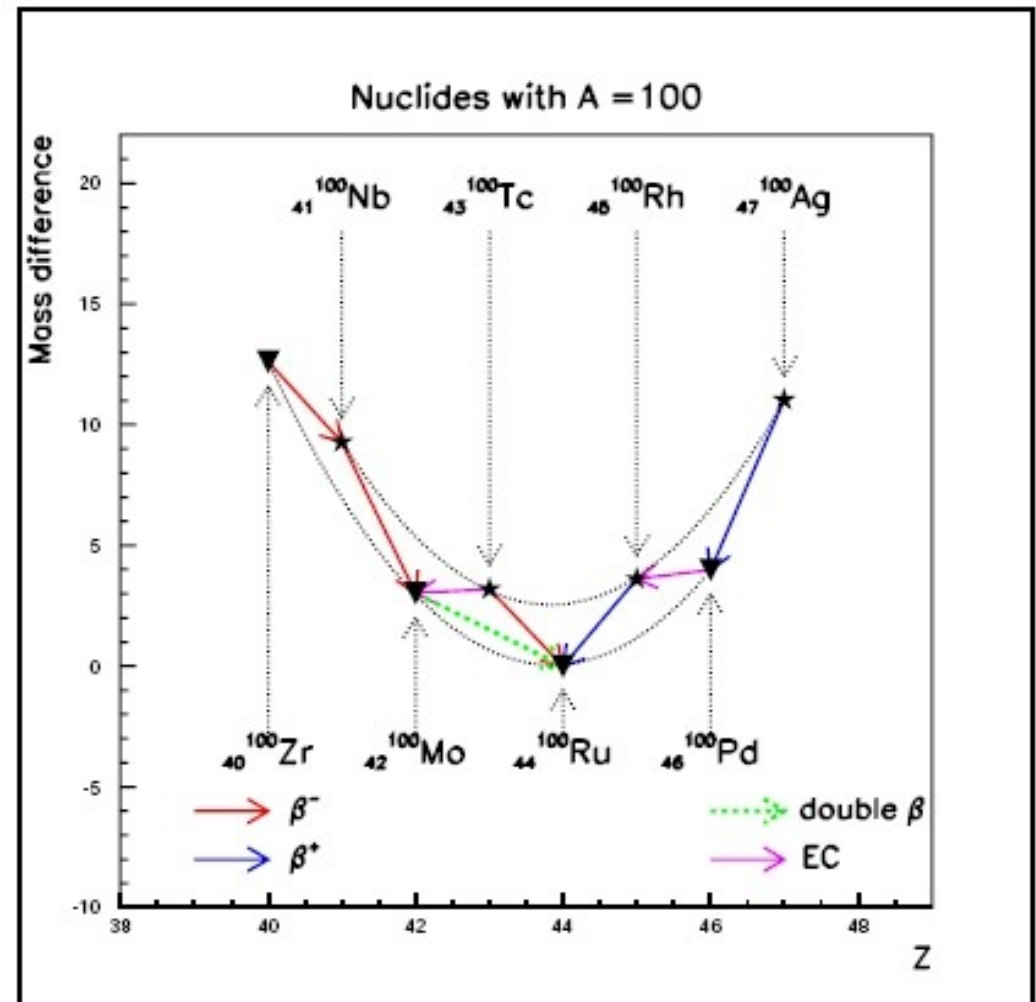
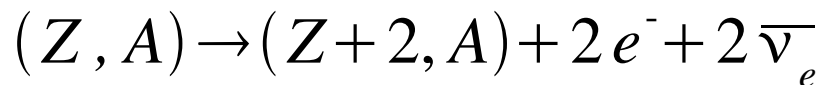
$m_{\nu} = 7 \text{ eV}$

$m_{\nu} = 4 \text{ eV}$

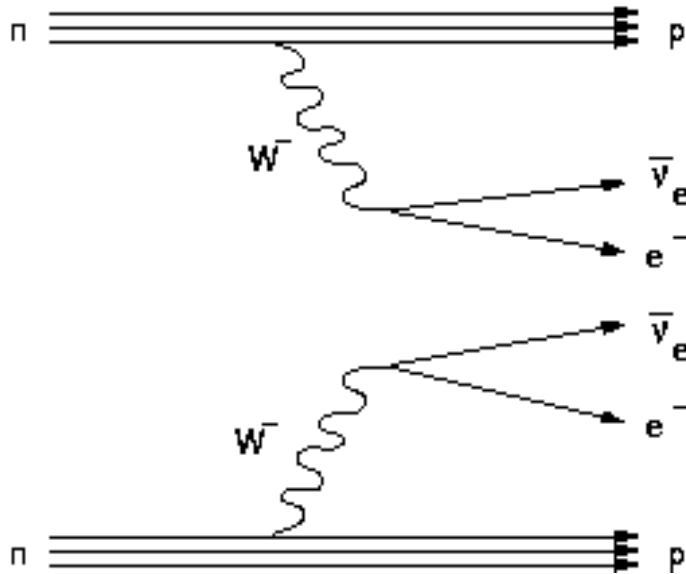
# $2\nu\beta\beta$ Decay

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

In some nuclei  $\beta$  decay is forbidden but double beta decay is not



# $2\nu\beta\beta$ Decay



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

Calculable  
phase space

Nuclear  
matrix element

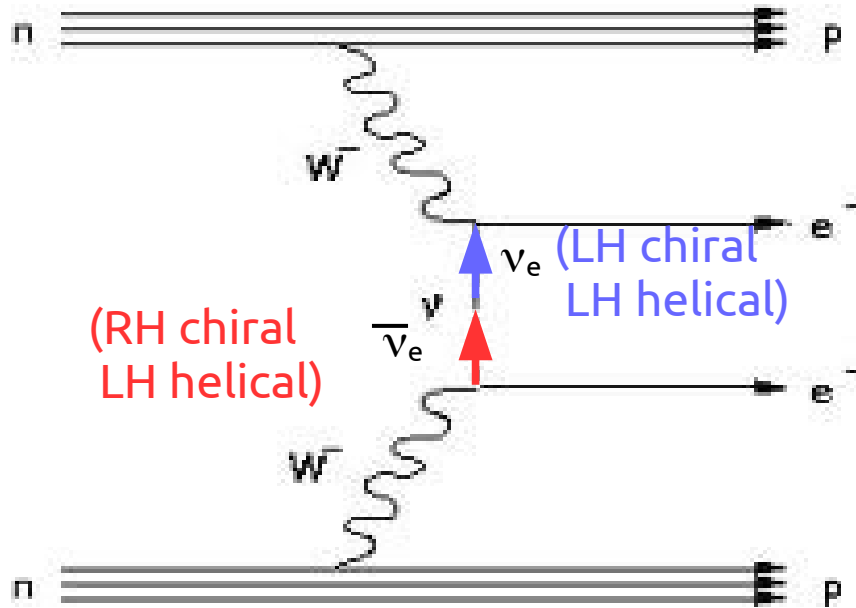
- Second order process in perturbation theory
- Severe test for nuclear matrix element calculation
- Nuclear structure effects cause variations in the nuclear matrix elements of factors of 10

# $2\nu\beta\beta$ Decay

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

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

# Neutrinoless $\beta\beta$ Decay



## Requirements

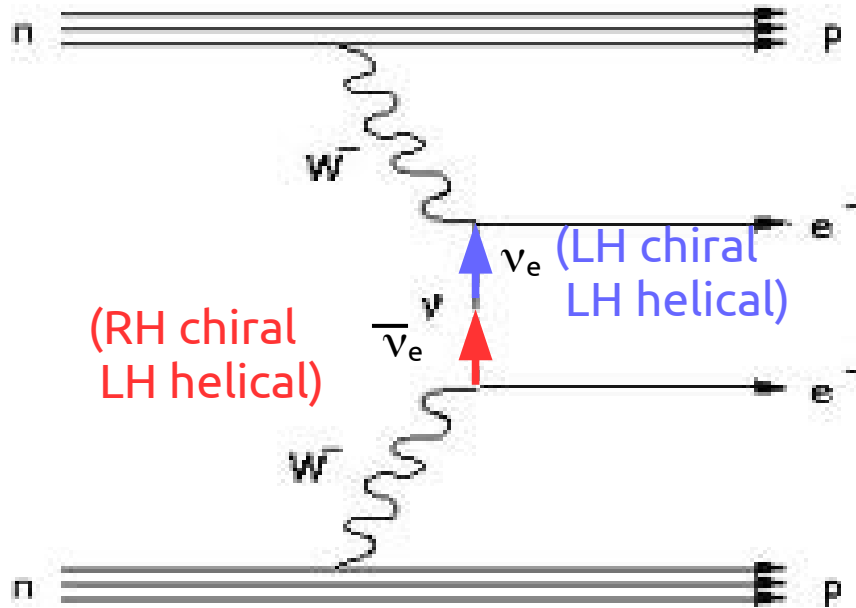
- Neutrino must have mass
- Neutrino is Majorana
- Violation of lepton number conservation

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

$\uparrow$  helicity states       $\uparrow$

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

# Neutrinoless $\beta\beta$ Decay



## Requirements

- Neutrino must have mass
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- Violation of lepton number conservation

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

↑ helicity states ↑

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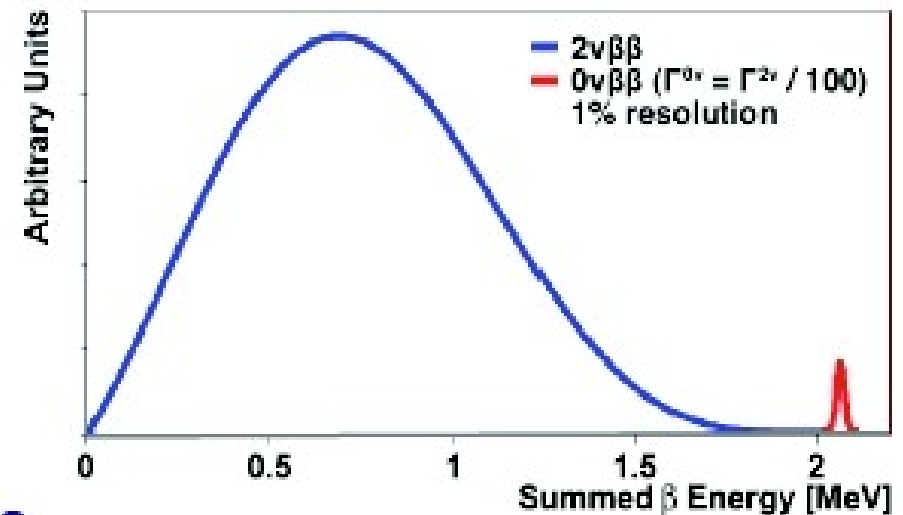
# Experimental Requirements

*Extremely* slow decay rates

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

Best case,  
0 background !

$\propto$  Source Mass  $\cdot$  time<sub>exp</sub>



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  $2\nu\beta\beta$  ( $\sim T_{1/2} \sim 10^{19} - 10^{21}$  years)

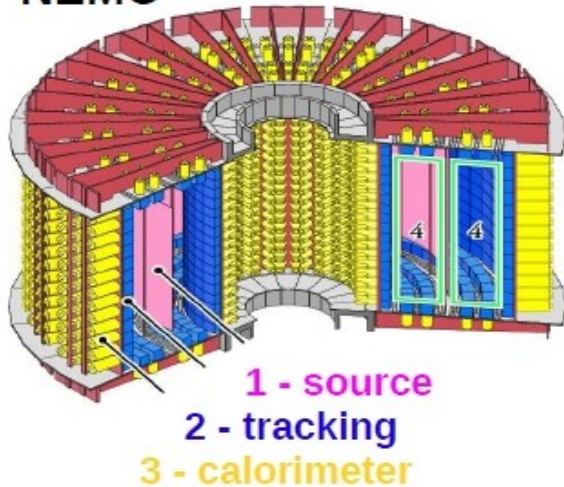
Extremely low (near-zero) backgrounds in the  $0\nu\beta\beta$  peak region

- requires ultra-clean radiopure materials

- the ability to discriminate signal from background

# Types of experiments

## NEMO



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

- $2e^-$  are detected separately
  - different channels of  $0\nu\text{DBD}$  can be distinguished
- **particle identification**
  - background suppression
- **poor energy resolution**
  - important  $2\nu\text{DBD}$  background (limitation on isotope choice)



### 2. the detector is itself the source

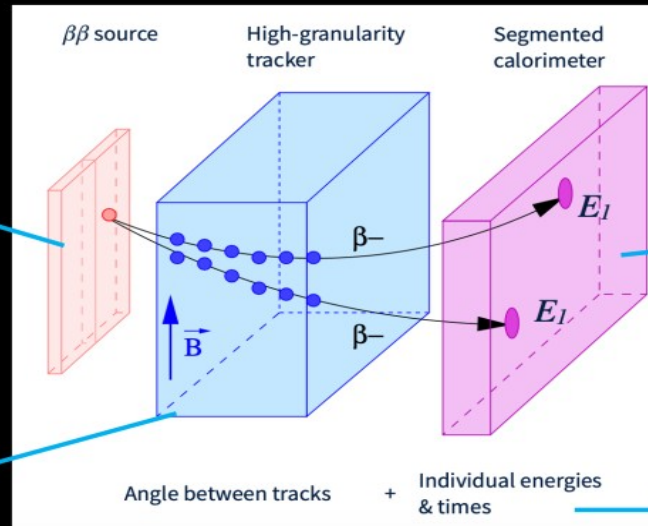
- **solid state detectors**
  - several candidates, high resolution  
no info on kinematic  
techniques for background suppression
- **gaseous detectors for Xe**

# SuperNEMO

6.23kg  $^{82}\text{Se}$   
in SuperNEMO  
Demonstrator



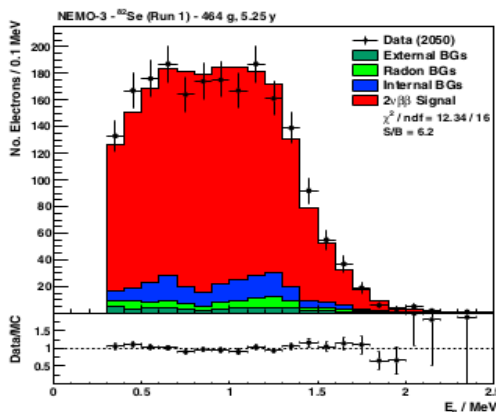
2034 Geiger cells



712 optical modules  
 $1.8\% \sigma/E$  at 3MeV



Excellent background discrimination  
Probe mechanisms and nuclear effects

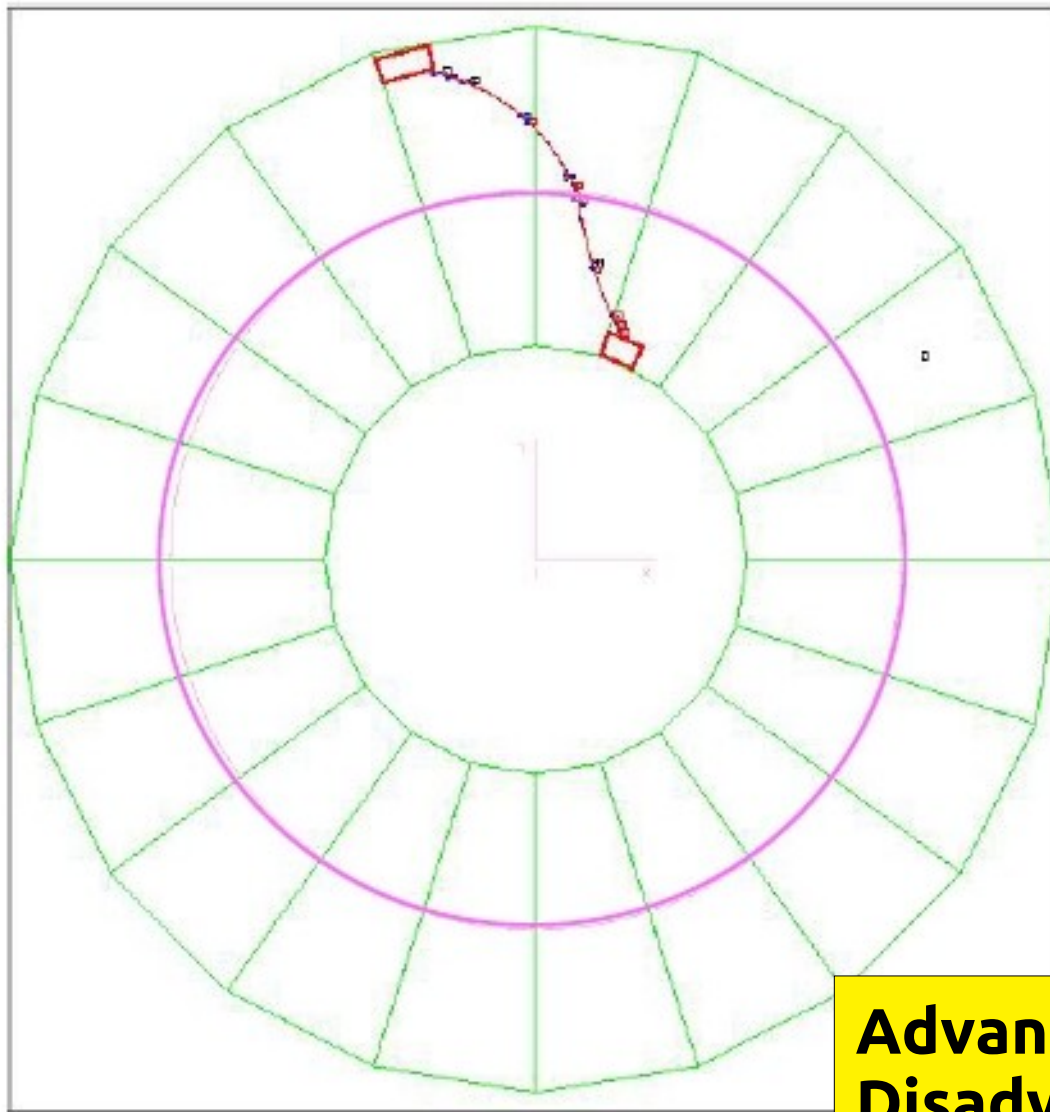


(b) Single-state Dominated (SSD)

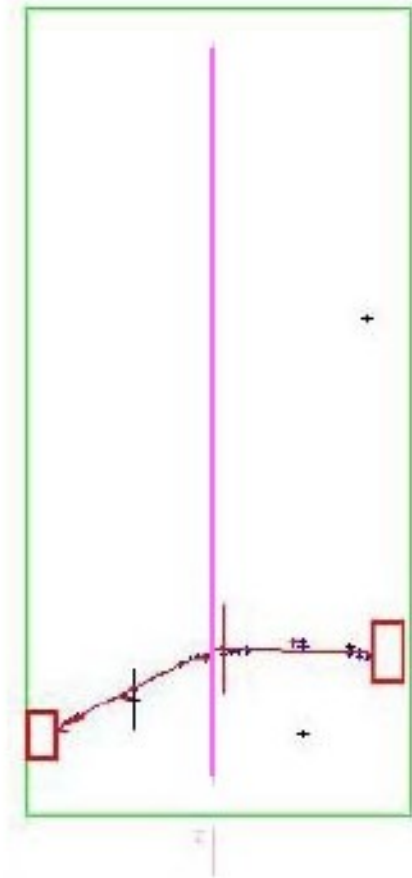
single  
electron  
energy  
distribution  
from 2bb  
decay using  
 $^{82}\text{Se}$

Energy	2.995 eV
Isotope	$^{82}\text{Se}$
Type	Tracker
Start	2023
Physics	$m_{\beta\beta}$

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



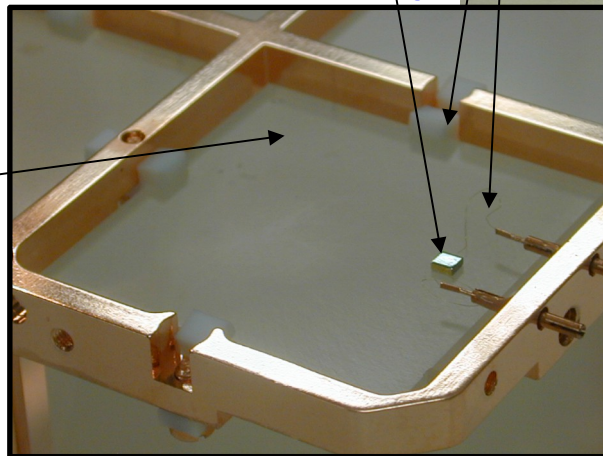
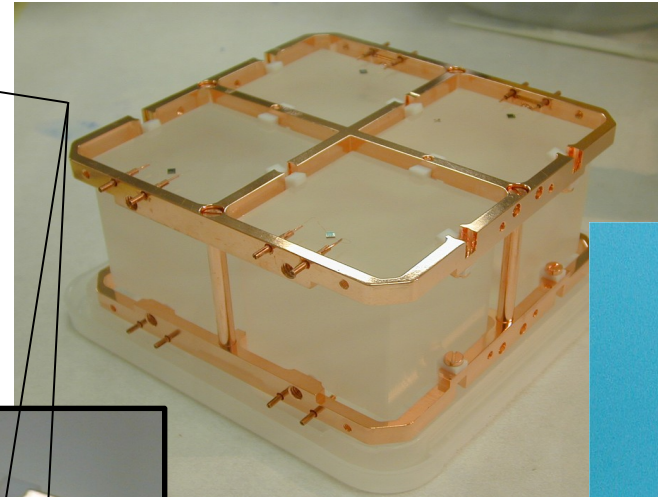
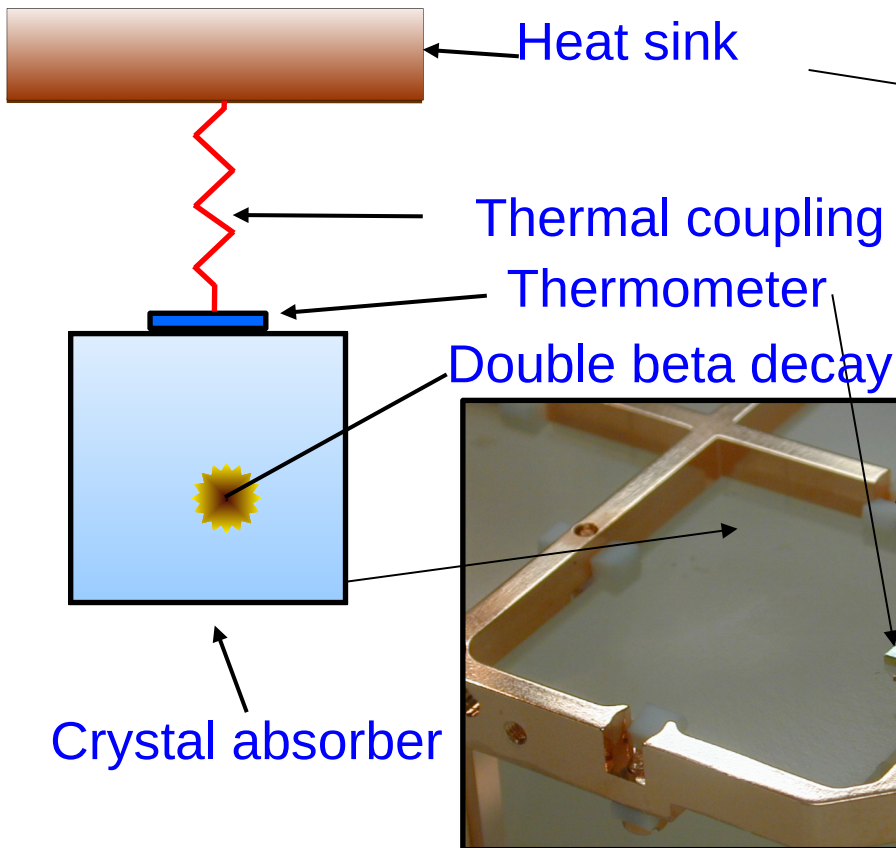
Top view



Side view

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

# Bolometry : Cuore



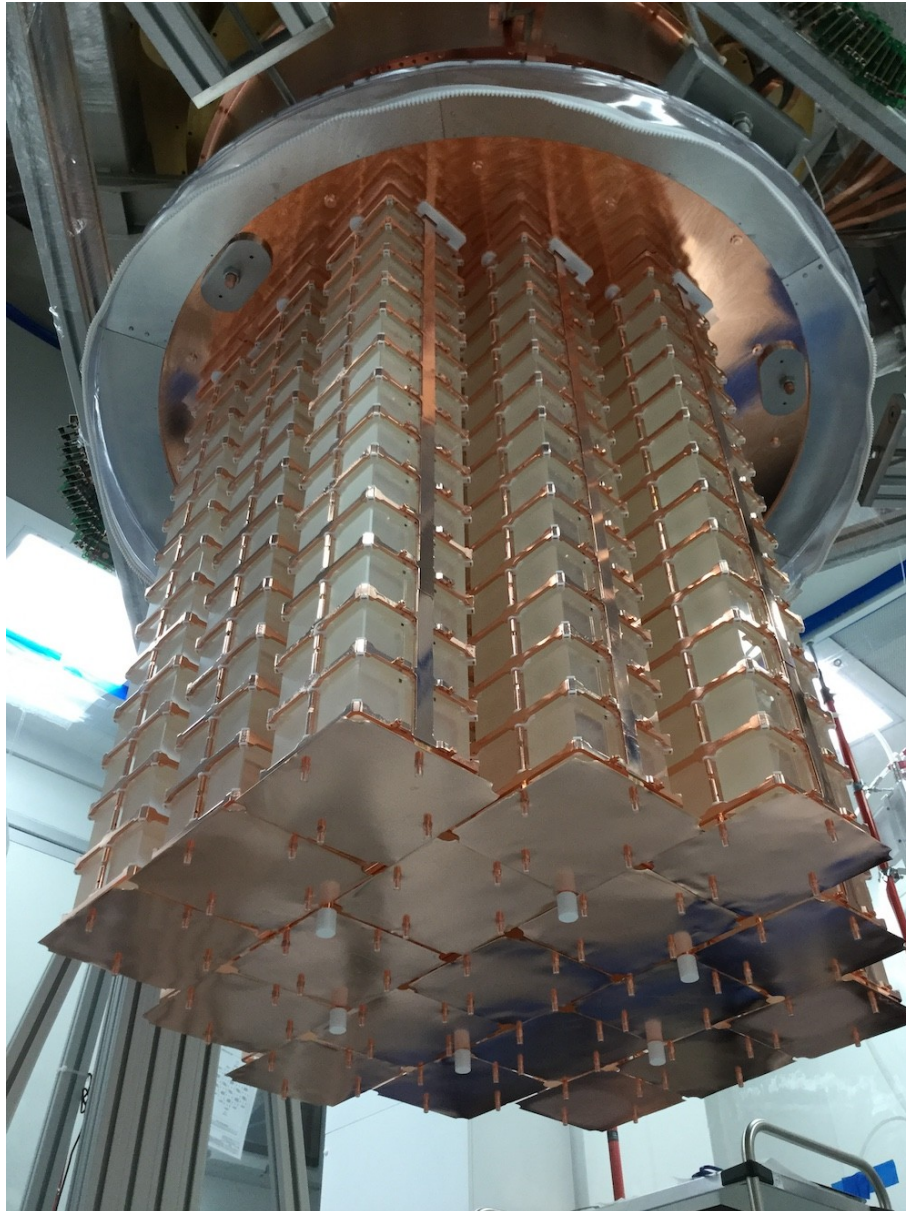
**example: 750 g of  $\text{TeO}_2$  @ 10 mK**

$C \sim T^3$  (Debye)  $\Rightarrow C \sim 2 \times 10^{-9}$  J/K

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

$\Rightarrow \Delta U \sim 10$  eV

# Cuore

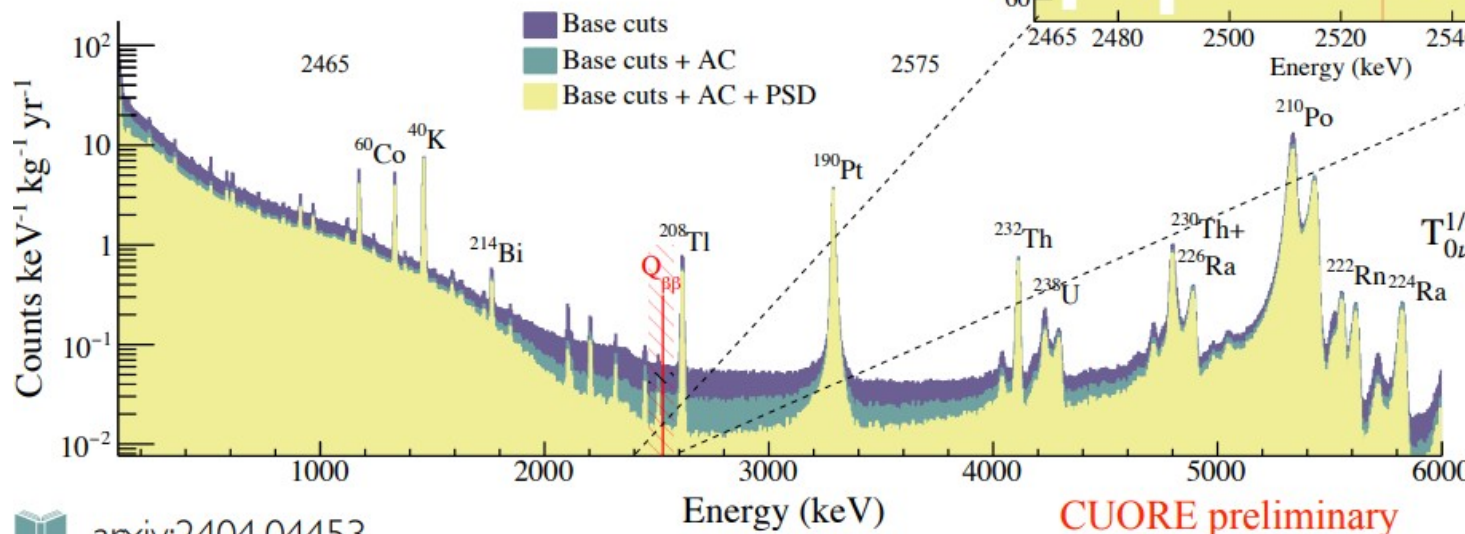
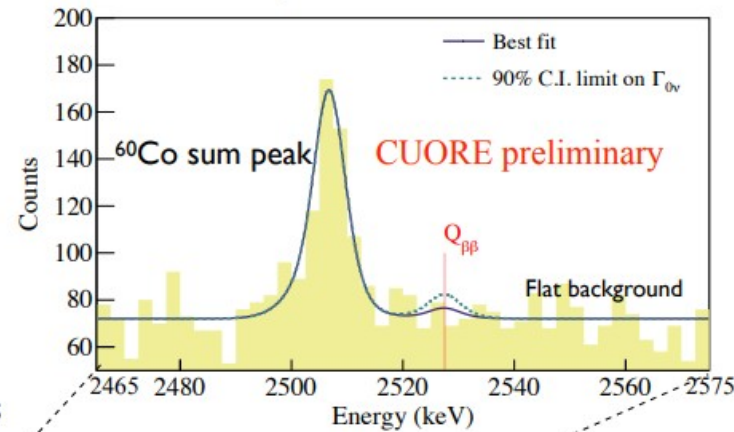


- ▶ 19 towers of 52 5x5x5 cm<sup>3</sup> TeO<sub>2</sub> crystals
- ▶ Total mass of 742 kg of TeO<sub>2</sub>
- ▶ 0.5 kg of  $0\nu\beta\beta$  isotope <sup>120</sup>Te
- ▶ Crystals held at 10 mK

Energy	2.527 eV
Isotope	<sup>130</sup> Te
Type	Bolometer
Operations	2020-2024
Physics	$m_{\beta\beta}$

# Cuore Results

- Total analysis cut efficiency **93.4(18) %**
- Unbinned Bayesian fit with  $\Gamma_{0\nu\beta\beta} > 0$
- No evidence of  $0\nu\beta\beta$  and new limit on  $^{130}\text{Te}$  half-life  $T_{0\nu\beta\beta}^{1/2} > 3.8 \cdot 10^{25}$  yr (90% C.I.)



- Frequentist fit
- $T_{0\nu\beta\beta}^{1/2} > 3.7 \cdot 10^{25}$  yr (90% C.L.)

Average background index  
 $b = (1.42 \pm 0.02) \cdot 10^{-2}$   
 (counts/keV/kg/yr)

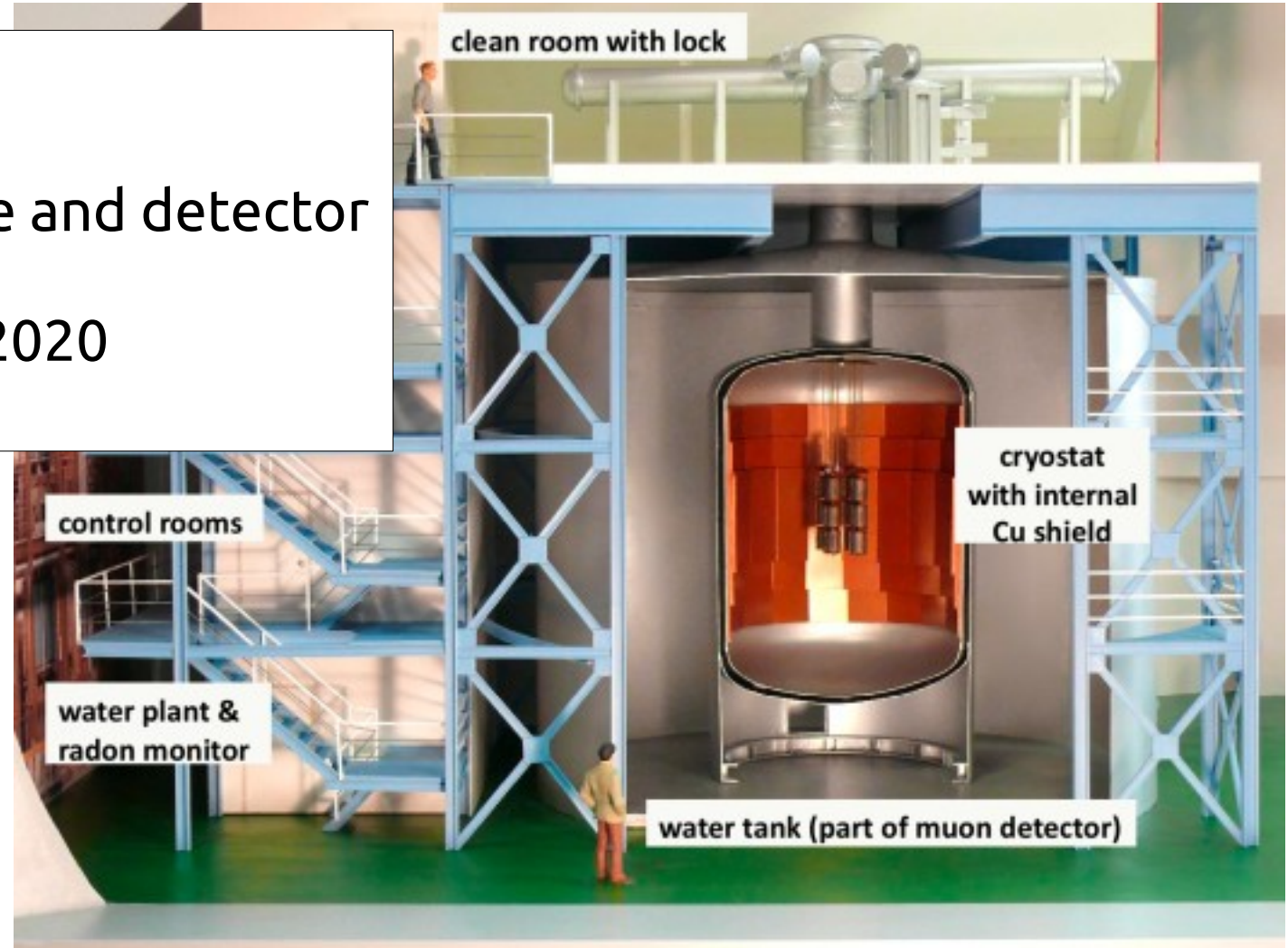
# CUPID



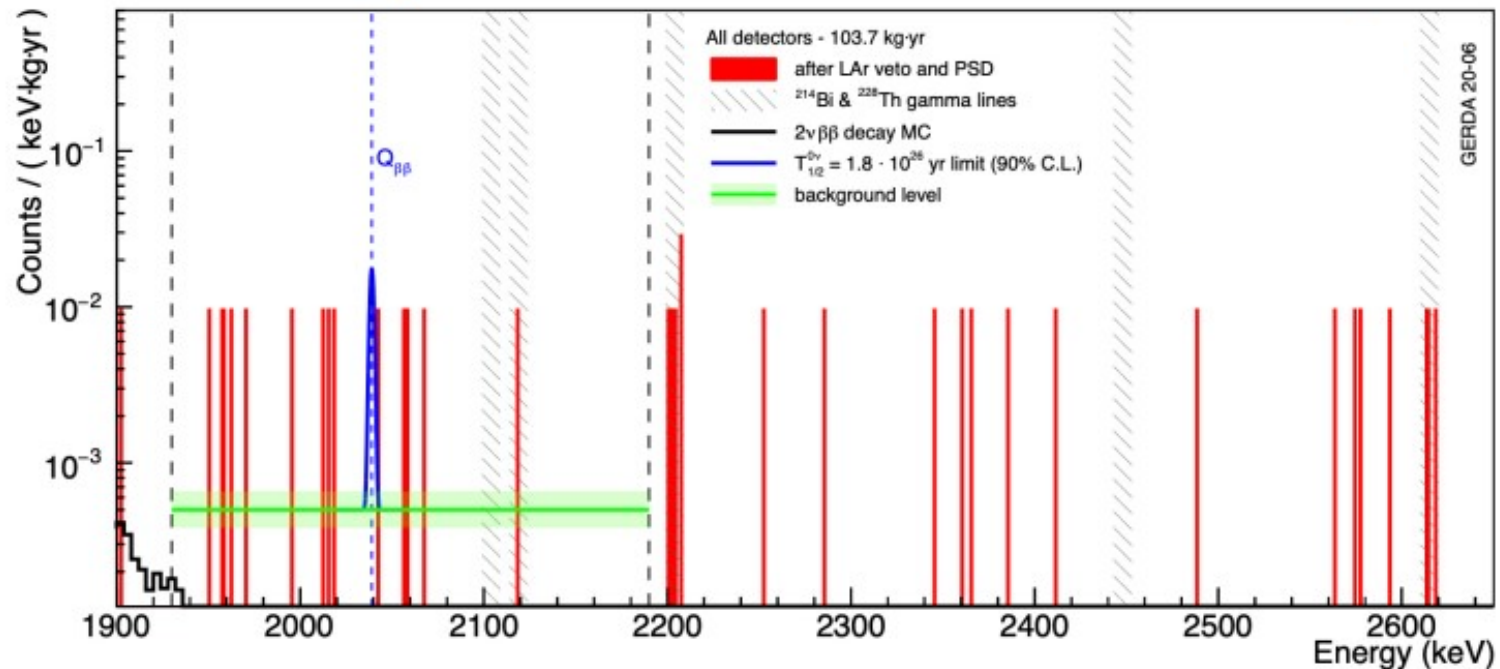
- CUPID to overcome CUORE limitations and continue the  $0\nu\beta\beta$  decay search with cryogenic calorimeters - solid bases from CUORE, CUPID-0, CUPID-Mo
- Isotope:  $^{130}\text{Te}$ ,  $^{\text{nat}}\text{Te}$  (i.a.  $\sim 34\%$ )  $\rightarrow$   $^{100}\text{Mo}$ , enrichment necessary (95%)  
 $Q_{\beta\beta} \sim 2528 \text{ keV} \rightarrow \sim 3034 \text{ keV}$  (larger phase space, lower bkg)  
Absorber:  $\text{TeO}_2 \rightarrow \text{Li}_2\text{MoO}_4$   
Mass: 742 kg (206 kg)  $\text{TeO}_2$  ( $^{130}\text{Te}$ )  $\rightarrow$  450 kg (240 kg)  $\text{Li}_2\text{MoO}_4$  ( $^{100}\text{Mo}$ )  
 988 crystals (19 towers)  $\rightarrow$  1596 crystals (57 towers)
- Single channel (heat) readout  $\rightarrow$  double (light & heat) readout for PID  
 Top & Bottom Ge light detectors with Neganov-Luke amplification
- Same cryostat with an additional muon veto to achieve a background level of  $10^{-4}$  counts/keV/kg/yr and a factor  $\sim 5$  improvement in the sensitivity

# GERDA

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



# Final results from GERDAII



Frequentist analysis\*:

- ✓ Median sensitivity for limit setting:  
 $1.8 \times 10^{26}$  yr (90% CL)
- ✓ Best fit → no signal  
 $T_{1/2}^{0\nu} > 1.8 \times 10^{26}$  yr (90% CL)

Bayesian analysis\*:

- ✓ Median sensitivity for limit setting:  
 $1.4 \times 10^{26}$  yr (90% CI)
- $T_{1/2}^{0\nu} > 1.4 \times 10^{26}$  yr (90% CI)

# LEGEND 200 - 1000

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

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

## LEGEND-200

- 200 kg target mass
- background  $\sim 10^{-4}$  cts/keV/kg/yr
- just started data taking!

projected sensitivity in 5 years:

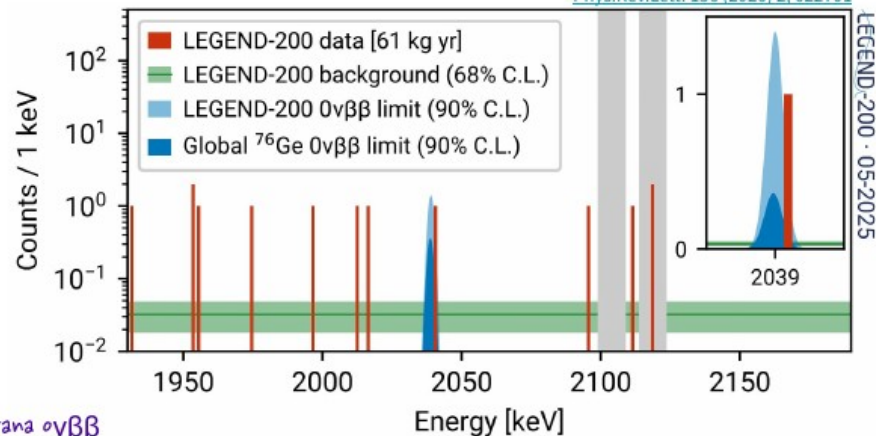
$$T_{1/2} > 10^{27} \text{ yr}, m_{\text{bb}} < 27\text{-}63 \text{ meV}$$

$$m < 75\text{--}200 \text{ meV}$$



## LEGEND-1000

- 1000 kg of target mass
  - background  $\sim 10^{-5}$  cts/keV/kg/yr
  - recently ranked as highest priority experiment by DOE
  - discovery machine for all IO parameter space
  - Reaches into NO parameter space
  - Construction starts 2026/7
- $$m_{\beta\beta} < 9\text{--}21 \text{ meV}$$

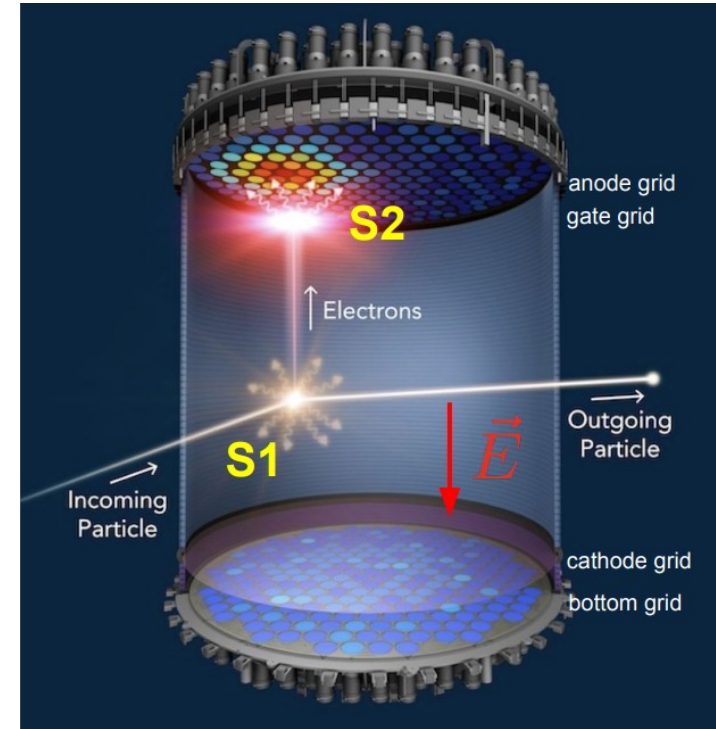
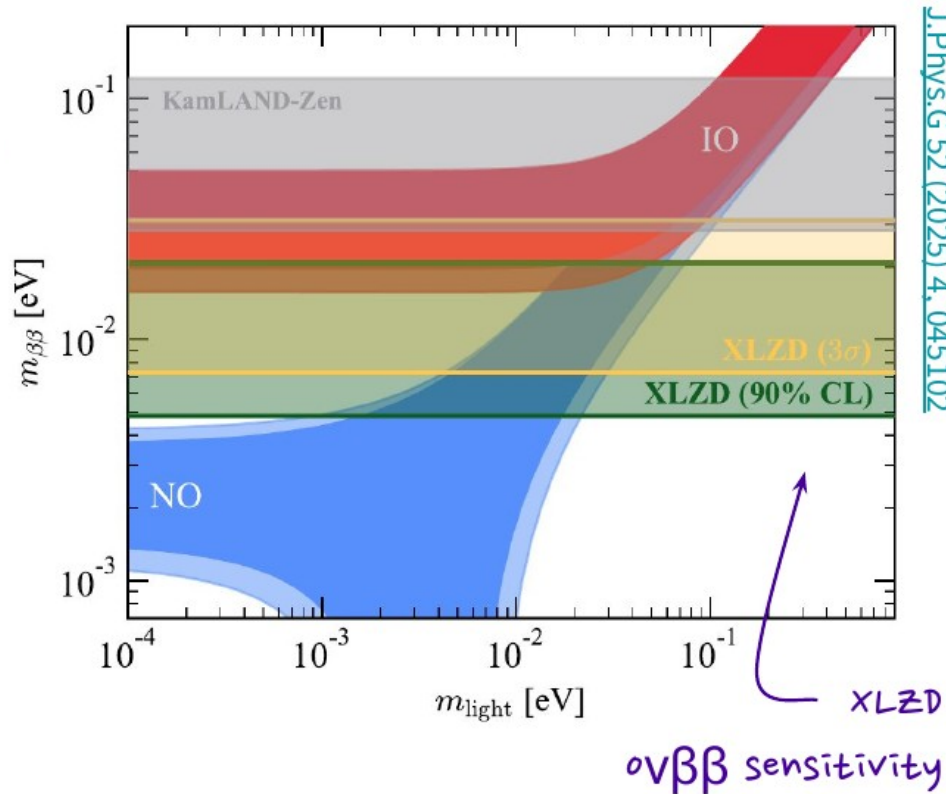


Energy	2.038 eV
Isotope	$^{76}\text{Ge}$
Type	Ge semiconductor
Operations	2022-
Physics	$0\nu\beta\beta/2\nu\beta\beta, m_{\beta\beta}$

# Noble gas/liquid TPCs

LZ/XLZD – liquid  $^{136}\text{Xe}$  fill

- ▶ Primarily dark matter exps
- ▶ High resolution 3D TPC



Energy	2.458 eV
Isotope	$^{136}\text{Xe}$
Type	Dual-phase TPC
Operations	2021-2028
Physics	$m_{\beta\beta}$ , solar

# Future Program

Experiment	Isotope	Mass	Technique	Present Status	Location
CANDLES-III [124]	$^{48}\text{Ca}$	305 kg	$^{nat}\text{CaF}_2$ scint. crystals	Operating	Kamioka
CDEX-1 [125]	$^{76}\text{Ge}$	1 kg	$^{enr}\text{Ge}$ semicond. det.	Prototype	CJPL
CDEX-300 $\nu$ [125]	$^{76}\text{Ge}$	225 kg	$^{enr}\text{Ge}$ semicond. det.	Construction	CJPL
LEGEND-200 [16]	$^{76}\text{Ge}$	200 kg	$^{enr}\text{Ge}$ semicond. det.	Commissioning	LNGS
LEGEND-1000 [16]	$^{76}\text{Ge}$	1 ton	$^{enr}\text{Ge}$ semicond. det.	Proposal	
CUPID-0 [19]	$^{82}\text{Se}$	10 kg	$\text{Zn}^{enr}\text{Se}$ scint. bolometers	Prototype	LNGS
SuperNEMO-Dem [126]	$^{82}\text{Se}$	7 kg	$^{enr}\text{Se}$ foils/tracking	Operation	Modane
SuperNEMO [126]	$^{82}\text{Se}$	100 kg	$^{enr}\text{Se}$ foils/tracking	Proposal	Modane
Selena [127]	$^{82}\text{Se}$		$^{enr}\text{Se}$ , CMOS	Development	
IFC [128]	$^{82}\text{Se}$		ion drift $\text{SeF}_6$ TPC	Development	
CUPID-Mo [17]	$^{100}\text{Mo}$	4 kg	$\text{Li}^{enr}\text{MoO}_4$ , scint. bolom.	Prototype	LNGS
AMoRE-I [129]	$^{100}\text{Mo}$	6 kg	$^{40}\text{Ca}^{100}\text{MoO}_4$ bolometers	Operation	Yang Yang
AMoRE-II [129]	$^{100}\text{Mo}$	200 kg	$^{40}\text{Ca}^{100}\text{MoO}_4$ bolometers	Construction	Yemilab
CROSS [130]	$^{100}\text{Mo}$	5 kg	$\text{Li}_2^{100}\text{MoO}_4$ , surf. coat bolom.	Prototype	Canfranc
BINGO [131]	$^{100}\text{Mo}$		$\text{Li}^{enr}\text{MoO}_4$	Development	LNGS
CUPID [28]	$^{100}\text{Mo}$	450 kg	$\text{Li}^{enr}\text{MoO}_4$ , scint. bolom.	Proposal	LNGS
China-Europe [132]	$^{116}\text{Cd}$		$^{enr}\text{CdWO}_4$ scint. crystals	Development	CJPL
COBRA-XDEM [133]	$^{116}\text{Cd}$	0.32 kg	$^{nat}\text{Cd}$ CZT semicond. det.	Operation	LNGS
Nano-Tracking [134]	$^{116}\text{Cd}$		$^{nat}\text{CdTe}$ , det.	Development	
TIN.TIN [135]	$^{124}\text{Sn}$		Tin bolometers	Development	INO
CUORE [10]	$^{130}\text{Te}$	1 ton	$\text{TeO}_2$ bolometers	Operating	LNGS
SNO+ [136]	$^{130}\text{Te}$	3.9 t	0.5-3% $^{nat}\text{Te}$ loaded liq. scint.	Commissioning	SNOLab
nEXO [29]	$^{136}\text{Xe}$	5 t	Liq. $^{enr}\text{Xe}$ TPC/scint.	Proposal	
NEXT-100 [137]	$^{136}\text{Xe}$	100 kg	gas TPC	Construction	Canfranc
NEXT-HD [137]	$^{136}\text{Xe}$	1 ton	gas TPC	Proposal	Canfranc
AXEL [138]	$^{136}\text{Xe}$		gas TPC	Prototype	
KamLAND-Zen-800 [13]	$^{136}\text{Xe}$	745 kg	$^{enr}\text{Xe}$ dissolved in liq. scint.	Operating	Kamioka
KamLAND2-Zen [41]	$^{136}\text{Xe}$		$^{enr}\text{Xe}$ dissolved in liq. scint.	Development	Kamioka
LZ [139]	$^{136}\text{Xe}$	600 kg	Dual phase Xe TPC, nat./enr. Xe	Operation	SURF
PandaX-4T [119]	$^{136}\text{Xe}$	3.7 ton	Dual phase nat. Xe TPC	Operation	CJPL
XENONnT [140]	$^{136}\text{Xe}$	5.9 ton	Dual phase Xe TPC	Operating	LNGS
DARWIN [141]	$^{136}\text{Xe}$	50 ton	Dual phase Xe TPC	Proposal	LNGS
R2D2 [142]	$^{136}\text{Xe}$		Spherical Xe TPC	Development	
LAr TPC [143]	$^{136}\text{Xe}$	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	

(as of 2022)

arXiv:2212.11099

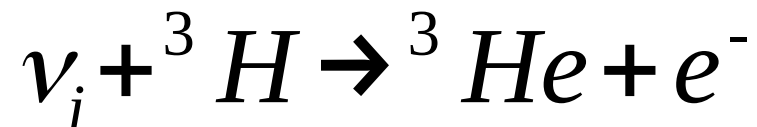
# Direct mass measurements

• Tritium $\beta$ decay	$\left( \sum_i  U_{ei} ^2 m_i^2 \right)^{\frac{1}{2}}$	$< 0.4 \text{ eV}$ CRES $< 0.04 \text{ eV?}$
• $0\nu 2\beta$ decay	$\left  \sum_i U_{ei}^2 m_i \right $	$< 0.18 \text{ eV}$
• Cosmology	$\sum_i m_i < 0.3 \text{ eV}$	Model dependent
• Pion decay	$m_{\nu\mu} < 190 \text{ keV}$	Fairly pointless
• Tau decay	$m_{\nu\tau} < 18.2 \text{ MeV}$	Entirely pointless

# Question

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

Hint : Consider neutrino capture on Tritium

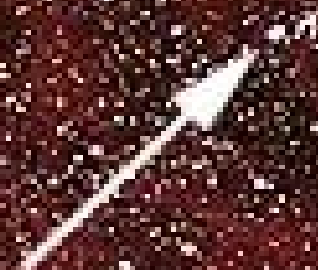


The amplitude is

$$Amp \sim 1 - 2h \sqrt{E^2 - m^2}$$

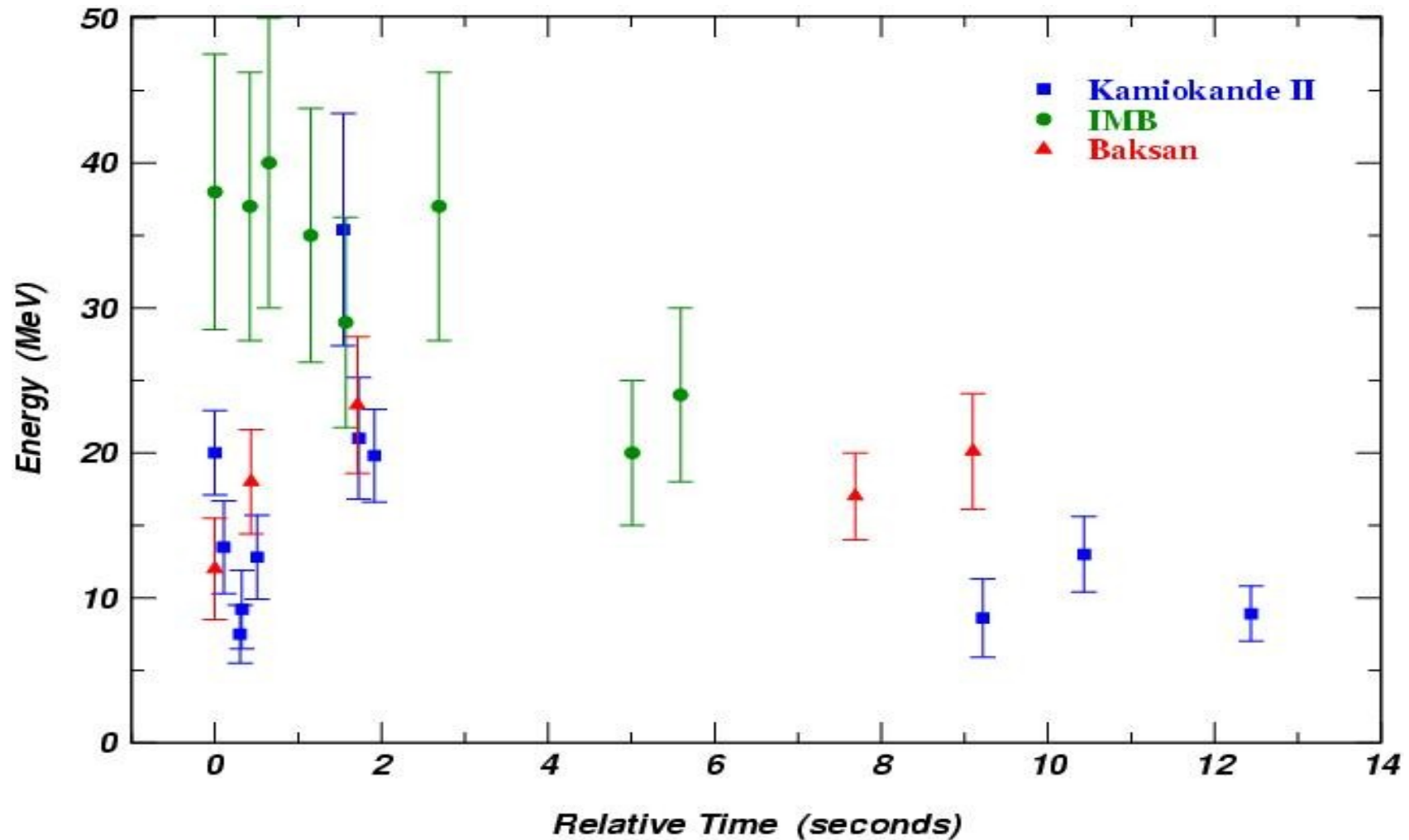
where  $h$  is the helicity of the neutrino state

SN1987A



# 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)

$$m_{\nu_e} < 5.7 \text{ eV} (95 \text{ CL})$$

# 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

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

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

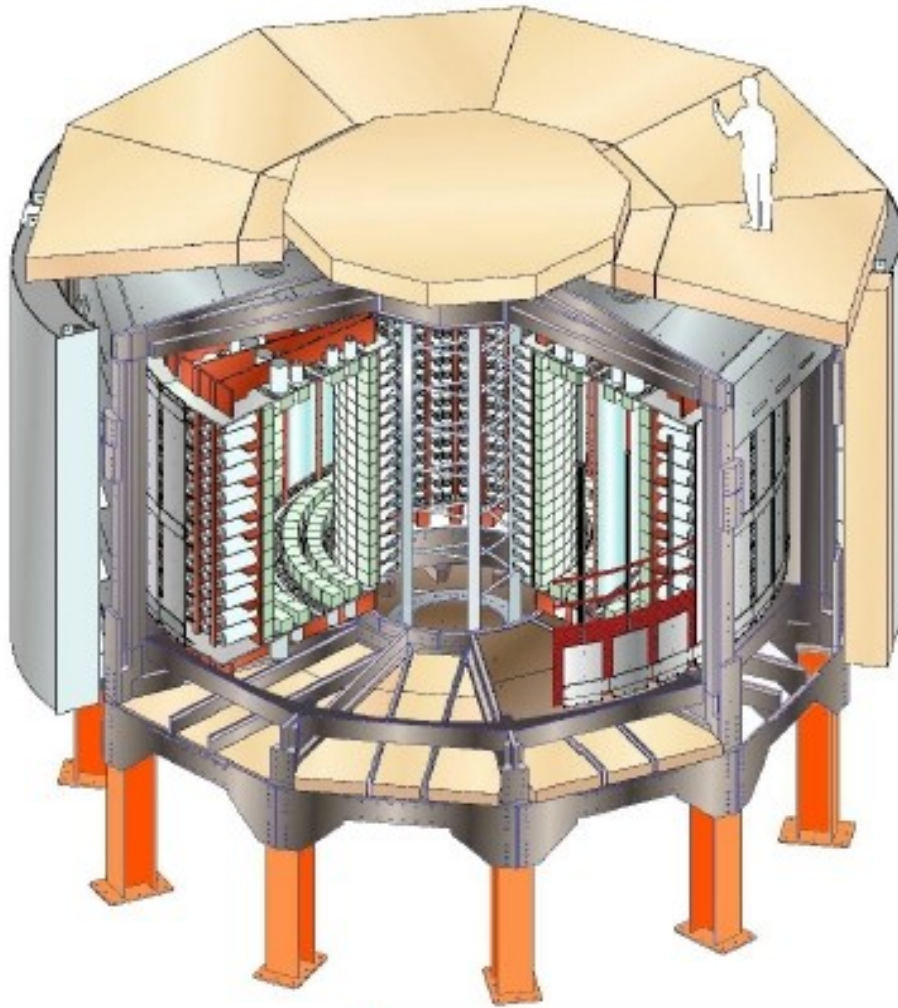
Observable masses are the eigenvalues of the diagonalised mass matrix ( $m_1, m_2$ )

$$\tilde{M} = Z^{-1} M Z = \begin{pmatrix} \tilde{m}_1 & 0 \\ 0 & \tilde{m}_2 \end{pmatrix}$$

$$\tilde{m}_{1,2} = \frac{1}{2} \left[ (m_L + m_R) \pm \sqrt{(m_L - m_R)^2 + 4 m_D^2} \right]$$

Mixing matrix

# Passive Source - NEMO3



Source: 10 kg of  $\beta\beta$  isotopes  
cylindrical,  $S = 20 \text{ m}^2$ ,  $60 \text{ mg/cm}^2$

Tracking detector:

drift wire chamber operating  
in Geiger mode (6180 cells)

Gas: He + 4% ethyl alcohol + 1% Ar + 0.1% H<sub>2</sub>O

Calorimeter:

1940 plastic scintillators  
coupled to low radioactivity PMTs

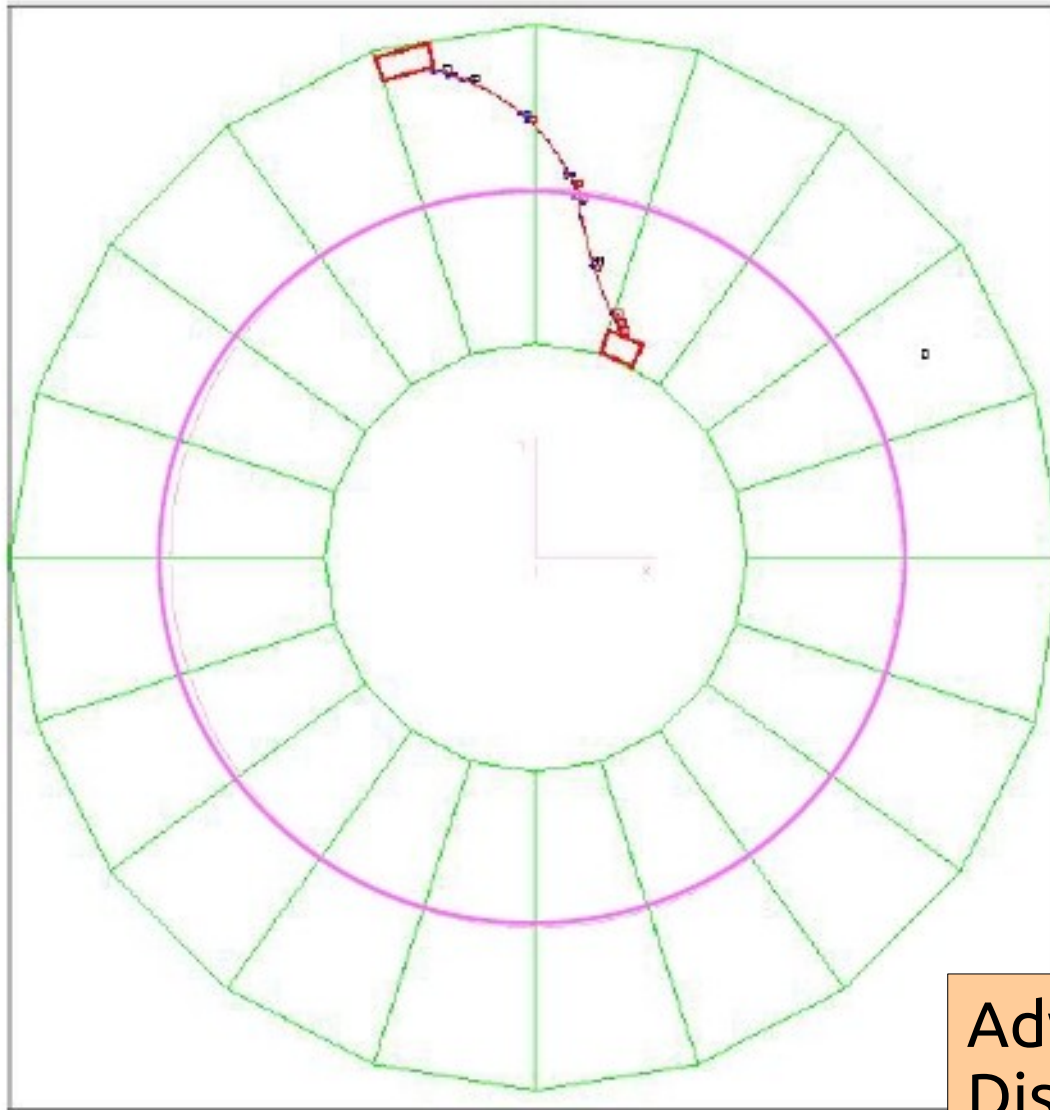
Magnetic field: 25 Gauss

Gamma shield: Pure Iron (18 cm)

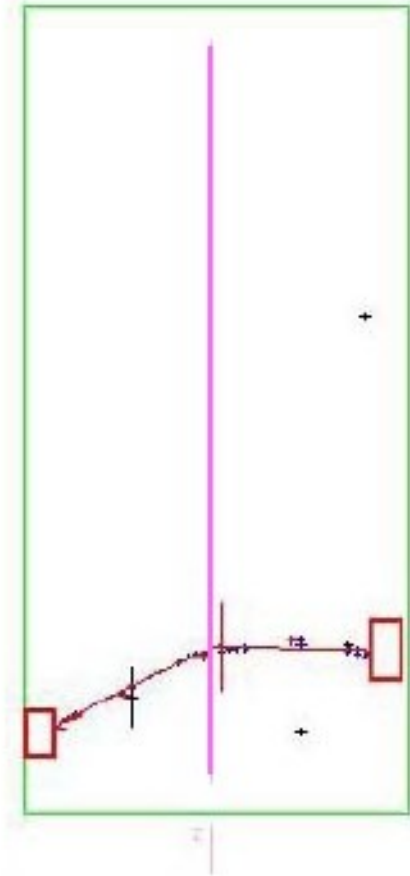
Neutron shield: borated water  
+ Wood

Background:  $n$  ( $^{214}\text{Pb}$  at  $208\text{Tl}$   $\gamma$  2.6 MeV)  
Able to identify  $e^-$ ,  $e^+$ ,  $\gamma$  and  $\alpha$

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



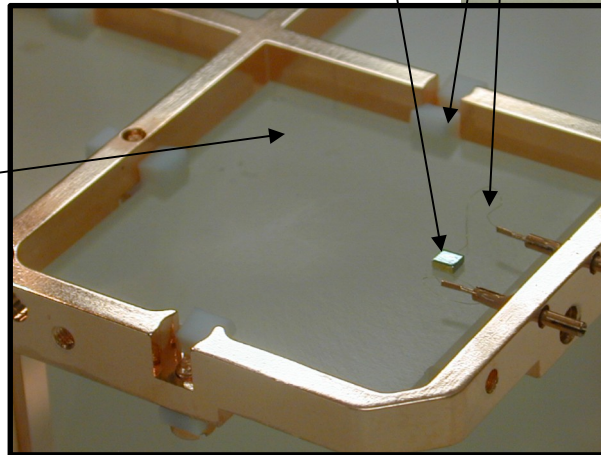
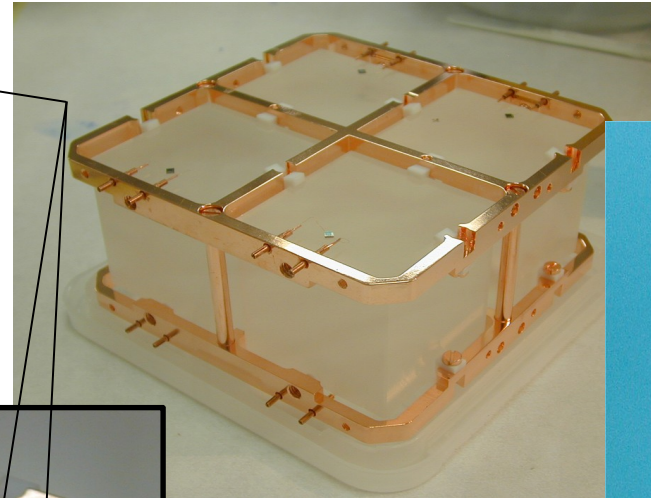
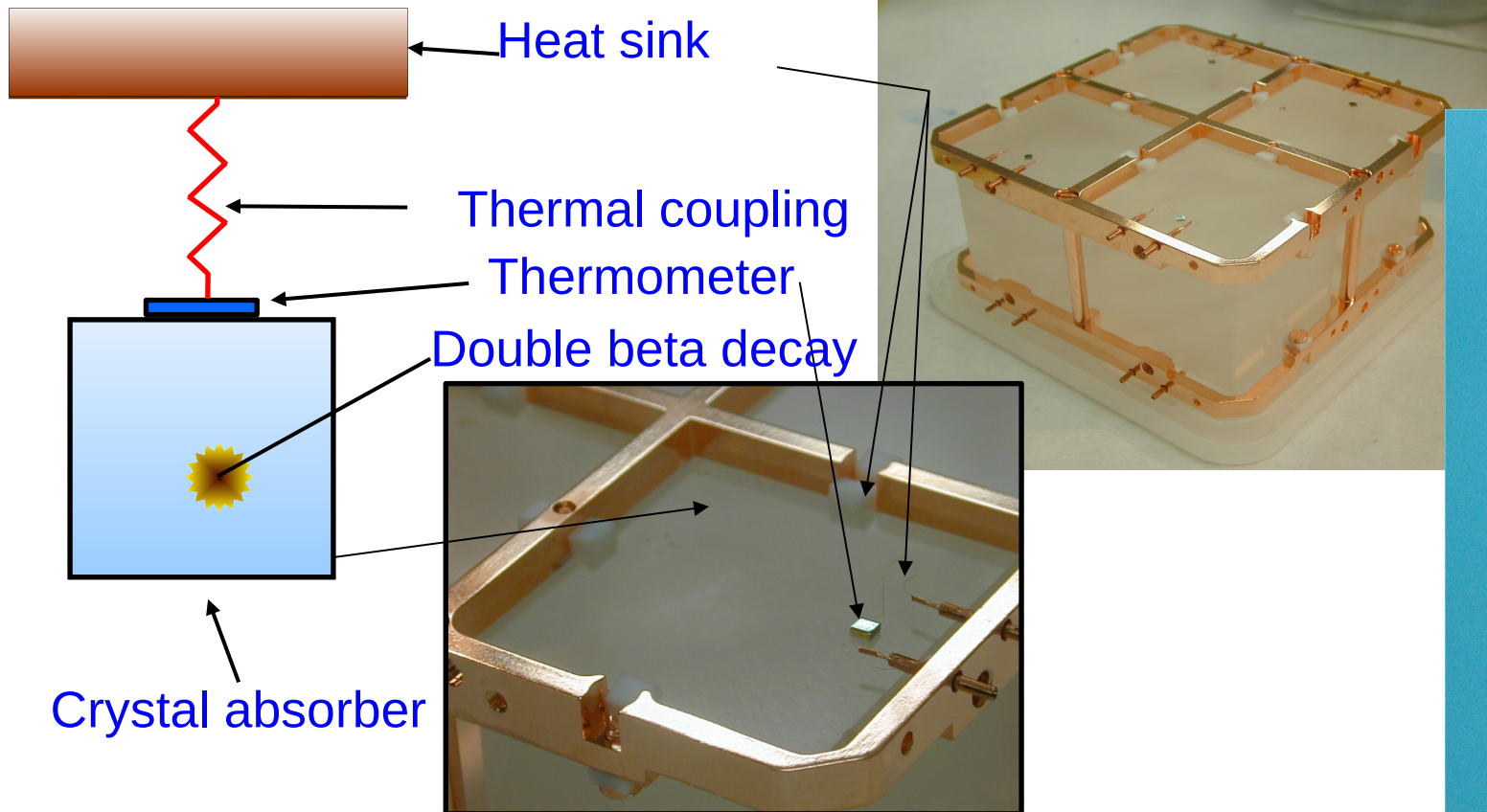
Top view



Side view

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

# Cuoricino/Cuore



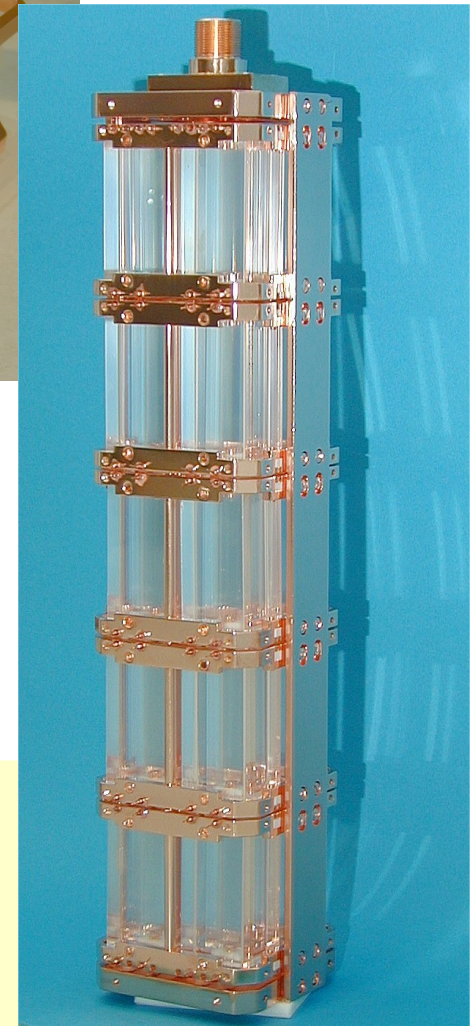
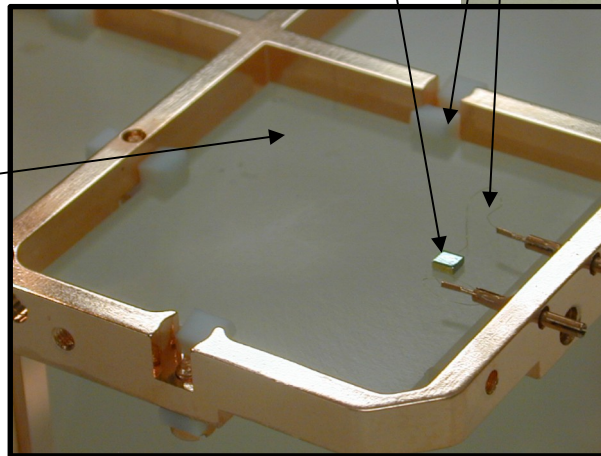
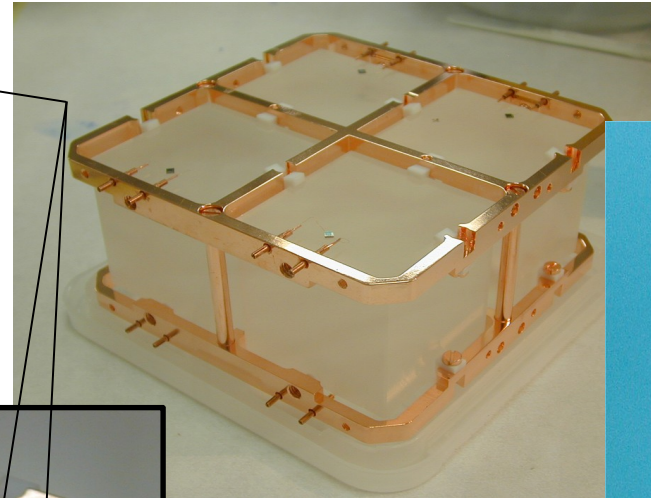
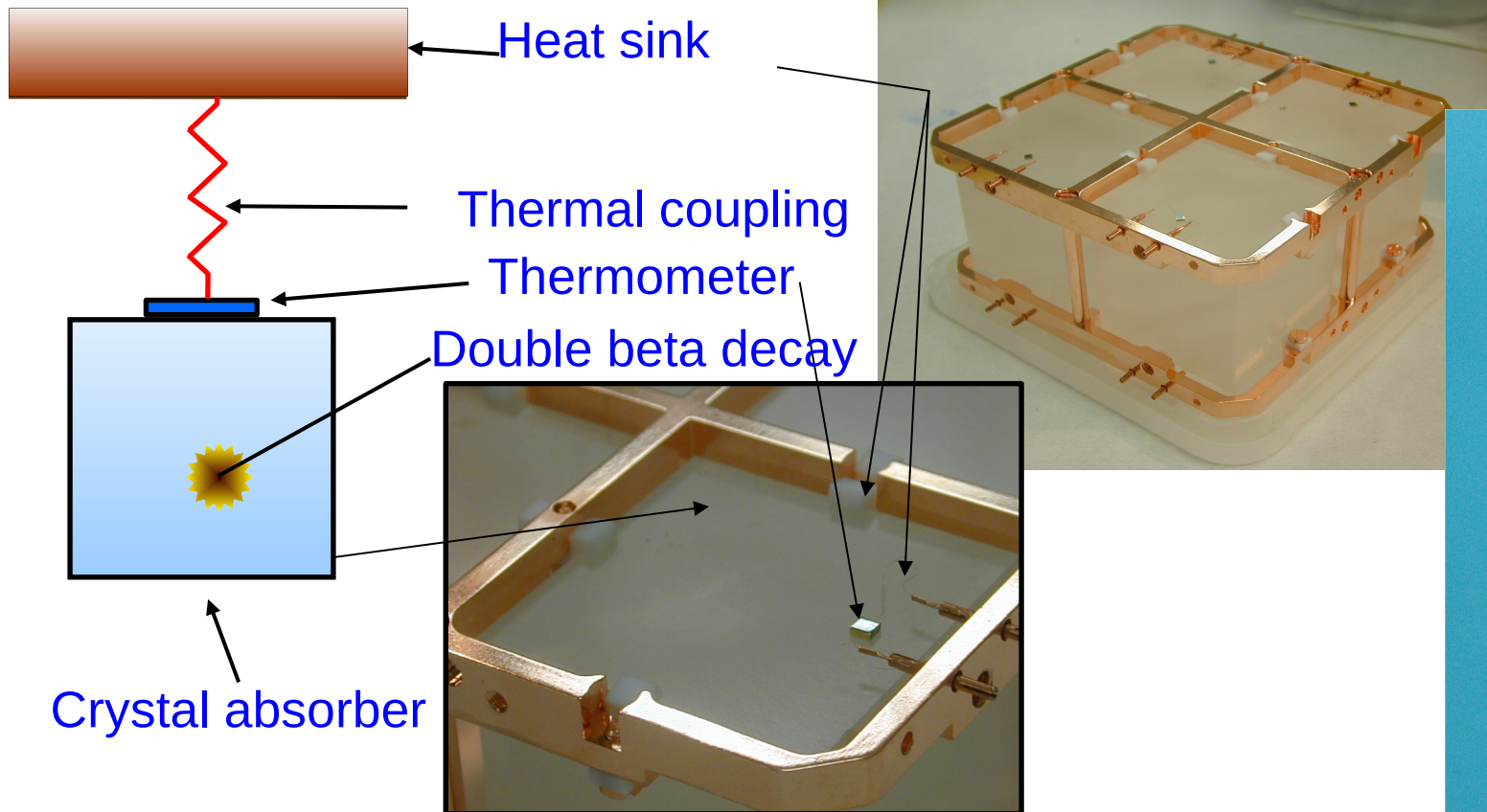
**example: 750 g of  $\text{TeO}_2$  @ 10 mK**

$C \sim T^3$  (Debye)  $\Rightarrow C \sim 2 \times 10^{-9}$  J/K

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

$\Rightarrow \Delta U \sim 10$  eV

# Cuoricino/Cuore



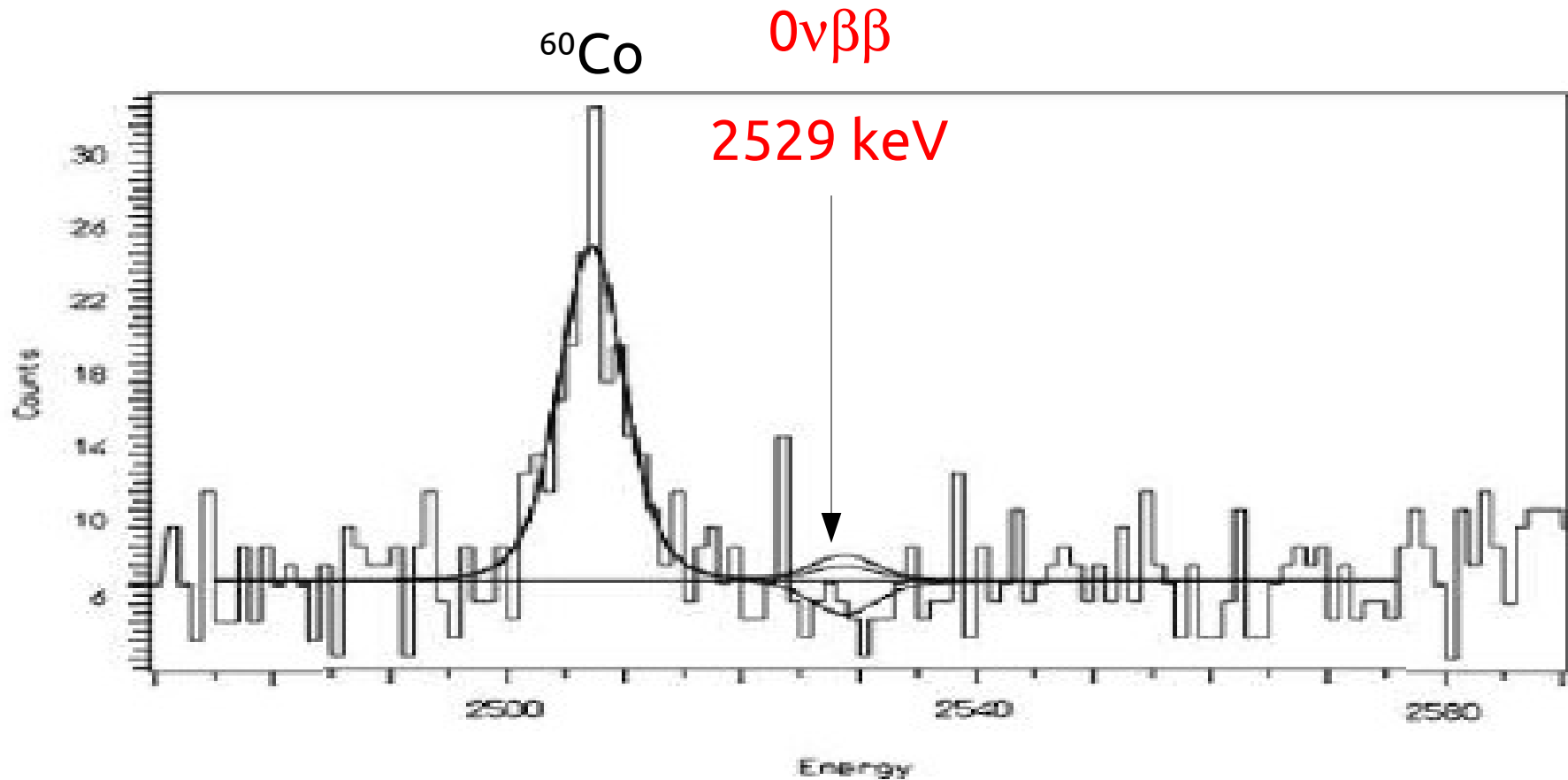
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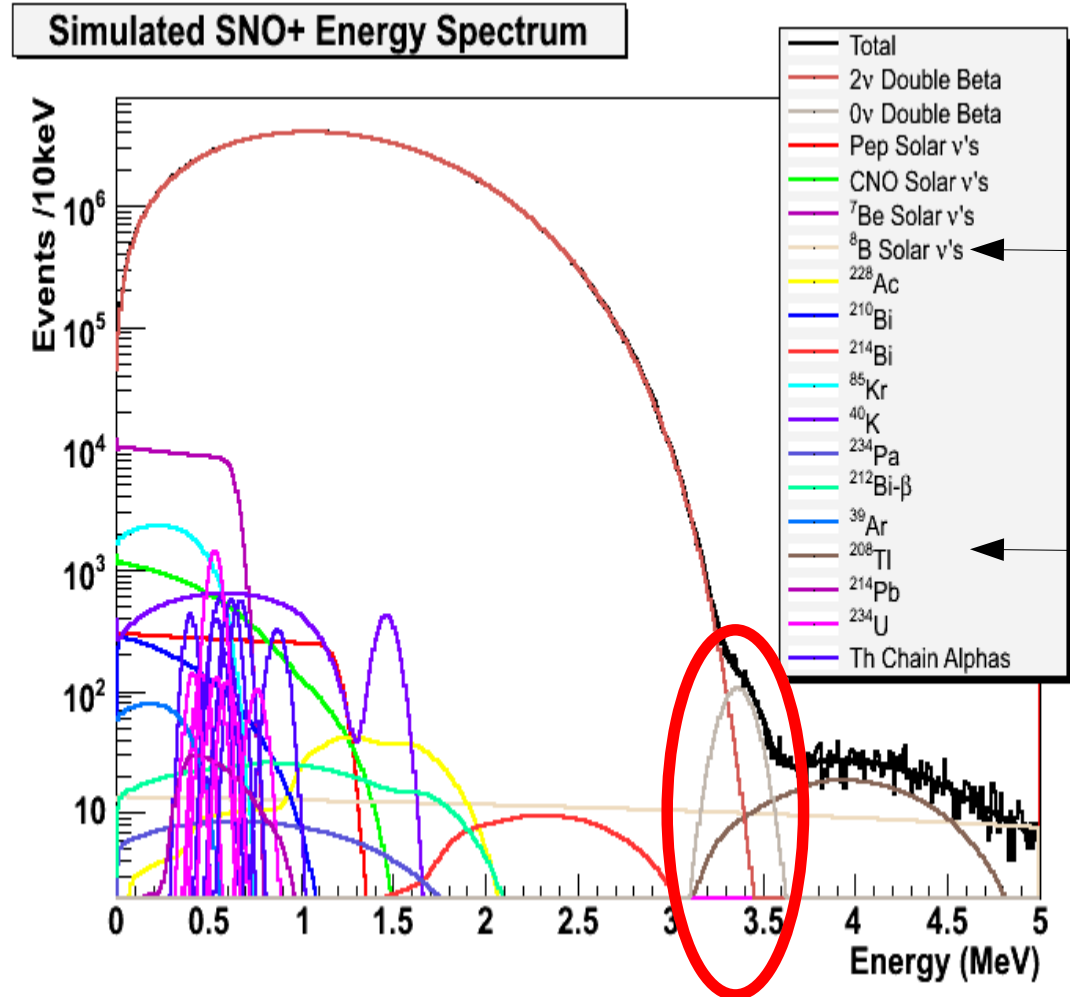
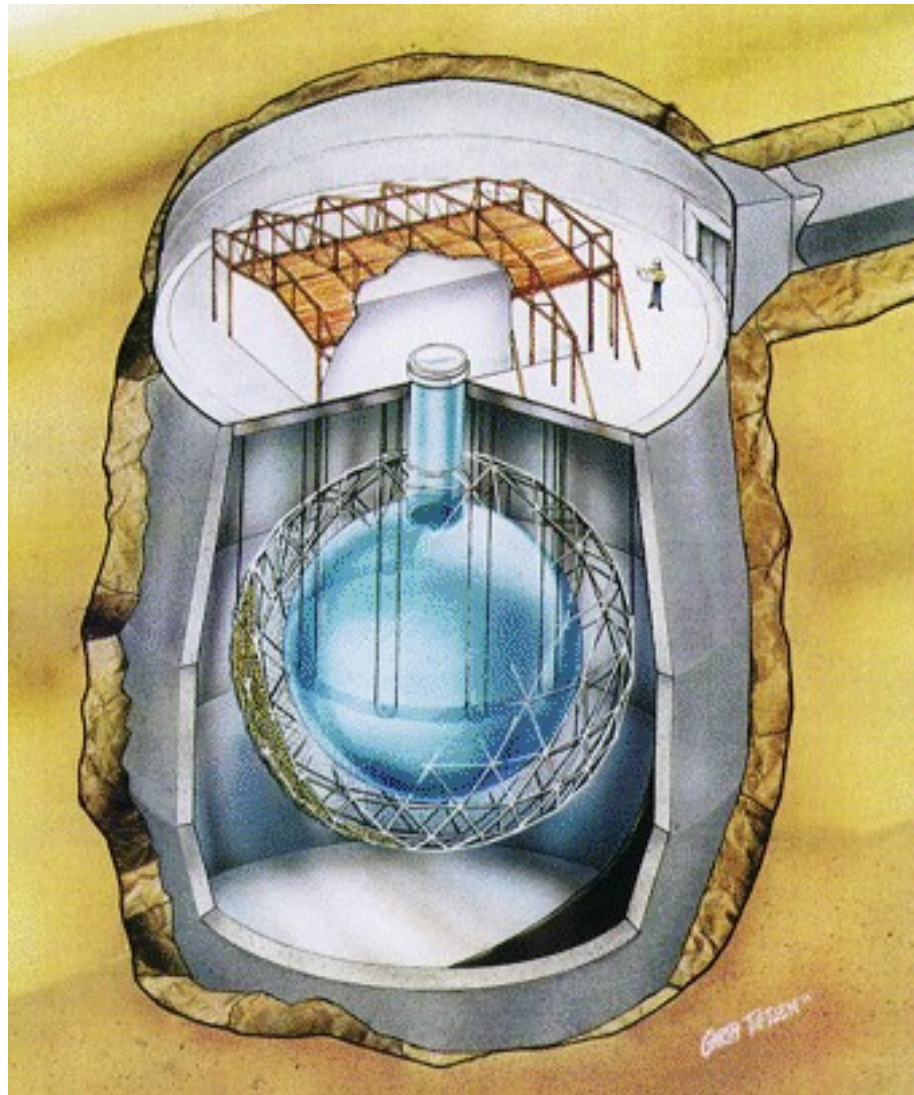
$\Rightarrow \Delta U \sim 10$  eV

# Cuoricino Results



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

# SNO+



<sup>150</sup>Nd loaded -  $m_\nu < 80$  meV

# 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

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

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

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

$$\tilde{M} = Z^{-1} M Z = \begin{pmatrix} \tilde{m}_1 & 0 \\ 0 & \tilde{m}_2 \end{pmatrix}$$

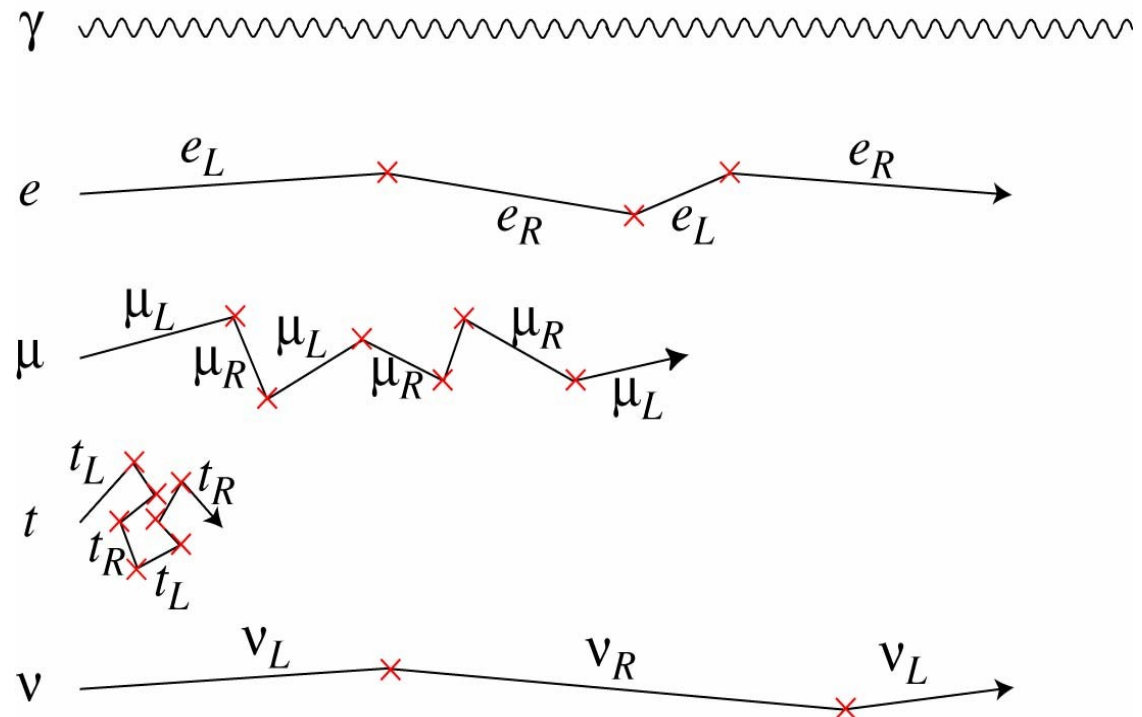
Mixing matrix

$$\tilde{m}_{1,2} = \frac{1}{2} \left[ (m_L + m_R) \pm \sqrt{(m_L - m_R)^2 + 4 m_D^2} \right]$$

# Two ways to go

## Dirac neutrinos

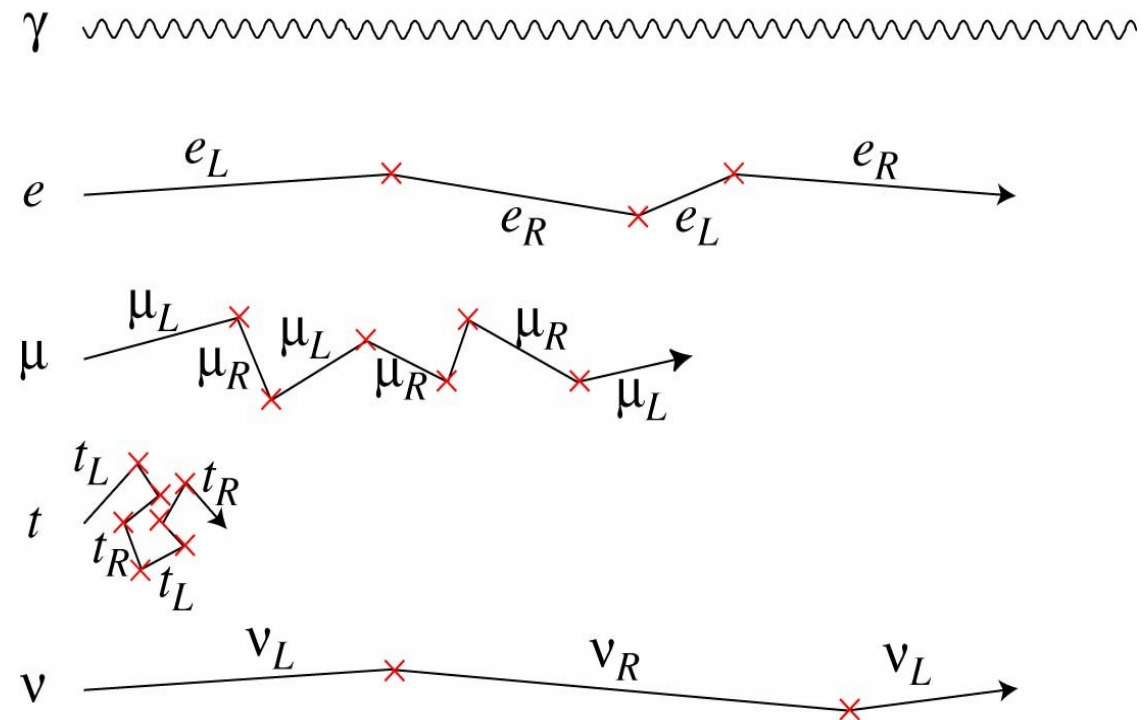
- There are new particles (right handed neutrinos) after all
- Why haven't we seen them?
- They must only exist to give neutrinos mass
- Still have to solve the question of their very very weak coupling



# Two ways to go

## Majorana neutrinos

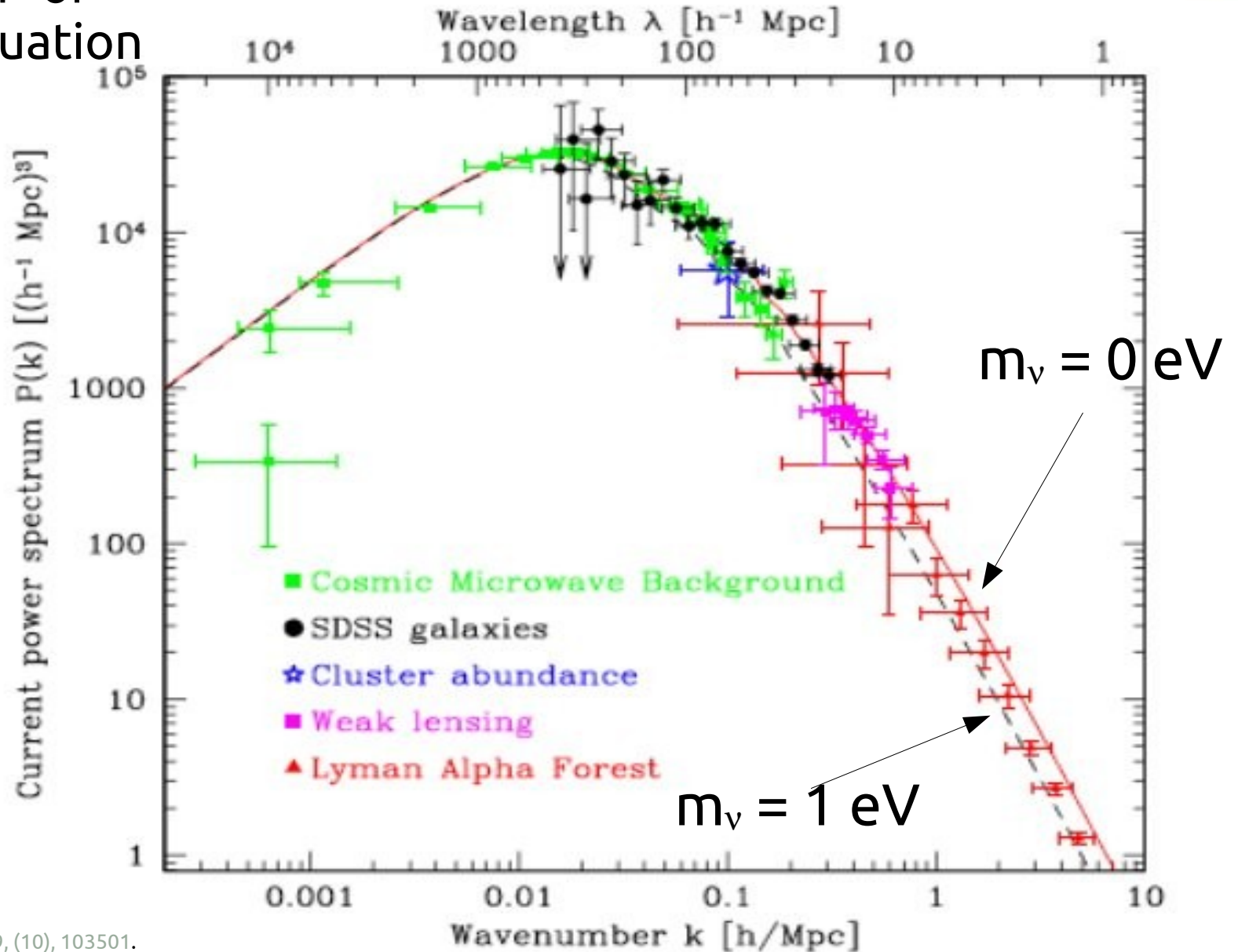
- There are new particles (right handed neutrinos) after all
- If I pass a neutrino and look back I will see a right-handed thing
- Must be a right-handed anti-neutrino
- No fundamental difference between neutrinos and anti-neutrinos



(Theorists Favourite!)

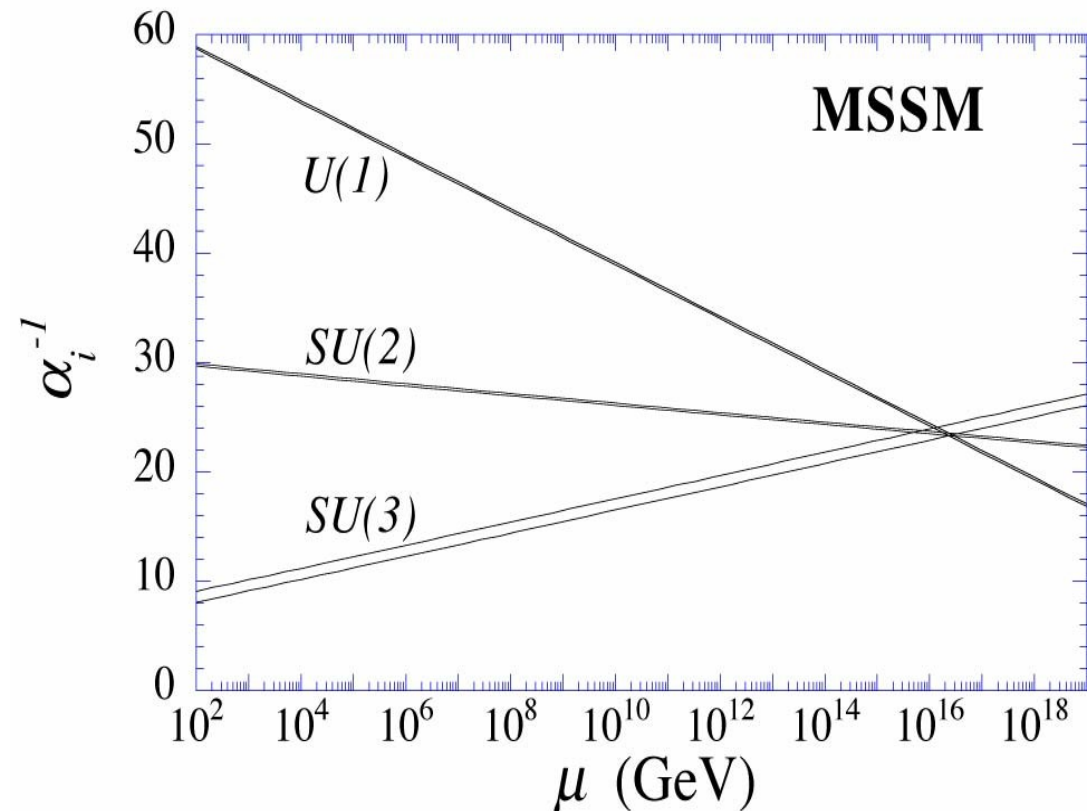
# Power spectra

“Wavelength” of  
density fluctuation



# 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- $\beta$ decay

ITEP

$T_2$  in complex molecule  
magn. spectrometer (Tret'yakov)

$m_\nu$

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

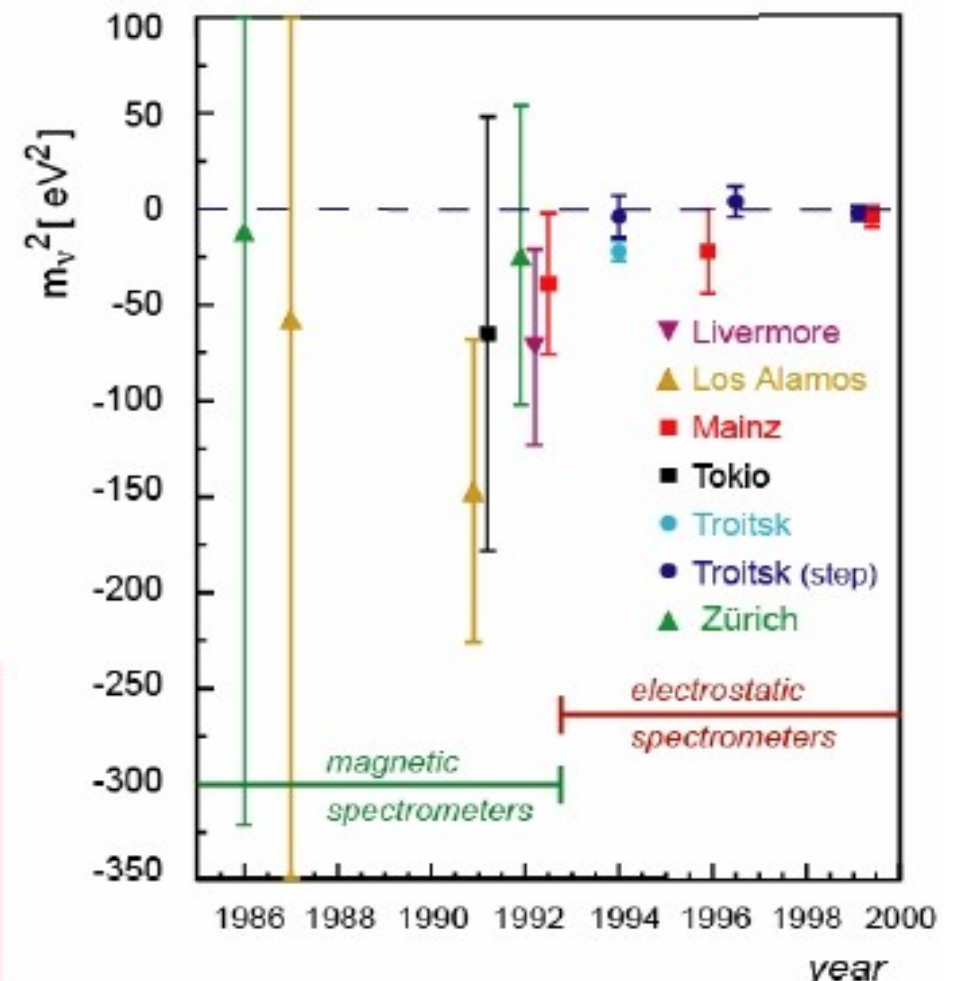
< 2.05 eV

Mainz (1994-today)

frozen  $T_2$  - source  
electrostat. spectrometer

< 2.3 eV

experimental results



# 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

$$L_{mass} = m \bar{\nu}_m \nu_m + M \bar{N}_m N_m = \begin{pmatrix} \bar{\nu}_m & \bar{N}_m \end{pmatrix} \begin{pmatrix} m & 0 \\ 0 & M \end{pmatrix} \begin{pmatrix} \nu_m \\ N_m \end{pmatrix} \quad \begin{array}{l} \text{Written in the mass basis} \\ \text{States of definite mass} \end{array}$$

Can write the mass eigenstates in terms of the Majorana fields

**Mass Eigenstates  
(Physical particles)**

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

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

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

**Majorana field**

$$L_{mass} = \frac{1}{2} \begin{pmatrix} \bar{\nu}_L^C & \bar{N}_R \end{pmatrix} \underbrace{\begin{pmatrix} c & -s \\ s & c \end{pmatrix}^{-1} \begin{pmatrix} m & 0 \\ 0 & M \end{pmatrix} \begin{pmatrix} c & -s \\ s & c \end{pmatrix}}_{\text{off-diagonal mass matrix}} \begin{pmatrix} \nu_L \\ N_R^C \end{pmatrix} \quad \begin{array}{l} \text{Written in the} \\ \text{Chiral basis} \end{array}$$

off-diagonal mass matrix

# Katrin on the move

