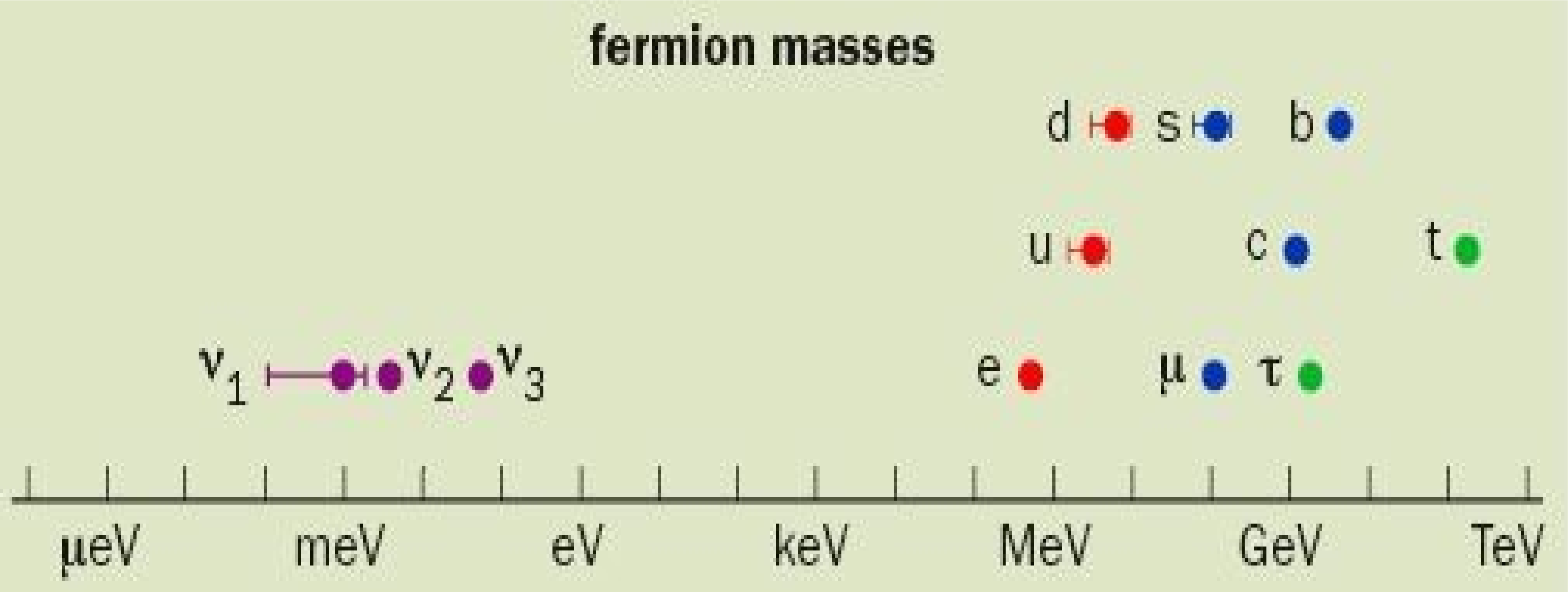
Lecture 2

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

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

Can rewrite mass term in terms of chiral states

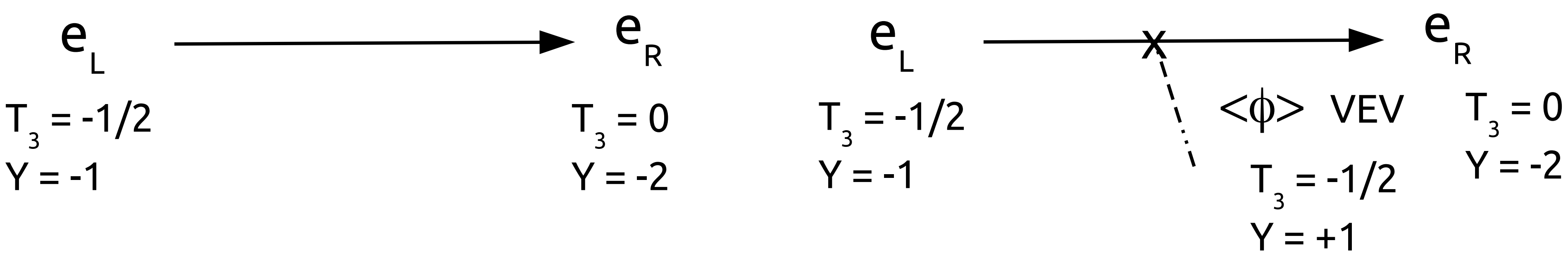
$$L_{mass} = m_D \overline{\psi}\psi = m_D(\overline{\psi_L} + \overline{\psi_R})(\psi_L + \psi_R) = m_D(\overline{\psi_L}\psi_R + \overline{\psi_R}\psi_L)$$

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

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



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

$T_3 = 0$

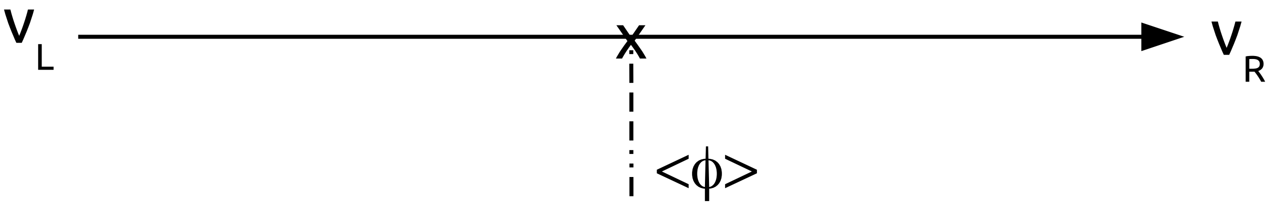
$Y = -2$

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

- 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

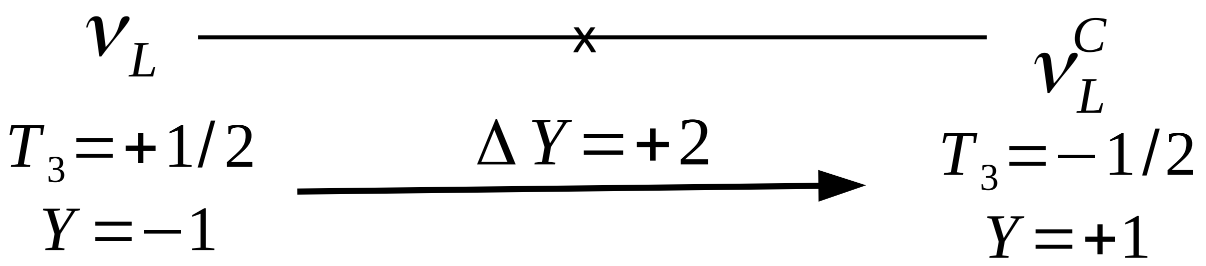
$$L_{Maj} = \frac{1}{2} m_L \left(\overline{\nu^C}\,\nu + \overline{\nu}\,\nu^C \right) = \frac{1}{2} m_L \left(\overline{\nu_L^C}\,\nu_L + \overline{\nu_L}\,\nu_L^C \right)$$

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

Damn it!

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

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



ν_L ν_L^C

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

$Y = -1$ $Y = +1$

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

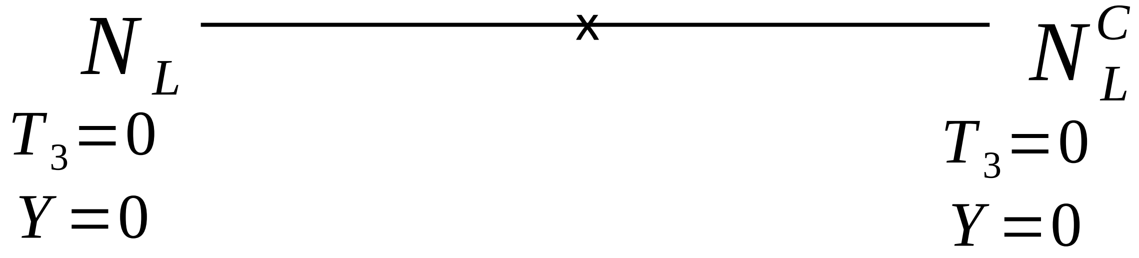
The most general mass term combines all of these

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

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

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

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



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

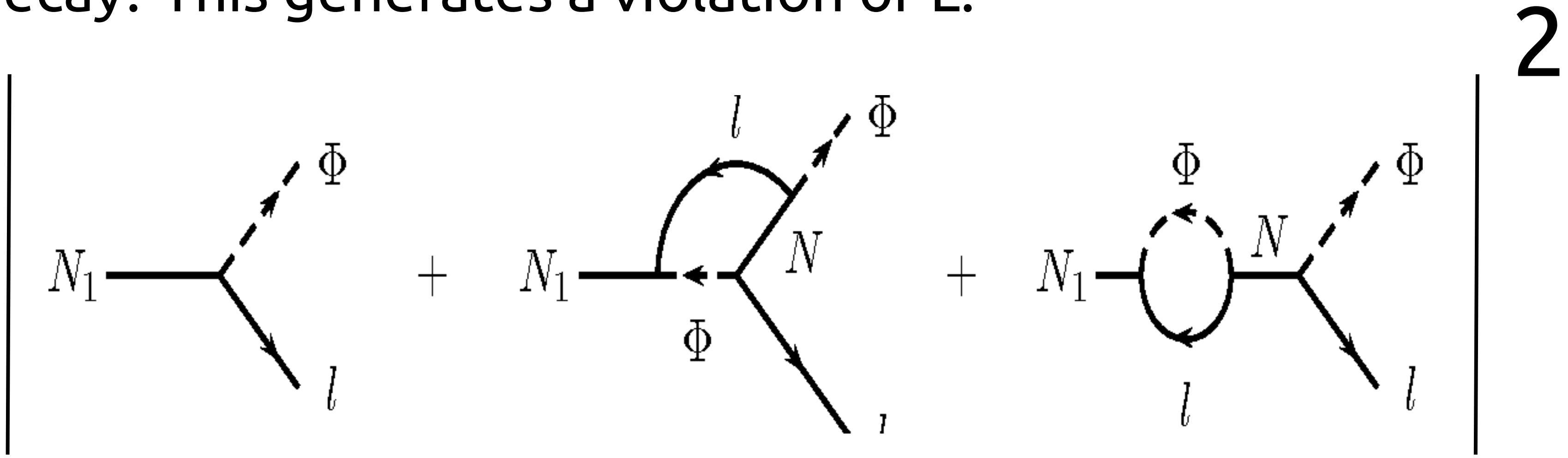
- Mass of “our” neutrino suppressed by the GUT scale
- $\Lambda \approx 10^{16}$ GeV → m $\approx (250)^2/10^{16} \approx$ 10 meV
- Currently our only “natural” way to explain why the neutrino mass is so much smaller than other Dirac particles

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

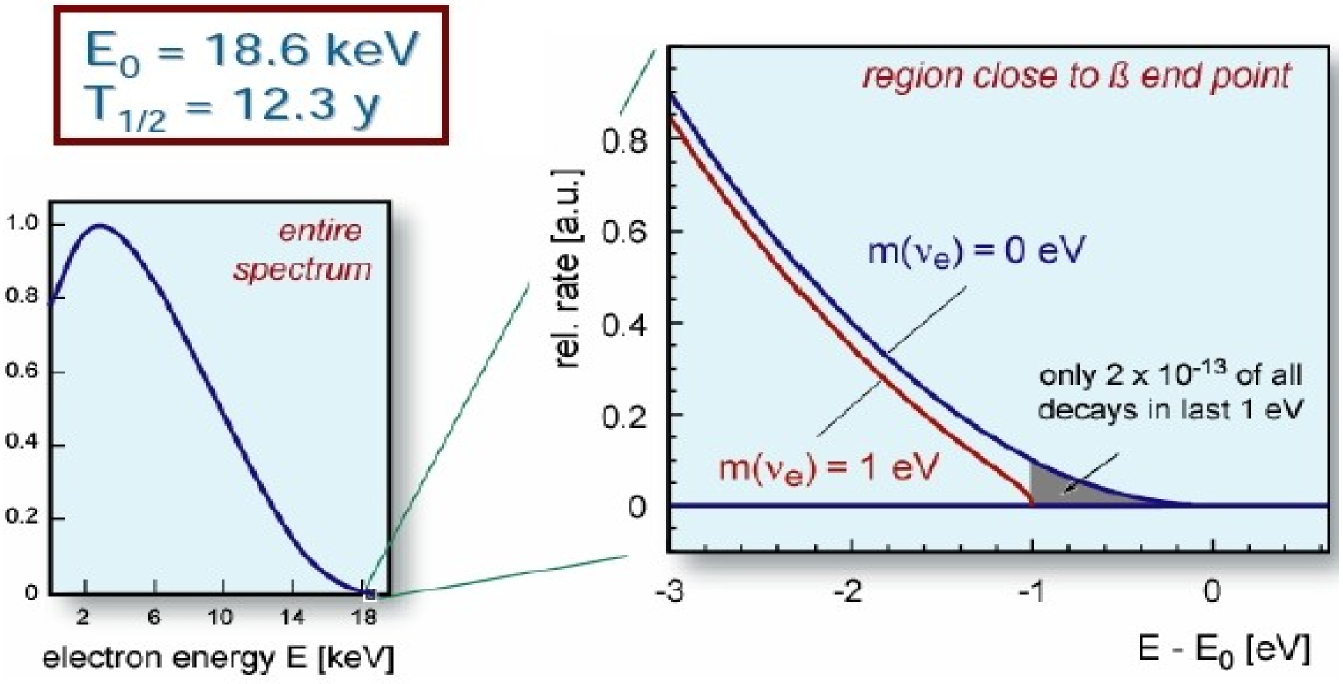
(Attempts at) mass measurements

ν_e mass

Measurement of ν_e mass from kinematics of β decay.

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

Observable is m_ν^2



Requirements

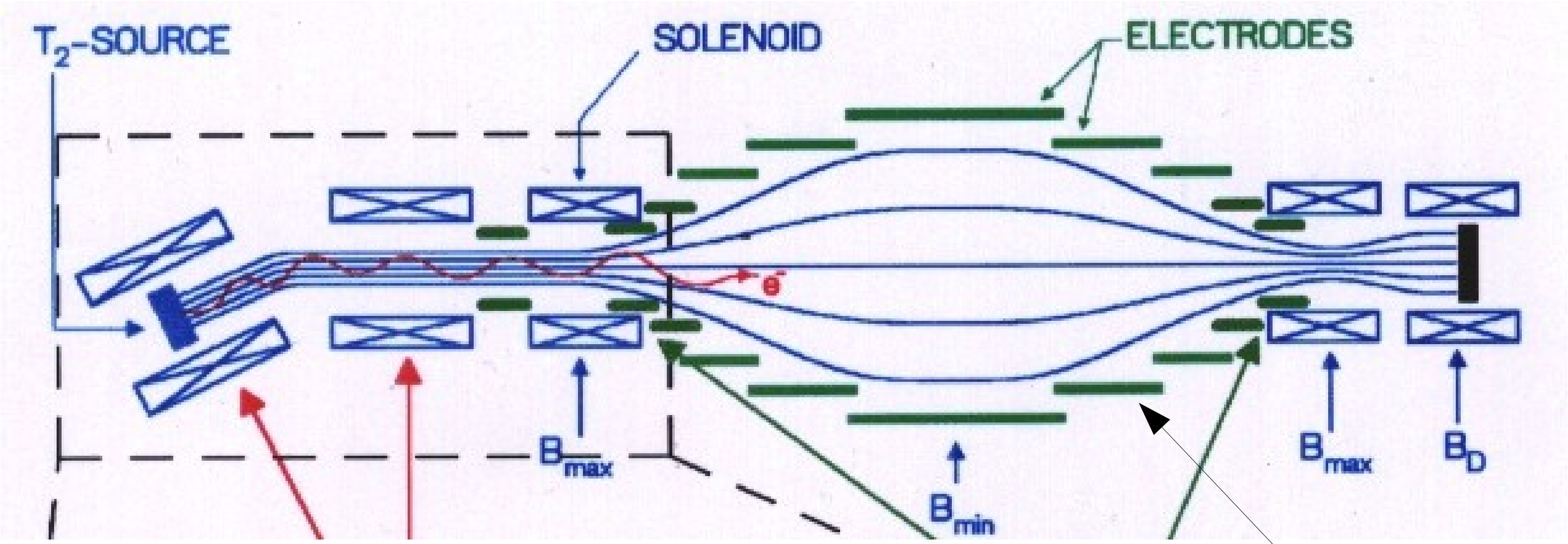
- # electrons close to the endpoint should be large
- Good (and well-understood) electron energy resolution
- No (or minimal) electron energy loss within the source
- Minimal atomic and nuclear final state effects, of excited transitions

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

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

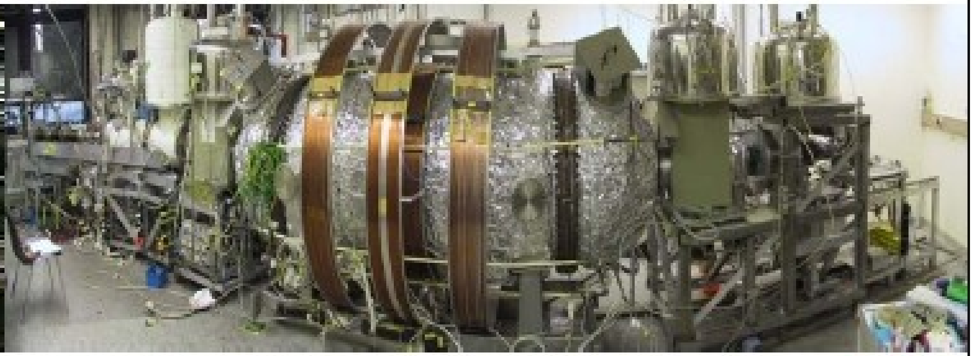
Troitsk

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

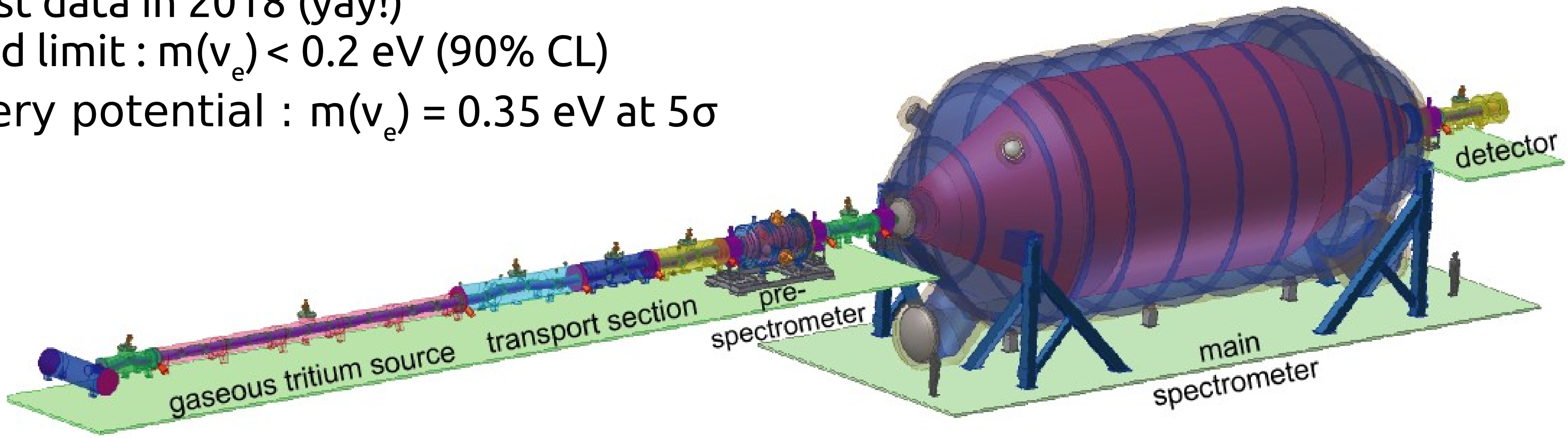
$m_\nu^2 = -1.2 \pm 2.2 \pm 2.1\ \mathrm{eV}^2$

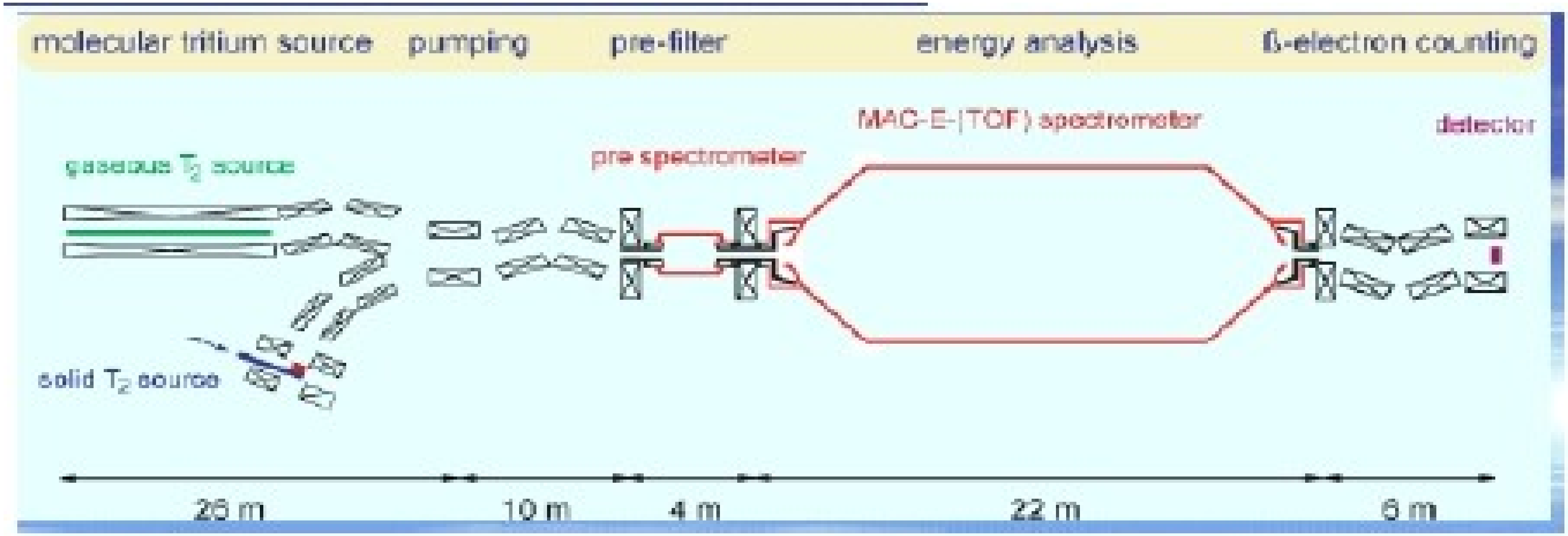
$m_\nu \leq 2.2\ \mathrm{eV}$ (95% CL.)

Both experiments have reached the intrinsic limit of their sensitivity.

KATRIN

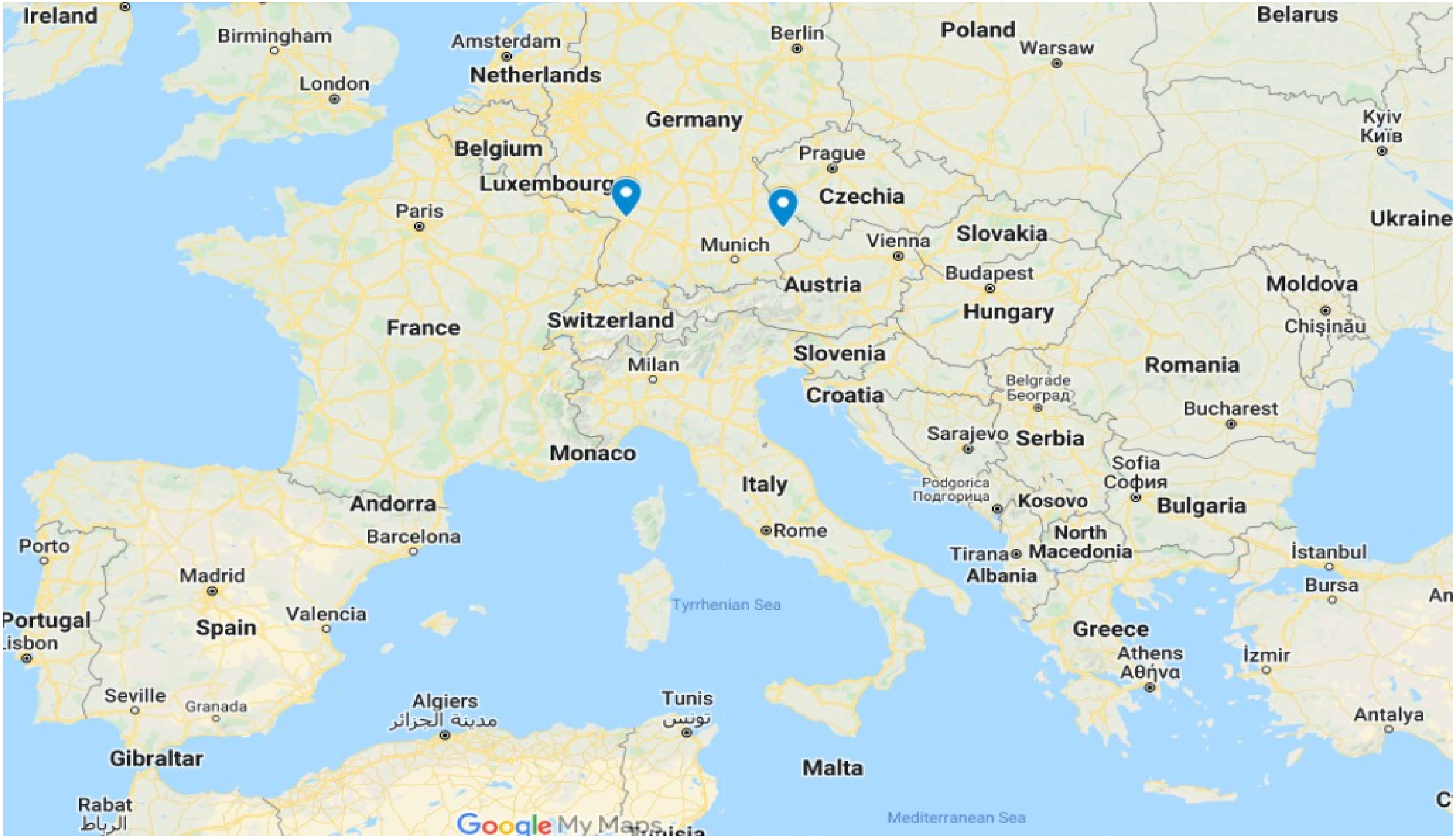
Took first data in 2018 (yay!)
Expected limit : $m(v_e) < 0.2$ eV (90% CL)
Discovery potential : $m(v_e) = 0.35$ eV at 5σ



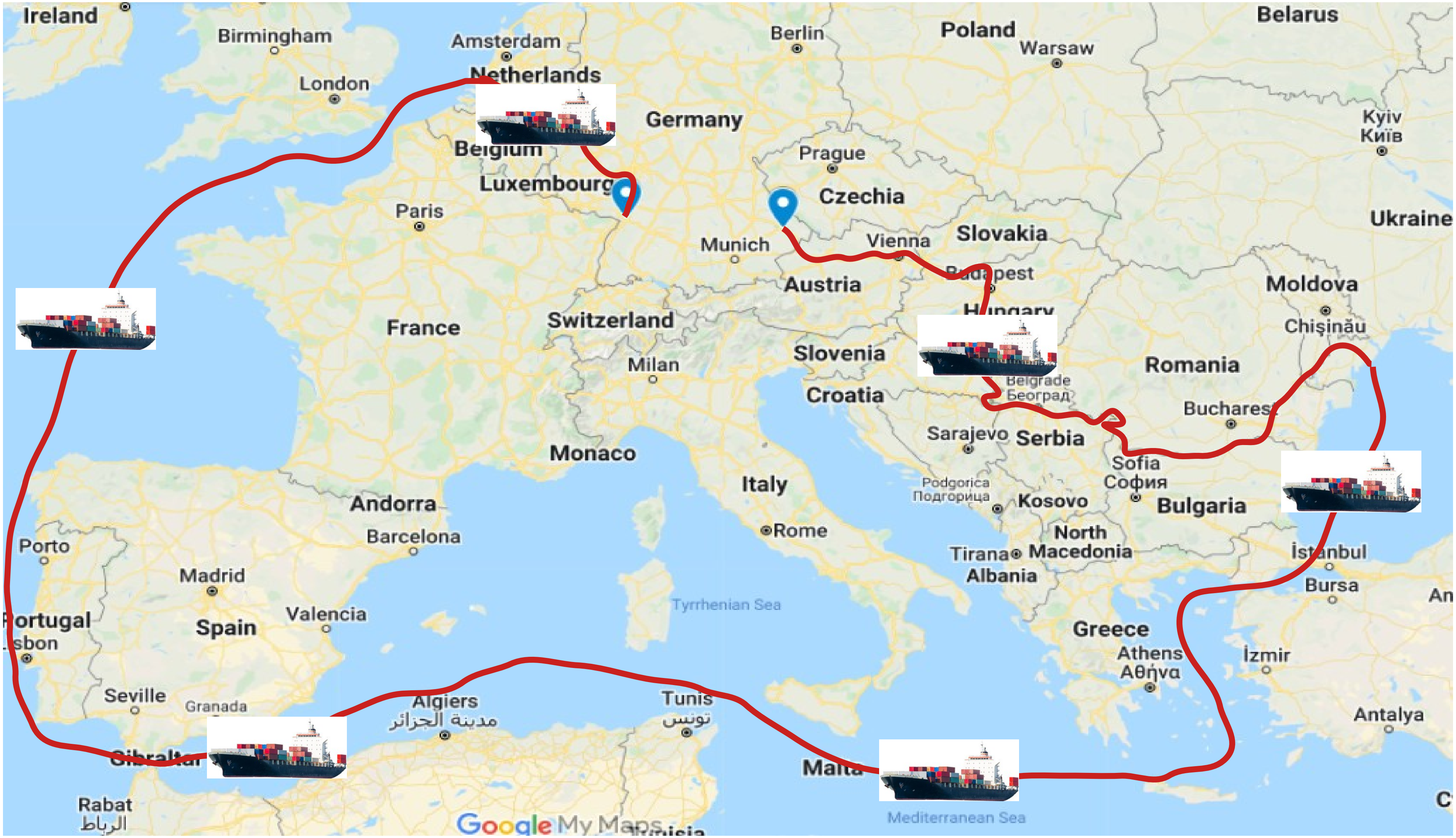


KATRIN on the move

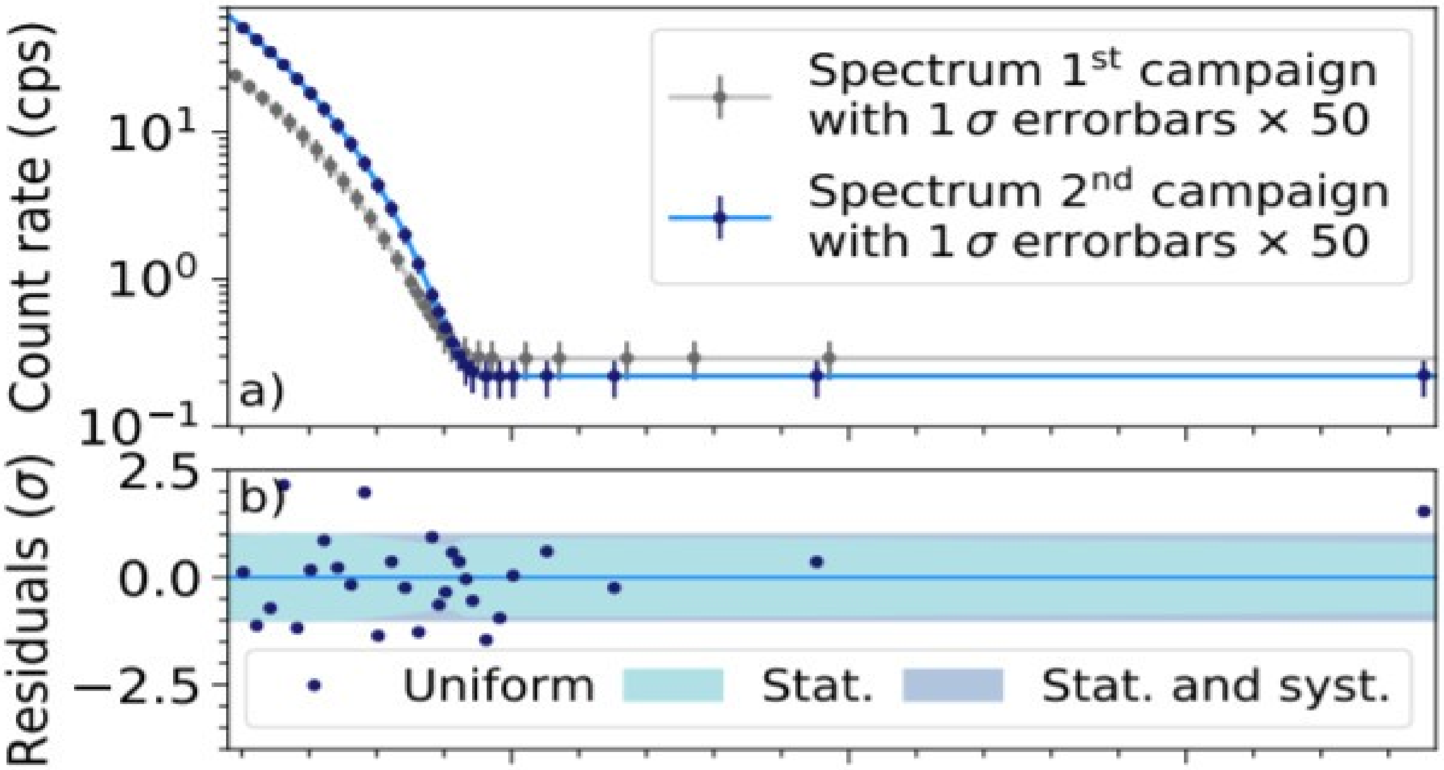
Katrin on the move



Katrin on the move



Latest KATRIN result



5.2 million β-electrons

Statistics limited

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

$$m_\nu < 0.9\ eV @ 90\% CL$$

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

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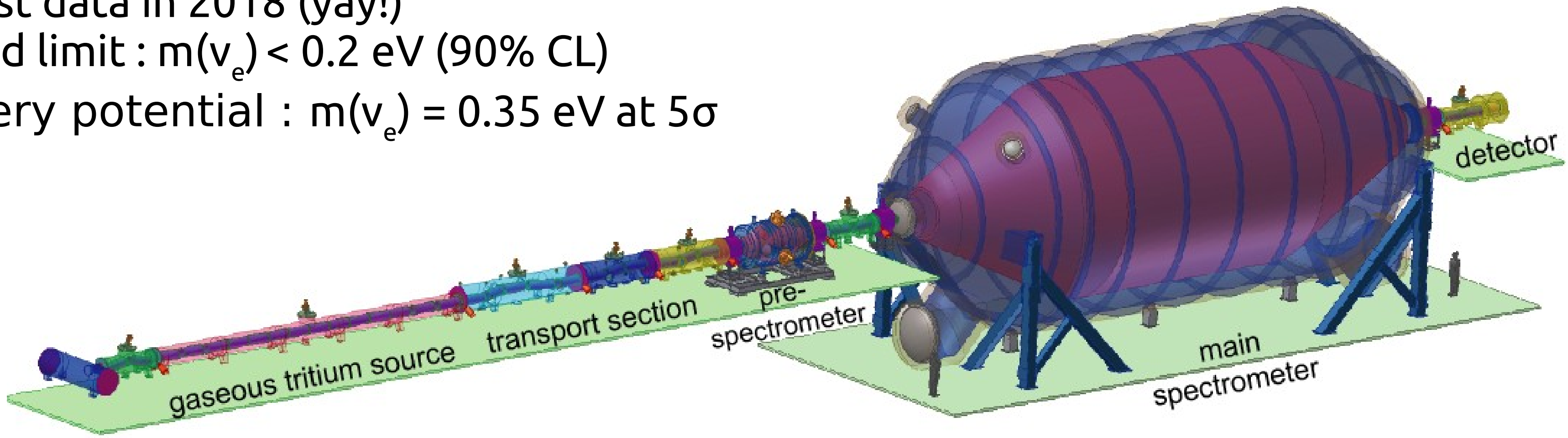
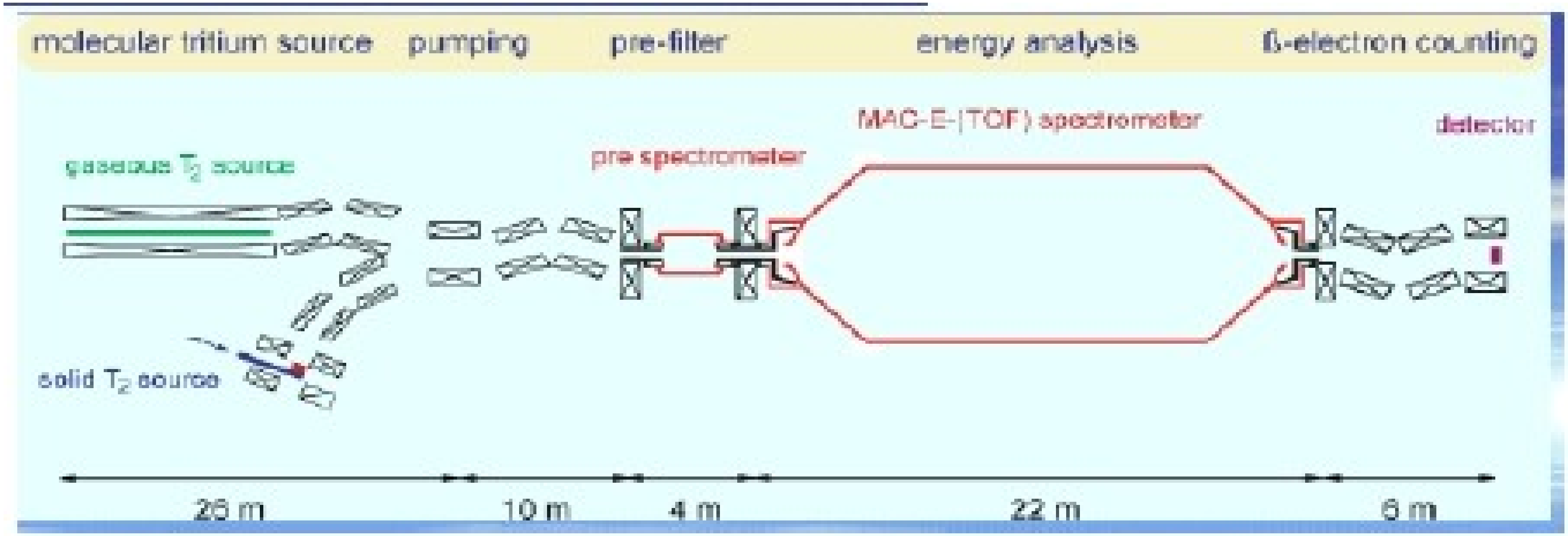
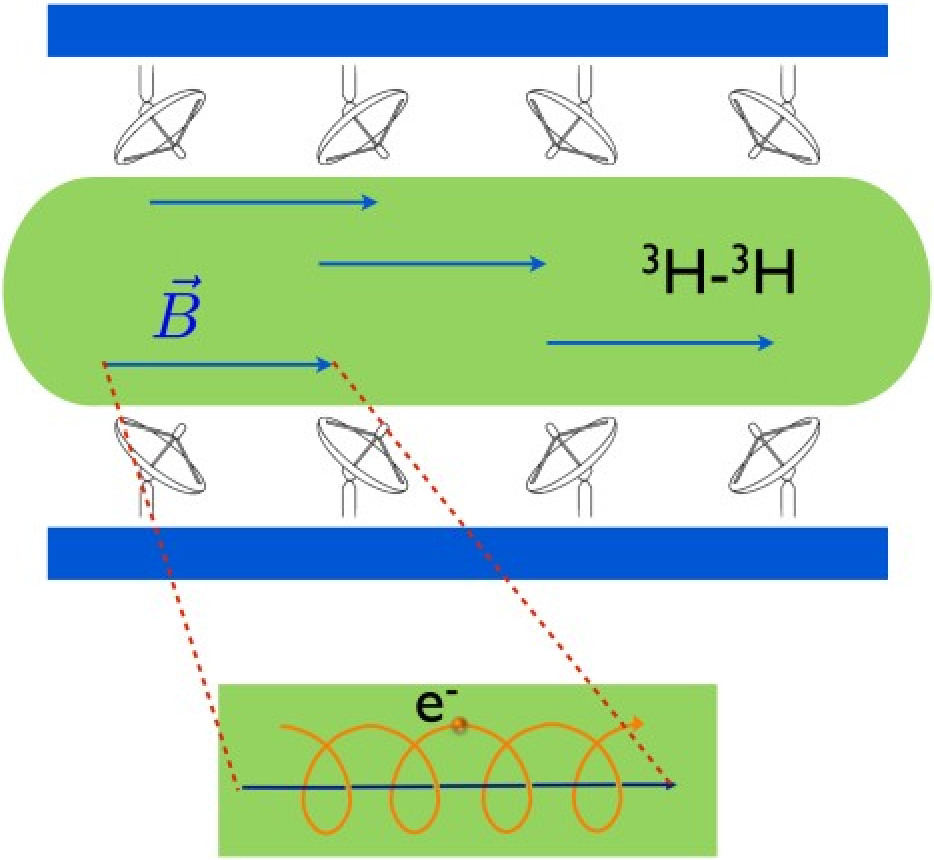




Cyclotron Radiation Emission Spectroscopy



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

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

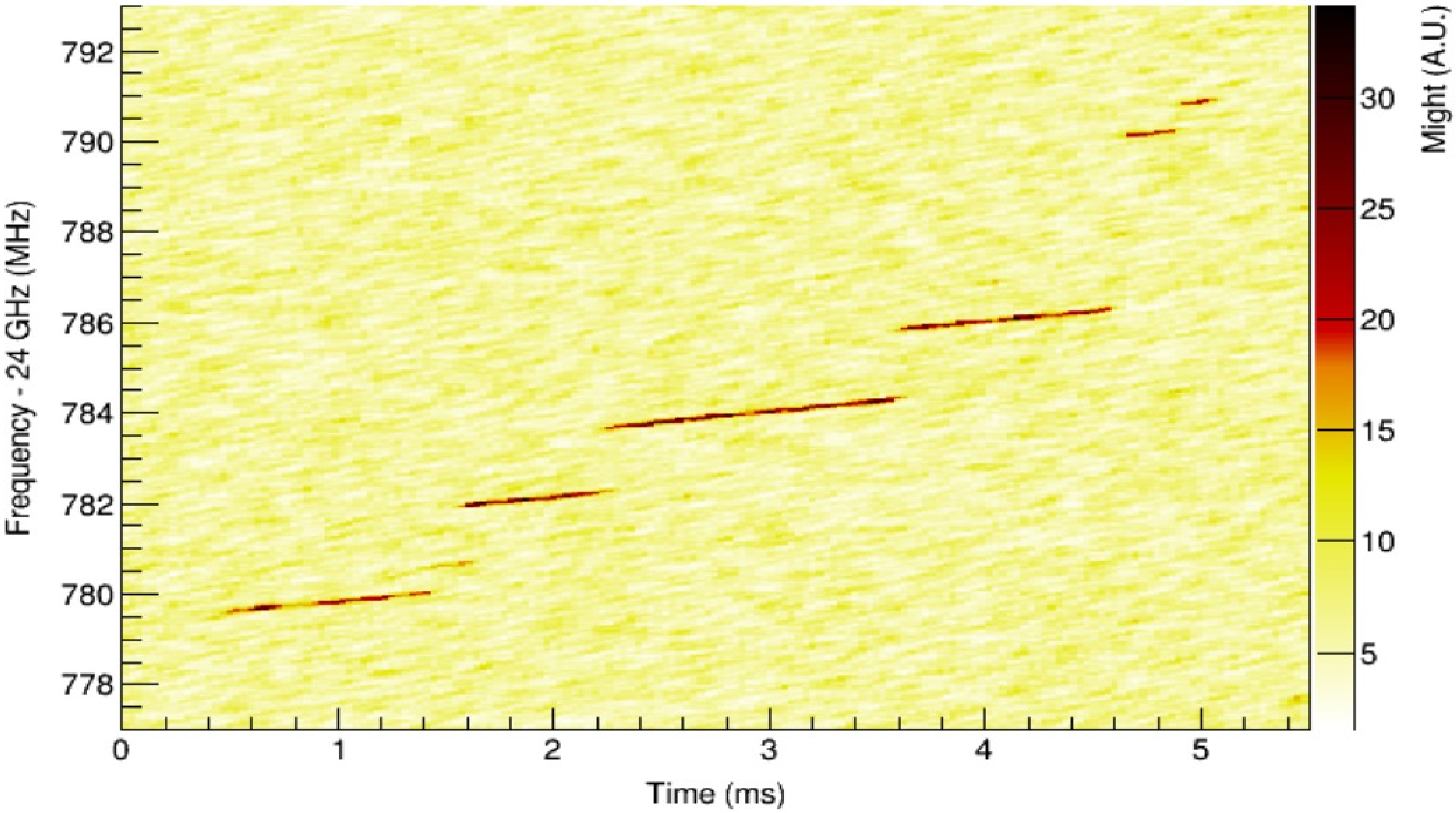
- Measures electron energy from the frequency of the cyclotron radiation!

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

- $m_\nu < 40$ meV

Project 8

Project 8 Demonstrator – Decay in tritium



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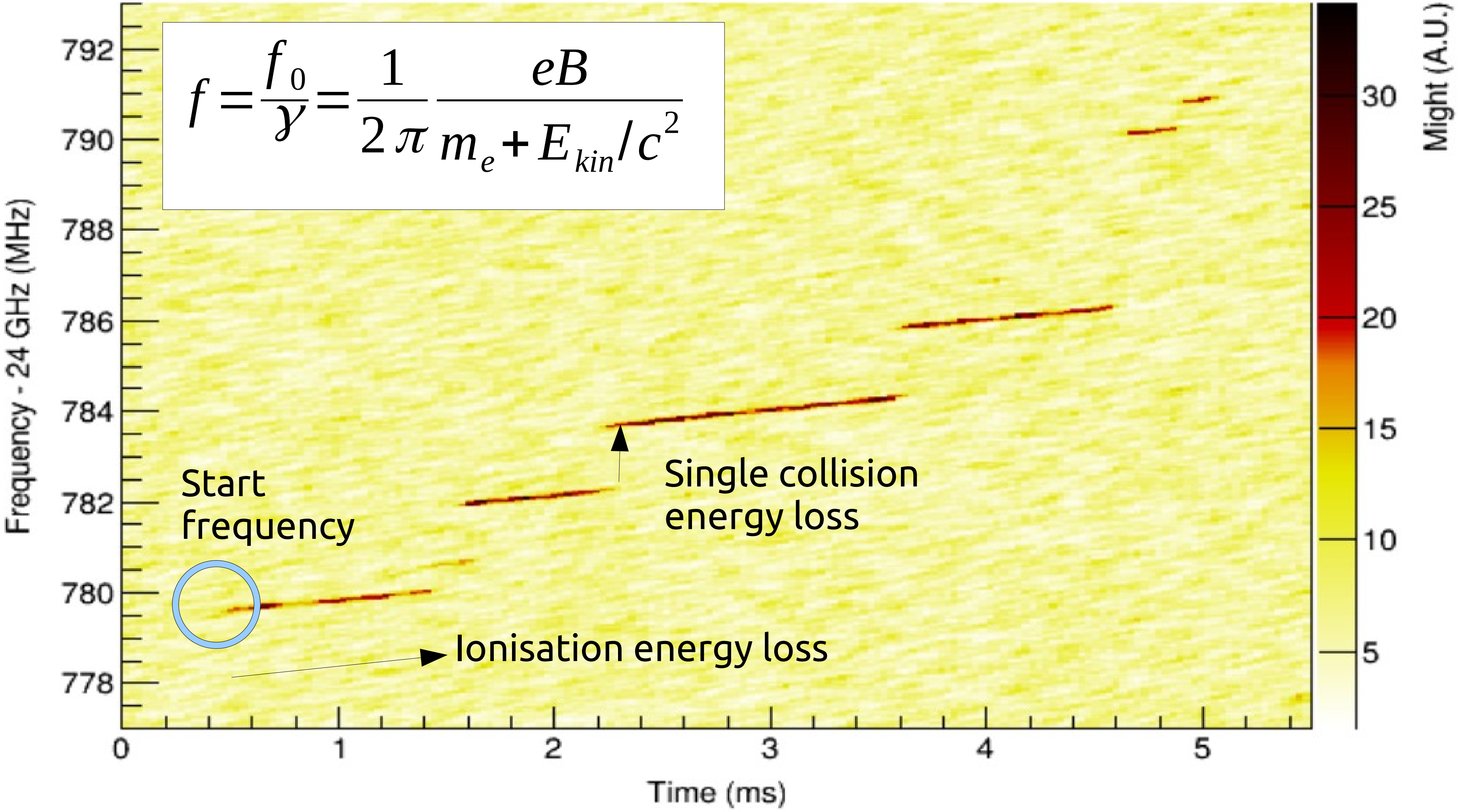


$$f=\frac{f_0}{\gamma}=\frac{1}{2\pi}\frac{eB}{m_e+E_{kin}/c^2}$$

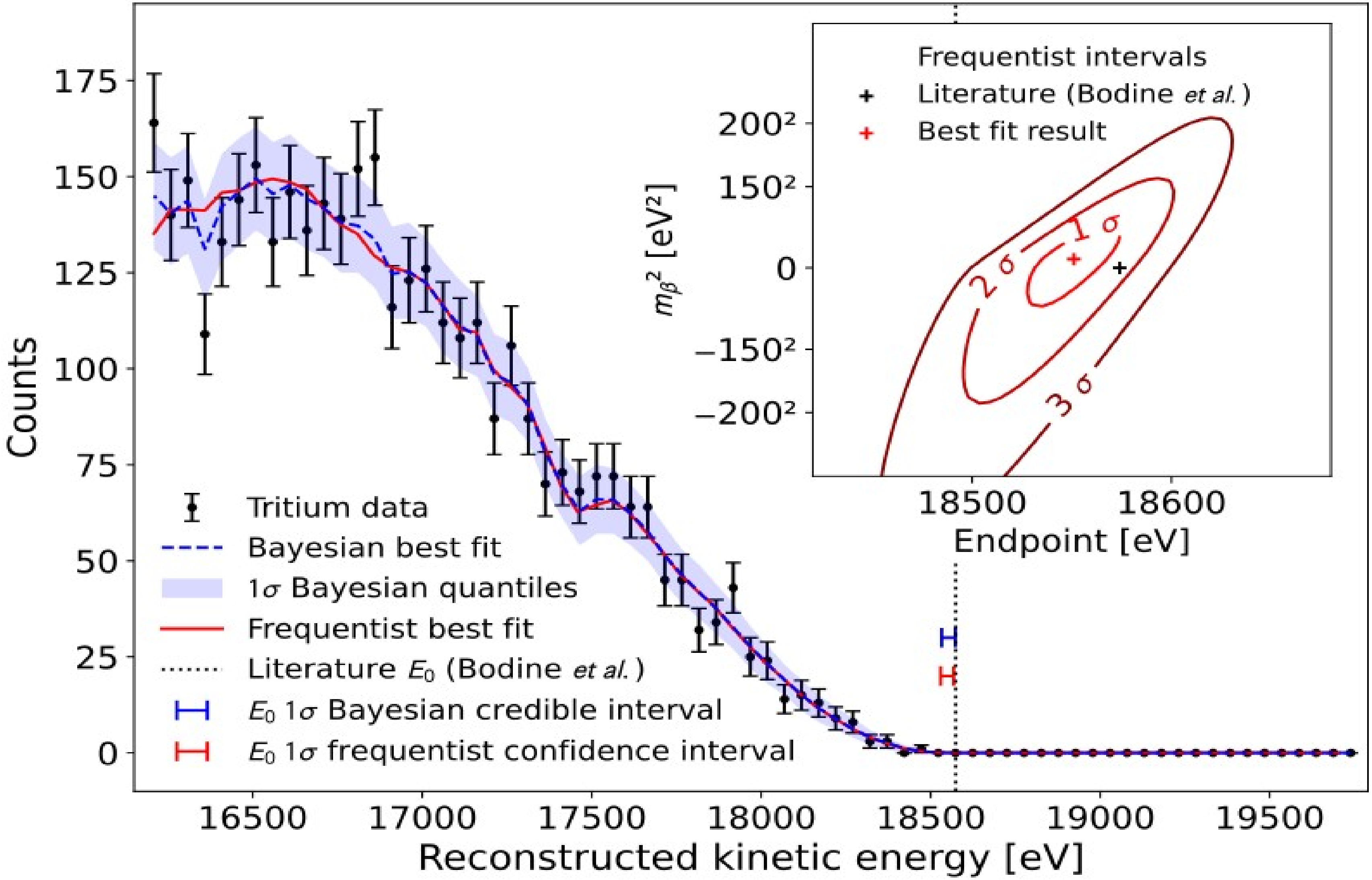
Start frequency

Single collision energy loss

Ionisation energy loss

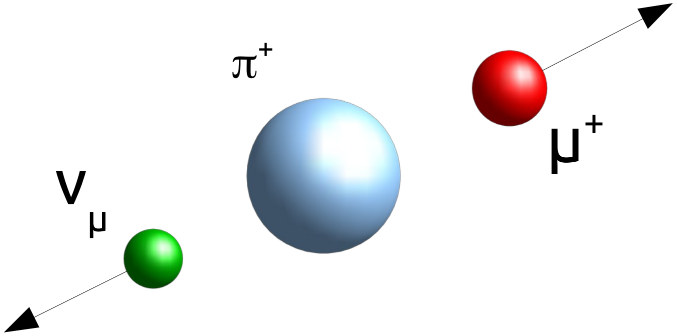
β-decay from CRES

prototype proof-of-principle



ν_μ mass

Easiest way is to use pion decay at rest



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

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

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

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

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

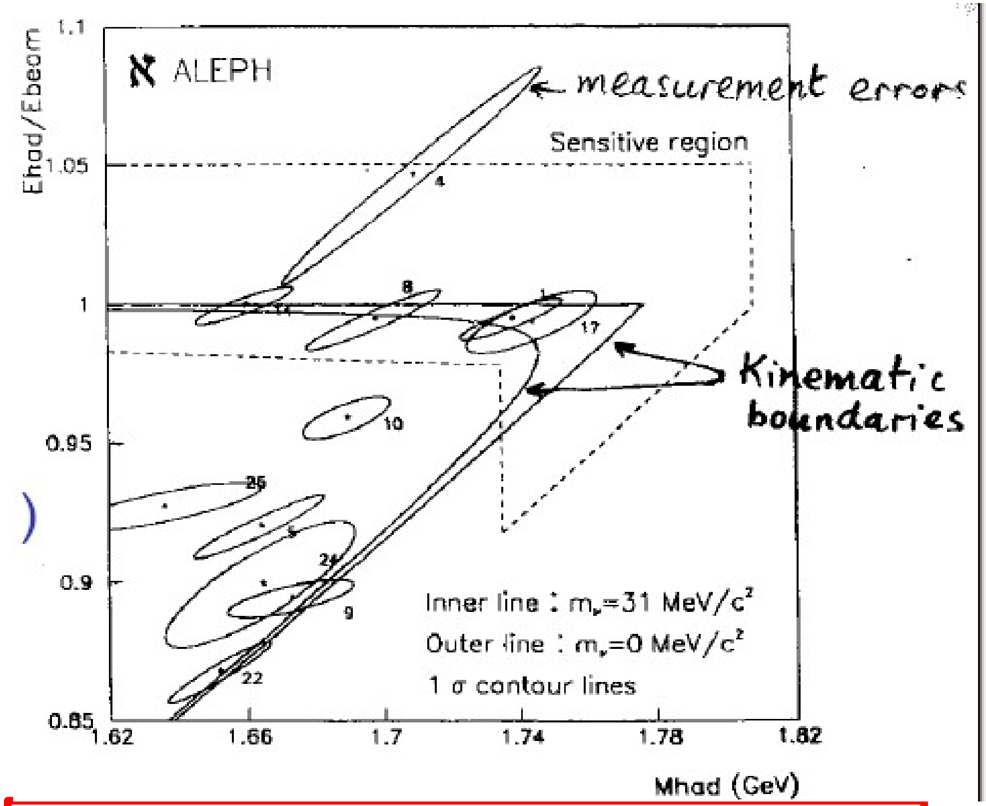
$$m_\nu < 190\, keV \,(90\,\%\, CL)$$

ν_τ mass

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

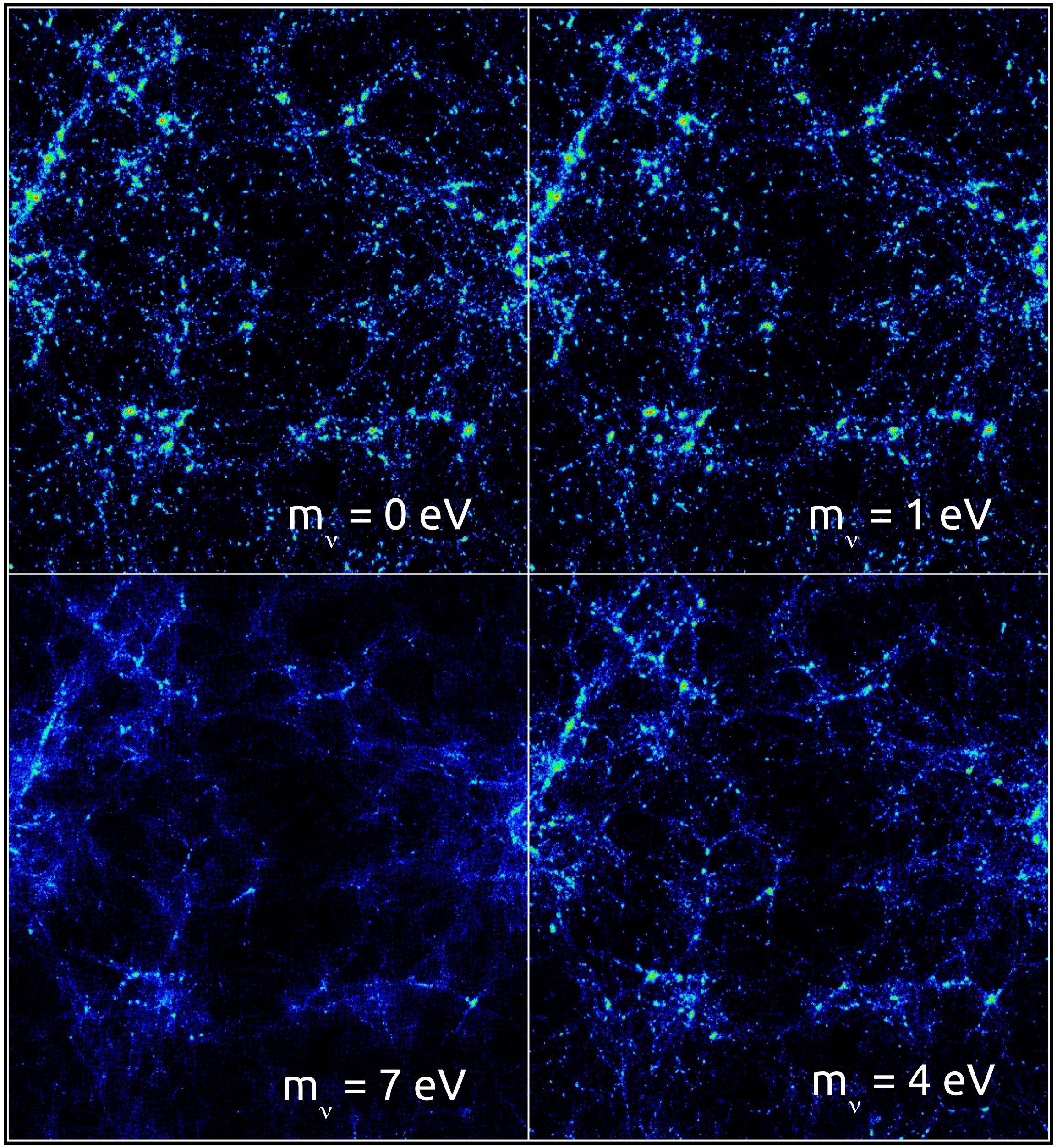
↳ $\tau \to \nu_\tau + 5\pi^{+-}(\pi^0)$

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



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

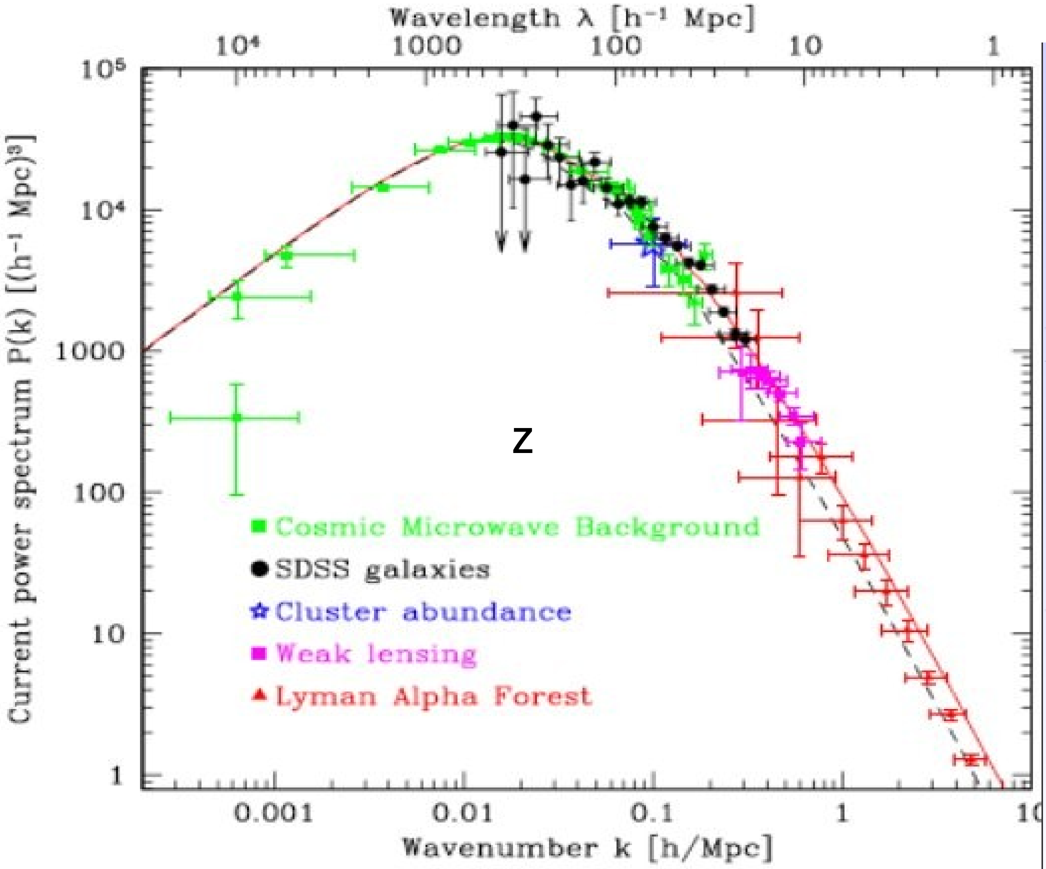
Cosmology

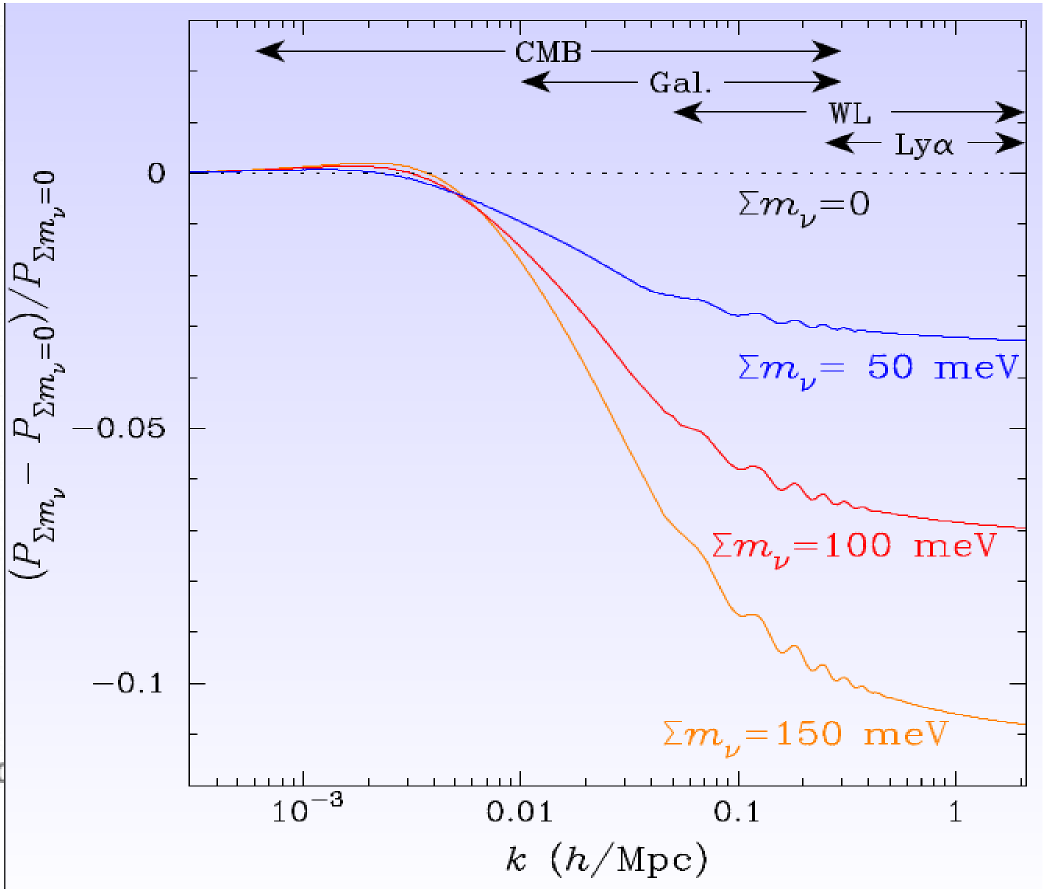


- Density fluctuations are affected by neutrino mass in the early universe
- model dependent
- WMAP,2dF,ACBAR, CBI,PLANCK, BOSS, BAO, SDSS

Power spectra

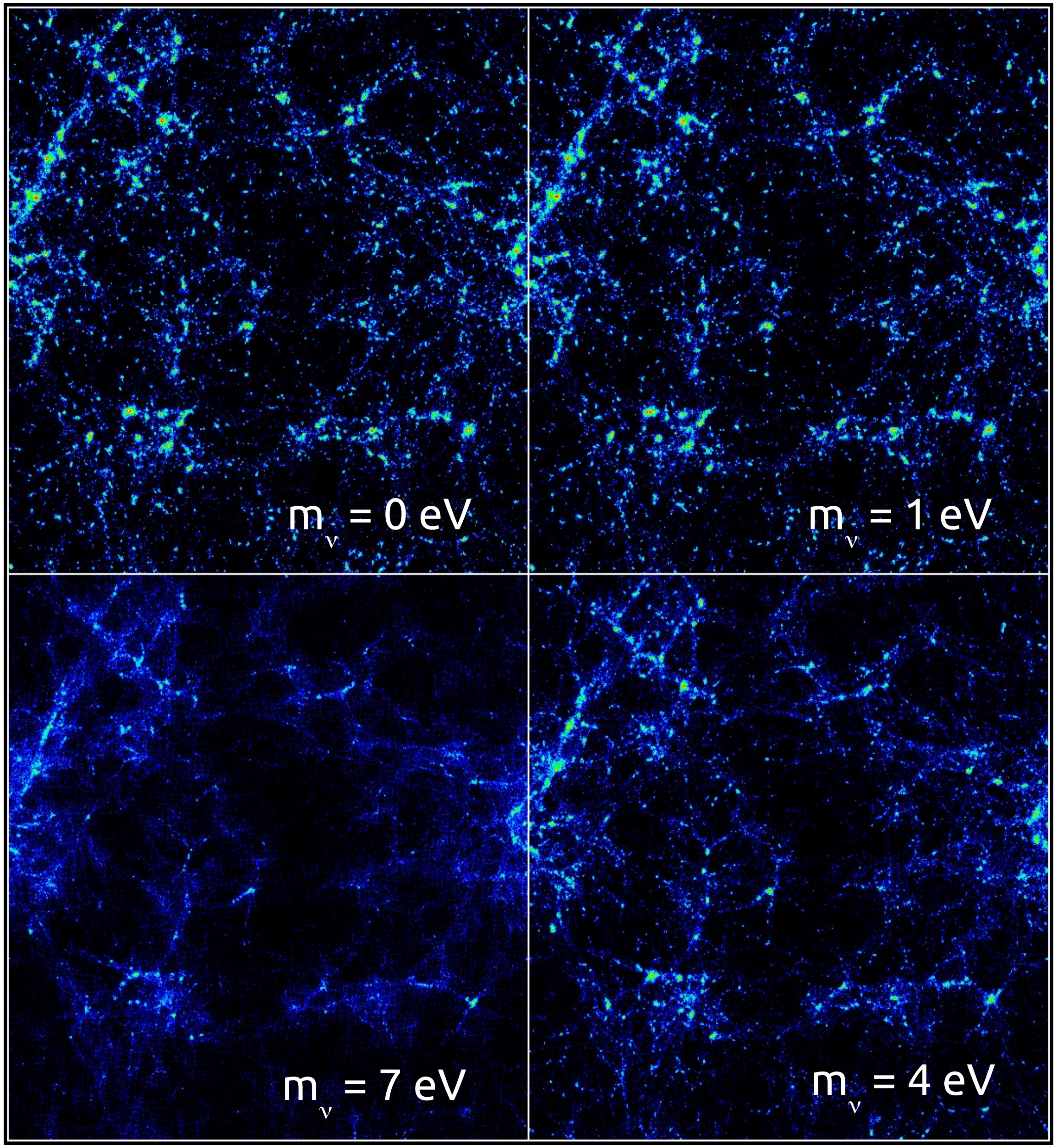
“Wavelength” of density fluctuation





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

Cosmology



- Density fluctuations are affected by neutrino mass in the early universe
- model dependent
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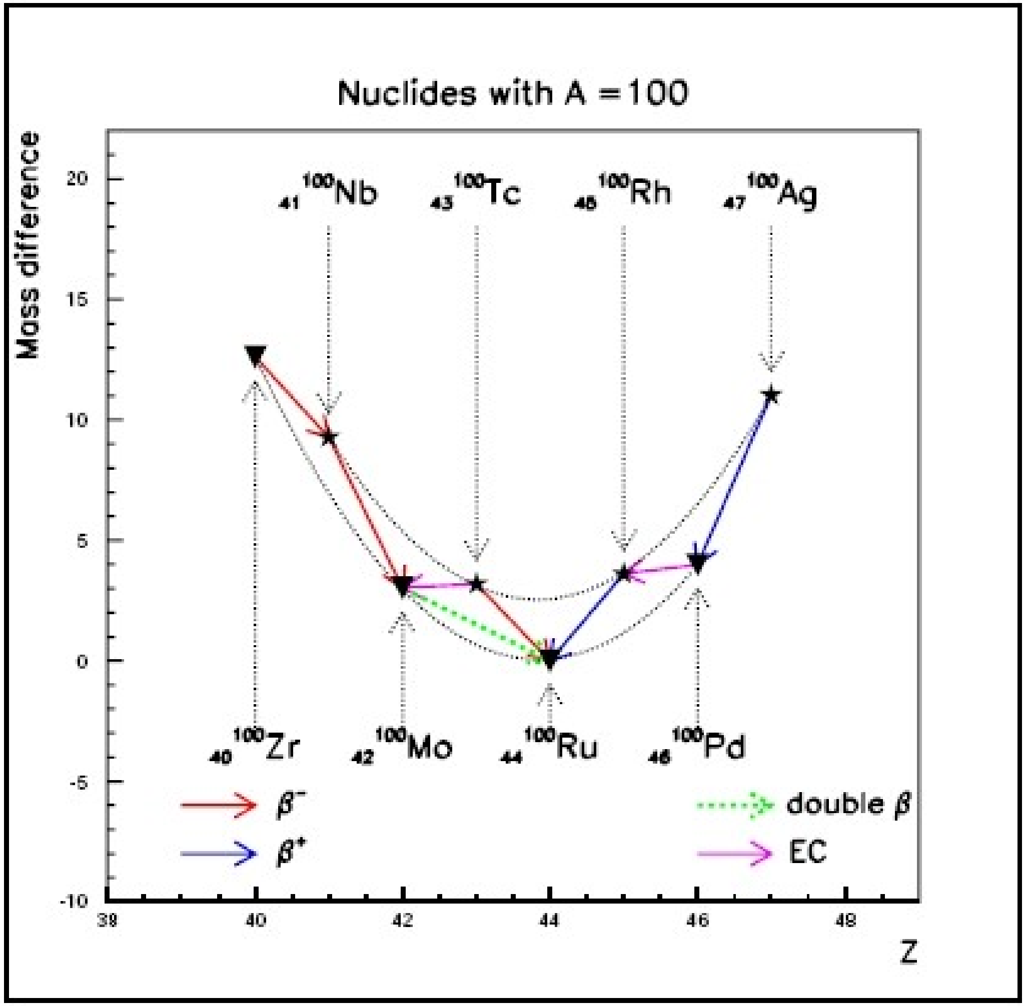
$$\boxed{\sum m_{\nu_i} \leq (0.09 - 0.26\, eV)}$$

2vββ Decay

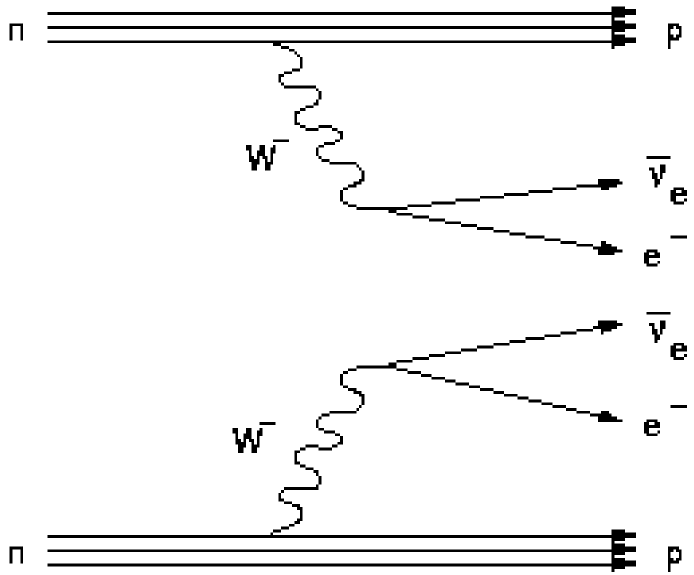
Neutrinoless double beta decay is considered a golden channel for the measurement of neutrino mass.

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

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



2vββ Decay



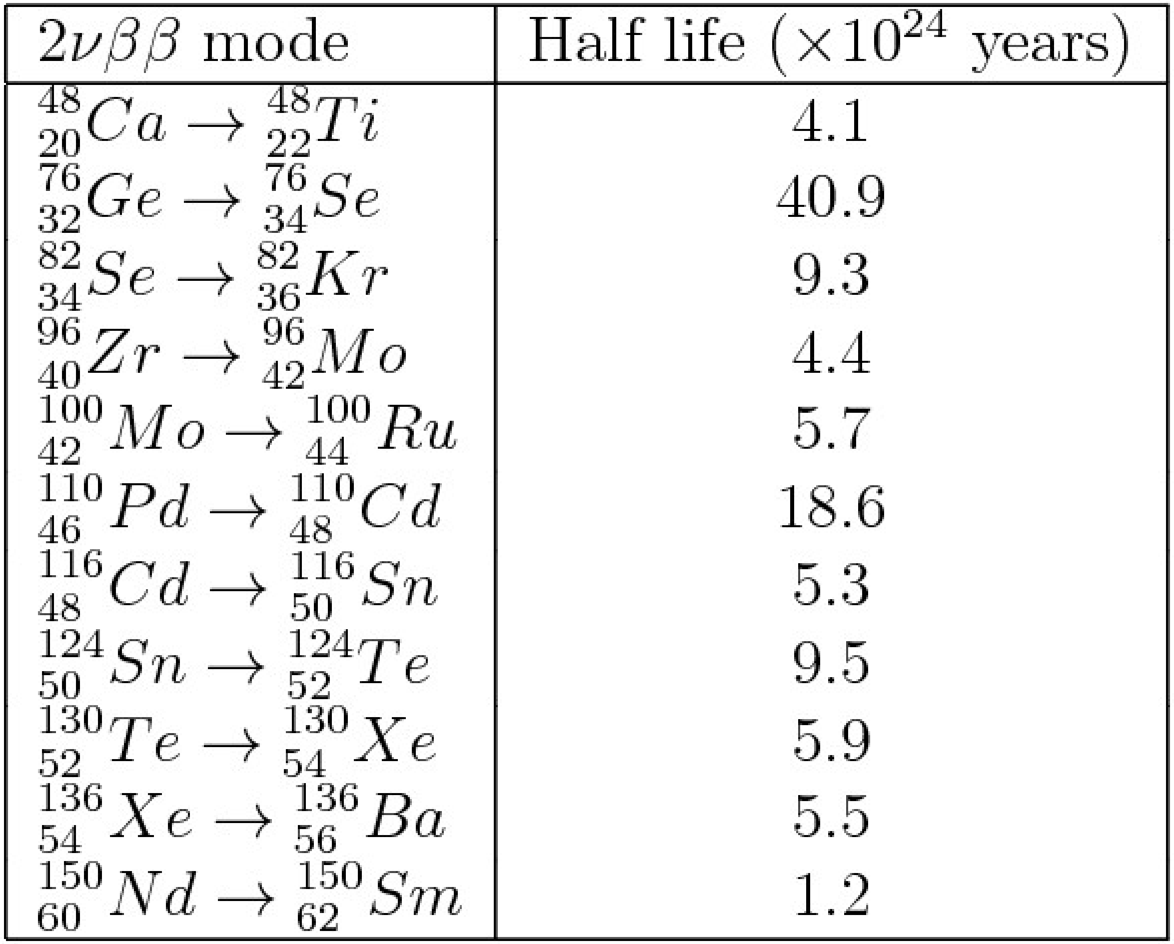
$$\left[T_{1/2}^{2\nu}\right]^{-1} = G^{2\nu}(Q,Z)\left|M^{2\nu}\right|^2$$

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

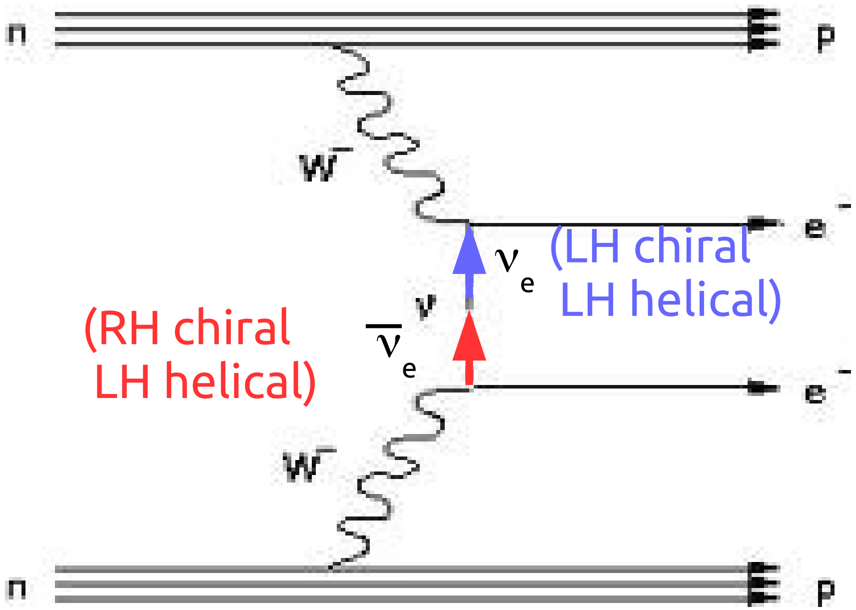
2vββ Decay



$2\nu\beta\beta$ 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

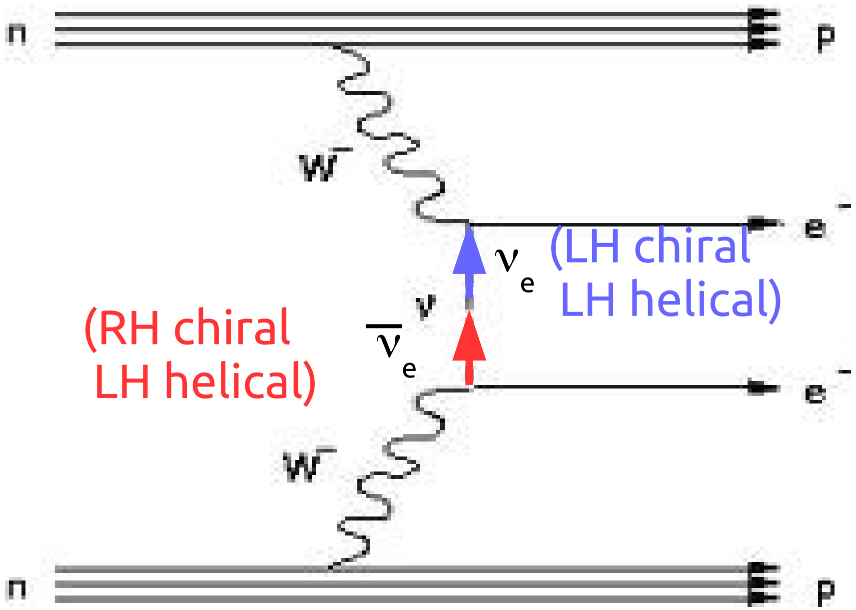
- Neutrino must have mass
- Neutrino is Majorana
- Violation of lepton number conservation

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

helicity states

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

Neutrinoless ββ Decay



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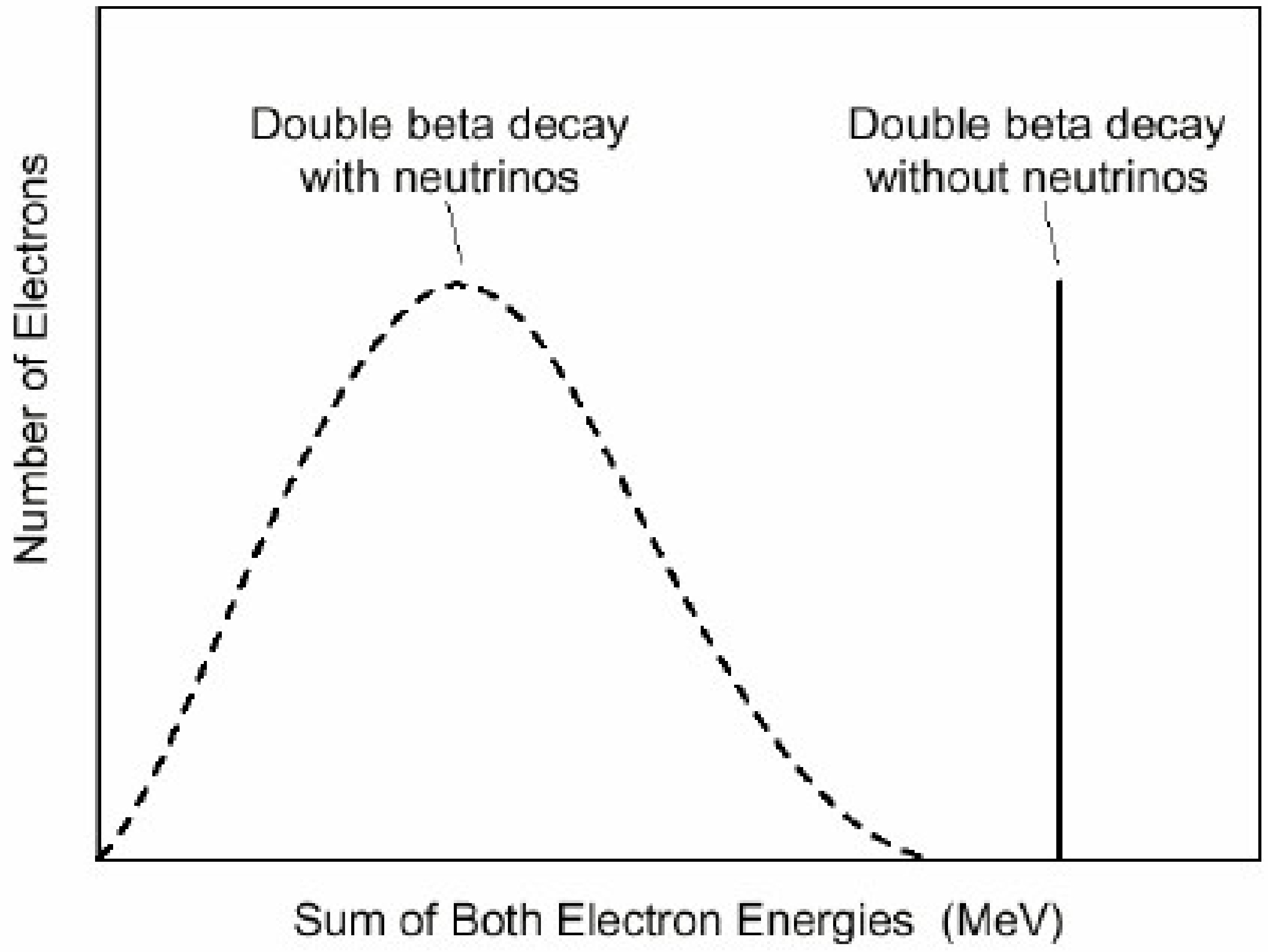
helicity states

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

0vββ signal

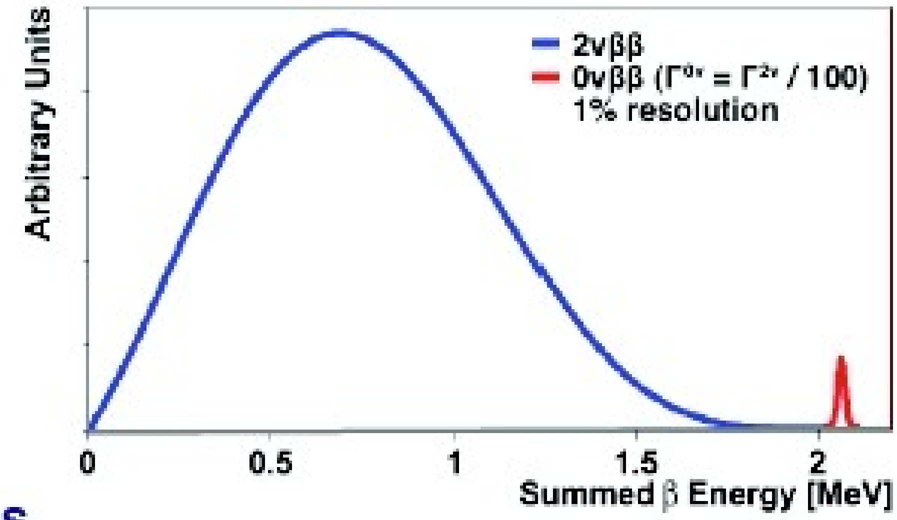

Double beta decay
with neutrinos
Double beta decay
without neutrinos
Number of Electrons
Sum of Both Electron Energies (MeV)

Experimental Requirements

Extremely slow decay rates

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

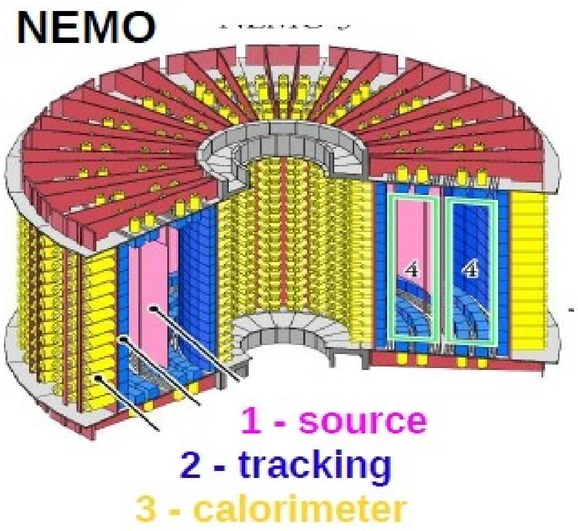
Best case, **0 background !**	$\propto$ Source Mass • time$_{exp}$



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

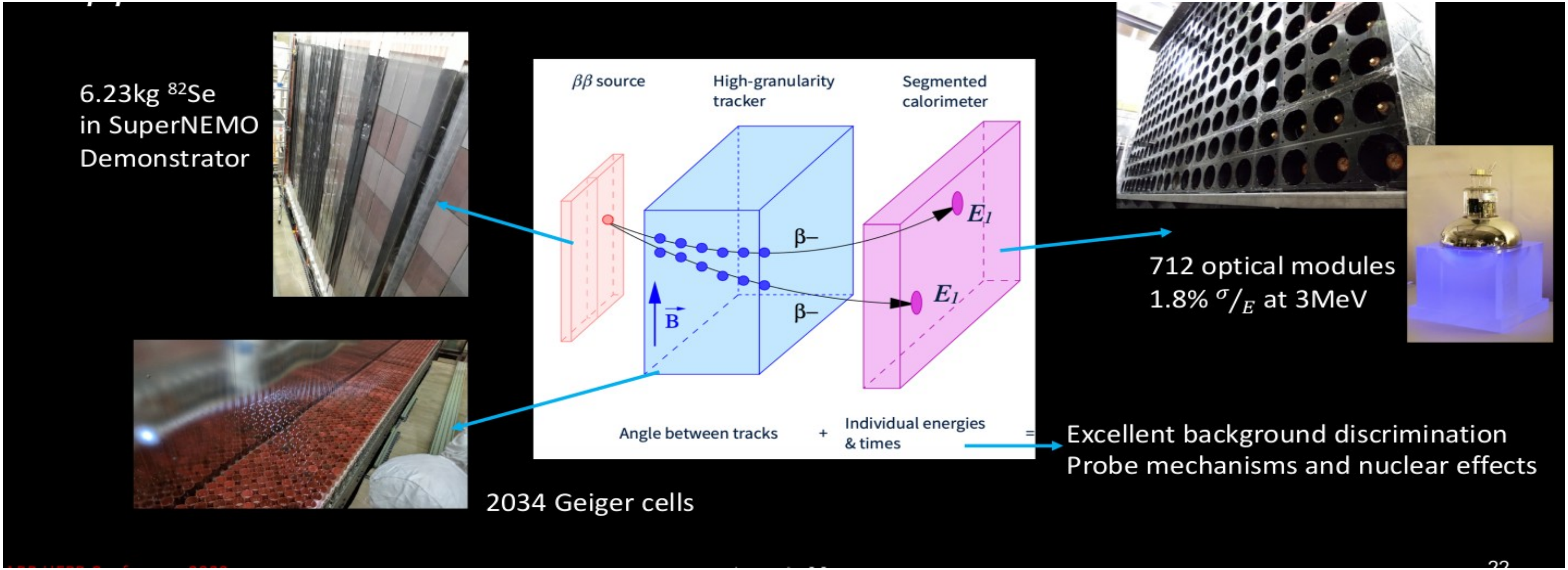
- **2e$^-$ are detected separately**
  - → different channels of 0νDBD can be distinguished
- **particle identification**
  - → background suppression
- **poor energy resolution**
  - → important 2νDBD background (limitation on isotope choice)

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

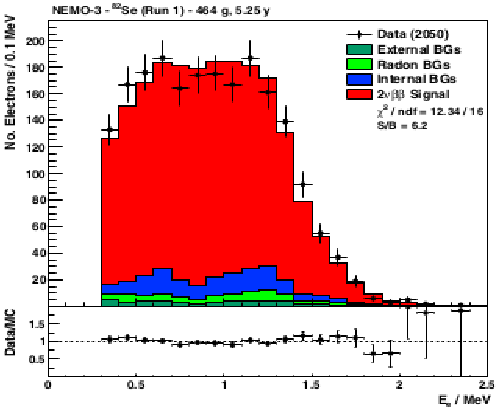


6.23kg ^{82}Se
in SuperNEMO
Demonstrator

712 optical modules
1.8% $^{\sigma}/_{E}$ at 3MeV

Excellent background discrimination
Probe mechanisms and nuclear effects

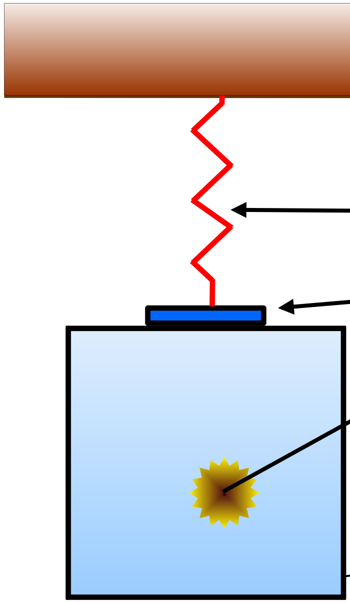
2034 Geiger cells



(b) Single-state Dominated (SSD)

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

Bolometry : Cuore



Heat sink

Thermal coupling

Thermometer

Double beta decay

Crystal absorber

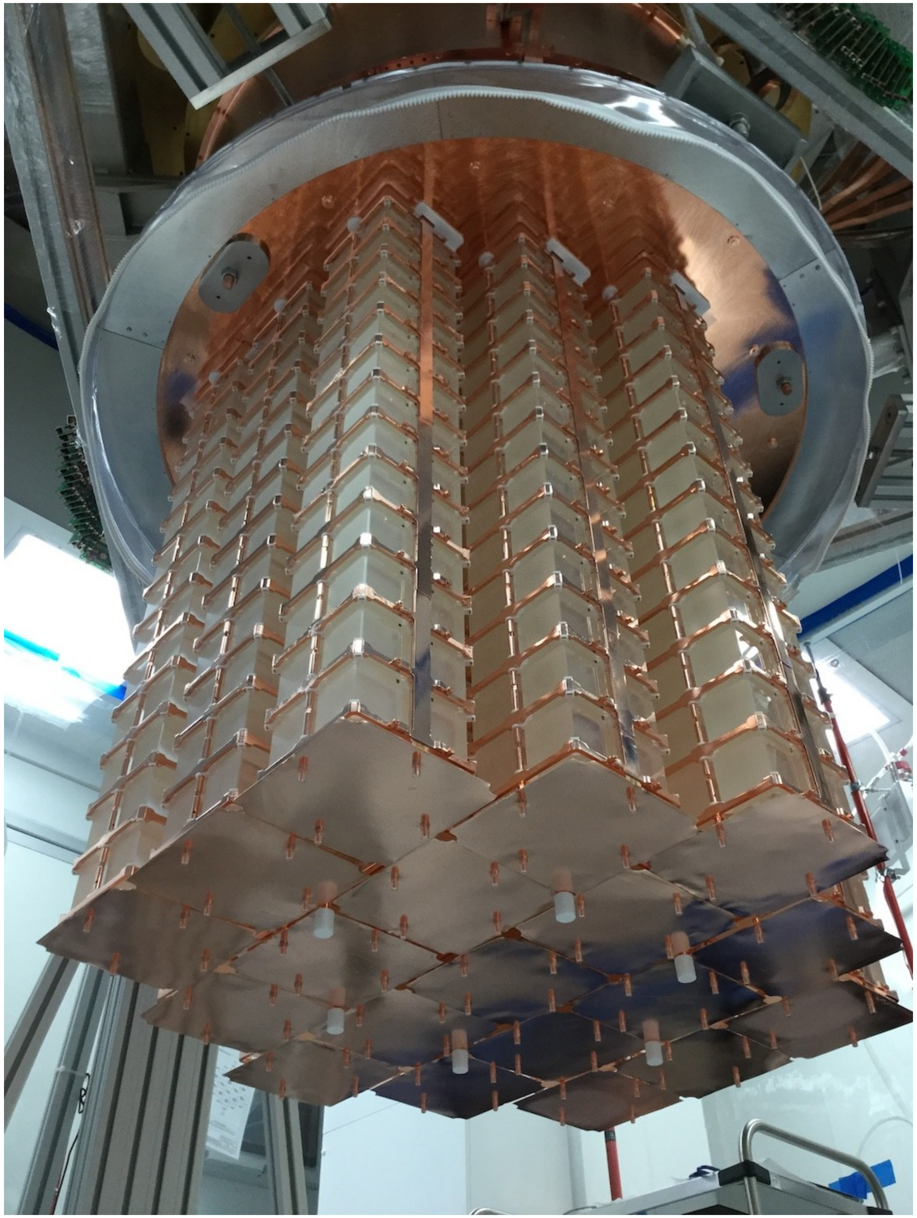
example: 750 g of TeO_2 @ 10 mK

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

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

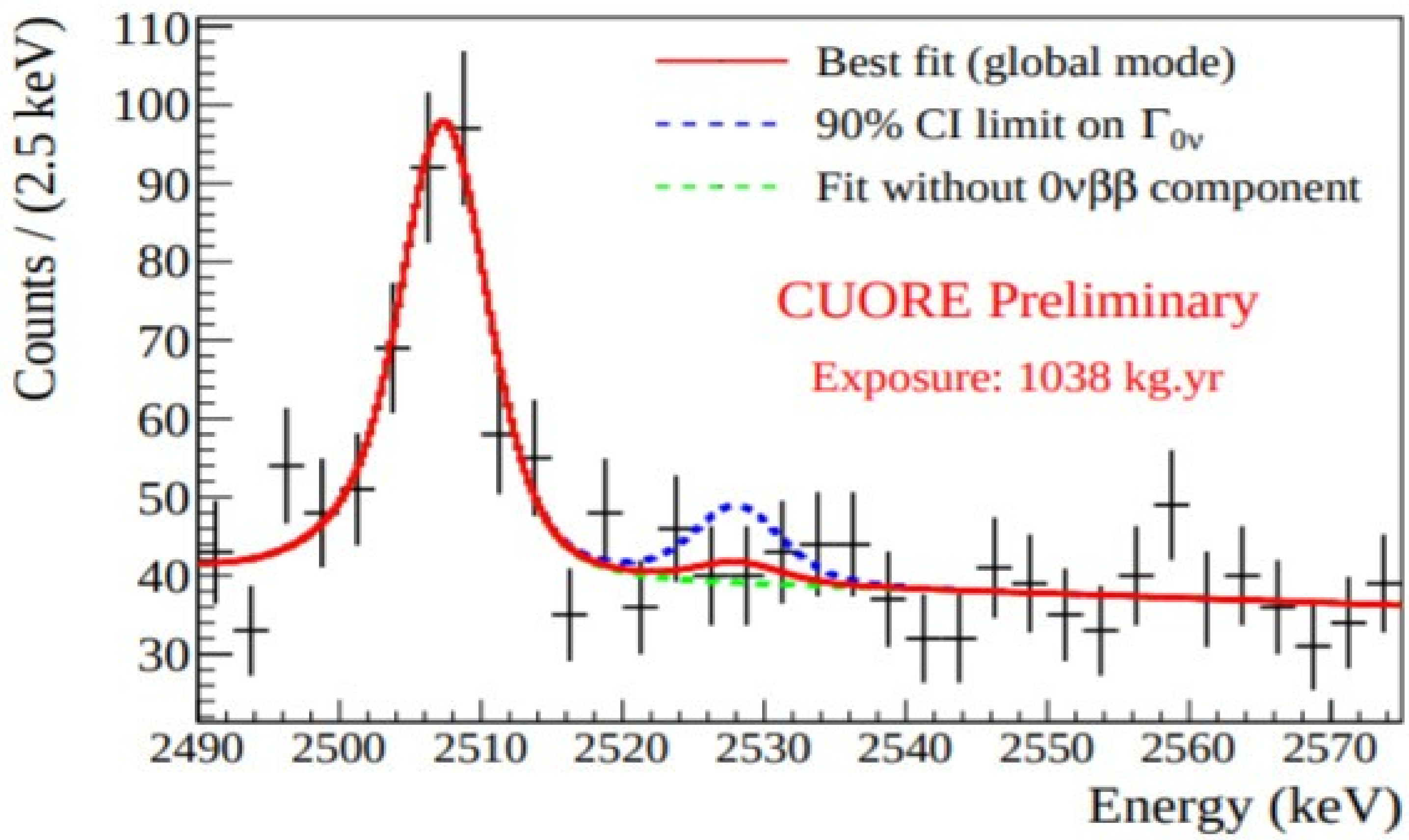
$\Rightarrow \Delta U \sim 10$ eV

Cuore



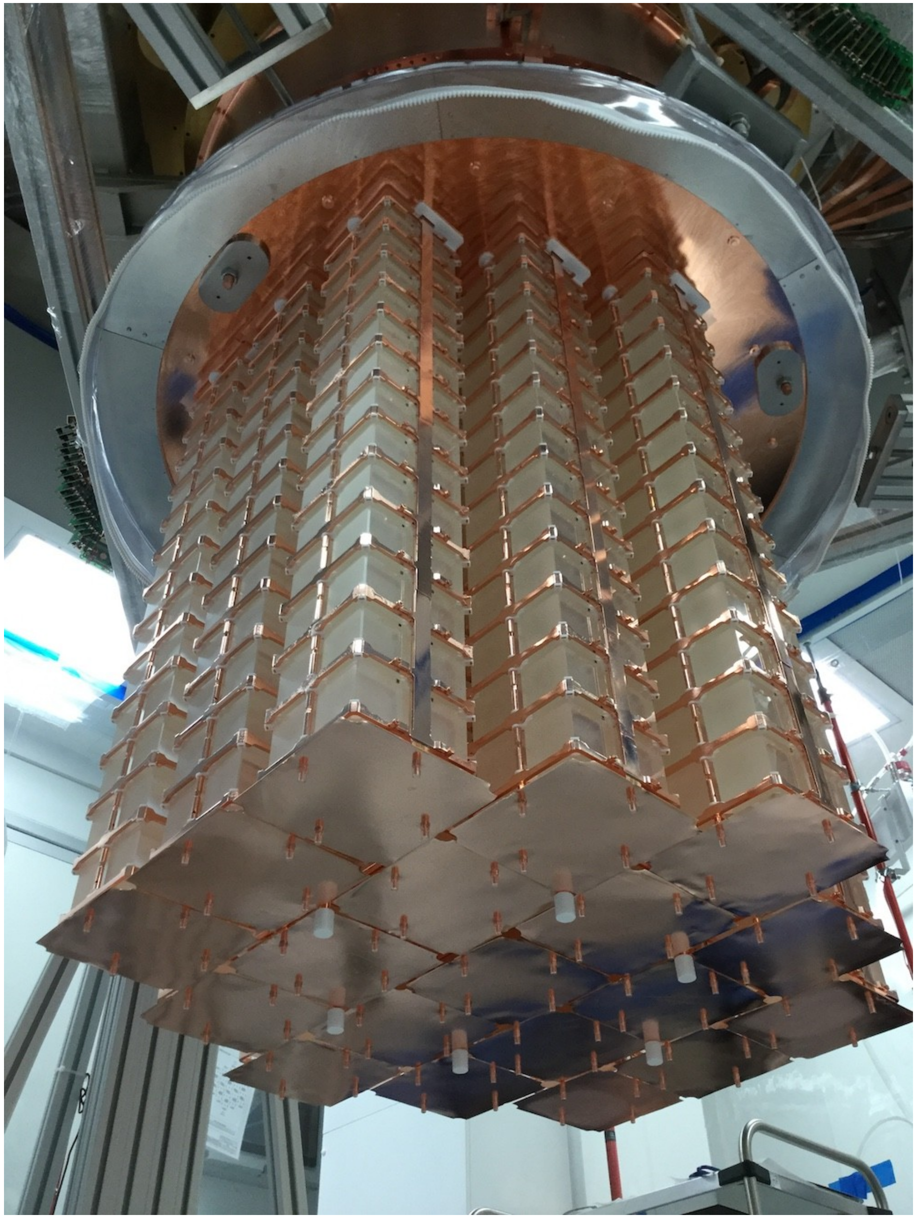
- 19 towers of 52 5x5x5 cm^3 TeO_2 crystals
- Total mass of 742 kg of TeO_2
- 0.5 kg of $0\nu\beta\beta$ isotope ^{120}Te
- Crystals held at 10 mK

Cuore Results



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

Cuore



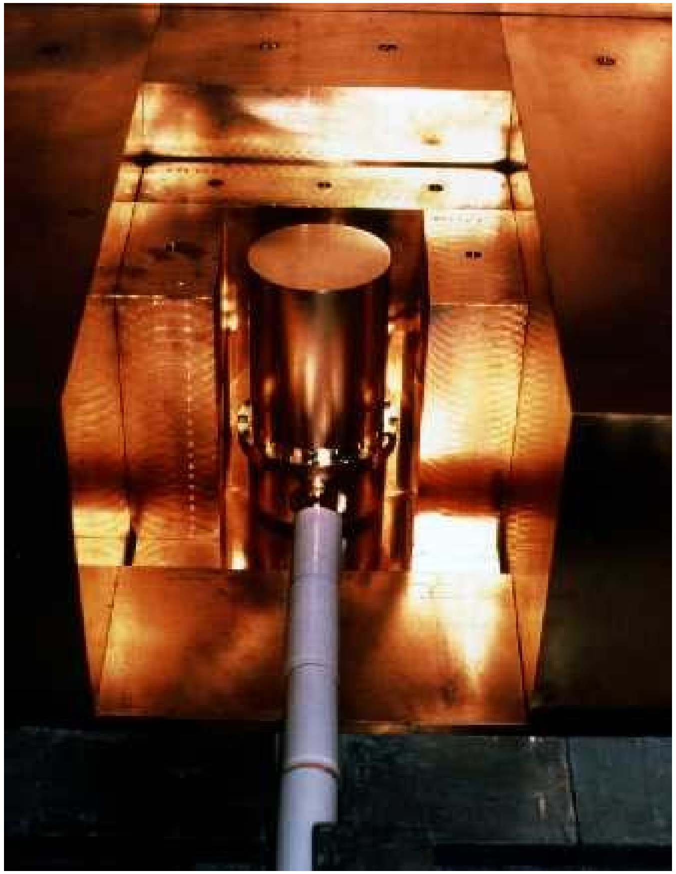
- Infrastructure now being developed for use in
- CUPID
- Will use 4 kg 95% enriched $Li_2{}^{100}MoO$

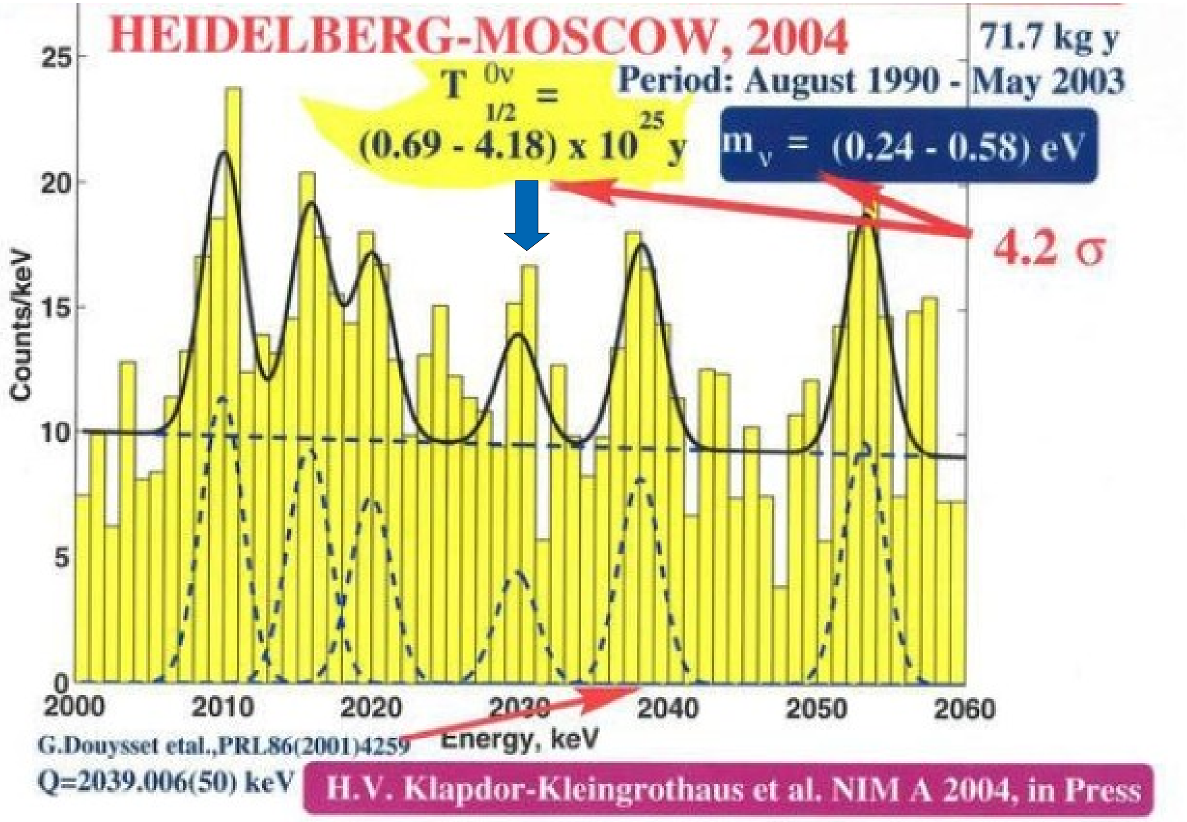
Heidelberg-Moscow (HdM)

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

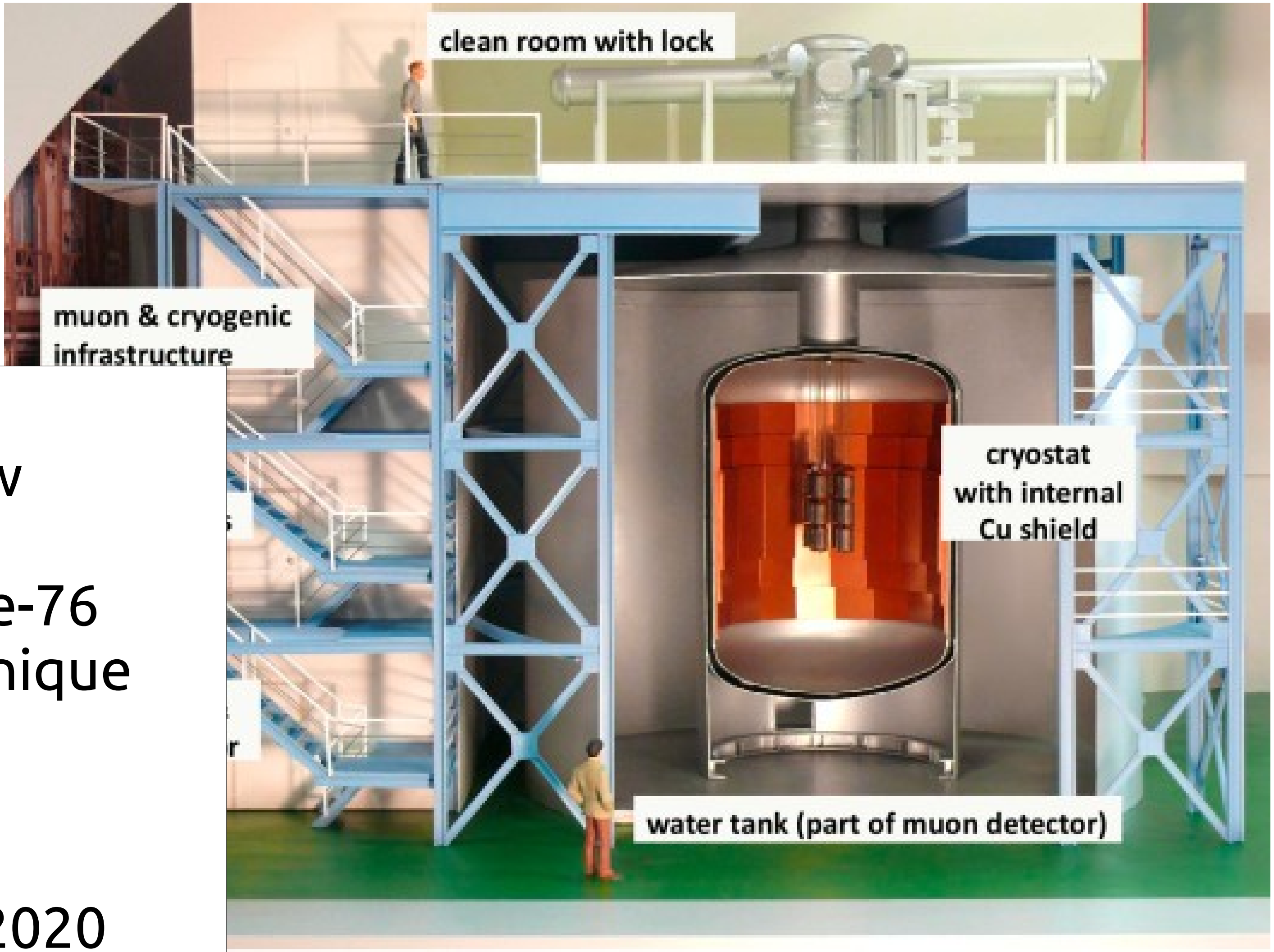
0νββ electrons detected by Ge detectors themselves

Sum of electron energy is measured



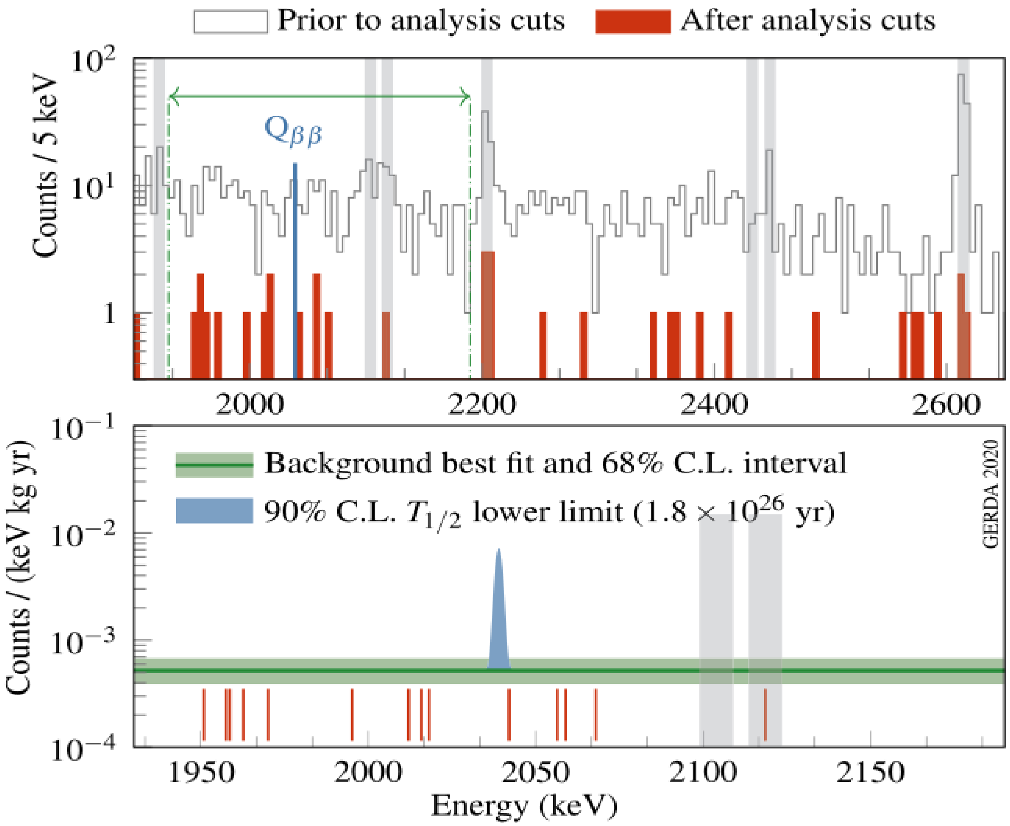


GERDA



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

GERDA



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

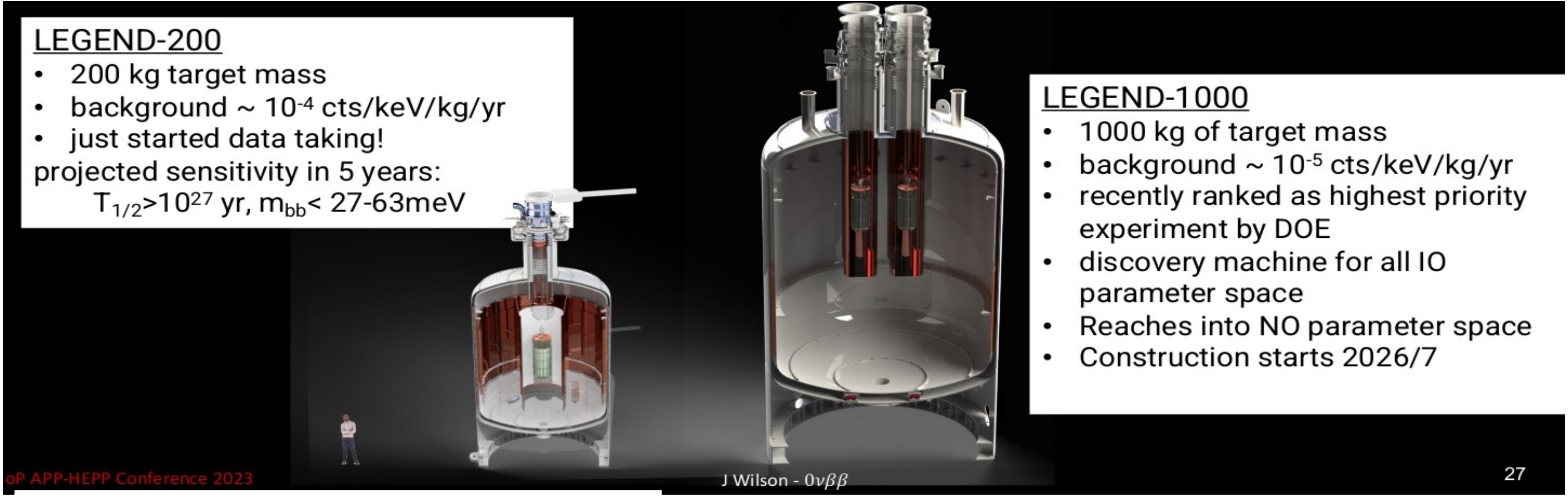
$m(\nu_e) < 79\text{-}180$ meV @ 90% CL

Inconsistent with HdM, but not definitive

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

LEGEND 200 - 1000

A phased ^{76}Ge 0νββ decay program
Sensitivity increased by two orders of magnitude : $t_{1/2} > 10^{28}$ years



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

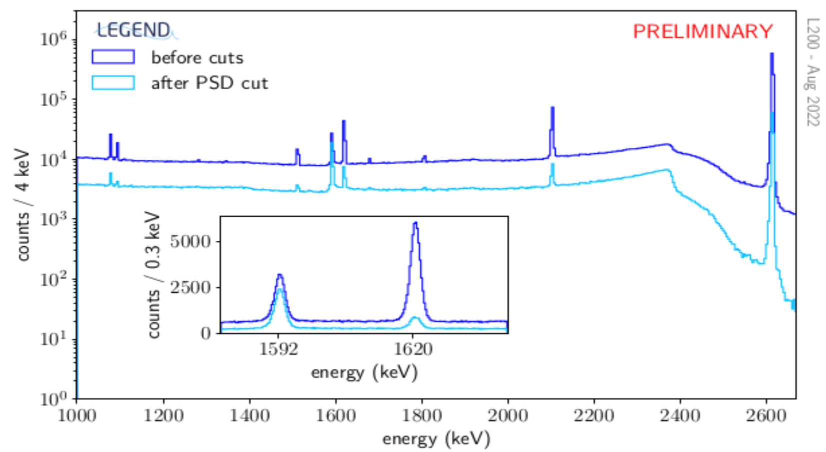
projected sensitivity in 5 years:
$T_{1/2}>10^{27}$ yr, $m_{bb}<$ 27-63meV

LEGEND-1000
- 1000 kg of target mass
- background ~ 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

oP APP-HEPP Conference 2023

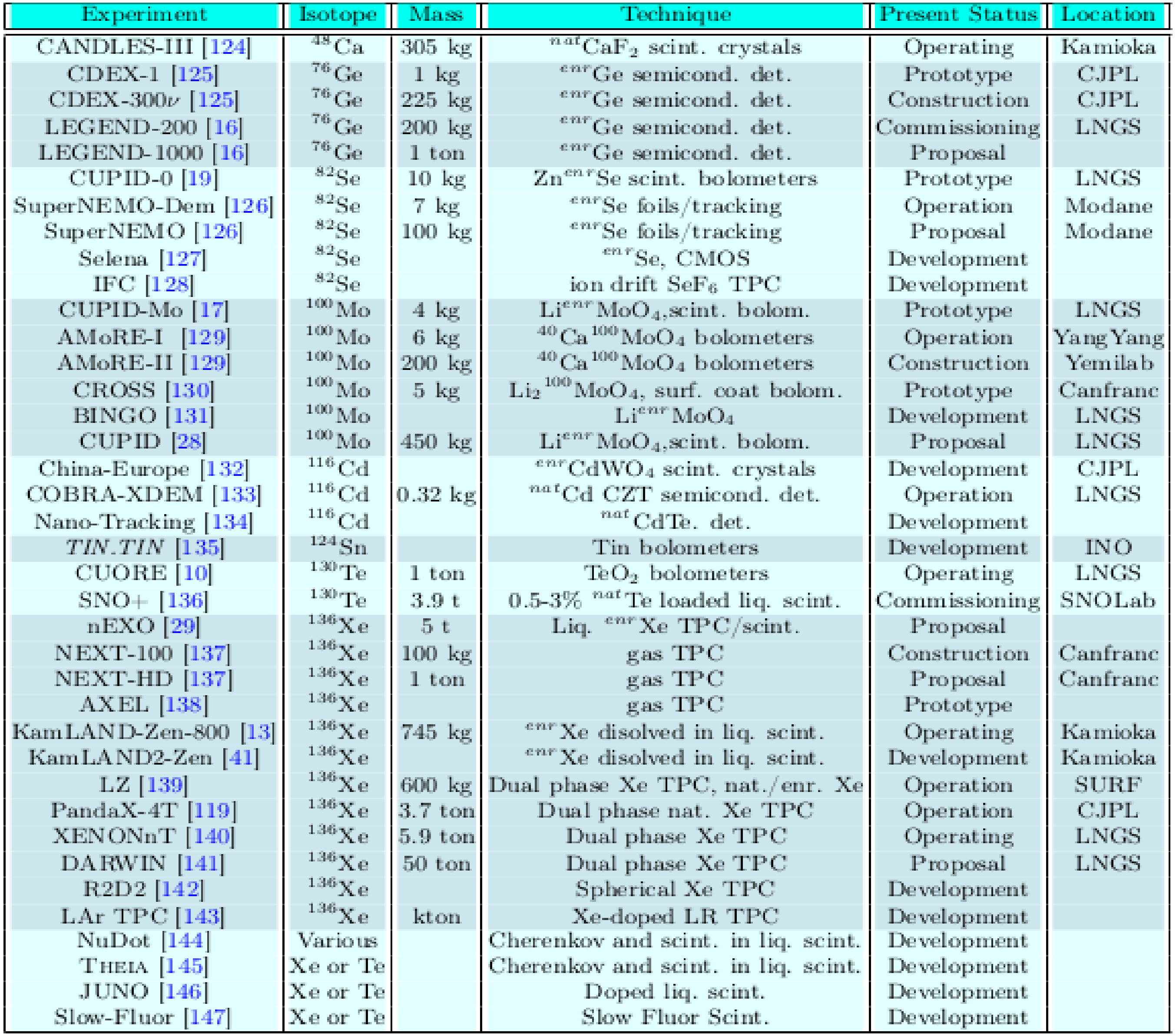
J Wilson - $0\nu\beta\beta$

27



- 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	$\left(\sum_i \lvert U_{ei}{}^2\rvert m_i^2\right)^{\frac{1}{2}}$	< 0.9 eV CRES < 0.09 eV?
0v2β decay	$\left\lvert\sum_i U_{ei}^2 m_i\right\rvert$	<0.18 eV $<m_{\beta\beta}>$=440 meV from HM
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? What about an indirect approach?

SN1987A

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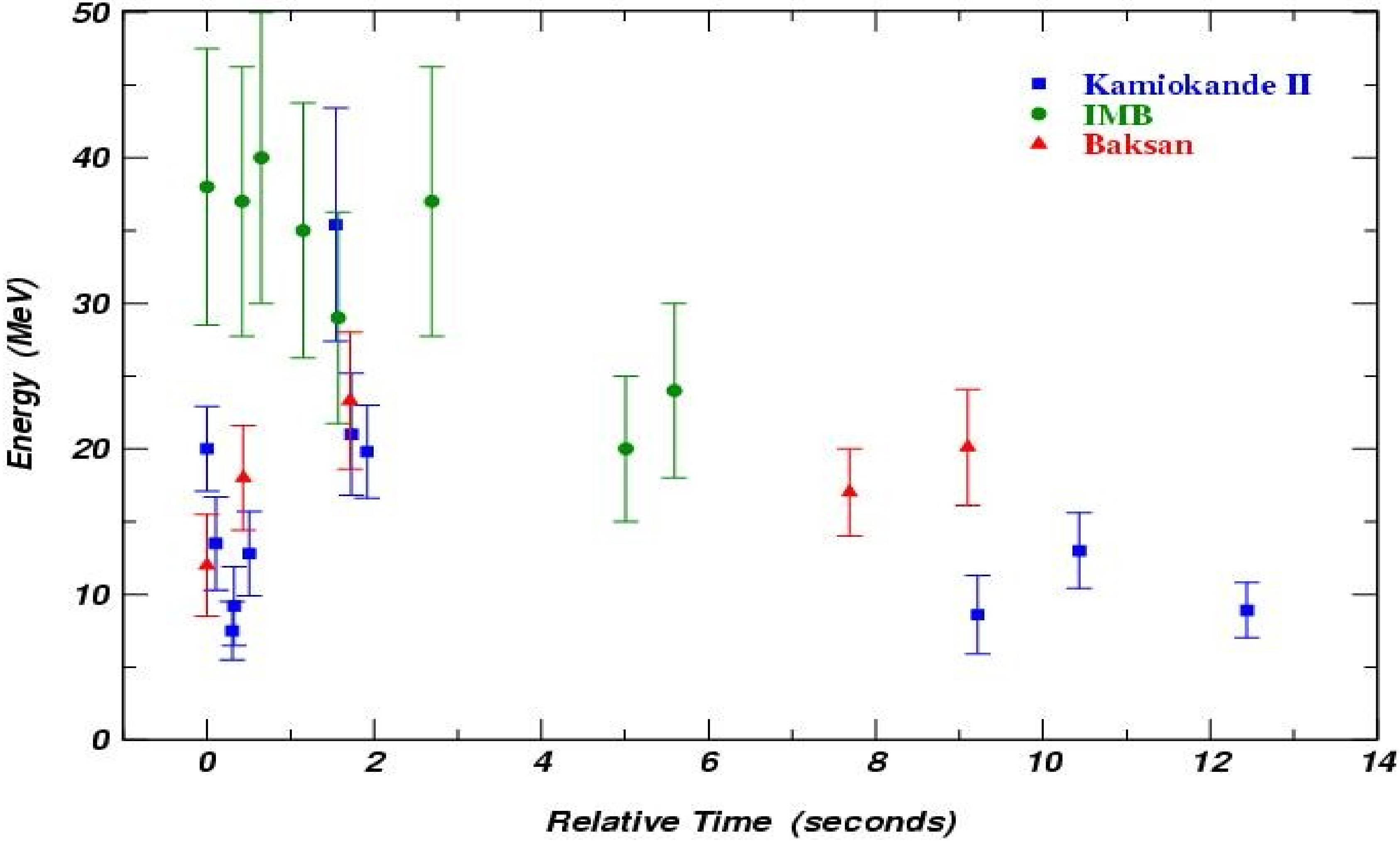
Neutrinos detected

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)

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

The General Mass Term

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

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

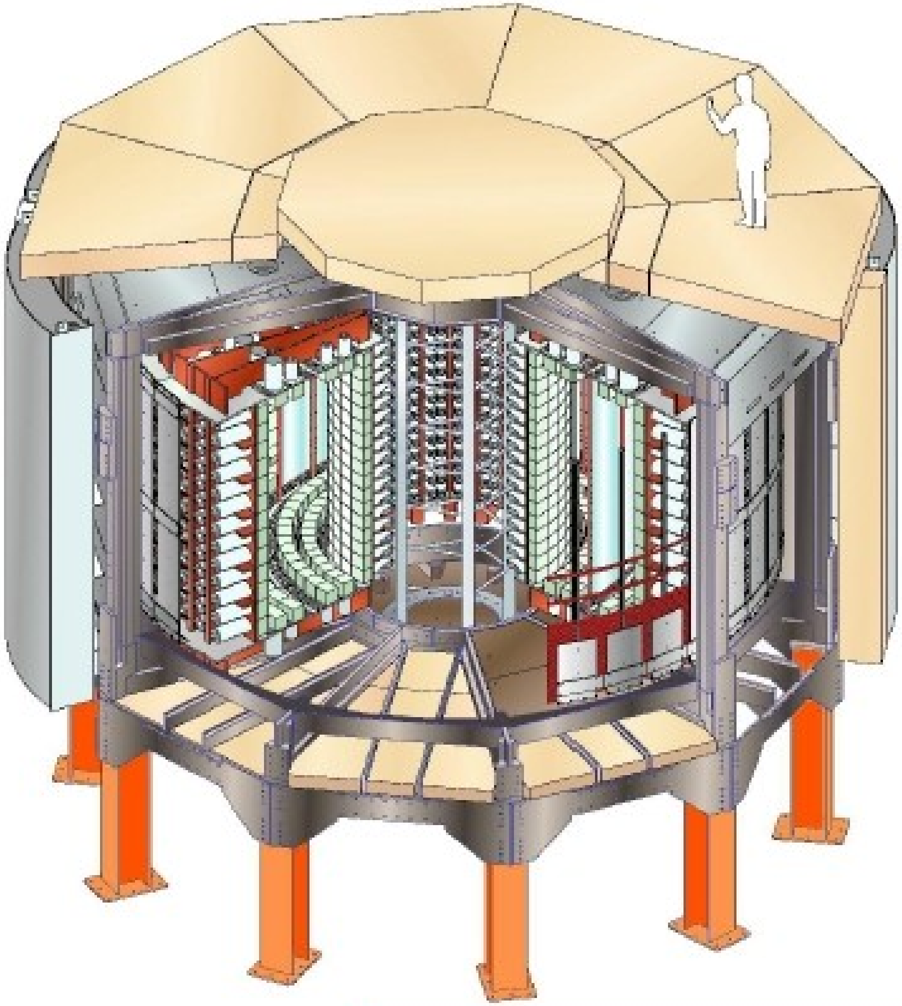
$$n \equiv \begin{pmatrix} n_L \\ n_R^C \end{pmatrix} \rightarrow L_{mass} = -\frac{1}{2}\left[\overline{n^C} M n + \bar{n} M n^C\right] \quad with \quad M = \begin{pmatrix} m_L & m_D \\ m_D & m_R \end{pmatrix}$$

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

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

Mixing matrix

Passive Source - NEMO3



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

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

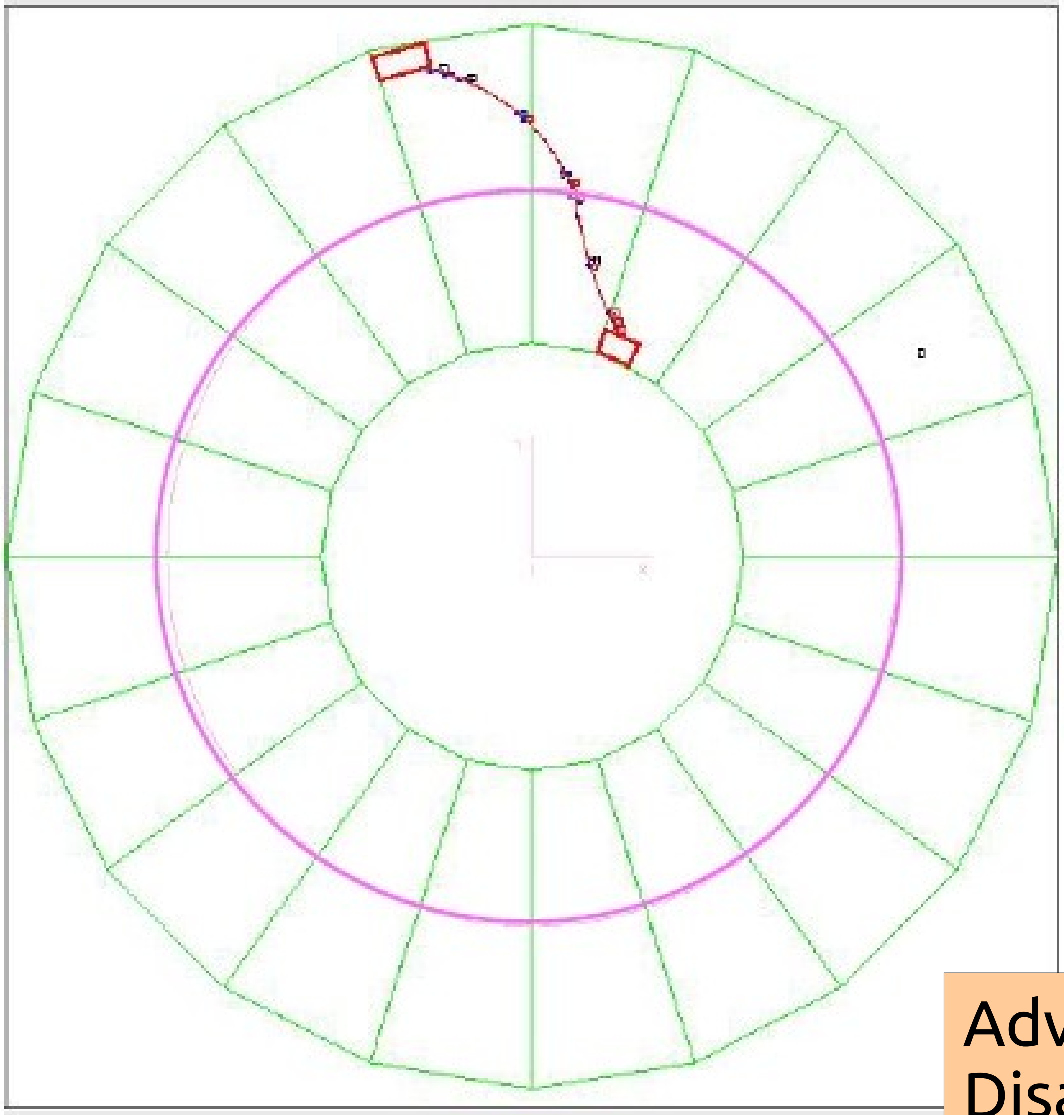
Calorimeter:
1940 plastic scintillators
coupled to low radioactivity PMTs

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

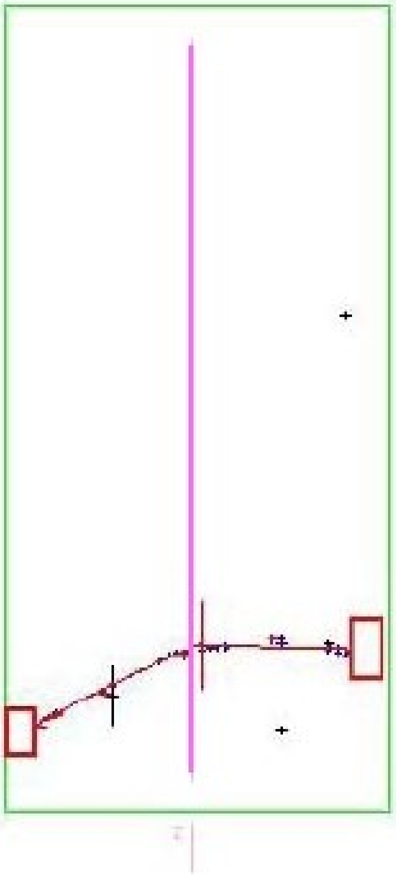
Background: natural radioactivity, mainly ^{214}Bi et ^{208}Tl (~2.6 MeV)

⇒ Able to identify e^-, e^+, γ and α

Typical ββ2ν event observed from ^{100}Mo



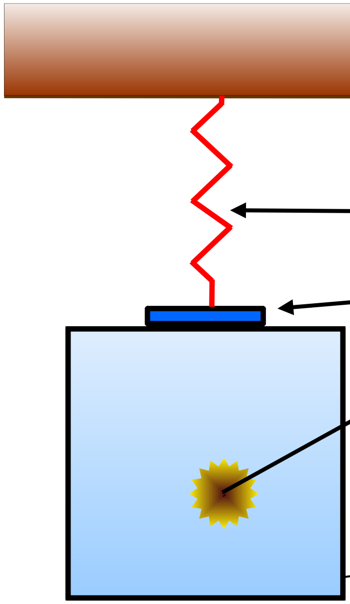
Top view



Side view

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

Cuoricino/Cuore



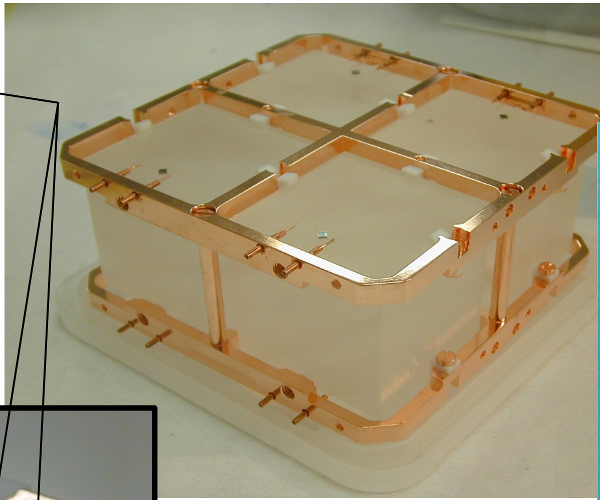
Heat sink

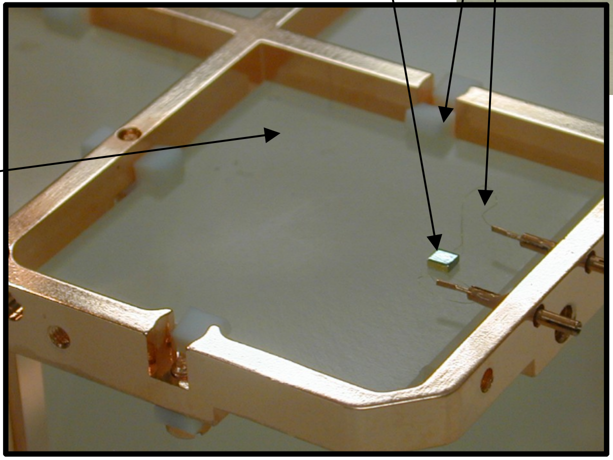
Thermal coupling

Thermometer

Double beta decay

Crystal absorber





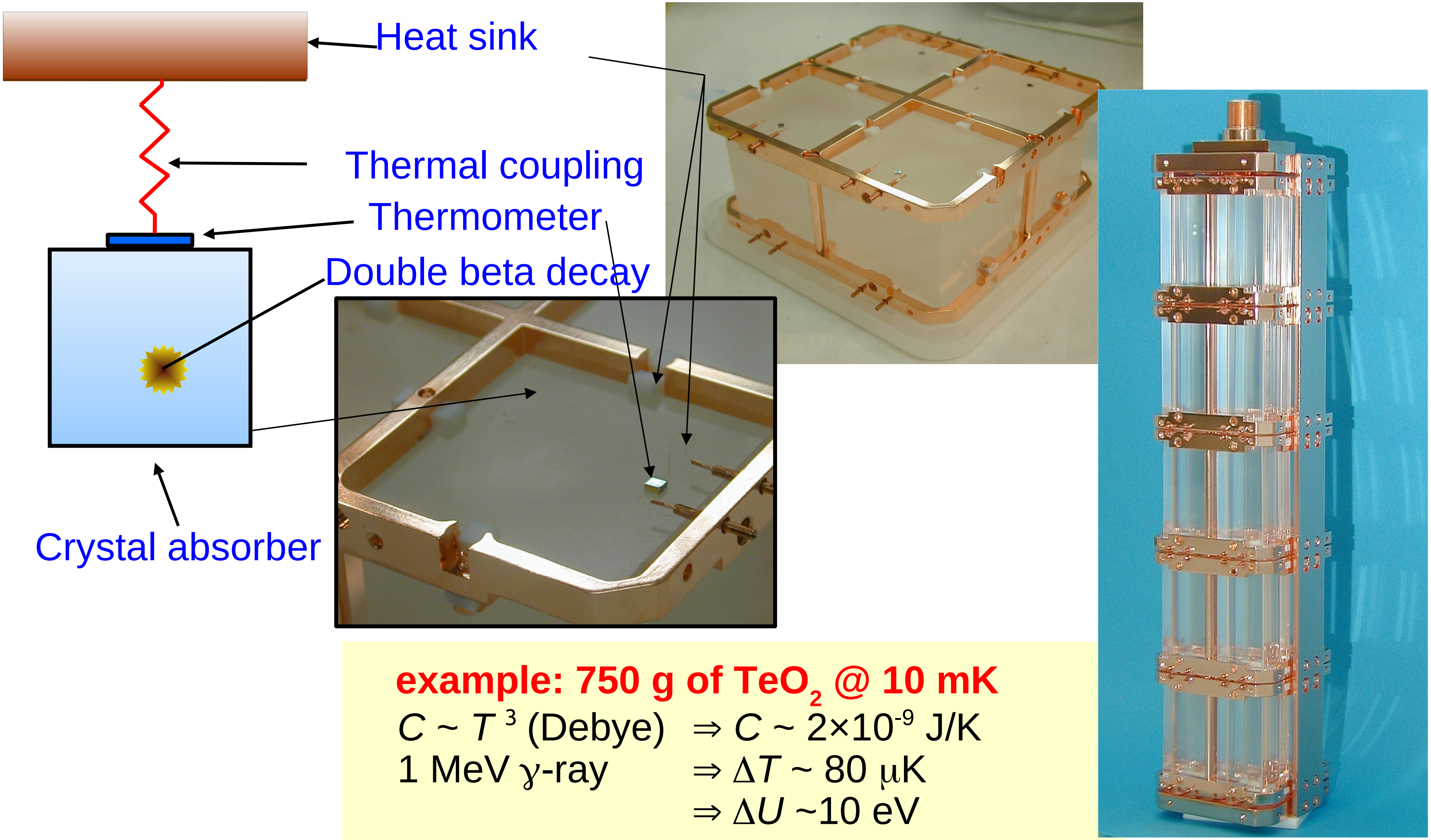
example: 750 g of TeO$_2$ @ 10 mK

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

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

⇒ $\Delta U \sim 10$ eV

Cuoricino/Cuore



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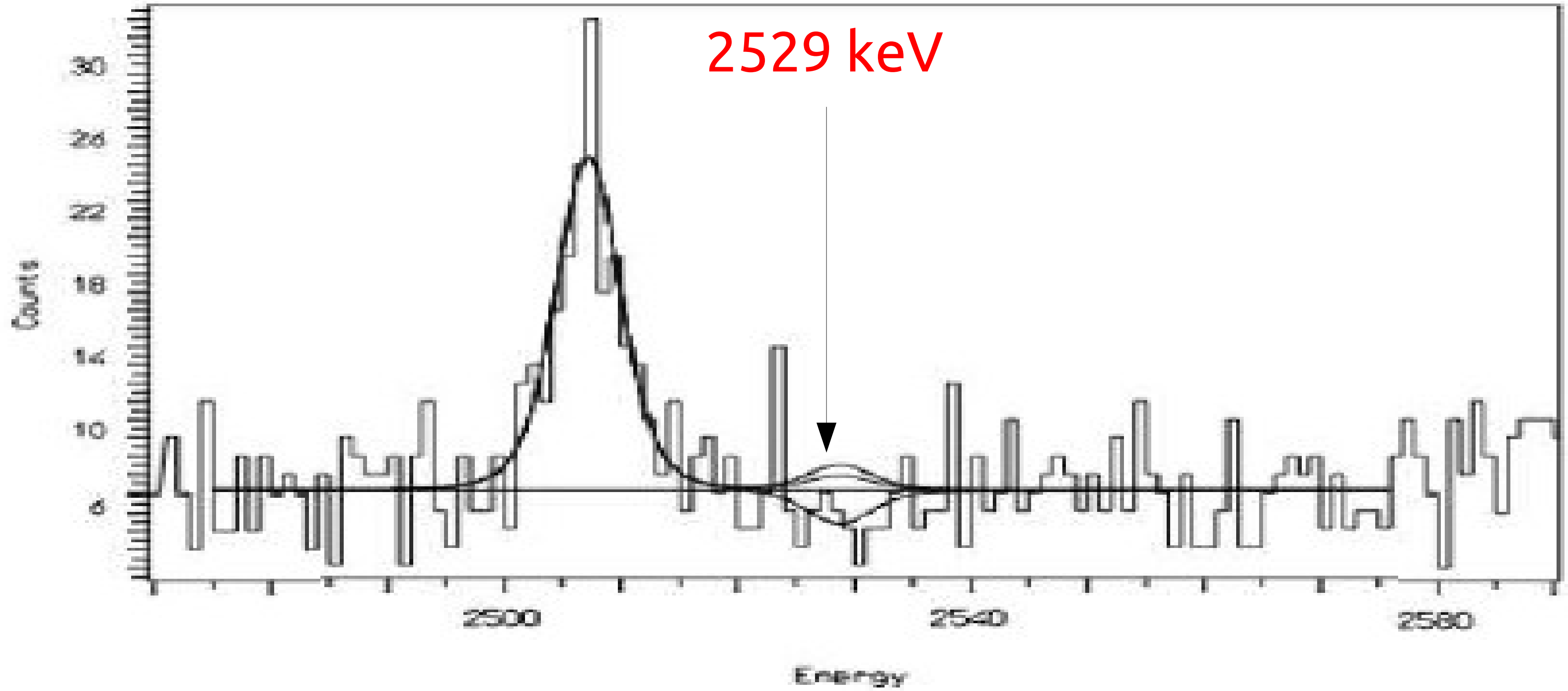
Cuoricino Results



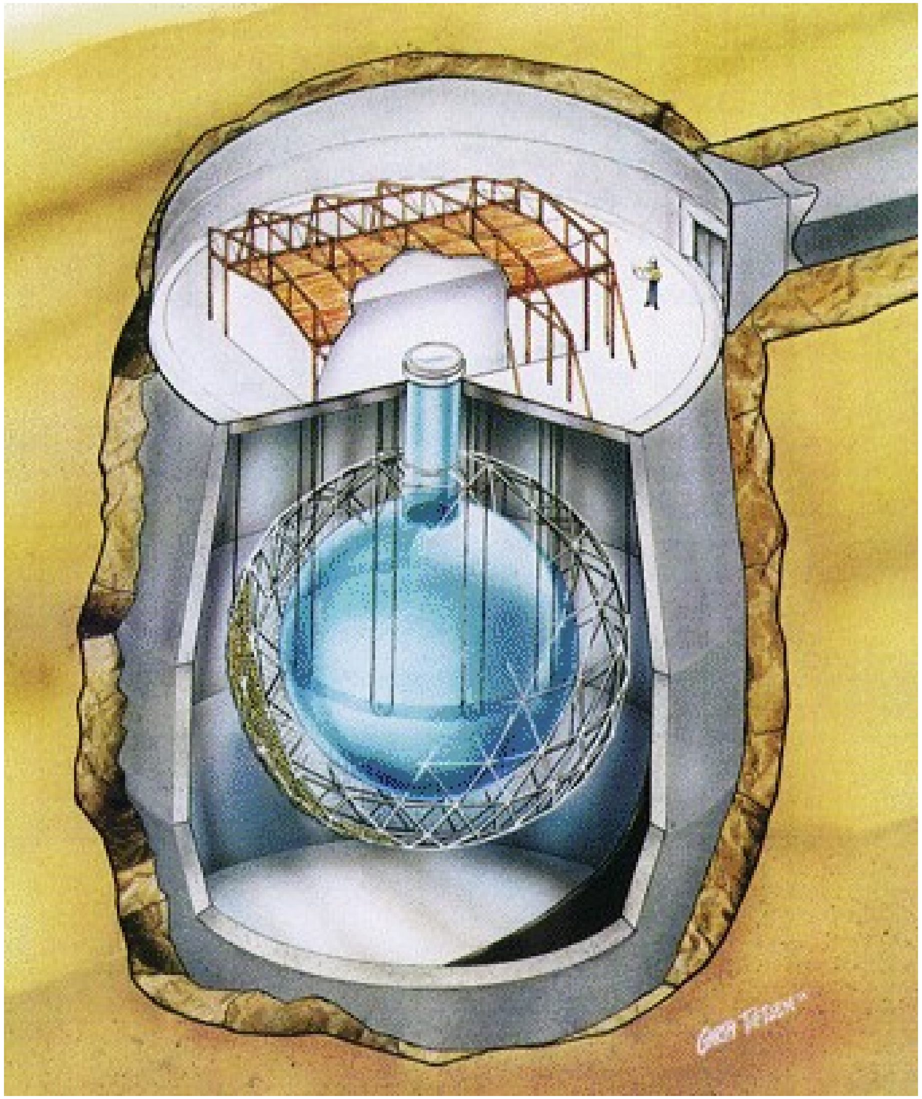
^{60}Co

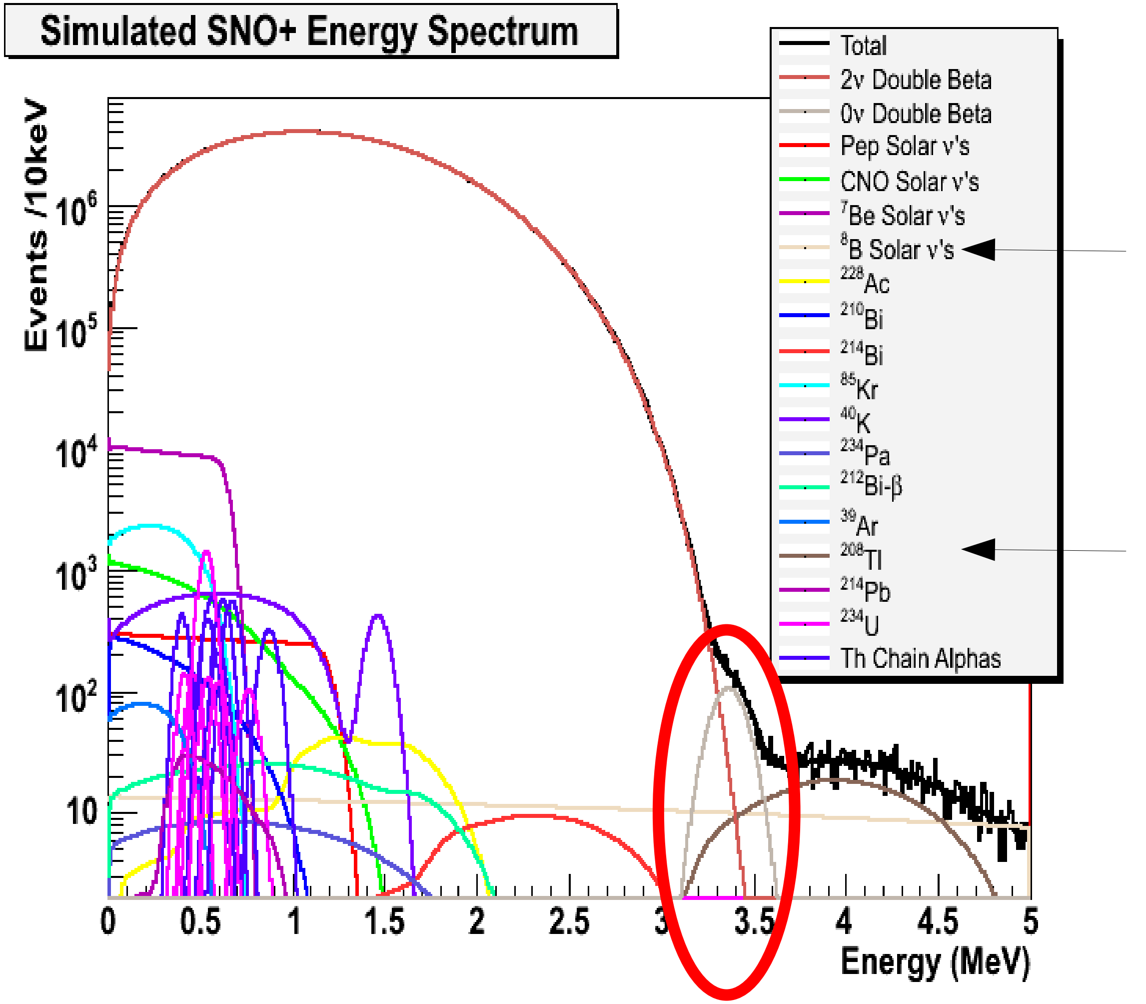
0νββ

2529 keV

$$T^{0\nu}_{1/2} > 3.0\times10^{24}\,years \;\Rightarrow\; \langle m_{\nu}\rangle < 0.68\,eV$$

SNO+





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

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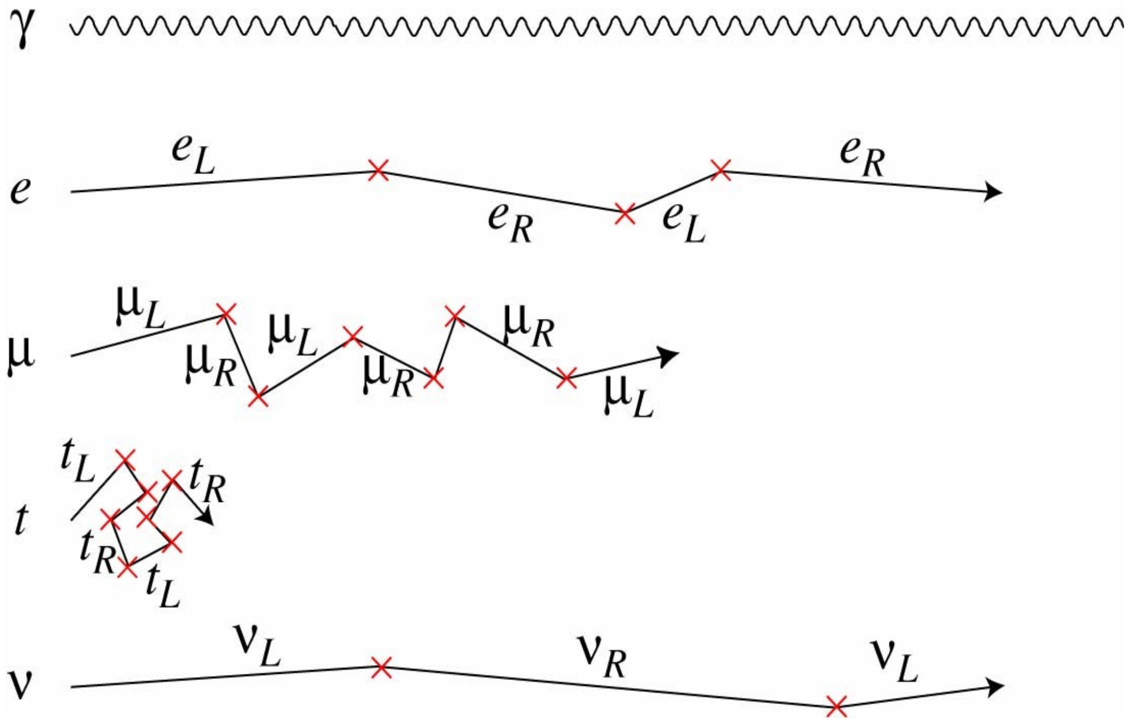
Mixing matrix

Two ways to go

Dirac neutrinos

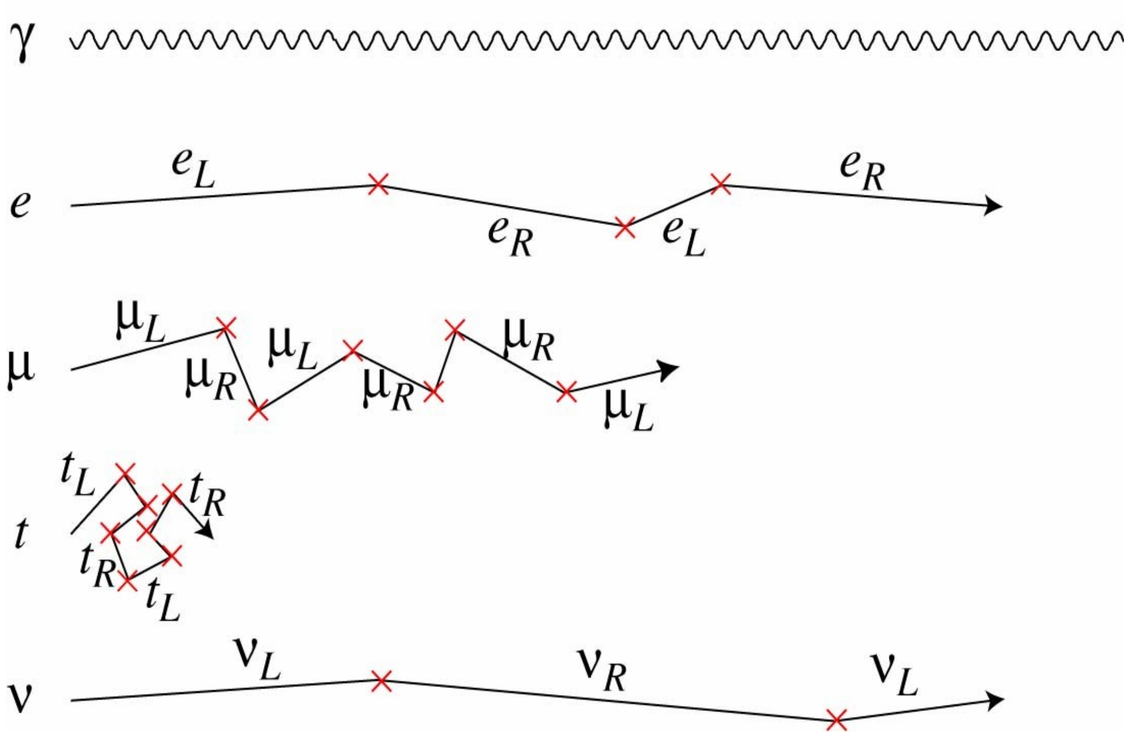
- There are new particles (right handed neutrinos) after all
- Why haven't we seen them?
- They must only exist to give neutrinos mass
- Still have to solve the question of their very very weak coupling



Two ways to go

Majorana neutrinos

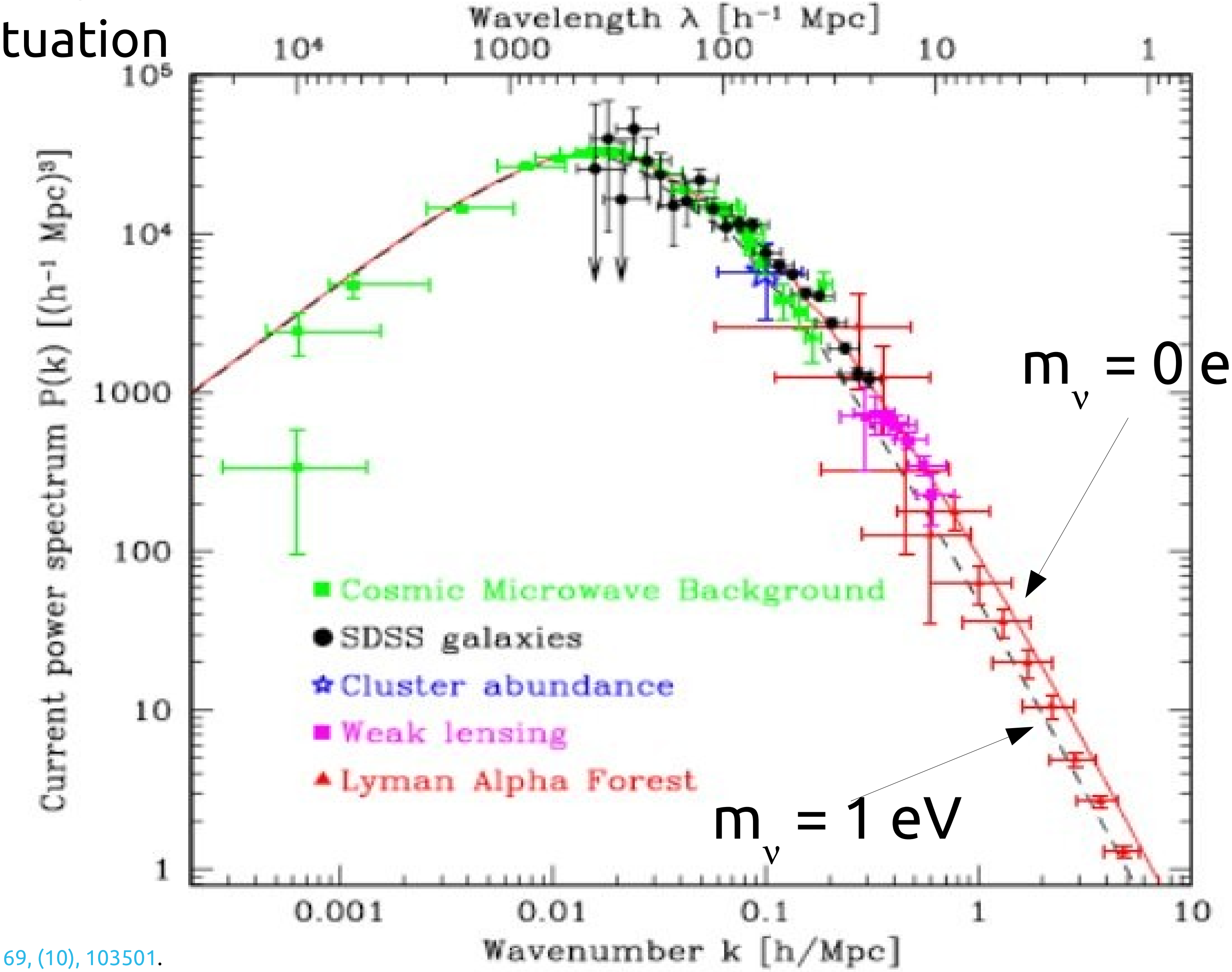
- There are new particles (right handed neutrinos) after all
- If I pass a neutrino and look back I will see a right-handed thing
- Must be a right-handed anti-neutrino
- No fundamental difference between neutrinos and anti-neutrinos



(Theorists Favourite!)

Power spectra

“Wavelength” of density fluctuation



$m_\nu = 0$ eV

$m_\nu = 1$ eV

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

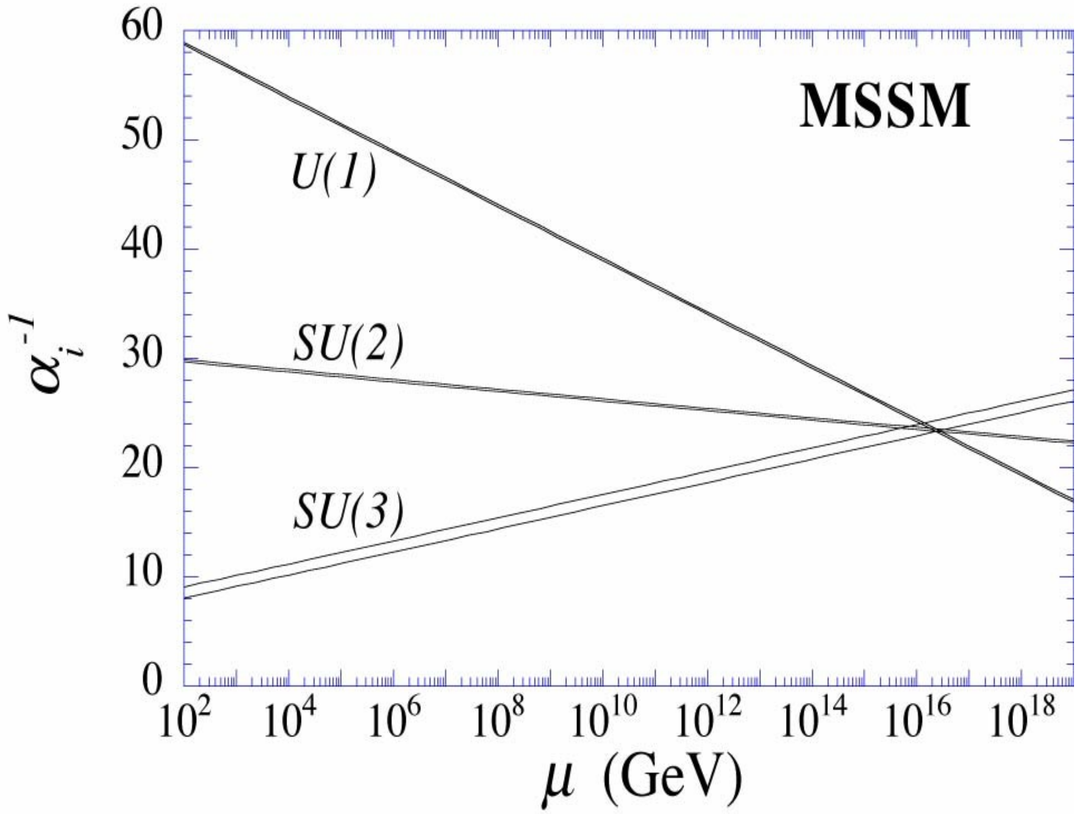
Seesaw and GUTs

- 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

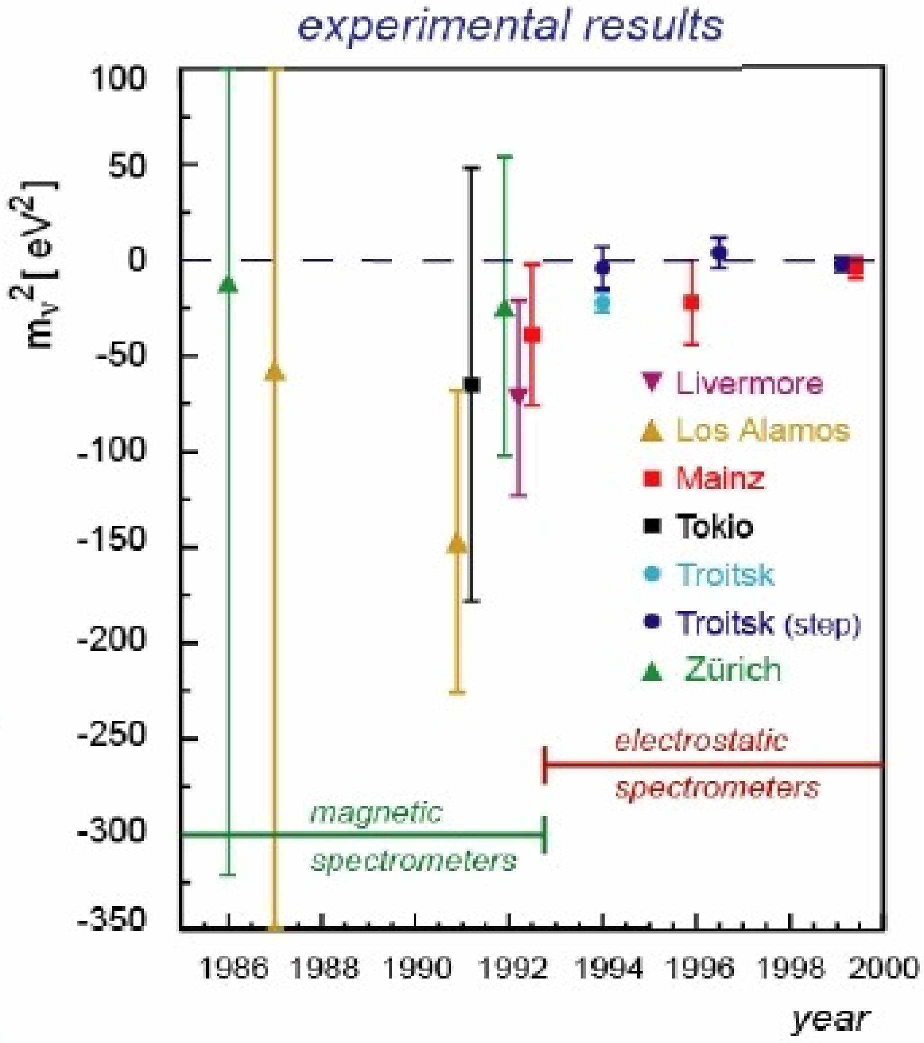
- Probing of GUT scale physics using light neutrinos!



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

History of Tritium-β decay

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



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

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

Written in the mass basis
States of definite mass

Can write the mass eigenstates in terms of the Majorana fields

Mass Eigenstates
(Physical particles)

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

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

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

Majorana field

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

Written in the
Chiral basis

Katrin on the move