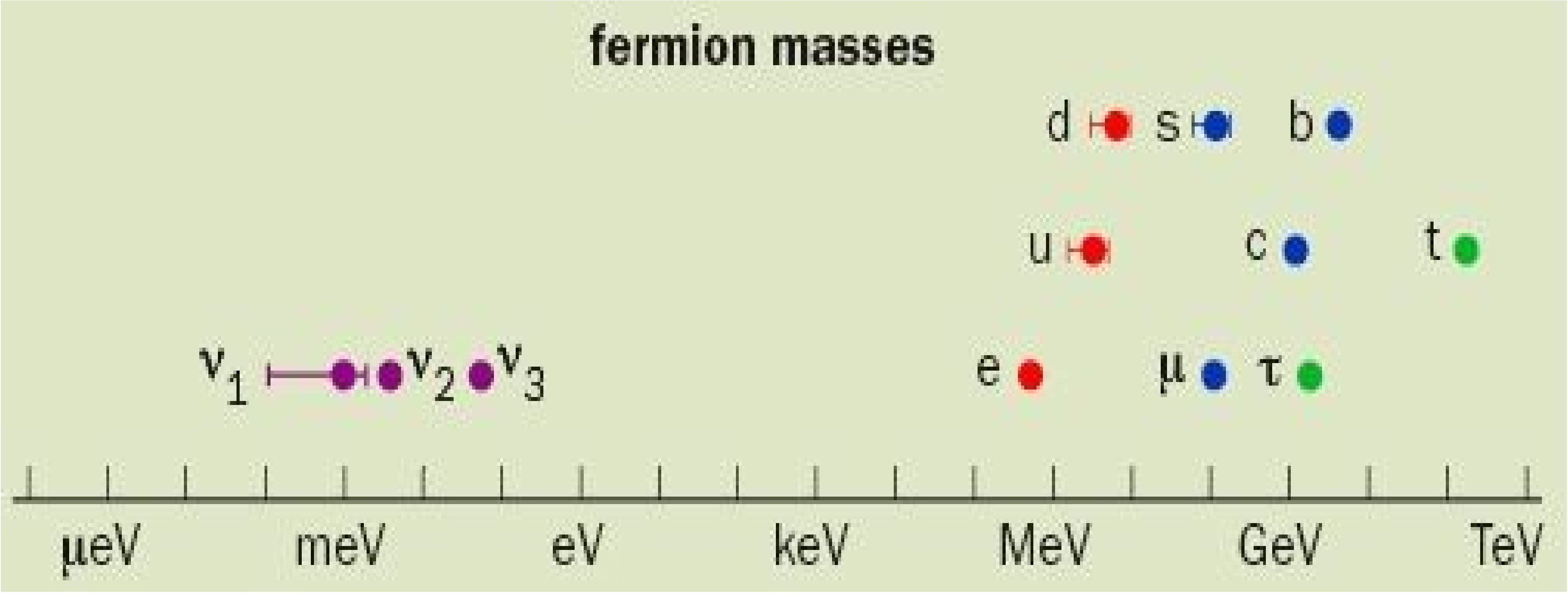
Lecture 2

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

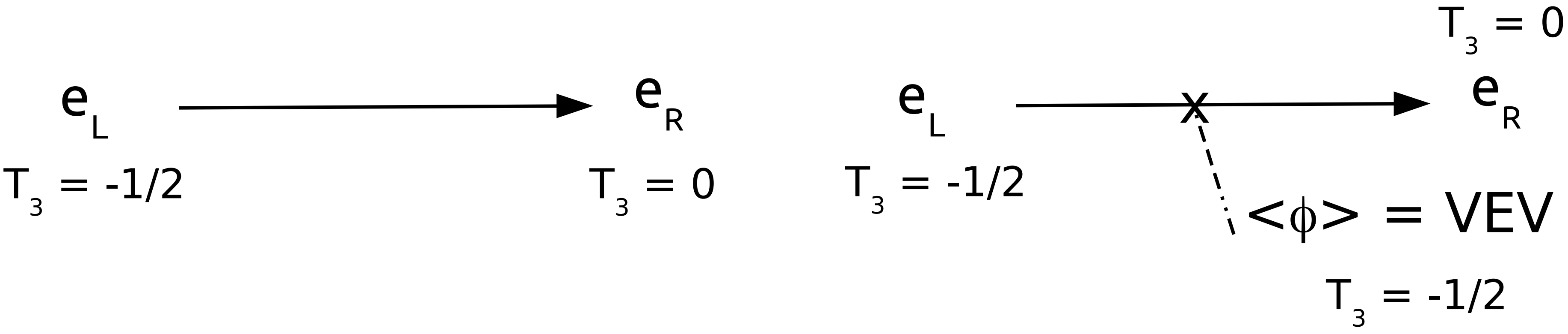
$$L_{mass} = m_D \overline{\psi}\psi = m_D(\overline{\psi_L} + \overline{\psi_R})(\psi_L + \psi_R) = m_D(\overline{\psi_L}\psi_R + \overline{\psi_R}\psi_L)$$

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

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

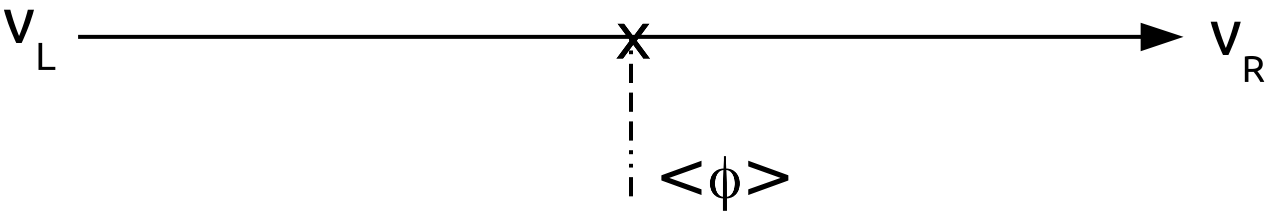


Dirac mass : $m_D = Y_\psi\langle\phi\rangle$ $\langle\phi\rangle = 246\,GeV$

- 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

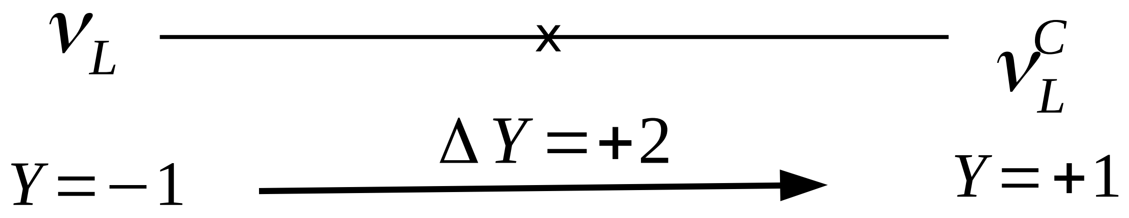
$$L_{Maj} = \frac{1}{2} m_L \left(\overline{\nu^C} \nu + \overline{\nu} \nu^C \right) = \frac{1}{2} m_L \left(\overline{\nu_L^C} \nu_L + \overline{\nu_L} \nu_L^C \right)$$

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

Damn

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

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



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.

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

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

right-handed
heavy neutral lepton

“our” neutrino

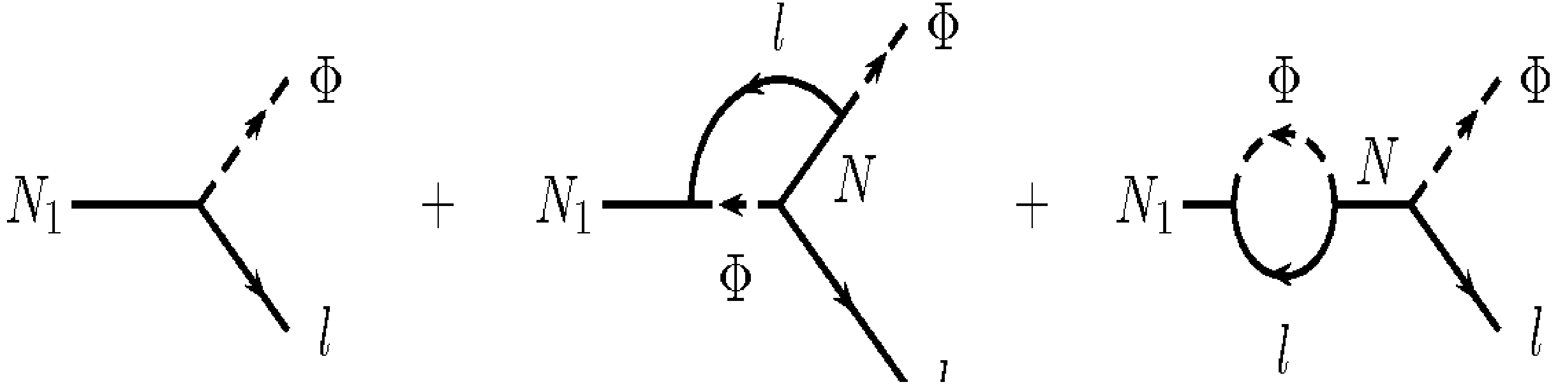
- Mass of “our” neutrino suppressed by the GUT scale
- Currently our only “natural” way to explain why the neutrino mass is so much smaller than other Dirac particles

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 (via non perturbative *sphaleron* transitions 🤷)

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

This idea requires

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

Leptogenesis

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(via non perturbative *sphaleron* transitions 🤷)

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

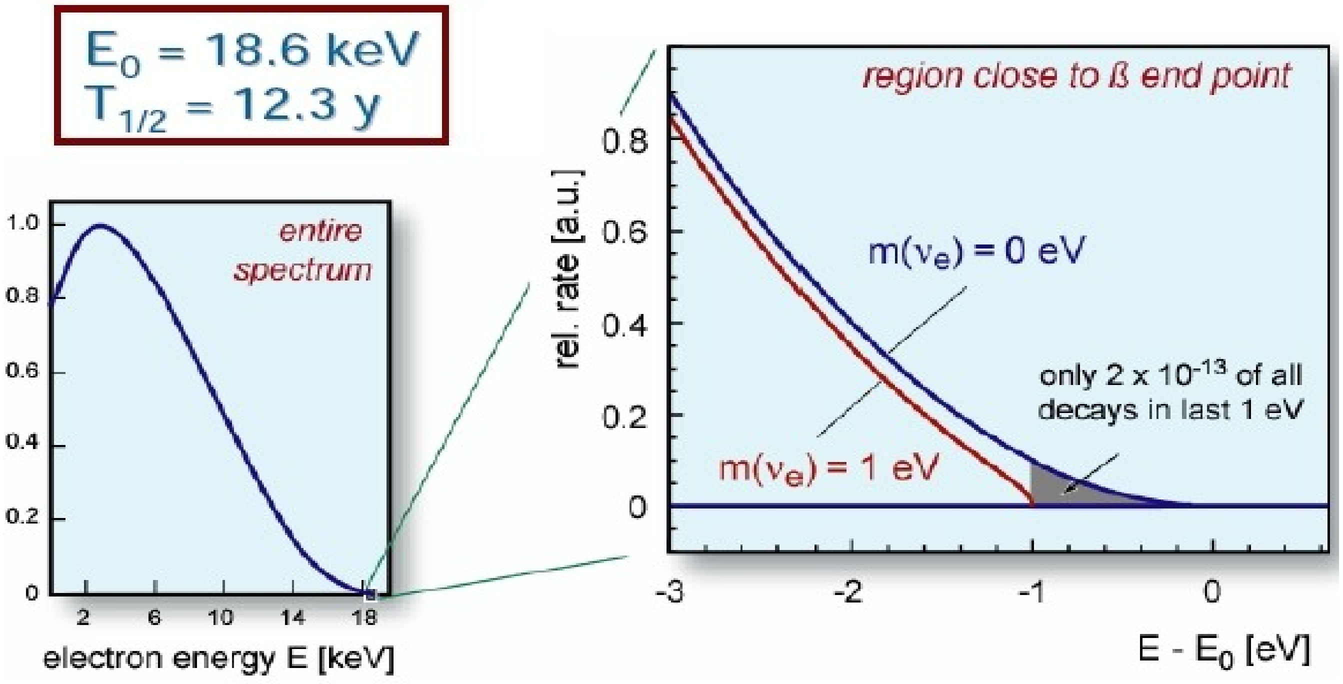
(Attempts at) mass measurements

ν_e mass

Measurement of ν_e mass from kinematics of β decay.

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

Observable is m_ν^2



Requirements

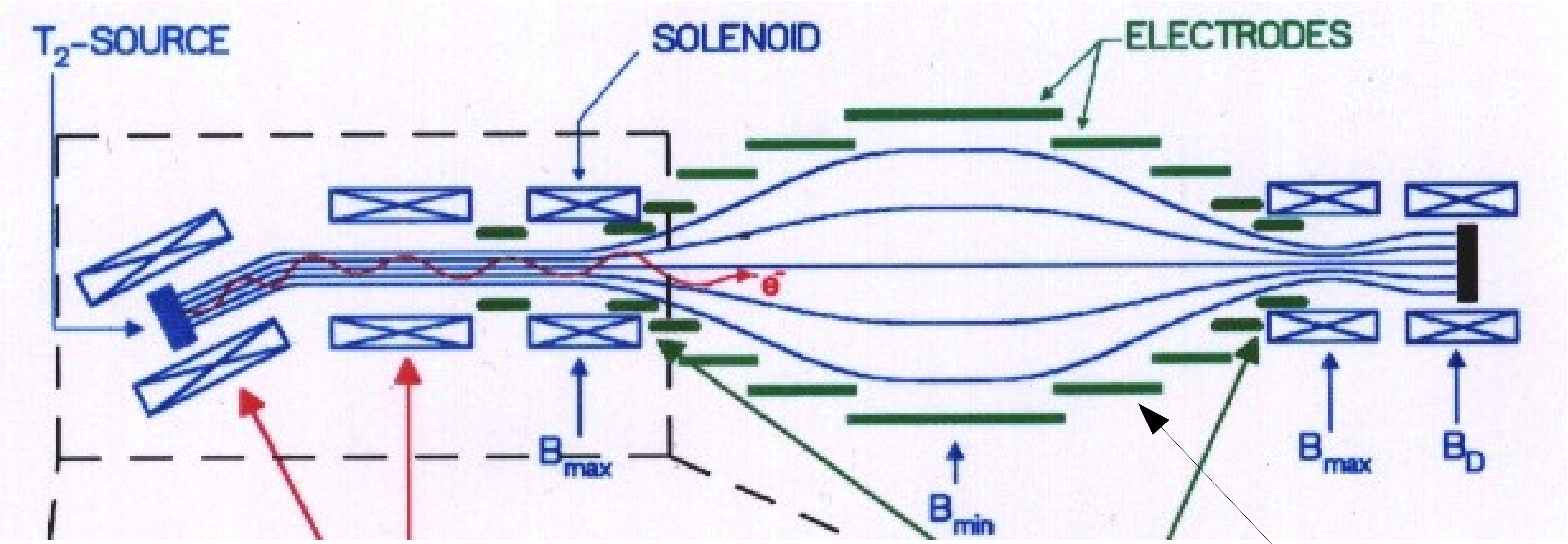
- # electrons close to the endpoint should be large
- Good (and well-understood) electron energy resolution
- No (or minimal) electron energy loss within the source
- Minimal atomic and nuclear final state effects, of excited transitions

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

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

Mainz Experiment

The current standard for tritium beta decay experiments



- 2π acceptance
- High energy resolution

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

Electrostatic
MAC-E Filter

Present Status

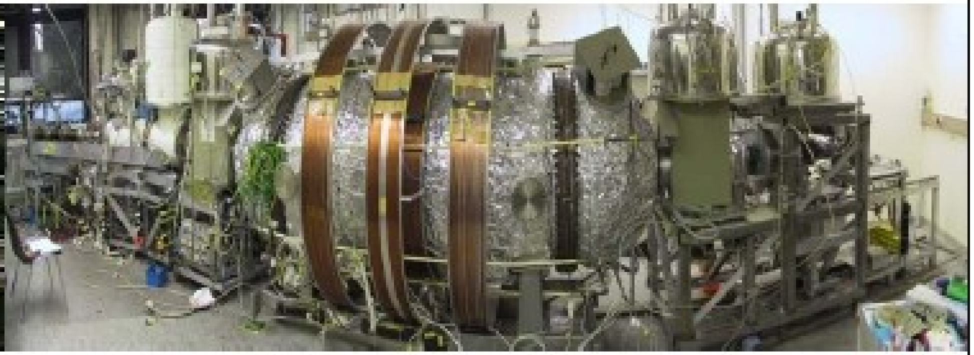
Troitsk

windowless gaseous T_2 source

analysis 1994 to 1999, 2001

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

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



Mainz

quench condensed solid T_2 source

analysis 1998/99, 2001/02

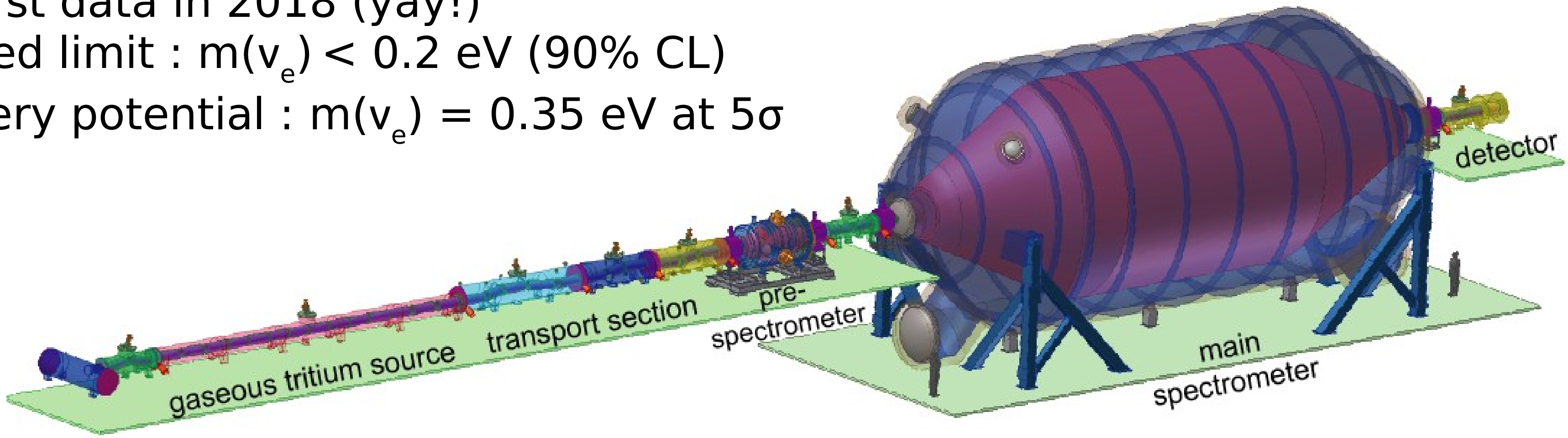
$m_\nu^2 = -1.2 \pm 2.2 \pm 2.1\ \mathrm{eV}^2$

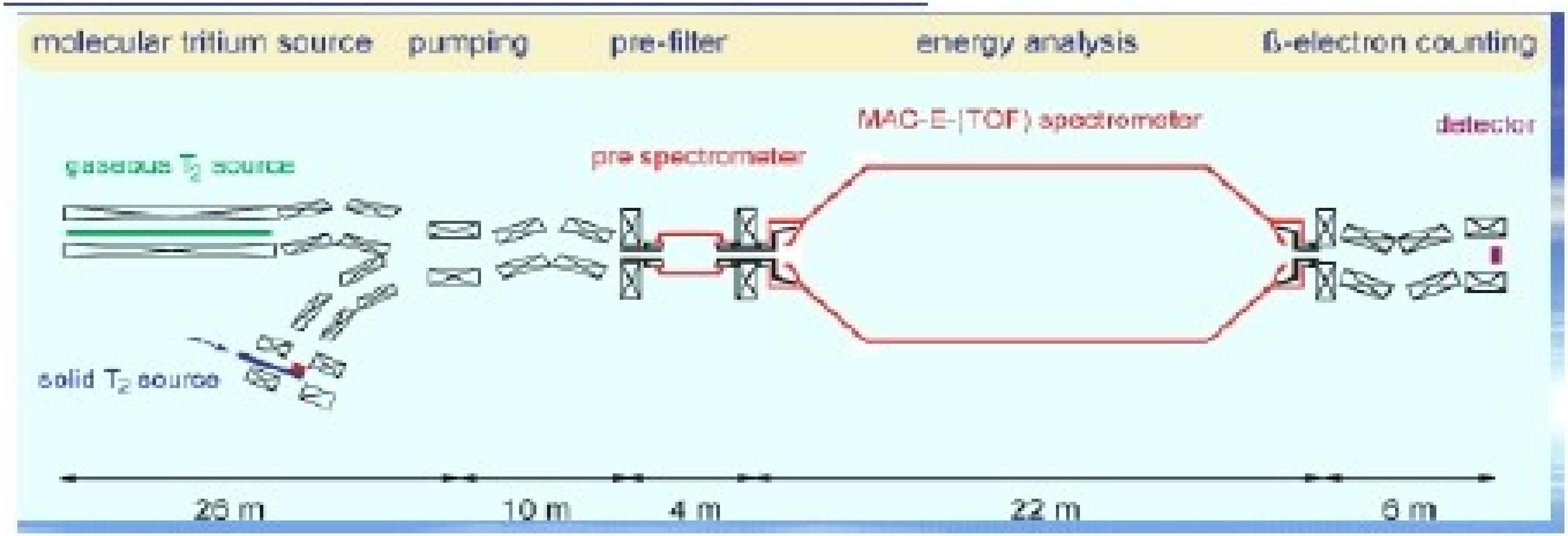
$m_\nu \leq$ 2.2 eV (95% CL.)

Both experiments have reached the intrinsic limit of their sensitivity.

KATRIN

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

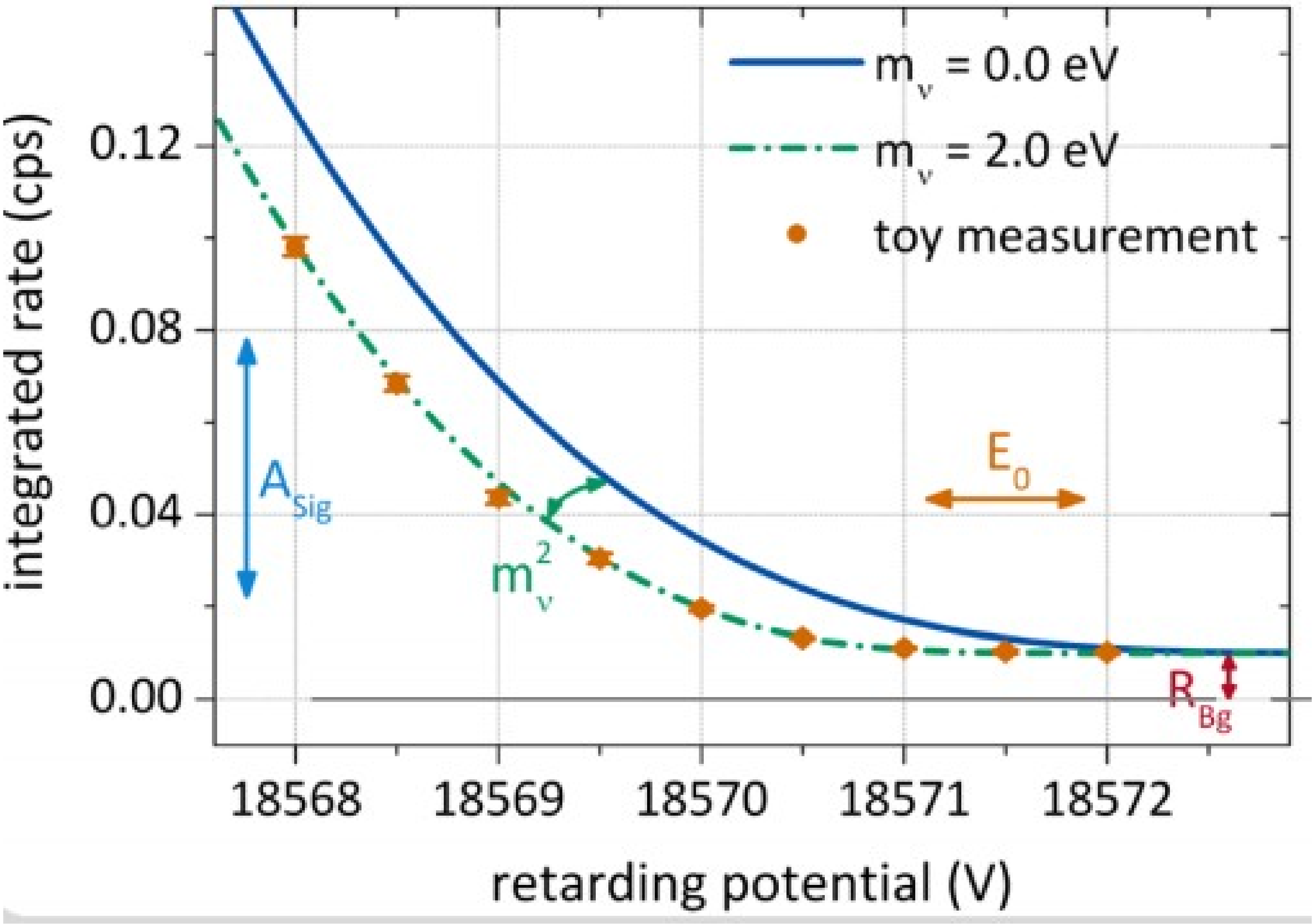




Katrin on the move

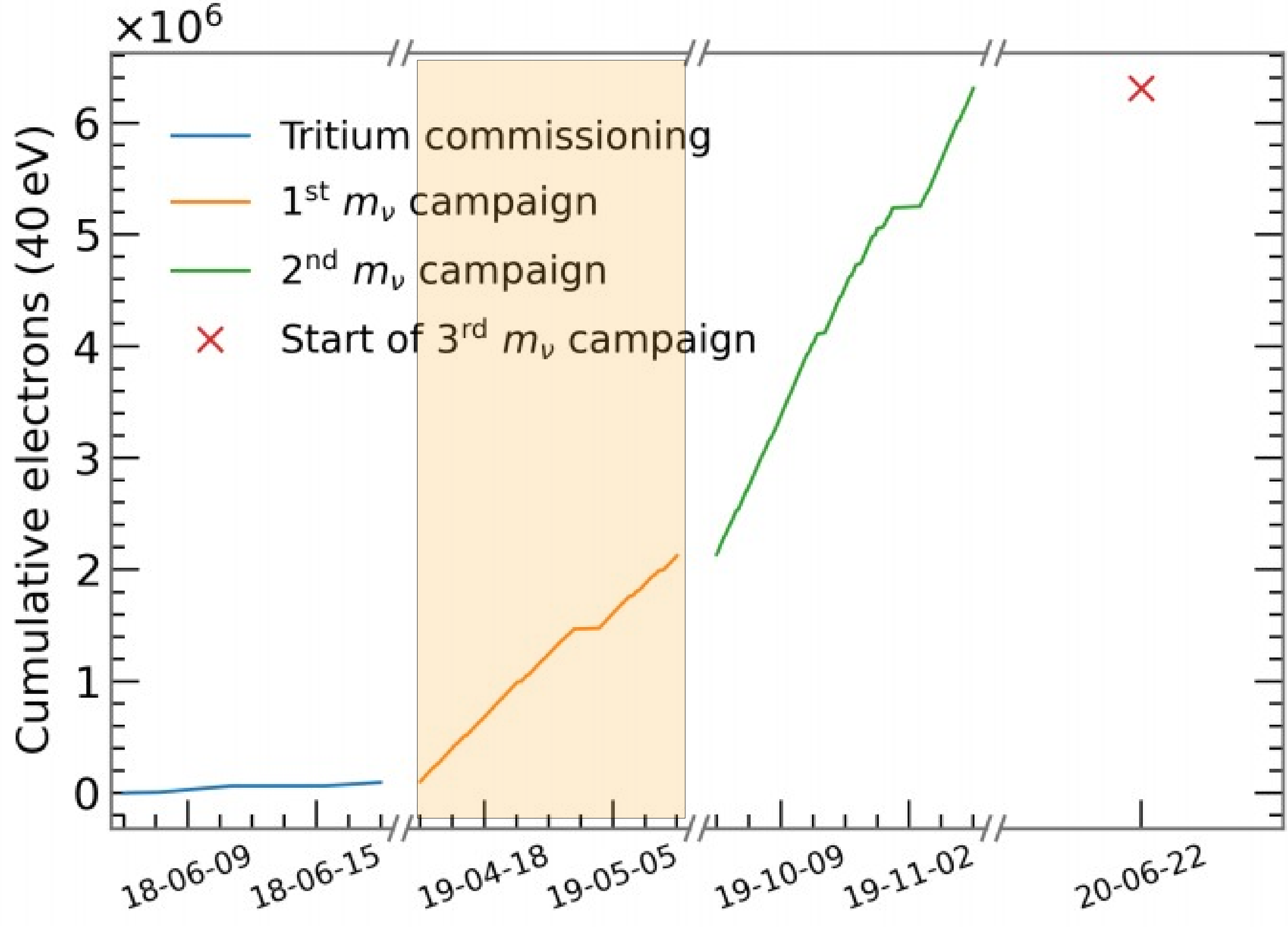
KATRIN on the move

Katrin data



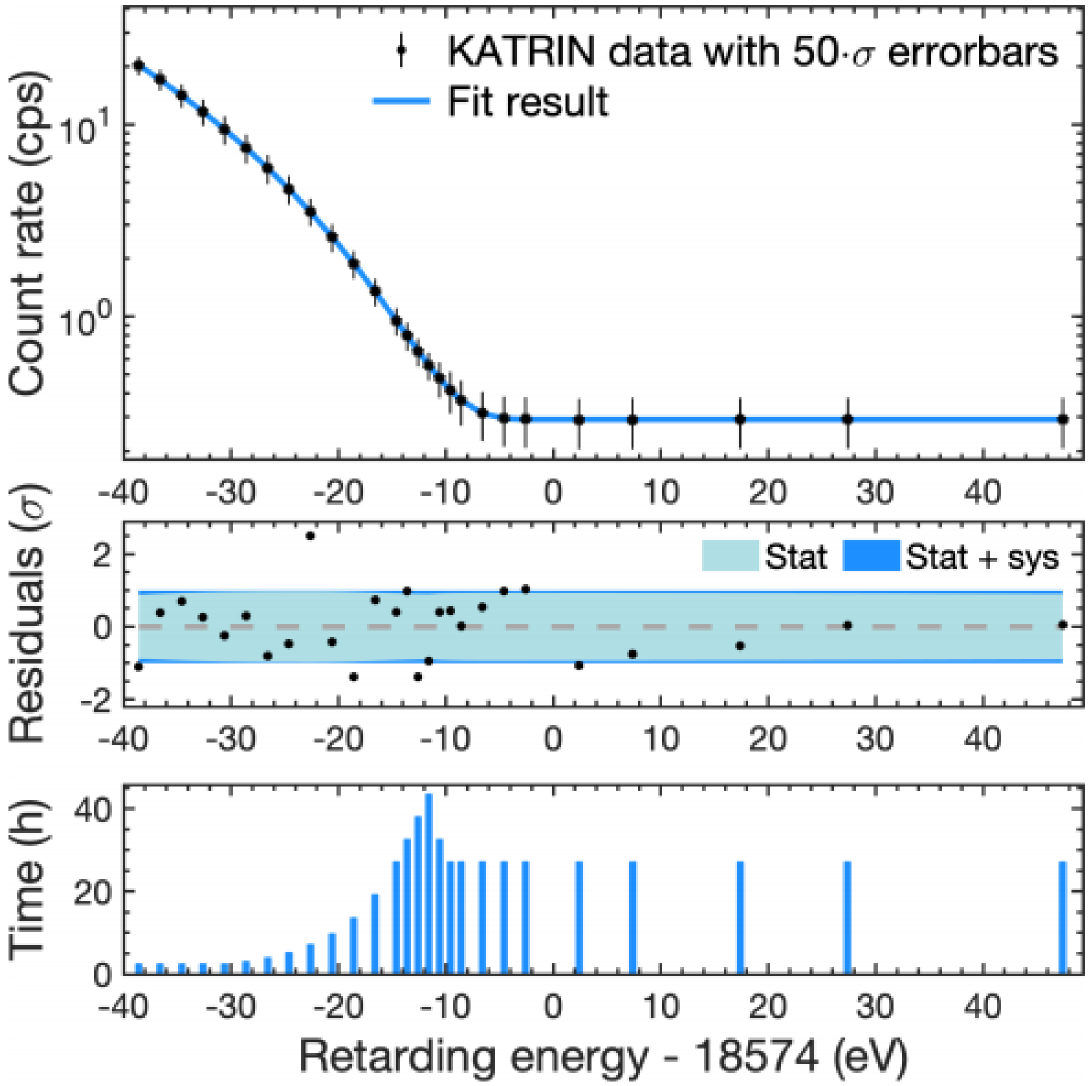
m_ν = 0.0 eV
m_ν = 2.0 eV
toy measurement
integrated rate (cps)
0.12
0.08
0.04
0.00
A_{Sig}
m_ν^2
E_0
R_{Bg}
18568
18569
18570
18571
18572
retarding potential (V)

KATRIN Data-taking



As of Neutrino 2020 (June 2020)

First KATRIN result



- 2 million electrons
- Fit for electron neutrino mass:

$$m_\nu^2 = \left(-1.0 \pm 1.0\right) \; eV^2$$

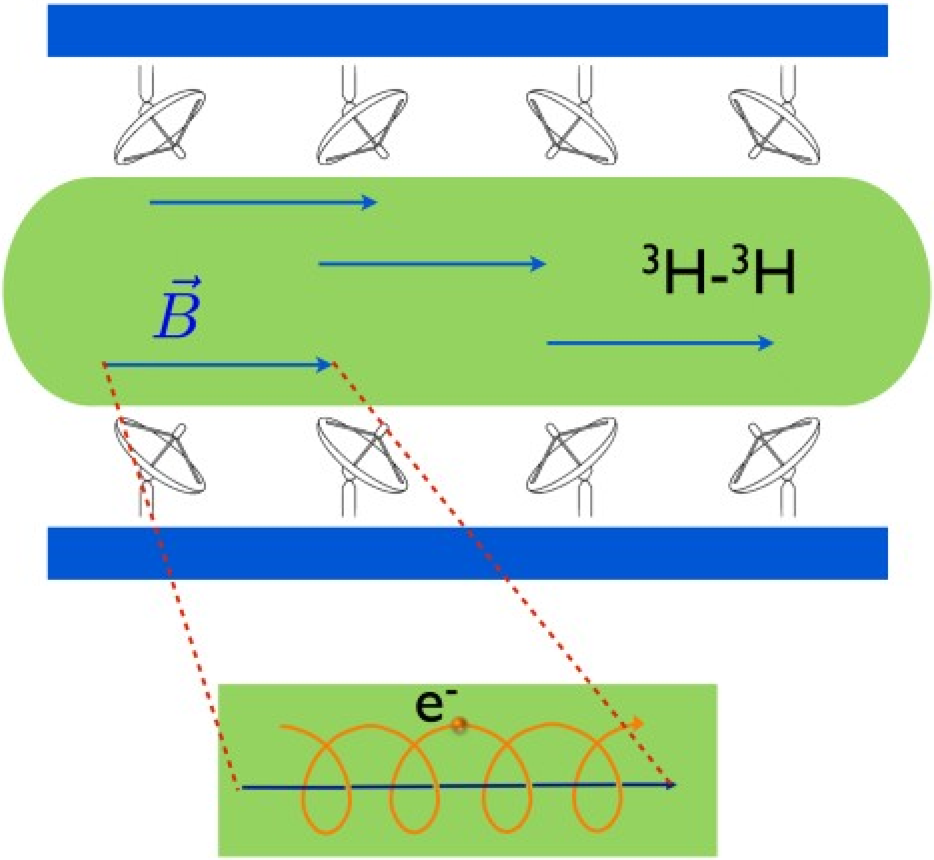
- Upper limit

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

As of Neutrino 2020 (June 2020)

Project 8

Project 8



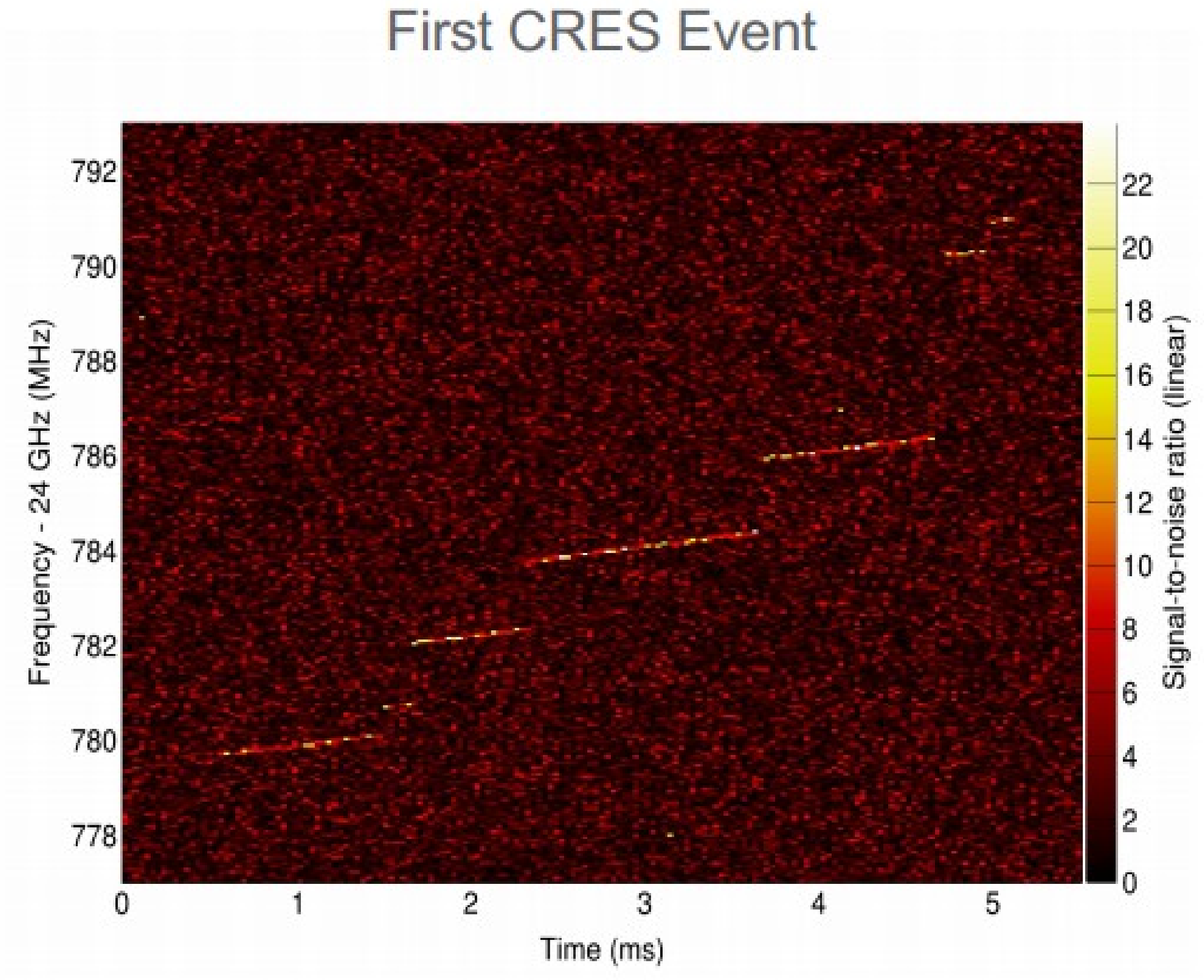
- Tritium beta decay in a magnetic field.
- Electron from beta decay spirals around the field lines
- Emits cyclotron radiation at a particular frequency

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

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

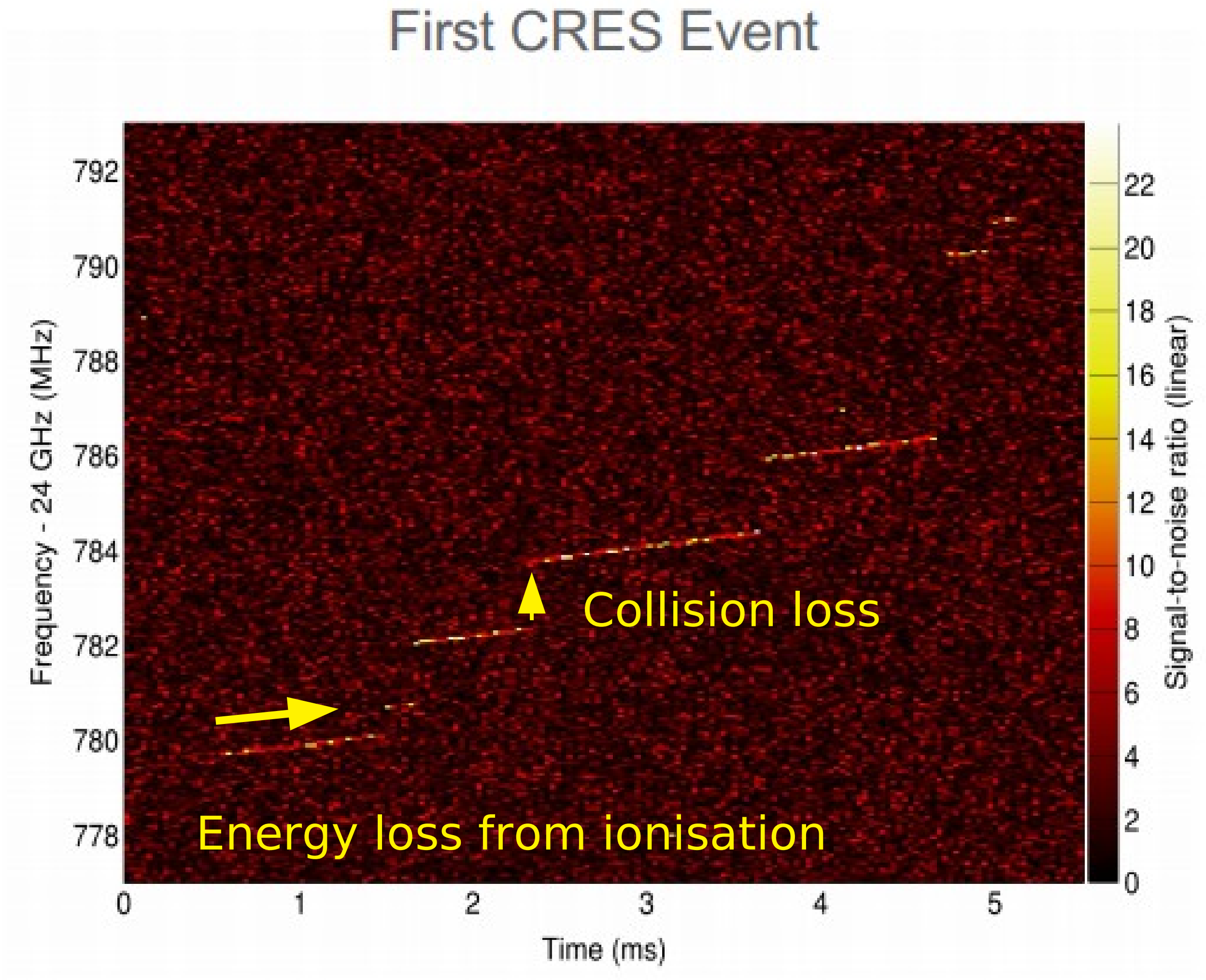
Project 8

Project 8 Demonstrator



Project 8

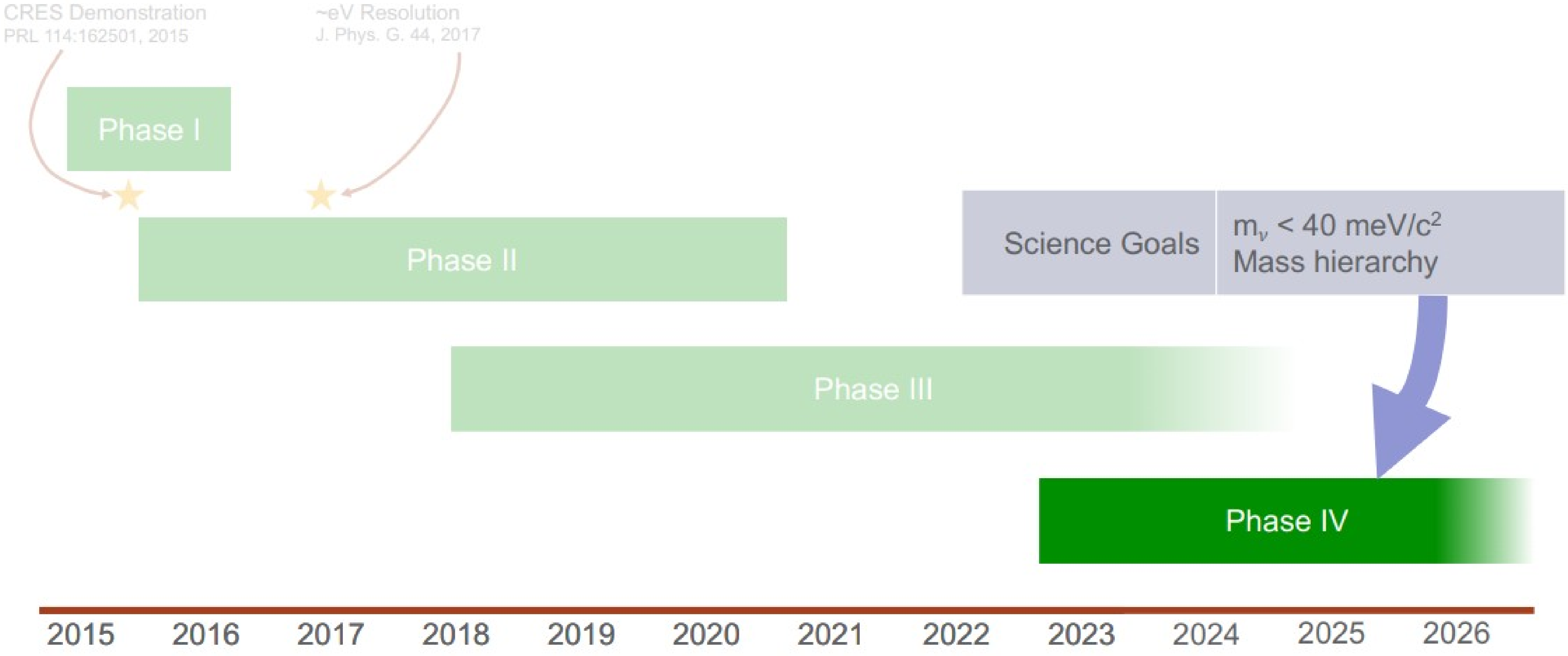
Project 8 Demonstrator


First CRES Event

Collision loss

Energy loss from ionisation

Project 8



CRES Demonstration
PRL 114:162501, 2015

~eV Resolution
J. Phys. G. 44, 2017

Phase I

Phase II

Science Goals

m_ν < 40 meV/c^2
Mass hierarchy

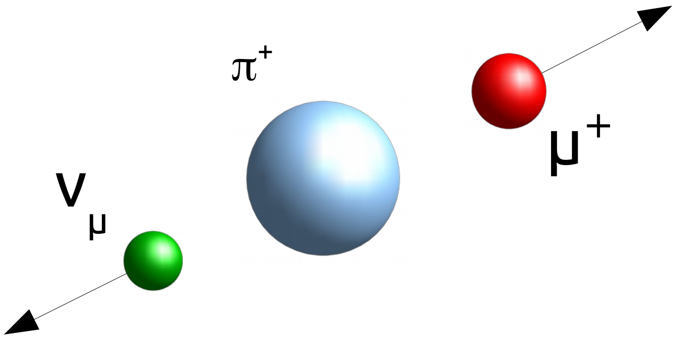
Phase III

Phase IV

2015 2016 2017 2018 2019 2020 2021 2022 2023 2024 2025 2026

ν_μ mass

Easiest way is to use pion decay at rest



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

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

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

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

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

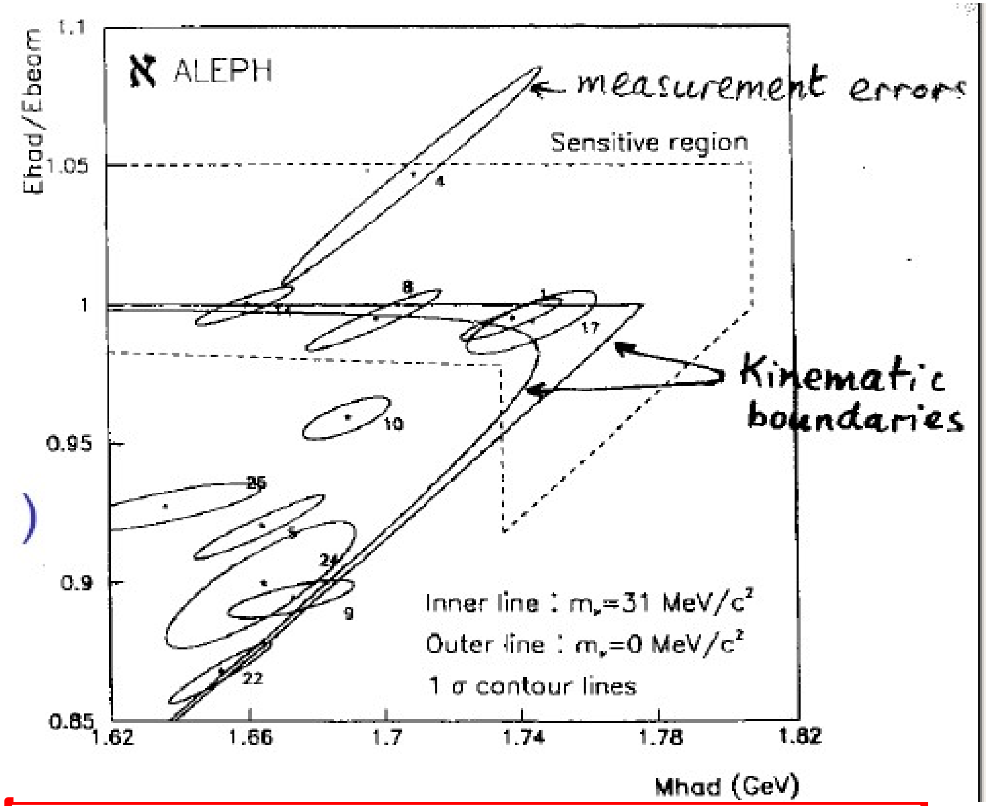
$$m_\nu < 190\, keV\, (90\,\%\, CL)$$

ν_τ mass

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

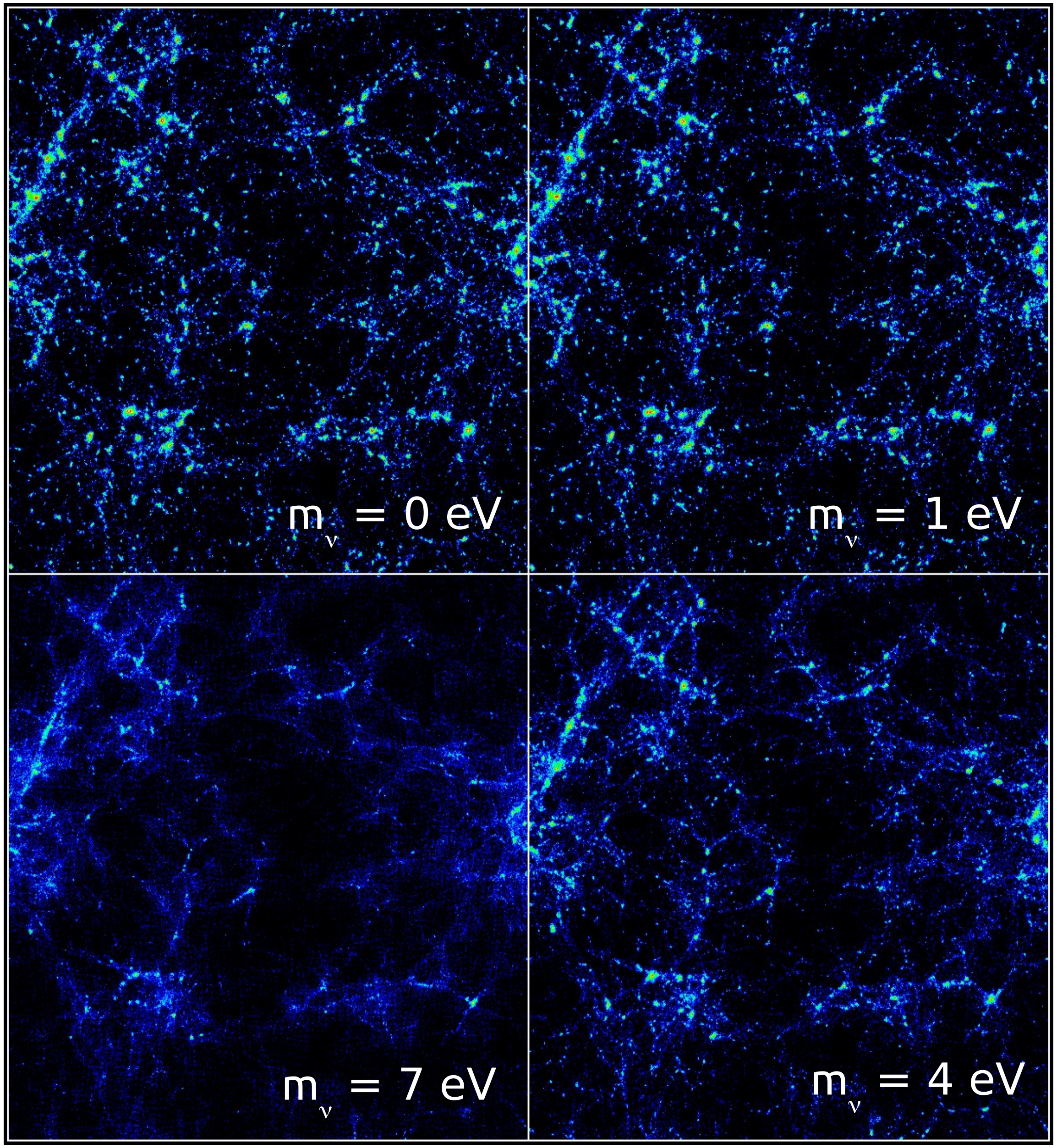
$$\hookrightarrow \; \tau \rightarrow \nu_\tau + 5\pi^{+-}(\pi^0)$$

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



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

Cosmology



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

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

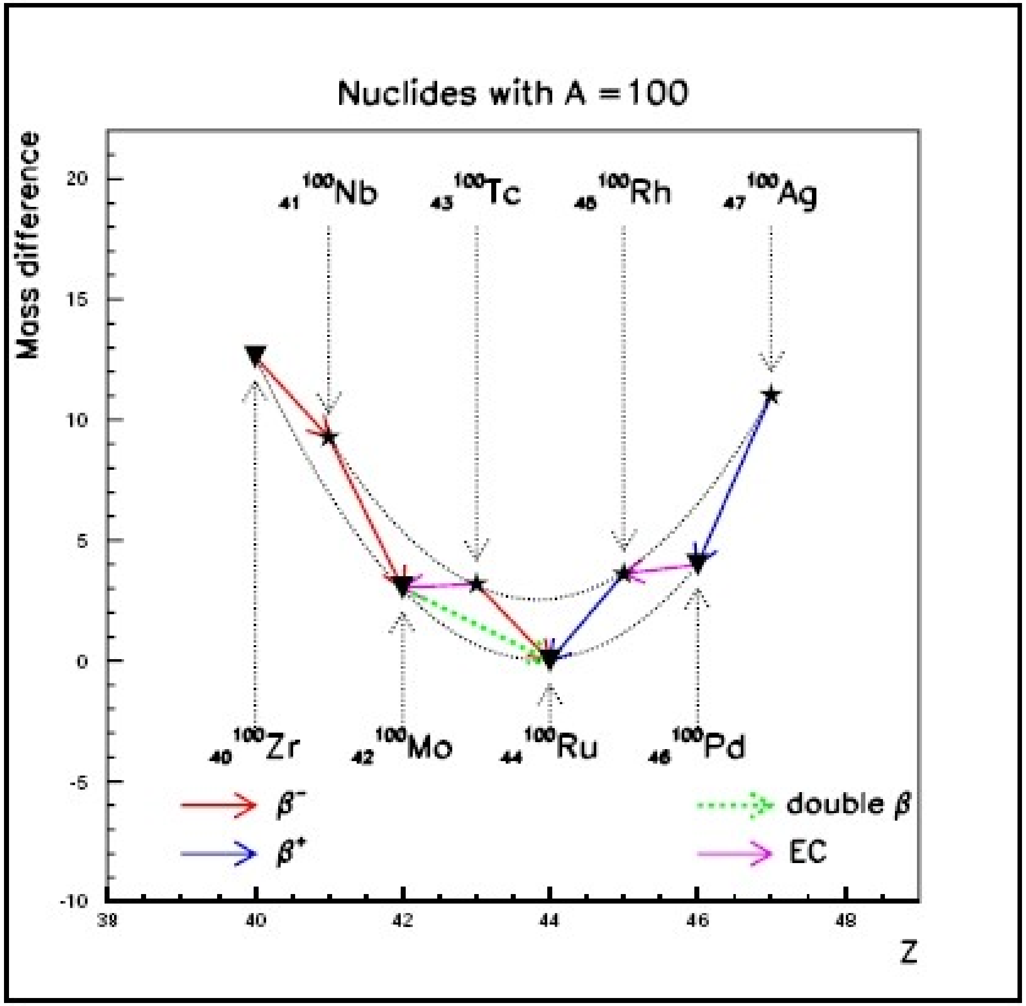
(rather model dependent)

2vββ Decay

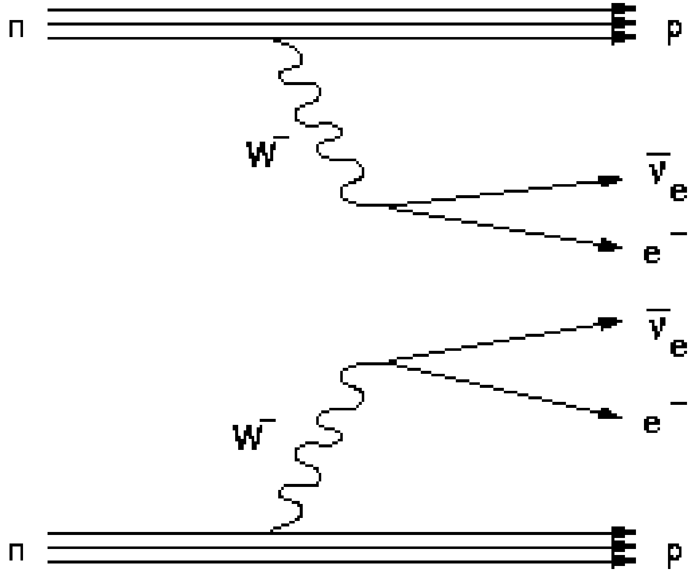
Neutrinoless double beta decay is considered a golden channel for the measurement of neutrino mass.

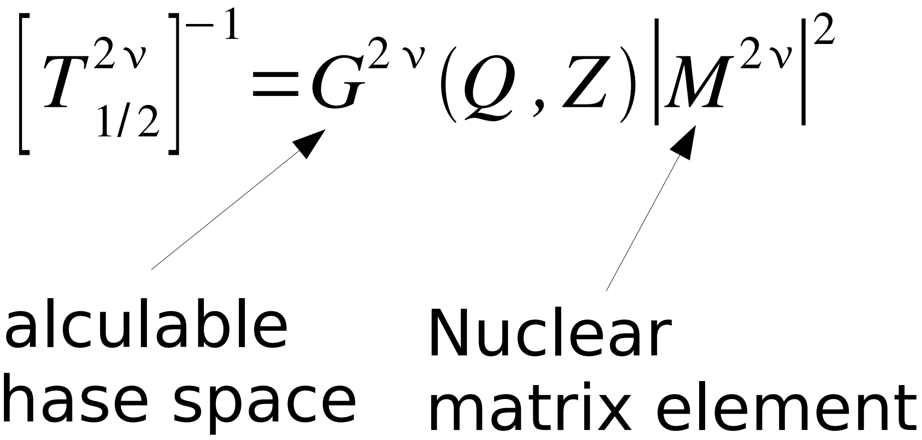
In some nuclei β decay is forbidden but double beta decay is not

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



2νββ Decay





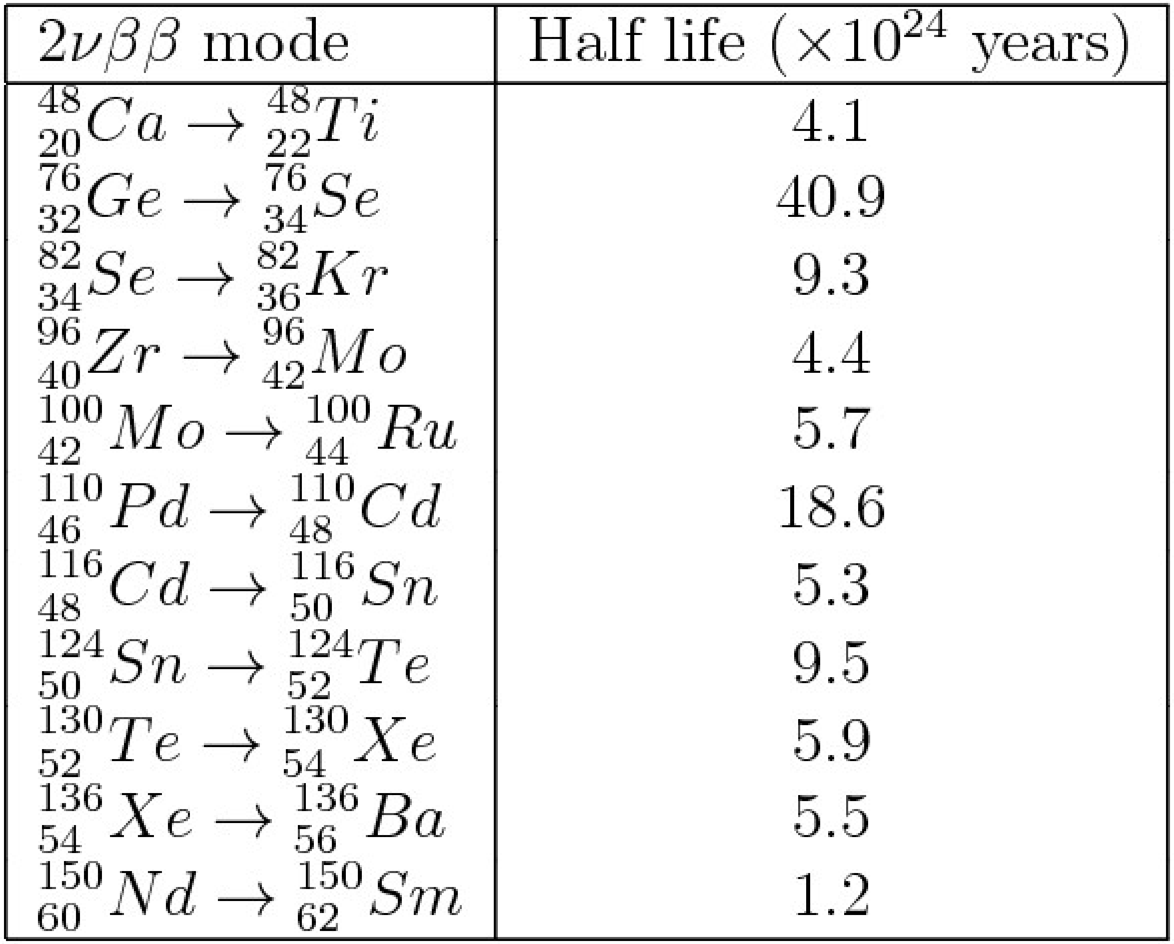
$$\left[T^{2\nu}_{1/2}\right]^{-1} = G^{2\nu}(Q,Z)\left|M^{2\nu}\right|^2$$

Calculable phase space

Nuclear matrix element

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

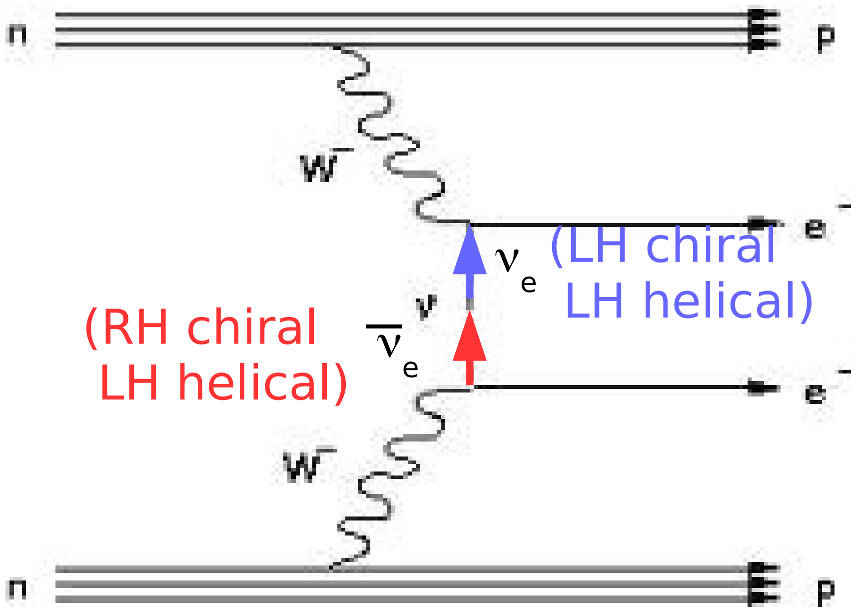
2νββ Decay



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

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

Neutrinoless ββ Decay



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

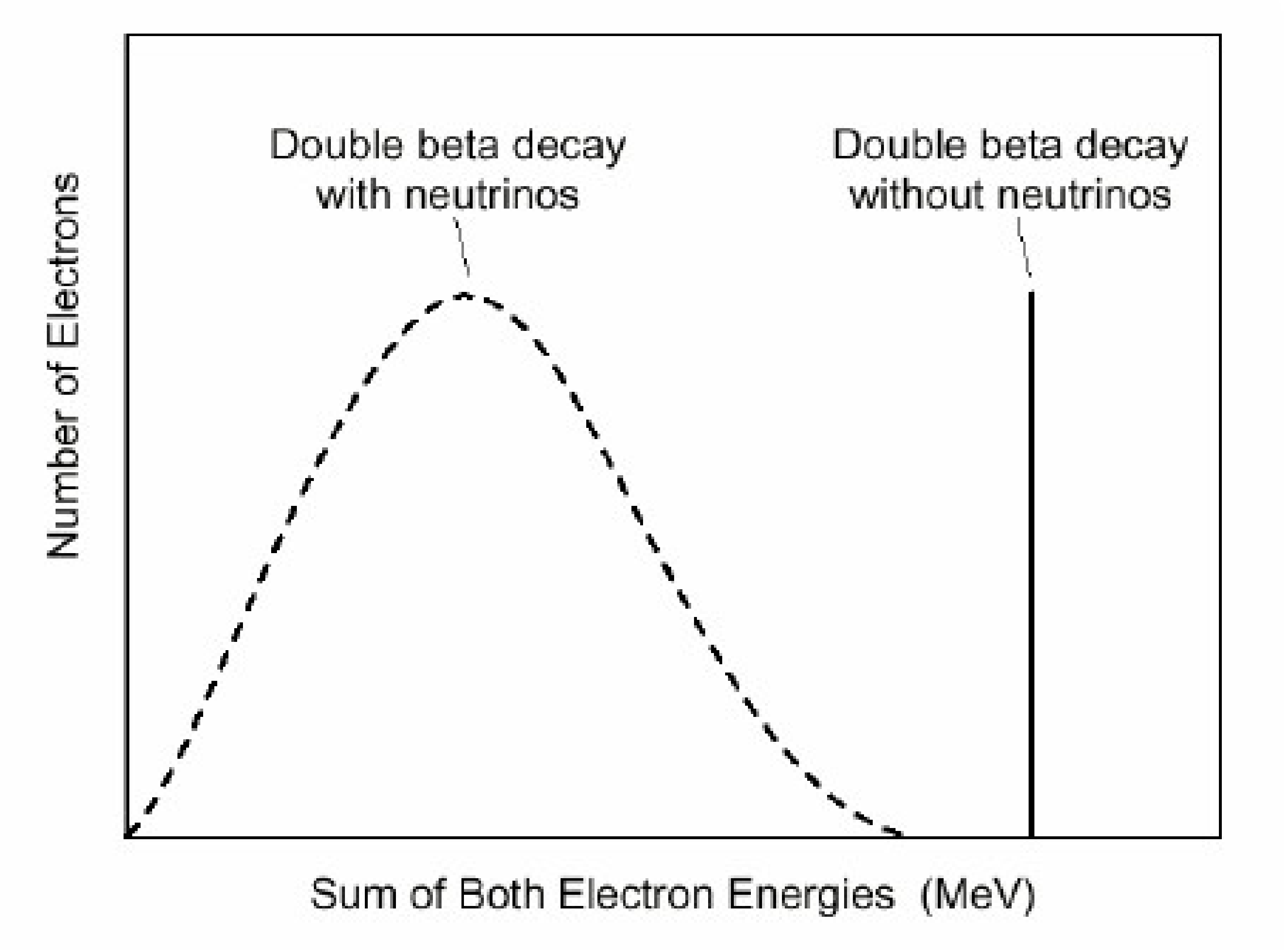
helicity states

<u>Requirements</u>

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

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

0νββ signal

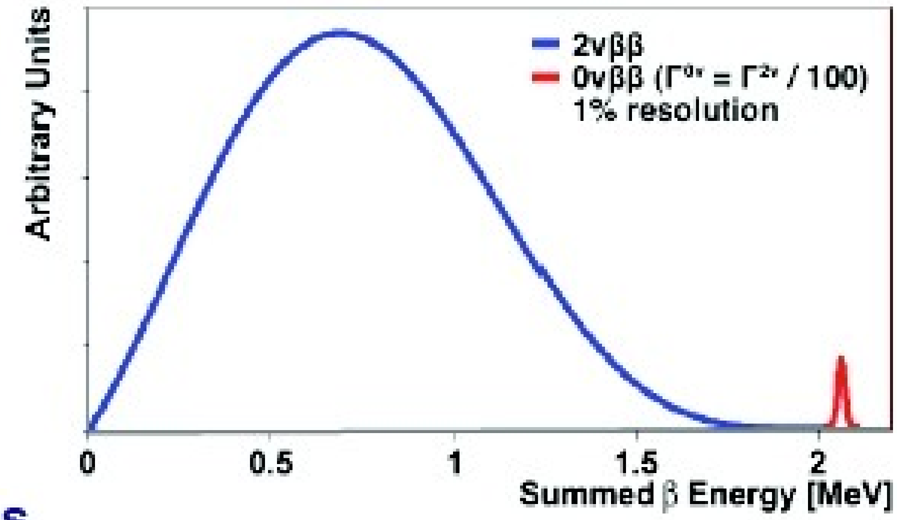

Double beta decay with neutrinos
Double beta decay without neutrinos
Number of Electrons
Sum of Both Electron Energies (MeV)

Experimental Requirements

Extremely slow decay rates

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

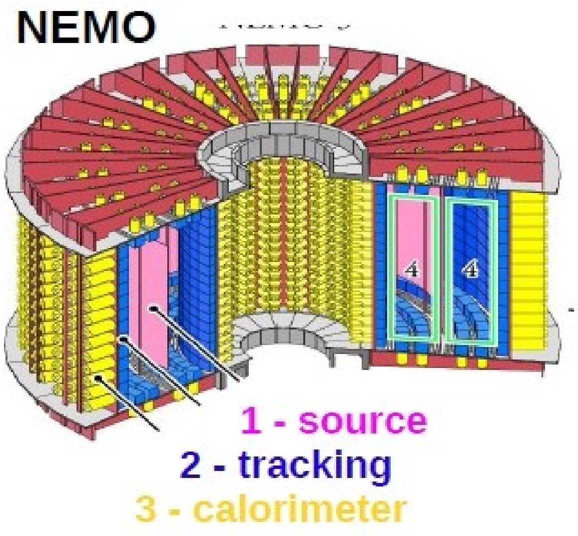
Best case, **0 background !**	$\propto$ Source Mass • time_{exp}



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

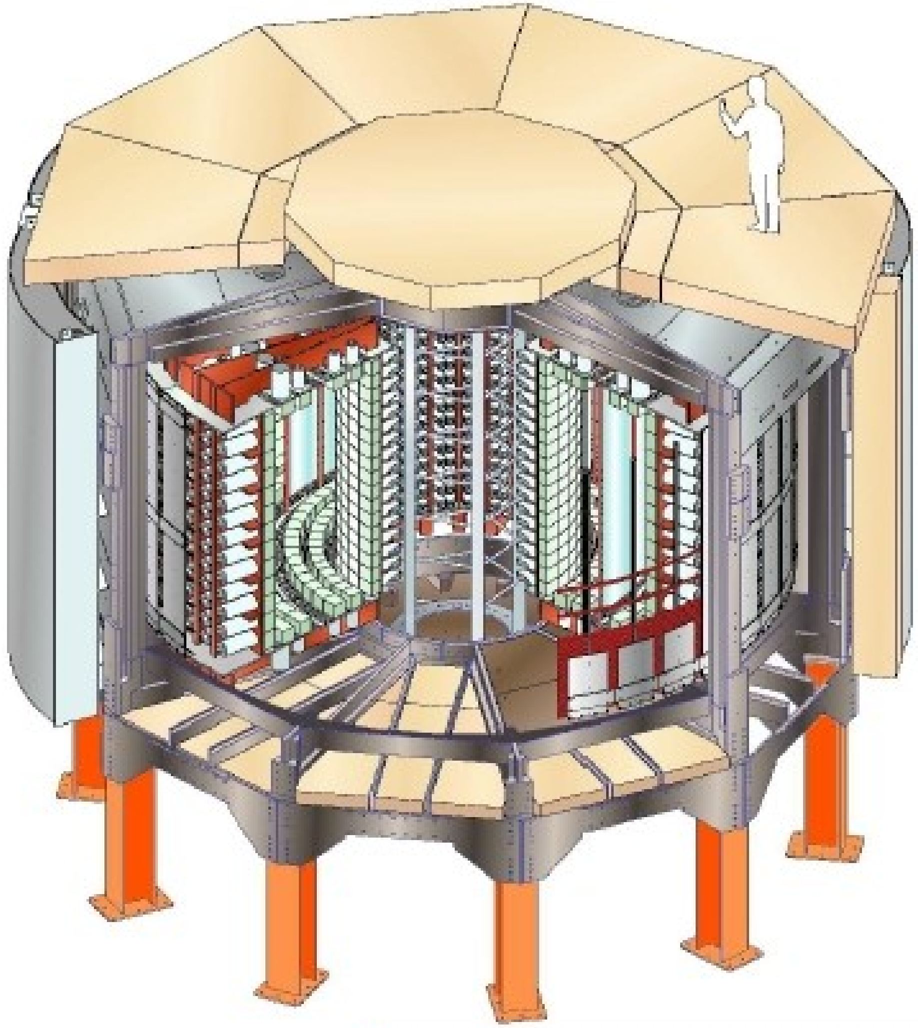
- **$2e^-$ are detected separately**
  → different channels of 0νDBD can be distinguished
- **particle identification**
  → background suppression
- **poor energy resolution**
  → important 2νDBD background
  (limitation on isotope choice)

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**

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

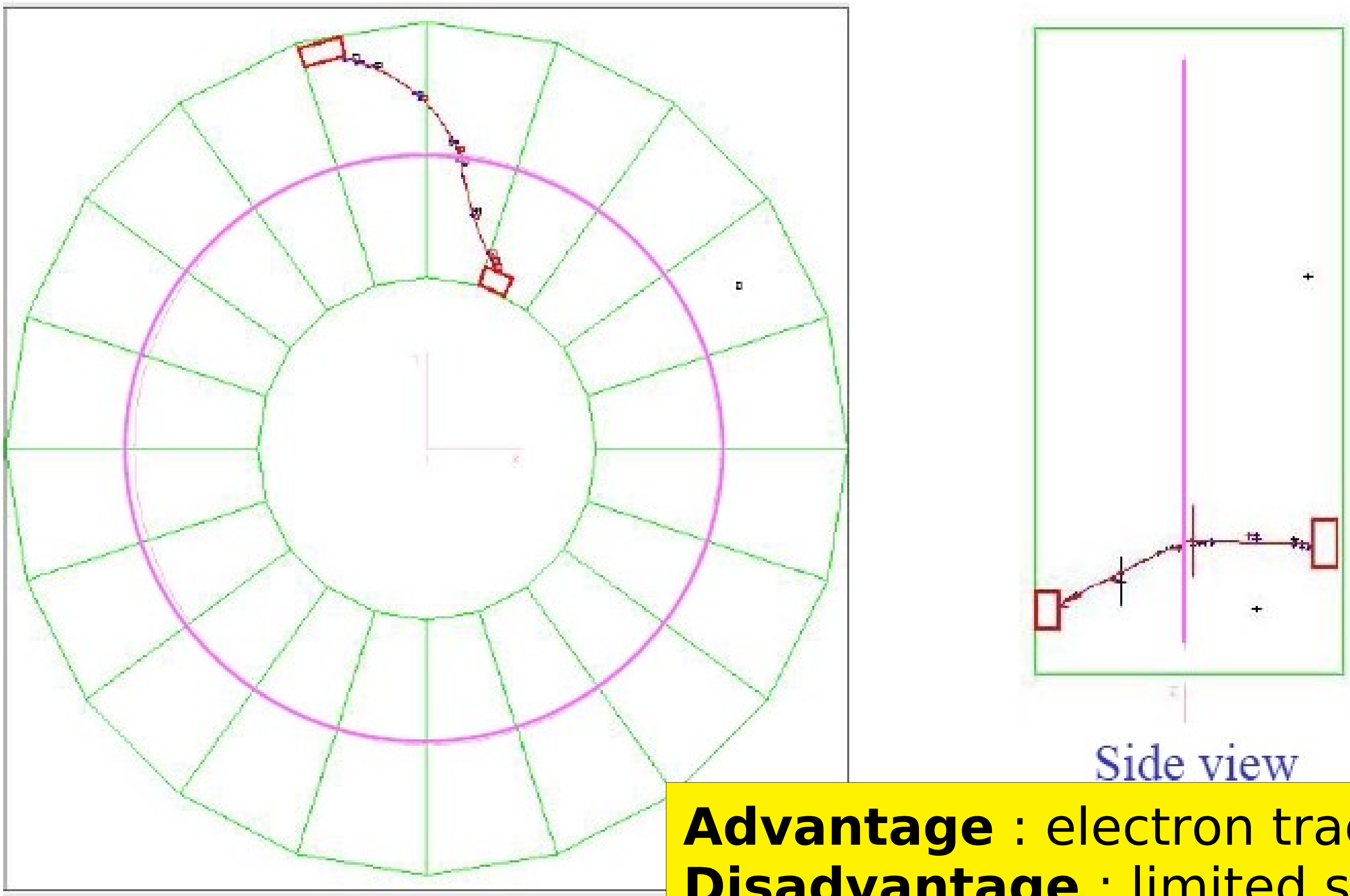
Calorimeter:
1940 plastic scintillators
coupled to low radioactivity PMTs

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^+, γ and α

Typical ββ2ν event observed from ^{100}Mo

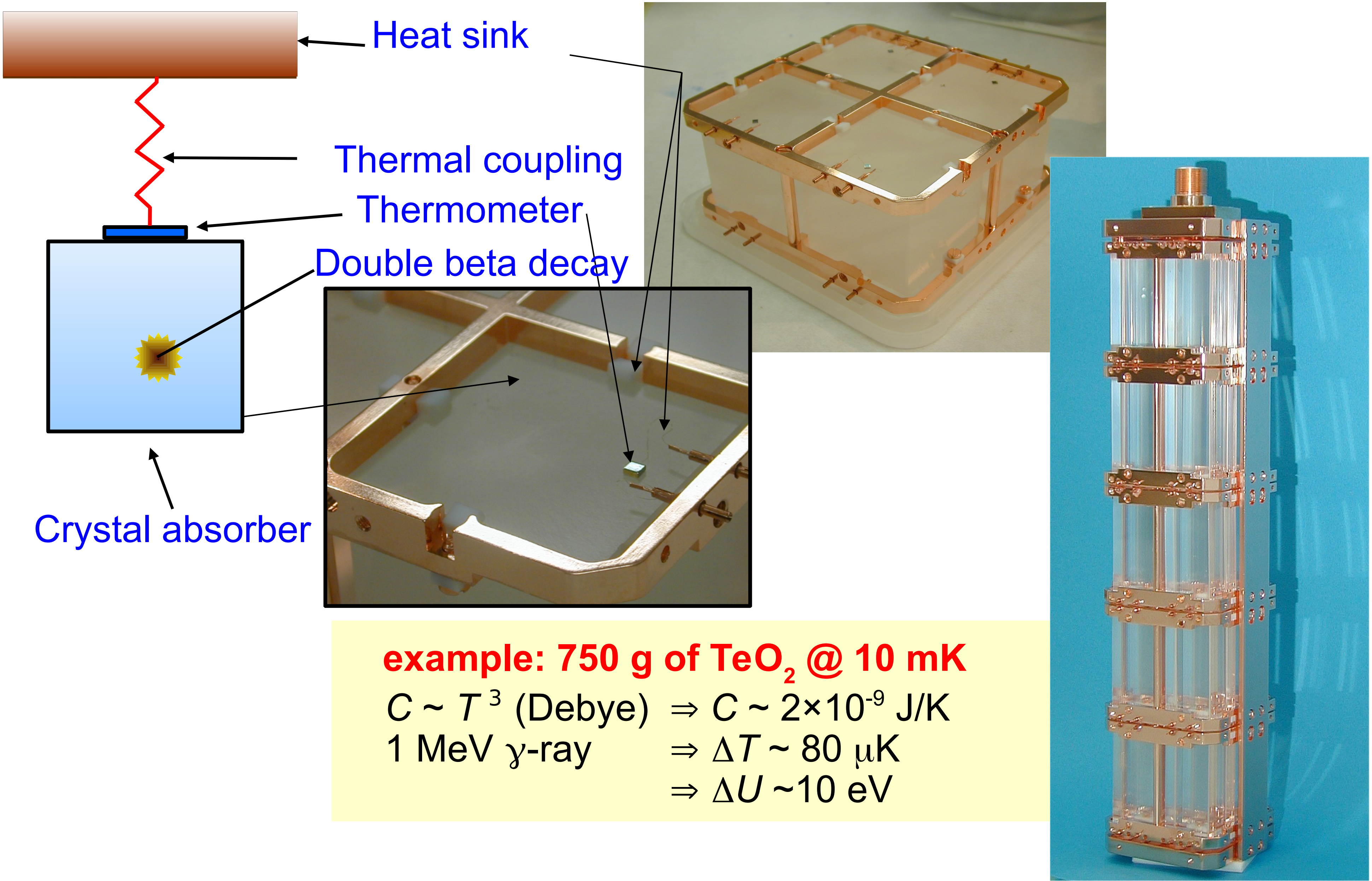


Top view

Side view

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

Bolometry : Cuore



Heat sink

Thermal coupling

Thermometer

Double beta decay

Crystal absorber

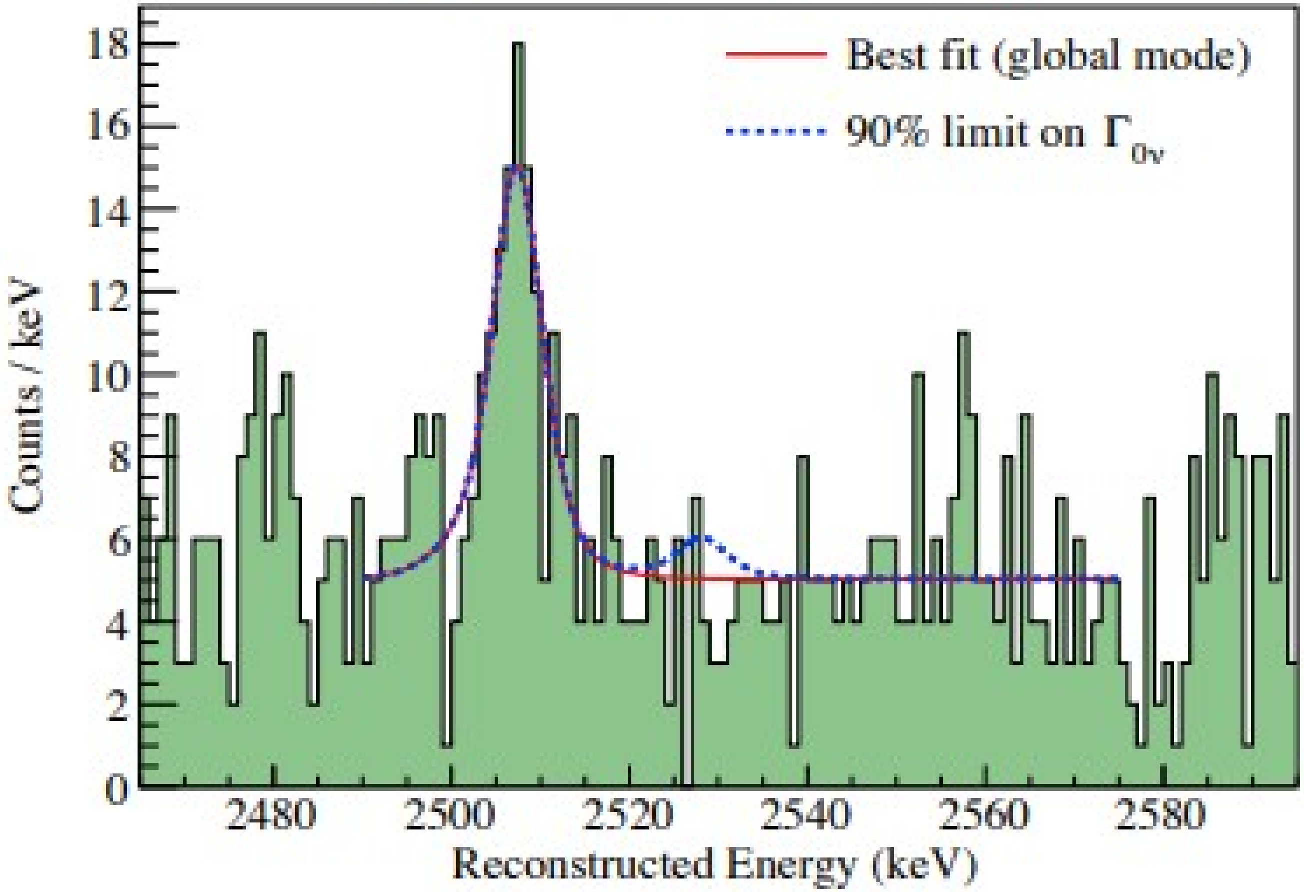
example: 750 g of TeO_2 @ 10 mK

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

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

$\Rightarrow \Delta U \sim 10$ eV

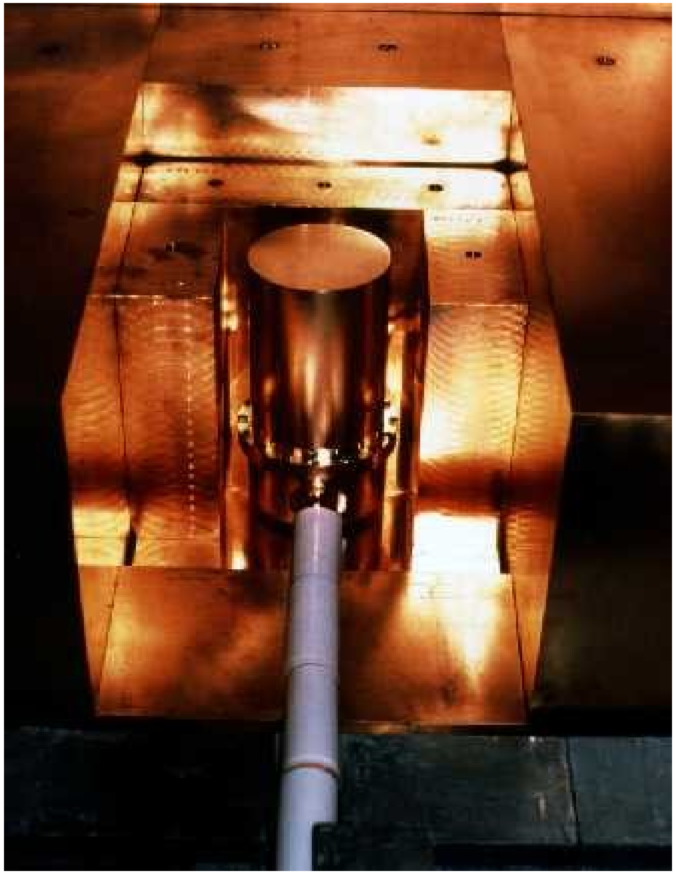
Cuore Results

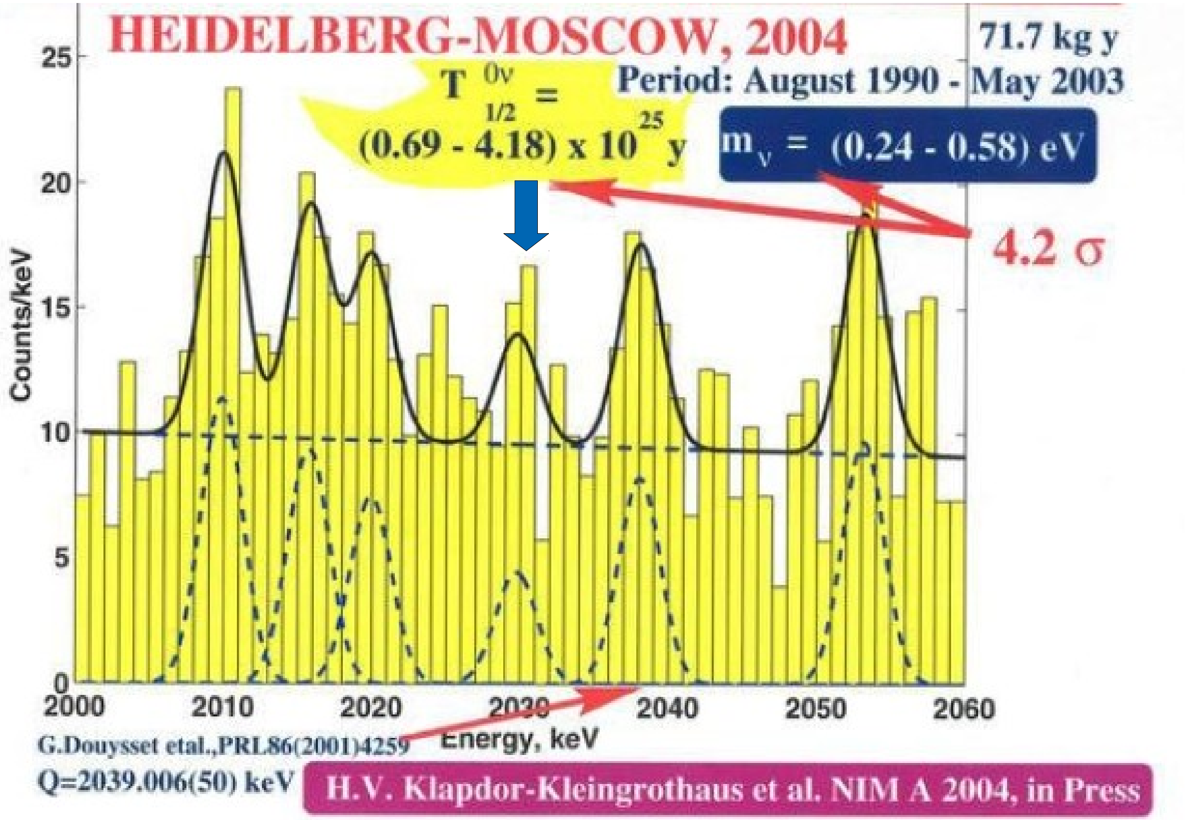


$$T_{1/2}^{0\nu} > 3.2\times 10^{25}\, years \;\Rightarrow\; \langle m_\nu \rangle < 0.76 - 3.5\, eV$$

Heidelberg-Moscow (HdM)

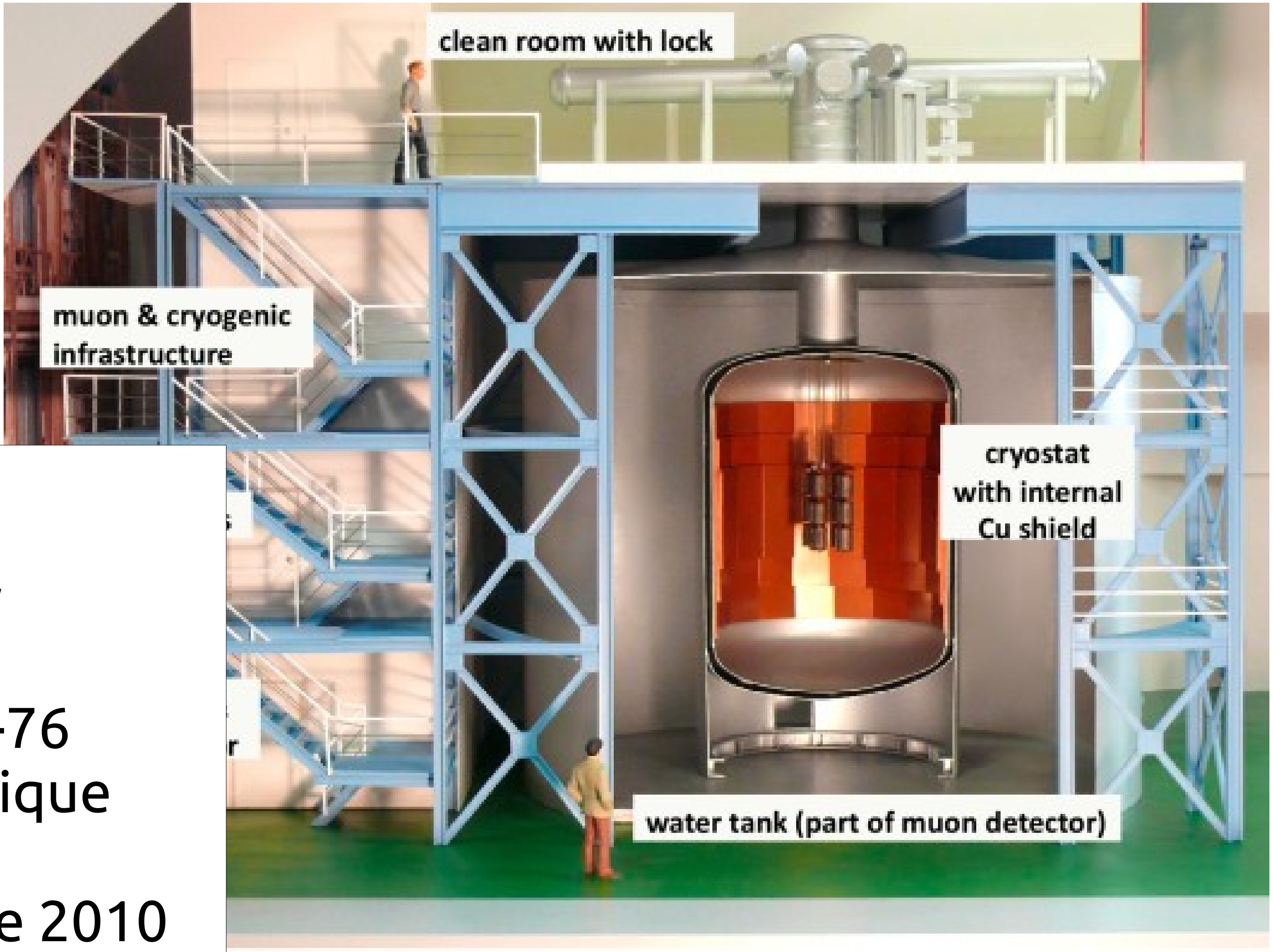
11 kg of Ge enriched to 86% of ^{76}Ge in the form of 5 Ge diodes surrounded by Cu,Pb,Bn shielding
0vββ electrons detected by Ge detectors themselves
Sum of electron energy is measured





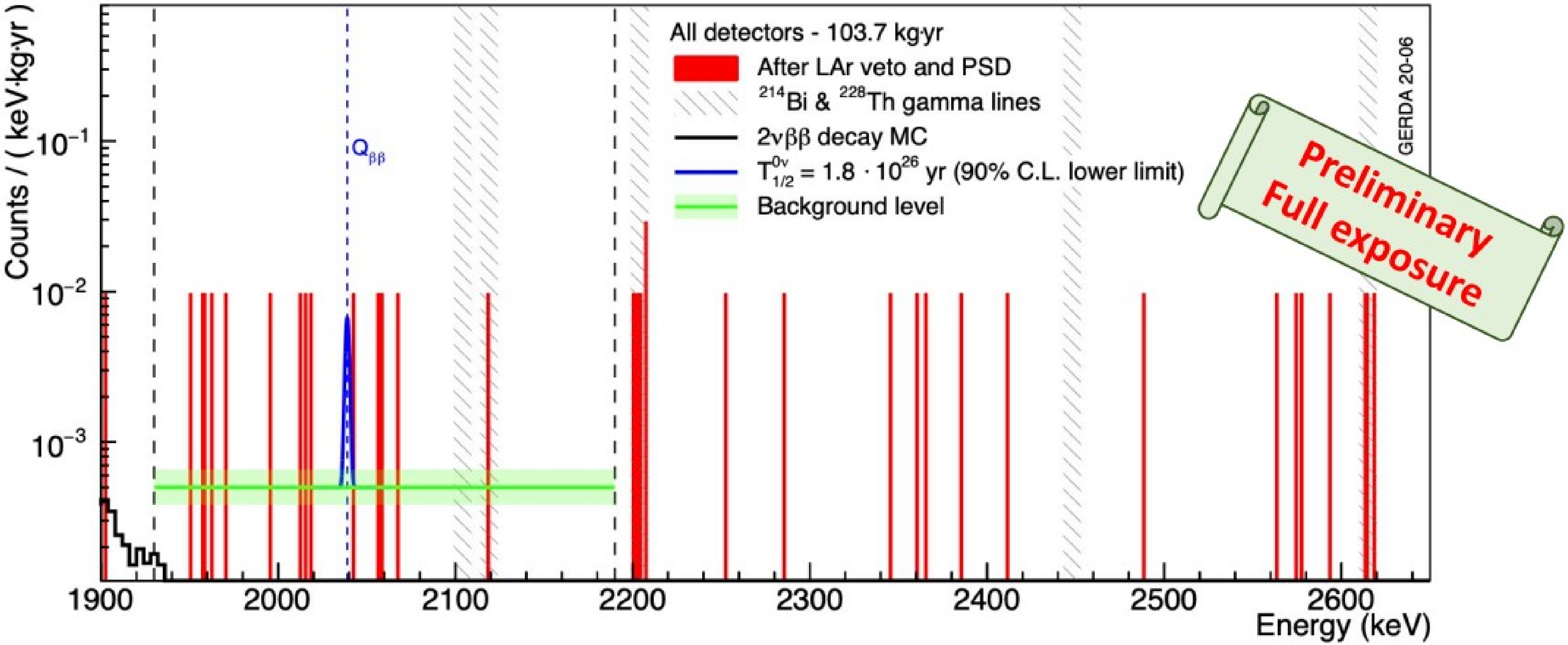
G.Douysset etal.,PRL86(2001)4259
Q=2039.006(50) keV
H.V. Klapdor-Kleingrothaus et al. NIM A 2004, in Press

GERDA



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

GERDA



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

$m(\nu_e) < 260$ meV @ 90% CL

Inconsistent with HdM, but not definitive (yet)

Future Program

Collaboration	Isotope	Technique	mass ($0\nu\beta\beta$ isotope)	Status
CANDLES-III	^{48}Ca	305 kg CaF$_2$ crystals in liquid scintillator	0.3 kg	Operating
CANDLES-IV	^{48}Ca	CaF$_2$ scintillating bolometers	TBD	R&D
GERDA	^{76}Ge	Point contact Ge in active LAr	44 kg	Complete
MAJORANA DEMONSTRATOR	^{76}Ge	Point contact Ge in Lead	30 kg	Operating
LEGEND 200	^{76}Ge	Point contact Ge in active LAr	200 kg	Construction
LEGEND 1000	^{76}Ge	Point contact Ge in active LAr	1 tonne	R&D
SuperNEMO Demonstrator	^{82}Se	Foils with tracking	7 kg	Construction
SELENA	^{82}Se	Se CCDs	<1 kg	R&D
NvDEx	^{82}Se	SeF$_6$ high pressure gas TPC	50 kg	R&D
ZICOS	^{96}Zr	10% ^{nat}Zr in liquid scintillator	45 kg	R&D
AMoRE-I	^{100}Mo	^{40}CaMoO$_4$ scintillating bolometers	6 kg	Construction
AMoRE-II	^{100}Mo	Li$_2$MoO$_4$ scintillating bolometers	100 kg	Construction
CUPID	^{100}Mo	Li$_2$MoO$_4$ scintillating bolometers	250 kg	R&D
COBRA	^{116}Cd/^{130}Te	CdZnTe detectors	10 kg	Operating
CUORE	^{130}Te	TeO$_2$ Bolometer	206 kg	Operating
SNO+	^{130}Te	0.5% ^{nat}Te in liquid scintillator	1300 kg	Construction
SNO+ Phase II	^{130}Te	2.5% ^{nat}Te in liquid scintillator	8 tonnes	R&D
Theia-Te	^{130}Te	5% ^{nat}Te in liquid scintillator	31 tonnes	R&D
KamLAND-Zen 400	^{136}Xe	2.7% in liquid scintillator	370 kg	Complete
KamLAND-Zen 800	^{136}Xe	2.7% in liquid scintillator	750 kg	Operating
KamLAND2-Zen	^{136}Xe	2.7% in liquid scintillator	~tonne	R&D
EXO-200	^{136}Xe	Xe liquid TPC	160 kg	Complete
nEXO	^{136}Xe	Xe liquid TPC	5 tonnes	R&D
NEXT-WHITE	^{136}Xe	High pressure GXe TPC	~5 kg	Operating
NEXT-100	^{136}Xe	High pressure GXe TPC	100 kg	Construction
PandaX	^{136}Xe	High pressure GXe TPC	~tonne	R&D
AXEL	^{136}Xe	High pressure GXe TPC	~tonne	R&D
DARWIN	^{136}Xe	^{nat}Xe liquid TPC	3.5 tonnes	R&D
LZ	^{136}Xe	^{nat}Xe liquid TPC		R&D
Theia-Xe	^{136}Xe	3% in liquid scintillator	50 tonnes	R&D

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R&D	Construction	Operating	Complete

Direct mass measurements

Tritium β decay	$\left(\sum_i \left\lvert U_{ei}{}^2\right\rvert m_i^2\right)^{\frac{1}{2}}$	< 0.9 eV
0v2β decay	$\left\lvert\sum_i U_{ei}^2 m_i\right\rvert$	<0.3 eV $<m_{\beta\beta}>$=440 meV from HM
Cosmology	$\sum_i m_i < 0.15\,eV$	Model dependent
Pion decay	$m_{\nu\mu} < 190\,keV$	Fairly pointless
Tau decay	$m_{\nu\tau} < 18.2\,MeV$	Entirely pointless

Question

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