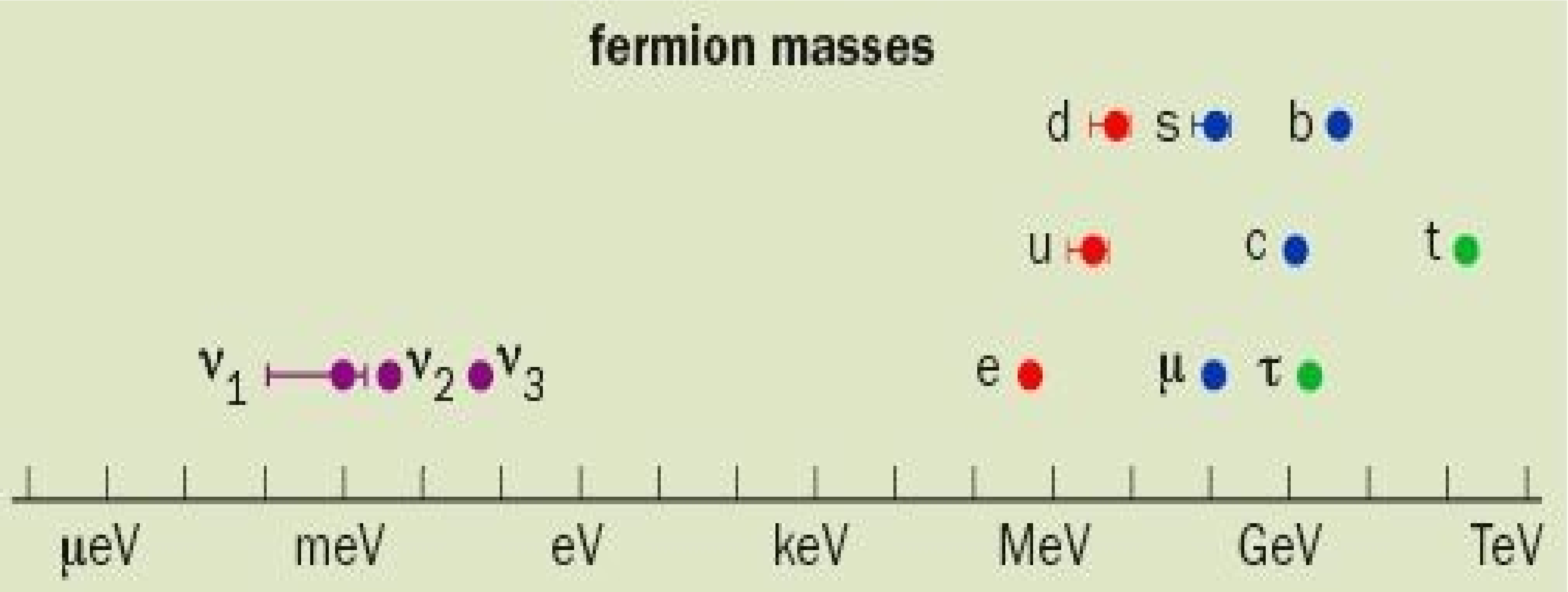
Lecture 3

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

In the Standard Model neutrinos are assumed to be massless
If they are not, we need to work out a way of putting them in.

Neutrinos are fermions and obey the Dirac Equation, so there might be a Dirac Lagrangian term for the neutrino fields

$$L_\nu = \overline{n}\left(i\gamma\cdot\partial - m_D\right)n \;\Rightarrow\; \boxed{m_D\overline{n}n}$$

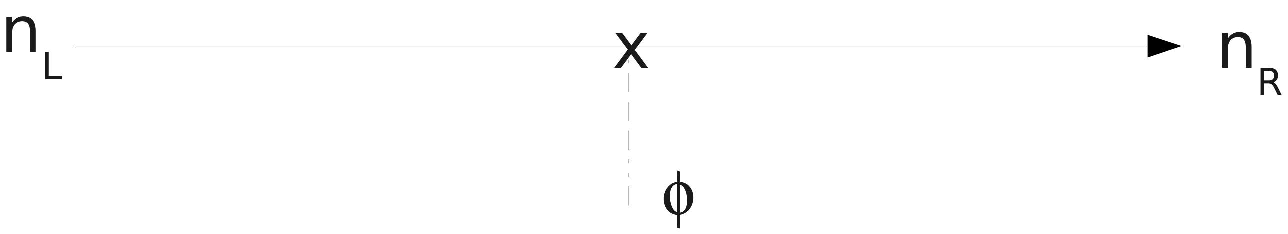
Dirac mass term

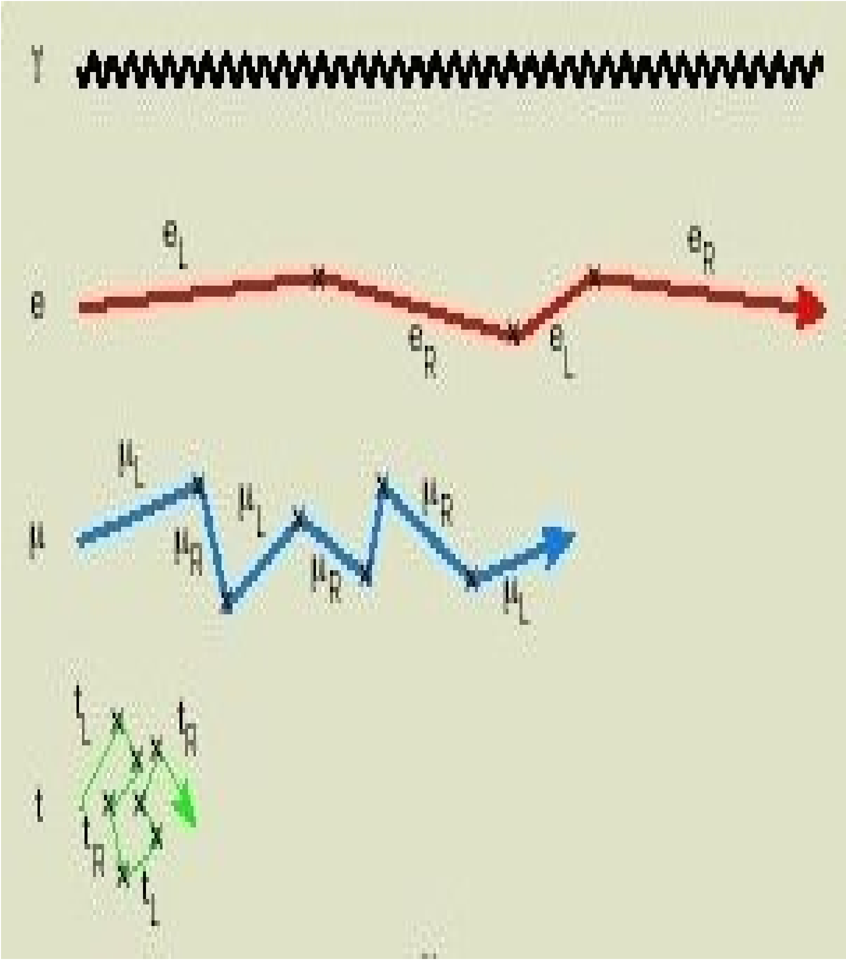
Not antineutrino. This is the adjoint neutrino spinor : $\overline{n} = n^\dagger\gamma_0$

$$L_{mass} = m_D\overline{n}n = m_D\left(\overline{n_L} + \overline{n_R}\right)\left(n_L + n_R\right) = m_D\left(\overline{n_L}n_R + \overline{n_R}n_L\right)$$

Mass term is the coupling between the left- and right-handed chiral neutrino states. To conserve gauge invariance we need to introduce the Higgs field and spontaneous symmetry breaking. The Dirac mass term explicitly conserves lepton number

ν Dirac Mass





Dirac Mass

Higgs mechanism : $m_D = G_\nu \frac{\langle h \rangle}{\sqrt{2}}$

$< h > \sim 246\, GeV$ Vacuum Expectation Value

Hang on, but...

- Small m_ν → smaller G_ν $(< 10^{-13})$
- Addition to SM of a sterile n_R that is a distinct state

Majorana Neutrinos

Mass term involves a left- and a right-handed field. For neutrinos we know that the left-handed field exists. In 1937, Ettore Majorana wondered if you could make a right-handed field from the left-handed one and form a mass term that way

$n_L^C = C\,\overline{n_L}^T$ is a right-handed field

Can form a *Majorana* neutrino : $n = n_L + n_L^C$ which is self-conjugate. That is, the particle is identical to the antiparticle

Clearly this can only happen for neutral particles. A majorana electron, for example, would violate charge conservation. The neutrino is the only fermion with potential to be Majorana.

We can also now write down a mass term for Majorana neutrinos

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

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

Damn

It turns out that you can't actually form this Majorana term with the left-handed neutrino field in the Standard Model

n_L $I_3 = 1/2$, $Y = -1$

$\overline{n_L^C}\, n_L$ $I_3 = 1$, $Y = -2$

To couple to the Higgs field you need to find a Higgs with Y = +2 and I_3 = -1 - that is a Higgs 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)

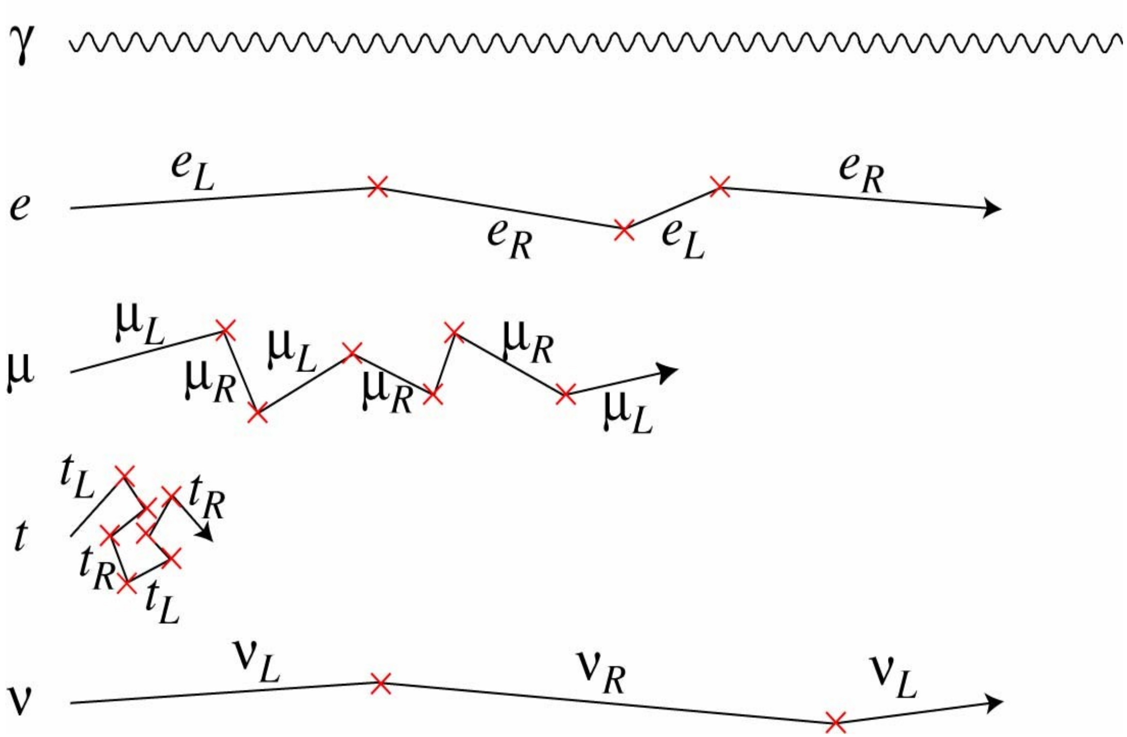
We are forced then to consider the existence of another right-handed neutrino field even in the case of Majorana neutrinos. This would be a singlet with I_3 = 0 and Y=0 which can couple to the Standard Model Higgs.

The existence of neutrino mass implies physics beyond the Standard Model, either from a right-handed state needed for the standard mass mechanism, or a Higgs triplet, or a new mass mechanism.

Two ways to go

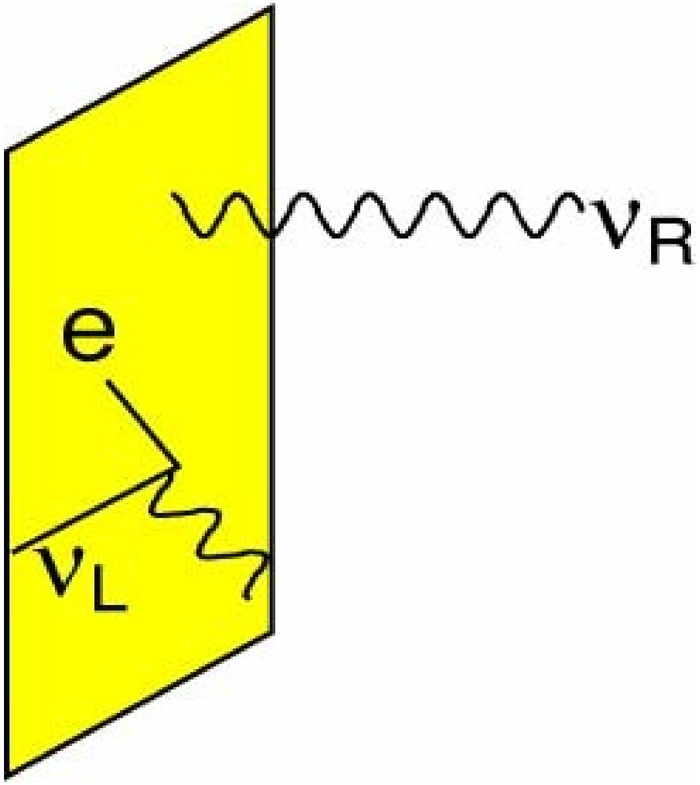
Dirac neutrinos

- There are new particles (right handed neutrinos) after all
- Why haven't we seen them?
- They must be *very very* weakly coupled
- Why?



Extra Dimensions?

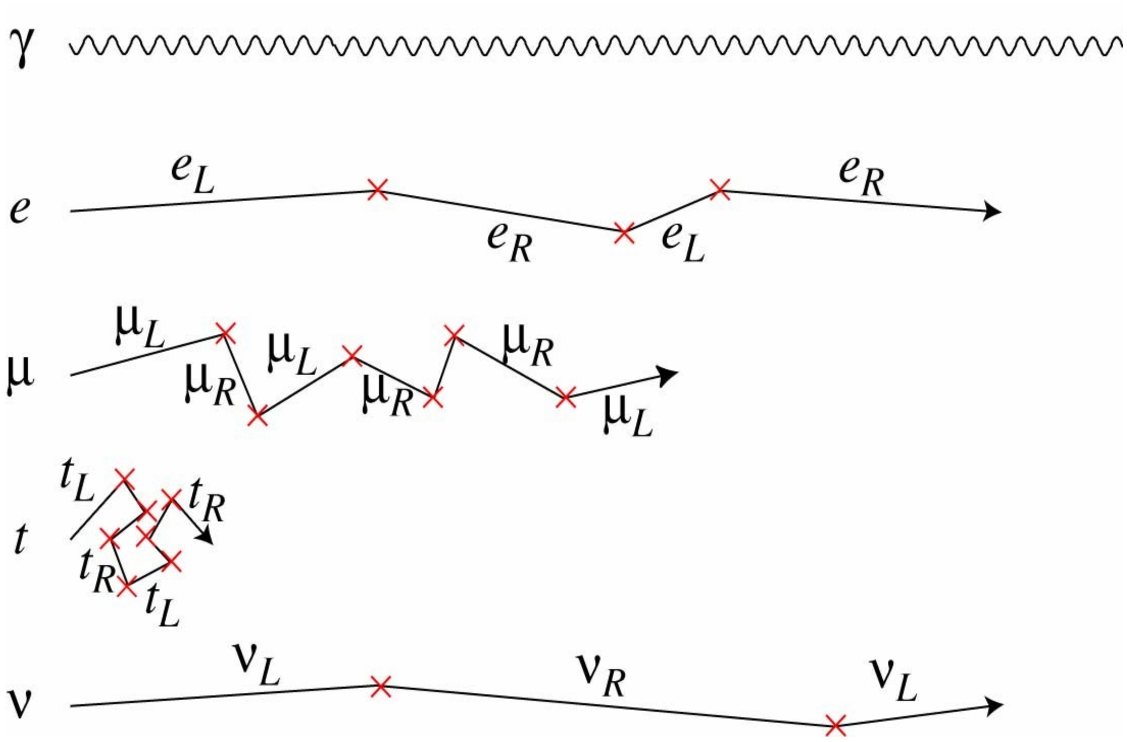
- All charged particles are on a 3-brane
- Right handed neutrinos are standard model gauge singlets
- Can they propagate in the bulk?
- We are not seeing most of the coupling in the 3-dimensional world. This could make the neutrino mass small.
- Same explanation as the weakness of gravity?!



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!)

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

Seesaw Mechanism

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

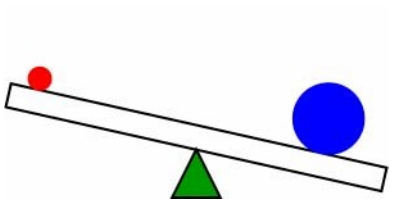
Suppose $m_L = 0$, $m_R \gg m_D$ and $m_D \sim$ quark/charged lepton mass

$$\tilde{m}_1 = \frac{m_D^2}{m_R} = m_n$$

the physical field m_n now naturally has a very small mass ("our" neutrino)

$$\tilde{m}_2 = m_R\left(1 + \frac{m_D^2}{m_R^2}\right) \approx m_R = m_N$$

The field m_N now has a very large mass ($\sim 10^{15}$ GeV)



Leptogenesis

Seesaw mechanism requires a GUT scale heavy Majorana neutrino partner.

Cosmologically, B-L must be conserved (baryon number - lepton number)

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

To keep B-L conserved one needs to violate B as well.

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?

Need to find out whether neutrino is Majorana or not.

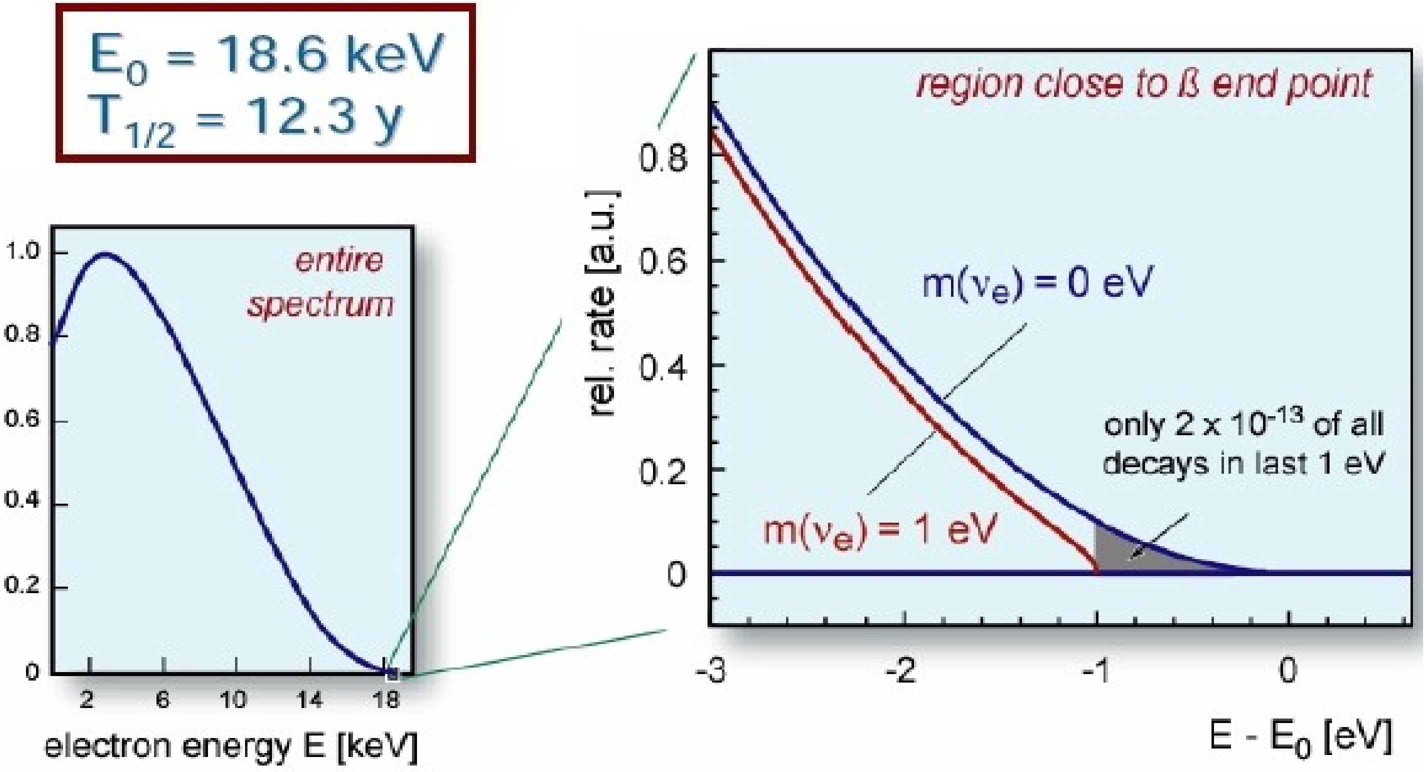
(Attempts at) mass measurements

β decay

Measurement of ν 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

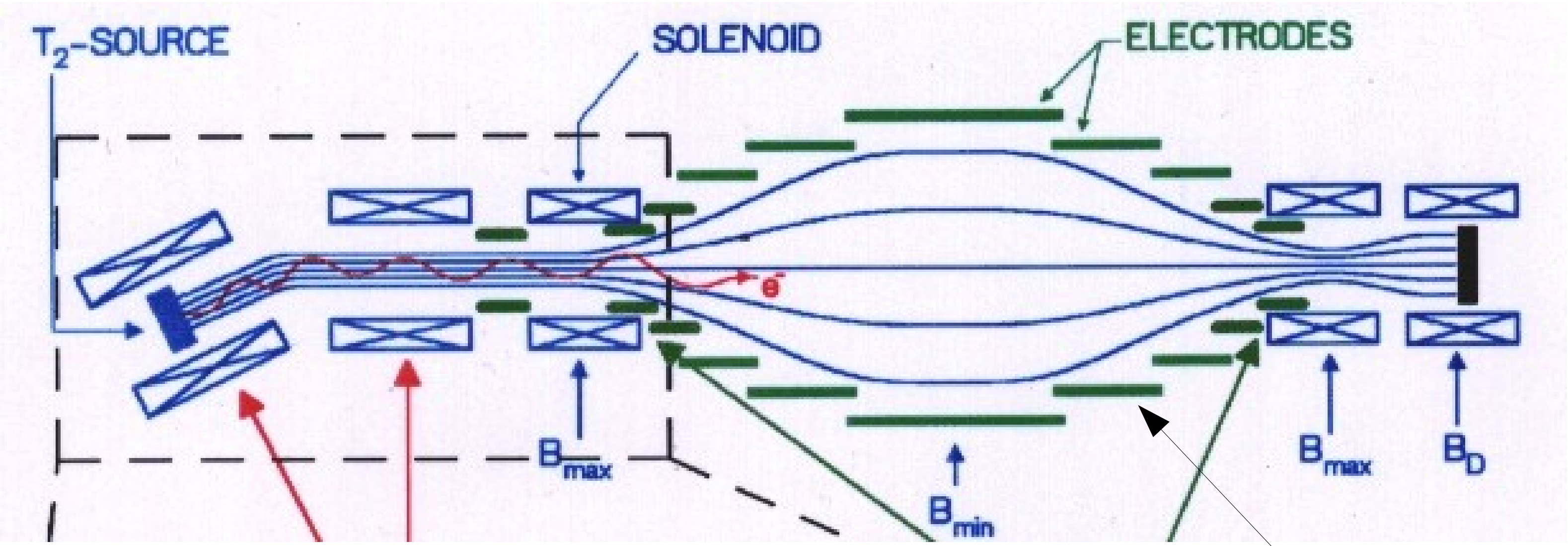
- The number of electrons close to the endpoint should be large
- Good (and well-understood) electron energy resolution
- No (or minimal) electron energy loss within the source
- Minimal atomic and nuclear final state effects, of excited transitions

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

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

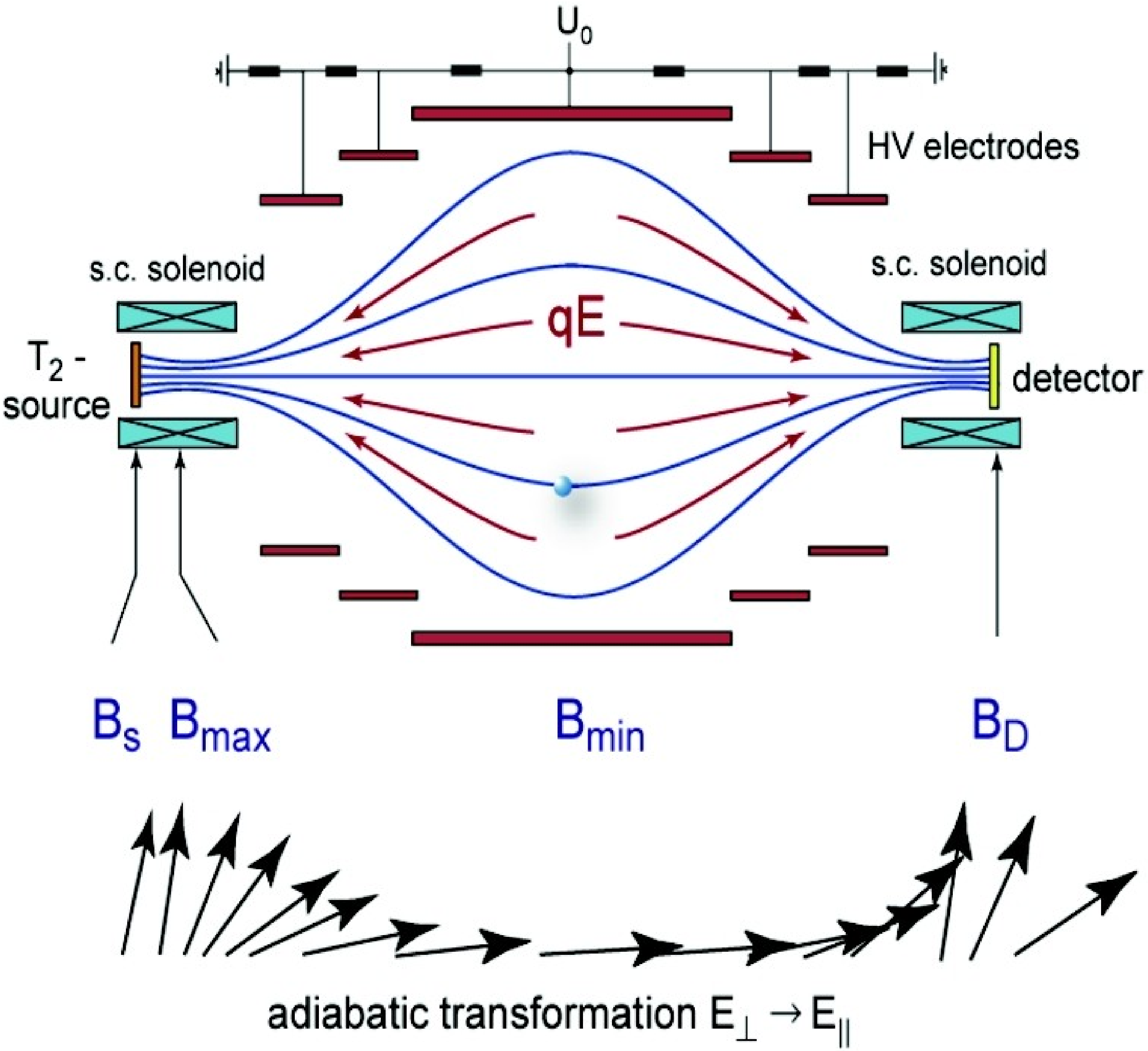


- 2π acceptance
- High energy resolution

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

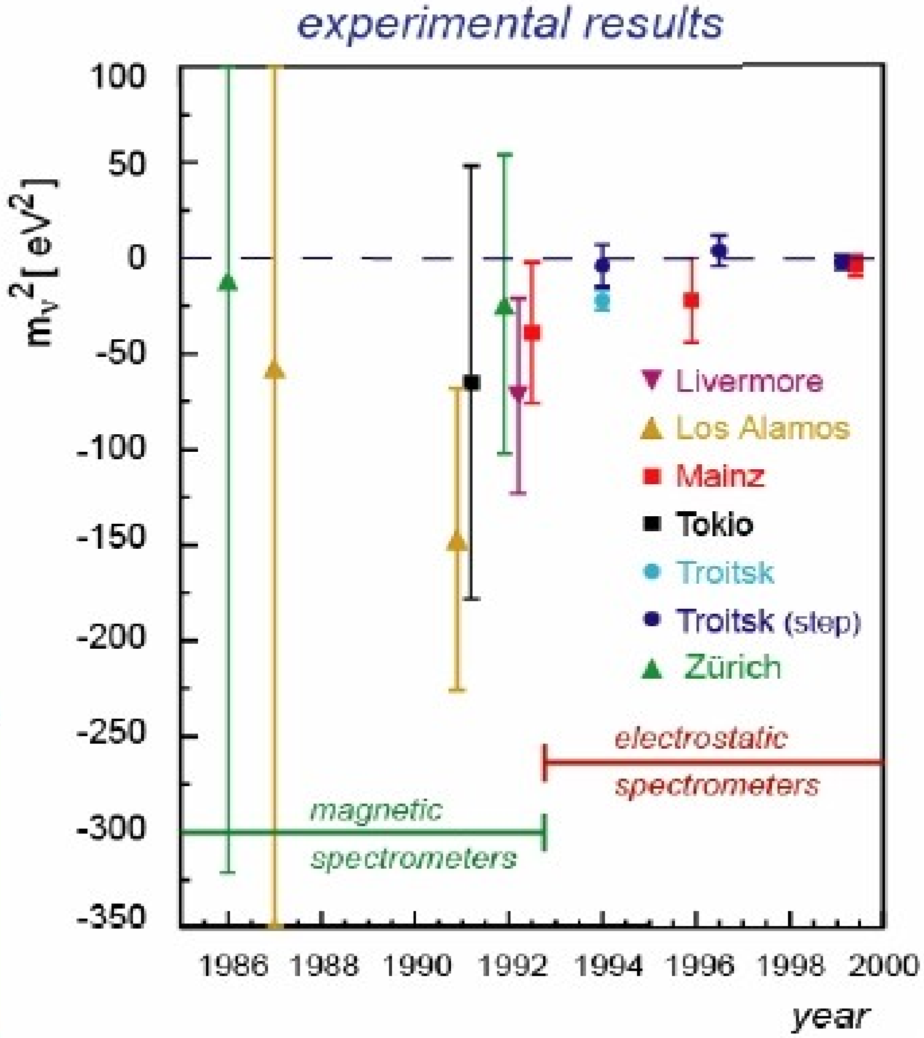
Electrostatic
MAC-E Filter

MAC-E Filters



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



Present Status

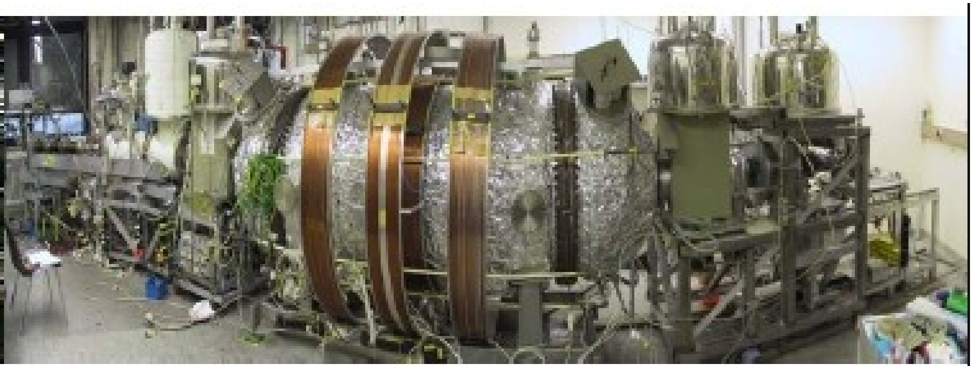
Troitsk

windowless gaseous T_2 source

analysis 1994 to 1999, 2001

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

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



Mainz

quench condensed solid T_2 source

analysis 1998/99, 2001/02

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

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

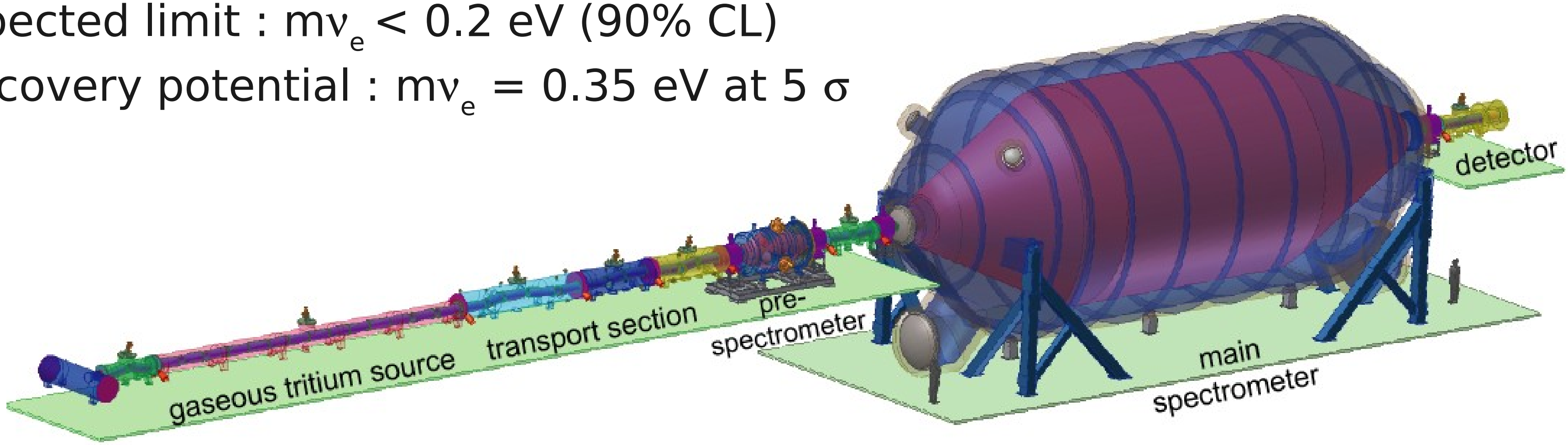
Both experiments have reached the intrinsic limit of their sensitivity.

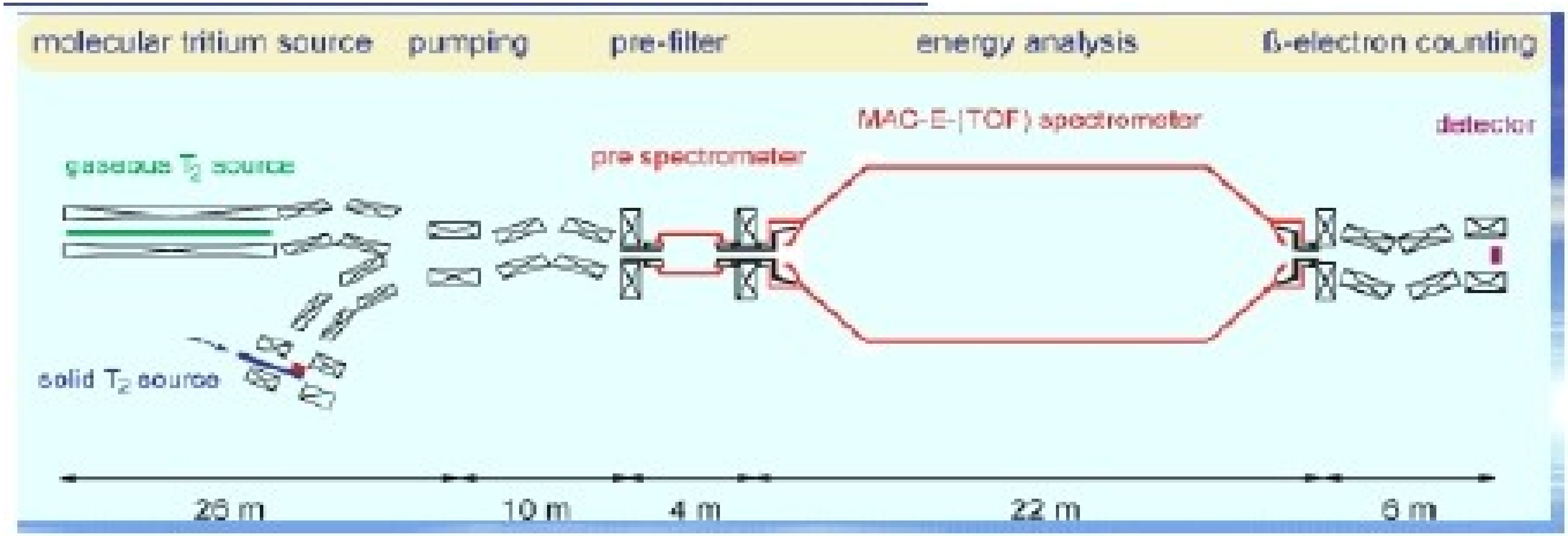
KATRIN

Due to start 2012

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

Discovery potential : $m\nu_e = 0.35$ eV at 5 σ

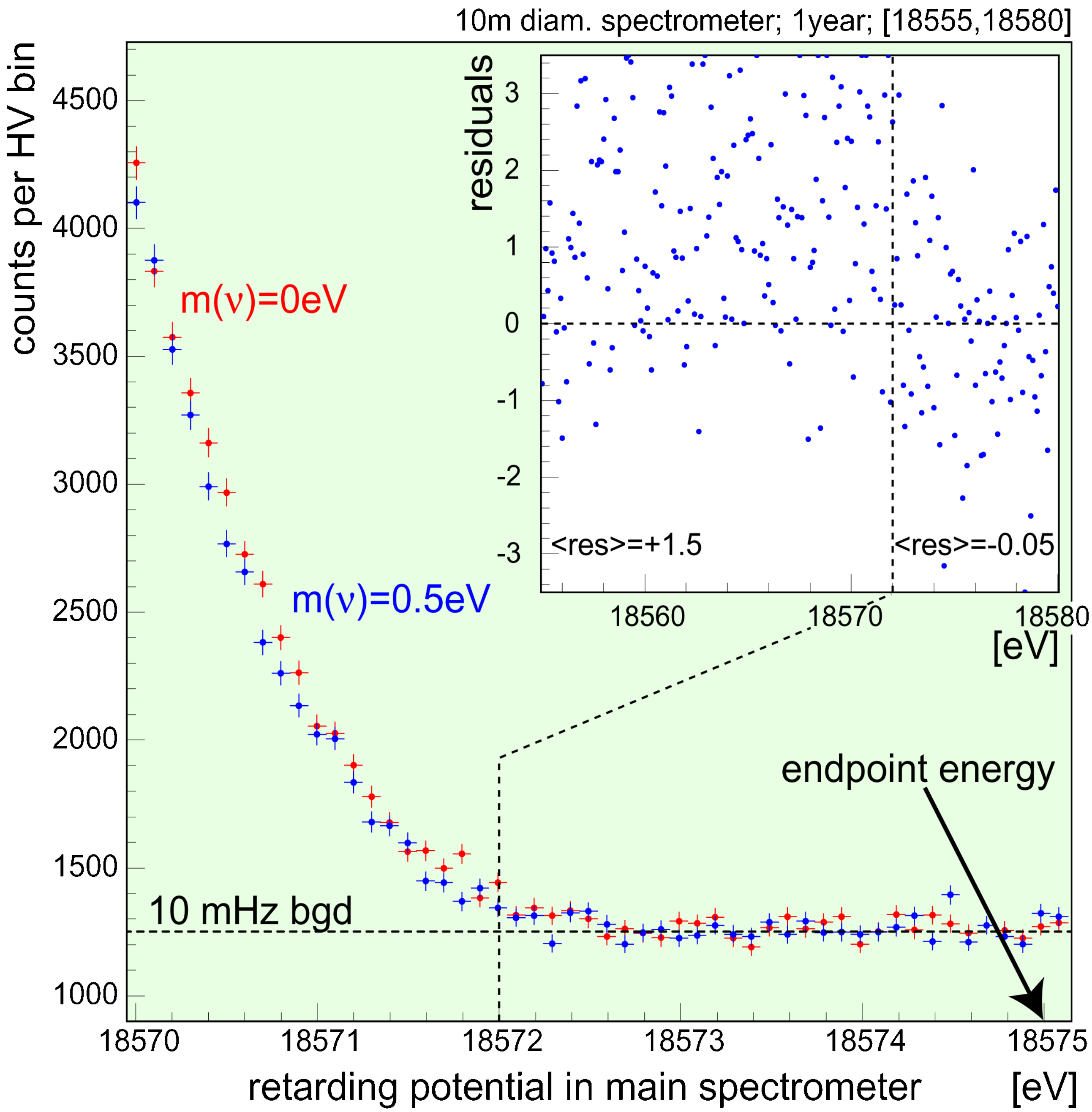




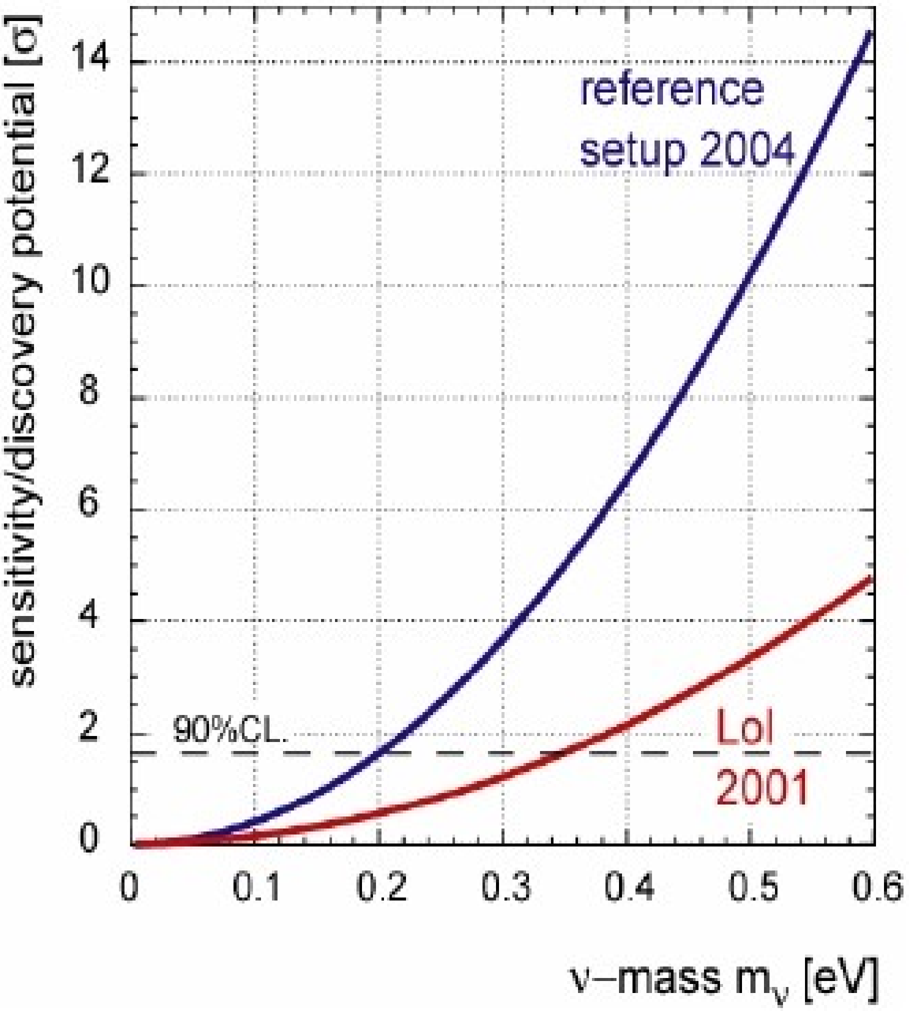
KATRIN on the move

Katrin on the move

Katrin data


10m diam. spectrometer; 1year; [18555,18580]
counts per HV bin
4500
4000
3500
3000
2500
2000
1500
1000
m(ν)=0eV
m(ν)=0.5eV
10 mHz bgd
endpoint energy
18570
18571
18572
18573
18574
18575
retarding potential in main spectrometer
[eV]
residuals
3
2
1
0
-1
-2
-3
<res>=+1.5
<res>=-0.05
18560
18570
18580
[eV]

KATRIN Sensitivity

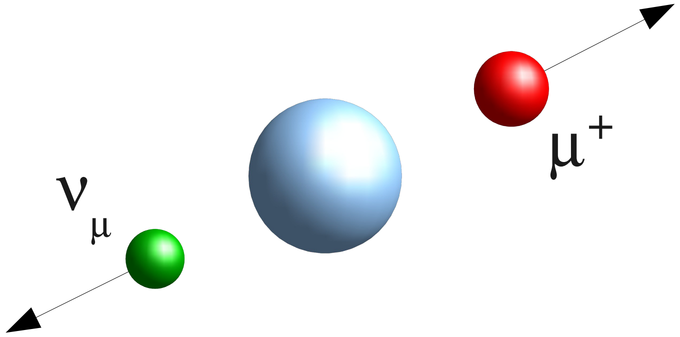


sensitivity (90% CL)
m(ν) < 0.2 eV

discovery potential
m(ν) = 0.35 eV (5σ)

ν_μ mass

Easiest way is to use pion decay at rest



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

$$m_\pi = 139.56995 \pm 0.00035\, MeV$$

$$m_\mu = 105.658358 \pm 0.000005\, MeV$$

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

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

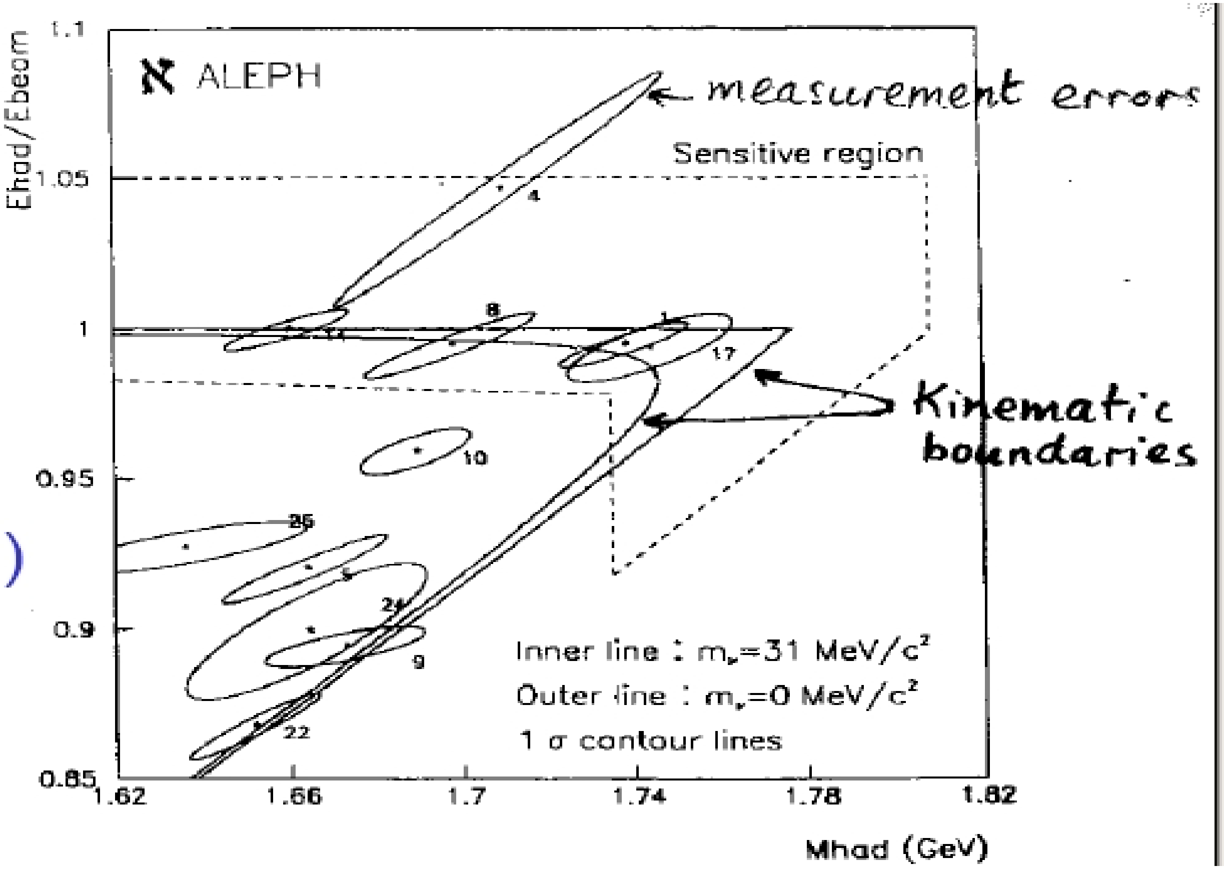
$$\boxed{m_\nu < 170\, keV\, (90\,\%\, CL)}$$

ν_τ mass

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

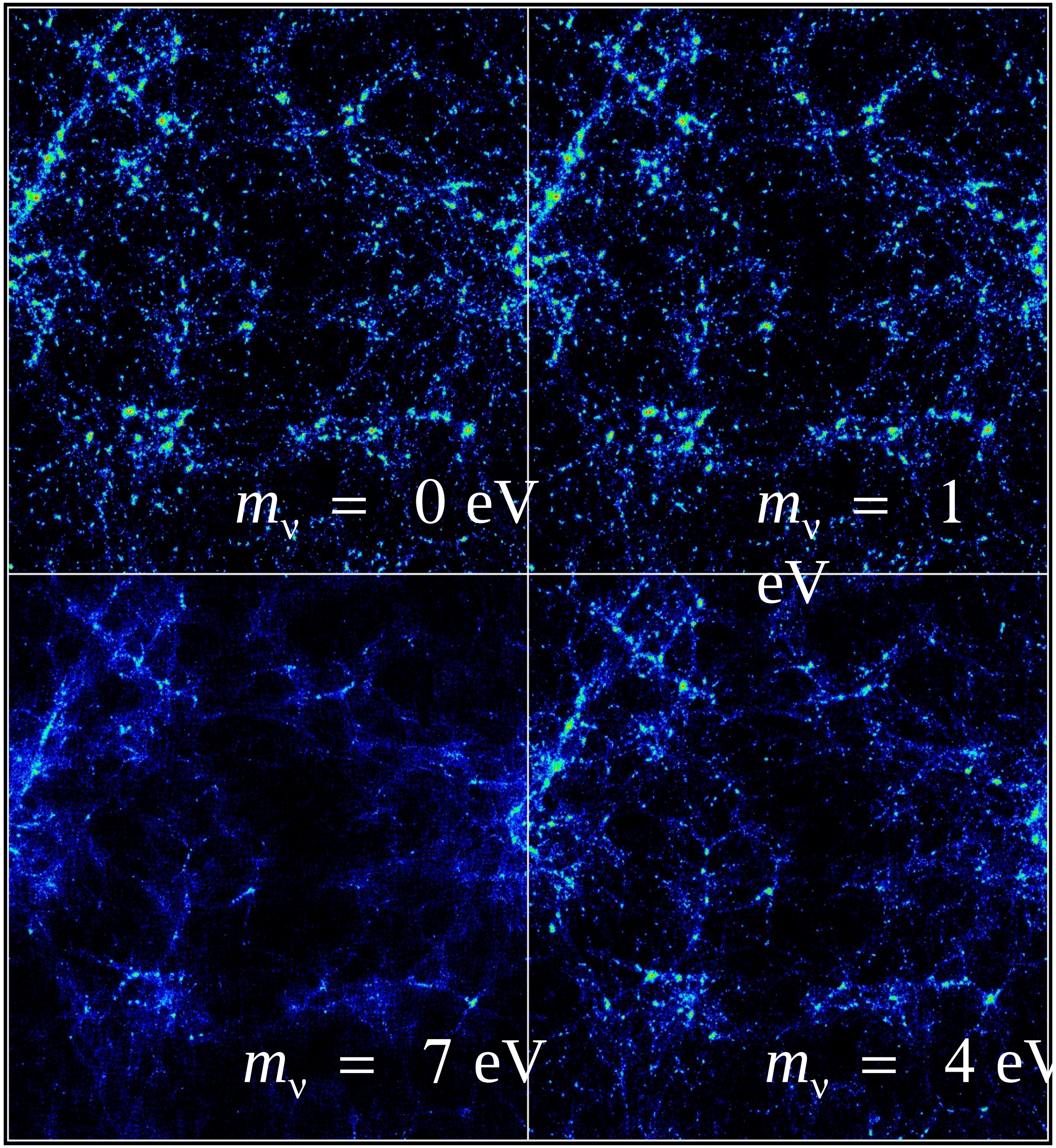
$$\hookrightarrow \tau \to \nu_\tau + 5\pi^{+-} (\pi^0)$$

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



$$\boxed{m_\tau < 15.5\, MeV\, (95\%\, CL)}$$

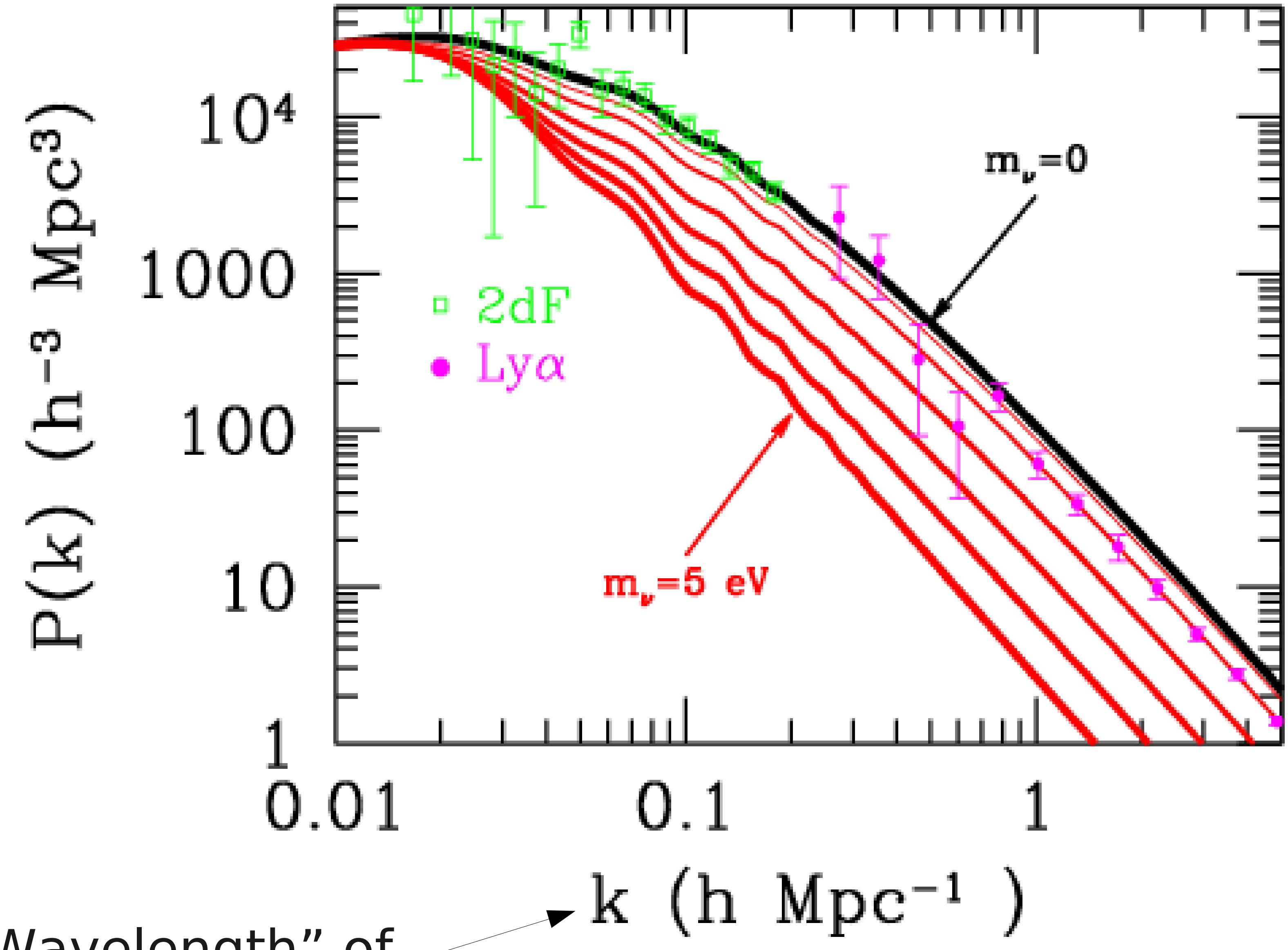
Cosmology



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

$$\sum m_{\nu_i} < 0.7\,eV$$

Power spectra



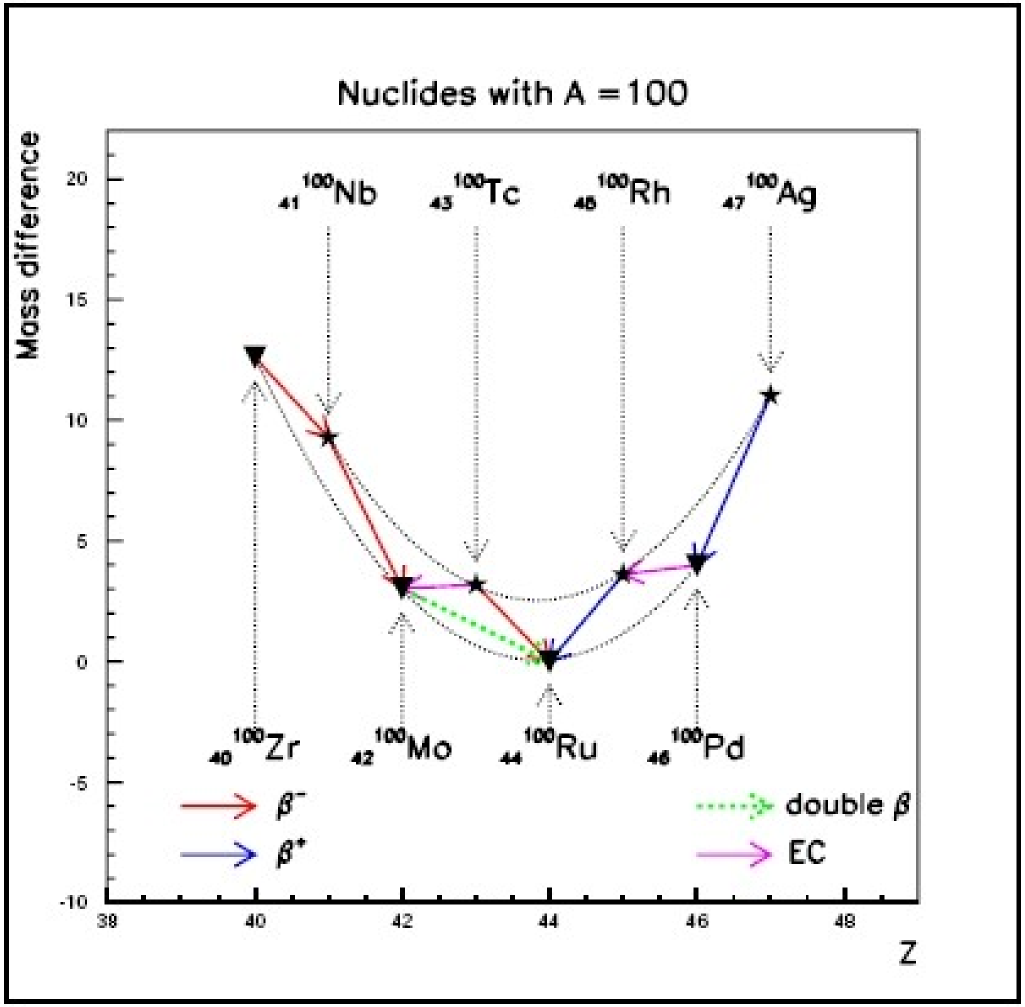
“1/Wavelength” of density fluctuation

2νββ Decay

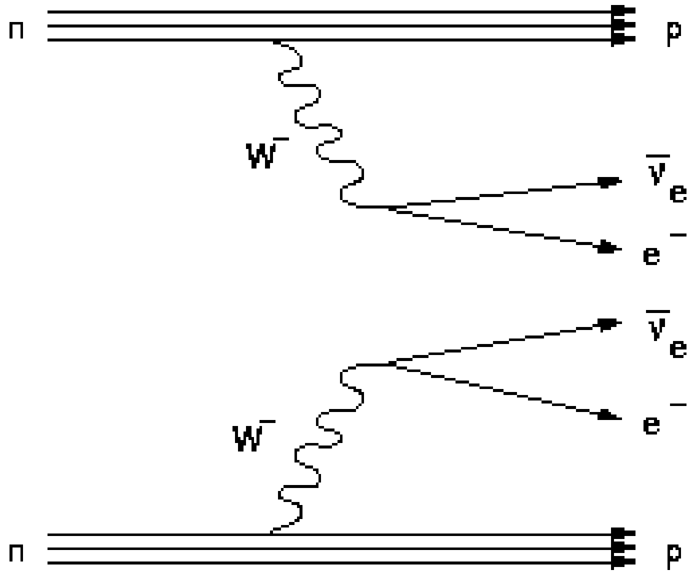
Neutrinoless double beta decay is considered a golden channel for the measurement of neutrino mass.

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

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



2νββ Decay



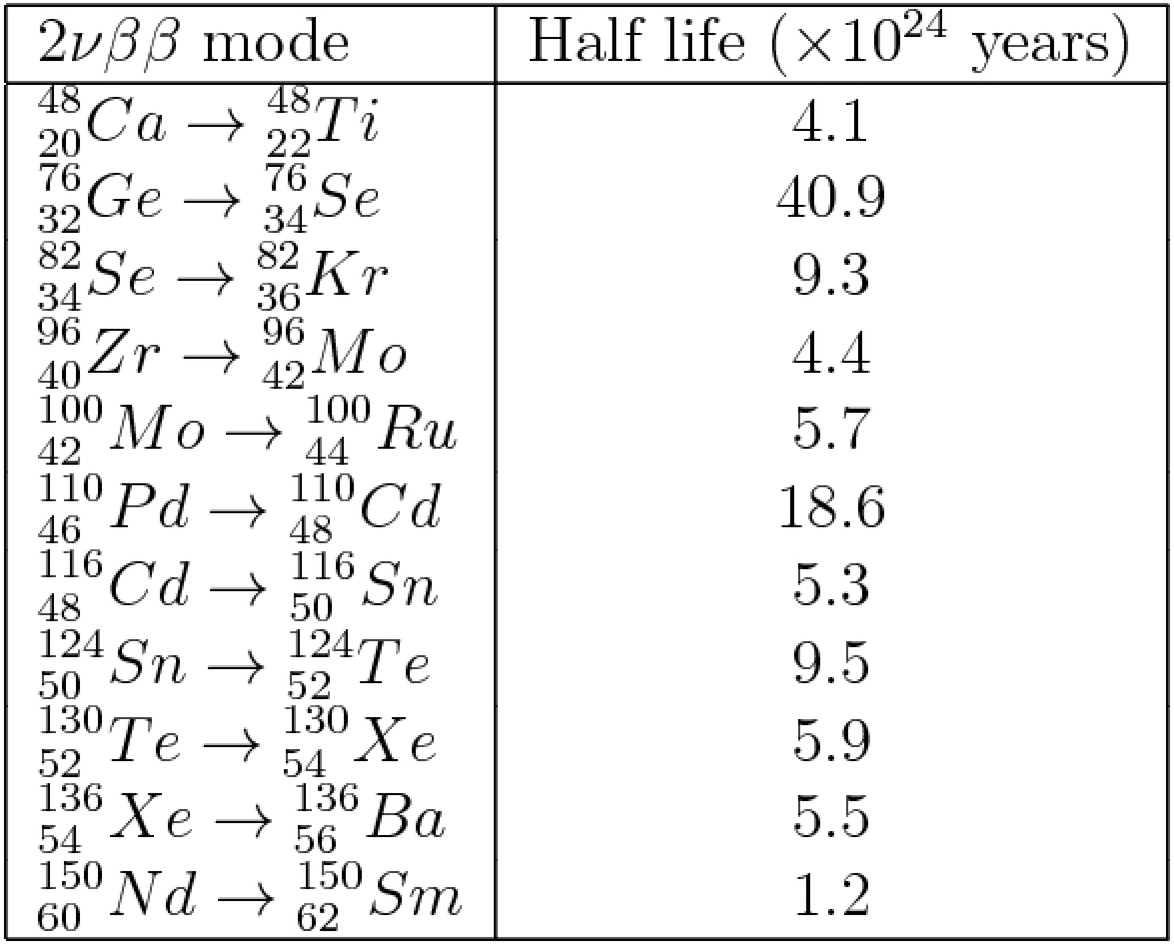
$$\left[T^{2\nu}_{1/2}\right]^{-1} = G^{2\nu}(Q,Z)\left|M^{2\nu}\right|^{2}$$

Calculable phase space

Nuclear matrix element

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

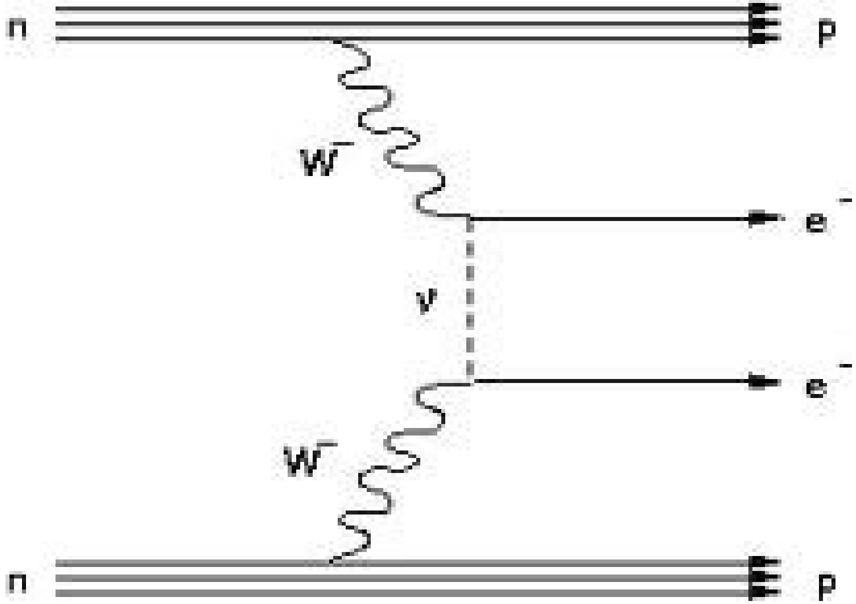
2νββ Decay



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

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

Neutrinoless ββ Decay



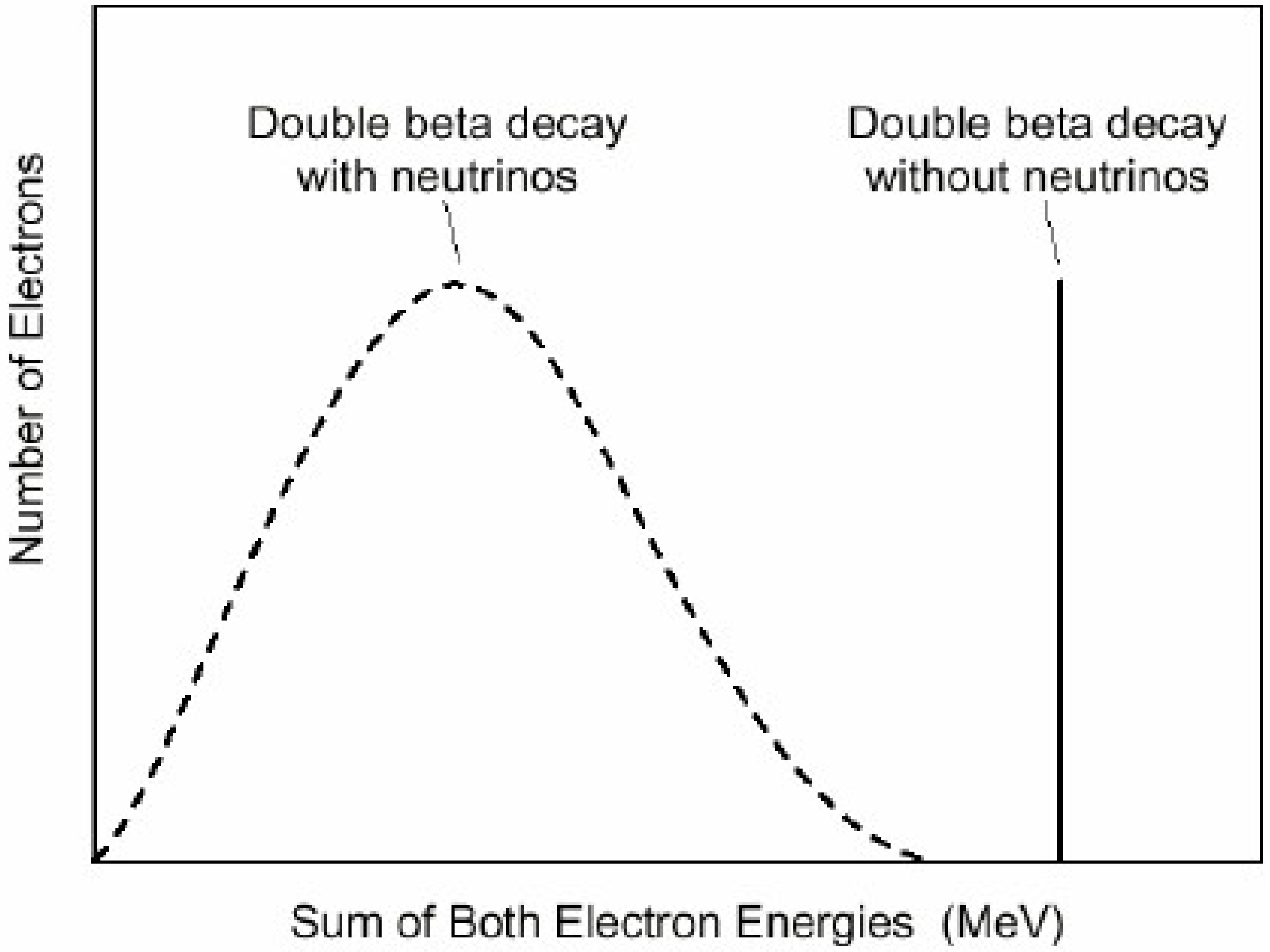
- Neutrino must have mass
- Neutrino is a *Majorana* particle
- Violation of lepton number conservation

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

helicity states

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

0νββ signal

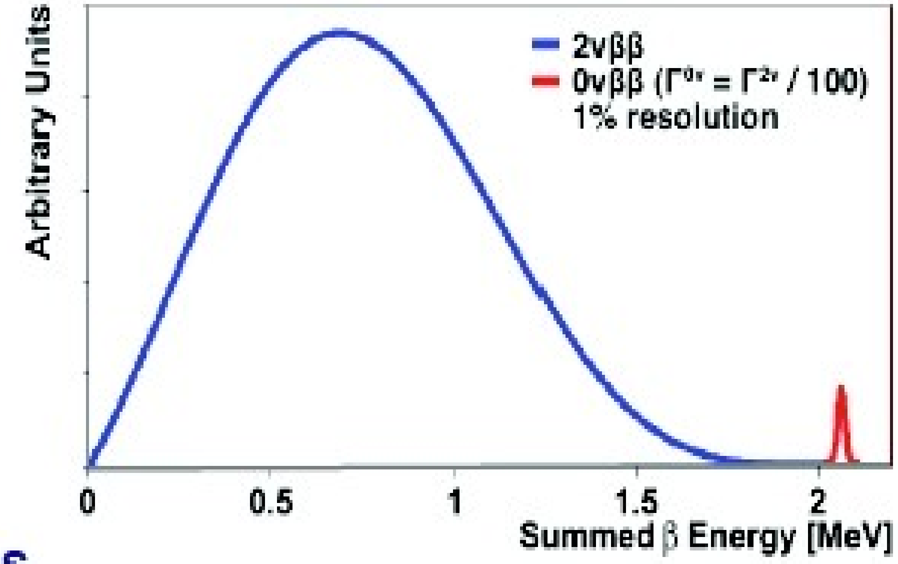

Double beta decay
with neutrinos
Double beta decay
without neutrinos
Number of Electrons
Sum of Both Electron Energies (MeV)

Experimental Requirements

Extremely slow decay rates

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

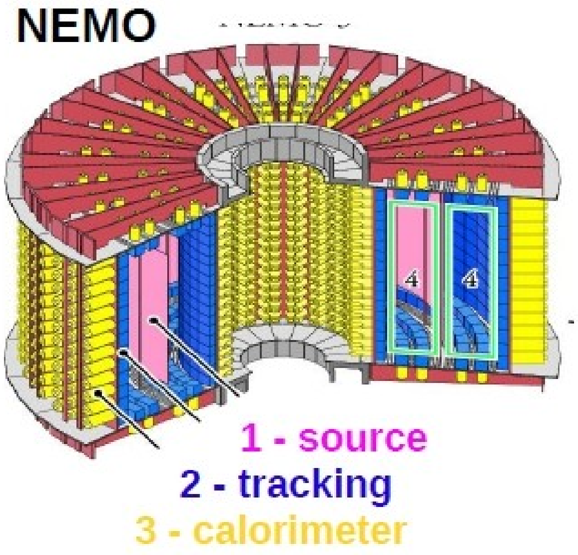
Best case, 0 background !	∝ Source Mass • time_{exp}



Requires

- Large, highly efficient source mass
  - detector as source
- Best possible energy resolution
  - minimize 0νββ peak ROI to maximize S/B
  - separate from 0νββ from irreducible 2νββ (~ $T_{1/2} \sim 10^{19} - 10^{21}$ years)
- Extremely low (near-zero) backgrounds in the 0νββ 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)

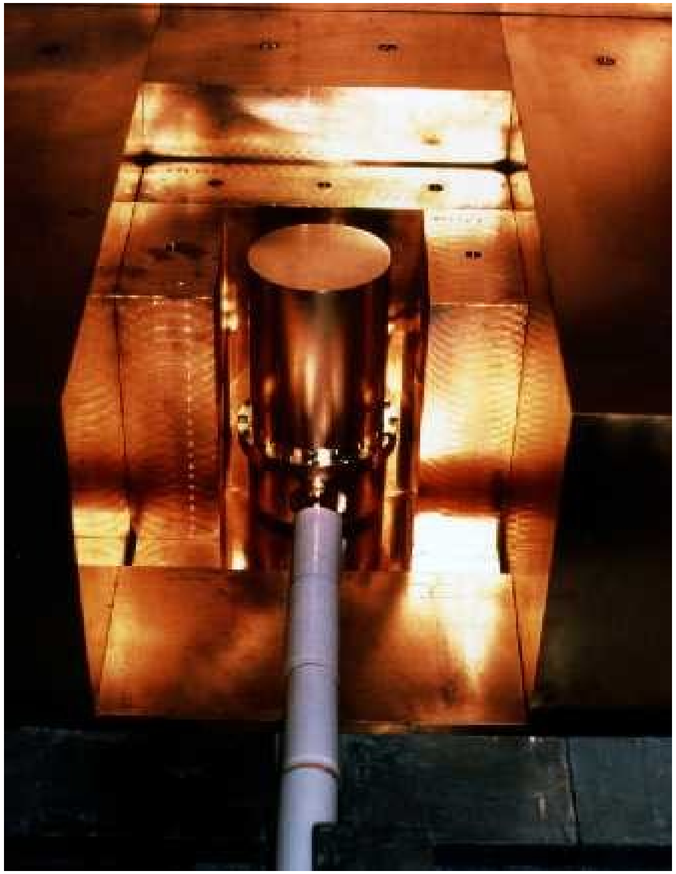
2. the detector is itself the source

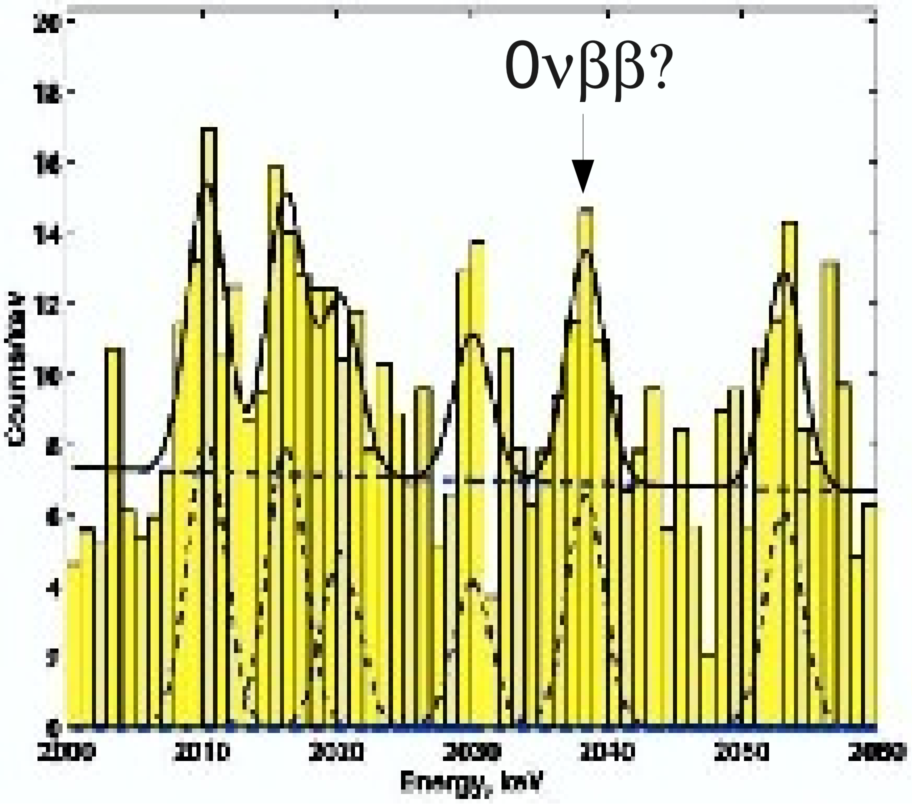
- **solid state detectors**
  → several candidates, high resolution
  no info on kinematic
  techniques for background suppression

- **gaseous detectors for Xe**

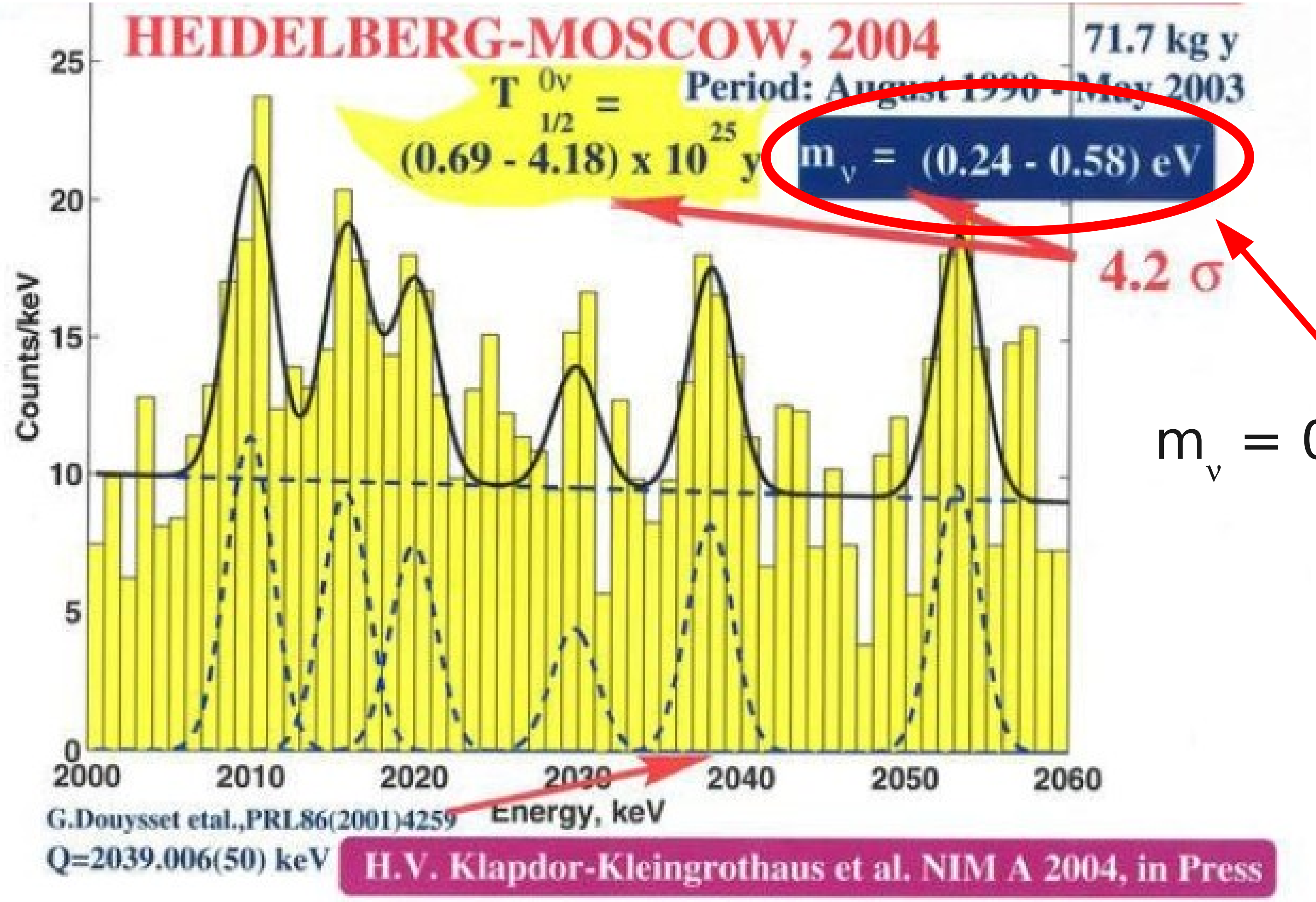
Heidelberg-Moscow

11 kg of Ge enriched to 86% of ^{76}Ge in the form of 5 Ge diode
surrounded by Cu,Pb,Bn shielding
0νββ electrons detected by Ge detectors themselves
Only sum of electron energy measured



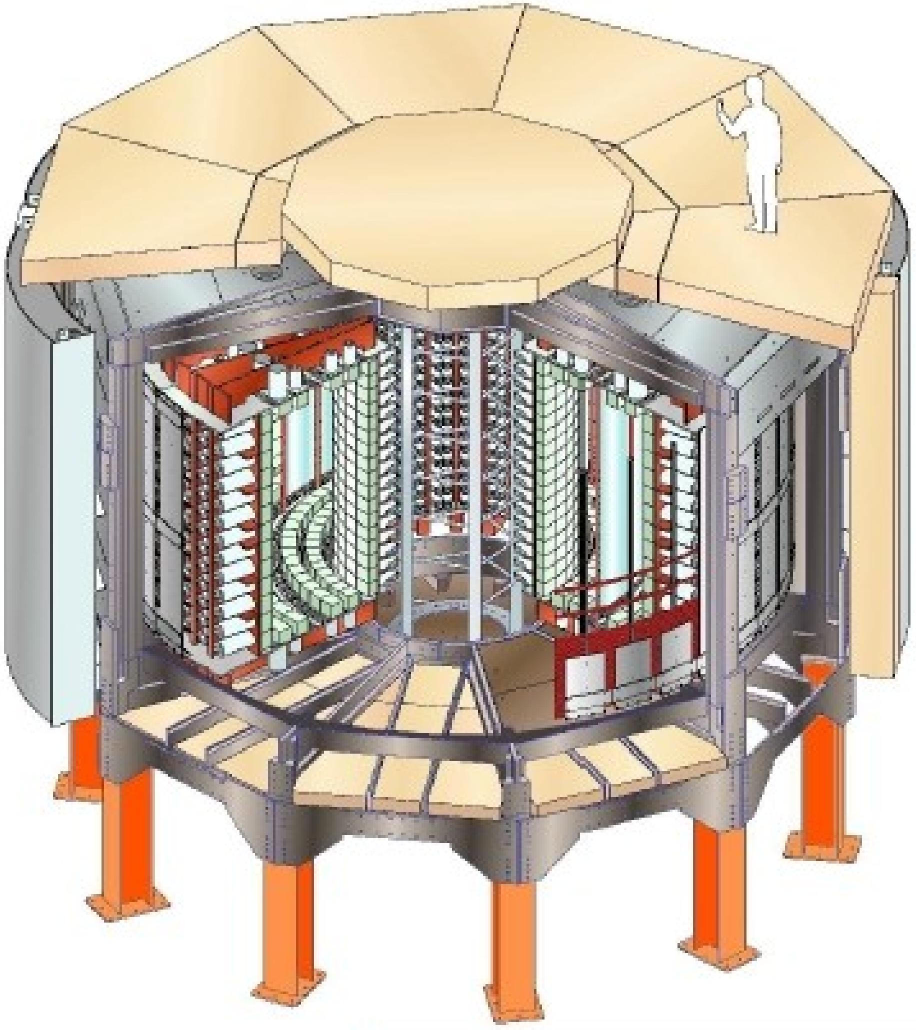


Heidelberg-Moscow



m_ν = 0.4 eV

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

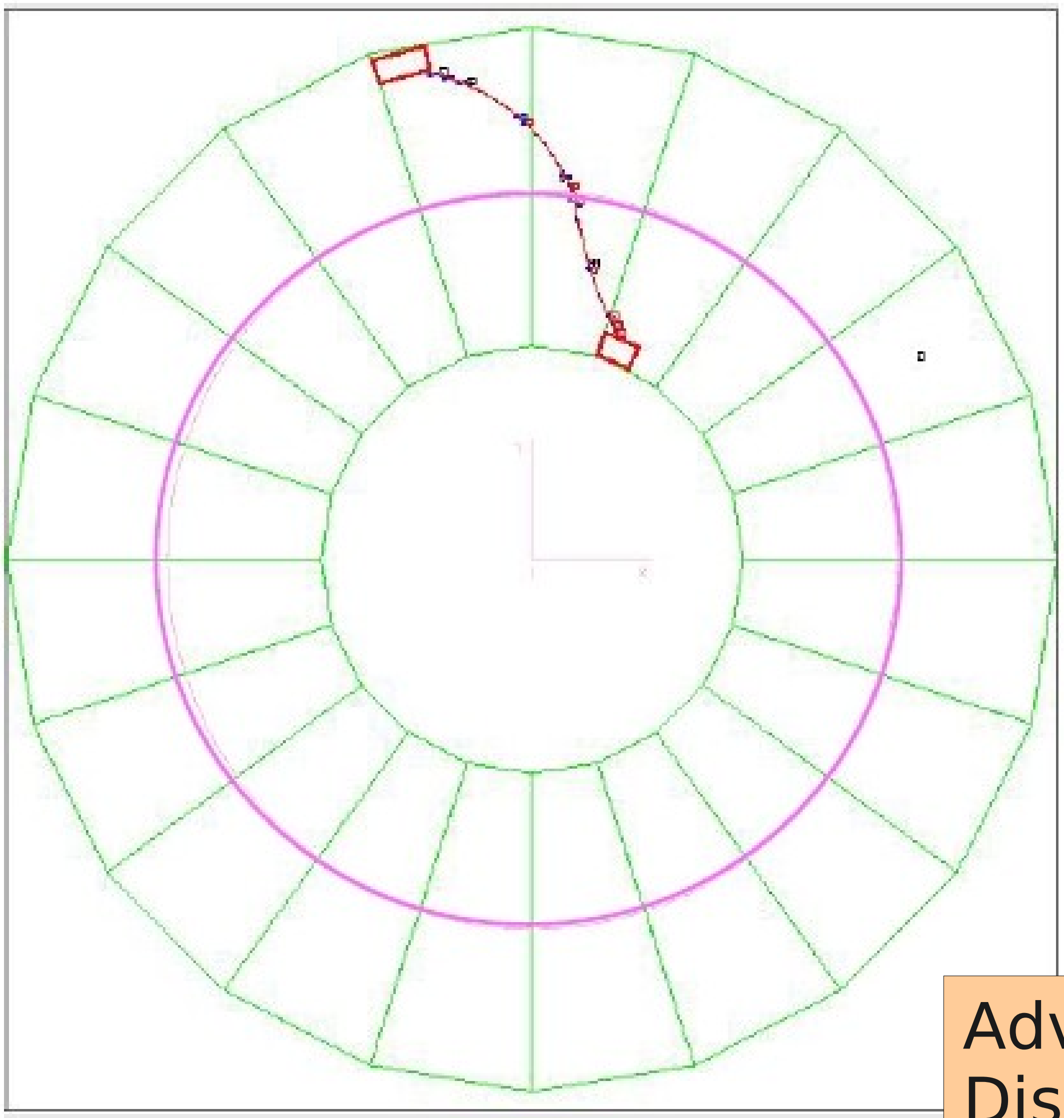
Calorimeter:
1940 plastic scintillators
coupled to low radioactivity PMTs

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

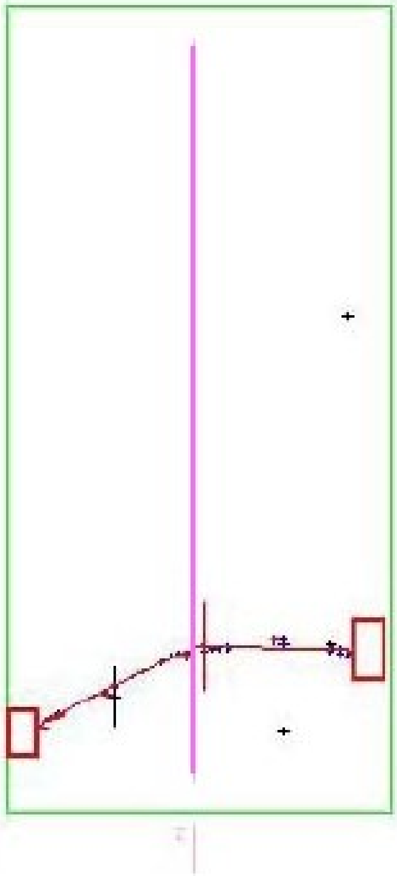
Background: n[illegible]2.6 MeV)

⇒ Able to identify e$^-$, e$^+$, γ and α

Typical ββ2ν event observed from ^{100}Mo



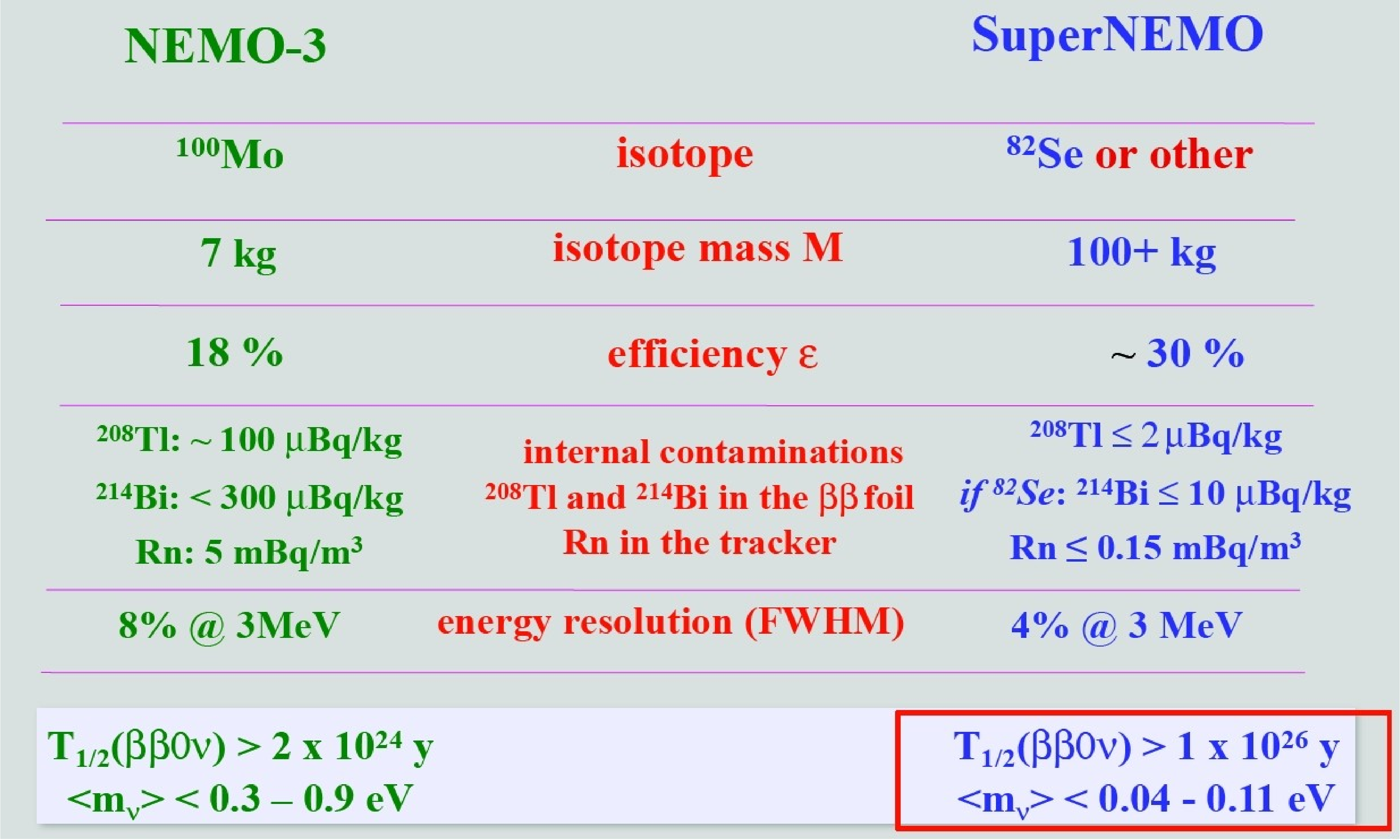
Top view



Side view

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

Nemo to SuperNemo

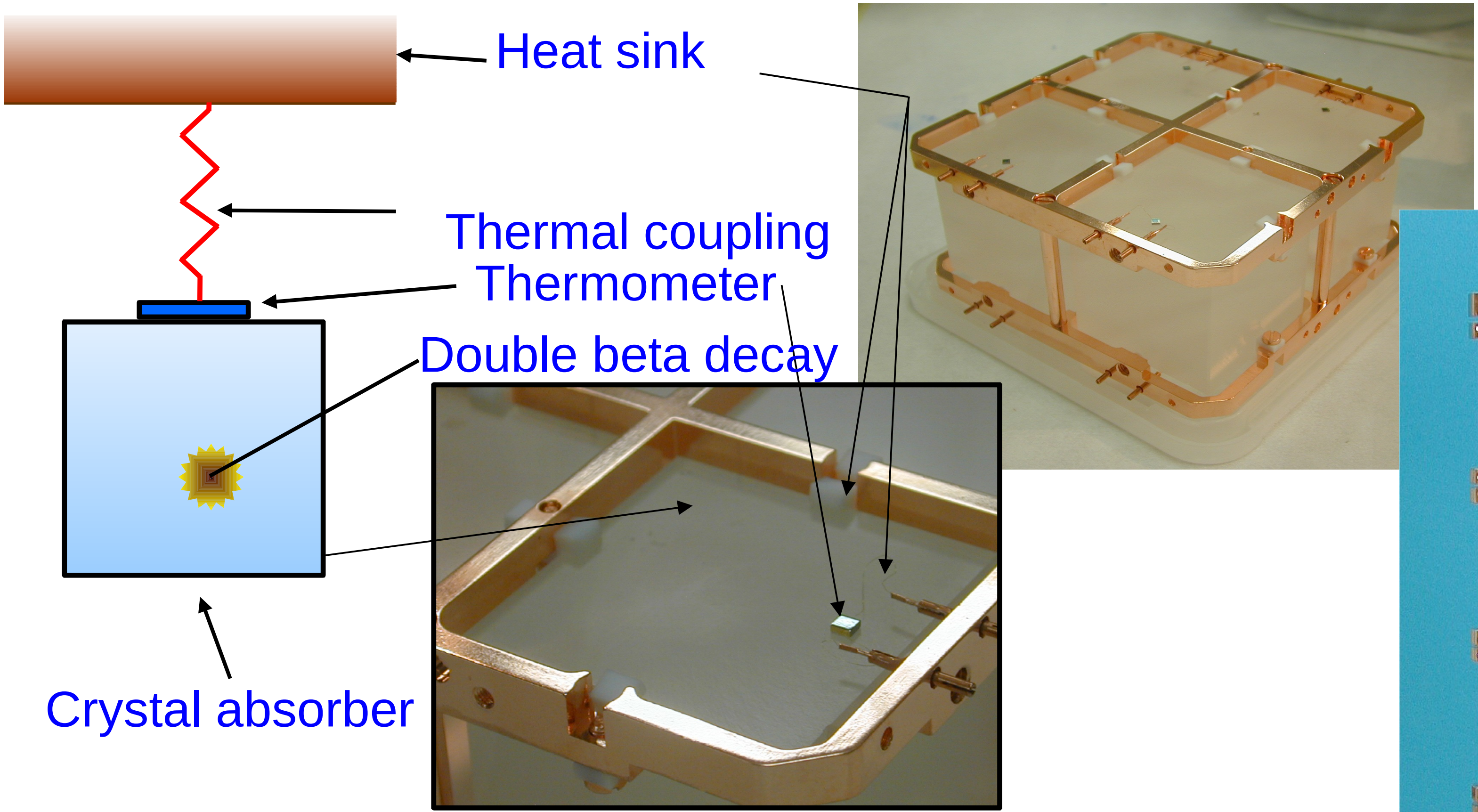


NEMO-3		SuperNEMO
^{100}Mo	isotope	^{82}Se or other
7 kg	isotope mass M	100+ kg
18 %	efficiency ε	~ 30 %
^{208}Tl: ~ 100 μBq/kg ^{214}Bi: < 300 μBq/kg Rn: 5 mBq/m^3	internal contaminations ^{208}Tl and ^{214}Bi in the $\beta\beta$ foil Rn in the tracker	^{208}Tl $\leq$ 2 μBq/kg *if* ^{82}*Se*: ^{214}Bi $\leq$ 10 μBq/kg Rn $\leq$ 0.15 mBq/m^3
8% @ 3MeV	energy resolution (FWHM)	4% @ 3 MeV

$T_{1/2}(\beta\beta0\nu) > 2 \times 10^{24}$ y
$\langle m_\nu \rangle < 0.3 – 0.9$ eV

$T_{1/2}(\beta\beta0\nu) > 1 \times 10^{26}$ y
$\langle m_\nu \rangle < 0.04 - 0.11$ eV

Cuoricino/Cuore



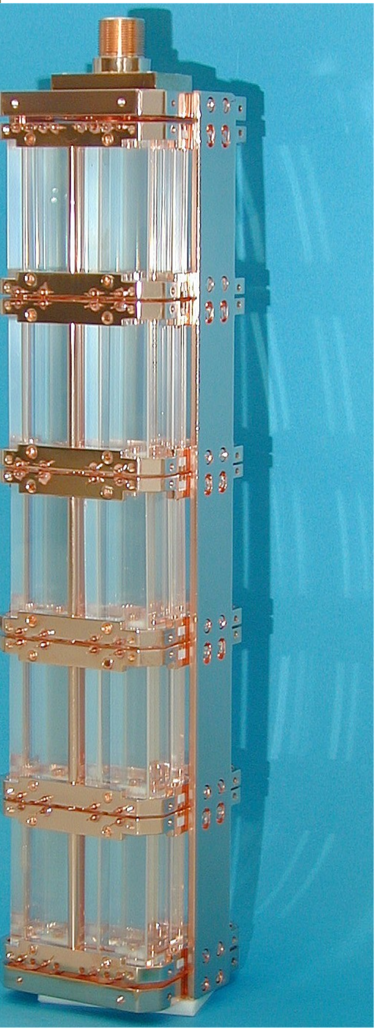
Heat sink

Thermal coupling

Thermometer

Double beta decay

Crystal absorber



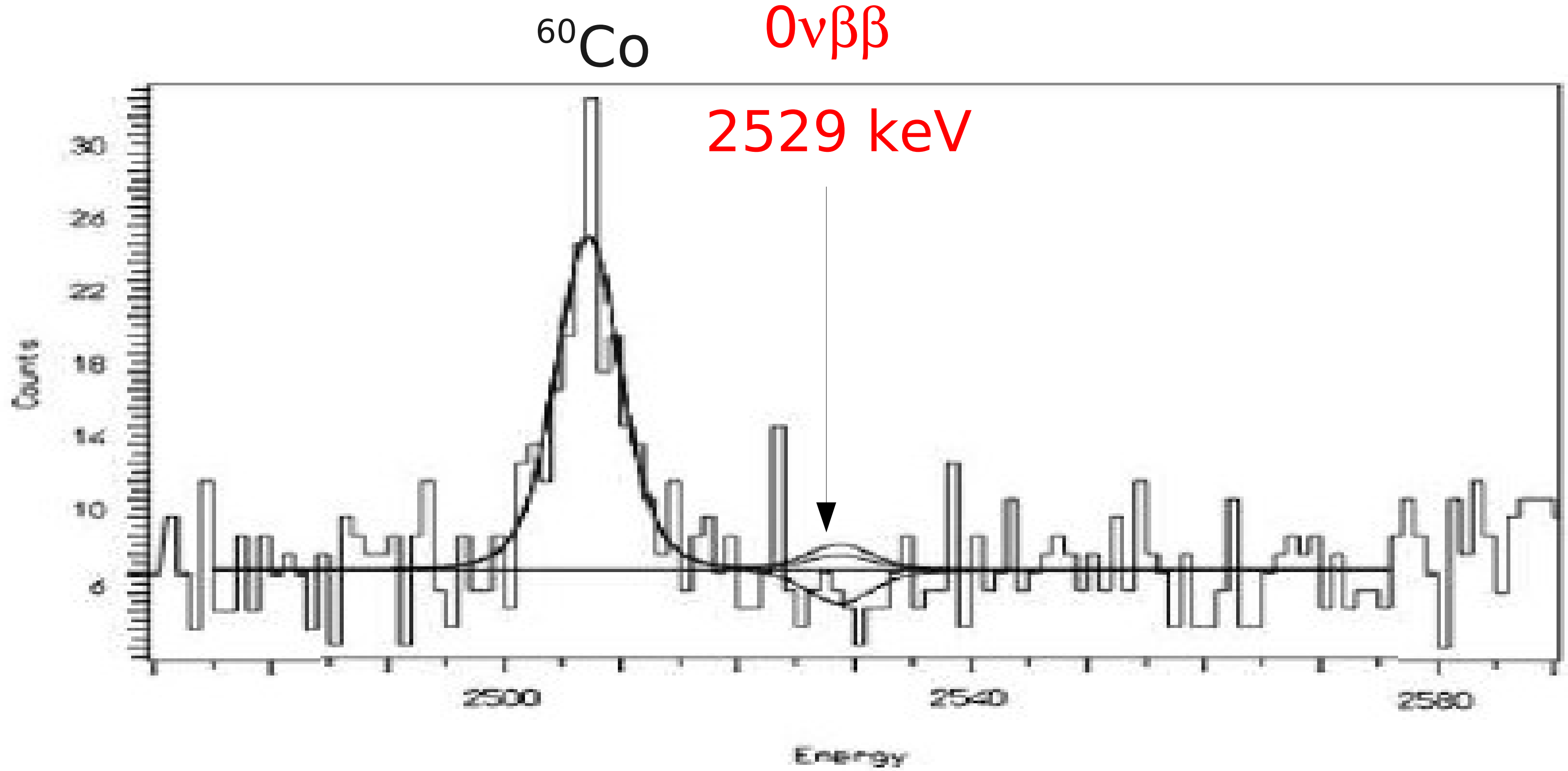
example: 750 g of TeO_2 @ 10 mK

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

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

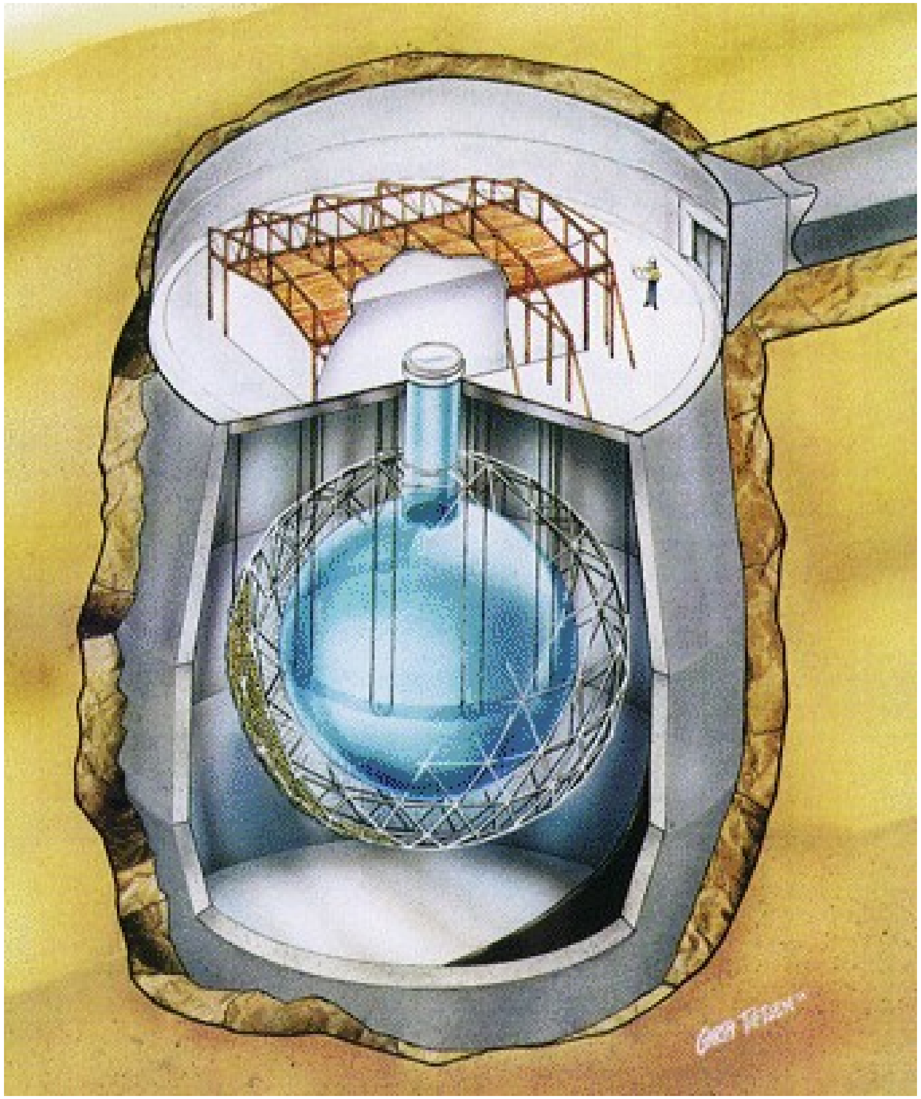
$\Rightarrow \Delta U \sim 10$ eV

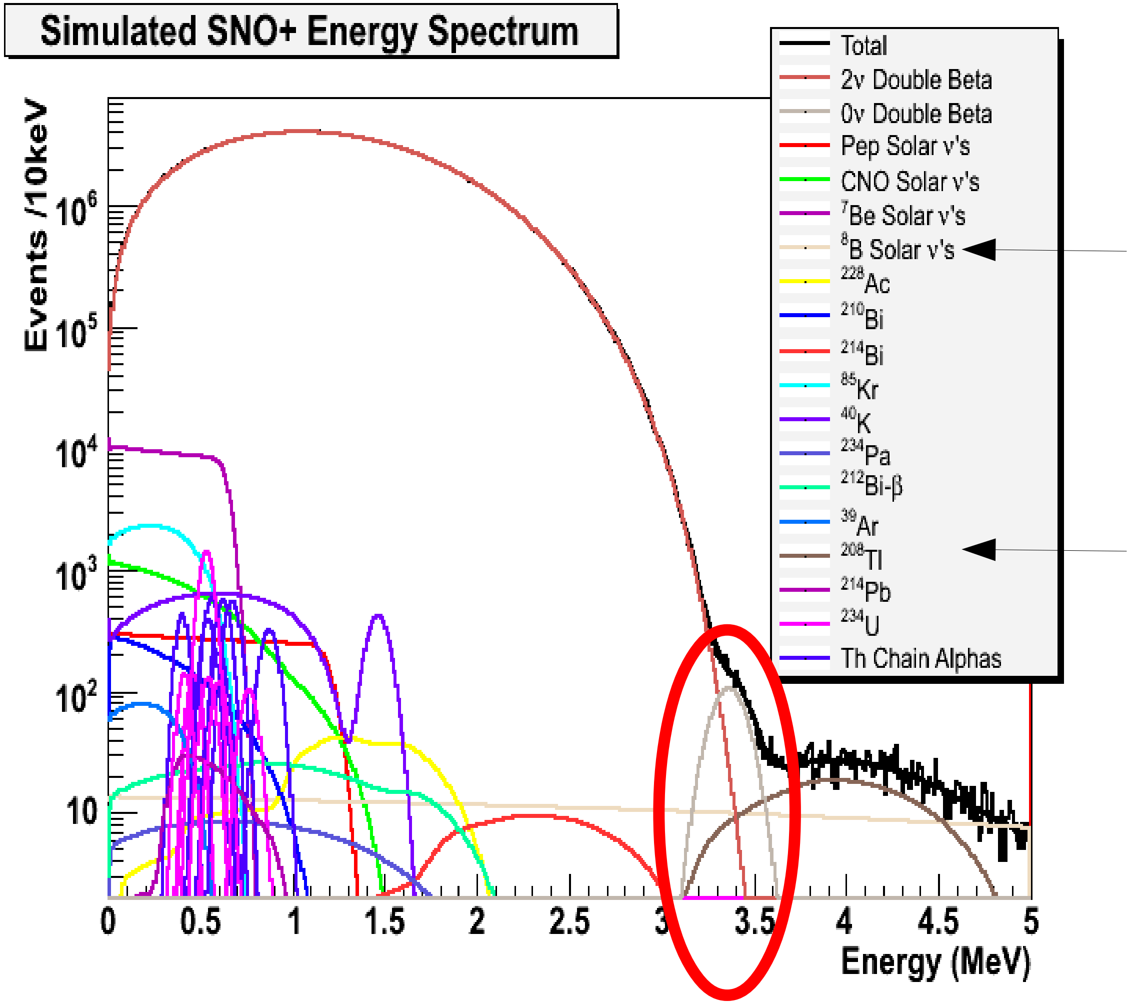
Cuoricino Results



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

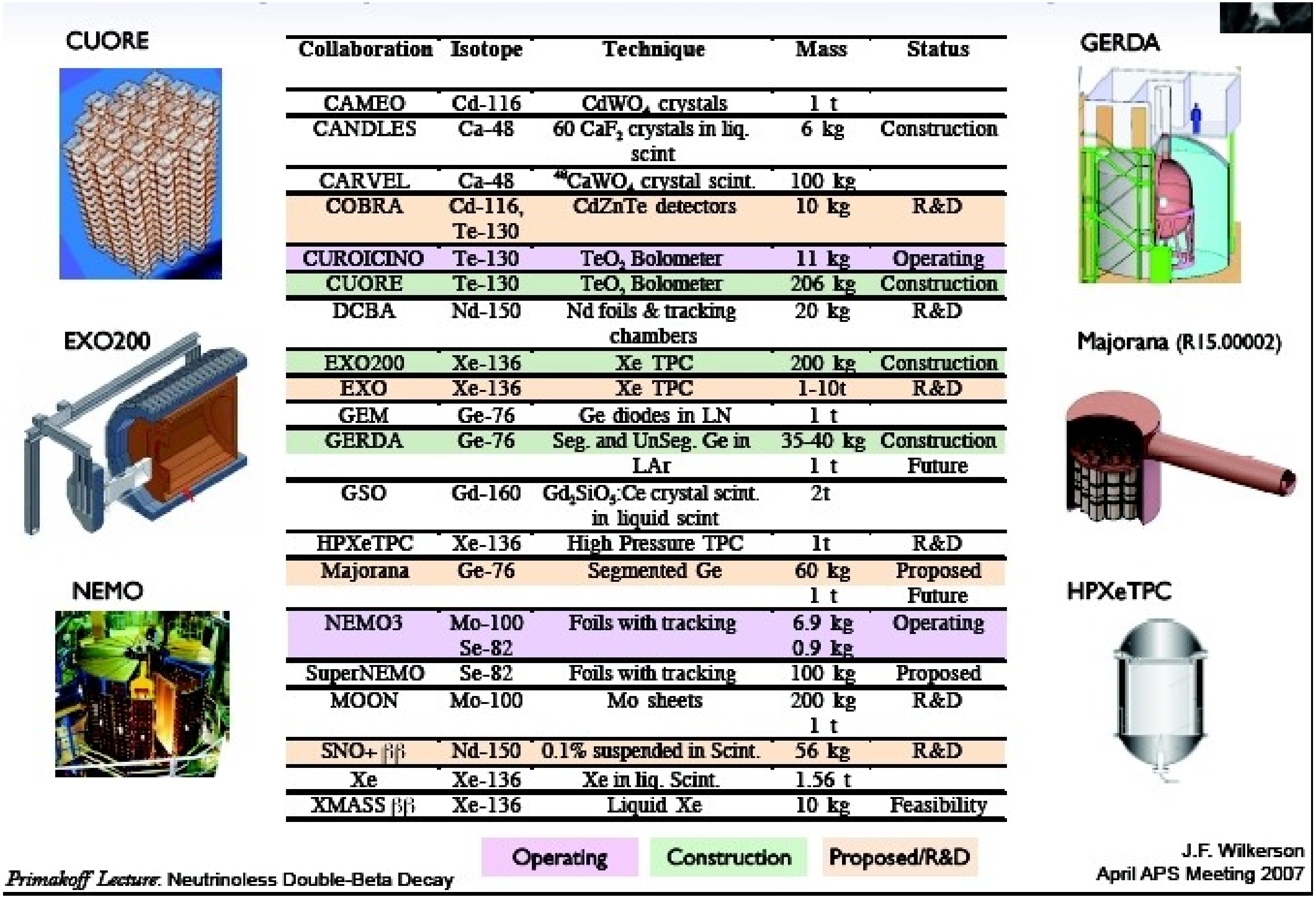
SNO+





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

Future Program



CUORE

EXO200

NEMO

Collaboration	Isotope	Technique	Mass	Status
CAMEO	Cd-116	CdWO$_4$ crystals	1 t	
CANDLES	Ca-48	60 CaF$_2$ crystals in liq. scint	6 kg	Construction
CARVEL	Ca-48	^{48}CaWO$_4$ crystal scint.	100 kg	
COBRA	Cd-116, Te-130	CdZnTe detectors	10 kg	R&D
CUROICINO	Te-130	TeO$_2$ Bolometer	11 kg	Operating
CUORE	Te-130	TeO$_2$ Bolometer	206 kg	Construction
DCBA	Nd-150	Nd foils & tracking chambers	20 kg	R&D
EXO200	Xe-136	Xe TPC	200 kg	Construction
EXO	Xe-136	Xe TPC	1-10t	R&D
GEM	Ge-76	Ge diodes in LN	1 t	
GERDA	Ge-76	Seg. and UnSeg. Ge in LAr	35-40 kg 1 t	Construction Future
GSO	Gd-160	Gd$_2$SiO$_5$:Ce crystal scint. in liquid scint	2t	
HPXeTPC	Xe-136	High Pressure TPC	1t	R&D
Majorana	Ge-76	Segmented Ge	60 kg 1 t	Proposed Future
NEMO3	Mo-100 Se-82	Foils with tracking	6.9 kg 0.9 kg	Operating
SuperNEMO	Se-82	Foils with tracking	100 kg	Proposed
MOON	Mo-100	Mo sheets	200 kg 1 t	R&D
SNO+ ββ	Nd-150	0.1% suspended in Scint.	56 kg	R&D
Xe	Xe-136	Xe in liq. Scint.	1.56 t	
XMASS ββ	Xe-136	Liquid Xe	10 kg	Feasibility

GERDA

Majorana (R15.00002)

HPXeTPC

Operating Construction Proposed/R&D

Primakoff Lecture: Neutrinoless Double-Beta Decay

J.F. Wilkerson
April APS Meeting 2007