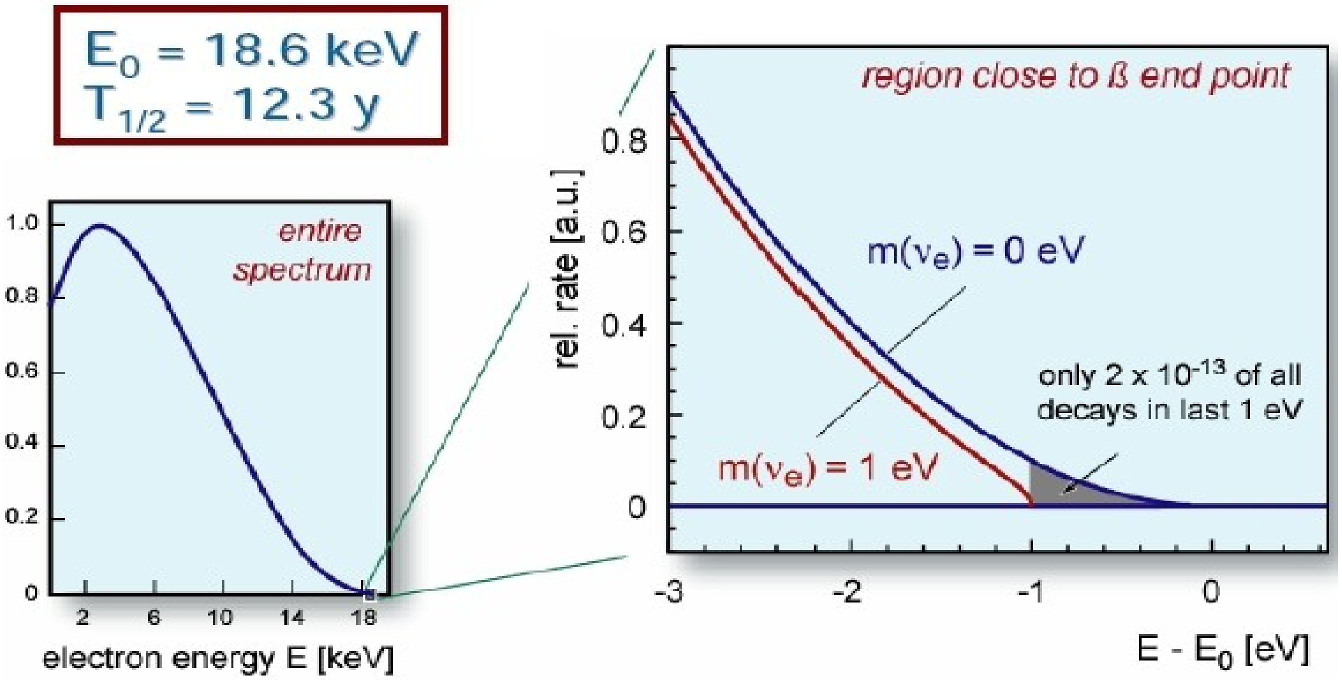
Neutrino Mass Measurements

β decay

Measurement of ν mass from kinematics of β decay.

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

Observable is m_ν^2



Requirements for experiment

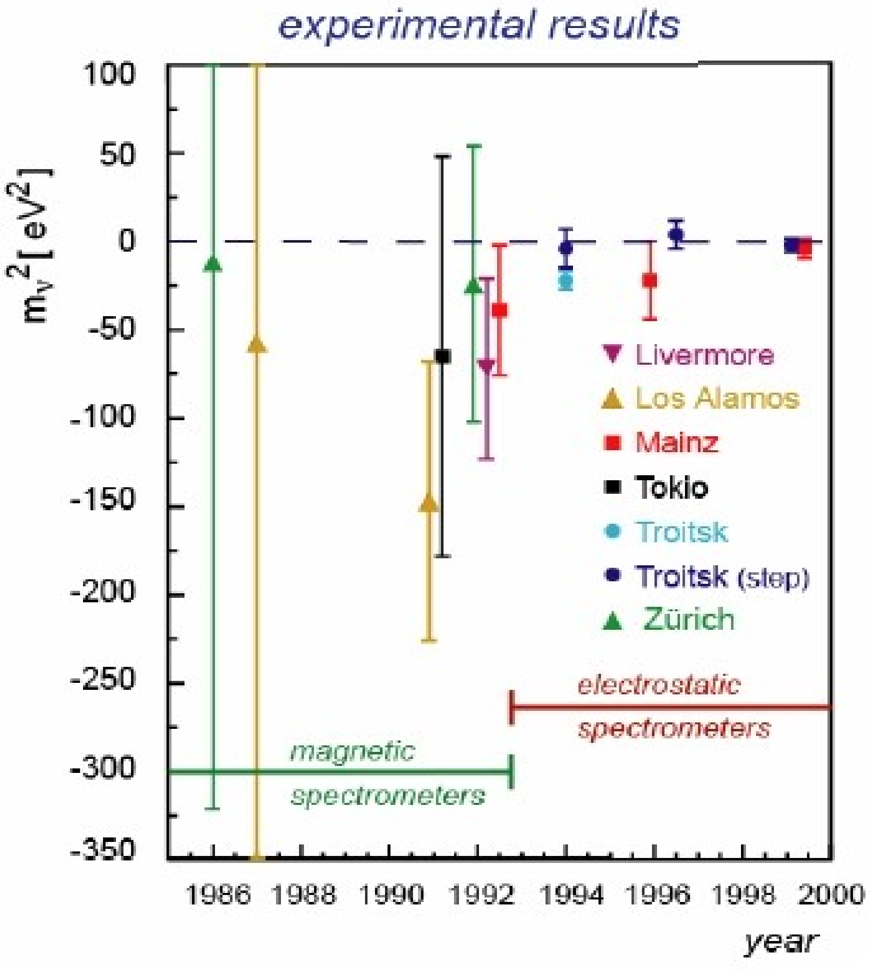
- The number of electrons close to the endpoint should be small
- Good (and well-understood) electron energy resolution
- No (or minimal) electron energy loss within the source
- Minimal atomic and nuclear final state effects, of excited transitions

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

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

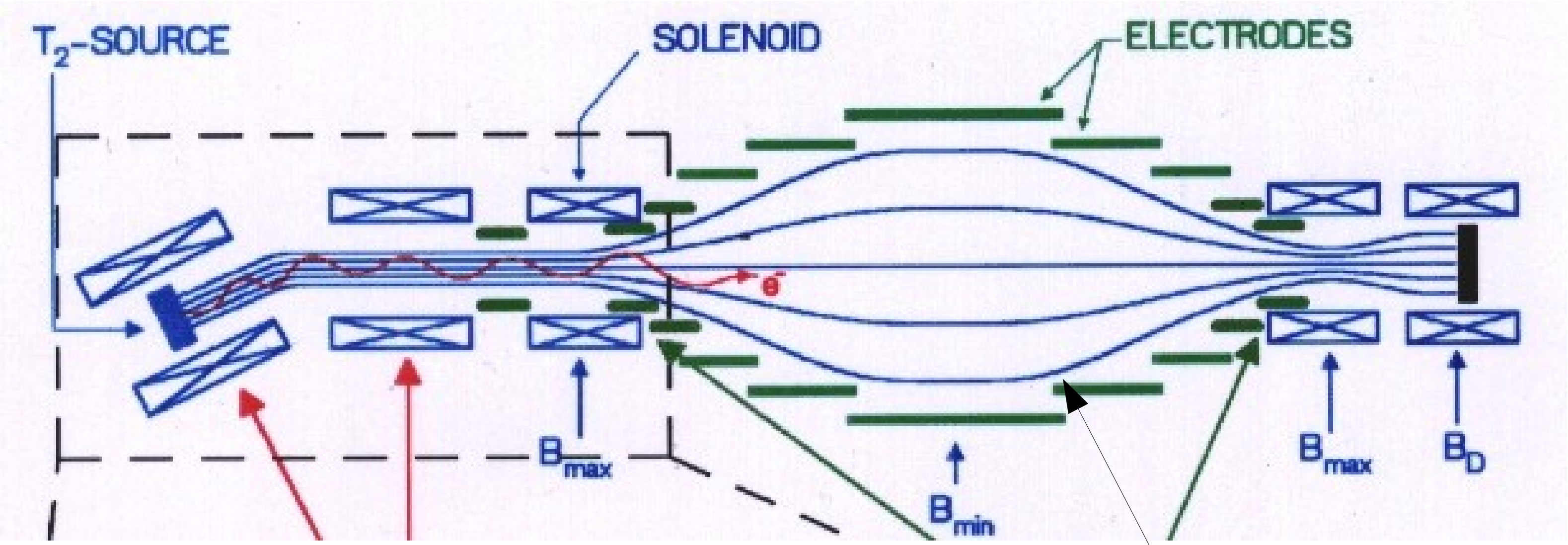
History of tritium-β decay results

	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



Mainz Experiment

The current standard for tritium beta decay experiments



Electrostatic Filter

- 2π acceptance
- High energy resolution

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

Present Status

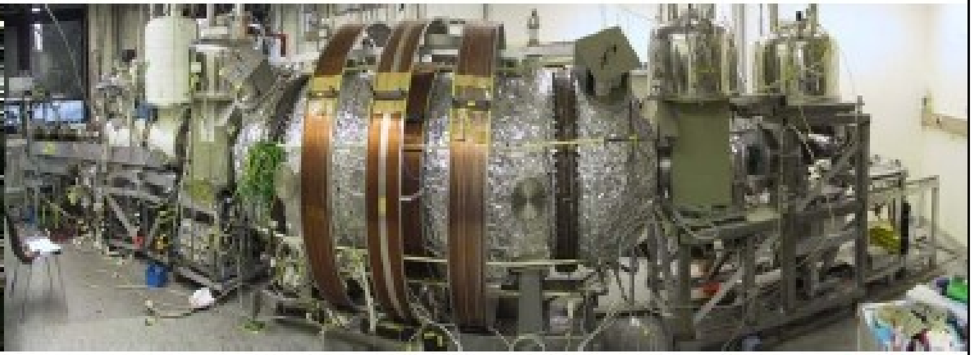
Troitsk

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.)

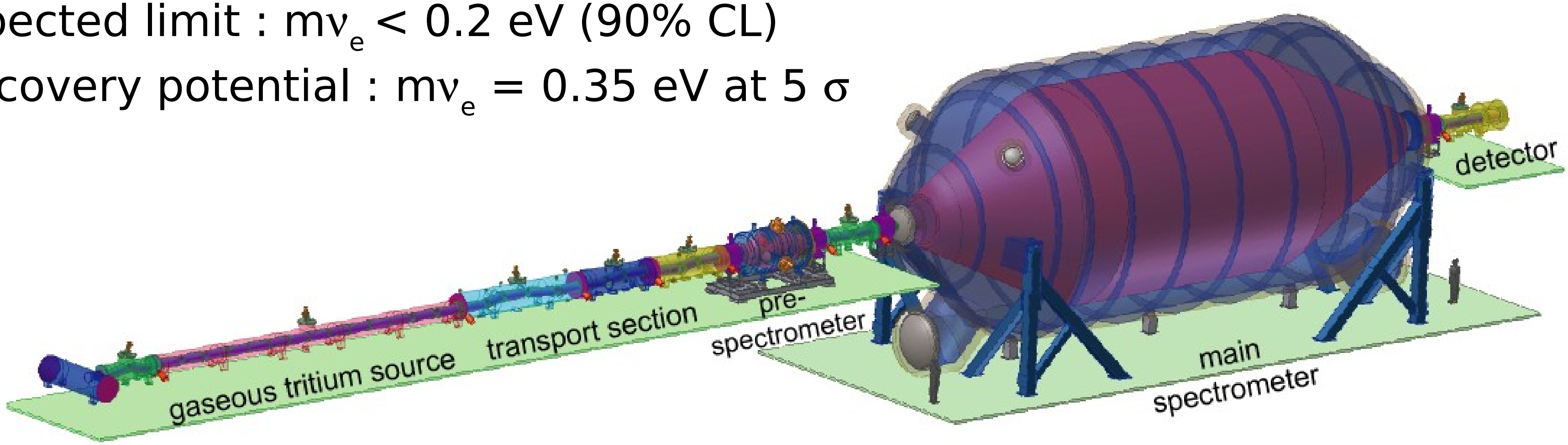
Both experiments have reached the intrinsic limit of their sensitivity.

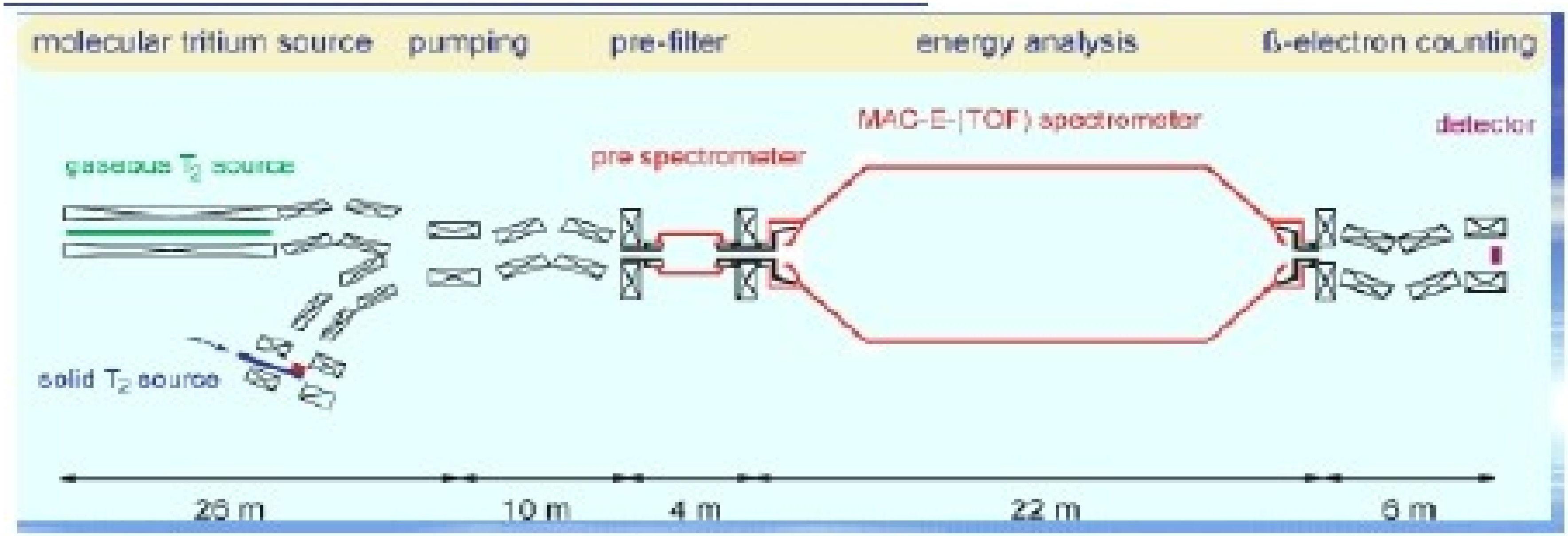
KATRIN

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

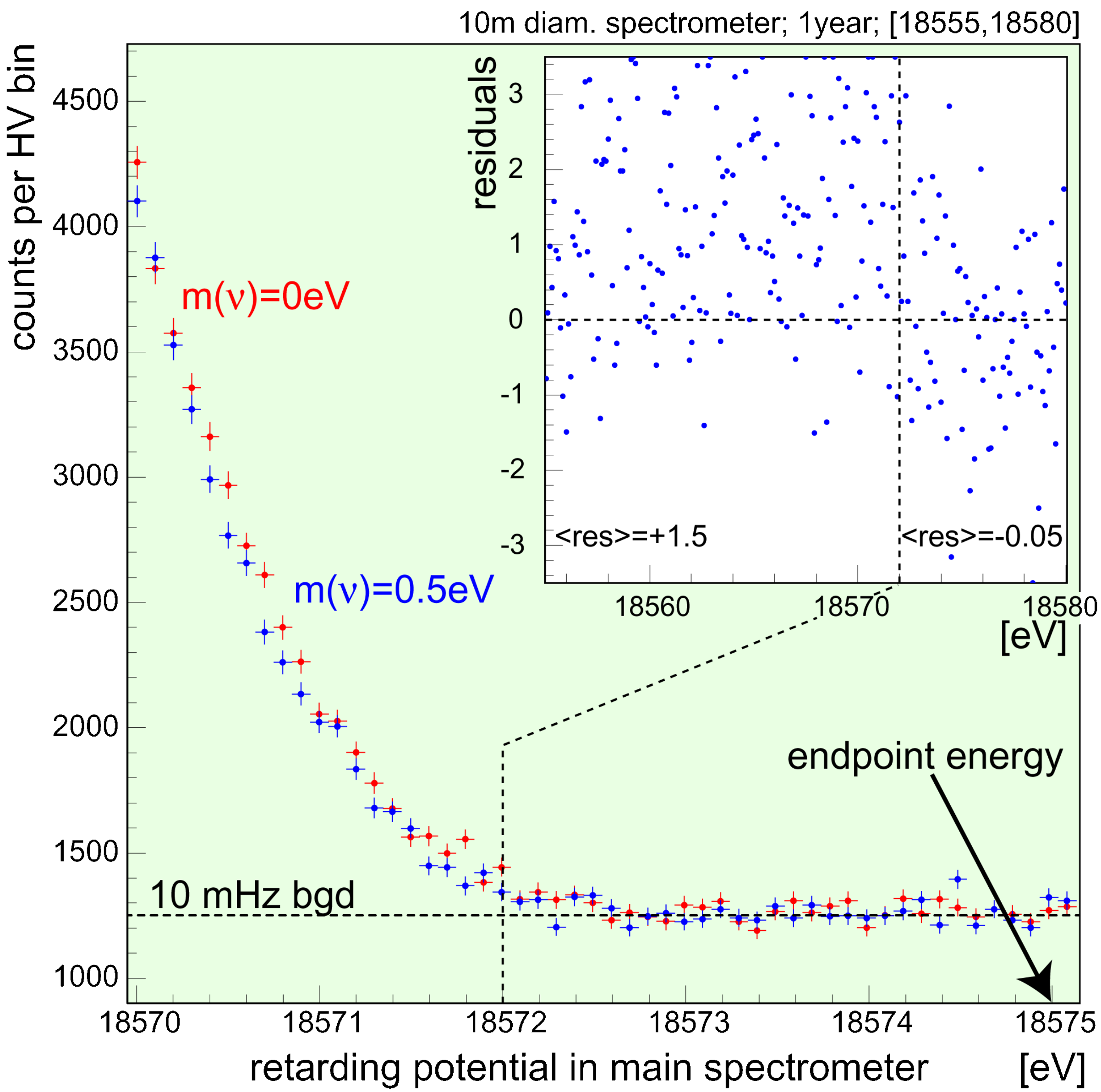




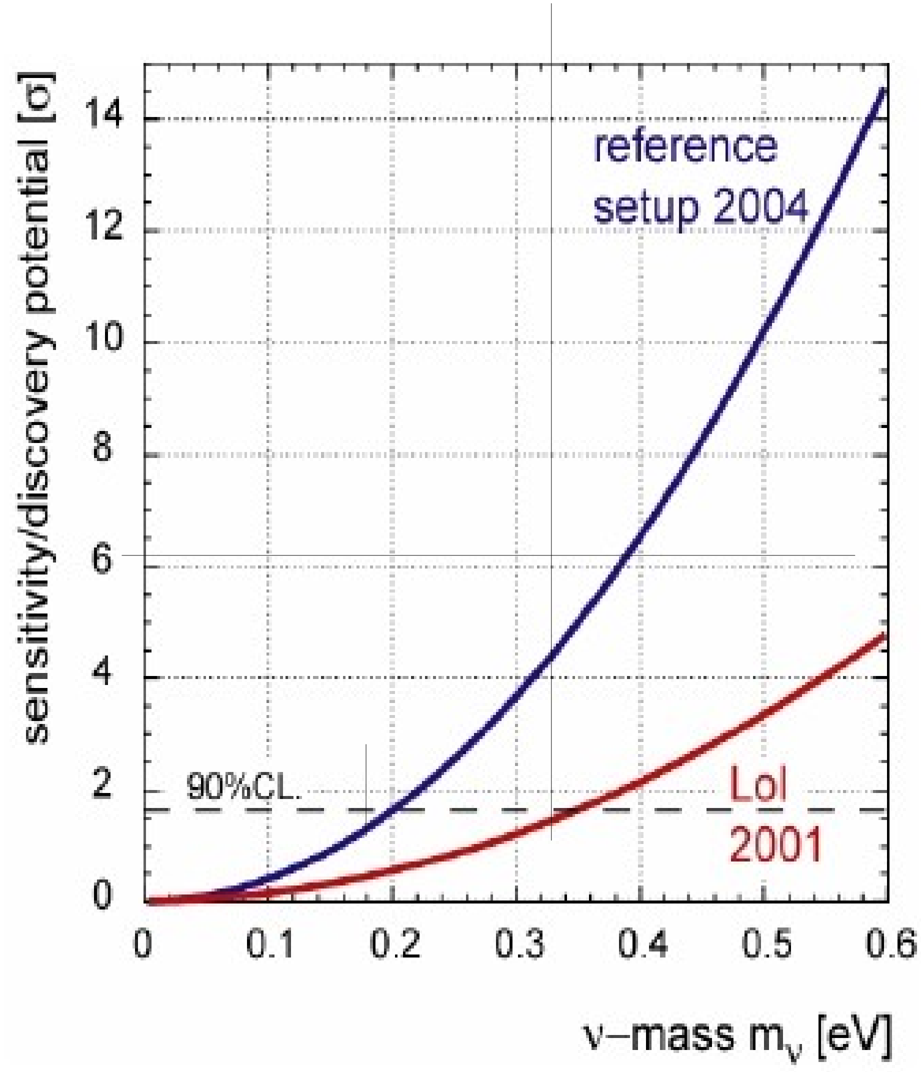
KATRIN on the move

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



3 year run period

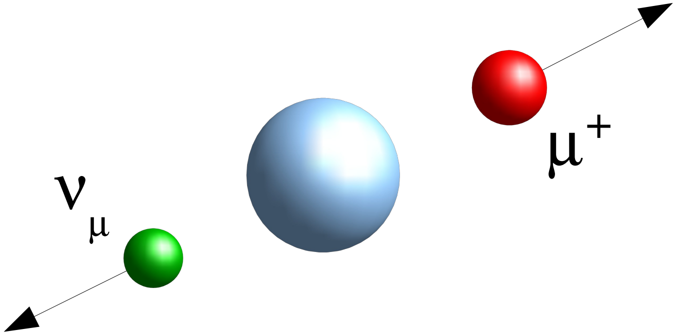
sensitivity (90% CL)
m(ν) < 0.2 eV

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

Starts in 2016

ν_μ mass

Easiest way is to use pion decay at rest



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

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

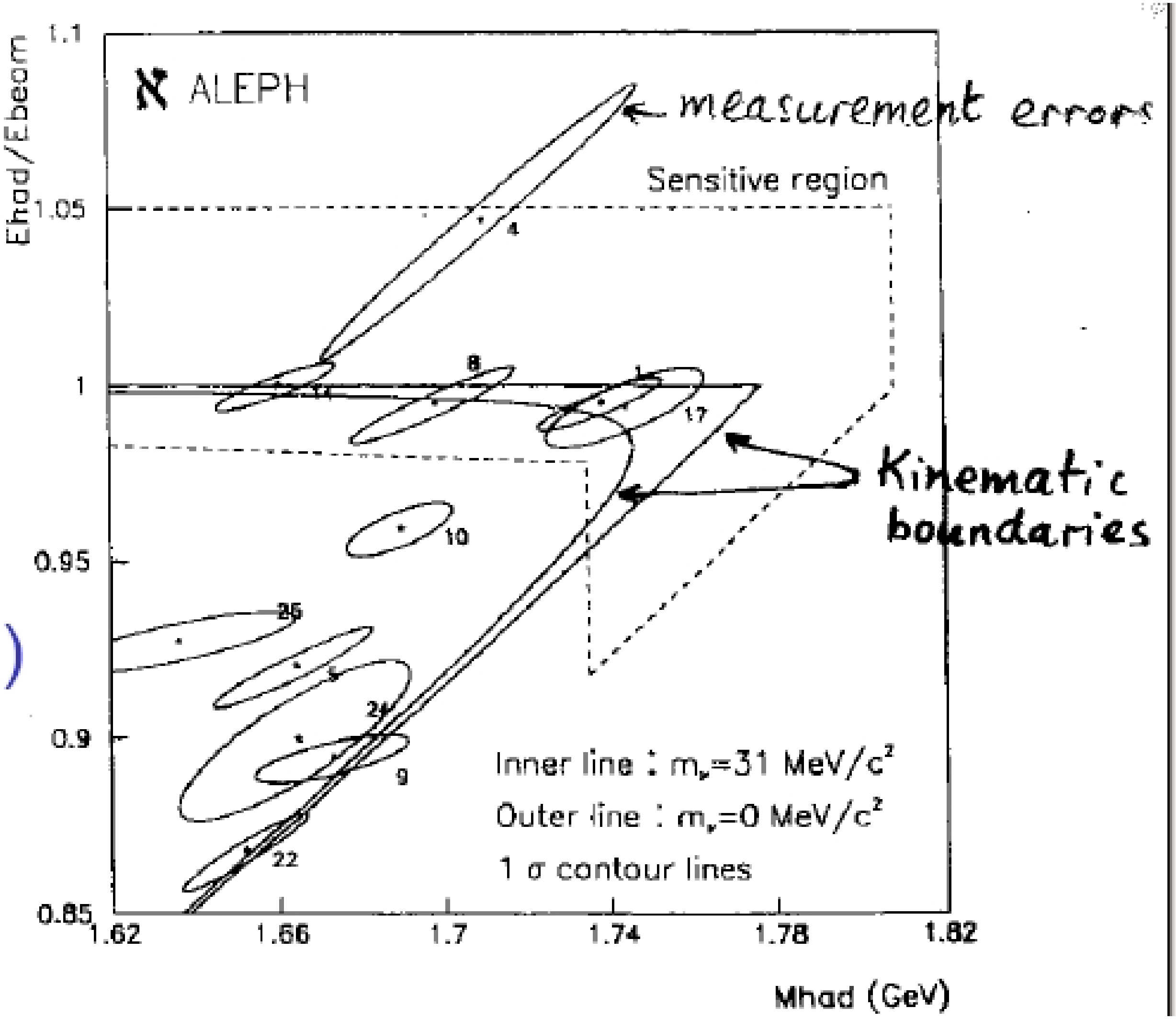
$$m_\mu = 105.658358 \pm 0.000005\, MeV$$

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

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

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

ν_τ mass

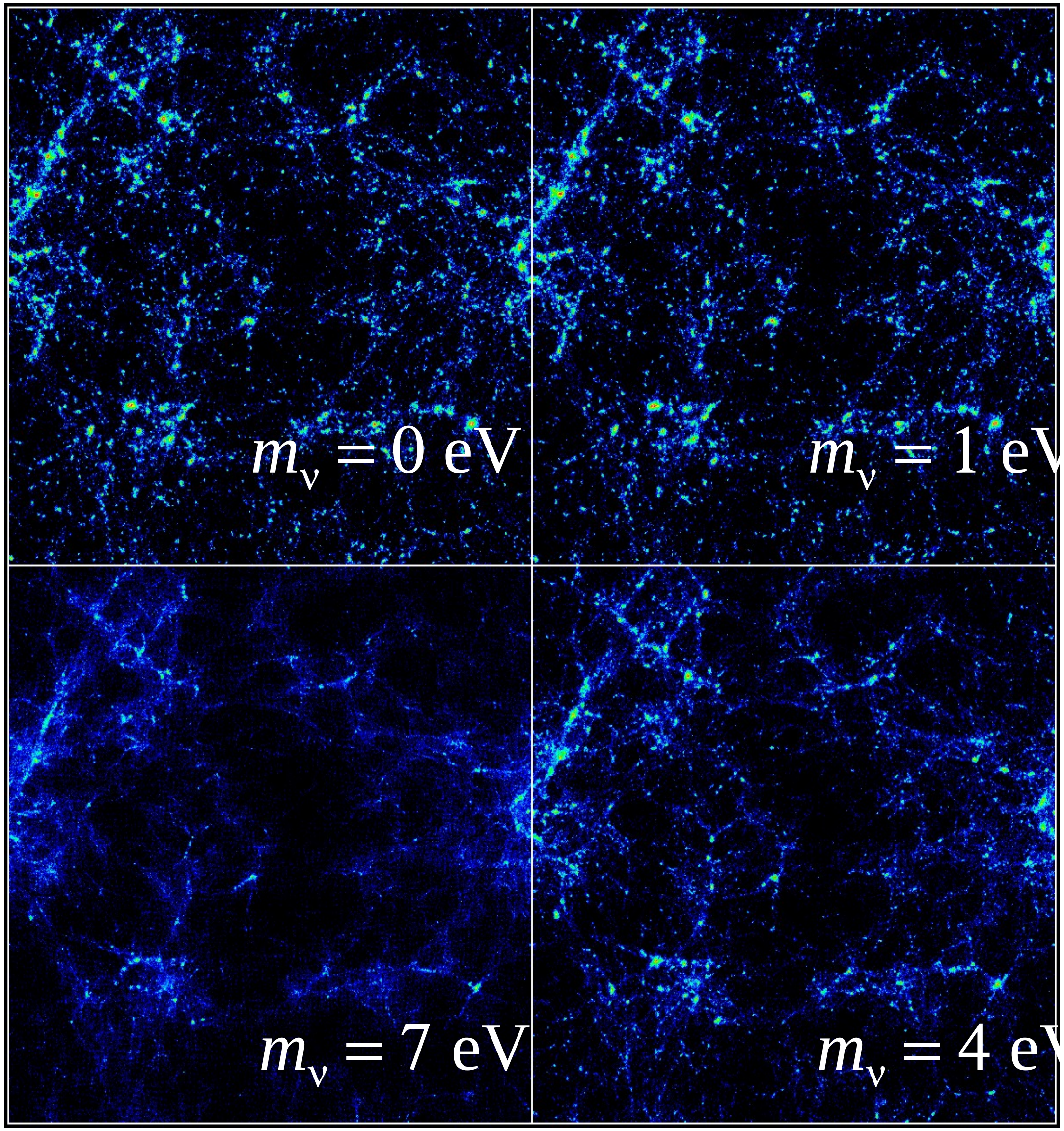


$$e^+e^- \rightarrow \tau^+\tau^-$$

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

$$\boxed{m_\tau < 18.2\, MeV\, (95\,\%\, CL)}$$

Cosmology



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

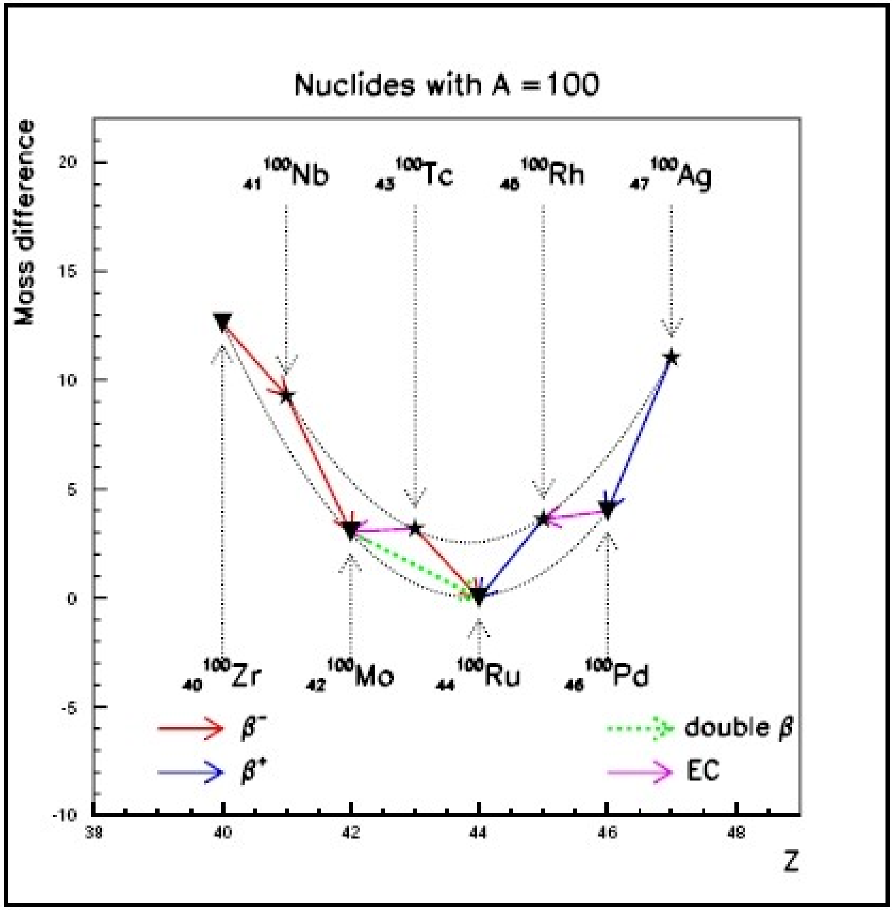
$$\sum m_{\nu_i} < 0.3\,eV$$

2νββ Decay

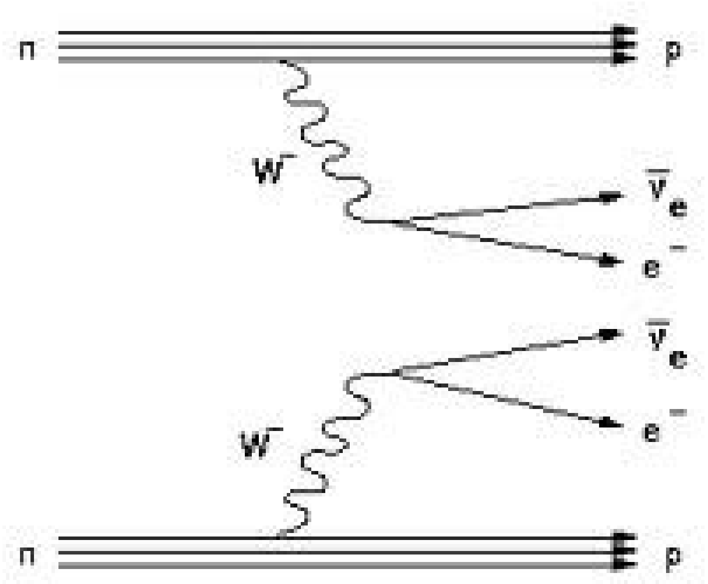
Neutrinoless double beta decay is considered a golden channel for the measurement of neutrino mass.

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



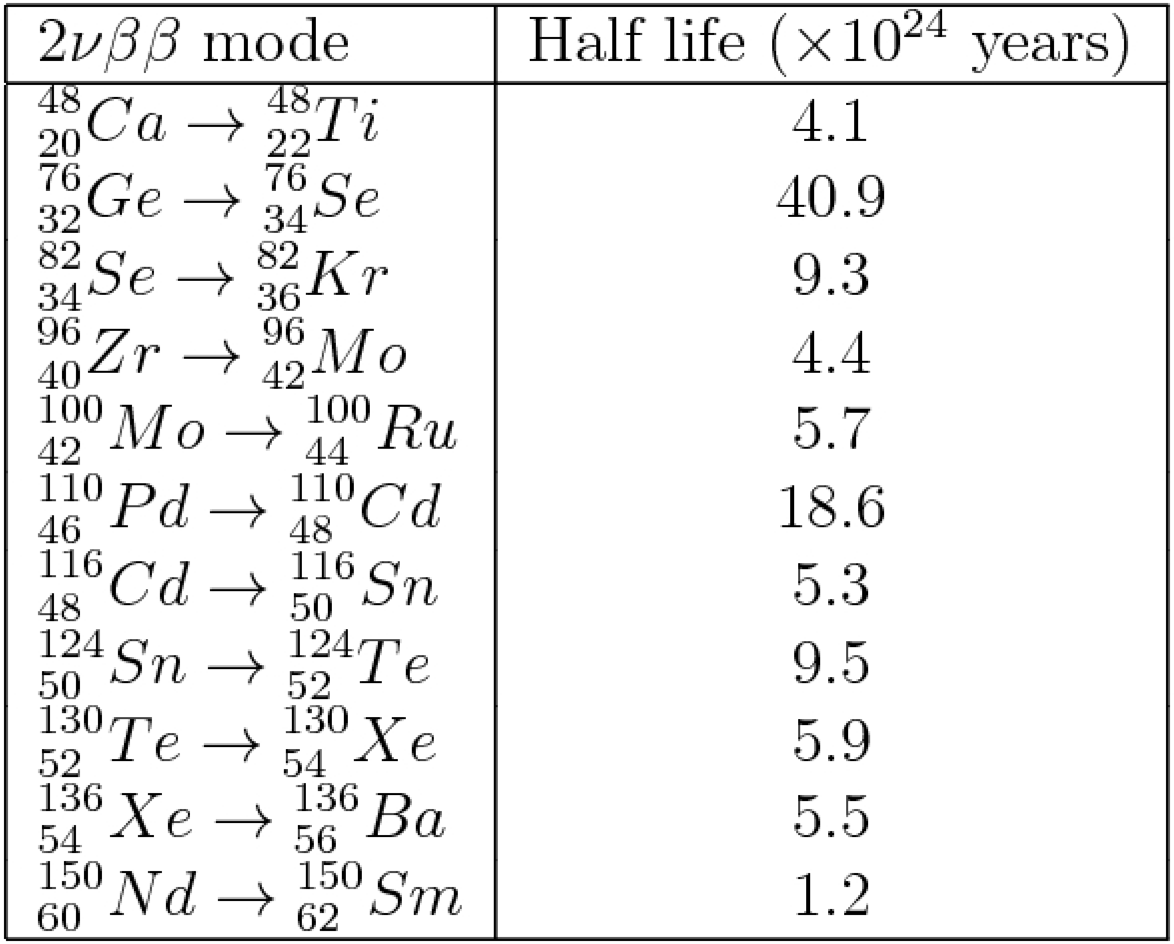
$$\left[T_{1/2}^{2\nu}\right]^{-1} = G^{2\nu}(Q,Z)\left|M^{2\nu}\right|^{2}$$

Calculable phase space

Nuclear matrix element

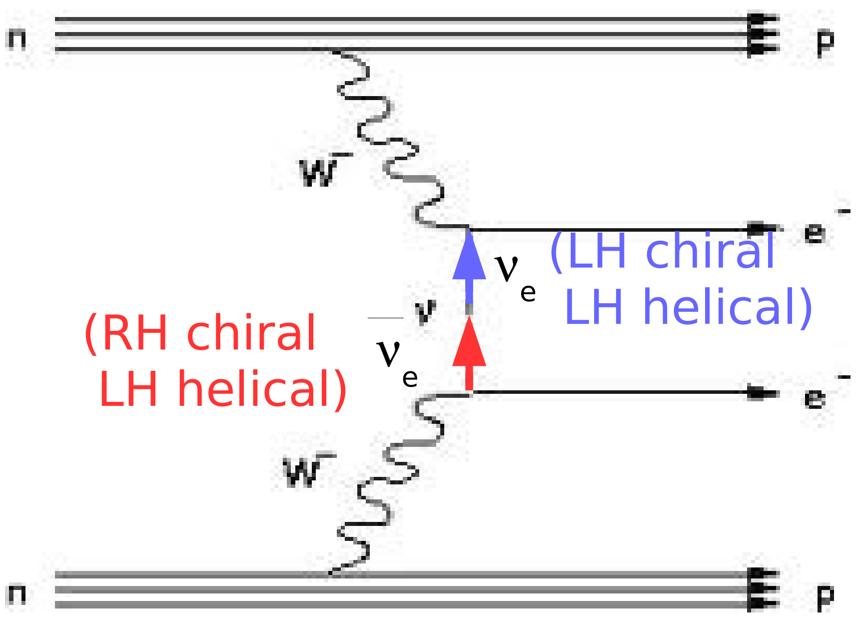
- Second order process in perturbation theory
- Severe test for nuclear matrix element calculation
- Nuclear structure effects cause variations in the nuclear matrix elements of factors of 10

2νββ Decay



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

Neutrinoless ββ Decay



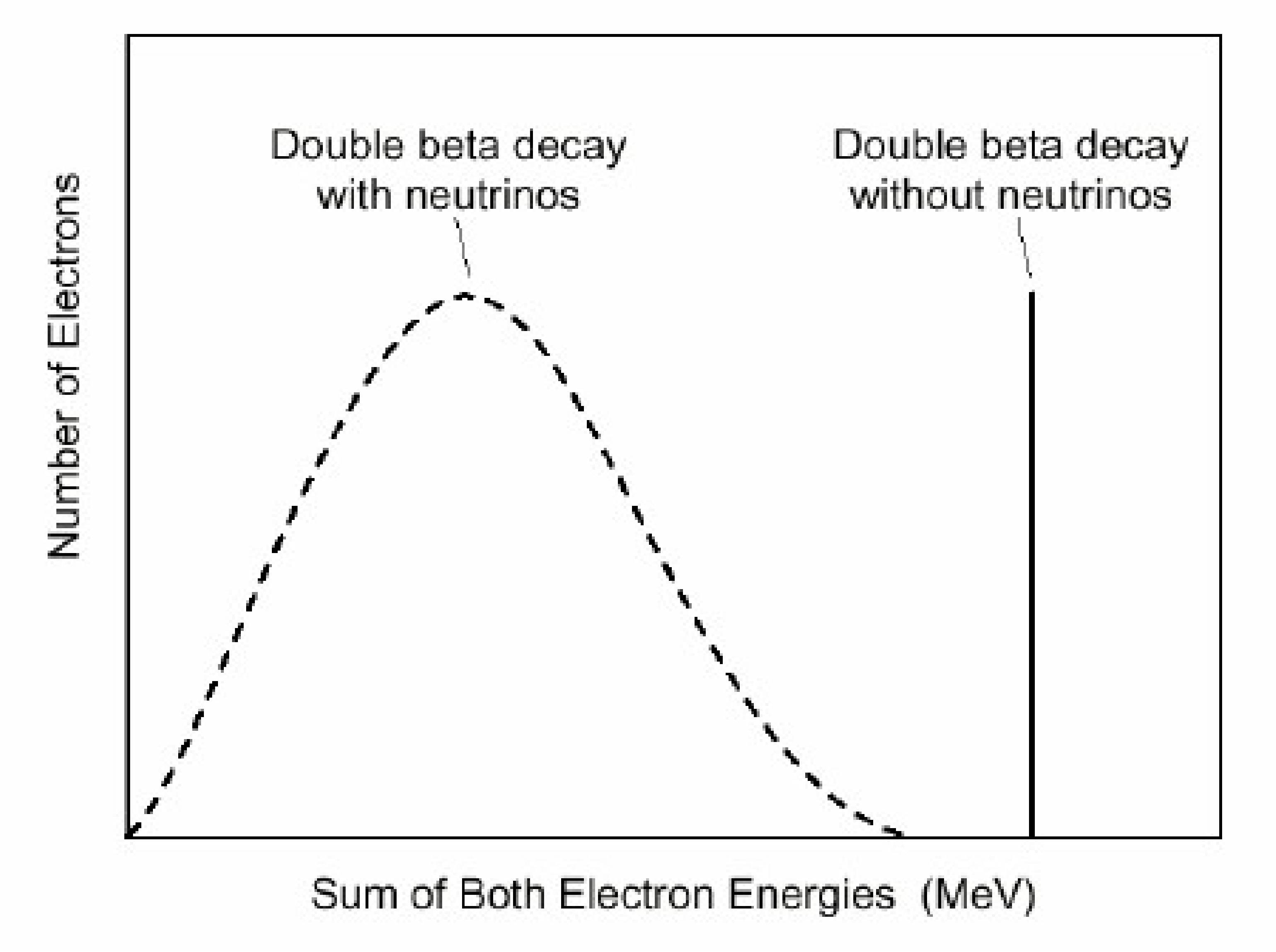
$$\nu_L = \nu_{h=-1} + \frac{m}{E}\nu_{h=+1}$$

helicity states

- Neutrino must have mass
- Neutrino is a *Majorana* particle
- Violation of lepton number conservation
- Experiments are crucial to understanding

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

What is the signal?

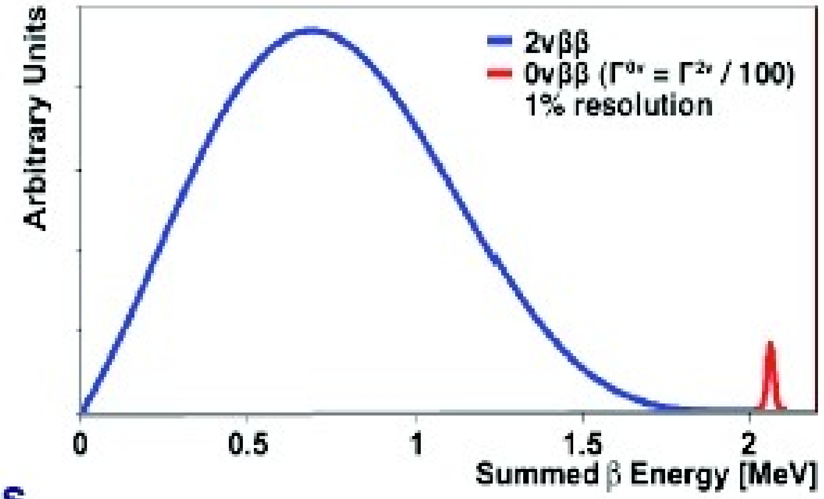


Experimental Requirements

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}

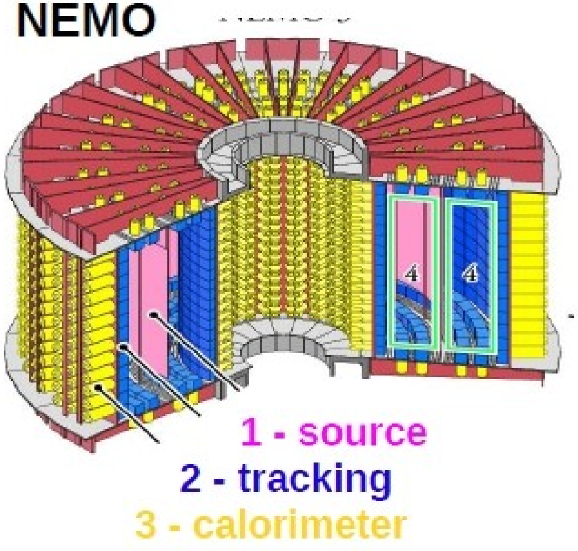


Requires

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

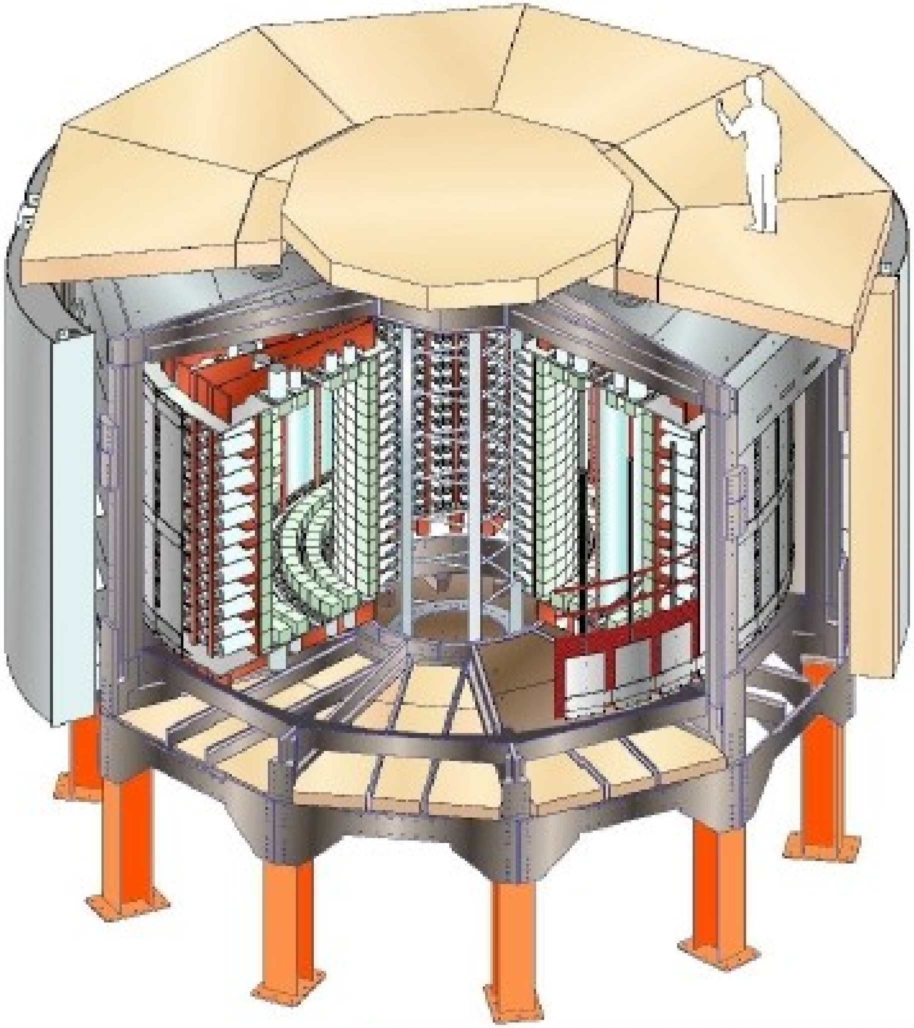
- **$2e^-$ are detected separately**
  → different channels of 0νDBD can be distinguished
- **particle identification**
  → background suppression
- **poor energy resolution**
  → important 2νDBD background
  (limitation on isotope choice)

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

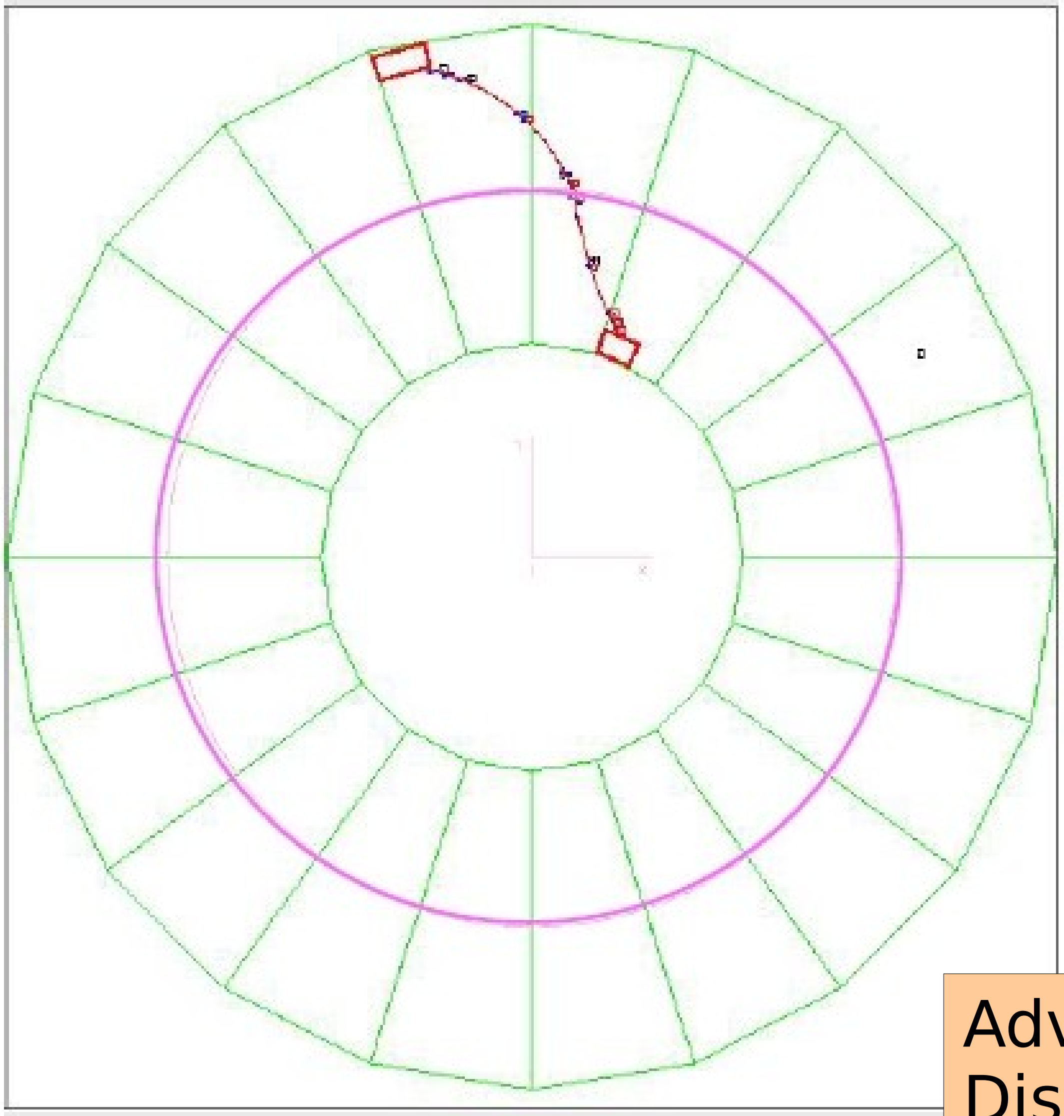
Calorimeter:
1940 plastic scintillators
coupled to low radioactivity PMTs

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

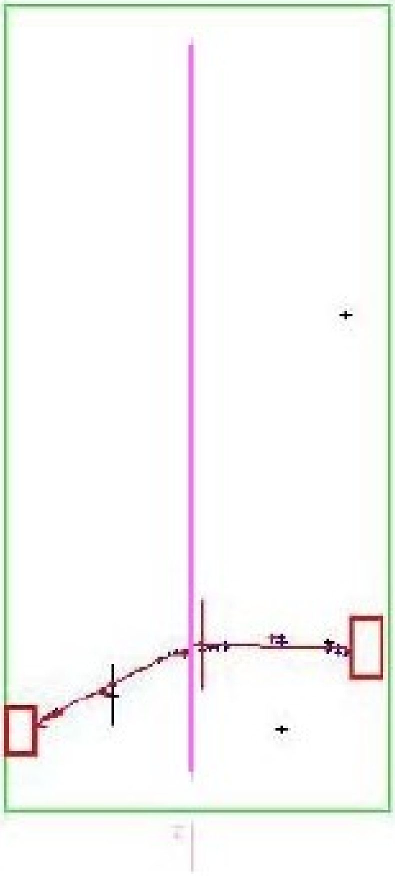
Background: n 2.6 MeV)

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

Typical ββ2ν event observed from ^{100}Mo



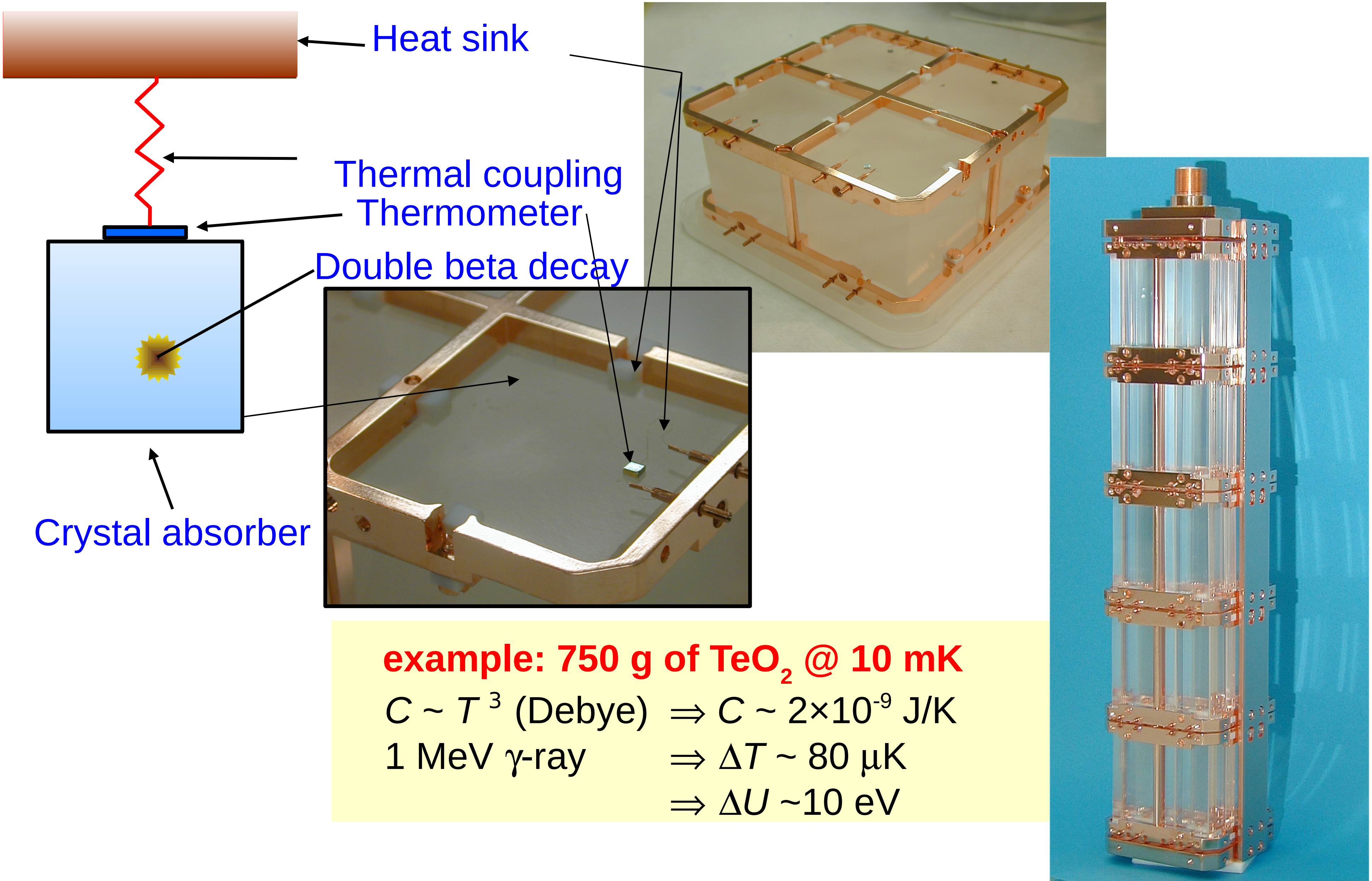
Top view



Side view

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

Cuoricino/Cuore



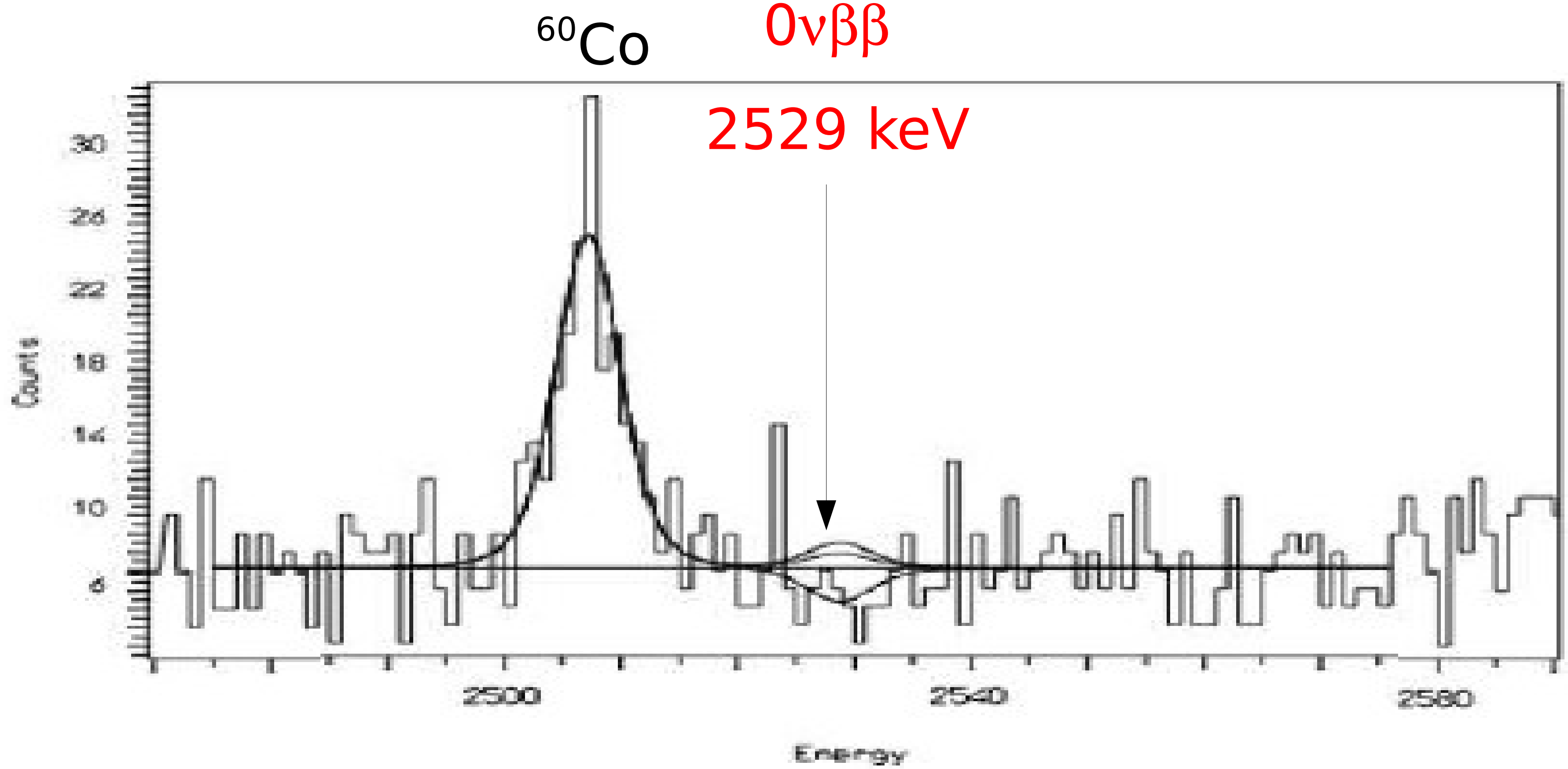
example: 750 g of TeO$_2$ @ 10 mK

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

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

$\Rightarrow \Delta U \sim 10$ eV

Cuoricino Results



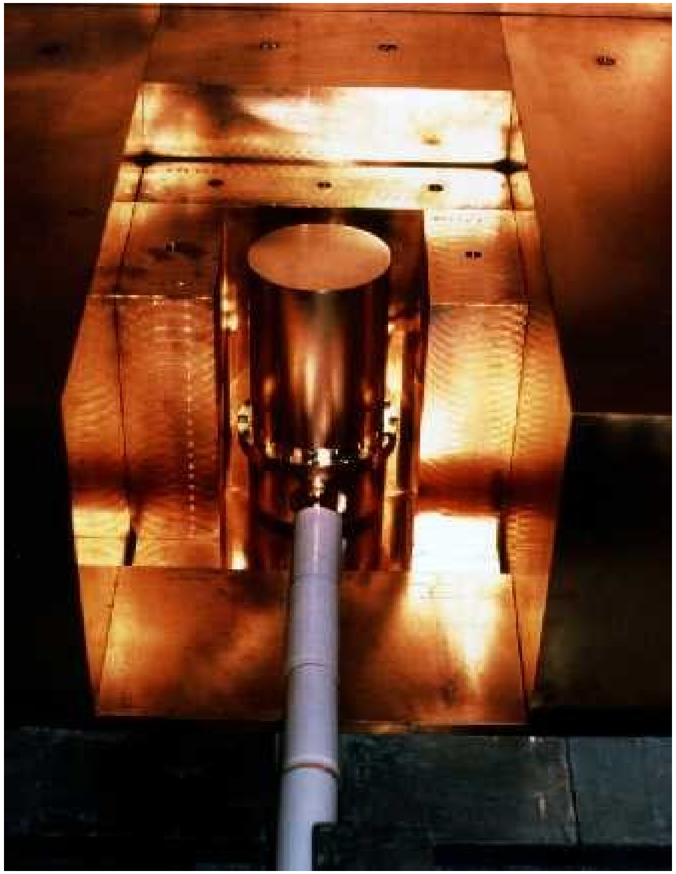
$$T^{0\nu}_{1/2} > 3.0\times10^{24}\,years \;\Rightarrow\; \langle m_\nu \rangle < 0.68\,eV$$

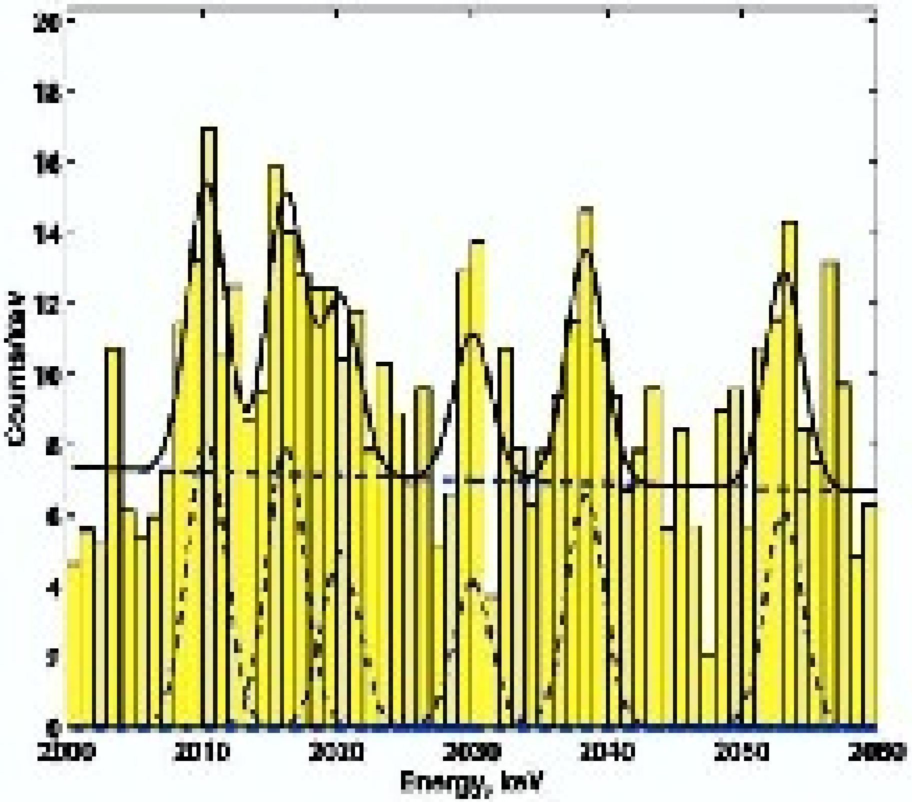
Heidelberg-Moscow

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

$0\nu\beta\beta$ electrons detected by Ge detectors themselves

Only sum of electron energy measured





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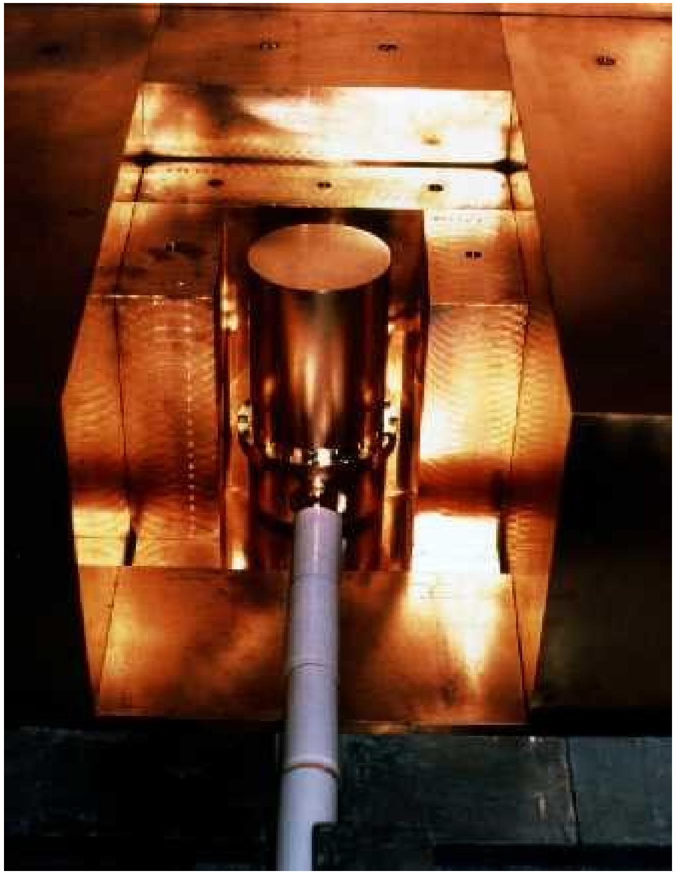
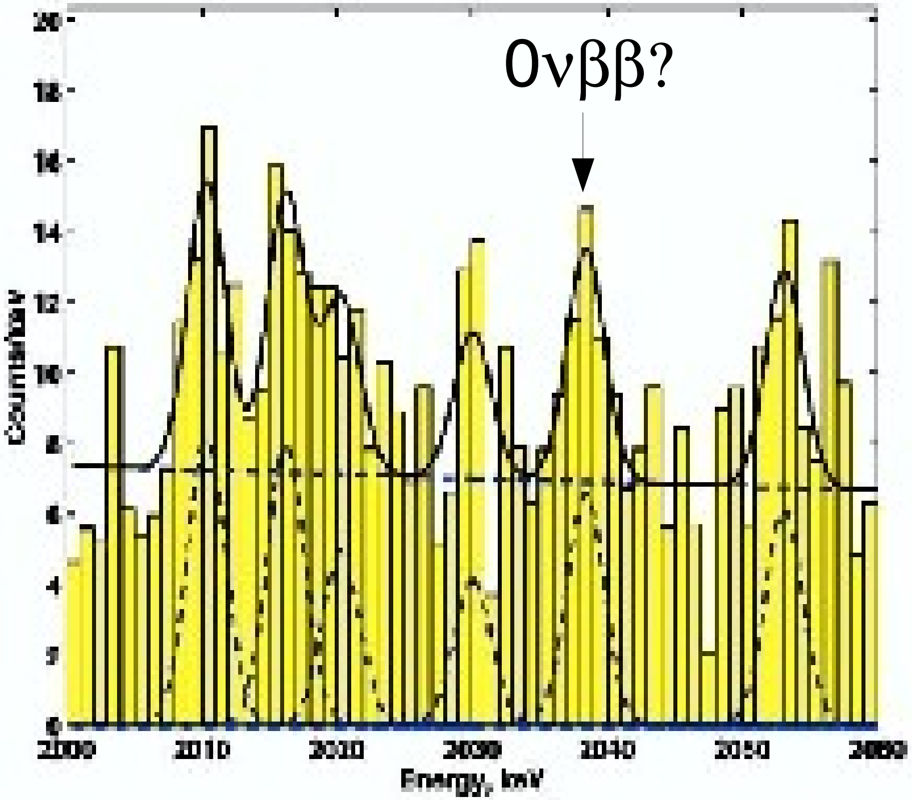
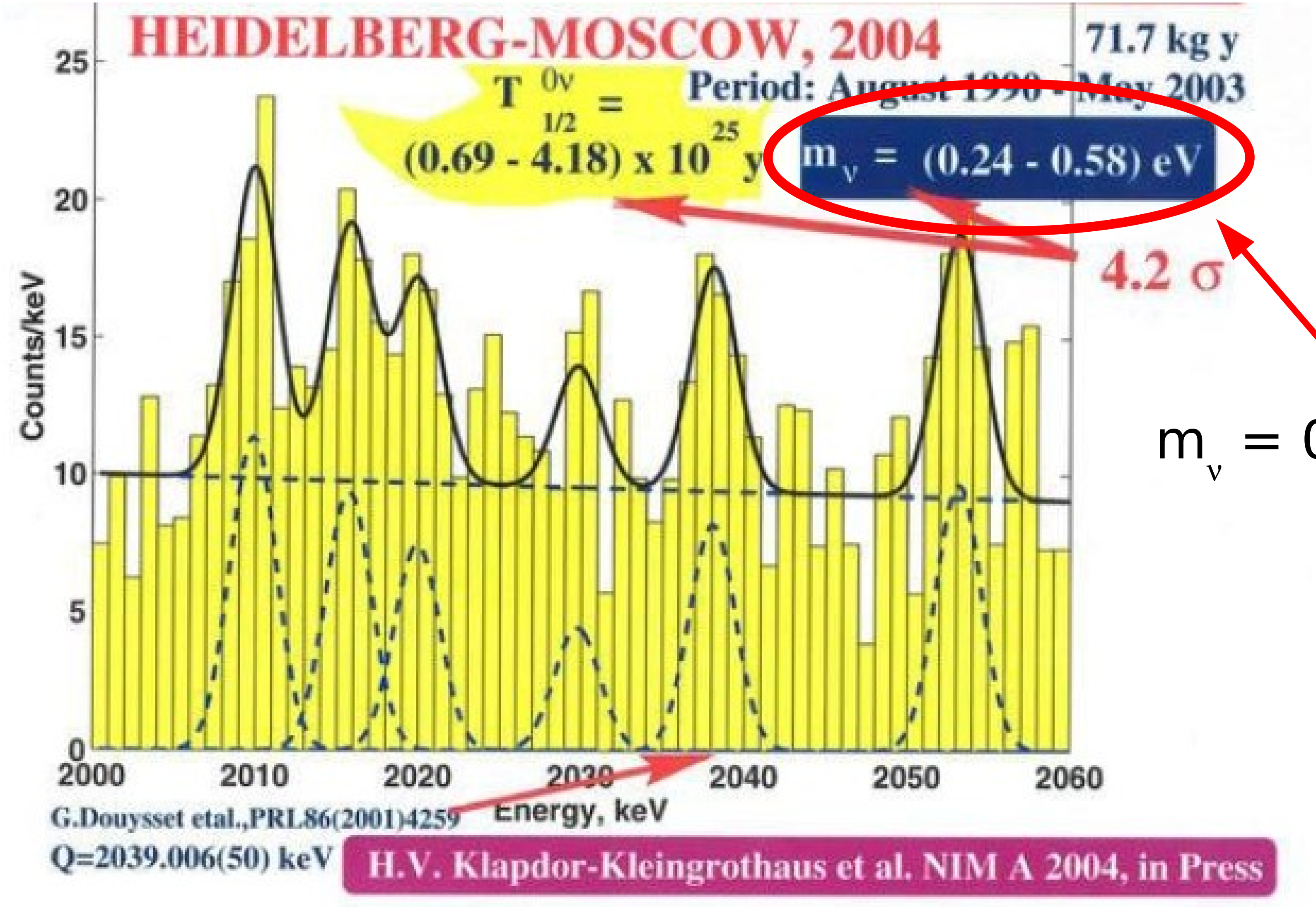


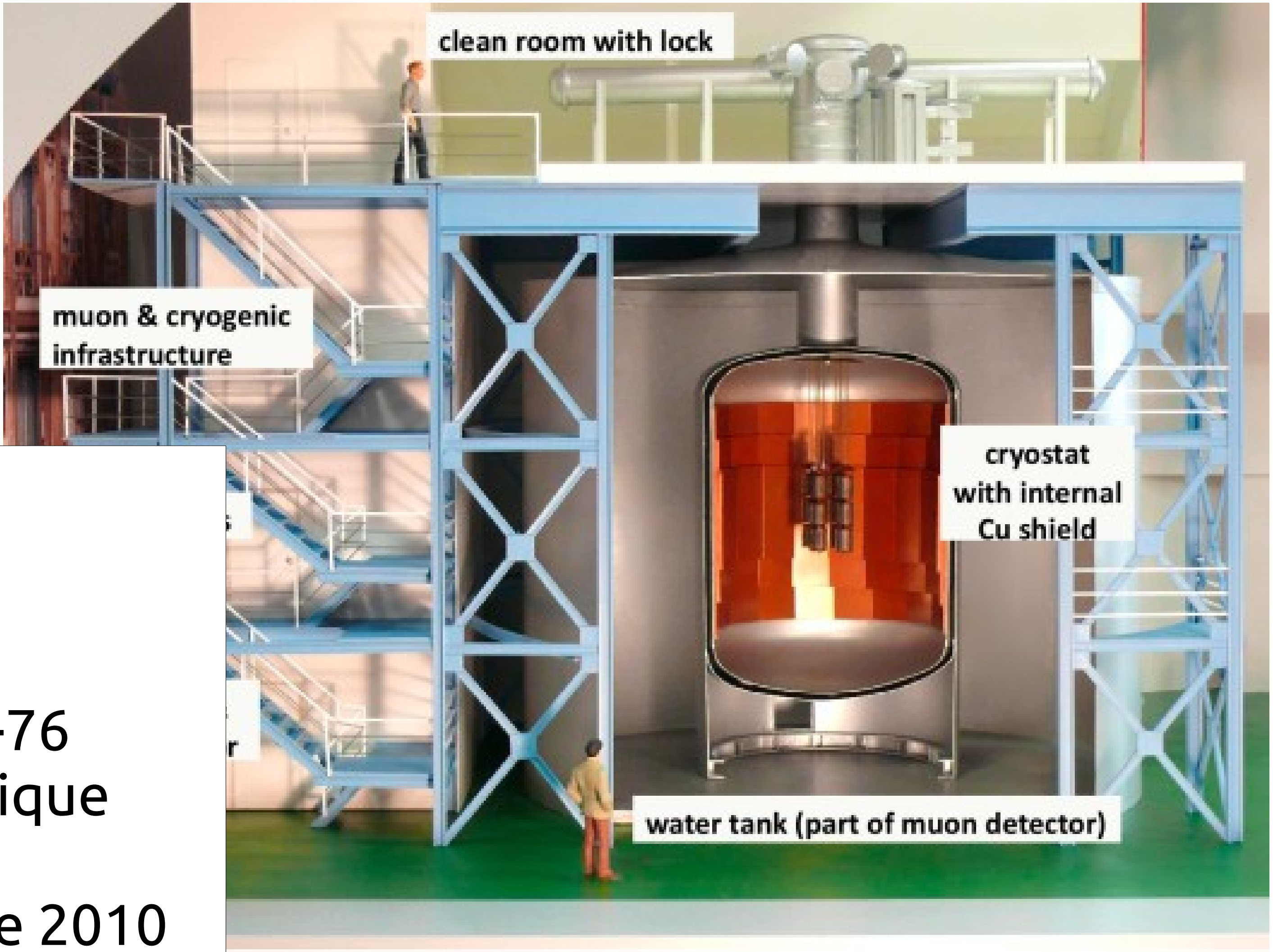


Heidelberg-Moscow



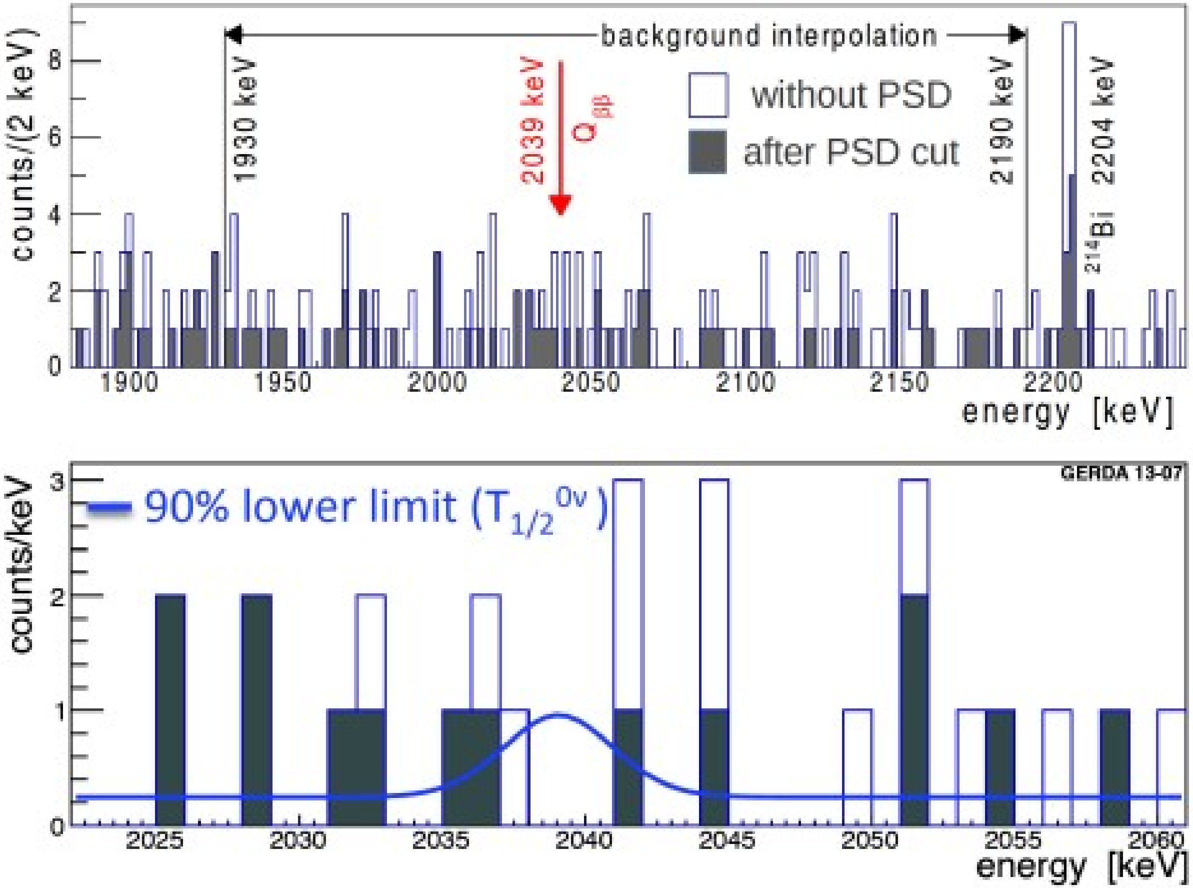
m_ν = 0.4 eV

GERDA



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

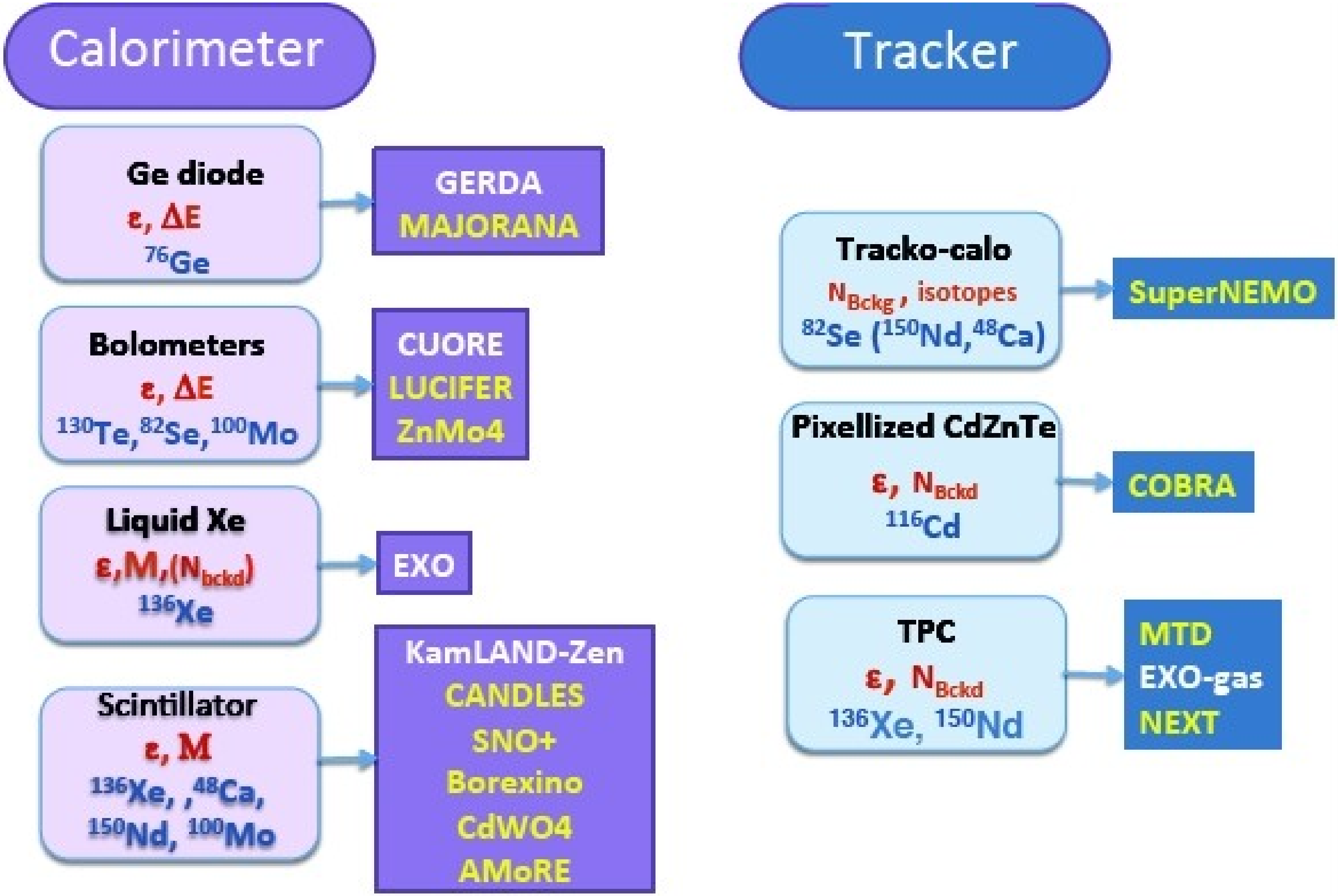
GERDA



$t_{1/2}$ > 2.1 x 10^{25} yr @ 90% CL

Inconsistent with HdM, but not definitive (yet)

Future Program



Calorimeter

Ge diode
ε, ΔE
^{76}Ge
→ GERDA, MAJORANA

Bolometers
ε, ΔE
^{130}Te, ^{82}Se, ^{100}Mo
→ CUORE, LUCIFER, ZnMo4

Liquid Xe
ε, M, (N_{bckd})
^{136}Xe
→ EXO

Scintillator
ε, M
^{136}Xe, ,^{48}Ca,
^{150}Nd, ^{100}Mo
→ KamLAND-Zen, CANDLES, SNO+, Borexino, CdWO4, AMoRE

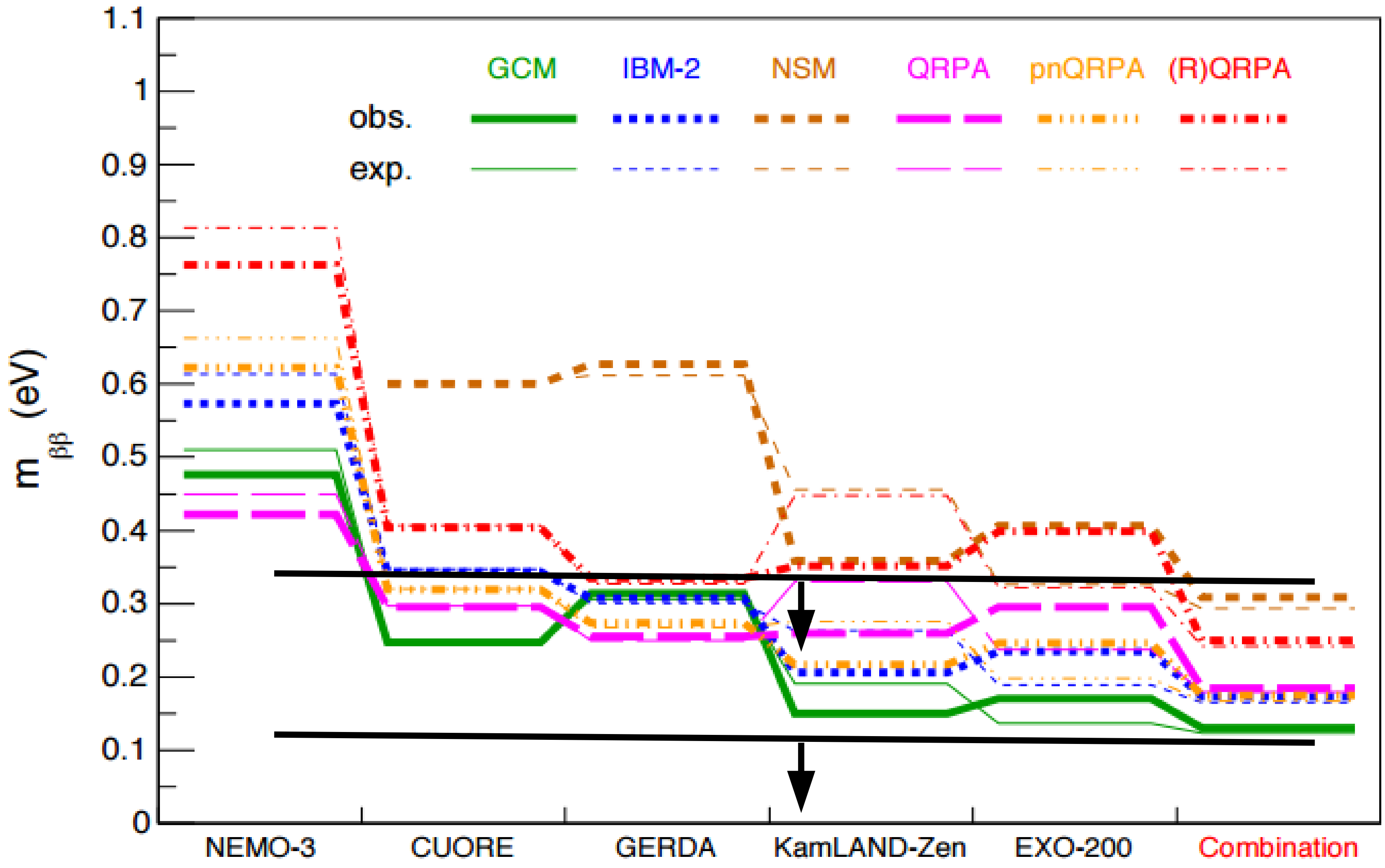
Tracker

Tracko-calo
N_{Bckg}, isotopes
^{82}Se (^{150}Nd, ^{48}Ca)
→ SuperNEMO

Pixellized CdZnTe
ε, N_{Bckd}
^{116}Cd
→ COBRA

TPC
ε, N_{Bckd}
^{136}Xe, ^{150}Nd
→ MTD, EXO-gas, NEXT

Current global limit



Absolute mass status

Tritium β decay	$< m_\beta >$	< 2.3 eV Katrin extends sensitivity to 0.2 eV
0ν2β decay	$\left\|\sum_i U_{ei}^2 m_i\right\|$	<0.3-1.2 eV <mββ><300 meV
Cosmology	$\sum_{i=e,\mu,\tau} m_i < 0.7\, eV$	
Pion decay	$m_{\nu_\mu} < 190\, keV$	
Tau decay	$m_{\nu\tau} < 18.2\, MeV$	

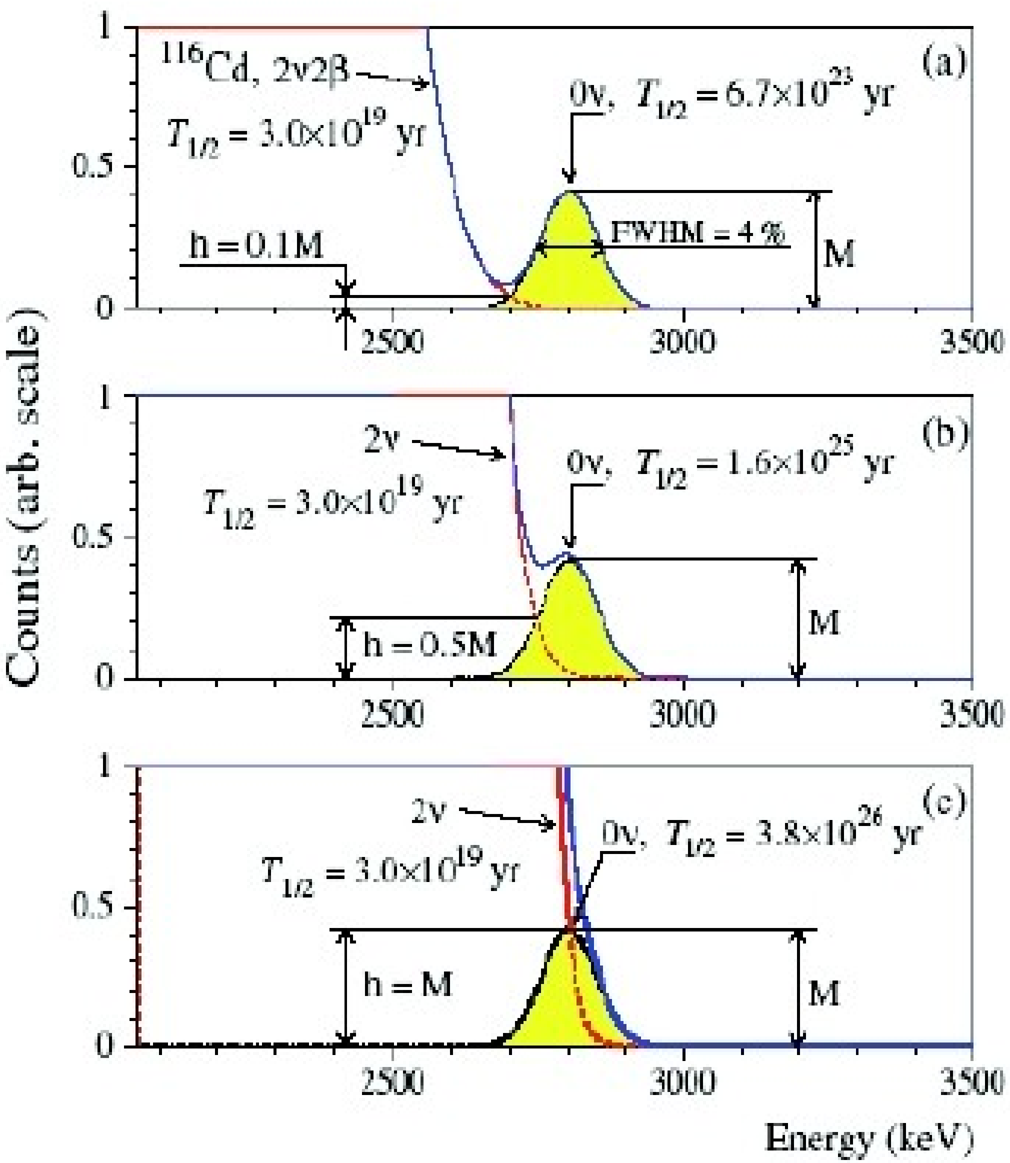
Requirements for experiment

- The number of electrons close to the endpoint should be small
- 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

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

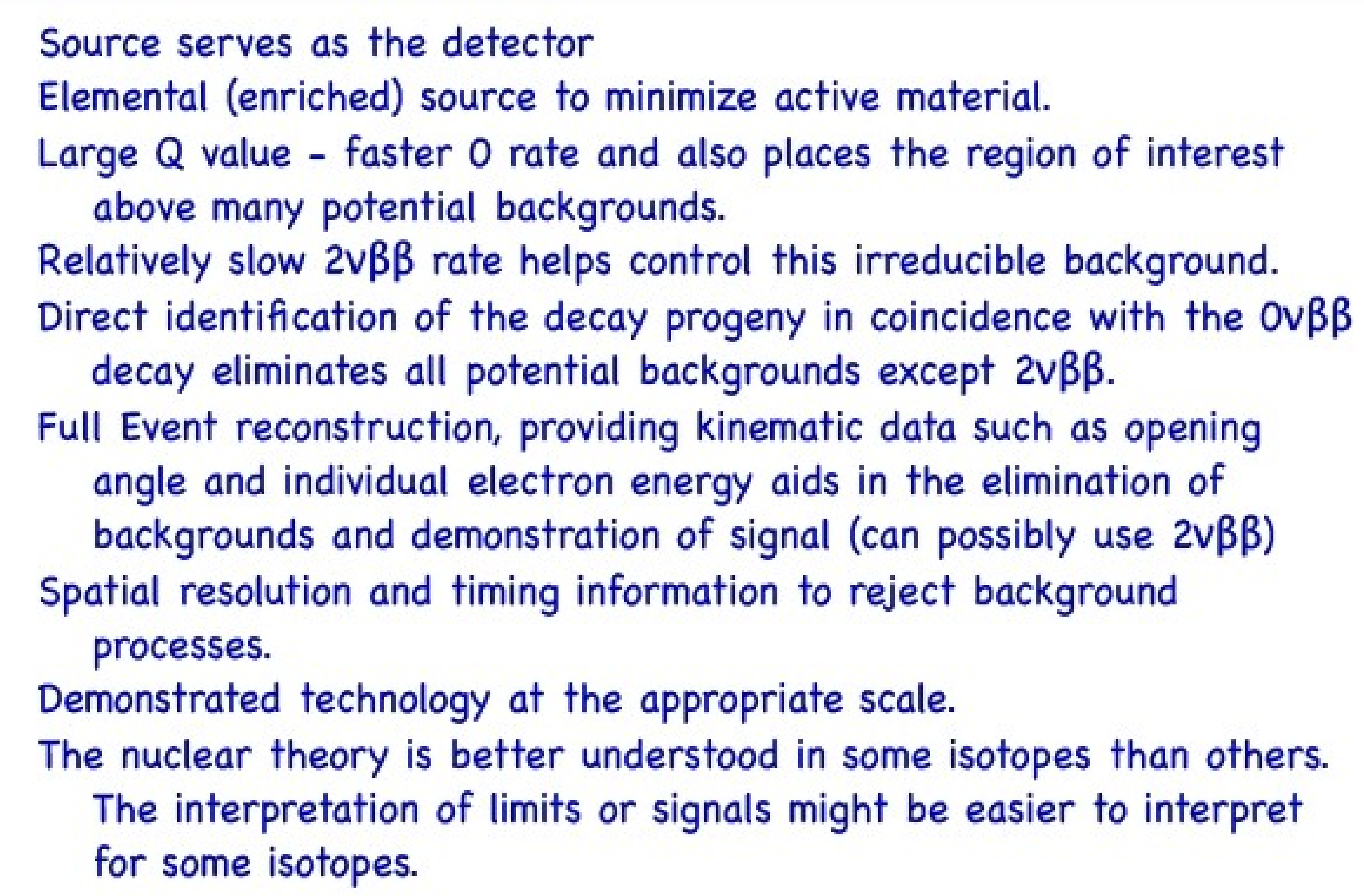
Endpoint is at 18574 eV
No molecular excitation above 18547 eV
Only 10^{-9} electrons in this region
Gaseous so you can have a very large source

Experimentally



From Zdesenko, Danevich, Tretyak, J. Phys. G 30 (2004) 971

The Ideal Detector



Source serves as the detector

Elemental (enriched) source to minimize active material.

Large Q value - faster 0 rate and also places the region of interest above many potential backgrounds.

Relatively slow $2\nu\beta\beta$ rate helps control this irreducible background.

Direct identification of the decay progeny in coincidence with the $0\nu\beta\beta$ decay eliminates all potential backgrounds except $2\nu\beta\beta$.

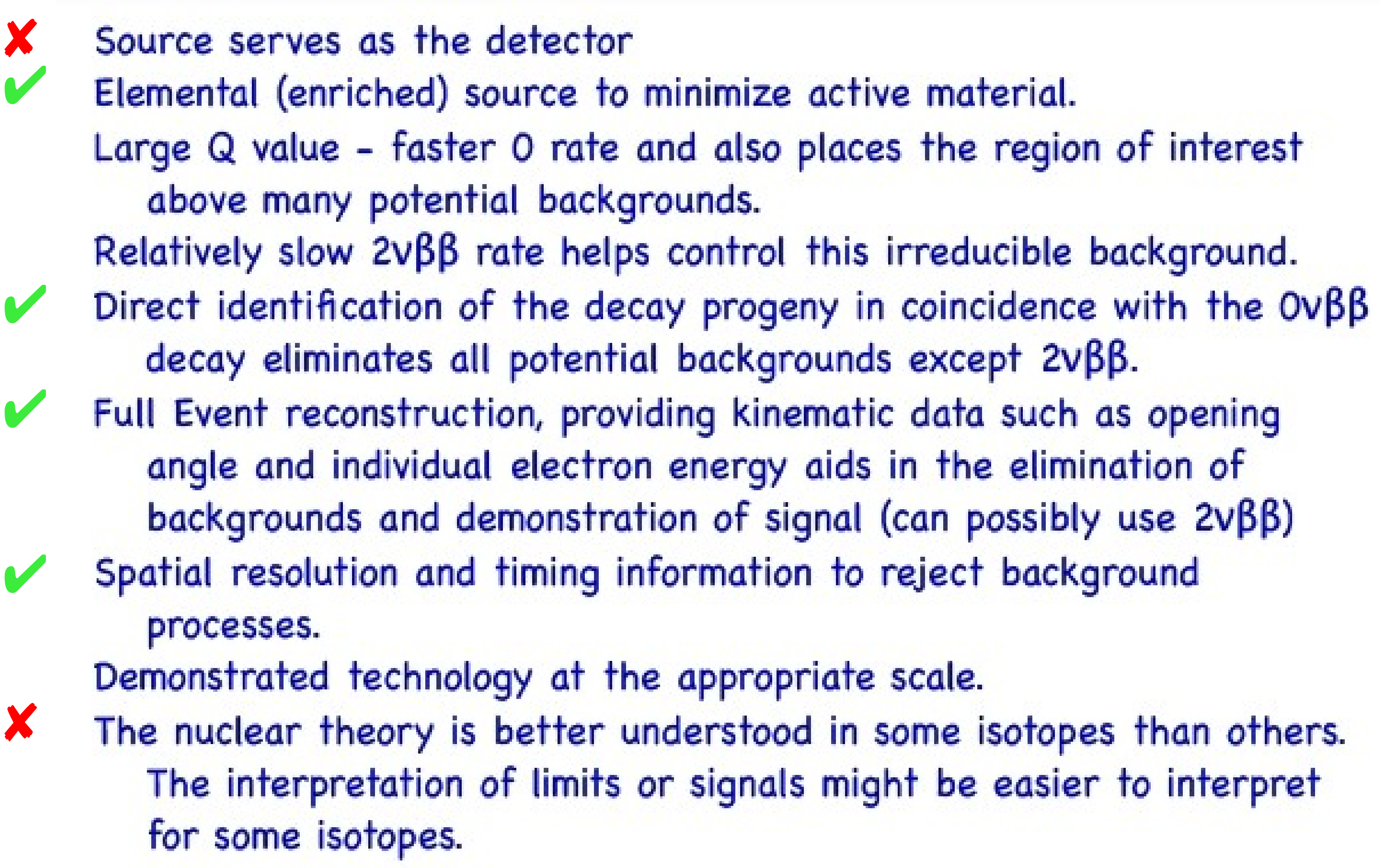
Full Event reconstruction, providing kinematic data such as opening angle and individual electron energy aids in the elimination of backgrounds and demonstration of signal (can possibly use $2\nu\beta\beta$)

Spatial resolution and timing information to reject background processes.

Demonstrated technology at the appropriate scale.

The nuclear theory is better understood in some isotopes than others. The interpretation of limits or signals might be easier to interpret for some isotopes.

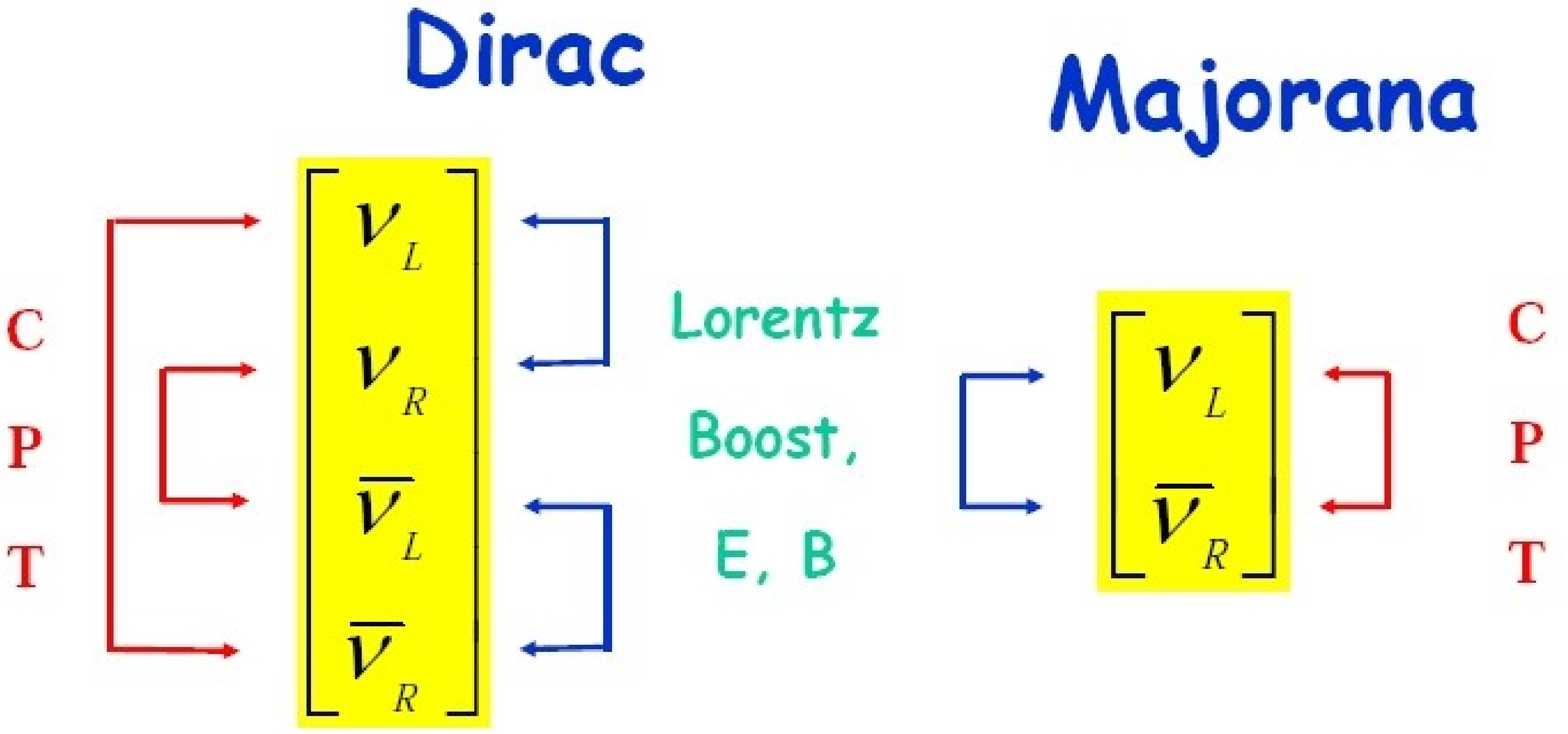
NEMO3



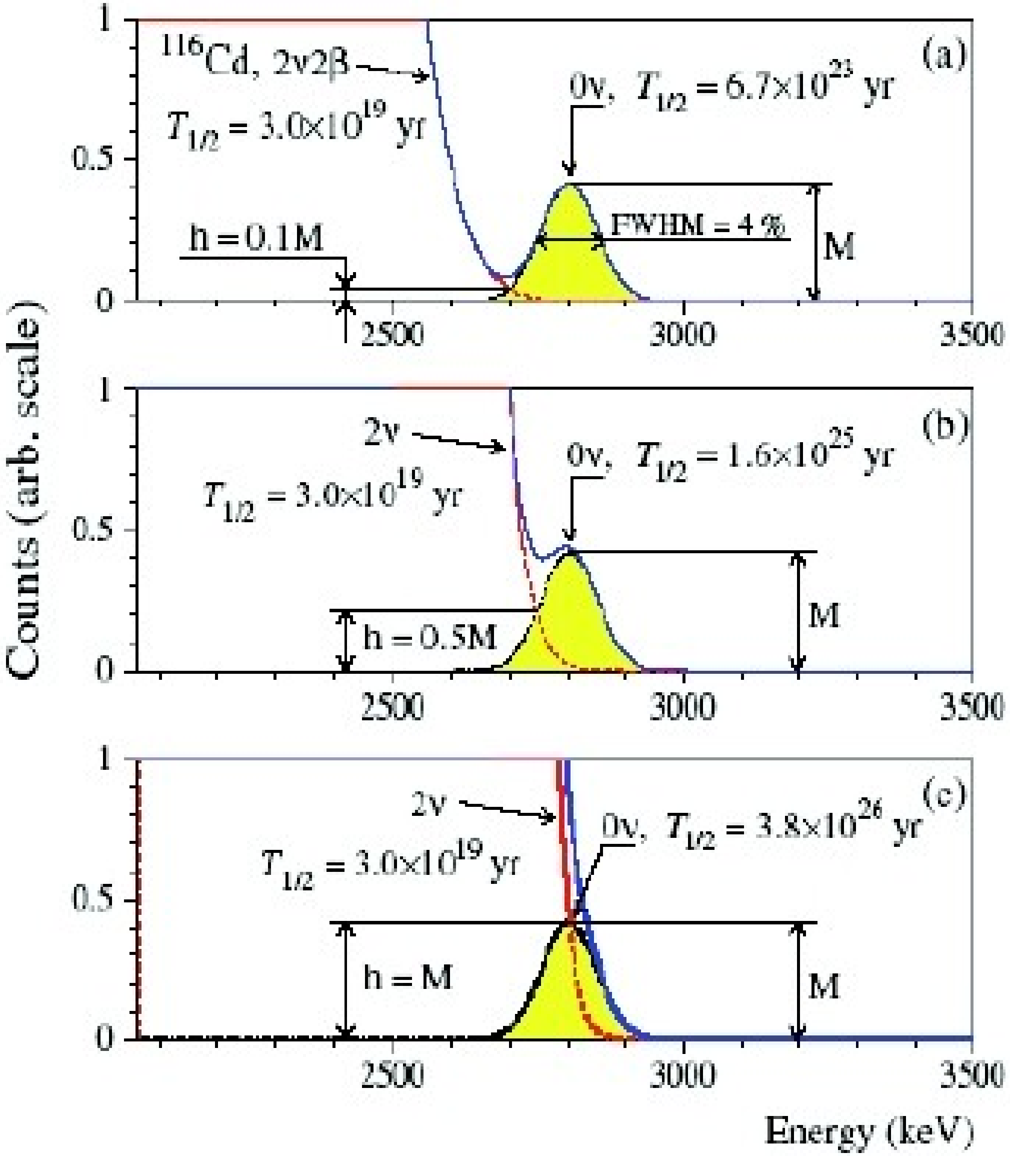
- ✗ Source serves as the detector
- ✓ Elemental (enriched) source to minimize active material.
- Large Q value - faster 0 rate and also places the region of interest above many potential backgrounds.
- Relatively slow 2νββ rate helps control this irreducible background.
- ✓ Direct identification of the decay progeny in coincidence with the 0νββ decay eliminates all potential backgrounds except 2νββ.
- ✓ Full Event reconstruction, providing kinematic data such as opening angle and individual electron energy aids in the elimination of backgrounds and demonstration of signal (can possibly use 2νββ)
- ✓ Spatial resolution and timing information to reject background processes.
- Demonstrated technology at the appropriate scale.
- ✗ The nuclear theory is better understood in some isotopes than others. The interpretation of limits or signals might be easier to interpret for some isotopes.

Dirac vs Majorana

A Dirac particle is different from it's antiparticle (e.g. electron and positron). A majorana particle is the same as it's antiparticle.



Experimentally



From Zdesenko, Danevich, Tretyak, J. Phys. G 30 (2004) 971

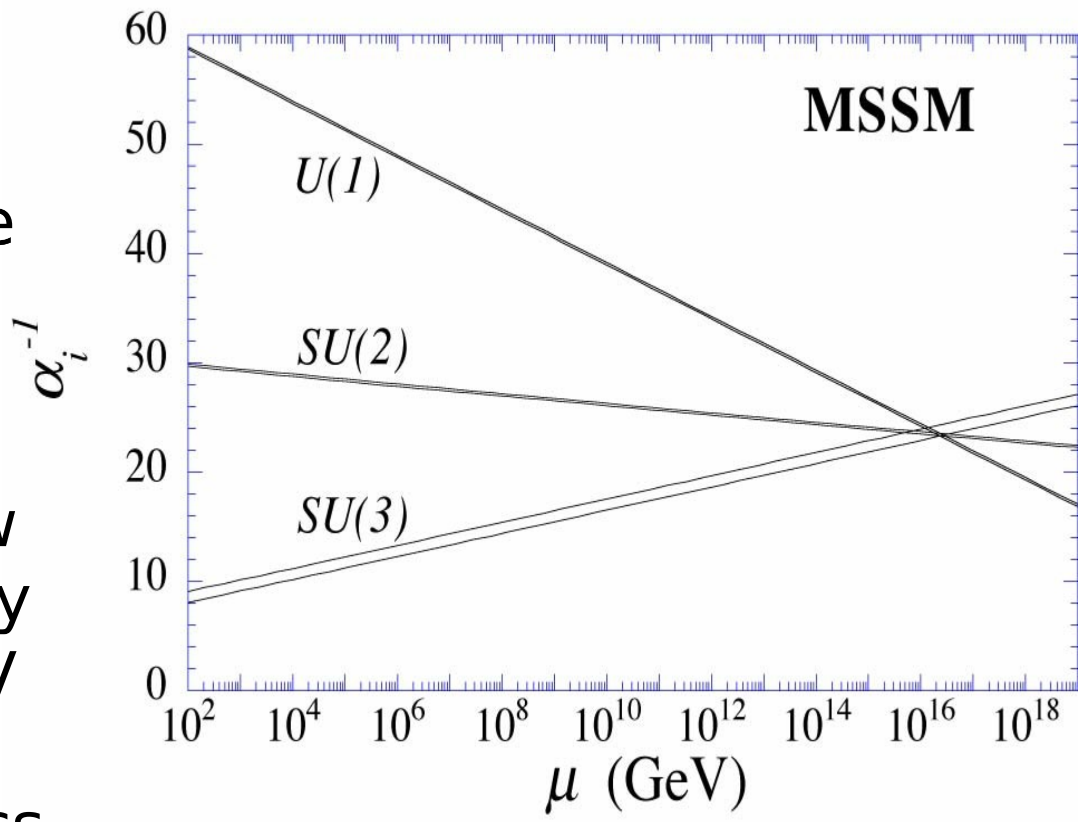
Seesaw and GUTs

- Electromagnetic, strong and weak forces have very different strengths

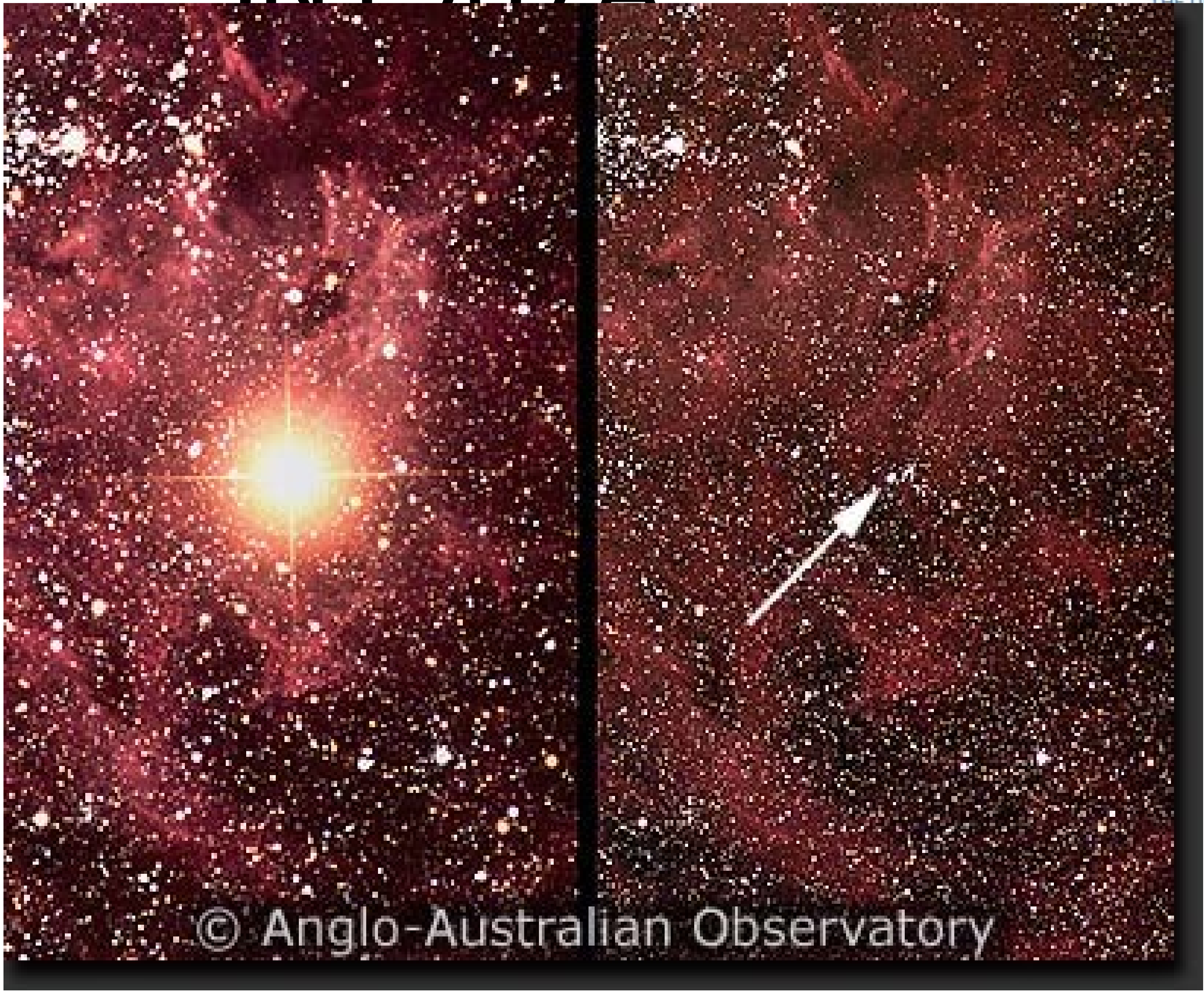
- If supersymmetry is valid their strengths are the same at around 10^{16} GeV

- To explain light neutrino masses through the see-saw mechanics, we need a heavy neutrino with mass 10^{16} GeV

- Probing of GUT scale physics using light neutrinos!



SN1987A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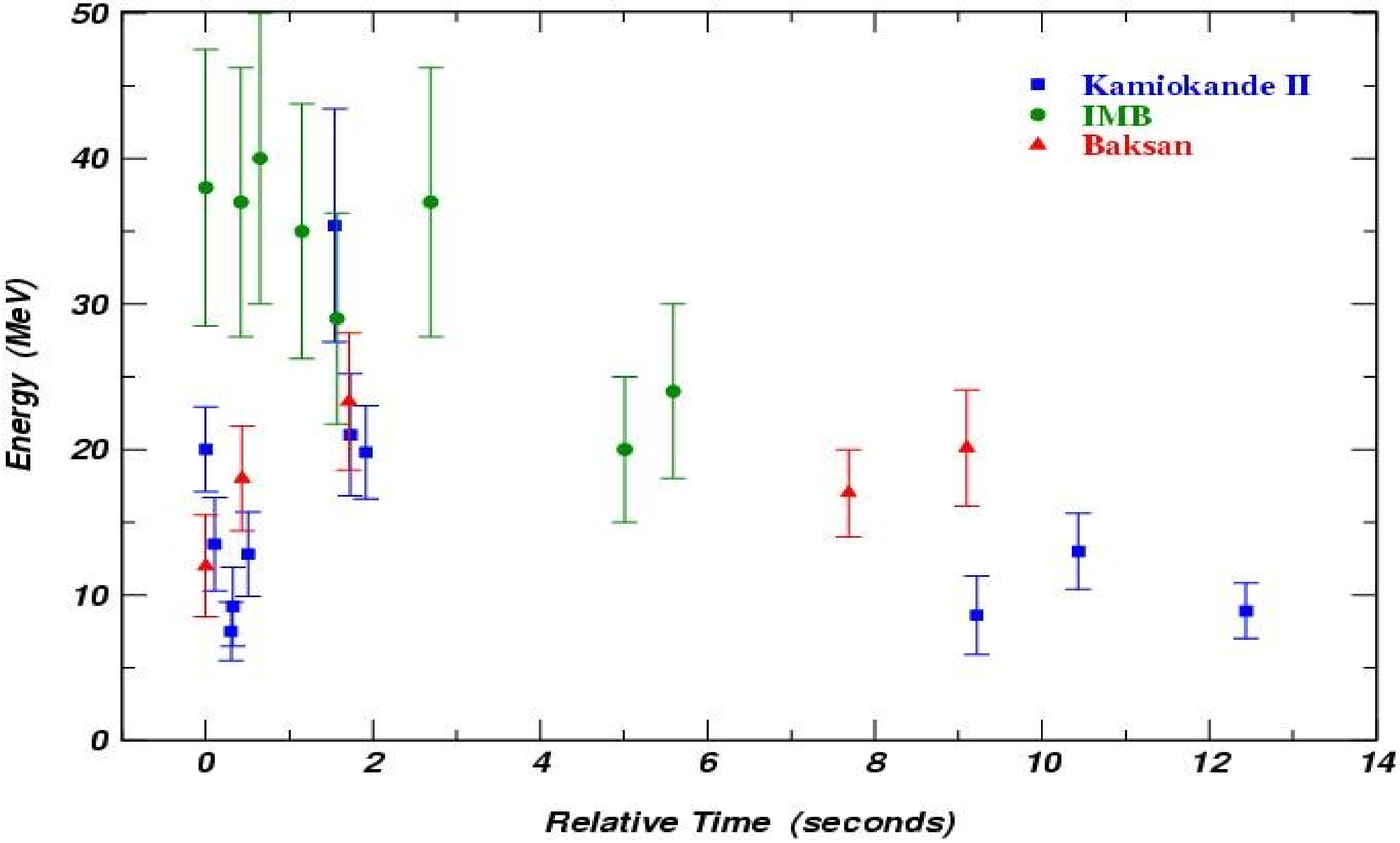
Neutrinos detected

Four neutrino detectors operating at the time

Kamiokande II, IMB, BST, Mont Blanc



Mass from Velocity

The neutrinos had travelled 180,000 light years – enough for small mass differences to show up as a difference in arrival times

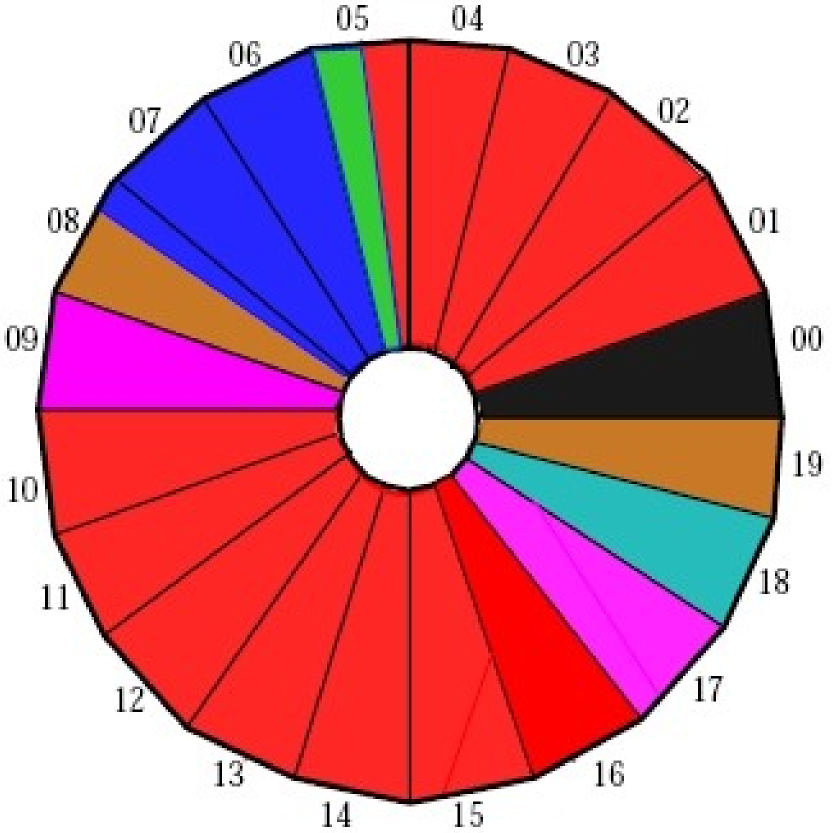
$$t_F = t - t_0 = \frac{L}{v} = \frac{L}{c}\frac{E_\nu}{p_\nu}c \sim \frac{L}{c}\left(1 + \frac{m_\nu^2 c^4}{2E^2}\right)$$

$$\delta t = t_j - t_i = \delta t_0 + \frac{L m_\nu^2}{2c}\left(\frac{1}{E_j^2} - \frac{1}{E_i^2}\right)$$

Estimate dependent on models of supernova process (emission intervals, size of the neutrino shell etc)

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

NEMO3 Sources



^{100}Mo	**6.914 kg**	$Q_{\beta\beta}$ = 3034 keV
^{82}Se	**0.932 kg**	$Q_{\beta\beta}$ = 2995 keV

ββ0ν search

~ 5 kg ^{100}Mo purified in INL (USA)

ββ2ν measurement

^{116}Cd	**405 g**	$Q_{\beta\beta}$ = 2805 keV
^{96}Zr	**9.4 g**	$Q_{\beta\beta}$ = 3350 keV
^{150}Nd	**37.0 g**	$Q_{\beta\beta}$ = 3367 keV
^{48}Ca	**7.0 g**	$Q_{\beta\beta}$ = 4272 keV
^{130}Te	**454 g**	$Q_{\beta\beta}$ = 2529 keV
^{nat}Te	**491 g**	
Cu	**621 g**	

External bkg measurement

(All enriched isotopes produced in Russia)