Measuring of neutrino mass with tritium beta-decay

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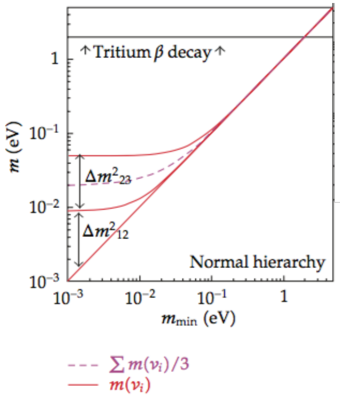
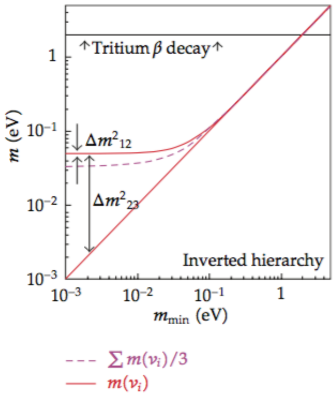
Outline

- Introduction
- Neutrino mass in β-decay. Theory.
- Why tritium?
- History of m_ν searches
- Best limits: Troitsk, Mainz
- Near future: Katrin
- Alternatives: $^{187}\mathrm{Re}$
- What if $m_\mu < 0.2$ meV?
- Sterile neutrino searches in tritium β-decay
    - Motivation: keV neutrino as Dark matter
    - Lab searches: Troitsk

Neutrino are massive





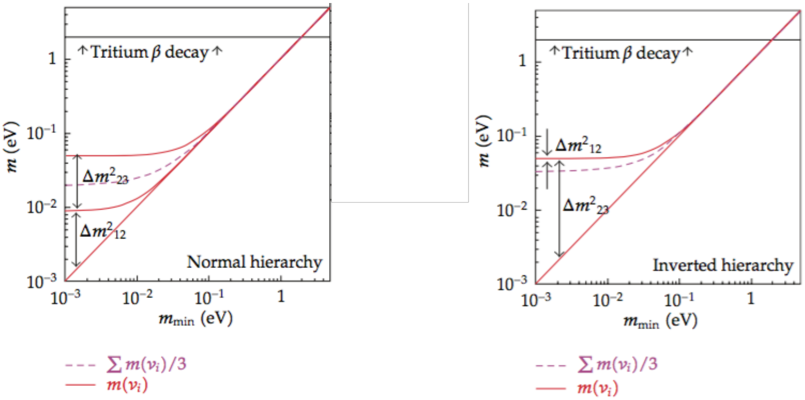
$$\nu_\alpha = \sum_i U_{\alpha i}\, \nu_i$$

Two of neutrino mass states have $m(\nu_i) > 0$, for at least one $m(\nu_i) > 0.05$ eV

Revolution in physics! See lectures by Boris Kayser

How to measure neutrino mass?

Neutrino are massive



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How to measure neutrino mass?

How to measure neutrino mass?

- Indirect
  - Cosmology
  - Astrophysics
- Direct
  - Neutrinoless β-decay.
  - Kinematics of β-decay.

No solid signal, only bounds so far.

Astrophysical limits

In 1987, two dozen on neutrinos from SN in Large Magellanic cloud were detected by Kamiokande II, IMB and Baksan:

- $\Delta t \approx 10$ s
- $E_{\rm min} \approx 10$ MeV and $E_{\rm max} \approx 40$ MeV

Spread due to rest mass after travelling distance L

$$\frac{\Delta t}{L} = \frac{m_\nu^2}{2E_{\rm min}^2}$$

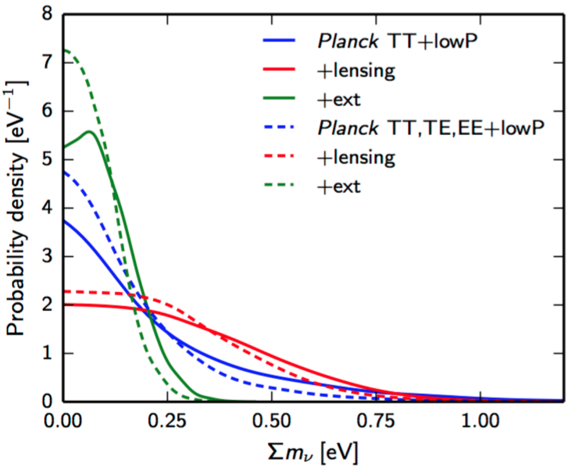
Limit on neutrino mass $m_\nu < 11$ eV *Bahcall and Glashow (1987)*

Recent analysis $m_\nu < 5.7$ eV *Loredo and Lamb (2002)*

JUNO may place limit $m_\nu < 1$ eV if another SN will happen soon.

See lecture by Irene Tamborra

Cosmological limits

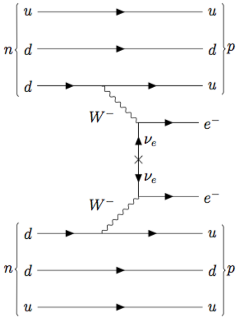


$\sum m_\nu < 0.21$ eV (Planck TT+lowP+BAO) *Planck 2015 results*

See lectures by Gianpiero Mangano

Neutrinoless β-decay limits

Possible if neutrino is a Majorana particle



$$m_{\beta\beta} = \sum_k U_{ek}^2 \, m_k$$

Experiment	Isotope	$T_{1/2}^{0\nu\beta\beta}$ (y)	$m_{\beta\beta}$ (eV)
GERDA	^{76}Ge	$> 2.1 \cdot 10^{25}$	$< (0.2 - 0.4)$
NEMO-3	^{100}Mo	$> 1.1 \cdot 10^{24}$	$< (0.3 - 0.8)$
CUORICINO	^{130}Te	$> 2.8 \cdot 10^{24}$	$< (0.30 - 0.71)$
EXO-200	^{136}Xe	$> 1.1 \cdot 10^{25}$	$< (0.19 - 0.45)$
KamLAND-Zen	^{136}Xe	$> 1.9 \cdot 10^{25}$	$< (0.12 - 0.25)$

From Dragoun and Venos (2015)

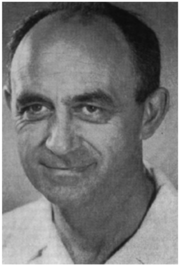
See lectures by Alexander Barabash

Neutrino mass signature in β-decay

$$E^2 = p^2 + m^2$$

Neutrino mass is tiny. If p is large, it will be difficult to see m.
E.g. $\pi \to \mu + \nu_\mu$ gives $m_{\nu_\mu} < 190\ \mathrm{keV}$.

One has to go to situations where ν is non-relativistic.



E. Fermi

Versuch einer Theorie der β-Strahlen. I[1]).

Von **E. Fermi** in Rom.

Mit 3 Abbildungen. (Eingegangen am 16. Januar 1934.)

E. Fermi, Z. Physik 88 (1934)

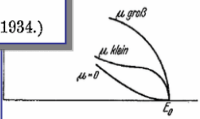
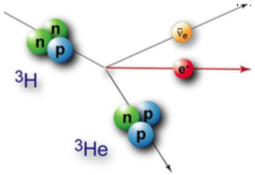


Fig. 1.

β-decay endpoint!

β-decay

$$ {}^{A}_{Z}X \rightarrow {}^{\;\;\;A}_{Z+1}X' + e^{-} + \bar{\nu}_e $$

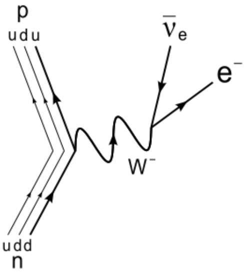


$$ \Gamma = 2\pi \sum \int |M^2| df $$

$df = df_e\, df_\nu$, since even for free neutron decay the recoil proton can carry at most 0.05% of the reaction Q-value. But internal excitations of X' should be included.

$$ df_i = \frac{p^2 dp\, d\Omega}{(2\pi)^3} = \frac{p\, p_0\, dp_0\, d\Omega}{(2\pi)^3} $$

- $E \equiv p_0 - m$ kinetic energy of electrons
- $\varepsilon \equiv E_0 - E$ neutrino energy, where
- $E_0 \equiv \max(E) = Q - E_{rec} - E_{ex}$ is called endpoint energy, Q - total energy release.



Electron spectrum (contribution of one channel)

$$ \dot{N}(E) \equiv \frac{d\dot{N}}{dE} \propto |M^2|\, p\,(E + m_e)\,\varepsilon\,\sqrt{\varepsilon^2 - m_\nu^2} $$

Kurie plot

Electron spectrum (contribution of one channel)

$$\dot{N}(E) \equiv \frac{d\dot{N}}{dE} \propto |M^2|\, p\,(E + m_e)\, \varepsilon \sqrt{\varepsilon^2 - m_\nu^2}$$

Near endpoint it behaves as

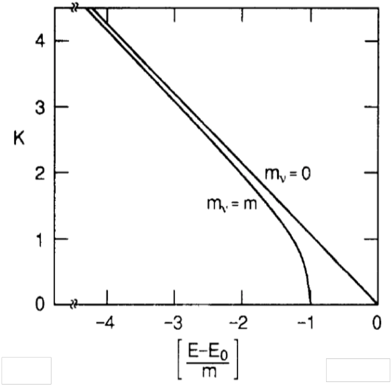
$$K^2(E) \propto \varepsilon \sqrt{\varepsilon^2 - m_\nu^2}$$

- For $m_\nu = 0$

$$K(E) \propto \varepsilon = (E - E_0)$$

- For $m_\nu \neq 0$

$$K(E) \propto \frac{E - E_0}{m_\nu} \left[1 - \frac{m_\nu^2}{(E - E_0)^2}\right]^{1/4}$$



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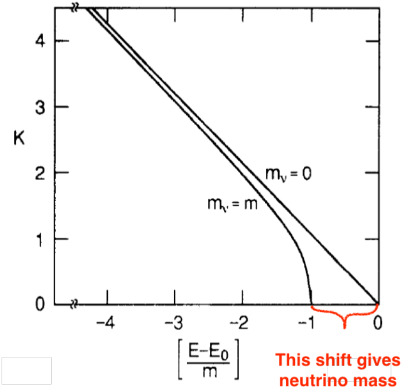


Neutrino masses in β-decay

Electron spectrum (contribution of one channel)

$$\dot{N}(E) \equiv \frac{d\dot{N}}{dE} \propto |M^2|\, p\,(E + m_e)\, \varepsilon\, \sqrt{\varepsilon^2 - m_\nu^2}$$

Contributions from channels with different X' excitations and different neutrino mass states has to be summed up with corresponding probabilities

$$S(E) = \sum_i P_i \dot{N}_i(E)$$

1. Neutrino mass states.

In fact, several neutrino mass states mix into ν_e

$$\nu_e = \sum_i U_{ei} \nu_i$$

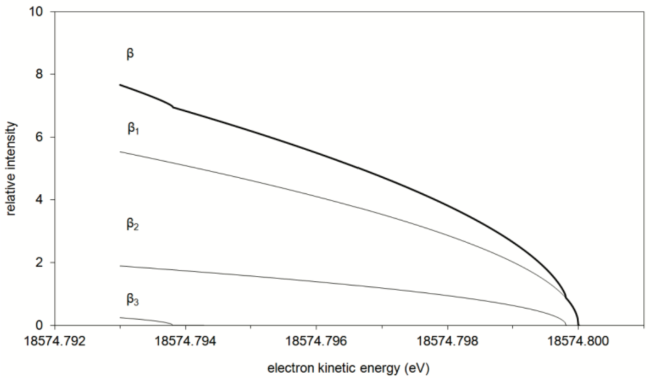
We know for sure about 3 of them.

But sterile neutrinos may also exist and contribute.

Spectrum is modified accordingly

$$S(E) = \sum_i |U_{ei}|^2 S(E, m_i^2)$$

Neutrino masses in β-decay



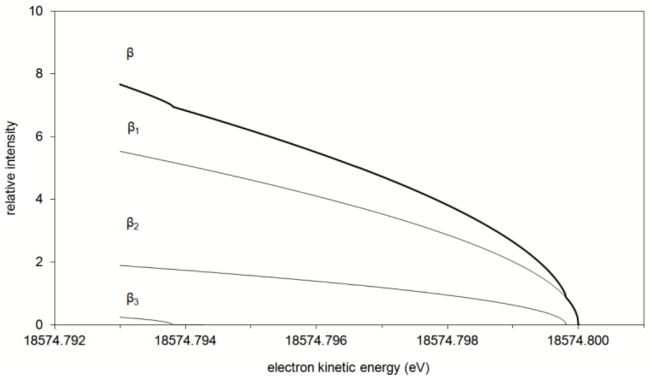
$$S(E) = \sum_i |U_{ei}|^2 S(E, m_i^2)$$

Assumptions: $E_0 = 18.575 \text{ keV}$,
U^2 and mass differences - motivated by oscillations experiments

$$m_1 = 200 \text{ meV}$$
$$m_2 = 200.19 \text{ meV}$$
$$m_3 = 206.19 \text{ meV}$$

From Dragoun and Venos (2015)

Neutrino masses in β-decay



$$S(E) = \sum_i |U_{ei}|^2 S(E, m_i^2)$$

If this fine structure cannot be resolved, we can expand for $\varepsilon \gg m^2(\nu_i)$

$$S(E) = \sum_i |U_{ei}|^2 \, \varepsilon \sqrt{\varepsilon^2 - m_i^2} = \varepsilon^2 - \frac{1}{2} \sum_i |U_{ei}|^2 \, m_i^2$$

Effective electron neutrino mass for β-decay

$$m^2(\nu_e) = \sum |U_{ei}|^2 \, m_i^2$$

Final states X'

Electron spectrum (contribution of one channel)

$$\dot{N}(E) \equiv \frac{d\dot{N}}{dE} \propto |M^2|\, p\,(E + m_e)\, \varepsilon \sqrt{\varepsilon^2 - m_\nu^2}$$

Contributions from channels with different X' excitations and different neutrino mass states has to be summed up with corresponding probabilities

$$S(E) = \sum_i P_i \dot{N}_i(E)$$

2. X' excitations

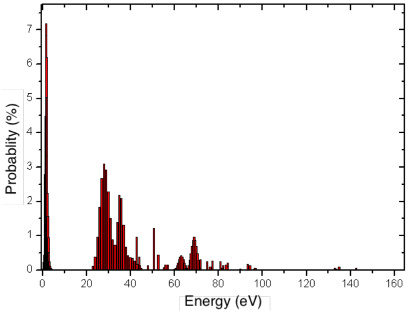
Reminder:

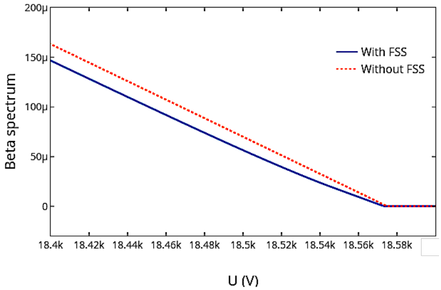
- $E \equiv p_0 - m_e$ kinetic energy of electrons
- $\varepsilon \equiv E_0 - E$ neutrino energy, where
- $E_0 \equiv \max(E) = Q - E_{rec} - E_{ex}$ is called endpoint energy

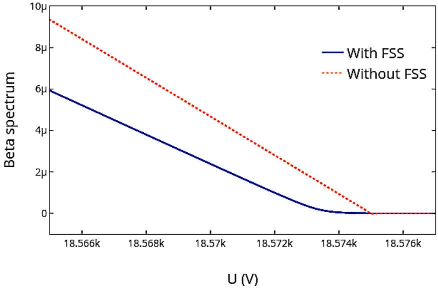
Final states X'

Excitations of ${}^3\mathrm{He\,T}^+$ molecule and their contribution into Kurie plot in the case of tritium β-decay (T_2 molecule).

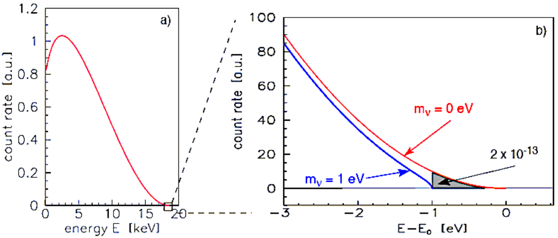
A. Nozik, Troitsk nu-mass







Challenges



- Statistics
  - With good energy resolution it is difficult to get good statistics at the end of the spectrum
- Systematics
  - Several sources, specific to a particular experiment
  - But energy losses are universal
- Theory
  - Final states should be properly included

Element of choice.

Tritium. Radioactive isotope of hydrogen, $^{3}\mathrm{H}$, aka T.

Tritium β-decays into helium-3

$$T \to {}^{3}\mathrm{He} + e^{-} + \bar{\nu}_e$$

and releases

$$Q \approx E_0 = 18.6 \text{ keV}$$

of energy in the process, with half-life time

$$\tau = 12.32 \pm 0.02 \text{ yr}$$

.

Why Tritium?

- The unusually low energy released in tritium β-decay.
  - Relative energy resolution is finite, say $\Delta E/E \sim 10^{-4}$. We need to see structure at 1 eV scale. This limits E_0.
  - Also difficult to work with spectrometers at higher voltage.
- Simple matrix element
- Simple spectrum of final states

History

- m_ν should be much smaller than the electron mass.

  Fermi (1934)

- Measurements of the β-spectrum of ^{35}S, where $E_0 \approx 167$ keV, using magnetic spectrometer, gave $m_{\nu_e} < 5$ keV

  Cook et al. (1948)

- Since then all best limits from **tritium**:
  - Proportional counters, $m_{\nu_e} < 0.5$ keV

    Hanna, Pontecorvo (1949)

  - Magnetic spectrometer, $m_{\nu_e} < 250$ eV

    Langer and Moffat (1952)

  - Retarding-potential spectrometer $m_{\nu_e} < 200$ eV

    Salgo and Staub (1969)

  - Magnetic spectrometers
    - $m_{\nu_e} < 120$ eV — *Daris and St.-Pierre (1969)*
    - $m_{\nu_e} < 55$ eV — *Bergkvist (1972)*
    - $m_{\nu_e} < 35$ eV — *Tretyakov et al (1976)*
    - $14 \leq m_{\nu_e} \leq 46$ eV at 99% — *Lubimov et al (1980)*
    - $17 \leq m_{\nu_e} \leq 40$ eV at 99% — *Lubimov et al (1987)*

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1948: First experiment with tritium

$T \rightarrow {}^{3}He + e^{-} + \underline{18{,}6\ кэВ}$

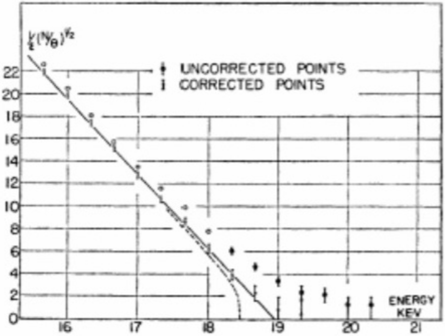
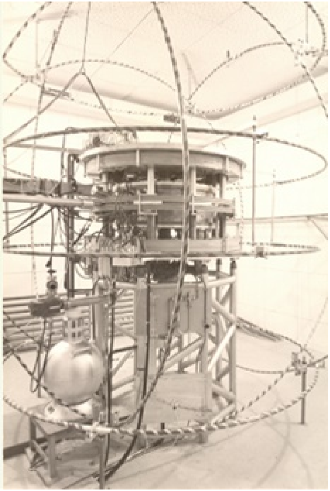


FIG. 2. "Kurie" plot of the end of the H^3 spectrum. The theoretical curve (shown dotted) corresponding to a finite neutrino mass of 500 ev (or 1 kev —see text) has been included for comparison.

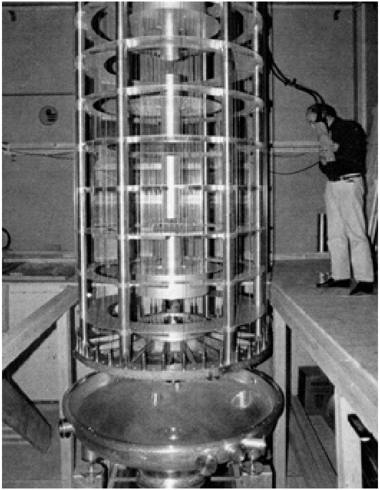
Hanna G.C. and Pontecorvo B., Phys. Rev. 75 (1949) 983

History. Magnetic spectrometers.



Spectrometer with radial focusing and axial defocusing

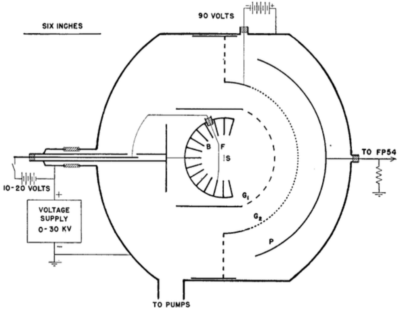
Daniel, Jahn, Kuntze & Martin (1970)



Toroidal magnetic spectrometer of the Tretyakov type installed at the Zurich University *Tretyakov (1973)*

"Simple" spectrometers:

Retarding potential

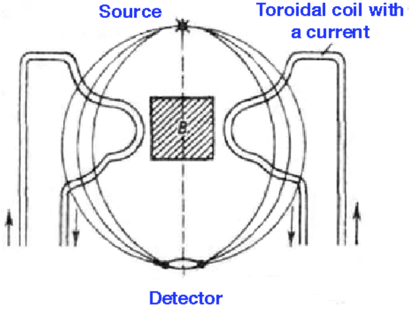


Hamilton and Gross (1950)

Only electrons with energy larger than potential can overcome potential and are counted.

Spectrum can be measured by varying electric field strength

Magnetic



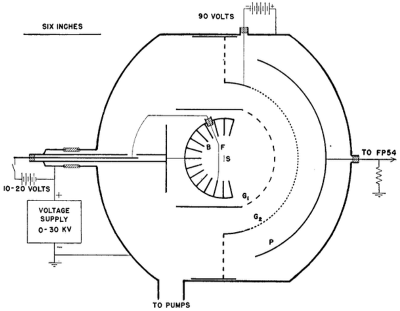
Tretyakov (1973)

Electrons of equal energies emitted at different angles are collected in one spot.

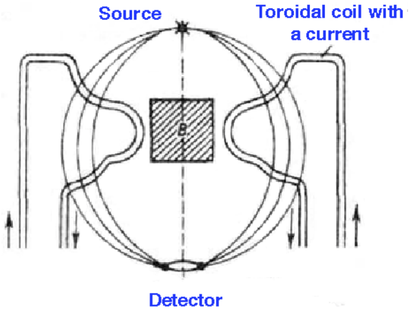
Spectrum can be measured by varying magnetic field strength.

"Simple" spectrometers:

Retarding potential



Magnetic



Shortcomings of "simple" solutions

- Good energy resolution -> a source should be small
- Small source -> Low luminosity
- Tritium was implanted -> Spectrum distorted by final states -> Fake discovery.

New generation of experiments

- Gaseous source with circulating molecular tritium
  - Theoretical spectrum of final states of the $(\mathrm{T}^3\mathrm{He})^+$ molecular ion is better known than that of complex solid sources
  - The energy losses of β-particles within tritium gas can be determined more precisely than in the case of solid sources.

Developed at at the Los Alamos National Laboratory

Robertson et al. (1991)

And also at Lawrence Livermore National Laboratory. However, their tritium β-spectrum showed an anomalous structure near the endpoint yielding an unphysical result $m_{\nu_e} = -130 \pm 20$ eV

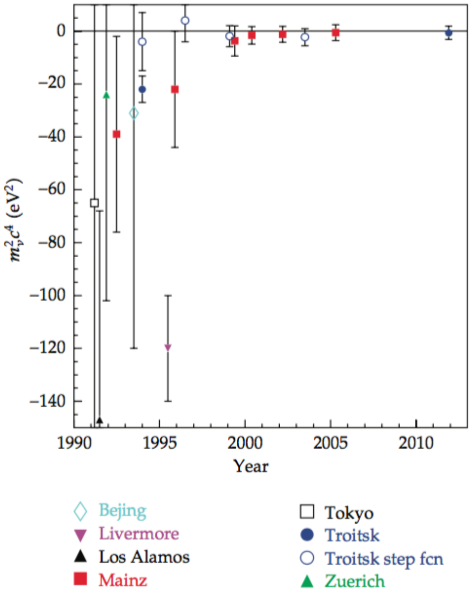
Stoeffl and Decman (1995)

Exploration of the $17 \leq m_{\nu_e} \leq 40$ eV claim

Experiment	Spectrometer	Source	m^2_ν (eV^2)	m_ν (eV) at 90% CL
Kawakami *et al.* Tokyo, 1991	Magnetic, $\pi\sqrt{2}$	Solid; cadmium salt of tritiated $C_{20}H_{40}O_2$	$-65 \pm 85_{stat} \pm 65_{syst}$	< 11
Robertson *et al.* Los Alamos, 1991	Magnetic, toroidal	Gaseous tritium molecules	$-147 \pm 68_{stat} \pm 41_{syst}$	< 6
Holzschuh *et al.* Zurich, 1992	Magnetic, toroidal	Solid; tritiated octadecyltrichlorosilan	$-24 \pm 48_{stat} \pm 61_{syst}$	< 10
Weinheimer *et al.* Mainz, 1993	Electrostatic retardation with magnetic collimation	Solid, frozen tritium Molecules	$-39 \pm 34_{stat} \pm 15_{syst}$	< 6
Sun Hancheng *et al.* Beijing, 1993	Magnetic, $\pi\sqrt{2}$	Solid; tritiated $C_{14}H_{15}T_6O_2N_3$	$-31 \pm 75_{stat} \pm 48_{syst}$	< 11

From Dragoun and Venos (2015)

Exploration of the $17 \leq m_{\nu_e} \leq 40$ eV claim

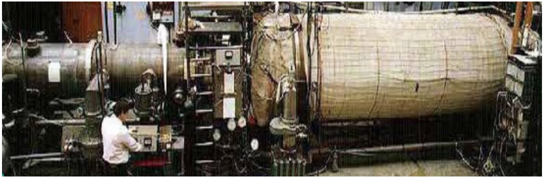


From Drexlin et al (2013)

Current best limit: $m_{\nu_e} < 1.8$ eV, combined

- Troitsk

Windowless Gaseous Tritium Source (WGTS)



2011 re-analysis of selected data from 1994-2004

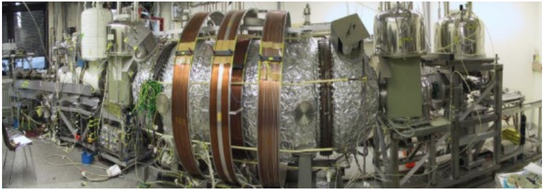
$$m^2_{\nu_e} = (-0.67 \pm 1.89 \pm 1.68)\ \text{eV}^2$$

$$m_{\nu_e} < 2.05\ \text{eV}\ (95\%\ \text{C.L.})$$

Aseev et al (2011)

- Mainz

Quench condensed tritium source



2004 final analysis of Mainz phase II data from 1998-2001

$$m^2_{\nu_e} = (-0.6 \pm 2.2 \pm 2.1)\ \text{eV}^2$$

$$m_{\nu_e} < 2.3\ \text{eV}\ (95\%\ \text{C.L.})$$

Kraus et al (2005)

Both used MAC-E filter as a spectrometer –
Magnetic Adiabatic Collimation with an Electrostatic Filter

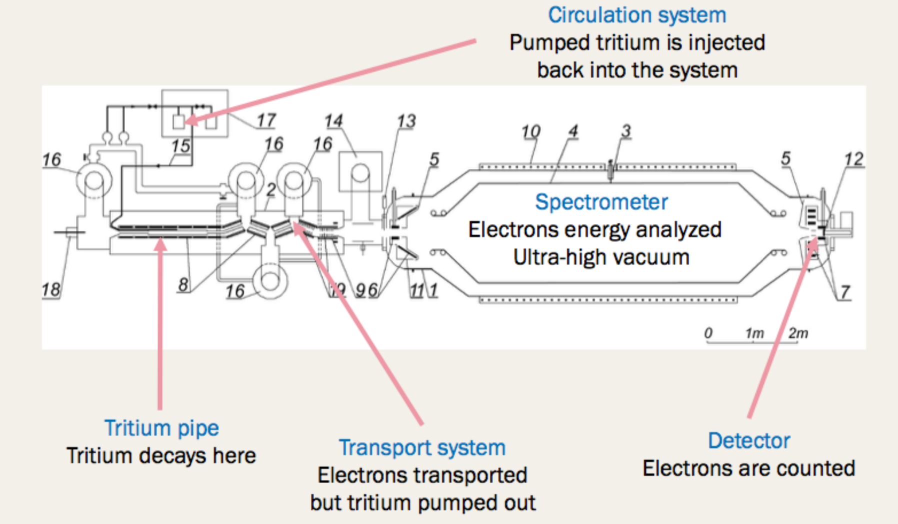
Troitsk ν-mass experiment

V.M. Lobashev

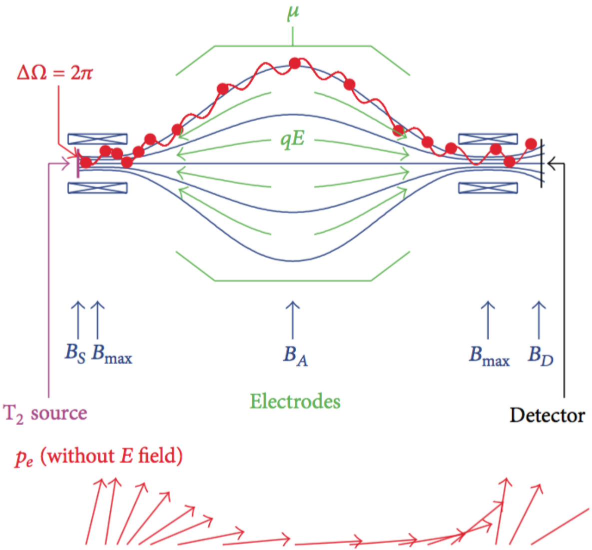
Troitsk ν-mass experiment

WGTS + MAC-E filter

Note:The same will be employed at KATRIN, upscaled



MAC-E filter principle



$$\mu = \frac{E_\perp}{B} = \text{const}$$

Energy resolution

$$\frac{\Delta E}{E} = \frac{B_{\text{min}}}{B_{\text{max}}}$$

MAC-E filter principle

For measuring β-spectrum suggested in:

A METHOD FOR MEASURING THE ELECTRON ANTINEUTRINO REST MASS

V.M. LOBASHEV

Institute for Nuclear Research of the Academy of Sciences of the USSR, Profsoyuznaya 7a, Moscow, USSR

P.E. SPIVAK

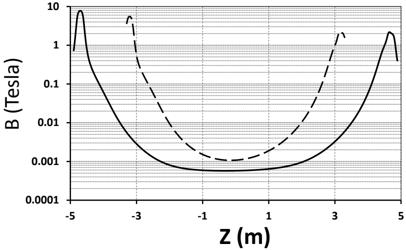
I.V. Kurchatov Institute of Atomic Energy, Ploshchad' Kurchatova 46, Moscow 123182, USSR

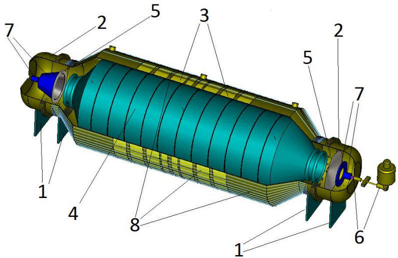
Received 13 June 1984 and in revised form 6 May 1985

A method is proposed for measuring the tritium beta spectrum in order to determine the electron antineutrino rest mass. This method includes an electrostatic integral spectrometer with adiabatic collimation. The use of a source in the form of atomic polarized tritium in a strong magnetic field or of a gaseous molecular source is considered.

Developed independently by Mainz and Troitsk.

Troitsk spectrometer





Energy resolution of Troitsk is 1.5 eV at highest energies 18 keV

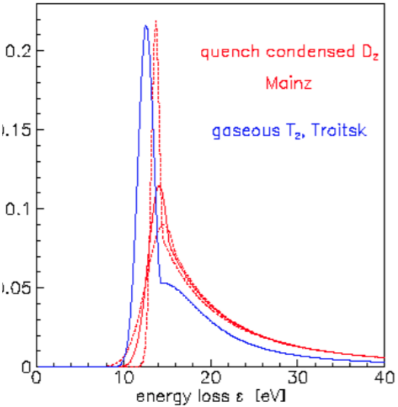
Systematics

Troitsk

1. Final state spectrum ambiguity.
2. Uncertainty of source thickness and related energy losses.
3. Uncertainty in parameters of the trapping effect.

Mainz

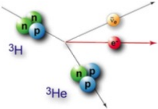
- Instead of collisions in T_2 gas, energy losses are in a solid film.
- Item 3 is absent, but instead inhomogeneity of the solid source and generated electric charge.

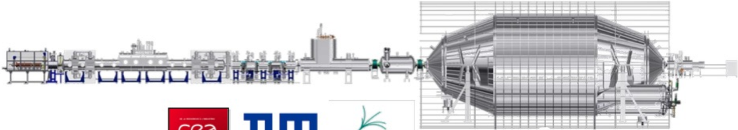


Aseev et al. (2000)

Near Future: KATRIN

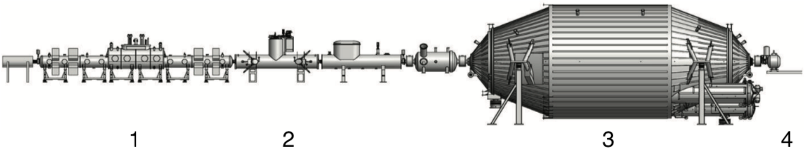
- **Karlsruhe Tritium Neutrino Experiment**
  - **direct ν–mass experiment** at Tritium Laboratory (TLK) of KIT
  - international collaboration: ~130 members
    from 6 countries: D, US, CZ, RUS, F, ES





- **18 institutions:**

Near Future: KATRIN



1. WGTS), where 10^{11} electrons are produced per second by the β-decay of molecular high-purity tritium gas.
2. Transport and pumping sections, where the tritium flow is reduced by more than 14 orders of magnitude.
3. MAC-E filter (the largest UHV recipient in the world)
4. Detector (148 pixels)

More details in review Drexlin et al (2013)

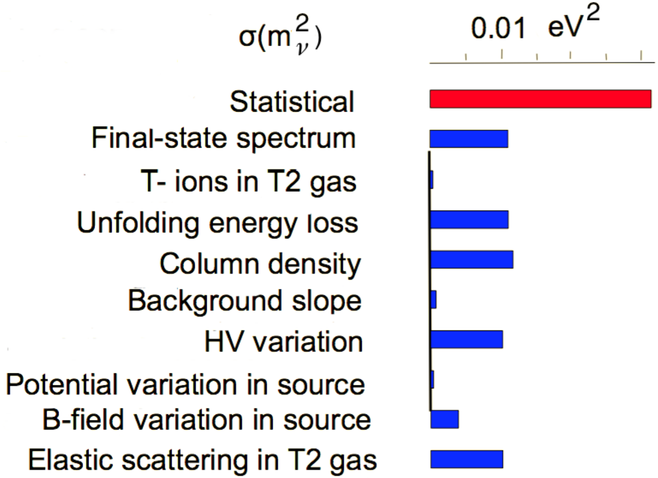
Near Future: KATRIN

Near Future: KATRIN

Near Future: KATRIN

- KATRIN aims to improve the m_{ν_e} sensitivity by a factor of 10 from 2 eV to 200 meV at 90% C.L.
- This requires increase of the source strength by a factor of 100 and of the measurement time by a factor of 10
  - WGTS and MAC-E-Filter of an unprecedented sizes will enable to increase the luminosity by two orders of magnitude in comparison to Mainz and Troitsk
- Order of magnitude better control of systematic effects is also required

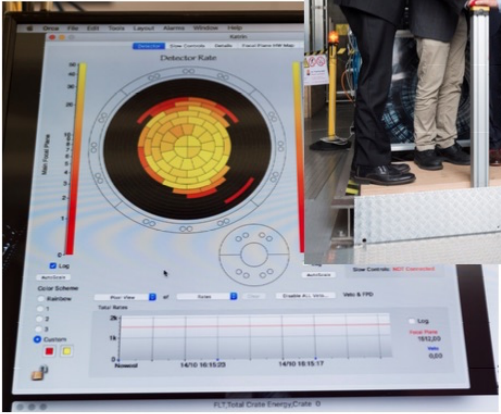
Errors budjet



$\sigma(m_\nu^2)$total = 0.025 eV^2
$m_\nu <$ 0.2 eV (90 % CL)

KATRIN status

14.10.2016
“First Light”



KATRIN status

- Study, removal and correction of backgrounds. New sources:
  - Radon - taken care of.
  - Rydberg atoms. This may degrade sensitivity up to $m_\nu \approx 240$ meV.
- Resent two week calibrations with ^{83}Kr
- May 2018. First tritium at 1% of nominal density:
  - Limits on m_{ν_e} at 1 eV level
  - Trial 1 keV sterile neutrino searches
- If everything OK, then steady increase of tritium up to nominal.

Alternatives: $^{187}\mathrm{Re}$

$$^{187}\mathrm{Re} \rightarrow {}^{187}\mathrm{Os} + \mathrm{e}^{-} + \bar{\nu}_{\mathrm{e}}$$

Lowest known endpoint energy

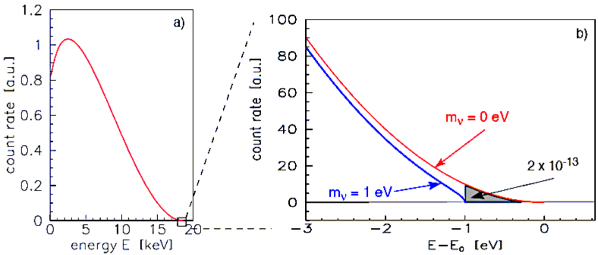
Requires use of microcalorimeters

pros: total E measured except E_ν

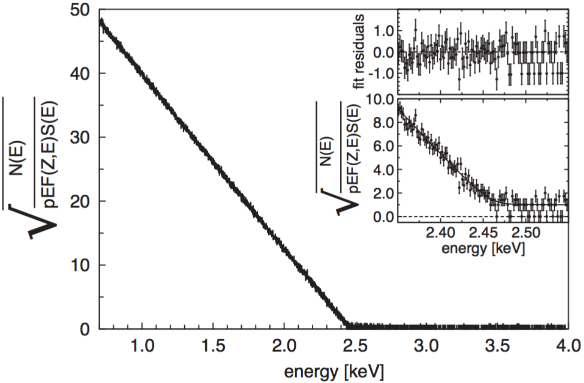
- Complications concerning final states after a β-decay and of electron energy losses within a source can be eliminated

cons: Small subsection of β-spectrum sensitive to m_ν cannot be selected

- To avoid pile up, a large number of microcalorimeters is required



MiBeta experiment



Results:

Sisti, et al. (2004)

- 10^7 decays with 8 detectors collected in one year
- $E_0 = 2.46$ keV, $\tau = 4.3 \times 10^{10}$ yr
- $m_{\nu_e} < 15$ eV

Alternatives: ^{187}Re

How to improve it?
MARE: Microcalorimeter Arrays for a Rhenium Experiment

e.g. E. Ferri et al. (2012)

Improving MiBeta limit by a factor 100 would require to increase the statistics by a factor 10^8, i.e. to collect 10^{15} decays.

MARE needs:

- Several large arrays of 10^4 detectors each.
- Each pixel should have activity of few counts per second.
- The measurement should last up to ten years to collect 10^{14} β-decays.

Systematics:

- Background
- Pile-up
- Detector response function
- Theoretical spectral shape of the ^{187}Re β-decay
- Beta Environmental Fine Structure

Alternatives: $^{187}\mathrm{Re}$

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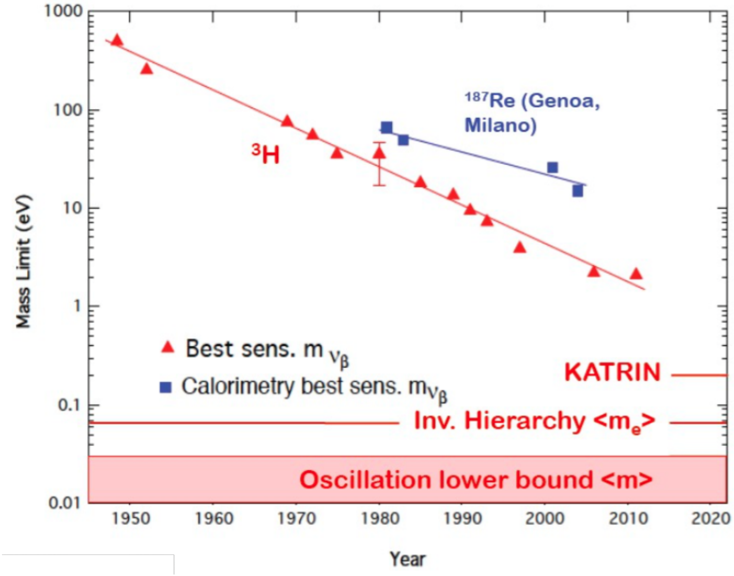
- Beta Environmental Fine Structure

Alternatives: ^{163}Ho

See lecture by Loredana Gastaldo

m_ν limits from β-decay

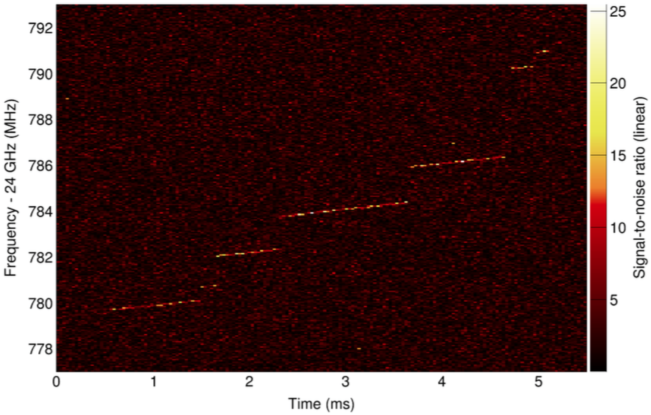


Wilkerson and Robertson

What if $m_\nu < 0.2$ eV ?

Project 8. The final goal of collaboration is to reach a sensitivity to m_ν to a level of 0.05 eV.

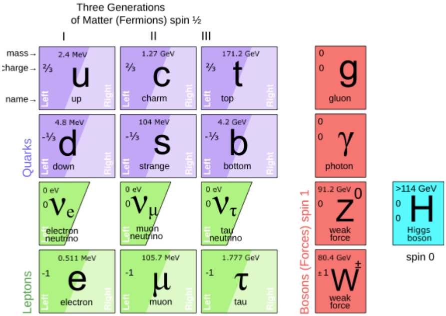
Idea. Precision spectroscopy of cyclotron radiation emitted by tritium decay electrons. Concept has been proven recently by Project 8 for single electrons.



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

Asner et al., 2014

Standard Model



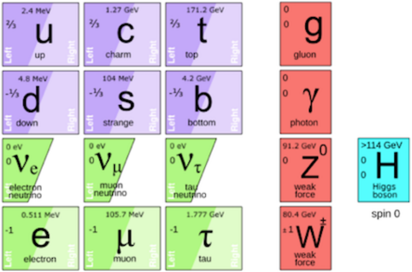
The Standard Model does not explain

- Neutrino oscillations
- Dark matter
- Baryon asymmetry of the Universe

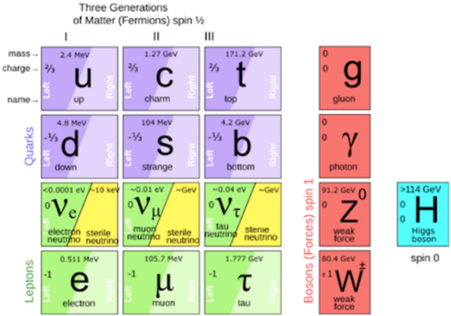
We need new physics

Sterile Neutrino

Standard Model



Extension with ν_R

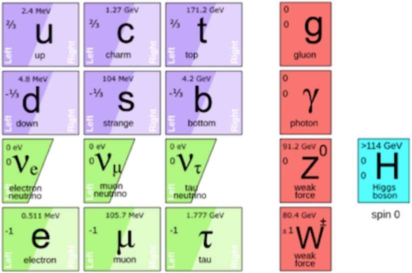


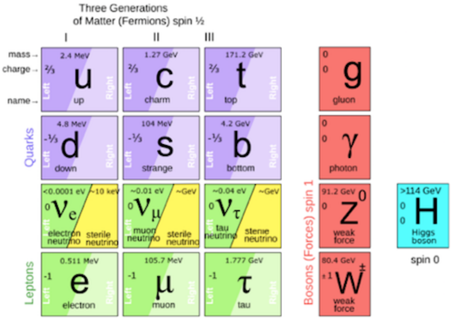
Key question - mass of ν_R

See lectures by Steve King

Consider Standard Model with minimal extention to include right handed neutrinos N_j, $j = 1, 2, 3$

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\bar{N}_j \partial_\mu \gamma^\mu N_j - \left[\lambda_{ji} N_j (H L_i) + \frac{M_{ji}}{2} N_j N_i + \text{h.c.} \right]$$





Sterile Neutrino

Consider Standard Model with minimal extention to include right handed neutrinos N_j, $j = 1, 2, 3$

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\bar{N}_j \partial_\mu \gamma^\mu N_j - \left[\lambda_{ji} N_j (H L_i) + \frac{M_{ji}}{2} \, N_j N_i + {\rm h.c.} \right]$$

Here $\langle H \rangle = v = 174 \text{ GeV}$,
M - Majorana mass of sterile neutrino, $m_D = \lambda v$ - Dirac mass,

If $\lambda v \ll M$ the see-saw formula works

$$m_\nu = -m_D \frac{1}{M} m_D^T$$

Right handed neutrino - the easiest way to explain neutrino masses.

Scale M cannot be extracted from low-energy experiments:
multiply m_D by x and M by x^2, m_ν does not change.

Sterile Neutrino

Consider Standard Model with minimal extention to include right handed neutrinos N_j, $j = 1, 2, 3$

$$\mathcal{L} = \mathcal{L}_{\mathrm{SM}} + i\bar{N}_j \partial_\mu \gamma^\mu N_j - \left[\lambda_{ji} N_j (H L_i) + \frac{M_{ji}}{2} \, N_j N_i + \text{h.c.} \right]$$

This model can explain a number of observations:

- **Non-zero neutrino mass and oscillations,**

$$m_\nu = m_D M^{-1} m_D^T$$

- **Baryon asymmetry, if** $M_1 \gtrsim 10^8 \ \mathrm{GeV}$

Fukugita & Yanagida, (86)

See lecture by Sacha Davidson on leptogenesis

Sterile Neutrino

Consider Standard Model with minimal extention to include right handed neutrinos N_j, $j = 1, 2, 3$

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\bar{N}_j \partial_\mu \gamma^\mu N_j - \left[\lambda_{ji} N_j (H L_i) + \frac{M_{ji}}{2} \, N_j N_i + {\rm h.c.} \right]$$

This model can explain a number of observations:

- **Dark matter, if** $M_1 \gtrsim$ keV

Dodelson & Widrow (94)

- **Dark matter and Baryon asymmetry, if** $M_1 \gtrsim$ keV **and** $M_2, M_3 \sim$ GeV

Akhmedov, Rubakov & Smirnov (98)

Asaka & Shaposhnikov (05)

See lecture by Nicolao Fornengo on Dark matter

Lightest sterile neutrino as dark matter

We have to find models and parameter ranges where sterile neutrino:

- Are produced in correct amounts
- Are relatively stable
- Do not contradict cosmological and astrophysical constraints

Recent review on a keV Sterile Neutrino Dark Matter, arXiv: 1602.04816

Lightest sterile neutrino abundance

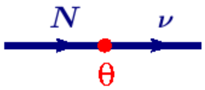
Production mechanisms

- Directly in inflaton decays. *Shaposhnikov & I.T. (06)*

- Active-sterile oscillations. *Dodelson & Widrow (94)*

  Important parameter - mixing of active and sterile neutrino

$$\theta^2 = \frac{1}{M_1^2} \sum_{i=e\mu\tau} |\lambda^{1i} v|^2$$



Resulting abundance:

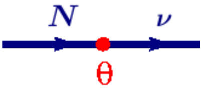
$$\Omega_s \sim \Omega_m \frac{\sin^2(2\theta)}{10^{-7}} \left(\frac{M}{1\ \mathrm{keV}}\right)^2$$

Lightest sterile neutrino as dark matter

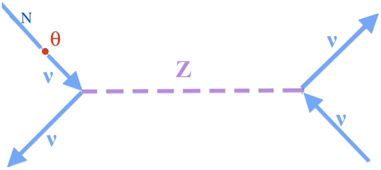
Lifetime

Important parameter - mixing of active and sterile neutrino

$$\theta^2 = \frac{1}{M_1^2} \sum_{i=e\mu\tau} |\lambda^{1i} v|^2$$



Main decay mode $N \to 3\nu$



Sterile neutrino can be long-living

Lifetime:

$$\tau_{N_1} = 5 \times 10^{26}\,\mathrm{sec} \left(\frac{1\ \mathrm{keV}}{M}\right)^5 \left(\frac{10^{-8}}{\theta^2}\right)$$

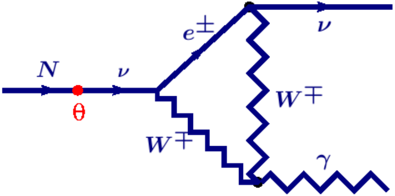
Light from dark matter

- Photon energy:

$$E_\gamma = \frac{M_1}{2}$$

- Radiative decay width

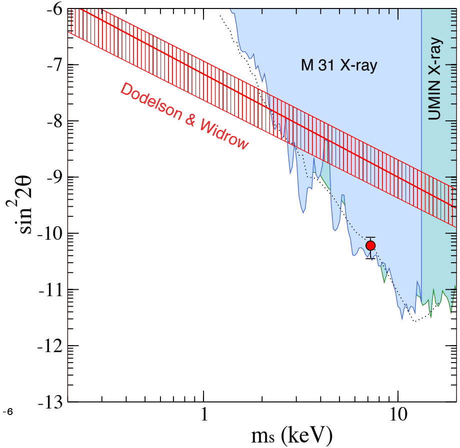
$$\Gamma = \frac{9\alpha_{\rm EM} G_F^2}{256\pi^4}\,\theta^2\,M_1^5$$

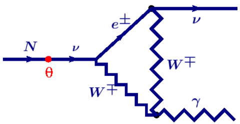


Dark matter made of sterile neutrino is not completely dark

Dolgov & Hansen (2000)

Bounds from X-ray astronomy





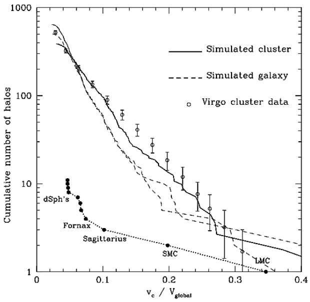
Dark matter made of sterile neutrino is not completely dark, $N \to (\nu_e, \gamma)$

Best place to look for the decay line - dwarf satellite galaxies

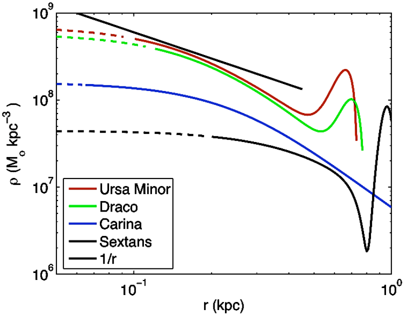
Boyarsky, Neronov, Ruchayskiy, Shaposhnikov & I. T. (2006)

Cold Dark matter puzzles

CDM problems at small scales



Small number of dSph

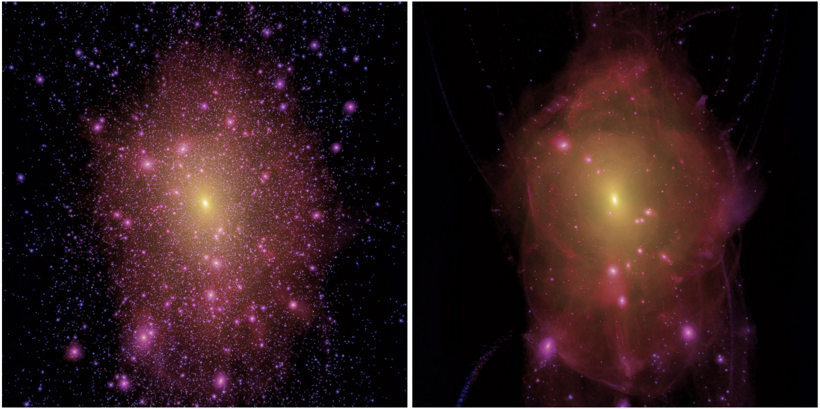


Absence of cusps in density profiles of dSph

Warm dark matter

Galaxy halo:

CDM WDM



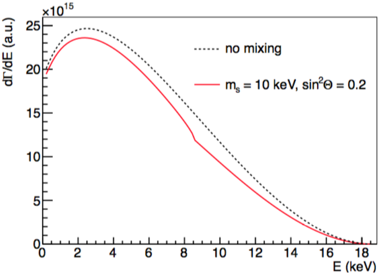
2 keV sterile neutrino gives better fit to data

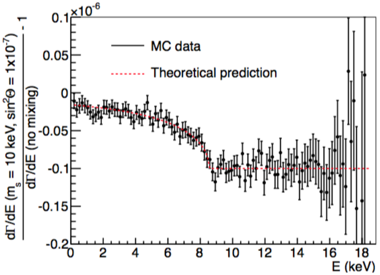
Lovell et al, 2011

Lab searches

In the presence of sterile neutrino it spectrum of tritium β-decay is modified

$$S(E) = (1 - U_{e4}^2)\, S(E, m_1) + U_{e4}^2\, S(E, m_4^2)$$

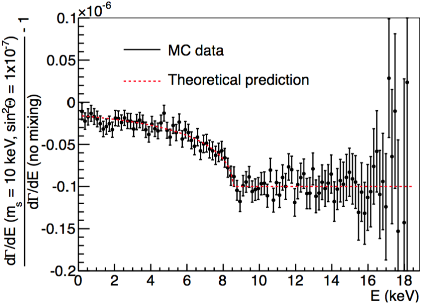


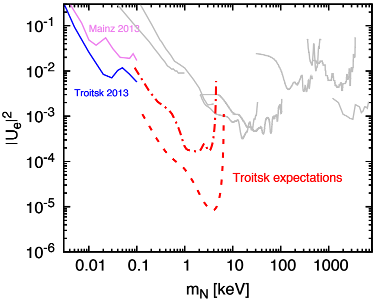


Such spectrum distortions can be looked for

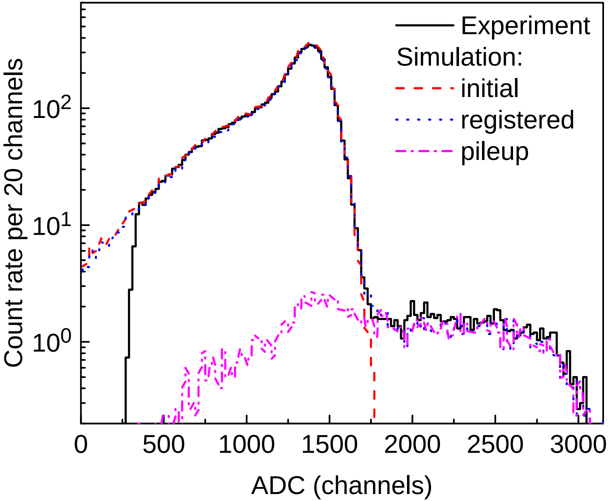
Lab searches

keV scale sterile neutrino searches have started in Troitsk last year



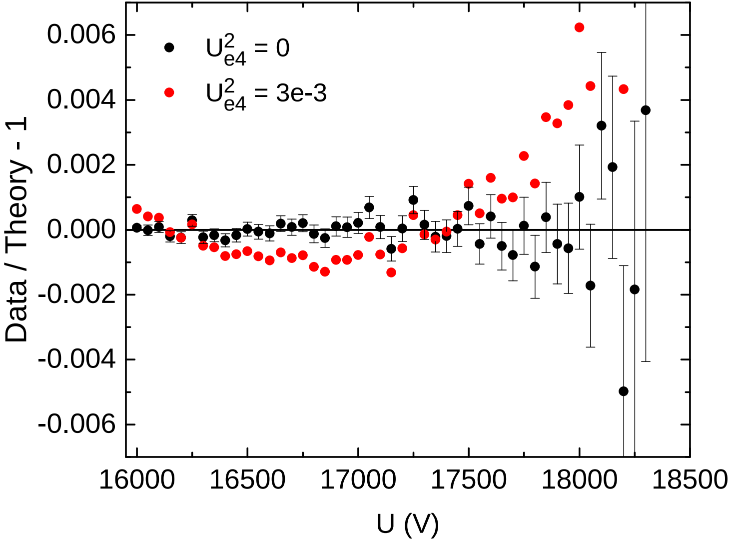


Systematics



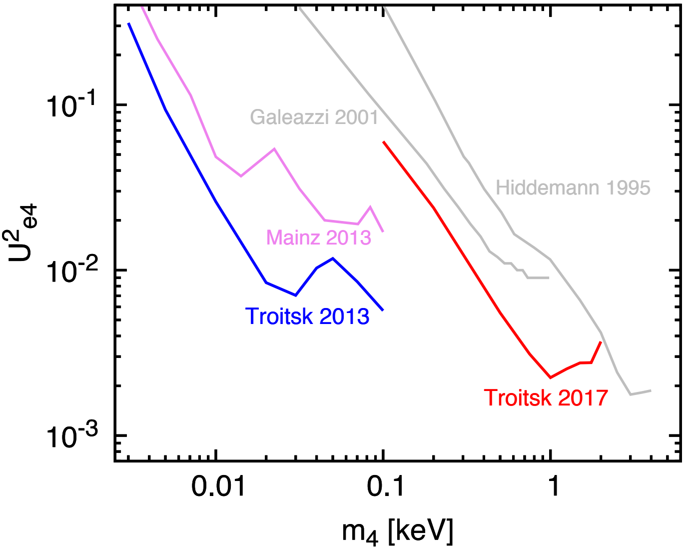
Amplitude spectrum of the detector

Tritium β-decay spectra



Recent precision measurements at Troitsk

Bounds on sterile neutrino from Tritium β-spectra



At the end of the run 06.2017 in Troitsk.

Conclusions

- Measuring of neutrino mass is extremely important since $m_\nu \neq 0$ is the only fact which contradicts the Standard Model.
- It can be measured:
  - Cosmologically. But this is model dependent and indirect.
  - In neutrinoless β-decay. But only if ν is a Majorana particle.
  - **Beta-decay. Universal route and required anyway.**

Stay tuned