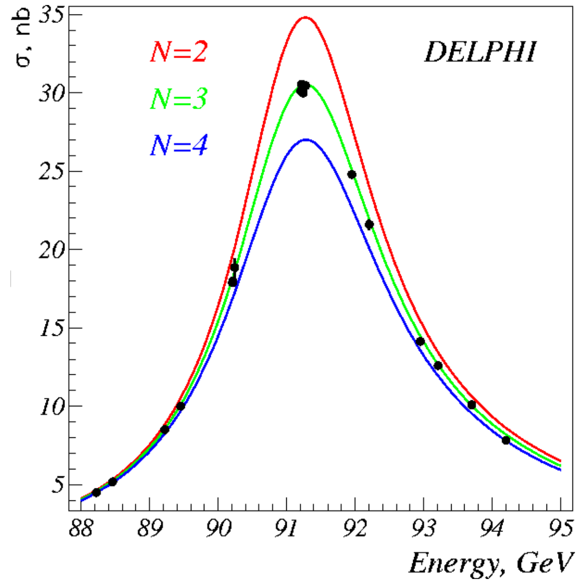
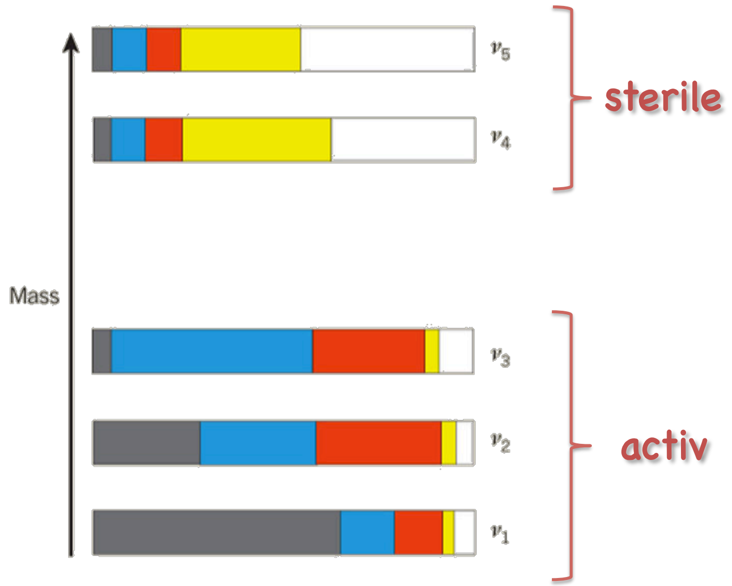
3.2 Sterile Neutrinos

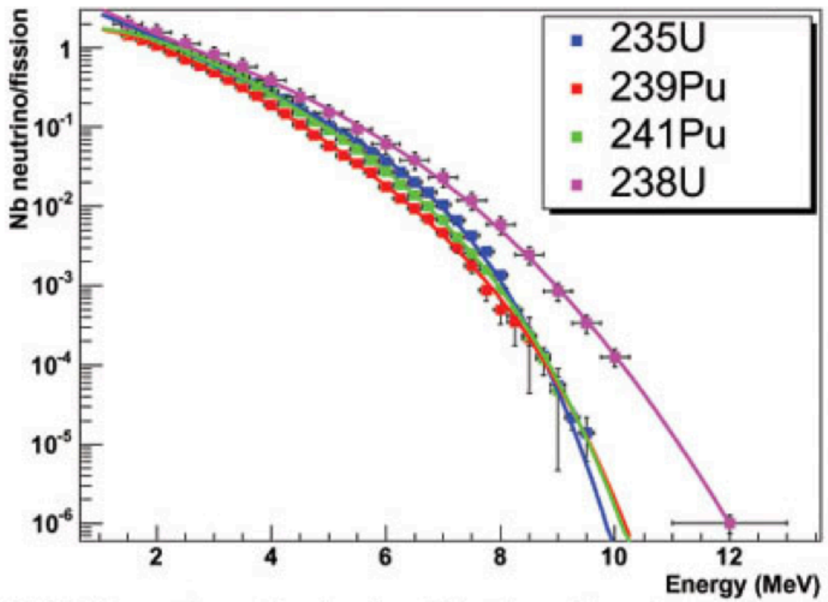
Three active neutrinos in Z^0-decay



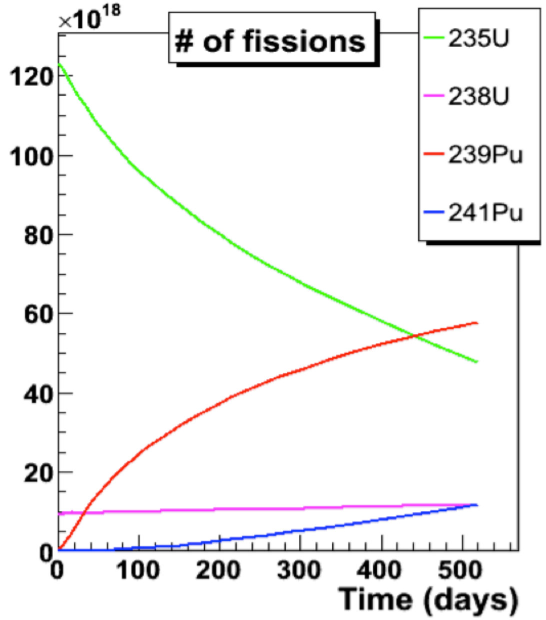
Active and sterile neutrinos (3+2)



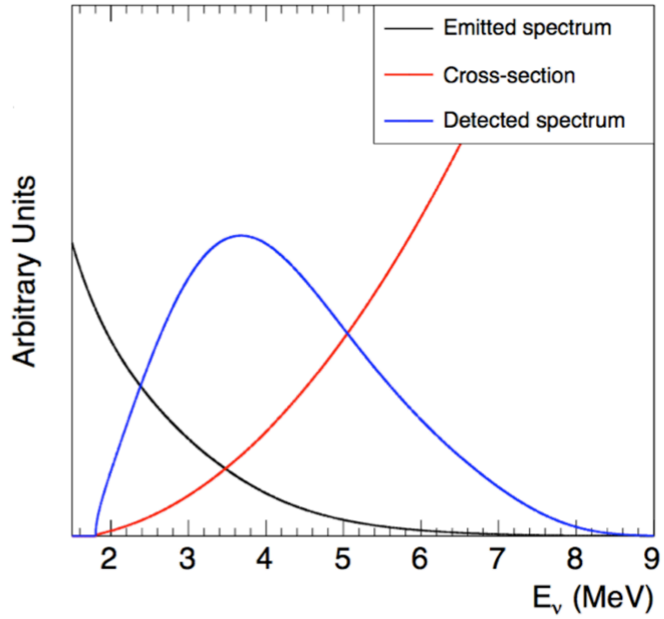
Contribution to reactor spectrum



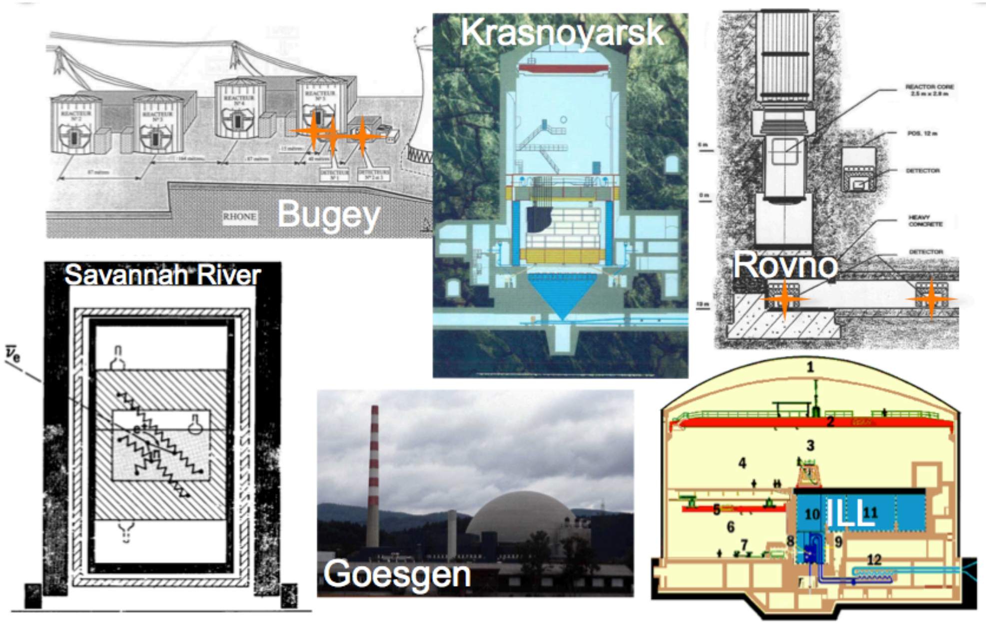
Nuclear burn-off



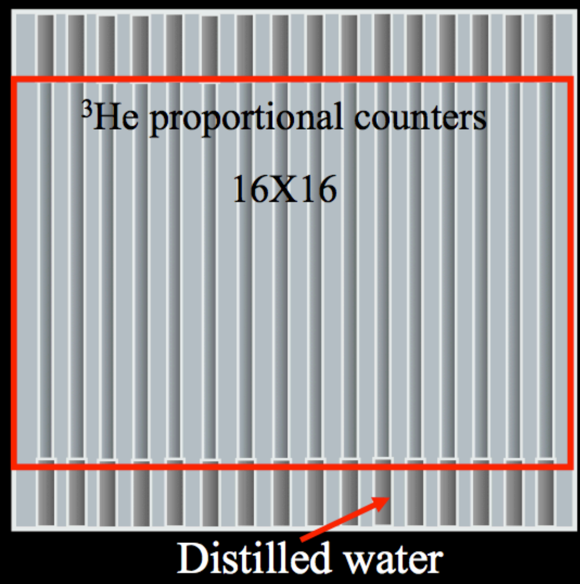
Spectrum and cross section



Reactor experiments at short baselines



Budget-4 Experiment



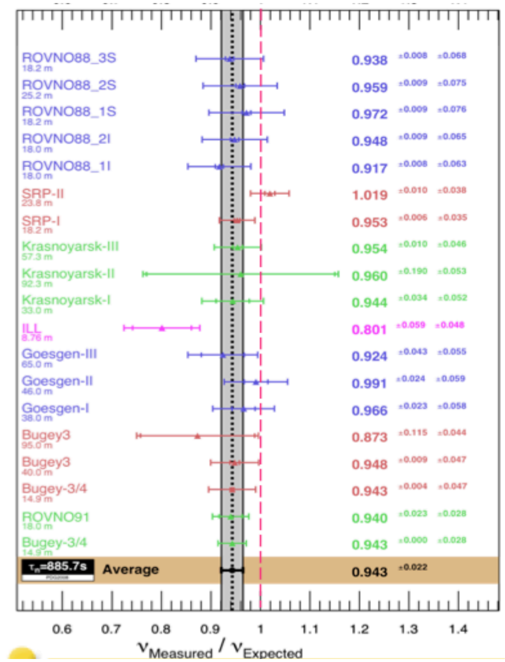
3.2 Sterile Neutrinos

Overview of experiments

#	result	Det. type	τ_n (s)	^{235}U	^{239}Pu	^{238}U	^{241}Pu	old	new	err(%)	corr(%)	L(m)
1	Bugey-4	^{3}He+H$_2$O	888.7	0.538	0.328	0.078	0.056	0.987	0.942	3.0	3.0	15
2	ROVNO91	^{3}He+H$_2$O	888.6	0.614	0.274	0.074	0.038	0.985	0.940	3.9	3.0	18
3	Bugey-3-I	^{6}Li-LS	889	0.538	0.328	0.078	0.056	0.988	0.946	4.8	4.8	15
4	Bugey-3-II	^{6}Li-LS	889	0.538	0.328	0.078	0.056	0.994	0.952	4.9	4.8	40
5	Bugey-3-III	^{6}Li-LS	889	0.538	0.328	0.078	0.056	0.915	0.876	14.1	4.8	95
6	Goesgen-I	^{3}He+LS	897	0.620	0.274	0.074	0.042	1.018	0.966	6.5	6.0	38
7	Goesgen-II	^{3}He+LS	897	0.584	0.298	0.068	0.050	1.045	0.992	6.5	6.0	45
8	Goesgen-II	^{3}He+LS	897	0.543	0.329	0.070	0.058	0.975	0.925	7.6	6.0	65
9	ILL	^{3}He+LS	889	$\simeq 1$	—	—	—	0.832	0.802	9.5	6.0	9
10	Krasn. I	^{3}He+PE	899	$\simeq 1$	—	—	—	1.013	0.936	5.8	4.9	33
11	Krasn. II	^{3}He+PE	899	$\simeq 1$	—	—	—	1.031	0.953	20.3	4.9	92
12	Krasn. III	^{3}He+PE	899	$\simeq 1$	—	—	—	0.989	0.947	4.9	4.9	57
13	SRP I	Gd-LS	887	$\simeq 1$	—	—	—	0.987	0.952	3.7	3.7	18
14	SRP II	Gd-LS	887	$\simeq 1$	—	—	—	1.055	1.018	3.8	3.7	24
15	ROVNO88-1I	^{3}He+PE	898.8	0.607	0.277	0.074	0.042	0.969	0.917	6.9	6.9	18
16	ROVNO88-2I	^{3}He+PE	898.8	0.603	0.276	0.076	0.045	1.001	0.948	6.9	6.9	18
17	ROVNO88-1S	Gd-LS	898.8	0.606	0.277	0.074	0.043	1.026	0.972	7.8	7.2	18
18	ROVNO88-2S	Gd-LS	898.8	0.557	0.313	0.076	0.054	1.013	0.959	7.8	7.2	25
19	ROVNO88-3S	Gd-LS	898.8	0.606	0.274	0.074	0.046	0.990	0.938	7.2	7.2	18

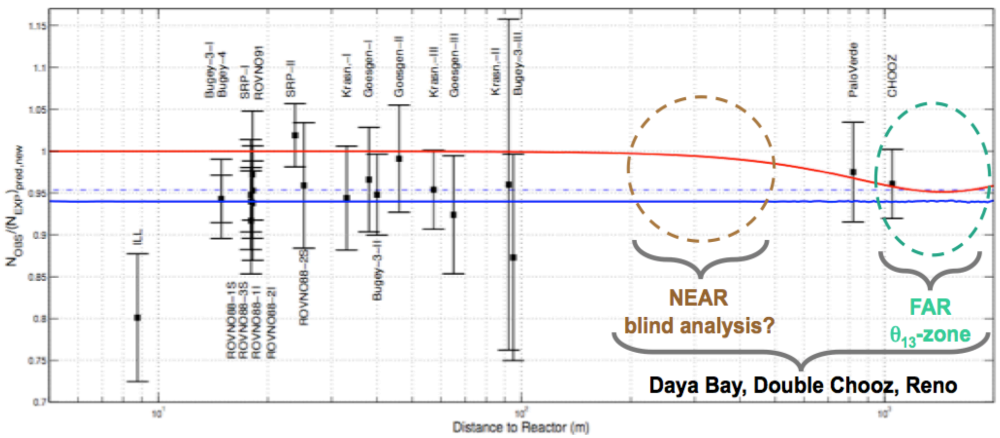
3.2 Sterile Neutrinos

Experimental results vs. expectation



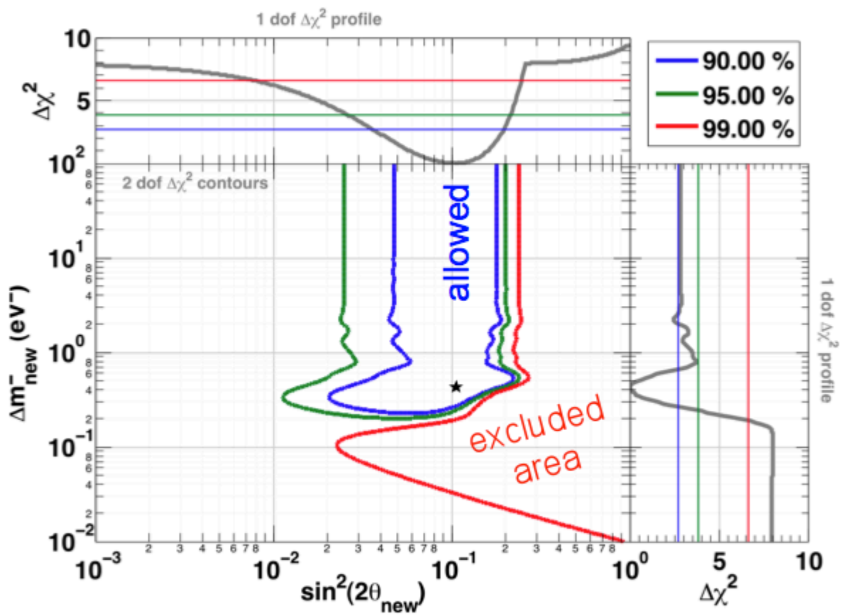
3.2 Sterile Neutrinos

P_{ee}(L): Old and new scenario

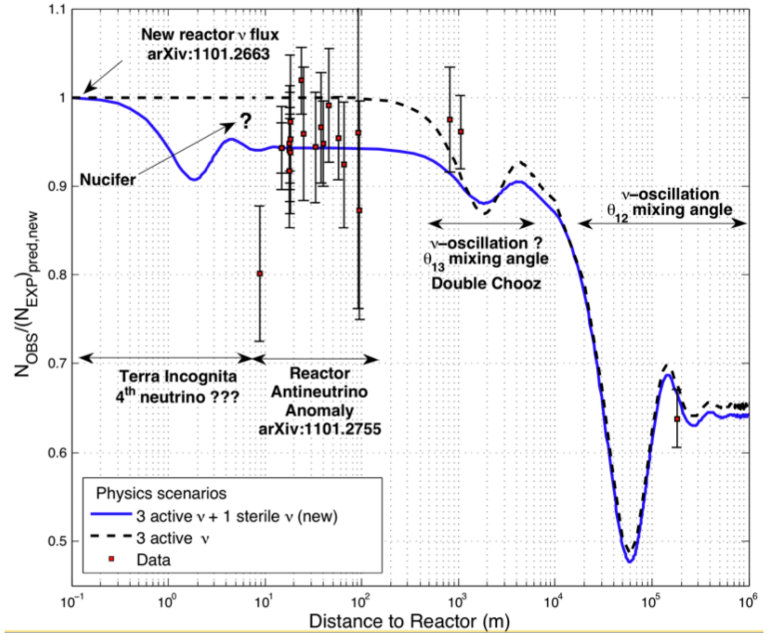


3.2 Sterile Neutrinos

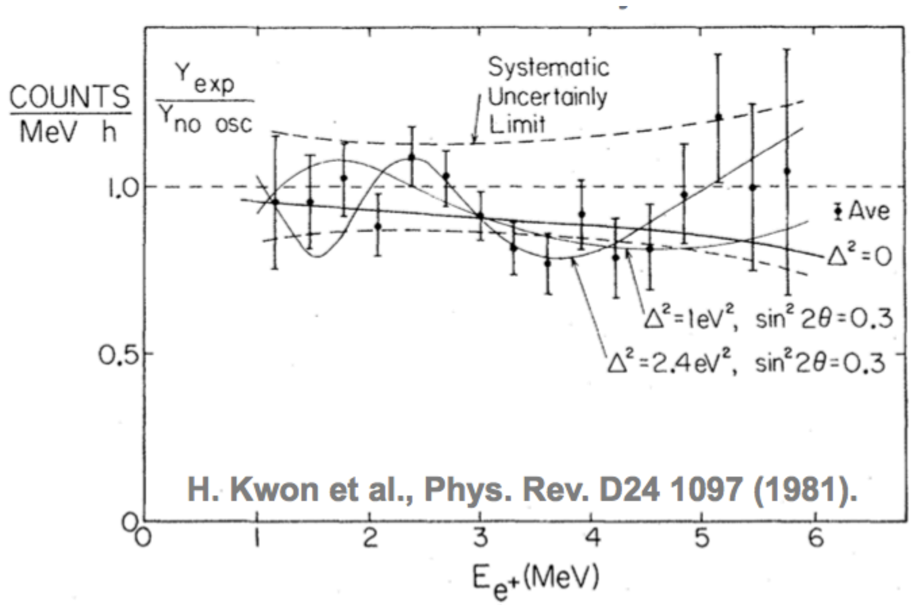
Oscillation parameters for sterile ν's



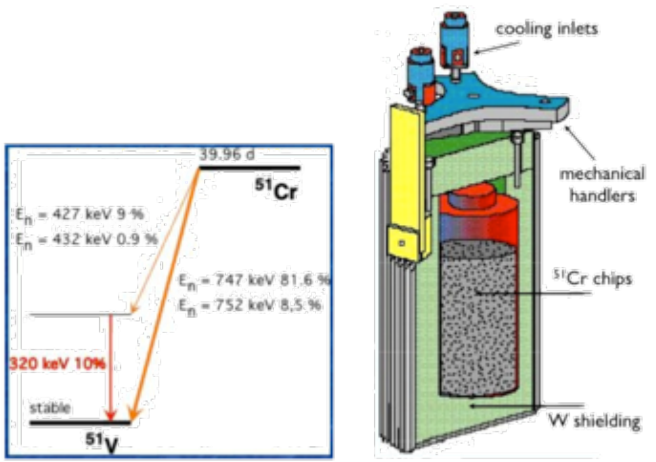
Sterile Neutrinos: $P_{ee}(L)$



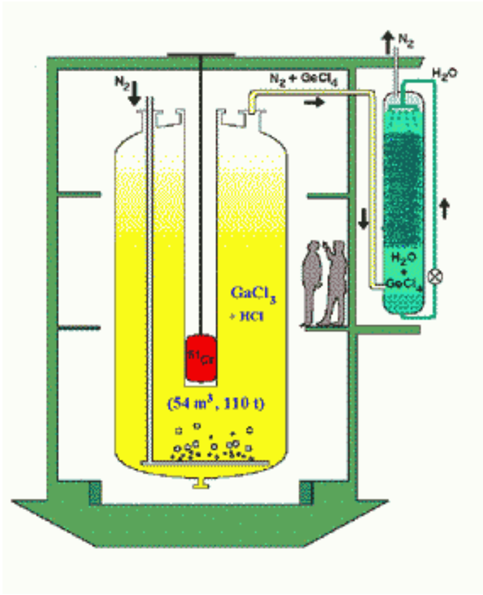
Neutrino spectrum at ILL experiment



EC neutrino source: ^{51}Cr

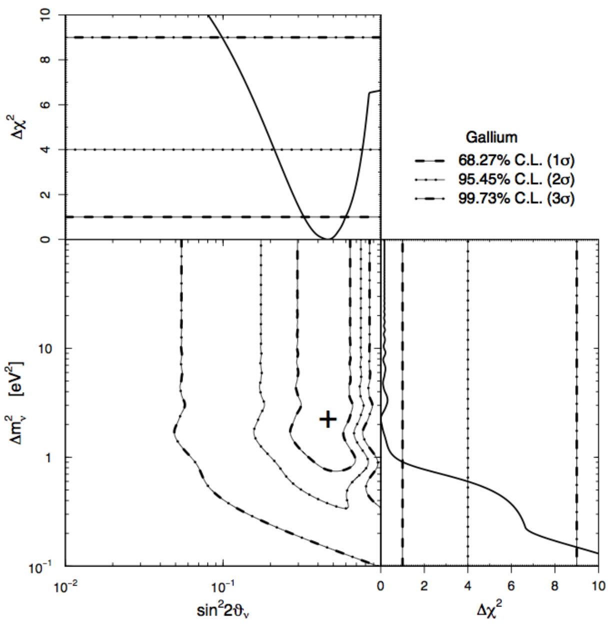


Calibration of the GALLEX experiment



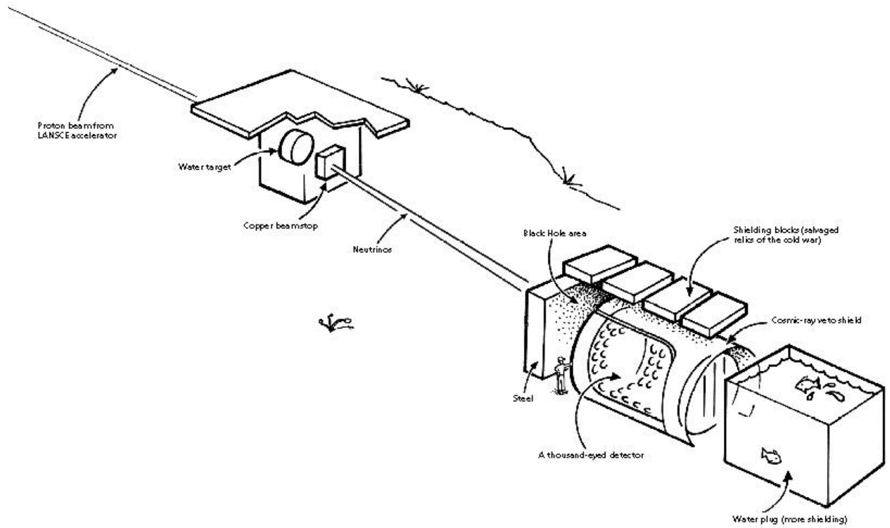
3.2 Sterile Neutrinos

Oscillation parameters from Gallium anomaly



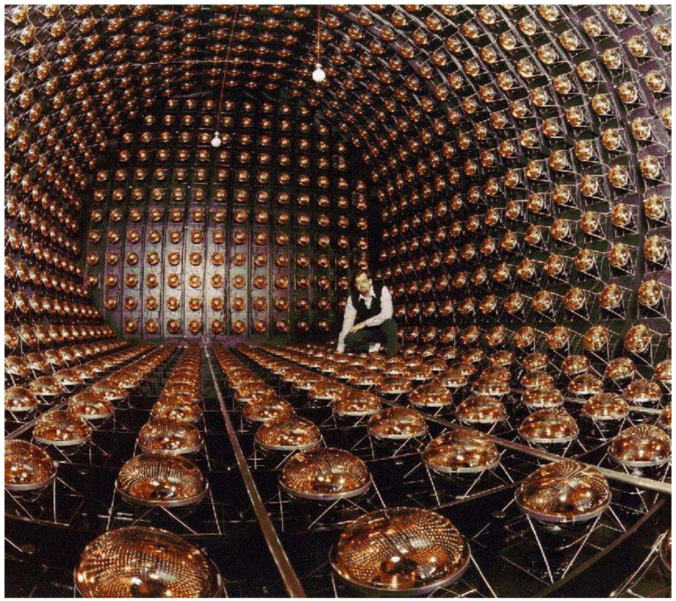
3.2 Sterile Neutrinos

LSND experimental setup



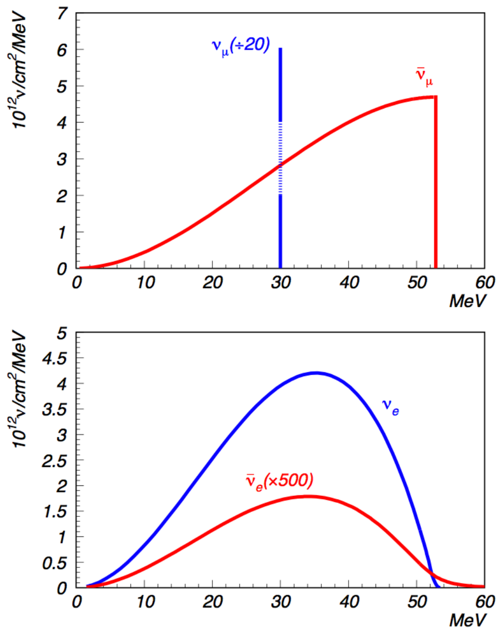
3.2 Sterile Neutrinos

LSND detector view

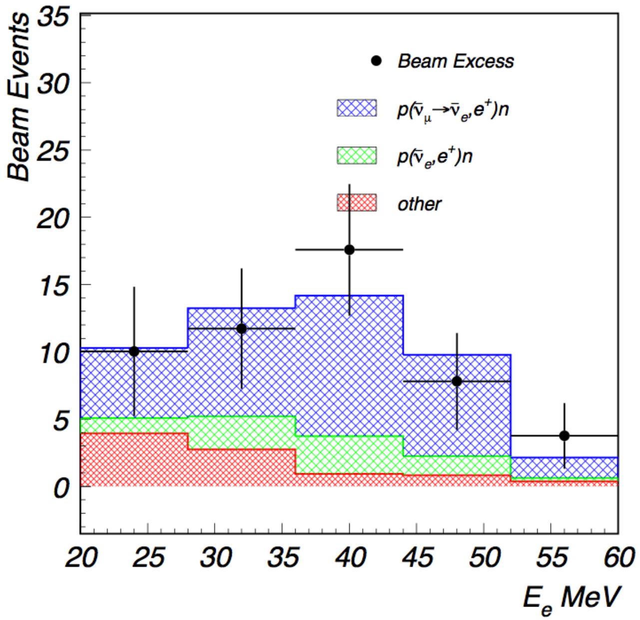


3.2 Sterile Neutrinos

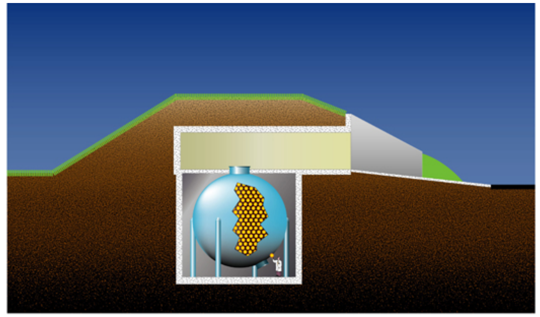
LSND beam spectrum

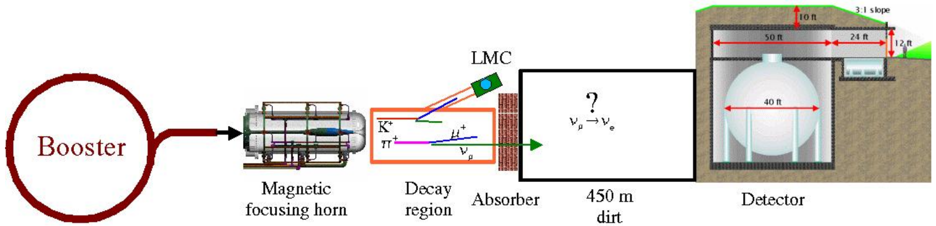


LSND result

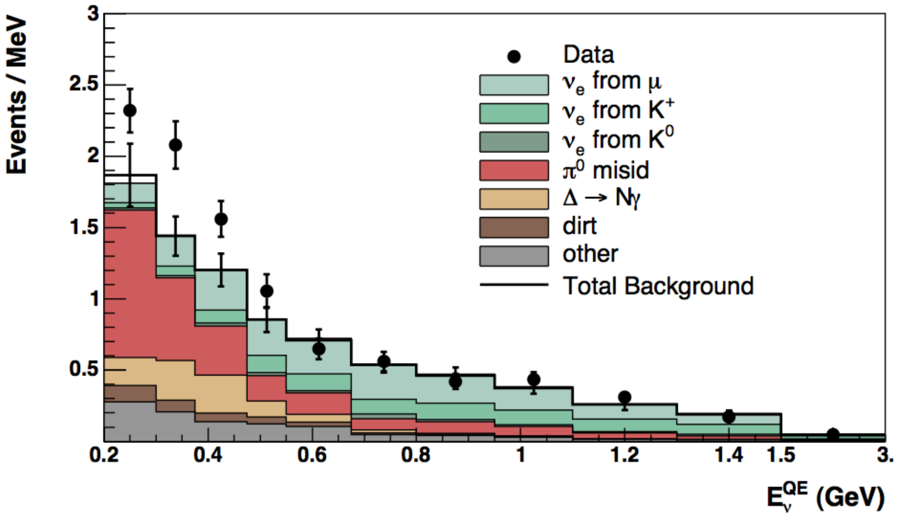


MiniBooNE beam setup

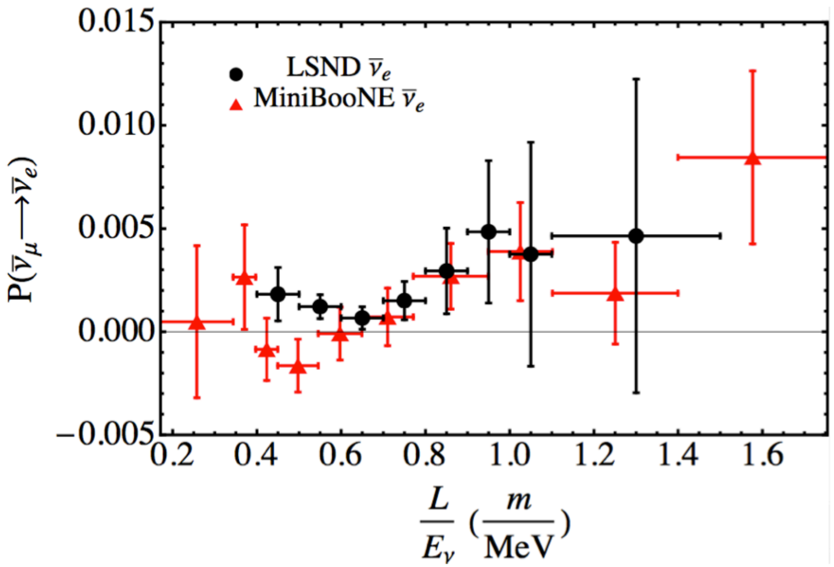




MiniBOONE ν_e-excess

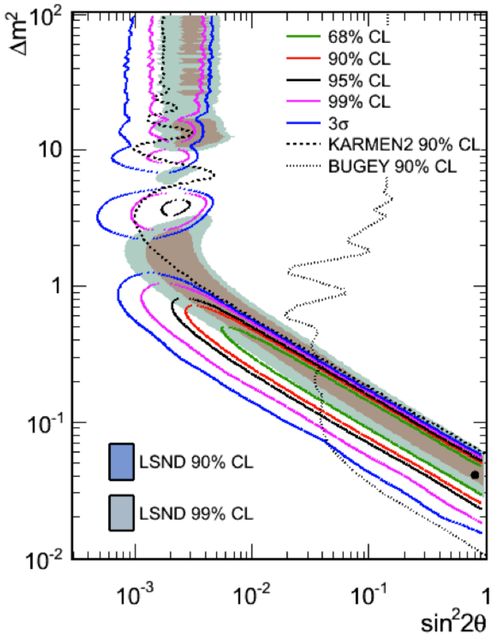


LSND + MiniBooNE L/E analysis



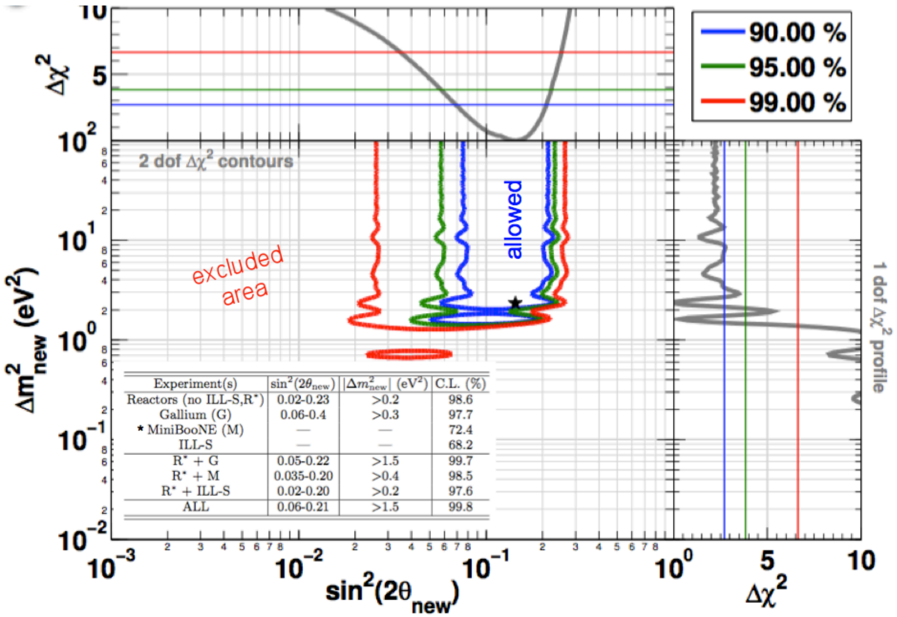
3.2 Sterile Neutrinos

LSND + MiniBooNE oscillation parameters



3.2 Sterile Neutrinos

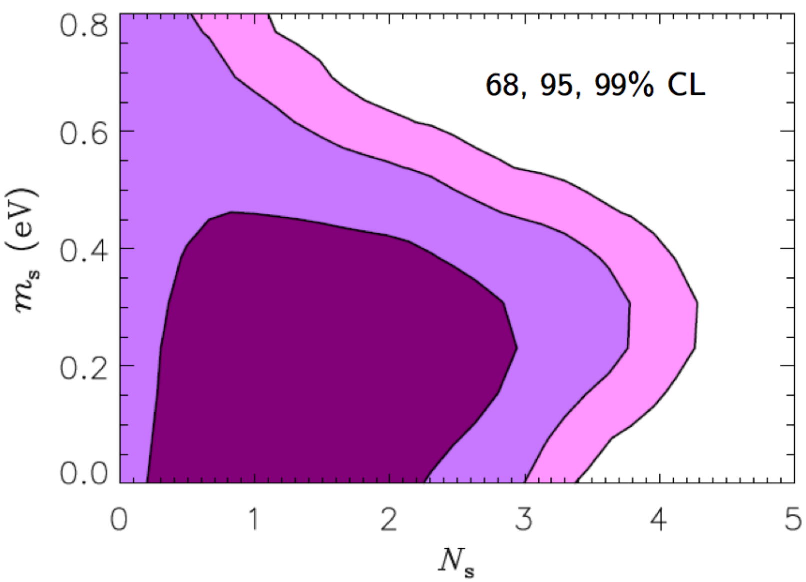
Oscillation parameters for all experiments



Experiment(s)	$\sin^2(2\theta_{new})$	$\lvert\Delta m^2_{new}\rvert$ (eV^2)	C.L. (%)
Reactors (no ILL-S,R*)	0.02-0.23	>0.2	98.6
Gallium (G)	0.06-0.4	>0.3	97.7
★ MiniBooNE (M)	—	—	72.4
ILL-S	—	—	68.2
R* + G	0.05-0.22	>1.5	99.7
R* + M	0.035-0.20	>0.4	98.5
R* + ILL-S	0.02-0.20	>0.2	97.6
ALL	0.06-0.21	>1.5	99.8

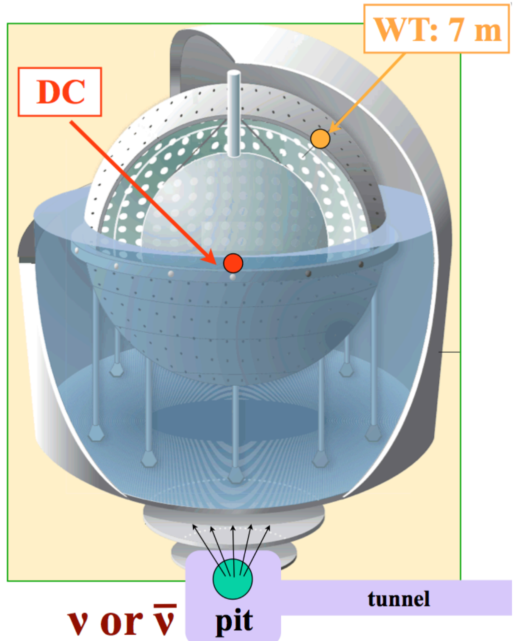
3.2 Sterile Neutrinos

Input from cosmology: ν_s number/mass

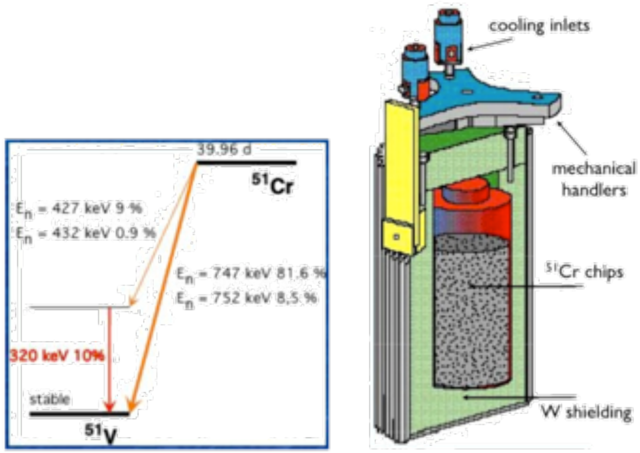


3.2 Sterile Neutrinos

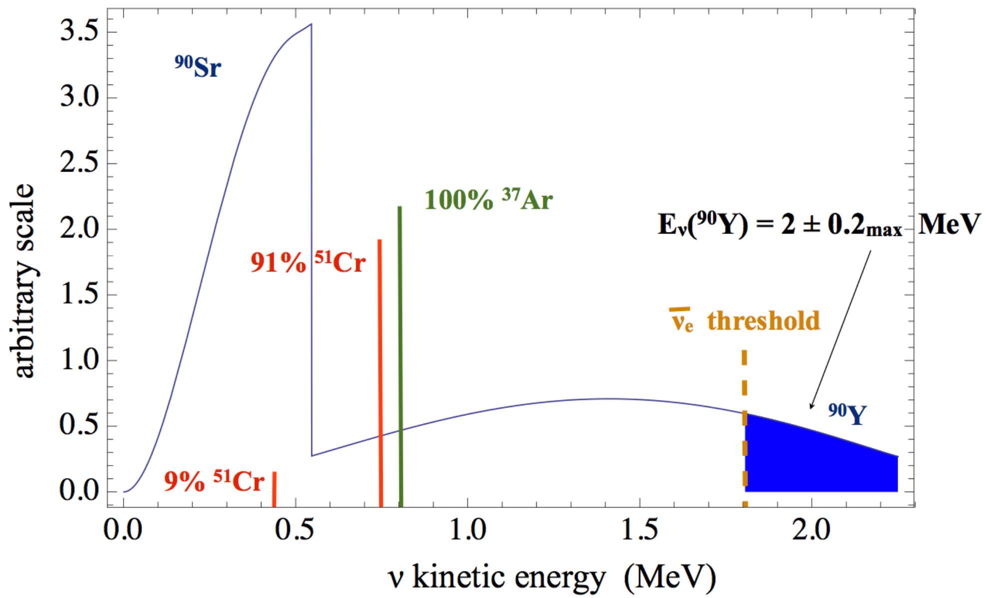
Radioactive source in Borexino (SOX)



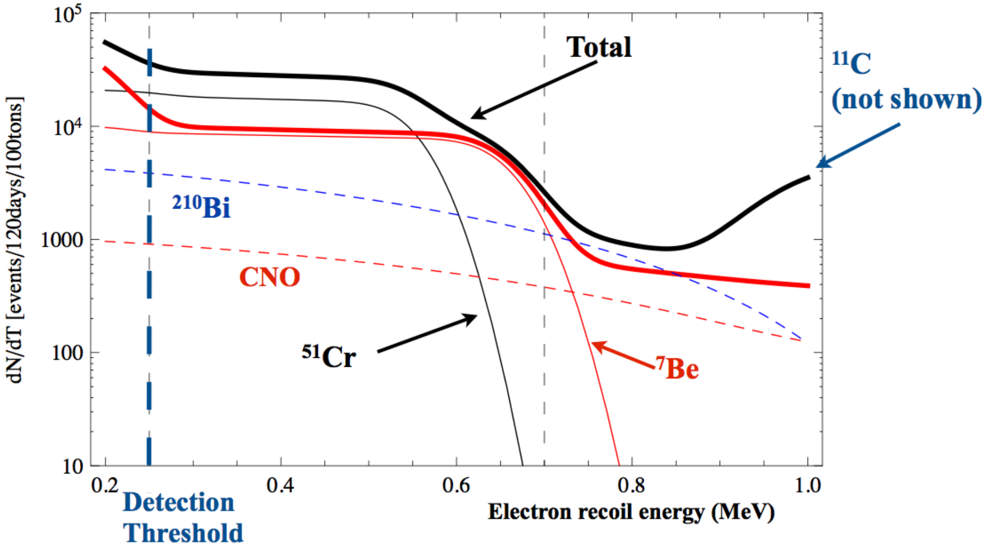
Chromium source (^{51}Cr, EC)



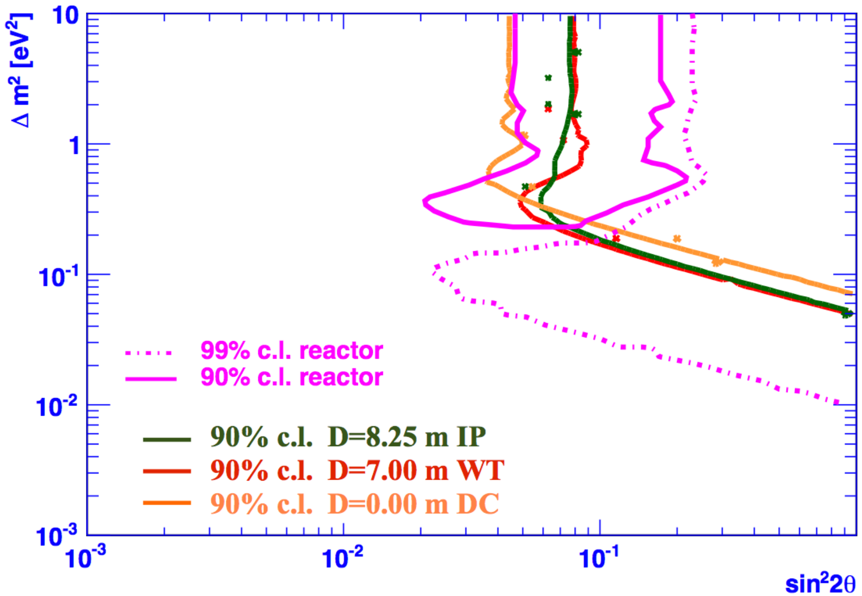
ν-spektra of radioactive sources



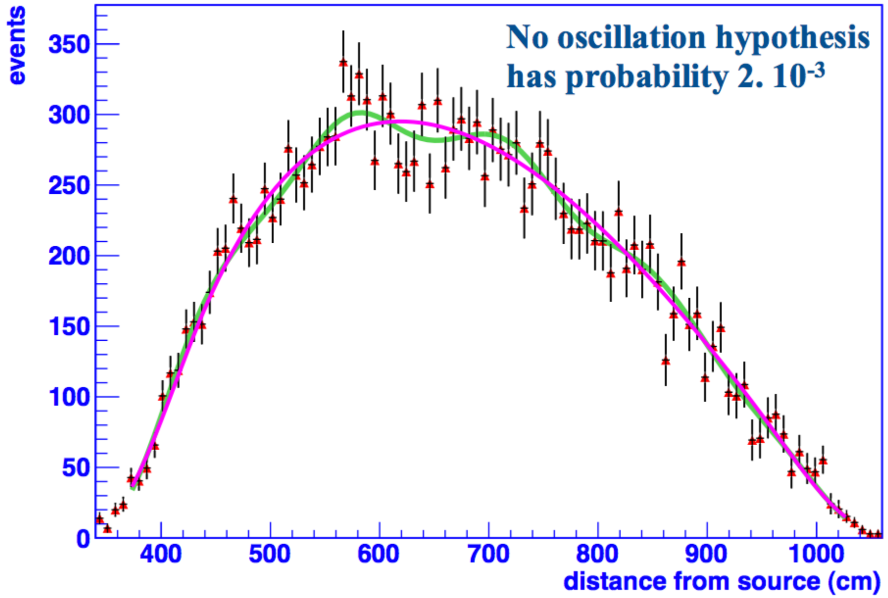
Signal and background spectra



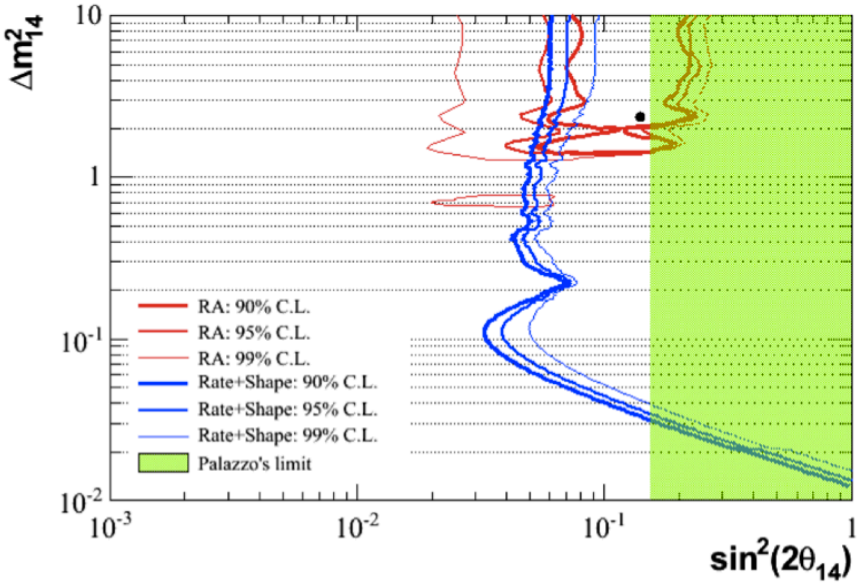
Sensitivity of rate-only analysis



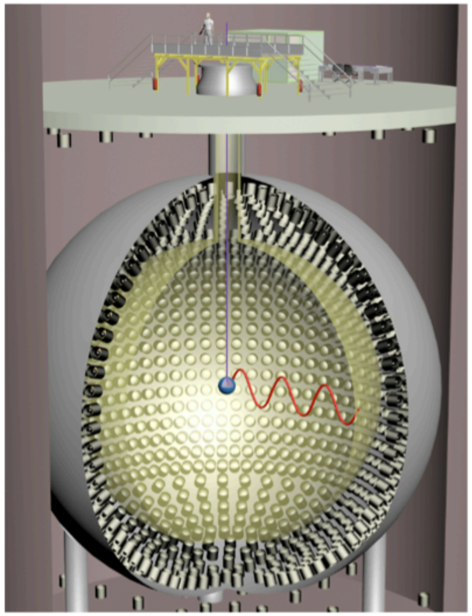
Spatial oscillation pattern $P_{ee}(L)$



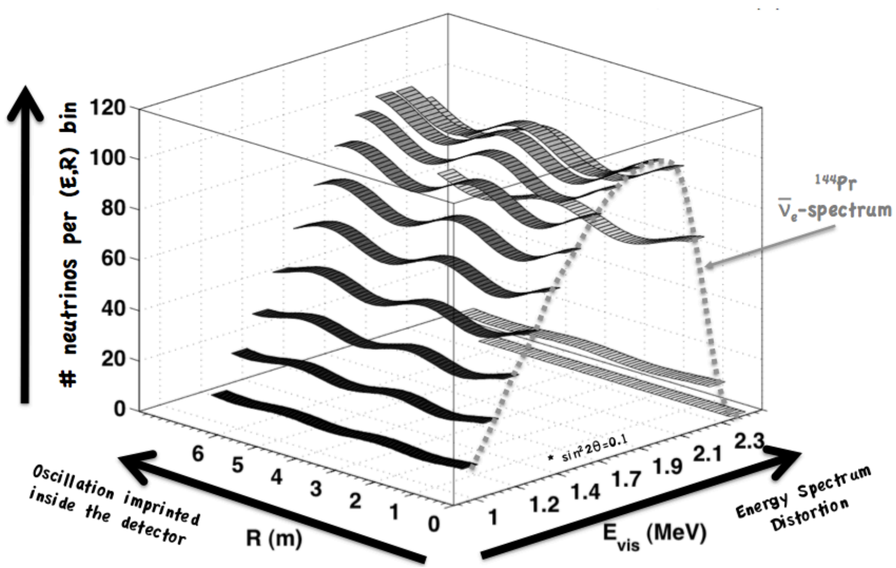
Sensitivity rate+shape analysis



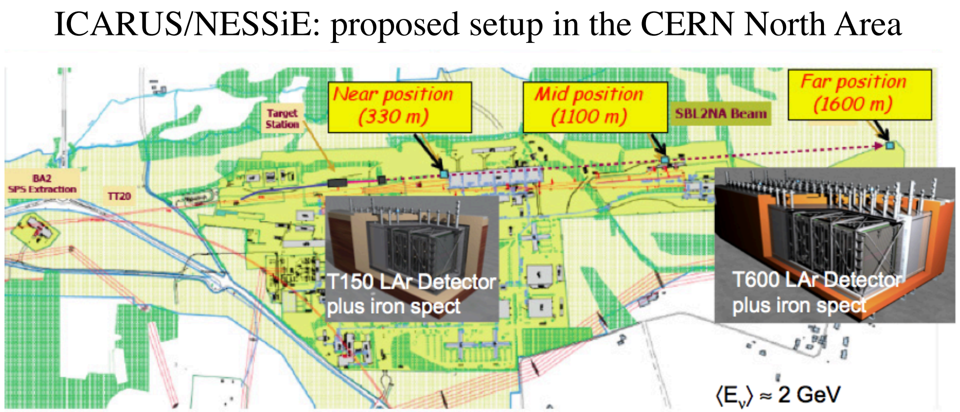
CeLAND – Antineutrino source at center



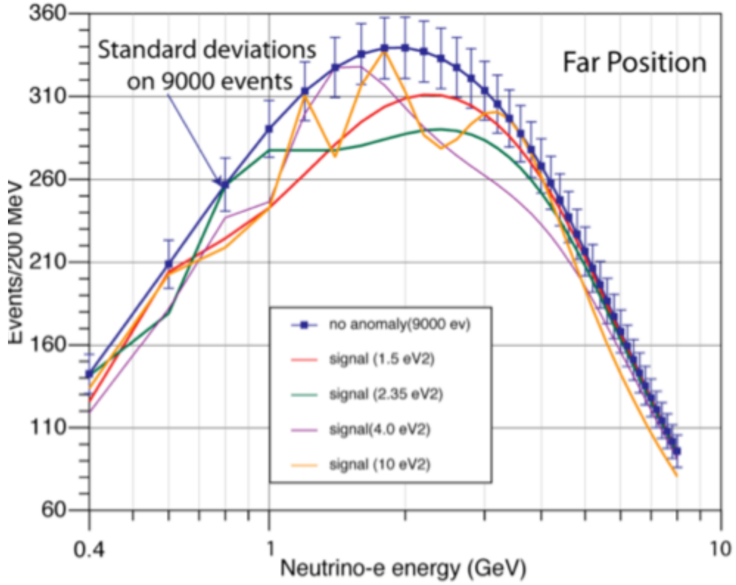
Oscillation pattern for antineutrinos



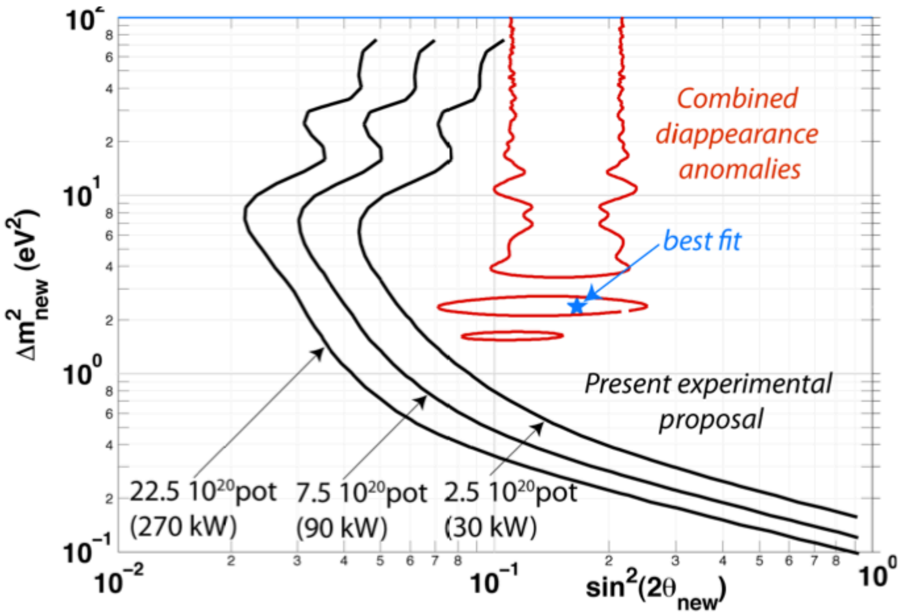
Very short baseline oscillations



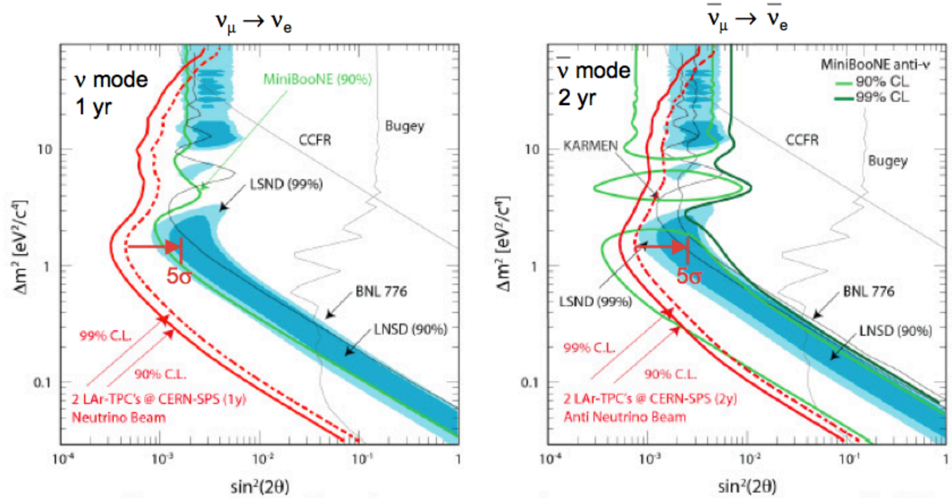
Spectral deformation at far detector



Sensitivity to $\nu_e \rightarrow \nu_s$ disappearance



Sensitivity to $\nu_\mu \rightarrow \nu_e$ appearance



3.2 Sterile Neutrinos

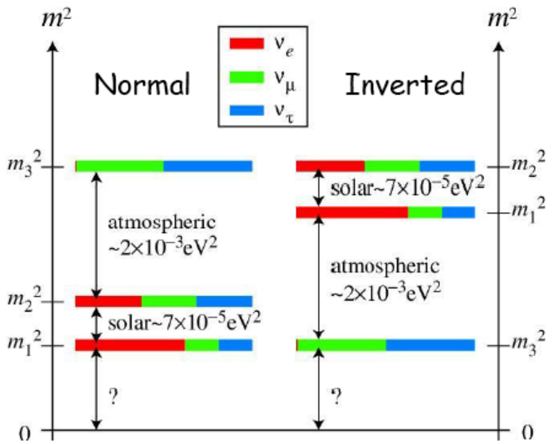
MicroBooNE + LAr1kton setup

proposed setup at Fermilab

3.3 Direct neutrino mass measurements

3.3 Direct neutrino mass measurements

Neutrino mass hierarchy



Normal hierarchy

$$m_1 = 0$$
$$m_2 = \sqrt{\Delta m^2_{\rm sol}} = 9\,\mathrm{meV}$$
$$m_3 = \sqrt{\Delta m^2_{\rm atm}} = 50\,\mathrm{meV}$$

Inverted hierarchy

$$m_3 = 0$$
$$m_1 = \sqrt{\Delta m^2_{\rm atm}} = 50\,\mathrm{meV}$$
$$m_2 = \sqrt{\Delta m^2_{\rm atm}} + \sqrt{\Delta m^2_{\rm sol}} = 59\,\mathrm{meV}$$

3.3 Direct neutrino mass measurements

Ways to determine the neutrino mass

- beta-decay endpoint measurements
- neutrino-less double-beta decay
- cosmology

Beta decay

- Decay energy

$$E_0 = m(Z,A) - [m(Z+1,A) + m_e + m_\nu]$$

- Decay probability: Fermi‘s Golden Rule

$$\frac{\mathrm{d}^2N}{\mathrm{d}t\mathrm{d}E} = \frac{2\pi}{\hbar}|\langle f|H|i\rangle|^2 \cdot \rho(E) \cdot F(Z,E)$$

E	kinetic energy of the electron
E_e	total energy of the electron, $E_e = m_e + E$
$\langle f\|H\|i\rangle$	transition matrix element
H	weak Hamilton operator
$\rho(E)$	density of final states
$F(Z,E)$	Fermi function (corrects for Coulomb effects of nucleus on $e^\pm$

Phase space factor

- of electron

$$\mathrm{d}n_e = \frac{V\cdot 4\pi p_e^2 \mathrm{d}p_e}{h^3} = \frac{V\cdot 4\pi p_e E_e \mathrm{d}E_e}{h^3}$$

- of neutrino

$$\mathrm{d}n_\nu = \frac{V\cdot 4\pi p_\nu^2 \mathrm{d}p_\nu}{h^3} = \frac{V\cdot 4\pi p_\nu E_\nu \mathrm{d}E_\nu}{h^3}$$

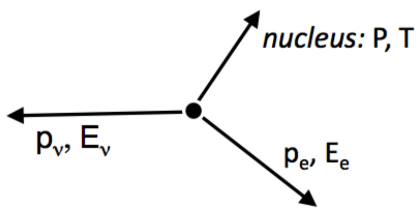
- combined

$$\rho(E) = \frac{\mathrm{d}^2 n}{\mathrm{d}E_e\mathrm{d}E_\nu} = \frac{16\pi^2V^2}{h^6} p_e E_e \cdot p_\nu E_\nu \cdot 2$$

Kinematics and phase space factor

- Energy and momentum conservation

$$\begin{aligned} \vec{P} + \vec{p}_e + \vec{p}_\nu &= 0 \\ T + E_\nu + E &= E_0 \end{aligned}$$



- For massless neutrino (m_ν=0)

$$p_\nu = \frac{E_\nu}{c} = \frac{E_0 - E}{c}$$

- Applying kinematic bounds to the phase space factor

$$\rho(E) = \frac{32\pi^2V^2}{h^6} p_e(E+m_e)(E_0-E)^2$$

Matrix element and decay probability

- Transition matrix element couples electron, neutrino and nucleus:

$$|\langle f|H|i\rangle|^2 \approx g^2|\Phi_e(0)|^2|\Phi_\nu(0)|^2|\mathcal{M}_{if}|^2 \approx g^2\frac{1}{V^2}|\mathcal{M}_{if}|^2$$

g	weak coupling constant
$\Phi_e(0), \Phi_\nu(0)$	fermion wave functions inside the nucleon, $\|\Phi\|^2 \propto V^{-1}$
$\mathcal{M}_{if}$	nuclear matrix element

- Inserting phase space and matrix element result into Fermi‘s Golden Rule, one obtain the decay probability

$$\frac{\mathrm{d}^2N}{\mathrm{d}t\mathrm{d}E} = \frac{g^2}{2\pi c^3\hbar^7}|\mathcal{M}_{if}|^2 \cdot p_e(E+m_e)(E_0-E)^2 \cdot F(Z,E)$$

Matrix element and decay probability

- Transition matrix element couples electron, neutrino and nucleus:

$$|\langle f|H|i\rangle|^2 \approx g^2|\Phi_e(0)|^2|\Phi_\nu(0)|^2|\mathcal{M}_{if}|^2 \approx g^2\frac{1}{V^2}|\mathcal{M}_{if}|^2$$

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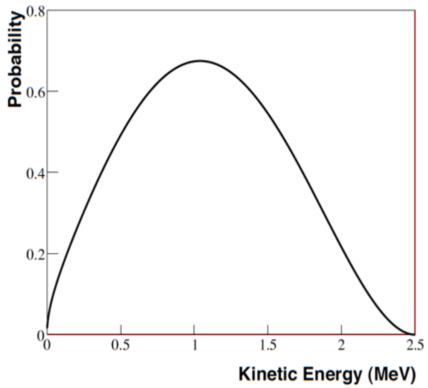
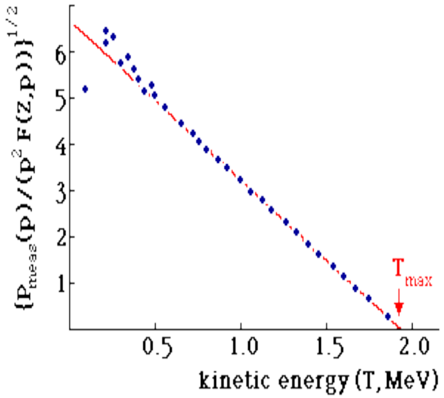
Kurie plot for beta-decay spectrum





Beta decay spectrum → Kurie plot

$$\sqrt{\frac{N(p_e)}{p_e^2F(Z,E)}} = B\cdot(E_0-E)$$

Influence of non-zero neutrino mass

A non-zero mass becomes visible as an increased slope close to the endpoint E_0.

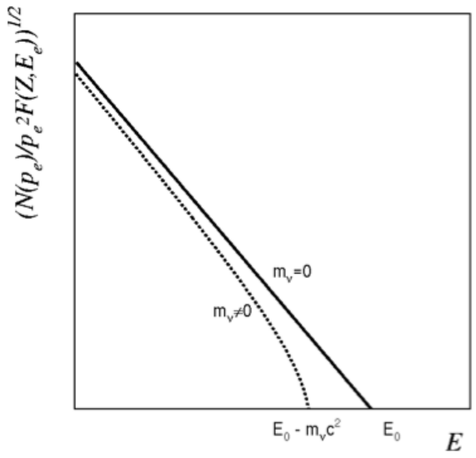
If $m_\nu > 0$: $p_\nu = \sqrt{E_\nu^2 - m_\nu^2}$ and

$$\rho(E) = \frac{V^2}{4\pi^4\hbar^6}\cdot p_e(E+m_e)\cdot(E_0-E)\sqrt{(E_0-E)^2-m_\nu^2}$$

Therefore, a deforming term is added to the Kurie diagram:

$$\sqrt{\frac{N(p_e)}{p_e^2F(Z,E)}} = B\cdot(E_0-E)\cdot\sqrt[4]{1-\left(\frac{m_\nu}{E_0-E}\right)^2}$$

Kurie plot for non-zero neutrino mass



→ The effect of m_ν becomes visible if $E_0 - E \approx m_\nu$, so close to the spectral endpoint.

→ For β-decay experiments, it is important that the spectral shape is changed. In principle, no exact knowledge of E_0 is needed.

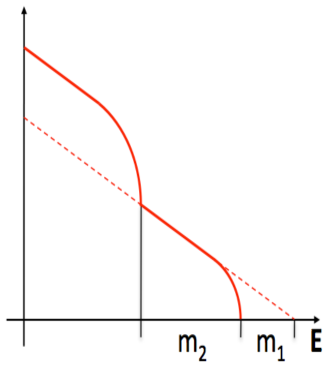
Influence of neutrino mass eigenstates

The ν_e from β-decay can be observed in 1 of the 3 mass eigenstates:

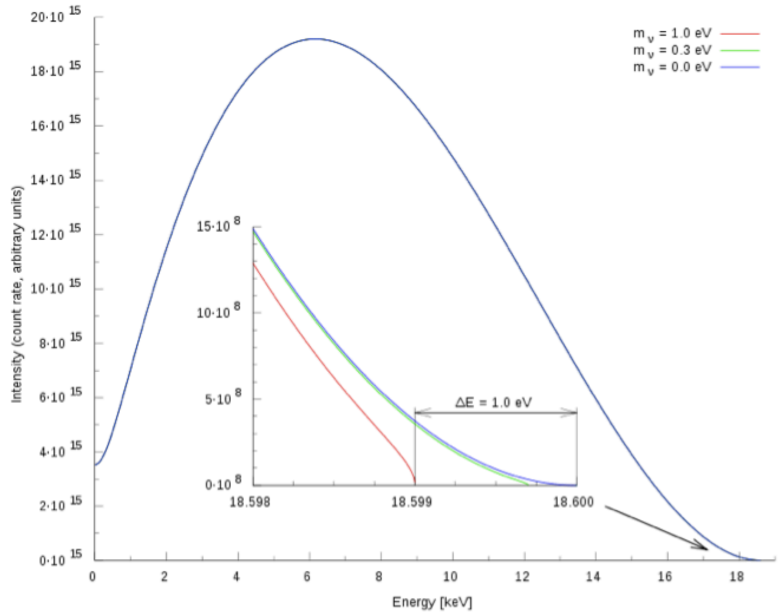
- For a hierarchical ordering of neutrino masses, each m_i corresponds to a kink at $E = (E_0 - m_i)$ close to the spectral endpoint.
- If these difference cannot be resolved, i.e. the neutrino masses are degenerate, the effective ν_e mass measured is the *incoherent* sum of the mass eigenstates

$$m_\beta^2 = \sum_i |U_{ei}|^2 m_i^2$$

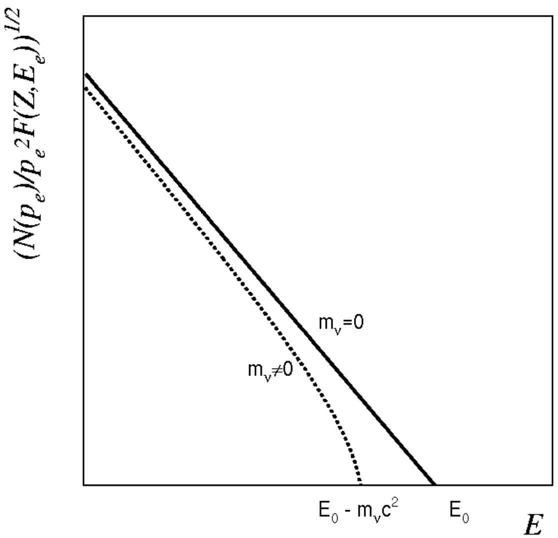
- Additional sterile neutrinos might be detected due to an extra kink at larger neutrino mass



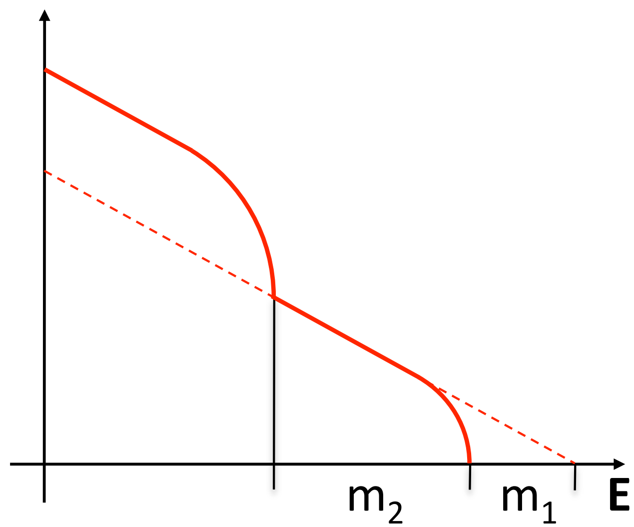
Tritium β-decay spectrum



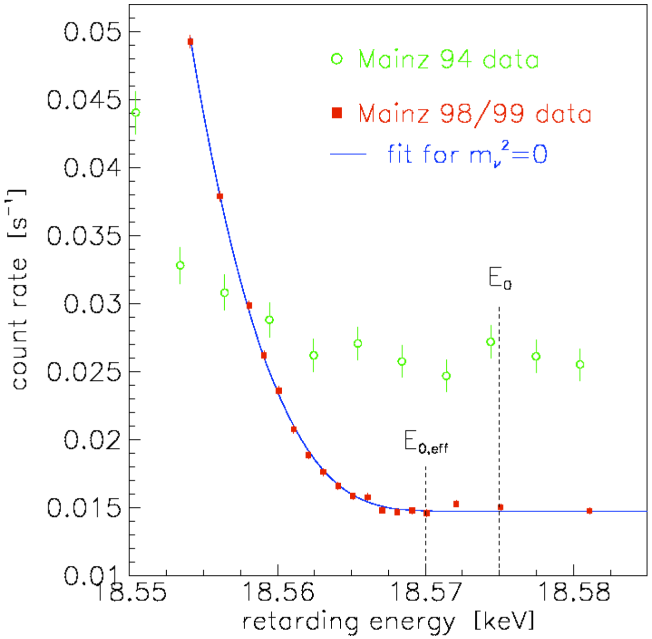
Kurie plot – effect of neutrino mass



Sensitivity to sterile neutrinos

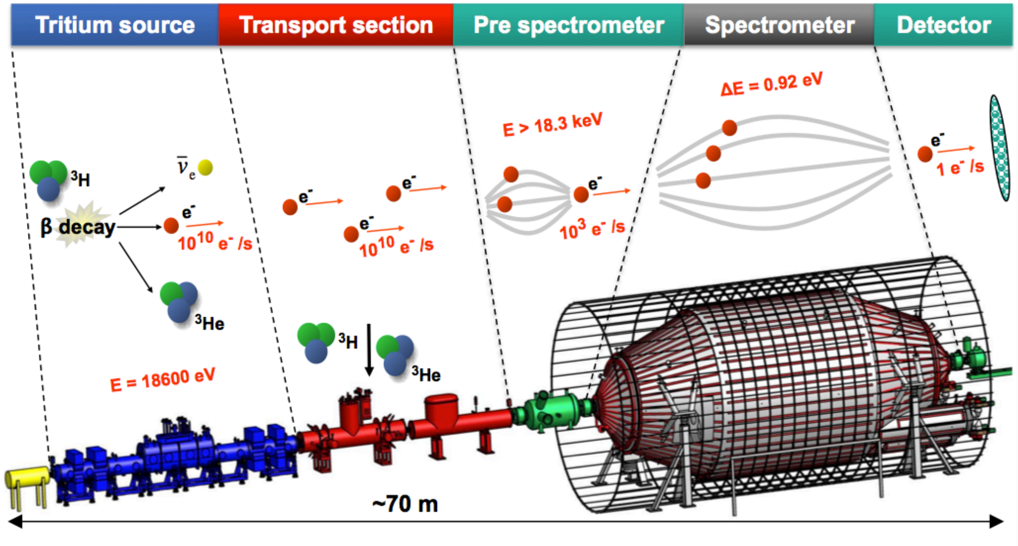


Mainz experimental result

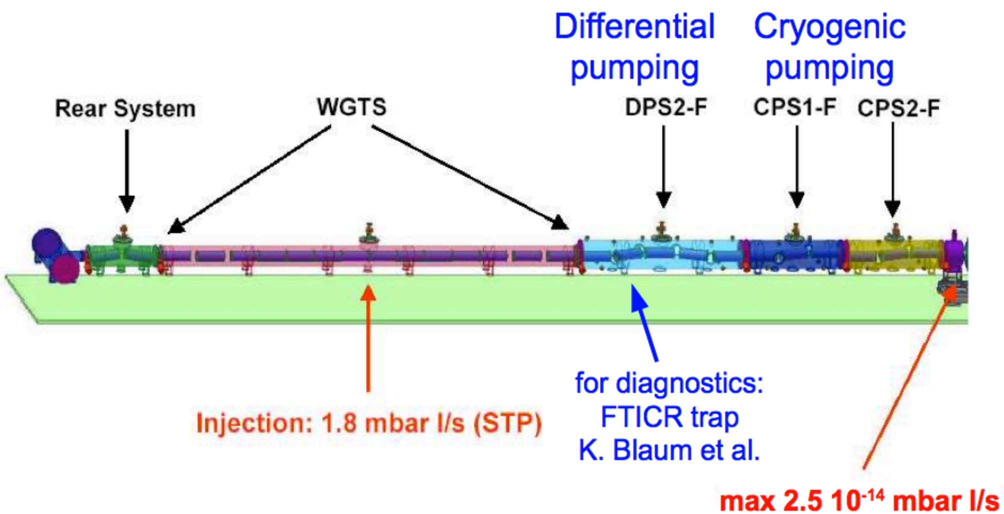


m_ν < 2.2eV (95% C.L.)

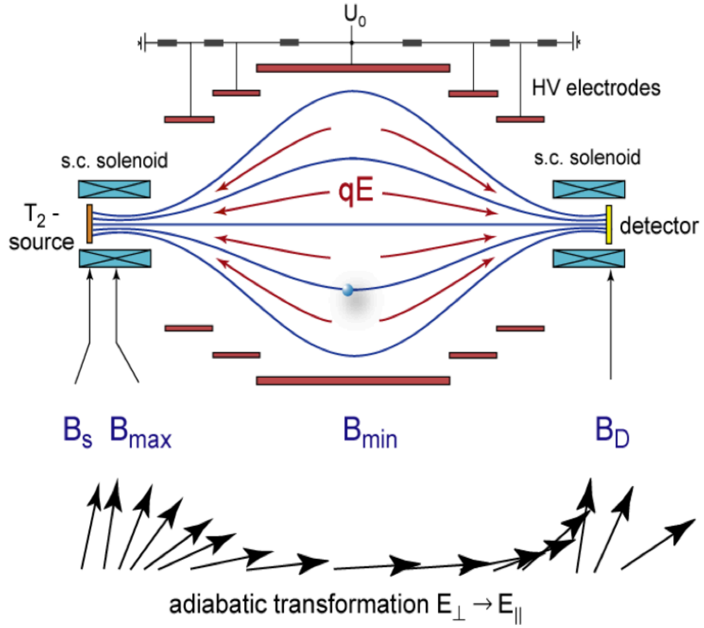
KATRIN Layout



Windowless gaseous tritium source



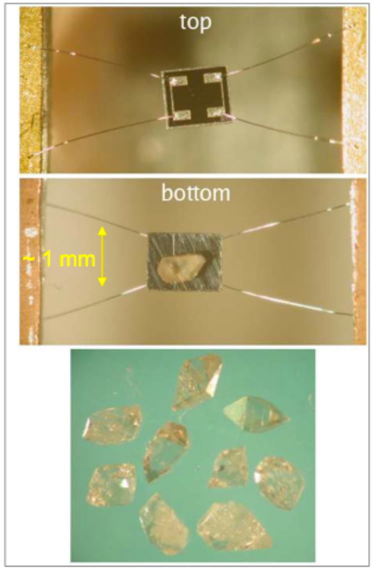
KATRIN: Concept for MAC-E Filter

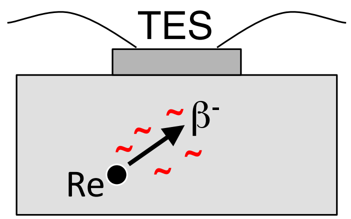


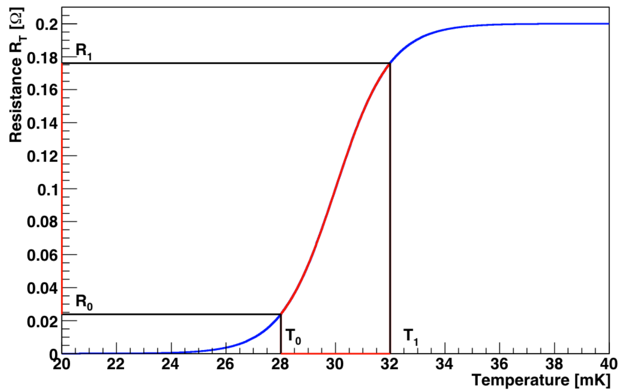
3.3 Direct neutrino mass measurements
KATRIN MAC-E Filter

3.3 Direct neutrino mass measurements
Rhenium crystals

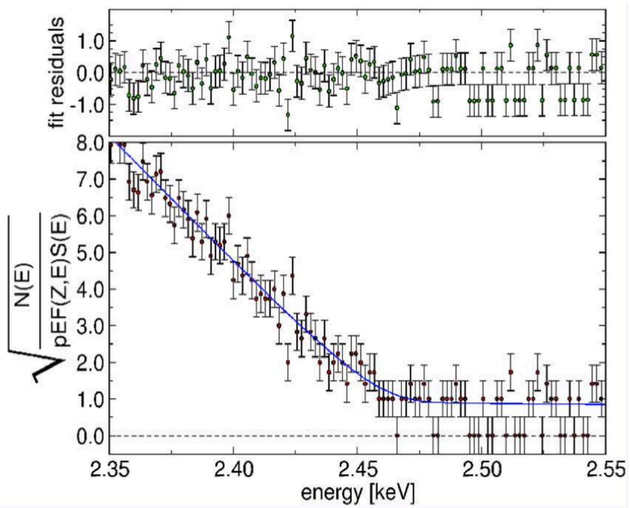
$AgReO_4$ (10 * 250 -350 mg)







3.3 Direct neutrino mass measurements
MIBETA Results



m_ν < 26eV (95% C.L.)