Detecting Sterile Neutrinos with KATRIN

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KATRIN Experiment

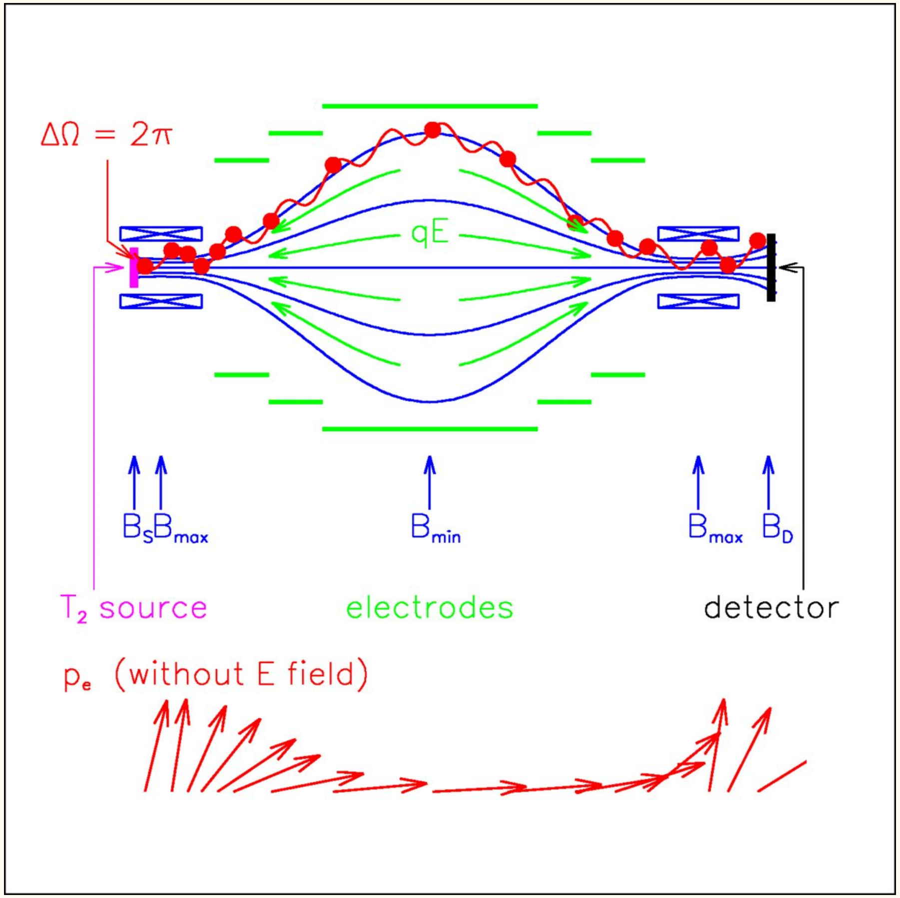
1. Measure the β-spectrum of T-3 β-decay.

$$^{3}\mathrm{T} \rightarrow {}^{3}\mathrm{He} + e^{-} + \overline{\nu}_e$$

2. The end-point of β-spectrum is dependent on mass states of neutrinos.

3. **MAC-E-Filters** - Pass filter integration and/or ToF spectroscopy.

4. Aims to achieve sub-eV E resolution.



Effect of a Sterile on Beta Spectrum

1. Beta decay generates electron neutrinos, which are a superposition of mass eigenstates.

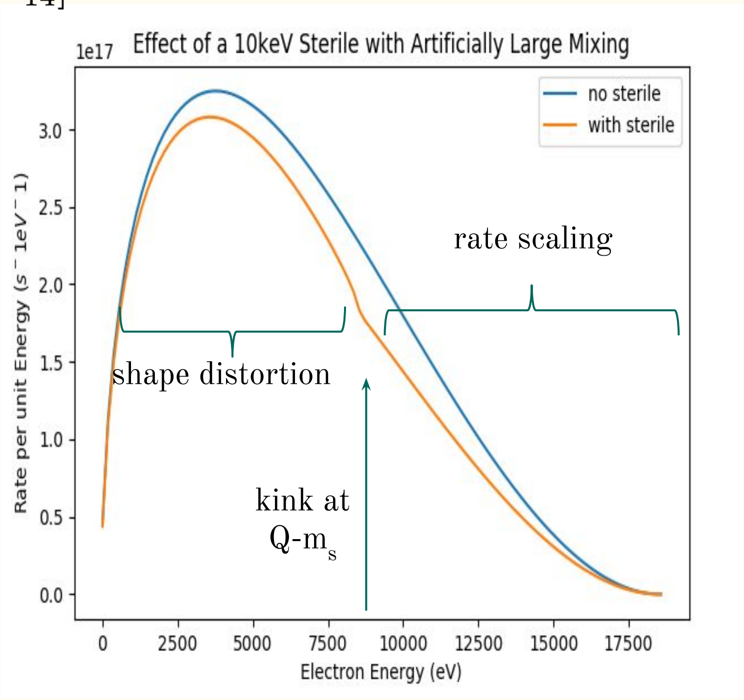
$$\beta(K_e, Q, [U_{ei}], [m_{\nu_i}]) = C \cdot F(Z=2, K_e) E_e p_e \sum_{i,j} [p_i (Q - W_i - Ke) |U_{ej}|^2 \sqrt{(Q - W_i - Ke)^2 - m_j^2}]$$

$$[U_{ei}] = [c_{12} c_{13} c_{14} \quad e^{i\phi_{12}} c_{13} c_{14} s_{14} \quad e^{i\delta_{cp}} s_{13} c_{14} \quad s_{14}]$$

2. The electron energy spectrum is therefore a superposition of spectra from each mass eigenstate.

3. Aside: Assuming $m_1 \approx m_2 \approx m_3 \ll m_s$ the spectrum can be approximated as a sum of two parts, one from decays with an effective active state, and one from decays with a sterile state.

- There is a 'kink' at the sterile mass, of height determined by the $|U_{es}|$
- Below this energy the shape is distorted



(Plot using unrealistically large mixing for visibility)

The Analysis

Analysis Outline

Exclusion Limits from Statistics

- Generate expected spectrum for a given sterile mass, mixing
- Fit the spectrum with the null hypothesis and calculate χ^2
- Perform this for a grid of sterile masses and mixing angles
- Get mass sensitivity from 1-D profile

Preamble

χ^2 Profiles

Goodness of fit is equivalent to the χ^2 of the fit of the binned spectrum to the null hypothesis

$$\sum^{N} \frac{(O_i - E_i(\theta))^2}{\sigma^2} = \chi^2$$

χ^2 increases with mixing angle, as the difference between the two spectra becomes more pronounced.

χ^2 also increases with sterile mass, as a greater span of the spectrum is affected.

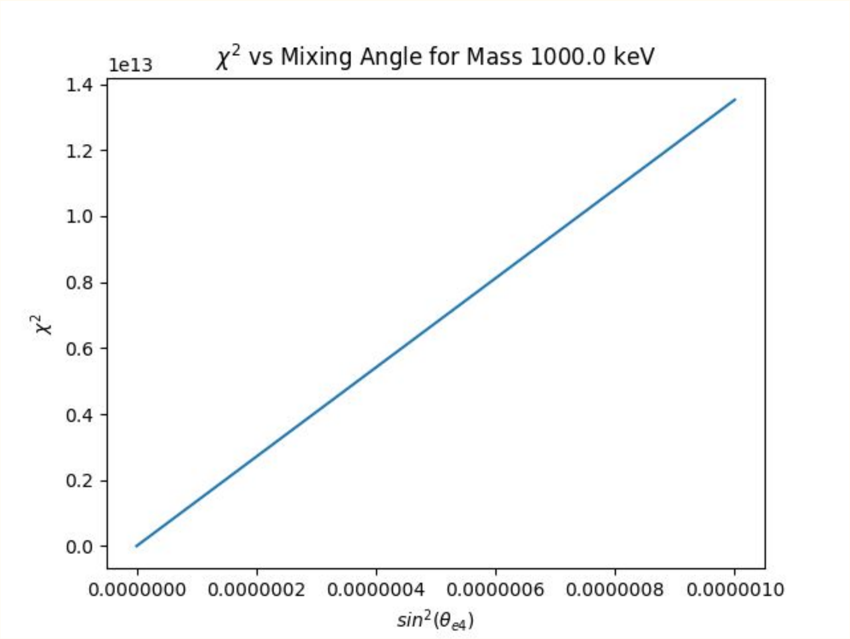
Phase Space Considered

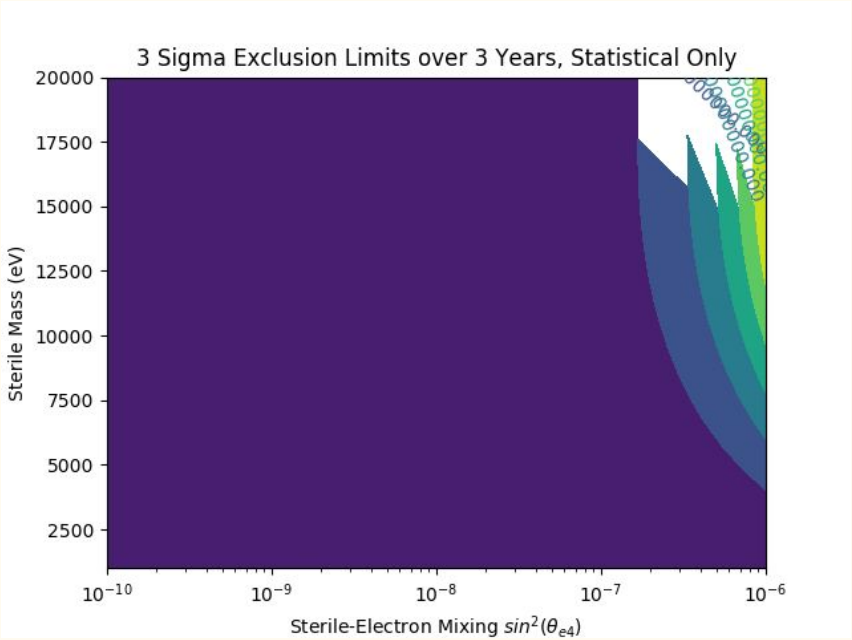
The beta decay spectrum was binned into 100 bins from 0 to the Tritium end-point of 18keV

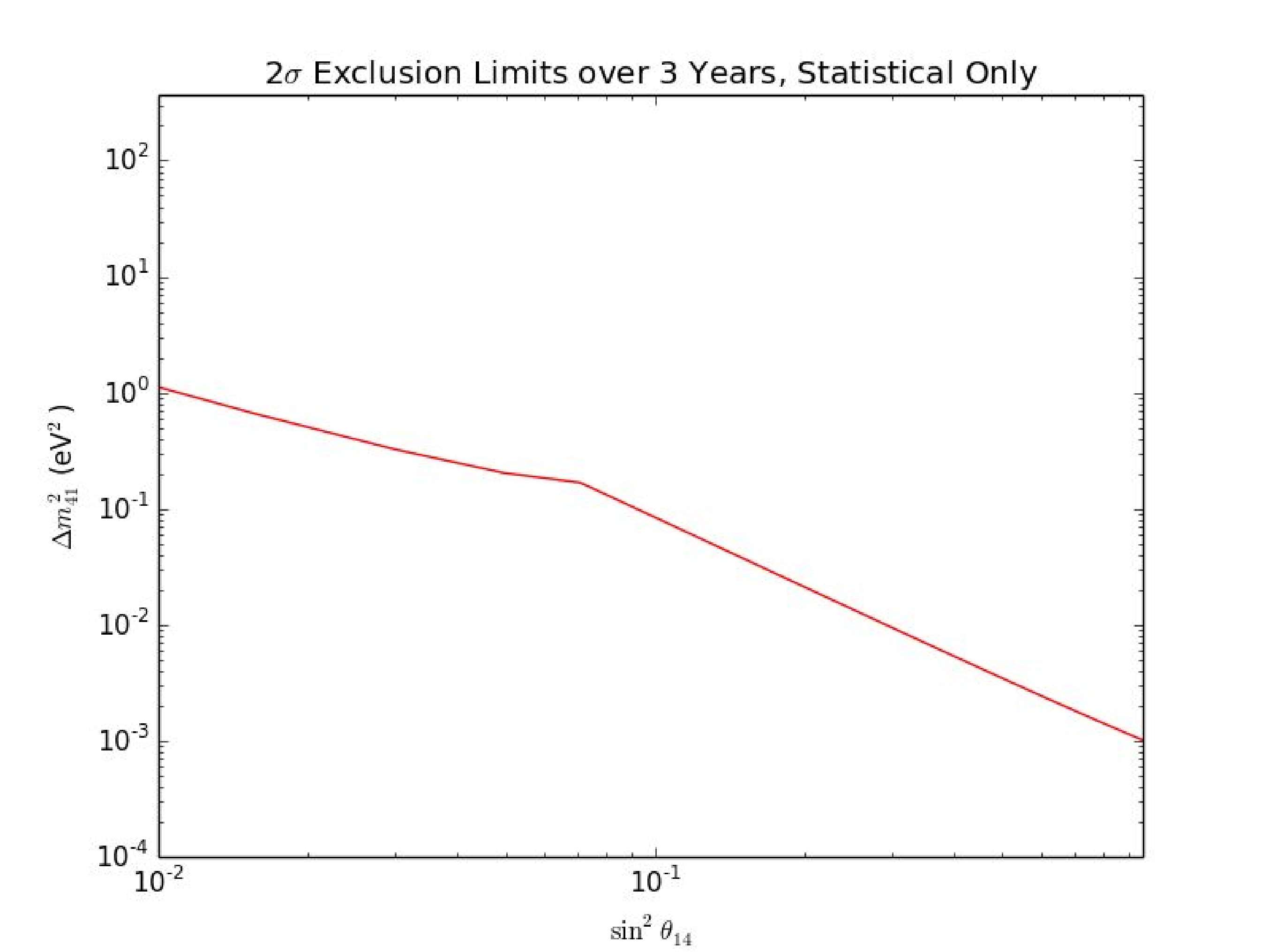
Sterile masses in the range 1-20keV were considered, in 20 steps

The range of sterile mixings considered spanned $10^{-6} \geq \mathrm{Sin}^2(\theta_{e4}) \geq 10^{-10}$ in 30 steps

Exclusion Profiles

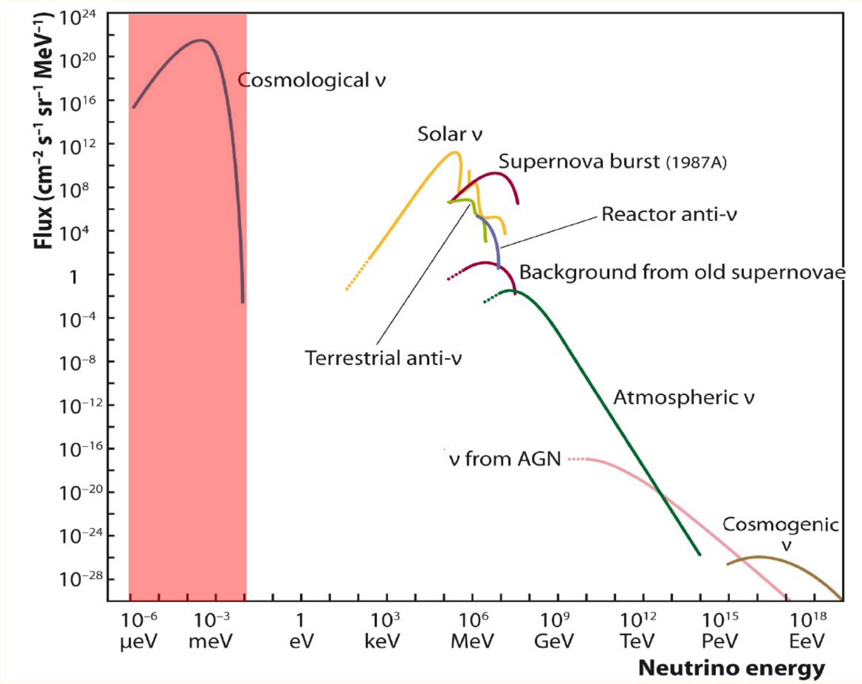






2σ Exclusion Limits over 3 Years, Statistical Only
Δm_{41}^2 (eV^2)
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-2}
10^{-1}
$\sin^2 \theta_{14}$

Search for Relic Neutrinos



The energy scale of relic neutrinos

1. Relic neutrinos (cosmic neutrino background) were generated ~1s after big bang.

2. Average energy ~1e-4 eV.

3. May be detected by β-spectral measurement of neutrino capture:

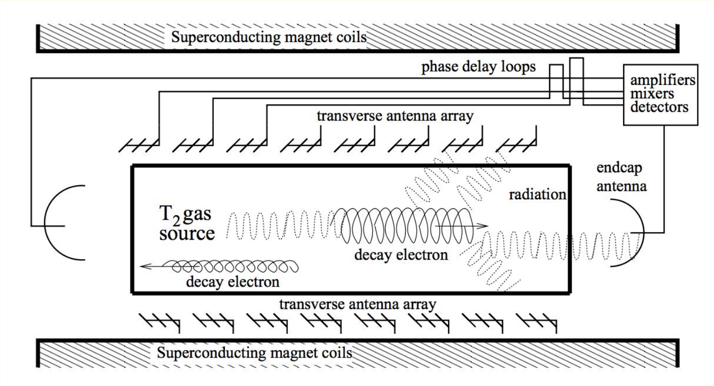
$$\nu_e + {}^3\mathrm{T} \rightarrow {}^3\mathrm{He} + e^-$$

4. The PTOLEMY and Project-8 experiments aim to detect relic neutrinos.

Project-8

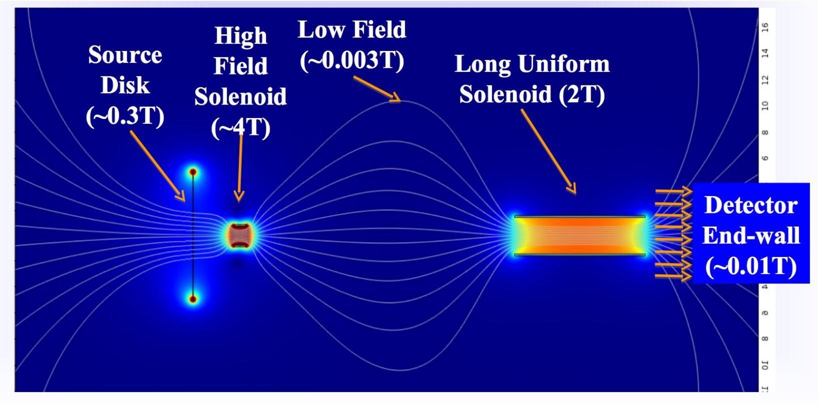
- Measure the cyclotron radiation of β traveling in constant B.
- The frequency of radiation is dependent on Ke

$$f_\gamma \equiv \frac{\omega_c}{2\pi\gamma} = \frac{1}{2\pi} \frac{eB}{m_e + K_e/c^2}$$

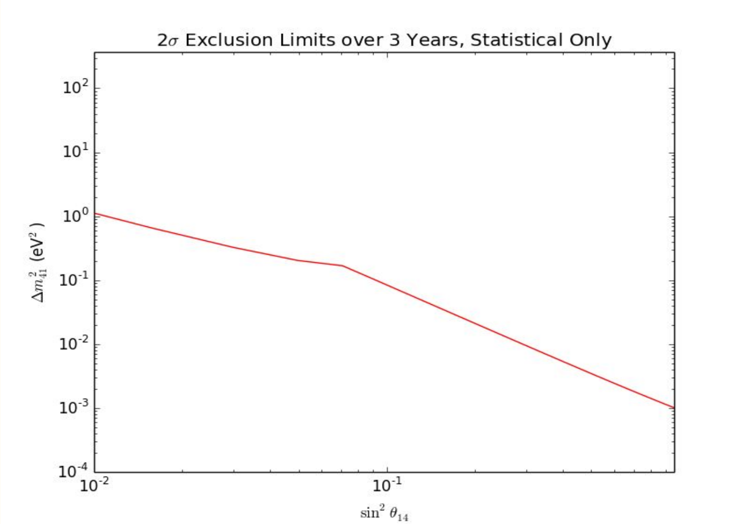


PTOLEMY

- Graphene held atomic tritium target to reduce the energy loss by the scattering in source.
- Use time-of-flight coincidence with the RF cyclotron radiation signal to trigger detection.
- Cryogenic calorimeter as the energy detector.



Conclusions



- From our optimistic contour plot KATRIN will be sensitive to:
  - $\Delta m^2_{41} \gtrsim 10^{-3}$ eV^2
- Multiple sources of systematics would be incorporated into a more complete analysis:
  - Excitations of the daughter nuclei reduce the available energy and shift the effective Q
  - Energy resolution of the MAC-E filter will smear the beta spectrum
  - Accounting for the presence of HT in the T_2 gas
  - Accounting for atomic corrections to the released energy

- **Problems that need to be solved for relic neutrino detection**
  - The E resolution is still too poor relative to the mass of neutrino.
  - The signal of tritium β-decay is now the background of the rare neutrino capture. Background subtraction is must be very effective.