Bounds on sterile neutrino using full kinematic reconstruction of radioactive decays

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Outline

1. Implications for light sterile neutrino
2. Full kinematic reconstruction experiment
   - General consideration
   - Required precision and backgrounds
3. Existing experiments
   - ^{38m}K β decay
   - ^{37}Ar EC decay
4. Conclusions

Reading: Behr, Gwinner, arXiv:0810.3942 [nucl-ex]
FB, Shaposhnikov, PRD,75,053005(2007)

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Standard Model and neutrino masses

SM: gauge bosons: γ, $W^{\pm}$, Z, g; Higgs boson H;

three matter generations: $L = \binom{\nu_L}{e_L}$, e_R; $Q = \binom{u_L}{d_L}$, d_R, u_R

- Describes
  - all experiments dealing with electroweak and strong interactions
- Does not describe
  - Neutrino oscillations
  - Dark matter (Ω_{DM})
  - Baryon asymmetry
  - Dark energy (Ω_Λ)
  - Inflation
  - Gravity
- A lot can be explained by just adding three singlet neutrinos—νMSM

Asaka, Shaposhnikov, 05

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  Asaka, Shaposhnikov, 05

The scales for see-saw (νMSM)

The active neutrino masses m_ν are expressed from the Dirac masses m_D and singlet neutrino Majorana masses M by *see-saw* formula

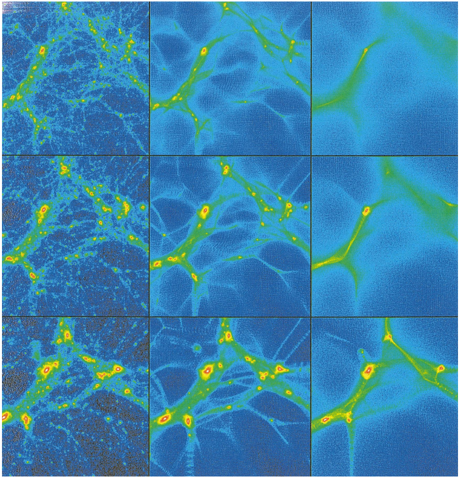
$$m_\nu = \frac{m_D}{M^2}$$

Two “natural” options:

- All the Yukawa couplings are of the same order.
  Then the new energy scale is introduced for the singlet neutrinos, $M \sim 10^{10} - 10^{15}$ GeV.
- $M \sim$ SM scale, but the Yukawa couplings (or m_D) are very small

Sterile neutrino Dark Matter

2-50 keV sterile neutrino is a natural Warm Dark Matter candidate



The evolution of the particle distributions in phase space. A small halo of mass $2 \times 10^{11} h^{-1} M_{\odot}$ has been selected for comparative study in (left to right) ΛCDM, ΛWDM, and ΛWDM power spectrum but without thermal velocities. From bottom to top: $Z = 8$, 1, and 0.

Bode, Ostriker, Turok'01

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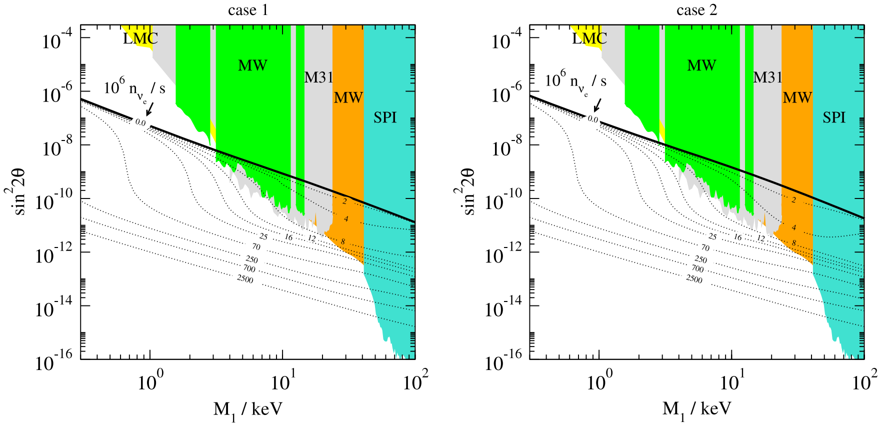
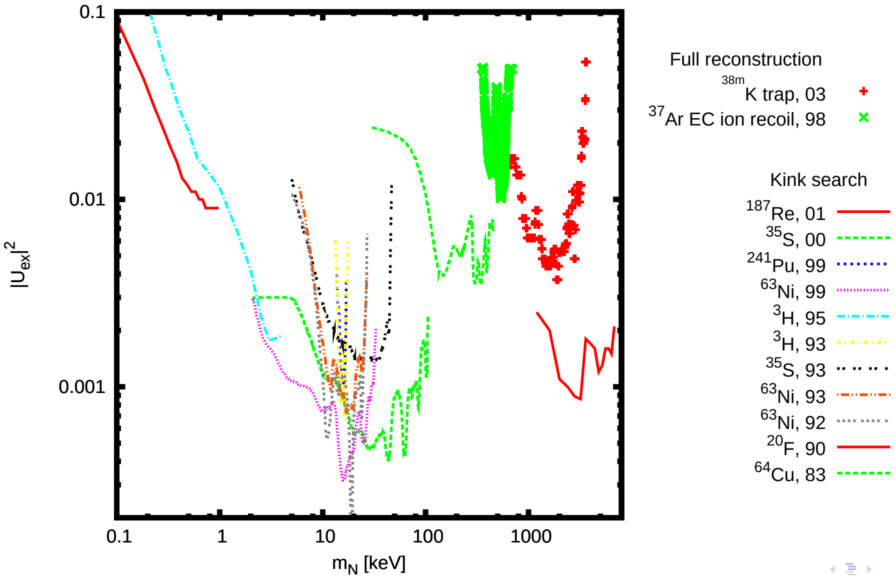


Asaka, Shapohnikov 05; Laine, Shaposhnikov 08

Existing sterile ν bounds



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Possibilities of (light) sterile neutrino search

- *Creation* and *detection* in the lab
- Creation somewhere and *detection* in the lab
- *Creation* in the lab without subsequent detection

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Creation and detection

Suppressed by mixing angle θ^4

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X-ray experiments

Sterile N in the DM clouds decay by the channel $N \to \nu\gamma$ providing the X-ray line with $E_\gamma = M/2$.
Limit on θ^2 can be deduced as far as Ω_{DM} is known

- *Creation* in the lab without subsequent detection

Possibilities of (light) sterile neutrino search

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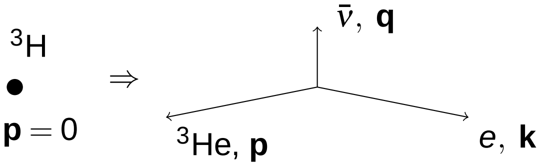
- Forbidden decays
- Decay kinematics

Partial kinematics: kink search in electron beta decay spectrum.

- Large statistics to see the effect ($\sqrt{N}$ statistical error)
- Excellent theoretical knowledge of the decay spectrum is needed (c.f. 17 keV neutrino “discovery”)

Full kinematics: event-by-event mass measurement!

Beta decay kinematics



Neutrino mass is reconstructed from observed momenta

$$m_\nu^2 = (Q - E_p^{\mathrm{kin}} - E_e^{\mathrm{kin}})^2 - (\mathbf{p} + \mathbf{k})^2$$

For ^{3}H: $Q = 18.591$ keV

- Typical ion energy $E_p^{\mathrm{kin}} \sim 1$ eV or $|\mathbf{p}| \sim 100$ keV
- Typical electron energy $E_e^{\mathrm{kin}} \sim 10$ keV

Possible experimental setup

- Cold and compact ^{3}H source
- Time of flight measurement of the recoil ^{3}He ion, using position sensitive detector for 3d momentum reconstruction
- Electron momentum measurement
  - Time of flight
    - Needs decay moment trigger—Lyman photon from the excited ^{3}He ion ($\sim$25% of the decays)?
  - Spectrometer for the electron energy measurement
    - Electron itself can be used to determine the decay moment.

Required precision of momentum measurement

- To measure $m_\nu \sim \mathrm{keV}$ one needs precision in momentum $\Delta\mathbf{p}, \Delta\mathbf{k} \sim \mathrm{keV}$.
- For ^{3}H decay this means precision $\frac{\Delta p}{p} \sim 1\%$
- For other isotopes $\frac{\Delta p}{p} \sim \frac{\Delta p}{\sqrt{m_e Q}}$
  Isotopes with higher energy release Q require better momentum measurement

Thermal noise

Nonzero thermal velocity $\langle \mathbf{v}^2 \rangle = 3T/M$ of the decaying atom imitates some nonzero neutrino mass in usual beta decays

$$m_\nu^{\text{eff}\,2} \simeq m_\nu^2 + M^2\mathbf{v}^2 - 2M\mathbf{v}(\mathbf{p}+\mathbf{k})$$

Temperature constraint

$$T \lesssim \frac{0.7\times 10^{-3}}{\log(1/\theta^2)} \left(\frac{m_s}{1\text{ keV}}\right)^4 \left(\frac{6\text{ GeV}}{M}\right) \left(\frac{18.6\text{ keV}}{Q}\right)^2 (1\,\mathrm{K})$$

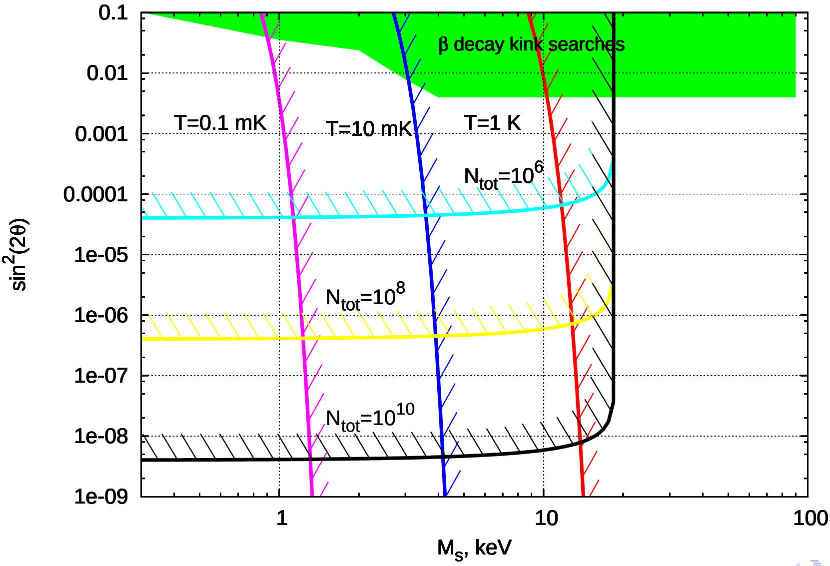
"slow" neutrino cut $(\mathbf{p}+\mathbf{k})^2 \lesssim 3MT$ reduces the constraint

$$T \lesssim \frac{1}{\log(1/\theta^2)} \left(\frac{m_s}{1\text{ keV}}\right)^2 \left(\frac{6\text{ GeV}}{M}\right) (1\,\mathrm{K})$$

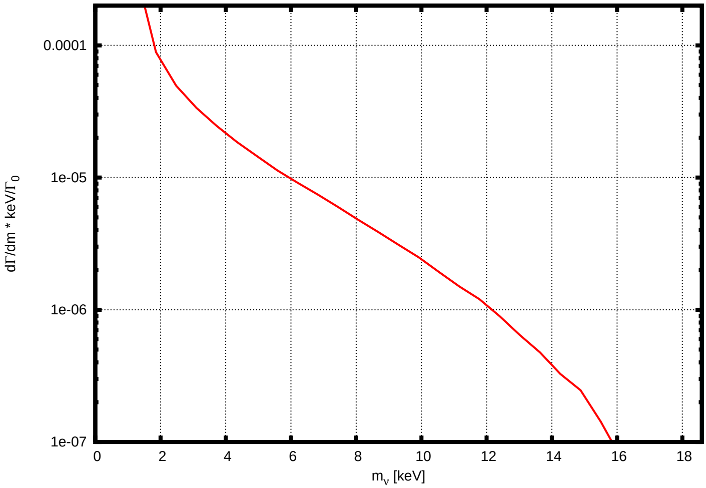
and luminosity… $T \sim 1\,\mathrm{K}$ $\quad Br(\mathbf{p}+\mathbf{k} < 1\,\mathrm{keV}) \sim 3\times 10^{-4}$

$T \sim 0.01\,\mathrm{K}$ $\quad Br(\mathbf{p}+\mathbf{k} < 0.1\,\mathrm{keV}) \sim 3\times 10^{-7}$

Optimistic prospects (zero background)



Background from radiative decay $^3\mathrm{H} \to {}^3\mathrm{He} + e + \bar{\nu}_e + \gamma$



$N(E_\gamma > 1\,\mathrm{keV})/N_{total} \sim 4 \times 10^{-5}$

Ideal requirements for the experiment

- Momentum measurement with precision $\delta p/p \sim 1\%$
- Source
  - Temperature $\sim 0.1 - 10\,\mathrm{mK}$
  - Size $\sim 1\,\mathrm{mm}$ (depends on the momentum measurement device)
  - Quantity $> 10^7$ ^{3}H (in case no background, 100% efficiency, 1 year of observation)

Existing cooling techniques

- Supersonic jets
  - $T \sim 0.1\,\mathrm{K}$, density $10^{11} - 10^{12}\,\mathrm{cm}^{-3}$ ($10^{15}\,\mathrm{cm}^{-3}$?)
- Magnetic trapping of decelerated supersonic jet of H atoms, $T \sim 0.1\,\mathrm{K}$
  Hogan et al., PRL101,143001(2008)
- Single-photon atomic cooling
  Price et al., PRL100,093004(2008)
  1.5×10^5 of ^{87}Rb atoms in an optical trap
  $100\,\mu\mathrm{m} \times 100\,\mu\mathrm{m} \times 130\,\mu\mathrm{m}$ at $7\,\mu\mathrm{K}$
  Cooling of H is promised

Other backgrounds

- Tritium molecule dissociation
  - Should not be a major problem—very large momentum distortion
- Scattering/interactions in the source

Possible variations of the experimental setup:

- Other isotopes
  - Easier to capture, shorter lifetime
- Electron capture instead of beta decay
  - 2-body kinematics

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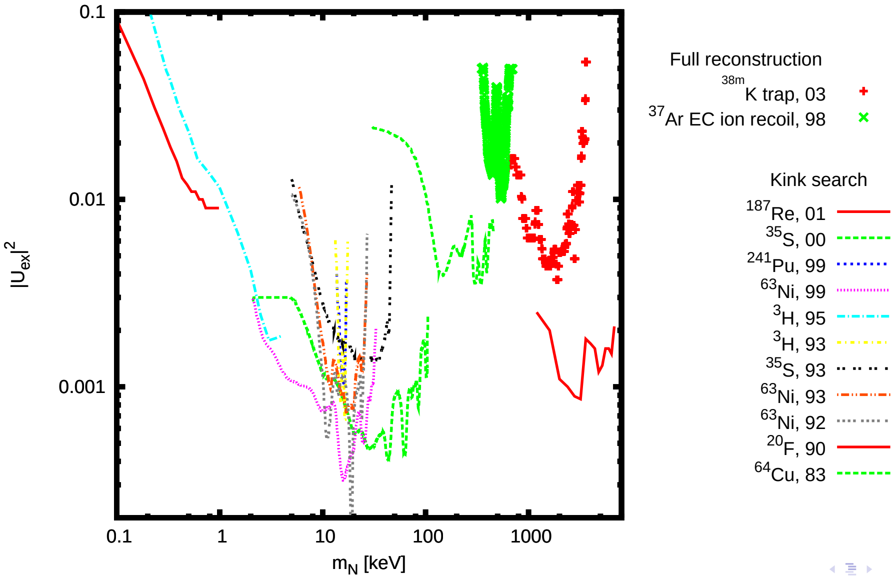
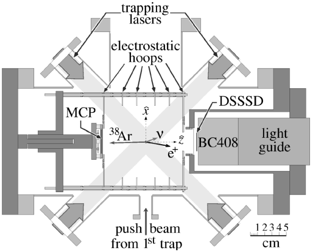
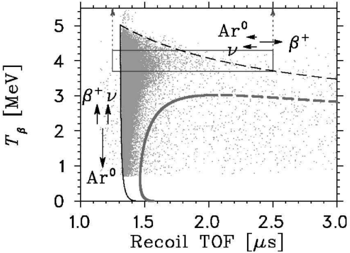


^{38m}K β decay





TRIUMF, Canada

^{38m}K

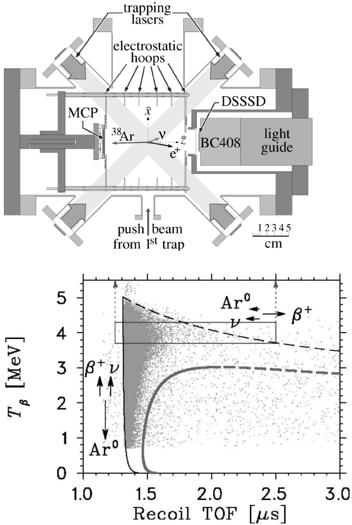
$t_{1/2} = 0.924$ s

$Q_{\beta^+} = 5.022$ MeV

trap lifetime 45 s

Trinczek et al., PRL90(2003)012501

^{38m}K β decay



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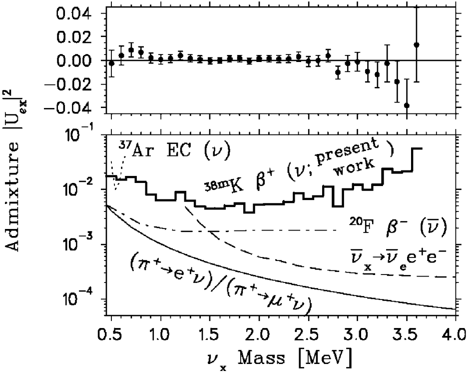

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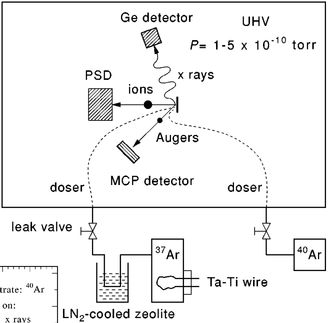
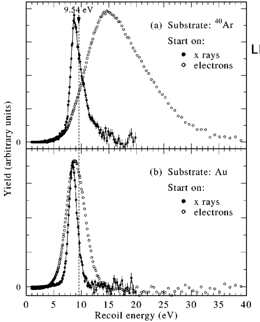
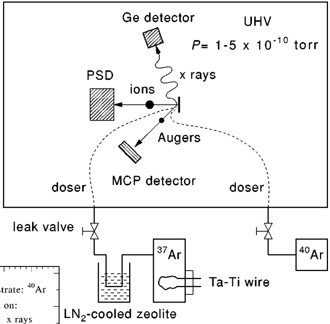


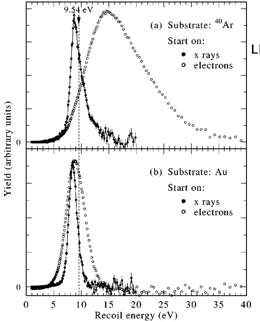


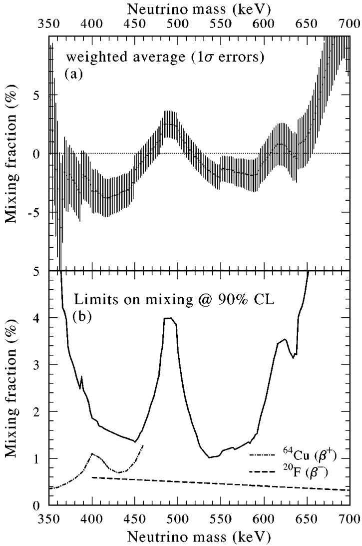
^{37}Ar $t_{1/2} = 35.04$ days
$Q = 813.5$ keV
^{37}Ar on the layer of Au or ^{40}Ar

Hindi et al., PRC58(1998)2512

^{37}Ar EC decay







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Conclusions

- Search for the relatively light keV scale sterile neutrino is an interesting experimental task
- Improvement of existing bounds $|U_{ex}|^2 \lesssim 10^{-3}$ can be possible by experiments with event-by-event measurement of the neutrino mass by full kinematic reconstruction
- For light sterile neutrino isotopes with small decay energy and small mass are good — ^3H
- Detailed study of these type of experiments is needed!
- Excellent experimental techniques exist and are constantly improving!

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