Searching for dark matter sterile neutrino in laboratory

hep-ph/0611352

Fedor Bezrukov, Mikhail Shaposhnikov
`Fedor.Bezrukov@epfl.ch`, `Mikhail.Shaposhnikov@epfl.ch`
Institut de Théorie des Phénomènes Physiques,
Ecole Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland

ÉCOLE POLYTECHNIQUE
FÉDÉRALE DE LAUSANNE

Abstract

If the dark matter of the Universe is made of sterile neutrinos with the mass in keV region they can be searched for with the help of X-ray satellites. We discuss the prospects of *laboratory* experiments that can be competitive and complimentary to Space missions. We argue that the detailed study of β decays of tritium and other nuclei with the help of Cold Target Recoil Ion Momentum Spectroscopy (COLTRIMS) can potentially enter into interesting parameter range and even supersede the current astronomical bounds on the properties of dark matter sterile neutrino.

1 Astrophysics, Cosmology, and Sterile Neutrino

The nature of Dark Matter (DM) in the Universe is a puzzle. Many different hypothetical particles coming from physics beyond the Standard Model (SM) were proposed to play a role of dark matter particle; none of them have been discovered yet. Here we consider the for a search of one of the dark matter candidates: sterile neutrino with the mass in keV region.

Here is the case for sterile neutrino as a dark matter particle. There are not that many experimental facts in particle physics which cannot be described by the Standard Model. These are neutrino oscillations (neutrinos of the SM are exactly massless and do not oscillate), dark matter (the SM does not have any stable neutral massive particle) and baryon asymmetry of the Universe (substantial deviations from thermal equilibrium, needed for baryogenesis, are absent for experimentally allowed mass of the Higgs boson). This calls for an extension of the SM. The most economic one, that can describe all these phenomena in a unified way is the νMSM. In the model (see insert) three leptonic singlets (other names for them are right-handed, Majorana or sterile neutrinos) are added, making the structure of quark and lepton sectors of the theory similar. The Majorana nature of singlet fermions leads to non-zero masses for active neutrinos and, therefore, to neutrino oscillations, solving in this way one of the SM problems. The lightest of these new particles with the mass in keV region can have a lifetime greater than that of the Universe and thus can play a role of (warm) dark matter. The preference for keV mass scale is coming from the cosmological structure formation arguments related to the missing satellites problem (see Fig. 1) and to cuspy DM distributions in cold dark matter cosmologies.

The presence of two other heavier fermions with the mass in $\mathcal{O}(1)$ GeV region leads to generation of baryon asymmetry of the Universe via resonant sterile neutrino oscillations and electroweak sphalerons. These fermions can also be searched for in particle physics experiments with high intensity proton beams, and, possibly, rare meson decays.

2 Search for sterile neutrino

Creation and Detection Suppressed by θ^4, therefore most probably impossible.

Detection only Sterile neutrinos are created somewhere else in large amounts and then *detected* in the laboratory. The X-ray Space experiments are exactly of this type: the number density of sterile neutrinos is fixed by the DM mass density, and the limits on the X-ray flux give directly the limit on θ^2 rather than θ^4 as in the previous case. Knowing decay width for the $N \to \nu+\gamma$ channel $\Gamma(N_1\to\nu+\gamma) = 1.38\times10^{-22}\sin^2(2\Theta)\left(\frac{M_1}{1\,\mathrm{keV}}\right)^5 \mathrm{s}^{-1}$ and sterile neutrino density from DM density one can deduce the limit on the mixing angle from the flux X-ray observations. The searched signal here is the X-ray line with energy $E = M_1/2$. Existing constraints are presented in Fig. 3
(Boyarsky, Neronov, Ruchayskiy, Shaposhnikov'06).

Creation only It is possible to analyze kinematics in the beta decay to register creation of keV neutrino. Simplest thing would be to use just the beta spectrum, but due to very small mixing angle distinguishing the kink in the signal from the physical background is impossible (c.f. limits from kink searches in Fig. 3 and story about 17 keV neutrino discovery).

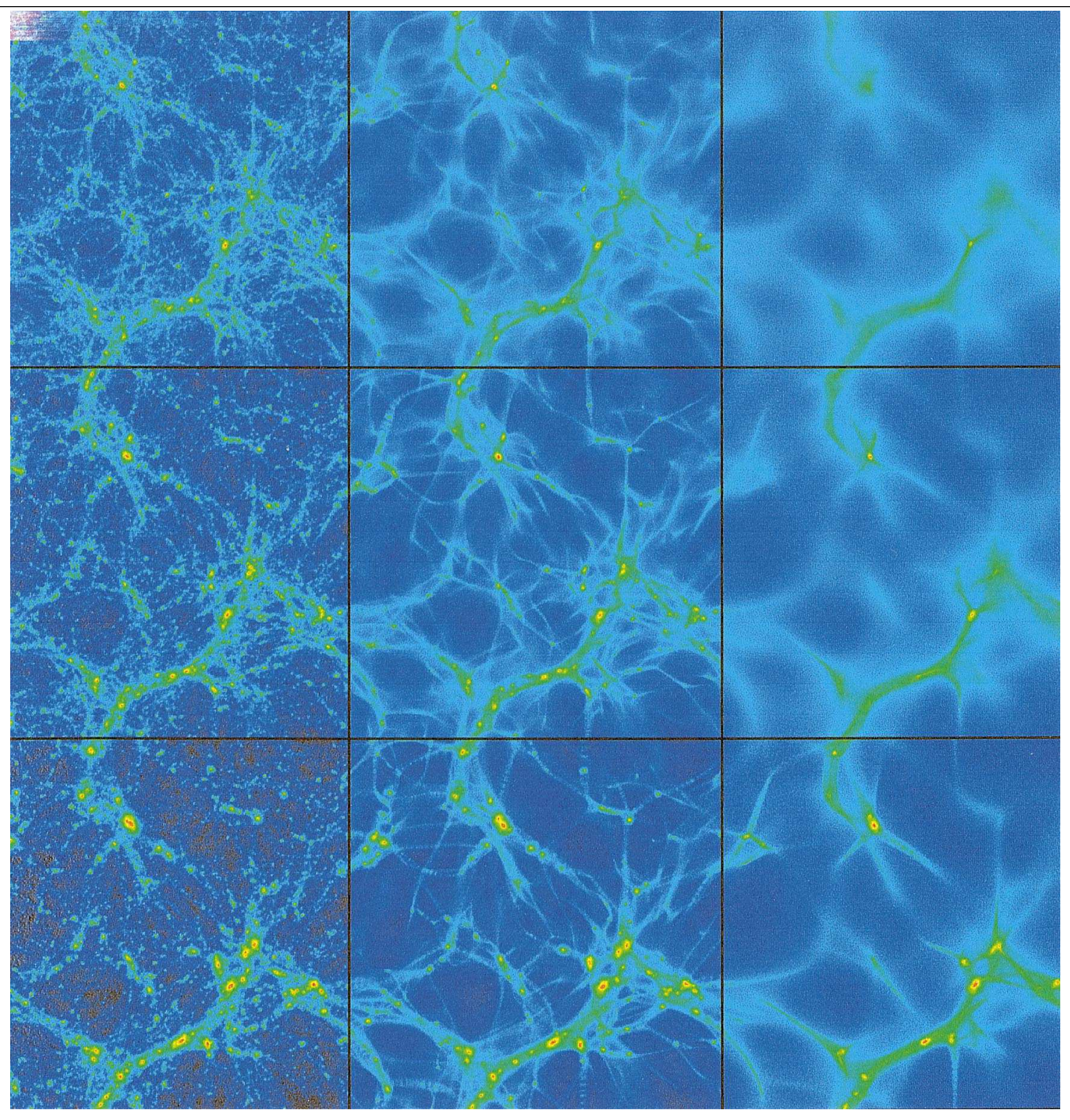


Figure 1: The evolution of the particle distributions in phase space. A small halo of mass $2\times10^{11}h^{-1}M_\odot$ has been selected for comparative study in (left to right) ΛCDM, ΛWDM, and ΛWDM power spectrum but without thermal velocities. From bottom to top: $Z = 8$, 1, and 0. Bode, Ostriker, Turok'01

νMSM Model Summary

Standard Model with addition of 3 right-handed SU(2)×U(1) singlet neutrinos

$$\mathscr{L}_{\nu MSM} = \overline{N}_I i\partial\!\!\!/ N_I - f_{I\alpha}H\overline{N}_I L_\alpha - \frac{M_I}{2}\overline{N_I^c}N_I + h.c.$$

Dirac mass term: $M^D = f\langle H\rangle$ Majorana mass term: M_I

H — Higgs doublet

L_α — left lepton doublet, $\alpha = e,\mu,\tau$

Analogous to the masses in the quark sector

"Simplest", Gauge-invariant and renormalizable extension

PLB 631 (2005) 151, T.Asaka, S.Blanchet, M.Shaposhnikov

PLB 620 (2005) 17, T.Asaka, M.Shaposhnikov

See-saw mechanism leads to admixture of sterile neutrinos in flavour states $\nu_\alpha \to \nu_\alpha + \theta_\alpha N$, where $\alpha = e,\ \mu,\ \tau$, $\theta^2 = \sum\theta_\alpha^2 \simeq (M_D/M_I)^2$.

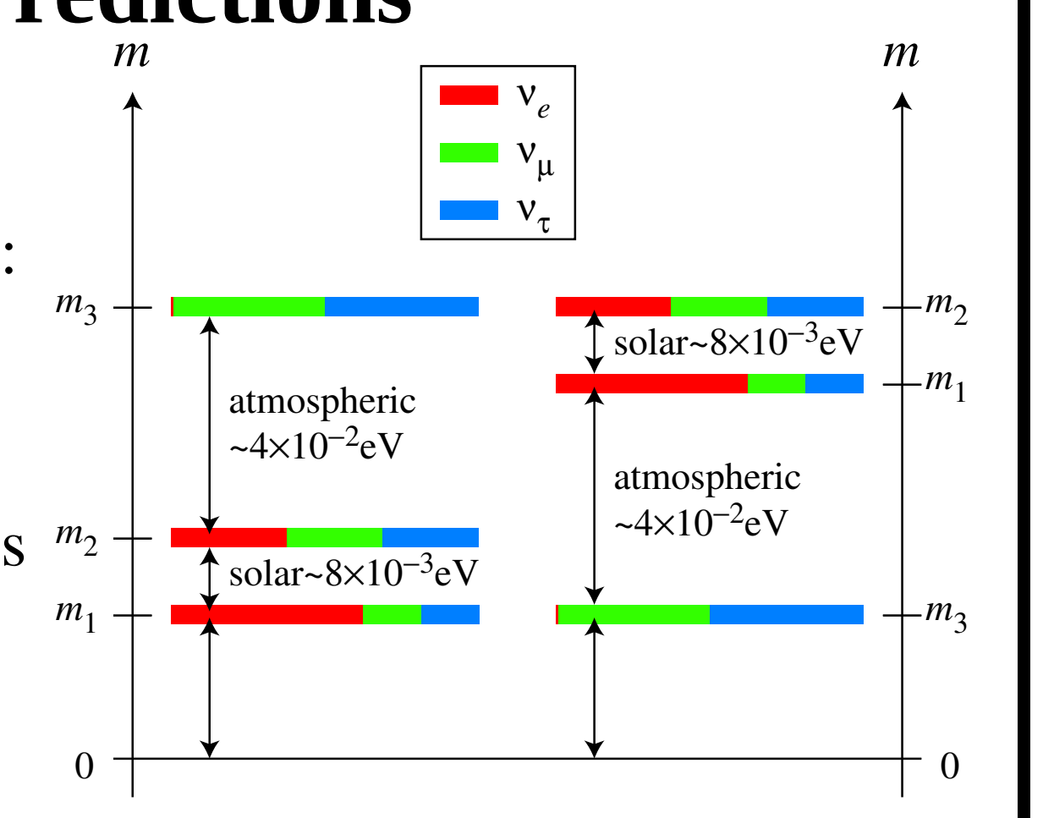
- Typical parameters

  $M_1 > 0.3$ keV is the Warm Dark Matter neutrino

  $\Theta_1 < 10^{-2} - 10^{-6}$ depending on mass (see X-ray constraints in Fig. 3)

  $M_2 \simeq M_3 \sim 1-20$ GeV, generates baryon asymmetry (but may be lighter, up to about 50 MeV)

νMSM Predictions



Lightest active neutrino is very light:

$m_{\text{lightest}} \lesssim 10^{-5}$ eV

Both normal and inverted hierarchies are possible

$0\nu\beta\beta$ mass: $m_{ee} = \left|\sum_i m_i V_{ei}^2\right|$

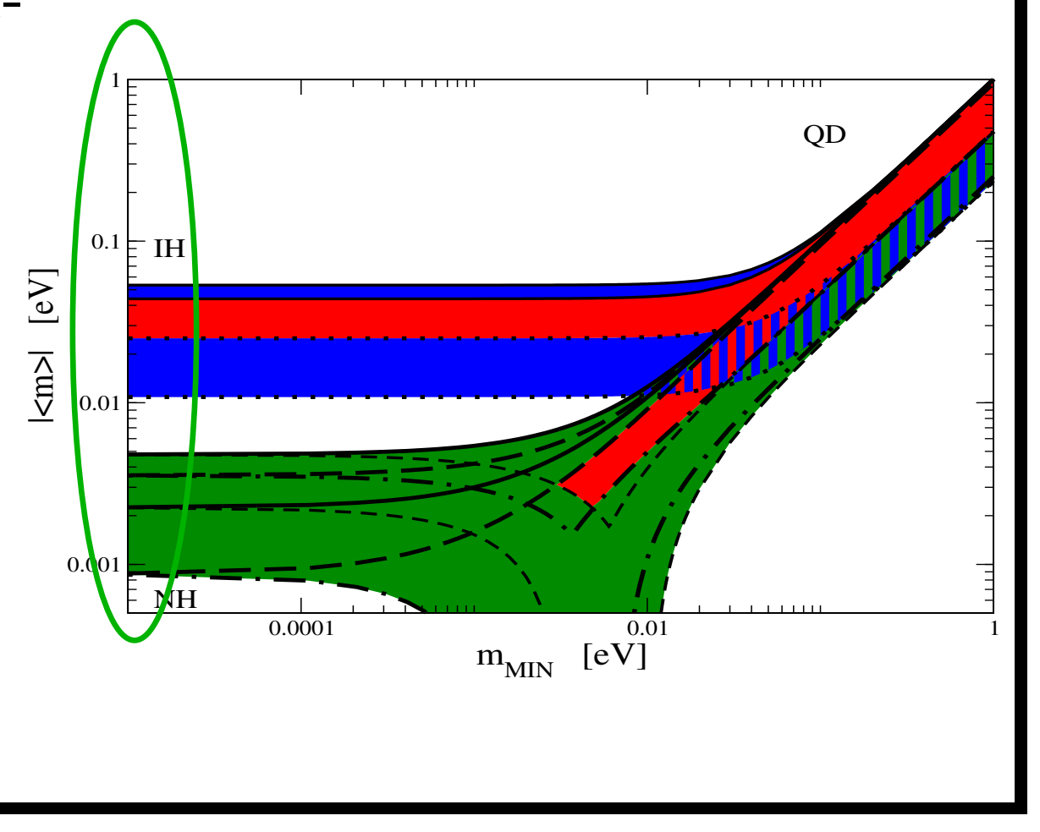
Bezrukov'05: For normal active neutrino mass hierarchy:

$$1.3\ \text{meV} < m_{\beta\beta}^{NH} < 3.4\ \text{meV}$$

for inverted hierarchy:

$$13\ \text{meV} < m_{\beta\beta}^{IH} < 50\ \text{meV}$$

(Smaller for light $M_{2,3}$).

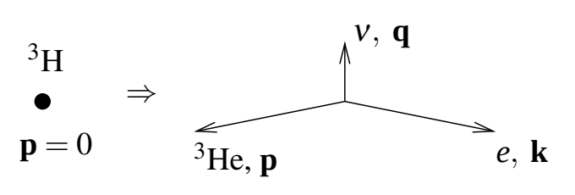


However *full kinematics reconstruction* is possible

3 Full β decay kinematics experiment

Neutrino mass is reconstructed from observed momenta

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



For ^3H: $Q = 18.591$ keV

- Typical ion energy $E_p^{\text{kin}} \sim 1$ eV or $|\mathbf{p}| \sim 100$ keV $\Rightarrow$ speed $v \sim 10^4\mathrm{m/s}$
- Typical electron energy $E_e^{\text{kin}} \sim 10$ keV

Time of flight measurement of ion momenta!

Existing COLTRIMS (Cold Target Recoil Ion Momentum Spectroscopy, see Fig. 2) experiments are able to measure very small ion recoil. They are utilized for investigation of the dynamics of ionization transitions in atoms and molecules. The ion momenta is determined by time of flight measurement. A small electric field is applied to the decay region to extract charged ions into the drift region. After the drift region the ions are detected by a position sensitive detector, which allows to determine both the direction of the momenta and the time of flight. A similar technology is applied for the electron detector. The decay moment needed for the time of flight measurement can be tagged by registering the Lyman photon emission of the excited ion. Or, in alternative setup, electron energy can be measured by different means and the electron itself used for time tagging. Precisions currently achieved with such apparatus are of the order of 0.2 keV for ion momentum. According to Dorner,2000 it is possible to achieve sensitivity for measuring normal active neutrino masses of 10 eV for each single event; the accuracy needed for the case of sterile neutrinos is considerably less than that as the mass of N is expected to be in the keV region.

Temperature requirements for the source (absence of noise from active neutrino events)

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

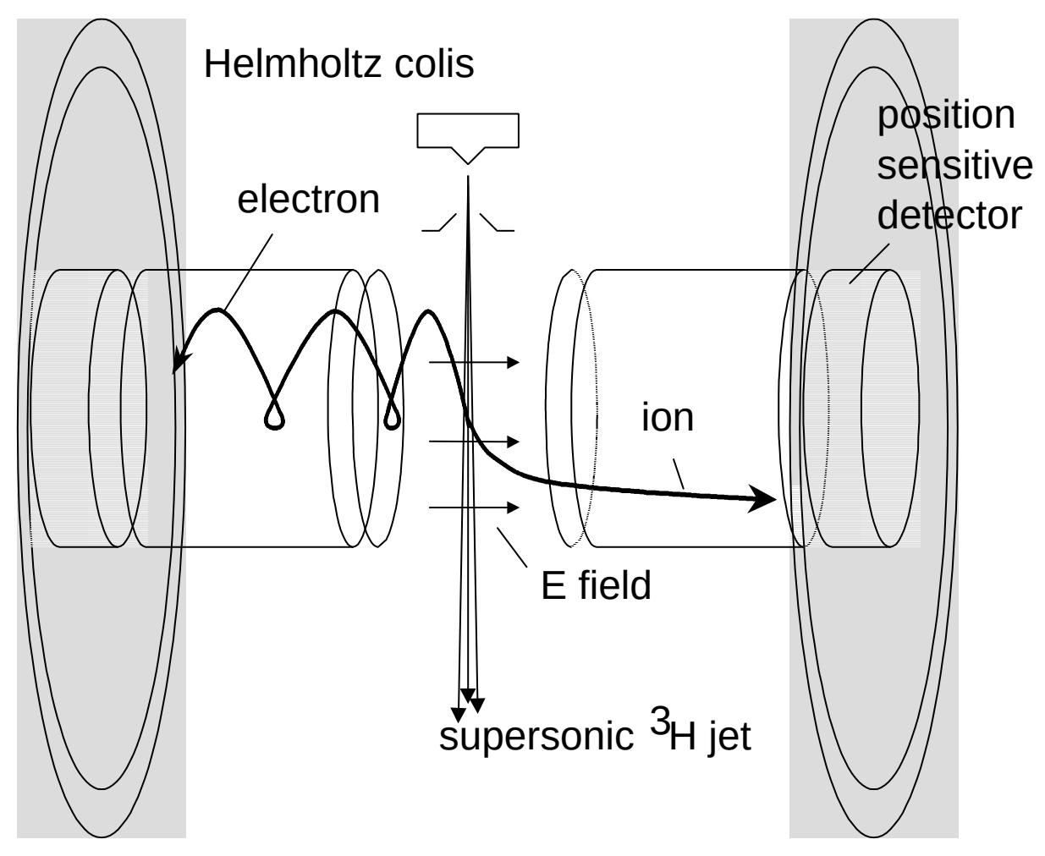
One cat make cut on ion and electron momenta, $(\mathbf{p}+\mathbf{k})^2 \lesssim 3MT$, (creation of "slow" neutrinos). The temperature requirements are then much weaker

$$T \lesssim \frac{1.5}{\log(1/\theta^2)}\left(\frac{m_s}{1\ \text{keV}}\right)^2\left(\frac{4\ \text{GeV}}{M}\right)(1\ \text{K})$$

Number of decays with kinematic cut on the momenta is much smaller then Q and m_s, the number of sterile neutrino events can be estimated as $N_{\text{events}} \simeq \theta^2\sqrt{1-(m_s/Q)}N_{\text{tot}}$.

Estimates shown in Fig. 3 demonstrates that the proposed experiment is very challenging compared to existing kink search experiments, but can reach into the interesting parameter region!

Of course, the X-ray bounds presented here is a rather challenging goal, but not impossible, and in case if not all the Dark Matter is composed of sterile neutrinos, larger values of mixing angle are also interesting.



Possible variants:

- Another source isotope
- Laser colling technique
- Other electron spectrometer

Figure 2: Cold-Target Recoil-Ion-Momentum Spectroscopy

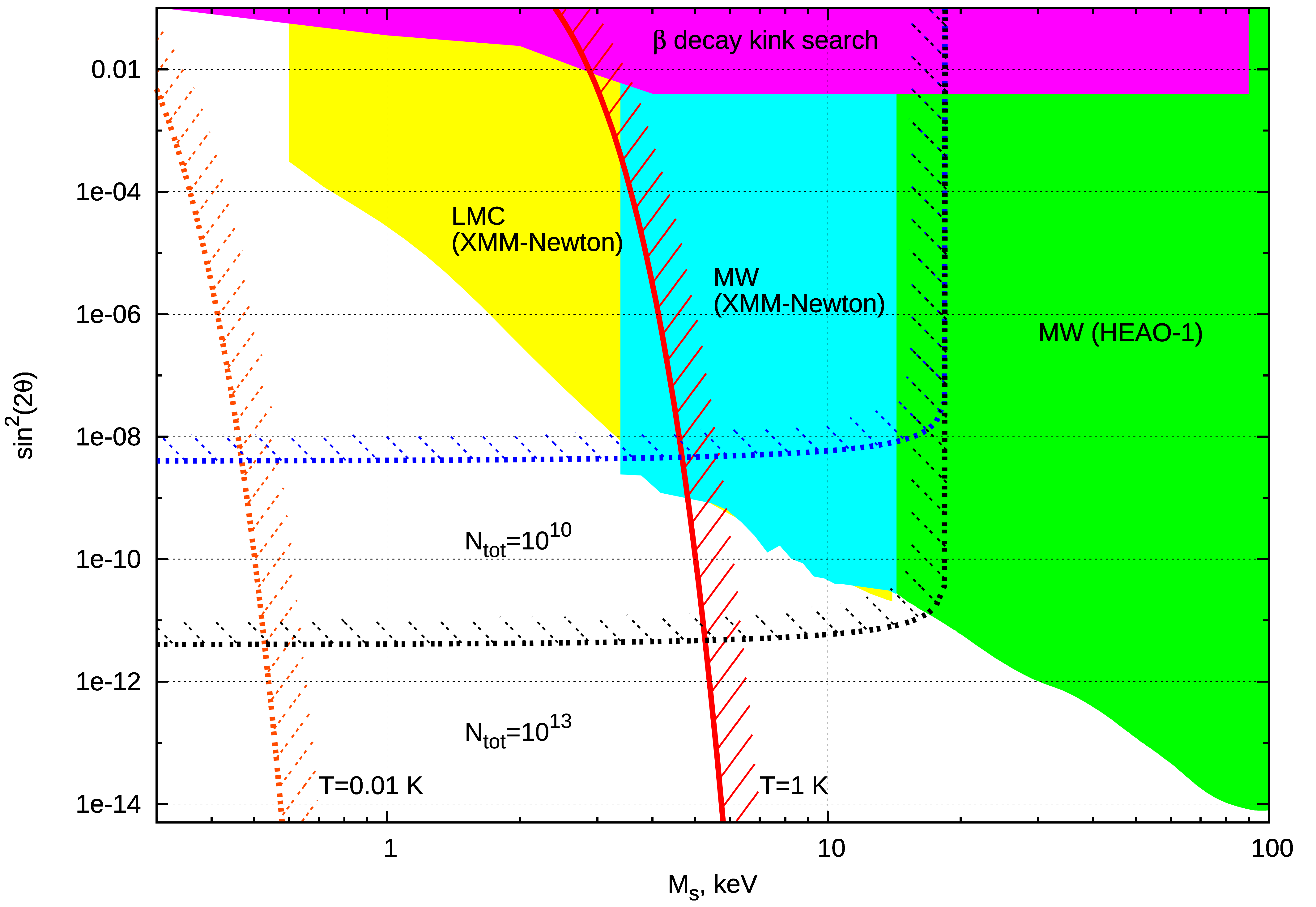


Figure 3: Constraints on the mixing angle θ of sterile neutrino with active neutrino from X-ray observations of Large Magellanic Clouds and Milky Way by XMM-Newton and Milky Way by HEAO-1 satellites. Two nearly vertical lines correspond to the bound on the mass from the thermal background with $T = 0.01$ K and 1 K. Two horizontal lines are limits from the total number of registered decays, corresponding to $N = 10^{10}$ and $N = 10^{13}$. A kinematic cut on reconstructed neutrino momenta $\tilde{\mathbf{q}}^2 < 3MT$ was used. β decay kink search bounds from PDG-06 are shown for reference.