# $\nu$MSM and its experimental tests

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# Outline


1. The $\nu$MSM Model
   - The aim
   - Model content and Lagrangian
   - Properties
2. Bounds and Predictions
   - Constraints
   - Predictions
3. Experimental features
   - X-rays observations
   - $0\nu\beta\beta$ decay
   - Beta decay kinematics
   - Heavy sterile neutrinos searches

# Standard Model—Success and Problems

Gauge fields (interactions) – $\gamma$, $W^{\pm}$, $Z$, $g$

Higgs boson $H$

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

- Describes
  - all experiments dealing with electroweak and strong interactions
- Does not describe
  - Neutrino oscillations
  - Dark matter ($\Omega_{DM}$) — sterile neutrino as WDM
  - Baryon asymmetry — leptogenesis via sterile neutrino oscillations
  - Dark energy ($\Omega_{\Lambda}$)
    Inflation
    Gravity

$\nu$MSM explains this    and does not explain this

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# $\nu$MSM Lagrangian

Most general renormalizable Lagrangian for 3 additional right-handed neutrinos $N_I$

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

Extra coupling constants:

3 Majorana masses $M_i$

15 new Yukawa couplings
(Dirac mass matrix $M^D = f\langle H\rangle$ has 3 Dirac masses,
6 mixing angles and 6 CP-violating phases)

18 new parameters in total

PLB 631 (2005) 151, T.Asaka, S.Blanchet, M.Shaposhnikov PLB 620 (2005) 17, T.Asaka, M.Shaposhnikov

# $\nu$ masses and mixings

$M_I \gg M^D$ — "seesaw" mechanism is working:

3 heavy neutrinos with masses $M_I$

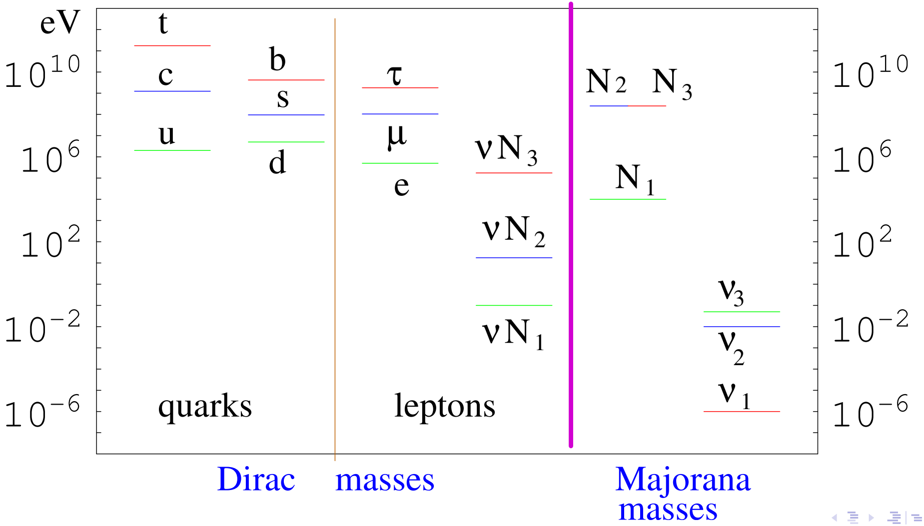
Light neutrino masses $$M^\nu = -(M^D)^T \frac{1}{M_I} M^D$$

$$U^T M^\nu U = \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix}$$

Mixings: flavor state $\nu_\alpha = U_{\alpha i}\nu_i + \Theta_{\alpha I} N_I^c$

Active-sterile mixings $$\Theta_{\alpha I} = \frac{(M^D)^\dagger_{\alpha I}}{M_I} \ll 1$$

# The spectrum of $\nu$MSM



# DM keV neutrino constraints

$N_1$ with the keV scale mass provides the Warm Dark Matter

Mass bounds

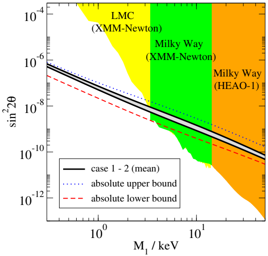
- Tremaine-Gunn bound $M_1 \gtrsim 0.3$ keV
- Lyman-$\alpha$ bound $M_1 \gtrsim 11.6$ keV or 8 keV

Mixing angle bound

- X-ray observation

Production mechanism

- Dodelson-Widrow (thermal) scenario (ruled out)
- Primordial abundance – physics at higher energies
  - Entropy production
  - Lepton asymmetries
  - Production from inflaton decay
  - etc.



# Baryon Asymmetry

Baryogenesis via Leptogenesis (using heavier sterile $N_2$ and $N_3$)

- Generation of lepton asymmetry in active neutrino sector via CP-violating neutrino oscillations
- Conversion of lepton asymmetry to baryon asymmetry by sphaleron transformations, conserving $B+L$

$$\frac{n_B}{s} = 2\times 10^{-10}\delta_{CP}\left(\frac{10^{-6}}{\Delta M_{32}^2/M_3^2}\right)^{\frac{2}{3}}\left(\frac{M_3}{10\text{ GeV}}\right)^{\frac{5}{3}}$$

and $M_{2,3}\sim 10$ GeV. $\delta_{CP}$ describes CP in sterile sector. In Universe: $\frac{n_B}{s}\simeq(8.8\div 9.8)\times 10^{-11}$

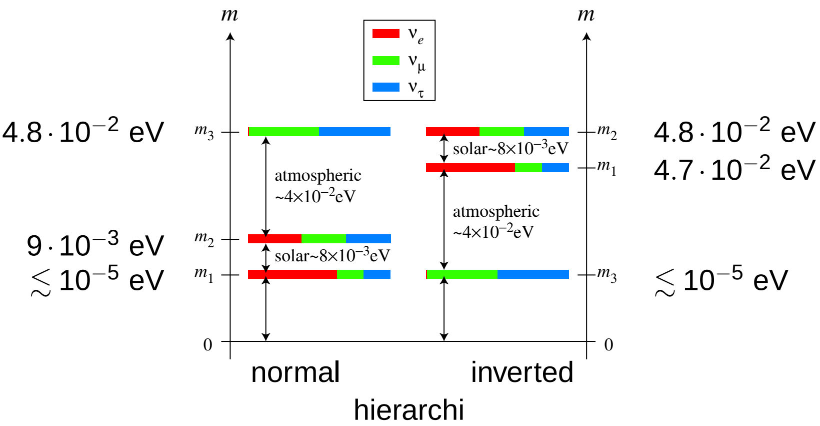
- Should not thermalize before sphaleron processes stop:
  $\Theta_{2,3} < 2\kappa\times 10^{-8}\left(\frac{\text{GeV}}{M_{2,3}}\right)^2$
  ($\kappa\simeq 1(2)$ for normal(inverted) hierarchy)

T. Asaka, M. Shaposhnikov, 2005

# Active neutrino masses — prediction!

## The mass of the lightest active neutrino:

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



# Are any experiments possible?

# X-ray observations

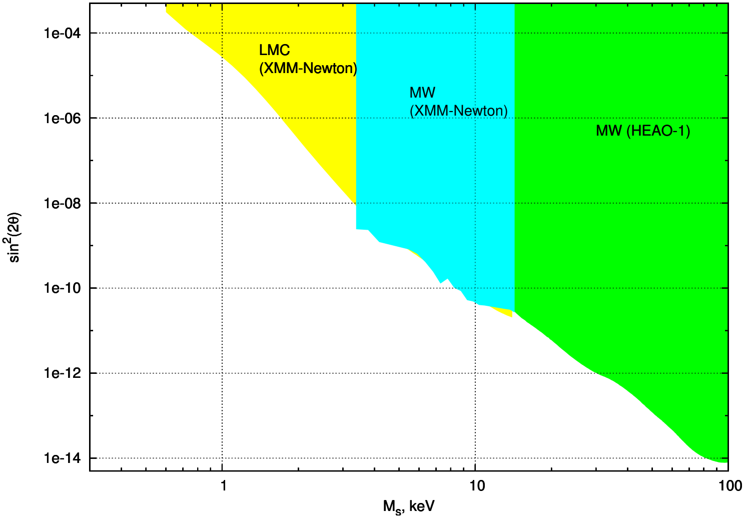
- Second main $N_1$ decay mode is the two particle radiative decay:

$$\Gamma(N_1 \to \nu + \gamma) = 1.38 \times 10^{-22} \sin^2(2\Theta_1) \left( \frac{M_1}{1\ \text{keV}} \right)^5 \text{s}^{-1}$$

- X-ray line with $E = M_1/2$ is emitted from the Dark Matter halos
- Knowing the DM density it is possible to constraint the mixing angle from the search for such line
- Existing experiments like XMM-Newton, HEAO provide the stringent bound on the mixing angle $\Theta_1$
- Dedicated experiments with good energy resolutions and not necessarily good angular resolution are needed!

M.Boyarsky, O.Ruchaysky, M.Shaposhnikov, 2006

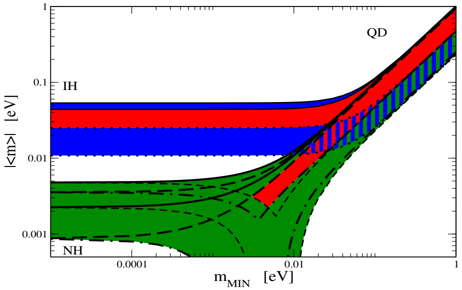
# X-ray observations




M.Boyarsky, O.Ruchaysky, M.Shaposhnikov, 2006

# $0\nu\beta\beta$ effective Majorana mass

$$m_{ee} = \left|\sum_i m_i V_{ei}^2\right|$$




- contribution from $N_1$ is negligible $|M_1 \Theta_{e1}^2| \leq 10^{-5}$ eV
- For $N_1$ coupled with heavier active neutrinos its contribution is always negative

$$m_{ee} < \left|\sum_i m_i V_{ei}^2\right|$$

smaller prediction

F. Bezrukov, 2006

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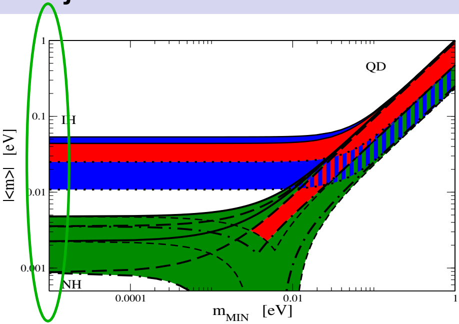


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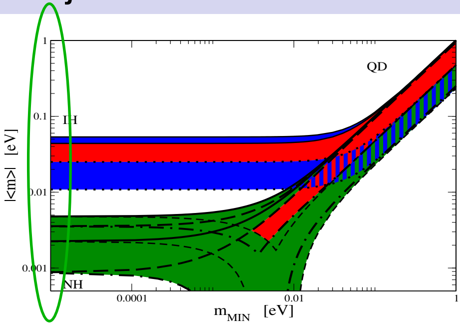


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# Possibilities of sterile neutrino search

*Creation* in the lab without subsequent detection

- Decay kinematics

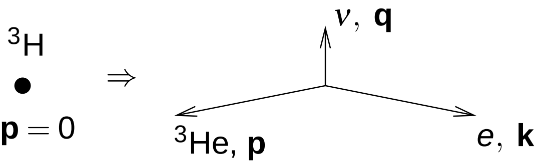
  Partial kinematics kink search in electron beta decay spectrum.
  - Extremely large statistics to see the effect ($\sqrt{N}$ statistical error)
  - Excellent theoretical knowledge of the decay spectrum is needed (c.f. 17 keV neutrino “discovery”)

  Not working

  Full kinematics event-by-event mass measurement

  May work

# 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 $^3H$: $Q = 18.591$ keV

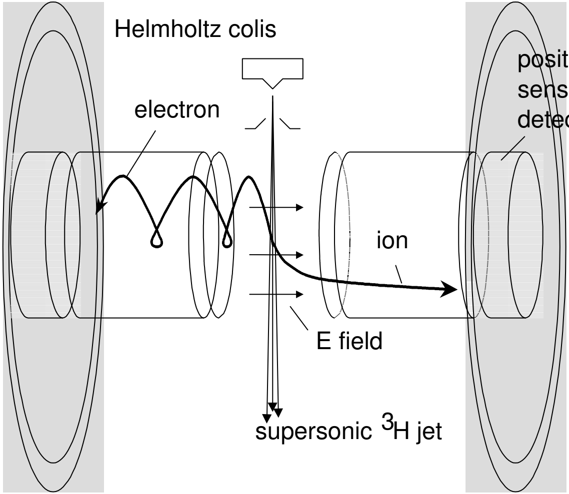
- Typical ion energy $E_p^{\mathrm{kin}} \sim 1$ eV or $|\mathbf{p}| \sim 100$ keV $\Rightarrow$ speed $v \sim 10^4 \mathrm{m/s}$
- Typical electron energy $E_e^{\mathrm{kin}} \sim 10$ keV

Time of flight measurement of ion momenta!

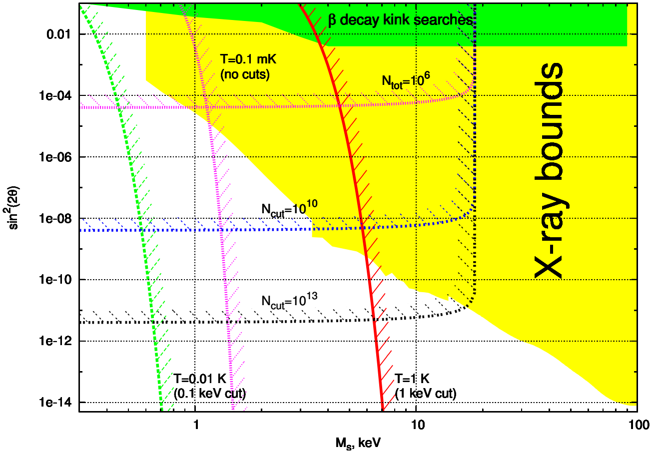
F. Bezrukov, M. Shaposhnikov, 2007

# COLTRIMS setup

Cold-Target Recoil-Ion-Momentum Spectroscopy



# Optimistic prospects



# Heavy $N$ mixing angle constraints

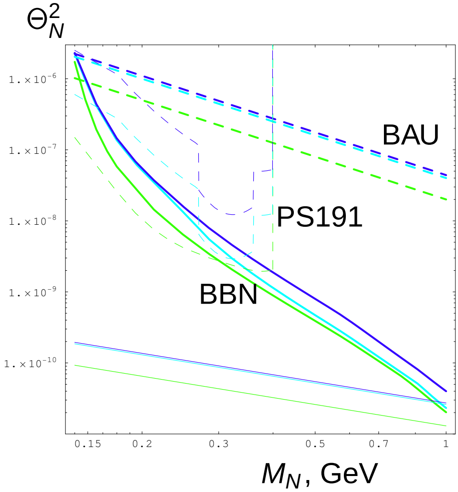
Baryon asymmetry constraint:

$$\Theta_{2,3} < 2\kappa \times 10^{-8} \left(\frac{\text{GeV}}{M_{2,3}}\right)^2$$

BBN bound: $\tau_{N_{2,3}} < 0.1$ s

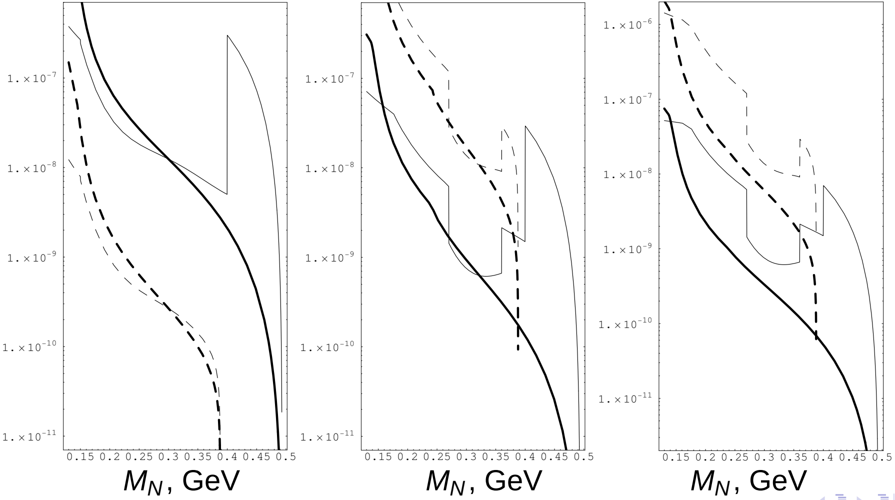
CERN PS191 bound

D.Gorbunov, M.Shaposhnikov, 2007



# K decays

Br($K \to eN_I$) solid line; Br($K \to \mu N_I$) dashed line;

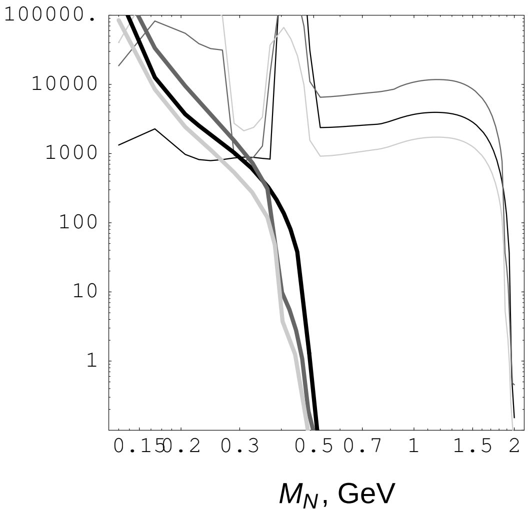


# N decays

Creation of N in beam dump (CNGS beam)

Search for N decays ($N \to l^+ l^- \nu$, $N \to \pi^0 \nu$, etc.)

Number of events in 5 m long detector



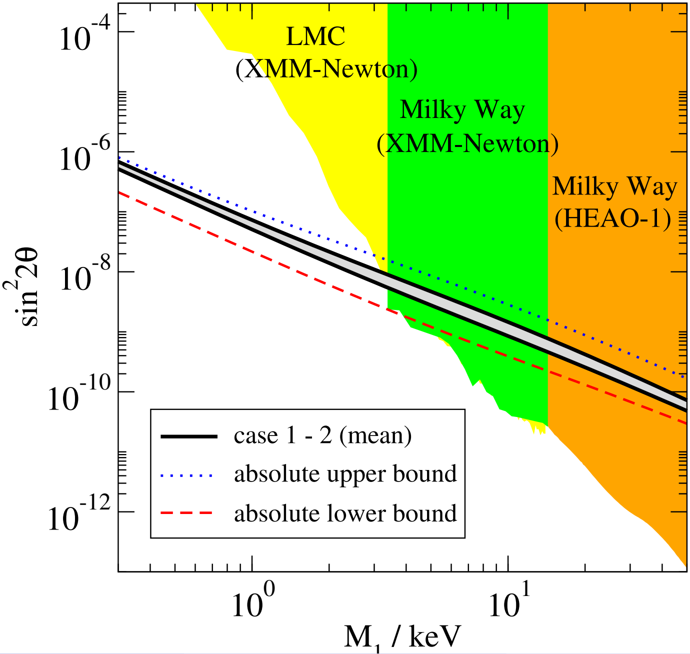
# Conclusions

- $\nu$MSM — the simplest Standard Model extension with right handed neutrinos provides keV neutrino as a WDM candidate, predicts the mass of lightest active neutrino to be very small, provides mechanism for baryon asymmetry generation
- Possible searches for Dark Matter keV sterile neutrino
  - X-ray observations — indirect evidence
  - $0\nu\beta\beta$ decay — may constraint the model
  - Full kinematics measurement of beta decay in the laboratory
- Possible searches for “heavy” sterile neutrinos responsible for baryogenesis
  - $K$ decays
  - sterile neutrino decays searches

  Surely constrains the model for $M_N < M_K$.

# Conclusions

Experiments are possible!


LMC
(XMM-Newton)
Milky Way
(XMM-Newton)
Milky Way
(HEAO-1)
$10^{-4}$
$10^{-6}$
$10^{-8}$
$10^{-10}$
$10^{-12}$
$\sin^2 2\theta$
$10^0$
$10^1$
$M_1$ / keV
case 1 - 2 (mean)
absolute upper bound
absolute lower bound