

# $\nu$ MSM and its experimental consequences

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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) –  $\gamma, W^\pm, Z, g$

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

- 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

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# $\nu$ MSM particle content

36 quark states:

$$\begin{array}{llll}
 (u, d)_L, & (c, s)_L, & (t, b)_L & \text{and} & u_R, & d_R, & c_R, & s_R, & t_R, & b_R \\
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 \end{array}$$

9+3 leptonic states:

$$(e, \nu_e)_L, \quad (\mu, \nu_\mu)_L, \quad (\tau, \nu_\tau)_L \quad \text{and} \quad N_1, \quad e_R, \quad N_2, \quad \mu_R, \quad N_3, \quad \tau_R$$

$SU(3) \times SU(2) \times U(1)$  — 12 gauge bosons (8+3+1)

one Higgs doublet

Leptonic sector has the same structure as the quark sector

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# $\nu$ MSM Lagrangian

Most general renormalizable lagrangian

$$\mathcal{L}_{\nu\text{MSM}} = \mathcal{L}_{\text{MSM}} + \bar{N}_I i \not{\partial} N_I - f_{I\alpha} H \bar{N}_I L_\alpha - \frac{M_I}{2} \bar{N}_I^c N_I + \text{h.c.}$$

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

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

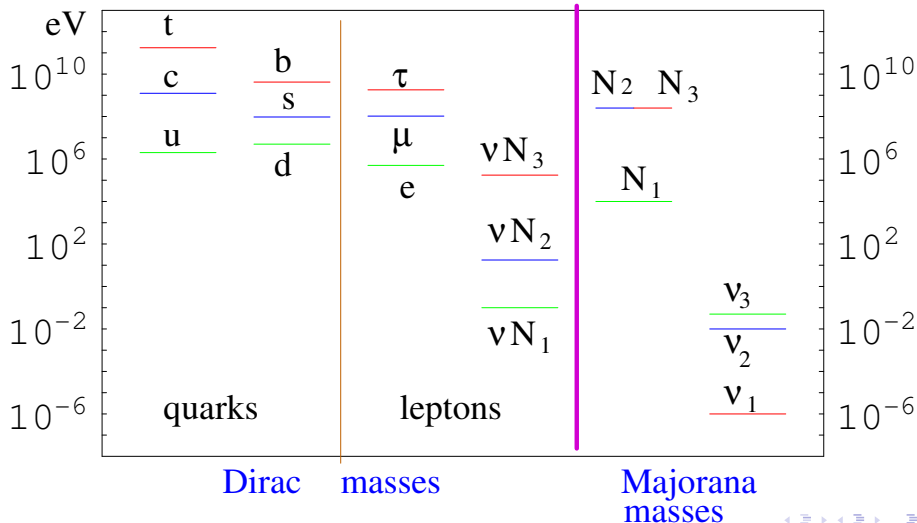
$$U^T M^\nu U = \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix}$$

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

Active-sterile mixings

$$\Theta_{\alpha I} = \frac{(M^D)_{\alpha I}^\dagger}{M_I} \ll 1$$

# The spectrum of $\nu$ MSM



# DM keV neutrino constraints

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

## Mass bounds

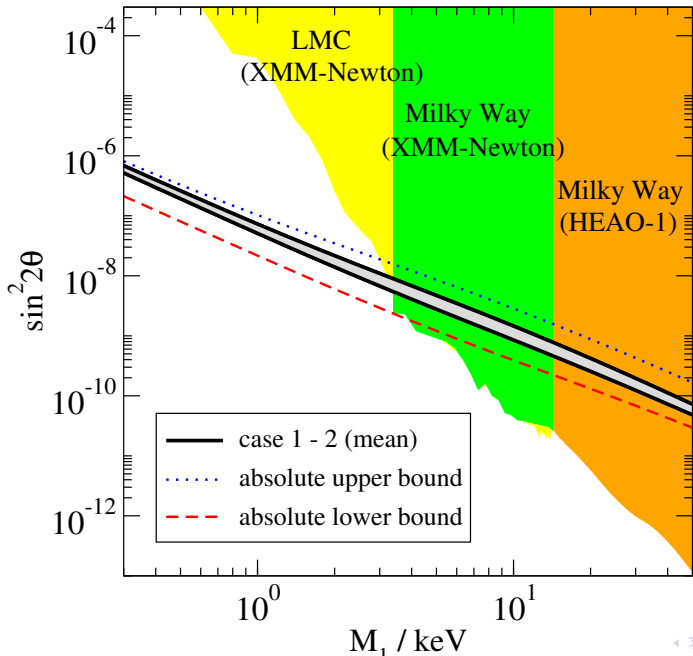
- Tremaine-Gunn bound  $M_1 \gtrsim 0.3$  keV
- Lyman- $\alpha$  bound  $M_1 \gtrsim 11.6$  keV or 8 keV

## Mixing angle bound

- X-ray observation

## Production mechanism

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



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# 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  $M_{2,3} \sim 10 \text{ GeV}$ .  $\delta_{CP}$  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:

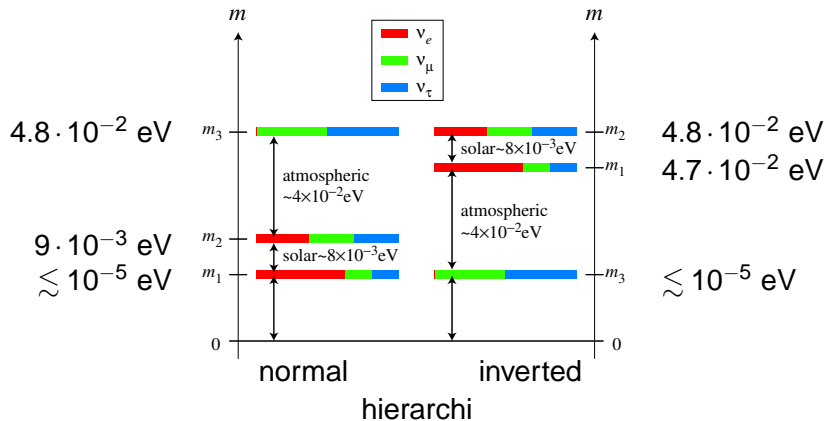
$$\Theta_{2,3} < 2\kappa \times 10^{-8} \left( \frac{\text{GeV}}{M_{2,3}} \right)^2$$

( $\kappa \simeq 1(2)$  for normal(inverted) hierarchy)

# 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

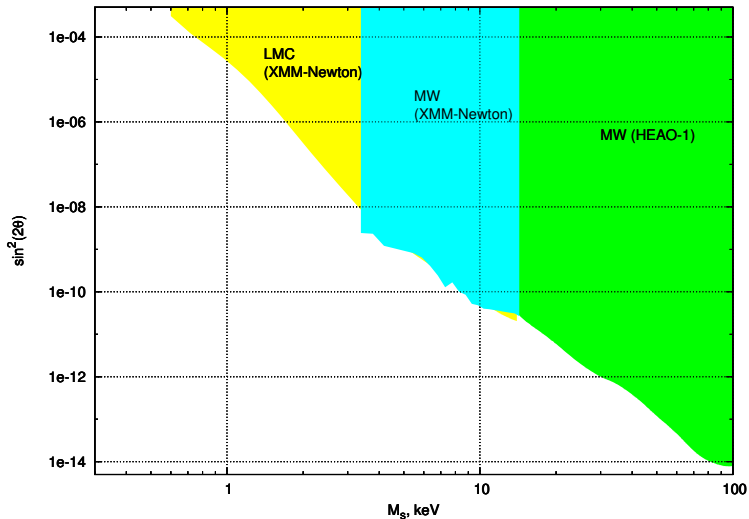
- Second main  $N_1$  decay mode is two particle radiative decay:

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

- 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

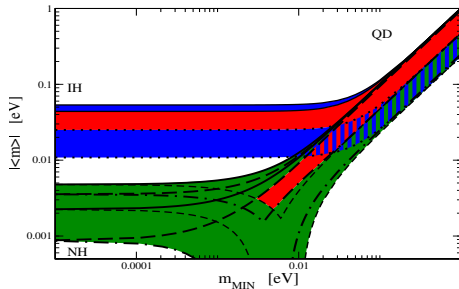
# X-ray observations



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

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

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



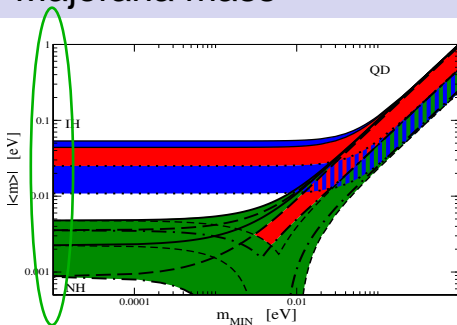
- contribution from  $N_1$  is negligible  $|M_1 \Theta_{e1}^2| \leq 10^{-5}$  eV
- For  $N_1$  coupled with heavier active neutrinos its contribution is always negative

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

smaller prediction

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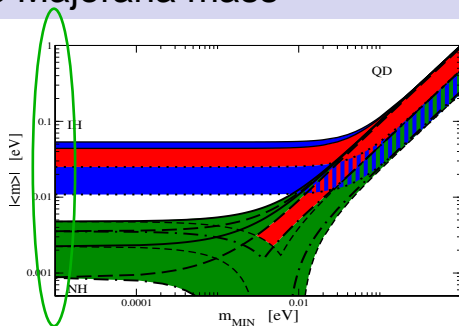
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# Possibilities of sterile neutrino search

*Creation* in the lab without subsequent detection

- Decay kinematics

**Partial kinematics** kink search in electron beta decay spectrum.

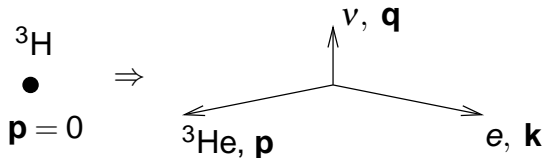
- ▶ Extremely large statistics to see the effect ( $\sqrt{N}$  statistical error)
- ▶ Excellent theoretical knowledge of the decay spectrum is needed (c.f. 17 keV neutrino “discovery”)

Not working

**Full kinematics** event-by-event mass measurement

May work

# Beta decay kinematics



Neutrino mass is reconstructed from observed momenta

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

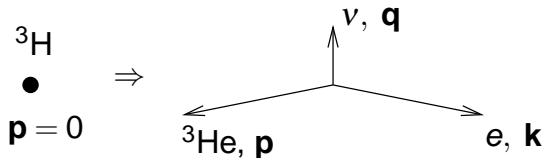
For  ${}^3\text{H}$ :  $Q = 18.591 \text{ keV}$

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

Time of flight measurement of ion momenta!

F. Bezrukov, M. Shaposhnikov, 2007

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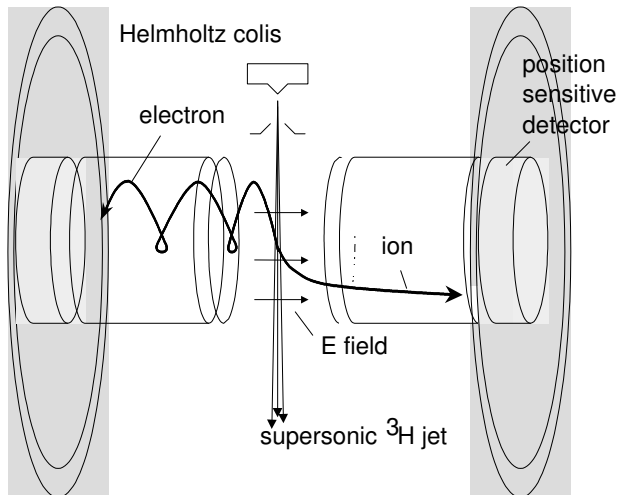
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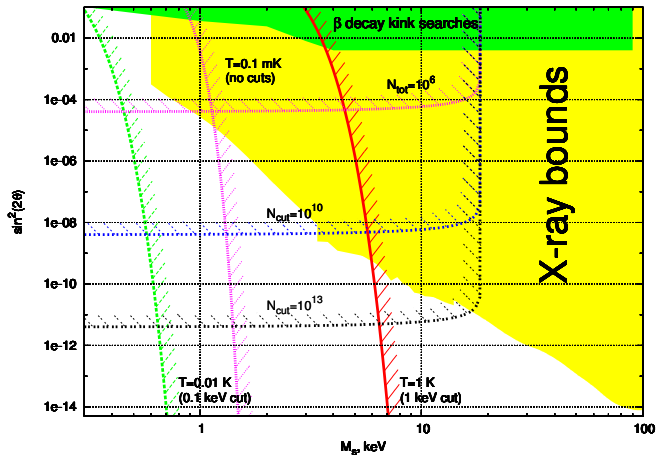
F. Bezrukov, M. Shaposhnikov, 2007

# COLTRIMS setup

## Cold-Target Recoil-Ion-Momentum Spectroscopy



# Optimistic prospects



# Experimental problems

- Bremsstrahlung gammas provide **large background**
- Source densities (high statistics, no scattering)

Variations:

- Other isotopes
- Electron capture instead of beta decay

An experimental challenge, of course!

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# Heavy $N$ mixing angle constraints

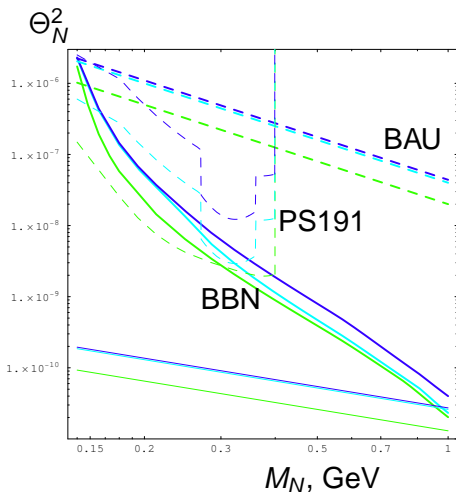
Baryon asymmetry constraint:

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

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

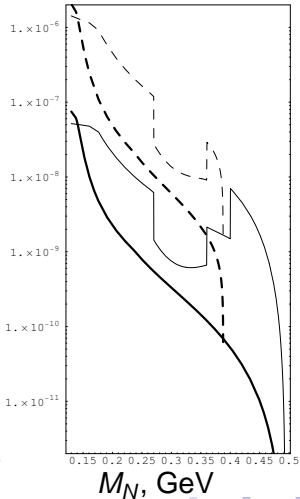
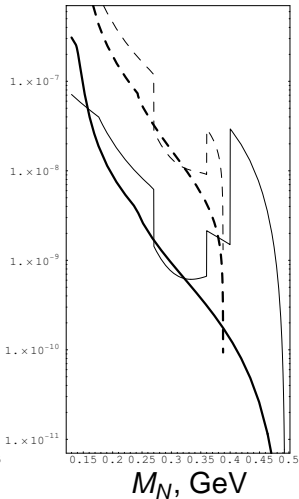
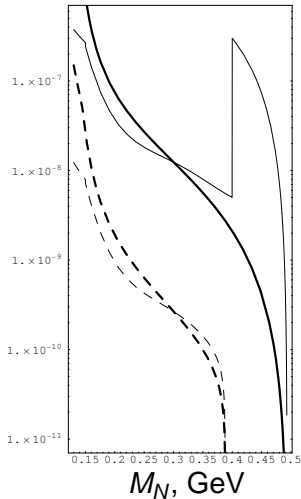
CERN PS191 bound

D. Gorbunov, M. Shaposhnikov, in preparation



# K decays

$\text{Br}(K \rightarrow e N_i)$  solid line;  $\text{Br}(K \rightarrow \mu N_i)$  dashed line;

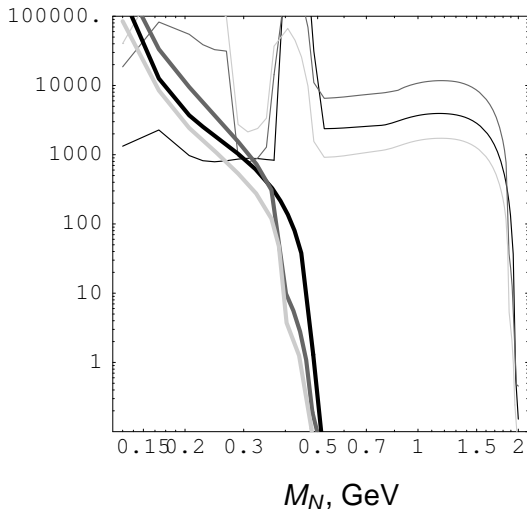


# N decays

Creation of  $N$  in beam dump (CNGS beam)

Search for  $N$  decays  
 ( $N \rightarrow l^+ l^- \nu$ ,  $N \rightarrow \pi^0 \nu$ ,  
 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!