keV scale sterile neutrino as Dark Matter

or the simplest way to explain everything

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Outline

1. Introduction
2. The model – νMSM
3. Astrophysical/Cosmological bounds
   - Lifetime
   - X-ray bounds
   - DM generation mechanisms
   - Structure formation
   - Constraints on heavier sterile neutrinos $N_{2,3}$
4. Predictions and laboratory searches
   - Lightest active neutrino mass
   - keV sterile neutrino: $0\nu\beta\beta$ decay
   - Other laboratory searches

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Standard Model – goods

Particle content

Gauge fields ($SU(3)_c \times SU(2)_W \times U(1)_Y$): γ, $W^{\pm}$, Z, g

Higgs doublet (1,2,1)

Matter:

	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	$U(1)_{em}$
$\begin{pmatrix} u \\ d \end{pmatrix}_L$	3	2	+1/3	$\begin{pmatrix} +2/3 \\ -1/3 \end{pmatrix}$
u_R	3	1	+4/3	+2/3
d_R	3	1	-2/3	-1/3
$\begin{pmatrix} \nu_e \\ e \end{pmatrix}_L$	1	2	-1	$\begin{pmatrix} 0 \\ -1 \end{pmatrix}$
e_R	1	1	-2	-1

× 3 generations

Describes (except for very few things)

- all laboratory experiments – electromagnetism, nuclear processes, etc.
- all processes in the evolution of the Universe after the Big Bang Nucleosynthesis ($T < 1$ MeV, $t > 1$sec)

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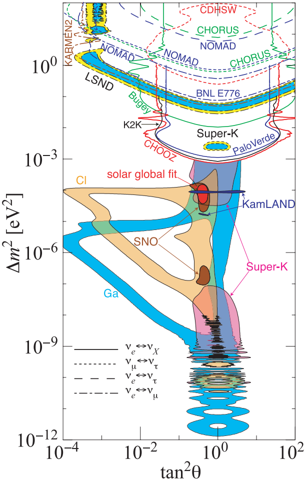
Standard Model – problems (experimental!)

- Neutrino oscillations
- Baryon asymmetry of the Universe
- Dark Matter
- Dark Energy
- Inflation

Standard Model – problems (experimental!)

- Neutrino oscillations

Δm^2_{21}	$8.2^{+0.6}_{-0.5} \times 10^{-5}$ eV^2
θ_{12}	$32.3^{\circ}{}^{+2.7}_{-2.4}$
$\lvert\Delta m^2_{32}\rvert$	$2.0^{+0.6}_{-0.4} \times 10^{-3}$ eV^2
$\sin^2 2\theta_{23}$	> 0.94
$\sin^2 2\theta_{13}$	< 0.11



http://hitoshi.berkeley.edu/neutrino

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Standard Model – problems (experimental!)

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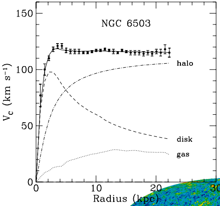
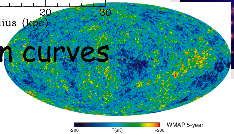


Rotation curves



CMB fluctuations

Gravitational lensing

"Bullet" cluster

- Dark Energy
- Inflation

Standard Model – problems solution

Can be explained with sterile (right-handed) neutrinos

- Neutrino oscillations
- Baryon asymmetry of the Universe
- Dark Matter

Asaka, Shaposhnikov, 05

- Dark Energy – hard to explain naturally, but can be present provided for extreme finetuning
- Inflation – can be explained by non-minimally coupling of the Higgs with gravity FB, Shaposhnikov'08

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νMSM

Particle content

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Higgs doublet (1,2,1)

Matter:

	$SU(3)_c$	$SU(2)_W$	$U(1)_Y$	$U(1)_{em}$
$\binom{u}{d}_L$	3	2	+1/3	$\binom{+2/3}{-1/3}$
u_R	3	1	+4/3	+2/3
d_R	3	1	-2/3	-1/3
$\binom{\nu_e}{e}_L$	1	2	-1	$\binom{0}{-1}$
e_R	1	1	-2	-1
N	1	1	0	0

× 3 generations

Lepton sector is similar to the quark sector (with addition of the Majorana masses for N)

νMSM Lagrangian

- Lorentz invariant
- Renormalizable

Lagrangian

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

- Dirac masses: $M^D_{I\alpha} = f_{I\alpha} \langle H \rangle$
- Majorana masses: M_I

Asaka, Blanchet, Shaposhnikov, 2005 Asaka, Shaposhnikov, 2005

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ν masses and mixings

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

Diagonalising mass matrix

$$\begin{pmatrix} 0 & M_D \\ M_D^T & M_I \end{pmatrix} \Rightarrow \begin{pmatrix} -(M^D)^T \frac{1}{M_I} M^D & 0 \\ 0 & M_I \end{pmatrix}$$

3 heavy neutrinos with masses M_I

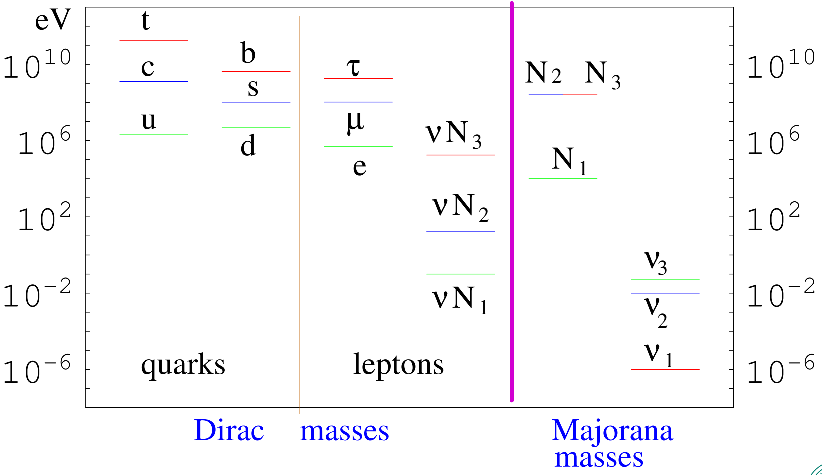
Light neutrino masses $\quad M^\nu = -(M^D)^T \dfrac{1}{M_I} M^D$

$$U^T M^\nu U = \mathrm{diag}(m_1, m_2, m_3)$$

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

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

The spectrum of νMSM



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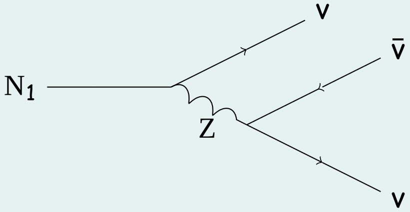
Lifetime

To be a viable Dark Matter N_1 should live longer, than the age of the Universe

Main decay channel: $N_1 \longrightarrow \bar{\nu}\nu\nu$, $N_1 \longrightarrow \bar{\nu}\bar{\nu}\nu$



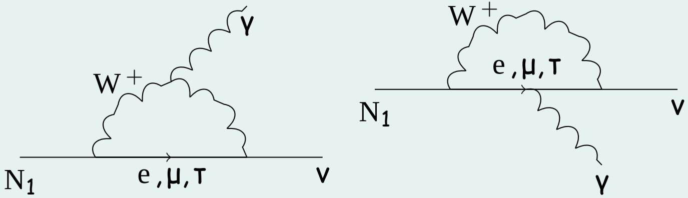
$$\tau = 5 \times 10^{23}\,\text{sec} \left(\frac{M_1}{1\text{keV}}\right)^{-5} \left(\frac{\theta_1^2}{10^{-5}}\right)^{-1}$$

Age of the Universe $\sim 10^{17}$ sec

Not very constraining, in fact

Radiative decay

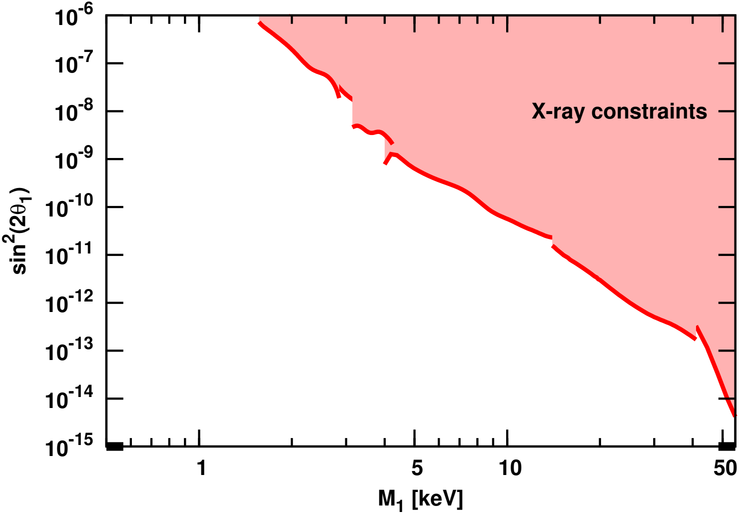
Second decay channel: $N \longrightarrow \nu\gamma$



$$\Gamma \simeq 5.5 \times 10^{-27} \left(\frac{\theta_1^2}{10^{-5}}\right) \left(\frac{M_1}{1\text{keV}}\right)^5 s^{-1}$$

- Monochromatic: $E_\gamma = M_1/2$
- We should see an X-ray ($\sim$ keV) line coming from everywhere in the sky

Astrophysical constraints



DM generation

Produced by mixing from the active neutrinos

$$\Gamma_N \sim \Gamma_\nu \theta_M^2(T)$$

where $\Gamma_\nu \sim G_F^2 T^5$ is the rate of active neutrino production, and $\theta_M(T)$ is a temperature (and momentum)-dependent mixing angle:

$$\theta_1^2 \to \theta_M^2(T) \simeq \frac{\theta_1^2}{\left(1 + \frac{2p}{M_1^2}(b(p,T) \pm c(T))\right)^2 + \theta_1^2} .$$

$$b(p,T) = \frac{16 G_F^2}{\pi \alpha_W} p (2 + \cos^2\theta_W) \frac{7\pi^2 T^4}{360}$$

$$c(T) = 3\sqrt{2} G_F \left(1 + \sin^2\theta_W\right)(n_{\nu_e} - n_{\bar{\nu}_e})$$

Production: Non-resonant (b dominates) or Resonant ($c \sim b$)

Other generation mechanisms

- The sterile neutrino does not enter thermal equilibrium during evolution
- Initial abundance is important
  - In the plain νMSM it is neglidgible F.B., Gorbunov, Shaposhnikov 08
  - May be produced with some other physics before thermal evolution – e.g. inflaton decay Shaposhnikov, Tkachev 06; Anisimov, Bartocci, F.B., 08
- DM abundance may also be diluted by entropy production from the out-of-equilibrium decay of some particle (heavier sterile neutrino) happening after DM production

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Bounds from observed structure in the Universe

- Look at the compact object with DM (dwarf spheroidals)
  - Check that sterile neutrinos can "fit" there – Pauli blocking

$$M_{DEG} > 0.5\text{keV}$$

  - Stricter bound – phase space density arguments

$$M > 1-2\text{keV}$$

Tremaine, Gunn 79; Gorbunov, Khmelnitsky, Rubakov 08; Boyarsky, Ruchayskiy, Iakubovskyi 08

- Light sterile neutrino being relativistic after decoupling provides cut off in the structure formation at smaller (sub-Mpc) scales.
- Presence of this cut off can be searched by the analysis of the Lyman-a absorption line of the intergallactic hydrogen.
  - For Non Resonant production – $m > 8$keV.
  - For Resonant production – $m > 2$keV (dependent on model lepton asymmetry)

Boyarsky, Lesgourgues, Ruchayskiy, Viel 08

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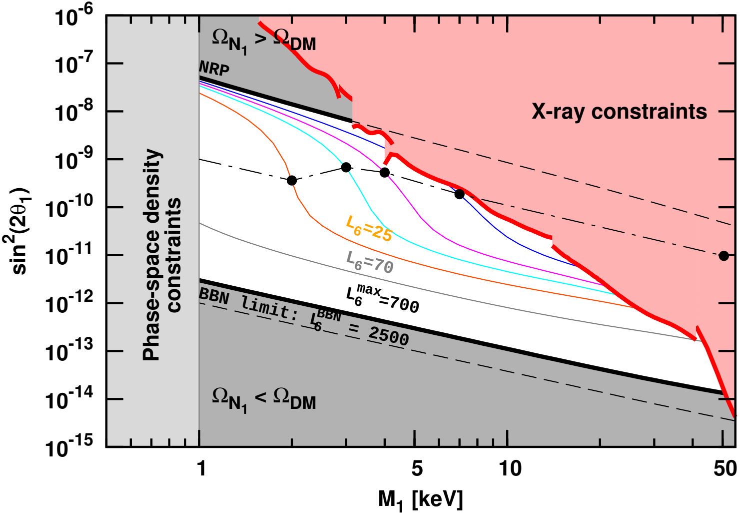
Astrophysical constraints



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. δ_{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

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Big Bang Nucleosynthesis

- No additional degrees of freedom decaying during nucleosynthesis are allowed
- This roughly limits the heavier sterile neutrino $N_{2,3}$ lifetime

BBN bound

$$\tau_{1,2} \lesssim 0.1 \sec$$

A. Dolgov, S. Hansen, G. Raffelt, D. Semikoz, 2000

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Active neutrino masses - prediction!

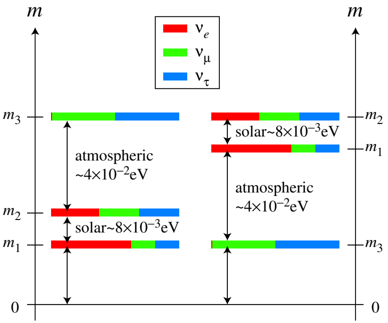
The mass of the lightest active neutrino:

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

$4.8 \cdot 10^{-2}$ eV

$9 \cdot 10^{-3}$ eV

$\lesssim 10^{-5}$ eV



$4.8 \cdot 10^{-2}$ eV

$4.7 \cdot 10^{-2}$ eV

$\lesssim 10^{-5}$ eV

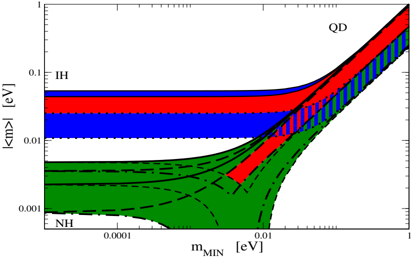
normal | inverted

hierarchy

No neutrino mass seen by KATRIN!

0νββ effective Majorana mass (GERDA!)

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



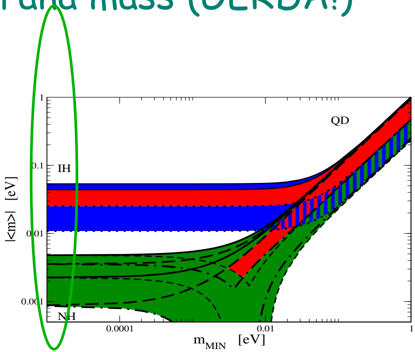
- contribution from N_1 is negligible $|M_1 \theta_{e1}^2| \leq 10^{-5}$ eV
- For N_1 coupled with heavier active neutrinos its contribution is always negative
  $m_{ee} < \left| \sum_i m_i V_{ei}^2 \right|$ smaller prediction

$$m_{ee} < 50 \times 10^{-3} \text{ eV}$$

F.B., 2006

0νββ effective Majorana mass (GERDA!)

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



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F.B., 2006

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Other laboratory searches

- Search for keV sterile neutrino by full kinematic reconstruction of β decay of $^3\mathrm{H}$ F.B., Shaposhnikov 07
- Search for heavier sterile neutrinos of νMSM in dedeicated experiments with high intensity proton beams or in K, D decays Gorbunov, Shaposhnikov, 07
- Nothing but the Higgs boson with the mass 128 GeV < $\mathrm{M_H}$ < 180 GeV found on LHC F.B., Magnin, Shaposhnikov, 08; De Simone, Hertzberg, Wilczek 08

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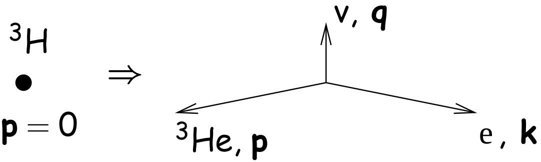
N_1 search: beta decay kinematics



Neutrino mass is reconstructed from observed momenta

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

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

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

Time of flight measurement of ion momenta! (COLTRIMS)

F.B., M. Shaposhnikov, 2007

Heavier sterile neutrino $N_{2,3}$ properties

- $M_{2,3} > m_\pi$ (likely)
- Mixings
  - Lower bound—should decay before BBN $\tau \lesssim 0.1 sec$
  - Upper bound—should not thermalise before generation of BAU $\Theta_{2,3} < 2\kappa \times 10^{-8} \left(\frac{GeV}{M_{2,3}}\right)^2$
- Decay modes

$$N \longrightarrow \mu e \nu,\ \pi^0 \nu,\ \pi e,\ \mu^+ \mu^- \nu,\ \pi\mu,\ Ke,\ K\mu,\ \eta\nu, \rho\nu, \ldots$$

- Production

$$K^\pm \longrightarrow l_\alpha^\pm N_I\ ,\ K_L \longrightarrow \pi^\mp l_\alpha^\pm N_I\ ,$$

$$D_s \longrightarrow \eta^{(\prime)} l_\alpha N_I\ ,\ D \longrightarrow K l_\alpha N_I\ ,\ D_s \longrightarrow \varphi l_\alpha N_I\ ,\ D \longrightarrow K^* l_\alpha N_I$$

D. Gorbunov, M.Shaposhnikov, 2007

$N_{2,3}$: Processess to look for

- Neutrino production hadron decays: kinematics
  - Missing energy in K decays
  - Peaks in momentum of charged leptons for two body decays
- Neutrino decays into SM particles: “nothing” to leptons and hadrons
  - Beam target experiments with high intensity proton beam, detector (preferably not dense) after the shielding.

D. Gorbunov, M.Shaposhnikov, 2007

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Conclusions

- νMSM – Standard Model with three right handed neutrinos
  - sterile neutrino with the mass $1-50\,\mathrm{keV}$ – Dark Matter
  - two sterile neutrinos with masses $\sim$ GeV – Baryon asymmetry
  - see-saw mechanism – neutrino oscillations
- It is not always needed to invent complicated new physics to explain Nature!