Minimal Extension of the Standard Model of Particle Physics

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Outline

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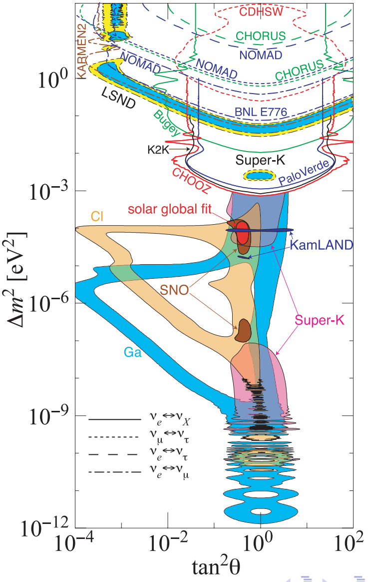
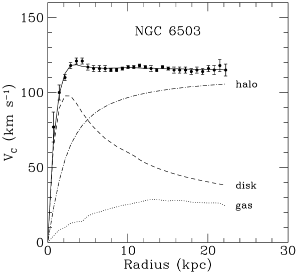
Neutrino Oscillations: Masses and Mixing



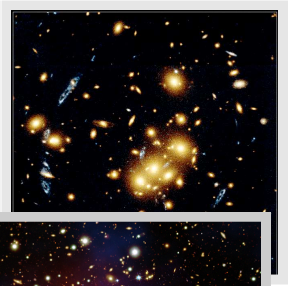
http://hitoshi.berkeley.edu/neutrino

Baryons and Dark Matter in Astrophysics

Rotation curves



Gravitational lensing



“Bullet” cluster

Baryons and Dark Matter in Cosmology

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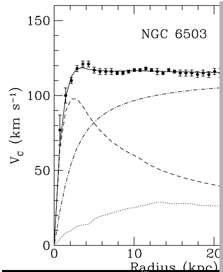
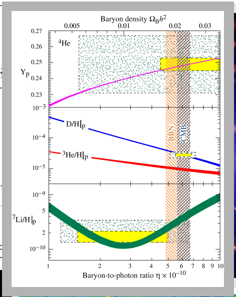


BBN



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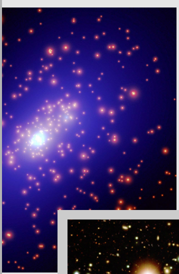

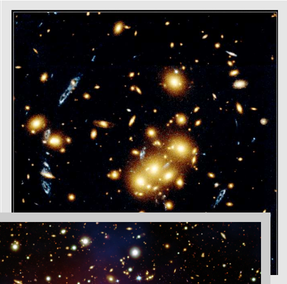

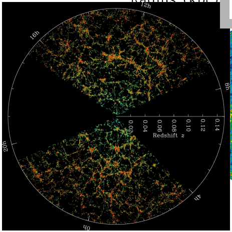

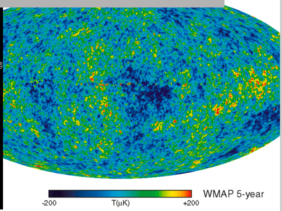

Structures

CMB fluctuations

“Bullet” cluster

Standard Model: Success and Problems

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

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 (Ω_{DM}) — sterile neutrino as DM
  - Baryon asymmetry — leptogenesis via sterile neutrino oscillations
  - Dark energy (Ω_Λ)
  - Inflation
  - Strong CP
  - Gauge hierarchy
  - Quantum gravity

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  - Inflation — R^2, $RH^\dagger H$, ...
  - Strong CP — changing topology, ...
  - Gauge hierarchy — No scales!
  - Quantum gravity

νMSM explains these

explained by Plank-scale physics ?

Outline

νMSM Particle Content

36 quark states:

$(u,d)_L,\quad (c,s)_L,\quad (t,b)_L$ and $u_R,\ d_R,\ c_R,\ s_R,\ t_R,\ b_R$

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9+3 leptonic states:

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

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

one Higgs doublet

Leptonic sector has similar structure as the quark sector

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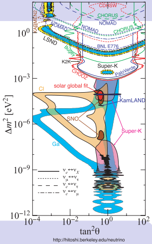
Leptonic sector has similar structure as the quark sector

νMSM Lagrangian



- Let us try to use as little “new physics” as possible
- Require to get the correct neutrino oscillations
- Explain DM and baryon asymmetry of the Universe

Lagrangian

Most general renormalizable with 3 right-handed neutrinos N_I

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

Extra coupling constants:

3 Majorana masses M_i — Asaka, Blanchet, Shaposhnikov, 2005

15 new Yukawa couplings — Asaka, Shaposhnikov, 2005
(Dirac mass matrix $M^D = f\langle H\rangle$ has 3 Dirac masses,
6 mixing angles and 6 CP-violating phases)

ν Masses and Mixings: "seesaw" from $f_{I\alpha}H\overline{N}_I L_\alpha$

$M_I \gg M^D = f\,v$ – says nothing about M_I ! dangerous: $\delta m_h^2 \propto M_I^2$

3 heavy neutrinos with masses M_I similar to quark masses

Light neutrino masses $$M^\nu = -(M^D)^T \frac{1}{M_I} M^D \propto f^2 \frac{v^2}{M_I}$$

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

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

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

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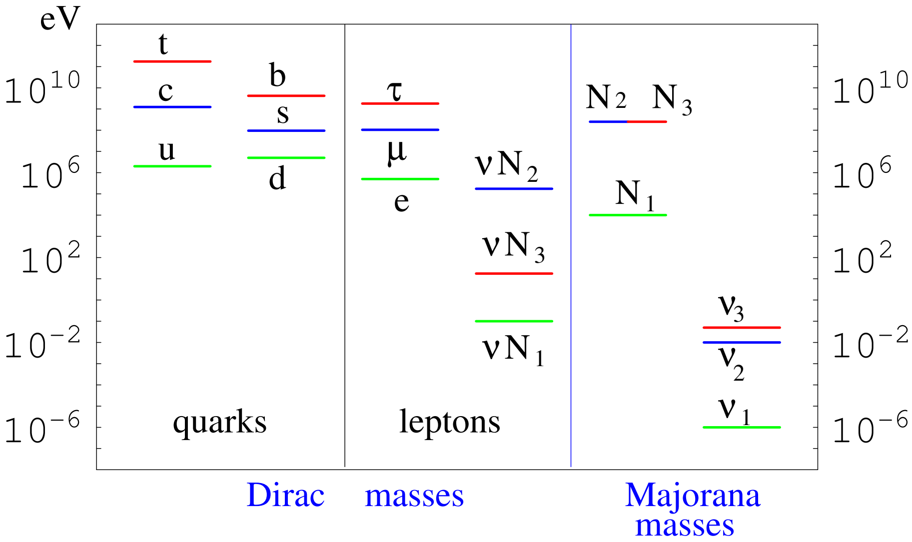
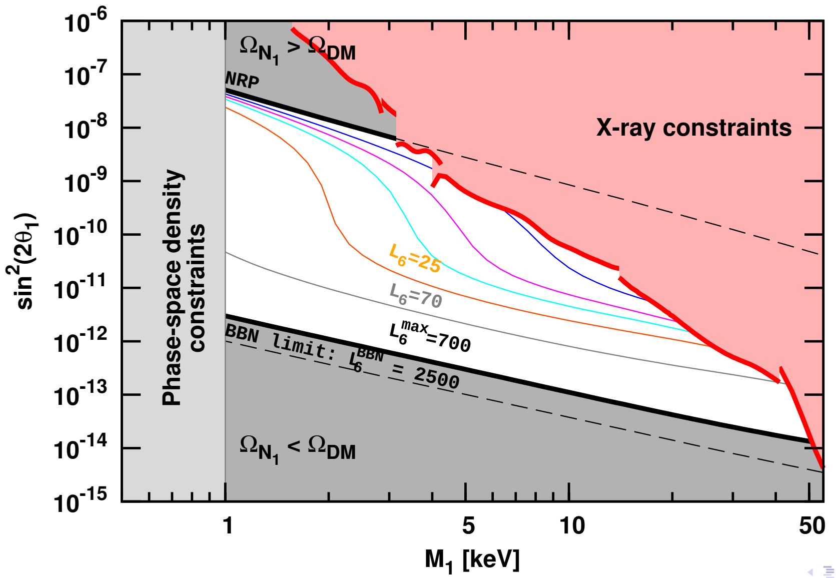
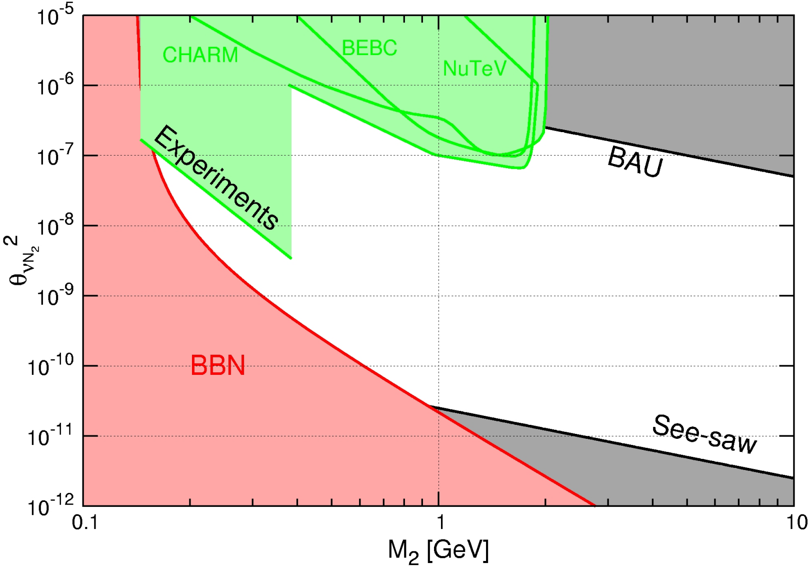
Spectrum of νMSM



DM – lightest sterile neutrino N_1



BAU – heaviest sterile neutrinos $N_{2,3}$



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Conclusions

- νMSM — the simplest Standard Model extension with right handed neutrinos provides
  - active neutrino masses and mixing angles
  - 1-50 keV neutrino as DM
  - mechanism for baryon asymmetry generation
- Possible searches for Dark Matter keV sterile neutrino
  - X-ray observations — indirect evidence
  - $0\nu\beta\beta$ decay — very small rate, $m_\nu \lesssim 10^{-5}$ eV
  - Full kinematics measurement of beta decay in the laboratory ?
- Possible searches for “heavy” sterile neutrinos responsible for baryogenesis
  - sterile neutrino from K, D, B, τ decays with Br$\simeq 10^{-6} - 10^{-10}$
  - sterile neutrino decays searches: CNGS, T2K, etc.

Model with $M_N < M_K$ can be fully explored experimentally