Sterile Neutrino Dark Matter

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II International Winter School–Seminar “Petrov’s Readings”
on Gravity, Astrophysics and Cosmology,
Kazan University,
Kazan, Tatarstan, 08.12.2016

Phenomenological problems of the Standard Model

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 : active neutrino masses via mixing
  - Dark matter (Ω_{DM}) : sterile neutrino as DM
  - Baryon asymmetry : leptogenesis via sterile neutrino decays or oscillations

- Sterile neutrinos explain the oscillations
- and the cosmological problems

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Sterile neutrinos: NEW ingredients

One of the optional physics beyond the SM:

sterile: new fermions uncharged under the SM gauge group
neutrino: explain observed oscillations by mixing with SM (active) neutrinos

Attractive features:

- possible to achieve within renormalizable theory
- only $N = 2$ Majorana neutrinos needed
- baryon asymmetry via leptogenesis
- dark matter (with $N \geq 3$ at least)
- light(?) sterile neutrinos might be responsible for neutrino anomalies. . . ?

Disappointing feature:

Major part of parameter space is UNTESTABLE

Outline

Outline

Introducing neutrinos

W. Pauli (1930)

- Conserves the energy (experimental positron spectrum is continuous !)

$$\text{Nucleus}\,(A,Z) \to \text{Nucleus}\,(A,Z+1) \,+\, e + ?$$

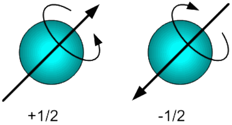
- Conserves the angular momentum (fermions! spins! Chemistry... Pauli principle)

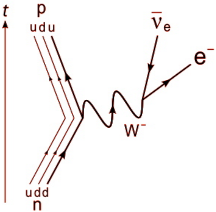
$$n \;\to\; p + e + \bar{\nu}_e$$

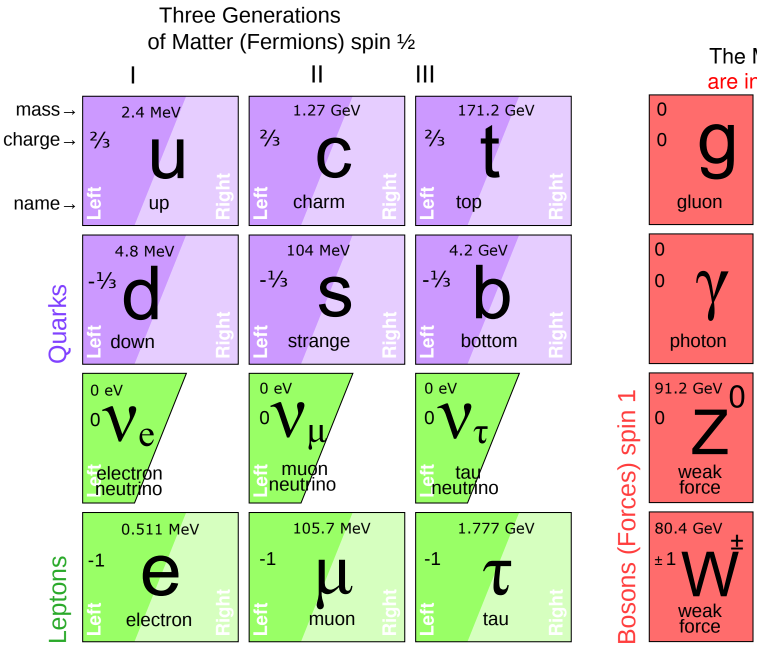
$$\text{Spins:}\;\; \frac{1}{2} \;\to\; \frac{1}{2} \quad \frac{1}{2} \quad \frac{1}{2}$$

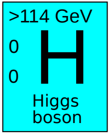
- Conserves leptonic numbers L_e, L_μ, L_τ

$$L_e(n) = 0 \implies L_e(\bar{\nu}_e) = -L_e(e)$$
$$L_e(\nu_e) = -L_e(\bar{\nu}_e)$$









spin 0

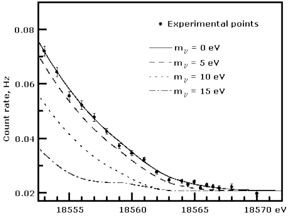
$m_H \approx 125\,\mathrm{GeV}$

The Matter generations
are indistinguishable by
electric
weak and
strong
forces

distinguishable
by gravity
and Yukawa
forces

Direct searches for m_ν: cut in e-spectrum

$$\mathrm{T} \to {}^3\mathrm{He} + e + \bar{\nu}_e$$
$$(pnn) \to (ppn) + e + \bar{\nu}_e$$



INR RAS, 1990-2000 years: $m_{\bar{\nu}_e} \lesssim 2\,\mathrm{eV}$

Cosmology:

- noticable contribution to Dark Matter at $m_{\bar{\nu}_e} \sim 20\,\mathrm{eV}$
- present limits from cosmology:

$$\sum_i m_{\nu_i} \lesssim 0.4\,\mathrm{eV}$$

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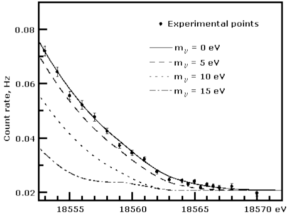

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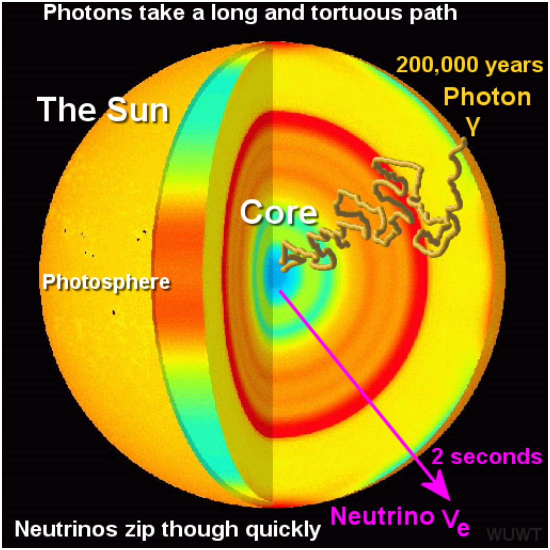
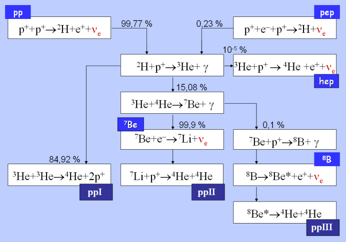
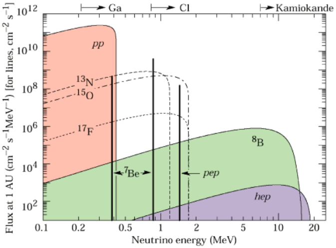
Solar neutrinos: fusion $p + p \to D + e^{+} + \nu_e, \ldots$



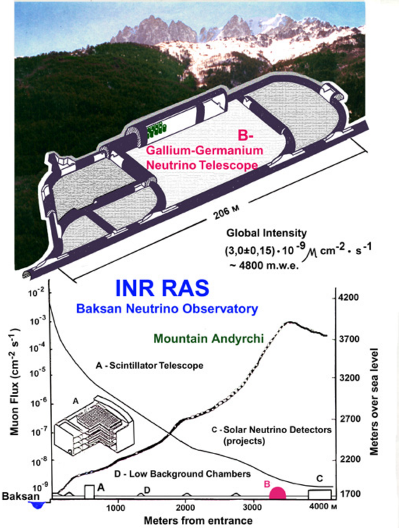


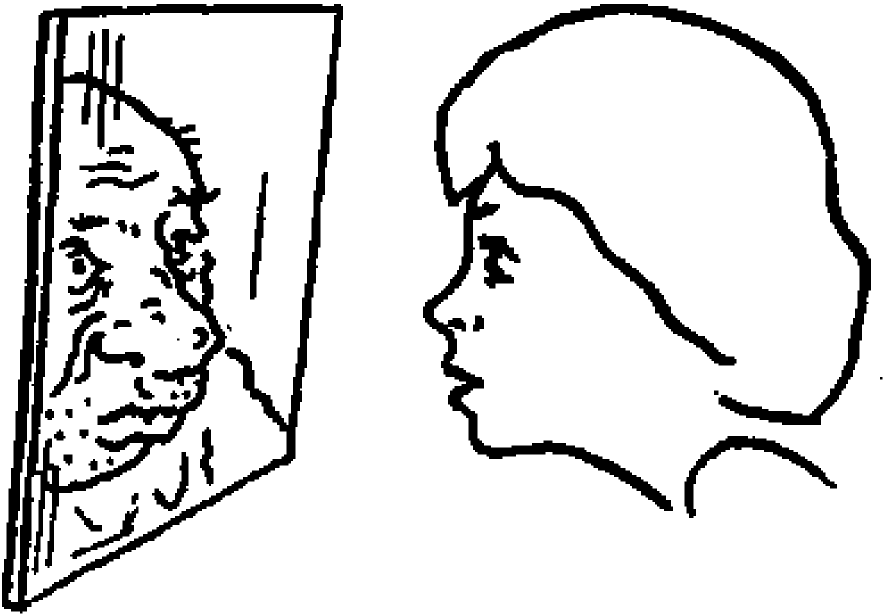


Measurement of the solar neutrino flux

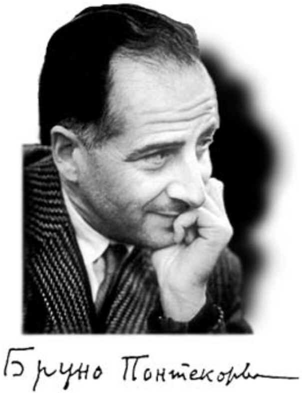
Sun: $p+p \to {}^2H + e^+ + \nu_e$

Earth: ${}^{71}\mathrm{Ga} + \nu_e \to {}^{71}\mathrm{Ge} + e^-$





Solar neutrino deficit!!! confirmed (2 Nobel Prizes)



All neutrinos interact similarly: can mix !

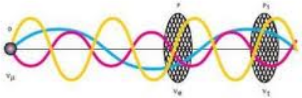
$$\nu_e \to \nu_\mu$$

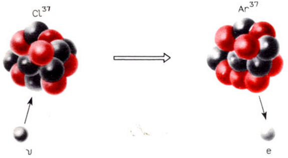
processes are forbidden in SM with massless neutrinos

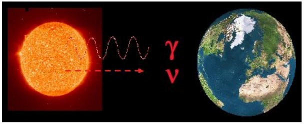
Something must distinguish flavors

Neutrinos are massive!

SM in incomplete!







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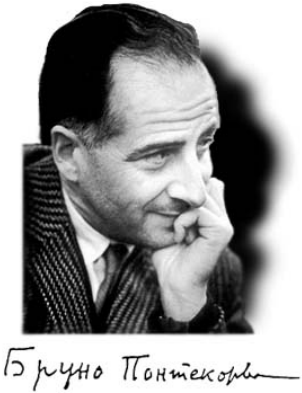

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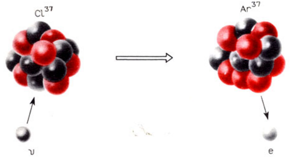

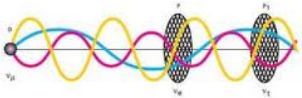

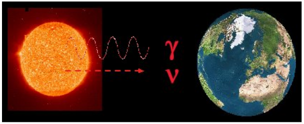

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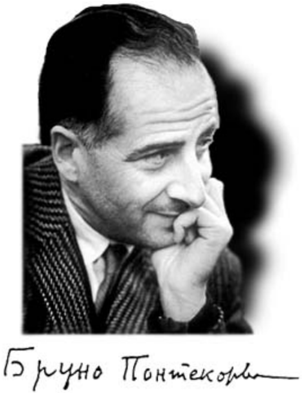

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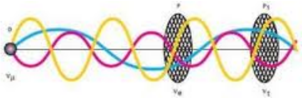
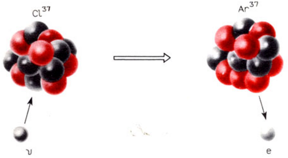
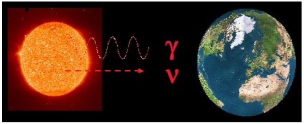






Description of neutrino oscillations (I)

- Two bases: gauge $|\nu_\alpha\rangle$, $\alpha = e,\ \mu,\ \tau$ and mass $|\nu_i\rangle$, $i = 1,2,3$

$$|\nu_i\rangle = U_{\alpha i}|\nu_\alpha\rangle \qquad \text{with unitary PMNS } 3\times 3 \text{ matrix} \quad U_{\alpha i}$$

- Neutrino mass matrix is then

$$M_{\alpha\beta} = \langle\nu_\alpha|M|\nu_\beta\rangle = (UM^{(m)}U^\dagger)_{\alpha\beta}\ , \quad \text{where} \quad M^{(m)}_{ij} = m_i\delta_{ij}\ .$$

- Free neutrino evolution in time and space

$$|\nu_j(t)\rangle = \mathrm{e}^{-im_jt}|\nu_j(0)\rangle \qquad |\nu_j(t,L)\rangle = \mathrm{e}^{-i\left(E_jt-p_jL\right)}|\nu_j(0)\rangle\ ,$$

in ultrarelativistic case

$$p_j = \sqrt{E^2 - m_j^2} = E - m_j^2/2E \qquad |\nu_j(L)\rangle = \mathrm{e}^{-i\frac{m_j^2}{2E}L}|\nu_j(0)\rangle\ .$$

Description of neutrino oscillations (II)

- Neutrino effective Hamiltonian

$$|\nu_j(L)\rangle = \mathrm{e}^{-i\frac{m_j^2}{2E}L}|\nu_j(0)\rangle \quad \to H_{eff} = \frac{M^2}{2E}$$

- Transition amplitude of neutrino ν_α to neutrino ν_β is

$$A(\alpha\to\beta) = \sum_j \langle\nu_\beta|\nu_j(L)\rangle\langle\nu_j(0)|\nu_\alpha\rangle = \sum_j \langle\nu_\beta|\nu_j\rangle \mathrm{e}^{-i\frac{m_j^2}{2E}L}\langle\nu_j|\nu_\alpha\rangle = \sum_j U_{\beta j}\mathrm{e}^{-i\frac{m_j^2}{2E}L}U^*_{\alpha j}$$

- and the transition probability $\Delta m_{ji}^2 \equiv m_j^2 - m_i^2$

$$P(\nu_\alpha\to\nu_\beta) = |A(\alpha\to\beta)|^2$$
$$= \delta_{\alpha\beta} - 4\sum_{j>i}\mathrm{Re}[U^*_{\alpha j}U_{\beta j}U_{\alpha i}U^*_{\beta i}]\sin^2\left(\frac{\Delta m_{ji}^2}{4E}L\right)$$
$$+2\sum_{j>i}\mathrm{Im}[U^*_{\alpha j}U_{\beta j}U_{\alpha i}U^*_{\beta i}]\sin\left(\frac{\Delta m_{ji}^2}{2E}L\right),$$

Description of neutrino oscillations (III)

- Two-neutrino oscillations: transition probability

$$P(\nu_\alpha \to \nu_{\beta\neq\alpha}) = \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2}{4E} L\right) ,$$

- Two-neutrino oscillations: survival probability

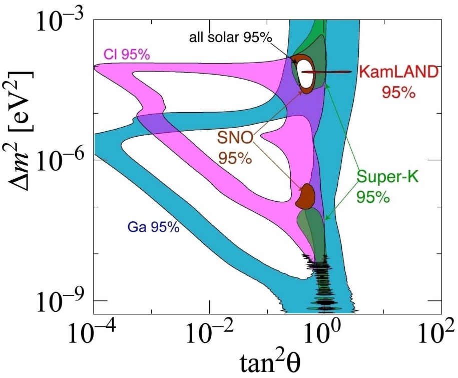
$$P(\nu_\alpha \to \nu_\alpha) = 1 - \sin^2 2\theta \cdot \sin^2\left(\frac{\Delta m^2}{4E} L\right)$$

- Oscillation length

$$L_{osc} = \frac{4\pi E}{\Delta m^2} = (2.5\ \text{km}) \cdot \frac{E}{\text{GeV}} \frac{\text{eV}^2}{\Delta m^2}$$

Neutrino oscillations: masses and mixing angles

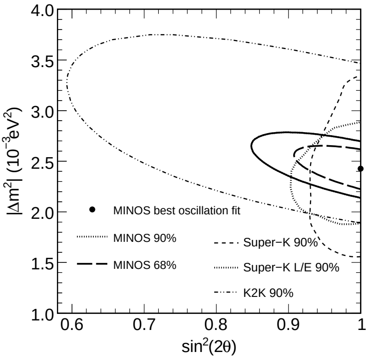
Solar 2×2 "subsector"



http://hitoshi.berkeley.edu/neutrino/

$m_1 > 0.008\,\text{eV}$

Atmospheric 2×2 "subsector"



arXiv:0806.2237

$m_2 > 0.05\,\text{eV}$

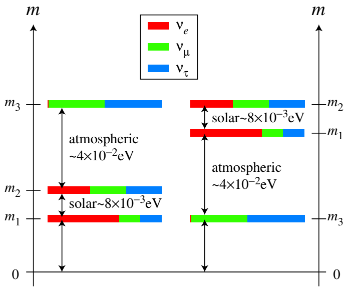
DAYA-BAY, RENO, T2K: $\sin^2 2\theta_{13} \approx 0.08$

Active neutrinos: normal and inverted hierarchy

Only mass squared are fixed, neutrino masses are model-dependent

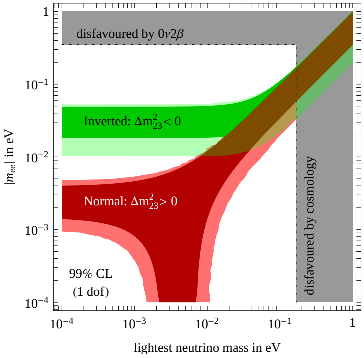
to be determined by T2K&Novνae

CP ??



normal inverted

hierarchy



$$|m_{ee}| = \left|\sum U_{ei}^2 m_i\right|,$$ if Majorana masses 1205.3867

Outline

Active neutrino masses without new fields

Dimension-5 operator $\Delta L = 2$

$$\mathscr{L}^{(5)} = \frac{\beta_L}{4\Lambda} F_{\alpha\beta} \bar{L}_\alpha \tilde{H} H^\dagger L^c_\beta + \text{h.c.}$$

L_α are SM leptonic doublets, $\alpha = 1,2,3$, $\tilde{H}_a = \varepsilon_{ab} H^*_b$, $a,b = 1,2$; in a unitary gauge $H^T = \left(0, (v+h)/\sqrt{2}\right)$ and

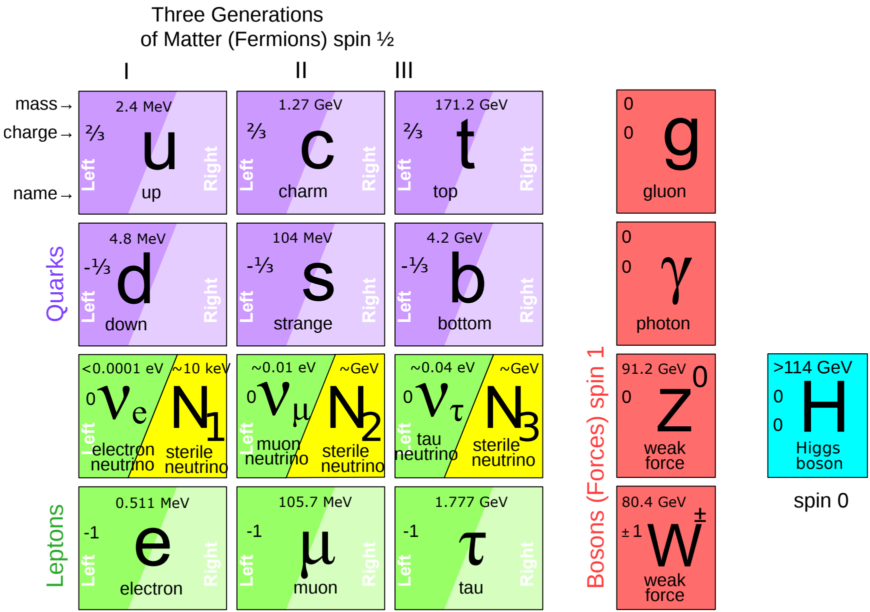
$$\mathscr{L}^{(5)}_{\nu\nu} = \frac{\beta_L v^2}{4\Lambda} \frac{F_{\alpha\beta}}{2} \bar{\nu}_\alpha \nu^c_\beta + \text{h.c.}$$

hence

$$\Lambda \sim 3 \times 10^{14}\,\text{GeV} \times \beta_L \times \left(\frac{3 \times 10^{-3}\,\text{eV}^2}{\Delta m^2_{\text{atm}}}\right)^{1/2}$$

The model has to be UV-completed at the neutrino scale $\Lambda_\nu < \Lambda$

What is beyond the neutrino scale Λ_ν ?


Three Generations
of Matter (Fermions) spin ½
I
II
III
mass →
charge →
name →
2.4 MeV
⅔
u
up
1.27 GeV
⅔
c
charm
171.2 GeV
⅔
t
top
0
0
g
gluon
Quarks
4.8 MeV
-⅓
d
down
104 MeV
-⅓
s
strange
4.2 GeV
-⅓
b
bottom
0
0
γ
photon
<0.0001 eV
~10 keV
0
ν_e
N_1
electron neutrino
sterile neutrino
~0.01 eV
~GeV
0
ν_μ
N_2
muon neutrino
sterile neutrino
~0.04 eV
~GeV
0
ν_τ
N_3
tau neutrino
sterile neutrino
Bosons (Forces) spin 1
91.2 GeV
0
Z^0
weak force
>114 GeV
0
0
H
Higgs boson
spin 0
Leptons
0.511 MeV
-1
e
electron
105.7 MeV
-1
μ
muon
1.777 GeV
-1
τ
tau
80.4 GeV
±1
$W^\pm$
weak force
Left
Right

Sterile neutrino lagrangian

Most general renormalizable with 2(3...) right-handed neutrinos N_I

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

Parameters to be determined from experiments

9(7): active neutrino sector

- 2 Δm_{ij}^2: oscillation experiments
- 3 θ_{ij}: oscillation experiments
- 1 CP-phase: oscillation experiments
- 2(1) Majorana phases: $0\nu ee$, $0\nu\mu\mu$
- 1(0) m_ν: ${}^3\text{H} \to {}^3\text{He} + e + \bar{\nu}_e$, cosmology, ...

11: $N = 2$ sterile neutrinos (works if $m_\nu = 0$!!!)

- 2: Majorana masses M_{N_I}
- 9: New Yukawa couplings $f_{\alpha I}$ which form
  - 2: Dirac masses $M^D = f\langle H \rangle$
  - 3+1: mixing angles
  - 2+1: CP-violating phases

4 new parameters in total

18: $N = 3$ sterile neutrinos:

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Profit: can suggest why neutrinos are so light, $m_\nu \sim 0.1 - 0.01$ eV

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check number! ✍

Profit: can suggest why neutrinos are so light, $m_\nu \sim 0.1 - 0.01$ eV

Seesaw mechanism: $M_N \gg 1\,\text{eV}$

With $m_{active} \lesssim 1\,\text{eV}$ we work in the seesaw (type I) regime:

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

When Higgs gains $\langle H\rangle = v/\sqrt{2}$ we get in neutrino sector triplet Higgs ϕ (type II) $\bar{L}\phi L \to m_\nu \nu\nu$

$$\mathscr{V}_N = v\,\frac{f_{\alpha I}}{\sqrt{2}}\,\overline{\nu}_\alpha N_I + \frac{M_{N_I}}{2}\overline{N}_I^c N_I + \text{h.c.} = \left(\overline{\nu}_1, \dots \overline{N}_1^c \dots\right) \begin{pmatrix} 0 & v\,\frac{\hat{f}}{\sqrt{2}} \\ v\,\frac{\hat{f}^\dagger}{\sqrt{2}} & \hat{M}_N \end{pmatrix} \left(\nu_1, \dots N_1 \dots\right)^{\mathrm{T}}$$

Then for $M_N \gg \hat{M}^D = v\,\frac{\hat{f}}{\sqrt{2}}$ we find the eigenvalues:

$$\simeq \hat{M}_N \quad \text{and} \quad \hat{M}^\nu = -(\hat{M}^D)^\dagger \frac{1}{\hat{M}_N}\hat{M}^D \propto f^2 \frac{v^2}{M_N} \lll M_N$$

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

active-active mixing: $U^\dagger \hat{M}^\nu U = diag\,(m_1, m_2, m_3)$

active-sterile mixing: $\theta_{\alpha I} = \frac{(M^D)^\dagger_{\alpha I}}{M_I} \propto \hat{f}^\dagger \frac{v}{M_N} \ll 1$

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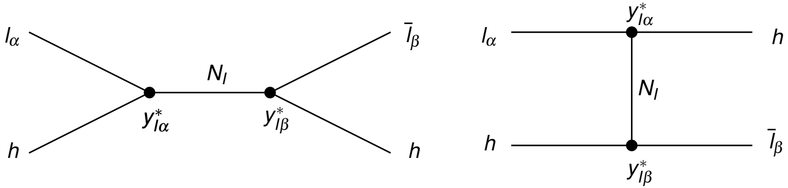
Producing the effective dim-5 operator at $M_N \to \infty$

i.e., integrating out the Heavy Sterile neutrinos



thus we obtain

$$\propto \frac{y^2}{M_N} lhlh \quad \to \quad \frac{(LH)(LH)}{\Lambda}$$

Outline

Seesaw mechanism: sterile neutrino scale

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SEESAW says nothing about the sterile neutrino scale M_I !

Unitarity: $f \lesssim 1 \quad \Longrightarrow \quad M_N \lesssim 3 \times 10^{14}\,\text{GeV} \times \left(\frac{3{\cdot}10^{-3}\,\text{eV}^2}{\Delta m^2_{atm}}\right)^{1/2} \longrightarrow \Lambda$ in $(LH)^2/\Lambda$

At given M_N without fine tuning the scale of Yukawas $\hat{f}$ and strength of active-sterile mixing $\theta_{\alpha I} = \frac{(M^D)^\dagger_{\alpha I}}{M_I} \propto \hat{f}\frac{v}{M_N} \ll 1$ are fixed

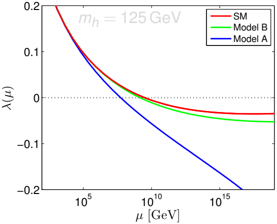
1203.3825

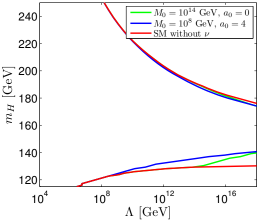
With fine tuning in $\hat{f}^\dagger \hat{f}$ can have larger f:

and change the Higgs mass window

$$\frac{d\lambda}{d\log\mu} \propto \lambda^2 + \lambda\, tr(\hat{f}^\dagger \hat{f}) - tr(\hat{f}^\dagger \hat{f} \hat{f}^\dagger \hat{f})$$

$$m_h^2 = 2\lambda v^2$$





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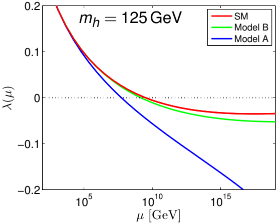

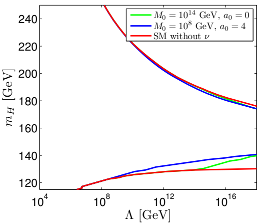

Where is sterile neutrino scale?

eigenvalues: $\simeq \hat{M}_N$ and $\hat{M}^\nu = -\hat{M}^{D\,T}\frac{1}{\hat{M}_N}\hat{M}^D \propto f^2\frac{v^2}{M_N} \lll M_N$

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Integrating out sterile neutrinos get dim-5 operator $\quad -f_{\alpha I}\bar{L}_\alpha\tilde{H}N_I - \frac{M_{N_I}}{2}\bar{N}_I^c N_I \to f^2(LH)^2/M_N$

SM Higgs without NP at EW-scale favors sterile neutrinos at EW-scale (or below) !

- Majorana mass violates scale-invarinace $\Longrightarrow$ finite corrections $\quad \delta m_h^2 \propto f^2 M_N^2$
- Scale invariance helps to abandon infinite corrections $\quad \delta m_h^2 \propto f^2\Lambda^2 M_N^2$
- In SM scale invariance is broken by the Higgs mass and running of coupling constants
  $T^\mu_\mu \propto \beta(\alpha)\times\hat{O} + \left(m_h^2 + \alpha\Lambda^2\right)\times h^2 \quad \Longrightarrow$ quadratic divergences are irrelevant

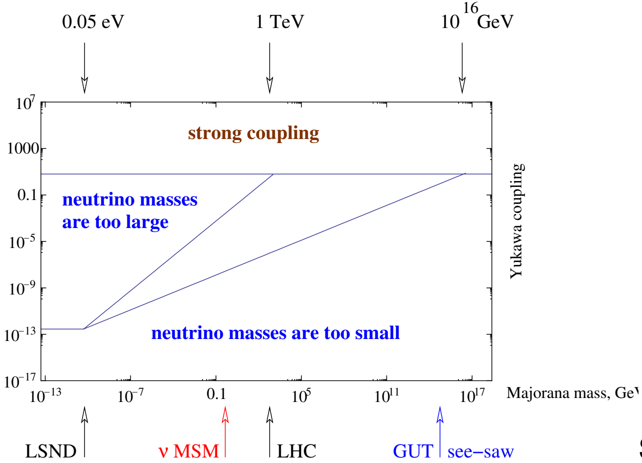
W.Bardeen (1995)

Sterile neutrino mass scale: $\hat{M}_\nu = -v^2 \hat{f}^T \hat{M}_N^{-1} \hat{f}$

NB: With fine tuning in $\hat{M}_N$ and $\hat{f}$ we can get a hierarchy in sterile neutrino masses, and 1 keV and even 1 eV sterile neutrinos

$L_e - L_\mu - L_\tau$ or discrete symmetries
Froggatt-Nielsen mechanism

Extended seesaw



Seesaw diagram

Outline

Bonus: depends on the sterile neutrino mass range

NB: With fine tuning in $\hat{M}_N$ and $\hat{f}^\dagger \hat{f}$ we can get a hierarchy in sterile neutrino masses, and 1 keV and even 1 eV sterile neutrinos

$L_e - L_\mu - L_\tau$ or discrete symmetries

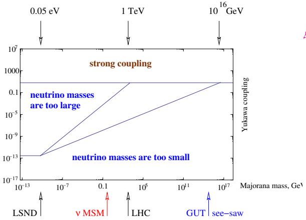
Froggatt-Nielsen mechanism

Extended seesaw

Prove:

If $\mathrm{Tr}[f^\dagger f]v^2 > \mathrm{Tr}[\hat{M}_N^\dagger \hat{M}_N]$

Then Max $m_i^2 > \mathrm{Tr}[f^\dagger f]v^2$



There are different regions:

$M_N \sim$ 1 eV-5 GeV

- keV-scale dark matter
- BAU via leptogenesis
- Neutrino anomalies (1 eV sterile neutrinos?)

direct searches!

$M_N \sim$ 50 GeV-5 TeV

- BAU via leptogenesis

$f \sim 10^{-6} \simeq Y_e$

but with fine tuning or new global or gauge symmetries (e.g. $SU(2)_L \times SU(2)_R$)

direct searches at LHC

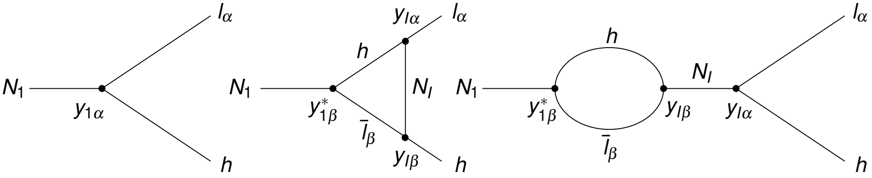
$M_N \sim 10^{12}$-10^{14} GeV

- BAU via leptogenesis

$f \simeq 0.01 - 1$

Untestable. . . ?

Lepton asymmetry δ at 1-loop level $\quad y_{I\alpha}\bar{L}_\alpha N_I \widetilde{H}$



$$\Gamma(N_1 \to lh) = \frac{M_1}{8\pi} \cdot \sum_\alpha \left| y_{1\alpha} + \frac{1}{8\pi} \sum_{\beta,I} f\left(\frac{M_1}{M_I}\right) \cdot y^*_{1\beta} y_{I\alpha} y_{I\beta} \right|^2 , \quad m_\nu \ll M_I$$

$$\delta \equiv \frac{\Gamma(N_1 \to lh) - \Gamma(N_1 \to \bar{l}h)}{\Gamma_{tot}} = \frac{1}{8\pi} \sum_{I=2,3} f\left(\frac{M_1}{M_I}\right) \cdot \frac{\mathrm{Im}\left(\sum_\alpha y_{1\alpha} y^*_{I\alpha}\right)^2}{\sum_\gamma |y_{1\gamma}|^2} .$$

$$M_{2,3} \gg M_1 \;, f\left(\frac{M_1}{M_I}\right) = -\frac{3}{2}\frac{M_1}{M_I} , \quad \delta = -\frac{3\,M_1}{16\pi} \frac{1}{\sum_\gamma |y_{1\gamma}|^2} \sum_{\alpha\beta I} \mathrm{Im}\left[y_{1\alpha} y_{1\beta} \left(y^*_{I\alpha} \frac{1}{M_I} y^*_{I\beta} \right) \right] .$$

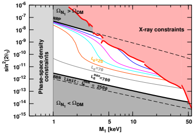
Heavy sterile neutrinos: $M_N \simeq 1\,\text{keV-}5\,\text{GeV}$ νMSM

T.Asaka, S.Blanchet, M.Shaposhnikov (2005)

- Good fact: small finite quantum corrections $\delta m_H^2 \propto f^2 M_N^2 \ll m_H^2$
  True low-energy scale modification of the SM
- Good fact: At $T > 100\,\text{GeV}$ active-sterile neutrino oscillations produce lepton asymmetry in the early Universe, if $\Delta M_N \ll M_N$ E.Akhmedov, V.Rubakov, A.Smirnov (1998)
- To make phenomenologically complete: Dark Matter?
  - NOT a seesaw neutrino! $m_\nu \ll m_{atm,sol}$ general statement

    $$\tau_{N\to 3\nu} \sim 1/\left(G_F^2 M_N^5 \theta_{\alpha N}^2\right) \sim 1/\left(G_F^2 M_N^4 m_\nu\right) \sim 10^{11}\,\text{yr}\,(10\,\text{keV}/M_N)^4$$

    either decay or equilibrate and then contribute to hot dark matter
  - production in primordial plasma due to mixing with active neutrinos is ruled out from searches at X-ray telescopes



$$\Gamma_{N\to\nu\gamma} \simeq 5.5\times 10^{-22}\theta_1^2\left(\frac{M_1}{1\text{ keV}}\right)^5 \text{s}^{-1}$$ a narrow line $(\delta E_\gamma/E_\gamma \sim v \sim 10^{-3})$ at $E_\gamma = M_N/2$

  - Possible for 1-50 keV (WDM-CDM range) either with further unbelievable fine-tuning in M_{N_I} ($\Delta M_N \sim 10^{-7}$ eV) to get $L \gg B$ and use the resonant production or with ANOTHER source of production, e.g. inflaton decays..

M.Shaposhnikov, I.Tkachev (2006), F.Bezrukov, D.G. (2009)

Light sterile neutrinos: $M_N \lesssim 1\,\text{eV}$

- For $M_N \sim m_\nu$ generally the active-sterile mixing is not small, $\theta_{se} \sim 1 - 0.1 \ldots$
  Is it dangerous? acceptable? preferable?
- Some 5 years ago It was preferable!
- They participate with active neutrinos in oscillations...
  (Neutrino anomalies at:
  LSND, gallium experiments, MiniBooNE, reactor experiments)

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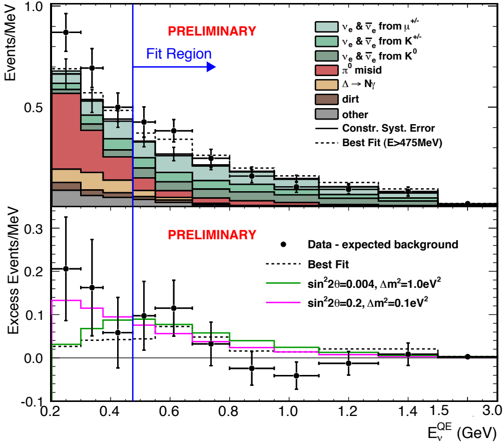
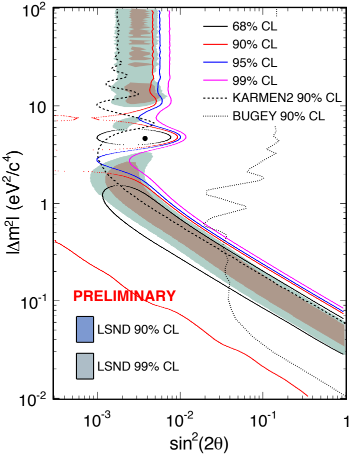
LSND & MiniBooNE anomalies in $\bar{\nu}_\mu \to \bar{\nu}_e$



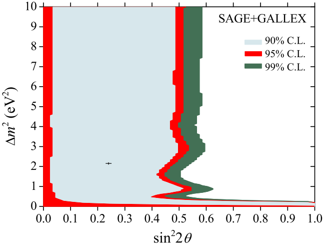


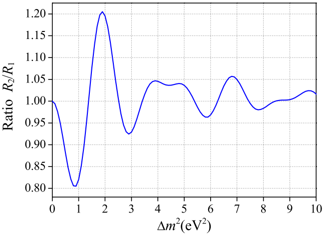
ν_e for ν_μ mode at MiniBooNE: no LSND-like effects,
However Low energy excess of ν_e
Explanation by $\nu_\mu \to N$, $N \to \gamma\nu$, S.Gninenko (2007,2010)

NuFuct2011, 1201.1519

LSND-like oscillations are preferable only at 90%CL

Gallium anomaly: SAGE and GALLEX, $\nu_e \to N$?



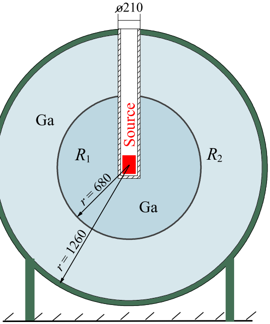


for $\sin^2 2\theta = 0.3$

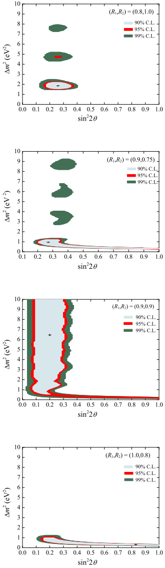
^{71}Ga$\to$^{71}Ge
due to ^{51}Cr and ^{37}Ar sources

$$\frac{N^{obs}}{N^{exp}} = 0.87 \pm 0.05$$

SAGE proposal of the test: 1006.2103

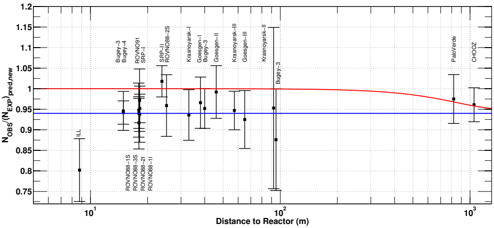


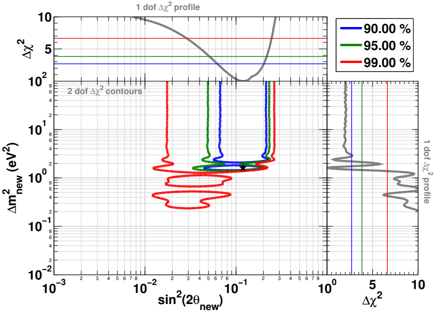
intensive ν-source ^{51}Cr



Reactor anomaly: $\bar{\nu}_e \to N$?

G.Mention et al. (2011)





Deficite due to 6% correction to $\bar{\nu}_e$ budget

- new nuclear rates
- new neutron life-time:

$$\tau_n : 926\,\mathrm{s} \to 886\,\mathrm{s}$$

However: the value of uncertainty remains the same, $\sim 3\%\ldots$

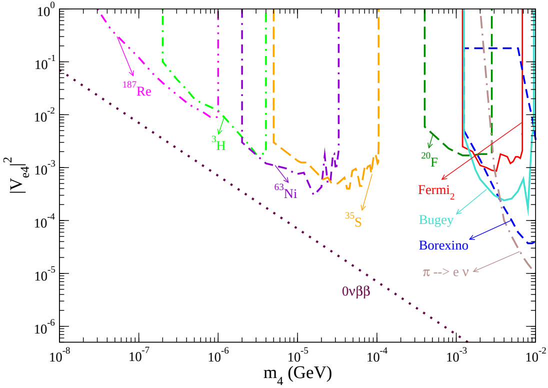
Combined fit to Reactor and Gallium data

Bunch of proposals to test the anomaly...

see 1204.5379

Light sterile neutrinos: $M_N \lesssim 1$ eV

Essentially no bounds from kink searches, and even from $0\nu\beta\beta$



0901.3589: $0\nu\beta\beta$-bound is stronger by 10, 1205.3867

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  (Neutrino anomalies at:
  LSND, gallium experiments, MiniBooNE, reactor experiments)
- No contribution to SM processes:

$$\mathrm{Br}^{\mathrm{SM}}_{W\to\mu\bar{\nu}} = \mathrm{Br}_{W\to\mu\bar{\nu}} + \mathrm{Br}_{W\to\mu\bar{N}} = \mathrm{Br}^{\mathrm{SM}}_{W\to\mu\bar{\nu}} \times \cos^2\theta + \mathrm{Br}^{\mathrm{SM}}_{W\to\mu\bar{\nu}} \times \sin^2\theta$$

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- Impact on astrophysics (say, SN explosion) — e.g., G.Raffelt (2010)
- We certainly change cosmology... (BBN, CMB, structure formation, etc.)

$$\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\right]\rho_\gamma\,, \qquad \Omega_\nu = \frac{\sum m_{\nu_i}}{93\,h^2\,\mathrm{eV}}$$

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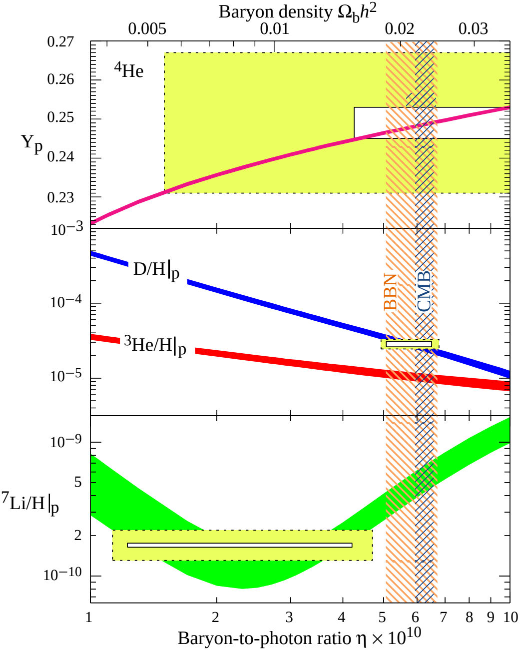
- We certainly change cosmology... (BBN, CMB, structure formation, etc.)

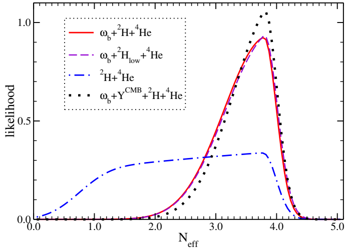
$$\rho_r = \left[1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\right]\rho_\gamma\,, \qquad \Omega_\nu = \frac{\sum m_{\nu_i}}{93\,h^2\,\mathrm{eV}}$$



$$Y_p = 0.2581 \pm 0.025\,,$$

$$D/H\big|_p = (2.87 \pm 0.21) \times 10^{-5}$$

1103.1261



similar results from other recent studies including structure formation

1001.4440, 1001.5218, 1202.2889

$N_\nu < 4.2$ @ 95%CL

$N_\nu < 4.3$ with shorter neutron's life...

Light sterile neutrinos at recombination and later

With larger N_ν and fixed Ω_M we get later RD/MD transition, hence:

- DM perturbations start to grow $\delta\rho_{DM}/\rho_{DM} \propto a$ later
- gravity potential evolution changes later
- oscillations in baryon-photon plasma change

CMB is sensitive to $\left(T_{eq} - T_{rec}\right)$!

LSS is sensitive to T_{eq}
if initial $\delta\rho_{DM}/\rho_{DM}$ is fixed

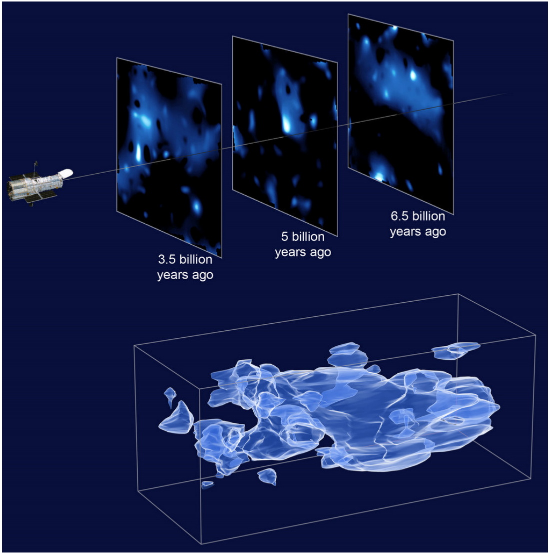
Sterile neutrinos become nonrelativistic at $T \sim M_{\nu_s}/3 \sim 0.1 - 0.3$ eV ...

- neutrinos start to contribute to $\rho_M \propto 1/a^3$
- neutrino perturbations of large lengths contribute to DM perturbations $\delta\rho_M$
- neutrino perturbations of small scales disappear because of free streaming (Landau damping)
- oscillations in baryon-photon plasma change

LSS is sensitive to both N_ν and M_{ν_s}...
Not to forget about active neutrino masses!

1 eV neutrino contributes to dark matter but only a tiny amount!

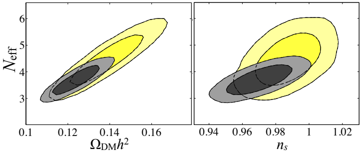
LSS: SZ-clusters, Weak lensing of CMB



- ΔN_ν amplifies shear power: cancel with quintessence contribution and flattening of spectrum, $n_s \to 1$
- M_N reduces power

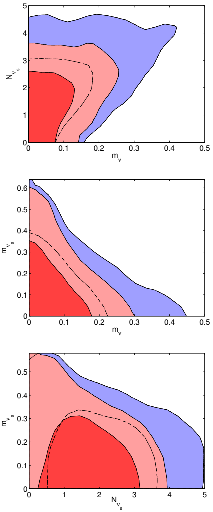
$$N_{eff} = 3 \to M_\nu < 0.46\,\text{eV}$$
$$M_\nu = 0 \to N_{eff} = 3.8 \pm 0.4$$
$$M_\nu < 0.62\,\text{eV} \to N_{eff} = 3.9 \pm 0.4$$

1212.3608



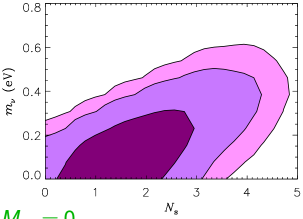
Combined analysis for sterile and active neutrinos

WMAP7+LRG+HST

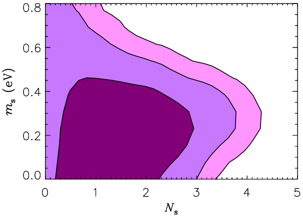


flat ΛCDM 1102.4774

CMB+SDSS+HST



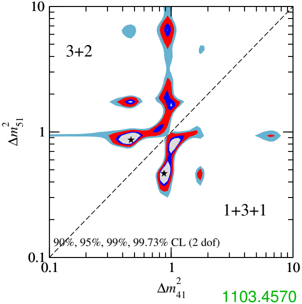
$M_{\nu_s} = 0$



$m_\nu = 0$

flat ΛCDM 1006.5276

LSND+MiniBooNE



1103.4570

"3+1" :

$\Delta m^2_{41} = 1.76\,\mathrm{eV}^2$, $|U_{e4}| = 0.151$

"3+2" :

$\Delta m^2_{41} = 0.46\,\mathrm{eV}^2$, $|U_{e4}| = 0.108$

$\Delta m^2_{51} = 0.89\,\mathrm{eV}^2$, $|U_{e5}| = 0.124$

BBN rules out "3+2"

For "3+1" to allow $M_N \gtrsim 1$ eV for CMB and LSS we need a new ingredient

talk by A.Starobinsky

Light sterile neutrinos: $M_N \lesssim 1$ eV

- For $M_N \sim m_\nu$ generally the active-sterile mixing is not small, $\theta_{se} \sim 1 - 0.1 \ldots$
  Is it dangerous? acceptable? preferable?
- Some 5 years ago It was preferable! Now it seems forbidden
- They participate with active neutrinos in oscillations...
  (Neutrino anomalies at:
  LSND, gallium experiments, MiniBooNE, reactor experiments)
- No contribution to SM processes:

$$\mathrm{Br}^{\mathrm{SM}}_{W\to\mu\bar{\nu}} = \mathrm{Br}_{W\to\mu\bar{\nu}} + \mathrm{Br}_{W\to\mu\bar{N}} = \mathrm{Br}^{\mathrm{SM}}_{W\to\mu\bar{\nu}} \times \cos^2\theta + \mathrm{Br}^{\mathrm{SM}}_{W\to\mu\bar{\nu}} \times \sin^2\theta$$

$$\mathrm{Br}^{\mathrm{SM}}_{Z\to\nu\bar{\nu}} = \mathrm{Br}_{Z\to\nu\bar{\nu}} + \mathrm{Br}_{Z\to N\bar{\nu}} + \mathrm{Br}_{Z\to\nu\bar{N}} + \mathrm{Br}_{Z\to N\bar{N}} = \mathrm{Br}^{\mathrm{SM}}_{Z\to\nu\bar{\nu}} \times \cos^4\theta$$
$$+ \mathrm{Br}^{\mathrm{SM}}_{Z\to\nu\bar{\nu}} \times \cos^2\theta \times \sin^2\theta + \mathrm{Br}^{\mathrm{SM}}_{Z\to\nu\bar{\nu}} \times \sin^2\theta \times \cos^2\theta + \mathrm{Br}^{\mathrm{SM}}_{Z\to\nu\bar{\nu}} \times \sin^4\theta$$

- Impact on astrophysics (say, SN explosion, if needed) e.g., G.Raffelt (2010)
- We certainly change cosmology...
  (BBN, CMB, structure formation, etc.)
- Either special symmetry or not a seesaw: 1 eV by hand
  possible motivation: Mirror World?

Light sterile neutrinos: $M_N \lesssim 1$ eV

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$$\mathrm{Br}^{\mathrm{SM}}_{Z\to\nu\bar{\nu}} = \mathrm{Br}_{Z\to\nu\bar{\nu}} + \mathrm{Br}_{Z\to N\bar{\nu}} + \mathrm{Br}_{Z\to\nu\bar{N}} + \mathrm{Br}_{Z\to N\bar{N}} = \mathrm{Br}^{\mathrm{SM}}_{Z\to\nu\bar{\nu}} \times \cos^4\theta$$
$$+ \mathrm{Br}^{\mathrm{SM}}_{Z\to\nu\bar{\nu}} \times \cos^2\theta \times \sin^2\theta + \mathrm{Br}^{\mathrm{SM}}_{Z\to\nu\bar{\nu}} \times \sin^2\theta \times \cos^2\theta + \mathrm{Br}^{\mathrm{SM}}_{Z\to\nu\bar{\nu}} \times \sin^4\theta$$

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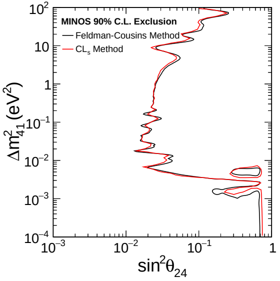
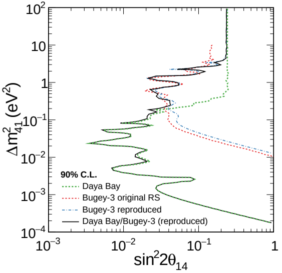
Experiment Daya Bay: $\bar{\nu}_e \to \bar{\nu}_e$

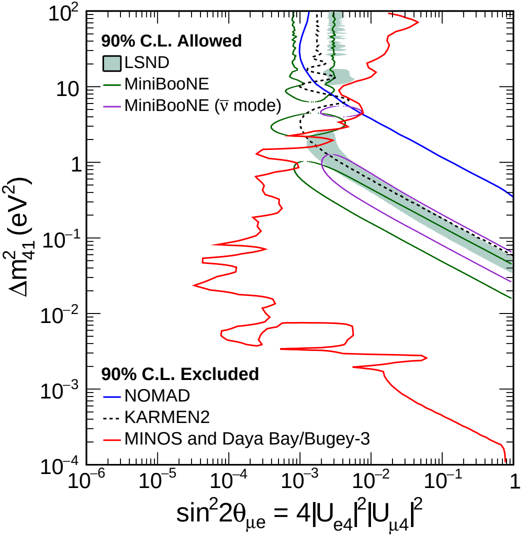
Experiment MINOS: $\bar{\nu}_\mu \to \bar{\nu}_\mu$, $\nu_\mu \to \nu_\mu$,

Looks like the anomaly is closed . . . ?

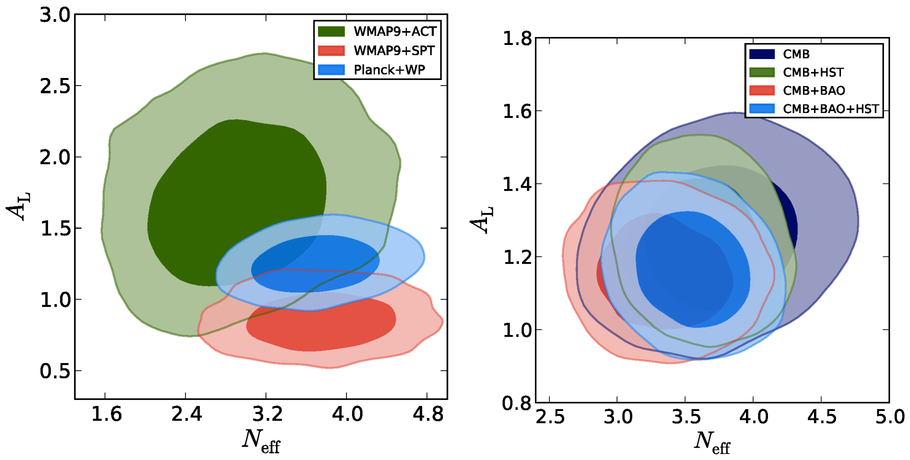
1607.01177







CMB lensing is far from canonical



1304.6217

Outline

Interplay: Standard Model and Cosmology

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

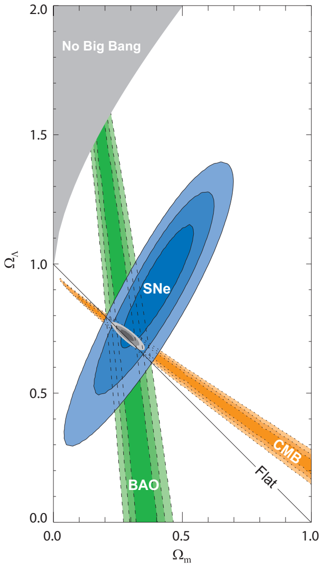
- SM Describes
  - all experiments dealing with electroweak and strong interactions
- SM fails to describe (PHENO) (THEORY)

(PHENO)	(THEORY)
Neutrino oscillations	Dark energy (Ω_Λ)
Dark matter (Ω_{DM})	Strong CP-problem
Baryon asymmetry (Ω_B)	Gauge hierarchy
Inflationary stage	Quantum gravity

Cosmology asks for new physics and limits neutrino mass

severely constrains many BSM relaxation..?

Astrophysical and cosmological data are in agreement



$$\left(\frac{\dot{a}}{a}\right)^2 = H^2(t) = \frac{8\pi}{3} G \rho_{\text{density}}^{\text{energy}}$$

$$\rho_{\text{density}}^{\text{energy}} = \rho_{\text{radiation}} + \rho_{\text{matter}}^{\text{ordinary}} + \rho_{\text{matter}}^{\text{dark}} + \rho_\Lambda$$

$$\rho_{\text{radiation}} \propto 1/a^4(t)\,, \quad \rho_{\text{matter}} \propto 1/a^3(t)\,, \quad \rho_\Lambda = \text{const}$$

$$\frac{3H_0^2}{8\pi G} = \rho_{\text{density}}^{\text{energy}}(t_0) \equiv \rho_c \approx 0.53 \times 10^{-5}\,\frac{\text{GeV}}{\text{cm}^3}$$

Radiation: $\Omega_\gamma \equiv \frac{\rho_\gamma}{\rho_c} = 0.5 \times 10^{-4}$

Baryons (H, He): $\Omega_B \equiv \frac{\rho_B}{\rho_c} = 0.05$

Neutrino: $\Omega_\nu \equiv \frac{\sum \rho_{\nu_i}}{\rho_c} < 0.01$

$N_\nu \simeq 3\,,\ \sum m_\nu \lesssim 0.2\,\text{eV}$

Dark matter: $\Omega_{DM} \equiv \frac{\rho_{DM}}{\rho_c} = 0.27$

Dark energy: $\Omega_\Lambda \equiv \frac{\rho_\Lambda}{\rho_c} = 0.68$

Dark Matter Properties

- dust-like pressureless component, $p = 0$
- clumping substance, gets confined in structures

If particles (or compact macroscopic objects):

1. stable on cosmological time-scale
2. electrically neutral
3. decoupled from visible matter
4. nonrelativistic long before RD/MD-transition, $v_{RD/MD} \lesssim 10^{-3}$
   free streaming prevents formation of small-scale structures

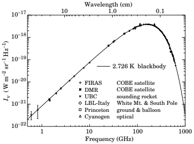
Key observable: matter perturbations

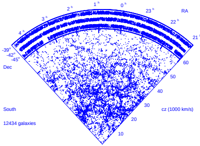
- CMB is isotropic, but “up to corrections, of course...”
  1. Earth movement with respect to CMB
     $$\frac{\Delta T_{\text{dipole}}}{T} \sim 10^{-3}$$
  2. More complex anisotropy: $\frac{\Delta T}{T} \sim 10^{-4}$
- There were matter inhomogenities $\Delta\rho/\rho \sim \Delta T/T$ at the stage of recombination ($e + p \to \gamma + H^*$) $\Longrightarrow$

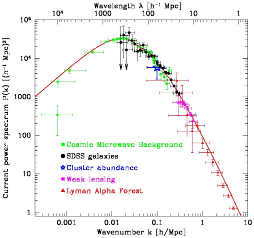
  Jeans instability in the system of gravitating particles at rest $\Longrightarrow$ $\Delta\rho/\rho \nearrow$ galaxies (CDM halos)
- $\Delta\rho_{DM}/\rho_{DM} \propto a \propto 1/T$ from $T = 0.8\,\text{eV}$,
  while $\Delta\rho_B/\rho_B \propto a \propto 1/T$ only after recombination
  $T = 0.25\,\text{eV}$

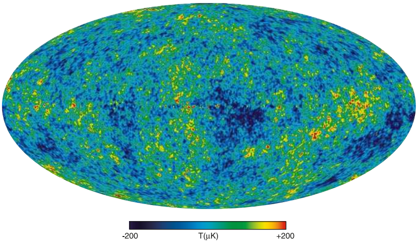
  without DM total growth factor would be 1100

  not enough to explain structures!

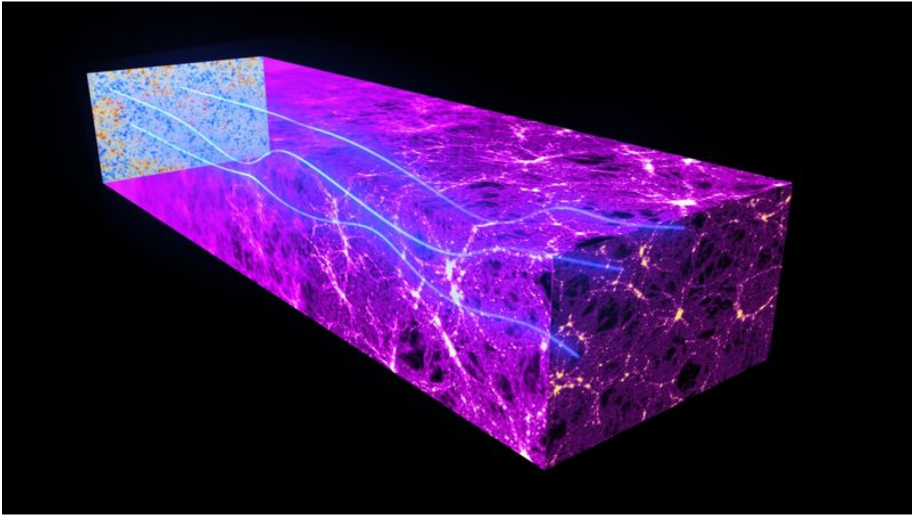








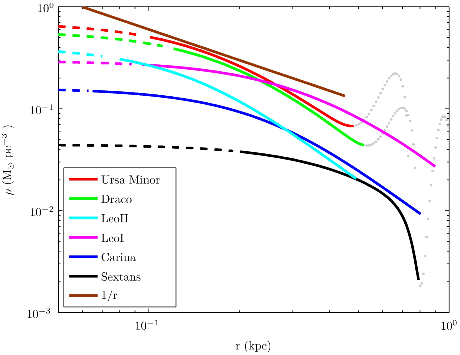
On top of that: propagation in expanding Universe



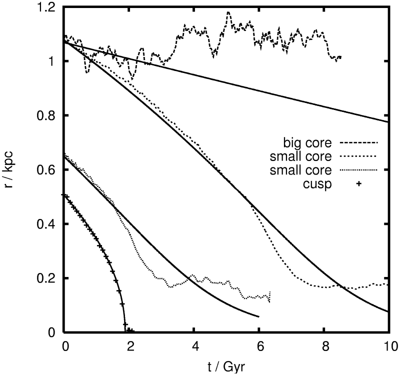
CDM Problems at small-scales ...?

- NFW profile fits nicely DM in galaxy clusters $\rho \propto r^{-1}(r+r_c)^{-2}$
- Dwarf galaxy density profiles: $\rho_M(r) \propto r^{-(0.5-1.5)}$ cusp
  most DM-dominated objects

Cores observed (?)

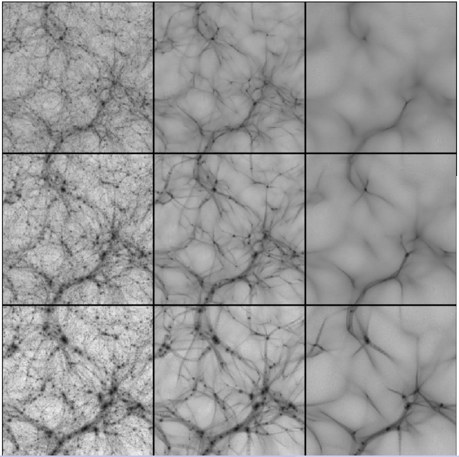


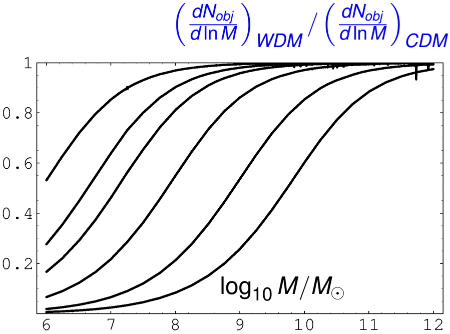
5 Clusters in the Fornax dSph



CDM Problems . . . ?

- Missing satellites: $\frac{dN_{obj}}{d\ln M} \propto \frac{1}{M}$ no-scale 100 instead of 1000
- "Too big to fail" problem
- Solved (?) by Warm Dark Matter (sterile neutrino, gravitino) free-streaming





Dark Matter properties from cosmology: $p = 0$

(If) particles:

1. stable on cosmological time-scale
   requires new (almost) conserved quantum number
2. produced in the early Universe
   some time before RD/MD-transition ($T = 0.8\,\text{eV}$)
3. nonrelativistic particles long before RD/MD-transition ($T = 0.8\,\text{eV}$)
   (either Cold or Warm, $v_{RD/MD} \lesssim 10^{-3}$)
   Otherwise no small-size structures, like dwarf galaxies:
   smoothed out by free streaming
   If were in thermal equilibrium: $M_X \gtrsim 1$ keV
4. (almost) collisionless $p = 0$, $v_{\text{sound}} = 0$
5. (almost) electrically neutral CMB distortion
6. all matter inhomogeneities (perturbations) are adiabatic:

$$\delta\left(\frac{n_B}{n_{DM}}\right) = \delta\left(\frac{n_B}{n_\gamma}\right) = \delta\left(\frac{n_\nu}{n_\gamma}\right) = 0$$

Dark Matter properties from astrophysics

1. stable on cosmological time-scale
2. (almost) collisionless — to form ellipsoidal halos
3. (almost) electrically neutral — to be Dark
4. stability of globular stellar clusters — $M_X \lesssim 10^3 M_\odot \approx 10^{61}$ GeV
   otherwise too strong tidal forces
5. confinement in a galaxy: — quantum physics!

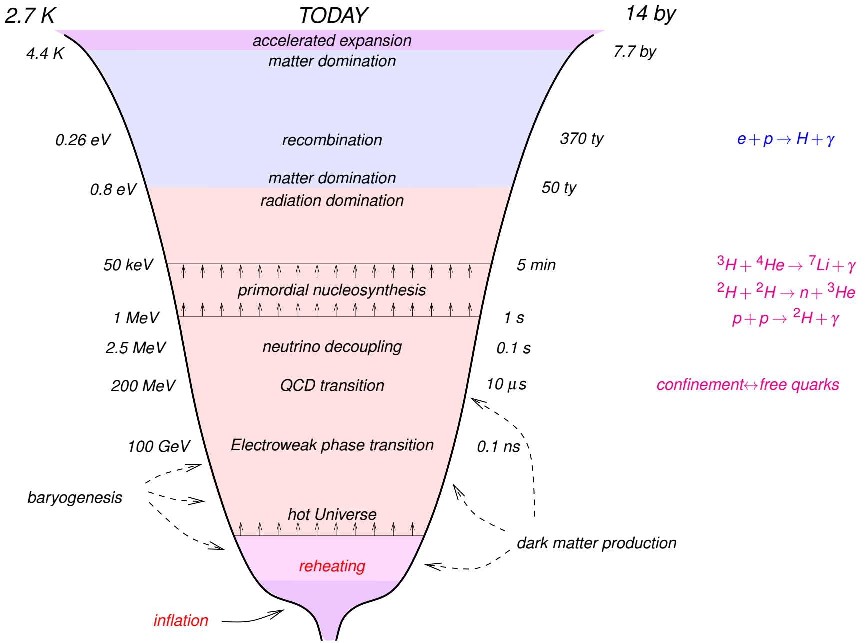
   de Broglie wavelength: $\lambda = 2\pi/(M_\mathrm{X} v_\mathrm{X}) < l_\mathrm{galaxy}$, — for bosons

   in a galaxy $v_\mathrm{X} \sim 0.5 \cdot 10^{-3}$ $\longrightarrow$ $M_\mathrm{X} \gtrsim 3 \cdot 10^{-22}$ eV

   for fermions

   Pauli blocking: — $M_\mathrm{X} \gtrsim 750$ eV

$$f(\mathbf{p},\mathbf{x}) = \frac{\rho_\mathrm{X}(\mathbf{x})}{M_\mathrm{X}} \cdot \frac{1}{\left(\sqrt{2\pi} M_\mathrm{X} v_\mathrm{X}\right)^3} \cdot \mathrm{e}^{-\frac{\mathbf{p}^2}{2M_\mathrm{X}^2 v_\mathrm{X}^2}} \Bigg|_{\mathbf{p}=0} \leq \frac{g_\mathrm{X}}{(2\pi)^3}$$


2.7 K
TODAY
14 by
accelerated expansion
4.4 K
matter domination
7.7 by
0.26 eV
recombination
370 ty
$e + p \to H + \gamma$
matter domination
0.8 eV
radiation domination
50 ty
50 keV
5 min
$^3H + {}^4He \to {}^7Li + \gamma$
primordial nucleosynthesis
$^2H + {}^2H \to n + {}^3He$
1 MeV
1 s
$p + p \to {}^2H + \gamma$
2.5 MeV
neutrino decoupling
0.1 s
200 MeV
QCD transition
10 μs
confinement↔free quarks
100 GeV
Electroweak phase transition
0.1 ns
baryogenesis
hot Universe
dark matter production
reheating
inflation

Microscopic processes in the expanding Universe

A competition between scattering, decays, etc and expansion

for general processes one should solve kinetic equations

$$\frac{dn_{X_i}}{dt} + 3Hn_{X_i} = \sum(production - destruction)$$

Boltzmann equation in a comoving volume: $\frac{d}{dt}\left(n\,a^3\right) = a^3\int\dots$

production:

$$\sigma(A+B\to X+C)n_An_B,\quad \Gamma(D\to E+X)n_D\cdot M_D/E_D,\quad \text{etc}$$

desrtuction:

$$\sigma(A+X\to C+B)n_An_X,\quad \Gamma(X\to F+G)n_X\cdot M_X/E_X,\quad \text{etc}$$

Fast direct and inverse processes, $\Gamma \gtrsim H$, are in equilibrium,

$\sum(\ ) = 0$ and thermalize particles

Decoupling of relativistic Dark Matter

Assumptions

1. DM particles are in equlibrium in plasma
2. DM decouple from plasma at temperature $T_d \gtrsim M_X$, so they are relativistic (e.g. neutrino)

$$n_X(T_d) = g_X \cdot \begin{pmatrix} 1 \\ \frac{3}{4} \end{pmatrix} \cdot \frac{\zeta(3)}{\pi^2} T_d^3$$

Later on useful

$$n_X a^3 = \text{const}\,, \qquad s a^3 = \text{const} \qquad \Longrightarrow \qquad \frac{n_X}{s} = \text{const} = \# \frac{g_X}{g_*(T_d)}$$

DM particle mass M_X fixes Ω_X:

$$\Omega_X = \frac{M_X \cdot n_{X,0}}{\rho_c} = \frac{M_X \cdot s_0}{\rho_c} \frac{n}{s} \approx 0.2 \times \frac{M_X}{100\ \text{eV}} \left(\frac{g_X}{2}\right) \cdot \left(\frac{100}{g_*(T_d)}\right)$$

– NO heavy stable feebly coupled to SM particles !

– NO realistic DM models:

Pauli blocking prevents fermionic DM

$$\frac{p_X}{M_X} \propto \frac{a_d}{a} \sim \frac{3T}{M_X} \left(\frac{g_*(T)}{g_*(T_d)}\right)^{1/3}$$

too energetic for the proper structure formation

Decoupling of relativistic Dark Matter

Can we save the relativistic Dark Matter ??

one can try, say, nonstandard cosmological evolution

with entropy production

1. hot stage (radiation domination) $\rho \propto 1/a^4$
2. add new nonrelativistic particles decoupled from plasma $\rho \propto 1/a^3$
3. later they start to dominate
   intermediate stage of matter domination terminates before BBN !!
4. both relativistic DM density and entropy density drop
5. new nonrelativistic particles decay reheating the Universe $T > 3\,\text{MeV}$
   entropy production

Outline

Dark Matter: non-thermal production

1. in the primordial plasma of SM particles (via scatterings, oscillations):

   gravitino

   sterile neutrino of 1-50 keV

2. at phase transitions:

   axion of $10^{-4} - 10^{-7}$ eV

   Q-balls

   strangelets (?)

3. during reheating (after inflation?):

   black holes

   any guy coupled (only) to inflaton

   - perturbatively: inflaton decays

     production by external (inflaton) field

   - non-perturbatively: Bose-enhancement of

     coherent production by external field

4. while the Universe expands:

   gravity produces any particles at $H \sim M_X$

Sterile neutrino: well-motivated Dark Matter

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

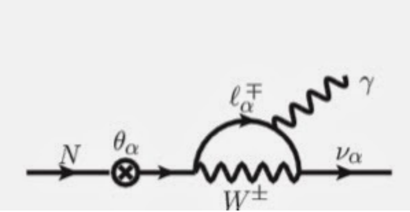
- massive fermions giving mass to active neutrino through mixing

$$m_a \sim \frac{f^2 v^2}{M_N^2} M_N \sim \theta^2 M_N$$

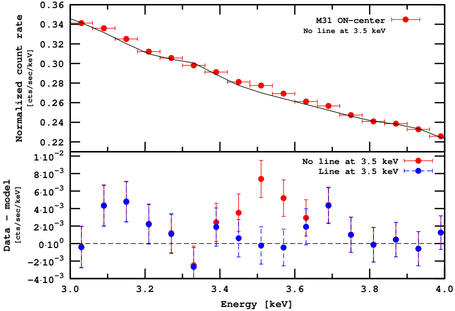
- unstable, but exceeding the age of the Universe at condition

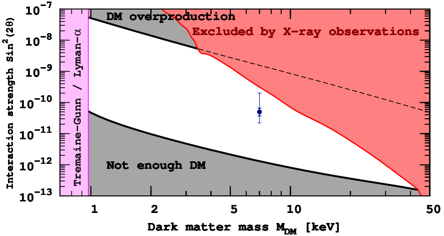
$$\theta^2 < 1.5 \times 10^{-7} \left(\frac{50\,\text{keV}}{M_N} \right)^5$$

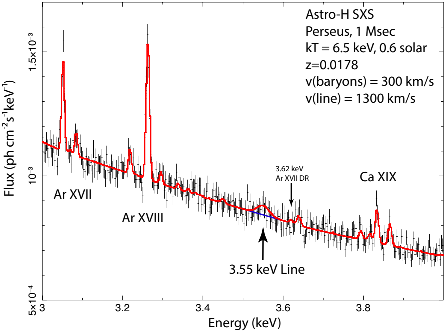
- can be searched for because of two-body radiative decay



Dark Matter decay observed in X-ray?







Stacking signals from many galaxies, especially Perseus cluster, then Andromeda

1402.2301, 1402.4119

Production in oscillations

$$\frac{\partial}{\partial t} f_s - H\mathbf{p}\,\frac{\partial}{\partial \mathbf{p}} f_s = \Gamma_\alpha\, P(\nu_\alpha \to \nu_s)\, f_\alpha(t,\mathbf{p})\,.$$

where $\Gamma_\alpha \sim G_F^2 T^4 E$ is the weak interaction rate in plasma

$$P(\nu_\alpha \to \nu_s) = \sin^2 2\theta_\alpha^{\rm mat} \cdot \sin^2\left(\frac{t}{2t_\alpha^{\rm mat}}\right),$$

$$t_\alpha^{\rm mat} = \frac{t_\alpha^{vac}}{\sqrt{\sin^2 2\theta_\alpha + (\cos 2\theta_\alpha - V_{\alpha\alpha}\cdot t_\alpha^{vac})^2}},$$

$$\sin 2\theta_\alpha^{\rm mat} = \frac{t_\alpha^{\rm mat}}{t_\alpha^{vac}}\cdot \sin 2\theta_\alpha\,, \quad t_\alpha^{vac} = \frac{2E}{M_N^2}$$

and effective plasma potential for active neutrinos

$$V_{\alpha\alpha} \sim -\#G_F^2 T^4 E + \#G_F T^2 \mu_{L_\alpha}$$

resonant production in the lepton asymmetric plasma BAU-DM connection?

Sterile neutrino Dark Matter

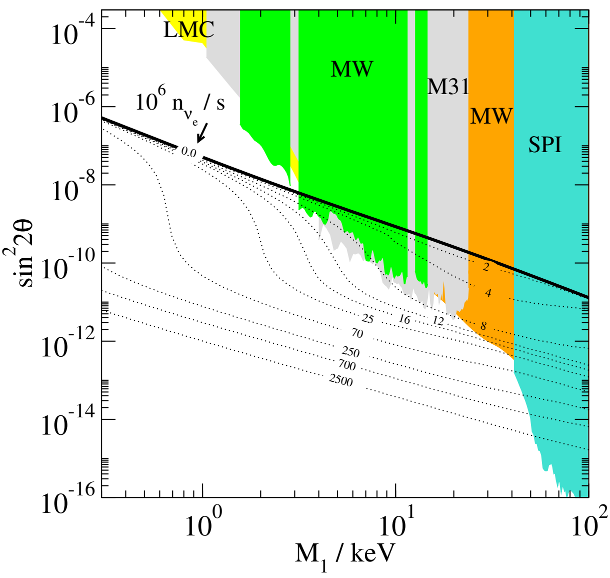
$\sin^2 2\theta$, n_{ν_e} and M_N
to saturate Ω_{DM}

- larger asymmetry
  $10^6\, n_{\nu_e}/s > 2500$
  is forbidden by BBN
- above the solid line
  "0.0" $\qquad \Omega_N > \Omega_{DM}$
- selected upper limits
  from X-ray telescopes
- recall $m > 0.75$ keV for
  fermionic DM

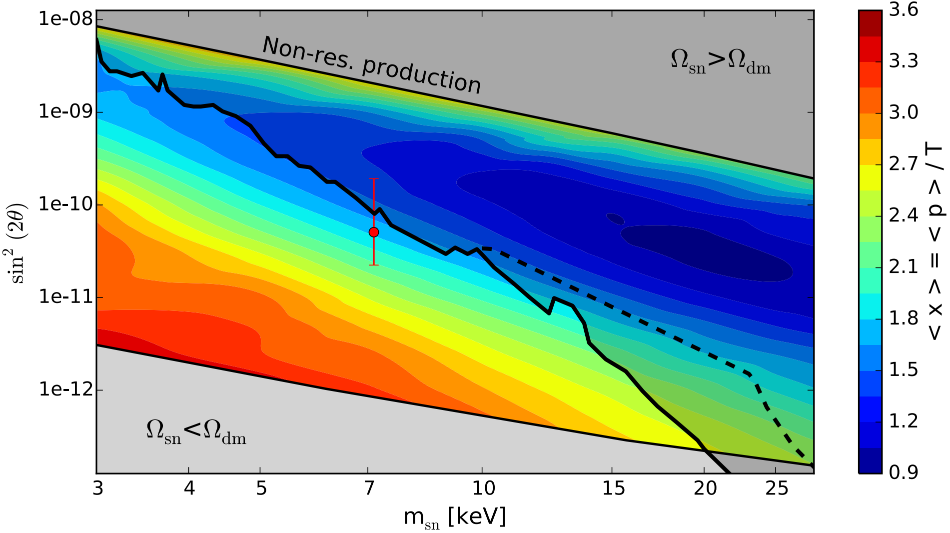
  It can be refined

  with estimates of
  neutrino velocities

case 1



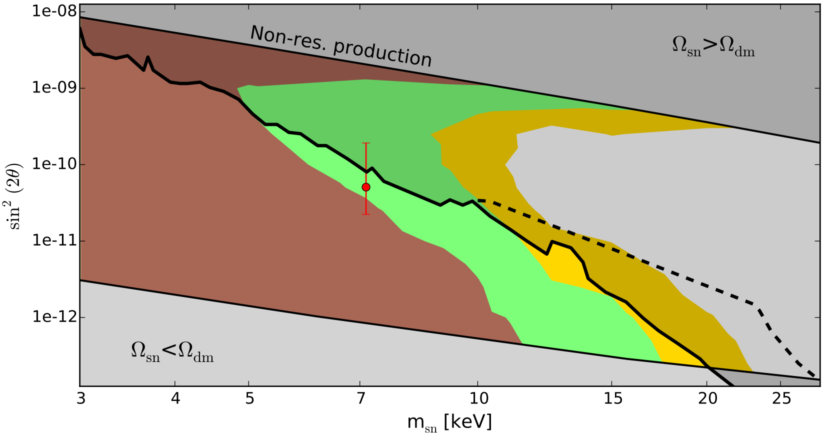
Sterile neutrino Dark Matter



A.Schneider (2016)

Sterile neutrino Dark Matter: ... gone?

A.Schneider (2016)

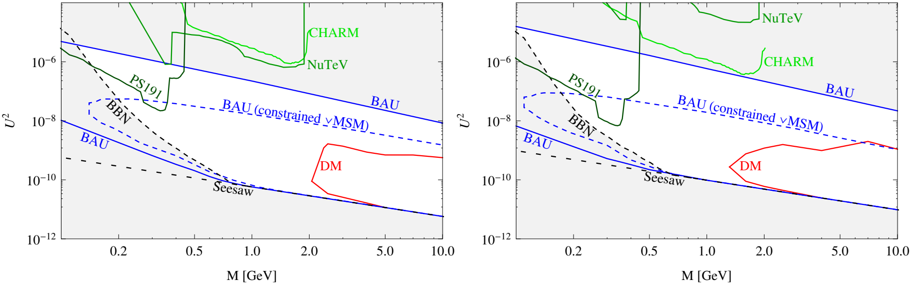


brown: MW satellite counts

green and yellow: Lyman-α

production by inflaton

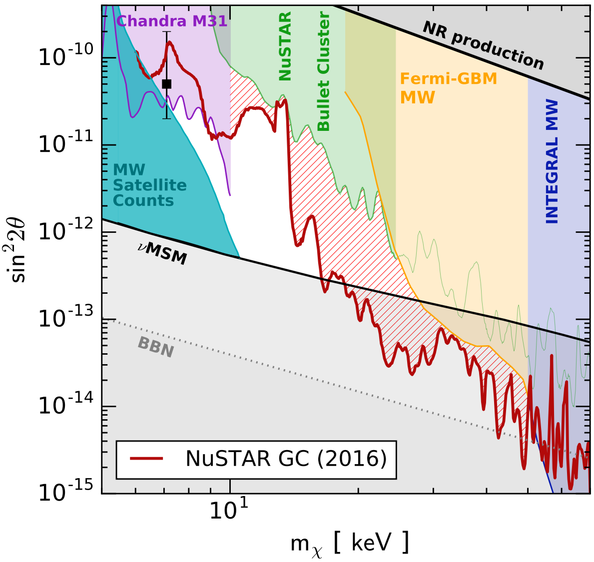
νMSM parameter space with resonant DM



L.Canetti, M.Drewes, M.Shaposhnikov 1204.3902

νMSM is severely constrained

1609.00667

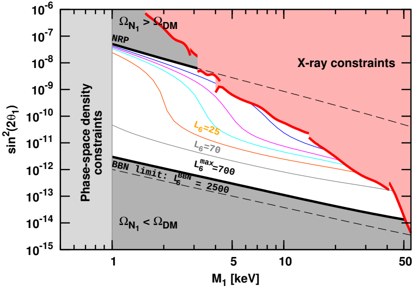


Lightest sterile neutrino N_1 as Dark Matter

Non-resonant production
(active-sterile mixing) is ruled out

Resonant production (lepton asymmetry) requires $\Delta M_{2,3} \lesssim 10^{-16}$ GeV

arXiv:0804.4542, 0901.0011, 1006.4008



Dark Matter production
from inflaton decays in plasma at $T \sim m_\chi$

Not seesaw neutrino!

M.Shaposhnikov, I.Tkachev (2006)

$$M_{N_I} \bar{N}_I^c N_I \leftrightarrow f_I X \bar{N}_I N_I$$

Can be “naturally” Warm ($250\,\text{MeV} < m_\chi < 1.8\,\text{GeV}$)

F.Bezrukov, D.G. (2009)

$$M_1 \lesssim 15 \times \left(\frac{m_\chi}{300\ \text{MeV}} \right) \text{keV}$$

Outline

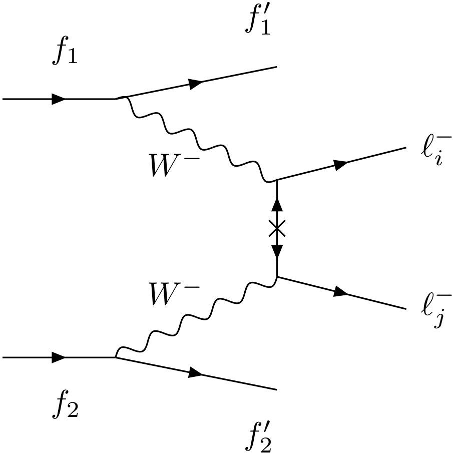
Summary on sterile neutrinos

- Most economic explanation of neutrino oscillations within renormalizable approach:
  $N = 2$ Majorana neutrinos
- Capable of explaining baryon asymmetry of the Universe
  easily even with $\theta_{13} = \delta_{CP} = 0$
- One more neutrino can serve as (naturally Warm) dark matter
  this specia does not explain oscillations!
  there are allowed mechanisms of DM sterile neutrino productions
- 1 eV- sterile neutrino is forbidden in cosmology, anomalies (LSND, . . .) are gone...? dark radiation

Backup slides

Indirect searches: $\Delta L = 2$ processes

$0\nu\beta\beta$
$D^+ \to \mu^+\mu^+K^-, \ldots$
$t \to b\mu^+\mu^+W^-$



for light sterile neutrinos

$$\langle m\rangle^2_{\ell_i\ell_j} = \left|\sum_I U_{\ell_i I} U_{\ell_j I} M_{N_I}\right|^2$$

for heavy sterile neutrinos

$$\left|\sum_I \frac{V_{\ell_i I} V_{\ell_j I}}{M_{N_I}}\right|^2,$$