eV-Scale Sterile Neutrinos and Cosmology - Compatible or Not?

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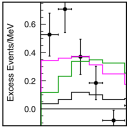
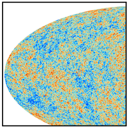
January 30, 2015

Outline



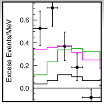
Anomalies

Cosmology



X χ φ

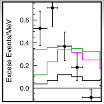
Model Extensions



Neutrino Anomalies

Three different types of experiments can be explained using an eV sterile neutrino:

- Accelerator experiments observe ν_e in a ν_μ-beam incompatible with other ν-oscillations. (LSND and MiniBooNE)
- Calibration of gallium solar neutrino detectors give a small but significant deficit. (GALLEX and SAGE)
- The $\bar{\nu}_e$ flux measured from nuclear reactors is a few percent smaller than expected.



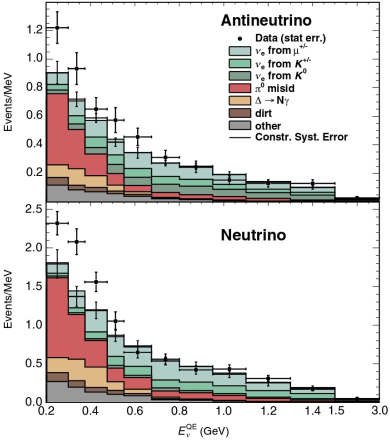
Accelerator Experiments

- LSND observed an excess of ν_e in a ν_μ-beam.

  LSND Collaboration, 2001 (arxiv:hep-ex/0104049)

- MiniBooNE was supposed to test the excess, and found similar results.

- Combined with KARMEN and ICARUS, only $\delta m^2 \sim 0.5\mathrm{eV}^2$ is allowed.

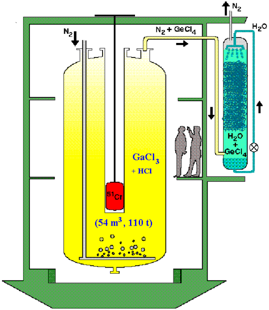


MiniBooNE Collaboration, 2013

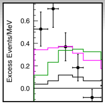
(arxiv:1303.2588)

Gallium Detectors

- Goal: measure neutrinos from the Sun.
- Calibrated using strong radioactive sources.
- Deficit in measured neutrinos: $R_{\text{measured}}/R_{\text{expected}} = 0.86 \pm 0.05$.



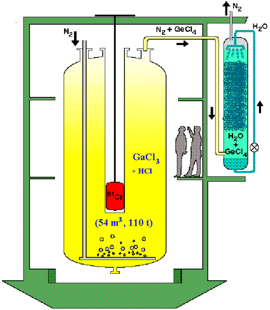
GALLEX experiment (SAGE similar)



Gallium Detectors

- Goal: measure neutrinos from the Sun.
- Calibrated using strong radioactive sources.
- Deficit in measured neutrinos: $R_{\text{measured}}/R_{\text{expected}} = 0.86 \pm 0.05$.
- Corresponds to $\delta m^2_{\text{new}} \gtrsim 0.35\text{eV}^2$.

(Giunti and Laveder, 2011, arxiv:1006.3244)



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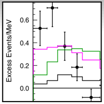
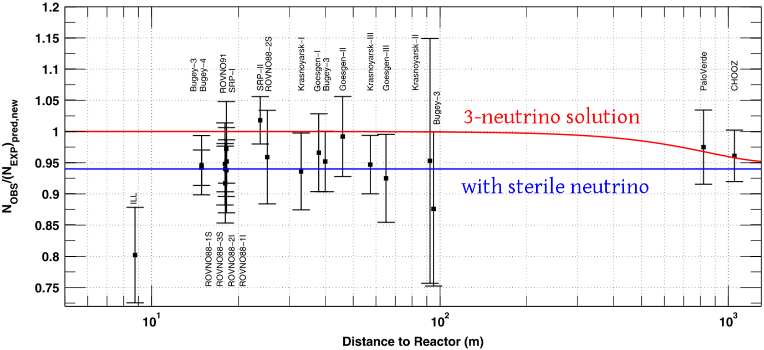
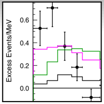


Reactor Anti-neutrinos



Anomaly points to $\delta m^2_{\mathrm{new}} > 1.5\mathrm{eV}^2$.

Mention et al. 2011 (arXiv:1101.2755)



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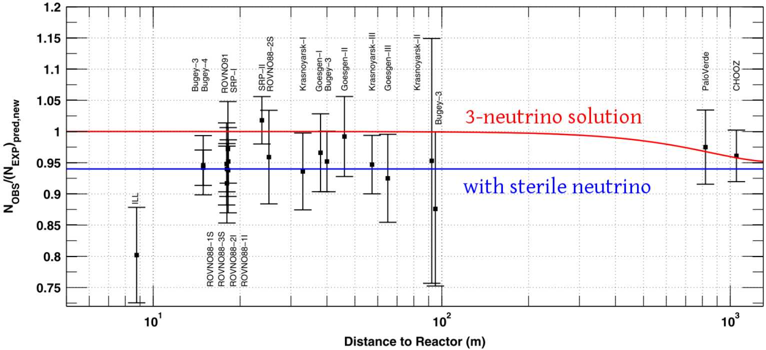
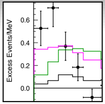


Anomaly points to $\delta m^2_{\rm new} > 1.5 {\rm eV}^2$.

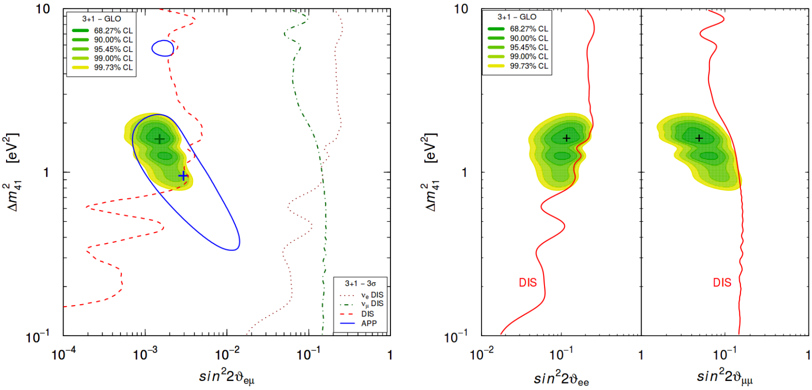
Mention et al. 2011 (arXiv:1101.2755)

Larger uncertainty claimed by another group.

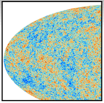
(Hayes et al. 2013 arXiv:1309.4146)



Neutrino Anomalies - Global Fit



C. Giunti, M. Laveder, Y.F. Li and H.W. Long, 2013 (arxiv:1308.5288)



Cosmological Probes

Modifying neutrino physics can affect several aspects of cosmology:

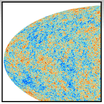
- Big bang nucleosynthesis (BBN) via a changed expansion rate and modified nuclear reactions.
- The cosmological microwave background radiation (CMB) via a changed expansion rate and anisotropic stress.
- Large scale structures (LSS) via small scale damping.

Describing Neutrinos

The number of neutrinos is

$$N_{\text{eff}} \equiv \frac{\rho_{\nu,\text{rel}}}{\rho_{\nu 0}}, \qquad \rho_{\nu 0} \equiv \frac{7}{8}\left(\frac{T_\nu}{T_\gamma}\right)^4 \rho_\gamma .$$

$N_{\text{eff}} = 3$ in the Standard Model, but other relativistic degrees of freedom will also enter.
$N_{\text{eff}} > 3$ effects the expansion of the Universe.

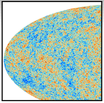


Big Bang Nucleosynthesis

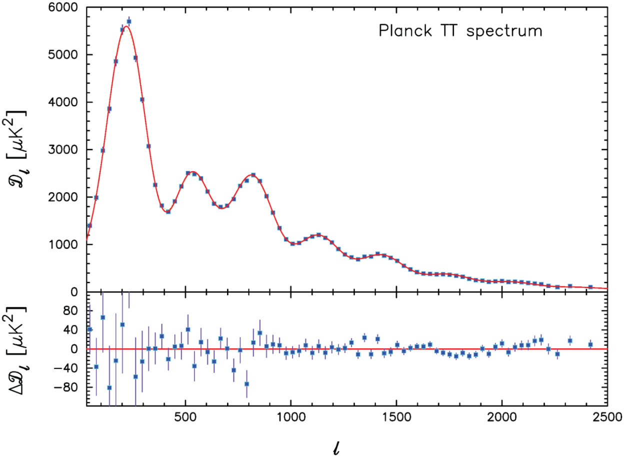
- ^{4}He content is controlled by n_n/n_p.
- N_{eff} effects H, and thereby the energy at which $p + e^- \leftrightarrow n + \nu_e$ freezes out.
- There are also smaller effects on the abundance of other elements.

Some of the latest limits:

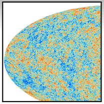
- ^{2}D: $N_{\text{eff}} = 3.0 \pm 0.5 (1\sigma)$. Pettini and Cooke, 2012 (arxiv:1205.3785)
- ^{4}He, ^{2}D: $N_{\text{eff}} < 4.0$ at 95% confidence. Mangano and Serpico, 2011 (arxiv:1103.1261)
- ^{4}He: $N_{\text{eff}} = 3.68^{+0.80}_{-0.70} (2\sigma)$. Izotov and Thuan, 2010 (arxiv:1001.4440)



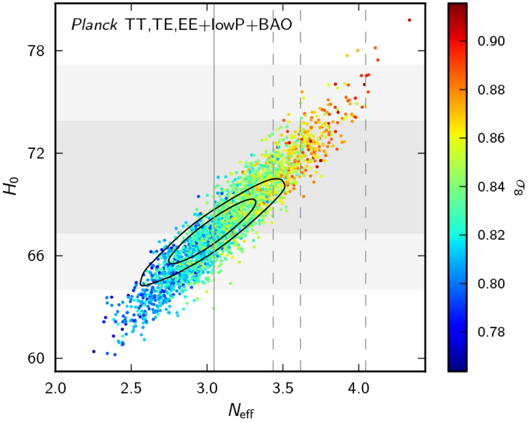
Cosmological Microwave Background



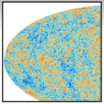
Ade et al., 2013 (arxiv:1303.5076)



Cosmological Microwave Background



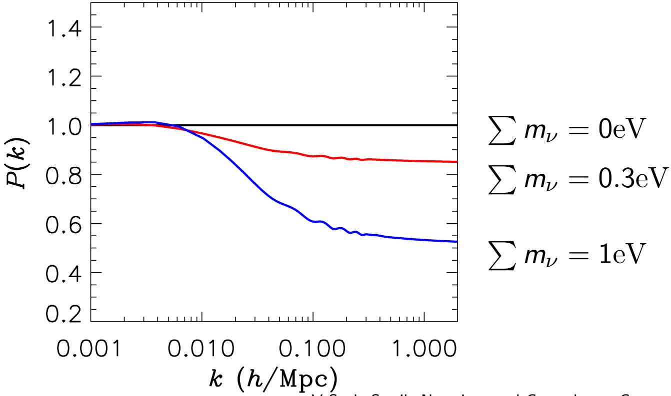
http://public.planck.fr/resultats



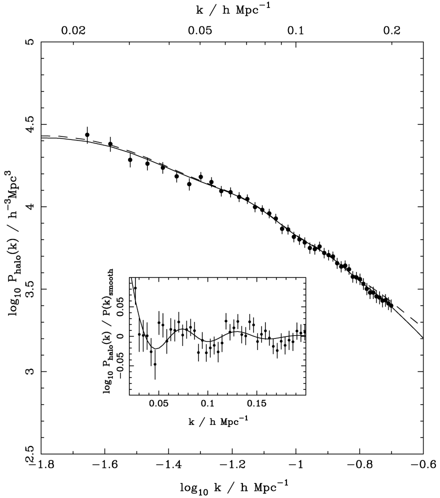
Large Scale Structure

Neutrino mass damps formation of structures below the free streaming length.

Matter power spectrum:



Large Scale Structure

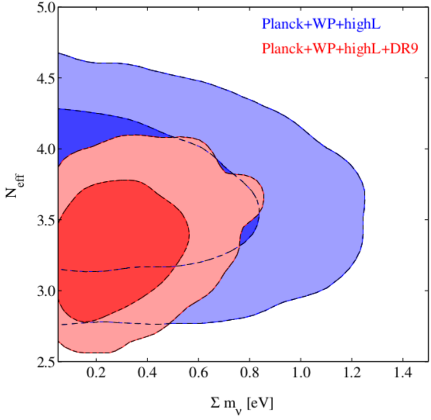


Luminous Red Galaxies spectrum, SDSS DR-7

Reid et al., 2009

(arXiv:0907.1659)

Large Scale Structure

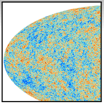


Archidiacono et al., 2013

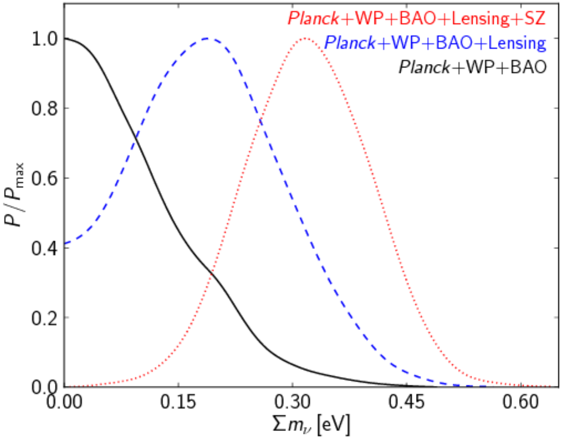
(arXiv:1307.0637)

Marginalized constraints:

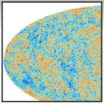
- Planck + WP: $N_{\rm eff} = 3.65 \pm 0.38$, $\sum m_\nu < 1.03\mathrm{eV}$.
- Planck + WP + highL + DR9: $N_{\rm eff} = 3.33 \pm 0.31$, $\sum m_\nu < 0.66\mathrm{eV}$.



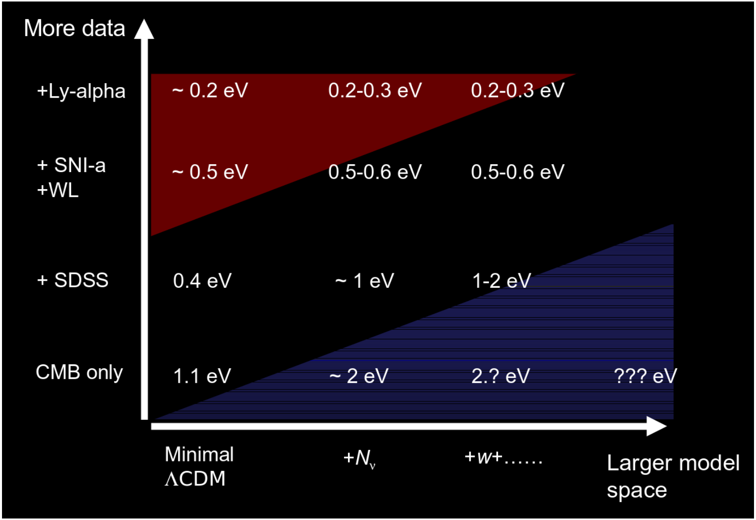
Large Scale Structure



Battye and Moss (arXiv:1308.5870)



Model Dependence, $\sum m_\nu$



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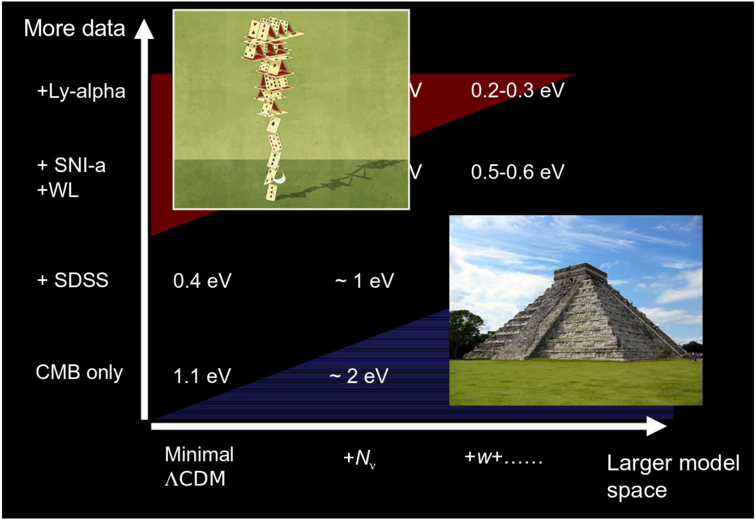
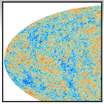
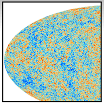




Summary

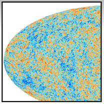
$$\Delta N_{\mathrm{eff}} \lesssim 1, \; \sum_i m_{\nu_i} < 1\mathrm{eV}.$$

No room for a thermal, $1\mathrm{eV}$ sterile neutrino.



eV-scale Sterile Neutrinos in Cosmology

- Sterile $\sim$ no electro-weak or strong coupling.
- Mixed with active neutrinos.
- Non-resonant production if heavier than active neutrinos.
- Resonant production if lighter than active neutrinos, or non-standard matter potentials are present.
- Contributes to ΔN_{eff} and $\sum_i m_{\nu_i}$.



Quantum Kinetic Equations

Describe ν_a, ν_s- oscillations using a density matrix:

$$\rho = \begin{pmatrix} \rho_{aa} & \rho_{as} \\ \rho_{sa} & \rho_{ss} \end{pmatrix}$$

Which evolved according to the quantum kinetic equations:

$$i\frac{d\rho}{dt} = [H(\rho), \rho] + C(\rho)$$

$$H(\rho) = \begin{pmatrix} -\frac{\delta m^2}{2p}\cos 2\theta + V_{\mathrm{matter}} & \frac{\delta m^2}{2p}\sin 2\theta \\ \frac{\delta m^2}{2p}\sin 2\theta & \frac{\delta m^2}{2p}\cos 2\theta - V_{\mathrm{matter}} \end{pmatrix}$$

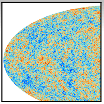
$C(\rho)$ is the higher order collision term treating non-forward scattering.
V_{matter} is the potential induced by forward scattering with the background.

Thermalisation

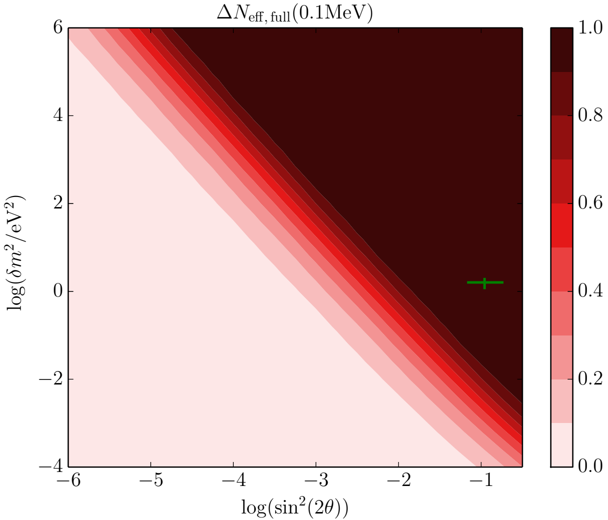
- Resonant conversion:
  - Diagonal term in H is 0.
  - MSW-like oscillations.
- Small angle oscillations:

$$\Gamma_{\text{thermalise}} = \frac{1}{2}\sin^2(2\theta_m)\Gamma_\nu$$

  - $\Gamma_\nu \approx \langle \sigma v \rangle n_e$.
  - $\sin^2(2\theta_m)$ also depends on background.
  - Compare $\Gamma_{\text{thermalise}}$ to Hubble expansion rate.



Thermalisation - Full Collision Term



Modifications to Cosmology

- Modified primordial power spectrum. Gariazzo, Giunti and Laveder, 2014 (arXiv:1412.7405)
- Low reheating temperature. Rehagen and Gelmini, 2014, (arXiv:1402.0607)
- Dilution by decay of heavy particles. Fuller, Kishimoto and Kusenko, 2011, (arXiv:1110.6479)
- Large lepton asymmetry. Foot and Volkas, 1995, Hannestad et al. 2012 (arxiv:1204.5861), Saviano et al. 2014 (arxiv:1302.1200)

Large Lepton Asymmetry

Cosmology allows for a large lepton asymmetry
(Remember that the baryon asymmetry $\sim 10^{-10}$)

$$L = \sum_f \frac{n_f - n_{\bar{f}}}{n_f} \sim 10^{-1}.$$

This gives rise to a modified matter potential

$$V_L = \frac{2\sqrt{2}\zeta(3)}{\pi^2} G_F T^3 L^{(a)}$$

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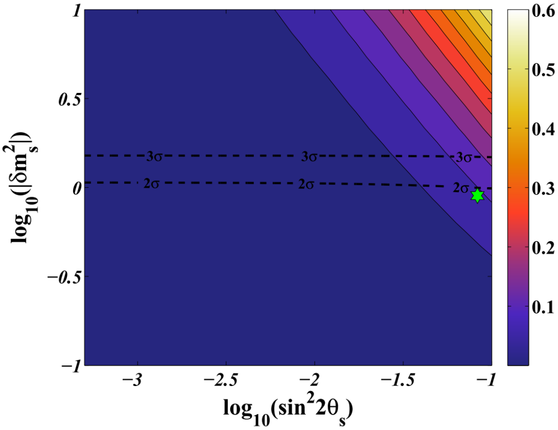
$$L^{(e)} = \left(\frac{1}{2} + 2\sin^2\theta_W\right) L_e + \left(\frac{1}{2} - 2\sin^2\theta_W\right) L_p - \frac{1}{2} L_n + 2L_{\nu_e} + L_{\nu_\mu} + L_{\nu_\tau}$$

$L \sim 10^{-2} \Rightarrow$ Suppress both small angle oscillations and resonant production until after ν decoupling.

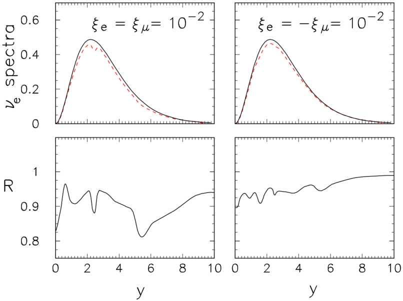
Large Lepton Asymmetry - Thermalisation



S. Hannestad, I. Tamborra, and T. Tram 2012 (arxiv:1204.5861)

Large Lepton Asymmetry

- There is some tension with BBN due to the spectral distortions.
- A mechanism to produce the large lepton asymmetry is missing.
- Possible problems with $\sum_i m_{\nu_i}$ due to partly thermalised ν_s after ν decoupling.



Saviano et al., 2013 (arxiv:1302.1200)

Modifications to Particle Physics

Sterile - sterile interactions:

Vector couplings. Hannestad, RSH and Tram 2013 (arXiv:1310.5926), Dasgupta and Kopp, 2013 (arXiv:0805.3300), Saviano et al. 2014 (arXiv:1409.1680)

- Similar to known weak physics.
- Typical boson masses: MeV - GeV.
- Interaction strength decreases with temperature as usual for weak interactions.

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Pseudoscalar couplings. Babu and Rothstein, 1992, Bento and Berezhiani 2001 (arxiv:hep-ph/0108064), Archidiacono et al. 2014 (arXiv:1404.5915)

- Well motivated by extended neutrino models, e.g. majorons.
- Typical boson masses: $\lesssim \mathrm{meV}$.
- Interaction grows as temperature decreases giving rise to some counter-intuitive phenomena.

Vector Models

Hannestad, RSH, Tram, 2013 (arXiv:1310.5926)

Fermi-like interaction:

$$G_X = \frac{g_X^2}{M_X^2} \gg G_F$$

$$V_s = \frac{16 G_X}{3\sqrt{2} M_X^2} p u_{\nu_s}$$

$$\Gamma_s = G_X^2 p T_{\nu_s}^4 n_{\nu_s}$$

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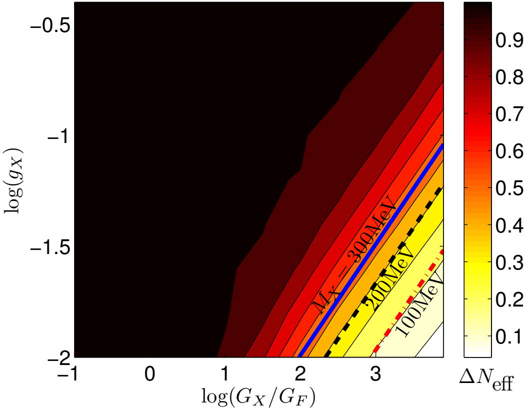
$$\Gamma_{\rm thermalise} \propto \sin^2(2\theta_m)\Gamma_\nu \propto \frac{M_X^4}{G_X^2} G_X^2 \propto M_X^4$$

$\Rightarrow$ Light mediator suppresses thermalisation.

Vector Models

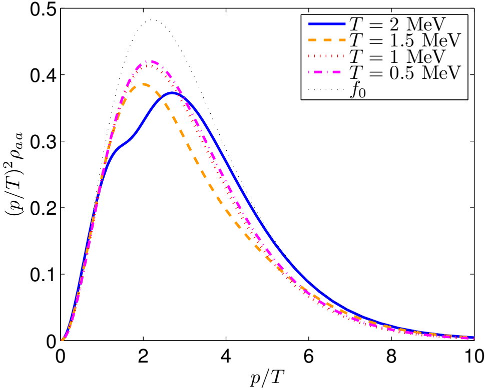


Hannestad, RSH, and Tram 2013 (arXiv:1310.5926)

Vector Models - BBN

Non-thermal neutrino spectra might change BBN significantly.

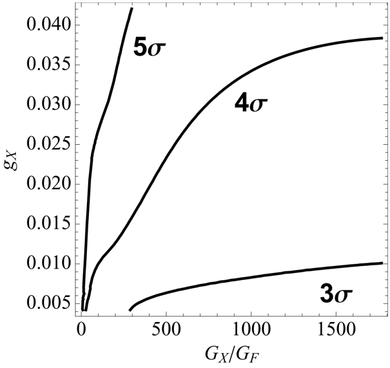
$G_X = 300 G_F, g_x = 0.025 \Rightarrow M_x = 424\mathrm{MeV}$



Hannestad, RSH, and Tram 2013 (arXiv:1310.5926)

Vector Models - BBN

Exclusion plot using ^{2}H-data.

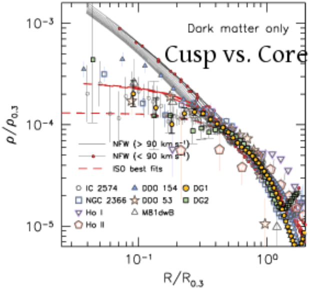


- Bounds can be weakened by raising the baryon density.
- A small $m_X \lesssim 1\mathrm{MeV}$ will delay the thermalisation until $T \lesssim 0.1\mathrm{MeV}$ and avoid BBN bounds.

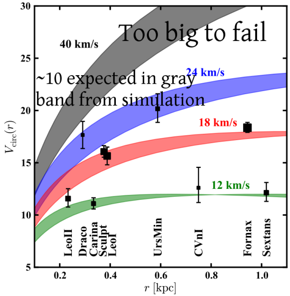
Saviano et al., 2014 (arXiv:1409.1680)

Vector Models - DM

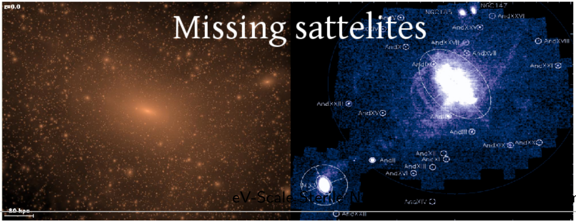
Oh et al., 2010 (arXiv:1011.2777)



Boylan-Kolchin et al., 2010 (arXiv:1111.2048)



Via Lactea simulation and PAndAS Survey



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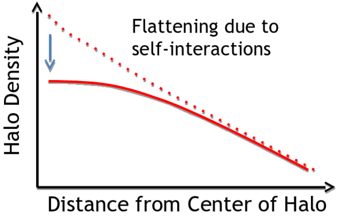
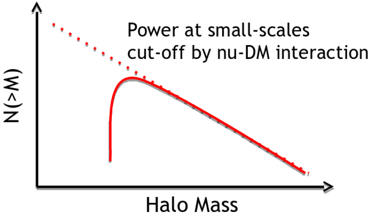


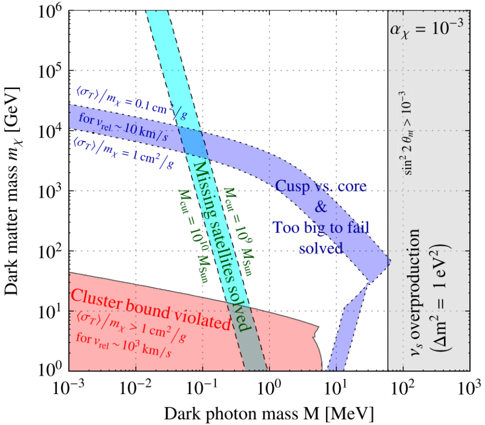


Core-Cusp problem solved using self-interactions. TBTF is also solved.

Missing Satellites solved using DM interactions with neutrinos, that leads to late kinetic decoupling

Basudep Dasgupta

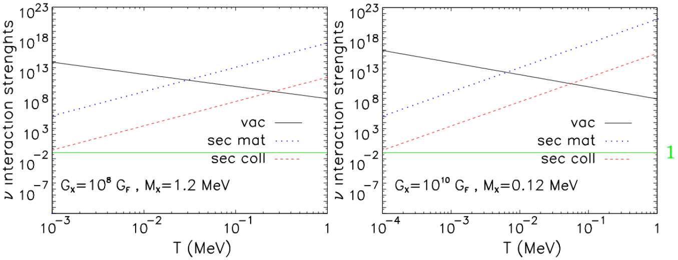
Vector Models - DM



Dasgupta and Kopp, 2013 (arXiv:0805.3300)

see also Bringmann, Hasenkamp and Kersten, 2013 (arXiv:1312.4947)

Vector Models - low T production of ν_s



Mirizzi et al., 2014 (arXiv:1410.1385)

- After no matter suppression, thermalisation via collisions is possible.
- Might conflict with bounds on $\sum_i m_{\nu_i}$.
- Not for all parameters. (Disregarding resonant conversion)
- Can dilute with more ν_s. Tang, 2014 (arXiv:1501.00059)

Summary

- eV-scale sterile neutrinos are incompatible with standard cosmology and particle physics.
- Different mechanisms can alleviate the tension, but some of them are constrained by other observables. I have reviewed three models today:
  - A large lepton asymmetry is pressed by constraints from BBN.
  - A sterile vector boson interaction gives problems with the neutrino mass bound.
  - A sterile pseudoscalar interaction seems promising, but has not been thoroughly examined yet.

Sterile neutrino constraints

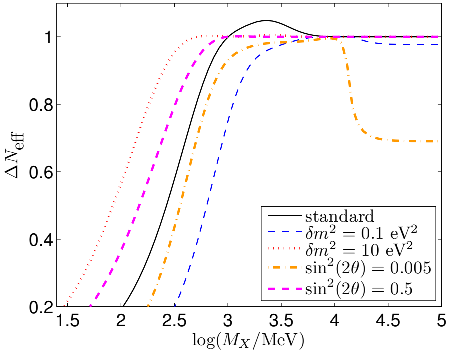
Dataset	Ω_m	σ_8	m_s^{eff}[eV]		ΔN_{eff}	
			68%CL	95%CL	68%CL	95%CL
Planck	$0.322^{+0.025}_{-0.030}$	$0.800^{+0.052}_{-0.031}$	< 0.34	< 0.86	$0.49^{+0.18}_{-0.42}$	< 1.07
Planck+Cluster	$0.304^{+0.026}_{-0.027}$	$0.745^{+0.023}_{-0.037}$	$0.54^{+0.26}_{-0.26}$	< 0.98	$0.84^{+0.32}_{-0.32}$	$0.84^{+0.63}_{-0.60}$
Planck+Cluster(B_M)	$0.295^{+0.019}_{-0.028}$	$0.794^{+0.040}_{-0.032}$	< 0.38	< 0.69	$0.85^{+0.28}_{-0.30}$	$0.85^{+0.56}_{-0.57}$
Planck+Cluster(BC)	$0.296^{+0.023}_{-0.028}$	$0.770^{+0.031}_{-0.036}$	$0.40^{+0.31}_{-0.19}$	< 0.81	$0.88^{+0.30}_{-0.29}$	$0.88^{+0.61}_{-0.60}$
Planck+BAO	$0.306^{+0.009}_{-0.009}$	$0.818^{+0.033}_{-0.026}$	< 0.19	< 0.43	$0.50^{+0.22}_{-0.39}$	< 1.04
Planck+Shear	$0.309^{+0.028}_{-0.028}$	$0.752^{+0.037}_{-0.043}$	$0.48^{+0.22}_{-0.38}$	< 0.99	$0.53^{+0.22}_{-0.37}$	< 1.30
Planck+Ly-α	$0.309^{+0.023}_{-0.024}$	$0.843^{+0.021}_{-0.021}$	< 0.11	< 0.27	$0.65^{+0.30}_{-0.38}$	< 1.49
Planck+BAO+Cluster	$0.303^{+0.009}_{-0.009}$	$0.744^{+0.013}_{-0.014}$	$0.53^{+0.12}_{-0.13}$	$0.53^{+0.26}_{-0.24}$	$0.81^{+0.31}_{-0.32}$	$0.81^{+0.60}_{-0.63}$
Planck+BAO+Cluster(B_M)	$0.303^{+0.007}_{-0.009}$	$0.782^{+0.020}_{-0.018}$	$0.35^{+0.13}_{-0.15}$	$0.35^{+0.27}_{-0.27}$	$0.81^{+0.29}_{-0.30}$	$0.81^{+0.60}_{-0.58}$
Planck+BAO+Shear	$0.305^{+0.09}_{-0.010}$	$0.753^{+0.023}_{-0.022}$	$0.44^{+0.16}_{-0.19}$	$0.44^{+0.34}_{-0.35}$	$0.45^{+0.14}_{-0.40}$	< 0.99
Planck+BAO+Ly-α	$0.305^{+0.09}_{-0.010}$	$0.844^{+0.020}_{-0.019}$	< 0.10	< 0.22	$0.61^{+0.28}_{-0.32}$	< 1.11
Planck+BAO+ Shear+Cluster(B_M)	$0.303^{+0.009}_{-0.009}$	$0.759^{+0.017}_{-0.020}$	$0.44^{+0.14}_{-0.14}$	$0.44^{+0.28}_{-0.26}$	$0.78^{+0.31}_{-0.30}$	$0.78^{+0.60}_{-0.59}$
Planck+BAO+Ly-α Shear+Cluster(B_M)	$0.293^{+0.009}_{-0.008}$	$0.794^{+0.016}_{-0.016}$	$0.26^{+0.11}_{-0.13}$	$0.26^{+0.22}_{-0.24}$	$0.82^{+0.27}_{-0.31}$	$0.82^{+0.55}_{-0.55}$

Costanzi et al. 2014 (arXiv:1407.8338)

Sterile Interactions

The mechanism is not very sensitive to the exact values of δm^2 and $\sin^2 2\theta$.

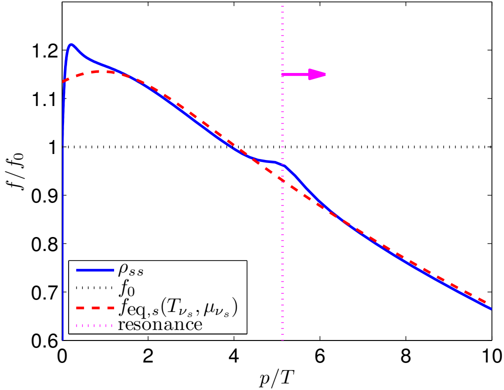
$$\delta m^2 = 1\mathrm{eV}^2, \sin^2(2\theta) = 0.05$$



Hannestad, RSH, and Tram 2013 (arXiv:1310.5926)

How Can $\Delta N_{\rm eff} > 1$?

The conversion is efficient at the resonance, where $\rho_{ss} < \rho_{aa} \sim f_0$, but not below the resonance where $\rho_{ss} > \rho_{aa}$.



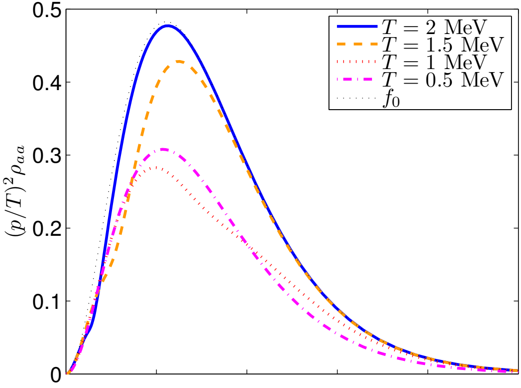
$T = 4.3 MeV$,
$\Delta N_{\rm eff} = 1$,
$\delta m^2 = 1{\rm eV}^2$,
$\sin^2 2\theta = 0.05$,
$G_X = G_F$, $g_X = 0.01$
$\Rightarrow M_X = 2.9{\rm GeV}$

Hannestad, RSH, and Tram 2013 (arXiv:1310.5926)

Effects on BBN - Open Questions

Non-thermal neutrino spectra might change BBN significantly.

$$G_X = 3000\,G_F, g_x = 0.025 \Rightarrow M_x = 134\mathrm{MeV}$$



Hannestad, RSH, and Tram 2013 (arXiv:1310.5926)