Invisibles Webinar

28 October 2014

Not So Sterile Neutrinos

Connections to DM and other astrophysics

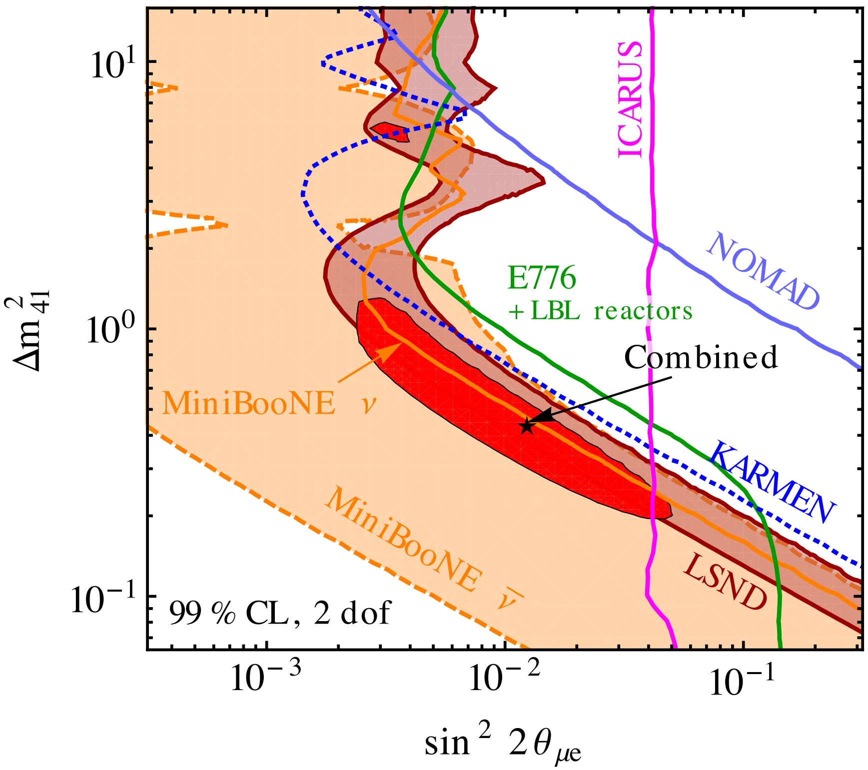
Basudeb Dasgupta

ICTP, Trieste

Why Sterile Neutrinos ?

- Generic extensions of SM
- Seesaw mechanism
- Baryogenesis via Leptogenesis
- Dark Matter (keV)
- X-ray lines (keV)
- Pulsar kicks (keV)
- Neutrino oscillations (eV)

Sterile Neutrinos at 1eV



Global fit to all appearance data is consistent, and 3+2 or 1+3+1 models are better fits than 3 only or 3+1.

Machado, Kopp, Maltoni, Schwetz (2013)

+ similar results by
Palazzo;
Giunti, Laveder, et al;
Conrad et al., …

If one takes the neutrino oscillation anomalies seriously, one needs 1 or 2 sterile neutrinos with large mixings

Active - Sterile Oscillations

$$\mathcal{L}_{\nu-\mathrm{mass}} = -\frac{M_{ij}}{2}\overline{\nu^c}_i\nu_j + h.c.$$

where, $$M_{ij} = \begin{pmatrix} 0_{3\times 3} & M^D_{3\times N} \\ \\ \ldots & M^M_{N\times N} \end{pmatrix}$$

which diagonalizes to $$M^{\mathrm{diag}}_{ij} = \begin{pmatrix} M_D M_M^{-1} M_D^T & 0 \\ \\ 0 & M_M \end{pmatrix}$$

N SM singlets mix with ordinary neutrinos and lead to 3 mostly active $(M^D)^2/(M^M)$ and N mostly sterile (M^M) neutrinos

Active-Sterile Oscillations

$$i\partial_t \begin{pmatrix} \nu_a \\ \nu_s \end{pmatrix} = \frac{\Delta m^2_{as}}{4E} \begin{pmatrix} \cos 2\theta_{as} & \sin 2\theta_{as} \\ -\sin 2\theta_{as} & \cos 2\theta_{as} \end{pmatrix} \begin{pmatrix} \nu_a \\ \nu_s \end{pmatrix}$$

Exactly like ordinary neutrino oscillations, but different parameters, in general.

Sterile neutrinos do not feel any MSW potentials from electrons, protons, neutrons etc.

Equivalent (to) Neutrinos

During the radiation dominated epoch in the expanding Universe

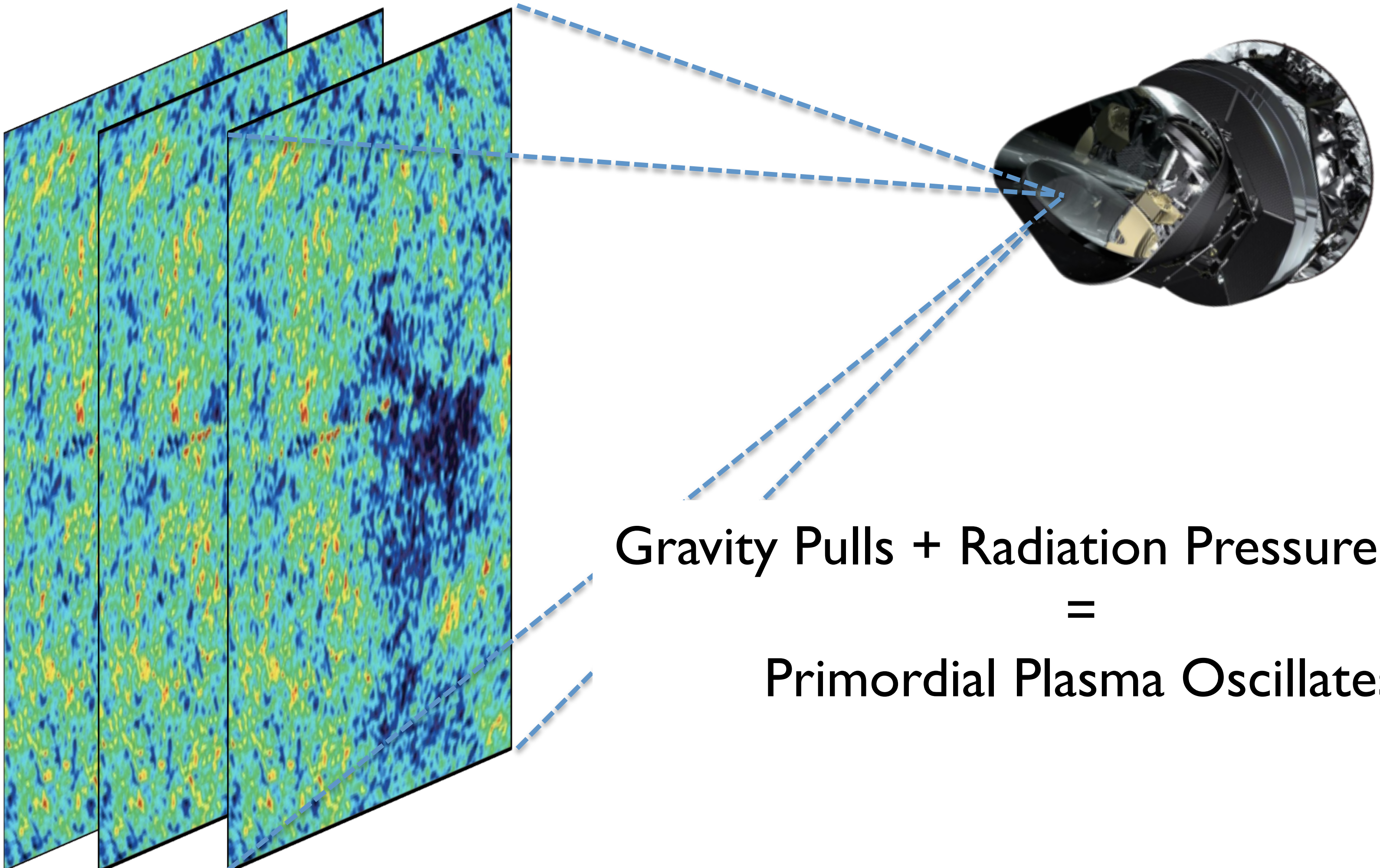
$$\rho = \sum_i \frac{\pi^2}{30} g_i T_i^4$$

where,
g = no. of states, for bosons
g = 7/8 x no. of states, for fermions

$$\rho = \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{\mathrm{eff}}\right)\rho_\gamma$$

Often we parametrize new relativistic dofs as if they were neutrinos. Why?

CMB in a Nutshell



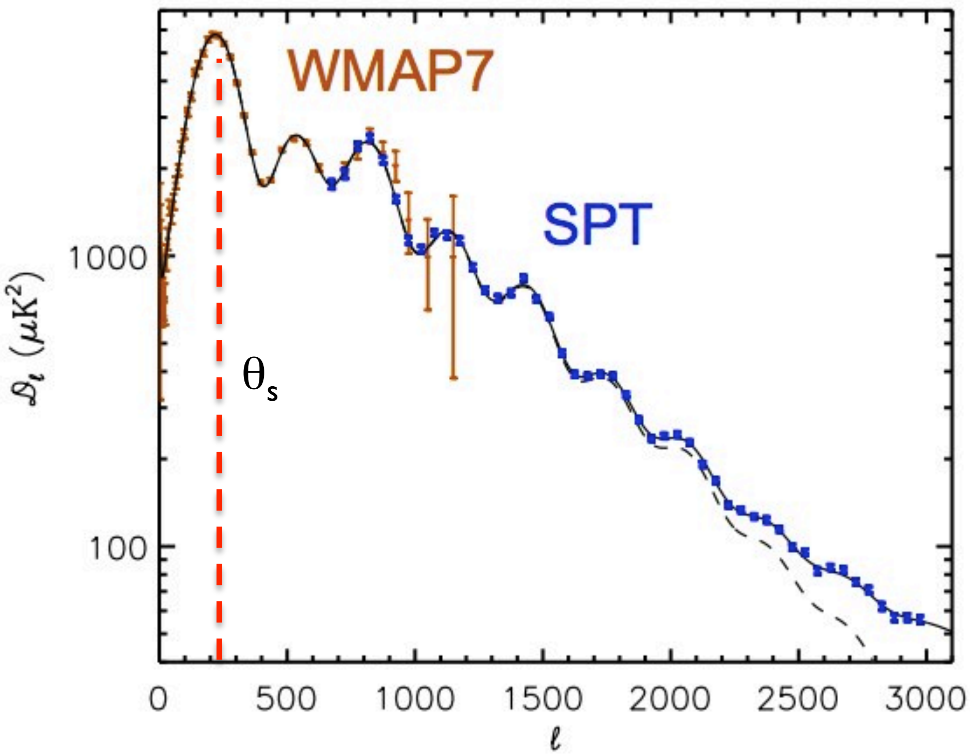
Gravity Pulls + Radiation Pressure Pushes

=

Primordial Plasma Oscillates

Oscillations leads to fluctuations in temperature and polarization of the CMB photons

What do we measure?

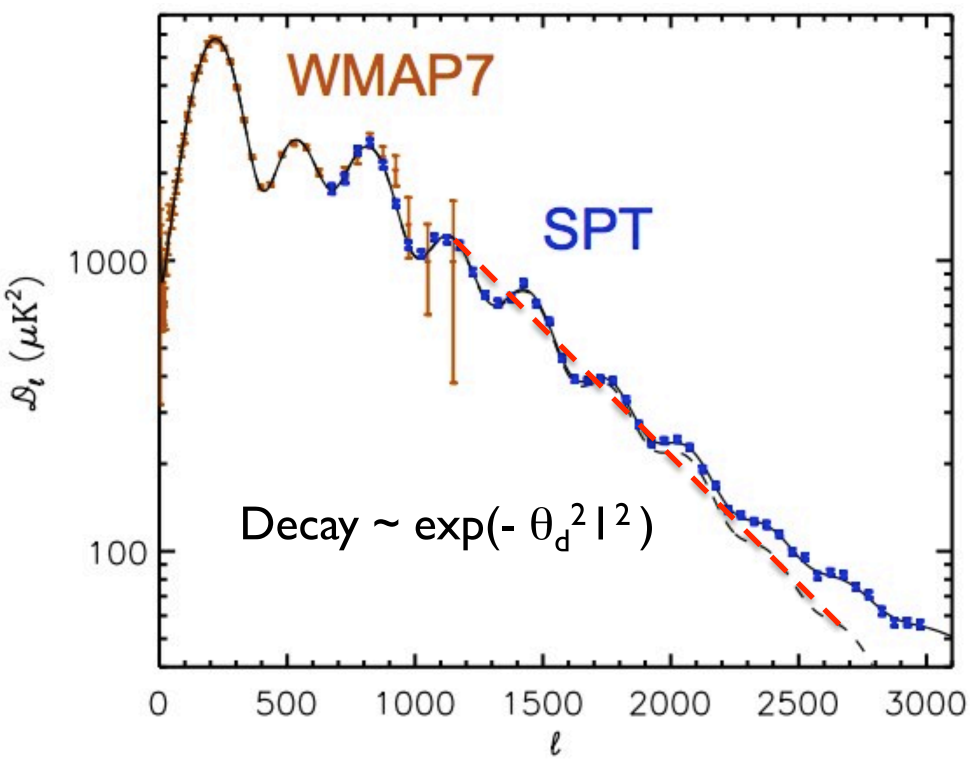


$$r_s \propto \int_0^{a_{\rm rec}} da \frac{c_s}{a^2 H}$$

r_{sound} is the max. size of the waves.
$\theta_s = r_s/D_A$

First peak measures the size of the sound horizon

What do we measure?



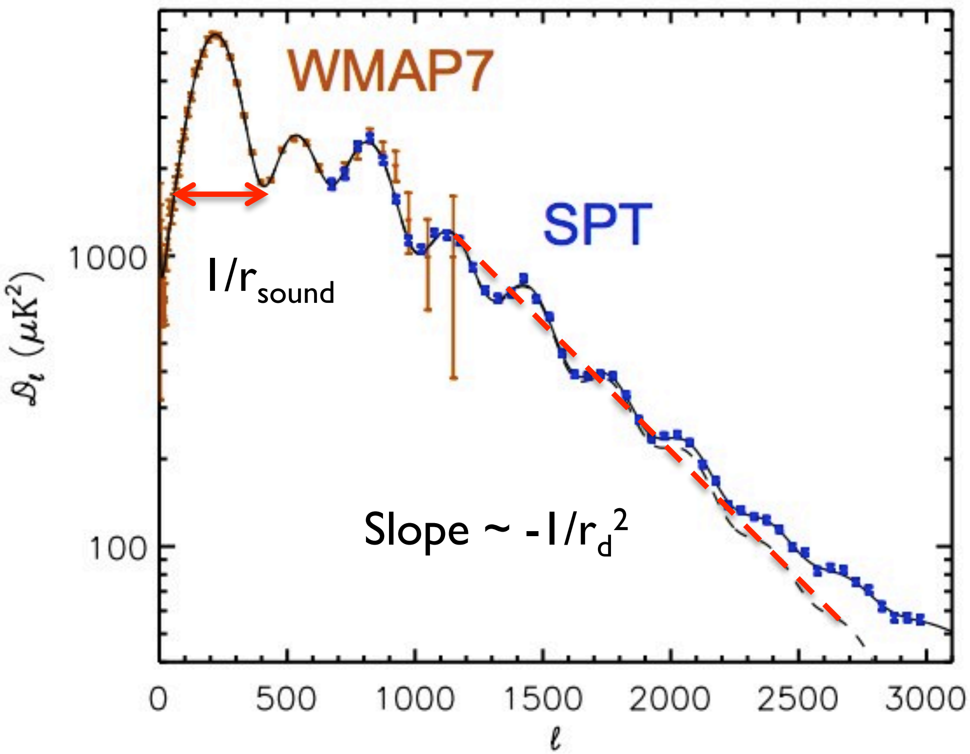
$$r_d^2 \propto \int_0^{a_{\rm rec}} da \frac{1}{a^3 H n_e \sigma_T}$$

r_d is the photon diffusion length

$\theta_d = r_d/D_A$

High multipoles measure diffusion length of photons in the plasma

What do we measure?



$$r_d \propto \frac{1}{\sqrt{H}}$$

$$r_s \propto \frac{1}{H}$$

$$\frac{r_d}{r_s} \propto \sqrt{H}$$

Together they allow us to measure H at the CMB epoch

Why neutrinos?

$$\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2 \propto (\rho_\gamma + \rho_{\rm mat} + \rho_\nu)$$

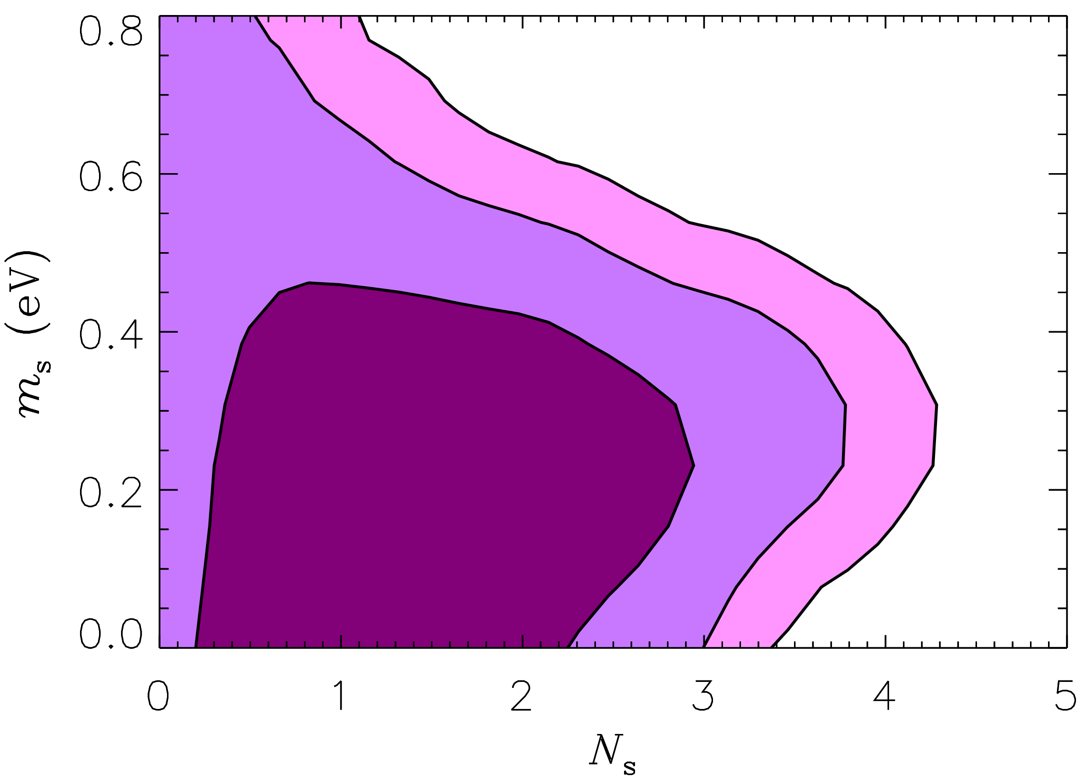
Extra radiation increases energy density, and thus the expansion rate

1. Photon density known, from CMB temperature=3K
2. Matter density known, from amplitudes of peaks

So, measuring H = measuring "neutrino" energy density

N.B.: Neutrinos = Any relativistic species except photons

A Blossoming Friendship …

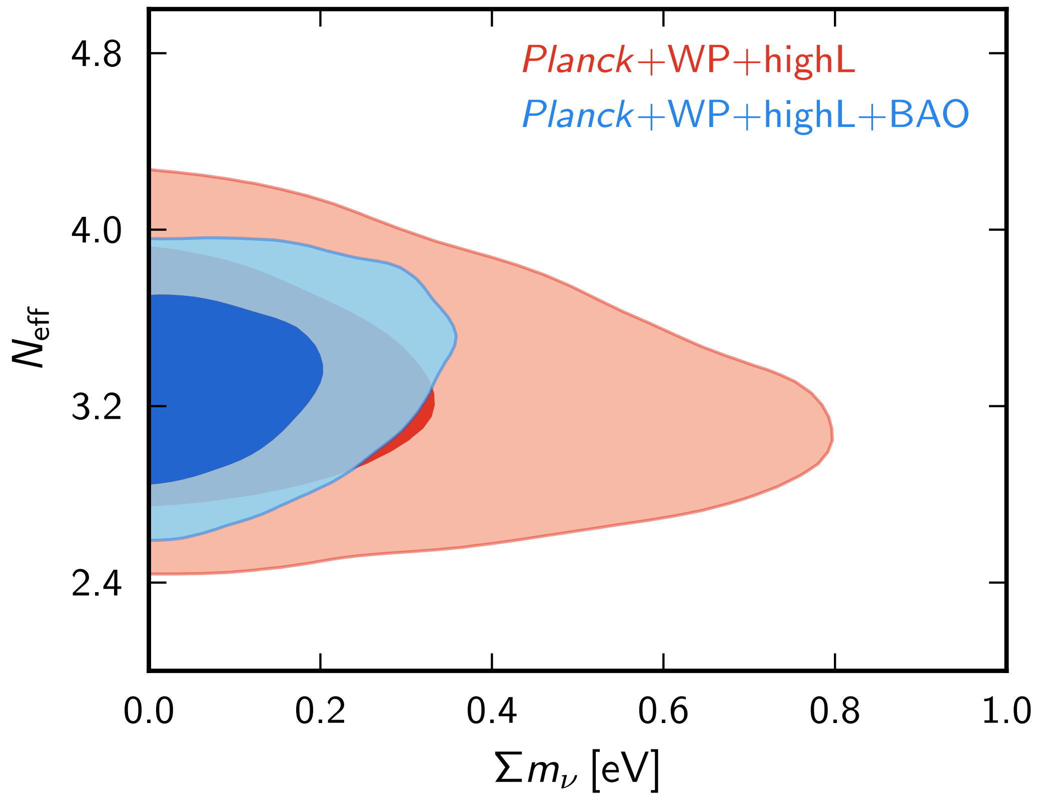


After WMAP-7 (+ LSS + small-scale CMB + H-HST) mild preference for extra radiation

"Cosmology seeking friendship with ... " extra radiation.

Hamann, Hannestad, Raffelt, Tamborrra, Wong (2010)

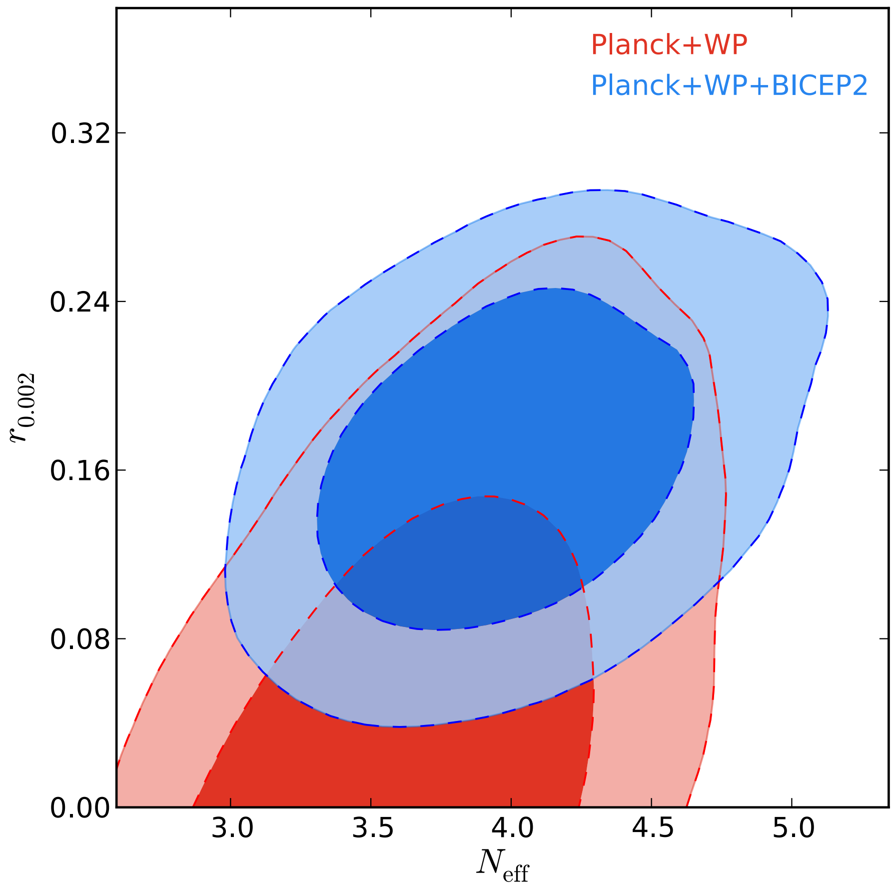
… Break-Up



No evidence for extra radiation!

Planck Collaboration (2013)

Friendship Renewed?



Planck and BICEP2 values of r come into closer agreement if there is extra radiation.

Giusarma, Valentino, Lattanzi, Melchiorri, Mena (2014, arXiv:1403.4852)

Dark Radiation Candidates

- Many possibilities with good motivations …
  - Thermal QCD axions (Strong CP)
  - Hidden Photons (Extra U(1)s, …)
  - Sterile Neutrinos (This talk)
  - …

Cosmological Sterile Neutrinos

- Vacuum mixing (Dodelson-Widrow)
  - Usual mixing of active-sterile.
  - Hot sterile nus.
- Resonant production (Shi-Fuller)
  - Steriles produced only via a MSW resonance that needs a large lepton asymmetry.
  - Cold/Warm sterile nus.
- …

Effective m and N

Often the temperature of the active neutrinos and the sterile neutrinos are not the same.

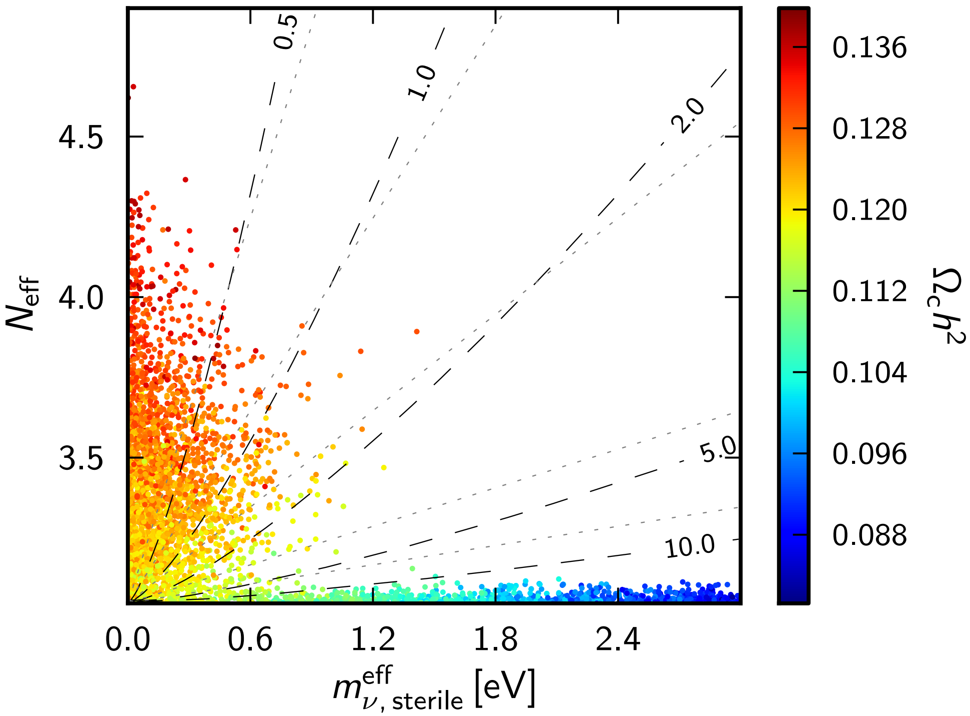
Even if sterile neutrinos were in equilibrium at some early temperature, the decay of SM (or Sterile) sector particles can lead to different temperatures.

Say the two were in thermal equilibrium above ~TeV, then

$$T_s = \left(\frac{g_*(T_\gamma)}{g_*(\mathrm{TeV})} \right)^{1/3} T_\gamma$$

So effective number and energy densities of sterile neutrinos can be different (lower). But typically oscillations bring them back in equilibrium, and this suppression is absent.

Endangered Sterile Neutrinos



Oscillation-friendly neutrinos are in tension with cosmology

$$\left.\begin{aligned} N_{\rm eff} &< 3.80 \\ m_{\nu,\,\rm sterile}^{\rm eff} &< 0.42\,\mathrm{eV} \end{aligned}\right\} \quad (95\%;\ \mathrm{CMB+BAO\ for}\ m_{\rm sterile}^{\rm thermal} < 10\,\mathrm{eV})\,. \tag{83}$$

These bounds are only marginally compatible with a fully thermalized sterile neutrino ($N_{\rm eff} \approx 4$) with sub-eV mass $m_{\rm sterile}^{\rm thermal} \approx m_{\nu,\,\rm sterile}^{\rm eff} < 0.5\,\mathrm{eV}$ that could explain the oscillation anomalies.

Planck Collaboration (2013)

Take Away # 1:
Strong cosmological bounds on a well-mixed light sterile neutrino.

Ways to avoid the constraint

- Large lepton asymmetry
  - Foot and Volkas (1995)
- Majorons
  - Babu and Rothstein (1992), Bento and Bereziani (2001),
- Very low reheating temperature
  - Gelmini, Palomarez-Ruiz, Pascoli (2004)
- Dilution by decay of exotic heavy particles
  - Fuller, Kishimoto, Kusenko (2011), Ho and Scherrer (2012), …
- ...

Not only avoid the constraint, but something better

Based on
Dasgupta and Kopp, Phys. Rev. Lett. 112 (2014)

The Not-So-Sterile Neutrino

$$\mathcal{L} = e_\nu \overline{\nu_s} \gamma_\mu \nu_s A'_\mu$$

Add to SM a sterile neutrino that has some gauge interaction via a new light gauge boson A.

Initially sterile and active sectors in equilibrium, and decouple at T > 100 GeV.

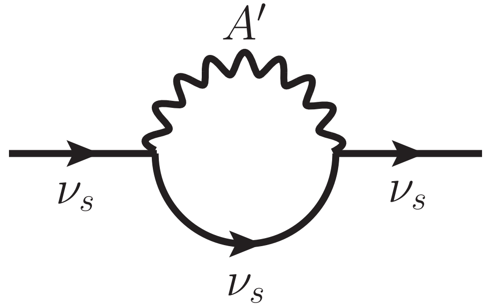
Because of energy injection into photons, $T_s = \left(\frac{g_*(T_\gamma)}{g_*(\mathrm{TeV})} \right)^{1/3} T_\gamma$

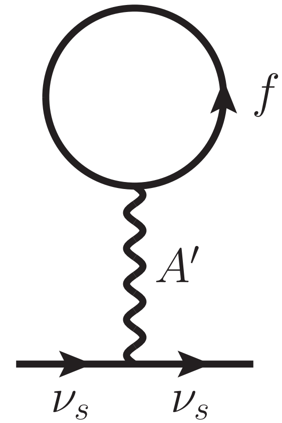
Leads to extra N_eff ~0.5 by BBN thermally.

What about oscillations?

Hansen, Hannestad, Tram (2014)
Dasgupta and Kopp (2014)

Thermal Masses

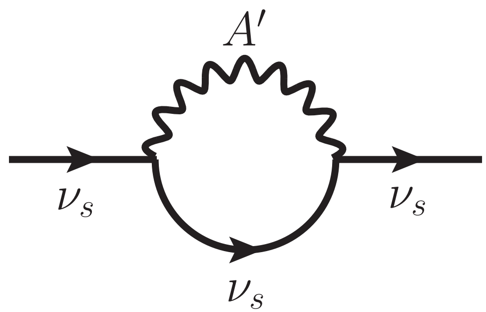


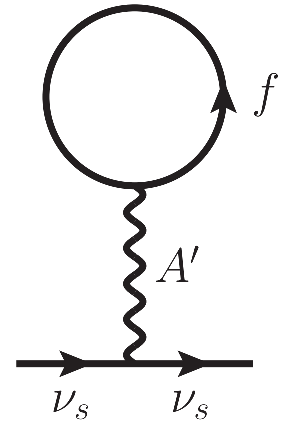


Sterile neutrinos acquire a "thermal mass" due to their interactions with virtual/real gauge bosons which can be quite large at high-T.

They are not produced by oscillations if this mass exceeds the active-sterile neutrino oscillation frequency.

Thermal Masses





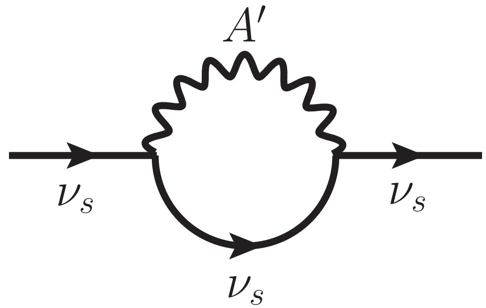
$$\Sigma(k) = (m - a\not{k} - b\not{u})P_L$$

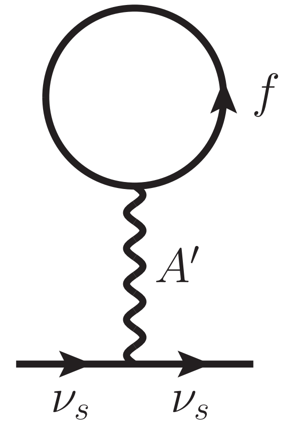
$$\det(\not{k} - \Sigma(k)) = 0$$

$$k^0 = |\mathbf{k}| + \frac{m^2}{2|\mathbf{k}|} - b$$

Ultrarelativistic

Thermal Masses



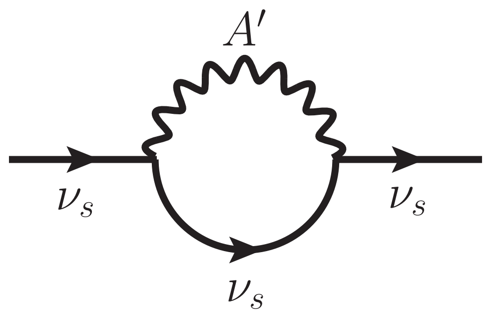


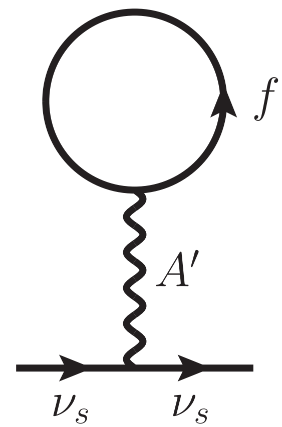
$$k^0 = |\mathbf{k}| + \frac{m^2}{2|\mathbf{k}|} - b \quad \Rightarrow \quad V_{\rm eff} \equiv -b$$

Ultrarelativistic

$$b = \frac{1}{2\mathbf{k}^2}\left[[(k^0)^2 - \mathbf{k}^2]\,\mathrm{tr}\,\not{u}\Sigma(k) - k^0\,\mathrm{tr}\,\not{k}\Sigma(k)\right]$$

Thermal Masses

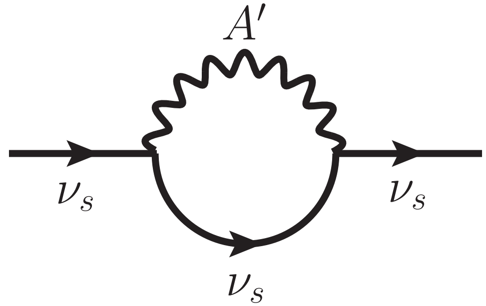


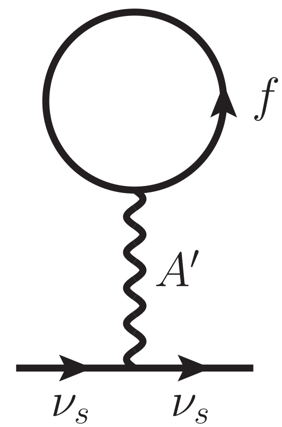


$$\Sigma_{\text{bubble}}(k) = -ie_\chi^2 \int \frac{d^4p}{(2\pi)^4} \gamma^\mu \, P_L \, iS(p+k) \, \gamma^\nu \, iD_{\mu\nu}(p) \, ,$$

$$\Sigma_{\text{tadpole}}(k) = ie_\chi^2 \gamma^\mu \, P_L \, iD_{\mu\nu}(0) \int \frac{d^4p}{(2\pi)^4} \, \text{tr}\left[\gamma^\nu \, P_L \, iS(p)\right]$$

Thermal Masses





$$S(p) = (\not{p} + m)\left[\frac{1}{p^2 - m^2} + i\Gamma_f(p)\right]$$

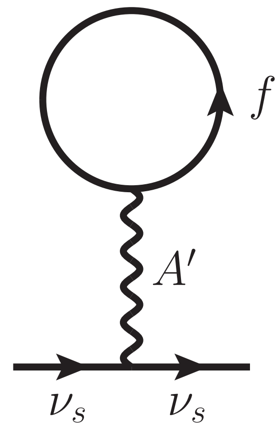
$$D_{\mu\nu}(p) = (-g_{\mu\nu})\left[\frac{1}{p^2 - M^2} - i\Gamma_b(p)\right]$$

(There's a typo in the arxiv version, and the journal version)

$$\Gamma_f(p) = 2\pi\delta(p^2 - m^2)\eta_f(p)$$

$$\Gamma_b(p) = 2\pi\delta(p^2 - M^2)\eta_b(p)$$

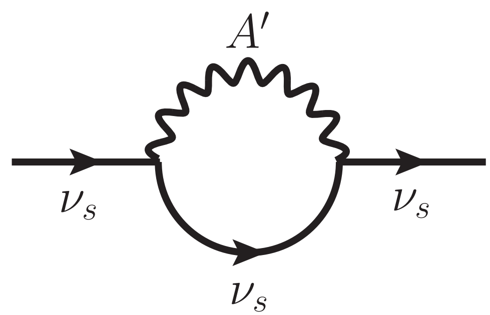
Thermal Masses



$$V_{\text{eff}}^{\text{tadpole}} \simeq \frac{2\pi\alpha_\chi}{M^2}(n_f - n_{\bar{f}})$$

Usual MSW term. We could assume an asymmetry in sterile neutrinos.

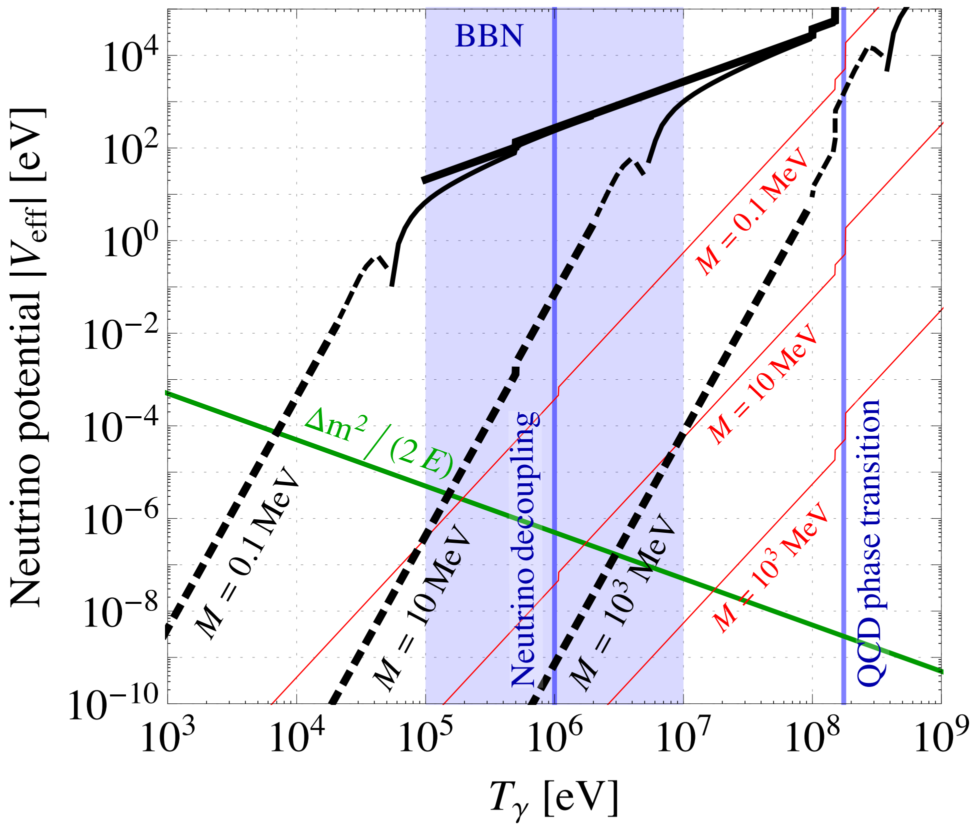
Thermal Masses



$$V_{\rm eff}^{\rm bubble} \simeq \begin{cases} -\dfrac{28\pi^3\alpha_\chi E T_s^4}{45 M^4} & \text{for } T_s, E \ll M \\ \\ +\dfrac{\pi\alpha_\chi T_s^2}{2E} & \text{for } T_s, E \gg M \end{cases}$$

Purely thermal contribution. Exists even with no asymmetry.

Thermal MSW Potential



If M < 10 MeV the thermal potential can be large

Dasgupta and Kopp (2014)

MSW suppression

$$\sin^2 2\theta_m = \frac{\sin^2 2\theta_0}{\left(\cos 2\theta_0 + \frac{2E}{\Delta m^2} V_{\text{eff}}\right)^2 + \sin^2 2\theta_0}$$

$$|V_{\text{eff}}| \gg \left| \frac{\Delta m^2}{2E} \right|$$

No production by oscillations. Also thermalization rate is similarly suppressed.

N_{eff} is increased by ~0.5 due to sterile neutrinos at BBN (much less at CMB)

Dasgupta and Kopp (2014)

Some Comments

- Detailed dynamics should consider MSW resonances
- Adiabaticity effects
- Non-forward scattering processes
- Sterile neutrino decoupling is slightly earlier than 1 MeV due to mixing angle suppression
- Tails of the thermal distribution
- V << T, so relativistic approximation holds

Full QKE

$$\dot{\mathbf{P}} = \mathbf{V} \times \mathbf{P} - D(P_x \mathbf{x} + P_y \mathbf{y}) + \dot{P}_0 \mathbf{z} \ ,$$

$$\dot{P}_0 = \Gamma \left[\frac{f_{\mathrm{eq}}}{f_0} - \frac{1}{2}(P_0 + P_z) \right]$$

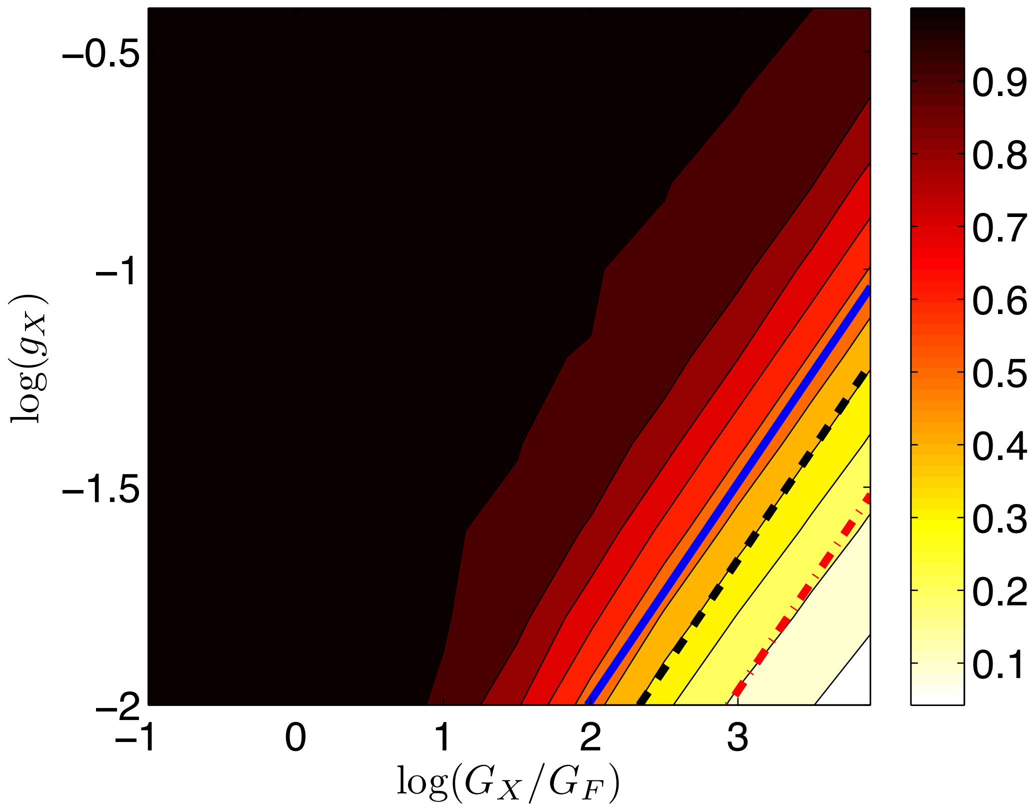
Besides oscillations, scattering processes also taken into account. The scattering rate is

$$\Gamma = C_a G_F^2 x T^5$$

$$D = \frac{1}{2}\Gamma \ .$$

Hansen, Hannestad, Tram (2014)

Fractional dofs from QKE

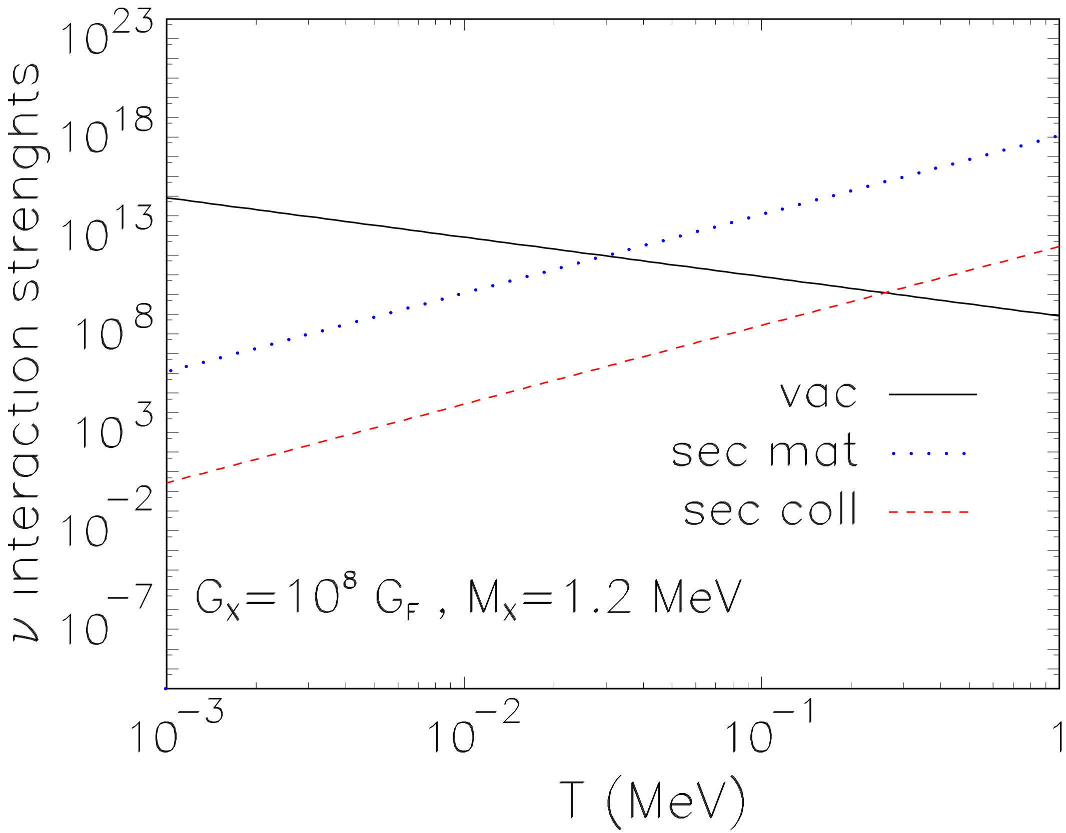


For ~100 MeV boson
One can easily suppress
N_eff to below 0.5

Hansen, Hannestad, Tram (2014)

Post-BBN Thermalization

Mirizzi, Mangano, Pisanti, Saviano (2014)



For ~1 MeV boson, one equilibrates sterile and active neutrinos through collisional decoherence

In some cases tension with mass bounds ☹

Speaker's note added: This constraint rules out almost all parameter space except two regions at M~1 MeV and g~10^-4 and at M ~ 0.1 MeV with g~0.1 (less obvious).

Comments

- Detailed dynamics should consider MSW resonances
- Adiabaticity effects
- Non-forward scattering processes
- Sterile neutrino decoupling is slightly earlier than 1 MeV due to mixing angle suppression
- Tails of the thermal distribution
- $V << T$, so relativistic approximation holds

Take Away # 2:
"Gauged"-sterile can avoid the bounds.

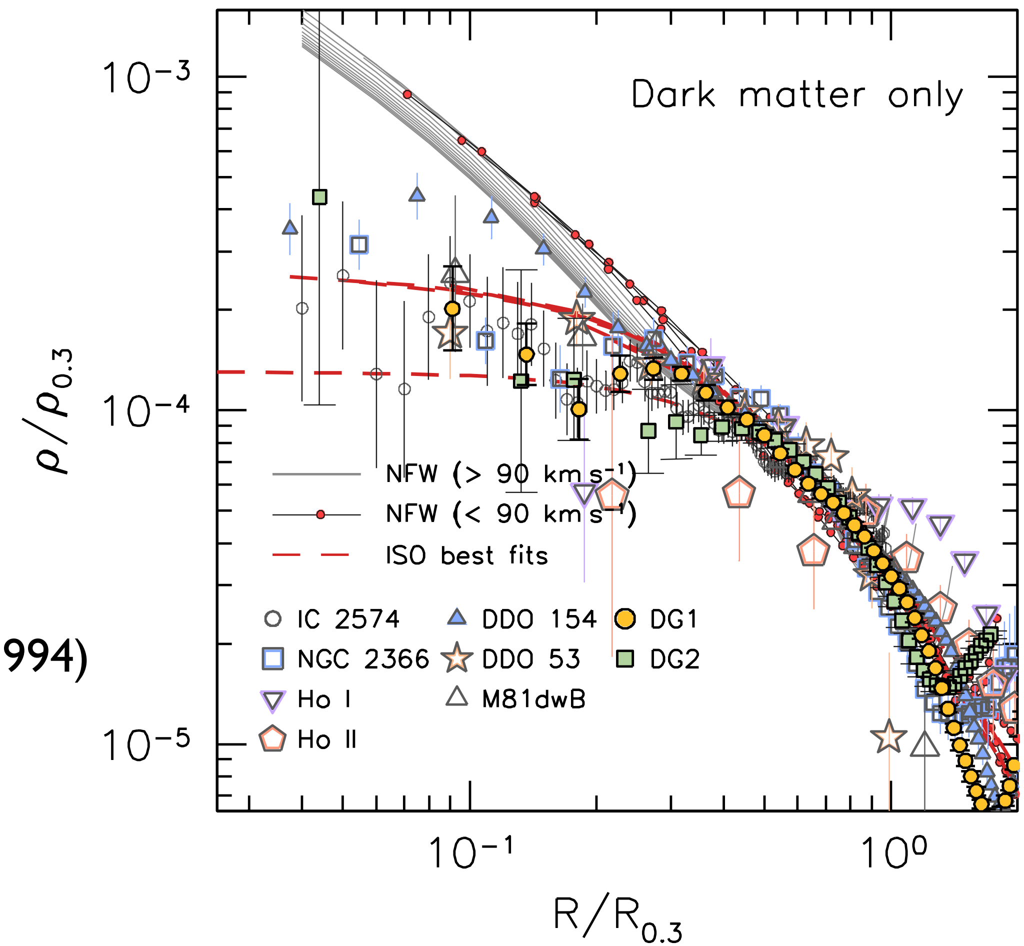
Unintended Consequences

Core-vs.-Cusp

Profiles of dwarf spheroidal galaxies don't seem to fit with that predicted by CDM simulations.

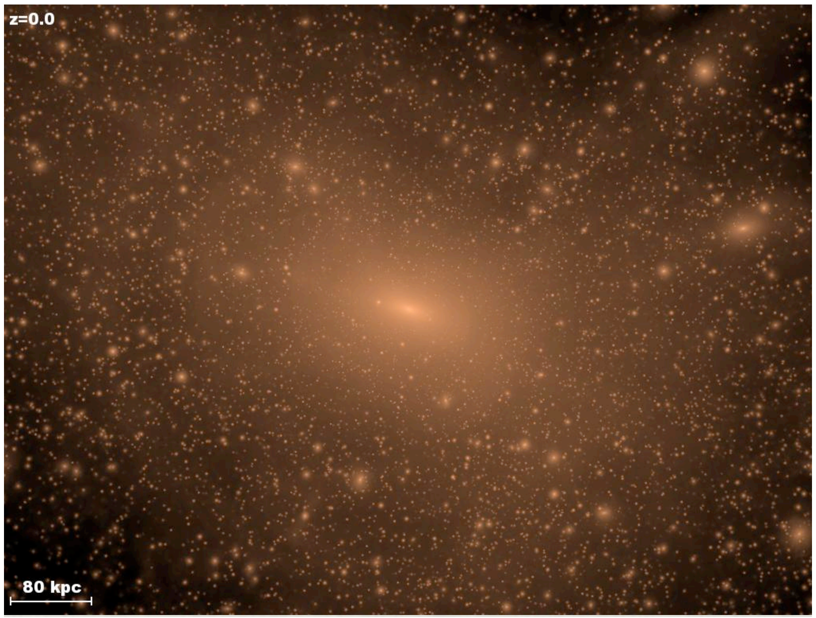
Observed galaxies have cores, where cusps are predicted.

Moore (1994); Flores and Primack (1994)

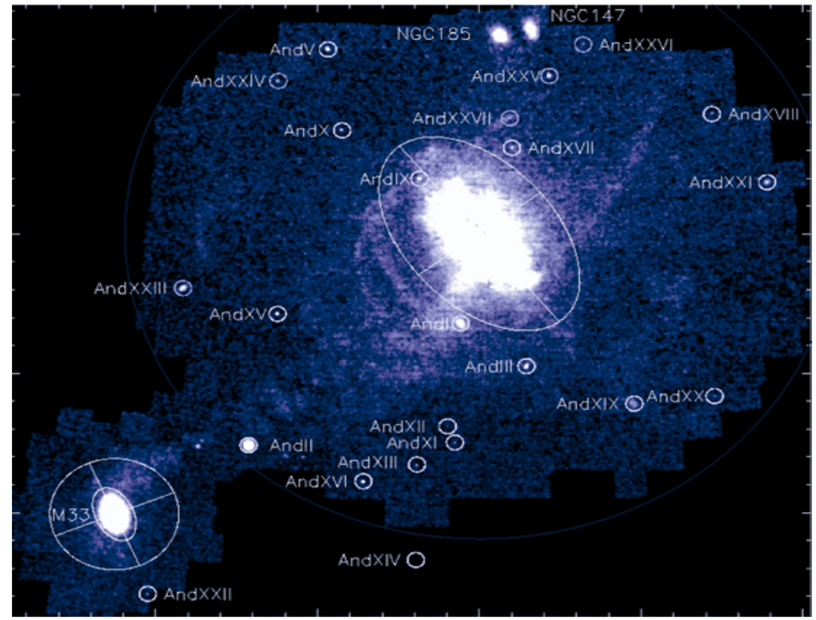


Oh et al. (2010)

Missing Satellites



Via Lactea simulation

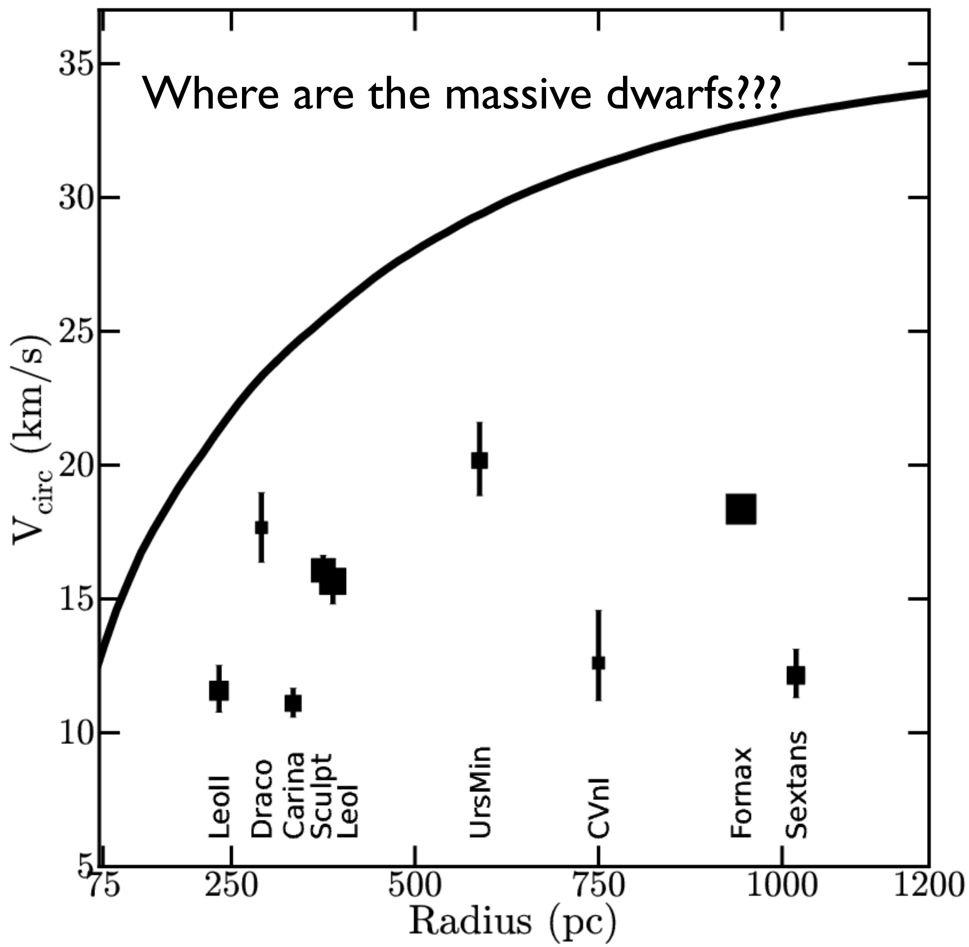


PAndAS Survey

Factor ~100 fewer MW-satellite galaxies seen

Klypin et al. (1999); Moore et al. (1999)

Too Big to Fail



Boylan-Kolchin, Kaplinghat, Bullock (2010)

How to address these problems?

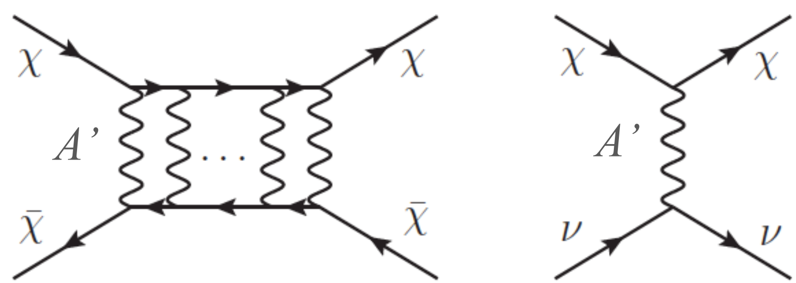
- Baryonic effects (Reionization, SN Feedback,…, Tidal stripping…)
  - DM core creation + Tidal stripping (TBTF)
  - Faint galaxies + Reionization (only MSP)
- Yukawa interactions of DM (can't solve MSP)
- DM-neutrino interactions (strong constraints)
- …

A DM-Neutrino Connection

$$\mathcal{L} = e_\chi \overline{\chi} \gamma_\mu \chi A'_\mu + e_\nu \overline{\nu_s} \gamma_\mu \nu_s A'_\mu$$

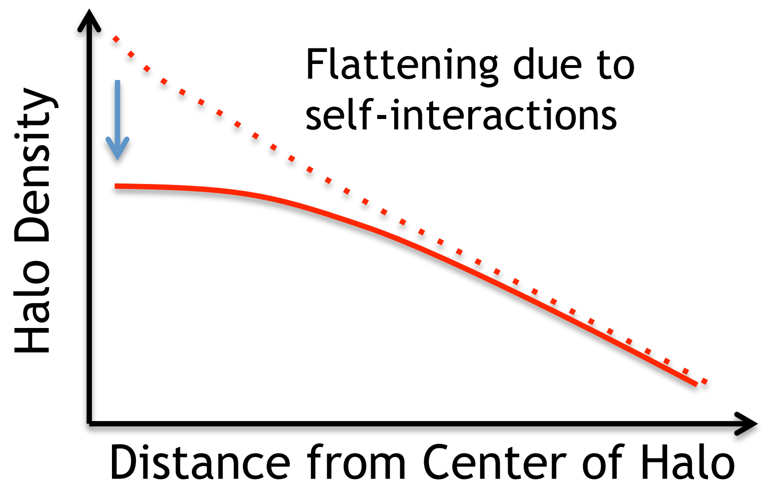
Assume that the new force couples to DM as well (coupling is taken to be same)

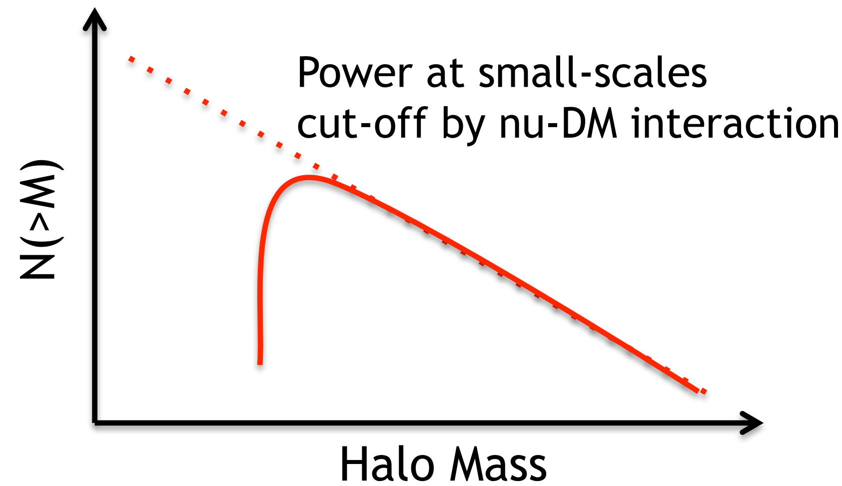
No new parameters are introduced.



Two new processes are automatically expected

A Neutrino-tempered DM





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

Van den Aarssen, Bringmann, Pfrommer (2012); Dasgupta and Kopp (2014)

Smoothening DM Cusps

Dwarf-sized halos do not have cusps due to DM-DM interactions mediated by A'.

What one needs is then DM-DM scattering cross section at the level of 0.1 cm^2 / g for velocities of dwarf galaxies (10 km/s).

Feng, Kaplinghat, Tu, Yu (2009); Loeb and Weiner (2011)

This is easily achieved by having a light mediator A' that enhances the cross section.

Explaining the Missing Satellites

The sterile neutrino-DM scattering keeps DM in kinetic equilibrium until somewhat later ($T_\chi/m_\chi\ n_\nu\ \sigma_{\nu\chi}$) ~ H

This erases structure at the smallest scales, and the smallest (dwarf) halos never form.

Boehm, Fayet, Schaeffer (2000); Loeb and Zaldarriaga (2005)

What one needs is then M_cut ~ 10^9 solar masses or so.

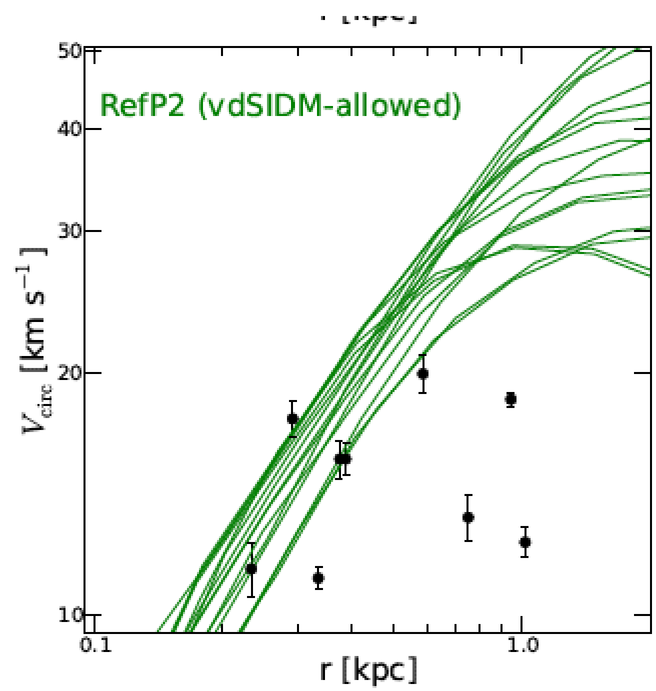
$$\frac{M_{\rm cut}}{M_{\rm Sun}} \simeq 3.2\times 10^{13}\,\alpha_\chi^{\frac{3}{2}}\left(\frac{T_s}{T_\gamma}\right)_{\rm kd}^{\frac{9}{2}}\left(\frac{\rm TeV}{m_\chi}\right)^{\frac{3}{4}}\left(\frac{\rm MeV}{M}\right)^{3}.$$

One needs a spin-1 mediator for this to work. Scalars lead to a small effect.

Addressing the TBTF problem

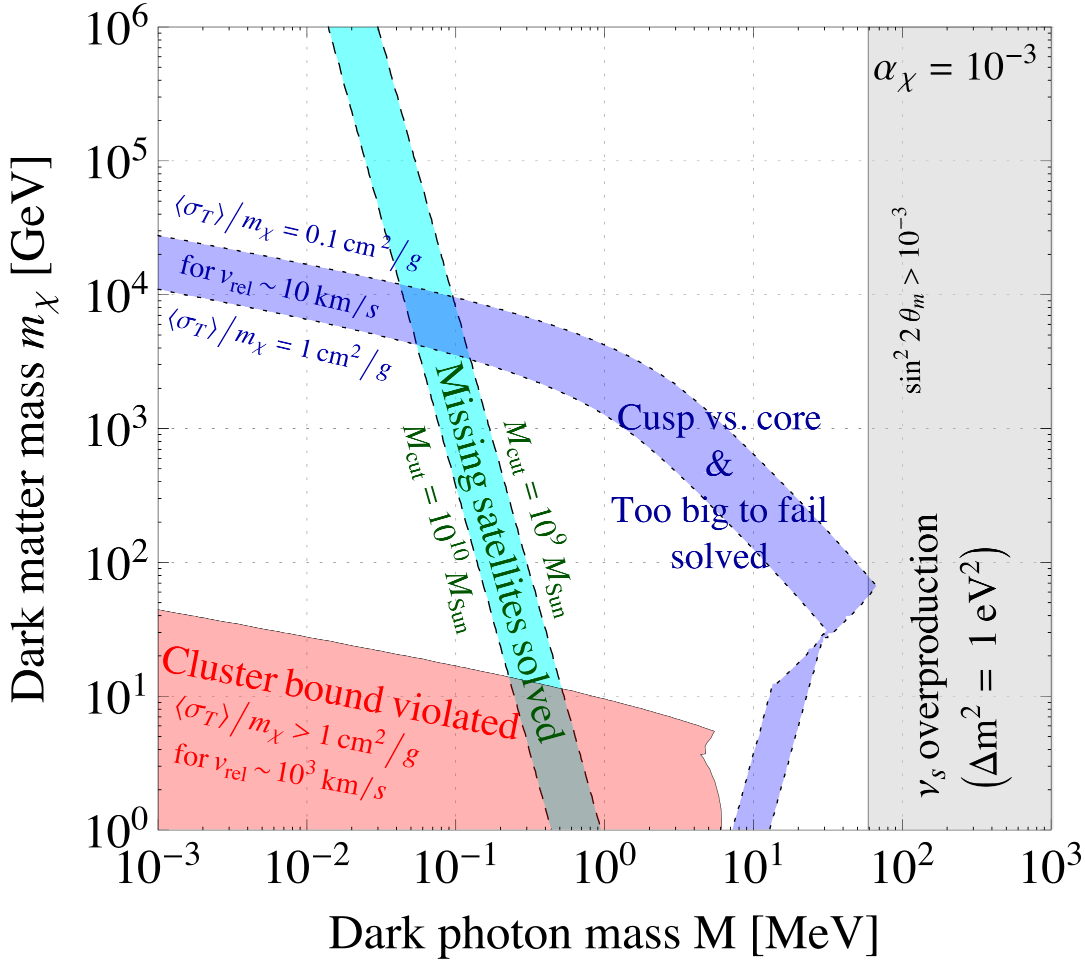
Dwarf-sized subhalos inside MW do not have cusps due to DM-DM interactions mediated by A'.

What one needs is then DM-DM scattering cross section at the level of 0.1 cm^2 / g for velocities of dwarf galaxies (10 km/s). This is the same condition as that for solving the core-cusp problem.



Zavala, Vogelsberger, Loeb (2012)

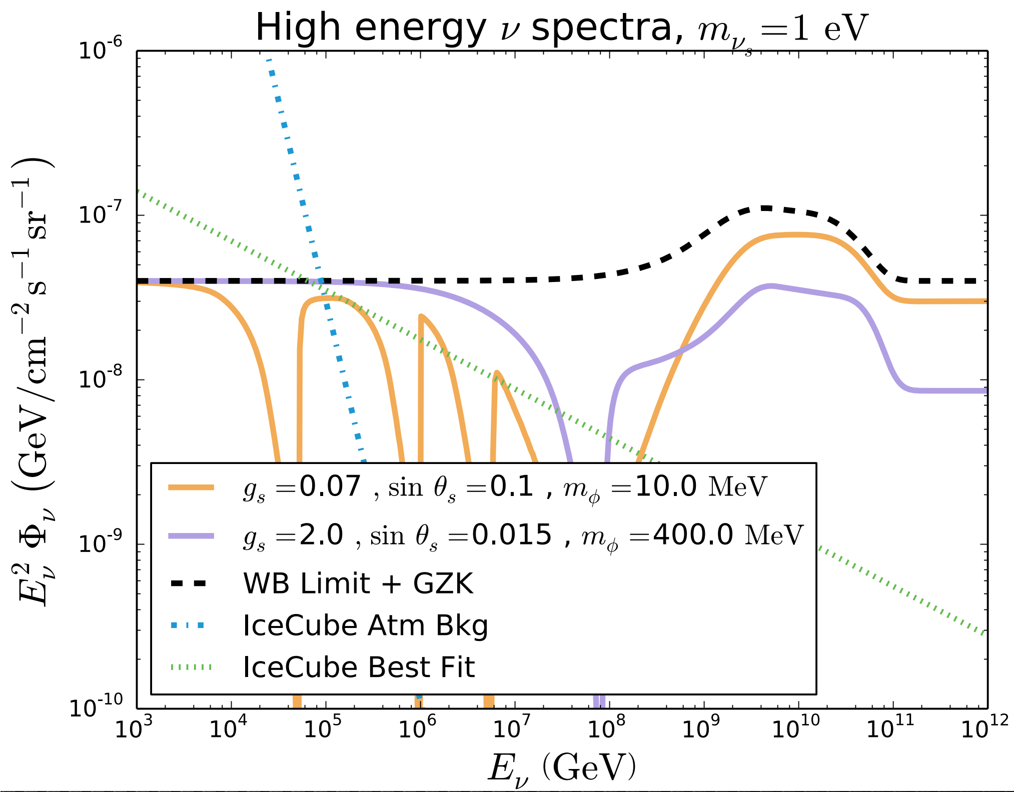
DM-Neutrino Concordance



One can explain $N_{\rm eff}$, Neutrino Oscillations, and All 3 DM problems, simultaneously

Dasgupta and Kopp (2014), see also follow up by Bringmann, Hasenkamp, Kersten (2014)

A Connection to PeV Neutrinos



Can lead to depletion of HE events around a PeV at IceCube

Cherry, Friedland, and Shoemaker (to appear)
Similar ideas in: Ioka and Murase (2014), Ng and Beacom (2014)

Take Away # 3:
Interesting astrophysical signatures

Summary

1. Strong cosmological bounds on a well-mixed light sterile neutrino.

2. Minor extensions to sterile neutrinos can avoid the cosmological bounds on dark radiation.

3. Hidden charged sterile neutrinos can explain DM behavior at small-scales, etc.

Bonus Material

Based on Chu and Dasgupta, published in PRL (Oct, 2014)

Getting Rid of Neutrinos

$$\mathcal{L}_{\rm dark} \ni \partial_\mu \phi^* \partial^\mu \phi + \mu_\phi^2 |\phi|^2 - \lambda_\phi |\phi|^4$$ Complex Scalar

$$+ i\bar{\chi}\gamma^\mu \partial_\mu \chi - M\bar{\chi}\chi - (\frac{f_{\rm d}}{\sqrt{2}}\phi\chi^T C\chi + h.c.)$$ Fermion

On spontaneous symmetry breaking

$$\phi \equiv (v_\phi + \rho + i\eta)/\sqrt{2}$$

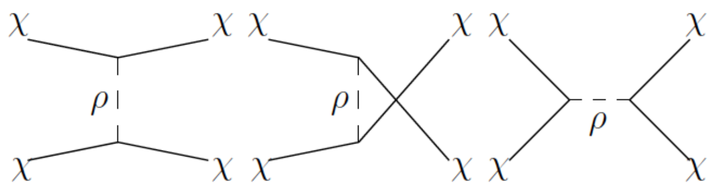
$$\chi_\pm \to -\chi_\pm \text{ and } (\rho, \eta) \to (\rho, \eta)$$

Residual Z2 symmetry ensures χ_- = DM is stable

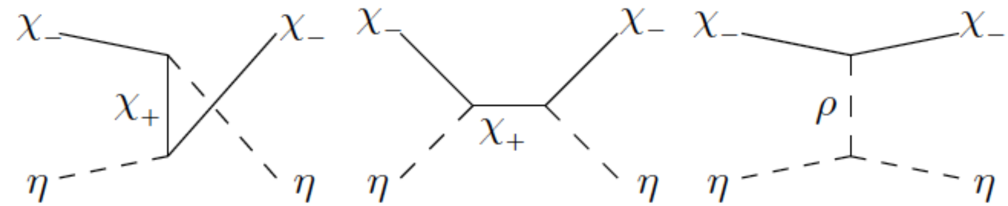
Also η = DR

Weinberg (2013)

DM + DR



DM-DM Scattering



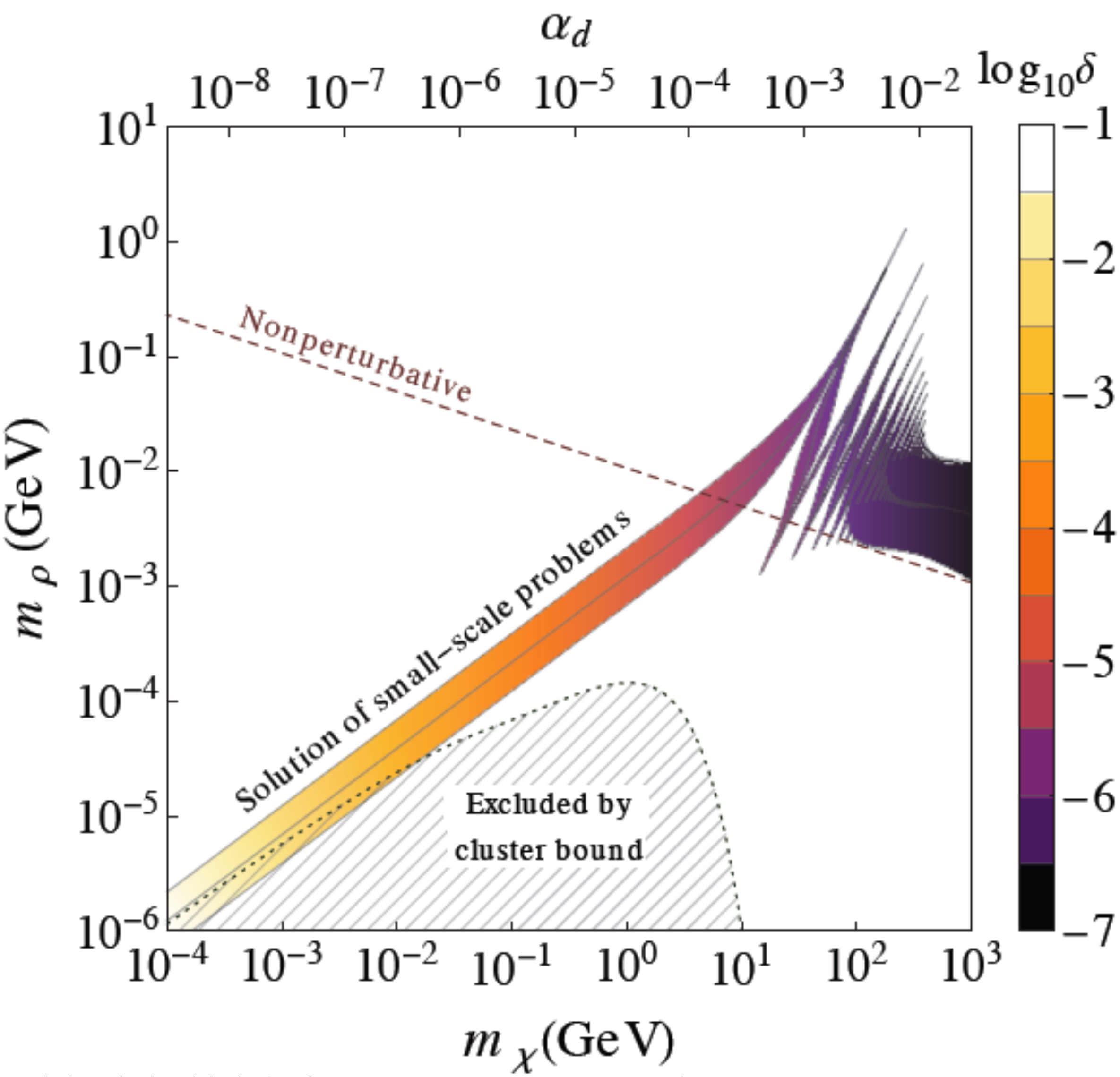
DM-DR Scattering

$$\sigma_T \simeq \frac{8\pi\alpha_{\rm d}^2}{m_\chi^2 v_{\rm rel}^4}\left[\log(1+R^2) - \frac{R^2}{1+R^2}\right] \qquad \sigma_{\eta\chi_-} = \frac{8\pi\alpha_{\rm d}^2\omega^4}{\Delta m_\chi^6}\left(1 + \frac{16\Delta m_\chi^2}{3m_\rho^2} + \frac{8\Delta m_\chi^4}{m_\rho^4}\right)$$

$$T_{\rm kd} \simeq 0.5\,{\rm keV}\,\frac{\delta}{10^{-4.5}}\left(\frac{m_\chi}{\rm GeV}\right)^{7/6}\left(\frac{10^{-4}}{\alpha_{\rm d}}\right)^{1/3}\xi_{\rm kd}^{-4/3}$$

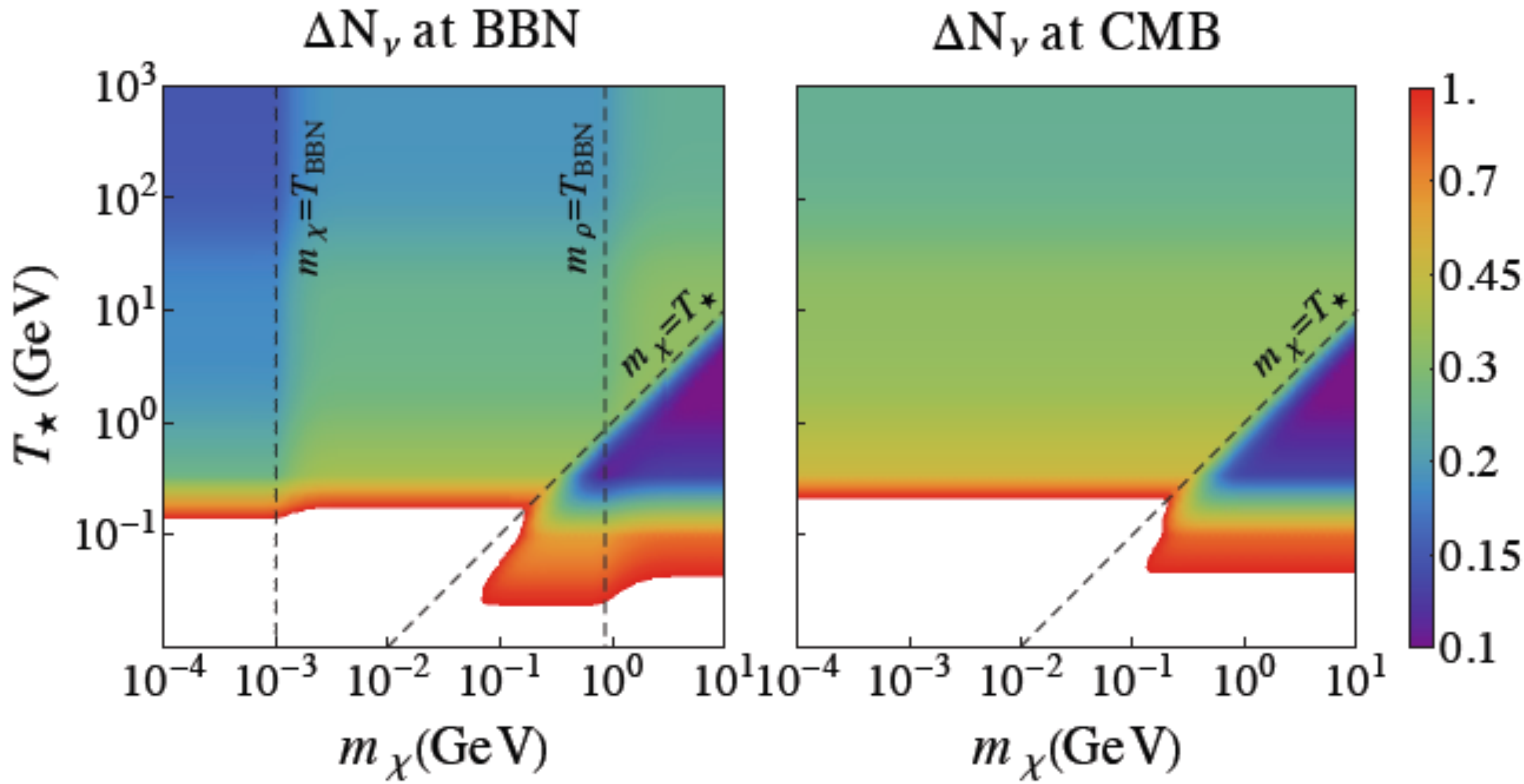
Chu and Dasgupta, 2014 (1404.6127, published in PRL)

Solving Small-Scale Problems



Chu and Dasgupta, 2014 (1404.6127, published in PRL)

Dark Radiation Predictions



Chu and Dasgupta, 2014 (1404.6127, published in PRL)