Sterile neutrinos with secret interactions

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"Updated constraints on non-standard neutrino interactions from Planck"
Maria Archidiacono, Steen Hannestad
JCAP 1407 (2014) 046, arXiv:1311.3873

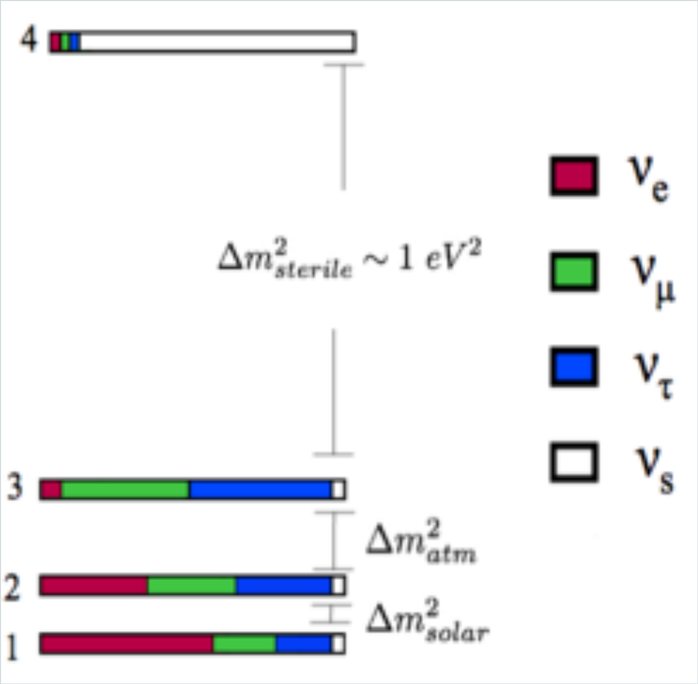
"Cosmology with self-interacting sterile neutrinos and dark matter - A pseudoscalar model"
Maria Archidiacono, Steen Hannestad, Rasmus Sloth Hansen, Thomas Tram
Phys.Rev. D91 (2015) 6, 065021, arXiv:1404.5915

"Sterile neutrinos with pseudoscalar self-interactions and cosmology"
Maria Archidiacono, Steen Hannestad, Rasmus Sloth Hansen, Thomas Tram
arXiv:1508.02504

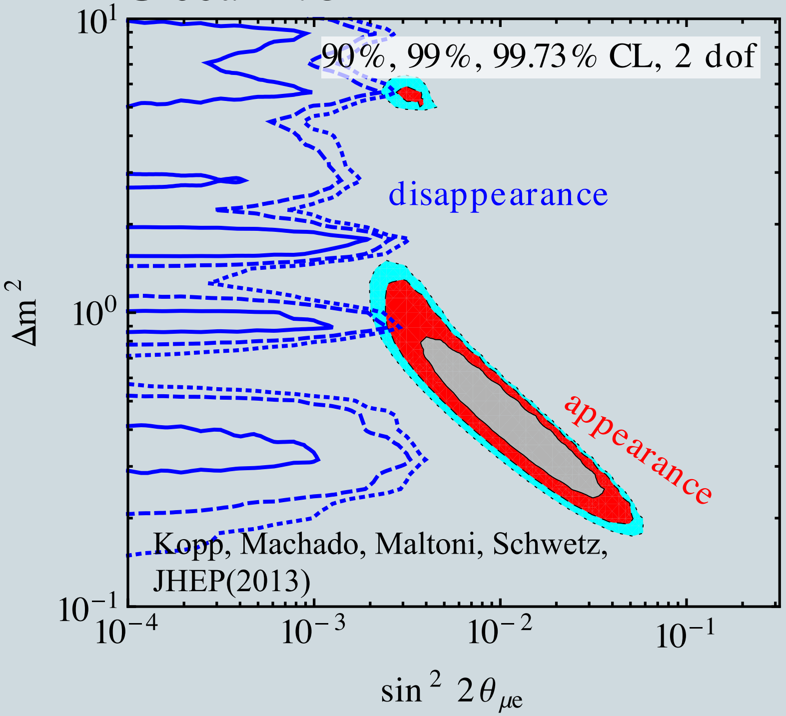
Oscillations

✧ Reactor anomaly (ν_e disappearence)
✧ Gallium anomaly (ν_e disappearence)
✧ LSND ($\nu_\mu \rightarrow \nu_e$ appearence)
✧ MiniBooNE ($\nu_\mu \rightarrow \nu_e$, $\nu_\mu \rightarrow \nu_e$ appearence)

Anomalies at the eV scale

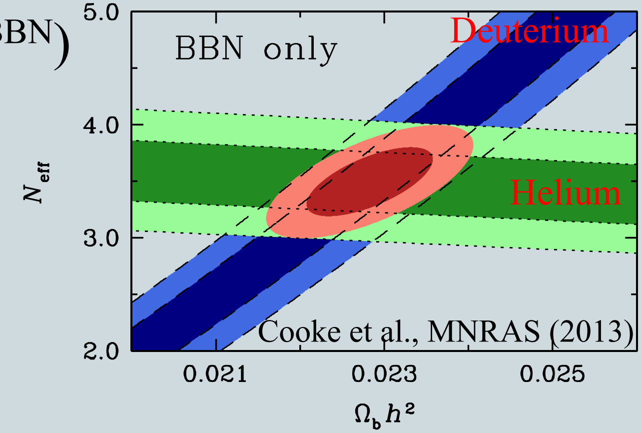


Global fit 3+1



Cosmology

- (Slightly) Too many neutrino species at BBN (ΔN_{eff}^{BBN})



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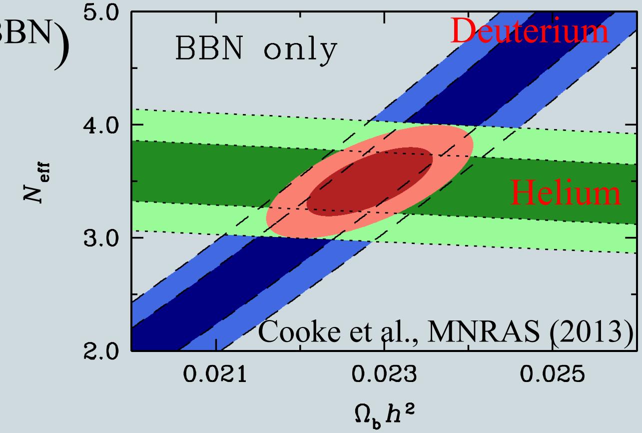

- Too much HDM energy density at CMB ($m_{\nu,s}\Delta N_{eff}^{CMB}$)

$$m_{eff}^{sterile} < 0.38\ eV$$

$$\Delta N_{eff}^{CMB} = n_{\nu,s} / n_{\nu}^{th} \qquad n_{\nu} = \frac{g}{2\pi^2}\int dp\ p^2 f_{\nu}(p)$$

(95% c.l.,
Planck2015 + lensing + BAO)

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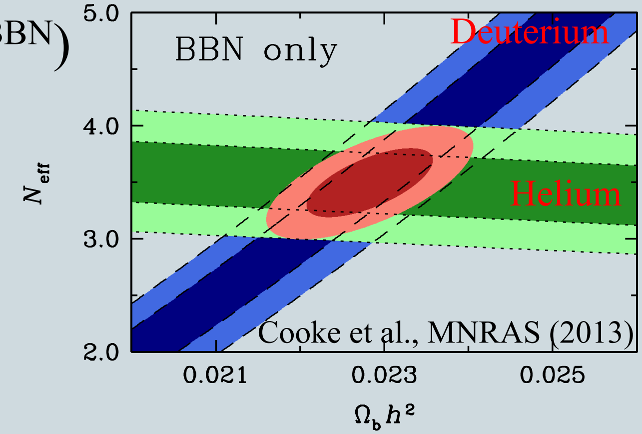

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Cuesta, Niro, Verde, (2015)

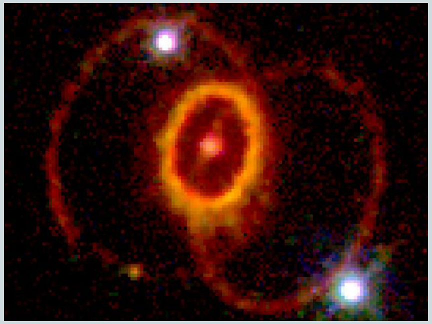
Pseudoscalar model

The sterile neutrino is coupled to a new light pseudoscalar (m_ϕ << 1eV)

$$L_{NS} \sim g_s \phi \bar{\nu}_s \gamma_5 \nu_s$$

No fifth force limits

Limits:



SN bounds:

$$\nu_e \nu_e \rightarrow \phi$$

$$g_e \leq 4 \times 10^{-7}$$

Farzan, PRD (2003)

$$g_s \leq g_e / \sin^2\theta_s = 3 \times 10^{-5}$$

Model dependent

$$\sin^2 2\theta_s = 0.05$$

Kopp et al., JHEP (2013)
Giunti et al. (2013)

0νββ decay

Bernatowicz et al. (1992)

Thermal history

- T > TeV ϕ particles are thermally produced
- T ~ GeV (g_s~10^{-5}) ν_s and ϕ in thermal equilibrium

  $$\nu_s \nu_s \leftrightarrow \phi\phi \qquad \langle \sigma |v| \rangle = \frac{g_s^4}{8\pi T_s^2}$$ in the relativistic limit

  one single tightly-coupled fluid

- T > 200MeV the dark sector decouples

$$T_\phi = \left(\frac{g_*(T_\gamma)}{g_*(1TeV)} \right)^{1/3} T_\nu^{SM} = 0.465 T_\nu^{SM}$$

- T ~ 10MeV neutrino oscillations become important

Early Universe: Flavour evolution

Density matrix

$$\rho = \frac{1}{2} f_0 \begin{pmatrix} P_a & P_x - iP_y \\ P_x + iP_y & P_s \end{pmatrix}$$

QKEs:

$$\dot{P}_a = V_x P_y + \Gamma_a \left[2 - P_a \right],$$ Repopulation

$$\dot{P}_s = -V_x P_y + \Gamma_s \left[2 \frac{f_{0,s}(T_s, \mu_s)}{f_0} - P_s \right],$$

$$\dot{P}_x = -V_z P_y - DP_x,$$

$$\dot{P}_y = V_z P_x - \frac{1}{2} V_x (P_a - P_s) - DP_y$$

Potentials:

$$V_x = \frac{\Delta m_s^2}{2p} \sin 2\theta_s,$$ Vacuum

Background ν

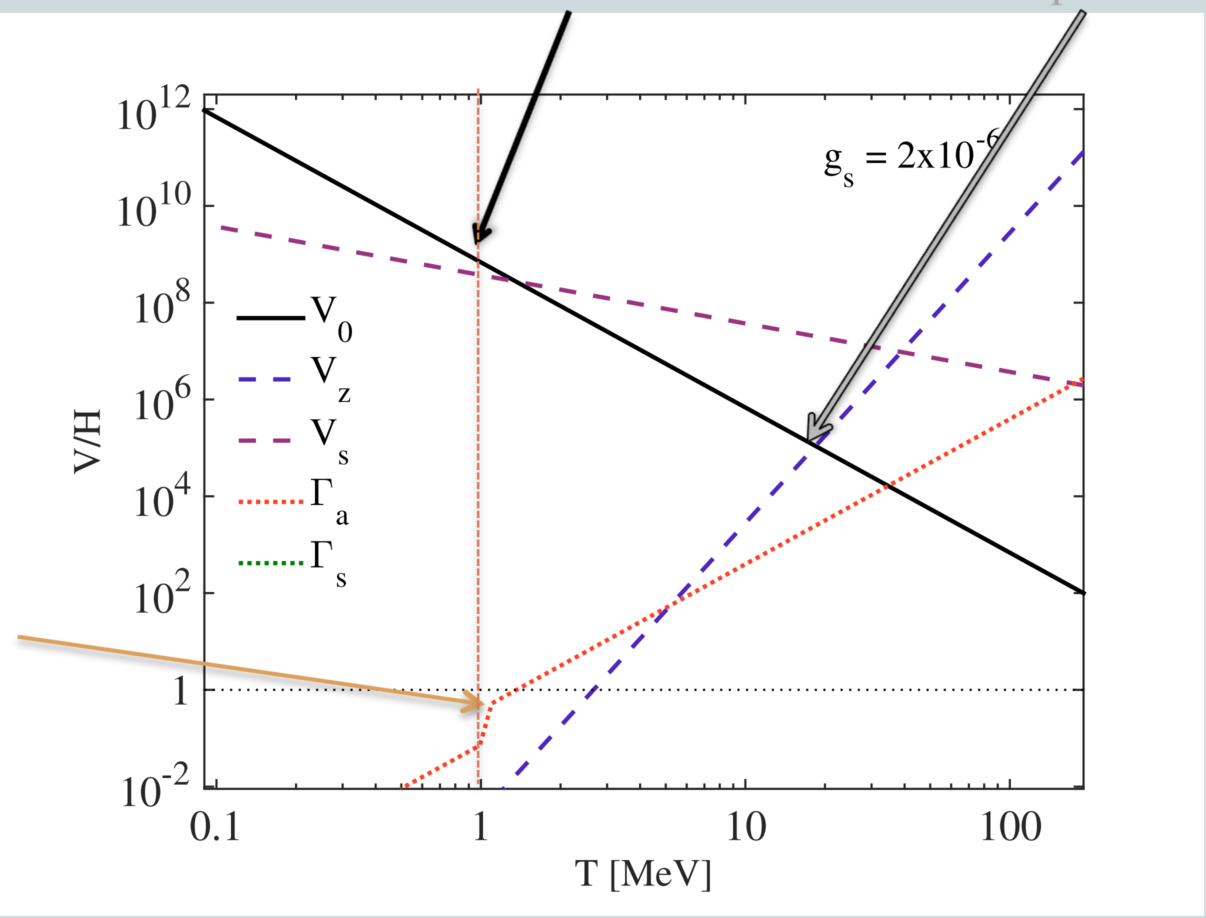
$$V_z = -\frac{\Delta m_s^2}{2p} \cos 2\theta_s - \frac{14\pi^2}{45\sqrt{2}} p \frac{G_F}{M_Z^2} T^4 n_a + V_s$$

$$V_s(p_s) = \frac{g_s^2}{8\pi^2 p_s} \int p\, dp (f_\phi + f_s) \sim 10^{-1} g_s^2 T_s$$

Damping: $D = \frac{1}{2}(\Gamma_a + \Gamma_s)$ Collisions: $\Gamma_a = C G_F^2 p T^4$ $\Gamma_s = \frac{g_s^4}{4\pi T_s^2} n_s$

Sterile neutrino production

Resonant production



Standard neutrino decoupling &~ n/p freeze-out

To prevent sterile neutrino thermalization, we need to suppress the mixing angle in matter, i.e.

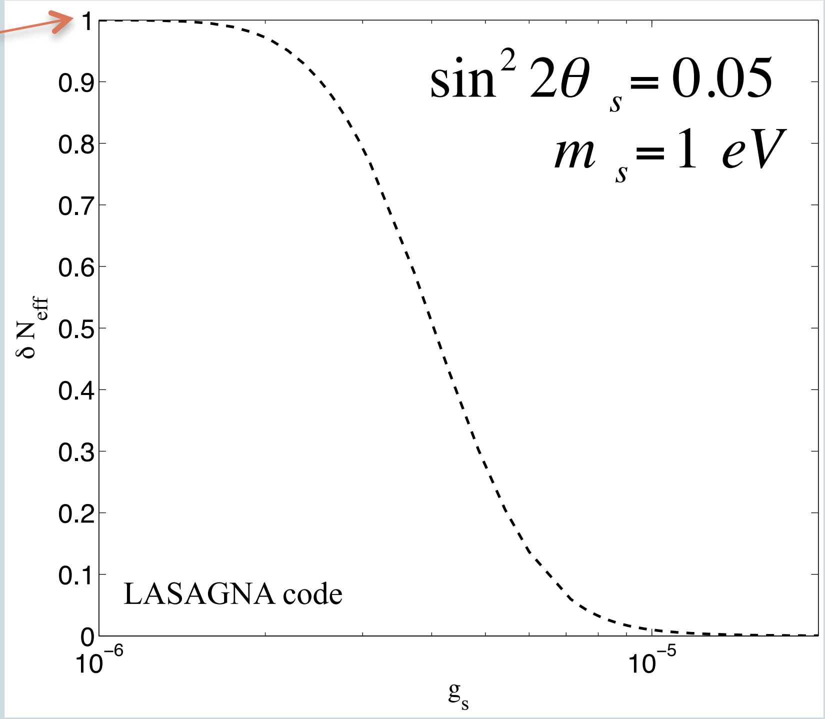
$$V_s >\sim \frac{\Delta m_s^2}{2p}$$

prior to standard neutrino decoupling

Sterile neutrinos at BBN

MA, Hannestad, Hansen, Tram, PRD (2014)

BBN bounds:
$\Delta N_{eff} \leq 1$ (95% c.l.)

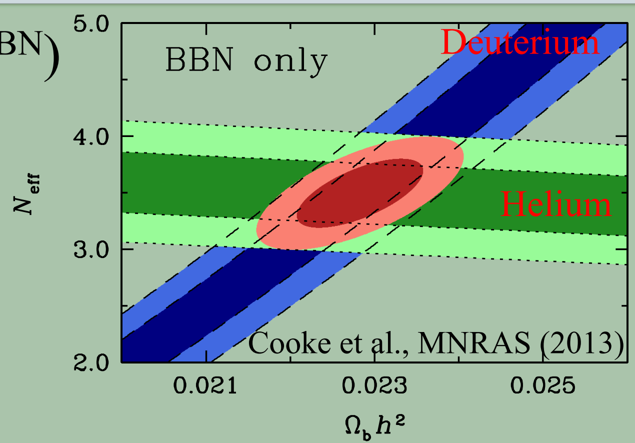


When sterile neutrinos are produced, they will create non-thermal distortions in the sterile neutrino distribution, and the sterile neutrino spectrum end up being somewhat non-thermal.

The transition between full thermalization and no thermalization occurs for coupling $10^{-6} < g_s < 10^{-5}$

Cosmology

✓ (Slightly) Too many neutrino species at BBN (ΔN_{eff}^{BBN})



- Too much HDM energy density at CMB ($m_{\nu,s} \Delta N_{eff}^{CMB}$)

$$\Delta N_{eff}^{CMB} = n_{\nu,s} / n_\nu^{th} \qquad n_\nu = \frac{g}{2\pi^2} \int dp\ p^2 f_\nu(p)$$

$$m_{eff}^{sterile} < 0.38\ eV$$

(95% c.l.,
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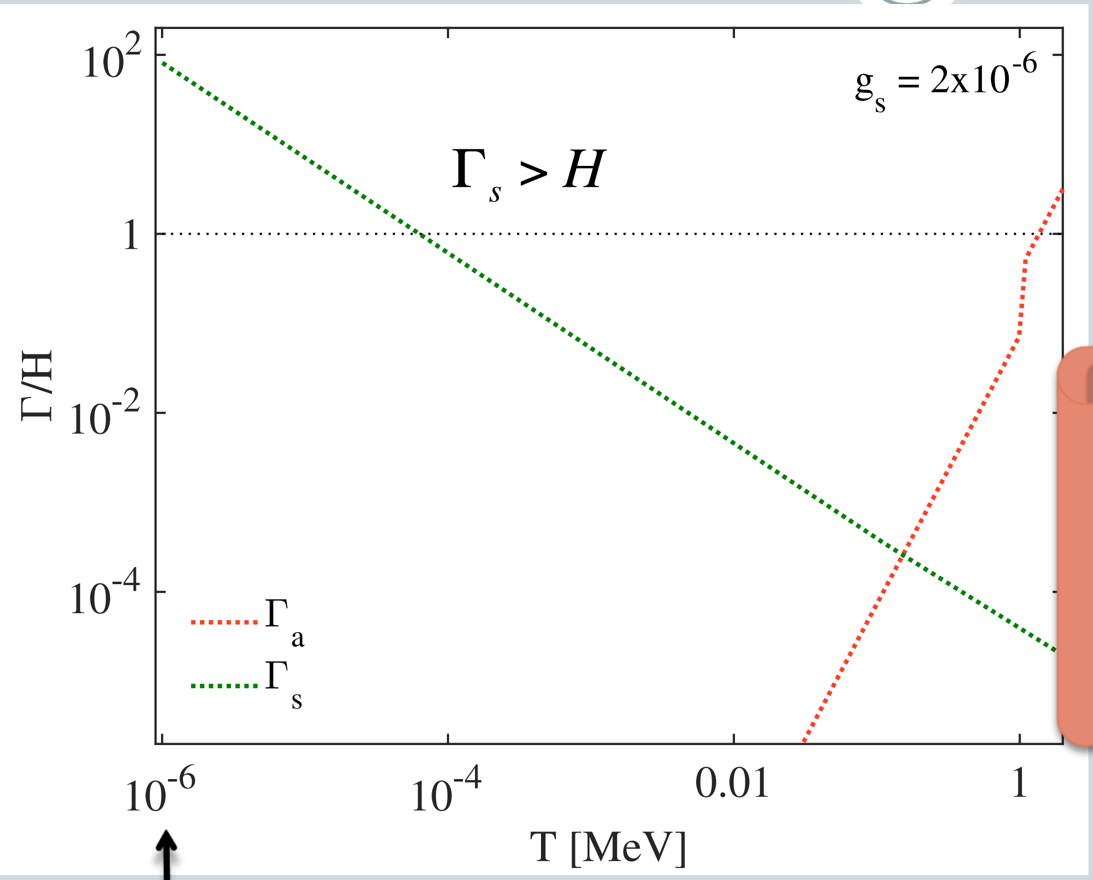
Late time phenomenology (1): $\nu_s - \phi$ interactions



Recombination

$$\Gamma_a = C G_F^2 p T^4 \qquad \Gamma_s = \frac{g_s^4}{4\pi T_s^2} n_s$$

The $\nu_s - \phi$ fluid becomes strongly interacting before neutrinos go non-relativistic around recombination

Low energy / late time process

Neutrino perturbations

Expansion in Legendre polynomials of the collisionless Boltzmann equation in Fourier space

$$\dot{\Psi}_0 = -k\frac{q}{\varepsilon}\Psi_1 + \frac{1}{6}\dot{h}\frac{d\ln f_0}{d\ln q}$$

$$\dot{\Psi}_1 = k\frac{q}{3\varepsilon}(\Psi_0 - 2\Psi_2)$$

$$\dot{\Psi}_2 = k\frac{q}{5\varepsilon}(2\Psi_1 - 3\Psi_3) - \left(\frac{1}{15}\dot{h} + \frac{2}{5}\dot{\eta}\right)\frac{d\ln f_0}{d\ln q}$$

$$\dot{\Psi}_l = k\frac{q}{(2l+1)\varepsilon}(l\Psi_{l-1} - (l+1)\Psi_{l+1}),\ l \geq 3$$

$$f(\vec{x},q,\hat{n},\tau) = f_0(q)\left[1 + \Psi(\vec{x},q,\hat{n},\tau)\right]$$

Neutrino perturbations

collisional
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Annihilation processes

Scattering processes

$\tau = (n\langle\sigma|v|\rangle)^{-1}$

Relaxation time approximation

Hannestad, JCAP (2005)
Hannestad & Scherrer, PRD (2000)
see
Oldengott,Rampf,Wong,JCAP (2015)
for the exact analytical solution

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Scattering processes

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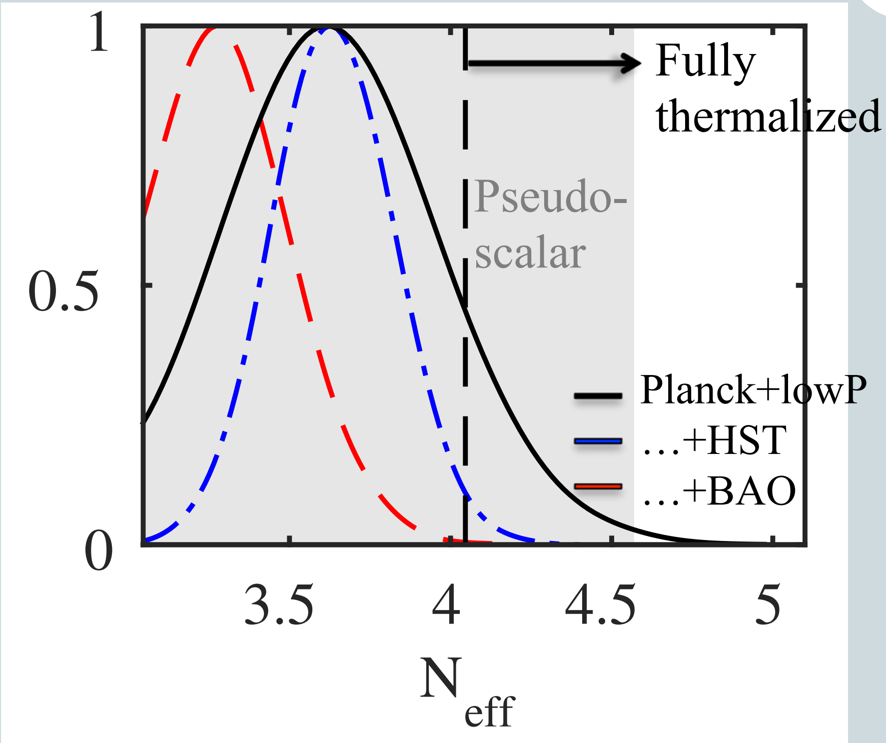
Relaxation time

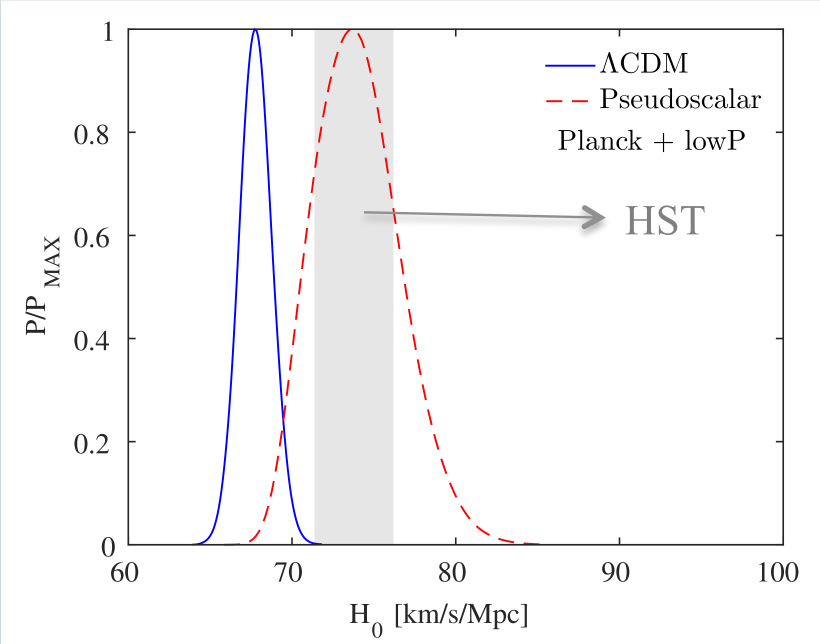
No free streaming
No anisotropic stress

Sterile neutrinos at CMB



MA, Hannestad, Hansen, Tram (2015)

Each value of g_s corresponds to one value of N_{eff}.
$N_{eff} \sim 3$ ➔ $g_s \geq 10^{-5}$
$N_{eff} \sim 4$ ➔ $g_s \leq 10^{-6}$



$\Delta\chi^2$ compatible with the standard ΛCDM model best-fit

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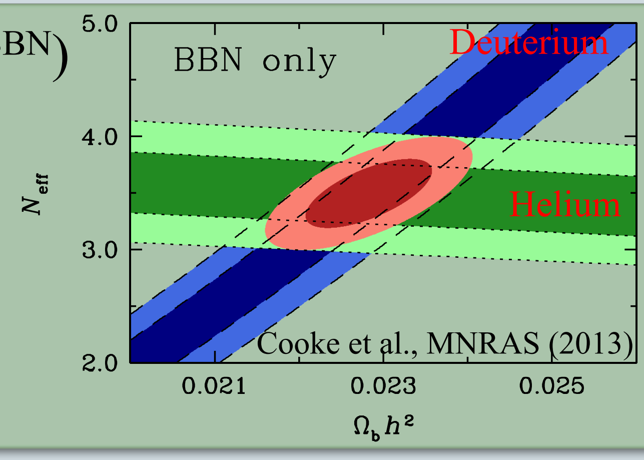

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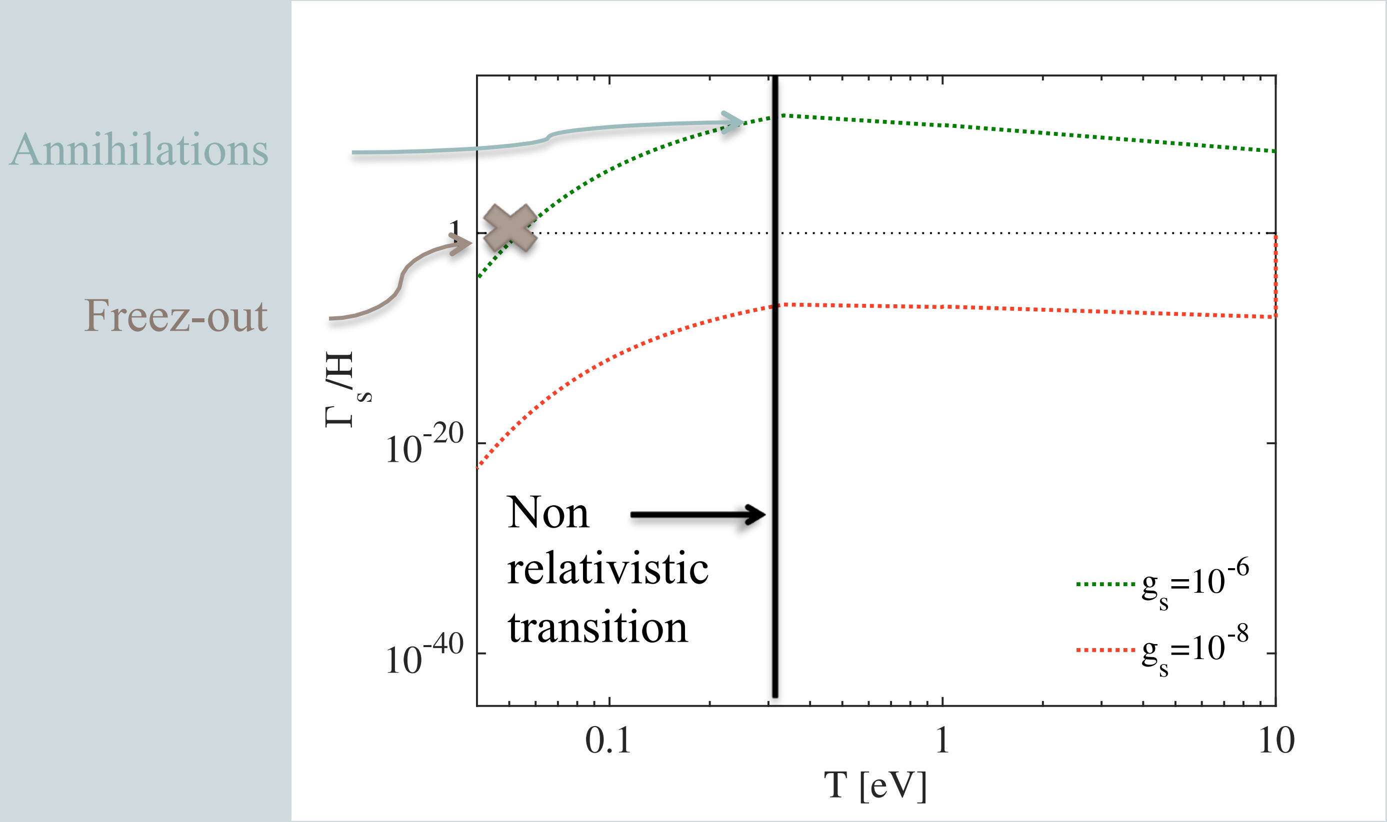
Late time phenomenology (2): $\nu_s - \phi$ annihilations

As soon as sterile neutrinos go non-relativistic, they start annihilating into pseudoscalars $\nu_s \bar{\nu}_s \rightarrow \phi\phi$



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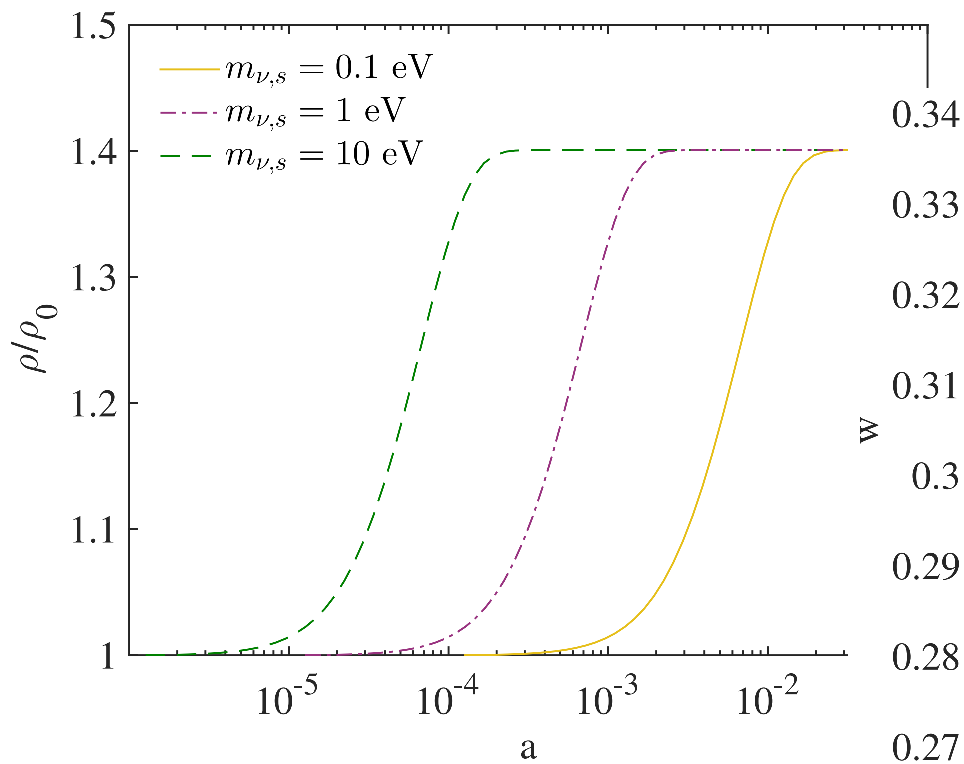
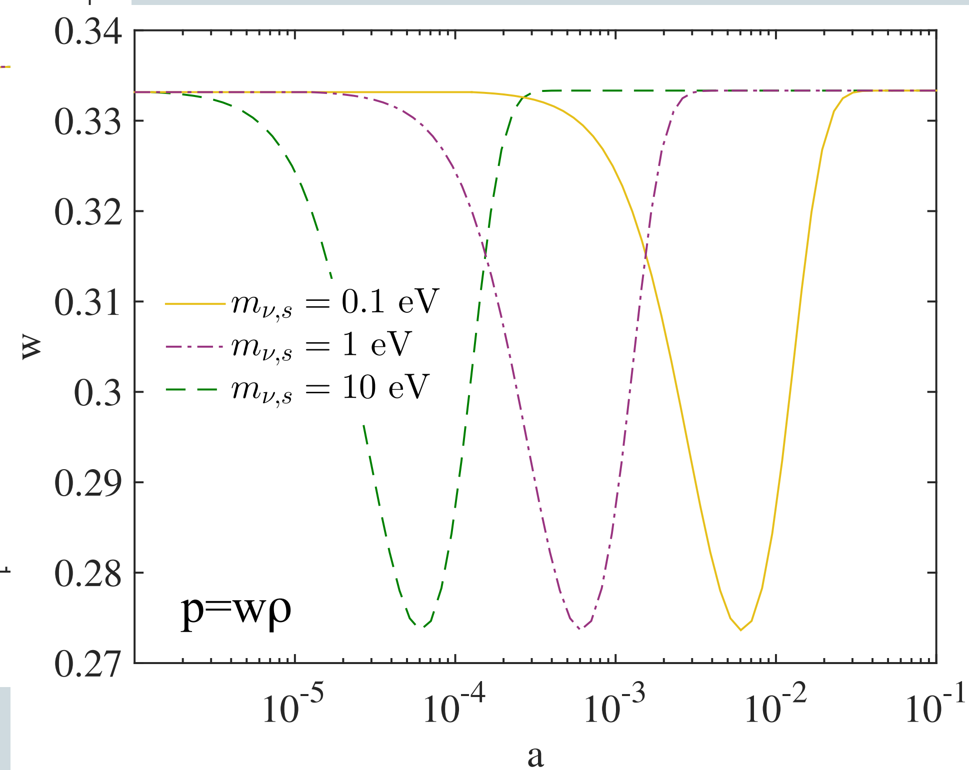
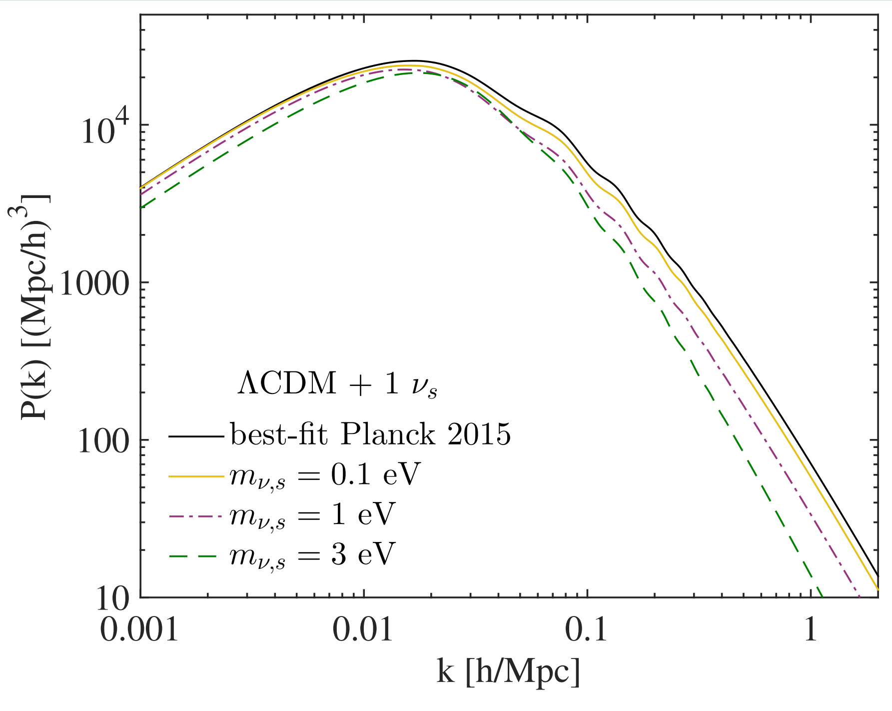


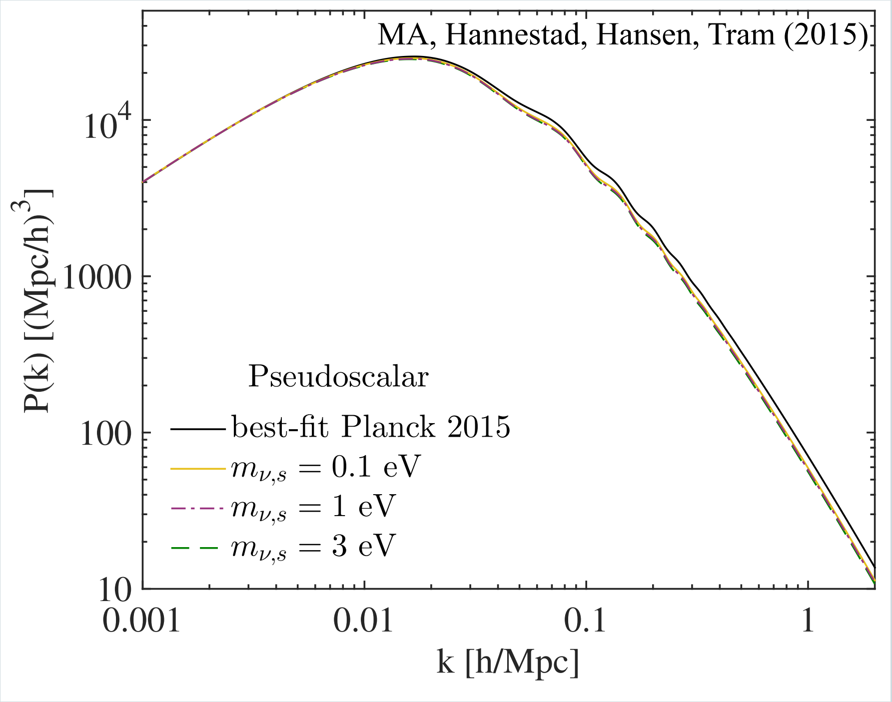
MA, Hannestad, Hansen, Tram (2015)

Sterile neutrino annihilations will heat up the scalars



Sterile neutrino mass and lss





Drawback of the MeV-scale vector boson Mirizzi et al., PRD (2014)

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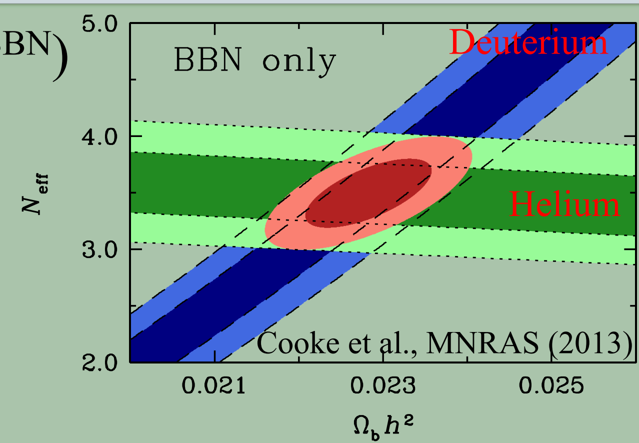

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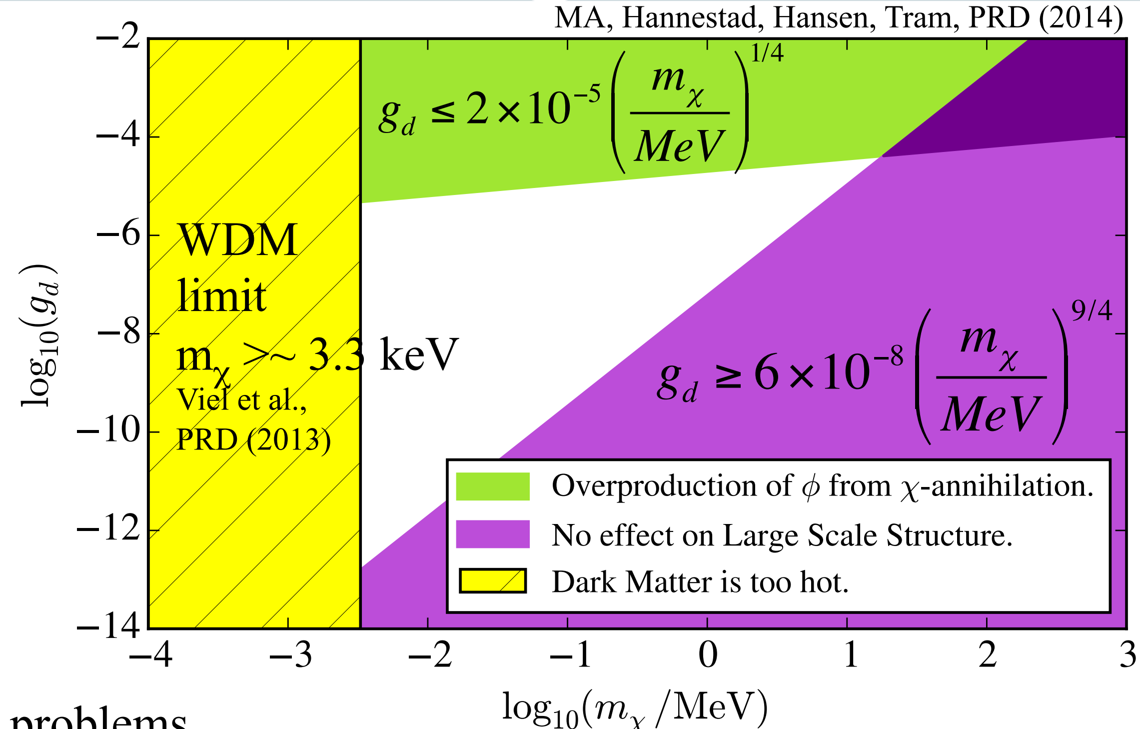
Coupling to DM

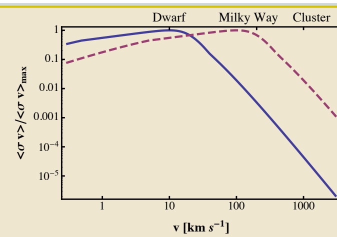


ΛCDM small scale problems

- ✓ "too big to fail"
- ✓ "cusp vs core"

DM – DM

- ✗ "missing satellites" DM - DR



Loeb & Weiner, PRL (2010)

Chu & Dasgupta, PRL (2014)

Conclusions

- ✓ "Secret" sterile neutrino self-interactions mediated by a light pseudoscalar can accommodate one additional massive sterile state in cosmology without spoiling CMB measurements and, at the same time, evading mass constraints

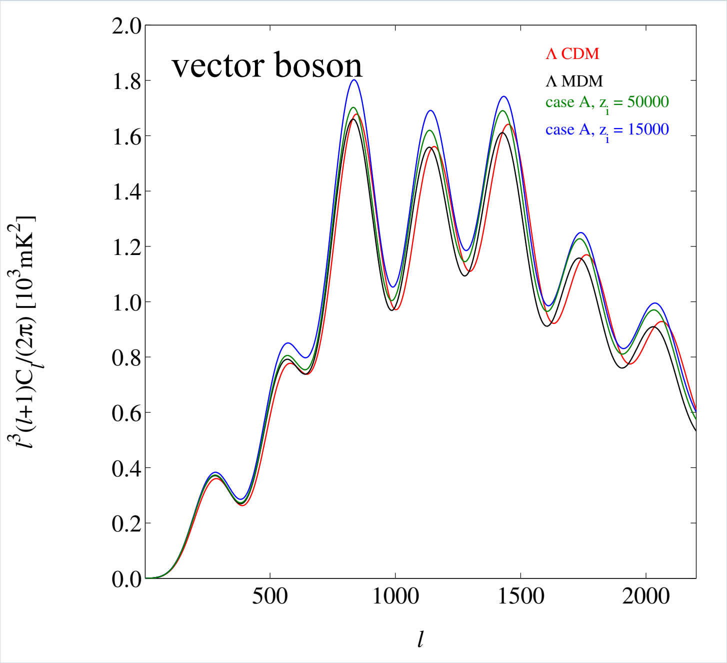
- ✓ "Secret" interactions might also solve the small scale problems of the cold dark matter paradigm

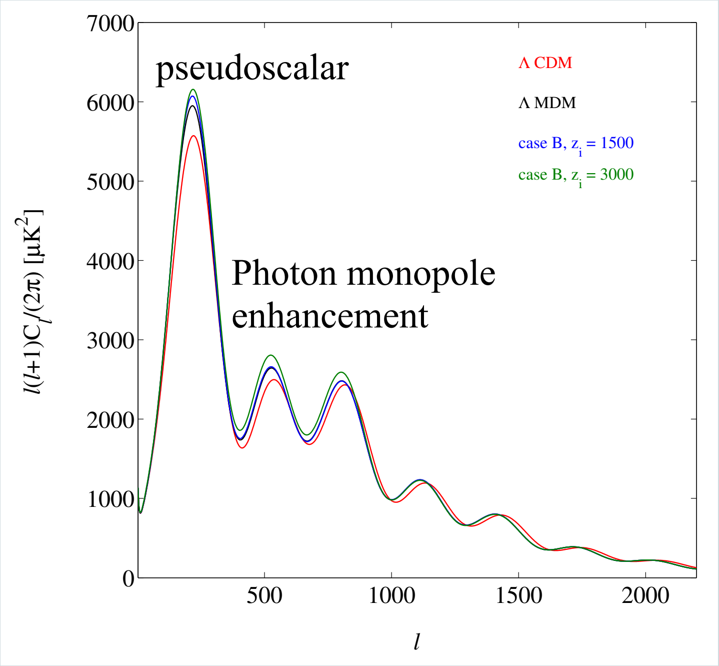
Backup slides

SM neutrino free streaming

Active neutrinos must be free streaming after z~5000

MA, Hannestad, JCAP (2013)

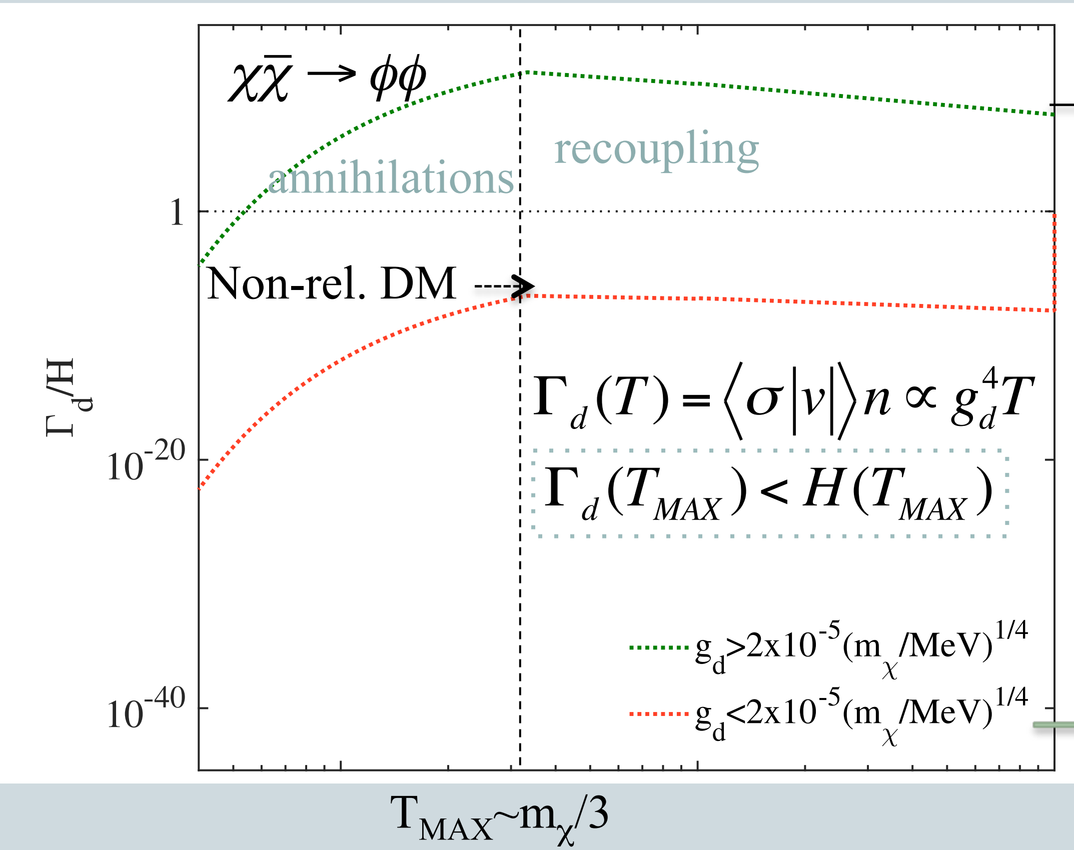




see also Cyr-Racine, Sigurdson, PRD (2013) and Forastieri, Lattanzi, Natoli (2015)

The interaction is confined to the sterile sector
The pseudoscalar coupling is diagonal in mass basis

Coupling to DM: not too strong



decoupled

$$g_d \le 2 \times 10^{-5} \left(\frac{m_\chi}{MeV} \right)^{1/4}$$

No Dark Acoustic Oscillations at CMB

i.e. no $\chi\phi \to \chi\phi$

if $m_\chi >> m_e$

and $\alpha_d << \alpha$

Coupling to DM: not too weak

Galactic Dynamics:

$$\frac{\tau_{scat}}{\tau_{dyn}} = \frac{2R^2}{3N_\chi \sigma} \quad \left\{ \quad \tau_{dyn} = \frac{2\pi R}{v} \qquad \tau_{scat} = \frac{1}{n\langle \sigma |v| \rangle} \qquad N_\chi = \frac{M_{gal}}{m_\chi} \right.$$

Hard scattering $\quad \sigma \sim 4\pi b^2 \qquad \frac{1}{2} m_\chi v^2 = \frac{\alpha_d}{m_\chi b^3} \qquad \alpha_d = \frac{g_d^2}{4\pi}$

The condition for having observable consequences on galactic dynamics is that the scattering time scale of DM self interactions is less than the age of the Universe.

Milky Way:

$$g_d \geq 6 \times 10^{-8} \left(\frac{m_\chi}{MeV} \right)^{9/4}$$

It is just a **lower bound**
It requires further investigation

Sommerfield enhancement

The effect of Sommerfeld enhancement can be safely neglected for all reasonable values of g_d