Sterile neutrinos with secret interactions

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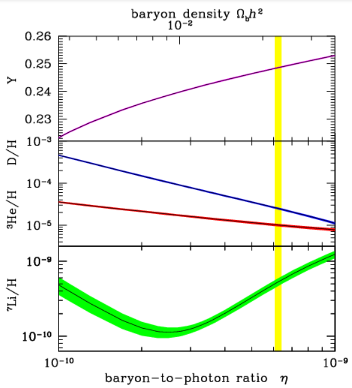
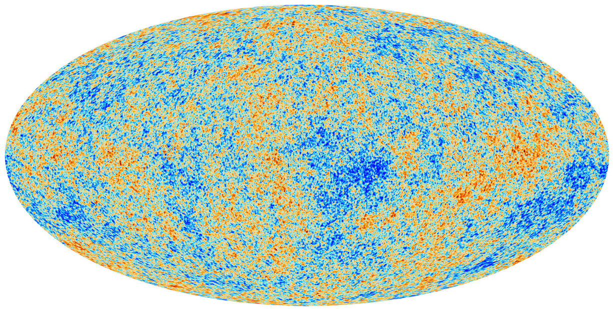
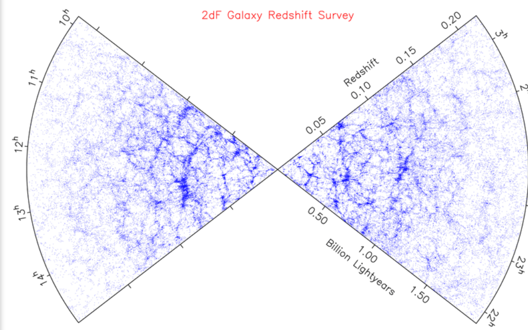
DESY Theory Workshop
26 – 29 September 2017
Fundamental physics in the cosmos:
The early, the large and the dark Universe

The case for sterile neutrinos







N_{eff} & flavour

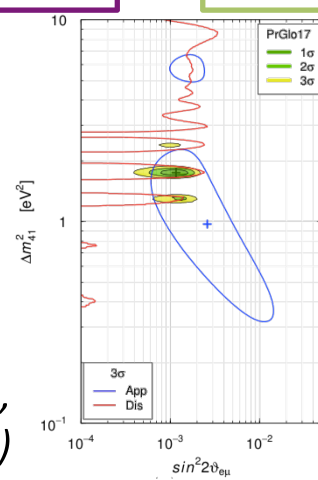
N_{eff} & (Σm_ν)

(N_{eff}) & Σm_ν

N_{eff} = 2.99 ± 0.20 (68%cl)

Σm_ν < 0.13 eV (95%cl)

Cuesta et al., Phys. Dark Univ (2016)

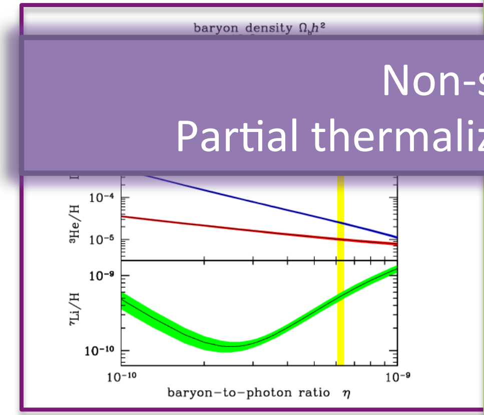


Gariazzo et al., Global fit (2017)

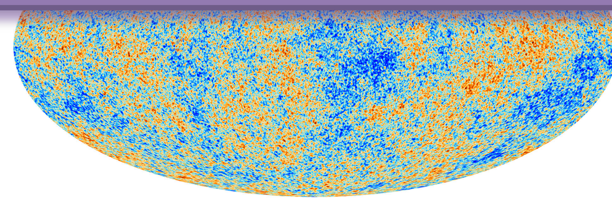
N_{eff} = 4.0…

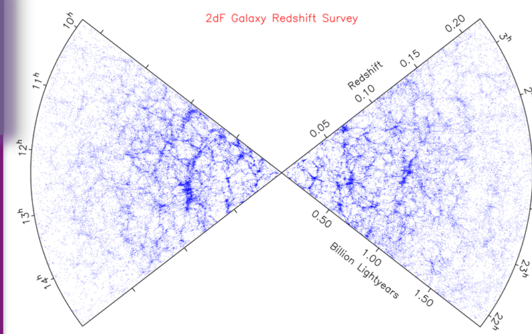
$\Sigma m_\nu \approx$ 1 eV

The case for sterile neutrinos



Non-standard physics:
Partial thermalization in the early Universe.





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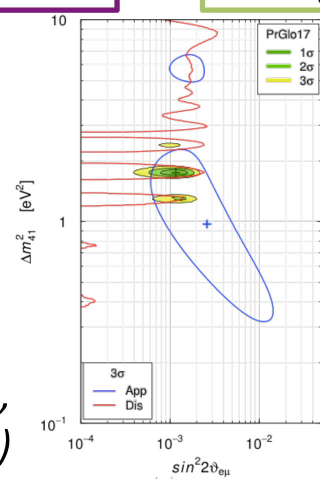

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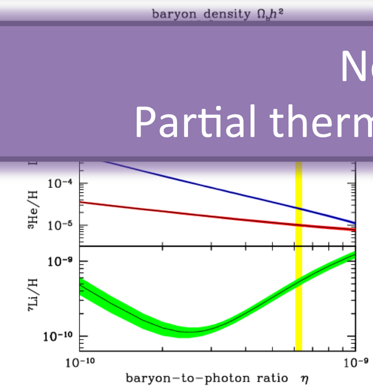

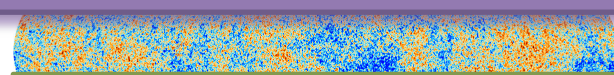

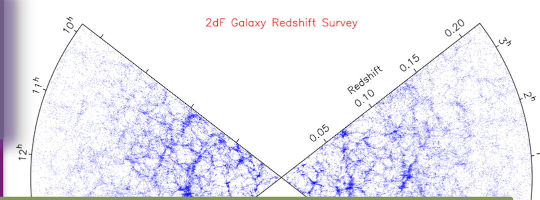

Non-standard physics:
Partial thermalization in the early Universe.

Non-standard physics:
To suppress their contribution to the HDM density

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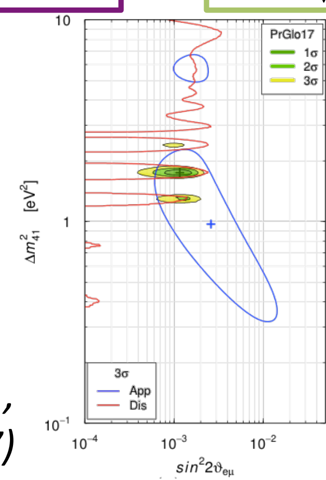


Gariazzo et al., Global fit (2017)

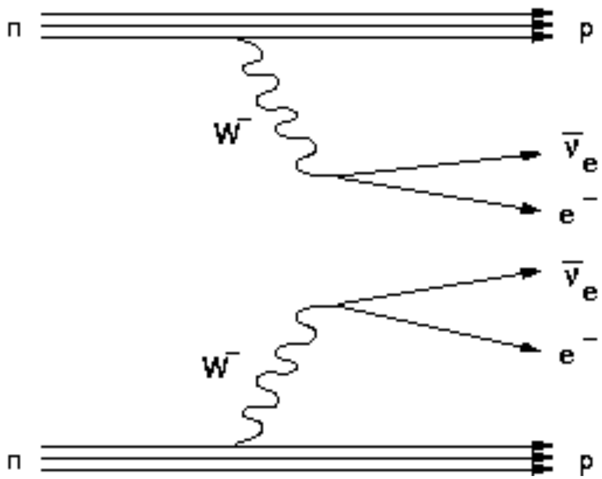
$N_{eff} = 4.0\ldots$
$\Sigma m_\nu \approx 1$ eV

ν_s secret interactions

The sterile neutrino is coupled to a new light pseudoscalar (Majoron models)

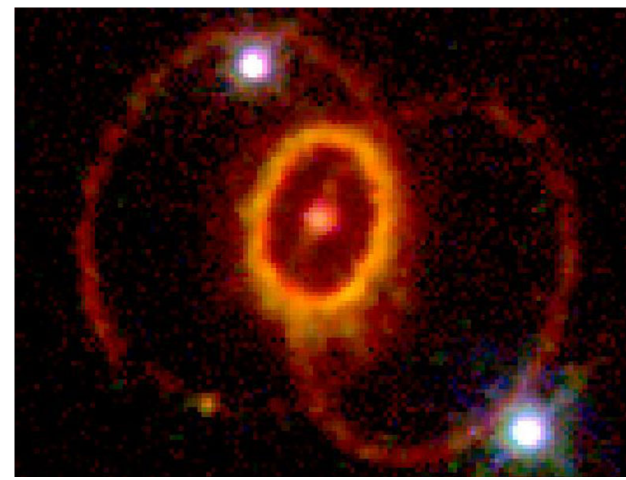
$$L_{\text{int}} \sim g_s \phi \bar{\nu}_s \gamma_5 \nu_s$$

Non-cosmological constraints:



$\beta\beta$ $g_e < 3 \times 10^{-5}$

Bernatowicz et al, PRL (1992)



SN energy loss $g_e < 4 \times 10^{-7}$
$g_s < 10^{-5}$

Farzan, PRD (2003)

Flavour evolution

Stodolsky, PRD (1987)

$$\rho(p,t)=\begin{pmatrix}\rho_{aa} & \rho_{as}\\ \rho_{sa} & \rho_{ss}\end{pmatrix}=\frac{f_0(p)}{2}\left[P_0(p,t)+\bar{\sigma}\times\bar{P}(p,t)\right];$$

$$\frac{d\bar{P}}{dt}=\bar{V}\times\bar{P}-D\bar{P}_T+\frac{R}{f_0}\hat{z}$$

$$\bar{V}=\bar{V}_{vacuum}+\bar{V}_{medium}+\bar{V}_s$$

$$V_{vaccum}=\frac{\Delta m^2}{2p}$$

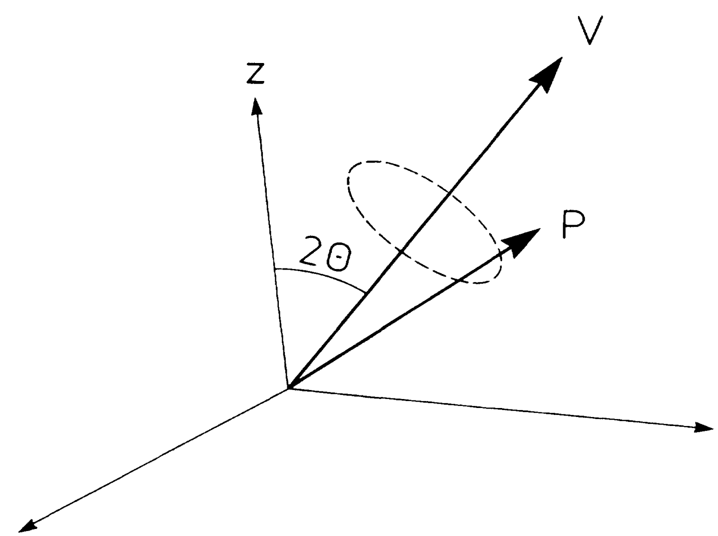
$$V_{medium}\propto\frac{G_F}{M_z^2}n_a pT^4$$

$$D=\frac{1}{2}\Gamma \quad \text{damping}$$

$$R=\Gamma\left(f_0-\frac{f_0}{2}(P_0+P_z)\right) \quad \text{repopulation}$$

$$\Gamma=\Gamma_a+\Gamma_s$$

$$\Gamma_a\propto G_F^2 pT^4$$



Early time phenomenology:

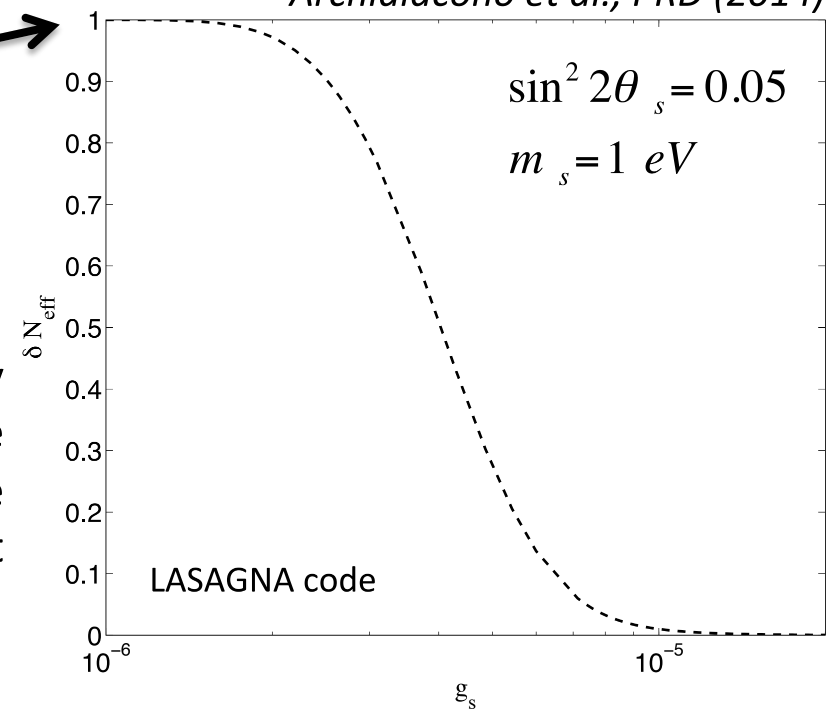
$$V_s(p_s)\sim 10^{-1}g_s^2T_s$$

$V_s > V_{vacuum}$ until $\frac{\Gamma_a}{H}>1$ (≈1MeV)

N_{eff} at BBN

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

Archidiacono et al., PRD (2014)



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.

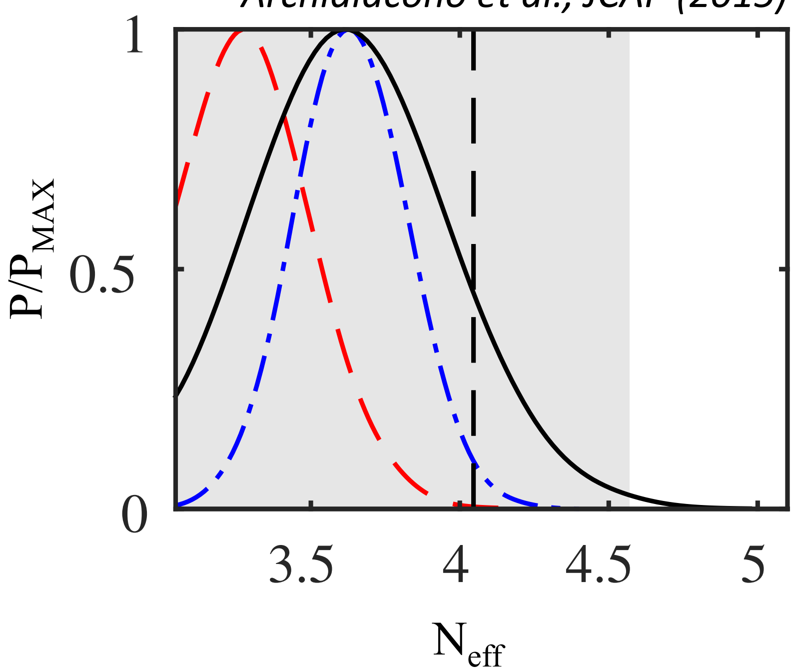
The transition between full thermalization and no thermalization occurs for coupling $10^{-6} < g_s < 10^{-5}$

N_{eff} at CMB

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

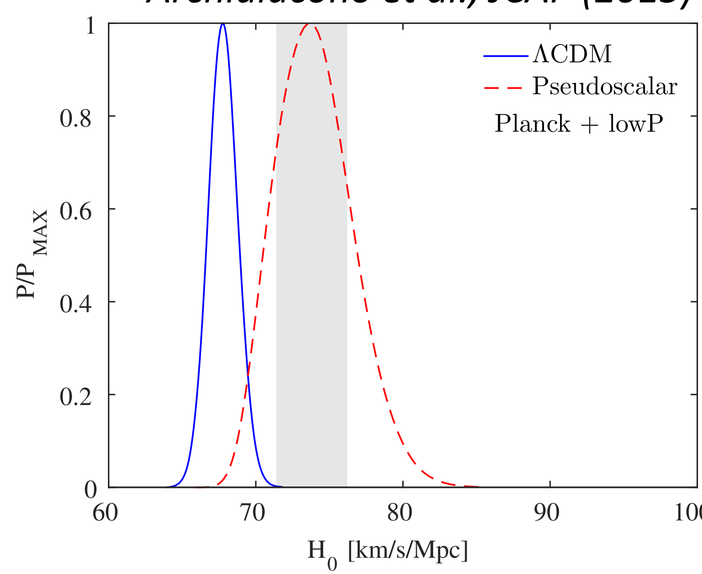
$$\Gamma_s = \frac{g_s^4}{4\pi T_s^2} n_s$$

Archidiacono et al., JCAP (2015)



Correlation between values of N_{eff} and values of g_s

Archidiacono et al., JCAP (2015)

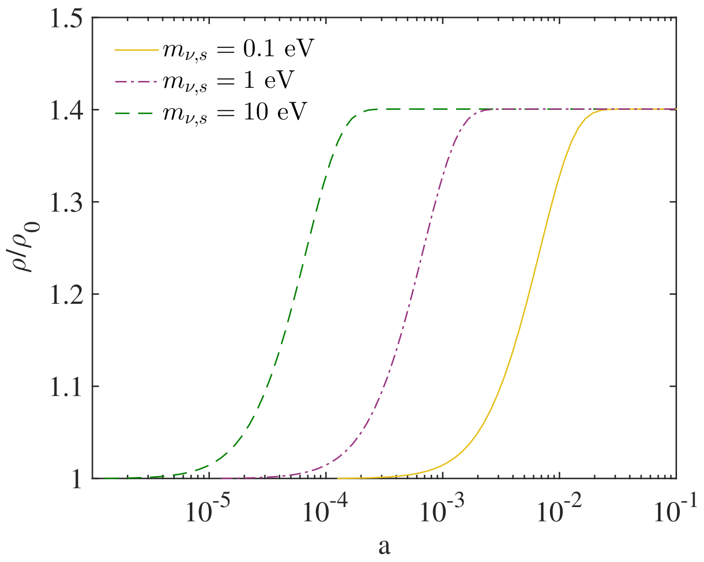


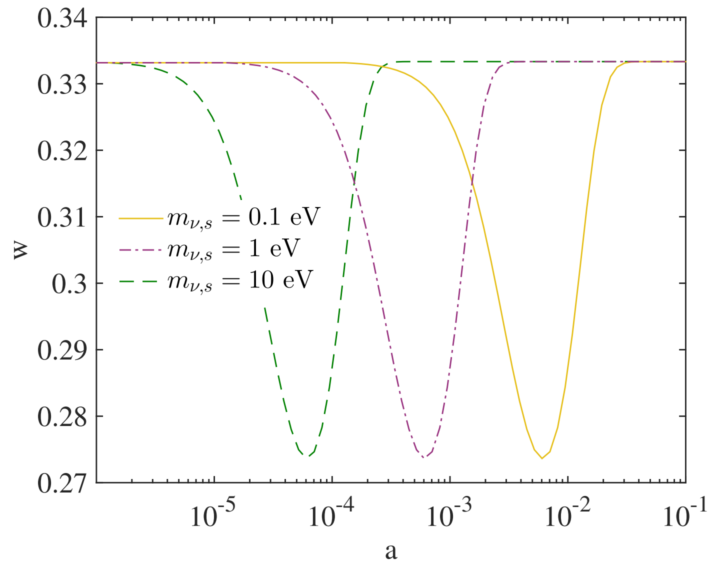
Consistent with HST

Σm_ν and LSS

As soon as sterile neutrinos go non-relativistic, they start annihilating into pseudoscalars.

Archidiacono et al., JCAP (2015)

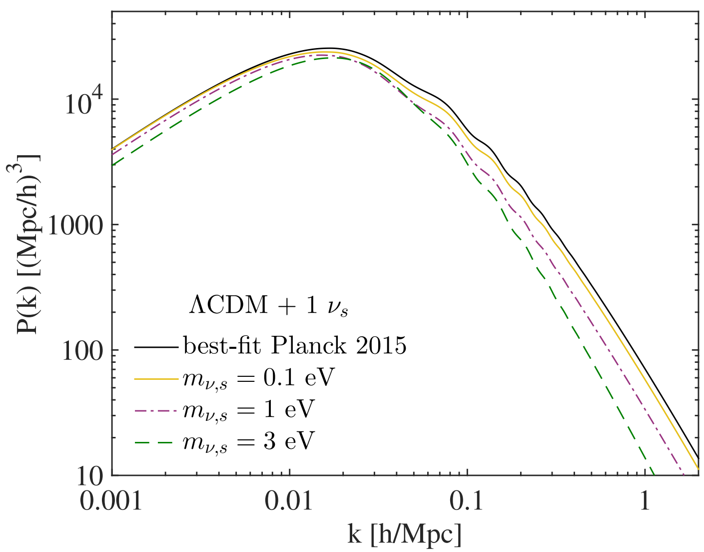


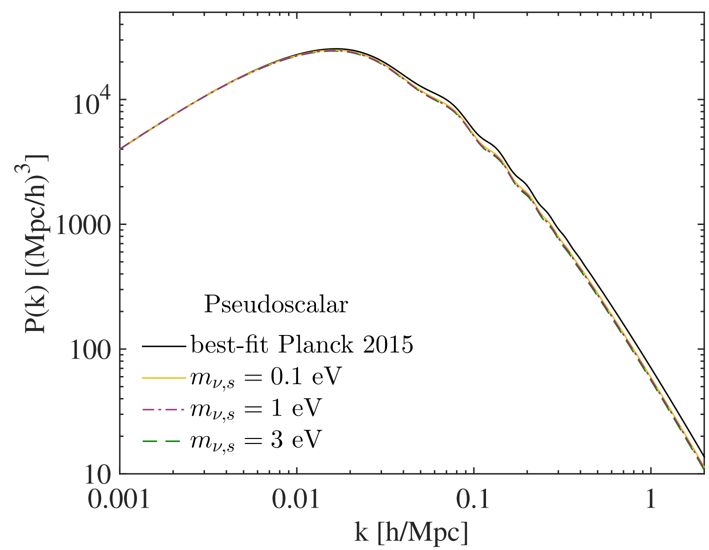


Σm_ν and LSS

Sterile neutrinos disappear from the cosmic neutrino background.
Neutrinoless Universe, Beacom et al., PRL (2004)

Archidiacono et al., JCAP (2015)

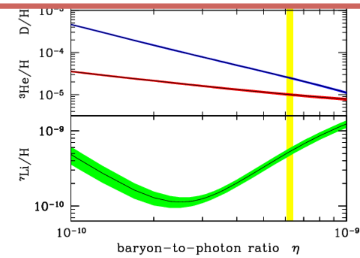


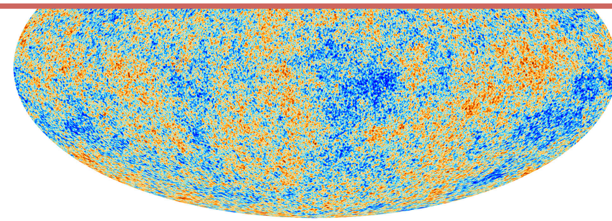


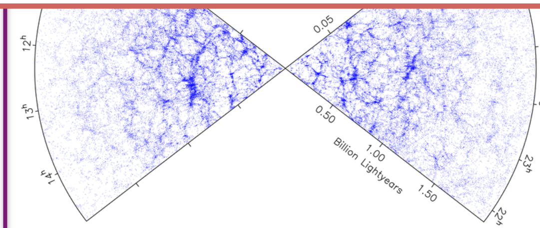
If the mediator is a massive MeV vector boson, then the late time phenomenology is different.
Hannestad et al., PRL(2013); Bringmann et al., JCAP (2014); Mirizzi et al., PRD (2014); Chu, Dasgupta, Kopp, JCAP (2015)

Conclusions

“Secret” sterile neutrino self-interactions mediated by a light pseudoscalar can accommodate one additional massive sterile state in cosmology without spoiling BBN, CMB and LSS constraints.







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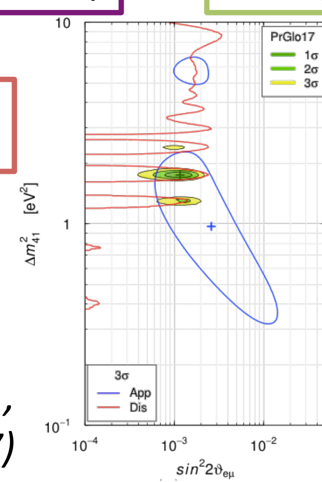
Cuesta et al., Phys. Dark Univ (2016)

$10^{-6} < g_s < 10^{-5}$

$m_\phi << m_s$



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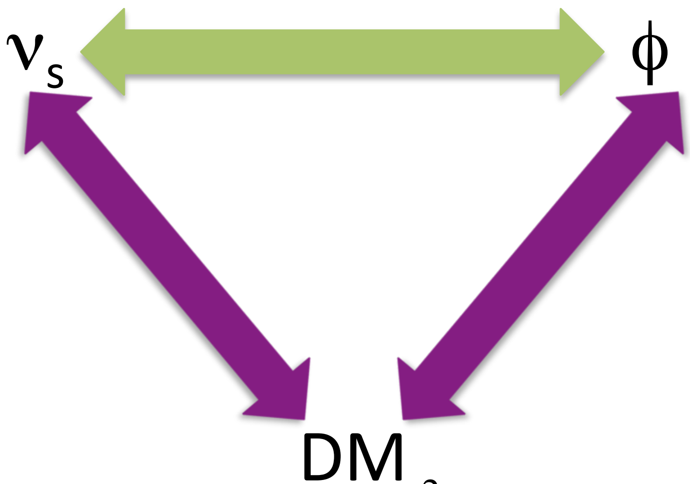
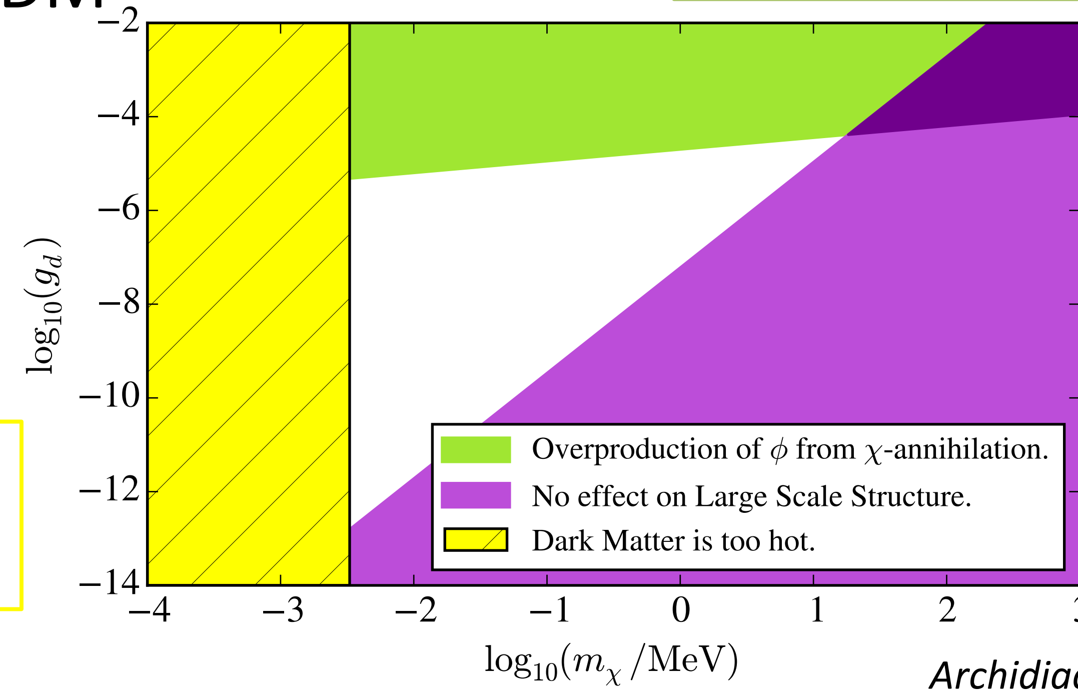
Outlook



Secret interactions might also solve the small scale problems of cold dark matter.

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

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



WDM limit
$m_\chi > 3.3$ keV
Viel et al. (2013)

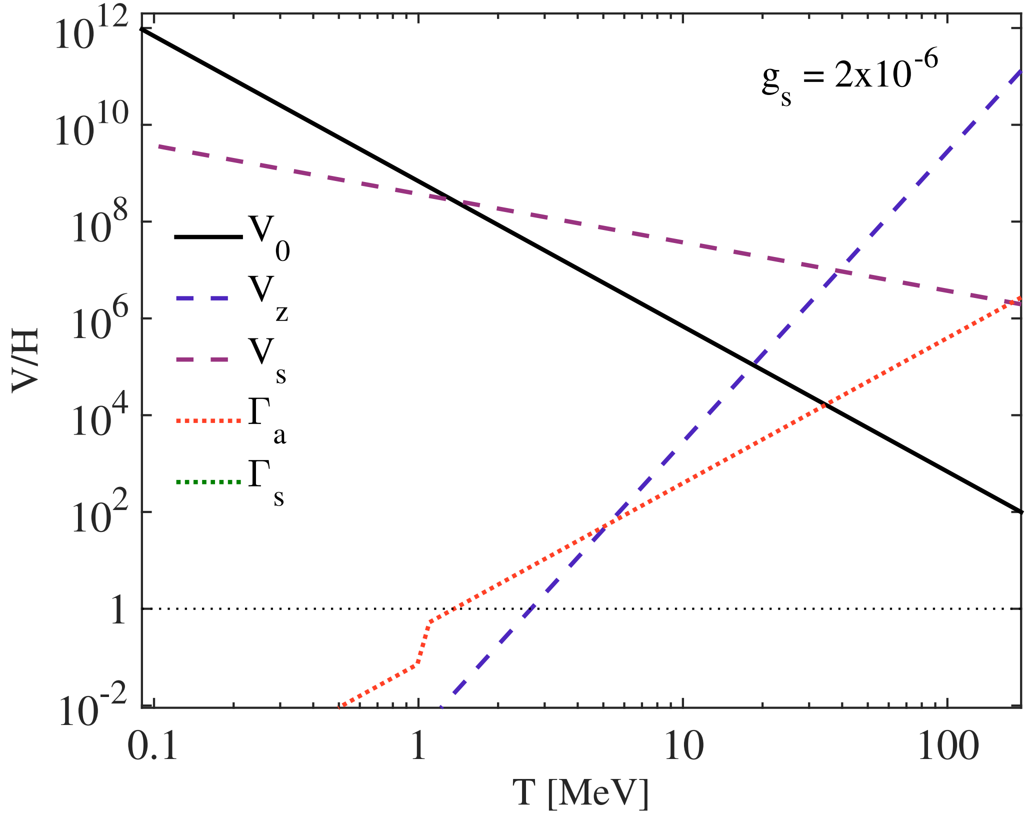
The scattering time scale of DM self interactions has to be less than the age of the Universe.

Archidiacono et al., PRD (2014)

Flavour oscillations

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

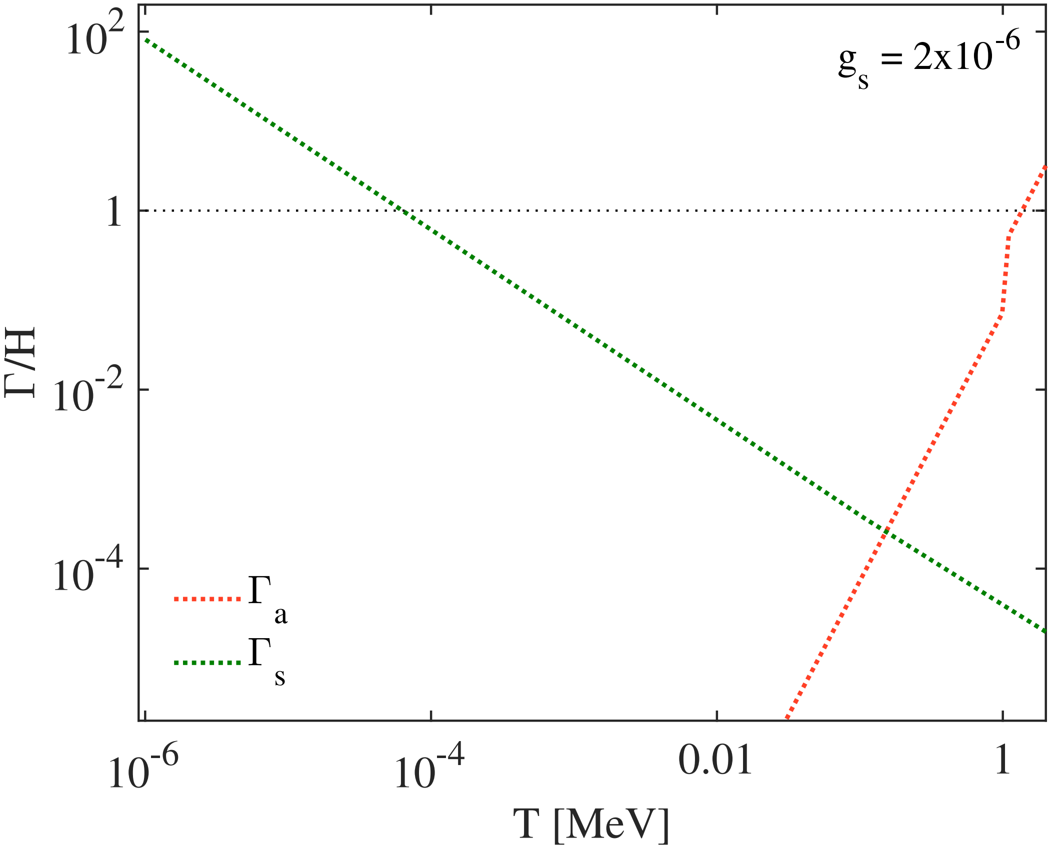
$$V_s(p_s) = \frac{g_s^2}{8\pi^2 p_s} \int p\, dp (f_\phi + f_s) \sim 10^{-1} g_s^2 T_s$$



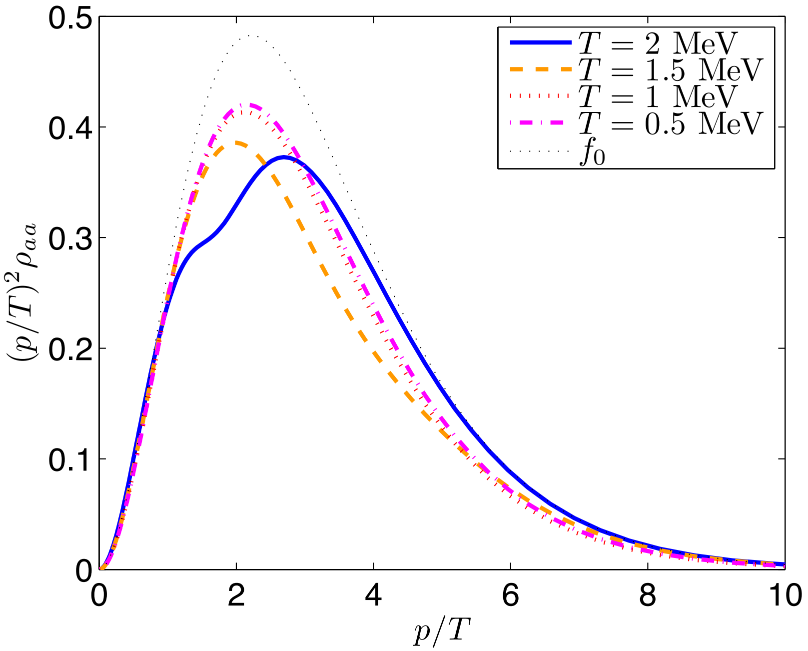
Collisional re-coupling

$$\Gamma_{\rm coll} = n_{\nu_s}\sigma \sim \begin{cases} n_{\nu_s} e_s^4 \frac{E^2}{M^4} & \text{for } T_s \ll M \\ n_{\nu_s} e_s^4 \frac{1}{E^2} & \text{for } T_s \gg M \end{cases}$$

$$\Gamma_s \simeq \frac{1}{2}\sin^2 2\theta_m \times \frac{3}{4} n_{\nu_a}^{\rm SM} \cdot \begin{cases} e_s^4 \frac{E^2}{M^4} & \text{for } T_s \ll M \\ e_s^4 \frac{1}{E^2} & \text{for } T_s \gg M \end{cases}$$



Neutrino PDF



Hannestad et al., PRL (2013)

DM-pseudoscalar

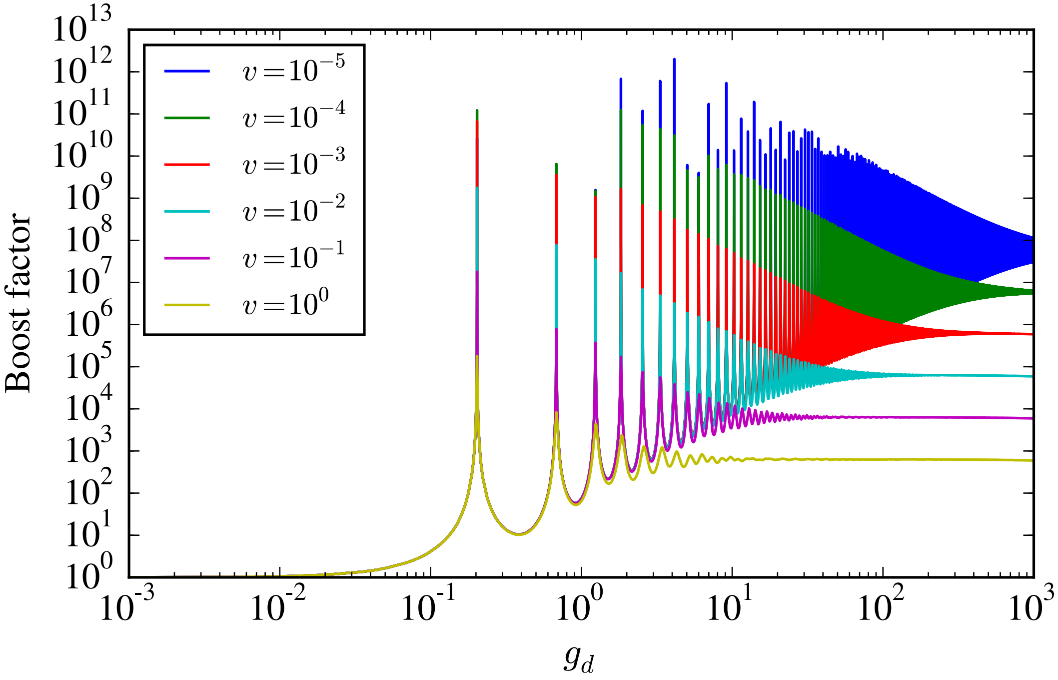
$$V(r) = -\frac{g_d^2}{m_\chi^2}\frac{e^{-m_\phi r}}{4\pi r^3}h(m_\phi r)\mathcal{S},$$

$$h(m_\phi, r) = 1 + m_\phi r + \tfrac{1}{3}(m_\phi r)^2$$

$$\Gamma_d(T) = \langle \sigma |v| \rangle n \propto g_d^4 T$$

$$\Gamma_d(T_{MAX} = m_\chi / 3) < H(T_{MAX} = m_\chi / 3)$$

Sommerfeld & pseudoscalar



Dark matter & pseudoscalar

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

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

Bellazzini et al., PRD (2013)
Ackerman et al., PRD (2009)