Secret Neutrino Interactions (a pseudoscalar model)

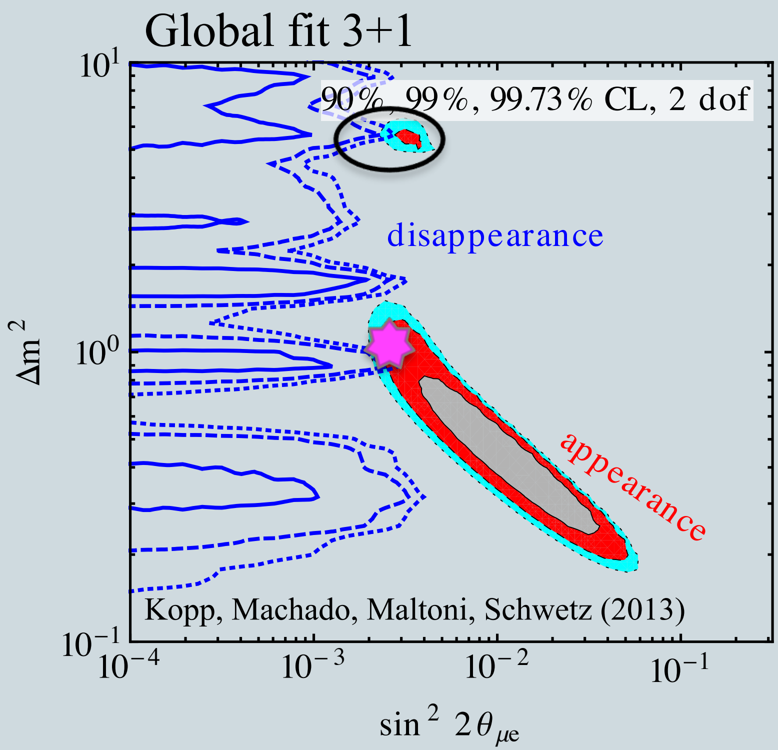
MARIA ARCHIDIACONO

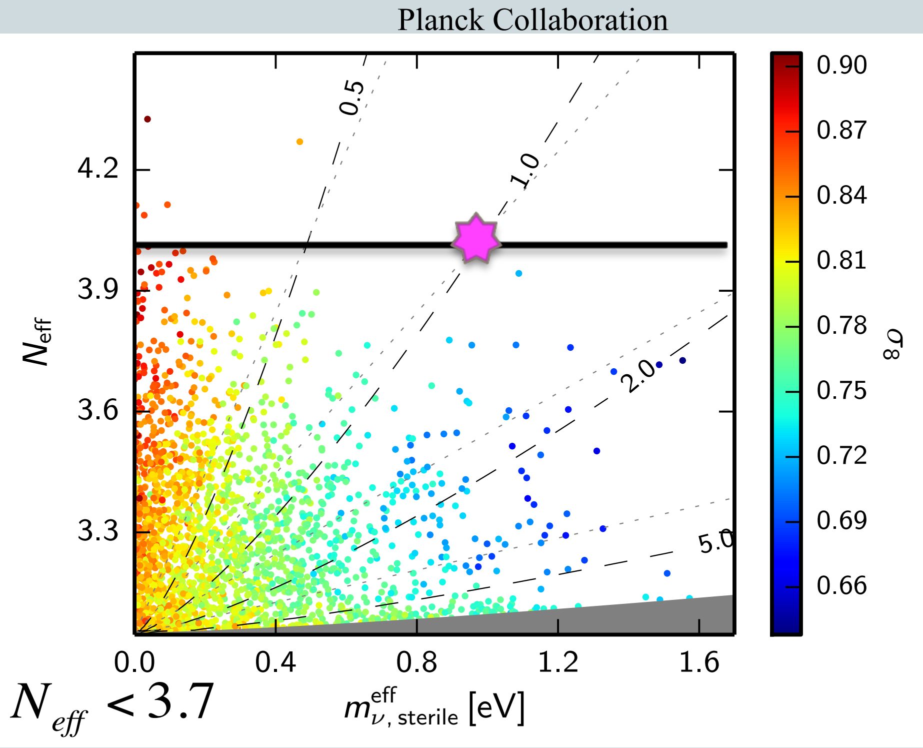
AARHUS UNIVERSITY

"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

Oscillations vs cosmology





$N_{eff} < 3.7$

$m_{eff}^{sterile} < 0.52\ eV$

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

Pseudoscalar model

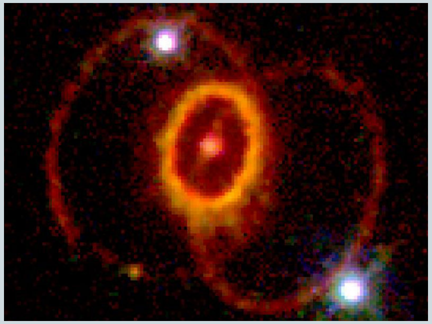
MeV scale vector boson
Talk by N. Saviano
& Refs

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

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

No fifth force limits

Limits:



SN bounds:

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

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

Farzan (2003)

0νββ decay

Bernatowicz et al. (1992)

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

Model dependent

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

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

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

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

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

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

Potentials:

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

Vacuum

Background ν

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

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

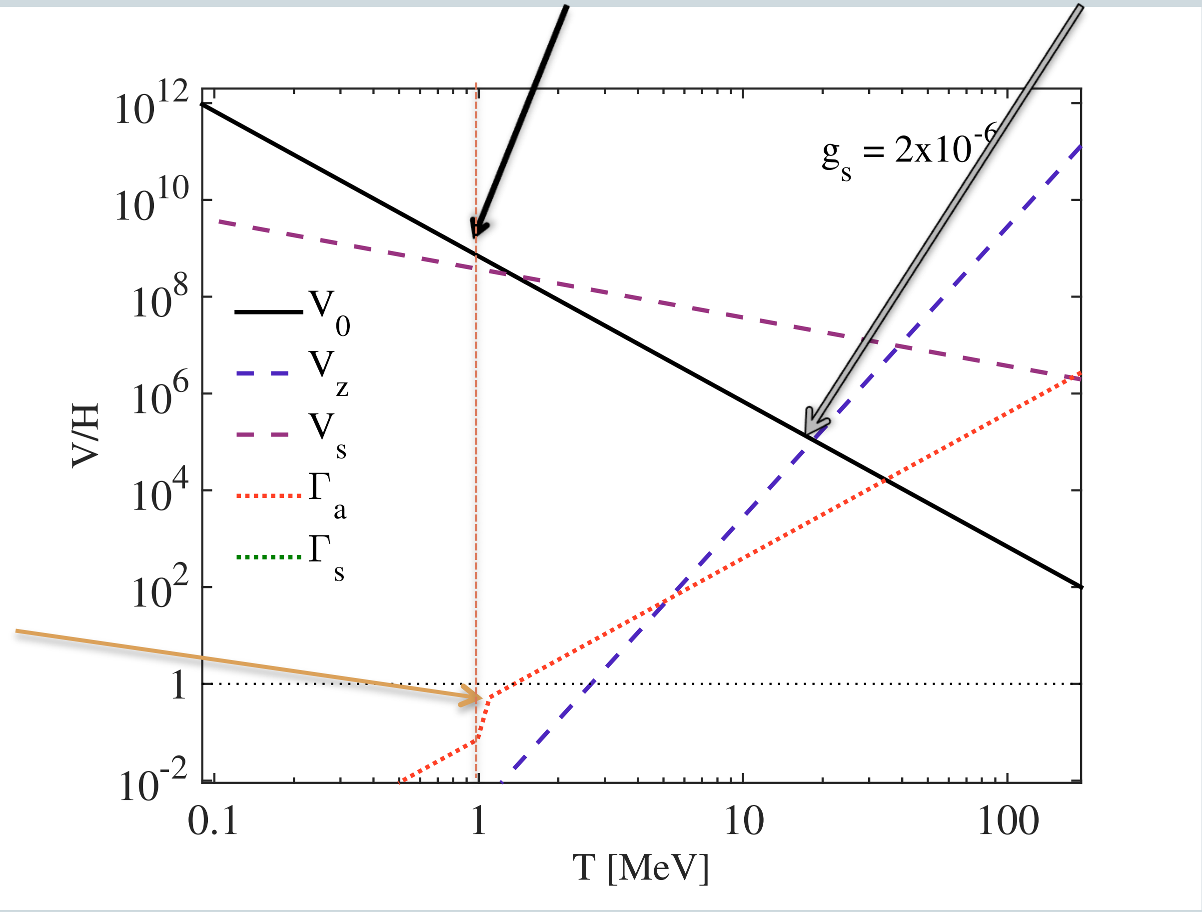
$$\Gamma_s = \frac{g_s^4}{4\pi T_s^2} n_s$$

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

Sterile neutrino production

Resonant 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.

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

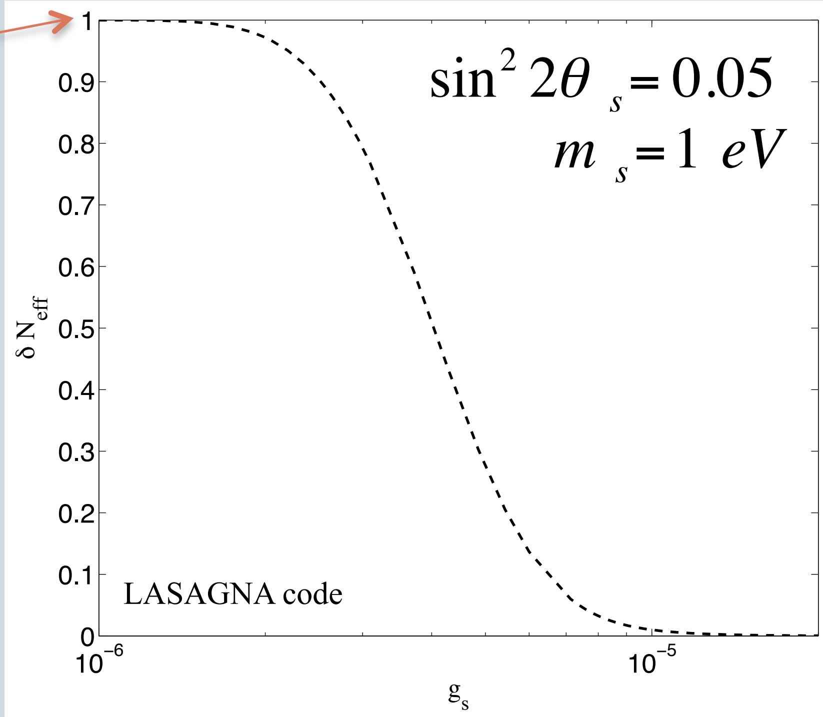
prior to standard neutrino decoupling

Solving the tension on N_{eff} at BBN

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

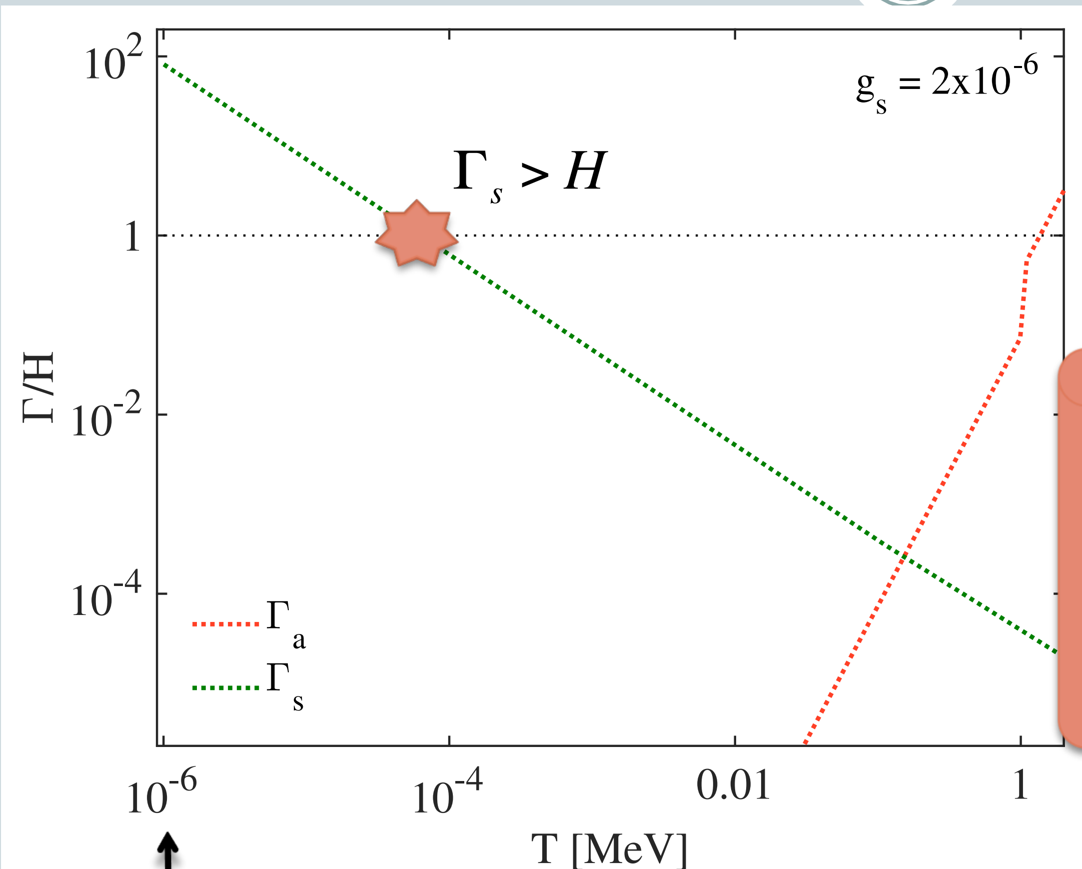
When sterile neutrinos are produced, they will create non-thermal distortions in the sterile neutrino distribution, and the sterile neutrino spectrum end up being somewhat non-thermal.

MA, Hannestad, Hansen, Tram (2014)



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

Late time phenomenology: $\nu_s - \phi$ 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

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

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

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

Energy-momentum conservation

$$\dot{\Psi}_2 = k\frac{q}{5\varepsilon}(2\Psi_1 - 3\Psi_3) - \left(\frac{1}{15}\dot{h} + \frac{2}{5}\dot{\eta}\right)\frac{d\ln f_0}{d\ln q} - \frac{\Psi_2}{\tau}$$

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

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

Relaxation time approximation

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

Hannestad (2005)
Hannestad & Scherrer (2000)

Neutrino perturbations

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

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Scattering processes

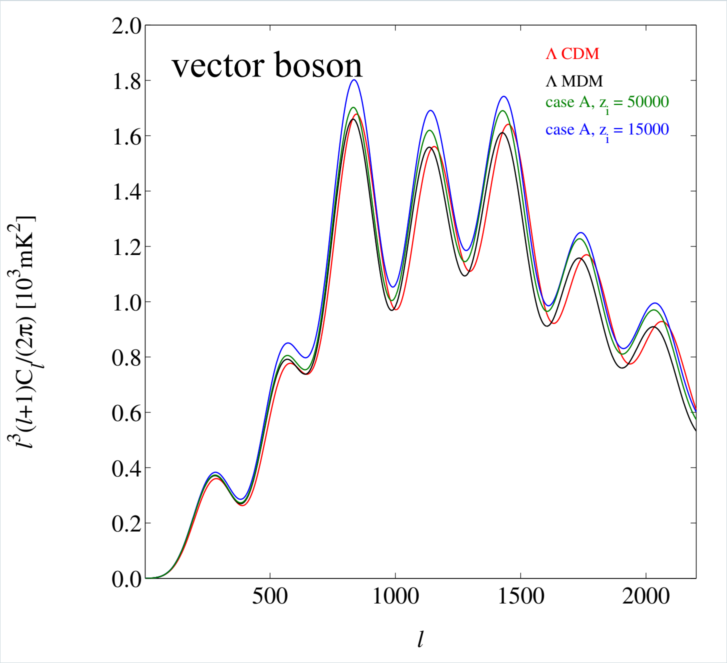
$\tau = (n\langle\sigma|v|\rangle)^{-1}$

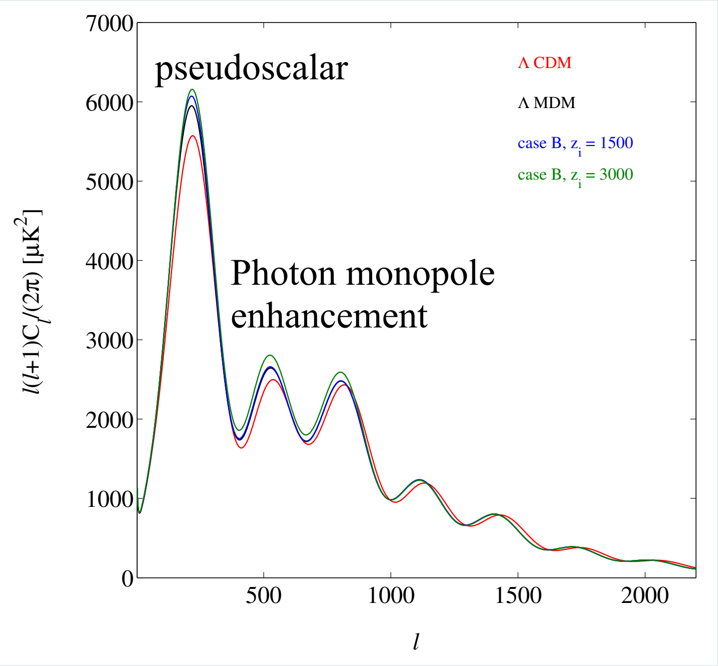
Relaxation time

No free streaming
No anisotropic stress

SM neutrino free streaming

Active neutrinos must be free streaming after z~5000

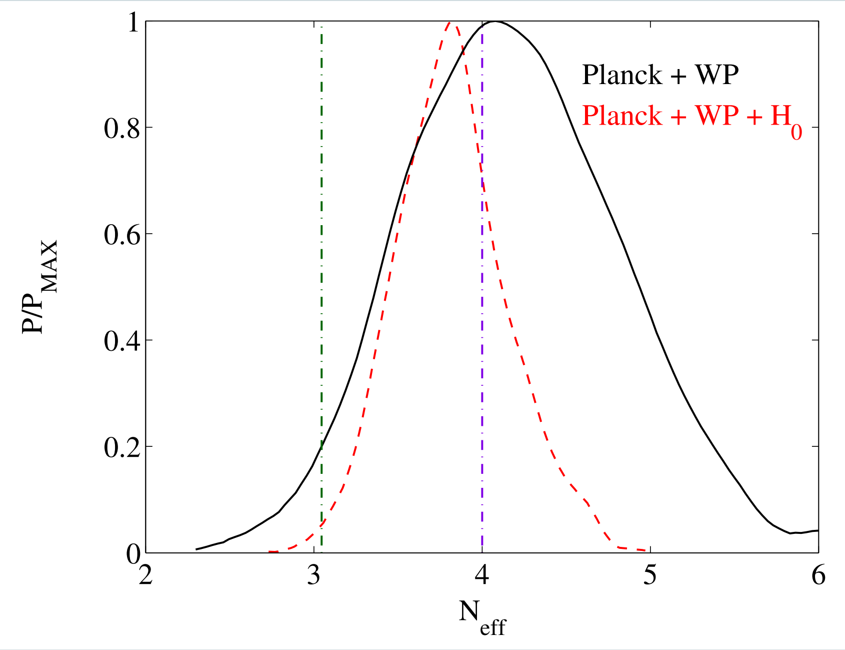




MA, Hannestad (2013) see also Cyr-Racine, Sigurdson (2013) and Forstieri, Lattanzi, Natoli (2015)

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

Solving the tension on N_{eff} at CMB

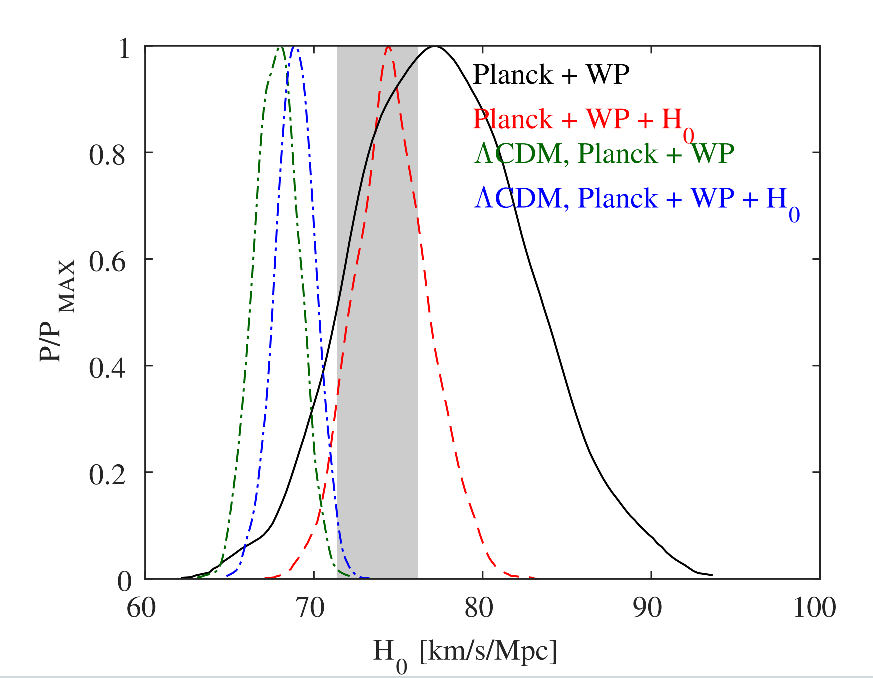


MA, Hannestad, Hansen, Tram (2014)

In the absence of "secret" interactions $N_{eff} < 3.7$ (95%c.l.)

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

…even a better fit than ΛCDM to current data, if H_0 is included

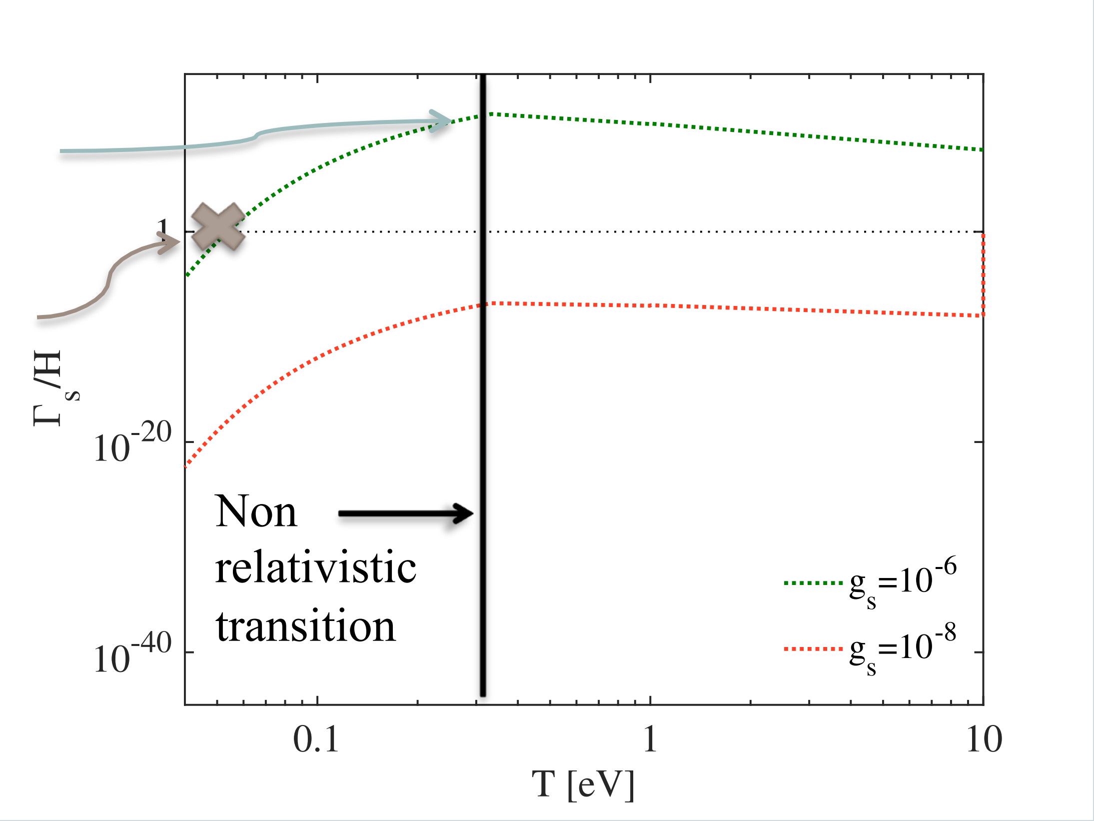


$\nu_s - \phi$ annihilations

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

Annihilations

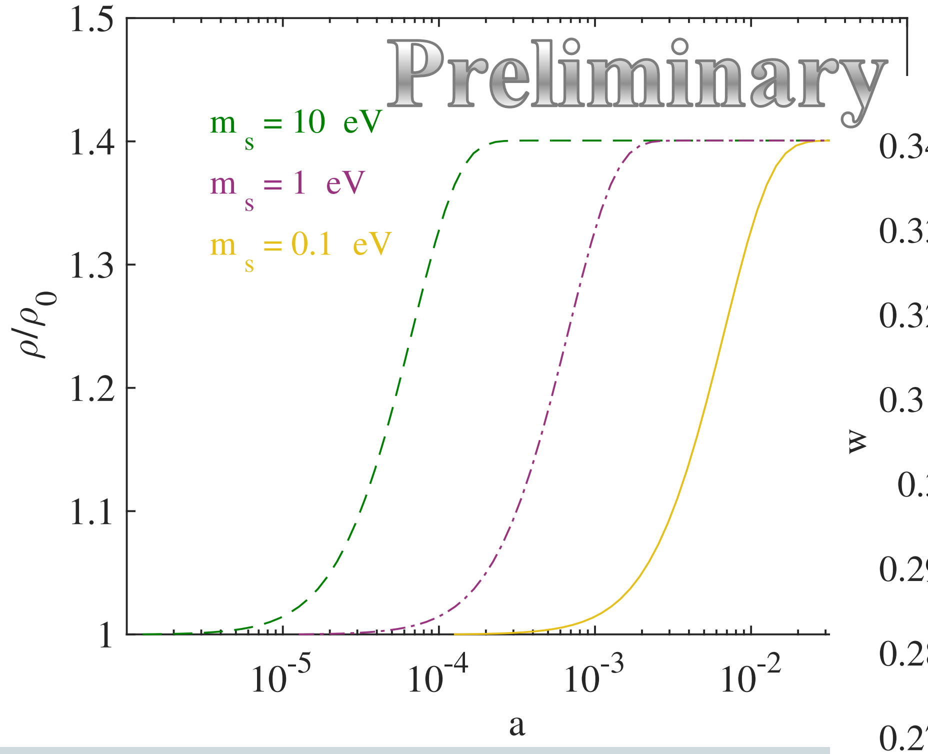
Freez-out

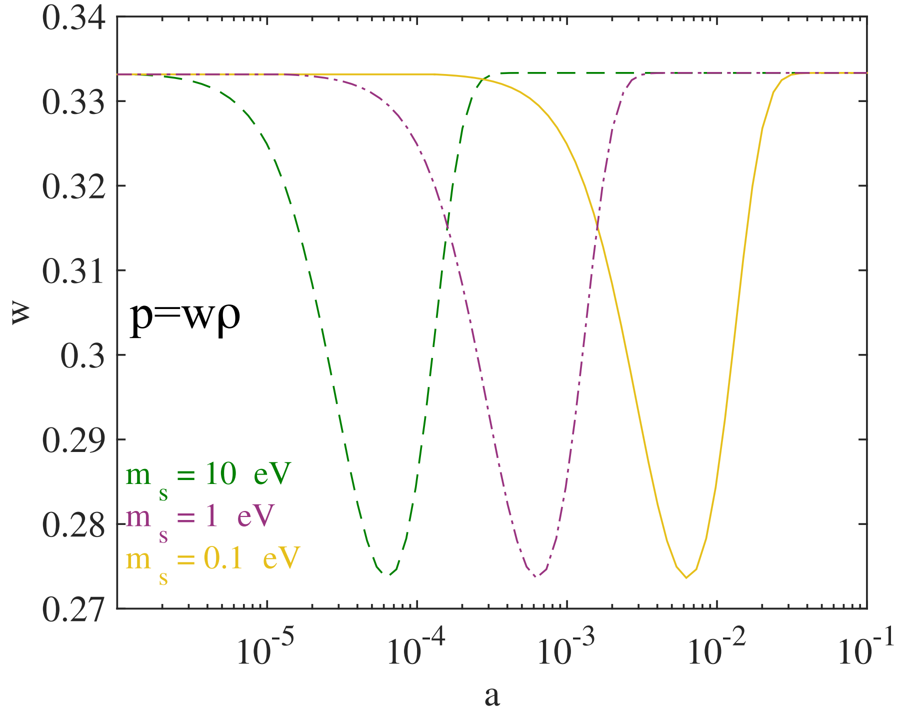


$\nu_s - \phi$ annihilations

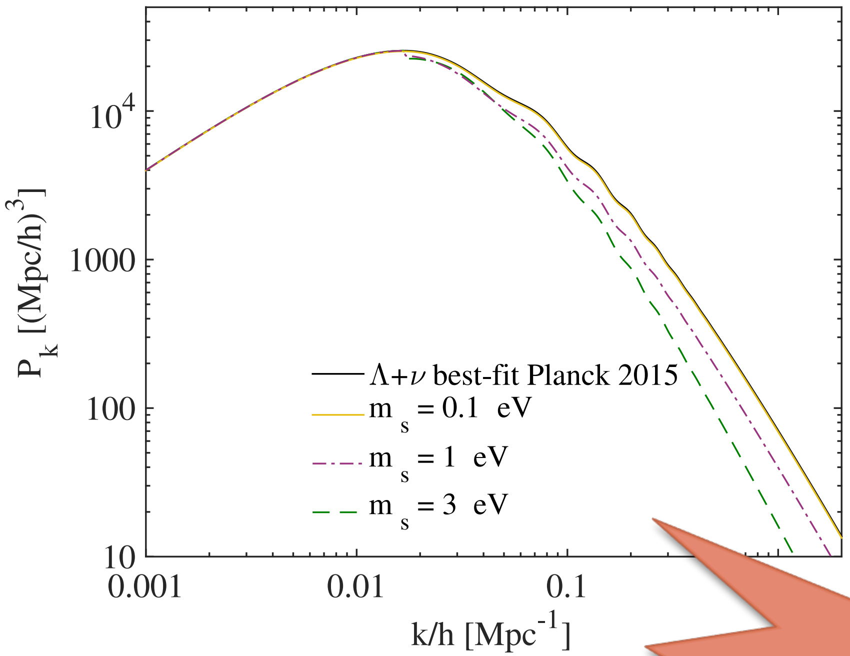
As soon as sterile neutrinos go non-relativistic, they start annihilating into pseudoscalars $\nu_s \bar{\nu}_s \rightarrow \phi\phi$

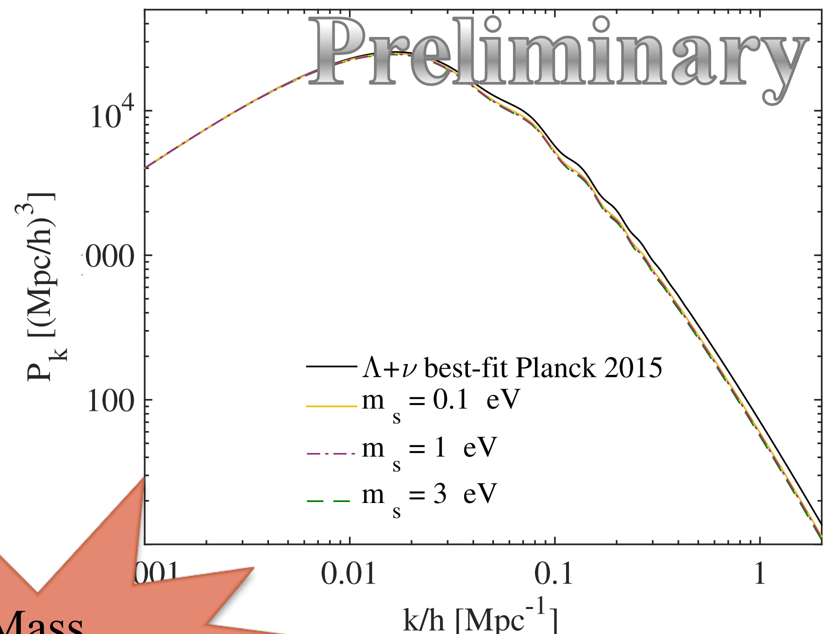
Sterile neutrino annihilations will heat up the scalars





Solving the tension on m_s



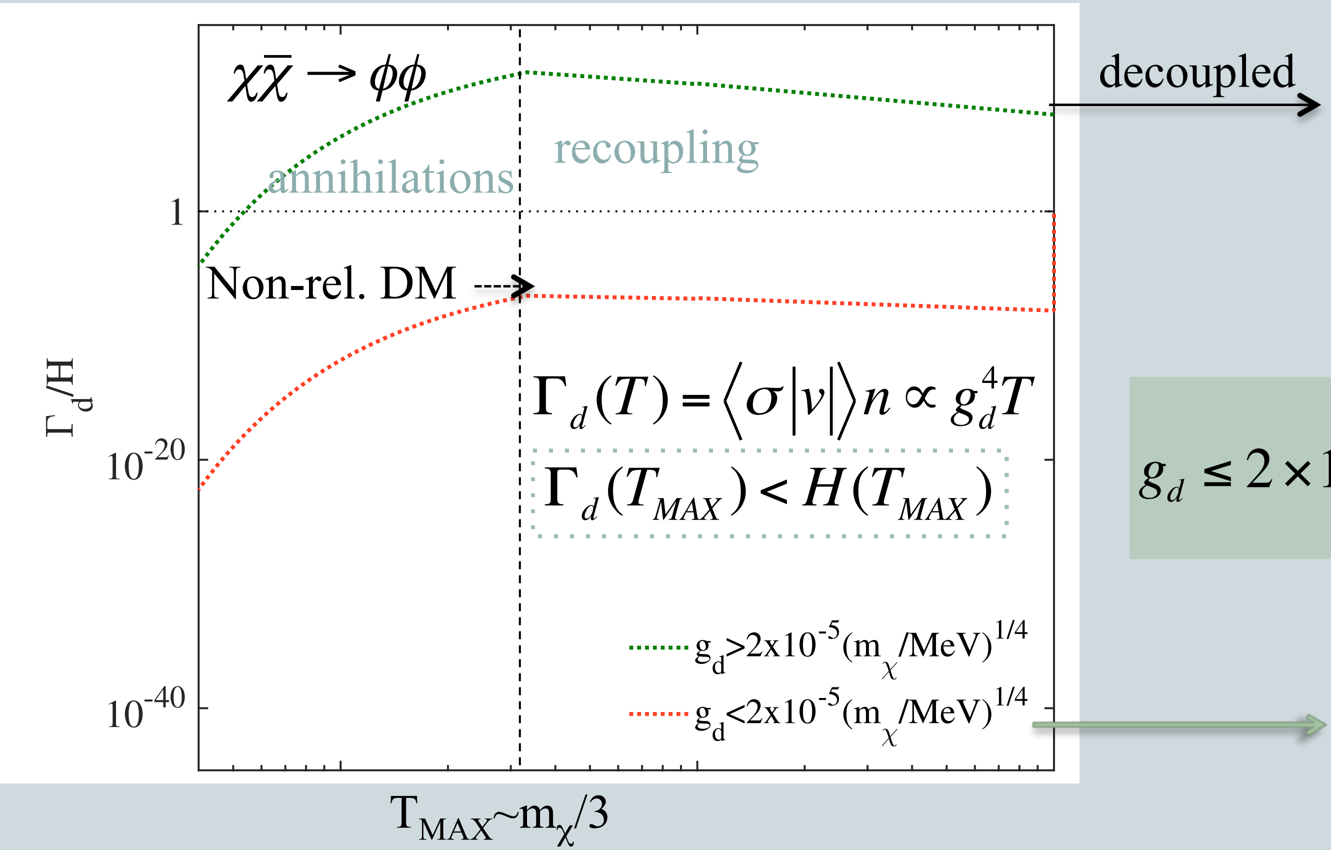


Mass constraints do not apply

Drawback of the MeV-scale vector boson Mirizzi et al. 2014

Talk by N. Saviano

Coupling to dark matter



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

No Dark Acoustic Oscillations at CMB
i.e. no $\chi\phi \to \chi\phi$
if $m_\chi >> m_e$
and $\alpha_d << \alpha$

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

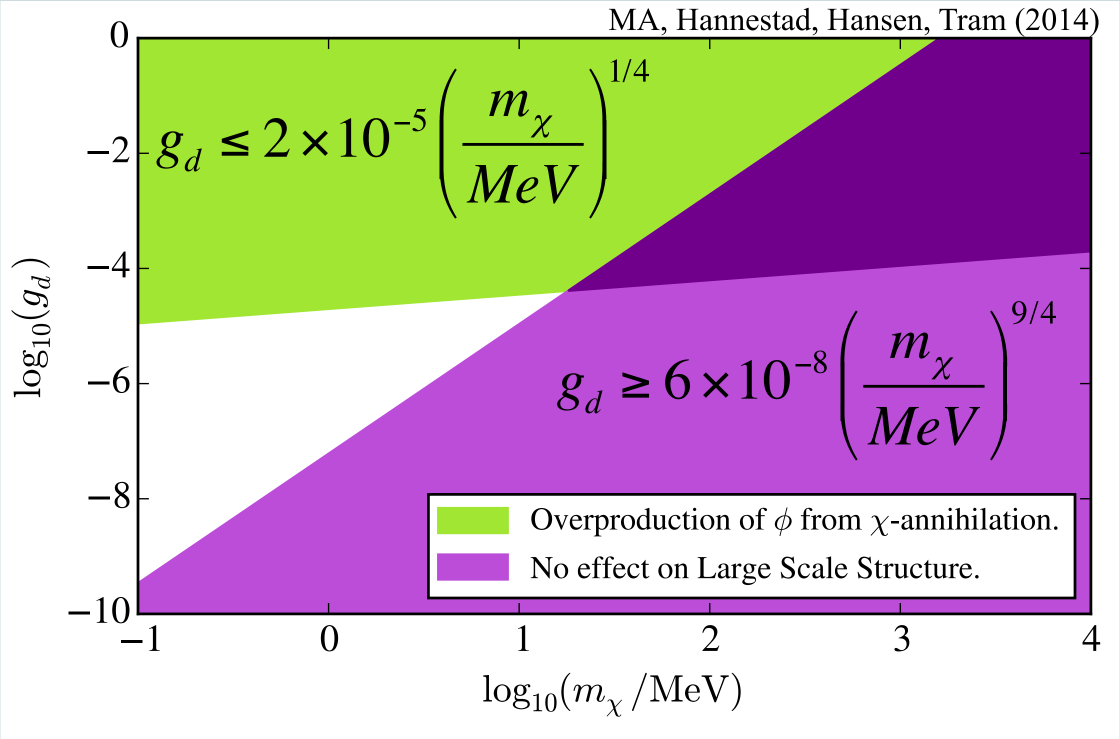
The condition for having observable consequences on galactic dynamics is that the scattering time scale of DM self interactions is less than the age of the Universe.

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

Bounds on dark matter coupling



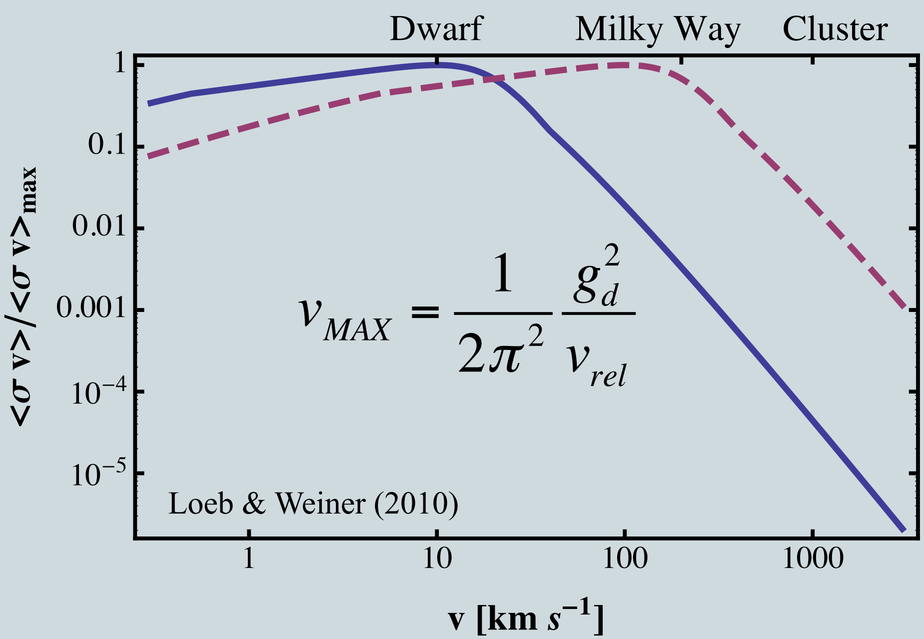
WDM limit

m_χ >~ 3.3 keV

Viel (2013)

Solving the small scale problems of CDM

(Baryon physics)



DM – DM:

- ✓ "too big to fail"
- ✓ "cusp vs core"
- ✗ "missing satellites"

Chu & Dasgupta (2014)
Dasgupta & Kopp (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

Sommerfield enhancement

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