Neutrinos in Cosmology

TEV PARTICLE ASTROPHYSICS

15 SEPT 2016, CERN

MARIA ARCHIDIACONO

RWTH AACHEN UNIVERSITY

"Pseudoscalar – sterile neutrino interactions: reconciling the cosmos with neutrino oscillations"
M. Archidiacono, S. Gariazzo, C. Giunti, Steen Hannestad, R. Hansen, M. Laveder, T.Tram
JCAP 08 (2016) 067, arXiv:1606.07673

Outline

- Neutrinos in cosmology:
  - CνB
  - cosmology & neutrino parameters
  - current status and future perspectives
- Sterile neutrinos: an open issue
- “Secret” interactions
- Conclusions

Cosmic Neutrino Background

Thermal equilibrium in the primordial plasma

$$\Gamma = n_{e^-} \langle \sigma v \rangle \approx G_F^2 T^5$$

When $\Gamma < H$ neutrinos decouple at

$$k_B T_{dec} = 1 MeV$$

HDM

$$e^+ e^- \leftrightarrow \gamma\gamma$$

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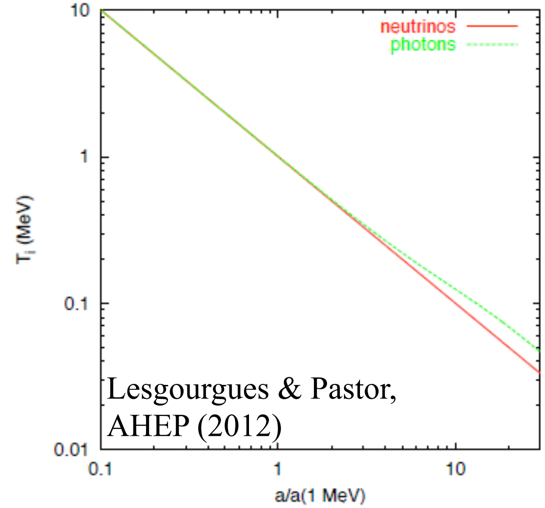
From entropy density conservation

$$T_\gamma / T_\nu = (11/4)^{1/3}$$

Nowadays $T_\nu = 1.95 K$ $\quad n_\nu = 113\ cm^{-3}$



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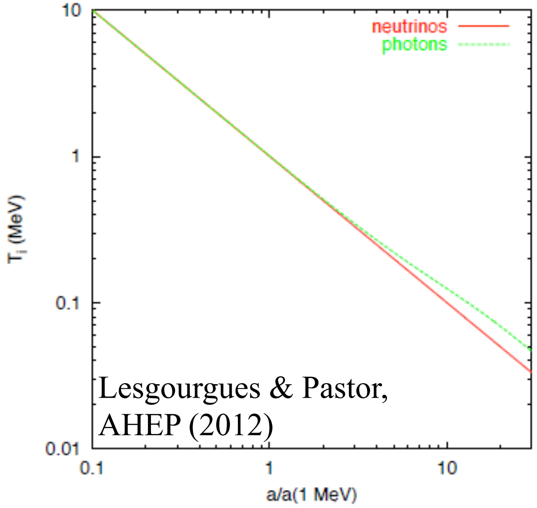

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Mangano et al., Nucl.Phys.B(2005)

Solving the q-dependent Boltzman eq. $N_{eff}^{SM} = 3.046$

flavour dependent corrections:

non instantaneous decoupling

+ finite temperature effects

Cosmology & neutrino parameters

➢ The effective number of relativistic degrees of freedom

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

$$N_{eff} \equiv \frac{\rho_{\nu a} + \rho_{extra\ rel}}{\rho_{1\nu a}^{SM}}$$

- It can be non-standard $N_{eff} = 3.046 + \Delta N_{eff}$
- It can be many things (not only neutrinos)
- It is not constant (it decreases when particles go non relativistic)

Cosmology & neutrino parameters

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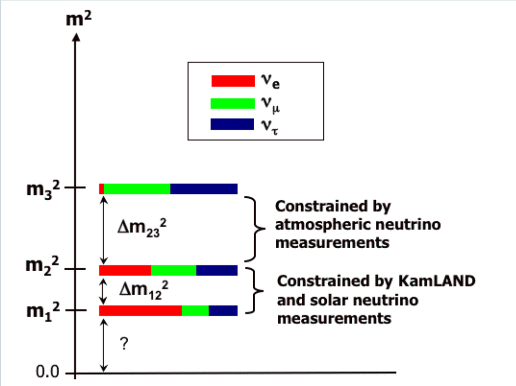
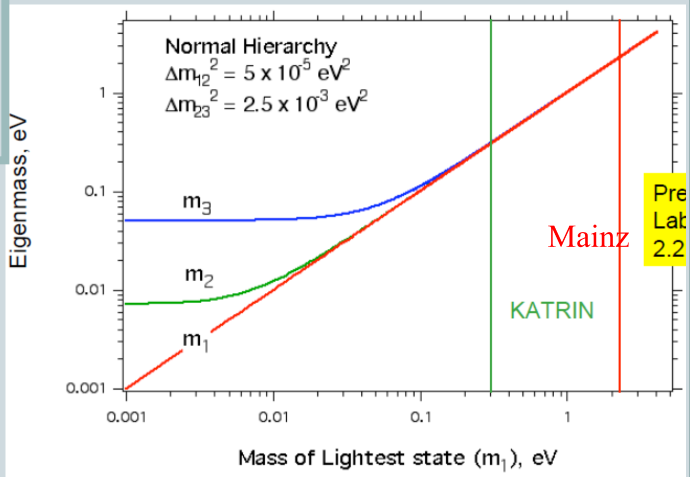
➢ The neutrino mass sum

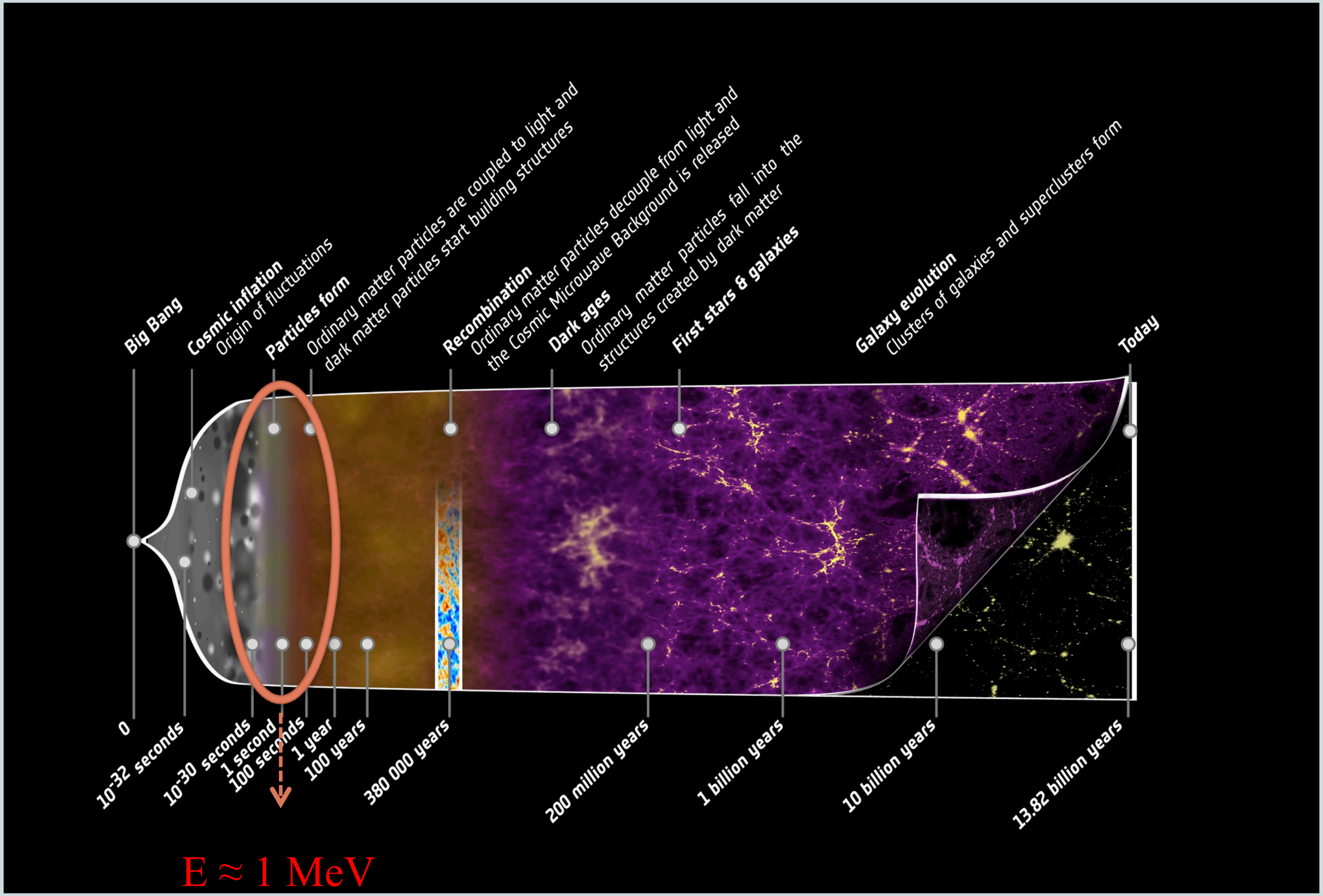
$$\Omega_\nu h^2 = \sum_{i=1}^{N_\nu} m_\nu / 93eV$$



Complementarity



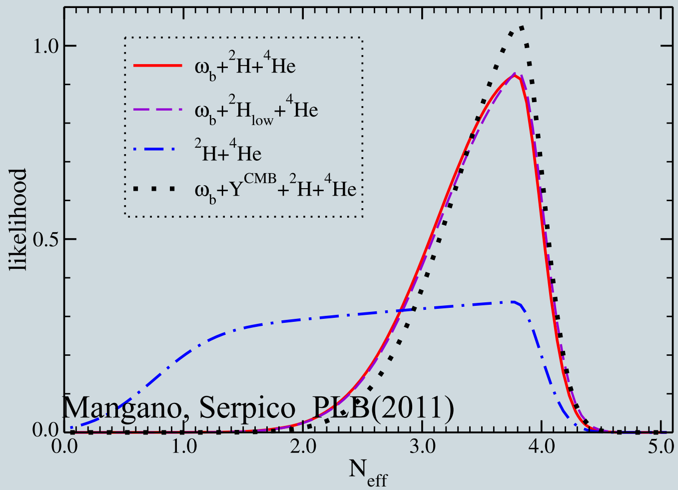
Cosmic History: N_{eff}, early Universe



Big Bang Nucleosynthesis

Increase of the expansion rate. Earlier freeze-out

Higher primordial ^{4}He abundance

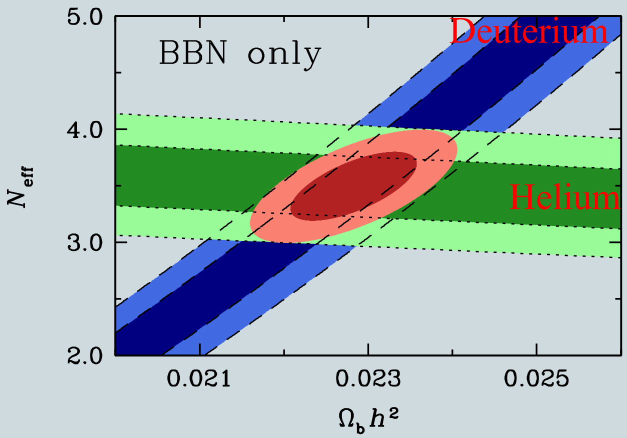


N_{eff} = 4.046 is excluded at 95% c.l.

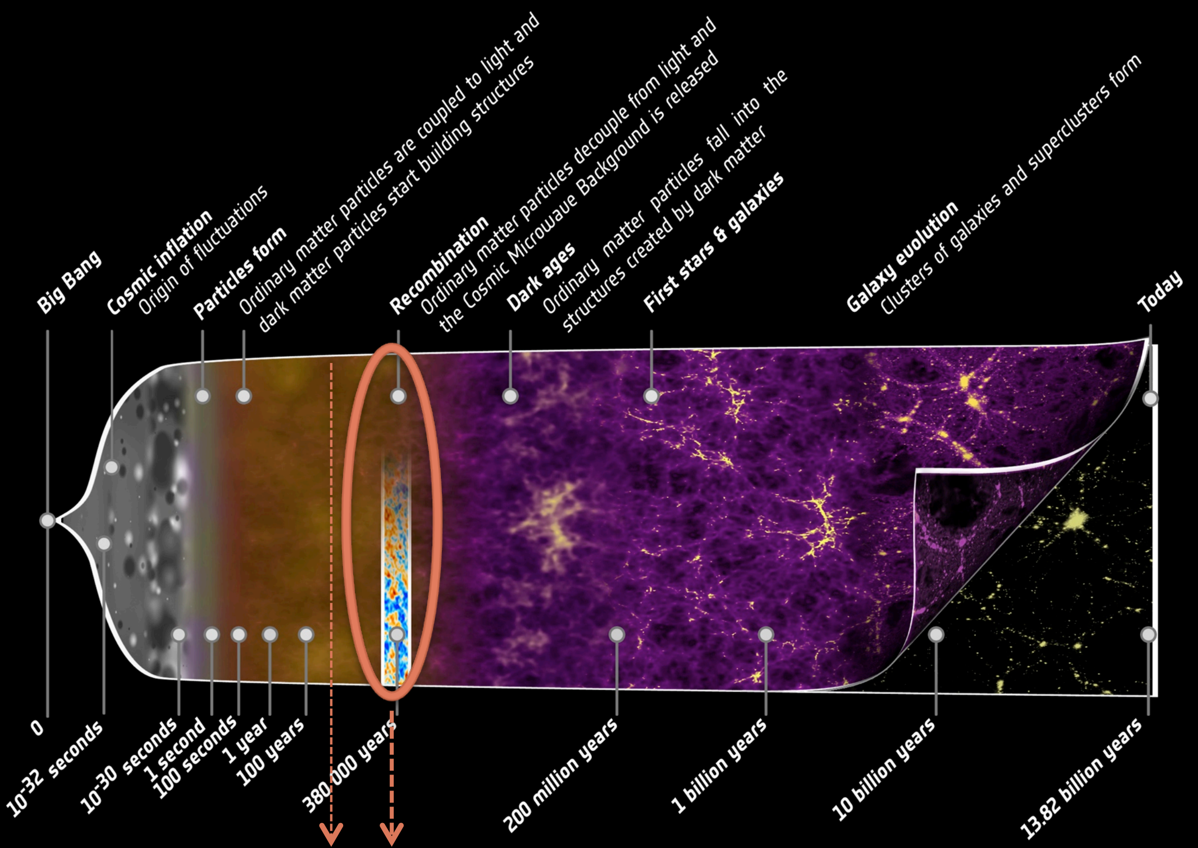
… N_{eff} is not constant!

$$N_{eff}^{BBN} \neq N_{eff}^{CMB}$$

Cooke et al., MNRAS (2013)

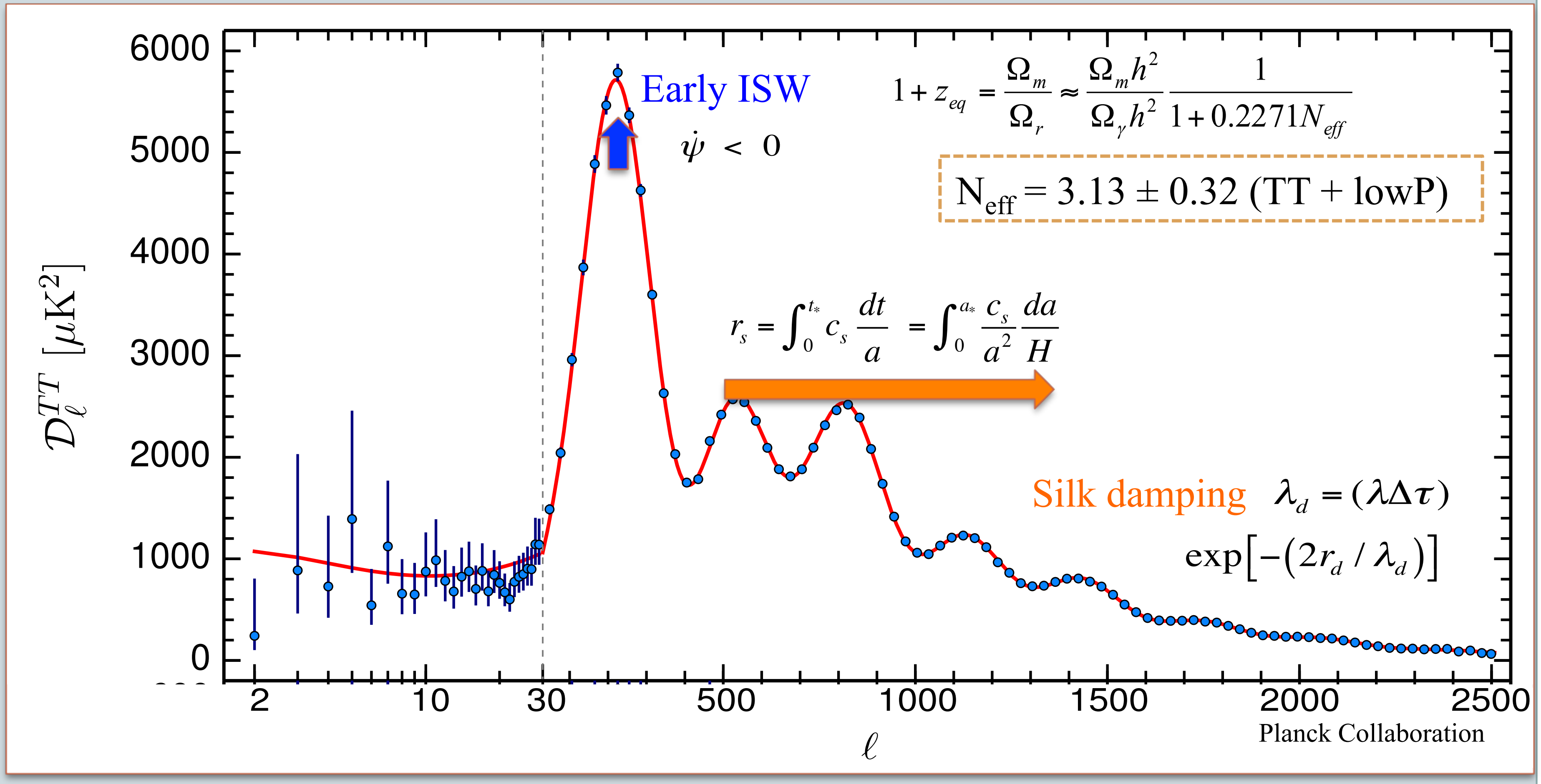


Cosmic History: N_{eff}, CMB

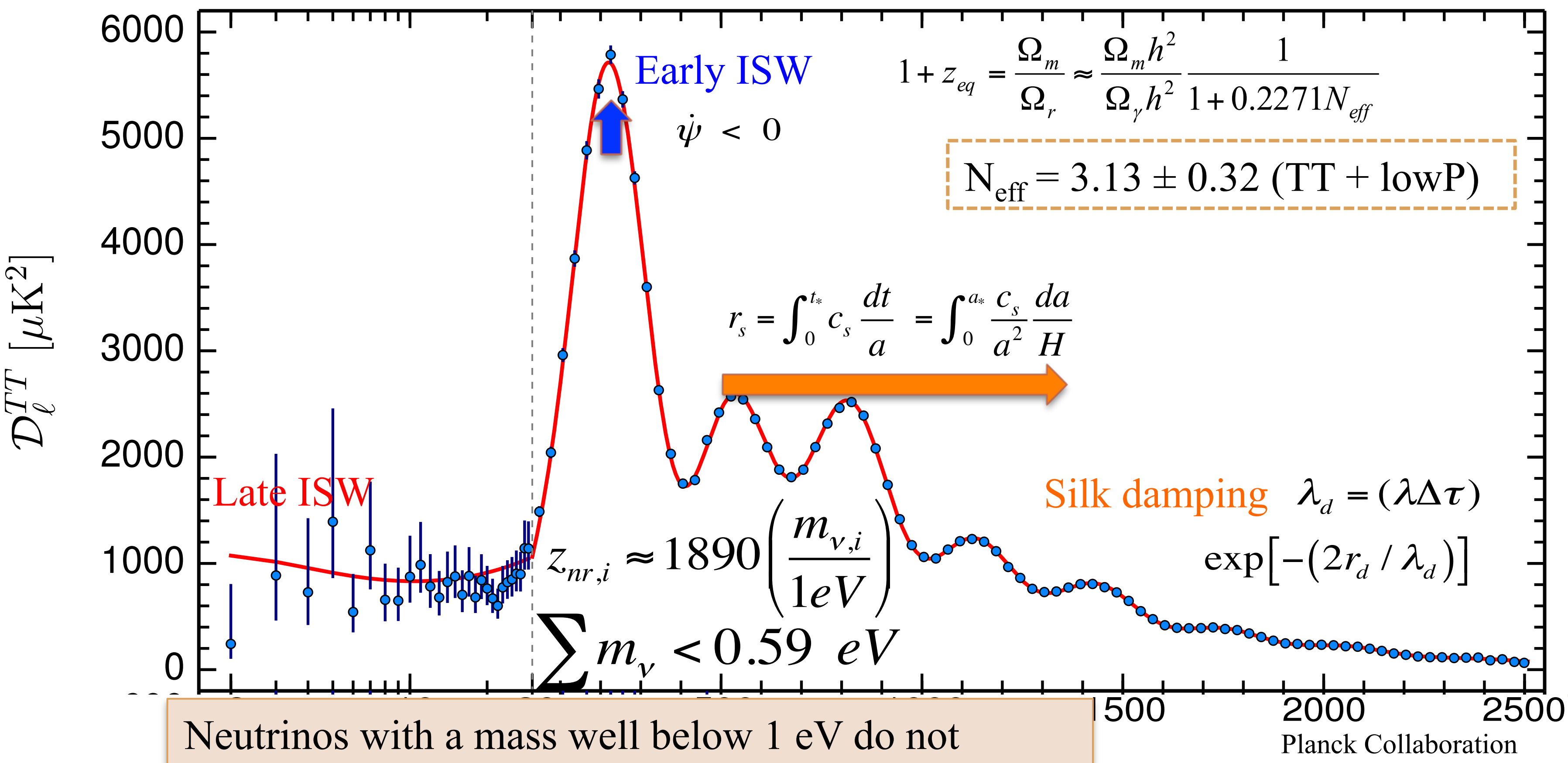


MReq: $z \approx 3500$ $z \approx 1100$ $E \approx 1$ eV

Temperature power spectrum

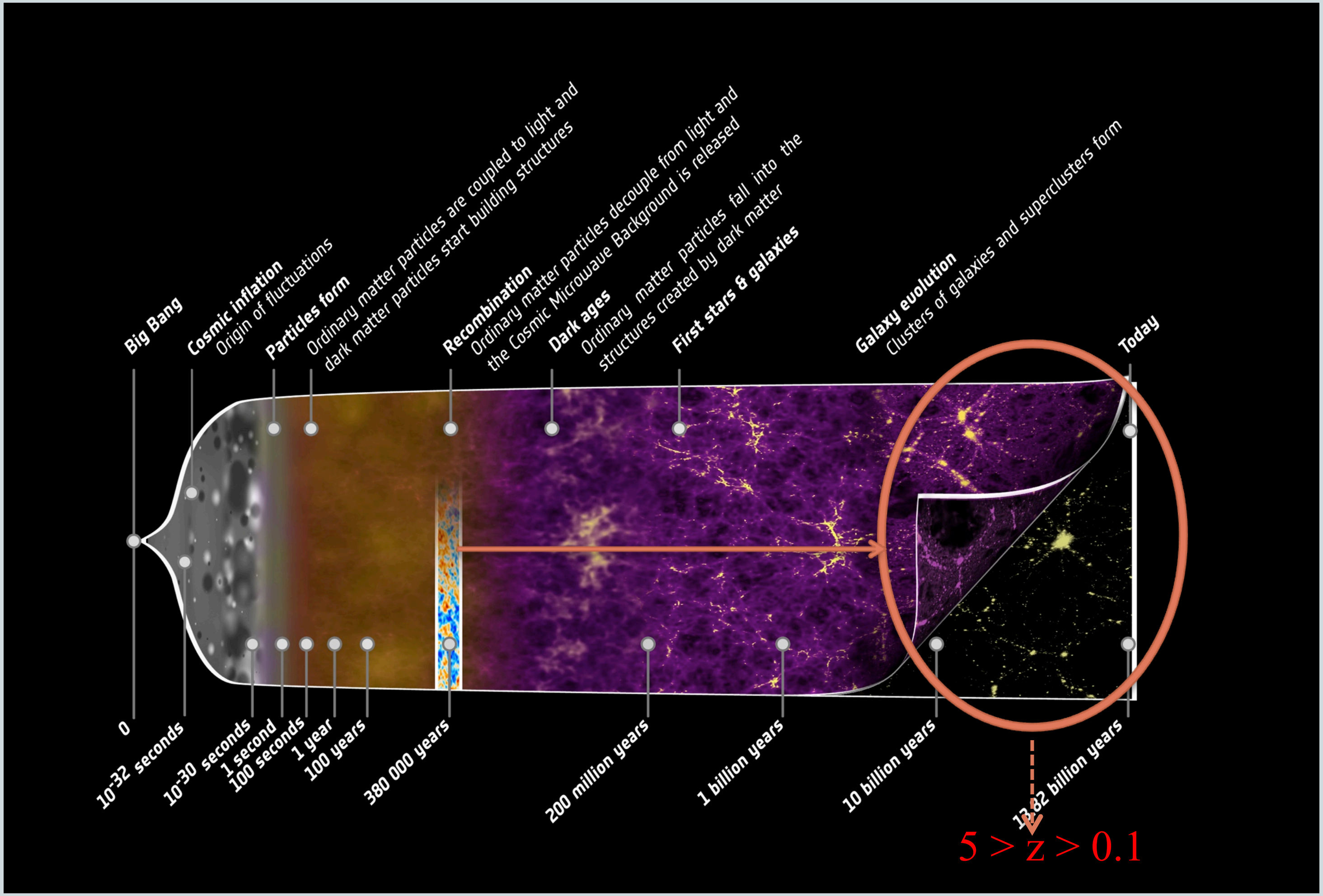


Temperature power spectrum



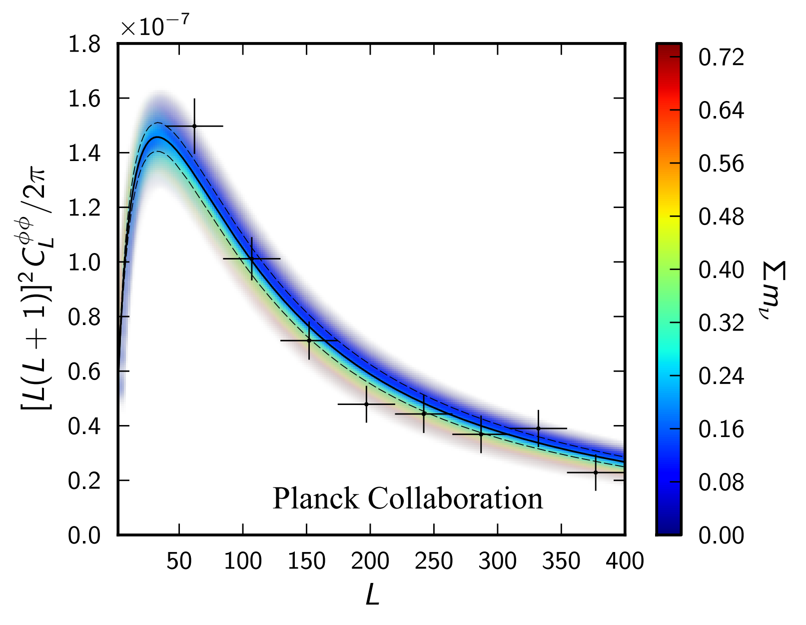
Neutrinos with a mass well below 1 eV do not directly affect the primary anisotropies of the CMB power spectrum

Cosmic History: m_ν, late times



CMB gravitational lensing

- Free-streaming $k_{FS} \approx H / v_{\nu}$
- Massive neutrinos slow down the growth of matter perturbations



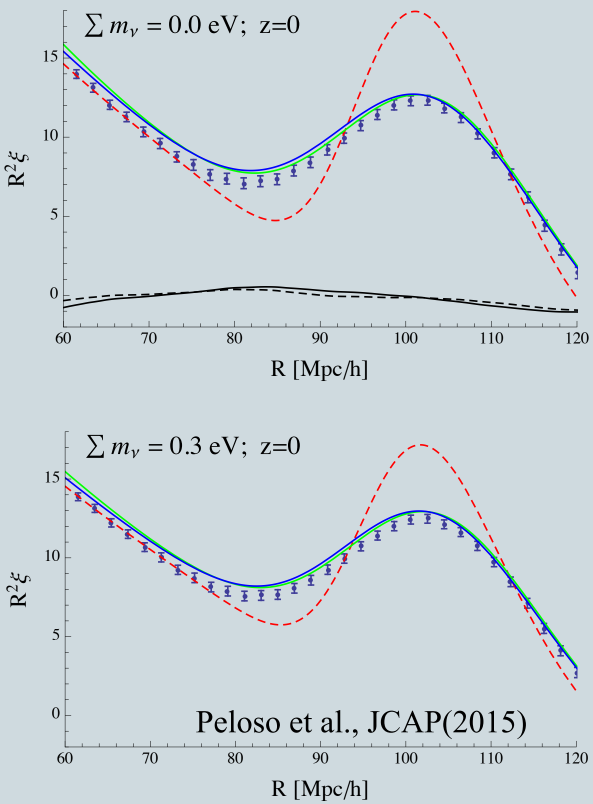
Suppression of lensing potential (plus CMB lensing on TT)

$$\sum m_{\nu} < 0.14 \ eV$$

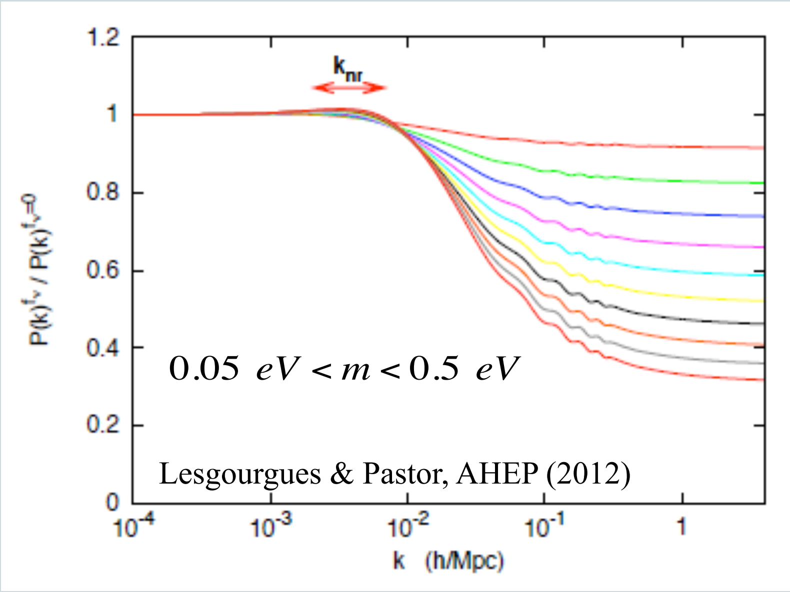
(95% c.l., TT + lowP + lensing) assuming three species of degenerate massive neutrinos

Large Scale Structure

BAO



MPK



$$\sum m_\nu < 0.16\ eV$$ 95% c.l.,

SDSS-III BOSS DR12 (2016)

Large Scale Structure

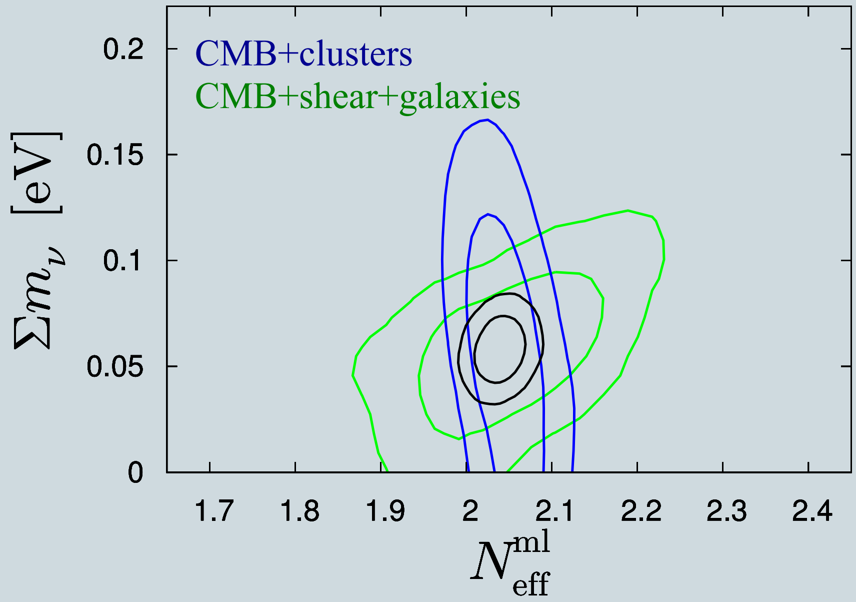
Euclid produces a legacy dataset with images and photometry of more than a billion galaxies and several million spectra, out to high redshifts z > 2.

$$N_{eff}^{fid} = 3.046 \qquad \sigma(N_{eff}) = 0.019$$

$$\Sigma m_\nu = 0.06\ eV \qquad \sigma(\Sigma m_\nu) = 0.0098\ eV$$

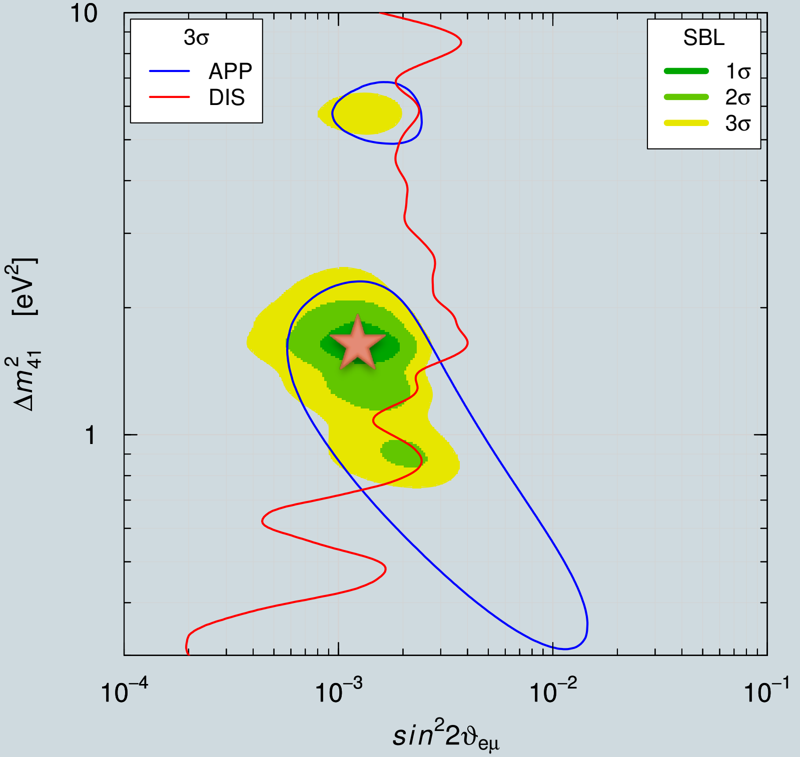
More than 5σ detection of neutrino mass

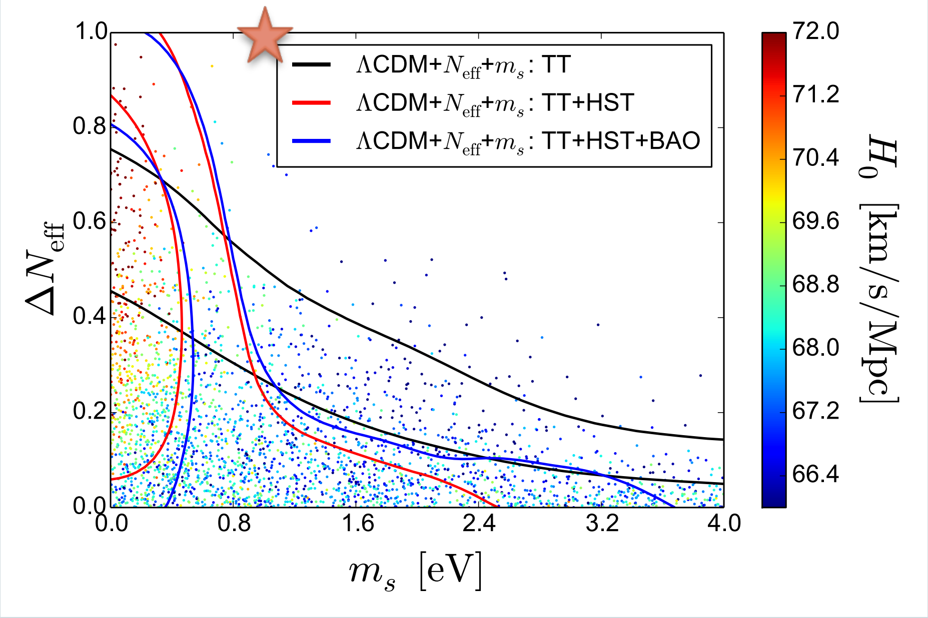
Basse, Bjaelde, Hamann, Hannestad, Wong, JCAP (2013)



Sterile Neutrinos

$$m_{eff}^{sterile} = (T_s / T_a)^3 m_{thermal}^{sterile} = (\Delta N_{eff})^{3/4} m_{thermal}^{sterile}$$





M. Archidiacono, S. Gariazzo, C. Giunti, S. Hannestad, R. Hansen, M. Laveder, T.Tram, JCAP (2016)

Solutions

How can cosmology face SBL? Partial thermalization:

- Non-standard interactions

  MA, Hannestad, Hansen, Tram, PRD (2015, 2016);
  Saviano et al., PRD (2014);
  Mirizzi et al., PRD (2014);
  Dasgupta, Kopp, PRL (2013, 2015);
  Hannestad, Hansen, Tram, PRL (2013)

- Lepton asymmetry

  Mirizzi, Saviano, Miele, Serpico (2012);
  Hannestad, Tamborra, Tram (2012)

- Low reheating temperature

  Rehagen, Gelimini (2014)

- Non-standard expansion rate at MeV scale

Pseudoscalar model

The sterile neutrino is coupled to a new light pseudoscalar

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

The phenomenologically success of the model relies on two things:

- g_s should be large enough to prevent full thermalisation of the sterile neutrino: $10^{-6} < g_s < 10^{-5}$ ➔ N_{eff}

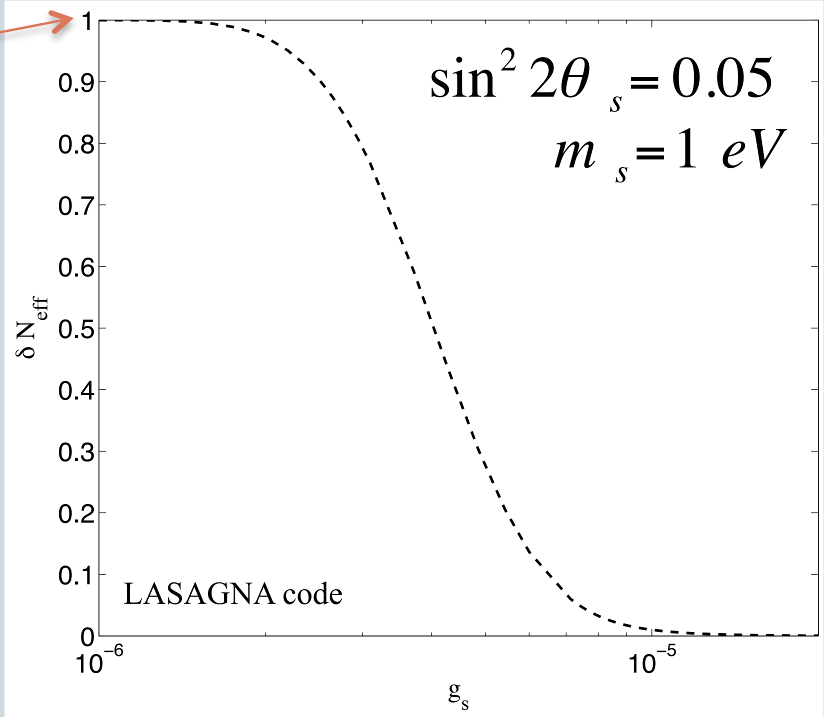
- ν_s must annihilate into φ at late time to avoid the mass bound from large scale structure: $m_\phi <\sim 0.1$ eV ➔ Σm_ν

Sterile neutrino number at BBN

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

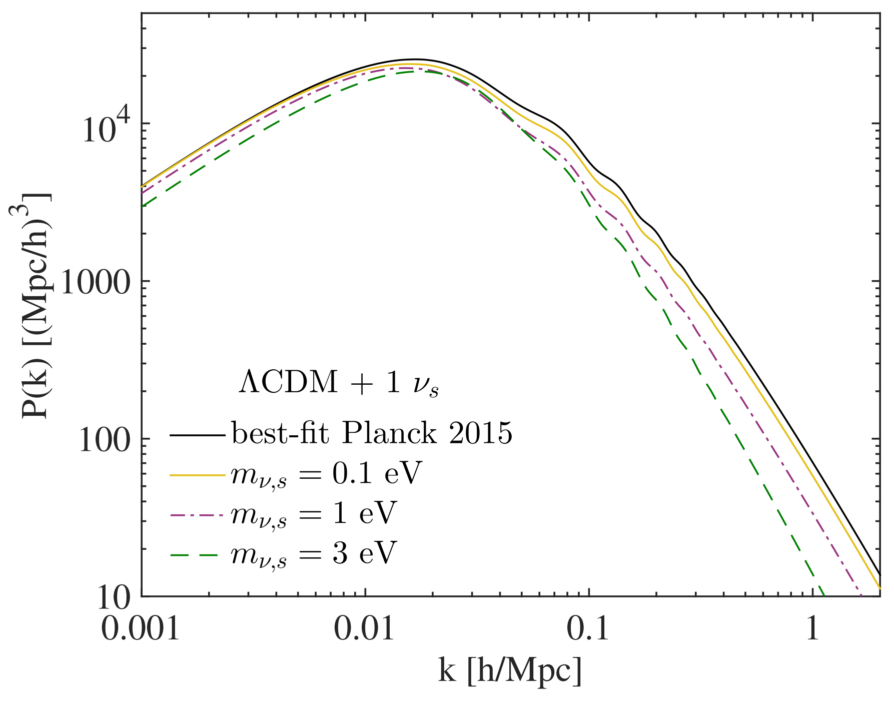
BBN bounds:
$\Delta N_{eff} \leq 1$ (95% c.l.)

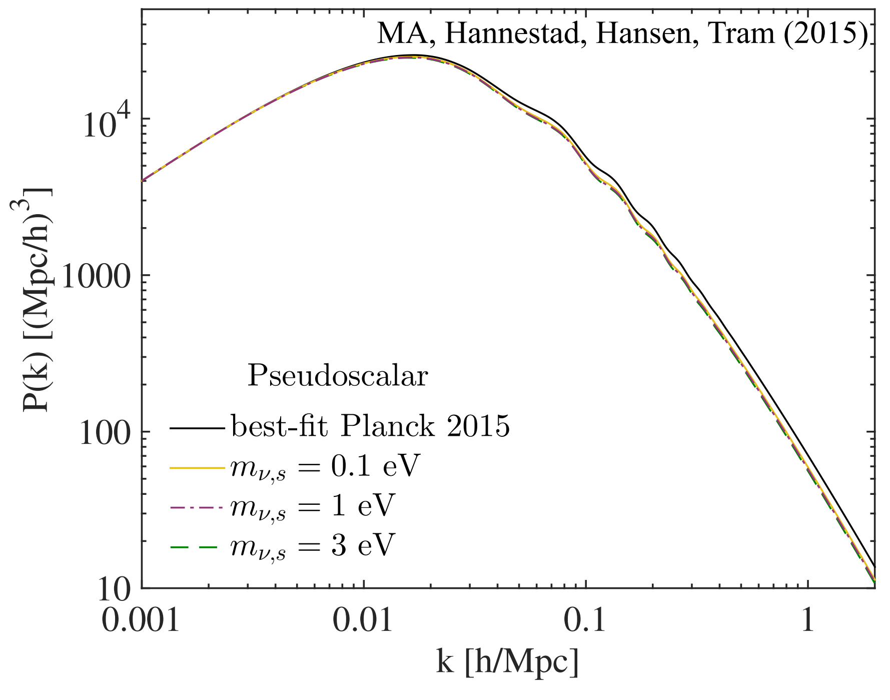
When sterile neutrinos are produced, they will create non-thermal distortions in the sterile neutrino distribution, and the sterile neutrino spectrum end up being somewhat non-thermal.



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

Sterile neutrino mass and LSS





CMB+HST+BAO

$$\Delta\chi^2 < 0$$

ref: ΛCDM

MA, et al., JCAP (2016)

Conclusions

- ✓ Cosmology is a powerful tool to constrain neutrino physics
- ✓ Despite the progress of precision cosmology, sterile neutrinos still represent an open question
- ✓ The tension between cosmology and oscillation experiments exacerbates the debate: SBL light sterile neutrinos are too many and too massive for cosmology
- ✓ "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

Backup

Thermal history

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

$$\nu_s \nu_s \leftrightarrow \phi\phi \quad \langle \sigma |v| \rangle = \frac{g_s^4}{8\pi T_s^2}$$ 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

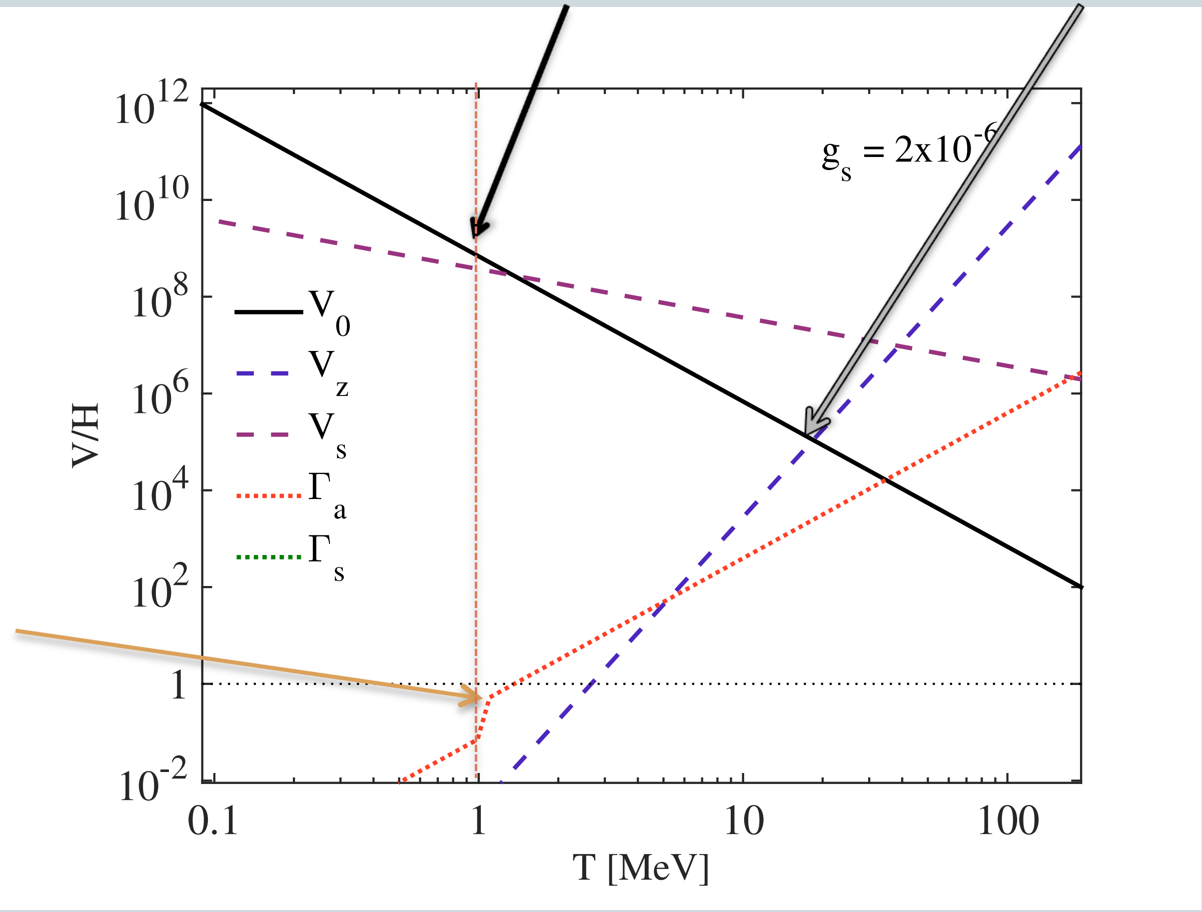
$$V_z = -\frac{\Delta m_s^2}{2p} \cos 2\theta_s - \frac{14\pi^2}{45\sqrt{2}} p \frac{G_F}{M_Z^2} T^4 n_a + V_s$$

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

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



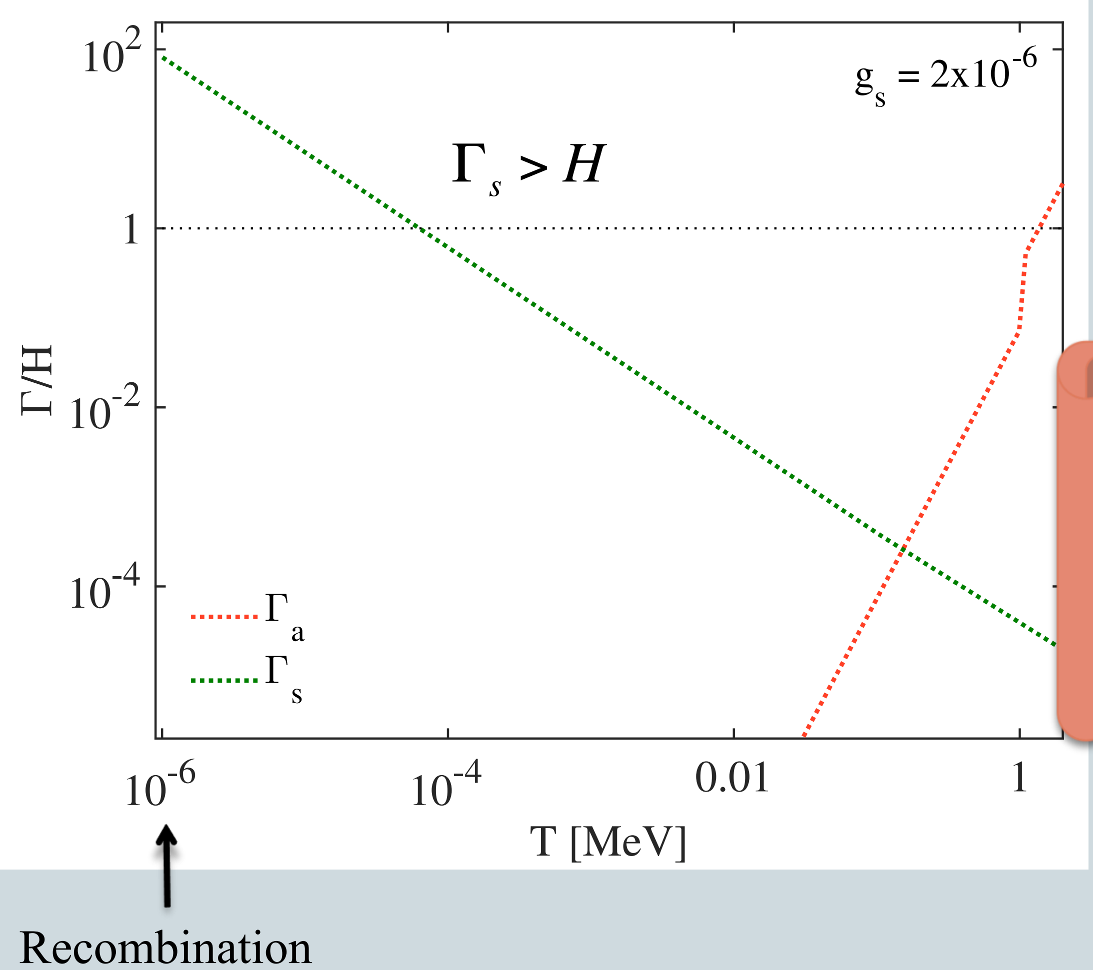
Standard neutrino decoupling &~ n/p freeze-out

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

Late time phenomenology (1): $\nu_s - \phi$ interactions



$$\Gamma_a = C G_F^2 p T^4$$

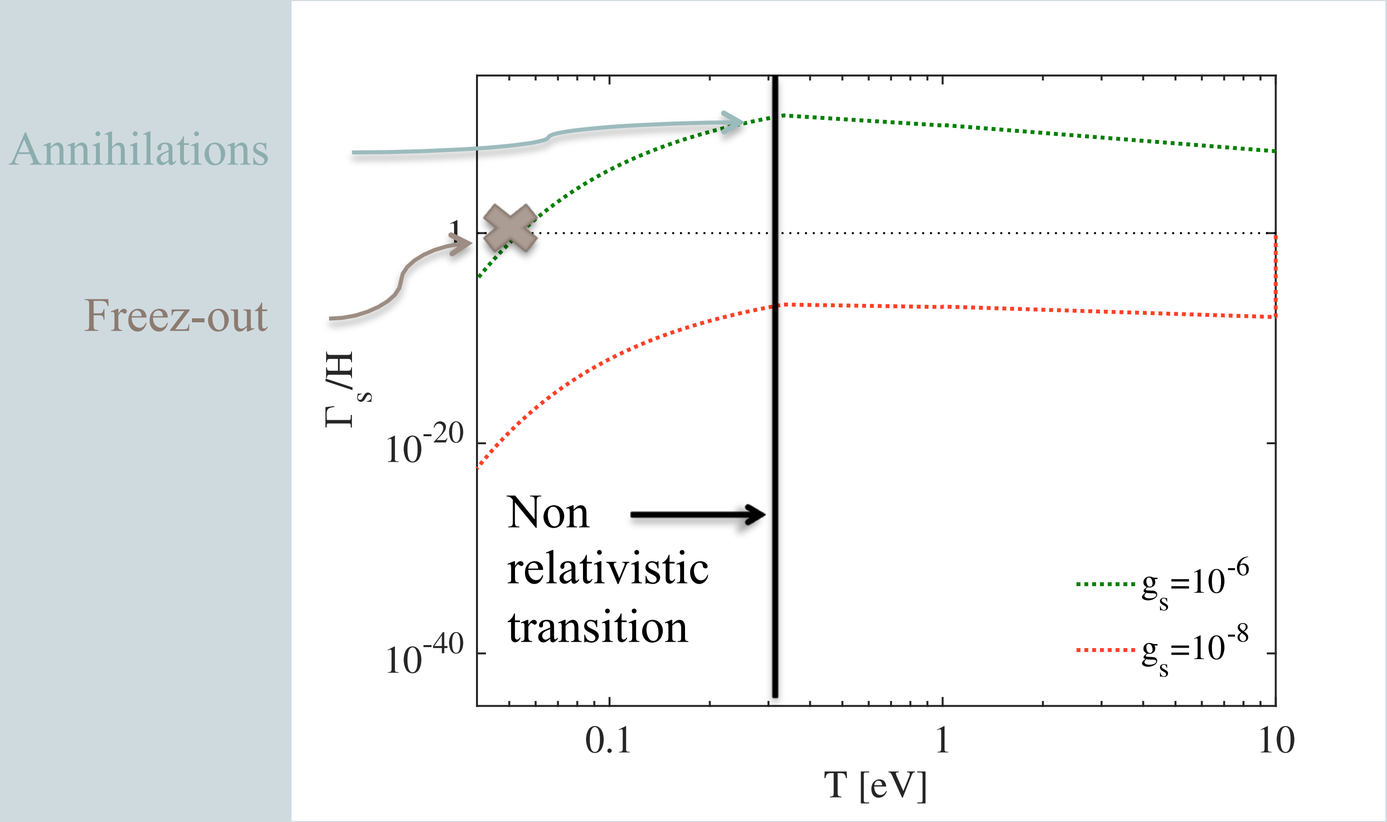
$$\Gamma_s = \frac{g_s^4}{4\pi T_s^2} n_s$$

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

Low energy / late time process

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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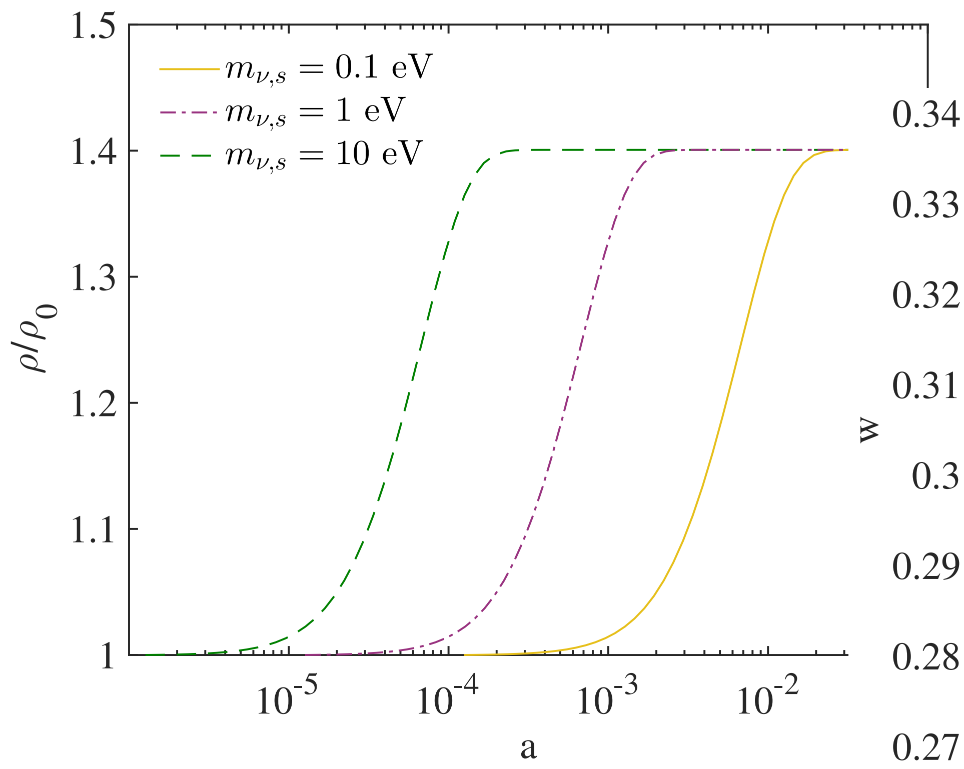
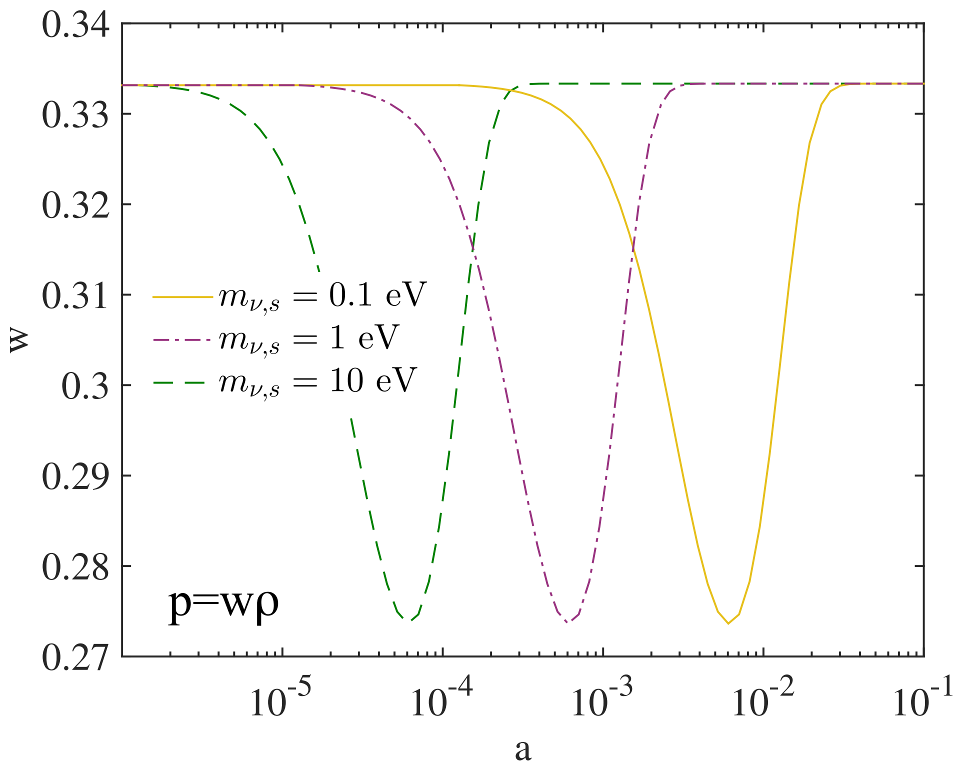
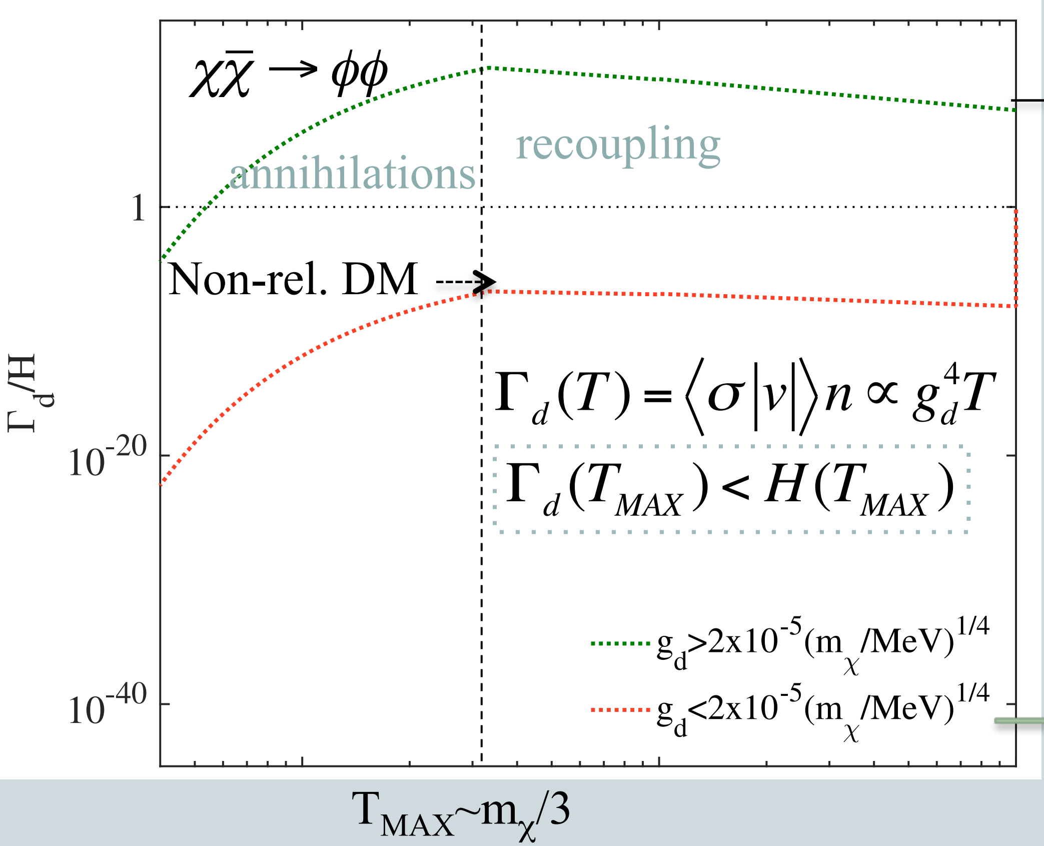
Sterile neutrino annihilations will heat up the scalars



MA, Hannestad, Hansen, Tram (2015)



Coupling to DM: not too strong



decoupled

$$g_d \leq 2\times10^{-5}\left(\frac{m_\chi}{MeV}\right)^{1/4}$$

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

Coupling to DM: not too weak

Galactic Dynamics:

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

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

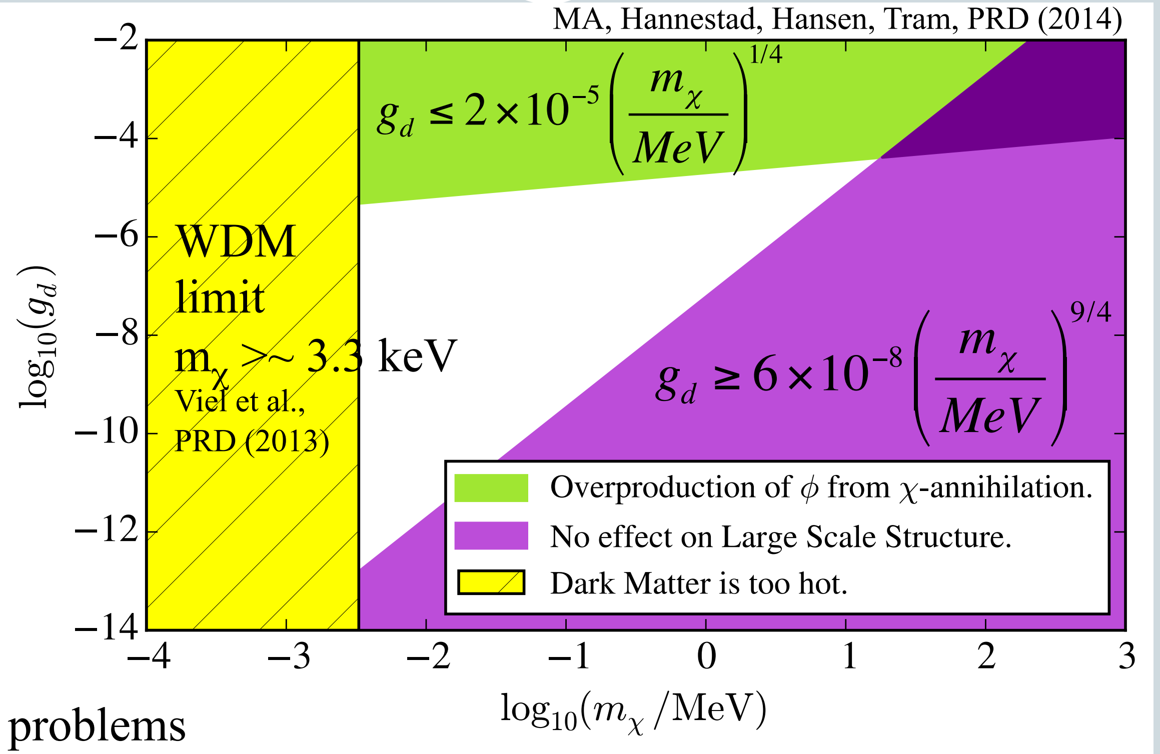
The condition for having observable consequences on galactic dynamics is that the scattering time scale of DM self interactions is less than the age of the Universe.

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

Coupling to DM

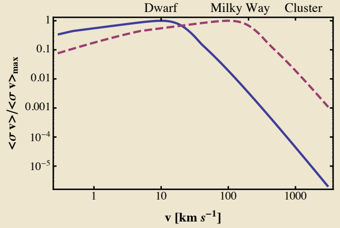


ΛCDM small scale problems

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

DM – DM

- ✗ "missing satellites" DM - DR



Loeb & Weiner, PRL (2010)

Chu & Dasgupta, PRL (2014)