Sterile neutrinos in cosmology: troubles or new physics

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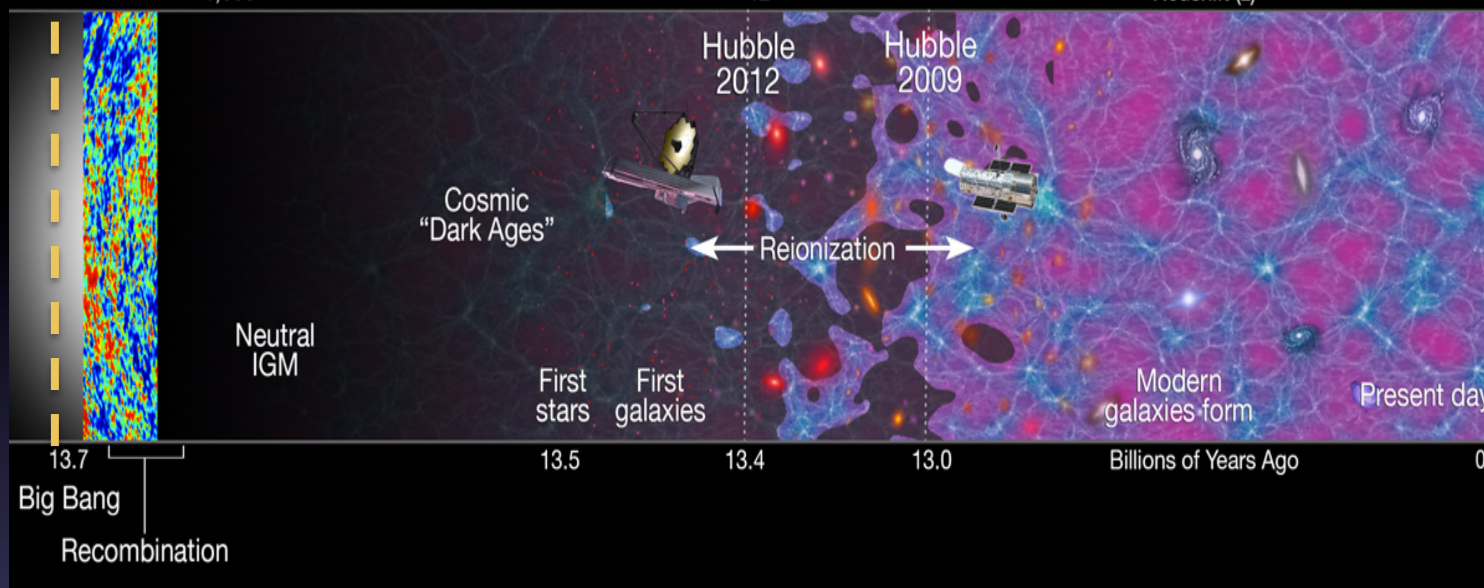
CrossTalk Workshop: The Fate of Sterile Neutrinos
Vrije Universiteit Brussel, 18 January 2017

Outline

- ➢ Measuring neutrinos with cosmology:
- Neutrino thermal history
- Observables
- Current Constraints
- ➢ Sterile neutrinos
- Troubles: tension between cosmology and oscillations
- New physics: secret interactions

Neutrino decoupling



In the primordial Universe weak interactions keep neutrinos in equilibrium with the heat bath.

$\Gamma \sim G_F^2 T^5 < H$

$T_{dec} \sim 1$ MeV $\rightarrow$ HDM

$e^+e^- \rightarrow \gamma\gamma$

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

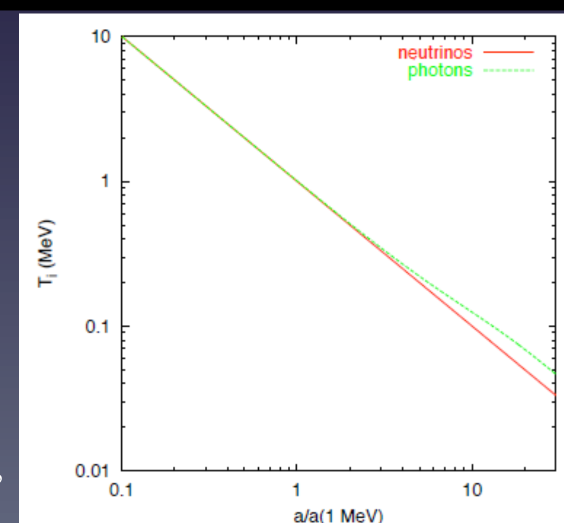
$T_\nu \sim 1/a$

$\Gamma_s \sim G_F^2 T^5 \sin^2\theta_s < H$

$T_{dec,s} \sim T_{dec} / \sin^2\theta_s$

$T_{\nu,s} / T_\gamma \sim (4/15)^{1/3}$

Lesgourgues & Pastor, AHEP (2012)



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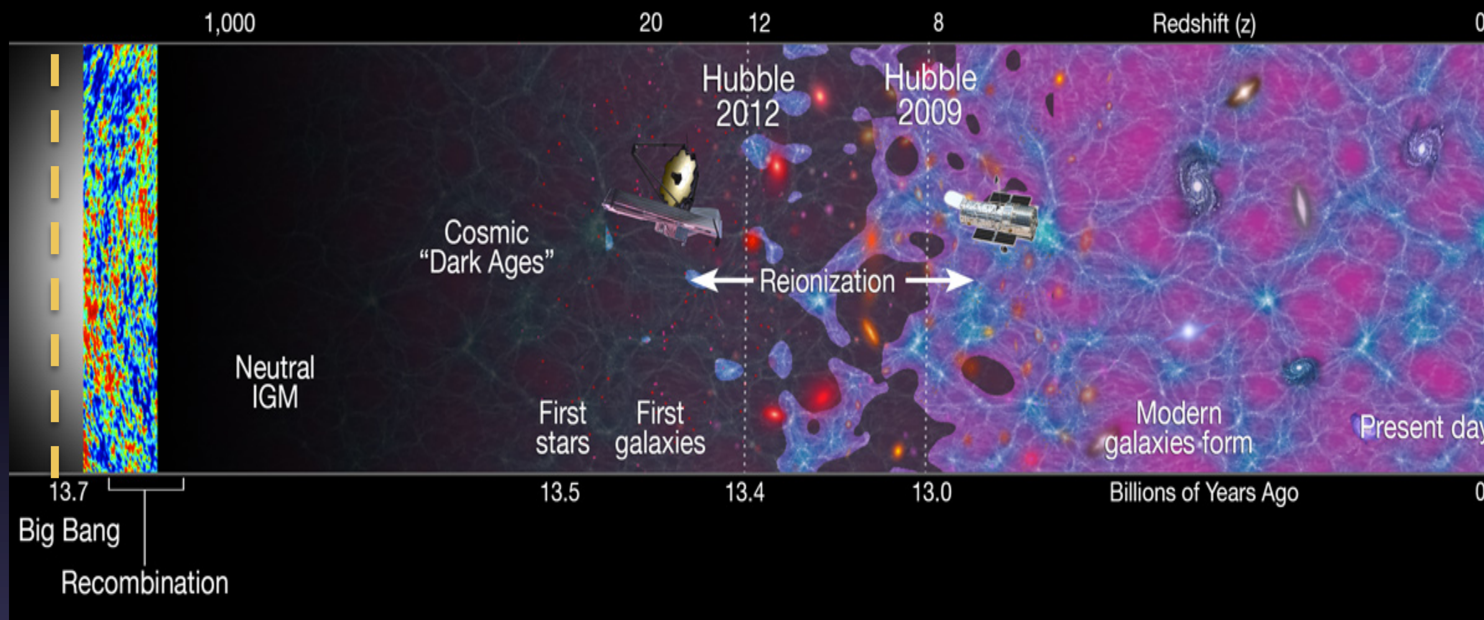
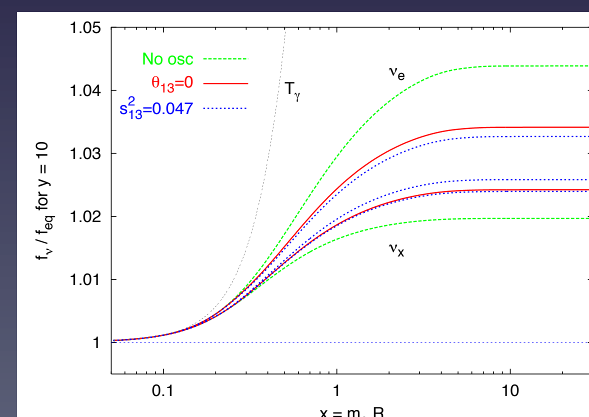


$$\rho_{rad} = \left[1+\frac{7}{8}\left(\frac{4}{11}\right)^{4/3} N_{eff}\right]\rho_{\gamma}$$

N_{eff} Effective number of relativistic degrees of freedom

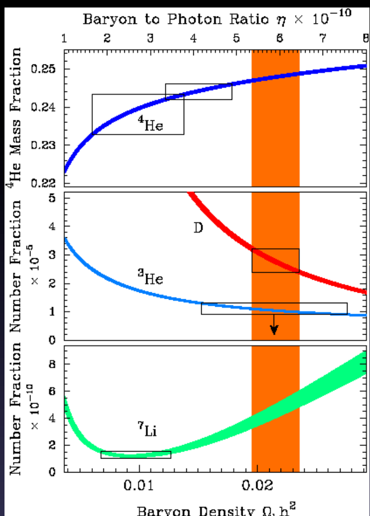
- ❖ Other relativistic relics can contribute to N_{eff}
- ❖ This equation holds after decoupling and as long as all neutrinos are relativistic
- ❖ $N_{eff,dec} \sim 3.046$
- ❖ + 1 sterile, $N_{eff,dec} \sim 4$

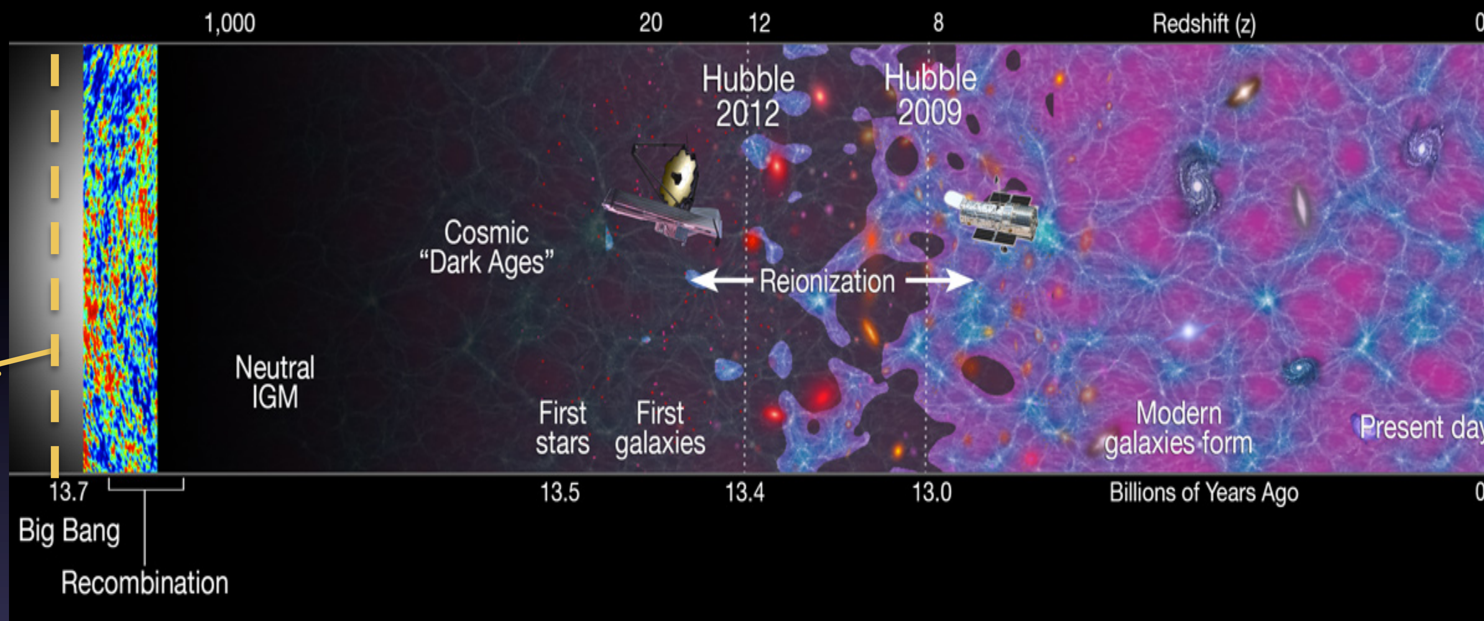


Mangano, Miele, Pastor, Pinto, Pisanti, Serpico, Nucl.Phys.B (2005)

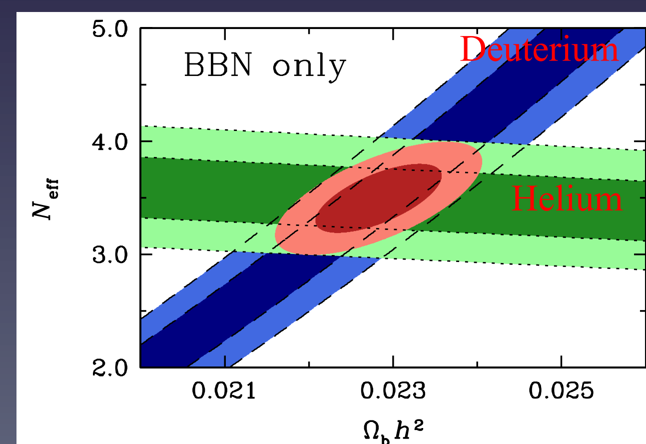
Neutrino number: impact on BBN

BBN T ~ 0.7 MeV





A larger N_{eff} (i.e. sterile neutrinos) increases the expansion rate of the Universe (Friedmann $H^2 \sim \rho_r \sim N_{eff}$) .
Earlier (T>0.7 MeV) freeze-out of reactions
(e.g. $n + \nu_e \rightarrow p + e^-$).
Larger neutron to proton ratio.
Higher primordial D and ^{4}He abundance



$\Delta N_{eff,BBN} = 0.66 \pm 0.45$ (BBN, 68% c.l.) Steigman, AHEP, (2012)
$N_{eff,BBN\text{-}CMB} = 3.28 \pm 0.28$ (BBN+CMB, 68% c.l.)

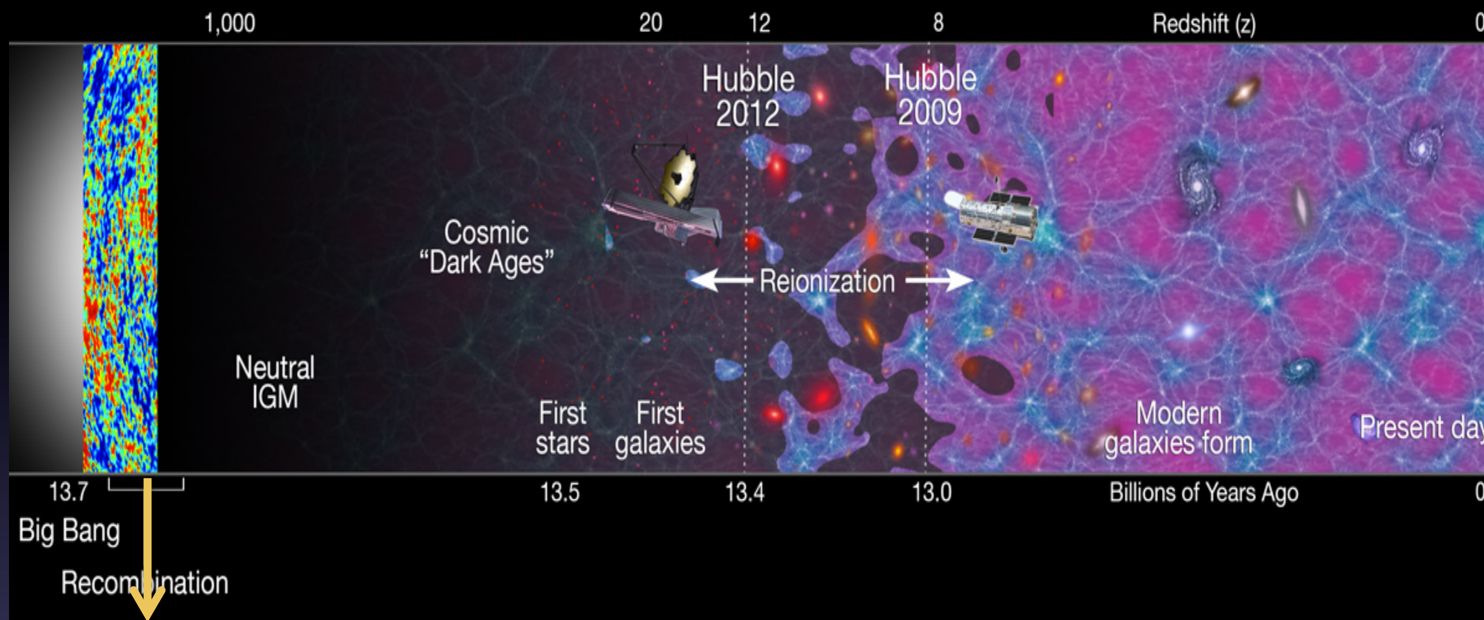
Cooke et al., APJ (2014)

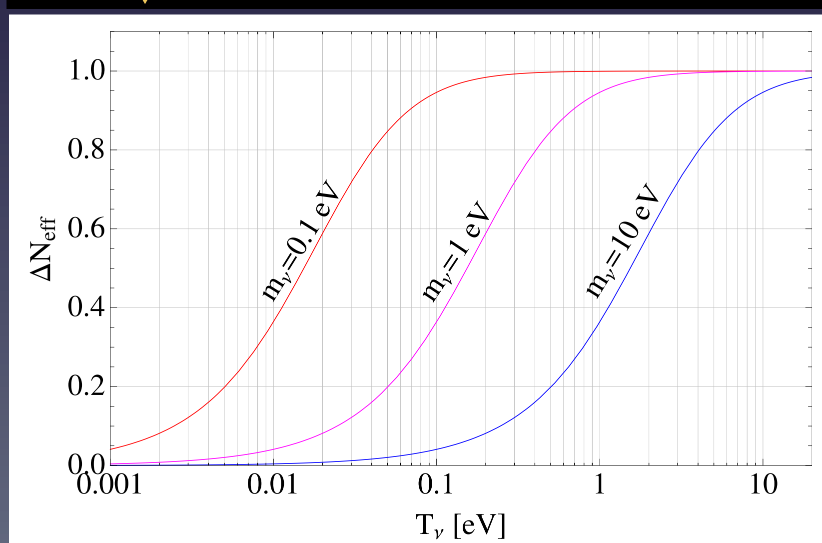
Neutrinos and CMB TT

CMB T ~ 1 eV

$T_{\nu,CMB}$ ~ 0.7 eV

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





$$\Delta N_{eff} = \frac{\rho_{\nu,s}}{\rho^{thermal}_{\nu,m=0}}\left(\frac{P_{\nu,s}/\rho_{\nu,s}}{1/3}\right)$$

$$\rho = \frac{g}{2\pi^2}\int dpEp^2 f(p)$$

$$P = \frac{g}{2\pi^2}\int dp\frac{P^4}{3E} f(p)$$

Jacques, Krauss, Lunardini
PRD (2013)

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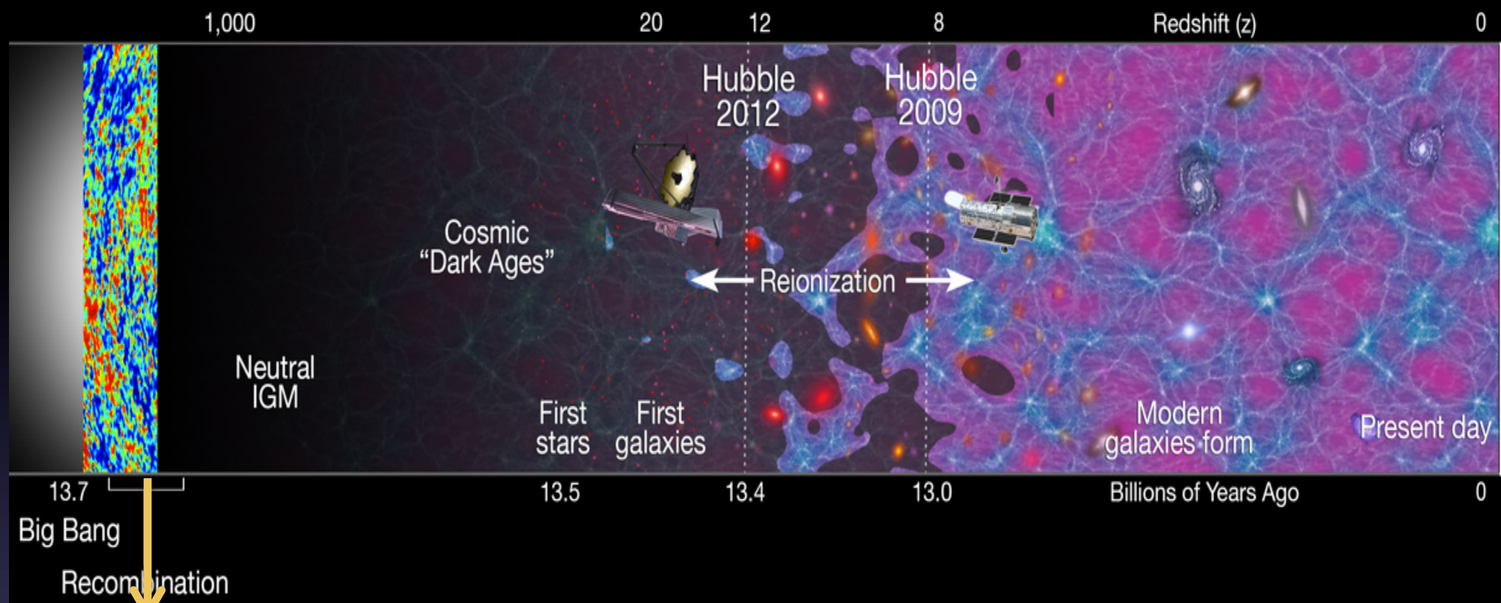
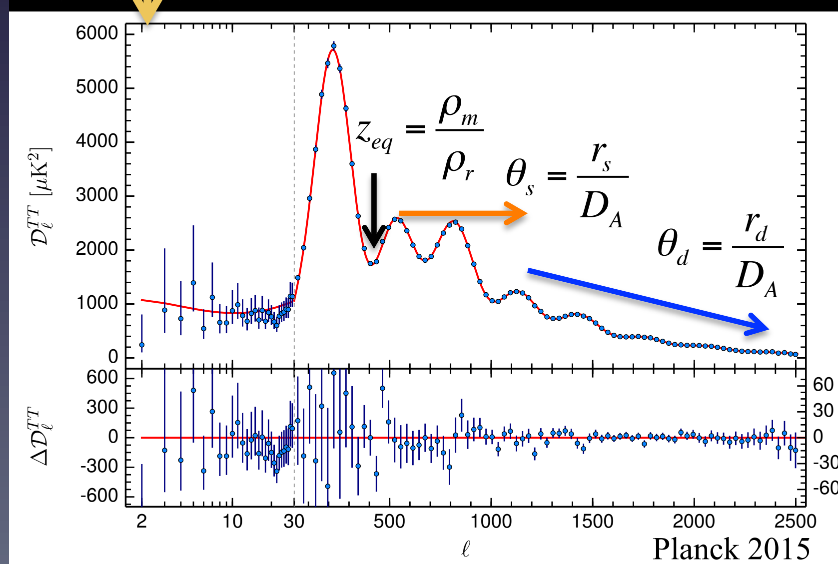


Increasing N_{eff} …

The shape of the spectrum is determined by ratios



1 Early ISW

$\dot{\varphi} < 0$

2 Shift of the peak position

$$r_s = \int_0^{t_*} c_s \, dt / a = \int_0^{a_*} \frac{c_s}{a^2} \frac{da}{H} \propto \frac{1}{H}$$

3 Silk damping

$$\exp\left[-\left(2r_d / \lambda_d\right)\right]$$

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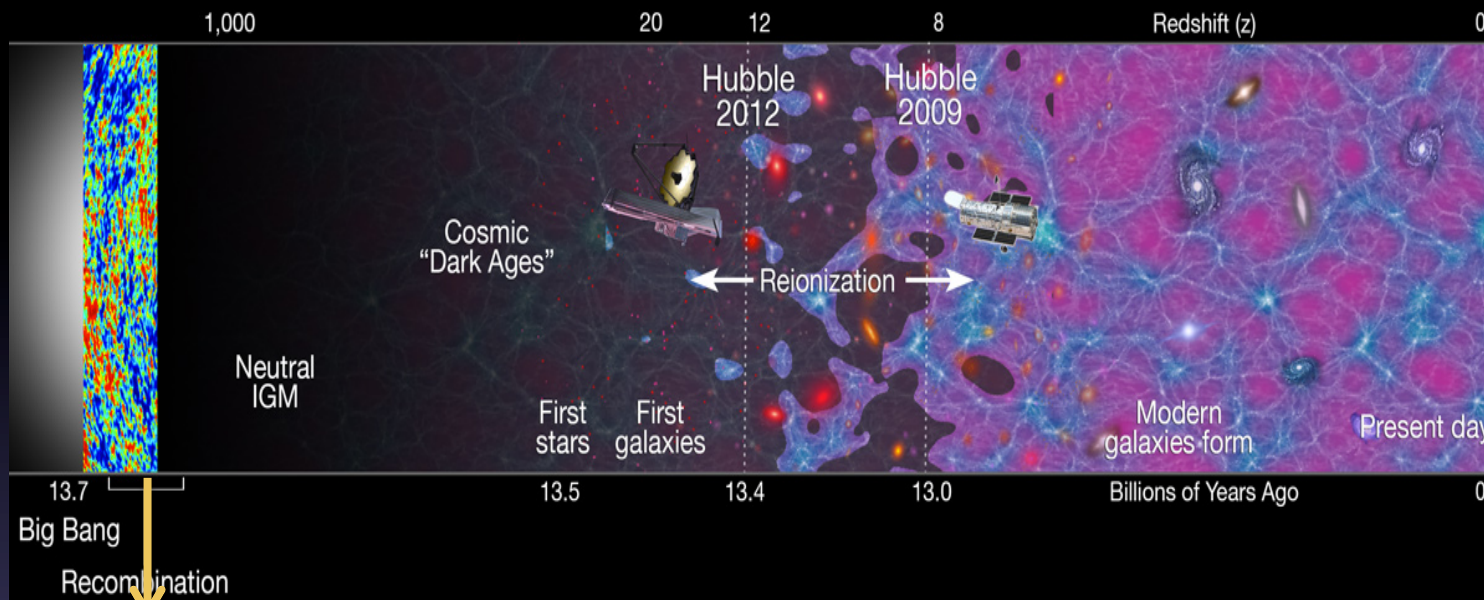

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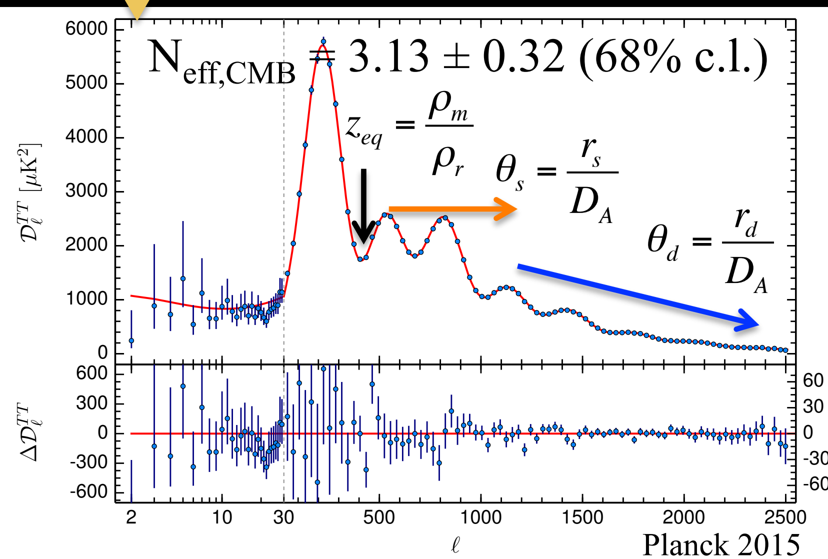

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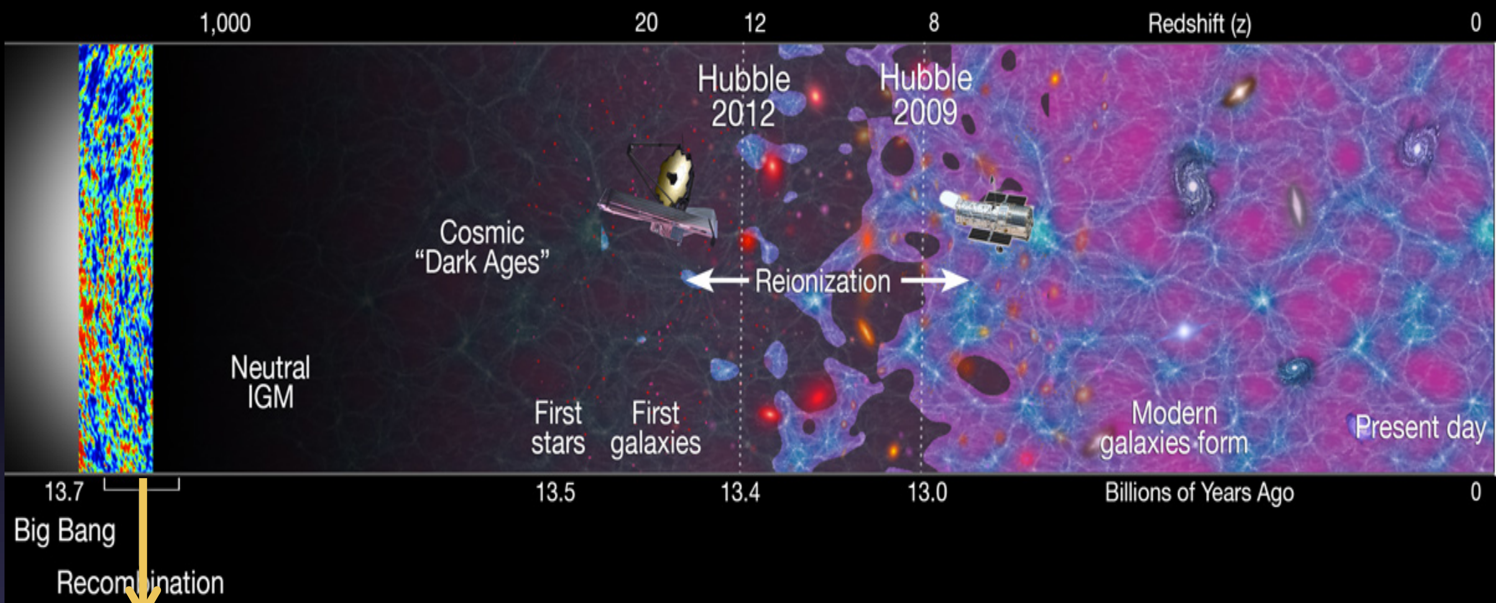

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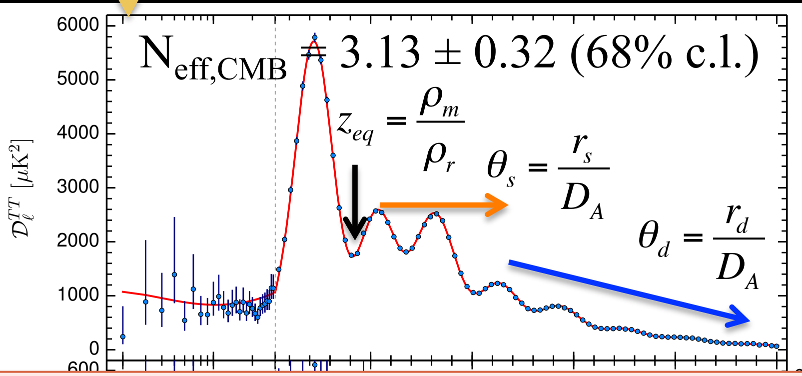
The shape of the spectrum is determined by ratios

Increasing Σm_ν …



1 Early ISW

$\dot{\varphi} < 0$

2 Shift of the peak position

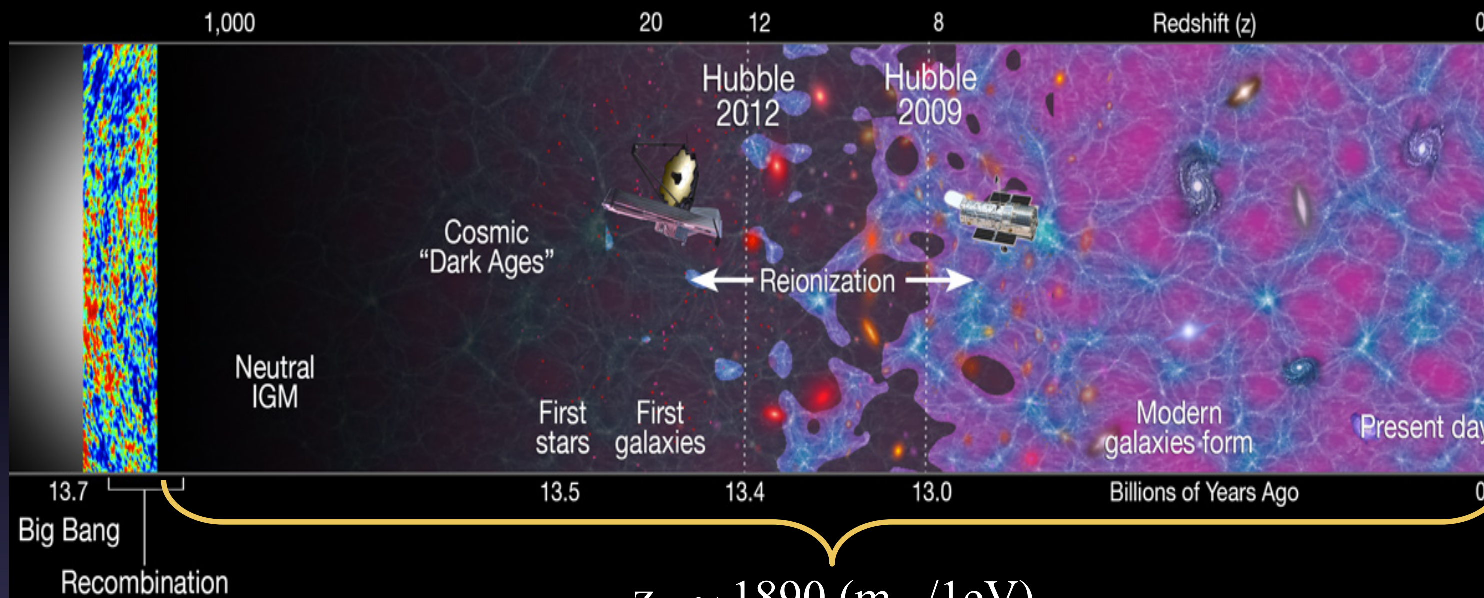
$$r_s = \int_0^{t_*} c_s\, dt / a = \int_0^{a_*} \frac{c_s}{a^2} \frac{da}{H} \propto \frac{1}{H}$$

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

$$\sum m_\nu < 0.59\ eV\ (95\%cl)$$

Neutrino non-relativistic transition

As long as neutrinos are relativistic they travel at the speed of light.



$z_{nr} \sim 1890\ (m_{\nu,i}/1\mathrm{eV})$

$$k_{nr,i}(z) \equiv \frac{H(z_{nr,i})}{(1+z_{nr,i})} = 0.0145 Mpc^{-1}\left(\frac{m_{\nu,i}}{1eV}\right)^{1/2}\Omega_m^{1/2}h$$

When neutrinos become non-relativistic, they travel through the Universe with a thermal velocity $v_{th,i} = \langle p\rangle/m_{\nu,i} \sim 3T_{\nu,i}/m_{\nu,i} \sim 150\ (1+z)\ (1\mathrm{eV}/m_{\nu,i})$ km/s

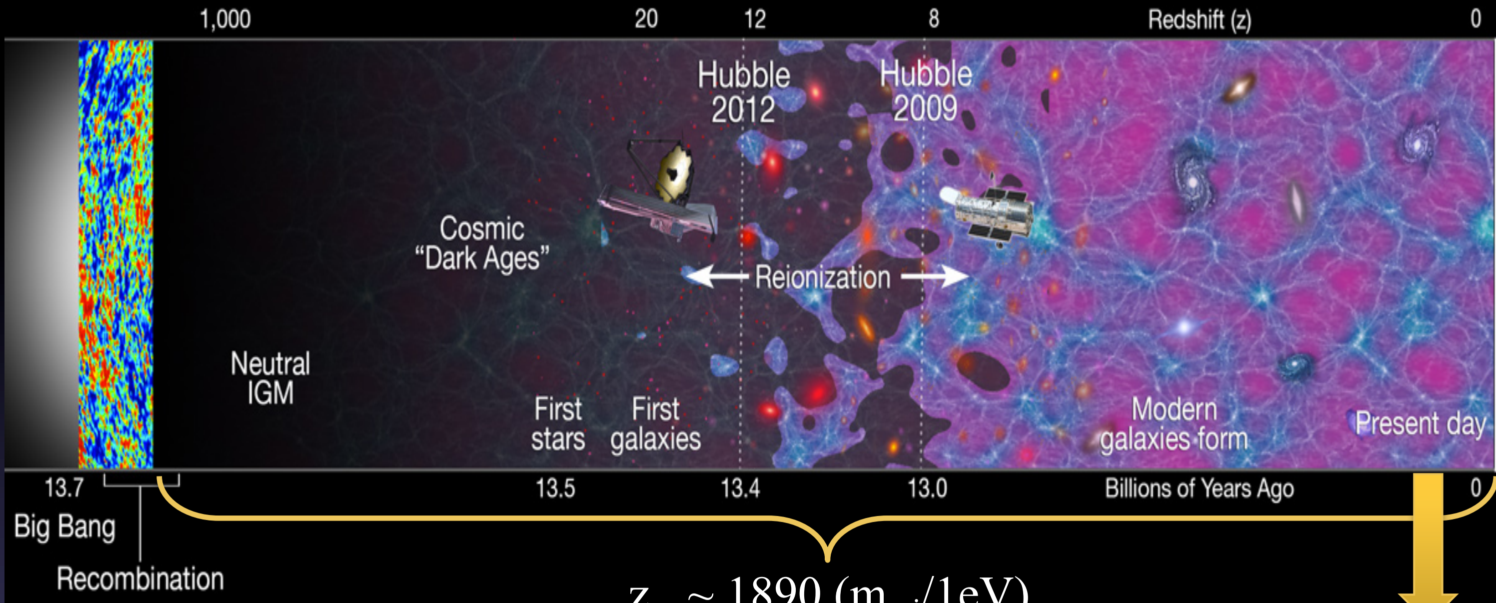
Neutrinos cannot be confined below the characteristic free-streaming scale defined by $v_{th,i}$.

$$k_{fs,i}(z) \equiv \sqrt{\frac{3}{2}}\frac{H(z)}{(1+z)v_{th,i}(z)} = 0.113 Mpc^{-1}\left(\frac{m_{\nu,i}}{1eV}\right)\left(\frac{\Omega_m h^2}{0.14}\frac{5}{1+z}\right)^{1/2}$$

Neutrino mass: impact on LSS

$$\Omega_\nu = \frac{\rho_\nu}{\rho_c} = \frac{\sum m_\nu}{h^2 93.14eV}$$

This formula does not account for the distortions in the neutrino distributions

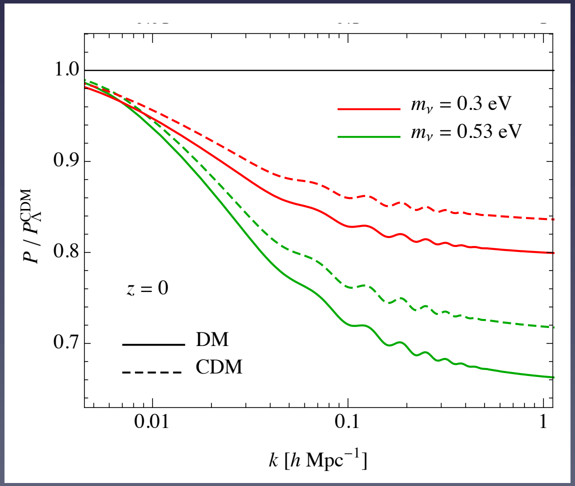


$z_{nr} \sim 1890\ (m_{\nu,i}/1eV)$

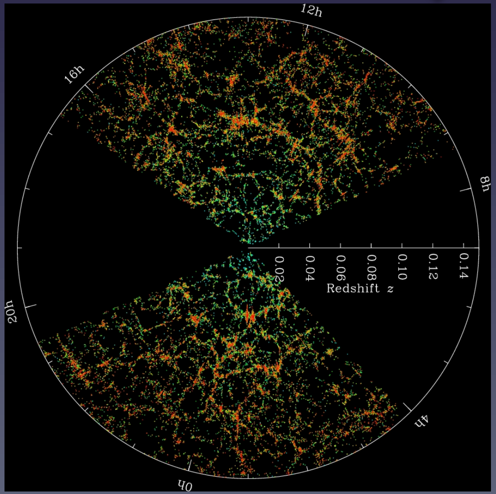
Planck15(TT+TE+EE+lowP)+
SDSS-DR7-P(k)+BAO

$$\sum m_\nu < 0.13\ eV\ \ (95\%cl)$$

Cuesta, Niro, Verde,
Phys. Dark Univ (2016)



Castorina et al., JCAP (2015)

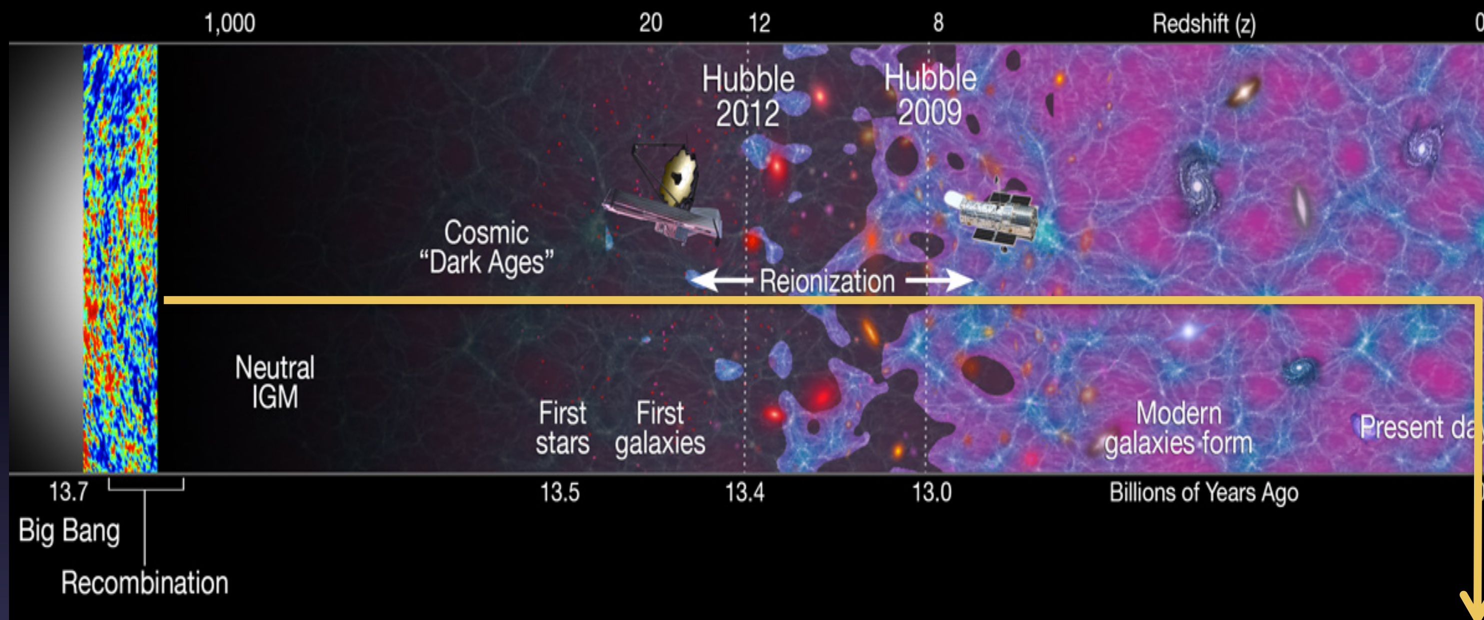


z~0-1

SDSS

Neutrinos and CMB lensing

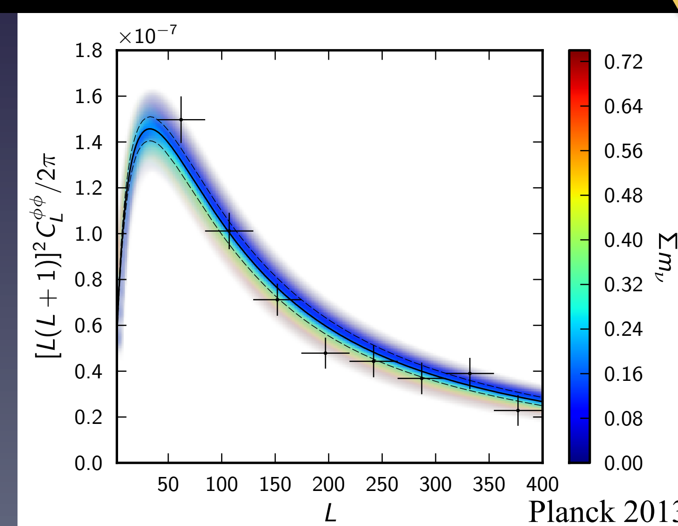
Massive neutrinos slow down the growth of matter perturbations



Suppression of lensing potential (plus CMB lensing on TT)

$$\sum m_\nu < 0.14\ eV\ (95\%cl)$$

(TT + lowP + lensing, Planck16) assuming three species of degenerate massive neutrinos



Where we stand

- Effective number of relativistic degrees of freedom

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

- Neutrino mass sum

$$\Omega_\nu = \frac{\rho_\nu}{\rho_c} = \frac{\sum m_\nu}{h^2 93.14 eV}$$

- Other relativistic relics can contribute to N_{eff}
- This equation holds after decoupling and as long as all neutrinos are relativistic

Model: ΛCDM + N_{eff}

$$N_{eff} = 3.13 \pm 0.32 \ (68\%cl)$$

- This formula does not account for the distortions in the neutrino distributions

Model: ΛCDM + Σm_ν

$$\sum m_\nu < 0.13 \ eV \ (95\%cl)$$

eV sterile neutrinos are too many and too massive for cosmology

Troubles

Tension between measurements

H_0 = (67.31 ± 0.96) km/s/Mpc   (68% c.l.) (Planck, ΛCDM)

H_0 = (73.24 ± 1.74) km/s/Mpc   (68% c.l.) (HST, Riess et al., Apj (2016))

3.4 σ tension

σ_8 tension between Planck and CFHTLens (Kilbinger at al., MNRAS(2013)),

alleviated by DES (Abbott at al., PRD(2016))

Two possible model extensions each one solving one tension

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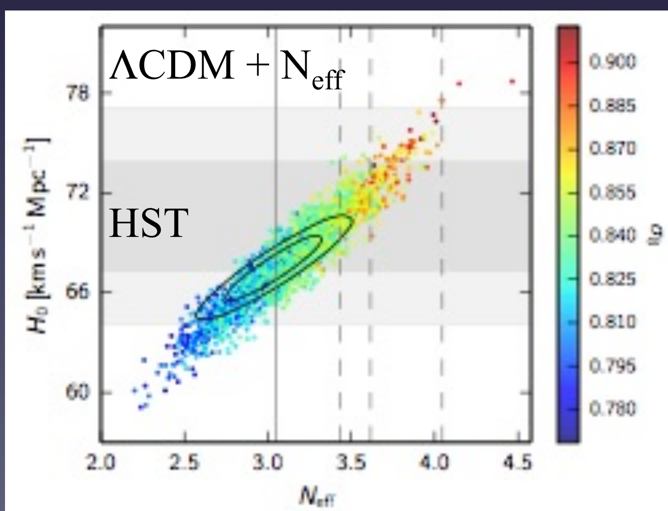

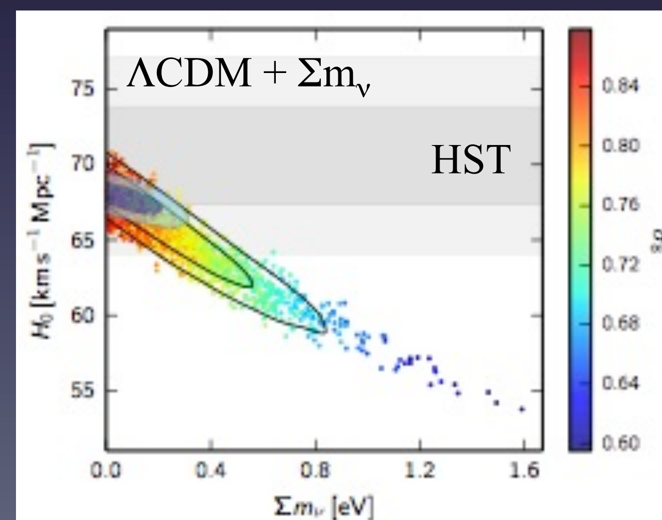

Planck 2015

Model extension: N_{eff}+$m^{eff}_{\nu, s}$

$\Lambda CDM + N_{eff} + m^{eff}_{\nu, s}$ $\quad (m^{eff}_{\nu, s} = m^{thermal}_{\nu, s} (T_{\nu,s}/T_{\nu})^3 = m^{thermal}_{\nu, s} (\Delta N_{eff})^{3/4})$

$N_{eff} < 3.7$ & $m^{eff}_{\nu, s} < 0.38$ eV (95% c.l.) (Planck + BAO)

The model extension does not represent an escape route!

- It does not alleviate the tension between Planck and low-z measurements
- eV sterile neutrinos are (still) too many and too massive for cosmology

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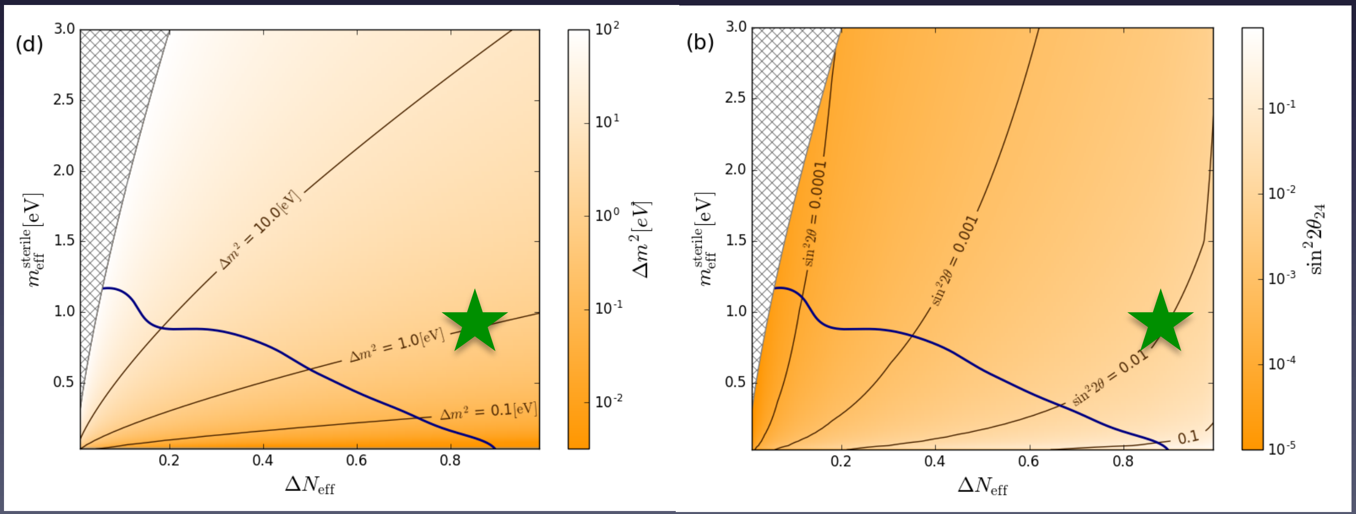
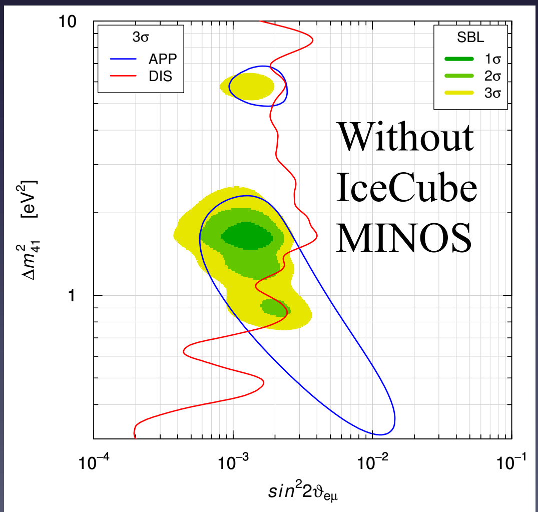


Bridle, Poole, Evans, Fernandez, Guzowski, Soldner-Rembold, PLB (2016)



MA, Gariazzo, Giunti, et al., JCAP (2016)

New Physics

Partial Thermalization

$$\Delta N_{eff} = \frac{\rho_{\nu,s}}{\rho_{\nu,m=0}^{thermal}}\left(\frac{P_{\nu,s}/\rho_{\nu,s}}{1/3}\right); \qquad \rho = \frac{g}{2\pi^2}\int dpEp^2 f(p)$$

Secret interactions

The sterile neutrino is coupled to a new light pseudoscalar ($m_\phi << 1$eV):

$$L_{int} \sim g_s \, \phi \, \nu^{-1}{}_s \, \gamma_5 \, \nu_s$$

No fifth force limit

SuperNova bounds derived from the energy loss argument:

$$\nu_e \, \nu_e \rightarrow \phi \, , \quad g_e < 4 \times 10^{-7}$$ Farzan, PRD (2003)

$$g_s < g_e / \sin^2\theta_s < 3 \times 10^{-5}$$ Model dependent

MeV vector boson, $L_{int} \sim g_s \, \nu^{-1}{}_s \, \gamma^\mu \, P_L \, \nu_s \, A_\mu$

Hannestad, Hansen, Tram, PRL(2013)

Dasgupta, Kopp, PRL (2013)

Saviano et al., PRD (2014)

Mirizzi et al., PRD (2014)

Chu, Dasgupta, Kopp, JCAP (2015)

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Saviano et al., PRD (2014)

Mirizzi et al., PRD (2014)

Chu, Dasgupta, Kopp, JCAP (2015)

Pseudoscalar thermal history

- T > TeV ϕ particles are thermally produced
- T ~ GeV ($g_s \sim 10^{-5}$) ν_s and ϕ in thermal equilibrium
- T > 200MeV the dark sector decouples
- T ~ 10MeV neutrino oscillations become important

➔ one single tightly-coupled fluid at low temperature

Secret interactions and BBN

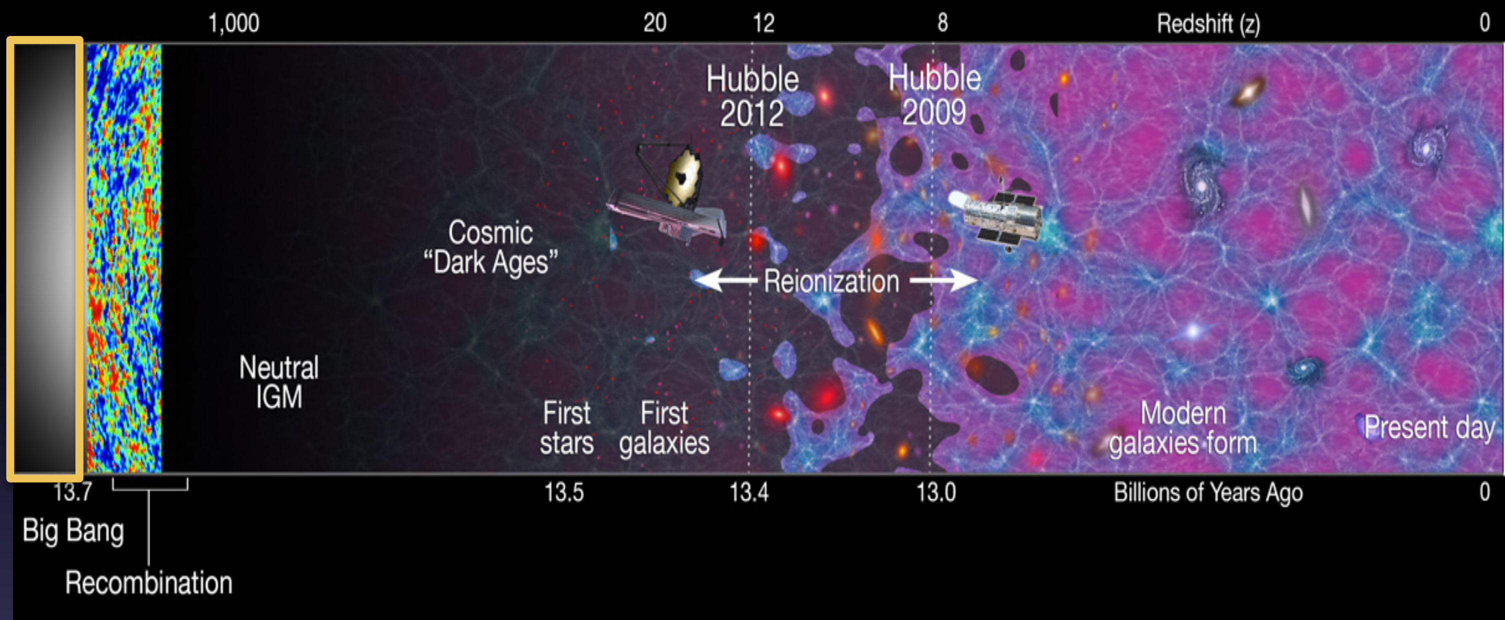
BBN T ~ 0.7 MeV

$N_{eff,BBN} = 3.28 \pm 0.28$ (BBN+CMB, 68% c.l.)

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

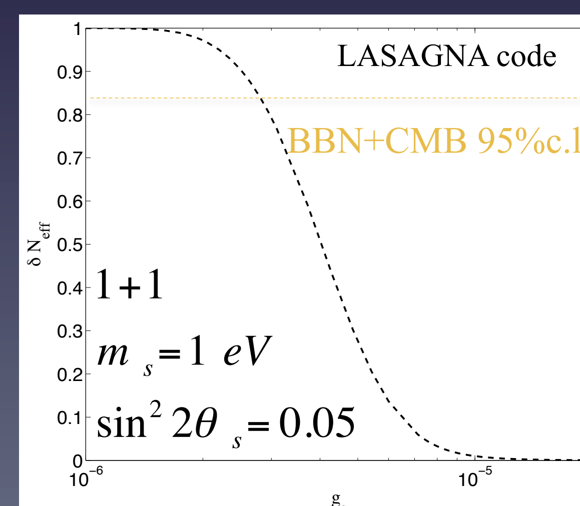
$$V_0(T) \sim \Delta m^2 / 2T$$

$$|V_s| > V_0 \Rightarrow g_s \geq 10^{-6}$$



The in medium mixing angle is suppressed and the sterile neutrino production is delayed, until after active neutrinos collisional decoupling. When sterile neutrinos are produced, the spectra turn out to be partially non-thermal.

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



Secret interactions and CMB

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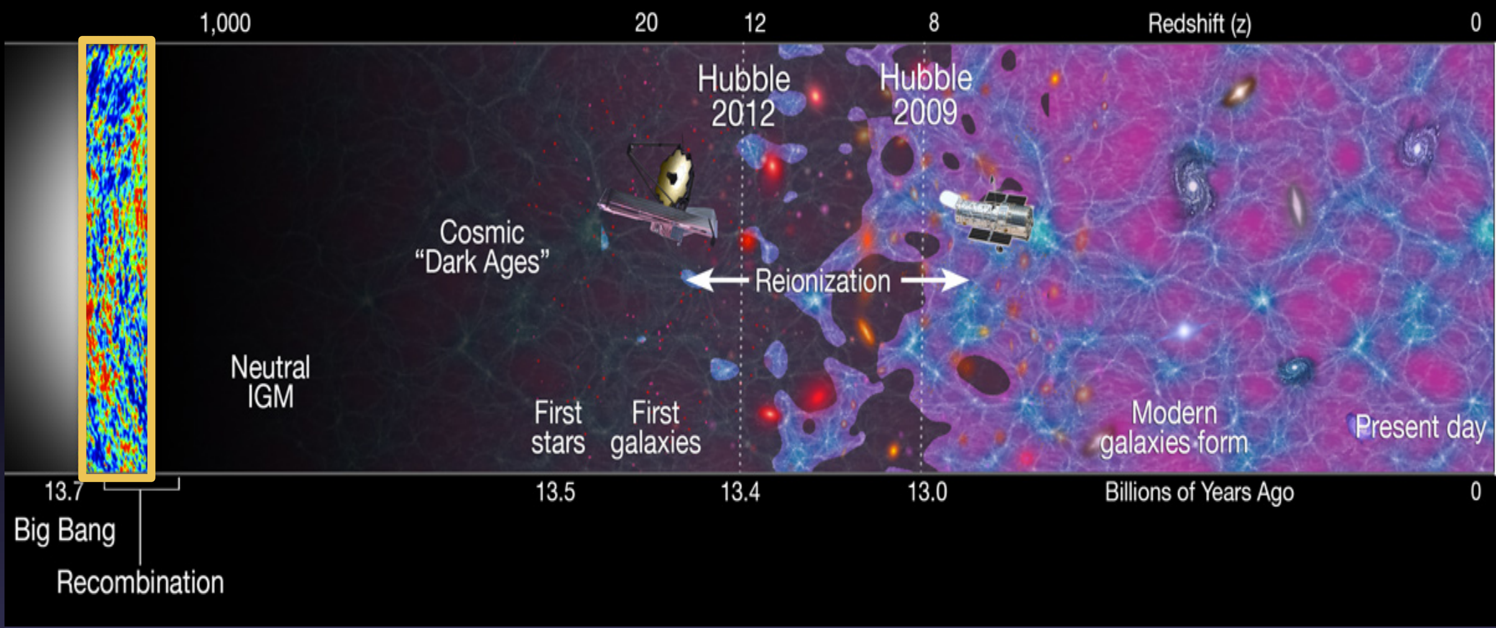
$$\Gamma_s = \frac{g_s^4}{4\pi T_s^2} n_s \propto T$$

$$H \propto T^2$$



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

Boltzman Hierarchy

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

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

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

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

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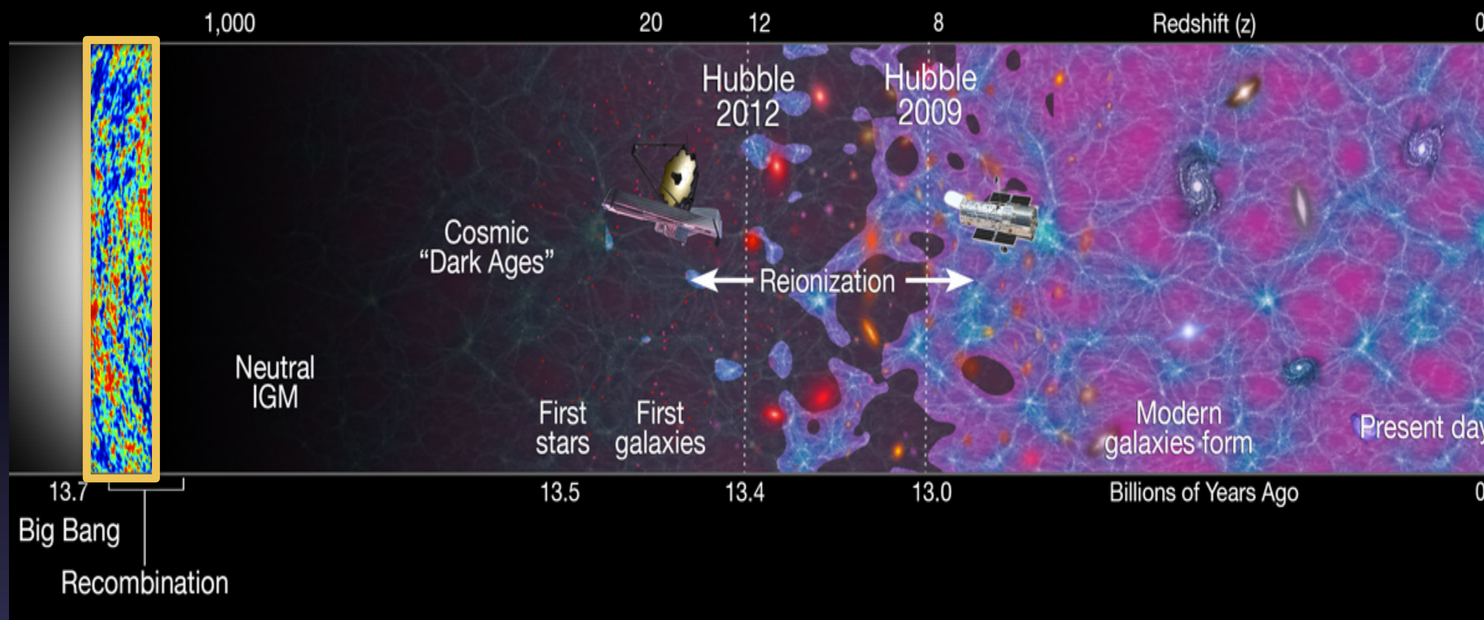
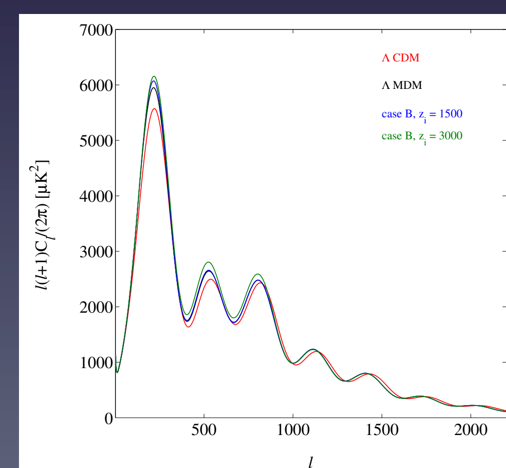


The $\nu_s - \phi$ fluid becomes strongly interacting before neutrinos go non-relativistic, around recombination.

If neutrinos are not free-streaming, then the photon monopole is enhanced. To be consistent with CMB, active neutrinos must be free-streaming at $z \sim 10^4$.
The interaction must be confined to the sterile sector.



MA, Hannestad, JCAP (2013)

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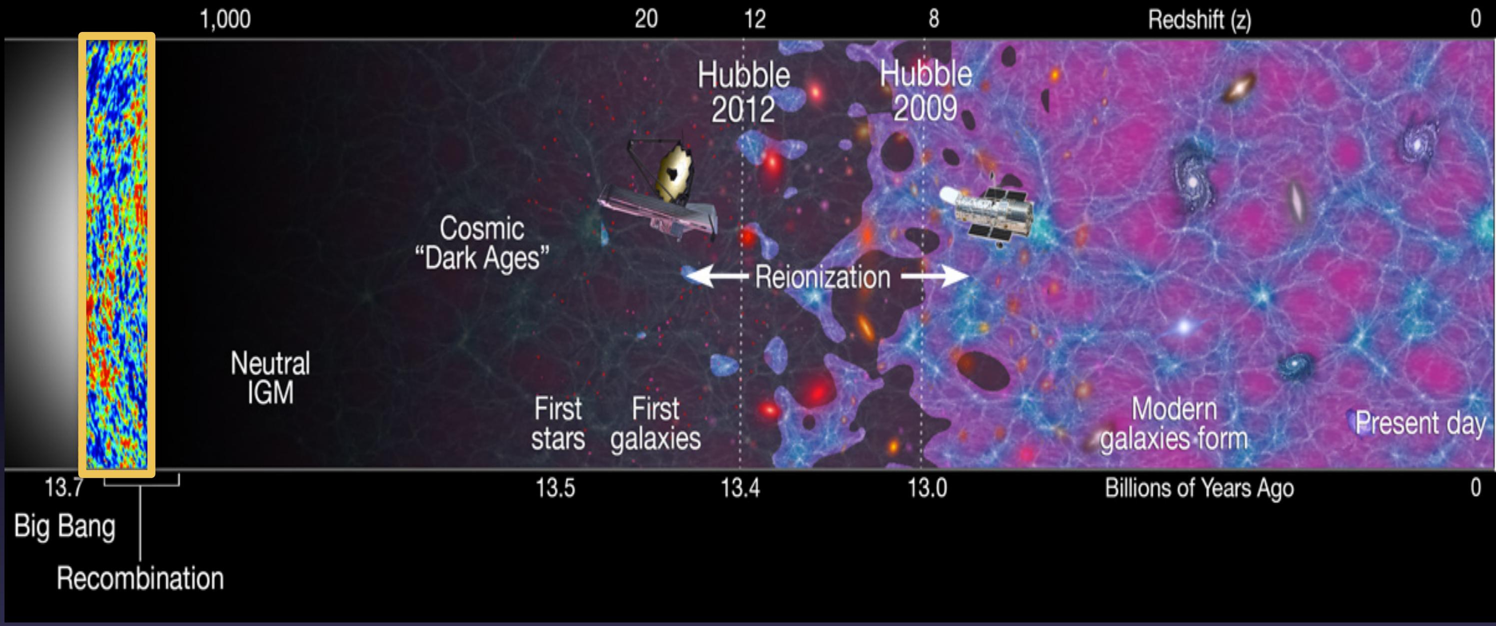

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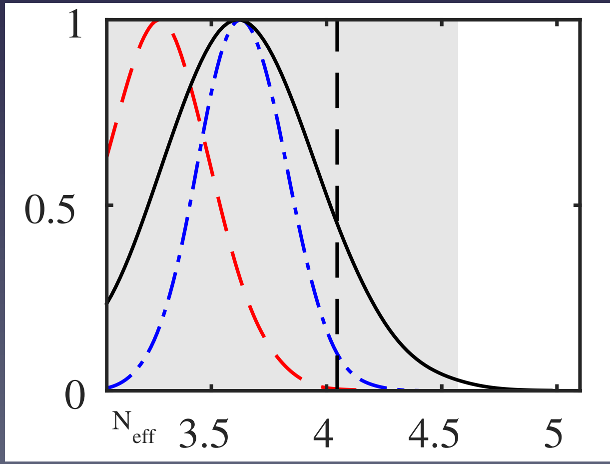
Correlation between values of N_{eff} and values of g_s



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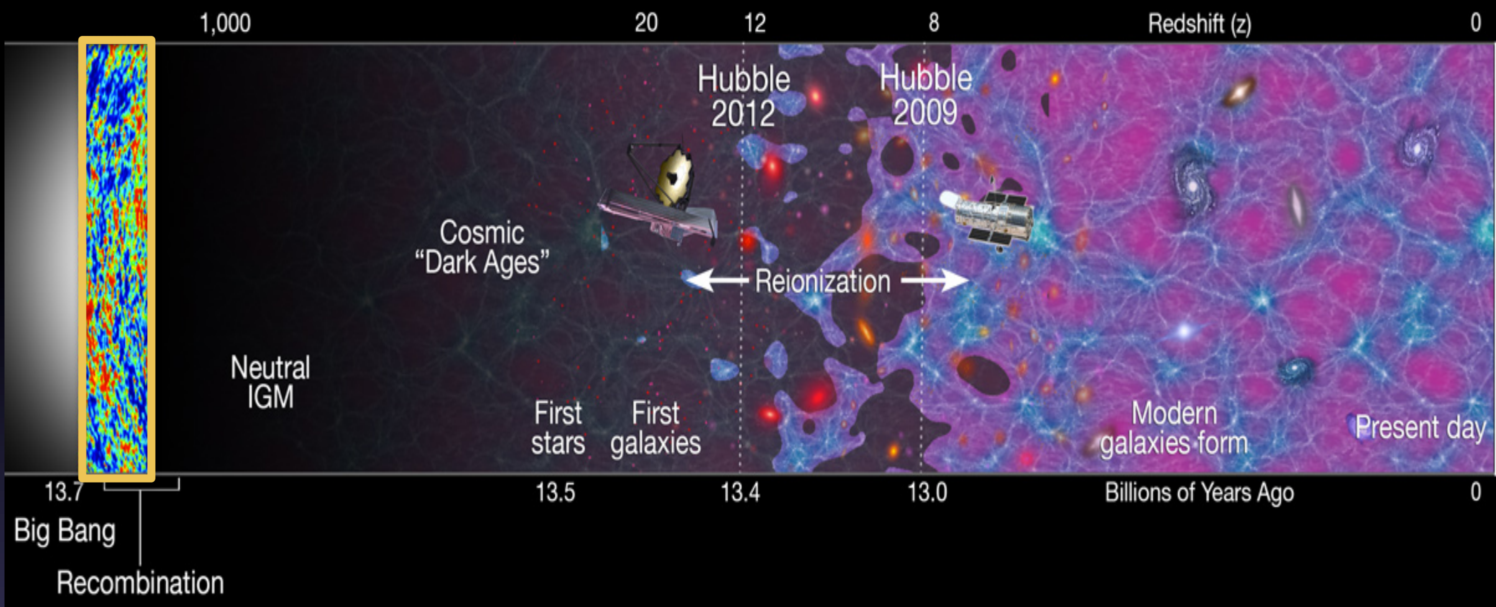
Secret interactions and CMB



CMB T ~ 1 eV

$N_{eff,CMB} = 3.13 \pm 0.32$
(68% c.l.)

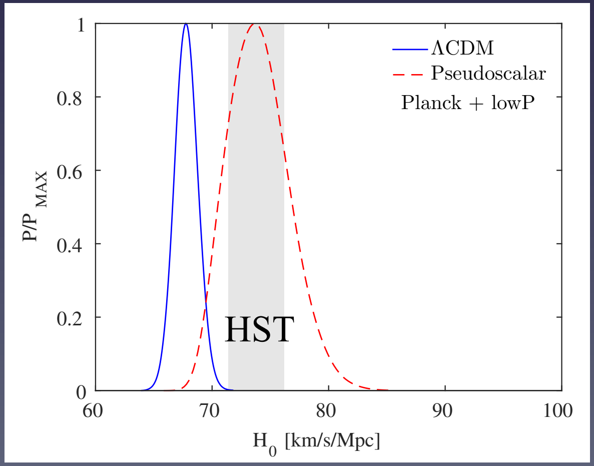
$$\Gamma_s = \frac{g_s^4}{4\pi T_s^2} n_s \propto T$$

$$H \propto T^2$$

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

If neutrinos are not free-streaming, then the photon monopole is enhanced. To be consistent with CMB, active neutrinos must be free-streaming at $z \sim 10^4$.
The interaction must be confined to the sterile sector.

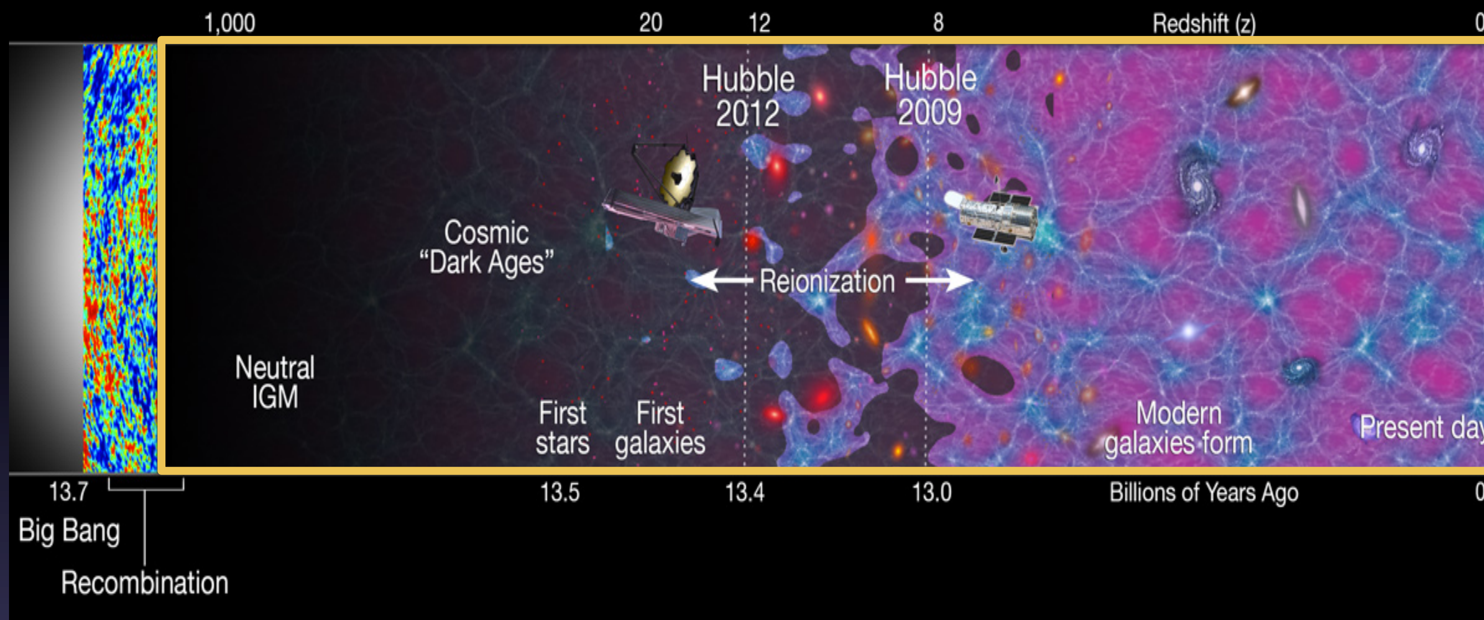
Consistency with HST



MA, Hannestad, Hansen, Tram, PRD (2015)

Secret interactions and LSS

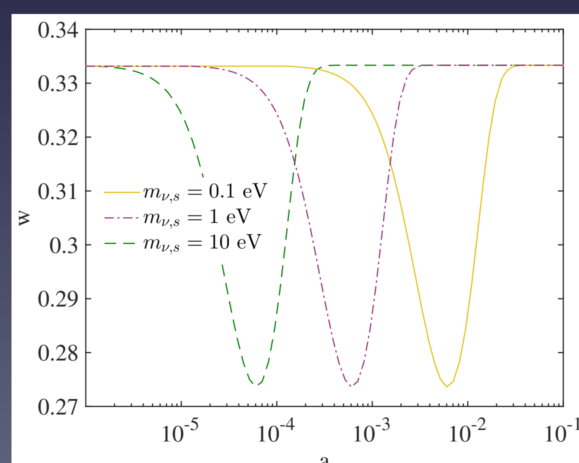
$\Sigma m_\nu < 0.13$ eV (CMB+LSS, 95% c.l.)

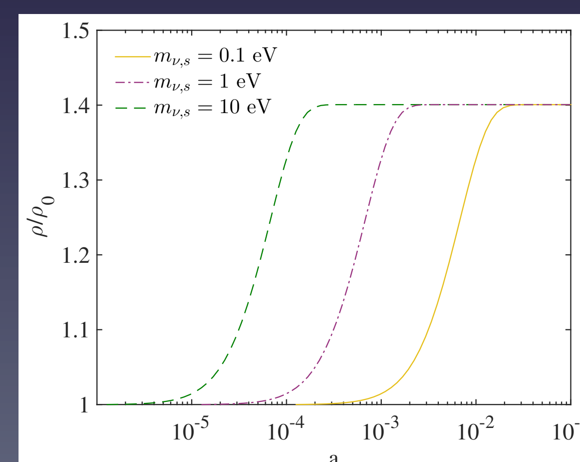


As soon as sterile neutrinos go non-relativistic, they start annihilating into pseudoscalars.

$\nu_s \nu_s \rightarrow \phi\, \phi$

The annihilations will heat up the fluid.





MA, Hannestad, Hansen, Tram, PRD (2015)

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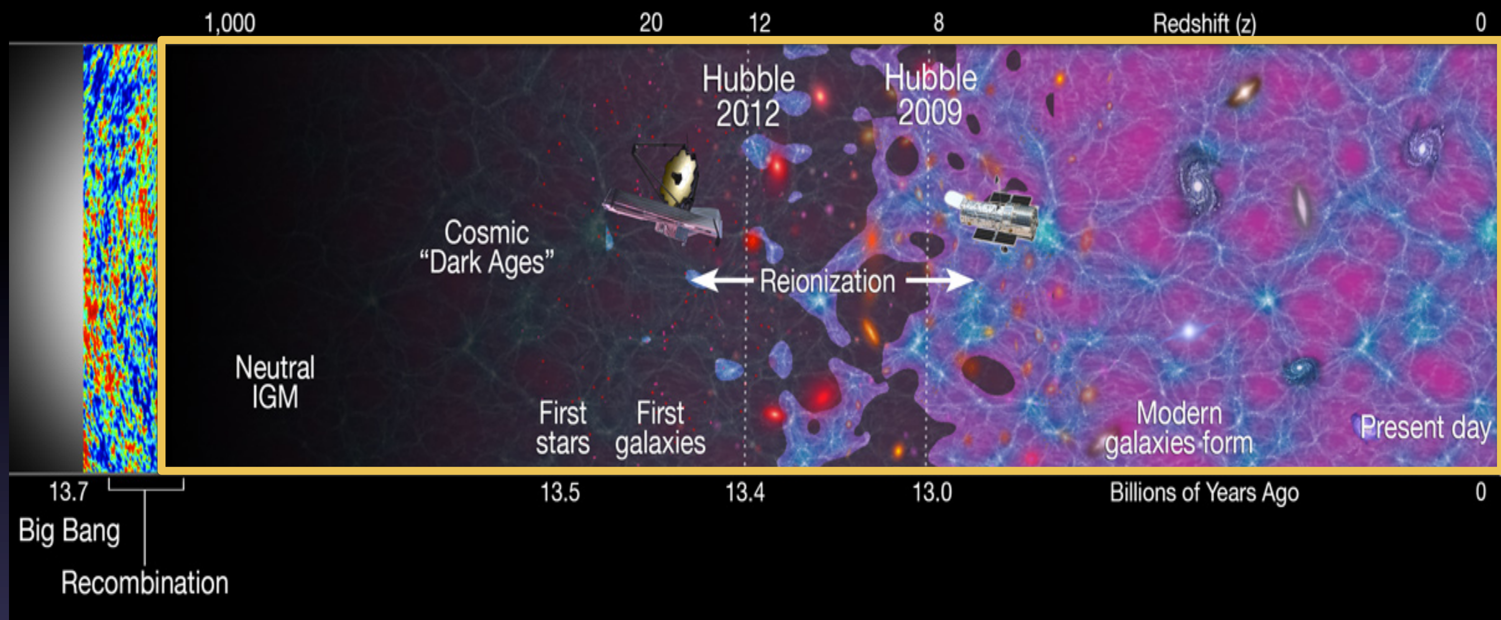

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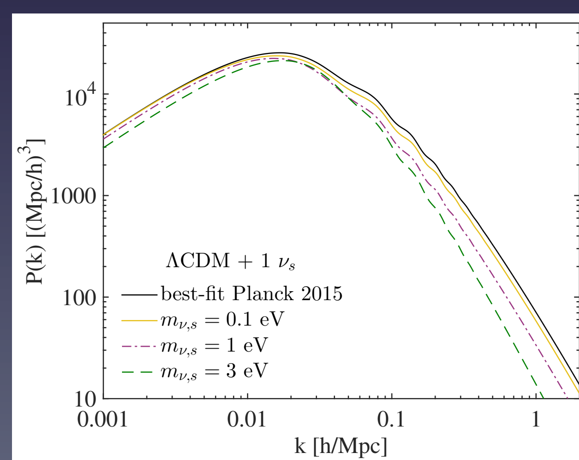
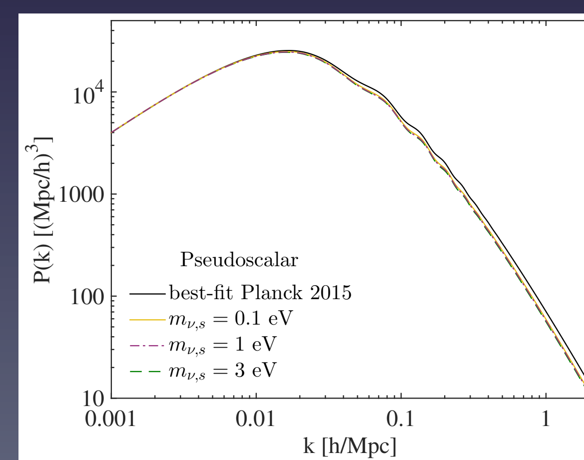




MA, Hannestad, Hansen, Tram, PRD (2015)

Conclusions

- Cosmology provides very tight constraints on neutrinos

  $N_{eff,CMB} = 3.13 \pm 0.32$ (CMB, 68% c.l.)

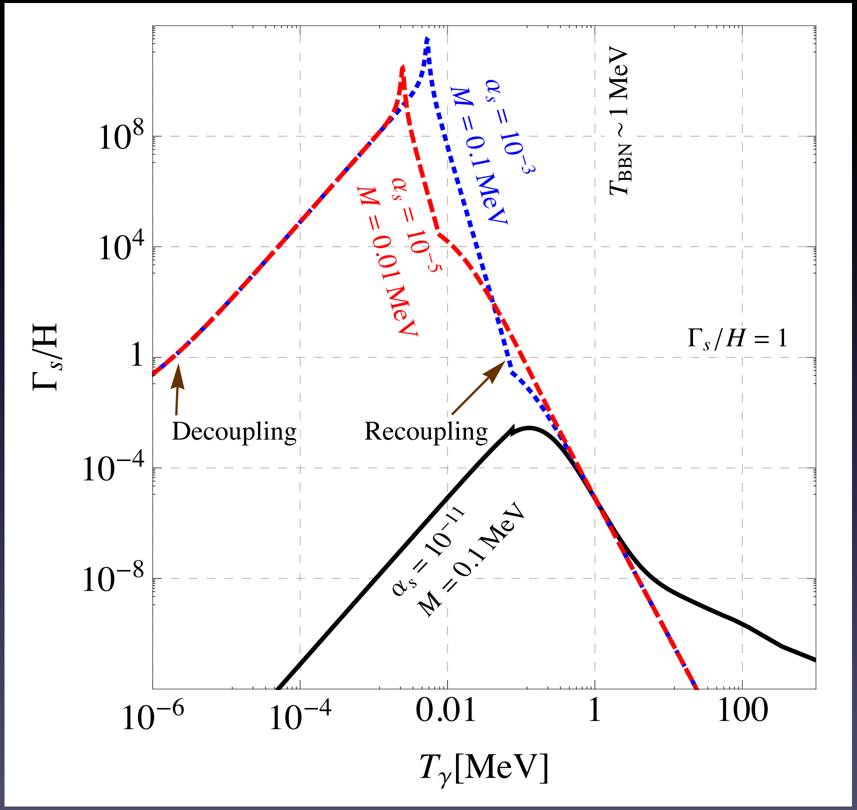
  $\Sigma m_\nu < 0.13$ (CMB+LSS, 95% c.l.)

- eV 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 by means of an early partial thermalization and a late annihilation.

Thank you for your attention

Backup

MeV vector boson



Chu, Dasgupta, Kopp, JCAP (2015)