Neutrinos and structure formation in the Universe

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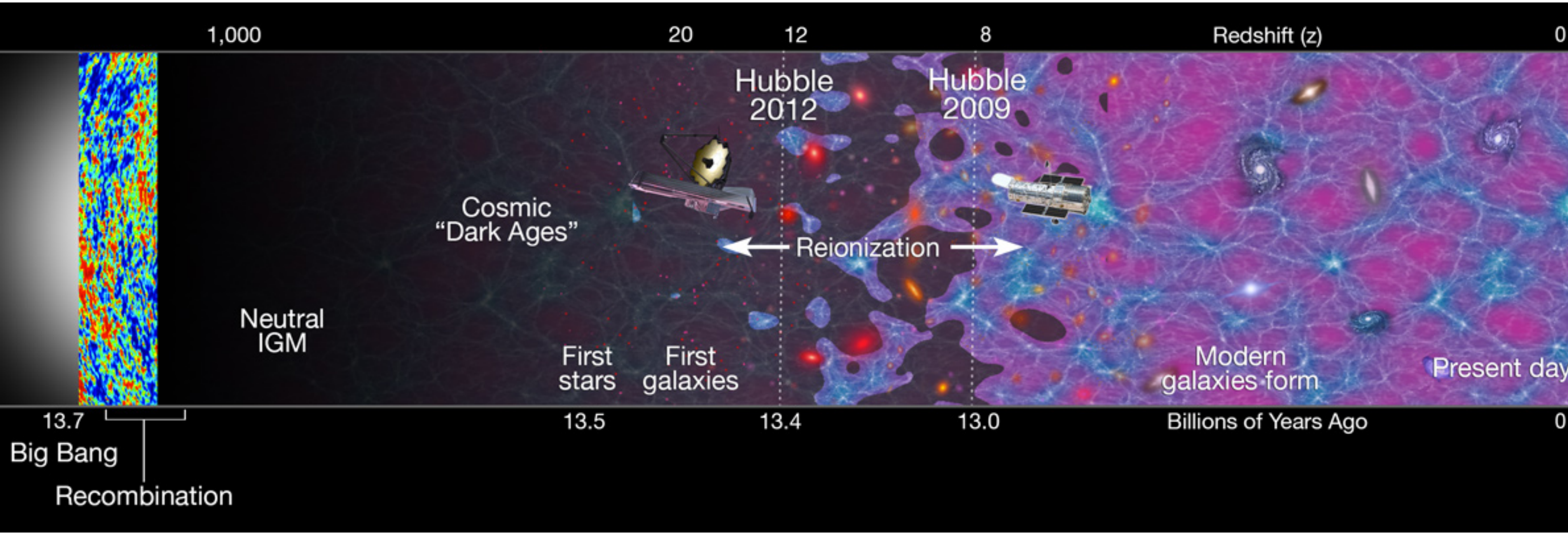
What cosmology can tell us about neutrinos

- Neutrino mass sum: more precise than β (KATRIN) and double β decay (GERDA), but more model dependent. Not sensitive to Dirac vs Majorana, mixing angles, phases …

- Hierarchy: not specifically sensitive to the hierarchy like NOνA, DUNE, PINGU, ORCA, Hyper-K, but the IH might be ruled out.

- Effective number of relativistic degrees of freedom, N_{eff}, (≈ Neutrino number)

Timeline



Temperature	Process	ν Constraints
$T_\gamma \sim 1$ MeV	ν decoupling	
$T_\gamma \sim 1$ MeV	BBN	Flavour, Number
$T_\gamma \sim 1$ eV	CMB	Number, (Mass)
$T_\nu \sim m_\nu / 3$	ν nr transition	
$T_\gamma \sim 0.2$ meV	Structure formation	Mass, (Number)

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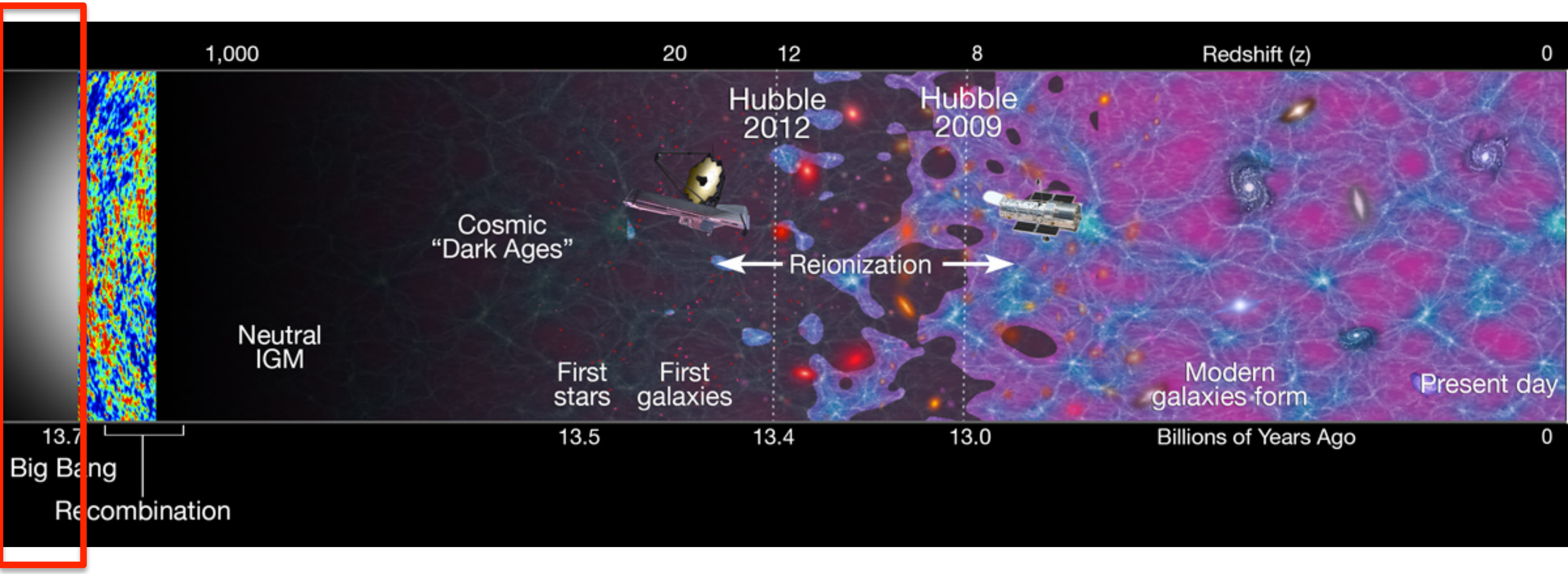

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Neutrino decoupling

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

$\Gamma \approx G_F^2\, T^5 < H$

$T_{dec} \approx 1$ MeV ➔ HDM

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

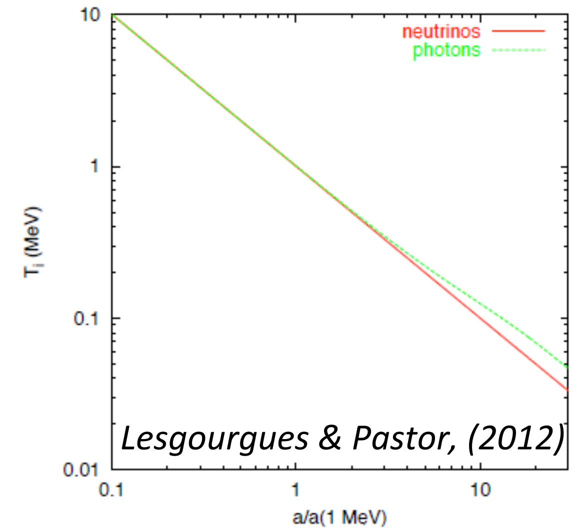
$T_\nu / T_\gamma = (4/11)^{1/3}$

$T_\nu \approx 1/a$

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

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

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

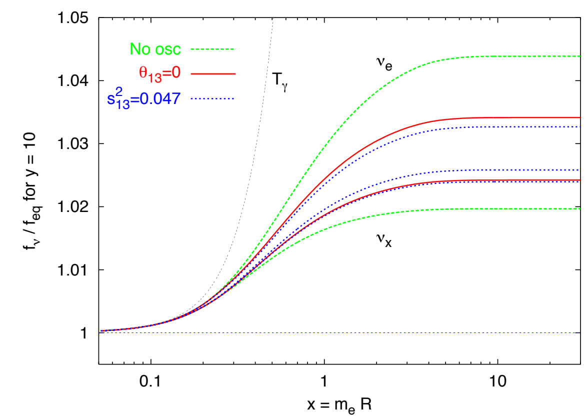


Lesgourgues & Pastor, (2012)

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

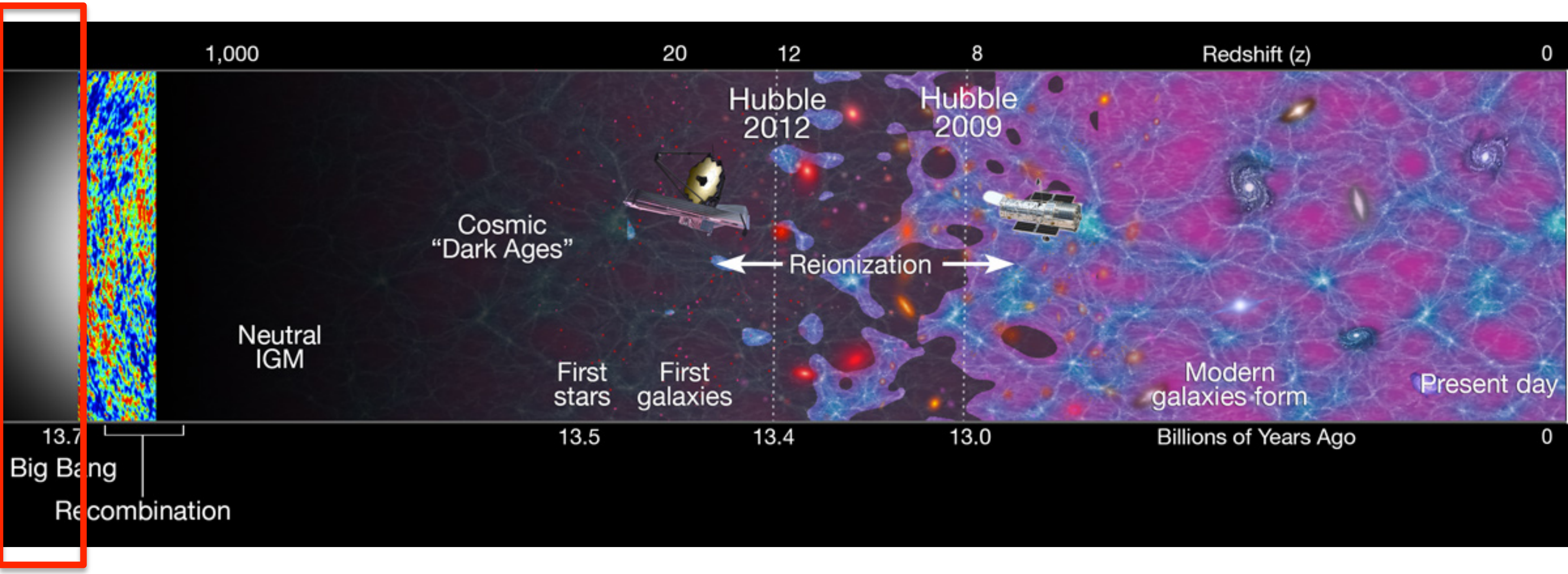
N_{eff} Effective number of relativistic
degrees of freedom

- Other relativistic relics can contribute to N_{eff}
- This equation holds after decoupling and as long as all neutrinos are relativistic
- $N_{eff,dec} = 3.046$



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

Timeline



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N_{eff} & BBN

Shortly after neutrino decoupling the weak interactions that kept neutrons and protons in statistical equilibrium freeze out.

$$H = \Gamma\big|_{T=T_{freeze}} \qquad T_{freeze} \approx 0.6 g_*^{1/6}\ MeV$$

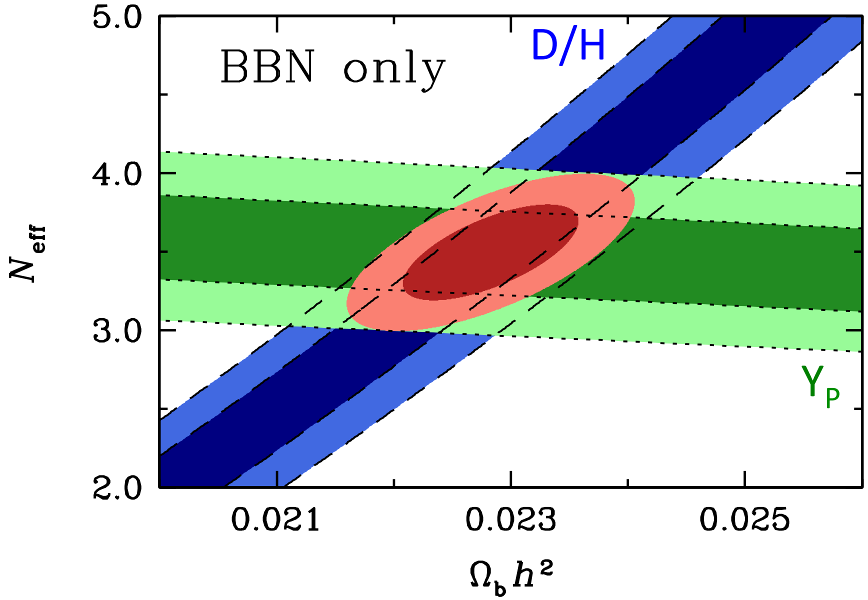
$$\left.\frac{n_n}{n_p}\right|_{T=T_{freeze}} \approx \exp\left(-\frac{(m_n - m_p)}{T_{freeze}}\right) \approx \frac{1}{6}$$

$$Y_P \approx \left.\frac{2n_n/n_p}{1+n_n/n_p}\right|_{T\approx 0.2\,MeV} \propto f(g_*, \Omega_b h^2)$$

$$g_* \rightarrow g_* + \frac{7}{4}\Delta N_{eff}$$

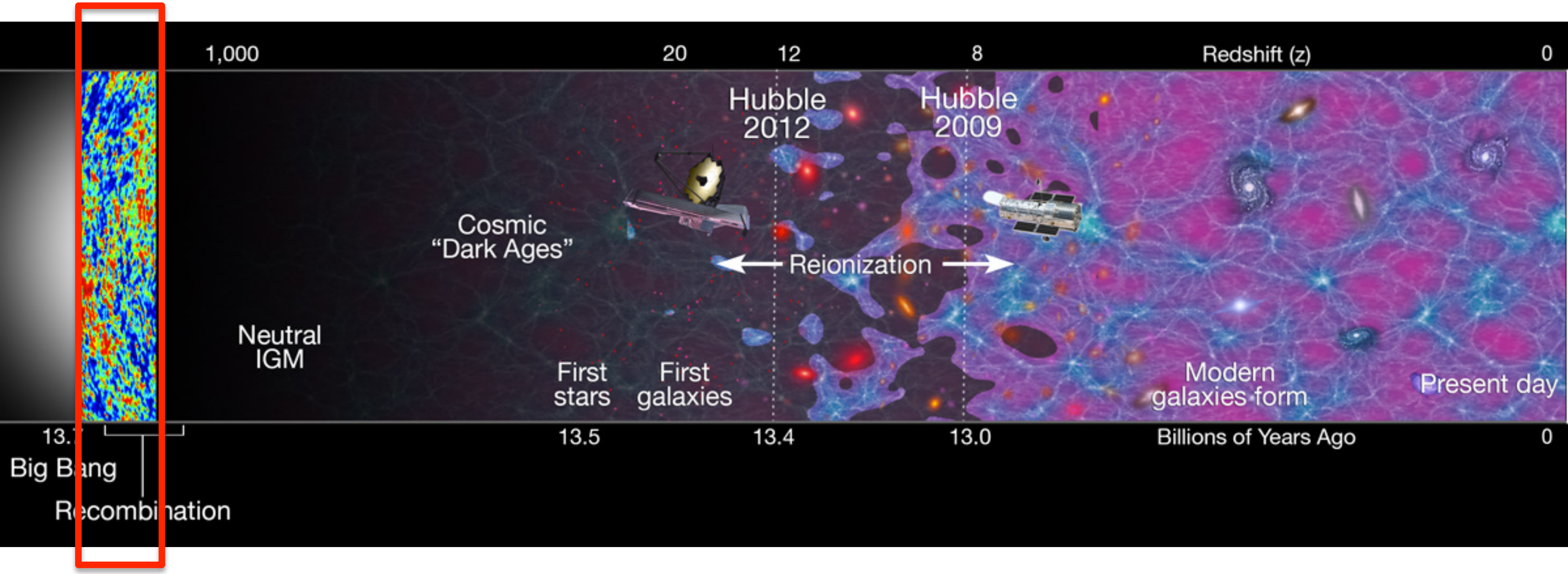
$$\left|Y_P^{theo} - Y_P^{obs}\right|_{\Omega_b} \rightarrow \Delta N_{eff}\big|_{\Omega_b}$$

Cooke et al., MNRAS (2013)



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

Timeline



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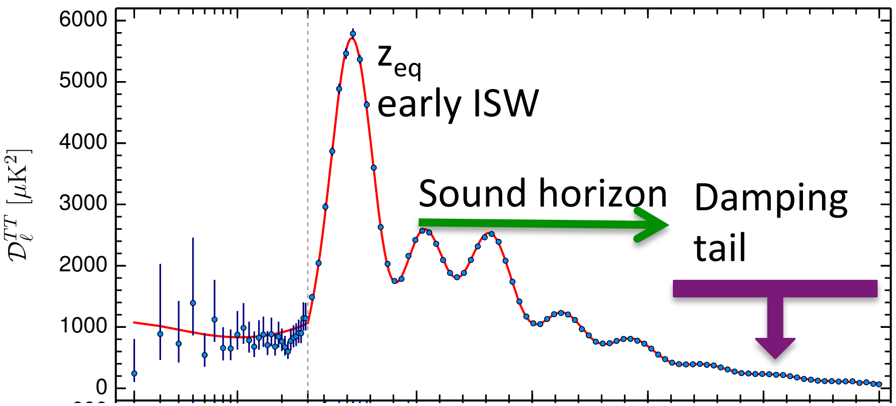
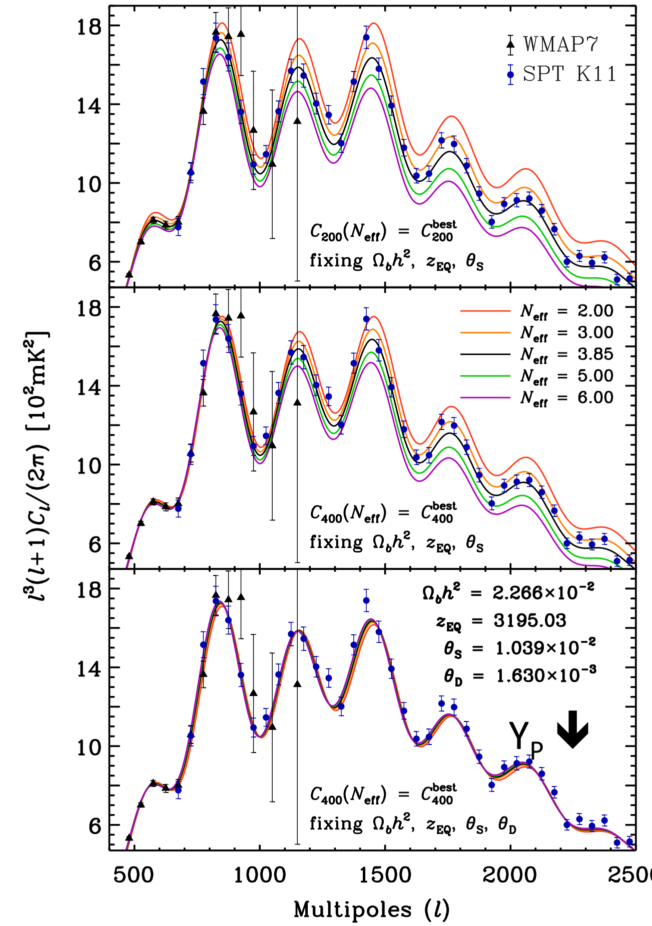
N_{eff} & CMB(TT)



$$r_s = \int_0^{a_*} \frac{c_s}{a^2}\frac{da}{H}$$

$$\theta_d = \frac{r_d}{D_A} \propto \frac{H^{-0.5}}{H^{-1}}$$

Hou et al., PRD (2013)



Background effects:

- expansion rate

Perturbation effects (free-streaming):

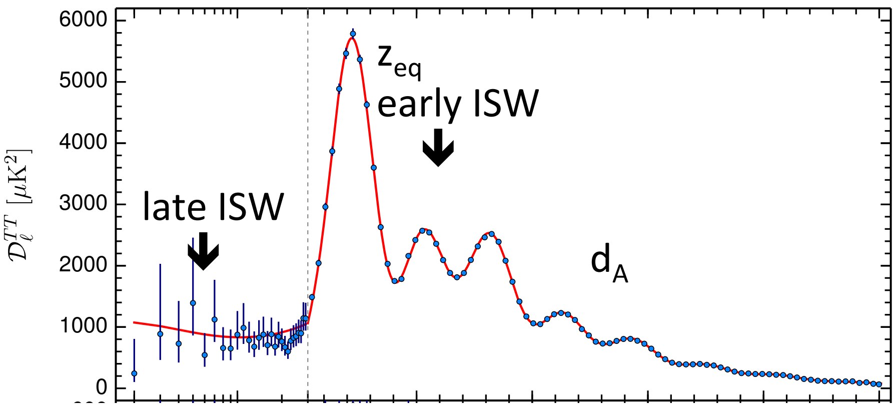
- phase shift in δ_γ
- overall amplitude suppression (anisotropic stress)

$$N_{eff}(CMB) = 2.99 \pm 0.20 \ \ (68\% cl)$$

No room for (thermalized) eV sterile neutrinos, unless new physics

Archidiacono et al., PRD (2015) & (2016)

Σm_ν & CMB(TT)



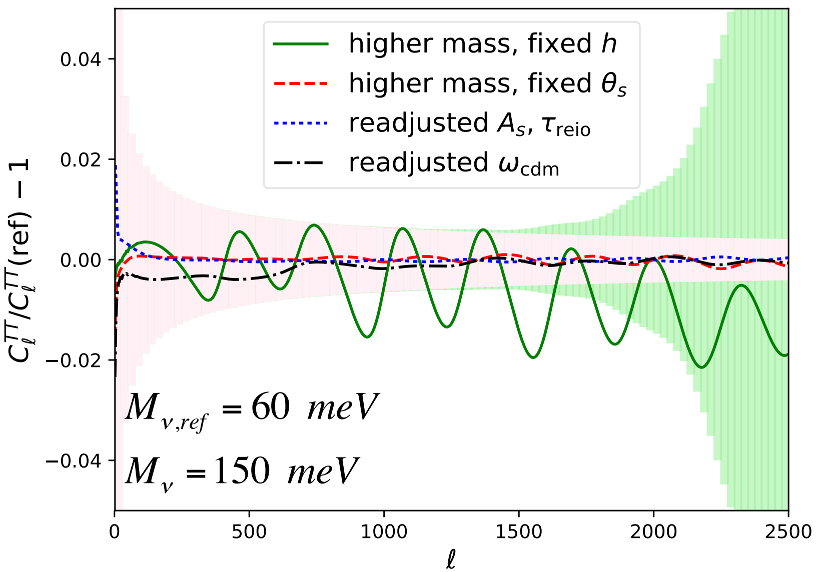
- Bakground effects (z_{eq}, d_A, lateISW)
- Perturbation effects (earlyISW)

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

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

$$\sum m_\nu < 0.59 \ \ eV \ (95\% c.l.)$$

Archidiacono, et al., JCAP (2017)



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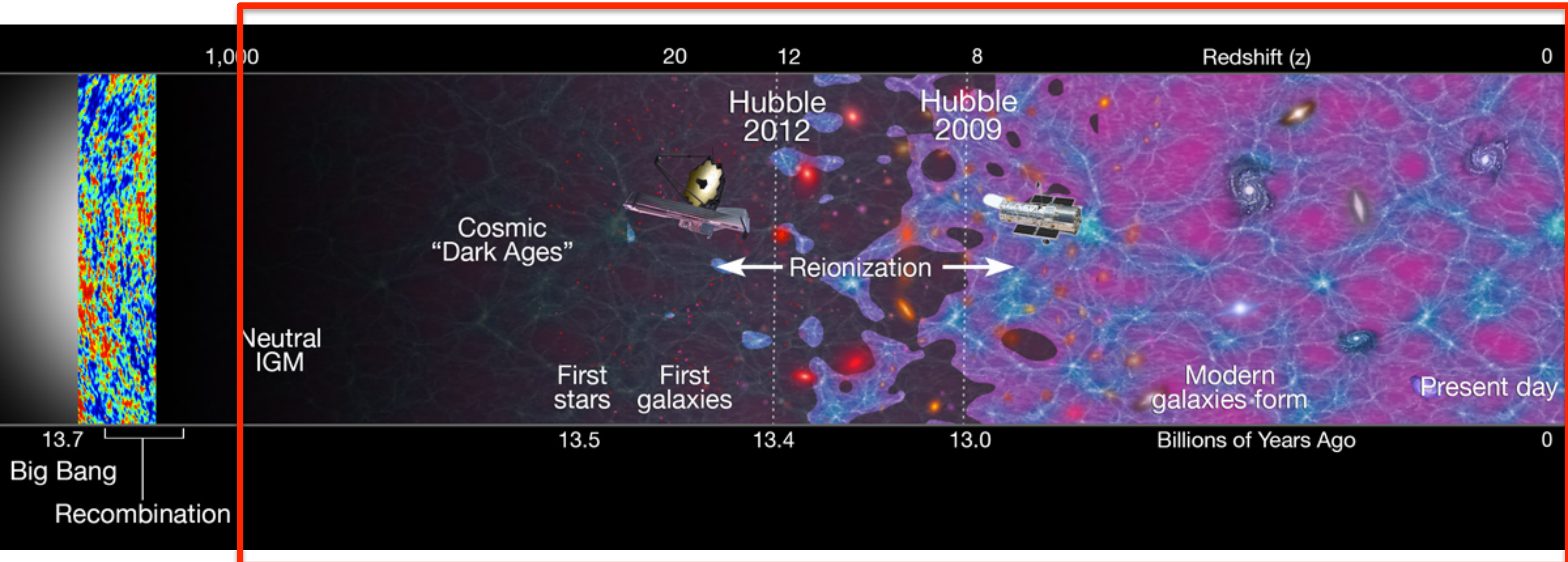

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Neutrino non-relativistic transition

As long as neutrinos are relativistic they travel at the speed of light.
When neutrinos become non-relativistic

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

they travel through the Universe with a thermal velocity

$$v_{th,i} = \langle p \rangle / m_{\nu,i} \approx 3T_{\nu,i}/m_{\nu,i} \approx 150\ (1+z)\ (1\text{eV}/m_{\nu,i})\ \text{km/s}$$

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

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

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

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HDM (eV ν)

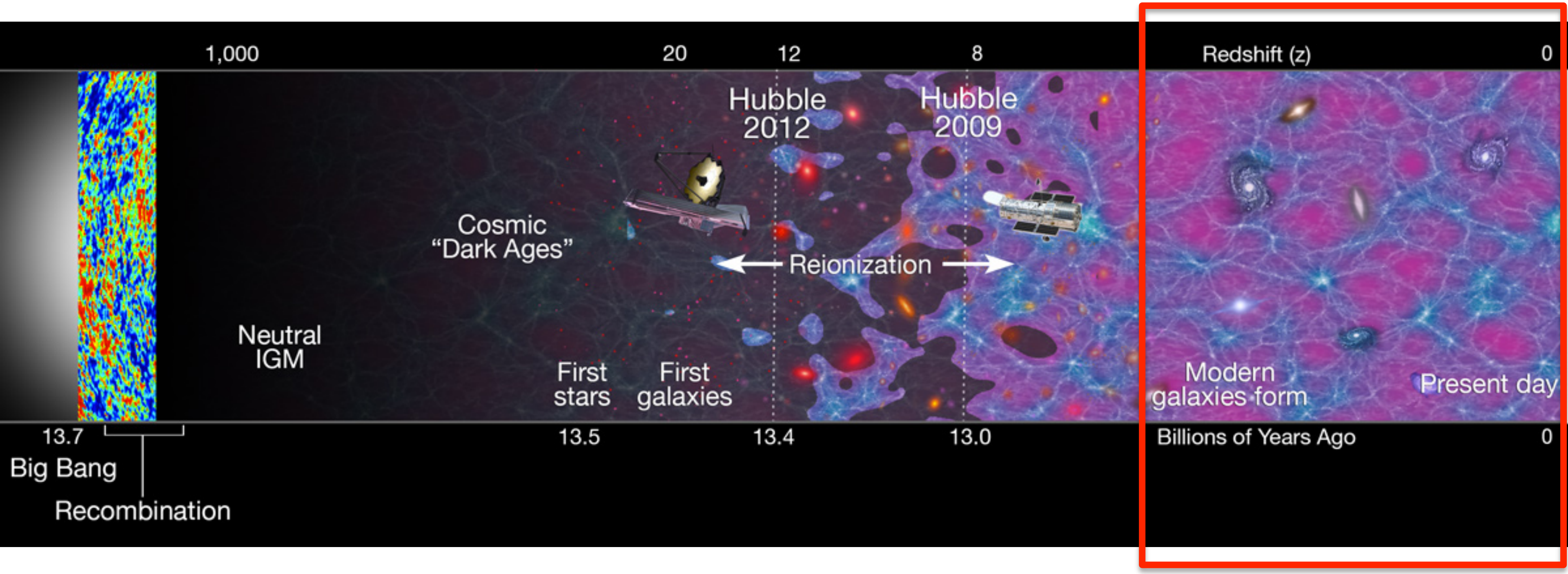
El Gordo Galaxy cluster

WDM (keV ν)

Fornax dSph

CDM

Timeline



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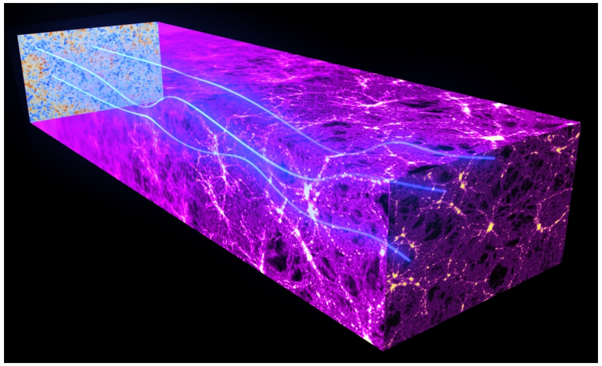
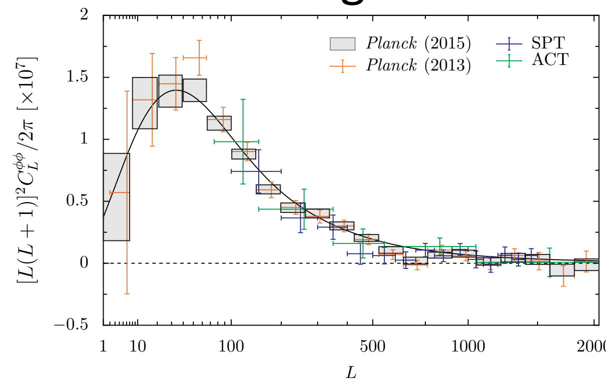
Large scale structure

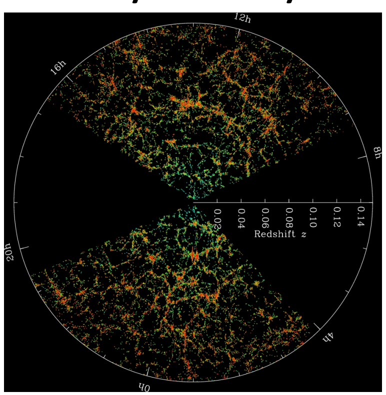
CMB



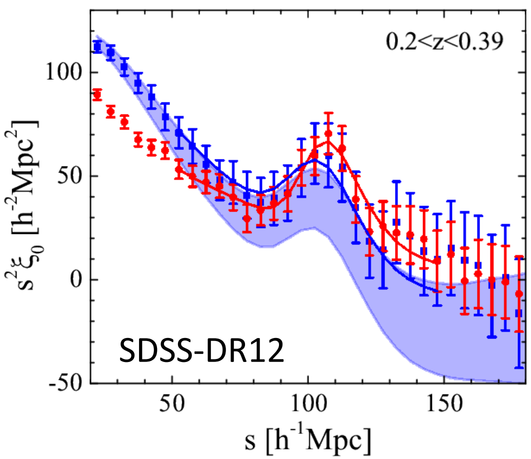
CMB lensing



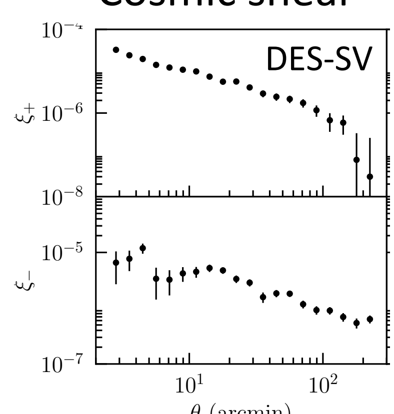
Galaxy surveys



BAO

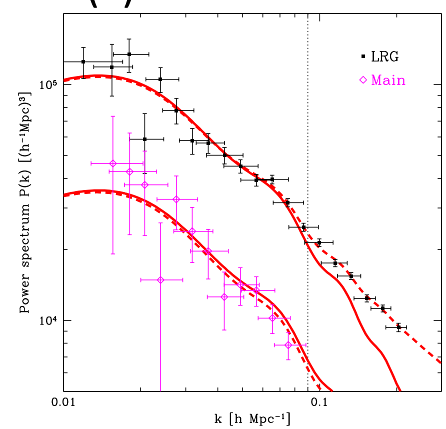


Cosmic shear



Troxel et al. (2017)

P(k)



Tegmark et al. PRD (2006)

Large scale structure

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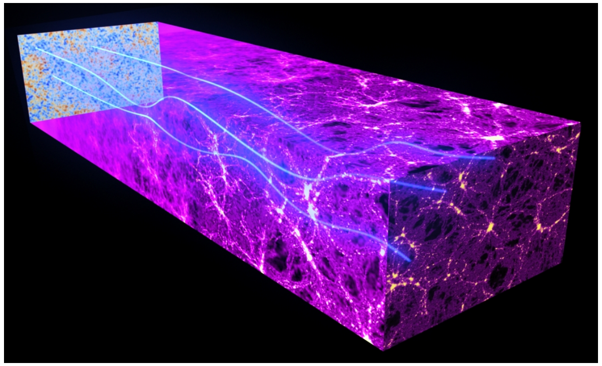

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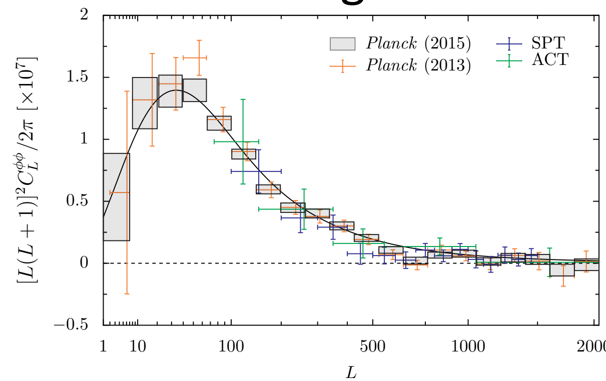

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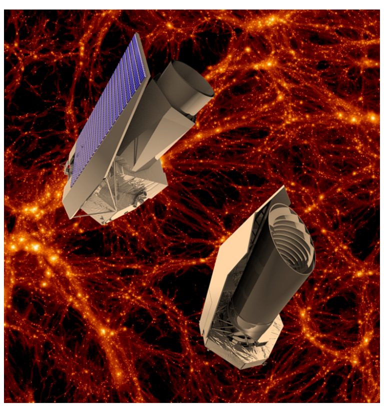
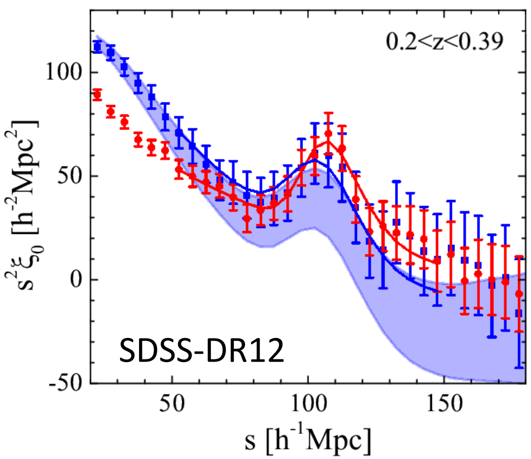


Euclid (2021)

1% accuracy

BAO



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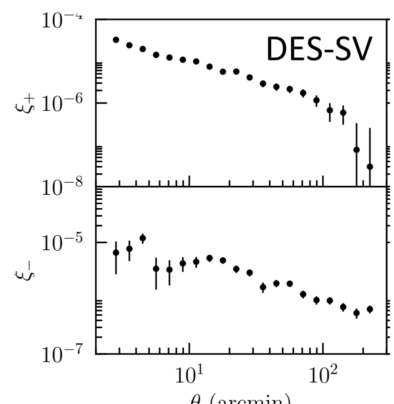
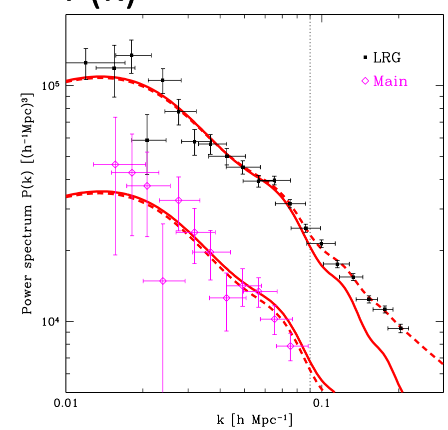


Troxel et al. (2017)

P(k)



Tegmark et al. PRD (2006)

Neutrinos & structure formation

See Talk of Professor Jochum

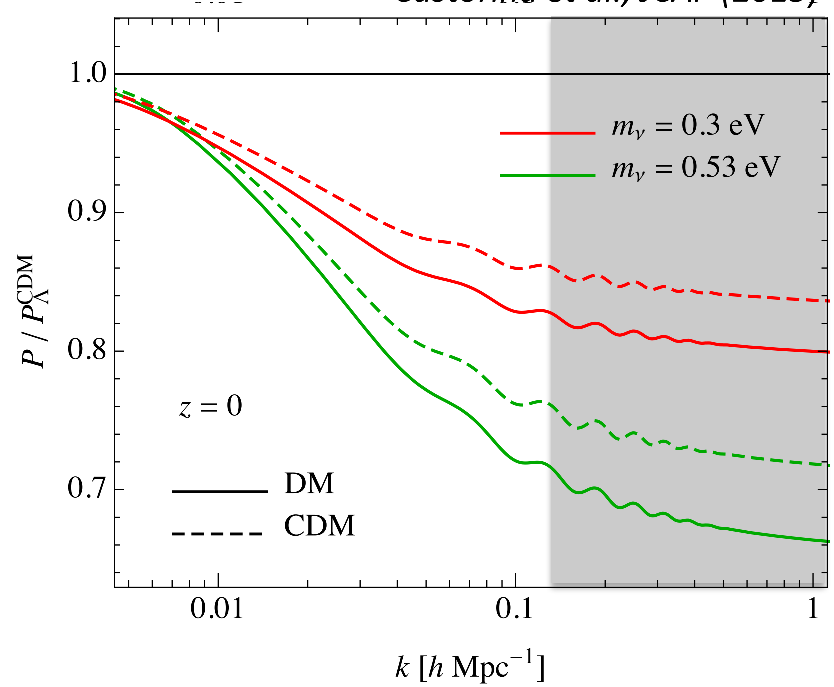
Castorina et al., JCAP (2015)

$$P(k,z) = \left\langle \left|\delta_m(k,z)\right|^2 \right\rangle$$

$$\delta_m = \frac{\delta\rho_m}{\bar{\rho}_m}$$

$$\frac{k^2}{a^2}\phi = -4\pi G(\delta\rho_m) \qquad \left(\delta\rho_\nu << \delta\rho_{cdm}\right)$$

$$H^2 = \frac{8\pi G}{3}\left(\rho_\gamma + \rho_b + \rho_{cdm} + \rho_\nu + \rho_\Lambda\right)$$



$\delta_{cdm} \propto a$ only cold dark matter

$\delta_{cdm} \propto a^{1-3/5 f_\nu}$ in the presence of ν
cdm+hdm=mdm

$$\frac{P(k)^{\Lambda MDM}}{P(k)^{\Lambda CDM}} \approx 1 - 8 f_\nu$$

Neutrino mass

- Current bounds

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)

- Future constraints

CMB+Euclid

$$M_{\nu,fid} = 60\ meV \quad \sigma(M_\nu) = 15\ meV$$

Archidiacono, Brinckmann, Lesgourgues, Poulin, JCAP (2017)
Archidiacono, Brinckmann, Clesse, Lesgourgues, Sprenger, in preparation

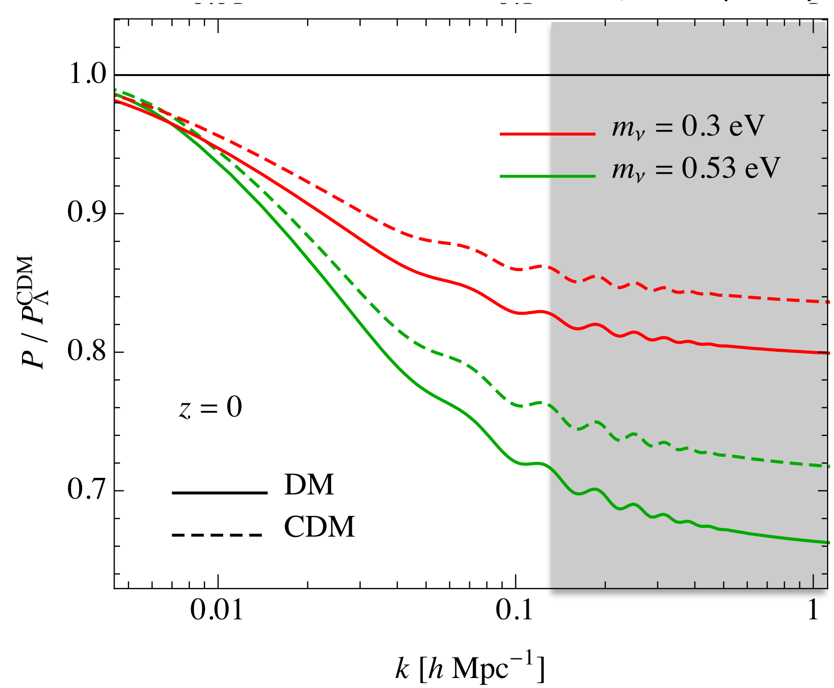
Caveat

Non-linearities	Bias	Degeneracies
Bird et al., MNRAS (2012)	*Castorina et al., JCAP (2014)*	*Archidiacono et al., JCAP (2017)*
Brandbyge et al., JCAP (2010)	*LoVerde, PRD (2014)*	
	Raccanelli et al., (2017)	

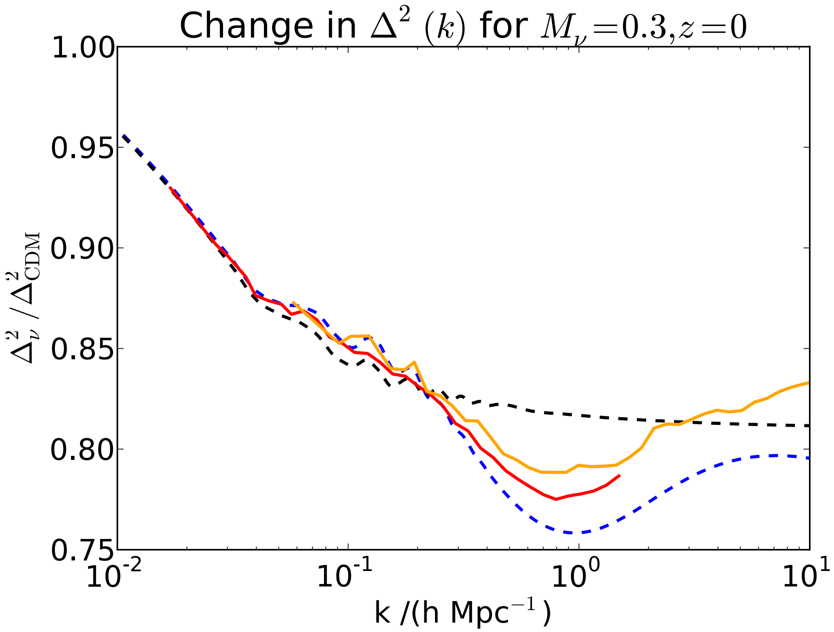
Non-linearities

How neutrinos should be implemented in cosmological simulations?

Castorina et al., JCAP (2015)



Bird et al., MNRAS (2012)

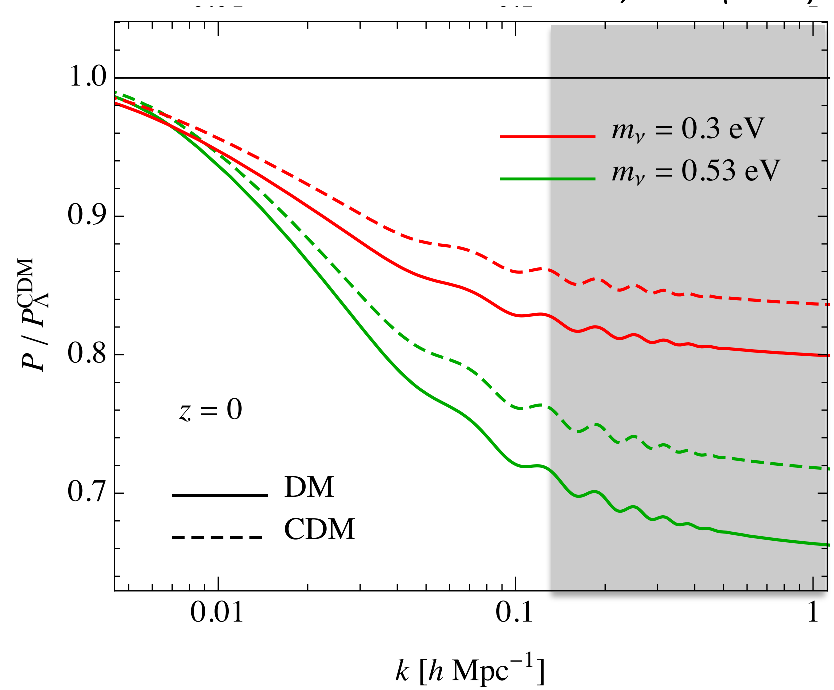


- Beyond linear order perturbation theory
  Fuhrer & Wong, JCAP (2015)
  Blas, et. al., JCAP (2014)
  Dupuy & Bernardeau, JCAP (2015)

- N-body simulations
  Hybrid methods: Brandbyge & Hannestad(2009/10)
  Semi-linear methods: Ali-Haimoud & Bird,(2012)

Non-linearities

Castorina et al., JCAP (2015)



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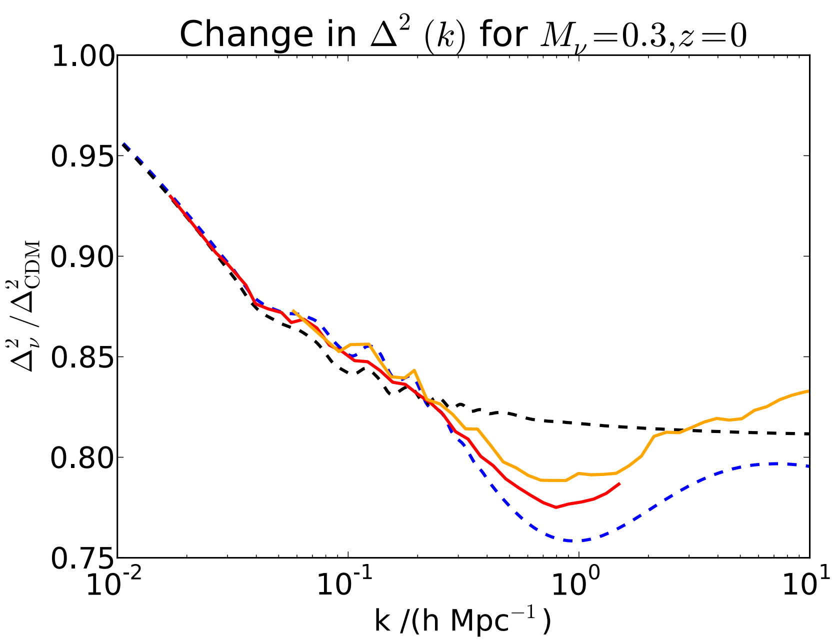

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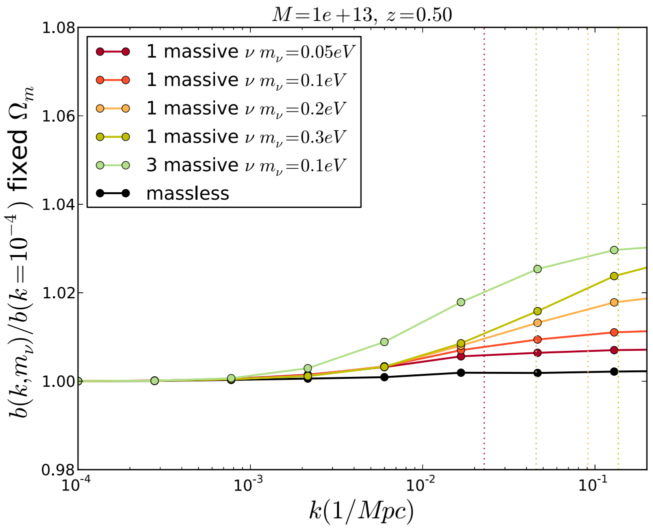
Baryonic feedback?

Bias & HMF

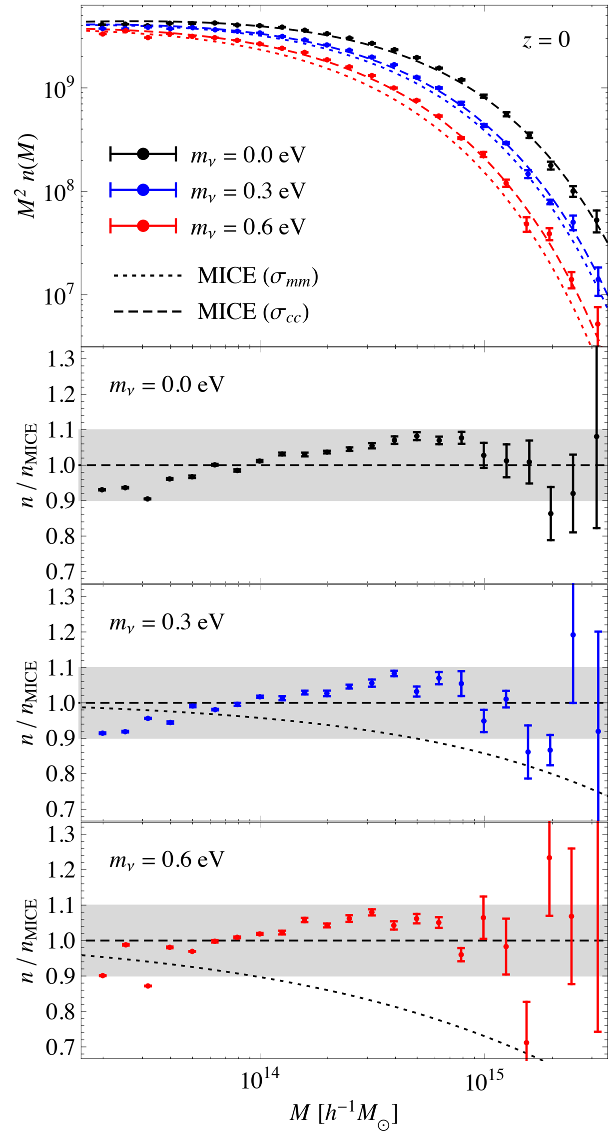
LoVerde, PRD (2014)



$$\delta_g \approx b\delta_m$$

$$\delta_m = \frac{\delta\rho_c + \delta\rho_\nu}{\rho_c + \rho_\nu} = f_c\delta_c + f_\nu\delta_\nu$$

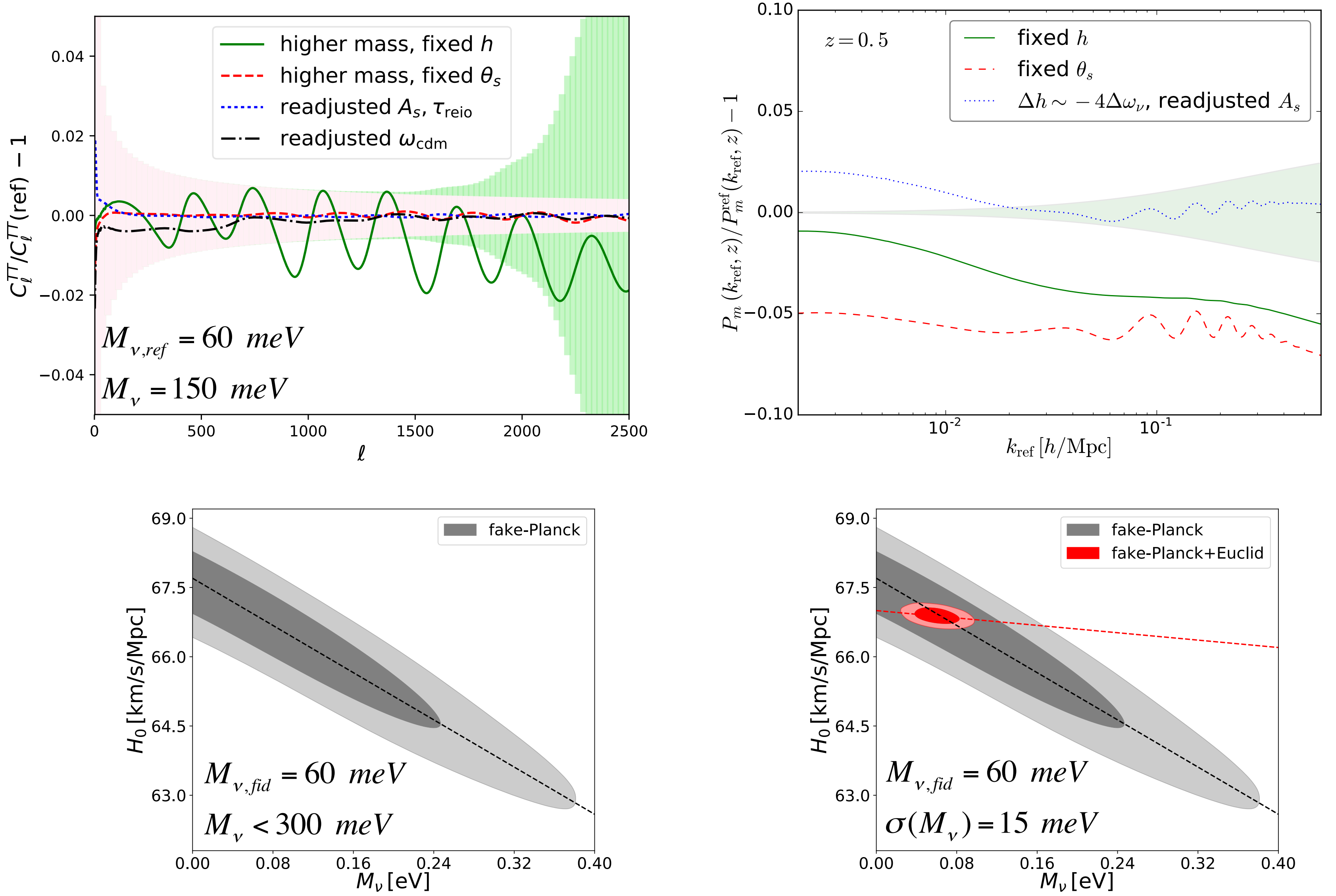
Castorina et al., JCAP (2015)



The variance of cdm-only yelds more universal results than the variance of the total matter.

Degeneracies & Model dependence

Archidiacono, et al., JCAP (2017)



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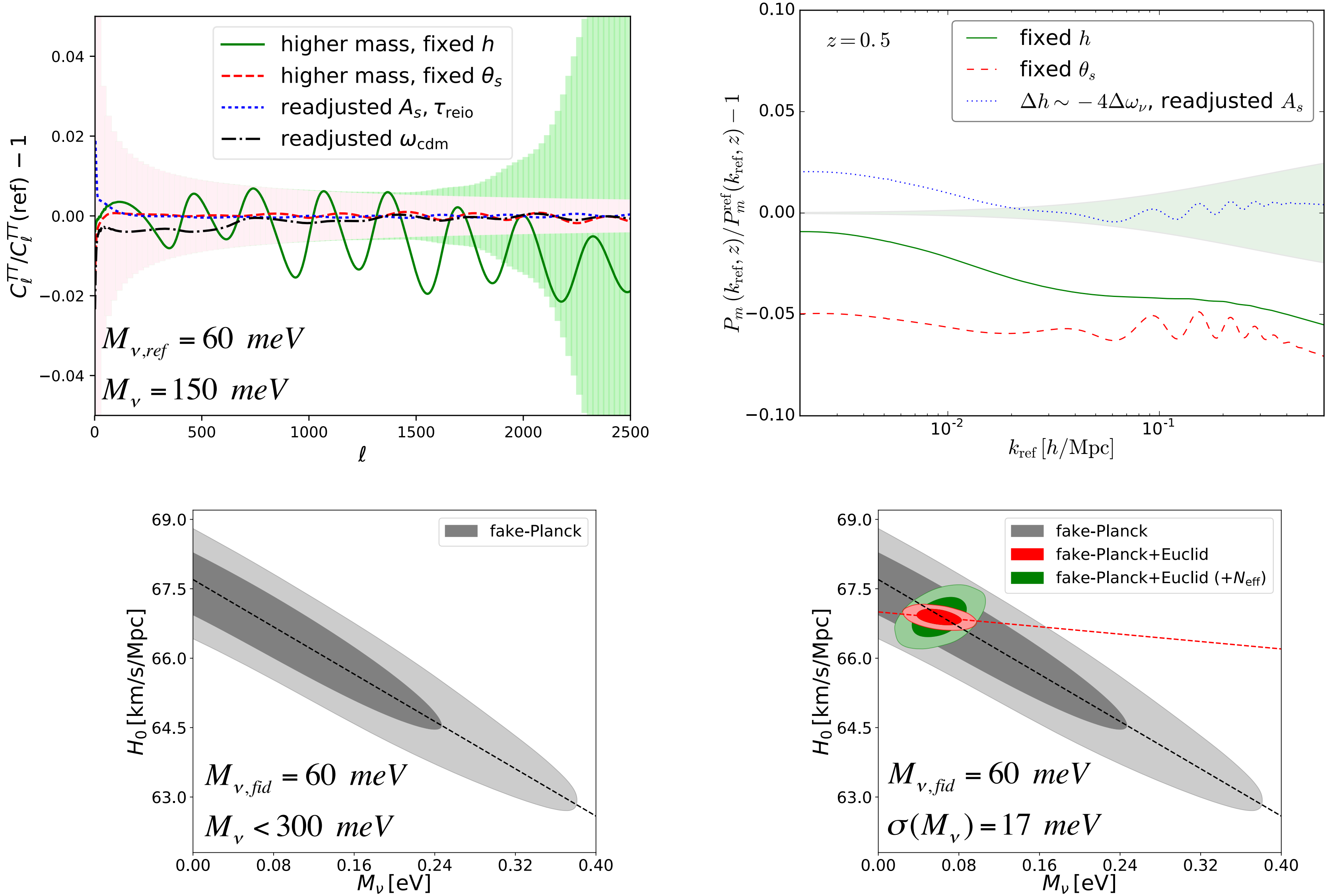

Conclusions

- Cosmology is a powerful tool to constrain neutrino physics, but the results have to be taken with a grain of salt (model & systematics-non linear scales)
- Future galaxy (and hydrogen) surveys will be able to pin down the neutrino mass sum in the minimal extension of the ΛCDM and having systematics under control.

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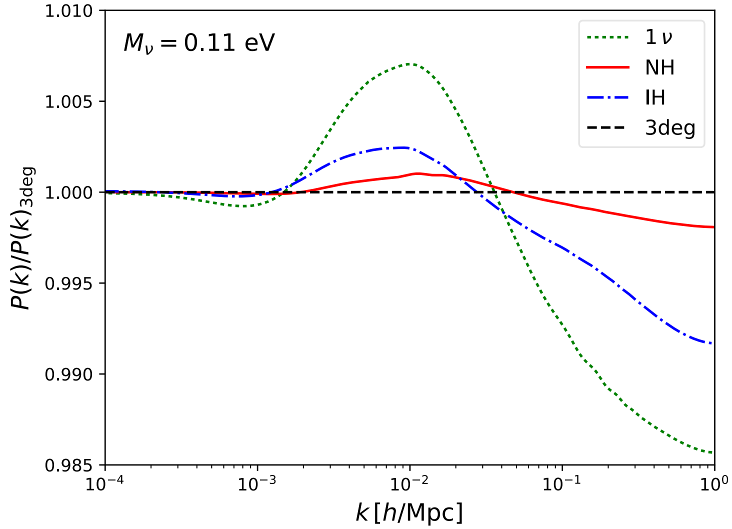
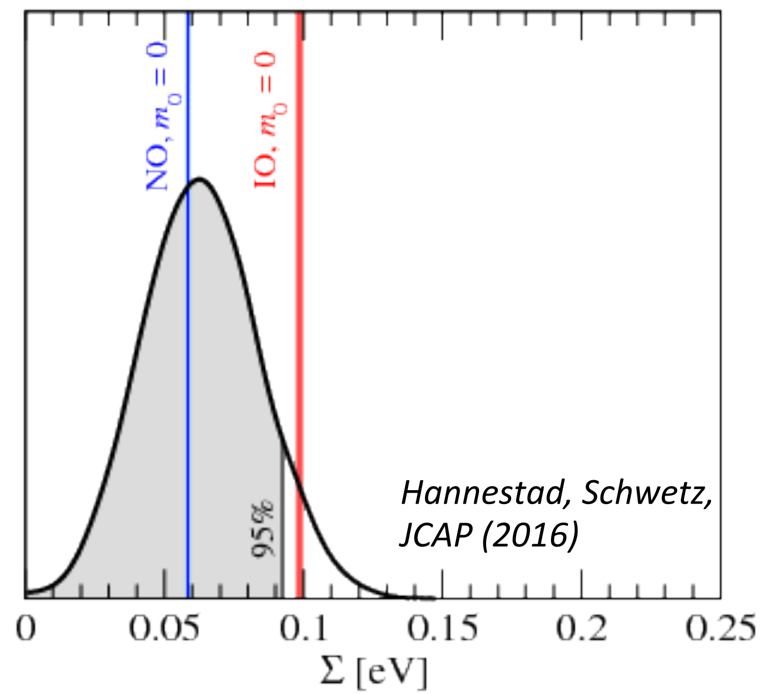
- Cosmology is a powerful tool to constrain neutrino physics, but the results have to be taken with a grain of salt (model & systematics-non linear scales)
- Future galaxy (and hydrogen) surveys will be able to pin down the neutrino mass sum in the minimal extension of the ΛCDM and having systematics under control.
- Take-home message: data tension ➔ model extension!

Vanilla ΛCDM model

Hierarchy

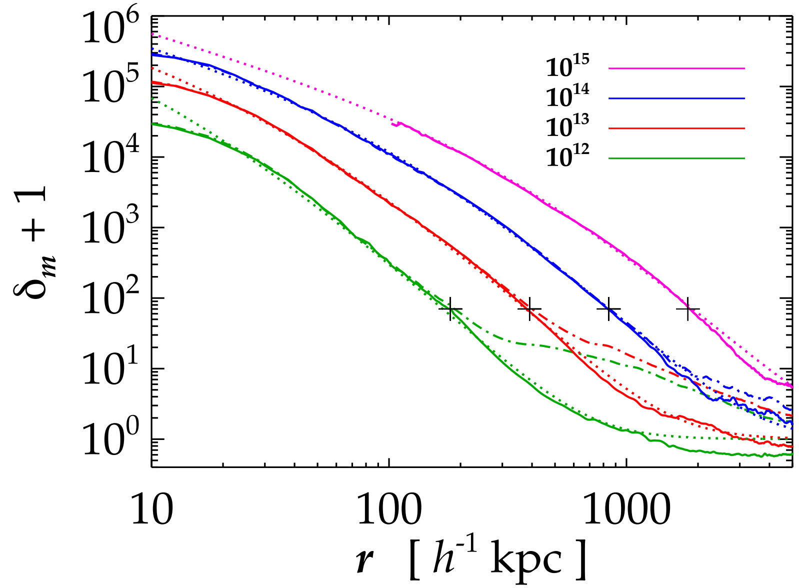


$$k > k_{nr} = 0.018\left(\frac{m_\nu}{eV}\right)^{1/2}\Omega_m^{1/2} h / Mpc$$



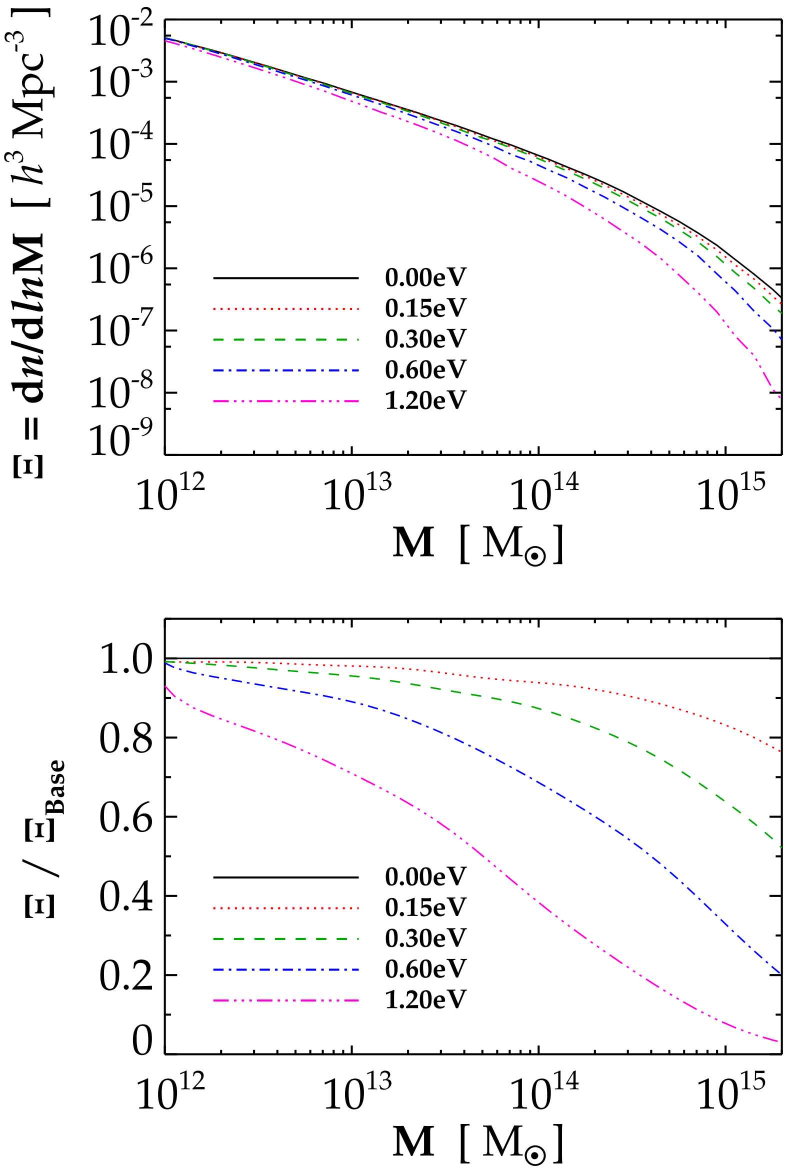
Hannestad, Schwetz, JCAP (2016)

Massive neutrinos & Halo profile



Brandbyge et al., JCAP (2010)

Massive neutrinos & HMF



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