What cosmology can tell us about neutrinos

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Outline

- Measuring neutrinos with cosmology:
  - Neutrino thermal history
  - Observables
  - Constraints
- Future: constraints and (perhaps) detection
- Conclusions

Timeline

Temperature	Process and Observables	ν Constraints
$T_\gamma \sim 1$ MeV ($z\sim10^8$)	ν decoupling	
$T_\gamma \sim 0.8$ MeV ($z\sim10^8$)	BBN	Flavour, Number
$T_\gamma \sim 1$ eV ($z\sim1100$)	CMB	Number, (Mass)
$T_\nu \sim m_\nu / 3$ ($z\sim1890*m_\nu$/eV)	ν nr transition	
$T_\gamma \sim 0.2$ meV ($z\sim0$)	LSS	Mass, (Number)

What Cosmology <u>cannot</u> tell us:

- Mixing angles
- Phases
- Dirac vs Majorana
- Hierarchy …

Neutrino decoupling

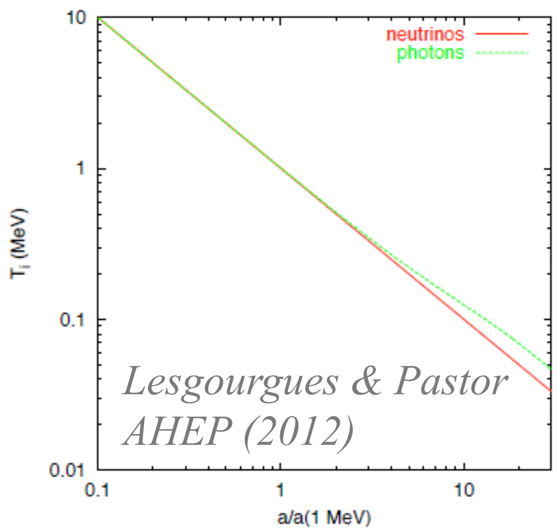
In the primordial Universe weak interactions keep neutrinos in equilibrium with the heat bath.

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

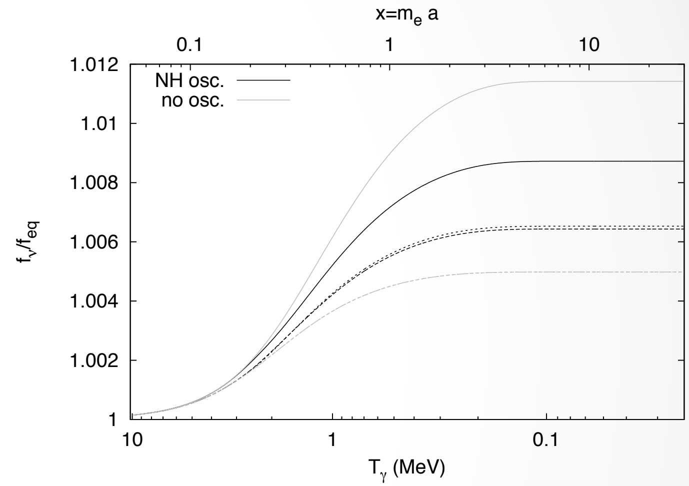
$T_{\nu,dec} \sim 1$ MeV ➔ HDM

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

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



de Salas & Pastor, JCAP (2016)



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

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
- ❖ $N_{eff}^{SM} = 3.045$ *deSalas & Pastor, JCAP (2016)*

Neutrino number and BBN

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

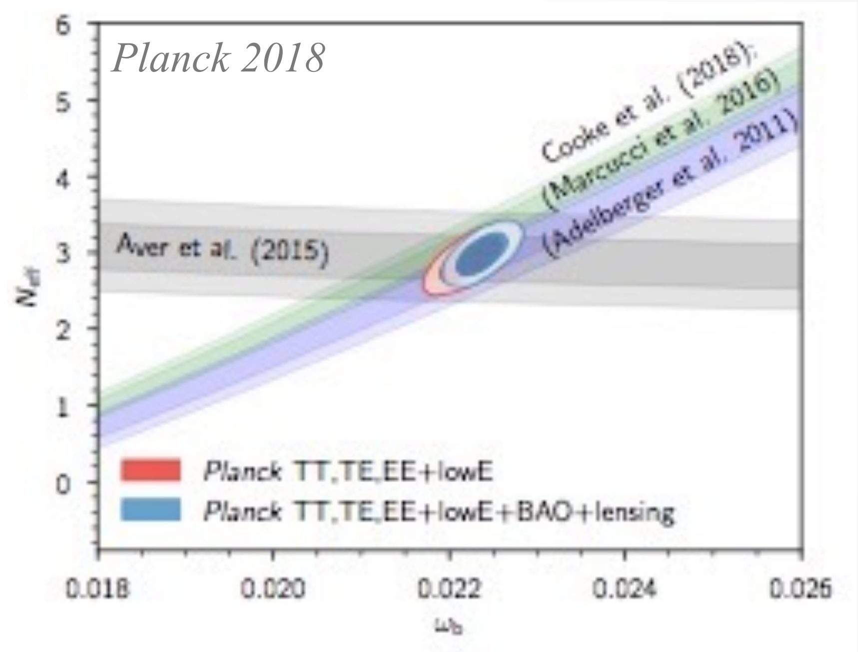
$$H = \Gamma\big|_{T=T_{freeze}} \qquad T_{freeze} \approx 0.6 g_*^{1/6}\ MeV$$

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

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

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

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

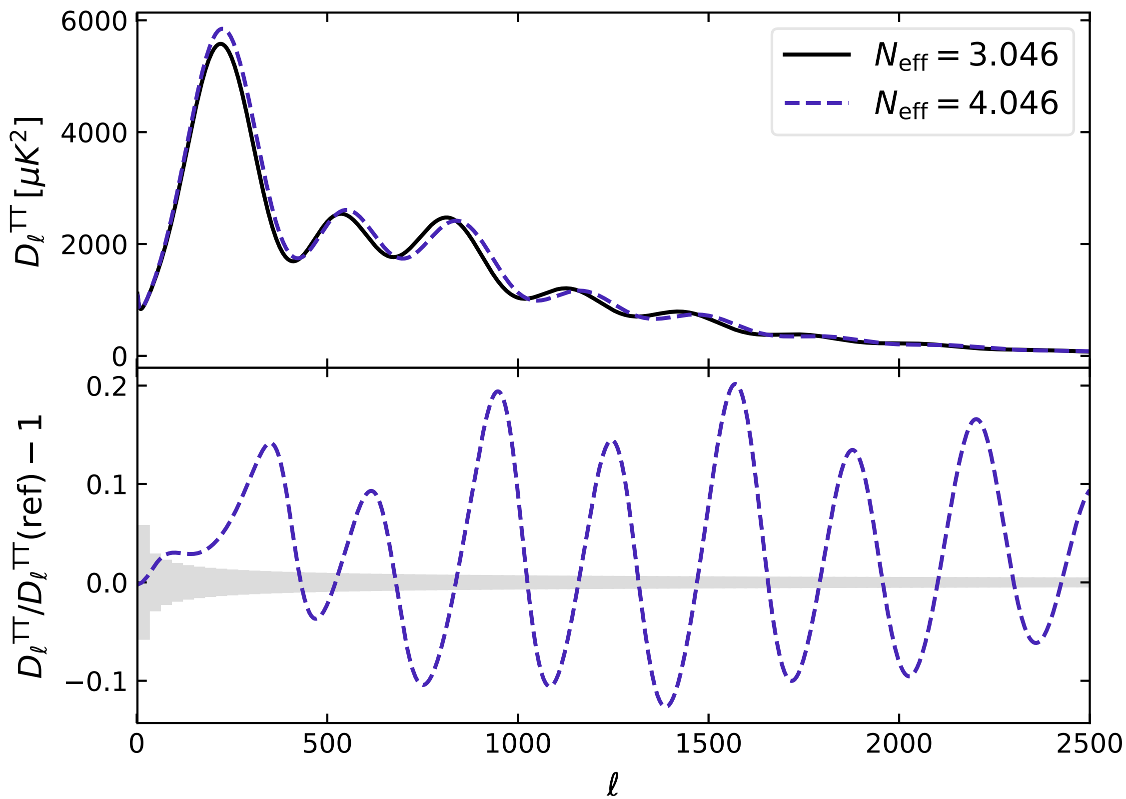


Planck TT,TE,EE + lowE + He *[Aver+ JCAP (2015)]* + D *[Cooke+ ApJ (2018)]*

N_{eff} = 2.89±0.29 (95% c.l.) experimental rate *Adelberger+ Rev. Mod. Phys (2011)*

N_{eff} = 3.05±0.27 (95% c.l.) theoretical rate *Marcucci+ PRL (2016)*

Neutrino number and CMB



- Early ISW

  $\dot{\varphi} < 0$

- Shift of the peak position

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

- Silk damping

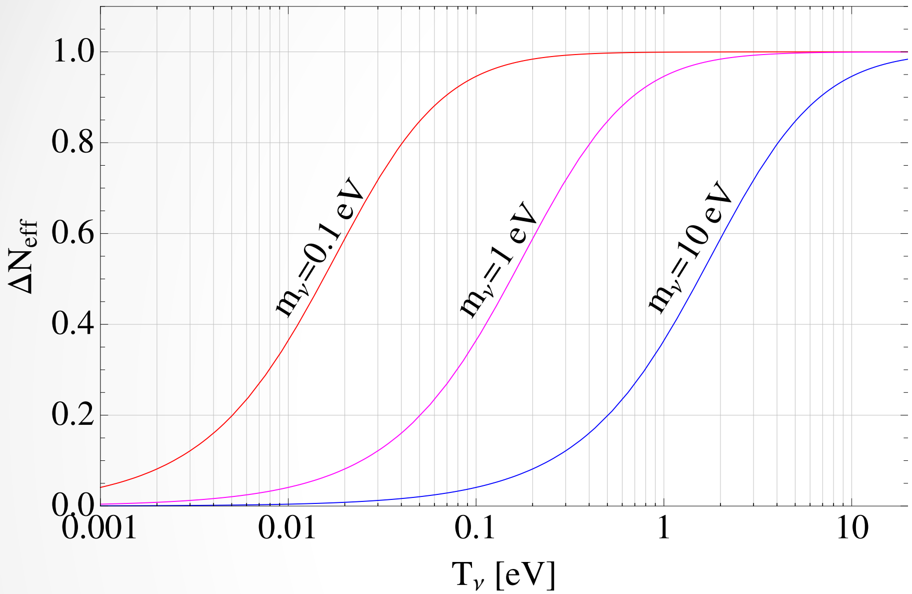
  $$\exp\left[-\left(2r_d / \lambda_d\right)^2\right]$$

Planck 2018 TT + lowE: $N_{eff} = 3.00^{+0.57}_{-0.53}$ (95%cl)

Planck 2018 TTTEEE + lowE: $N_{eff} = 2.92^{+0.36}_{-0.37}$ (95%cl)

Neutrino number and CMB

Jacques+ PRD (2013)



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

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

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

$$T_{\nu}|_{\gamma,dec} = 0.7\ \text{eV}$$

CMB: $N_{eff} = 2.92^{+0.36}_{-0.37}$ (95%cl)

Is a 10 eV “extra” neutrino consistent with CMB bounds? NO, it is not!

Neutrino mass and CMB

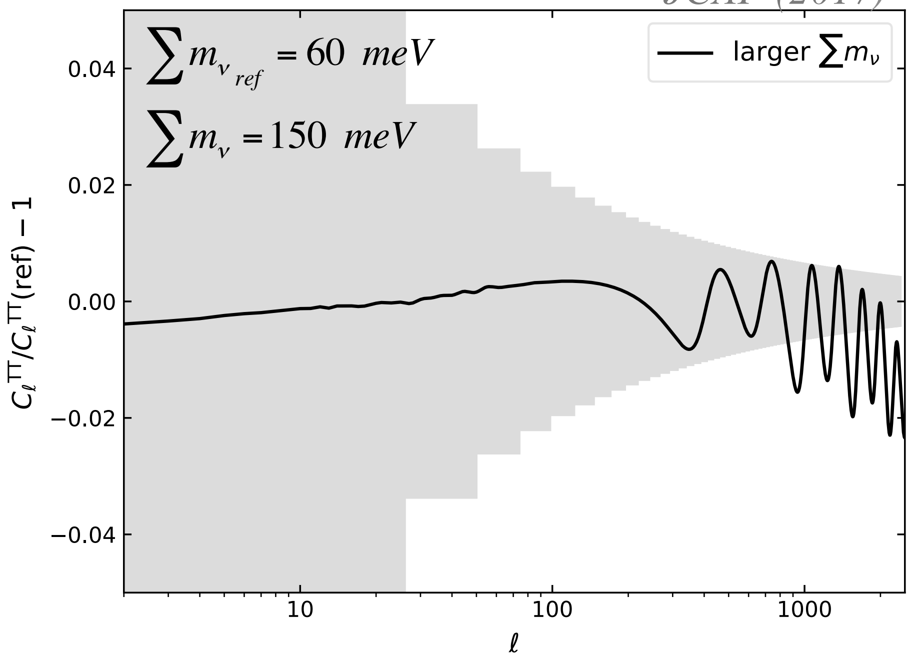
$$\Omega_\nu h^2 = \frac{\rho_\nu}{\rho_c} = \frac{\sum m_\nu}{93.14 eV}$$

Note: $m_1 = m_2 = m_3$

m_1, Δm^2_{sun}, Δm^2_{atm} ➔0.1% $\Delta P(k)/P(k)$

- Background effects (z_{eq}, d_A, z_Λ)
- Perturbation effects (early ISW)

MA, Brinckmann, Lesgourgues, Poulin JCAP (2017)



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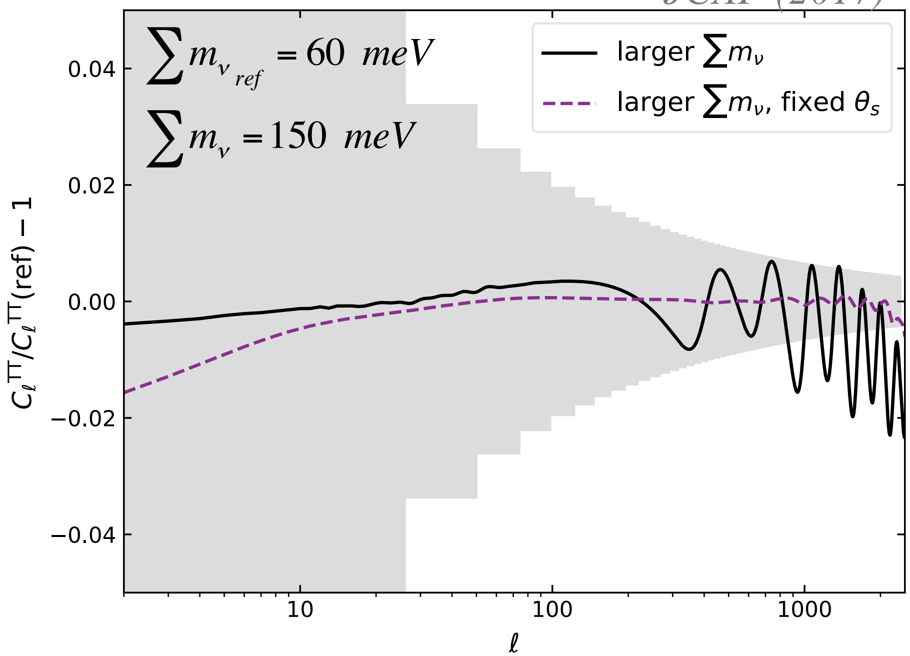


- Background effects (z_{eq}, d_A, z_Λ)
- Perturbation effects (early ISW)

➔ Correlation between M_ν and H_0 (TTTEEE) and also ω_{cdm} (TTTEEE+lensing)

Planck 2018 TT + lowE: $\Sigma m_\nu < 0.54$ eV (95%cl)

Planck 2018 TTTEEE + lowE: $\Sigma m_\nu < 0.26$ eV (95%cl)

➔ CMB data alone (even future cosmic variance limited CMB surveys) cannot measure M_ν

Neutrino non-relativistic transition

When neutrinos become non-relativistic

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

they travel through the Universe with a thermal velocity

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

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

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

Neutrino mass and LSS

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

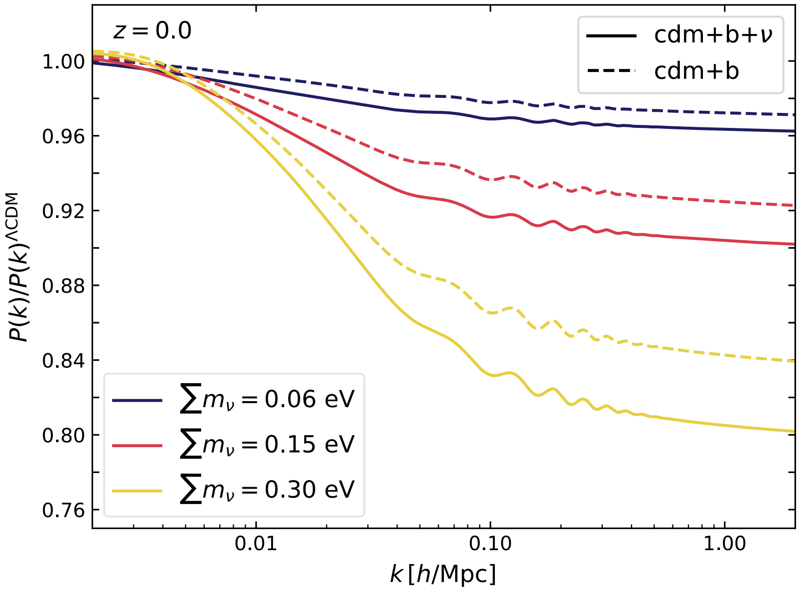
$$\delta_m = \frac{\delta\rho_m}{\bar{\rho}_m}$$

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

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

$$\delta_{cdm} \propto a$$

$$\delta_{cdm} \propto a^{1-3/5 f_\nu}$$



$$\frac{P_c(k)^\nu}{P_c(k)^{\Lambda CDM}} \approx 1 - 6 f_\nu$$

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

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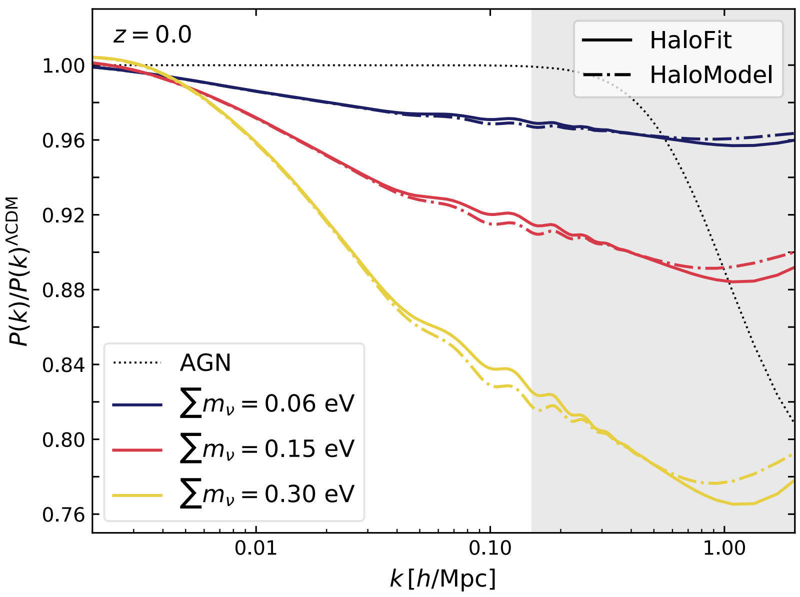

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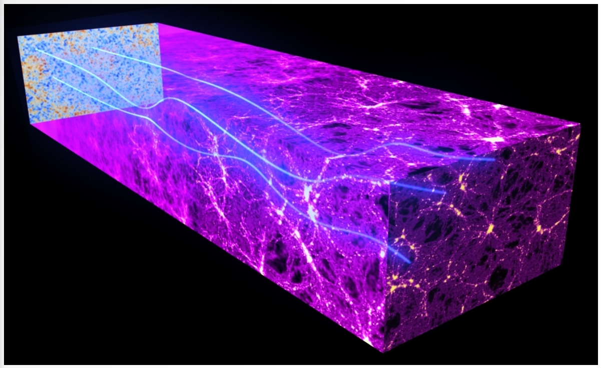
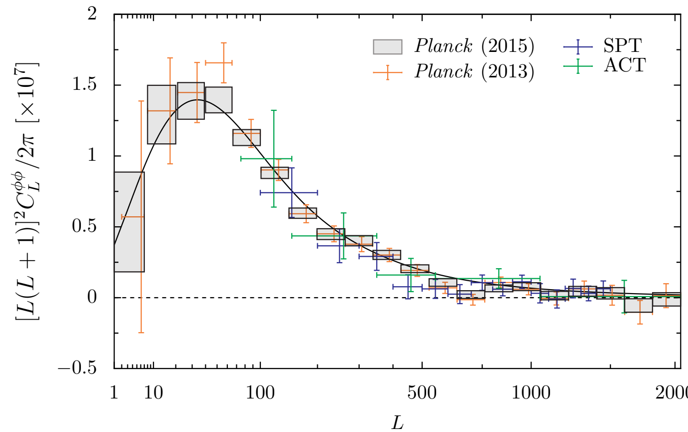
Neutrino mass and LSS

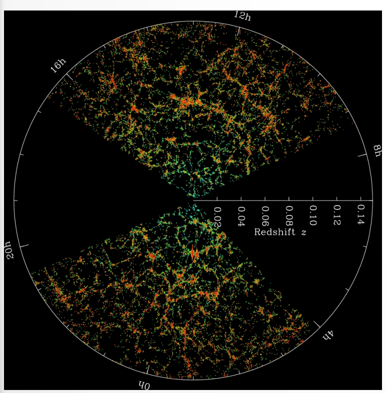
CMB



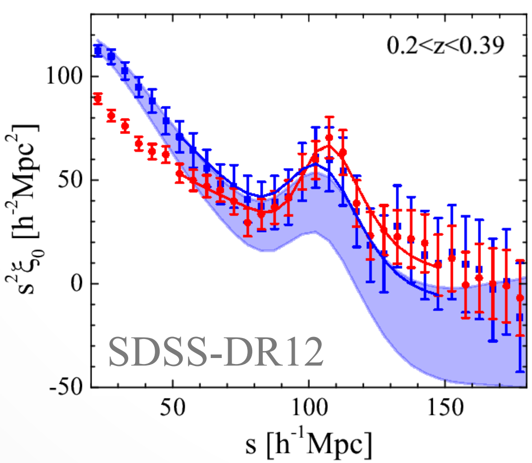
Lensing



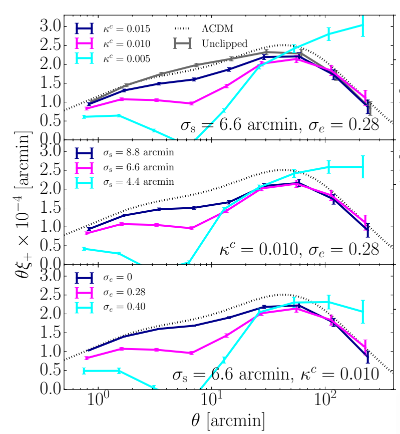
Galaxy surveys



BAO

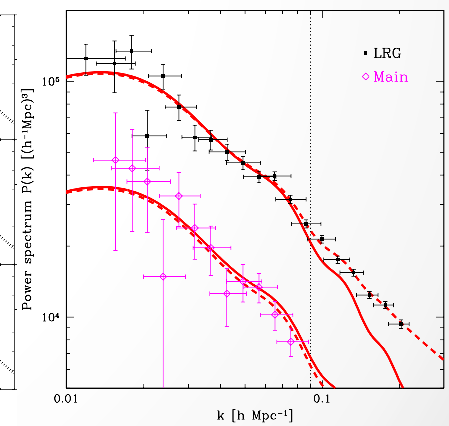


Cosmic shear



KiDS
Giblin+ MNRAS(2018)

Galaxy clustering

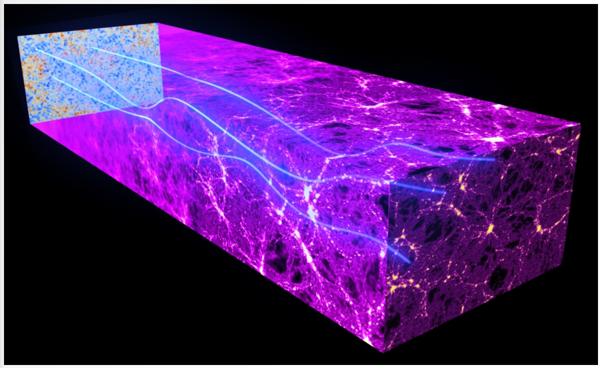


Tegmark+ PRD(2006)

...and more ... (e.g., RSD)

Neutrino mass and LSS

CMB



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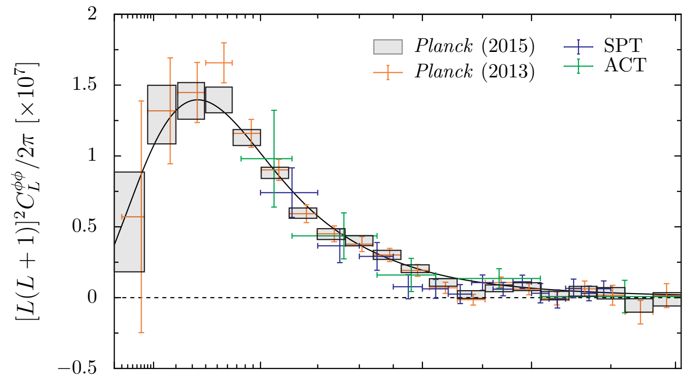
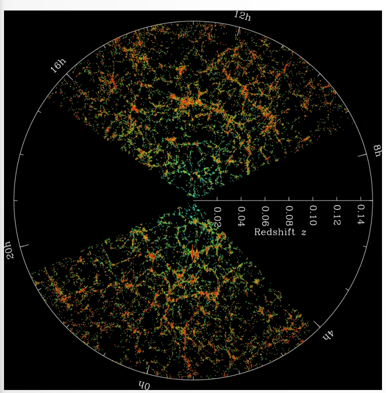
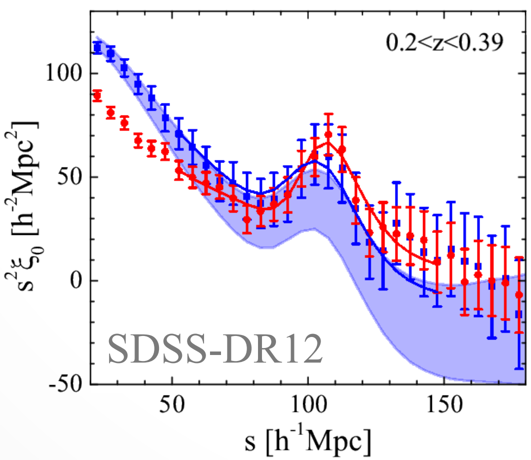
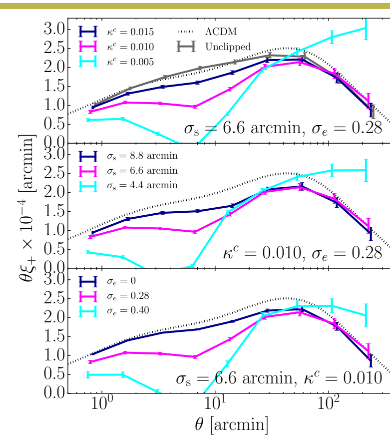


Planck 2018 TT,TE,EE+lowE+lensing+BAO:
$\Sigma m_\nu < 0.12$ eV (95%cl)

Galaxy surveys







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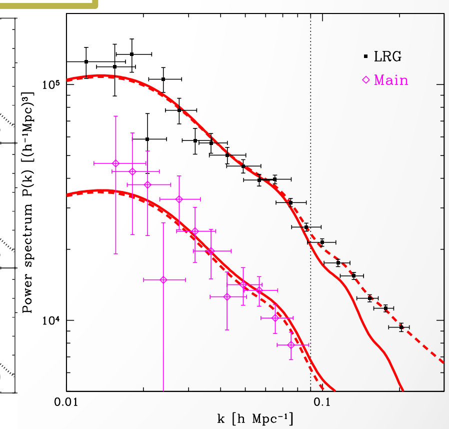

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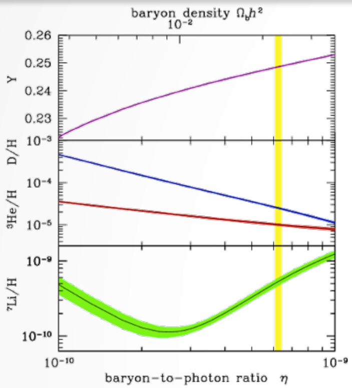
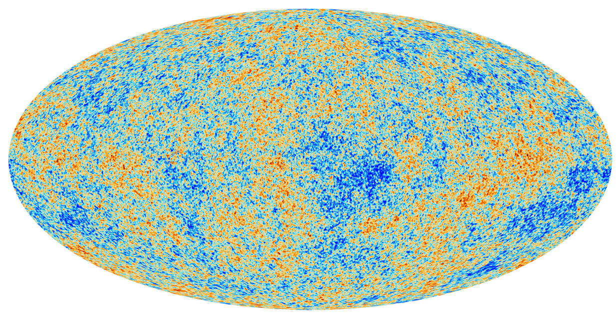
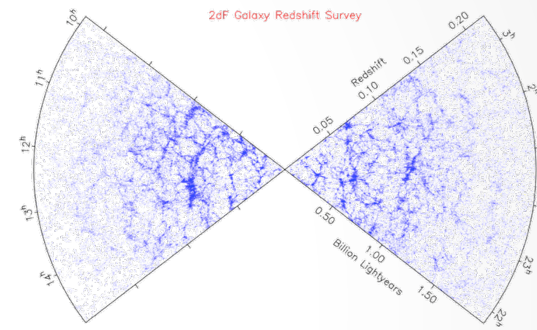
Where we stand

$z \sim 10^8$ (T ~1 MeV) | $z \sim 1100$ (T~1 eV) | $z<3$







N_{eff} & flavour | N_{eff} & (Σm_ν) | (N_{eff}) & Σm_ν

$N_{eff} = 2.92^{+0.36}_{-0.37}$ (95%cl)

TT,TE,EE + lowE

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… + lensing + BAO

Planck 2018

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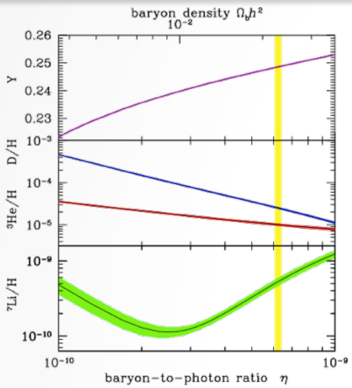

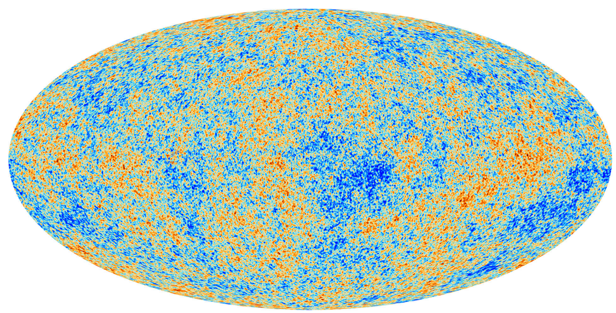

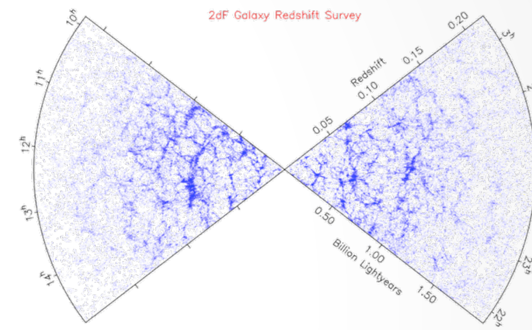

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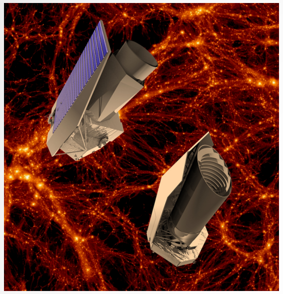
Planck 2018

eV ν_s are: too many and too heavy

Neutrino mass: future sensitivity



Euclid (2021)

1% accuracy:

galaxy clustering,

cosmic shear

SKA

21cm survey

Sprenger, MA, Brinckmann, Clesse, Lesgourgues, JCAP (2019) MCMC forecast

Fiducial = 0.06 eV equally distributed among 3 neutrino species

Conservative vs. Optimistic uncertainty on small scales

	Planck+Euclid	**Planck+Euclid+SKA1-IM**
Conservative	24 meV	18 meV
Optimistic	20 meV	15 meV

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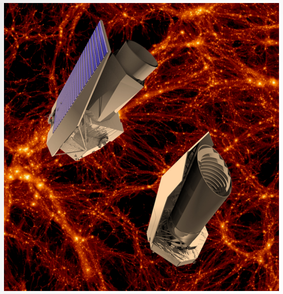

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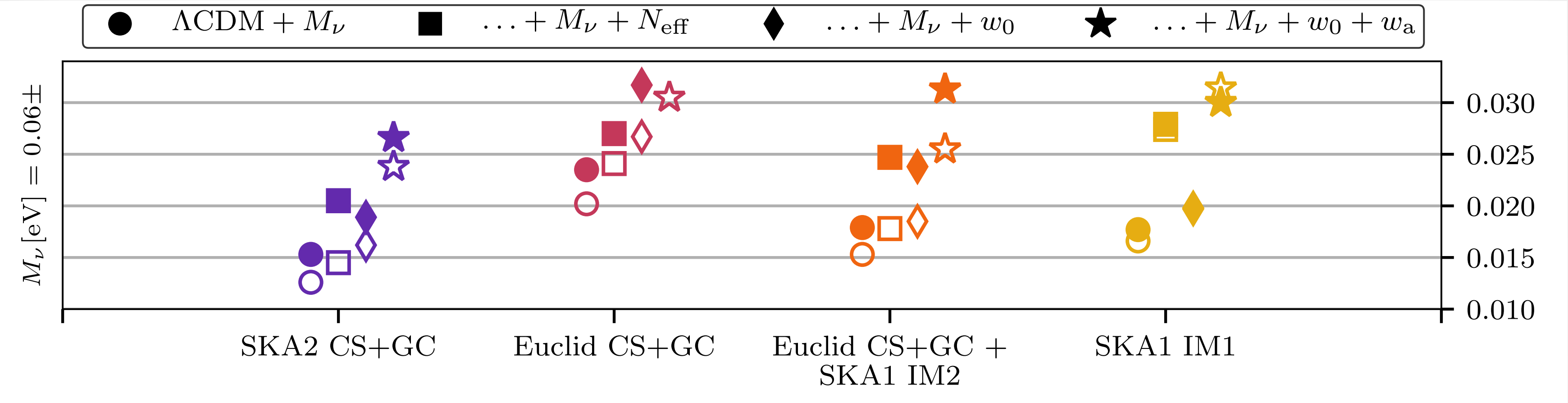
Note: IO indirectly disfavoured

Neutrino mass: model dependence



□ Conservative ■ Optimistic

Planck+Euclid	N_{eff}	w_0 (fixed w_a)	w_0 (+ w_a)	w_a
Conservative	0.065	0.0154	0.0285	0.099
Optimistic	0.046	0.0121	0.0214	0.071

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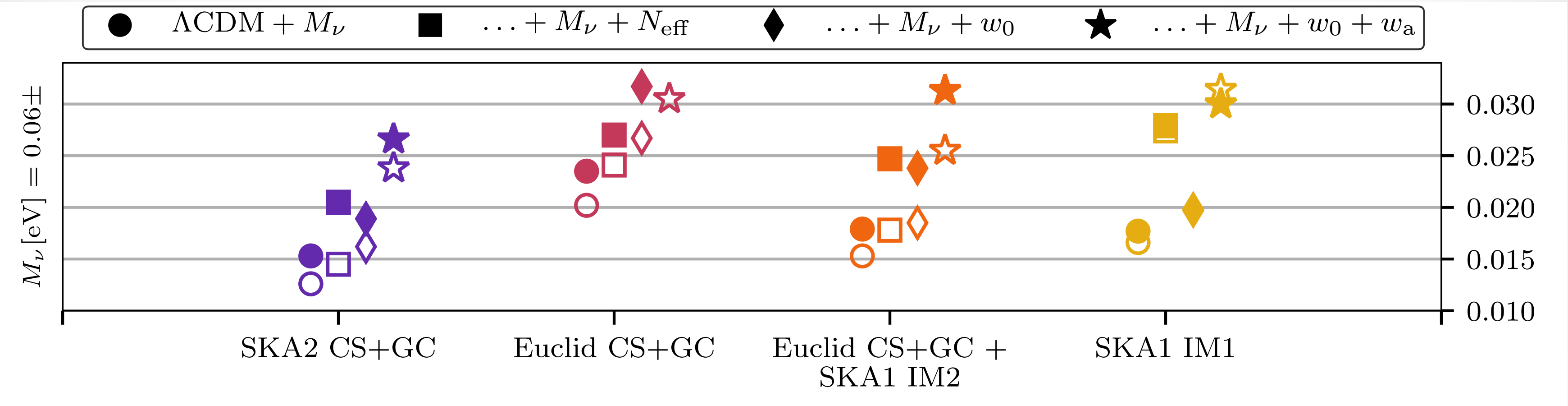

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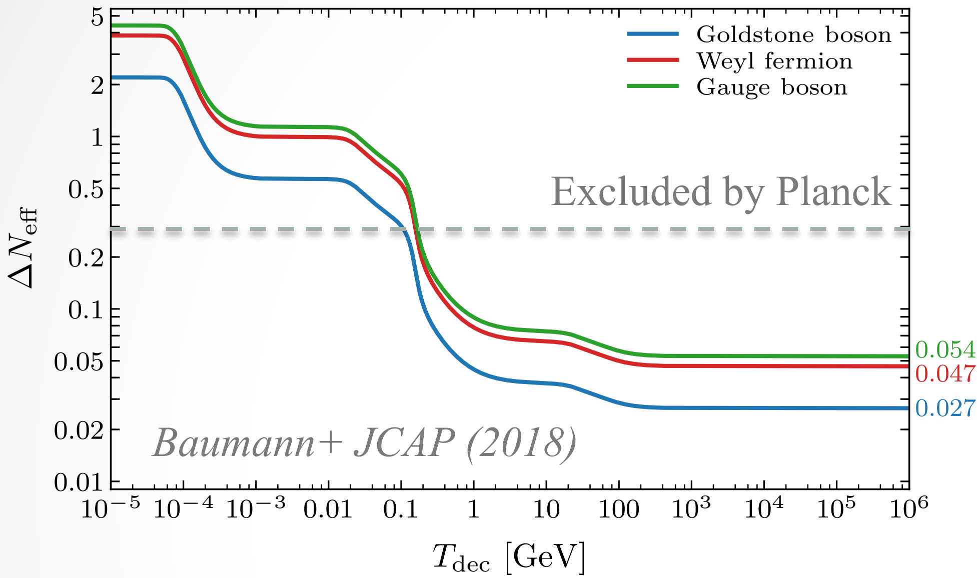
Neff: future sensitivity

Physics beyond the Standard Model



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

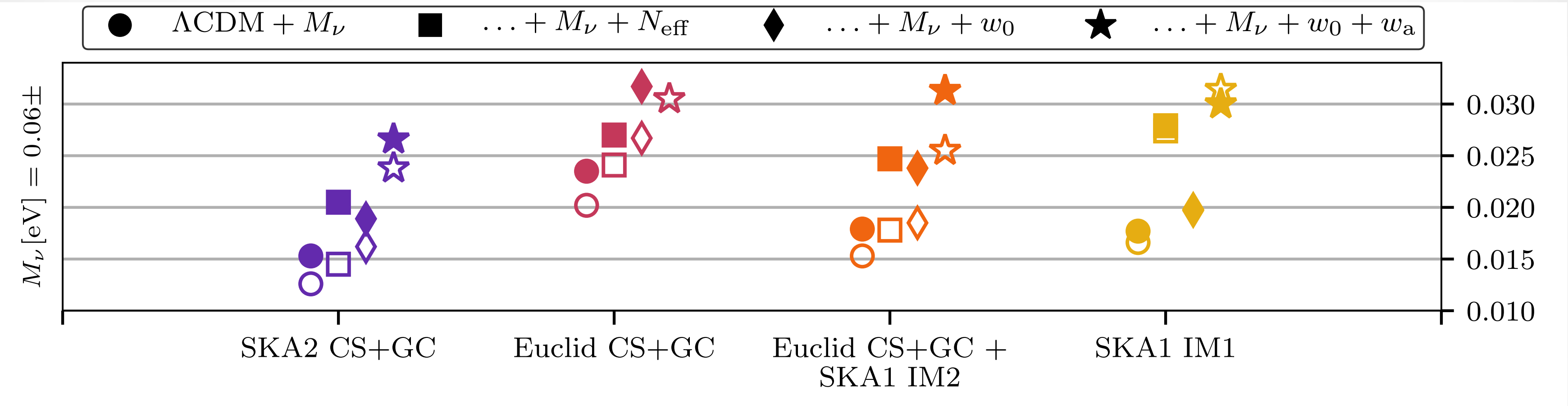
$$= \left(\frac{T_{\nu,extra}}{T^{thermal}_{\nu,m=0}}\right)^4\left(\frac{P_{\nu,extra}/\rho_{\nu,extra}}{1/3}\right)$$

} Future CMB + Euclid + SKA

Models that can be excluded:

- Neutrino Non-Standard interactions (solution of the H_0 tension)
- Non-Abelian Dark Matter (solution of the σ_8 tension)
- Self-Interacting Dark Matter (solution of the small scale crisis)
- …

Neutrino mass: model dependence



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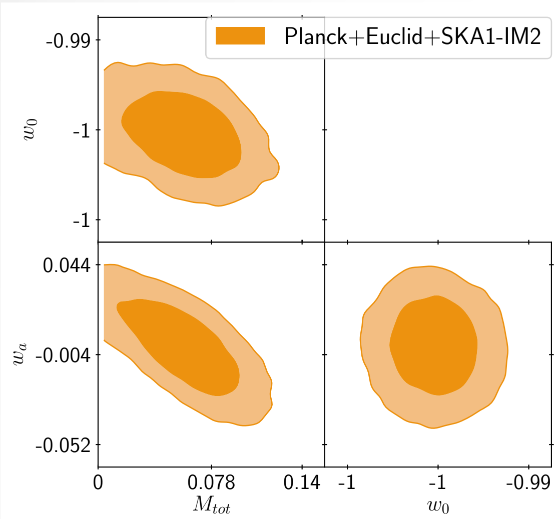
Brinckmann, Hooper, MA, Lesgourgues, Sprenger, JCAP (2019)

CLP: $w(a)=w_0+w_a(1-a)$

Neutrino mass and Dark Energy



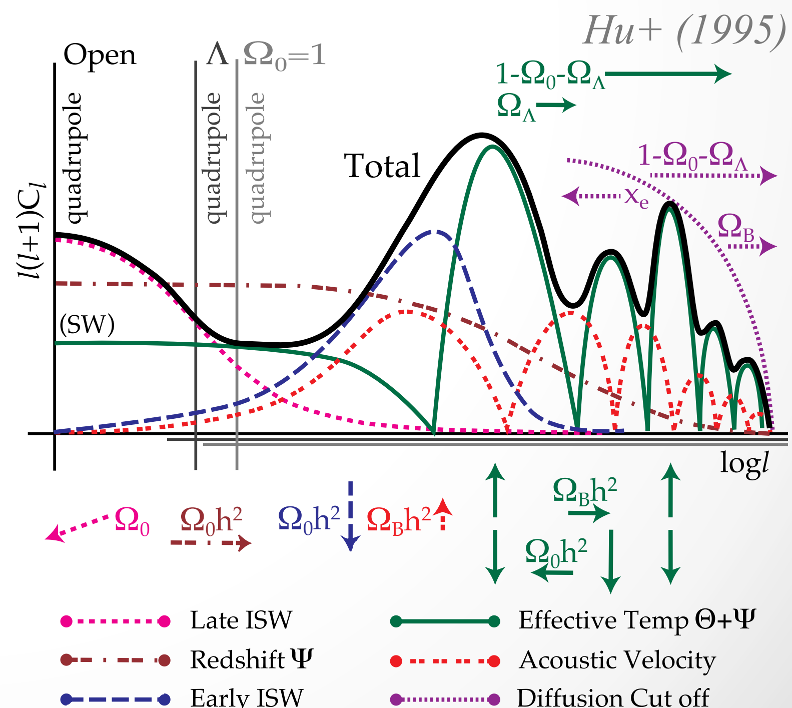
How to break the degeneracy?
ISW-galaxy clustering cross-correlation

(In alphabetical order) Maria Archidiacono, Alessandro Gruppuso, Massimiliano Lattanzi, Nicoletta Mauri, Marina Migliaccio, Diego Molinari, Paolo Natoli, Luca Pagano, Laura Patrizii, Gabriele Sirri, Matteo Tenti, Alessandro Renzi, and the Euclid CMBXC SWG

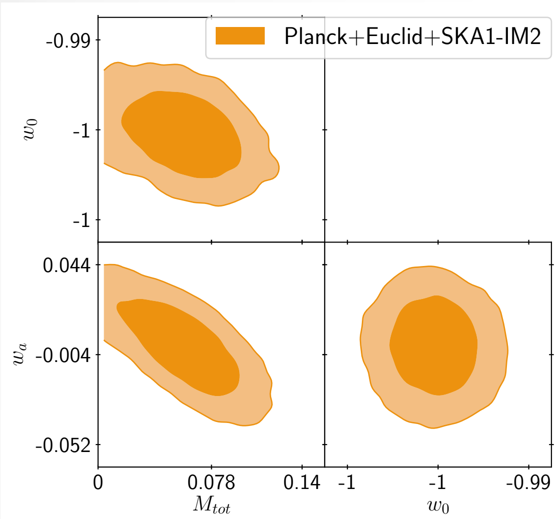
During Λ (or, more in general, DE) the gravitational potentials ϕ decay
➔ Late ISW

vs.

Growth of structure
➔ Galaxy clustering



Neutrino mass and Dark Energy



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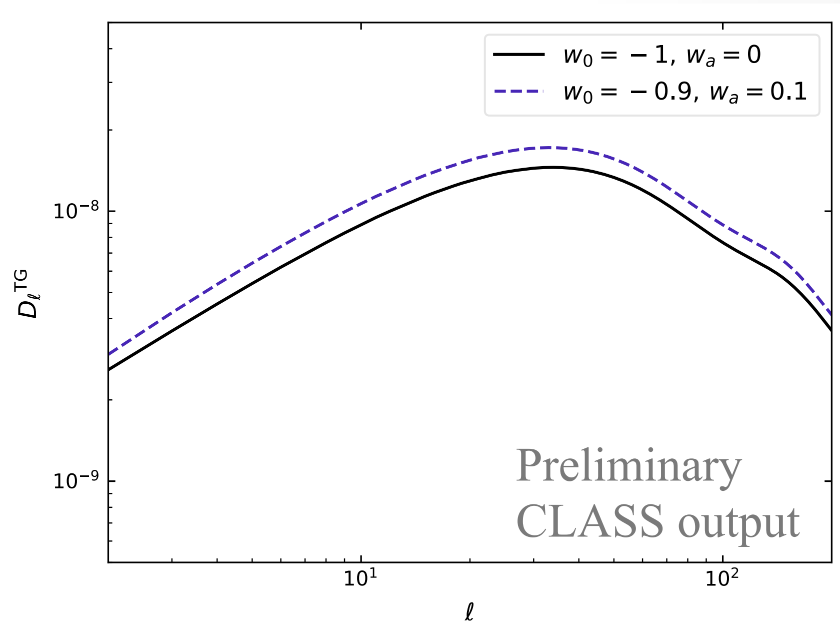


Conclusions

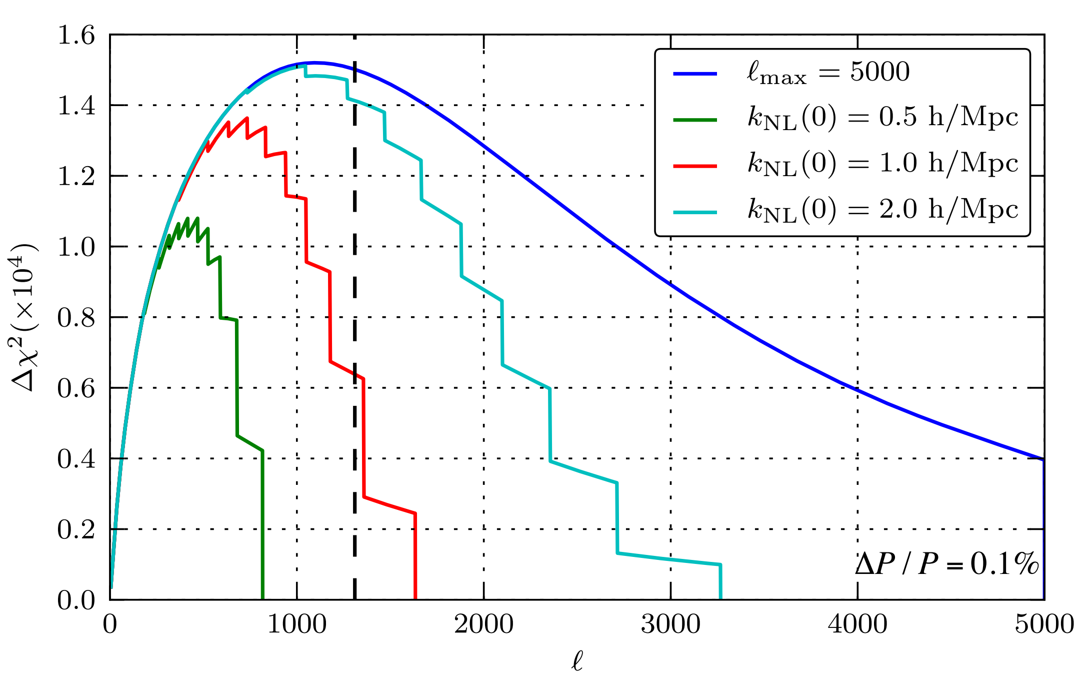
- Cosmology is a powerful tool to constrain neutrino physics, but the results have to be taken with a grain of salt because of model dependence
- Future galaxy and hydrogen surveys will be able to detect the neutrino mass sum in the minimal extension of the ΛCDM
- Ongoing work: ISW-GC Euclid CMBXC
- Complementarity with ground-based experiments (KATRIN $m_\beta < 1.1$ eV)

Conclusions

- Cosmology is a powerful tool to constrain neutrino physics, but the results have to be taken with a grain of salt because of model dependence
- Future galaxy and hydrogen surveys will be able to detect the neutrino mass sum in the minimal extension of the ΛCDM
- Ongoing work: ISW-GC Euclid CMBXC
- Complementarity with ground-based experiments (KATRIN $m_\beta < 1.1$ eV)

"The most exciting phrase to hear in science, the one that heralds new discoveries, is not 'Eureka!' but 'That's funny ...'" Isaac Asimov

Theoretical uncertainties: CS



k_{max}	$100\omega_b$	ω_{cdm}	θ_s	$\ln(10^{10}A_s)$	n_s	τ_{reio}	M_ν [eV]
0.5 h/Mpc	0.77	0.27	0.97	0.94	0.72	0.96	0.50
1.0 h/Mpc	0.76	0.27	0.94	0.95	0.70	0.98	0.41
2.0 h/Mpc	0.76	0.25	0.97	0.94	0.65	0.97	0.36
$l_{max} = 5000$	0.74	0.24	0.94	0.94	0.58	0.96	0.30
Planck only	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Sprenger, MA+ JCAP (2019)

$$k_{nl}(z) \propto k_{nl}(0)(1+z)^{2/(2+n_s)}$$

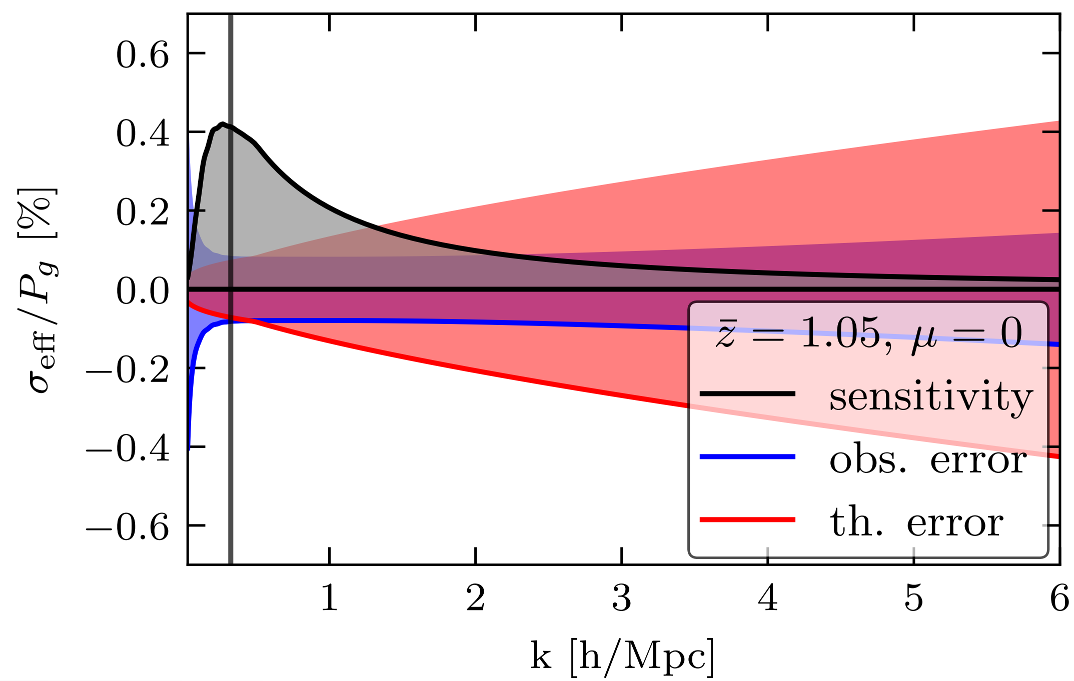
$$l_{\max}^{zi} = k_{nl}(z) \times \bar{r}_{peak}^{zi}$$

Conservative: $k_{nl}(0)$=0.5 h/Mpc

Optimistic: $k_{nl}(0)$=2.0 h/Mpc

	Planck+Euclid-CS
Conservative	43 meV
Optimistic	30 meV

Theoretical uncertainties: GC



Sprenger, MA+ JCAP (2019)

$$\frac{d\chi^2}{dk d\mu} = \left[\frac{\Delta P_g(k,\mu,\bar{z})}{\sigma_{eff}(k,\mu,\bar{z})}\right]^2$$

$$\sigma_{eff}(k,\mu,\bar{z}) = \sigma_{obs}(k,\mu,\bar{z})\left[k^2 \frac{V_r(\bar{z})}{2(2\pi)^2}\right]^{-1/2}$$

$$\sigma_{eff}(k,\mu,\bar{z}) \propto k^{-2}$$

$$\alpha = \frac{\delta P_g}{P_g} \begin{cases} 0.33\% \text{ at k=0.01 h/Mpc} \\ 1\% \text{ at k=0.3 h/Mpc} \\ 10\% \text{ at k=10 h/Mpc} \end{cases}$$

Conservative: $k_{nl}(0)$=0.2 h/Mpc

Optimistic: th. err. & $k_{max}(0)$=10 h/Mpc

	Planck+Euclid-GC
Conservative	26 meV
Optimistic	20 meV

Cosmological tensions

$H_0 = (67.4 \pm 0.5)$ km/s/Mpc (68% c.l.) (Planck TT,TE,EE+lowE, ΛCDM)

$H_0 = (74.03 \pm 1.42)$ km/s/Mpc (68% c.l.) *Riess+ Apj (2019)*

4.4 σ tension

σ_8 tension between Planck and CFHTLens, KiDS *Hildebrandt+ (2018)*

alleviated by DES *Abbott+ (2018)*

Two possible model extensions each one solving one tension