Neutrino constraints from future surveys

Maria Archidiacono

INFN Bologna and University of Bologna

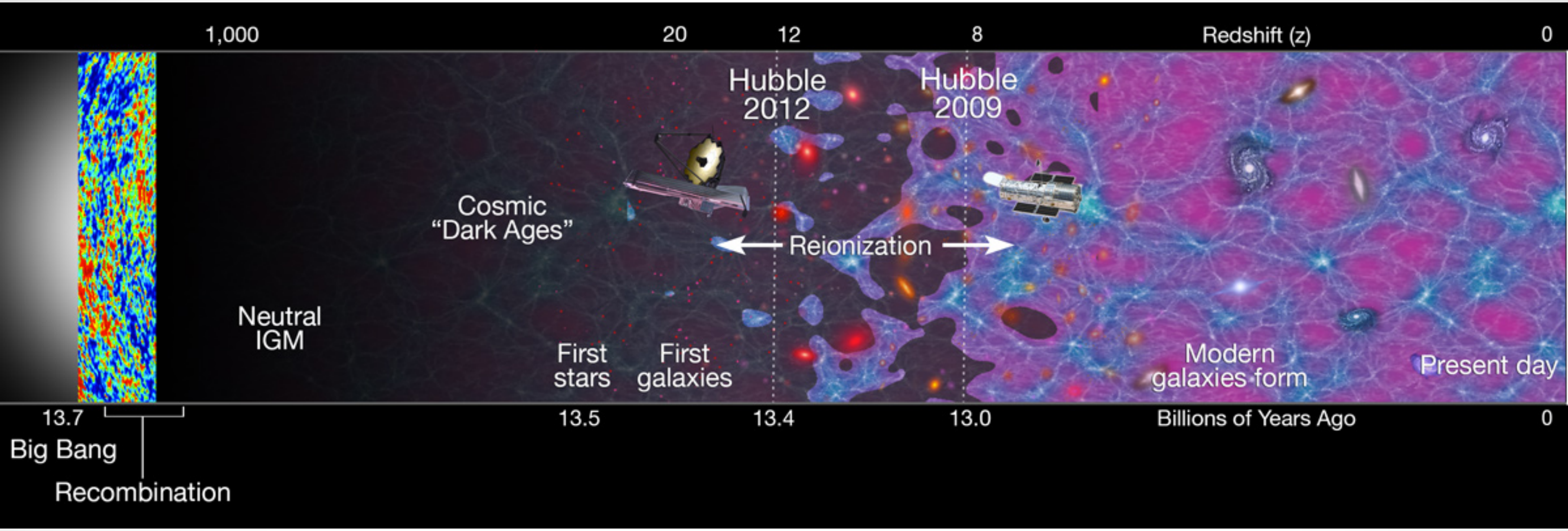
Archidiacono, Brinckmann, Lesgourgues, Poulin, JCAP (2017)

Vagnozzi, Brinckmann, Archidiacono, Freese, Gerbino, Lesgourgues, Sprenger, JCAP (2018)

Sprenger, Archidiacono, Brinckmann, Clesse, Lesgourgues, JCAP (2019)

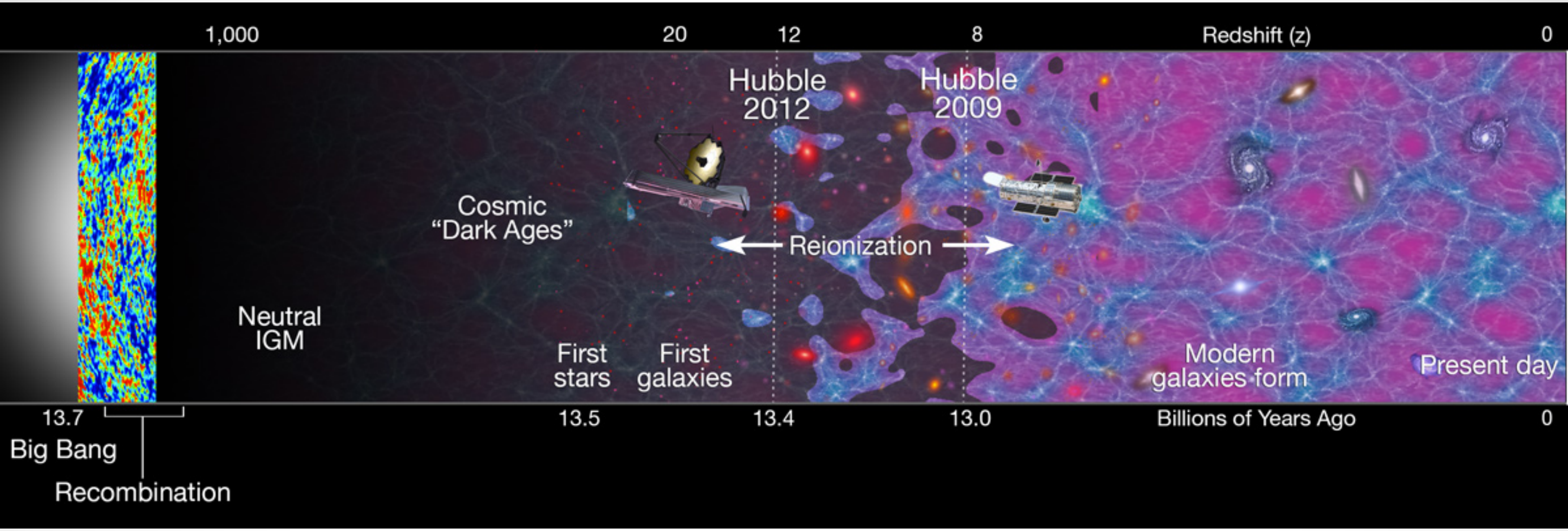
Particle and Astroparticle Theory Seminar, MPIK, Heidelberg, 15.04.2019

Timeline



Temperature	Process and Observables	ν Constraints
$T_\gamma \sim 1$ MeV	ν decoupling	
$T_\gamma \sim 0.8$ 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	LSS	Mass, (Number)

Timeline



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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

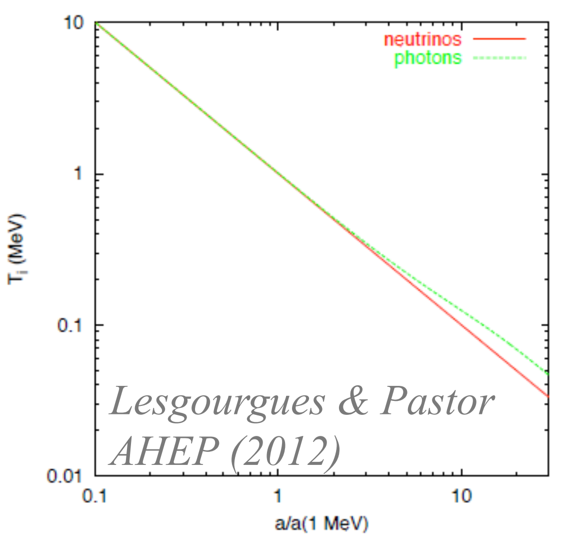
$e^+e^- \rightarrow \gamma\gamma$

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

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

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

$T_{\nu s} \leq T_\nu$



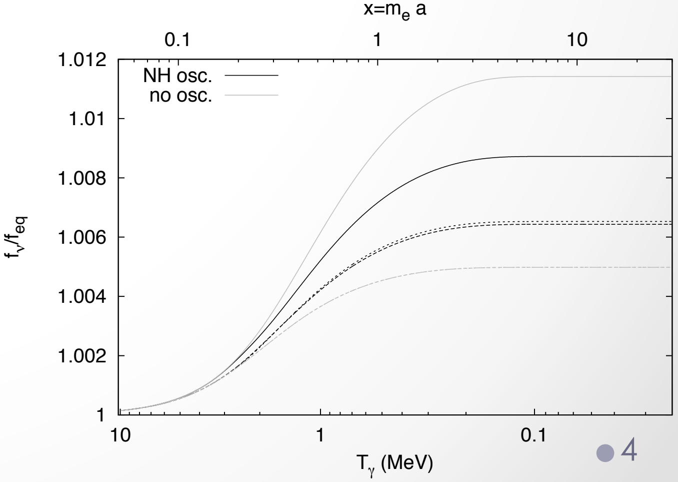
Lesgourgues & Pastor AHEP (2012)

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

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
- $N_{eff} = 3.045$
- 3 + 1 sterile, $N_{eff} \sim 4$

de Salas & Pastor JCAP (2016)



Neutrino number & BBN

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

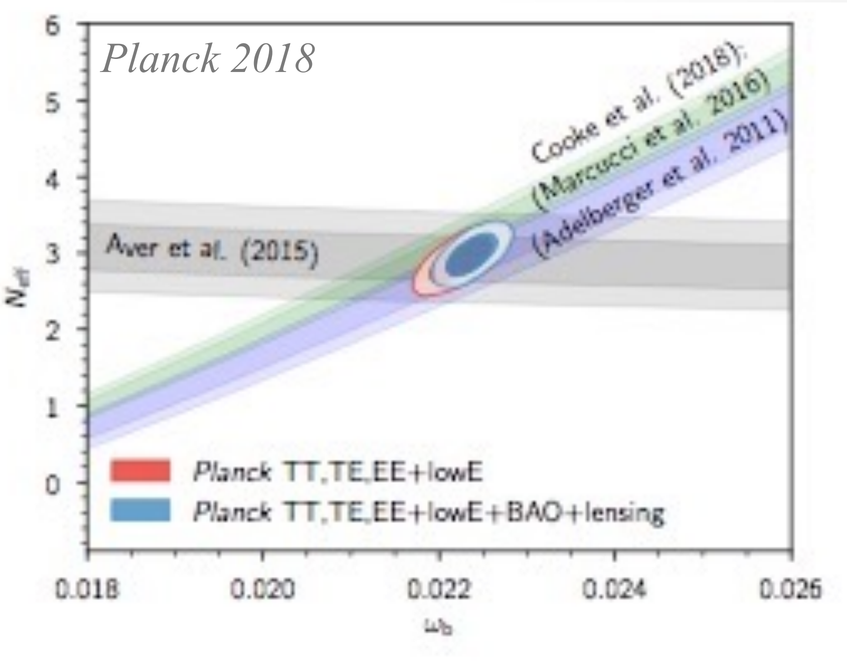
$$H = \Gamma\big|_{T=T_{freeze}} \qquad T_{freeze} \approx 0.6 g_*^{1/6}\ MeV$$

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

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

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

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

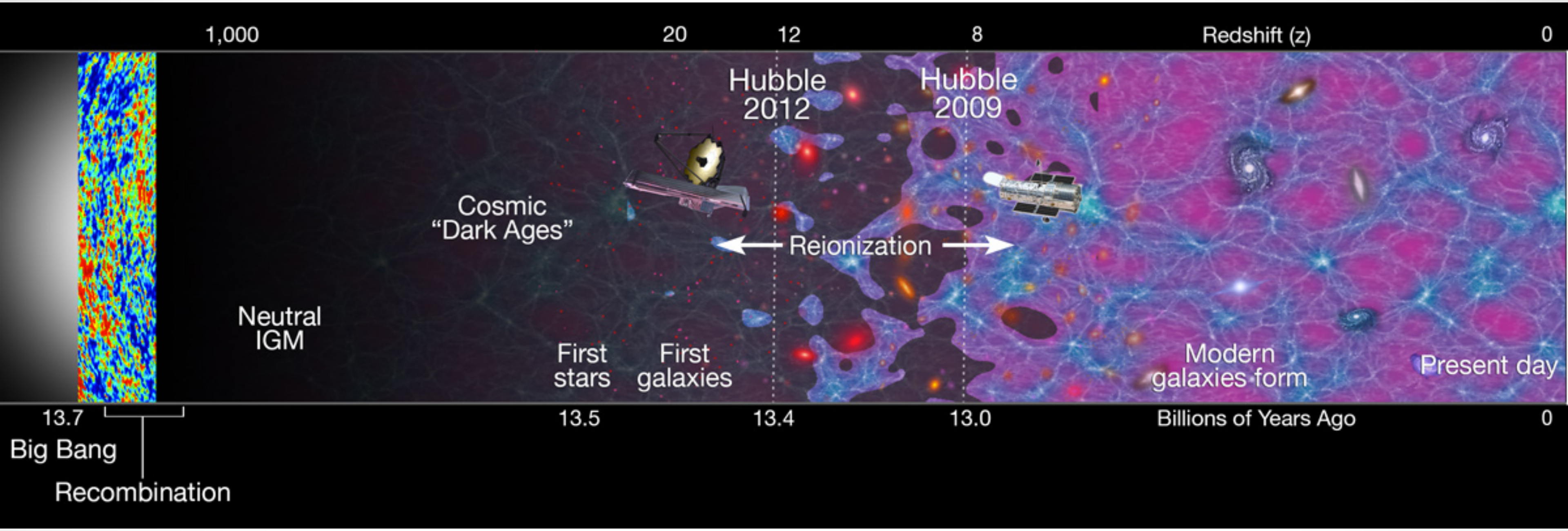


Planck TT,TE,EE + lowE + He *[Aver+ JCAP (2015)]* + D *[Cooke+ ApJ (2018)]*

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

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

Timeline



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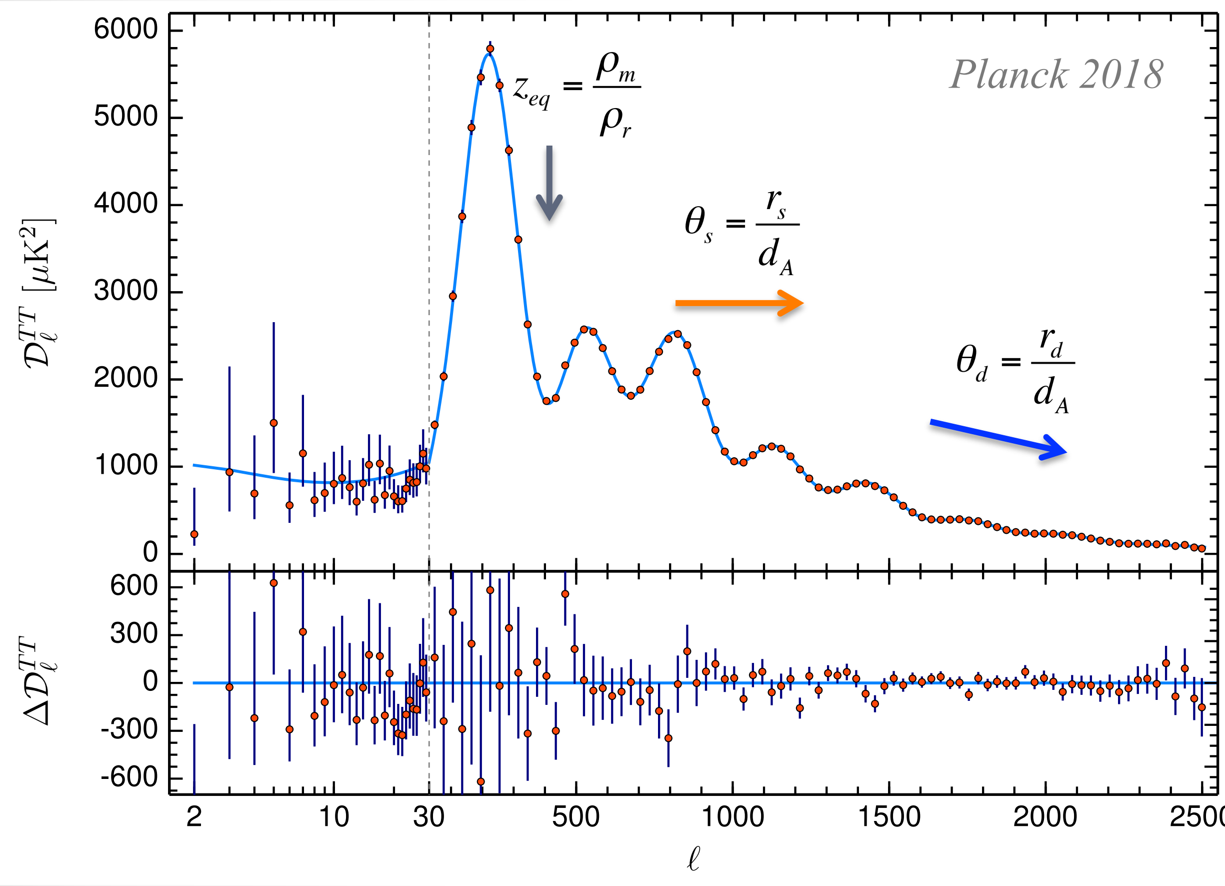
Neutrino number & CMB



- 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

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

Planck TT + lowE
ΛCDM+N_{eff}

$$\boxed{N_{eff} = 3.00^{+0.57}_{-0.53}\ (95\%\mathrm{cl})}$$

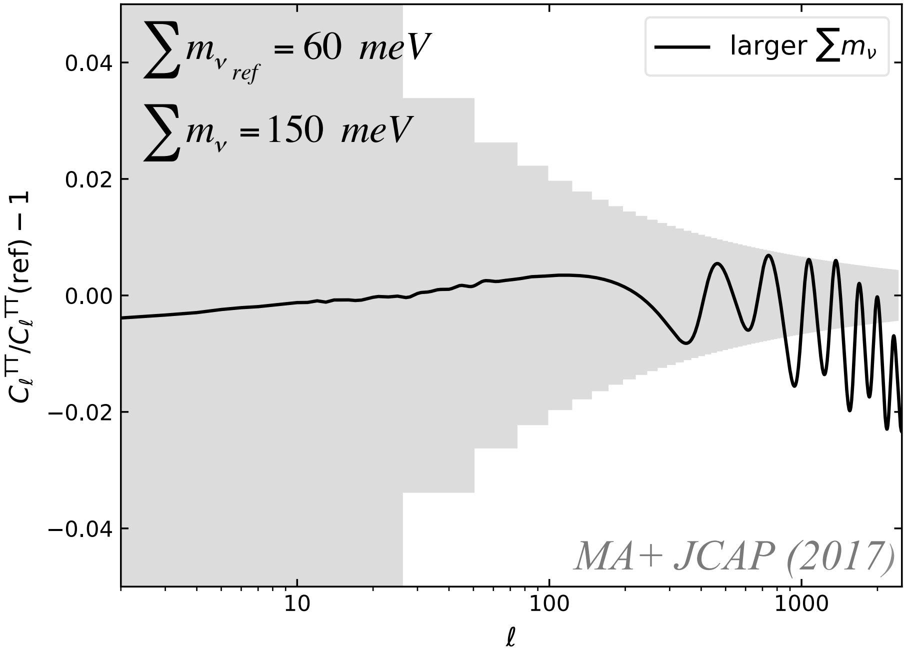
Neutrino mass & CMB

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

Note: $m_1=m_2=m_3$

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

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



MA+ JCAP (2017)

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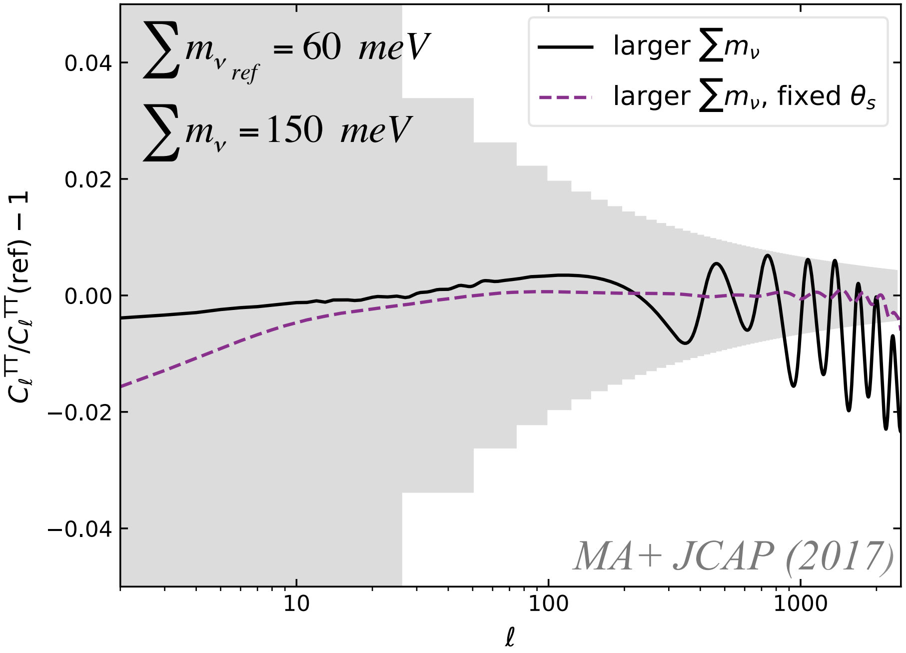


MA+ JCAP (2017)

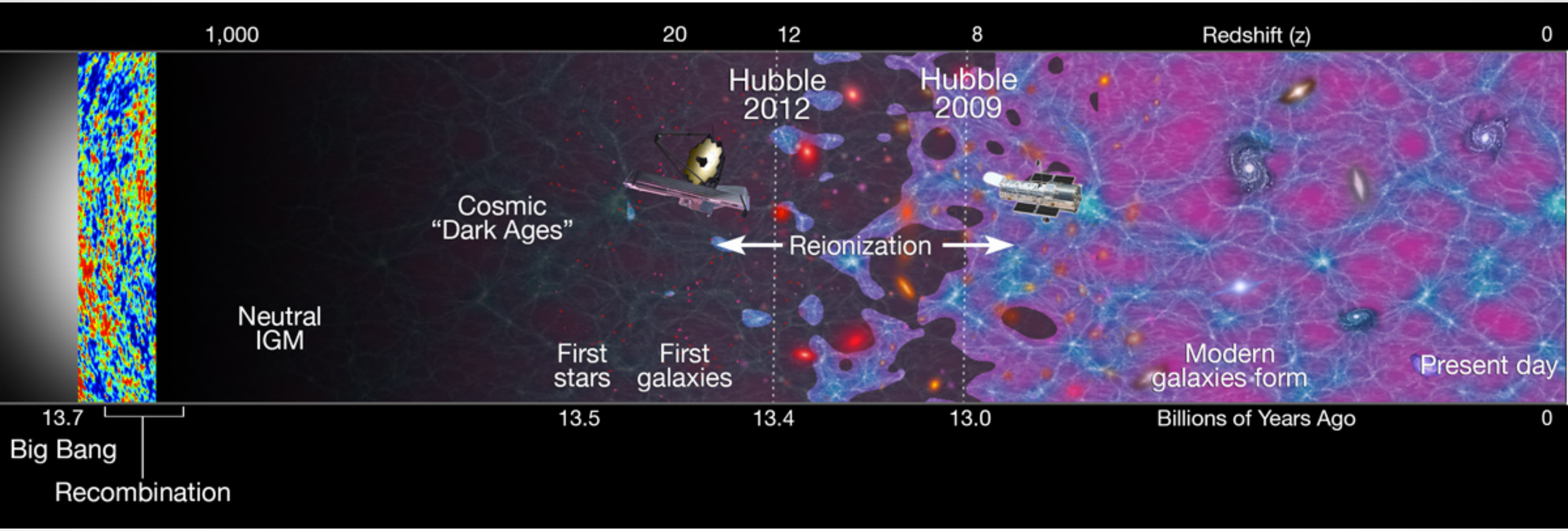
- Background effects (z_{eq}, d_A, z_Λ)
- Perturbation effects (early ISW)

➔ Correlation between M_ν and H_0 (and ω_{cdm})

Planck 2018 TTTEEE + lowE $\sum m_\nu < 0.26\ eV\ (95\% c.l.)$

➔CMB data alone (even from future CMB surveys) **cannot** measure M_ν

Timeline



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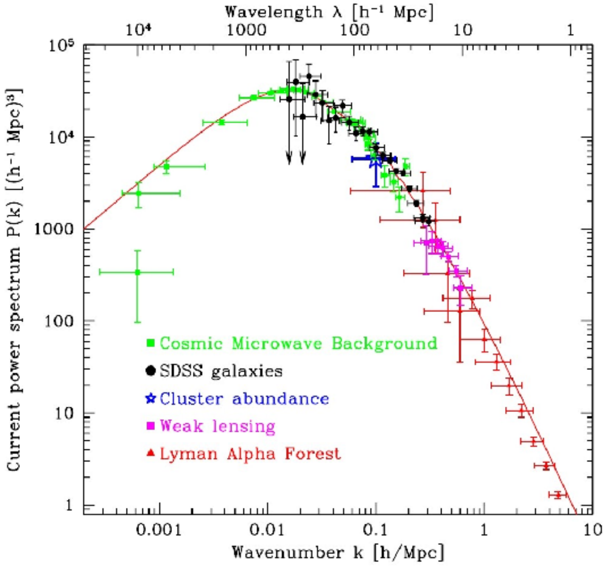
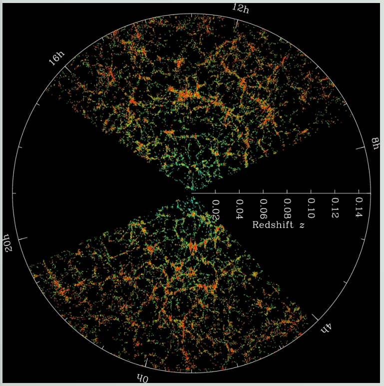
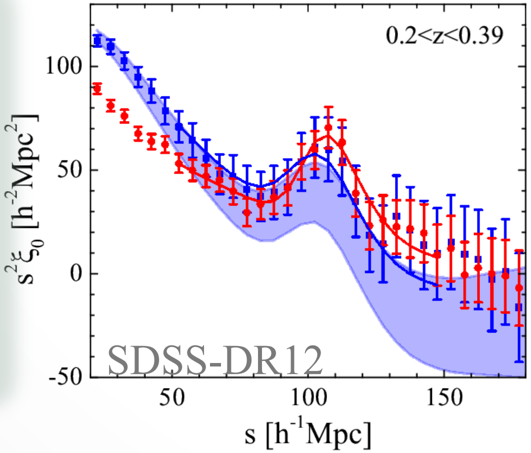
Observables



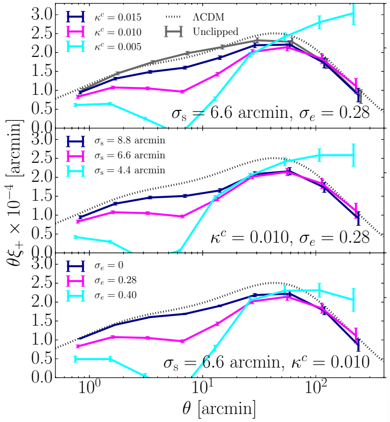
Galaxy surveys



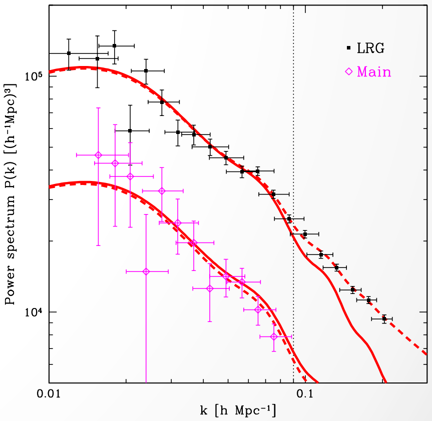
BAO



Cosmic shear



Galaxy clustering

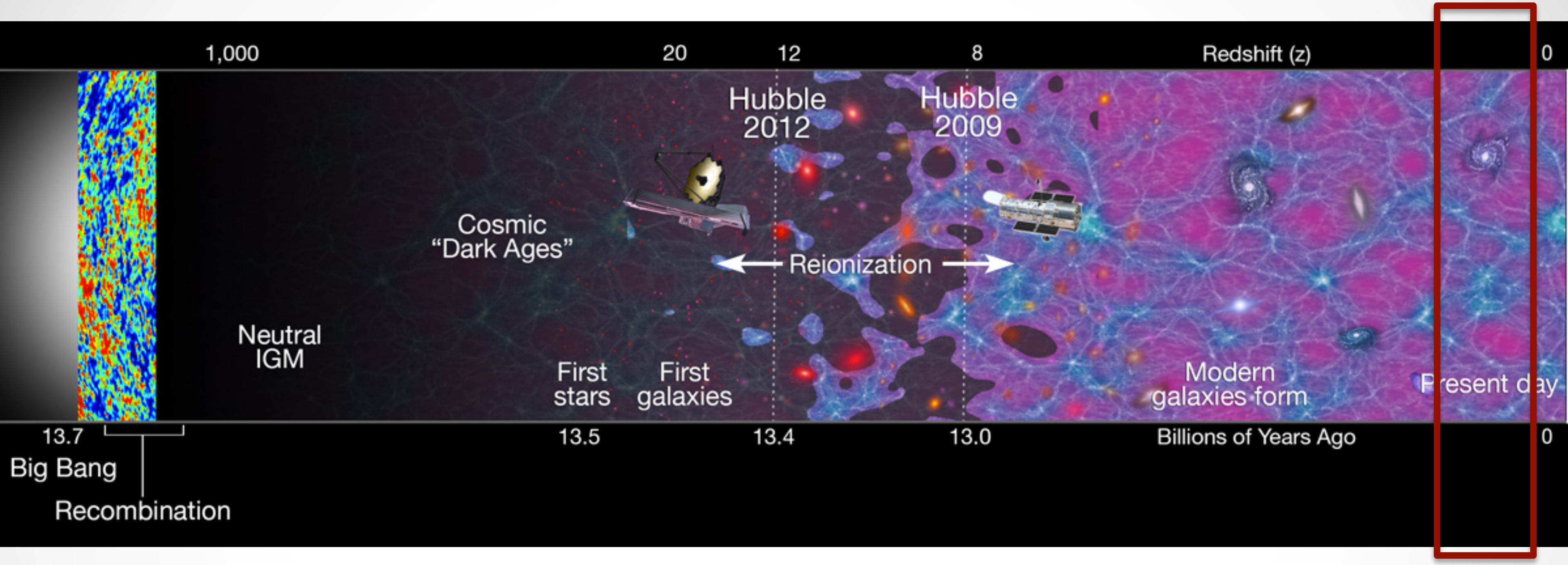


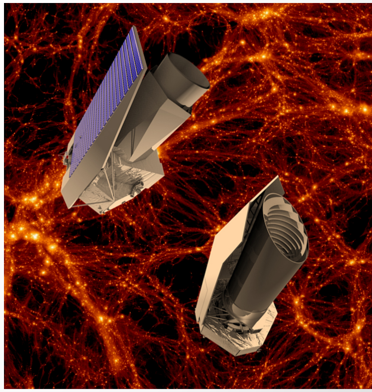
KiDS

Giblin+ MNRAS(2018)

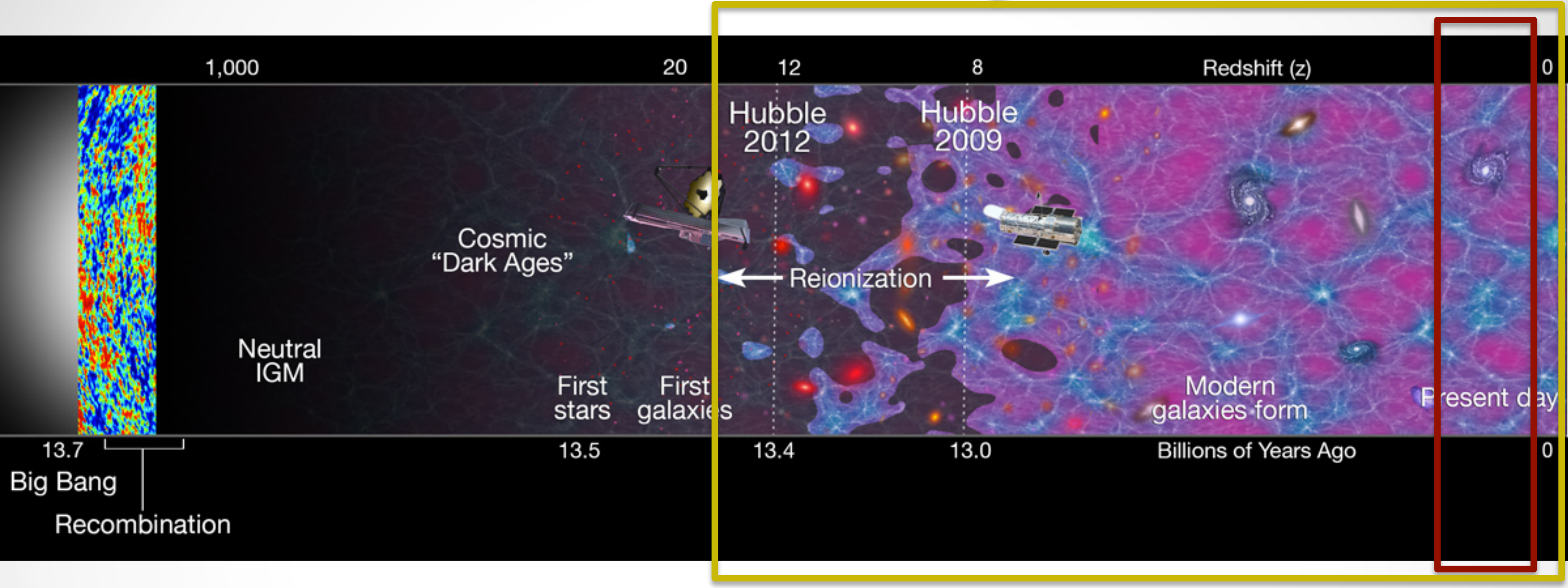
Tegmark+ PRD(2006)

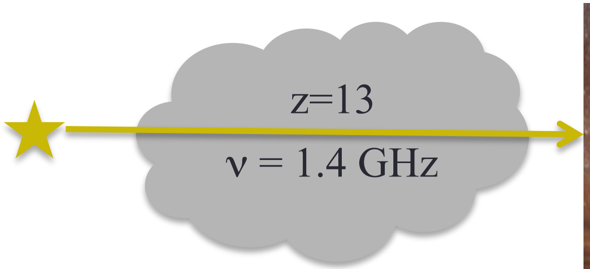
Future surveys





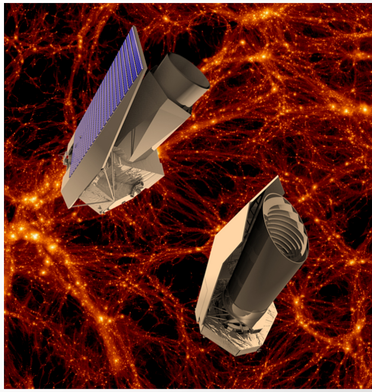
Future surveys





$z=13$

$\nu = 1.4$ GHz



$$P_{21}(k,z) = \Delta T_b^2 \, b_{HI}^2 \, P_m(k,z)$$

Neutrino non-relativistic transition

When neutrinos become non-relativistic

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

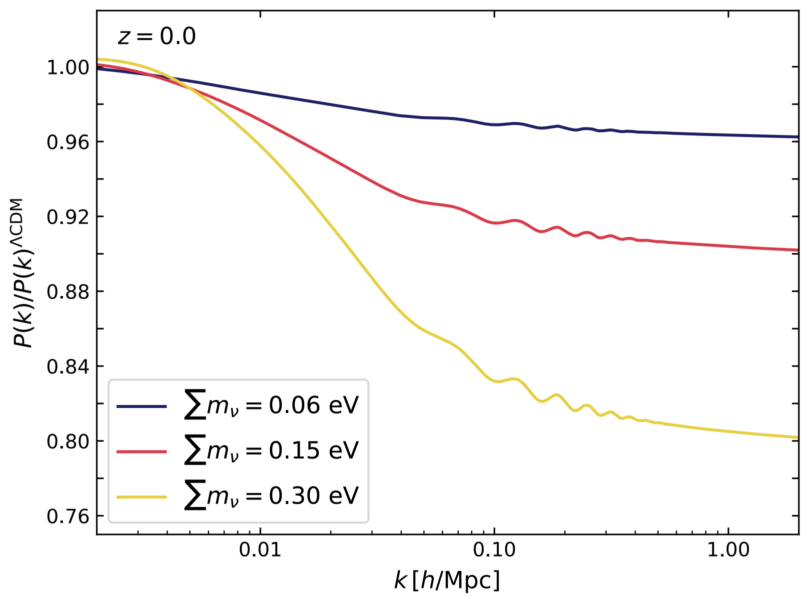
they travel through the Universe with a thermal velocity

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

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 & P(k)

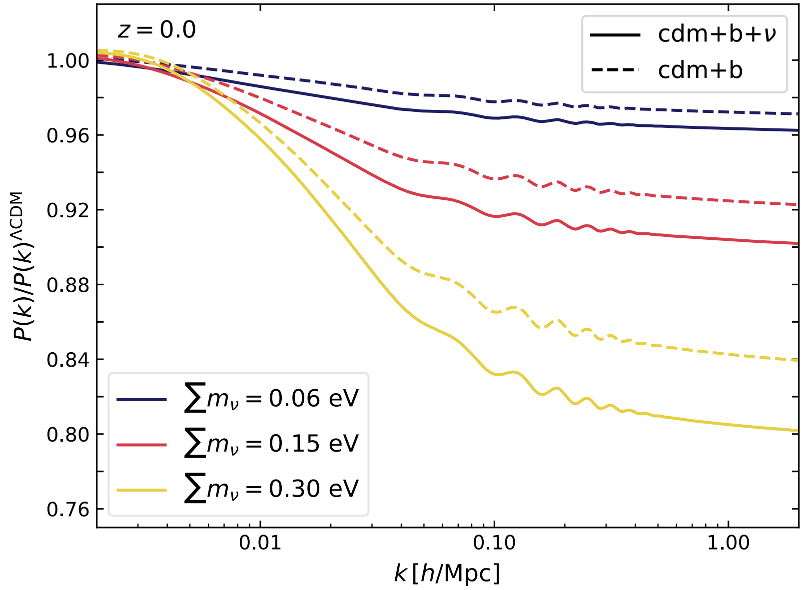


$\delta_{cdm} \propto a$ Massive neutrino Universe

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

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

Neutrino mass & $P_g(k)$



$\delta_{cdm} \propto a$ Massive neutrino Universe

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

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

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

Castorina+ JCAP (2014)

$$P_g(k,z) = b_{cb}^2(k,z) P_{cb}(k,z)$$

$$b_{cb}(k,z) = \sqrt{\frac{P_{hh}(k,z)}{P_{cb}(k,z)}}$$

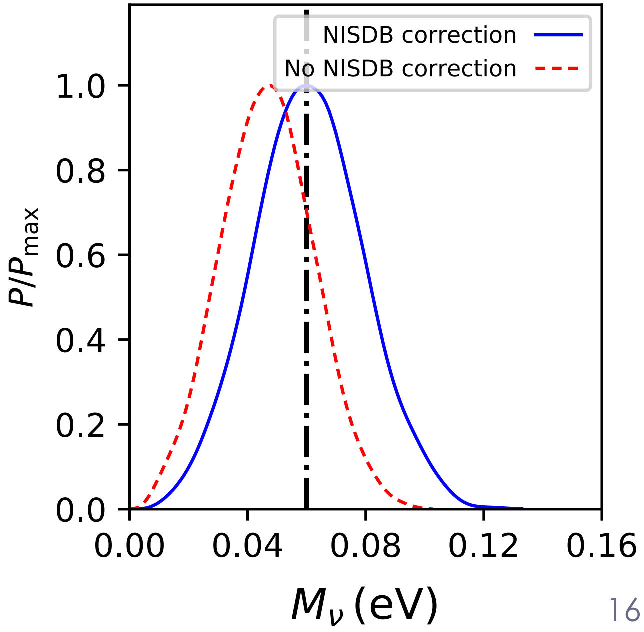
Planck+Euclid-GC

Fiducial Σm_ν=0.060 eV

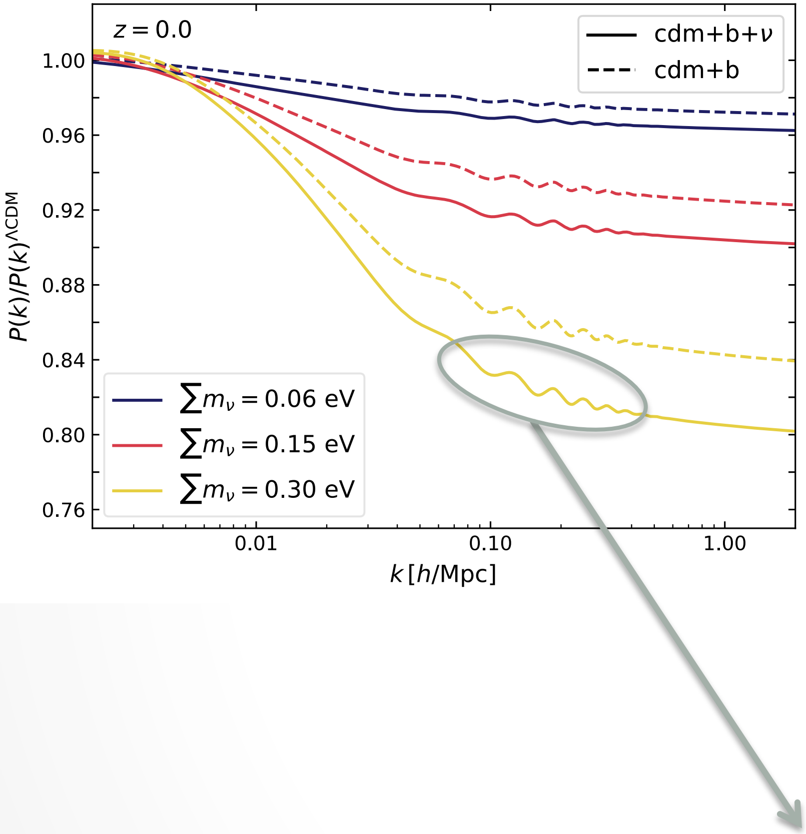
$\sigma(\Sigma m_\nu)$=0.015 eV

$\sigma(\Sigma m_\nu)$=0.019 eV

Vagnozzi+ JCAP (2018)



Neutrino mass & BAO



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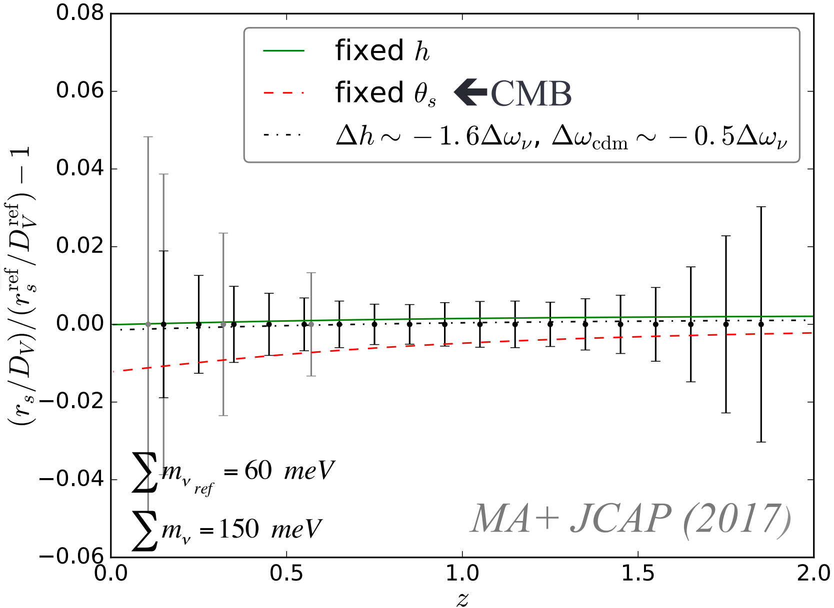
$$\boxed{\frac{P_m(k)^{\nu}}{P_m(k)^{\Lambda CDM}} \approx 1 - 8 f_\nu}$$

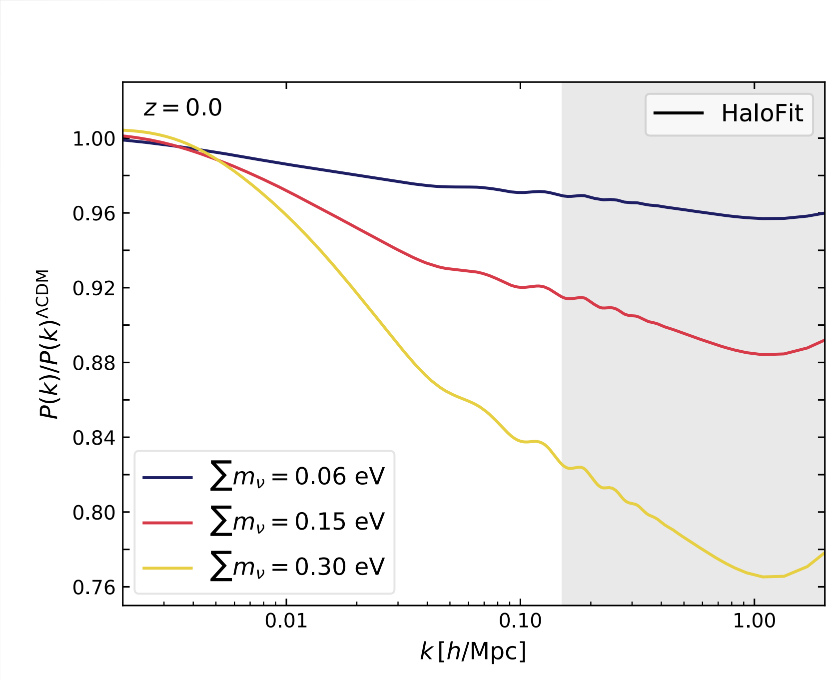
$$\frac{P_c(k)^{\nu}}{P_c(k)^{\Lambda CDM}} \approx 1 - 6 f_\nu$$

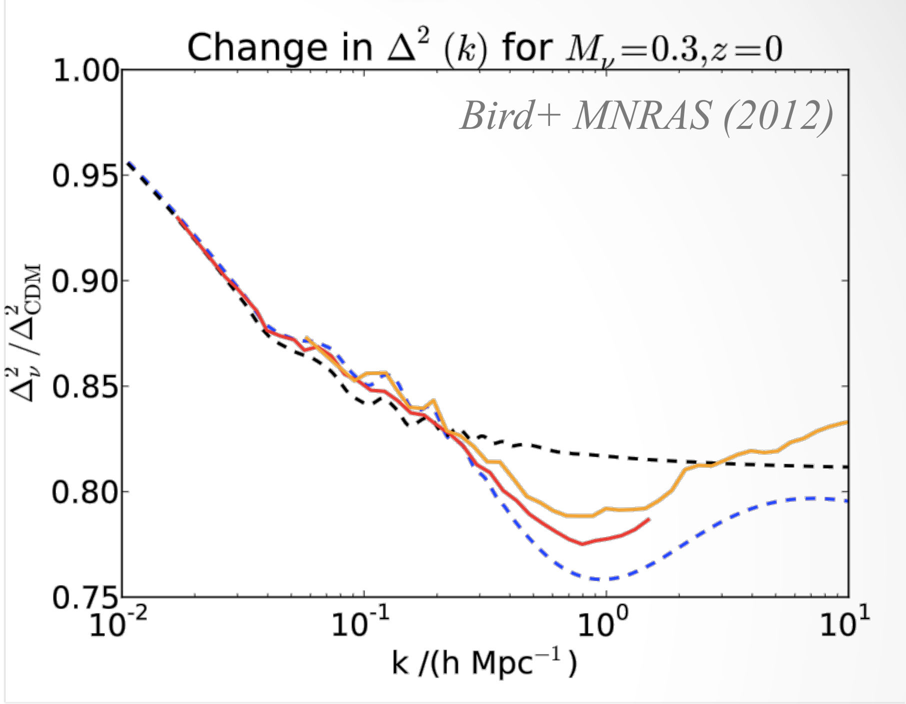


MA+ JCAP (2017)

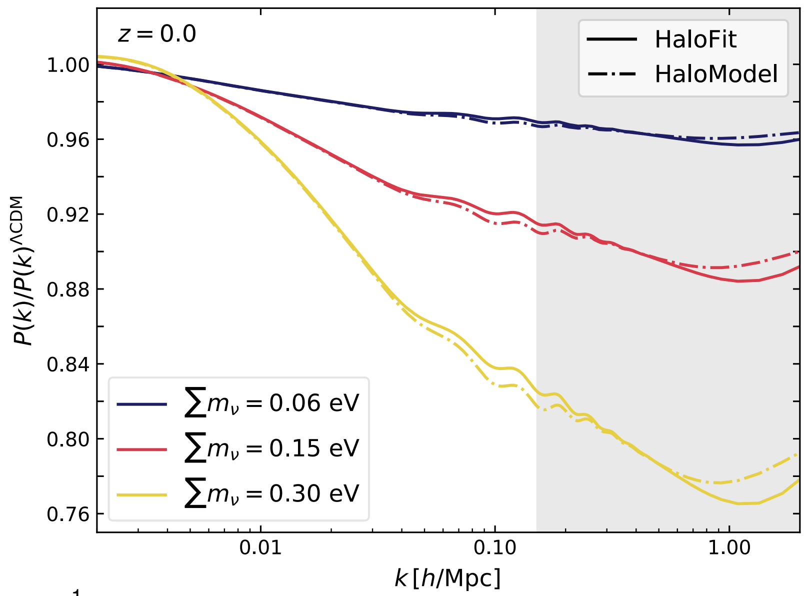
The strong degeneracy between M_ν and H_0 observed in the CMB cannot exist with BAO

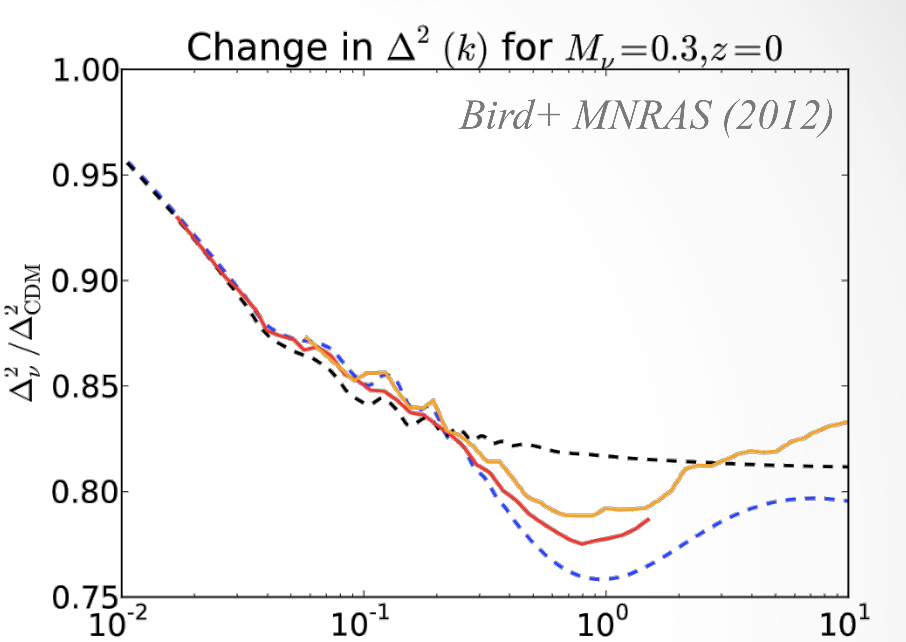
Neutrino mass & $P_{nl}(k)$

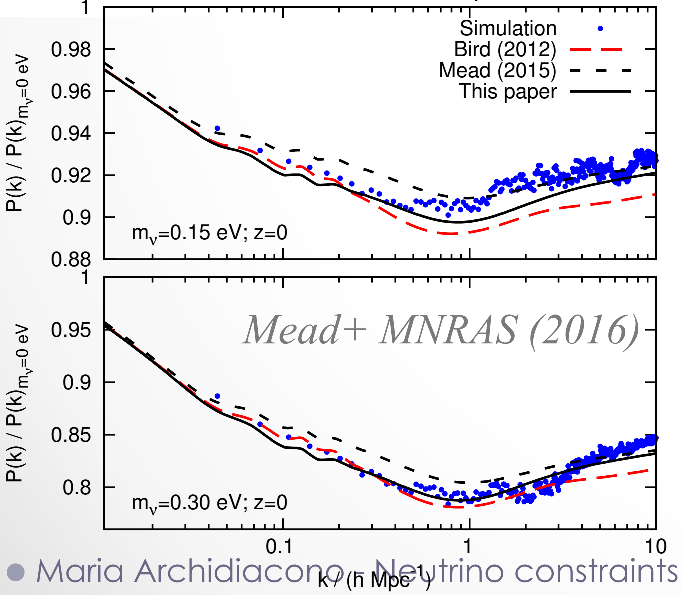


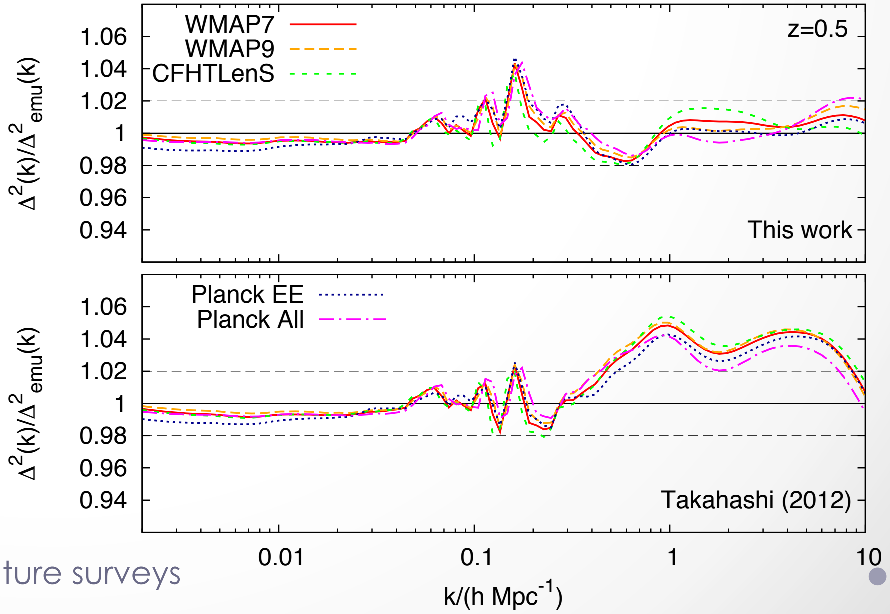


Neutrino mass & $P_{nl}(k)$

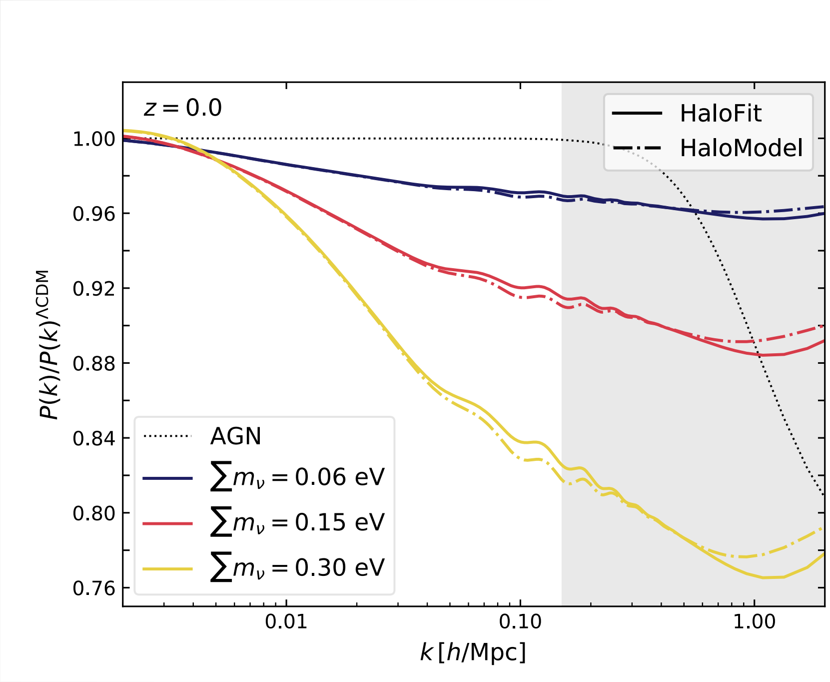




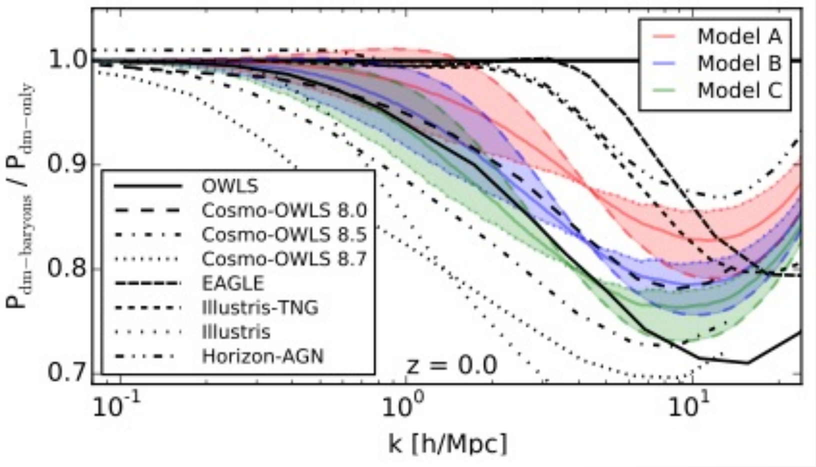


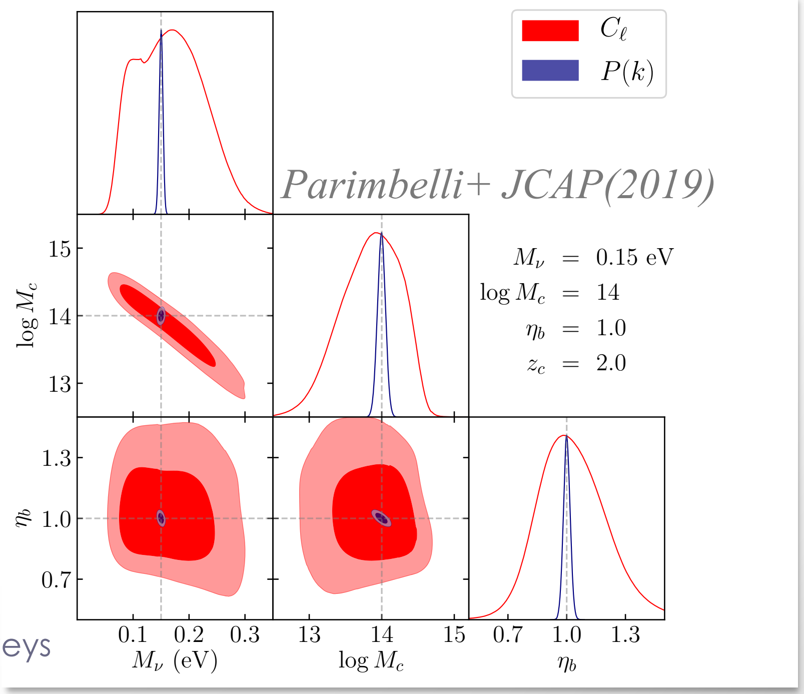


Neutrino mass & $P_{nl}(k)$+BF



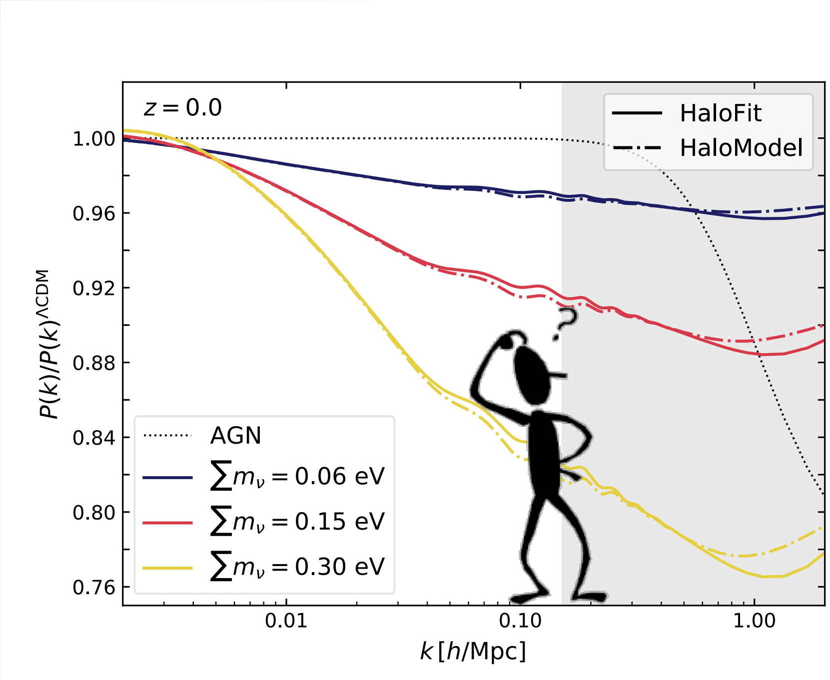
Schneider+ (2018)





Parimbelli+ JCAP(2019)

Neutrino mass & $P_{nl}(k)$+BF



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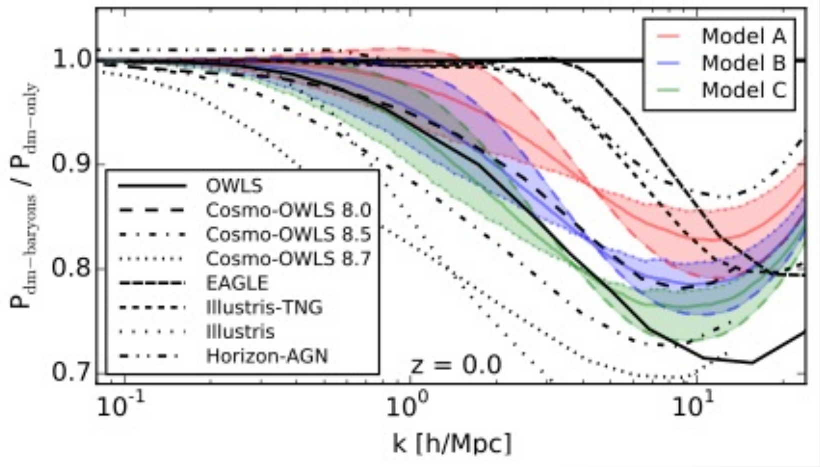
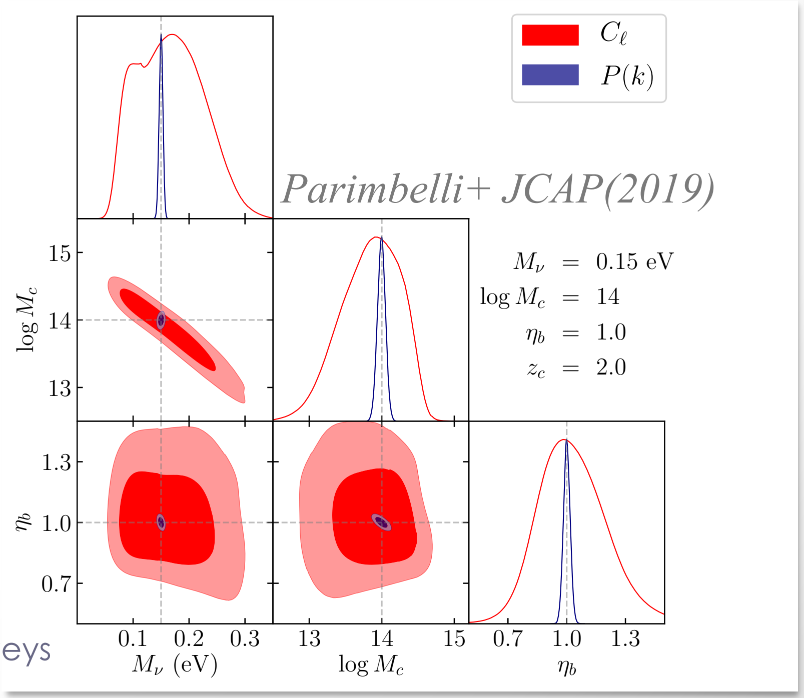
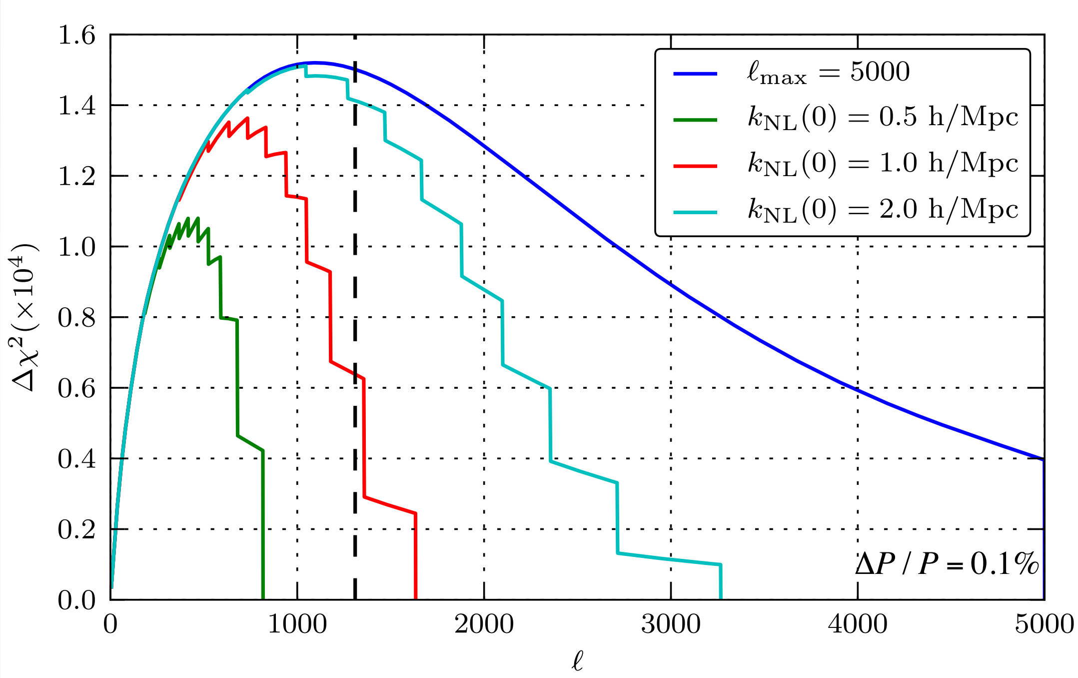




Parimbelli+ JCAP(2019)

How can we exploit the information without neglecting the uncertainties?

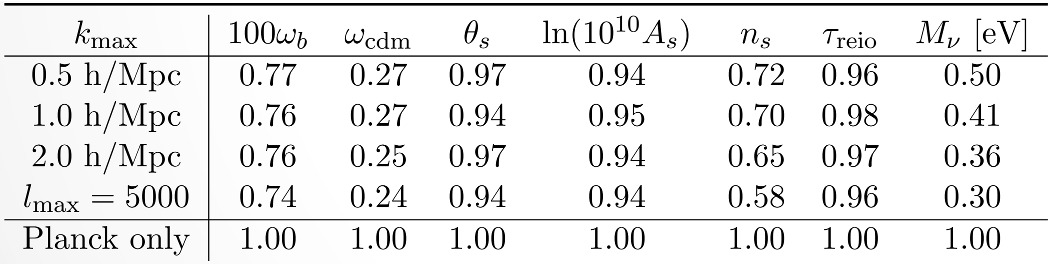
Theoretical uncertainties: CS-2D



Sprenger, MA+ JCAP (2019)

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

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



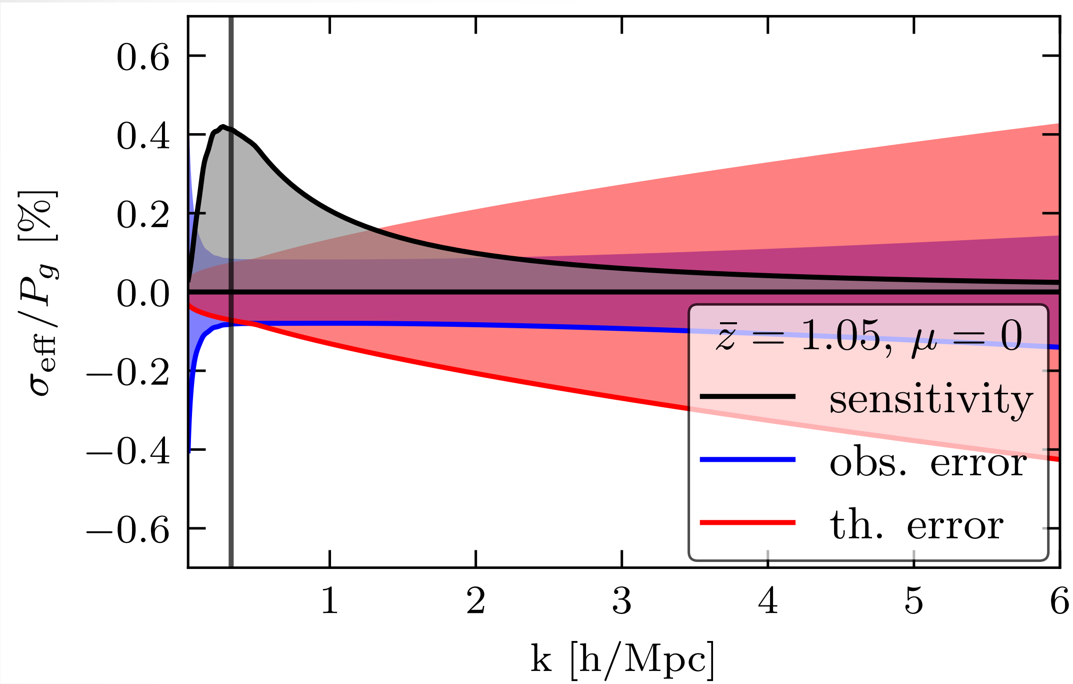
$k_{\max}$	$100\omega_b$	$\omega_{\rm cdm}$	θ_s	$\ln(10^{10}A_s)$	n_s	$\tau_{\rm reio}$	M_ν [eV]
0.5 h/Mpc	0.77	0.27	0.97	0.94	0.72	0.96	0.50
1.0 h/Mpc	0.76	0.27	0.94	0.95	0.70	0.98	0.41
2.0 h/Mpc	0.76	0.25	0.97	0.94	0.65	0.97	0.36
$l_{\max} = 5000$	0.74	0.24	0.94	0.94	0.58	0.96	0.30
Planck only	1.00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

	Planck+Euclid-CS
Conservative	43 meV
Optimistic	30 meV

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

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

Theoretical uncertainties: GC-3D



Sprenger, MA+ JCAP (2019)

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

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

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

$$\alpha = \frac{\delta P_g}{P_g}\left\{\begin{array}{ll}\text{0.33\% at k=0.01 h/Mpc} & \text{increasing with k}\\ \text{1\% at k=0.3 h/Mpc} & \text{decreasing with z}\\ \text{10\% at k=10 h/Mpc} & \end{array}\right.$$

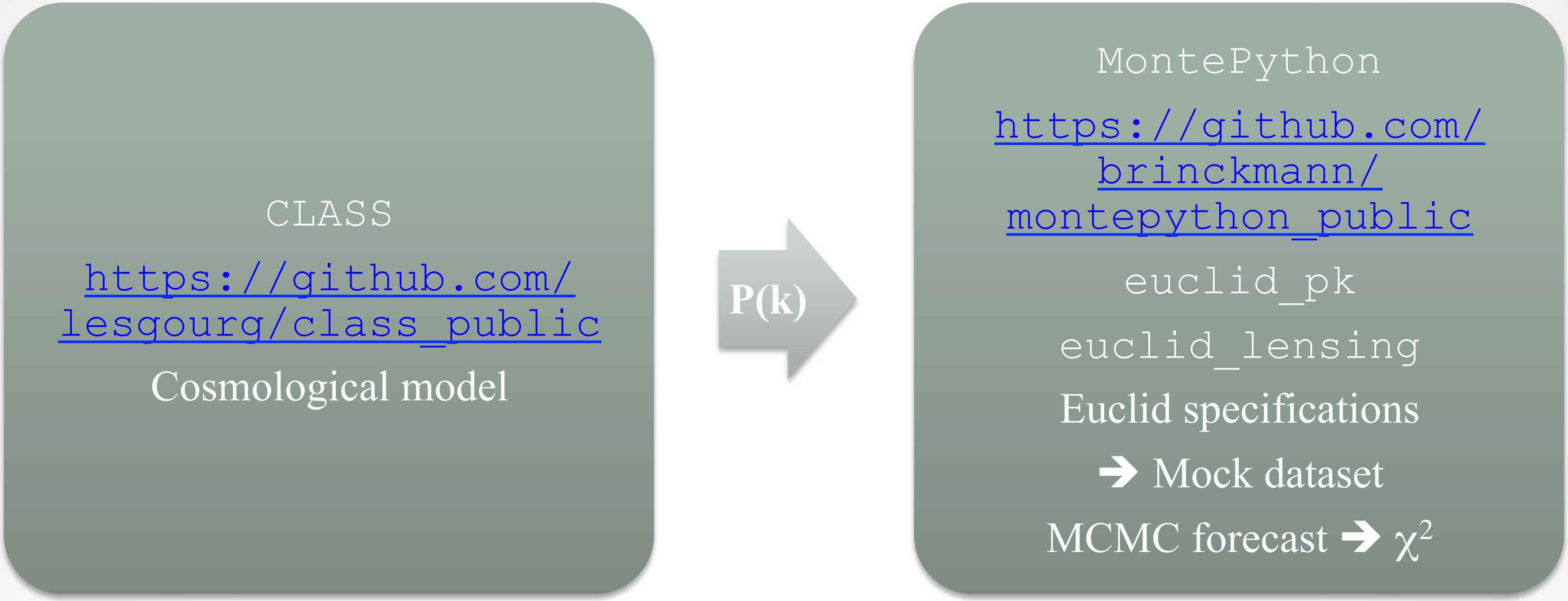
Conservative: $k_{nl}(0)$=0.2 h/Mpc

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

	Planck+Euclid-GC
Conservative	26 meV
Optimistic	20 meV

Future sensitivity to Σm_ν

Sprenger, MA+ JCAP (2019)



`CLASS`

[`https://github.com/lesgourg/class_public`](https://github.com/lesgourg/class_public)

Cosmological model

P(k)

`MontePython`

[`https://github.com/brinckmann/montepython_public`](https://github.com/brinckmann/montepython_public)

`euclid_pk`

`euclid_lensing`

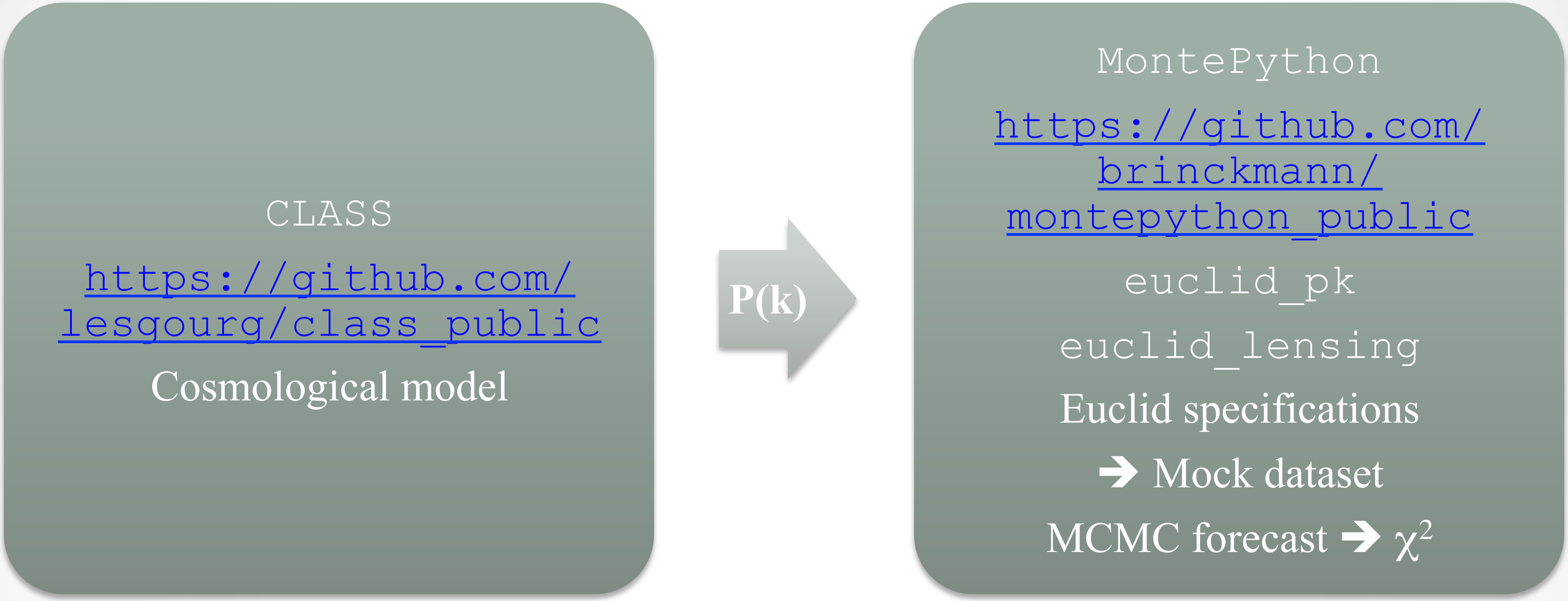
Euclid specifications

➔ Mock dataset

MCMC forecast ➔ χ^2

Future sensitivity to Σm_ν

Sprenger, MA+ JCAP (2019)



CLASS

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Cosmological model

P(k)

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https://github.com/brinckmann/montepython_public

`euclid_pk`

`euclid_lensing`

Euclid specifications

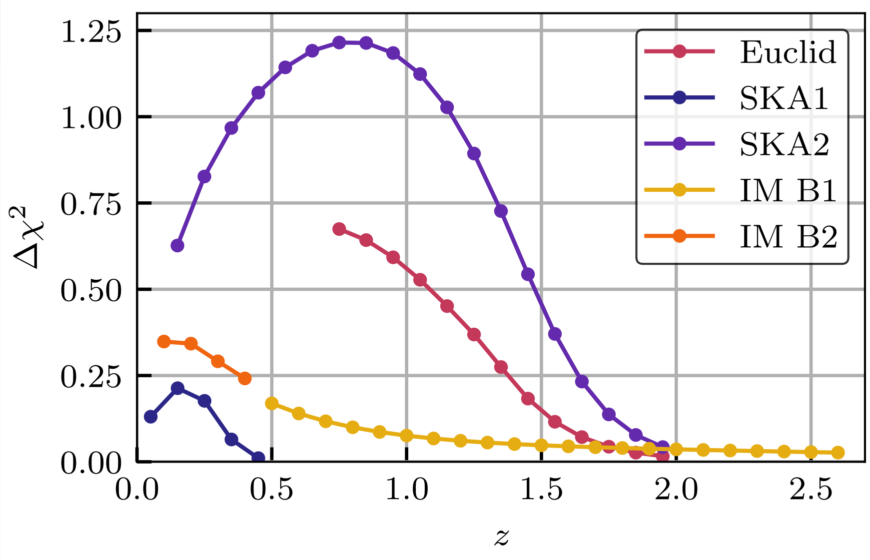
➔ Mock dataset

MCMC forecast ➔ χ^2

	Planck+Euclid
Conservative	24 meV
Optimistic	20 meV

Future sensitivity to Σm_ν

Sprenger, MA+ JCAP (2019)



`MontePython`

[`https://github.com/brinckmann/montepython_public`](https://github.com/brinckmann/montepython_public)

`ska_pk`

`ska_lensing`

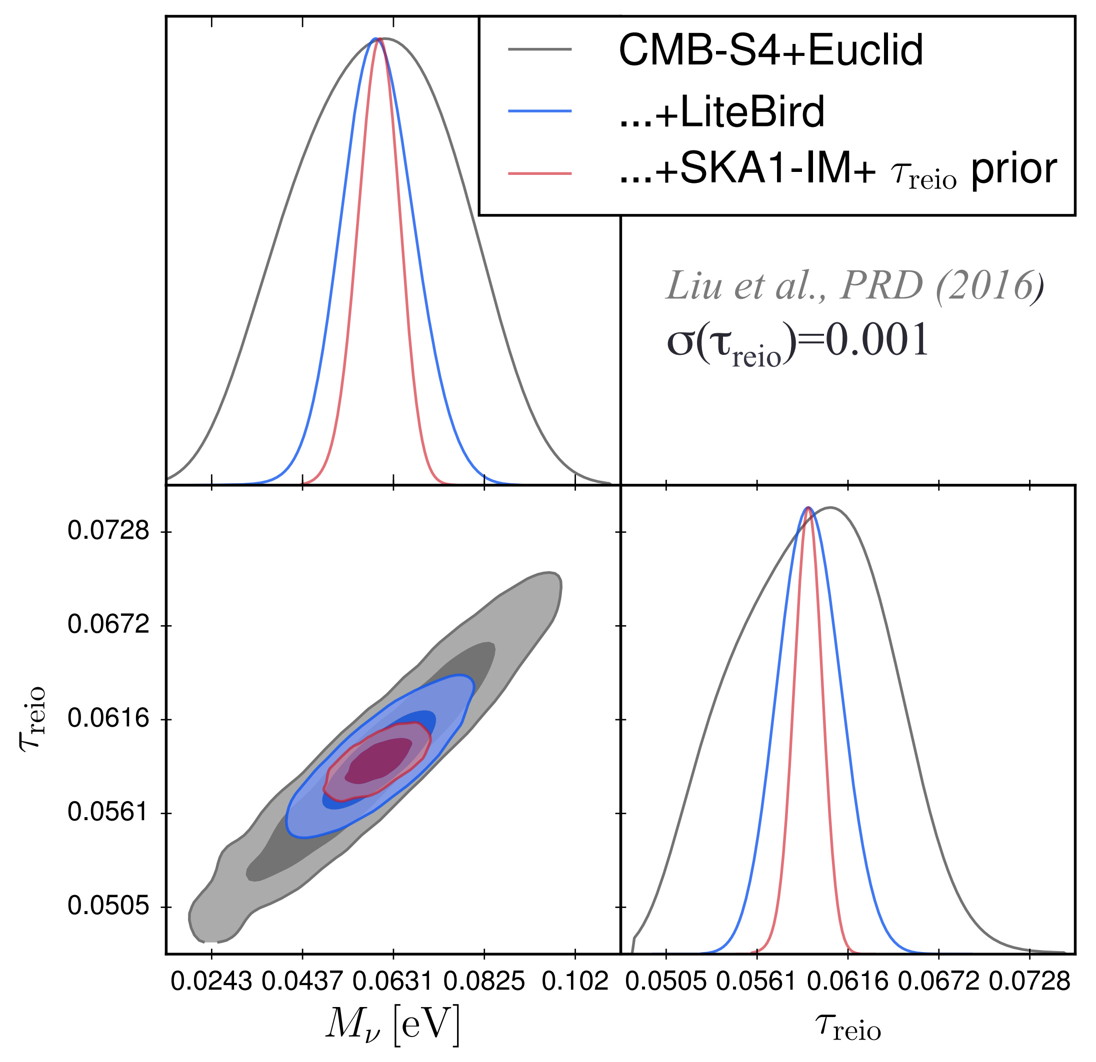
`ska_IM`

SKA specifications

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

Probe combination

Brinckmann, Hooper, MA+ JCAP (2019)

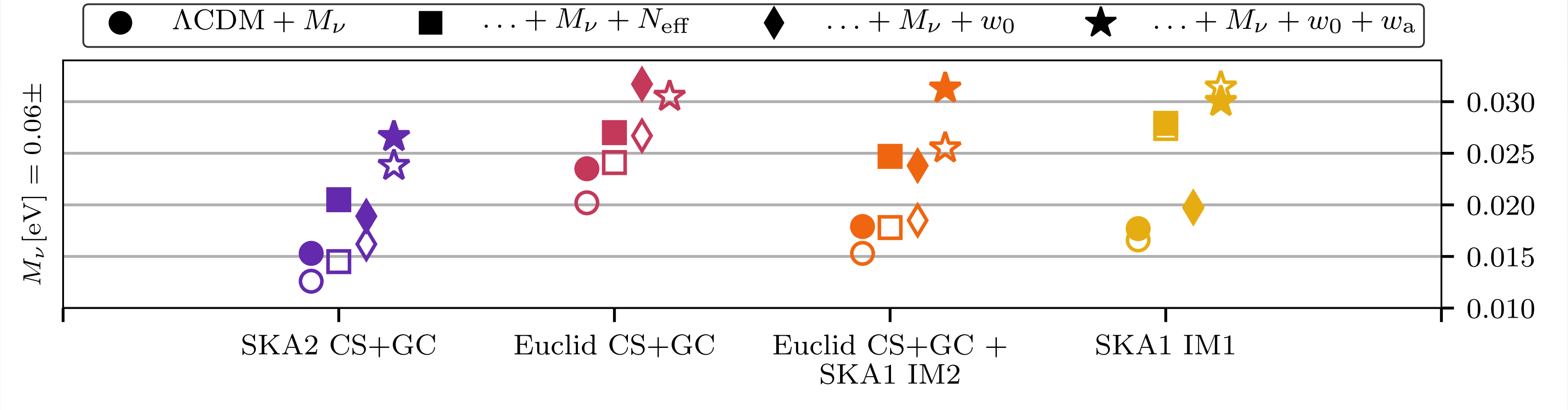


Liu et al., PRD (2016)

$\sigma(\tau_{\rm reio})=0.001$

Model dependence

Sprenger, MA+ JCAP (2019)



☐ 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

$N_{eff}^{SM} = 3.045$ *deSalas+ JCAP (2016)*

Conclusions

- Future galaxy and hydrogen surveys will be able to detect the neutrino mass sum in the minimal extension of the ΛCDM

- Caveats:
  - Systematic effects
  - Theoretical uncertainties
  - Model dependence

- Future constraints on N_{eff} might shed light on physics beyond the Standard Model

- Final remark: synergies with ground-based neutrino experiments