COSMOLOGY: HUBBLE CONSTANT AND NEUTRINOS

XVIII International Workshop
on Neutrino Telescopes
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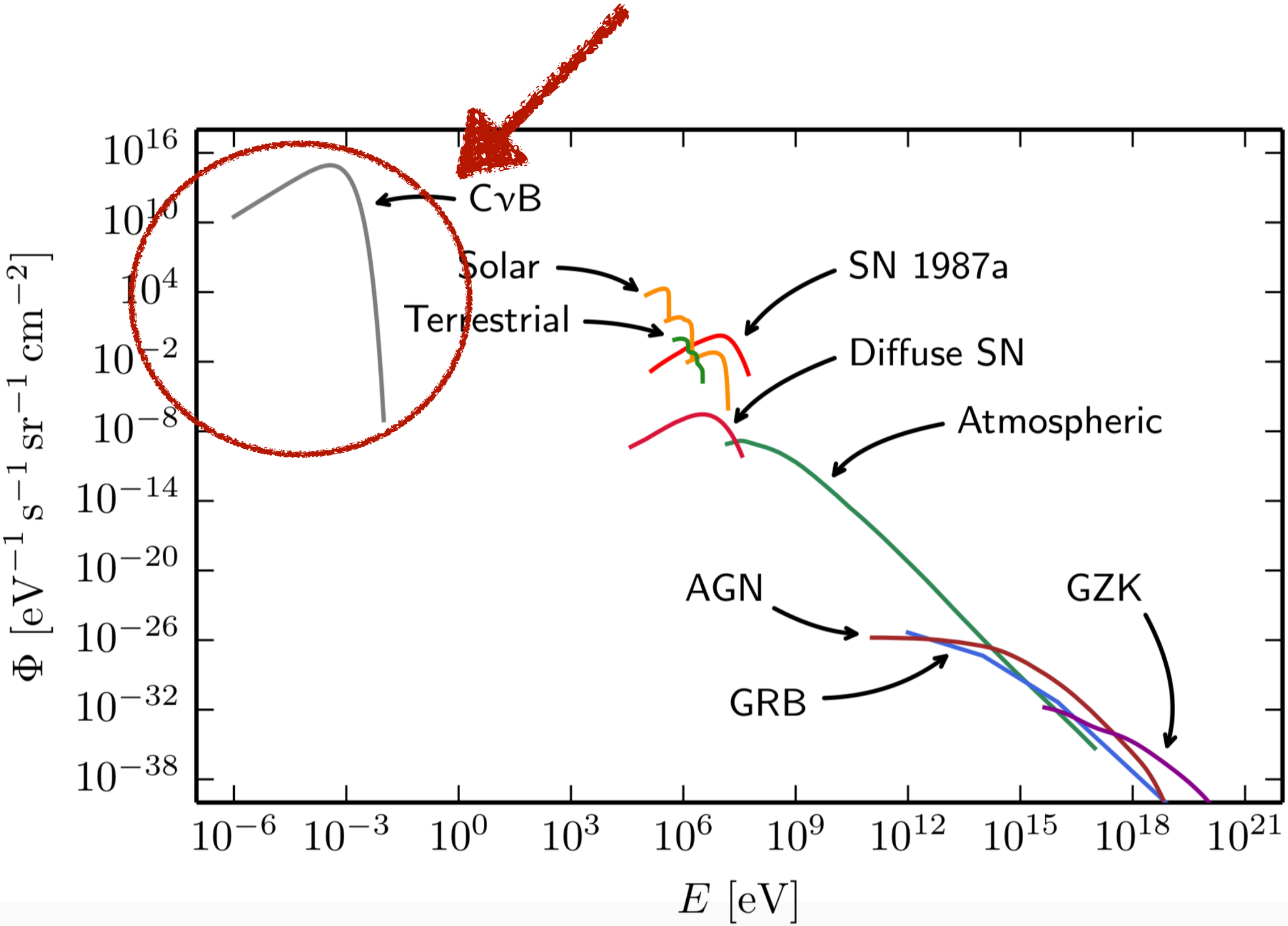
Martina Gerbino
Argonne National Laboratory



Adapted from Ali Kheirandish

Meet the Hubble constant H0

The Hubble constant is the present-day value of the expansion rate of the Universe

$$\frac{\dot{a}}{a} \equiv H(z)$$

$$H(z)^2 = H_0^2 \left[(\Omega_c + \Omega_b)(1+z)^3 + \Omega_\gamma (1+z)^4 + \Omega_\Lambda + \frac{\rho_\nu(z)}{\rho_{\mathrm{crit},0}} \right]$$

Why is it so important?

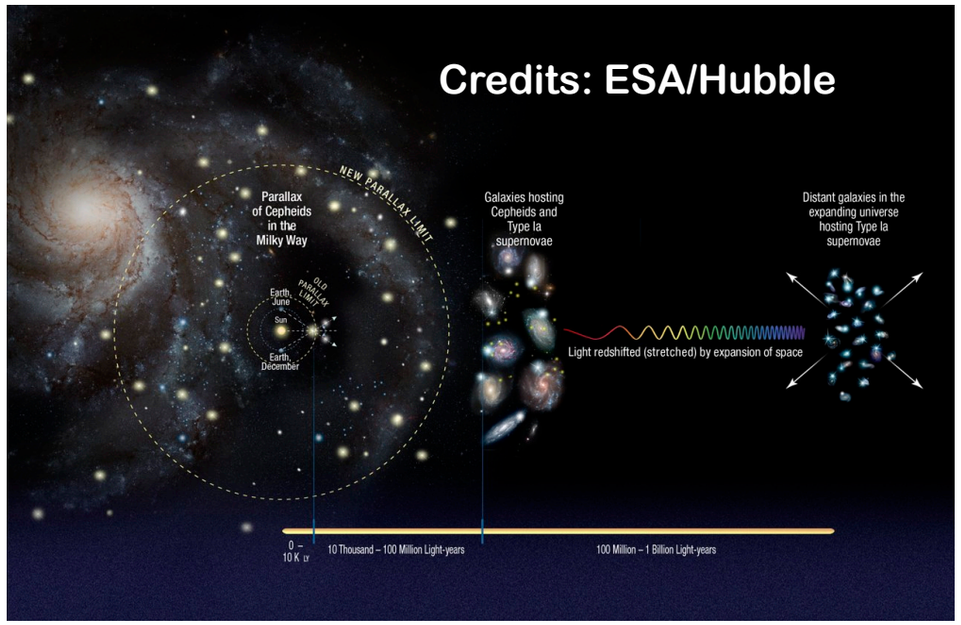
- It is one of the **key parameters** describing the Universe dynamics
- It is strictly related to the **expansion history and fate**
- It has the potential to **reveal new physics**

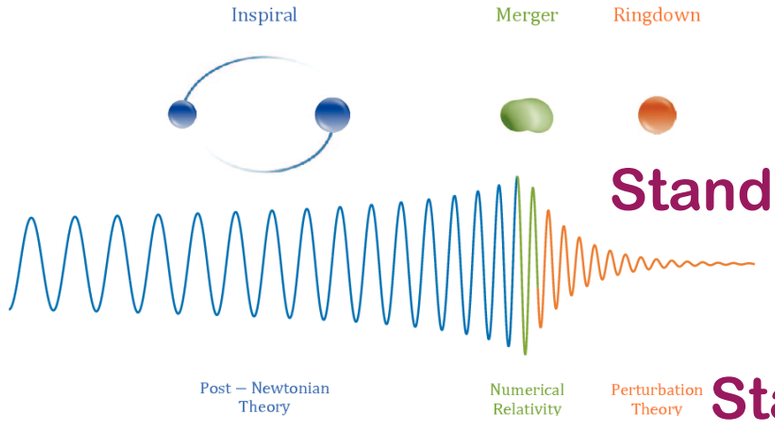
How to measure H0

Redshift increasing

Standard candles/distance ladder

1%



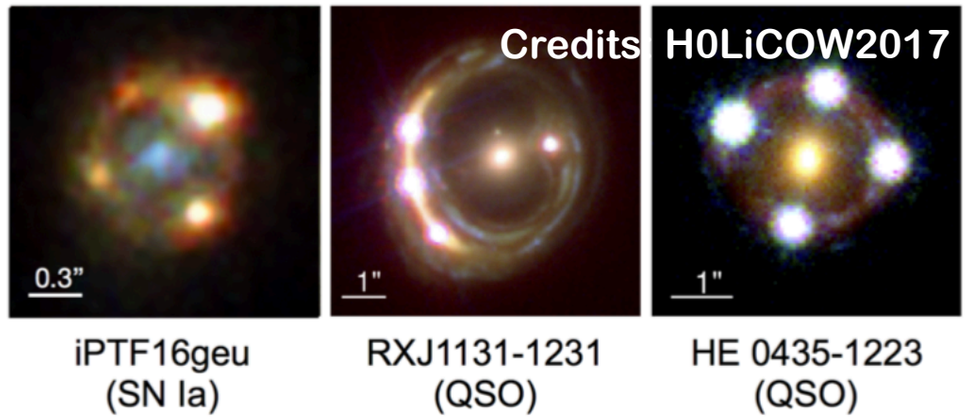


Standard sirens

10%

Standard clocks

3%



iPTF16geu (SN Ia) | RXJ1131-1231 (QSO) | HE 0435-1223 (QSO)

Standard rulers/inverse distance ladder

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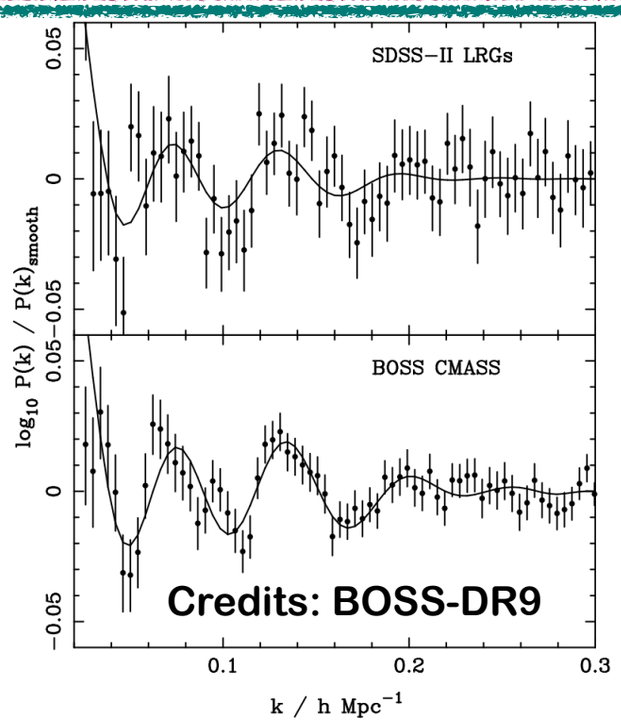
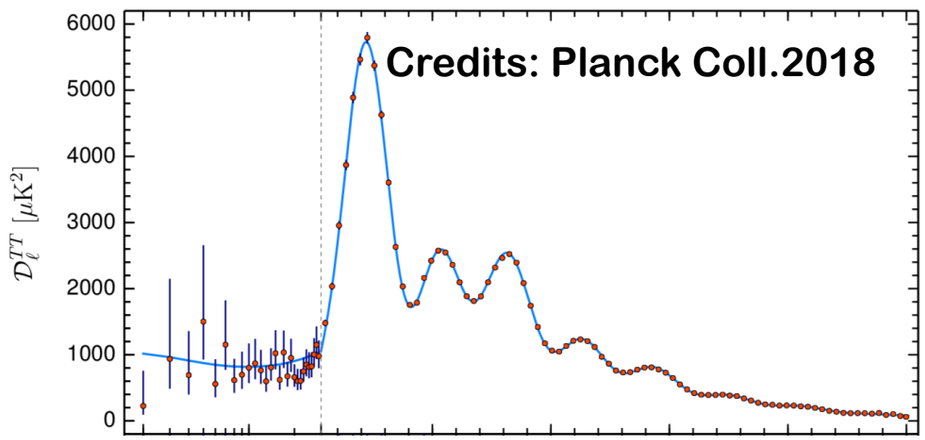
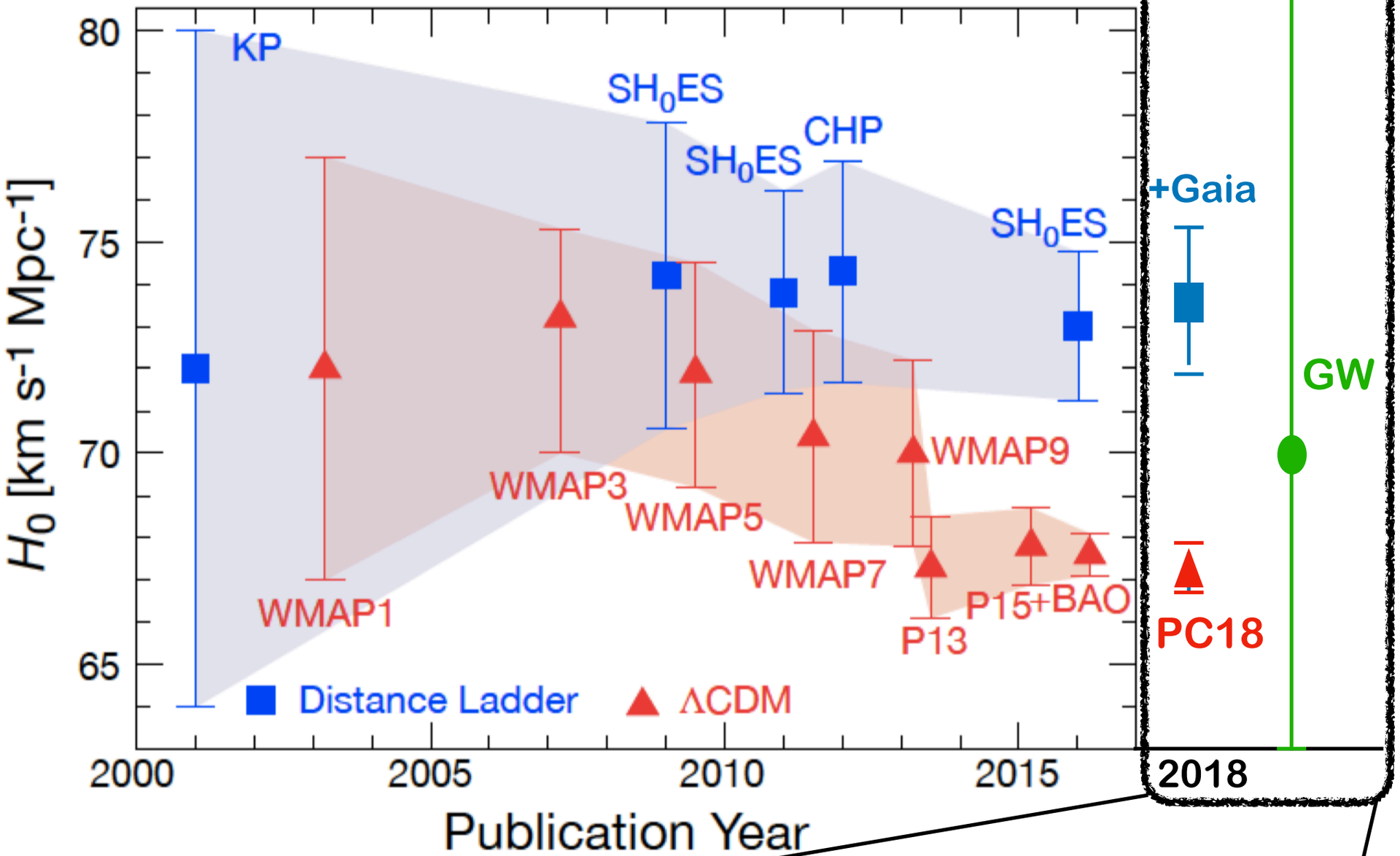




State of the art

Adapted from Freedman2017



$$H_0 = (73.52 \pm 1.62)\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

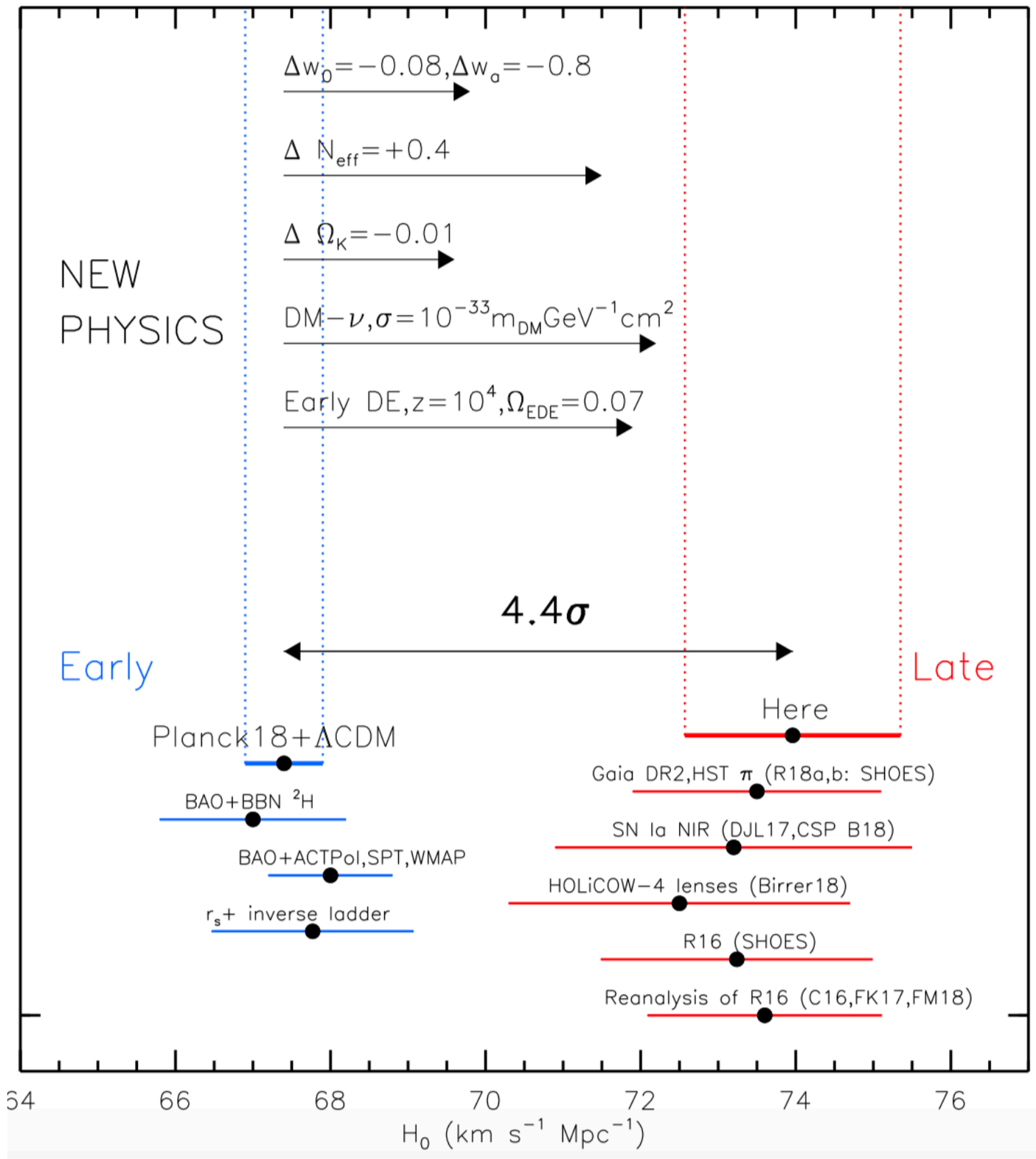
$$H_0 = (67.27 \pm 0.60)\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$$

3.6sigma tension in 2018

Riess+,2018

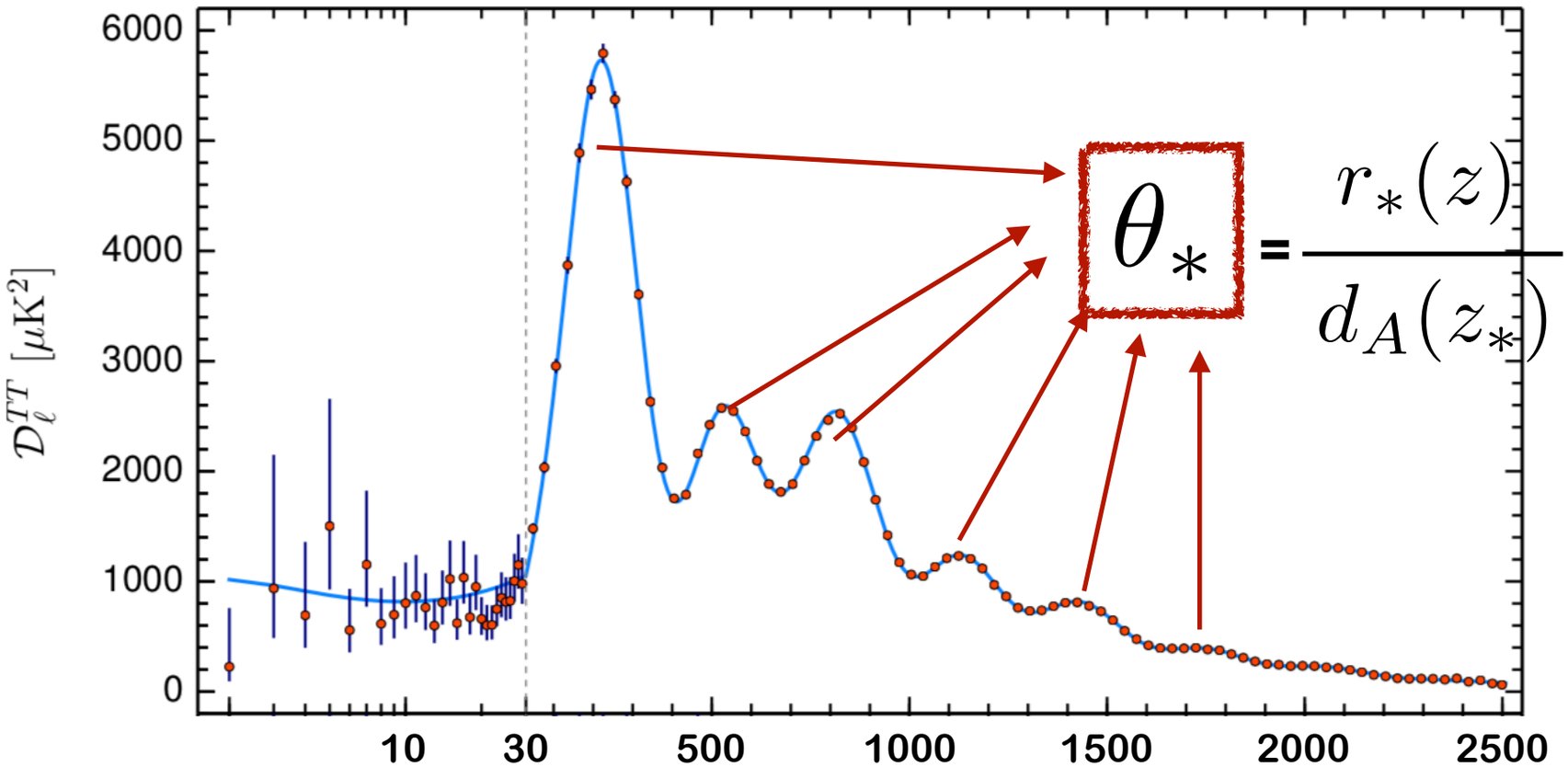
Planck Coll.VI,2018

State of the art - reboot



Riess+,2019

Solving the tension at high z



$$\theta_* = \frac{r_*(z)}{d_A(z_*)} = \frac{\int_{z_*}^{\infty} c_s \frac{dz}{H(z)}}{\int_0^{z_*} c \frac{dz}{H(z)}}$$

$$H_0 \equiv 100\, h\, \mathrm{km\, s^{-1}\, Mpc^{-1}}$$

$$\frac{r_*}{3000\,\mathrm{Mpc}} = \int_{z_*}^{\infty} \frac{c_s dz}{\left[\Omega_\gamma h^2 \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}} N_{\mathrm{eff}}\right)(1+z)^4 + \Omega_m h^2 (1+z)^3\right]^{1/2}}$$

$$\frac{d_A}{3000\,\mathrm{Mpc}} = \int_0^{z_*} \frac{dz}{\left[\Omega_m h^2 (1+z)^3 + \Omega_\Lambda h^2\right]^{1/2}}$$

Solving the tension at high z

What if the model is incorrect?

Several solutions suggested, with different shades of viability:

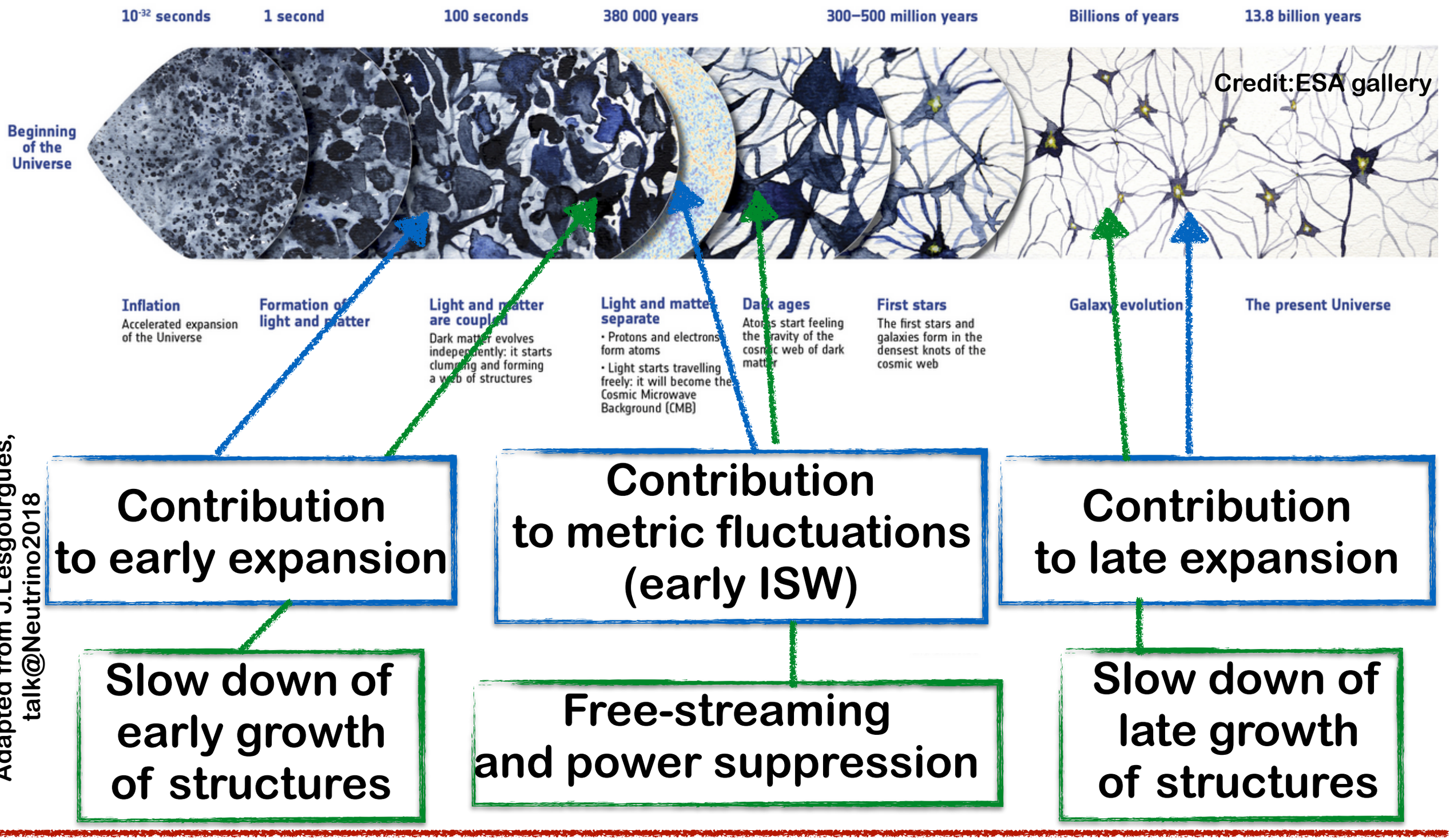
- **early dark energy**
- **curvature**
- **interacting dark sectors**
- **local void**
- **dynamical dark energy**
- **BSM neutrino physics**
- **decaying dark matter**
- **….**

Wilkinson+,2014; Berezhiani+,2015; Wu&Huterer,2017; DiValentino+,2017; Poulin+,2018; Planck Coll. VI,2018; Yang+,2018; Kreisch+,2019; …

Basics of neutrino cosmology

Relativistic | **Non-Relativistic**

$\rho_\nu \propto N_{\rm eff}$ | $\rho_\nu \propto \sum m_\nu$



Contribution to early expansion

Contribution to metric fluctuations (early ISW)

Contribution to late expansion

Slow down of early growth of structures

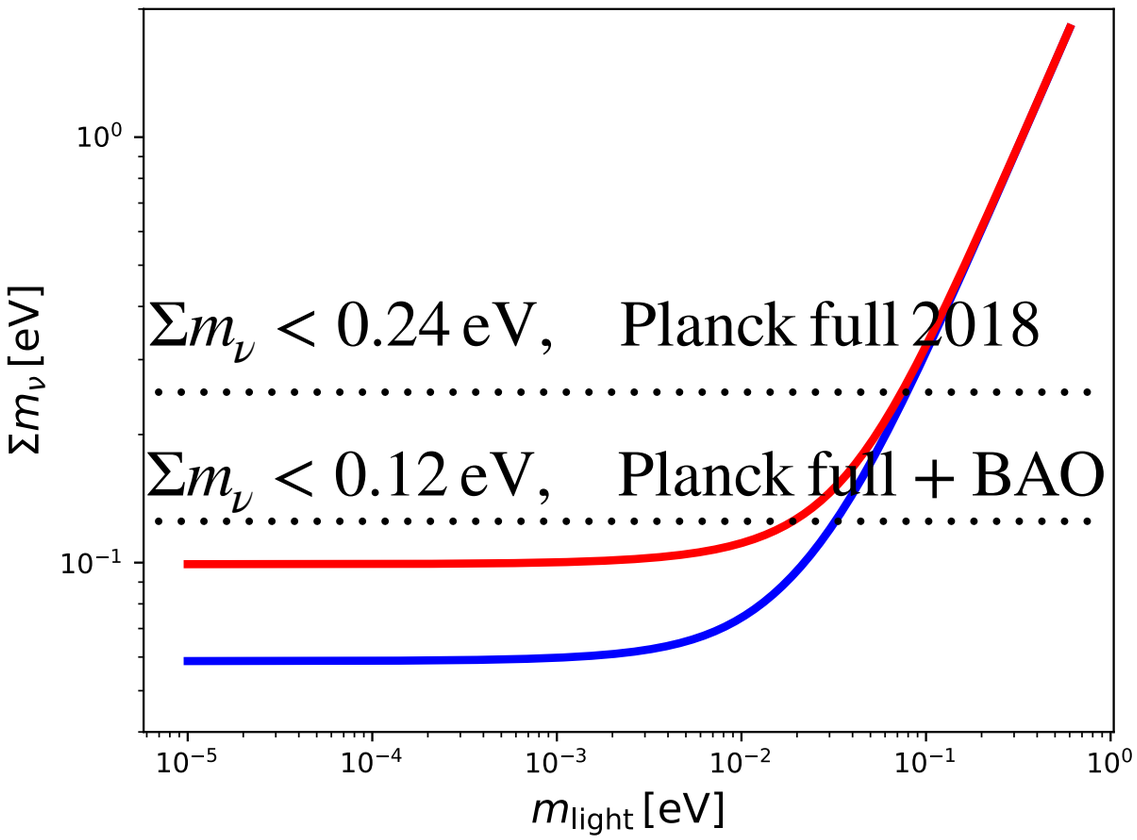
Free-streaming and power suppression

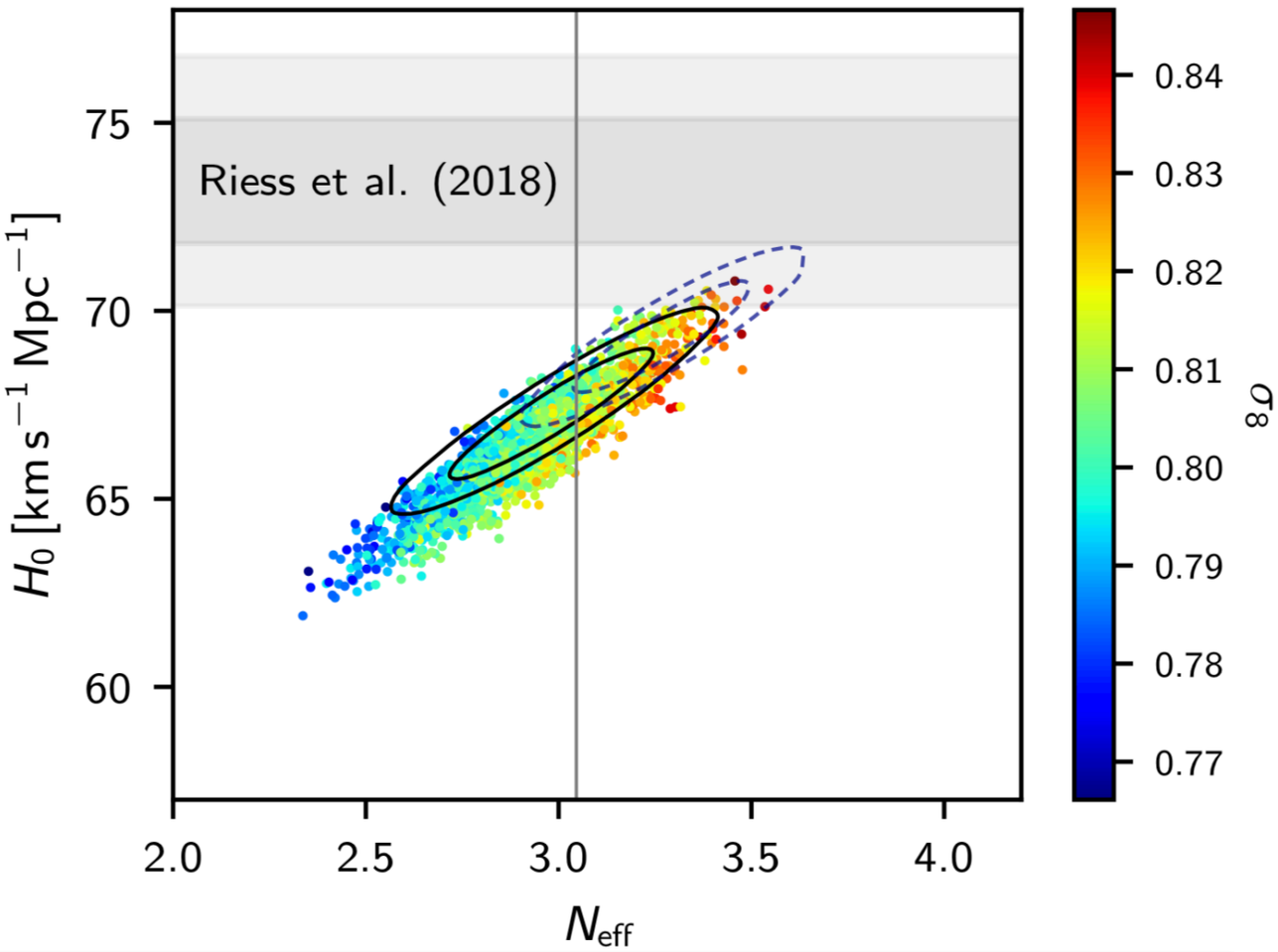
Slow down of late growth of structures

Adapted from J.Lesgourgues, talk@Neutrino2018

Constraints from CMB+LSS

Planck Collab. VI 2018





$N_{\mathrm{eff}} = 2.99^{+0.34}_{-0.33}$, 95 % *c . l .*, Planck2018 + BAO

Cosmology compatible with standard picture of three active, sub-eV neutrinos decoupling at ~1MeV and free-streaming

Note: Assuming LCDM. Figures may change in different cosmological scenarios

Solving the tension at high z

What if the model is incorrect?

Relieving the tension acting on the neutrino sector:

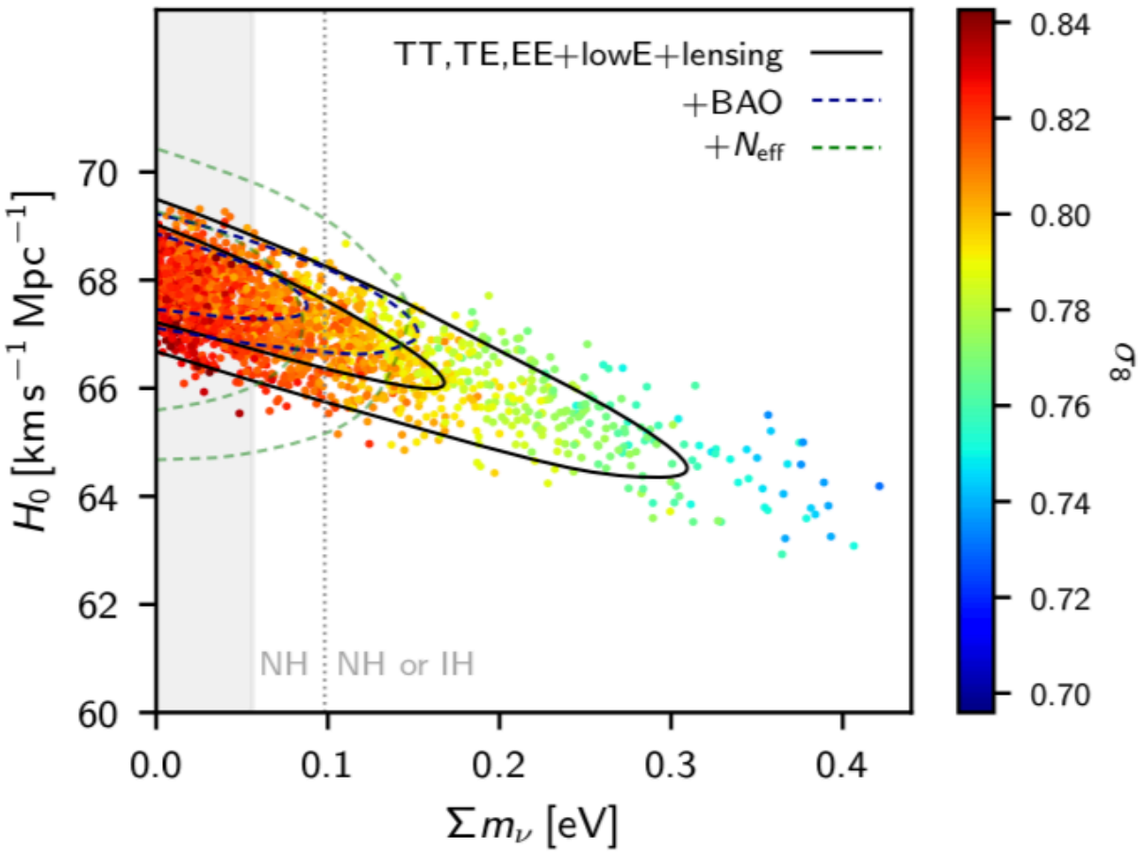
1) **massive neutrinos**

2) **additional relativistic species at recombination (e.g. light sterile)**

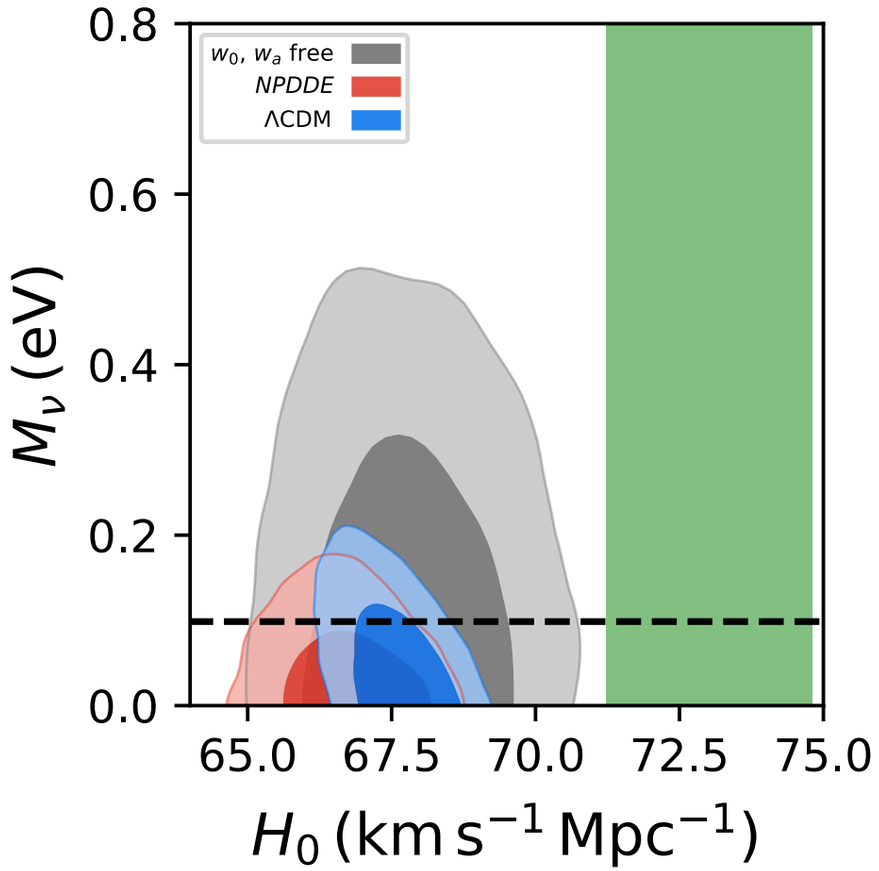
3) **neutrino non-standard interactions**

Relieving the tension with Sum mnu

Planck Collab. VI 2018



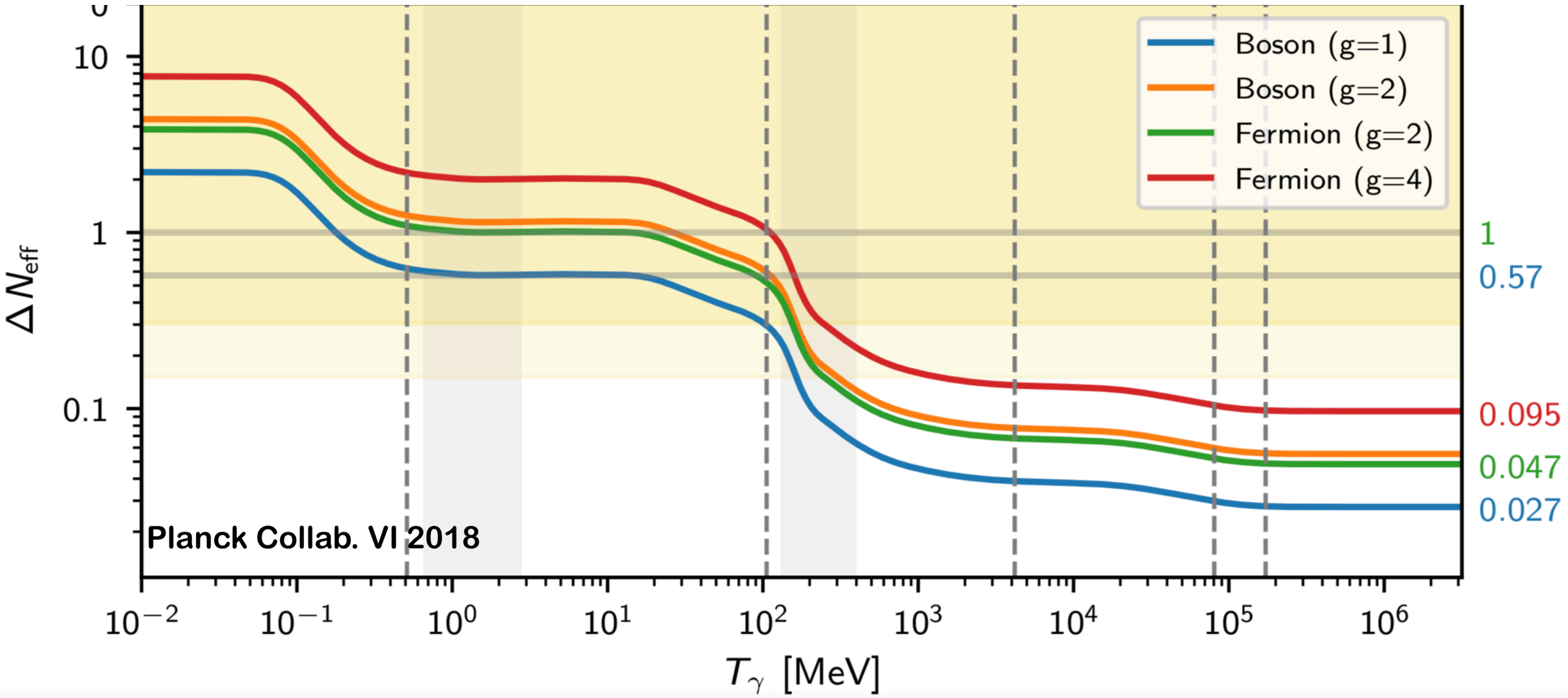
Vagnozzi+(incl MG),2018



$$\frac{r_*}{3000\,\mathrm{Mpc}} = \int_{z_*}^{\infty} \frac{c_s dz}{\left[\Omega_\gamma h^2 \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}} N_{\rm eff}\right)(1+z)^4 + \Omega_m h^2 (1+z)^3\right]^{1/2}}$$

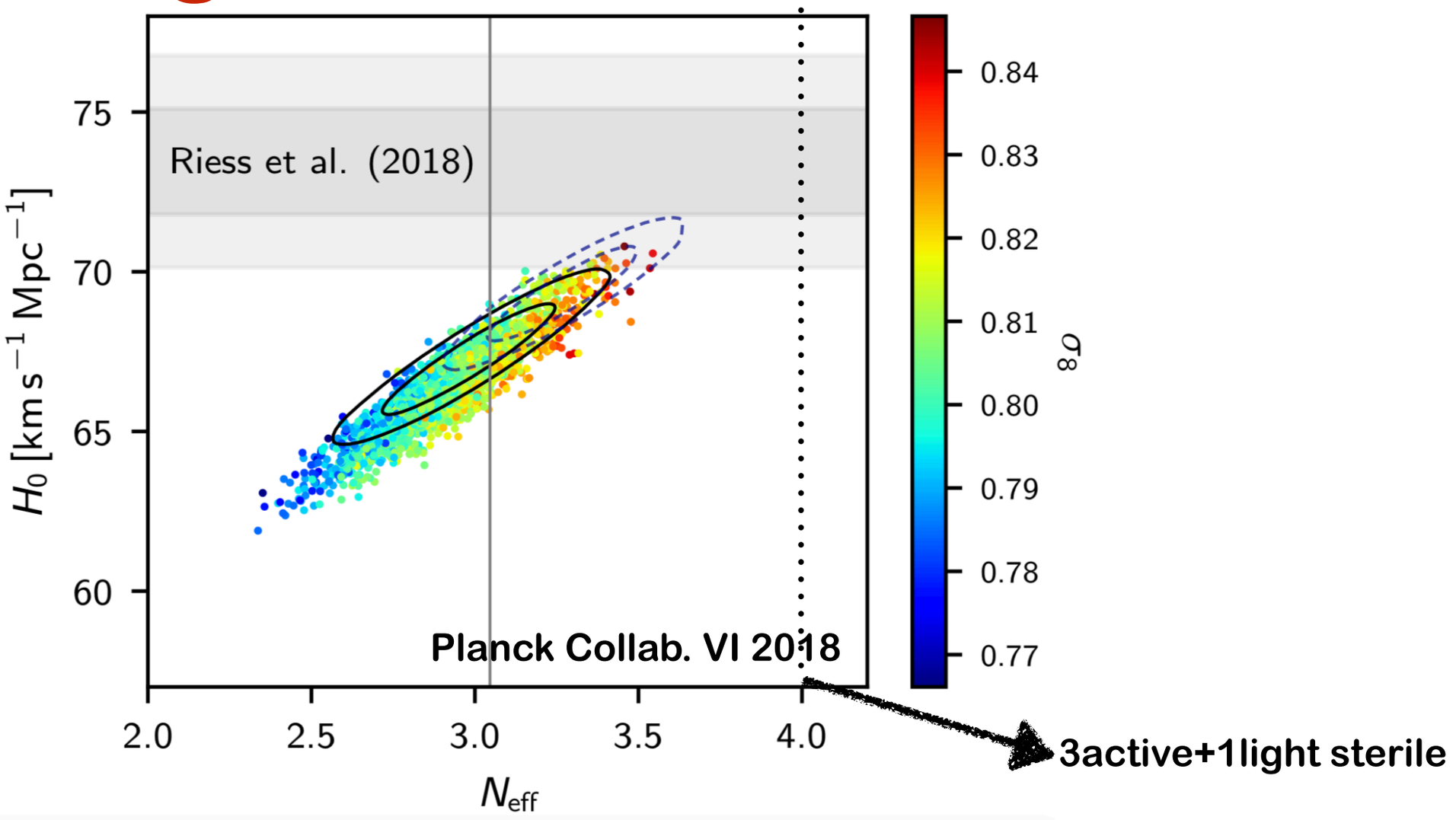
$$\frac{d_A}{3000\,\mathrm{Mpc}} = \int_0^{z_*} \frac{dz}{\left[\Omega_m h^2 (1+z)^3 + \Omega_\Lambda h^2\right]^{1/2}}$$

Relieving the tension with Neff



$$\rho_{\rm rad} = \rho_\gamma \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}} (N_{\rm eff,\nu} + \Delta N_{\rm eff})\right)$$

Relieving the tension with Neff

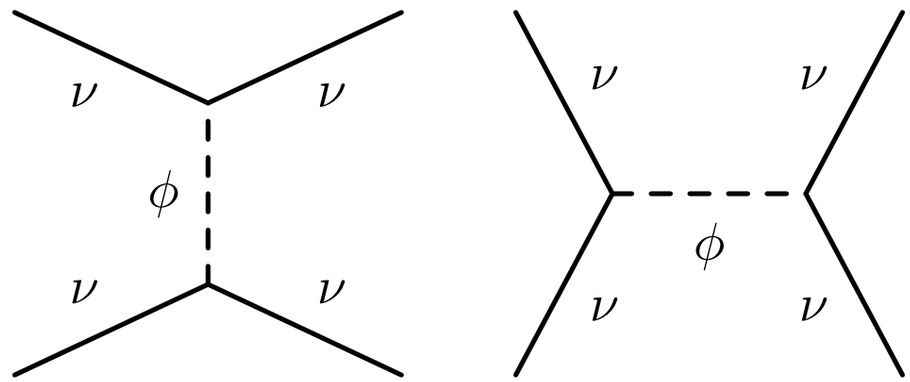


$$\frac{r_*}{3000\,\mathrm{Mpc}} = \int_{z_*}^{\infty} \frac{c_s dz}{\left[\Omega_\gamma h^2 \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}} N_{\rm eff}\right)(1+z)^4 + \Omega_m h^2 (1+z)^3\right]^{1/2}}$$

$$\frac{d_A}{3000\,\mathrm{Mpc}} = \int_0^{z_*} \frac{dz}{\left[\Omega_m h^2 (1+z)^3 + \Omega_\Lambda h^2\right]^{1/2}}$$

Relieving the tension with NuNSI

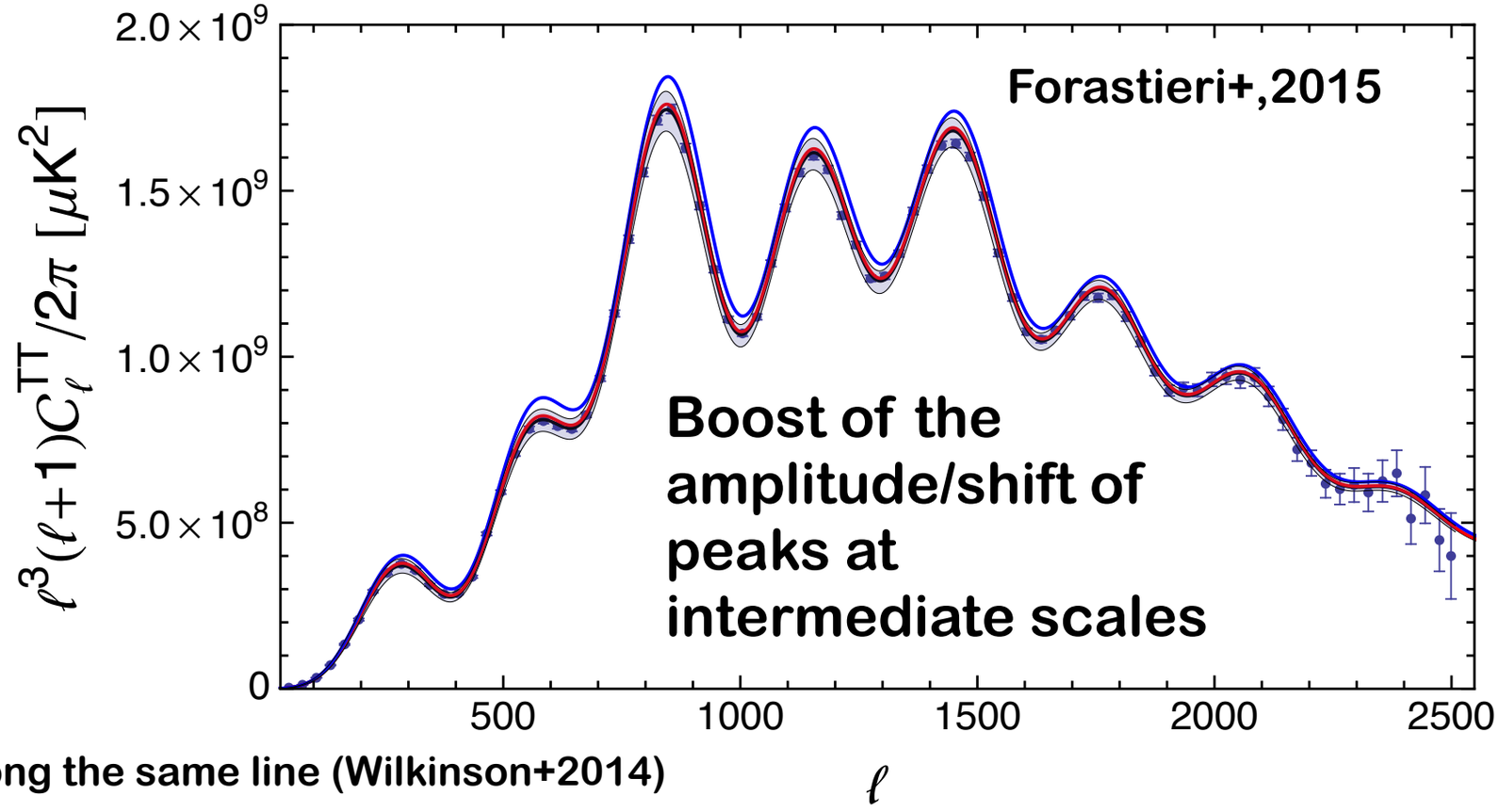
$$\mathcal{L} \supset h_{ij}\bar{\nu}_i^c \nu_j \phi + g_{ij}\bar{\nu}_i^c \gamma_5 \nu_j \phi + h.c.$$



Collisional processes can suppress stress and affect the perturbation evolution of cosmological neutrinos. The neutrino free-streaming nature is altered non-trivially.

Key feature: the absence of free-streaming particles in the photon-baryon oscillating fluid is compensated by a larger value of theta*

H0 increases



See also DM-nu interactions for a solution along the same line (Wilkinson+2014)

Relieving the tension with NuNSI

Light mediator (m<<keV):
H0 slightly increases,
not enough to solve the tension

Heavy mediator (m>keV), Mildly interacting (Geff<10^-4 MeV^-2):
H0 increases slightly
Note that cosmological parameters are very similar to standard LCDM+Neff+Sumnu

Heavy mediator (m>kEV), Strongly interacting (10^-2 MeV^-2<Geff<10^-1 MeV^-2):
tension relieved (for some choice of data).
Note that it comes with values of cosmological parameters very different from LCDM

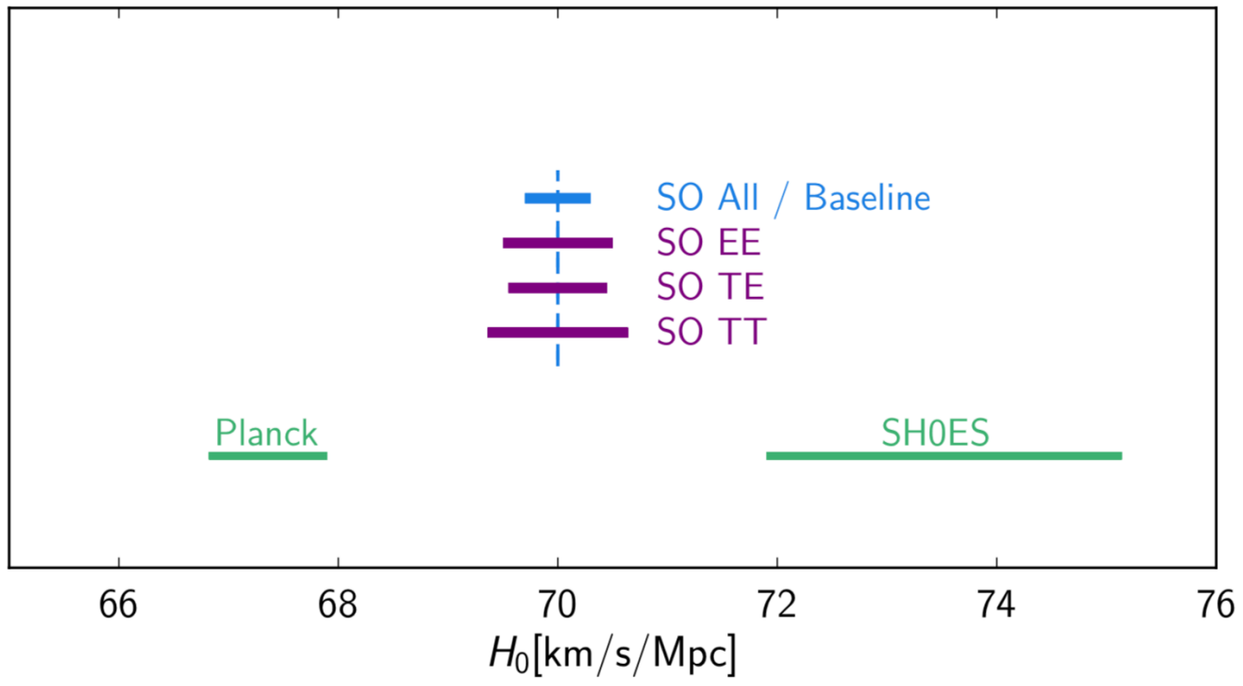
Forastieri+ 2015; Archidiacono & Hannestad 2013; Cyr-Racine & Sigurdson 2013; Kreisch+ 2019; Barenboim+ 2019; …

What next in cosmology

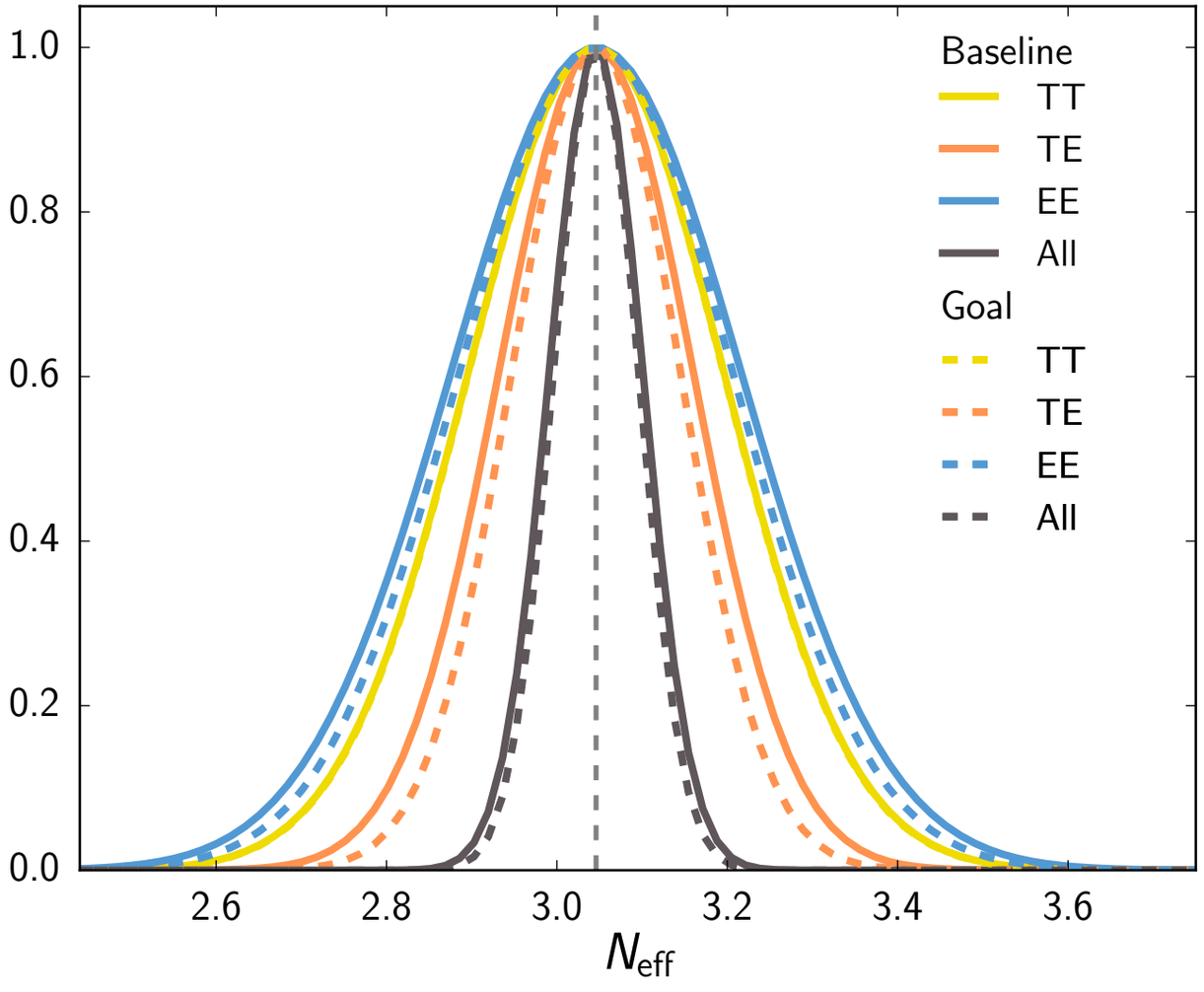
New estimates of H0 from upcoming CMB experiments

Internal redundancy (multi-channel sensitivity to H0)

Better sensitivity to Neff and non-standard nu physics from improved measurements of CMB polarisation



Simons Observatory Coll.,2018



What next in H0 measurements

Multi-probe approach to direct measurements of H0 (see e.g. Beaton+,Astro2020WP):

- **standard candles with improved geometrical distances**
- **standard sirens with increased statistics and source localization**
- **standard clocks with precise mass modelling**

Each probe can reach 1% measurement of H0

Conclusions

The H0 tension is one of the most intriguing and long-standing tension in cosmology

Many proposed solutions, spanning several areas: instrumental systematics, astrophysical systematics, theoretical systematics

Next decade will likely come with an answer to the H0 problem