HUBBLE TENSION WITH AN EXTRA RADIATION AND NEUTRINO DEGENERACY

YO TODA

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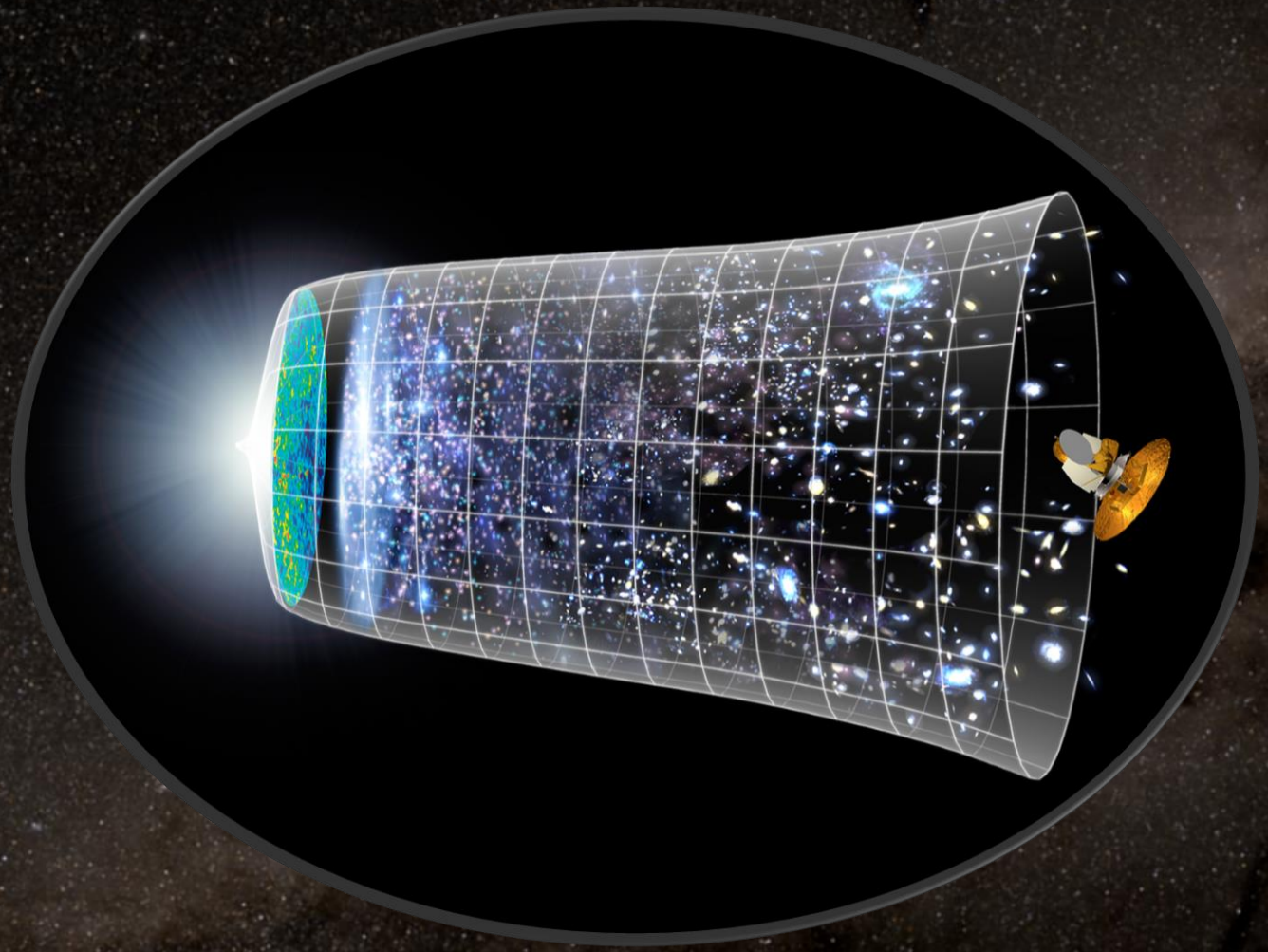
Osamu Seto, Yo Toda arXiv:2104.04381 [astro-ph.CO]



The Λ CDM model goes well in explaining the evolution of our Universe.

But
Hubble Tension

TODAY I WILL

Focus on the Extra radiation and neutrino degeneracy
to solve the Hubble tension

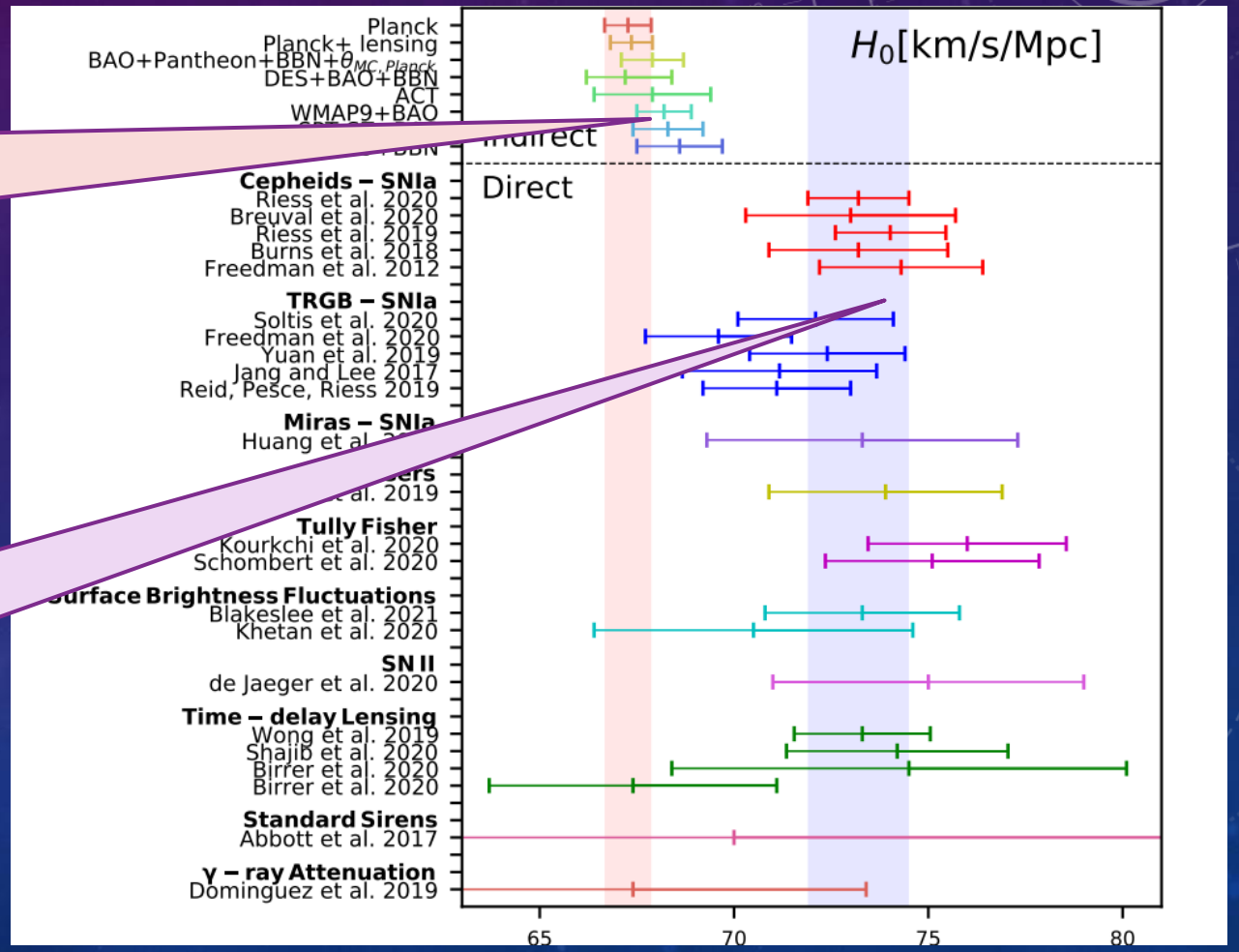
Treat extra radiation parameter N_{eff} as independent of degeneracy ξ
because we consider the sterile neutrinos or axions under the degeneracy

Conclude that
the combination of extra radiation and neutrino degeneracy
is the promising solutions

WHAT IS HUBBLE TENSION?

Distant observations suggest
$H_0 \fallingdotseq 67$ km/s/Mpc

Local observations suggest
$H_0 \fallingdotseq 74$ km/s/Mpc



Di Valentino, arXiv:2011.00246 [astro-ph.CO]

WHAT IS HUBBLE TENSION?

How is this derived?

Distant observations suggest
$H_0 \fallingdotseq 67$ km/s/Mpc

Local observations suggest
$H_0 \fallingdotseq 74$ km/s/Mpc

This tension may indicate
Beyond ΛCDM Physics

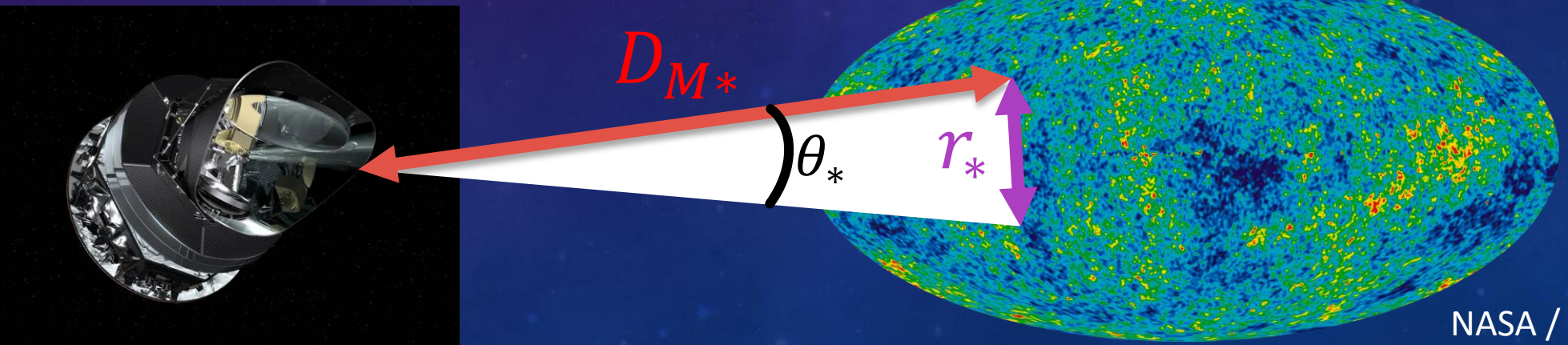
ANGULAR SIZE OF THE SOUND HORIZON

Directly Measured

Angular Size : $\theta_* = \frac{r_*}{D_{M*}} = (1.0411 \pm 0.0003) \times 10^{-2}$

$r_* = \int_0^{t_*} \frac{c_s d\tilde{t}}{a(\tilde{t})}$: comoving sound horizon at the recombination

$D_{M*} = \int_{t_*}^{t_0} \frac{d\tilde{t}}{a(\tilde{t})}$: comoving angular diameter distance



NASA / WMAP Science Team

ANGULAR SIZE OF THE SOUND HORIZON

Directly Measured

Angular Size : $\theta_* = \frac{r_*}{D_{M*}} = (1.0411 \pm 0.0003) \times 10^{-2}$

$$\propto H_0 \frac{1}{\sqrt{\rho \text{ in the early universe}}}$$

$$\because \frac{dt}{a(t)} = \frac{dz}{H_0\sqrt{\rho(z)/\rho_0}}$$

ρ : energy density

TO INCREASE H_0 …

Increase ρ in the early universe

EXTRA RADIATION

The relativistic degrees of freedom N_{eff}

(increased by dark radiation, axion, sterile neutrino …)

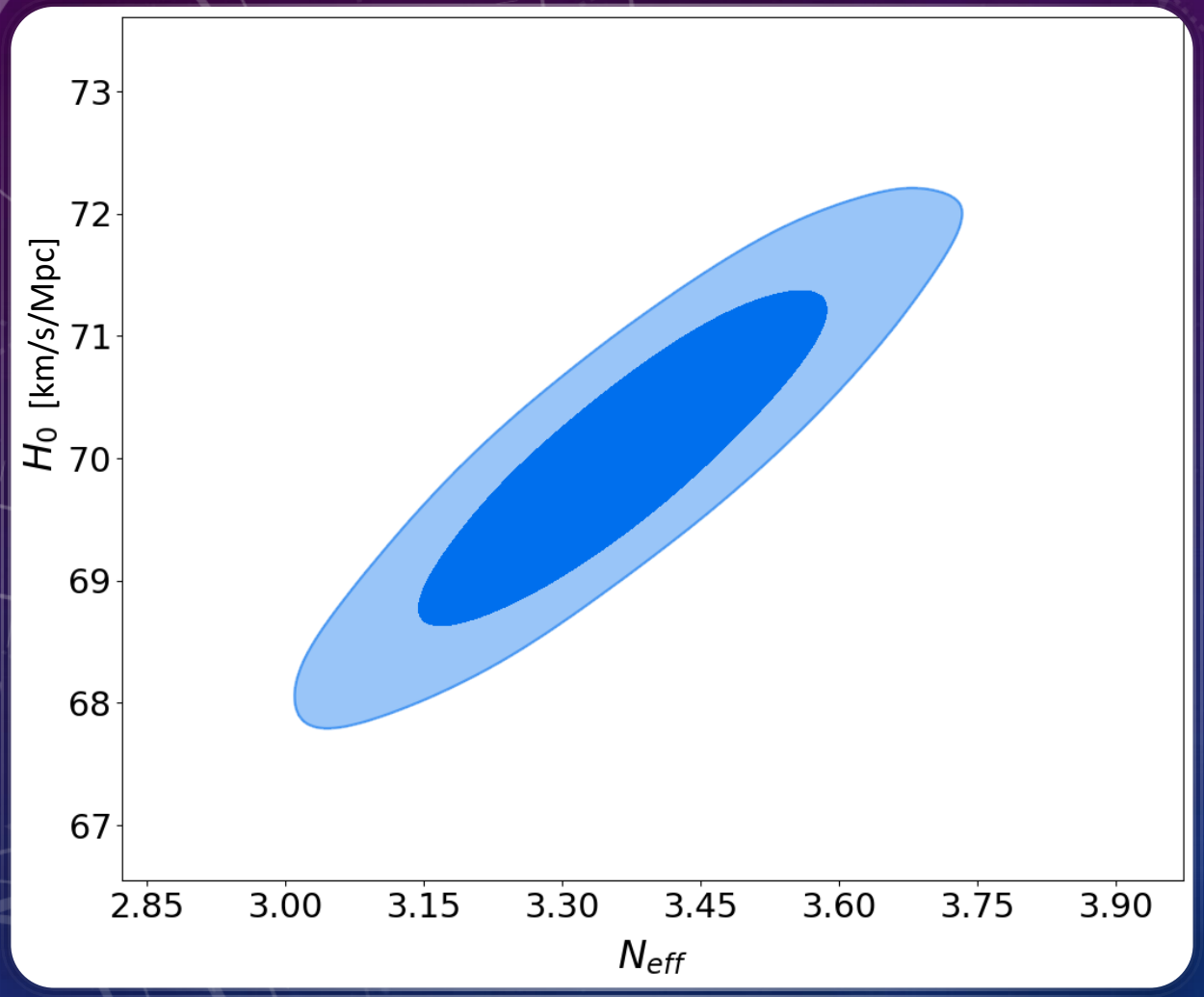
$$\rho_{\text{radiation}} = \left(1 + \frac{7}{8}\left(\frac{4}{11}\right)^{\frac{4}{3}} N_{\text{eff}}\right) * \rho_{\text{photon}}$$

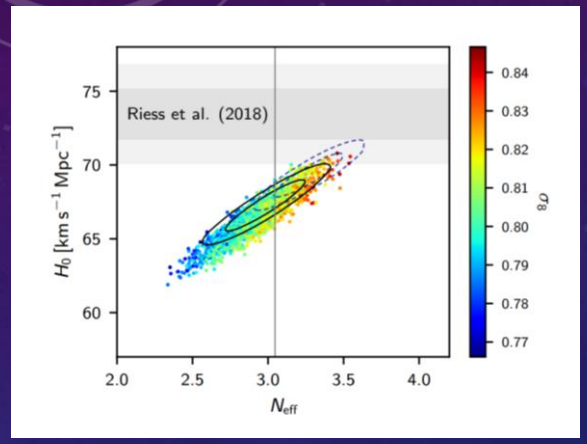
photon Neutrino + α

$$N_{\text{eff}} = 3 + 0.046 + (\text{Extra contribution})$$

neutrino e^+e^- annihilation

EXTRA RADIATION RELIVE THE HUBBLE TENSION





Planck 2018 results VI

arxiv:1807.06209

CMB only

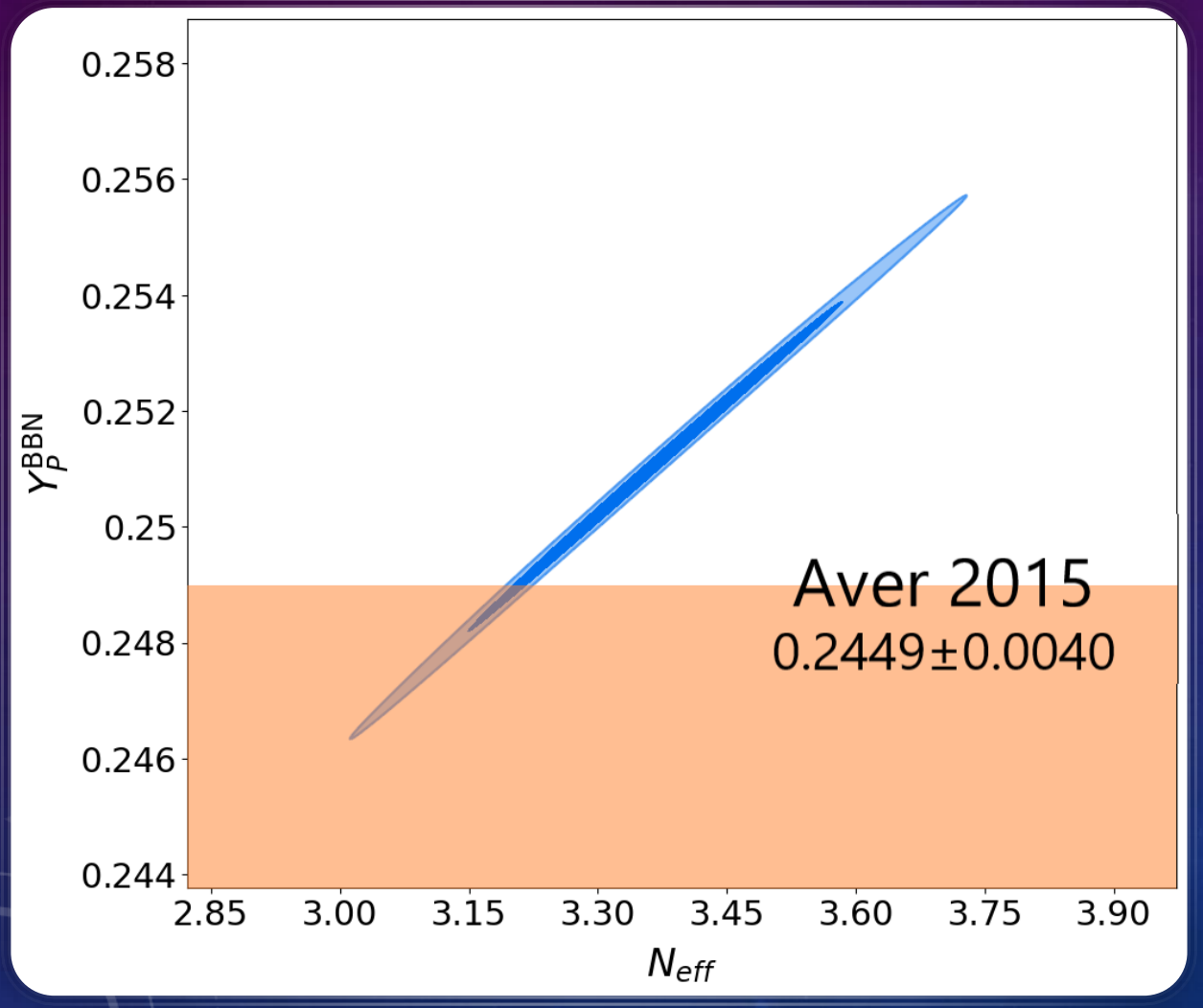
Higher $N_{\rm eff}$

increase H_0

$$N_{\rm eff} = 3.046 + (\text{Extra contribution})$$

Planck + Pantheon + BAO + R19

$N_{\rm eff}$ VS. HELIUM MASS FRACTION Y_P MEASUREMENT



Larger $N_{\rm eff}$
increase Y_P

$N_{\rm eff} = 3.046 + (\text{Extra contribution})$

Planck + Pantheon + BAO + R19

NEUTRINO DEGENERACY

The degeneracy parameter $\xi_i = \frac{\mu_{\nu i}}{T_\nu}$ $(i = e, \mu, \tau)$

$\mu_{\nu i}$: chemical potential for neutrino ν_i

T_ν :temperature of neutrinos

Distribution functions

$$f_\nu = \frac{1}{\exp(p/T_\nu - \xi_i) + 1}$$

$$f_{\bar{\nu}} = \frac{1}{\exp(p/T_\nu + \xi_i) + 1}$$

Number Densities of neutrinos and antineutrinos

$$n_{\nu_i} + n_{\bar{\nu}_i} \propto T_{\nu_i}^3 (2(\xi_i/\pi)^2 + (\xi_i/\pi)^4) \rightarrow N_{\text{eff}}$$

$$n_{\nu_i} - n_{\bar{\nu}_i} \propto T_{\nu_i}^3 (\pi^2 \xi_i + \xi_i^3) \rightarrow \text{BBN}$$

Positive electron neutrino degeneracy

$$n_{\nu_e} - n_{\bar{\nu}_e} \propto T_{\nu_e}^3(\pi^2\xi_e + \xi_e^3)$$

More neutrinos than antineutrinos

The process $p + \bar{\nu}_e \rightarrow n + e^+$ is suppressed than $n + \nu_e \rightarrow p + e^-$

Neutron-to-proton ratio decrease

Helium mass fraction Y_P Decrease

Number Densities of
neutrinos and antineutrinos

$$n_{\nu_i} + n_{\bar{\nu}_i} \propto T_{\nu_i}^3 (2(\xi_i/\pi)^2 + (\xi_i/\pi)^4)$$

$$\rightarrow \Delta N_{\text{eff}} = \frac{15}{7} \sum_i \left(2 \left(\frac{\xi_i}{\pi} \right)^2 + \left(\frac{\xi_i}{\pi} \right)^4 \right)$$

We consider

$|\xi_i| \leq 0.06 \rightarrow |\Delta N_{\text{eff}}| < 0.01$ Neglegeble

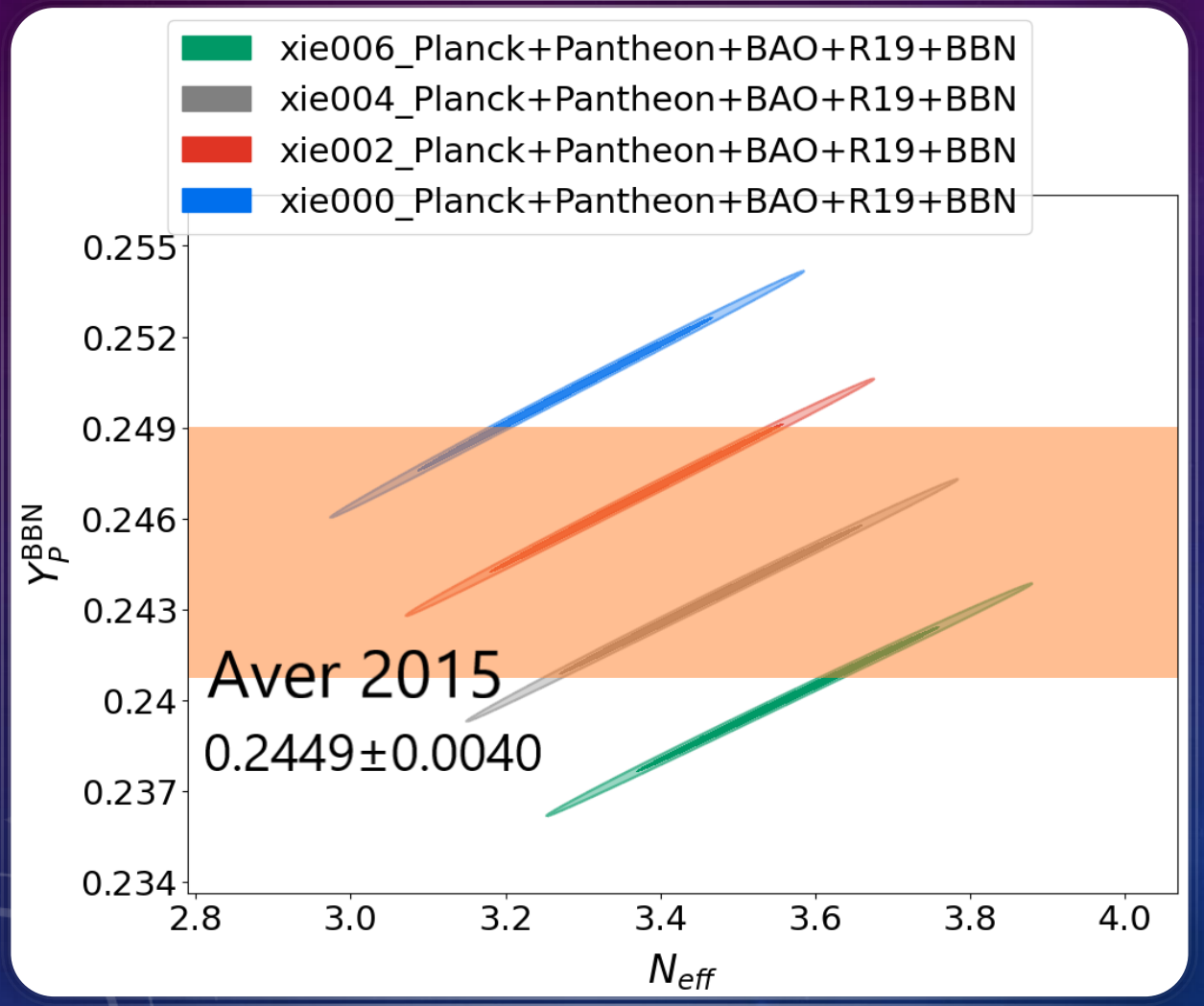
and

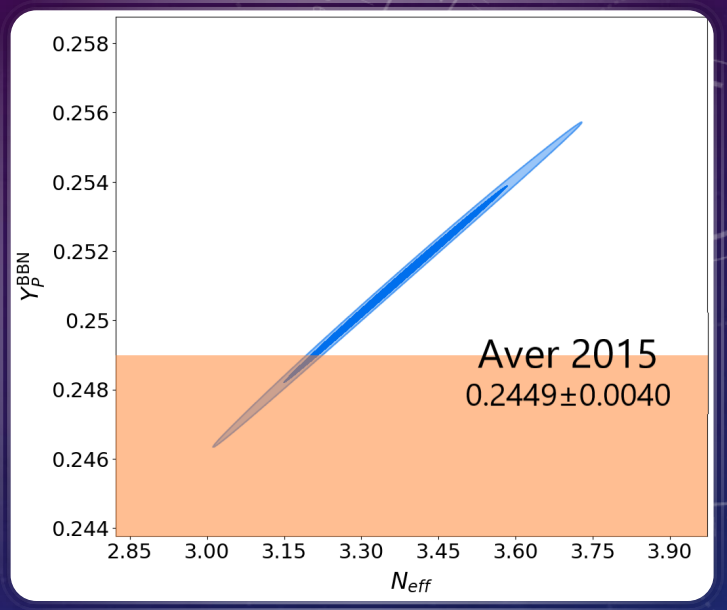
Extra radiation $\Delta N_{\text{eff}} \sim 0.5$

Next, I will show the results of analysis of

EXTRA RADIATION ΔN_{eff}
AND
ELECTRON NEUTRINO DEGENERACY ξ_e

Y_P VS. $N_{\rm eff}$ WITH THE DEGENERACY ξ_e





Larger $N_{\rm eff}$
increase Y_P

Larger ξ_e
decrease Y_P

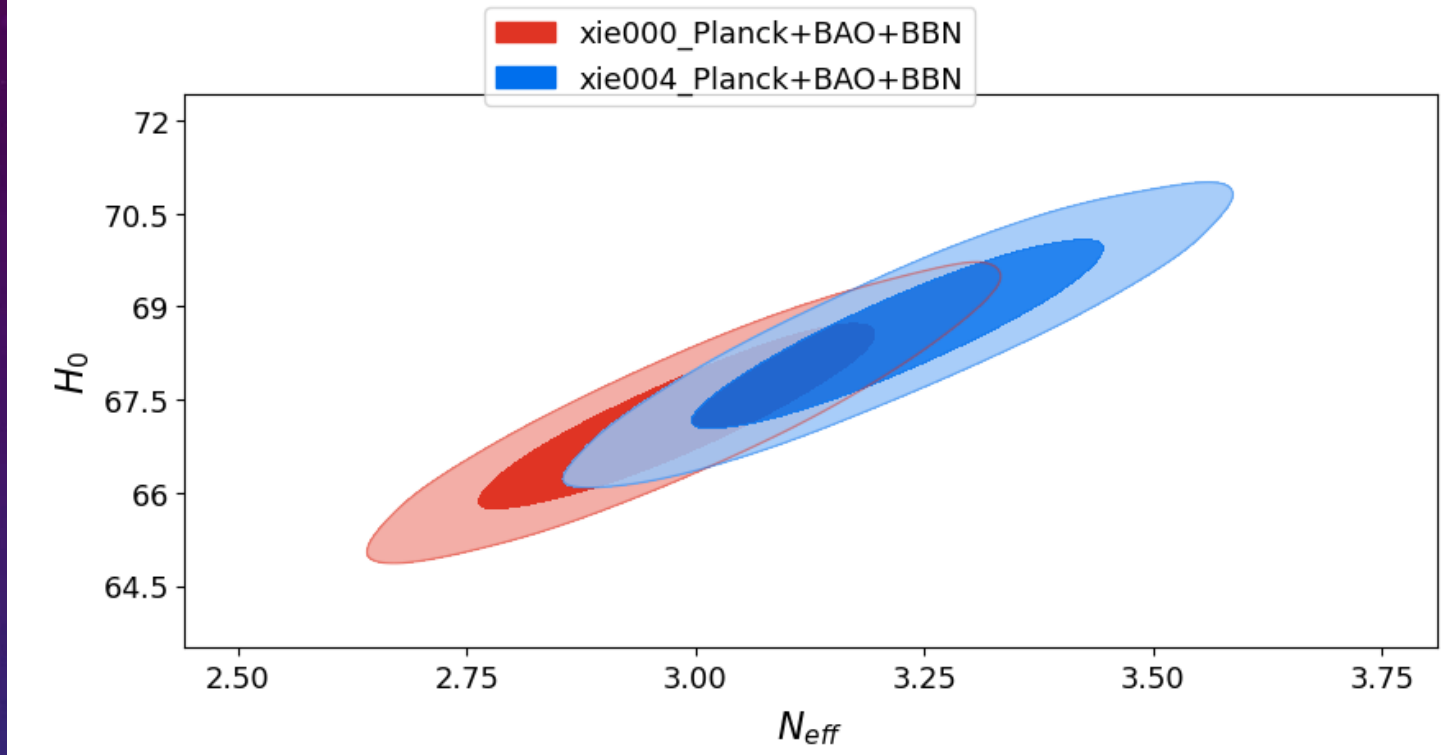
BEST-FIT

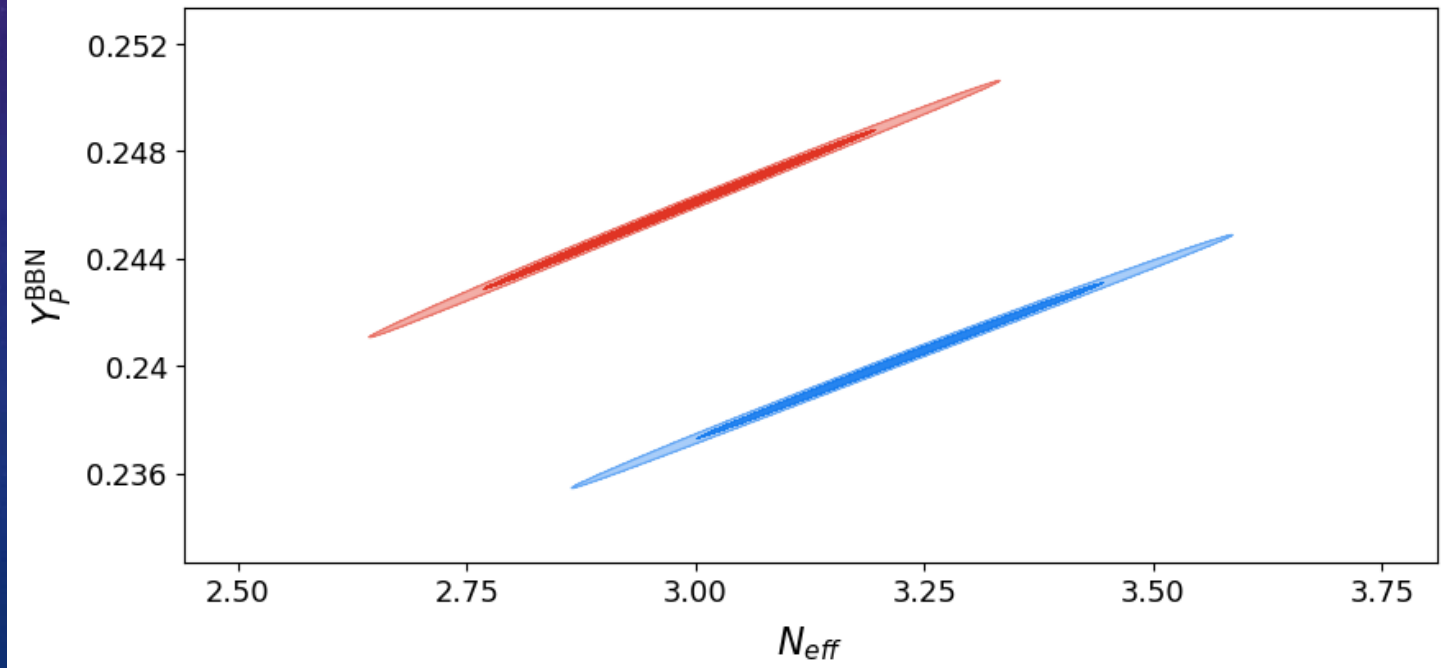
Parameter	ΛCDM	ξ_e=0	ξ_e=0.02	ξ_e=0.04	ξ_e=0.06
$N_{\rm eff}$	3.046	3.243	3.31264	3.45451	3.63353
H_0	68.218	69.632	69.7162	70.2582	71.701
Y_P	0.2468	0.2497	0.2460	0.2432	0.2410
$\chi^2_{\rm Cooke17}$	0.2977	0.1036	0.0611	0.0015	6.62848e-06
$\chi^2_{\rm Aver15}$	0.2161	1.4540	0.0753	0.1725	0.9673
$\chi^2_{\rm H074p03}$	16.7501	9.5927	9.2288	7.0555	2.6900
$\chi^2_{\rm JLA}$	1034.77	1034.74	1034.74	1034.75	1034.81
$\chi^2_{\rm prior}$	4.5083	4.3142	2.3132	3.1993	7.2315
$\chi^2_{\rm CMB}$	2779.73	2781.6	2783.9	2782.84	2783.71
$\chi^2_{\rm BAO}$	5.2445	5.8010	5.4053	5.3761	6.5744
$\chi^2_{\rm todal}$	3841.52	3837.61	3835.72	3833.39	3836.22

Y_P measurement

Local (direct) H_0 measurement

No Local Measurements w/ and w/o degeneracy ξ_e



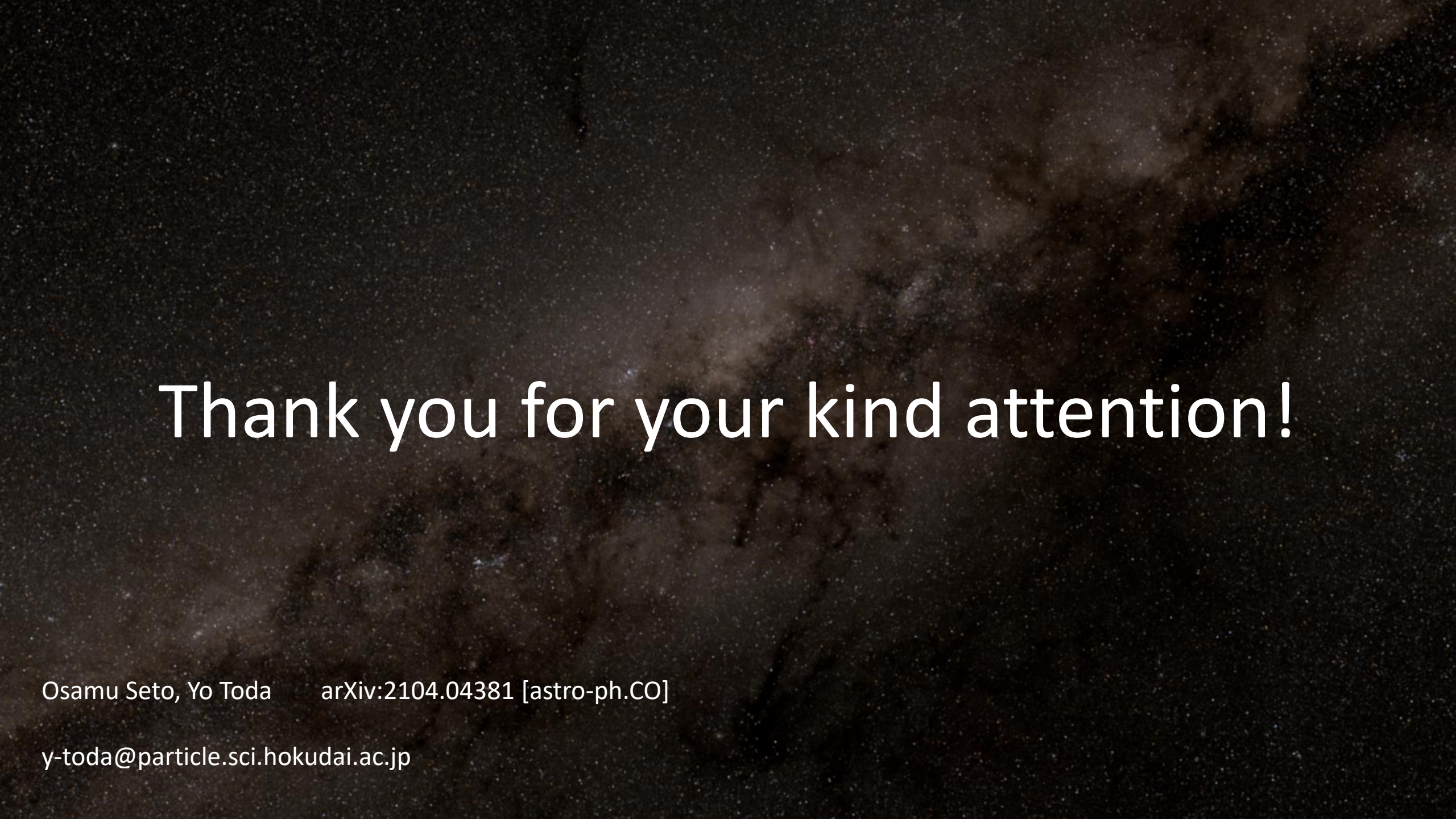


TAKE-HOME MESSAGE

- The combination of Extra radiation and Neutrino degeneracy are the promising solution of the Hubble tension

- Non-zero degenerate $\xi_e = 0.04$ and extra radiation $N_{\rm eff} = 3.45$ is the best-fit at the combination of CMB, BBN, BAO and the local measurements

- The model of particle physics which takes large neutrino degenerate and extra radiation is worth constructing



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