Tensions in cosmology and its implications for new physics

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Tensions in cosmology

Several tensions have been discussed in cosmology…

- The H_0 tension
- $S_8(\sigma_8)$ tension
- CMB hemispherical power asymmetry
- Helium (EMPRESS) anomaly

$\vdots$

Tensions in cosmology

Several tensions have been discussed in cosmology…

- The H_0 tension
- $S_8(\sigma_8)$ tension
- CMB hemispherical power asymmetry
- Helium (EMPRESS) anomaly (relatively new)

$\vdots$

The H_0 tension: a brief review

The Hubble constant H_0

- The Hubble constant H_0 is one of the most important parameters in cosmology.

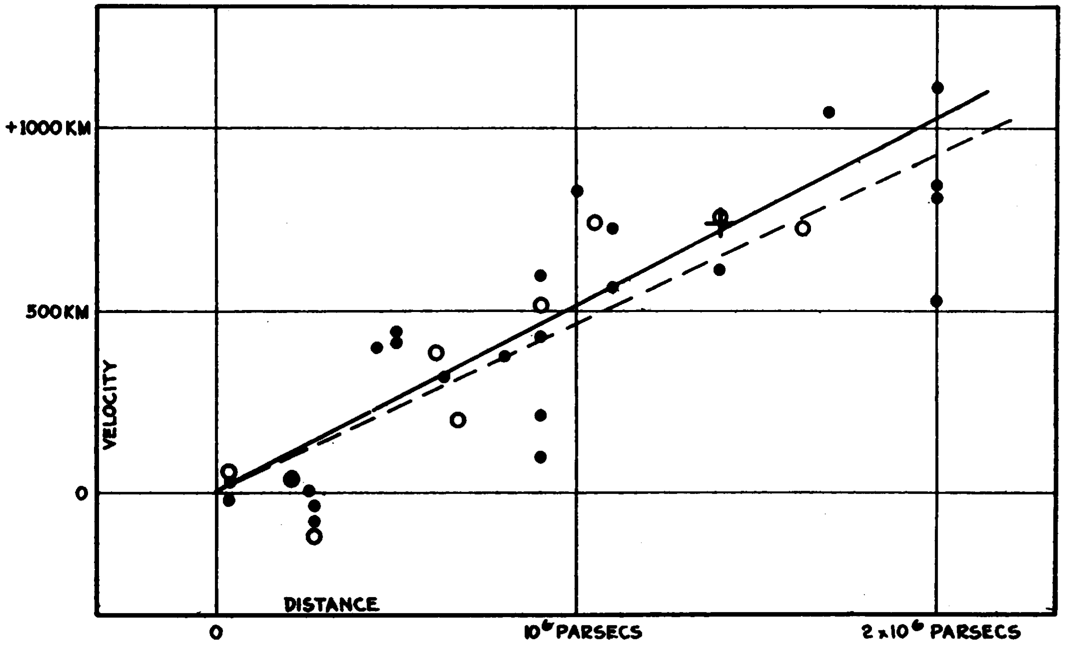
(a : scale factor)

$$H_0 = \frac{\dot{a}}{a}\bigg|_{t=t_0} = \left(\frac{1}{a}\frac{da}{dt}\bigg|_{t=t_0} \right)$$

: Expansion rate of the Universe

Hubble-Lemaître's law:

$$v = H_0 r$$



[Hubble, Proc. Natl. Acad. Sci., 15, 168 (1929)]

- H_0 is now precisely measured by:

  - local direct measurements

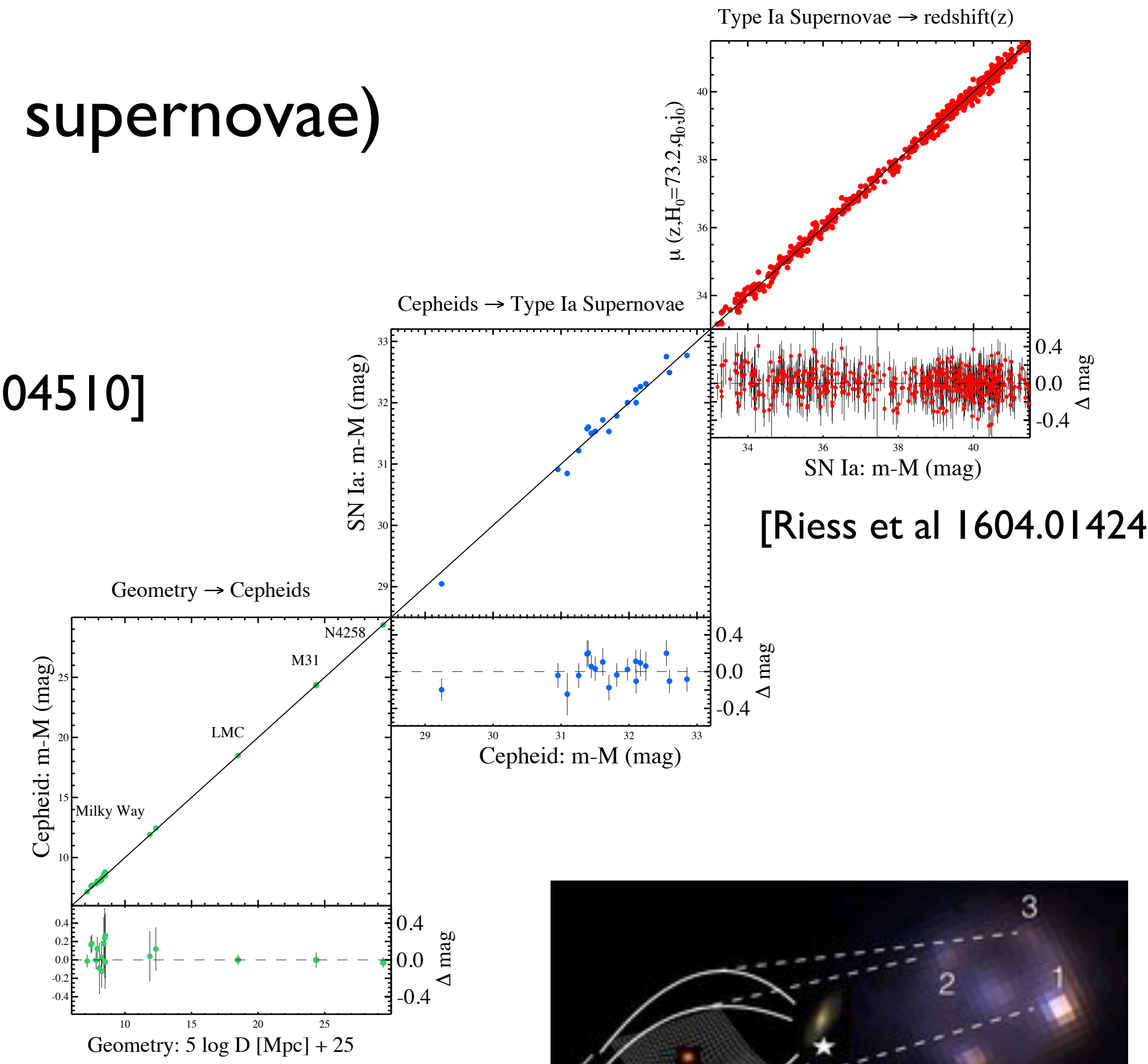
  - indirect measurements (CMB, BAO, …)

Local direct measurements of H_0

- Distance ladder (w/ Cepheid calibrated supernovae)

$$H_0 = 73.3 \pm 1.04 \text{ km/s/Mpc}$$

[Riess et al. 2112.04510]



[Riess et al 1604.01424]

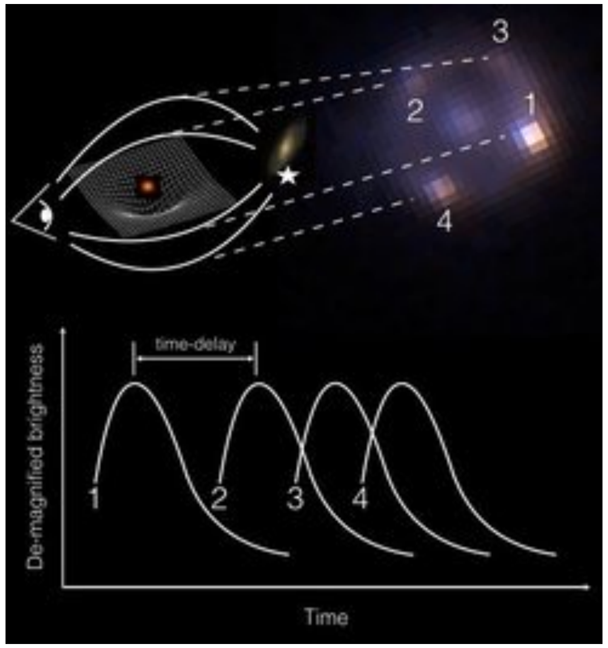
- Strong gravitational lensing

$$H_0 = 73.3^{+1.7}_{-1.8} \text{ km/s/Mpc}$$

[H0LiCOW: Wong et al. 1907.04869]

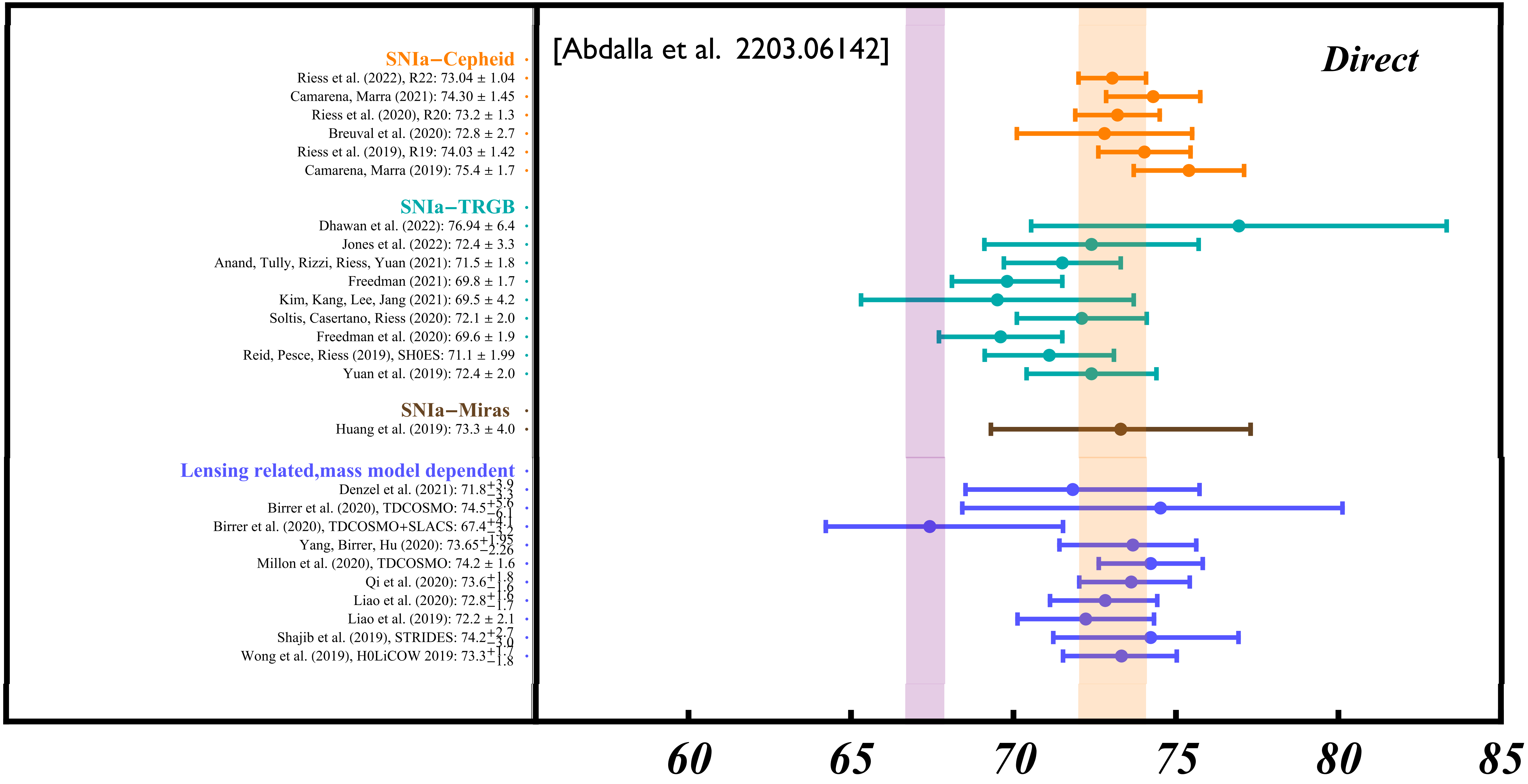
$$H_0 = 74.2^{+2.7}_{-3.0} \text{ km/s/Mpc}$$

[STRIDES: Shajib et al. 1910.06306]



[http://www.mpa-garching.mpg.de/500119/news20171204]

Local direct measurements of H_0



[Abdalla et al. 2203.06142]

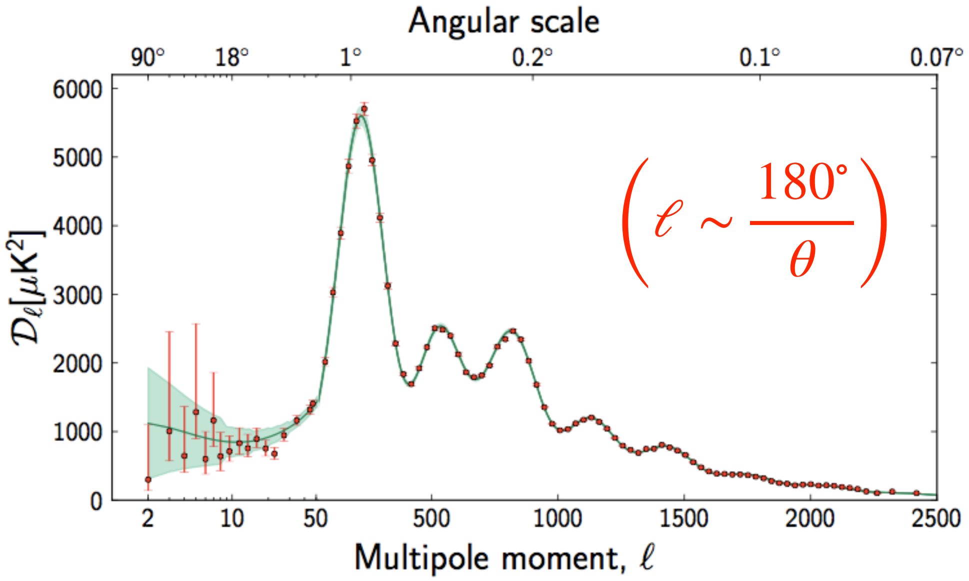
Most local measurements indicate $H_0 \sim 72 - 74$ [km/sec/Mpc]

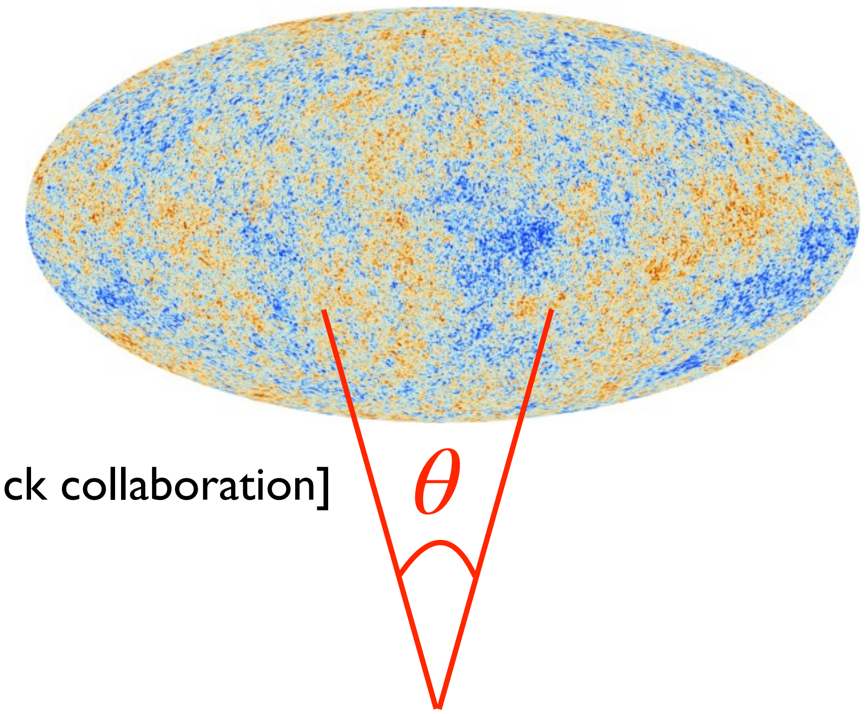
Indirect (early time) measurements of H_0

- CMB (Planck) [assuming ΛCDM model]

$$H_0 = 67.4 \pm 0.5 \text{ km/s/Mpc}$$

[Planck collaboration (2018) 1807.06209]



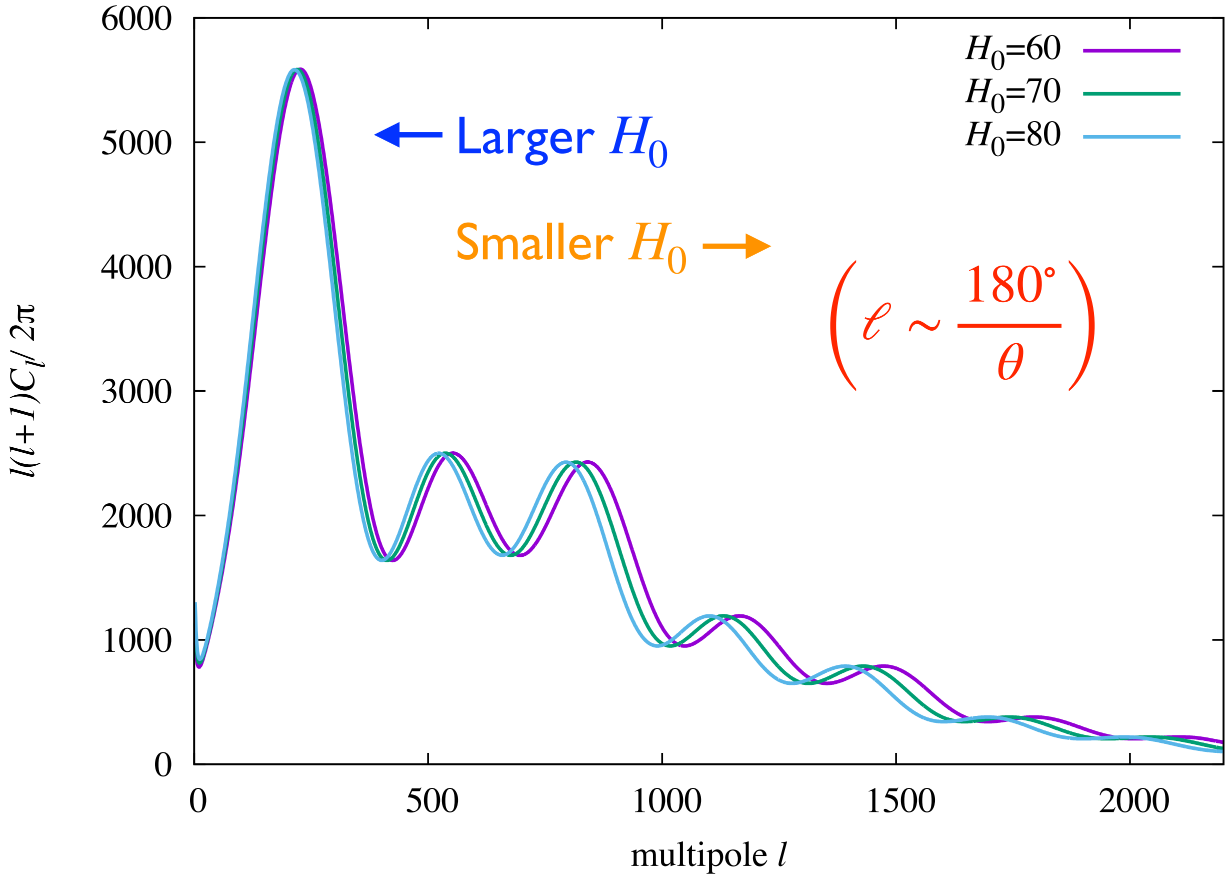


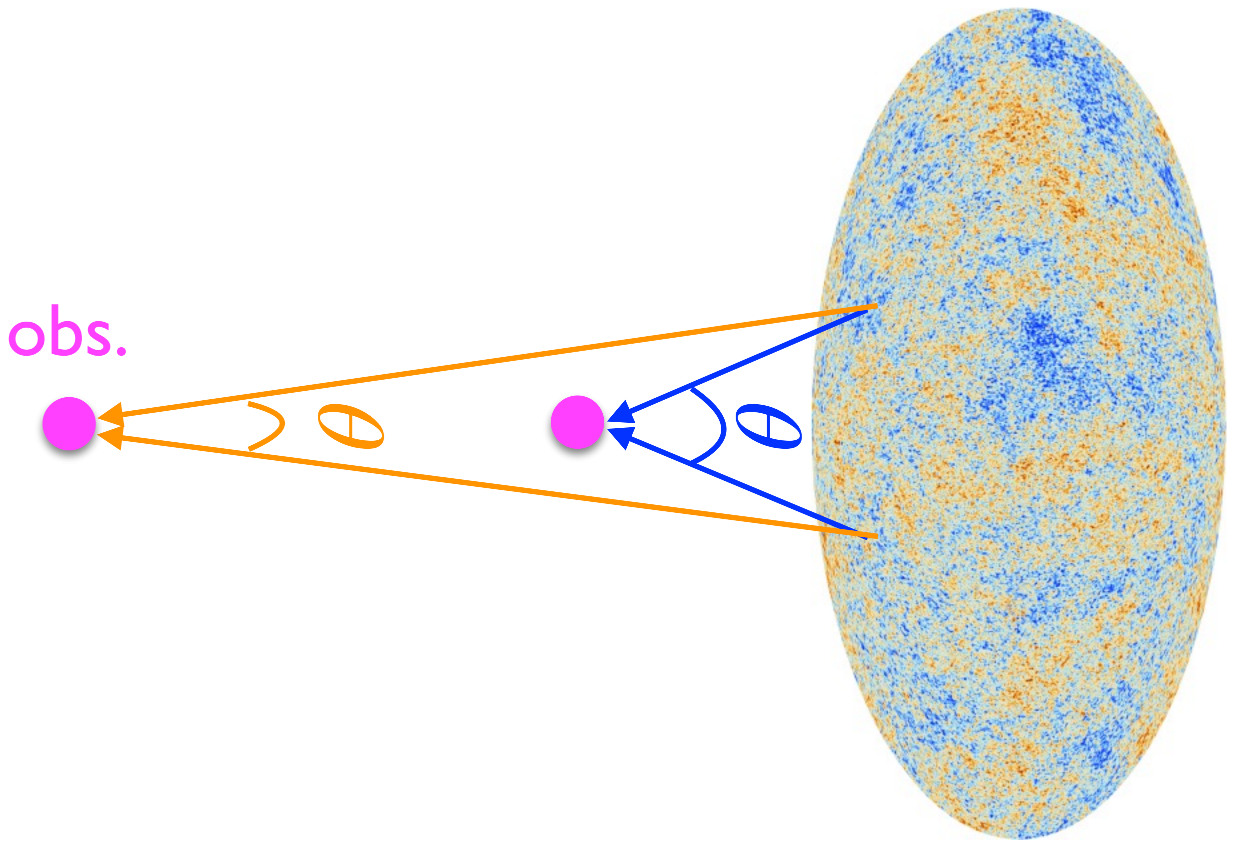
[Planck collaboration]

Indirect (early time) measurements of H_0

Large H_0 → Cosmic expansion is faster → Distance to LSS is nearer

Smaller H_0 → Cosmic expansion is slower → Distance to LSS is further





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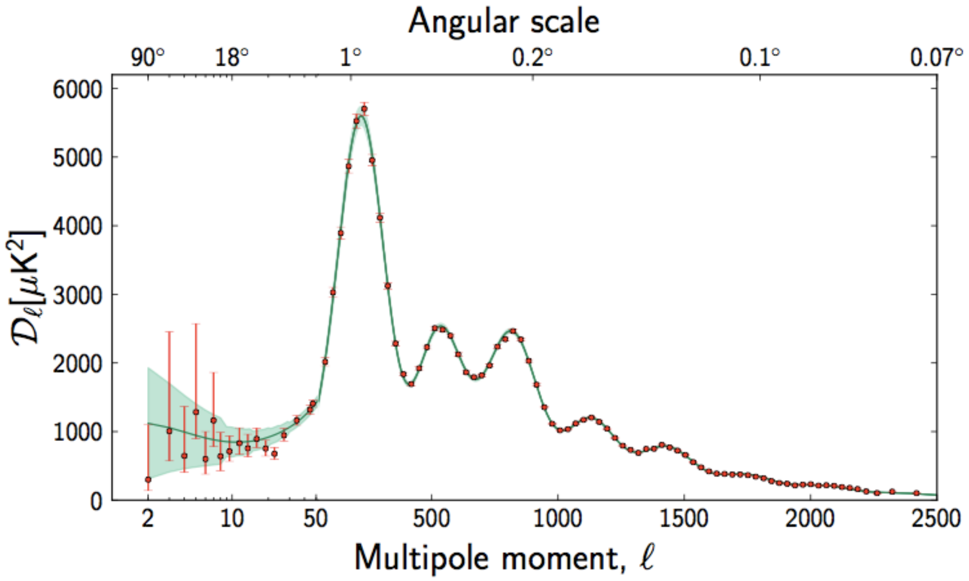

$$H_0 = 67.4 \pm 0.5 \text{ km/s/Mpc}$$

[Planck collaboration (2018) 1807.06209]

- CMB (ACT+WMAP) [assuming ΛCDM model]

$$H_0 = 67.7 \pm 1.1 \text{ km/s/Mpc}$$

[Aiola et al., 2007.07288]

- CMB (ACT) [assuming ΛCDM model]

$$H_0 = 67.9 \pm 1.5 \text{ km/s/Mpc}$$

[Aiola et al., 2007.07288]

- CMB (SPT-3G) [assuming ΛCDM model]

$$H_0 = 68.8 \pm 1.5 \text{ km/s/Mpc}$$

[Dutcher et al., 2101.01684]

Indirect (early time) measurements of H_0

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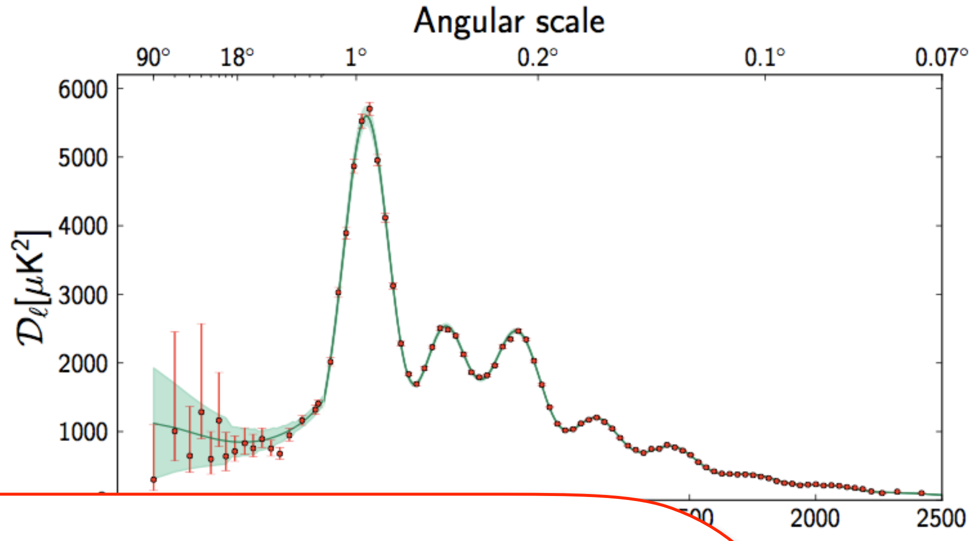

CMB observations indicate:

$$H_0 \sim 67 - 69 \ [\mathrm{km/sec/Mpc}]$$

$$H_0 = 67.9 \pm 1.5 \ \mathrm{km/s/Mpc}$$

[Aiola et al., 2007.07288]

- CMB (SPT-3G) [assuming ΛCDM model]

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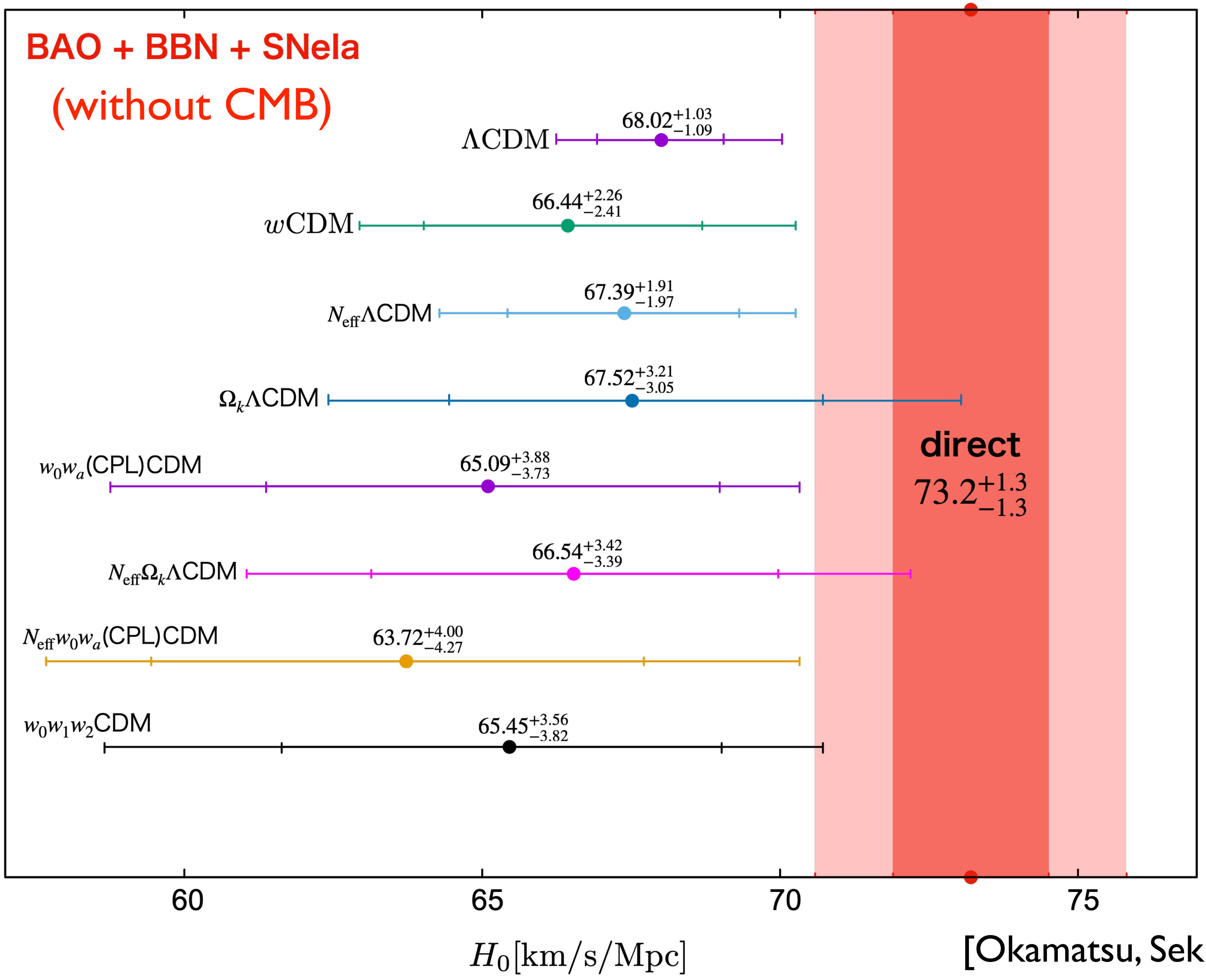
Indirect measurements of H_0 without CMB



[Okamatsu, Sekiguchi, TT 2105.12312]

Even without CMB data (also in extended models), one obtains $H_0 \sim 65 - 68$ [km/sec/Mpc].

Baryon acoustic oscillation (BAO)

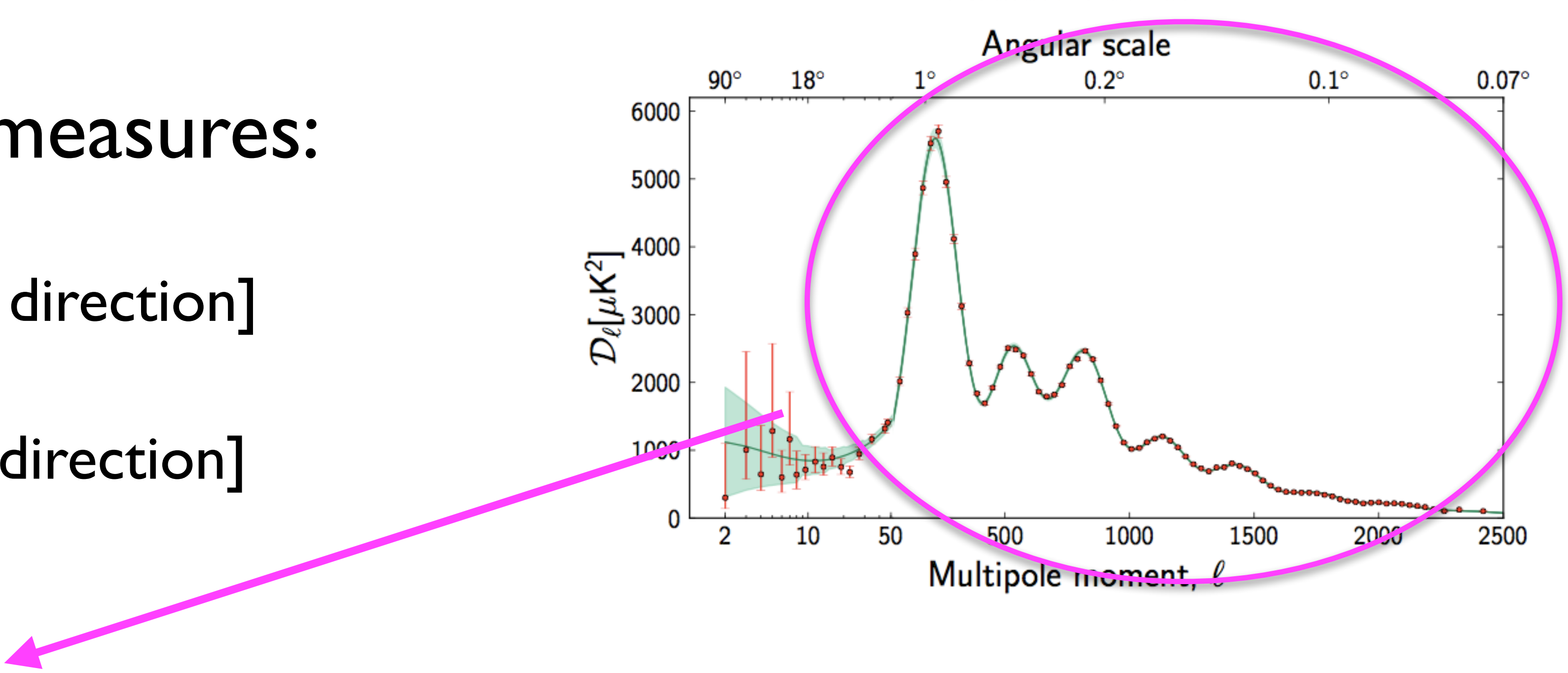
- Acoustic oscillation by photon-baryon fluid

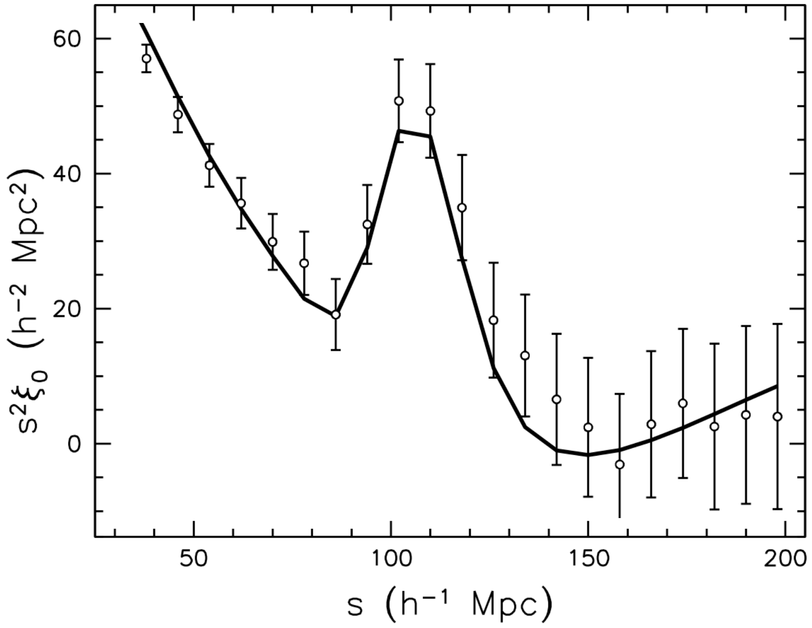
(until recombination)

$$\ddot{\delta} + k^2 c_s^2 \delta \simeq 0 \qquad \left(c_s = \frac{1}{\sqrt{3(1 + 3\rho_b/(4\rho_\gamma))}} \right)$$

- Baryon acoustic oscillation measures:

  - $r_s(z_*)/d_M(z)$ [transverse direction]
  - $r_s(z_*)\,H(z)$ [line of sight direction]





Correlation function
(galaxy distribution)

[Anderson et al., 1312.4877]

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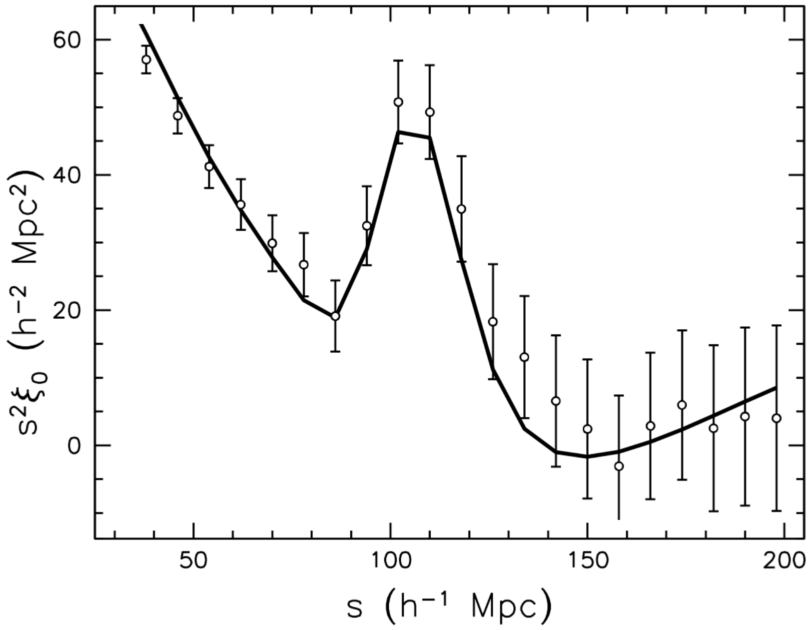

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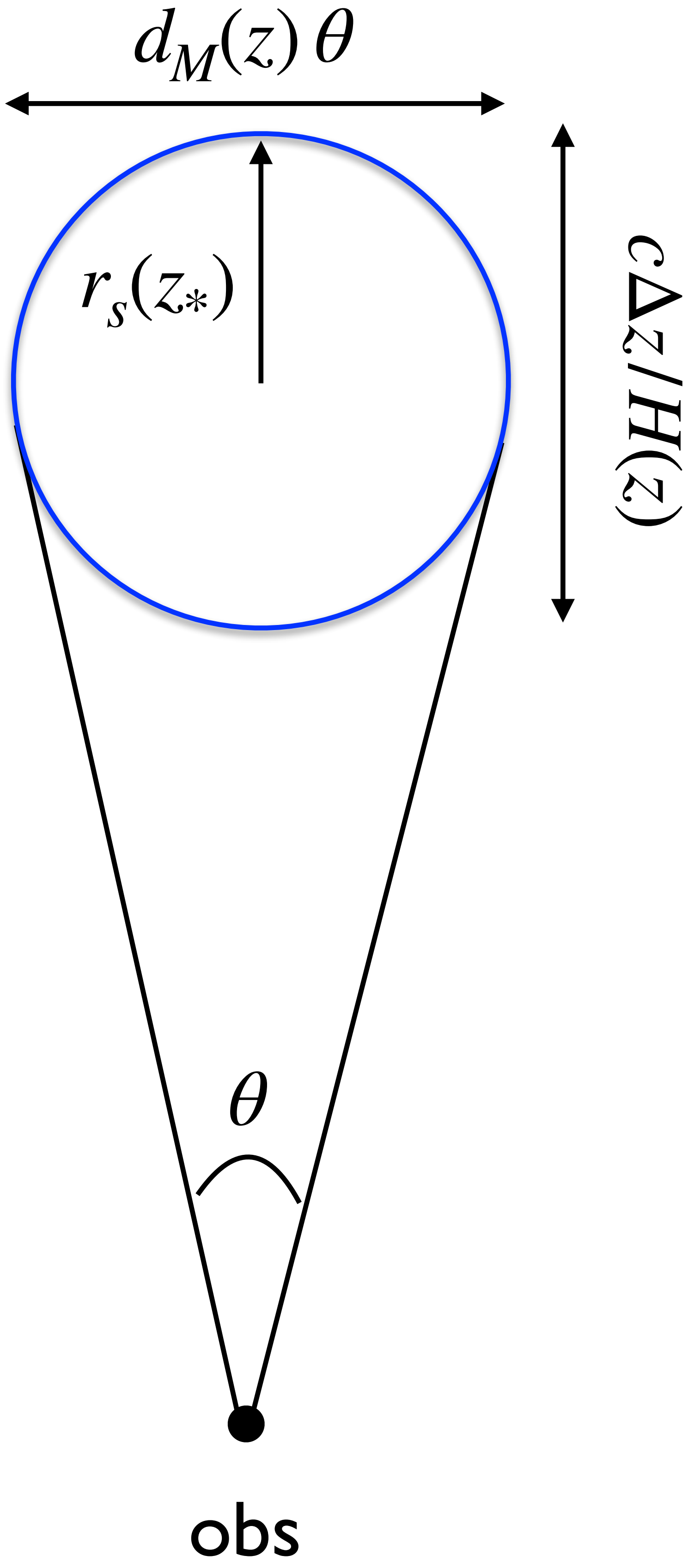
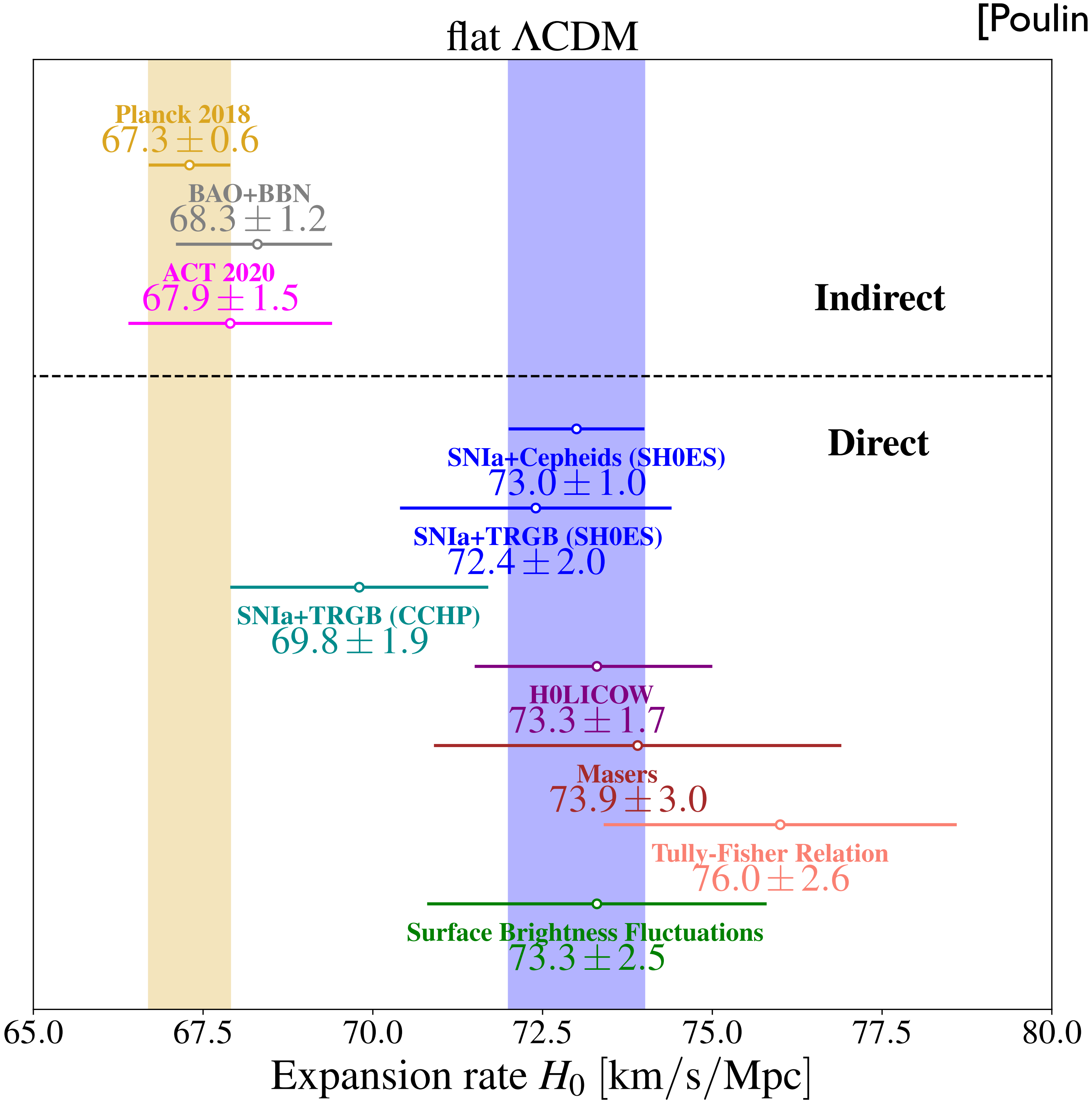


H_0 tension

[Poulin et al. 2302.09032]



Now ~5σ tension between direct (local) and indirect (early) measurements.

What’s the origin of the tension?

- Systematics in local direct measurements?

(Systematics in the distance ladder? [Efstathiou 2007.10716])

(Mass profile assumption in gravitational lensing [Birrer et al., 2007.02941])

. . . .

- Systematics in CMB (or other indirect measurements)?

(Planck internal inconsistency? [Planck collaboration 1807.06209])

(Implications from E-mode data [Addison 2102.00028])

. . . .

However, it would be hard to imagine that the systematics infer consistently low and high values of H_0 for direct (late-time) and indirect (early) measurements.

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However, it would be hard to imagine that the systematics infer consistently low and high values of H_0 for direct (late-time) and indirect (early) measurements.

Do we need extensions/modifications of the standard ΛCDM?

ΛCDM is a very successful model, but…

- The ΛCDM model is just a phenomenological model in the sense that:

  - Based on cold dark matter (CDM) whose identity is unknown.

  - Based on a cosmological constant (Λ), which is just one of the candidates for dark energy.

  - Based on almost scale-invariant primordial fluctuations (generated during inflation) although the actual mechanism of inflation is not understood yet.

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The Hubble tension may give some hint to understand these.

(or physics beyond the standard cosmological paradigm.)

How can one resolve the H_0 tension?

How can we resolve the H_0 tension?

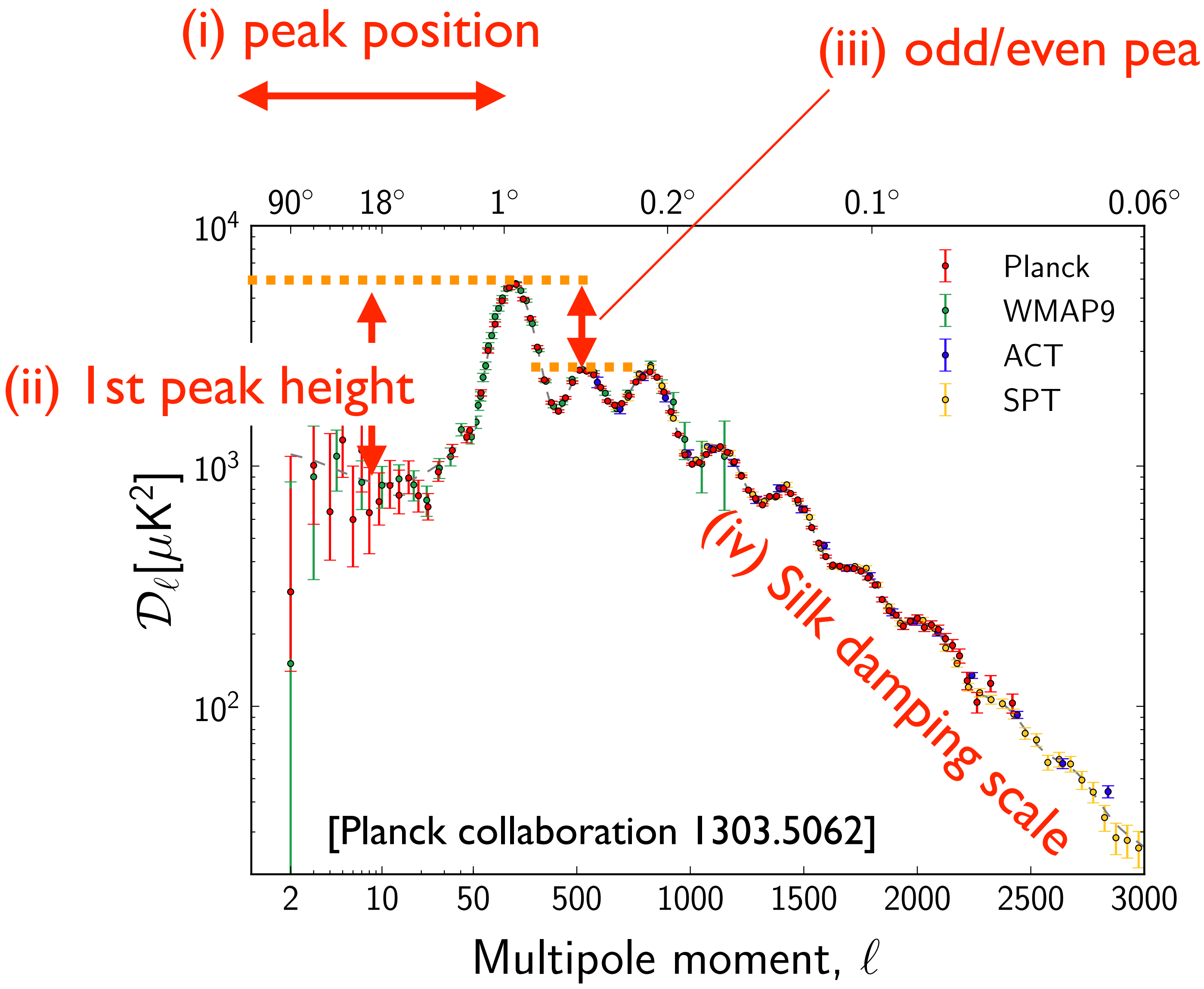
- The determination of H_0 from indirect measurement (e.g., CMB) depend on the model assumed in the analysis.

- Most works try to resolve the tension by extending/changing ΛCDM framework to obtain a higher H_0 from CMB (BAO/SNeIa…).

- However, it is very difficult to obtain a higher H_0 keeping a good fit to every data.

First of all, we need to keep a good fit to CMB…

- Some key quantities are useful to understand the fit to CMB data.



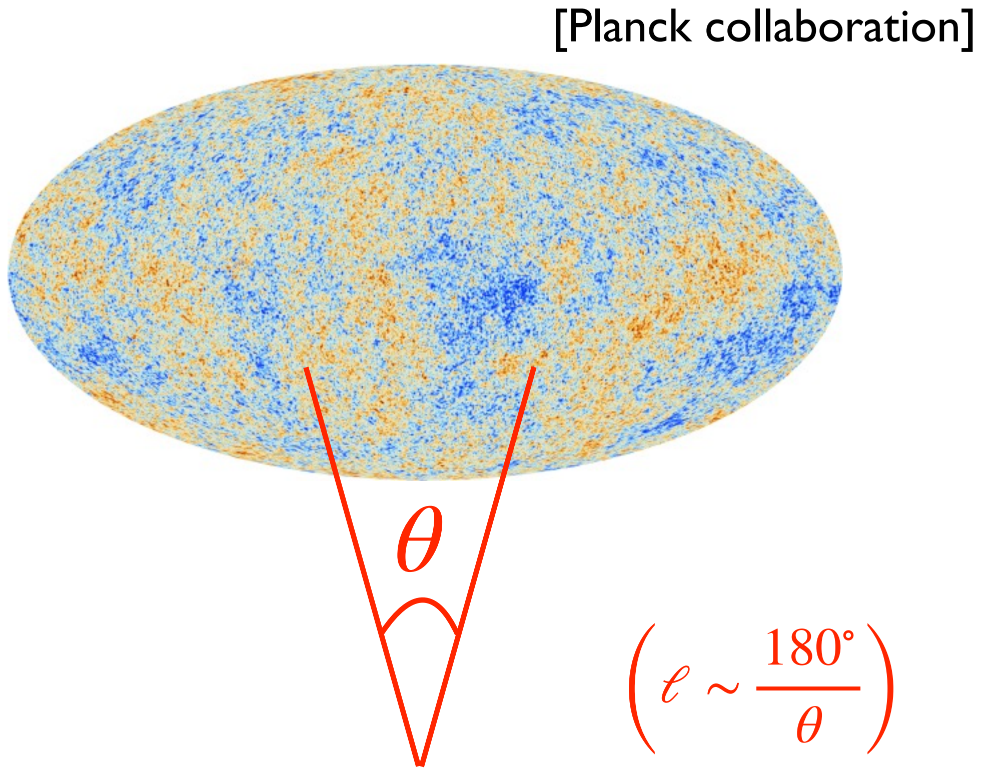
(i) peak position

(ii) 1st peak height

(iii) odd/even peak relative height

(iv) Silk damping scale

[Planck collaboration 1303.5062]



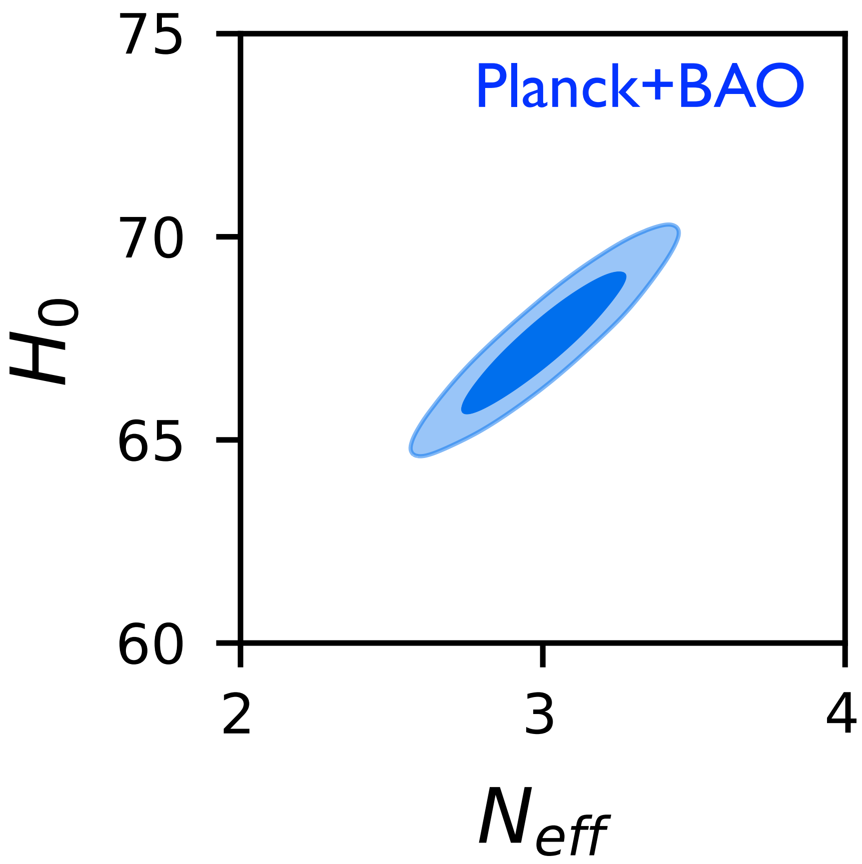
[Planck collaboration]

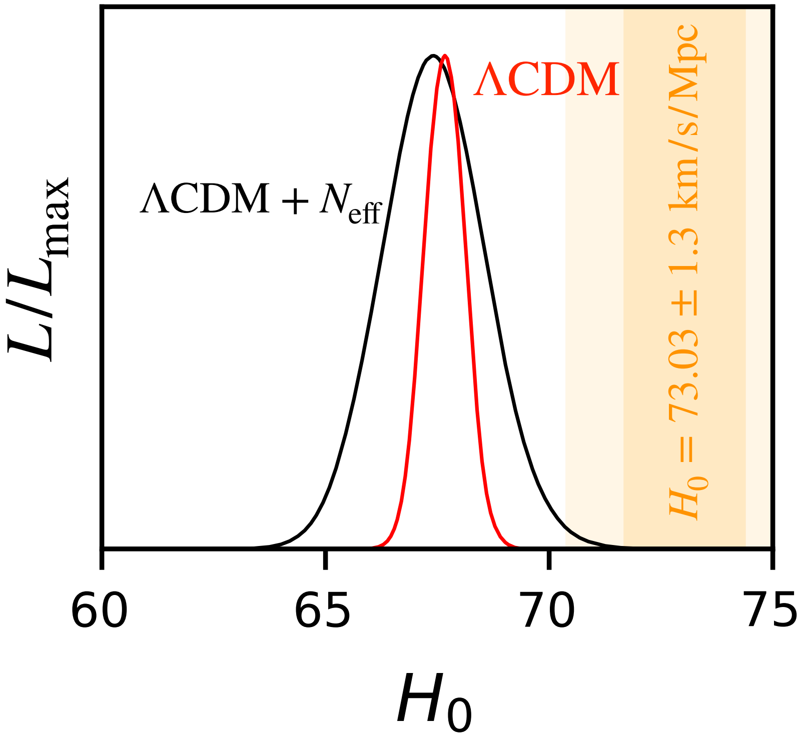
$$\left(\ell \sim \frac{180^\circ}{\theta}\right)$$

(i) ~ (iv) should not be modified (ΛCDM quite works well).

Example: ΛCDM + $N_{\rm eff}$ model

- $N_{\rm eff}$ (effective number of neutrinos, or dark radiation) is degenerate with H_0 in CMB





ΛCDM :

$$H_0 = 67.7 \pm 0.45\,{\rm km/s/Mpc}$$

ΛCDM + $N_{\rm eff}$:

$$H_0 = 67.4 \pm 1.15\,{\rm km/s/Mpc}$$

What’s the limitation in resolving the tension?

(NB: Just changing $N_{\rm eff}$ does not solve the tension.)

Position of acoustic peaks

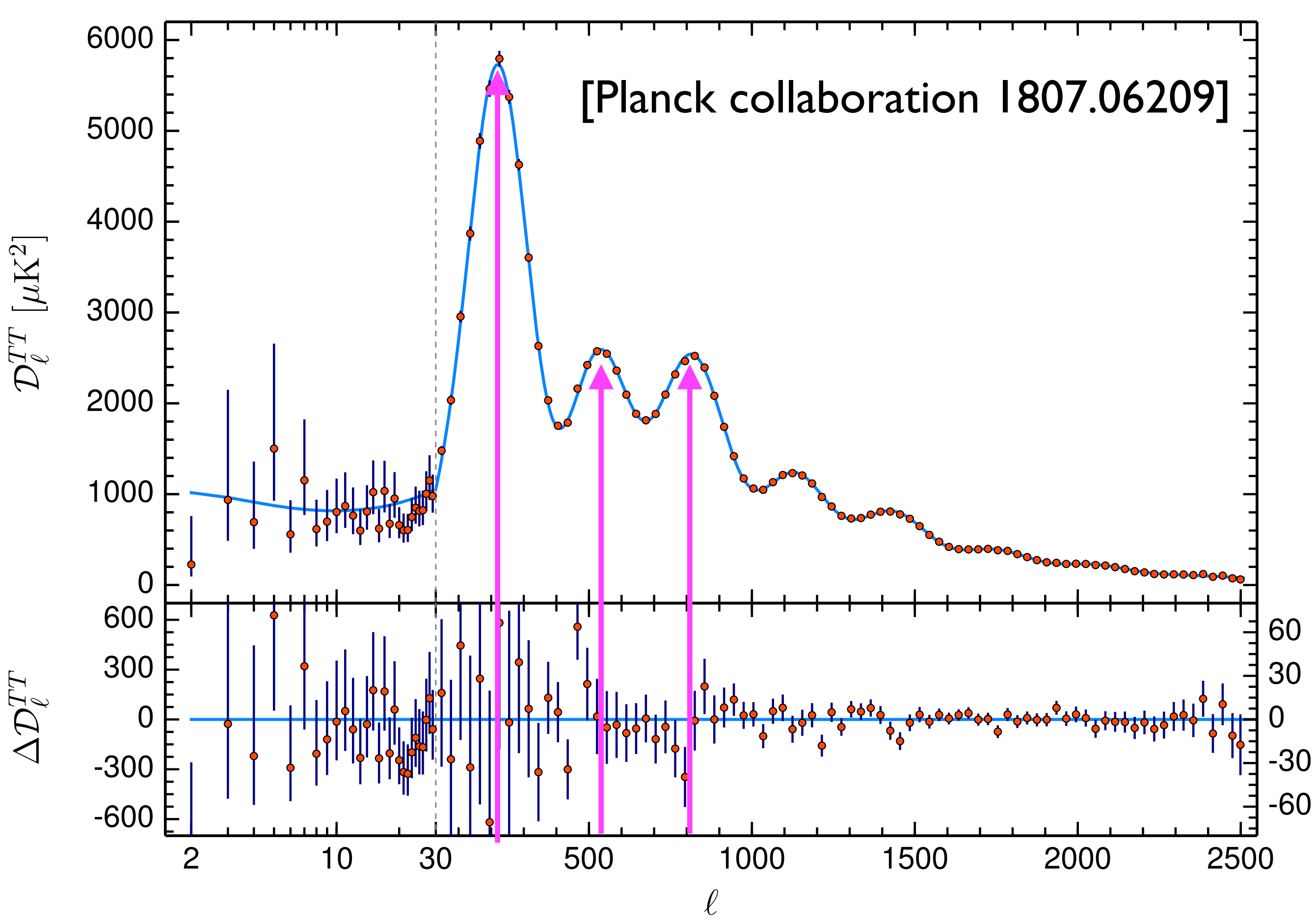
- Position of peaks can be well characterized by:

Acoustic scale: $\theta_s(z_*) = \dfrac{\boxed{r_s(z_*)}}{\boxed{D_M(z_*)}}$

(well determined)

Sound horizon
at recombination.

Angular diameter distance
to recombination



[Planck collaboration (2018) 1807.06209]

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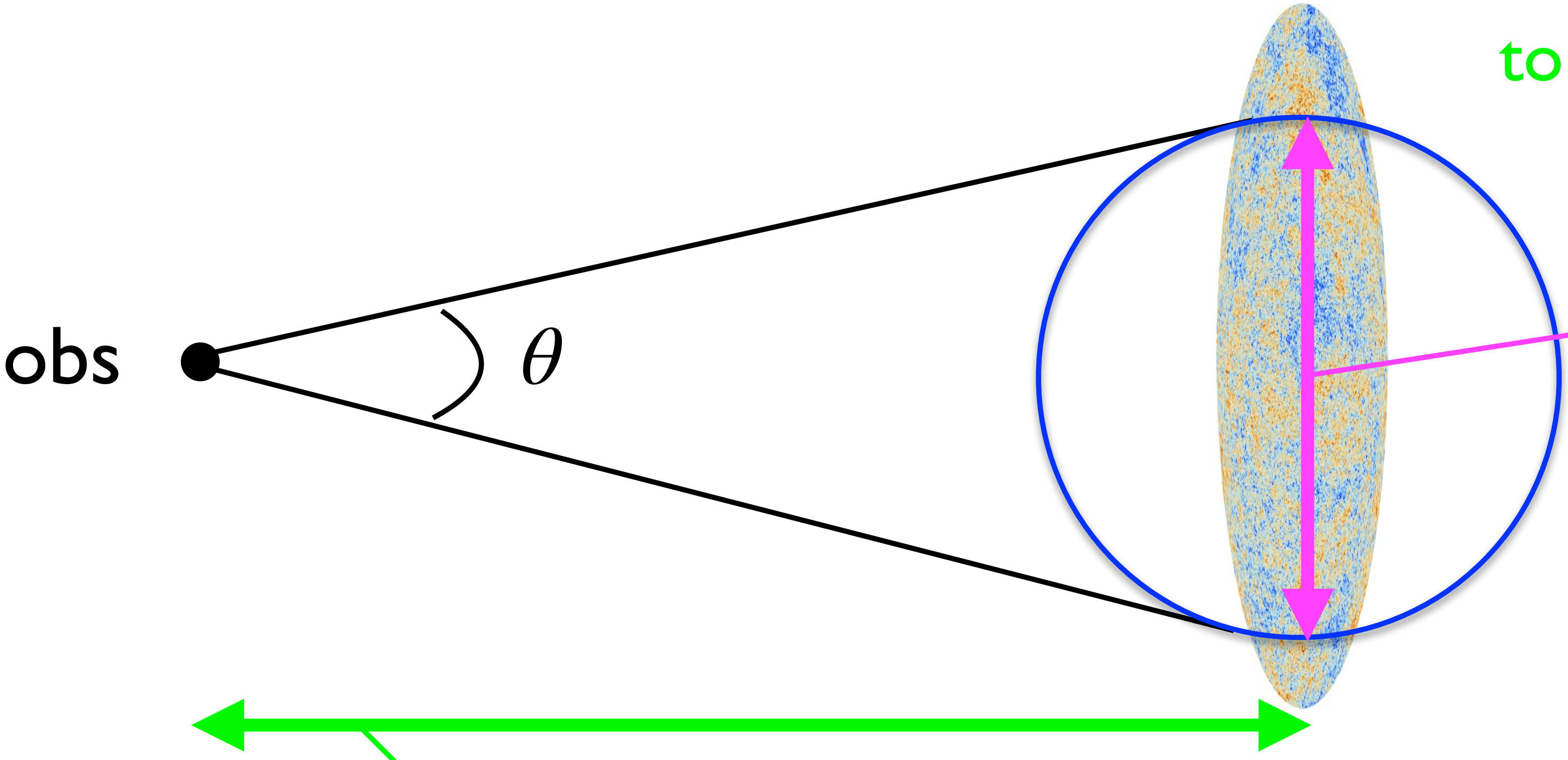


(almost independent on H_0 before recombination)

$$r_s(z_*) = \int_0^{t_*} c_s \frac{dt}{a(t)} = \int_{z_*}^{\infty} c_s \frac{dz}{H(z)}$$

Acoustic oscillation by
photon-baryon fluid

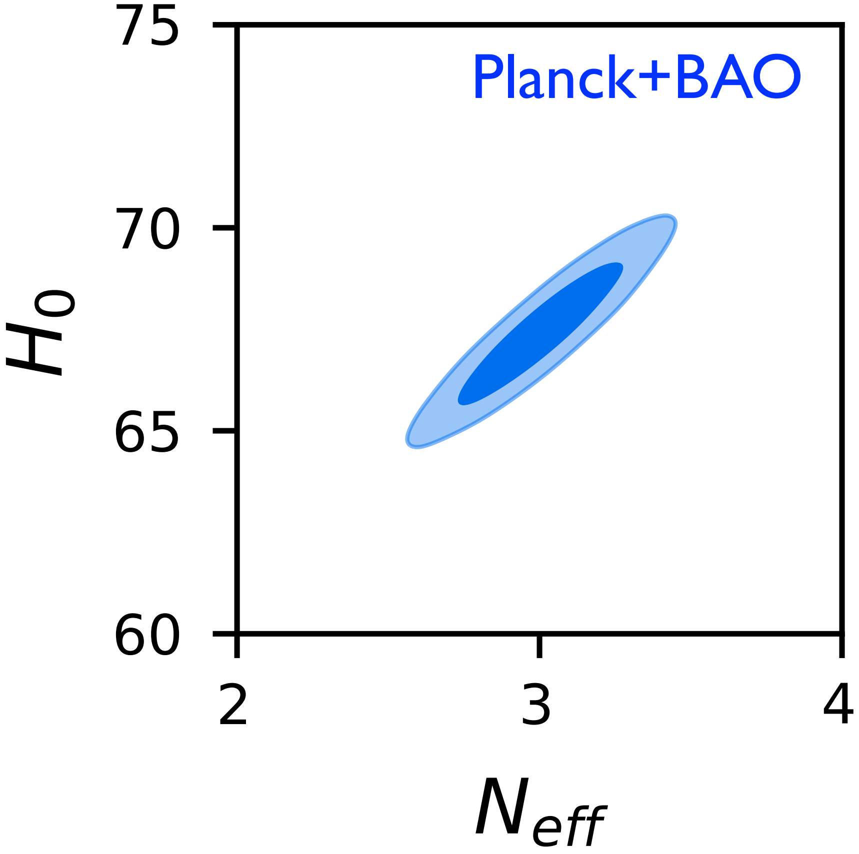
(until recombination)

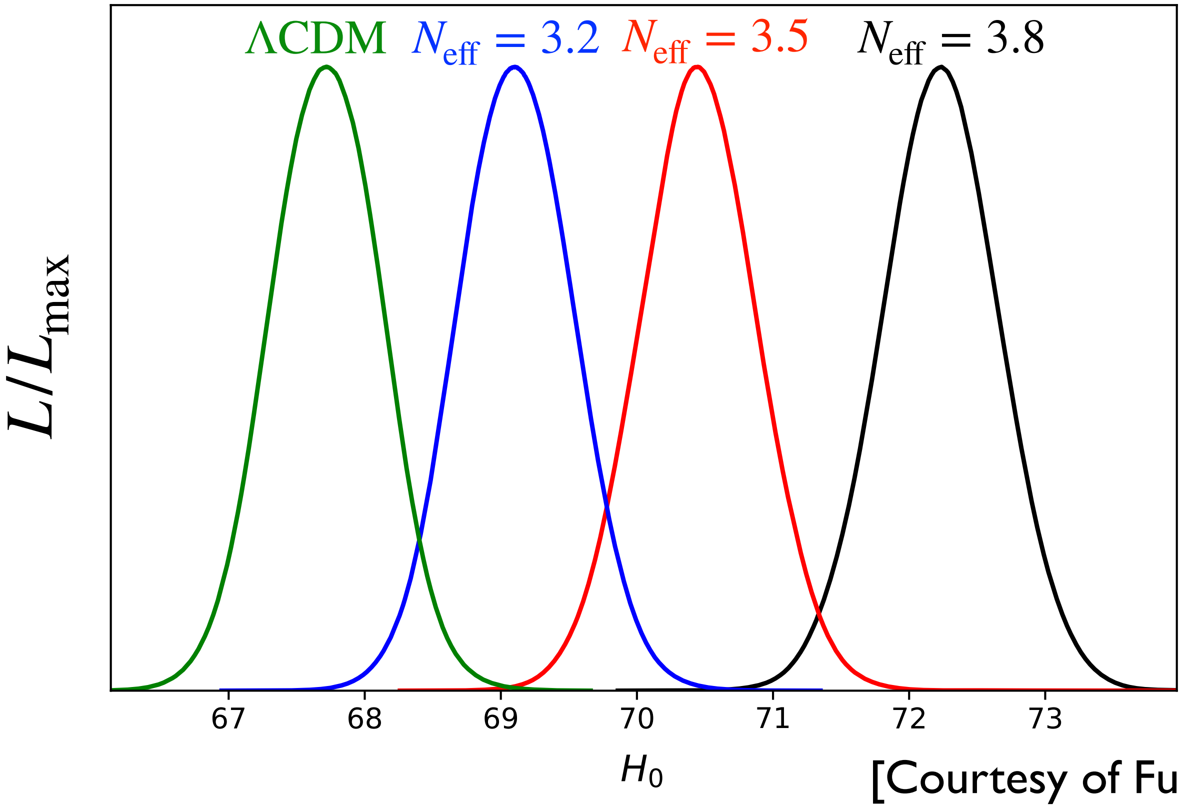
$$\ddot{\delta} + k^2 c_s^2 \delta \simeq 0$$

$$D_M(z_*) = \int_0^{z_*} \frac{dz}{H(z)} \propto 1/H_0$$

Caution! (1)

- When $N_{\rm eff}$ is fixed to some higher value, higher H_0 is superficially favored…





[Courtesy of Fumiya Okamatsu]

We need to evaluate the success of the model carefully…

(e.g. the minimum value of χ^2)

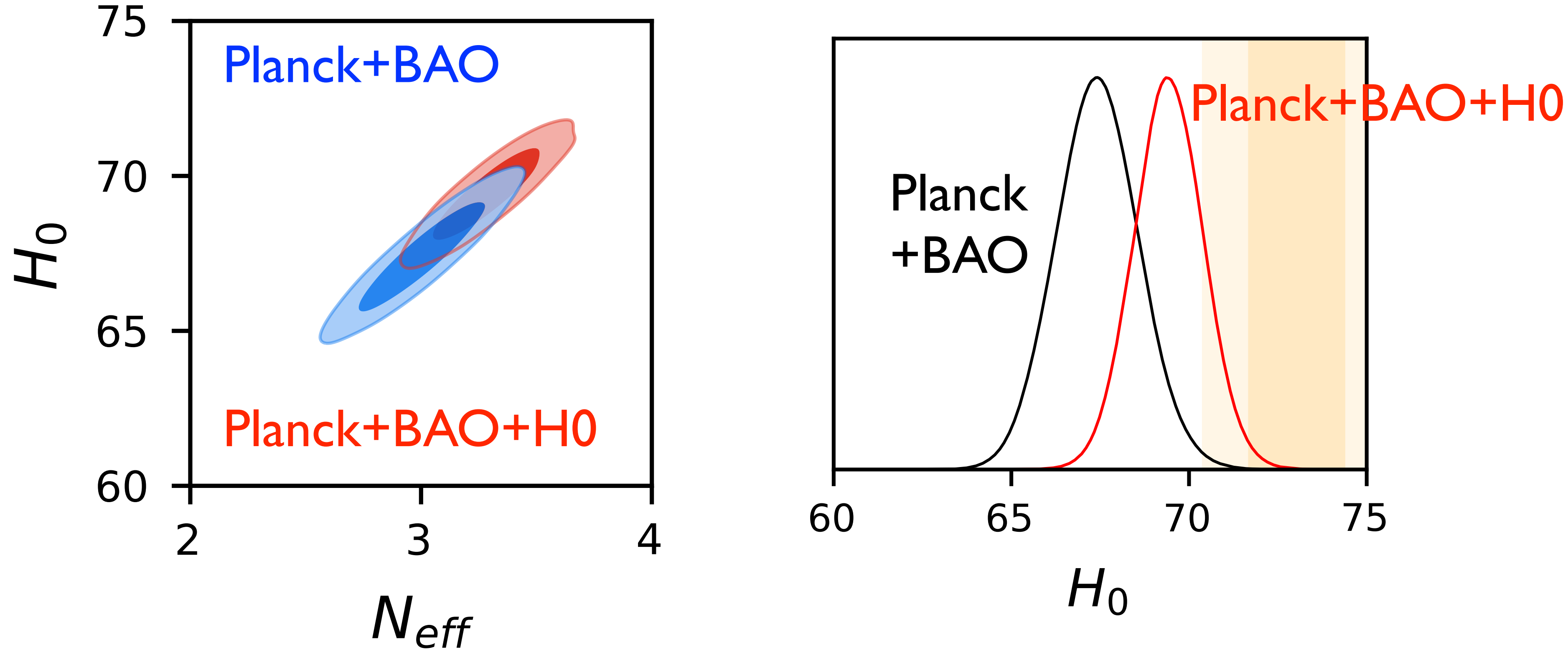
$\chi^2_{\rm min}(\Lambda{\rm CDM}) = 1911.9$ $\chi^2_{\rm min}(N_{\rm eff} = 3.2) = 1912.8$ $\chi^2_{\rm min}(N_{\rm eff} = 3.5) = 1914.8$ $\chi^2_{\rm min}(N_{\rm eff} = 3.8) = 1917.6$

Caution! (2)

- When the distribution for H_0 is broadened, the H_0 prior make the tension look less severe.

(Adding $H_0 = 73.3 \pm 1.04\ \mathrm{km/s/Mpc}$ in the analysis)

(In many analysis, this is done, but you need to be careful when interpreting the results.)



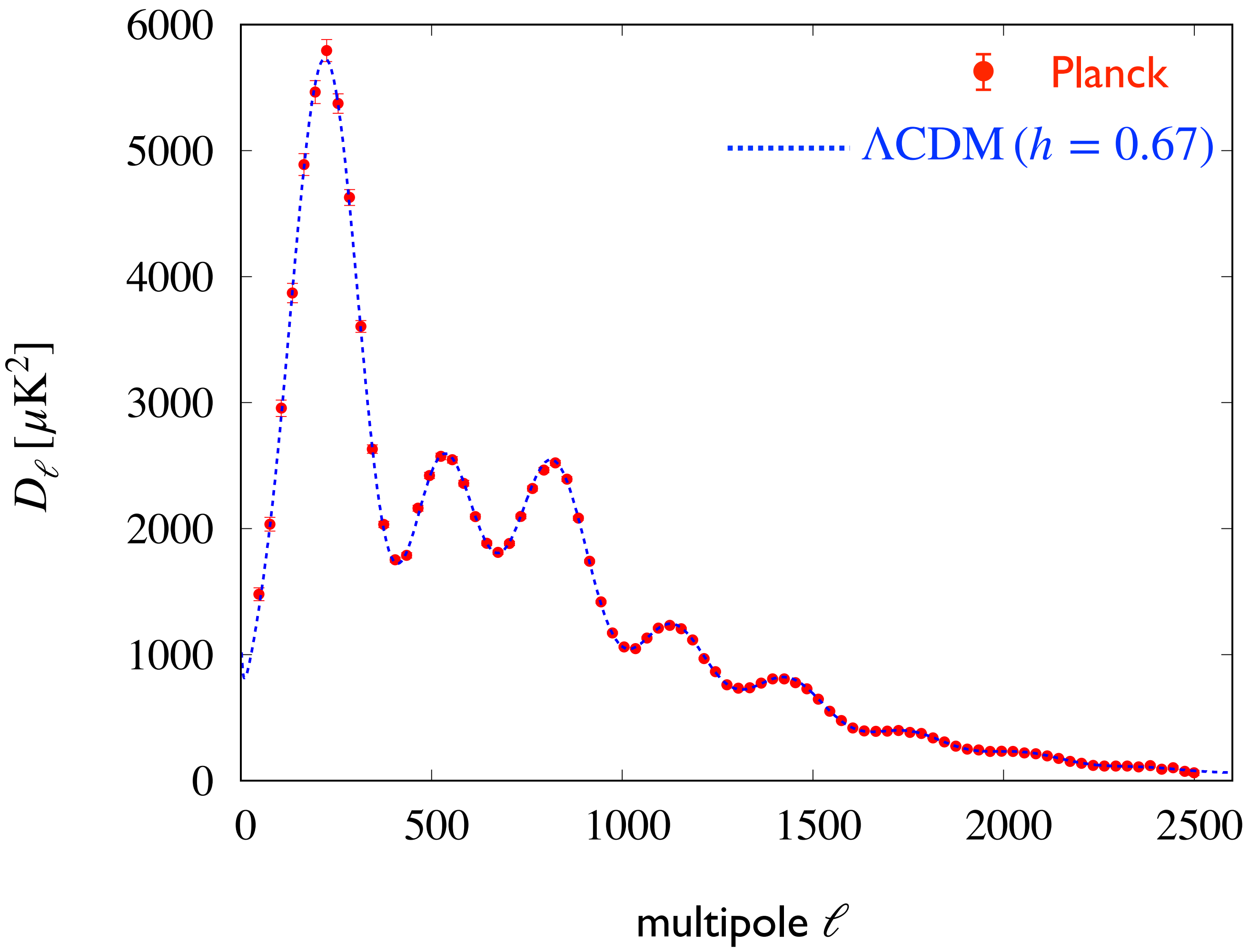
Planck+BAO: $H_0 = 67.44 \pm 1.12\ \mathrm{km/s/Mpc}\ \ (3.7\sigma)$

Planck+BAO+H0: $H_0 = 69.36 \pm 0.970\ \mathrm{km/s/Mpc}\ \ (2.6\sigma)$

Example: ΛCDM + $N_{\rm eff}$ model

- By increasing H_0, the position of acoustic peaks are shifted to smaller ℓ:

$(H_0 = 100\,h\ [\mathrm{km/sec/Mpc}])$



(← best-fit model)

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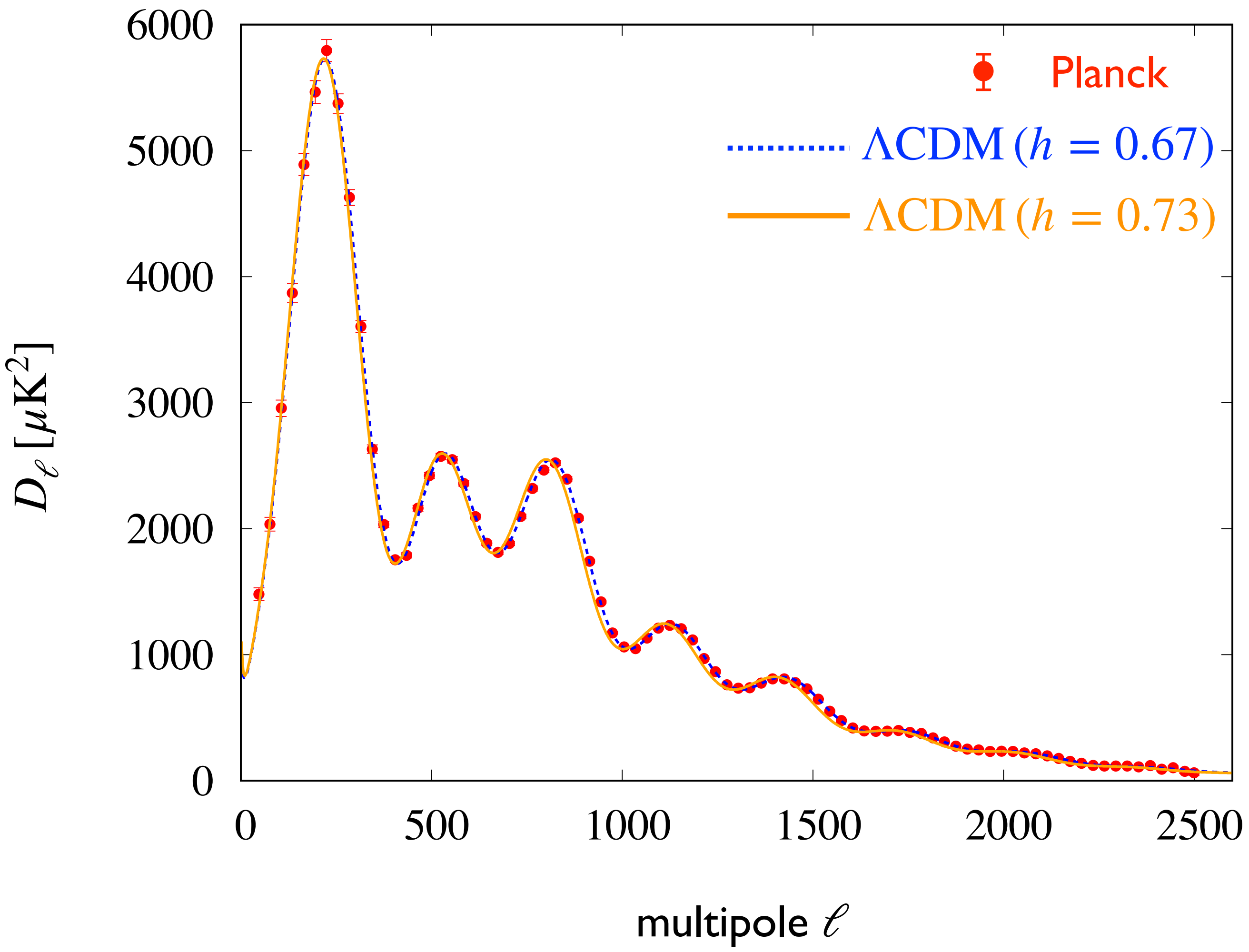

(← best-fit model)

(← model w/high H_0)

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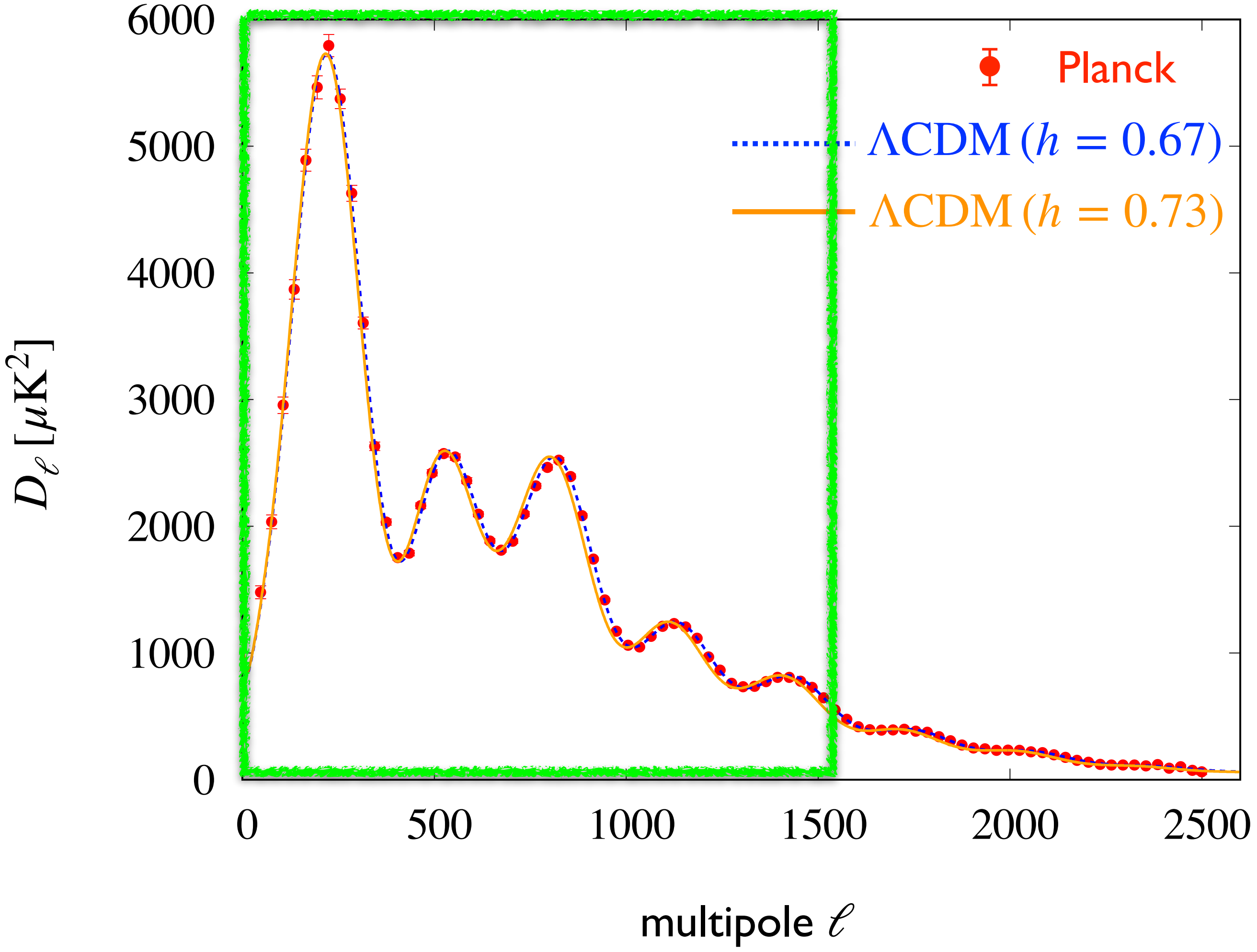

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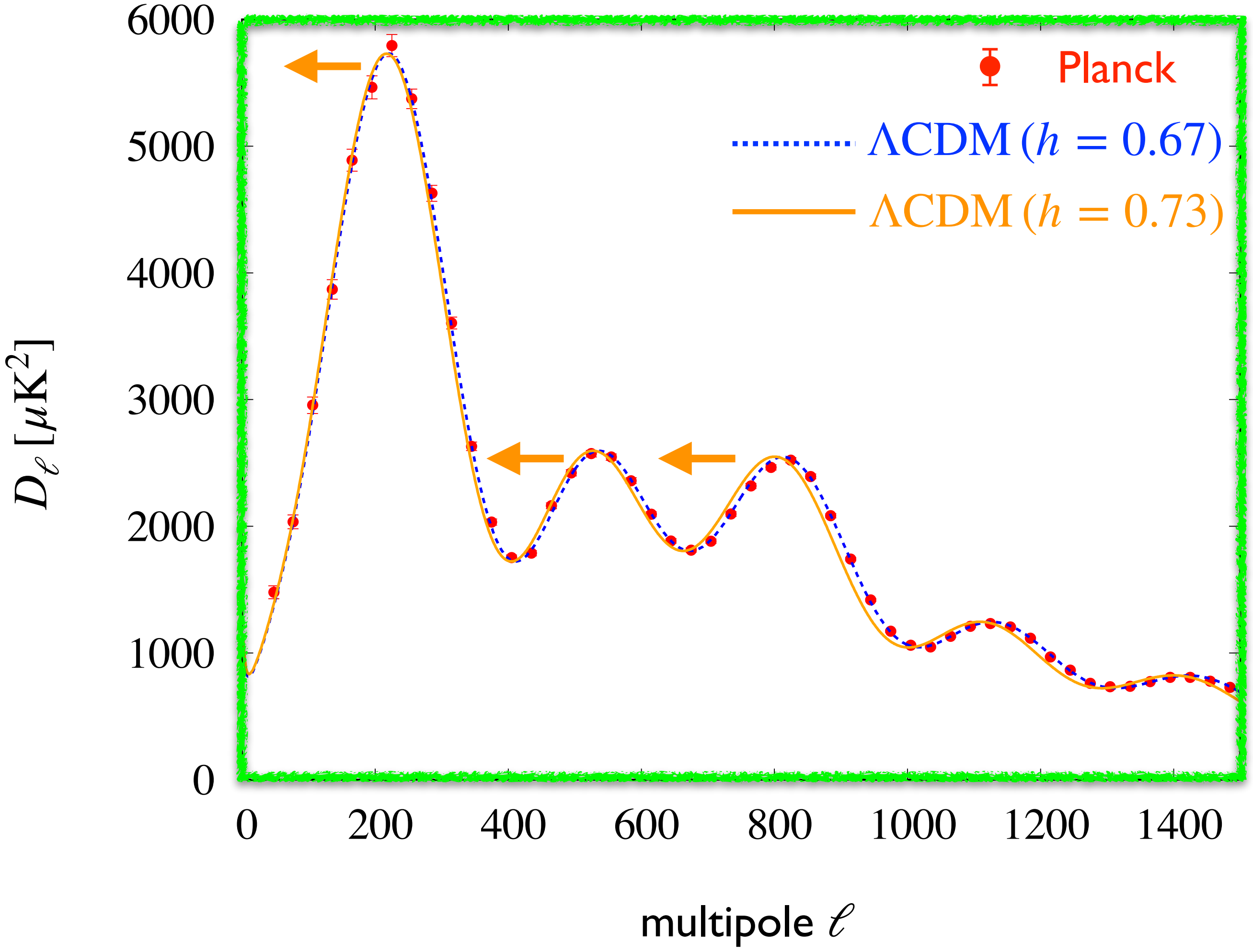
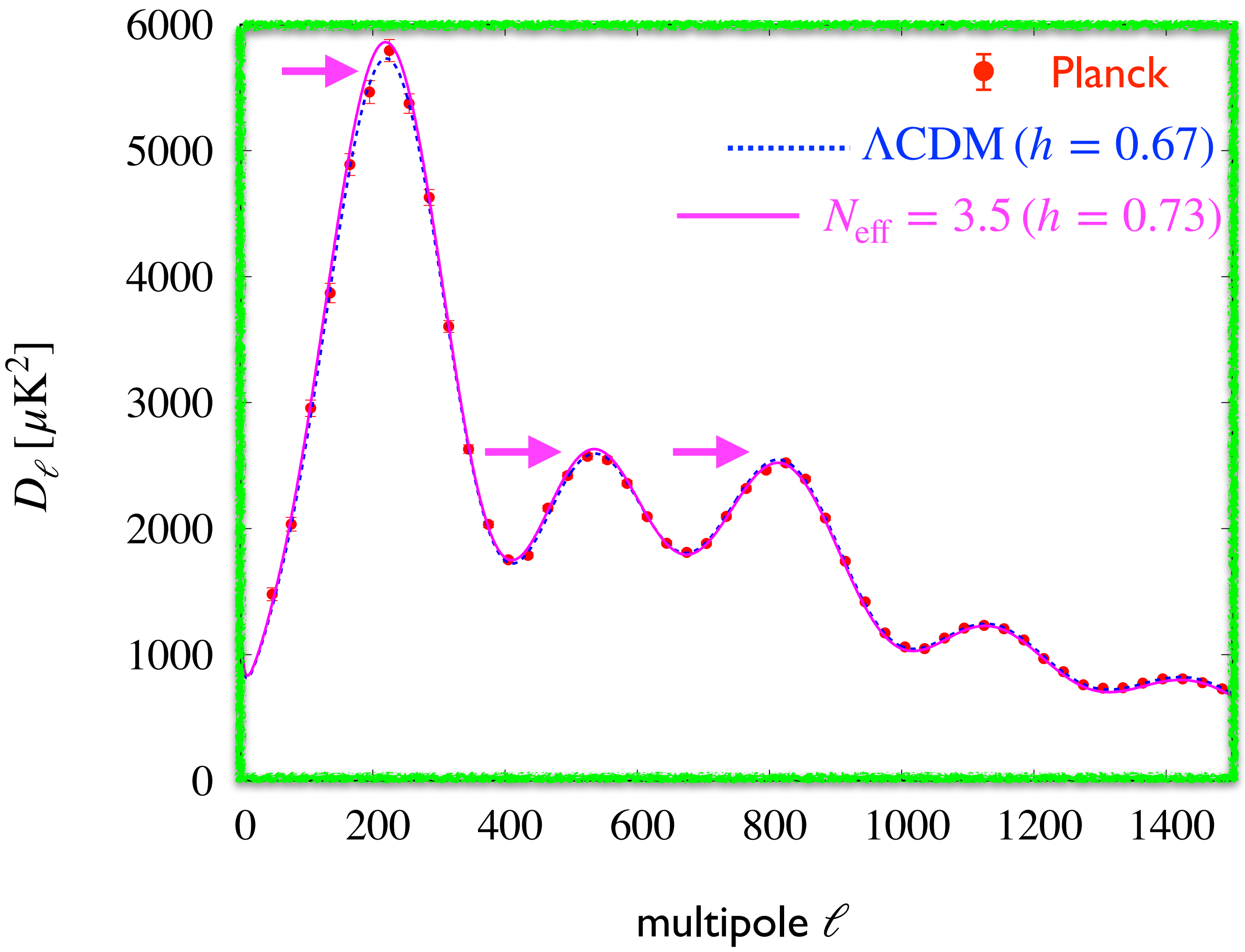


Example: ΛCDM + $N_{\rm eff}$ model

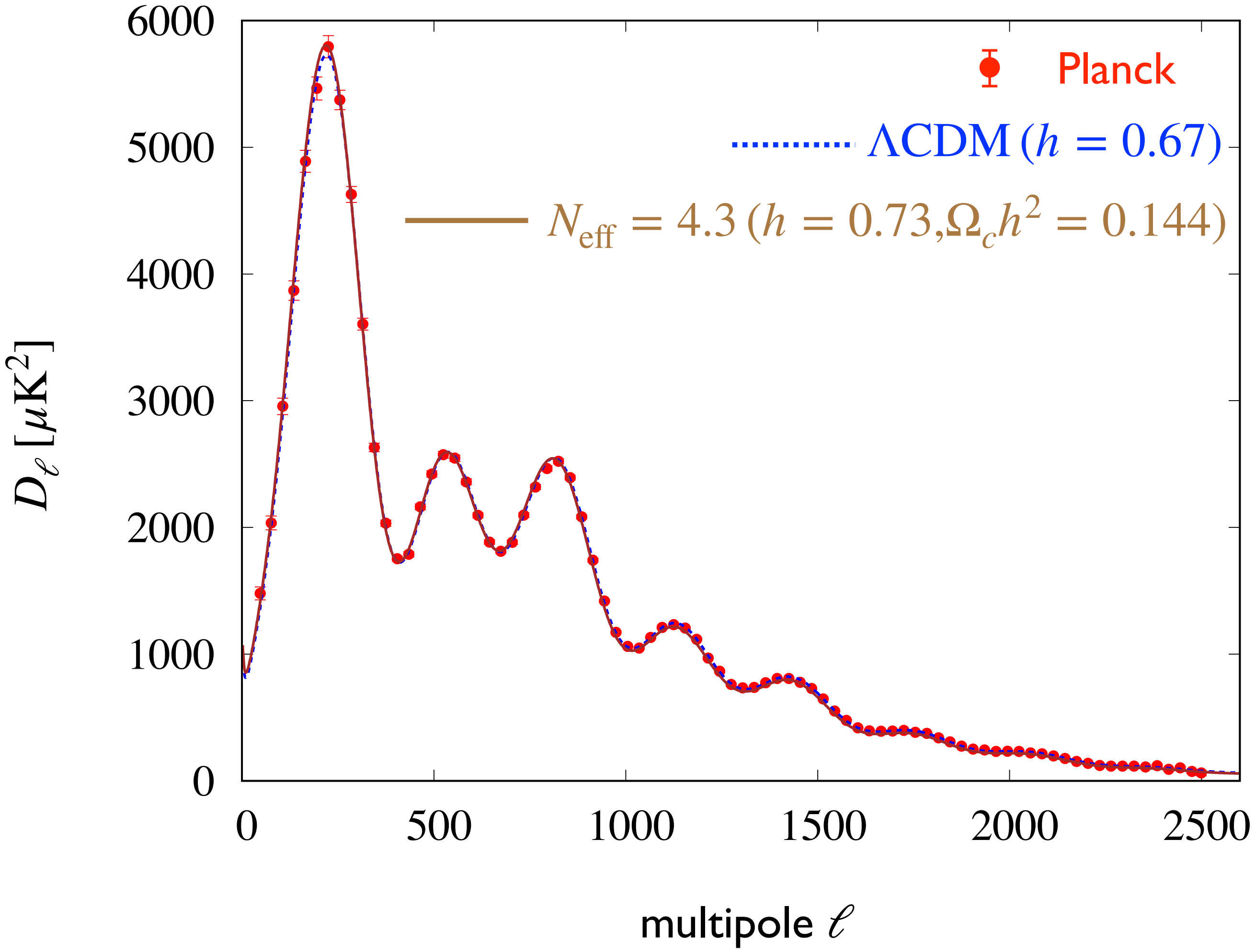
- However, larger $N_{\rm eff}$ can make the peak position back to a well-fitted value. (the sound horizon is reduced.)



But now the height of 1st peak is deviated from the best-fit one…

Example: ΛCDM + $N_{\rm eff}$ model

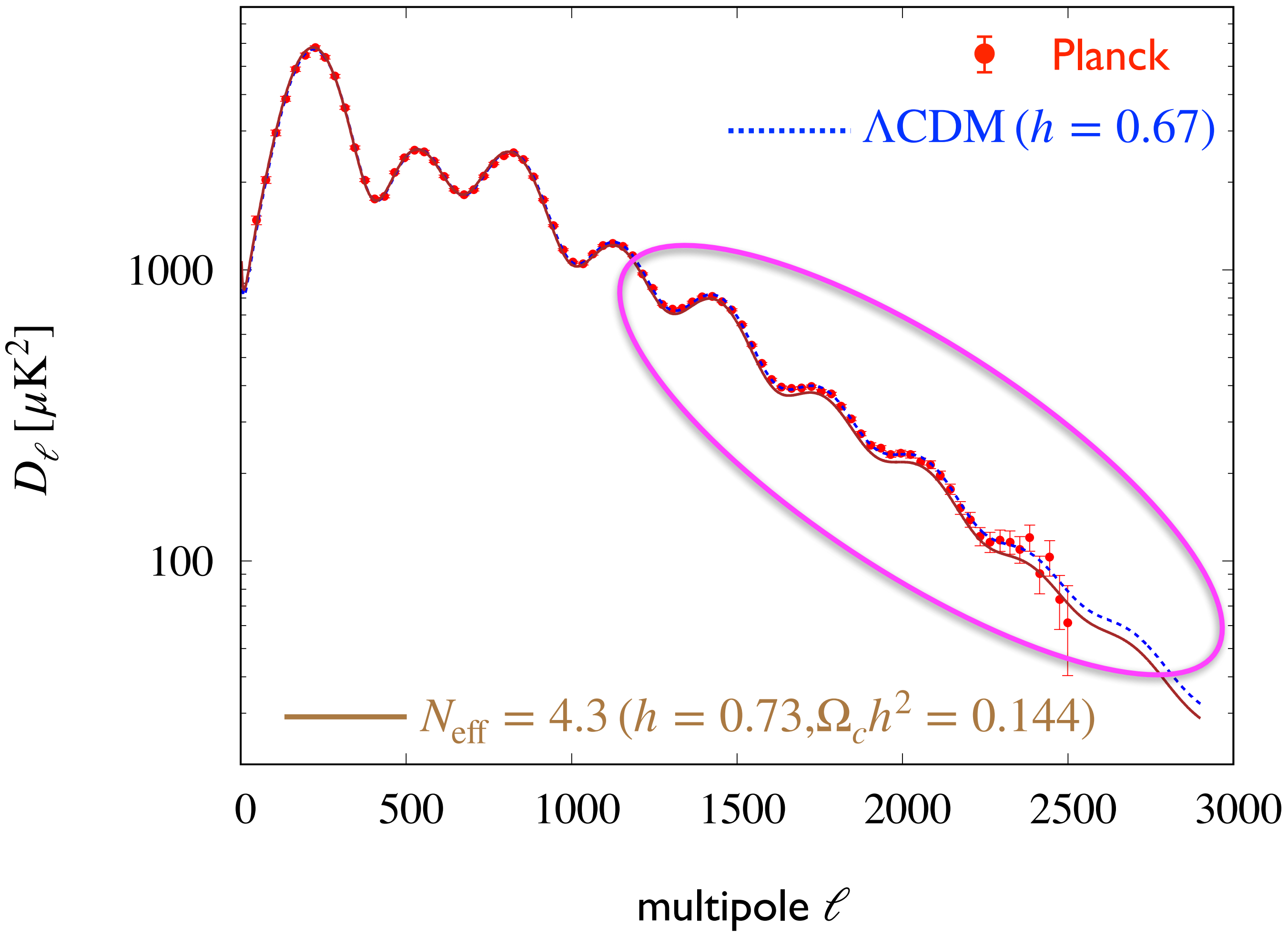
- By adjusting CDM density, rad-matter equality can be the same as the original ΛCDM model.



Looks perfect, but…

Example: ΛCDM + N_{eff} model

- On small scales, the diffusion (Silk) damping is affected…



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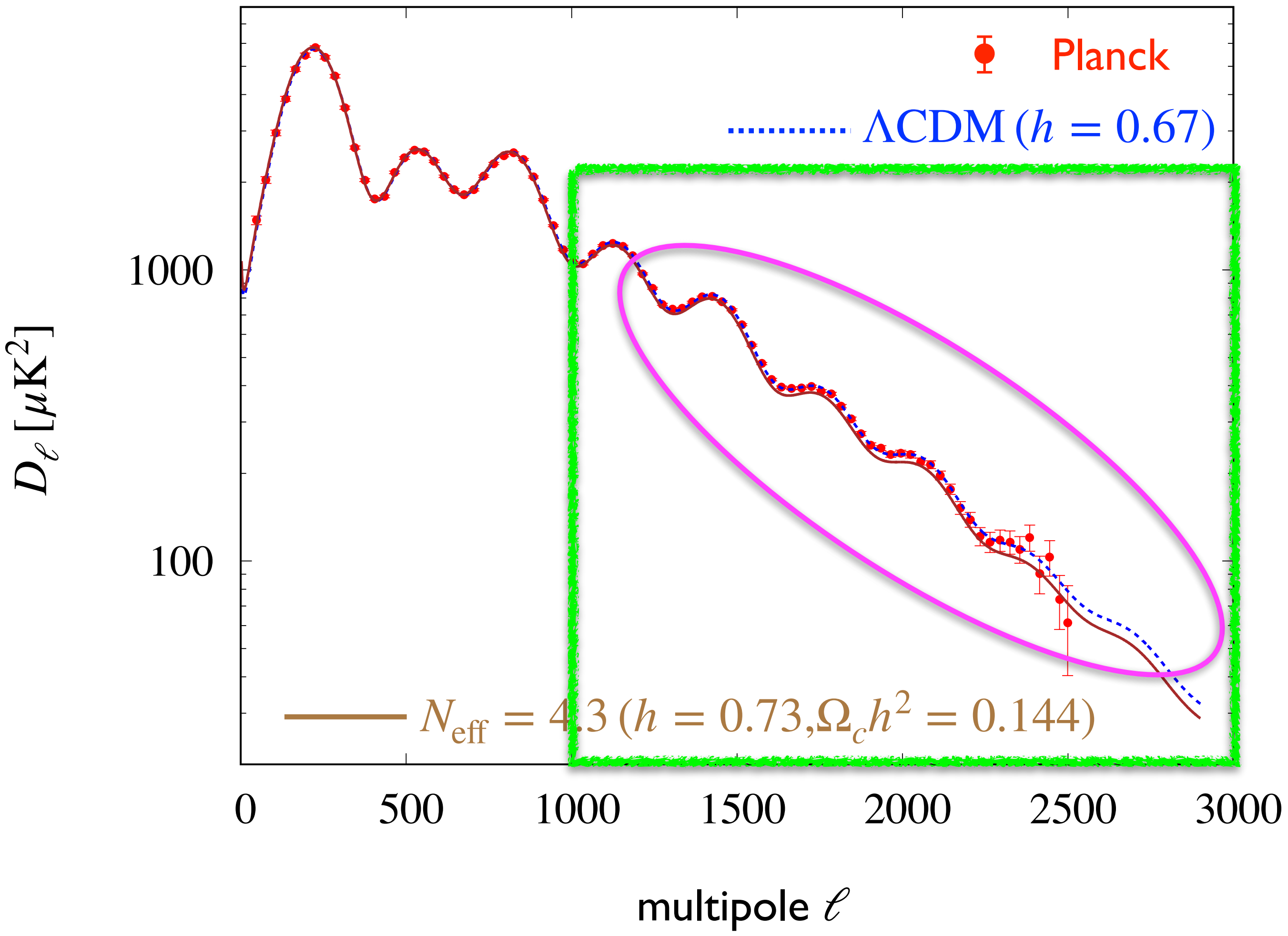

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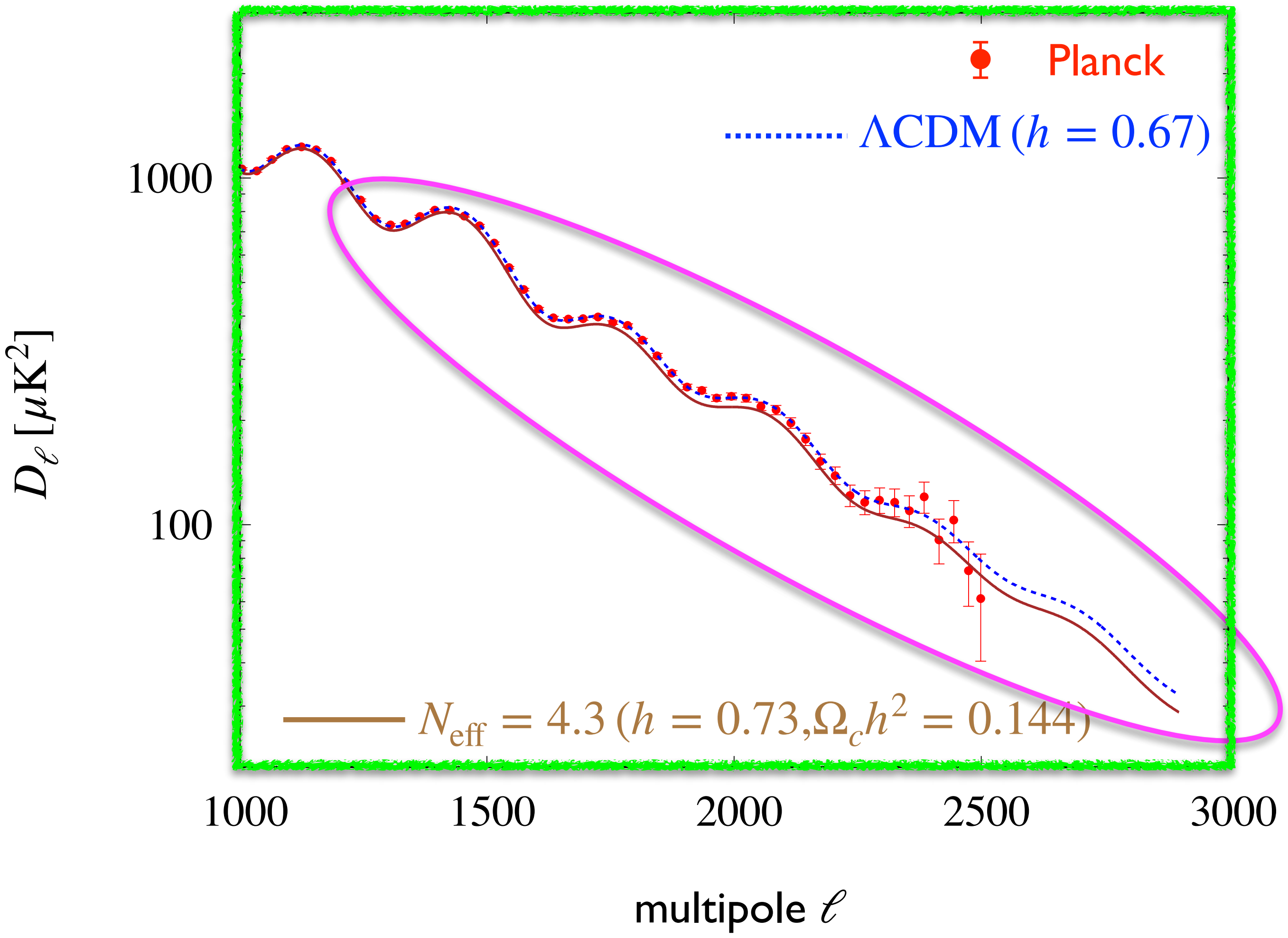


This change cannot be compensated by the change of other parameters.

→ This limits the ability of reducing the Hubble tension.

Many models have been proposed to resolve the tension…

(See e.g., reviews [Di Valentino et all. 2103.01183; Schöneberg et al. 2107.10291])

- Dark energy modification
  - early dark energy, various dark energy models…
- Interactions of dark sectors
  - DM-DE coupling, DM-DR coupling, …
- Modifying the recombination history
  - Varying electron mass, primordial magnetic fields, …
- Modified gravity

⋮

Proposed models to resolve the H_0 tension

- Example model list

Model	$\Delta N_{\rm param}$	M_B	Gaussian Tension	$Q_{\rm DMAP}$ Tension		$\Delta\chi^2$	ΔAIC		Finalist		
ΛCDM	0	-19.416 ± 0.012	4.4σ	4.5σ	X	0.00	0.00	X	X		
$\Delta N_{\rm ur}$	1	-19.395 ± 0.019	3.6σ	3.8σ	X	-6.10	-4.10	X	X		
SIDR	1	-19.385 ± 0.024	3.2σ	3.3σ	X	-9.57	-7.57	✓	✓	③	
mixed DR	2	-19.413 ± 0.036	3.3σ	3.4σ	X	-8.83	-4.83	X	X		
DR-DM	2	-19.388 ± 0.026	3.2σ	3.1σ	X	-8.92	-4.92	X	X		
SIν+DR	3	$-19.440^{+0.037}_{-0.039}$	3.8σ	3.9σ	X	-4.98	1.02	X	X		
Majoron	3	$-19.380^{+0.027}_{-0.021}$	3.0σ	2.9σ	✓	-15.49	-9.49	✓	✓	②	
primordial B	1	$-19.390^{+0.018}_{-0.024}$	3.5σ	3.5σ	X	-11.42	-9.42	✓	✓	③	bronze
varying m_e	1	-19.391 ± 0.034	2.9σ	2.9σ	✓	-12.27	-10.27	✓	✓	①	gold
varying m_e+Ω_k	2	-19.368 ± 0.048	2.0σ	1.9σ	✓	-17.26	-13.26	✓	✓	①	
EDE	3	$-19.390^{+0.016}_{-0.035}$	3.6σ	1.6σ	✓	-21.98	-15.98	✓	✓	②	
NEDE	3	$-19.380^{+0.023}_{-0.040}$	3.1σ	1.9σ	✓	-18.93	-12.93	✓	✓	②	silver
EMG	3	$-19.397^{+0.017}_{-0.023}$	3.7σ	2.3σ	✓	-18.56	-12.56	✓	✓	②	
CPL	2	-19.400 ± 0.020	3.7σ	4.1σ	X	-4.94	-0.94	X	X		
PEDE	0	-19.349 ± 0.013	2.7σ	2.8σ	✓	2.24	2.24	X	X		
GPEDE	1	-19.400 ± 0.022	3.6σ	4.6σ	X	-0.45	1.55	X	X		
DM $\rightarrow$ DR+WDM	2	-19.420 ± 0.012	4.5σ	4.5σ	X	-0.19	3.81	X	X		
DM $\rightarrow$ DR	2	-19.410 ± 0.011	4.3σ	4.5σ	X	-0.53	3.47	X	X		

[Schöneberg et al., "The H_0 Olympics" 2107.10291v2]

In many models, the tension is still larger than 3σ…

Quantifying the model success

[Schöneberg et al., 2107.10291]

- Gaussian tension: $\text{Significance} = \dfrac{\bar{H}_0|_D - \bar{H}_0|_{\rm SH0ES}}{\sqrt{\sigma_D^2 + \sigma_{\rm SH0ES}^2}}$ $(D : \text{data set})$

$\bar{H}_0|_{\rm SH0ES} = 73.2\ \text{km/s/Mpc}$

$\sigma_{\rm SH0ES} = 1.3\ \text{km/s/Mpc}$

→ quantifying the residual level of tension between direct (SH0ES) and indirect measurements

(This measure does not quantify how much χ^2 is improved.)

- QDMAP (Difference of the maximum a posteriori) tension: $\Delta\chi^2 = \chi^2_{\min,D+\rm SH0ES} - \chi^2_{\min,D}$

→ quantifying (in)consistency of direct and indirect measurements

(This measure is irrelevant to # of model parameters.)

- Akaike Information Criterium (AIC): $\Delta\text{AIC} = \chi^2_{\min,M} - \chi^2_{\min,\Lambda\rm CDM} + 2(N_M - M_{\Lambda\rm CDM})$

$(M : \text{model})$

→ quantifying how much the fit within model M improves compared to ΛCDM (with the penalty for # of free parameters.)

Varying electron mass model (+ Ω_k) [Sekiguchi, TT 2007.03381]

- Effects of time-varying electron mass m_e

  - Energy levels of hydrogen $E \propto m_e$ $\quad (\Delta_x = \delta x/x)$

    → $\boxed{\Delta_{m_e} = \Delta_{T_\gamma(a_*)} = -\Delta_{a_*}}$: recombination epoch a_* gets earlier

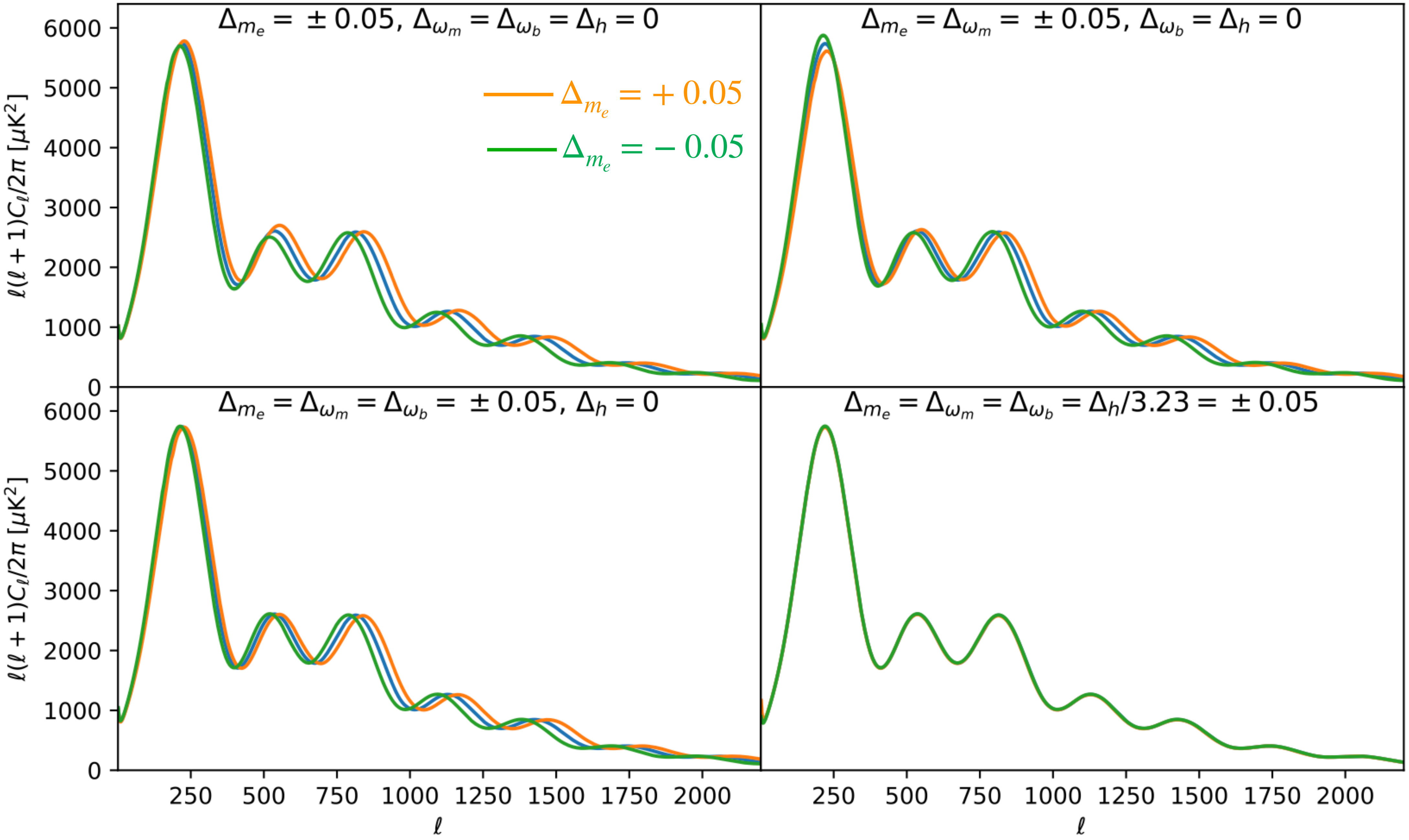
  - Thomson cross section $\sigma_T \propto m_e^{-2}$

    → affects the Silk damping scale

  - (Some other minor effects)

One can reduce the sound horizon at recombination without affecting the fit to CMB (by changing other cosmological parameters).

Varying electron mass model (+ Ω_k)

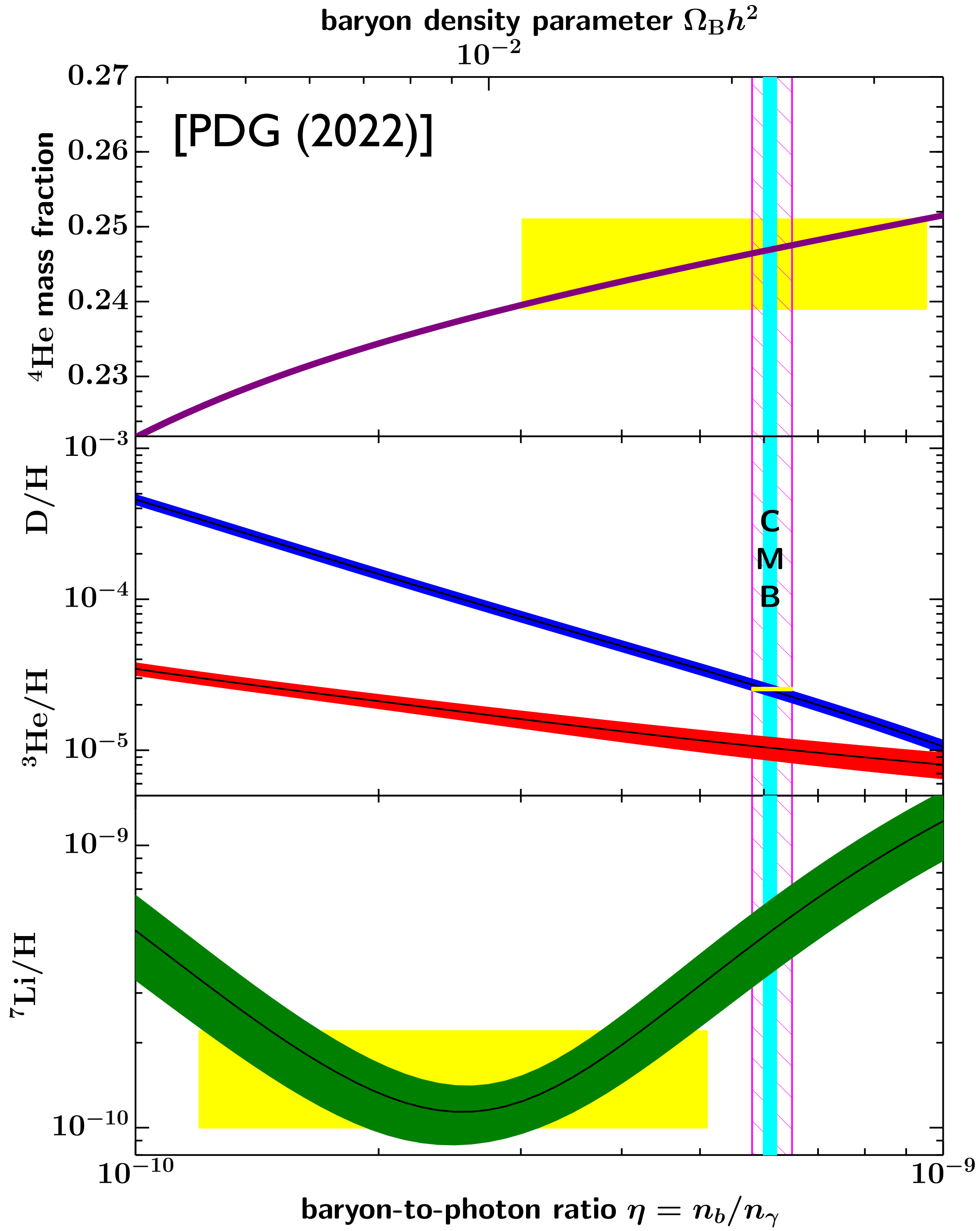


Effects can be almost perfectly canceled by changing other cosmological parameters.

Helium (EMPRESS) anomaly and the H_0 tension

Baryon density also affects BBN

- Abundances of light element (particularly deuterium D/H) are sensitive to baryon density.



Recent results on ^{4}He abundance from EMPRESS

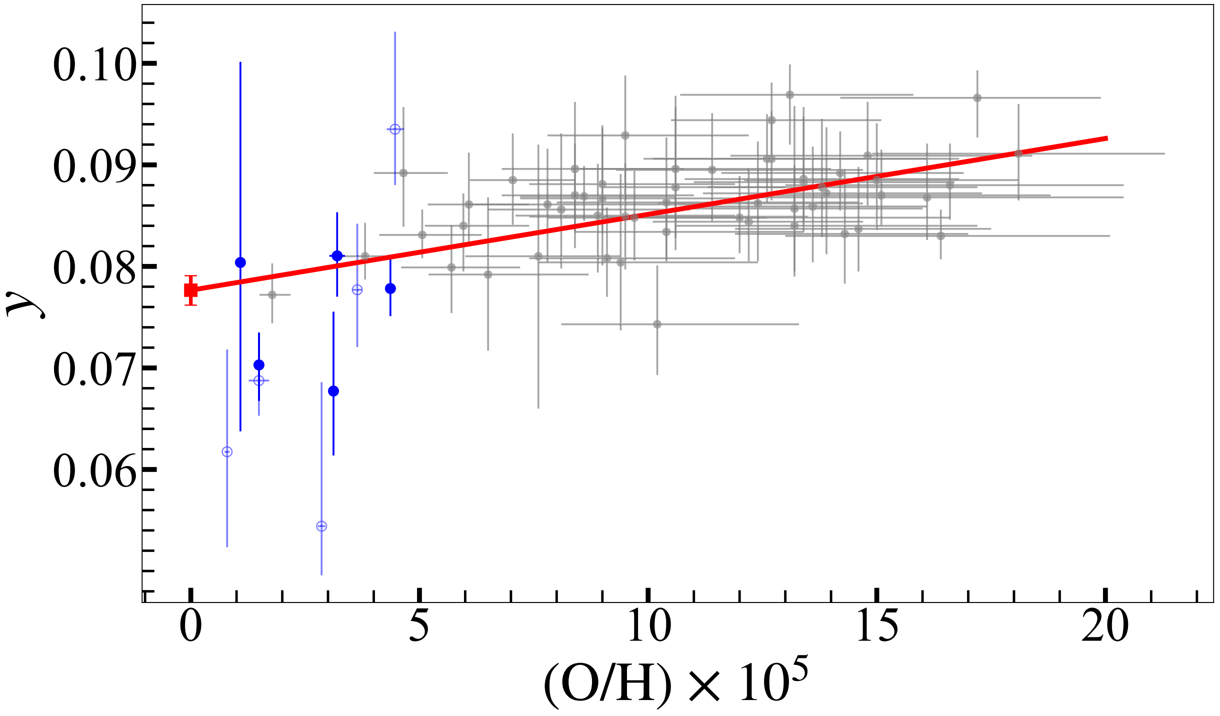
- Recent EMPRESS results: $Y_p = 0.2370^{+0.0033}_{-0.0034}$ [Matsumoto et al. 2203.09617]

Low Helium abundance has been obtained.

cf. previous results:
$Y_p = 0.2449 \pm 0.0040$ [Hsyu et al. 2005.12290]
$Y_p = 0.2436^{+0.0039}_{-0.0040}$ [Aver et al. 1503.08146]
$Y_p = 0.2462 \pm 0.0022$ [Kurichin et al. 2101.09127]

- EMPRESS observed 10 extremely metal-poor galaxies.

- Adding the data of 54 existing galaxies, the helium-4 abundance has been obtained.

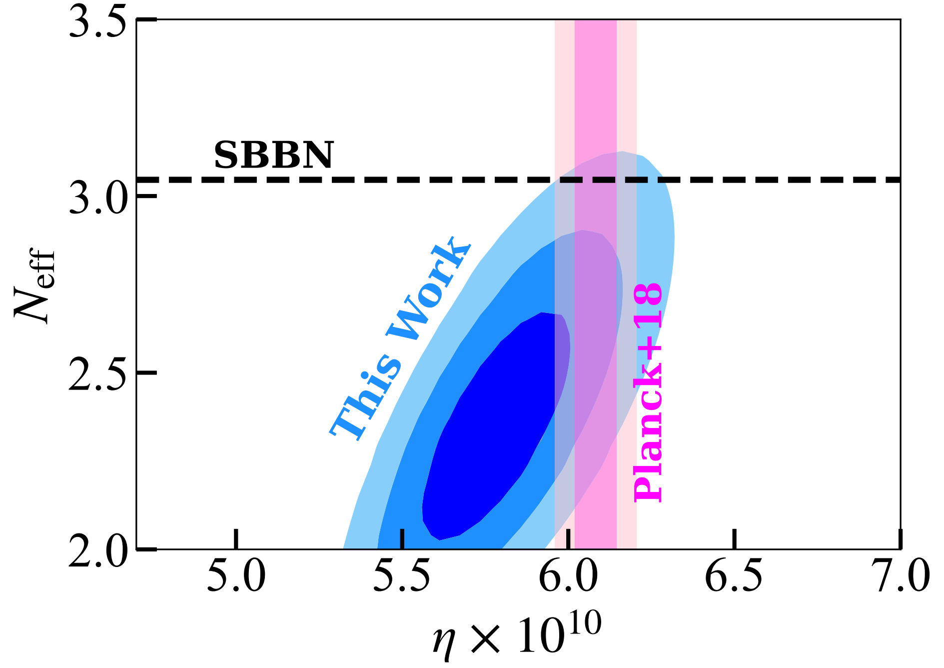


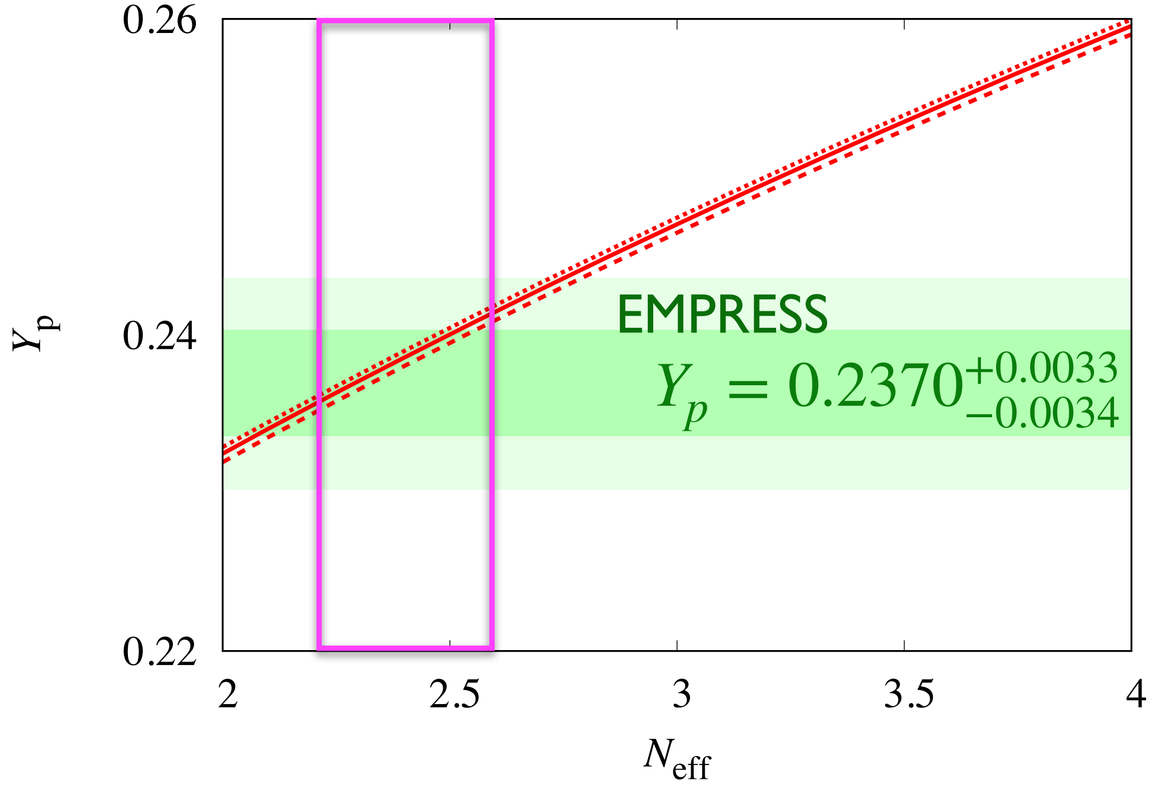
Recent results on ^{4}He abundance from EMPRESS

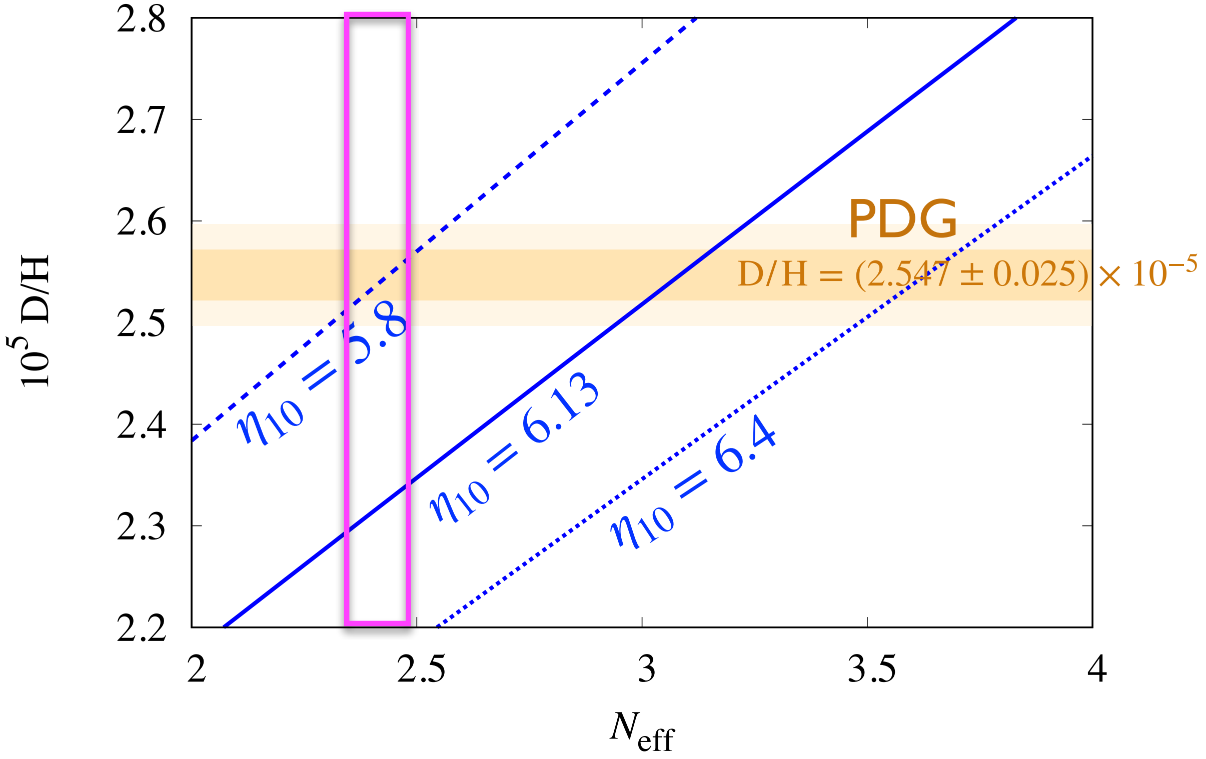
- EMPRESS results (+D/H) prefers a non-standard $N_{\rm eff}$ and (slightly) inconsistent baryon density with Planck.

(Helium anomaly)

[Matsumoto et al. 2203.09617]







EMPRESS prefers a low $N_{\rm eff}$ and low baryon density ?

Recent results on ^{4}He abundance from EMPRESS

- The chemical potential of electron neutrino may mitigate the anomaly

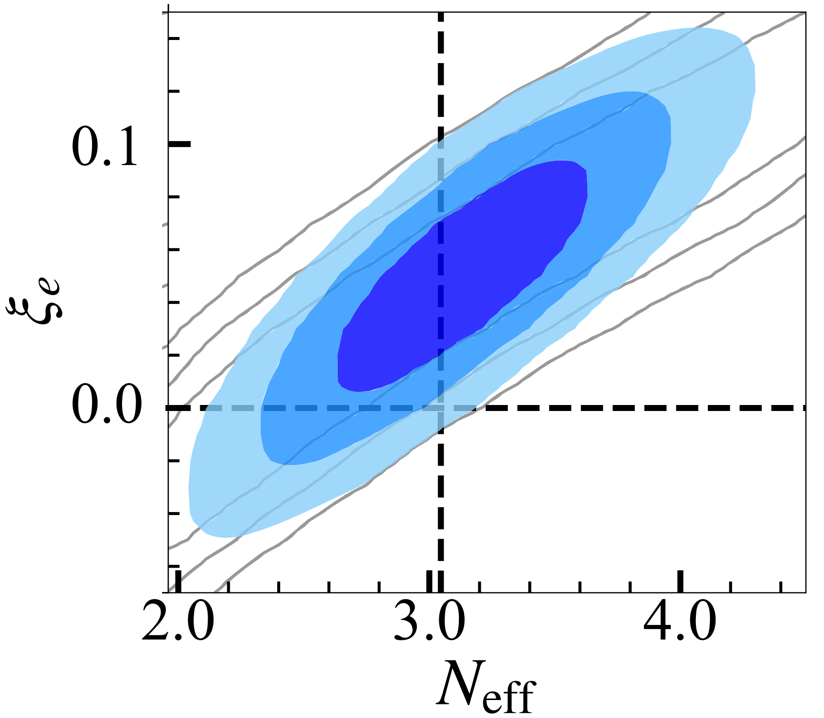
$$N_{\rm eff} = 3.22^{+0.33}_{-0.30} \qquad \xi_e = 0.05^{+0.03}_{-0.03}$$

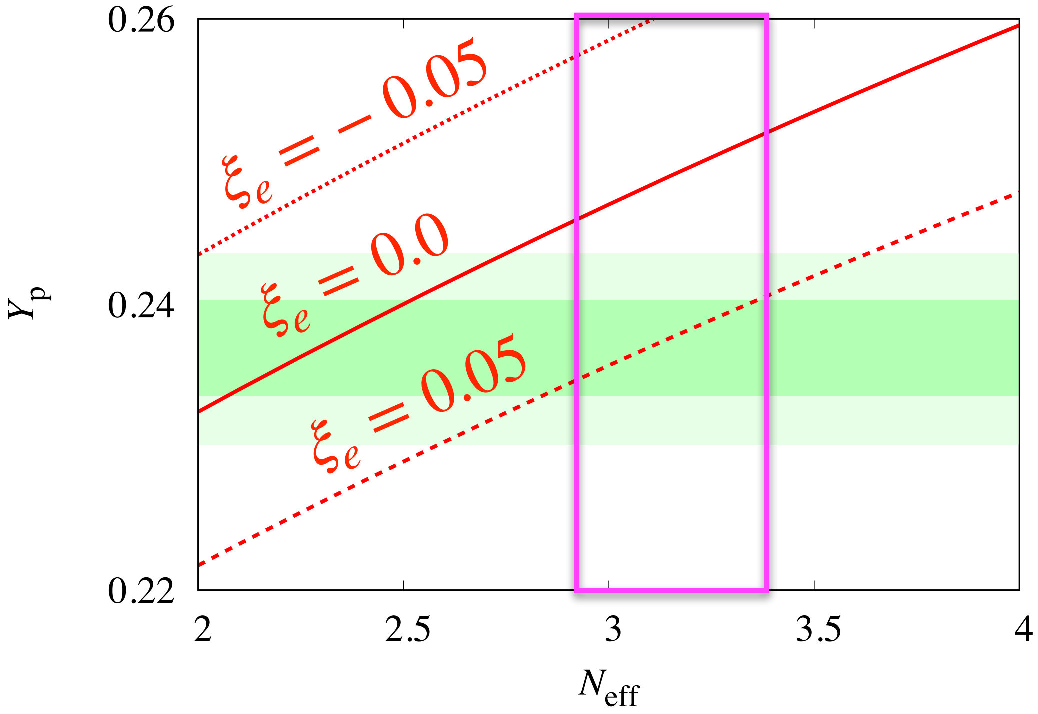
(Prior of $\eta_{10} = 6.132 \pm 0.038$ is adopted.)

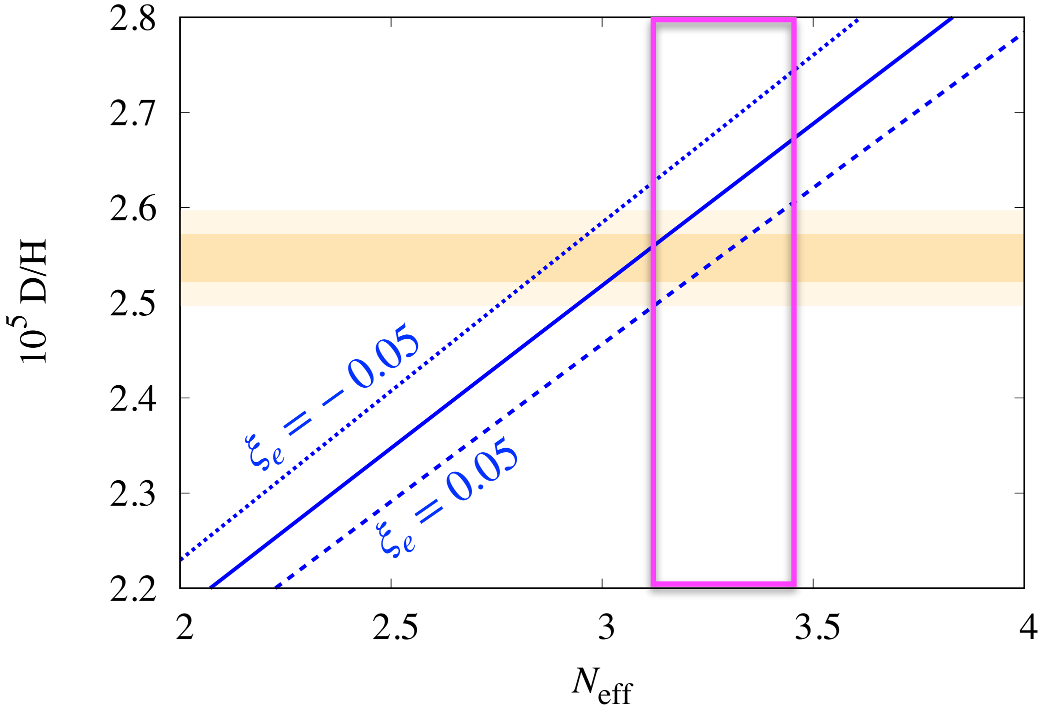
$$\eta_{10} = 10^{10}\eta = 10^{10}(n_b/n_\gamma)$$

Y_p is mostly determined by n/p ratio: $n/p \simeq \exp\left(-\frac{Q+\mu_{\nu_e}}{T_f}\right)$

[Matsumoto et al. 2203.09617]





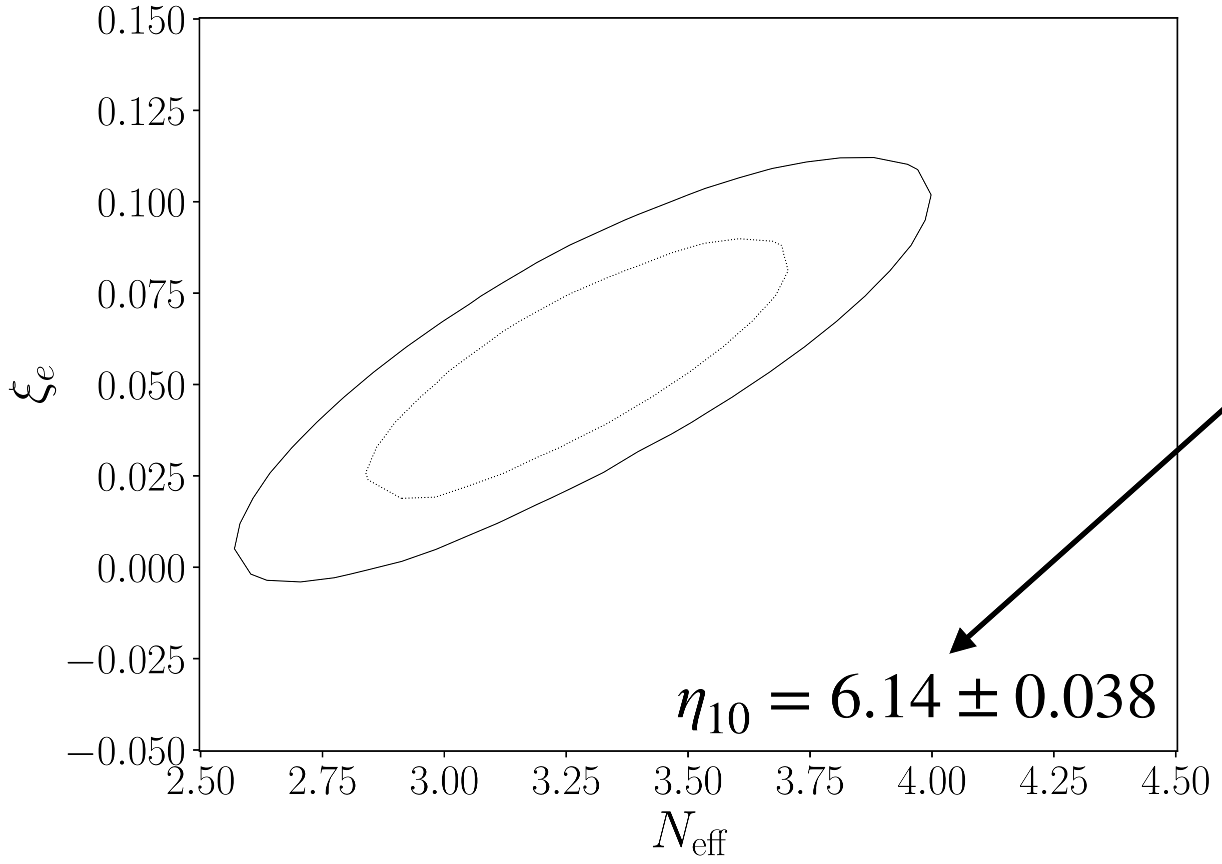


Large lepton asymmetry is suggested?

[See e.g., Kawasaki, Murai 2203.09713]

Impact of the H_0 tension to BBN

- With the baryon density suggested by Planck (in LCDM framework), larger $N_{\rm eff}$ and ξ_e are preferred.



$\eta_{10} = 6.14 \pm 0.038$

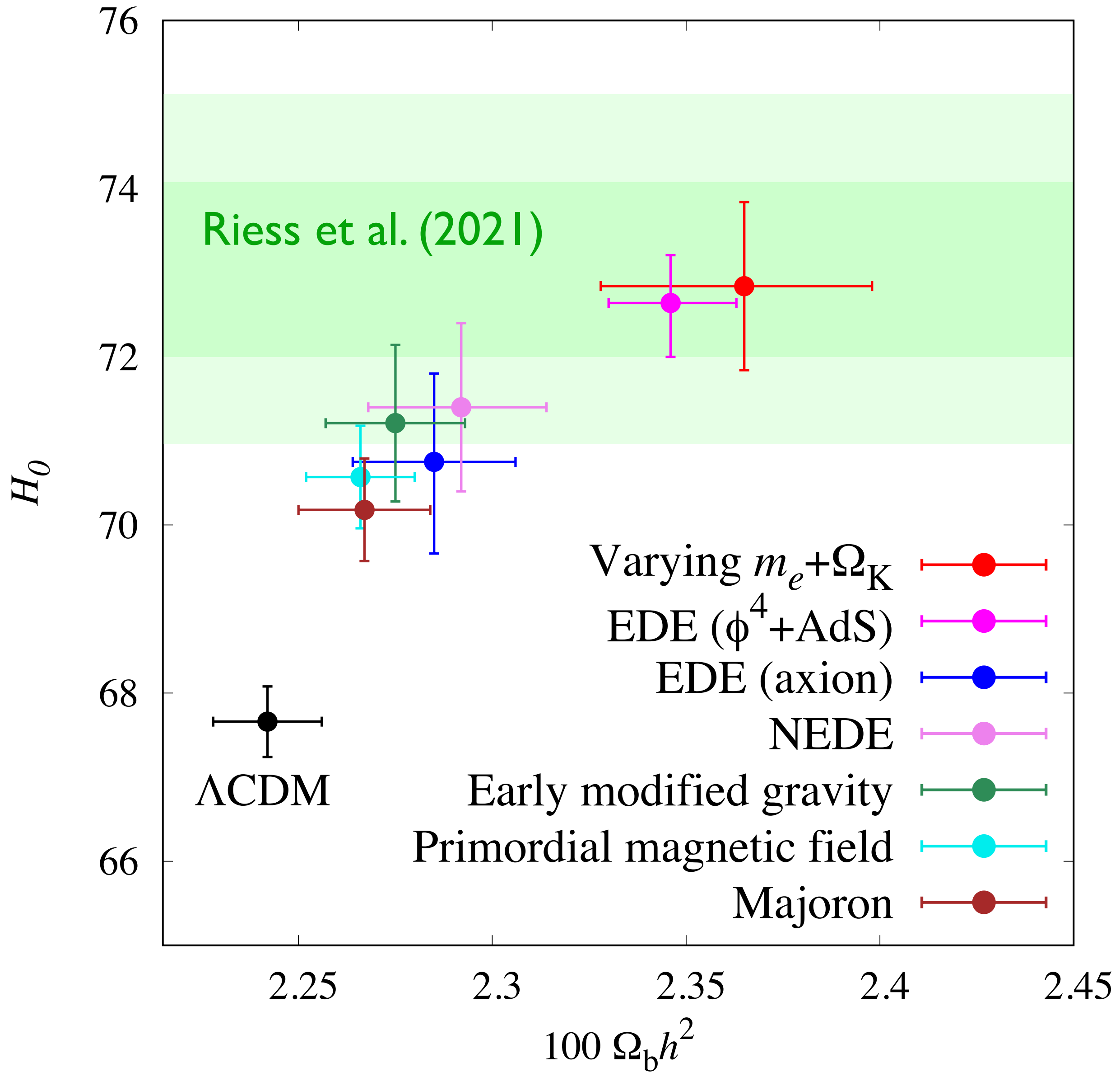
Obtained in ΛCDM

$$\eta_{10} = 10^{10}\eta = 10^{10}(n_b/n_\gamma)$$

[TT, Yamashita 2211.04087]

Baryon density in models for the H_0 tension

- Baryon density (obtained from CMB fitting) tends to be higher than ΛCDM in models proposed to resolve the H_0 tension.

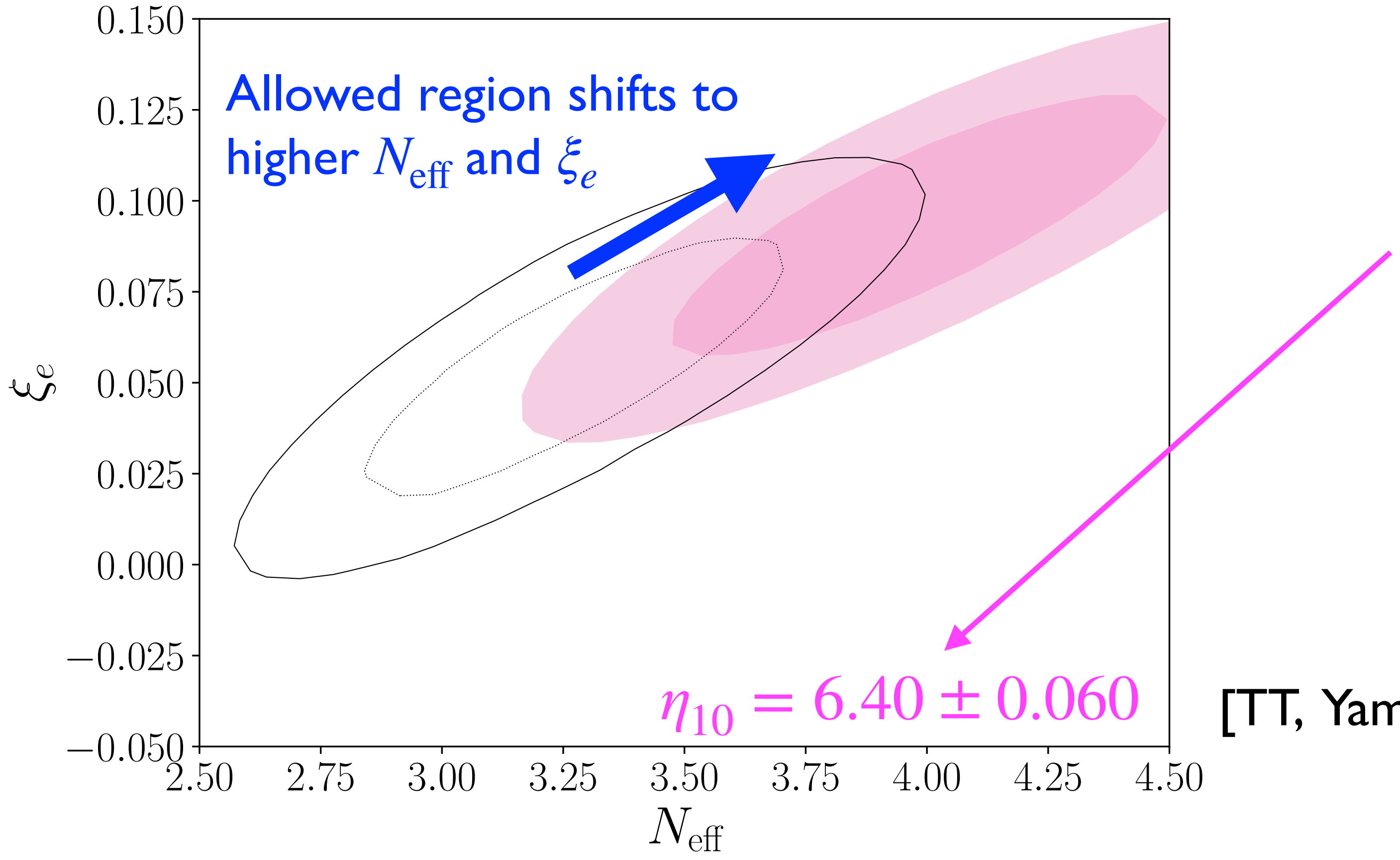


- When a higher H_0 is realized, the baryon density also gets larger.

- In particular, in models almost consistent with direct measurement of H_0, the baryon density is much higher than the ΛCDM.

Impact of the H_0 tension to BBN

- When the baryon density is high (suggested in models to resolve the H_0 tension), much larger N_{eff} and ξ_e are preferred.



Allowed region shifts to higher N_{eff} and ξ_e

$\eta_{10} = 6.40 \pm 0.060$

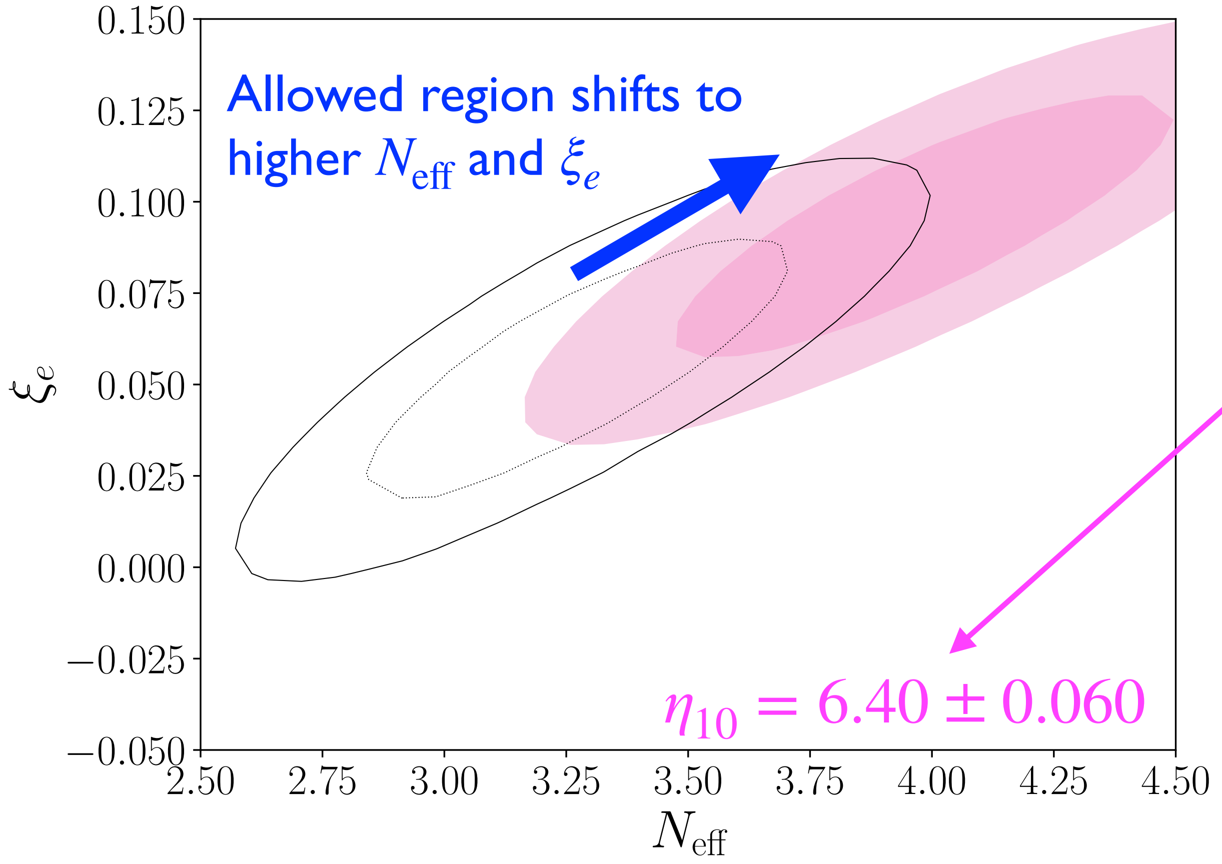
Suggested in models to resolve the H_0 tension

[TT, Yamashita 2211.04087]

EMPRESS Y_p results + the H_0 tension would indicate more non-standard cosmological model.

Impact of the H_0 tension to BBN

- When the baryon density is high (suggested in models to resolve the H_0 tension), much larger $N_{\rm eff}$ and ξ_e are preferred.



Suggested in models to resolve the H_0 tension

[TT, Yamashita 2211.04087]

EMPRESS Y_p results + the H_0 tension would indicate more non-standard cosmological model.

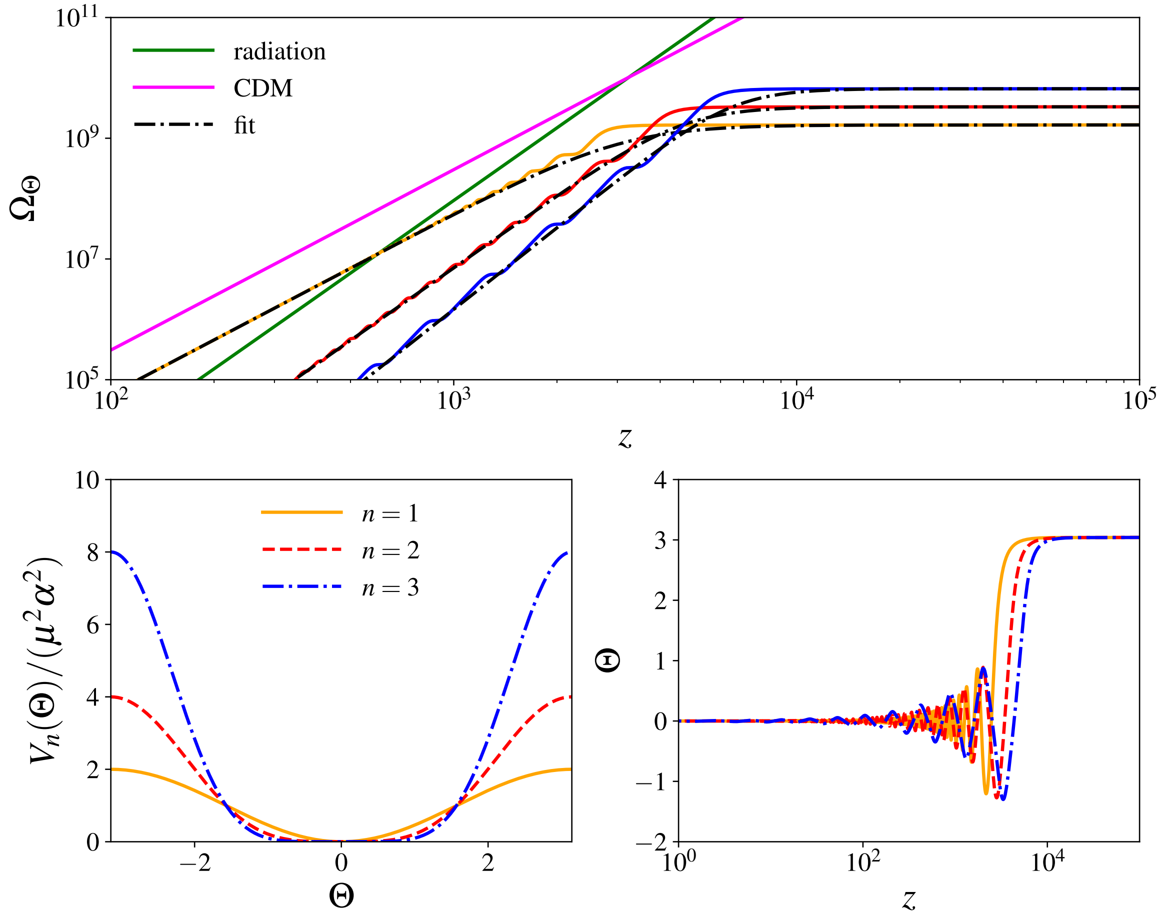
→ Early dark energy may relax the (EMPRESS) tension.

Early dark energy

- Early dark energy (EDE) is a dark energy-like component which can have a sizable energy fraction at some time.

  (But it needs to be diluted quickly not to affect the late time evolution.)

[Poulin et al., 1806.10608]



Example potential:

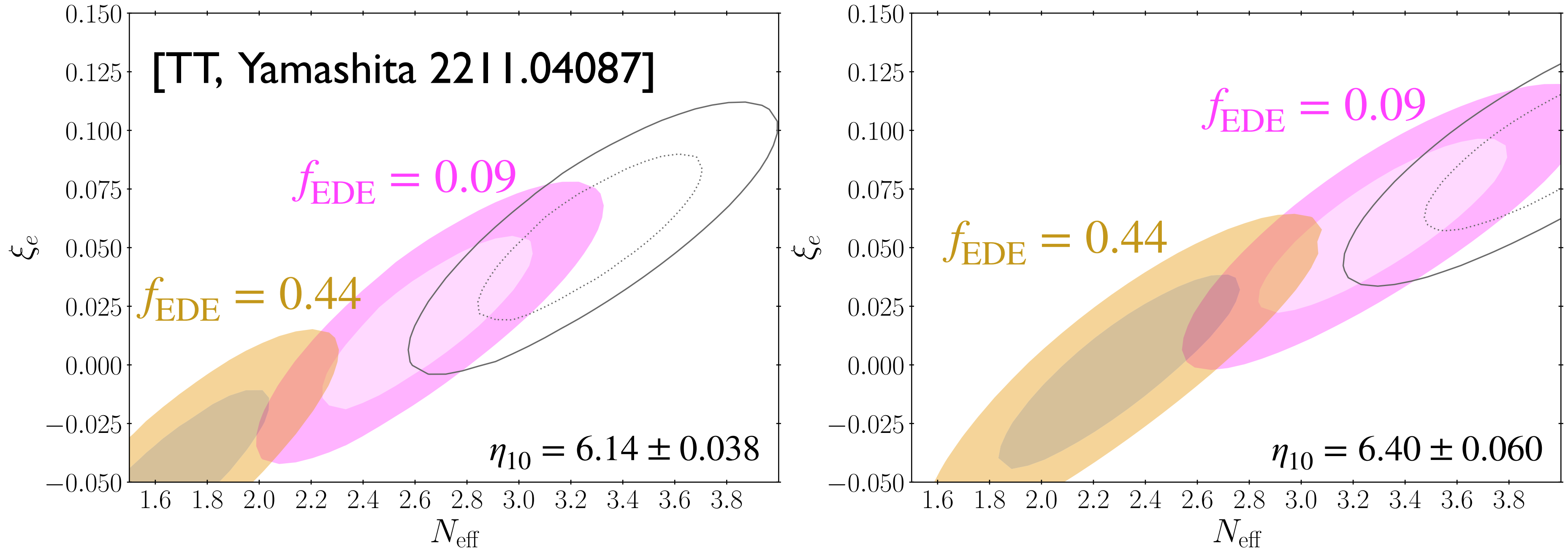
$$V(\phi) = \Lambda^4 \left[1 - \cos\frac{\phi}{f}\right]^n$$

When EDE has a sizable energy fraction at recombination epoch, it could resolve the H_0 tension.

→ We consider EDE having a sizable energy density fraction at around BBN epoch.

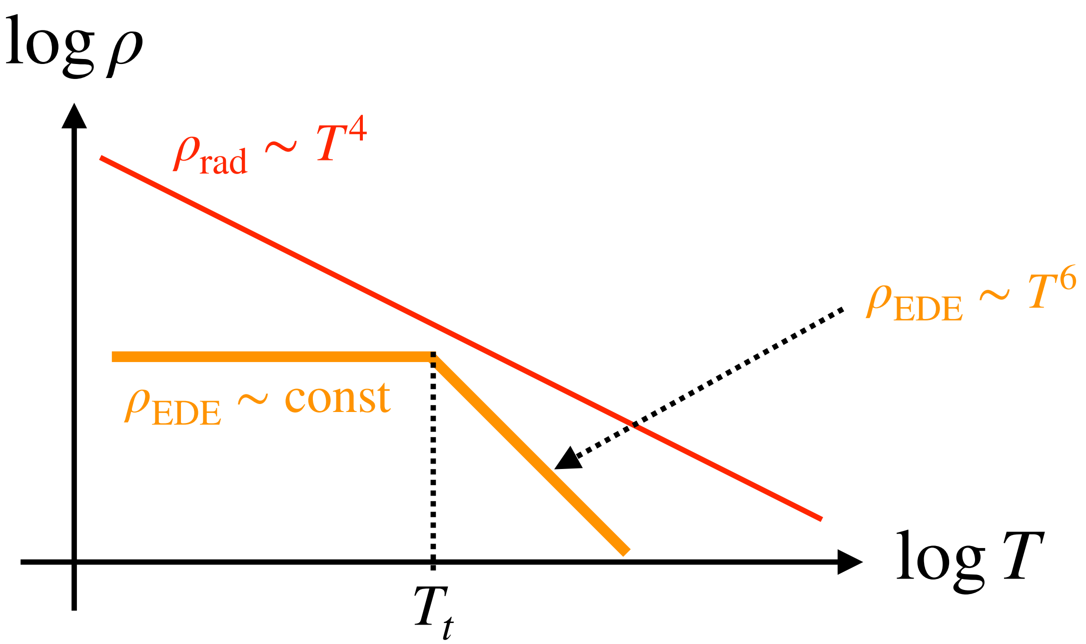
Early dark energy (during BBN) may help

- When early dark energy exists during BBN, $N_{\rm eff}$ and/or ξ_e can take the standard value.



EDE model I:

$$\rho_{\rm EDE,1} = \begin{cases} \rho_0 & (T \geq T_t)\,, \\ \rho_0 \left(\dfrac{T}{T_t}\right)^n & (T < T_t)\,, \end{cases}$$



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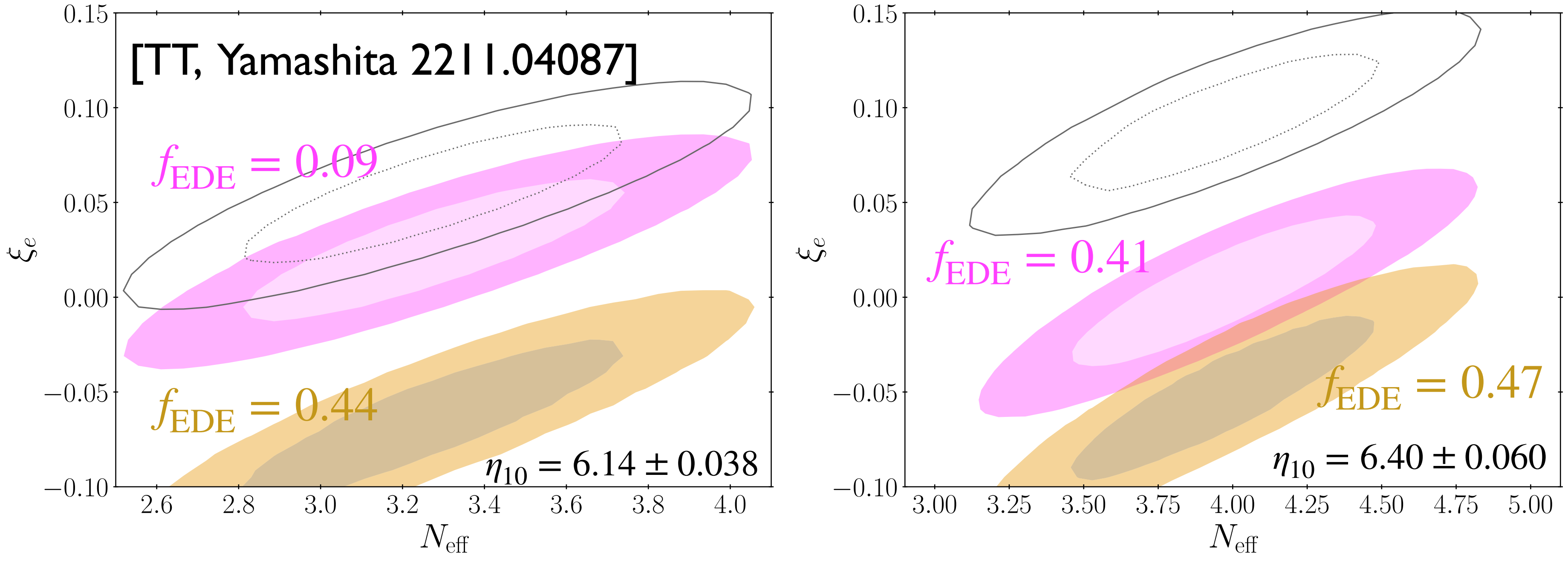
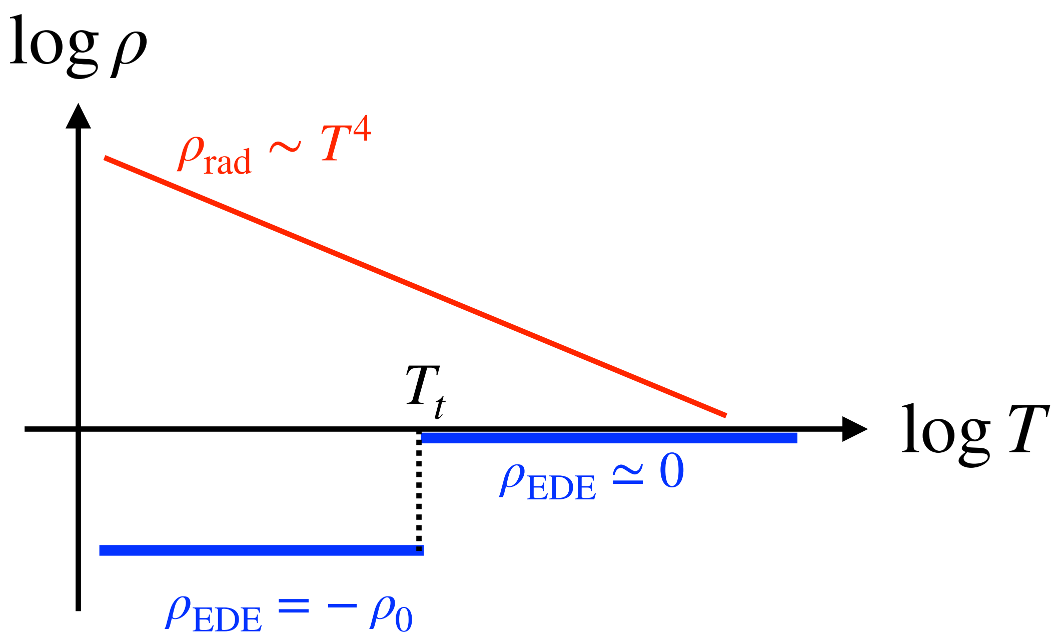

[TT, Yamashita 2211.04087]

EDE model II:

$$\rho_{\rm EDE,2} \begin{cases} = -\rho_0 & (T \geq T_t)\,, \\ \\ \simeq 0 & (T < T_t)\,, \end{cases}$$



Summary

- Several tensions are being discussed in cosmology.
  (H_0 tension, helium anomaly, $\ldots$)

- The origin of the tension may be (partially) systematics, however, it may imply extensions/modifications to $\Lambda\mathrm{CDM}$, which have been extensively investigated.

- The H_0 tension + helium anomaly may need more non-standard (beyond the standard) scenario.

- Tensions may give some hint beyond the standard paradigm of cosmology.