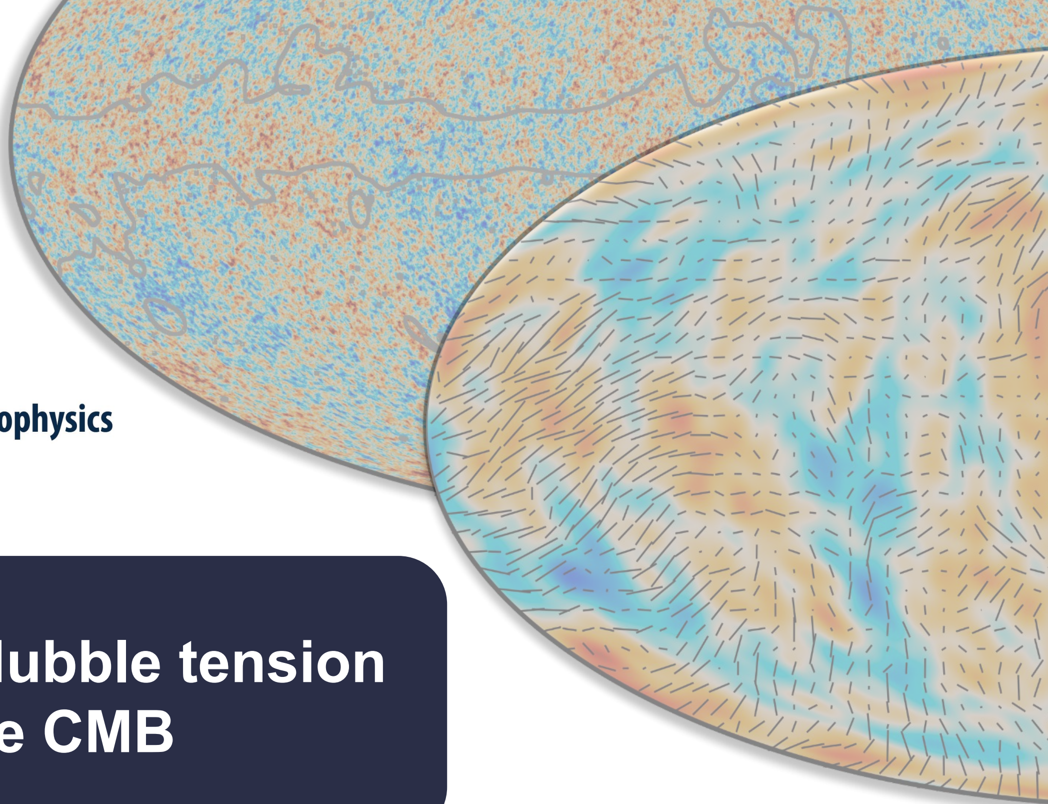

Studying the Hubble tension with the CMB

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link

02-12-22

The standard model of cosmology – ΛCDM model

FLRW metric

$$ds^2 = -c^2 dt^2 + a^2(t)\left(\frac{dr^2}{1-Kr^2} + r^2 d\Omega^2\right)$$

Friedmann equation

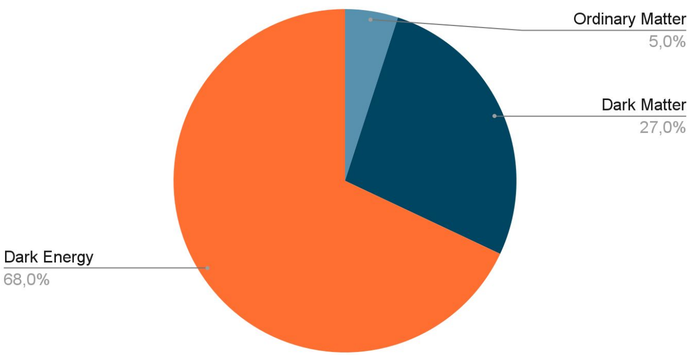
$$H^2(z) = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\left[(\rho_b^0 + \rho_c^0)(1+z)^3 + \rho_r^0(1+z)^4 + \rho_\Lambda\right]$$

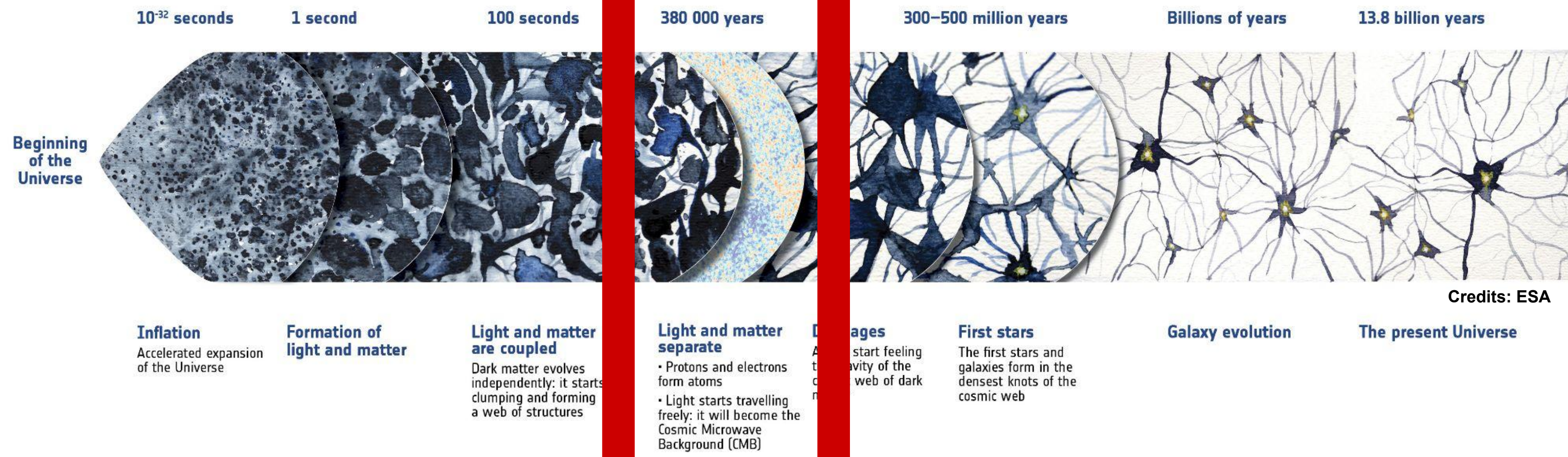
baryon

CDM

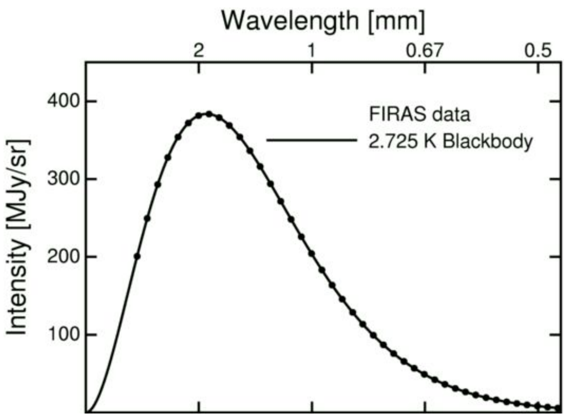
radiation

dark energy





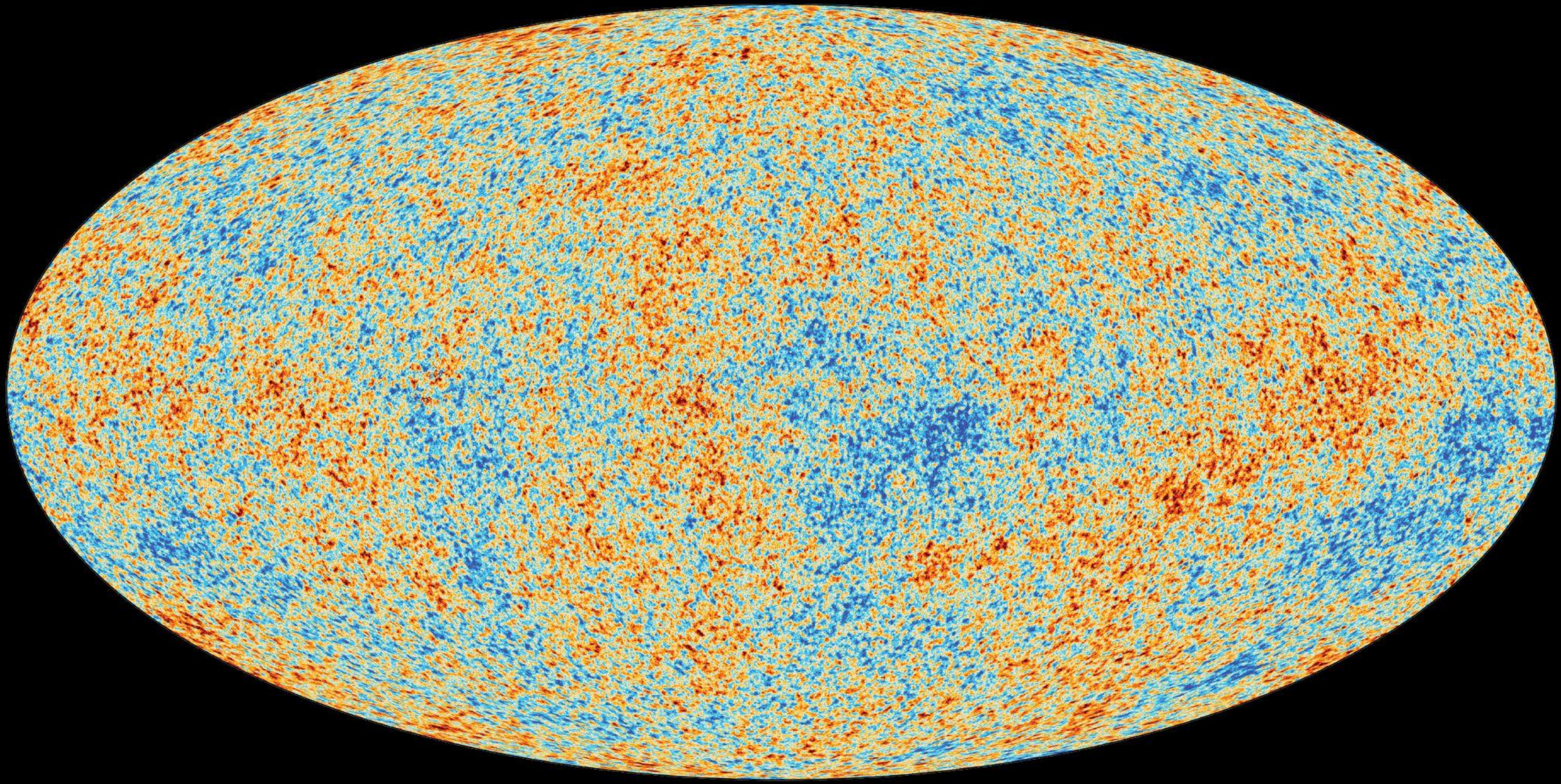
Credits: ESA



$\boxed{\text{Nearly isotropic}}$ blackbody spectrum at T = 2.725 K

$$\frac{\delta T}{T} \sim 10^{-5}$$

CMB temperature as measured by the Planck satellite

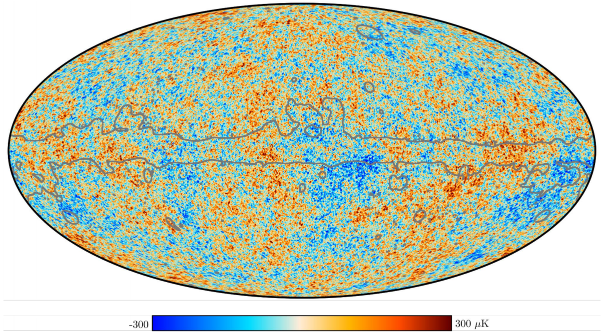


Credits: ESA

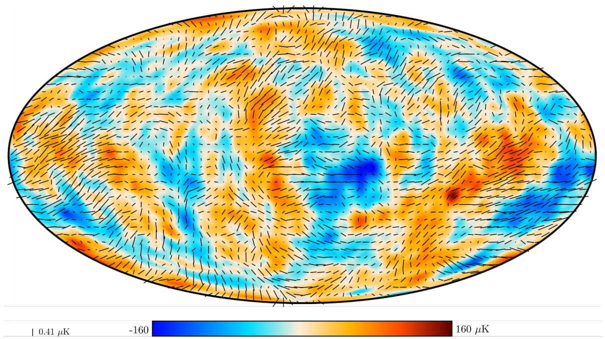
How to do cosmology from the CMB ?

Measuring the statistical properties of the CMB

Temperature



Polarization E-modes



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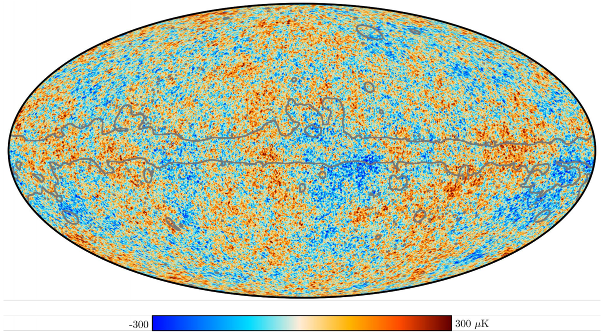
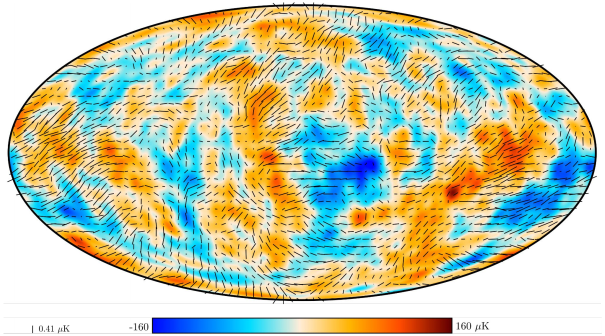


Polarization E-modes



Spherical harmonics

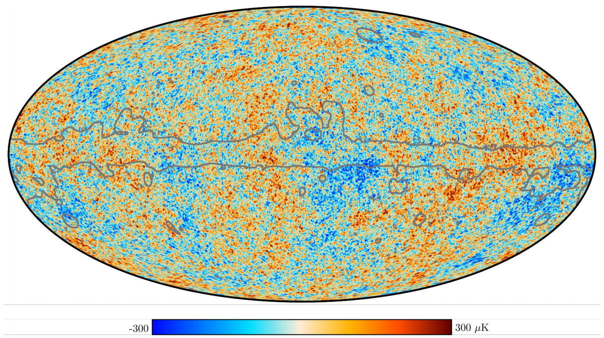
$$\delta T(\hat{n}) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m}^{T} Y_{\ell}^{m}(\theta, \phi)$$

$$\langle a_{\ell m}^{T} a_{\ell' m'}^{T*} \rangle = \delta_{\ell \ell'} \delta_{m m'} C_{\ell}^{TT}$$

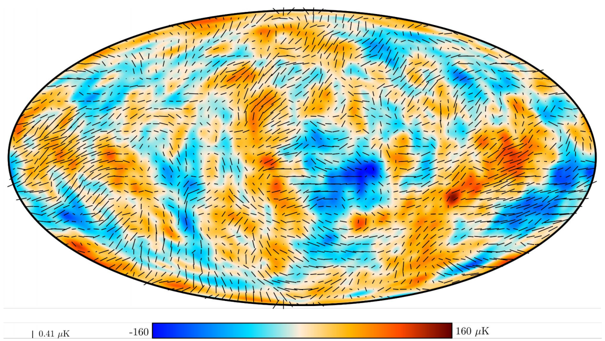
How to do cosmology from the CMB ?

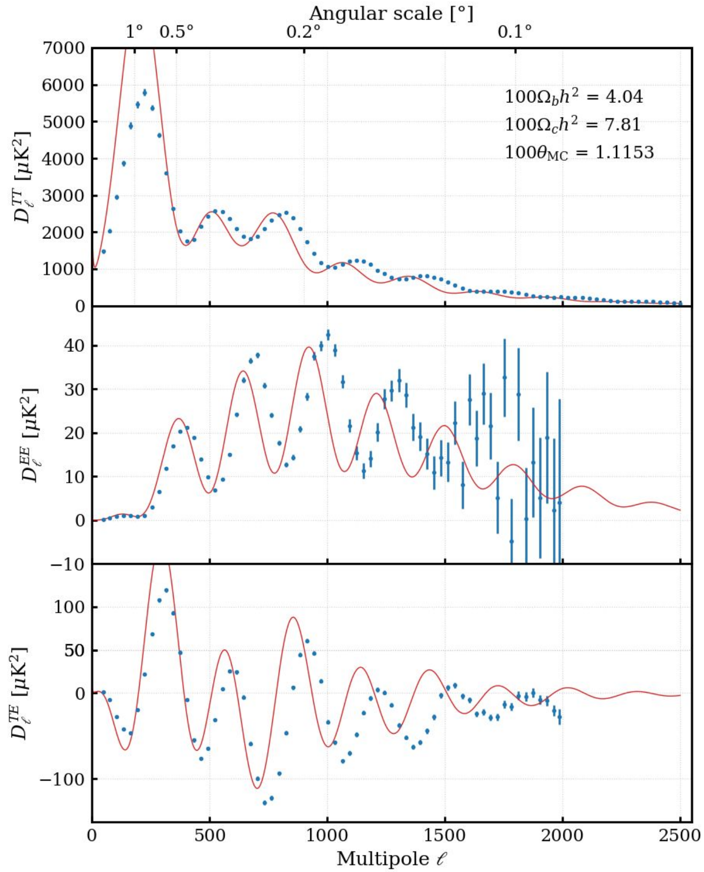
Measuring the statistical properties of the CMB

Temperature



Polarization E-modes

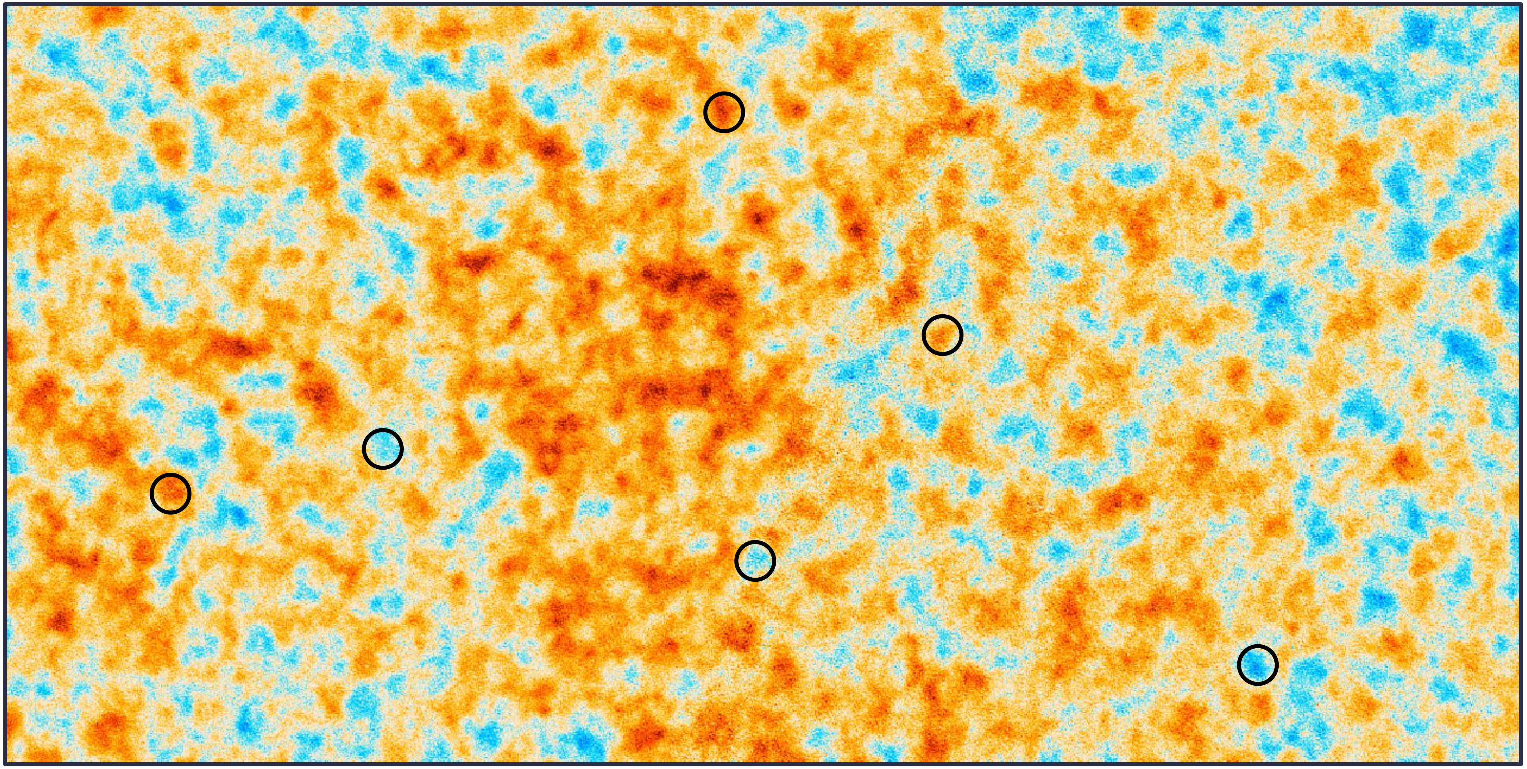




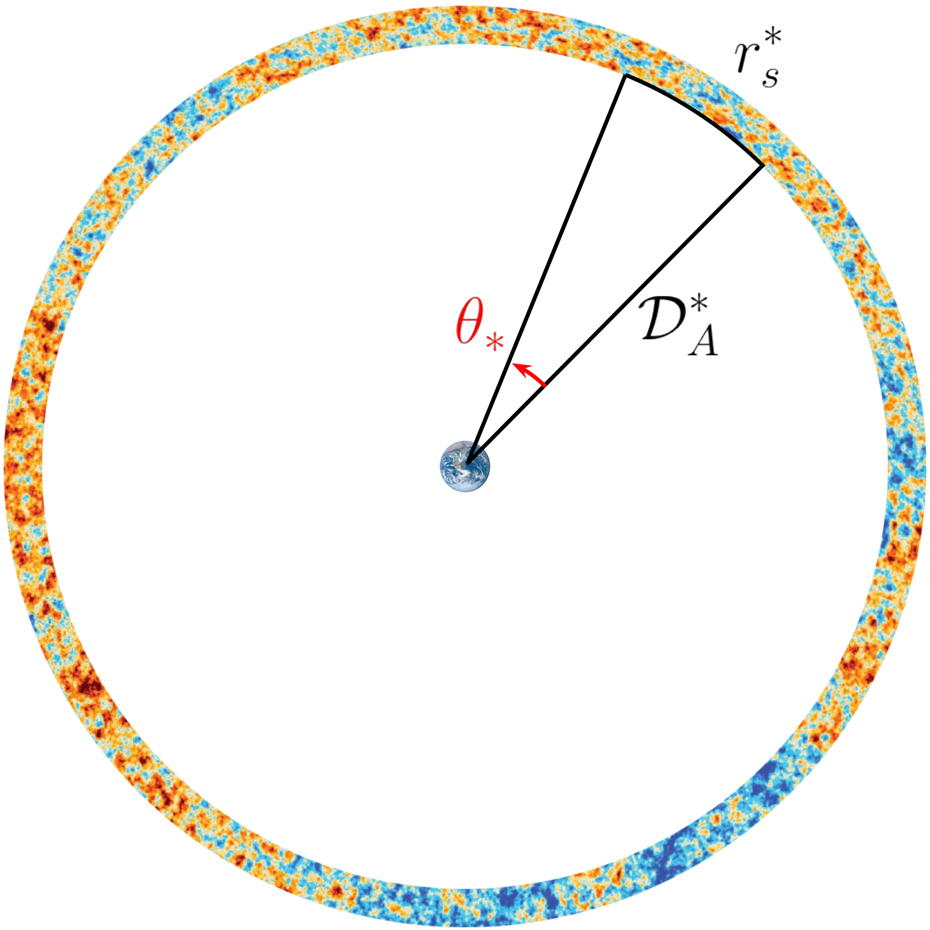
How to measure H_0 from the CMB ?

CMB standard ruler : **size of the sound horizon** at **decoupling** imprinted in the CMB radiation

z ~ 1100

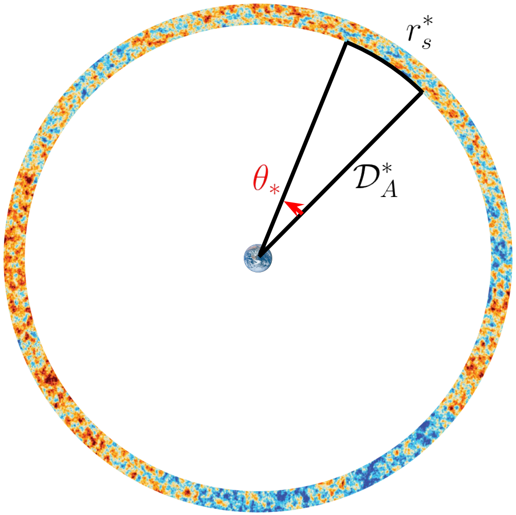


How to measure H_0 from the CMB ?



How to measure H_0 from the CMB ?

$$\theta_* = \frac{r_s^*}{\mathcal{D}_A^*} \longrightarrow r_s^* = \int_{z^*}^{\infty} \frac{dz}{H(z)} c_s(z)$$

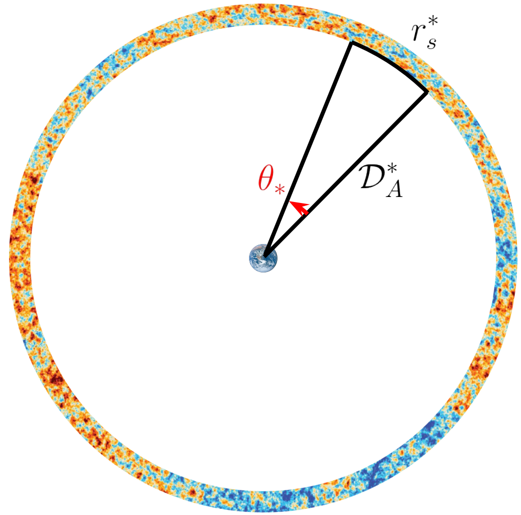


How to measure H_0 from the CMB ?

$$\theta_* = \frac{r_s^*}{\mathcal{D}_A^*} \longrightarrow r_s^* = \int_{z^*}^{\infty} \frac{dz}{H(z)} c_s(z)$$

$$c_s(z) = c\sqrt{\frac{1}{3\left[1 + 3\rho_b^0/4\rho_\gamma^0 (1+z)^{-1}\right]}}$$

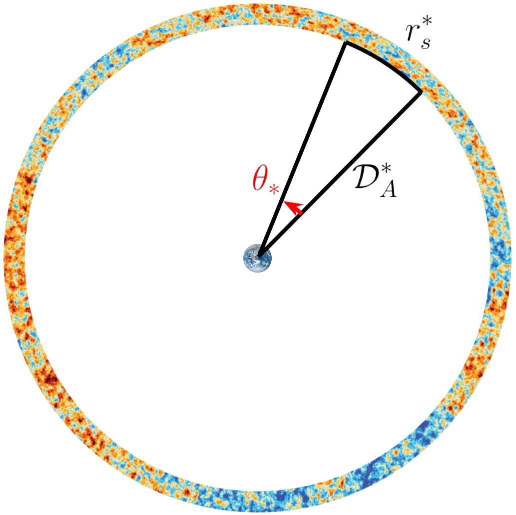
$$H^2_{\rm early}(z) = \frac{8\pi G}{3}\left[\rho_r^0(1+z)^4 + (\rho_b^0 + \rho_c^0)(1+z)^3\right]$$



How to measure H_0 from the CMB ?

Now $\mathcal{D}_A^*$ is known

$$\theta_* = \frac{r_s^*}{\mathcal{D}_A^*}$$

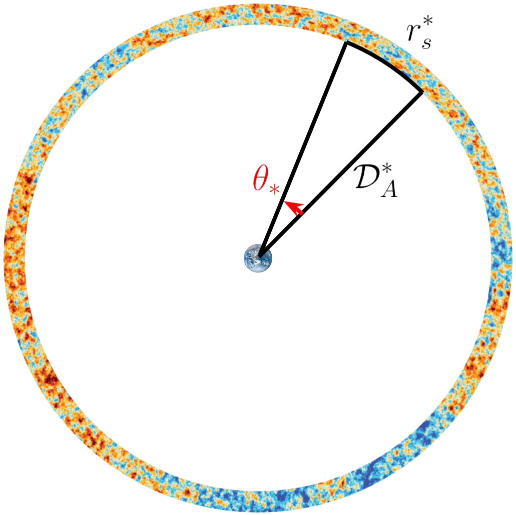


How to measure H_0 from the CMB ?

Now $\mathcal{D}_A^*$ is known

$$\theta_* = \frac{r_s^*}{\mathcal{D}_A^*}$$

$$\mathcal{D}_A^* = c \int_0^{z^*} \frac{dz}{H(z)}$$



How to measure H_0 from the CMB ?

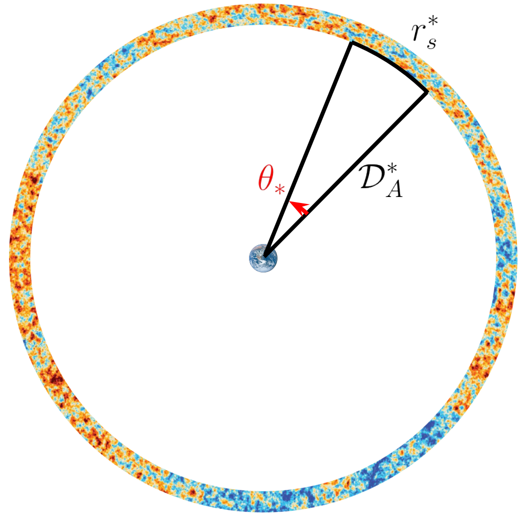
Now $\mathcal{D}_A^*$ is known

$$\theta_* = \frac{r_s^*}{\mathcal{D}_A^*}$$

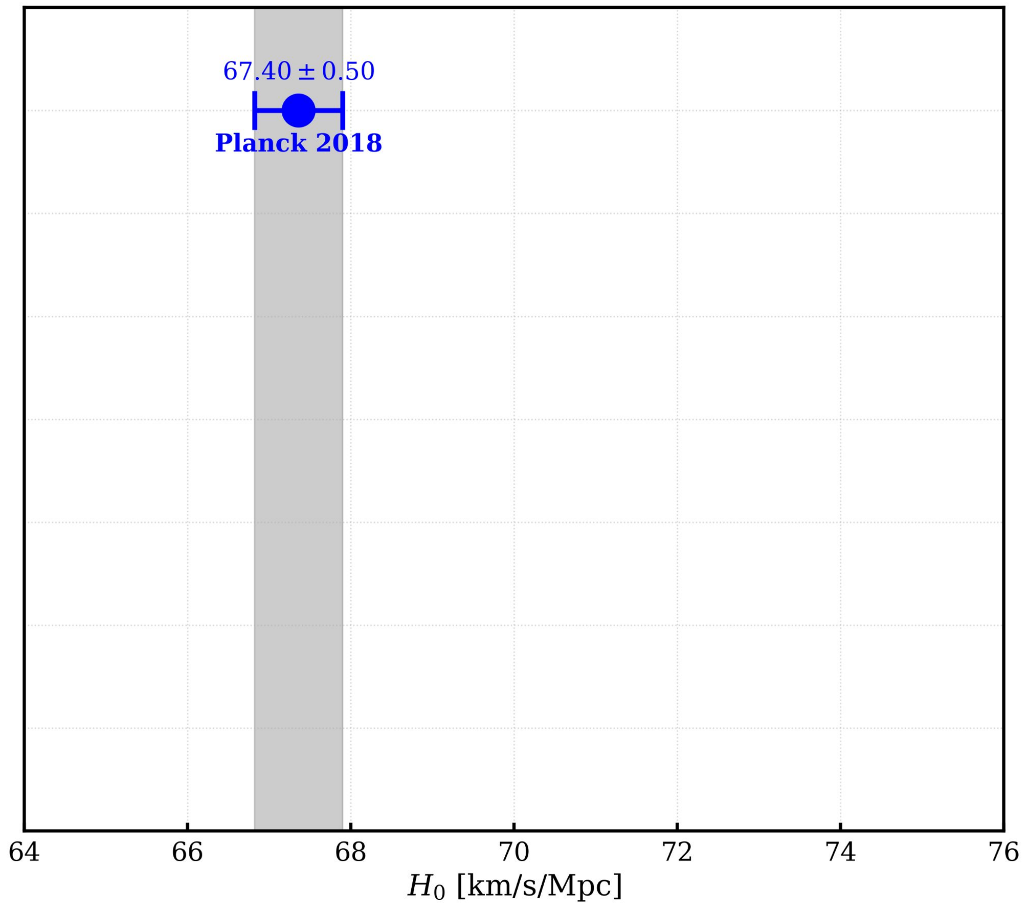
$$H_0^2 = \frac{8\pi G}{3}\left[\rho_b^0 + \rho_c^0 + \rho_\Lambda\right]$$

$$\mathcal{D}_A^* = c\int_0^{z^*} \frac{dz}{H(z)}$$

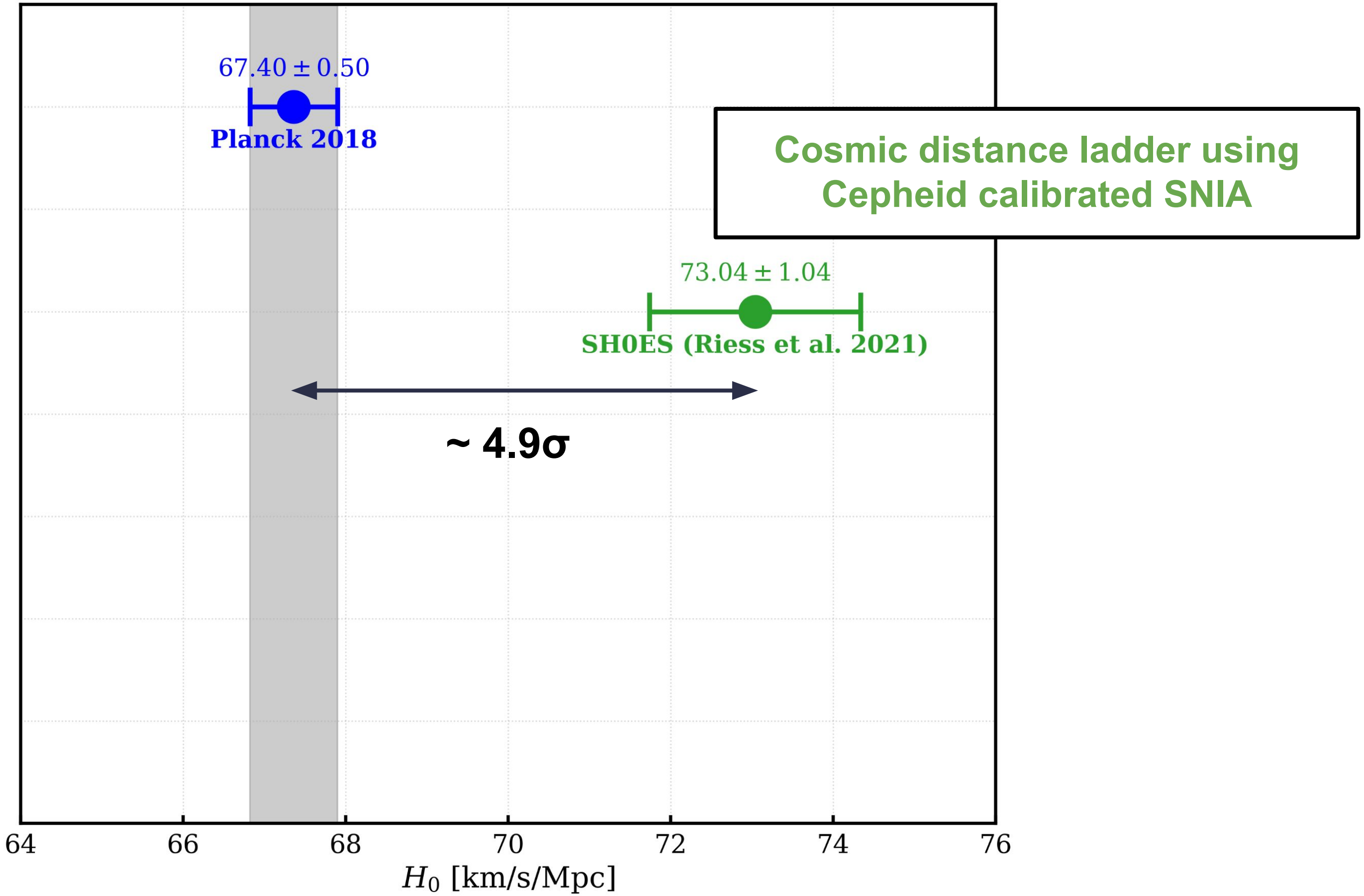
$$H_{\rm late}^2(z) = \frac{8\pi G}{3}\left[(\rho_b^0 + \rho_c^0)(1+z)^3 + \rho_\Lambda\right]$$



Measurement from Planck data …



… and here comes the tension



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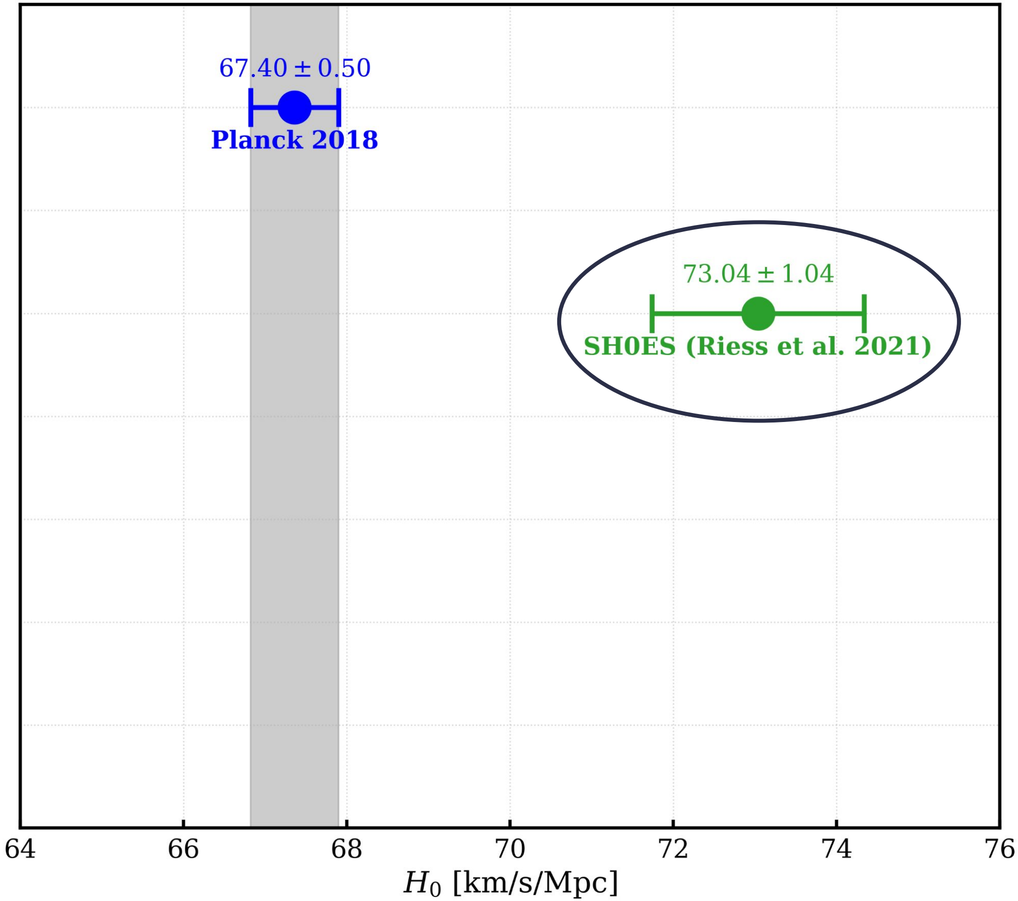
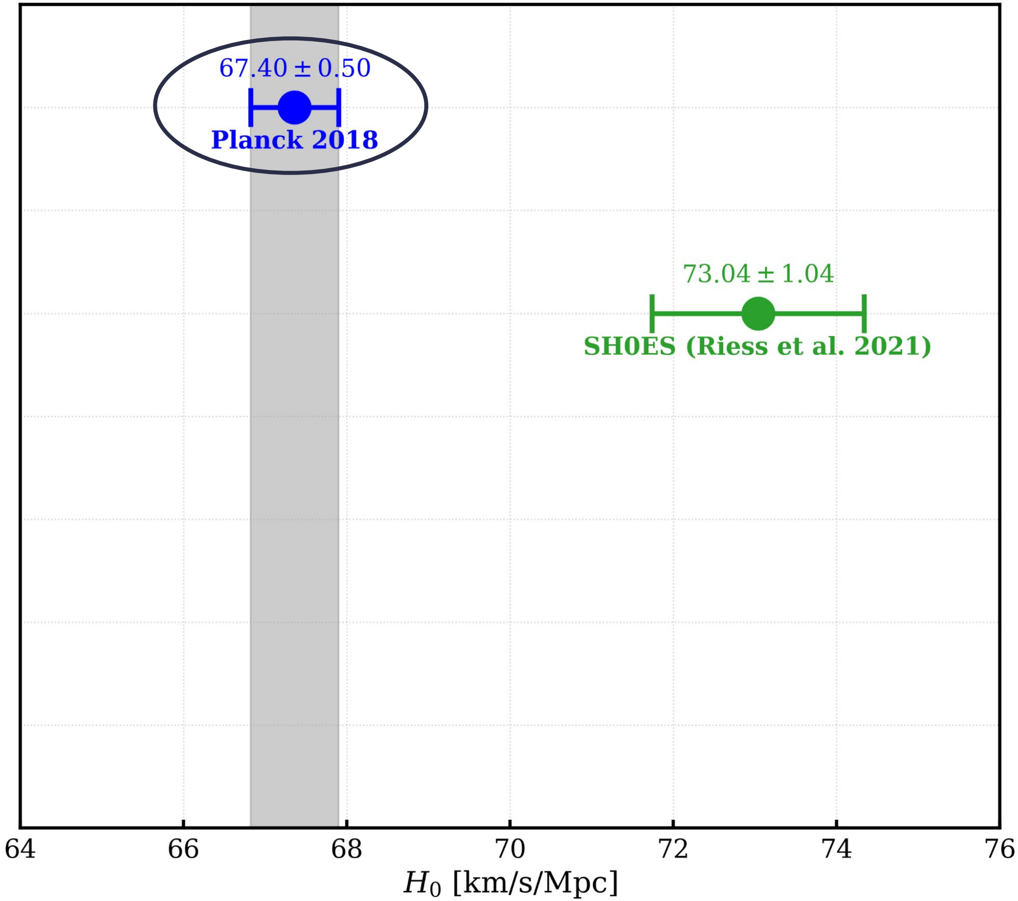


Option 1

Astrophysical biases affecting the local measurement of H_0

… and here comes the tension



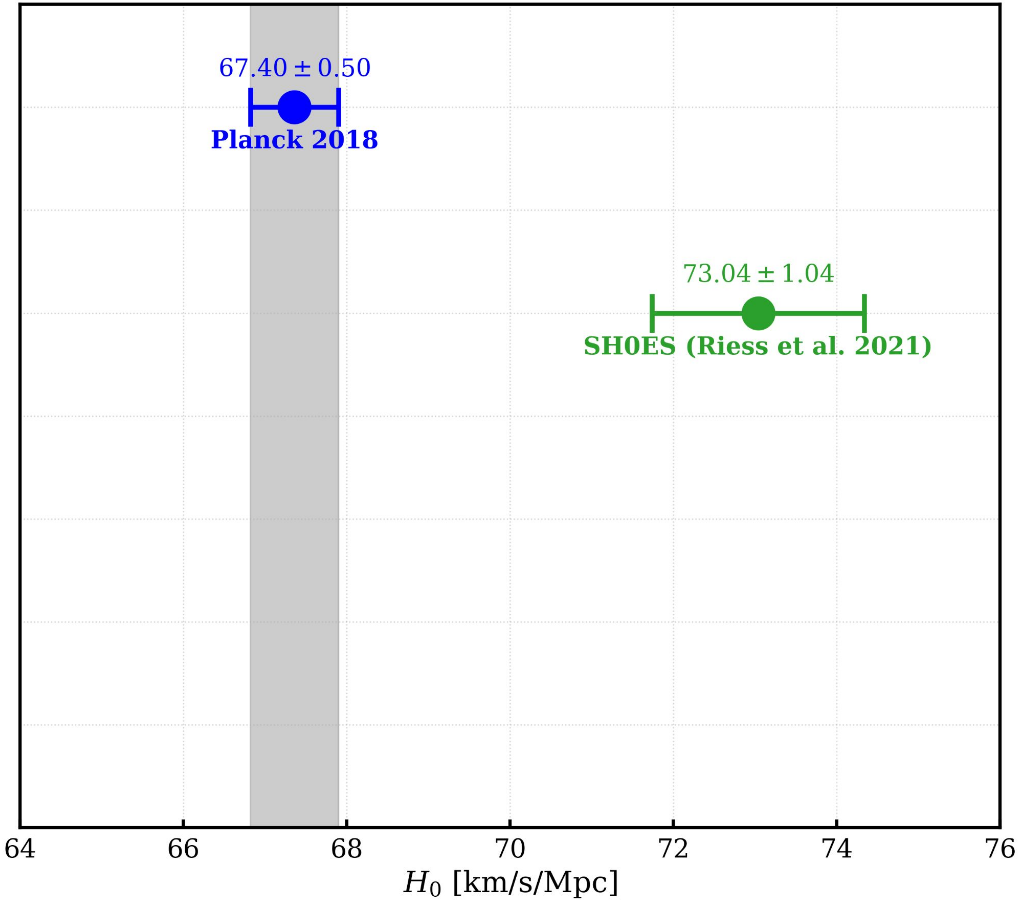
Option 1

Astrophysical biases affecting the local measurement of H_0

Option 2

Instrumental systematic effect biasing the value of H_0 inferred from the CMB

… and here comes the tension



Option 1

Astrophysical biases affecting the local measurement of H_0

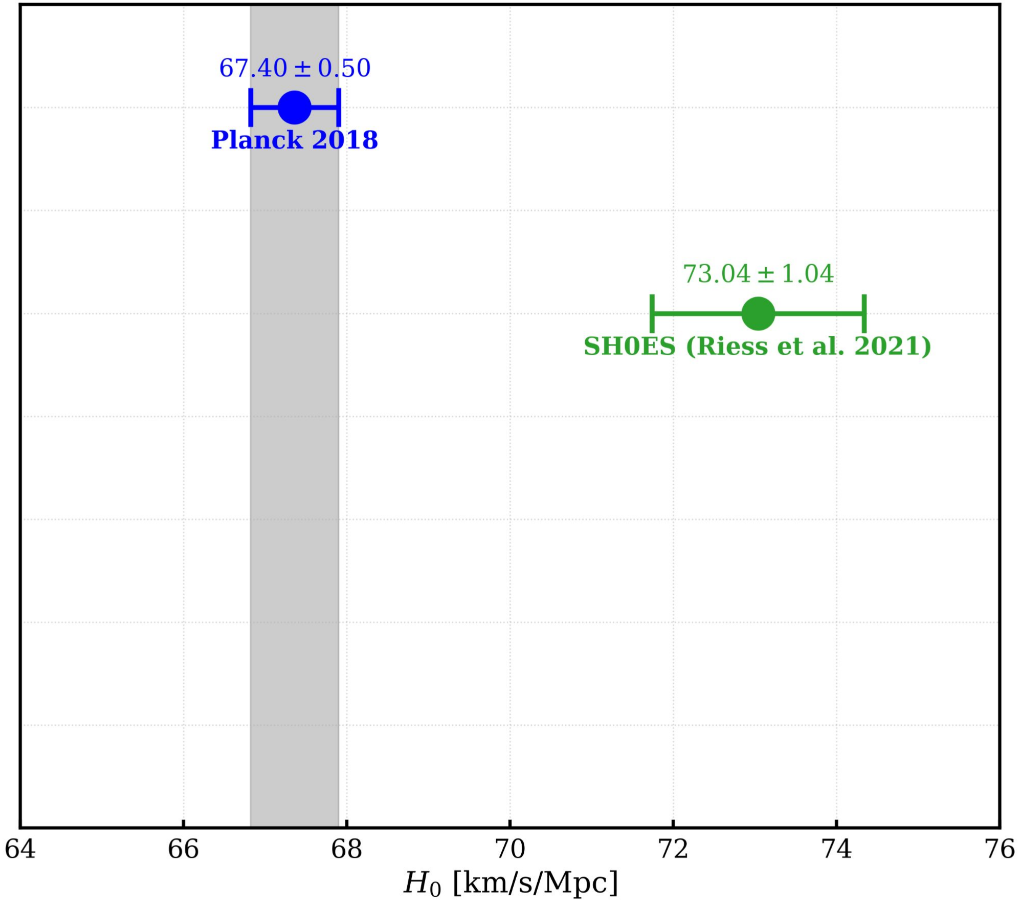
Option 2

Instrumental systematic effect biasing the value of H_0 inferred from the CMB

Option 3

Physics beyond ΛCDM

… and here comes the tension



Option 1

Astrophysical biases affecting the local measurement of H_0

Option 2

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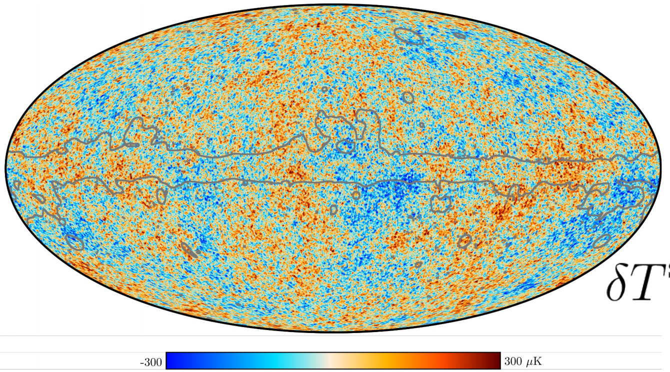
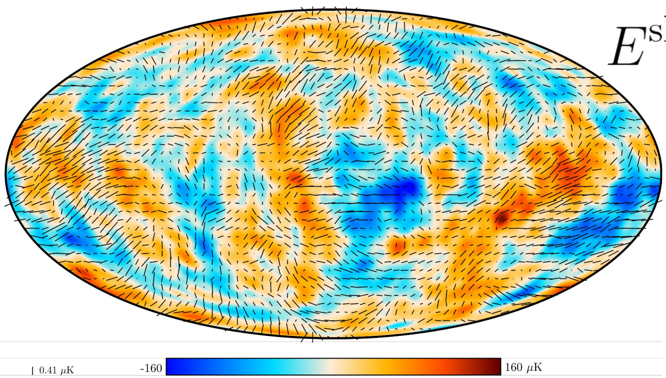
Option 3

Physics beyond ΛCDM

Systematics affecting the CMB



$\delta T^{\rm sky}(\hat{n})$



$E^{\rm sky}(\hat{n})$

$\mathcal{I}_{T/E}$

$$\delta T^{\rm obs}(\hat{n}) = \mathcal{I}_T * \delta T^{\rm sky}(\hat{n})$$
$$E^{\rm obs}(\hat{n}) = \mathcal{I}_E * E^{\rm sky}(\hat{n})$$

Systematics affecting the CMB

$$\delta T^{\mathrm{obs}}(\hat{n}) = \mathcal{I}_T * \delta T^{\mathrm{sky}}(\hat{n})$$
$$E^{\mathrm{obs}}(\hat{n}) = \mathcal{I}_E * E^{\mathrm{sky}}(\hat{n})$$

- **Finite angular resolution (beams)**

Beams

$$\mathcal{I}_T = \mathcal{F}_T * c * \boxed{B_T}$$
$$\mathcal{I}_E = \mathcal{F}_E * c * c_E * \boxed{B_E}$$

Systematics affecting the CMB

$$\delta T^{\rm obs}(\hat{n}) = \mathcal{I}_T * \delta T^{\rm sky}(\hat{n})$$
$$E^{\rm obs}(\hat{n}) = \mathcal{I}_E * E^{\rm sky}(\hat{n})$$

- **Finite angular resolution (beams)**
- **Calibration**

$$\mathcal{I}_T = \mathcal{F}_T * \boxed{c} * B_T$$
$$\mathcal{I}_E = \mathcal{F}_E * \boxed{c} * c_E * B_E$$

Calibration

Systematics affecting the CMB

$$\delta T^{\rm obs}(\hat{n}) = \mathcal{I}_T * \delta T^{\rm sky}(\hat{n})$$
$$E^{\rm obs}(\hat{n}) = \mathcal{I}_E * E^{\rm sky}(\hat{n})$$

- **Finite angular resolution (beams)**
- **Calibration**
- **Polarization efficiency**

$$\mathcal{I}_T = \mathcal{F}_T * c * B_T$$
$$\mathcal{I}_E = \mathcal{F}_E * c * \boxed{c_E} * B_E$$

Polarization efficiency

Systematics affecting the CMB

$$\delta T^{\rm obs}(\hat{n}) = \mathcal{I}_T * \delta T^{\rm sky}(\hat{n})$$
$$E^{\rm obs}(\hat{n}) = \mathcal{I}_E * E^{\rm sky}(\hat{n})$$

- **Finite angular resolution (beams)**
- **Calibration**
- **Polarization efficiency**
- **Transfer functions (map-making)**

$$\mathcal{I}_T = \boxed{\mathcal{F}_T} * c * B_T$$
$$\mathcal{I}_E = \boxed{\mathcal{F}_E} * c * c_E * B_E$$

Transfer functions

Systematics affecting the CMB

$$\delta T^{\rm obs}(\hat{n}) = \mathcal{I}_T * \delta T^{\rm sky}(\hat{n})$$
$$E^{\rm obs}(\hat{n}) = \mathcal{I}_E * E^{\rm sky}(\hat{n})$$

- **Finite angular resolution (beams)**
- **Calibration**
- **Polarization efficiency**
- **Transfer functions (map-making)**

These instrumental effects are
multiplicative in harmonic space

$$C_\ell^{TT,\rm obs} = (\mathcal{F}_\ell^T)^2 c^2 (B_\ell^T)^2 C_\ell^{TT}$$
$$C_\ell^{EE,\rm obs} = (\mathcal{F}_\ell^E)^2 c^2 c_E^2 (B_\ell^E)^2 C_\ell^{EE}$$
$$C_\ell^{TE,\rm obs} = \mathcal{F}_\ell^T \mathcal{F}_\ell^E c^2 c_E B_\ell^T B_\ell^E C_\ell^{EE}$$

Correlation coefficient between T and E

$$\mathcal{R}_\ell^{TE} = \frac{\left\langle a_{\ell m}^{T} a_{\ell m}^{E*} \right\rangle}{\sqrt{\left\langle a_{\ell m}^{T} a_{\ell m}^{T*} \right\rangle \left\langle a_{\ell m}^{E} a_{\ell m}^{E*} \right\rangle}} = \frac{C_\ell^{TE}}{\sqrt{C_\ell^{TT} C_\ell^{EE}}}$$

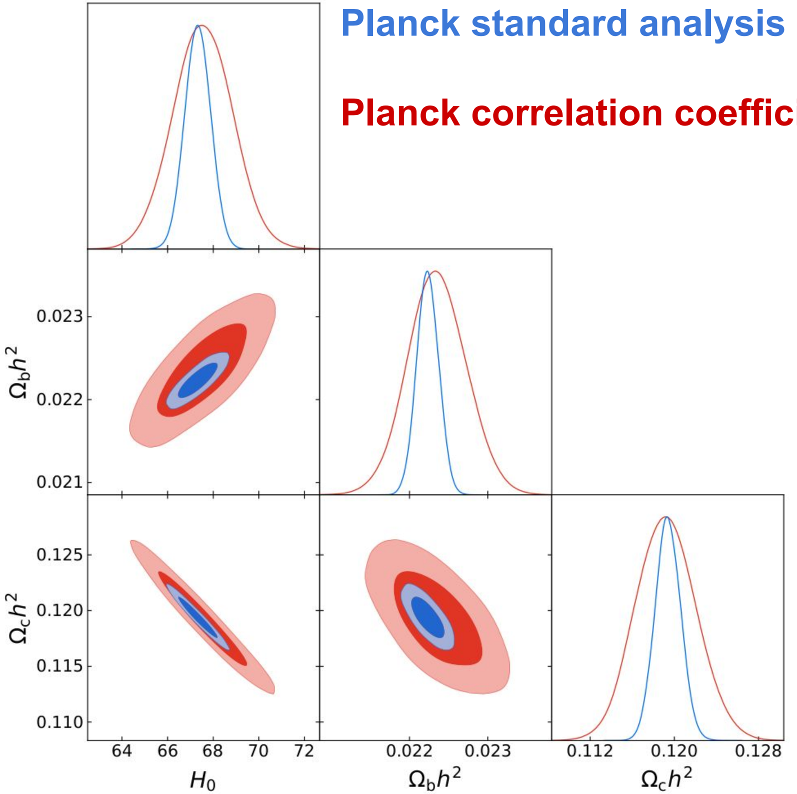
$$\mathcal{R}_\ell^{TE,\mathrm{obs}} = \frac{\mathcal{F}_\ell^{T} \mathcal{F}_\ell^{E} c^2 c_E B_\ell^{T} B_\ell^{E} C_\ell^{TE}}{\sqrt{(\mathcal{F}_\ell^{T})^2 c^2 (B_\ell^{T})^2 C_\ell^{TT} \times (\mathcal{F}_\ell^{E})^2 c^2 c_E^2 (B_\ell^{E})^2 C_\ell^{EE}}}$$

Correlation coefficient between T and E

$$\mathcal{R}_\ell^{TE} = \frac{\left\langle a_{\ell m}^T a_{\ell m}^{E*} \right\rangle}{\sqrt{\left\langle a_{\ell m}^T a_{\ell m}^{T*} \right\rangle \left\langle a_{\ell m}^E a_{\ell m}^{E*} \right\rangle}} = \frac{C_\ell^{TE}}{\sqrt{C_\ell^{TT} C_\ell^{EE}}}$$

$$\mathcal{R}_\ell^{TE,\mathrm{obs}} = \frac{\cancel{\mathcal{F}_\ell^T \mathcal{F}_\ell^E c^2 c_E B_\ell^T B_\ell^E} C_\ell^{TE}}{\sqrt{\cancel{(\mathcal{F}_\ell^T)^2 c^2 (B_\ell^T)^2} C_\ell^{TT} \times \cancel{(\mathcal{F}_\ell^E)^2 c^2 c_E^2 (B_\ell^E)^2} C_\ell^{EE}}} = \mathcal{R}_\ell^{TE}$$

Planck correlation coefficient



Planck standard analysis (C_ℓ)

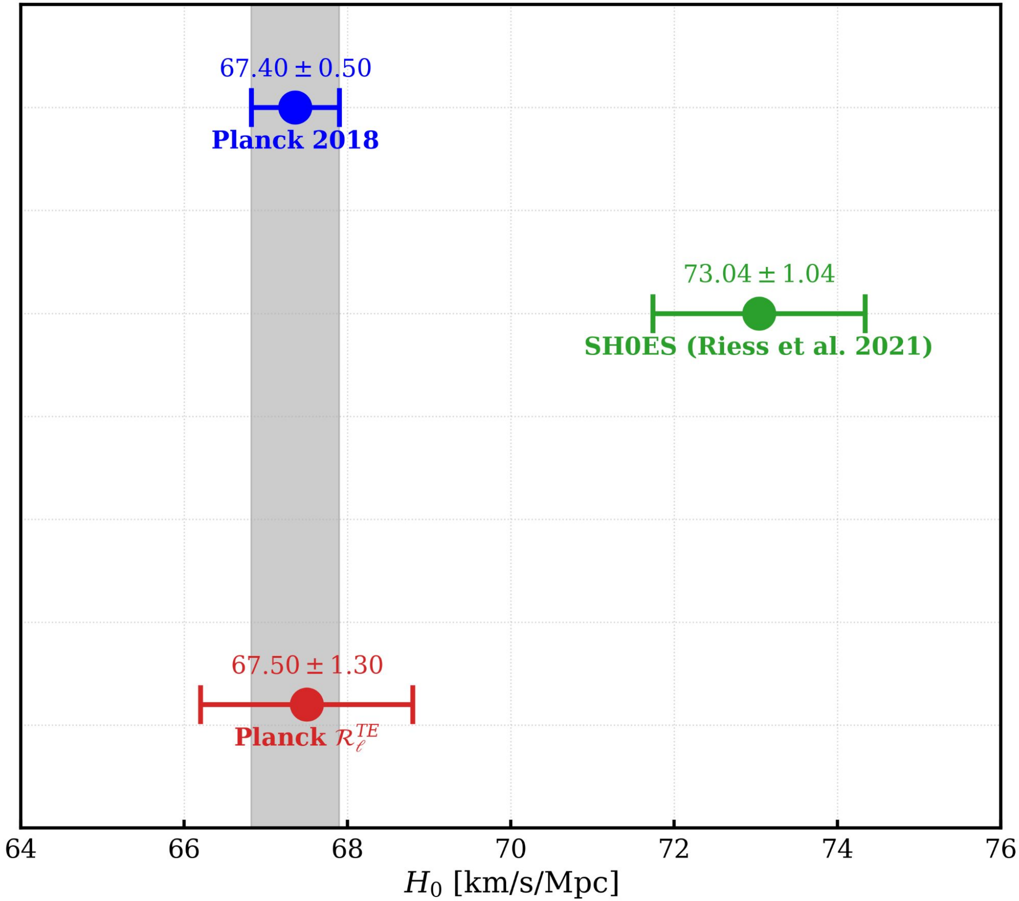
Planck correlation coefficient (R_ℓ^{TE})

3.3σ away from the latest SH0ES measurement

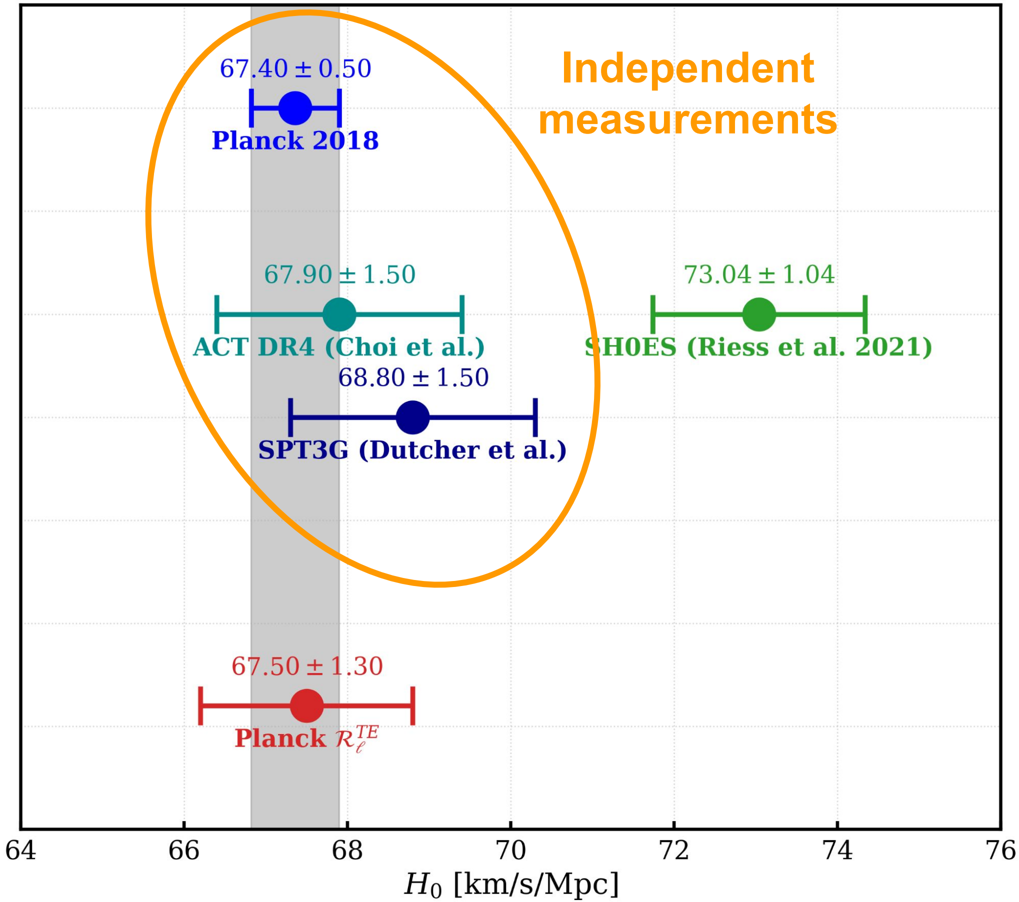
H_0 = 67.5 +/- 1.3 [km/s/Mpc]

La Posta+ 2021 [Phys. Rev. D 104, 023527]

Back to the Hubble tension …



… with additional constraints from the CMB



Option 1

Astrophysical biases affecting the local measurement of H_0

Option 2

Instrumental systematic effect biasing the value of H_0 inferred from the CMB

Option 3

Physics beyond ΛCDM

Early-time modification to ΛCDM

Motivation : higher $\mathbf{H_0}$ value $\Rightarrow$ lower $\mathbf{D_A}$

Early-time modification to ΛCDM

Motivation : higher $\mathbf{H_0}$ value ⇒ lower $\mathbf{D_A}$

$$\theta_* = \frac{r_s^*}{D_A^*} \longrightarrow$$

Decrease $r_s^* = \int_{z^*}^{\infty} \frac{dz}{H(z)} c_s(z)$

$$\frac{3H_{\mathrm{early}}^2(z)}{8\pi G} = \rho_r(z) + \rho_m(z)$$

Proposed solution : Early Dark Energy

Motivation : higher $\mathbf{H_0}$ value ⇒ lower $\mathbf{D_A}$

$$\theta_* = \frac{r_s^*}{D_A^*} \longrightarrow \textbf{Decrease } r_s^* = \int_{z^*}^{\infty} \frac{dz}{H(z)} c_s(z)$$

$$\frac{3H_{\rm early}^2(z)}{8\pi G} = \rho_r(z) + \rho_m(z) + \rho_{\rm EDE}(z)$$

Background evolution : $\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$ **axion-like potential**

$$V(\phi) = m^2 f^2 \left[1 - \cos\left(\frac{\phi}{f}\right)\right]^3$$

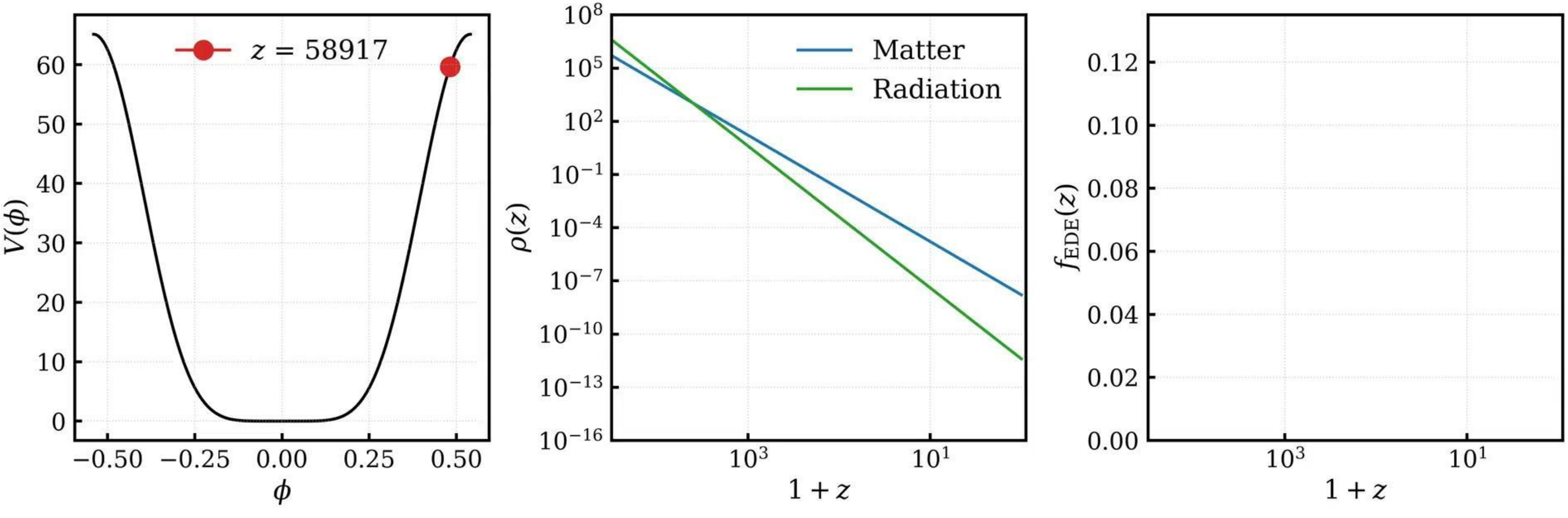
Poulin+19, Smith+19

Proposed solution : Early Dark Energy

$$\ddot{\phi} + \boxed{3H\dot{\phi}} + V'(\phi) = 0$$

The field is initially frozen due to Hubble friction (H >> m)

acts as dark energy (w= - 1)

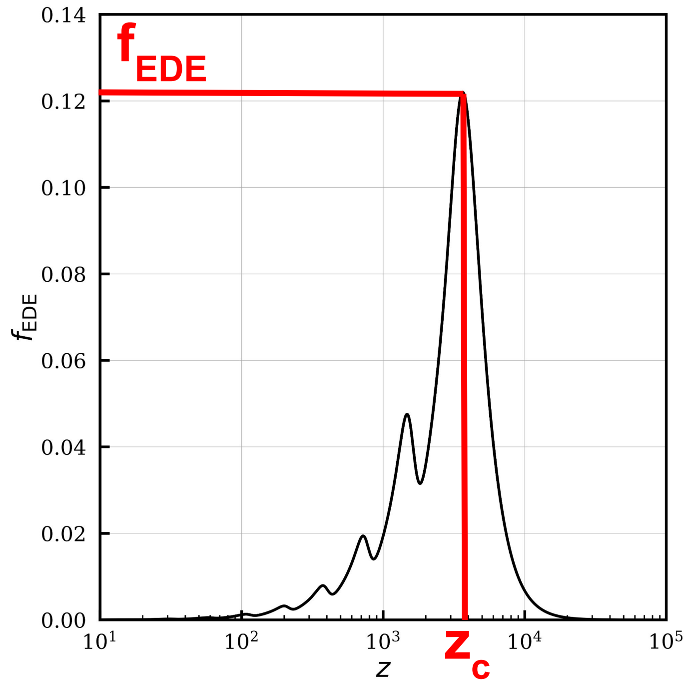


Proposed solution : Early Dark Energy

$$(m, f, \phi_i) \longrightarrow (f_{\mathrm{EDE}}, z_c, \phi_i)$$

Field parameters

Phenomenological parametrization

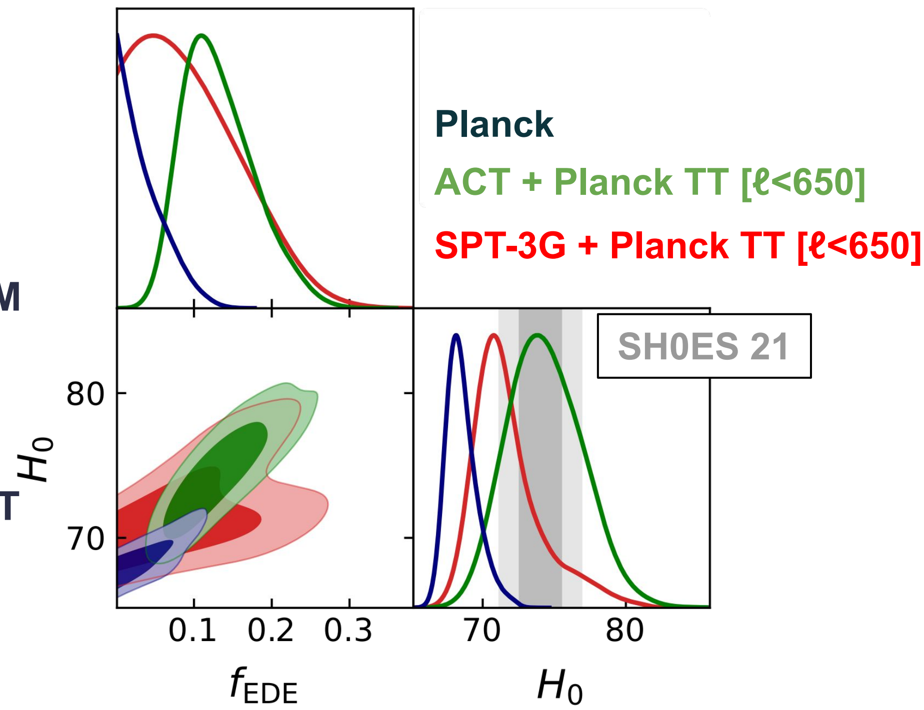


Summary

- Planck data alone do not favor high f_{EDE} values

- ACT DR4 data favors EDE over ΛCDM (with f_{EDE}~ 10%)

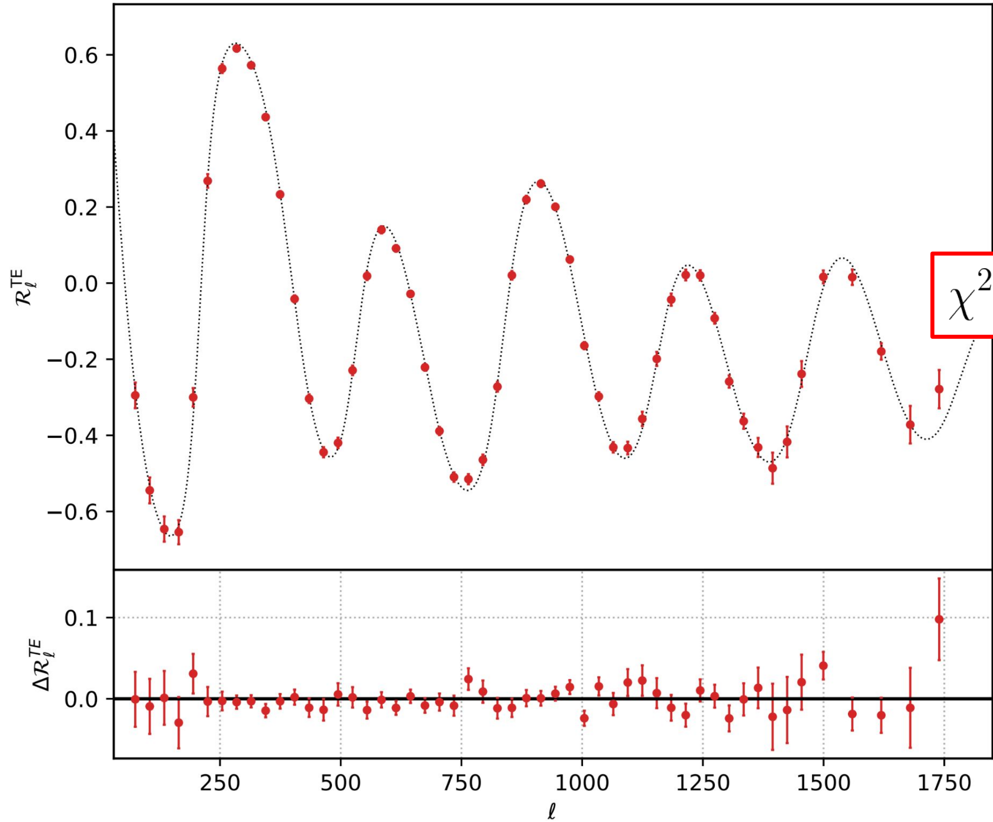
- SPT-3G is not as constraining as ACT and Planck on the EDE scenario



Hill+20, Hill+21, La Posta+22


e are currently analyzing high-precision
data from ACT that will help to constrain
extensions to LCDM

Planck correlation coefficient



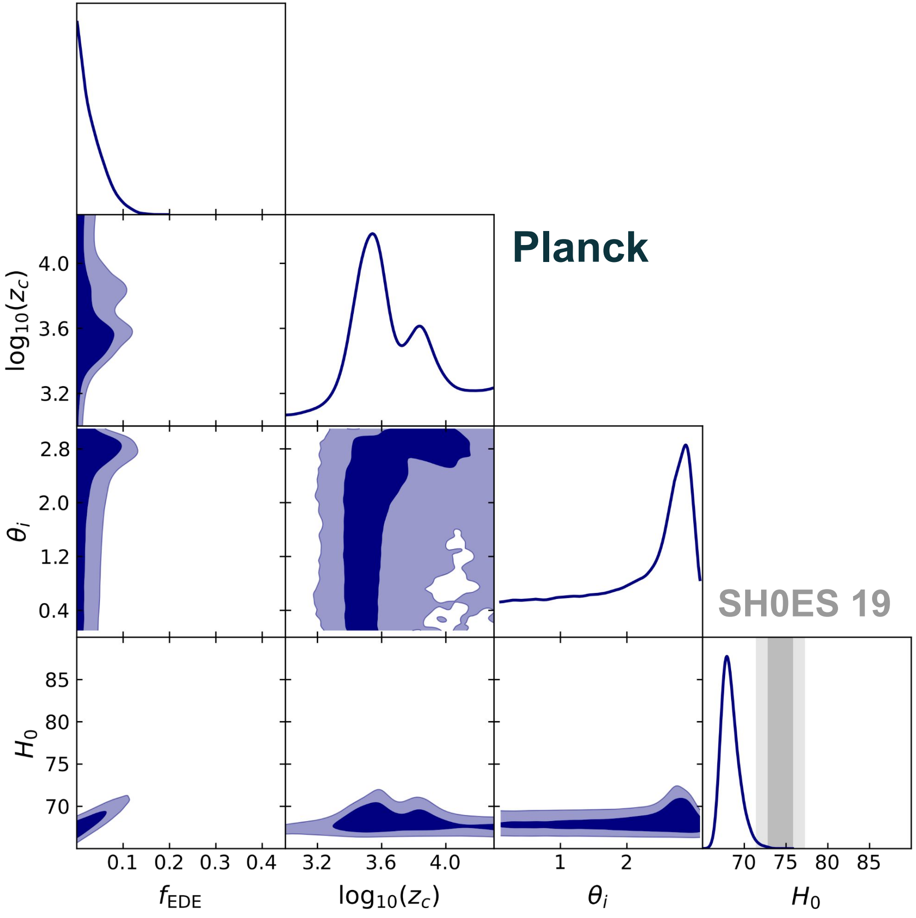
Bestfit from Planck TT,TE,EE

Planck correlation coefficient

$$\chi^2/\text{d.o.f} = 52.16/52\ (\text{PTE} = 0.47)$$

La Posta+ 2021 [Phys. Rev. D 104, 023527]

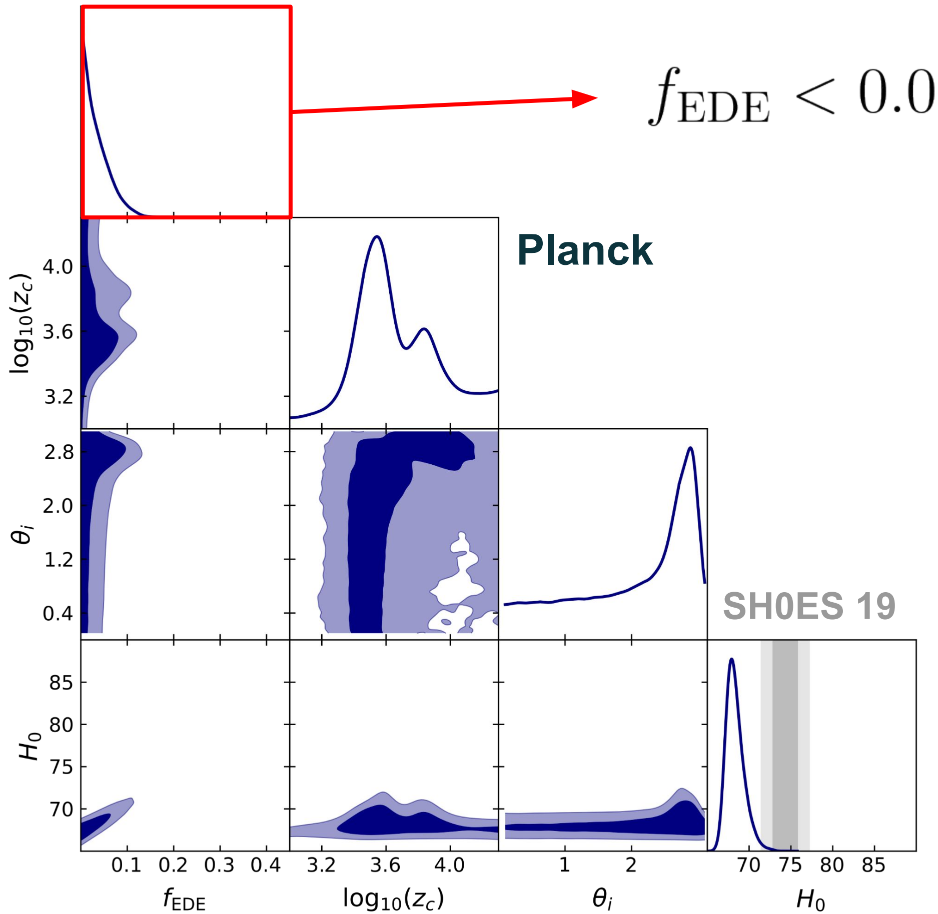
Constraints on EDE from Planck



Hill+ 2020

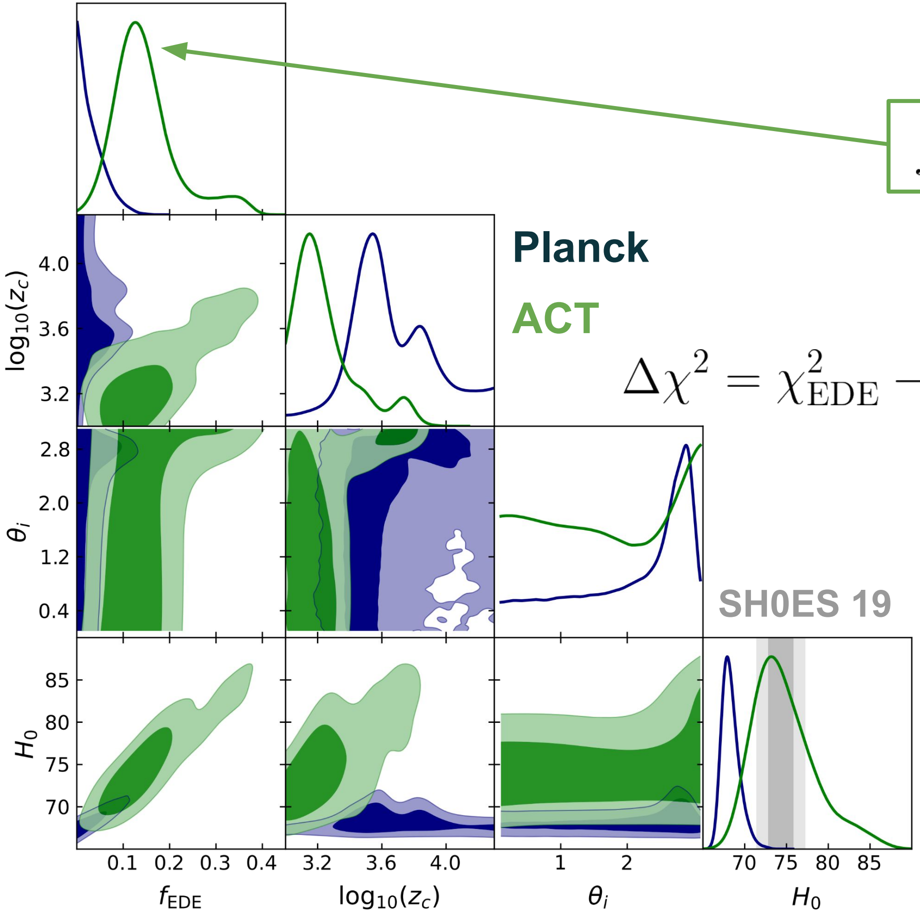
Constraints on EDE from Planck

$$f_{\mathrm{EDE}} < 0.087 \ (95\% \ \mathrm{C.L.})$$



Hill+ 2020

Constraints on EDE from ACT DR4



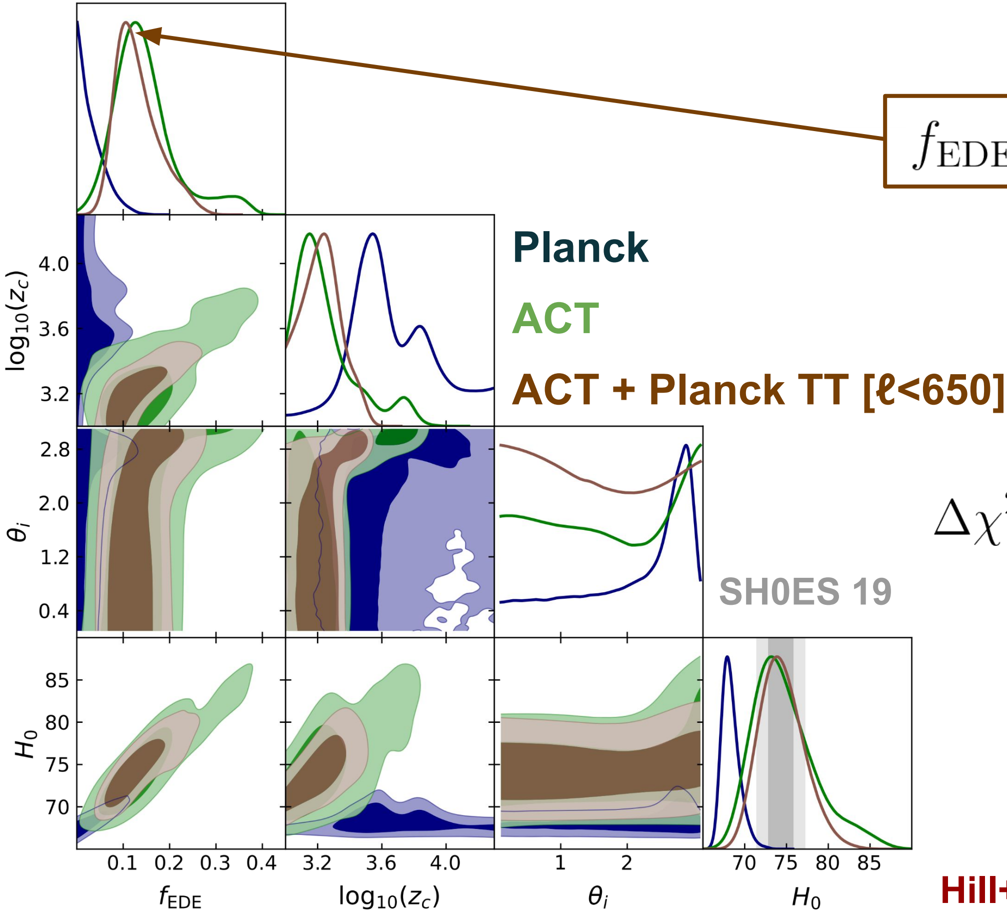
$$f_{\rm EDE} = 0.142^{+0.039}_{-0.072}\ (68\%\ \text{C.L.})$$

$$\Delta\chi^2 = \chi^2_{\rm EDE} - \chi^2_{\Lambda\rm CDM} = -8.7 \rightarrow$$

2.1σ preference in favor of EDE

Hill+...La Posta+... 2021

Constraints on EDE from ACT DR4

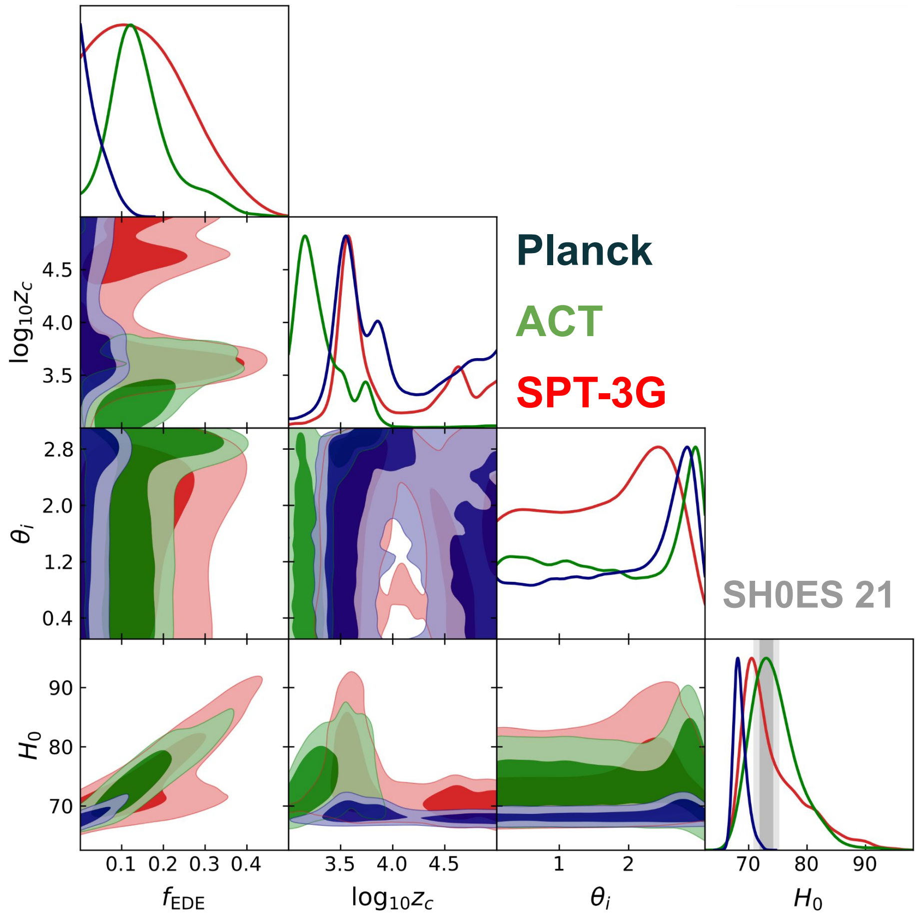


$$f_{\rm EDE} = 0.129^{+0.028}_{-0.055}\ (68\%\ \text{C.L.})$$

$$\Delta\chi^2 = -15.4$$ → **3.2σ preference in favor of EDE**

Hill+...La Posta+... 2021

Constraints on EDE from SPT-3G



La Posta+ 2021 [arXiv:2112.10754]