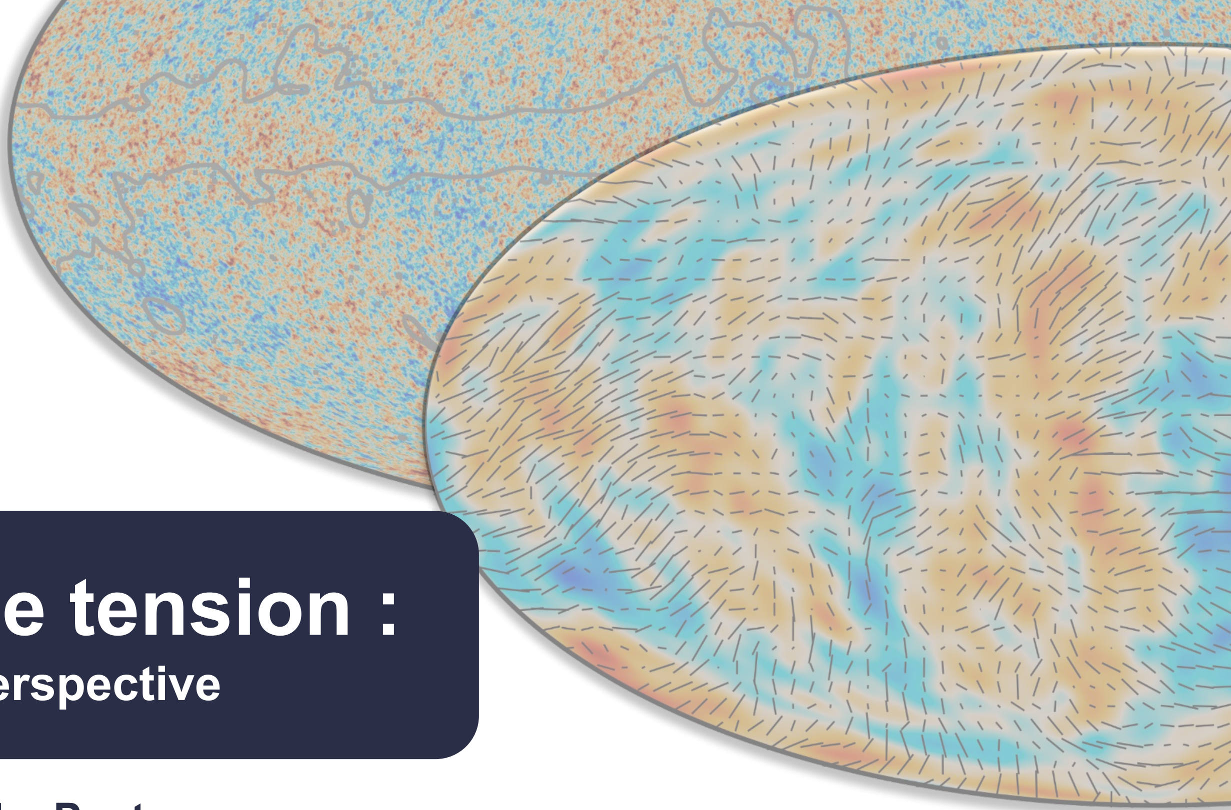


The Hubble tension :

a CMB perspective

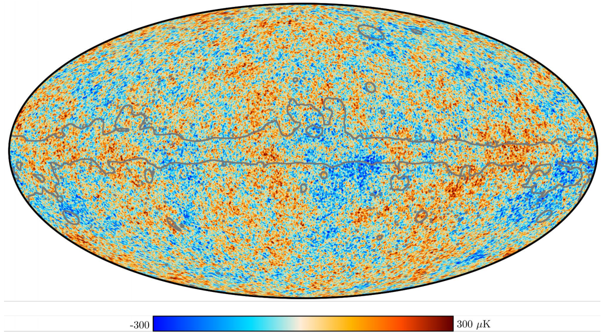
Adrien La Posta
IJClab

laposta@ijclab.in2p3.fr

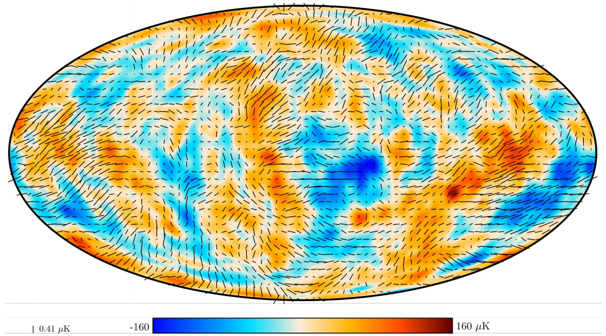
Webinaire Action Dark Energy - 20/01/22

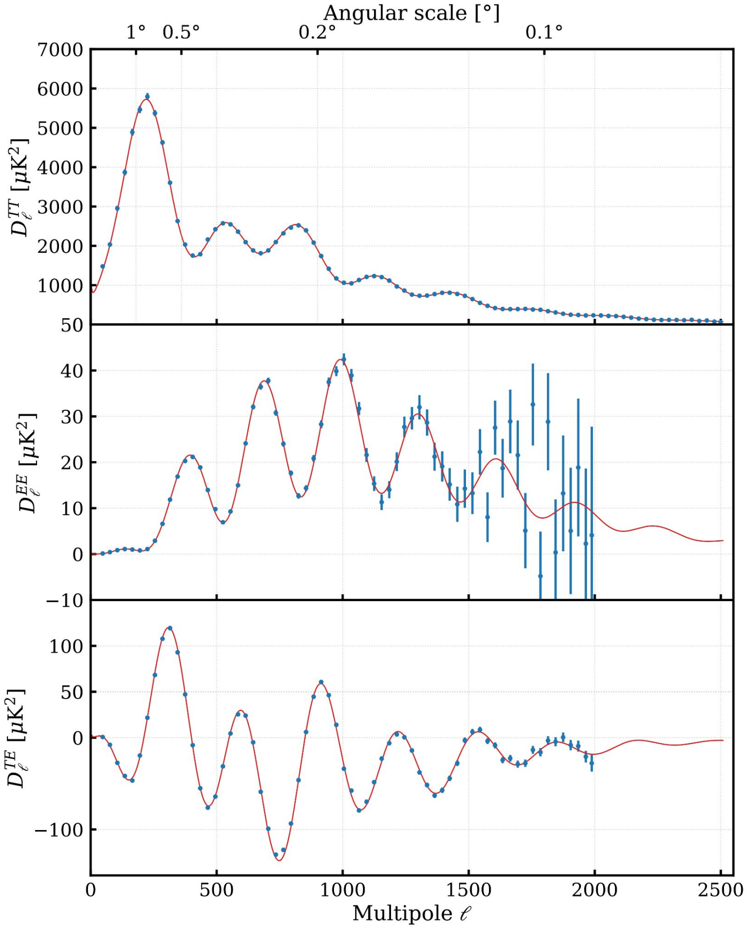
Measuring H_0 from the CMB

Temperature



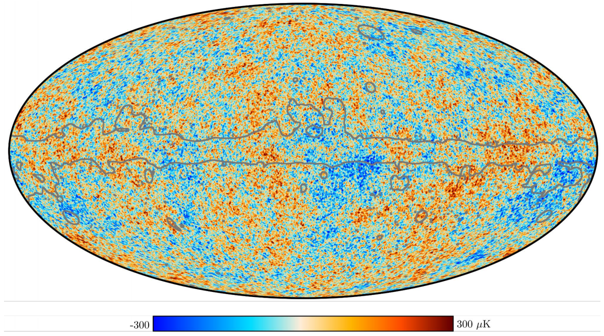
Polarization E-modes



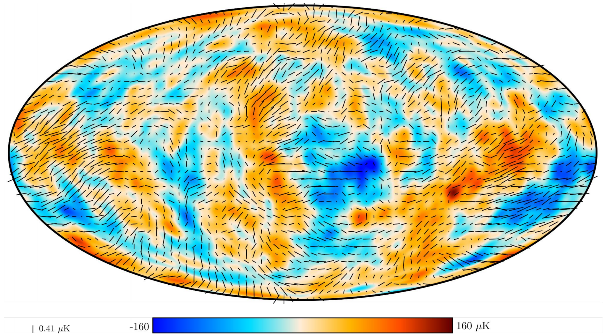


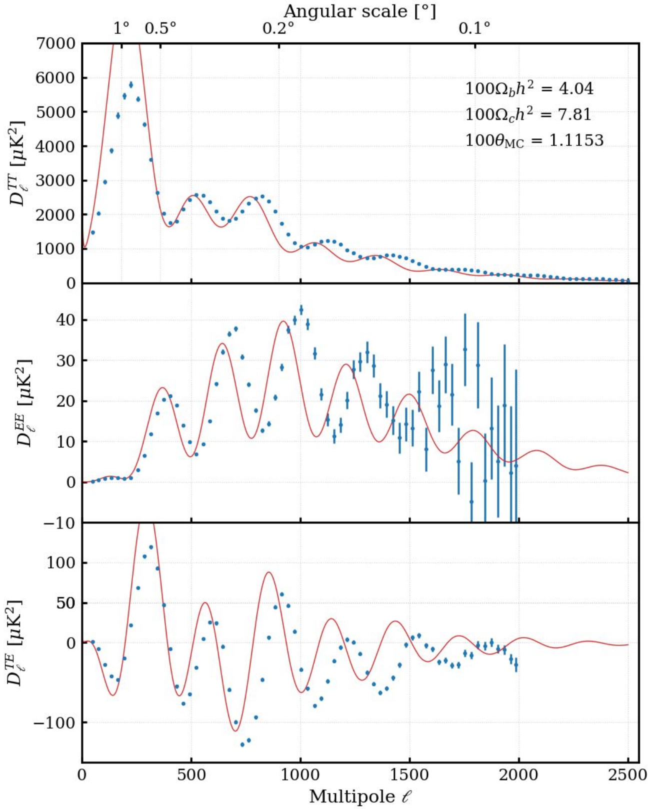
Measuring H_0 from the CMB

Temperature



Polarization E-modes





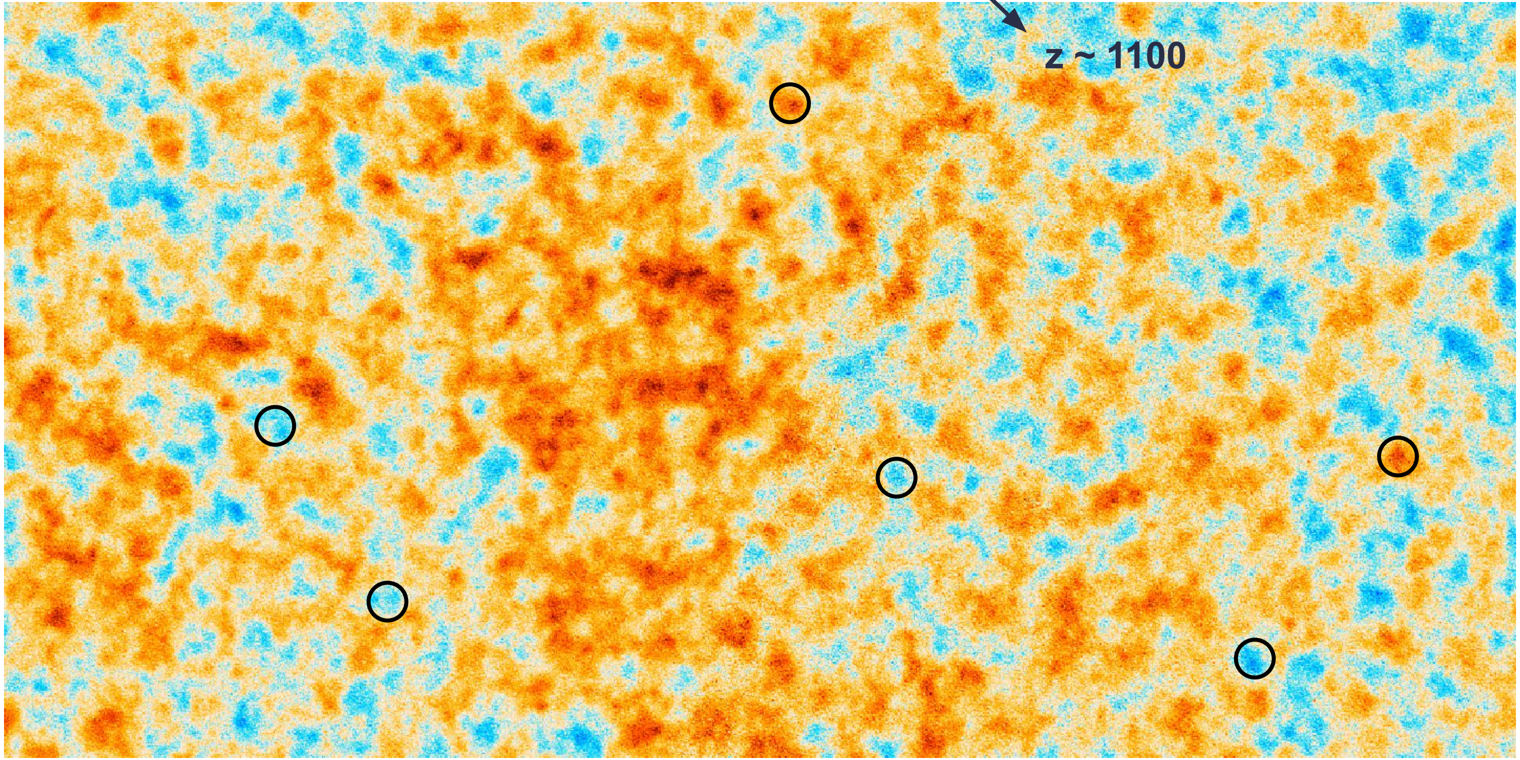
$\rightarrow \theta_* \quad \rho_b^0 \quad \rho_c^0$

Measuring H_0 from the CMB

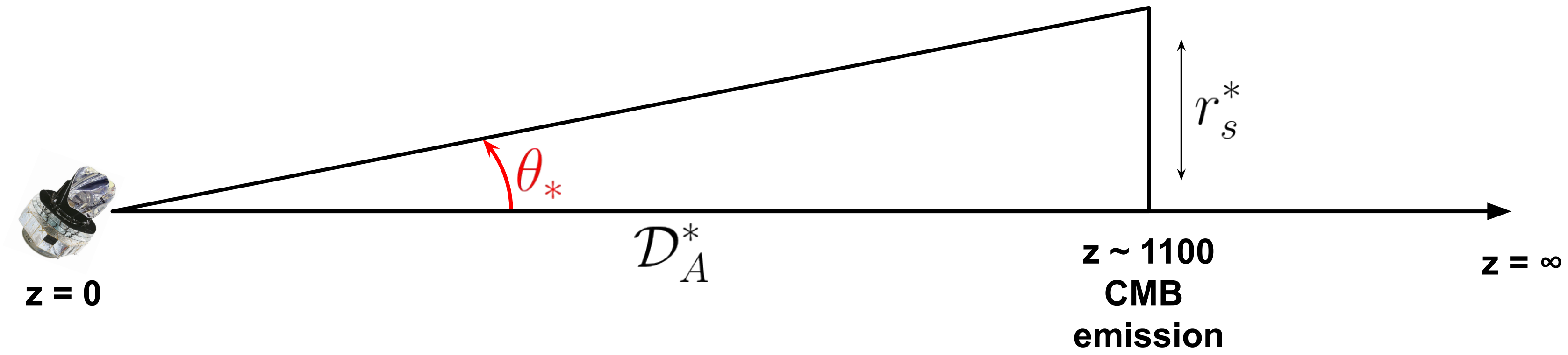
CMB standard ruler : **size of the sound horizon** at **decoupling** imprinted in the CMB radiation

Measuring H_0 from the CMB

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

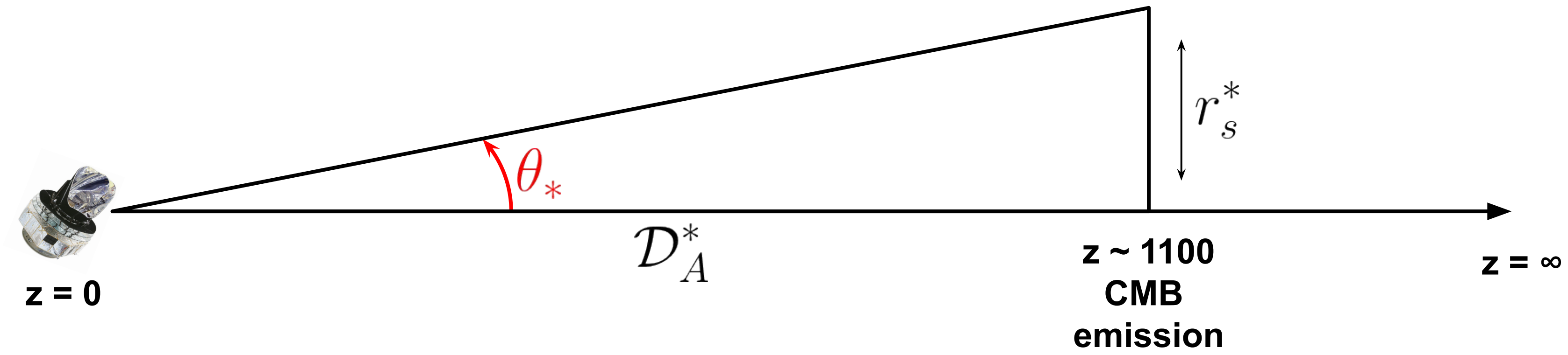


Measuring H_0 from the CMB



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

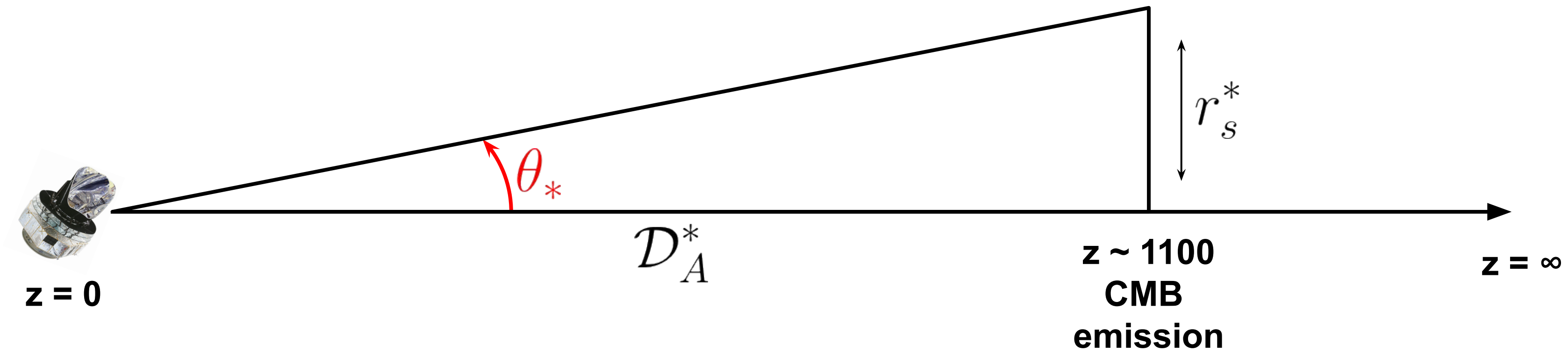
Measuring H_0 from the CMB



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

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

Measuring H_0 from the CMB



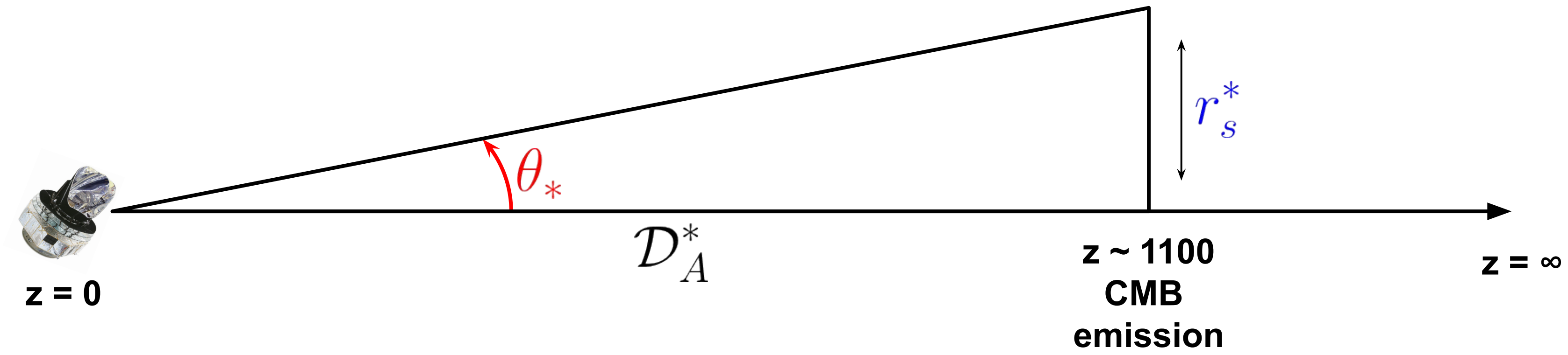
$$\theta_* = \frac{r_s^*}{\mathcal{D}_A^*}$$

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

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

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

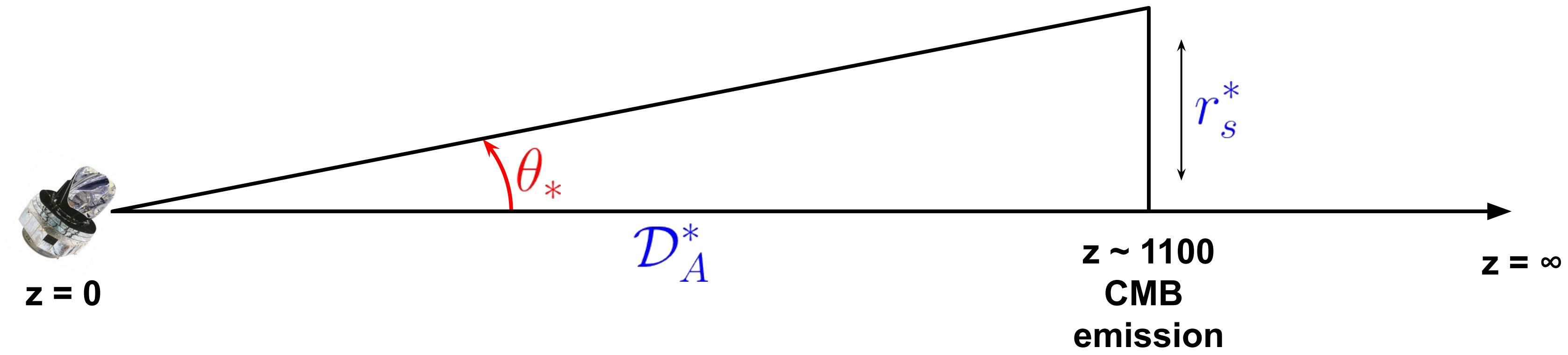
Measuring H_0 from the CMB



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

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

Measuring H_0 from the CMB

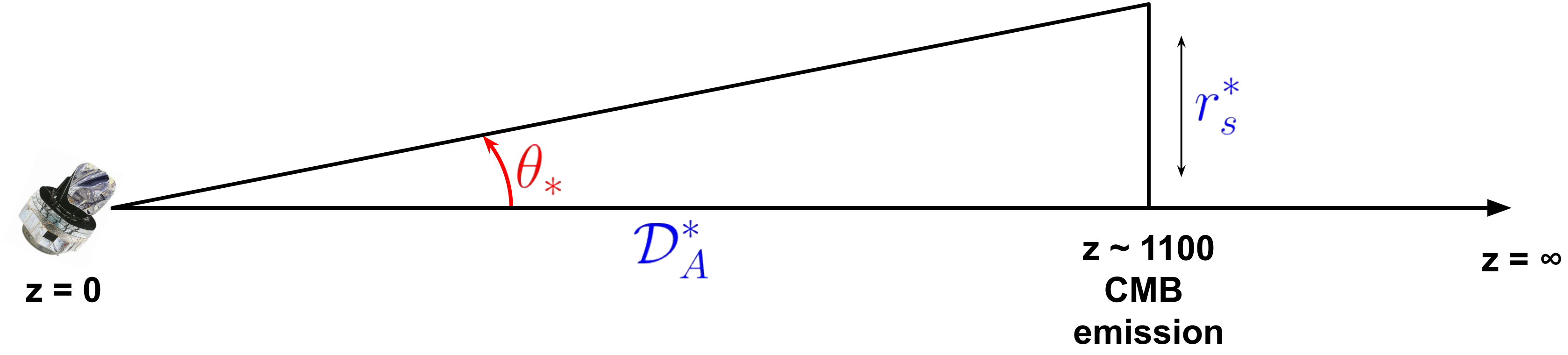


Now $\mathcal{D}_A^*$ is known

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

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

Measuring H_0 from the CMB



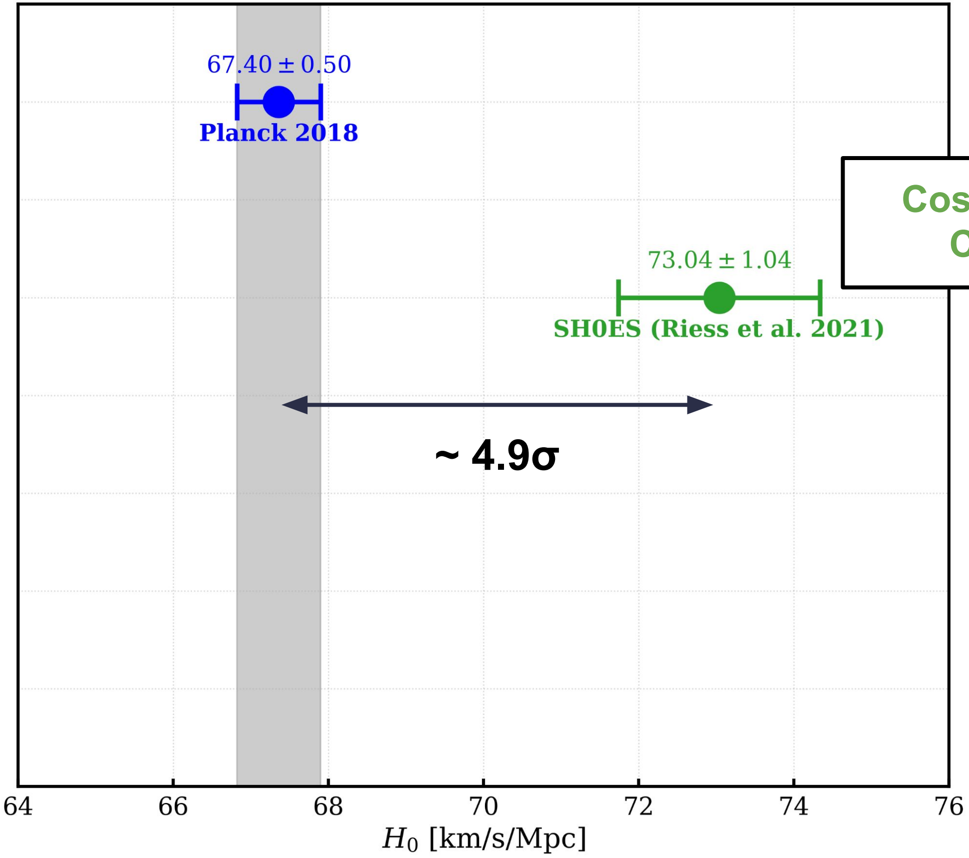
Now $\mathcal{D}_A^*$ is known

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

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

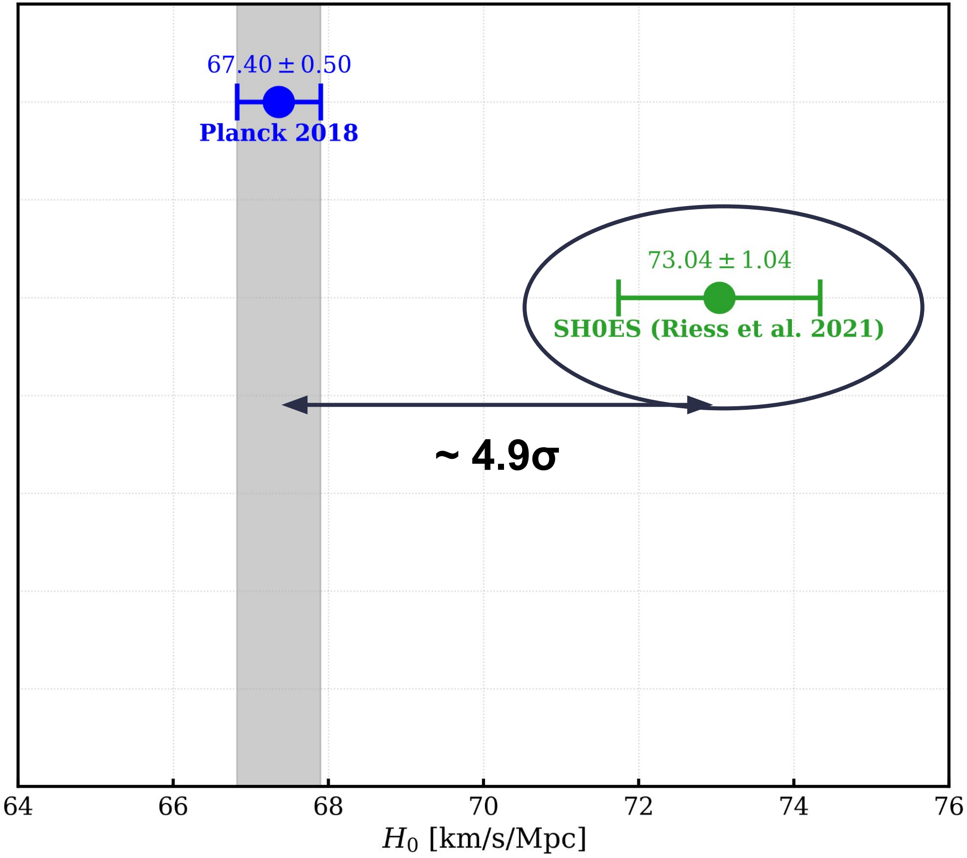
$$H_{\rm late}^2(z) = \frac{8\pi G}{3}\left[(\rho_b^0 + \rho_c^0)(1+z)^3 + \rho_\Lambda\right]$$

The Hubble tension as of today



Cosmic distance ladder using Cepheid calibrated SNIA

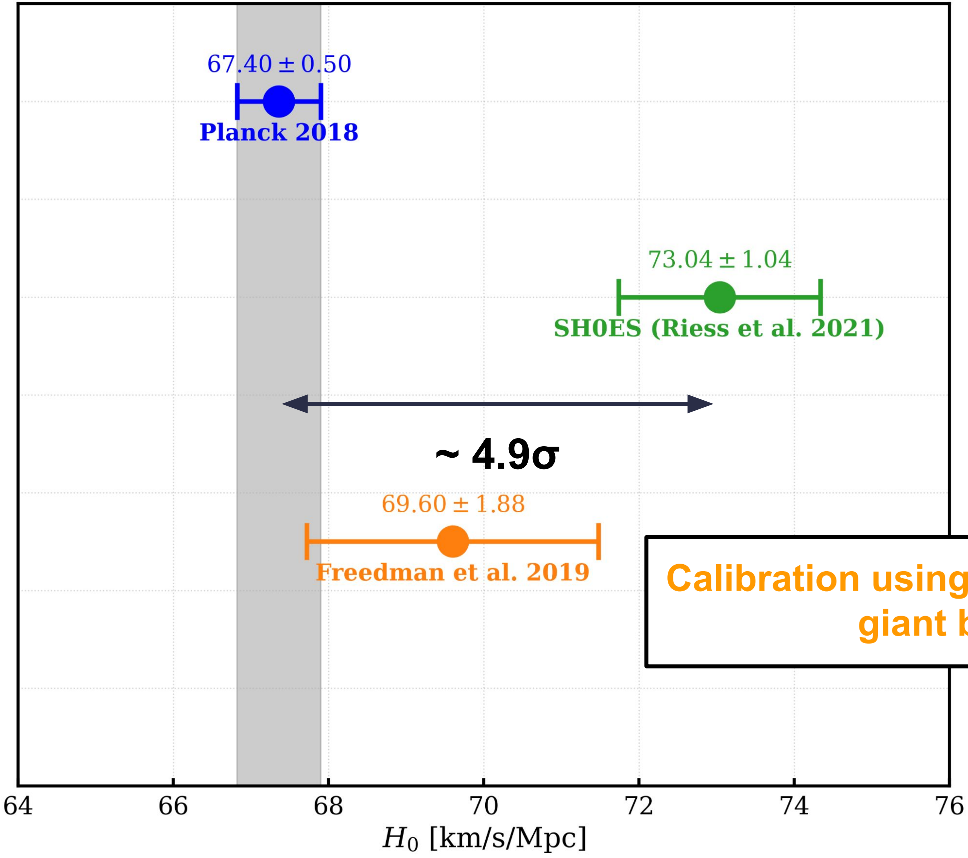
The Hubble tension as of today



Option 1

Astrophysical biases affecting the local measurement of H_0

The Hubble tension as of today

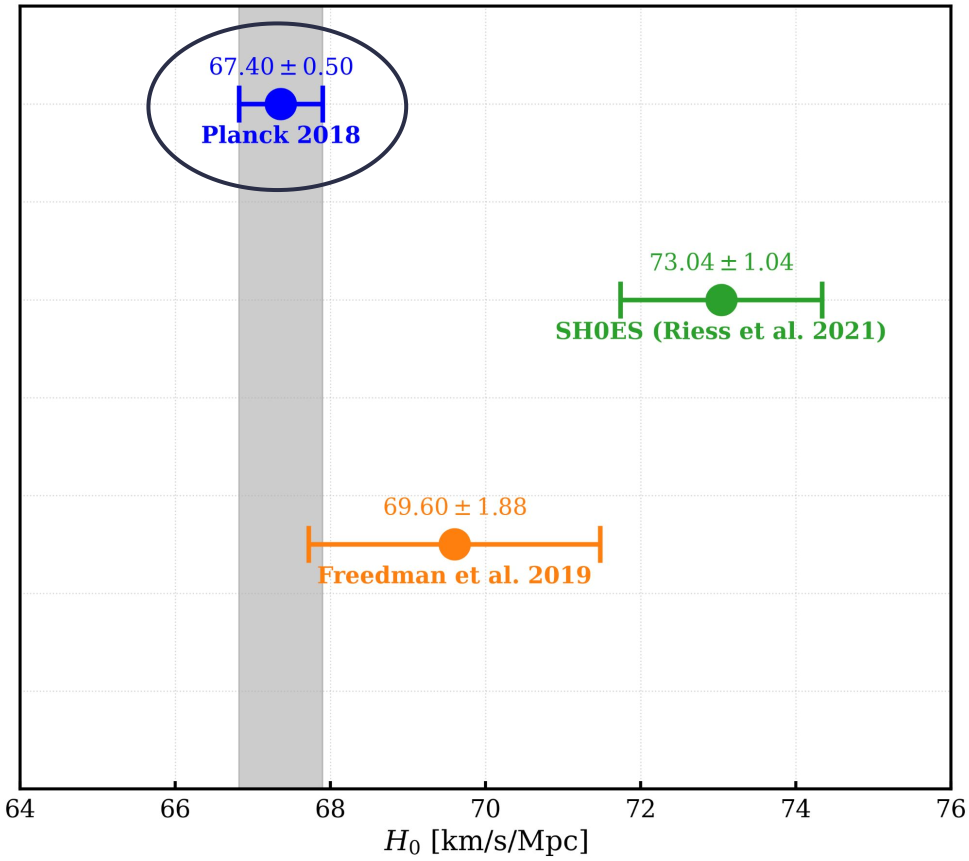


Calibration using the tip of the red giant branch

Option 1

Astrophysical biases affecting the local measurement of H_0

The Hubble tension as of today



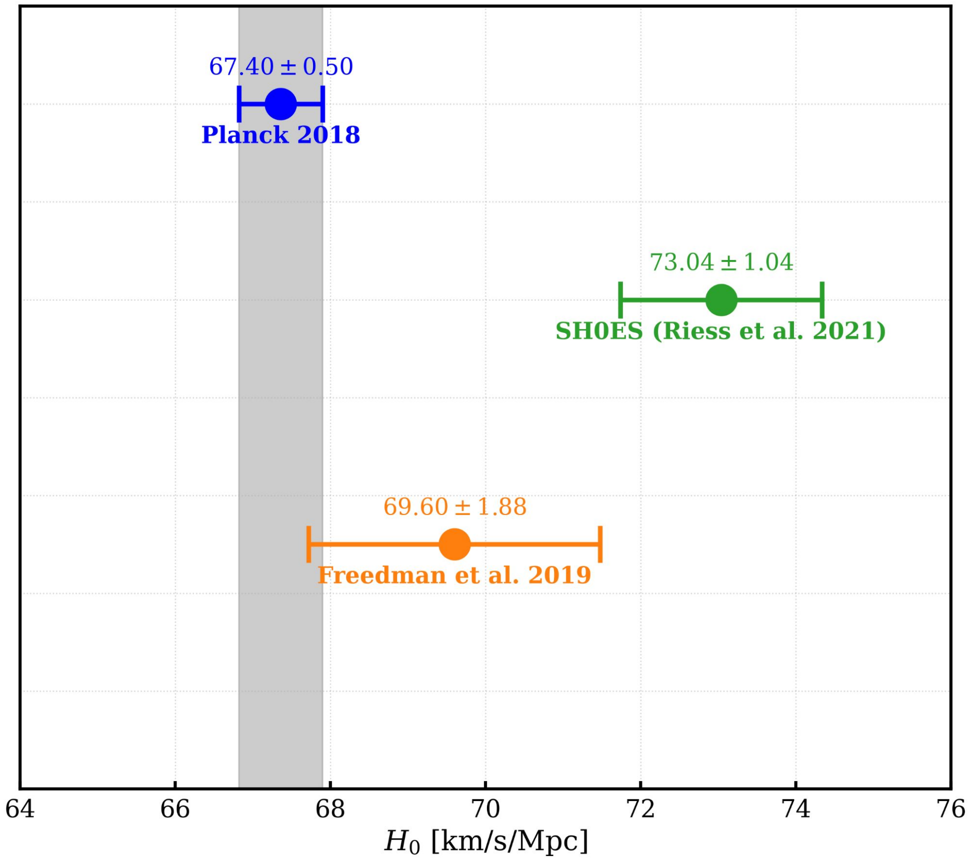
Option 1

Astrophysical biases affecting the local measurement of H_0

Option 2

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

The Hubble tension as of today



Option 1

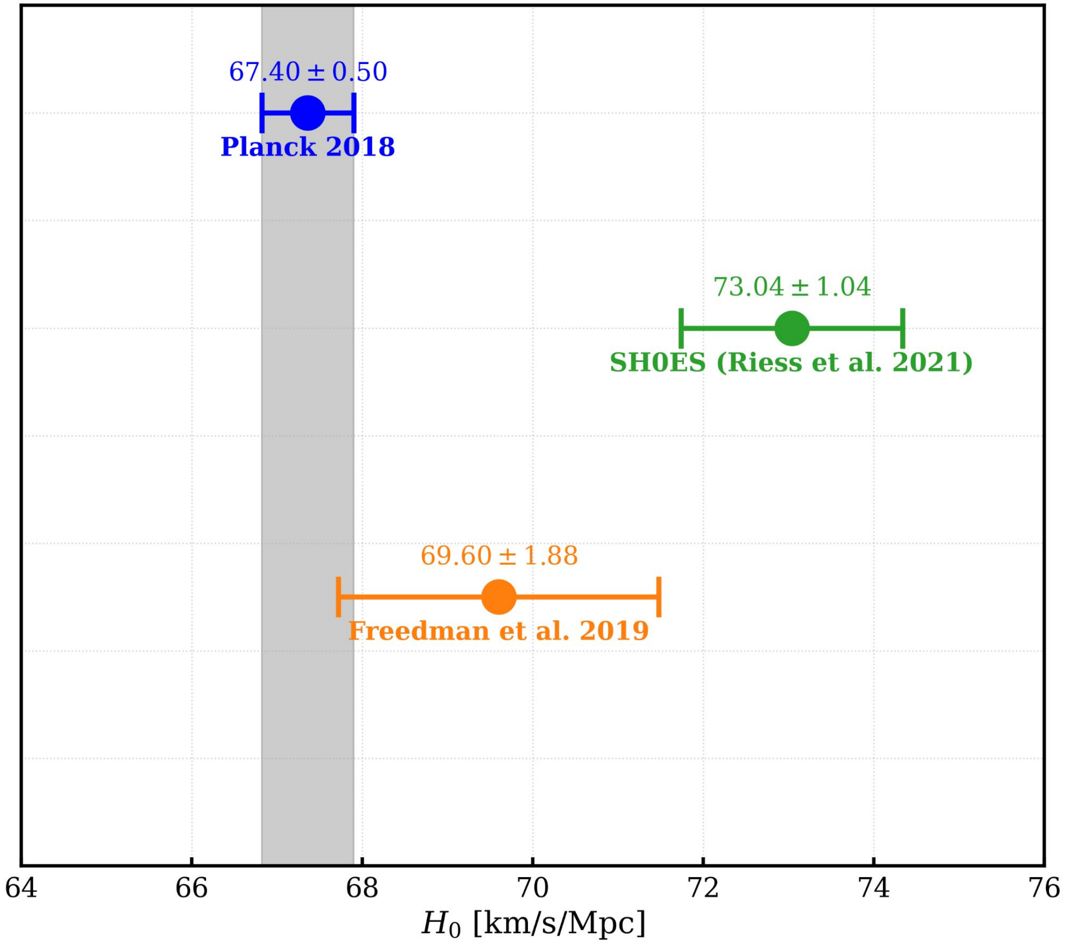
Astrophysical biases affecting the local measurement of H_0

Option 2

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

Option 3

Physics beyond ΛCDM



Option 1

Astrophysical biases affecting the local measurement of H_0

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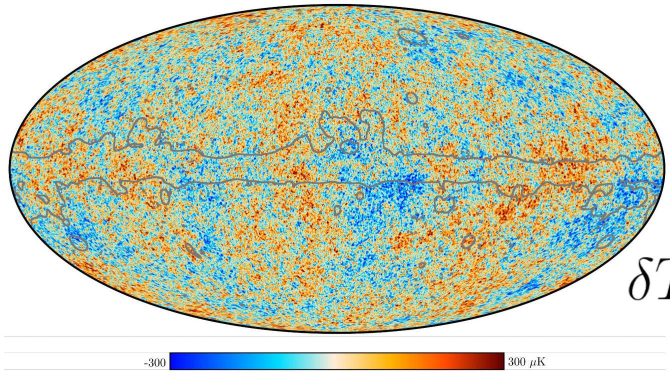
Instrumental systematic effect biasing the value of H_0 inferred from the CMB

Option 3

Physics beyond ΛCDM

Systematics in the CMB

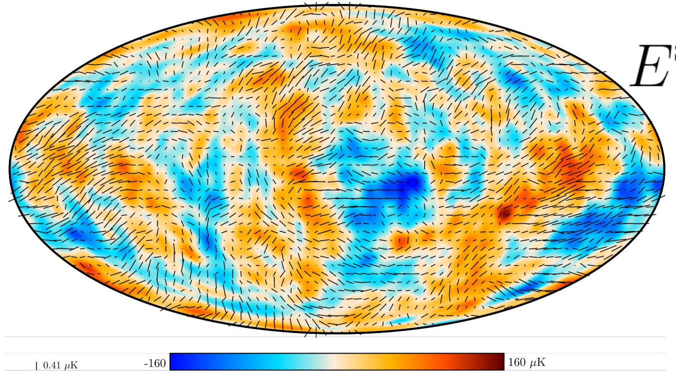


$\delta T^{\mathrm{sky}}(\hat{n})$

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

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

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



Systematics in the CMB

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

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

Systematics in the CMB

- **Finite angular resolution (beams)**

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

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

Temperature (Polarization) beam

Systematics in 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**

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

Global calibration

Systematics in 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)**
- **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 in 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)**
- **Calibration**
- **Polarization efficiency**
- **Transfer functions (map-making)**

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

Temperature (polarization) transfer function

Systematics in 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 of T and E modes

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

Correlation coefficient of T and E modes

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

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

Correlation coefficient of T and E modes

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

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

Correlation coefficient of T and E modes

- **The correlation coefficient is an observable insensitive to multiplicative biases**

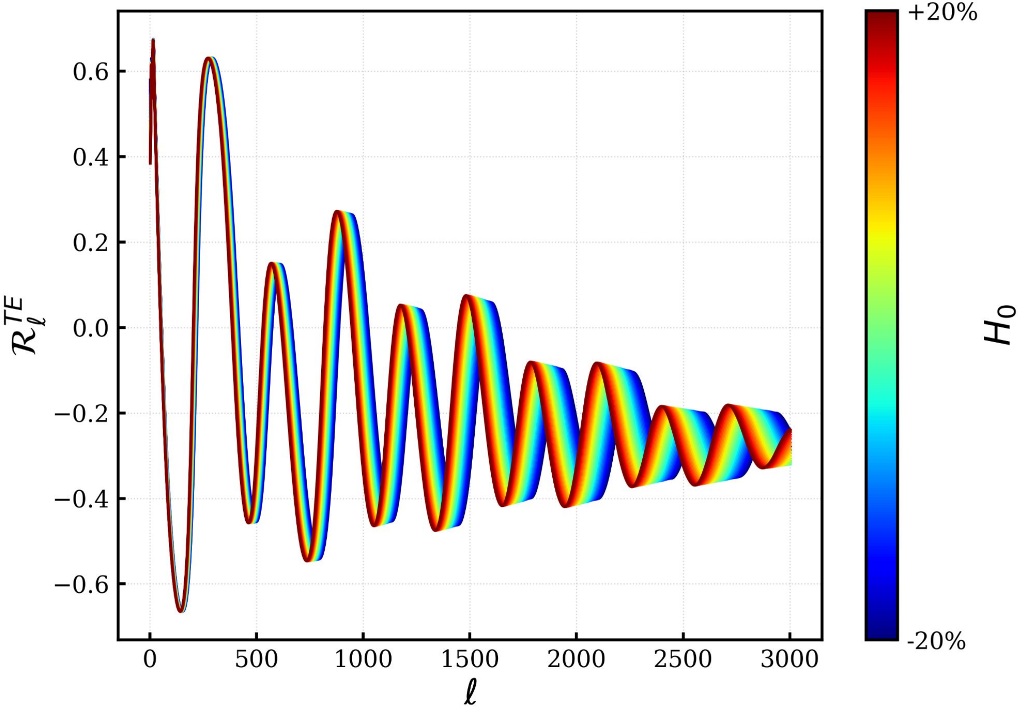
  → unbiased constraints on cosmological parameters

Correlation coefficient of T and E modes

- The correlation coefficient is an observable insensitive to multiplicative biases

  → unbiased constraints on cosmological parameters

- Particularly sensitive to H_0



Building a likelihood for R^{TE}

Gaussian likelihood based on a Planck multifrequency likelihood (HiLLiPoP)

3 frequencies : **100**, **143** and **217** GHz

$$\ln\mathcal{L} \simeq -\frac{1}{2}\left(\Delta\mathcal{R}^{\mathrm{vec}}\right)^{\mathrm{T}} \mathbf{\Xi}^{-1} \left(\Delta\mathcal{R}^{\mathrm{vec}}\right)$$

Building a likelihood for R^{TE}

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$$\ln\mathcal{L} \simeq -\frac{1}{2}\boxed{\left(\Delta\mathcal{R}^{\mathrm{vec}}\right)}^{\mathrm{T}}\,\boldsymbol{\Xi}^{-1}\left(\Delta\mathcal{R}^{\mathrm{vec}}\right)$$

$$\Delta\mathcal{R}_\ell^{TE,\nu_1\times\nu_2} = \hat{\mathcal{R}}_\ell^{TE,\nu_1\times\nu_2} - \mathcal{R}_\ell^{TE,\nu_1\times\nu_2,\mathrm{model}}$$

Building a likelihood for R^{TE}

Gaussian likelihood based on a Planck multifrequency likelihood (HiLLiPoP)

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Unbiased estimator (data)

Building a likelihood for R^{TE}

Gaussian likelihood based on a Planck multifrequency likelihood (HiLLiPoP)

3 frequencies : **100**, **143** and **217** GHz

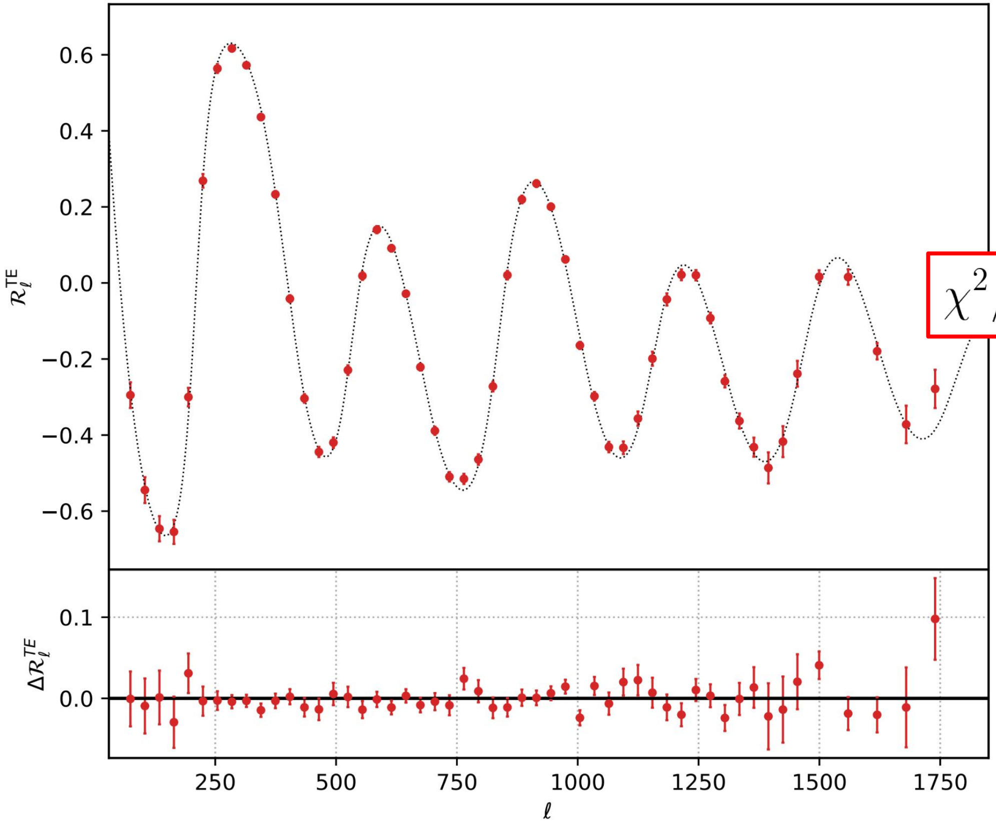
$$\ln\mathcal{L} \simeq -\frac{1}{2}\left(\Delta\mathcal{R}^{\mathrm{vec}}\right)^{\mathrm{T}} \boldsymbol{\Xi}^{-1}\left(\Delta\mathcal{R}^{\mathrm{vec}}\right)$$

$$\Delta\mathcal{R}_\ell^{TE,\nu_1\times\nu_2} = \boxed{\hat{\mathcal{R}}_\ell^{TE,\nu_1\times\nu_2}} - \boxed{\mathcal{R}_\ell^{TE,\nu_1\times\nu_2,\mathrm{model}}}$$

Unbiased estimator (data)

$$\frac{C_\ell^{TE,\nu_1\times\nu_2,\mathrm{model}}(p_{\mathrm{cosmo}},p_{\mathrm{fg}})}{\sqrt{C_\ell^{TT,\nu_1\times\nu_2,\mathrm{model}}(p_{\mathrm{cosmo}},p_{\mathrm{fg}})\,C_\ell^{EE,\nu_1\times\nu_2,\mathrm{model}}(p_{\mathrm{cosmo}},p_{\mathrm{fg}})}}$$

Planck correlation coefficient



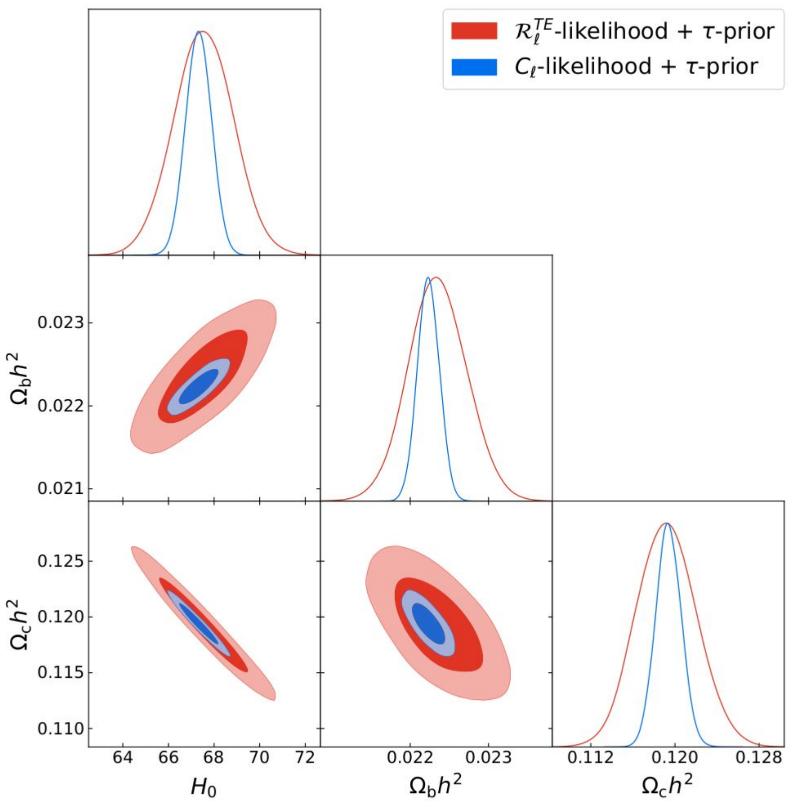
Bestfit from Planck TT,TE,EE

Planck correlation coefficient

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

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

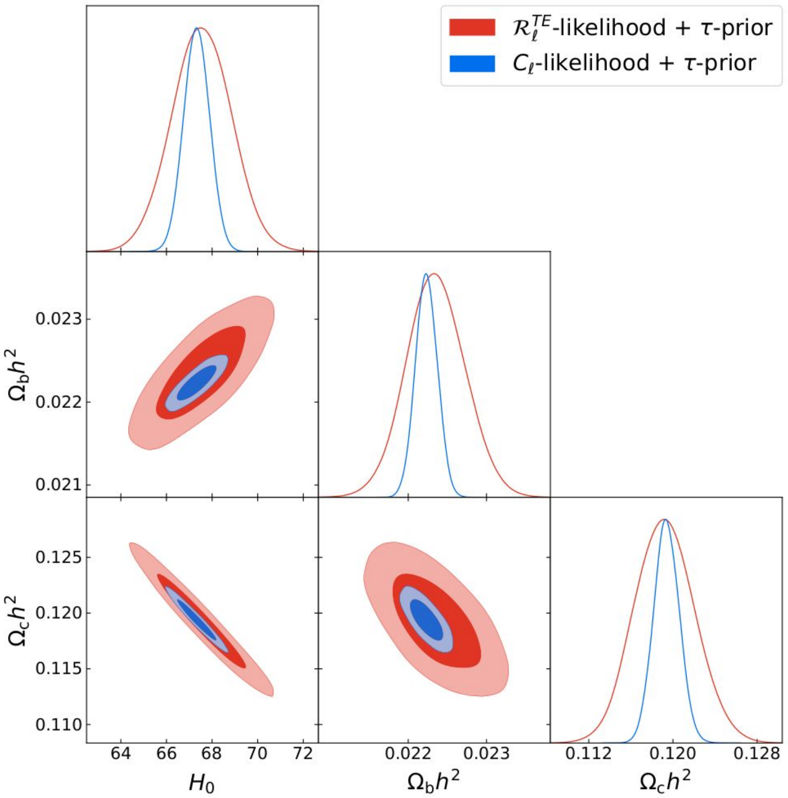
Cosmological results from R^{TE}



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

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

Cosmological results from R^{TE}

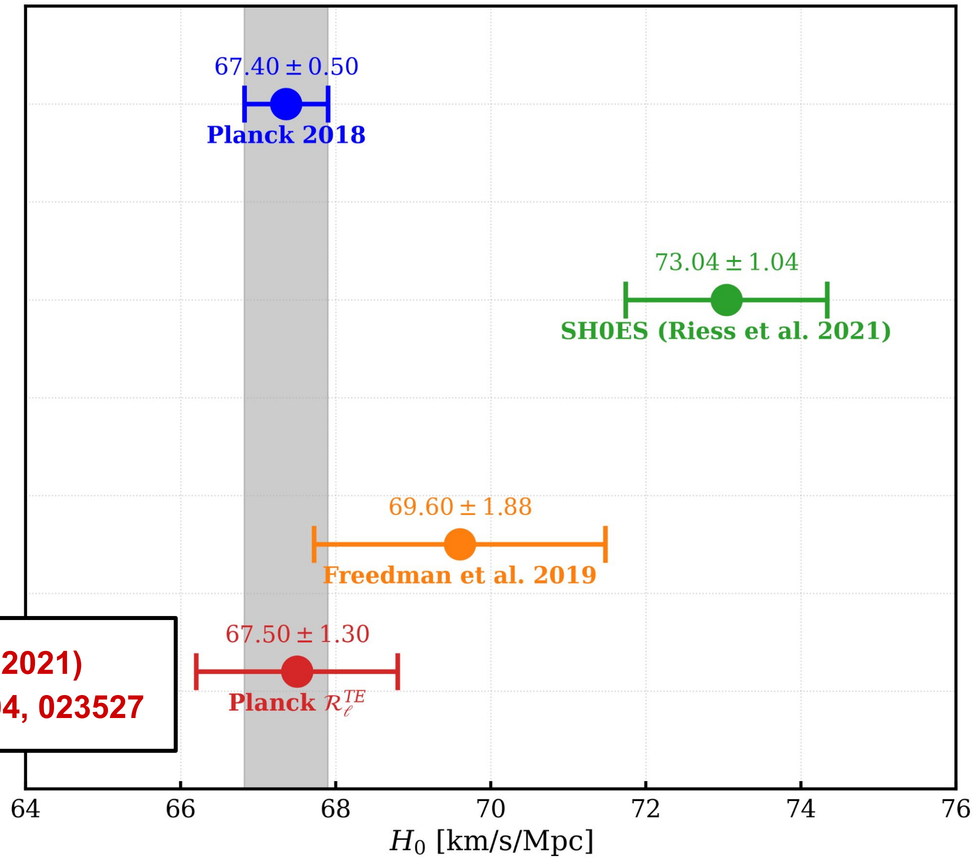


3.3σ away from the latest SH0ES measurement

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

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

Hubble tension



La Posta et al. (2021)
Phys. Rev. D 104, 023527

Independent measurements of H_0 from the ground

Independent measurements of H_0 from the ground

Atacama Cosmology Telescope

6m telescope in the Atacama desert
(Chile ~5000m high)

ACT DR4 (Choi+ 2020, Aiola+ 2020)

data collected from 2013 to 2016

Cosmological analysis on ~5400 deg^2

observed at 98 and 150 GHz

South Pole Telescope

10m primary mirror
(South Pole ~2800m high)

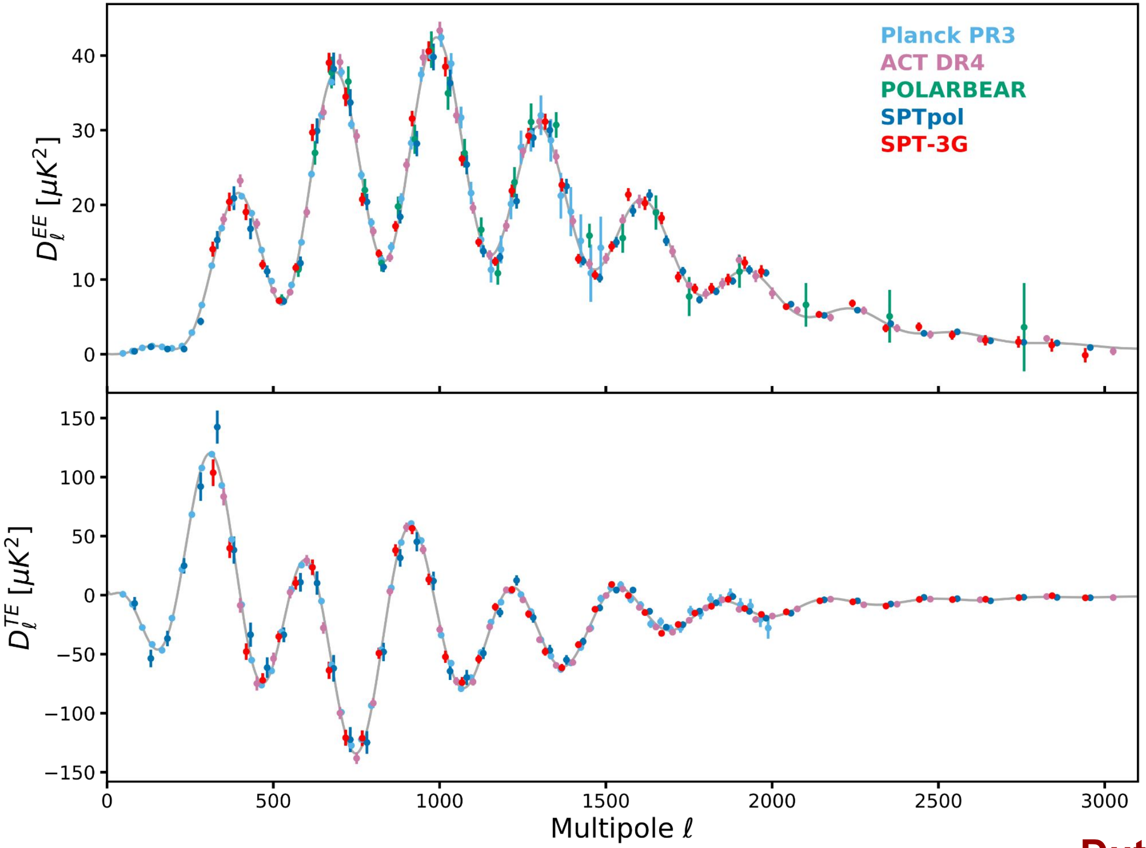
SPT-3G results (Dutcher+ 2021)

4 month period in 2018

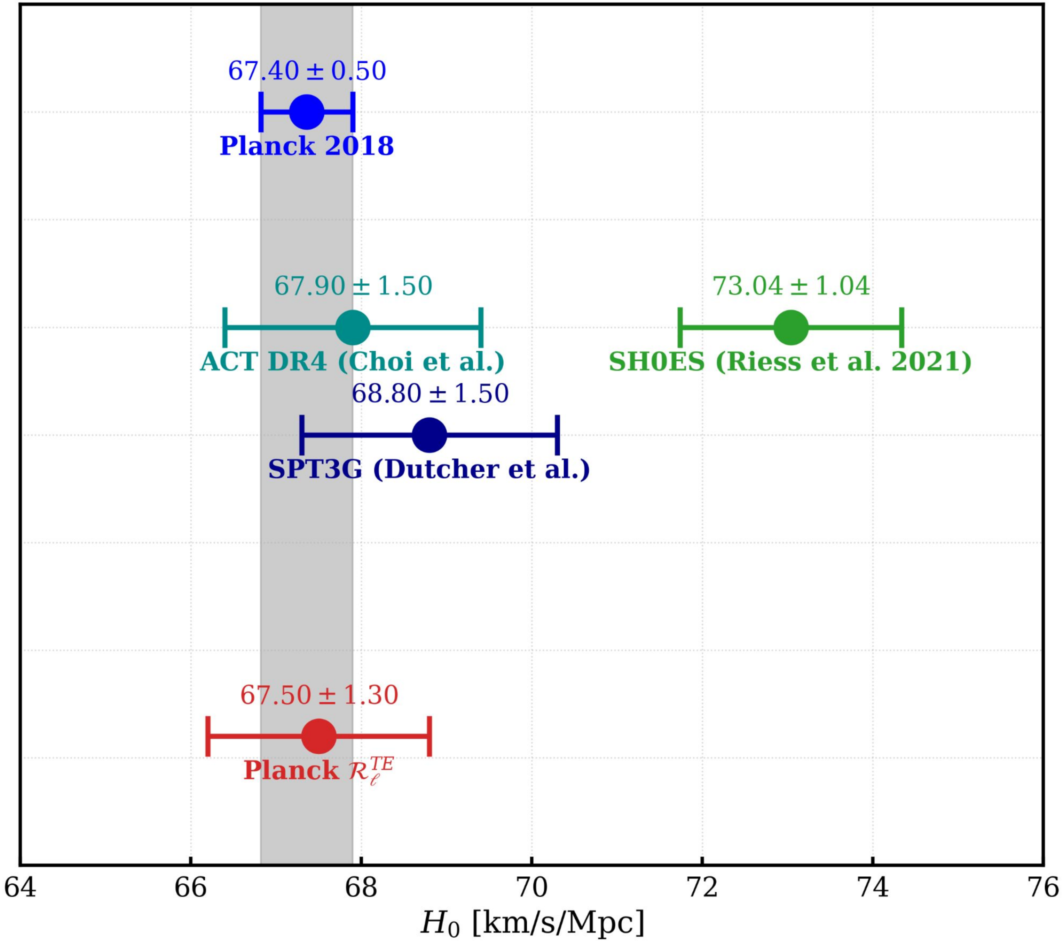
Cosmological analysis on ~1500 deg^2

observed at 95, 150 and 220 GHz

CMB Power Spectra



Dutcher+ 2021



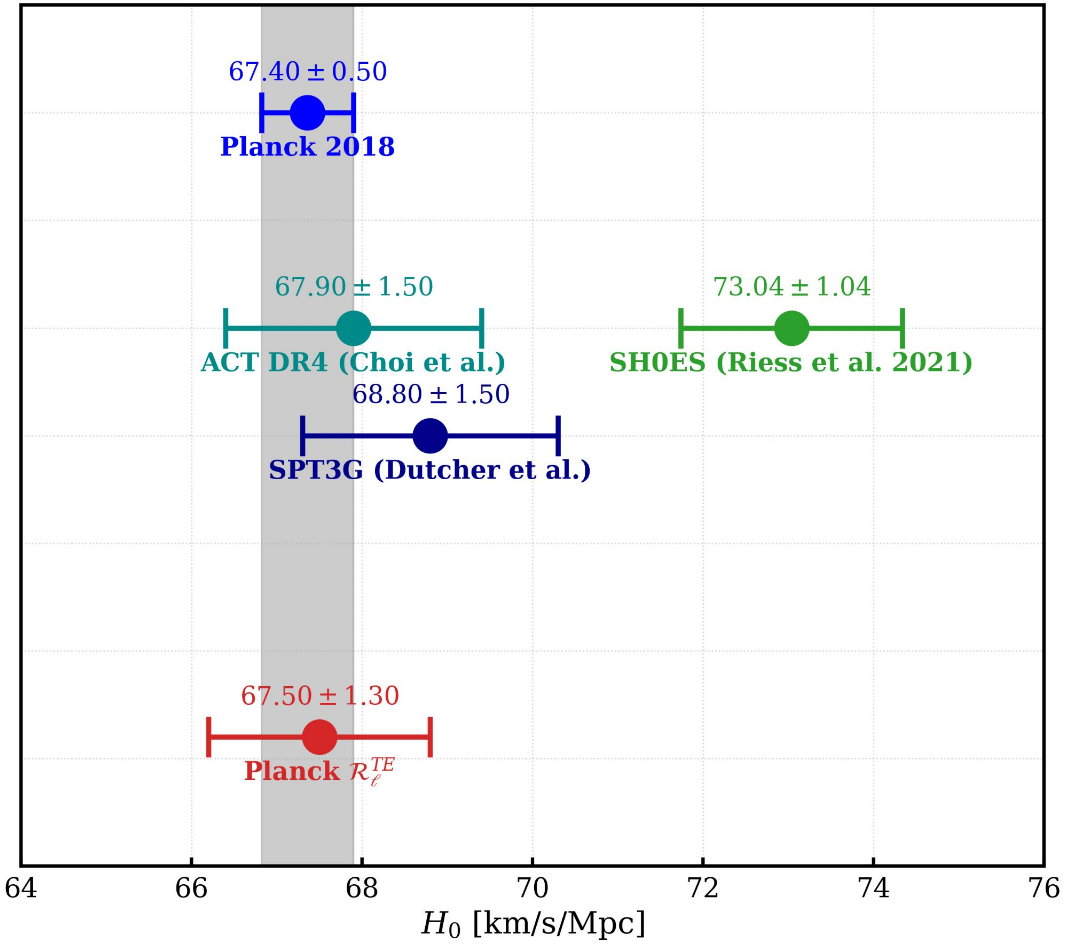
Option 2

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

↓

Hard to shift the CMB inferred H_0 with a systematic effect :

- **Independent measurements from Planck, ACT and SPT**
- **Constraint from the correlation coefficient, robust against multiplicative systematics**



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 : obtain a higher value of H_0 from the CMB

Early-time modification to ΛCDM

Motivation : obtain a higher value of H_0 from the CMB $\longrightarrow$ lower $\mathcal{D}_A^*$

Early-time modification to ΛCDM

Motivation : obtain a higher value of H_0 from the CMB ⟶ lower $\mathcal{D}_A^*$

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

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

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

Fixed by observations

One proposed solution : Early Dark Energy

Motivation : obtain a higher value of H_0 from the CMB $\longrightarrow$ lower $\mathcal{D}_A^*$

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

Fixed by observations

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

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

EDE phenomenology

The EDE component is described as a scalar field ϕ (Poulin+ 2019, Smith+ 2019)

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

axion-like potential

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

EDE phenomenology

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m : mass parameter

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m : mass parameter

f : decay constant

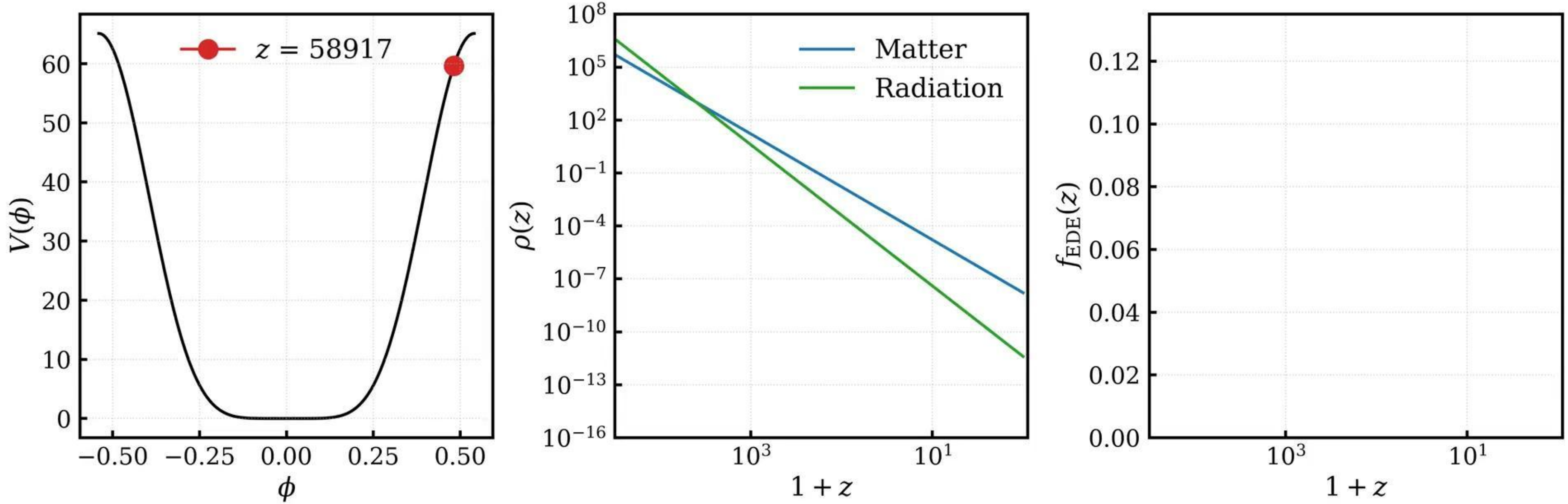
ϕ_i : initial field value

Early Dark Energy : frozen at early times

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

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

acts as dark energy (w= - 1)

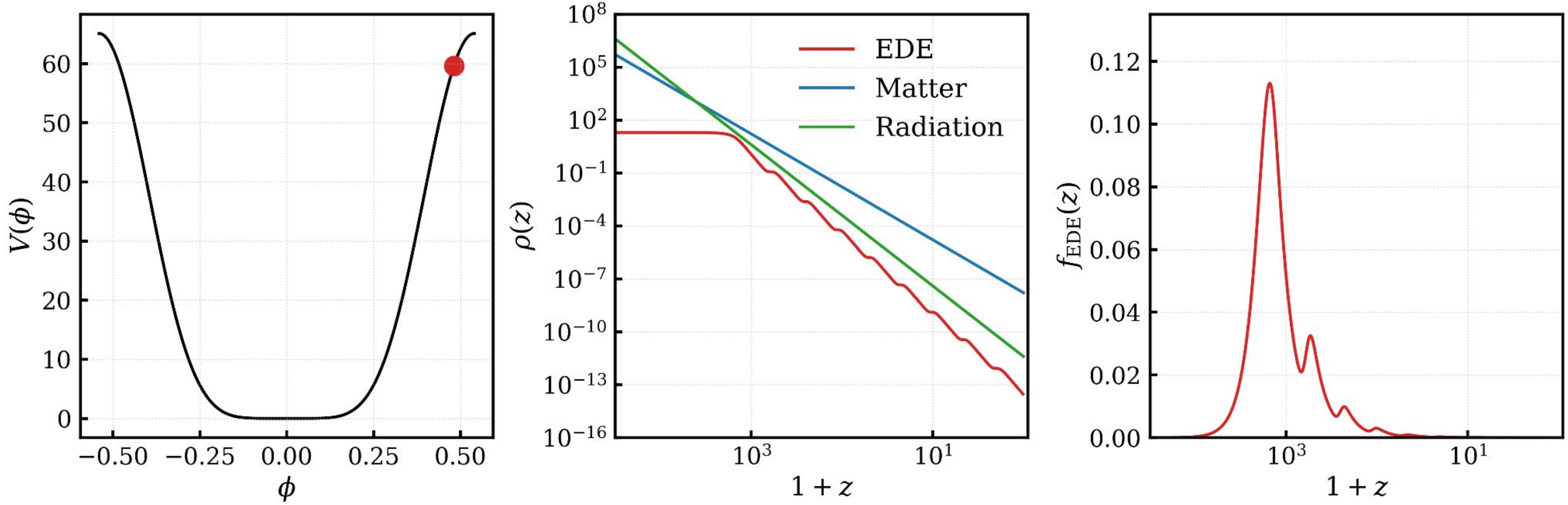


Early Dark Energy : frozen at early times

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

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

acts as dark energy (w= - 1)

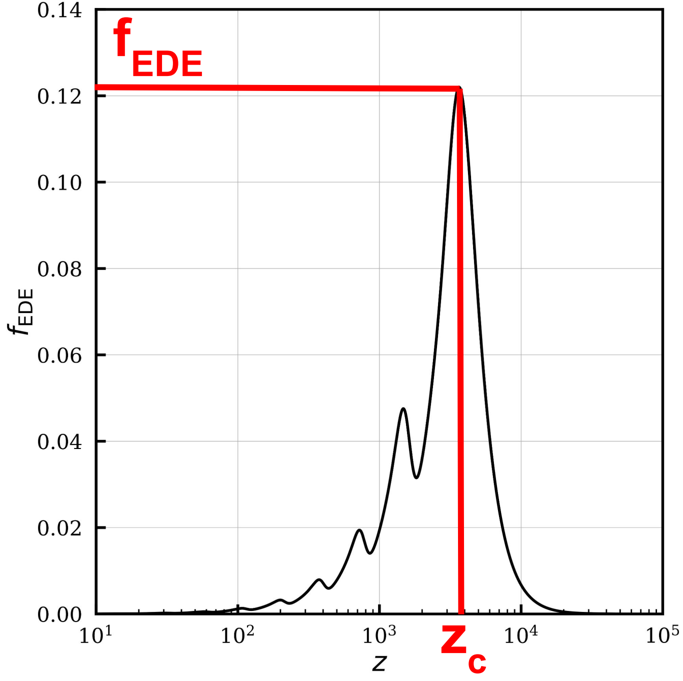


Early Dark Energy : phenomenological parametrization

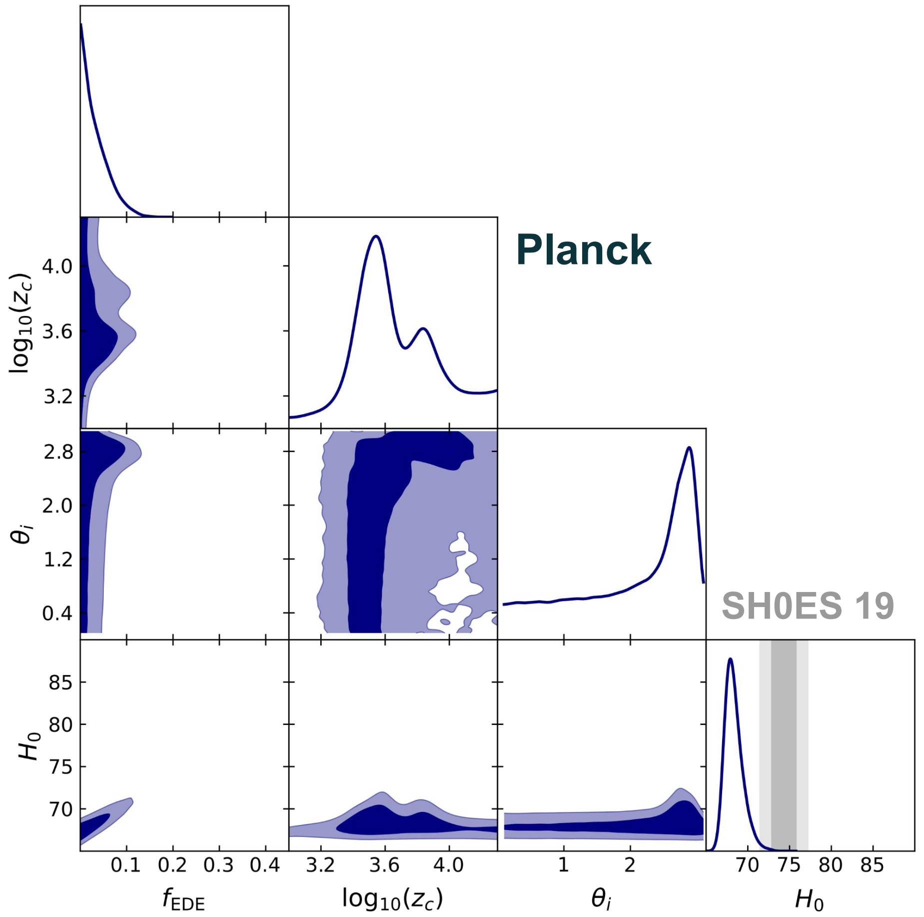
$$(m, f, \phi_i) \longrightarrow (f_{\mathrm{EDE}}, z_c, \phi_i)$$

Field parameters

Phenomenological parametrization

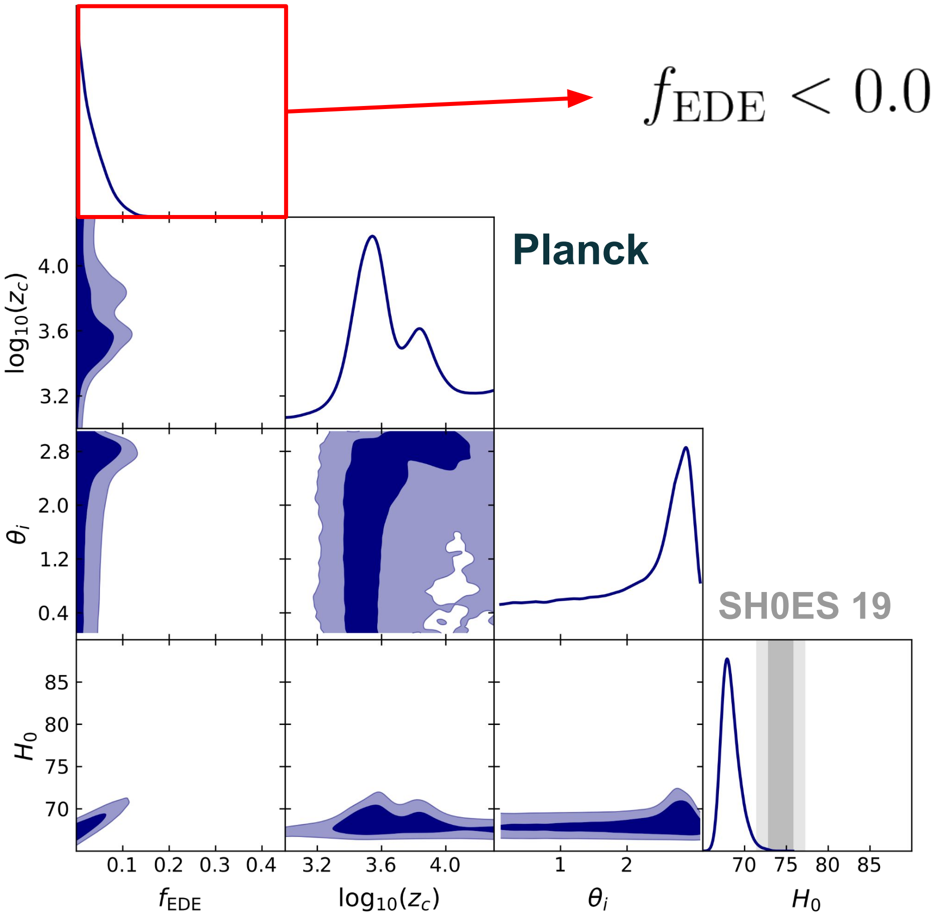


Constraints on EDE from Planck data



Hill+ 2020

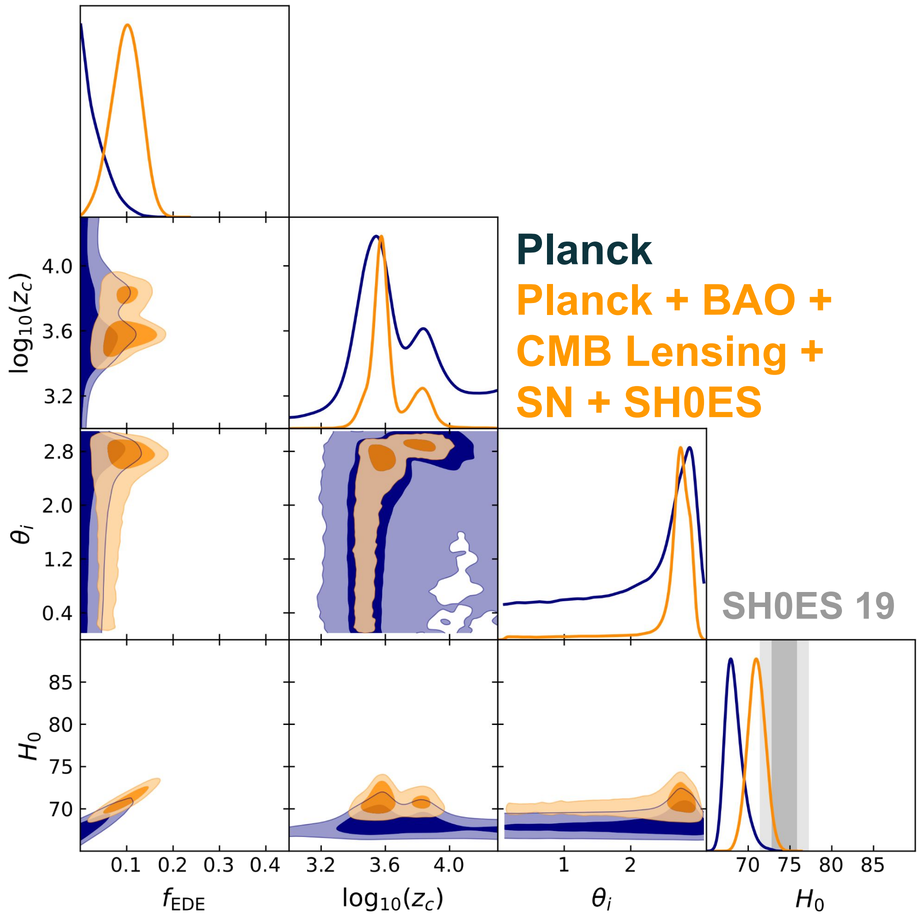
Constraints on EDE from Planck data



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

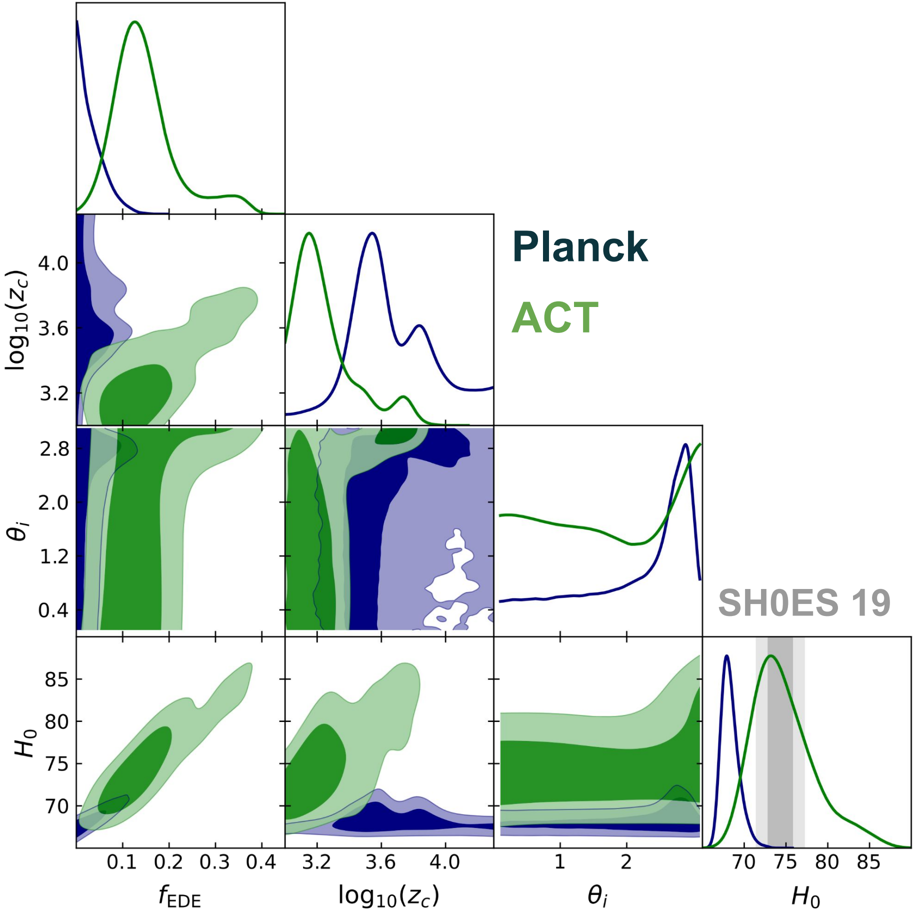
Hill+ 2020

Results for a combination of Planck and SH0ES data



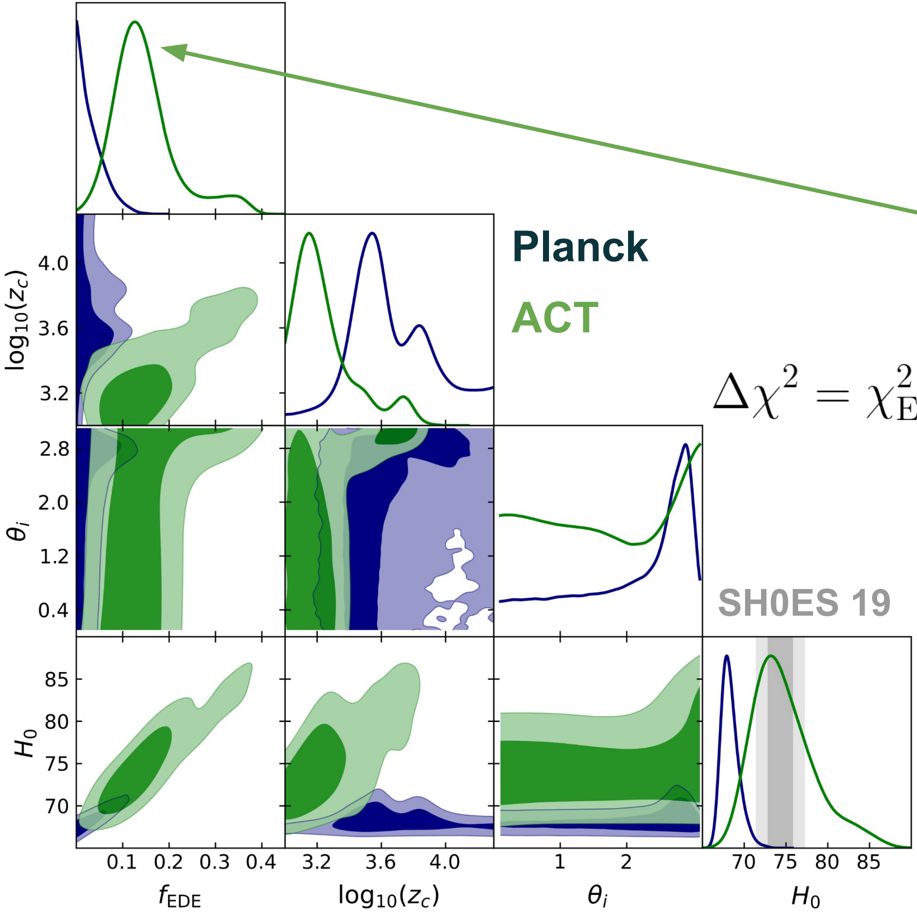
Poulin+ 2019, Smith+ 2019, Hill+ 2020

Additional constraints from ACTPol



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

Additional constraints from ACTPol



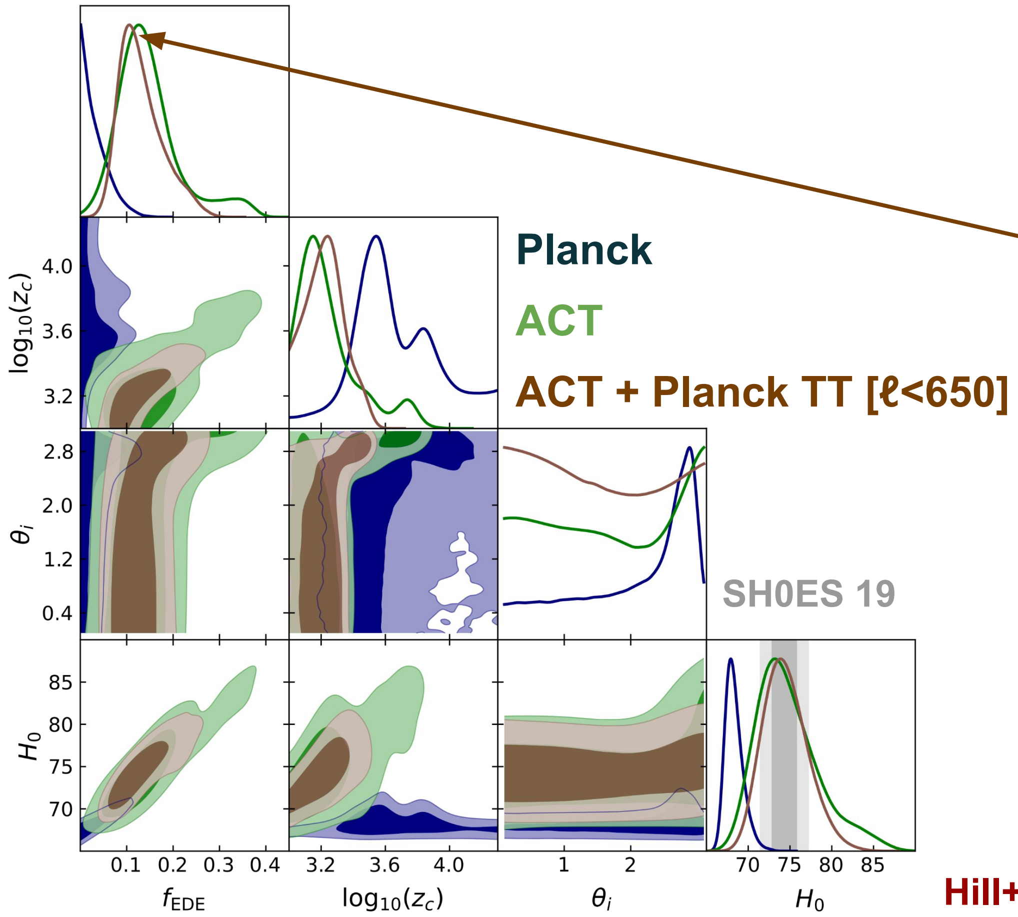
$$f_{\rm EDE} = 0.142^{+0.039}_{-0.072}\ (68\%\ \text{C.L.})$$

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

2.1σ preference in favor of EDE

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

Additional constraints from ACTPol



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

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

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

Summary of EDE results

- Planck data alone don't favor high f_{EDE} values (Hill+ 2020)
- Planck data in combination with SH0ES show a preference for non-zero f_{EDE} (Poulin+ 2019, Smith+ 2019)
- ACT data alone favors EDE over ΛCDM (Hill+...La Posta+... 2021)

Summary of EDE results

- Planck data alone don't favor high f_{EDE} values **(Hill+ 2020)**
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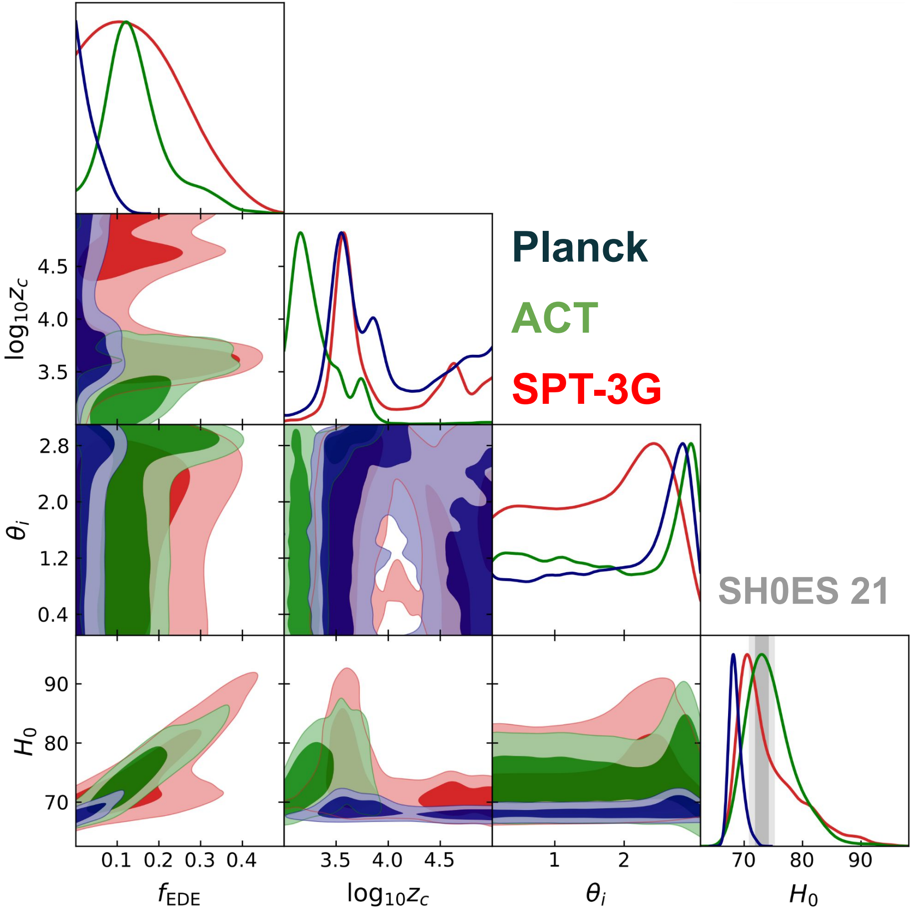
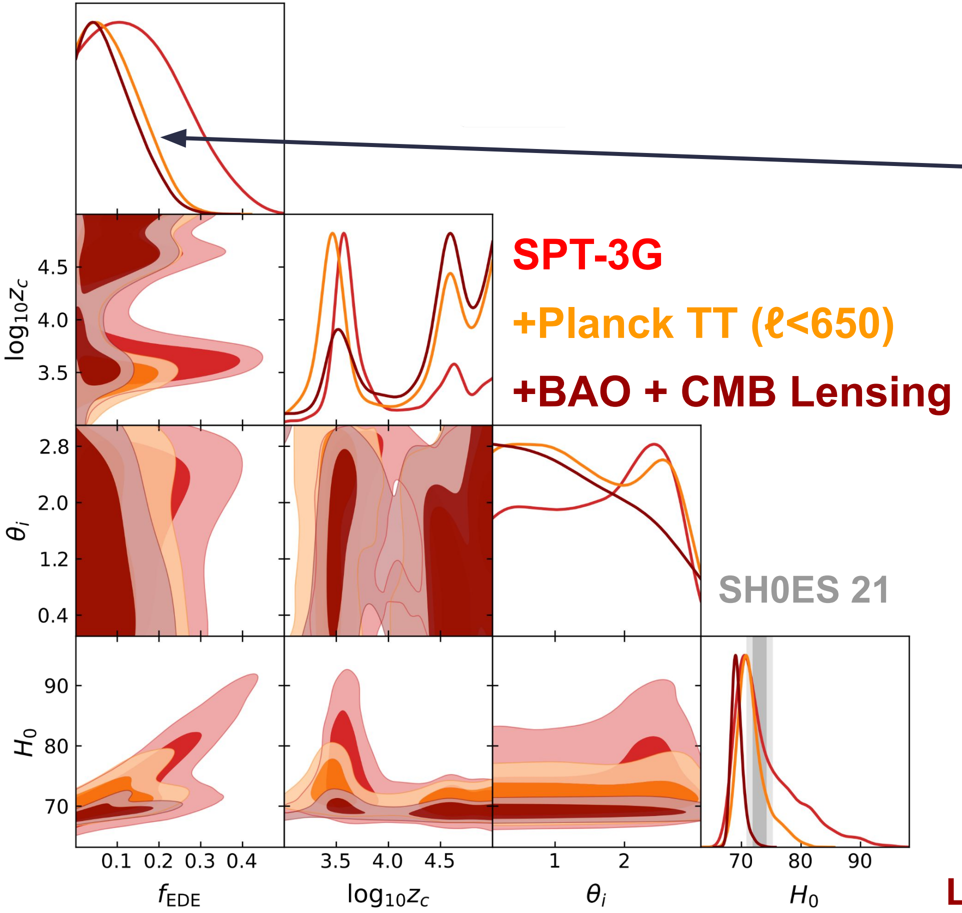
→ Motivates an analysis of EDE with public SPT-3G data

New results from SPT-3G public data



La Posta+ 2021 [arXiv:2112.10754]

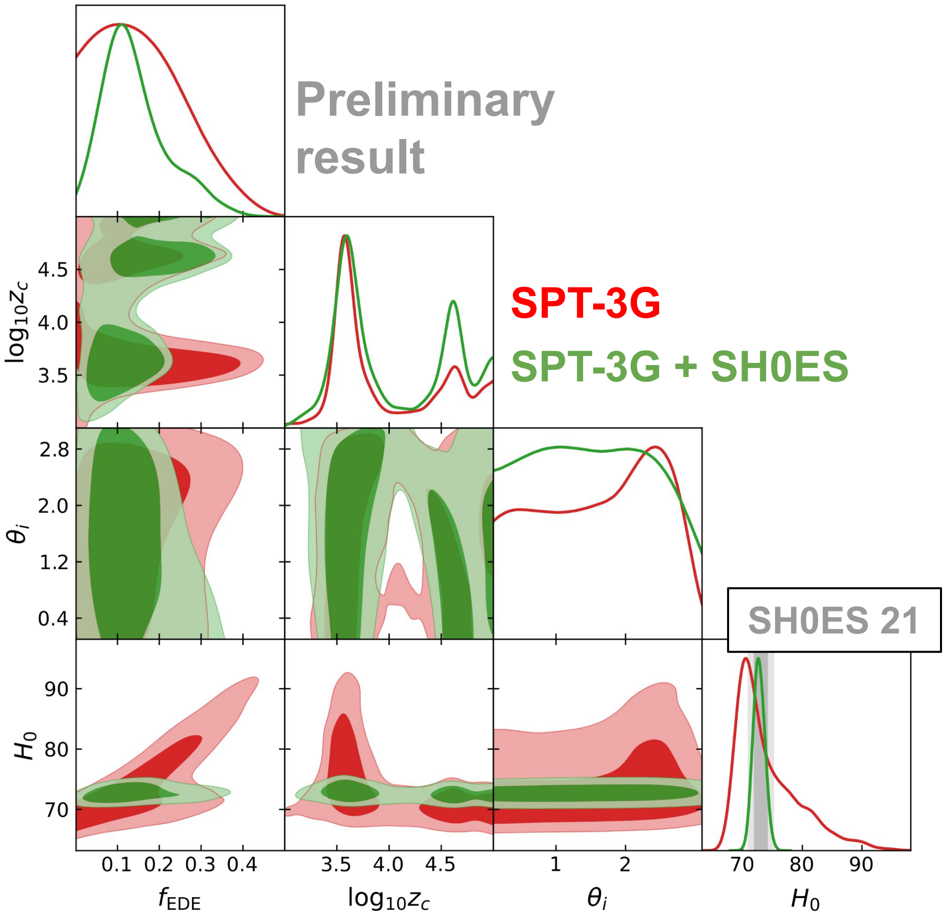
New results from SPT-3G public data



We tighten the constraint on f_{EDE} when we combine SPT3G and Planck TT (ℓ<650) or when we add LSS probes

La Posta+ 2021 [arXiv:2112.10754]

Combining with SH0ES constraint

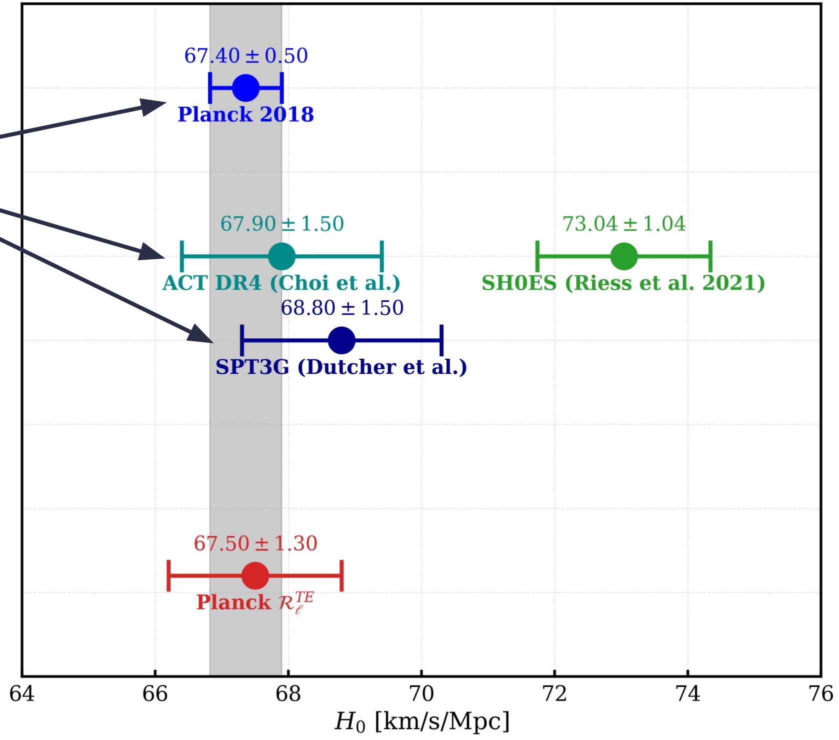


$$\Delta\chi^2_{\rm SPT-3G} = -6.3$$

improvement of the fit to SPT-3G data (with respect to ΛCDM)

Option 2 : Systematics in CMB data

- 3 independent measurements of H_0



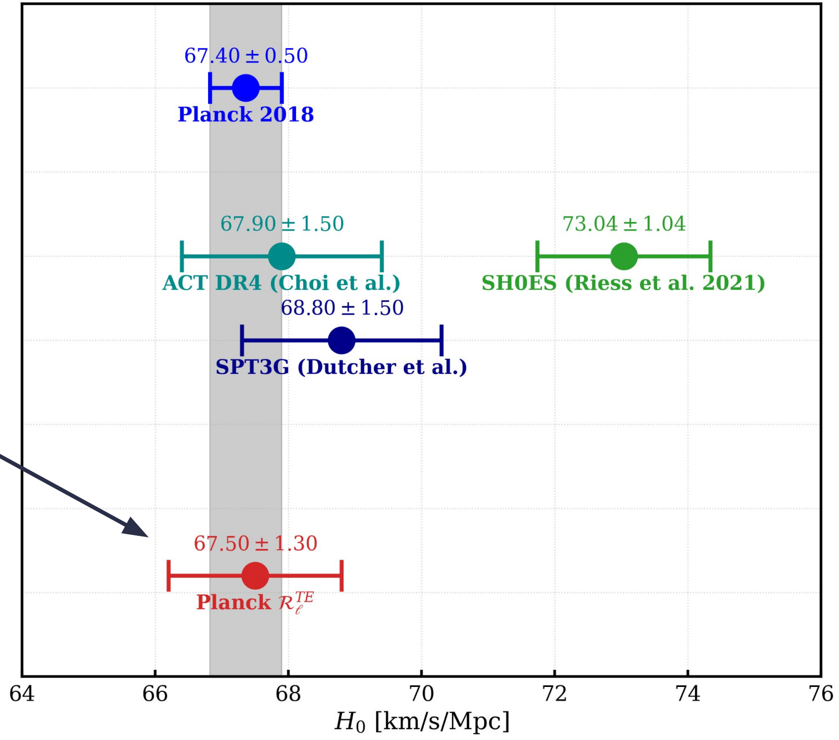
Conclusions

Option 2 : Systematics in CMB data

- 3 independent measurements of H_0

- Constraint from the **correlation coefficient** : insensitive to multiplicative systematic effects

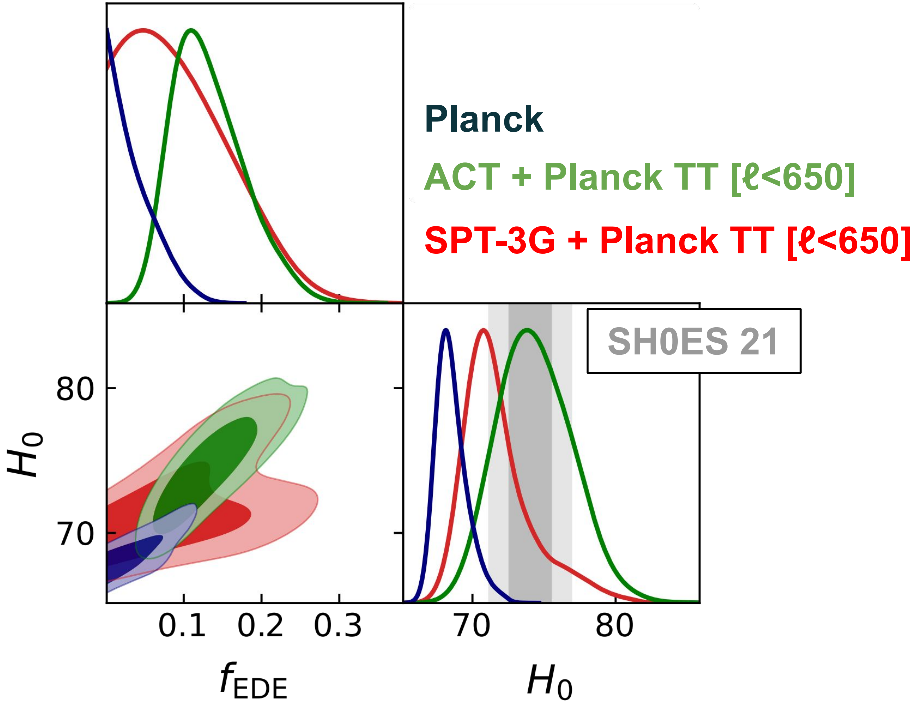
It's hard to solve the Hubble tension with systematics in CMB data



Conclusions

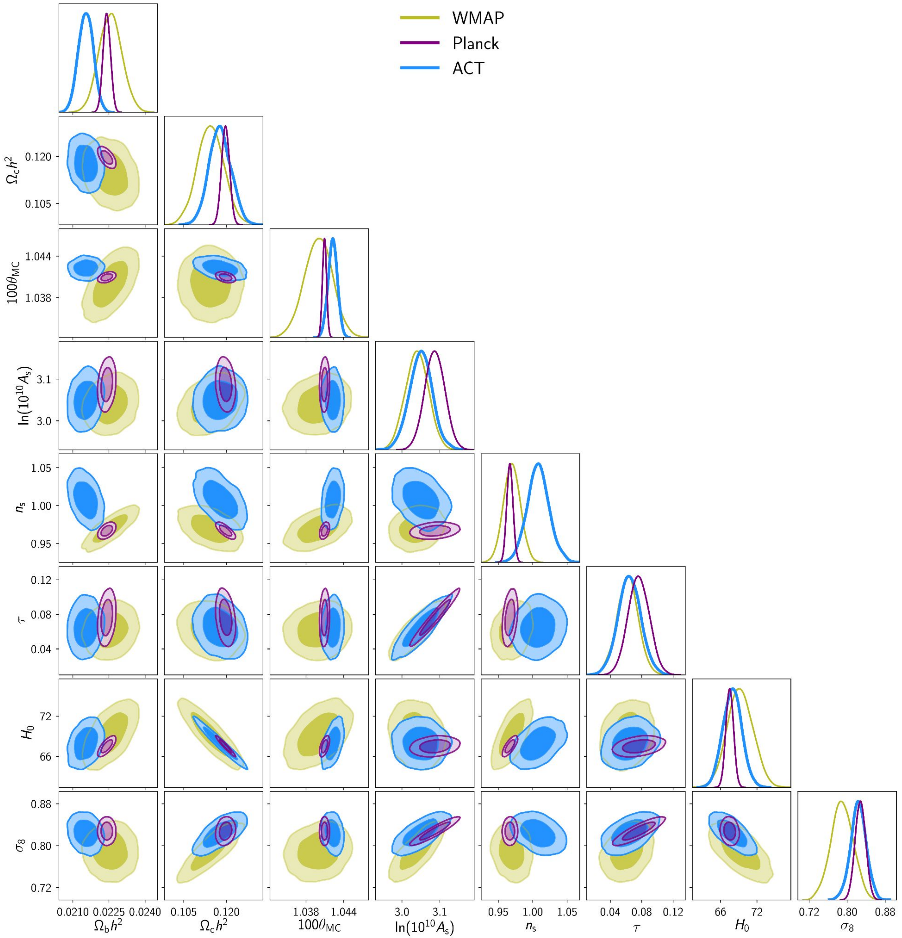
Option 3 : Beyond ΛCDM physics - Early Dark Energy

- Planck data alone do not favor high f_{EDE} values
- Planck + SH0ES show a preference for f_{EDE} ~ 10%
- ACT DR4 data favors EDE over ΛCDM (with f_{EDE}~ 10%)
- SPT-3G is not as constraining as ACT and Planck : but sees some degree of EDE when combined with SH0ES



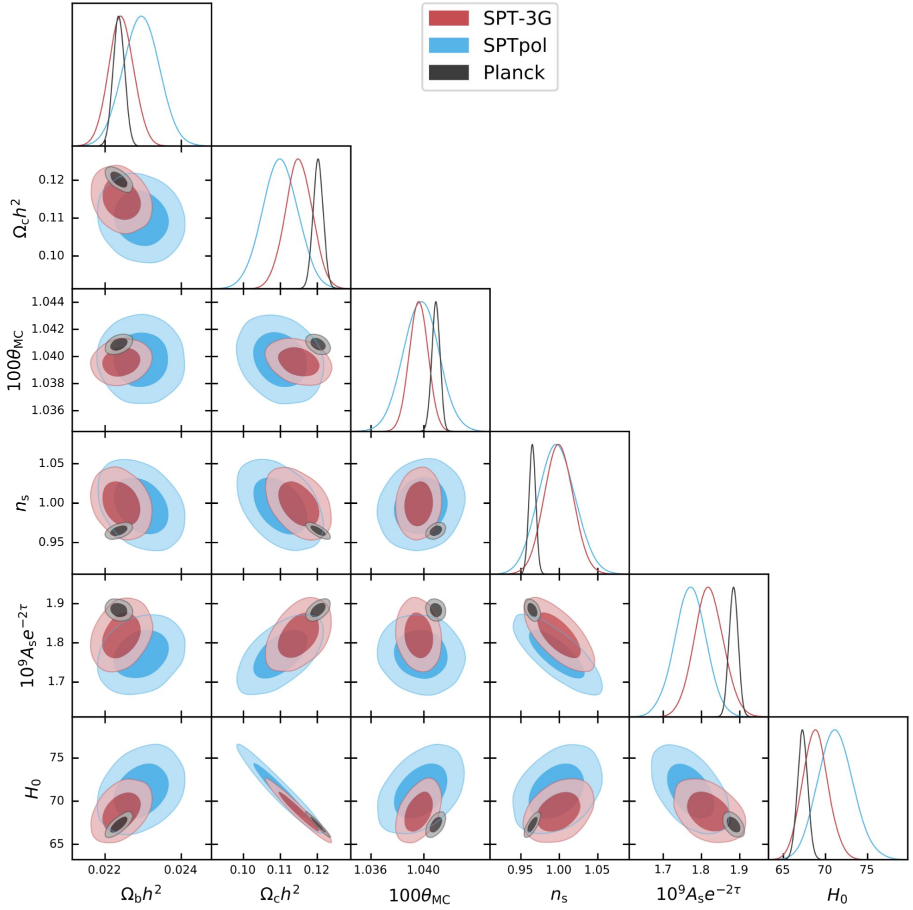
Extra-slides

ACTPol cosmology



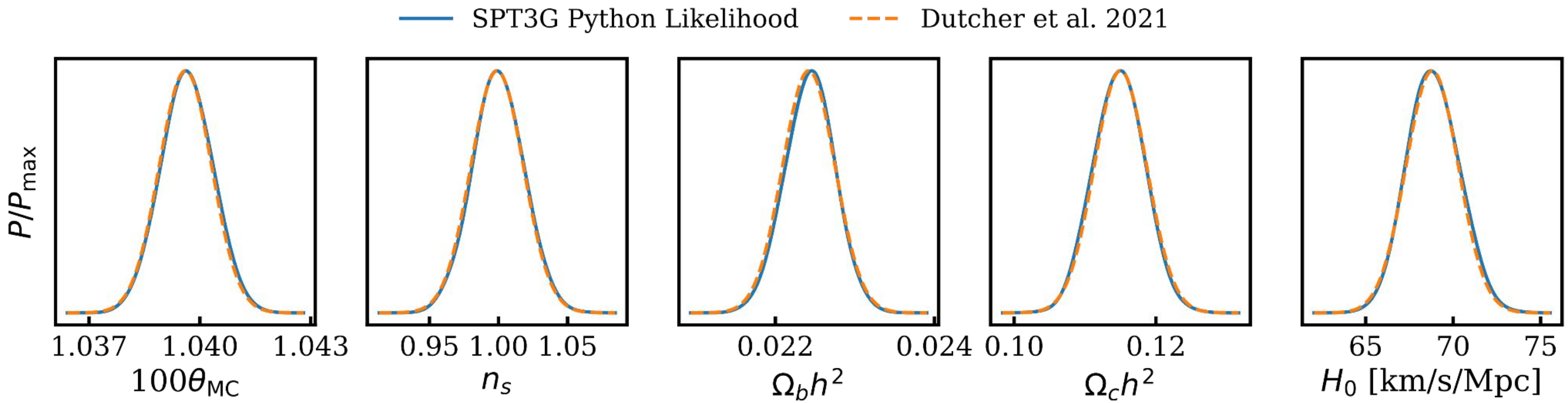
Aiola+ 2020

SPT-3G cosmology

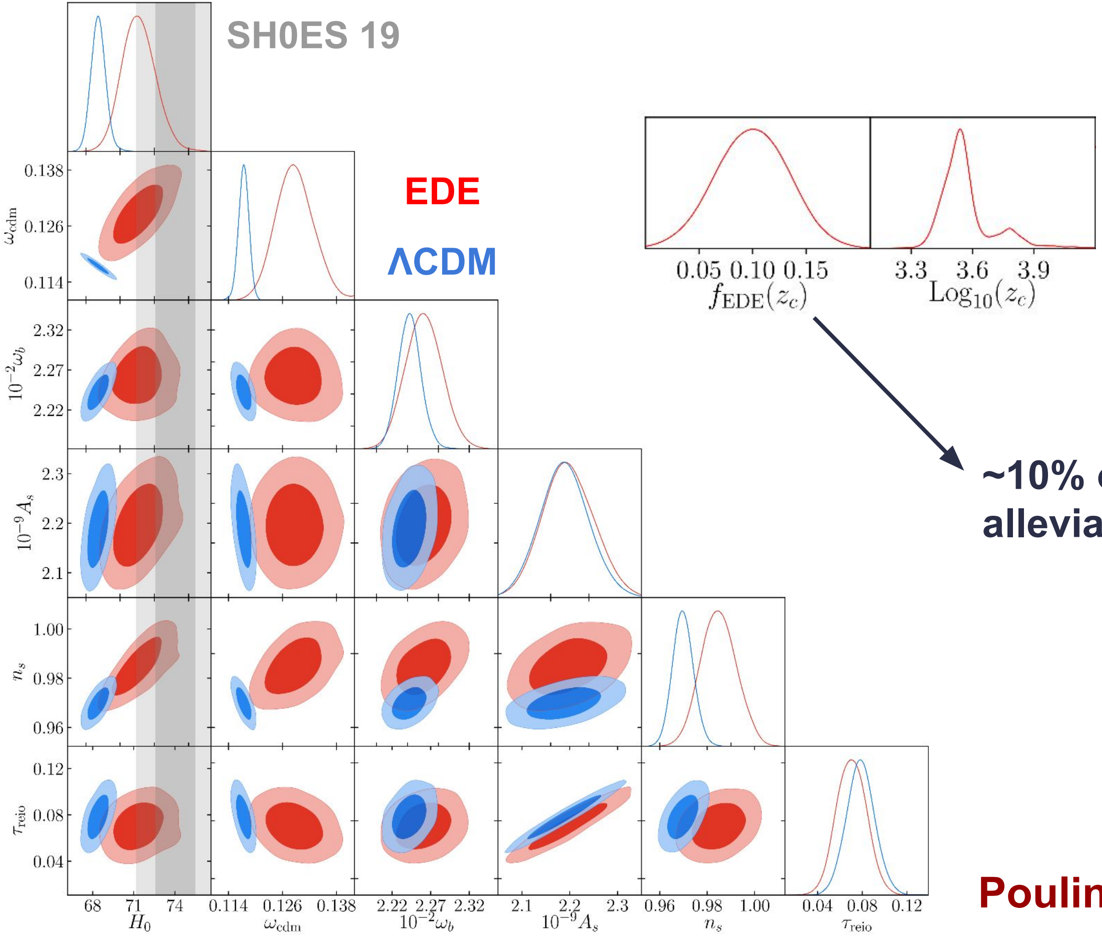


Dutcher+ 2021

SPT-3G python implementation



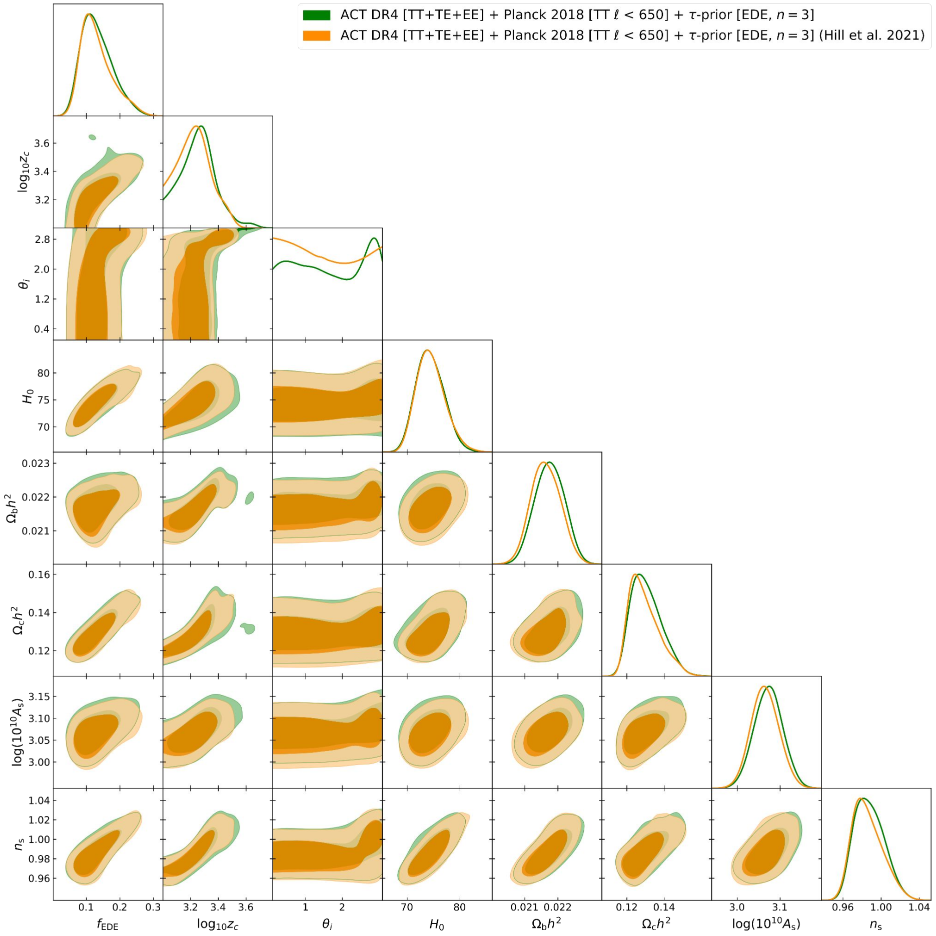
Results for a combination of Planck and SH0ES data



~10% of EDE is required to alleviate the tension

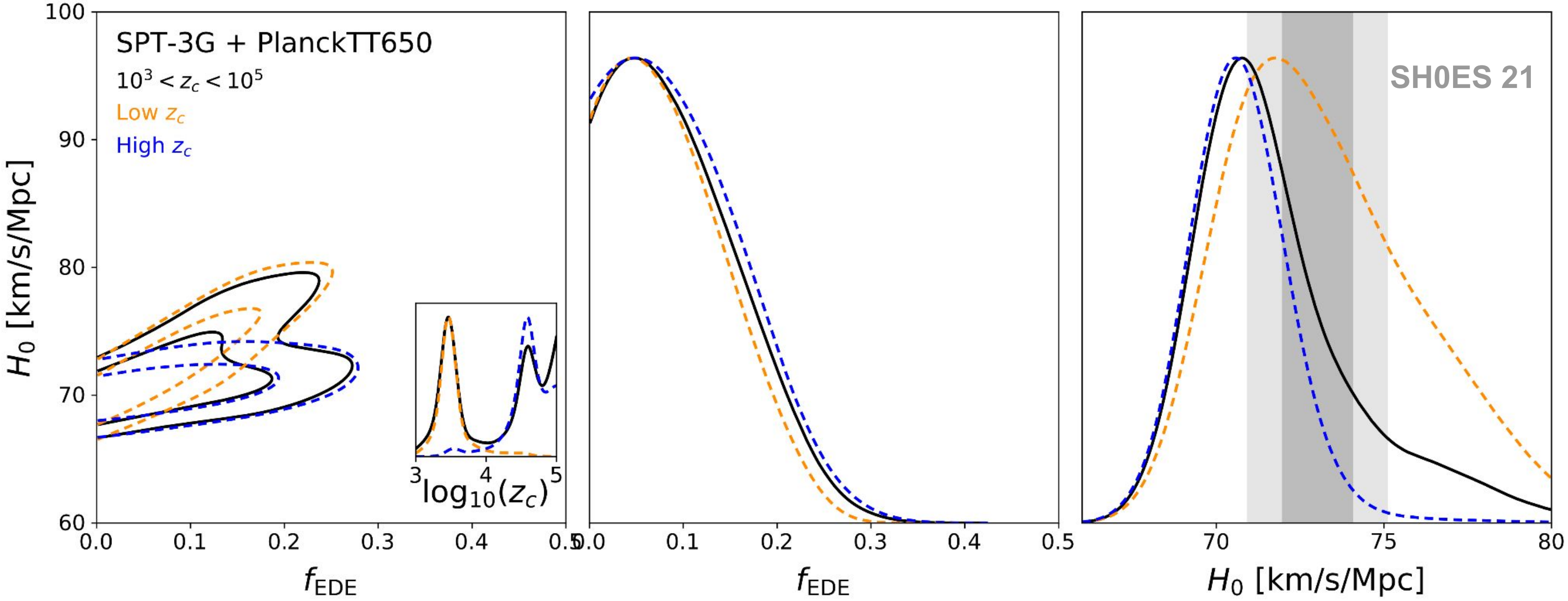
Poulin+2019, Smith+ 2019

CAMB/CLASS EDE models



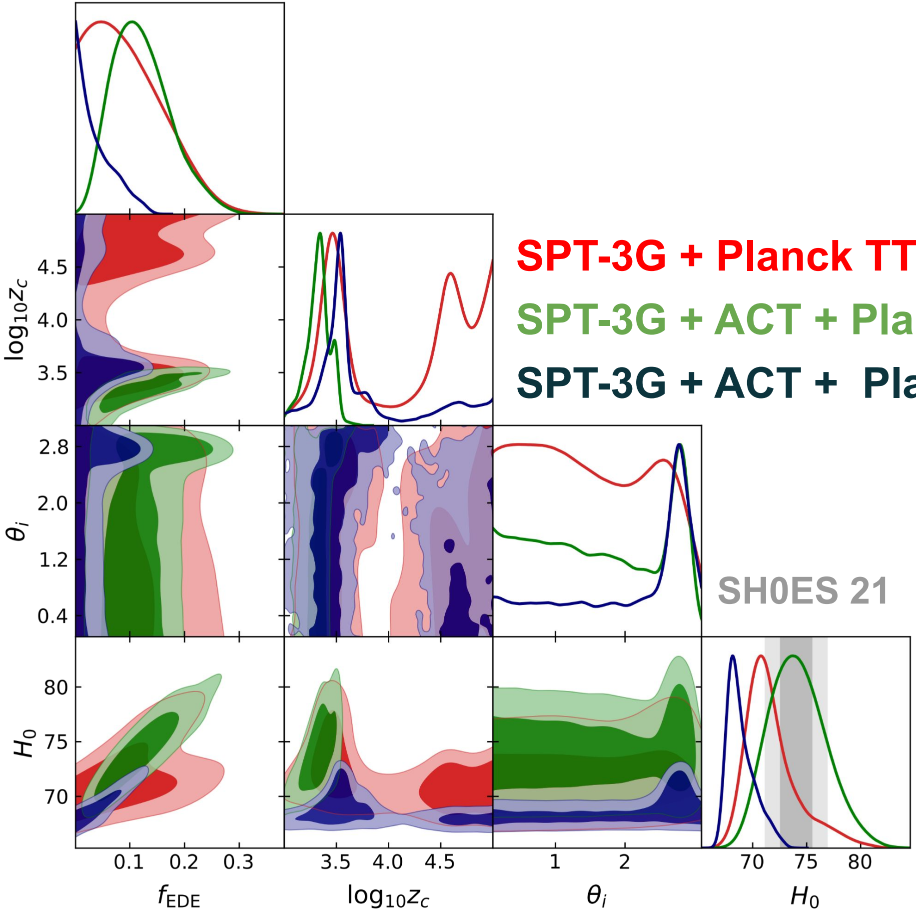
Hill+...La Posta+... 2021

Impact of the z_c prior



La Posta+ 2021 [arXiv:2112.10754]

Combining with other CMB datasets



SPT-3G + Planck TT [ℓ<650]

SPT-3G + ACT + Planck TT [ℓ<650]

SPT-3G + ACT + Planck

La Posta+ 2021 [arXiv:2112.10754]