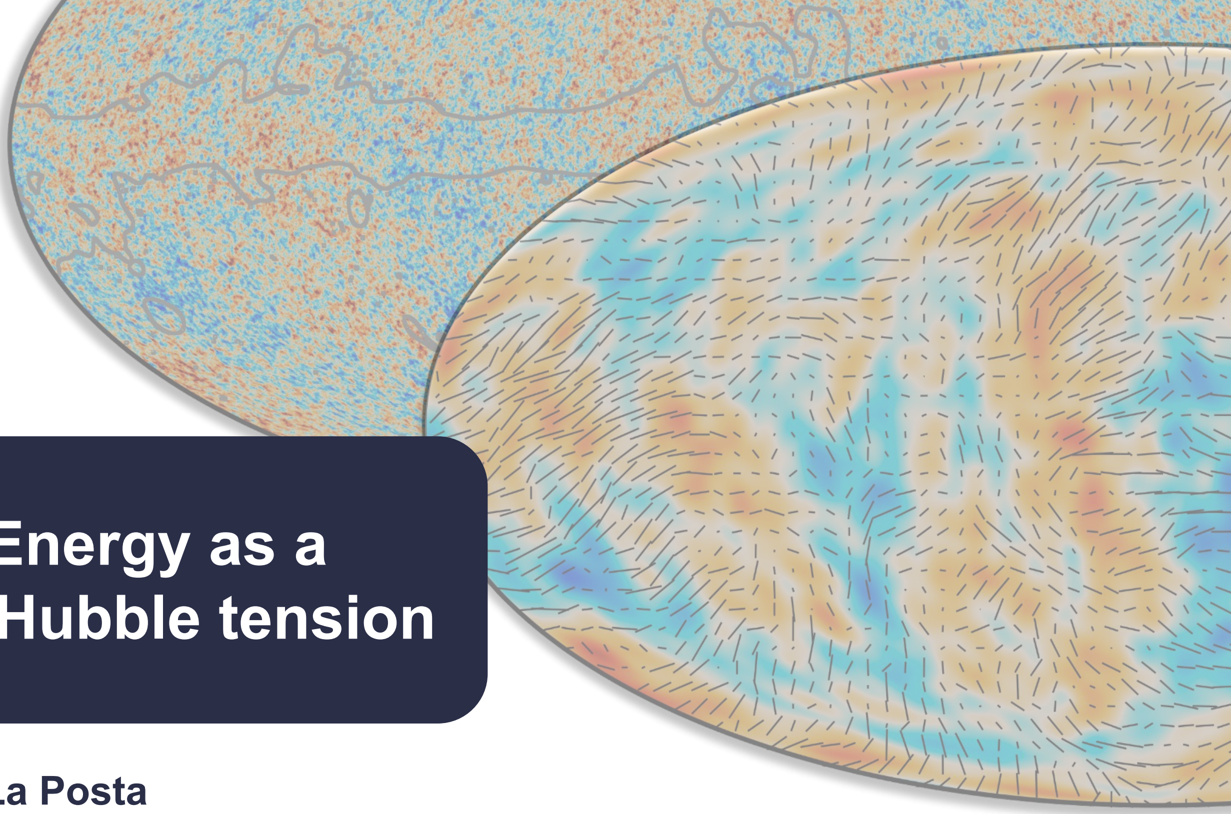


Early Dark Energy as a solution to the Hubble tension

Adrien La Posta
IJClab

link

laposta@ijclab.in2p3.fr

CosPT meeting - 06/12/22

The standard model of cosmology – ΛCDM model

FLRW metric

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

Friedmann equation

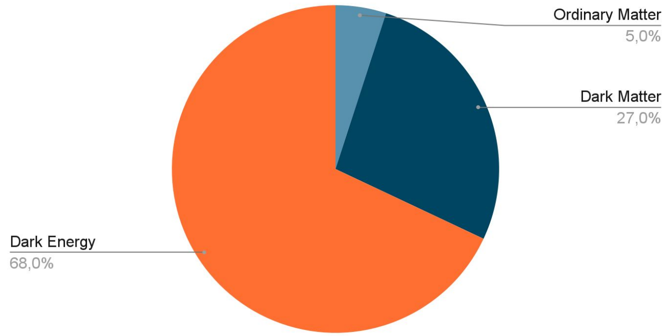
$$H^2(z) = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\left[(\rho_b^0 + \rho_c^0)(1+z)^3 + \rho_r^0(1+z)^4 + \rho_\Lambda\right]$$

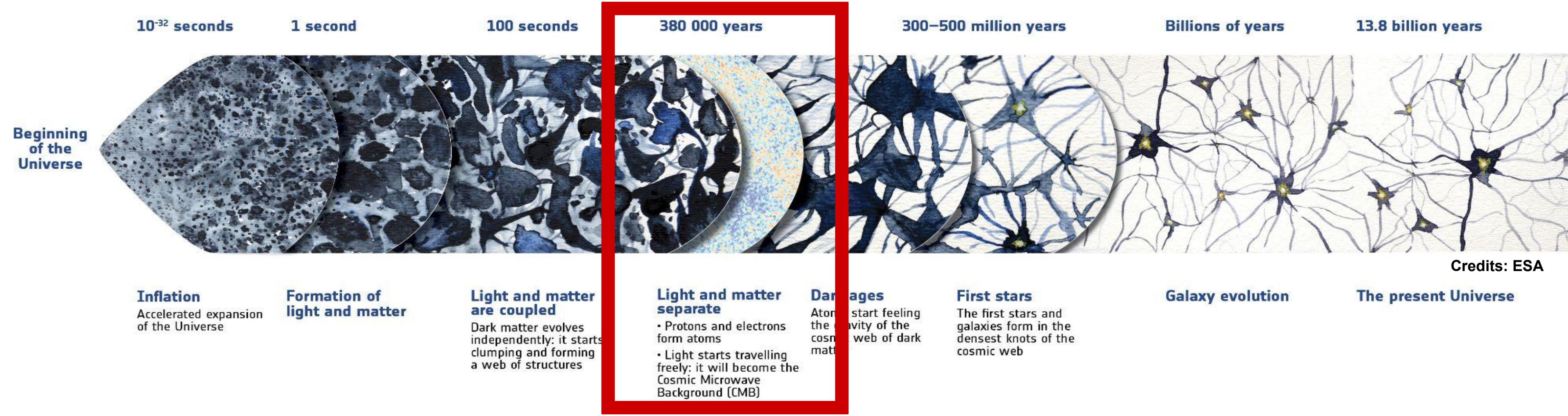
baryon

CDM

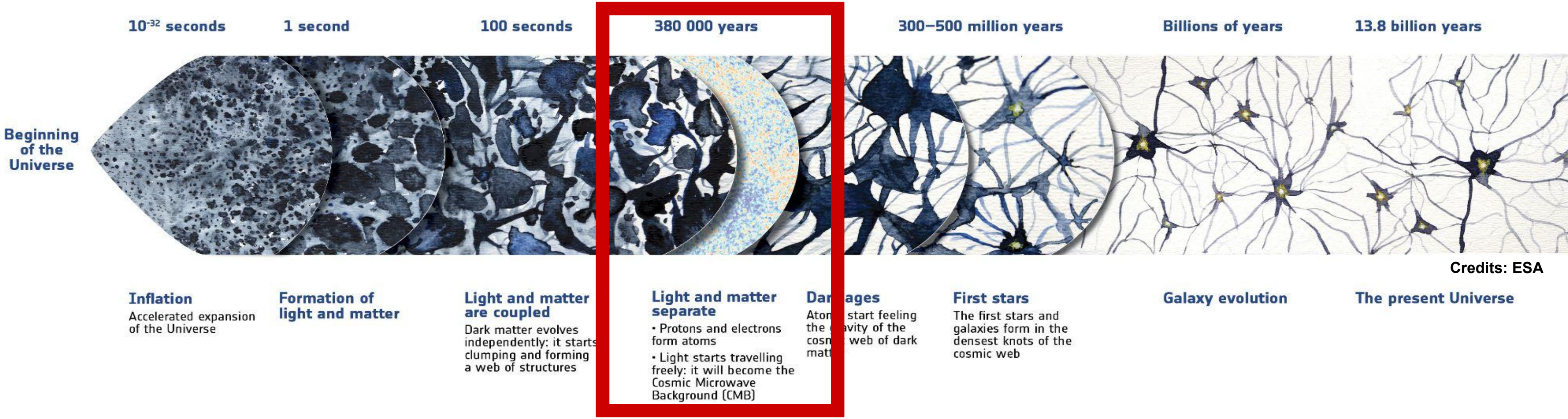
radiation

dark energy

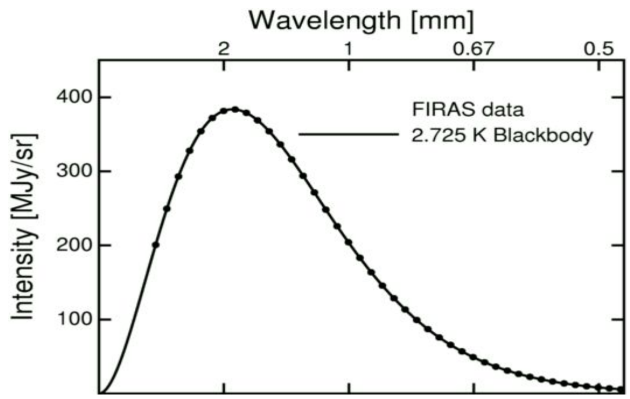



Beginning of the Universe
10^{-32} seconds
Inflation
Accelerated expansion of the Universe
1 second
Formation of light and matter
100 seconds
Light and matter are coupled
Dark matter evolves independently: it starts clumping and forming a web of structures
380 000 years
Light and matter separate
• Protons and electrons form atoms
• Light starts travelling freely: it will become the Cosmic Microwave Background (CMB)
Dar ages
start feeling
the avity of the
web of dark
300–500 million years
First stars
The first stars and galaxies form in the densest knots of the cosmic web
Billions of years
Galaxy evolution
13.8 billion years
The present Universe

Credits: ESA



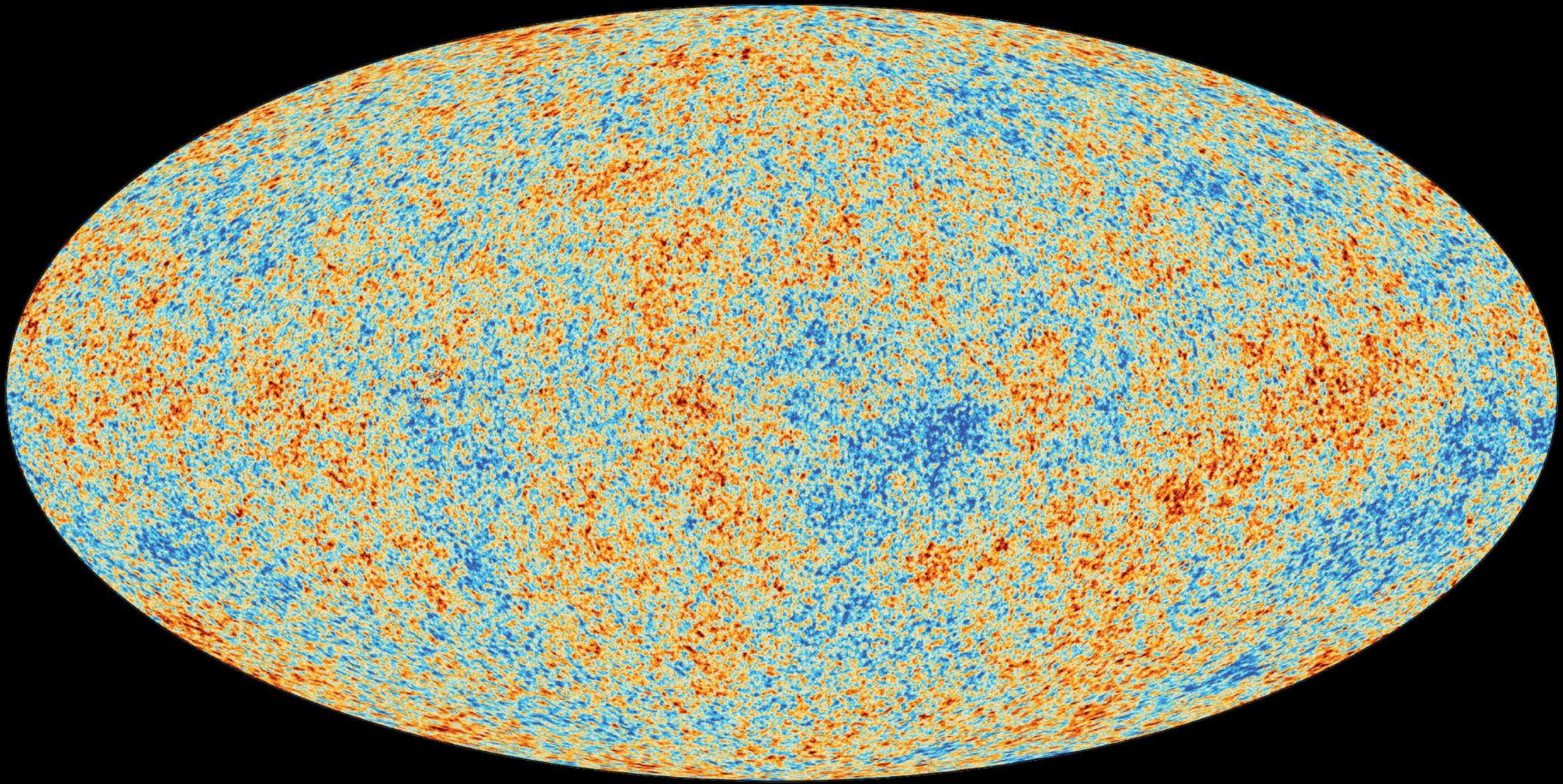
Credits: ESA



Nearly isotropic blackbody spectrum at T = 2.725 K

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

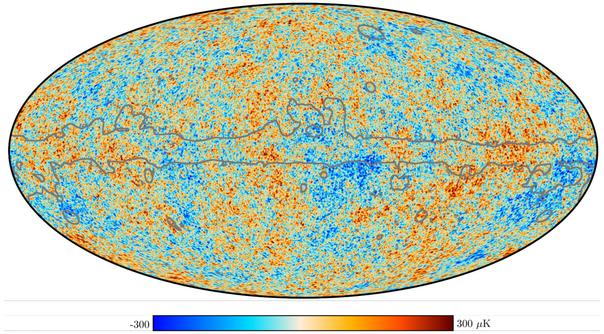
CMB temperature as measured by the Planck satellite



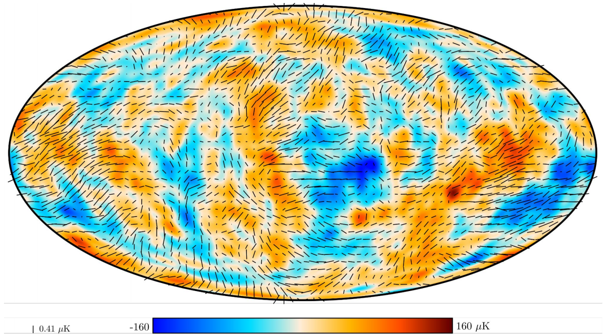
Credits: ESA

Measuring H_0 from the CMB

Temperature



Polarization E-modes



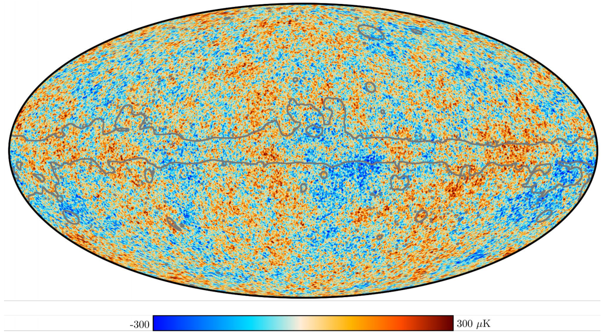
Spherical harmonics

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

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

Measuring H_0 from the CMB

Temperature



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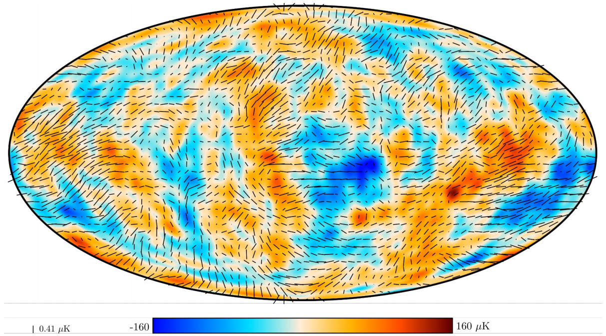
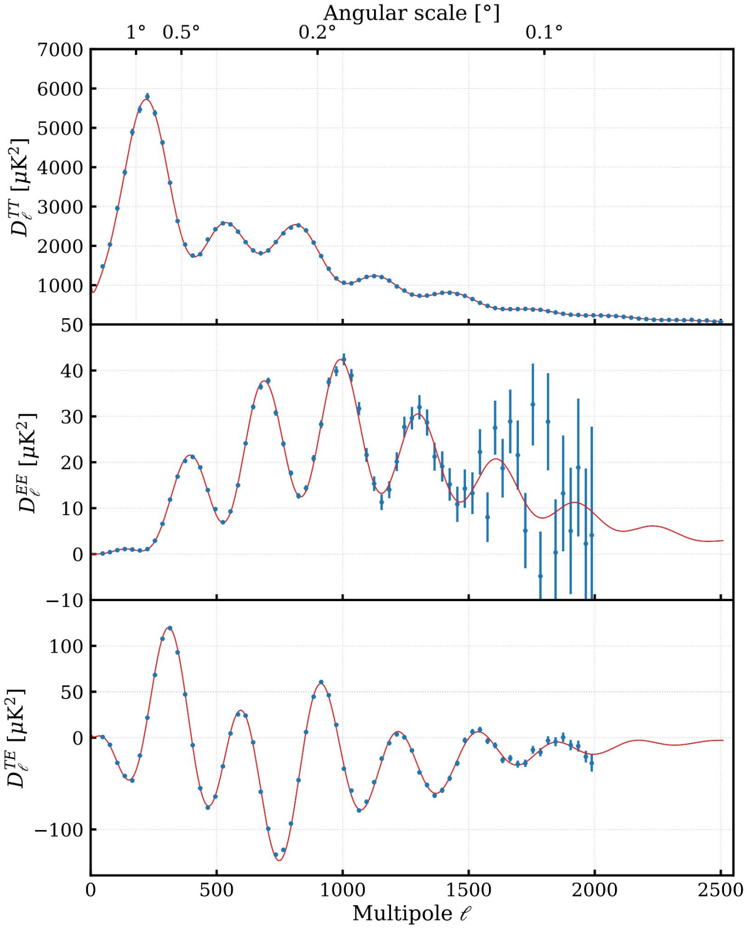
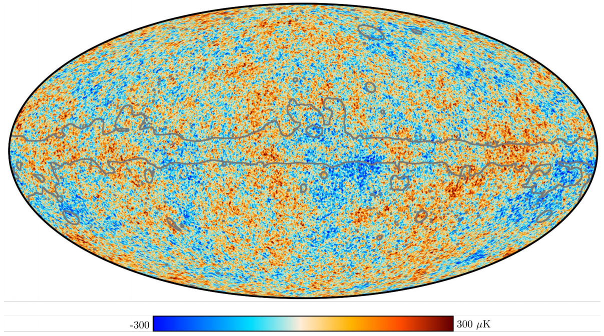


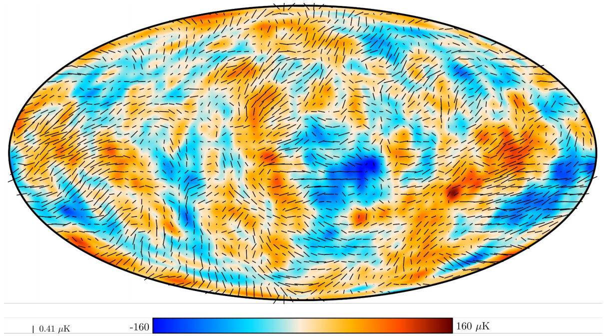


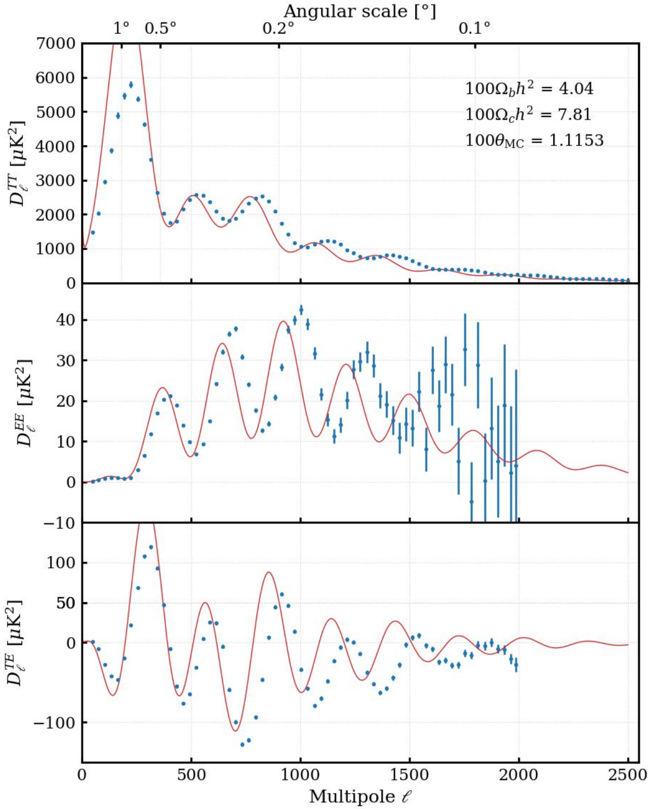
Measuring H_0 from the CMB

Temperature



Polarization E-modes





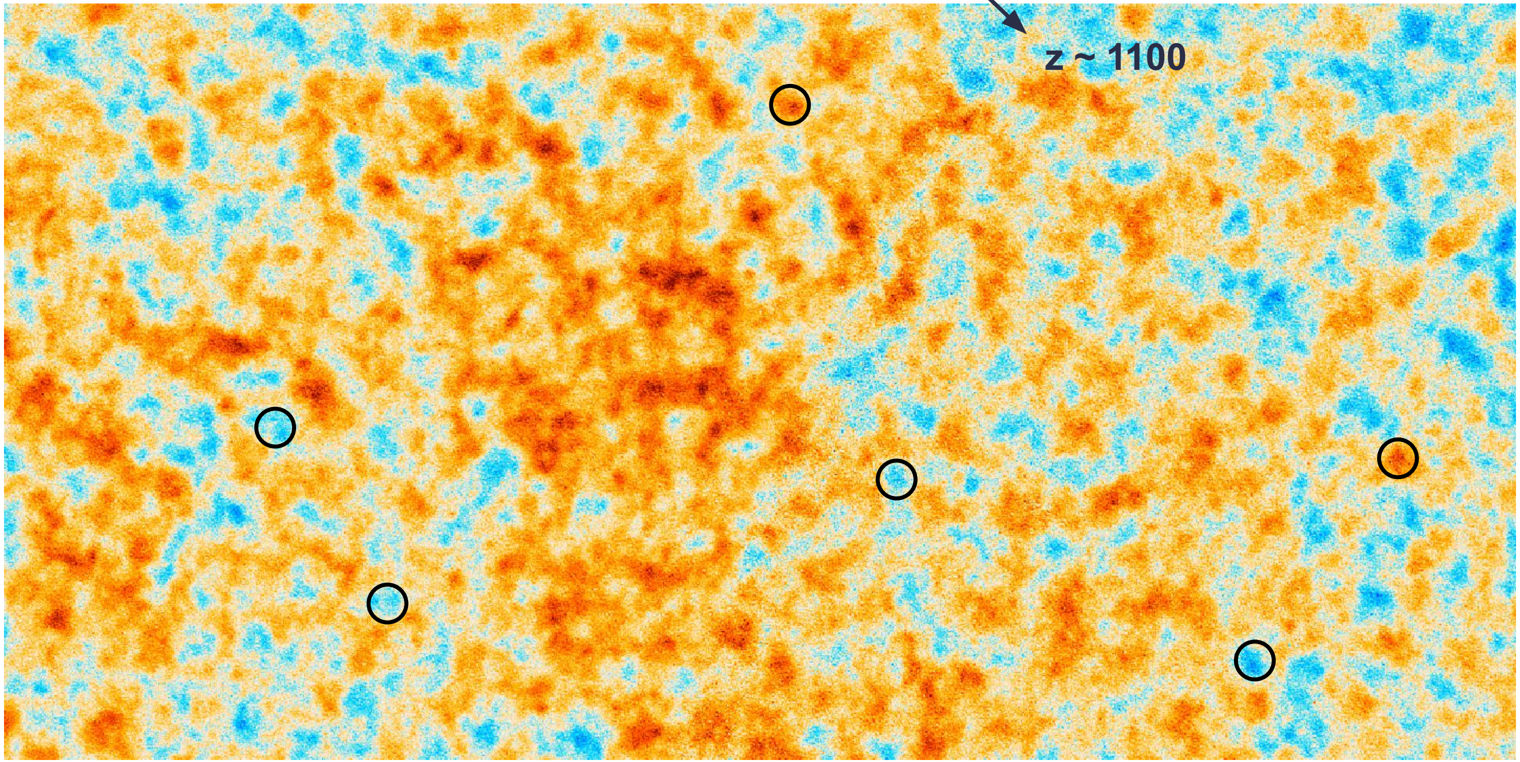
→ $\theta_* \quad \rho_b^0 \quad \rho_c^0$

Measuring H_0 from the CMB

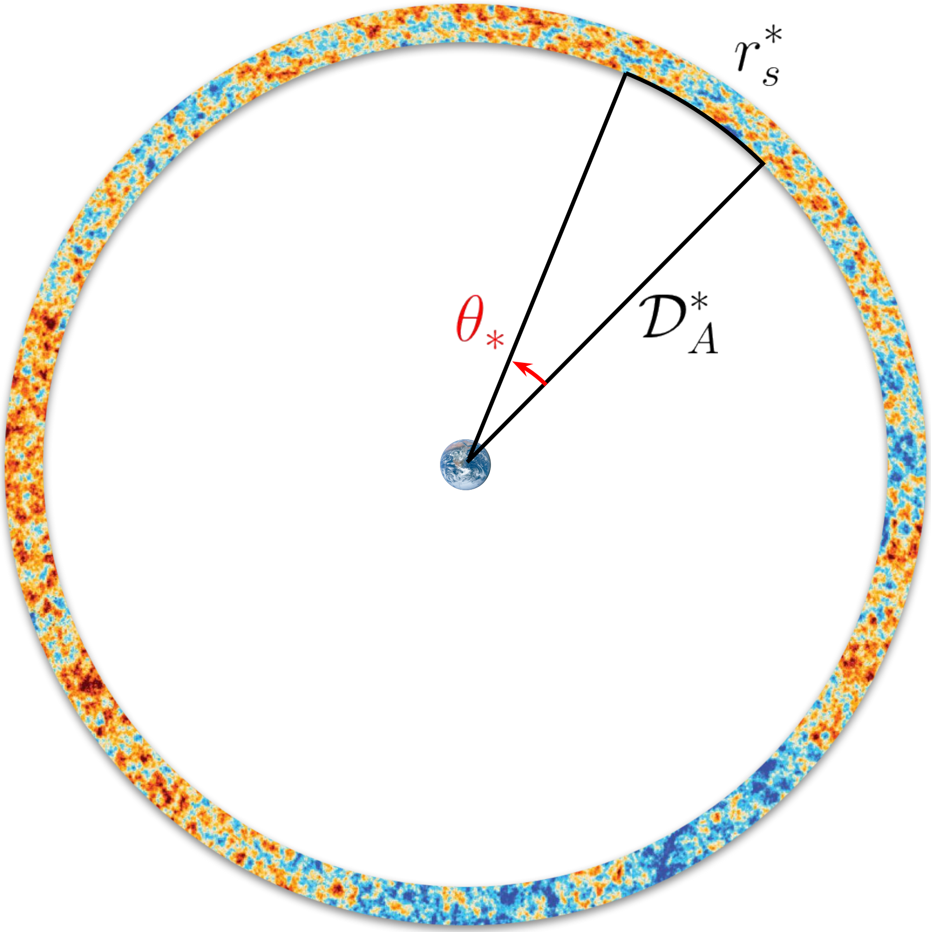
CMB standard ruler : **size of the sound horizon** at **decoupling** imprinted in the CMB radiation

Measuring H_0 from the CMB

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

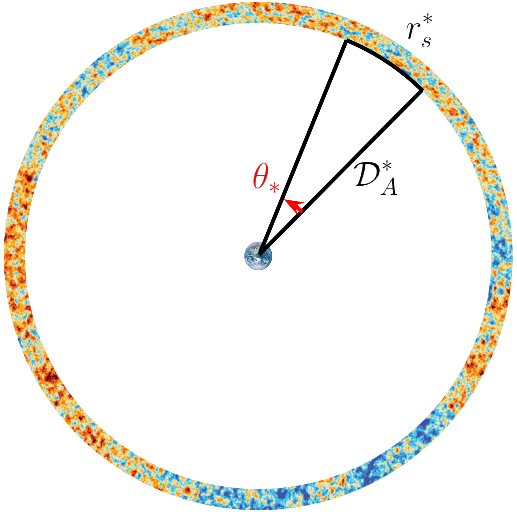


How to measure H_0 from the CMB ?



How to measure H_0 from the CMB ?

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



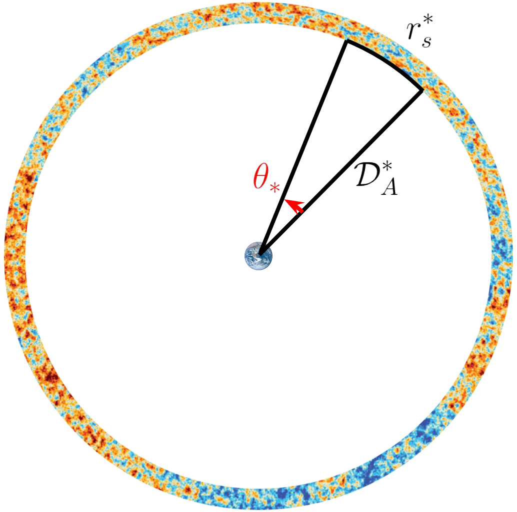
How to measure H_0 from the CMB ?

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

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

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

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



How to measure H_0 from the CMB ?

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

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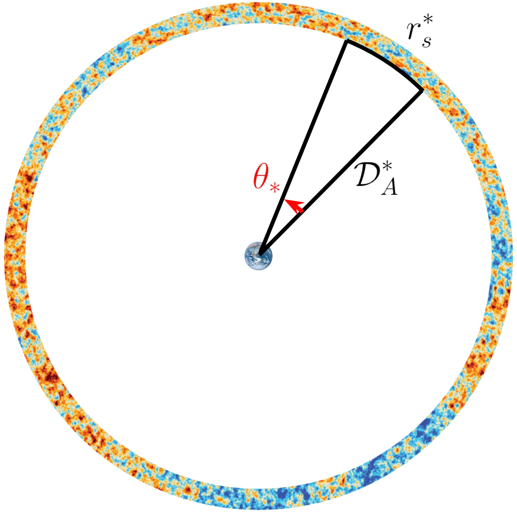

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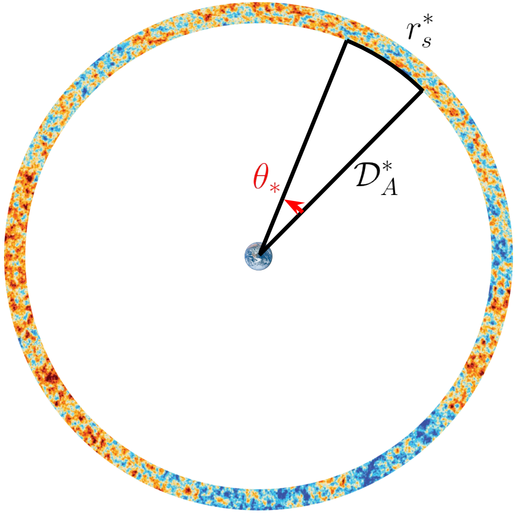
$$\mathcal{D}_A^* = c \int_0^{z^*} \frac{dz}{H(z)}$$



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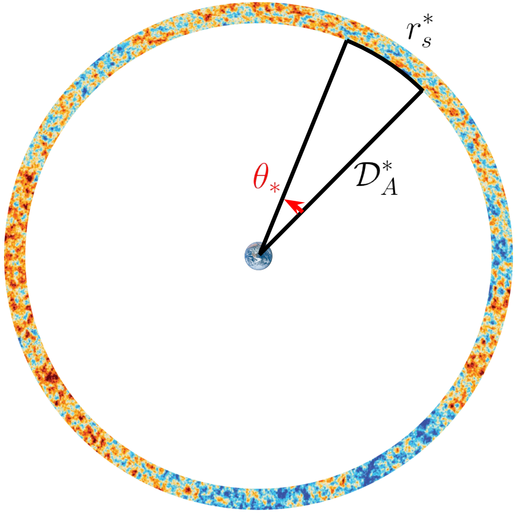
$$H_{\text{late}}^2(z) = \frac{8\pi G}{3}\left[(\rho_b^0 + \rho_c^0)(1+z)^3 + \rho_\Lambda\right]$$



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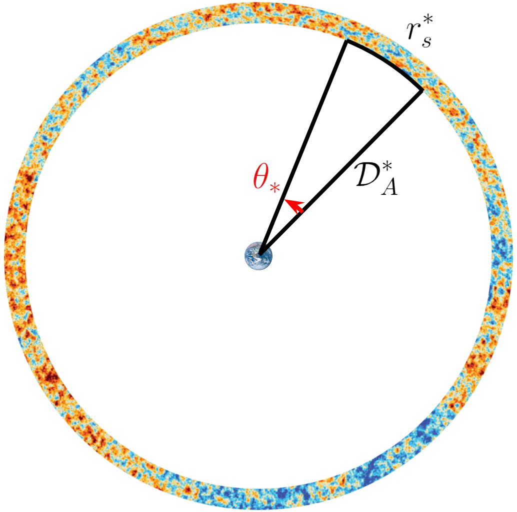
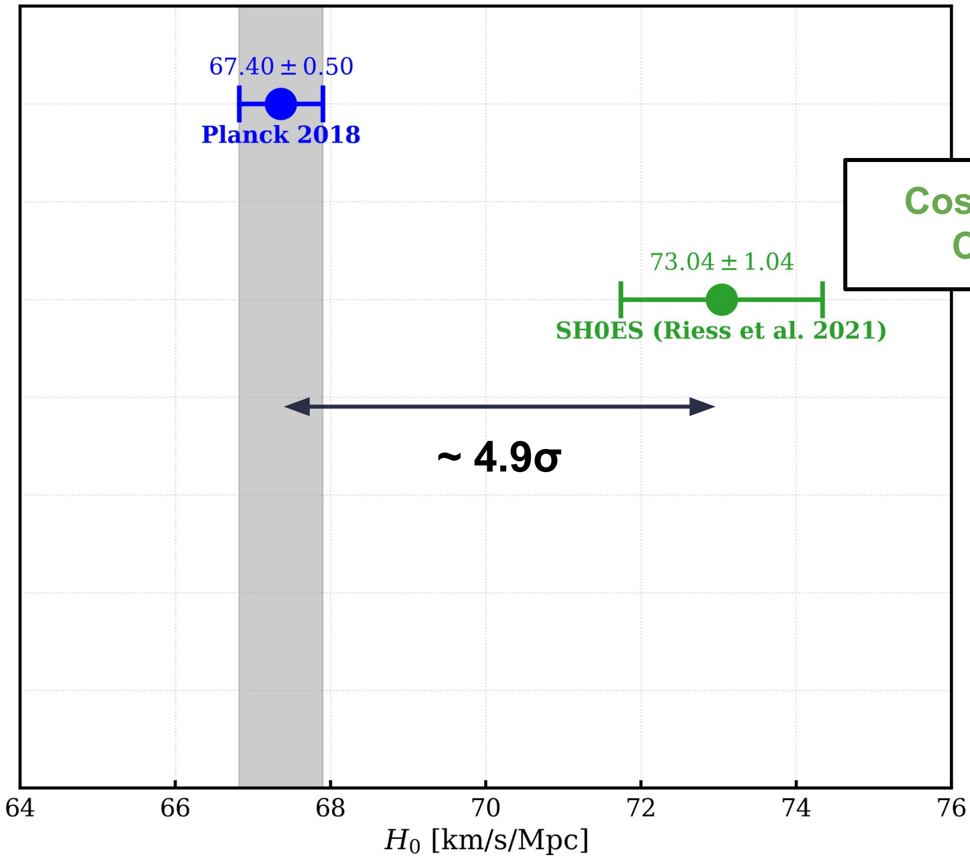
$$H_{\rm late}^2(z) = \frac{8\pi G}{3}\left[(\rho_b^0 + \rho_c^0)(1+z)^3 + \rho_\Lambda\right]$$

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

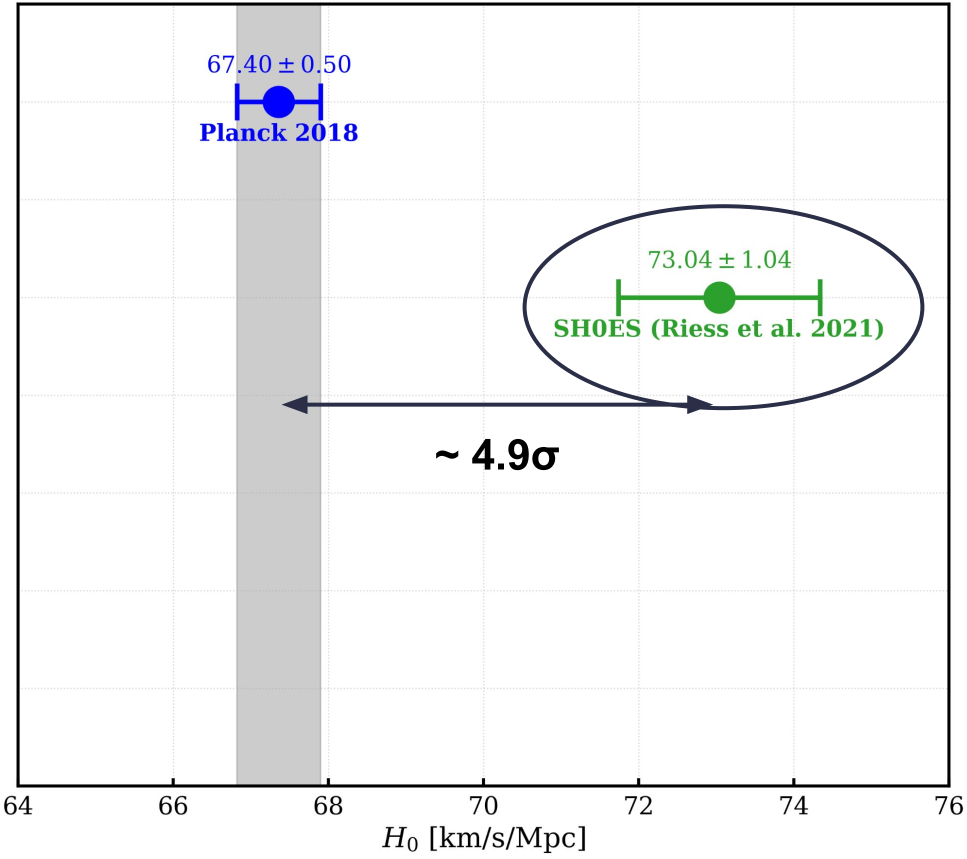


The Hubble tension as of today



Cosmic distance ladder using Cepheid calibrated SNIA

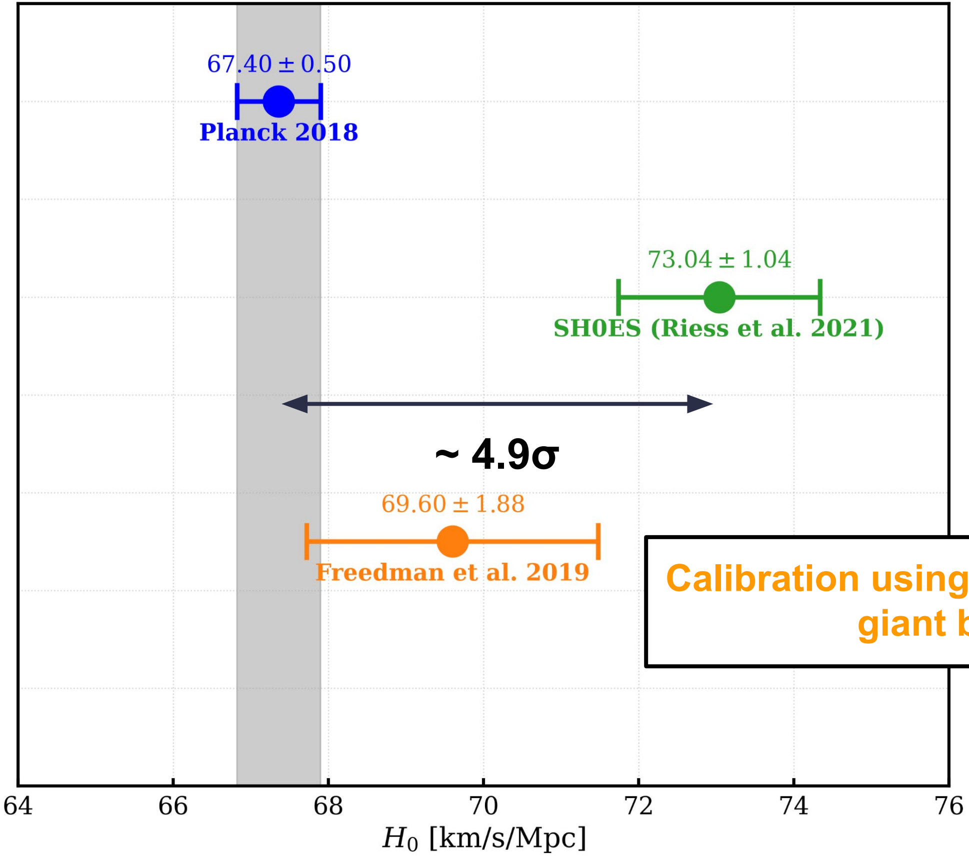
The Hubble tension as of today



Option 1

Astrophysical biases affecting the local measurement of H_0

The Hubble tension as of today

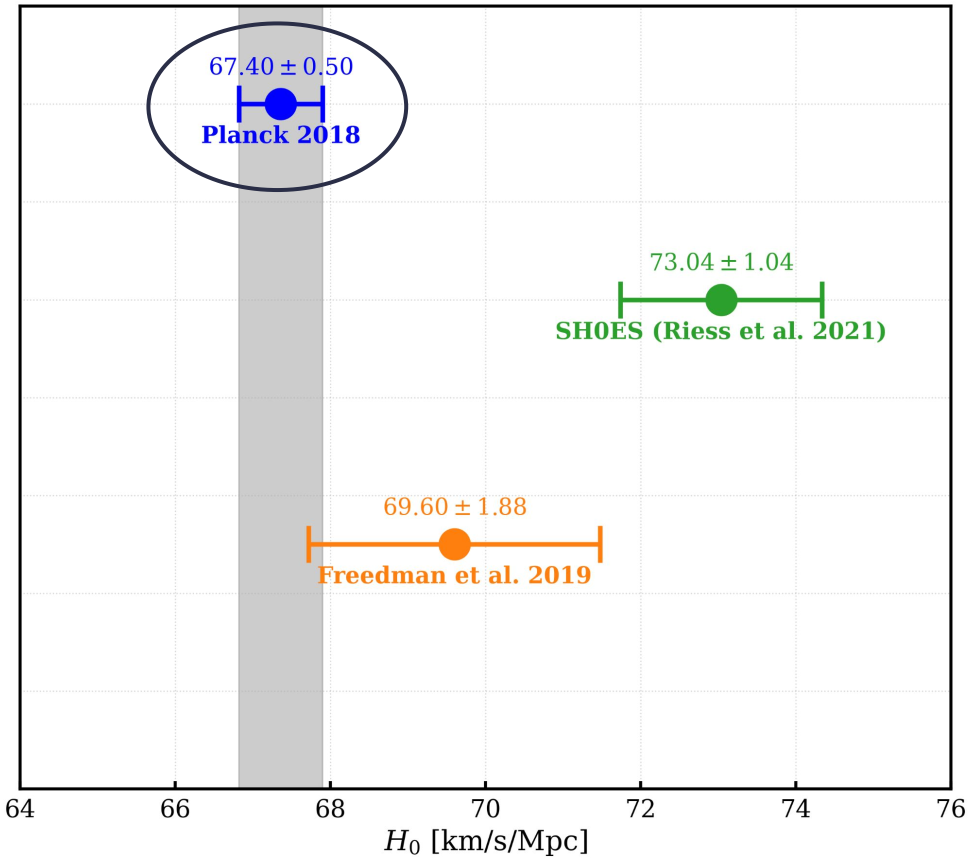


Option 1

Astrophysical biases affecting the local measurement of H_0

Calibration using the tip of the red giant branch

The Hubble tension as of today



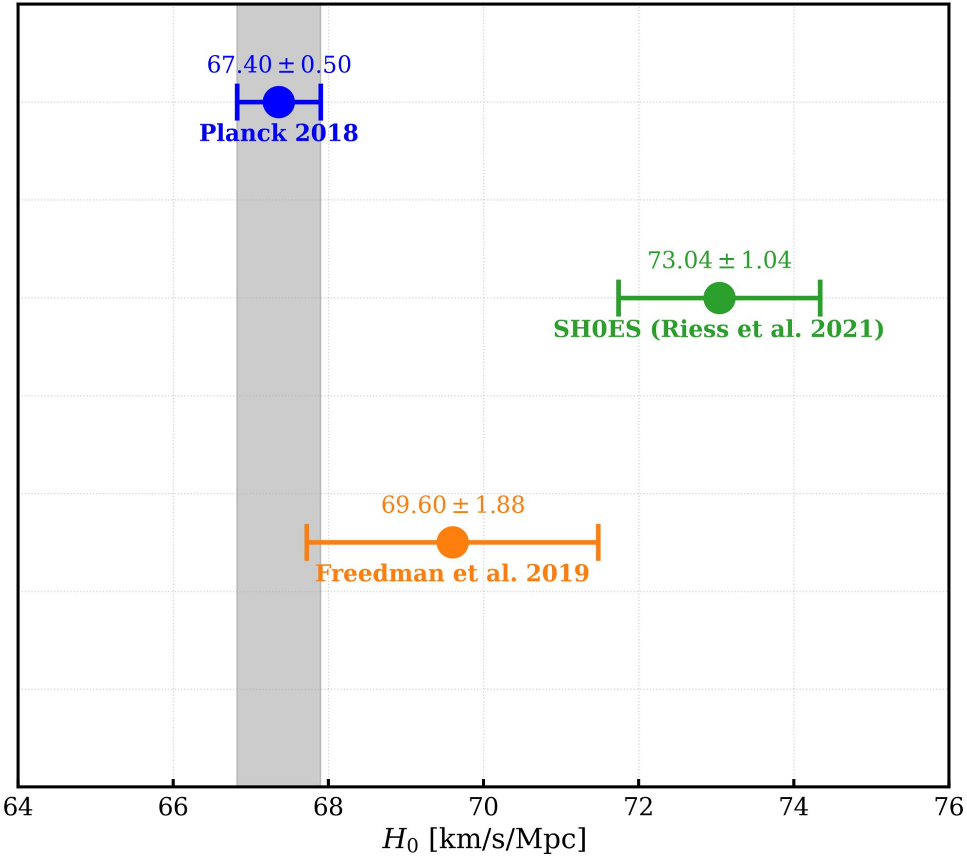
Option 1

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

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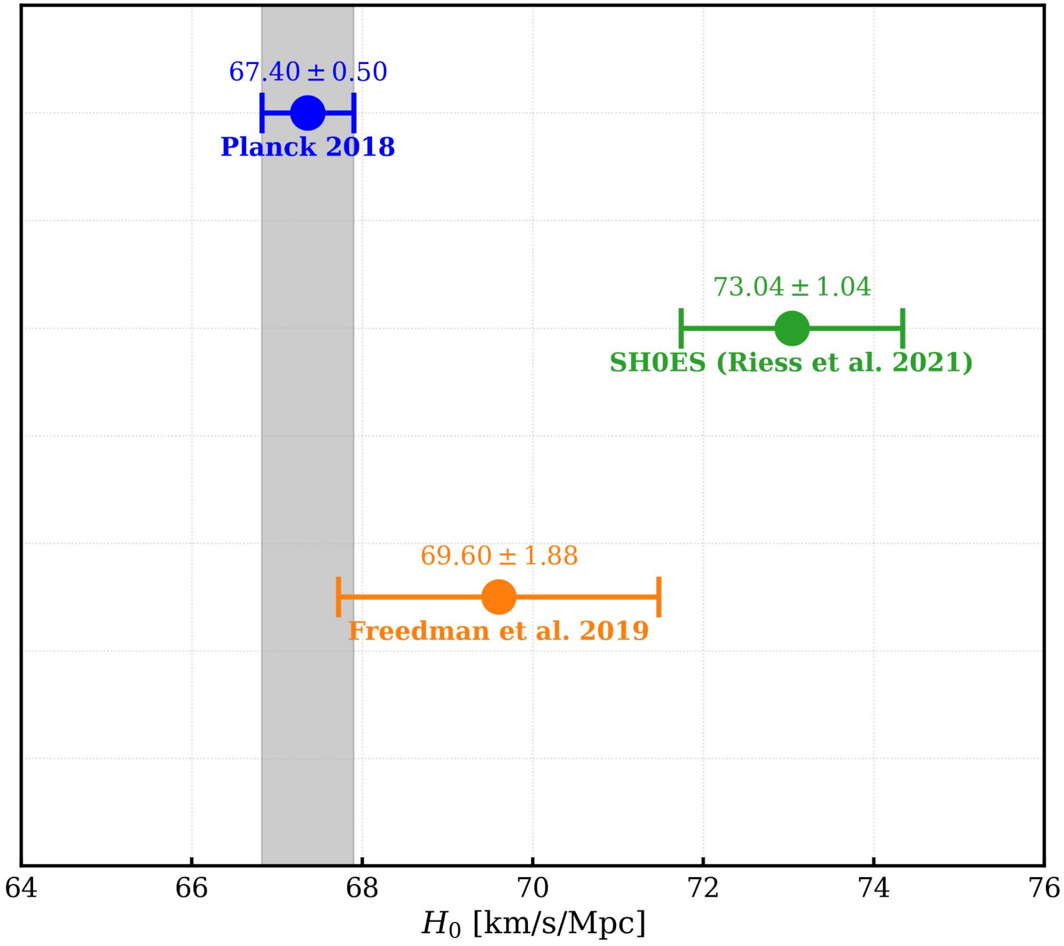
Instrumental systematic effect biasing the value of H_0 inferred from the CMB

Option 3

Physics beyond ΛCDM



Option 1

Astrophysical biases affecting the local measurement of H_0

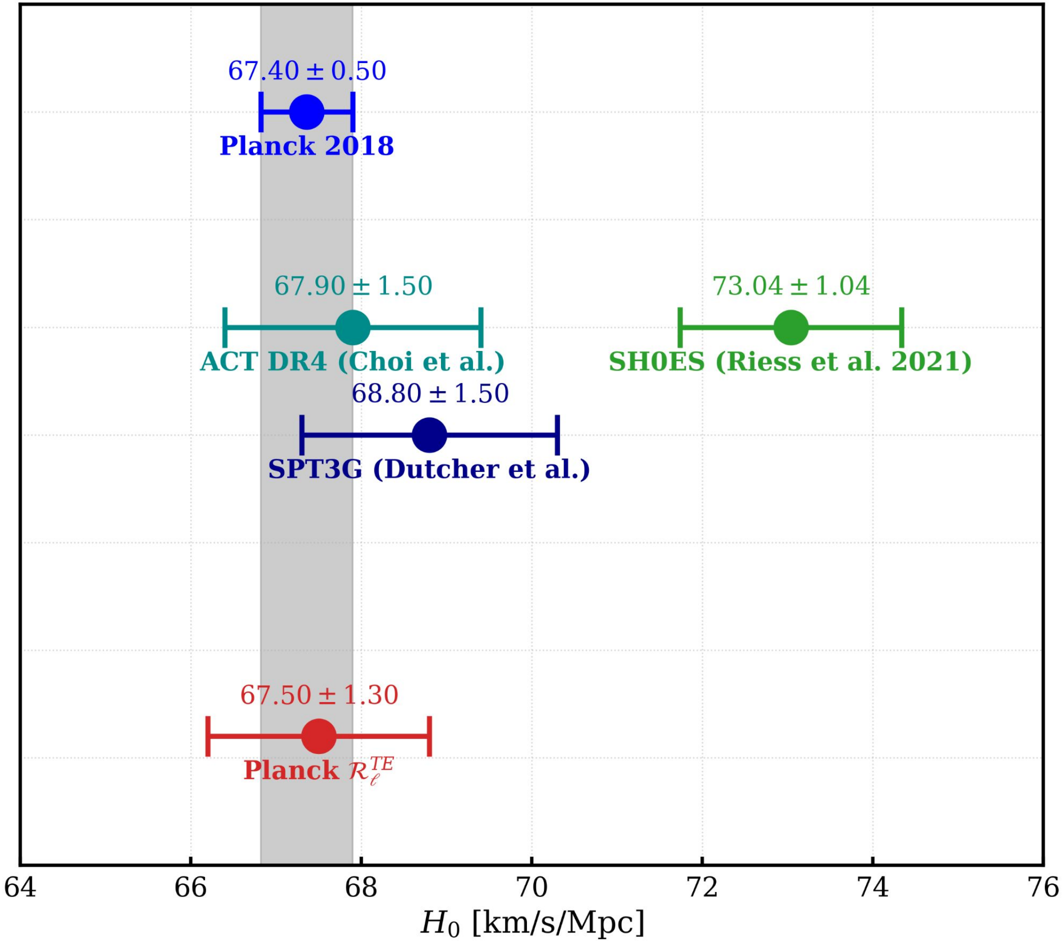
Option 2

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

Option 3

Physics beyond ΛCDM

Independent measurements of H_0 from the ground



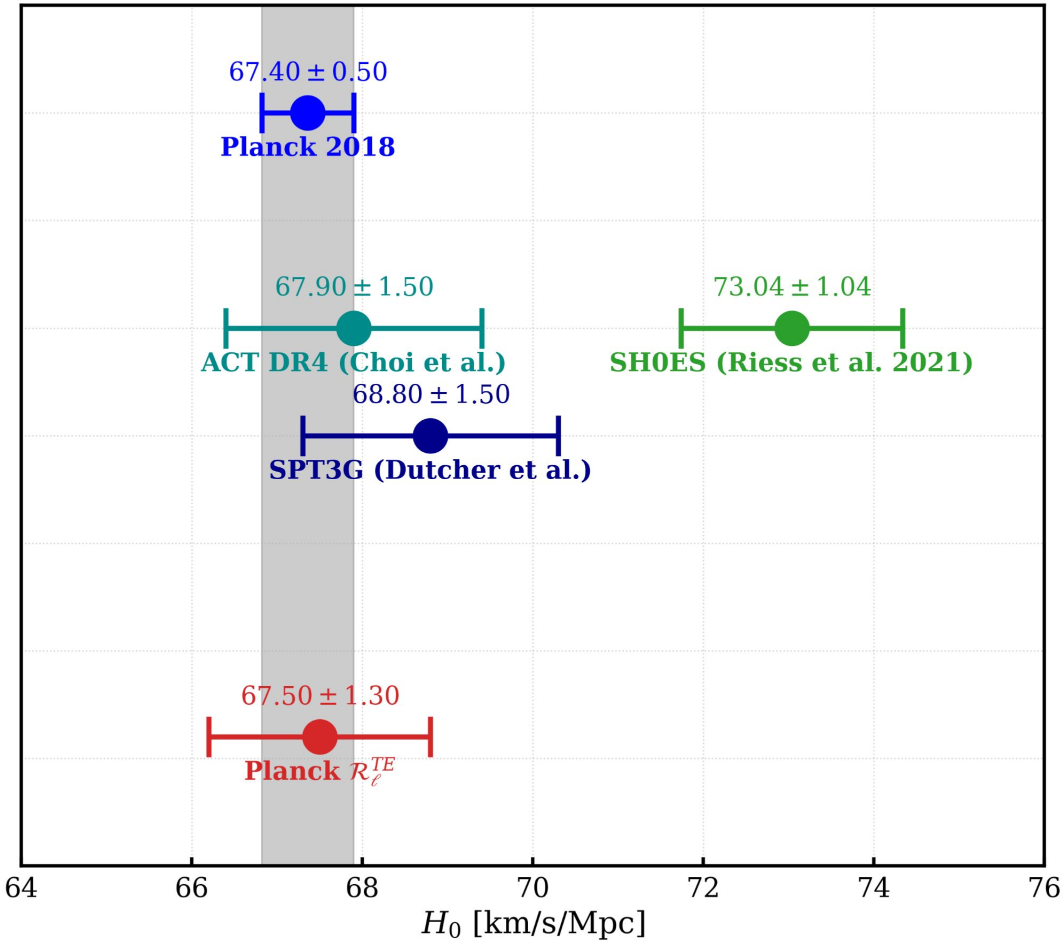
Option 2

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

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

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

Fixed by observations

One proposed solution : Early Dark Energy

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

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

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

θ_* → **Fixed by observations**

EDE phenomenology

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

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

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

axion-like potential

EDE phenomenology

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m : mass parameter

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f : decay constant

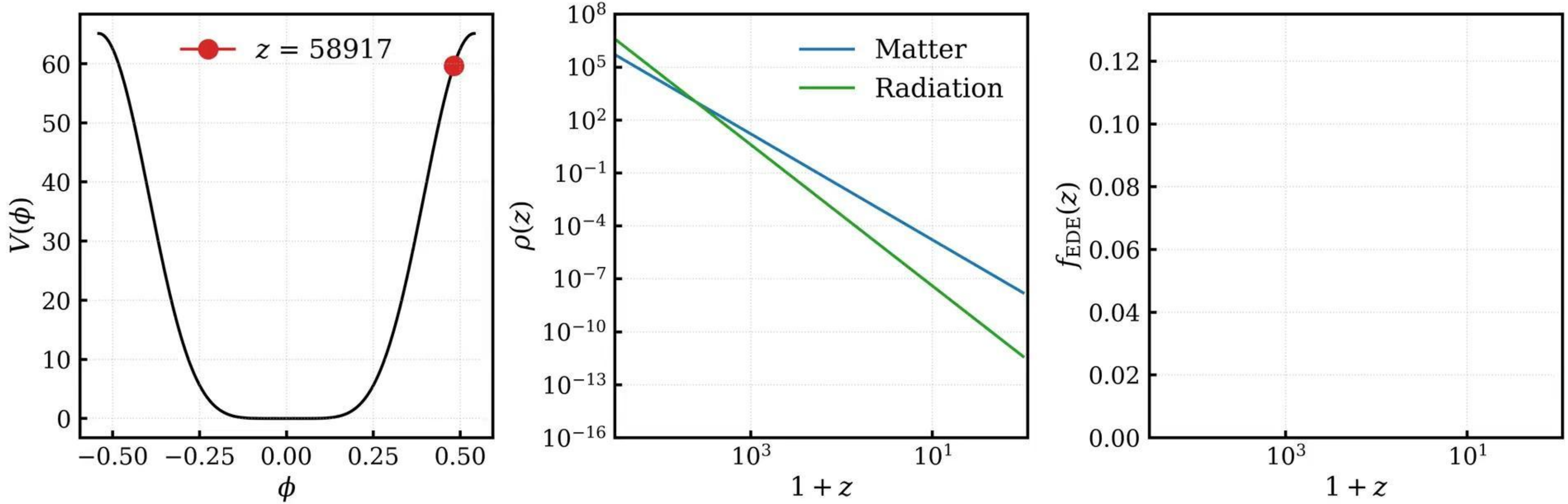
ϕ_i : initial field value

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)



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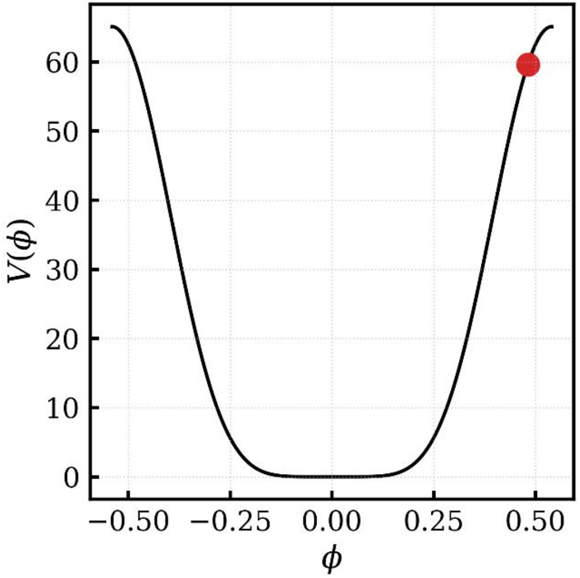
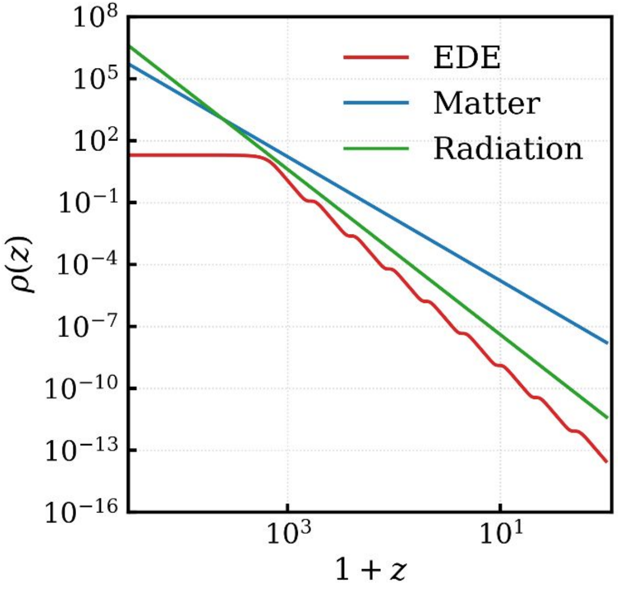
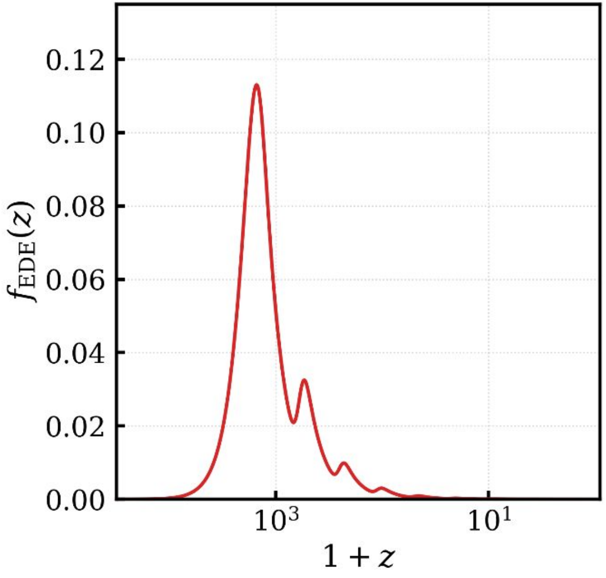




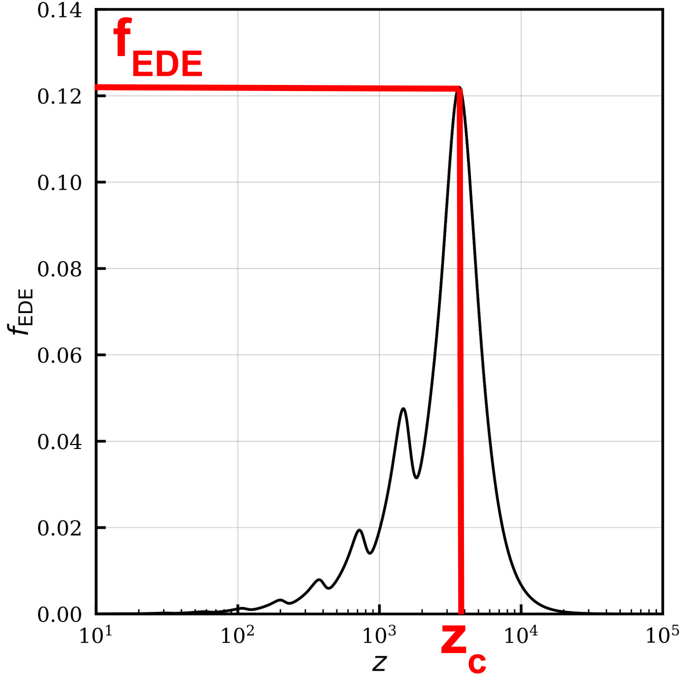


Early Dark Energy : phenomenological parametrization

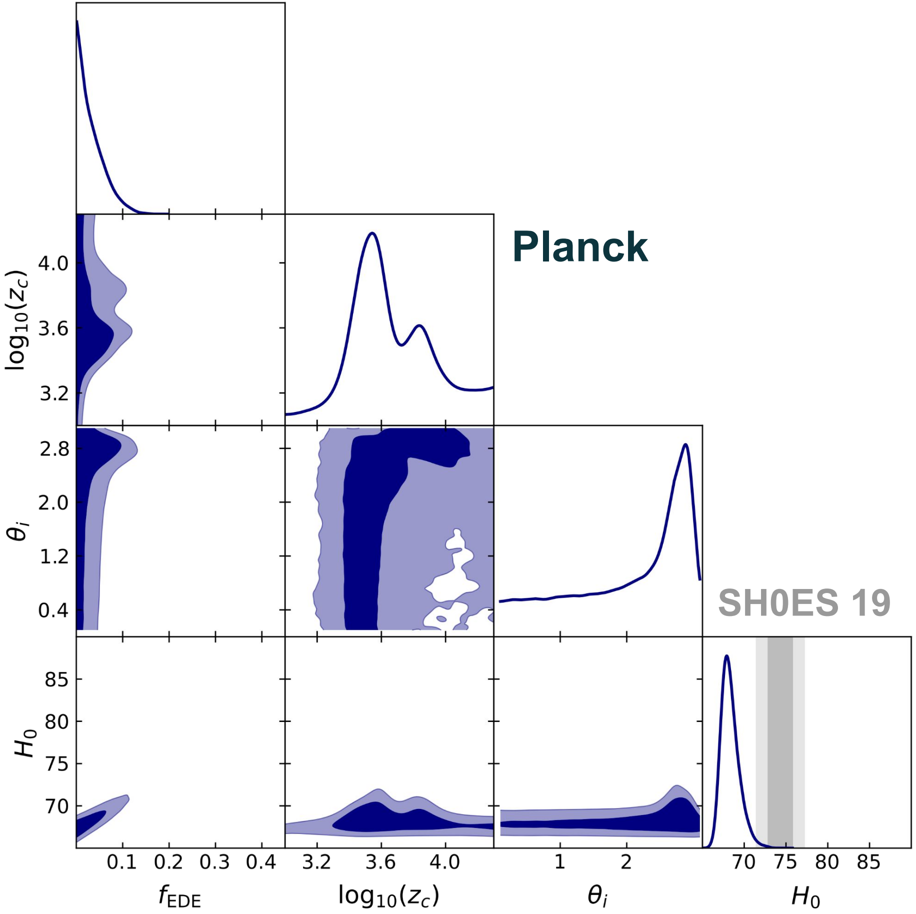
$$(m, f, \phi_i) \longrightarrow (f_{\mathrm{EDE}}, z_c, \phi_i)$$

Field parameters

Phenomenological parametrization

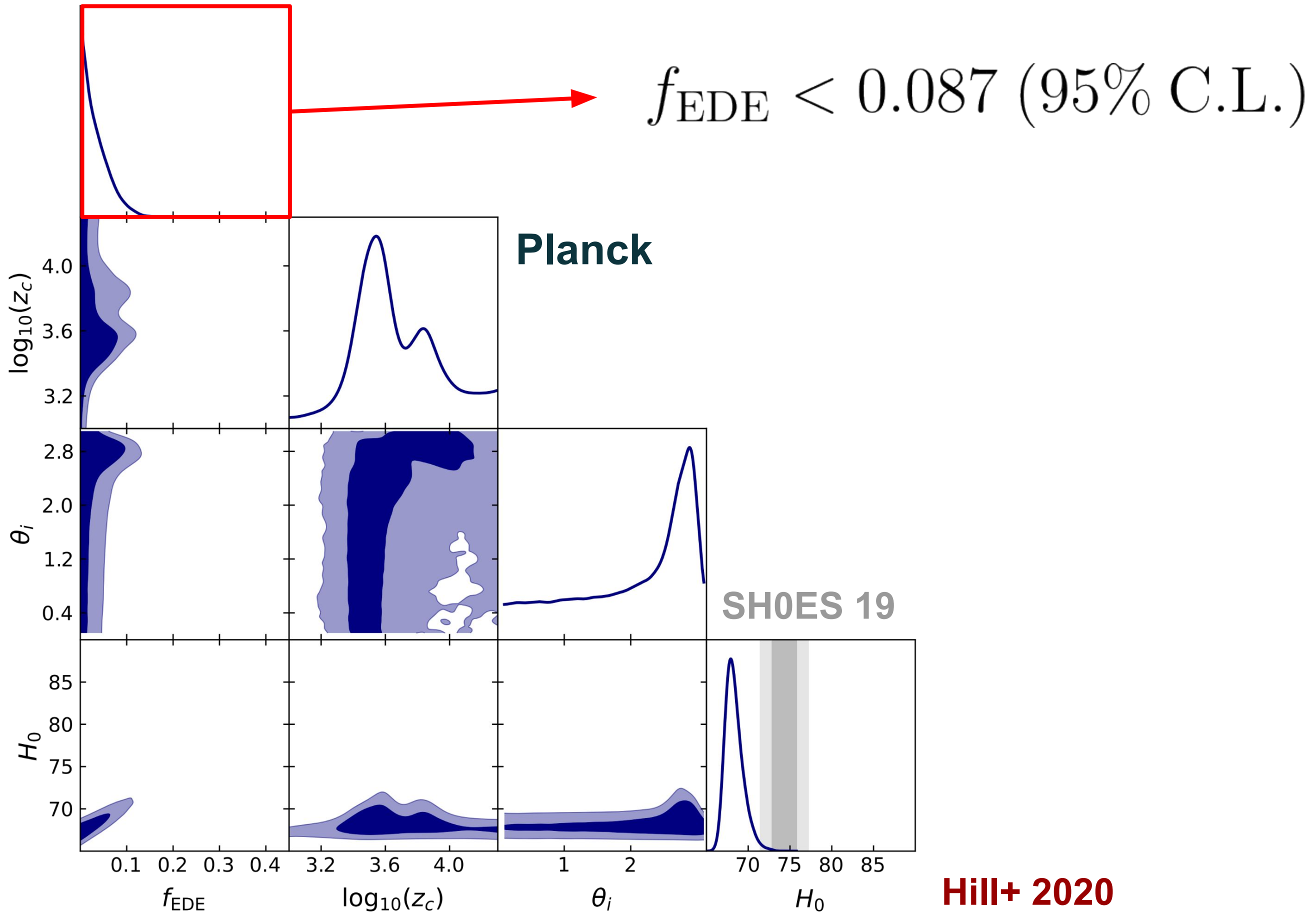


Constraints on EDE from Planck data



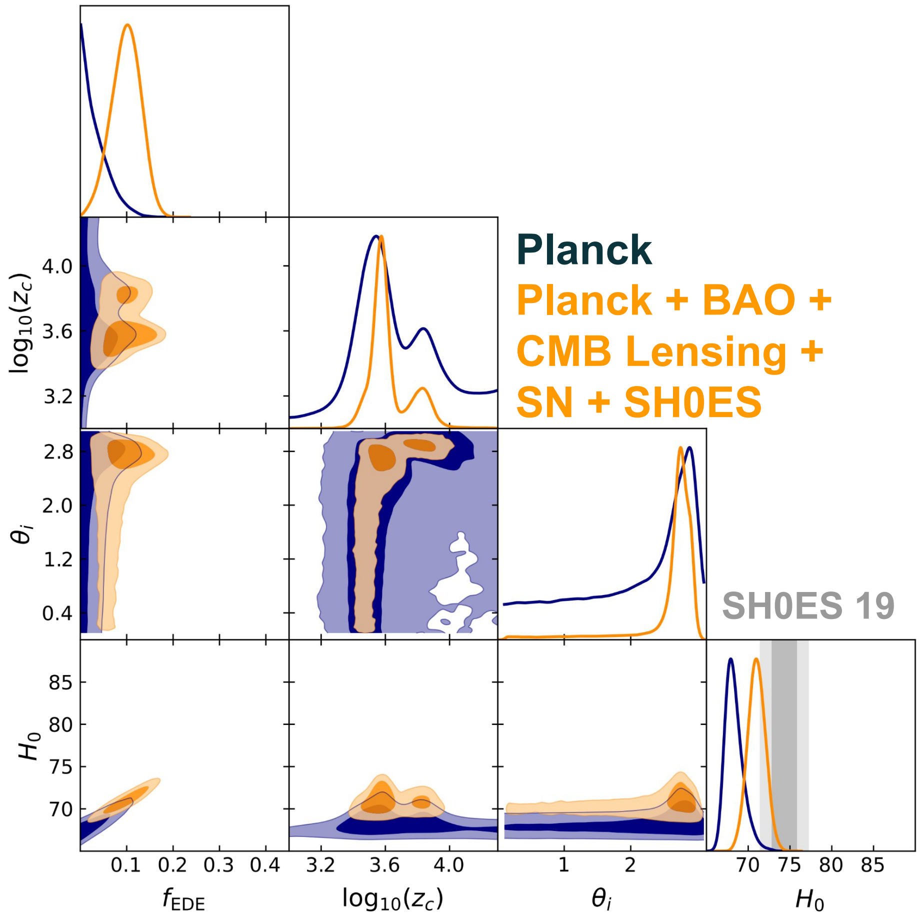
Hill+ 2020

Constraints on EDE from Planck data



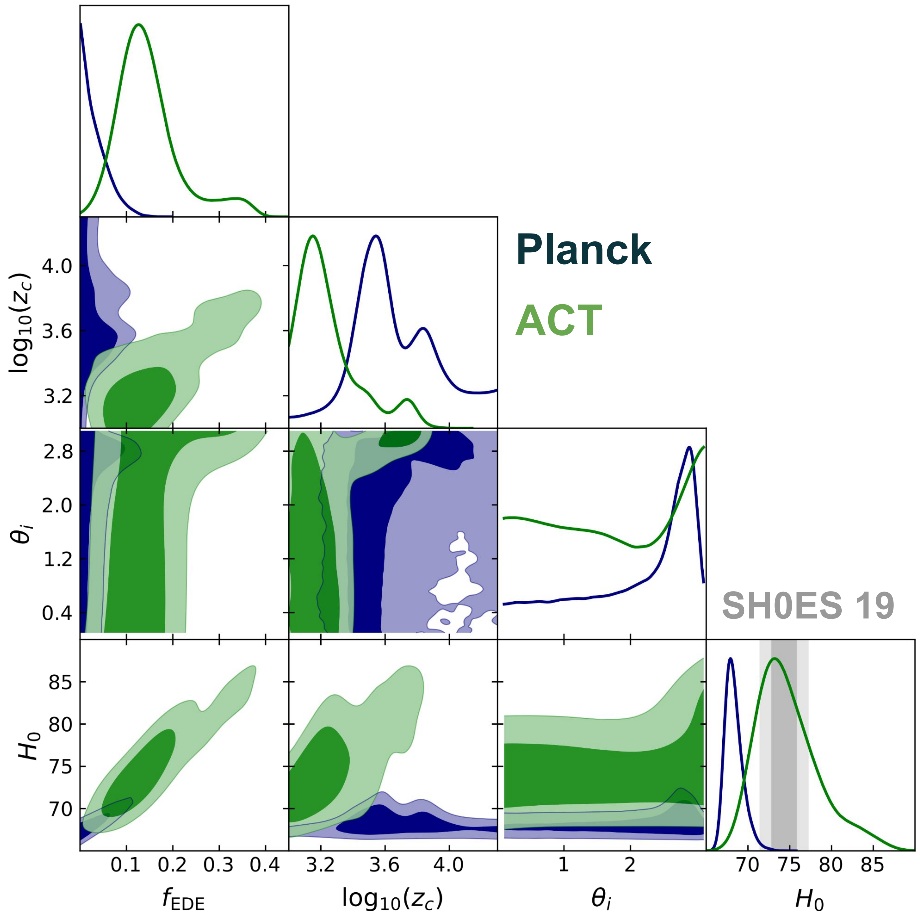
Hill+ 2020

Results for a combination of Planck and SH0ES data



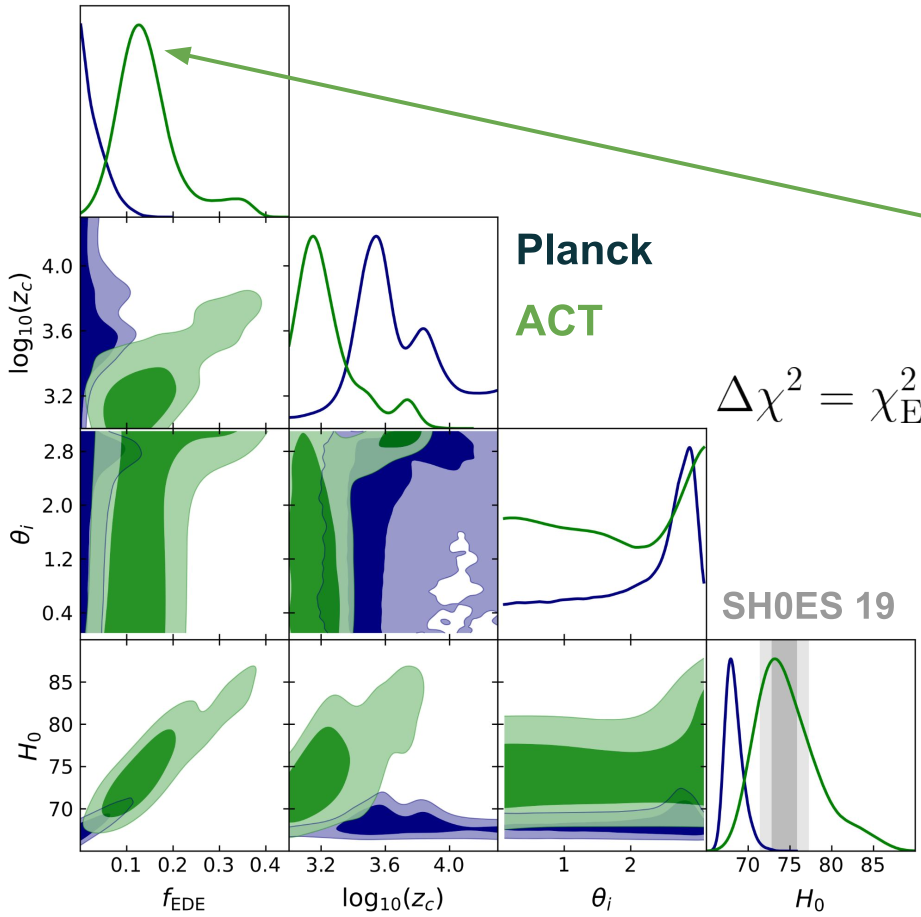
Poulin+ 2019, Smith+ 2019, Hill+ 2020

Additional constraints from ACTPol



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

Additional constraints from ACTPol

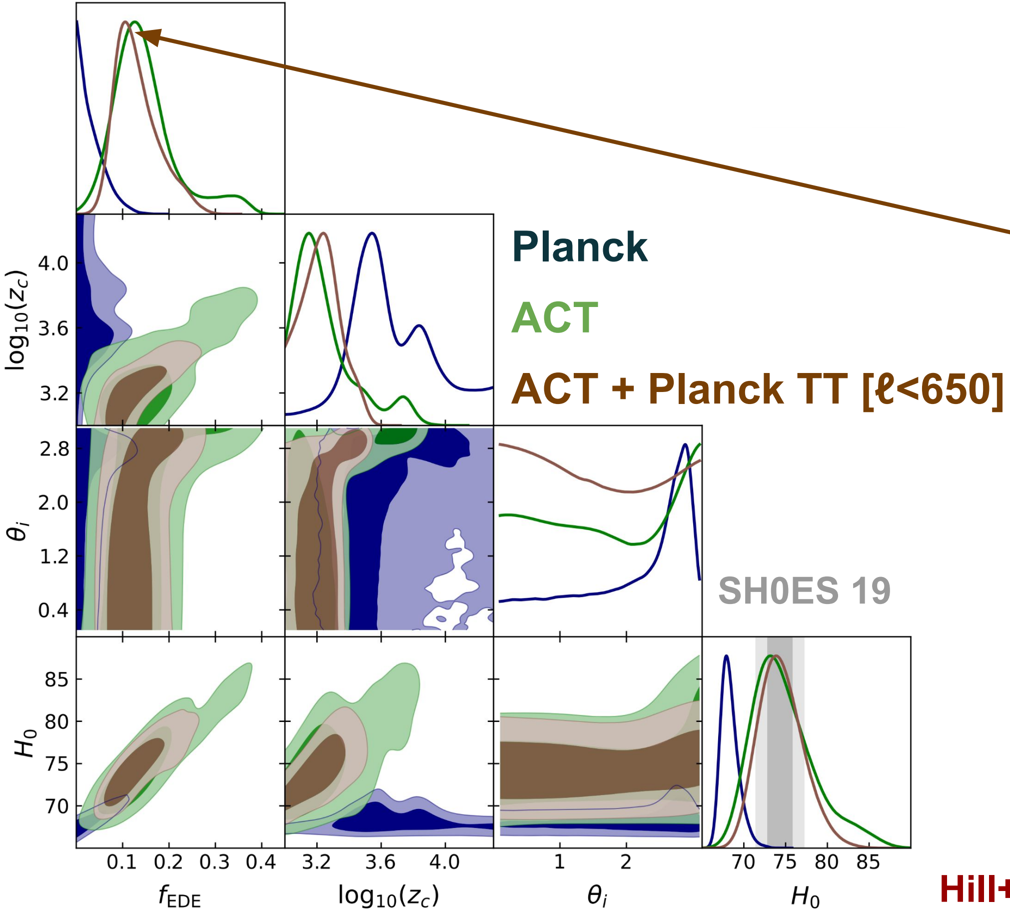


$$f_{\rm EDE} = 0.142^{+0.039}_{-0.072}\ (68\%\ \text{C.L.})$$

$$\Delta\chi^2 = \chi^2_{\rm EDE} - \chi^2_{\Lambda\rm CDM} = -8.7$$ → **2.1σ preference in favor of EDE**

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

Additional constraints from ACTPol



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

$\Delta\chi^2 = -15.4$ → **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)

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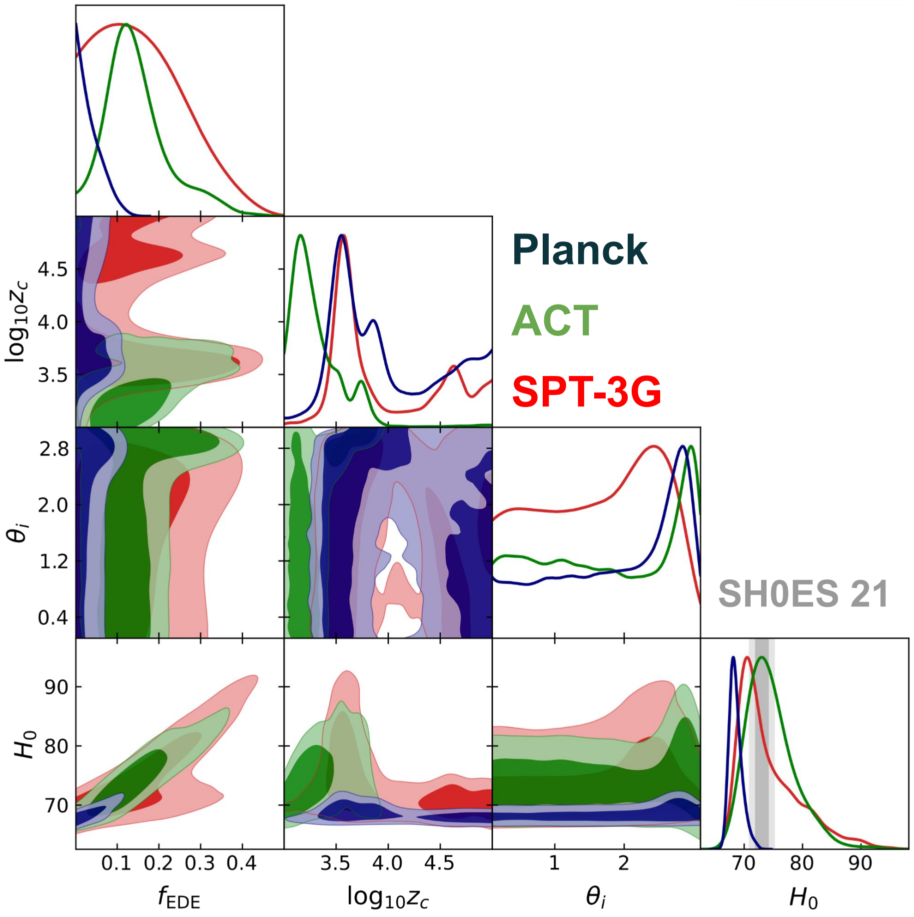
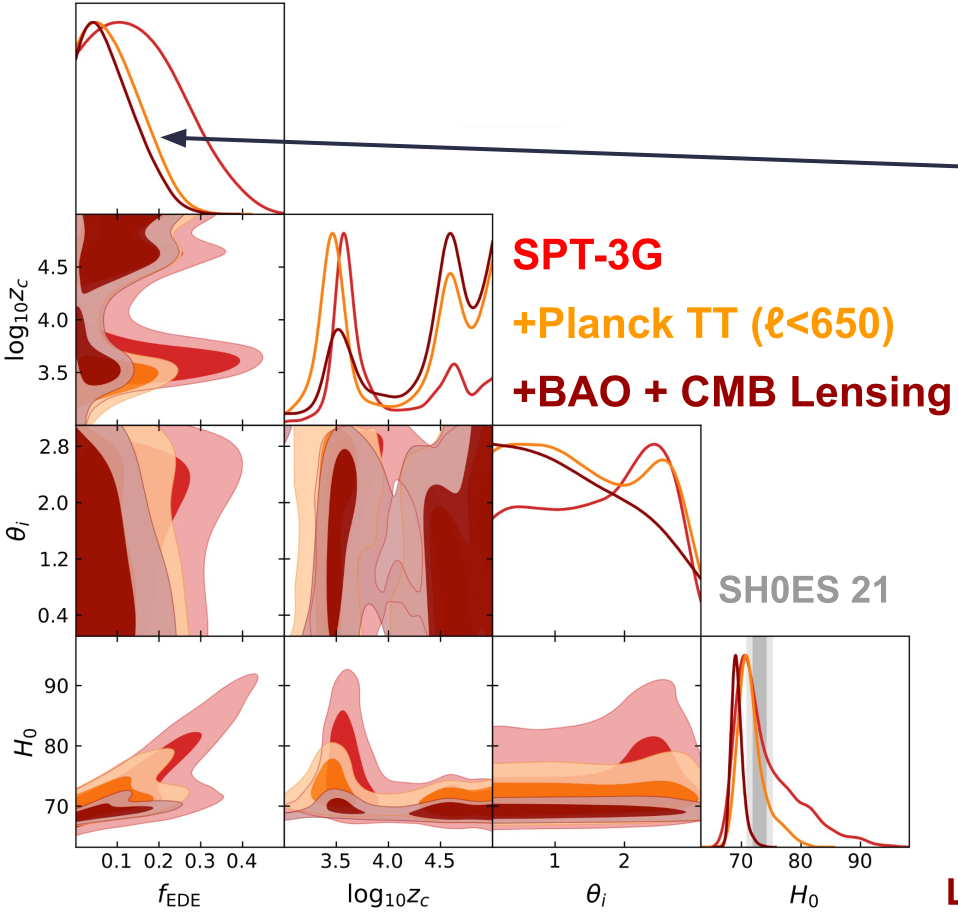
→ Motivates an analysis of EDE with public SPT-3G data

Constraints from SPT-3G public data



La Posta+ 2021 [arXiv:2112.10754]

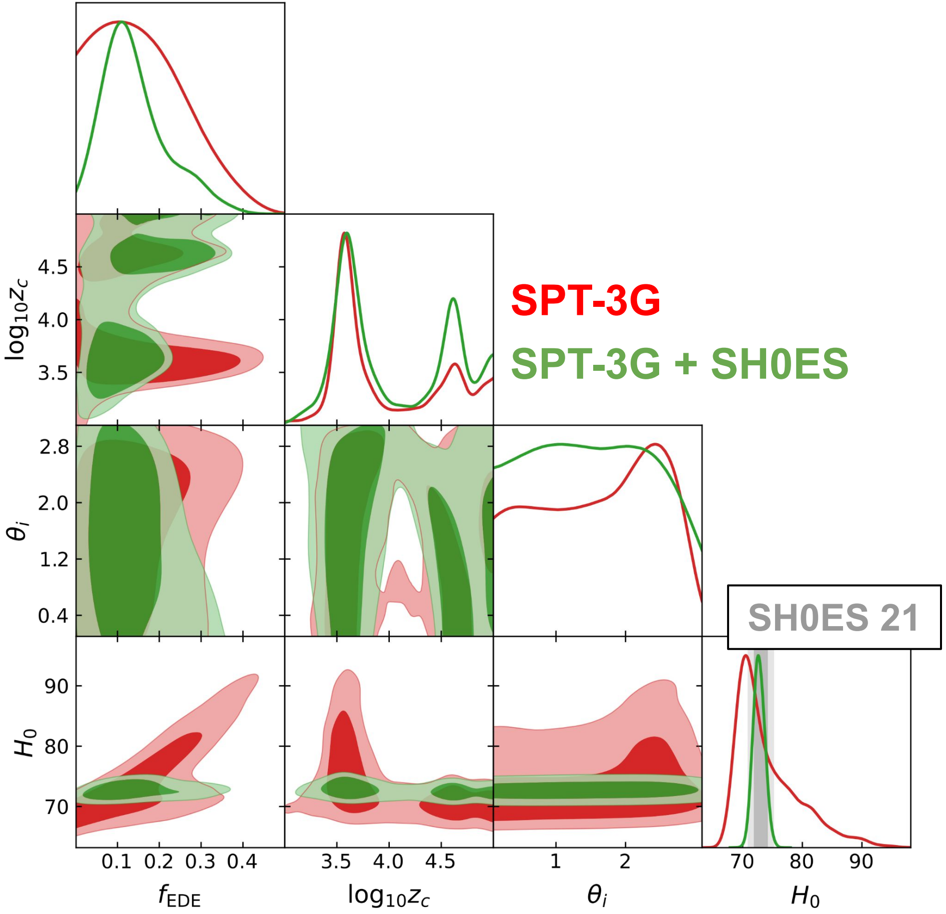
Constraints from SPT-3G public data



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

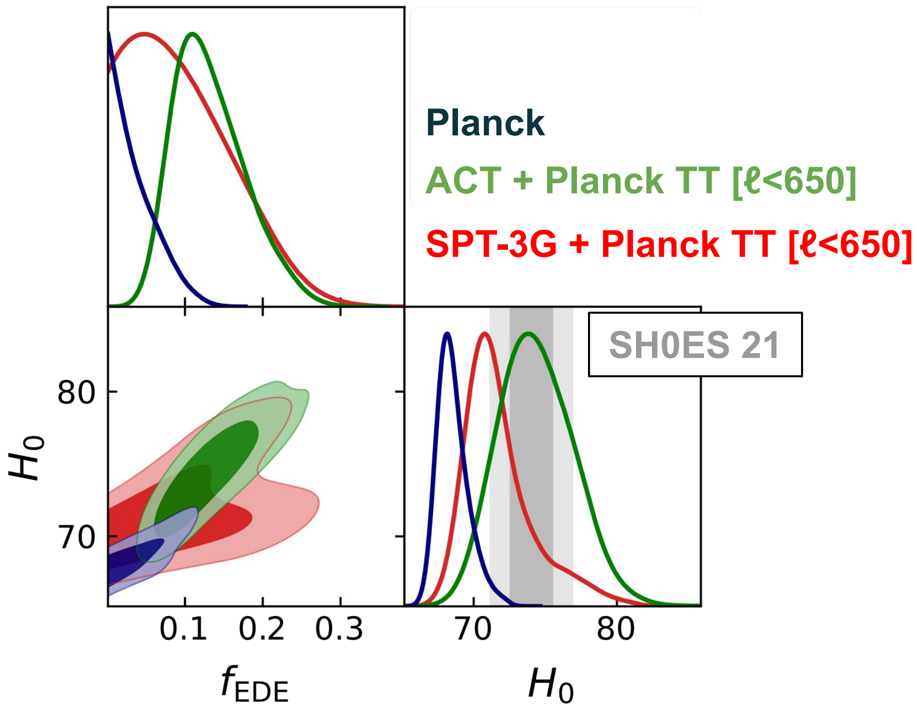


$$\Delta\chi^2_{\mathrm{SPT-3G}} = -6.3$$

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

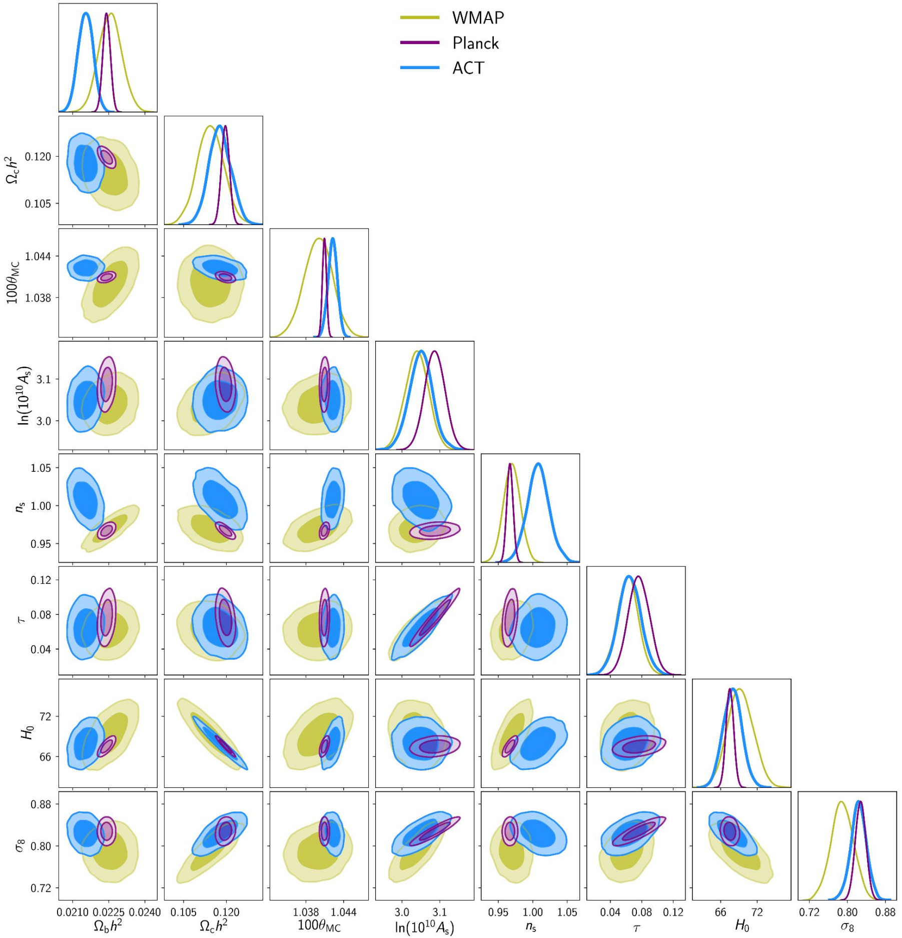
Conclusions

- 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



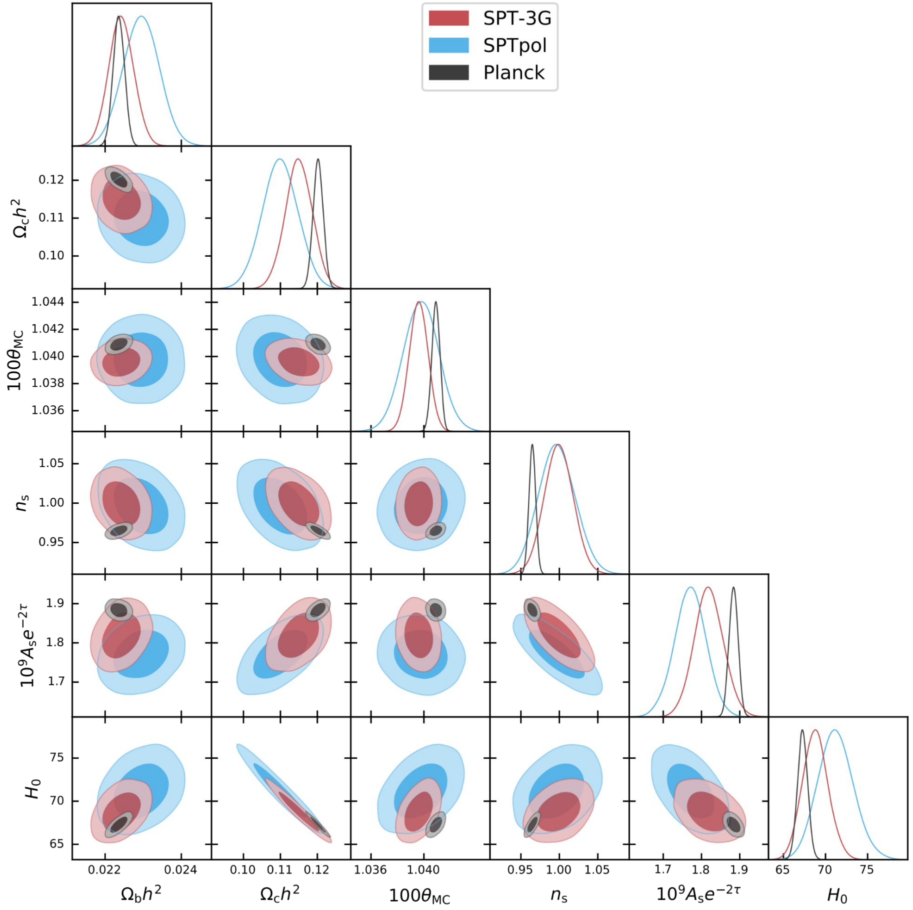
Extra-slides

ACTPol cosmology



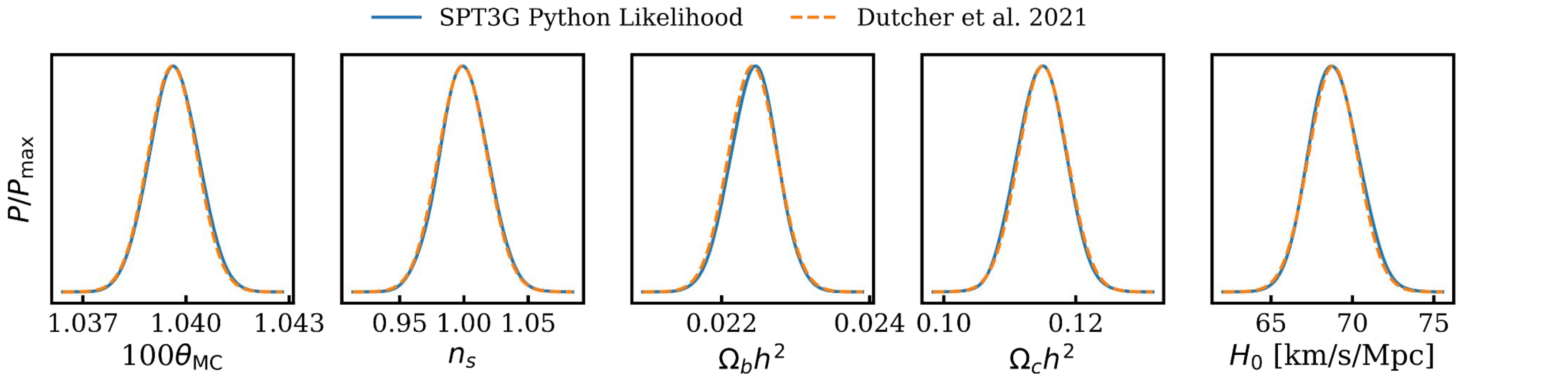
Aiola+ 2020

SPT-3G cosmology

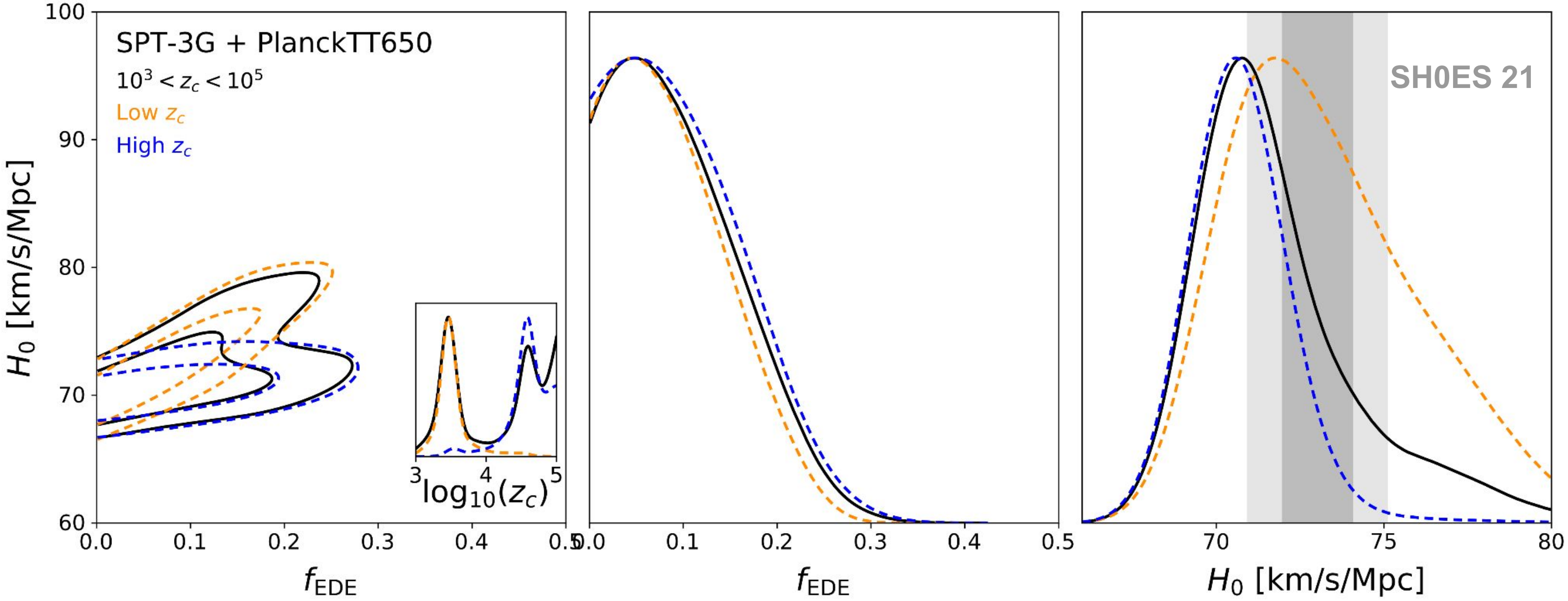


Dutcher+ 2021

SPT-3G python implementation

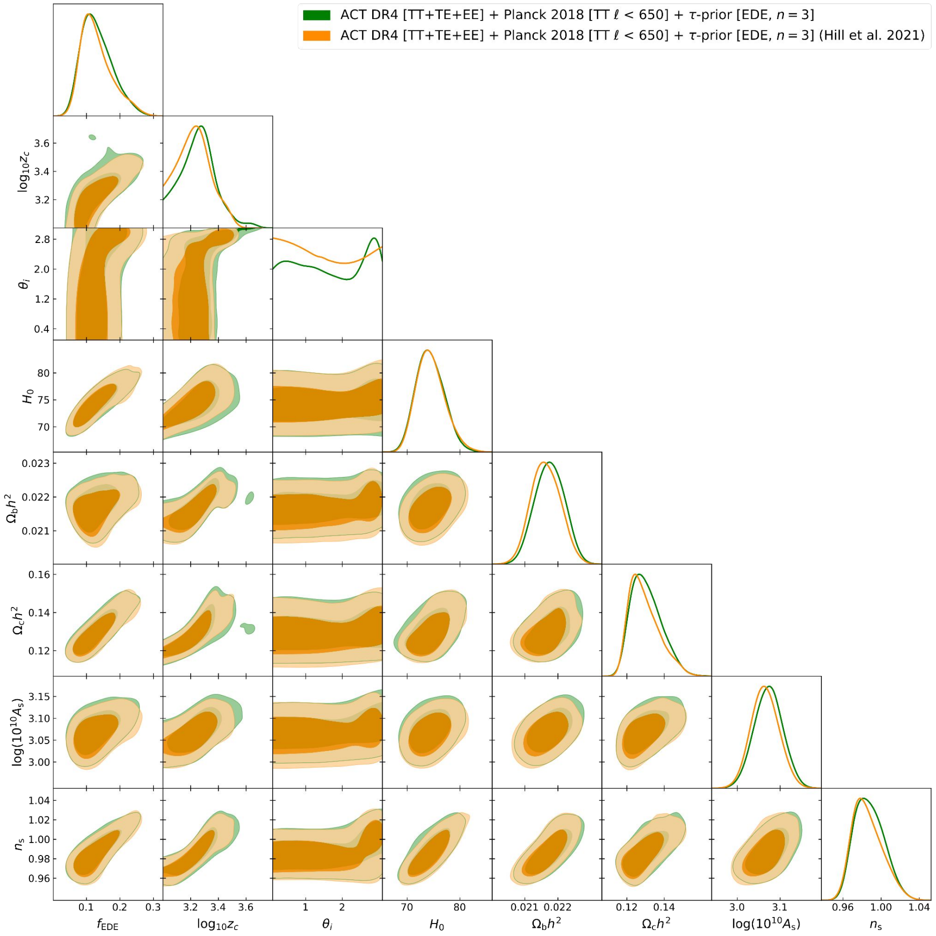


Impact of the z_c prior



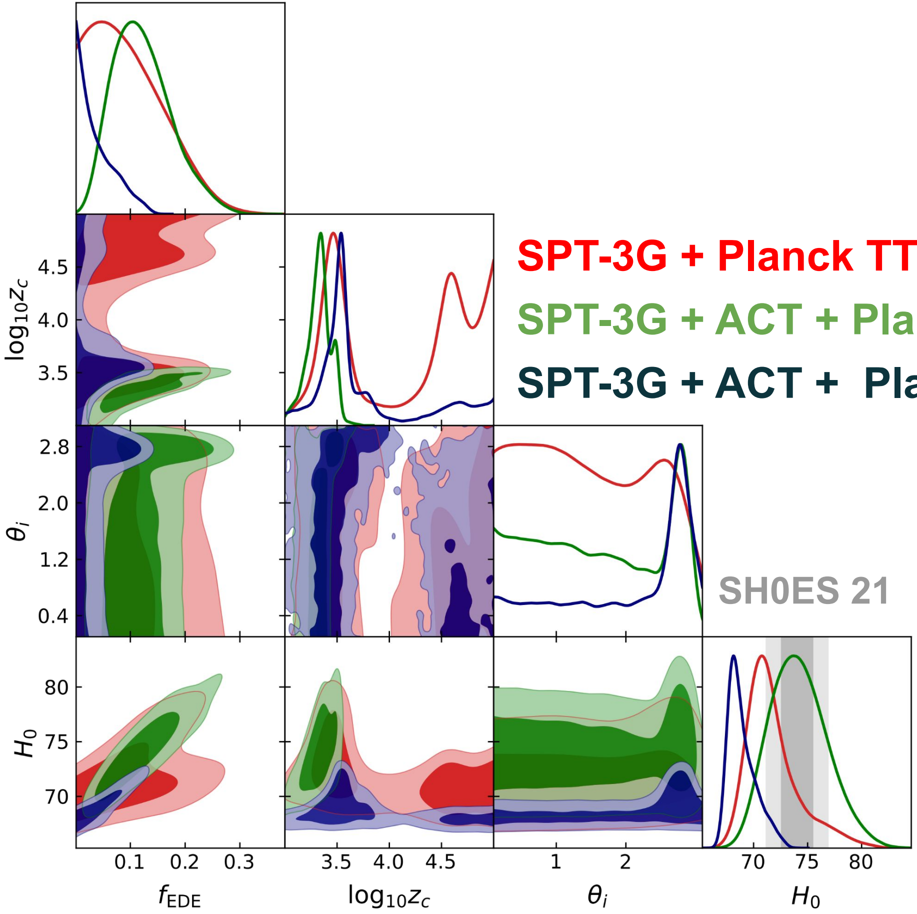
La Posta+ 2021 [arXiv:2112.10754]

CAMB/CLASS EDE models



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

Combining with other CMB datasets



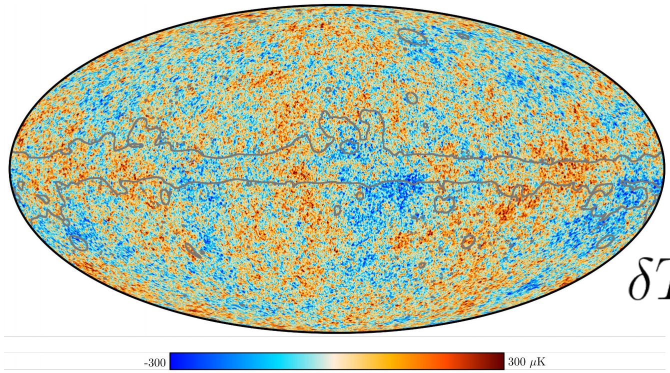
SPT-3G + Planck TT [ℓ<650]

SPT-3G + ACT + Planck TT [ℓ<650]

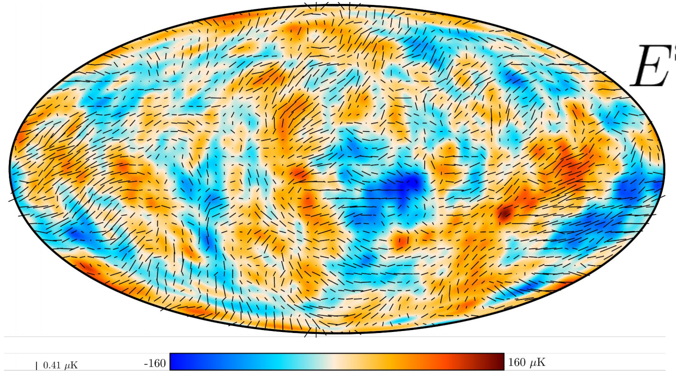
SPT-3G + ACT + Planck

La Posta+ 2021 [arXiv:2112.10754]

Systematics in the CMB



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



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

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

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

Systematics in the CMB

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

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

Systematics in the CMB

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

- **Finite angular resolution (beams)**

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

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

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

- **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 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)**

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

Temperature (polarization) transfer function

Systematics in the CMB

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

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

These instrumental effects are multiplicative in harmonic space

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

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

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

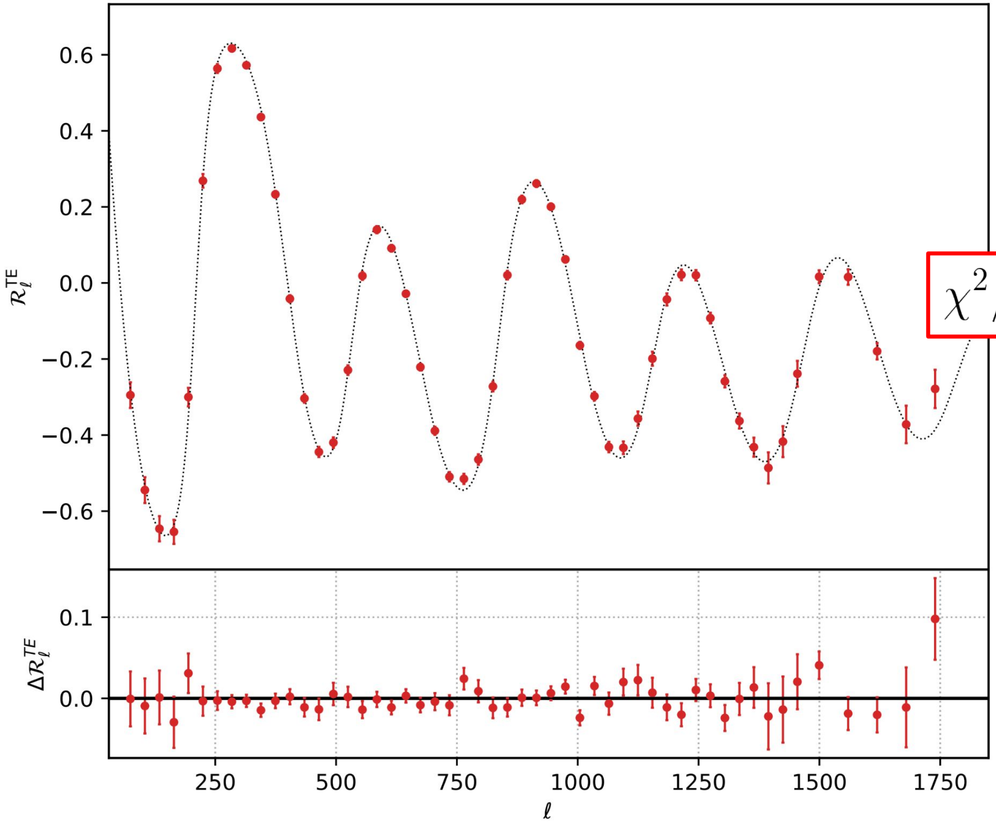
$$\mathcal{R}_\ell^{TE,\mathrm{obs}} = \frac{\mathcal{F}_\ell^T \mathcal{F}_\ell^E c^2 c_E B_\ell^T B_\ell^E C_\ell^{TE}}{\sqrt{(\mathcal{F}_\ell^T)^2 c^2 (B_\ell^T)^2 C_\ell^{TT} \times (\mathcal{F}_\ell^E)^2 c^2 c_E^2 (B_\ell^E)^2 C_\ell^{EE}}}$$

Correlation coefficient of T and E modes

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

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

Planck correlation coefficient



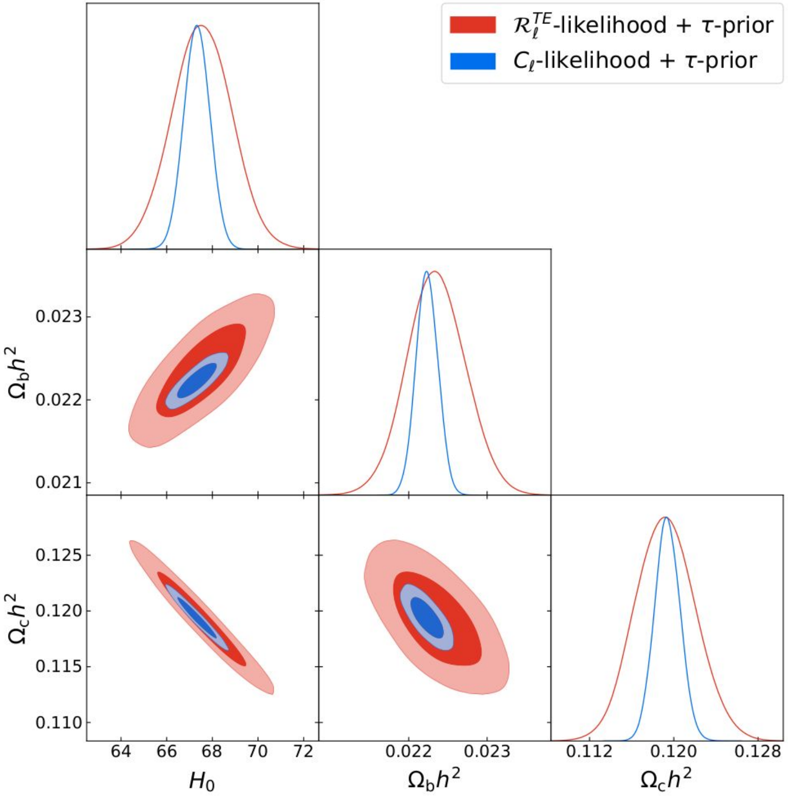
Bestfit from Planck TT,TE,EE

Planck correlation coefficient

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

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

Cosmological results from R^{TE}

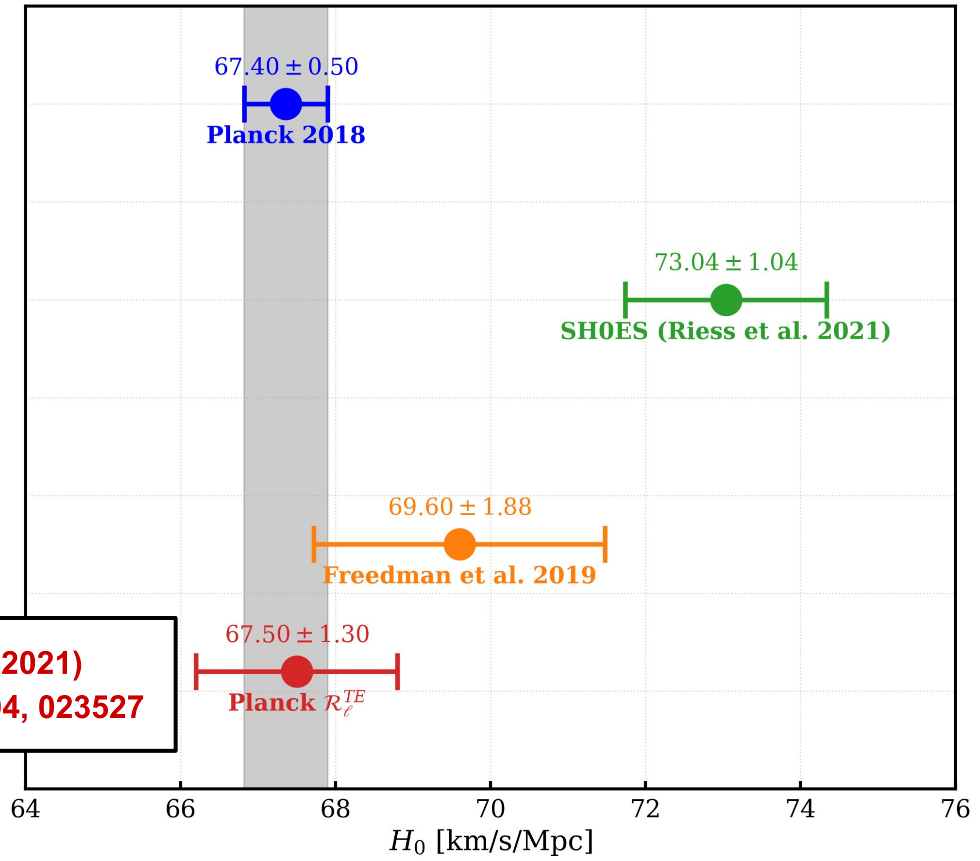


3.3σ away from the latest SH0ES measurement

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

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