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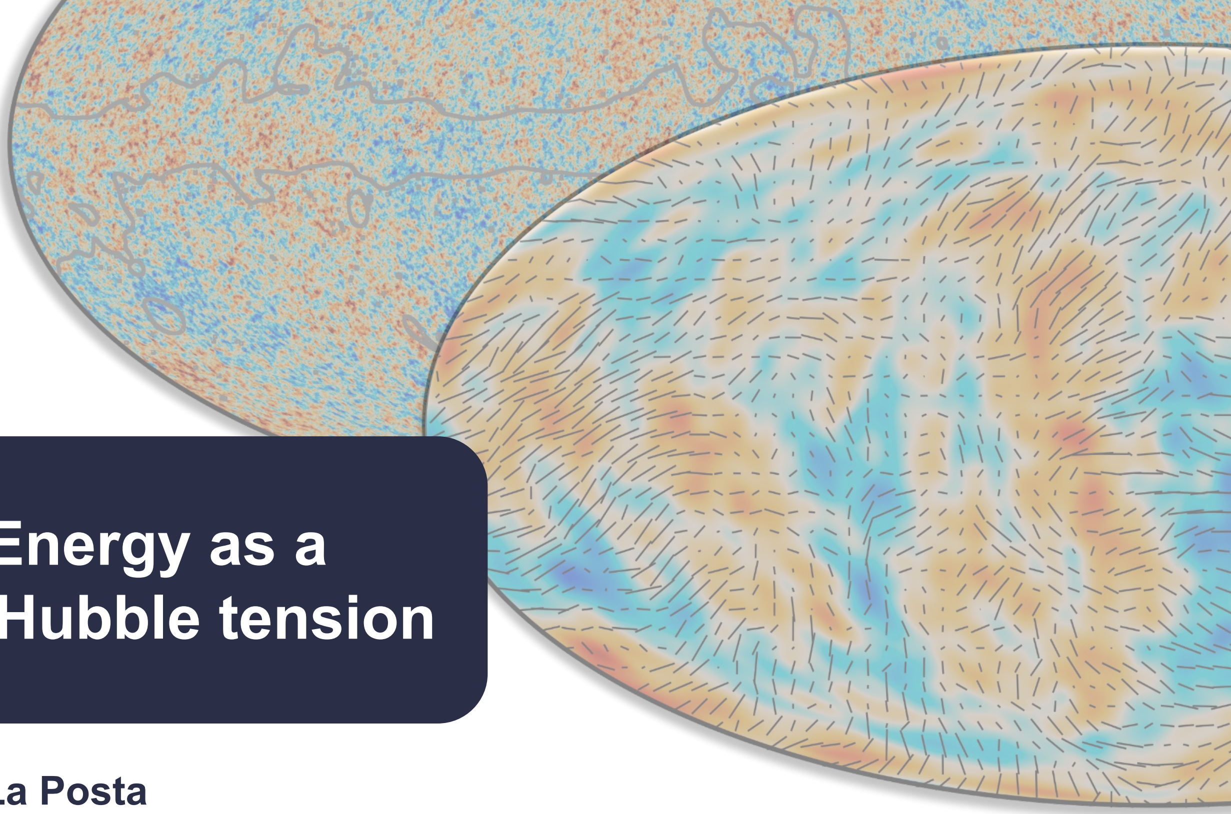
IJCLab Irène Joliot-Curie
Laboratoire de Physique des 2 Infinis
A2C Astroparticles, Astrophysics & Cosmology



# 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**

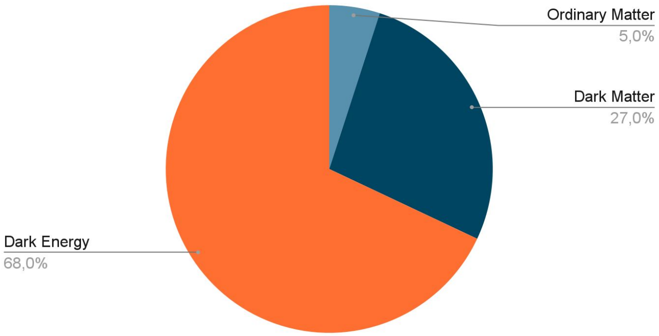
$$H^2(z) = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\left[(\rho_b^0 + \rho_c^0)(1+z)^3 + \rho_r^0(1+z)^4 + \rho_\Lambda\right]$$

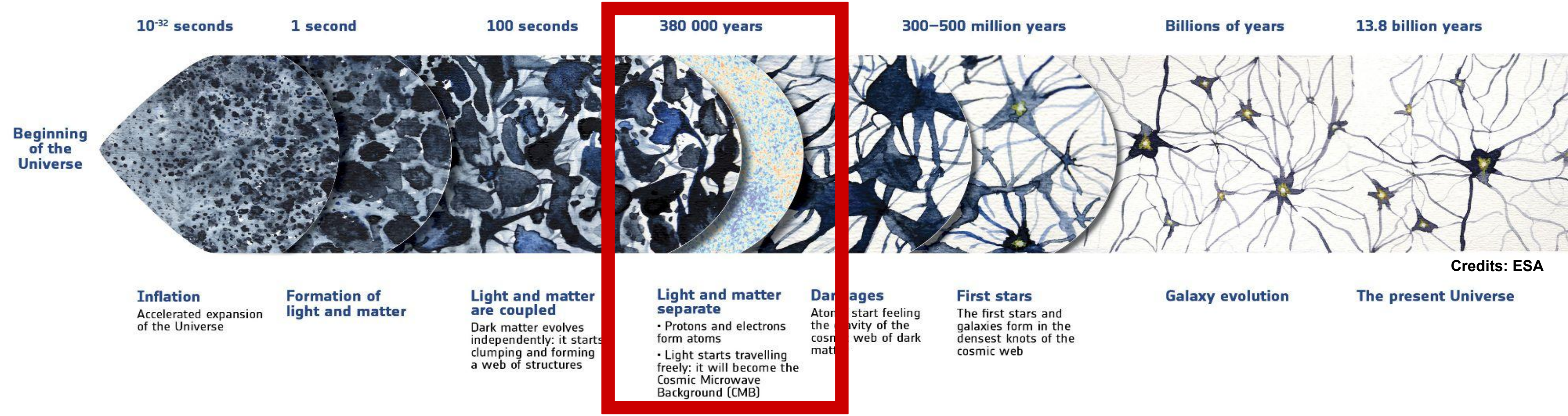
baryon

CDM

radiation

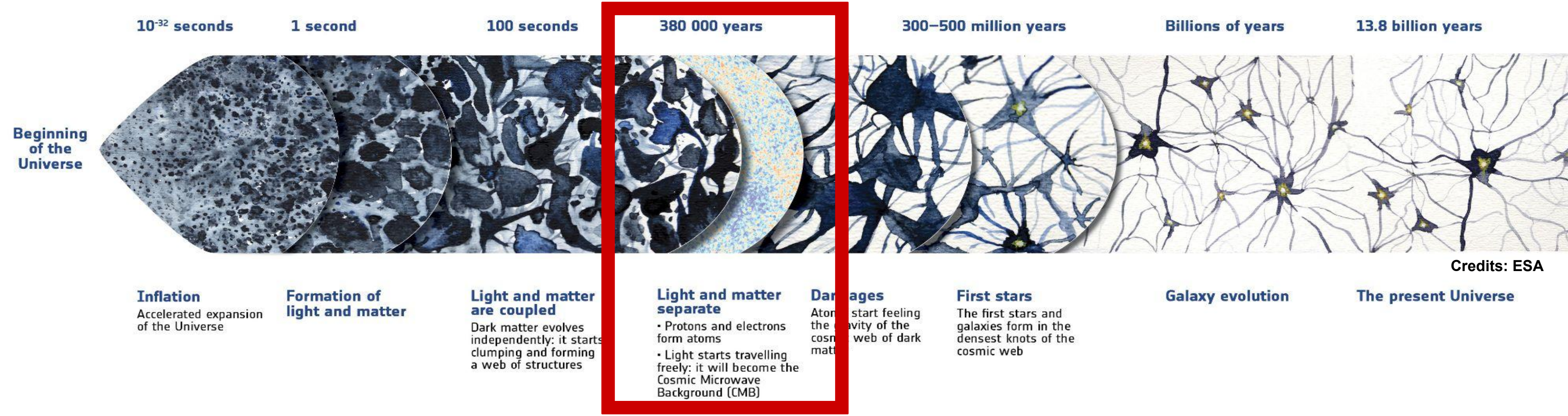
dark energy





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


Credits: ESA

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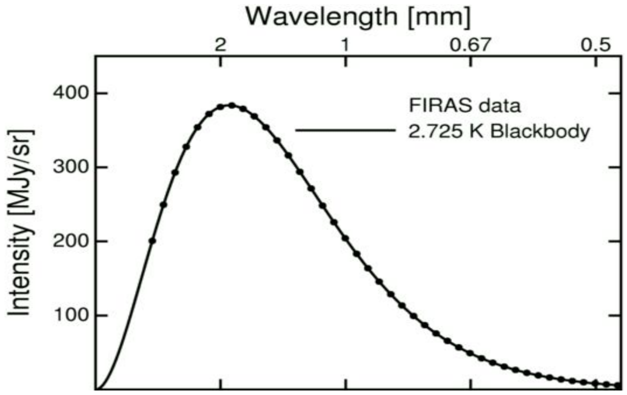
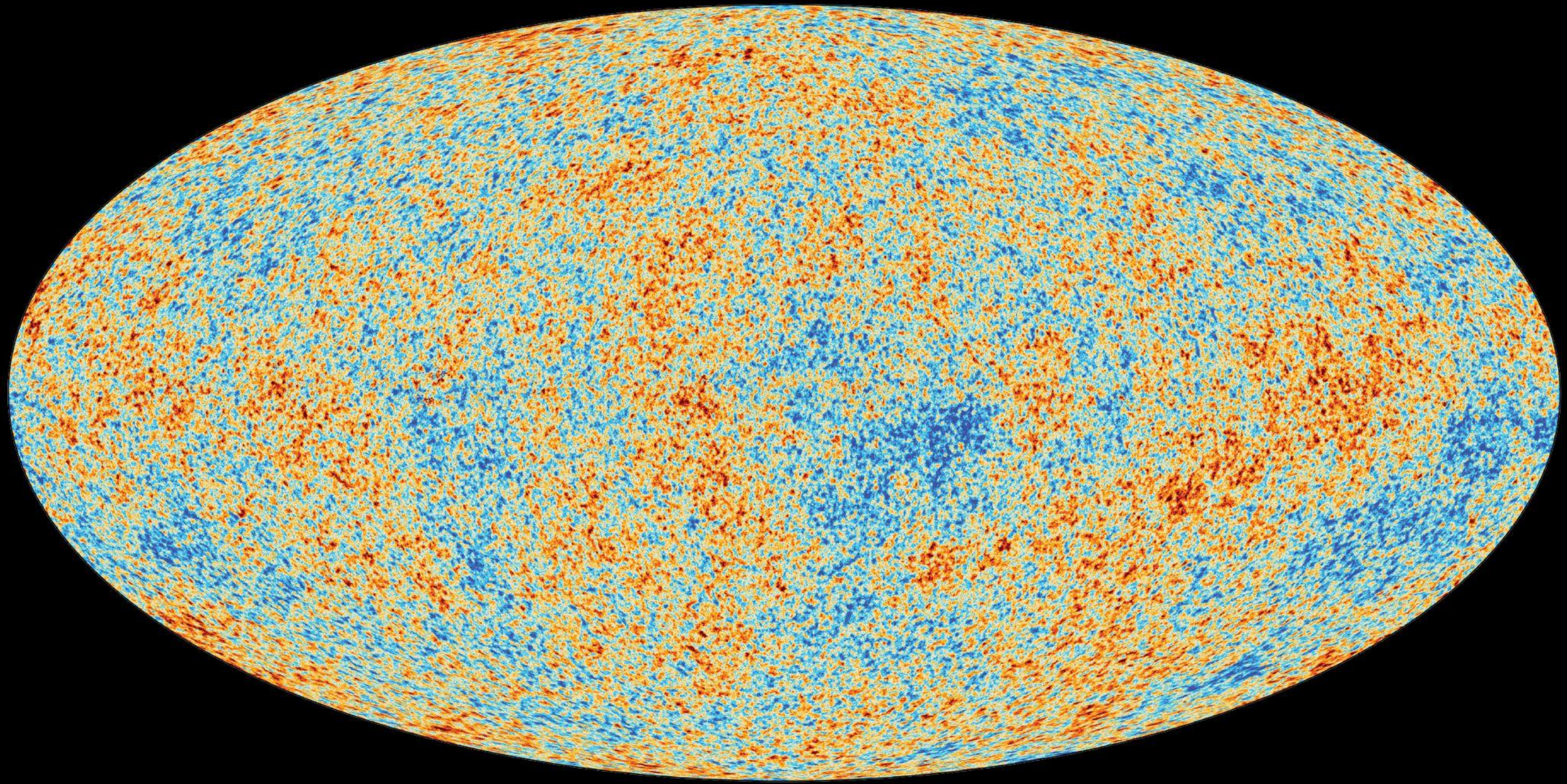



**Nearly isotropic blackbody spectrum at T = 2.725 K**

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

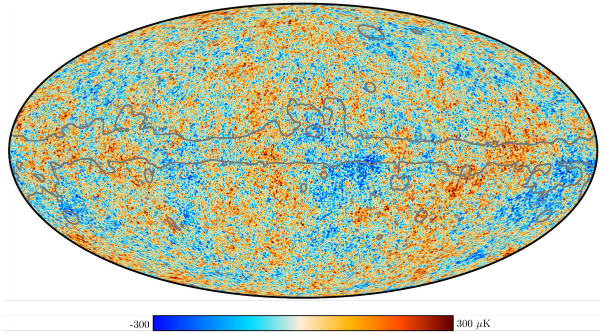
# CMB temperature as measured by the Planck satellite



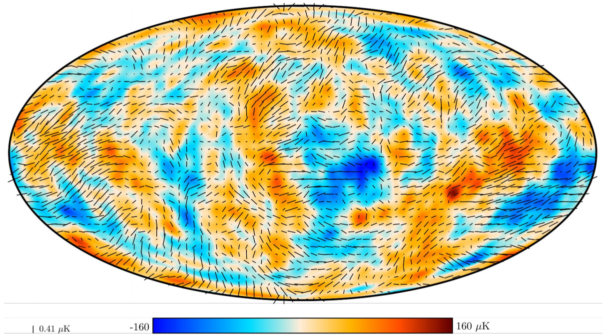
Credits: ESA

# Measuring $H_0$ from the CMB

## Temperature




## Polarization E-modes



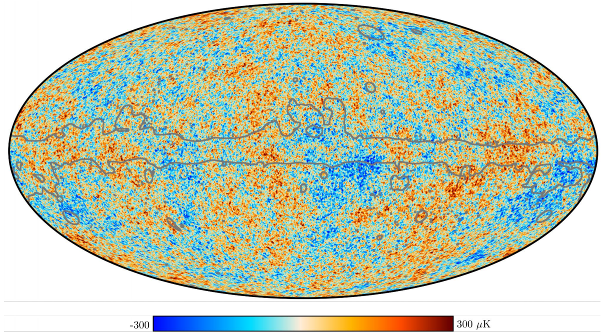

## Spherical harmonics

$$\delta T(\hat{n}) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a^T_{\ell m} Y^m_\ell(\theta, \phi)$$

$$\langle a^T_{\ell m} a^{T*}_{\ell' m'} \rangle = \delta_{\ell\ell'} \delta_{mm'} C^{TT}_\ell$$

# Measuring $H_0$ from the CMB

## Temperature

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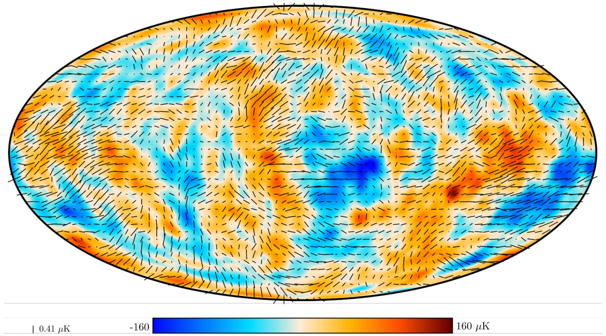
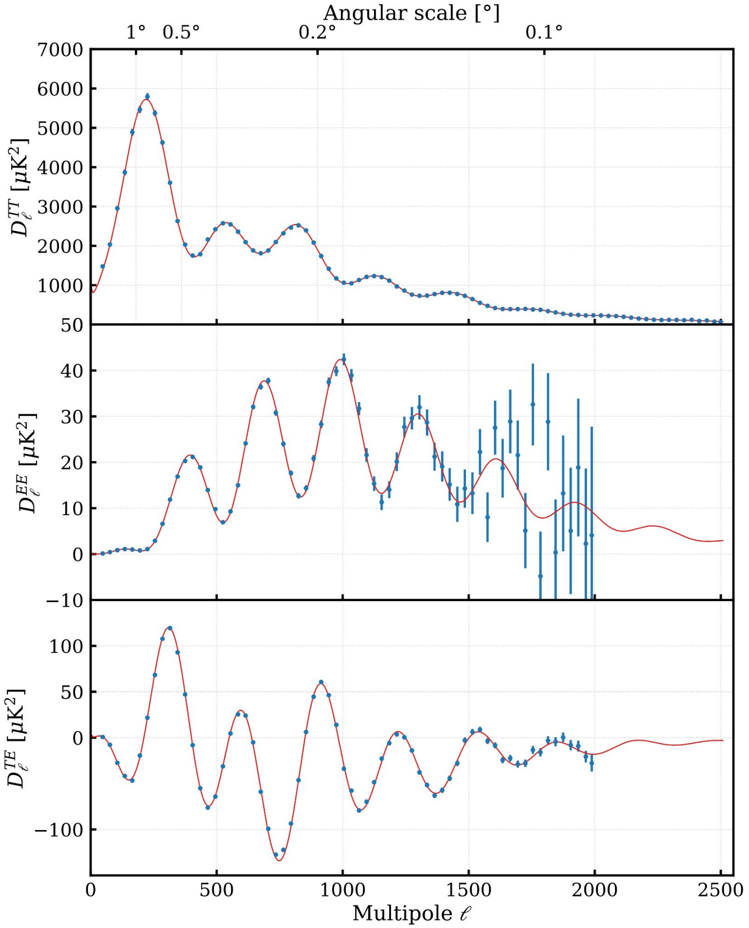
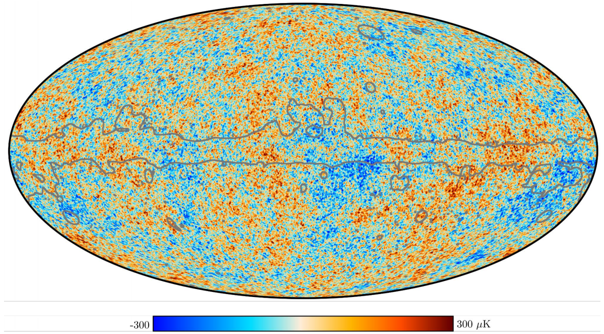


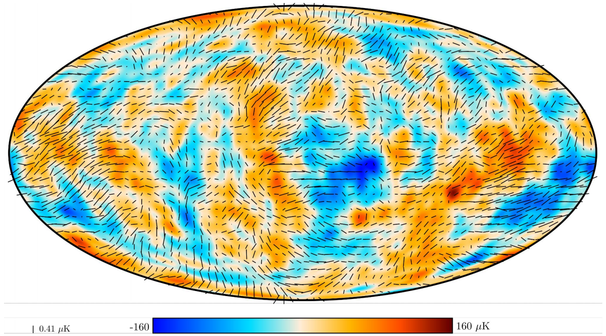
# Measuring $H_0$ from the CMB

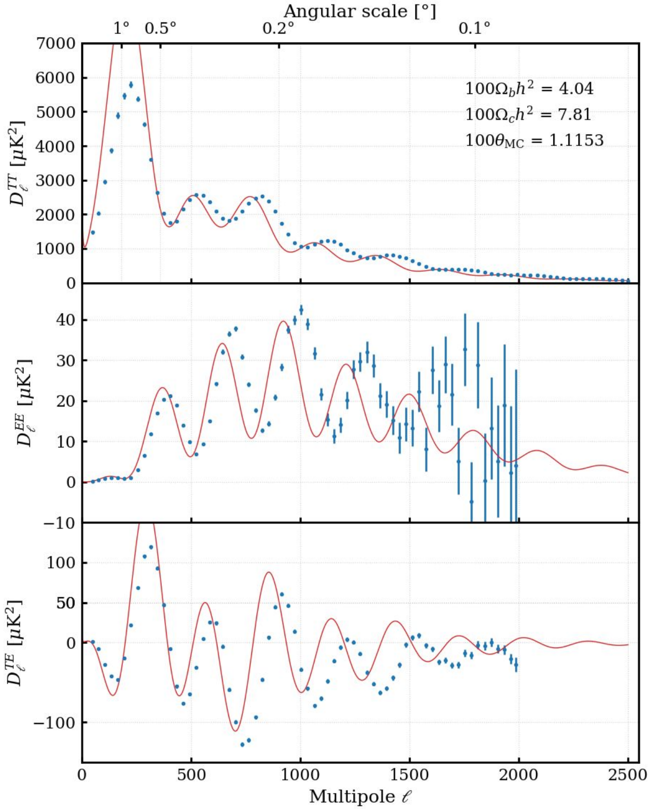


**Temperature**




**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

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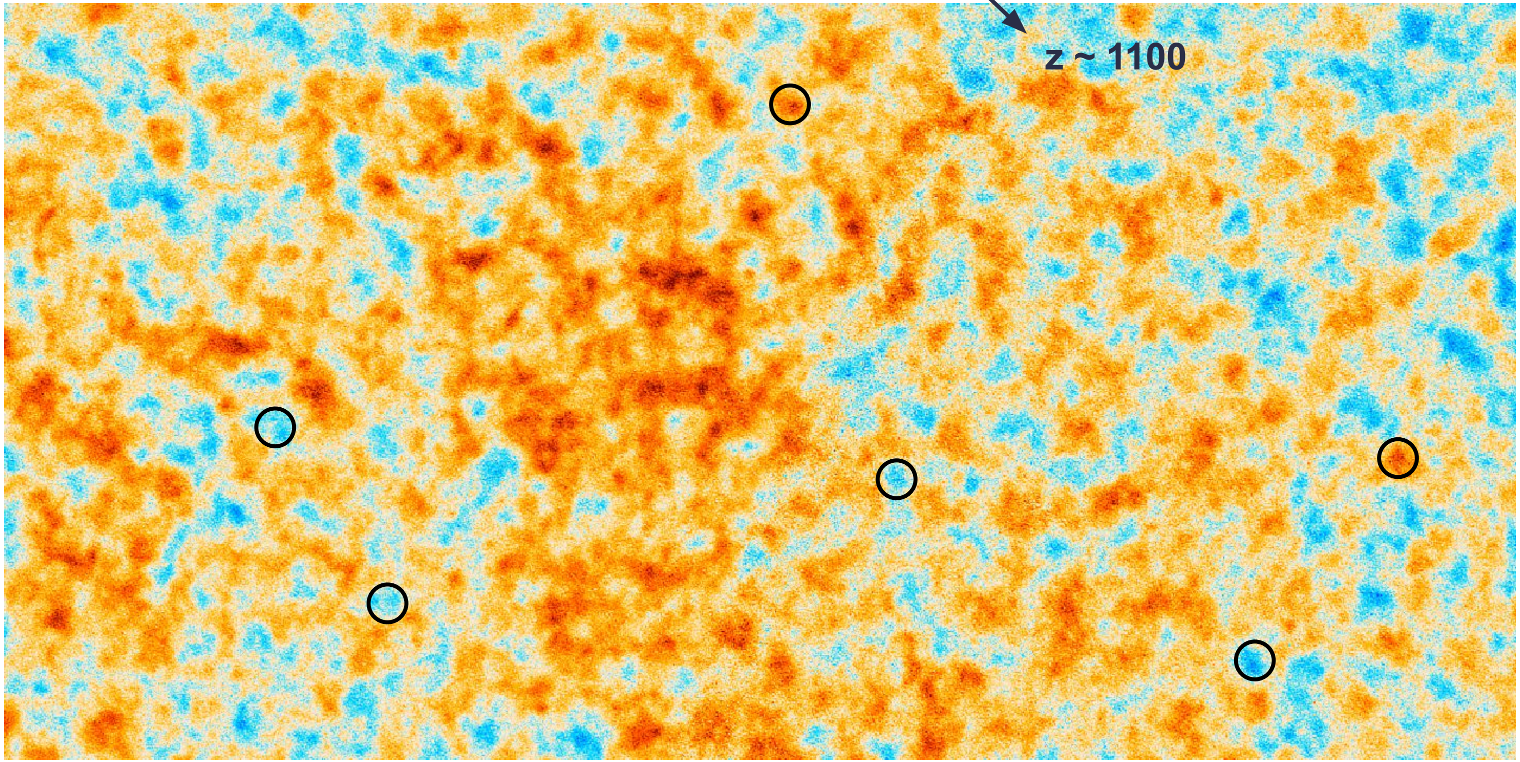
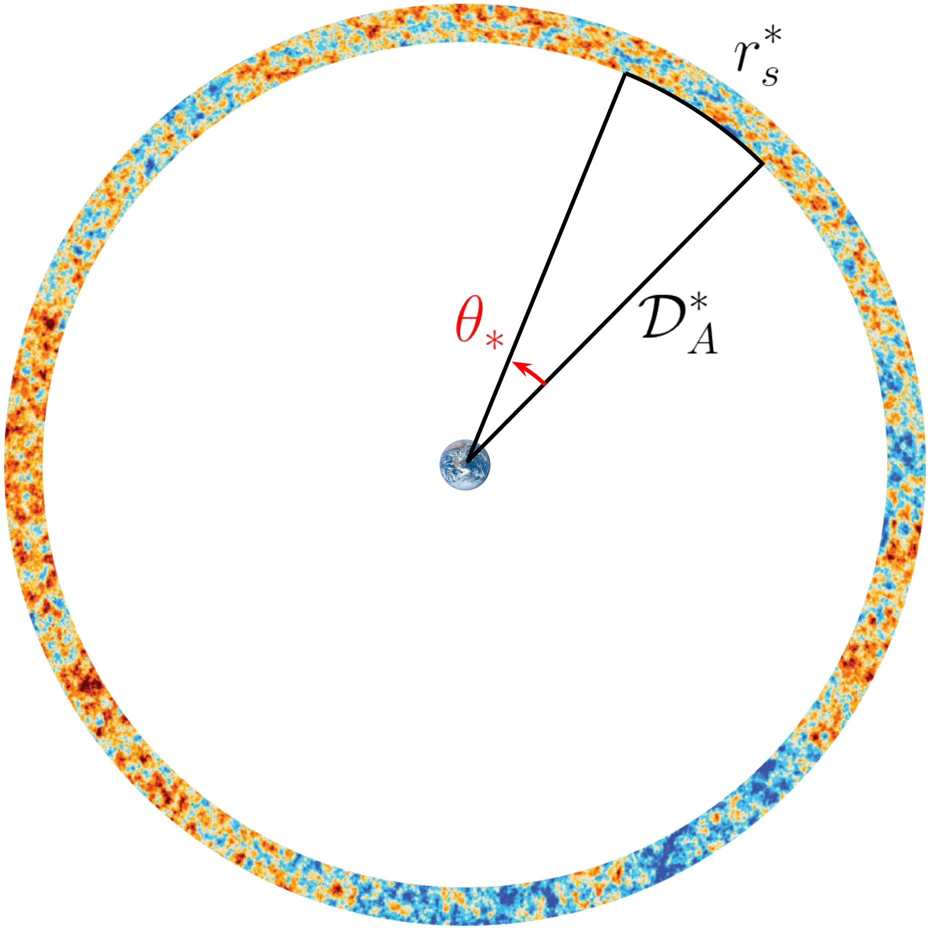


# How to measure $H_0$ from the CMB ?

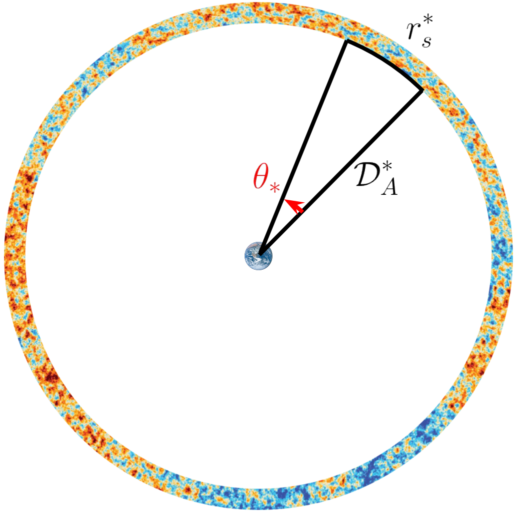




# How to measure $H_0$ from the CMB ?



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



# How to measure $H_0$ from the CMB ?

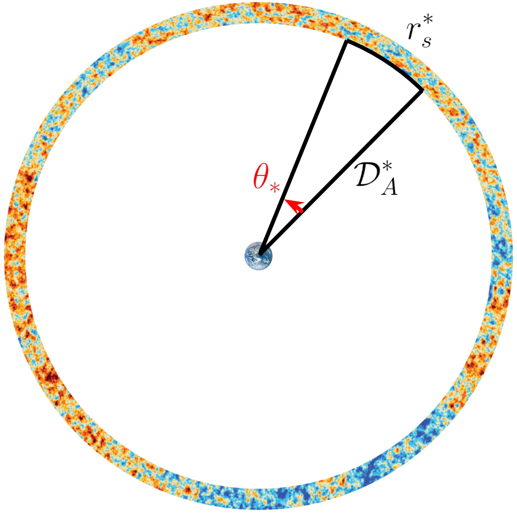


$$\theta_* = \frac{r_s^*}{\mathcal{D}_A^*}$$

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

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

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



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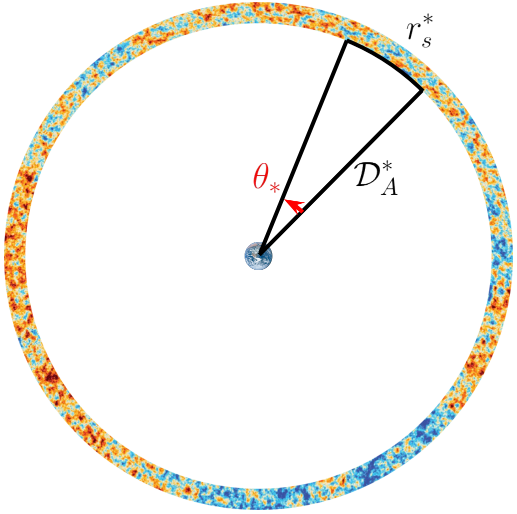
**Now** $\mathcal{D}_A^*$ **is known**

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



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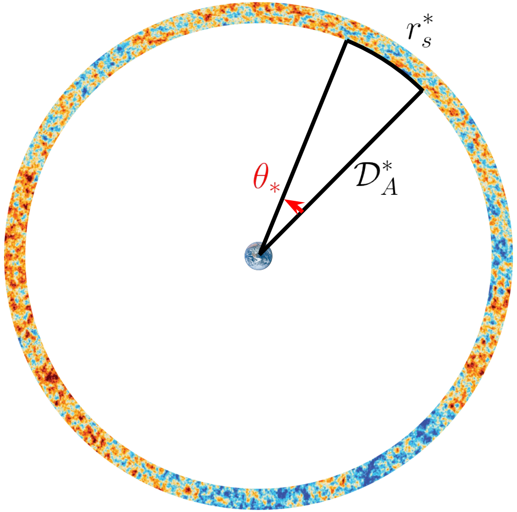

# How to measure $H_0$ from the CMB ?



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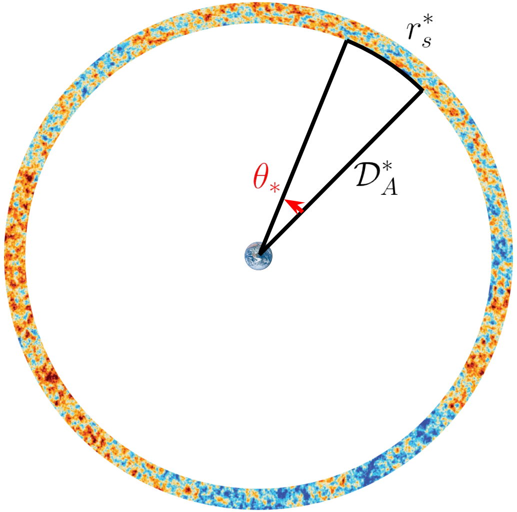
$$\theta_* = \frac{r_s^*}{\mathcal{D}_A^*}$$

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

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



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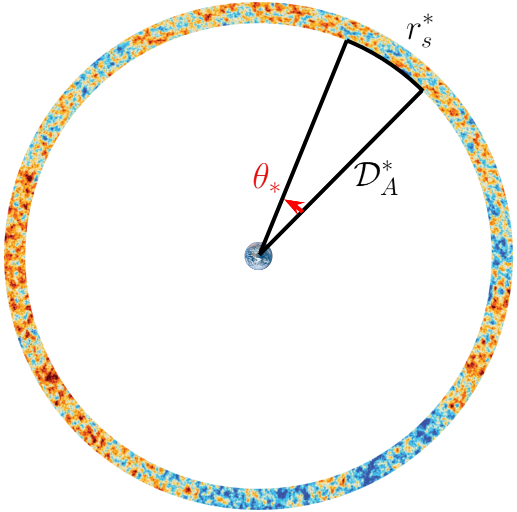
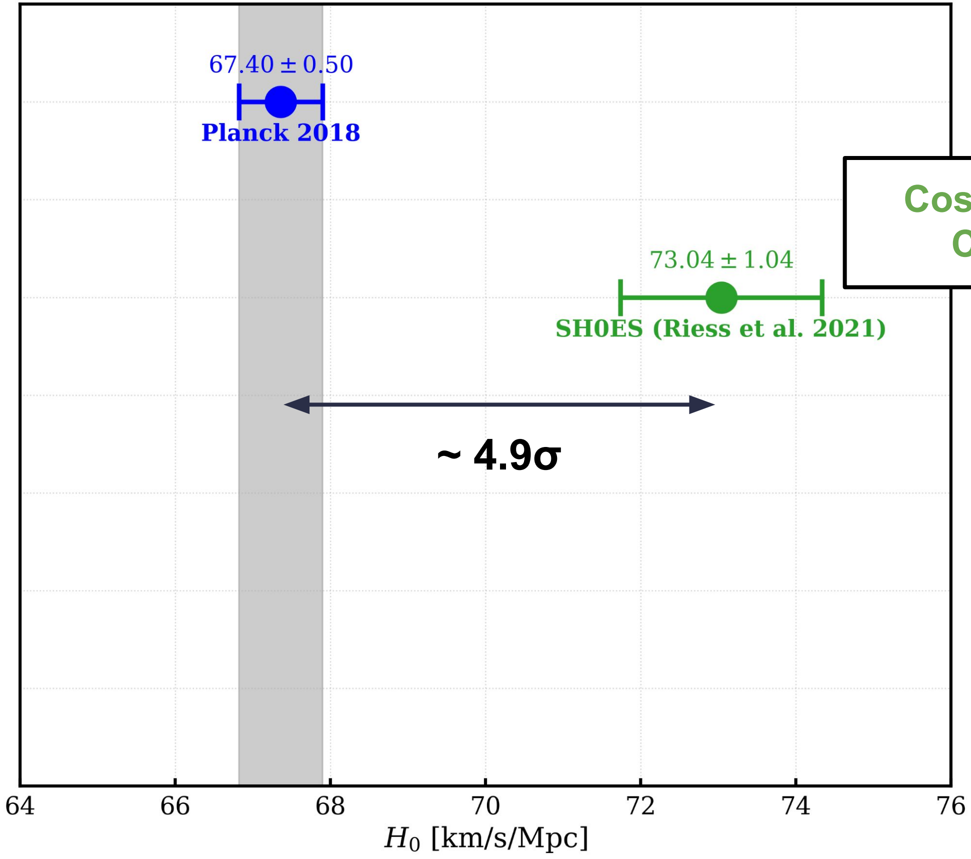
$$H^2_{\text{late}}(z) = \frac{8\pi G}{3}\left[(\rho_b^0 + \rho_c^0)(1+z)^3 + \rho_\Lambda\right]$$

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



# The Hubble tension as of today

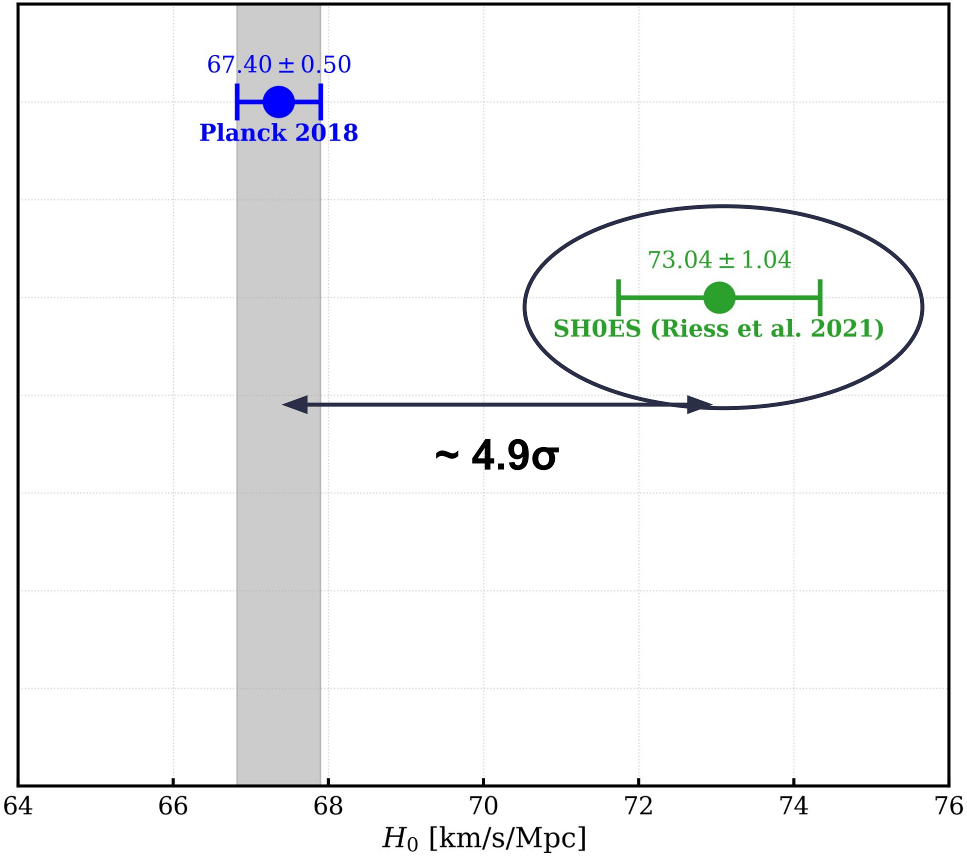





Cosmic distance ladder using Cepheid calibrated SNIA

# The Hubble tension as of today



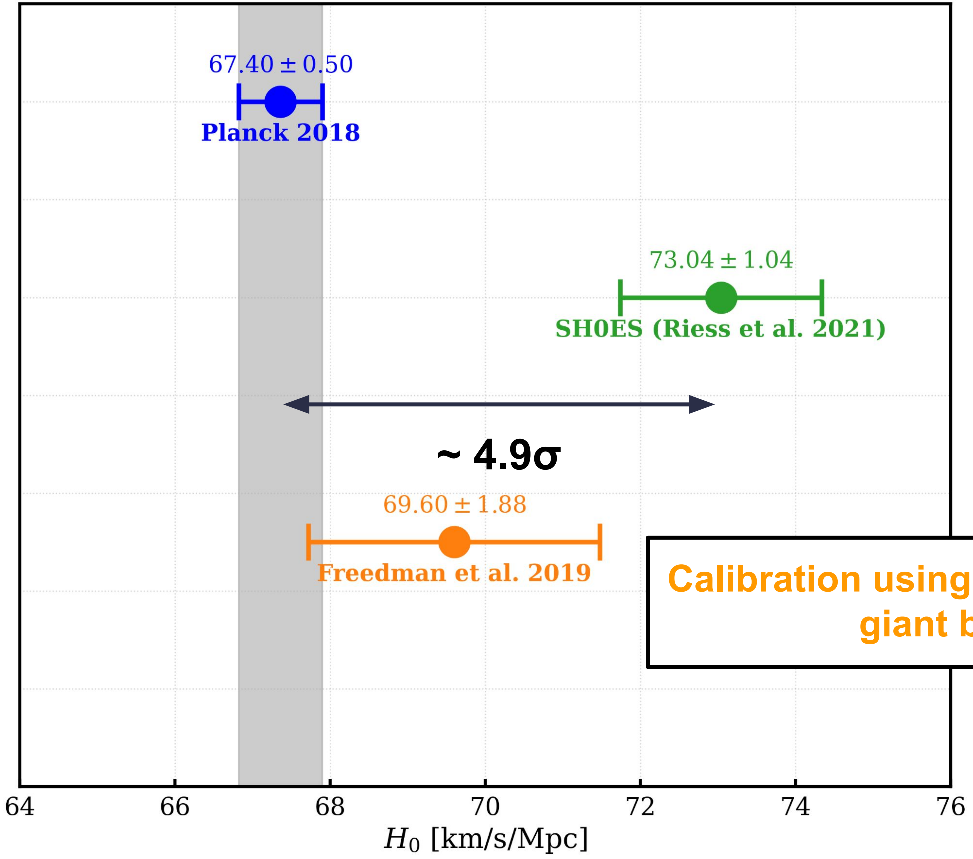



**Option 1**

**Astrophysical biases affecting the local measurement of $H_0$**

# The Hubble tension as of today





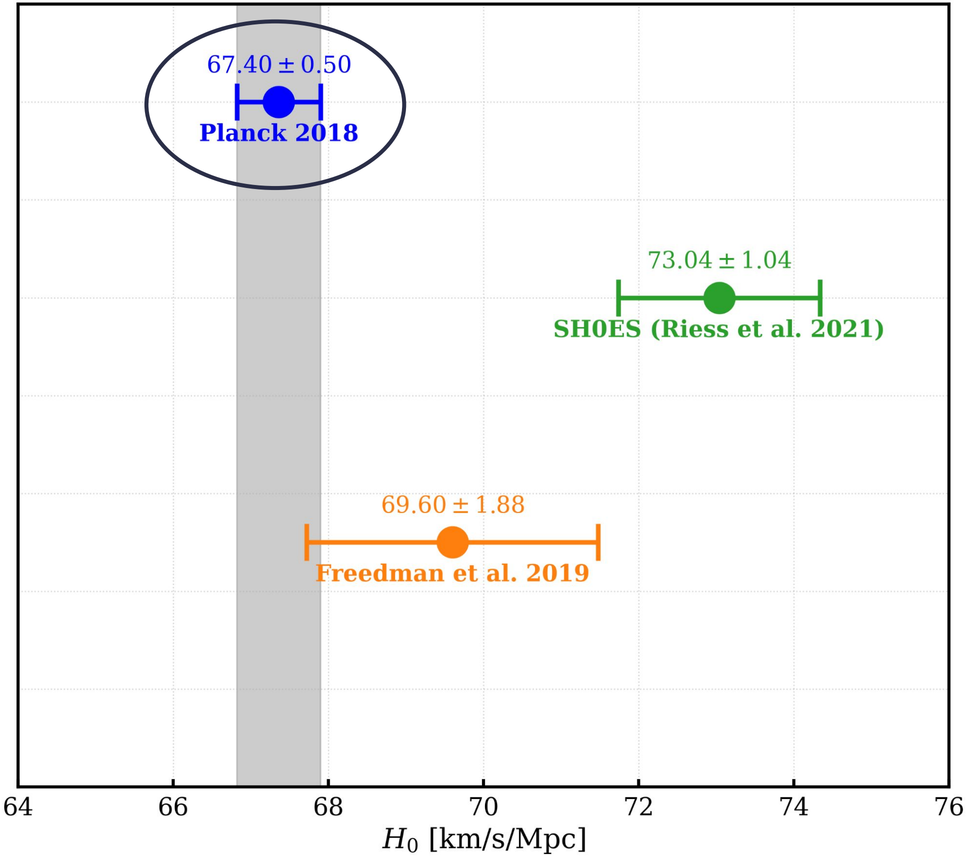

**Option 1**

**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**

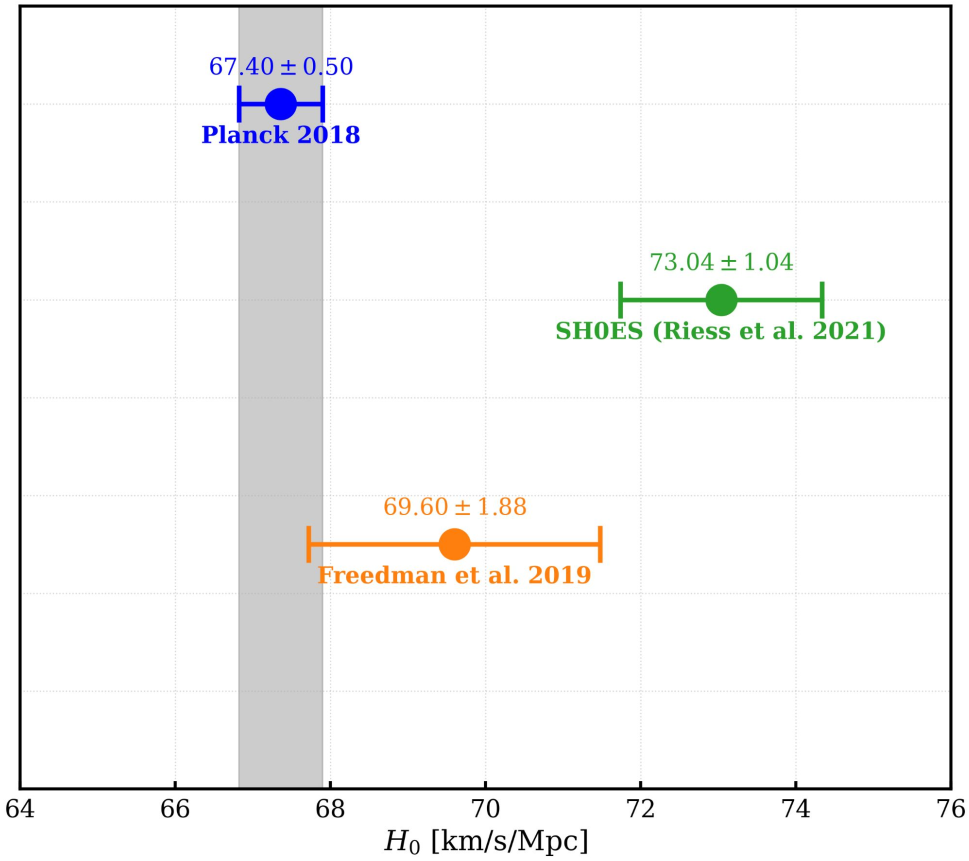
**Astrophysical biases affecting the local measurement of $H_0$**

**Option 2**

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

# The Hubble tension as of today



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**Astrophysical biases affecting the local measurement of $H_0$**

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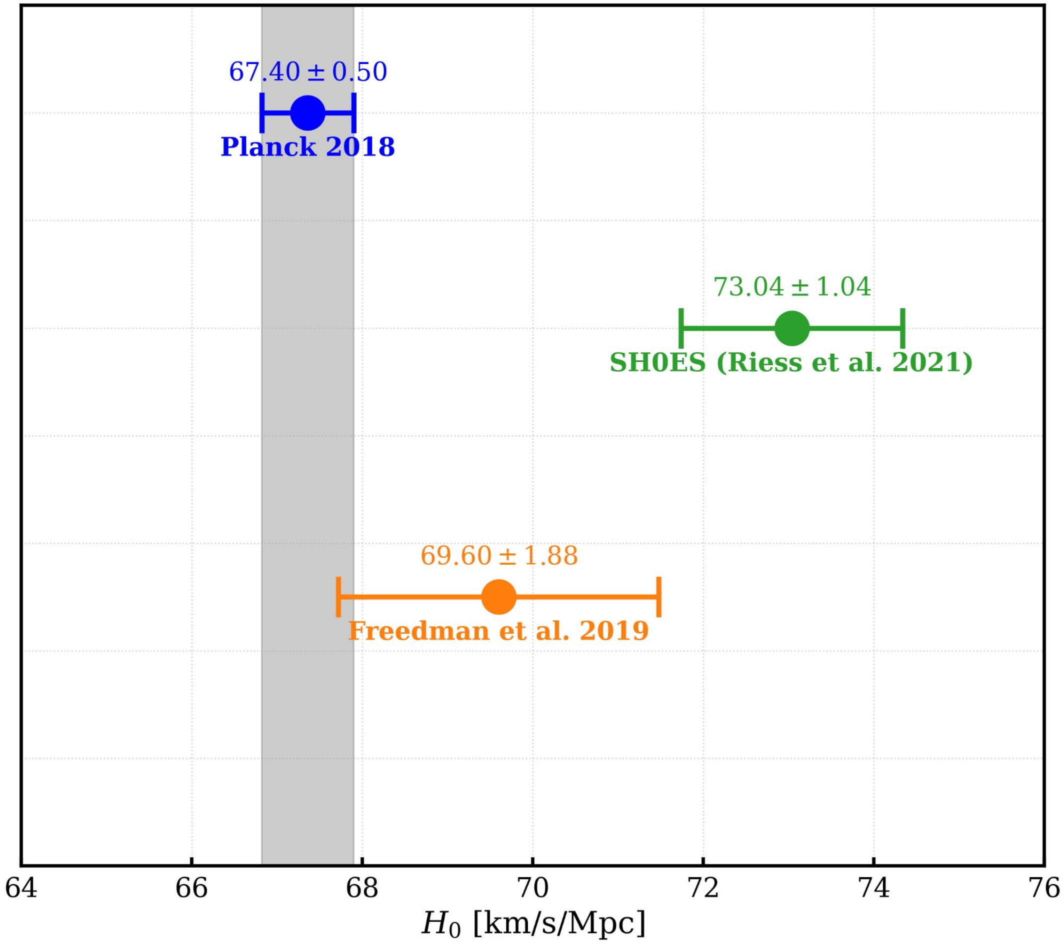
**Instrumental systematic effect biasing the value of $H_0$ inferred from the CMB**

**Option 3**

**Physics beyond ΛCDM**




Option 1

Astrophysical biases affecting the local measurement of $H_0$

**Option 2**

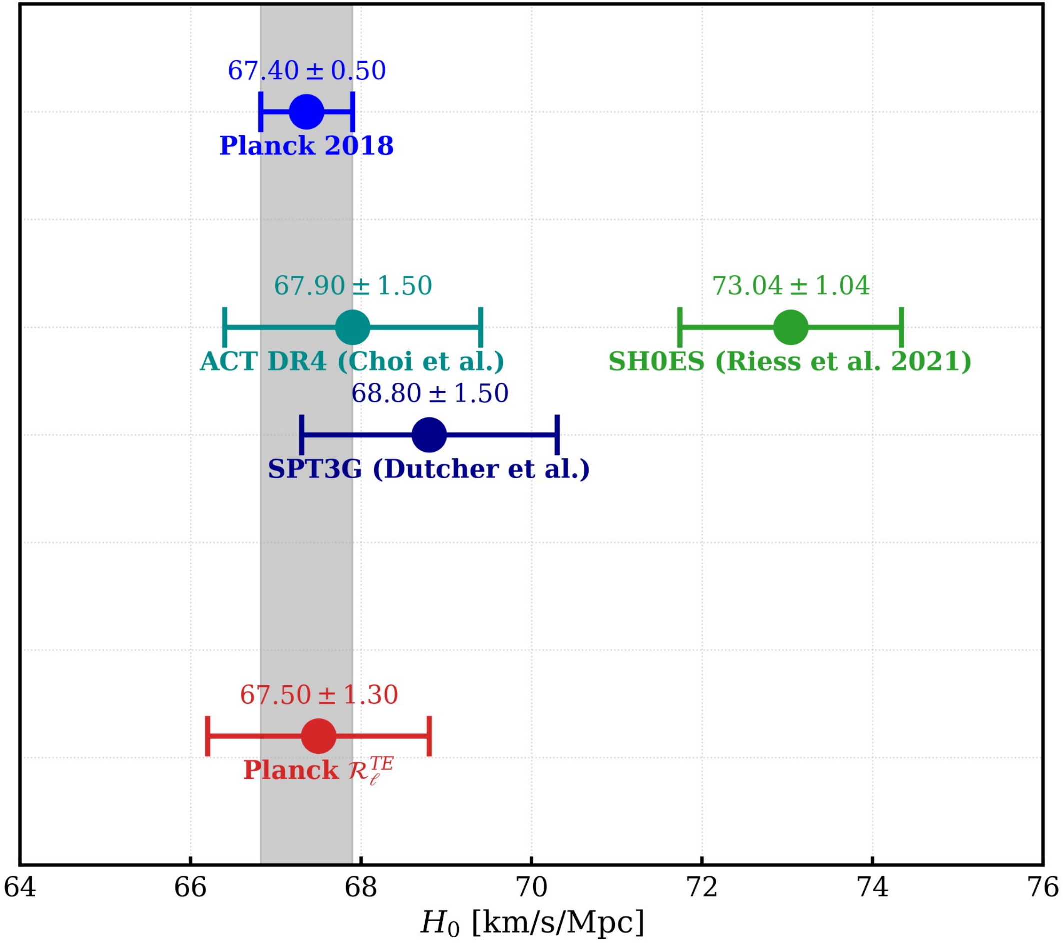
**Instrumental systematic effect biasing the value of $H_0$ inferred from the CMB**

Option 3

Physics beyond ΛCDM

# Independent measurements of $H_0$ from the ground





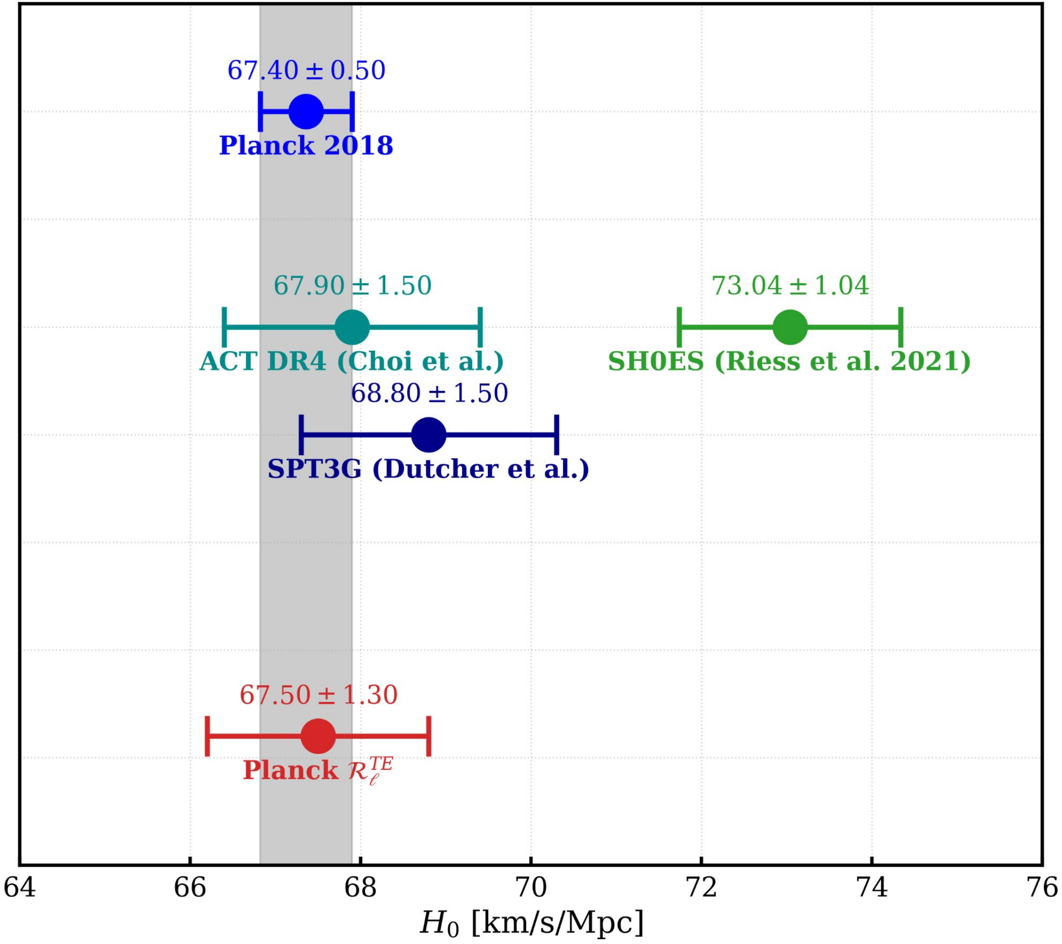

## Option 2

**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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# Early-time modification to ΛCDM



**Motivation :** obtain a higher value of $H_0$ from the CMB

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

$\theta_*$ → **Fixed by observations**

$H(z)$ →

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

# One proposed solution : Early Dark Energy



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

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

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

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

**Fixed by observations**

# EDE phenomenology



The EDE component is described as a scalar field $\phi$ (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**

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**f : decay constant**

**$\phi_i$ : initial field value**

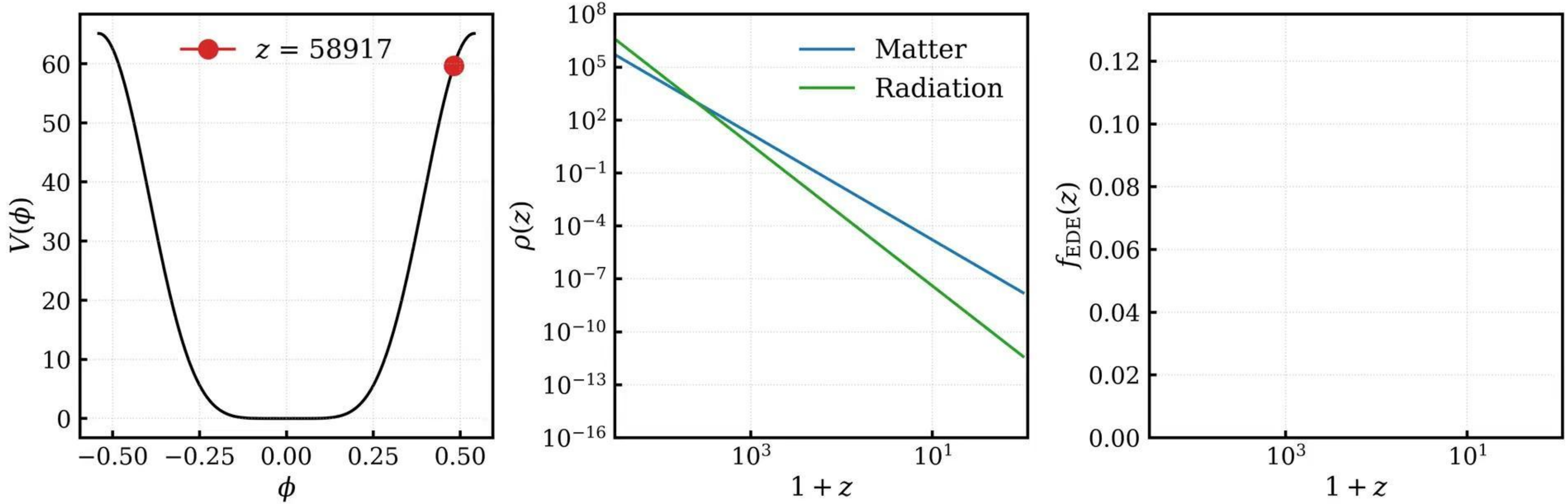
# Early Dark Energy : frozen at early times



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

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

acts as dark energy (w= - 1)



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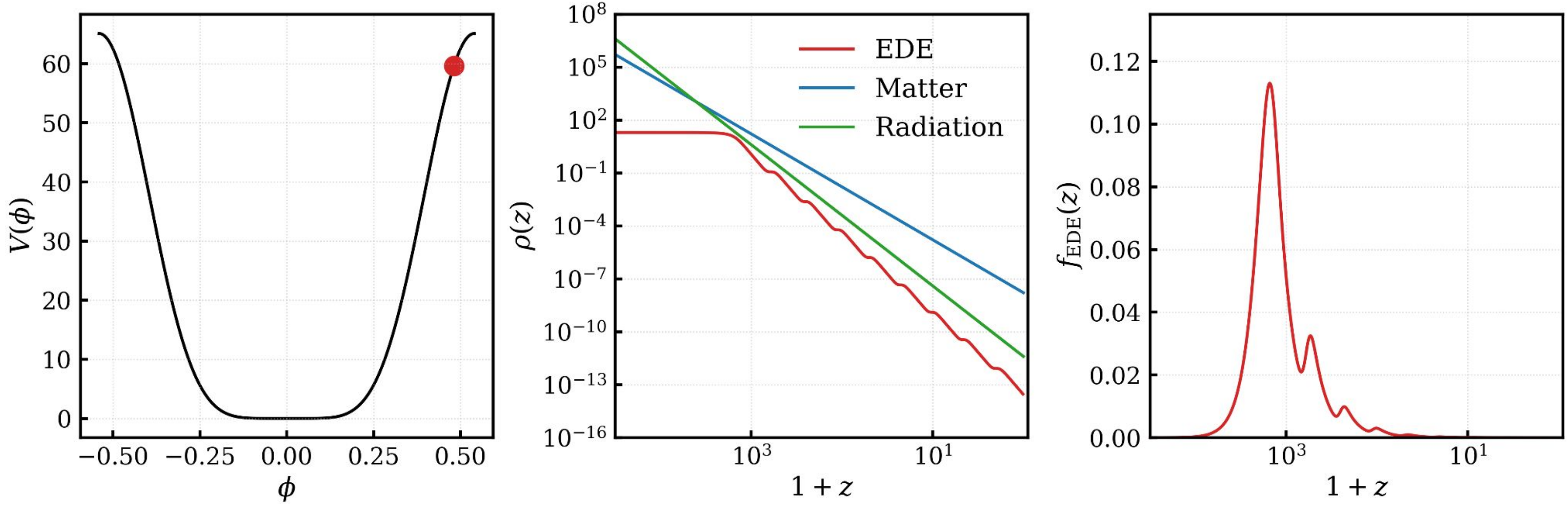
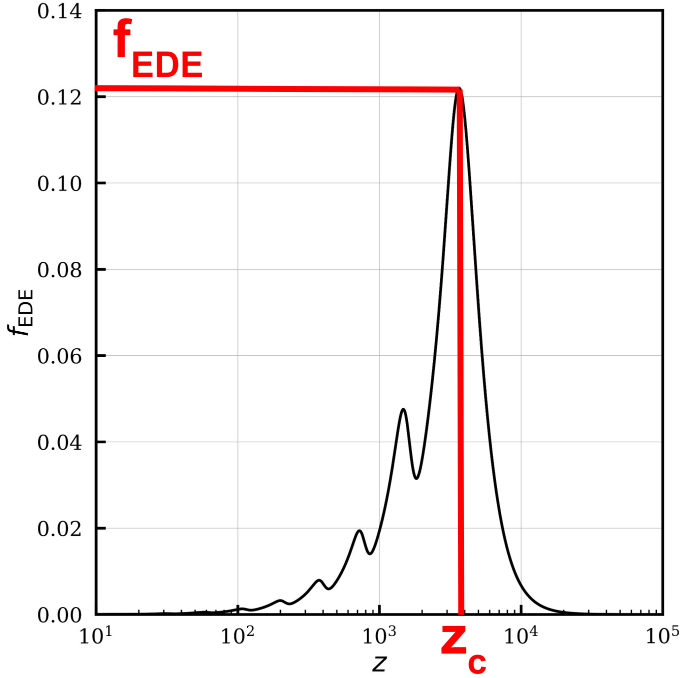


# Early Dark Energy : phenomenological parametrization 

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

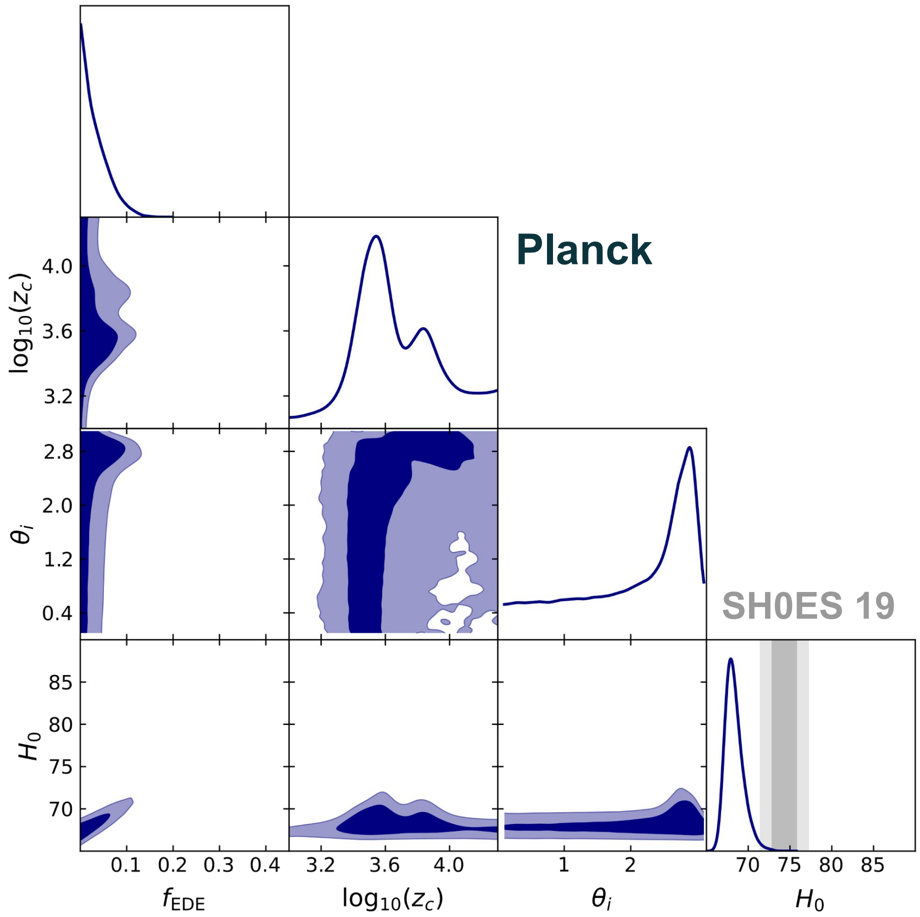
**Field parameters**

**Phenomenological parametrization**



# Constraints on EDE from Planck data

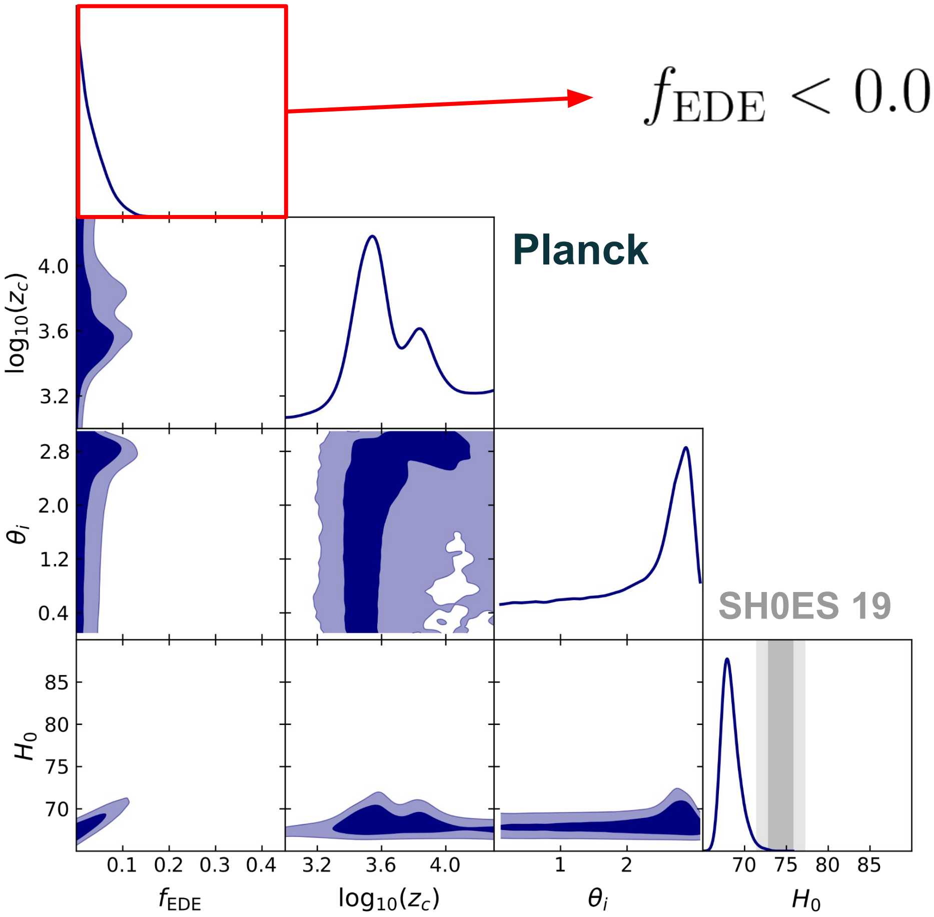





Hill+ 2020

# Constraints on EDE from Planck data



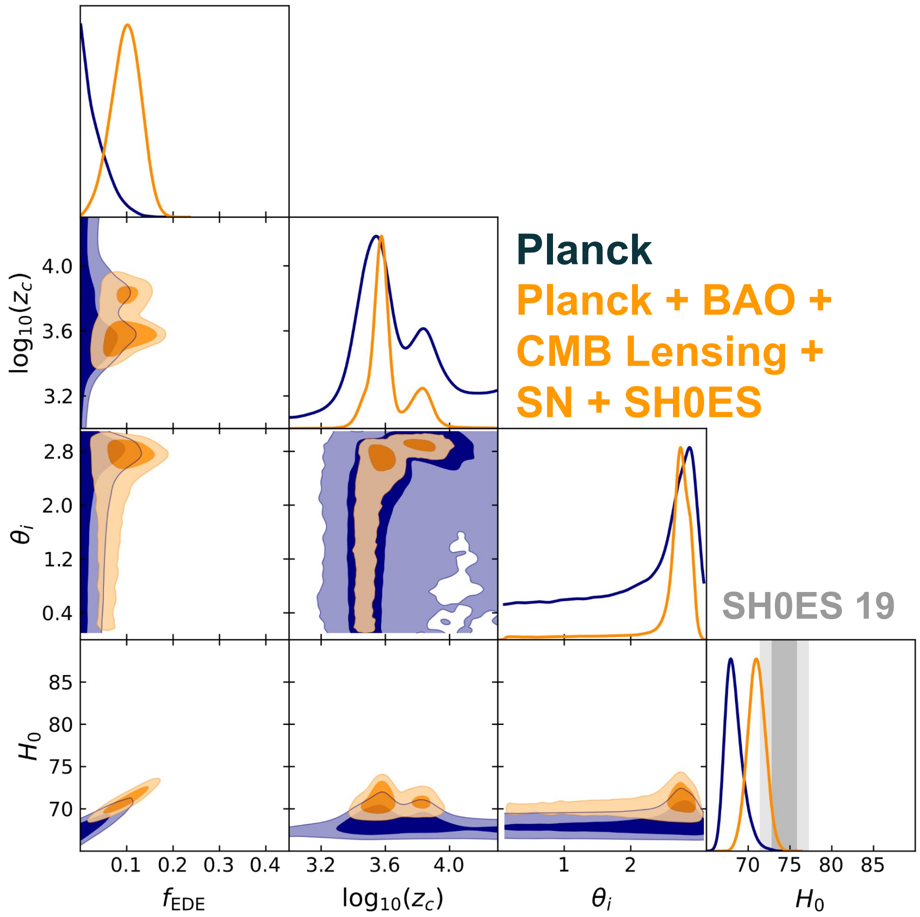



$$f_{\rm EDE} < 0.087 \ (95\% \ \text{C.L.})$$

Hill+ 2020

# Results for a combination of Planck and SH0ES data

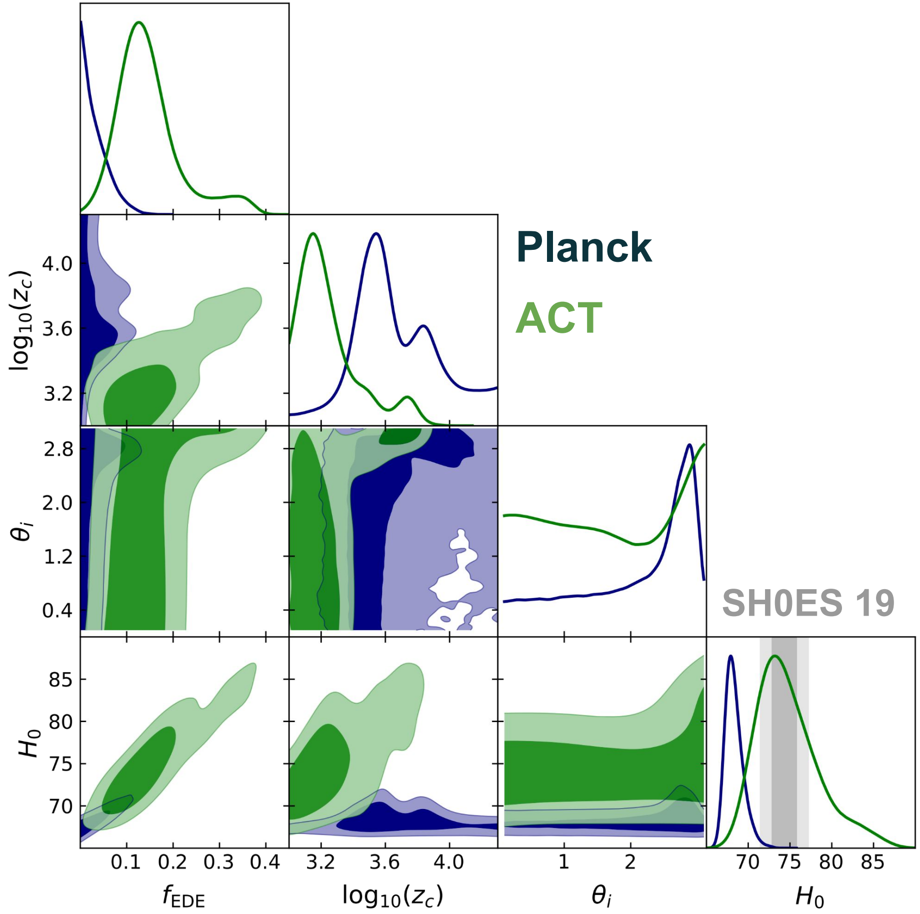





**Poulin+ 2019, Smith+ 2019, Hill+ 2020**

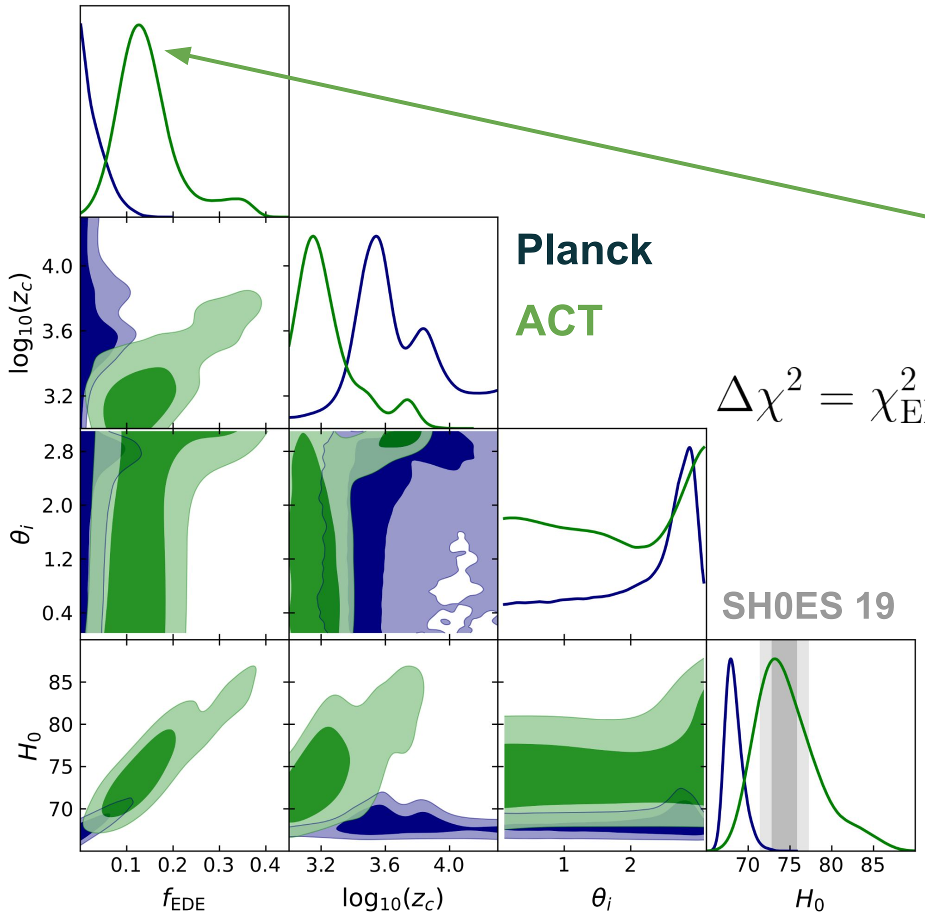
# Additional constraints from ACTPol






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

# Additional constraints from ACTPol



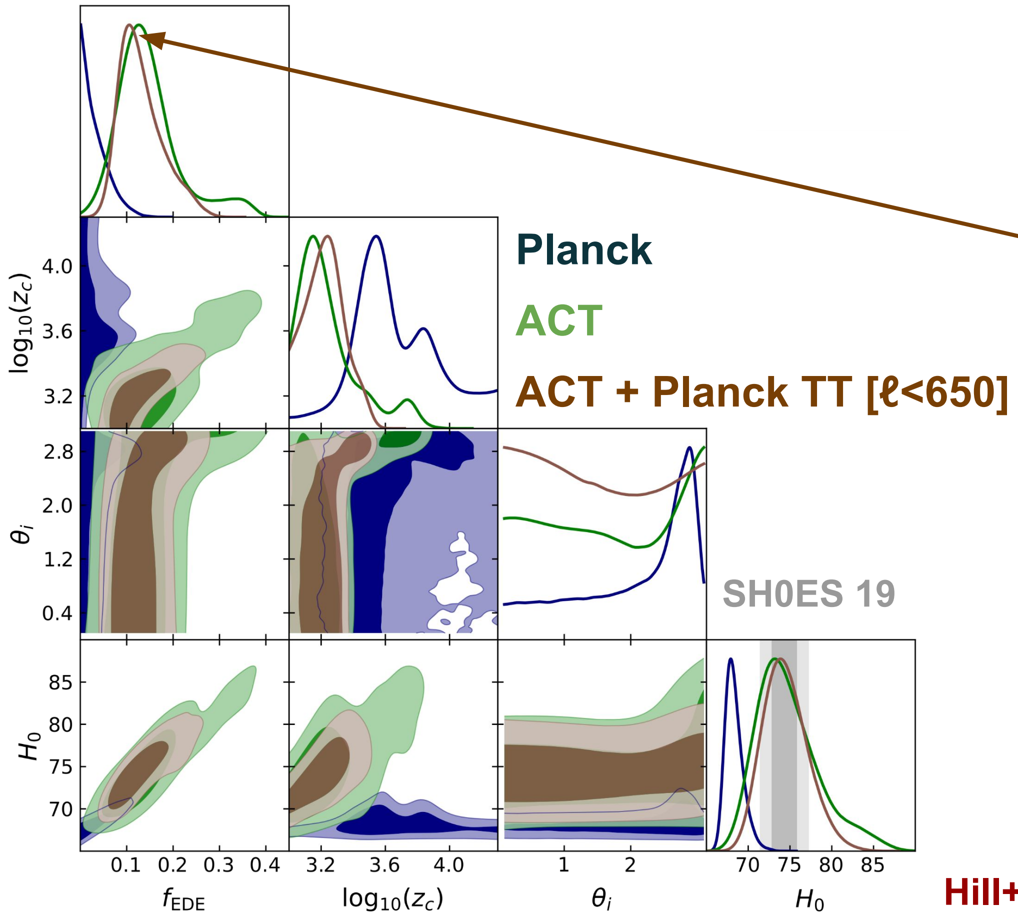

$$f_{\rm EDE} = 0.142^{+0.039}_{-0.072}\ (68\%\ {\rm C.L.})$$

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

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

# Additional constraints from ACTPol






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

$\Delta\chi^2 = -15.4$ → **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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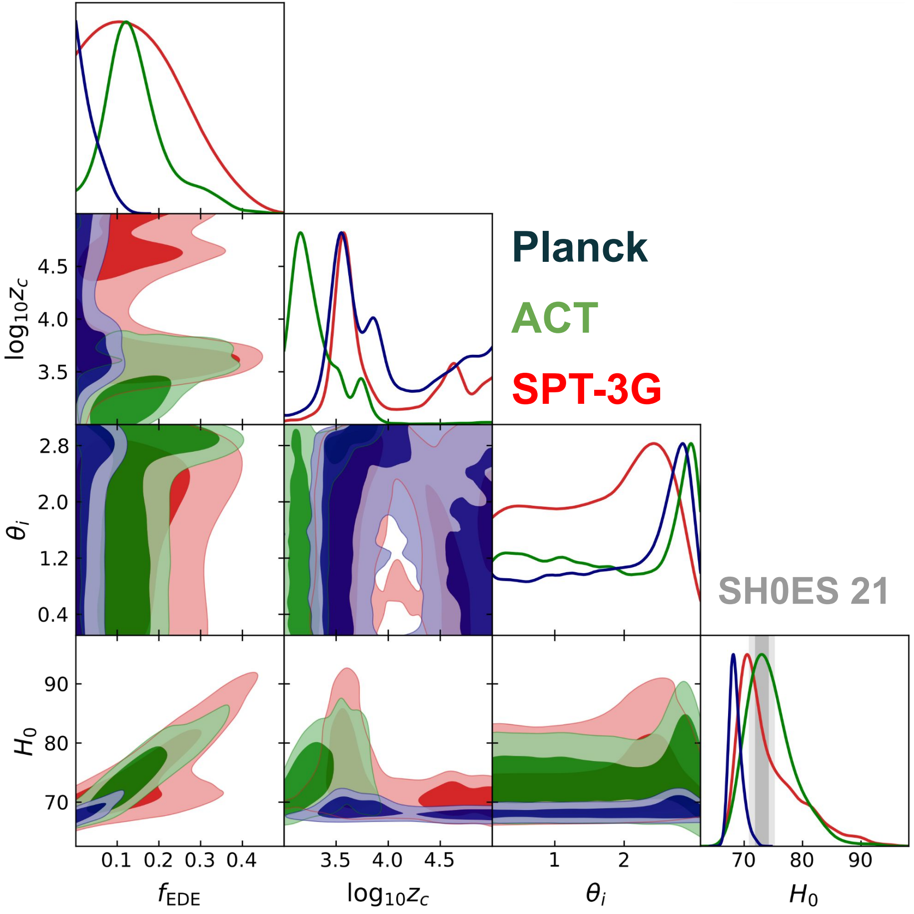
→ Motivates an analysis of EDE with public SPT-3G data

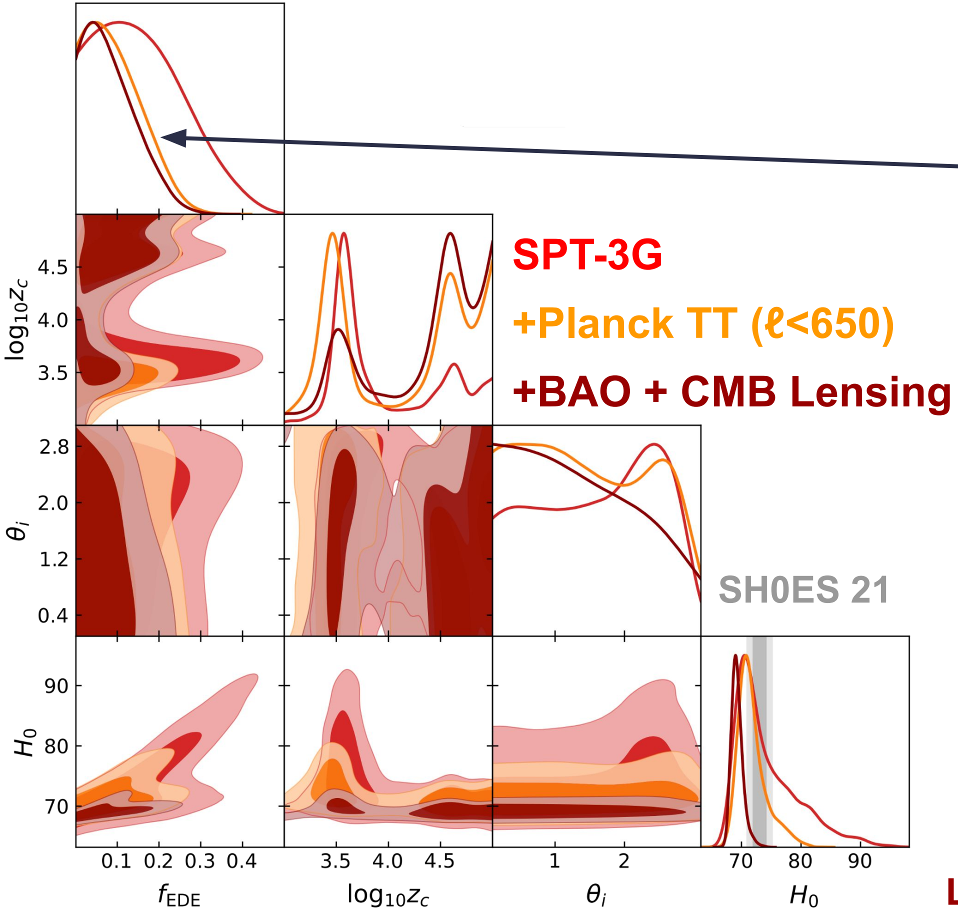
# Constraints from SPT-3G public data






La Posta+ 2021 [arXiv:2112.10754]

# Constraints from SPT-3G public data

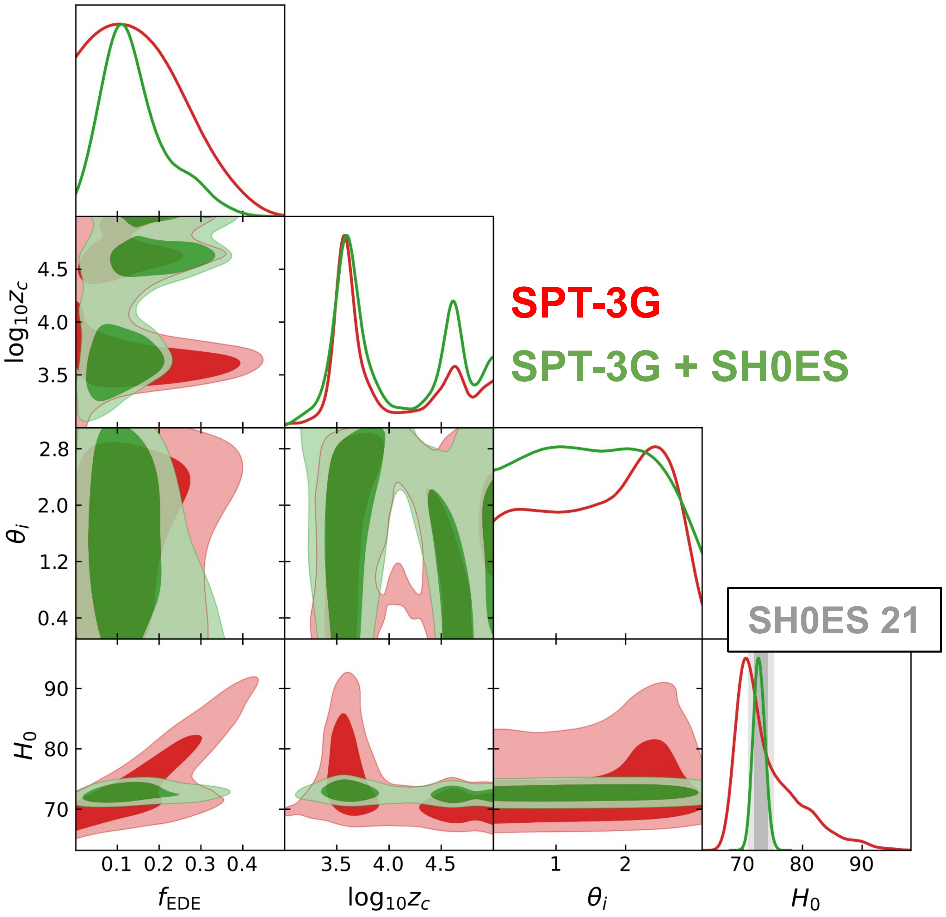



**We tighten the constraint on $f_{EDE}$ when we combine SPT3G and Planck TT (ℓ<650) or when we add LSS probes**

La Posta+ 2021 [arXiv:2112.10754]

# Combining with SH0ES constraint





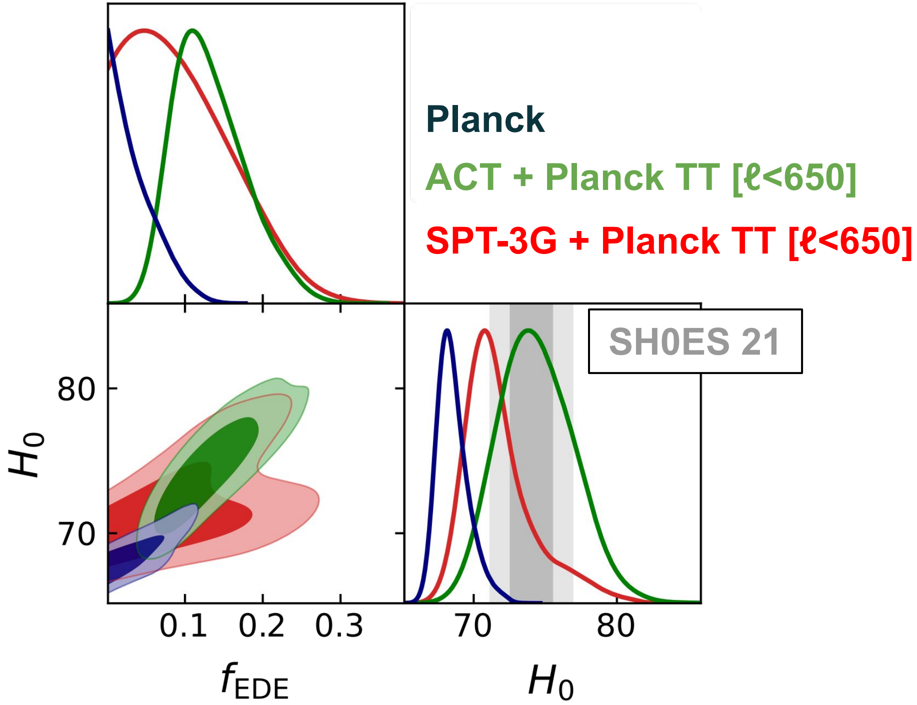

$$\Delta\chi^2_{\rm SPT-3G} = -6.3$$

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

# Conclusions

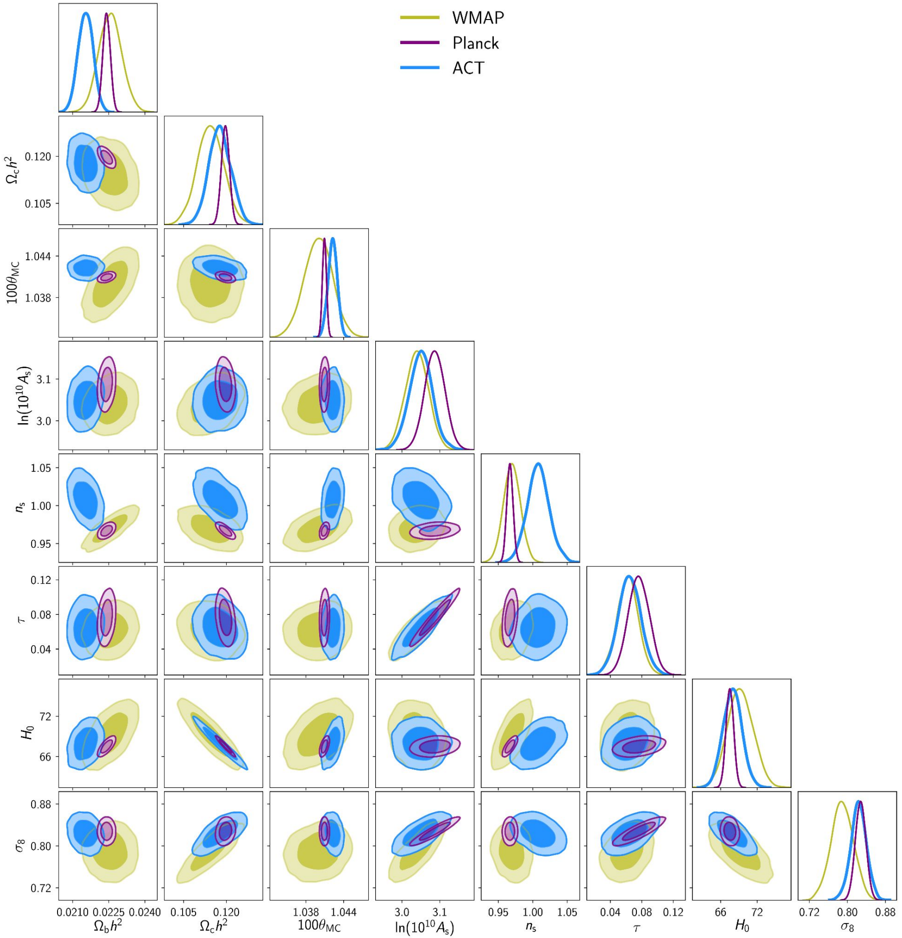


- Planck data alone do not favor high $f_{EDE}$ values
- Planck + SH0ES show a preference for $f_{EDE}$ ~ 10%
- ACT DR4 data favors EDE over ΛCDM (with $f_{EDE}$~ 10%)
- SPT-3G is not as constraining as ACT and Planck : but sees some degree of EDE when combined with SH0ES



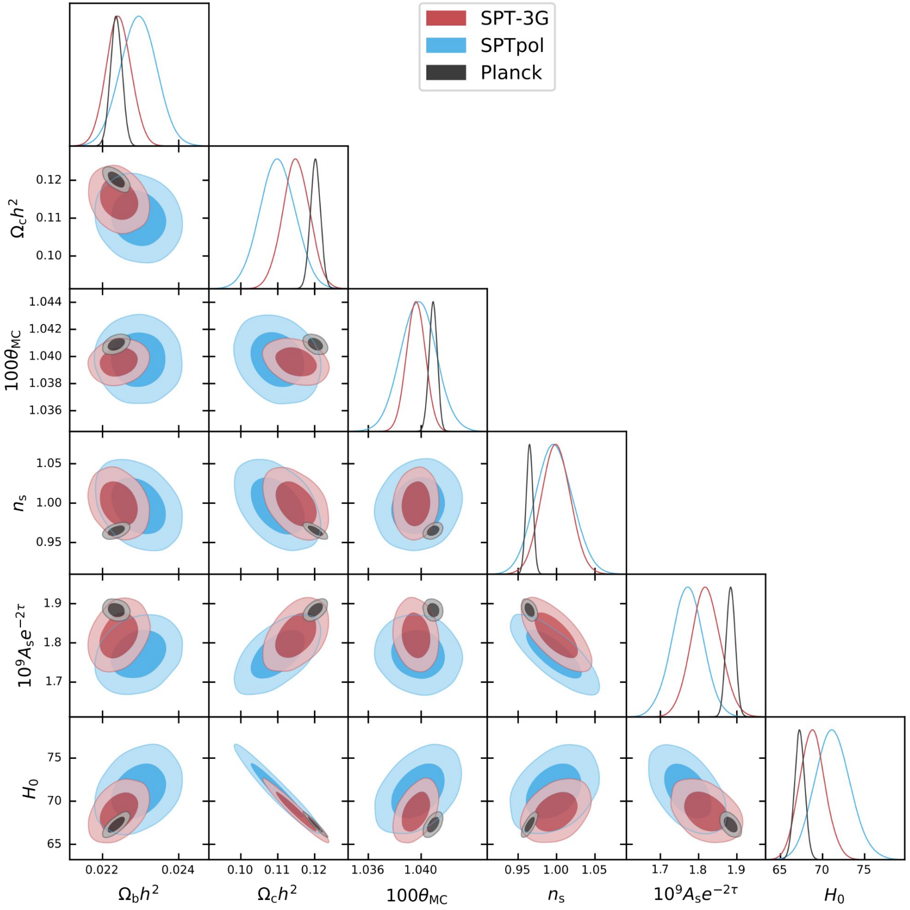
# Extra-slides

# ACTPol cosmology



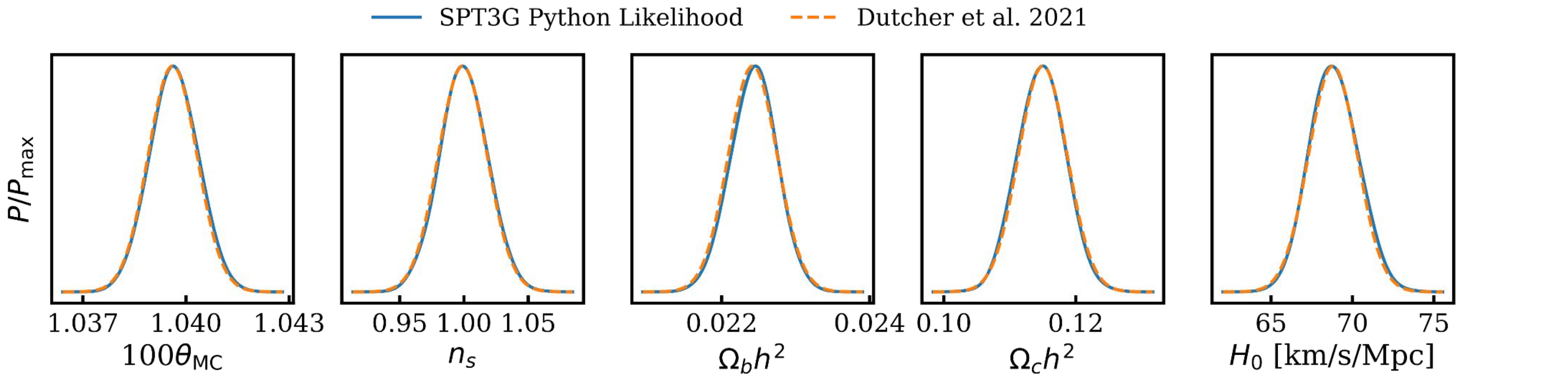

Aiola+ 2020

# SPT-3G cosmology

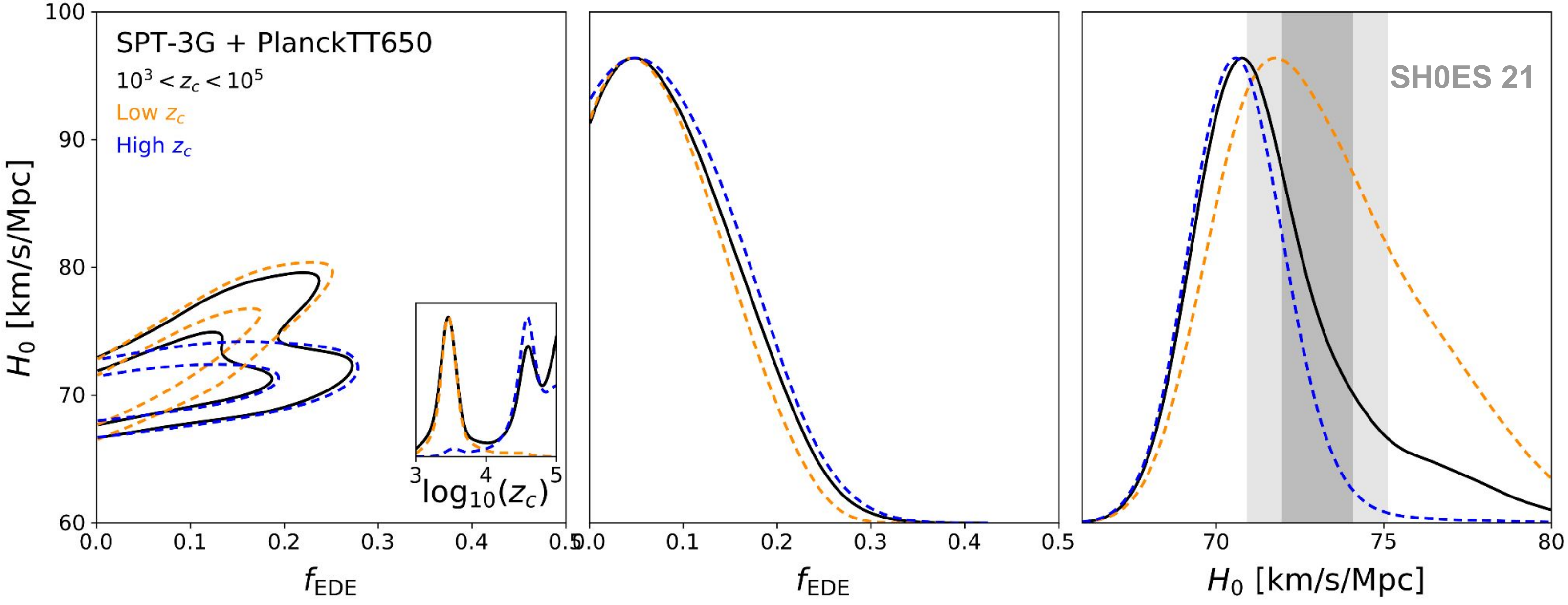



**Dutcher+ 2021**

# SPT-3G python implementation

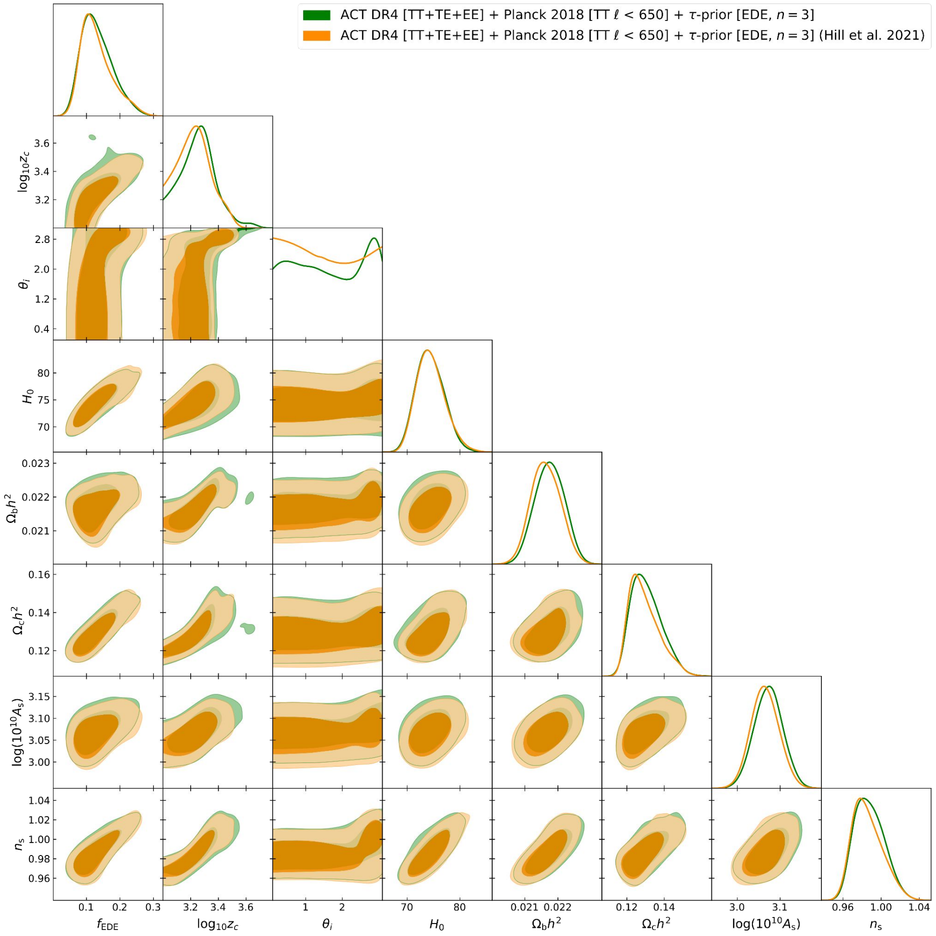


# Impact of the $z_c$ prior



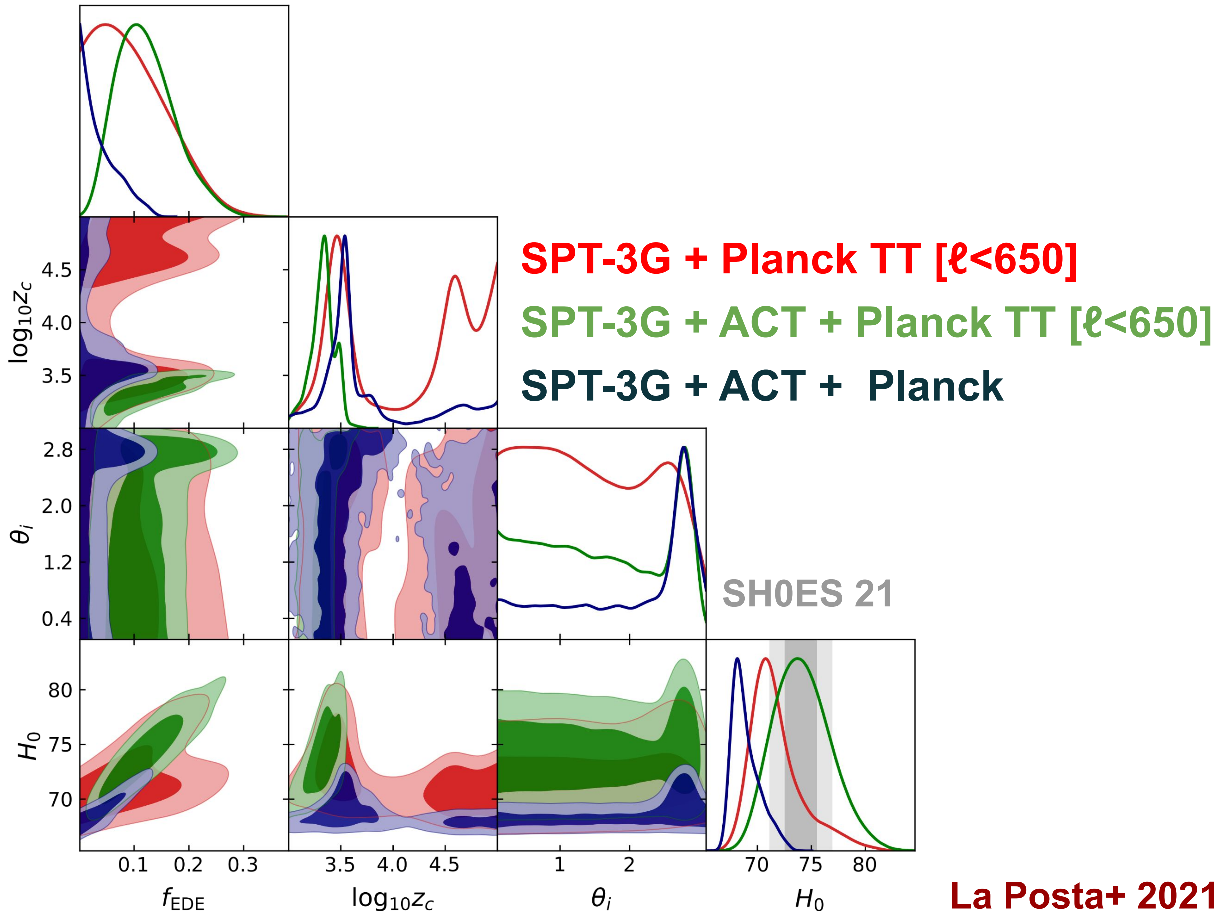

La Posta+ 2021 [arXiv:2112.10754]

# CAMB/CLASS EDE models



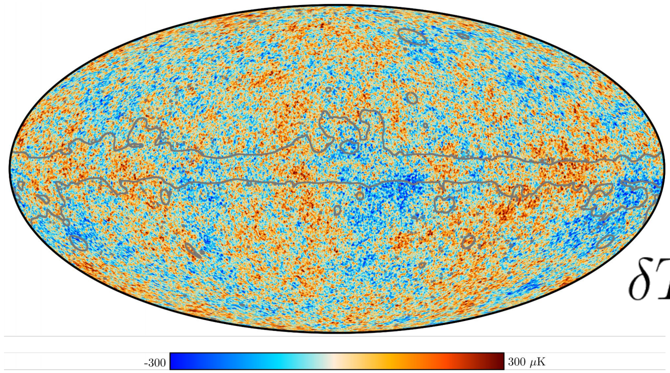

Hill+...La Posta+... 2021

# Combining with other CMB datasets

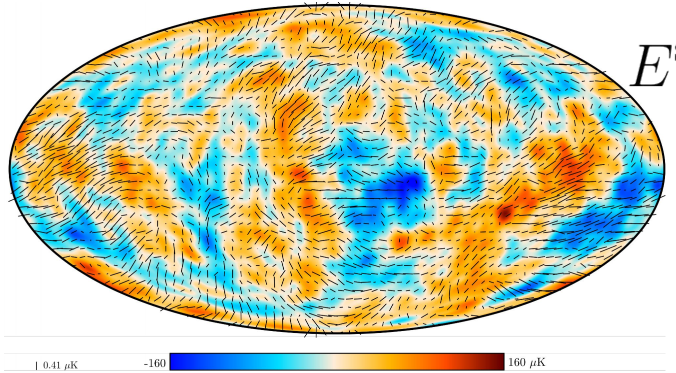



La Posta+ 2021 [arXiv:2112.10754]

# Systematics in the CMB




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




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

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

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

# Systematics in the CMB

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

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

# Systematics in the CMB

- **Finite angular resolution (beams)**

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

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

**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

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

- **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

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

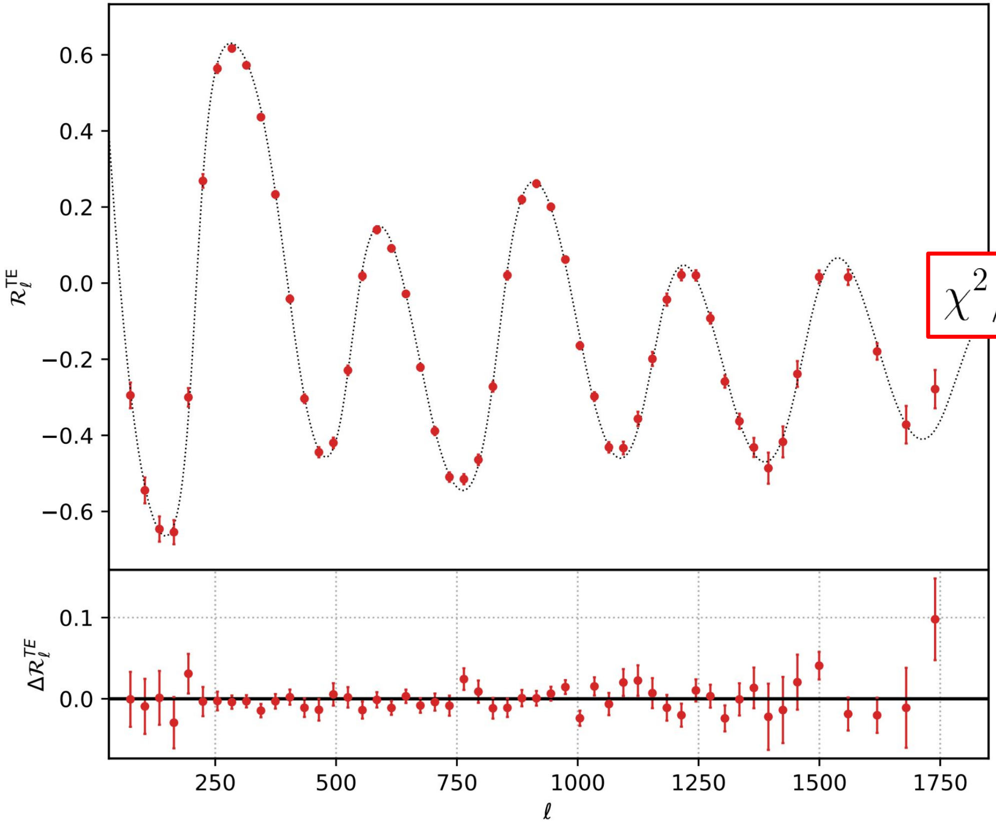
$$\mathcal{R}_\ell^{TE,\mathrm{obs}} = \frac{\mathcal{F}_\ell^{T} \mathcal{F}_\ell^{E} c^2 c_E B_\ell^{T} B_\ell^{E} C_\ell^{TE}}{\sqrt{(\mathcal{F}_\ell^{T})^2 c^2 (B_\ell^{T})^2 C_\ell^{TT} \times (\mathcal{F}_\ell^{E})^2 c^2 c_E^2 (B_\ell^{E})^2 C_\ell^{EE}}}$$

# Correlation coefficient 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



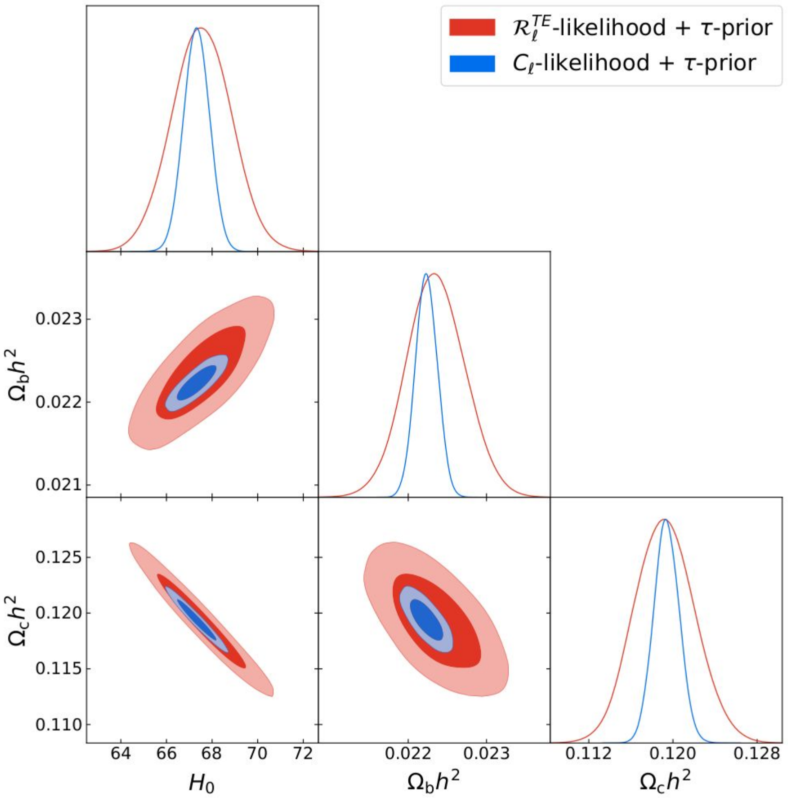

**Bestfit from Planck TT,TE,EE**

**Planck correlation coefficient**

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

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

# Cosmological results from $R^{TE}$

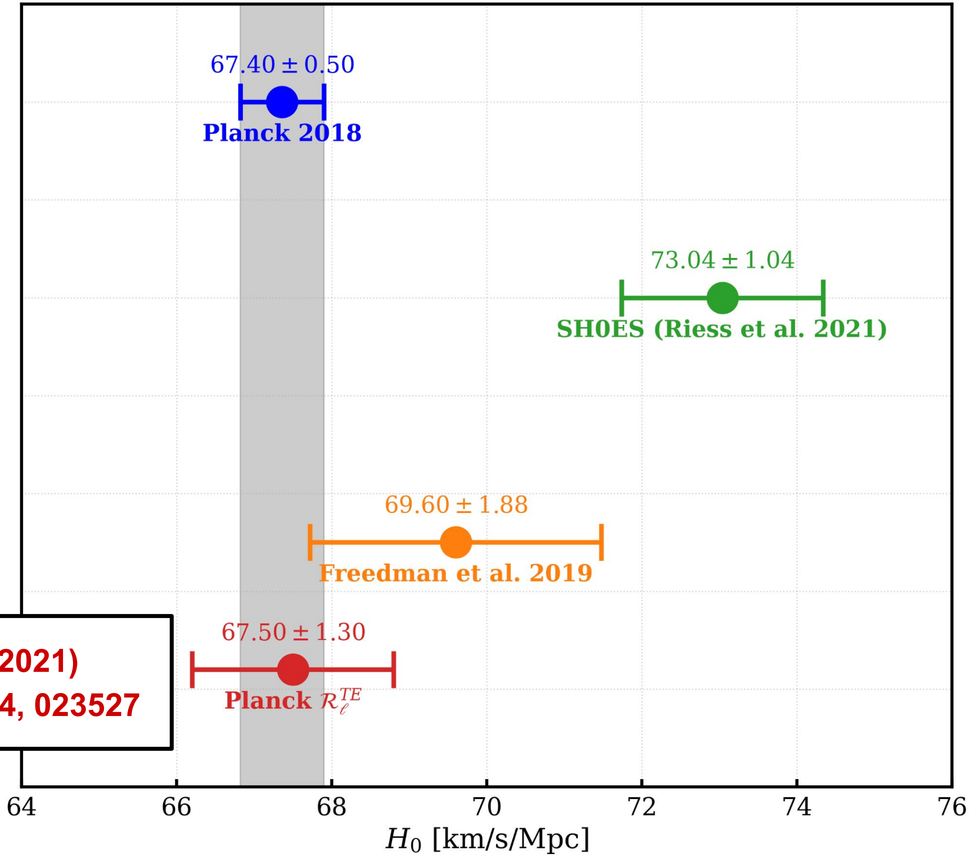



**3.3σ** away from the latest SH0ES measurement

**$H_0$ = 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