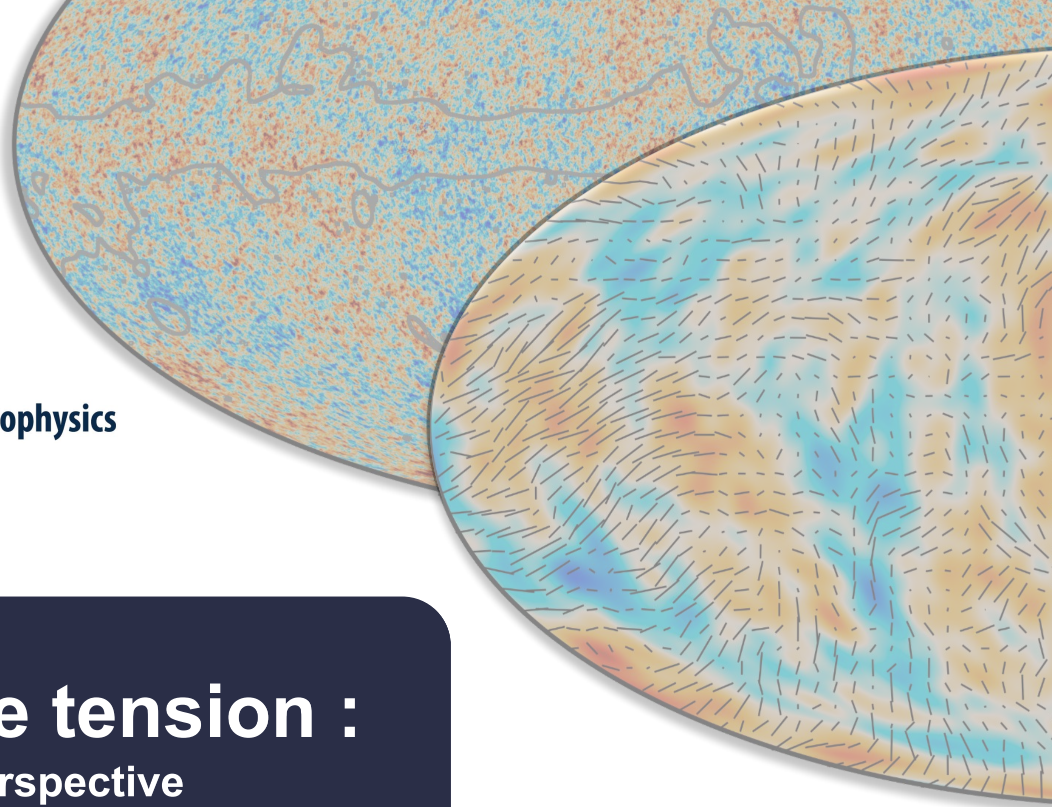

The Hubble tension :
a CMB perspective

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link CAT, Séminaire Doctorants– 08/06/22

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

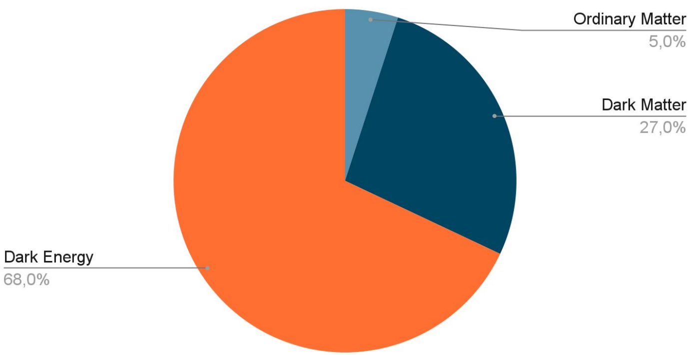
$$H^2(z) = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\left[(\rho_b^0 + \rho_c^0)(1+z)^3 + \rho_r^0(1+z)^4 + \rho_\Lambda\right]$$

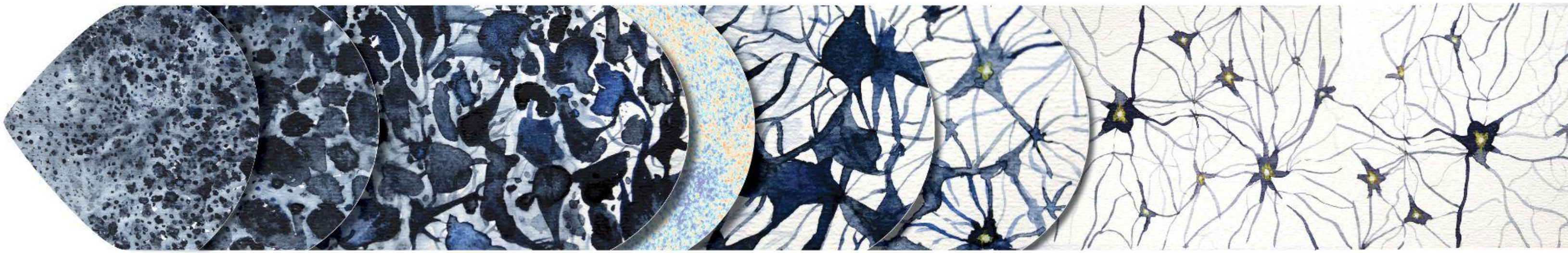
baryon

CDM

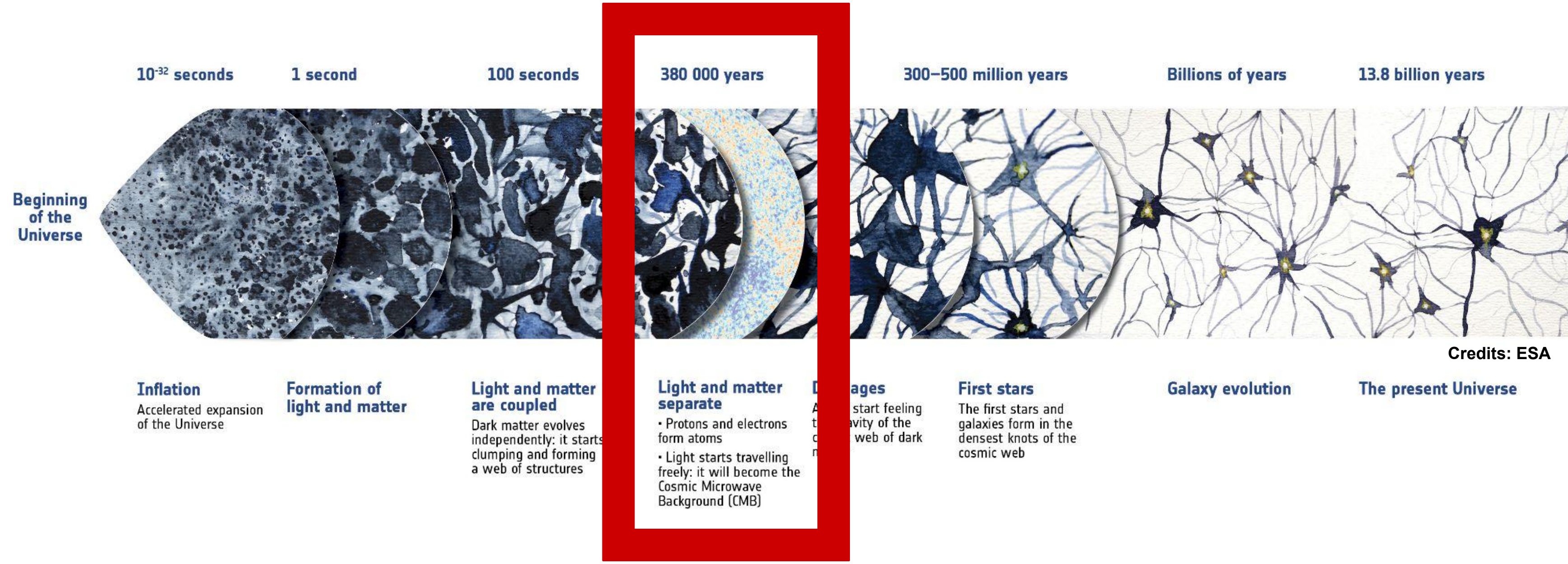
radiation

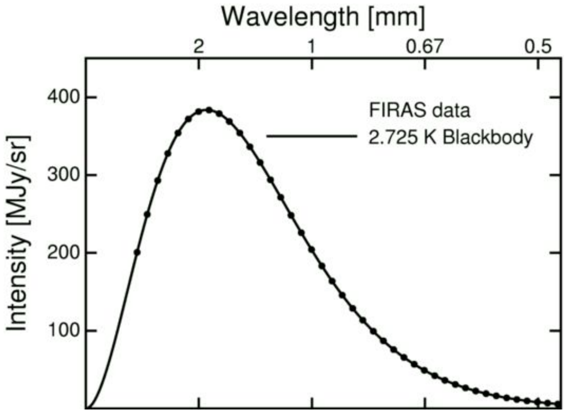
dark energy



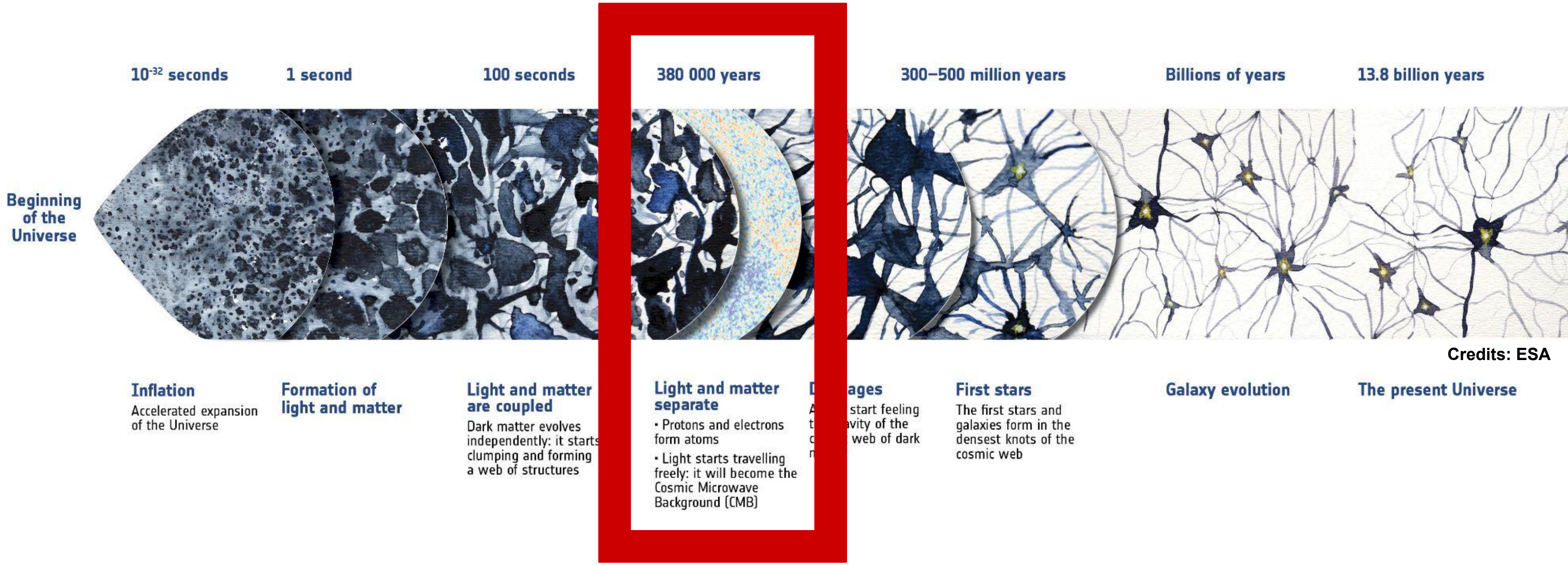

Beginning of the Universe
10^{-32} seconds
Inflation
Accelerated expansion of the Universe
1 second
Formation of light and matter
100 seconds
Light and matter are coupled
Dark matter evolves independently: it starts clumping and forming a web of structures
380 000 years
Light and matter separate
• Protons and electrons form atoms
• Light starts travelling freely: it will become the Cosmic Microwave Background (CMB)
Dark ages
Atoms start feeling the gravity of the cosmic web of dark matter
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

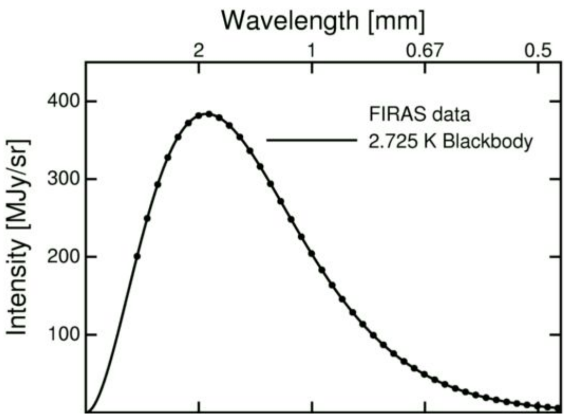
Credits: ESA





Nearly isotropic blackbody spectrum at T = 2.725 K

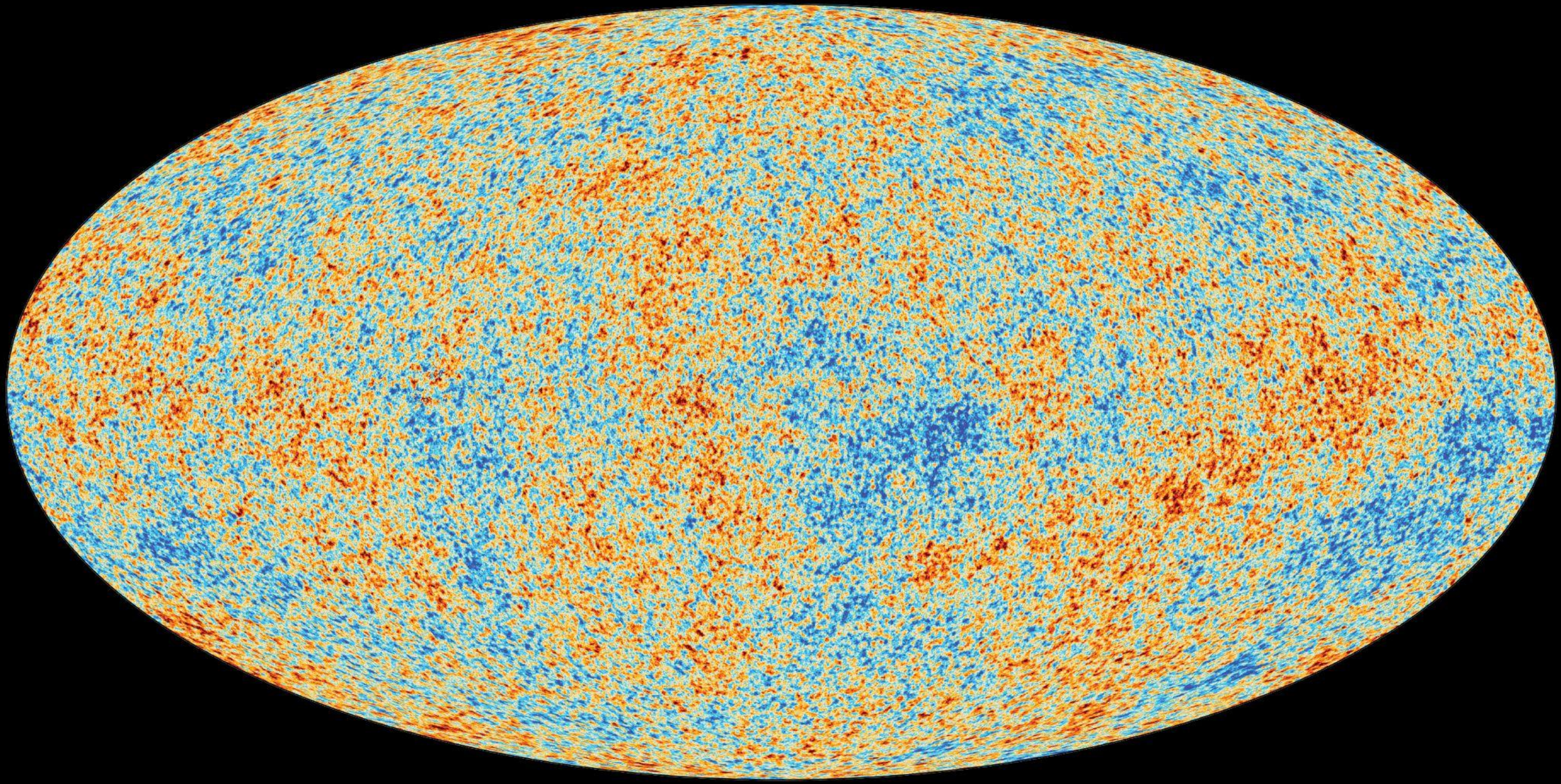




Nearly isotropic blackbody spectrum at T = 2.725 K

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

CMB temperature as measured by the Planck satellite

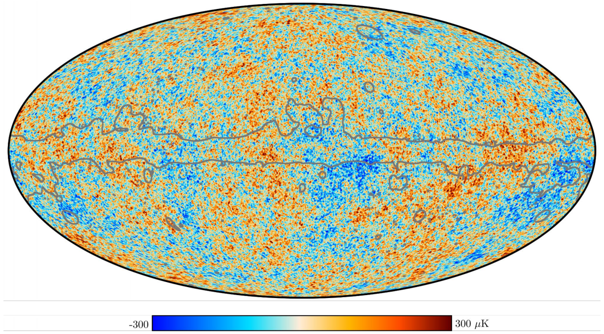


Credits: ESA

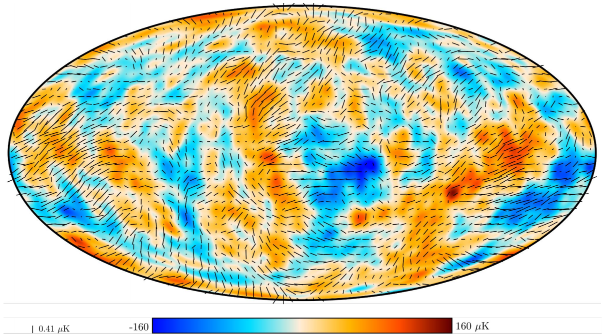
How to do cosmology from the CMB ?

Measuring the statistical properties of the CMB

Temperature



Polarization E-modes



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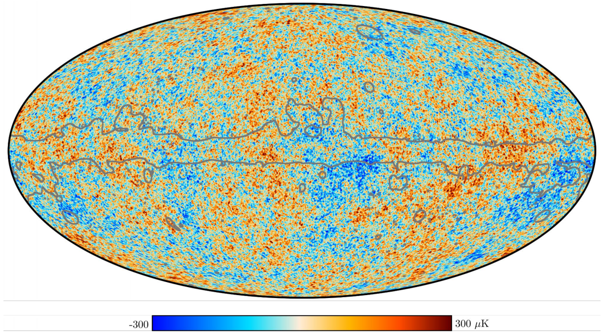
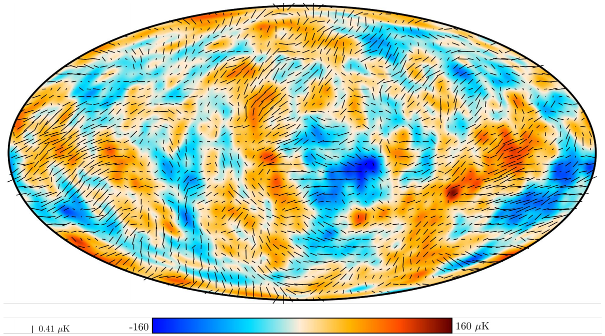


Polarization E-modes



Spherical harmonics

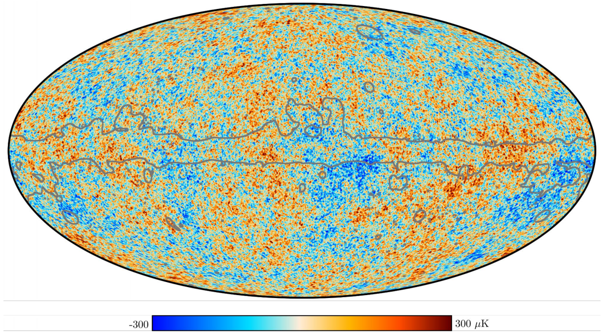
$$\delta T(\hat{n}) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m}^{T} Y_{\ell}^{m}(\theta, \phi)$$

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

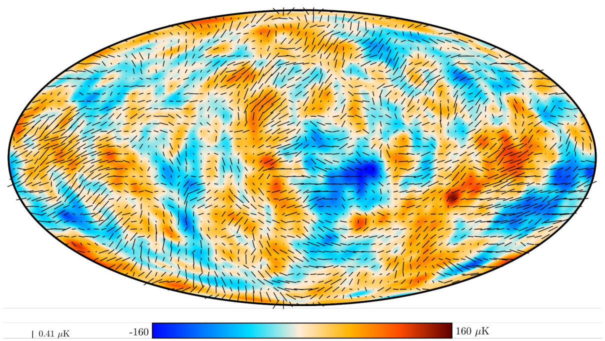
How to do cosmology from the CMB ?

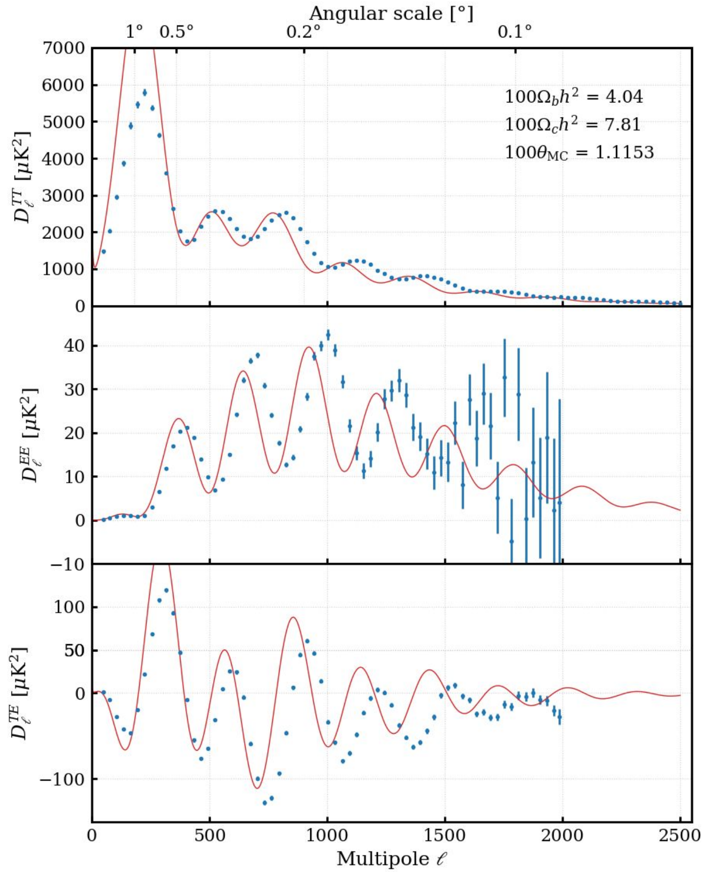
Measuring the statistical properties of the CMB

Temperature



Polarization E-modes

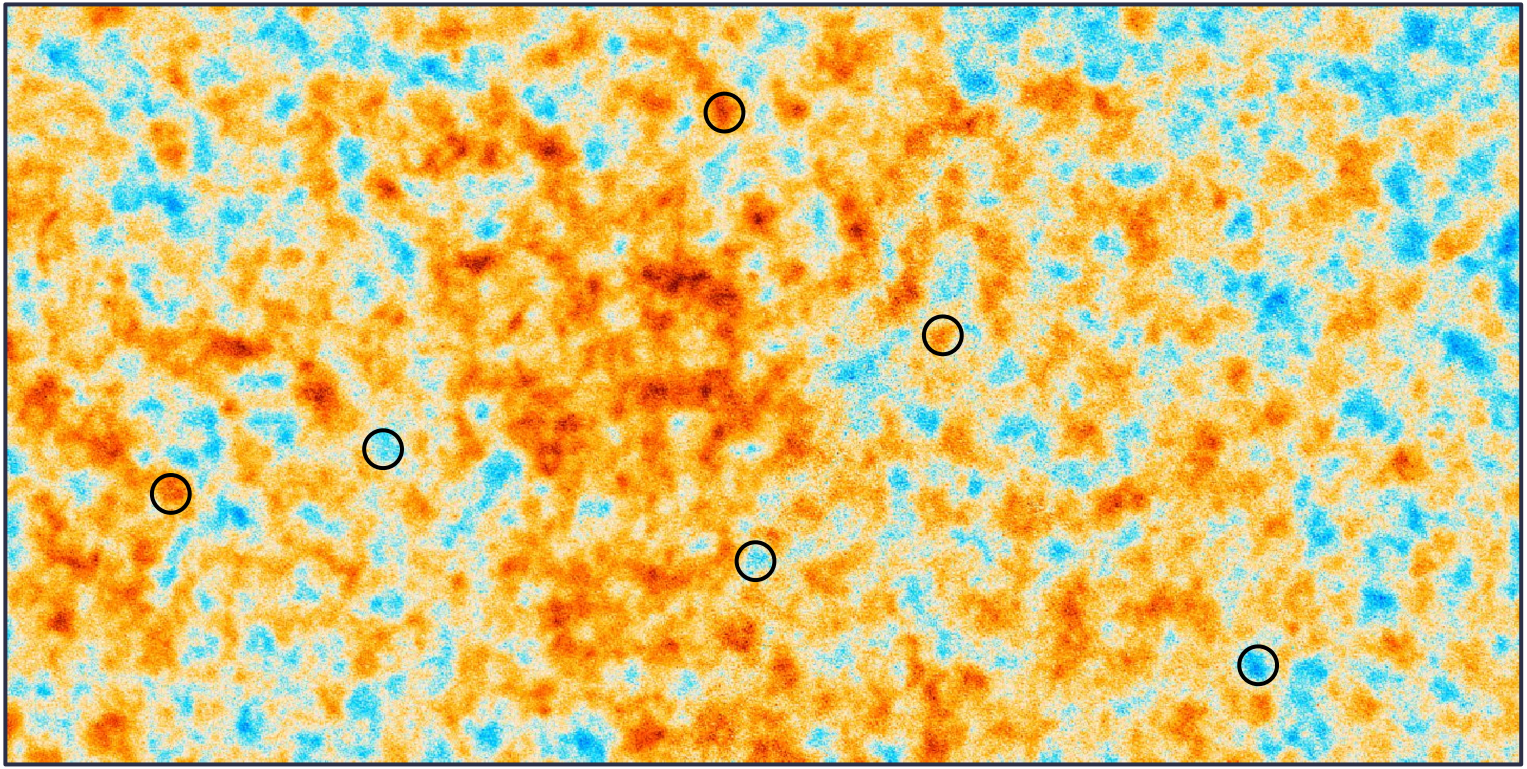




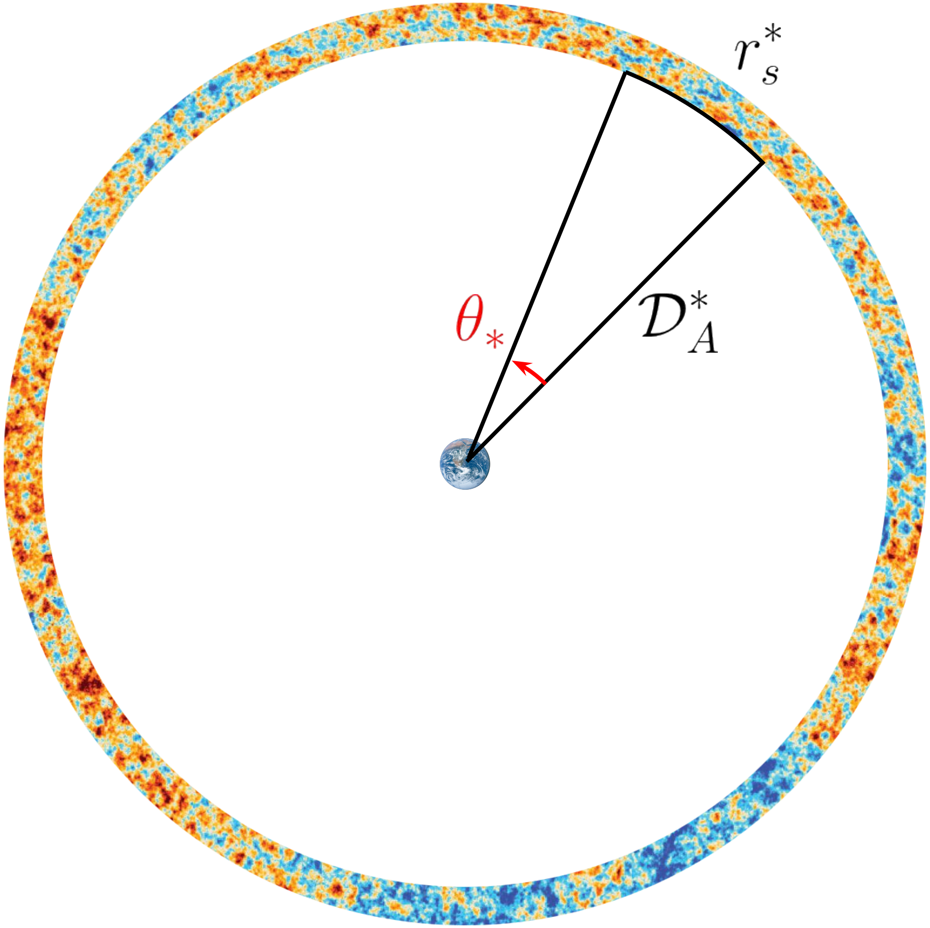
How to measure H_0 from the CMB ?

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

$z \sim 1100$

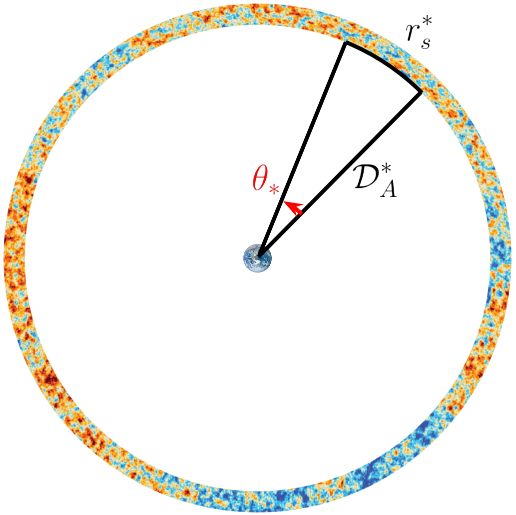


How to measure H_0 from the CMB ?



How to measure H_0 from the CMB ?

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

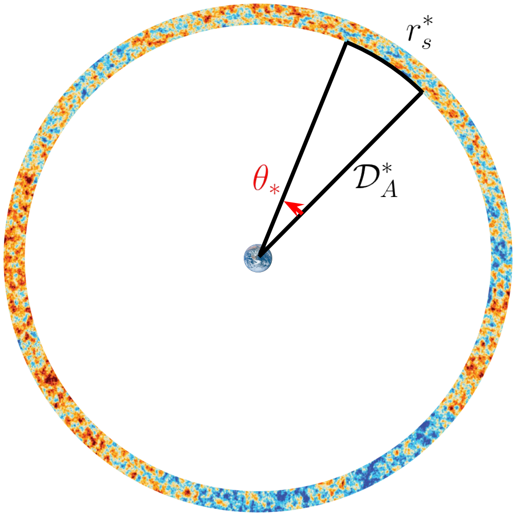


How to measure H_0 from the CMB ?

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

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

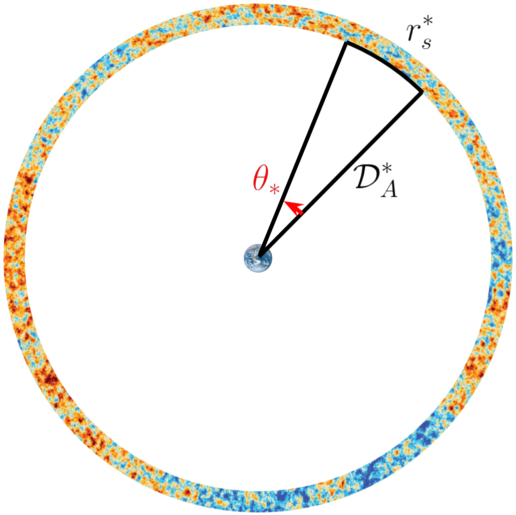
$$H^2_{\text{early}}(z) = \frac{8\pi G}{3}\left[\rho_r^0 (1+z)^4 + (\rho_b^0 + \rho_c^0)(1+z)^3\right]$$



How to measure H_0 from the CMB ?

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

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

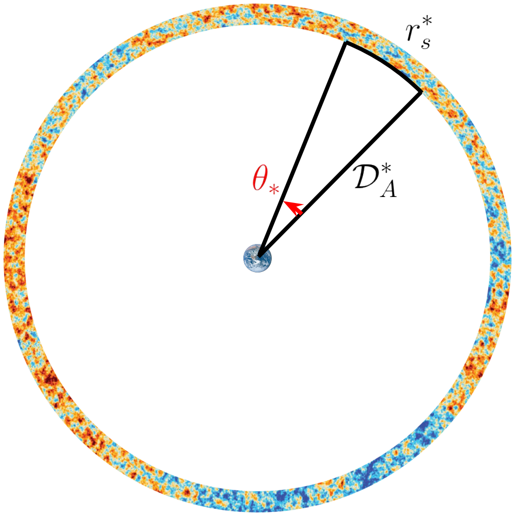


How to measure H_0 from the CMB ?

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 ?

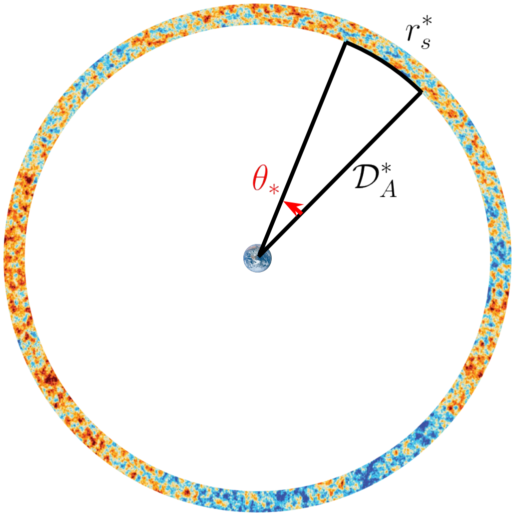
Now $\mathcal{D}_A^*$ is known

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

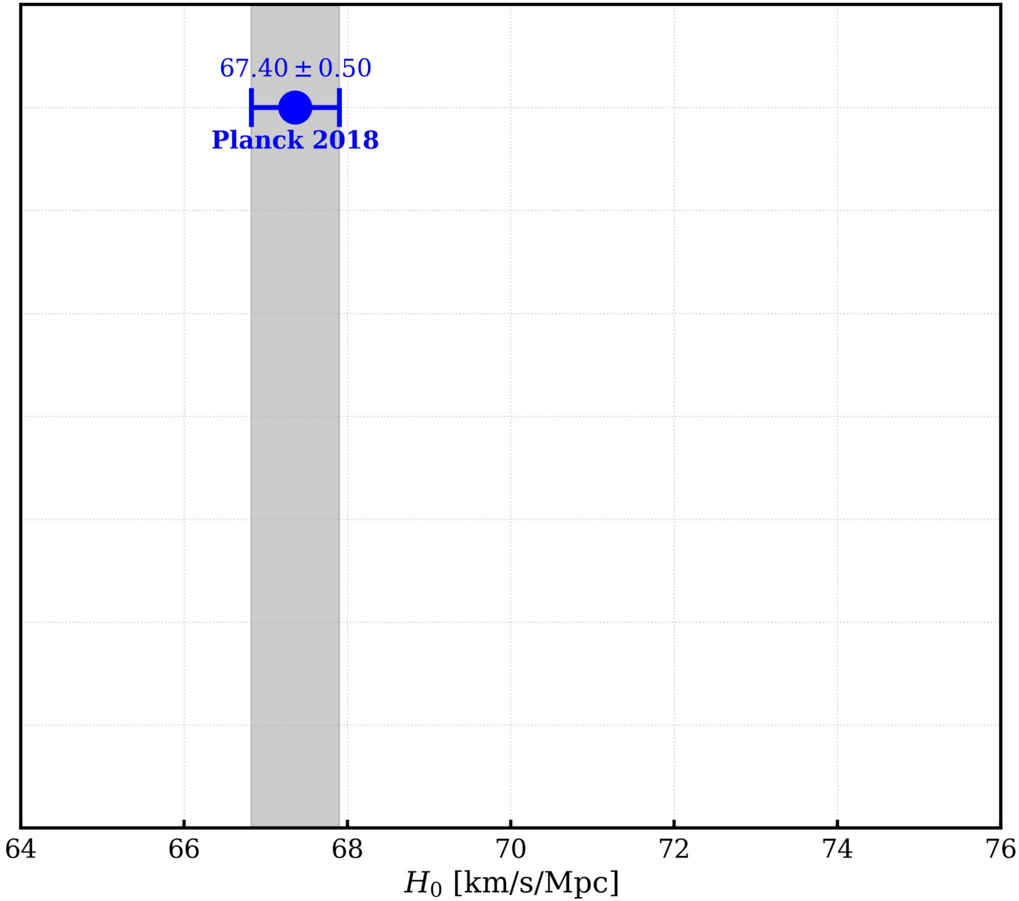
$$\mathcal{D}_A^* = c\int_0^{z^*} \frac{dz}{H(z)}$$

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

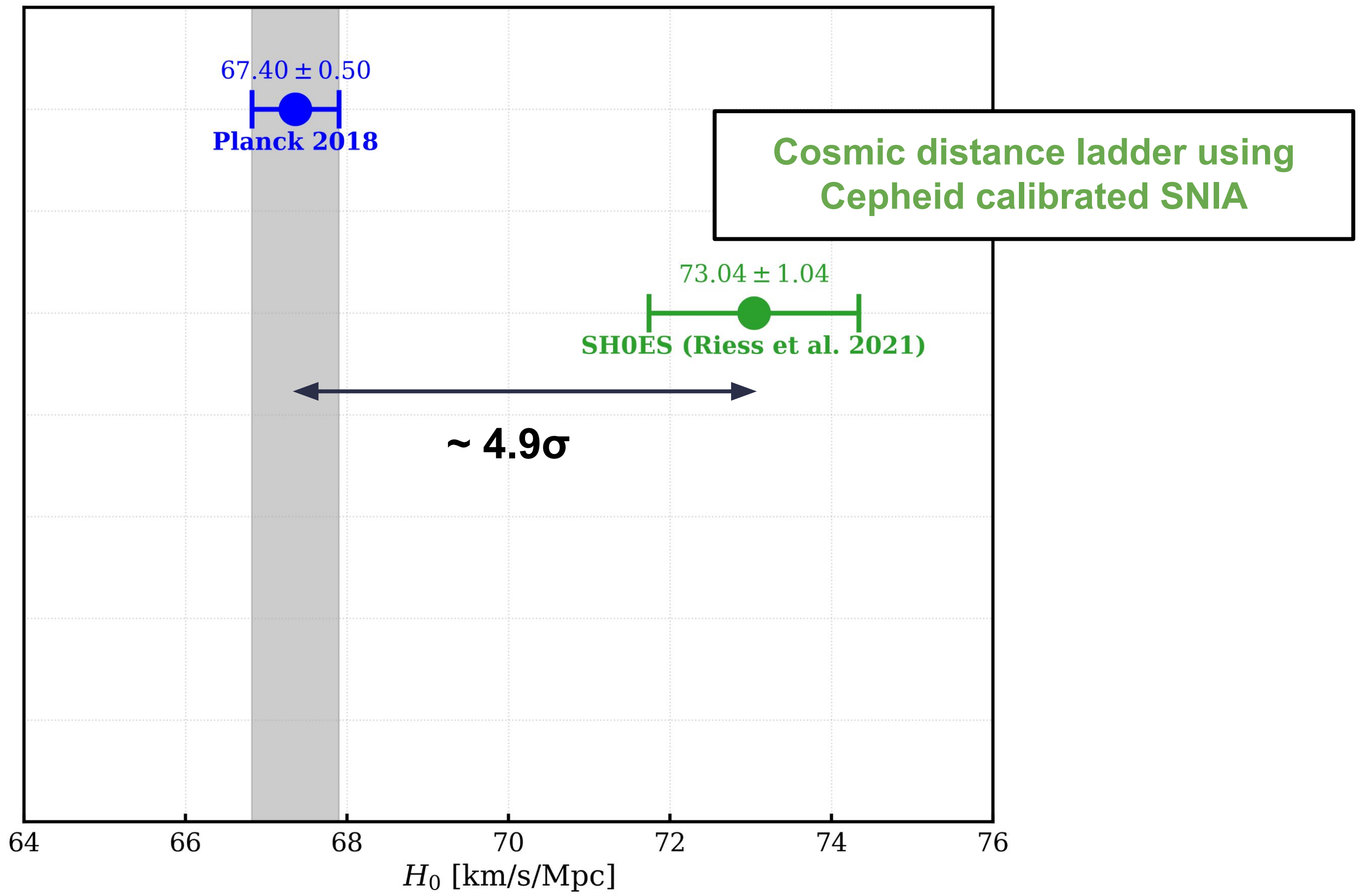
$$H_0^2 = \frac{8\pi G}{3}\left[\rho_b^0 + \rho_c^0 + \rho_\Lambda\right]$$



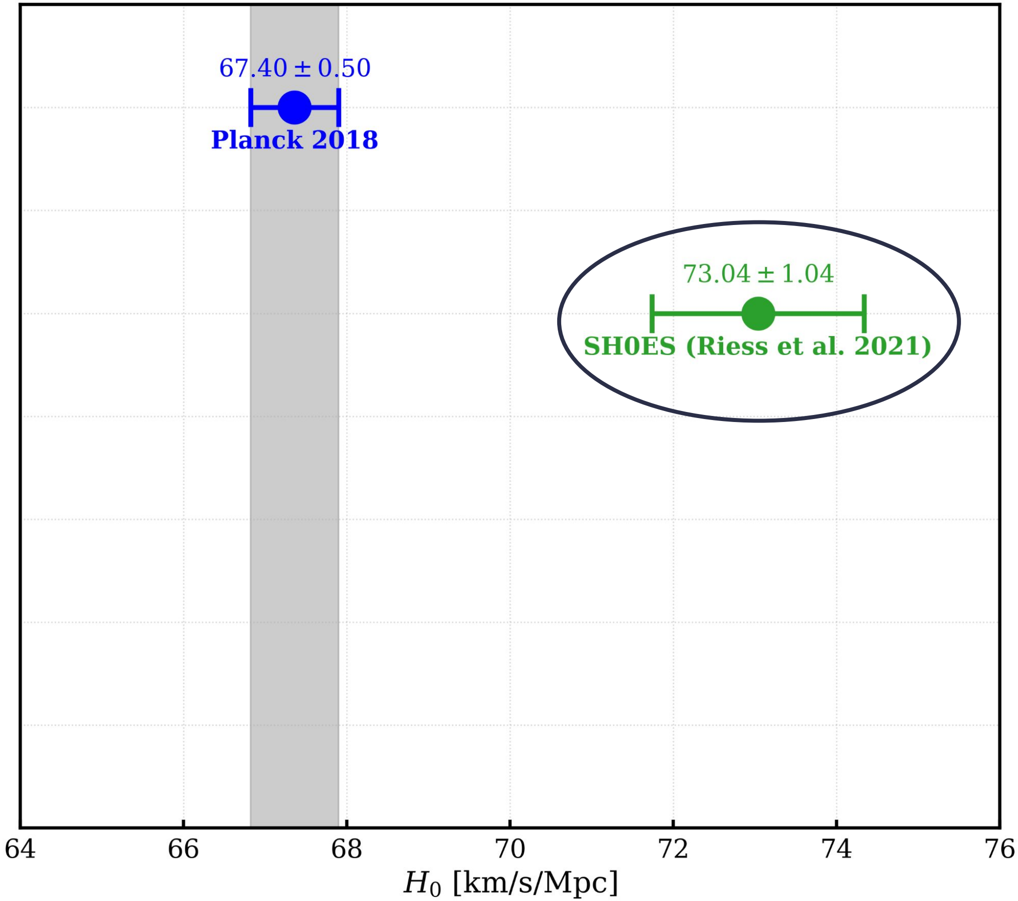
Measurement from Planck data …



… and here comes the tension



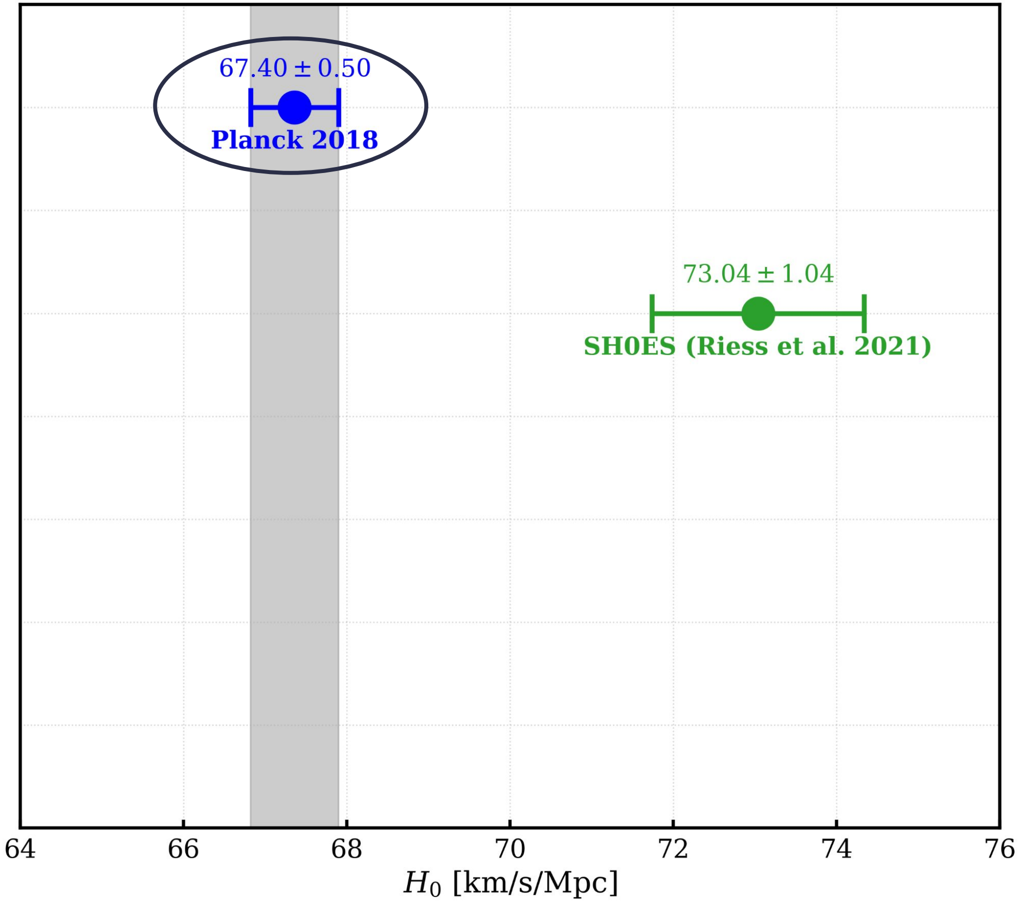
… and here comes the tension



Option 1

Astrophysical biases affecting the local measurement of H_0

… and here comes the tension



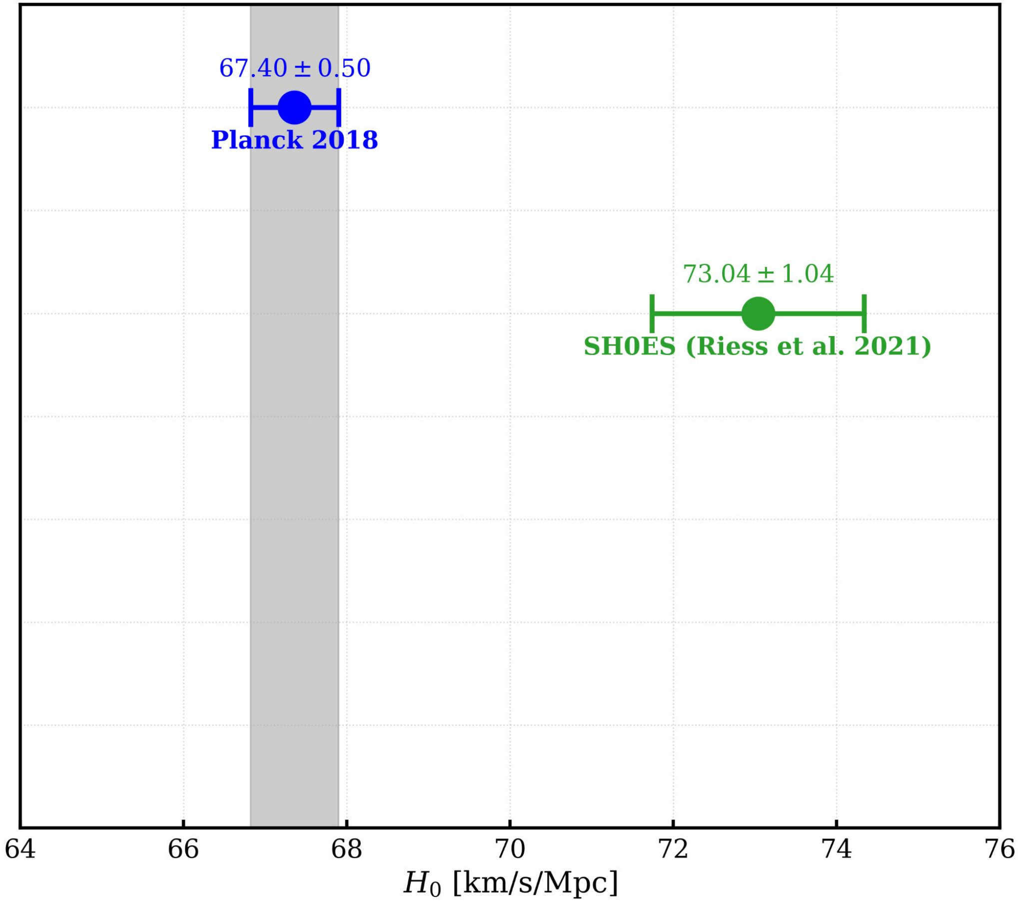
Option 1

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

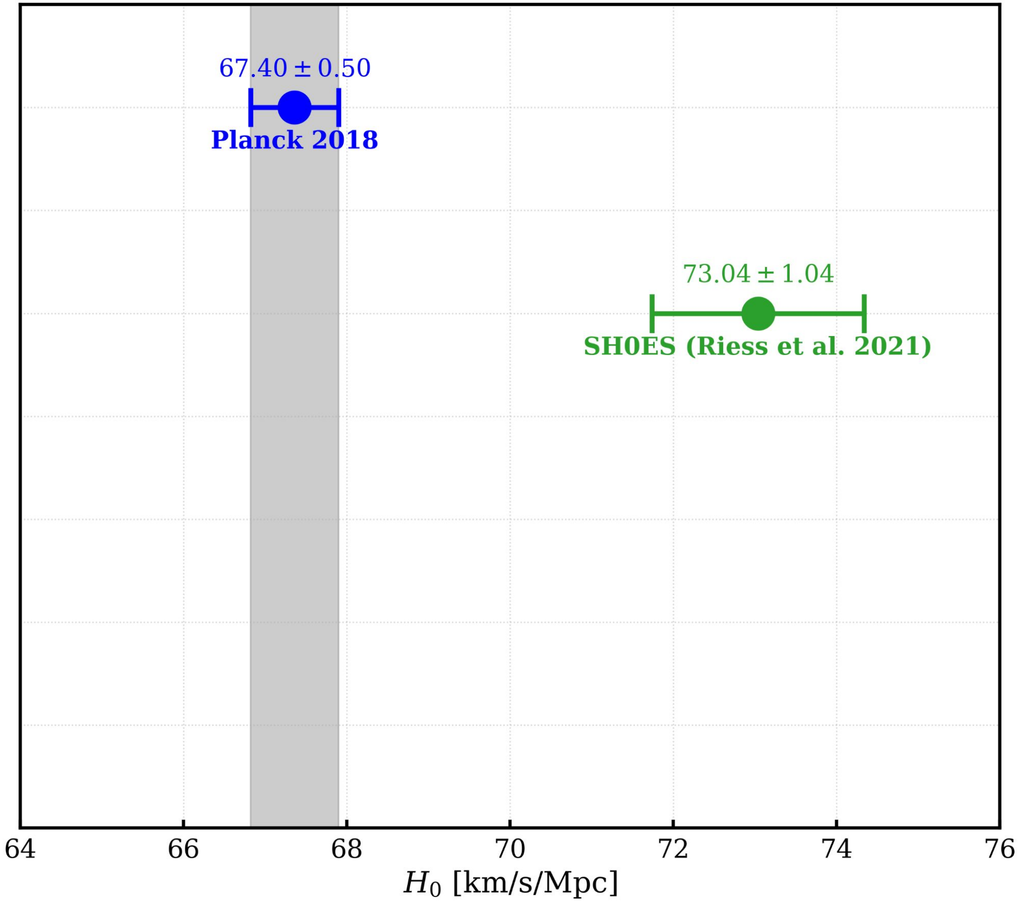
Option 2

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

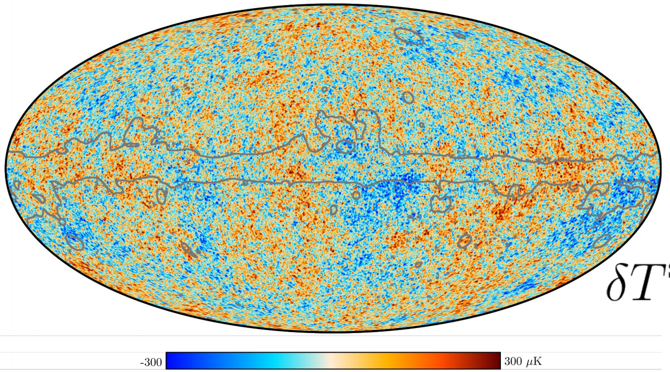
Option 2

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

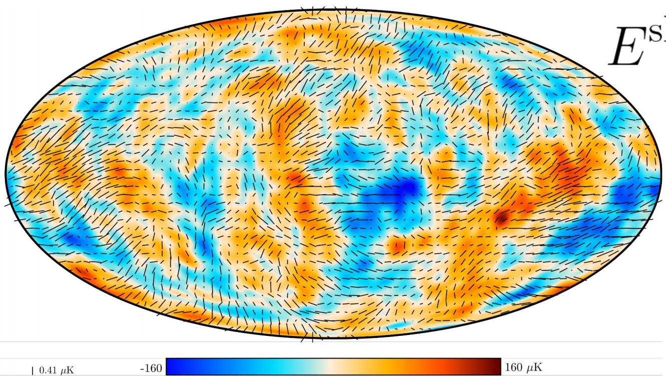
Option 3

Physics beyond ΛCDM

Systematics affecting the CMB

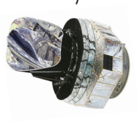


$\delta T^{\mathrm{sky}}(\hat{n})$



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

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



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

Systematics 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)**

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

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

- **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 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

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

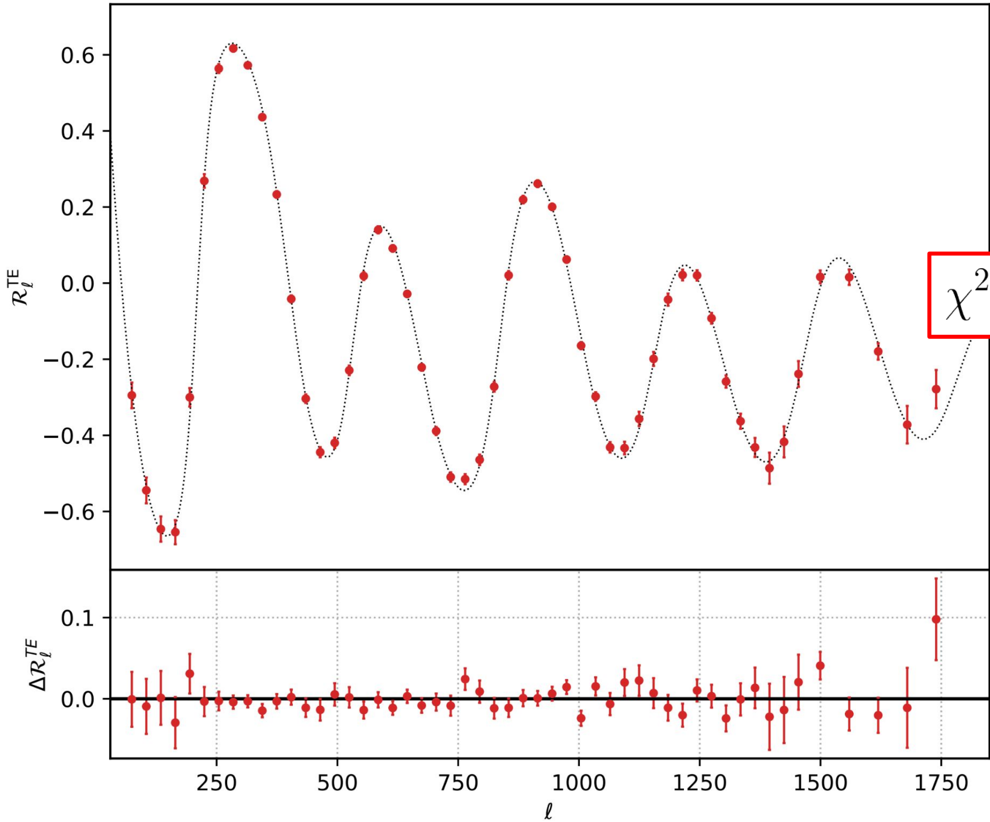
$$\mathcal{R}_\ell^{TE,\mathrm{obs}} = \frac{\mathcal{F}_\ell^{T} \mathcal{F}_\ell^{E} c^2 c_E B_\ell^{T} B_\ell^{E} C_\ell^{TE}}{\sqrt{(\mathcal{F}_\ell^{T})^2 c^2 (B_\ell^{T})^2 C_\ell^{TT} \times (\mathcal{F}_\ell^{E})^2 c^2 c_E^2 (B_\ell^{E})^2 C_\ell^{EE}}}$$

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



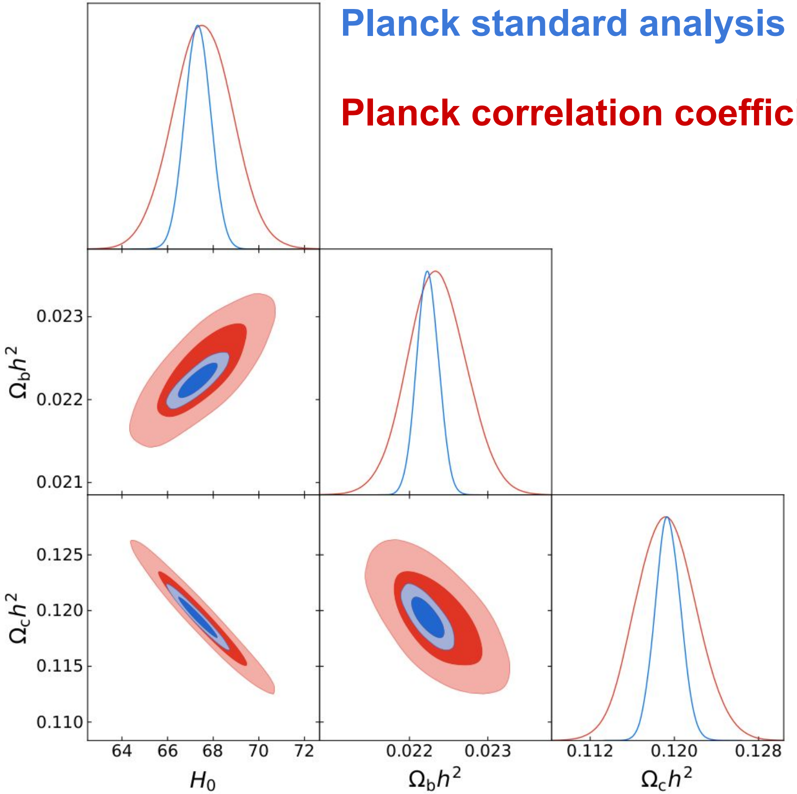
Bestfit from Planck TT,TE,EE

Planck correlation coefficient

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

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

Planck correlation coefficient



Planck standard analysis (C_ℓ)

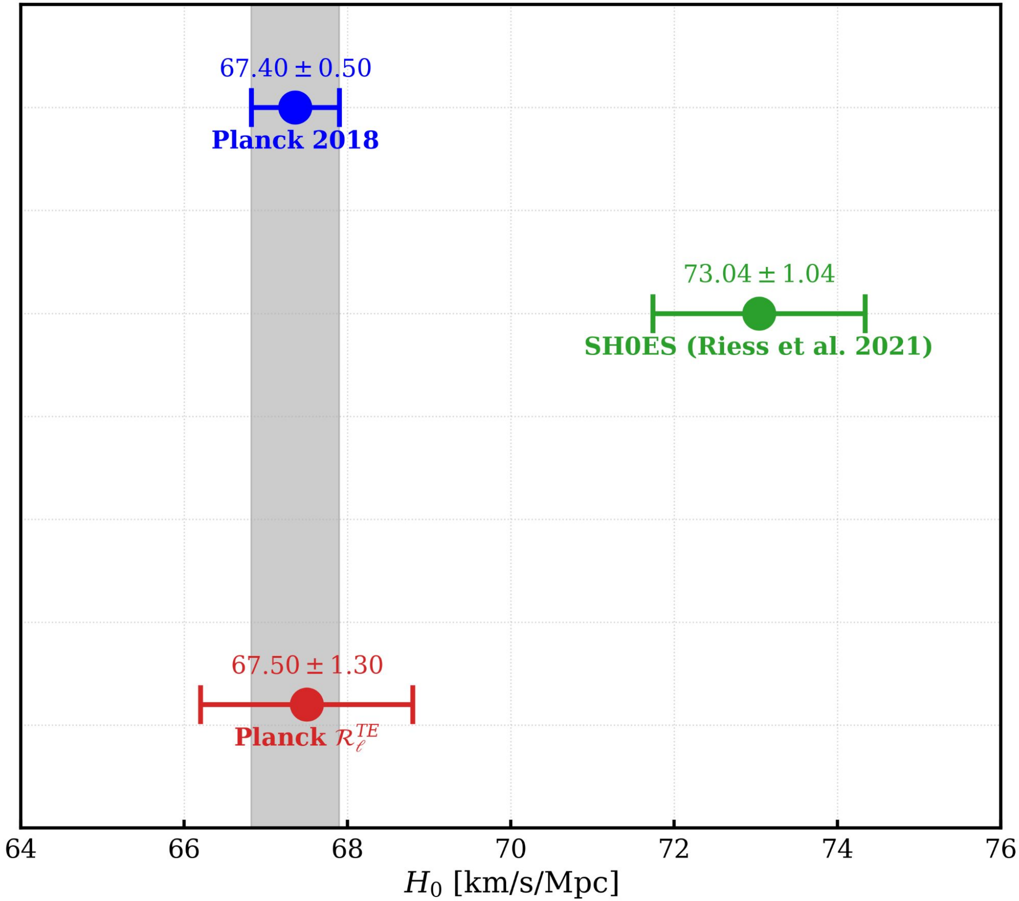
Planck correlation coefficient (R_ℓ^{TE})

3.3σ away from the latest SH0ES measurement

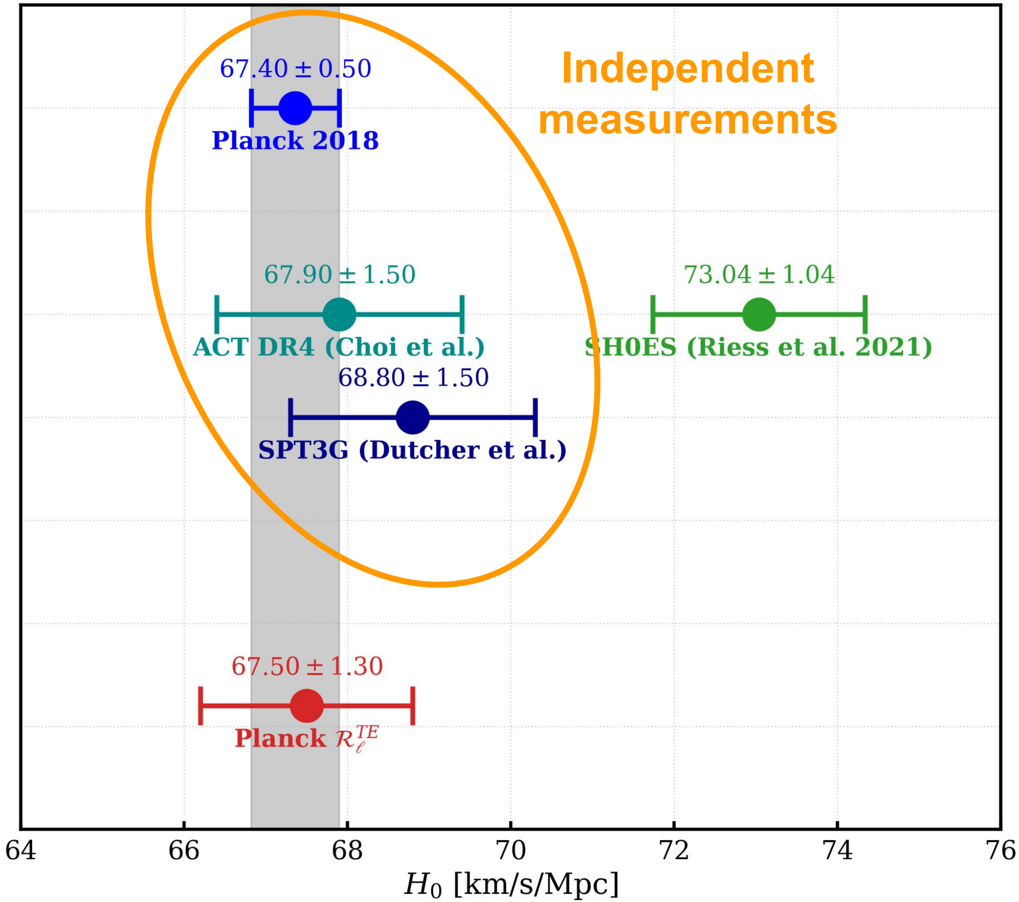
H_0 = 67.5 +/- 1.3 [km/s/Mpc]

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

Back to the Hubble tension …



… with additional constraints from the CMB



Option 1

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Option 3

Physics beyond ΛCDM

Beyond ΛCDM …

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

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

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

↓

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

Proposed solution : Early Dark Energy

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

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

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

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

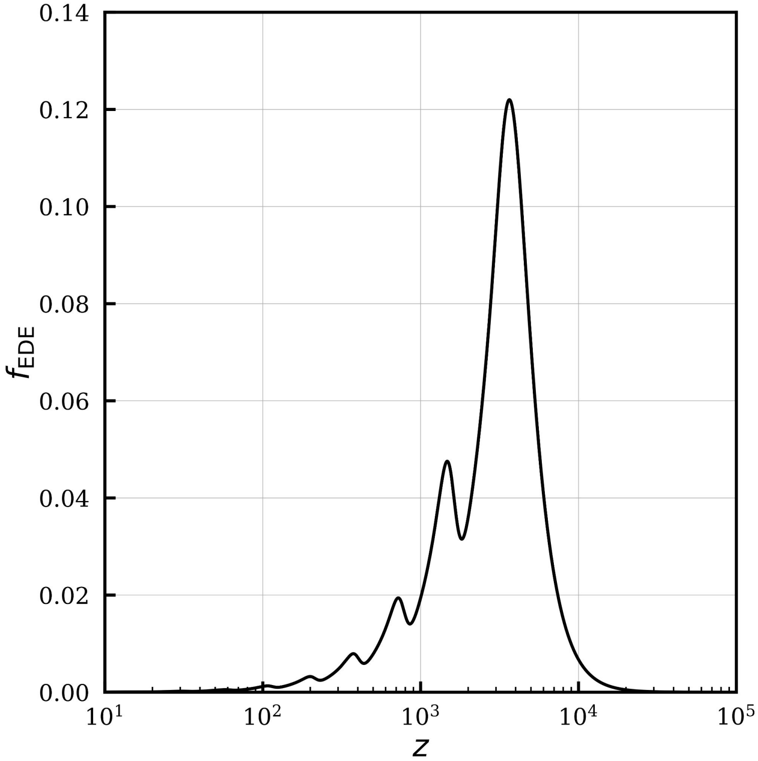
Background evolution : $\ddot{\phi} + 3H\dot{\phi} + V'(\phi) = 0$

axion-like potential

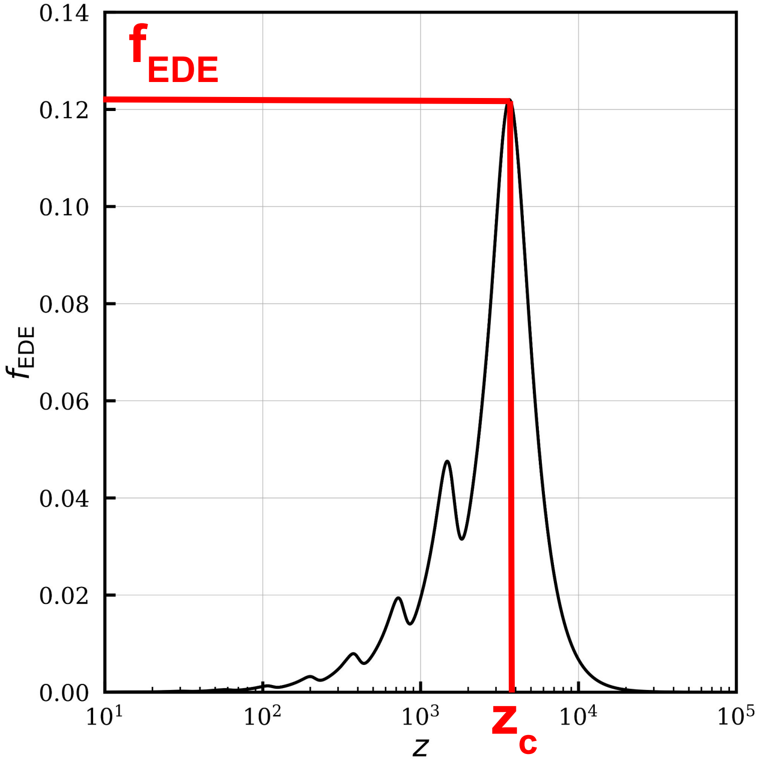
$$V(\phi) = m^2 f^2 \left[1 - \cos\left(\frac{\phi}{f}\right)\right]^3$$

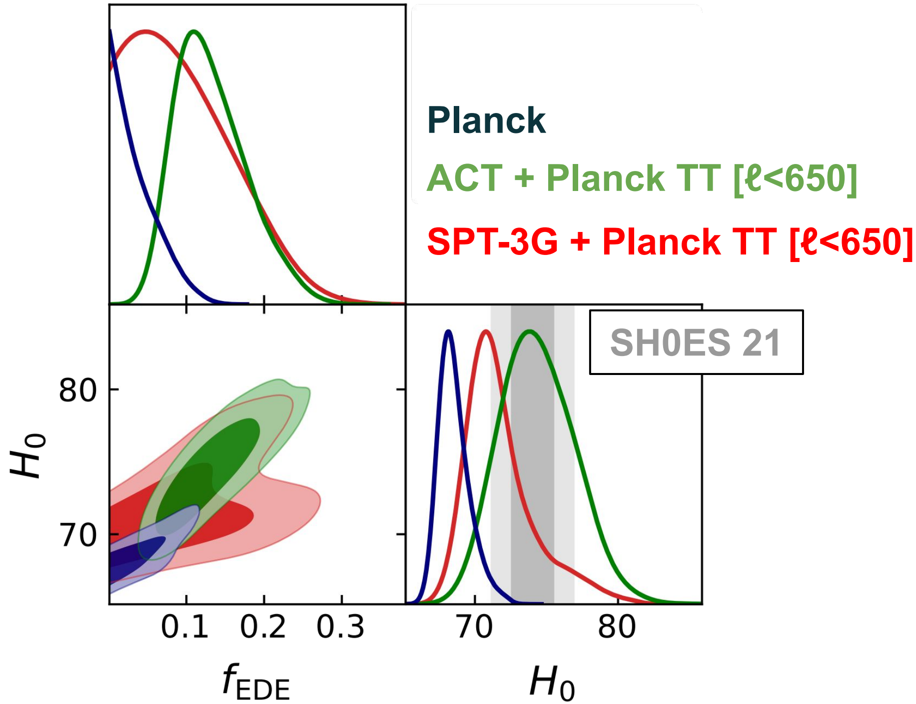
Poulin+ 19

Proposed solution : Early Dark Energy



Proposed solution : Early Dark Energy





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

Lots of data are now available from the Atacama Cosmology Telscope