From ΛCDM to EDE

Laura Herold

CosmoVerse Oct 17, 2024

Overview (1.5 - 2h)

- **Lecture part 1**: ΛCDM and the Hubble tension (50 min)
- Break (5 min)
- **Lecture part 2**: Early Dark Energy (30 min)
- **Exercises**: Notebooks to get familiar with Boltzmann solver CLASS (5 min) $\rightarrow$ “homework”

Outline Part 1: ΛCDM & the Hubble tension

1. Introduction: basic equations in a homogeneous & isotropic universe (Friedmann equations, matter content in the universe, defining distances)

2. Hubble tension: How does CMB constrain H_0?

3. How to solve the tension?

Introduction

Short “crash course” on cosmology

Basis: General Relativity

For more about GR, see Matteo Martinelli's lecture

- We will not go into details here but only sketch the rough idea
- Einstein Equations:

$$R^{\mu\nu} - \frac{R}{2} g^{\mu\nu} + \Lambda g^{\mu\nu} = 8\pi G T^{\mu\nu},$$

Ricci curvature tensor

metric

cosmological constant

energy-momentum tensor

"Matter tells space how to curve, space tells matter how to move" (Misner++ 1973)

Natural units: $c = 1$

General Relativity

- Solution for Einstein Equations for the universe as a whole?
- Cosmological Principle:

"On sufficiently large scales, the properties of the universe are the same for all observers."

or

"The universe is spatially homogeneous and isotropic on large scales."

General Relativity

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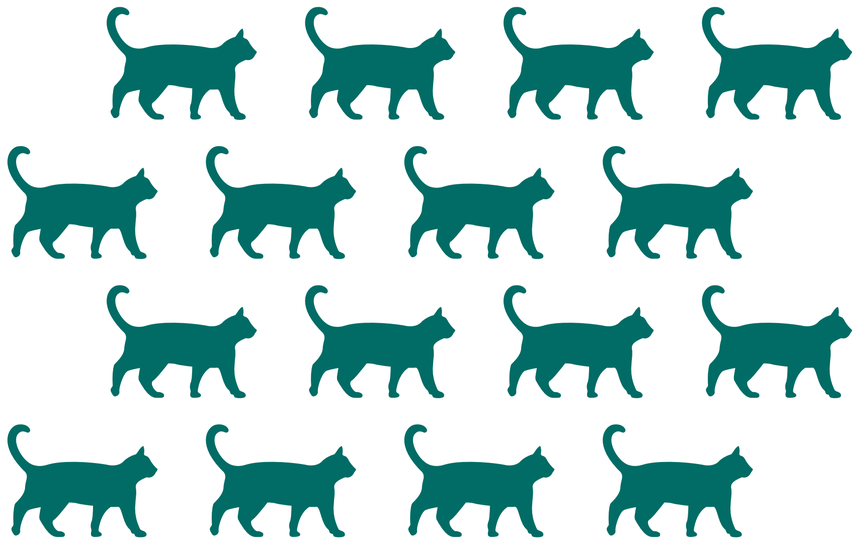
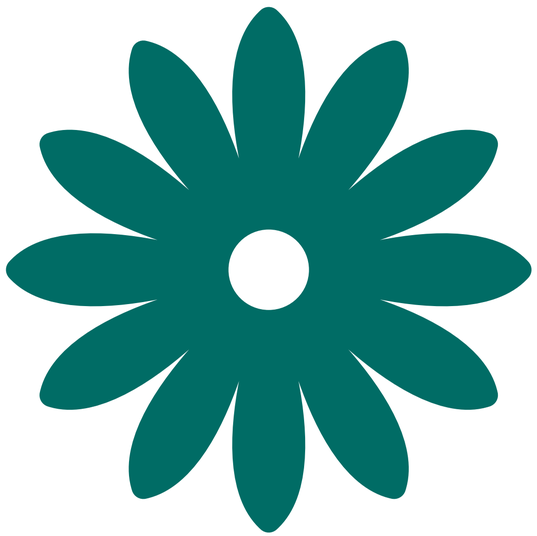
"the same in every point"

"the same in every direction"

Isotropic or homogeneous?



homogenous but not isotropic



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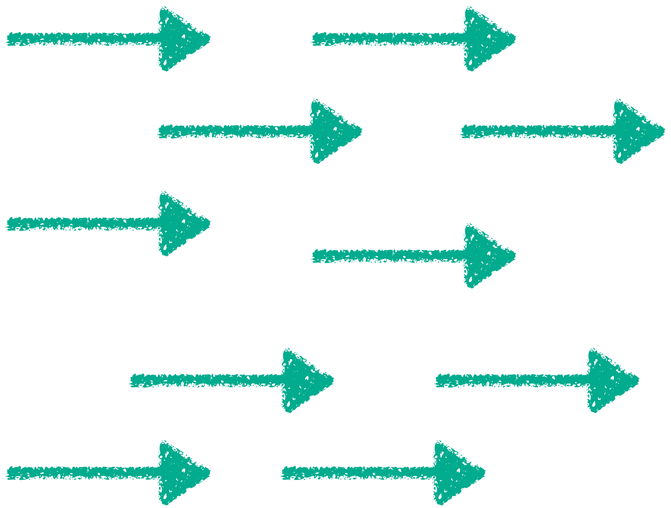

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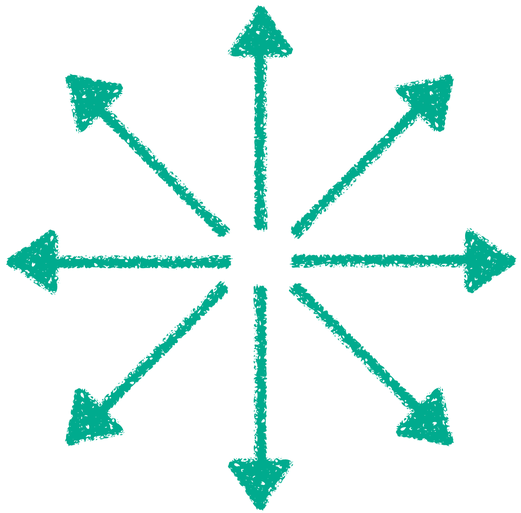

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Friedmann Equations

- Friedmann 1922, Robertson 1935, Walker 1937: For a spatially homogeneous and isotropic universe, the metric simplifies to

$$\mathrm{d}s^2 = -\,\mathrm{d}t^2 + a^2(t)\left[\frac{\mathrm{d}r^2}{1-kr^2} + r^2\mathrm{d}\Omega^2\right]$$

spacetime line element

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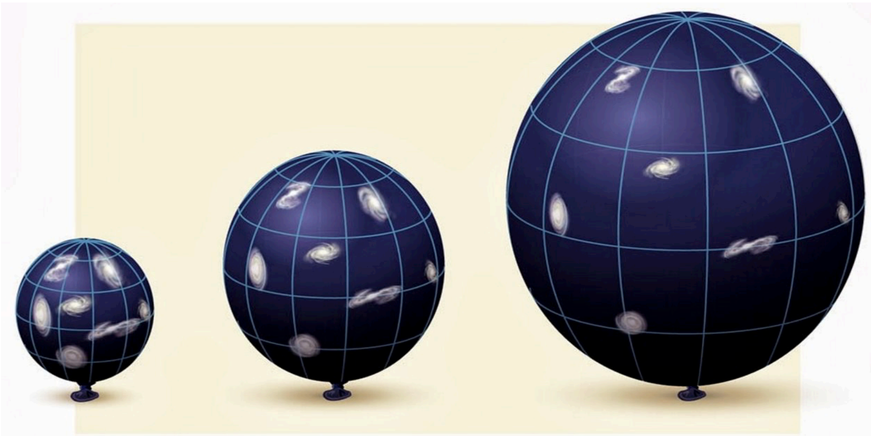

Figure credit: Bianchi, Rovelli, Kolb

$$a(t_{\mathrm{today}}) = a_0 = 1$$

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spacetime line element

scale factor

curvature parameter

$$k = \begin{cases} -1 & \text{hyperbolic} \\ 0 & \text{flat} \\ +1 & \text{spherical} \end{cases}$$

Friedmann Equations

- A perfect fluid is a fluid, which can be completely characterised by its (energy) density and pressure

- The energy momentum tensor of a perfect fluid is

$$T^{\mathrm{pf}}_{\mu\nu} = (\rho + p)\, u_\mu u_\nu + p g_{\mu\nu}$$

energy density pressure

- $u_\mu = \dot{x}_\mu$ is the 4-velocity of the observer

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Friedmann Equations

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$$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3} \quad \text{(i)}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3p) + \frac{\Lambda}{3} \quad \text{(ii)}$$

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- Inserting (ii) into the temporal derivative of (i), yields the continuity equation:

$$\dot{\rho} = -3(\rho + p)\frac{\dot{a}}{a} \quad \text{(iii)}$$

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- Where $\rho = \rho_{\text{tot}}$ is the energy density of the universe.
- If we define $\rho_k = -\frac{3}{8\pi G}\frac{k}{a^2}$ and $\rho_\Lambda = \frac{\Lambda}{8\pi G}$, one can rewrite (i) as

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho_{\text{tot}} \quad \text{(i)}$$

ΛCDM model $\rho_{\rm tot} = \rho_r + \rho_m + \rho_\Lambda + \cancel{\rho_k}$

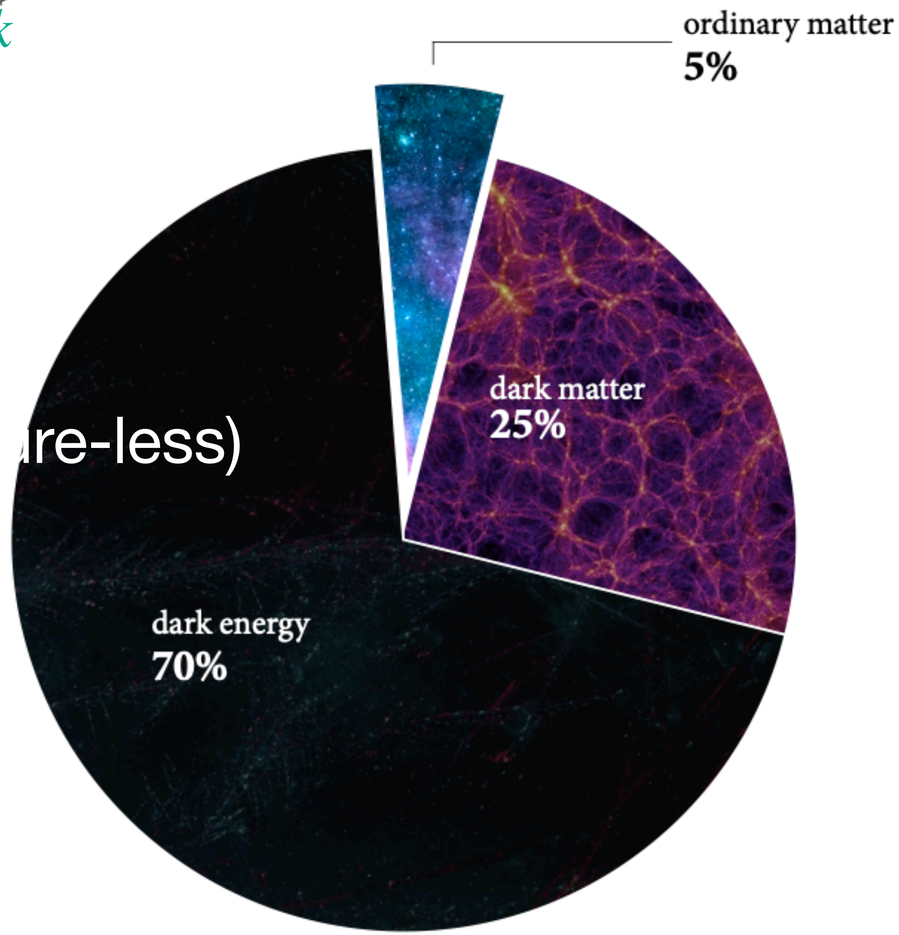

Figure credit: Florian Wolz

ΛCDM model $\rho_{\text{tot}} = \rho_r + \rho_m + \rho_\Lambda$

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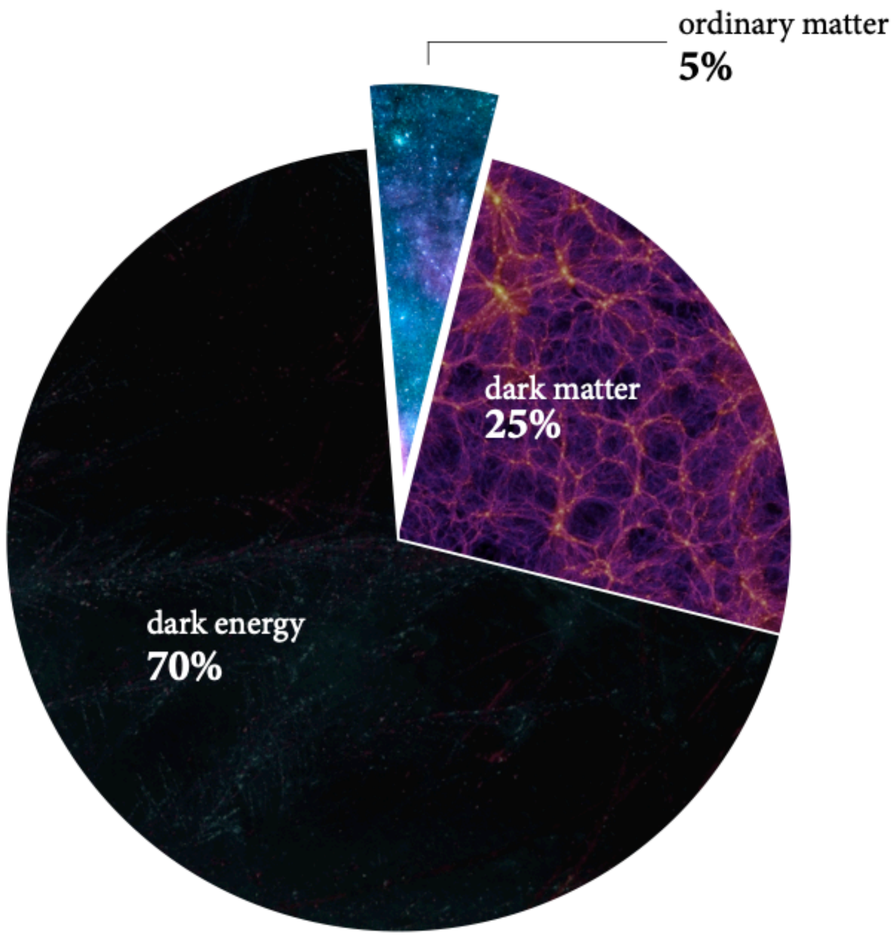

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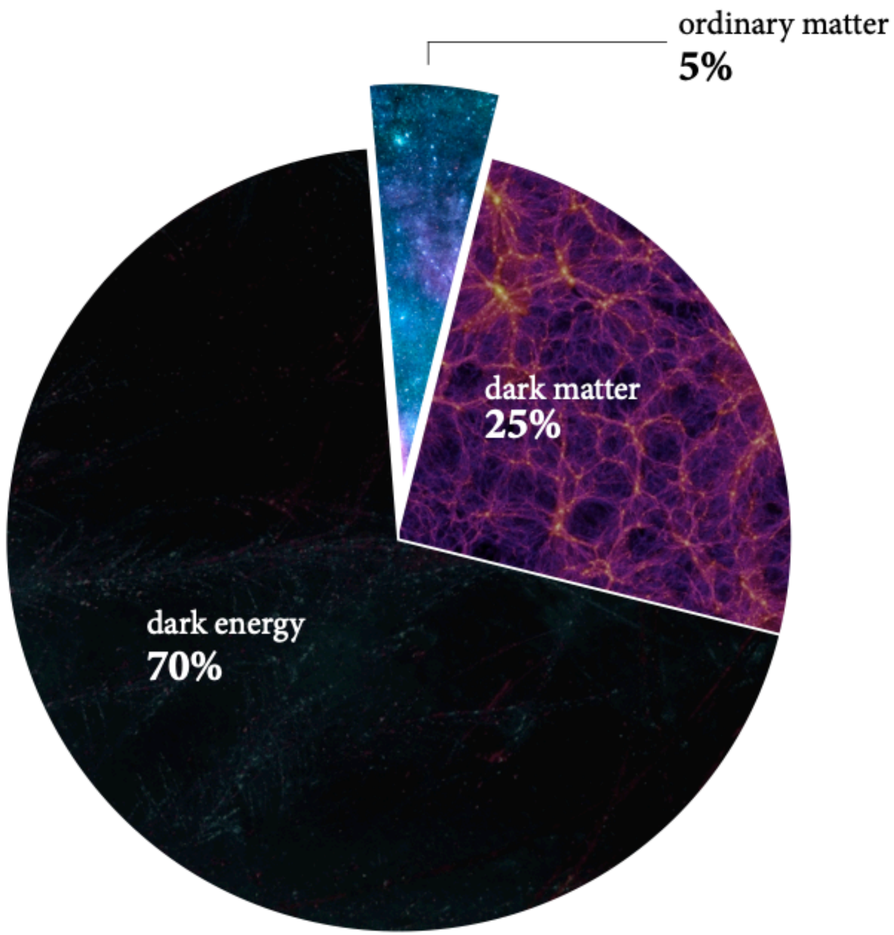
  - Dark matter and baryonic matter: $w = 0$



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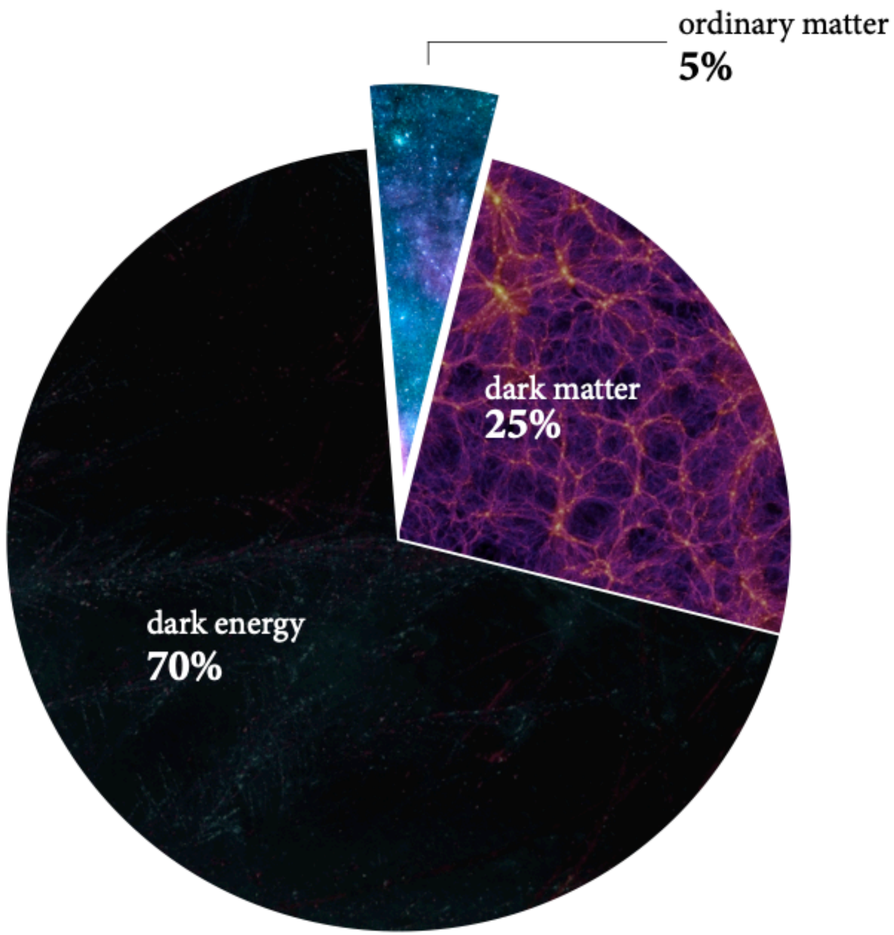

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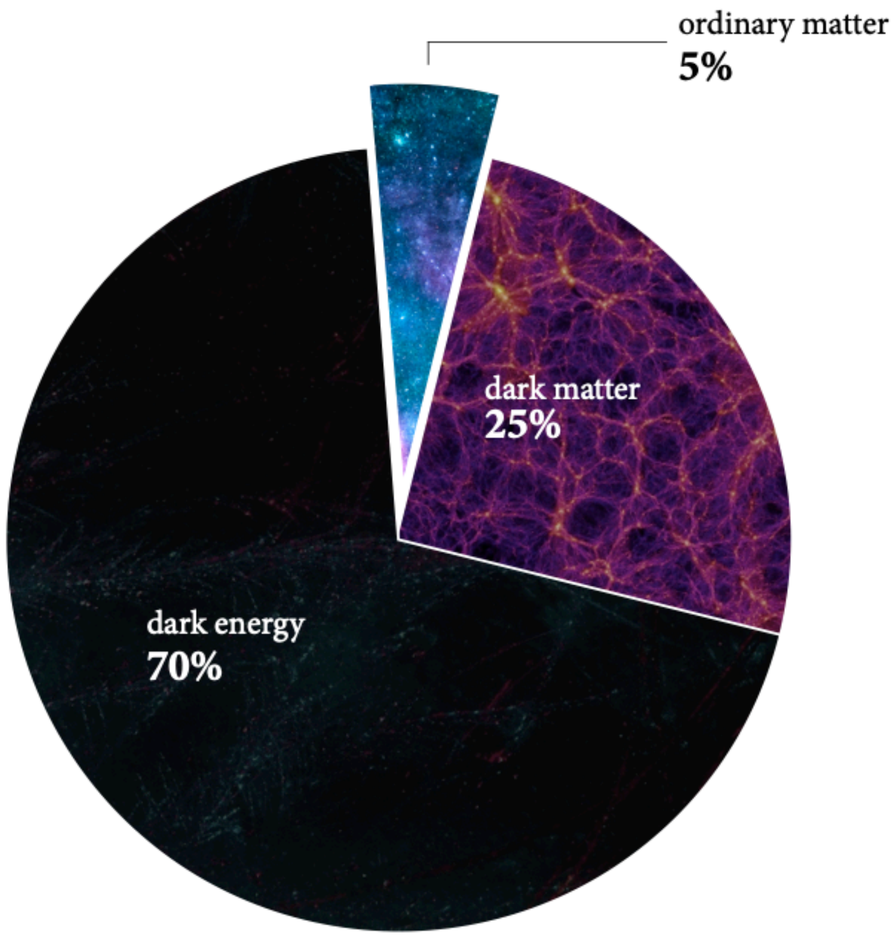
  - Dark energy: $w = -1$



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$$\boxed{\frac{\rho(a)}{\rho_0} = \left(\frac{a}{a_0}\right)^{-3(1+w)}}$$

The subscript 0 refers to the current time “today”

The Hubble parameter

- The first Friedmann equation describes the rate of expansion as a function of the energy content ρ of the universe:

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$$H_0 = H(t = t_0)$$

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$\Omega_{I,0} = \Omega_I(t_0) = \Omega_I$

Distances in an expanding universe

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physical size of the object

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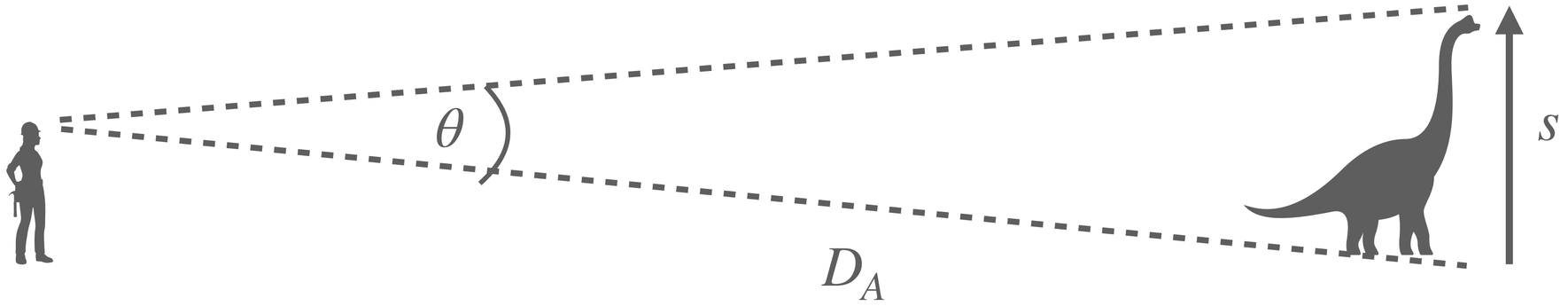

Distances in an expanding universe

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$$\theta = \frac{s}{D_A}$$

$$\boxed{D_A(t) = a(t)\,\chi(t) = \frac{1}{1+z(t)} \int_0^{z(t)} \frac{\mathrm{d}z'}{H(z')}}$$

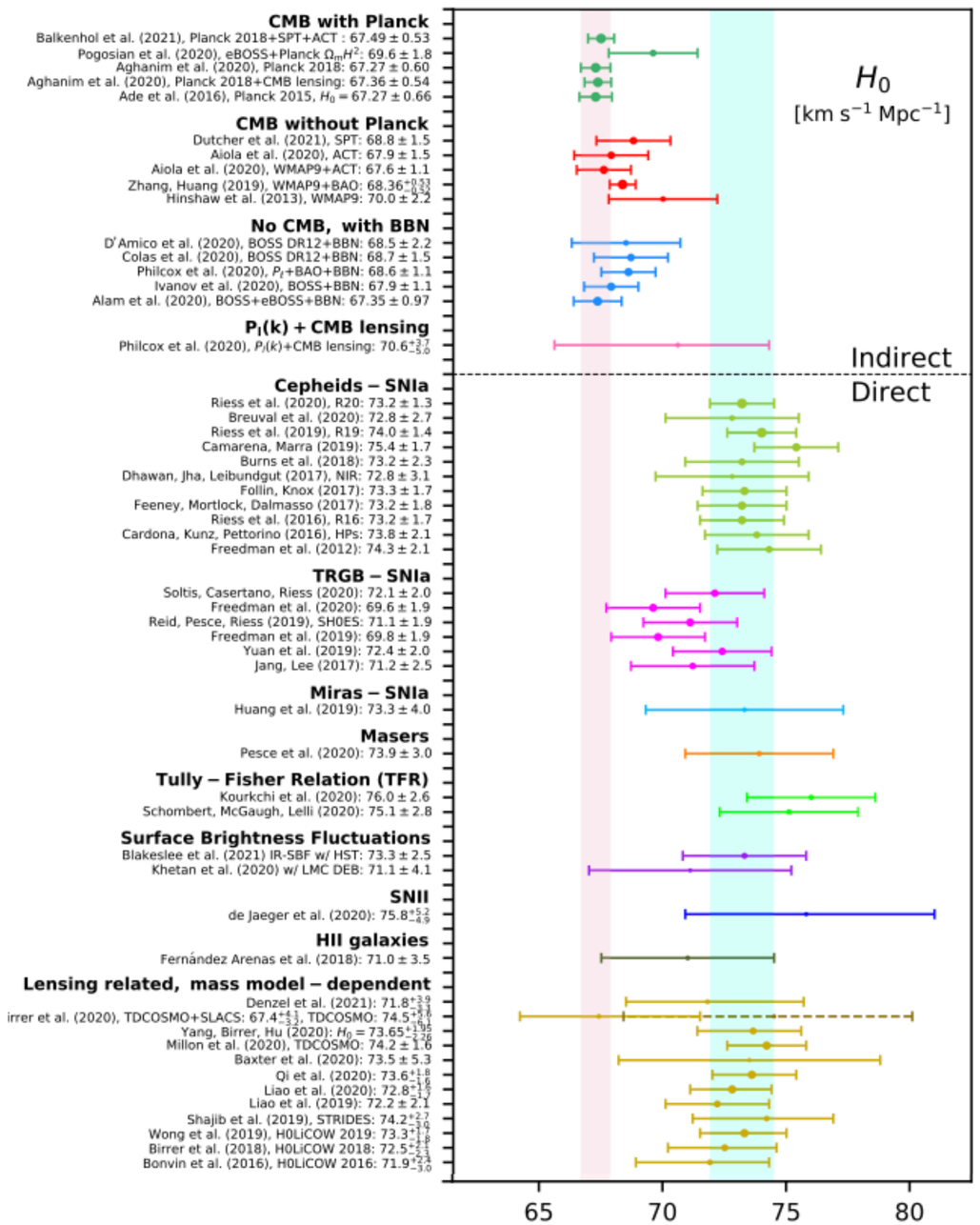
*To derive an equation for D_A, note that the proper size, s, of the object can also be expressed as $s = \chi(t)\,\theta \cdot a(t)$, where $\chi(t)\,\theta$ corresponds to the comoving size of the object.

How to solve the Hubble tension?

The Hubble tension

- Indirect measurements: cosmic microwave background (CMB), baryon acoustic oscillations (BAO), galaxy clustering

- Direct measurements: distance ladder (Cepheids, TRGB, SNe, …), gravitational lensing, …



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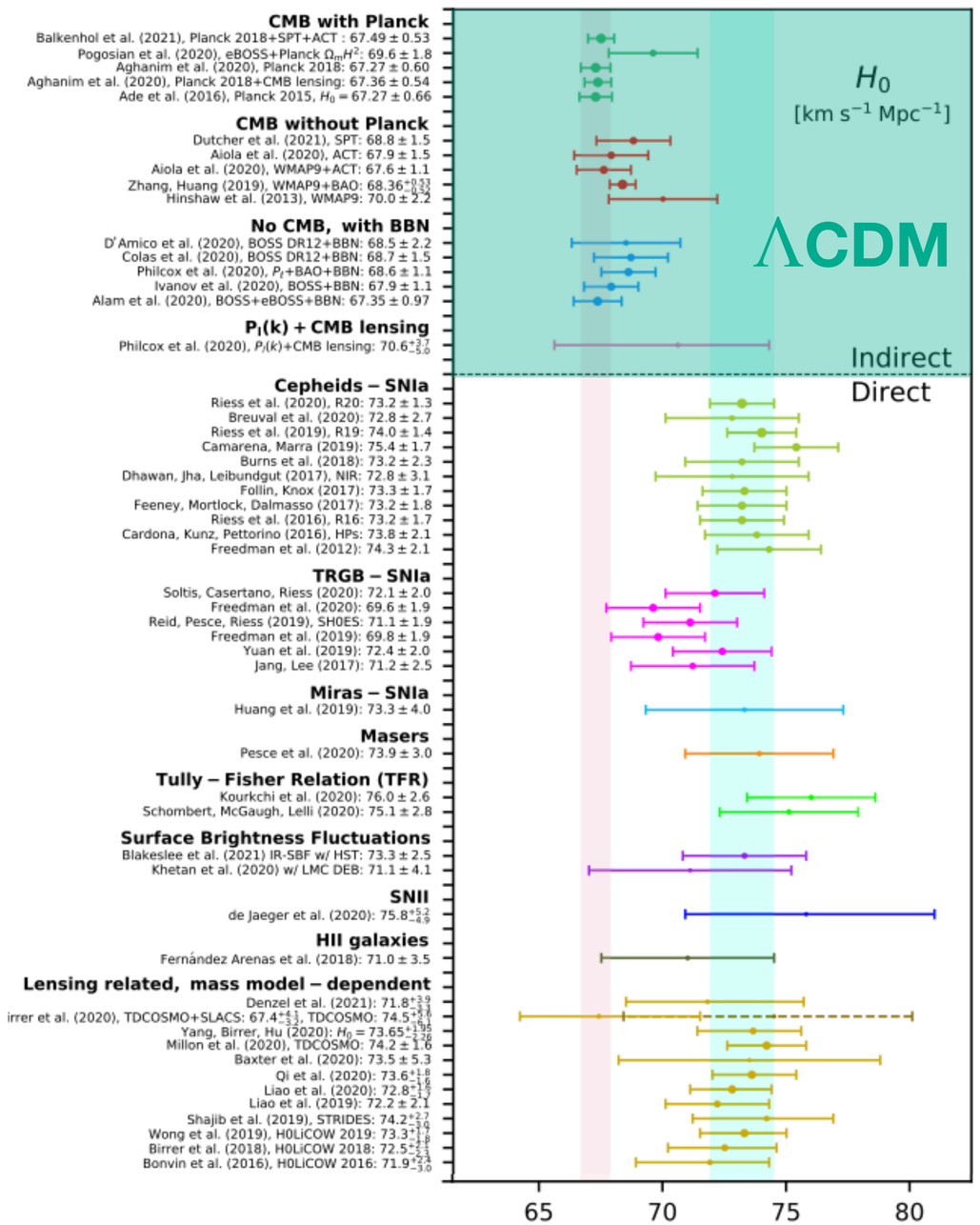

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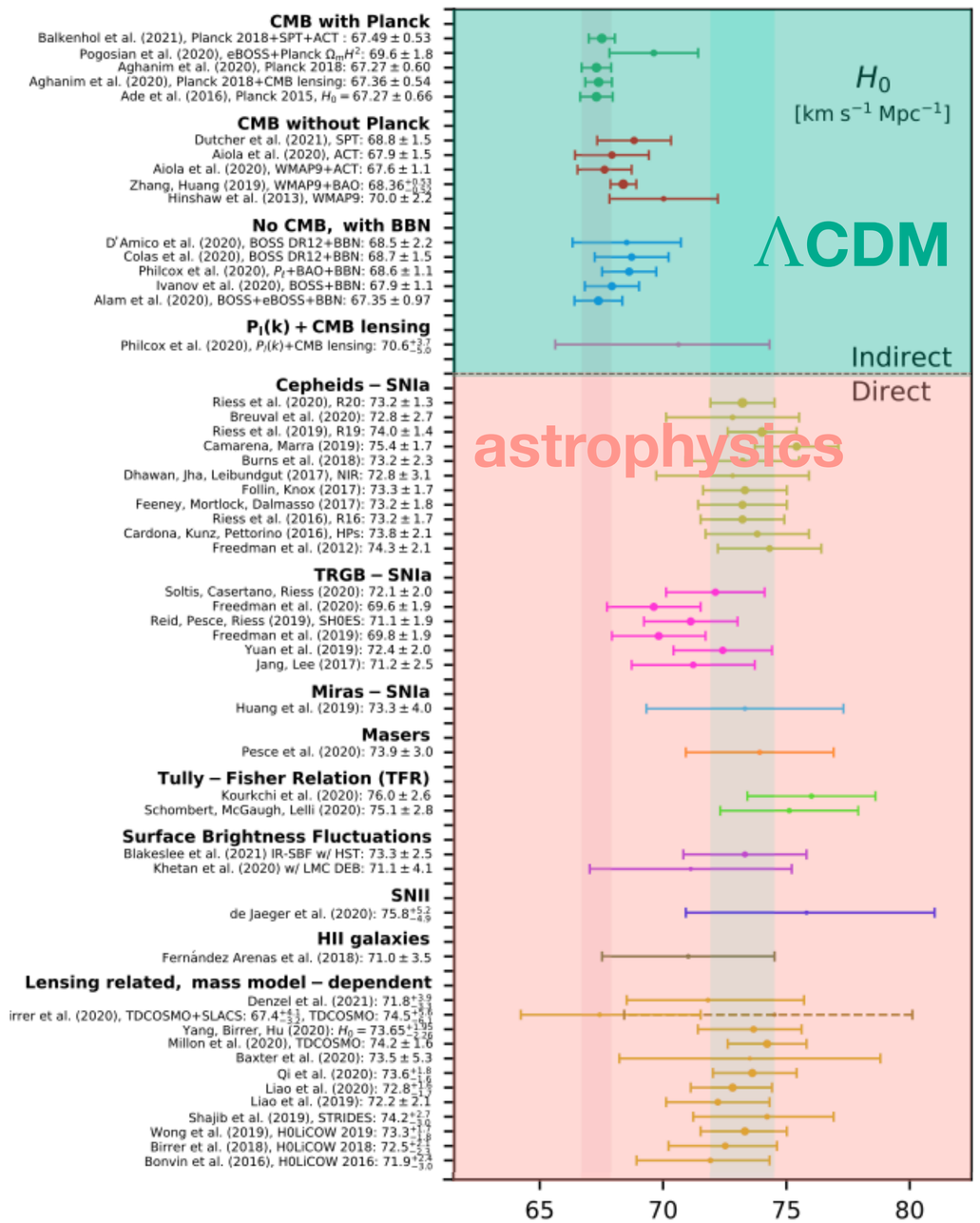
The Hubble tension

- Indirect measurements: cosmic microwave background (CMB), baryon acoustic oscillations (BAO), galaxy clustering → precise but model dependent

- Direct measurements: distance ladder (Cepheids, TRGB, SNe, …), gravitational lensing, … → less precise due to astrophysical modelling but independent of cosmological model



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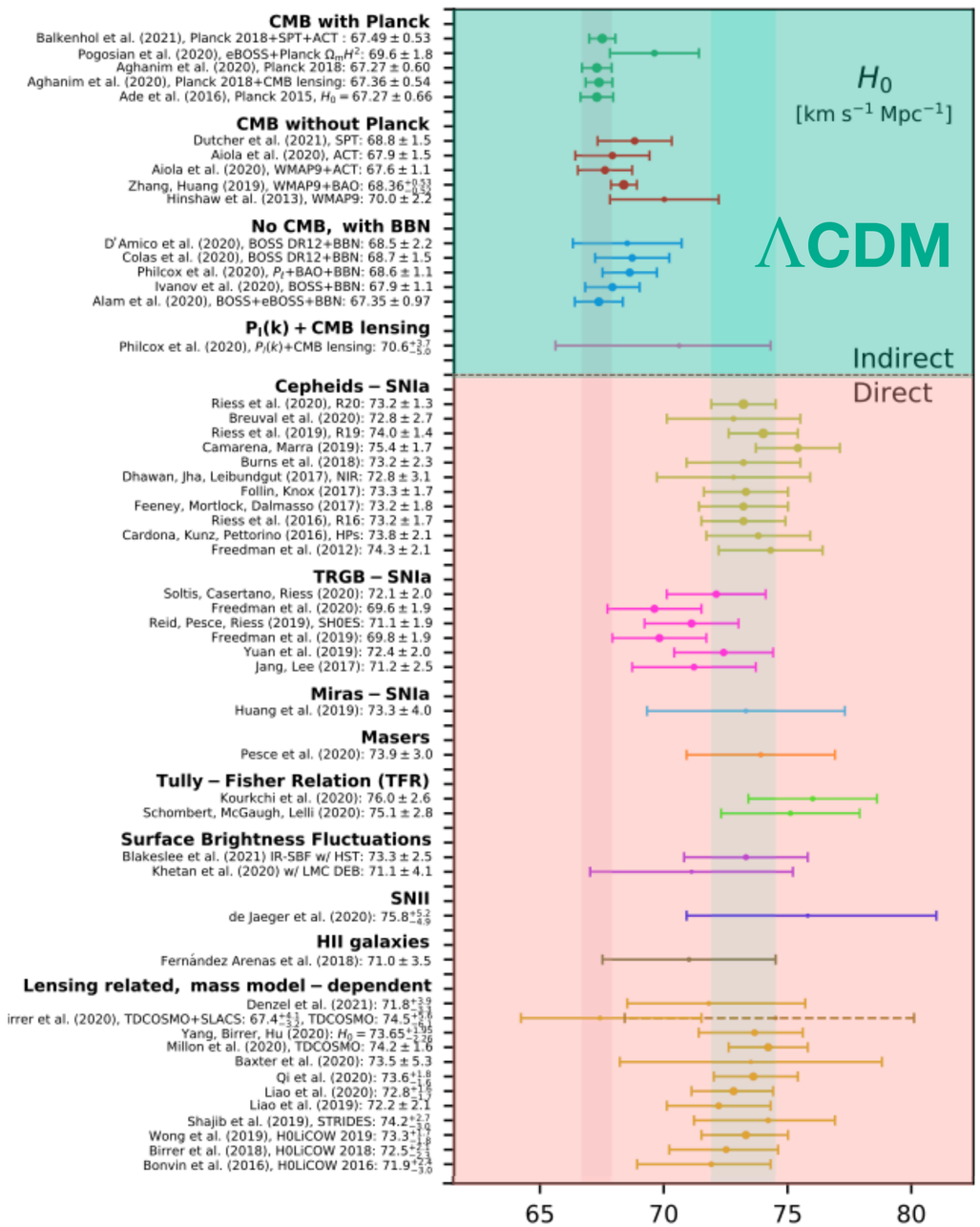
The Hubble tension

- General strategy to solve the H_0 tension: Assume direct measurements are correct and change cosmological model in order to *infer* a higher H_0
- Goal: "get CMB-H_0 to ~73 km/s/Mpc"



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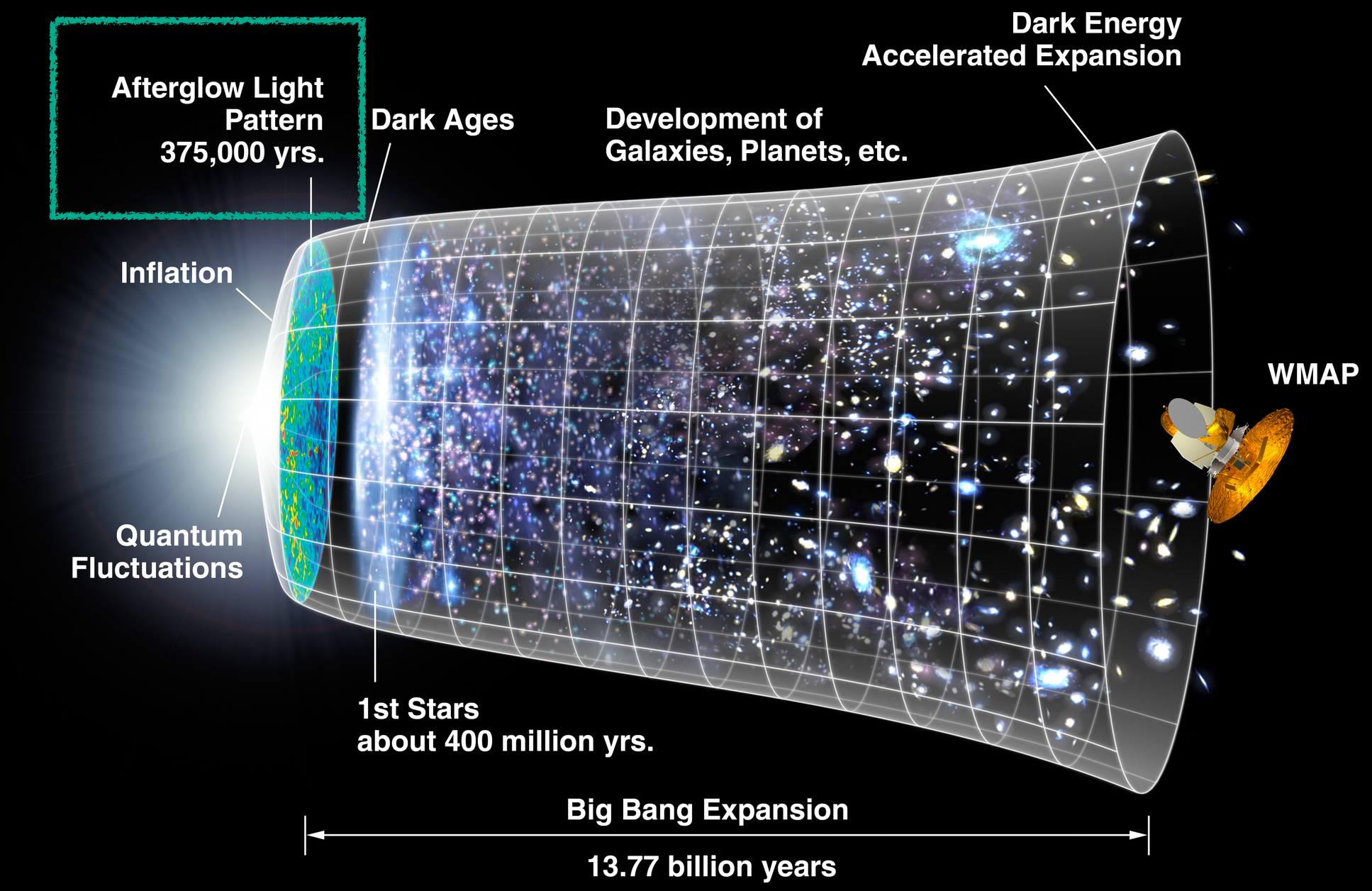
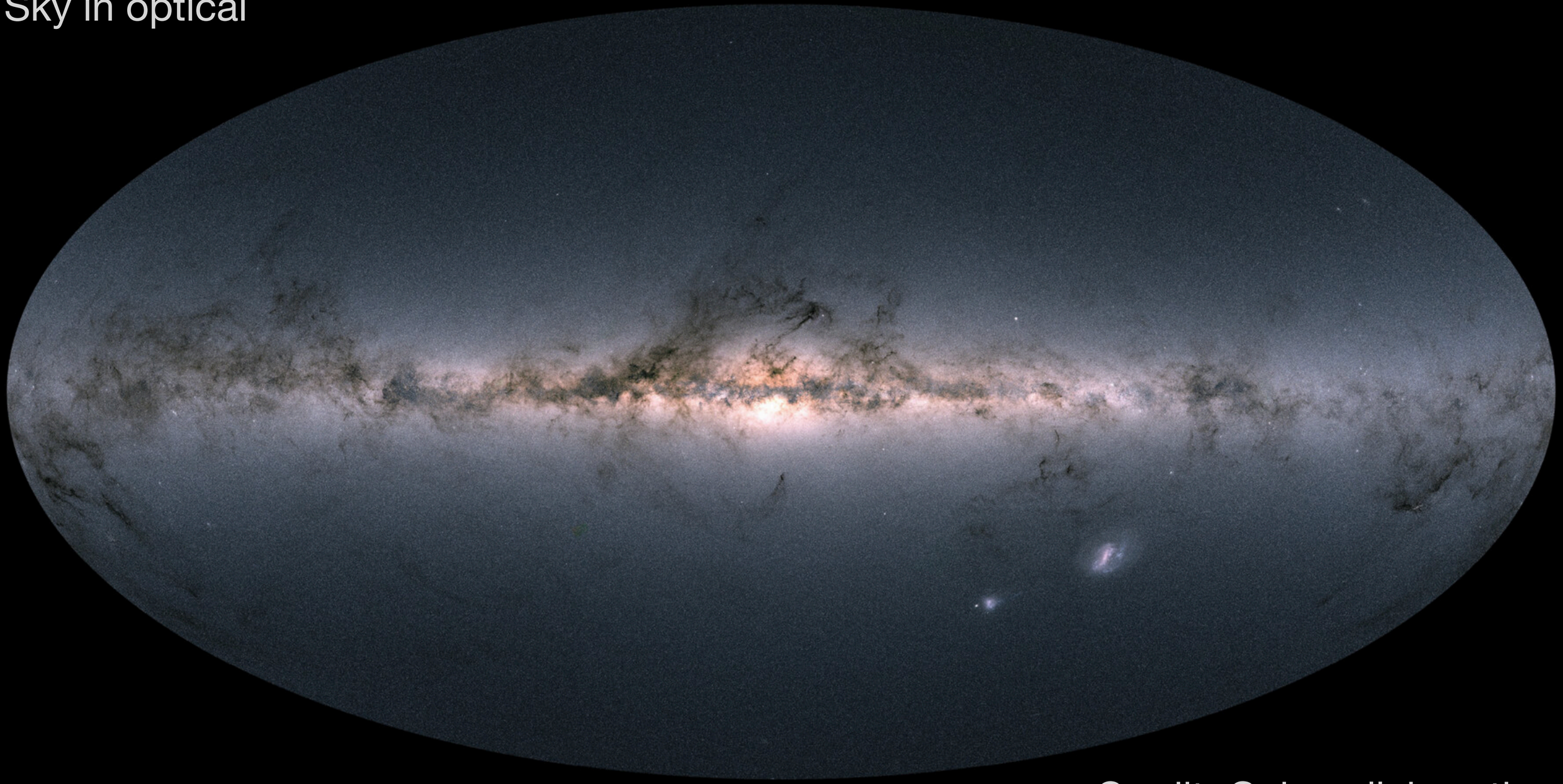
How does the CMB constrain H_0?

- In order to understand how we can solve the Hubble tension, we need to understand how the CMB constrains H_0
- The CMB provides the most important cosmological probe when it comes to constraining the parameters of the cosmological model with high accuracy
- However, it is an indirect probe of H_0: it depends on the cosmological model that is assumed → the CMB constrains the universe at early times and predicts H_0 today



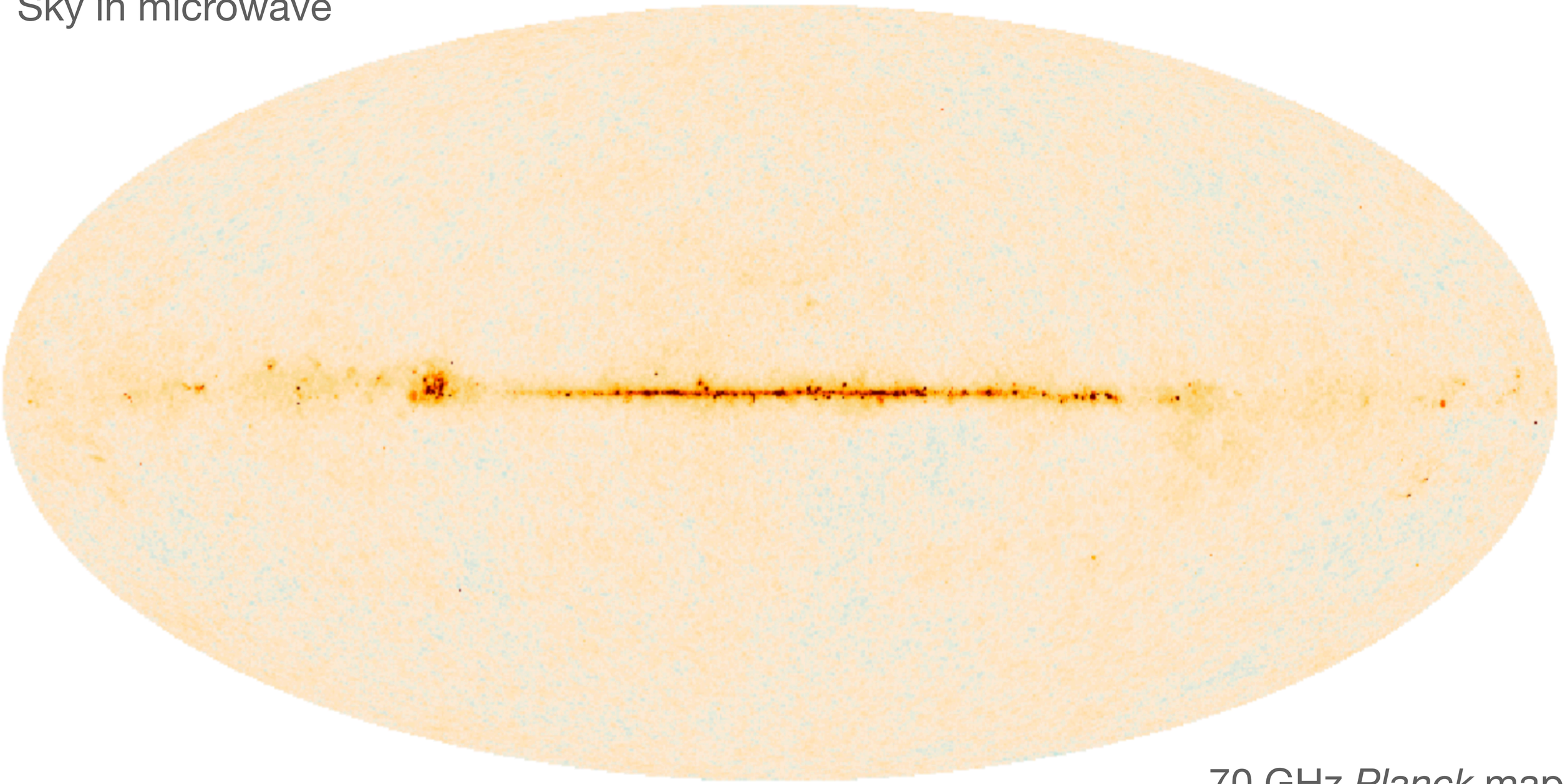
Credit: WMAP Collaboration

Sky in optical



Credit: Gaia collaboration

Sky in microwave



70 GHz *Planck* map

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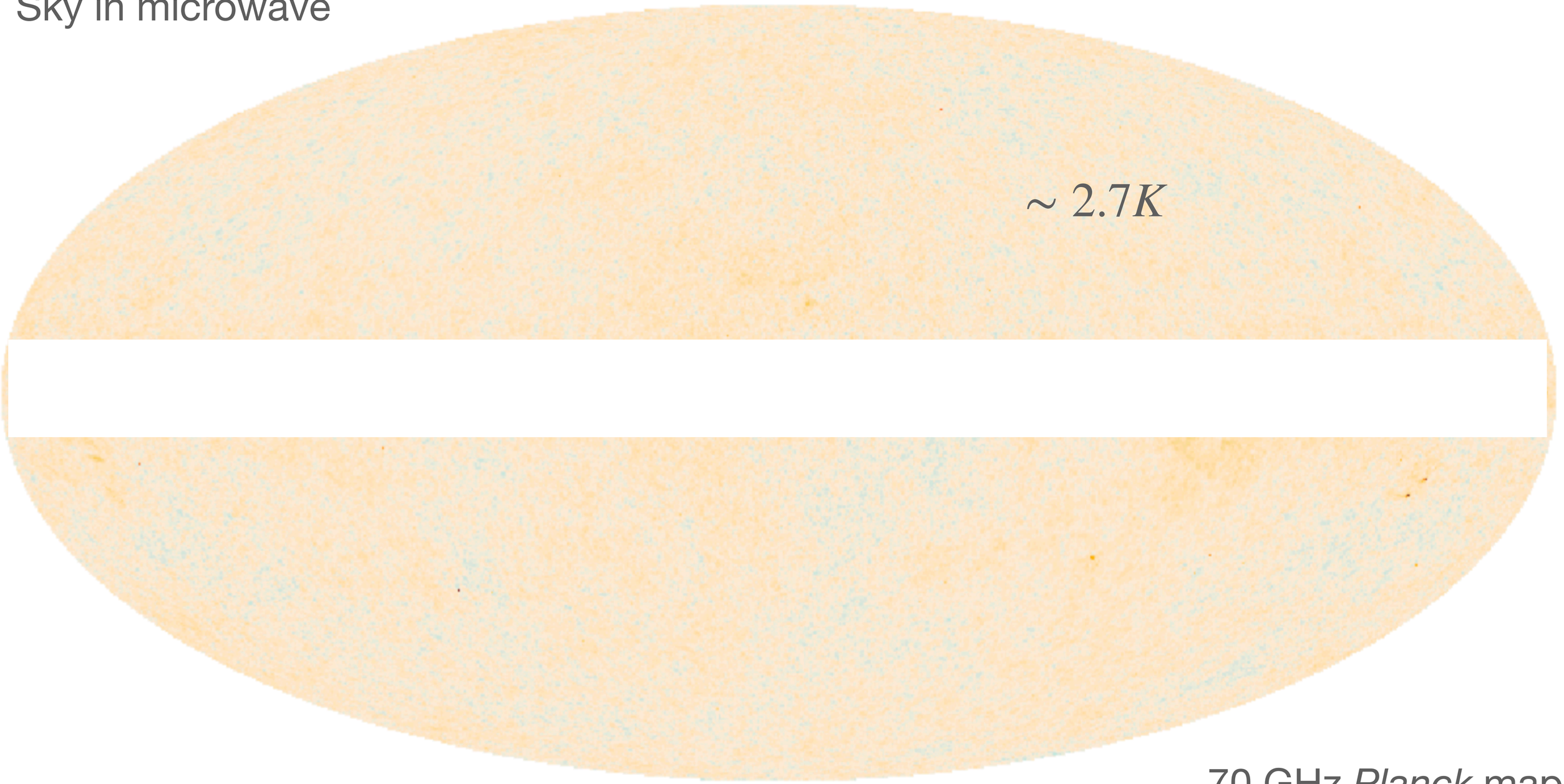

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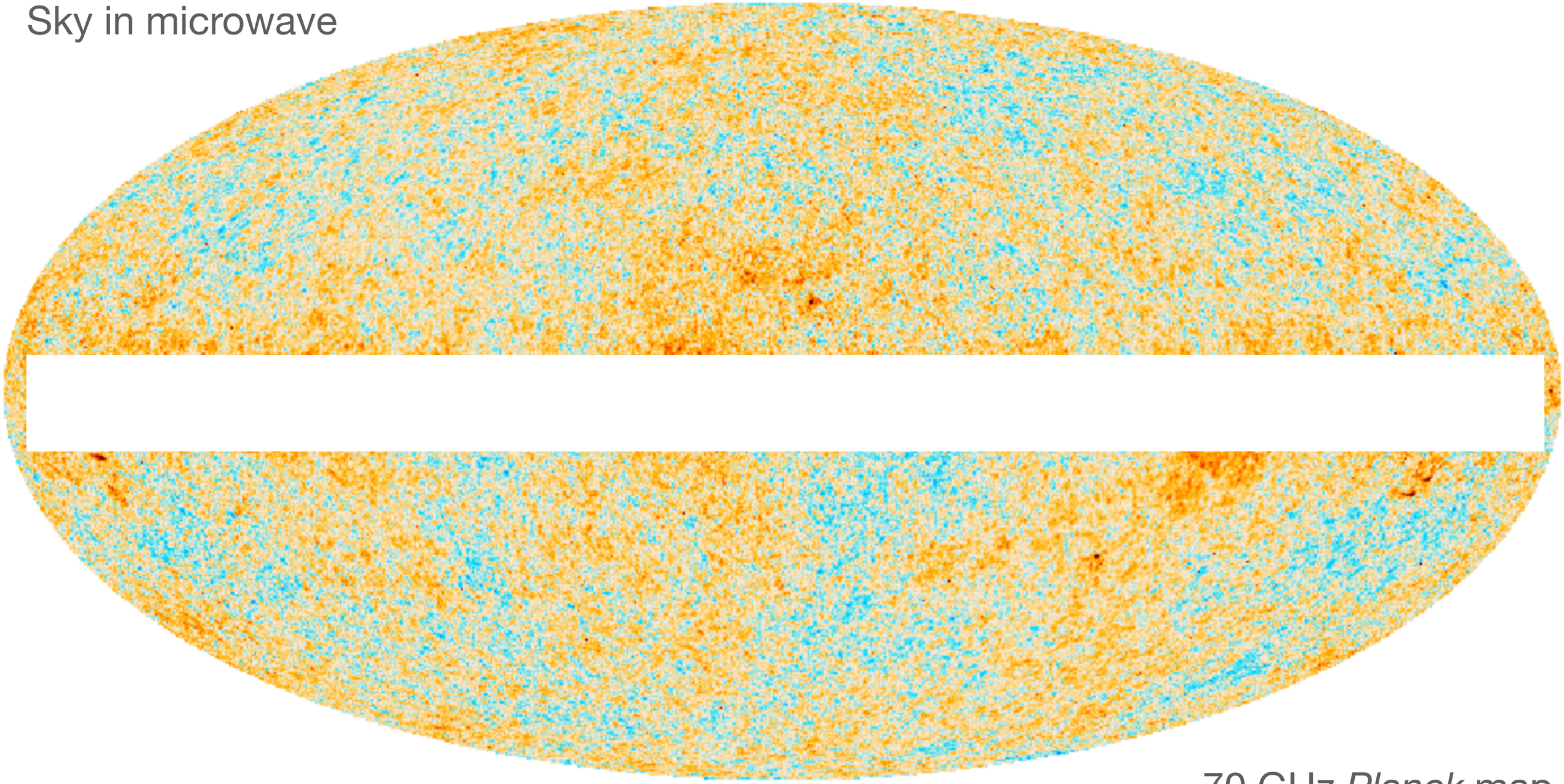

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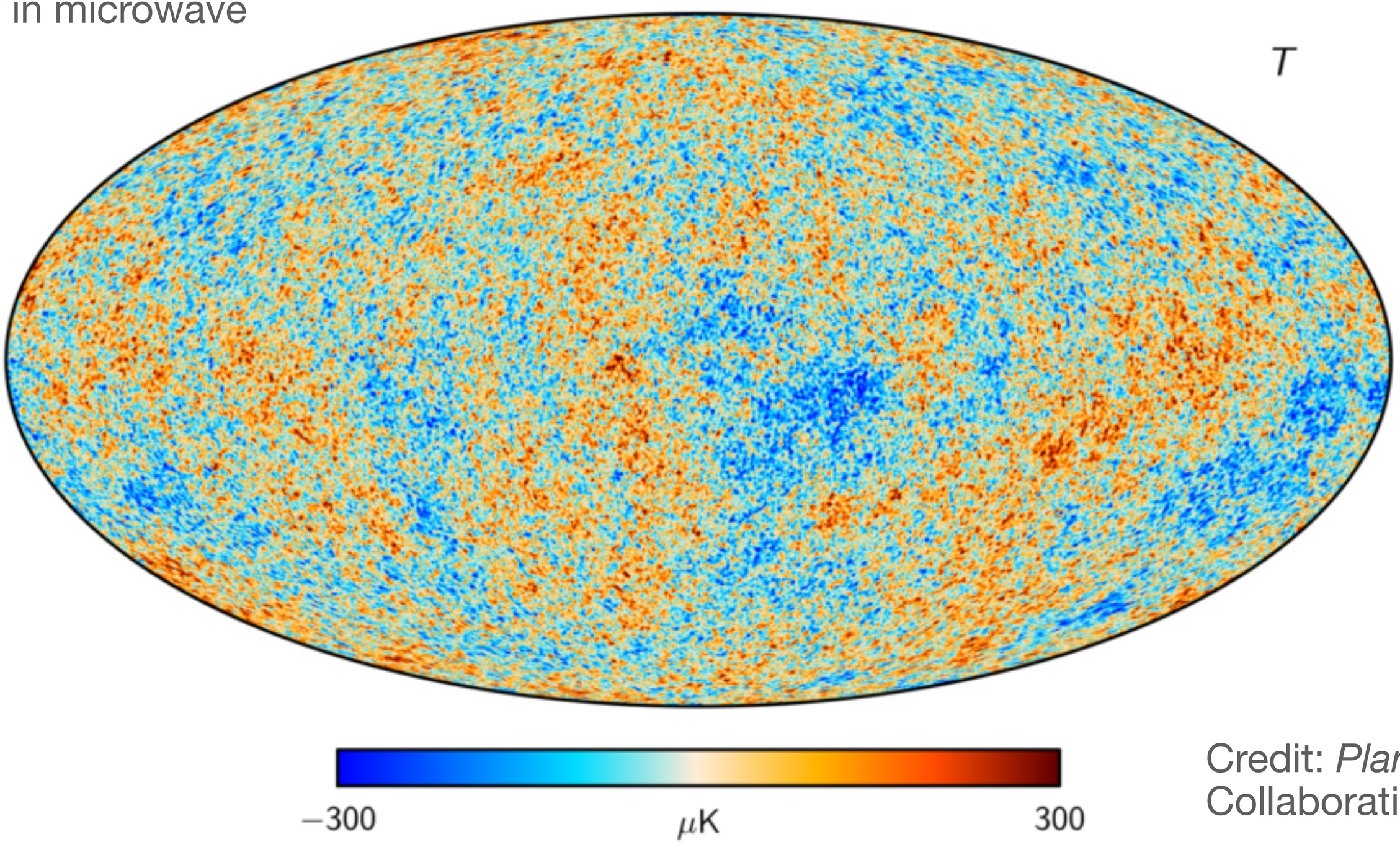
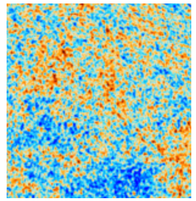


Credit: *Planck* Collaboration

The CMB

- How to analyse the CMB map with temperature fluctuations?
  - 1. Decompose the temperature fluctuations into a set of waves with various wavelength
  - 2. Plot the strength of each wavelength: Power spectrum
- In 1 dimension: decomposing into waves = Fourier transform
- On the unit sphere: decomposing into waves = Spherical harmonics decomposition

The CMB

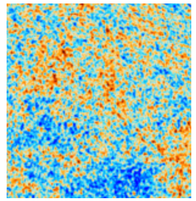


- Decompose temperature fluctuations: $\Delta T(\theta, \phi) = \sum_{\ell=0}^{\infty} \sum_{m=-\ell}^{\ell} a_{\ell m} \, Y_{\ell m}(\theta, \phi)$

coefficients

spherical harmonics

The CMB



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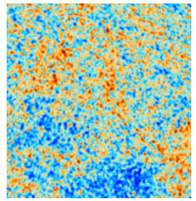
spherical harmonics

The CMB



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- ℓ defines the multipole, the higher ℓ the smaller the scale

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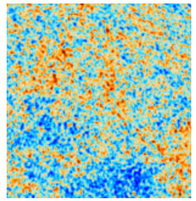

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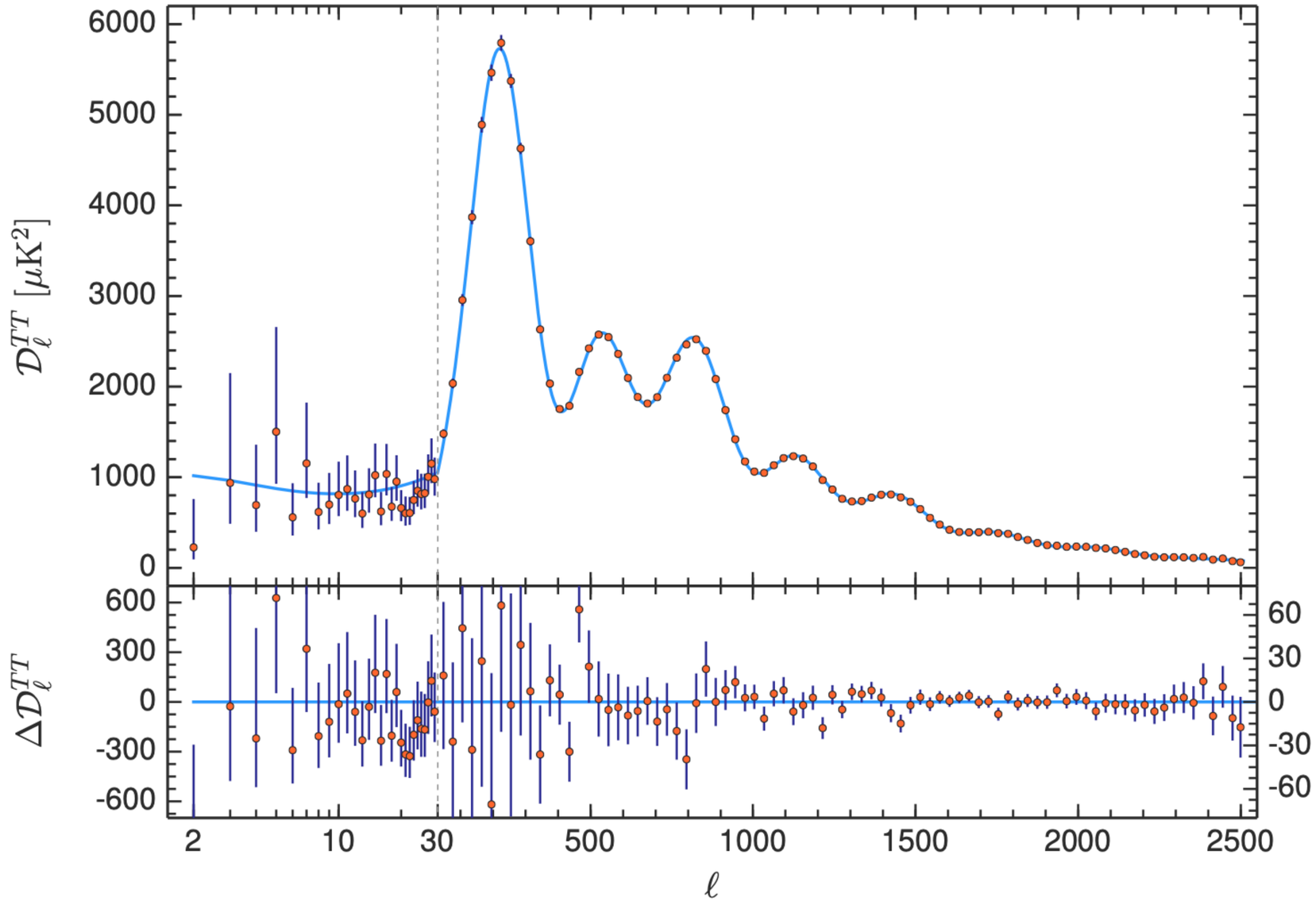
spherical harmonics

- The $a_{\ell m}$ contain the same information as the map itself
- ℓ defines the multipole, the higher ℓ the smaller the scale
- The power spectrum is then given by:

$$C_\ell = \frac{1}{2\ell + 1} \sum_{m=-\ell}^{\ell} a_{\ell,m} \, a^*_{\ell,m}$$

The CMB

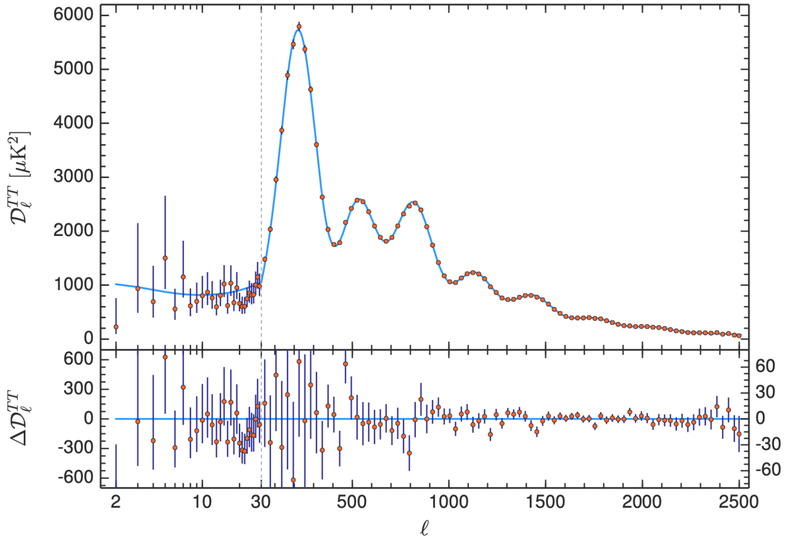
Planck Collaboration



$$D_\ell = \frac{\ell(\ell+1)}{2\pi} C_\ell$$

*You will need this in the hands-on session later

The CMB



How to analyse data like this?

- To predict the CMB power spectrum: one needs to solve full fluid-equations (the Boltzmann equations) for all components of the universe
- This can be done with cosmological Boltzmann solvers like CAMB (Lewis&Bridle 2002) and CLASS (Blas, Lesgourgues, Tram 2011)
- These Boltzmann solvers take as input the ΛCDM parameters and can be sampled within MCMC samplers

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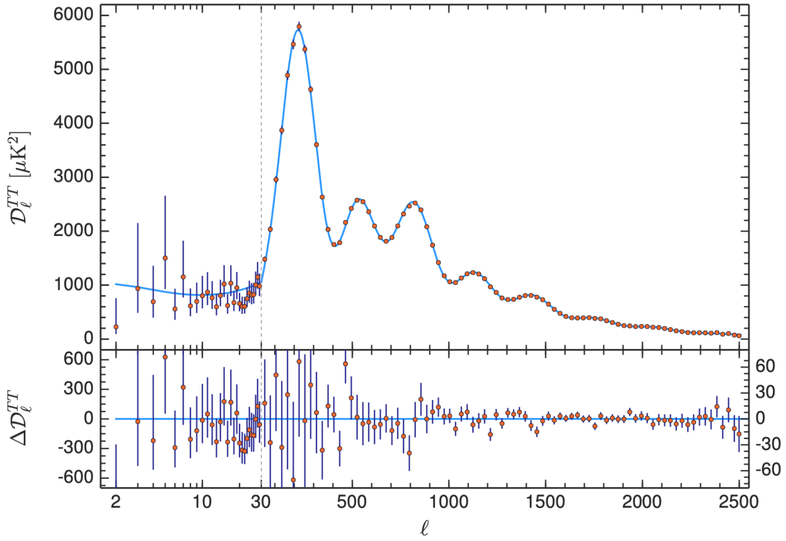
The CMB

ΛCDM model: 6 parameters



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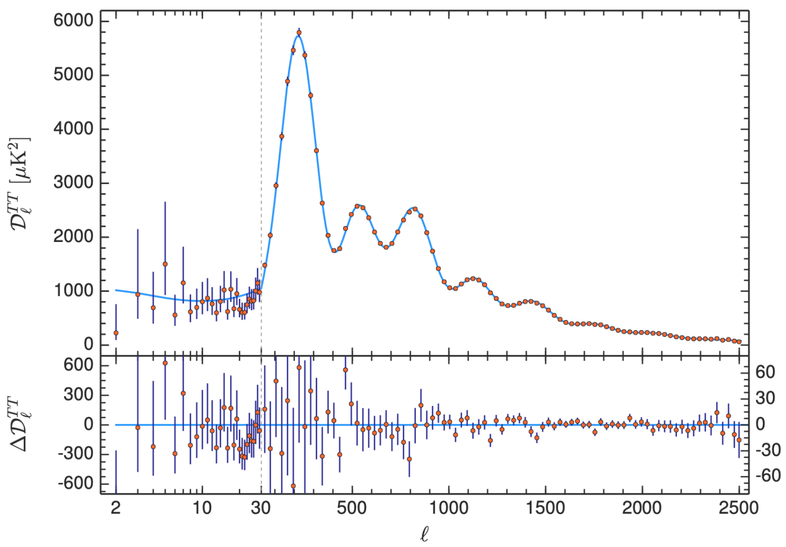

ΛCDM model: 6 parameters

- $\omega_{\rm cdm} = h^2\Omega_{\rm cdm}$:
- $\omega_b = h^2\Omega_b$:
- $h = H_0/(100\,{\rm km/s/Mpc})$:
- $\tau_{\rm reio}$:
- A_s:
- n_s:

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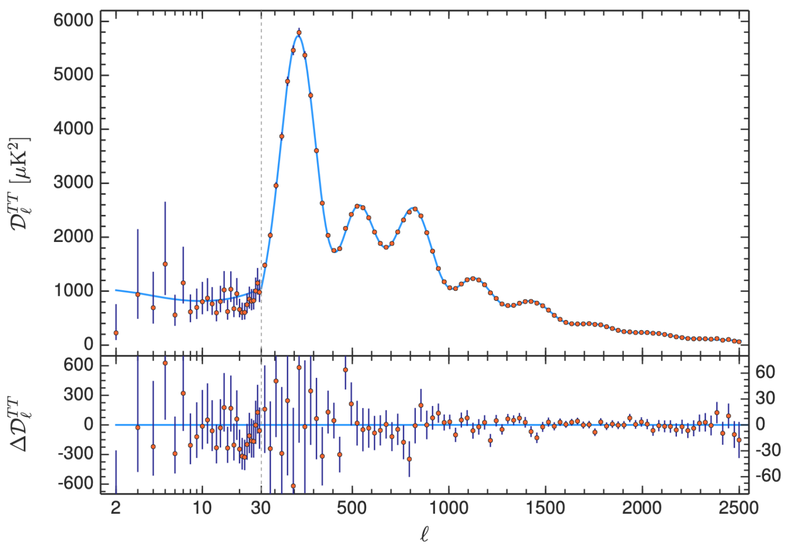
The CMB



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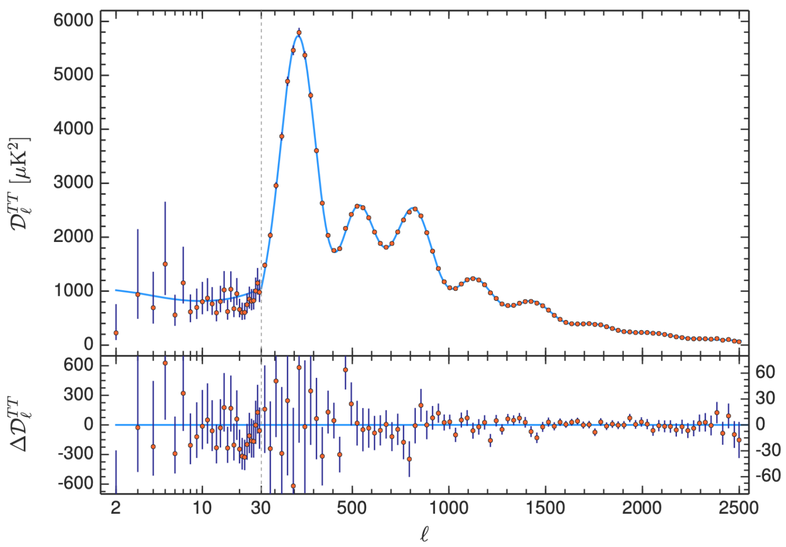

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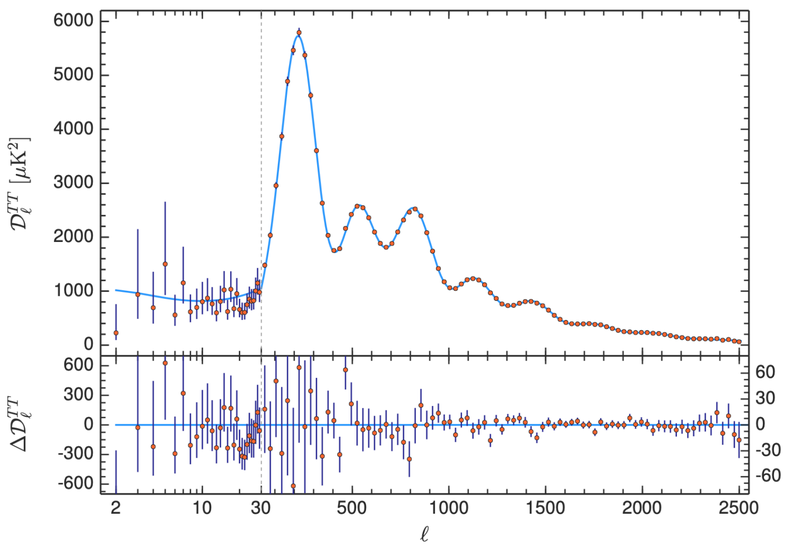

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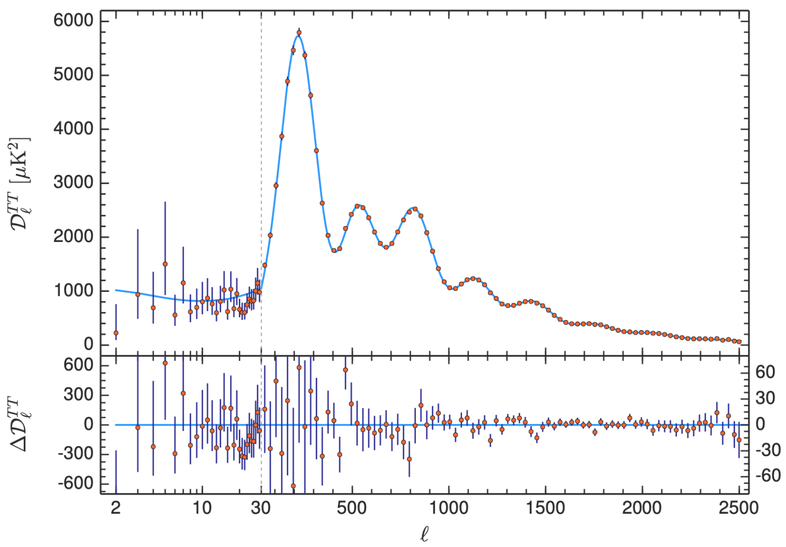
The CMB



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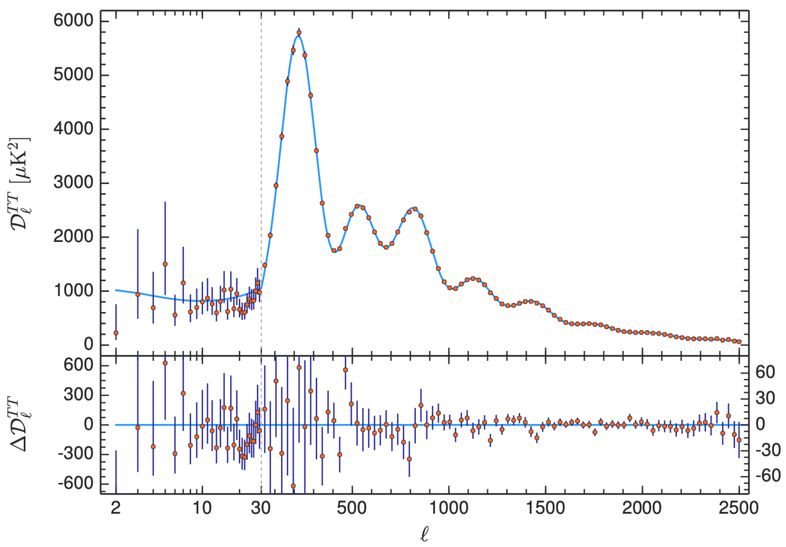

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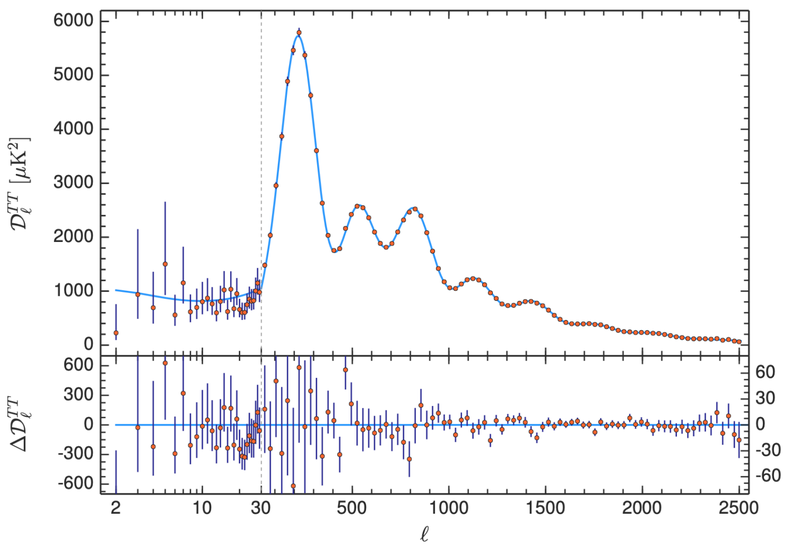

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- n_s: tilt of the primordial power spectrum

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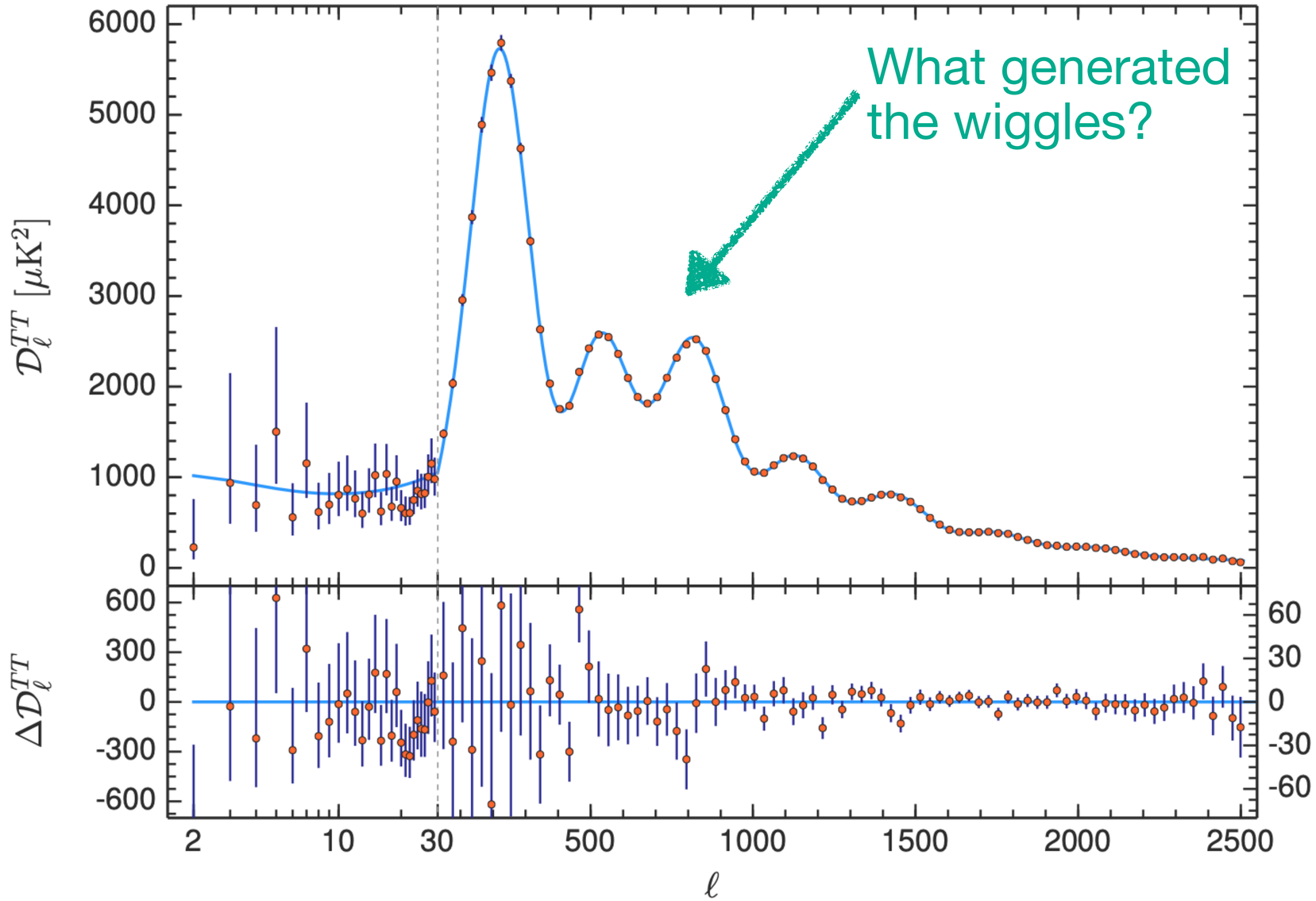
The CMB

Planck Collaboration



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The baryon acoustic oscillations (BAO)

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- Like rain drops on the water surface many waves overlap
- Once electrons and protons recombine, photons can travel freely → the density waves freeze

Credit: Mabel Amber

The baryon acoustic oscillations (BAO)

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- The sound waves travel from the big bang to the time of recombination t^* (when protons and electrons combine into atoms): $r_s = \int_0^{t^*} c_s(t)\ \mathrm{d}t$

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$$\frac{c_s(t)}{a(t)}$$

- While the sound waves travel, the universe expands. This slows down the sound waves in the comoving coordinate frame

The baryon acoustic oscillations (BAO)

- Comoving sound horizon:

$$r_s = \int_0^{t^*} \frac{c_s(t)}{a(t)} \, \mathrm{d}t$$

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$$r_s = \int_0^{t^*} \frac{c_s(t)}{a(t)}\,\mathrm{d}t = \int_0^{a^*} \frac{c_s(a)}{\dot{a}a}\,\mathrm{d}a$$

$$\frac{\mathrm{d}a}{\mathrm{d}t} = \dot{a}$$

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$$\frac{\mathrm{d}z}{\mathrm{d}a} = \frac{\mathrm{d}(1/a)}{\mathrm{d}a} = -\frac{1}{a^2}$$

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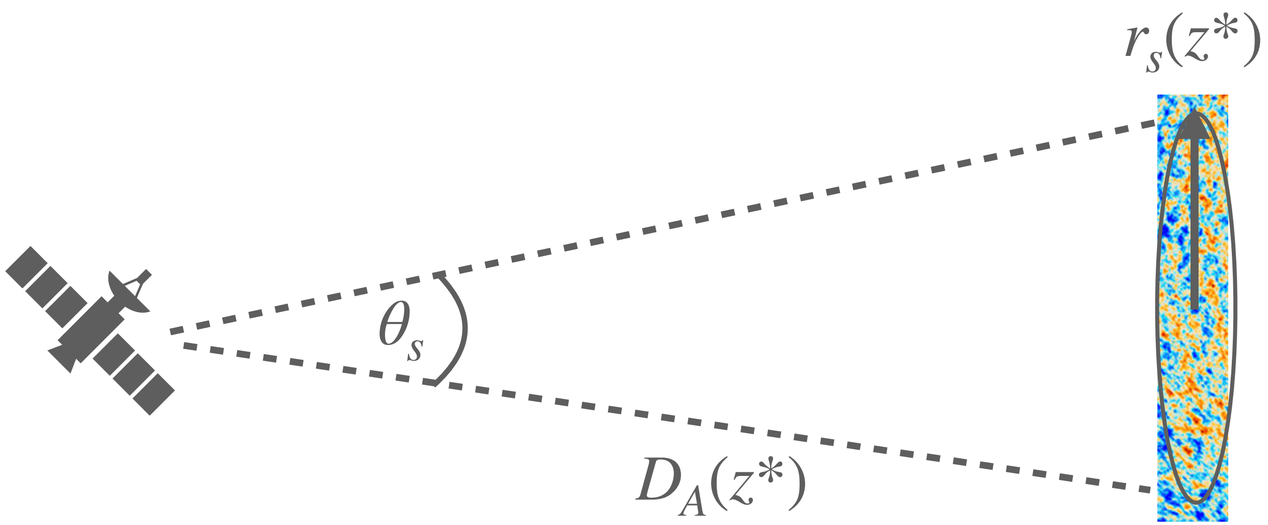
- The sound speed can be expressed as (e.g. Dodelson&Schmidt, 2020):

$$c_s(z) = \frac{1}{\sqrt{3(1+R(z))}}$$

- With R being the baryon-photon ratio:

$$R(z) = \frac{3\omega_b}{4\omega_\gamma}\frac{1}{1+z}$$

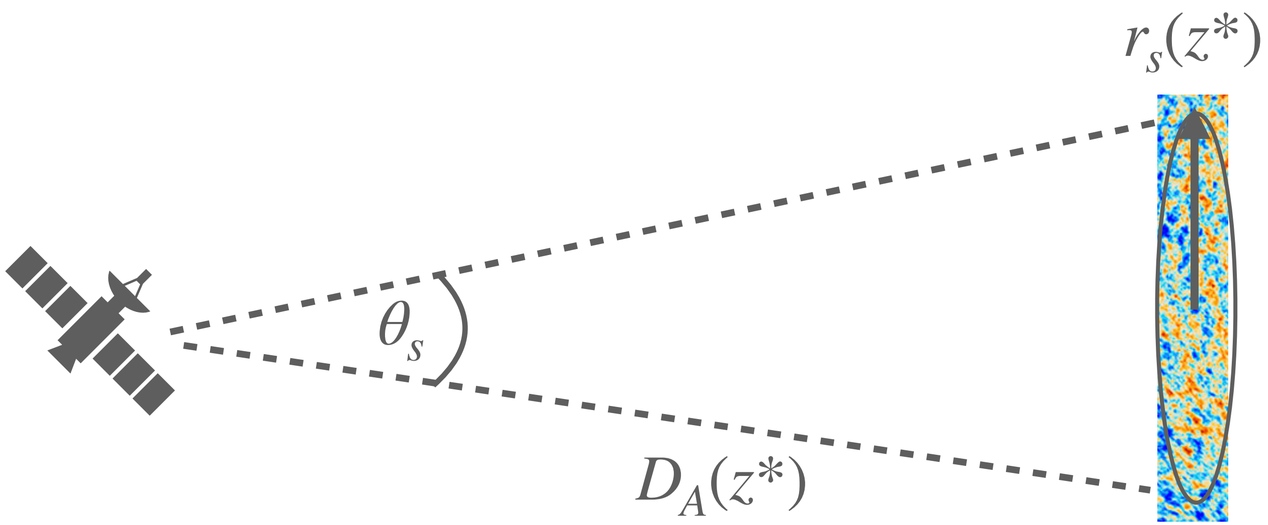
The baryon acoustic oscillations (BAO)



- What we observe is the *angular* size of the sound horizon θ_s

$$r_s^{\rm phys}(z^*) = a(z^*)\, r_s(z^*)$$

The baryon acoustic oscillations (BAO)



- What we observe is the *angular size of the sound horizon* θ_s
- In the small-angle approximation:

$$\theta_s = \frac{r_s^{\rm phys}(z^*)}{D_A(z^*)}$$

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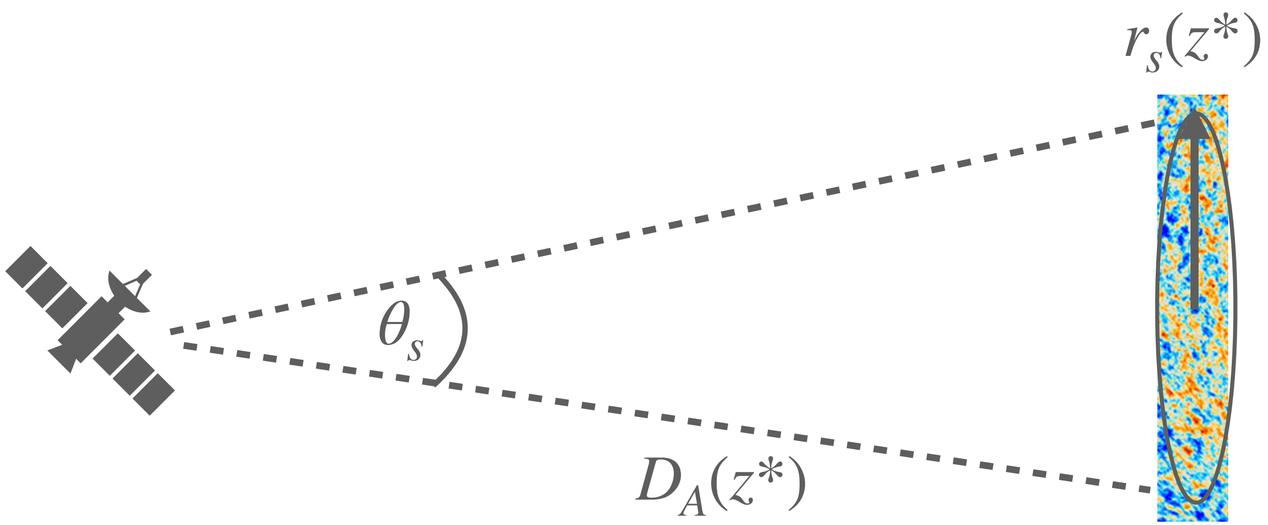

- What we observe is the *angular* size of the sound horizon θ_s
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$$\theta_s = \frac{r_s^{\rm phys}(z^*)}{D_A(z^*)}$$

- where the angular diameter distance is (see slide earlier):

$$D_A(t) = \int_0^{z(t)} \frac{{\rm d}z'}{H(z')}$$

$$r_s^{\rm phys}(z^*) = a(z^*)\, r_s(z^*)$$

How does the CMB constrain H_0?

- We know that the CMB directly constrains

$$\theta_s = \frac{r_s^{\rm phys}(z^*)}{D_A(z^*)} = \frac{\int_{z^*}^{\infty} c_s(z)\mathrm{d}z/H(z)}{\int_0^{z^*} \mathrm{d}z/H(z)}$$

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- Cosmology enters mainly over the Hubble parameter here:

$$H(z) = H_0\sqrt{\Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_\Lambda}$$

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- If we get Ω_r, Ω_m, Ω_Λ from somewhere else, this becomes an implicit equation for H_0 — How does the CMB constrain Ω_r, Ω_m, Ω_Λ?

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$\Omega_r \sim T_{\rm CMB}^4 \rightarrow$ measured by COBE FIRAS

Credit: Berkeley Center for Cosmological Physics

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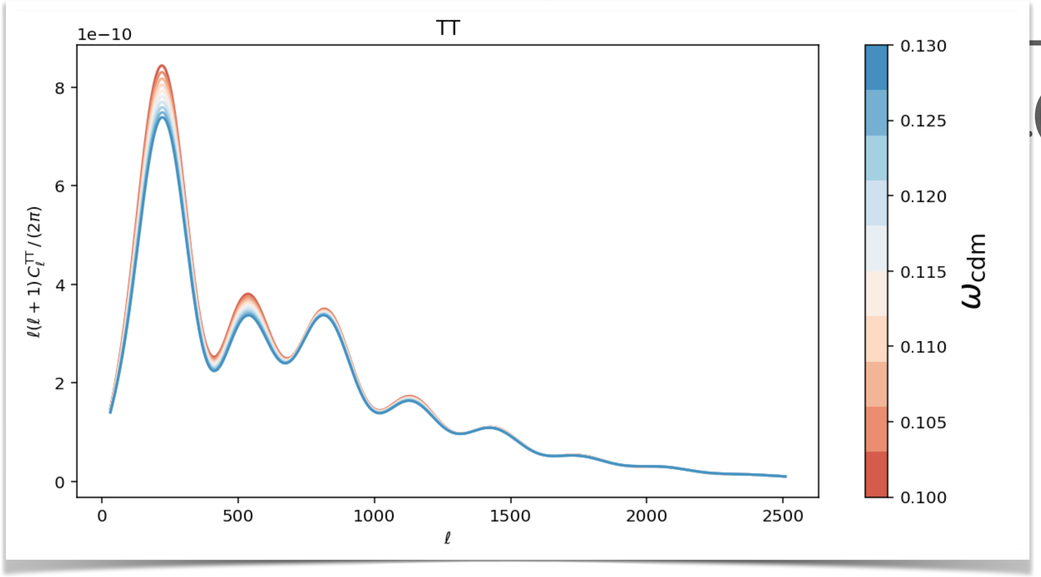

$$(1+z)^4 + \Omega_m(1+z)^3 + \Omega_\Lambda$$

$\omega_m \sim h^2\Omega_m$ can be obtained from the height of the acoustic peaks

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Ω_Λ can be obtained from
$\Omega_r + \Omega_m + \Omega_\Lambda = 1\ (k = 0)$

Solutions to the Hubble tension

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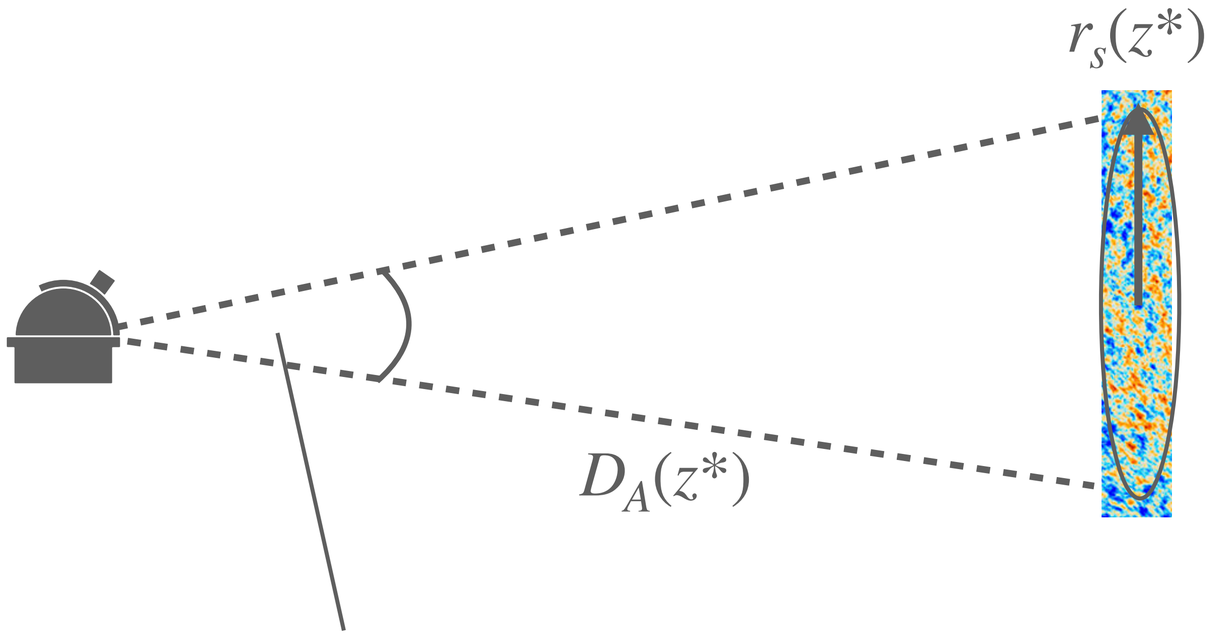

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- θ_s is measured precisely by CMB $\rightarrow \theta_s$ fixed
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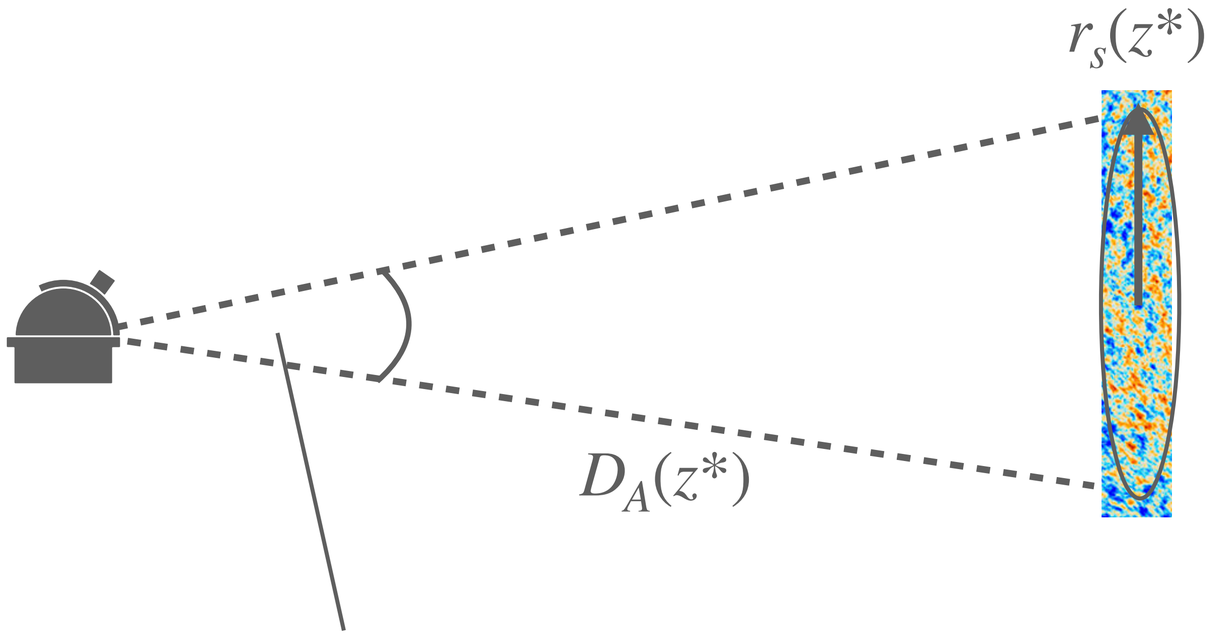
Solutions to the Hubble tension



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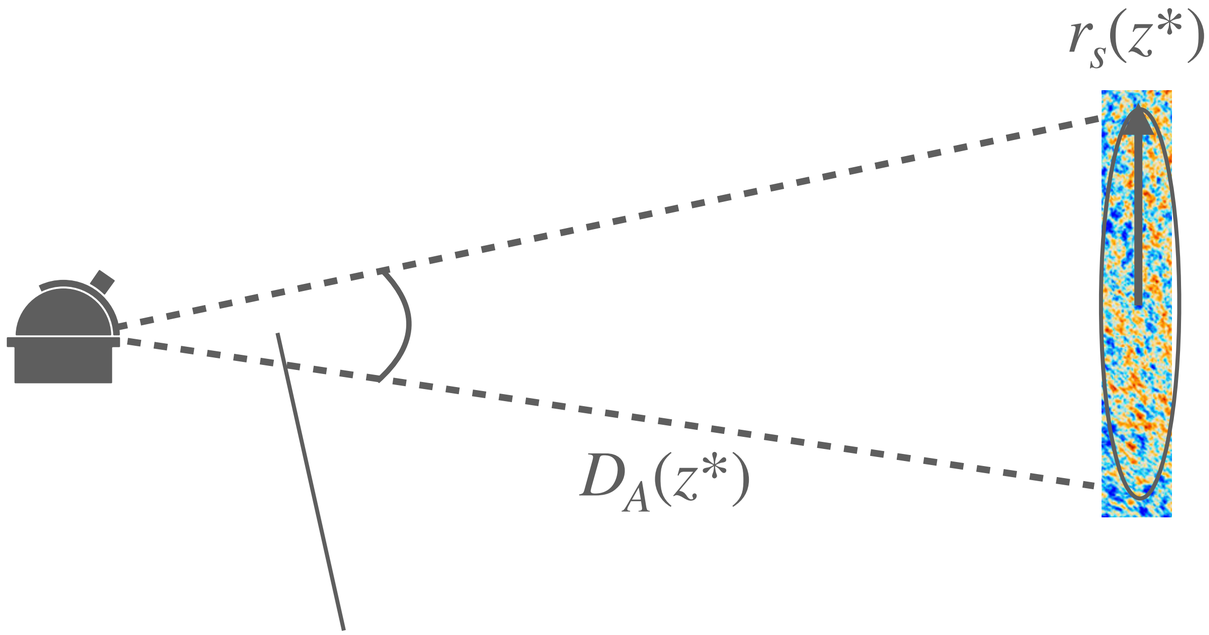

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Early-time solutions modify r_s

Late-time solutions modify D_A

Late-time solutions

- Modify $D_A(z^*) = \int_0^{z^*} \frac{\mathrm{d}z}{H(z)}$ by modifying the expansion rate between today (0) and recombination z^* (since $\Omega_r \approx 0$ at times after z^*):

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- However, $H(z)$ is well constrained by galaxy BAO data and supernova data
  $\rightarrow$ It is challenging to increase H_0 enough

- But there are some approaches (see other lectures)

Early-time solutions

- Modify $r_s = \int_{z^*}^{\infty} \frac{c_s(z)\ \mathrm{d}z}{H(z)}$ → 3 options:
  - modify z^*
  - modify $c_s(z)$
  - modify $H(z)$

Early-time solutions

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  - modify $c_s(z)$
  - **modify $H(z)$** →

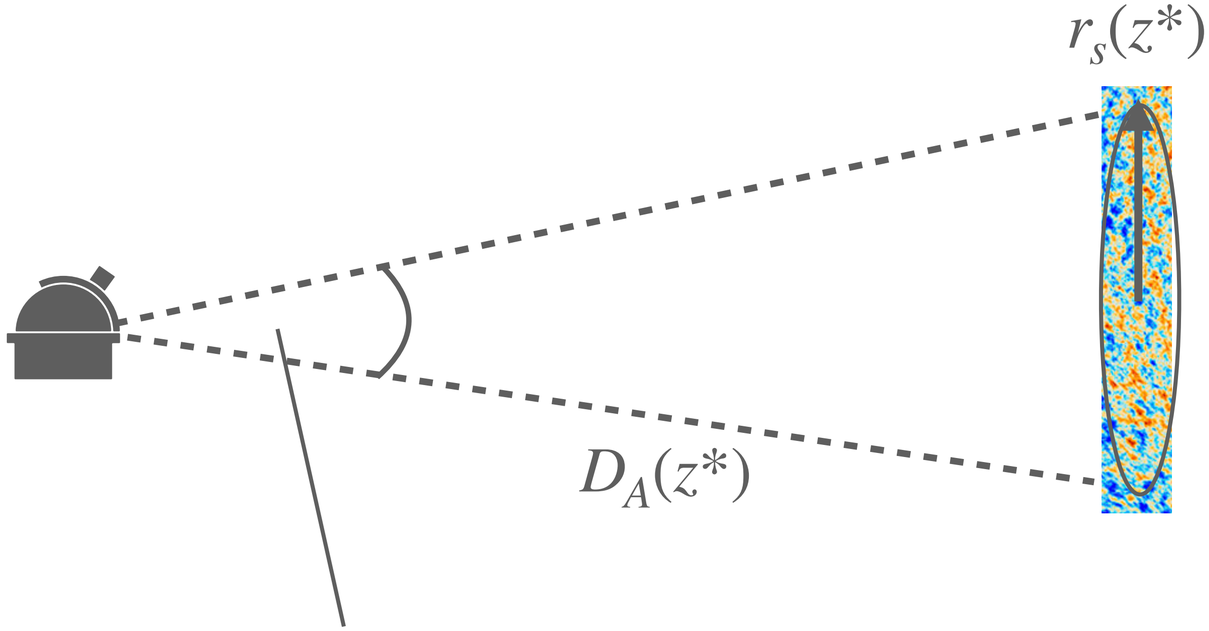
E.g. by introducing an energy density, which boosts the expansion rate before recombination z^* (at early times $\Omega_\Lambda \approx 0$):

$$H(z) = H_0\sqrt{\Omega_r(1+z)^4 + \Omega_m(1+z)^3 + \Omega_?}$$

This leads to a smaller r_s.

One (most successful?) idea is EDE

Idea behind Early Dark Energy



Angular scale of sound horizon θ_s measured with 0.03% precision by *Planck.*

$$\theta_s = \frac{r_s(z^*)}{D_A(z^*)} = \frac{\int_{z^*}^{\infty} c_s(z)\mathrm{d}z/H(z)}{\int_0^{z^*} \mathrm{d}z/H(z)}$$

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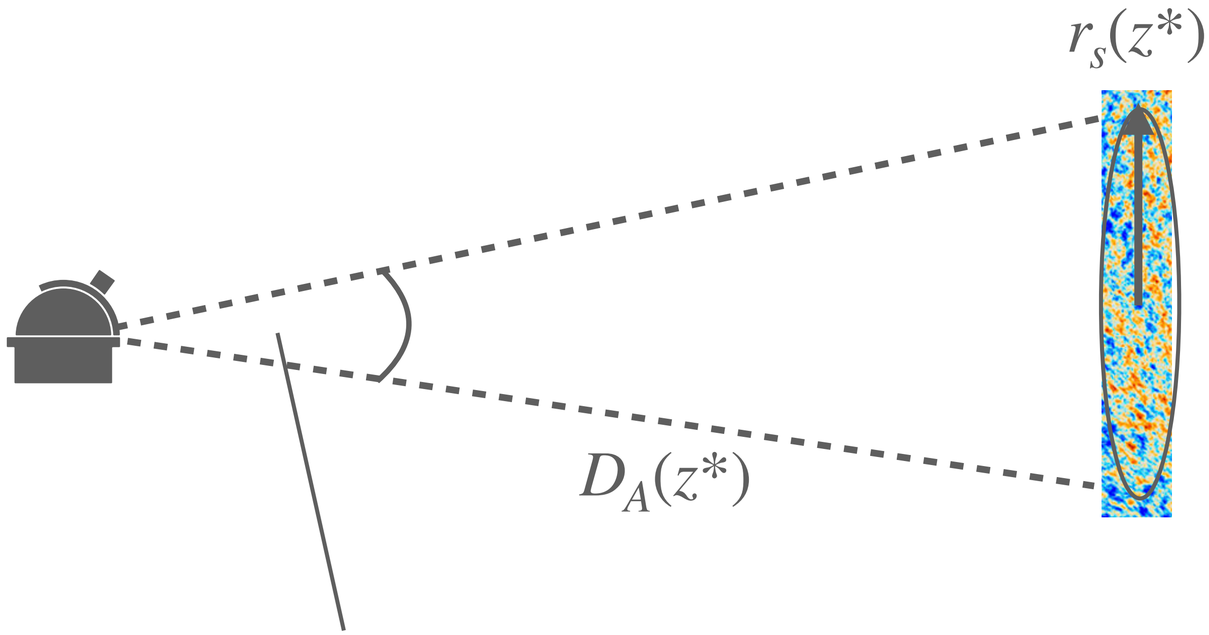

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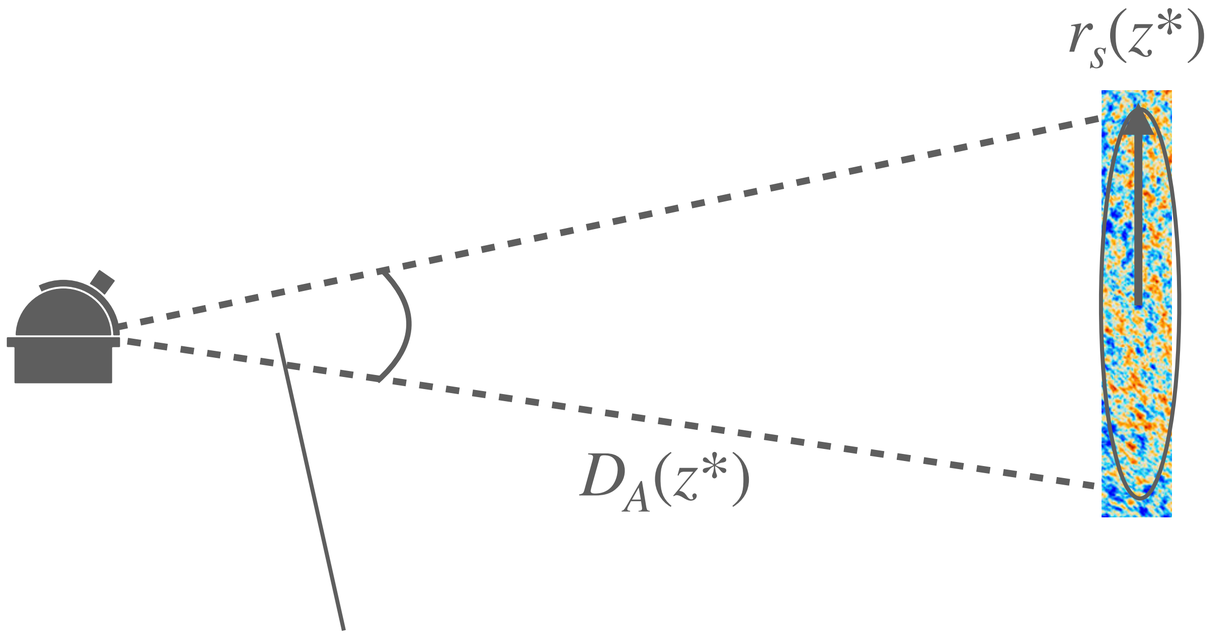

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↓ θ_s fixed

Angular diameter distance D_A decreases.

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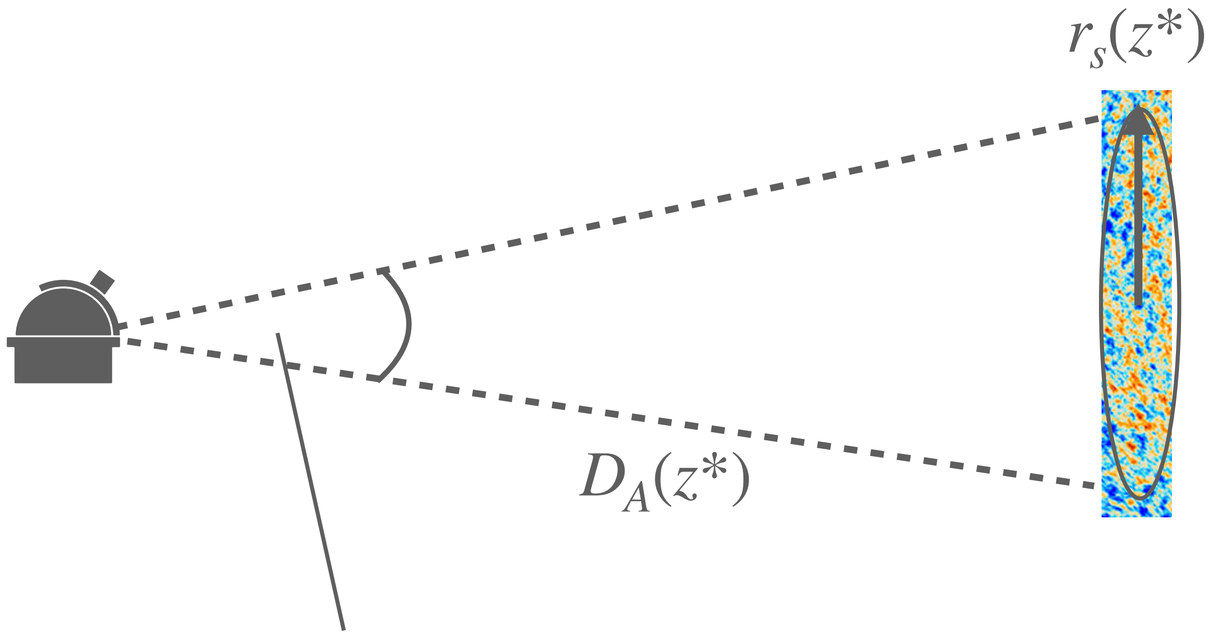

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Introducing an additional component before recombination reduces r_s.

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Angular diameter distance D_A decreases.

↓ $H(z) = H_0\sqrt{\Omega_m(z) + \Omega_r(z) + \Omega_\Lambda}$

H_0 increases.

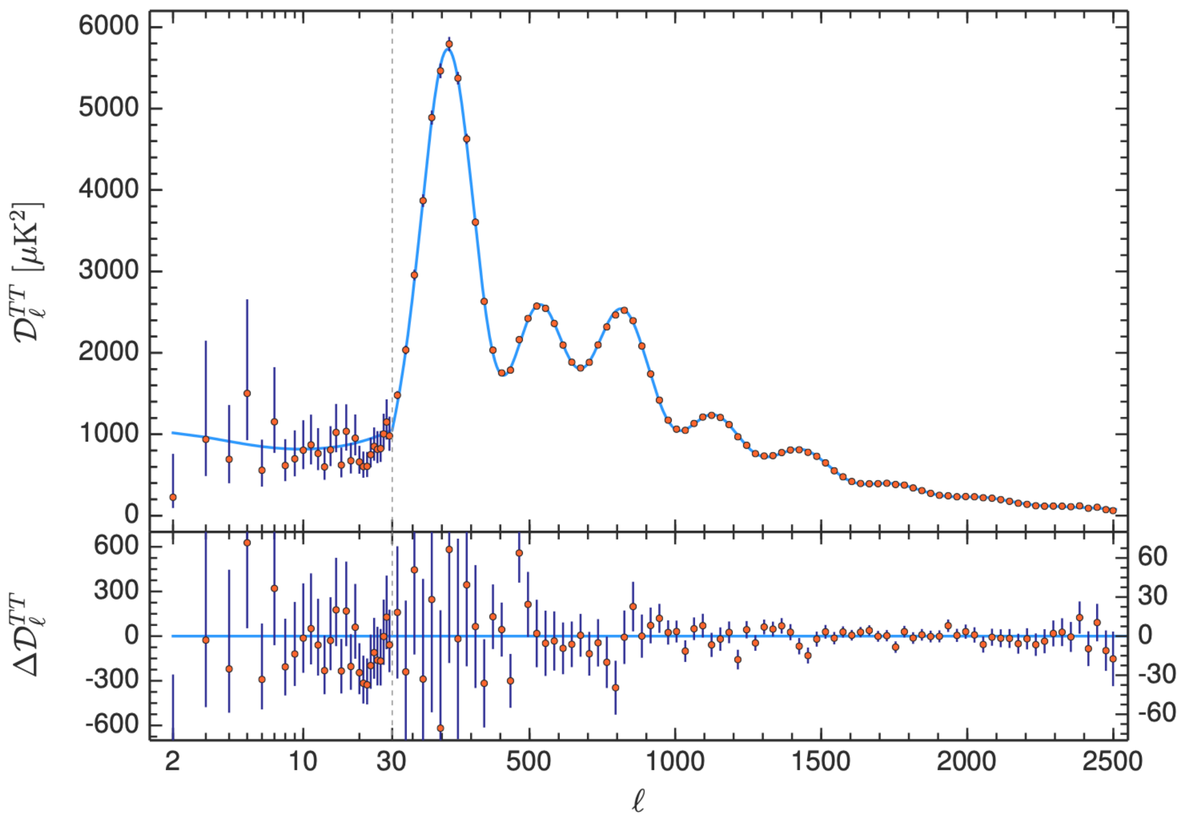
Recap Part 1

ΛCDM & the Hubble tension

- Friedmann equations, Hubble parameter, distances
- CMB basics
- BAO
- How the CMB constrains H_0
- Early- and late-universe solutions

$$\theta_s = \frac{r_s}{D_A(z^*)}$$

Planck Collaboration



Part 2: Early Dark Energy

From ΛCDM to EDE

Part 2: EDE

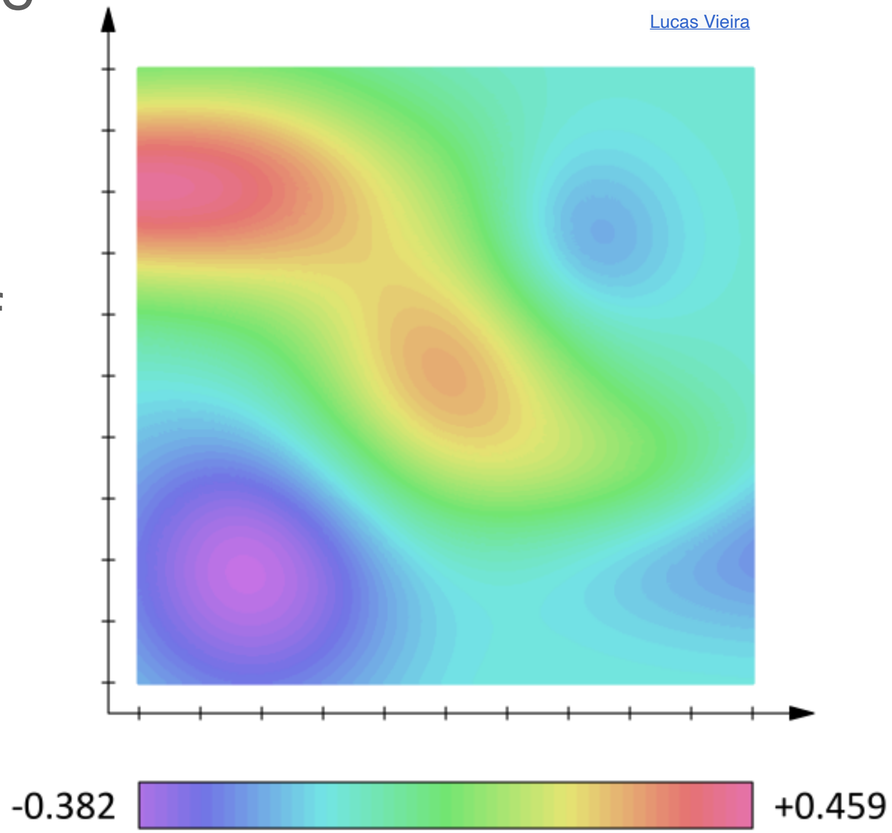
Laura Herold

CosmoVerse Oct 17, 2024

Scalar fields in an expanding spacetime

Intuition

- A scalar field $\phi(t, \vec{x})$ assigns each point in spacetime a single number
- Examples
  - Temperature, density, pressure,… as a function of position and time
  - Potential fields like the gravitational potential, electric potential
  - The inflaton driving inflation is most commonly a scalar field



temperature

Scalar field

Very similar to inflation: see William Giare's lecture

- The action of a scalar field minimally coupled to the metric is:

$$\mathcal{S}_\phi = \int \mathrm{d}^4x \sqrt{|\det(g)|} \left[-\frac{1}{2} g^{\mu\nu} \partial_\mu \phi \, \partial_\nu \phi - V(\phi) \right]$$

integral over whole spacetime

determinant of metric

kinetic term

potential term

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integral over whole spacetime

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potential term

- One can compute the energy momentum tensor of the scalar field via:

$$T_{\mu\nu} = \partial_\mu \phi \partial_\nu \phi - g_{\mu\nu} \left(\frac{1}{2} g^{\alpha\beta} \partial_\alpha \phi \partial_\beta \phi - V(\phi) \right)$$

Scalar field

- This gives for the energy-momentum tensor:

$$T_{\mu\nu} = \partial_\mu \phi \partial_\nu \phi - g_{\mu\nu} \left(\frac{1}{2} g^{\alpha\beta} \partial_\alpha \phi \partial_\beta \phi - V(\phi) \right) = \dot{\phi}^2 \delta^0_\mu \delta^0_\nu + \left[\frac{\dot{\phi}^2}{2} - V(\phi) \right] g_{\mu\nu}$$

Scalar field

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- By comparing $T_{\mu\nu}$ to the energy momentum tensor of the perfect fluid: $T_{\mu\nu} = (\rho + p)\delta^0_\mu\delta^0_\nu + pg_{\mu\nu}$, one can read off the energy density and pressure of the scalar field:

$$\rho_\phi = \frac{\dot{\phi}^2}{2} + V(\phi), \quad p_\phi = \frac{\dot{\phi}^2}{2} - V(\phi)\,.$$

Scalar field

- Inserting $\rho_\phi = \frac{\dot{\phi}^2}{2} + V(\phi), \quad p_\phi = \frac{\dot{\phi}^2}{2} - V(\phi)$ into the first Friedmann equation and the continuity equation yields:

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$$\boxed{\begin{aligned} H^2 &= \frac{8\pi G_{\mathrm{N}}}{3}\left(\frac{\dot{\phi}^2}{2} + V(\phi)\right) \\ \ddot{\phi} + 3H\dot{\phi} + \frac{\mathrm{d}V}{\mathrm{d}\phi} &= 0 \end{aligned}}$$

"Hubble friction"

Potential term

Scalar field

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- The second equation is the Klein-Gordon equation for a scalar field in an expanding space, where the second term ($3H\dot{\phi}$) is the Hubble-drag term and the third term ($\frac{1}{2}\mathrm{d}V/\mathrm{d}\phi$) is the potential-gradient term

Early Dark Energy

Short history of Early Dark Energy

- EDE has already been studied before the Hubble tension emerged in the context of quintessence models (Doran++ 2001, Wetterich++ 2004, Doran&Robbers 2006, Kamionkowski++ 2014)
- The axion-like EDE was proposed as a solution to the Hubble tension (Karwal&Kamionkowski 2016, Poulin++ 2018, 2019)
- There are many versions of the EDE model, but we will focus on the (most commonly studied) axion-like EDE model
- The axion-like EDE model is modelled as a scalar field

Early Dark Energy

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index n:

$n = 1$ "standard" axion; however: doesn't decay quickly enough

$n = 3$: is preferred value by the data (Poulin++ 2020)
$\rightarrow$ decays fast enough (commonly fixed in EDE data analysis)

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Free parameters of the model:

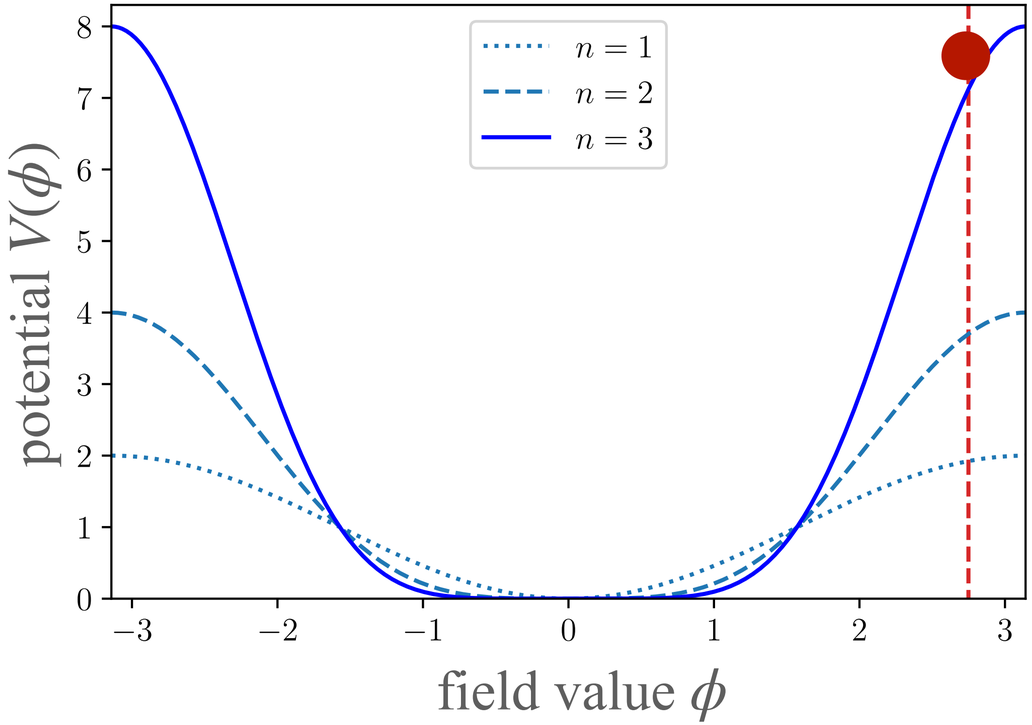
- m mass ($V_0 = m^2 f^2$)
- f "decay constant"
- $\theta_i = \phi_i/f$ initial value of the field
- $(n = 3)$

Early Dark Energy (EDE)

Kamionkowski++ 2014, Karwal & Kamionkowski 2016, Caldwell & Devulder 2018, Poulin++ 2019, …

Dynamics: $$\ddot{\phi} + 3H\dot{\phi} + \frac{\mathrm{d}V(\phi)}{\mathrm{d}\phi} = 0$$

- Initially: Hubble friction dominates: ϕ frozen —> behaves as DE



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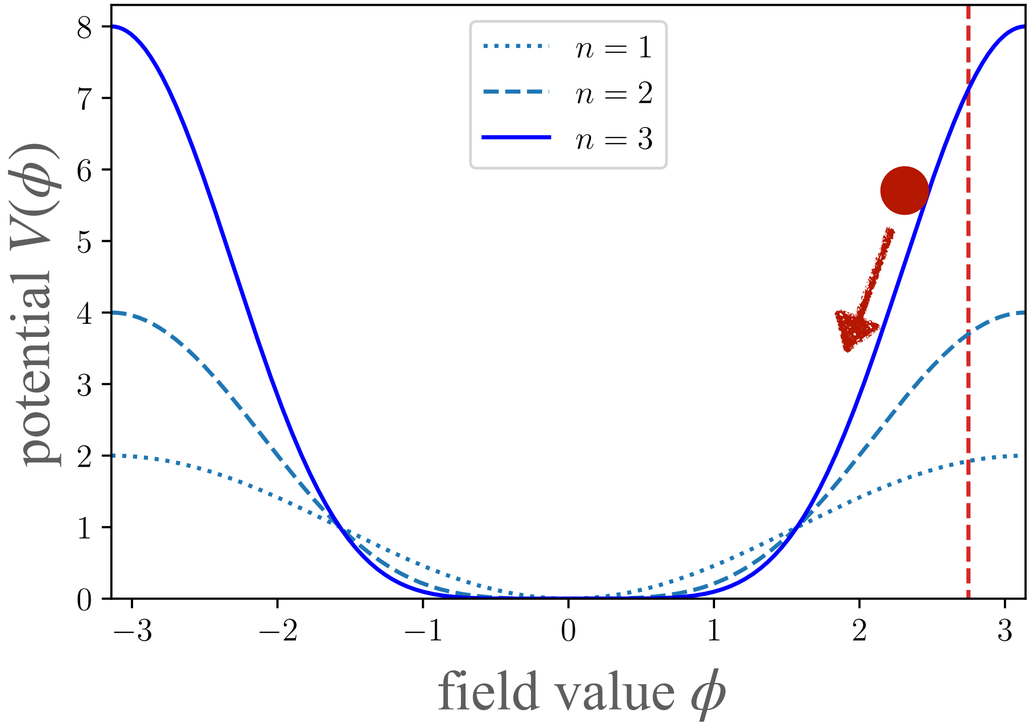

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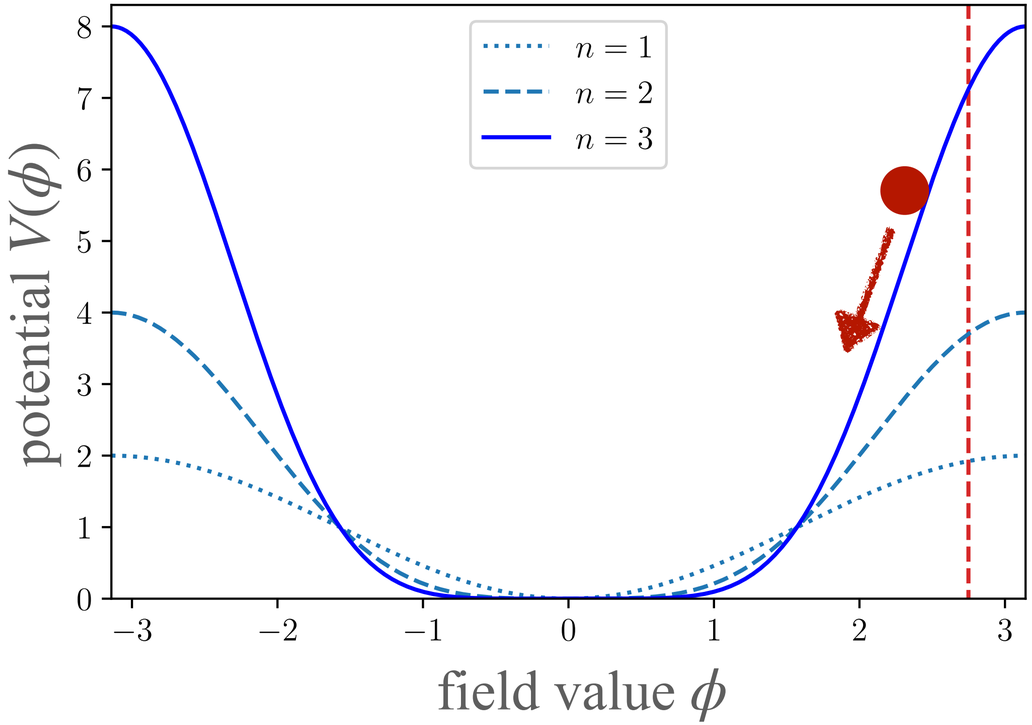

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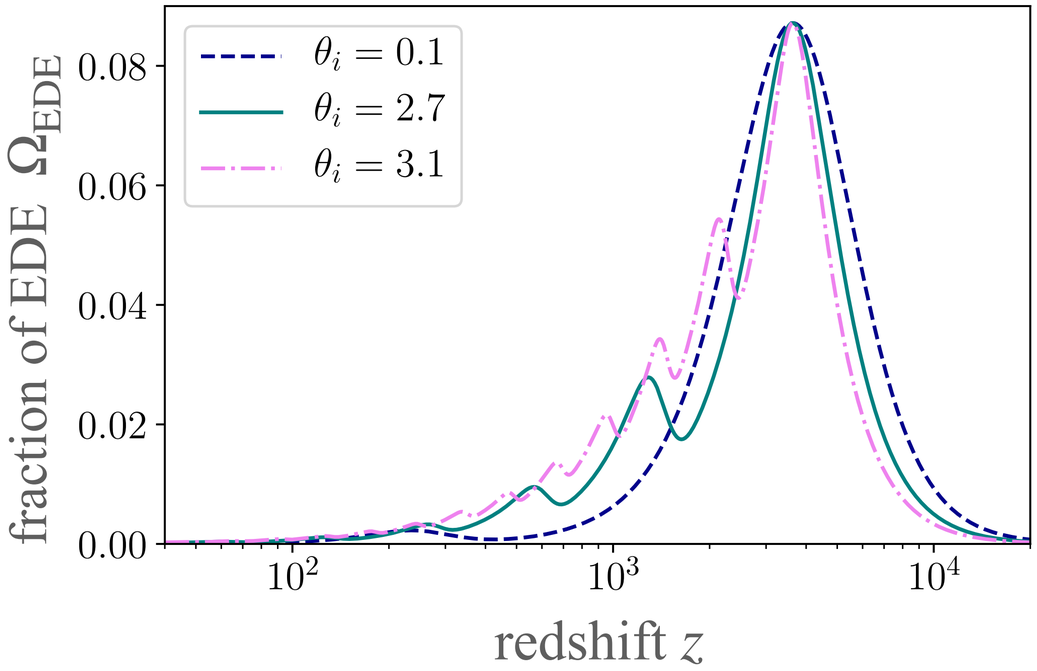

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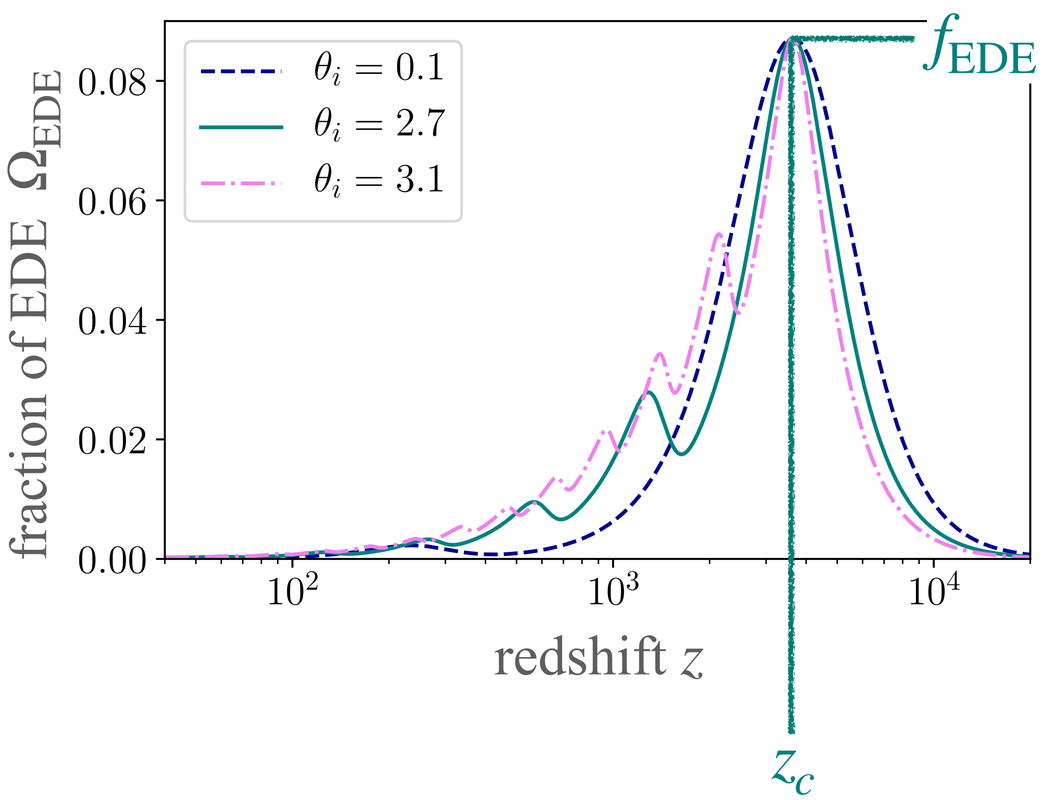

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$f_{\rm EDE}$, z_c, θ_i (3 additional parameters to ΛCDM)

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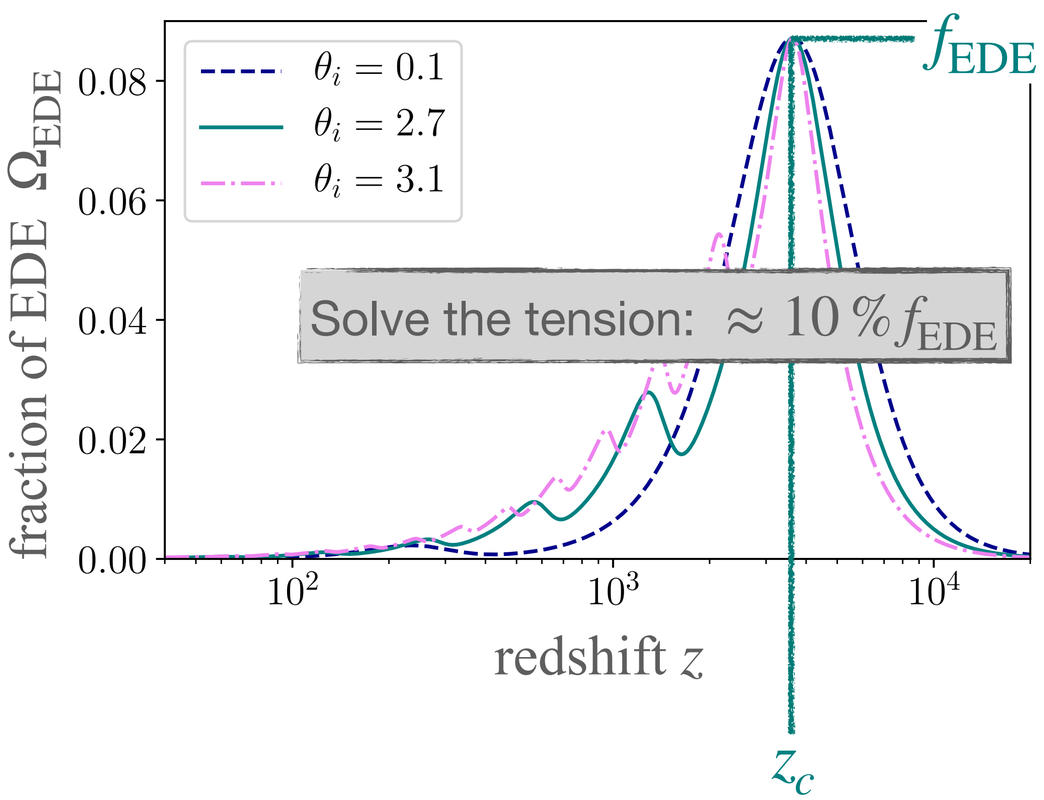

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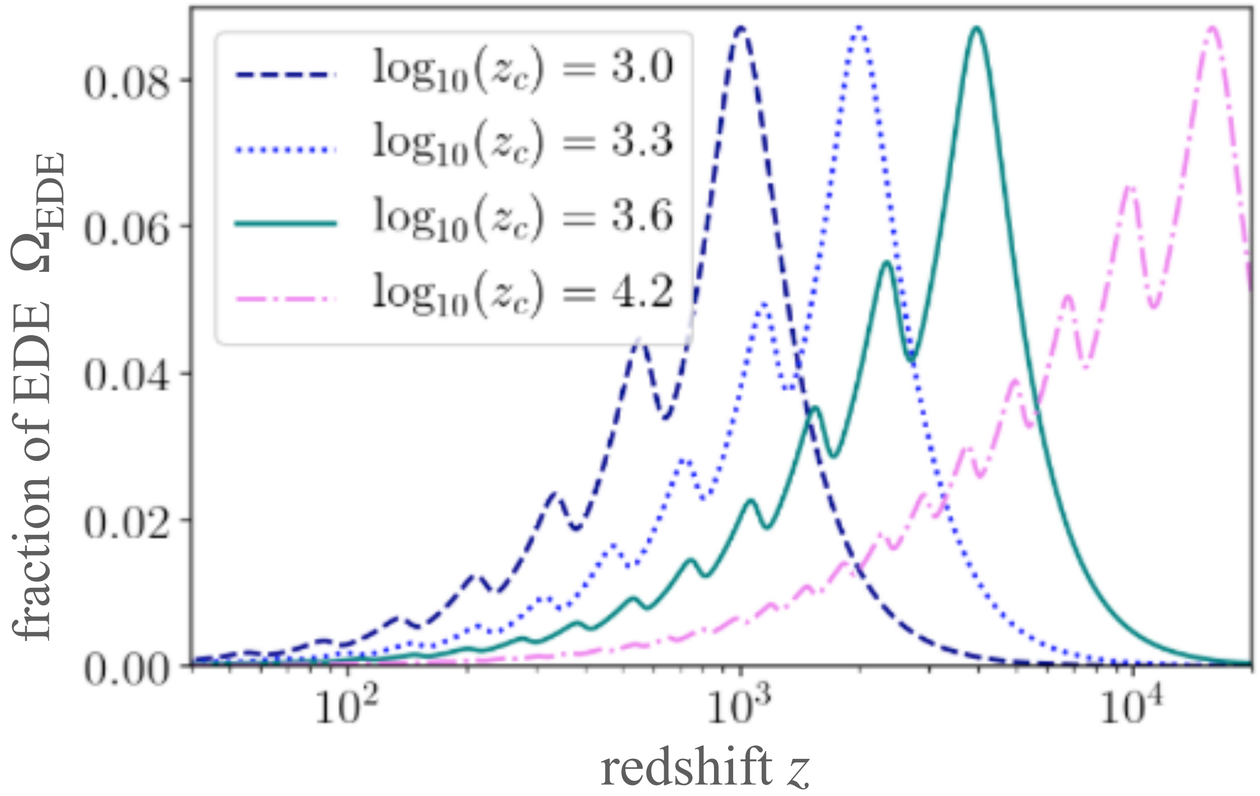
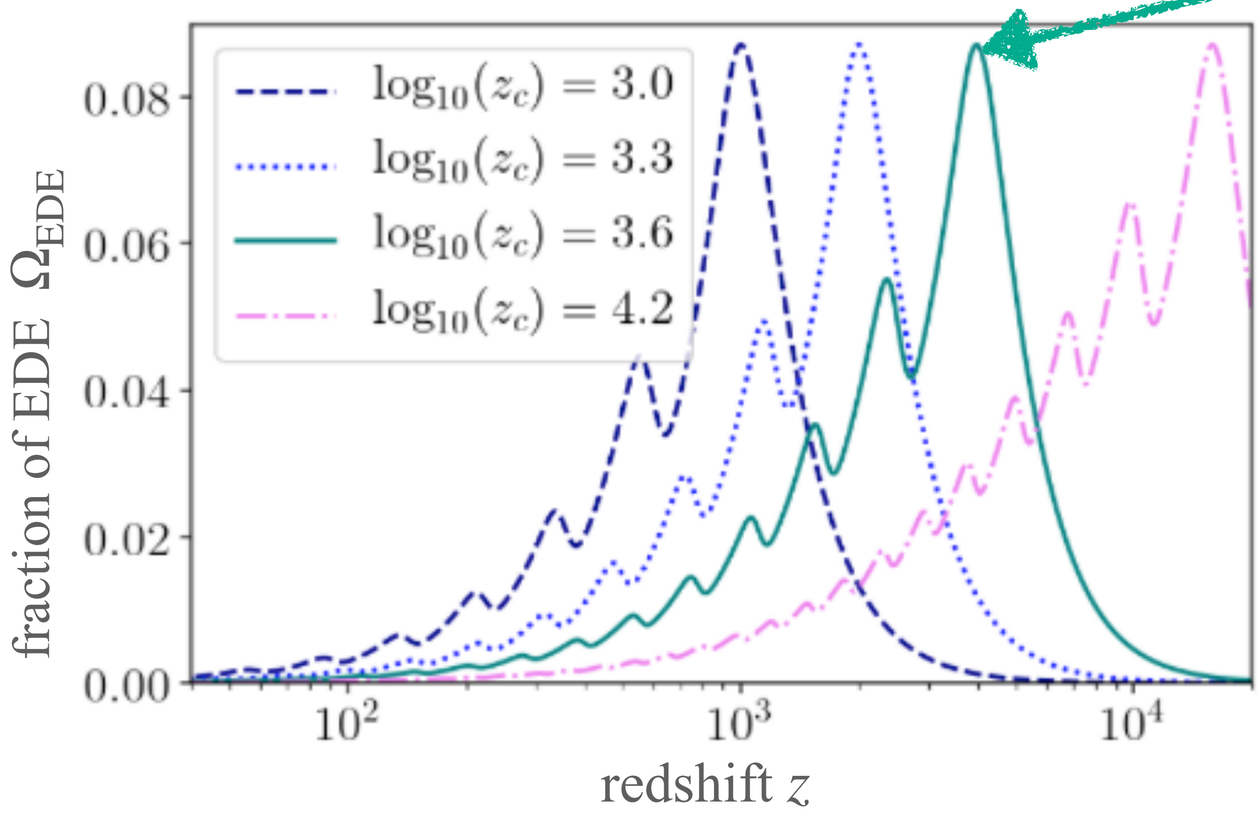


The critical redshift z_c determines when the field starts oscillating, hence when $\Omega_{\rm EDE}$ peaks

Early Dark Energy

$f_{\rm EDE} = \Omega_{\rm EDE}(z_c)$: determines the height of the peak



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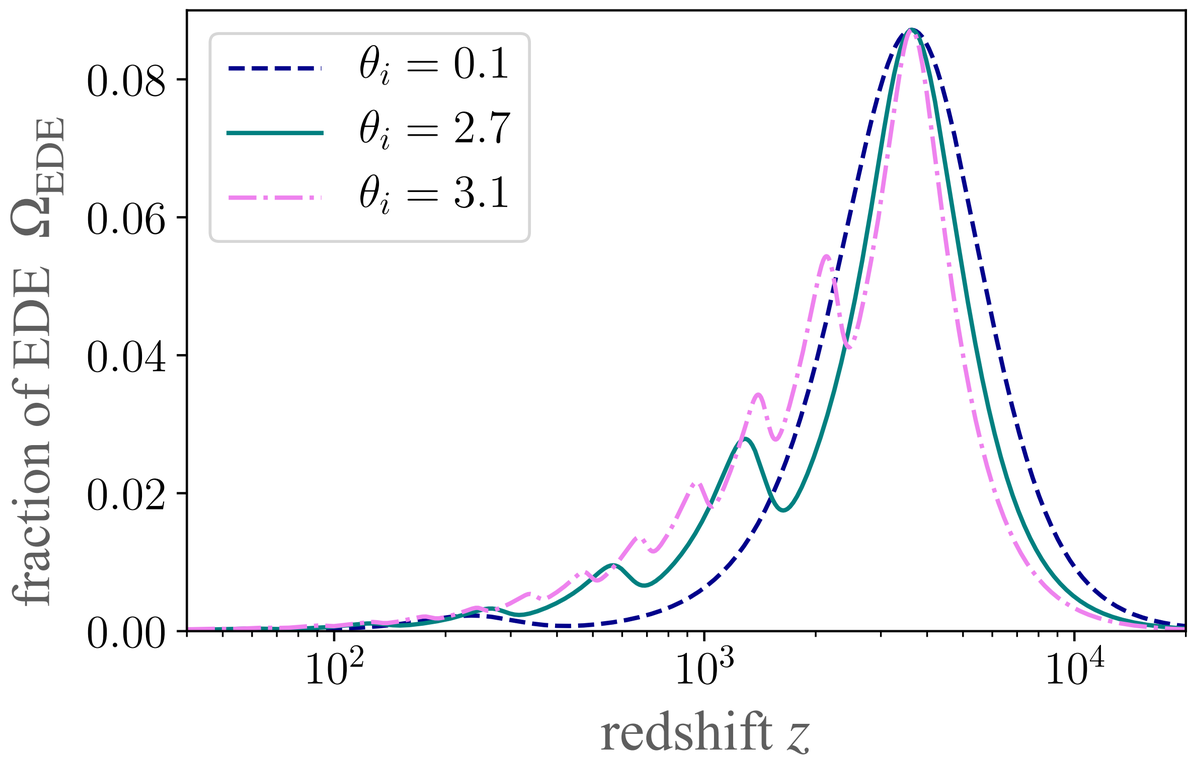
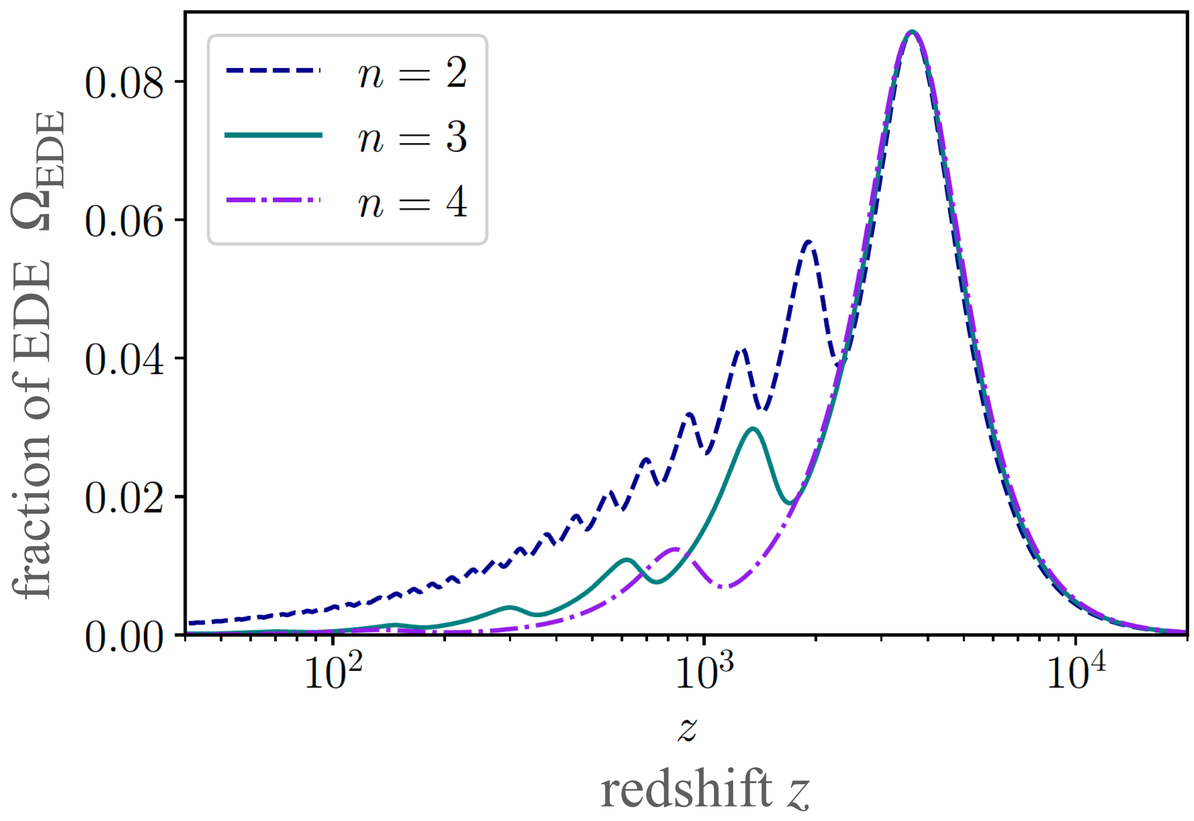


The initial value $\theta_i \in [0,\pi]$ determines how fast the field oscillates when it decays:

The closer to π the faster the oscillations

Early Dark Energy



The index $n = 1, 2, 3, \ldots$ determines how fast the field decays:

The higher n, the faster the decay

$n = 3$ was shown to fit the data best

Can EDE resolve the H_0 tension

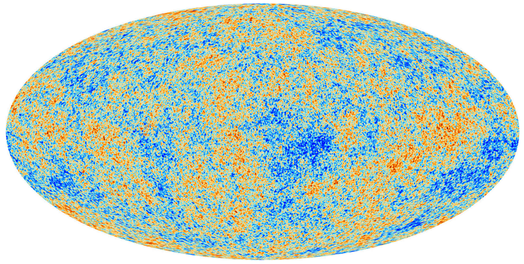
… and fit all available data sets?

Disclaimer: this review about constraints on EDE is **not** complete

Can EDE solve the H_0 tension and fit these data sets?

Data sets: Planck + 6dFGS + BOSS DR12 BAO/ RSD + Pantheon + SH0ES 2016

CMB (TT, TE, EE, lensing)



ESA

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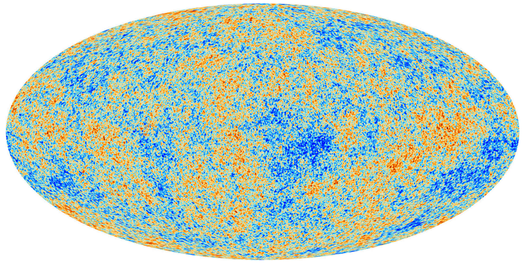
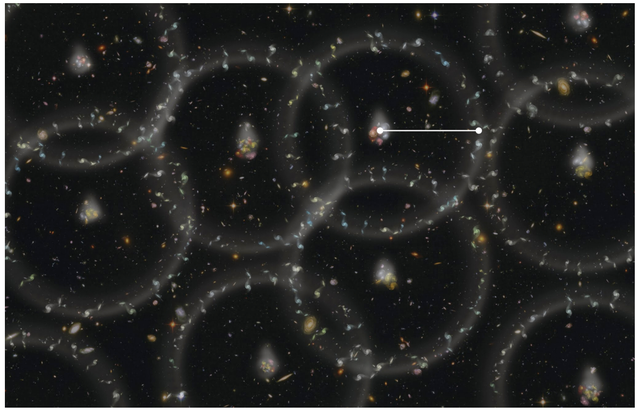
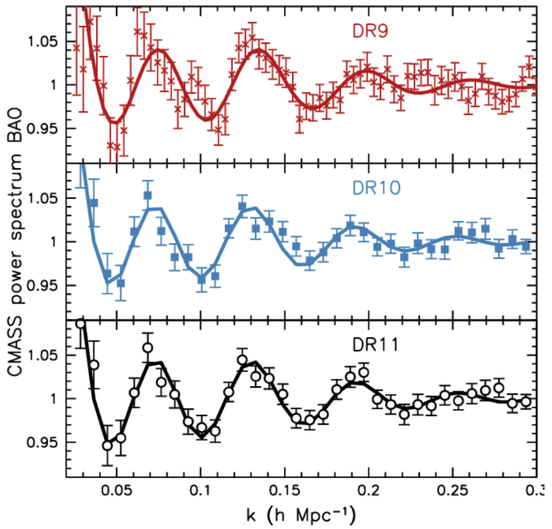


ESA

Baryon acoustic oscillations



BOSS collaboration



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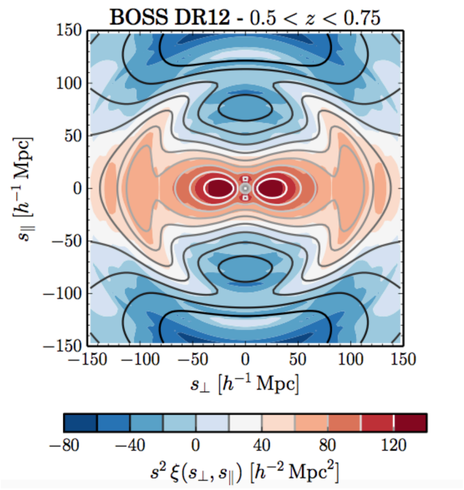
Redshift space distortions



BOSS collaboration (Sanchez++ 2016)

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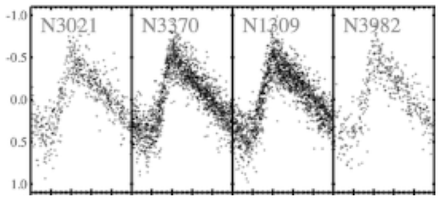
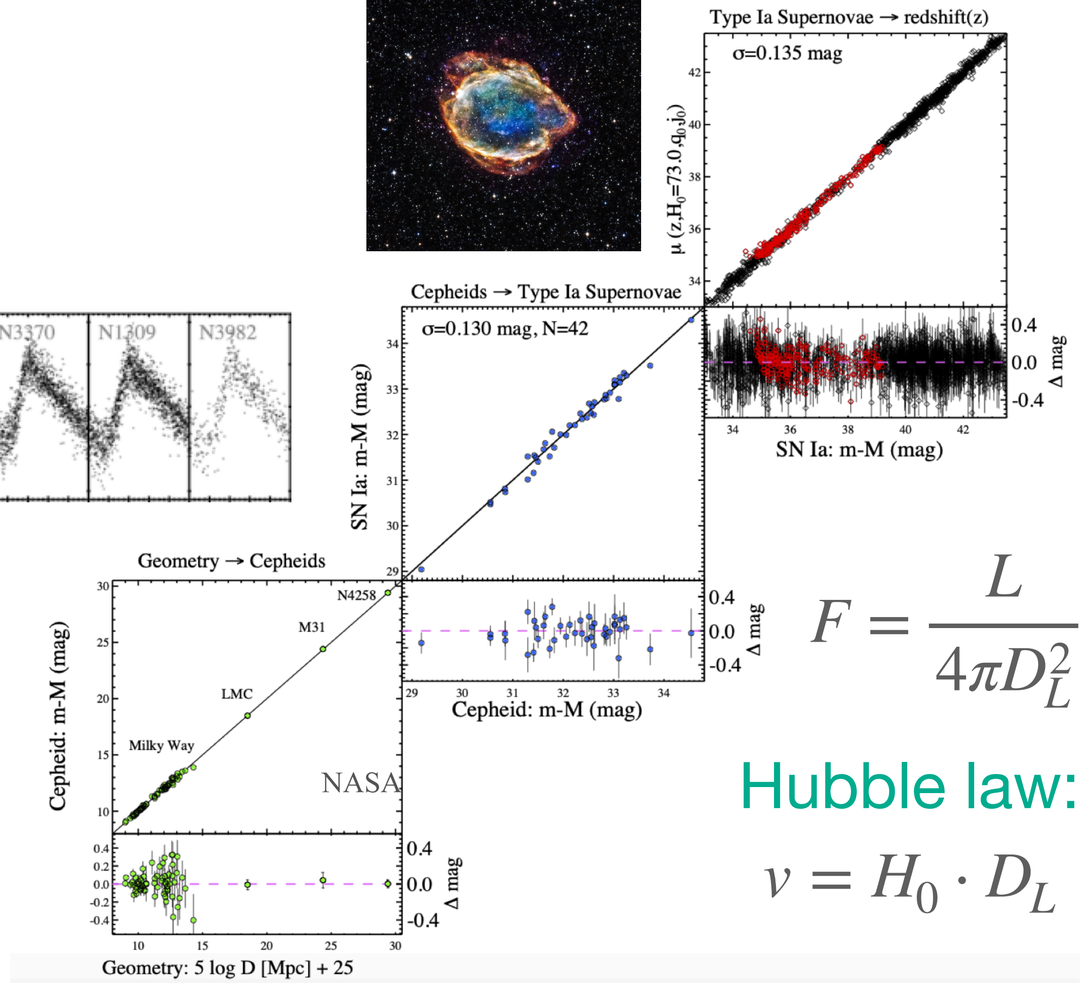
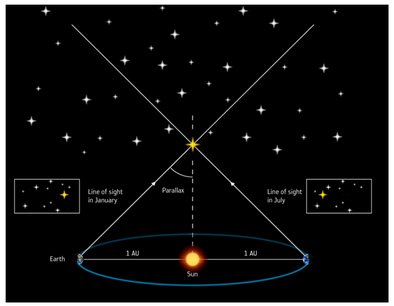
Cepheid-calibrated SNIa
(distance ladder)





Gaia col.



$$F = \frac{L}{4\pi D_L^2}$$

Hubble law:

$$v = H_0 \cdot D_L$$

SH0ES collaboration 2022 (Riess et al.)

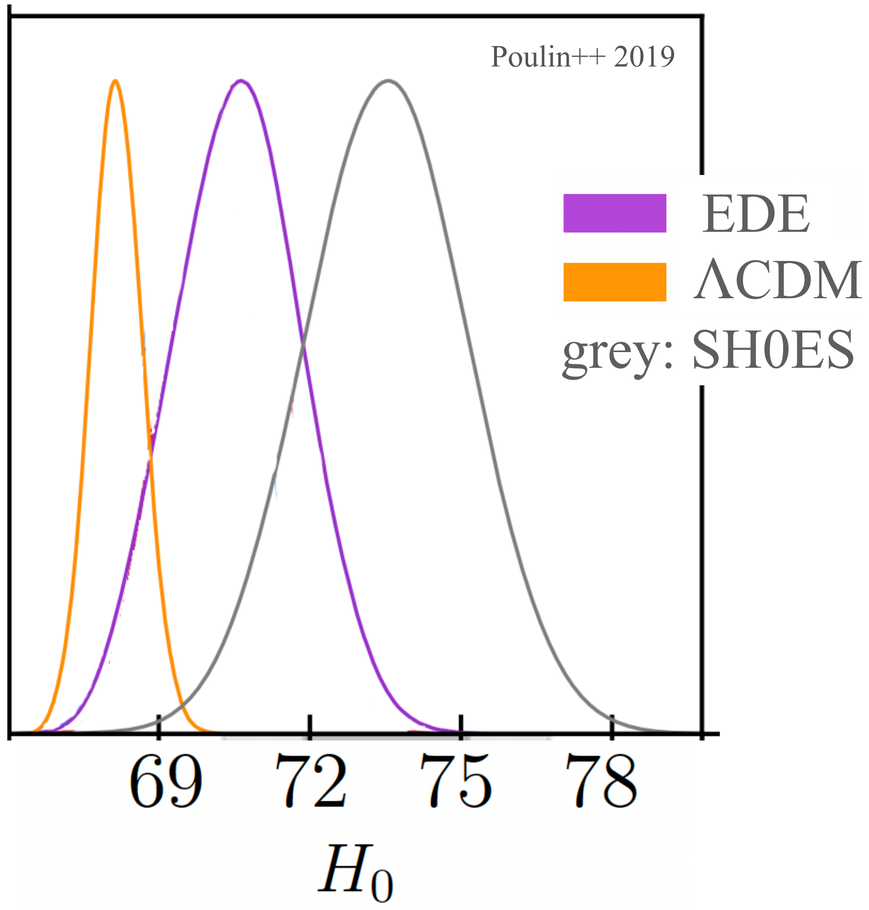
2019: EDE can solve the H_0 tension!

Poulin, Smith, Karwal, Kamionkowski, 2019

Data sets: Planck + 6dFGS + BOSS DR12 BAO/RSD + Pantheon + SH0ES 2016

- $f_{\rm EDE} = 0.107^{+0.035}_{-0.030}$ (mean $\pm 1\sigma$)
- $H_0 = 71.49 \pm 1.20$ km/s/Mpc

MCMC posterior



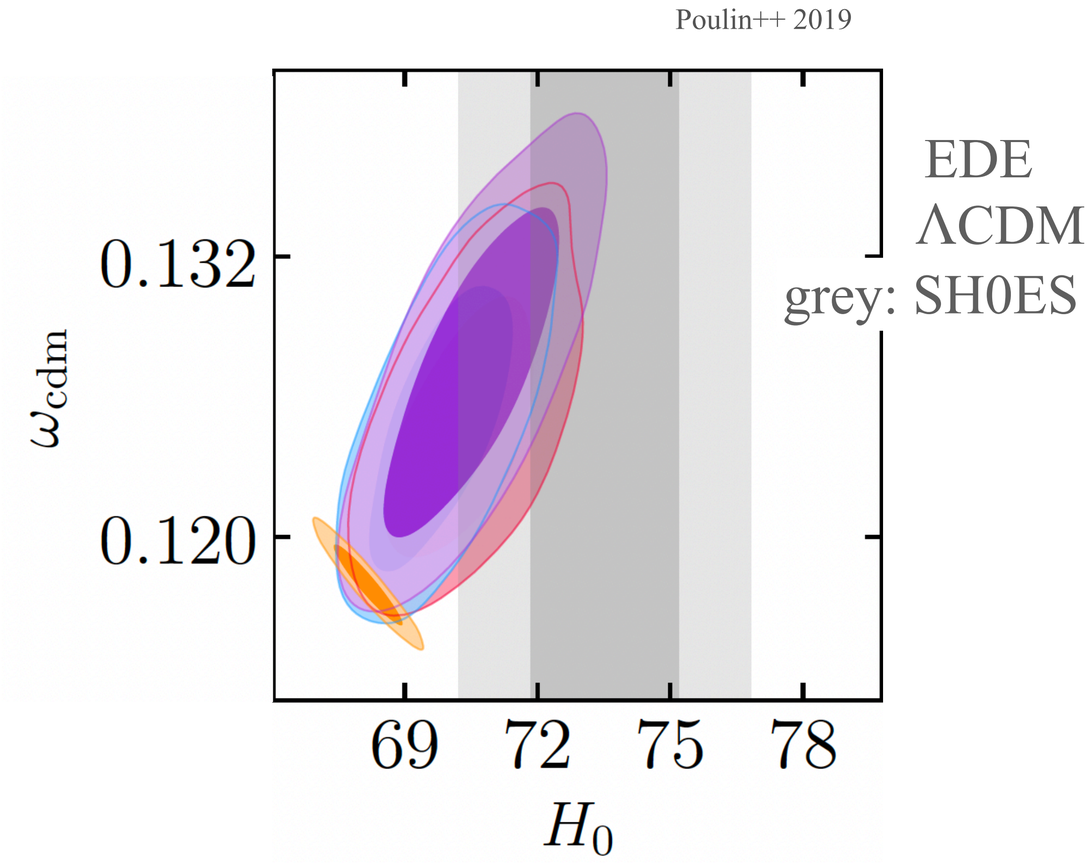
2019: EDE can solve the H_0 tension!

Poulin, Smith, Karwal, Kamionkowski, 2019

Data sets: Planck + 6dFGS + BOSS DR12 BAO/RSD + Pantheon + SH0ES 2016

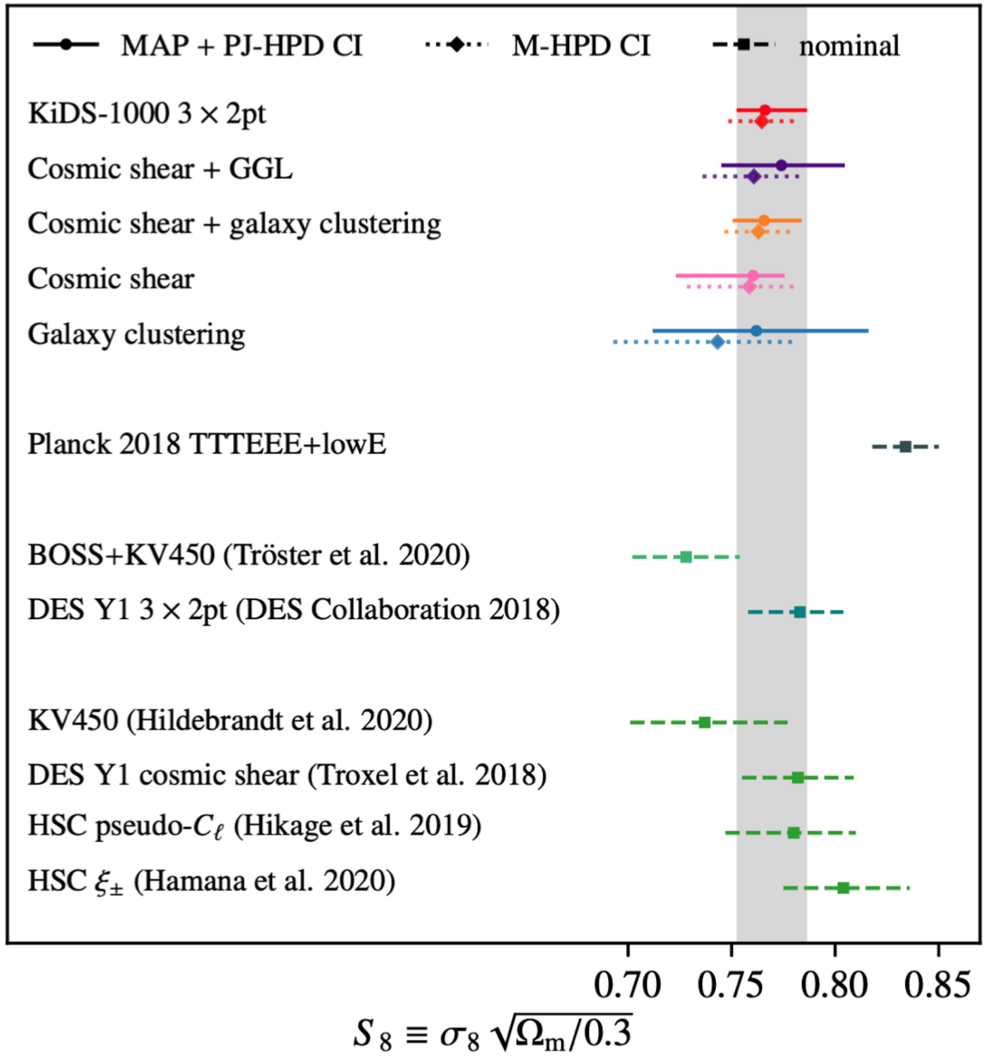
- $f_{\rm EDE} = 0.107^{+0.035}_{-0.030}$ (mean $\pm 1\sigma$)
- $H_0 = 71.49 \pm 1.20$ km/s/Mpc
- Also other parameters shift:
  EDE suppresses growth of perturbations at early times (eISW)
  $\rightarrow$ $\omega_{\rm CDM}$ and n_s increase

MCMC posterior



Aside: σ_8 discrepancy

Cosmology Intertwined 2021



$$\sigma_8^2 = \int dk^3 \, |W(k)|^2 P_{\rm lin}(k), \qquad S_8 = \sigma_8 \sqrt{\Omega_m/0.3}$$

Fourier transform of top-hat filter with radius 8 Mpc/h

linear matter power spectrum

Planck prefers 2-3 σ higher S_8 than weak lensing experiments (DES, KiDS, HSC)

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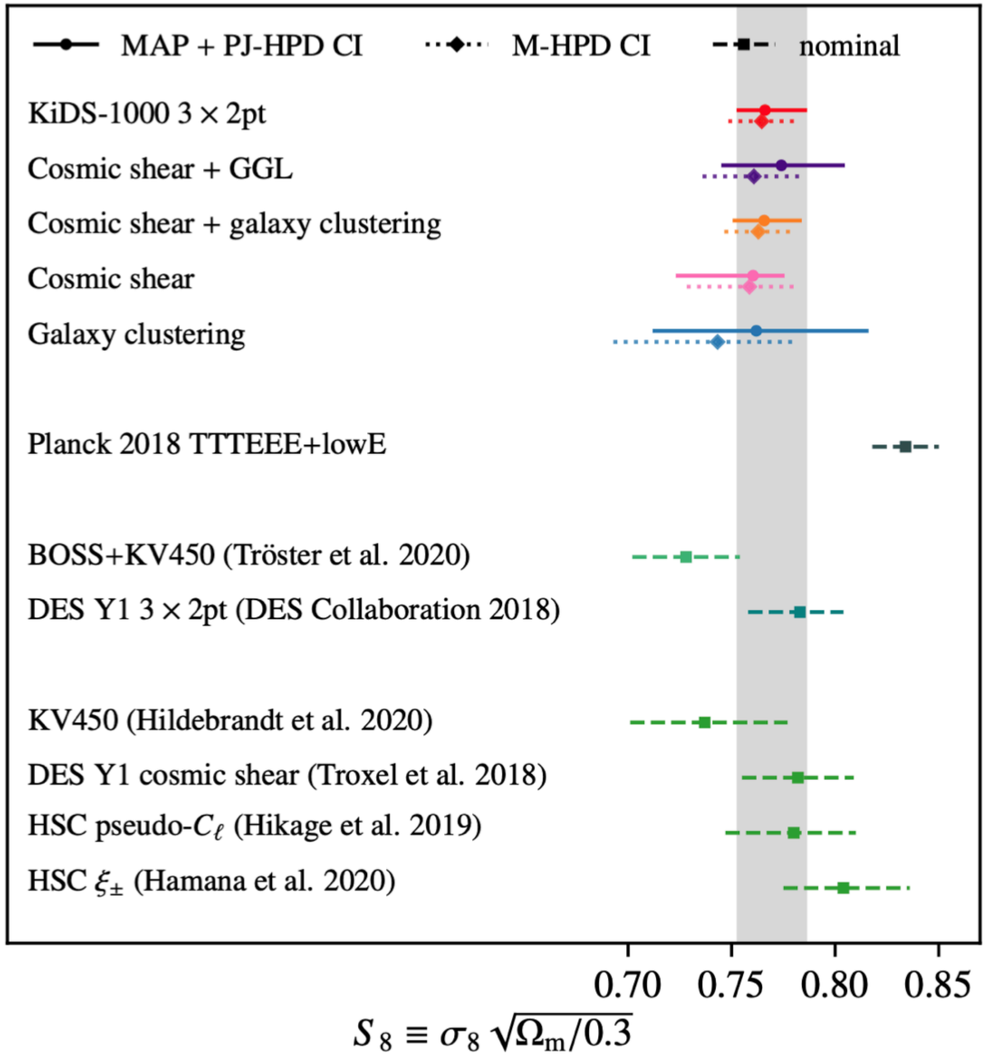

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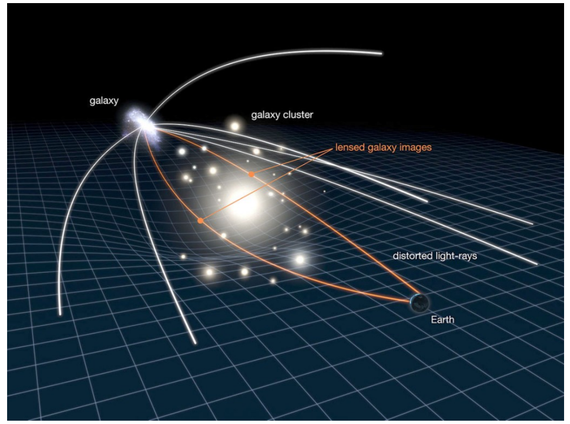


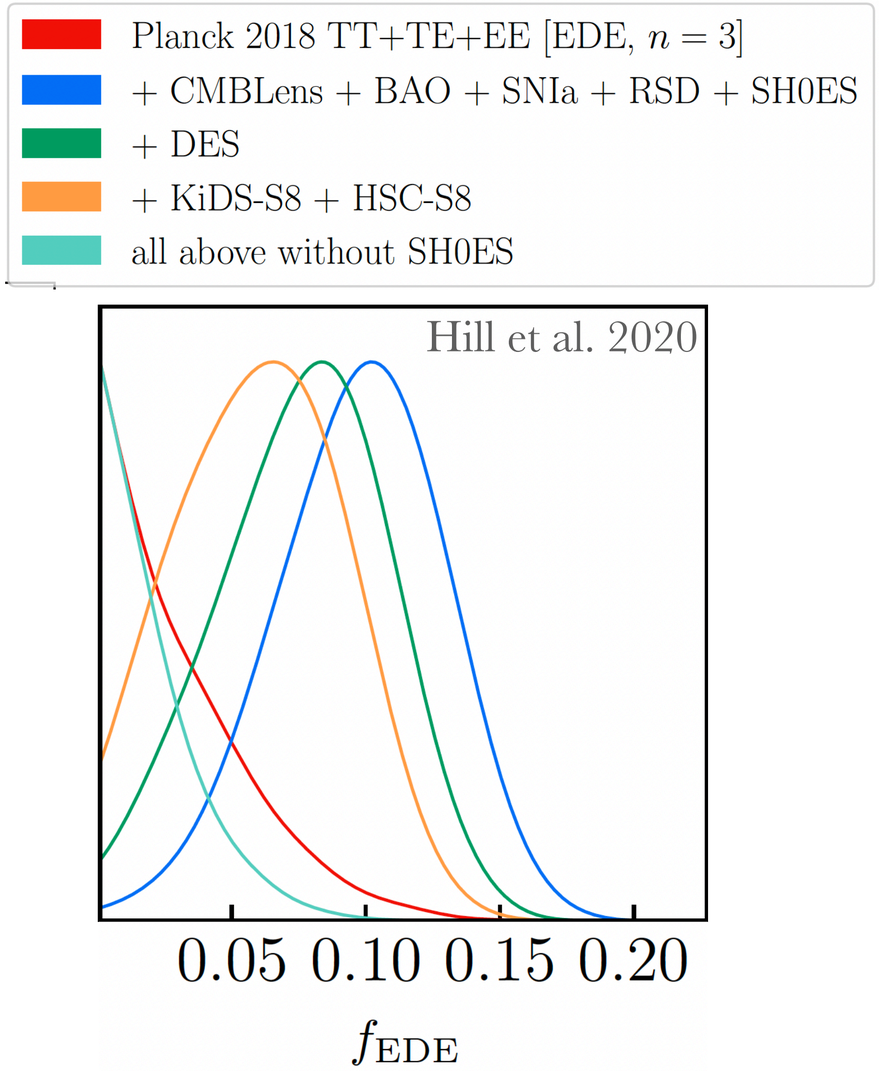
NASA

Adding LSS data: EDE is ruled out?

Hill et al. 2020; Murgia et al. 2021

Data sets: Planck + 6dFGS + BOSS DR12 BAO/RSD + Pantheon ~~+ SH0ES 2016~~ + DES + KiDS + HSC

- $f_{\rm EDE} < 0.06$ (95% C.L.)
- $H_0 = 68.92^{+0.57}_{-0.59}$ km/s/Mpc
- No SH0ES → no preference for EDE



Adding LSS data: EDE is ruled out?

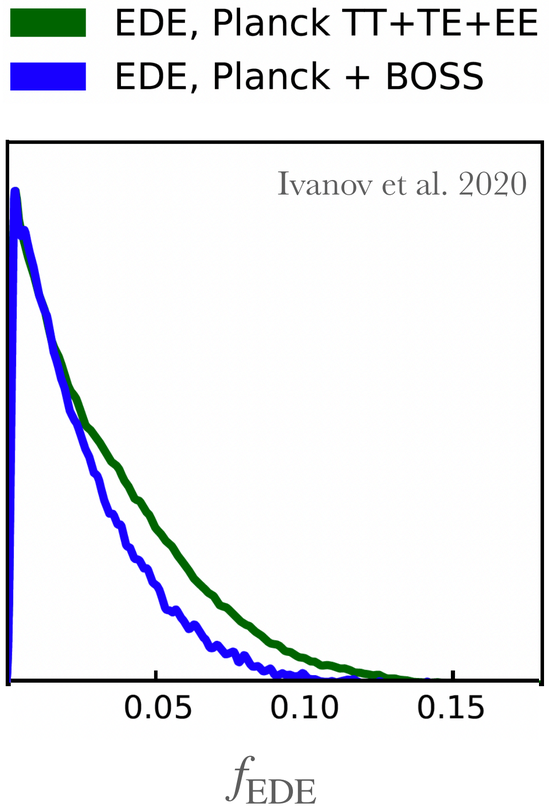
Ivanov et al. 2020; D'Amico et al. 2020

Data sets: Planck + BOSS DR12 BAO
+ full-shape analysis based on EFT of LSS

- $f_{\rm EDE} < 0.072$ (95% CL)
- $H_0 = 68.54^{+0.52}_{-0.95}$ km/s/Mpc

→ EDE cannot restore cosmological concordance

MCMC posterior



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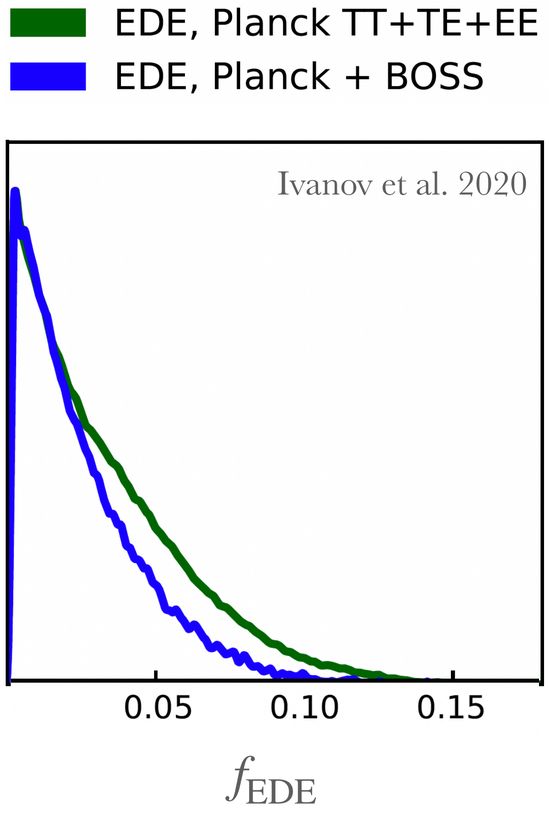
→ EDE cannot restore cosmological concordance

Could **volume effects** affect the results?

Smith++ 2020, Niedermann++ 2020, Smith++ 2021

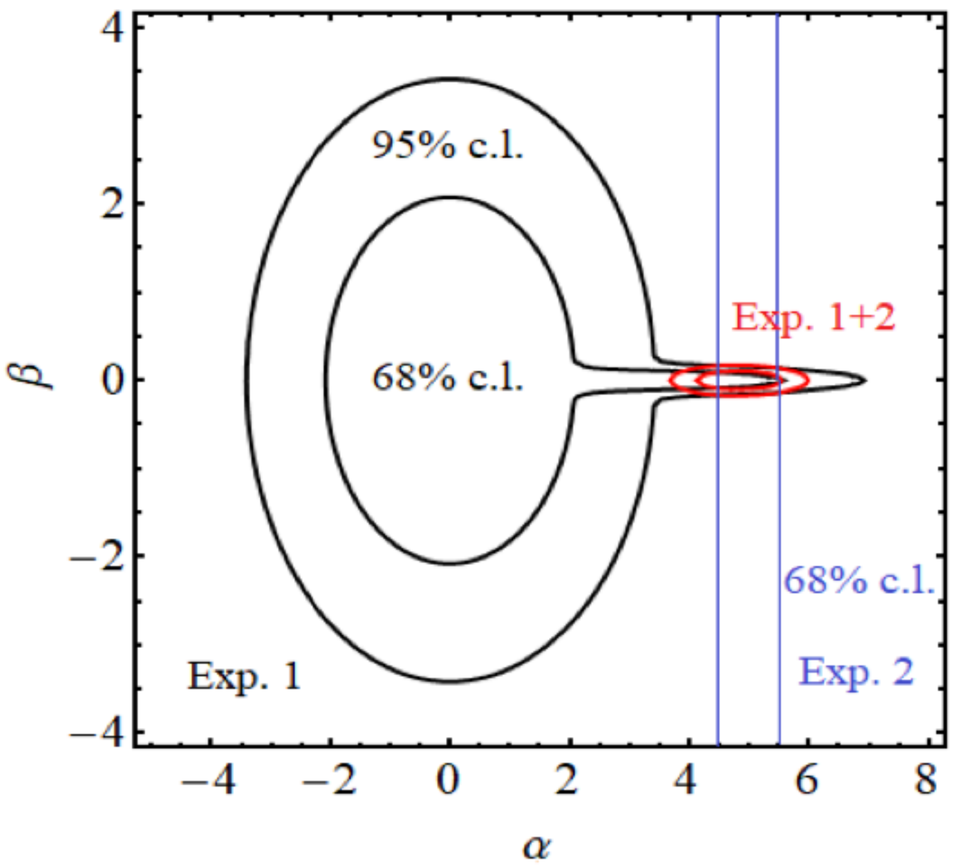
MCMC posterior

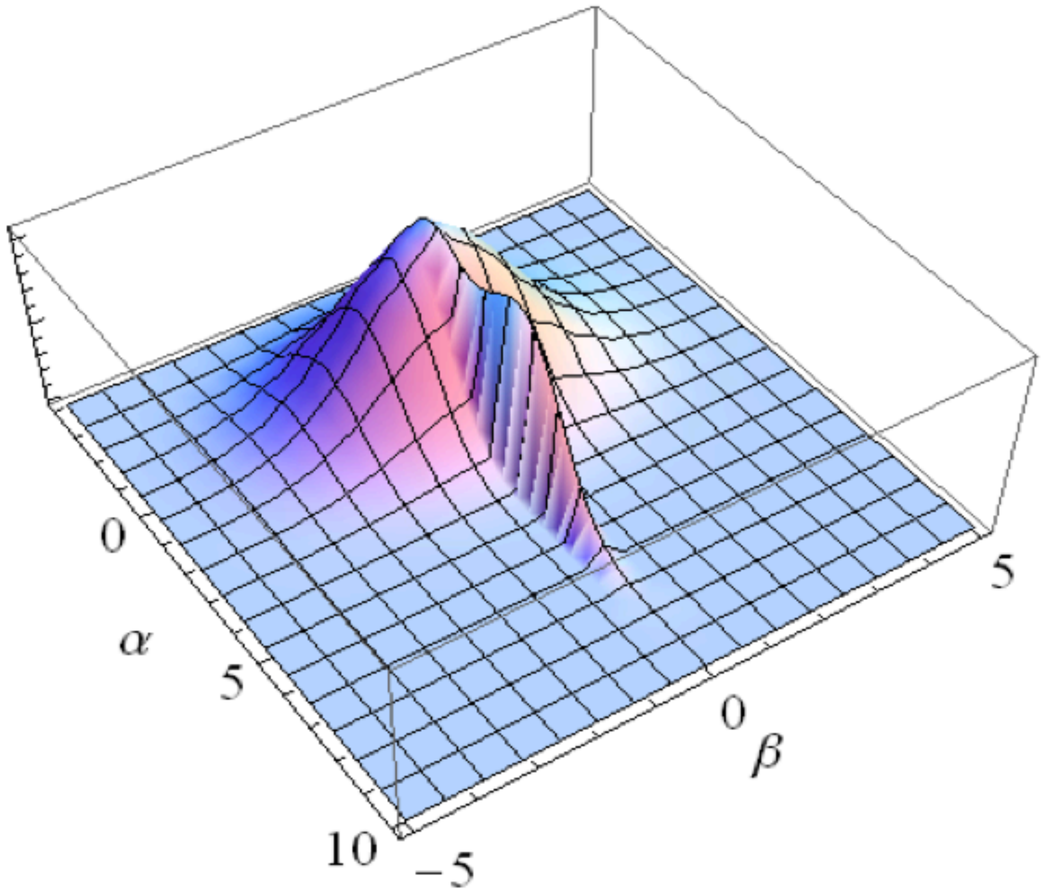


Toy example: Prior volume / projection effect

Gomez-Valent 2022

2D posterior





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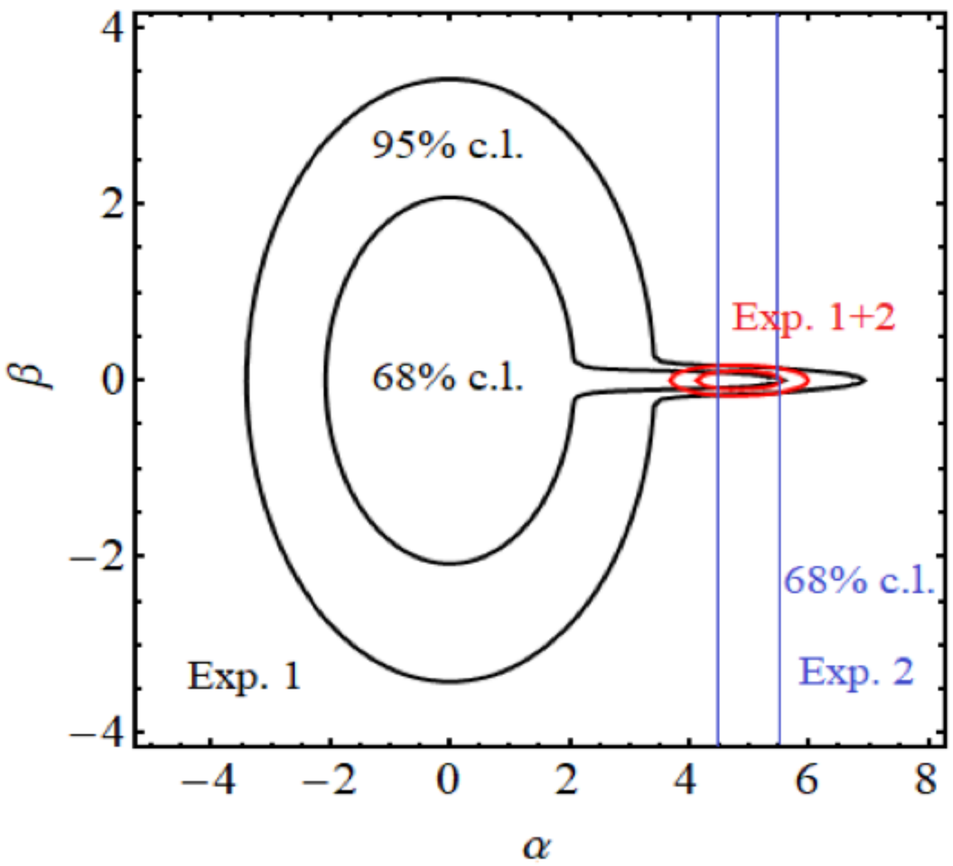
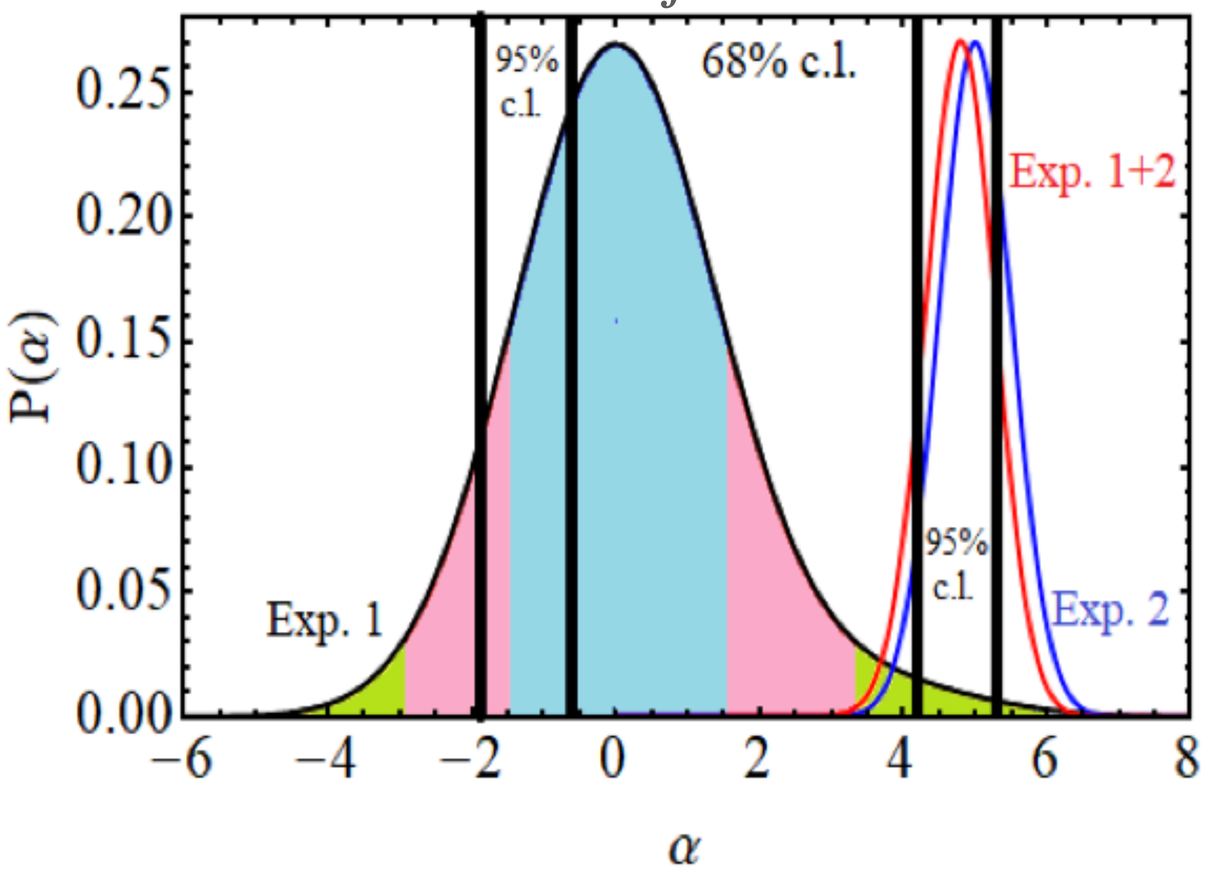


1D marginalized posterior of α

$$P(\alpha\,|\,\boldsymbol{x}) = \int d\beta\, P(\alpha, \beta\,|\,\boldsymbol{x})$$



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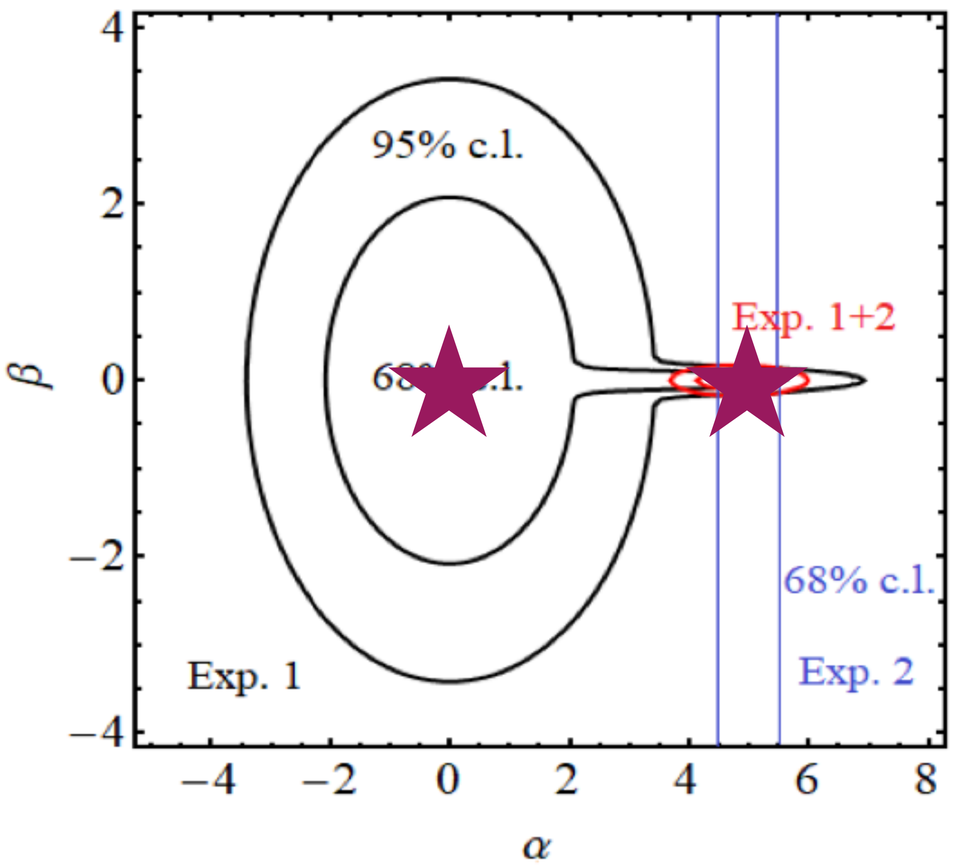

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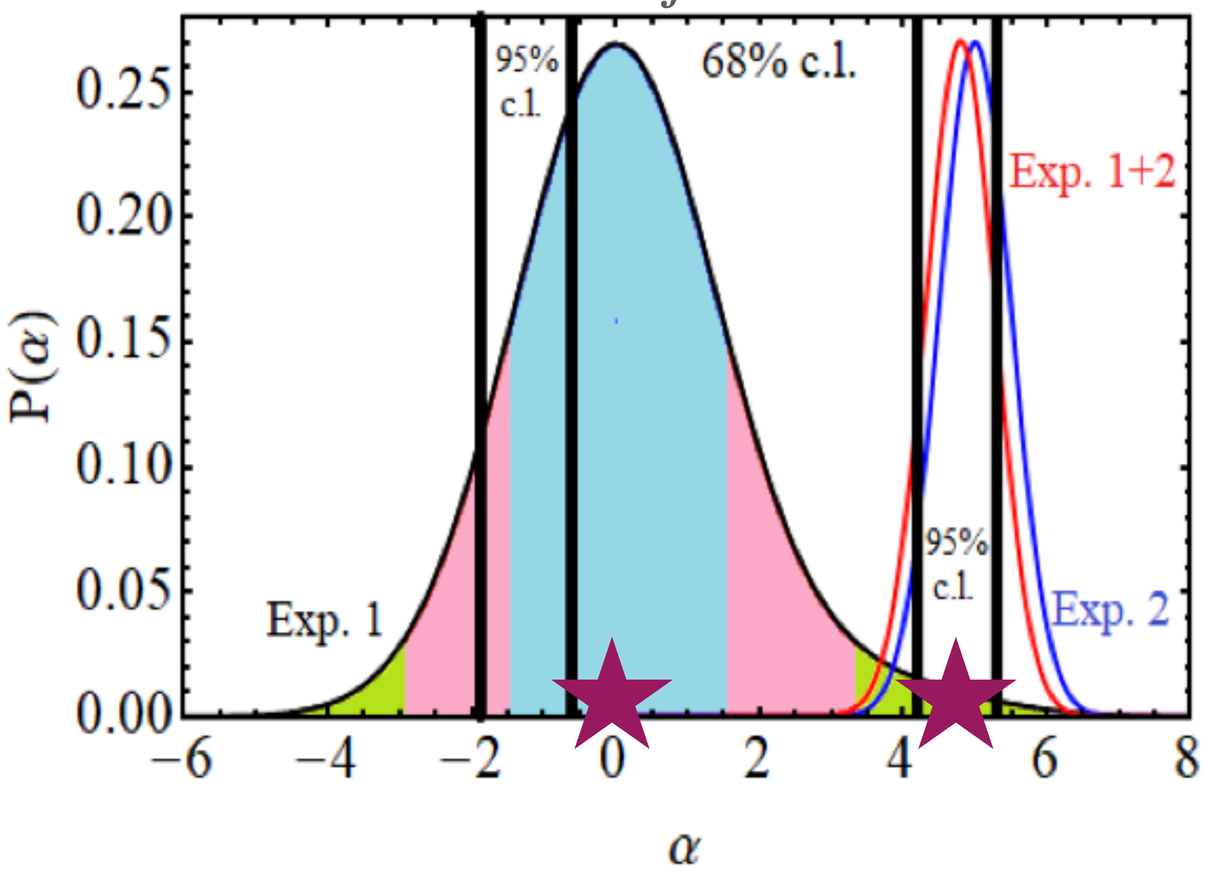
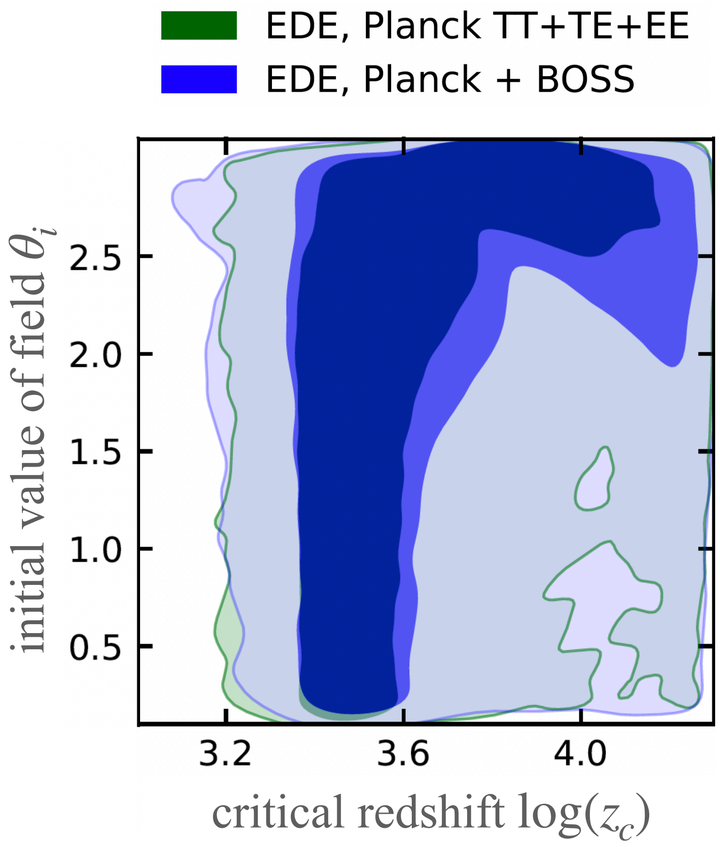


Prior volume / projection / marginalisation effects

…appear if the posterior is influenced by the prior volume.
Reasons:

- Model has too many parameters / data is not constraining.
- Posterior is very non-Gaussian.
- Parameter structure of the model generates large volume differences.

Ivanov et al. 2020



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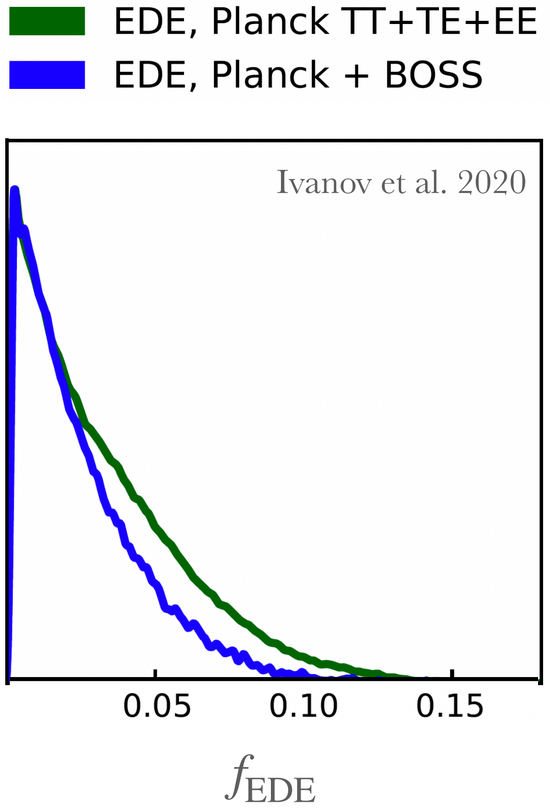

$f_{\rm EDE} \approx 0$: all values of z_c, θ_i unconstrained (ΛCDM limit)

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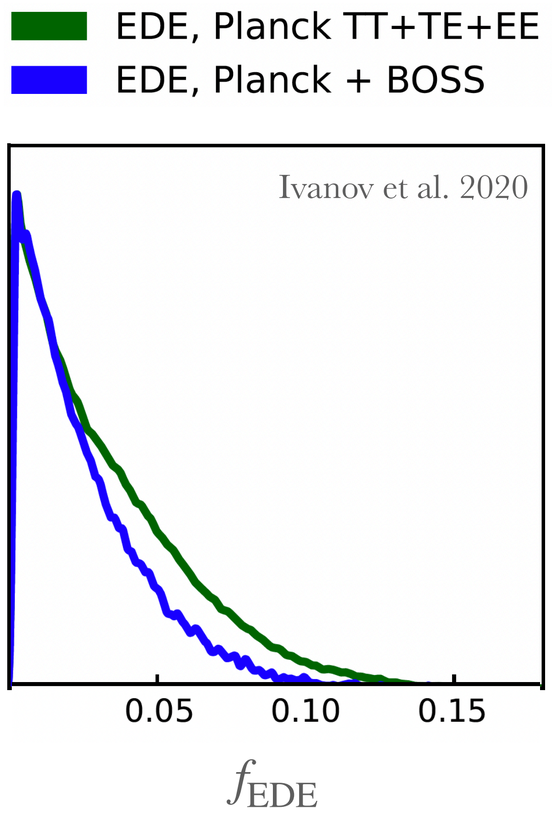
→ Bias in the marginalised posterior.



$f_{\rm EDE} \approx 0$: all values of z_c, θ_i unconstrained (ΛCDM limit)

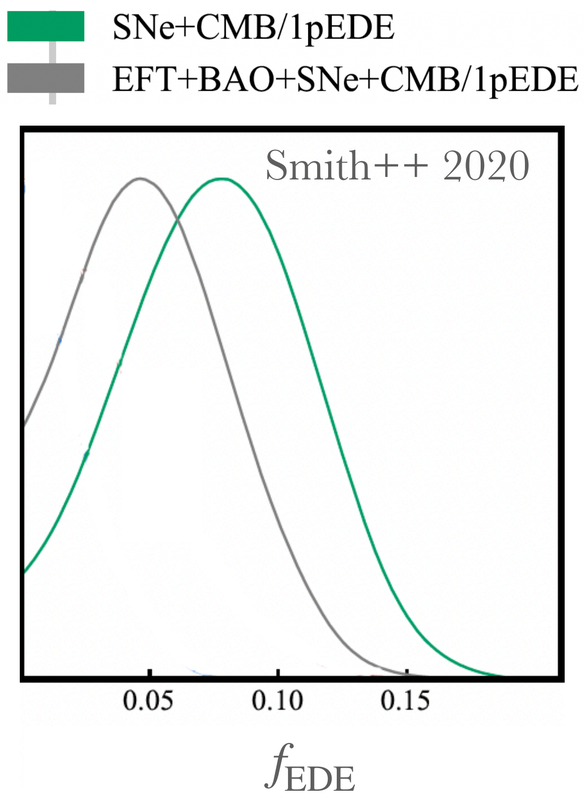
EDE is not ruled out by LSS?

Smith, Poulin, Bernal, Boddy, Kamionkowski, Murgia, 2020; Niedermann, Sloth, 2019 (for NEDE)

Data sets: Planck + BOSS DR12 BAO + full-shape analysis + Pantheon

- fixing z_c, θ_i to bestfit to *Planck* — "1-parameter model"
- $f_{\rm EDE} = 0.072 \pm 0.034$ (mean $\pm 1\sigma$)
- Same data set, but different conclusion than Ivanov et al., D'Amico et al., suspect volume effects

MCMC posterior



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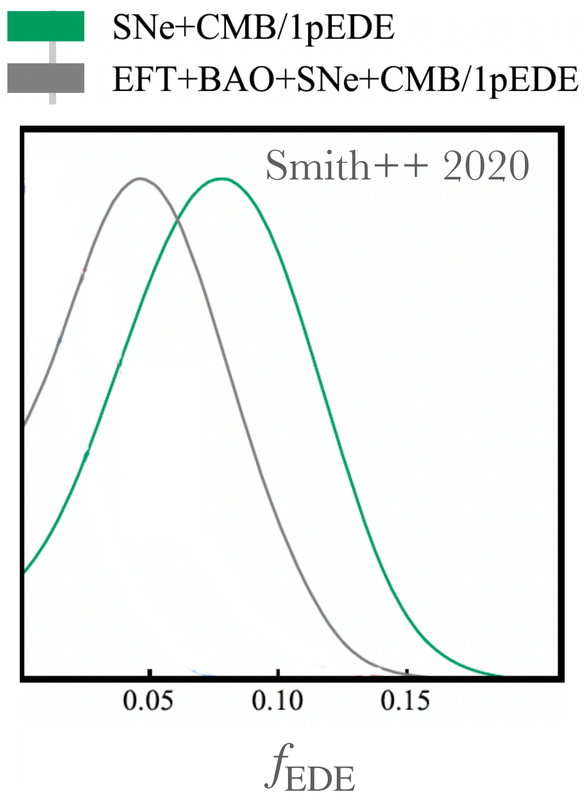
However: Not a full Bayesian analysis

MCMC posterior



Profile likelihood: Planck + BOSS

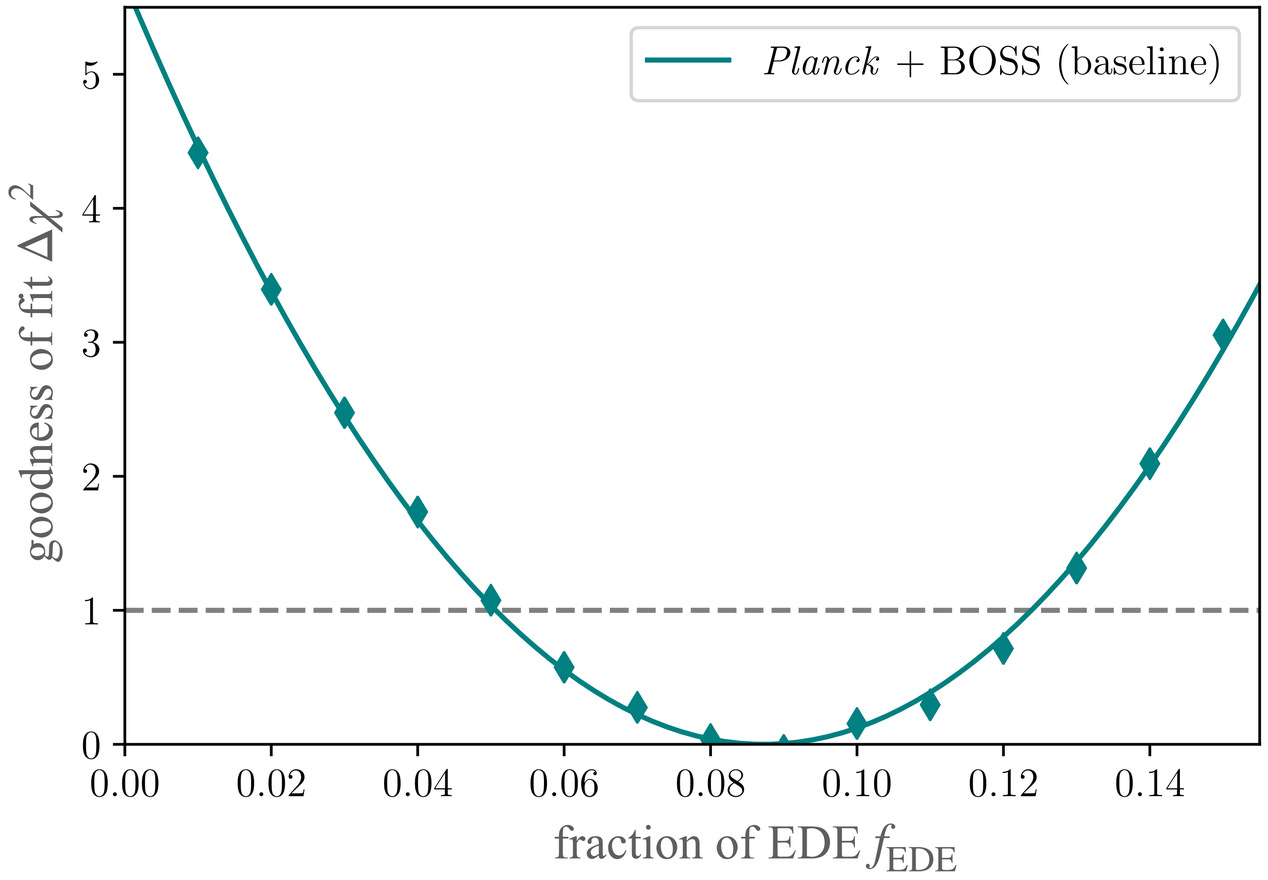
LH, Ferreira, Komatsu 2021; LH, Ferreira 2022

MCMC results:

- $f_{\rm EDE} < 0.072$ (95% C.L.),
  $H_0 = 68.55^{+0.62}_{-1.06}$ km/s/Mpc

Profile likelihood results:

- $f_{\rm EDE} = 0.087 \pm 0.037$,



Profile likelihood

LH, Ferreira 2022

MCMC results:

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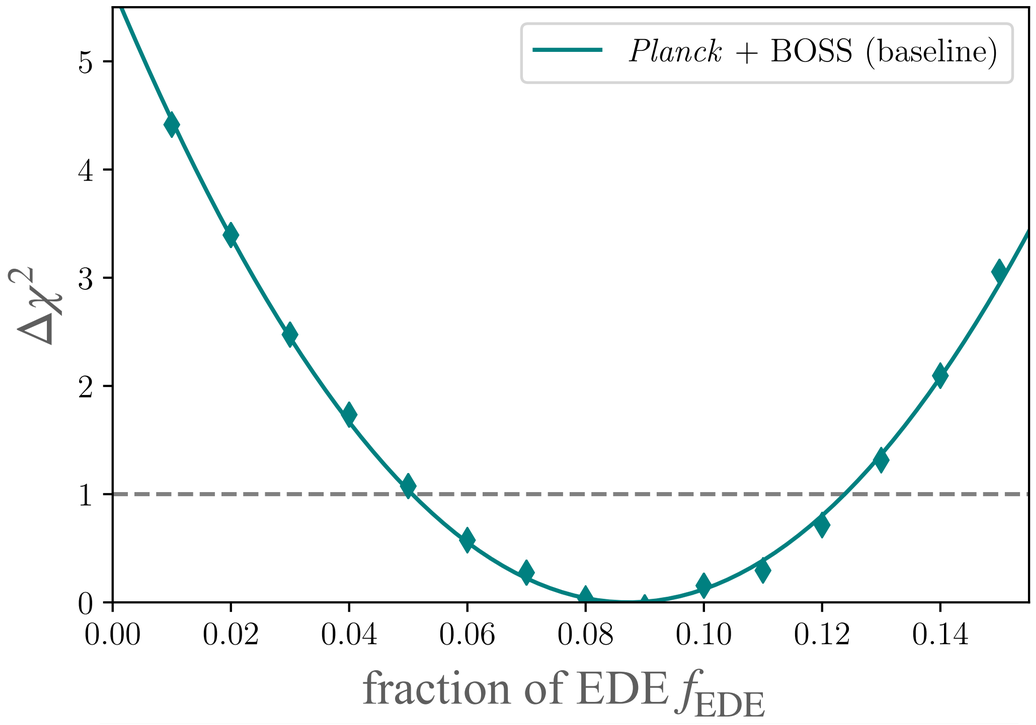
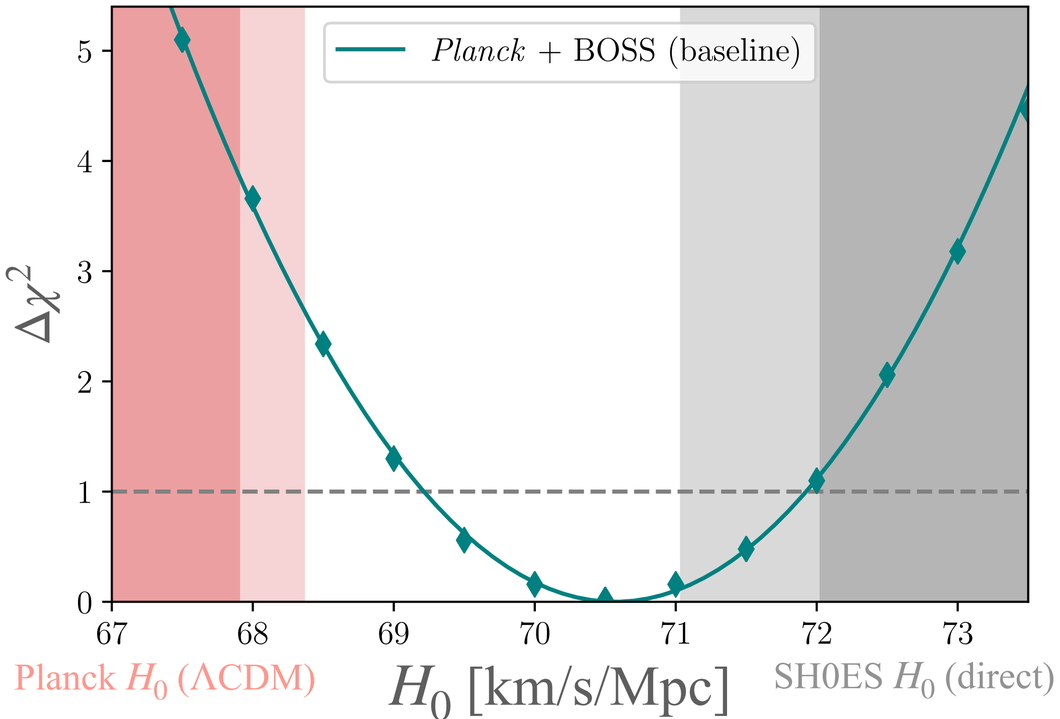
  $H_0 = 68.55^{+0.62}_{-1.06}$ km/s/Mpc

Profile likelihood results:

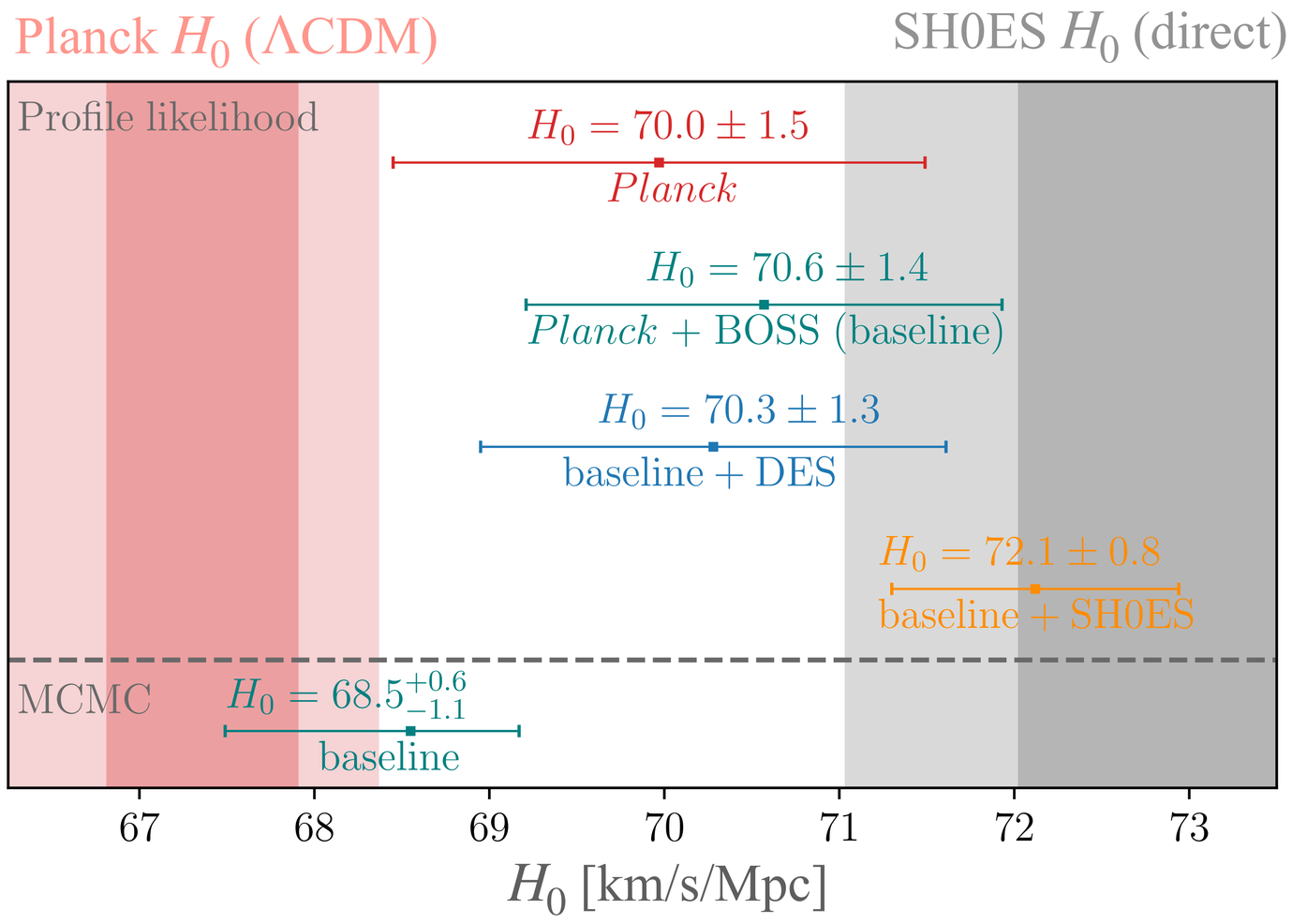
- $f_{\rm EDE} = 0.087 \pm 0.037$,
  $H_0 = 70.57 \pm 1.36$ km/s/Mpc
- Consistency with SH0ES at $1.4\,\sigma$
- However: S_8 tension worsens slightly
  (ΛCDM: 0.828, EDE: 0.840, DES: 0.776)





Profile likelihood — results

LH, Ferreira 2022

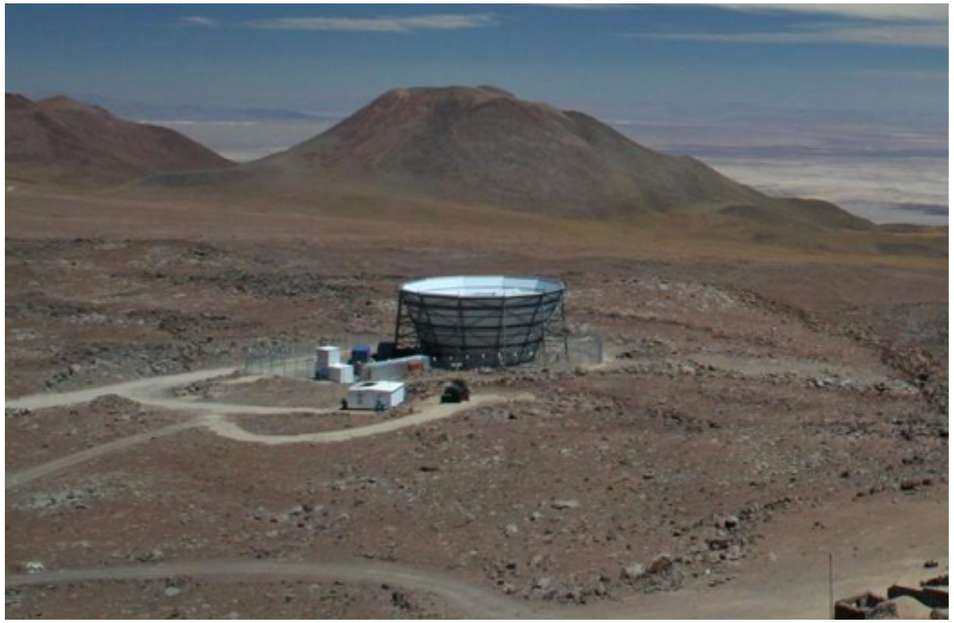


- Evidence for prior volume effects.
- H_0 in EDE model within $1.7\,\sigma$ of SH0ES measurement for all data sets (incl. galaxy clustering, weak lensing).
- EDE viable solution to Hubble tension.

Results from Atacama Cosmology Telescope

Hill et al. 2021, Poulin et al. 2021, Smith et al. 2022

Data sets: ACT DR4 + large-scale *Planck* TT+lensing + BOSS BAO (yellow line)



ACT collaboration

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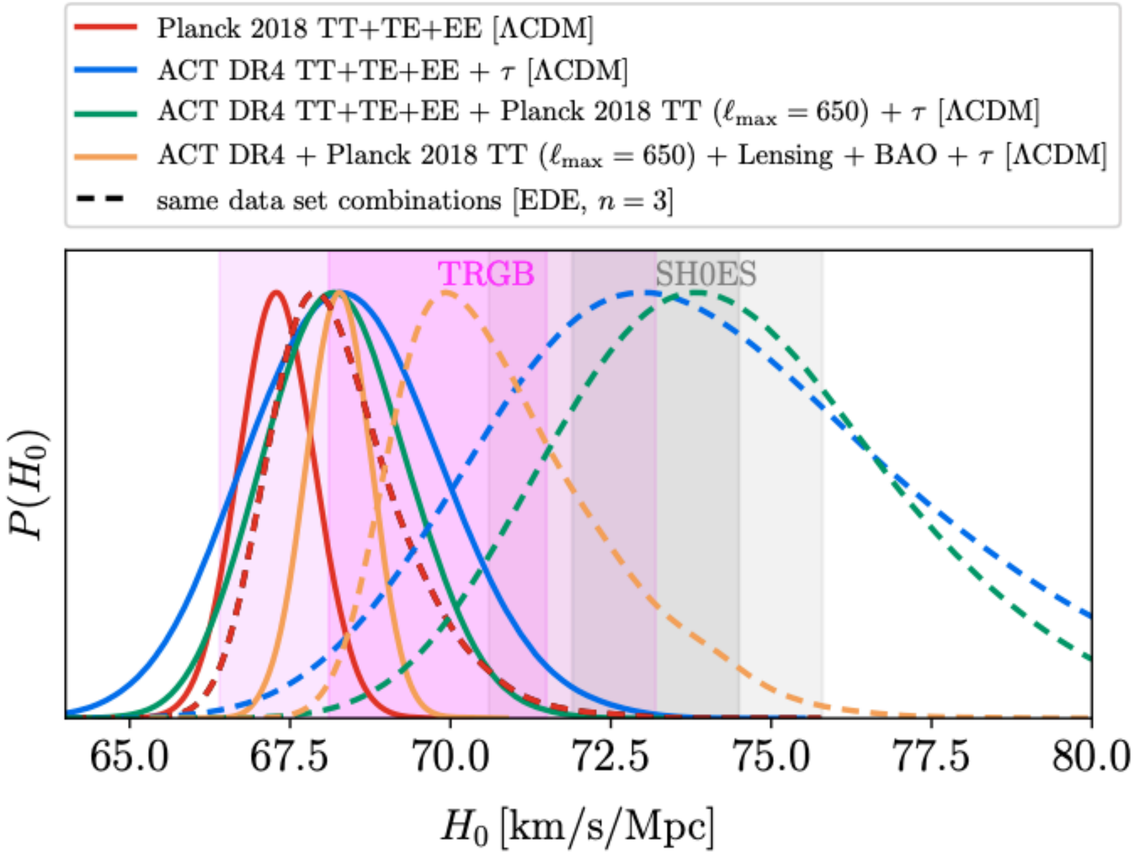
MCMC posterior

Hill et al. 2021



Data sets: ACT DR4 + large-scale *Planck* TT+lensing + BOSS BAO (yellow line)

- prefers the EDE model over ΛCDM by 2-3 σ
- $H_0 = 70.9^{+1.0}_{-2.0}$ km/s/Mpc, $f_{\rm EDE} = 0.091^{+0.020}_{-0.036}$
- Driven by ACT *TE+EE* power spectra

EDE constraints from South Pole Telescope

La Posta++ 2021, Smith++ 2022

Credit Luong-Van

EDE constraints from South Pole Telescope

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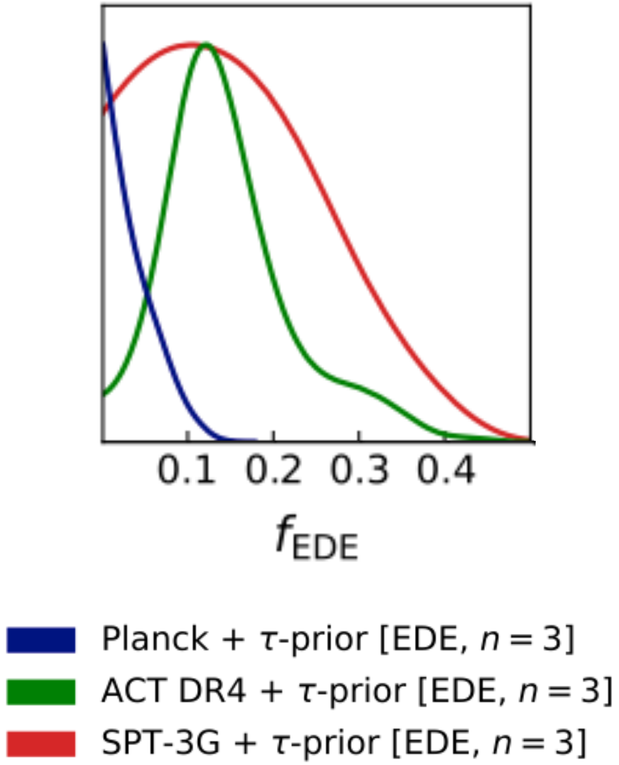
MCMC posterior

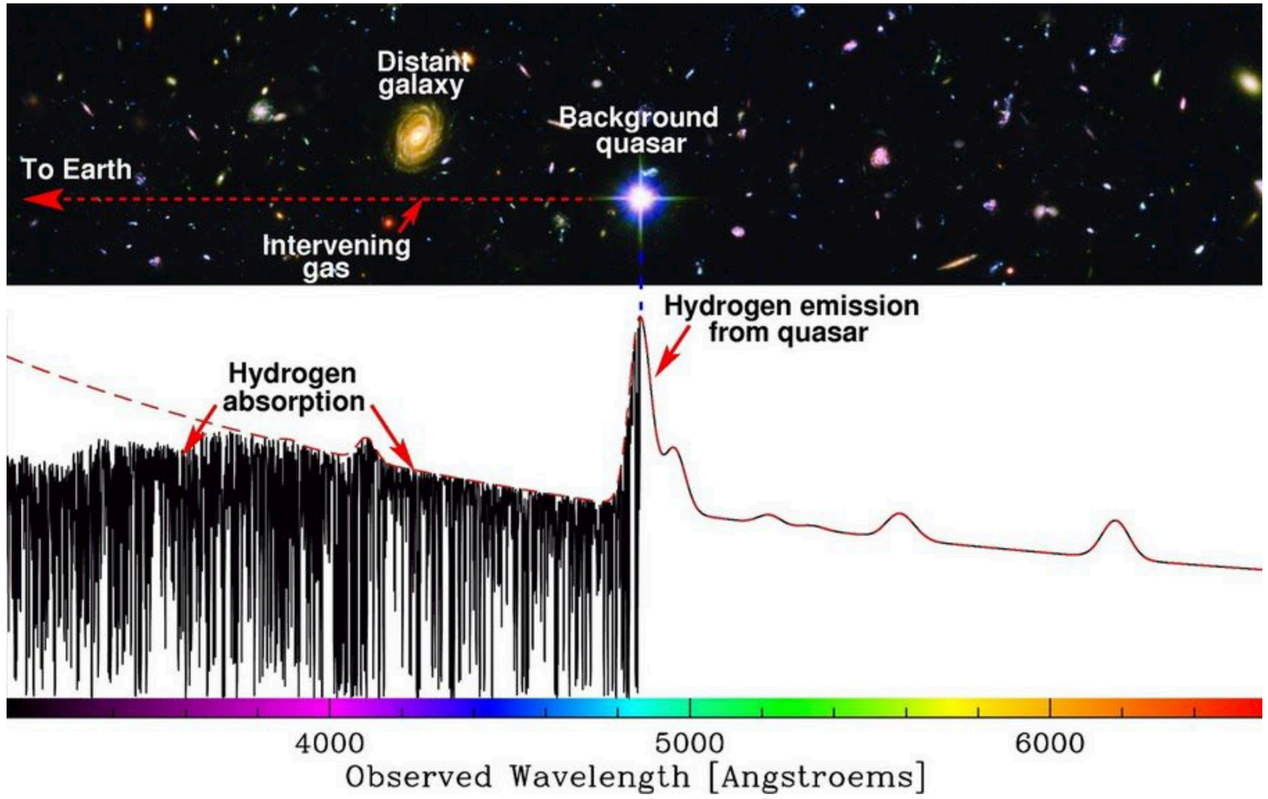
La Posta++ 2021



- SPT is consistent with ACT but with larger errorbar
- It is also consistent with $f_{\rm EDE} = 0$

EDE constraints from Ly-α forest

- Lyman-α forest constraints the matter power spectrum at small scales

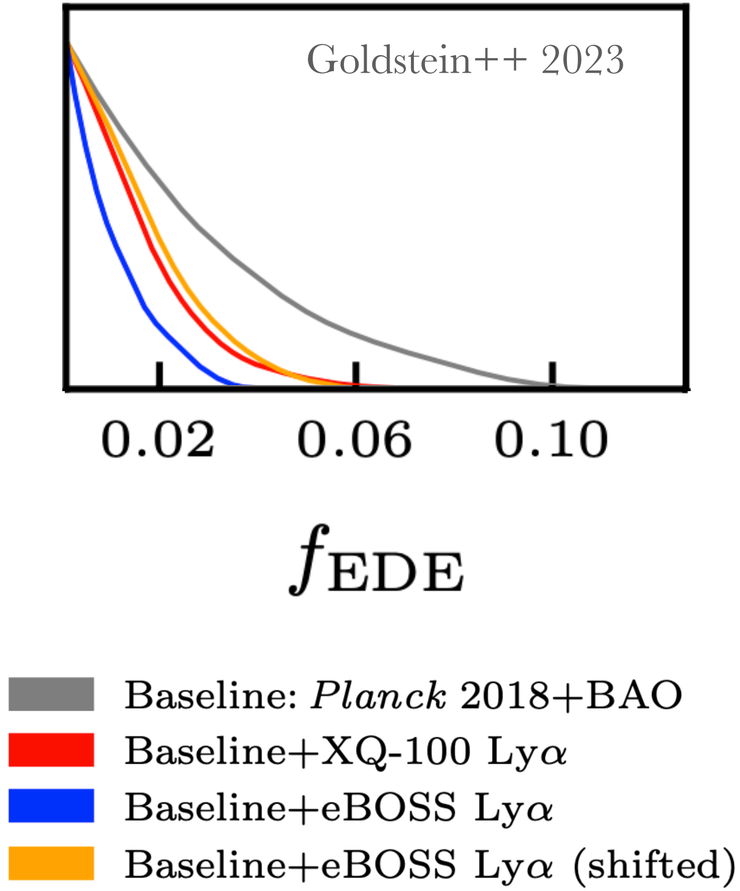


EDE constraints from Ly-α forest

Goldstein et al. 2023

- Lyman-α forest constraints the matter power spectrum at small scales
- Combined with Planck data, it gives very tight upper limits on $f_{\rm EDE}$
- However, there seem to be some internal discrepancies in Ly-α data, so EDE-constraints need to be taken with a grain of salt

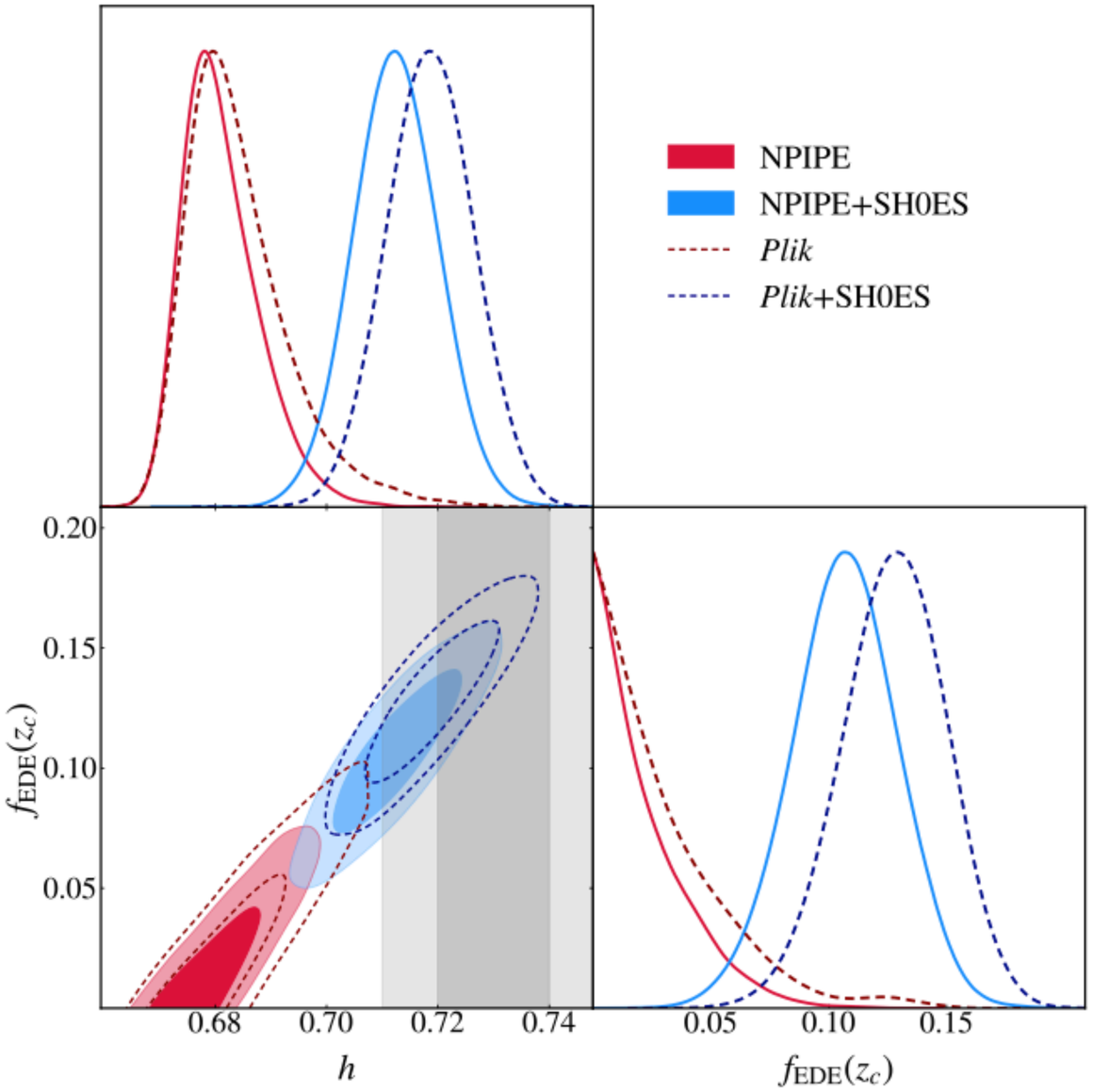
MCMC posterior



Alternative NPIPE *Planck* pipeline

Efstathiou et al. 2023

- An alternative Planck pipeline NPIPE
  - using more sky area at high frequencies
  - different analysis choices
  - reducing the ΛCDM residuals
- NPIPE gives tighter constraints on $f_{\rm EDE}$ in a Bayesian MCMC…



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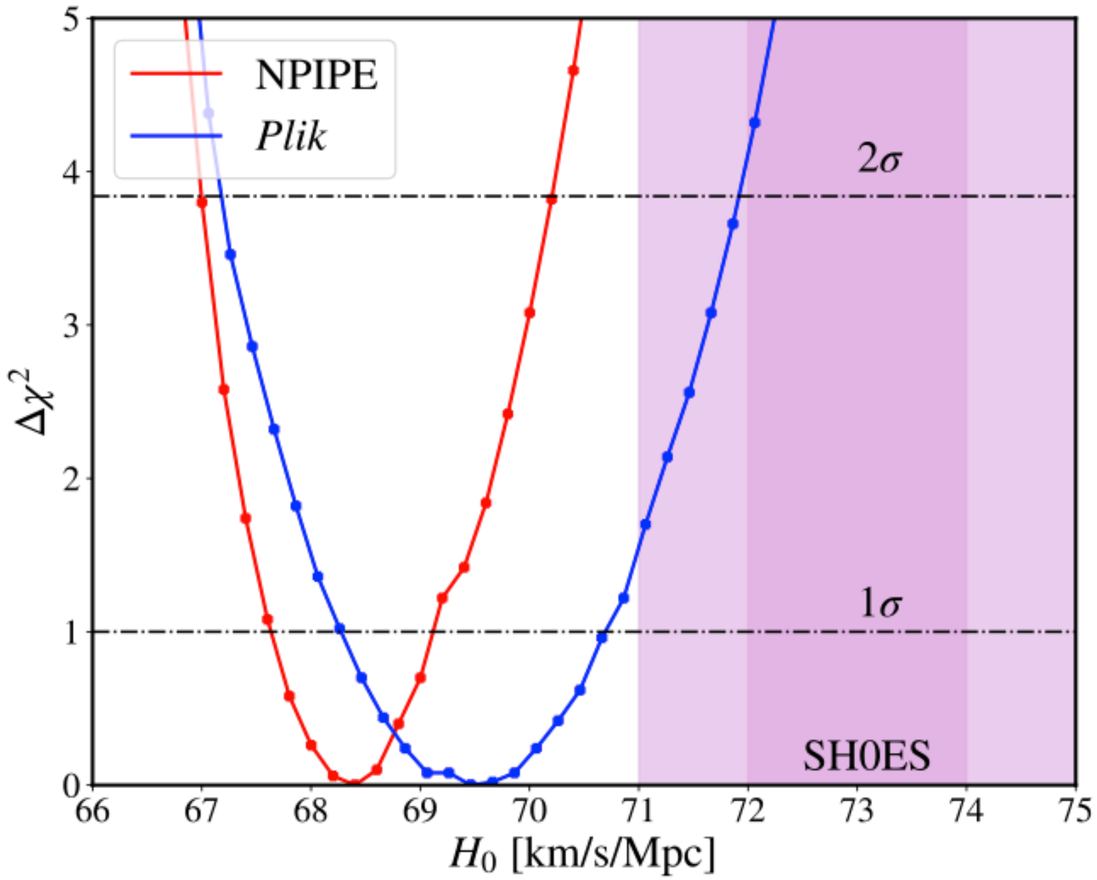

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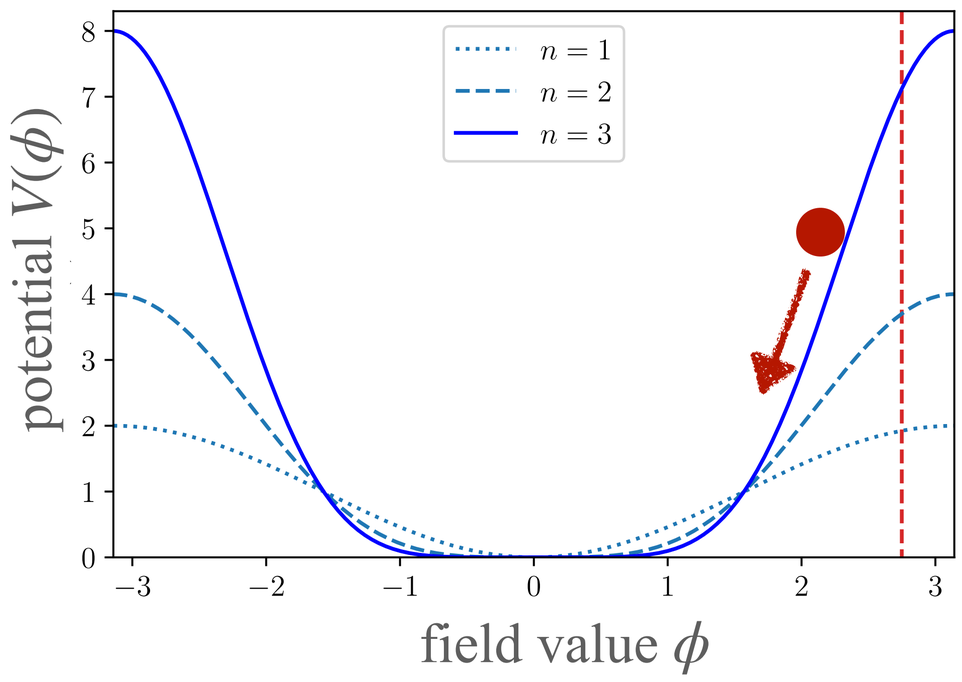
- More and more challenges for the axion-like EDE model
- No clear evidence other than Hubble tension
- EDE type models, which increase expansion rate prior to recombination still seem more promising models

$\rightarrow$ Need to be more creative in building models?

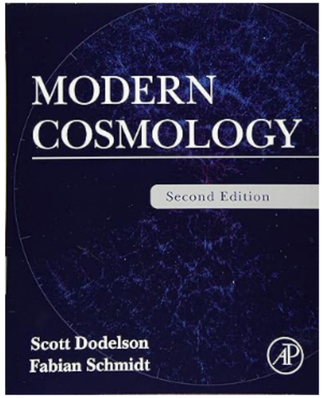
Recap Part 2

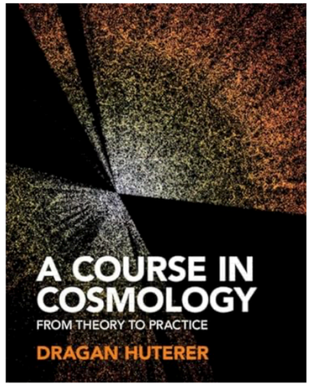
The Hubble Tension and Early Dark Energy

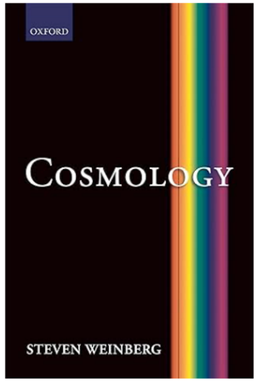
- The reason behind the Hubble tension is still unknown
- EDE: scalar field in an expanding universe with a "$1 - \cos$" potential
- EDE has a complicated parameter structure ($f_{\rm EDE}$, z_c, θ_i) and one needs to take care in the analysis
- However, there seem to be more indications that the simple canonical axion-like EDE model is disfavoured
- EDE-type solutions are still the "least unlikely" ones — Need to be more clever in constructing these models?



References







- Books: Dodelson&Schmidt “Modern Cosmology”, Weinberg: “Cosmology”, Huterer: “A course in cosmology”
- Komatsu “Physics of the Cosmic Microwave Background” (recorded lecture)
- Reviews about EDE:
  - Poulin et al. “The Ups and Downs of Early Dark Energy solutions to the Hubble tension: A review of models, hints and constraints circa 2023”
  - Kamionkowski&Riess: “The Hubble Tension and Early Dark Energy”

Thanks to:

Elisa Ferreira, **Eiichiro Komatsu** and, **Graeme Addison**, who inspired lectures & notebooks!

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Thanks to you for listening!