The Hubble tension: approaches, solutions and challenges

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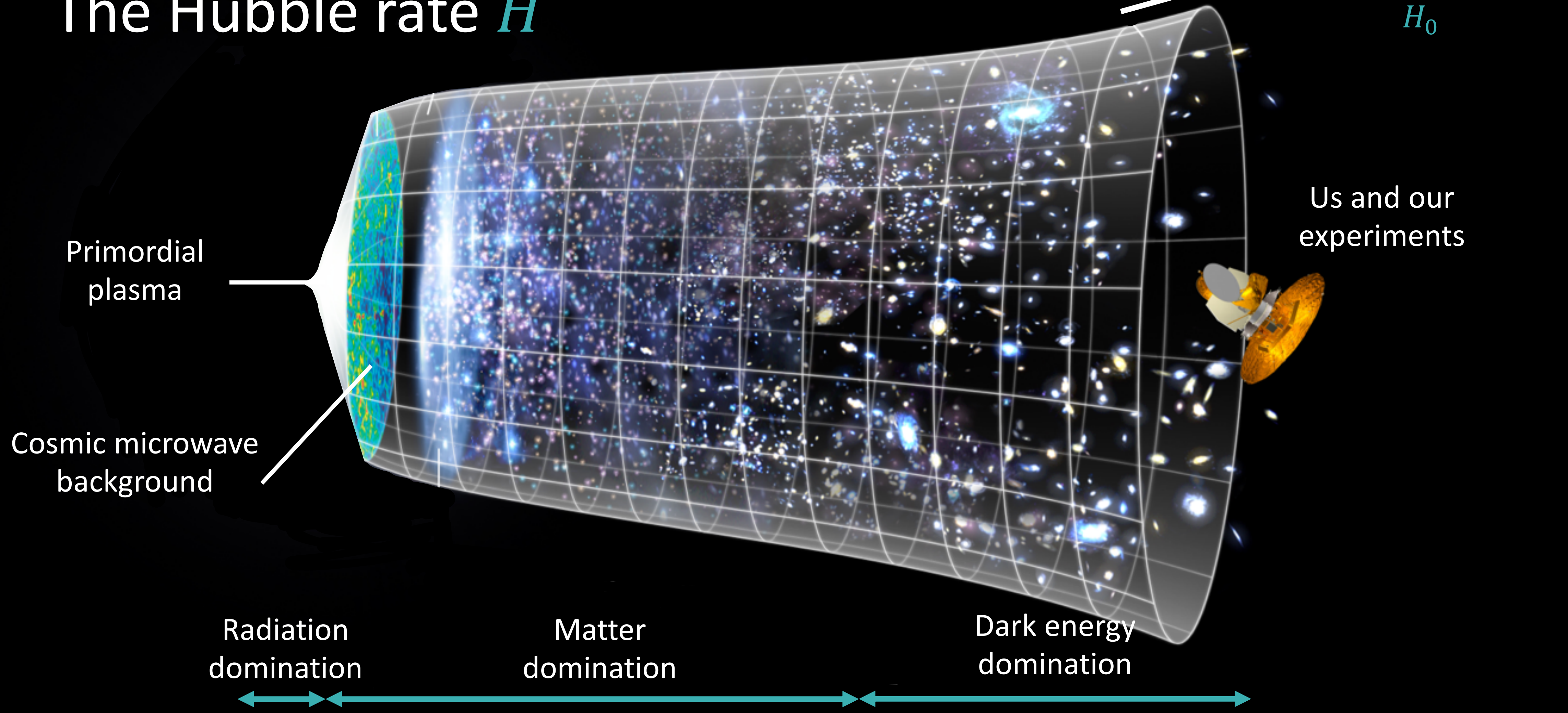
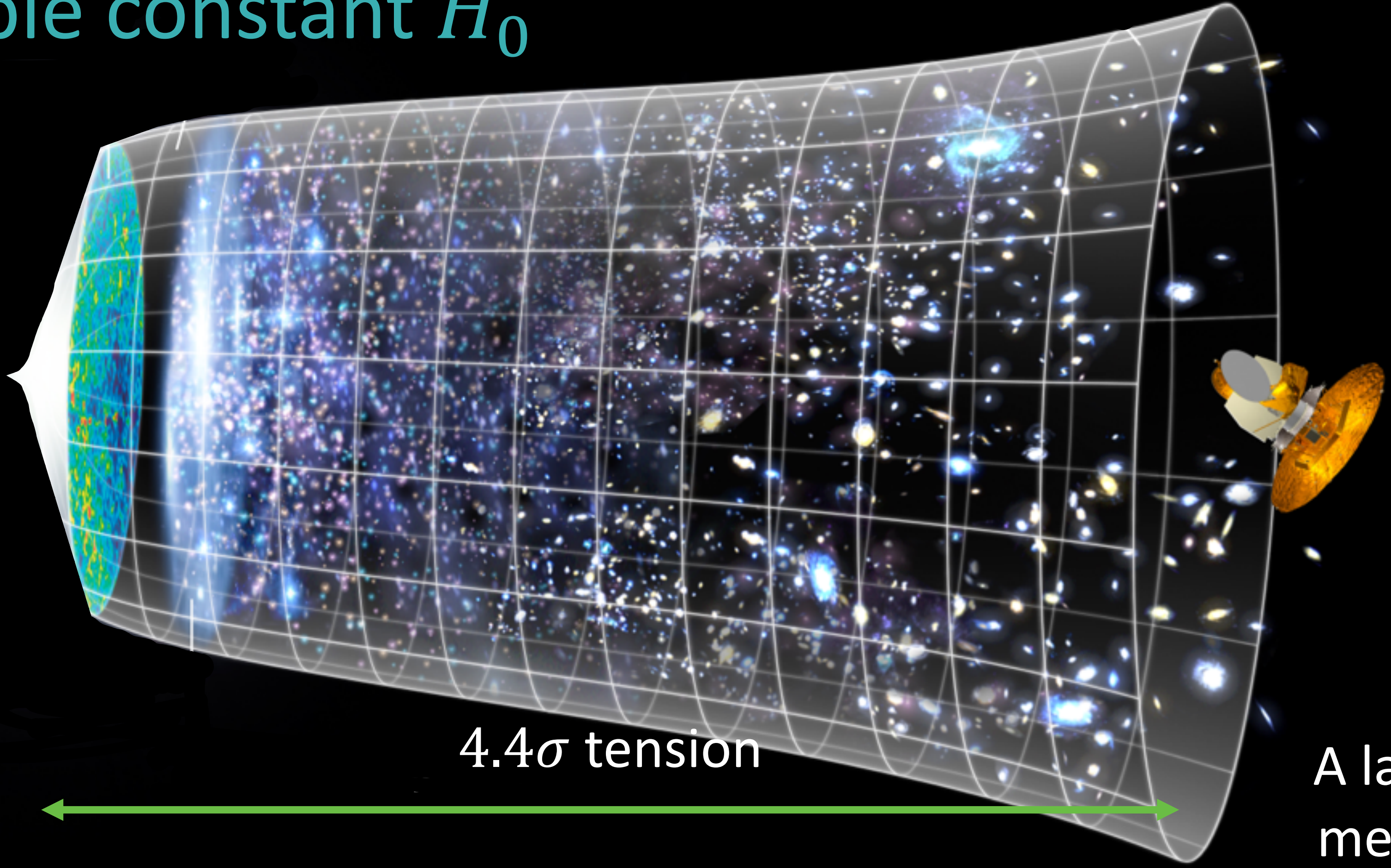
Based on work with: Vivian Poulin, Tristan L. Smith, Marc Kamionkowski, Daniel Grin, Kim Berghaus, Marco Raveri, Bhuvnesh Jain, Mark Trodden and Justin Khoury

The expansion of the Universe
The Hubble rate H



NASA/WMAP Science Team

The expansion of the Universe today
The Hubble constant H_0



4.4σ tension

An early-universe estimate

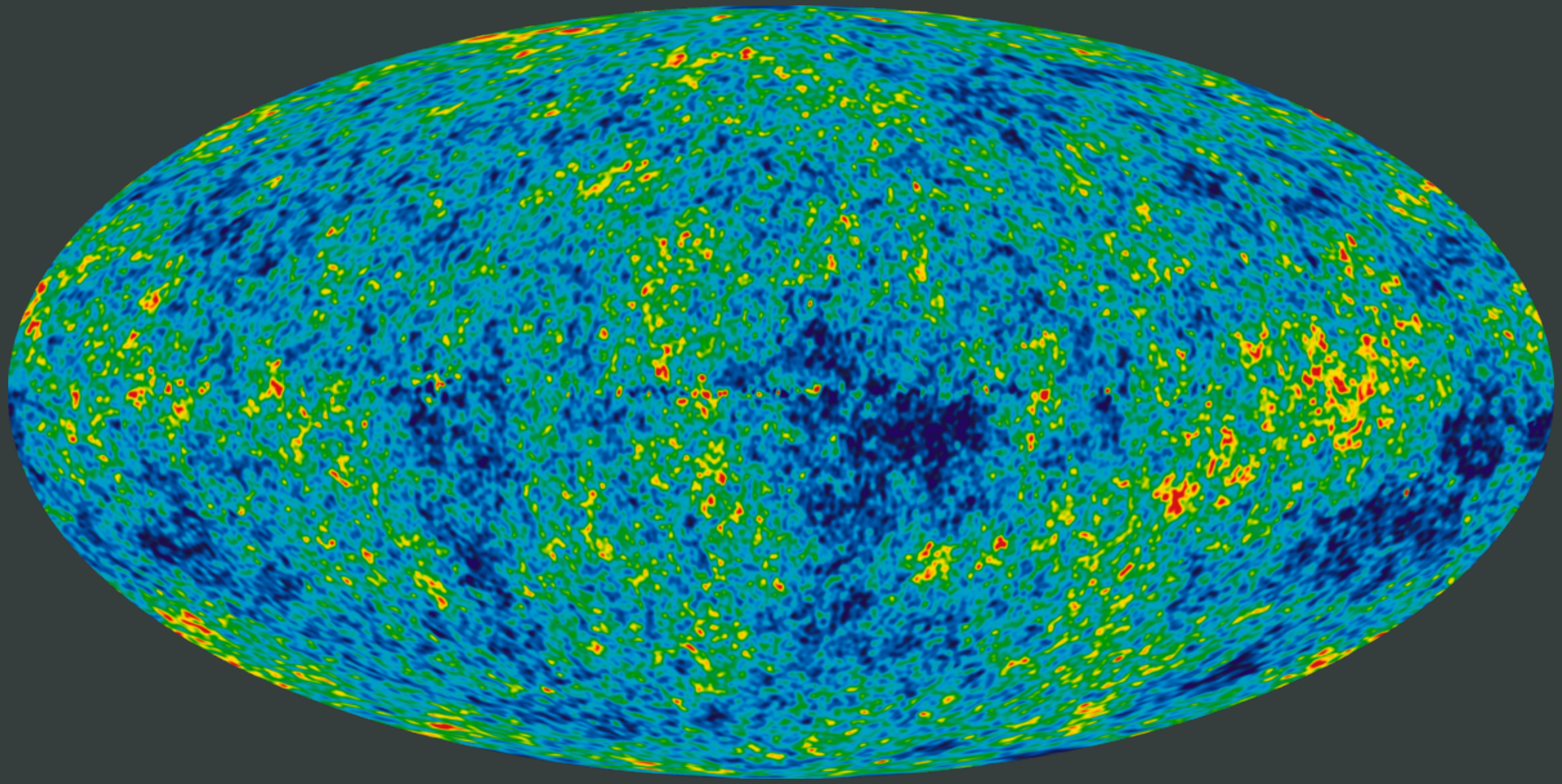
A late-universe measurement:

The Hubble tension

NASA/WMAP Science Team

Cosmic microwave background
The oldest light in the Universe

Density imprint produced by sound waves in the early universe



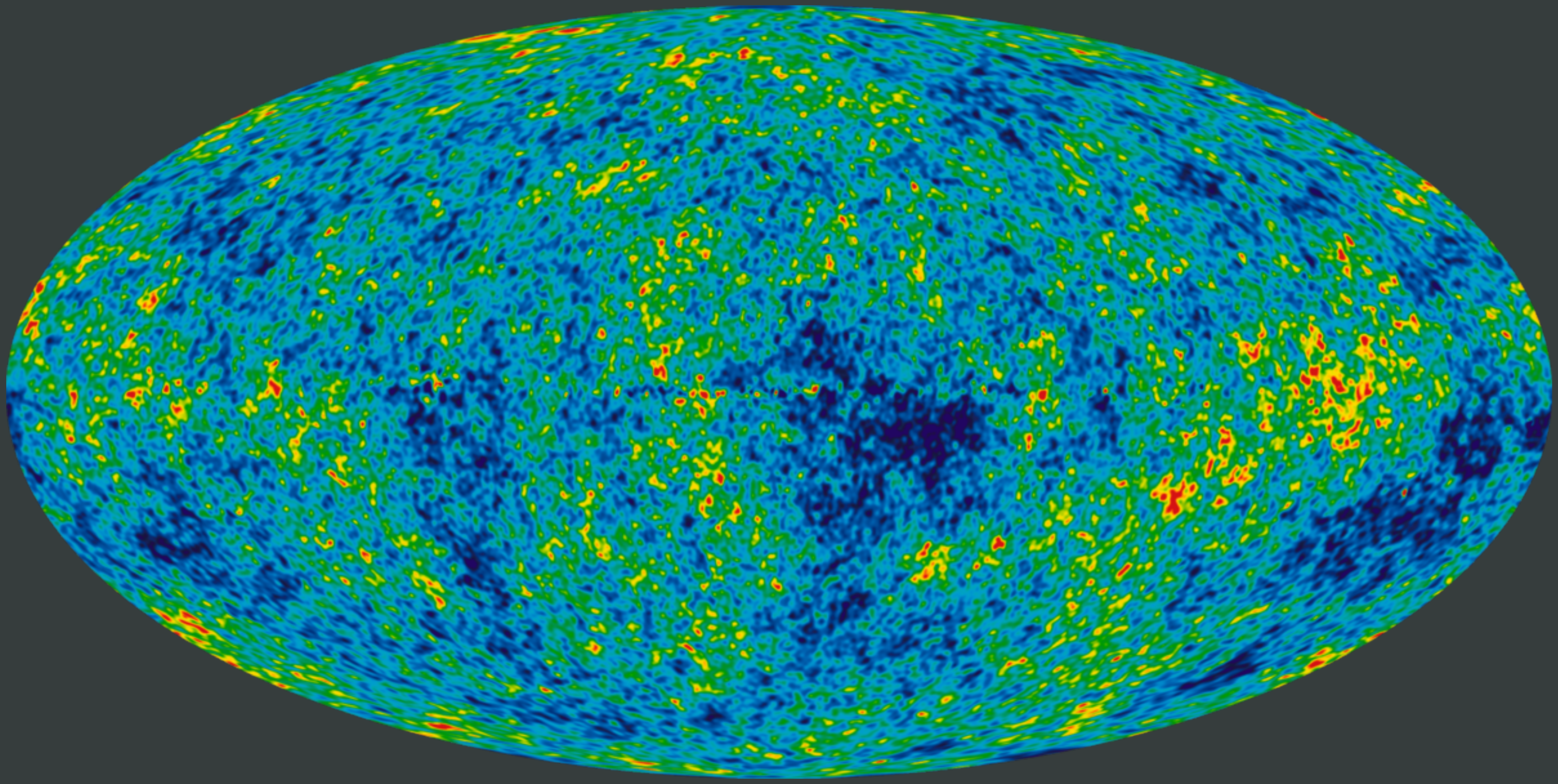
Source: WMAP

Cosmic microwave background
The oldest light in the Universe

Density imprint produced by sound waves in the early universe

Maximum variation at $\theta_* \sim 1°$ scales

Farthest distance that sound waves travelled $\sim r_s$
The sound horizon



Source: WMAP

The standard model of cosmology
ΛCDM

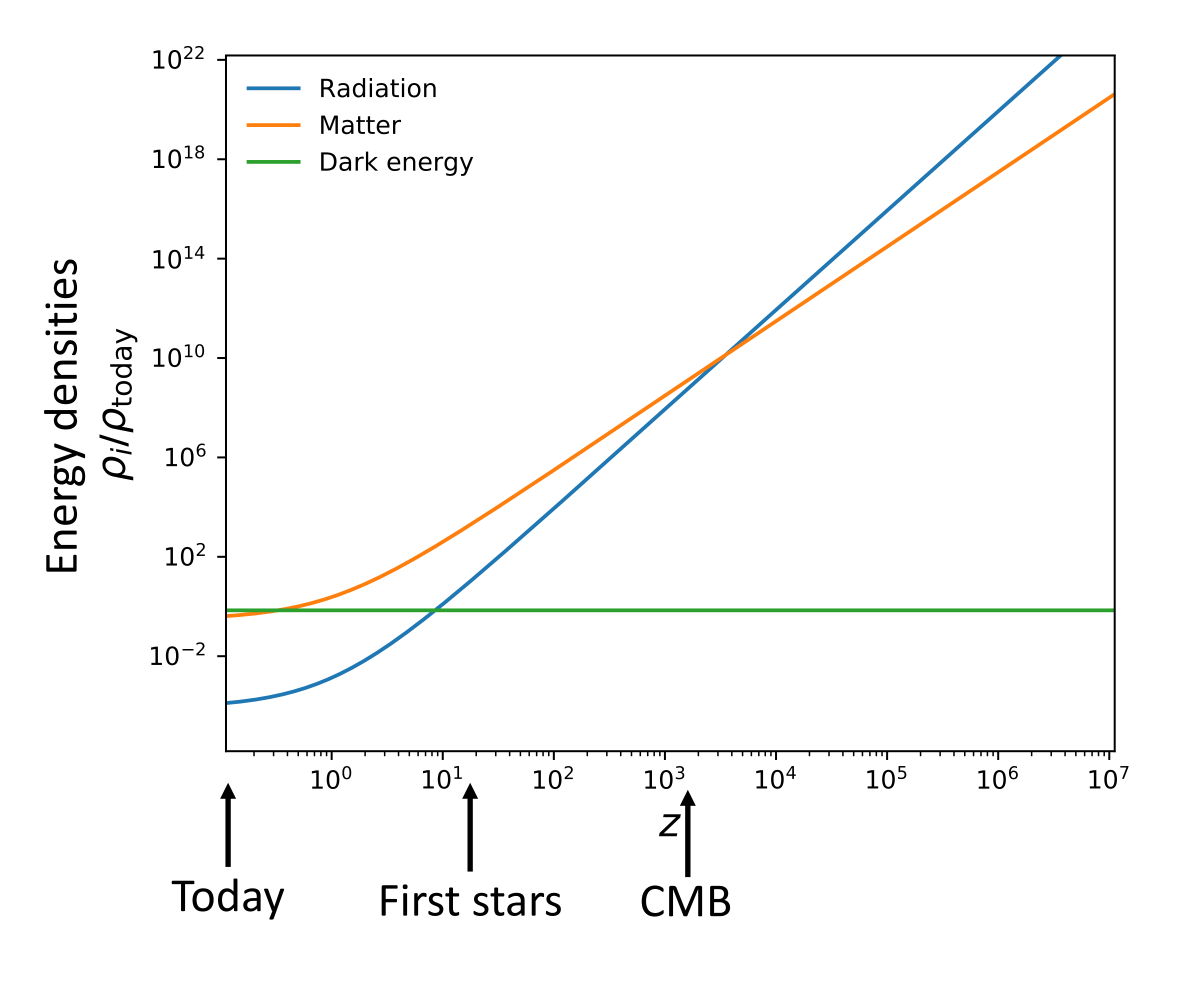
Matter density ∝ z^3
Cold dark matter
CDM

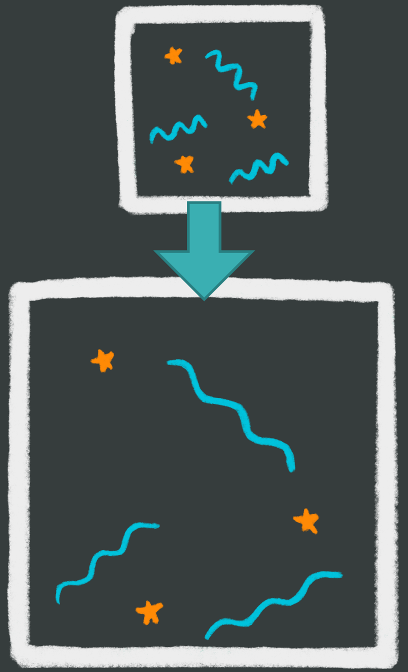
Radiation density ∝ z^4

Dark energy density ∝ z^0
Cosmological
constant Λ

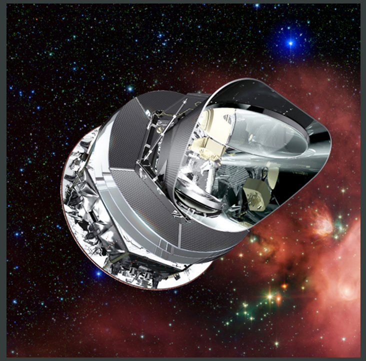
$$H(z) \propto \sqrt{\rho_{tot}(z)}$$

Expansion rate ∝ Energy content



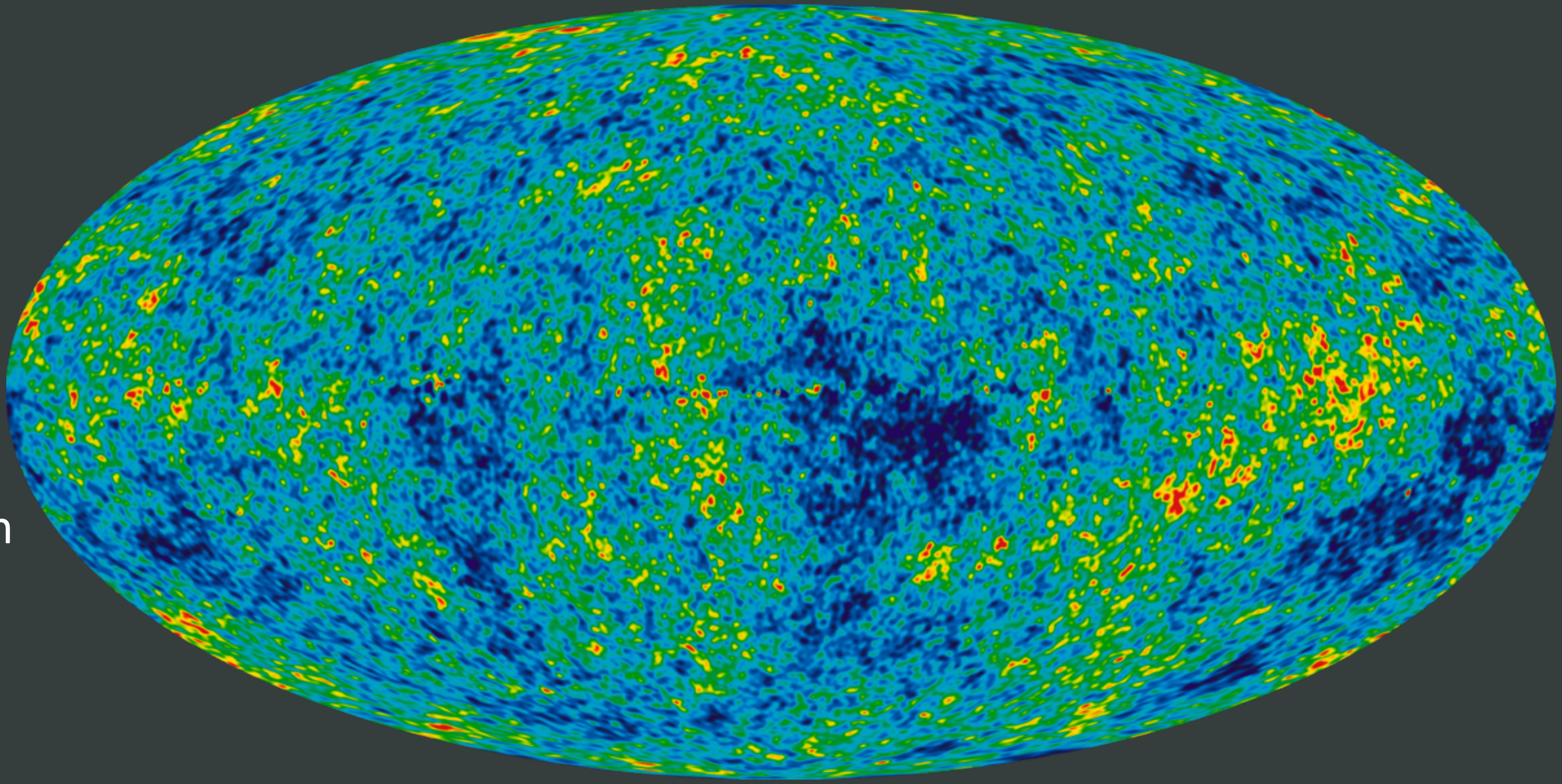


Cosmic microwave background and the ΛCDM model



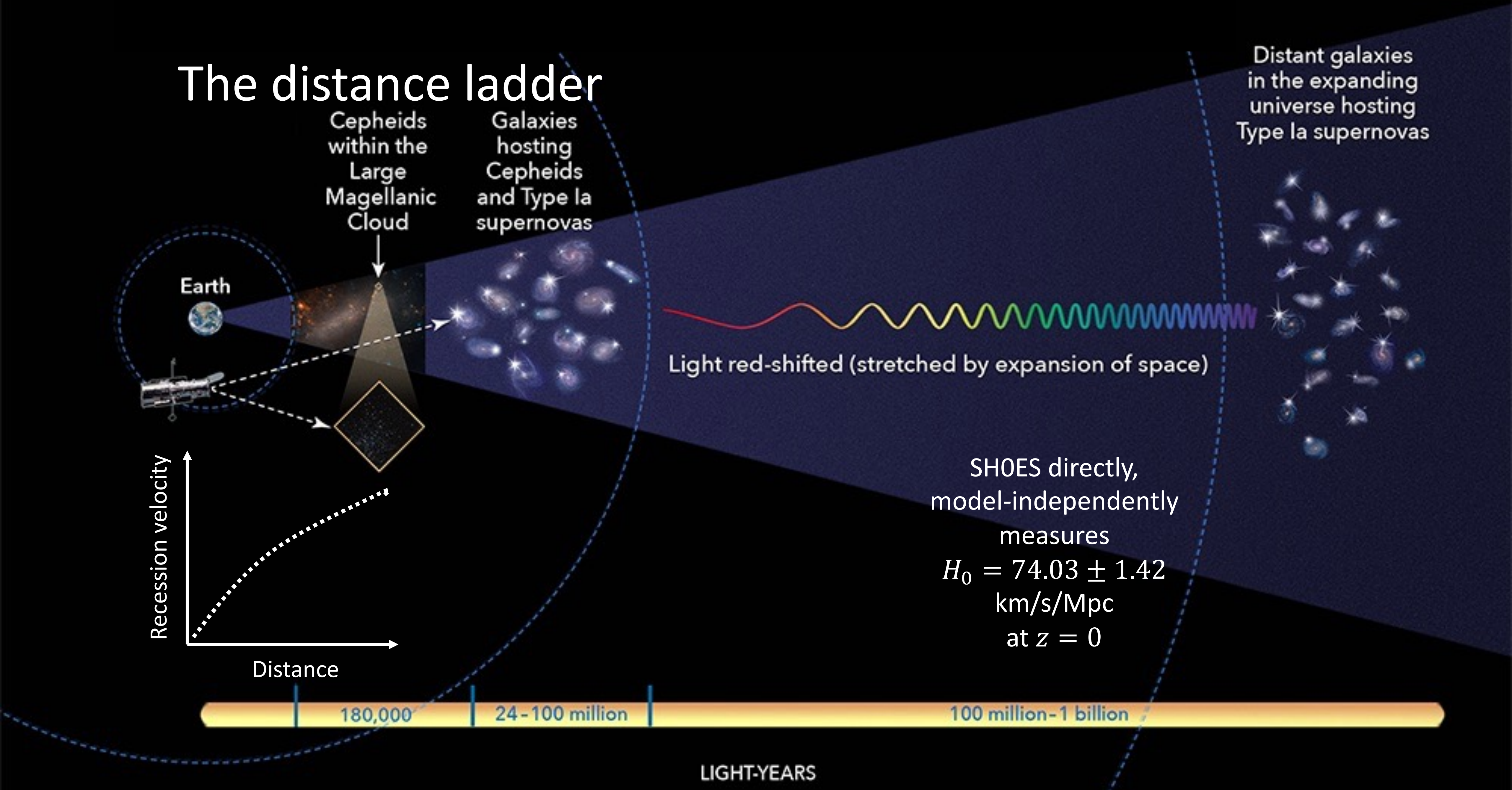
Planck fits ΛCDM to constrain $H_0 = 67.4 \pm 0.5$ km/s/Mpc by observing the Universe at early times

Planck [1807.06209]



Source: WMAP

The distance ladder



SH0ES directly, model-independently measures $H_0 = 74.03 \pm 1.42$ km/s/Mpc at $z = 0$

Hubble Space Telescope

The Hubble tension

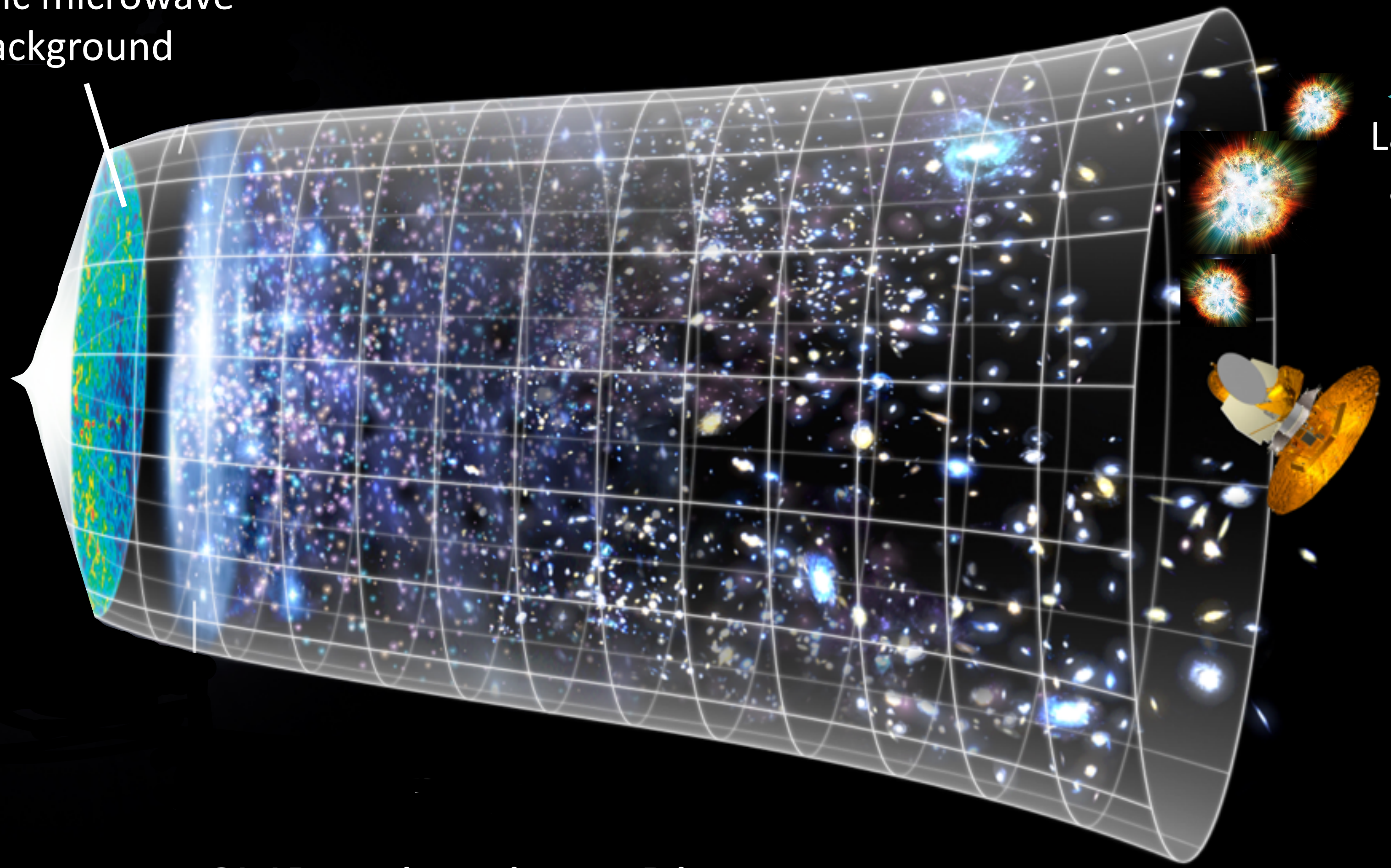
Fit ΛCDM to the early universe
$H_0 = 67.4 \pm 0.5$ km/s/Mpc

4.4σ tension

Directly measure in current universe
$H_0 = 74.03 \pm 1.42$ km/s/Mpc

Cosmic microwave background

Early universe + cosmological assumptions



Late universe + astrophysical assumptions

CMB estimation < Direct measurement

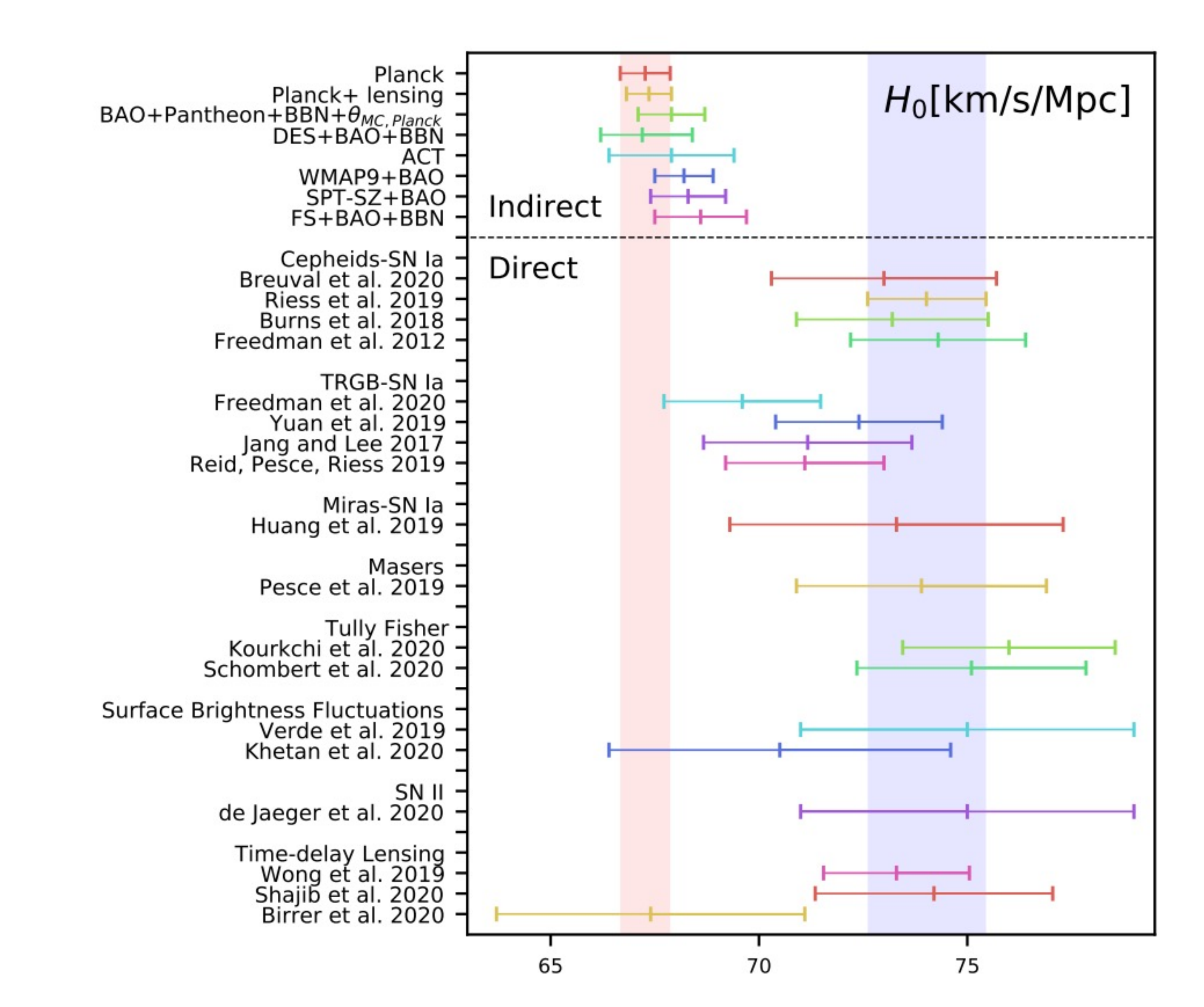
NASA/WMAP Science Team

The Hubble tension
Current state – headache

Discrepancy between the early and late universe?

Is ΛCDM wrong?

Di Valentino [2011.00246]

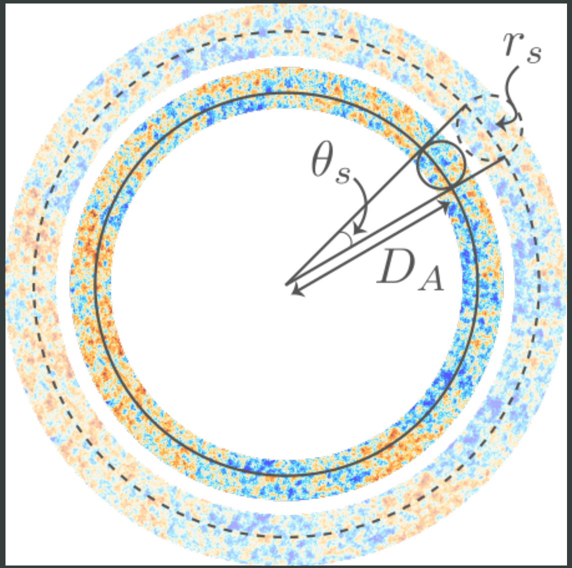


This talk

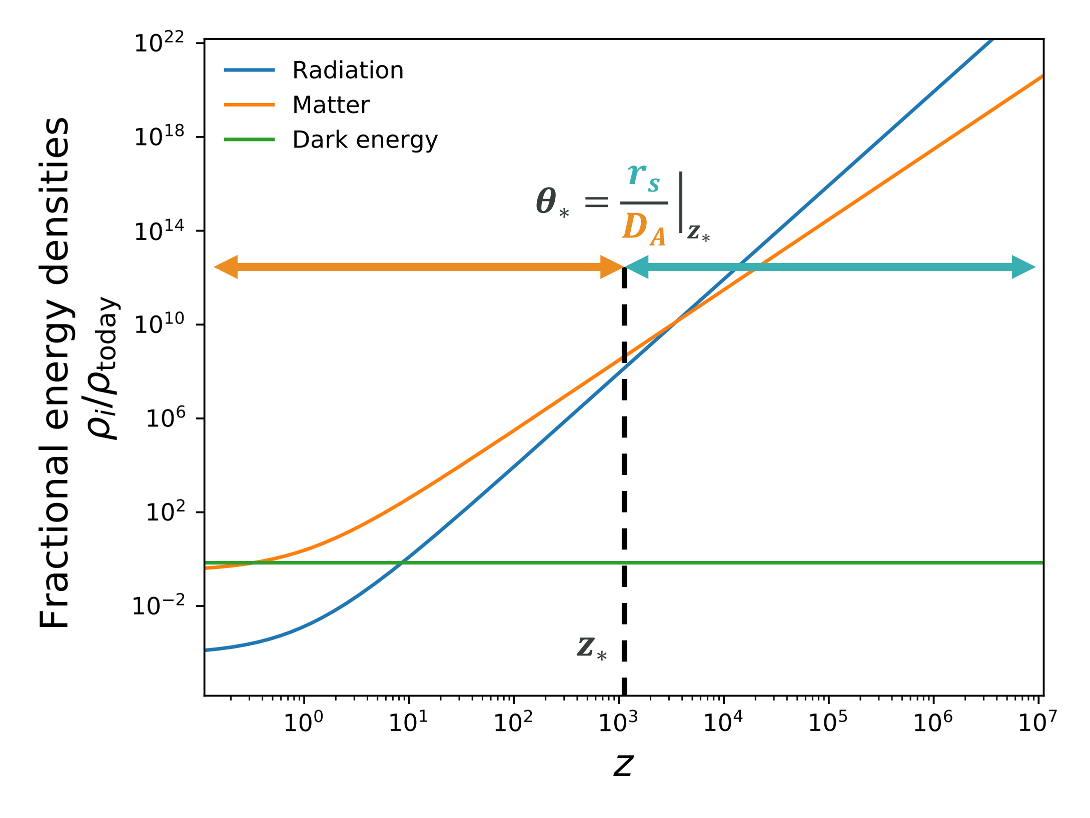
- Approaches to theoretically resolving the Hubble tension
- Solutions to H_0: early dark energy (EDE) models
- Challenges: the large-scale structure tension

When to add new physics?
Early universe

Precisely measured θ_* is an approximate proxy for CMB peak locations



Cartoon by Tristan L. Smith



$$D_A \propto 1/H_{post}$$

$$\theta_* \sim \frac{r_s}{1/H_{post}} \sim r_s H_0$$

For constant θ_* ,

$$r_s \propto 1/H_0$$

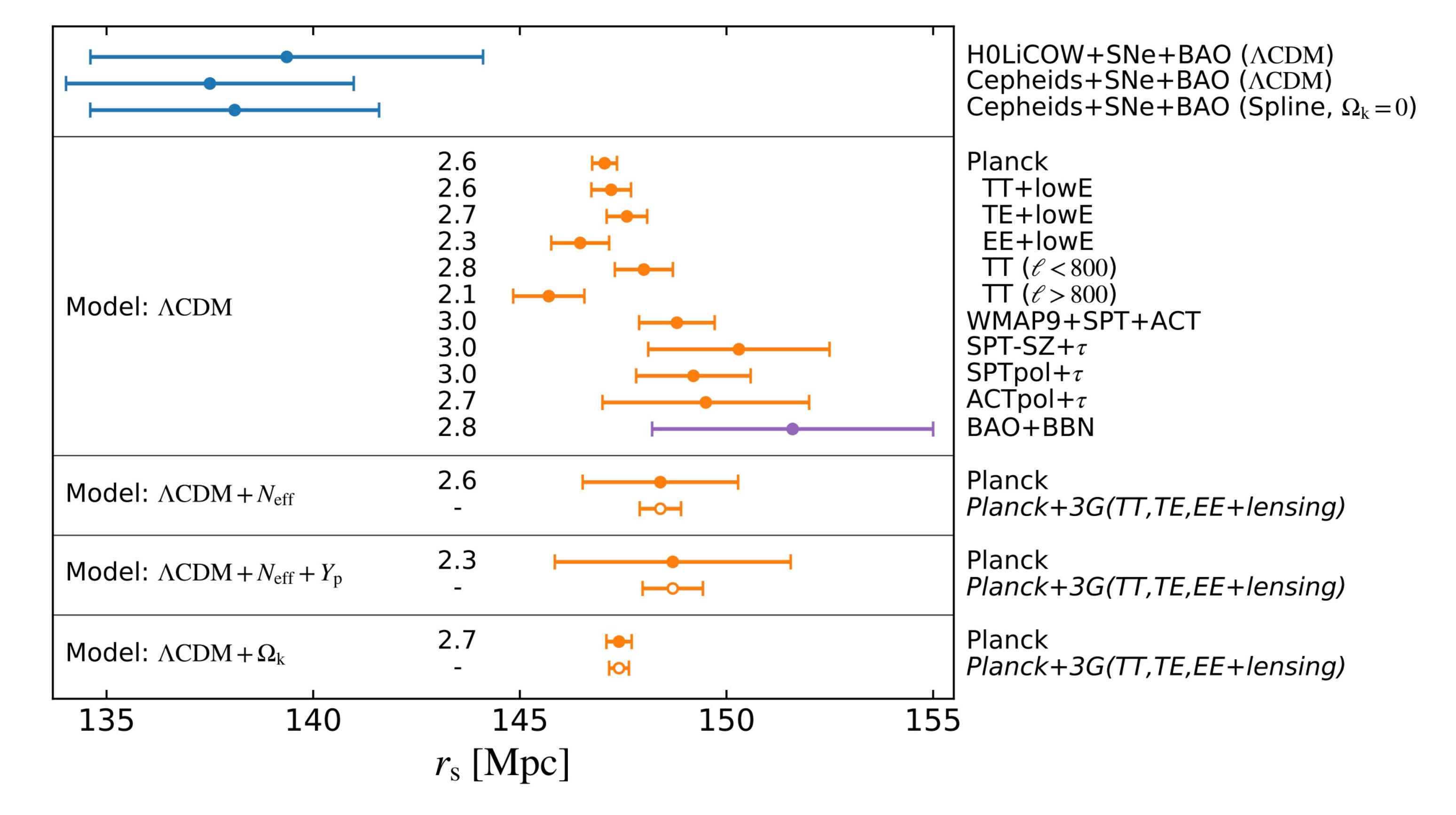
In support of an early universe modification:
Planck [1807.06209]
Bernal et al [1607.05617]
Evslin et al [1711.01051]
Aylor et al [1811.00537]

Hubble tension ⟷ Sound horizon tension

Distance ladder + BAO → r_s

CMB r_s + BAO → H_0

No CMB data



Higher H_0 measured

Lower H_0 inferred

Lower H_0 inferred

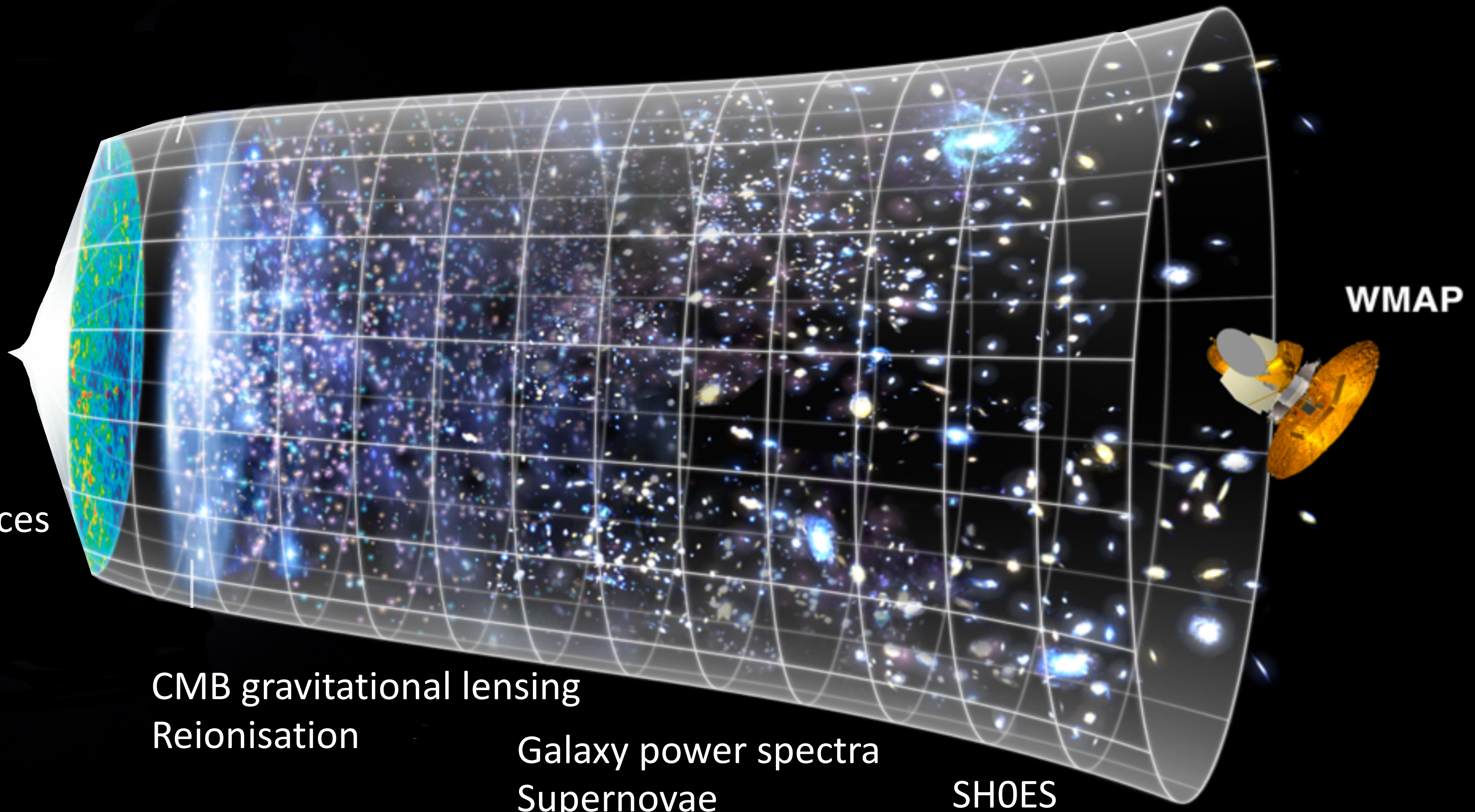
Aylor et al [1811.00537]

Approaches to a solution

Requirements:

- Keep θ_* fixed (or keep CMB peaks fixed) such that $r_S \propto 1/H_0$
- Decrease $r_s \propto 1/H_{pre}(z)$, so increase the pre-CMB expansion rate

How to add new physics?
Leave late universe unchanged



CMB spectra
Light element abundances

CMB gravitational lensing
Reionisation

Galaxy power spectra
Supernovae

SH0ES
Other independent H_0 measurements

Approaches to a solution

Requirements:

- Keep θ_* fixed (or keep CMB peaks fixed) such that $r_S \propto 1/H_0$
- Decrease $r_s \propto 1/H_{pre}(z)$, so increase the pre-CMB expansion rate
- Leave $D_A \propto 1/H_{post}(z)$ unchanged, so modification must disappear at late times

This talk

✓ Approaches to theoretically resolving the Hubble tension

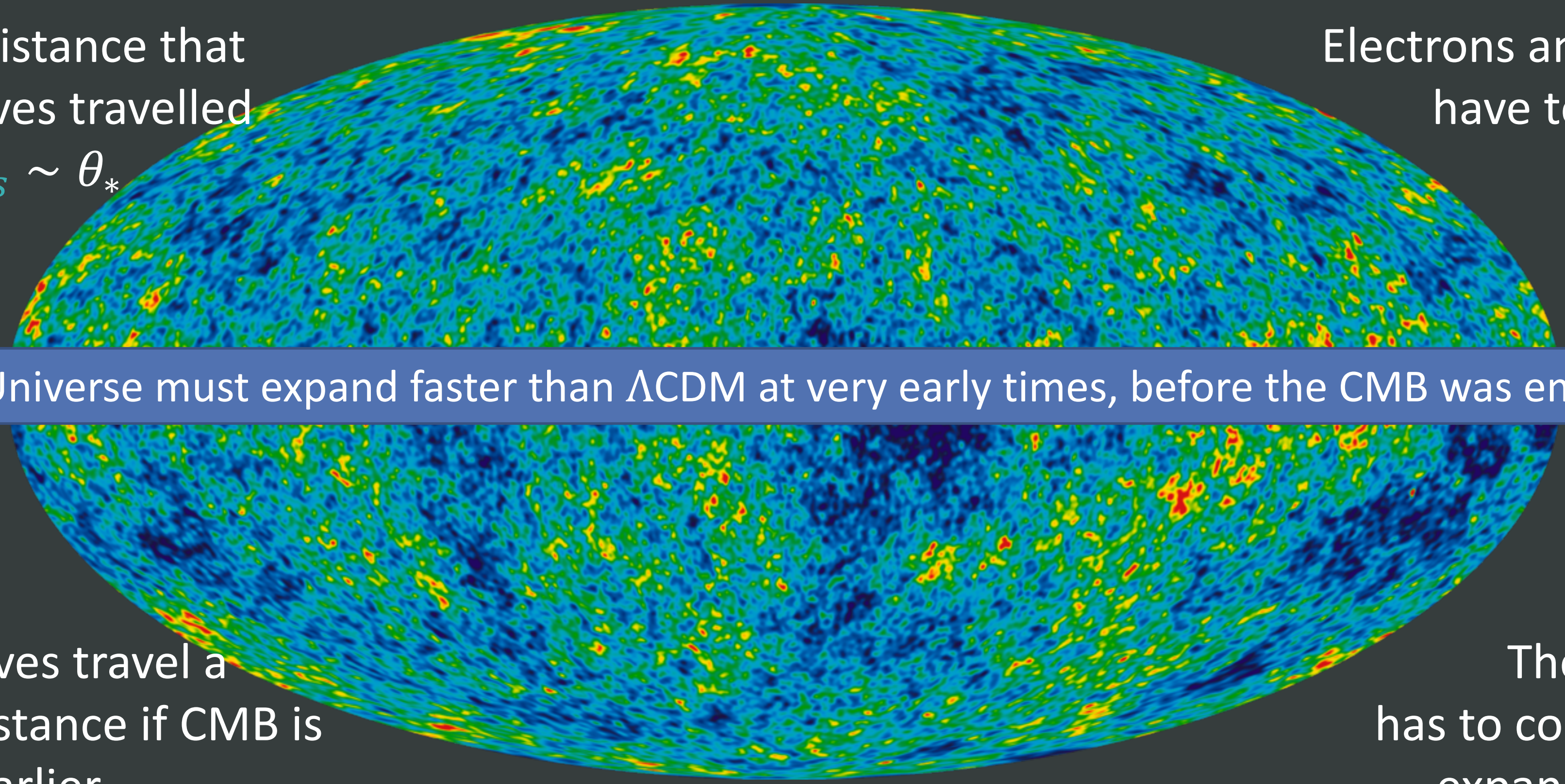
➡ Solutions to H_0: early dark energy (EDE) models

- Challenges: the large-scale structure tension

Hubble solutions
Reduce r_s

Farthest distance that sound waves travelled
$\sim r_s \sim \theta_*$

Electrons and protons have to combine sooner



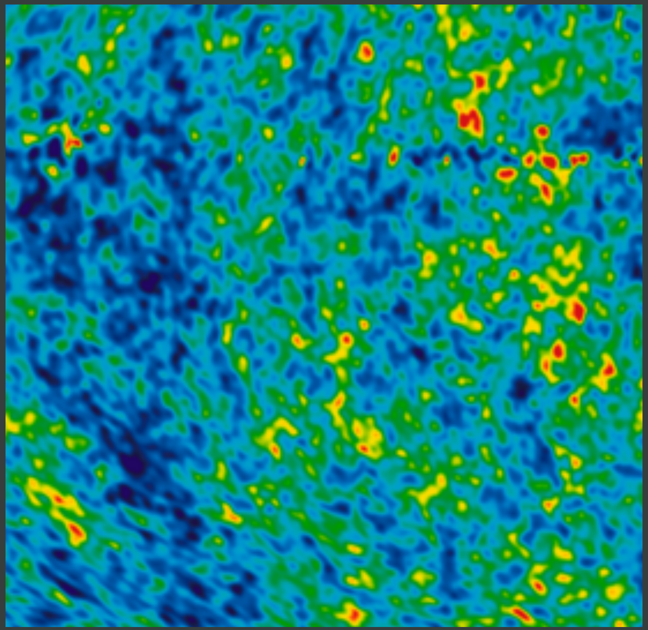
The Universe must expand faster than ΛCDM at very early times, before the CMB was emitted

Sound waves travel a shorter distance if CMB is emitted earlier

The Universe has to cool through expansion faster

WMAP, NASA

Hubble solutions
Effect of early dark energy



Observed CMB

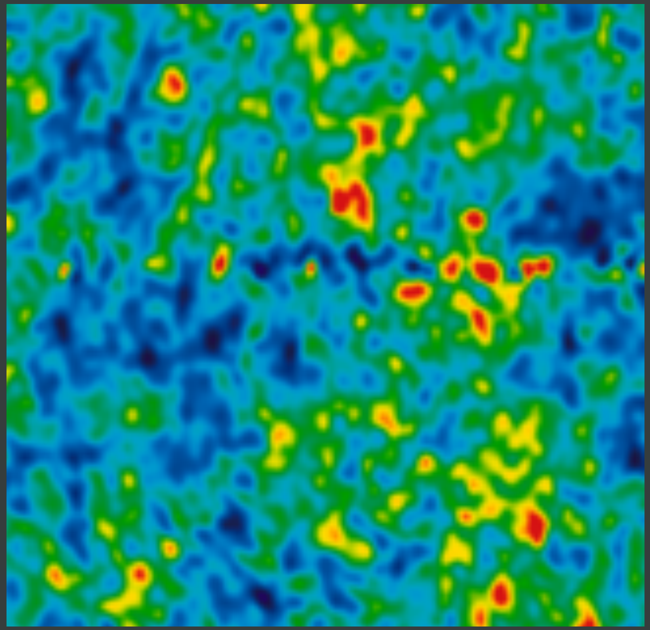
Increase

H_0

Decrease

r_s

Add
early dark energy



Disagreement with observed CMB

Approaches to a solution

Requirements:

✓ Keep θ_* fixed (or keep CMB peaks fixed) such that $r_S \propto 1/H_0$

✓ Decrease $r_s \propto 1/H_{pre}(z)$, so increase the pre-CMB expansion rate

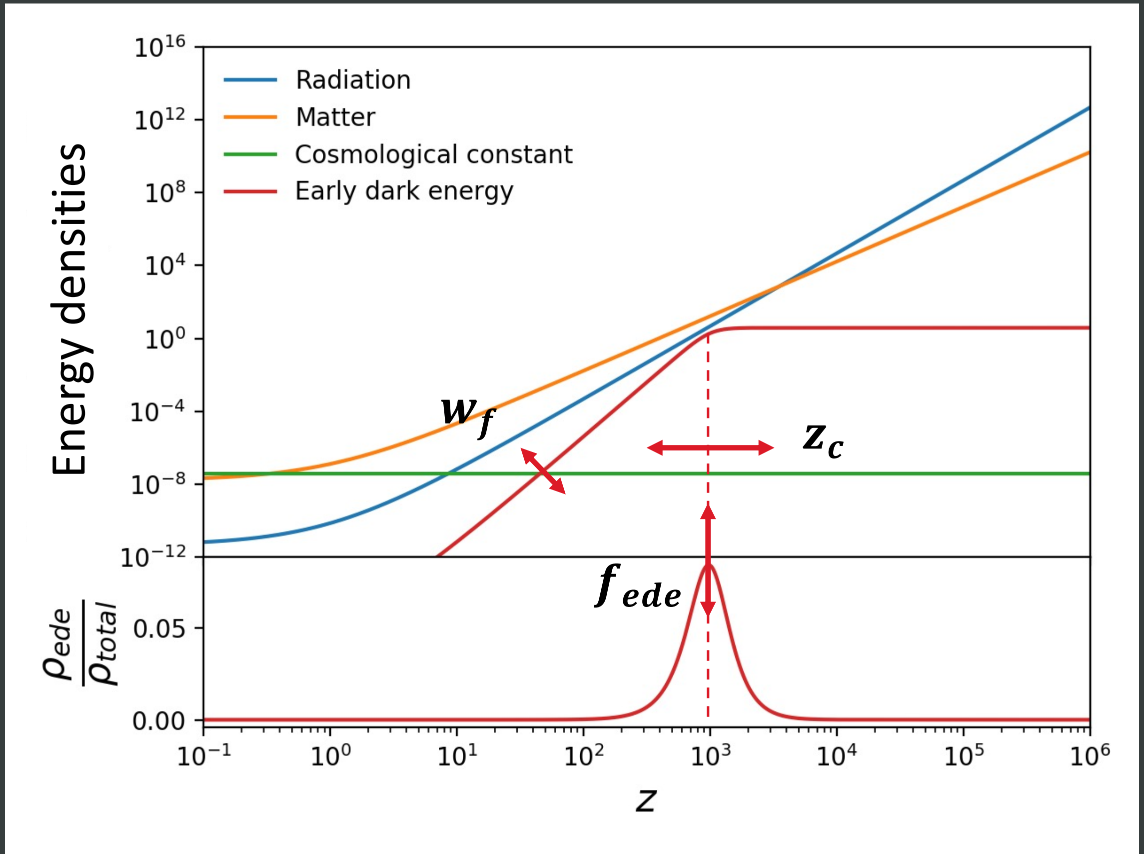
- Leave $D_A \propto 1/H_{post}(z)$ unchanged, so modification must disappear at late times

Early dark energy (EDE)

Additional energy component with the properties:

- Λ-like behaviour initially
- Then dilutes faster than matter as w_f
- Localised peak in $f_{ede} = \frac{\rho_{ede}}{\rho_{total}}$ at z_c

f_{ede} - how much EDE
z_c - when EDE appears
w_f (or n) - how fast is disappears



Approaches to a solution

Requirements:

✓ Keep θ_* fixed (or keep CMB peaks fixed) such that $r_S \propto 1/H_0$

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✓ Leave $D_A \propto 1/H_{post}(z)$ unchanged, so modification must disappear at late times

Early dark energy Models

- Dark energy at early times, the Hubble parameter, and the string axiverse
  TK & Kamionkowski [1608.01309]
- Cosmological implications of ultralight axionlike fields
  Poulin, TK et al [1806.10608]
- Early Dark Energy Can Resolve The Hubble Tension
  Poulin, TK et al [1811.04083]
- Thermal Friction as a Solution to the Hubble Tension
  Berghaus & TK [1911.06281]

- Dark energy from the string axiverse. Kamionkowski, Pradler & Walker [1409.0549]
- Rock 'n' Roll Solutions to the Hubble Tension. Agrawal et al [1904.01016]
- Axion-Dilaton Destabilization and the Hubble Tension. Alexander & McDonough [1904.08912]
- Acoustic Dark Energy: Potential Conversion of the Hubble Tension. Lin et al [1905.12618]
- Oscillating scalar fields and the Hubble tension: a resolution with novel signatures. Smith, Poulin, Amin [1908.06995]
- New Early Dark Energy. Neidermann & Sloth [1910.10739]
- Early Dark Energy from Massive Neutrinos as a Natural Resolution of the Hubble Tension. Sakstein & Trodden [1911.11760]
- Unifying Inflation with Early and Late-time Dark Energy in F(R) Gravity. Nojiri et al [1912.13128]
- Is the Hubble tension a hint of AdS phase around recombination? Ye & Piao [2001.02451]
- Unified framework for early dark energy from α-attractors. Braglia et al [2005.14053]
- A novel early Dark Energy model. Garcia, Castaneda, Tejeiro [2009.07357]
- Neutrino-Assisted Early Dark Energy: Theory and Cosmology. Gonzalez et al [2011.09895]

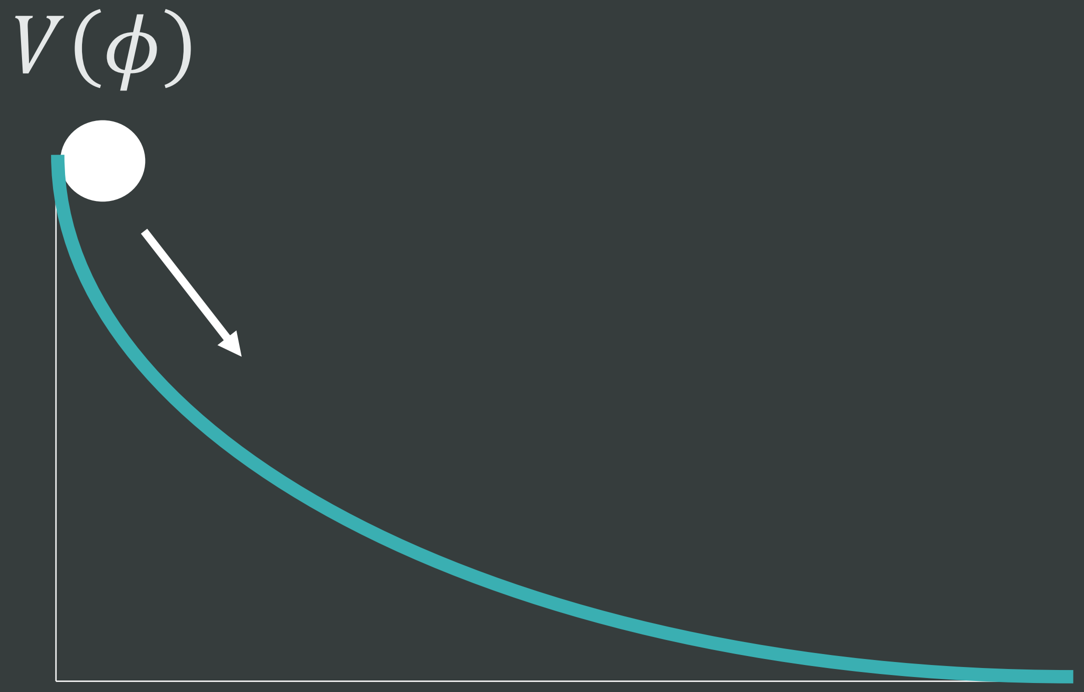
Early dark energy Models

Dissipative axion (DA)

Uncoupled scalar experiences Hubble friction. Uncoupled DR dilutes as $(1+z)^4$

$$\ddot{\phi} + (3H)\,\dot{\phi} + V_\phi = 0$$

$$\dot{\rho}_{dr} = -4H\rho_{dr}$$



Berghaus & Karwal [1911.06281]

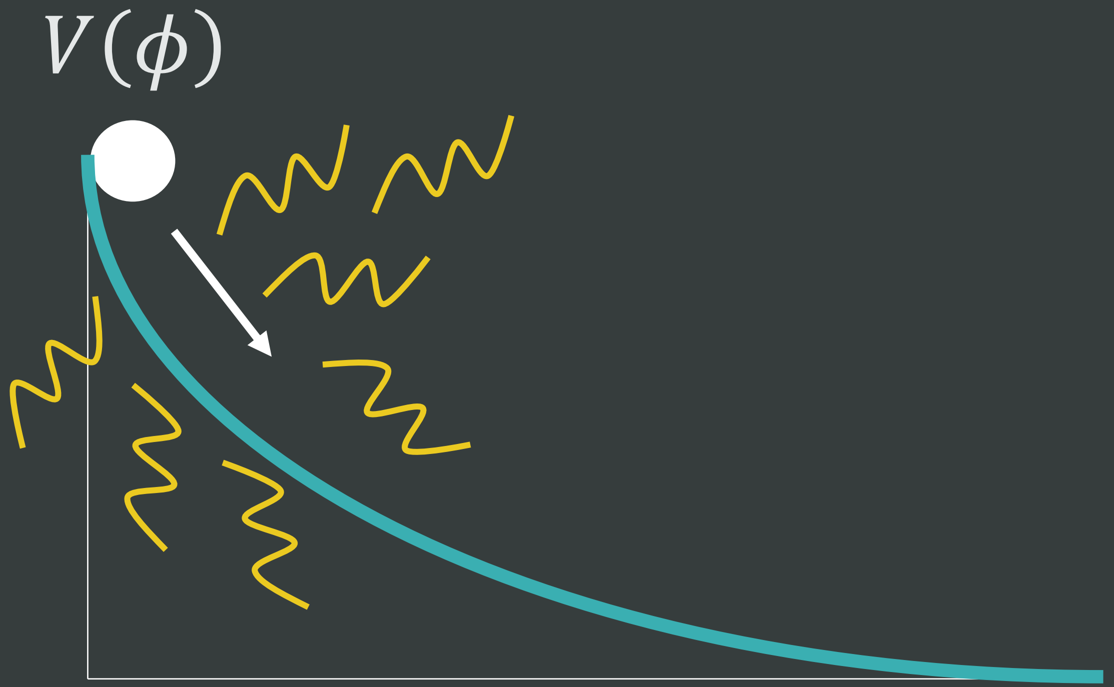
Early dark energy Models

Dissipative axion (DA)

Scalar coupled to DR additionally experiences thermal friction

$$\ddot{\phi} + \left(3H + \Upsilon(T_{dr})\right)\dot{\phi} + V_\phi = 0$$

$$\dot{\rho}_{dr} = -4H\rho_{dr} + \Upsilon(T_{dr})\dot{\phi}^2$$



Berghaus & Karwal [1911.06281]

Early dark energy Models

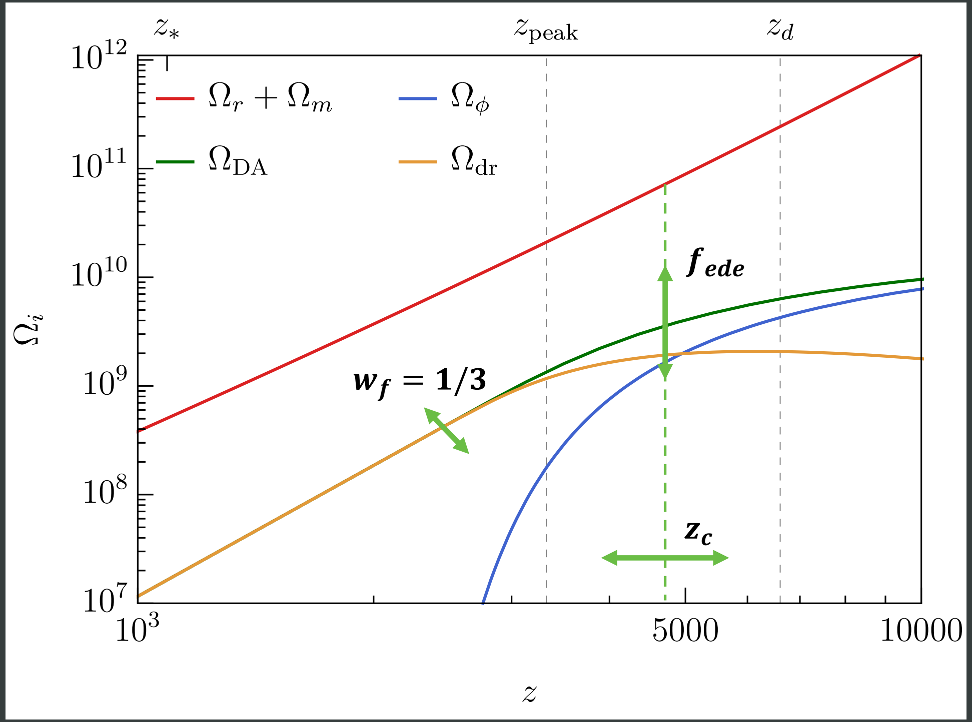
Dissipative axion (DA)

$$\ddot{\phi} + \left(3H + \Upsilon(T_{dr})\right)\dot{\phi} + V_{\phi} = 0$$

$$\dot{\rho}_{dr} = -4H\rho_{dr} + \Upsilon(T_{dr})\dot{\phi}^2$$

$$m, \phi_i \rightarrow f_{ede}$$
$$m, \Upsilon(\mathrm{T_{dr}}) \rightarrow z_c$$
$$w_f = 1/3$$

Robust to choice of $V(\phi)$



Berghaus & Karwal [1911.06281]

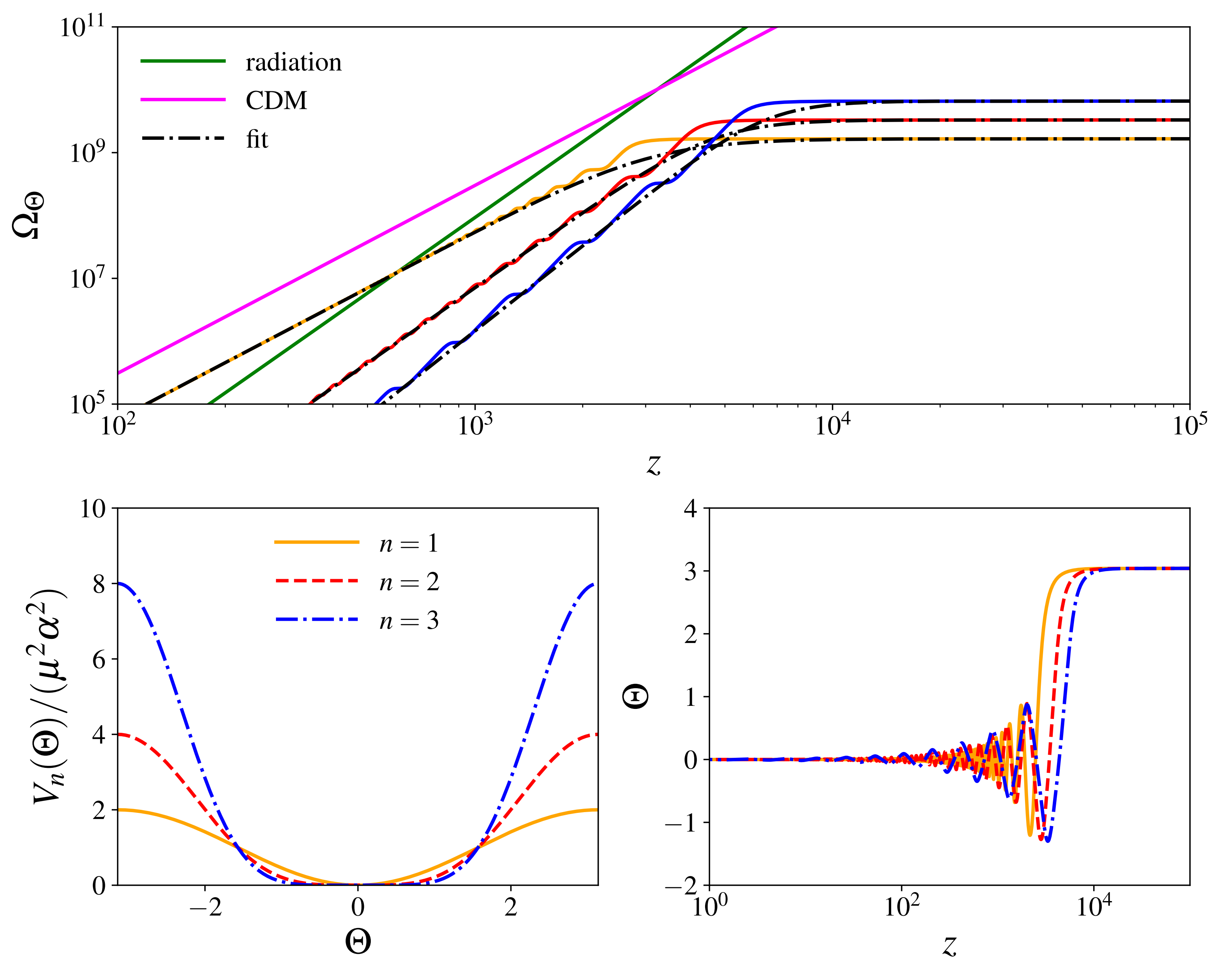
Early dark energy Models

Ultra-light axion-like (ULA) particles

$$V(\phi) \propto \left(1 - \cos(\phi)\right)^n$$

$$w_f = \frac{n-1}{n+1}$$

$$\phi_i\, , f\, , m \leftrightarrow f_{ede}\, , z_c$$

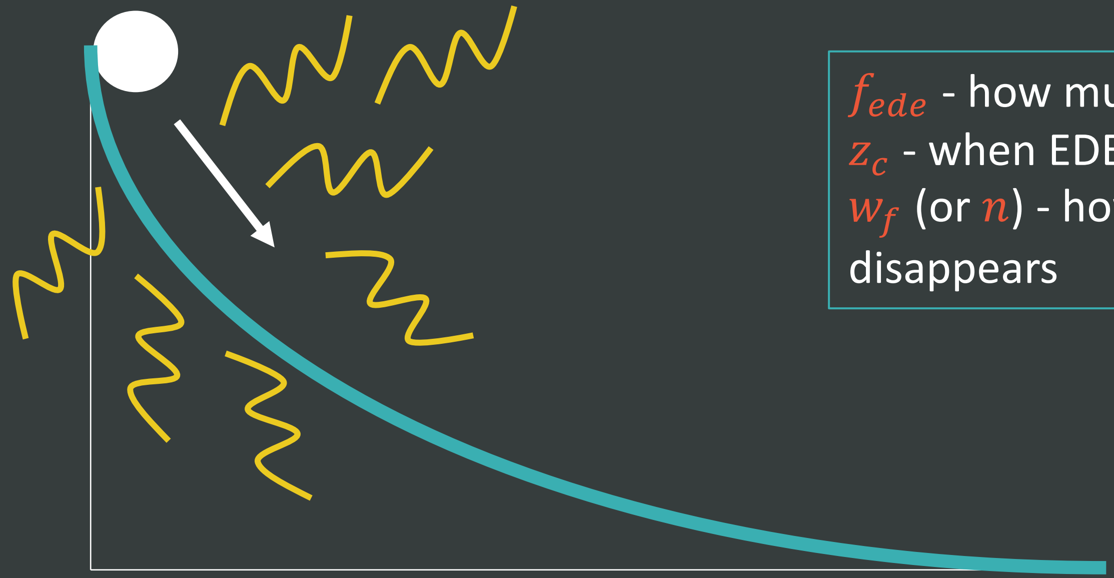


Poulin, TK, et al [arxiv:1806.10608]

Early dark energy Models

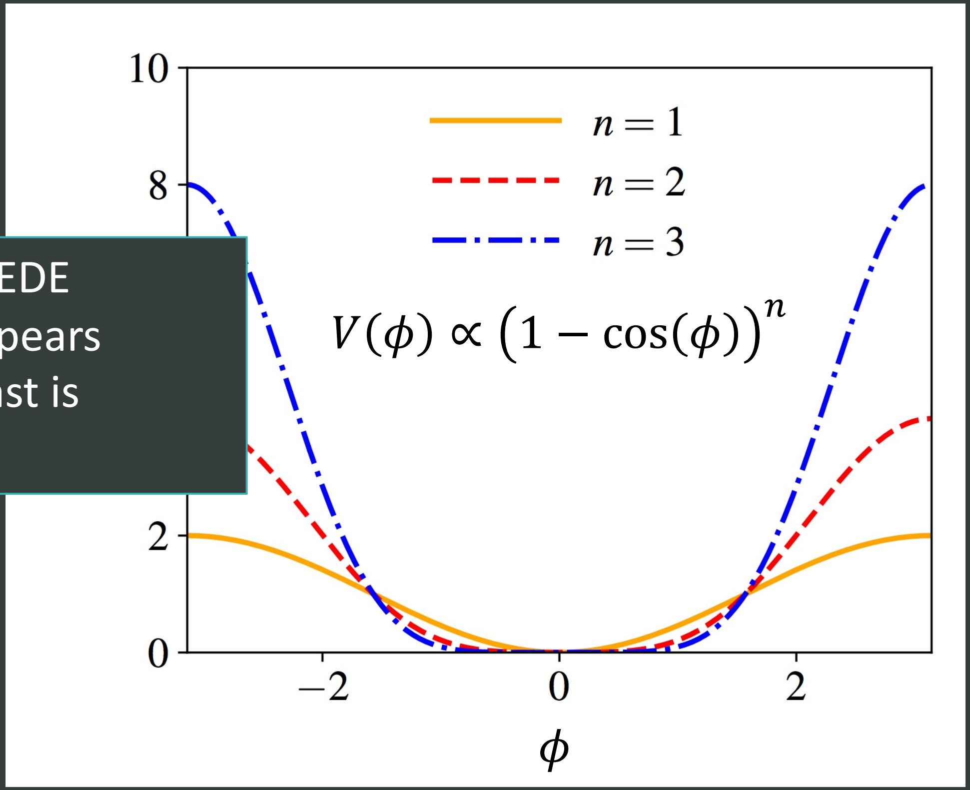
Dissipative Axion

$V(\phi) \sim \phi^2$



f_{ede} - how much EDE
z_c - when EDE appears
w_f (or n) - how fast is disappears

Ultra-light axion inspired (ULA) potential



Berghaus & Karwal [1911.06281]

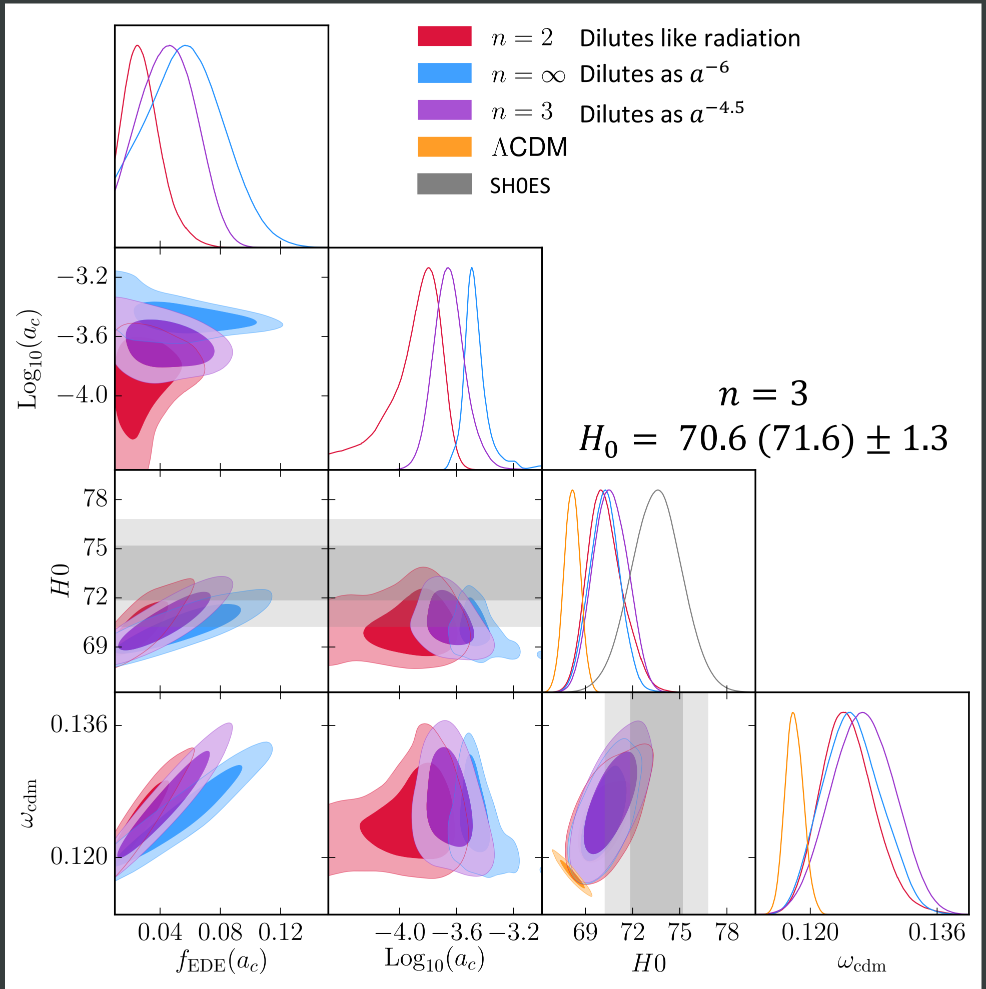
Poulin, TK, et al [arxiv:1806.10608]

Early dark energy Solutions

Based on

- CMB temperature, polarisation and lensing data from Planck 2015
- Local Hubble measurement from SH0ES 2018
- Baryon acoustic oscillations
- Pantheon supernovae

Phenomenological EDE (ULA fluid)



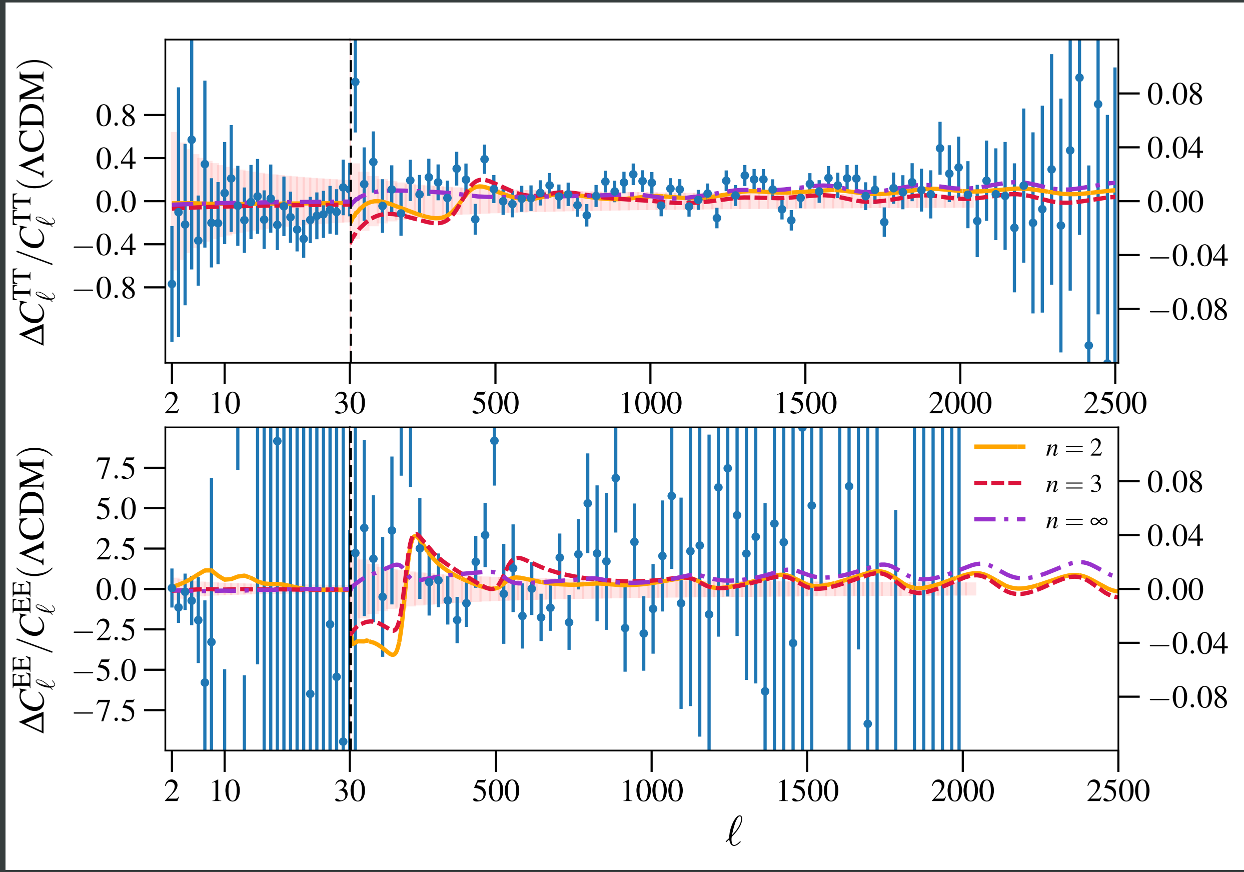
ω_{cdm} = fractional amount of cold dark matter today

$f_{ede}(a_c)$ = fractional energy density in the axion field at critical redshift $z_c \approx 1/a_c$

As before, $w_f = \frac{n-1}{n+1}$

Poulin, TK et al [1811.04083]

Early dark energy
Detection



Could detect EDE in cosmic-variance-limited, high-ell
CMB polarisation data

Poulin, TK et al [1811.04083]

Early dark energy
New concordance model?

This talk

- ✓ Approaches to theoretically resolving the Hubble tension
- ✓ Solutions to H_0: early dark energy (EDE) models
- ➜ Challenges: the large-scale structure tension

Fit ΛCDM to the early universe

$H_0 = 66.93 \pm 0.62$ km/s/Mpc

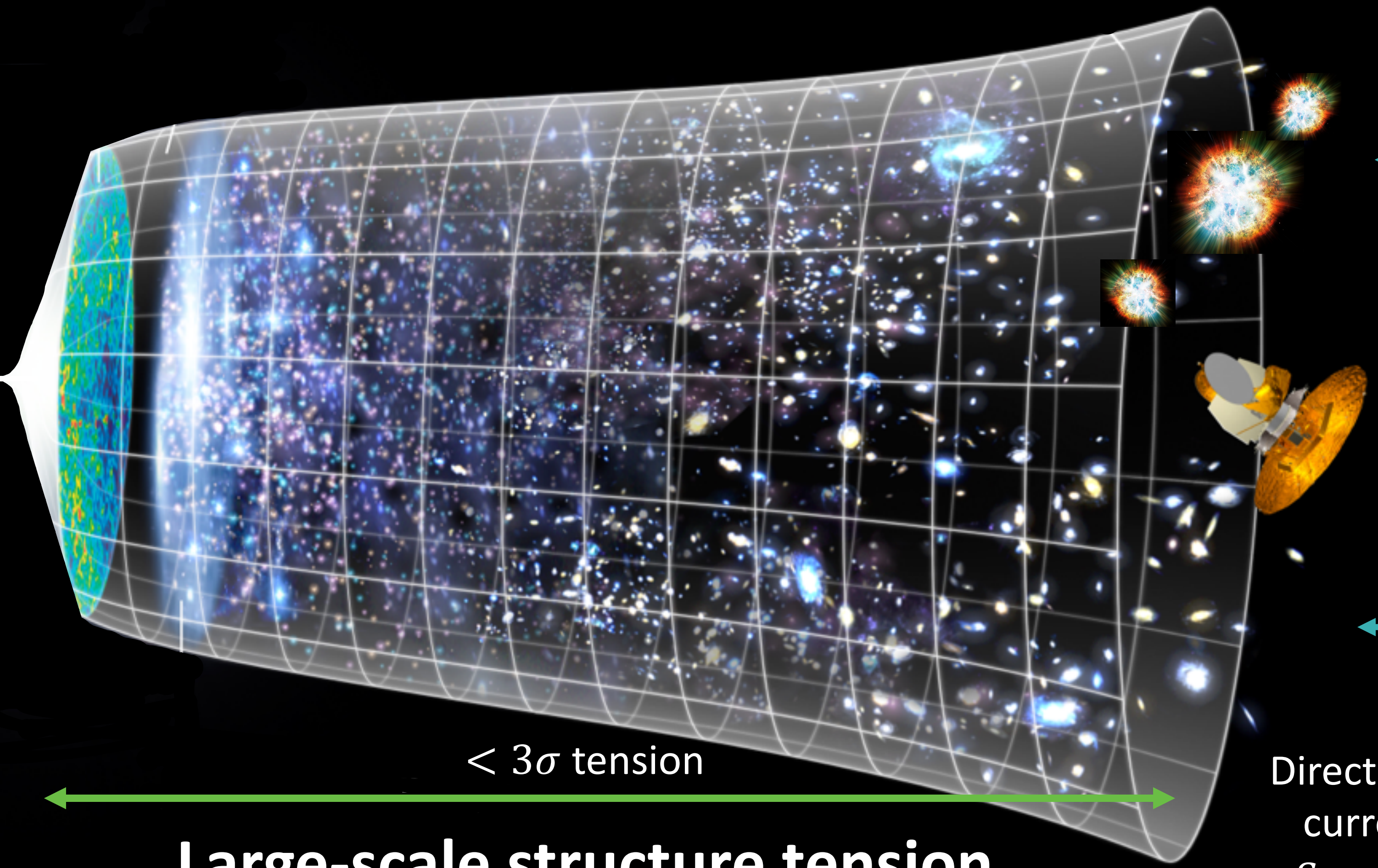
4.4σ tension

The Hubble tension

Directly measure in current universe

$H_0 = 74.03 \pm 1.42$ km/s/Mpc

Cosmic microwave background



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Fit ΛCDM to the early universe

$S_8 = 0.832 \pm 0.013$

$< 3\sigma$ tension

Large-scale structure tension

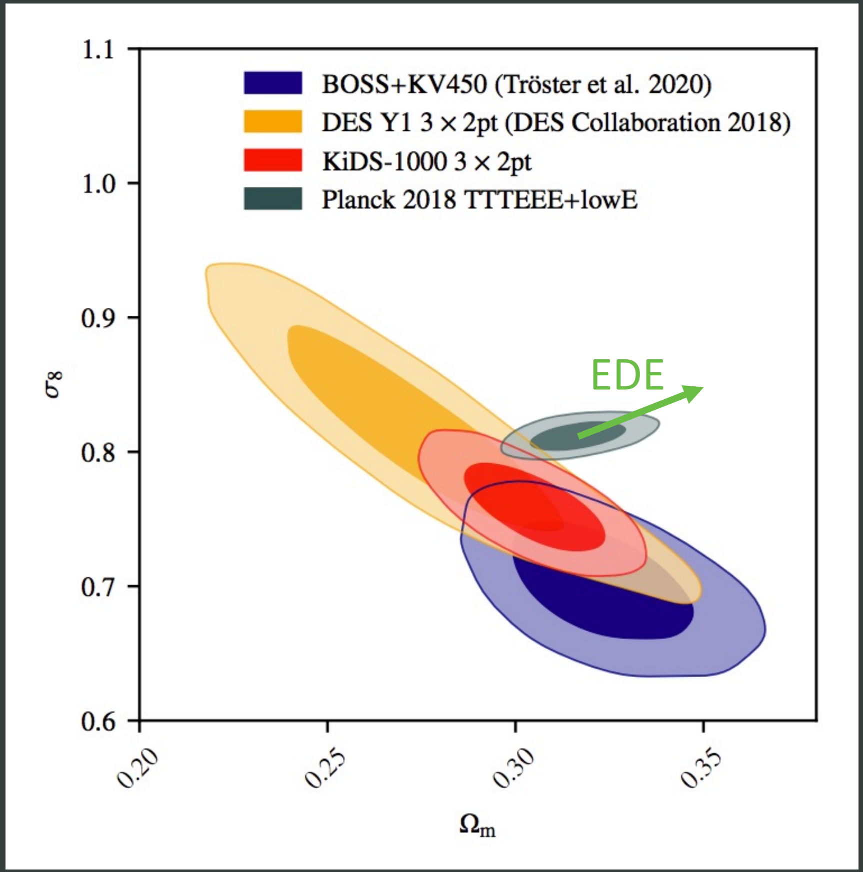
Directly observe the current universe

$S_8 = 0.766^{+0.020}_{-0.014}$

Challenges for EDE
Large-scale structure tension and implications

- Gap in our understanding of how matter clusters?
- Insight into dark matter?
- Relate to the small-scale structure problems of ΛCDM?
  - ΛCDM has difficulty with galaxy evolution
  - Density distribution of some galaxies – see a core but expect a cusp
  - Missing satellites – we expect more sub-halos than observed

Challenges for EDE
LSS tension



Heymans et al [2007.15632]

The S8 tension

Large-scale structure (LSS) directly observed in the late universe

$S_8 = \sigma_8\sqrt{\Omega_m/0.3}$ $<$

CMB-inferred value using ΛCDM

S_8

DES Y1 [1708.01530]	Consistent
KiDS+VIKING-450 [1812.06076]	2.3σ
KiDS-1000 [2007.15632]	3σ

Challenges for EDE
LSS tension in EDE and ΛCDM

Effect of LSS tension on EDE is stronger constraints

EDE with CMB
EDE with CMB+LSS
ΛCDM with CMB+LSS

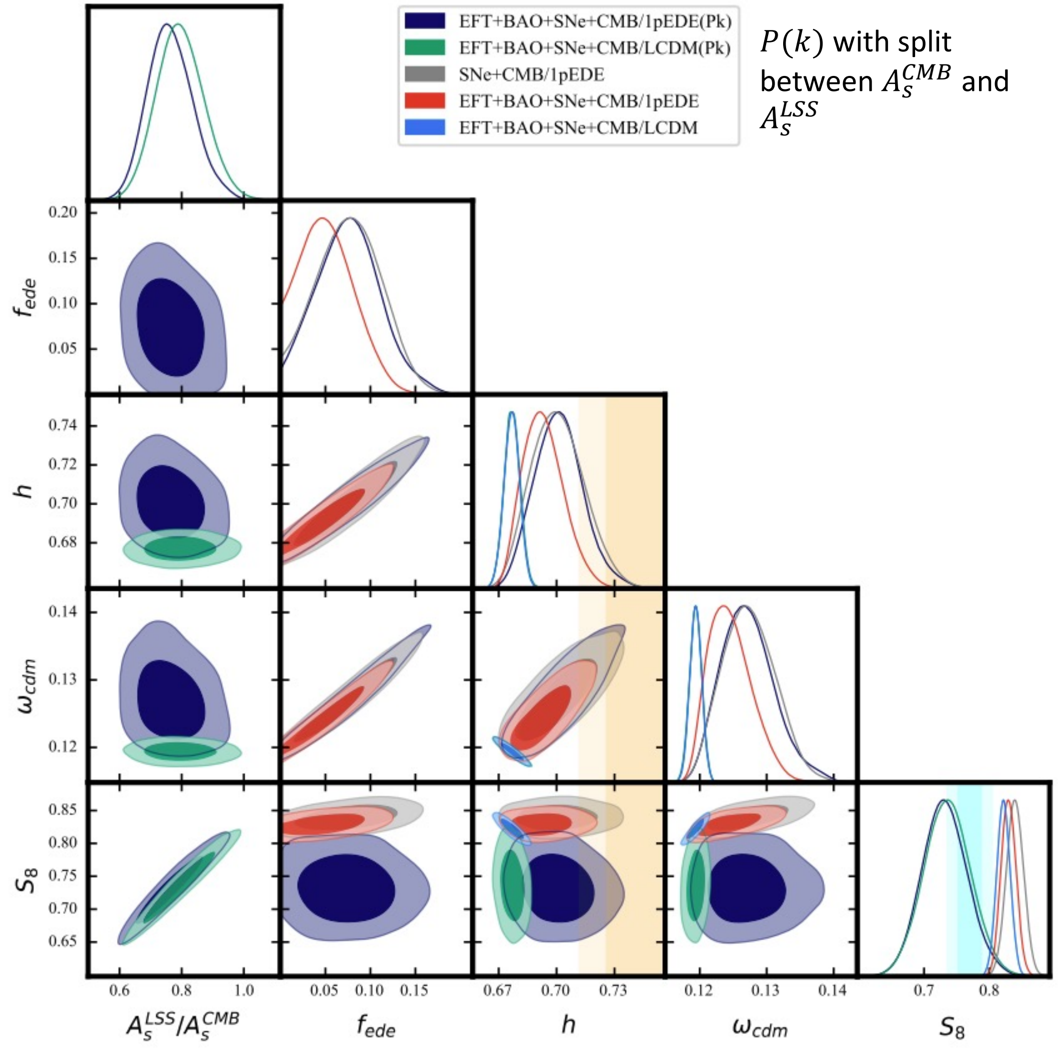
What is the origin of the discrepancy between LSS and CMB?

- Amplitude A_s of the primordial power spectrum

Exercise: allow LSS and CMB different A_s

ΛCDM with CMB+LSS+A_s split
EDE with CMB+LSS+A_s split

Tight EDE constraints disappear



$P(k)$ with split between A_s^{CMB} and A_s^{LSS}

Smith et al. [2009.10740]

Towards a new concordance model

Model to replace ΛCDM ?

Model	Tensions
ΛCDM	Both H_0 and LSS
ΛCDM+EDE	Only LSS
New concordance model	Neither

Figure:
a confused dog

To EDE and beyond

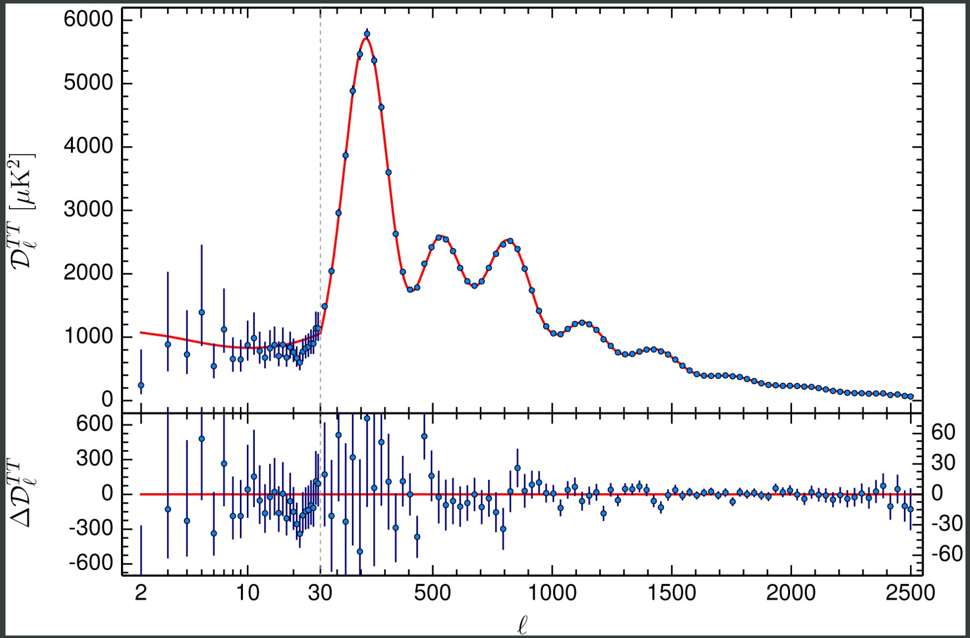
- Does the Hubble tension indicate new physics? Could a solution lie in the early universe?
- Early dark energy can resolve the Hubble tension
  - Several fundamental models for EDE, with varying success at solving the Hubble tension
  - The goodness of fit to cosmological data is not compromised by this addition
  - CMB data from ACT, SPT and CMB-S4 can test EDE
  - EDE faces challenges with the LSS tension [2003.07355] but this tension arises from within ΛCDM and is not introduced because of EDE [2009.10740]
  - Different avatars of EDE have different effects on the large-scale structure tension?
    - New EDE claims to find no tension with EFT of LSS [2009.00006]
    - EDE coupled to neutrinos might have implications for LSS [1911.11760]
  - EDE can be a stepping-stone as we search for the new concordance model of the Universe
  - Two independent solutions required for H_0 and LSS?
    - H_0 depends on background expansion
    - LSS depends on perturbation evolution
  - EDE models can be applied to other eras of cosmic expansion – to explain dark energy or inflation

New LSS, CMB data and further theoretical work might bring insight into the dark sector!

Randall Munroe, xkcd

ΛCDM Parameters

- $H_0 = 100h \text{ km s}^{-1}\text{Mpc}^{-1}$ - current value of the Hubble parameter
- $\omega_b = \Omega_b h^2$ - the fractional density of baryons in the Universe
- $\omega_c = \Omega_c h^2$ - the fractional density of cold dark matter in the Universe
- τ - the optical depth due to reionization
- $\ln(10^{10} A_s)$ – amplitude of the primordial power spectrum
- n_s - scalar spectrum power-law index



Source: Ade et al, A&A 2016