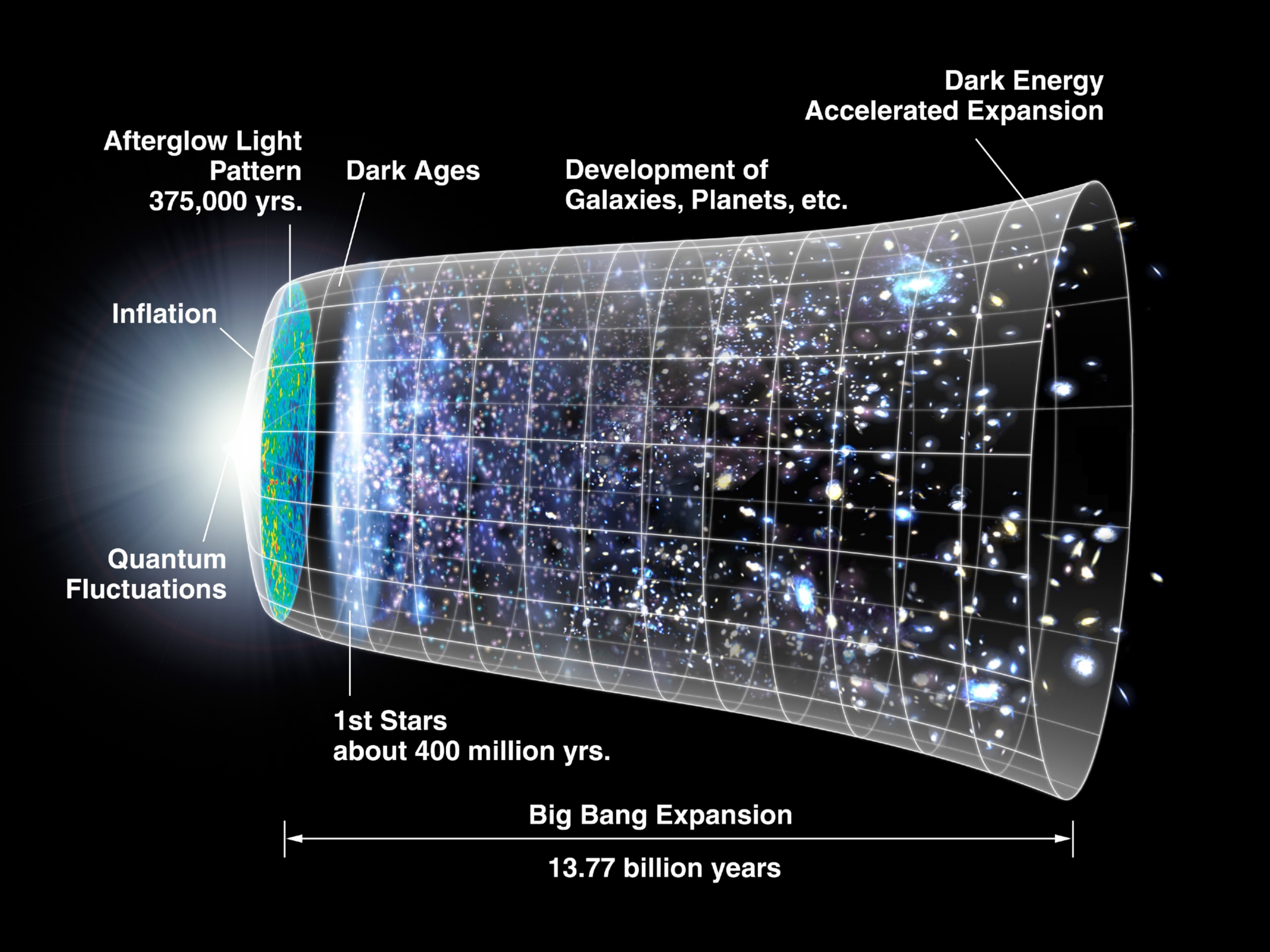
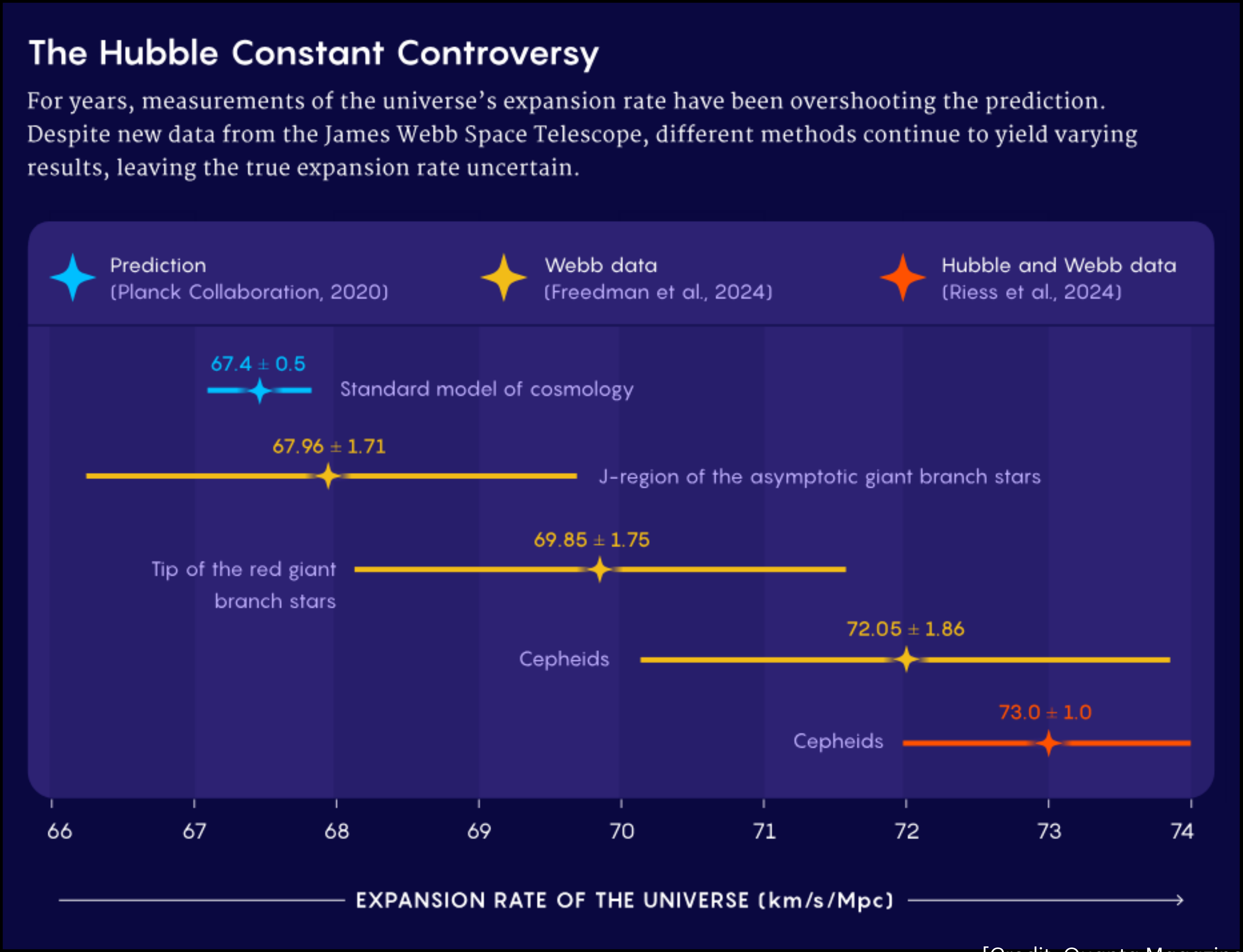
The Hubble Tension

Saturday Mornings of Theoretical Physics:
Cosmology and the Early Universe

Prateek Agrawal, University of Oxford, November 9, 2024


Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
375,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.77 billion years

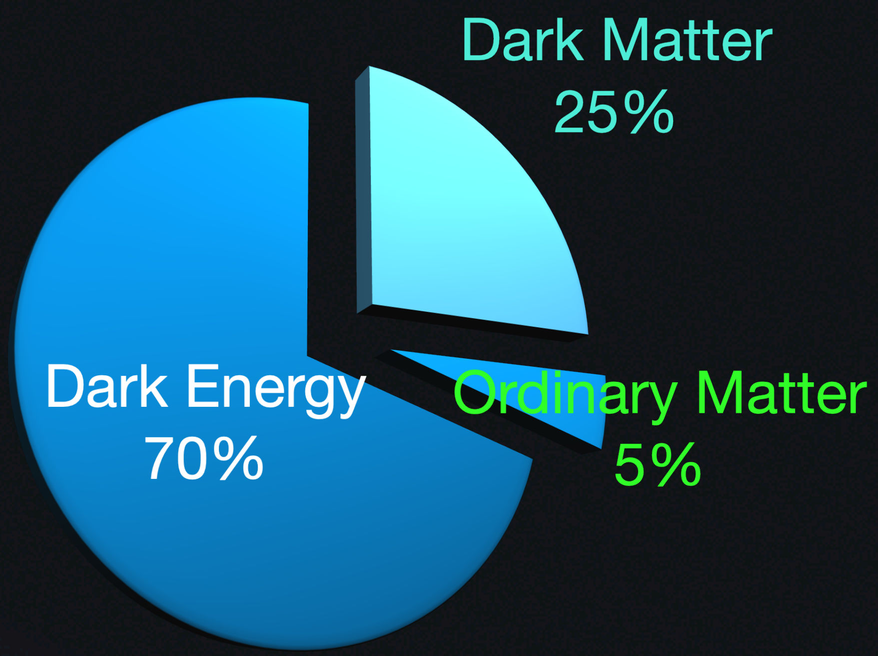


[Credit: Quanta Magazine]

My Interest in the Subject

The Dark Mysteries of the Universe

- The late universe is dominated by dark matter and dark energy
- So far we just know the gross properties of these
  - Total amount
  - Dark matter : small interactions with ordinary matter, non-relativistic
  - Dark energy: a constant
- Do they interact with themselves or each other?
- Is the dark energy a cosmological constant or an evolving field?
- Is there a new contribution ("Early Dark Energy") to the universe?



PA. Obied, Vafa [arXiv: 1906.08261]
PA, Cyr-Racine, Pinner, Randall [arXiv: 1904.01016]
PA, Obied, Steinhardt, Vafa [arXiv: 1806.09718]
PA, Obied [arXiv: 1811.00554]

The Standard Cosmological Model

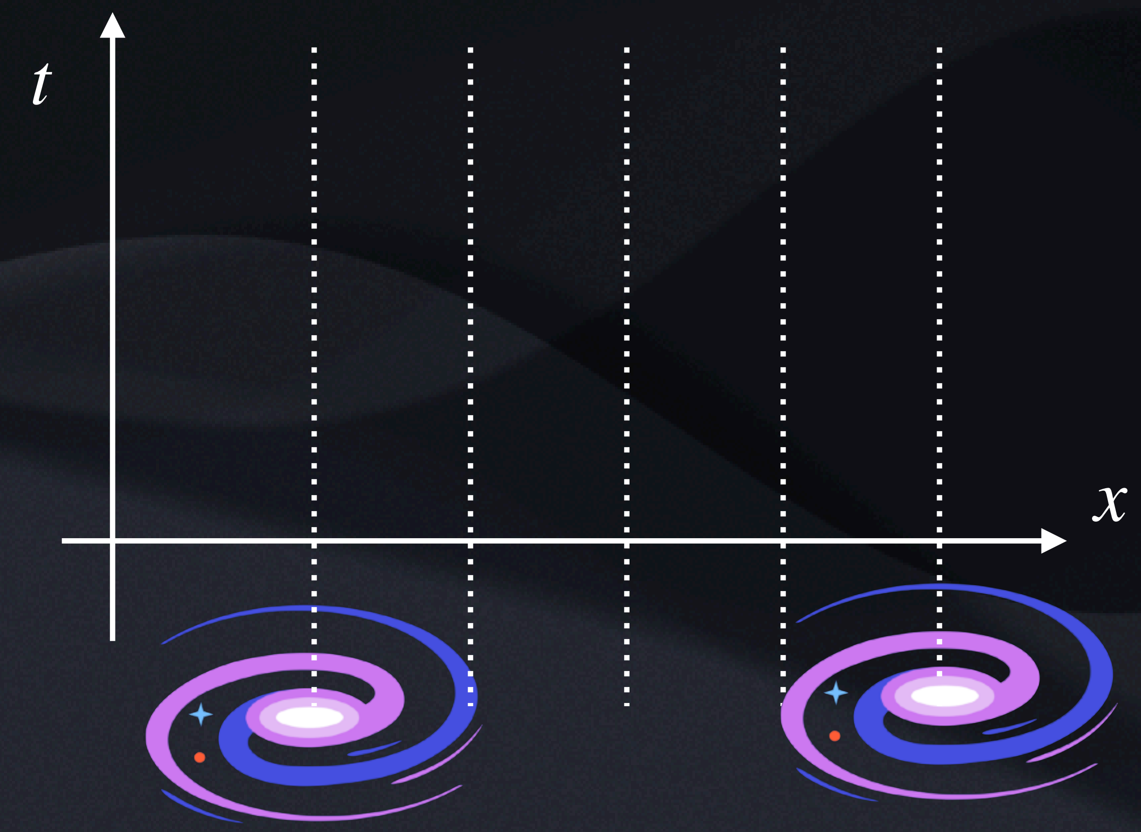
Background Cosmology

Homogeneous and Isotropic (and spatially flat)

- Friedmann-Lemaître-Robertson-Walker metric

$$ds^2 = dt^2 - a^2(t)\, d\vec{x}^2 \qquad H = \frac{\dot{a}(t)}{a(t)}$$

- The scale factor $a(t)$ captures the evolving spacetime



Geodesics
Fixed co-moving coordinates

Physical distance

$$\Delta d = a(t)\Delta x$$

Background Cosmology

Friedmann equations

- Einstein equations applied to the FLRW metric

$$\left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G}{3}\rho$$

(spatially flat universe)

- The energy density of the universe can be modeled as ideal fluids, characterized by their equation of state, or scaling of $\rho(a)$

$$H(a)^2 = H_0^2\left[\Omega_r\, a^{-4} + \Omega_m\, a^{-3} + \Omega_\Lambda\right]$$

Dark energy

$\rho_{\mathrm{dark-energy}} = \rho_{\Lambda,0}$

Radiation (photons, neutrinos)

$\rho_{\mathrm{radiation}} = \rho_{r,0}a^{-4}$

Matter (baryons, cold dark matter)

$\rho_{\mathrm{matter}} = \rho_{m,0}^2 a^{-3}$

Background Cosmology

Conformal time, Redshift

- Conformal time $dt = a d\eta$

$$ds^2 = a^2(\eta)\,(d\eta^2 - d\vec{x}^2)$$

- For photons $ds^2 = 0$, geodesics are straight lines
- Photon wavelength is proportional to the scale factor: redshift

$$(1 + z) \equiv \frac{1}{a}$$

- The cosmological clock:

time / conformal time (η) / redshift (z) / scale factor(a) / temperature

Distance Measures

Angular Diameter Distance (standard rulers)

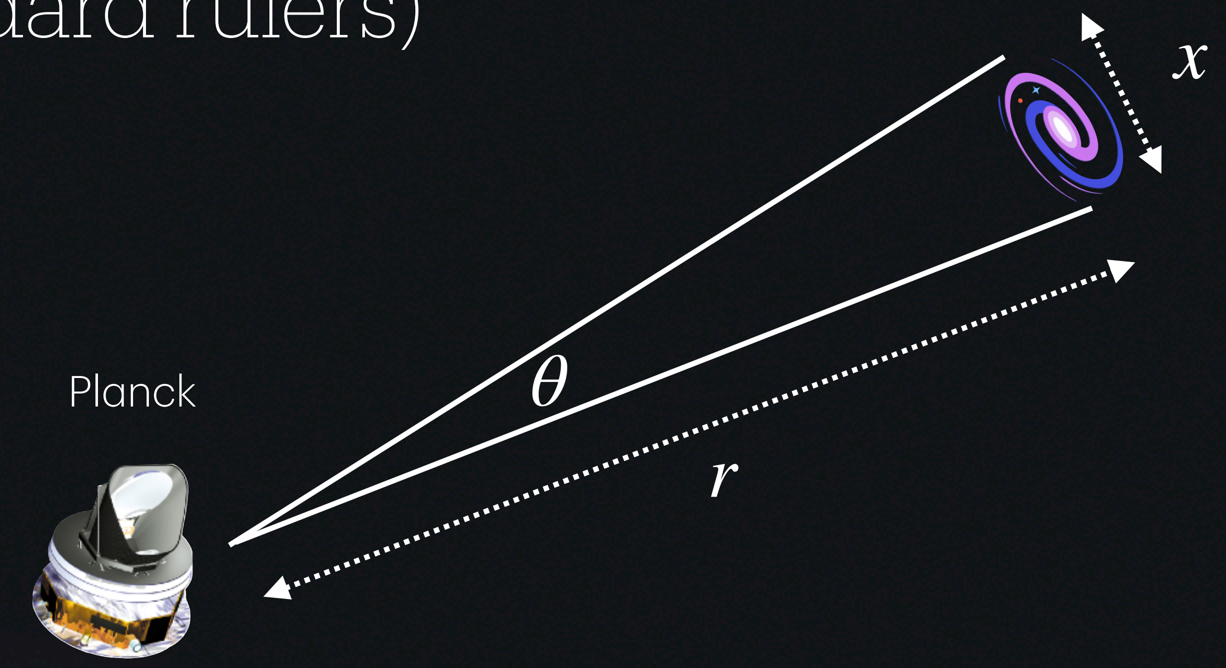
Definition

$$\theta = \frac{D}{d_A}$$

Measured Angle: θ

Physical size: D

Angular Diameter Distance: d_A



Physical size of object $D = a(\eta_e)x$

$$\theta = \frac{x}{r} = \frac{D}{a(\eta_e)\eta_e}$$

Emission time $\eta_e = r$

$$d_A = a(\eta_e)\eta_e = a(\eta_e)\int_{t_e}^{t_0}\frac{dt}{a} = a(\eta_e)\int_{a_e}^{1}\frac{da}{H(a)} = \frac{1}{1+z_e}\int_{z_e}^{0}\frac{dz}{H(z)}$$

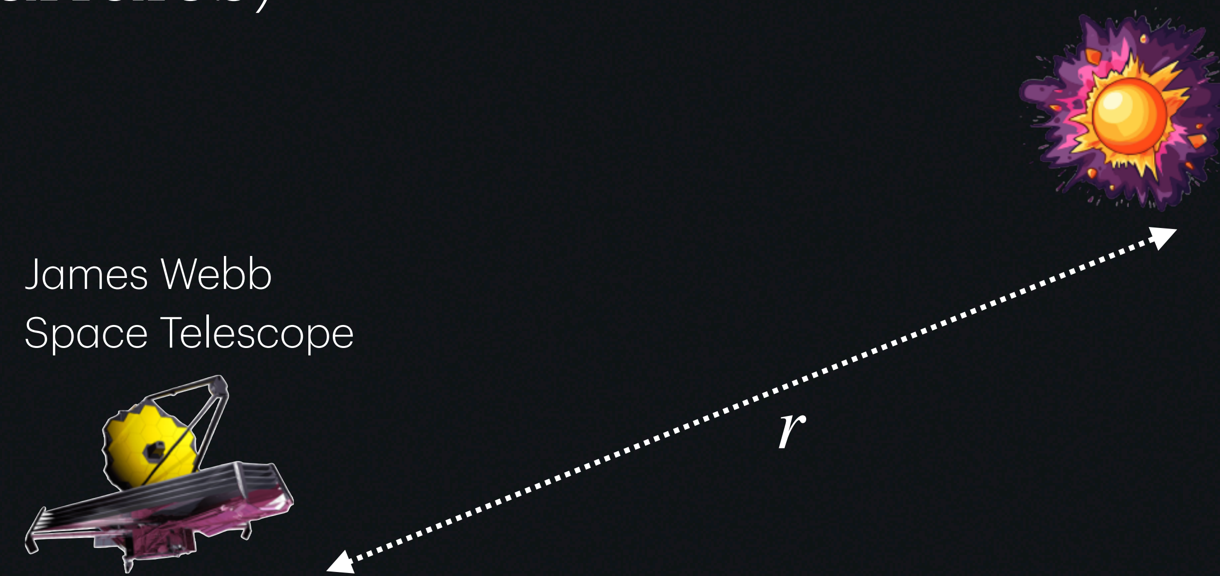
Distance Measures

Luminosity Distance (standard candles)

Definition

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

- F: Measured flux
- L: Intrinsic Luminosity
- d_L: Luminosity Distance



(coordinate area = physical area today)

Fraction of photons seen by detector of area A falls off as $\dfrac{A}{4\pi r^2}$

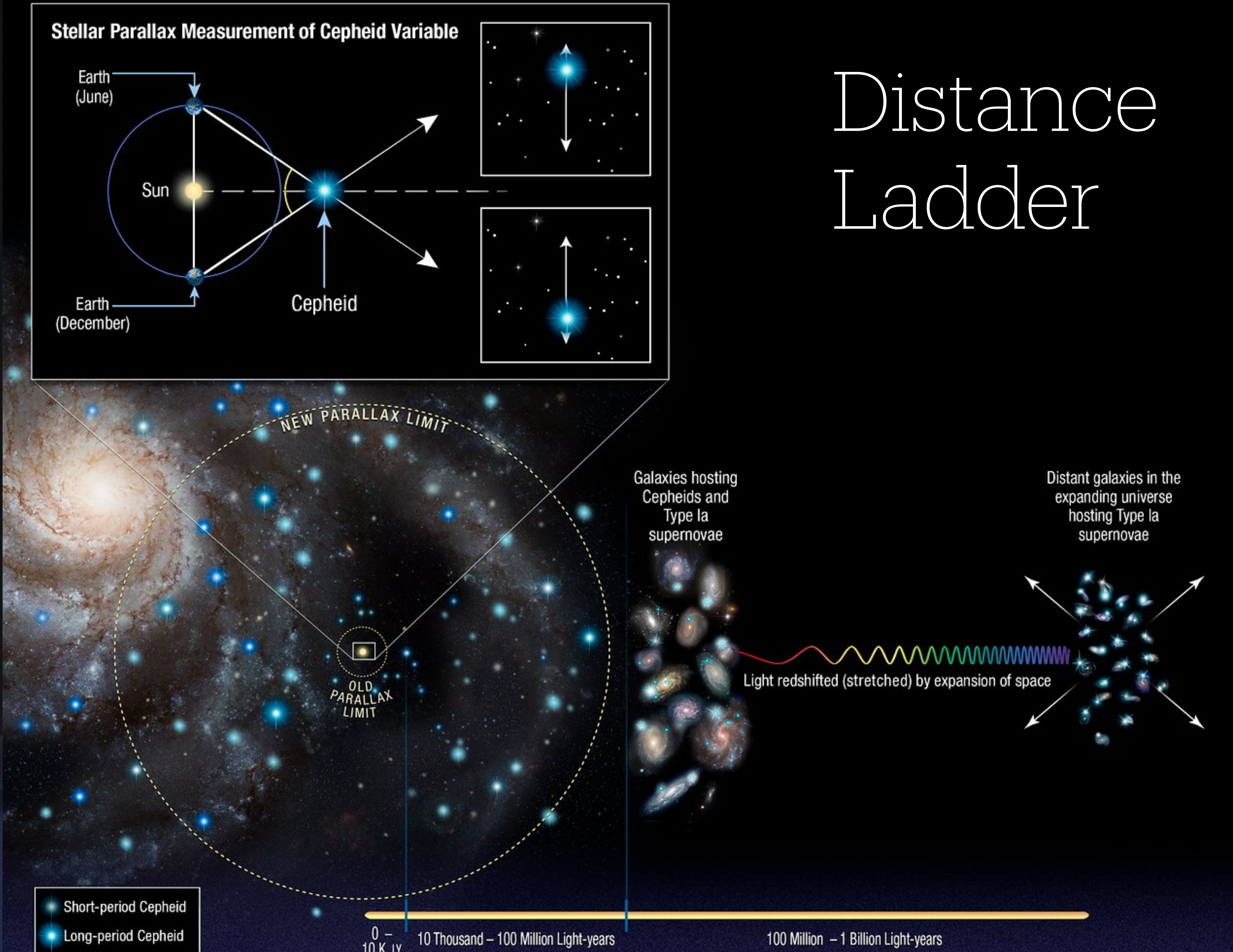
Rate of emission of photons redshifts by $1/(1+z_e)$

Energy of photons redshifts by $1/(1+z_e)$

$$d_L^2 = r^2(1+z_e)^2 = \frac{\eta_e^2}{a(\eta_e)^2}$$

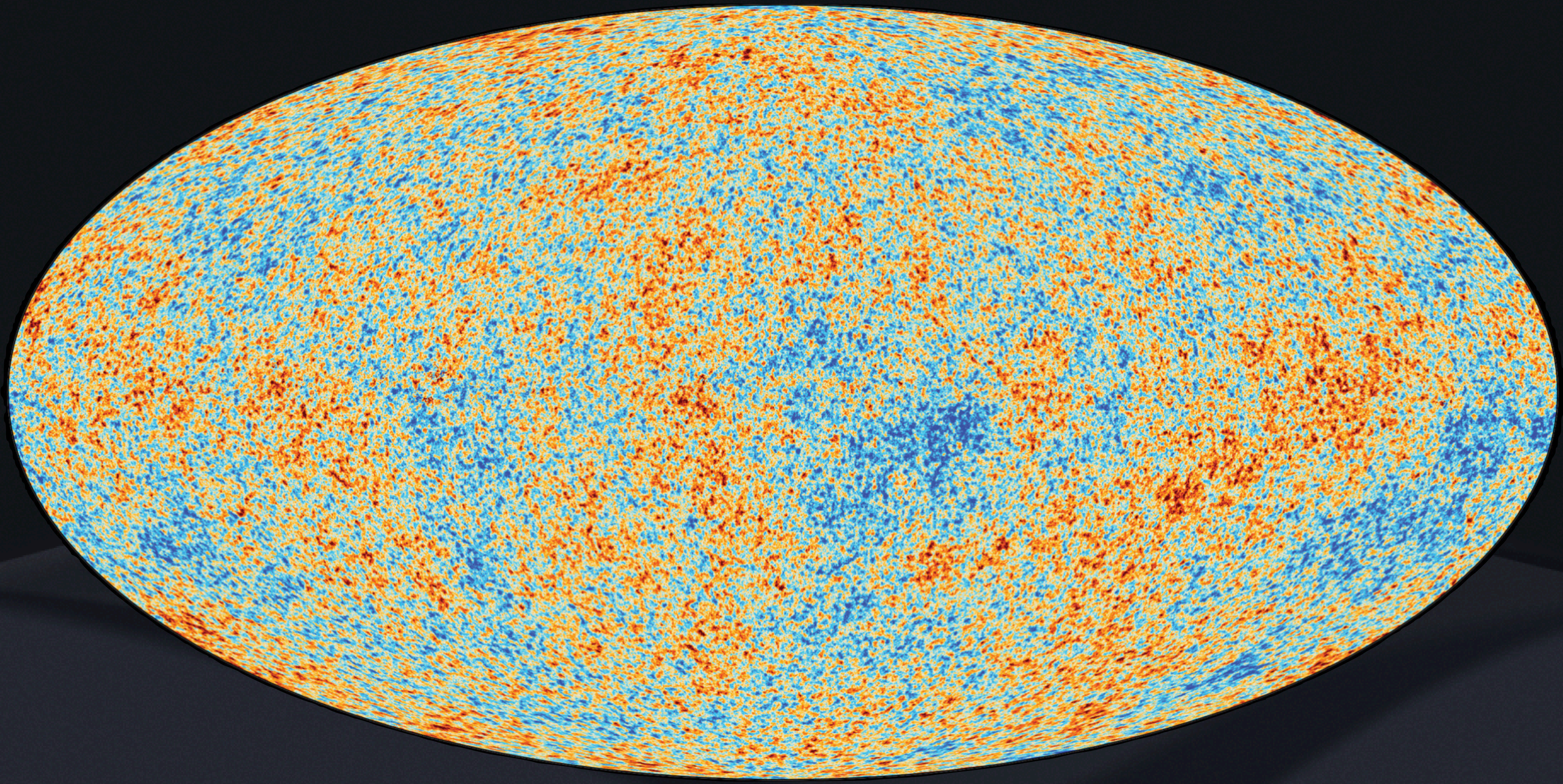
$$d_L = \frac{1}{a(\eta_e)}\int_{t_e}^{t_0}\frac{dt}{a} = \frac{1}{a(\eta_e)}\int_{a_e}^{1}\frac{da}{H(a)} = (1+z_e)\int_{z_e}^{0}\frac{dz}{H(z)}$$

Distance Ladder



[Credit: NASA, ESA, A. Feild (STScI), and A. Riess (STScI/JHU)]

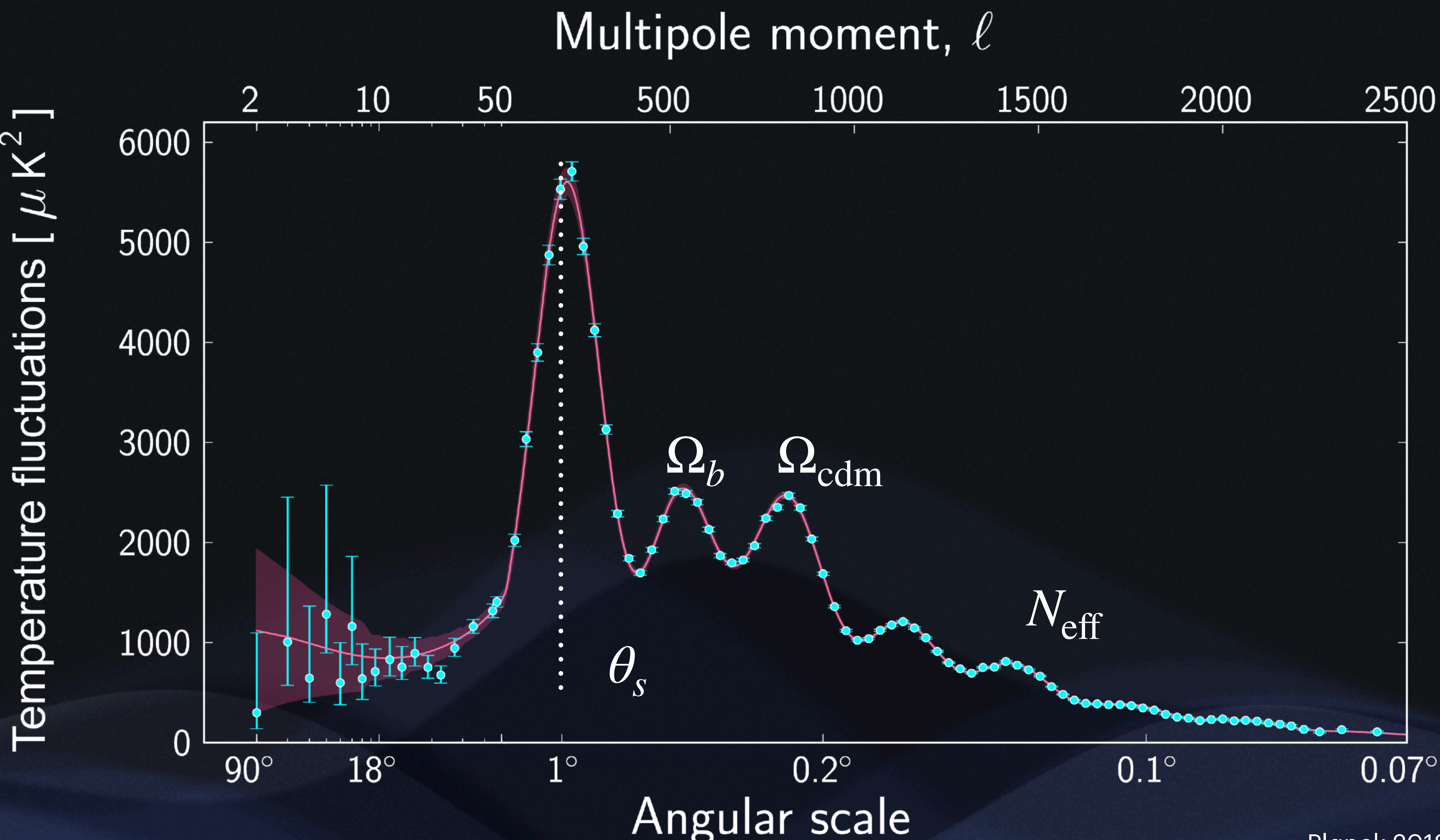
The Cosmic Microwave Background



Cosmological Fluctuations

- We owe the existence of interesting structures in the universe to the presence of primordial fluctuations, $\delta \equiv \dfrac{\delta\rho}{\rho} \sim 10^{-5}$
- The initial conditions for these fluctuations predict a "scale-invariant" spectrum, as e.g. predicted by simple theories of inflation
- Fluctuations can be treated in linear perturbation theory
- ΛCDM is a 6-parameter model that fits the CMB data very well

$$\Omega_b, \Omega_c, H_0, \tau, A_s, n_s$$



Planck 2018

Position of peaks correspond to physical wavelengths that resonate
Height of peaks are set by composition up of the oscillating plasma

CMB measurement of H_0

Measured to 0.03%

$$\theta_s = \frac{r_s}{d_A}$$

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

Comoving sound horizon

$$\frac{1}{1+z_*}\int_{z_*}^{0} \frac{dz}{H(z)}$$

Angular diameter distance

Comoving sound horizon is fixed by the physics at recombination

Early or late solutions

- Late: Keep CMB physics intact, modify evolution of $H(z)$ keeping d_A fixed
- Early: Change r_s and d_A, without modifying shape of $H(z)$

Solutions (?)

Late solutions

Modifying the dark sector?

$$\theta_s = \frac{r_s}{d_A}$$

Keep d_A fixed, change the shape of $H(z)$

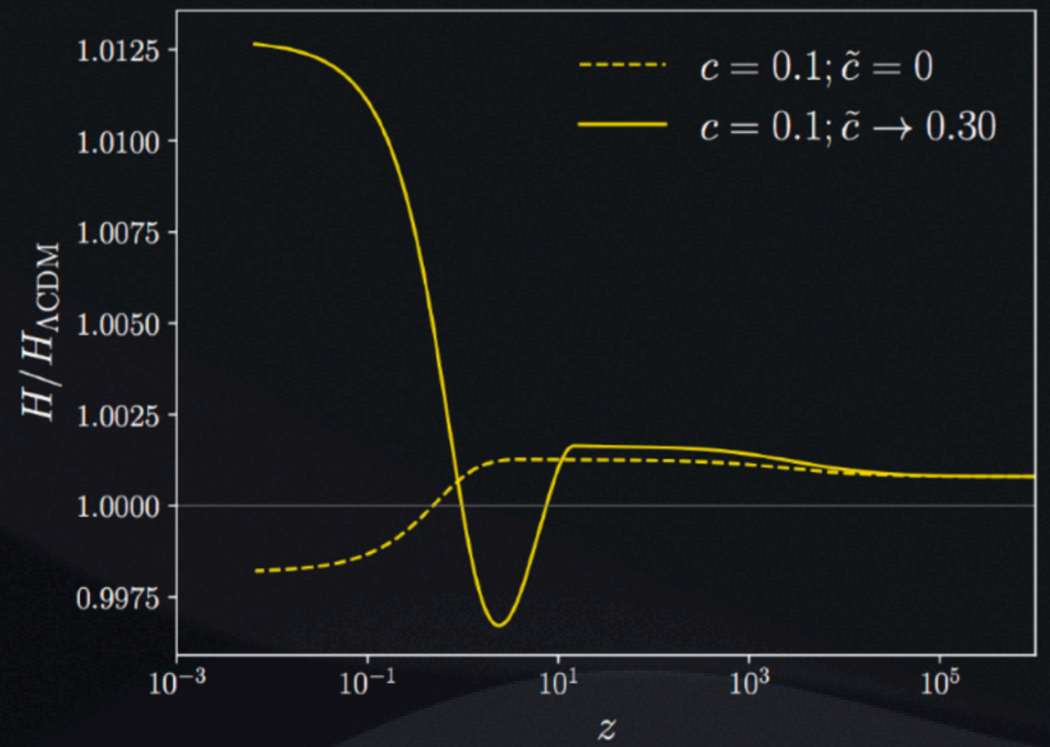
Example: String Swampland inspired model

Dark energy is a rolling scalar field

$$V(\phi) = V_0 \exp(-c\phi/M_{\rm pl})$$

Dark matter mass is also set by ϕ

$$m_{\rm DM} = m_0 \exp(-c'\phi/M_{\rm pl})$$



Ultimately ineffective at resolving the tension fully

[1906.08261] PA, Obied, Vafa

$$H_0 = 69.3 \text{ km/s/Mpc}$$

Including Baryon Acoustic Oscillation data, late solutions unlikely to work

Early solutions

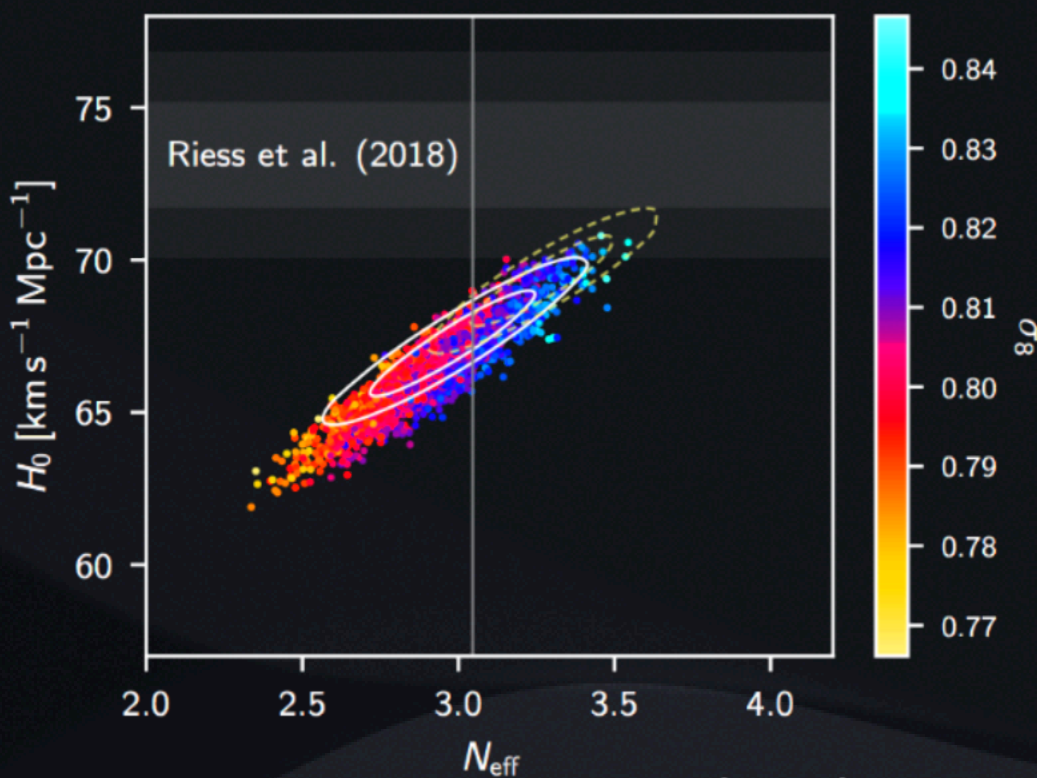
Modifying the dark sector?

$$\theta_s = \frac{r_s}{d_A}$$

Decrease r_s and d_A by ~7%, scaling H_0 higher

Compelling example: $N_{\rm eff}$

- Sterile neutrinos
- dark photons
- gravitons
- ...



Planck 2018

Need $N_{\rm eff} = 4.2$ (SM value 3.046)

- ✓ BAO
- ✓ SNe data
- ✓ SHOES
- ✗ CMB damping tail

Early Dark Energy: decrease r_s by energy injection sharply peaked at $z = 3000$

Future

Improved constraints from non-Cepheid observables

- Neutron star mergers: Gravitational waveform + redshift from optical counterpart

New Ideas in astrophysics (new population of stars)?

New ideas Beyond the Standard Model

- Many attempts, none truly satisfactory

Hubble Tension remains a mystery waiting for a resolution