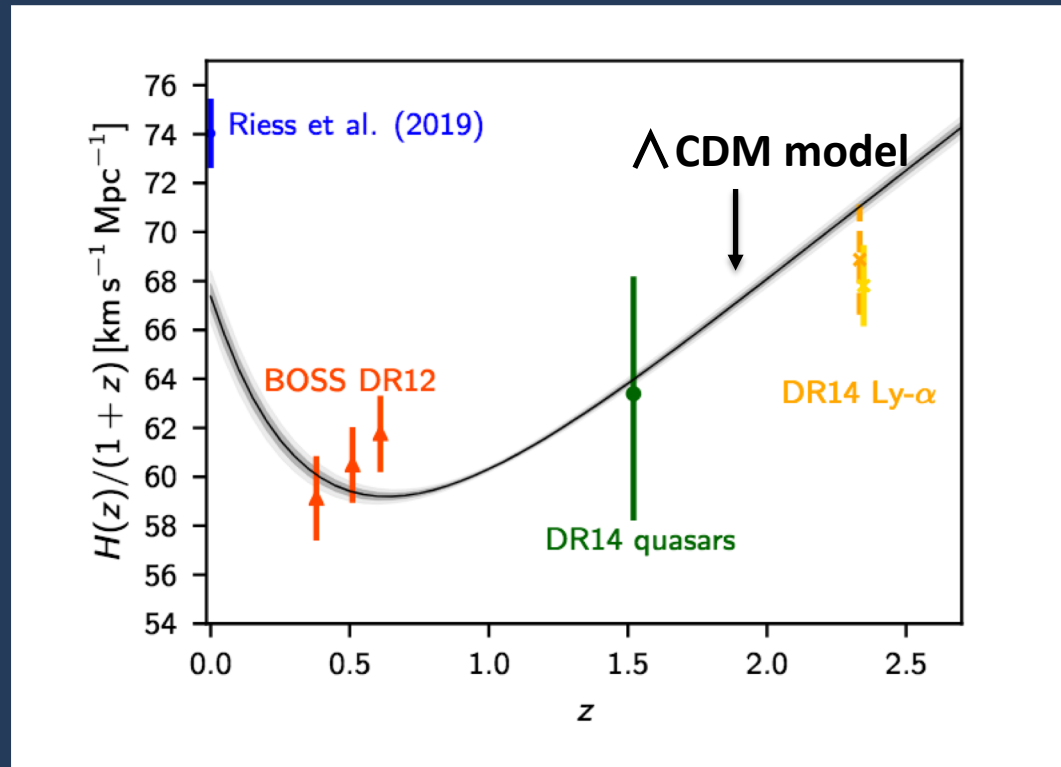
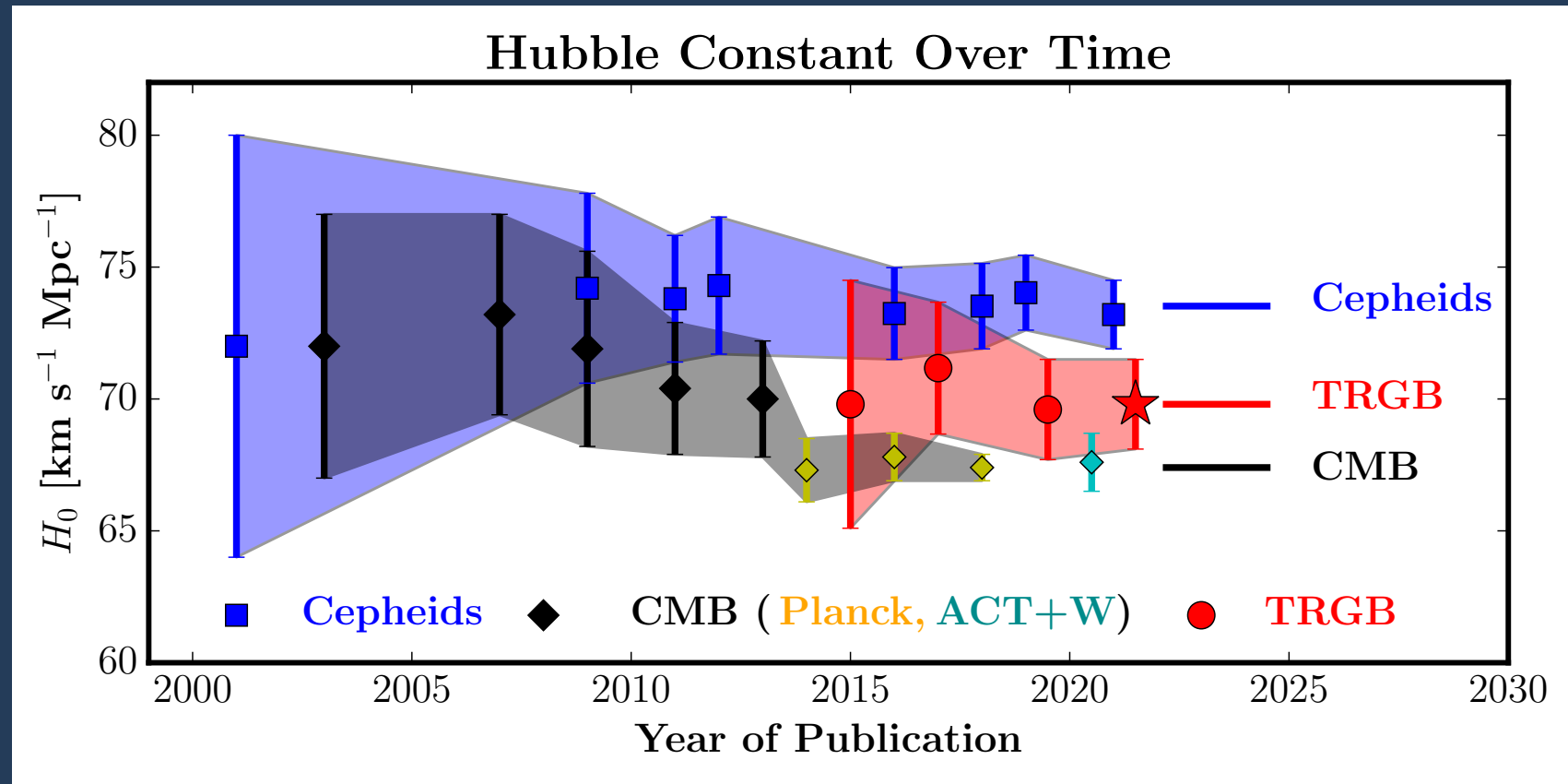


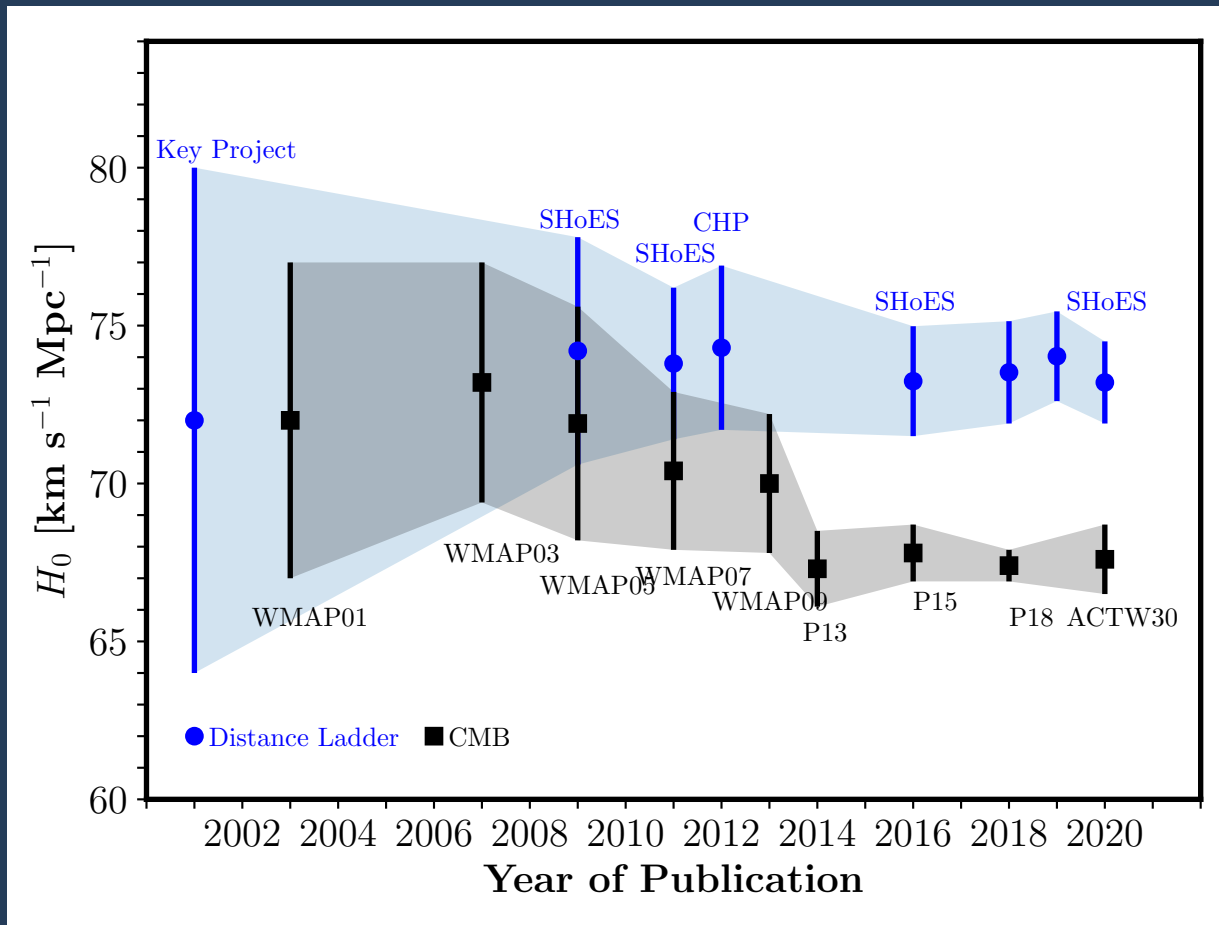
Co-moving Hubble Parameter as a Function of Redshift



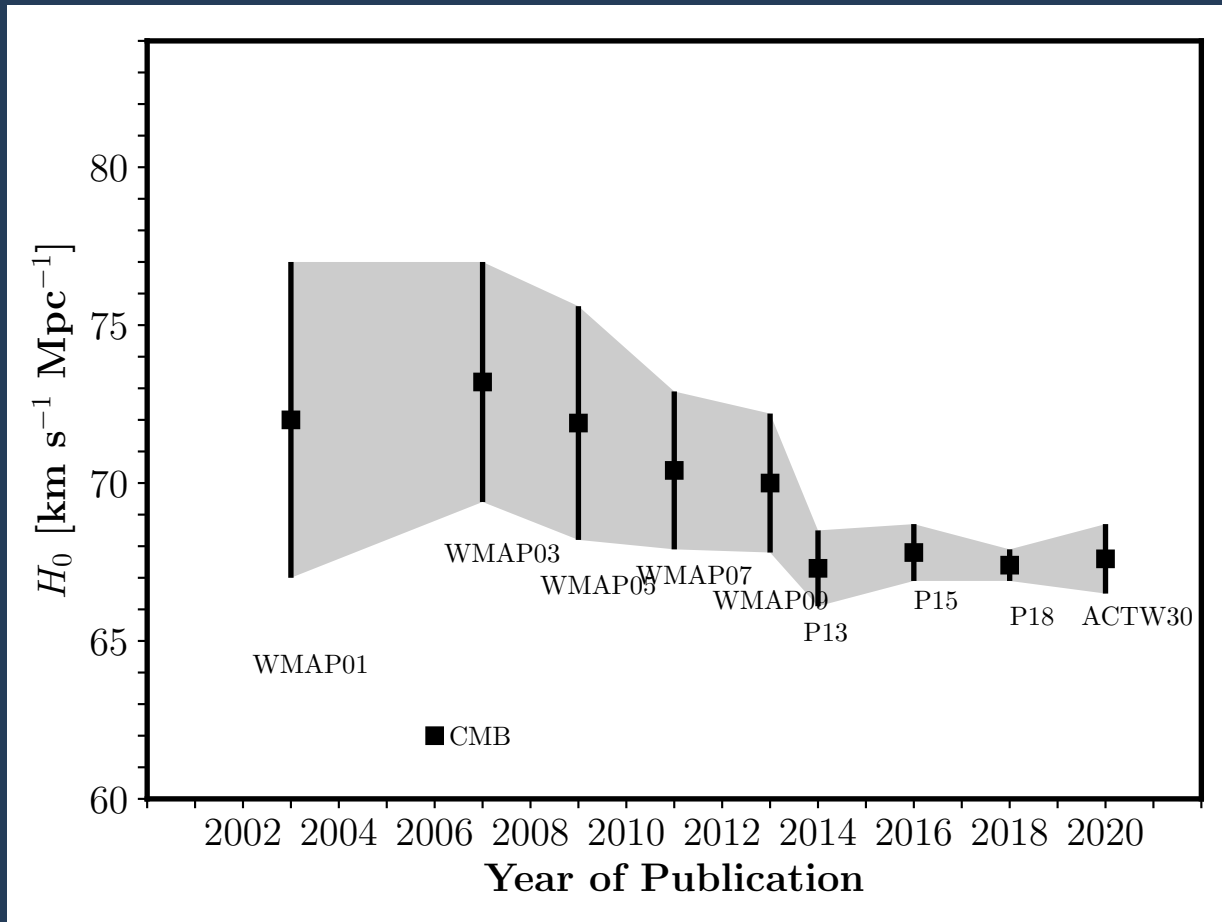
Recent Measurements of the Hubble Constant



Tension in the Hubble Constant

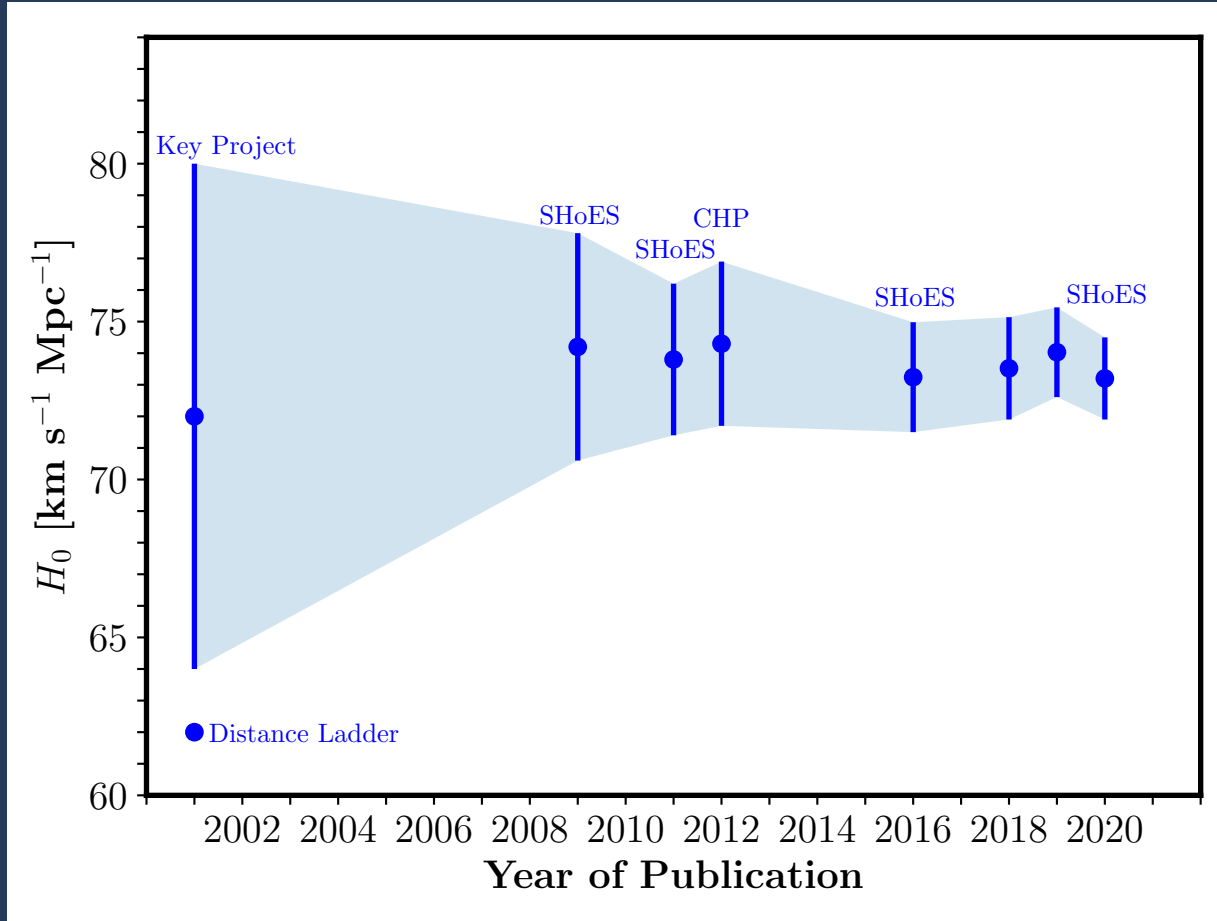


The Current Tension in H_0



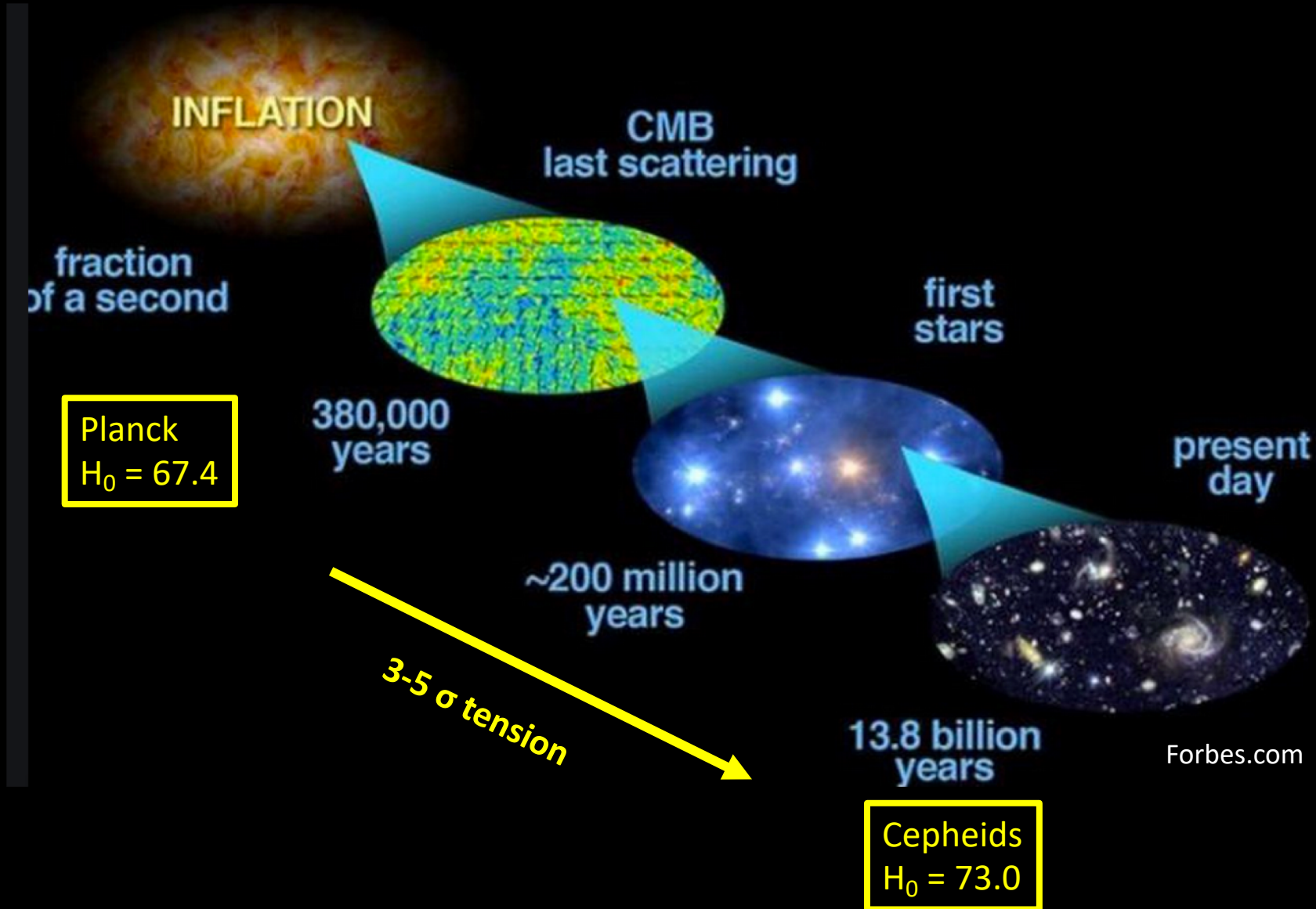
Updated from Freedman et al., 2017

The Current Tension in H_0

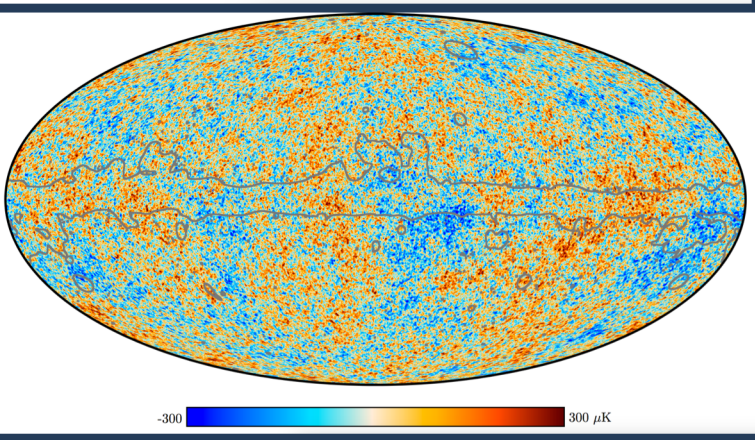
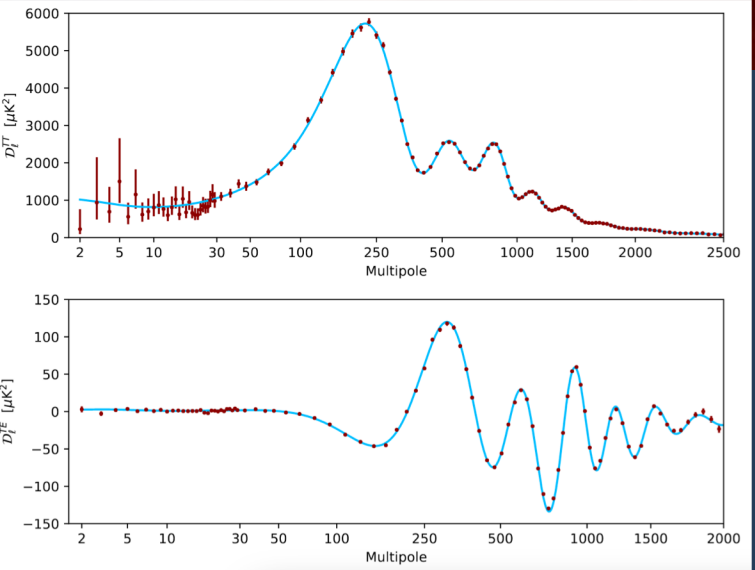
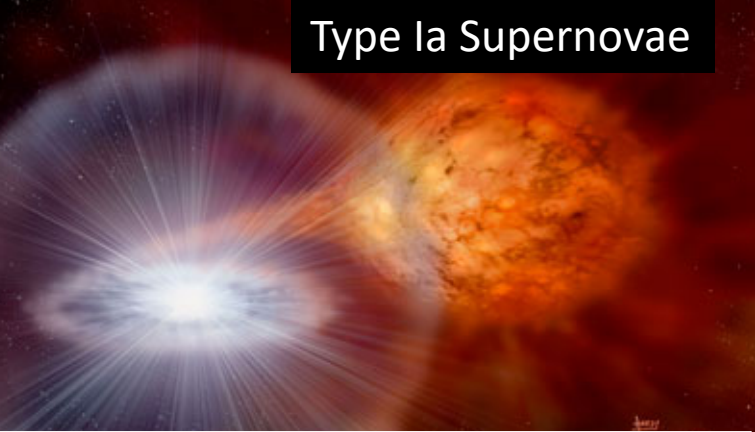


Updated from Freedman et al., 2017

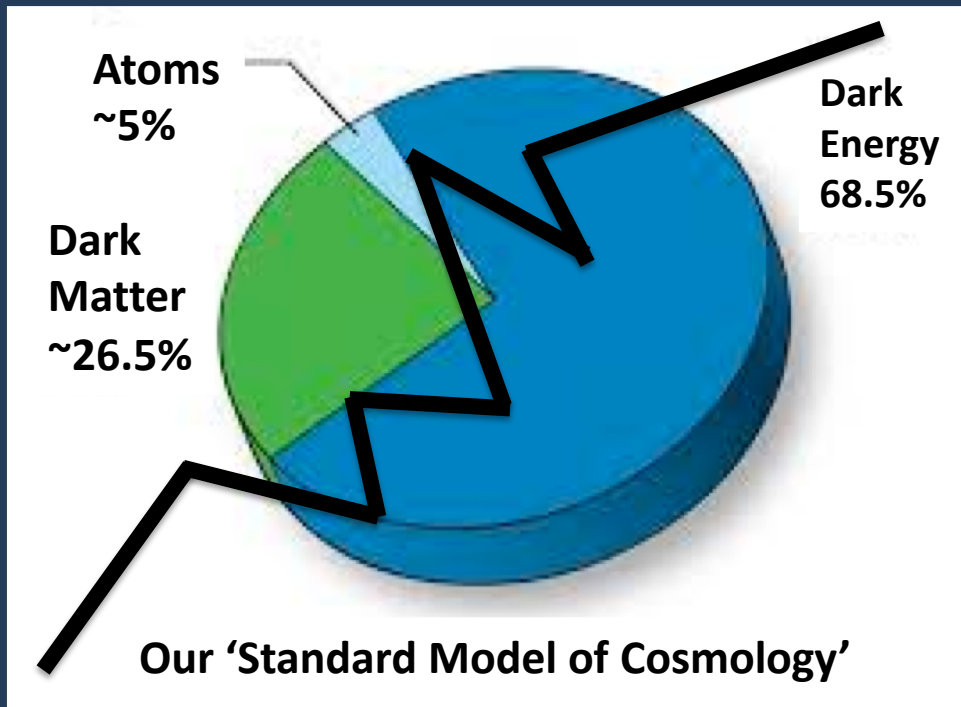
Tension in the Hubble Constant



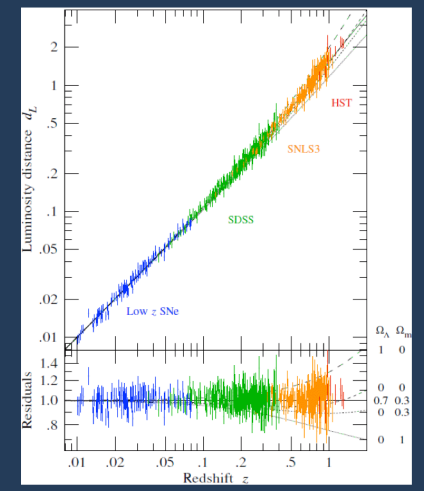
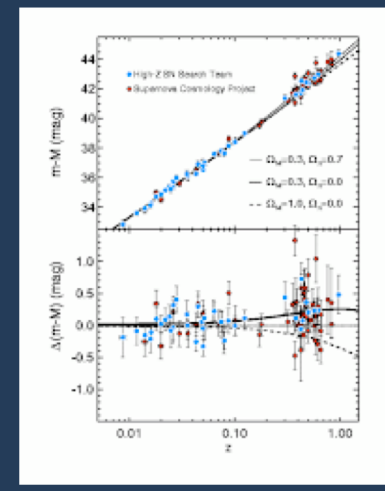
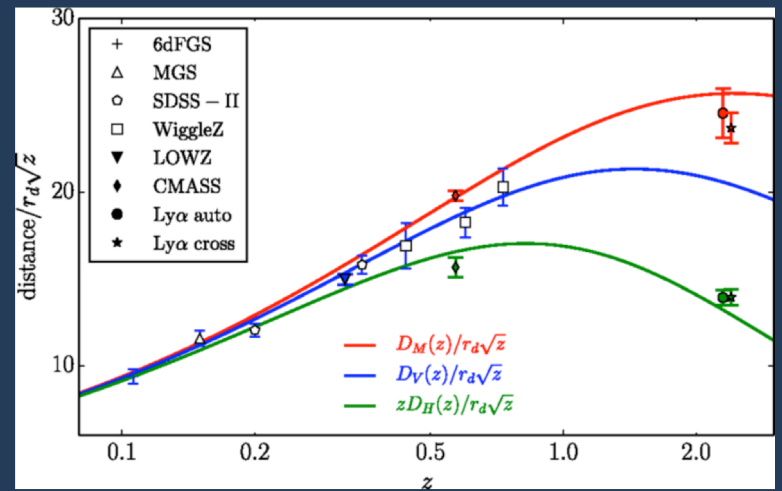
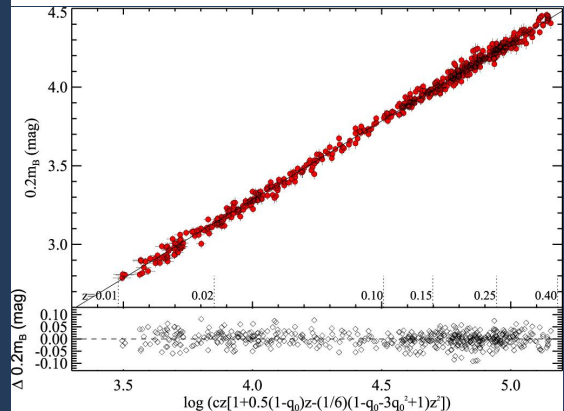
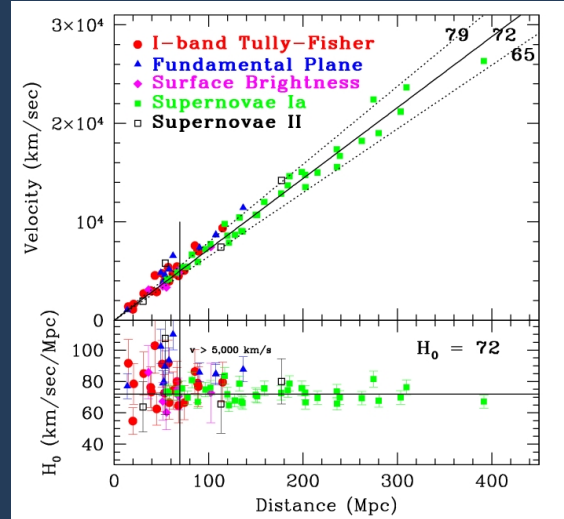
Type Ia Supernovae



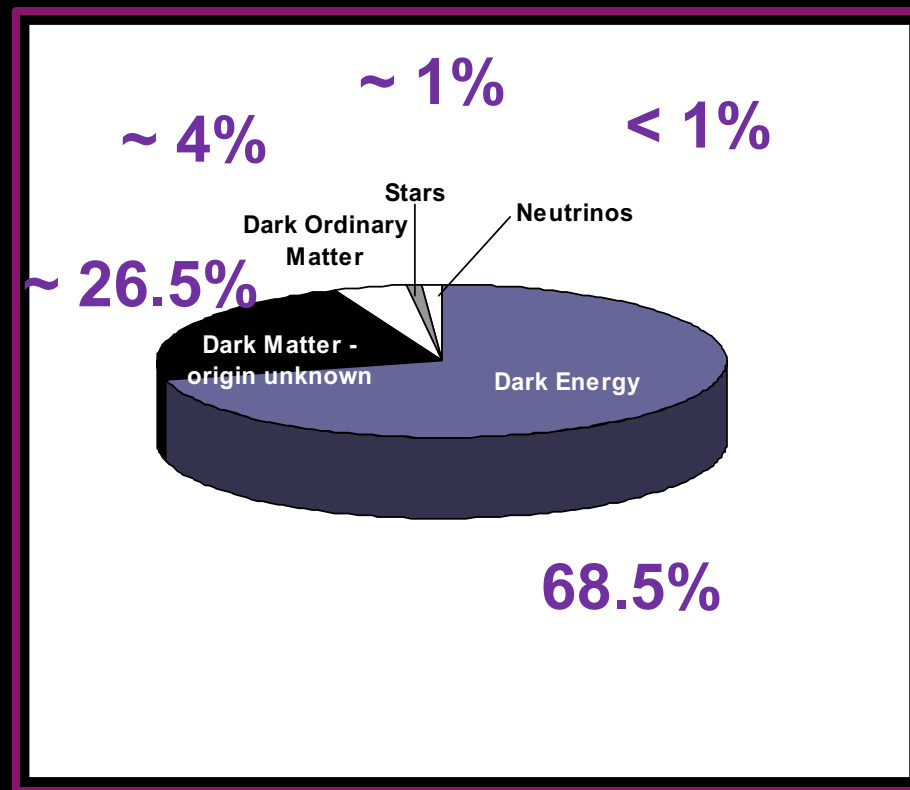
Are There Cracks in Our Standard Cosmological Model?



Our 'Standard Model of Cosmology'



The Standard Λ CDM Model



The Challenge:

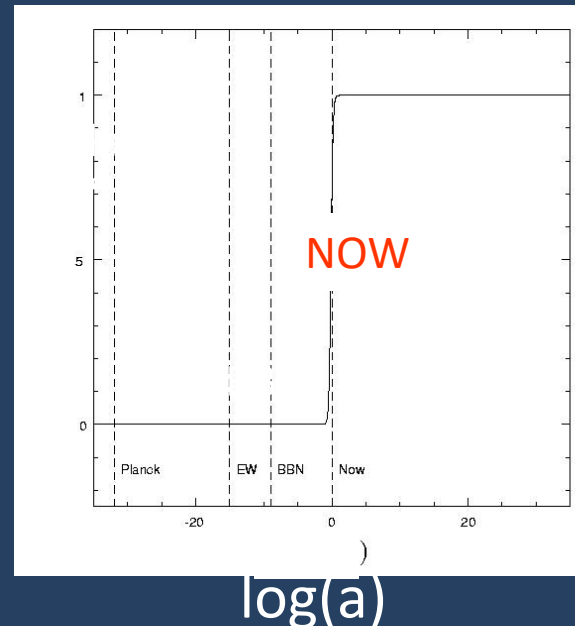
1. Why the small value?

Observed:	$\rho \sim 10^{-30} \text{ g cm}^{-3}$
Quantum gravity:	$\rho \sim 10^{+90} \text{ g cm}^{-3}$
Supersymmetry:	$\rho \sim 10^{+30} \text{ g cm}^{-3}$

“The mystery of the cosmological constant is probably the most pressing obstacle to significantly improving the models of elementary particle physics derived from string theory.”

Witten (2000)

2. Why now?



Carroll (2001)

Challenges for Cosmological Constant

1. Why is the energy of the vacuum so small?

- It is 120 orders of magnitude smaller than estimates from particle physics (If cut off at electroweak scale ~ 56 orders)

$$\Lambda = 8\pi G\rho_{\Lambda} \simeq \left(10^{29} \text{ cm}\right)^{-2} \simeq \left(10^{-33} \text{ eV}\right)^2$$

1. Coincidence problem:

- Why is $\Omega_{\Lambda} \sim \Omega_{\text{matter}}$?
- Why did it become dominant during the current epoch of cosmic evolution? Any earlier, it would have prevented structure from forming in the universe

What is Dark Energy ?

Einstein's GR allows for a pressure term and repulsive gravity:

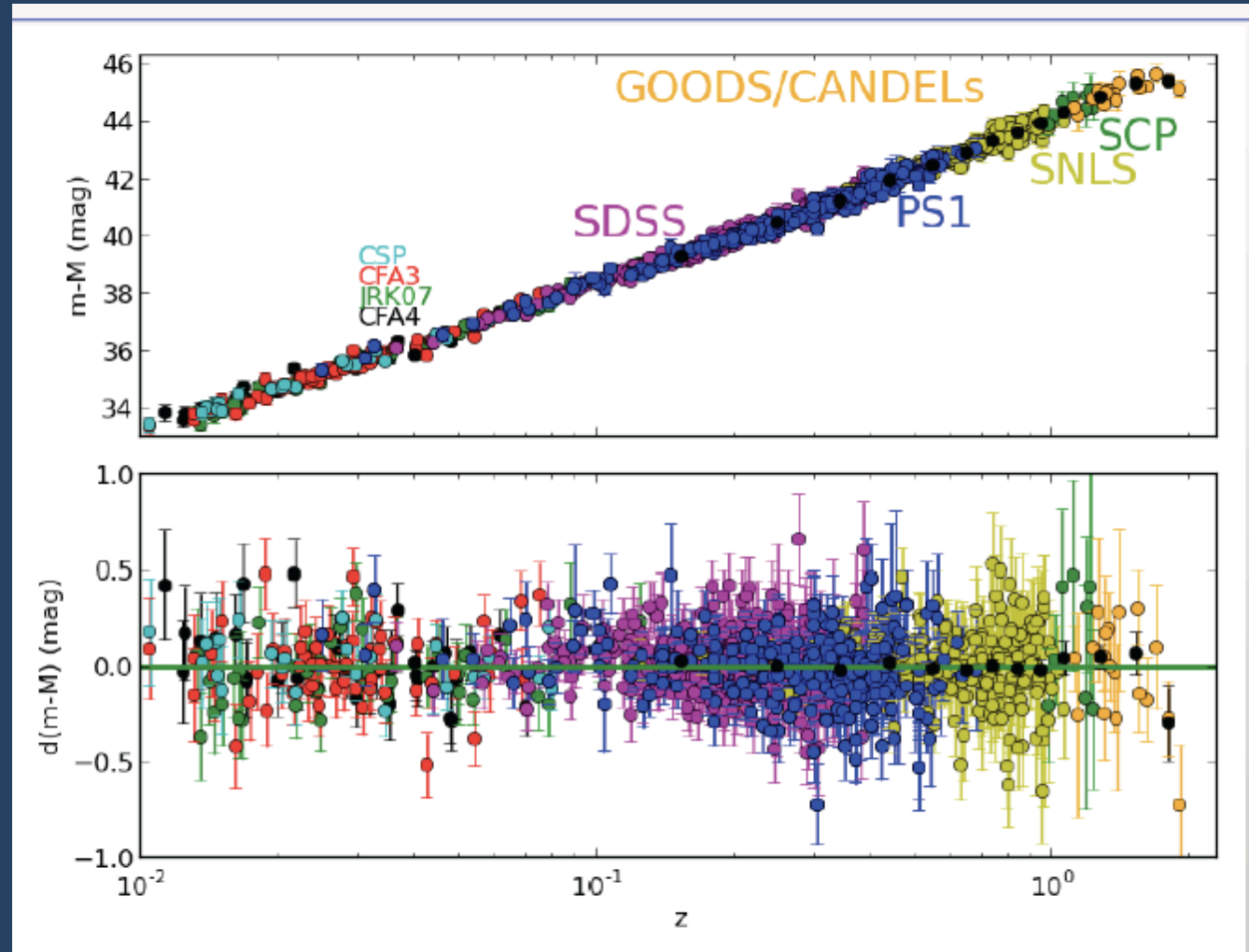
$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(\rho + 3P) + \frac{\Lambda}{3}$$

Repulsive gravity when $p < \frac{-\rho}{3}$

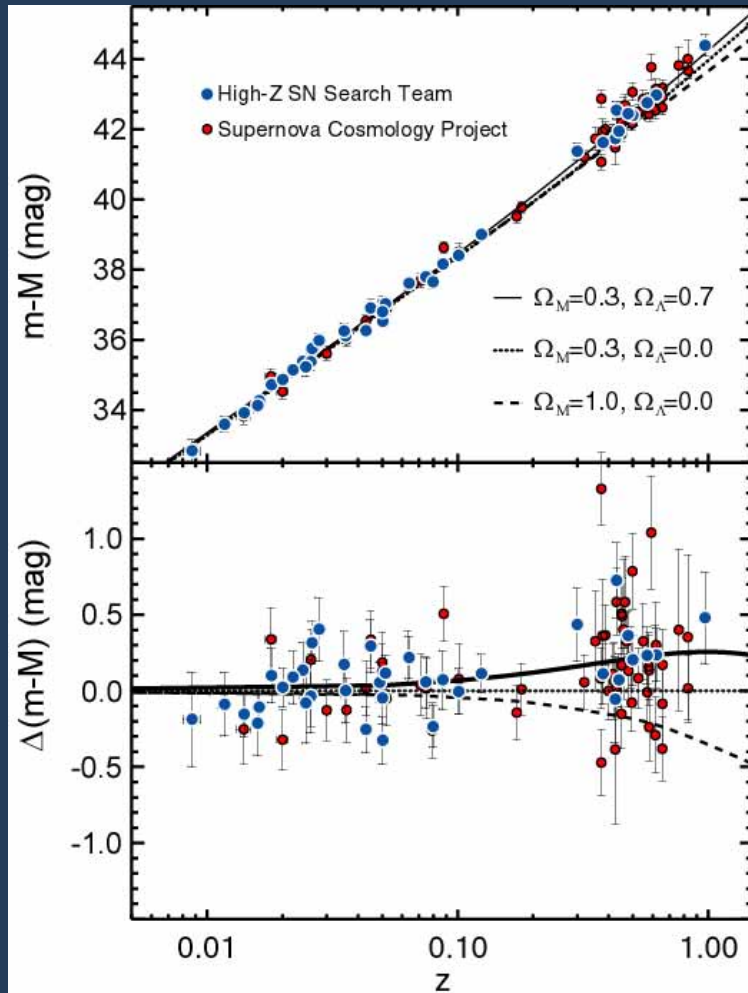
Elastic stuff $p < \frac{-\rho}{3}$ with repulsive gravity is called “dark energy”

Simplest example: Einstein's cosmological constant: $w = \frac{p}{\rho} = -1$

Recent Type Ia Supernova Hubble Diagram



First Supernova Cosmology Results (1998, 1998)

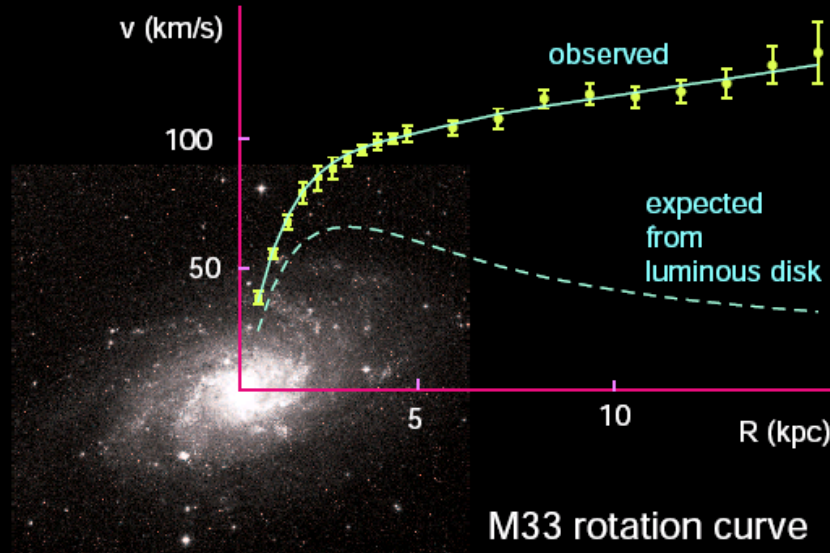


Results
inconsistent with
 $\Omega_m=1$ spatially
flat cosmology
(SN too faint)

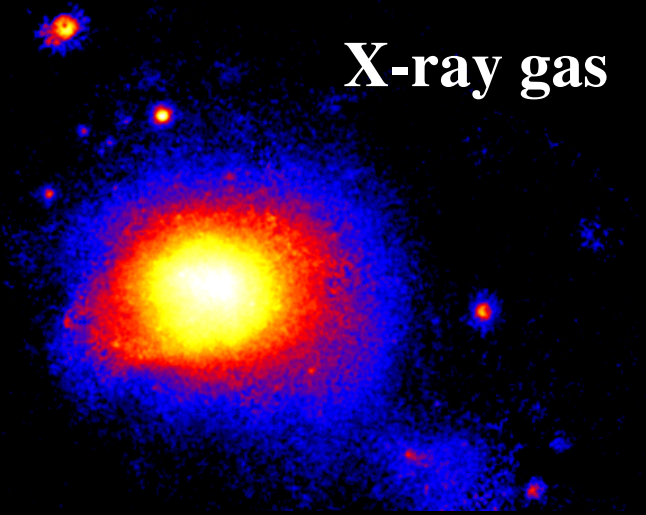
SN data favor
 $\Omega_\Lambda=0.7$

Evidence for Dark Matter

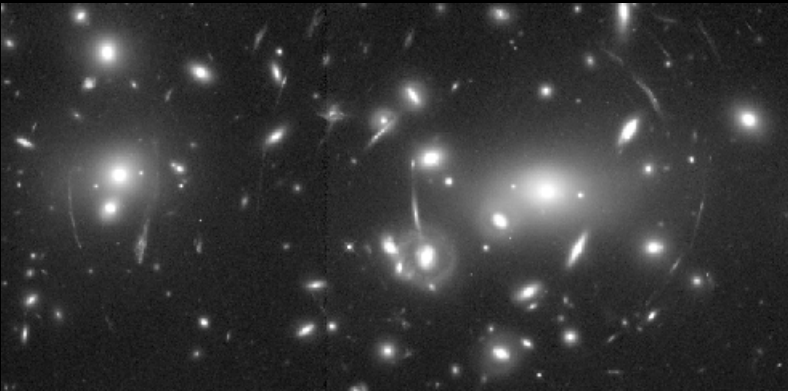
Galaxy kinematics



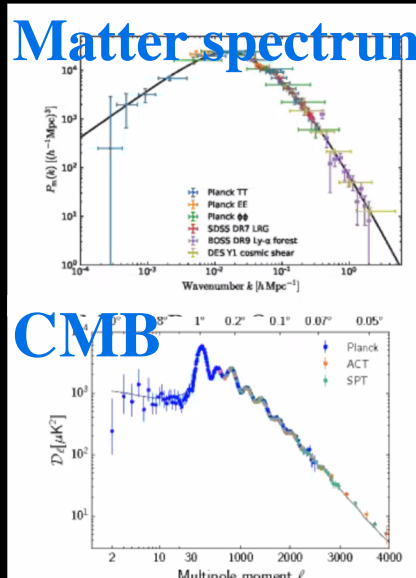
X-ray gas



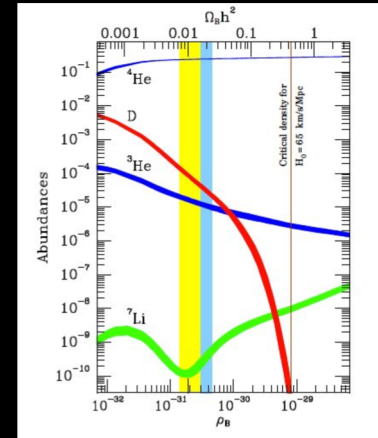
Gravitational Lensing



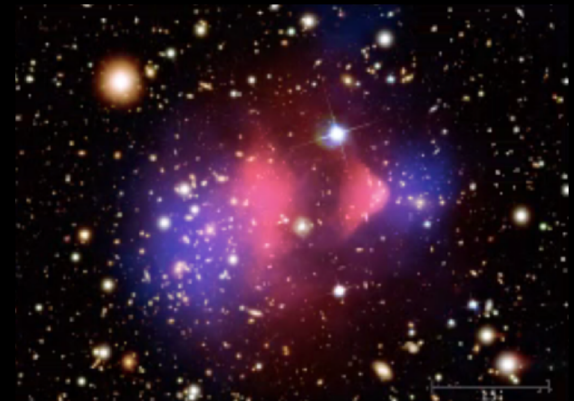
Matter spectrum

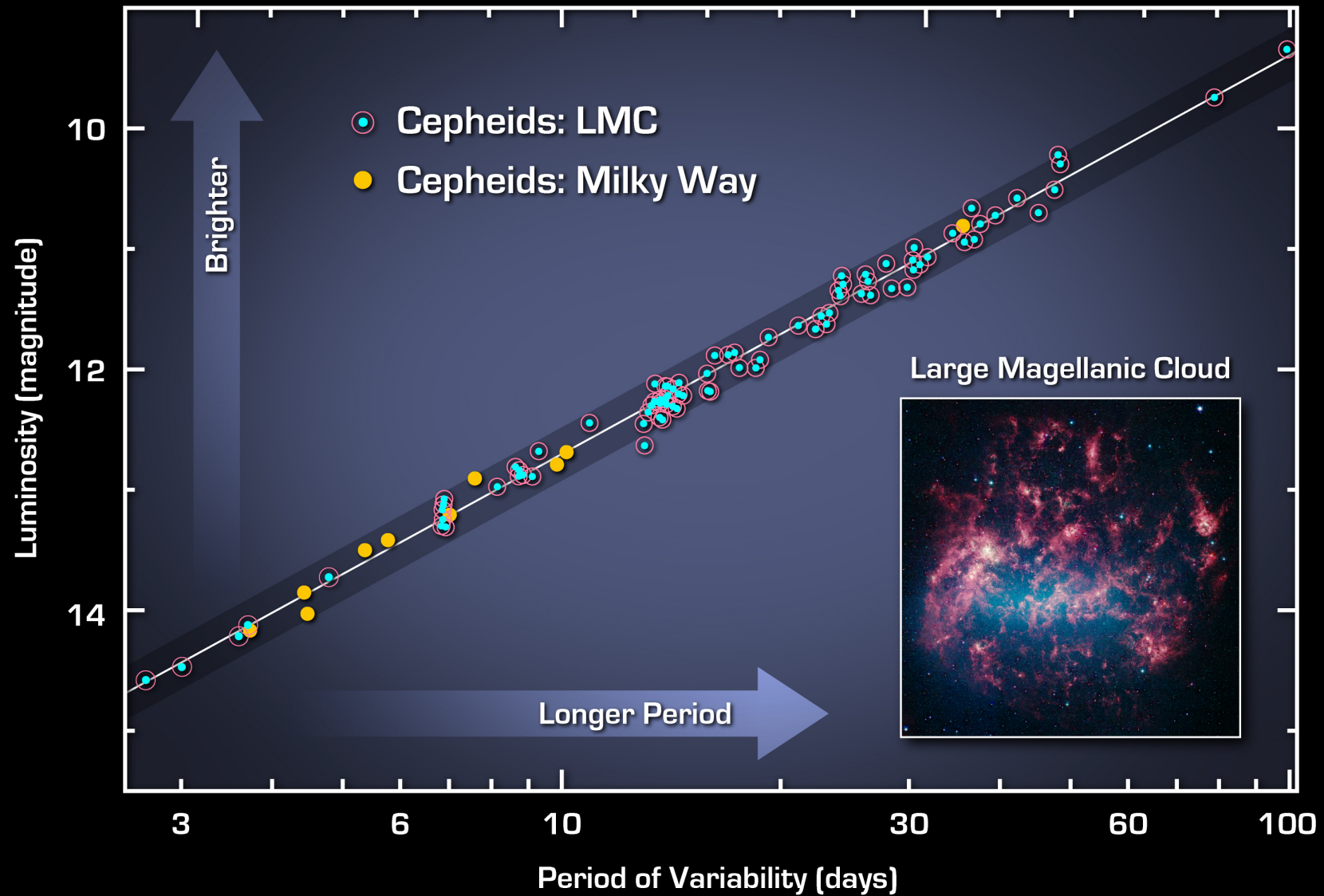


Light Elements



Cluster collisions





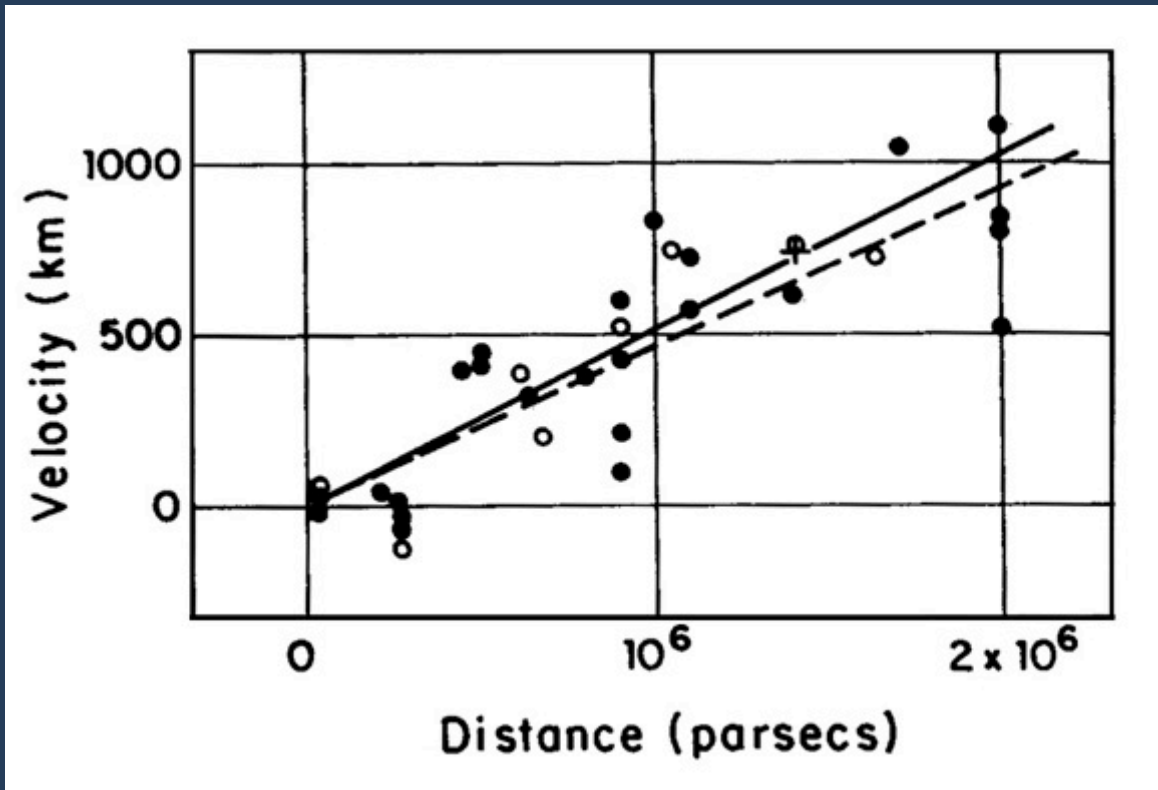
Calibrated Period-luminosity Relationship for Cepheids

Spitzer Space Telescope • IRAC

NASA / JPL-Caltech / W. Freedman (Carnegie)

ssc2012-13a

The Hubble-Lemaître Diagram



Hubble (1929)



The dynamics of the universe is governed by the Friedmann equation:

The diagram shows the Friedmann equation enclosed in a white rectangular box. Five white arrows point from external text labels to specific parts of the equation: 'Hubble parameter' points to H^2 , 'scale factor' points to a , 'density parameter' points to ρ , 'curvature' points to k , and 'cosmological constant' points to Λ . Below the 'scale factor' label, the formula $a = 1/(1+z)$ is written.

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

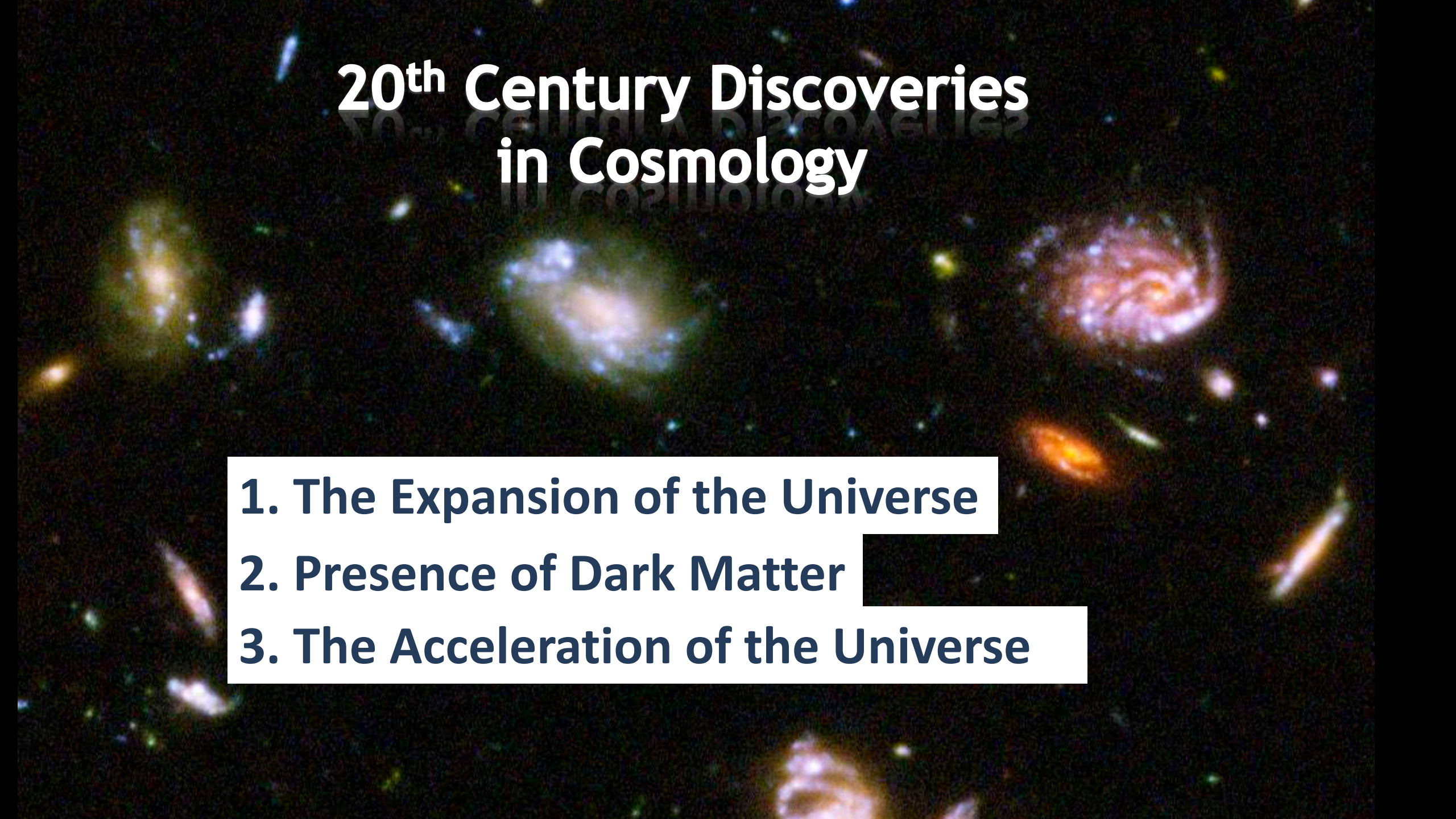
curvature

cosmological constant

density parameter

scale factor
 $a = 1/(1+z)$

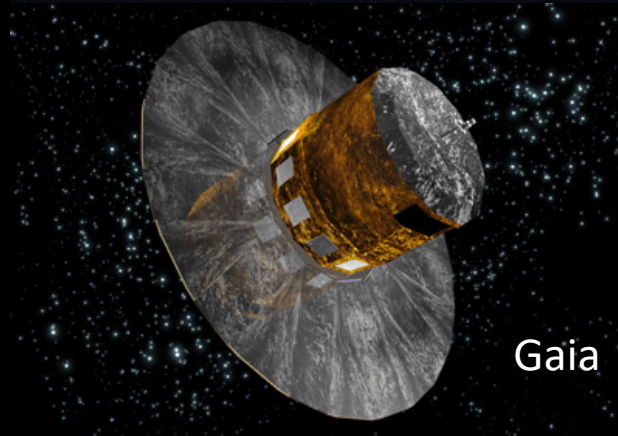
Hubble parameter



20th Century Discoveries in Cosmology

- 1. The Expansion of the Universe**
- 2. Presence of Dark Matter**
- 3. The Acceleration of the Universe**

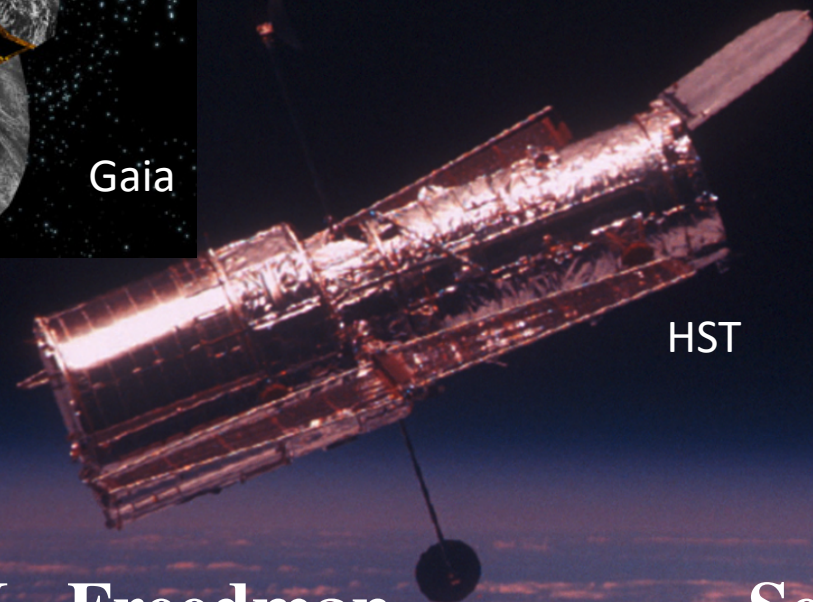
Observational Cosmology



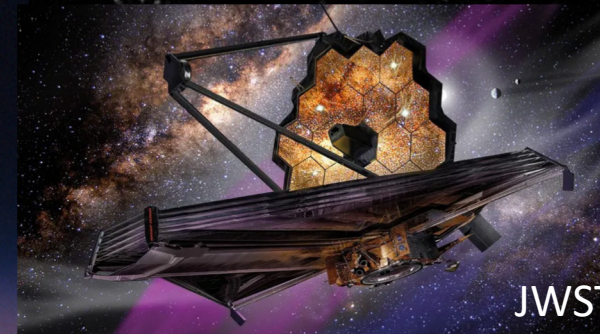
Gaia



Planck



HST



JWST

Wendy L. Freedman
University of Chicago

September 22,23 2022

Escola de Cosmologia
Pedra Azul Espirito Santo, Brazil