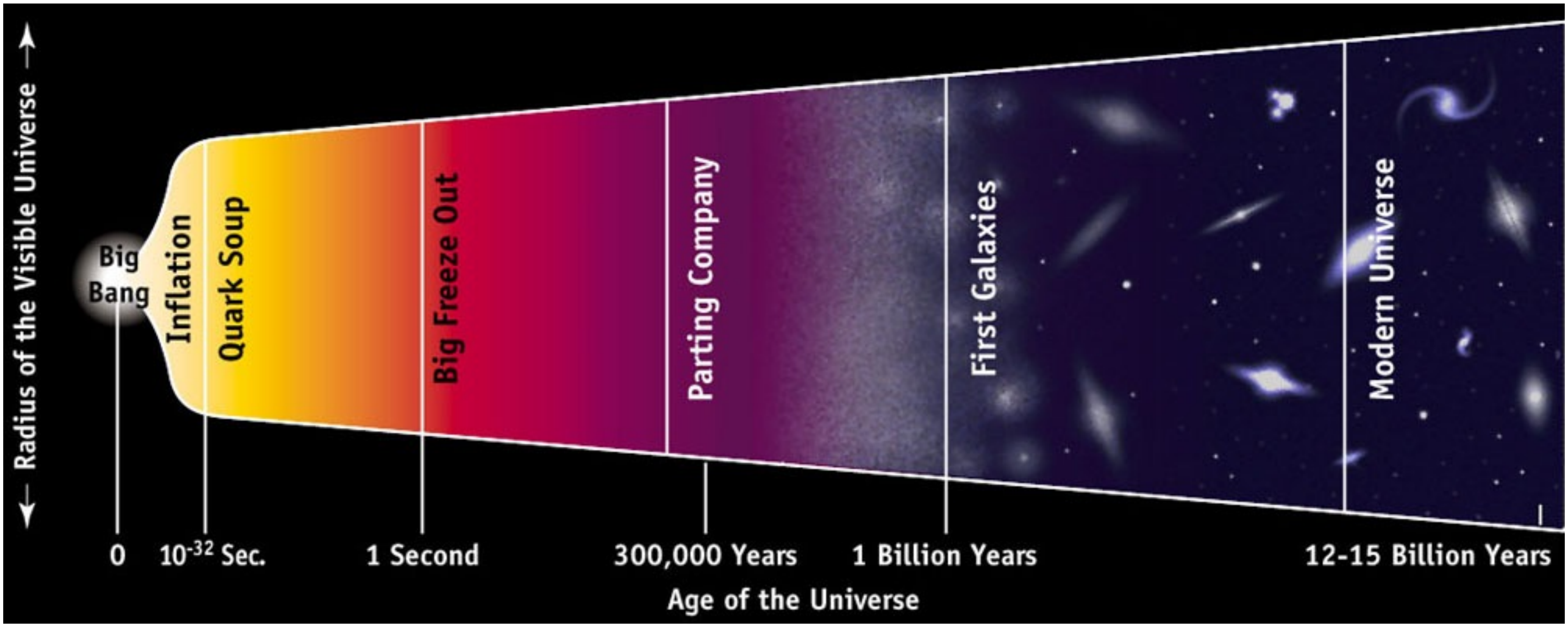
The Hubble Tension

Dragan Huterer
University of Michigan

Belgrade, BPU11
30 August, 2022

Timeline of the universe



Inflation

Dark Matter

Dark Energy

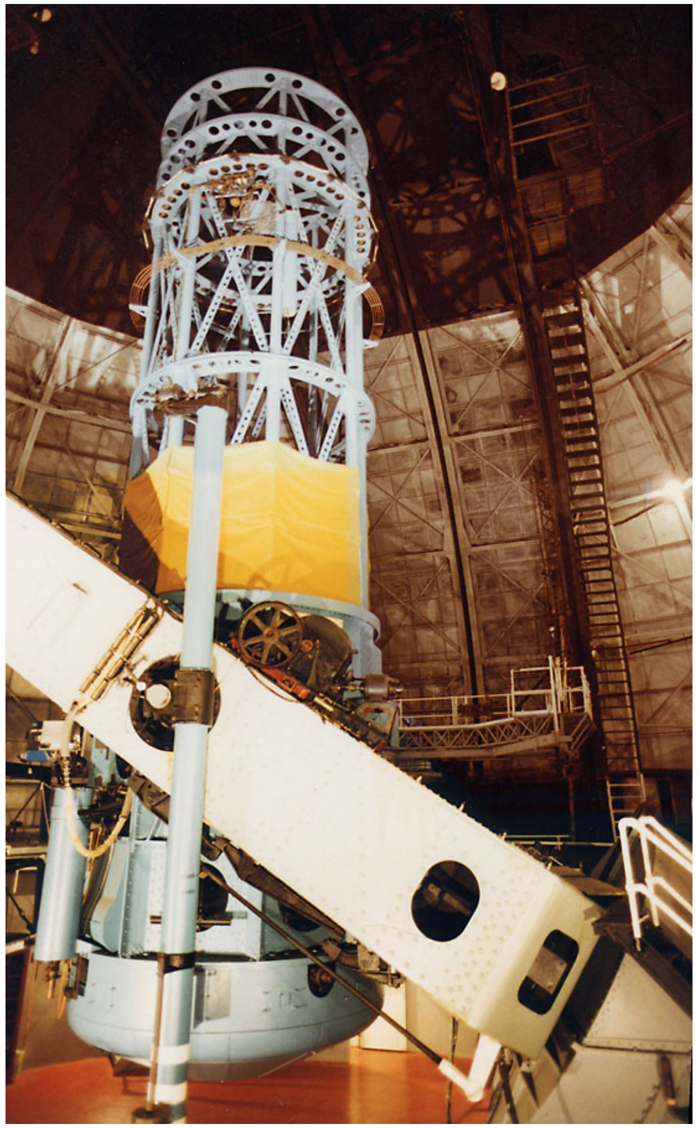
Part I: Distance-redshift relation in cosmology

Edwin Hubble and the Expansion of the Universe (1929)

In 1929 Hubble measured the red shift (or, redshift) of nearby galaxies and found that they nearly all move away from us

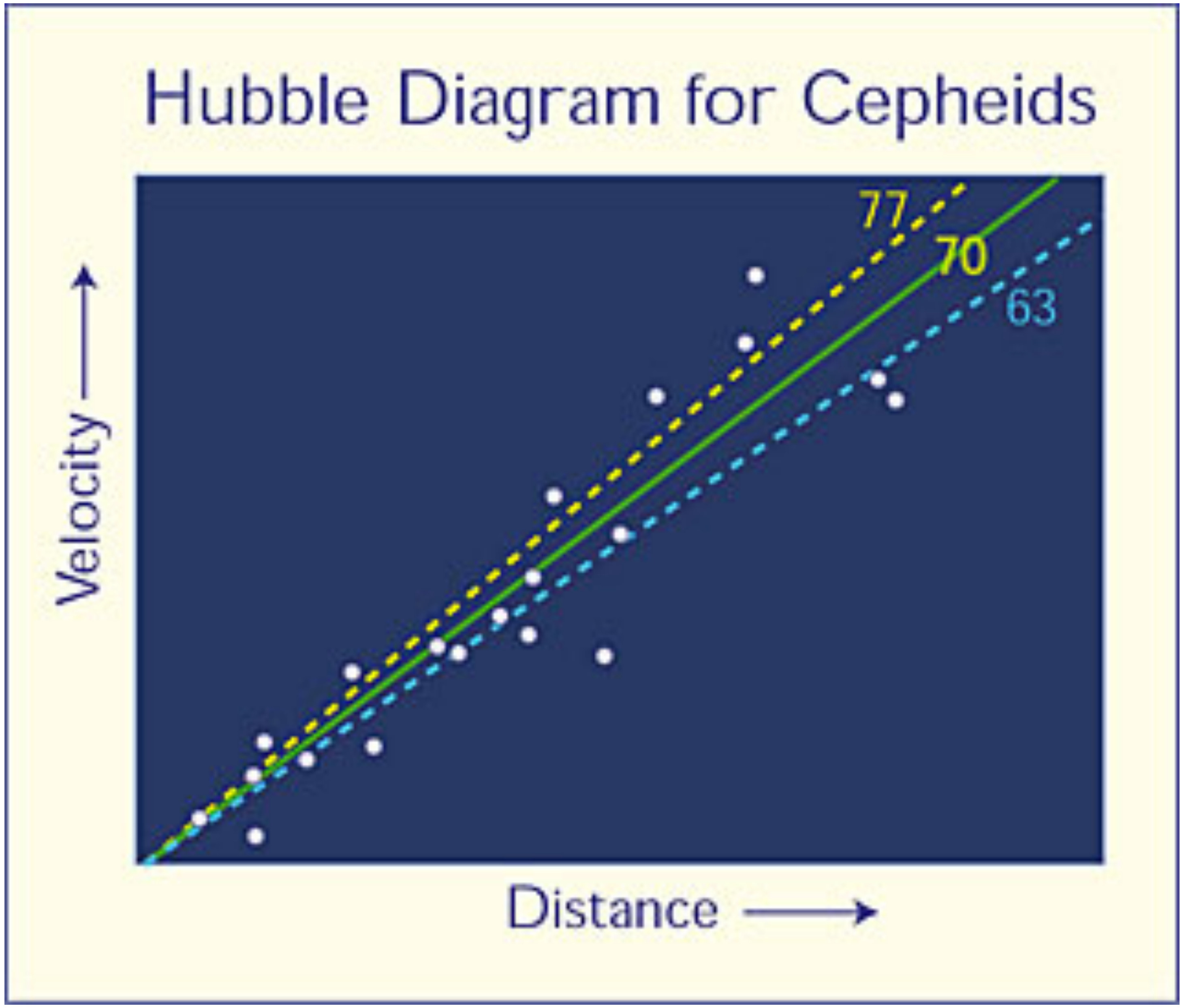
$\Rightarrow$

The Universe is Expanding!

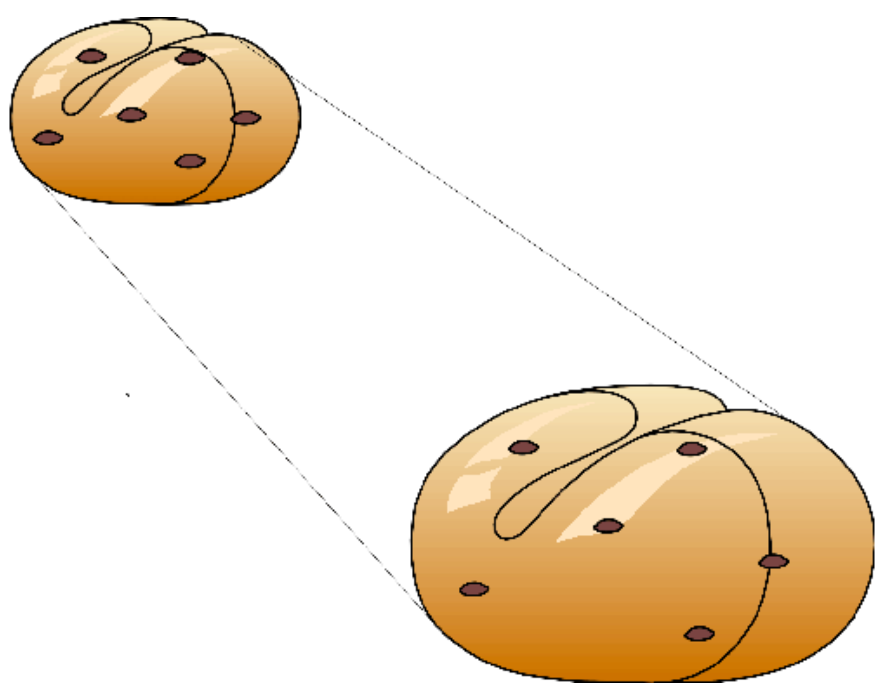


100 inch Hooker telescope
(Mt Wilson, CA)

Expanding spaces: bread & universe



Baking the raisin bread: the **farther** two raisins are, the **faster** they are receding



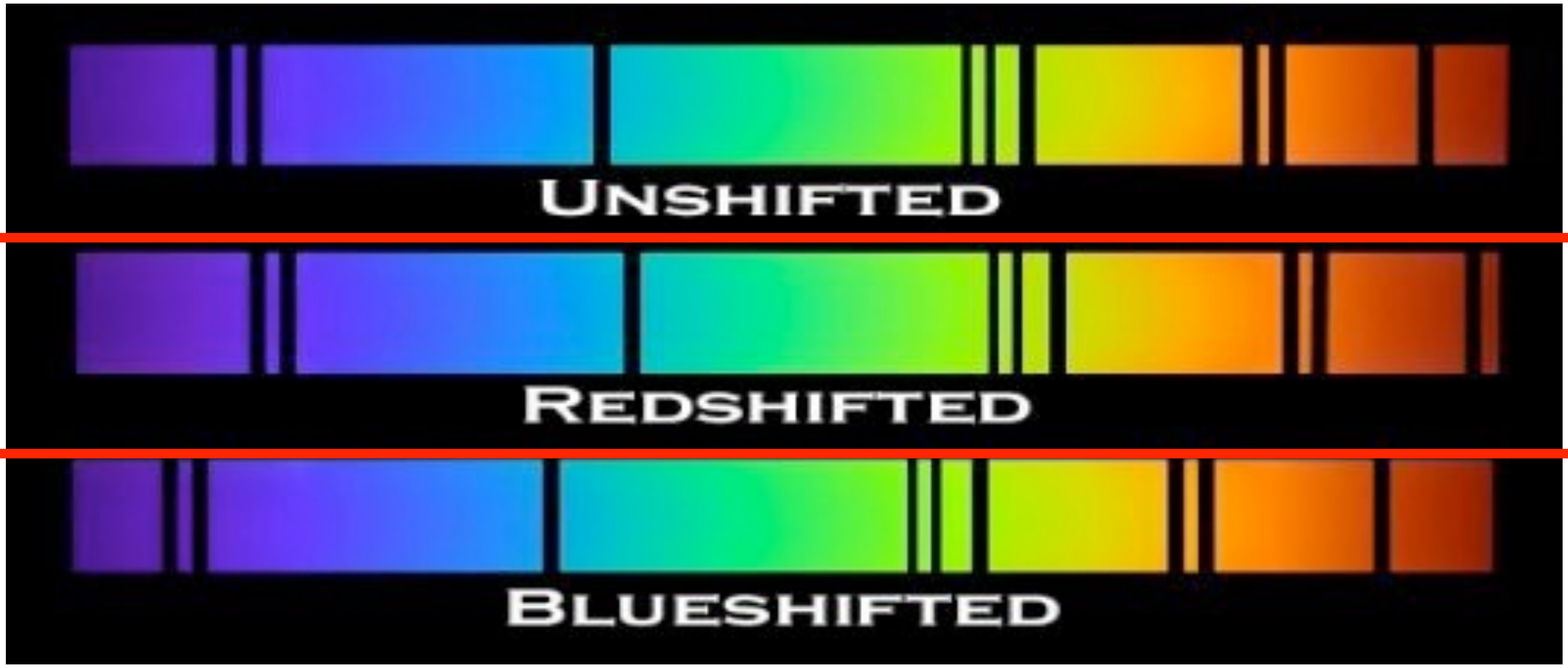
- Velocity is easy: from the Doppler recession of galaxy spectra
  (first done by astronomer Vesto Slipher, whom Hubble never credited)
- Distance is hard: from Cepheid variable stars

The Cosmological Redshift

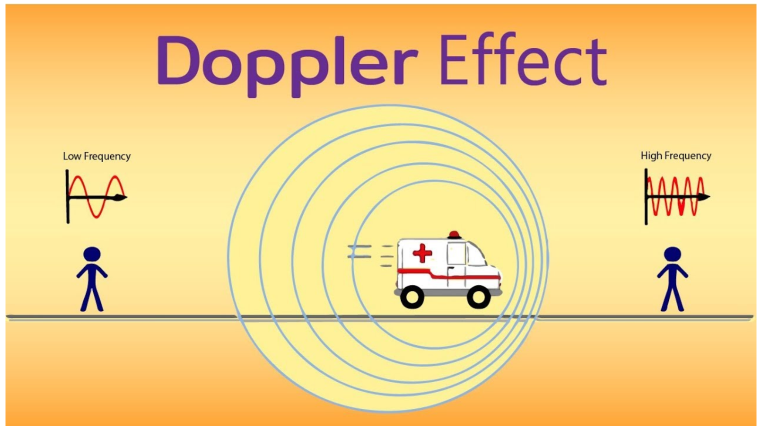
Determined by measuring the shift of known spectral lines from galaxies

← short wavelength

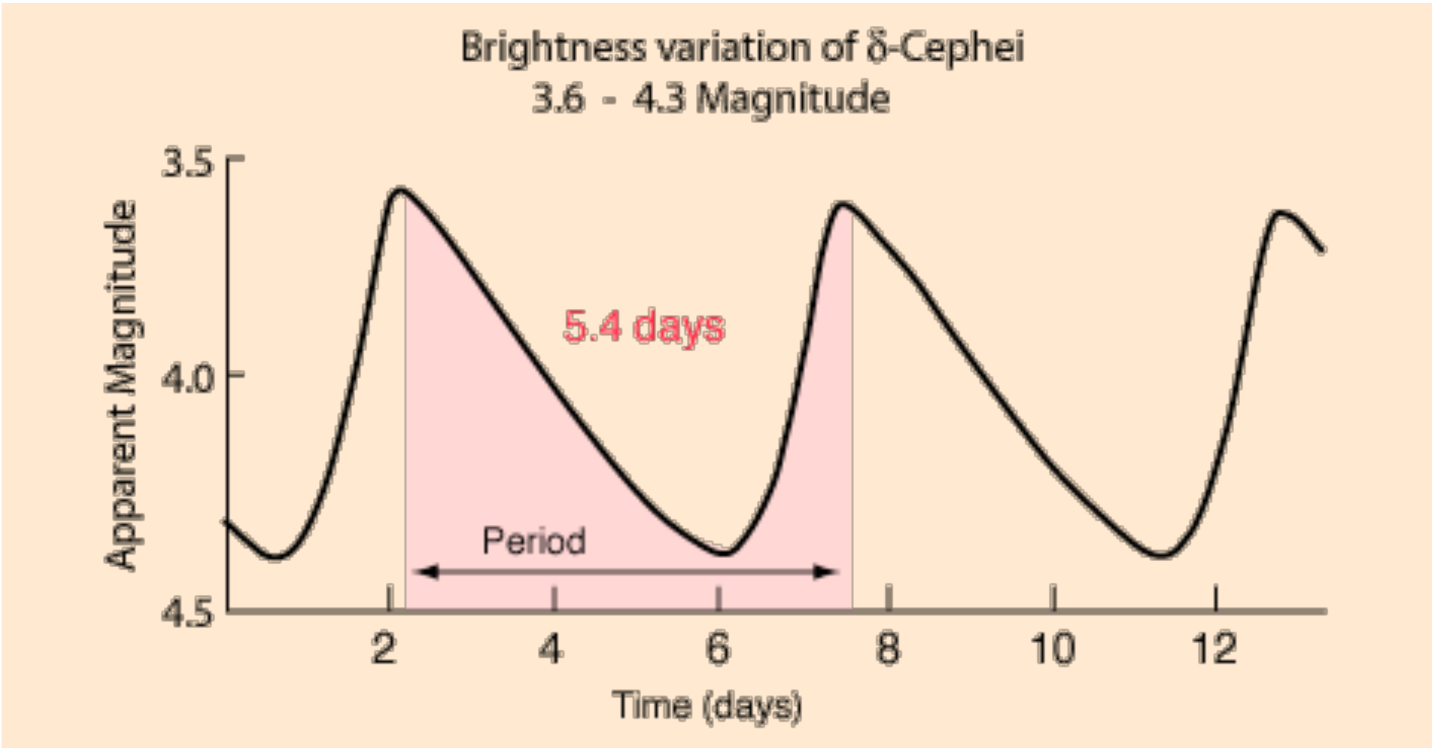
long wavelength →

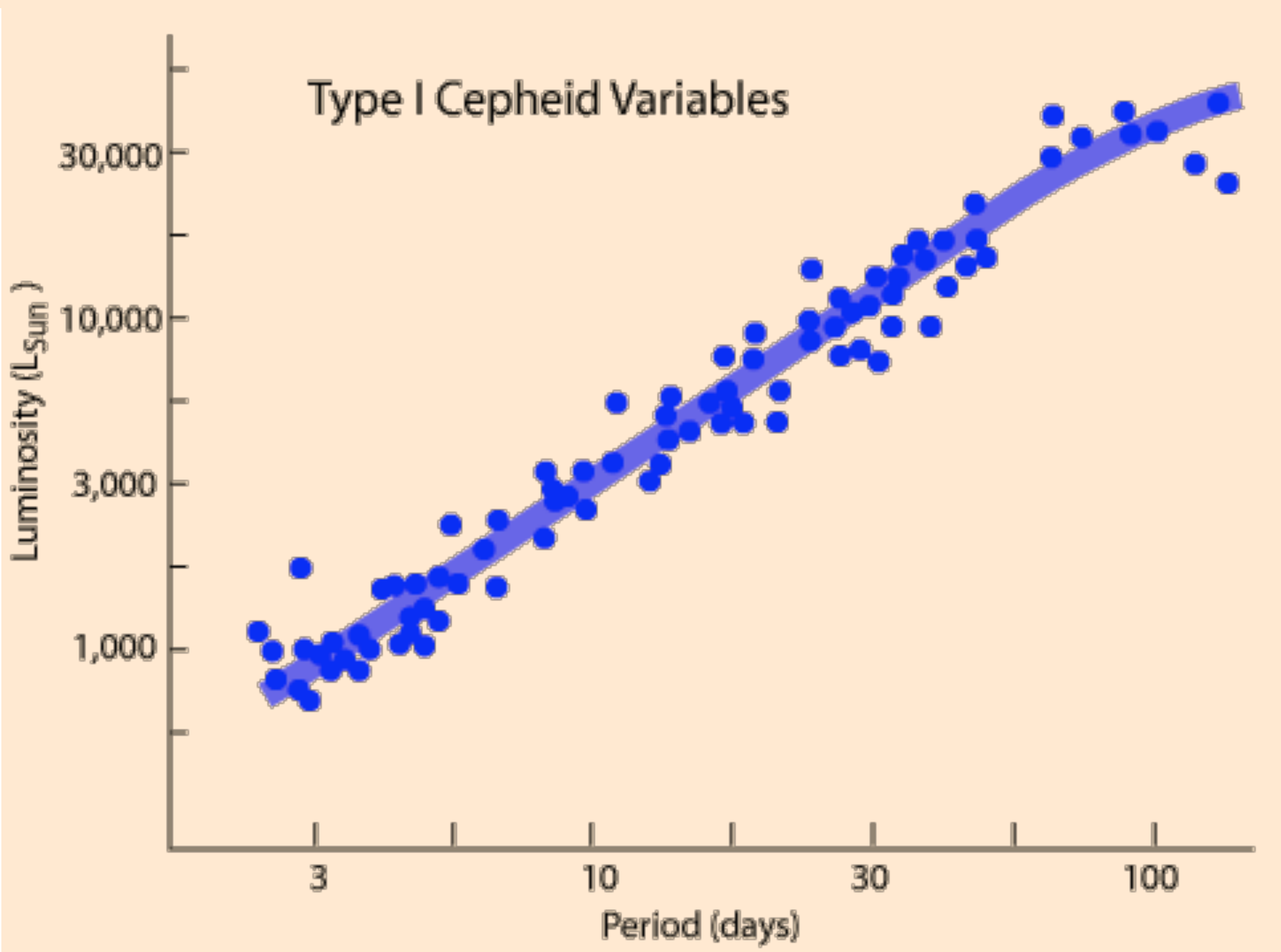


$$\frac{\lambda_{\rm obs}}{\lambda_{\rm emit}} = 1 + z$$

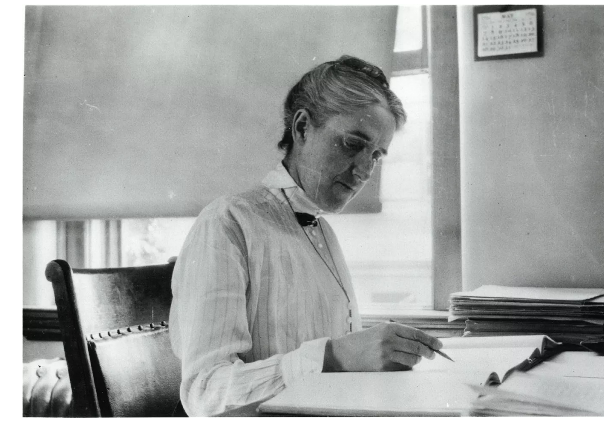


How to get **distances** to galaxies?





http://hyperphysics.phy-astr.gsu.edu/



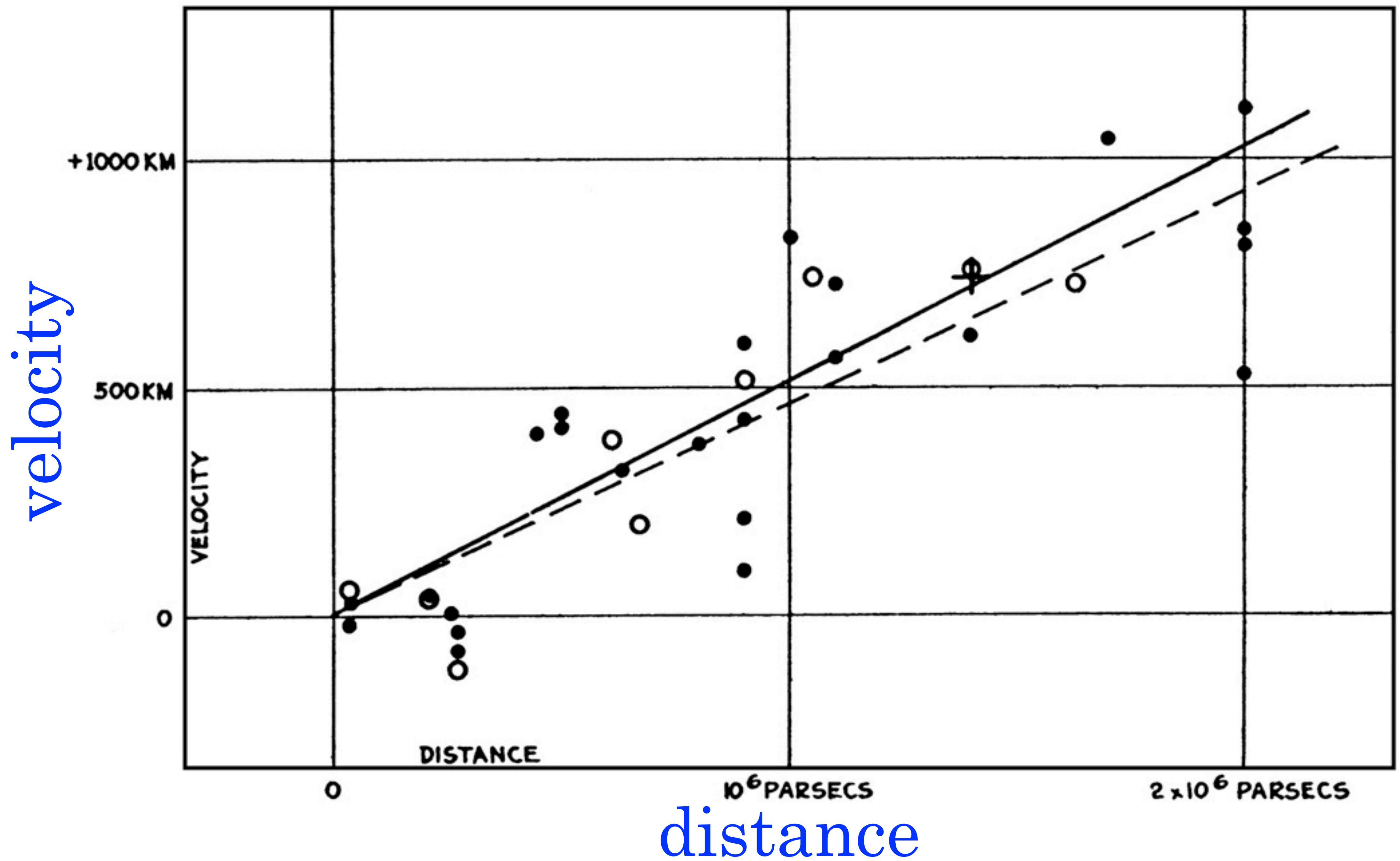
Cepheids
(variable stars)

- Empirical finding: Cepheids' period of pulsation is proportional to intrinsic luminosity
- Measure period
- Measure apparent luminosity (or, flux)
- Then, can get **distance**:

$$f = L / (4\pi d^2)$$

(f = flux
L = luminosity)

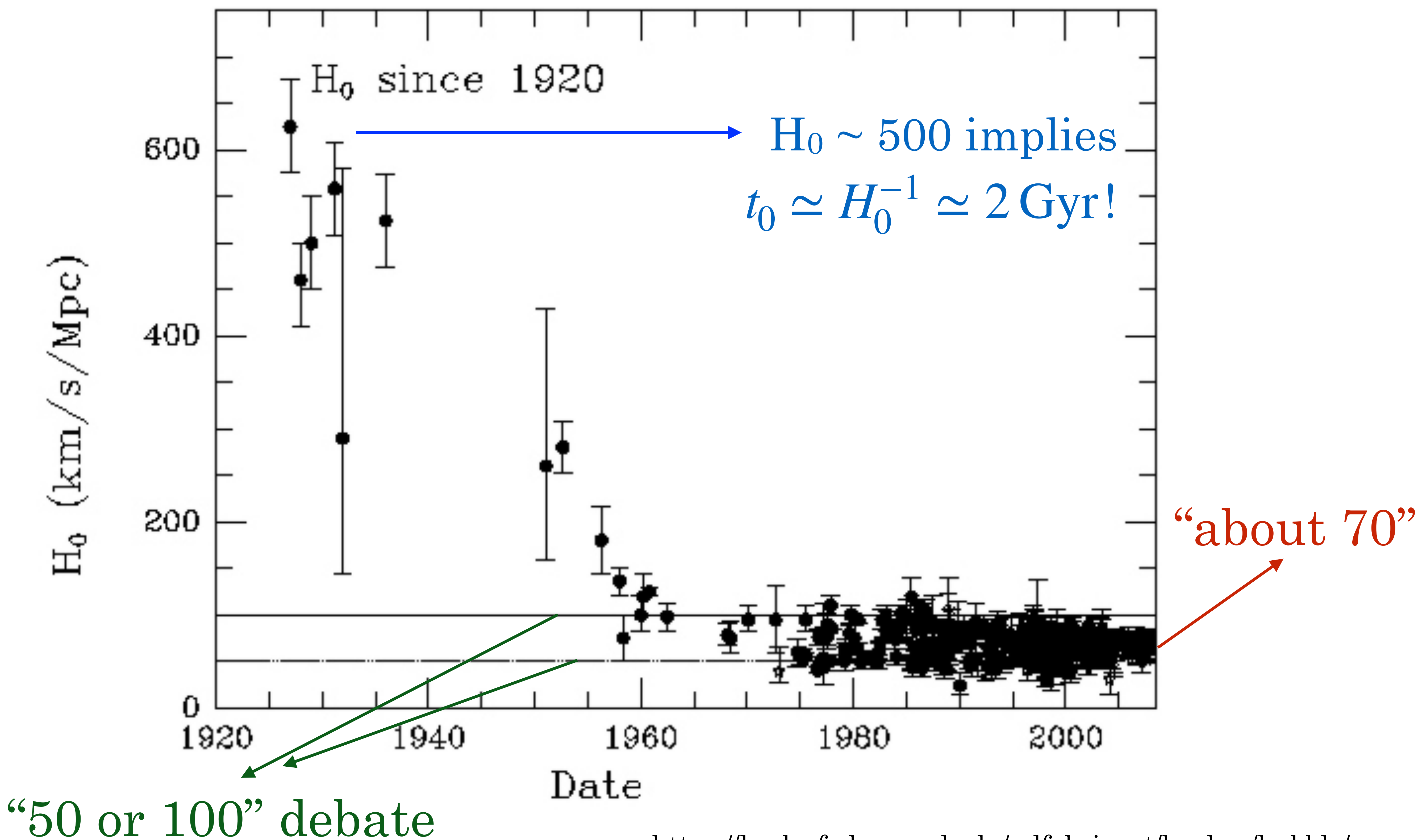
The original Hubble diagram (1929)



Slope of this relation (velocity vs. distance) is called the Hubble constant H_0.
Modern value:

$H_0 \approx 70$ km/sec/megaparsec (will return to H_0 later!)

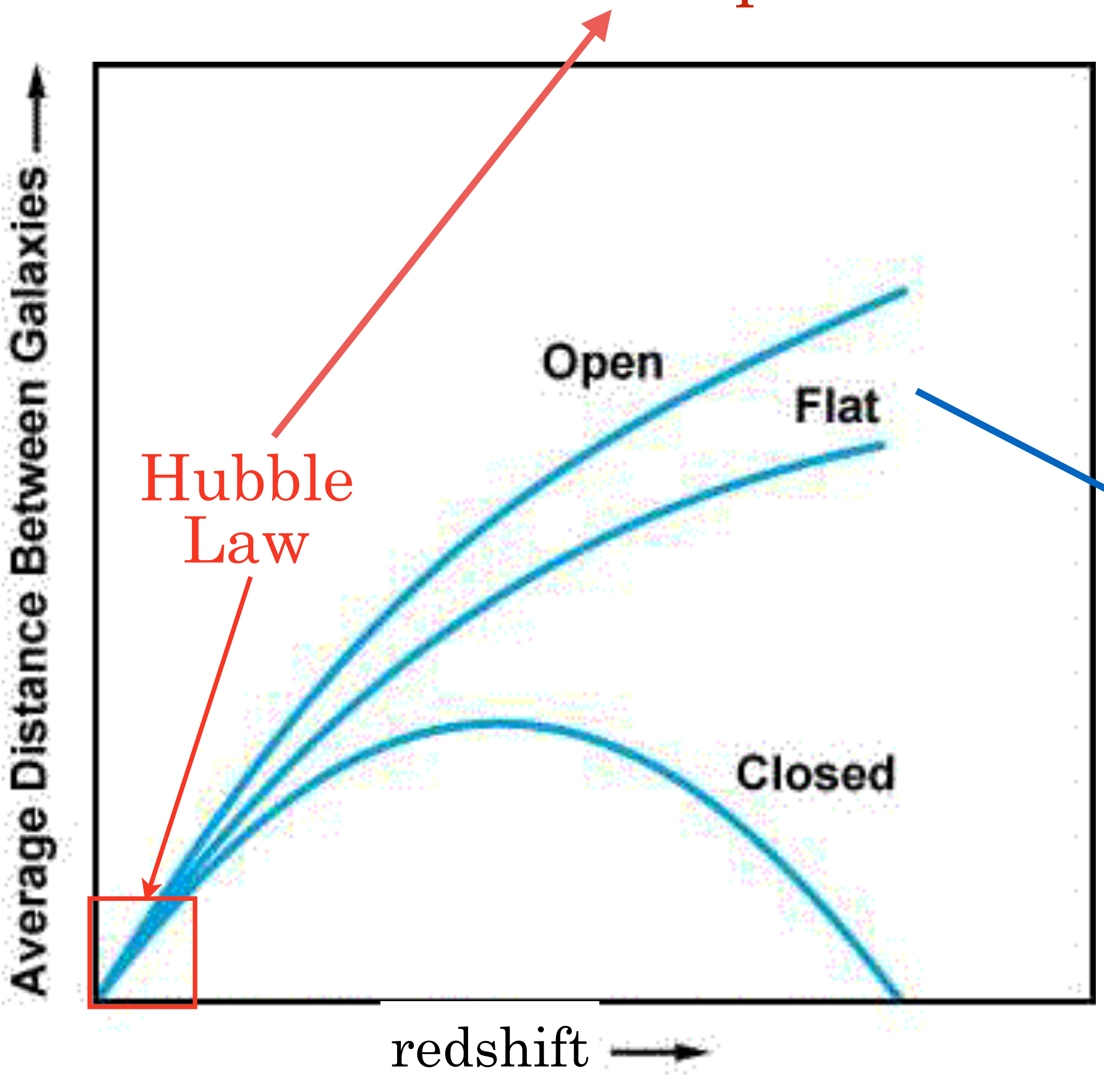
Brief history of H_0 measurements



https://lweb.cfa.harvard.edu/~dfabricant/huchra/hubble/

Distance vs redshift relation

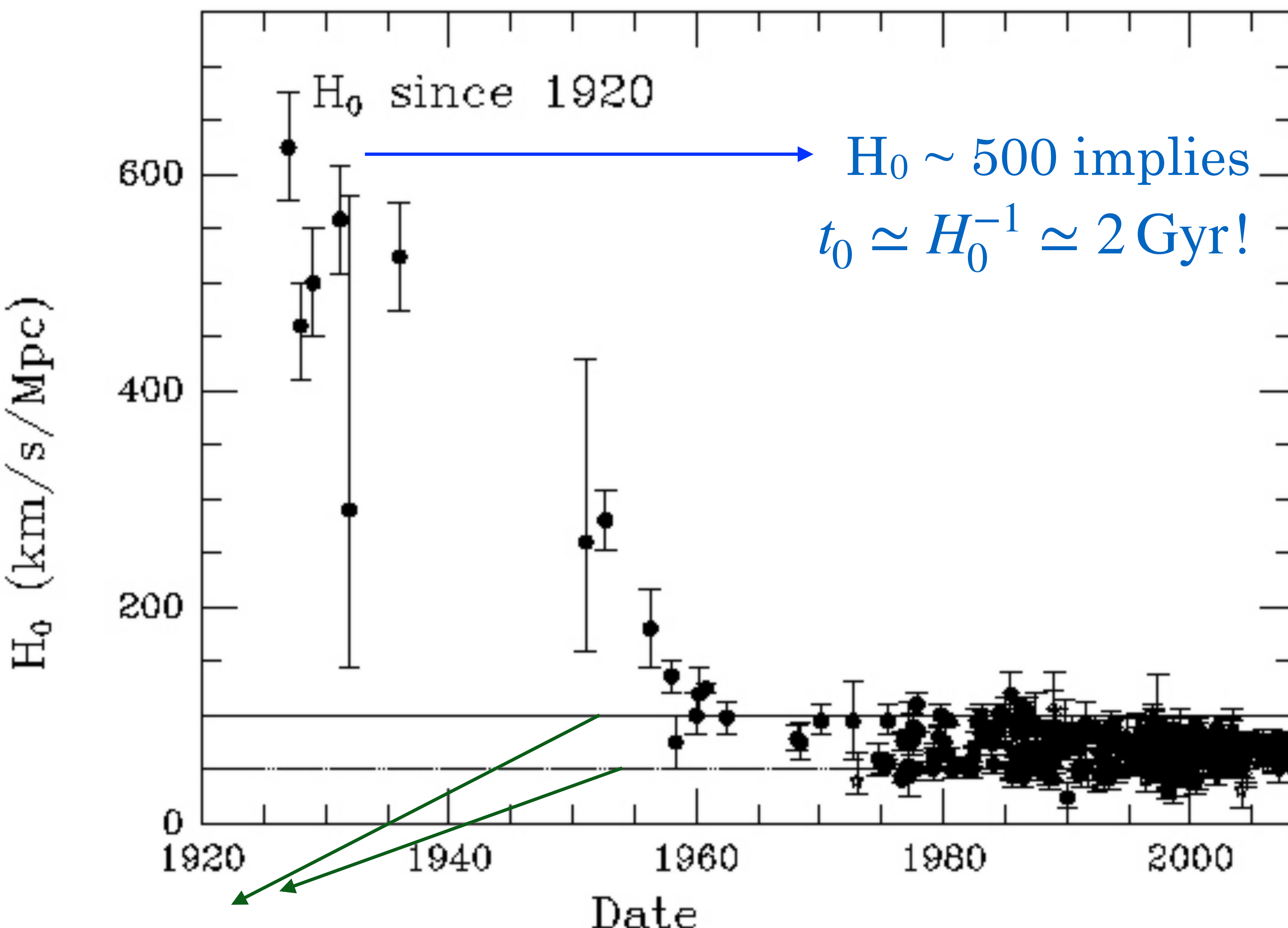
At low redshift, Hubble law
- depends only on H_0, cosmological-model independent



At high redshift, depends on the cosmological model:
- geometry (flat, open, closed)

or equivalently:
- amount of dark matter and dark energy

Here, we will only talk about H_0



H_0 ~ 500 implies

$t_0 \simeq H_0^{-1} \simeq 2\,\mathrm{Gyr}!$

"about 70"

"50 or 100" debate

https://lweb.cfa.harvard.edu/~dfabricant/huchra/hubble/

Part II: Cosmic Microwave Background (and H_0)

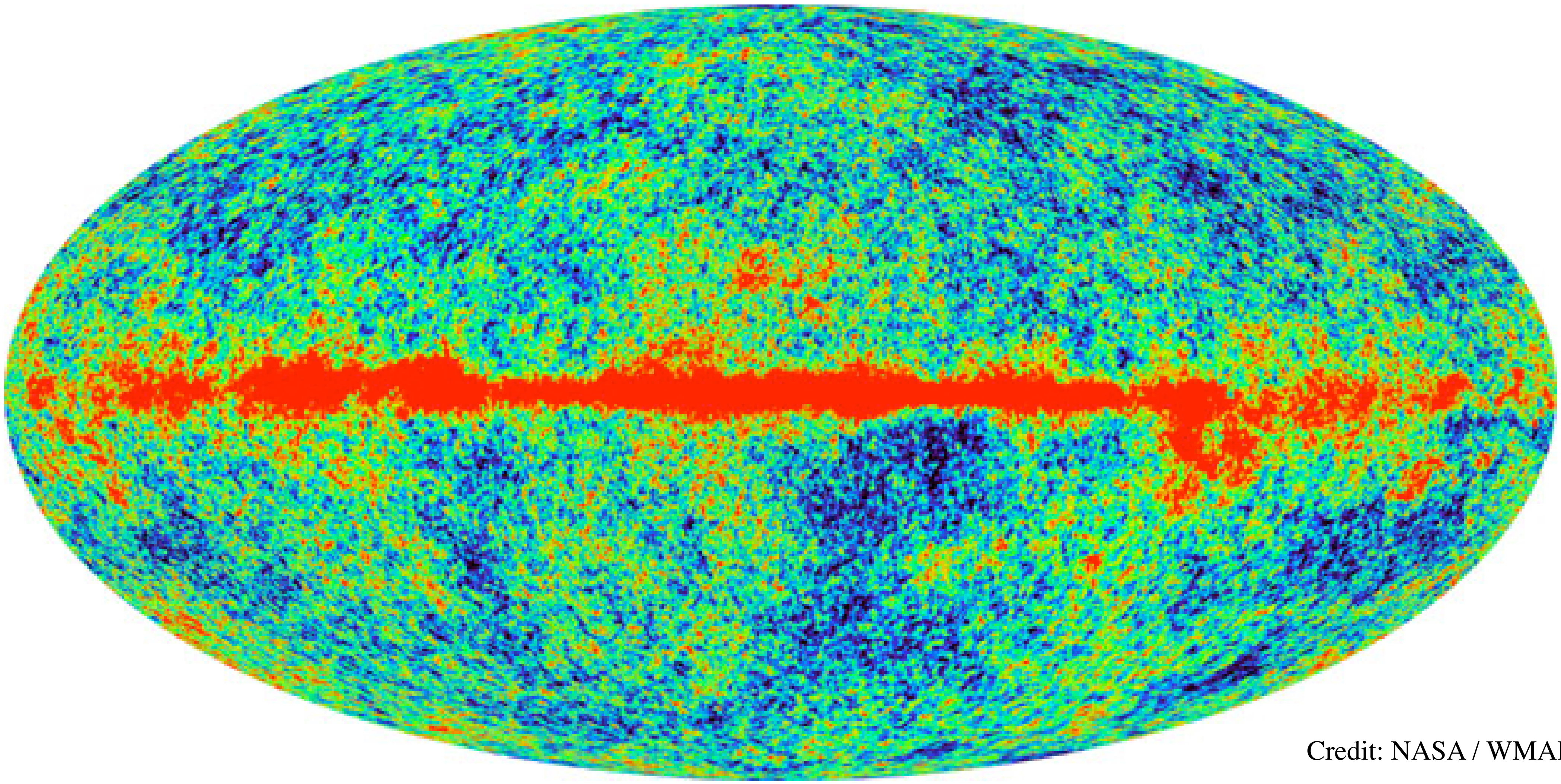
Cosmic microwave background (CMB): *almost* uniform

T=2.726 Kelvin

Penzias & Wilson, 1965
Camden Hill, NJ
(Nobel Prize 1978)

CMB **anisotropies**

Fluctuations 1 part in 100,000 (of 2.726 Kelvin)

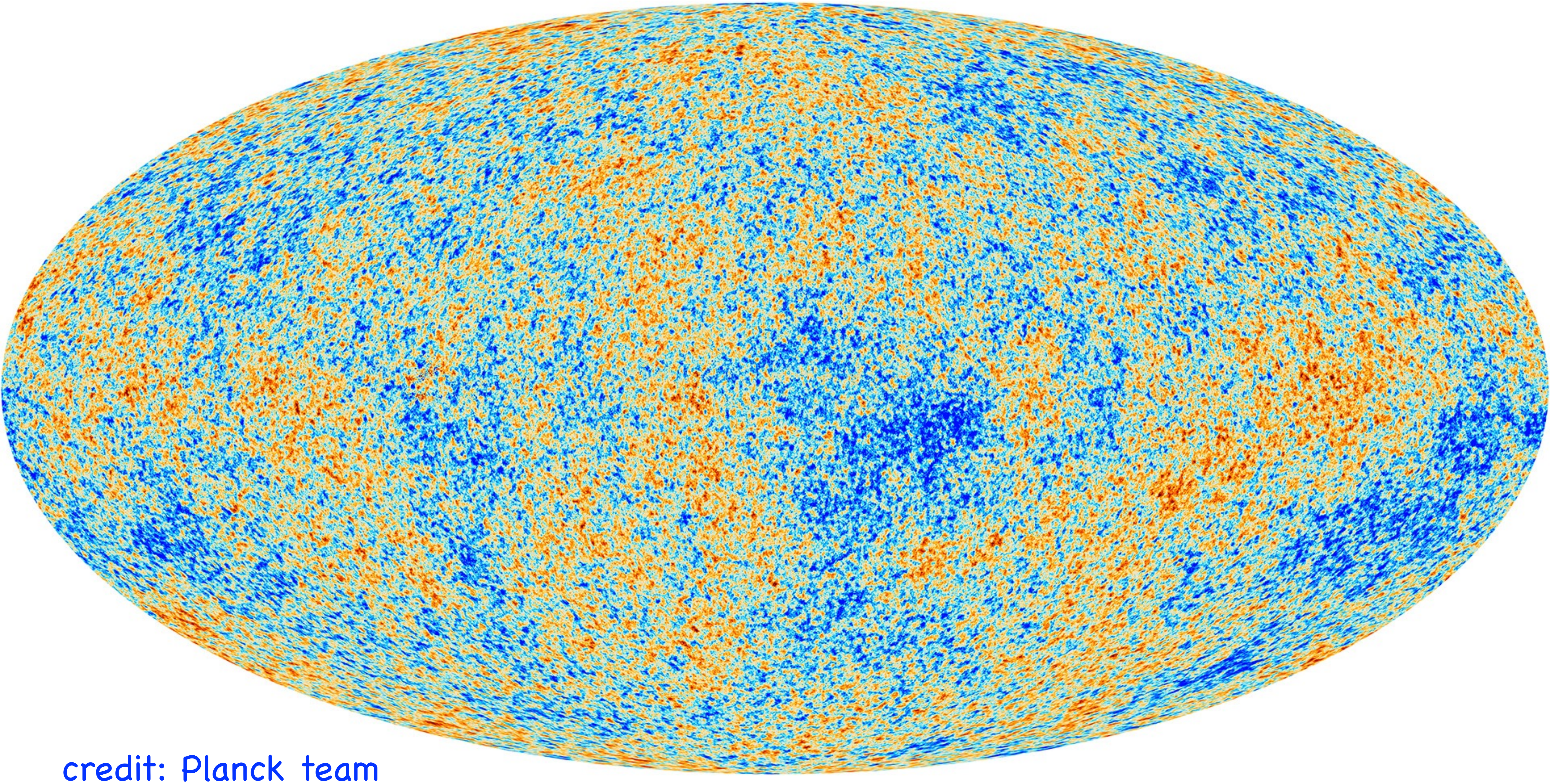


Credit: NASA / WMAP Science Team

Provides excellent measurements of:

- geometry of the universe
- age of the universe
- many other interesting things

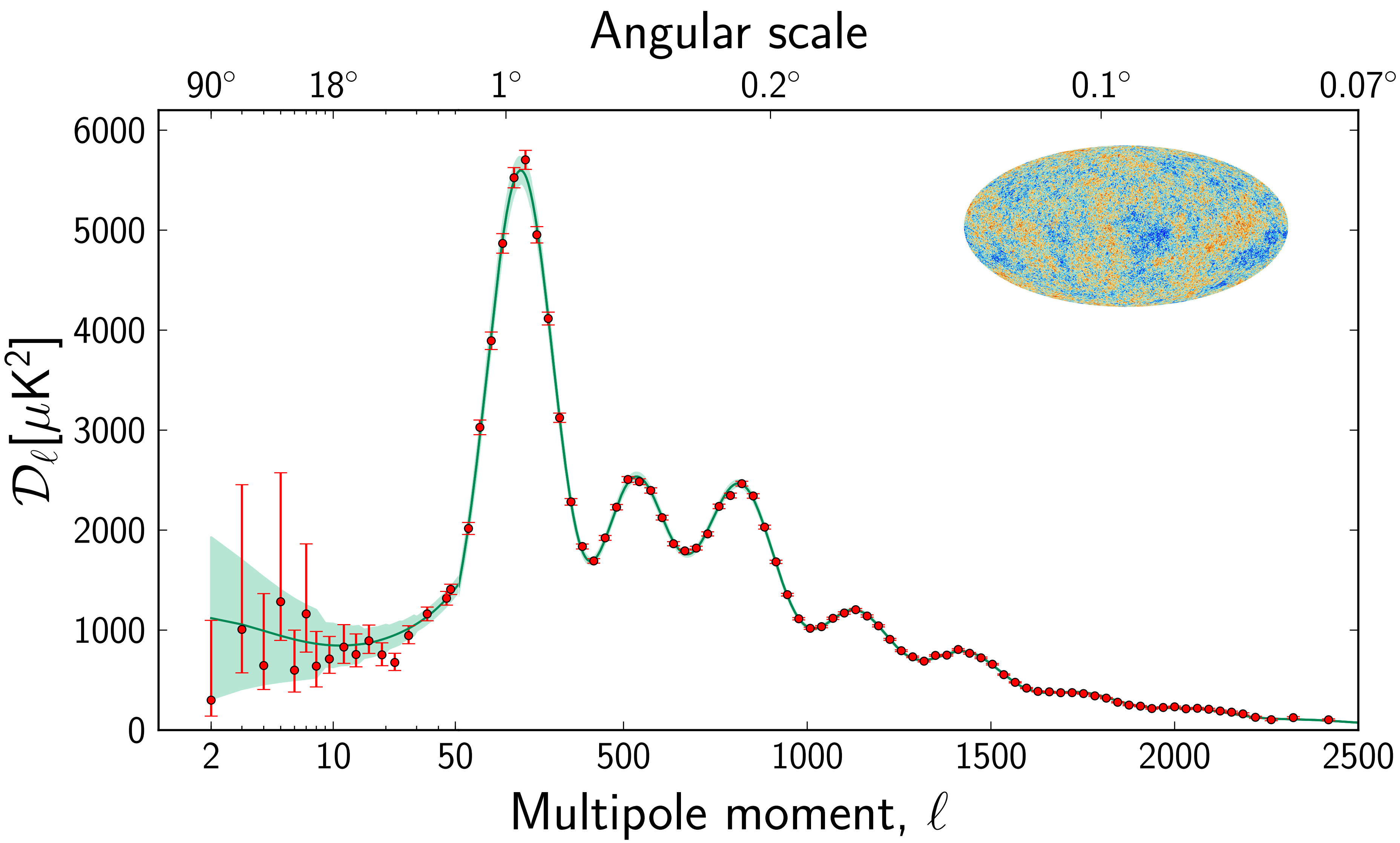
CMB Fluctuations as seen by Planck experiment



credit: Planck team

(Nobel Prize for discovery of fluctuations (in 1992): to COBE team members, in 2006)

The cosmic Rosetta Stone



Solid line: best-fit ΛCDM theoretical model

Points with error bars: Planck measurements

Green region: cosmic variance

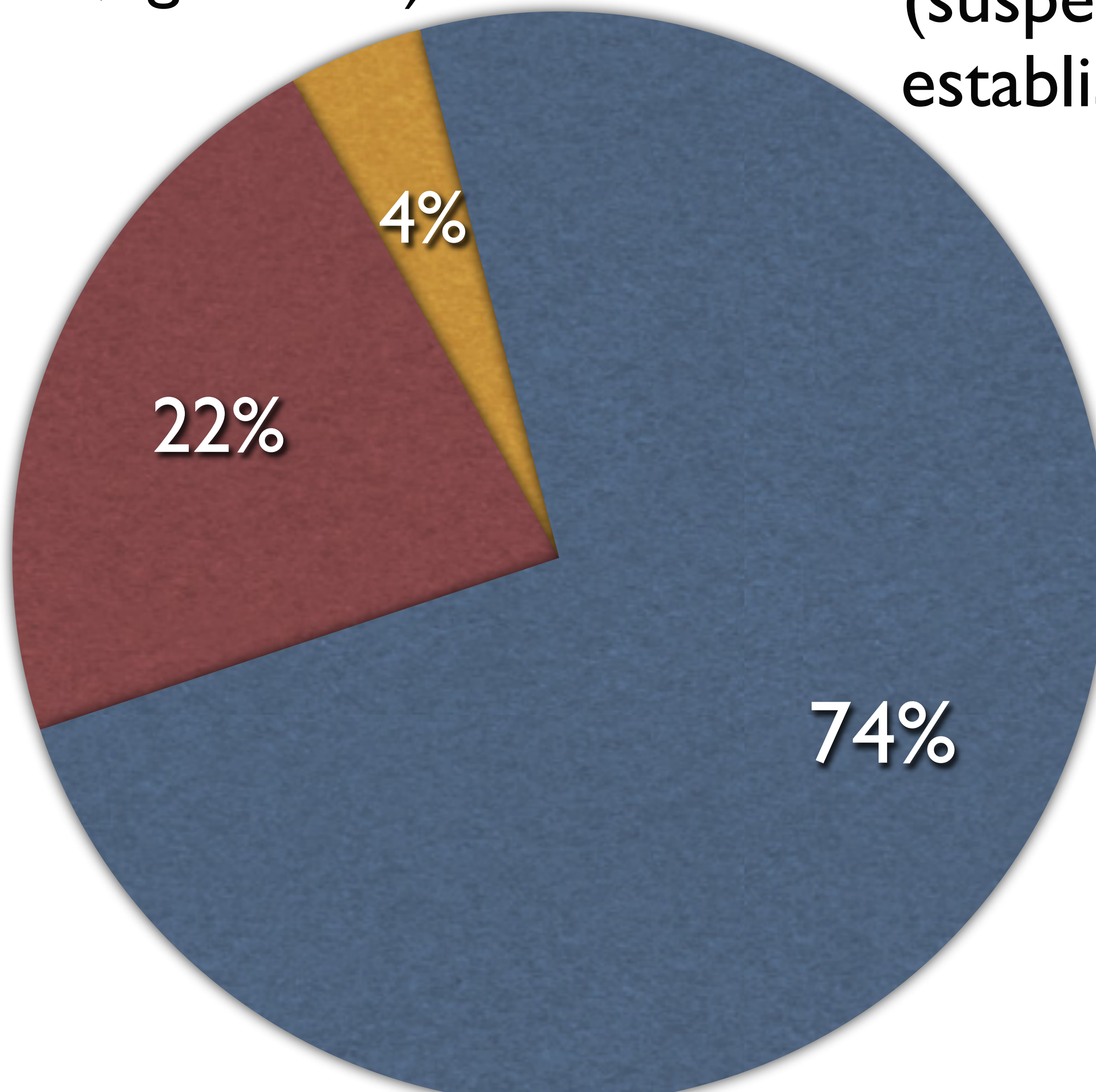
Clustering of cold and hot spots in the CMB is in fabulously good agreement with the predictions of cosmic inflation - a triumph of modern cosmology!

Makeup of universe today

Baryonic Matter
(stars 0.4%, gas 3.6%)

Dark Energy
(suspected since 1980s
established since 1998)

Dark Matter
(suspected since 1930s
established since 1970s)



Also:
radiation (0.01%)

Part III: The Hubble Tension

So H_0 is about 70 km/s/Mpc, right?

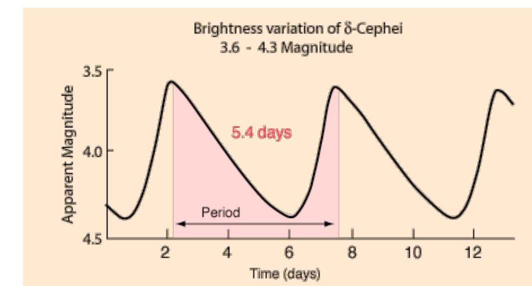
It's just a constant of nature, so why is its precise value interesting any more?

Breaking news:

Hubble tension!

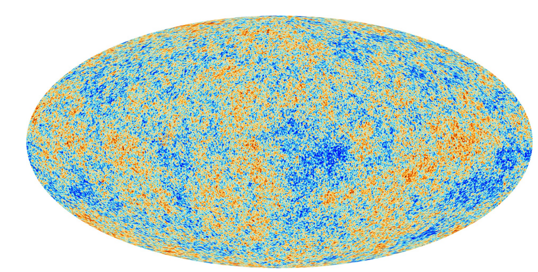
Type Ia supernovae + Cepheid distances give

$$H_0 = 73.04 \pm 1.04 \text{ (km/s/Mpc)}$$



Cosmic Microwave Anisotropies give

$$H_0 = 67.36 \pm 0.54 \text{ (km/s/Mpc)}$$

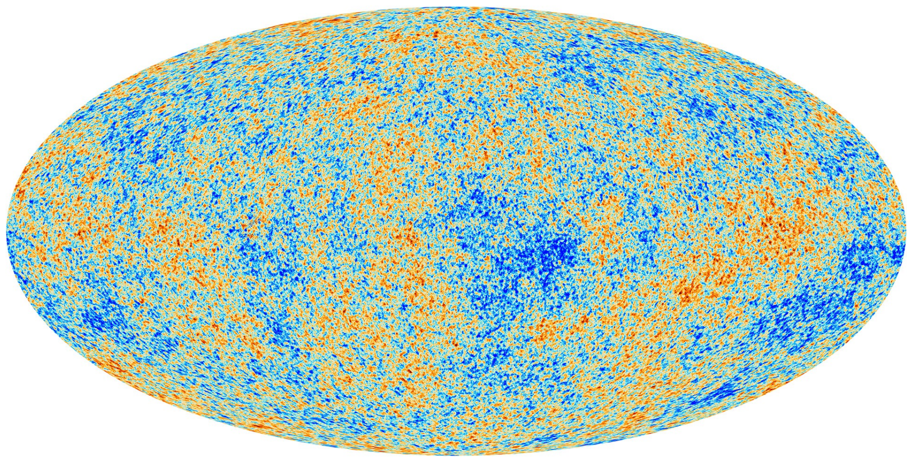


These two measurements are about five standard deviations (quoted errors) apart

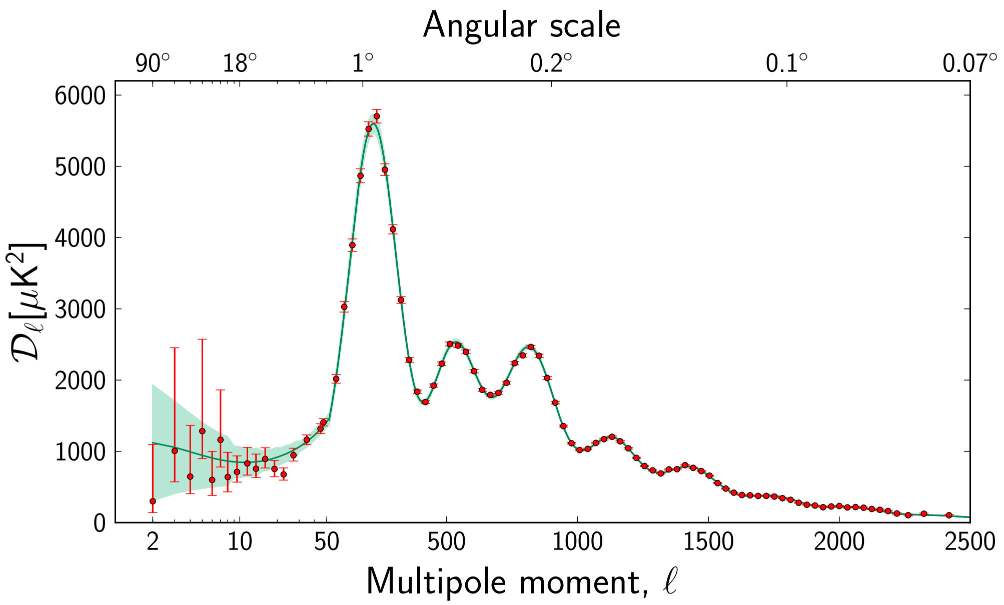
$\Longrightarrow$ discrepant at 99.99997% confidence

My short (5min) presentation on this: shorturl.at/abkpM

CMB measurement of H_0



H_0 is a “derived parameter” in the CMB - no special thing it does except change distances…

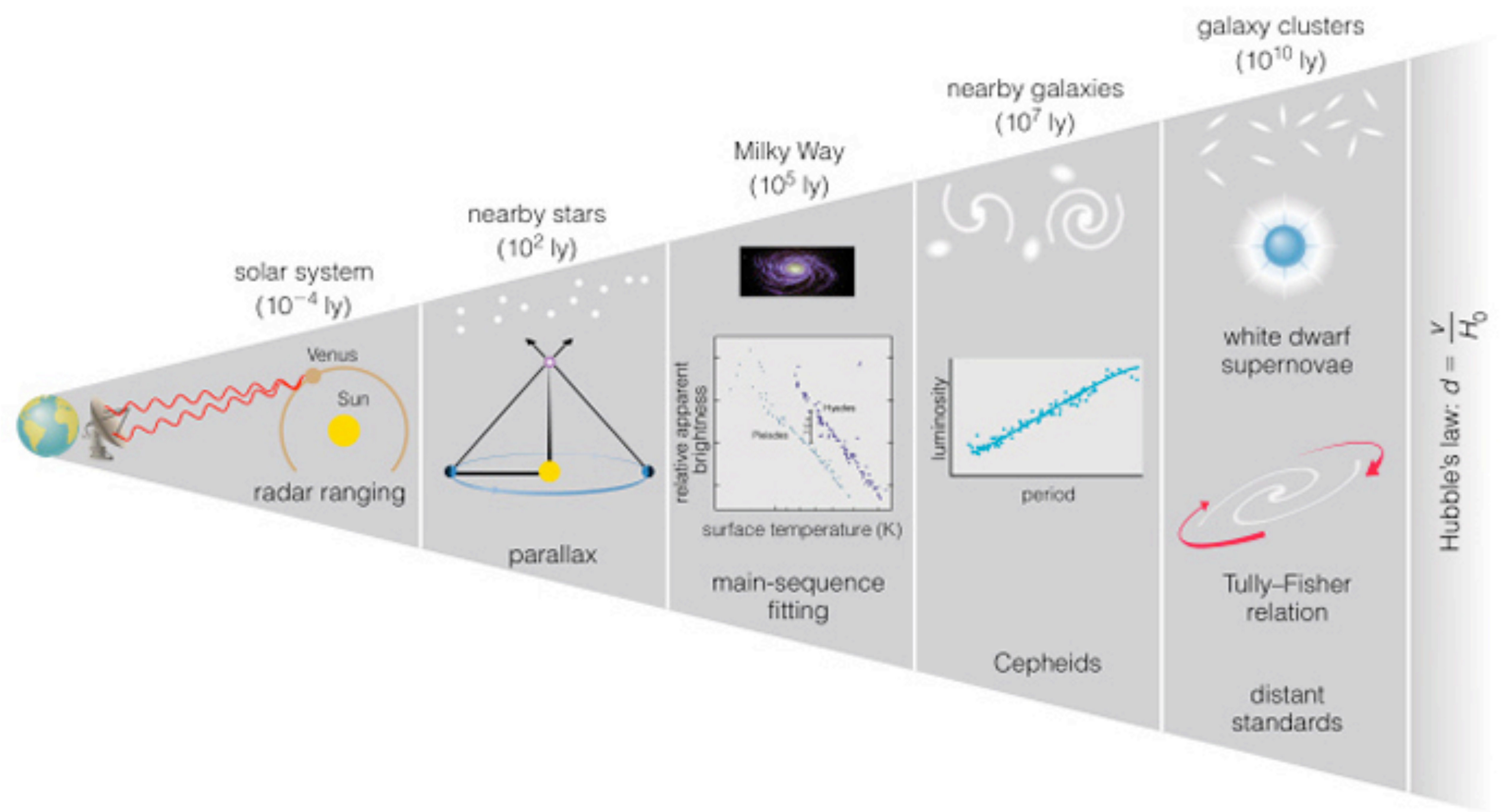


Planck (2020) finds:

$$H_0 = (67.36 \pm 0.54)\,\mathrm{km/s/Mpc} \quad \text{[flat LCDM]}$$

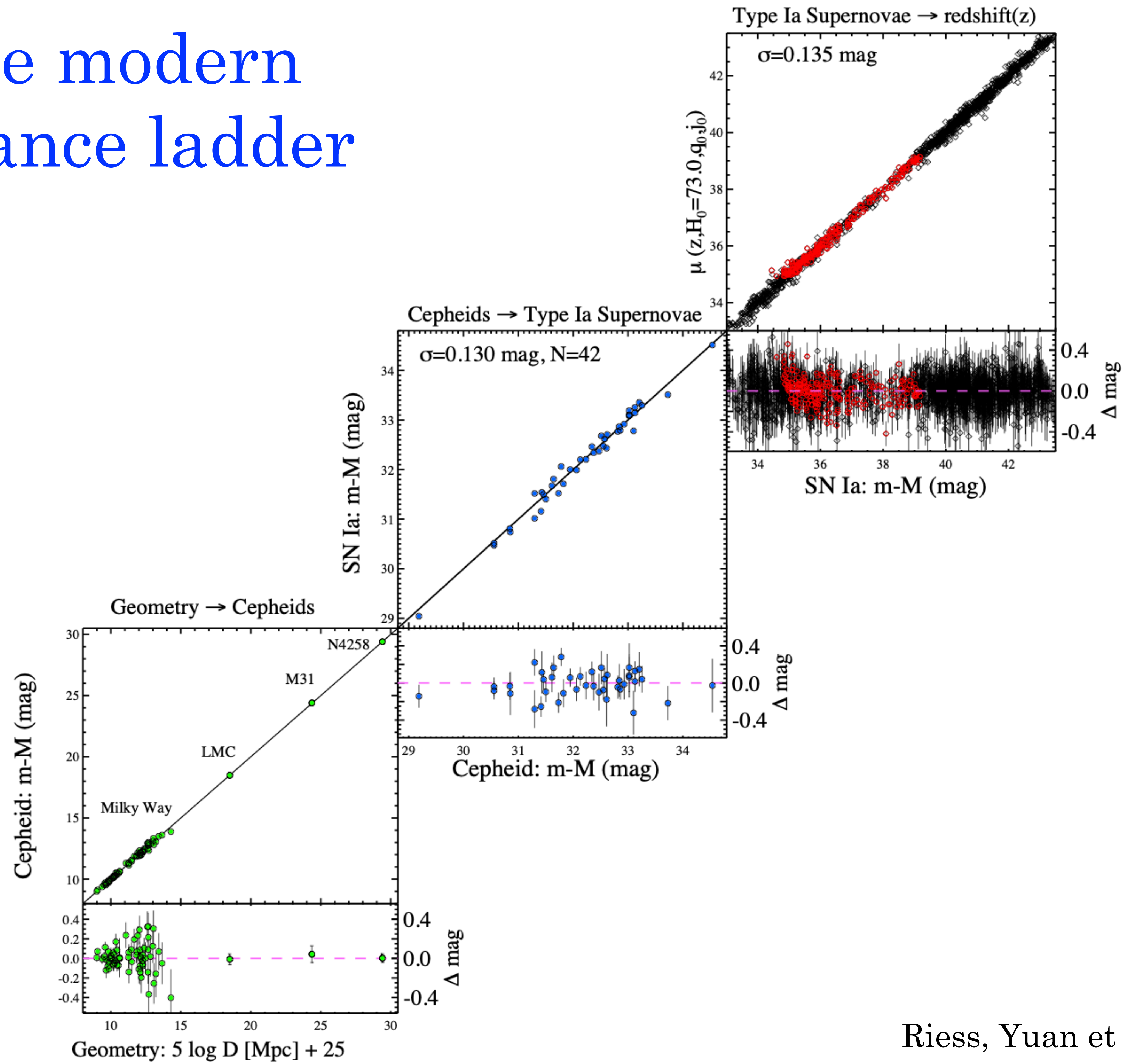
$$H_0 = (63.6 \pm 2.2)\,\mathrm{km/s/Mpc} \quad \text{[curved LCDM]}$$

Distance ladder measurement of H_0



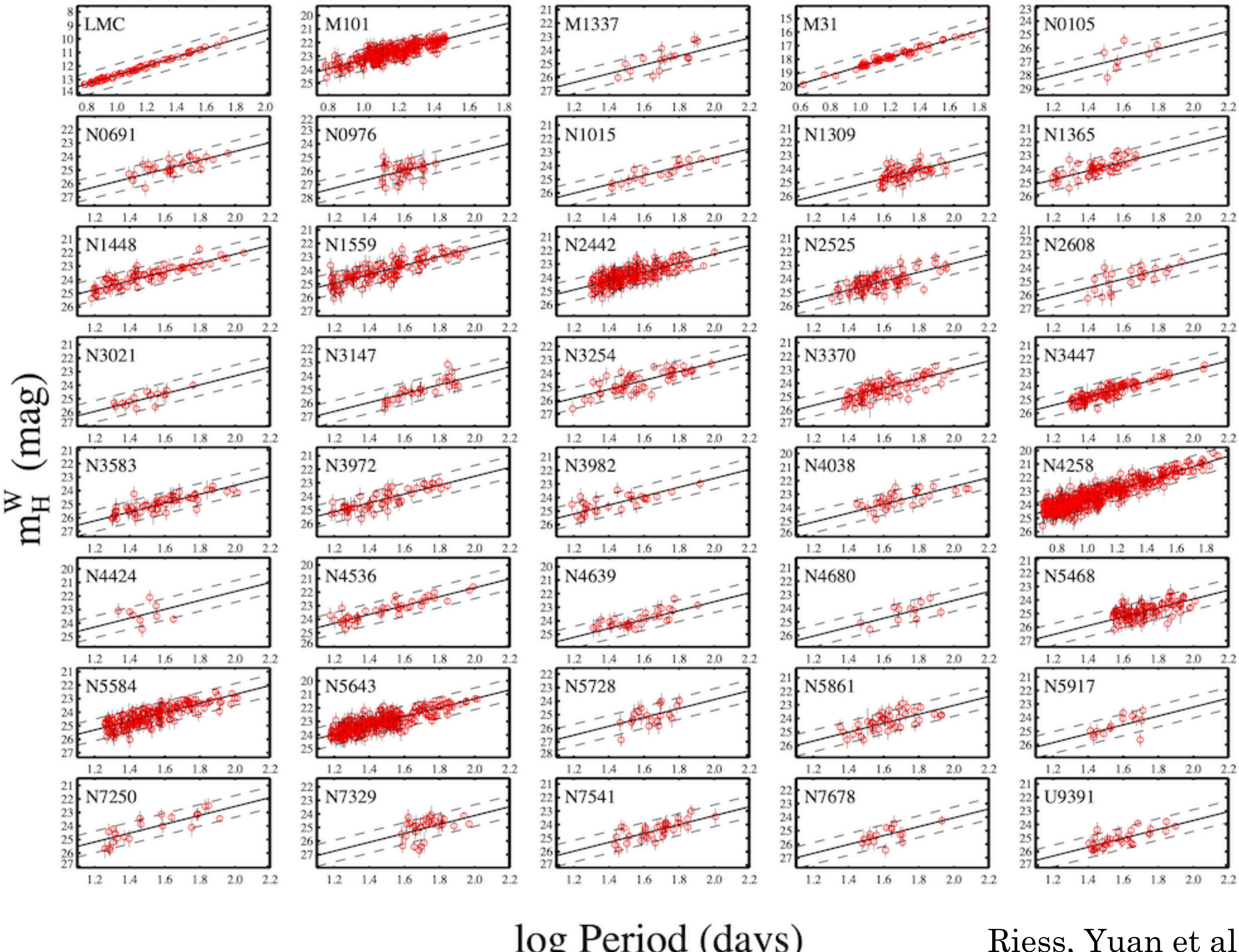
@Addison Wesley

The modern distance ladder



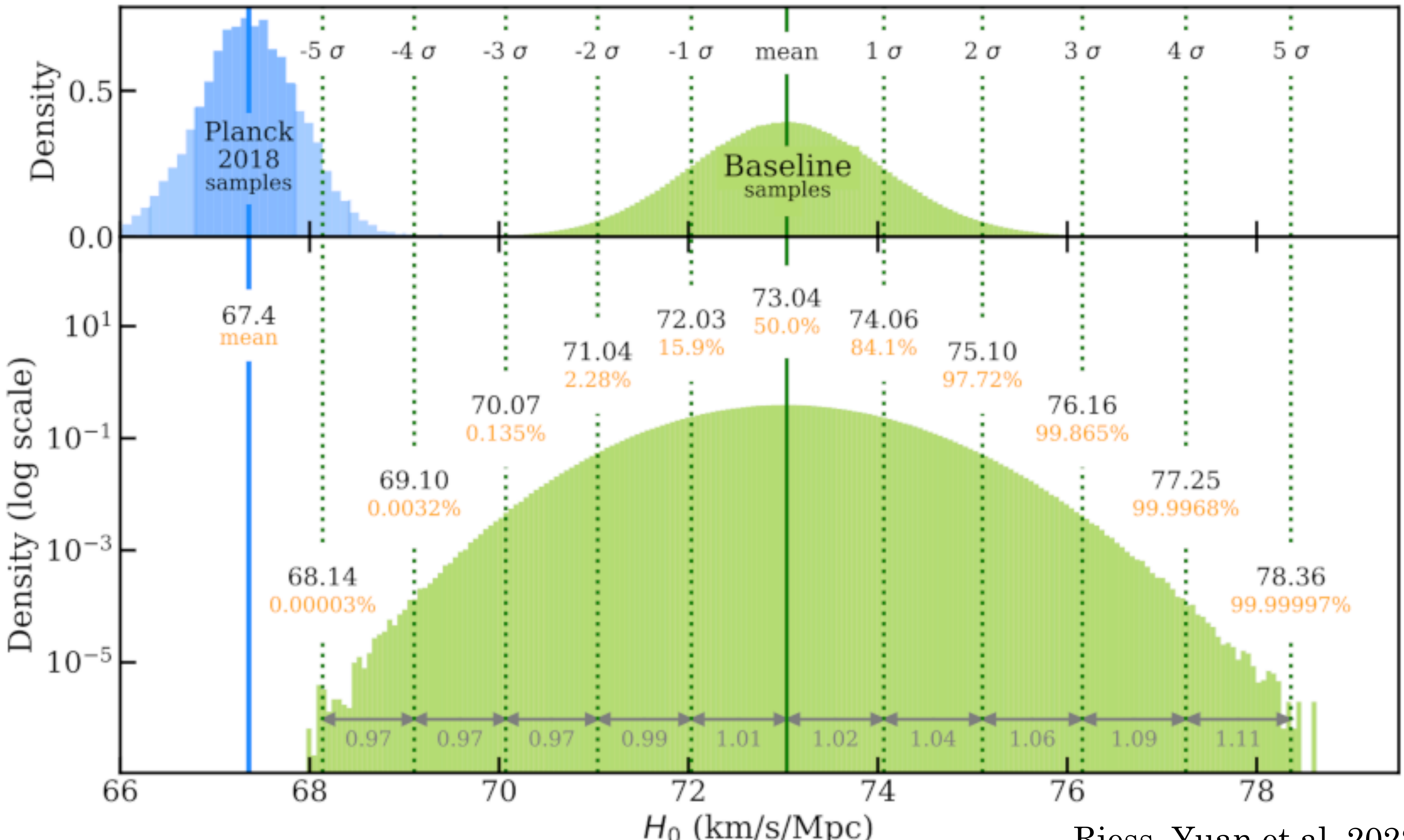
Riess, Yuan et al, 2022

Individual Cehpeids' (with SNIa in same galaxy) period-lum. relations



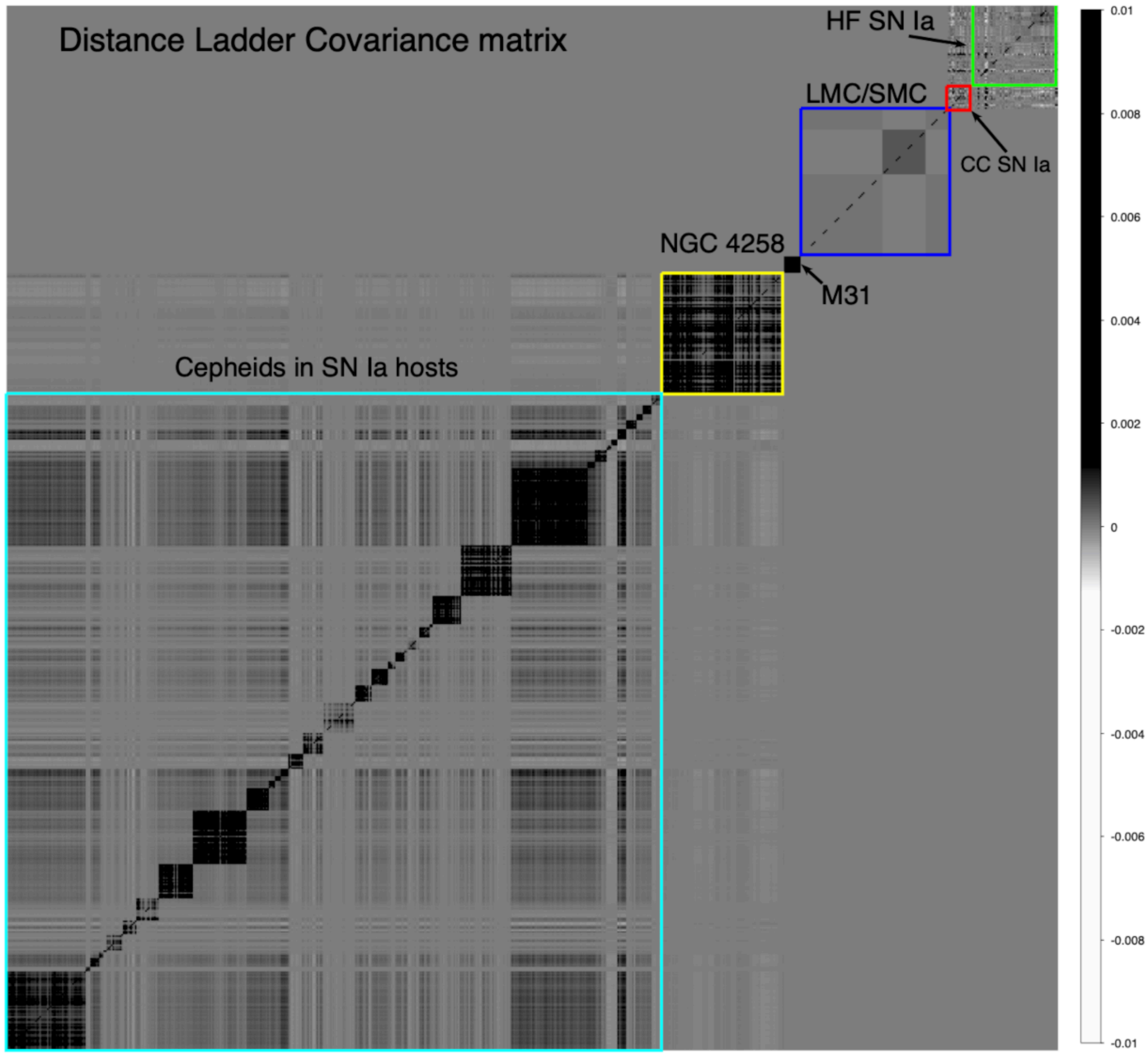
Riess, Yuan et al, 2022

Discrepancy between Planck and distance ladder H_0 is 5.0 sigma (99.99997%)



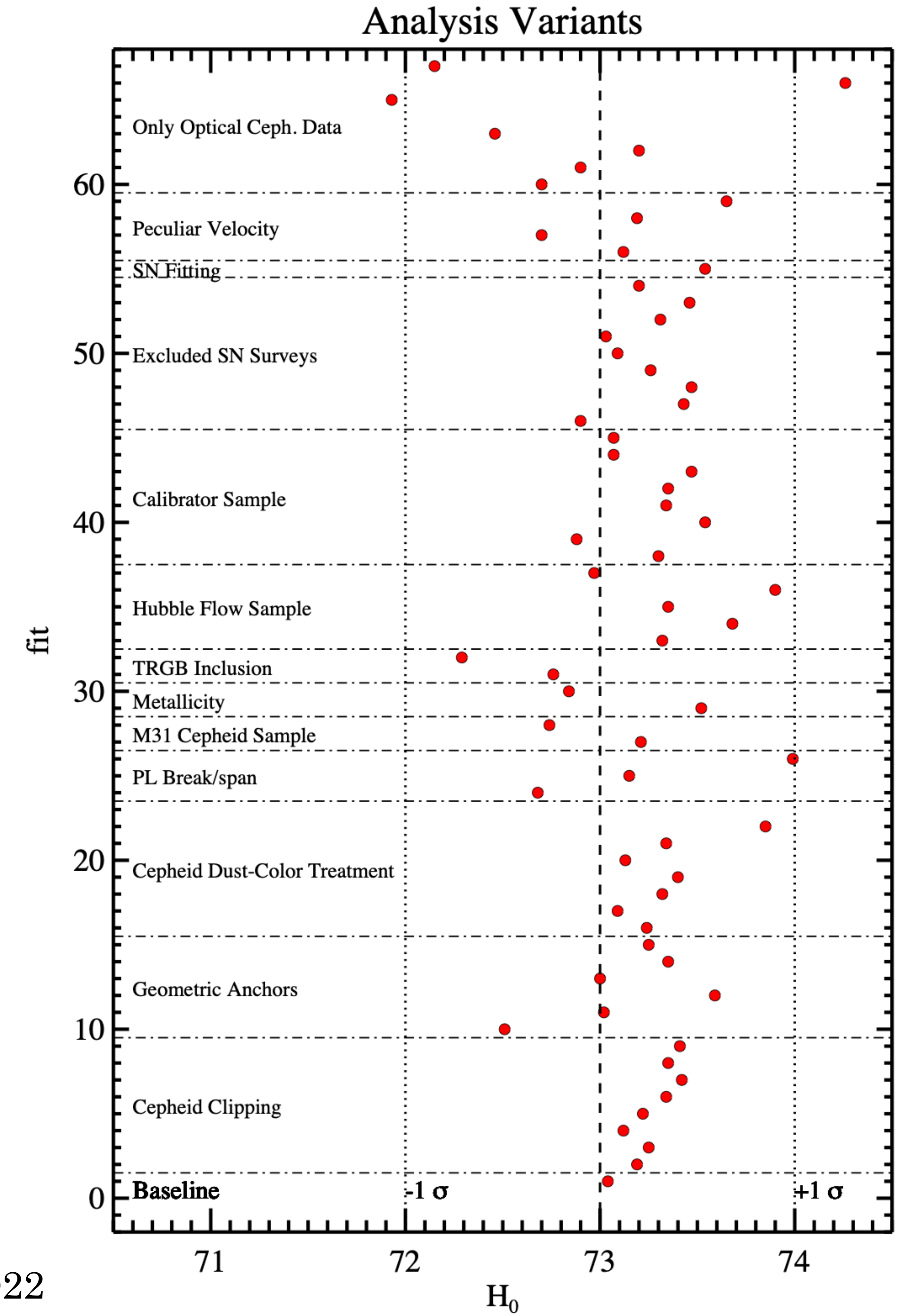
Riess, Yuan et al, 2022

Distance ladder:
Full covariance between the measurements



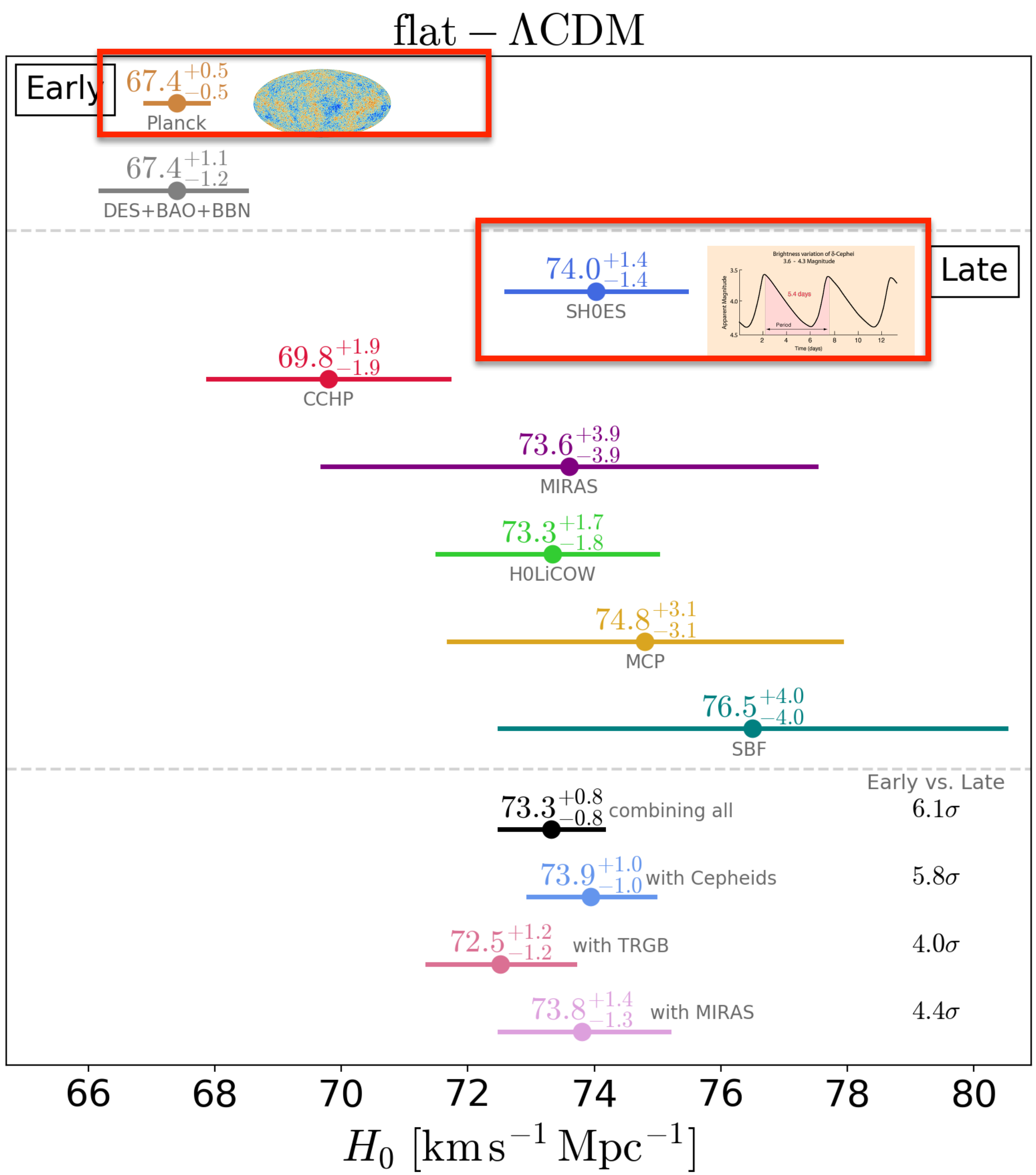
Riess, Yuan et al, 2022

Distance ladder: Robustness to variations in the analysis



Riess, Yuan et al, 2022

Hubble tension - a gift to cosmology!



Verde, Treu & Riess arXiv:1907.10625

- exciting, real tension in cosmology
- all major analysis very thorough
- no obvious systematics (as yet)
- theory models surprisingly hard to concoct

H_0 tension - theory

- There are literally hundreds of models out there
- However, there is only ONE simple model.

Sample/cosmic variance?

⇒ Global H_0 is ~67, but H_0 in our local volume is ~73

(equivalent to: "we live in a void")

However that model is completely ruled out.

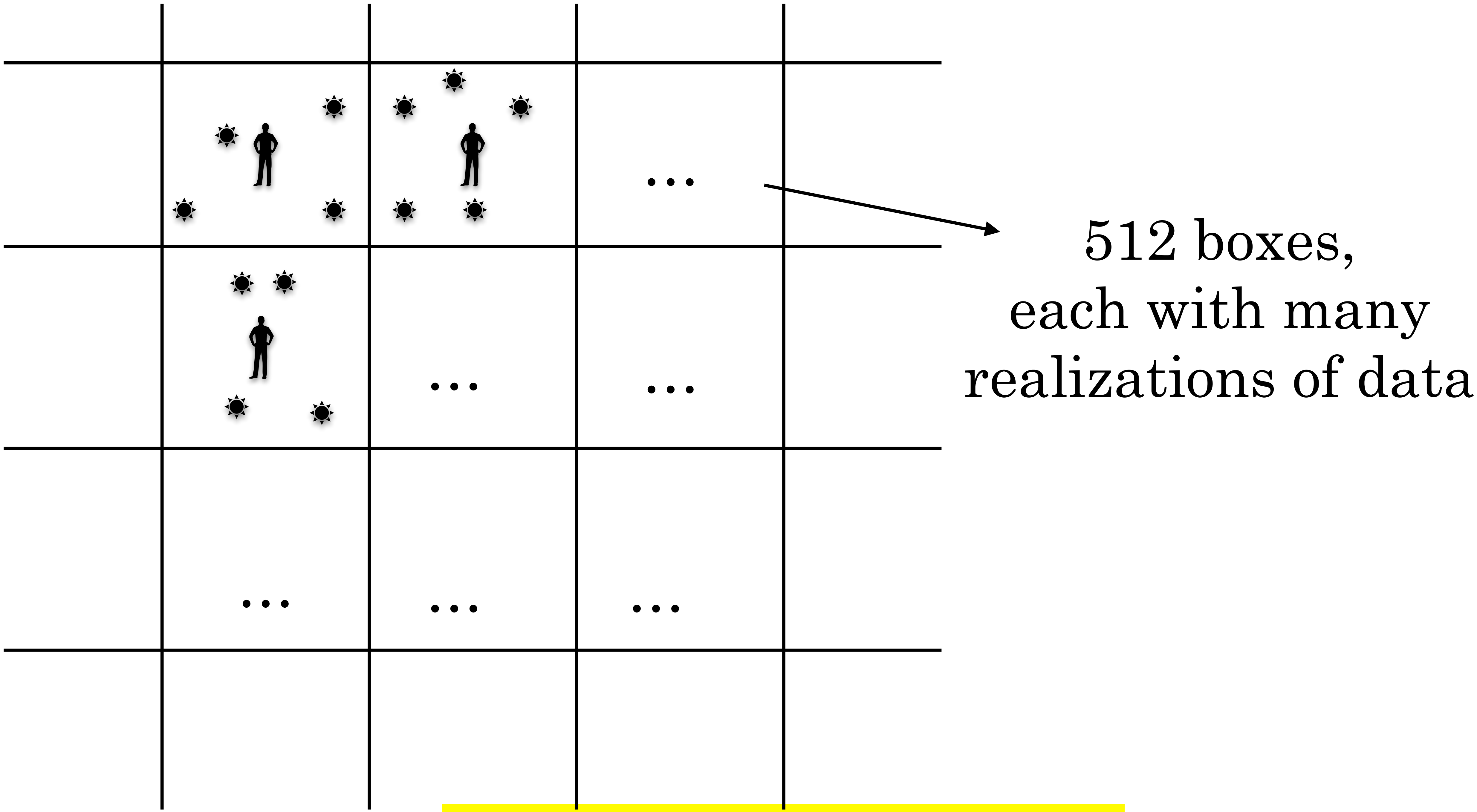
Wu & Huterer (2017), Kenworthy, Scolnic & Riess (2019)

essentially because local measurements map out a pretty big local volume (so cosmic variance is small)

$$\sigma^{\rm CV}(H_0) \simeq 0.3\,{\rm km/s/Mpc} \simeq \frac{1}{20}\,(H_0^{\rm SHOES} - H_0^{\rm CMB})$$

as explained on next slide…

In Wu & Huterer (2017), we determined the **sample variance** of H0 from the distance-ladder measurement both precisely and robustly by repeating the analysis about 3 million times *on numerical (Nbody) LCDM simulations*



$$\sigma^{CV}(H_0) \simeq 0.3\,\mathrm{km/s/Mpc}$$

H_0 tension - theory

This leaves hundreds of other proposed models, but most of them "unnatural" and fine-tuned.

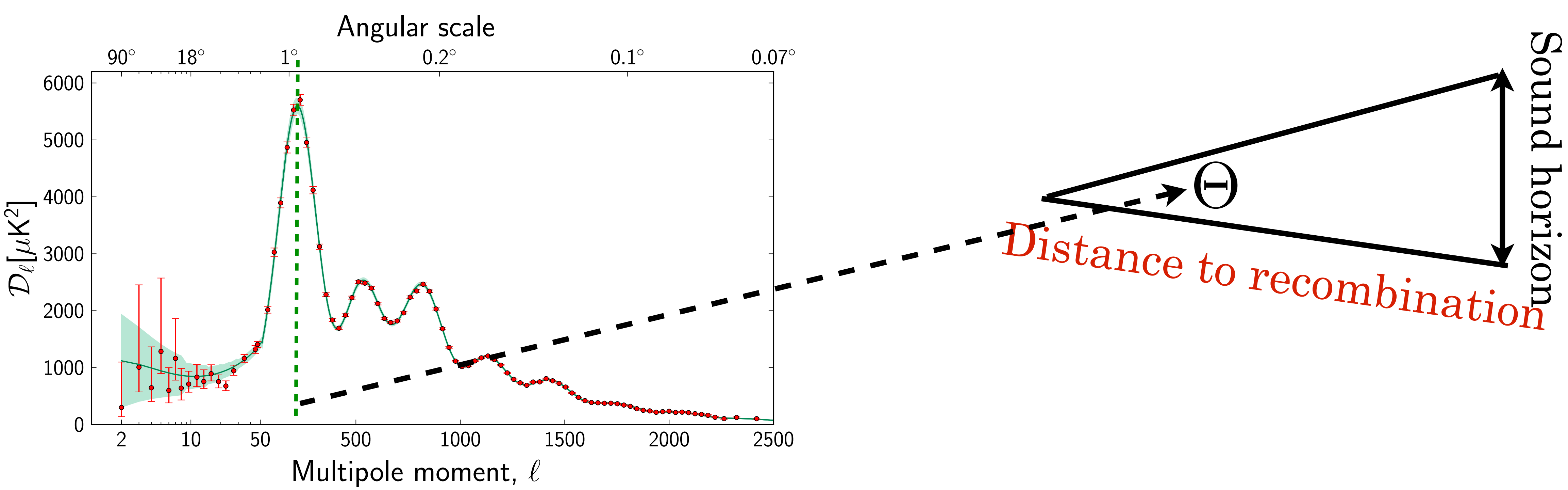
Most of them struggle to lift the global H_0 from 67 to 73 (despite being tuned)

In particular, majority of proposed solutions introduce new parameters, but are either
*** **unnatural**, or else
*** **do not substantially improve the fit to the data**

Concluding:
The overall notion that something (unexpected) changed between early and late universe is very exciting,
but no compelling solution yet.

H_0: flavor of “new theory” explanations

- Accept the local (distance-ladder) measurement of ~73 km/s/Mpc as true, global value
- Change theory so that the value from CMB comes out ~73 (rather than 67)
- Because angle to sound horizon θ is so well measured, and distance to recombination decreases with increasing H0, introduce new physics that **decreases the sound horizon**



Ongoing or upcoming "H_0 experiments":

- **CMB surveys:**
  - Atacama Cosmology Telescope (AdvACT; ground)
  - Simons Observatory (ground)
  - CMB-S4 (ground)
  - LiteBird (space)
- **Galaxy surveys from the ground**
  - Dark Energy Survey (DES)
  - Vera Rubin Telescope (LSST)
  - Hobby Eberly Telescope DE Experiment (HETDEX)
  - Dark Energy Spectroscopic Instrument (DESI)
- **Galaxy surveys from space:**
  - Euclid
  - Wide Field InfraRed Space Telescope (WFIRST)
  - James Webb Space Telescope (JWST)

Summary

- There is a statistically very significant (5-sigma) discrepancy between the Hubble constant measured by the CMB (~67 km/s/Mpc) and local, distance-ladder measurements (~73)

- Both measurements appear very reliable and have been tested against known systematics (though the CMB is certainly the more mature of the two)

- Theory explanations lag far behind. The "most reasonable" model, that of sample variance, is ruled out

- Hubble tension is a premier problem in cosmology today