Tension in the Cosmological Distance Scale

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Overview

1. Measuring distances to relatively nearby galaxies tells us the expansion rate of the universe, the Hubble constant (H_0), and therefore the *age of the universe*.
2. Measuring distances to remote galaxies tells us that the universe is *accelerating* (dark energy!)
3. Measuring the scale of thermal fluctuations in the very early universe tells us that the universe is very *flat*.

Unfortunately, when we try to combine these facts, they disagree at the 4 to 5-σ level.

Definitions

1 σ = agreement

2 σ = curiosity

3 σ = tension

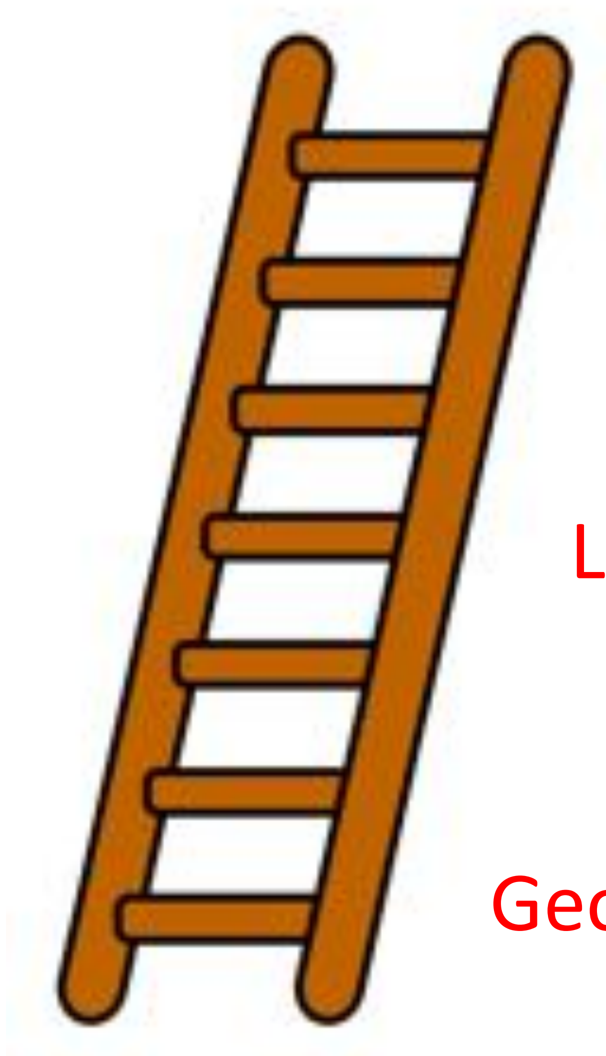
4 σ = disagreement

5 σ = crisis!

"You know that physicists are in a state of crisis when they start talking like philosophers."

Thomas Kuhn

The Distance Ladder

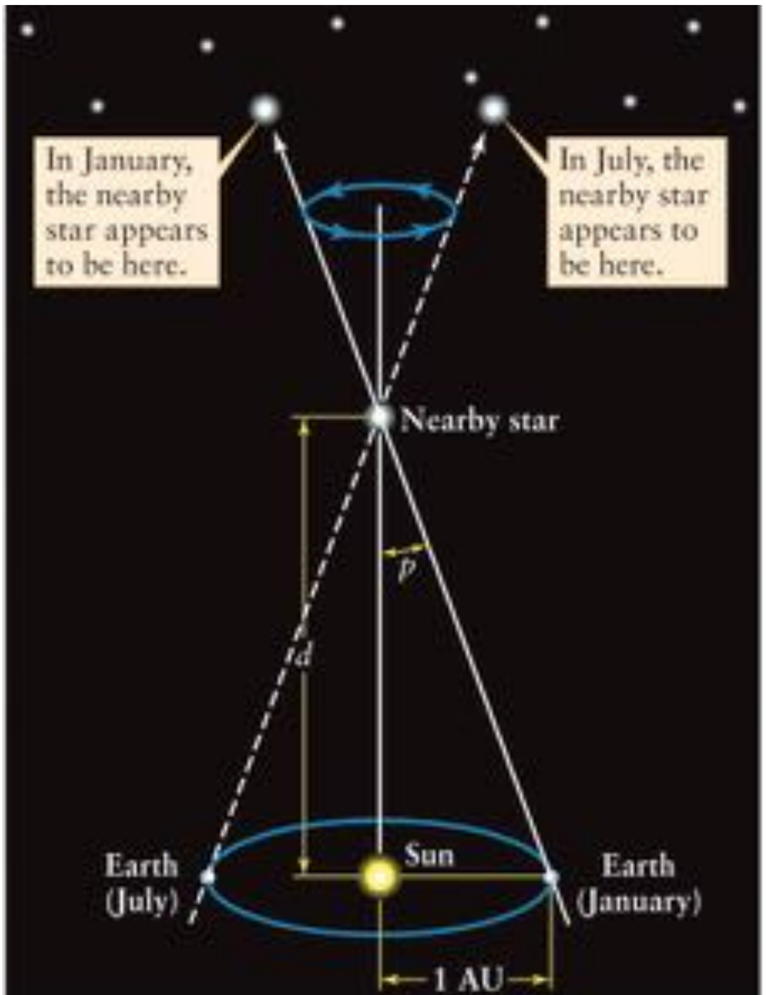


Dynamics

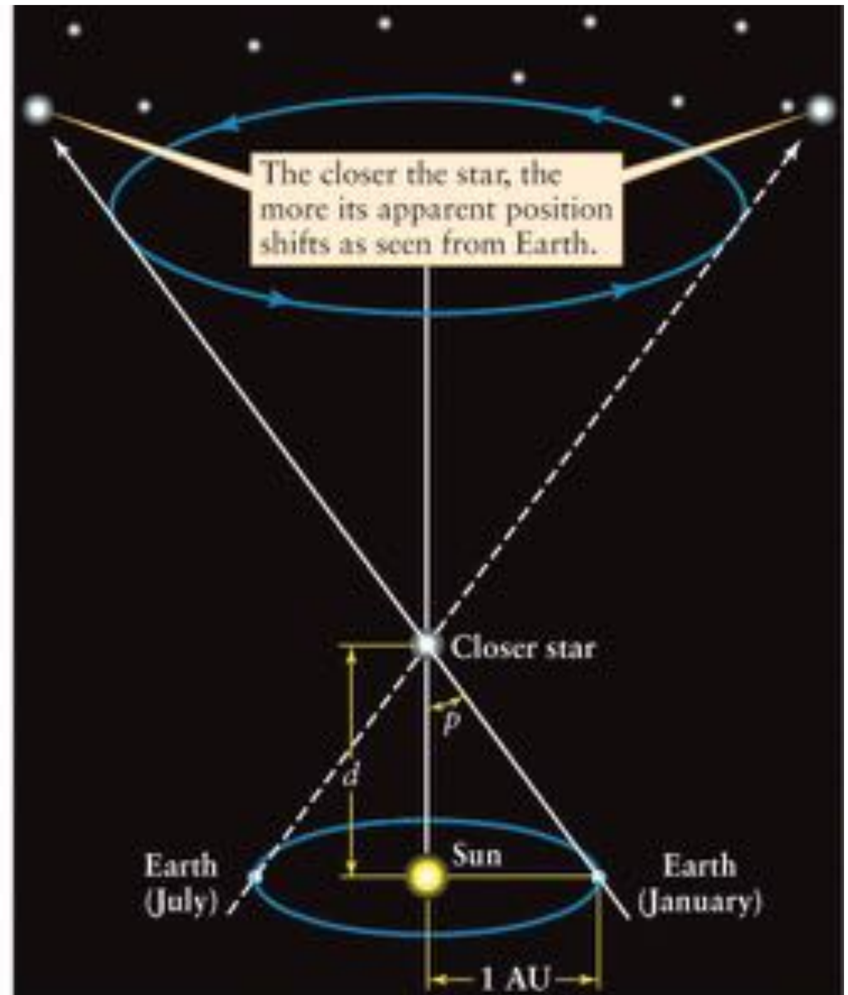
Luminosity

Geometry

Geometry 1: Parallax

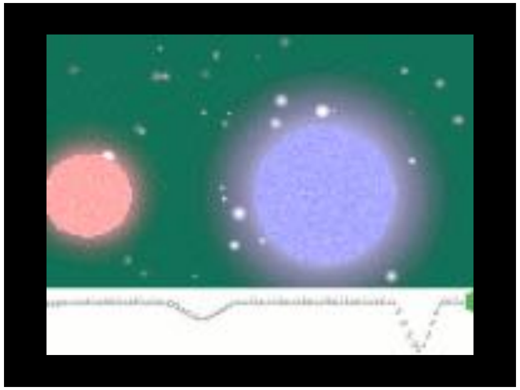


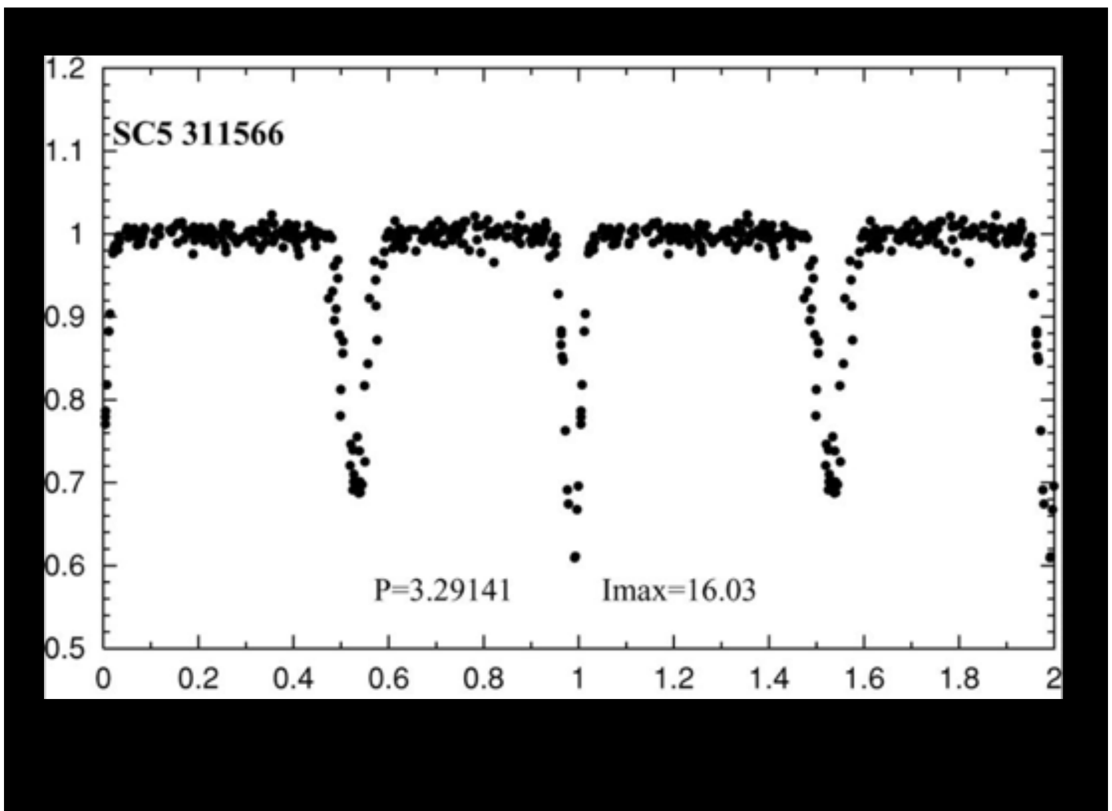
(a) Parallax of a nearby star



(b) Parallax of an even closer star

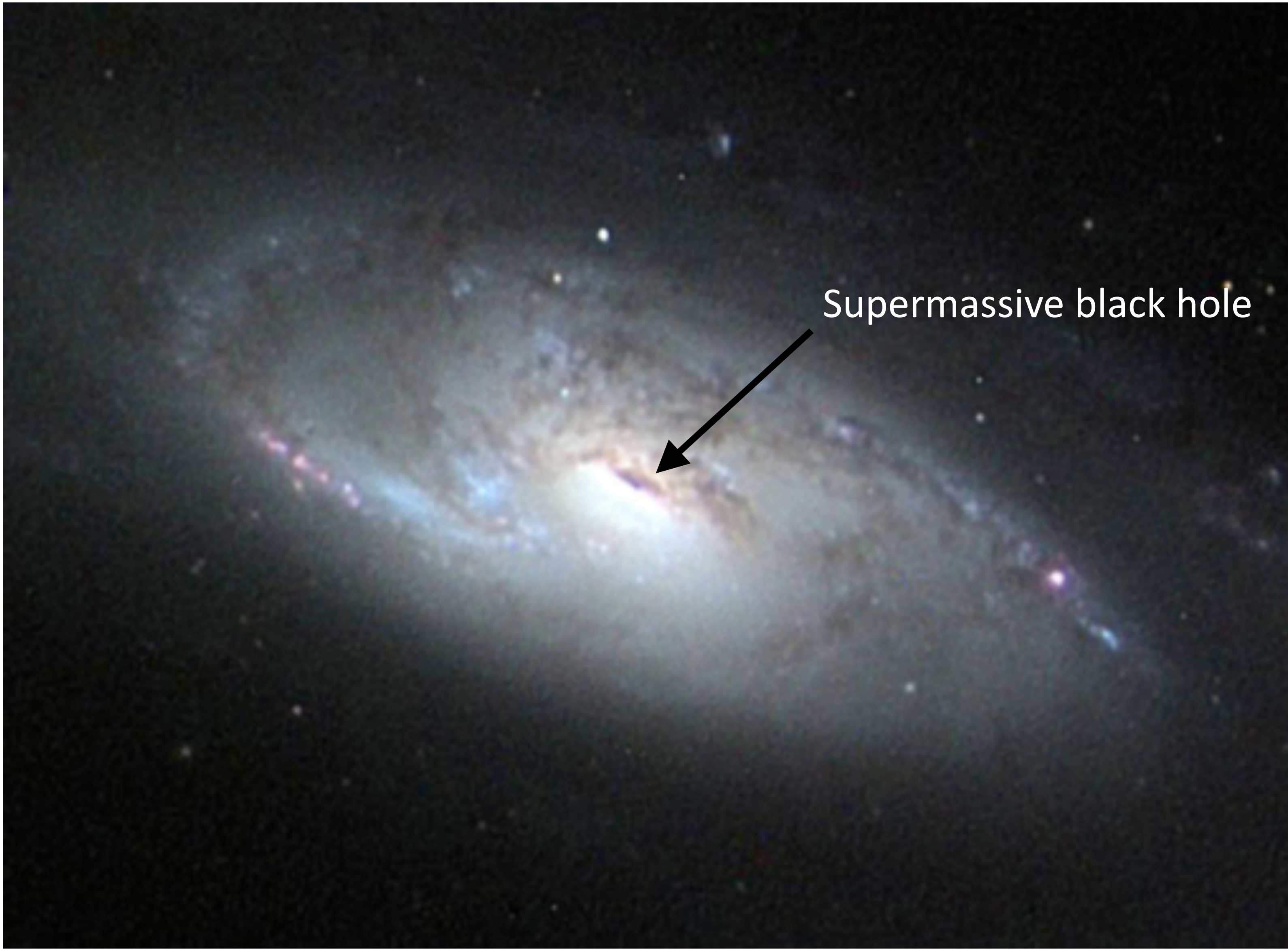
Geometry 2: *eclipsing binary stars*

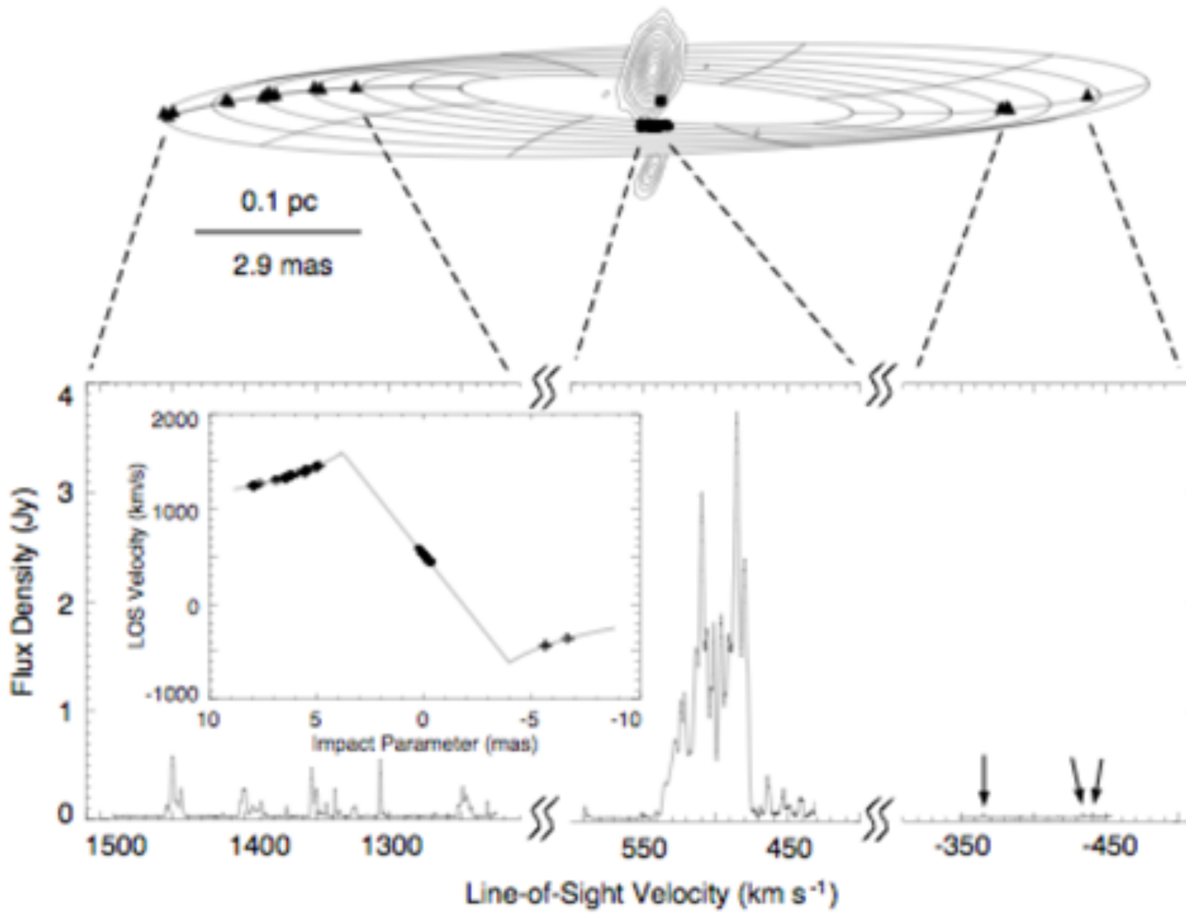




- Radial velocities give the mass (from Kepler's Law)
- Eclipses give stellar radii
- Surface brightness is estimated using the stellar spectra
- From these you can derive the luminosity and distance

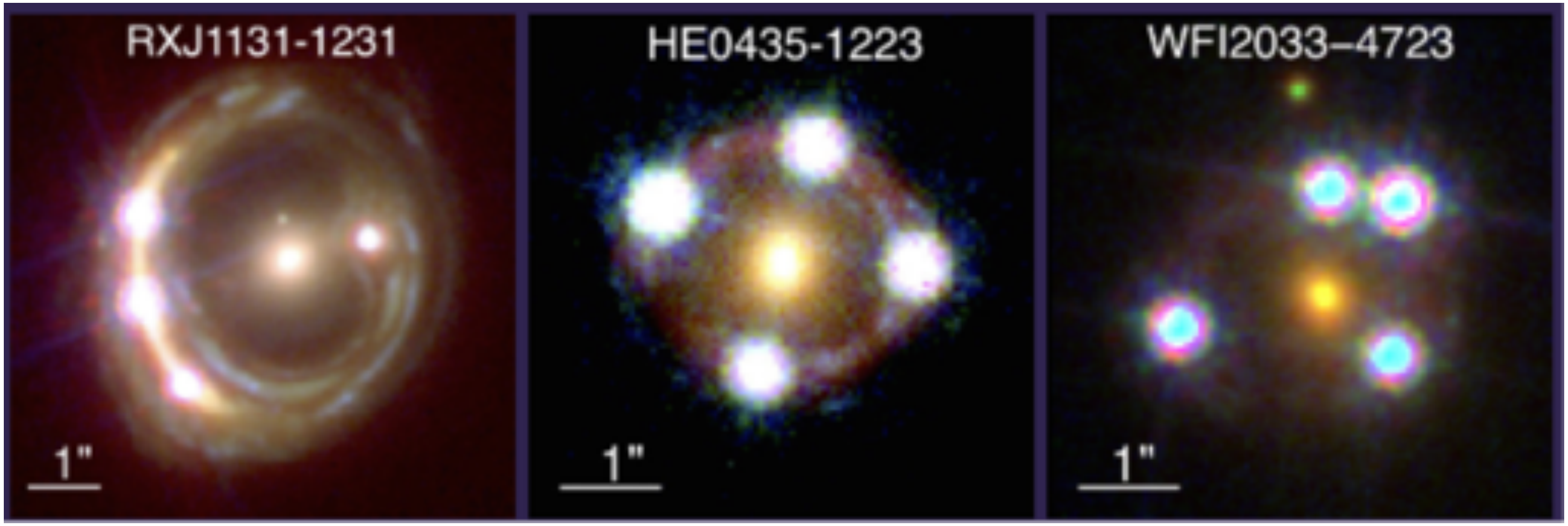
Geometry 3: NGC 4258 H_2O masers

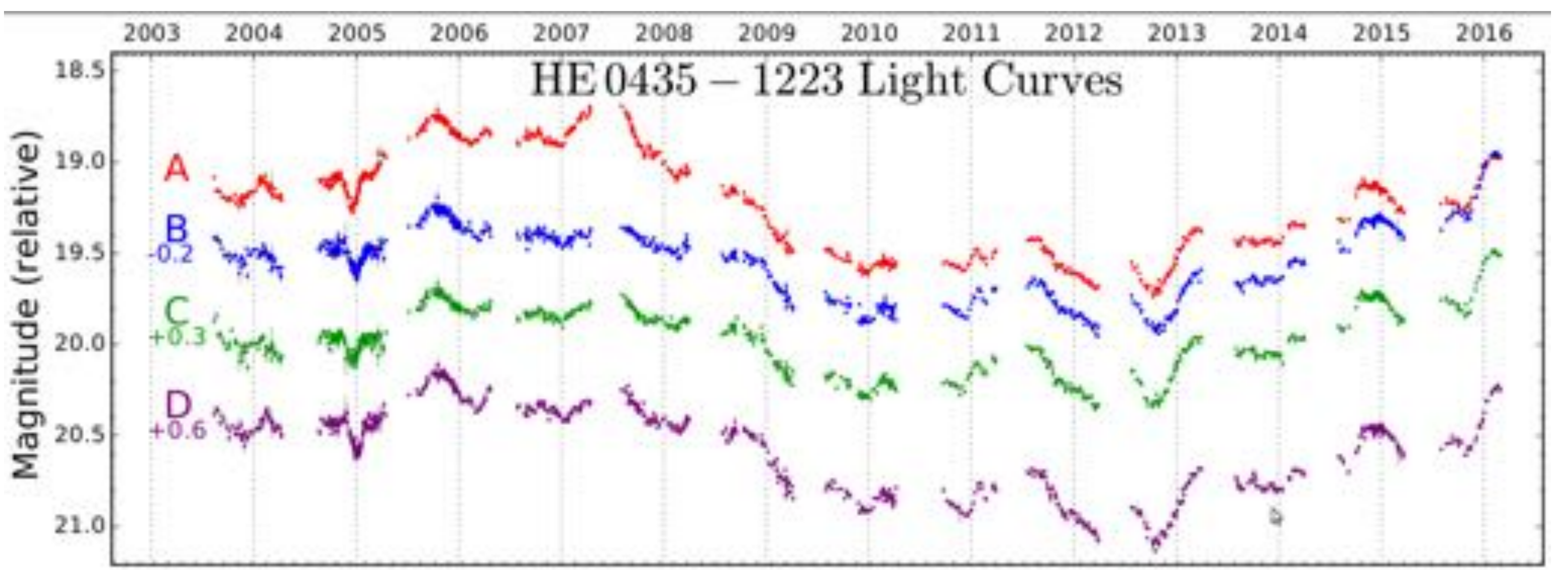




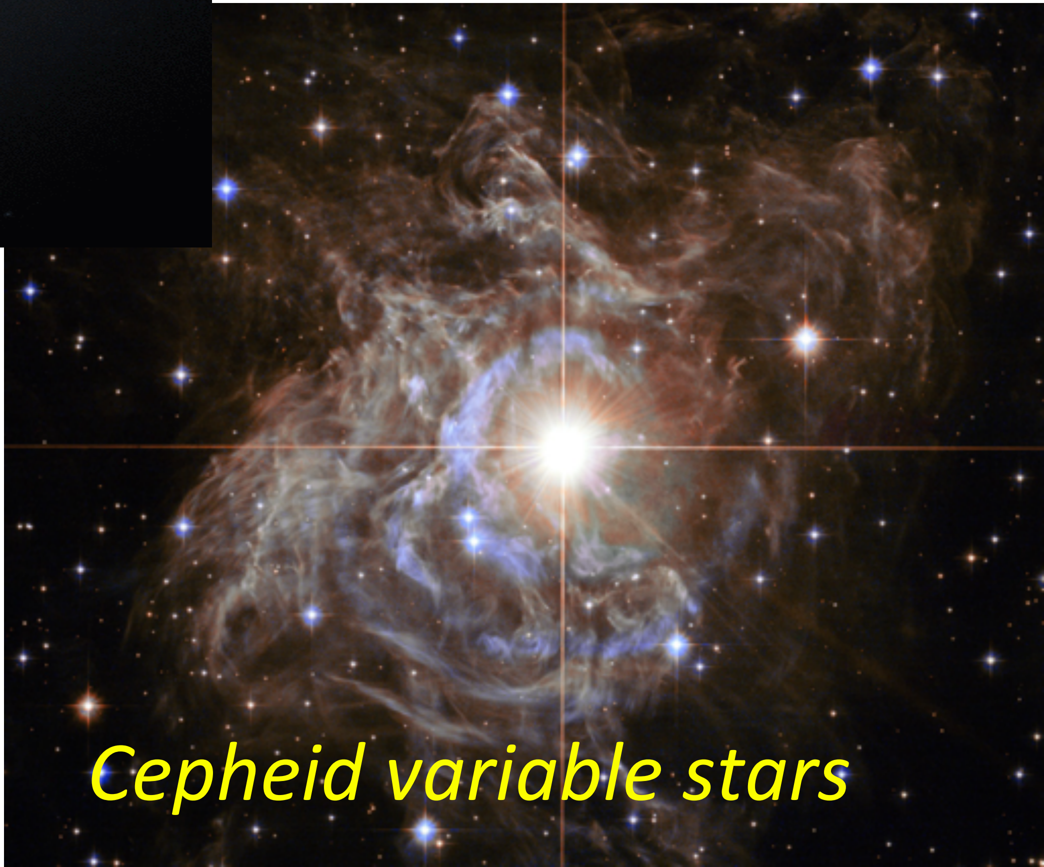
Geometrical distance from Kepler's Law

Gravitational Lenses

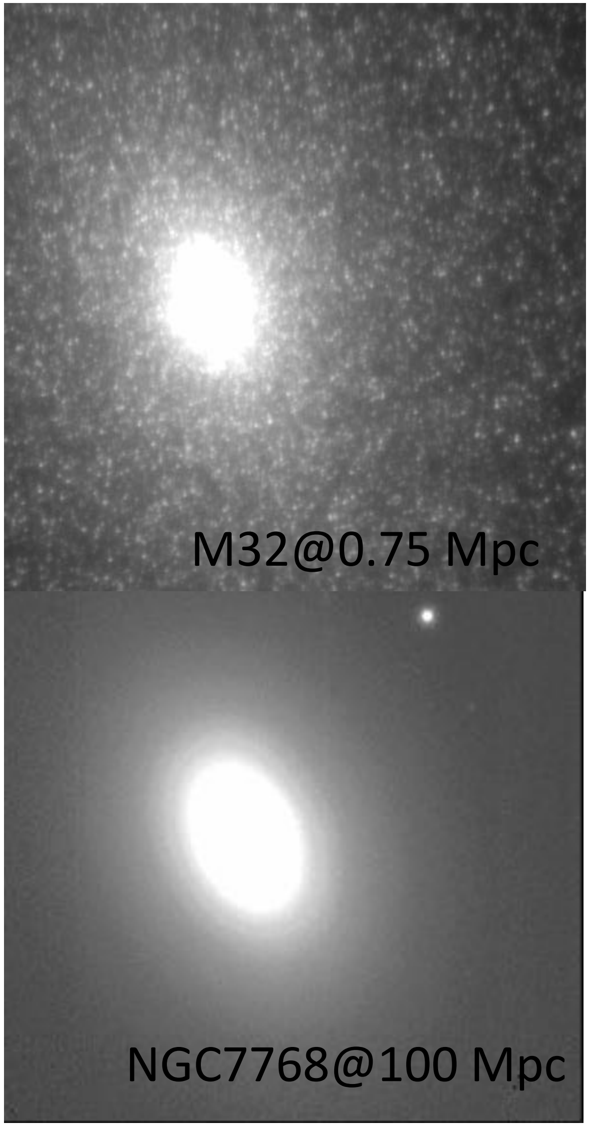


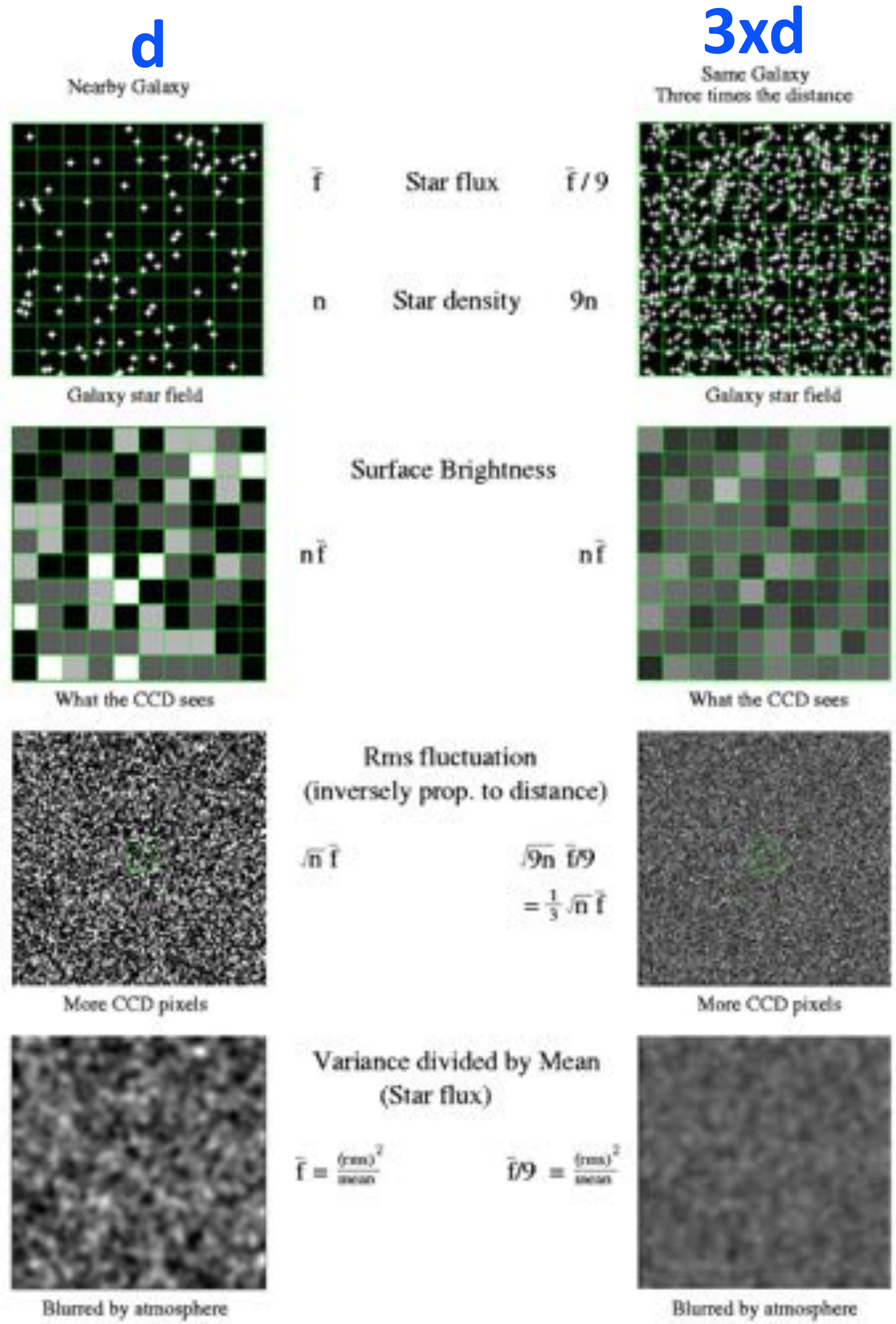


Luminosity Distances

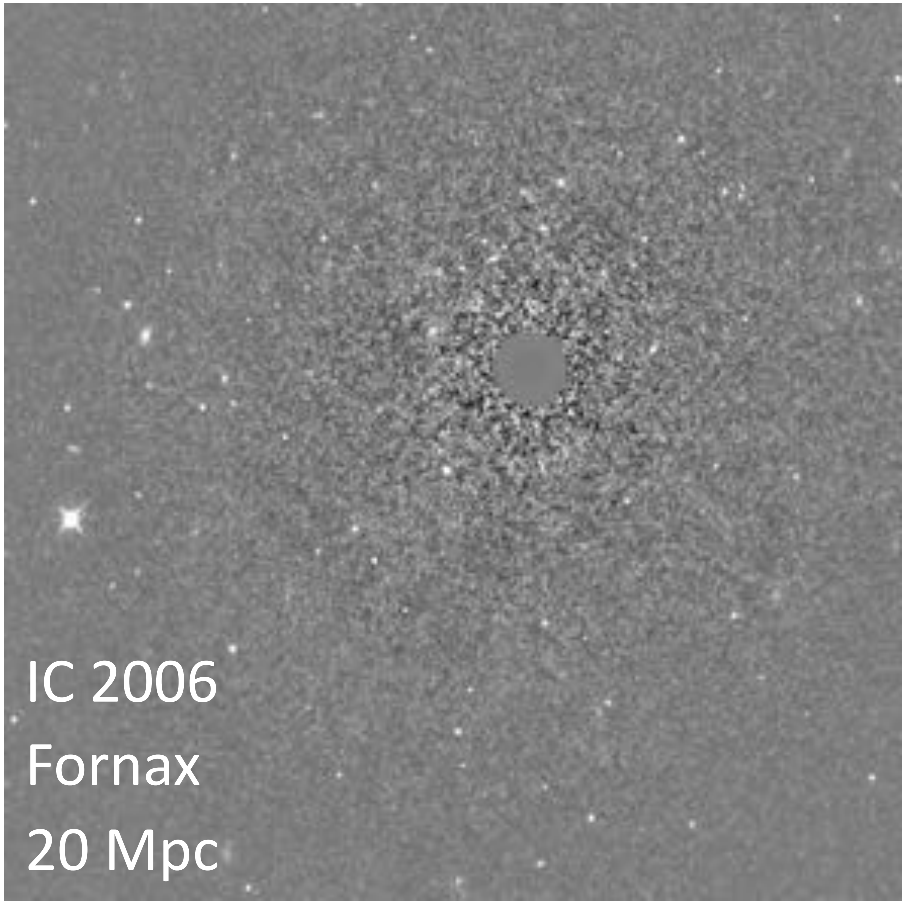


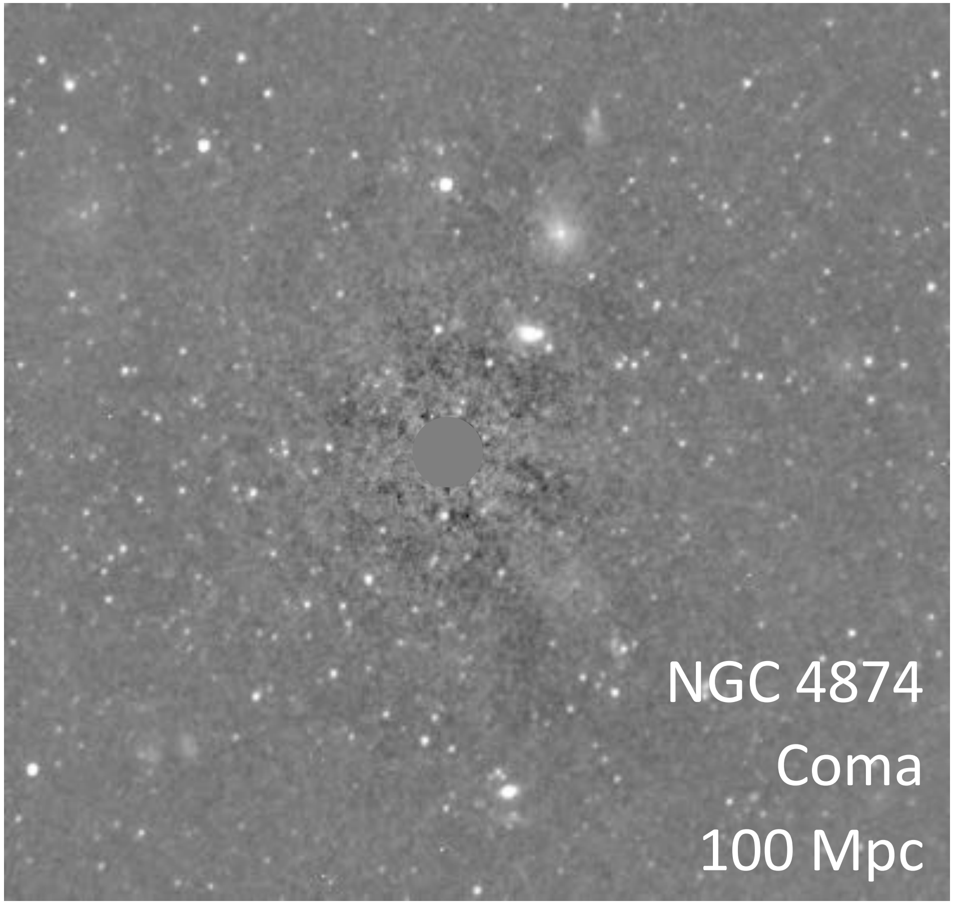
Surface Brightness Fluctuations



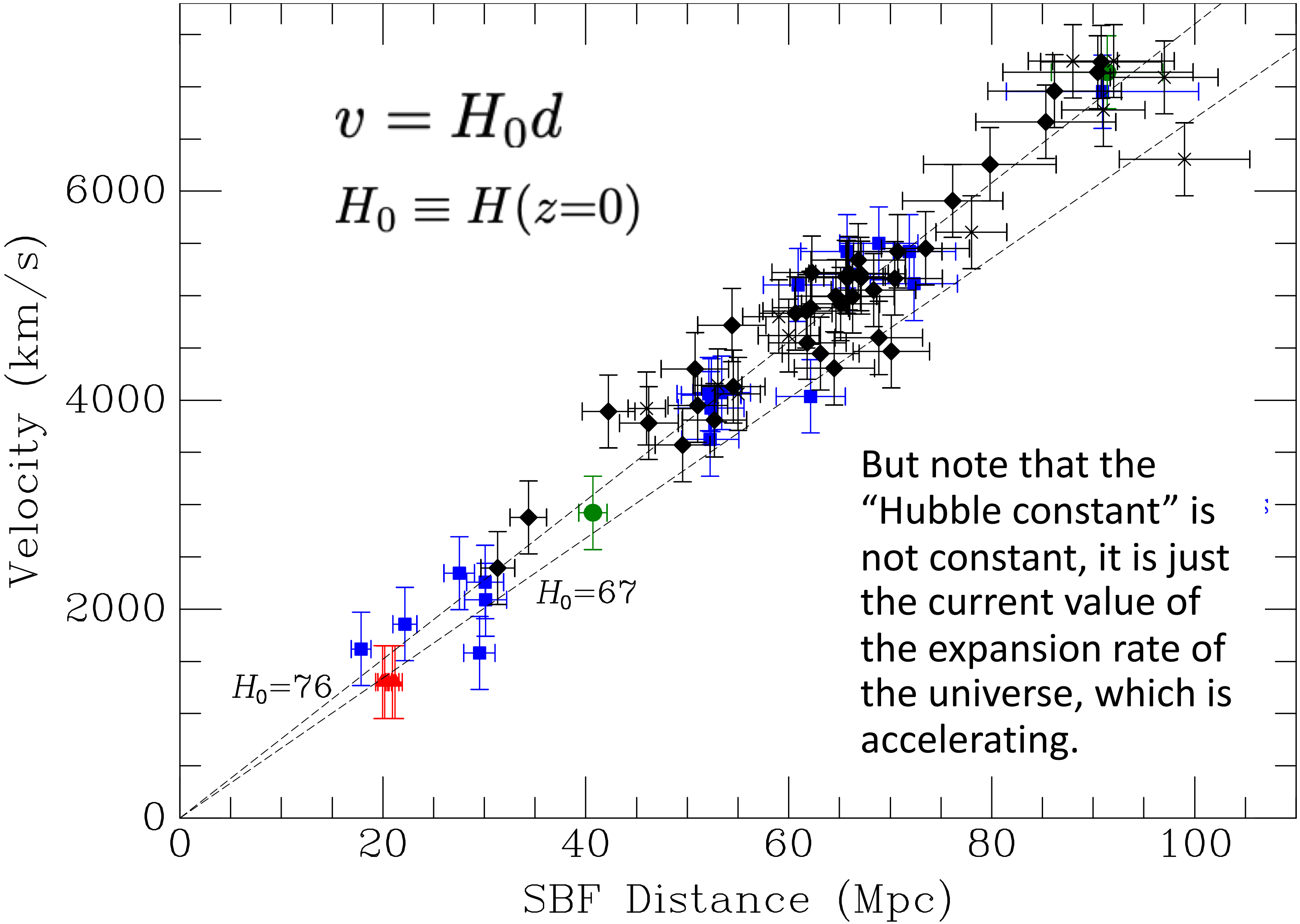


Distant galaxies appear smooth compared to nearby ones.



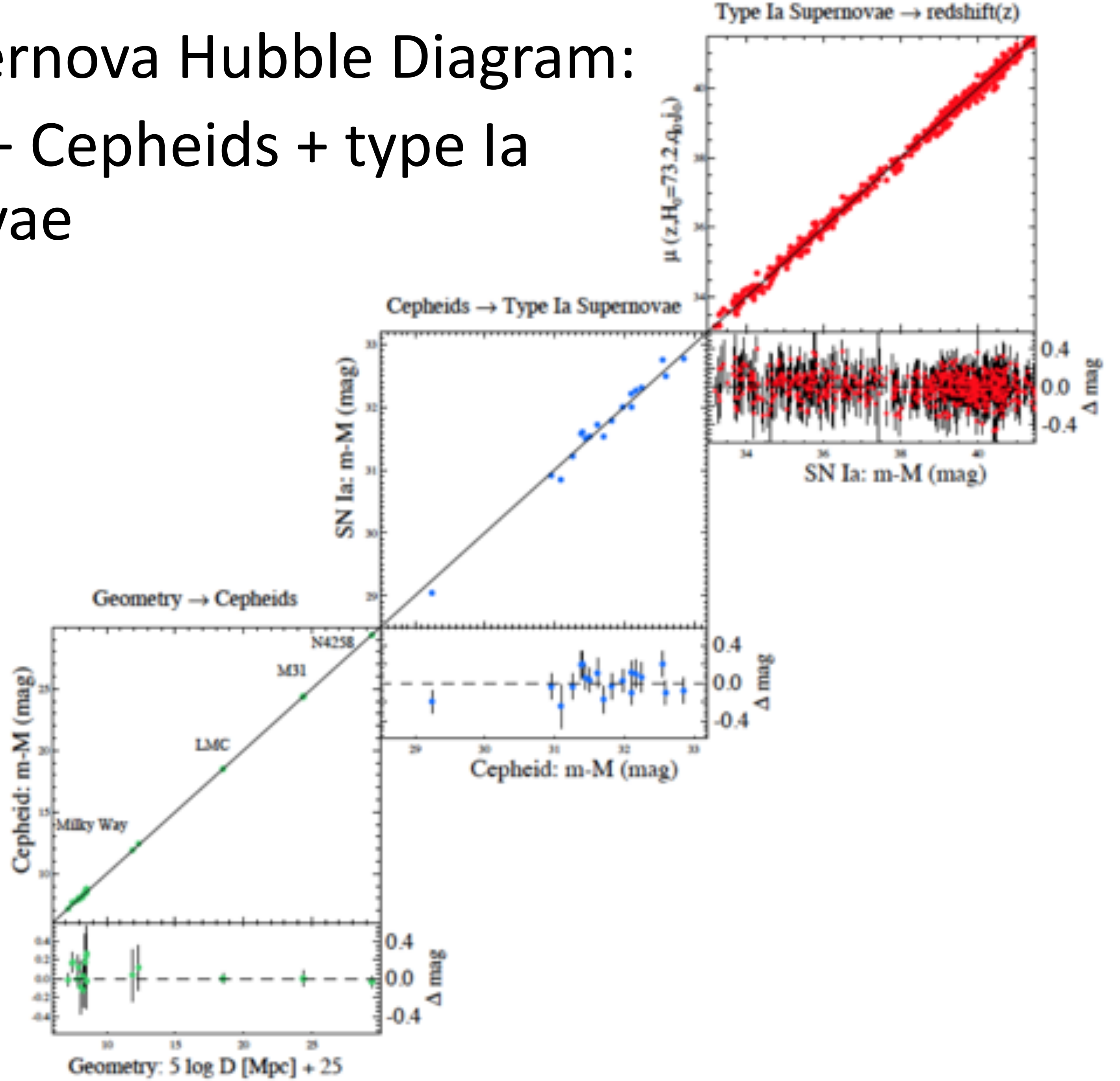


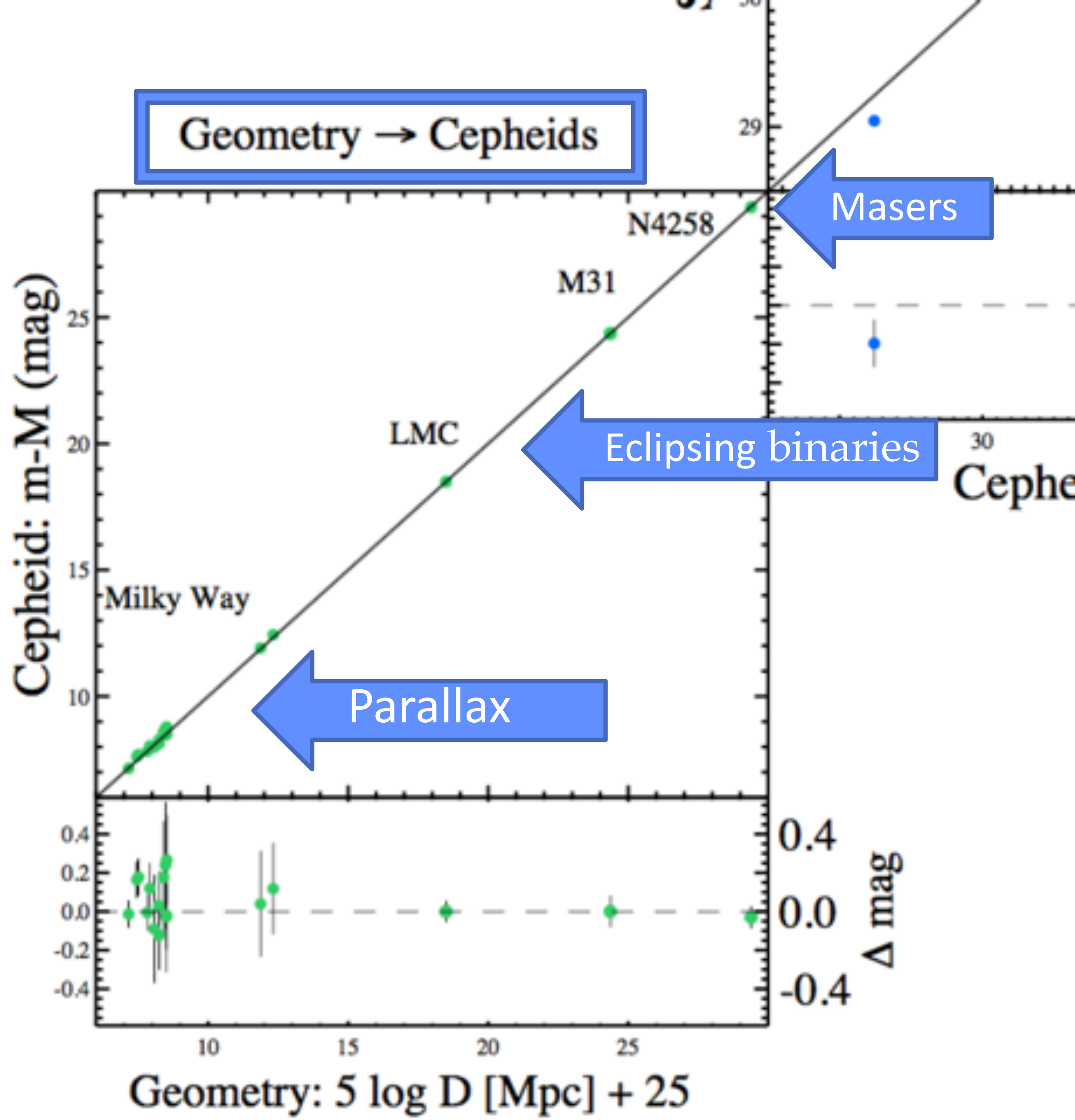
The Hubble Law



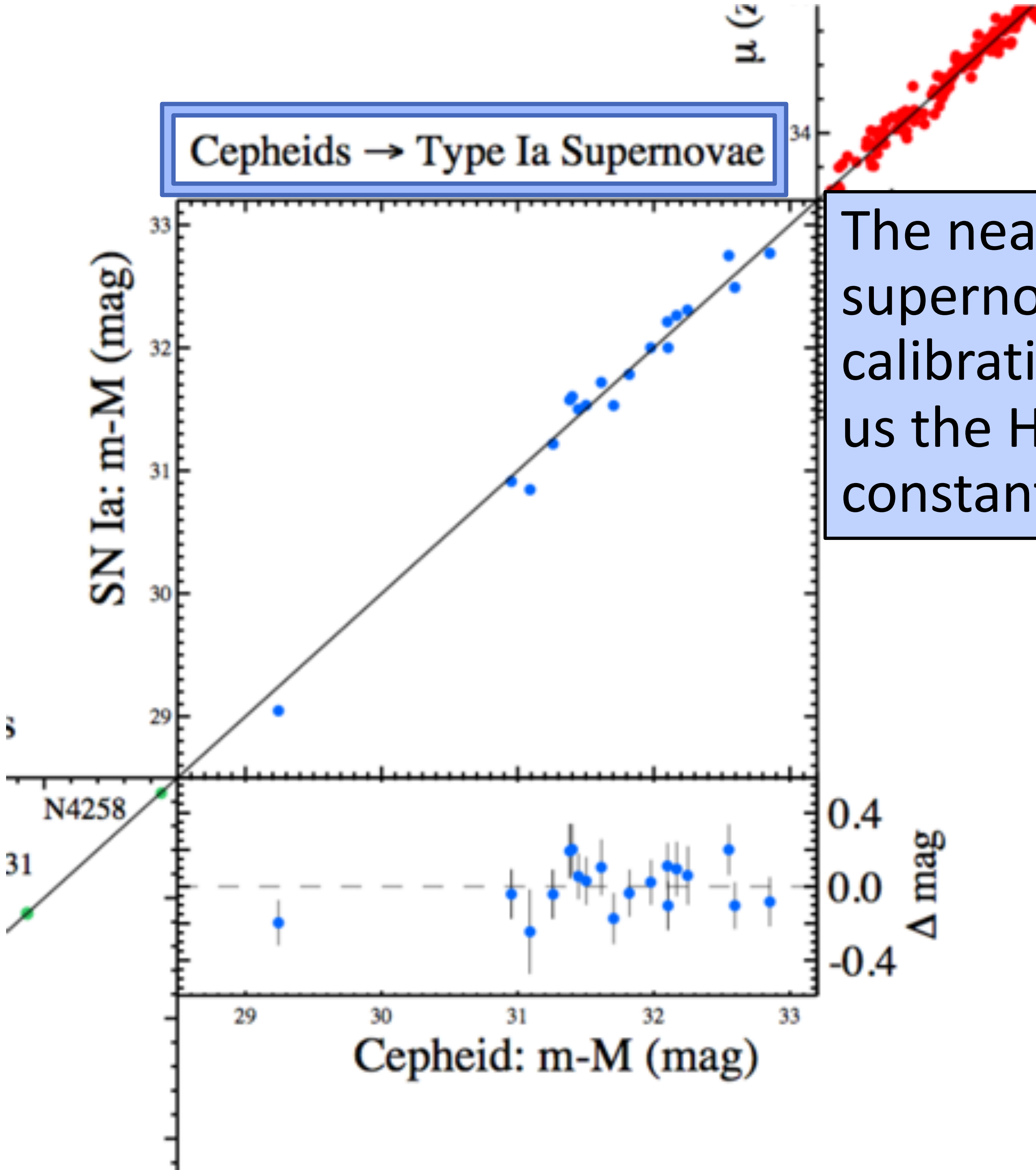
But note that the "Hubble constant" is not constant, it is just the current value of the expansion rate of the universe, which is accelerating.

The Supernova Hubble Diagram: Parallax + Cepheids + type Ia supernovae

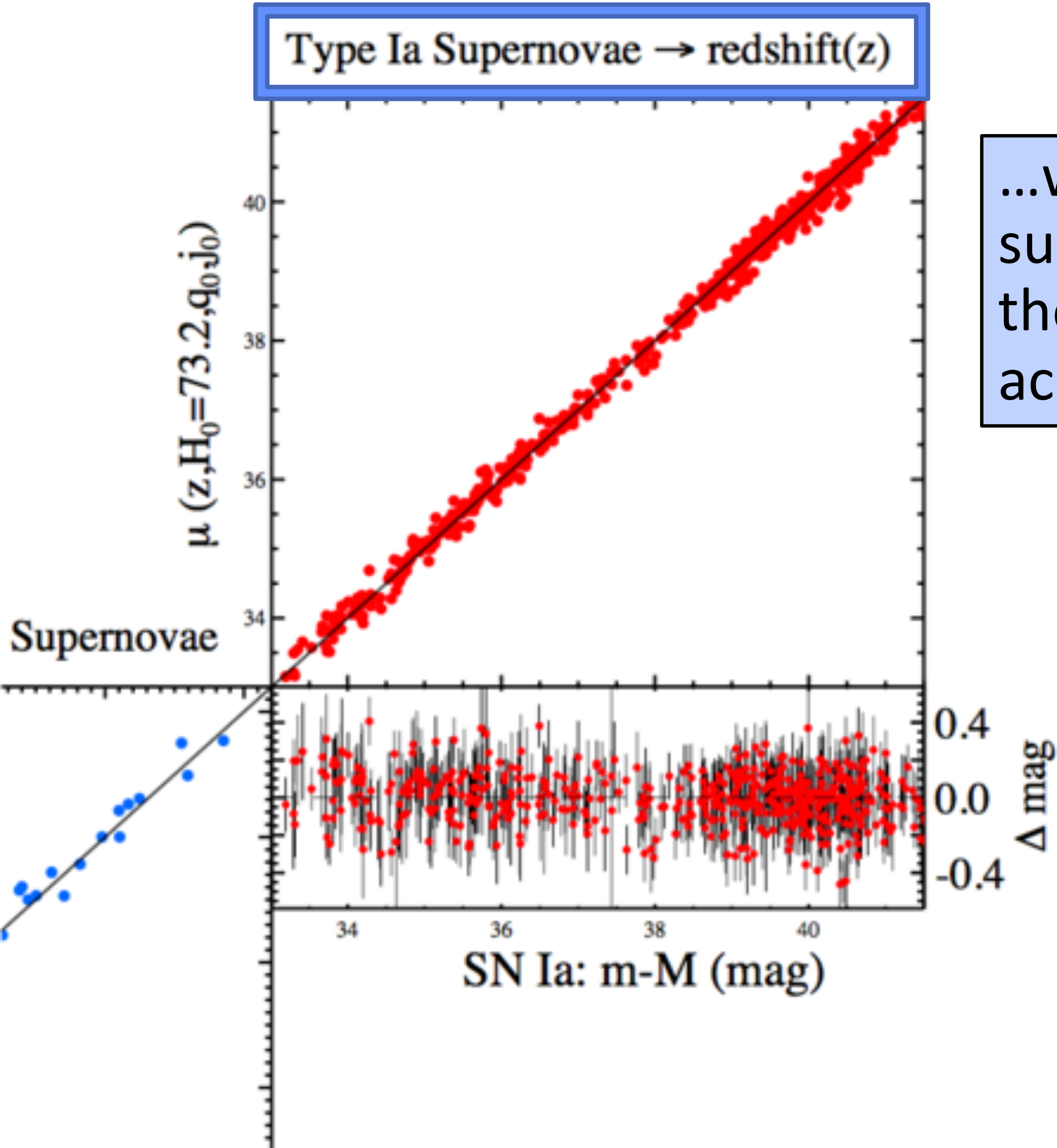




Geometry → Cepheids
Masers
Eclipsing binaries
Parallax
N4258
M31
LMC
Milky Way
Cepheid: m-M (mag)
Geometry: 5 log D [Mpc] + 25
Δ mag
0.4
0.0
-0.4
10
15
20
25
30
29

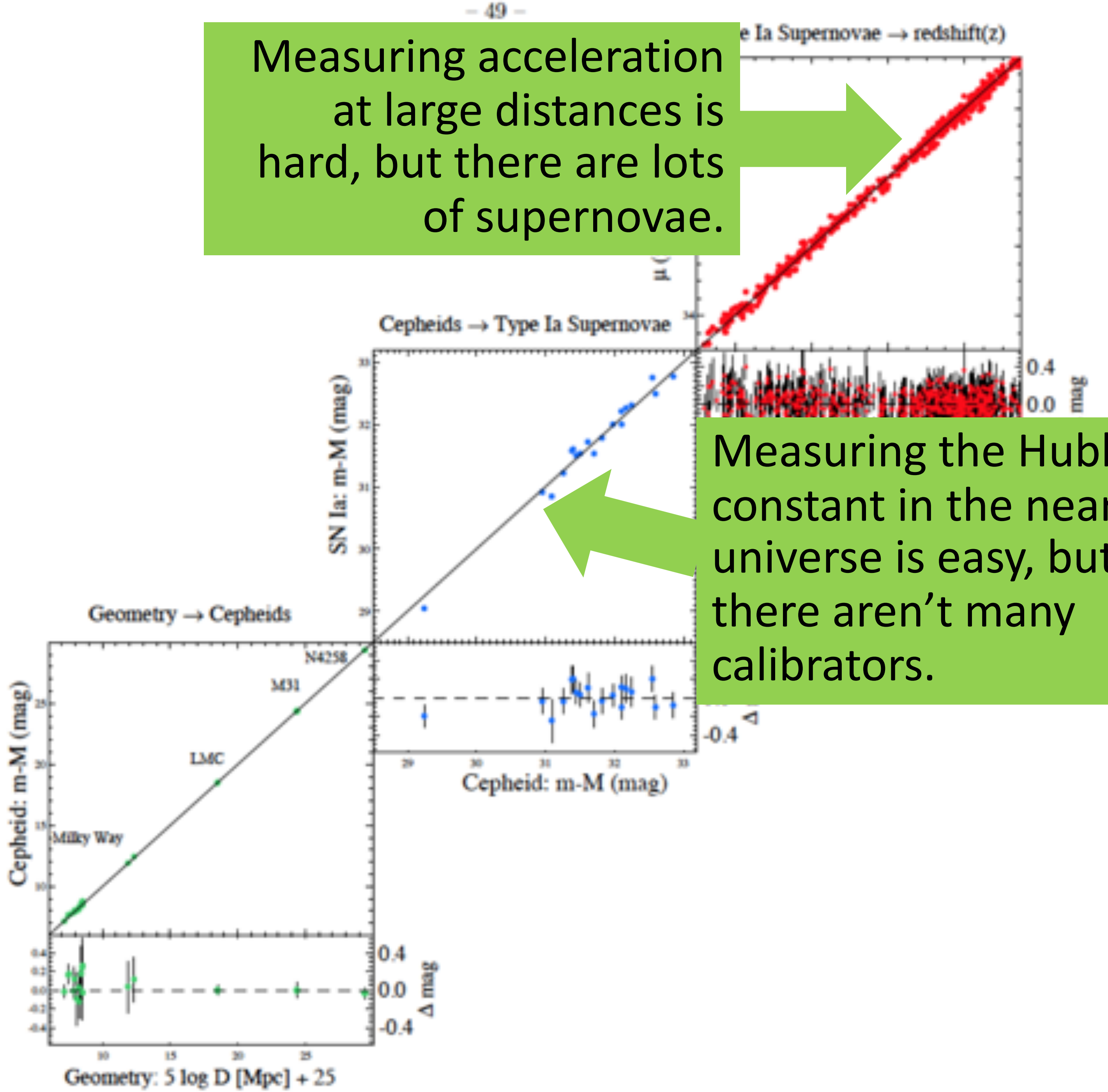


The nearby supernova calibration tells us the Hubble constant H_0 …

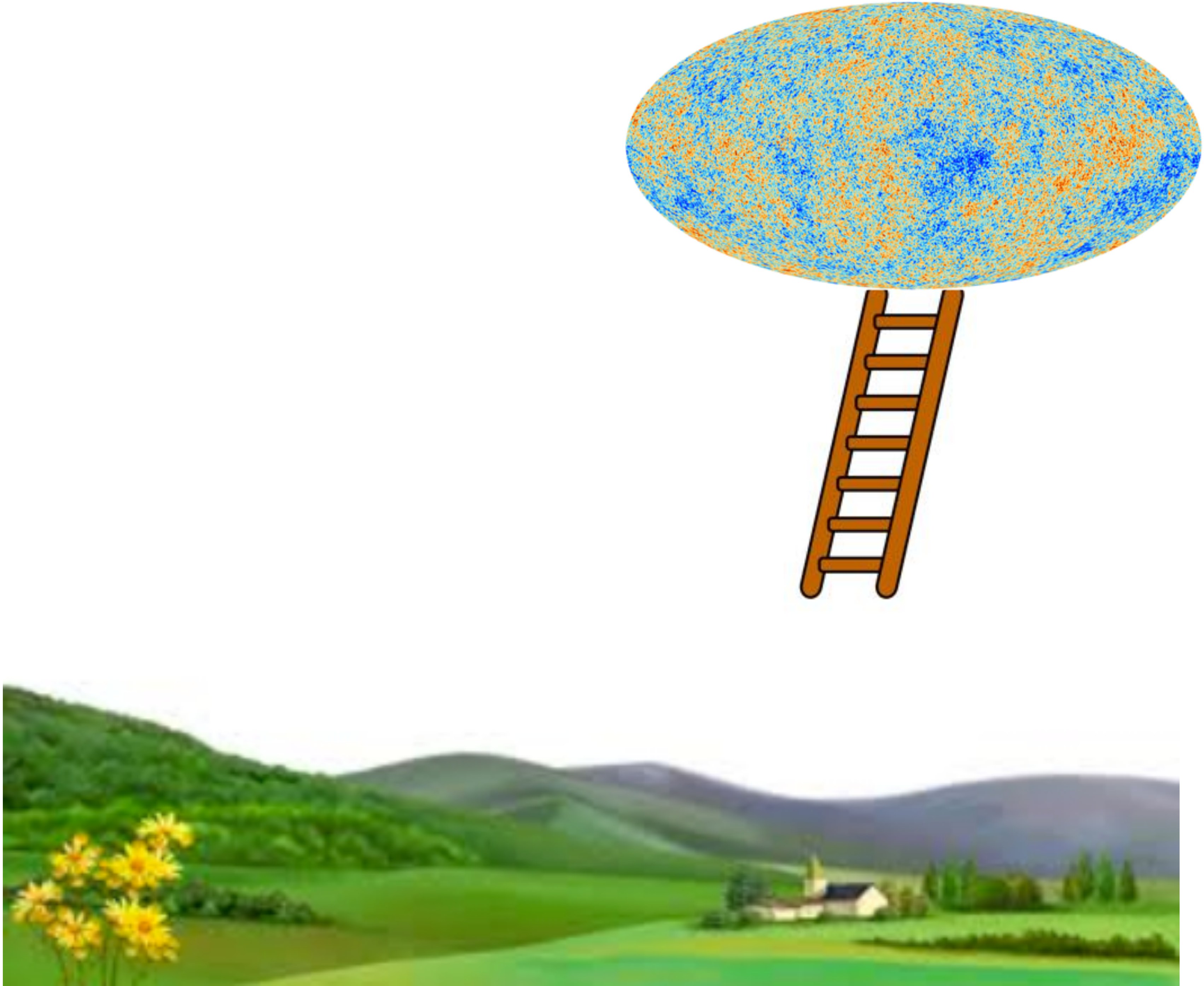


…while the distant supernovae reveal the presence of acceleration.

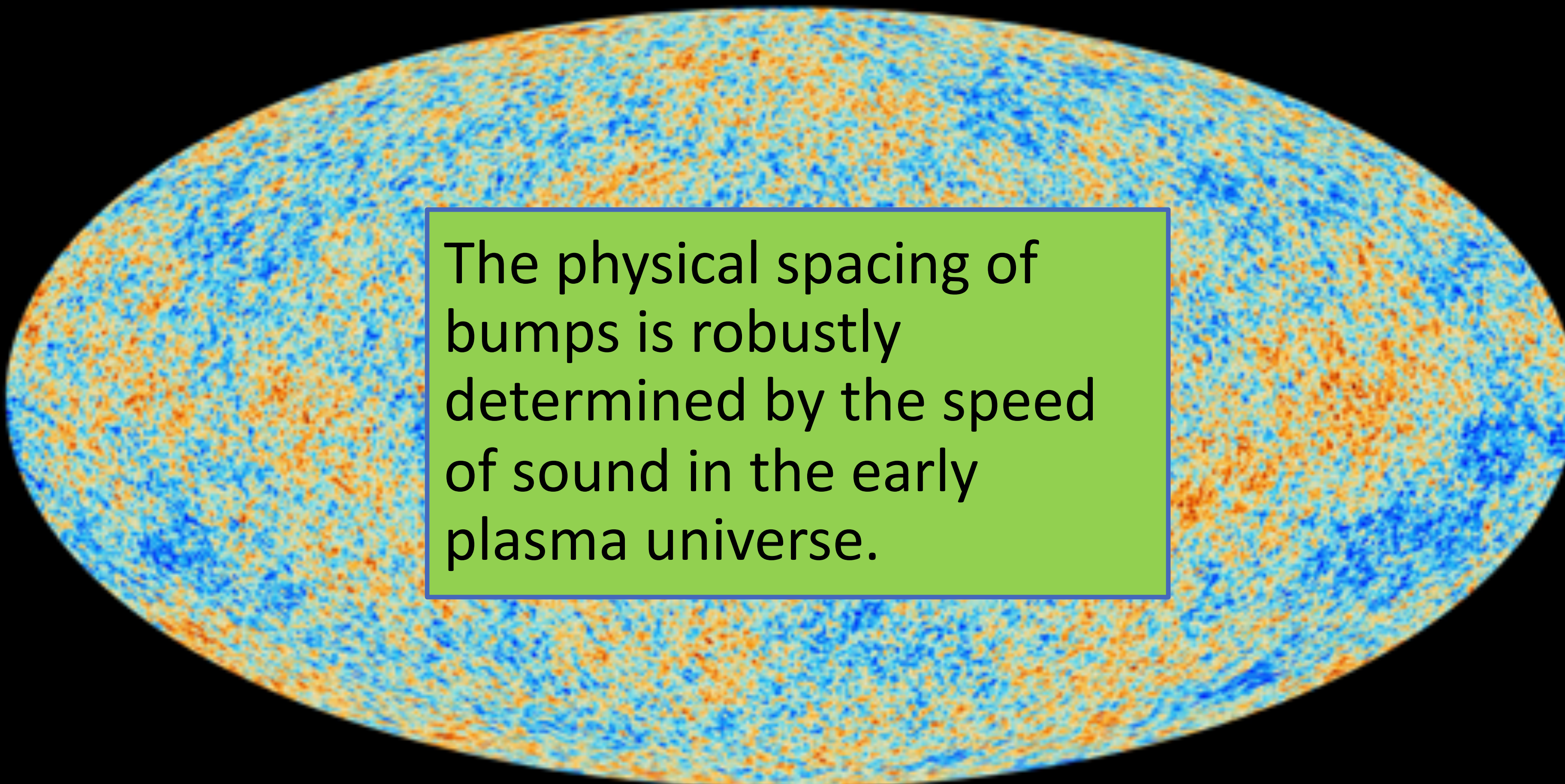
Measuring acceleration at large distances is hard, but there are lots of supernovae.



Measuring the Hubble constant in the nearby universe is easy, but there aren’t many calibrators.

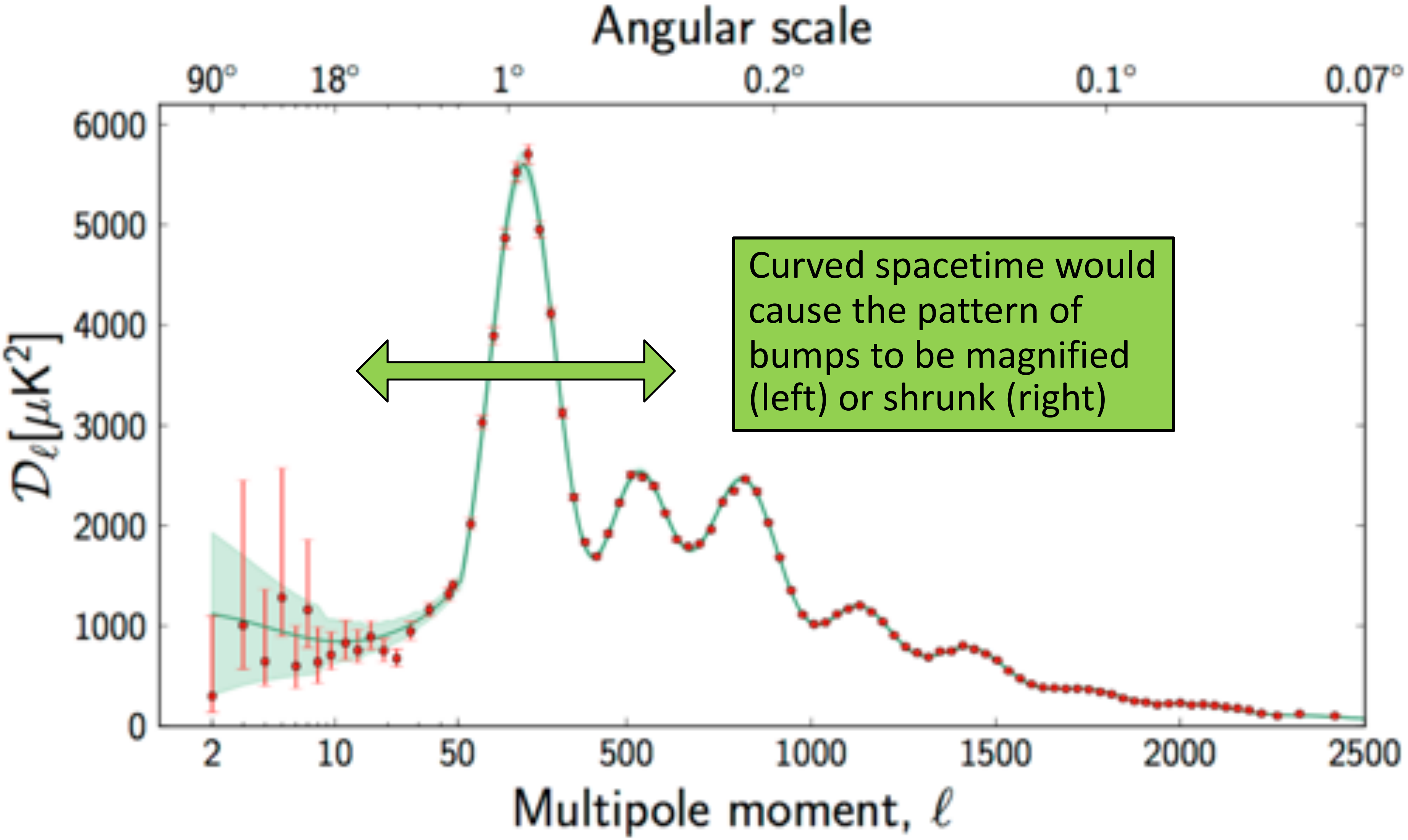


Fluctuations in the Cosmic Microwave Background Radiation (CMBR) tell us the universe is *flat*.



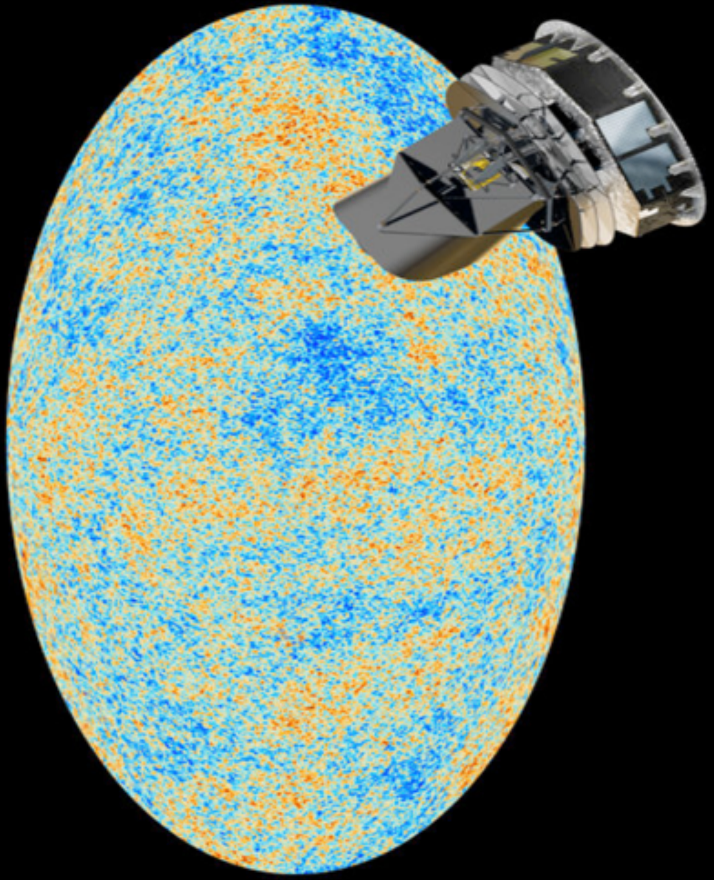
The physical spacing of bumps is robustly determined by the speed of sound in the early plasma universe.

The CMB spatial power spectrum



CMB Concordance Cosmology

- $\Omega_\Lambda = 0.6889 \pm 0.0056$
- $\Omega_m = 0.3111 \pm 0.0056$
- $\Omega_b = 0.0489 \pm 0.0003$
- $\Omega_k = 0.0007 \pm 0.004$
- $t_0 = 13.787 \pm 0.020$ Gyr
- $H_0 = 67.66 \pm 0.42$ km/s/Mpc
- $w = -1.04 \pm 0.1$
- z(reionization) $= 7.82 \pm 0.71$
- $N_{eff} = 2.99 \pm 0.34$
- Neutrino mass < 0.12 eV



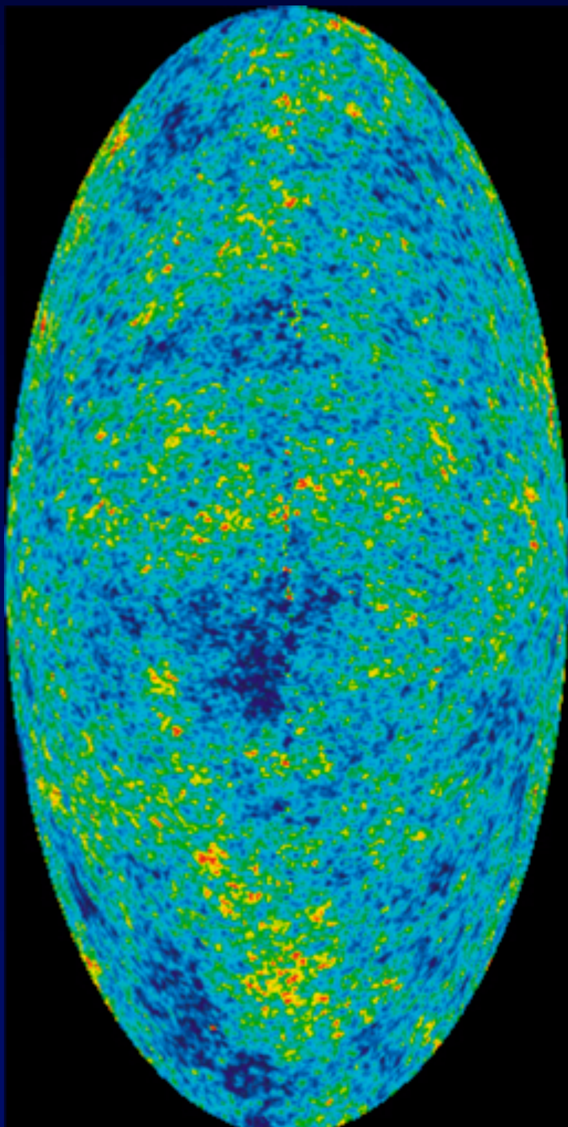
Joint constraints: Planck 2018 + lensing + BAO

CMB Concordance Cosmology

- $\Omega_\Lambda = 0.6889 \pm 0.0056$ Dark Energy dominates
- $\Omega_m = 0.3111 \pm 0.0056$ Gravitational matter
- $\Omega_b = 0.0489 \pm 0.0003$ Baryonic matter
- $\Omega_k = 0.0007 \pm 0.004$ Curvature of spacetime
- $t_0 = 13.787 \pm 0.020$ Gyr Age of the universe
- $H_0 = 67.66 \pm 0.42$ km/s/Mpc Expansion rate
- $w = -1.04 \pm 0.1$ Universal equation of state p/ρ
- z(reionization) $= 7.82 \pm 0.71$ When stars formed
- $N_{eff} = 2.99 \pm 0.34$ Number of neutrino species
- Neutrino mass < 0.12 eV Total neutrino mass

Joint constraints: Planck 2018 + lensing + BAO

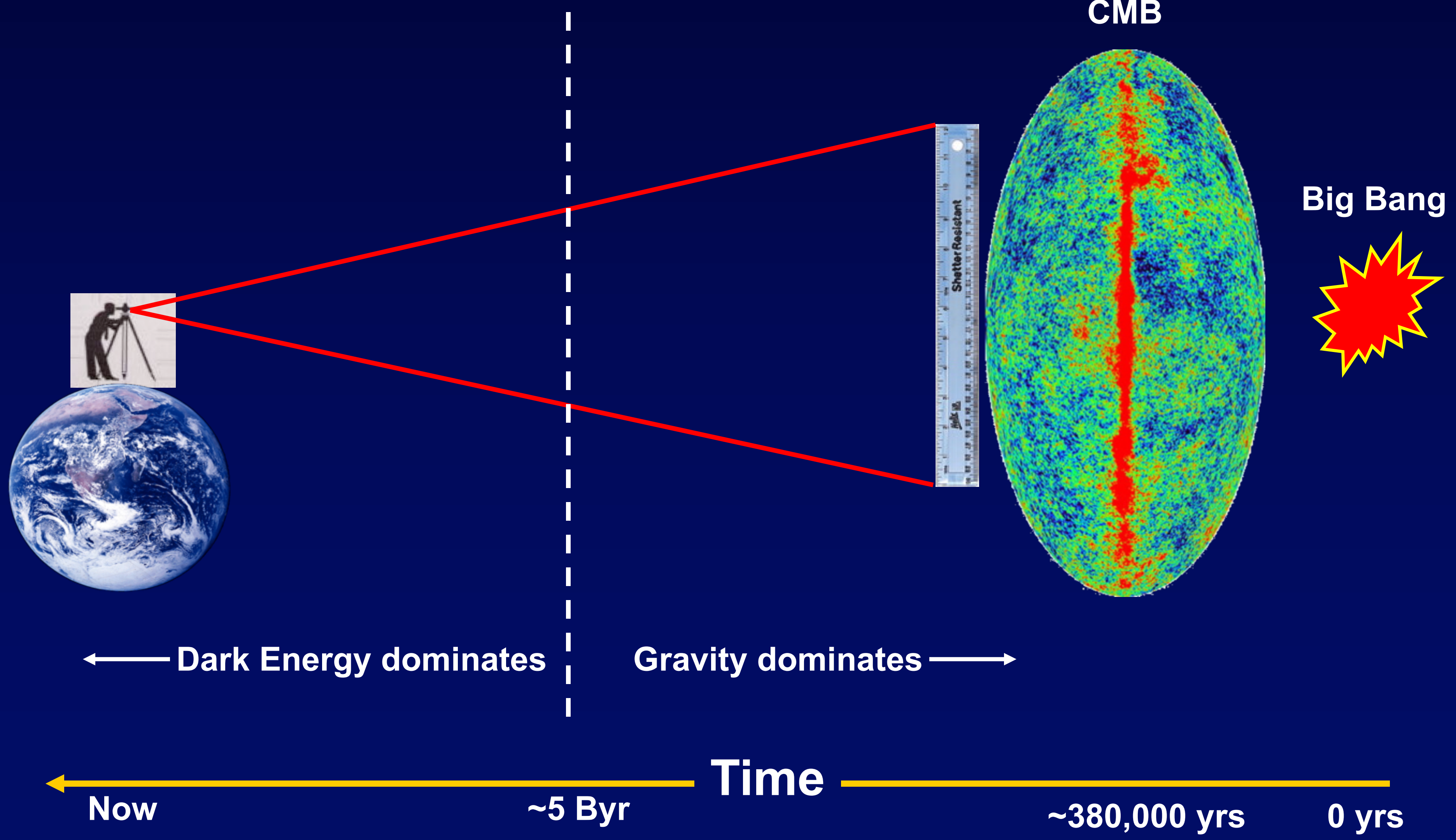
The CMB spatial power spectrum



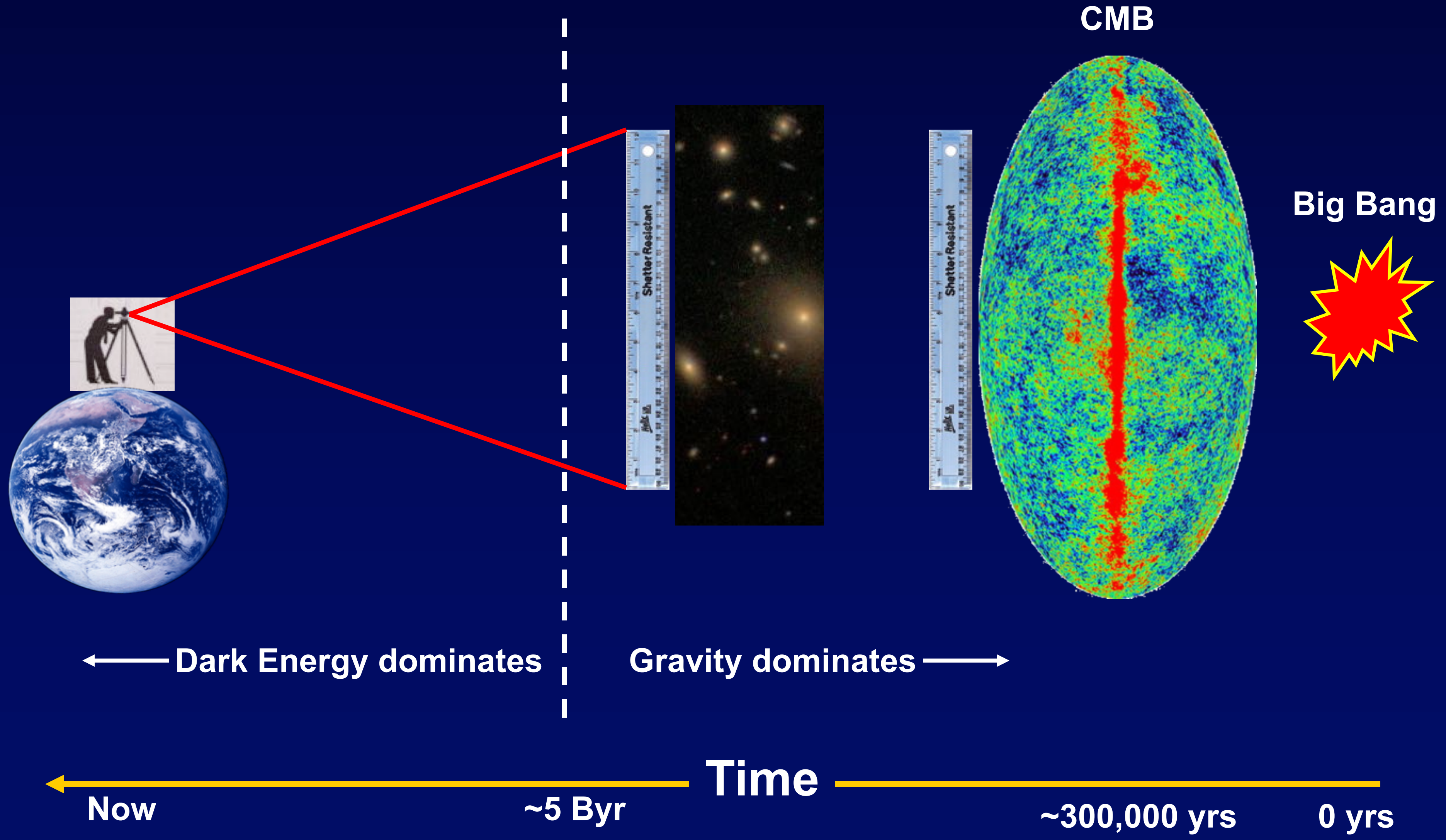
The same pattern of acoustic oscillations seen in the CMB power spectrum is imprinted on the distribution of galaxies today.

The preferred scale of the clumps is a standard ruler, which can be measured at different redshifts.

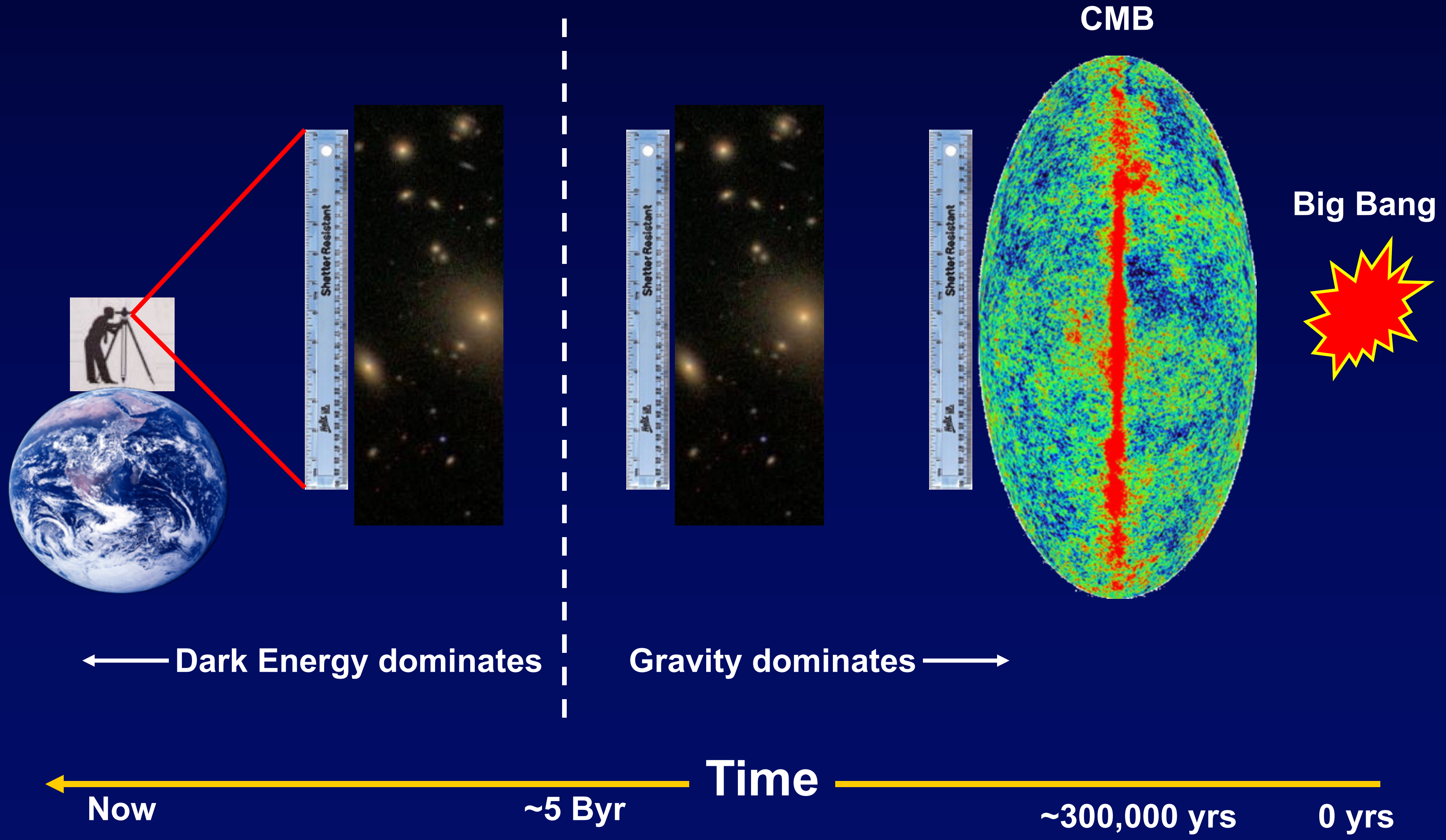
Measuring Cosmic Acceleration

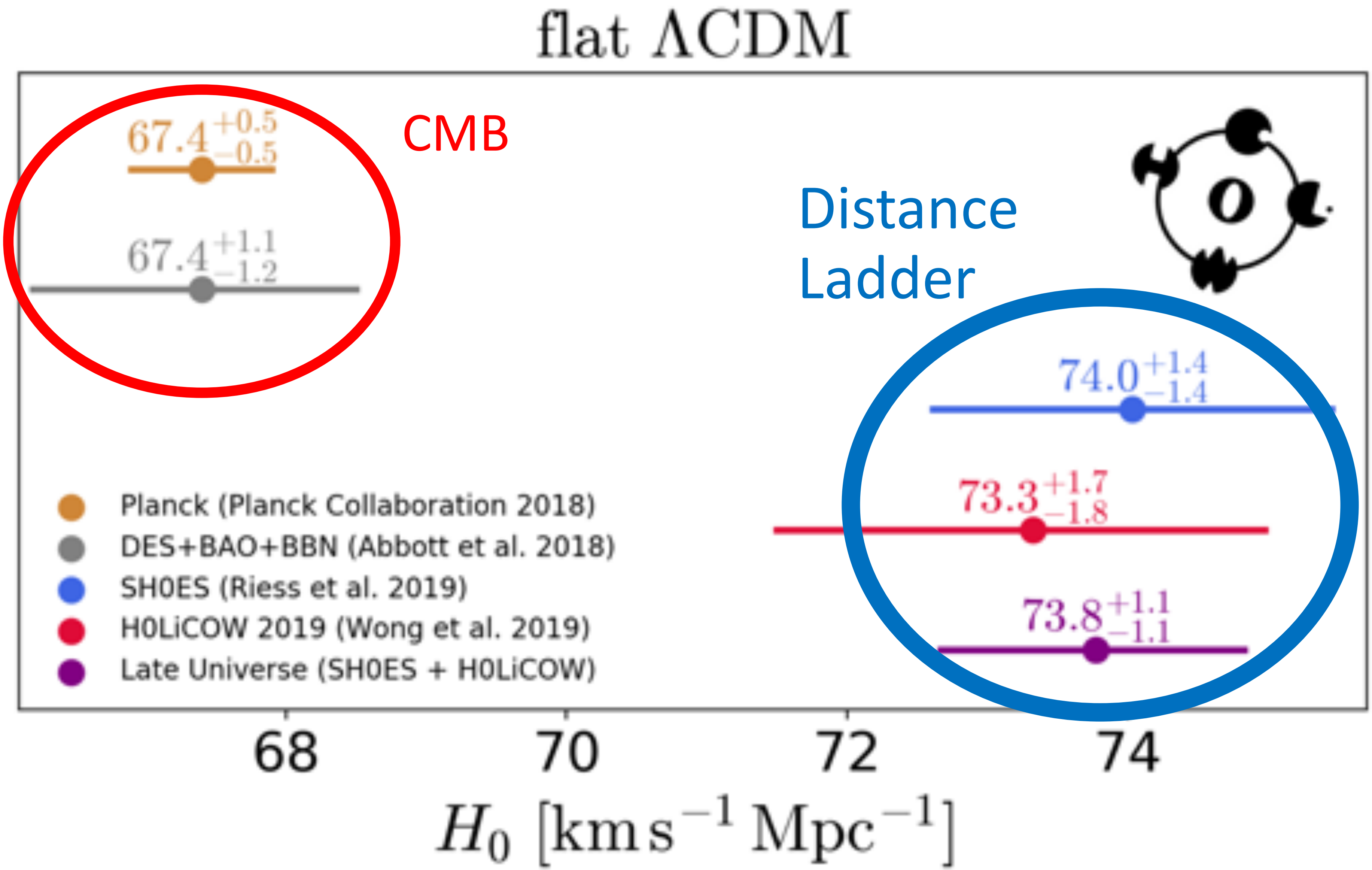


Measuring Cosmic Acceleration



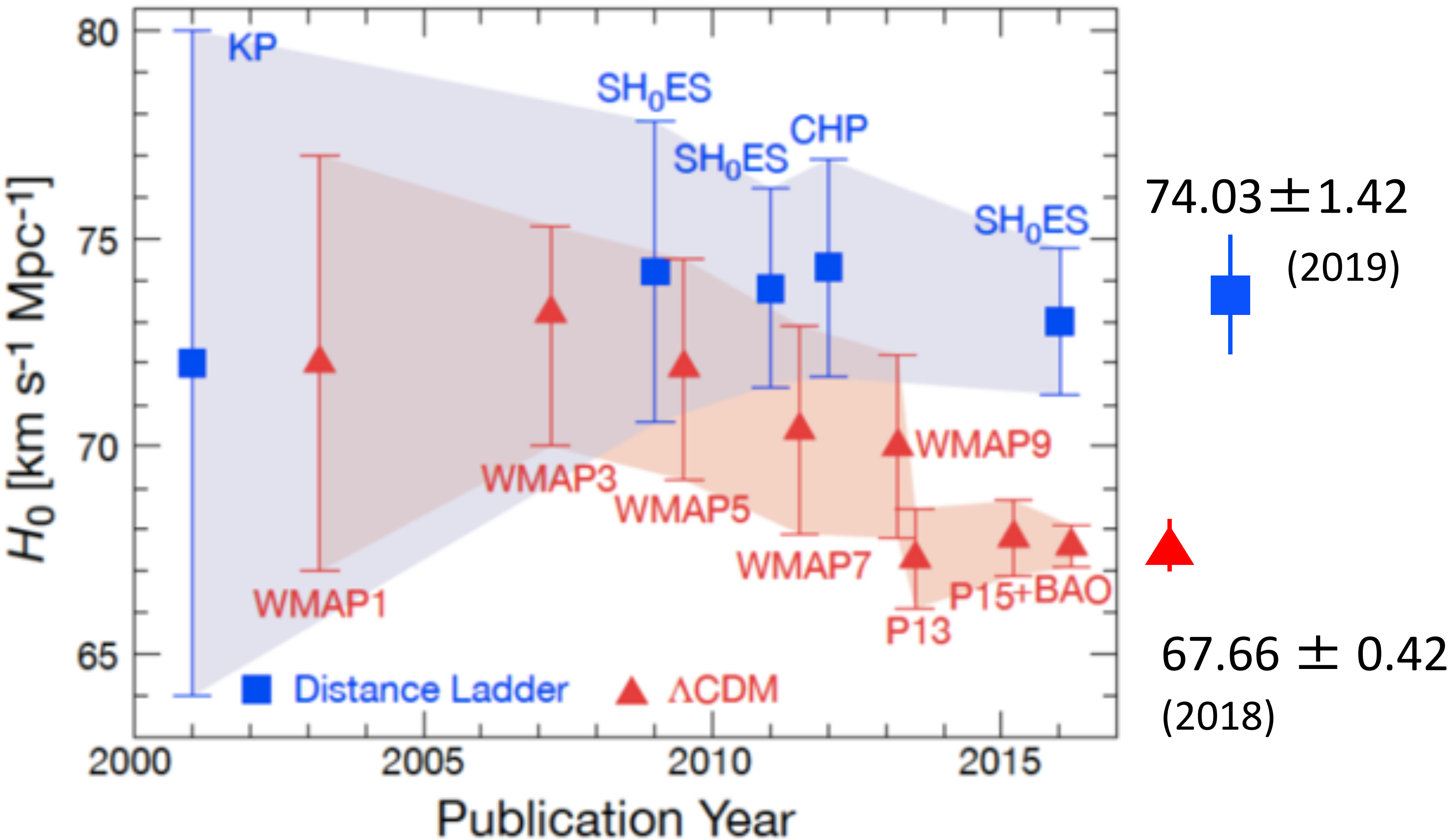
Measuring Cosmic Acceleration

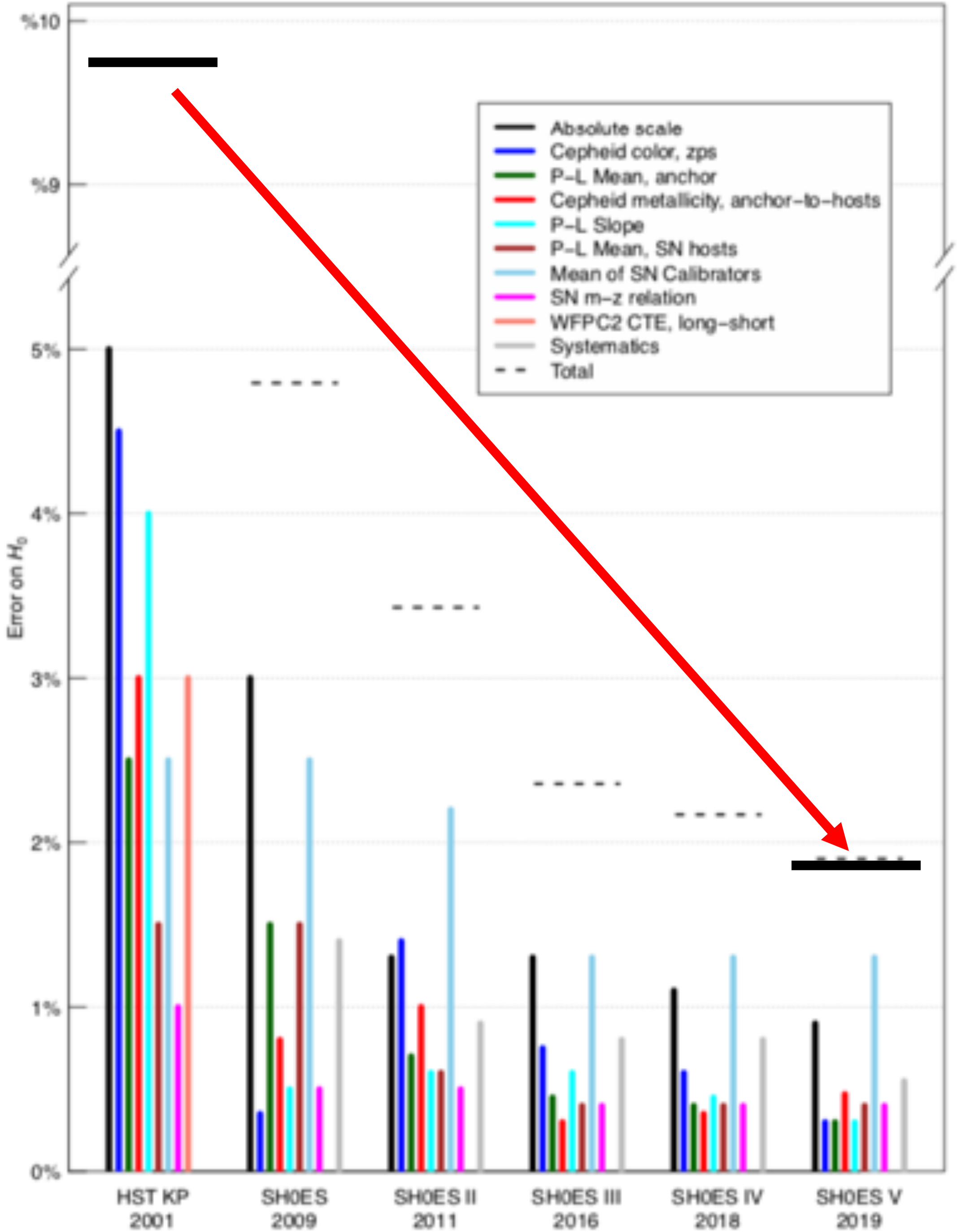




flat ΛCDM
CMB
Distance
Ladder
67.4 +0.5 −0.5
67.4 +1.1 −1.2
74.0 +1.4 −1.4
73.3 +1.7 −1.8
73.8 +1.1 −1.1
Planck (Planck Collaboration 2018)
DES+BAO+BBN (Abbott et al. 2018)
SH0ES (Riess et al. 2019)
H0LiCOW 2019 (Wong et al. 2019)
Late Universe (SH0ES + H0LiCOW)
68
70
72
74
H0 [km s−1 Mpc−1]

Tension between CMB and Cepheids+SNe is now ~4.4σ



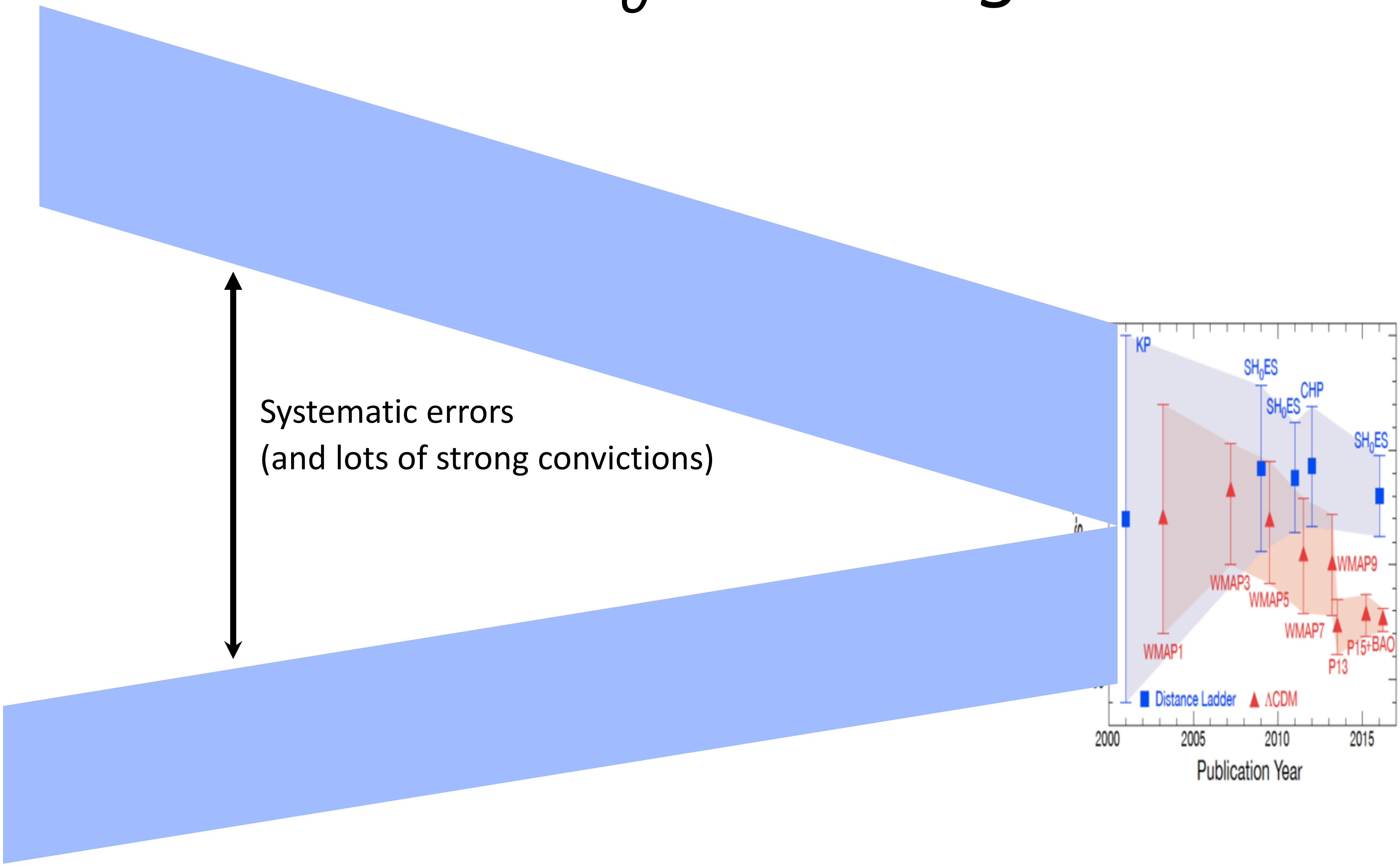


Statistical errors are reduced by repeated observations.

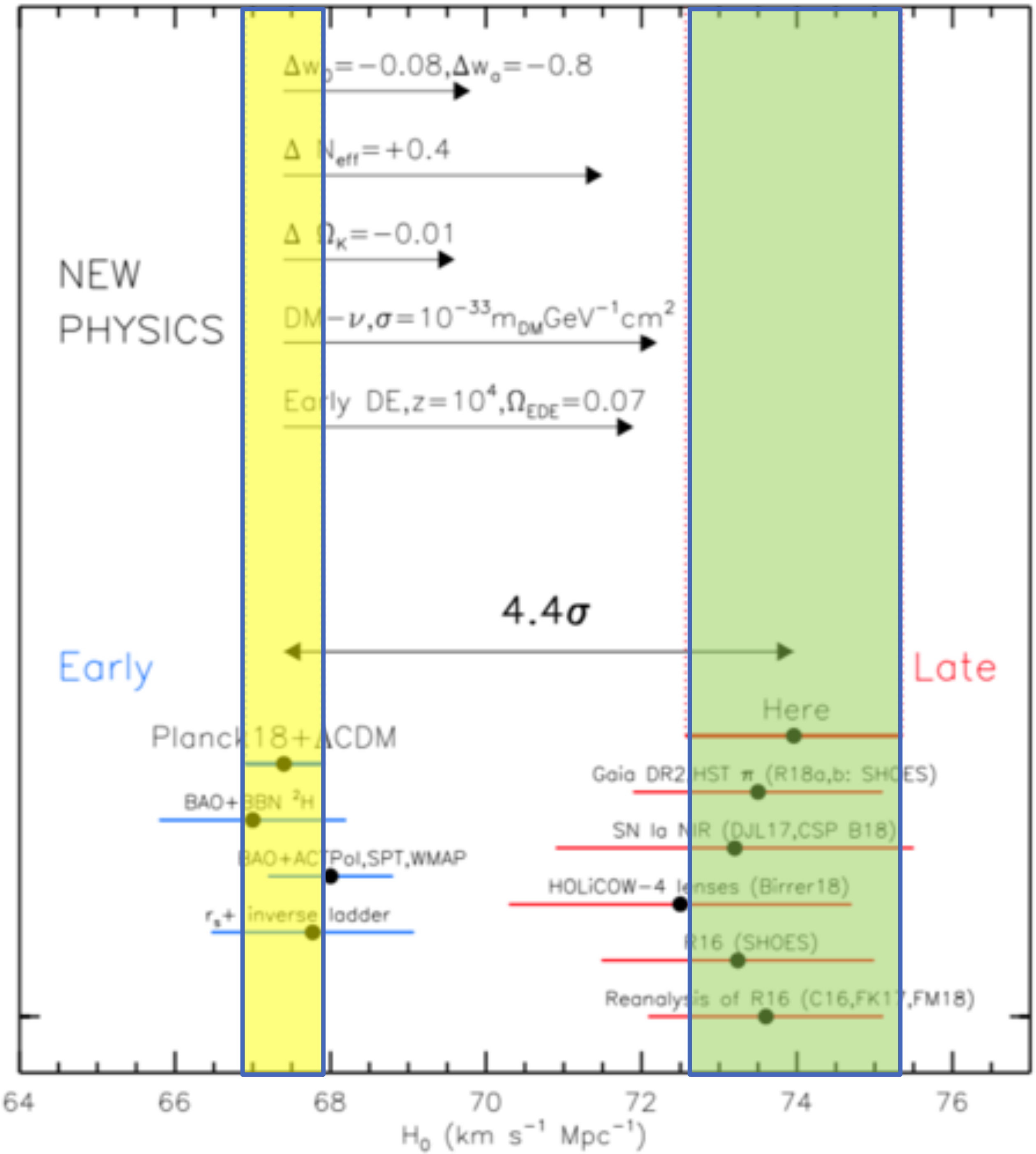
Systematic errors are reduced by developing different methods.


SNe
CMB

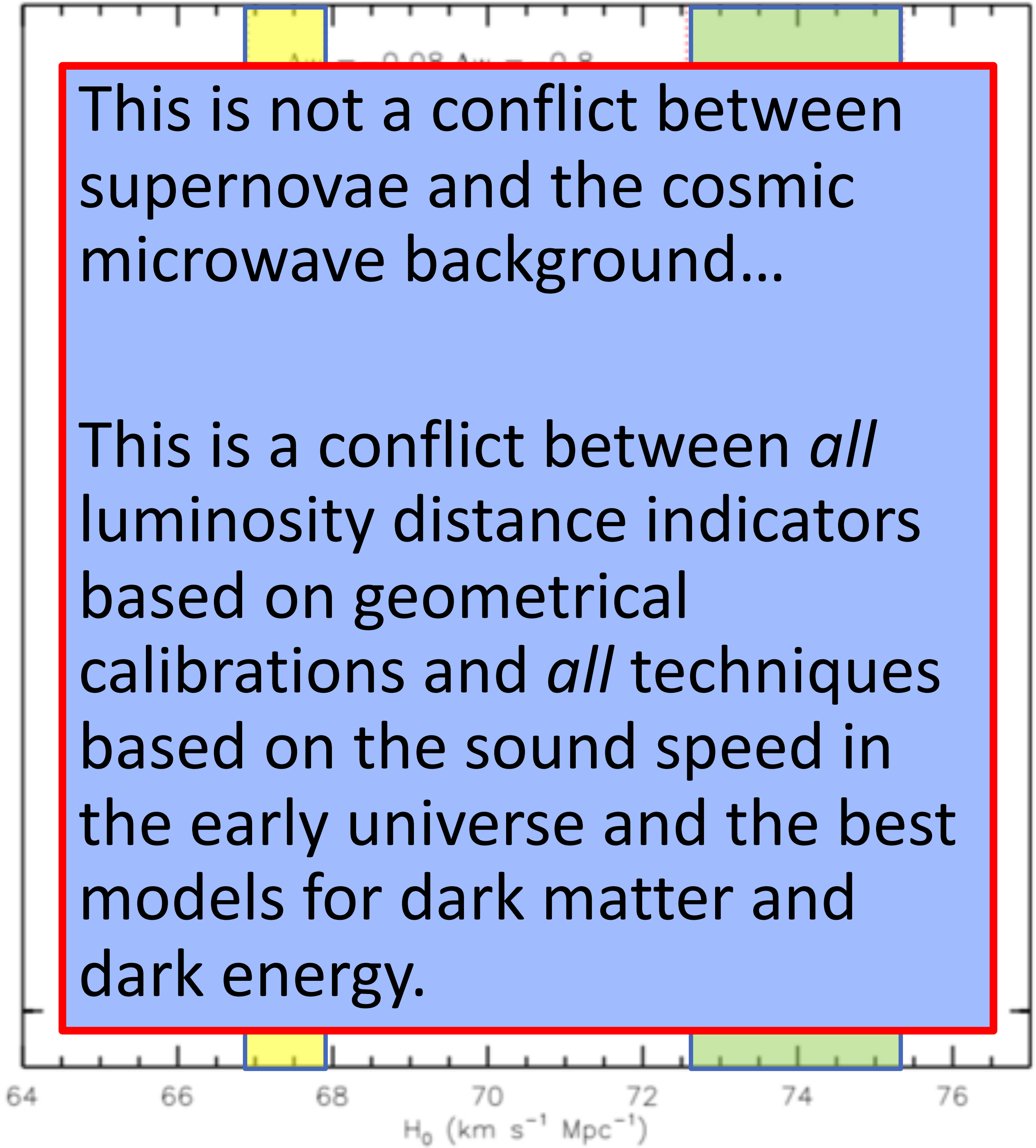
“Tension” in H_0 is nothing new…



Riess et al. 2019



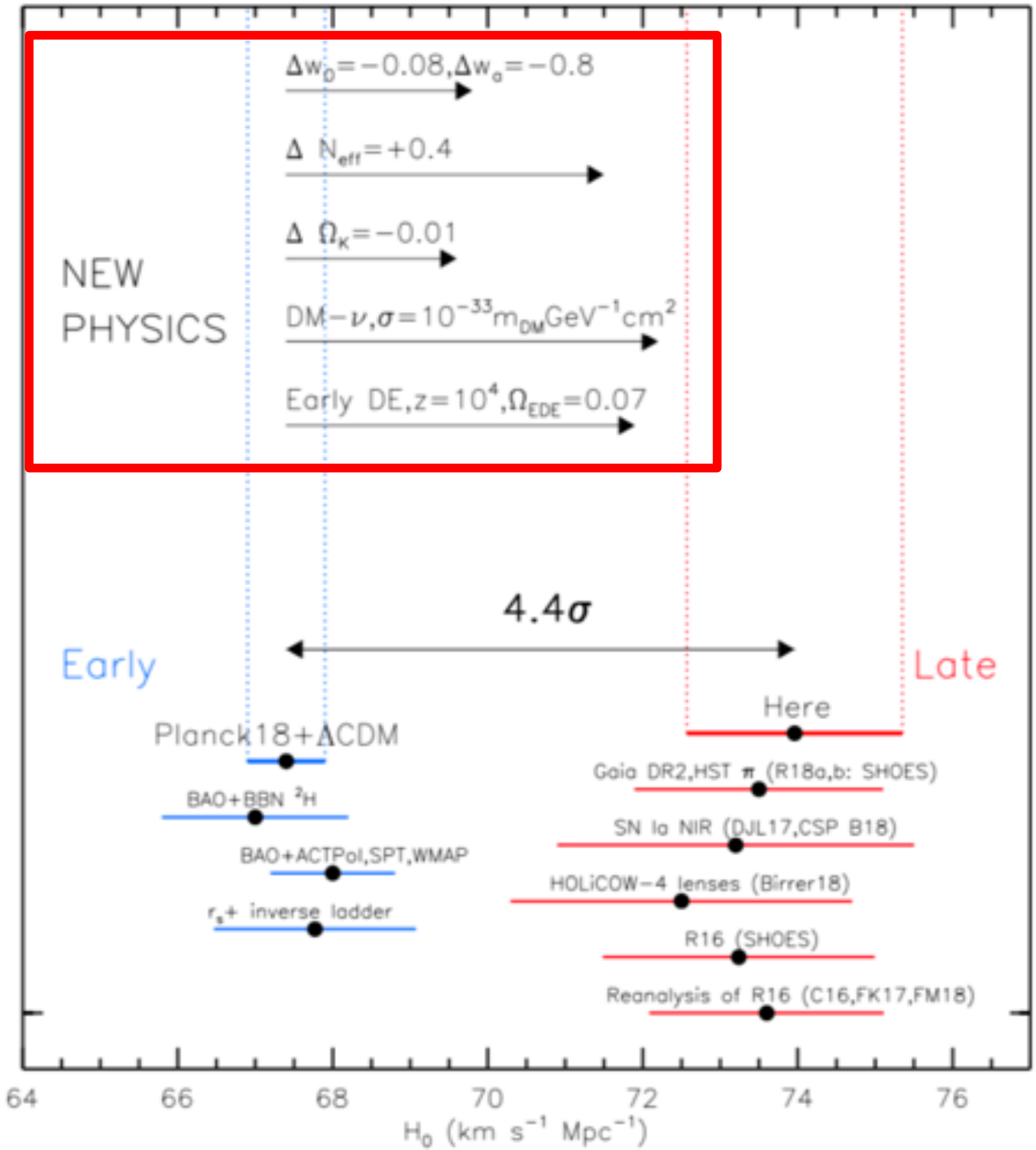
Riess et al. 2019



This is not a conflict between supernovae and the cosmic microwave background…

This is a conflict between *all* luminosity distance indicators based on geometrical calibrations and *all* techniques based on the sound speed in the early universe and the best models for dark matter and dark energy.

Riess et al. 2019



Possible Explanations

Horizon size or sound speed is wrong?

Additional relativistic particles or neutrino coupling?

Additional energy before recombination?

Combination of systematic zero point errors?

Possible Explanations

Horizon size or sound speed is wrong?

The problem is that changing one parameter creates disagreement in other parameters…tension in one area can be reduced but others get worse…

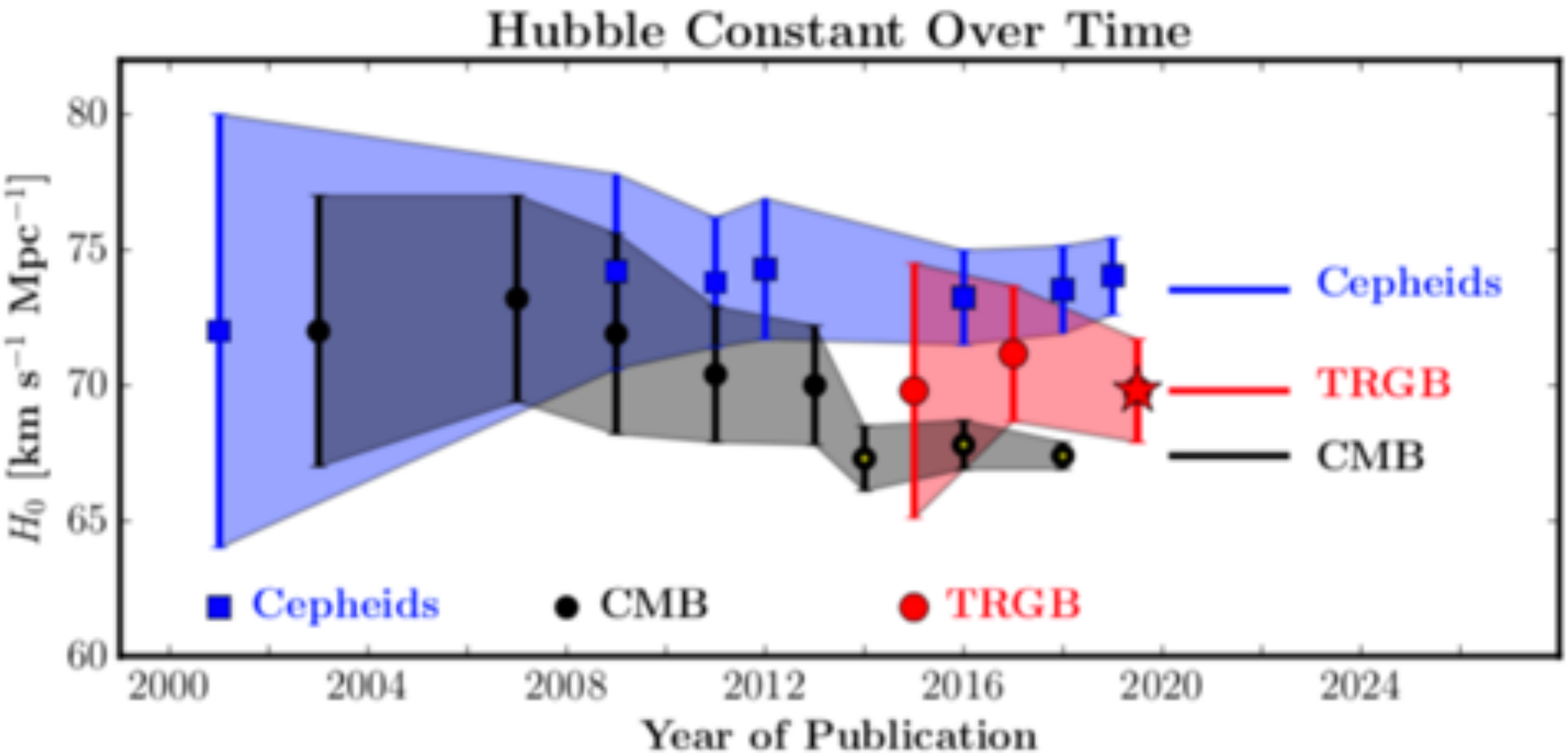
Addi… …ing?

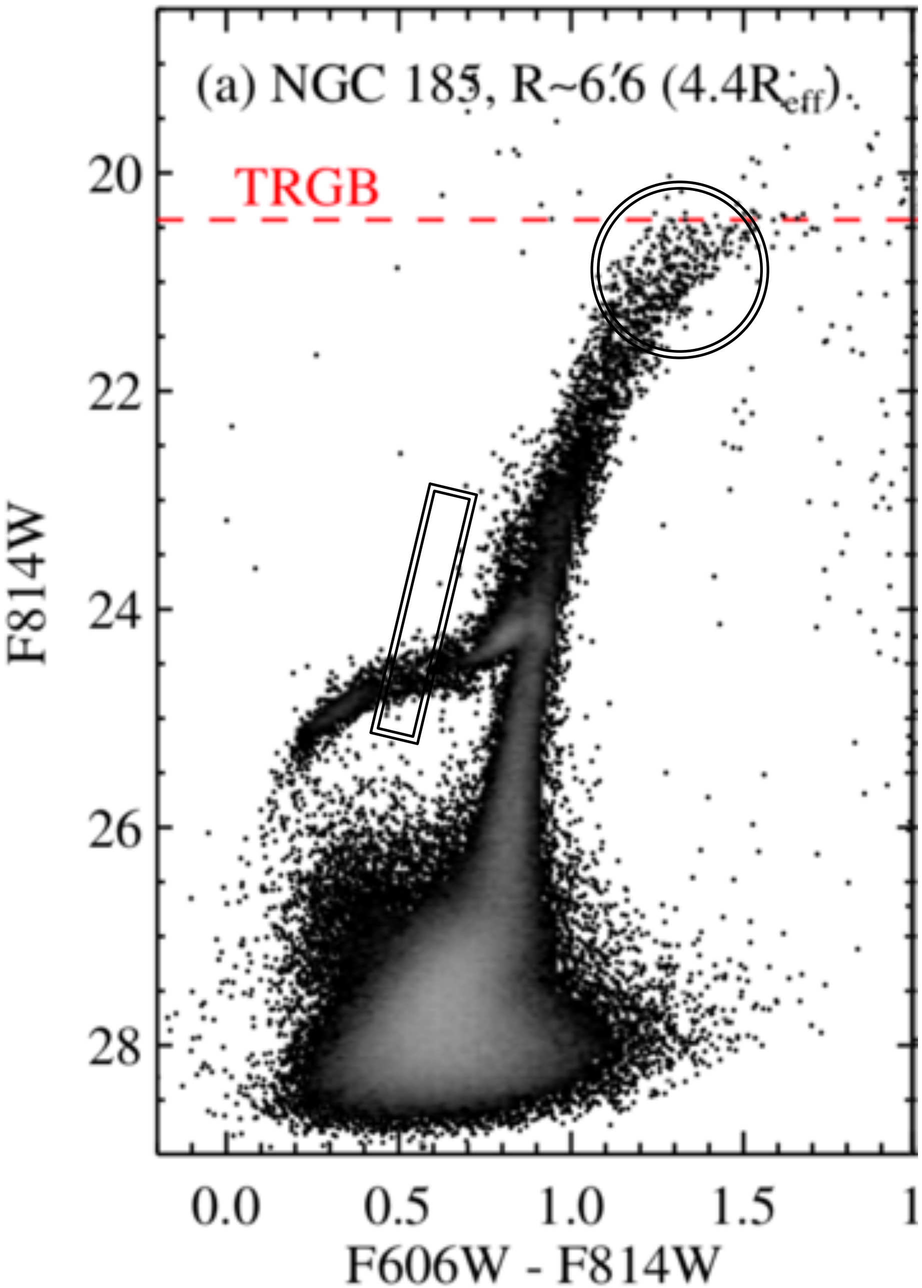
Addi…

Combination of systematic zero point errors?

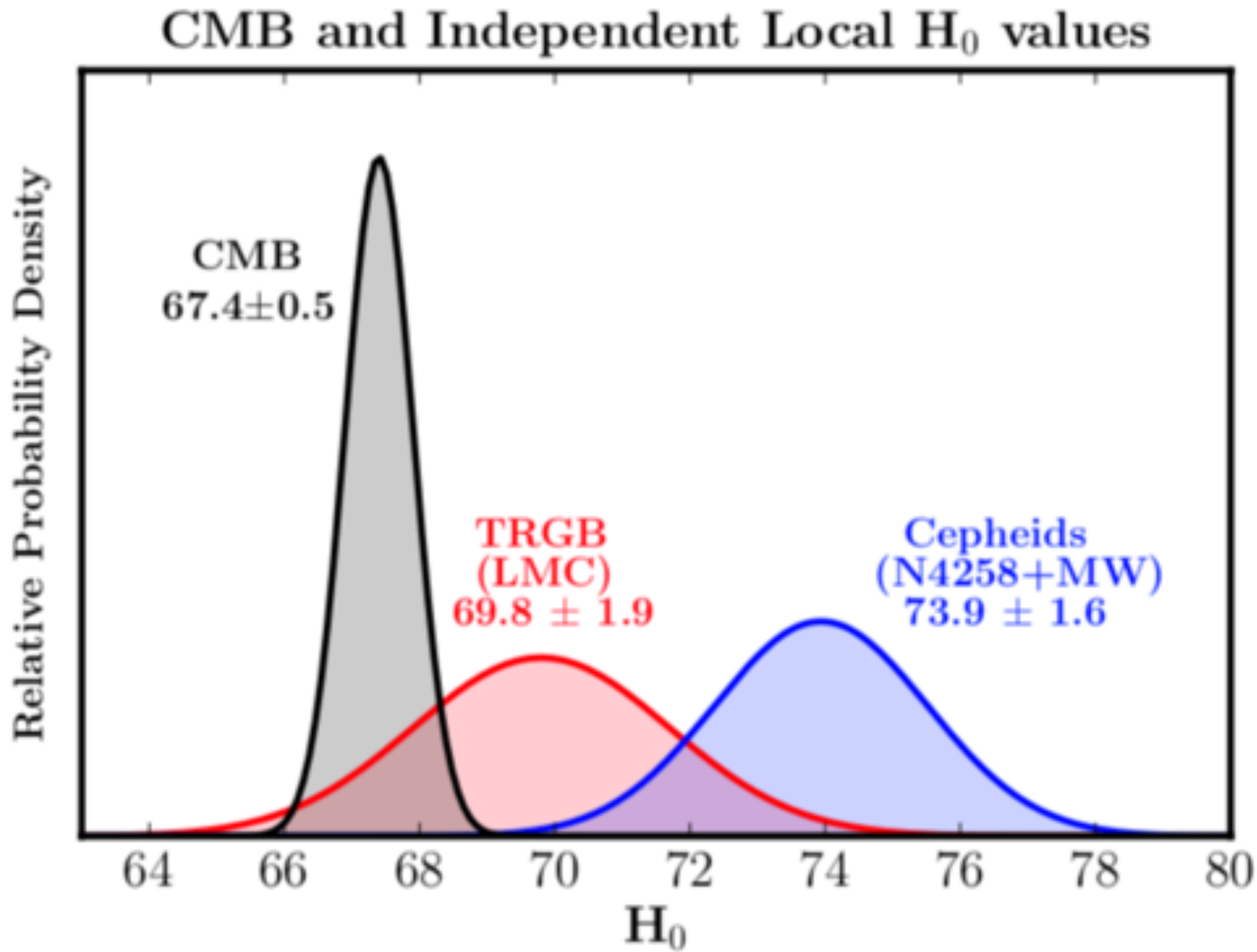
…but a zero point error of 9% affecting all the distance techniques is really hard to stomach.

Breaking news…

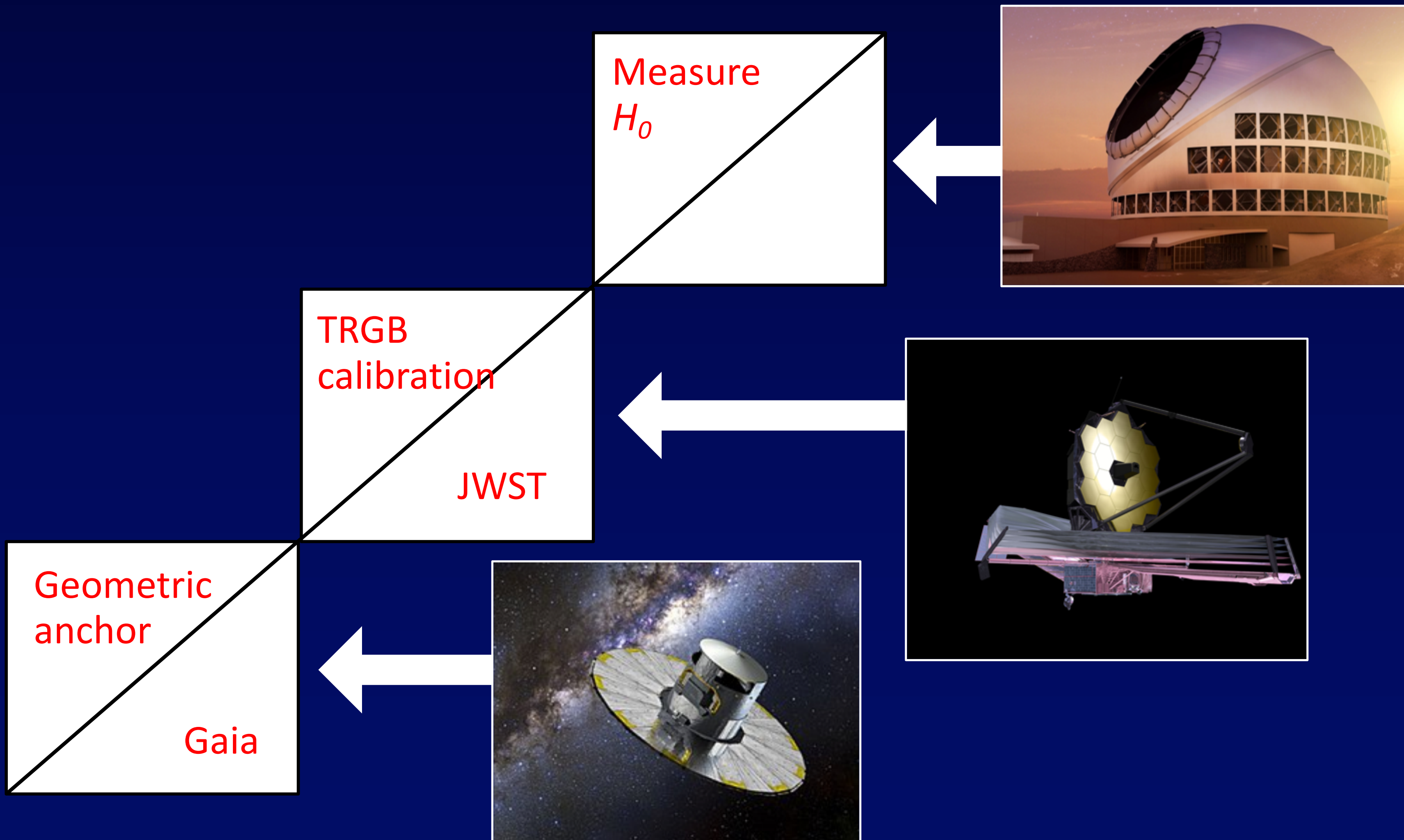




(a) NGC 185, R~6.′6 (4.4R$_{eff}$)
TRGB
F814W
F606W - F814W
20
22
24
26
28
0.0
0.5
1.0
1.5


CMB and Independent Local H0 values
Relative Probability Density
CMB
67.4±0.5
TRGB
(LMC)
69.8 ± 1.9
Cepheids
(N4258+MW)
73.9 ± 1.6
64
66
68
70
72
74
76
78
80
H0

An Independent Distance Ladder

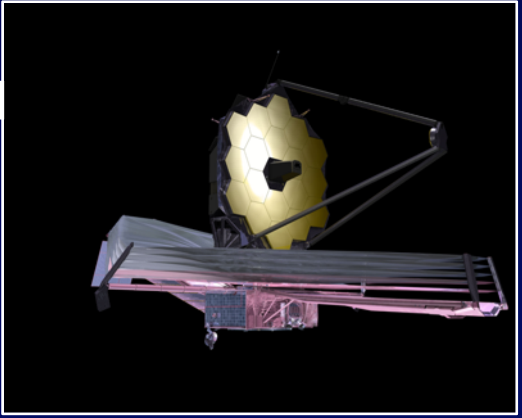


An Independent Distance Ladder

If we want to distinguish between exotic new physics and mundane calibration errors, we need new techniques and new telescopes.

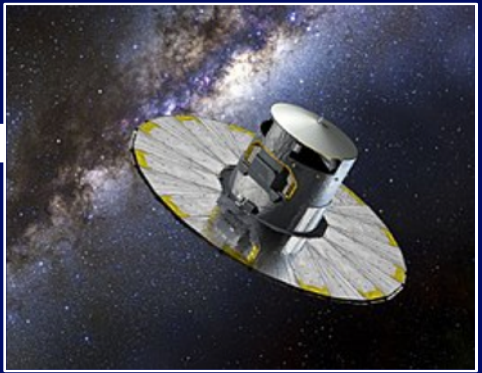
Measure H_0

JWST

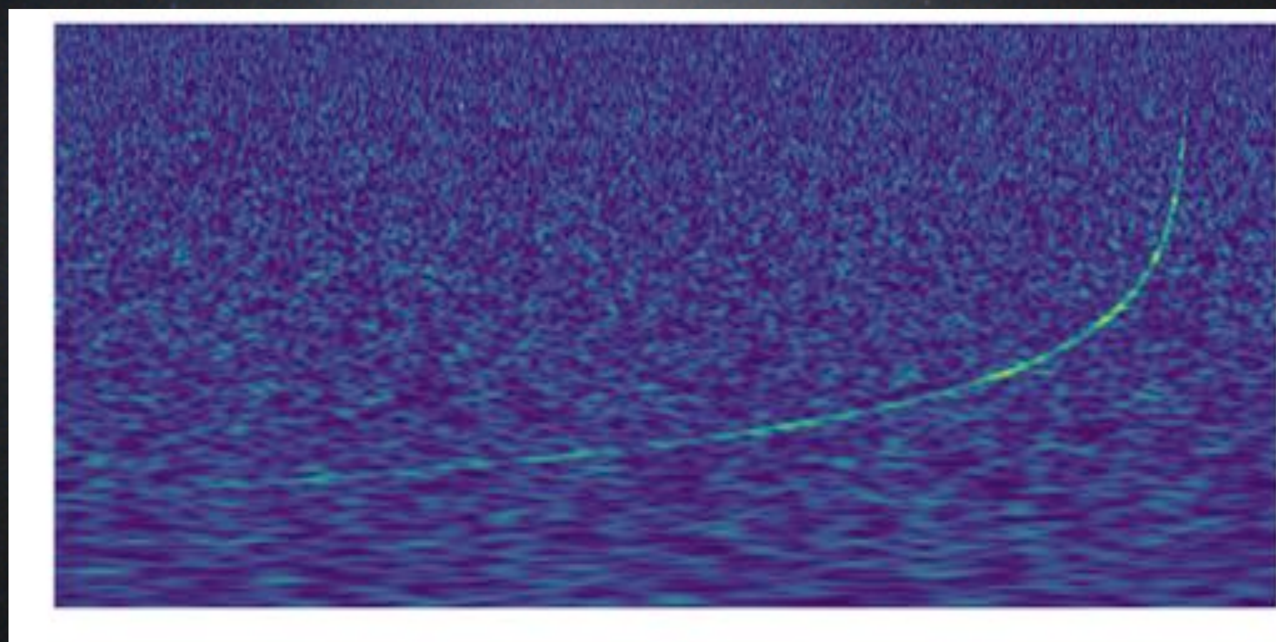


Geometric anchor

Gaia



“Standard Sirens”



2018: NGC4993

NASA and ESA