Louise Breuval

ESA Research Fellow
Space Telescope Science Institute
lbreuval@stsci.edu

The Hubble Tension & The Distance Ladder(s)

CosmoVerse School – Sofia – 25 May 2026

1) Introduction: The Hubble Constant (H_0)

2) Two ways to measure/infer H_0

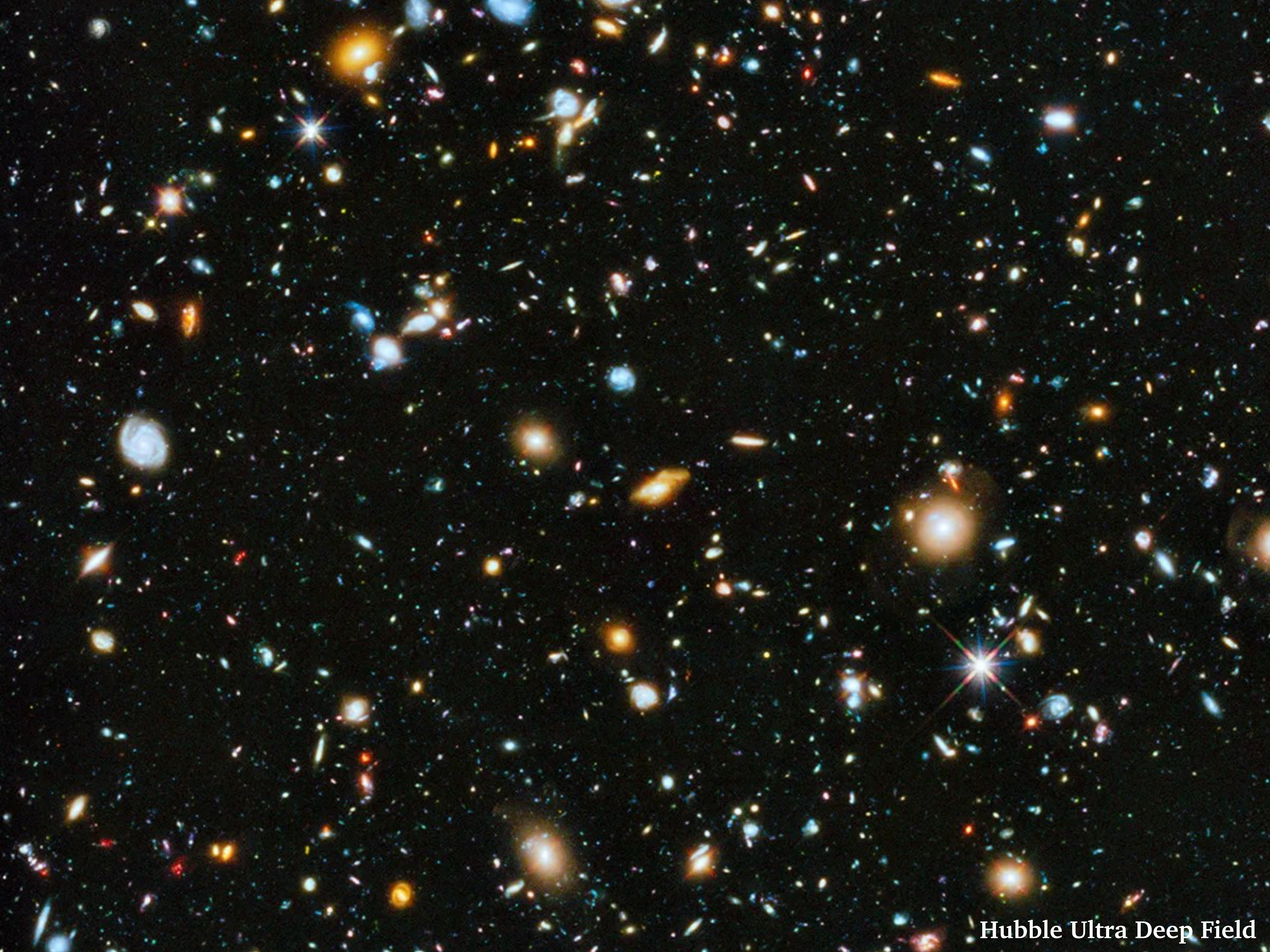
3) The Cepheid–SNIa distance ladder

4) Systematics in the Cepheid–SNIa distance ladder

5) An independent "Type II" distance ladder

6) Conclusion & Perspectives

1) **Introduction: The Hubble Constant (H0)**
2) Two ways to measure/infer H_0
3) The Cepheid–SNIa distance ladder
4) Systematics in the Cepheid–SNIa distance ladder
5) An independent "Type II" distance ladder
6) Conclusion & Perspectives


Hubble Ultra Deep Field

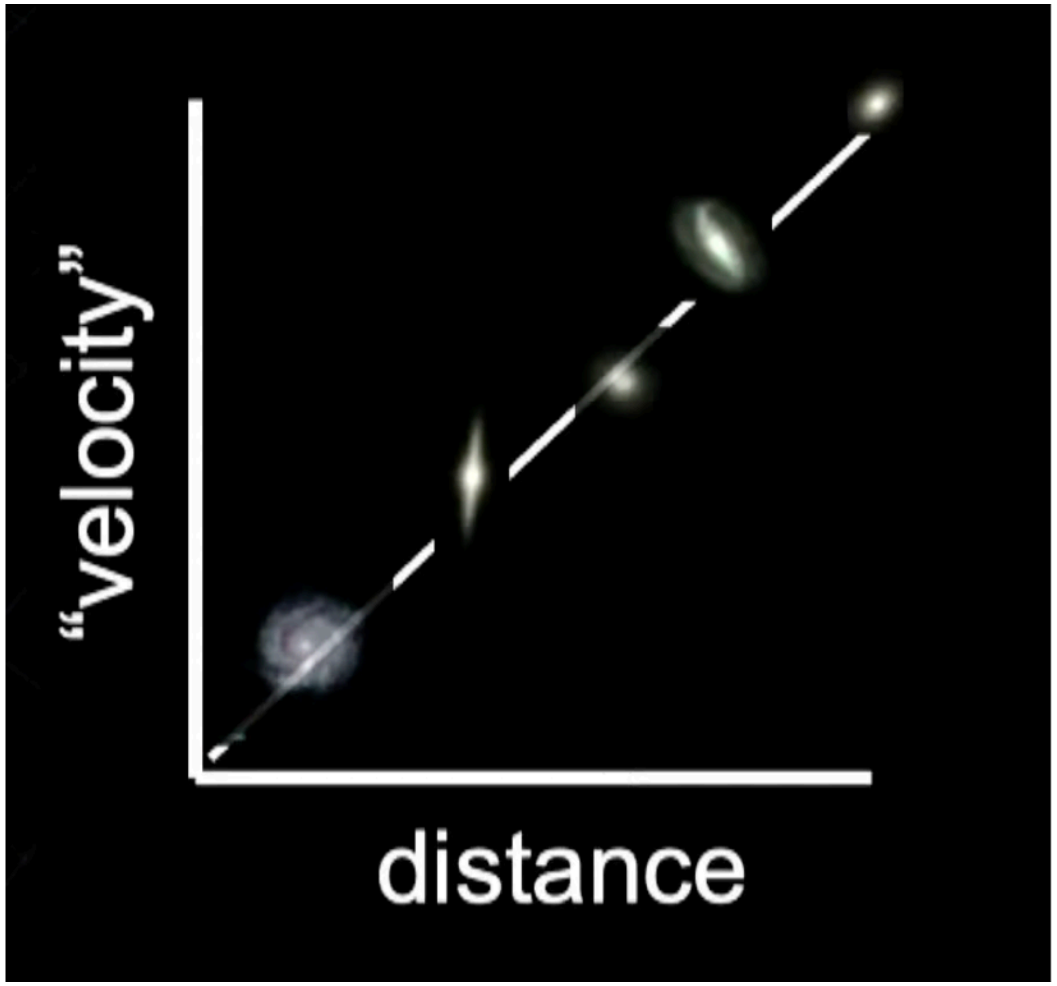
The Discovery of the Expanding Universe

✦ <u>1920</u>: "*The Great Debate*" between Harlow Shapley and Heber Curtis. Are the spiral nebulae outside of the Milky Way or part of it ?

The key to answer this question: **measure astronomical distances.**

→ Edwin Hubble: They are outside the Milky Way! The universe is made of multiple galaxies.

Edwin Hubble and the 2.5m telescope at Mount Wilson Observatory

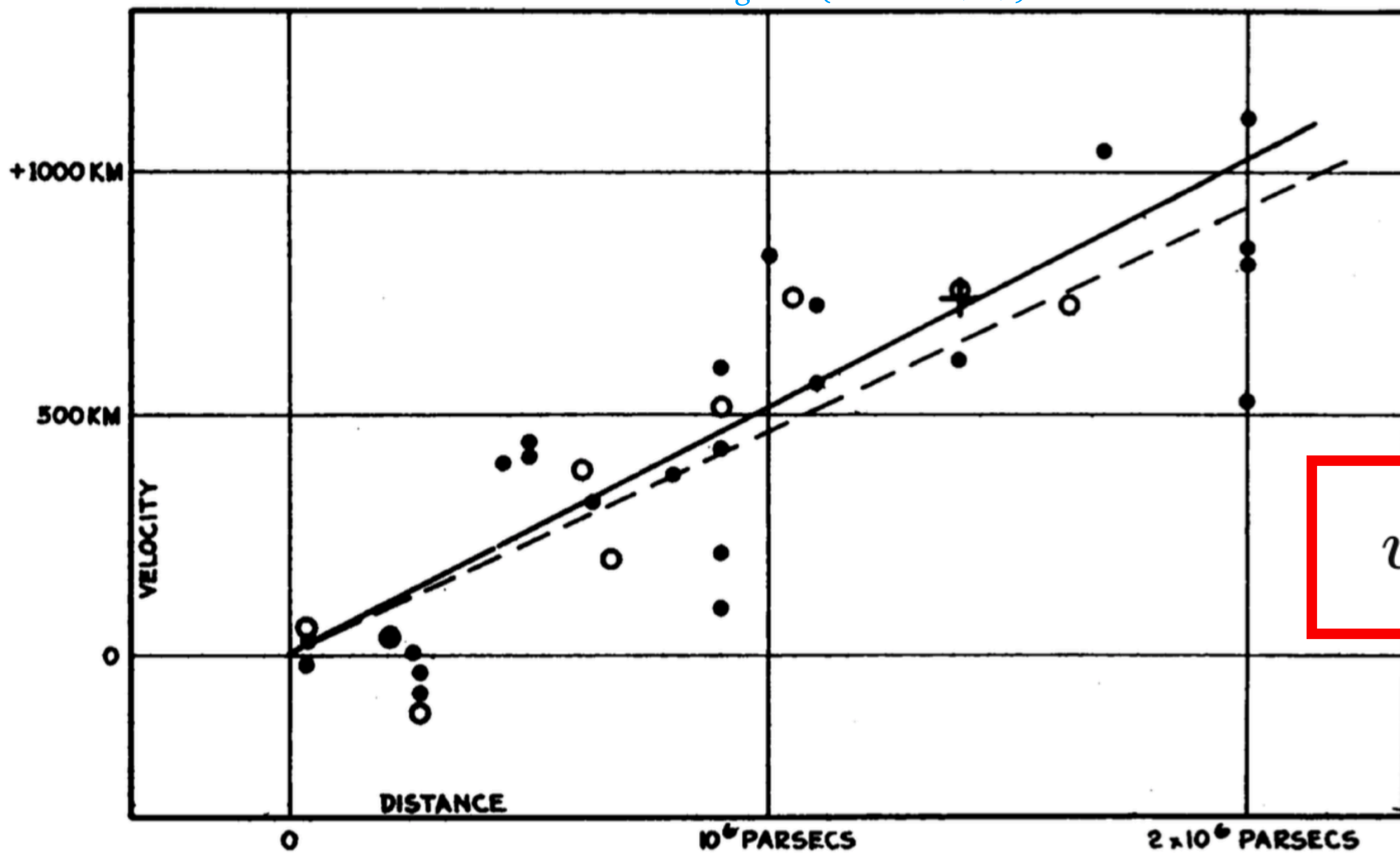


✦ <u>1929</u>: Edwin Hubble finds that the "escape velocity" of galaxies increases with their distance.

The Universe is expanding!

The Hubble Law

First Hubble Diagram (Hubble 1929)



velocity

distance

$$v = H_0 d$$

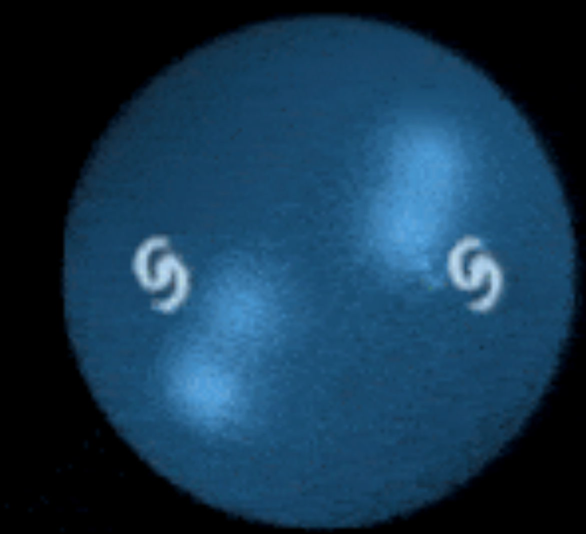
Redshift:

$$z = \frac{\lambda_{\rm obs} - \lambda_{\rm emit}}{\lambda_{\rm emit}}$$

$$v \approx cz$$

Standard Candles

The Universe is Expanding



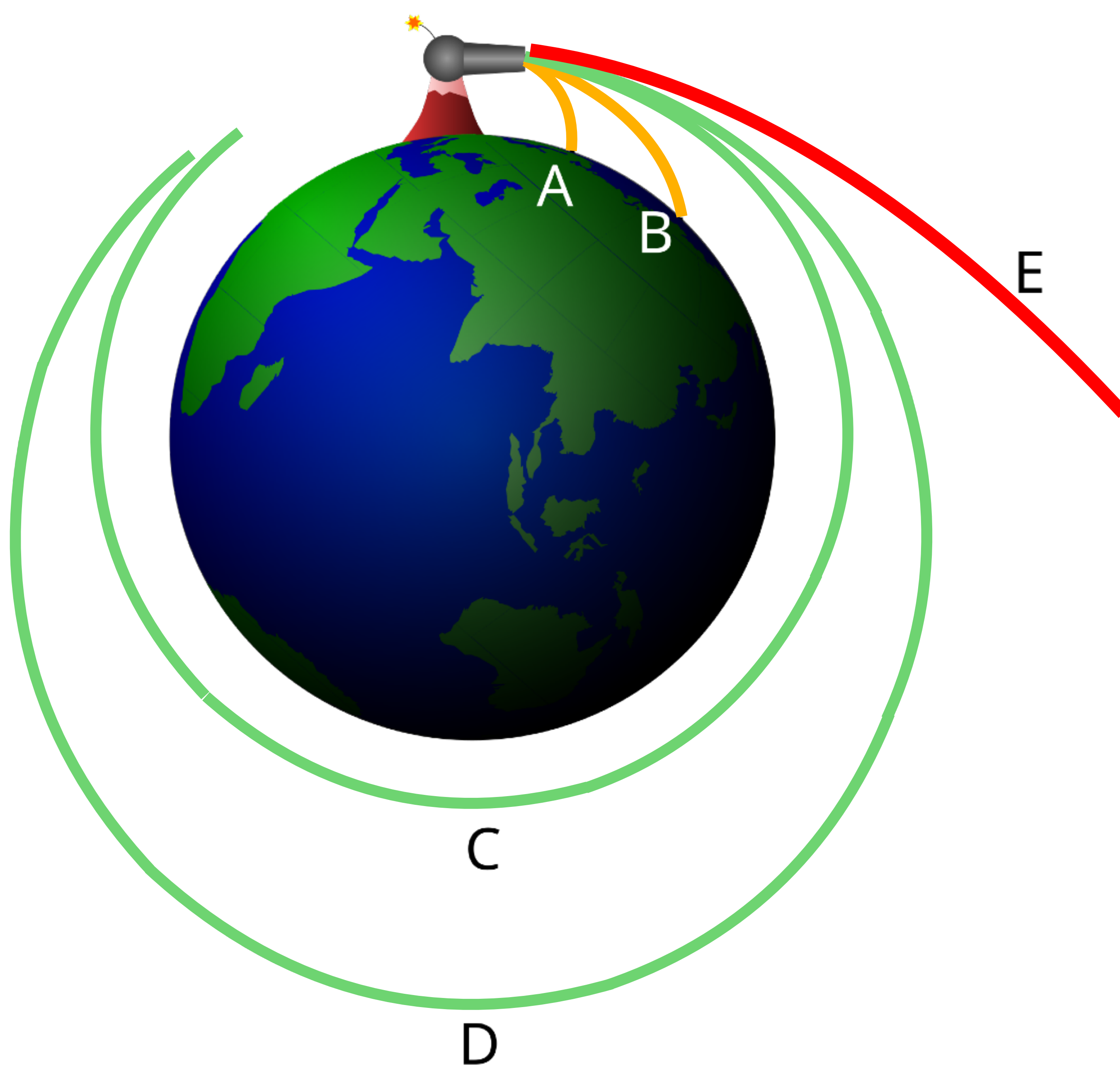
→ Expansion rather than motion through space

The possible fates of the Universe

A, B = speed is too low and/or Earth is too massive
→ "gravitation wins"

C, D = intermediate speed/mass

E = escape velocity reached, Earth is no longer massive enough to retain the ball
→ "velocity wins"

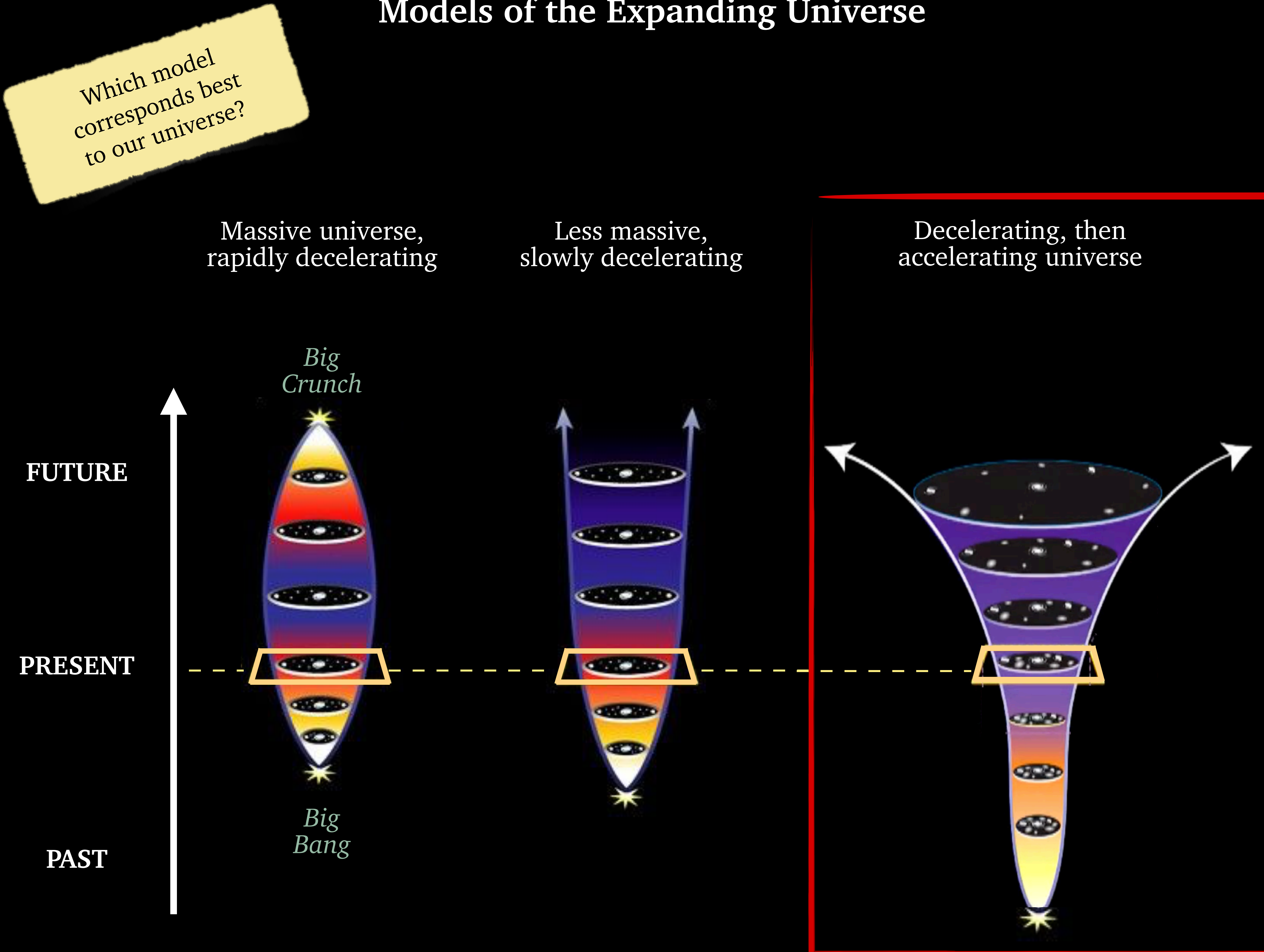


For the Universe:

A, B = the universe is massive enough, its self gravity will pull it back together

E = expansion is accelerating, due to the dominant presence of Dark Energy

Models of the Expanding Universe



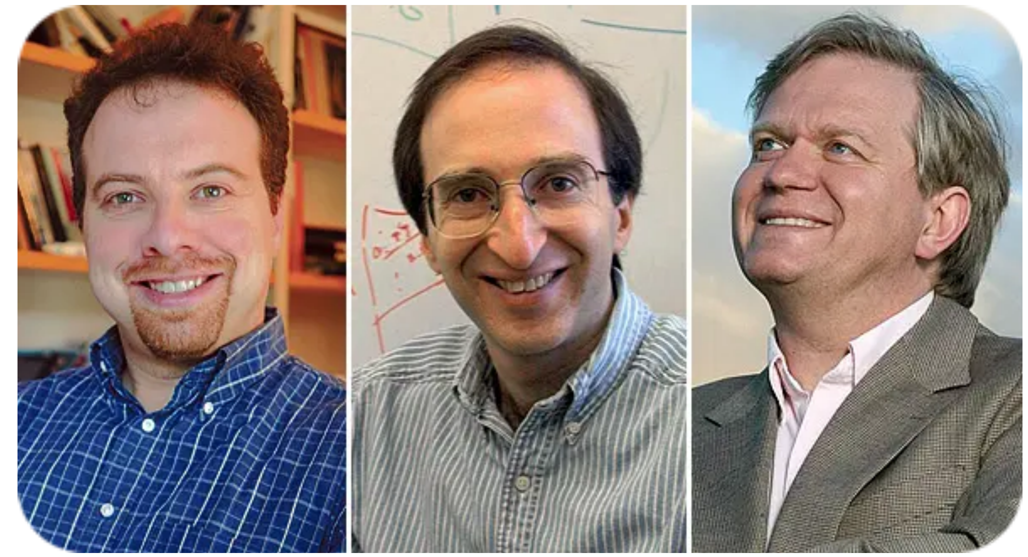
The Accelerating Expansion

- 1998: The Universe is in **<u>accelerated</u>** expansion!
  → positive cosmological constant: $\Omega_\Lambda > 0$

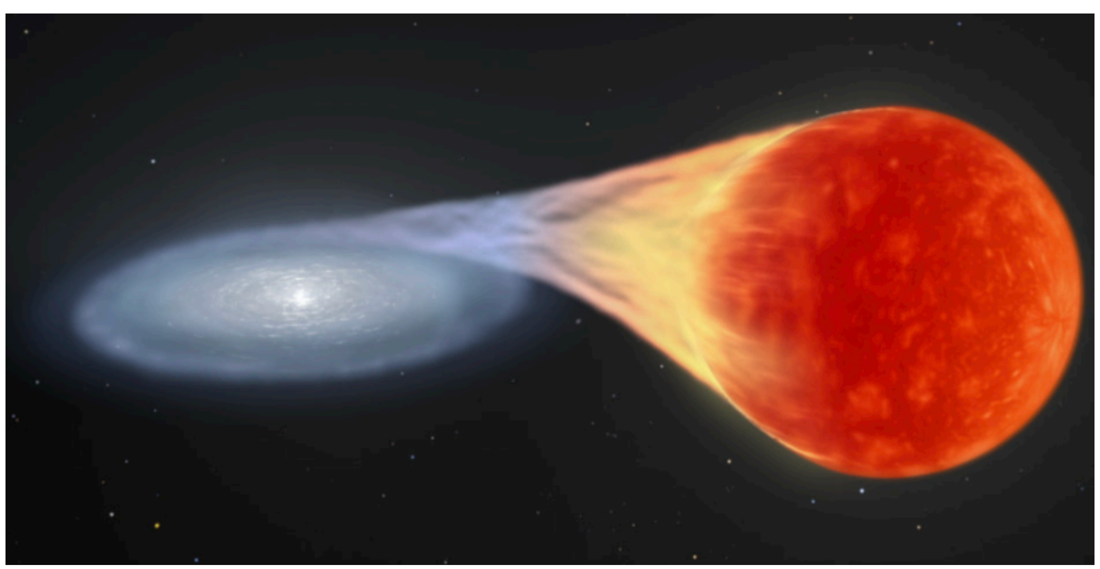
- Discovery by Saul Perlmutter (The Supernova Cosmology Project), Brian Schmidt and Adam Riess (The High-z Supernova Search Team).

- They measured distances and redshifts to Type Ia supernovae at large distances.

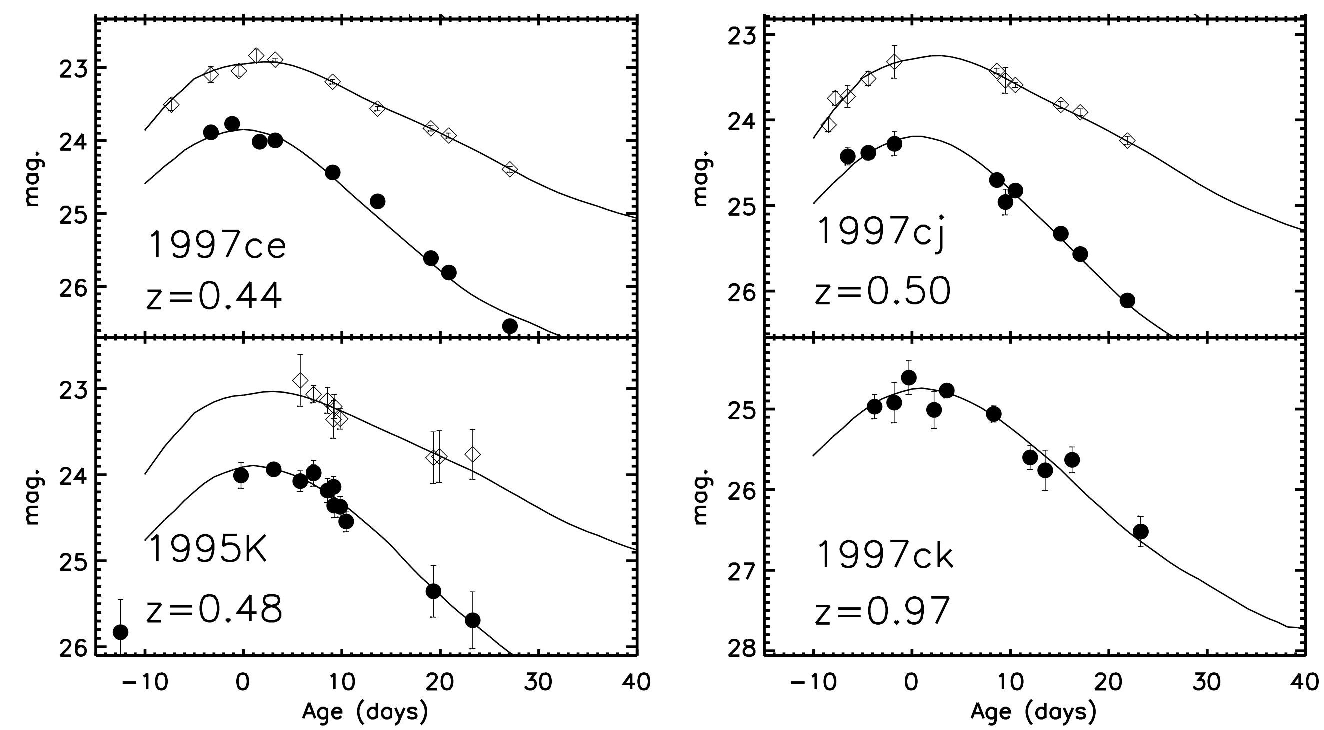
- Supernovae are distance indicators: explosion always occurs at the same mass, therefore at the same intrinsic luminosity. They are calibrated with Cepheids (see next session).



Adam Riess, Saul Perlmutter and Brian Schmidt, Nobel Laureates in Physics (2011)

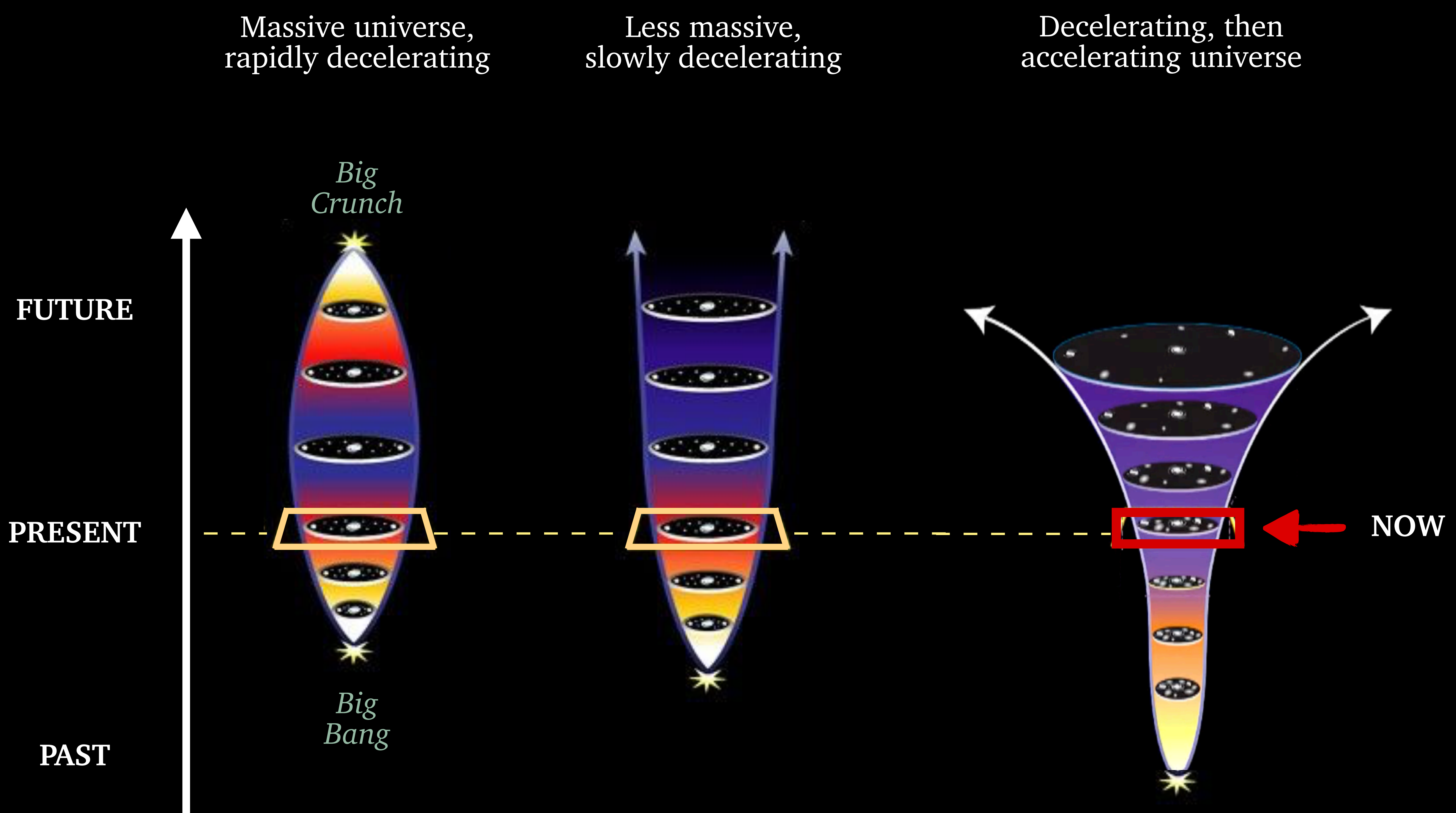


Explosion from thermonuclear detonation of a white dwarf star in a binary



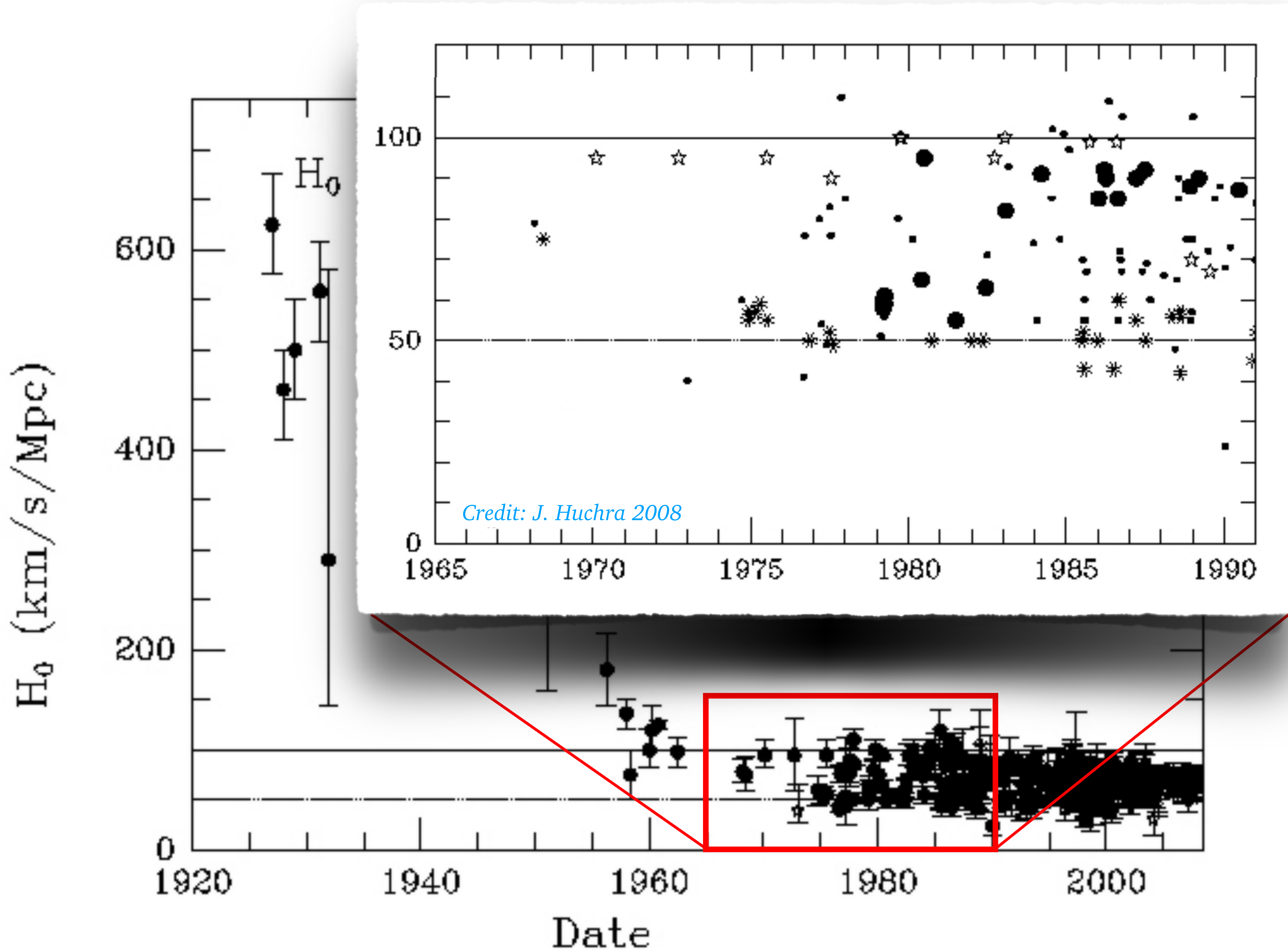
Supernovae light curves used to measure the accelerated expansion of the Universe (Riess et al. 1998)

Models of the Expanding Universe



Expansion history (at any time): H(t)
Hubble Constant: H(0)

The First Measurements of H_0



The Hubble Constant and the Age of the Universe

$1/H_0 = t_H$ ➞ Hubble time = age of the universe

- ✦ H_0 = 500 km/s/Mpc (Edwin Hubble) ➞ t_H = 1.95 Gyr
- ✦ H_0 = 73 km/s/Mpc (most recent update) ➞ t_H = 13.4 Gyr
- ✦ H_0 = 67 km/s/Mpc ➞ t_H = 14.6 Gyr

A fundamental parameter for cosmologists!

1) Introduction: The Hubble Constant (H_0)

2) Two ways to measure/infer H_0

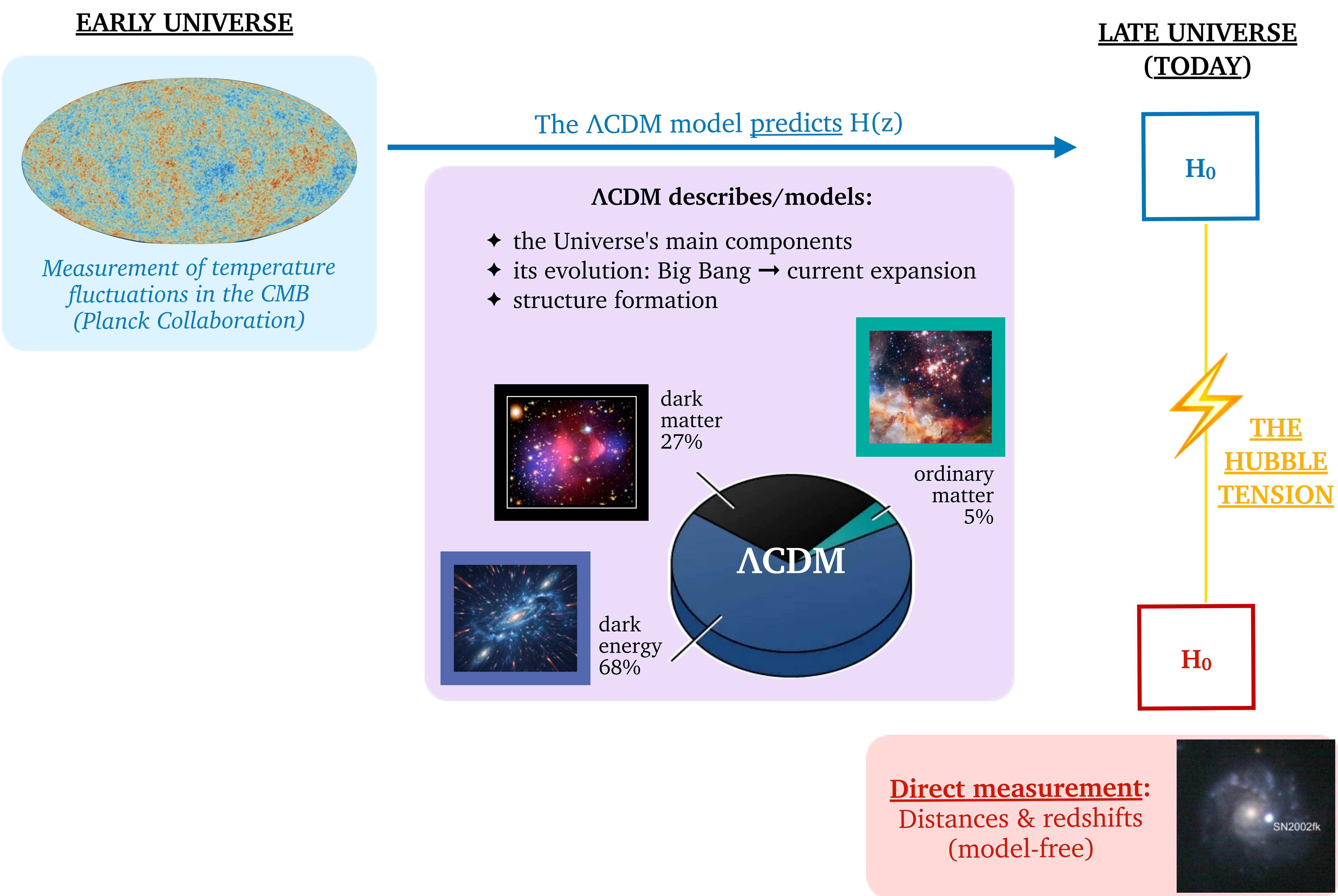
3) The Cepheid–SNIa distance ladder

4) Systematics in the Cepheid–SNIa distance ladder

5) An independent "Type II" distance ladder

6) Conclusion & Perspectives

Two ways to measure/infer H_0

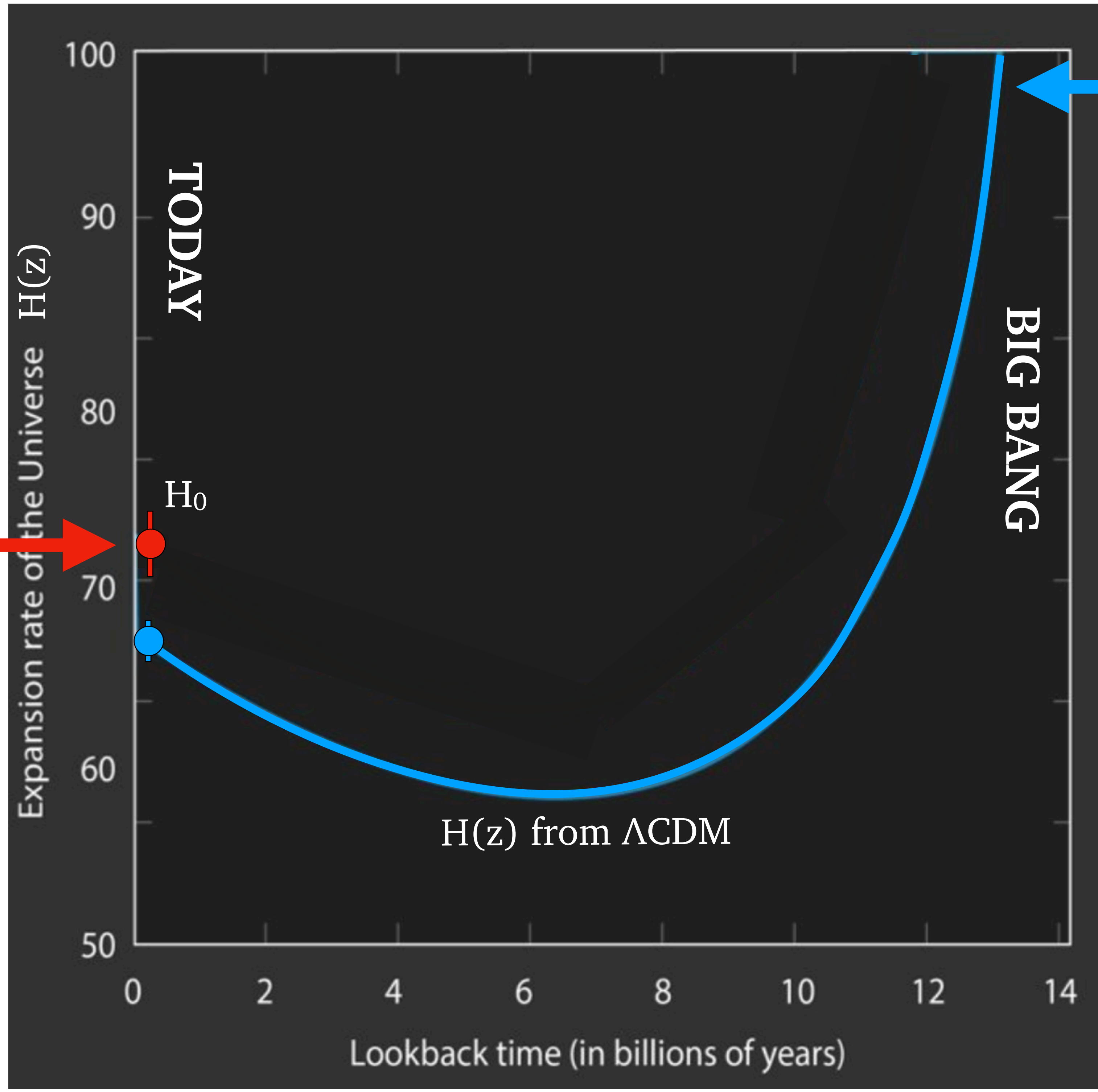


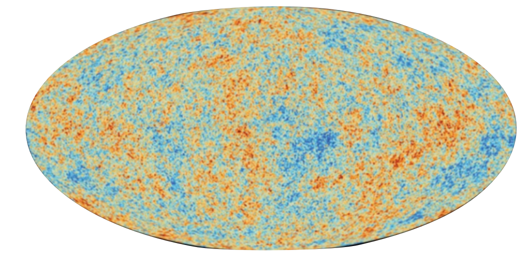
The Hubble Tension

Late Universe (direct) method:

Empirical distance ladder with Cepheids + supernovae Ia (model-free)

H_0= 73.17 ± 0.86 km/s/Mpc

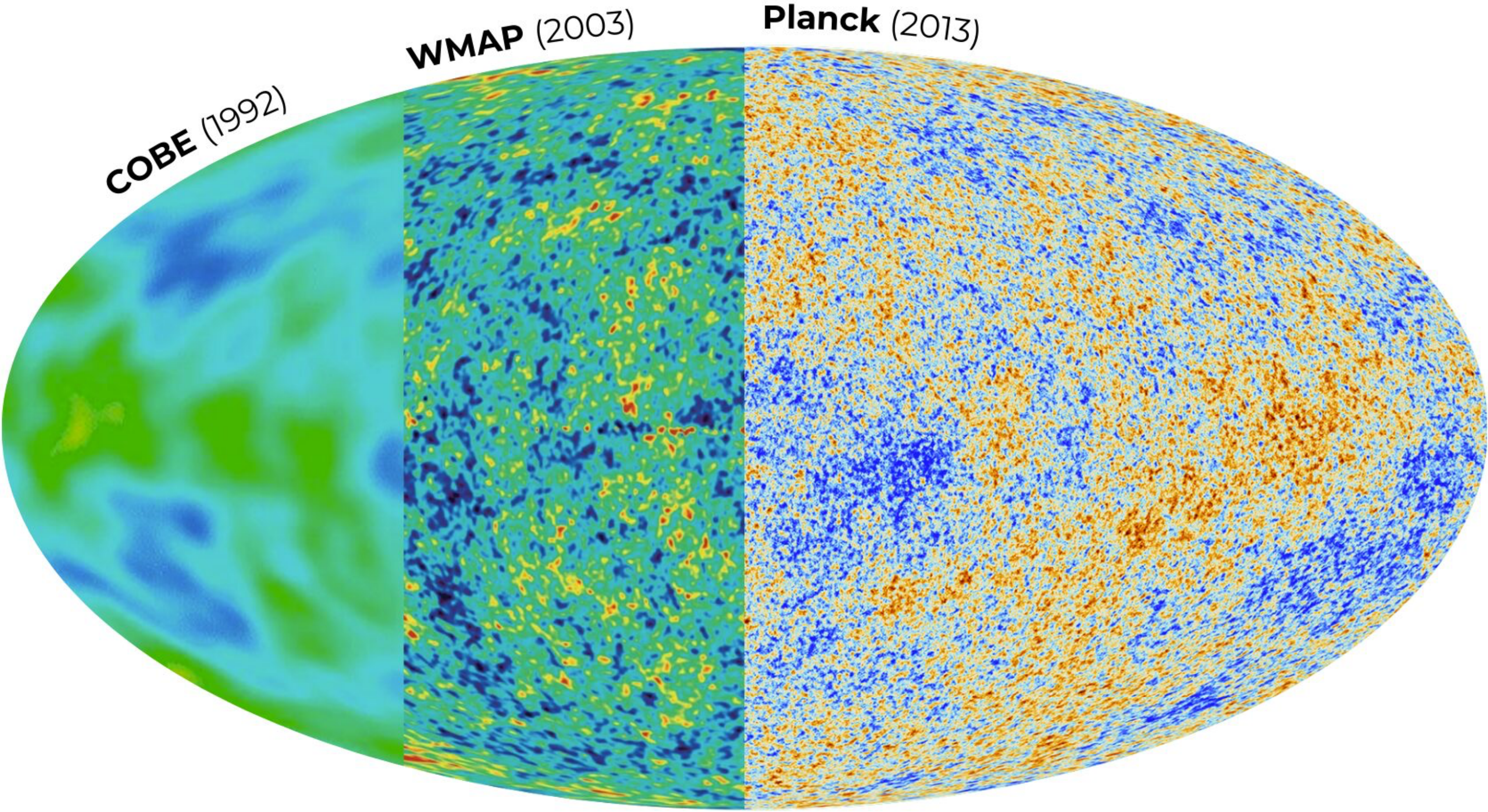




Early Universe (indirect) method:

Assuming the **ΛCDM model** and using the CMB fluctuation spectrum (Planck), we can **predict** the expansion history of the Universe and its **expansion rate today**

H_0=67.4 ± 0.5 km/s/Mpc



<u>Why should we worry about it?</u>

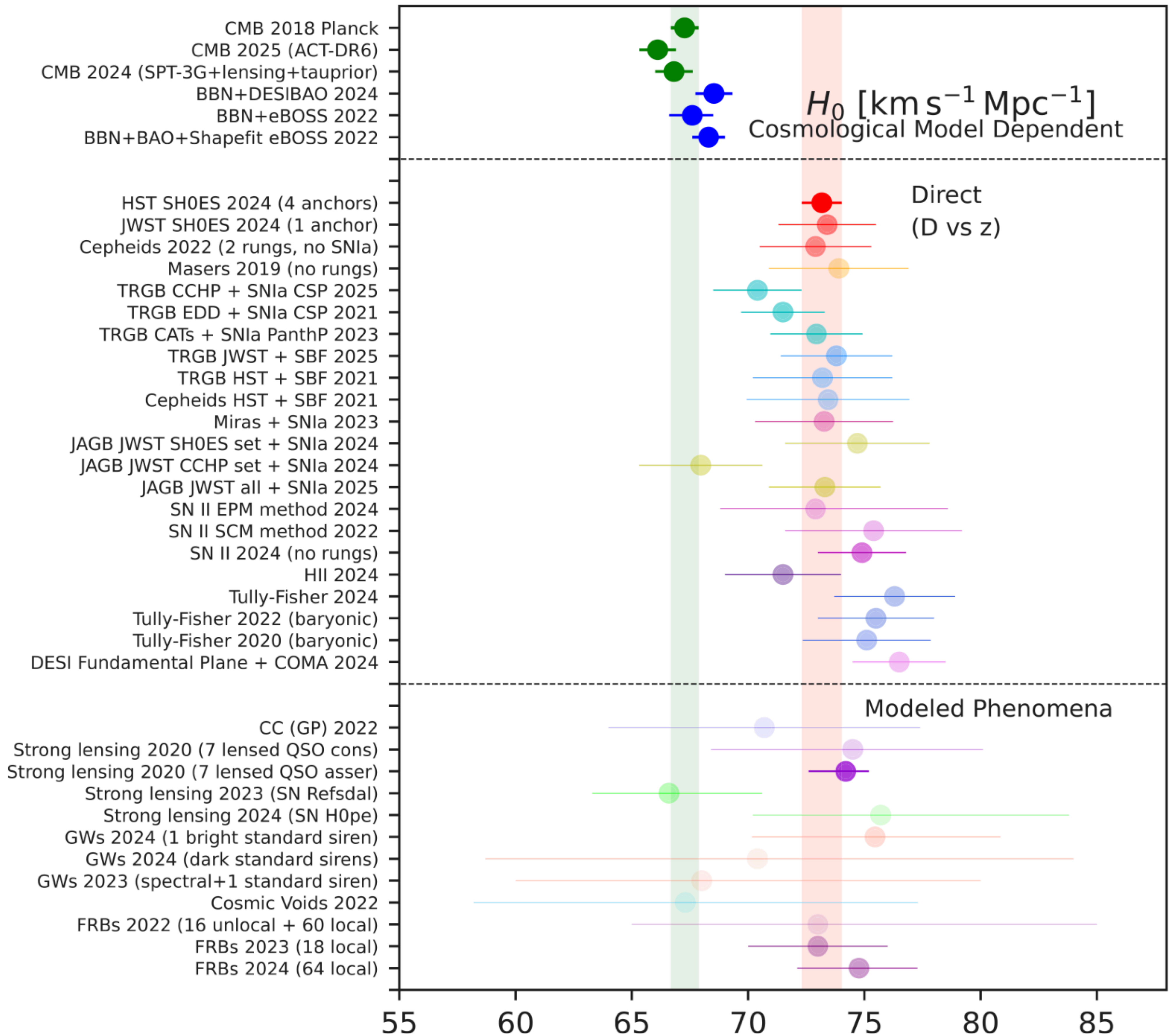
→ issue in CMB measurement?

→ issue in distance measurements?

→ issue with ΛCDM model?

<u>Direct measurement</u>:
Distances & redshifts
(model-free)

The Hubble Tension



The Hubble tension is not just a disagreement between two methods, or two teams.

It is a global disagreement between early universe values and late-universe measurements.

1) Introduction: The Hubble Constant (H_0)

2) Two ways to measure/infer H_0

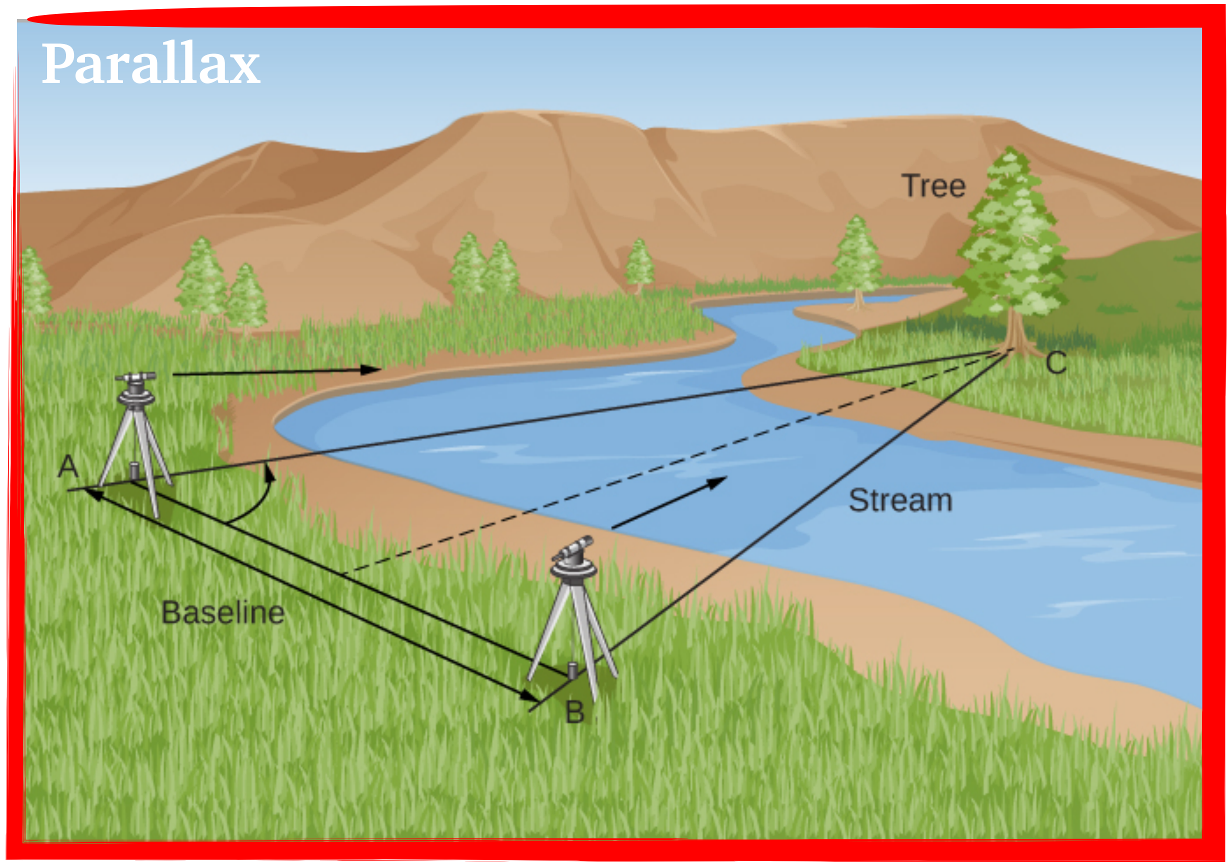
3) The Cepheid–SNIa distance ladder

4) Systematics in the Cepheid–SNIa distance ladder

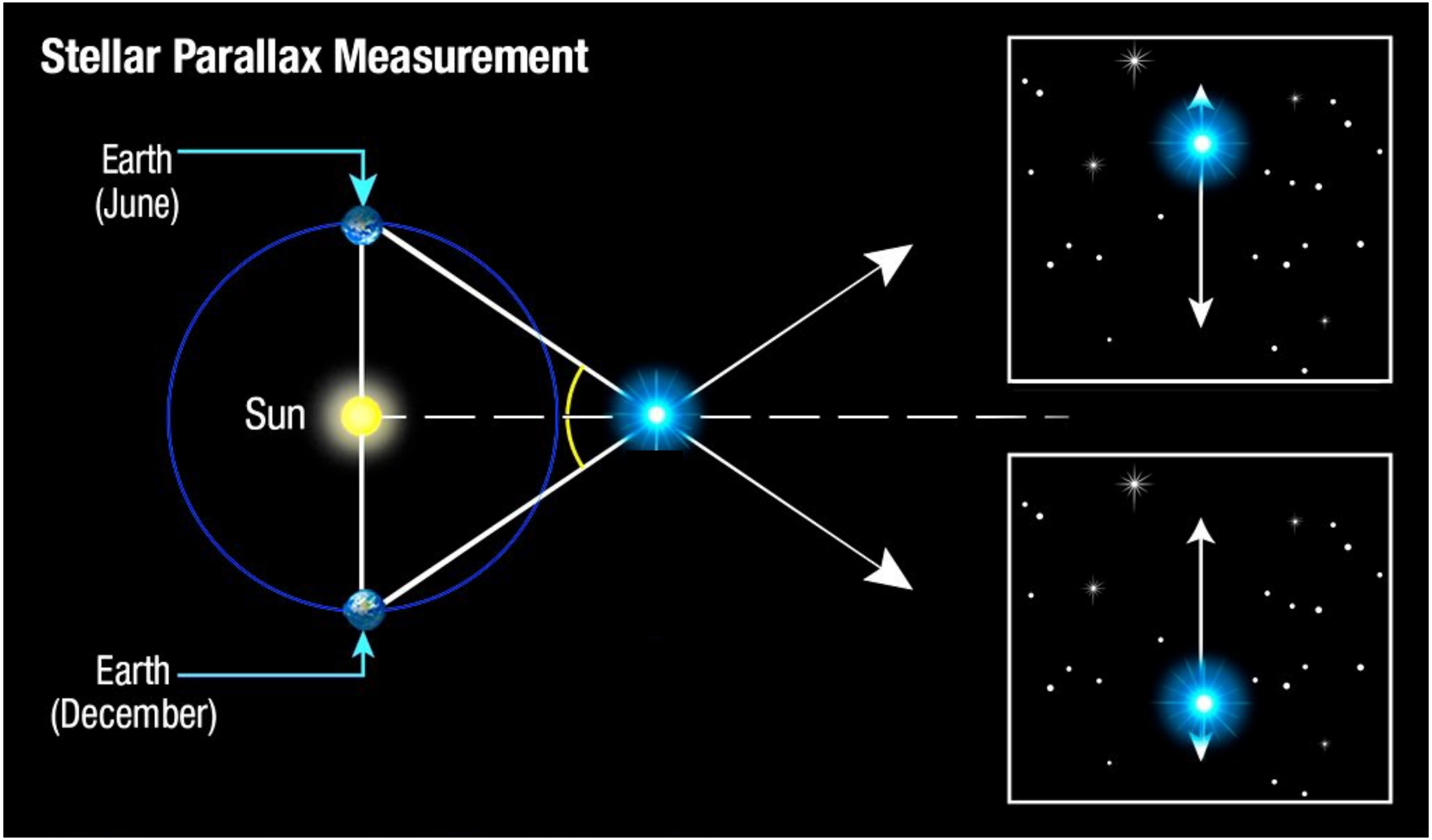
5) An independent "Type II" distance ladder

6) Conclusion & Perspectives

Measuring Distances on Earth



Measuring Distances in Space

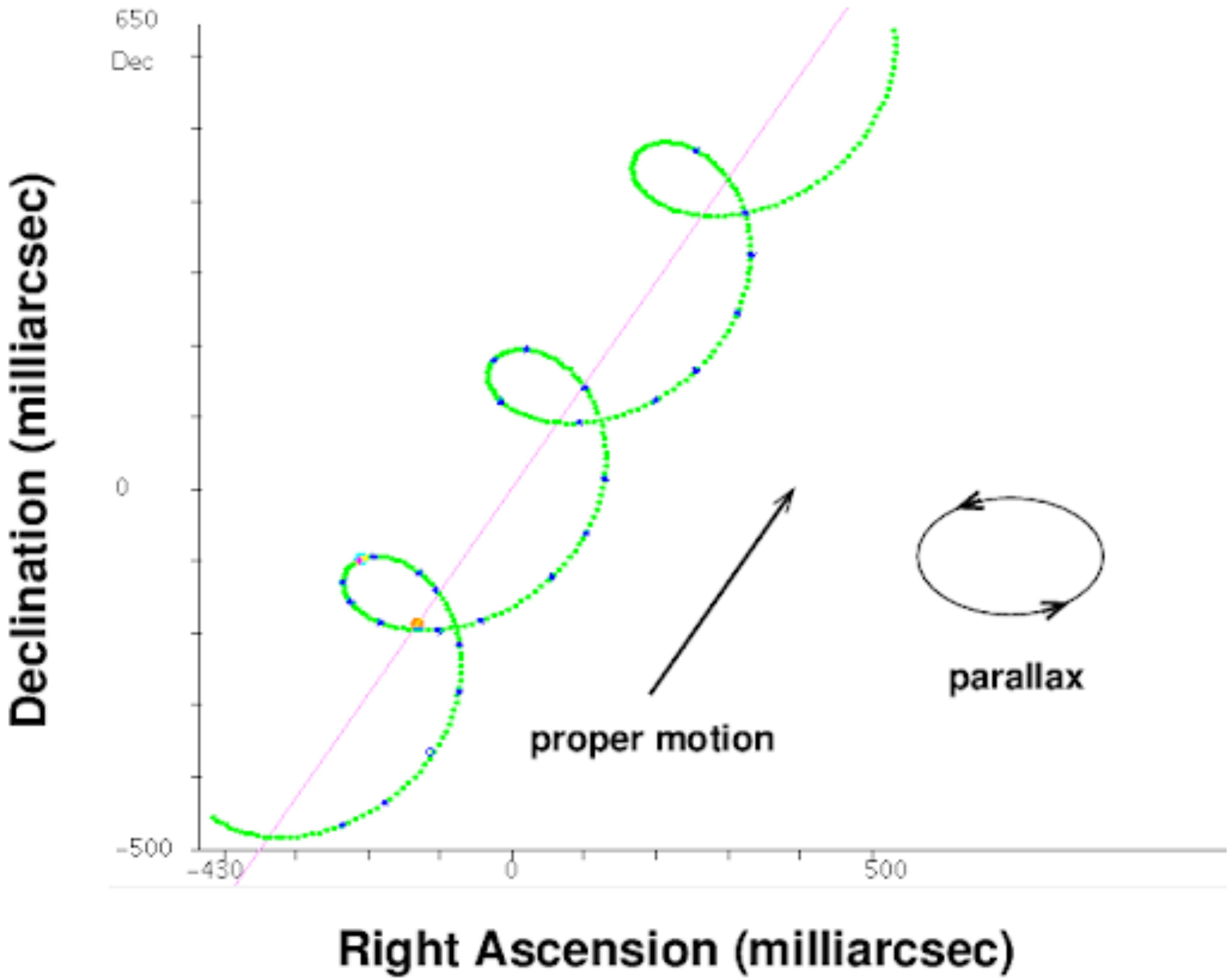


Parallax method (Credit: A. Feild, STScI, A. Riess, JHU/STScI)

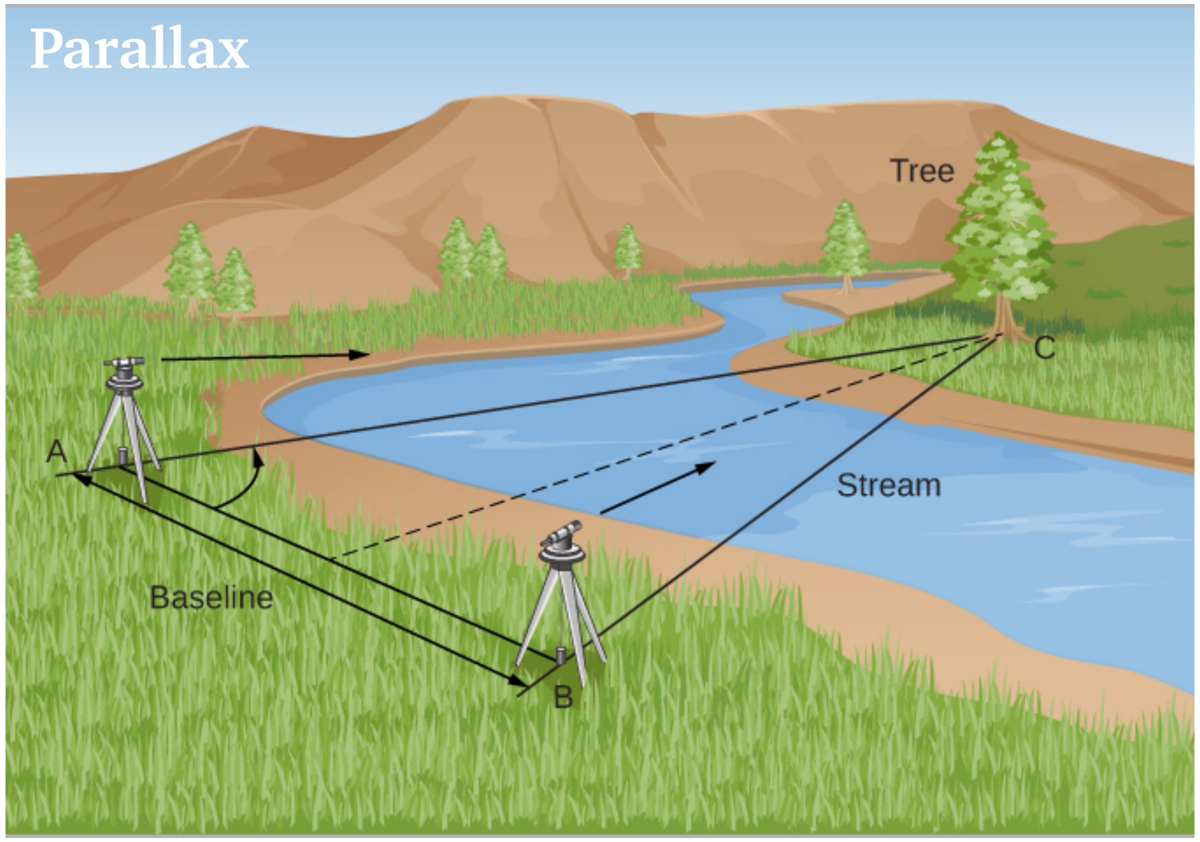
The Gaia Satellite (European Space Agency)

Gaia Parallaxes

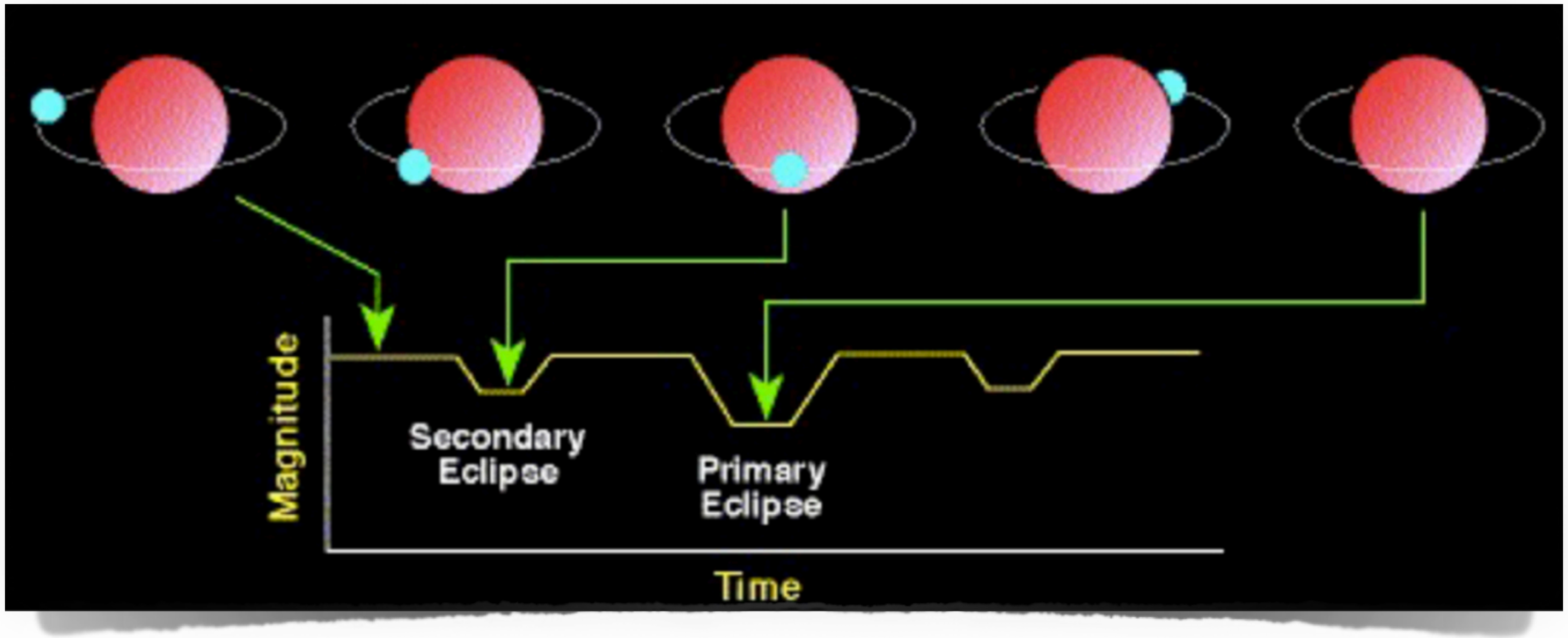
Gaia Parallaxes

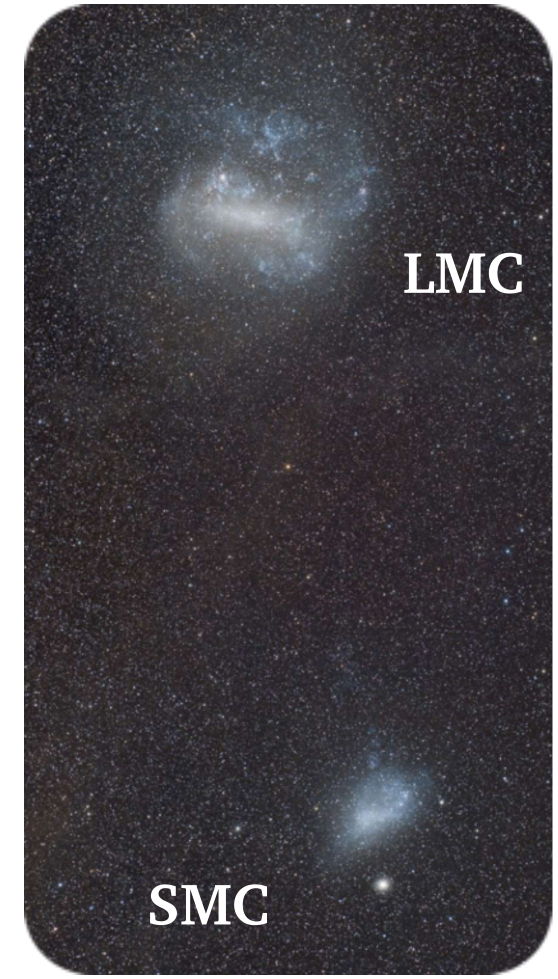


Measuring Distances on Earth

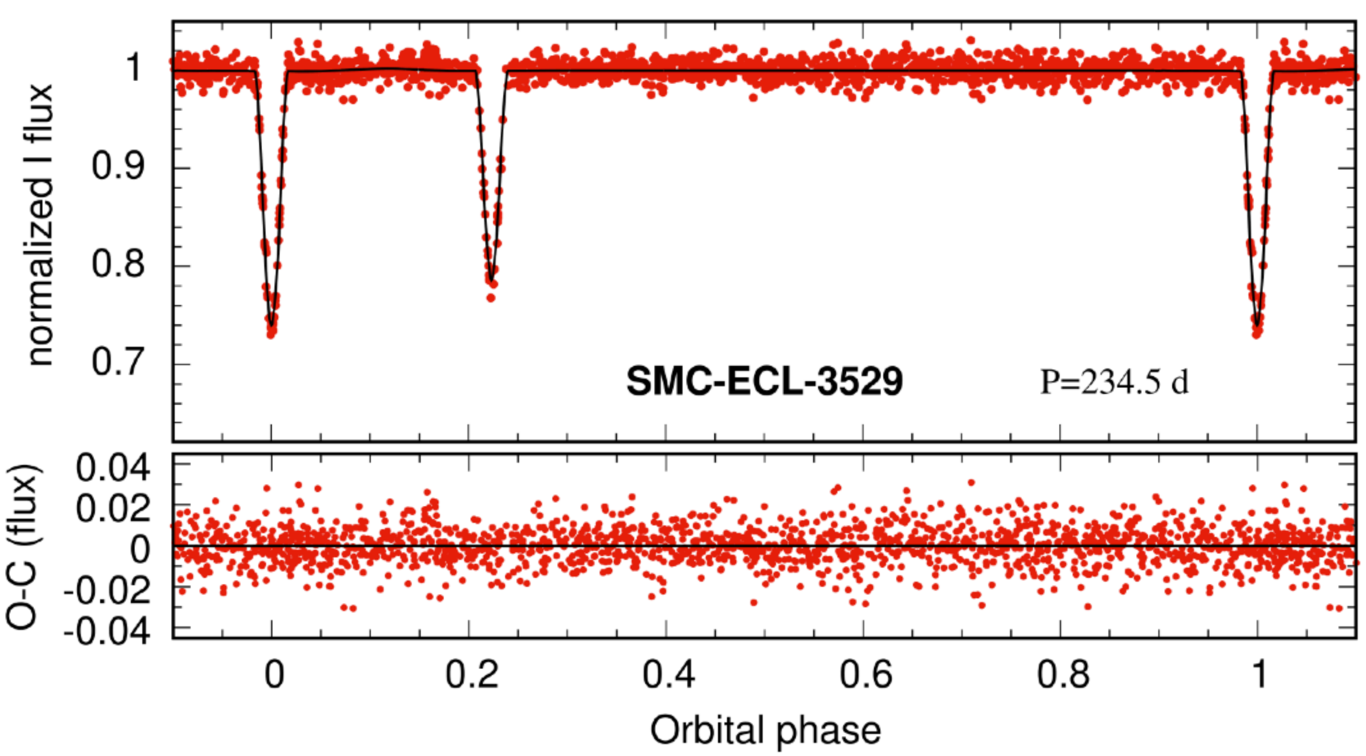


Detached Eclipsing Binaries

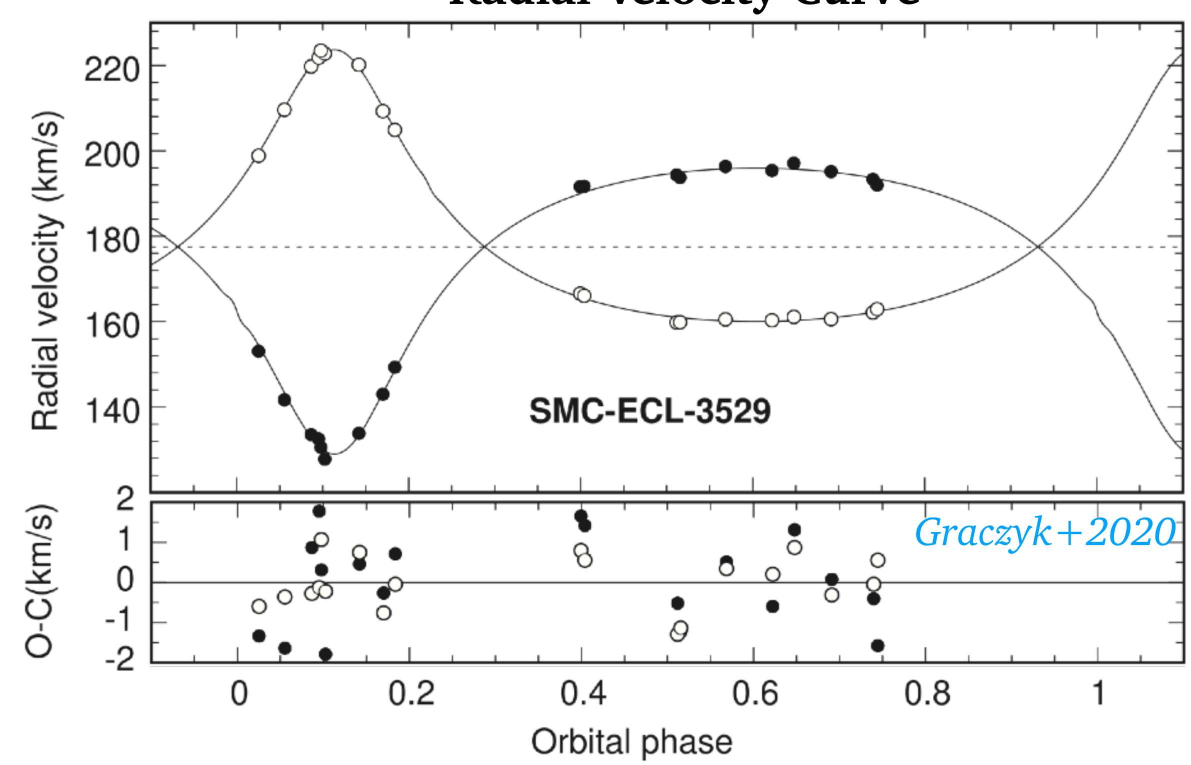




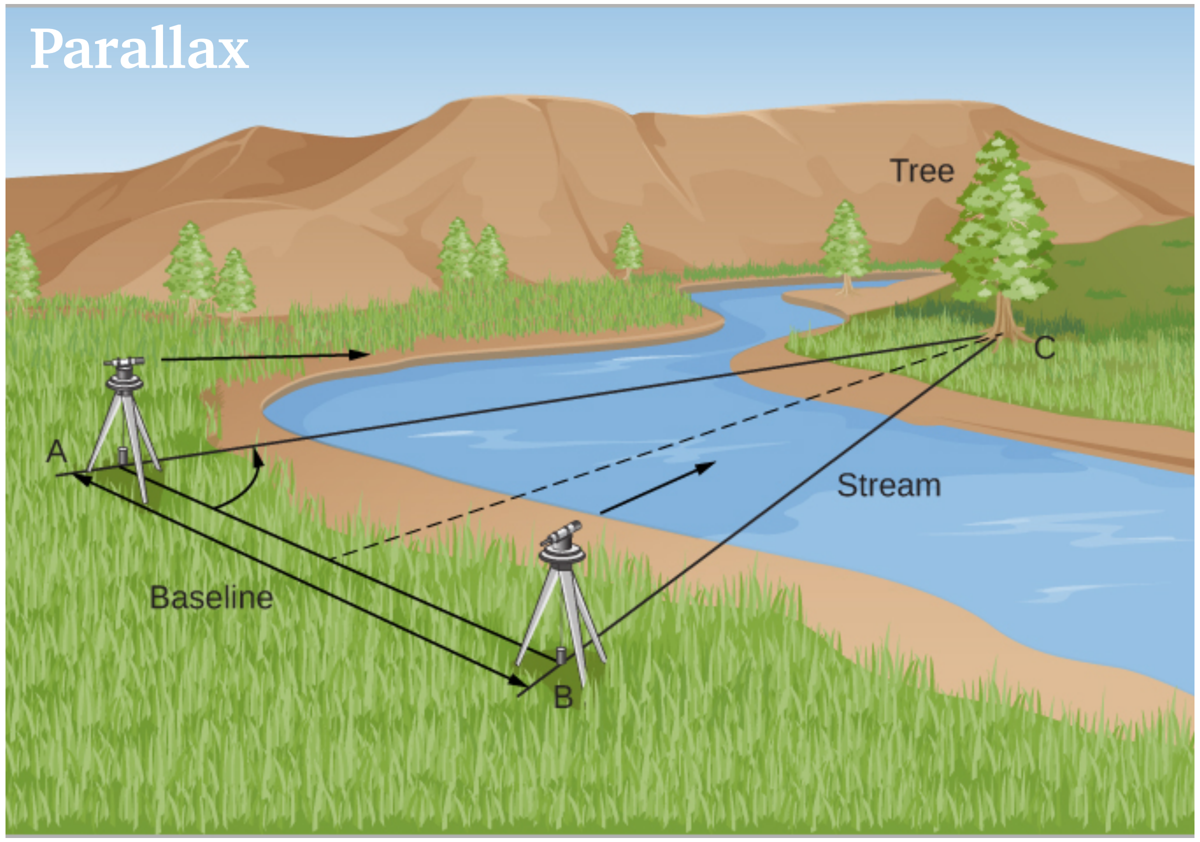
Light Curve



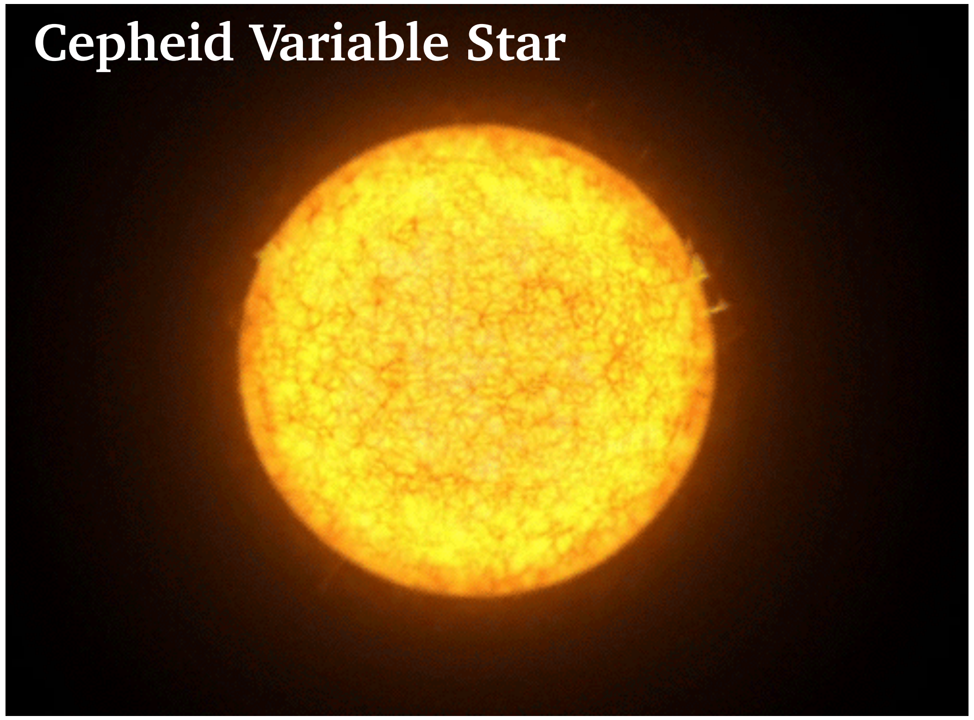
Radial Velocity Curve

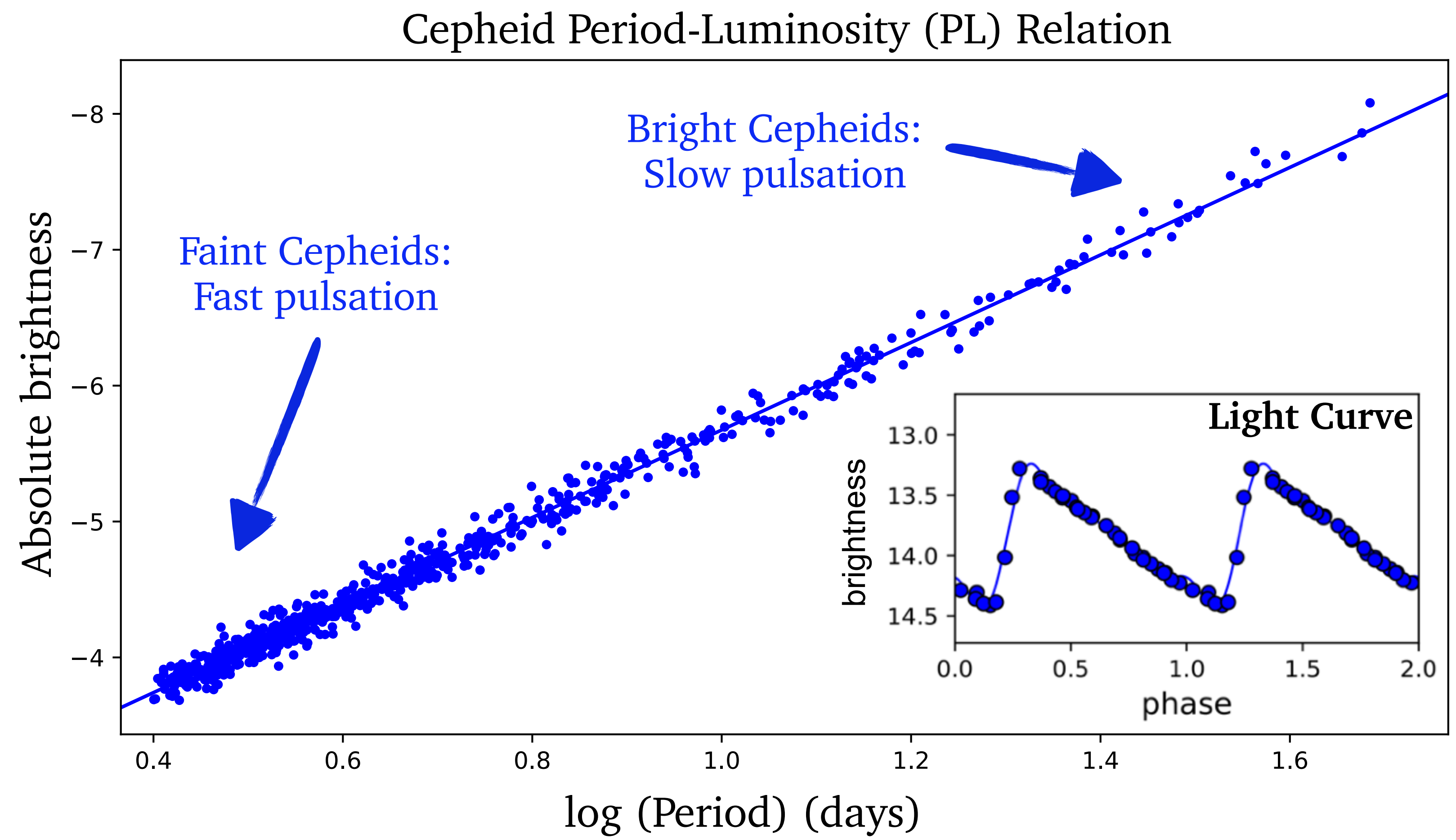


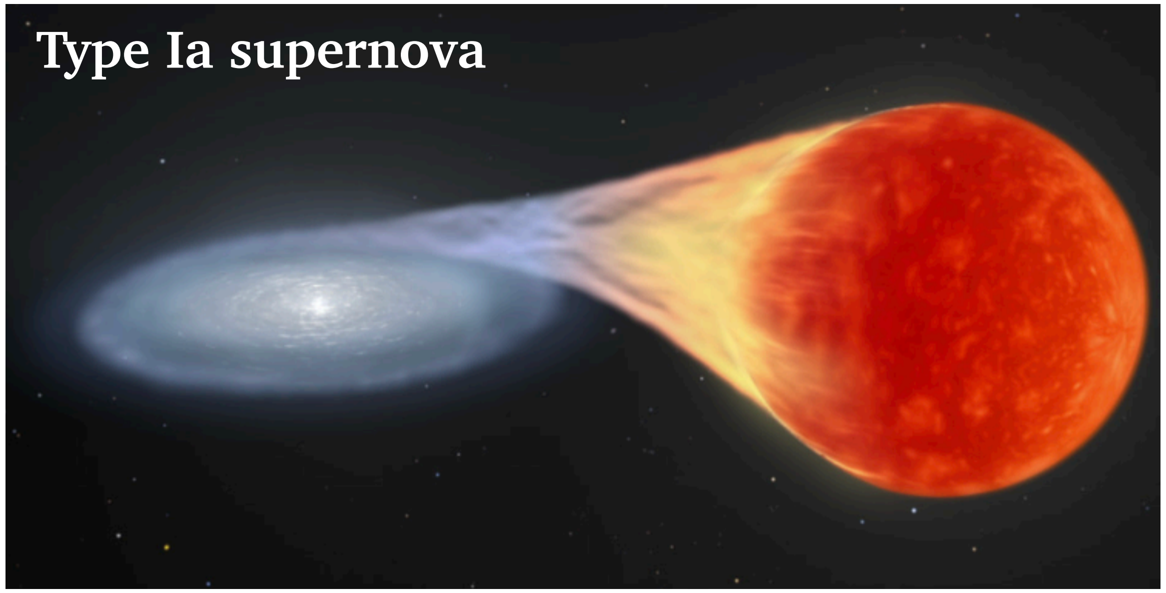
Measuring Distances on Earth



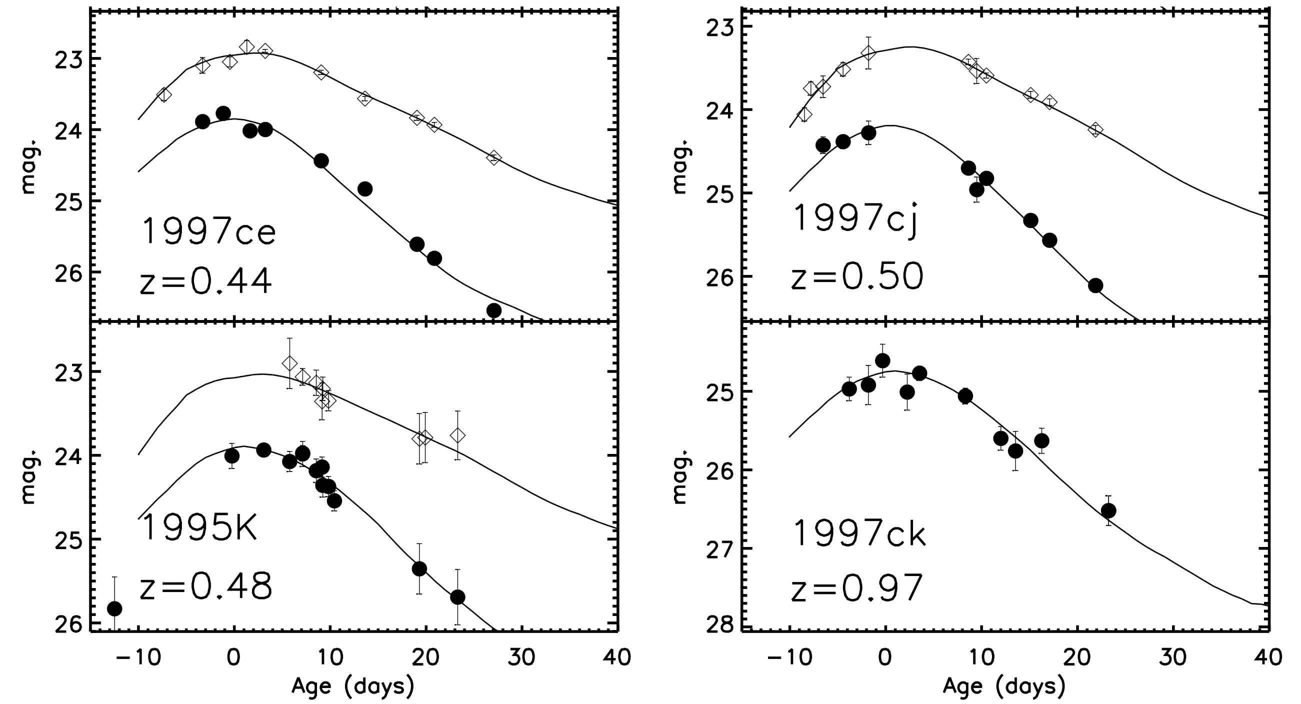
Standard Candles



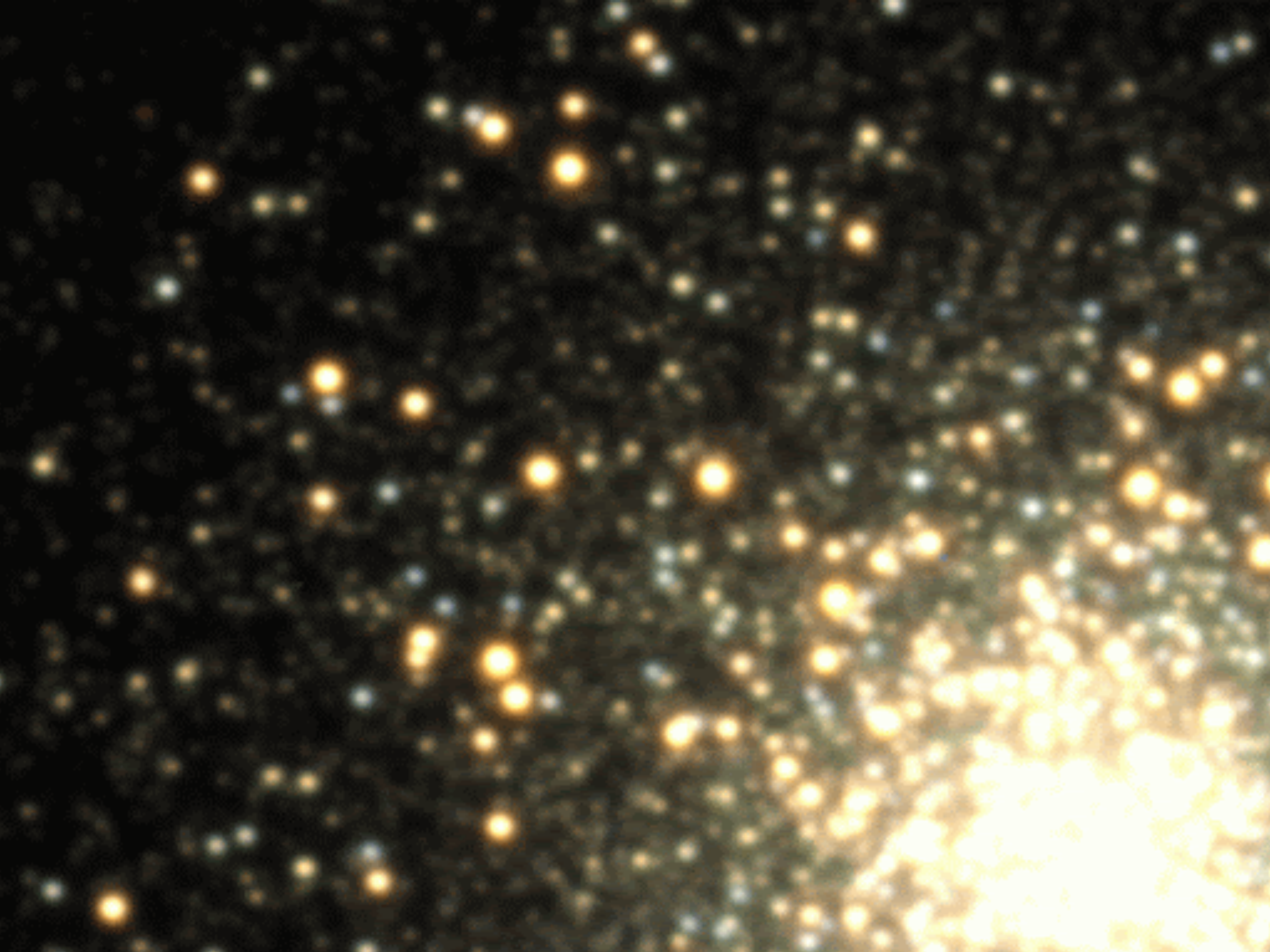




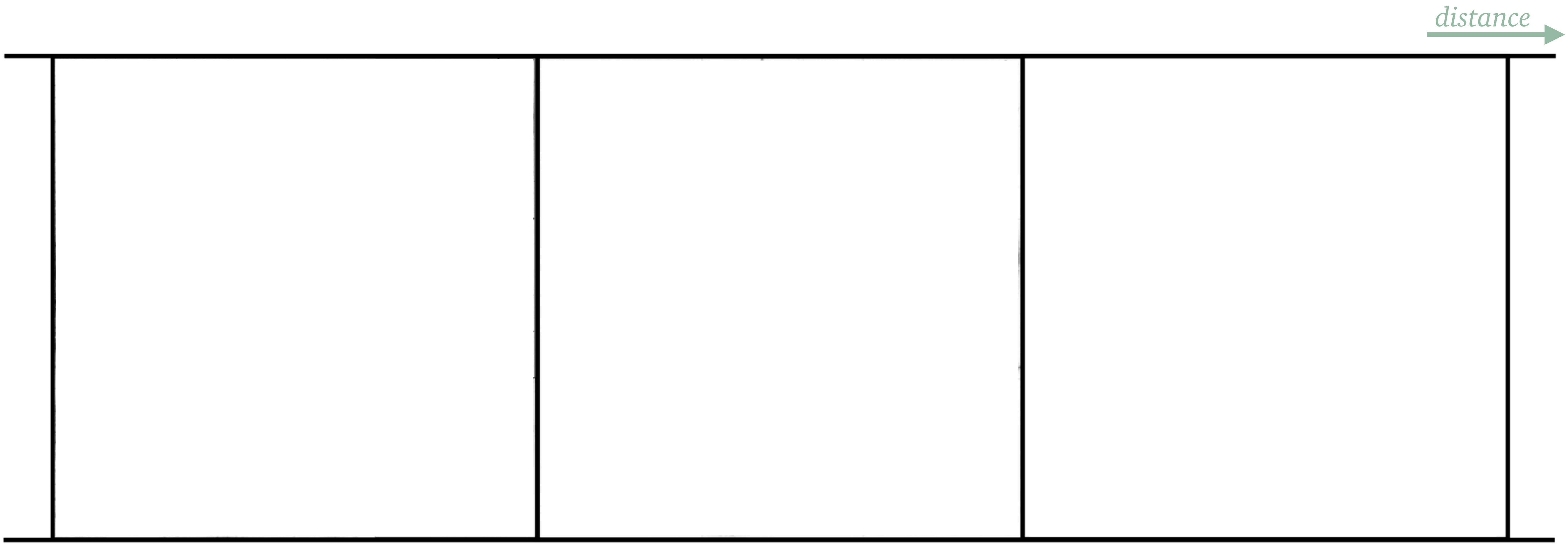
Explosion from thermonuclear detonation of a white dwarf star in a binary



SNIa light curves (Riess et al. 1998)



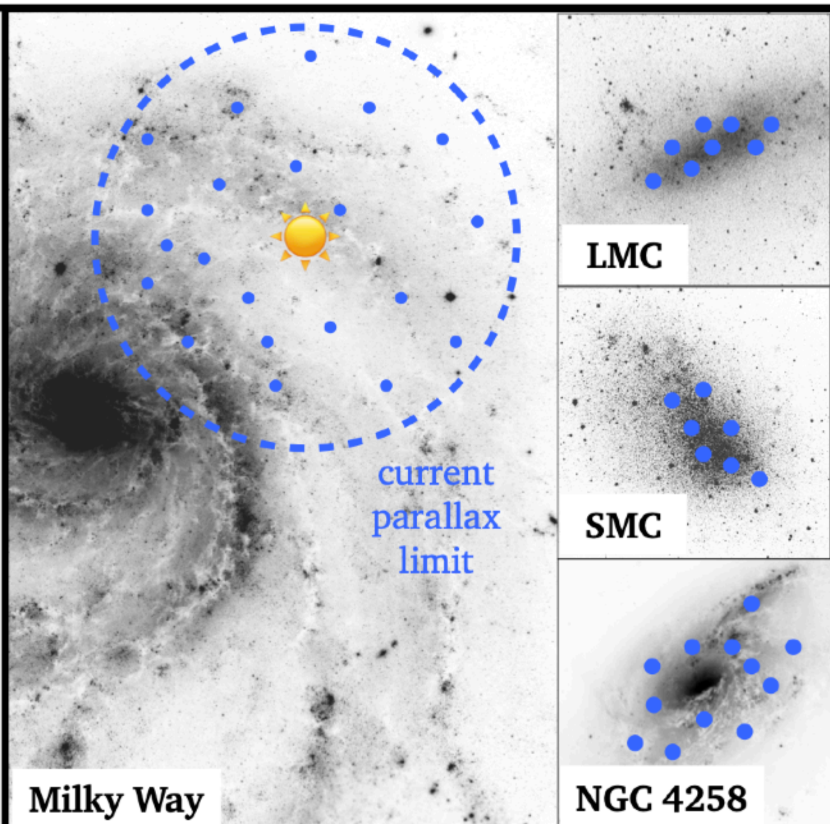
The Cepheid & SNIa Distance Ladder



The Cepheid & SNIa Distance Ladder

distance →

1st rung
Geometry → Cepheids in 4 anchor galaxies

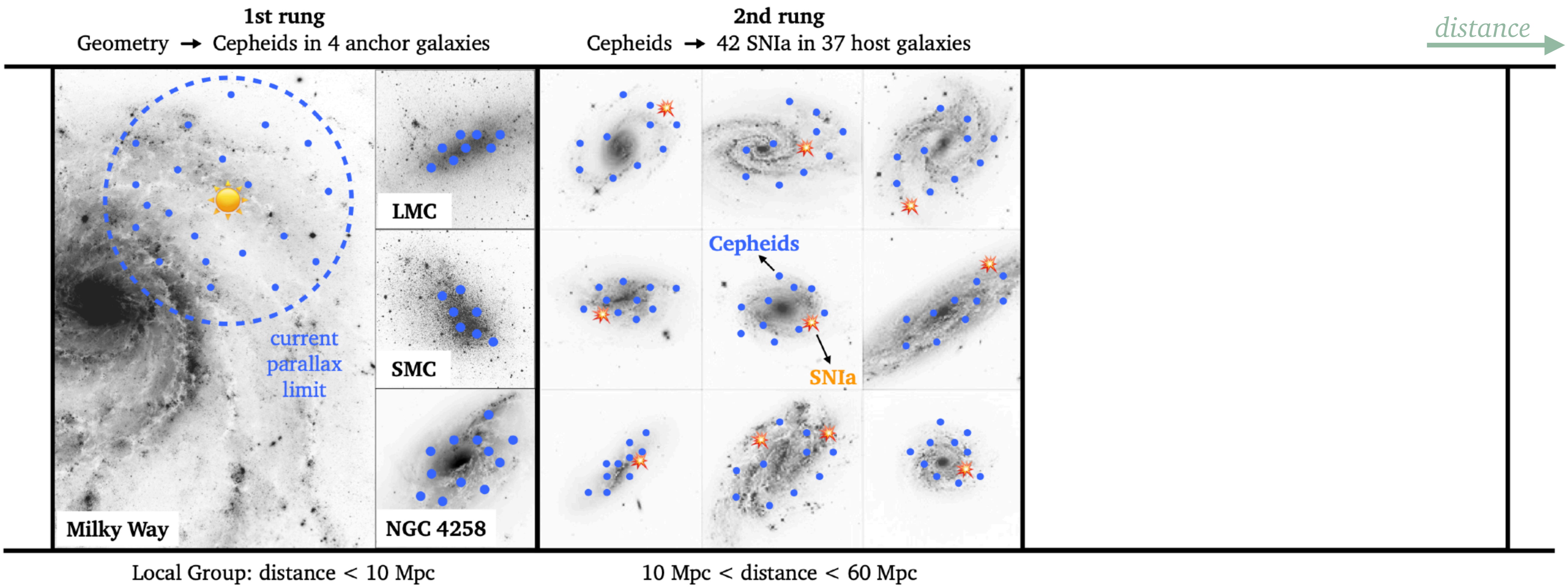


Local Group: distance < 10 Mpc

We use "**known**" distances in nearby galaxies to calibrate the absolute Period-Luminosity relation of Cepheids:

- Gaia parallaxes (Milky Way)
- Eclipsing binaries (LMC)
- Maser orbital motion (N4258)

The Cepheid & SNIa Distance Ladder



We use "**known**" distances in nearby galaxies to calibrate the absolute Period-Luminosity relation of Cepheids:

- Gaia parallaxes (Milky Way)
- Eclipsing binaries (LMC)
- Maser orbital motion (N4258)

We observe galaxies hosting **both** Cepheids and SNIa, and we assume Cepheid distances to calibrate SNIa.

→ Limited to the volume where Cepheids can be observed & by the number of nearby SNIa (1 SNIa/galaxy/100 years)

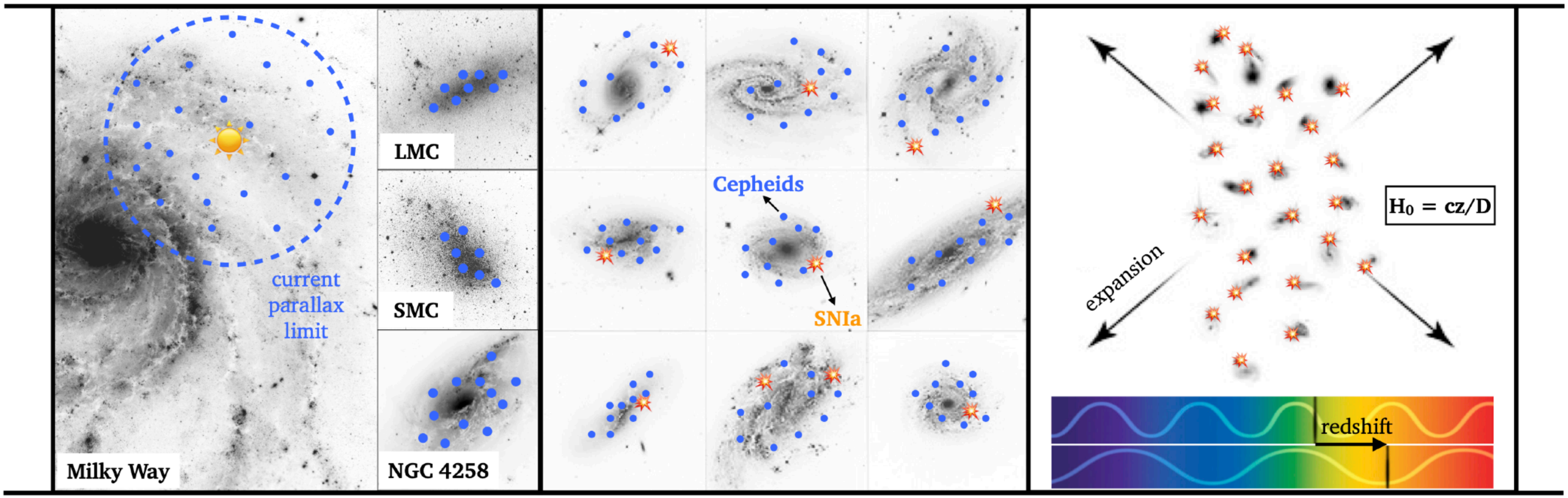
The Cepheid & SNIa Distance Ladder

1st rung
Geometry → Cepheids in 4 anchor galaxies

2nd rung
Cepheids → 42 SNIa in 37 host galaxies

3rd rung
277 SNIa → redshifts

distance →



Local Group: distance < 10 Mpc

10 Mpc < distance < 60 Mpc

0.02 < redshift (z) < 0.20 (Hubble Flow)

We use "**known**" distances in nearby galaxies to calibrate the absolute Period-Luminosity relation of Cepheids:

- Gaia parallaxes (Milky Way)
- Eclipsing binaries (LMC)
- Maser orbital motion (N4258)

We observe galaxies hosting **both** Cepheids and SNIa, and we assume Cepheid distances to calibrate SNIa.

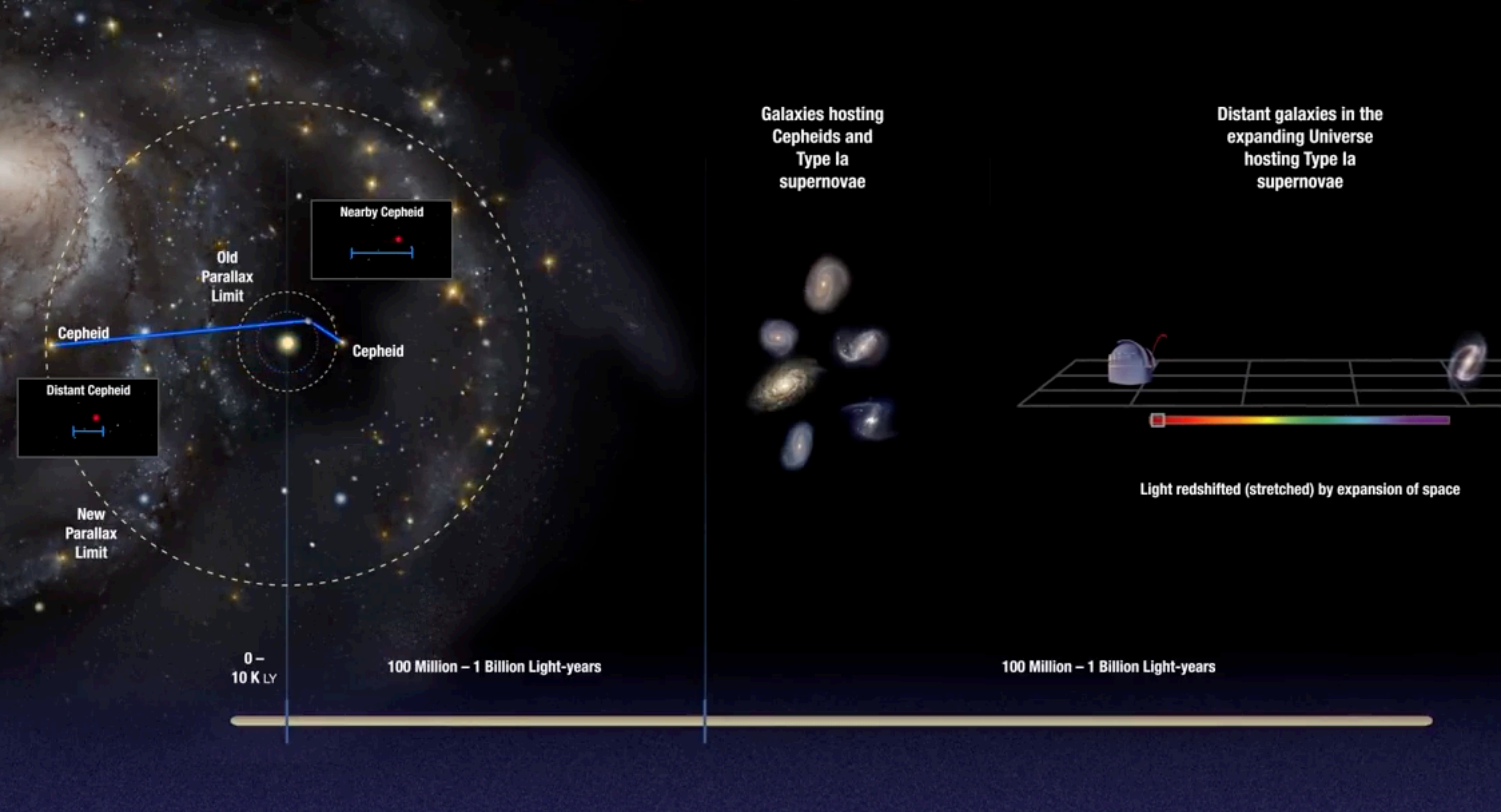
→ Limited to the volume where Cepheids can be observed & by the number of nearby SNIa (1 SNIa/galaxy/100 years)

Here, only SNIa are bright enough to be observed, Cepheids too faint.

→ Far enough to avoid local gravitational interactions

→ Close enough to measure H_0

Three Steps to Measuring the Expansion Rate of the Universe



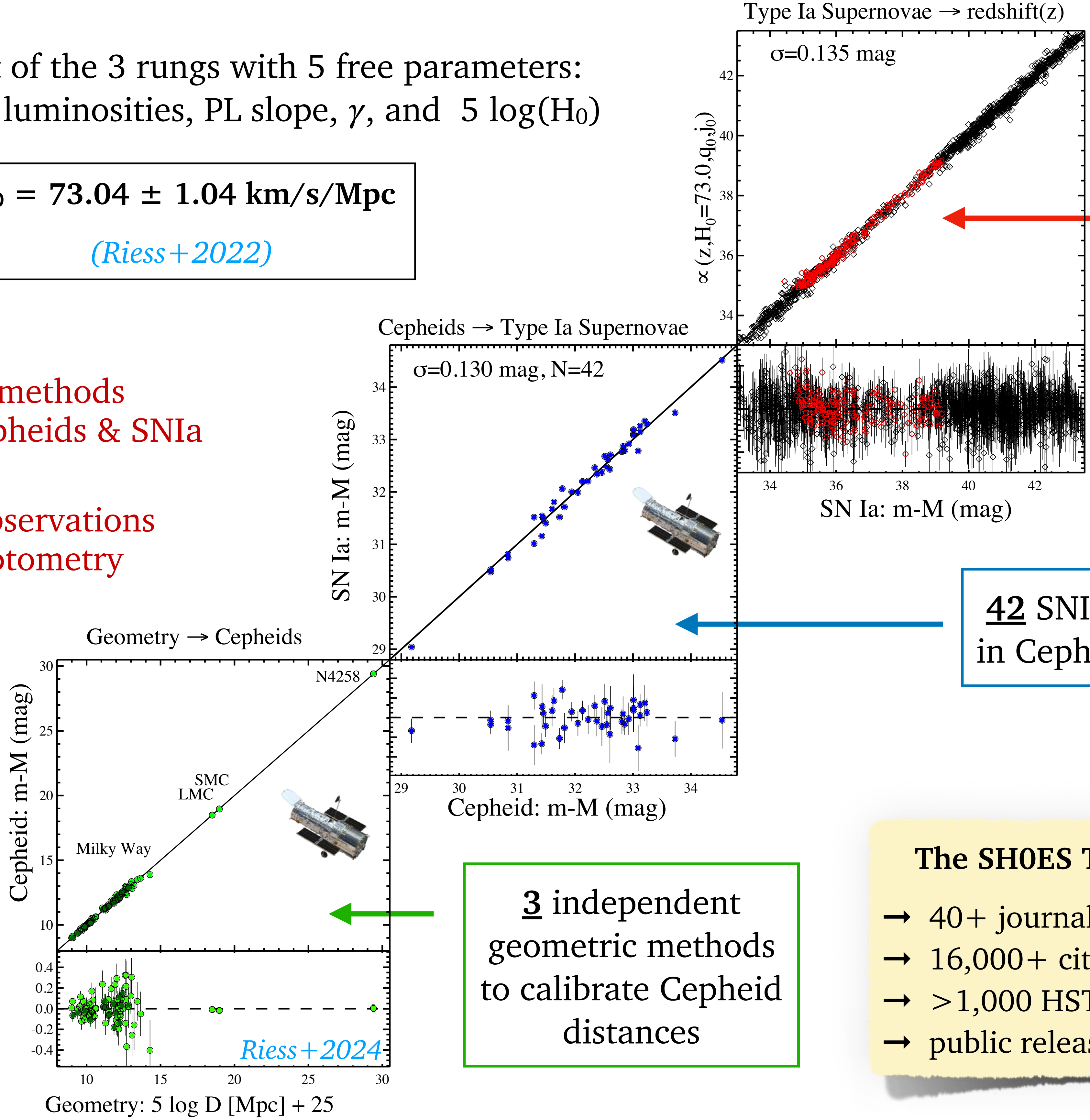
The Cepheid & SNIa Distance Ladder

- ✦ Use NIR & colors to minimize the effect of dust
- ✦ Simultaneous fit of the 3 rungs with 5 free parameters: Cepheid & SNIa luminosities, PL slope, γ, and $5\log(H_0)$

H_0 = 73.04 ± 1.04 km/s/Mpc

(Riess+2022)

- Best-understood methods
  ➞ physics of Cepheids & SNIa
- Homogeneous observations
  ➞ **only HST** photometry
- Largest number of objects
  ➞ populate sparser rungs



High quality data & calibration for ~**300** SNIa (Pantheon+, *Brout+2023*)

42 SNIa calibrators also in Cepheid hosts galaxies

3 independent geometric methods to calibrate Cepheid distances

The SH0ES Team (PI: A. Riess)

- ➞ 40+ journal papers
- ➞ 16,000+ citations since 2005
- ➞ >1,000 HST orbits, 20 proposals
- ➞ public release of data

1) Introduction: The Hubble Constant (H_0)

2) Two ways to measure/infer H_0

3) The Cepheid–SNIa distance ladder

4) Systematics in the Cepheid–SNIa distance ladder

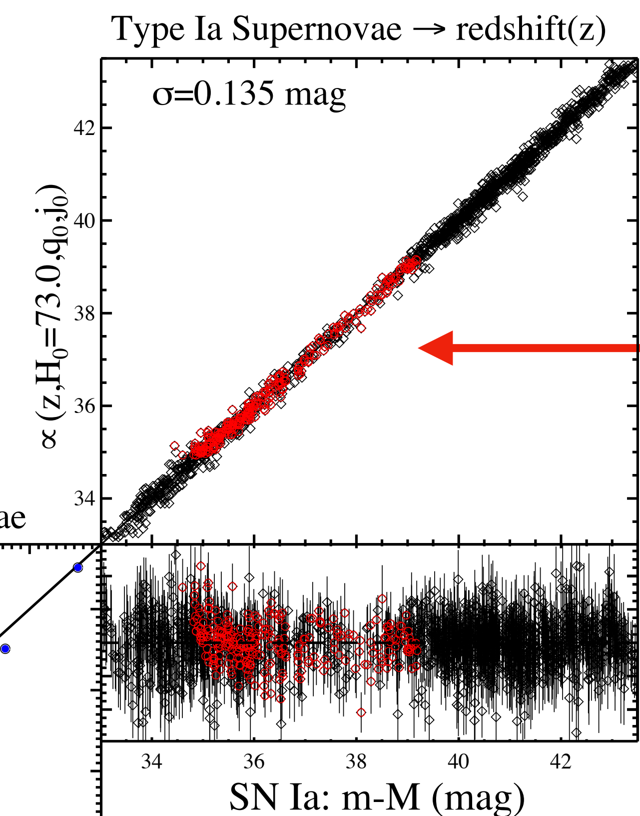
5) An independent "Type II" distance ladder

6) Conclusion & Perspectives

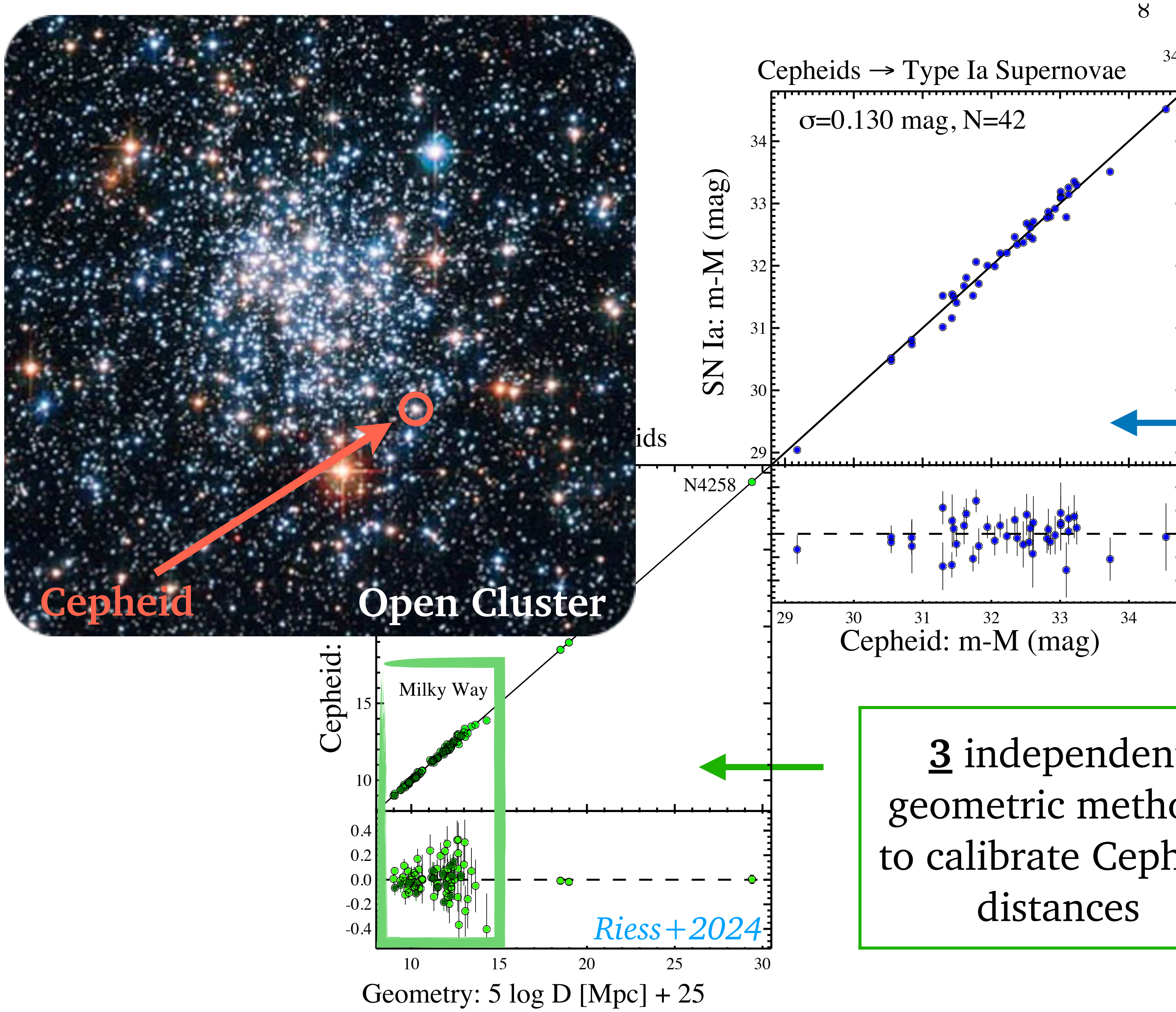
The Cepheid & SNIa Distance Ladder

Gaia parallaxes are well measured, but Cepheids are bright stars and require a small corrective term (parallax zero-point).

Alternative approach? 🤔



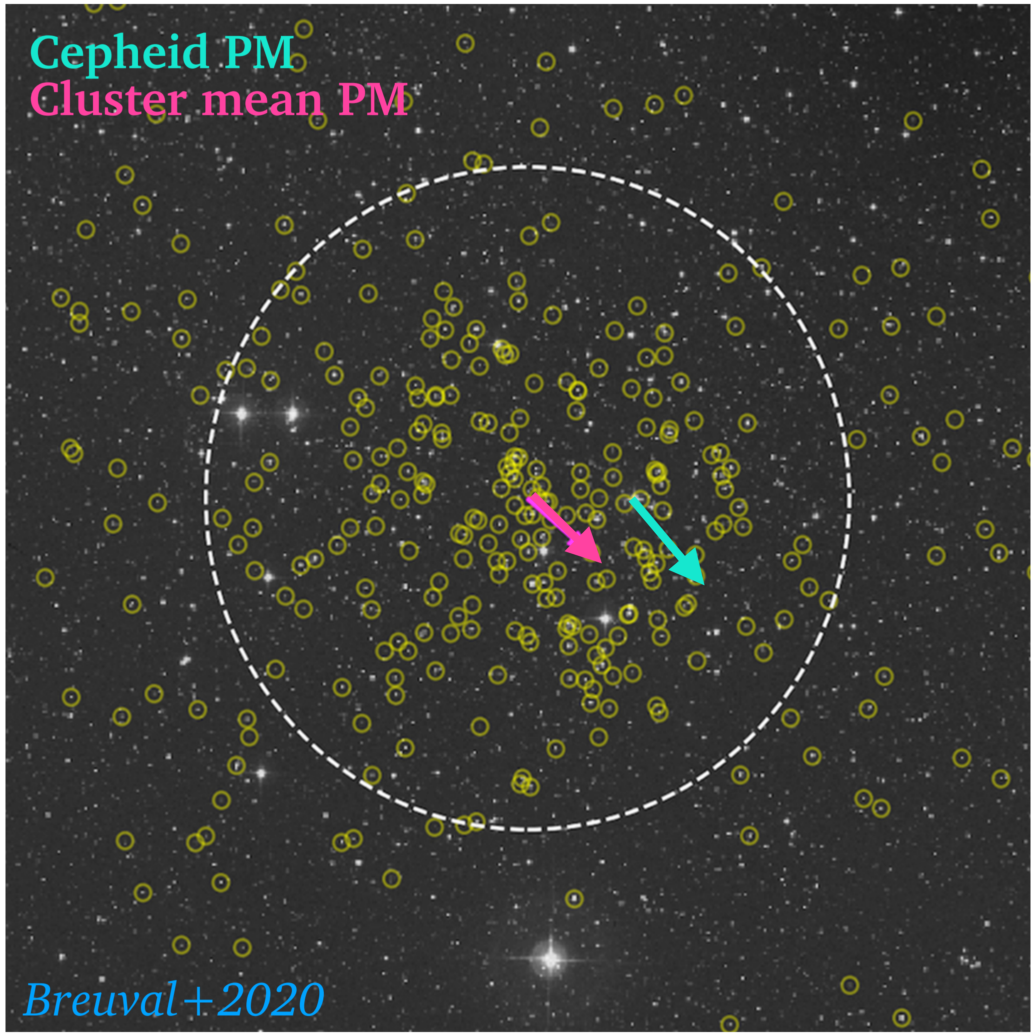
High quality data & calibration for ~**300** SNIa (Pantheon+, *Brout+2023*)



42 SNIa calibrators also in Cepheid hosts galaxies

3 independent geometric methods to calibrate Cepheid distances

Improving the Milky Way Calibration with Cepheids in Clusters

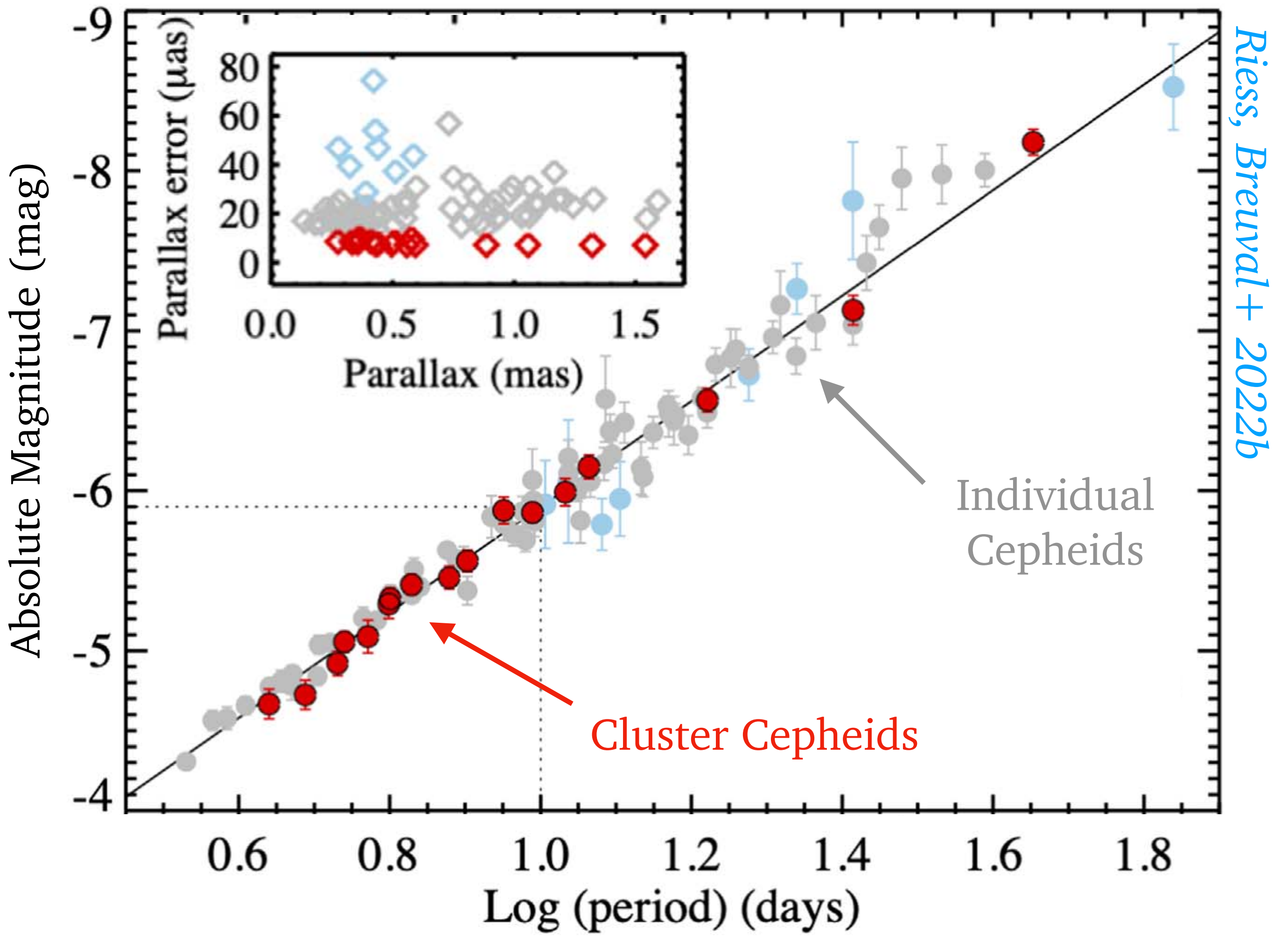


Open Clusters host >100 stars: Cluster mean parallaxes are **more precise** than those of individual Cepheids
Breuval+2020

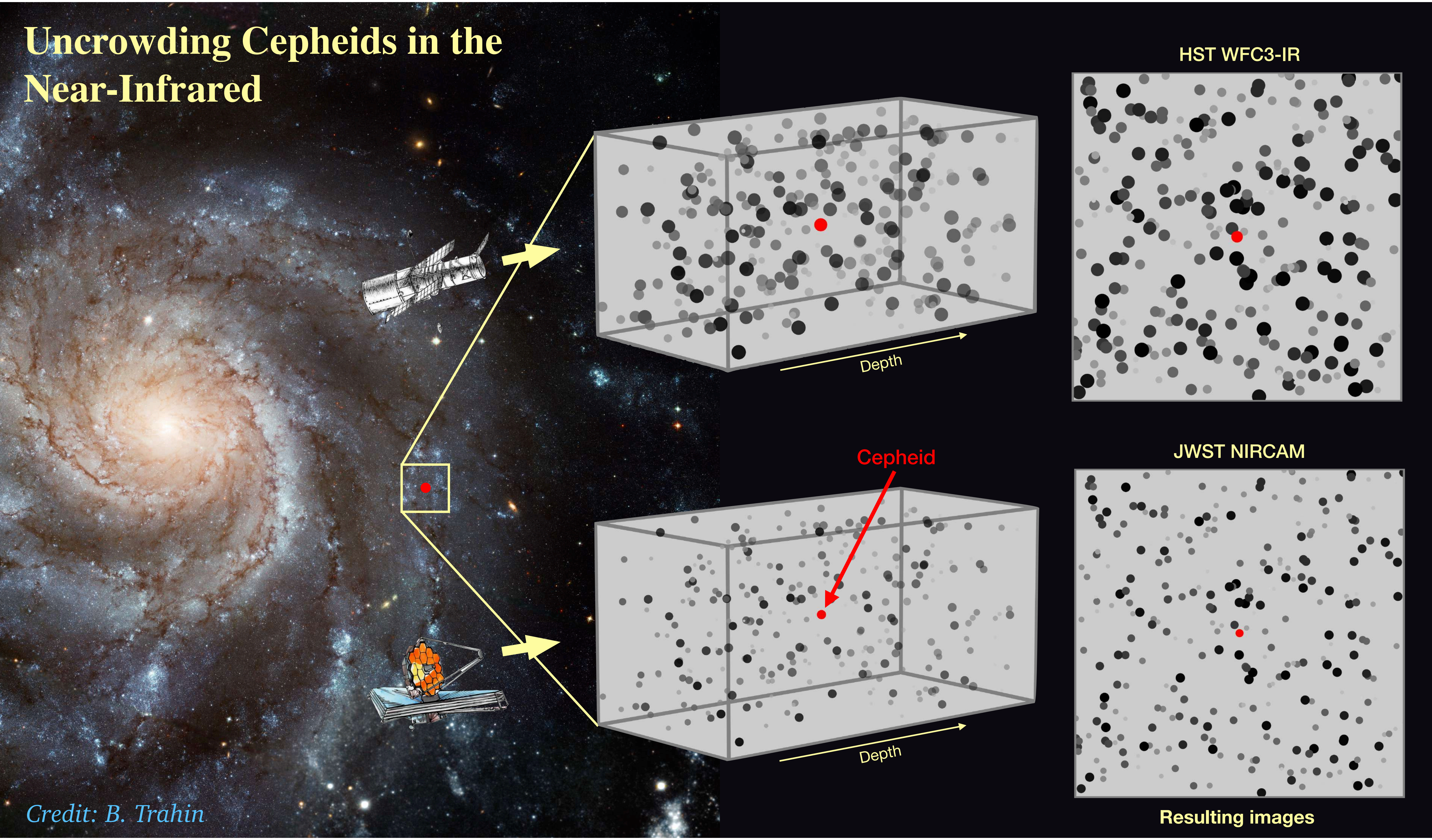
Cluster members are fainter than Cepheids, and Gaia parallaxes are **better calibrated** for fainter stars.

17 cluster Cepheids = as good as 75 individual Cepheids!
Consistent HST photometry (spatial scanning)
Riess+2022b

H_0 = 73.04 ± 1.04 km/s/Mpc (1.42 %)
↓
H_0 = 73.15 ± 0.97 km/s/Mpc (1.33 %)

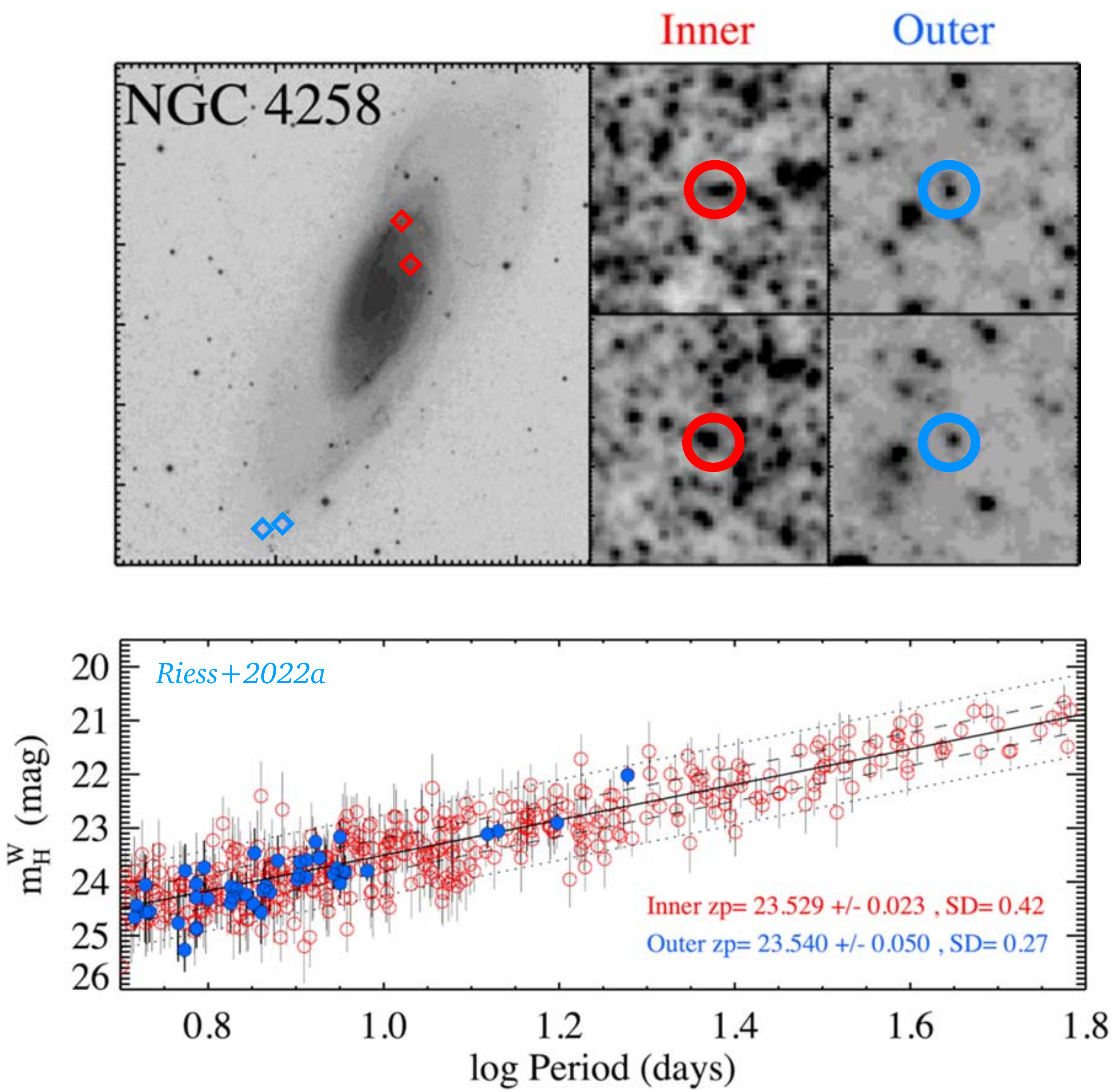


Crowding



→ NIR crowding is **not a systematic**: it is a bias that can be removed using artificial stars simulations, it produces additional scatter in the P-L relation (statistical noise)

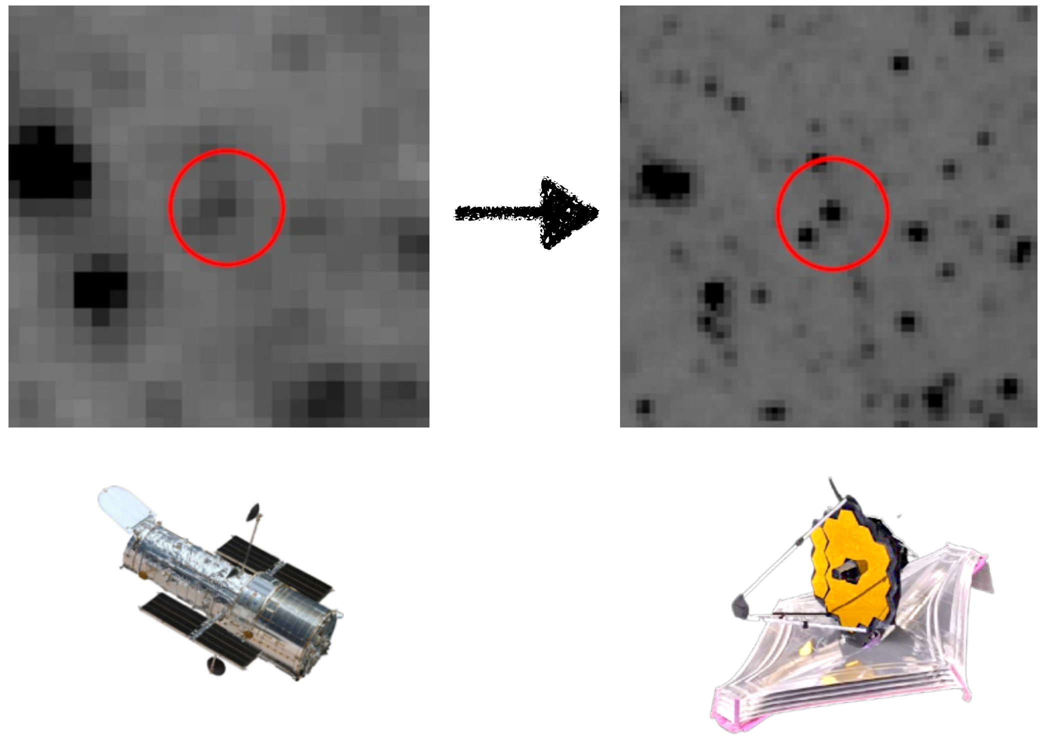
Crowding



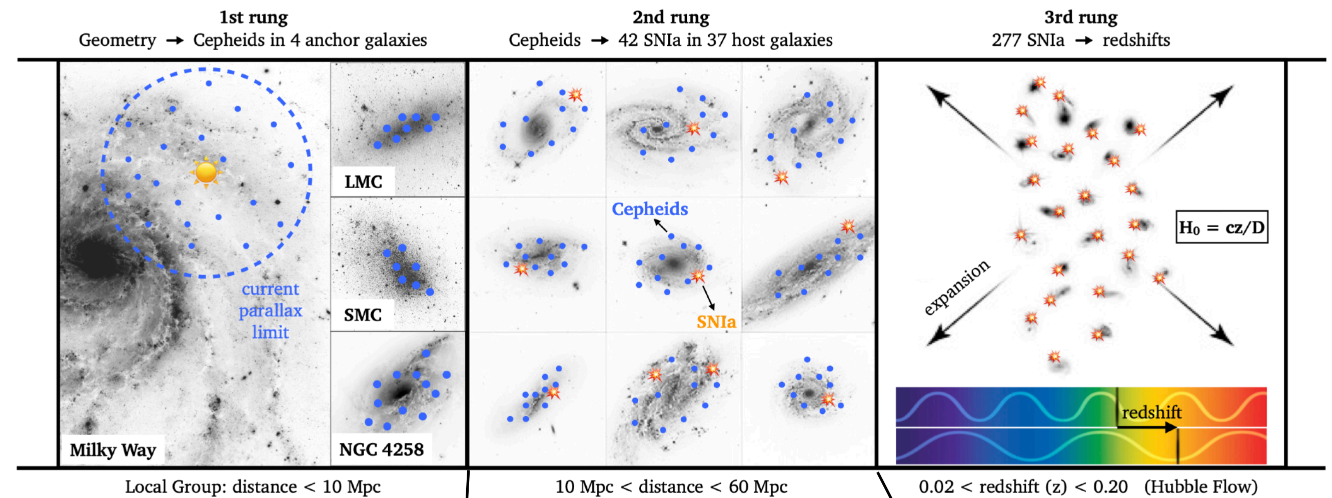
- ✦ Period-Luminosity relation is more scattered for stars in crowded regions.
- ✦ Previously corrected with artificial star tests.

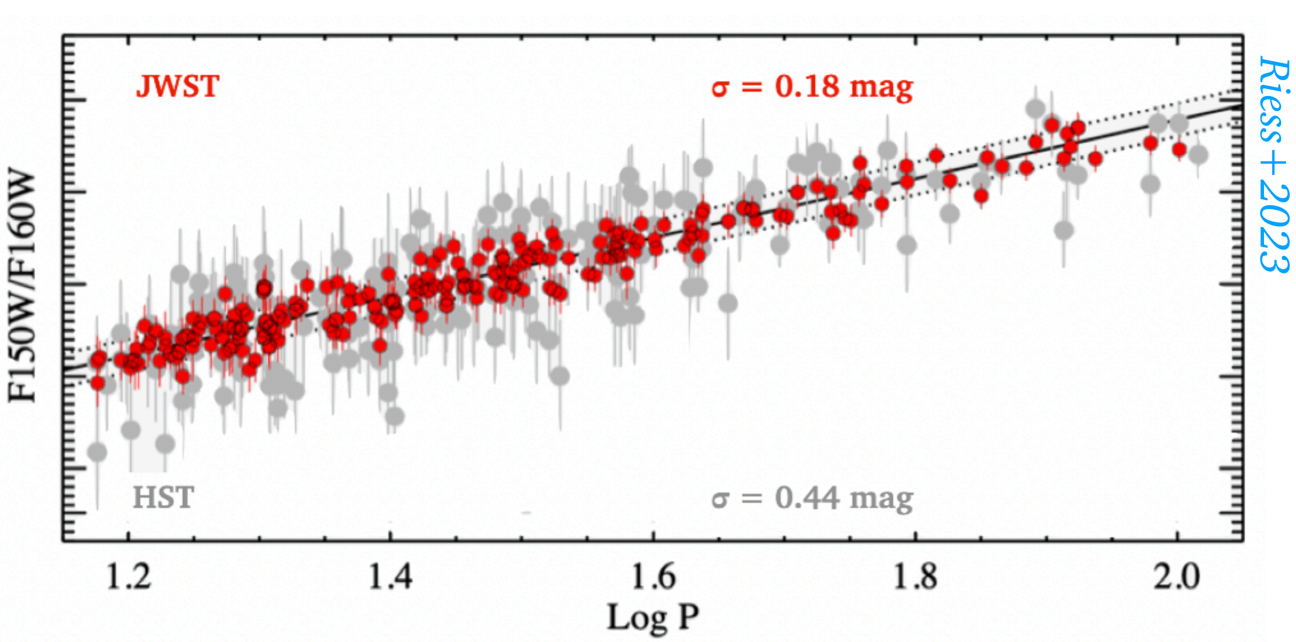
Crowding

HST 1.5 µm (F160W) JWST 1.5 µm (F150W)

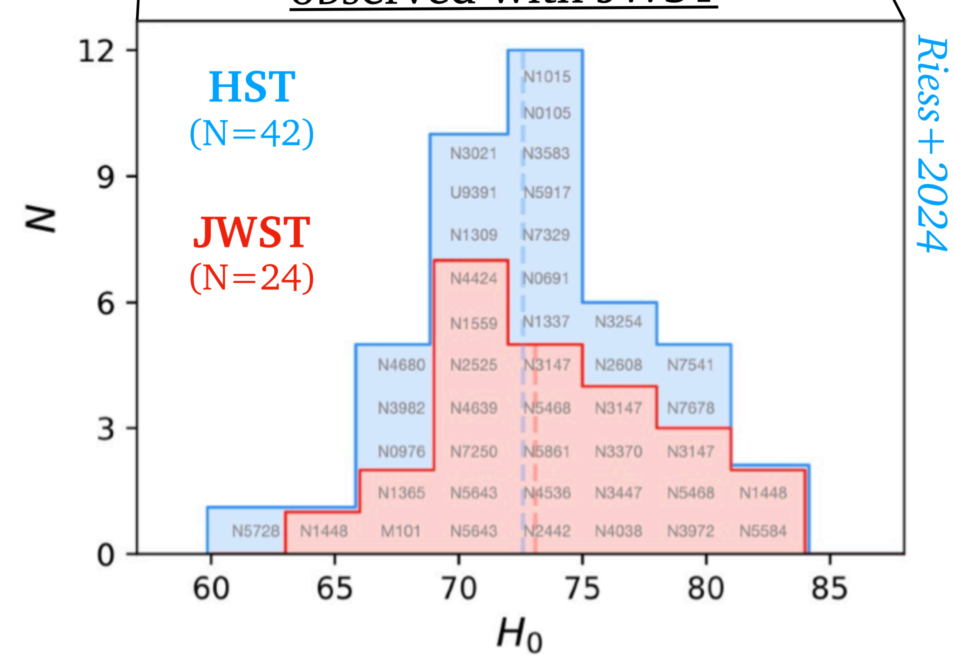


✓ Dispersion reduced by a factor 2.5
✓ Better precision for distances
✓ Excellent agreement with HST: no biais in H_0





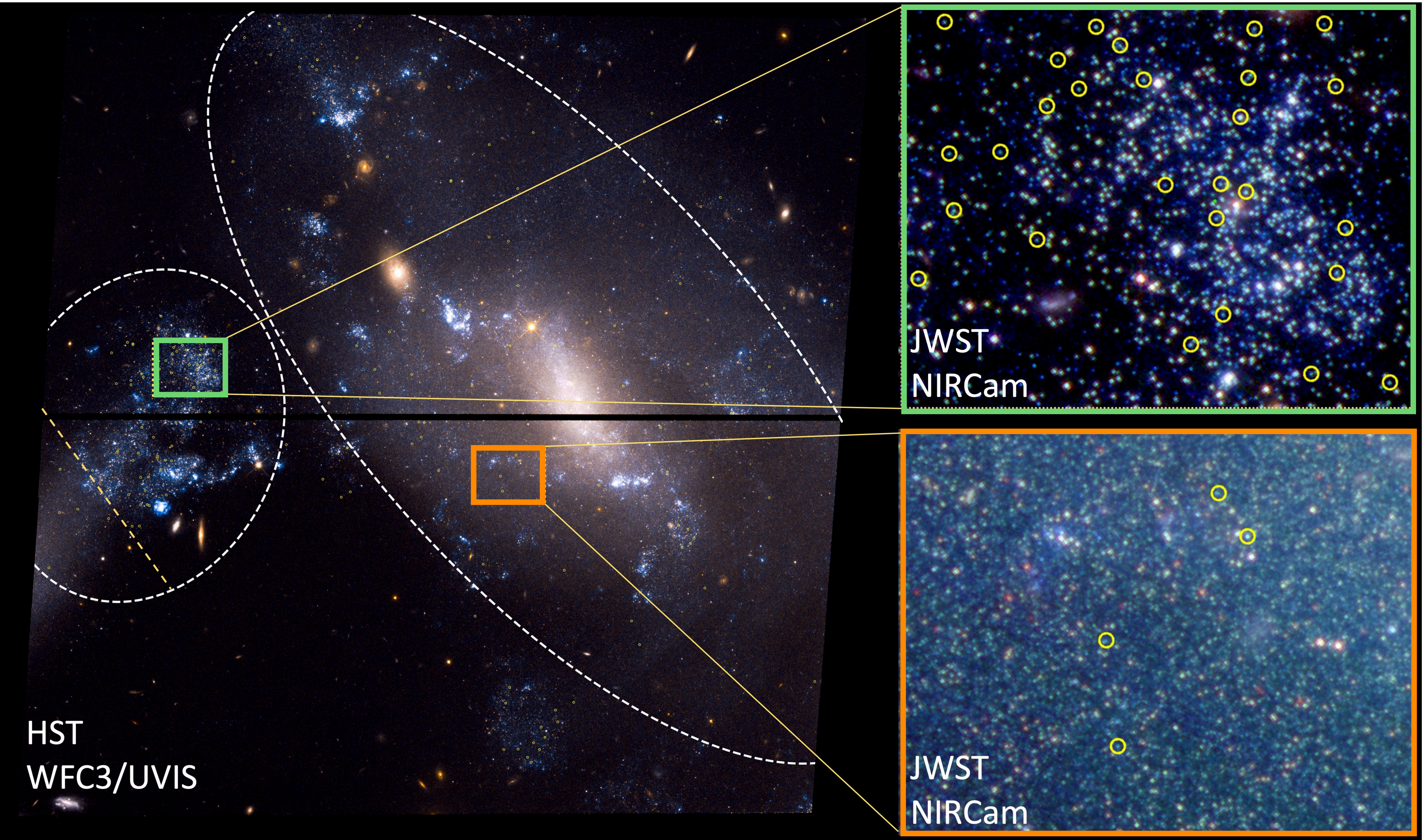
2nd rung galaxies (SNIa hosts) observed with JWST



The Perfect Host: NGC 3447

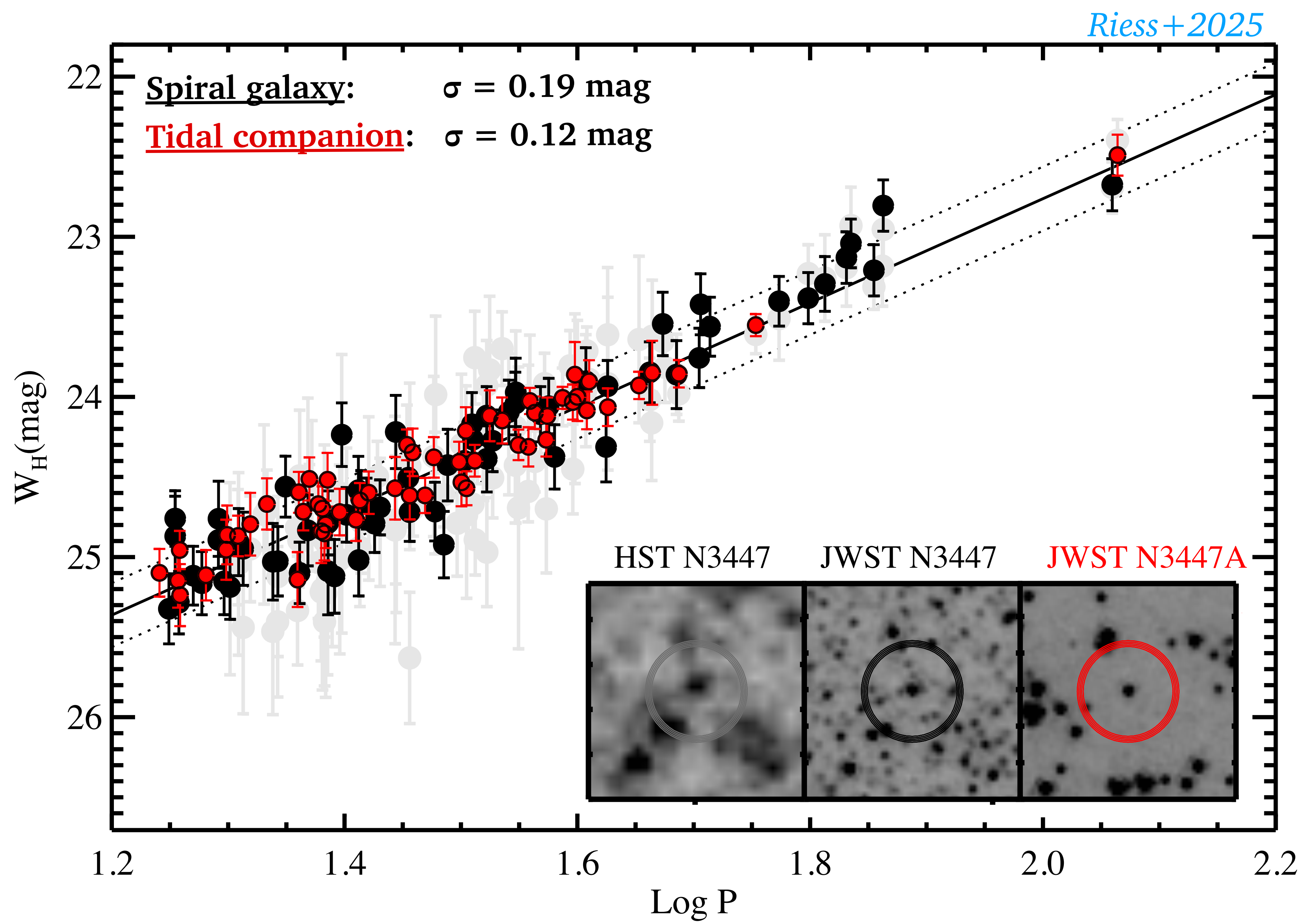
Spiral galaxy: Cepheids form on top of old populations.
Tidal companion: No old population → no background!

Riess+2025



The Perfect Host: NGC 3447

→ Further 50% reduction in dispersion compared to nominal JWST, tightest P-L relation outside Local Group



→ Again, **great agreement** between HST and JWST distances:
crowding is ruled out as a possible source of the Hubble tension

Conclusion on Crowding

THE ASTROPHYSICAL JOURNAL, 977:120 (18pp), 2024 December 10 https://doi.org/10.3847/1538-4357/ad8c21

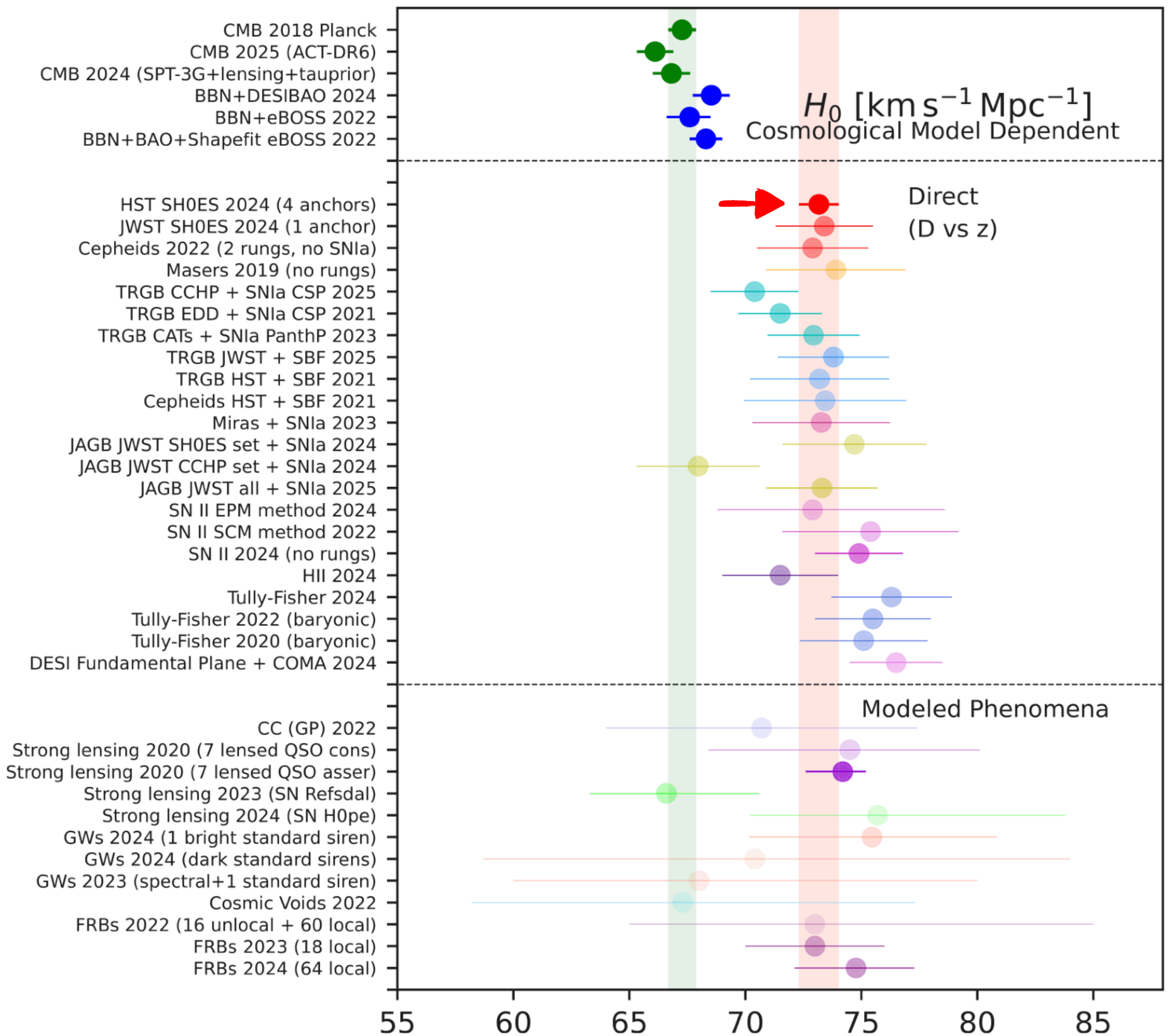
JWST Validates HST Distance Measurements: Selection of Supernova Subsample Explains Differences in JWST Estimates of Local H_0

Adam G. Riess[1,2], Dan Scolnic[3], Gagandeep S. Anand[1], Louise Breuval[2], Stefano Casertano[1], Lucas M. Macri[4], Siyang Li[2], Wenlong Yuan[2], Caroline D. Huang[5], Saurabh Jha[6], Yukei S. Murakami[2], Rachael Beaton[1], Dillon Brout[7], Tianrui Wu[3], Graeme E. Addison[2], Charles Bennett[2], Richard I. Anderson[8], Alexei V. Filippenko[9], and Anthony Carr[10,11]

[1] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
[2] Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA
[3] Department of Physics, Duke University, Durham, NC 27708, USA
[4] NSF NOIRLab, 950 N Cherry Avenue, Tucson, AZ 85719, USA
[5] Center for Astrophysics | Harvard & Smithsonian, 60 Garden Street, Cambridge, MA 02138, USA
[6] Department of Physics and Astronomy, Rutgers, The State University of New Jersey, 136 Frelinghuysen Road, Piscataway, NJ 08854, USA
[7] Departments of Astronomy and Physics, Boston University, Boston, MA 02215, USA
[8] Institute of Physics, École Polytechnique Fédérale de Lausanne (EPFL), Observatoire de Sauverny, 1290 Versoix, Switzerland
[9] Department of Astronomy, University of California, Berkeley, CA 94720-3411, USA
[10] School of Mathematics and Physics, University of Queensland, Brisbane, QLD 4072, Australia
[11] Korea Astronomy and Space Science Institute, Yuseong-gu, Daedeok-daero 776, Daejeon 34055, Republic of Korea
Received 2024 August 23; revised 2024 October 11; accepted 2024 October 13; published 2024 December 9

- ✦ HST and JWST Cepheid photometry in excellent agreement
- ✦ HST with 42 SNIa hosts and 4 anchors still provides the strongest constraint on H_0.
- ✦ H_0 **strongly depends** on the sample of SNIa host galaxies.
- ✦ JWST subsample still **too small** to say anything conclusive on the Hubble tension.

The Hubble Tension



All these recent improvements, and the growing confidence that we're not missing an "unknown" systematic, reinforce the Hubble Tension and improved the robustness of the Cepheid-SNIa distance ladder.

But...

Other techniques should/can be developed and refined! Especially if they are **independent** from Cepheids and SNIa

1) Introduction: The Hubble Constant (H_0)

2) Two ways to measure/infer H_0

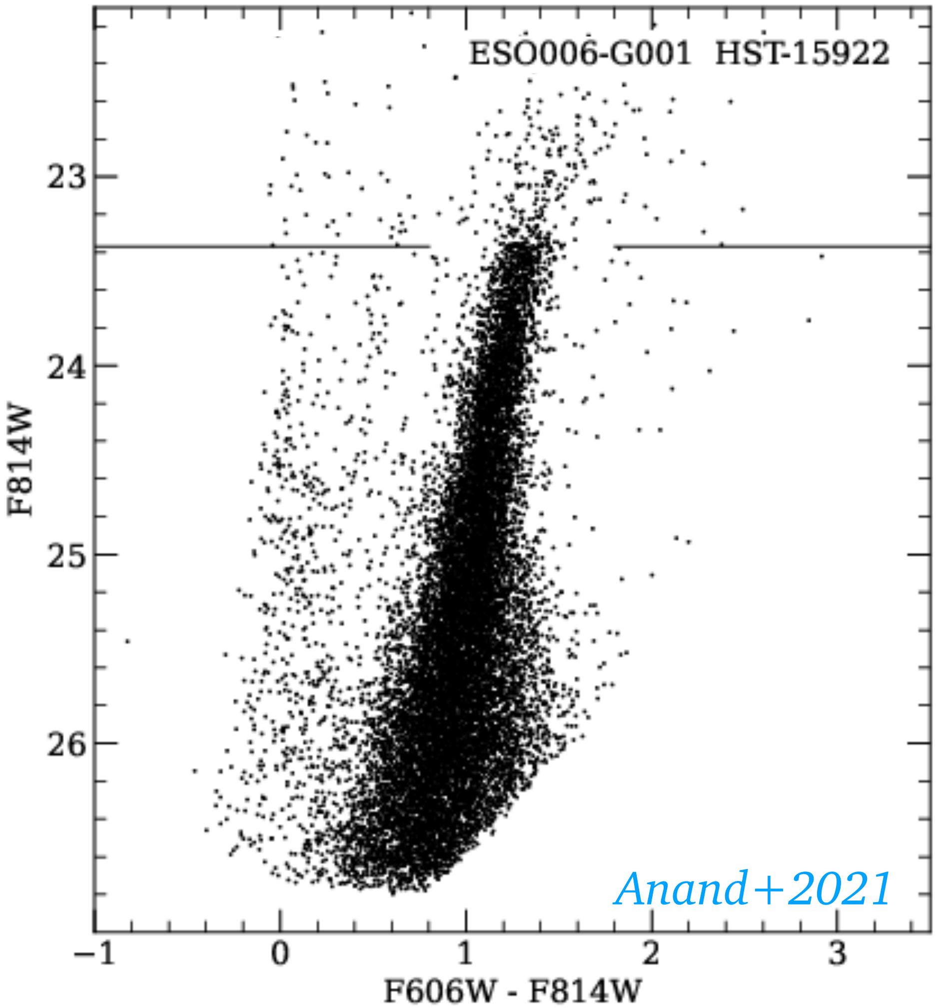
3) The Cepheid–SNIa distance ladder

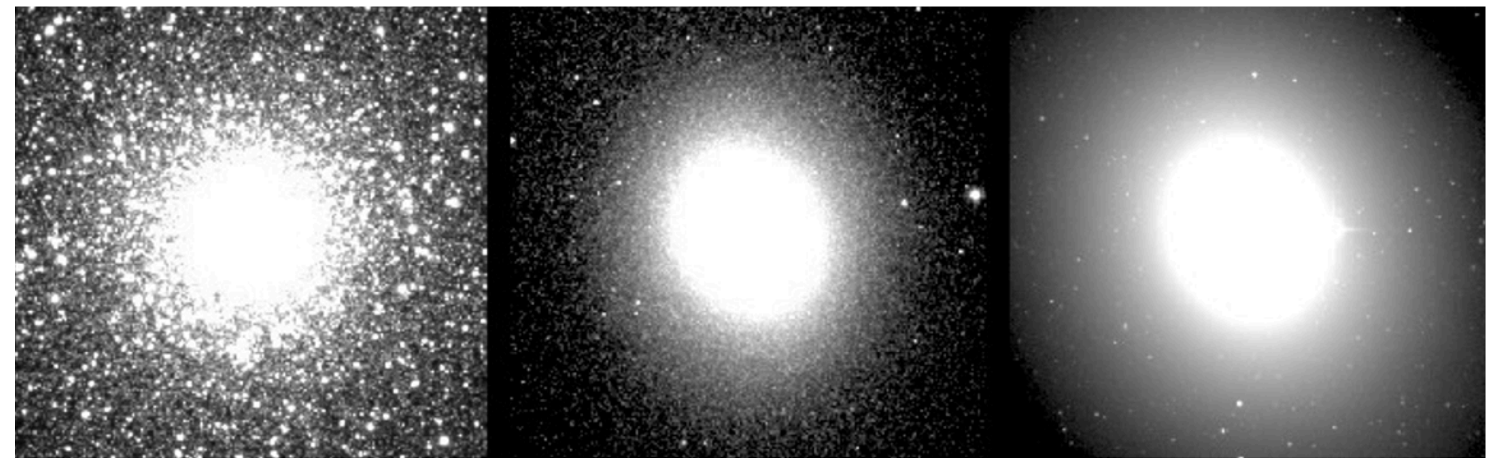
4) Systematics in the Cepheid–SNIa distance ladder

5) An independent "Type II" distance ladder

6) Conclusion & Perspectives

A Type II Distance Ladder with TRGB & SBF





Globular Cluster
10 kpc

M32
(Andromeda Satellite)
770 kpc

M49
(Virgo Cluster)
16 Mpc

Tip of the Red Giant Branch (TRGB)

✦ Correspond to the brightest ascent of red giant stars before they undergo the helium flash.

✦ Highly efficient: need less telescope time than Cepheids, don't have to measure a light curve

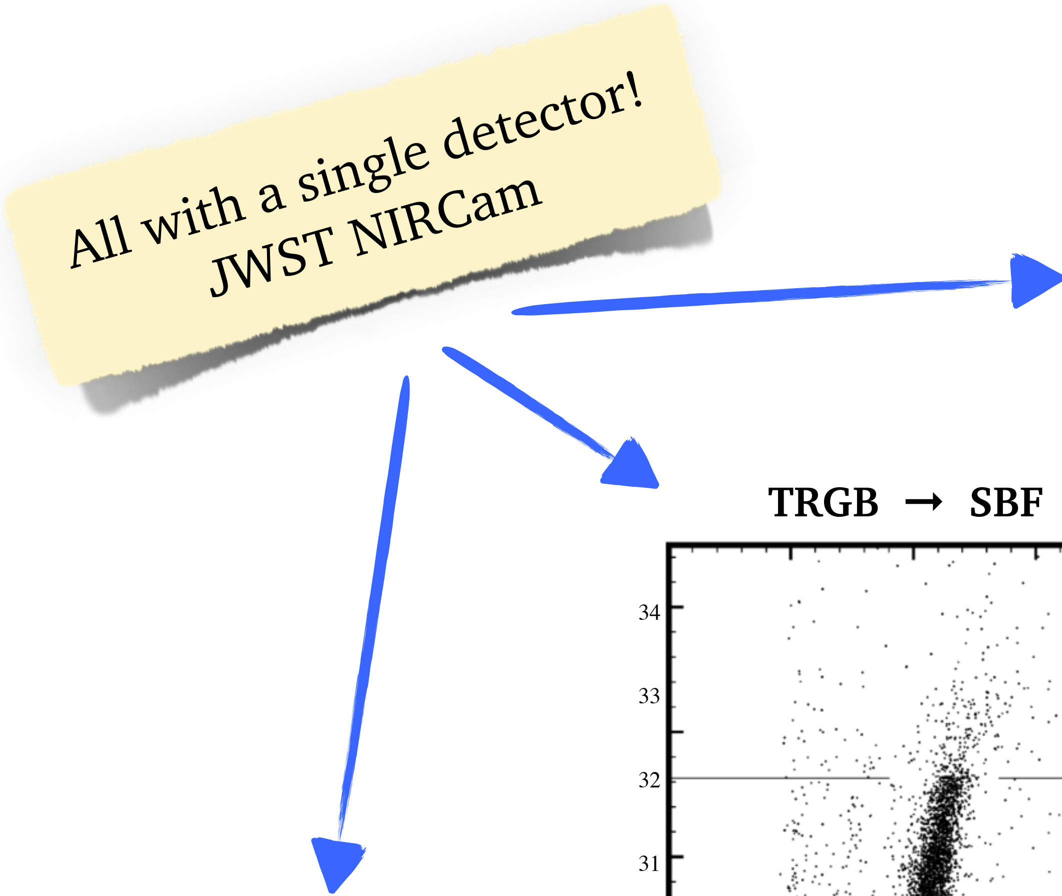
✦ Not limited to galaxies with young stellar populations (unlike Cepheids)

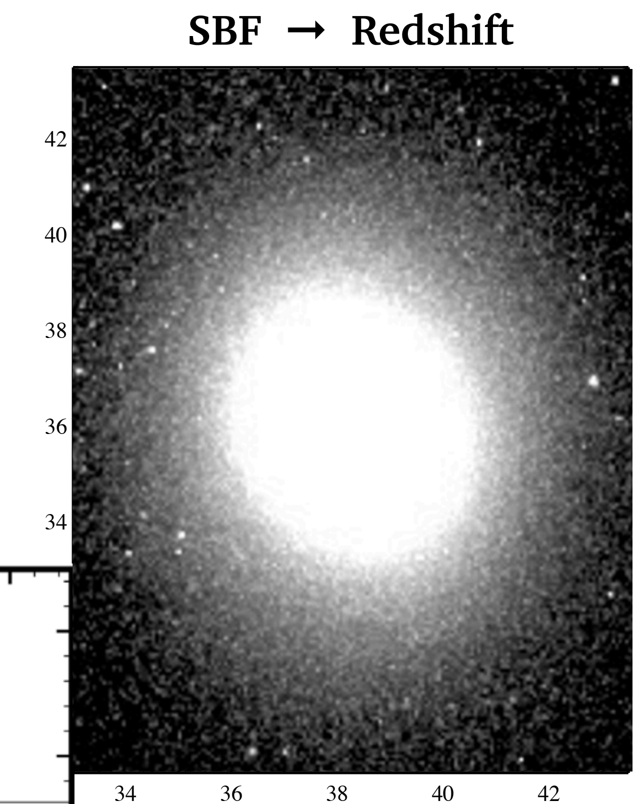
Surface Brightness Fluctuations (SBF)

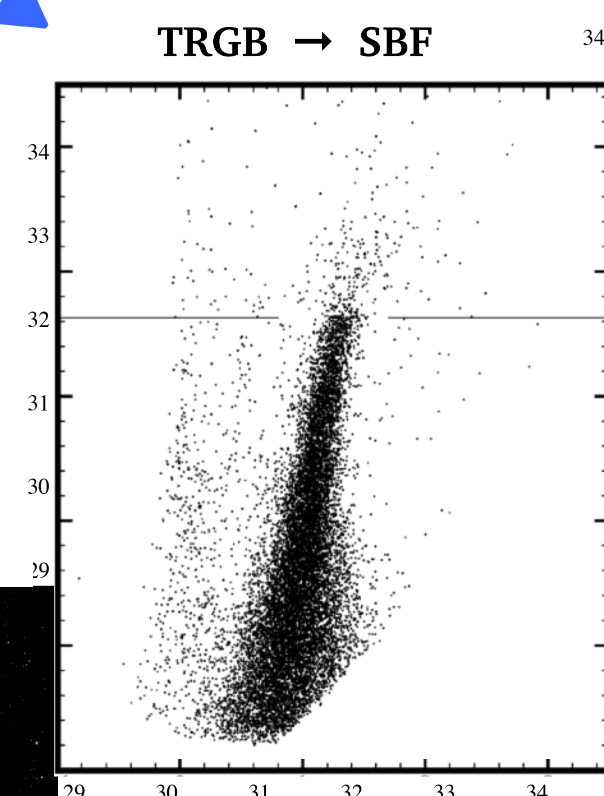
✦ Number of stars/pixel varies with galaxy distance, more distant galaxies look smoother.

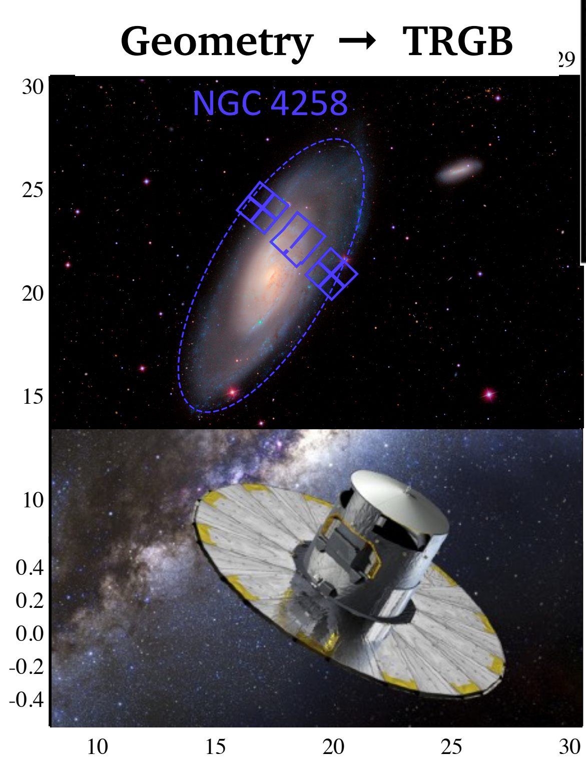
✦ SBF vs Type Ia supernovae:
- No shortage of targets
- Only need single epoch of data
- ~ 4-5% precision per target

A Type II Distance Ladder with TRGB & SBF









The TRGB-SBF Project:
awarded JWST time through 4 proposals
(PI/Co-PIs R. Tully, J. Jensen, G. Anand),
120 GO hours + 300 Survey targets

1) Introduction: The Hubble Constant (H_0)

2) Two ways to measure/infer H_0

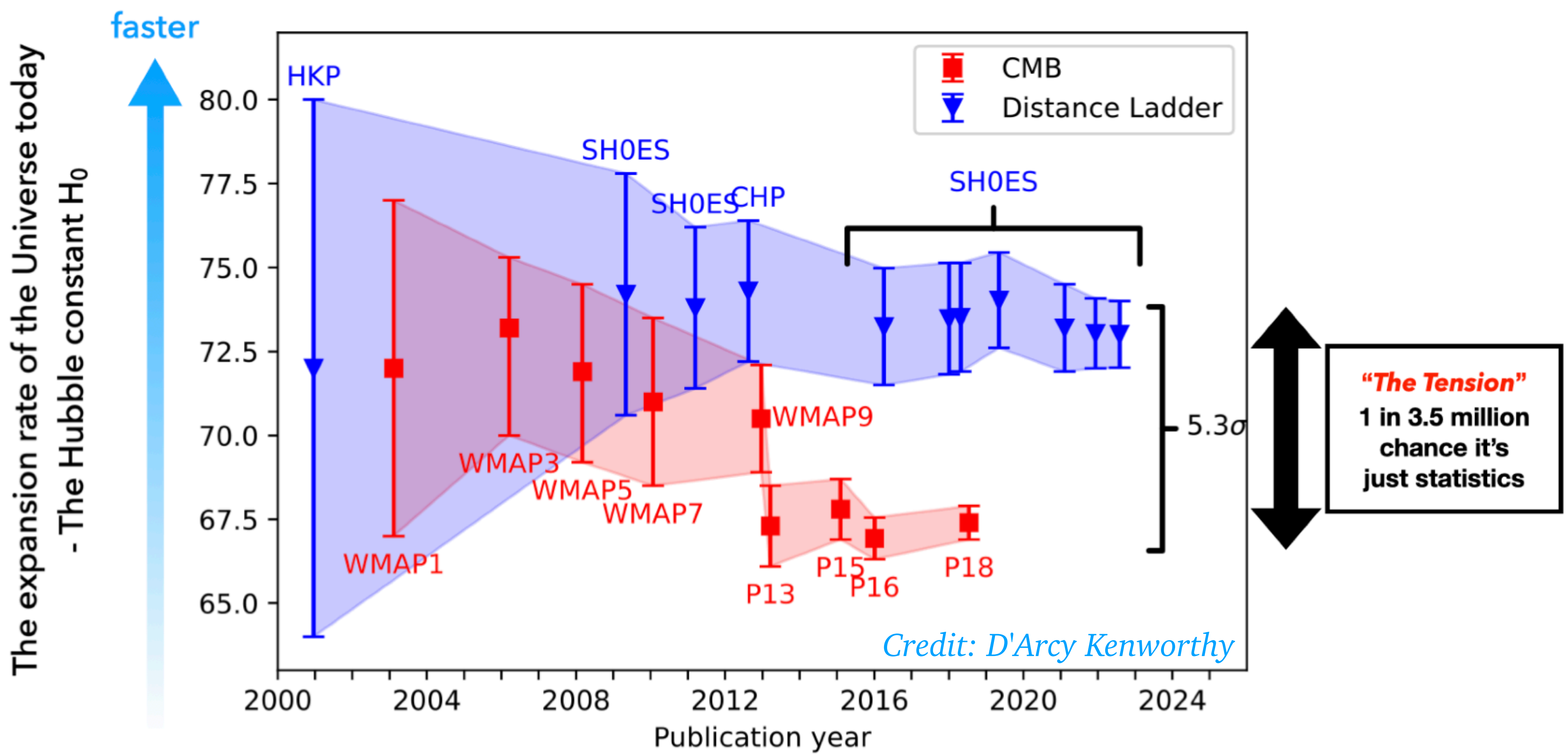
3) The Cepheid–SNIa distance ladder

4) Systematics in the Cepheid–SNIa distance ladder

5) An independent "Type II" distance ladder

6) Conclusion & Perspectives

Conclusion



Not just a Planck vs SH0ES issue. Some recent results:

- ***Parallel*** SNe Ia distance ladder focusing on early-type SN Ia hosts anchored to TRGB, $H_0 = 75.3 \pm 2.9$ km/s/Mpc *(Newman & Larison+25)*.

- ***Distance Network*** approach to combine various community results with appropriate covariance weighting, $H0 = 73.5 \pm 0.8$ km/s/Mpc *(The H0DN Collaboration, Casertano+2026)*.

What you will hear about this week

MONDAY

Distance ladder ✅
Hubble Tension ✅

Cepheids

The Cepheid Metallicity Dependence

TUESDAY

TRGB

Photometry

WEDNESDAY

TRGB

Supernovae Ia

THURSDAY

Supernovae Ia systematics

FRIDAY

Data Challenge

Why did Edwin Hubble measure a H_0 value 7x too high?

First Hubble Diagram (Hubble 1929)