Distance measurements (for H0) in Astronomy

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Dec 15, 2023

Outline

- Why to measure distances?

(e.g. Hubble Tension)

- How to measure distances?

- TRGB as distance indicators

- What can we do further more?

Part I

Why to measure distances?

Why to measure distances in astronomy?

- **Distance** is one of the most important Fundmental parameters in astronomy

- Stellar physics

Calibration of Period-Luminosity relation

- Structure of the Galaxy

e.g. ~8 kpc from the Sun to GC

- Cosmology & Hubble Tension

$$H_0 = \frac{v}{d} \quad (cz = H_0 r)$$

What is the Hubble Tension(哈勃常数危机)?

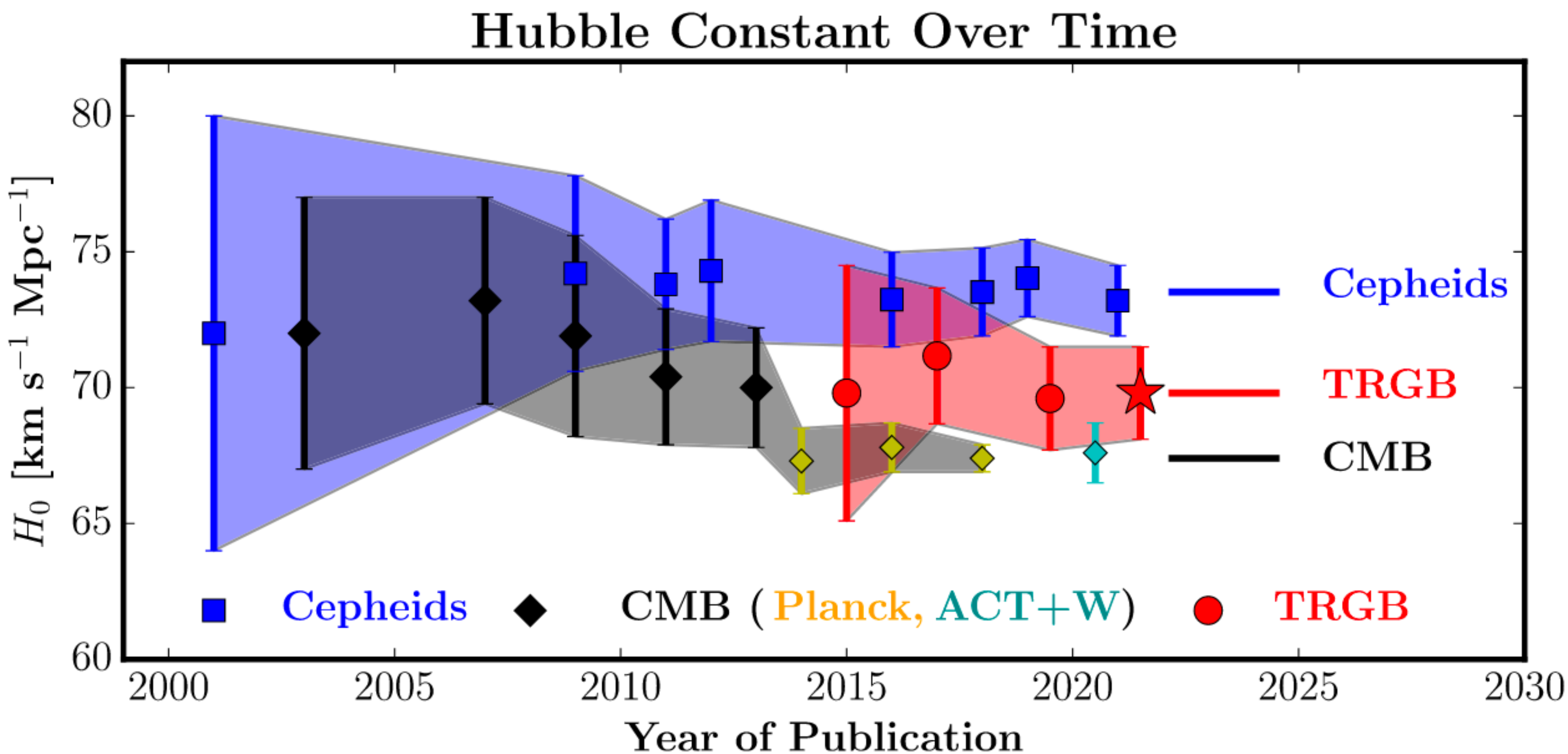
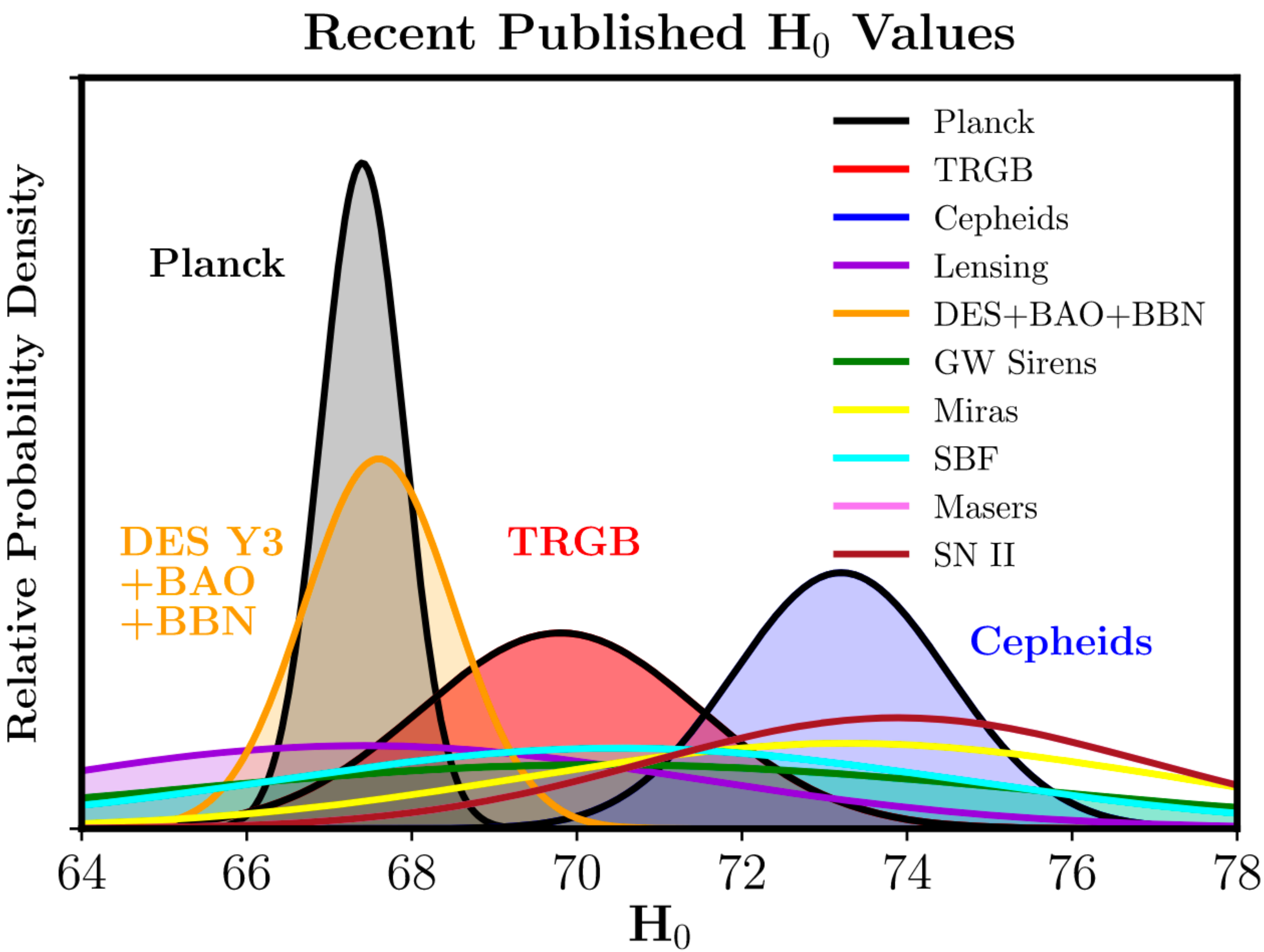


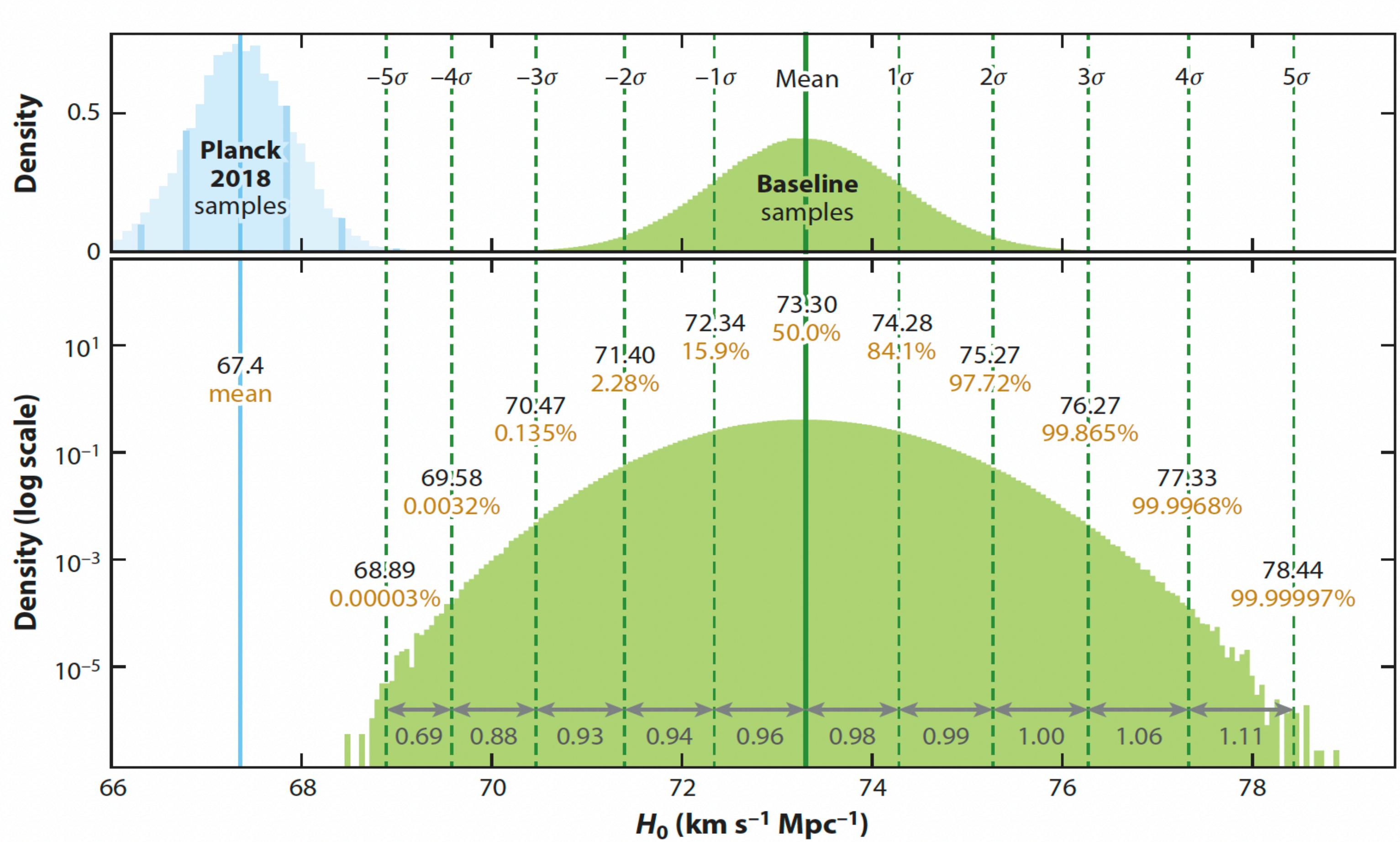
Figure 11. Summary of Hubble constant values in the past two decades based on Cepheid variables (blue squares), the TRGB (red circles and star), and estimates based on measurements of fluctuations in the CMB (WMAP: black diamonds; Planck: yellow diamonds; ACT + WMAP: cyan diamond). The CMB H_0 values assume a flat ΛCDM model. The CMB and Cepheid results straddle a range of 67–74 km s^{-1} Mpc^{-1}, with the TRGB results falling in the middle and overlapping the CMB results. The tension between the CMB and TRGB results amounts to only 1.3σ.

What is the Hubble Tension(哈勃常数危机)?



What is the Hubble Tension(哈勃常数危机)?

- Discrepancy of the H0 from observations and CMB and cosmological models, which is over 5σ.



Plank 2018 vs Observations

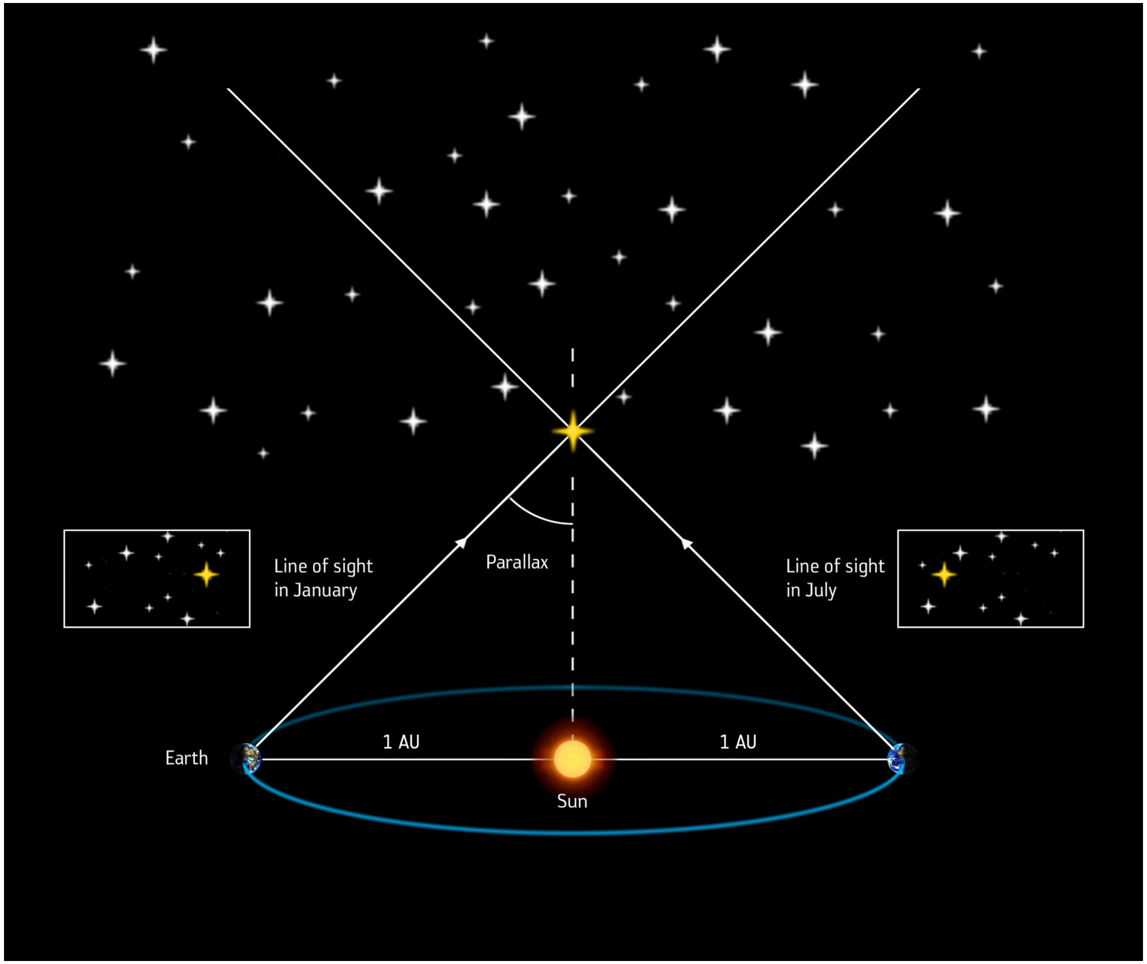
Part II

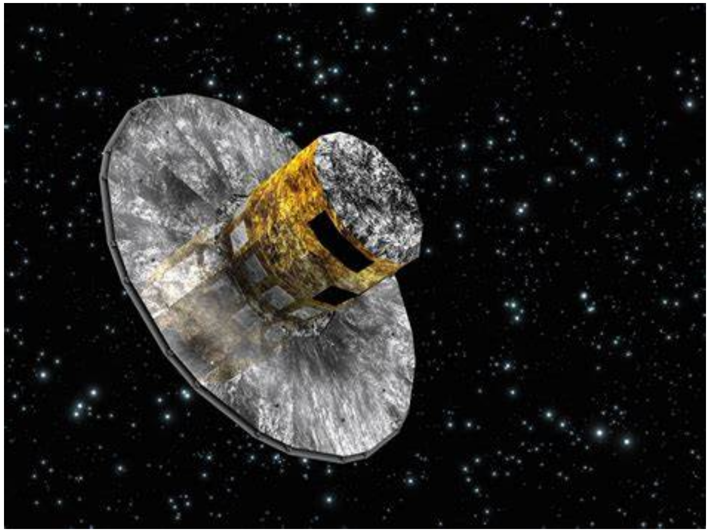
How to measure distances?

How to measure distances in astronomy?

(1) Astrometry-Parallax

e.g. *Hipparcos*, *Gaia* (for 1.8 billion stars)



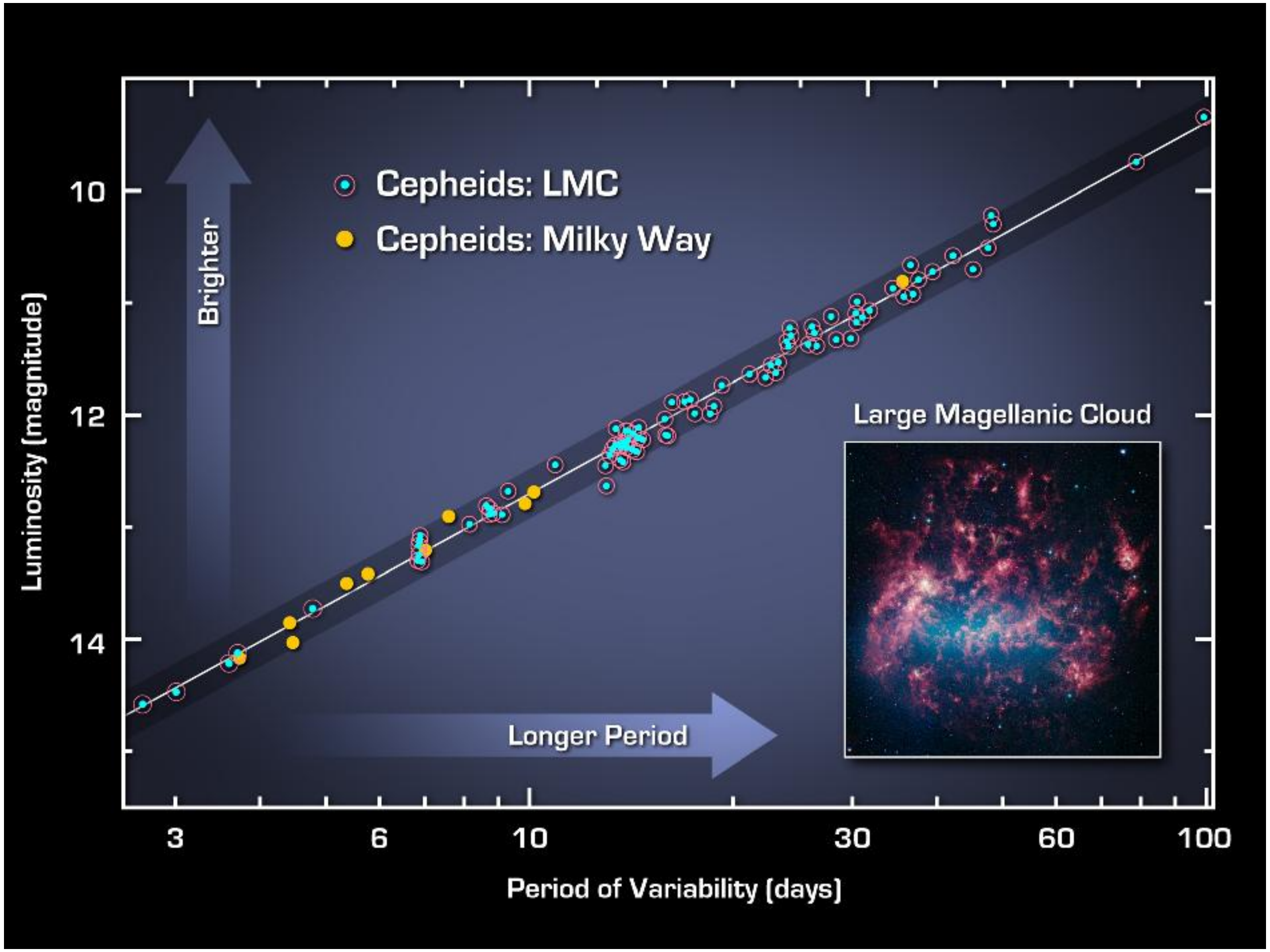


$$d(kpc) = \frac{1}{Parallax(mas)}$$

How to measure distances in astronomy?

(2) Distance indicators (tracers) - Standard candles

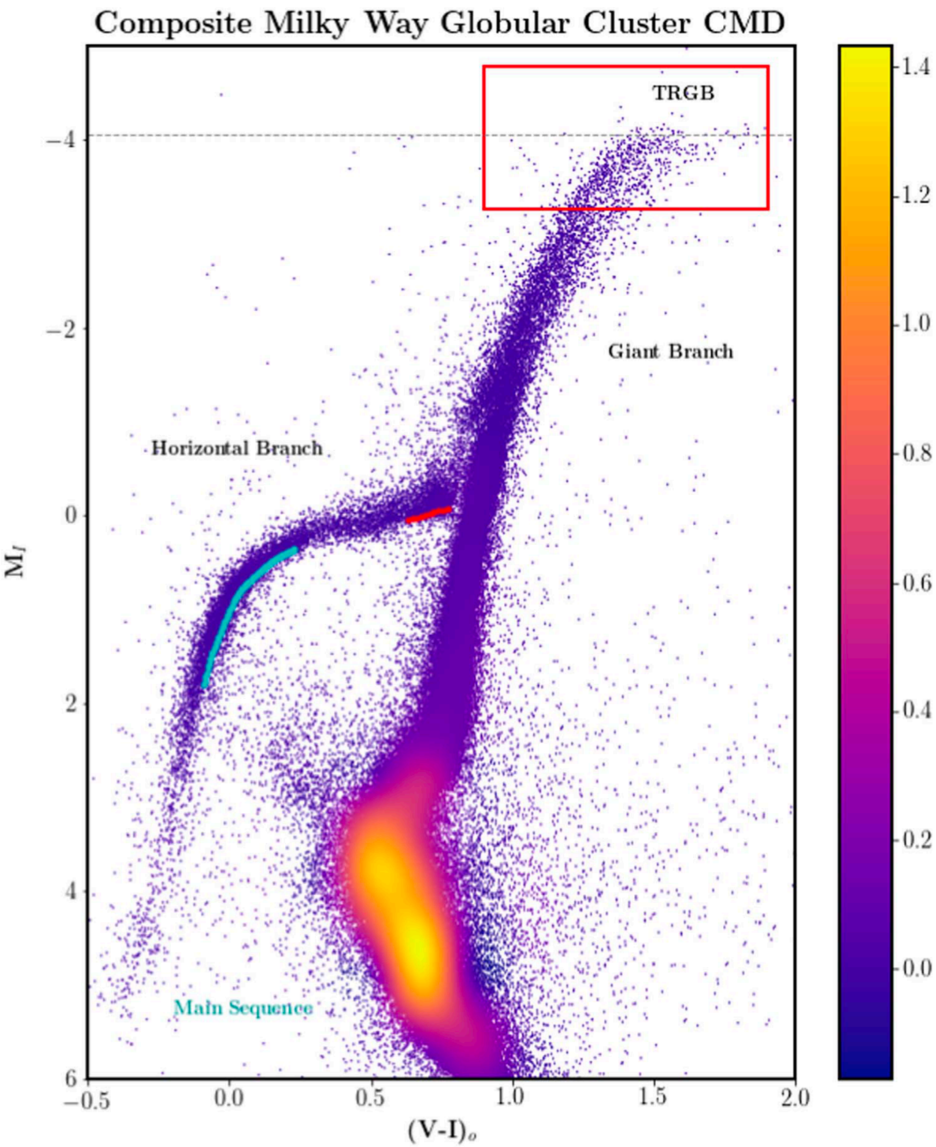
- ❖RR Lyrae
- ❖Cepheid



Credit: //www.stsci.edu

How to measure distances in astronomy?

(3) Tip of Red Giant Branch



Based on constant luminosity (-4 mag)

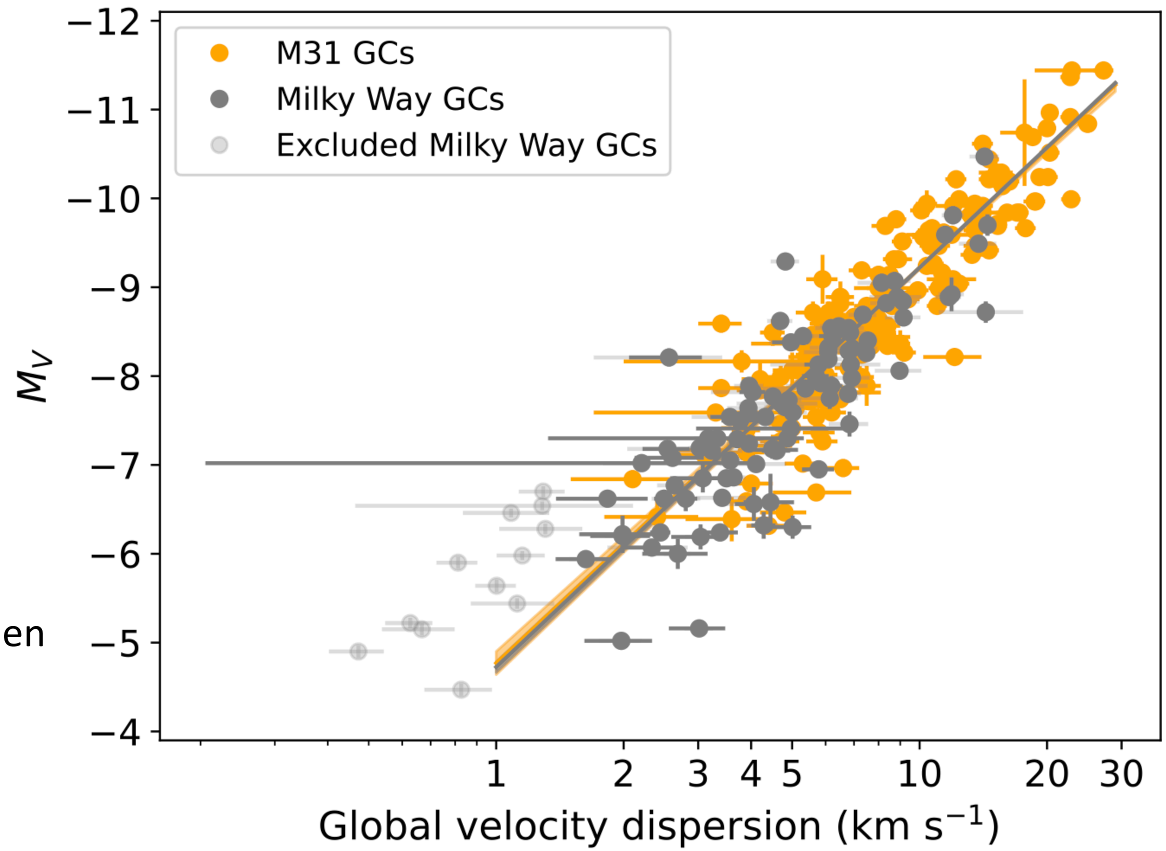
Freedman 2021, ApJ

How to measure distances in astronomy?

(4) Measure distances to galaxies with **globular cluster velocity dispersions**

$$\sigma_{\mathrm{gl}}^2 = \frac{M_{\mathrm{vir}}\, G}{7.5\, r_{\mathrm{hm}}}$$

$$M_V = \beta_0 + \beta_1 \log_{10}(\sigma_{\mathrm{gl}})$$



It actually depends on the relation between mass and luminosity of globulat clusters

Dubath & Grillmair 1997

arXiv:2312.01420,
accepted for publication in MNRAS

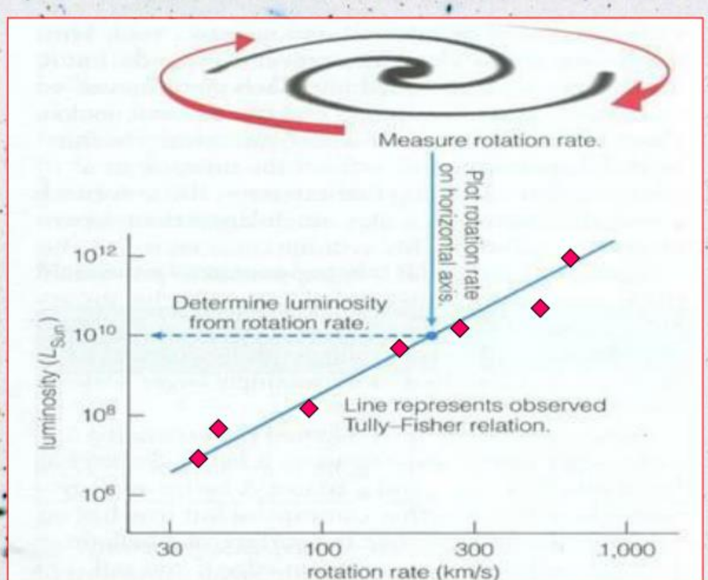
How to measure distances in astronomy?

(5) Tully-Fisher method

e.g. Width of 21cm HI line – Luminosity of galaxy

$$M = -6.25 \lg \frac{W_0}{sin i} - 3.5 \pm 0.3$$

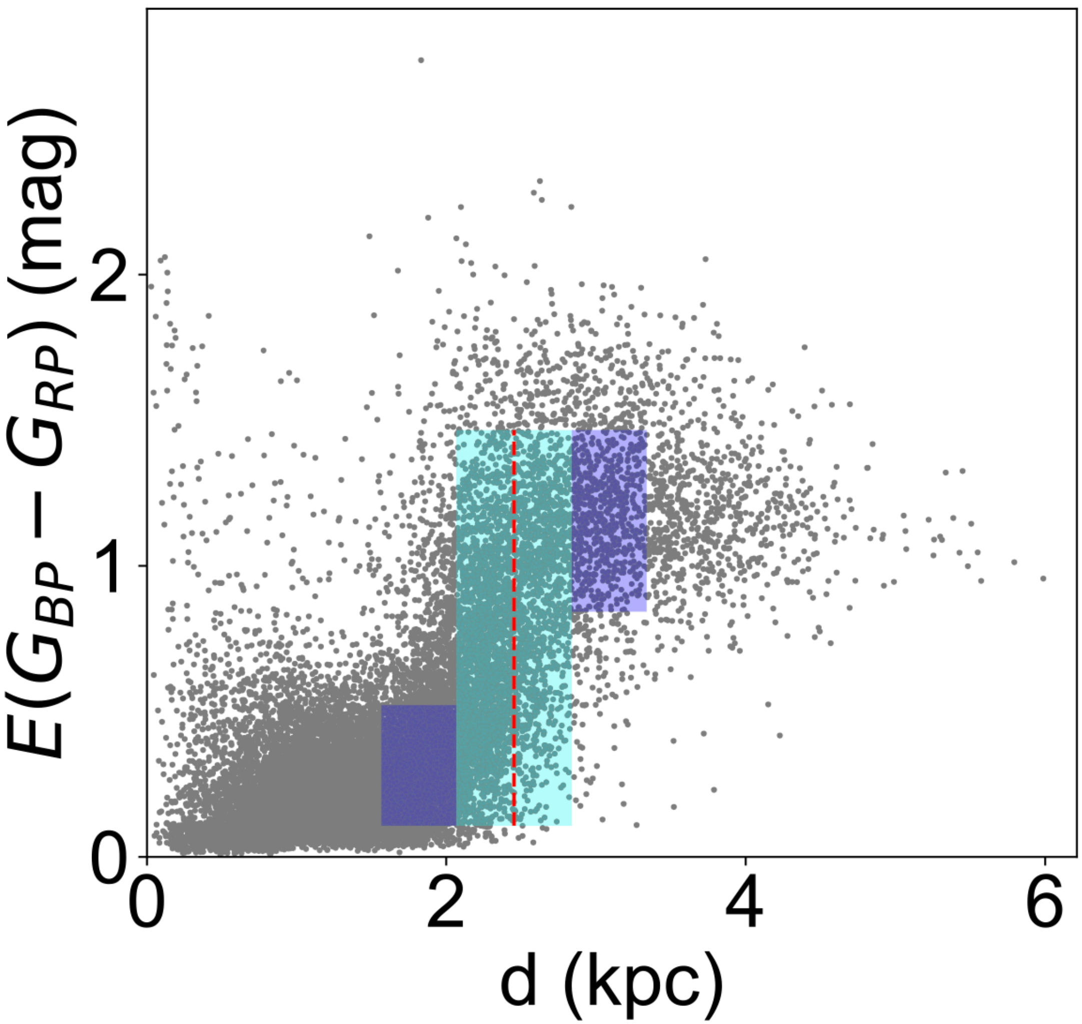
The Tully-Fisher (TF) relation is an empirically established correlation between the luminosity (L) of a spiral galaxy and its rotational velocity (V) (Tully-Fisher, 1977)



Credit: Irina Yegorova

How to measure distances in astronomy?

(6) Extinction (sudden change) to measure the distance of molecular clouds



Chen, Bing-Qiu + 2020, MNRAS

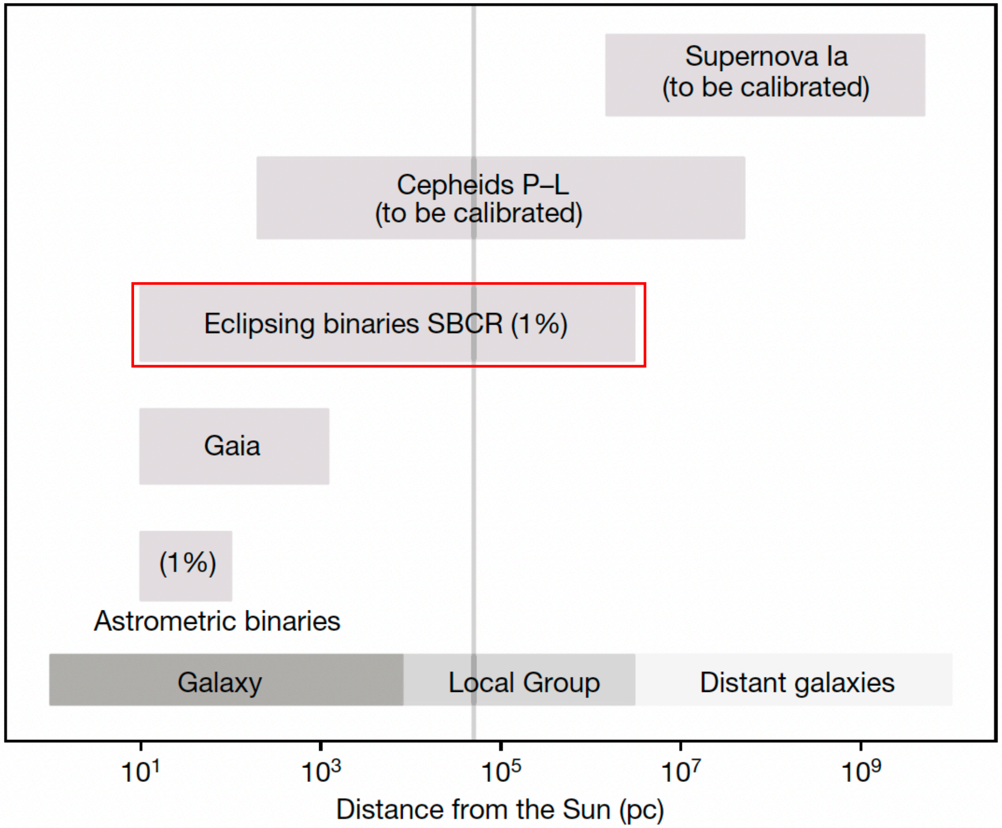
How to measure distances in astronomy?

(7) Eclipsing binaries as distance tracers

Table 1 | Distance moduli of the studied eclipsing binary systems

System OGLE-LMC-	RA (h min s)	Dec. (° ′ ″)	(*m* − *M*) (mag)	σ_{m-M} (mag)	Corr. (mag)
ECL-01866	04 52 15.28	−68:19:10.30	18.515	0.031	−0.028
ECL-03160	04 55 51.48	−69:13:48.00	18.474	0.013	−0.038
ECL-05430	05 01 51.74	−69:12:48.80	18.522	0.012	−0.028
ECL-06575	05 04 32.87	−69:20:51.00	18.483	0.011	−0.026
ECL-09114	05 10 19.64	−68:58:12.20	18.490	0.028	−0.009
ECL-09660	05 11 49.45	−67:05:45.20	18.465	0.019	0.029
ECL-09678	05 11 51.76	−69:31:01.10	18.501	0.018	−0.017
ECL-10567	05 14 01.89	−68:41:18.20	18.455	0.014	0.002
SC9-230659	05 14 06.04	−69:15:56.90	18.456	0.026	0.009
ECL-12669	05 19 12.80	−69:06:44.40	18.450	0.019	−0.002
ECL-12875	05 19 45.39	−69:44:38.50	18.453	0.026	−0.009
ECL-12933	05 19 53.69	−69:17:20.40	18.476	0.025	0.000
ECL-13360	05 20 59.46	−70:07:35.20	18.489	0.013	−0.004
ECL-13529	05 21 23.34	−70:33:00.00	18.498	0.016	0.005
ECL-15260	05 25 25.66	−69:33:40.50	18.453	0.034	0.003
ECL-18365	05 31 49.56	−71:13:28.30	18.479	0.021	0.033
ECL-18836	05 32 53.06	−68:59:12.30	18.473	0.018	0.026
ECL-21873	05 39 51.19	−67:53:00.50	18.445	0.014	0.059
ECL-24887	05 50 39.02	−69:14:20.70	18.515	0.023	0.045
ECL-25658	06 01 58.77	−68:30:55.10	18.423	0.016	0.076

The first, second and third columns give the name, right ascension and declination, respectively, of the systems studied. The fourth column gives the distance modulus. The fifth column gives the total statistical uncertainty for the mean distance modulus estimated on the basis of Monte Carlo simulations. The geometrical corrections calculated from the model[14] are given in the last column.



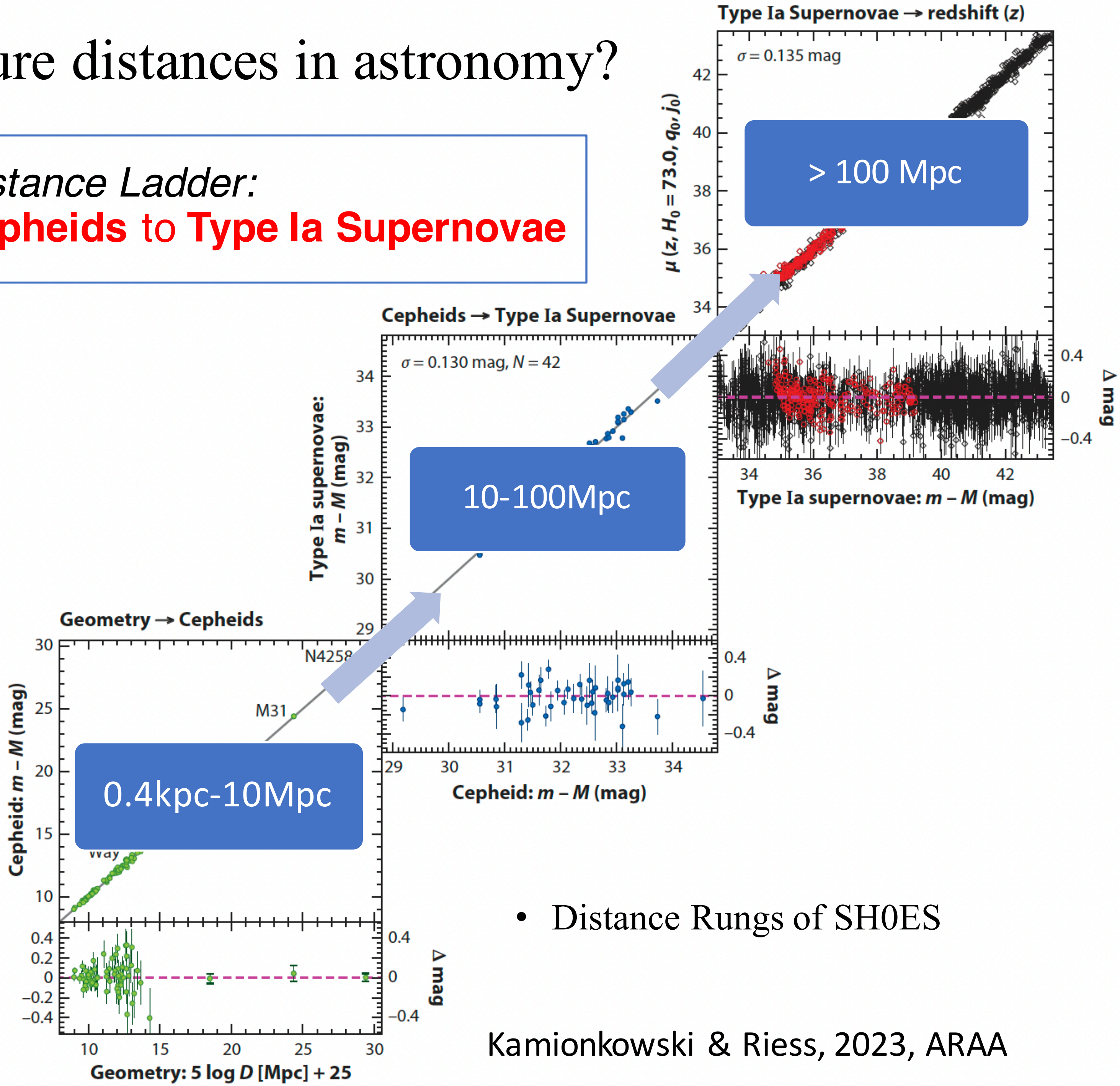
***49.59** ± 0.09 (statistical) ± 0.54 (systematic) kpc for LMC*

Pietrzyński et al., *2019, Nature, 567, 200*

How to measure distances in astronomy?

(8) *The Local Distance Ladder:*
Geometry to **Cepheids** to **Type Ia Supernovae**

LMC: 50 kpc
M31: 765 kpc
N4258: 7.58 Mpc



- Distance Rungs of SH0ES

Kamionkowski & Riess, 2023, ARAA

H0 measurement programs

- SH0ES (Supernovae and H0 for the Equation of State of dark energy)

PI: Riess, Adam (Awarded the Nobel prize of 2011)

- CCHP (Chicago-Carnegie Hubble Program)

PI: Freedman

Based on HST observations

- EDD (Extragalatic Distance Database) Tully et al. 2009, AJ, 138, 323

The Extragalactic Distance Database: The Color–Magnitude Diagrams/Tip of the Red Giant Branch Distance Catalog ,Anand+2021, AJ, 162, 80

Part III

TRGB as distance indicators

Assuming
Limiting magnitude: ~27 mag

$$m = M + 5 log d(pc) - 5 + A_V$$

- **RR Lyrae**

$M_V \sim 0\ mag$ (0.69 ± 0.10 mag). d~2.5 Mpc

- Tip of Red giant branch (**TRGB**)

$M_I = -4\ mag$ d~15 Mpc

- **Cepheid**

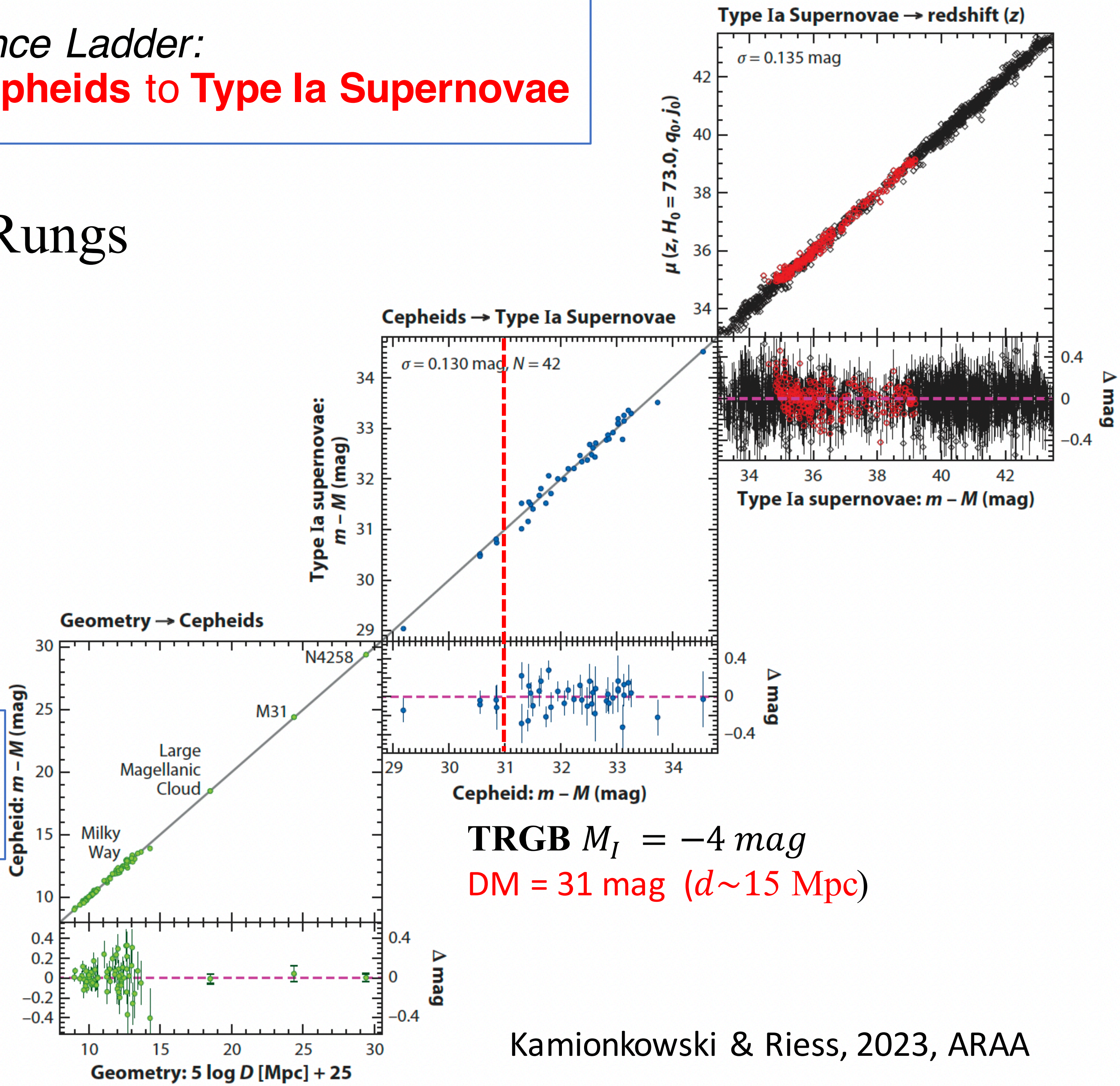
$M_V \sim -6\ mag$ d~40 Mpc

- **SN Ia**

$M_V \sim -19.3\ mag$ d~15000 Mpc

The Local Distance Ladder:
Geometry to **Cepheids** to **Type Ia Supernovae**

- Distance Rungs of SH0ES



LMC: 50 kpc
M31: 765 kpc
N4258: 7.58 Mpc

TRGB $M_I = -4\ mag$

DM = 31 mag (d~15 Mpc)

Kamionkowski & Riess, 2023, ARAA

TRGB as standard candles to calibrate SN Ia

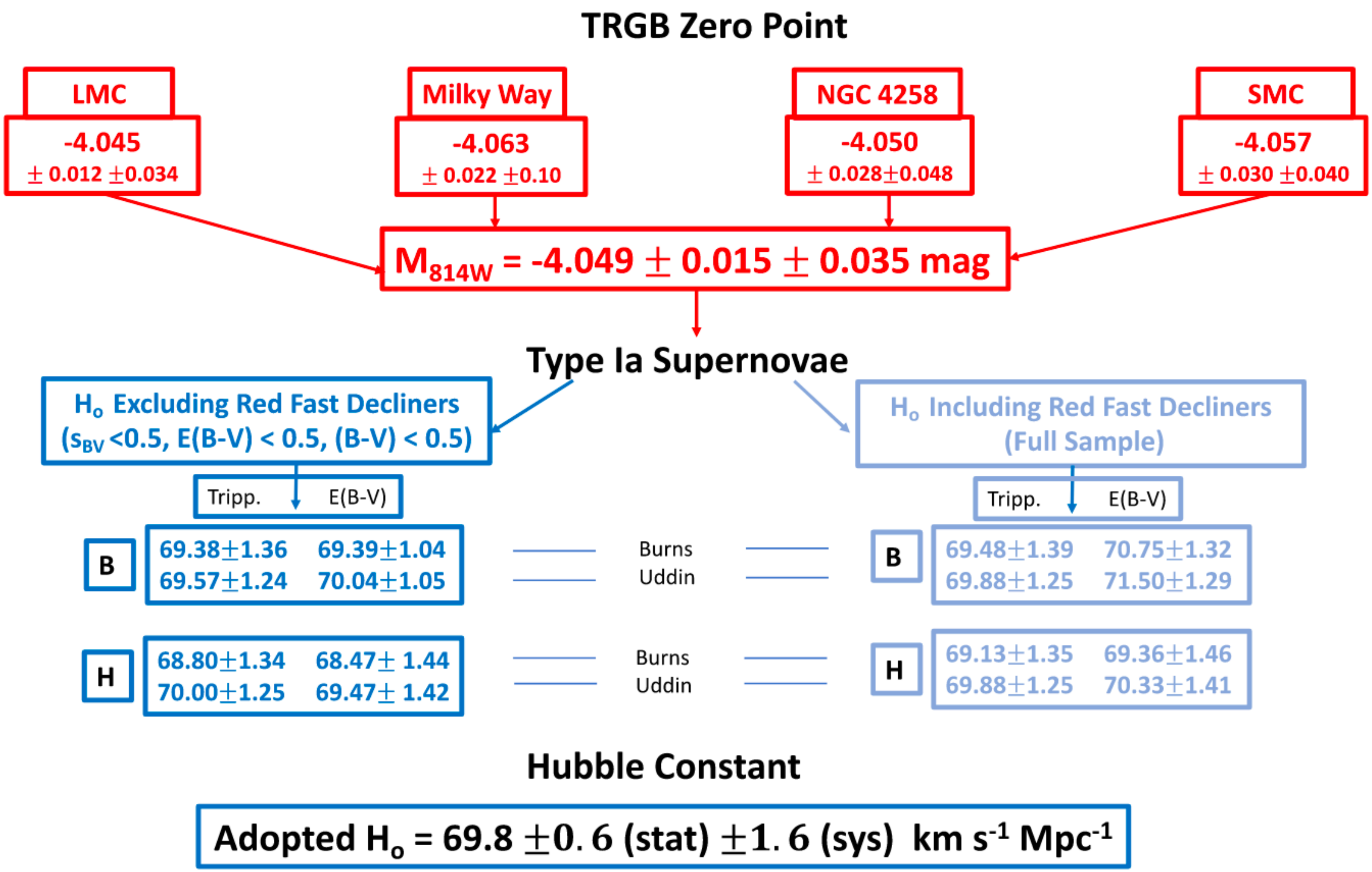
$$m = M + 5logd(pc) - 5 + A_V$$

$$\Delta M = \frac{5}{ln10}\frac{\Delta d}{d} \qquad \frac{\Delta d}{d} = \frac{\Delta H_0}{H_0}$$

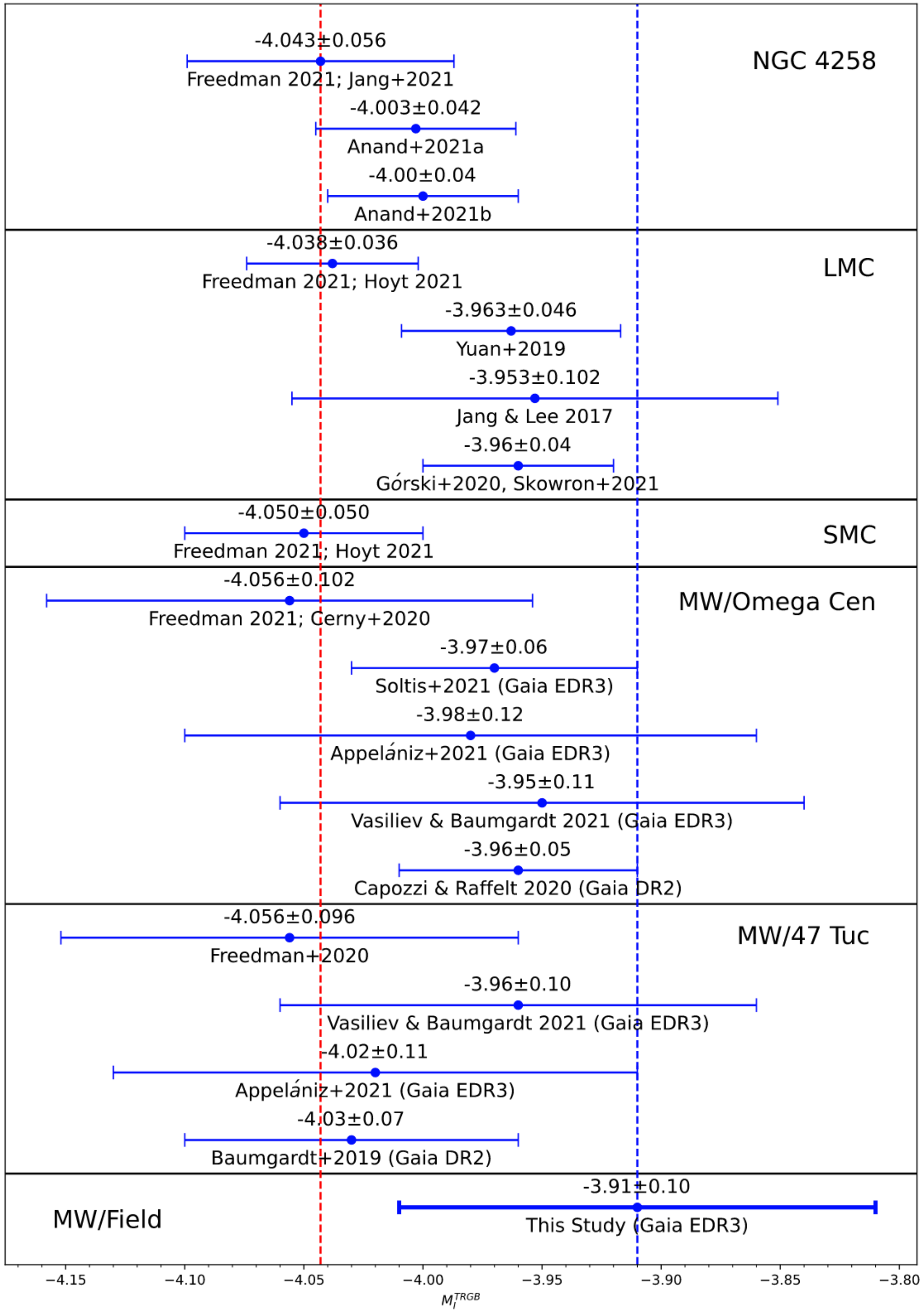
0.1 mag for ΔM, corresponding to $\frac{\Delta d}{d} \sim 4.6\%$,
and $\frac{\Delta H_0}{H_0} \sim 4.6\%$ ($\sim 3\sigma$ of H_0)

So, it's necessary to calibration TRGB precisionly.

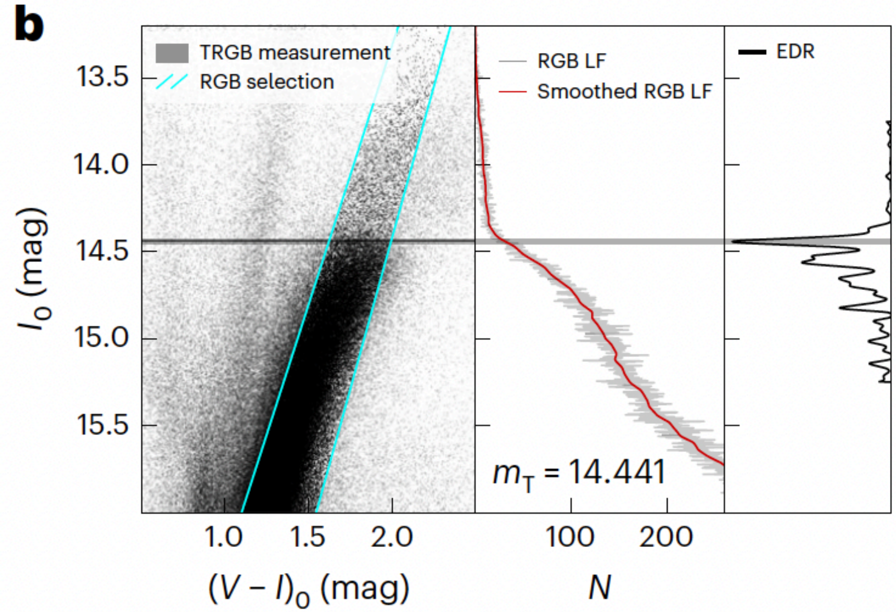
Reserches on calibrating TRGB zero-point (First rung)



Freedman 2021, ApJ



Li, Si-Yang et al. 2022, ApJ, 939, 96



Hoyt, 2023, Nature Astronomy, *Volume 7 590–601*

Part IV

What can we do further more?

Precisionly calibration of TRGB probably is the most feasible way to measure H0.

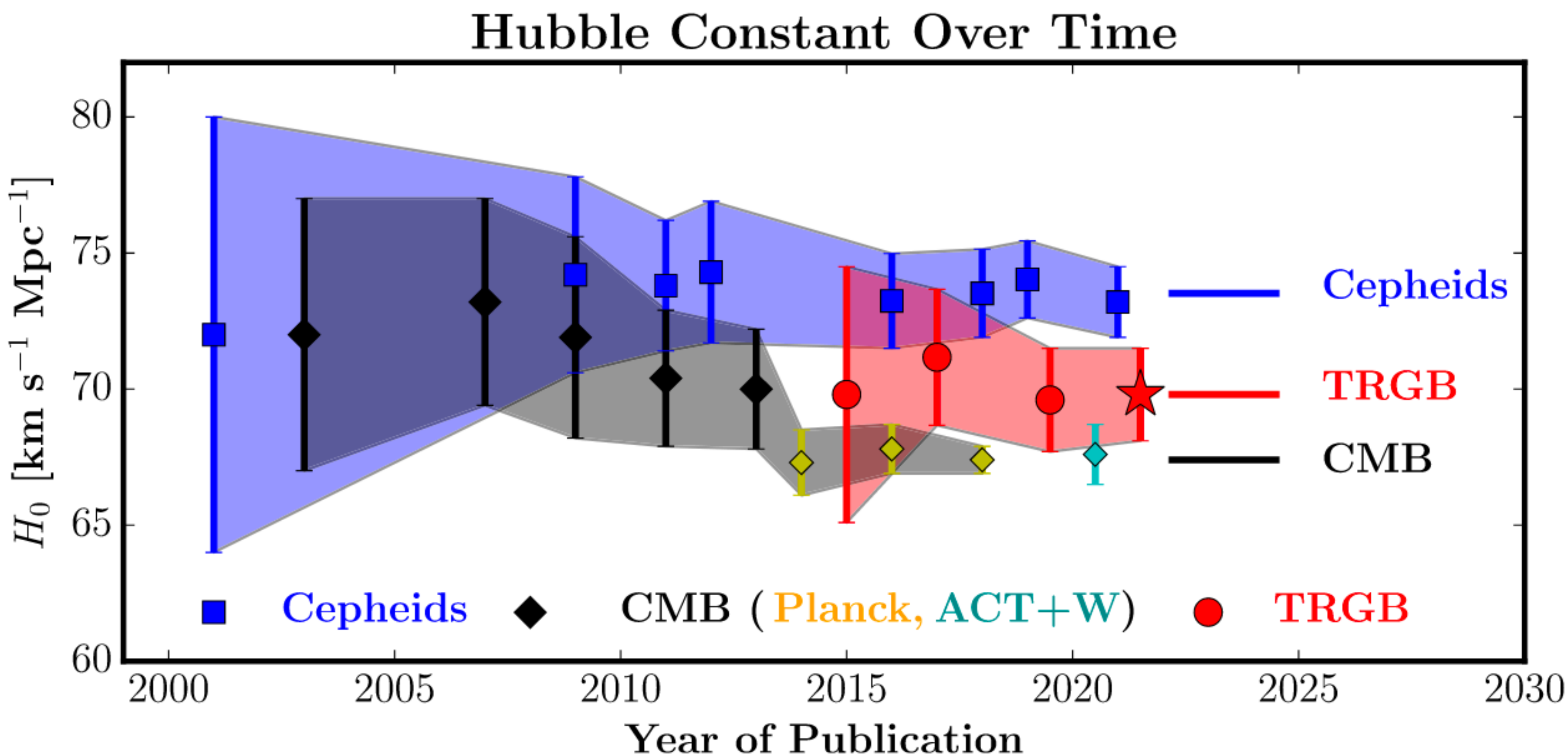
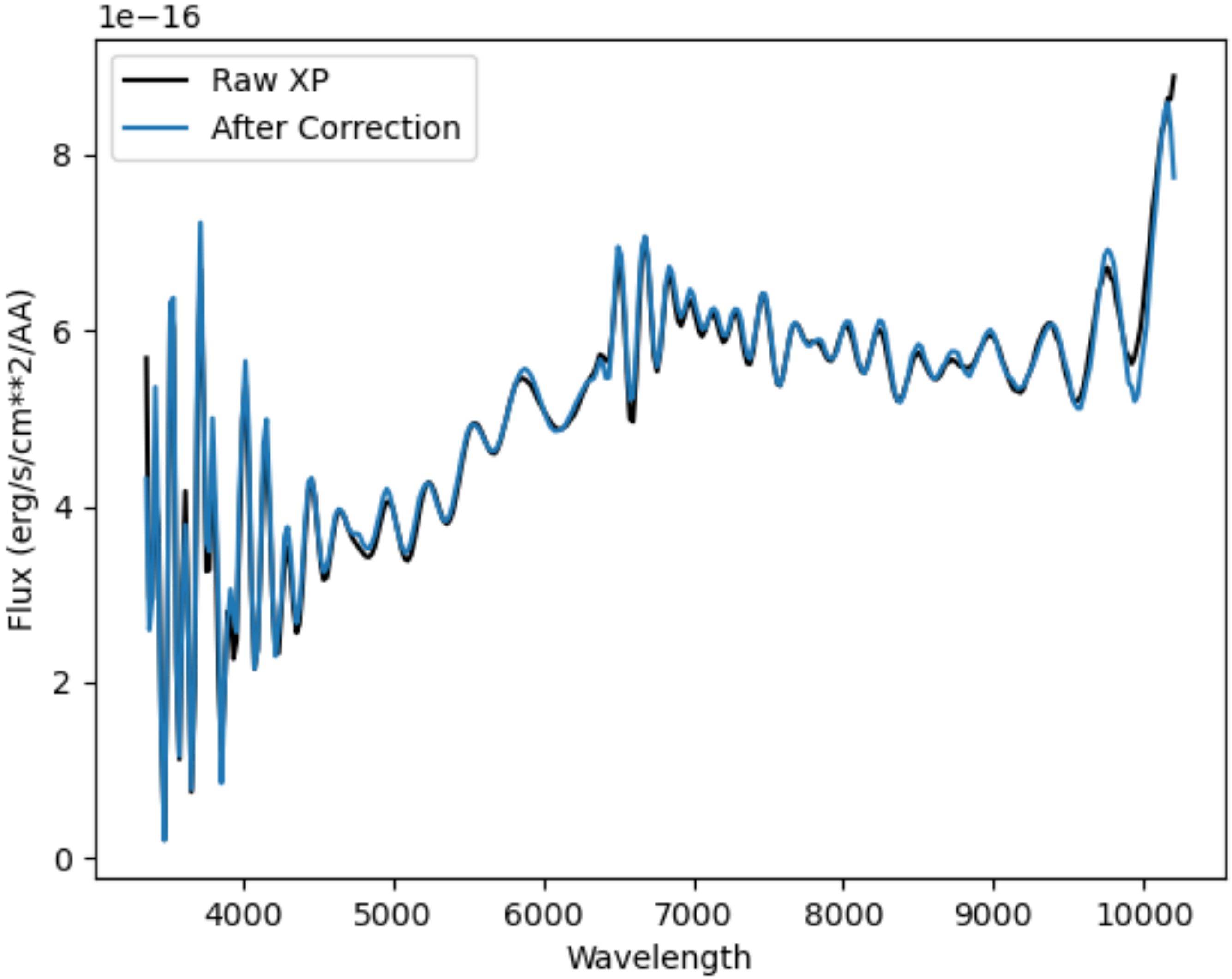


Figure 11. Summary of Hubble constant values in the past two decades based on Cepheid variables (blue squares), the TRGB (red circles and star), and estimates based on measurements of fluctuations in the CMB (WMAP: black diamonds; Planck: yellow diamonds; ACT + WMAP: cyan diamond). The CMB H_0 values assume a flat ΛCDM model. The CMB and Cepheid results straddle a range of 67–74 km s^{-1} Mpc^{-1}, with the TRGB results falling in the middle and overlapping the CMB results. The tension between the CMB and TRGB results amounts to only 1.3σ.

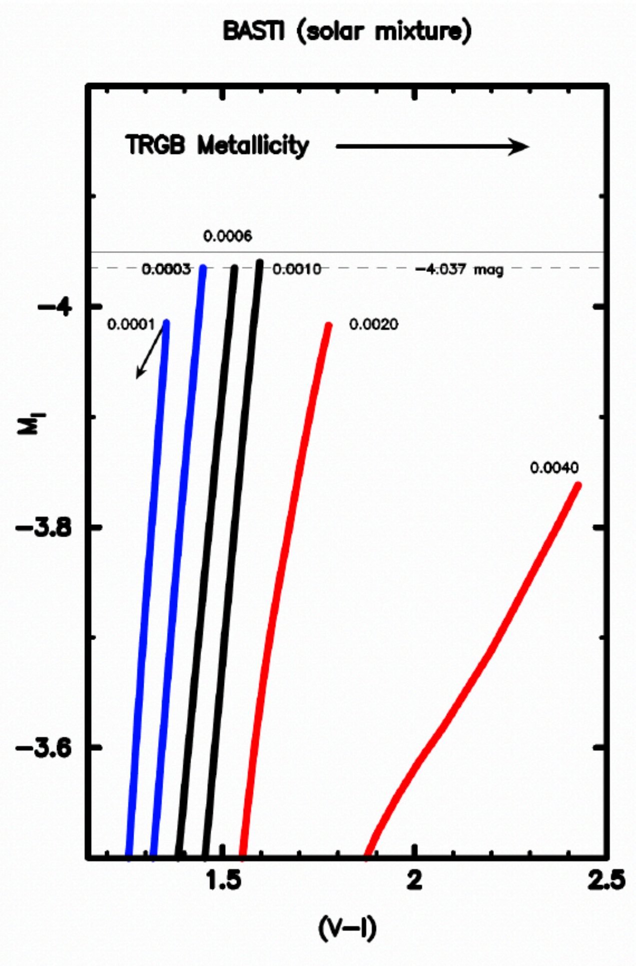
Calibration of TRGB

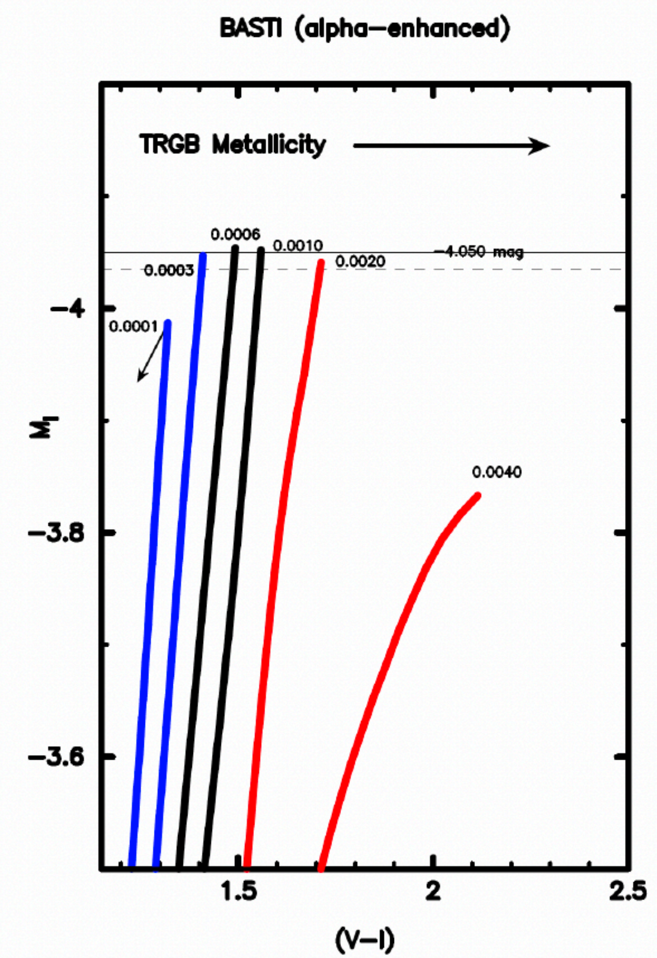


Calibration of TRGB

2-dimention calibration of TRGB (theoretical)

Analysis the influence of [Fe/H] (color) on the calibration of TRGB (MESA stellar code) Qiao, Ze-Xu, in prep.





Madore+2023, accepted
arxiv: 2311.05048

Calibration of TRGB

- Calibration of TRGB with CSST and Mephisto

CSST: ~27 mag (deep field)

Mephisto: 22.4 mag (Wide Survey i-band)

The Astrophysical Journal, 938:113 (15pp), 2022 October 20 https://doi.org/10.3847/1538-4357/ac8b7a

The Pantheon+ Analysis: The Full Data Set and Light-curve Release

Dan Scolnic[1], Dillon Brout[2,20], Anthony Carr[3], Adam G. Riess[4,5], Tamara M. Davis[3], Arianna Dwomoh[1], David O. Jones[6], Noor Ali[7], Pranav Charvu[1], Rebecca Chen[1], Erik R. Peterson[1], Brodie Popovic[1], Benjamin M. Rose[1], Charlotte M. Wood[8], Peter J. Brown[9,10], Ken Chambers[11], David A. Coulter[6], Kyle G. Dettman[12], Georgios Dimitriadis[13], Alexei V. Filippenko[14,15], Ryan J. Foley[6], Saurabh W. Jha[12], Charles D. Kilpatrick[16], Robert P. Kirshner[2,17], Yen-Chen Pan[18], Armin Rest[19], Cesar Rojas-Bravo[6], Matthew R. Siebert[6], Benjamin E. Stahl[14], and WeiKang Zheng[14]

1701 light curves of 1550 unique, spectroscopically confirmed Type Ia supernovae (SNe Ia)

SN Ia database

Summary

- About 10 methods to measure distance in astronomy
- TRGB zero-point →Calibration of SN Ia → SN Ia distance
- Precisionly zero-point of TRGB is probably the most feasible way to calibrate SN Ia to measure H0.
- From observations as well as numerical calculation(theoretical) to calibrate TRGB

Thanks