Towards a direct 1% measurement of the Hubble constant using standard candles

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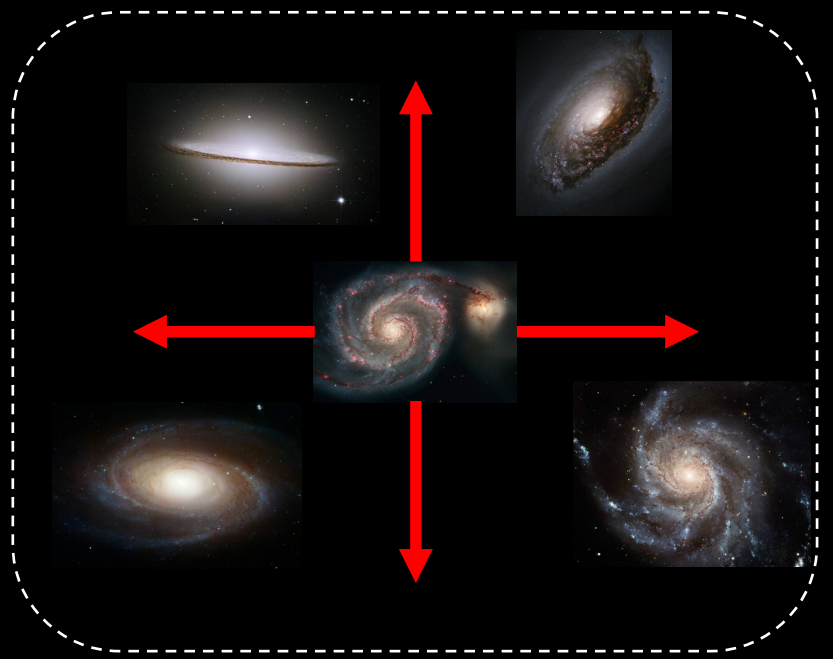
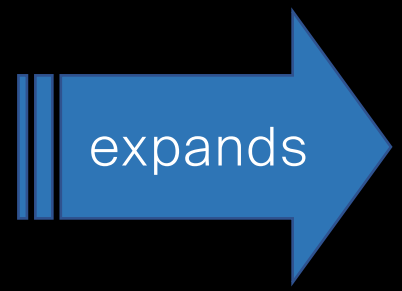
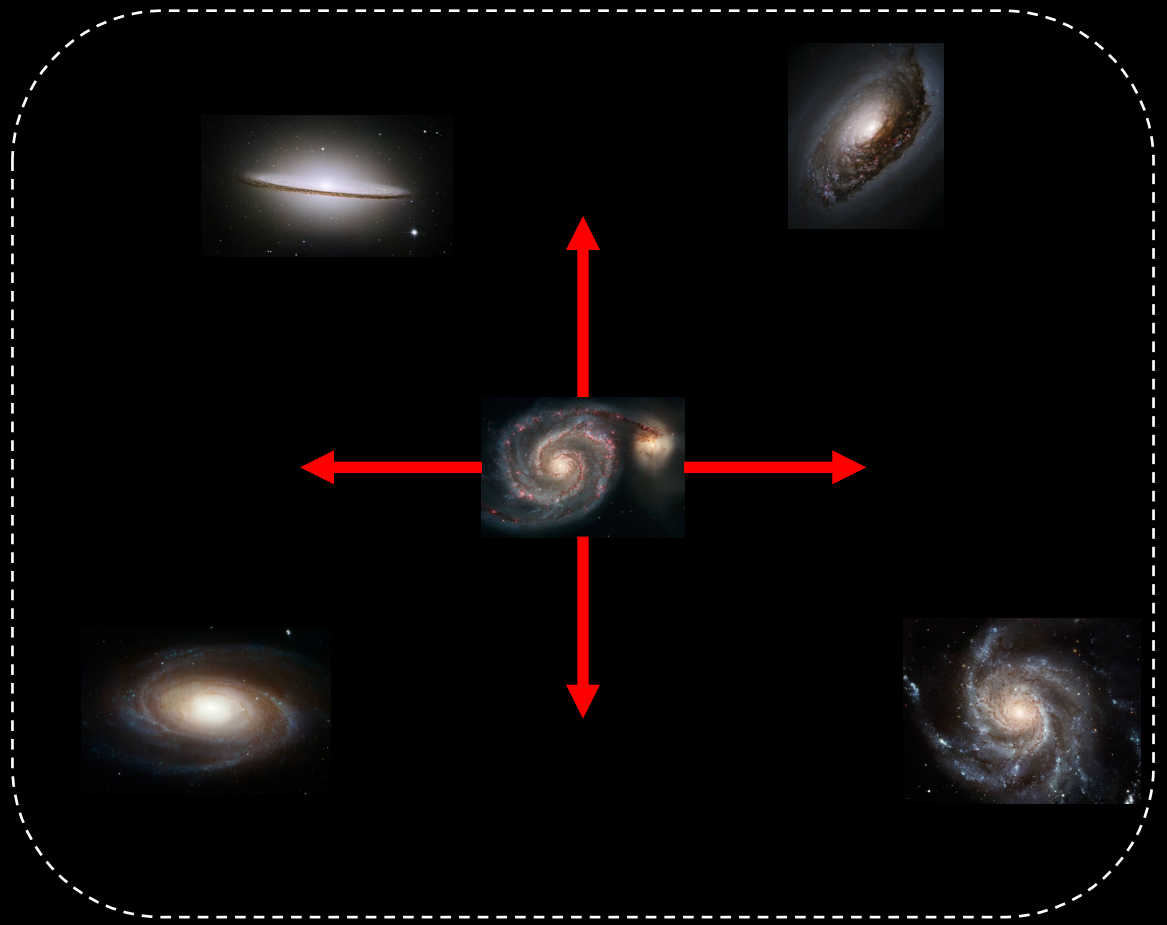
Hubble's Constant H_0 measures the expansion rate of the Universe today

$$H_0 = v/D$$

$$D_L = \frac{cz}{H_0}\left\{1 + \frac{1}{2}(1 - q_0)z - \frac{1}{6}\left[1 - q_0 - 3q_0^2 + j_0 \pm \frac{c^2}{H_0^2 R^2}\right]z^2 + O(z^3)\right\}$$



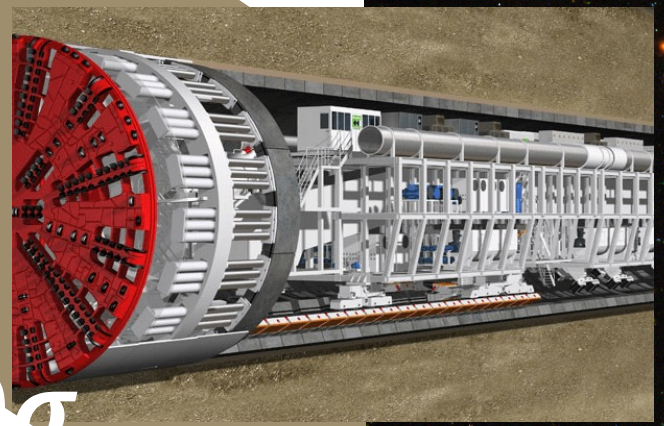


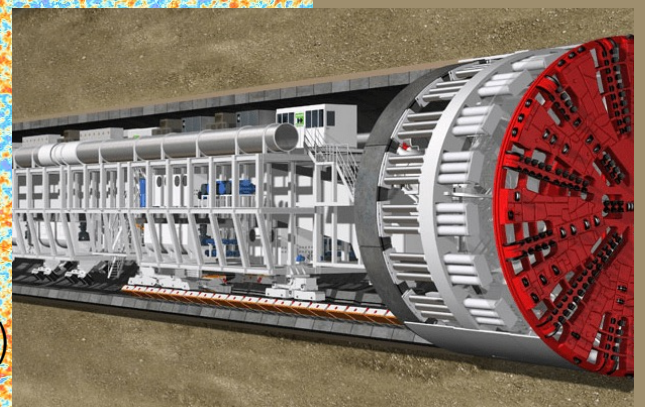


The Early Universe

H_0 as a cosmological end-to-end test

Today's Universe





$H_0 = 73.0 \pm 1.0$

8.1 %

$67.4 \pm 0.5 \ \frac{\text{km/s}}{\text{Mpc}}$

New Physics???

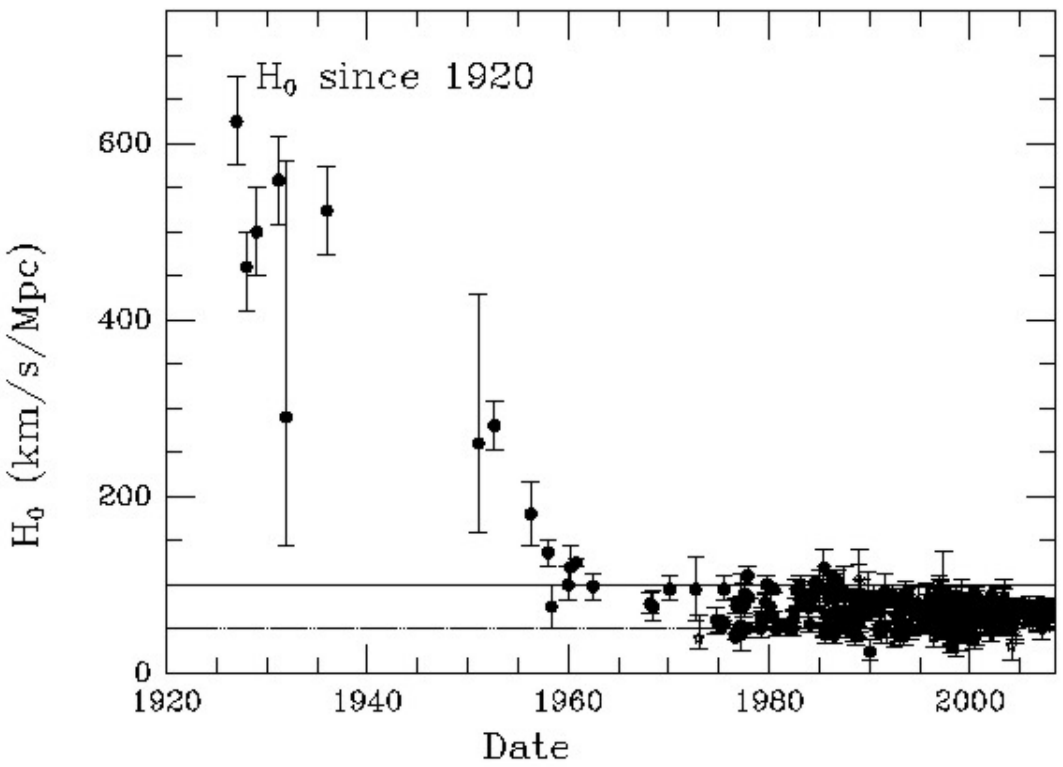
Planck VI (2018)

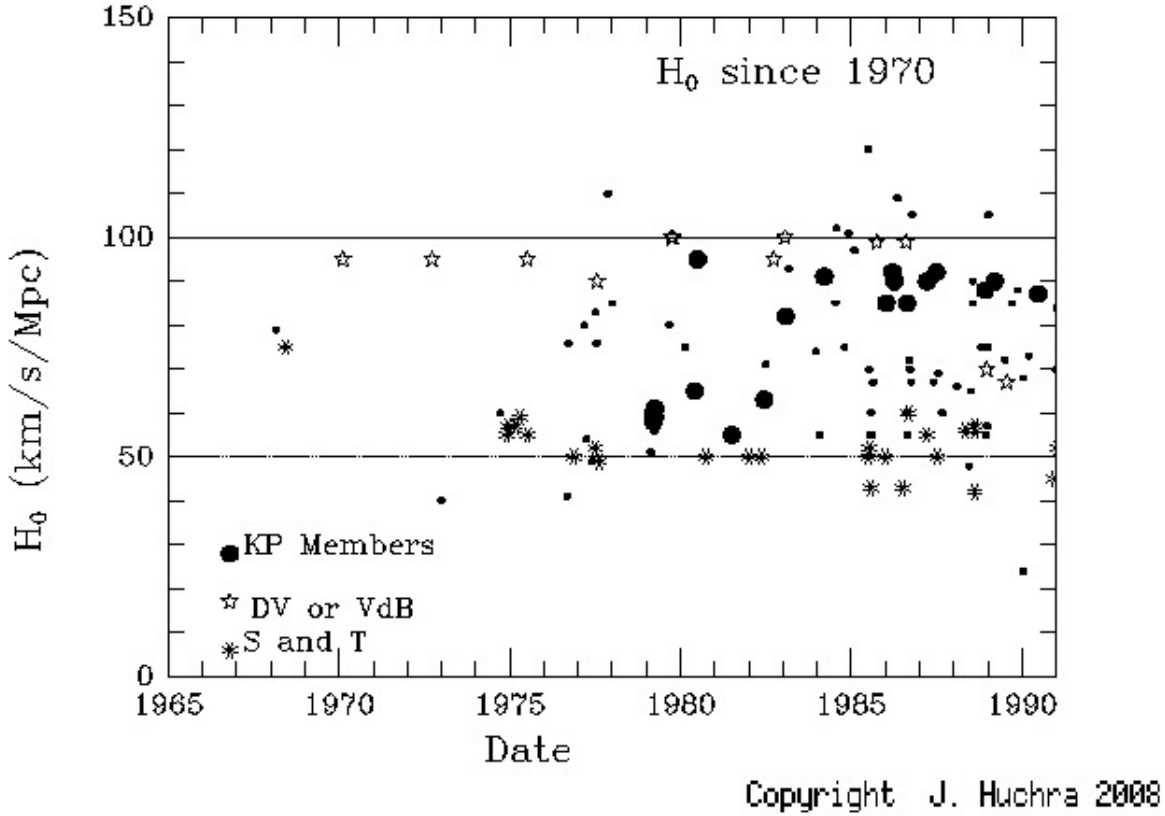
Riess et al. (2022a)

Hubble tension ...
... sounds familiar?

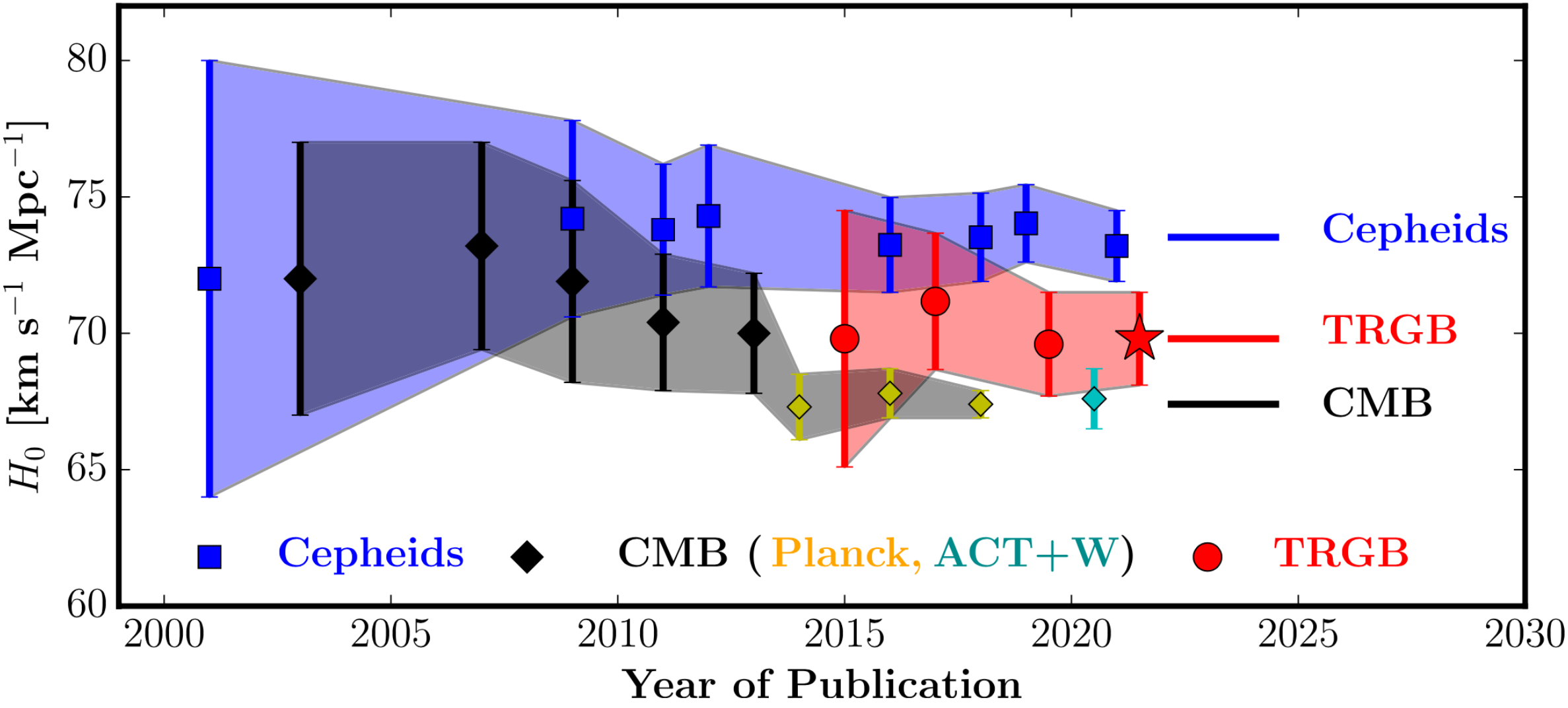
Then and now, two very different problems

The chequered history of Hubble's constant



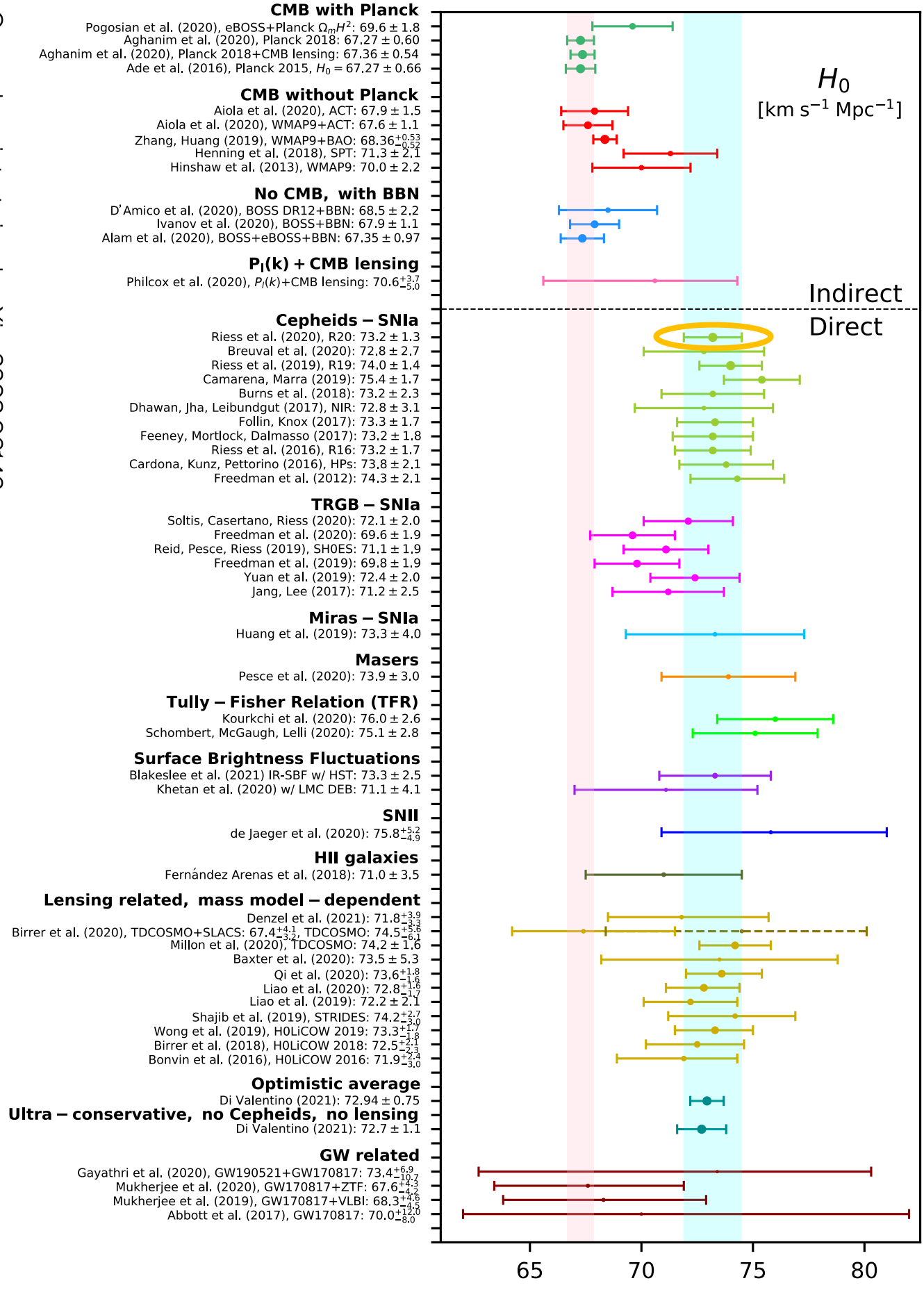


Storytelling...



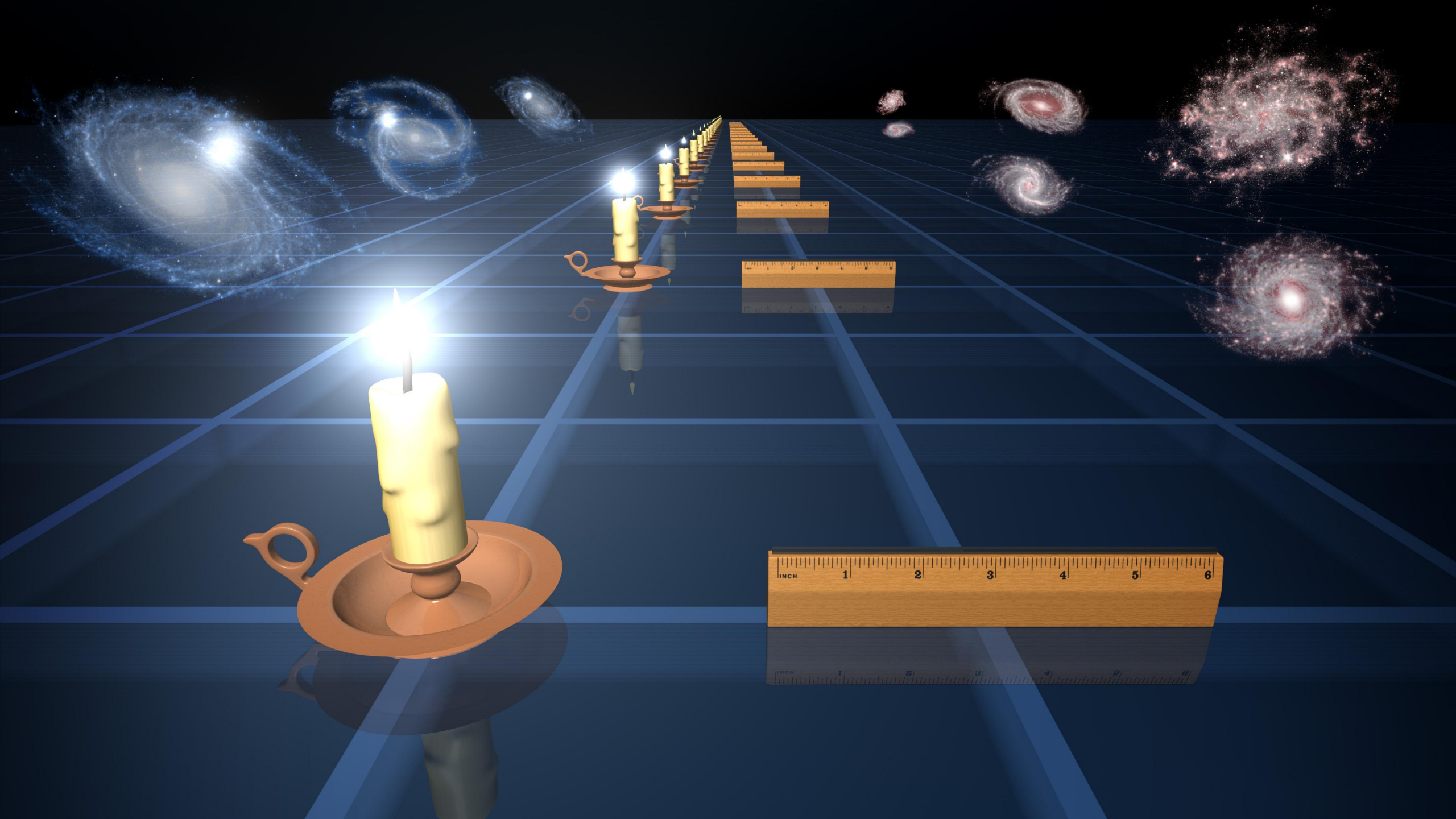
Freedman (2021)

The bigger picture



Cosmology intertwined, arXiv: 2203.06142

How does the distance scale measure H0?

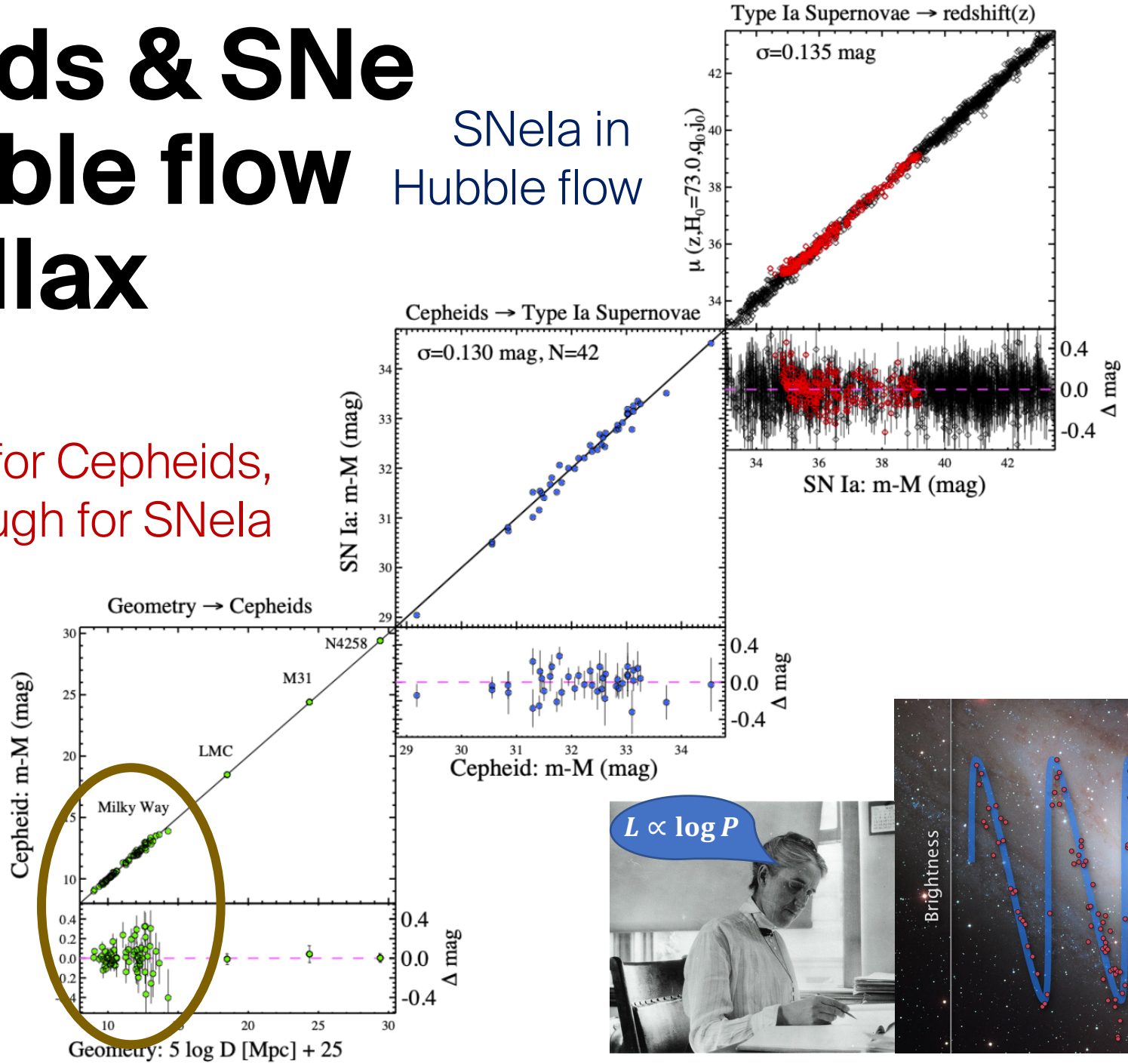

INCH
1
2
3
4
5
6

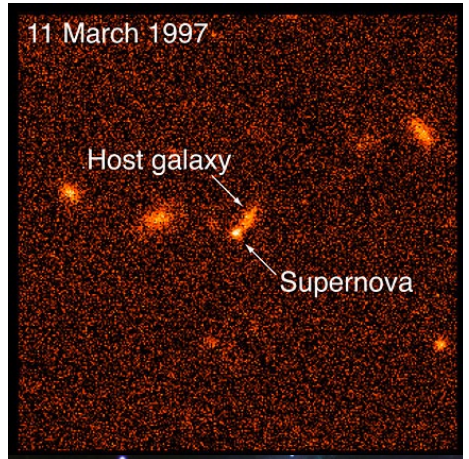
Cepheids & SNe tie Hubble flow to parallax

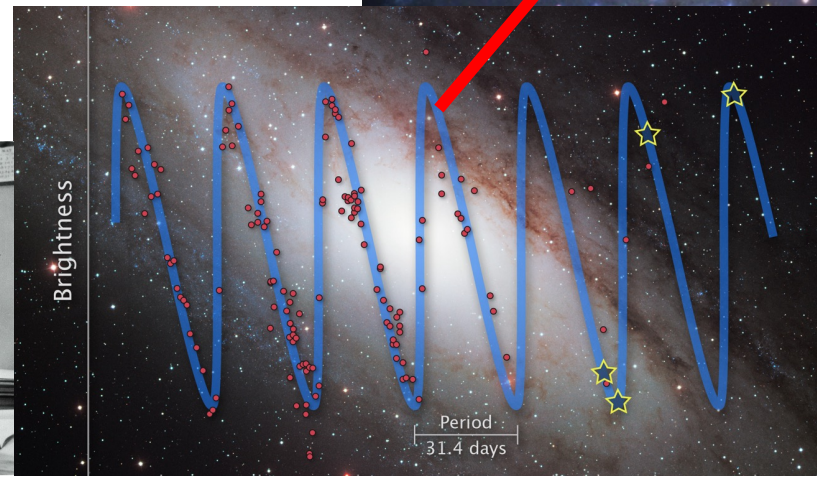
SNIa in Hubble flow

Close enough for Cepheids, far enough for SNIa

Gaia Parallaxes







Measuring H_0 to 1% requires tightly controlled systematics

SHOES project improvements of the distance ladder relative to HST key project

- Precise differential ladder anchored to accurate geometric distances
- Anchors
  - Geometric distances to LMC and NGC4258
  - Parallaxes of MW Cepheids
- Photometry
  - Exclusive use of HST photometric system (16 mag dynamic range) +NOW JWST!
  - Sophisticated background corrections, validated by amplitude ratios & light curves
- Experimental setup
  - Reduced sensitivity to reddening thanks to IR & reddening-free Wesenheit-magnitudes
  - Covariance included in distance ladder fit
  - 42 SNeIa in galaxies with known Cepheids
  - Clean sample of > 300 SNeIa in Hubble flow

$$W = H - \frac{A_H}{A_V - A_I}(V - I)$$

cf. Riess et al. (2016, 2022) & refs therein

Greatest gains on first rungs

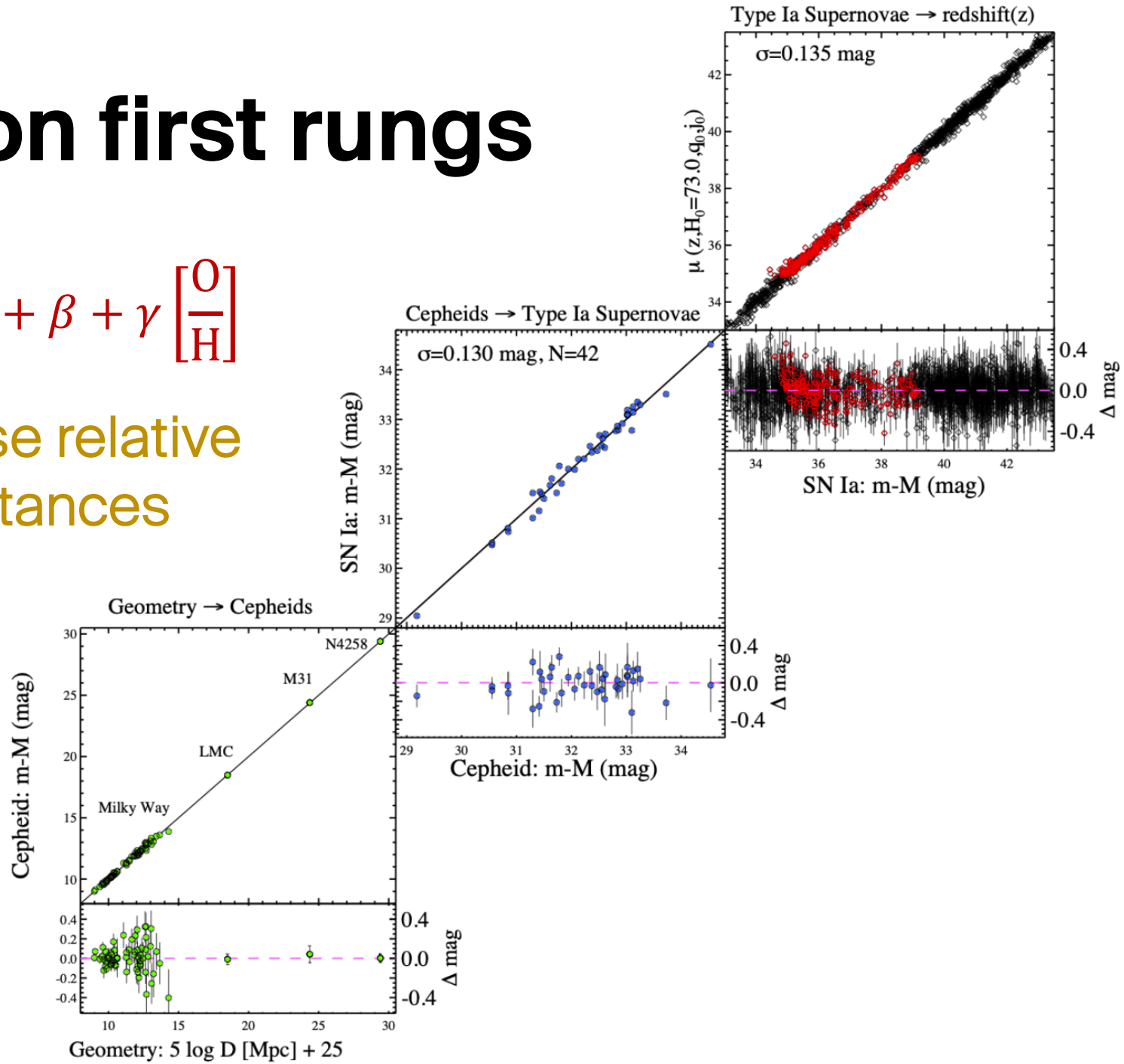
$$M = \alpha \log\left(\frac{P}{P_0}\right) + \beta + \gamma \left[\frac{\mathrm{O}}{\mathrm{H}}\right]$$

dominant uncertainties ⇒ Precise relative distances

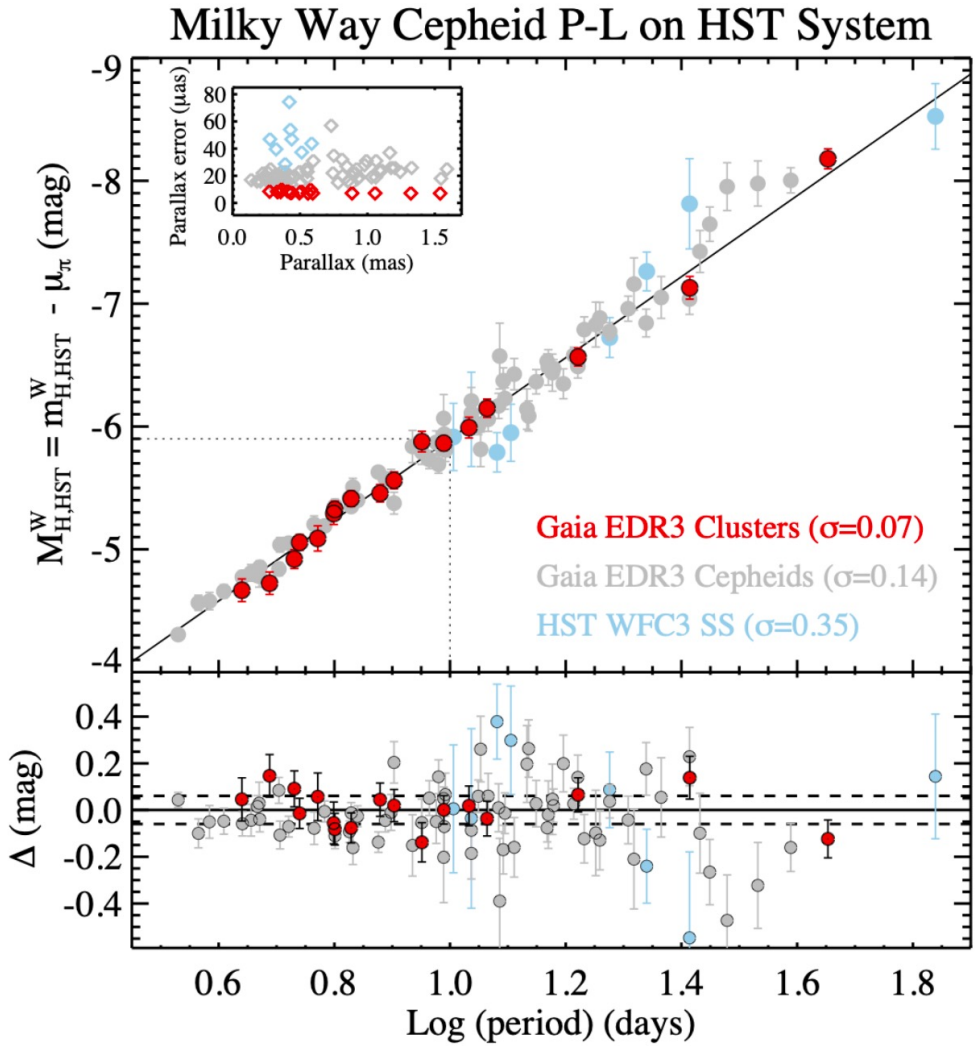
⇘

Accurate absolute calibration

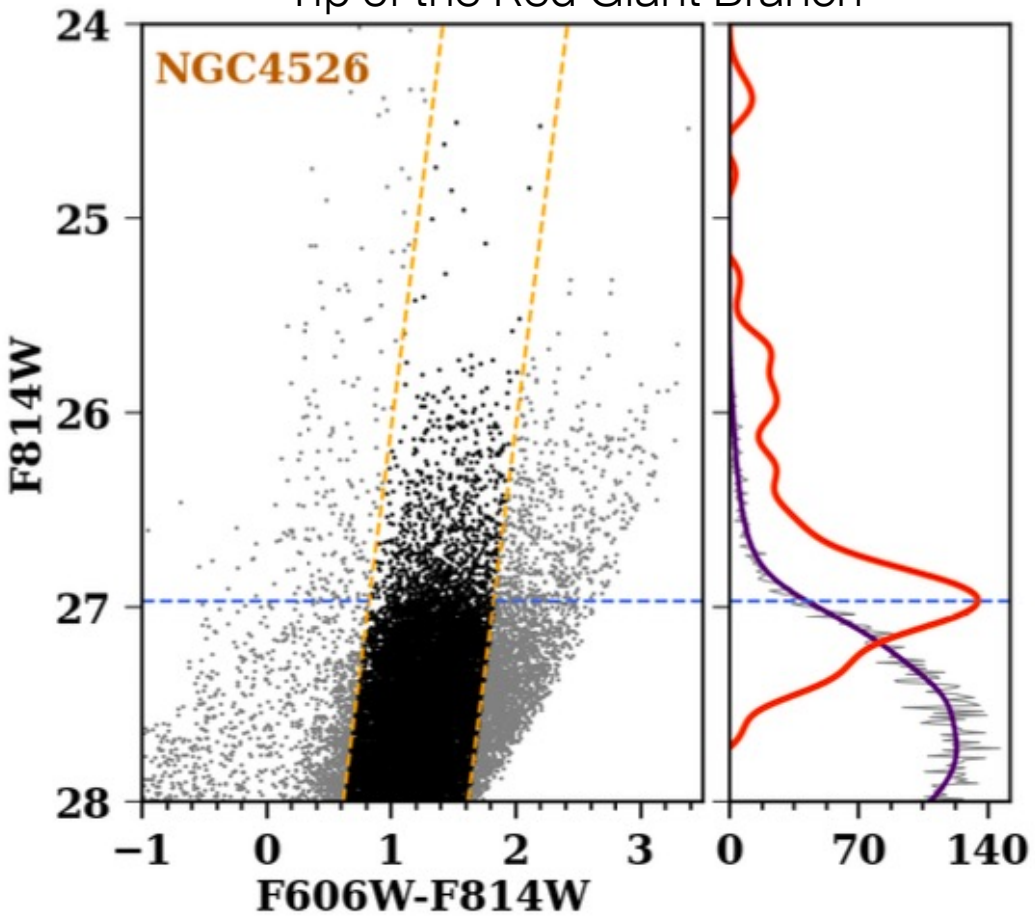
$$m - M = 5 \log d - 5 + A$$



Individual and *statistical* standard candles



Tip of the Red Giant Branch

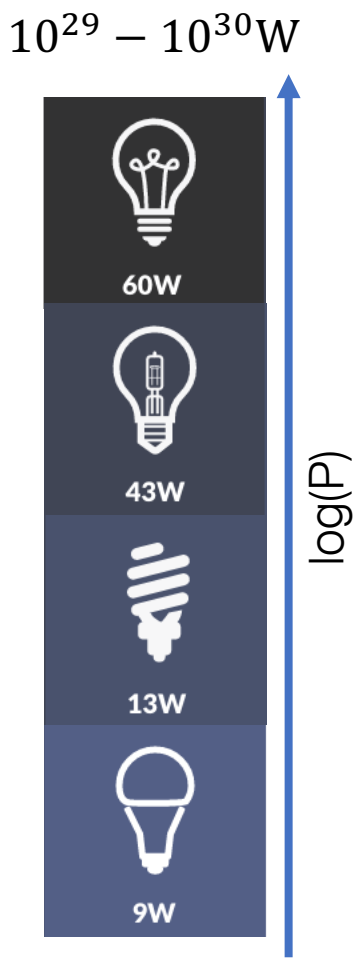


Stellar standard candles

- **Individual,** directly calibratable Period-luminosity relations
  - Classical Cepheids : best accuracy for H_0
  - Mira variables : interesting alternatives in JWST era
  - RR Lyrae stars : great for near-field cosmology (< 1 Mpc)
  - Other pulsating stars, e.g., type-II Cepheids, anomalous Cepheids
- **Statistical,** color magnitude diagram features
  - Tip of the red giant branch (TRGB) : ubiquitous, 30 years of usage
  - Carbon-rich AGB stars : exciting new kid on the block
  - Red Clump : useful at shorter distances

Note on calibration & standardization

- All standard candles require calibration and standardization
- Calibration: determines fiducial luminosity & how to standardize
- Standardization: corrects observed samples to match fiducial
- Leavitt law calibration:
  - Fiducial M: 10d Cepheid, Solar metallicity, H-band Wesenheit magnitude
  - Standardization: LL slope, metallicity difference, time dilation, etc.
    => all well calibrated and measurable (directly or by proxy)
  - LL scatter usefully constrains uncertainties
- TRGB:
  - Fiducial M: statistically determined inflection point of mixed-population luminosity functions, mostly in I-band (F814W)
  - Standardization: metallicity & age differences, algorithmic choices, etc.
    => no consensus, but good recent progress

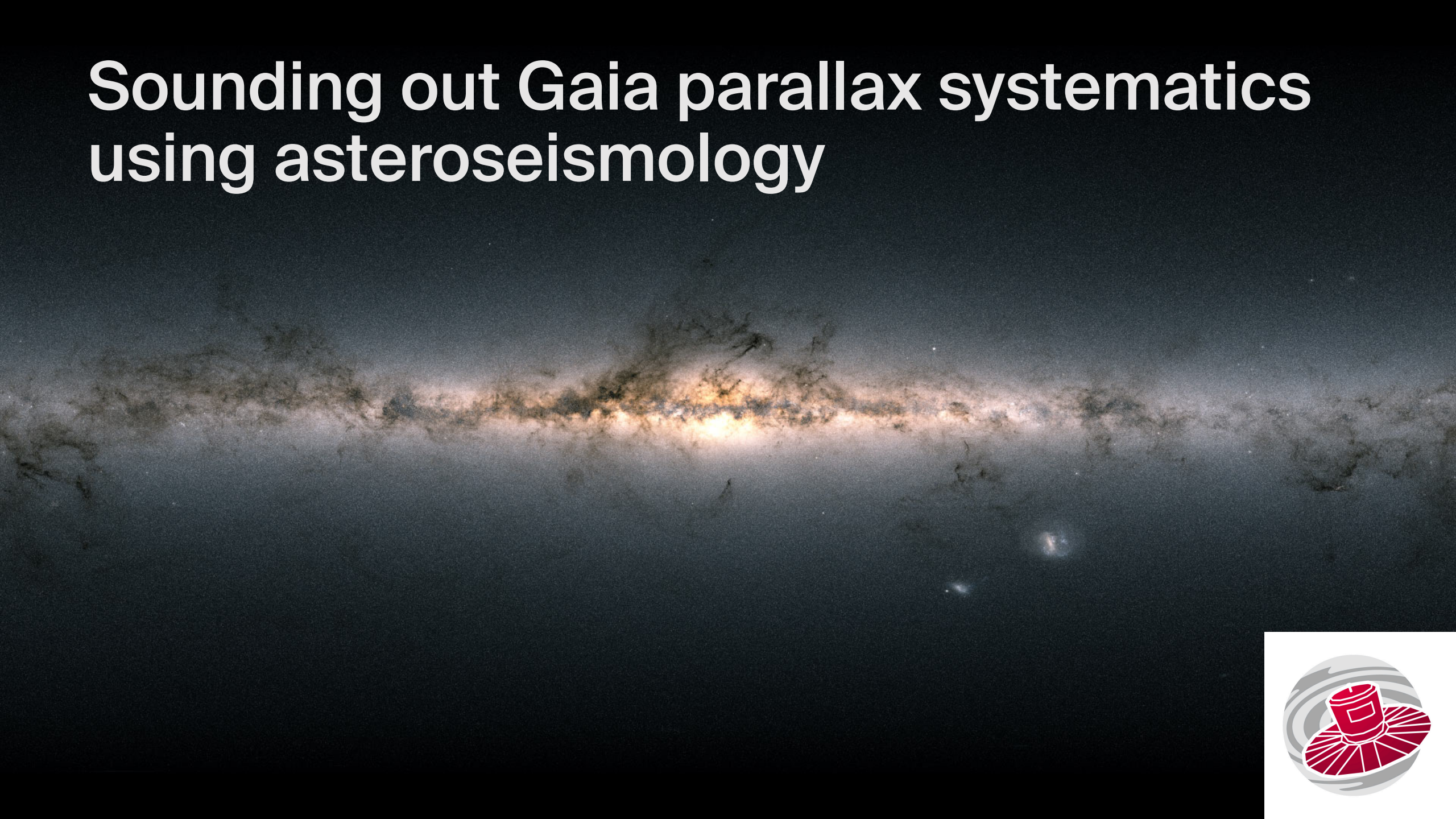


Absolute calibration for

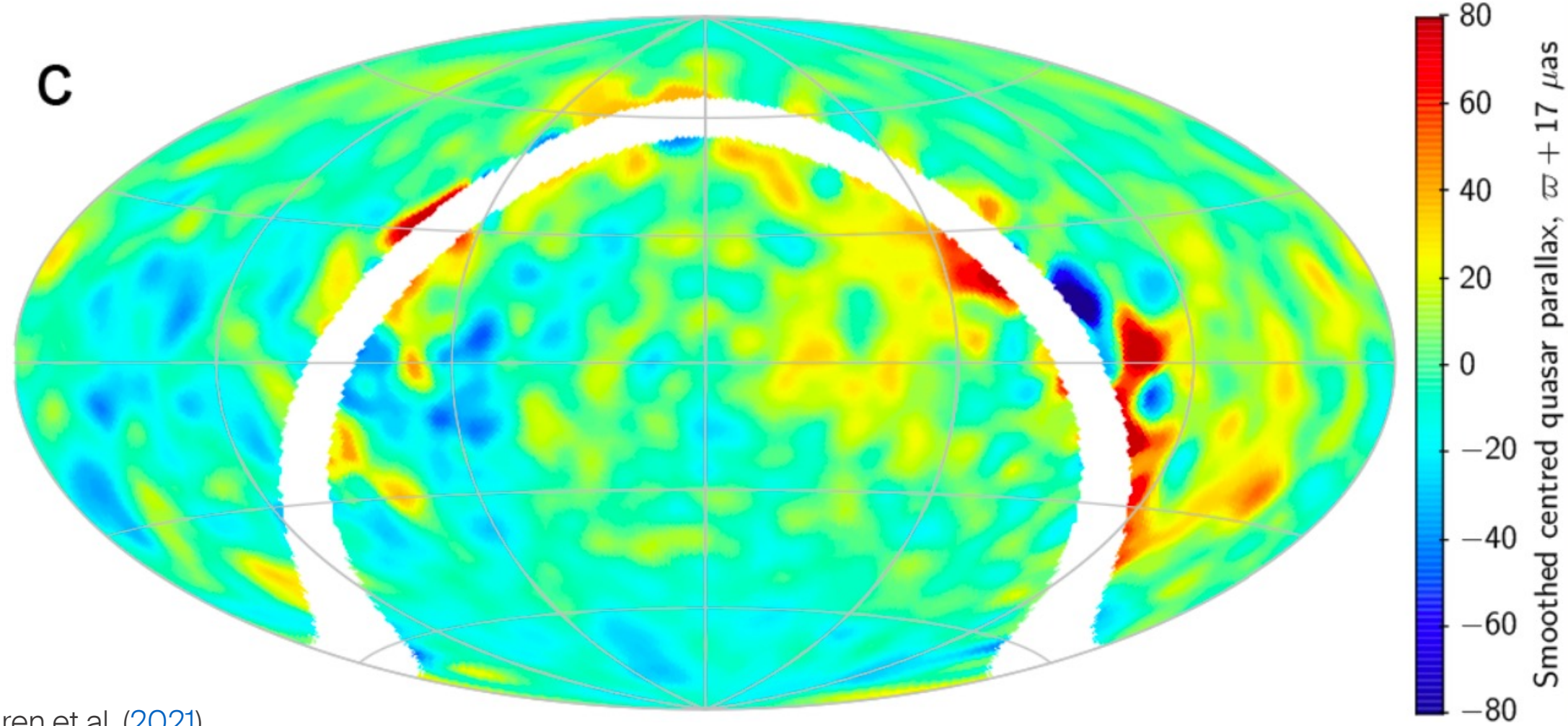
$\mu = m - M = 5\log(d) - 5$

(d in pc)

Sounding out Gaia parallax systematics using asteroseismology



Gaia parallax bias of ~20 μas (10% at 5kpc)

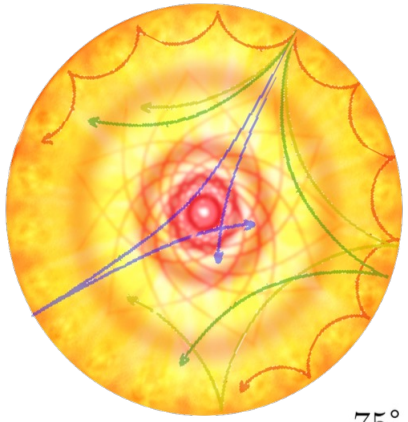


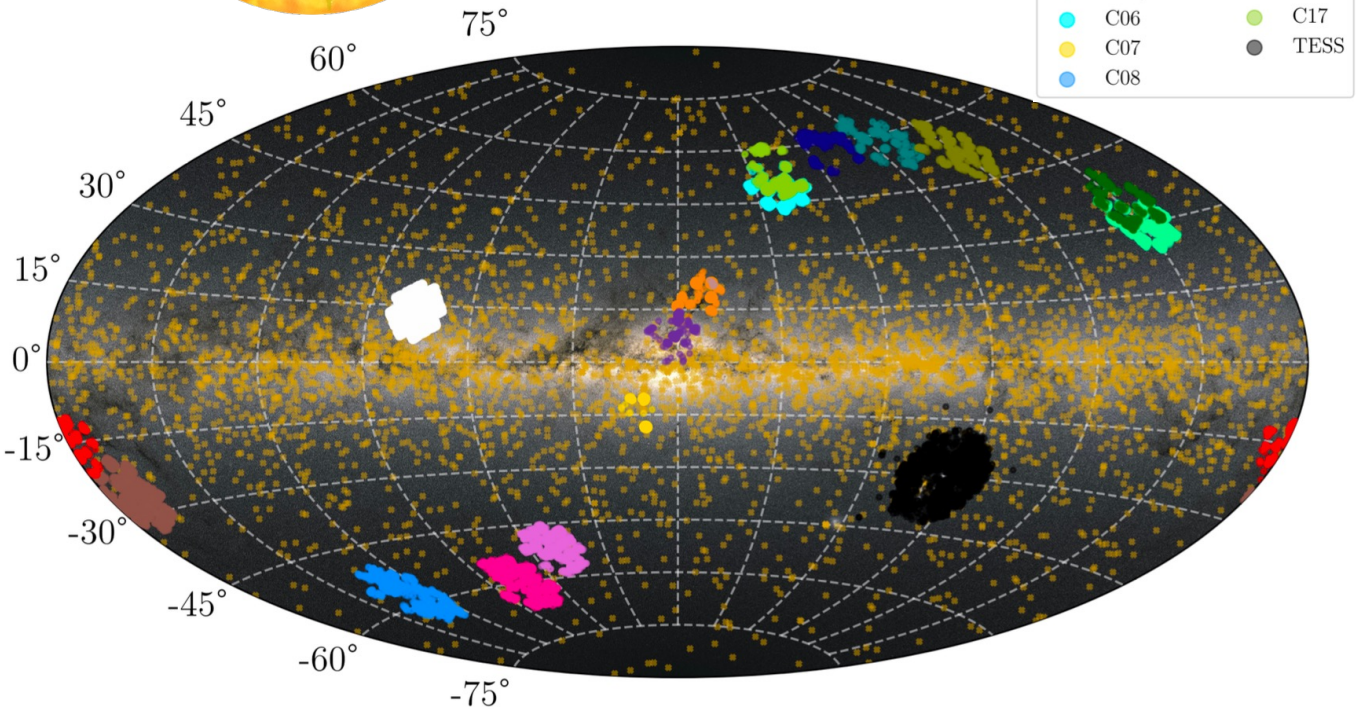
Lindegren et al. (2021)

Investigating Gaia parallax systematics by asteroseismology

Khan+ (2023, A&A 677, A21); Khan, RIA+ 2310.03654 (in press)

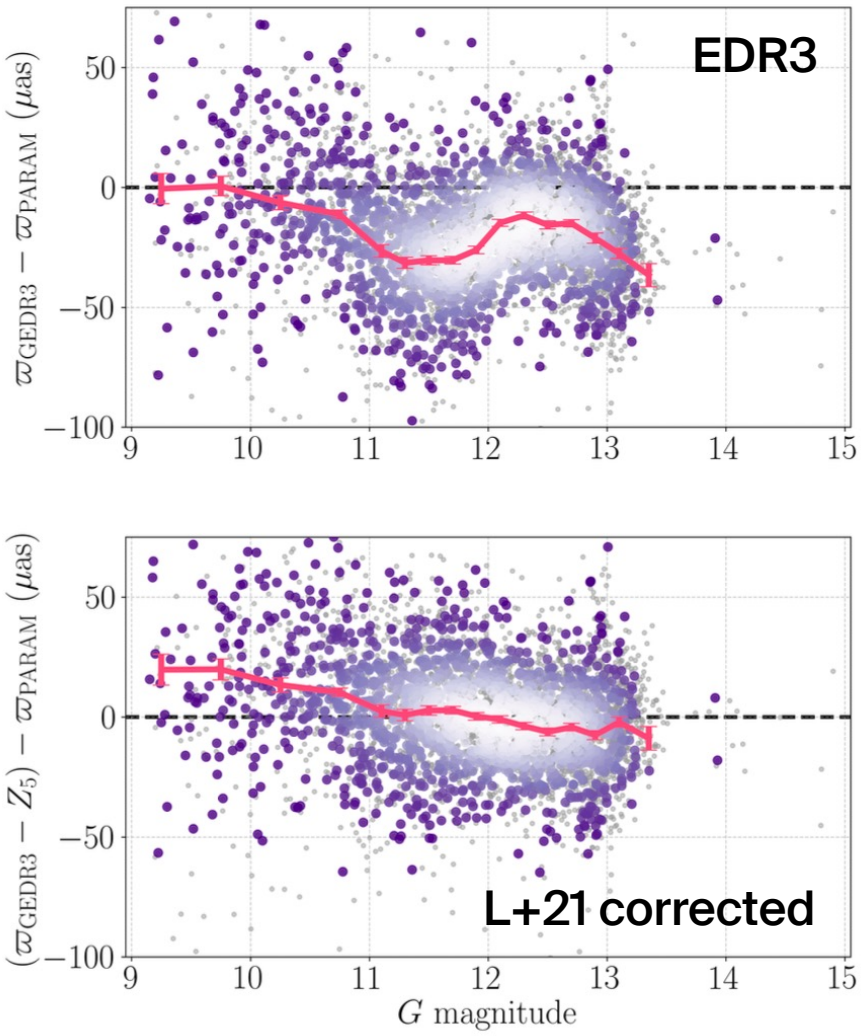
- Asteroseismology of 12’250 red giants, largest sample to date
- $M_{bol} \rightarrow \varpi$ using stellar models, spectroscopy & photometry
- 3’500 red clump giants best for parallax offset determination
- Systematics approx. 5-10μas
- Patchy but dense sky coverage for bright stars



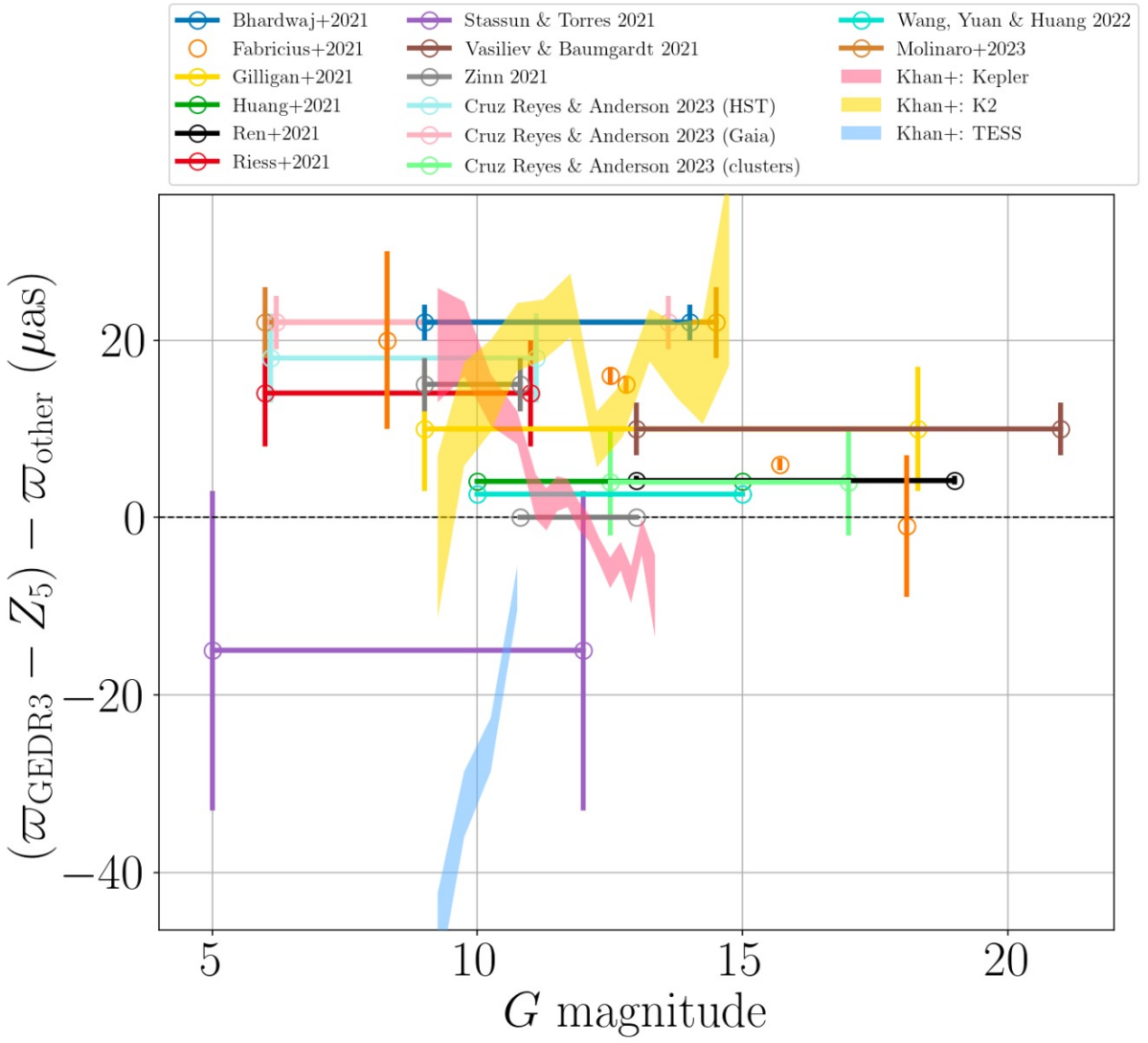


Offset complex, best range is G > 11 mag

Khan, RIA+ 2310.03654 (in press)



Residual parallax offset after L+21 correction

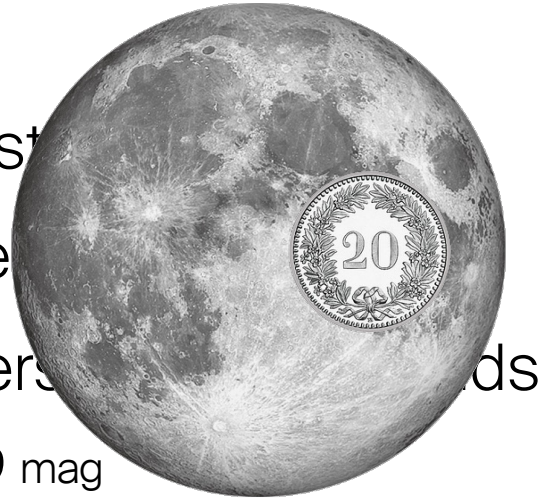


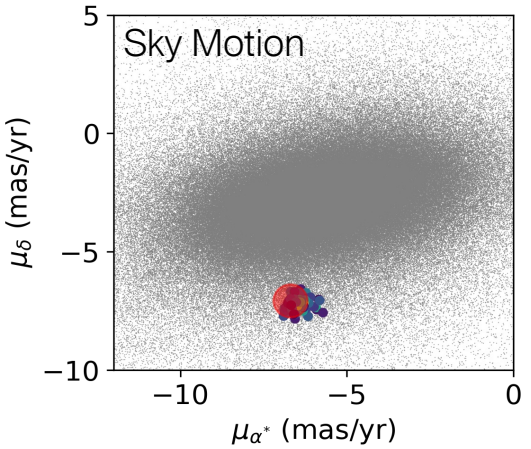
Calibrating Cepheids in the parallax sweet spot using open cluster member stars

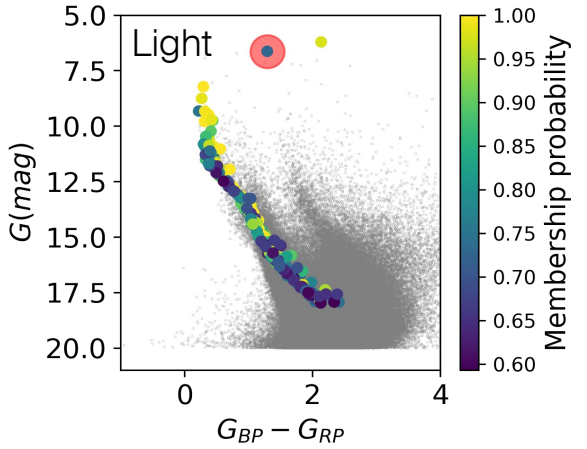
A 0.9% Cepheid luminosity calibration

Cruz Reyes & Anderson (2023), A&A 672, A85

- Mined Gaia for clusters near Cepheids
- Cluster parallax: best precision ($\propto \sqrt{N}$) and systematics
- 34 Cepheids in 28 clust
- Typical error: 7μas = re
- Combined fit 26 clusters ds
  - $M_{G,1}^{W} = -6.004 \pm 0.019$ mag
  - $\Delta\varpi_{Cep} = -19 \pm 3$ μas
- Gaia DR4: ~0.4% calibration







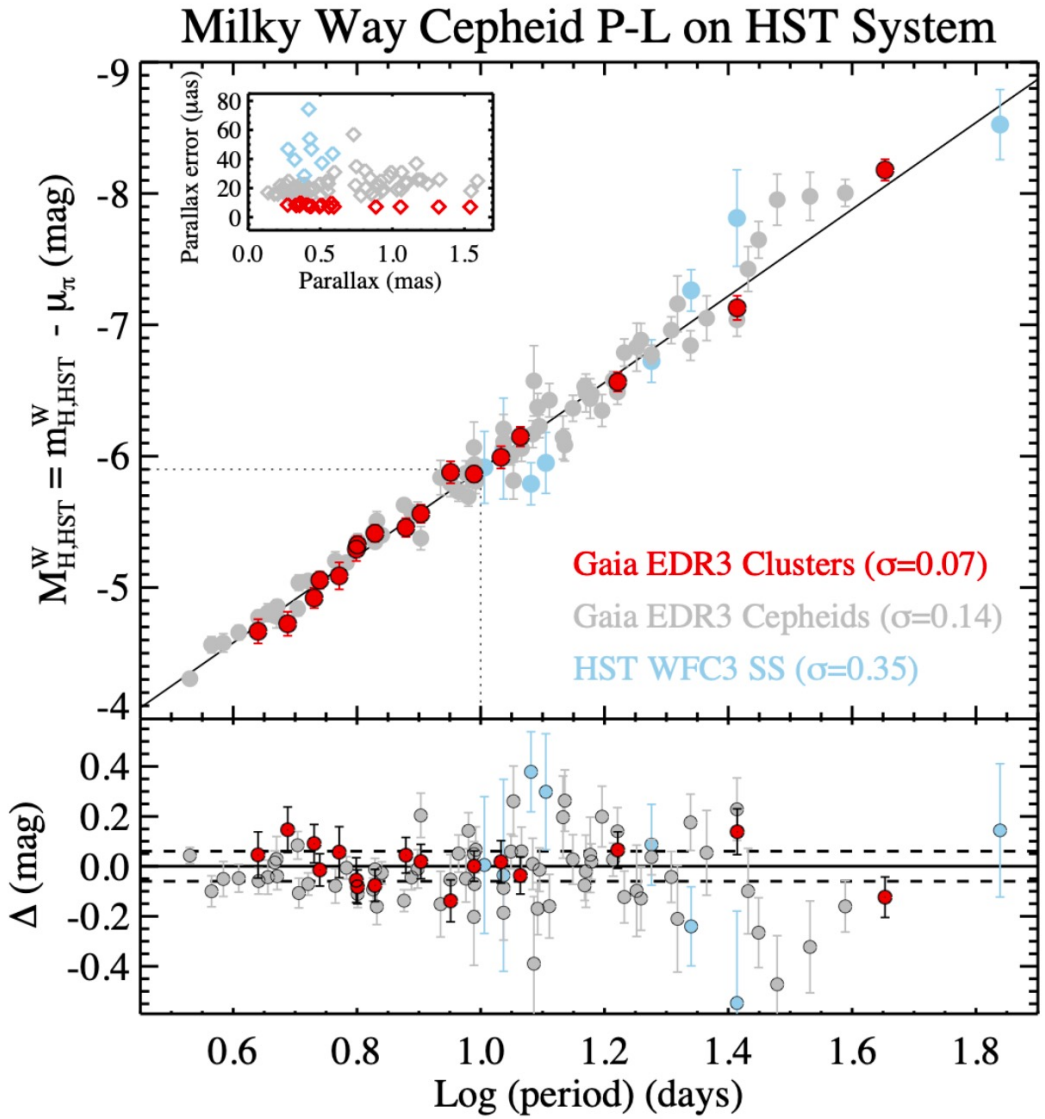
Cluster Cepheids grow Hubble tension

Riess et al. incl RIA (2022)

- HST IR photometry of 17 cluster Cepheids (Riess+22b)
- Cluster Cepheid LL: LMC-like dispersion
- 1 cluster Cepheid = 9 field Cepheids
- Riess+22b vs Cruz Reyes & RIA 22: separate astrometric modeling, average parallax difference $5\mu as$
- Combining $M^H_{W,1}$ as prior (Riess+22b):

$$H_0 = 73.15 \pm 0.97 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

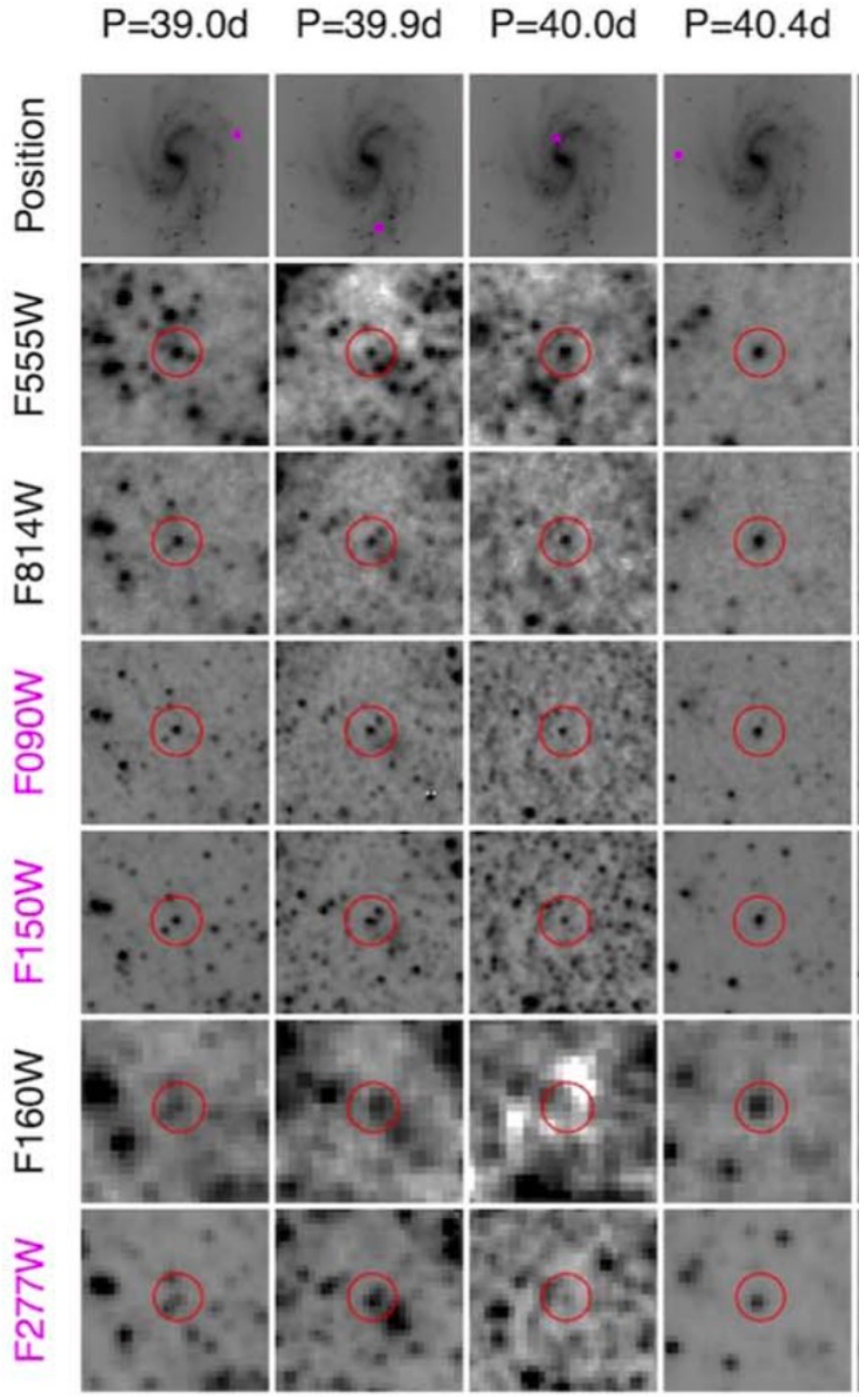
- 7% uncertainty reduction
- Tension increases **5.0 -> 5.3σ**



JWST uncrowds distant Cepheids

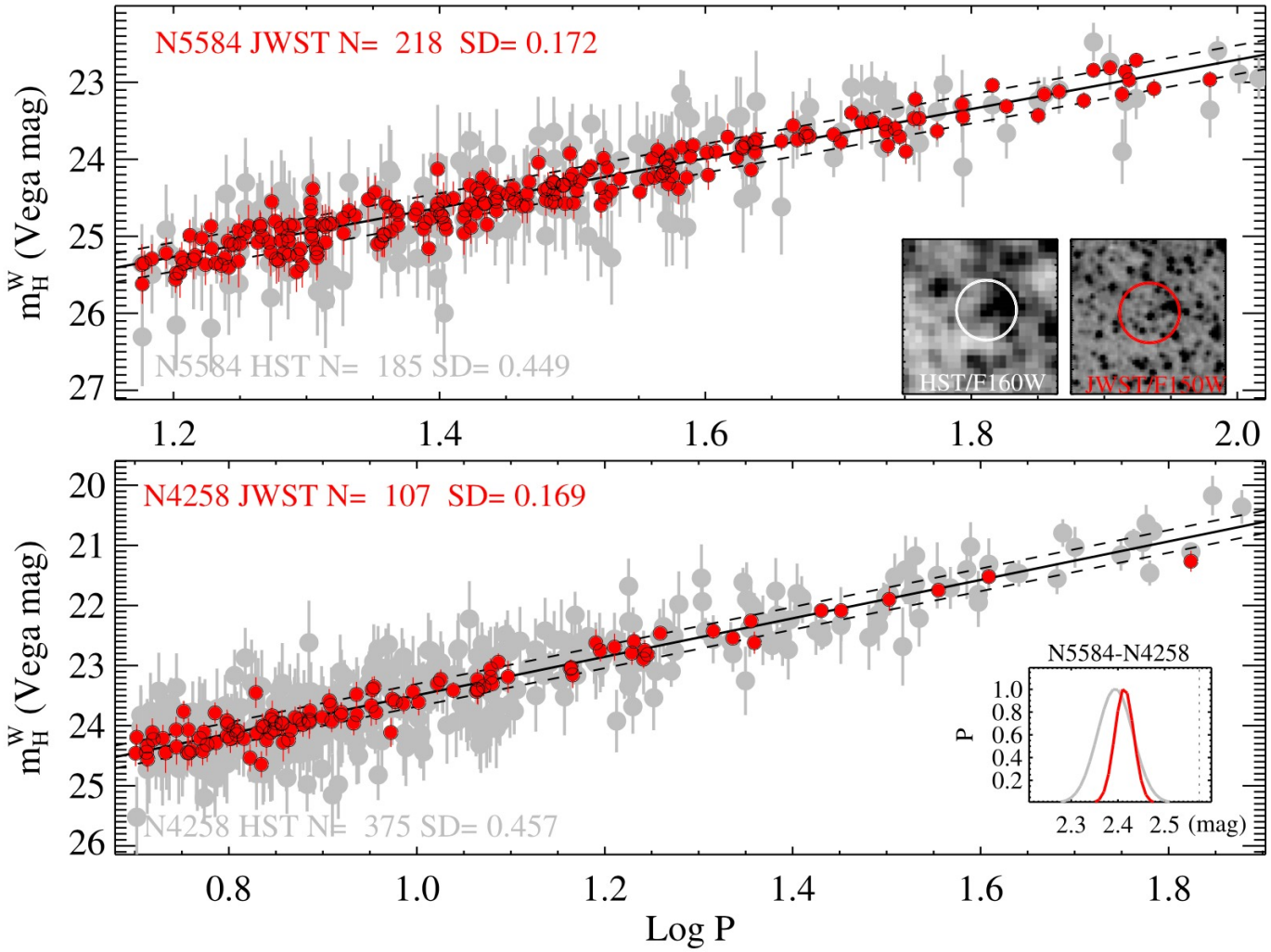
Riess et al., incl RIA (2023), ApJL 956, L18

- JWST : NIR spatial resolution slightly better than optical HST, 4x better than NIR HST
- Better source separation = lower uncertainty from crowding correction
- HST + JWST synergy: Optical and NIR photometry observed using similar spatial resolution
- Spoiler alert: Crowding does not solve the Hubble tension



JWST: HST unbiased & 2.5x less dispersion

Riess et al., incl RIA (2023), ApJL 956, L18



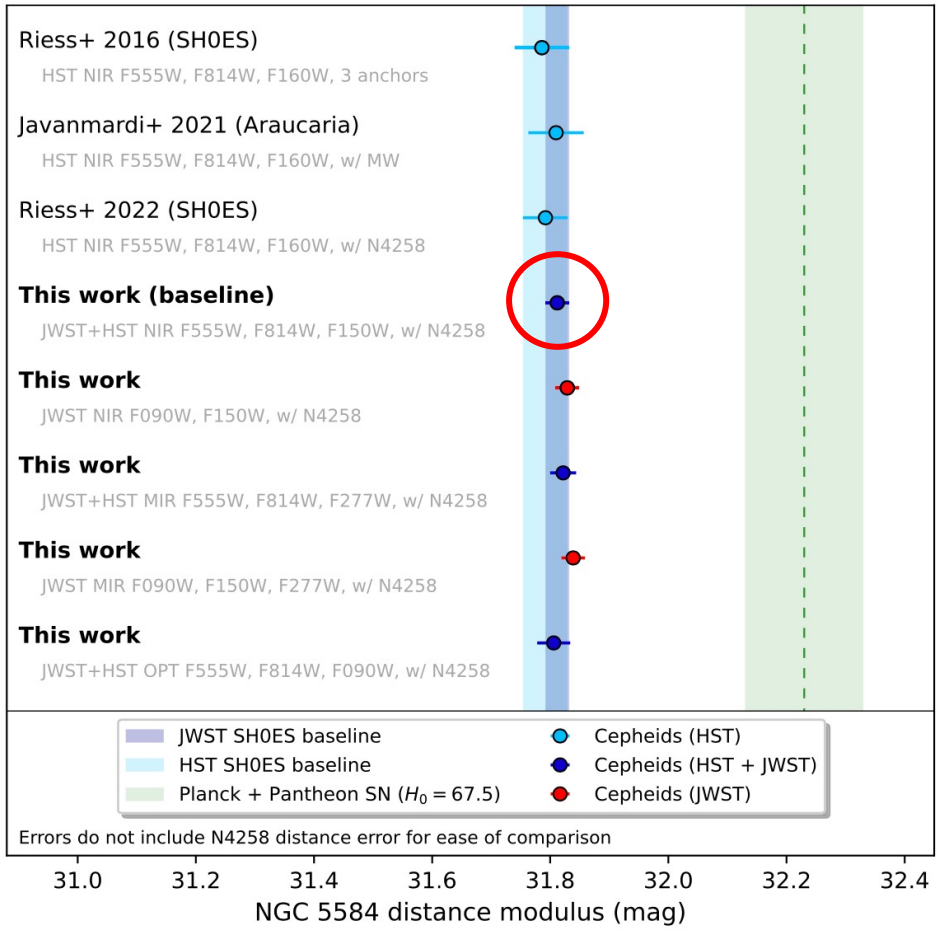
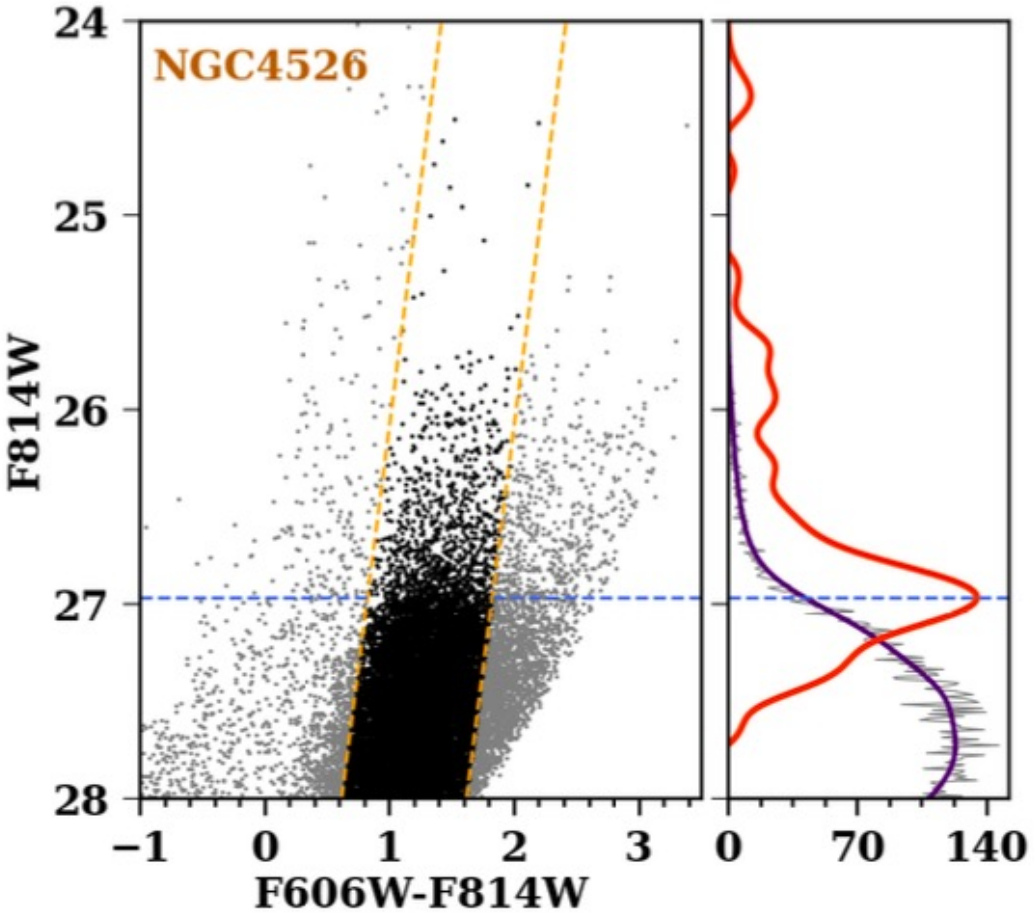
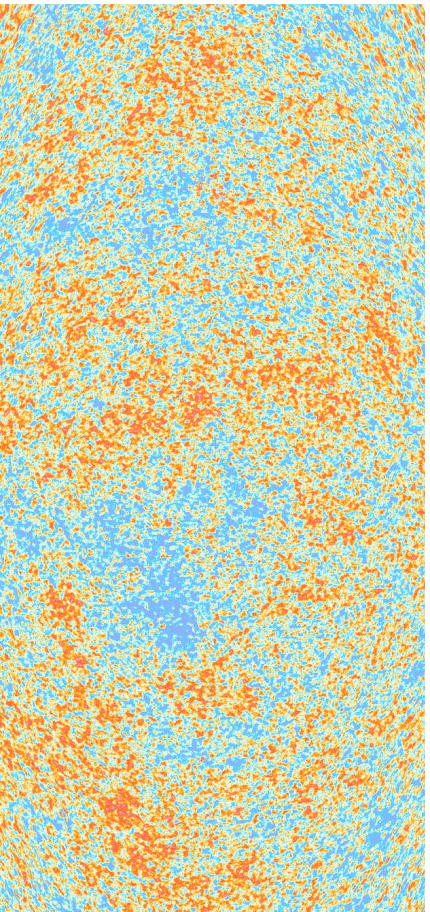


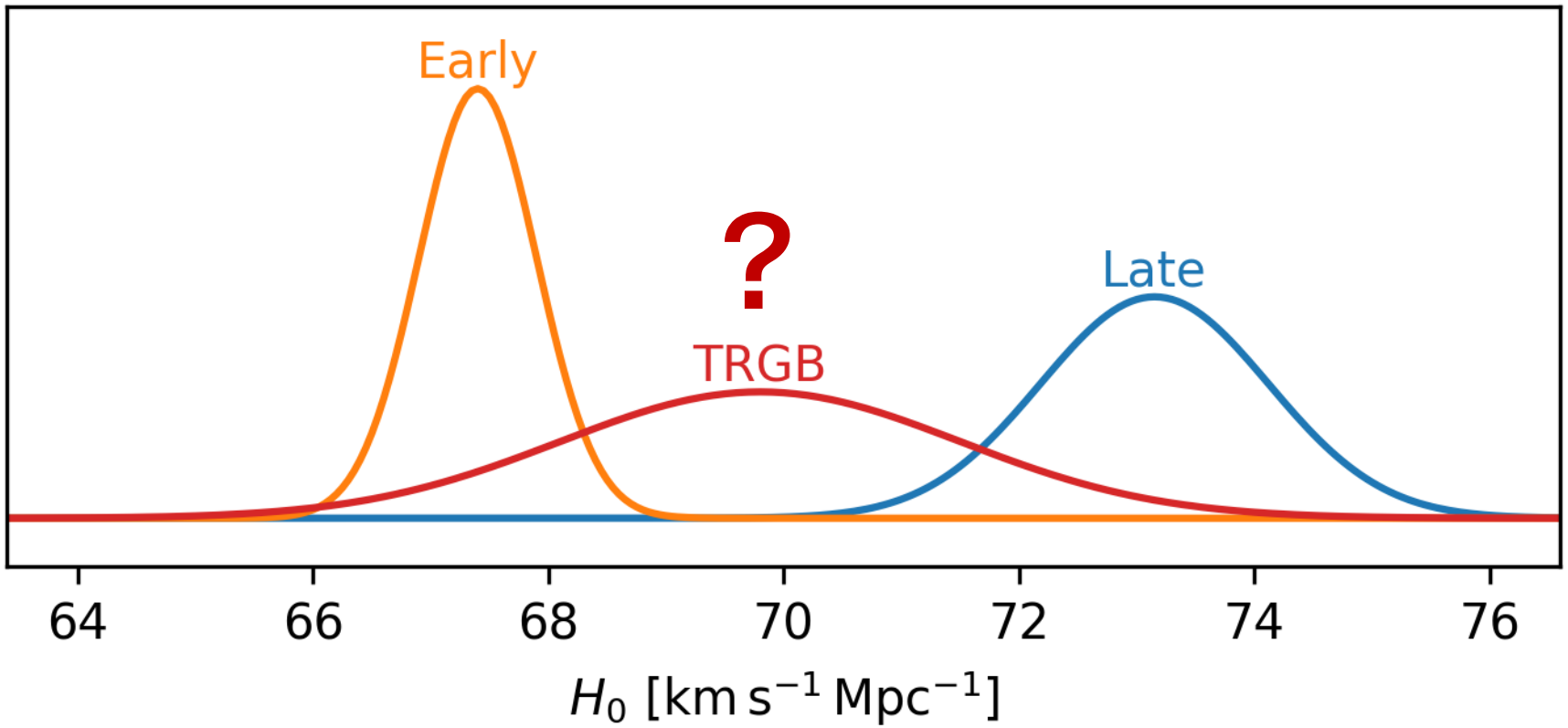
Figure 15. A comparison of Cepheid distance measures to NGC 5584.

New insights on TRGB calibration and standardization



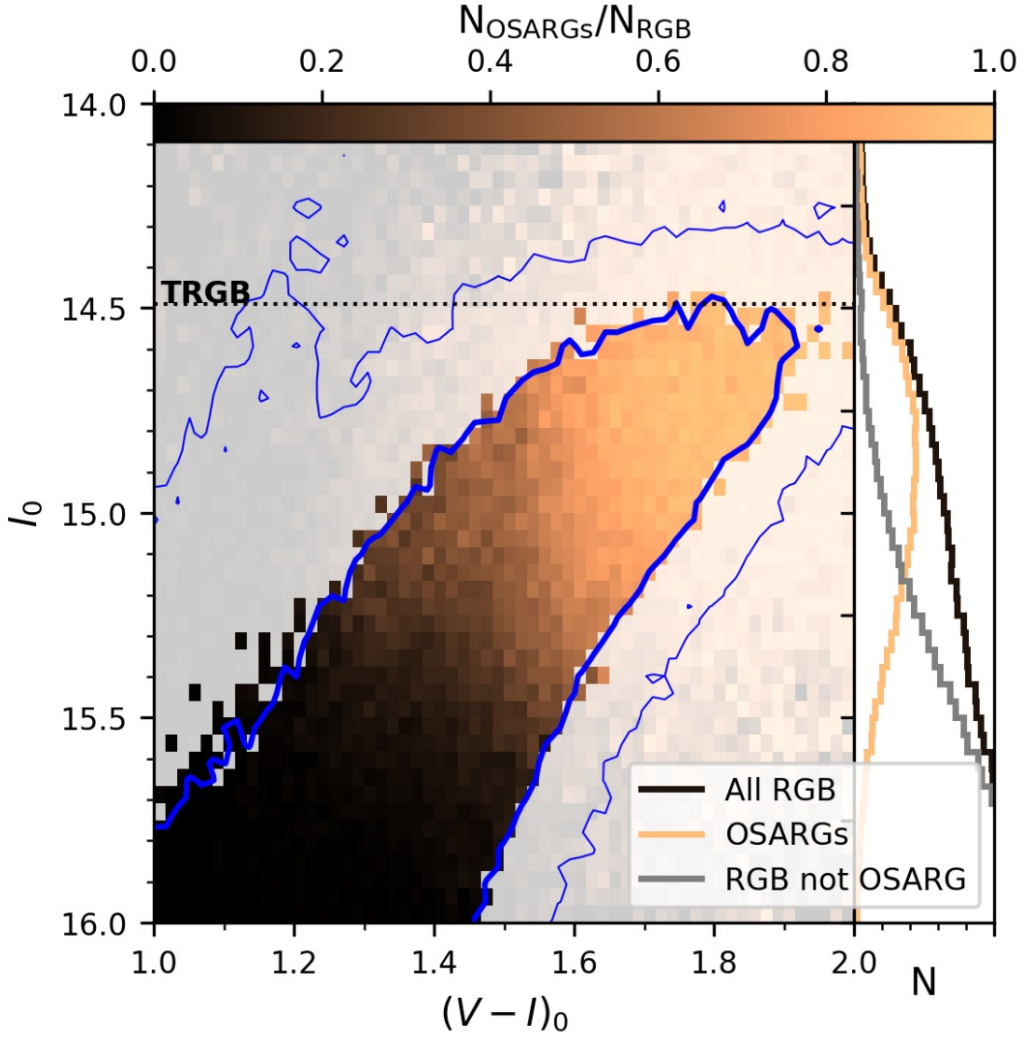
Reconciling standard candles



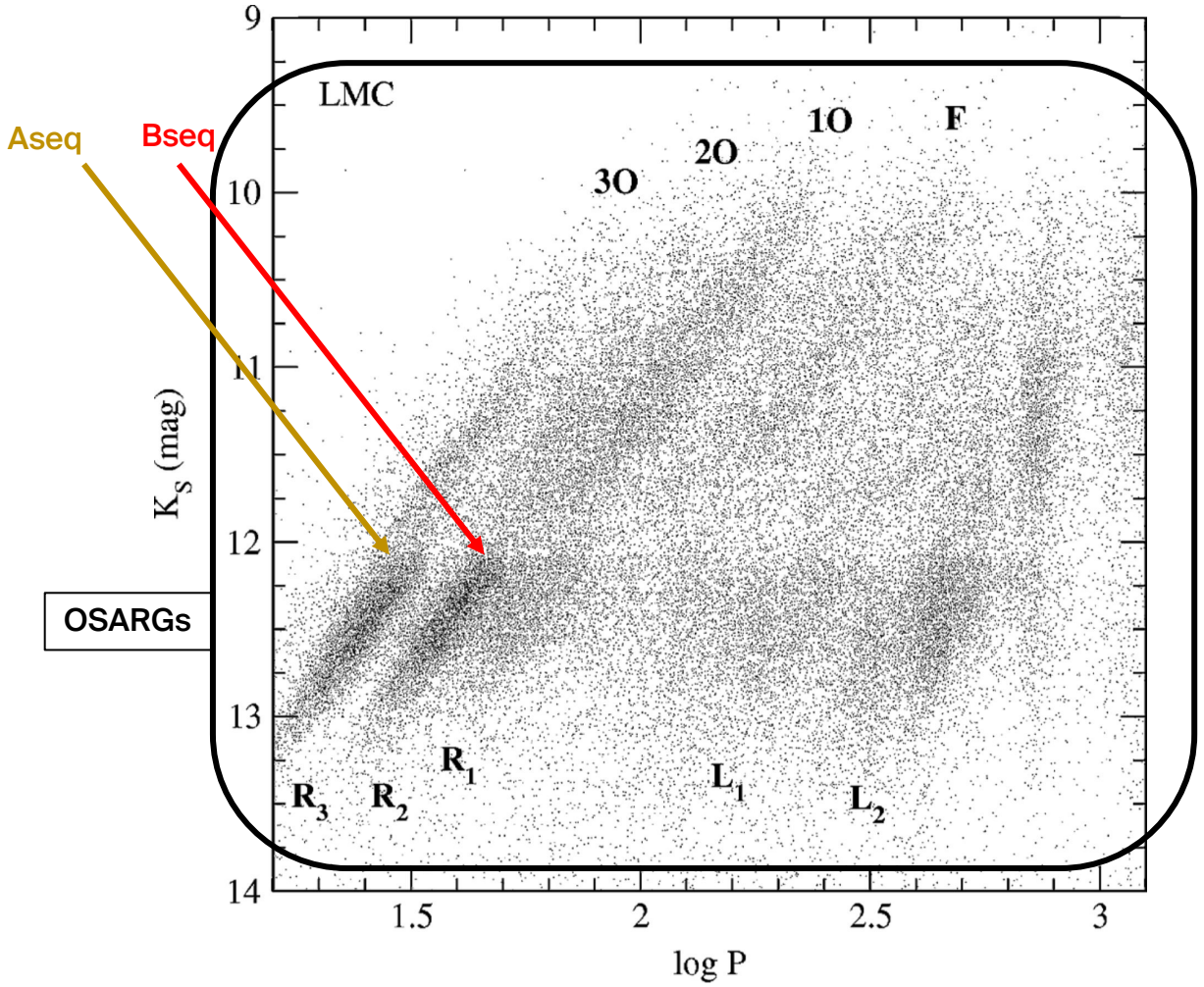


The TRGB is chock-full of variable stars

RIA et al. [2303.04790](2303.04790) (to be updated)



79'200 Small Amplitude Red Giants in OGLE-III



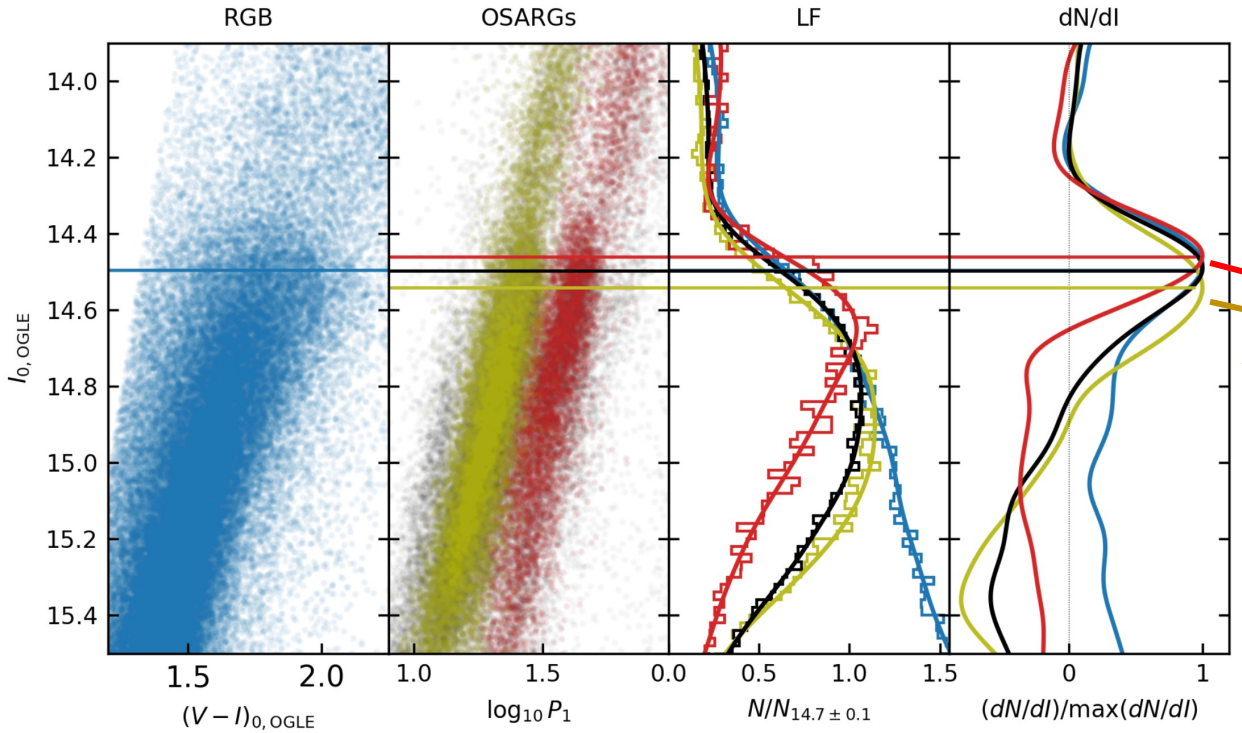
Ita et al. (2002); Kiss & Bedding (2003)

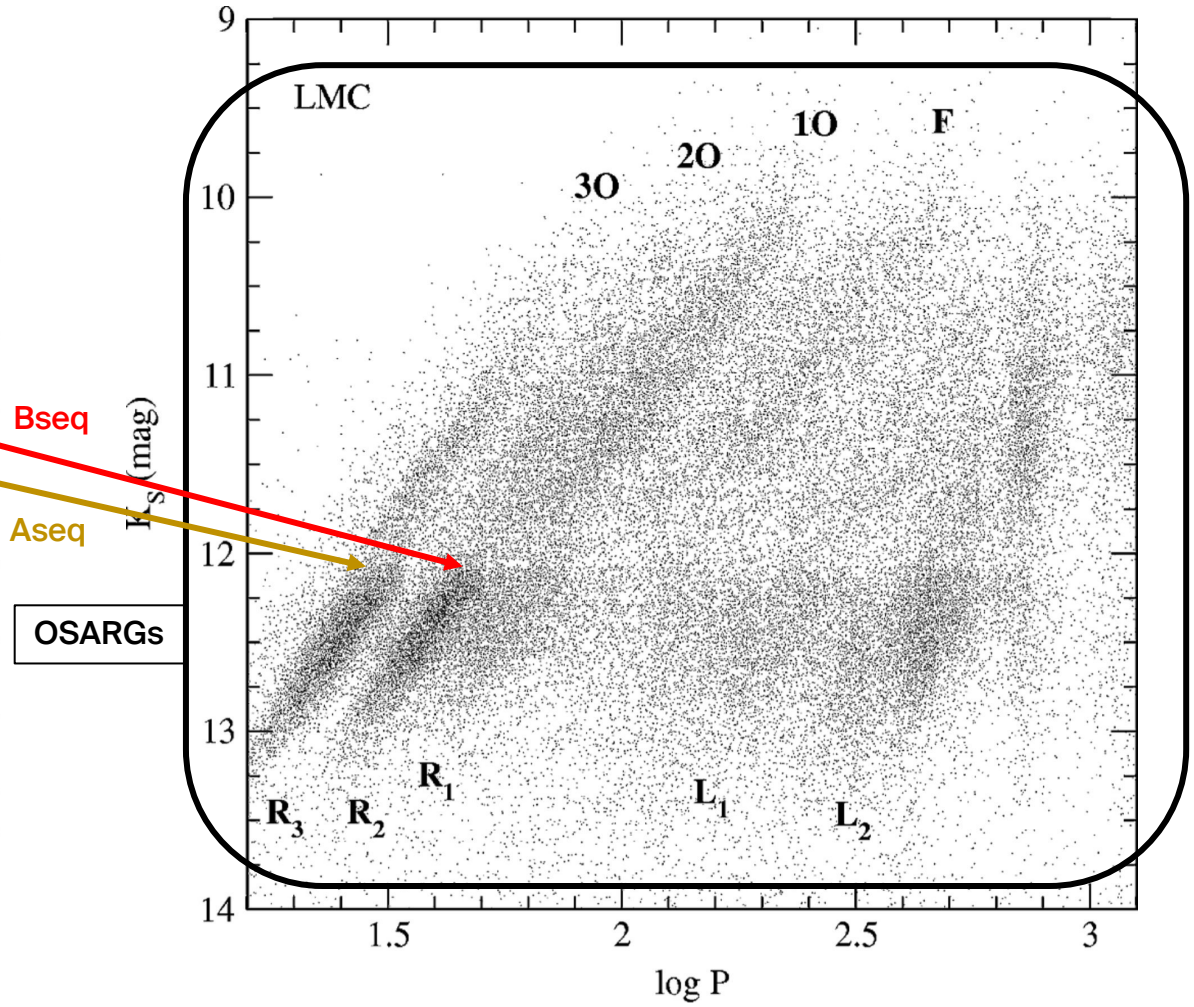
Twigs of the Red Giant Branch

RIA et al. 2303.04790 (to be updated)

79'200 Small Amplitude Red Giants in OGLE-III

A & B sequence differ by 4.5–5 sigma!

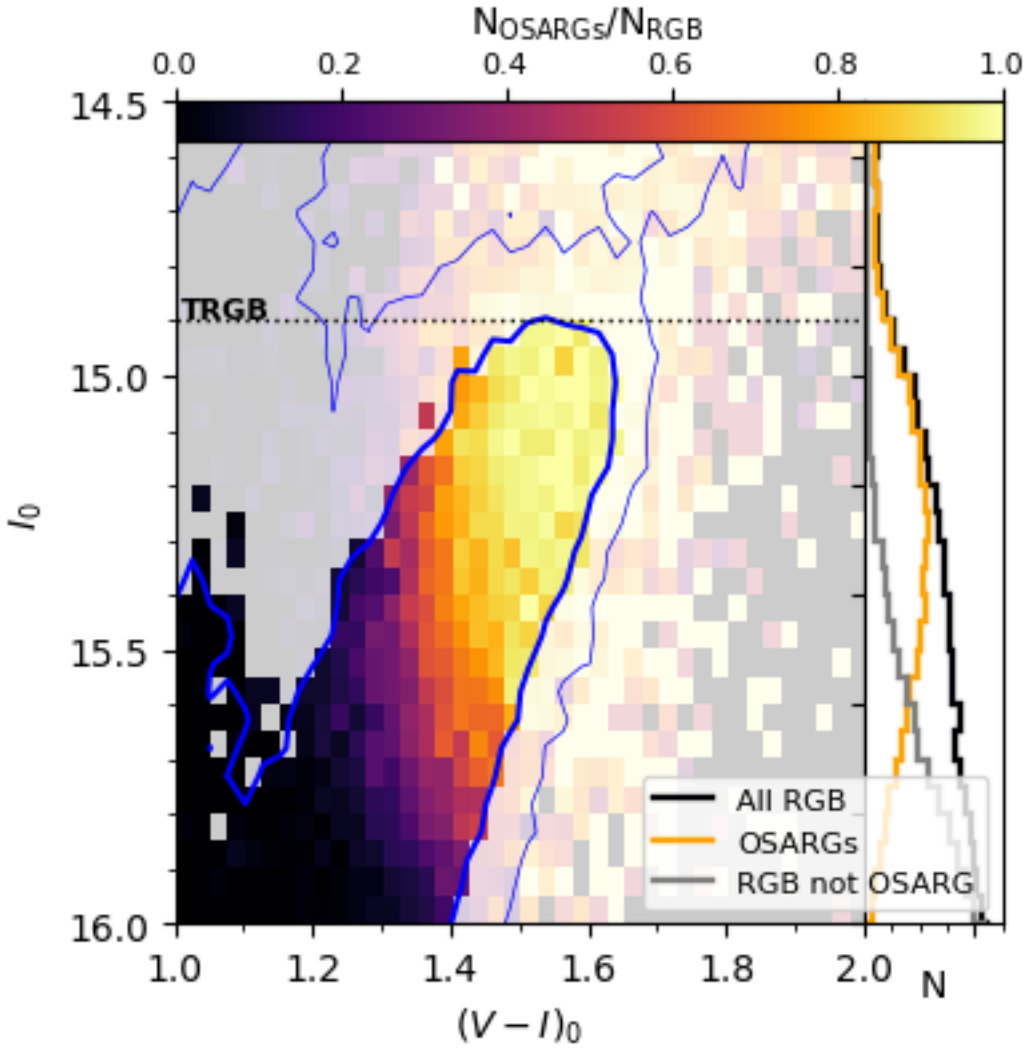


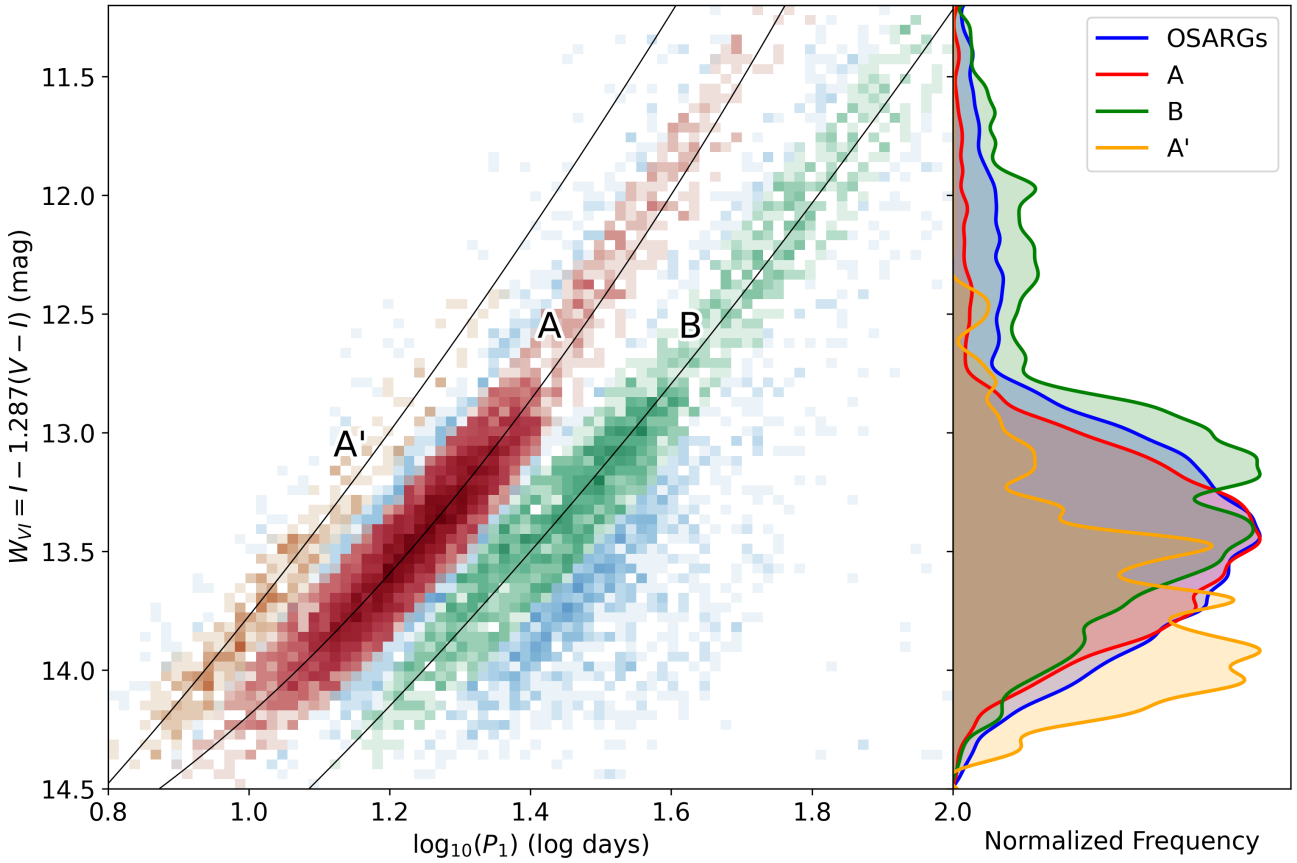


Ita et al. (2002); Kiss & Bedding (2003)

Twigs of the RGB in the SMC

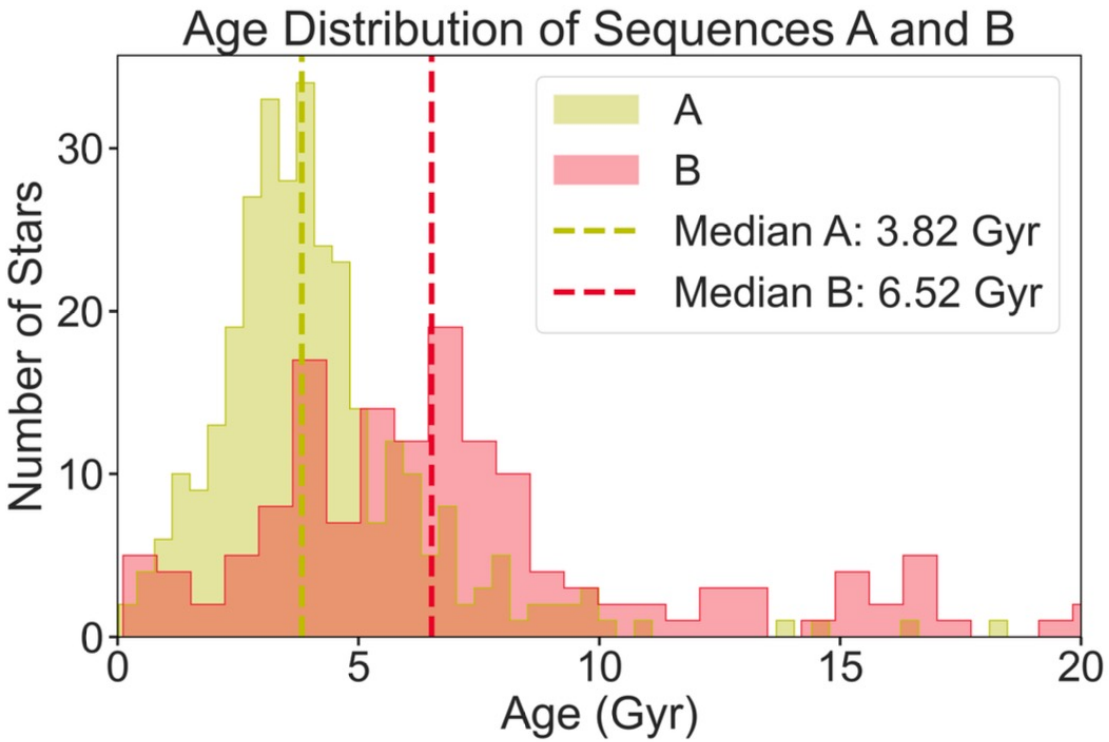
Koblischke & RIA (in prep.)

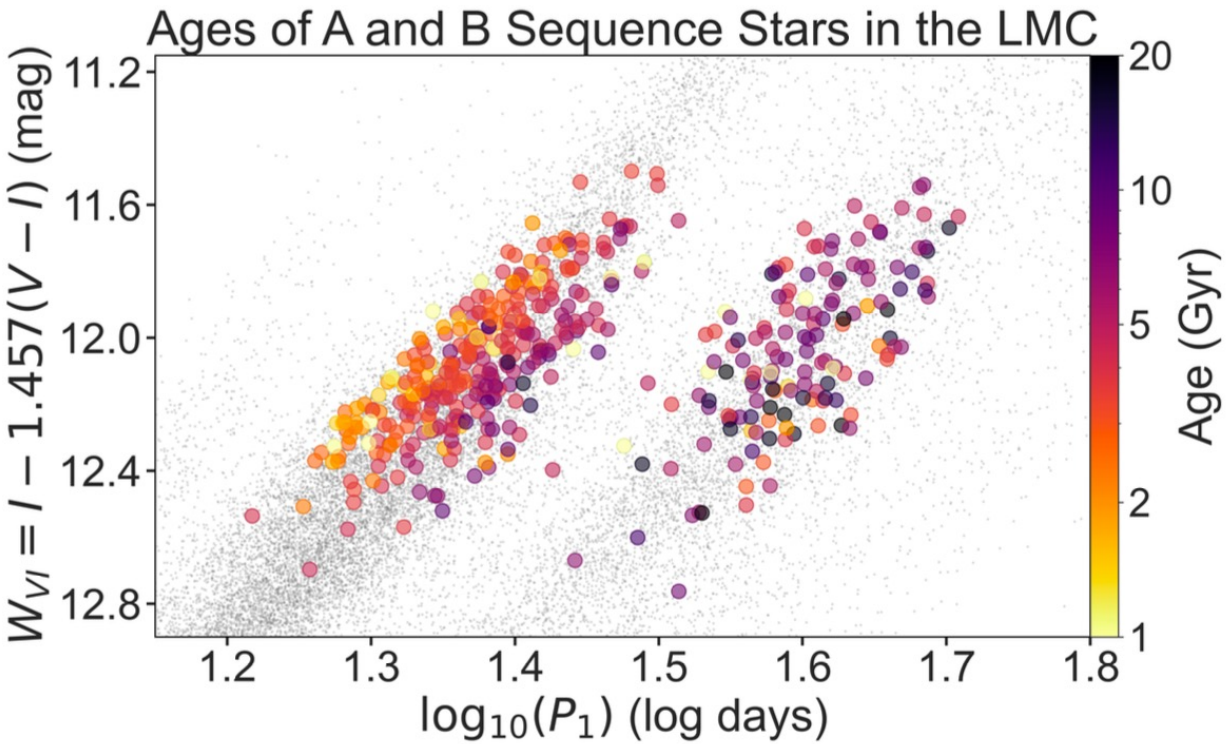




Variability elucidates RG diversity and allows standardization

RIA et al. 2303.04790 (to be updated)

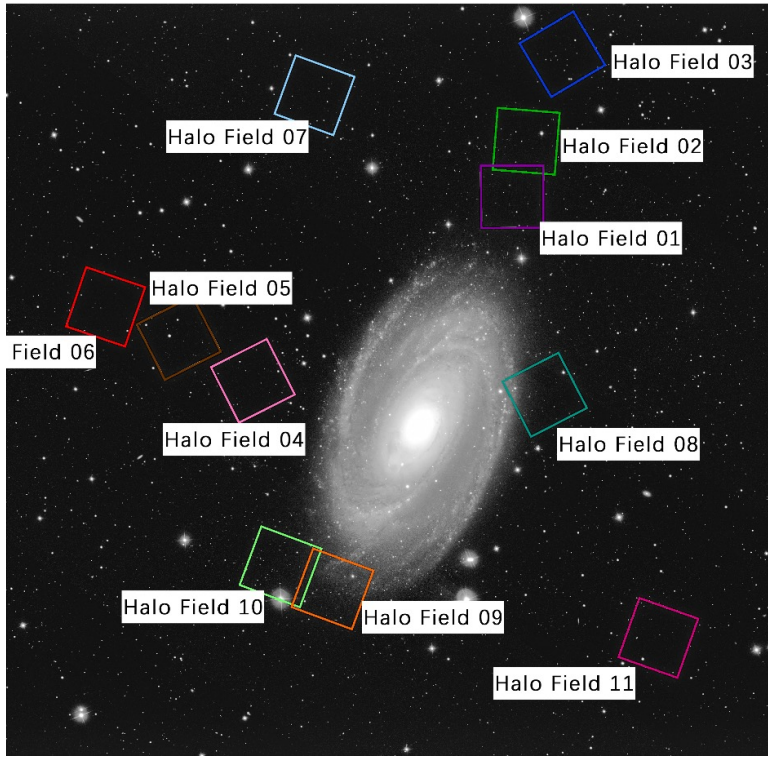


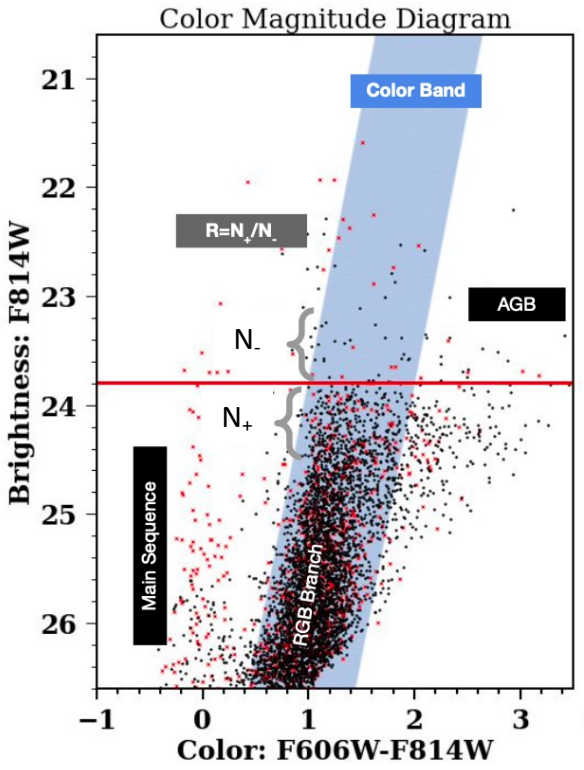


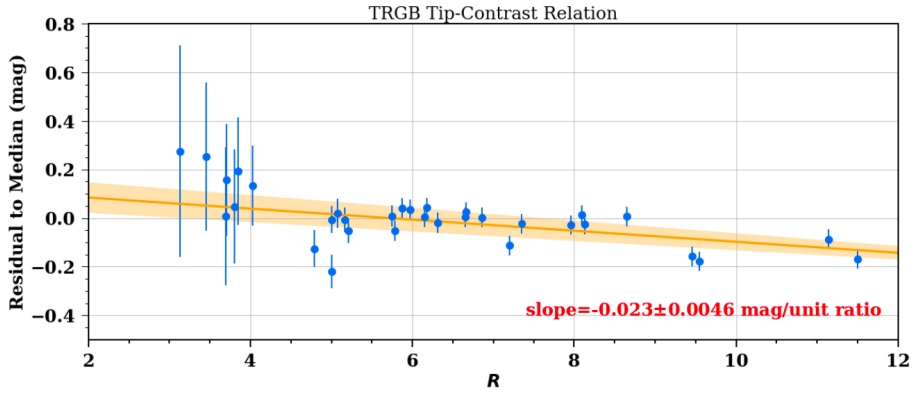
Ages from Povick et al. (2306.06348)

Standardizing m_{TRGB} using Tip Contrast Relation

Wu et al. (2022), Scolnic et al. incl. RIA (2304.06693)





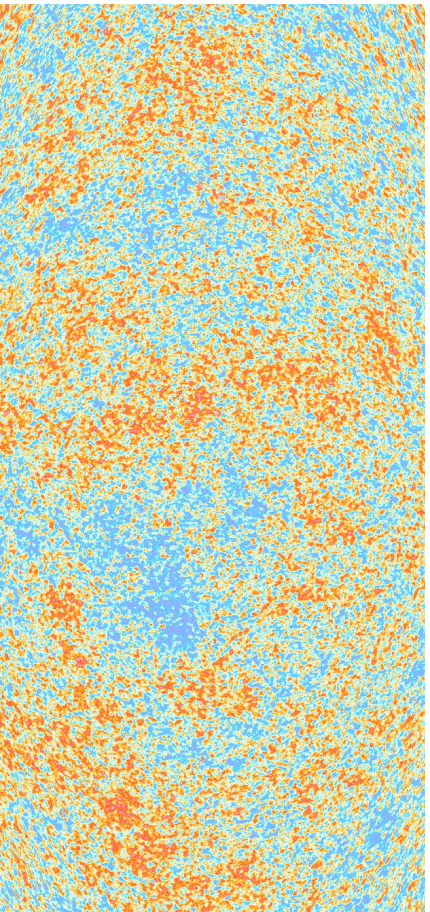


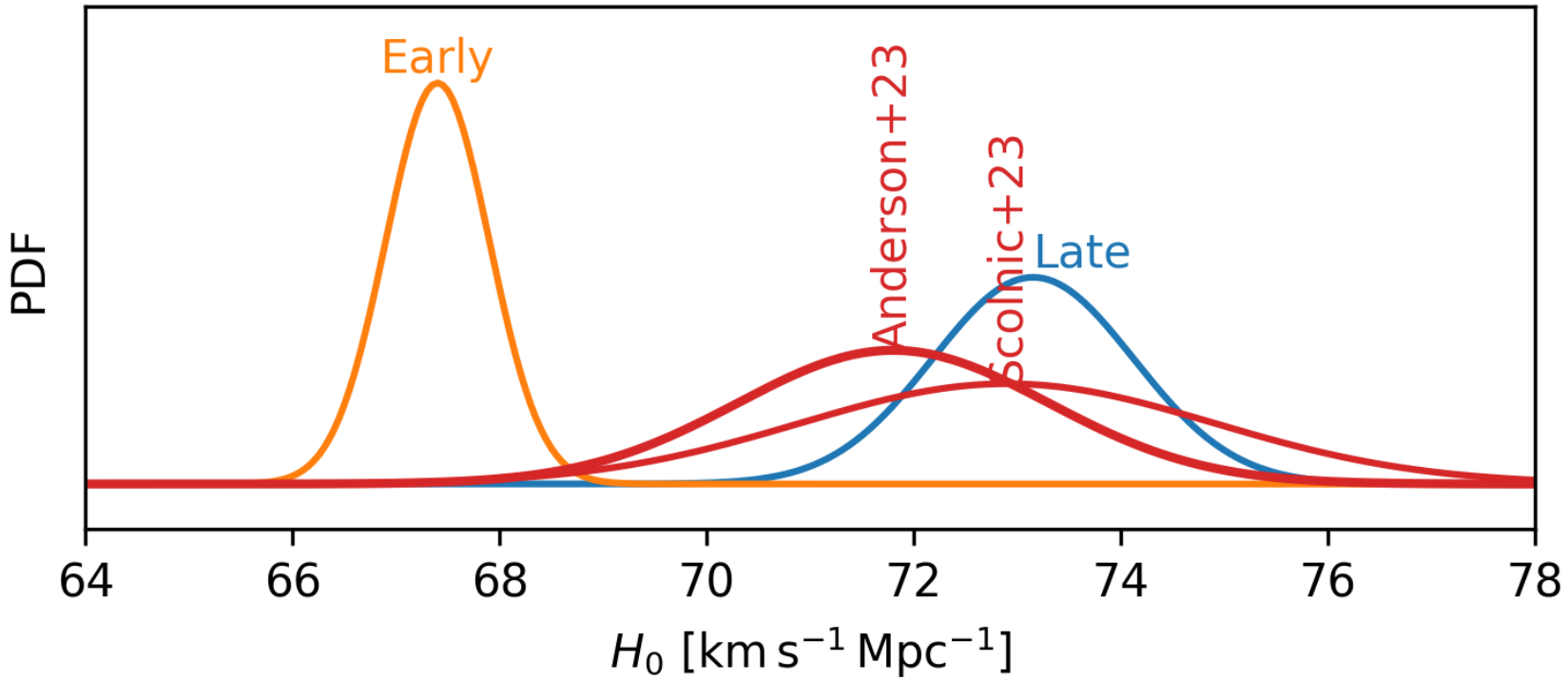
$$m_{I,\mathrm{TRGB}}^{R=4} = m_{I,\mathrm{TRGB}} - 0.021(R-4)$$

Scolnic+23: Pantheon+ SNIa & unsupervised, consistent TRGB measurements in SN hosts:
H_0 = 73.2 +/- 2.0 km/s/Mpc

R = N_+/N_-

Improved systematics increase TRGB-calibrated H0!





TRGB method improvements (smoothing, weighting, objectivity), population diversity, Tip-contrast-relation, Host galaxy reddening, Pantheon+ SNe, and more

Conclusions

Swiss National Science Foundation

European Research Council

Established by the European Commission

- Hubble tension cannot be argued away: all early and all late-Universe H0 values agree with each other, respectively
- ERC project **H1PStars**: extensive work in progress to improve systematics
- Cluster Cepheids provide best absolute calibration (Cruz Reyes + RIA 23)
- Cepheid systematics support 1% H0 (Spetsieri, RIA+ in prep)
- TRGB: ignore population diversity at your own peril (RIA+23)
- TRGB: standardization & Pantheon+ SNela: 72.9 ± 2.0 km/s/Mpc (Scolnic+23)
- JWST: crowding not the problem & improved uncertainties! (Riess+23)
- Relativistic effects relevant for 1% H0 measurements (RIA19, RIA22)

CA21136 - Addressing observational tensions in cosmology with systematics and fundamental physics (CosmoVerse)

- Main aims:
  - establish synergy between areas focusing on cosmological tensions
  - foster interdisciplinary network
  - confront growing challenges of tensions in cosmological surveys
  - Focus on inclusion across member countries and key communities
- Leads:
  Jackson Levi Said (Malta)
  Eleonora Di Valentino (Sheffield)

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EUROPEAN COOPERATION IN SCIENCE & TECHNOLOGY

Book | Apr 2024

The Hubble Constant Tension

https://link.springer.com/book/9789819901760

Editors: Eleonora Di Valentino, Dillon Brout

Covers measurements and solutions as well as analysis of the disagreements

Provides a comprehensive review of the H0 tension problem

Summarizes recent problems and discussions related to the Hubble constant

Part of the book series: Springer Series in Astrophysics and Cosmology (SSAC)

Thanks for your attention!

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Stay tuned!

www.epfl.ch/labs/scd