Systematics of stellar standard candles for an accurate distance ladder and H_0

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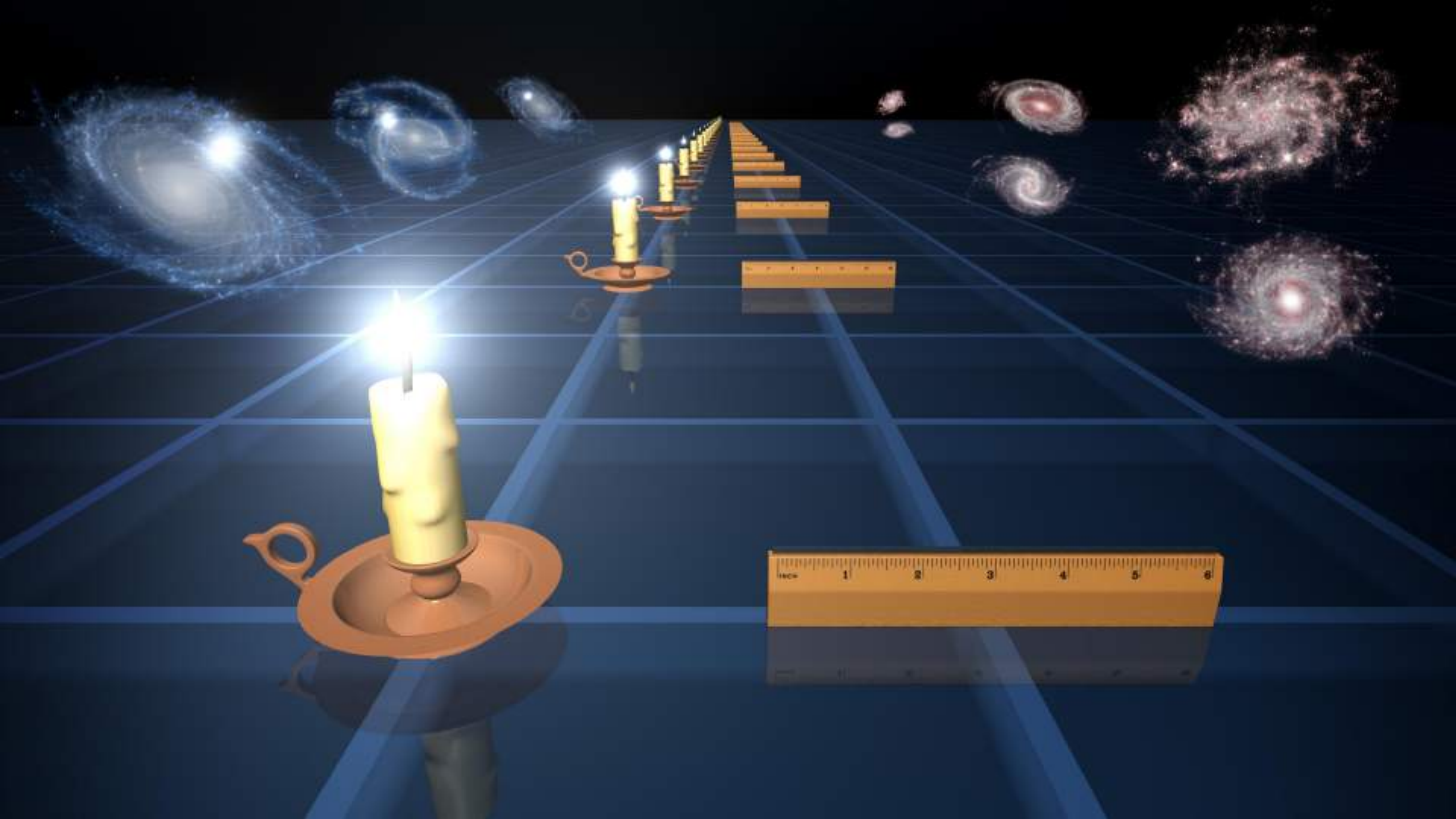
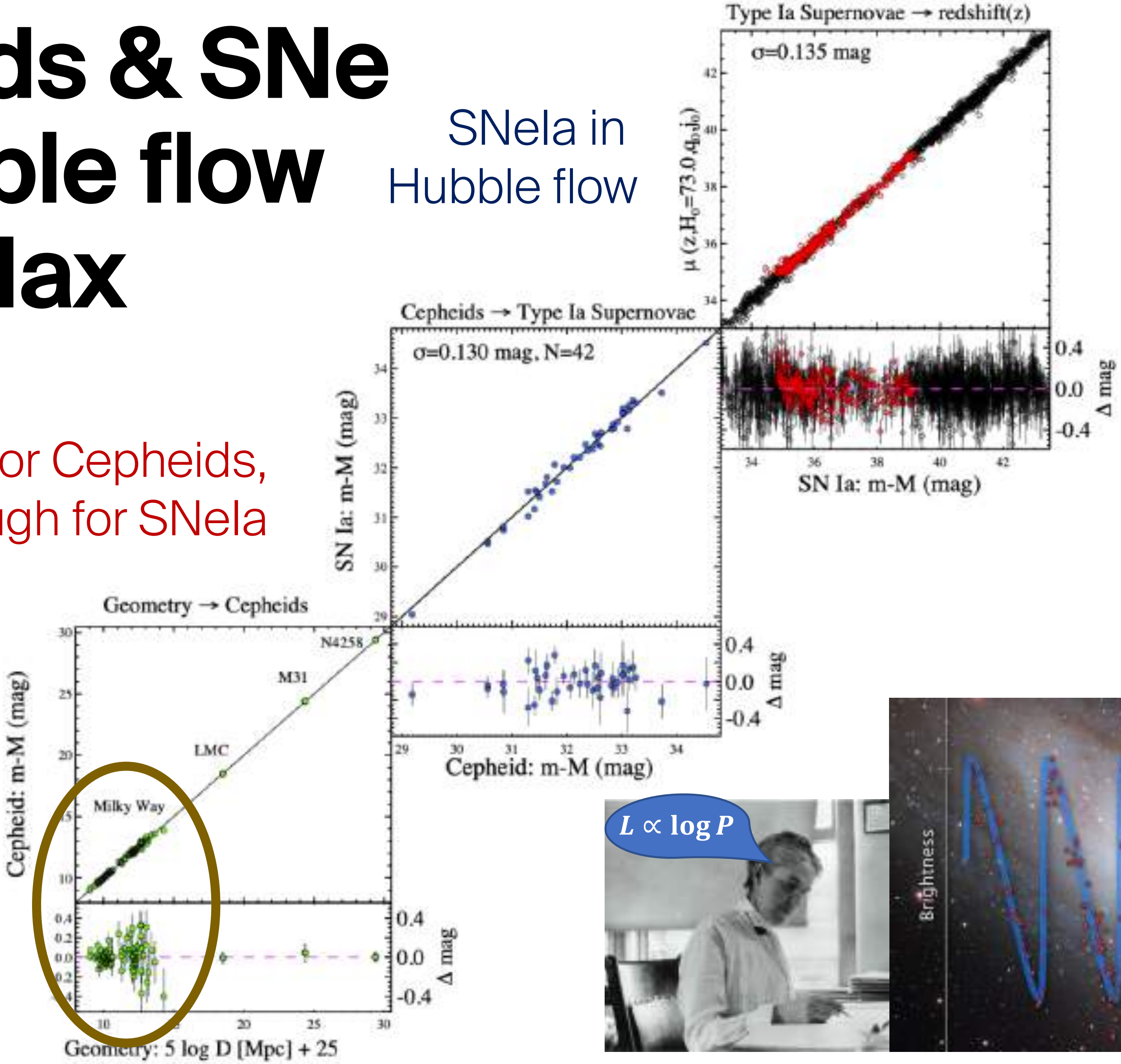

1 2 3 4 5 6

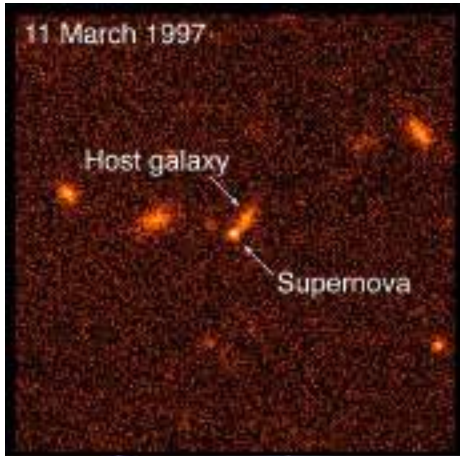
Cepheids & SNe tie Hubble flow to parallax

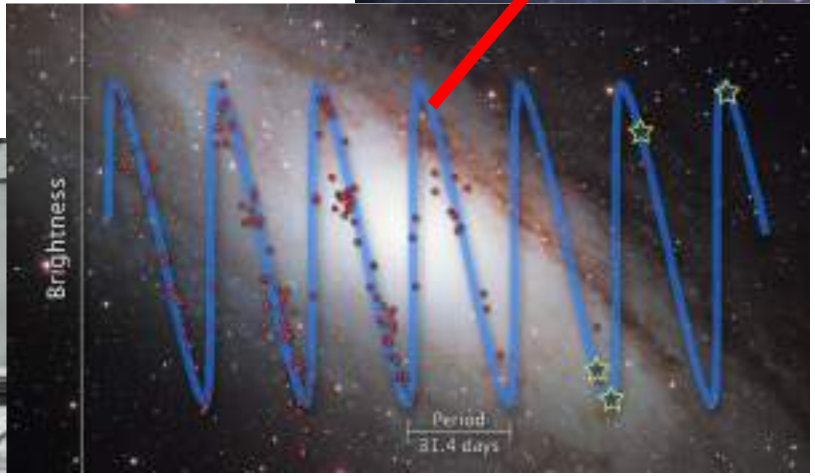
SNeIa in Hubble flow

Close enough for Cepheids, far enough for SNeIa

Gaia Parallaxes

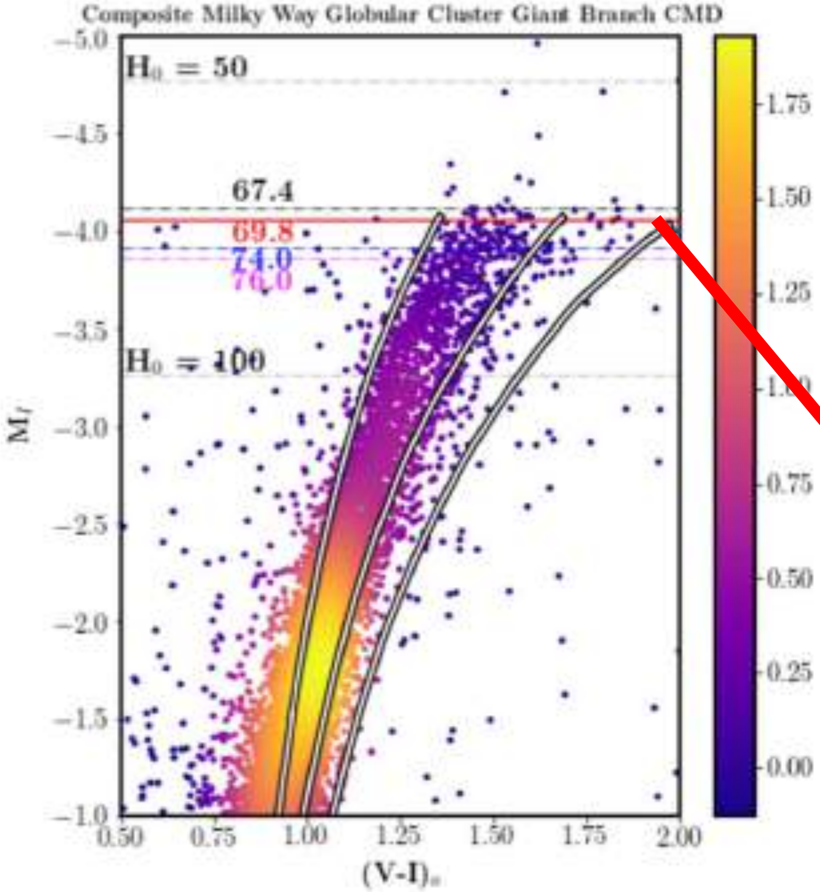




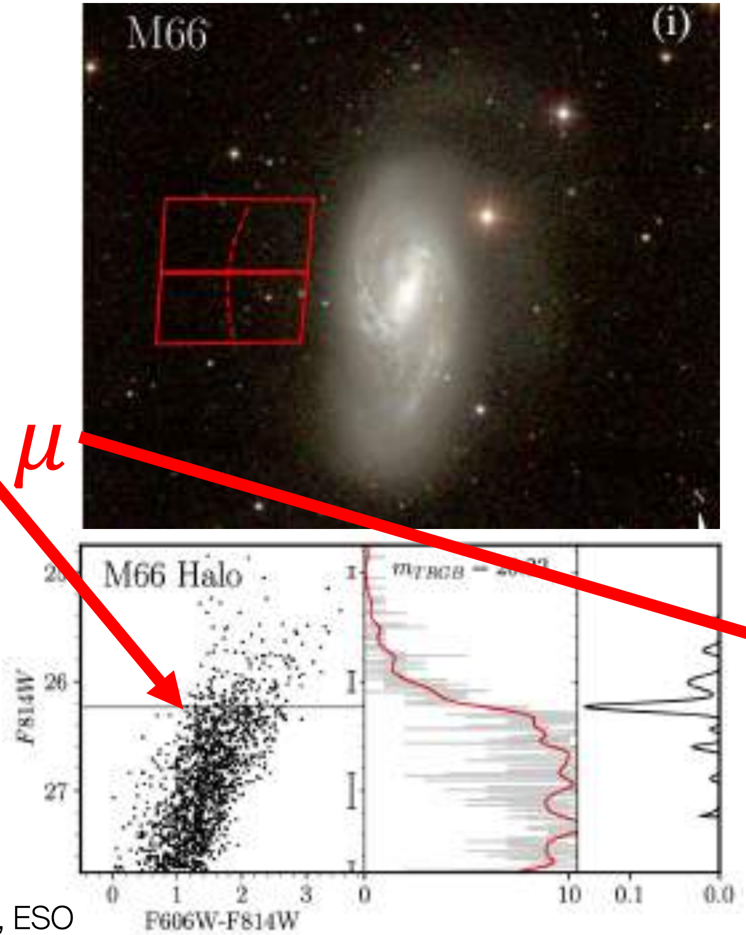


TRGB calibration of the distance ladder

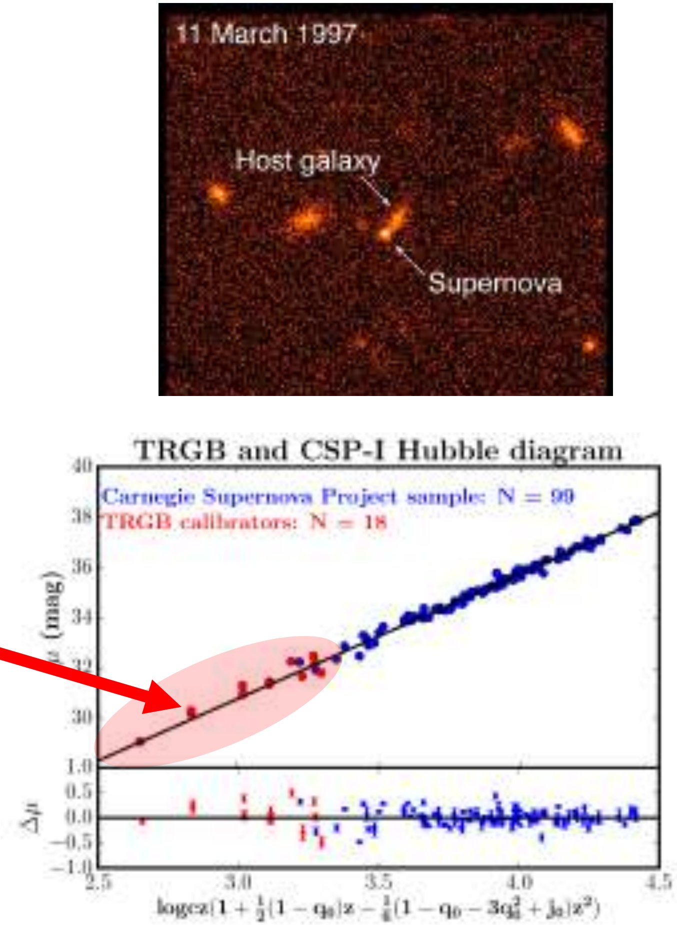
Absolute calibration of M_{TRGB}



Calibrating SNIa M_B using μ_{TRGB}



Tracing Hubble flow μ_{SNIa}



Credits: Freedman et al. (2019), Freedman (2021), Hoyt et al. (2019), ESO

Measuring H_0 to 1% requires tightly controlled systematics

Greatest gains on first rungs

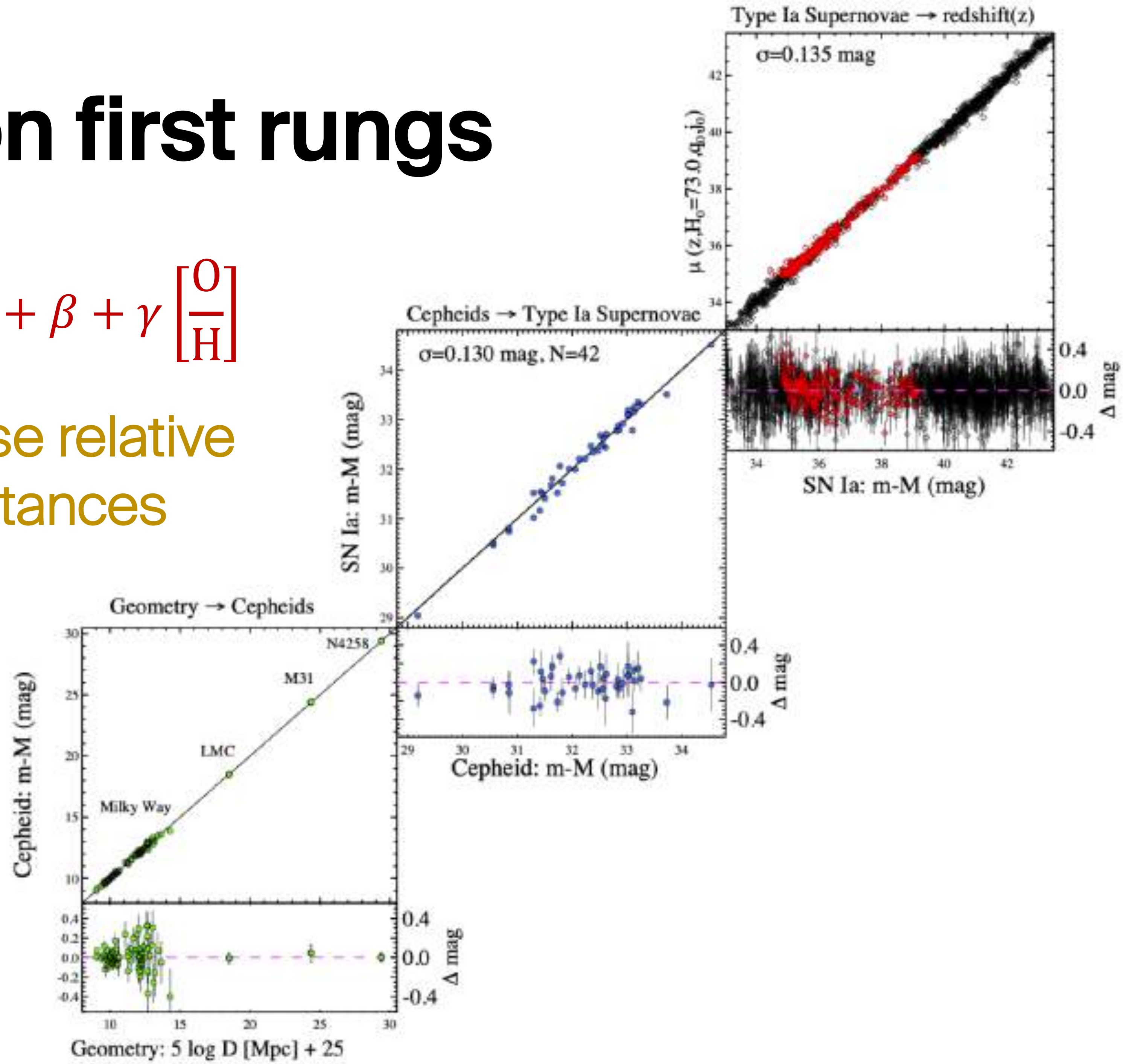
$$M = \alpha \log\left(\frac{P}{P_0}\right) + \beta + \gamma \left[\frac{\mathrm{O}}{\mathrm{H}}\right]$$

dominant uncertainties ⇨ Precise relative distances

⇘

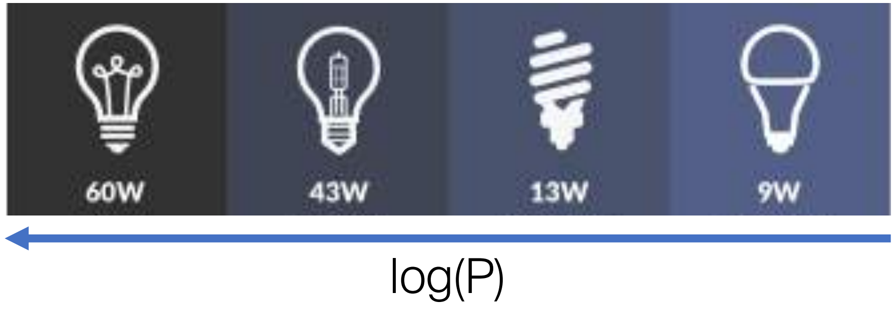
Accurate absolute calibration

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



Which candles and why?

Classical Cepheids are great for this!



$10^{29} - 10^{30}$W

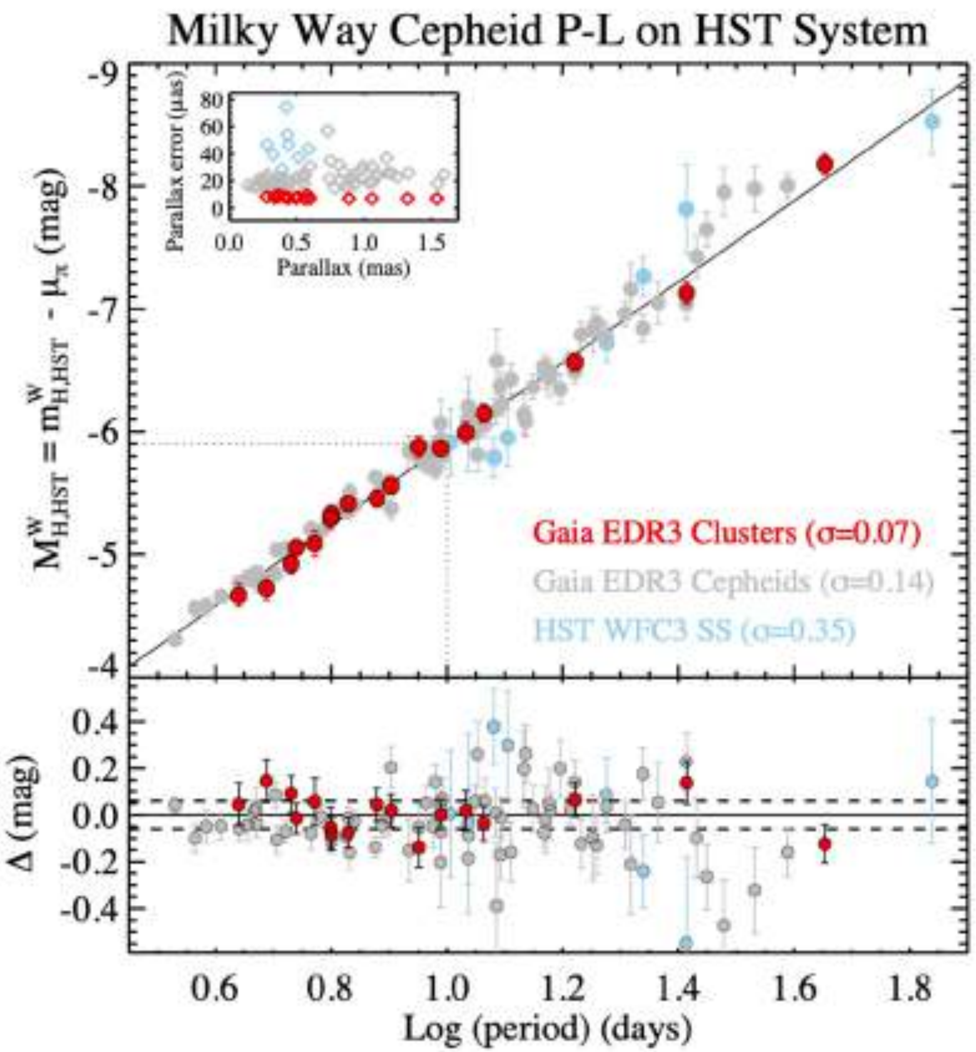
- Each Cepheid a standard candle
- Characteristic variability identifies individual Cepheids
- Tight scatter in PL relation constrains uncertainties
- Minimal contamination of PL-sequences by non-Cepheids
- Standard candle best understood by stellar evolution

cf. predictions & comprehensive tests in RIA+2016, *A&A* **591**, A8

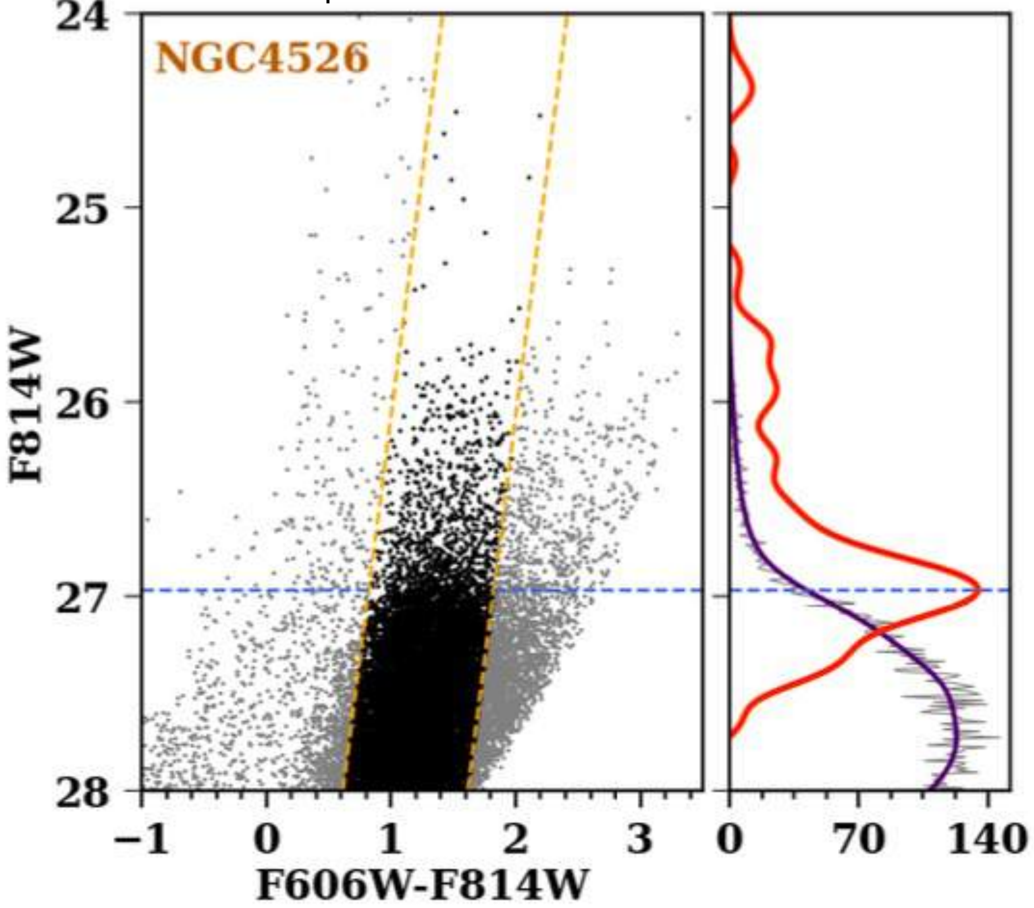
Other stellar standard candles

- **Individual,** directly calibratable Period-luminosity relations
  - Classical Cepheids : the undefeated champions for H_0
  - Mira variables : interesting alternatives in JWST era
  - RR Lyrae stars : great for near-field cosmology (< 1 Mpc)
  - Type-II Cepheids
  - Anomalous Cepheids
- **Statistical,** color magnitude diagram features
  - Tip of the red giant branch : best alternative to Cepheids at D < 20 Mpc
  - J-region AGB stars : the new kid on the block everyone wants to meet

Individual and *statistical* standard candles



Tip of the Red Giant Branch

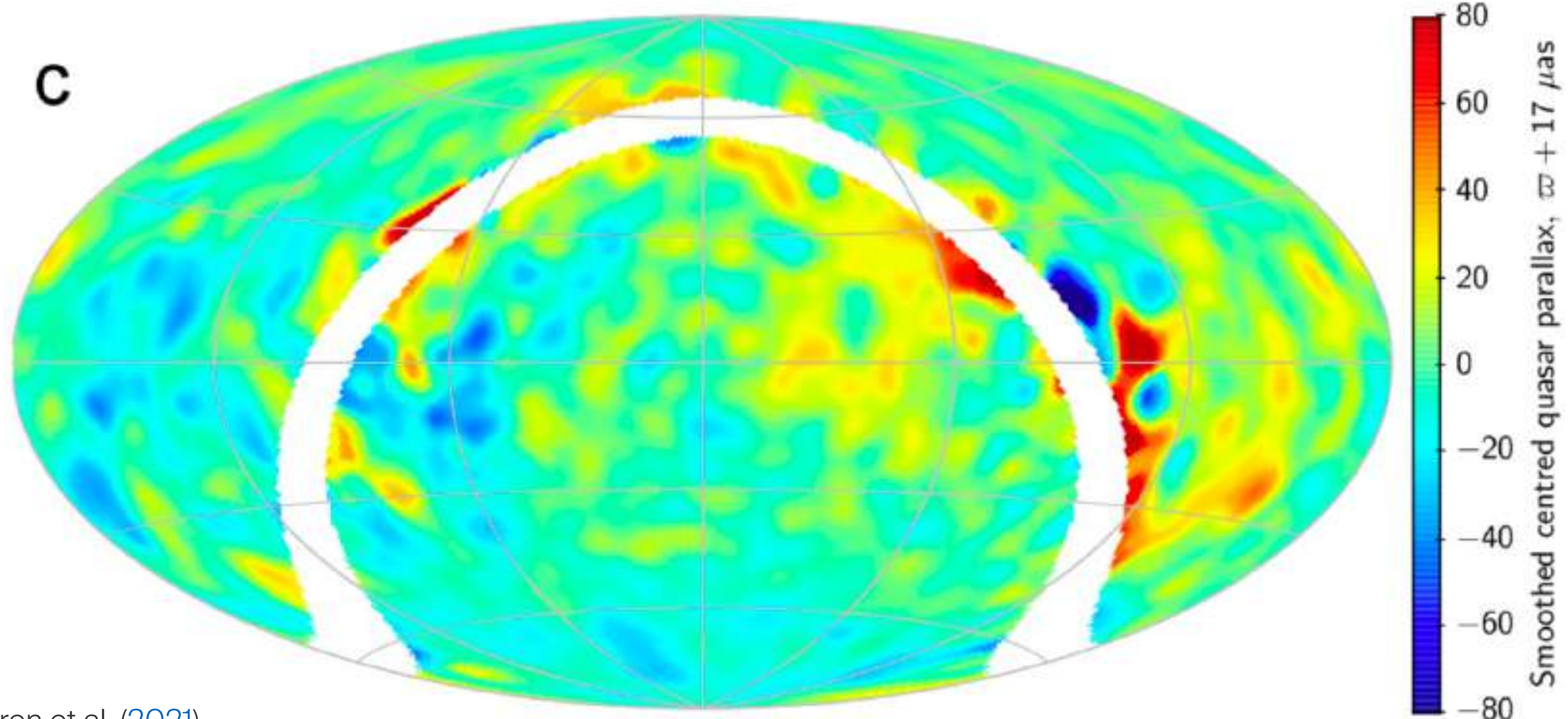


Absolute calibration of M for

$\mu = m - M = 5\log(d) + 25$

Individual standard candles: *Gaia* parallaxes

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

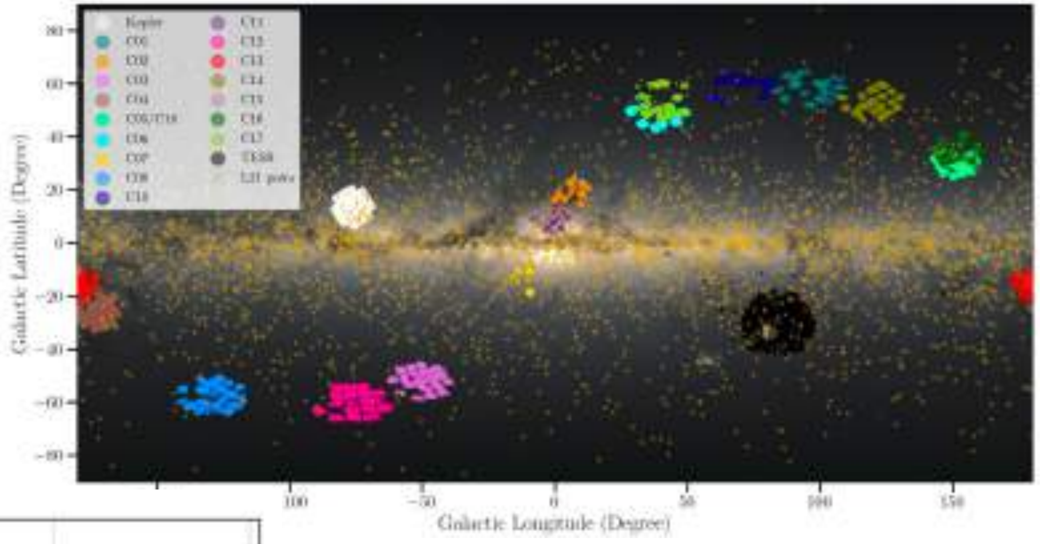


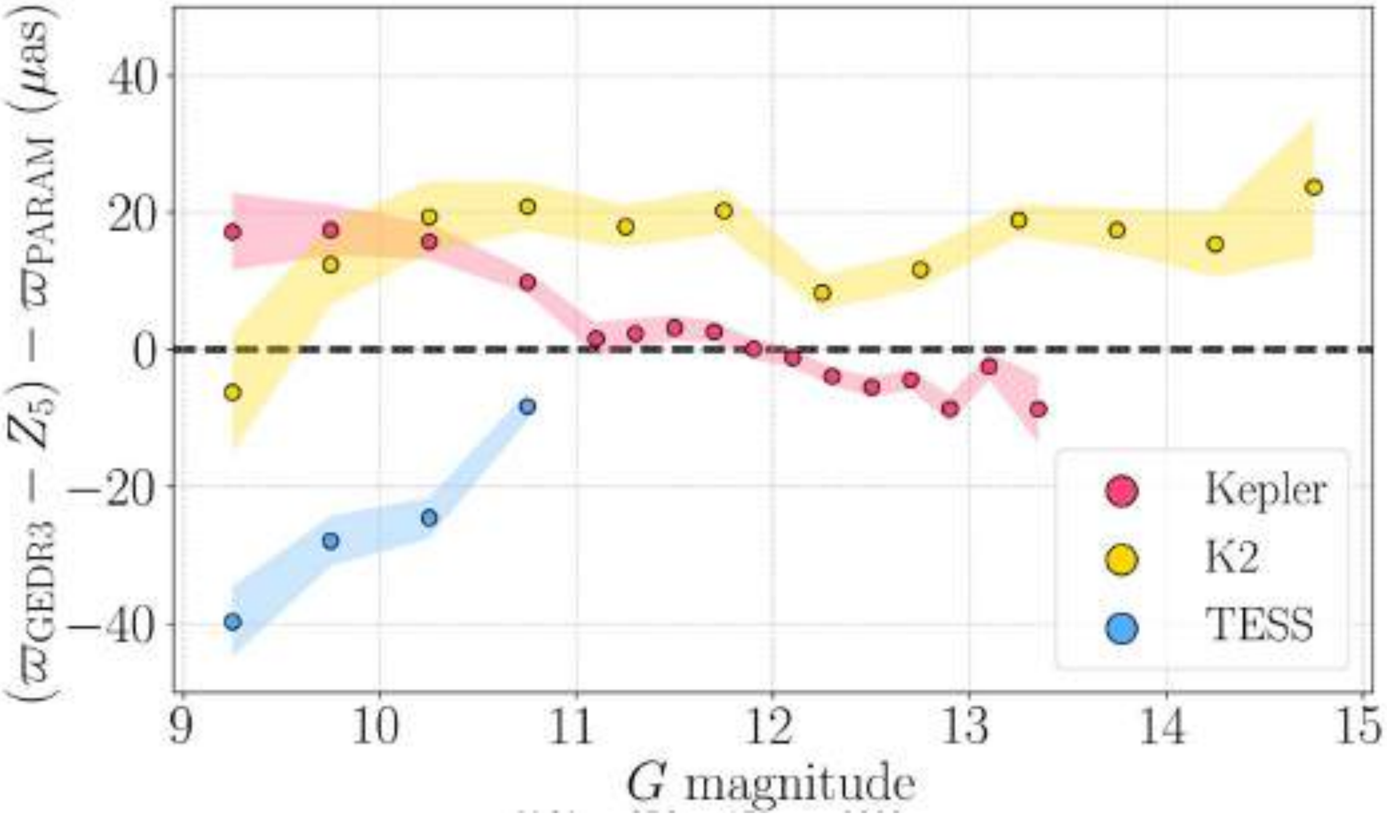
Lindegren et al. (2021)

Using stellar oscillations to ”sound out” Gaia systematics

Gaia parallax systematics by asteroseismology

Khan+ incl. Anderson 2023; Khan, Anderson + to be submitted



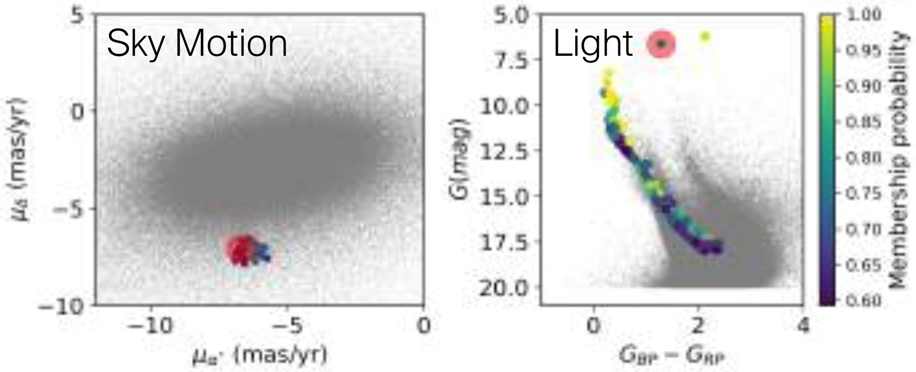


- Asteroseismology of red giants
- $M_{bol} \rightarrow \varpi$ via models, spectra & photometry
- 12’250 red clump giants
- Precise & homogeneous
- Systematics around 5-10μas

A 0.9% Cepheid luminosity calibration

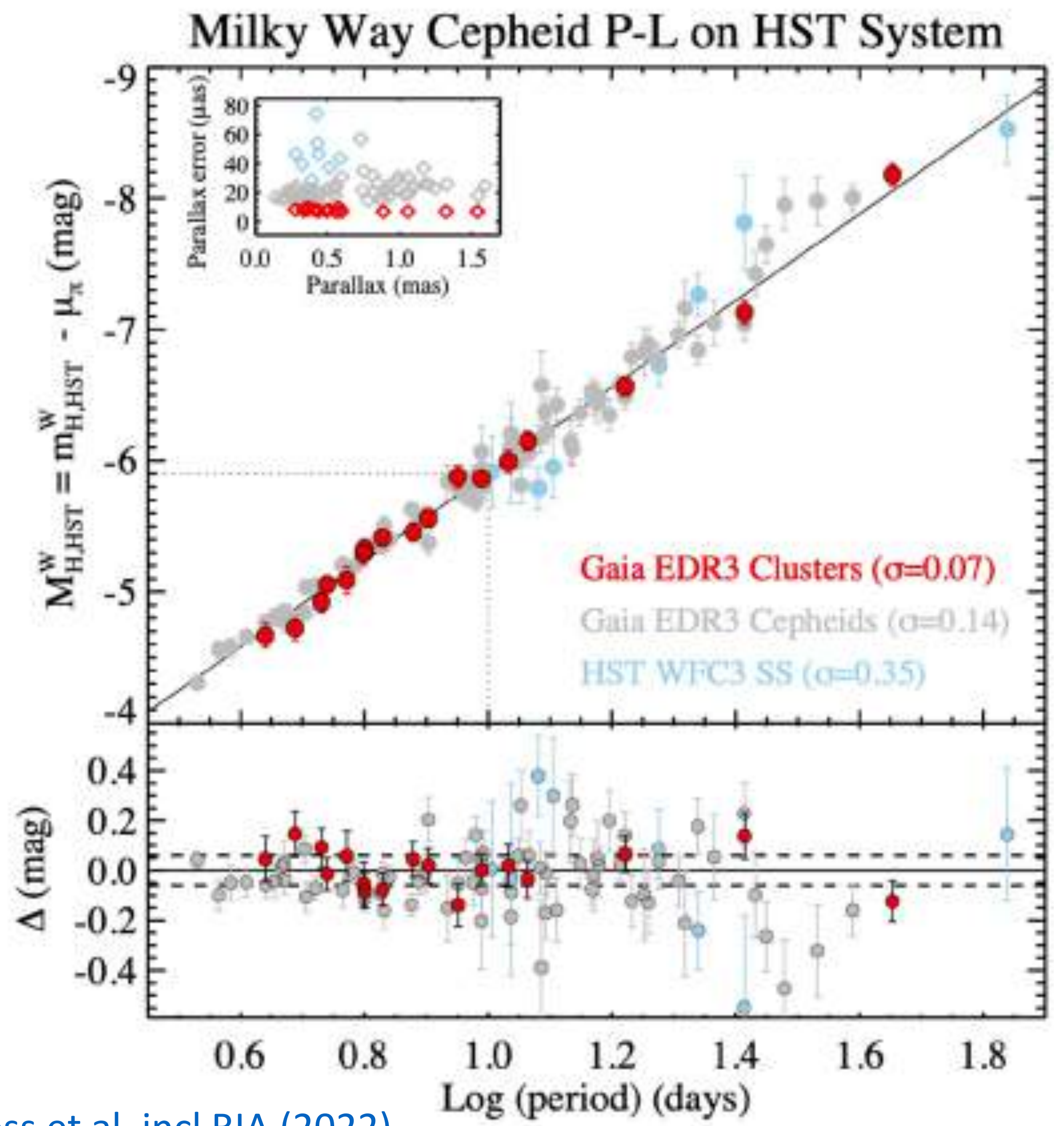
Cruz Reyes & Anderson (2023), A&A 672, A85

- Mined Gaia for clusters near Cepheids
- Cluster parallax: best precision ($\propto \sqrt{N}$) and systematics (cf. also Khan+ incl. Anderson 2023)
- 34 Cepheids in 28 clusters
- Typical error: 7μas = really tiny!
- Combined fit 26 clusters & 225 Cepheids
  - $M^W_{G,1} = -6.004 \pm 0.019$ mag
  - $\Delta\varpi_{Cep} = -19 \pm 3\ \mu$as
- Gaia DR4: ~0.4% calibration



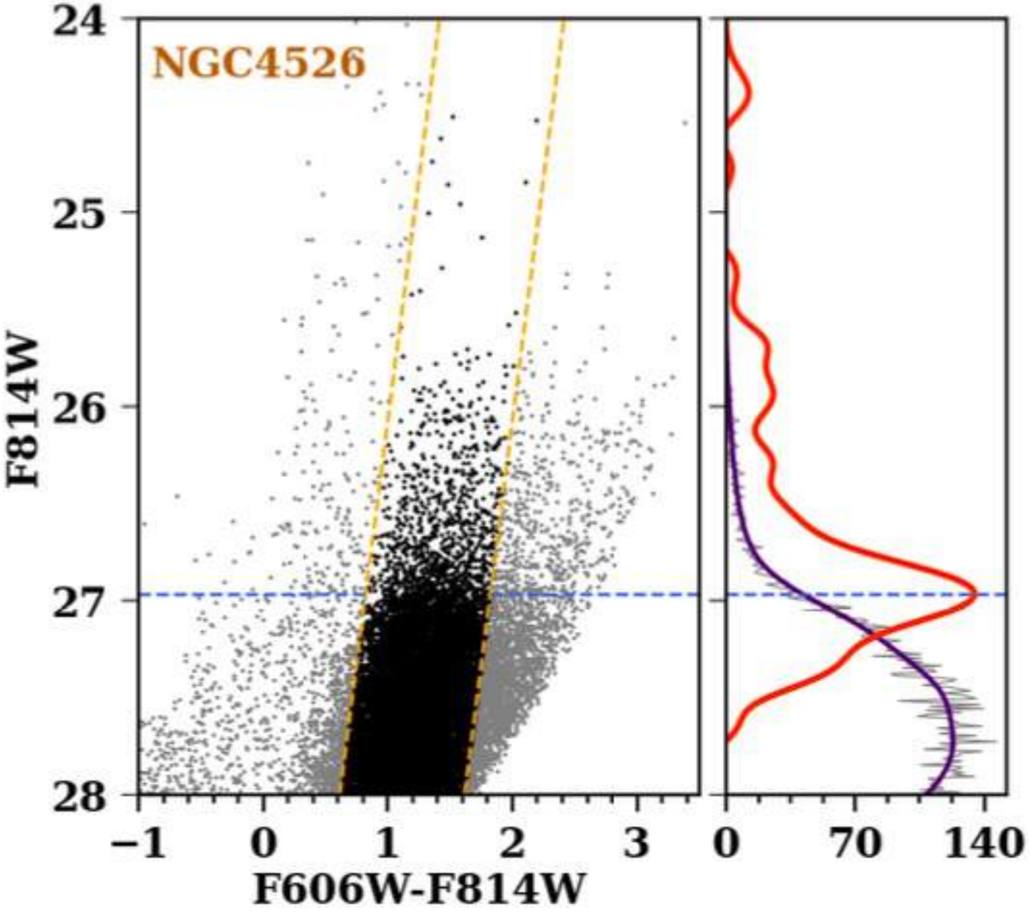
Cluster Cepheids grow Hubble tension

- 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 $M_{W,1}^{H}$ 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**



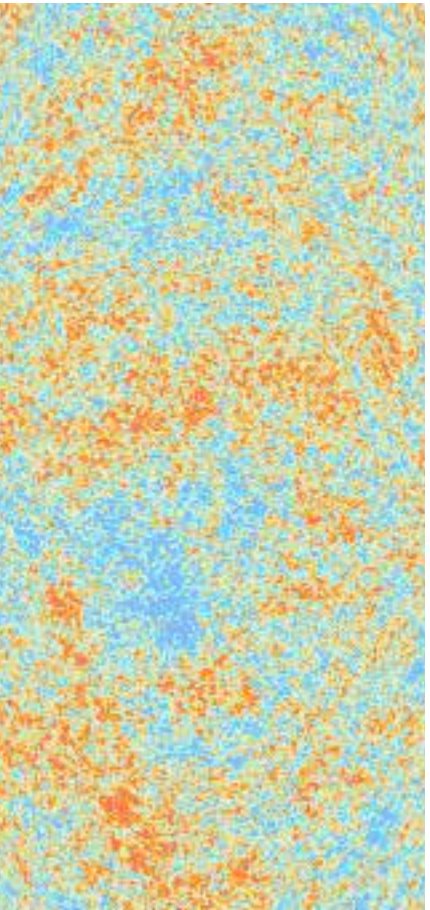
Riess et al. incl RIA (2022)

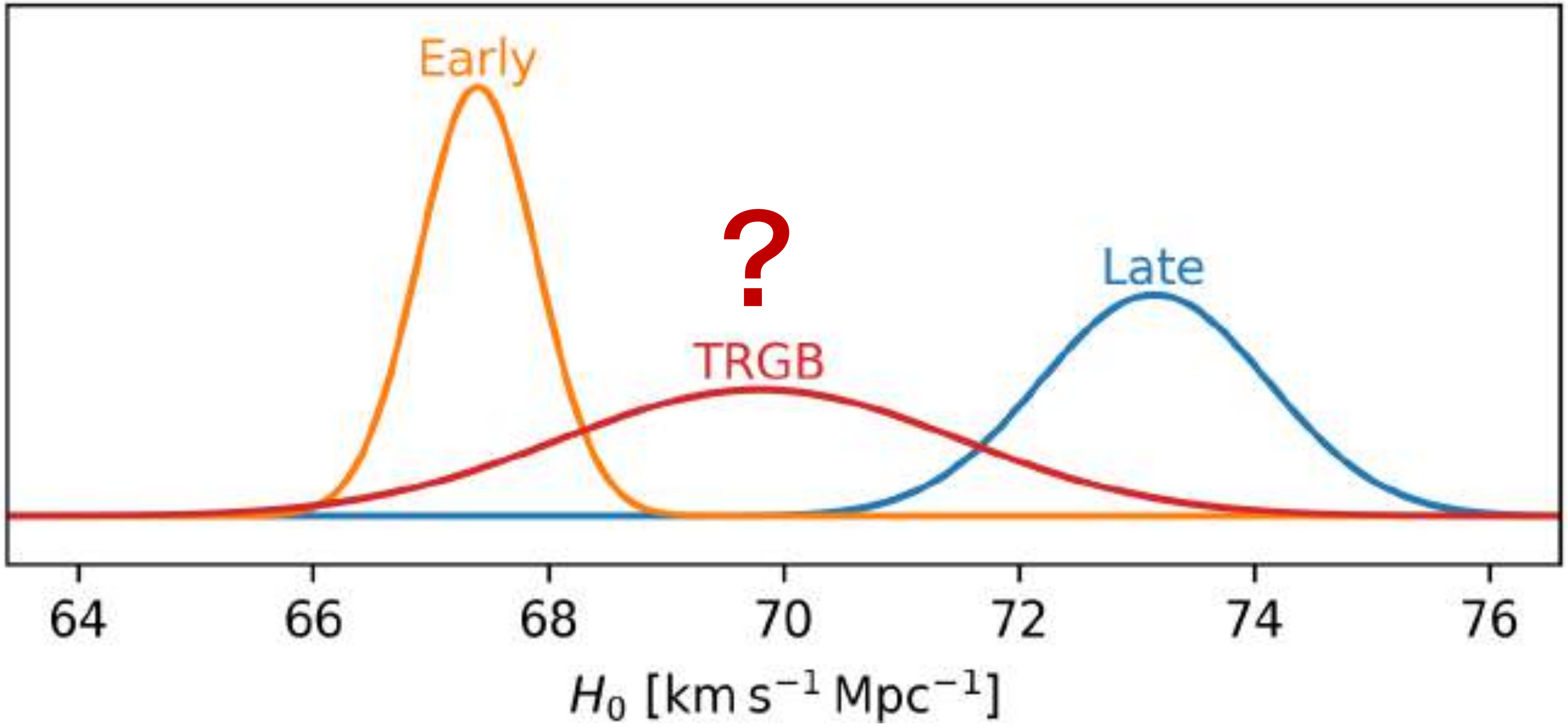
New insights on systematics of absolute TRGB calibration

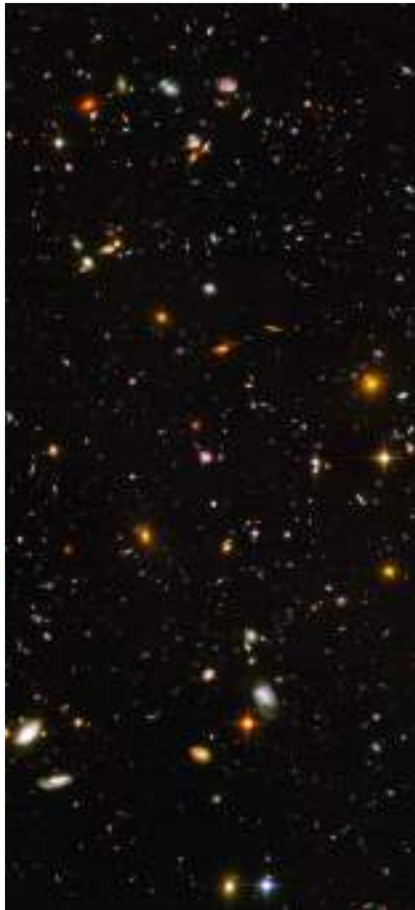


Can they reconcile Distance Ladders calibrated by TRGB and Cepheids?

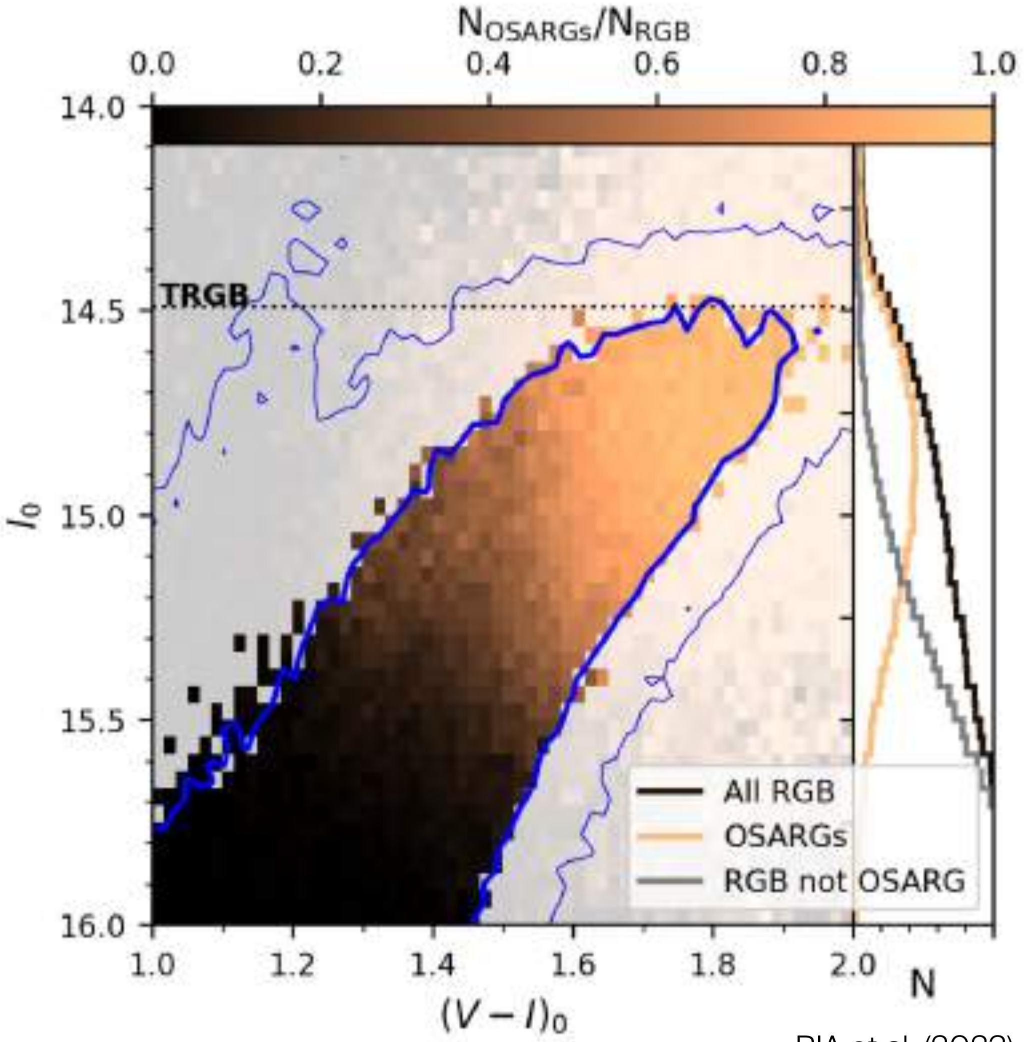
Reconciling standard candles





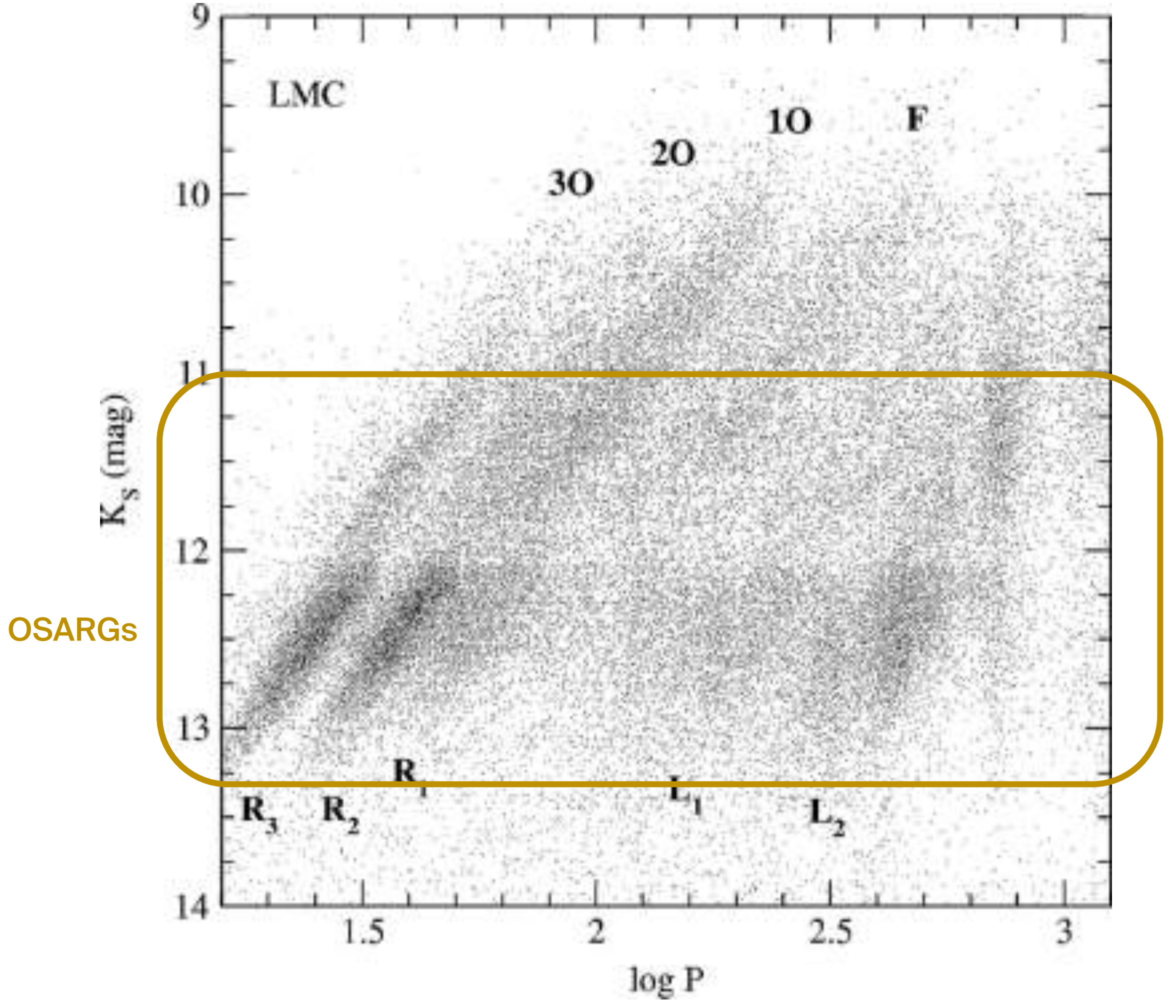


The TRGB is chock-full of variable stars



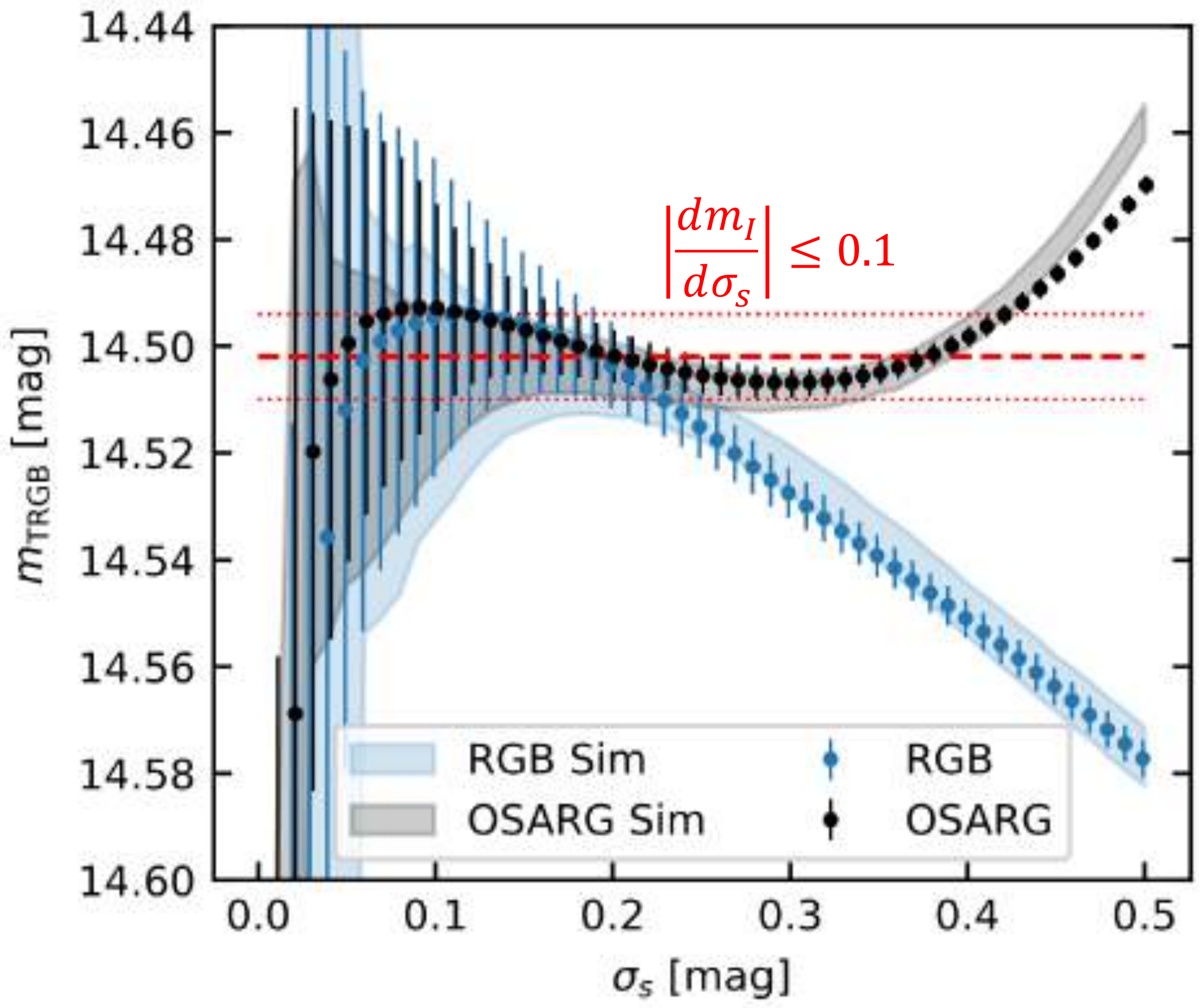
RIA et al. (2023)

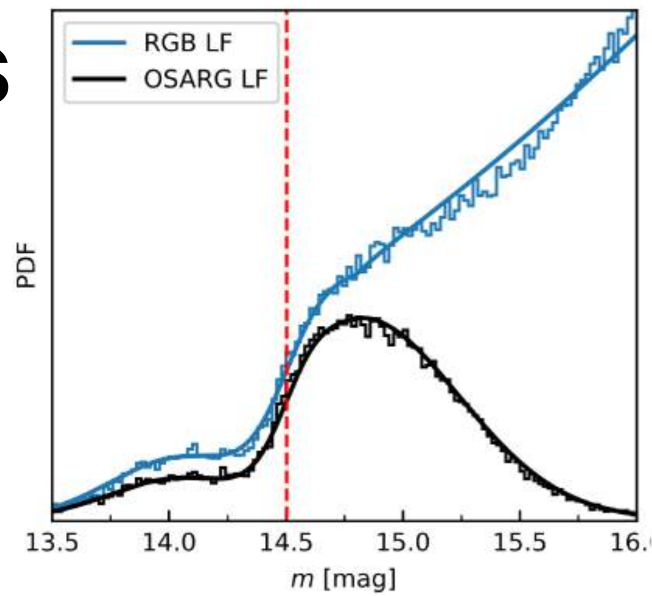
79'200 Small Amplitude Red Giants in OGLE-III

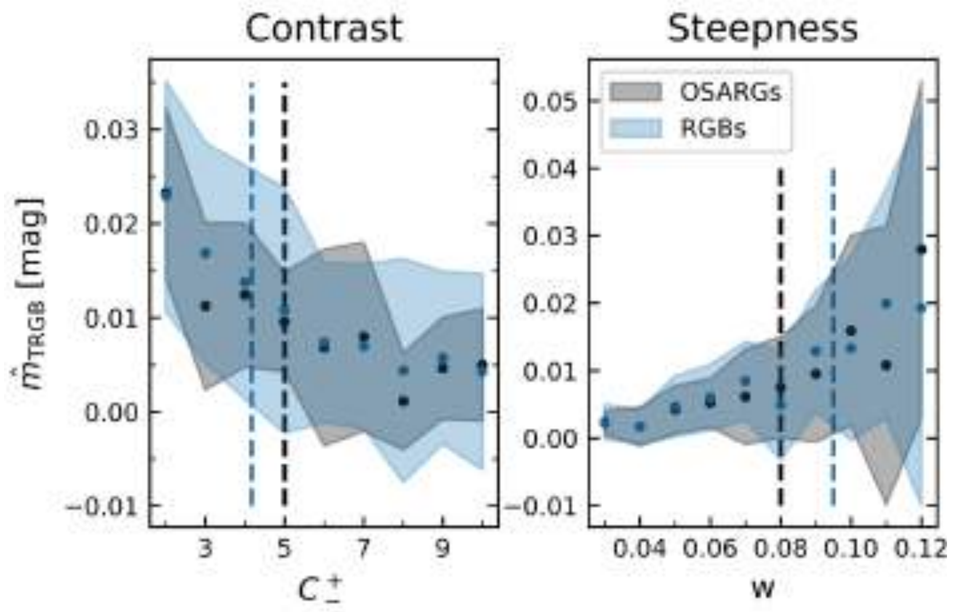


Ita et al. (2002); Kiss & Bedding (2003)

Insensitivity to smoothing bias



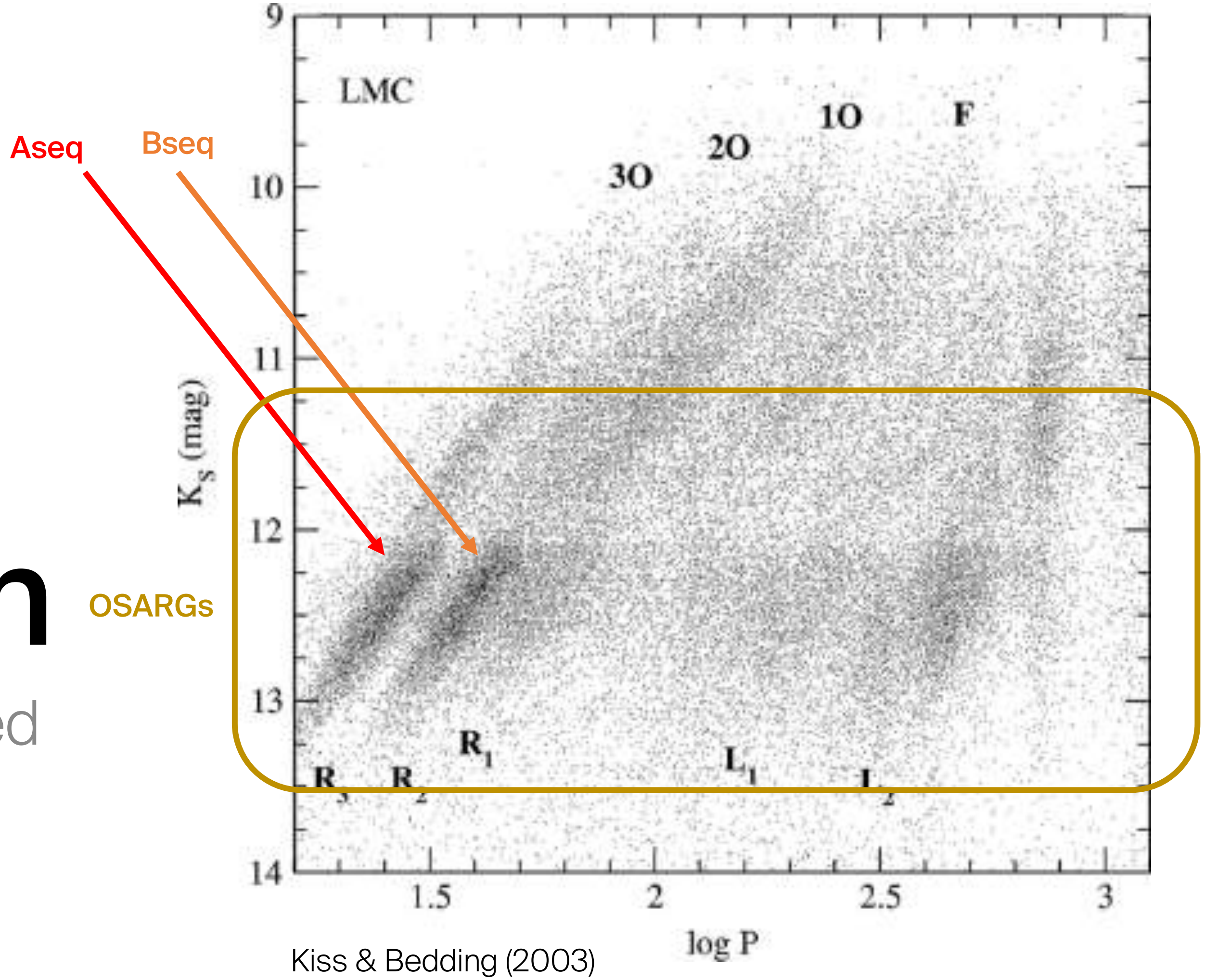




Twigs of the Red Giant Branch

Measuring variability-selected TRGB features

79’200 Small Amplitude Red Giants in OGLE-III



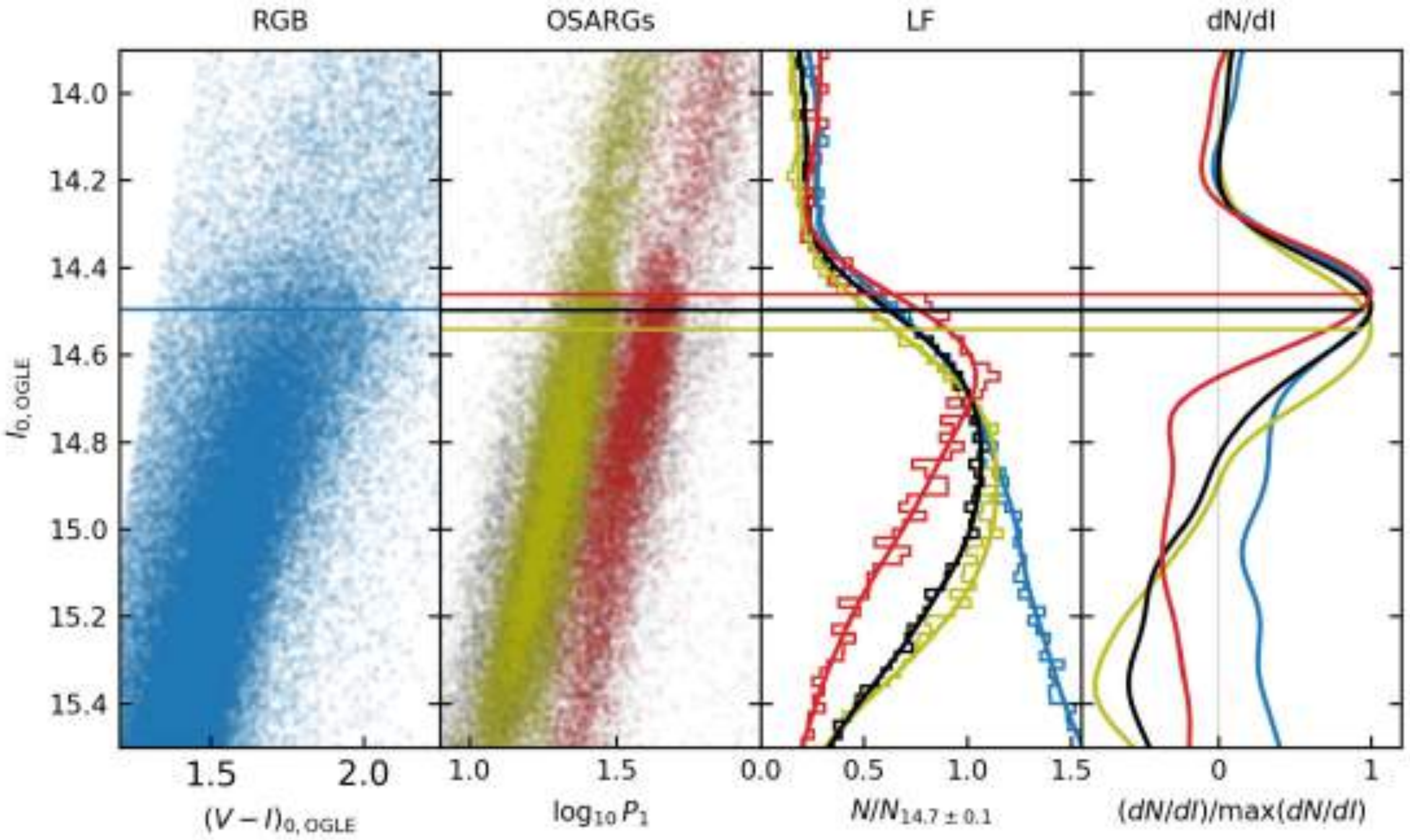
Kiss & Bedding (2003)

Twigs of the Red Giant Branch

RGBs are diverse stellar populations.

Variability-based selections yield multiple TRGB magnitudes!

sample	$I_{\mathrm{OGLE},0}$ (mag)	$I_{\mathrm{syn},0}$ (mag)
OSARGs	14.501 ± 0.010	14.497 ± 0.011
RGBs	14.495 ± 0.021	14.478 ± 0.029
RGBs †	14.527 ± 0.027	14.506 ± 0.035
Aseq	14.545 ± 0.013	14.543 ± 0.012
Bseq	14.459 ± 0.014	14.457 ± 0.015

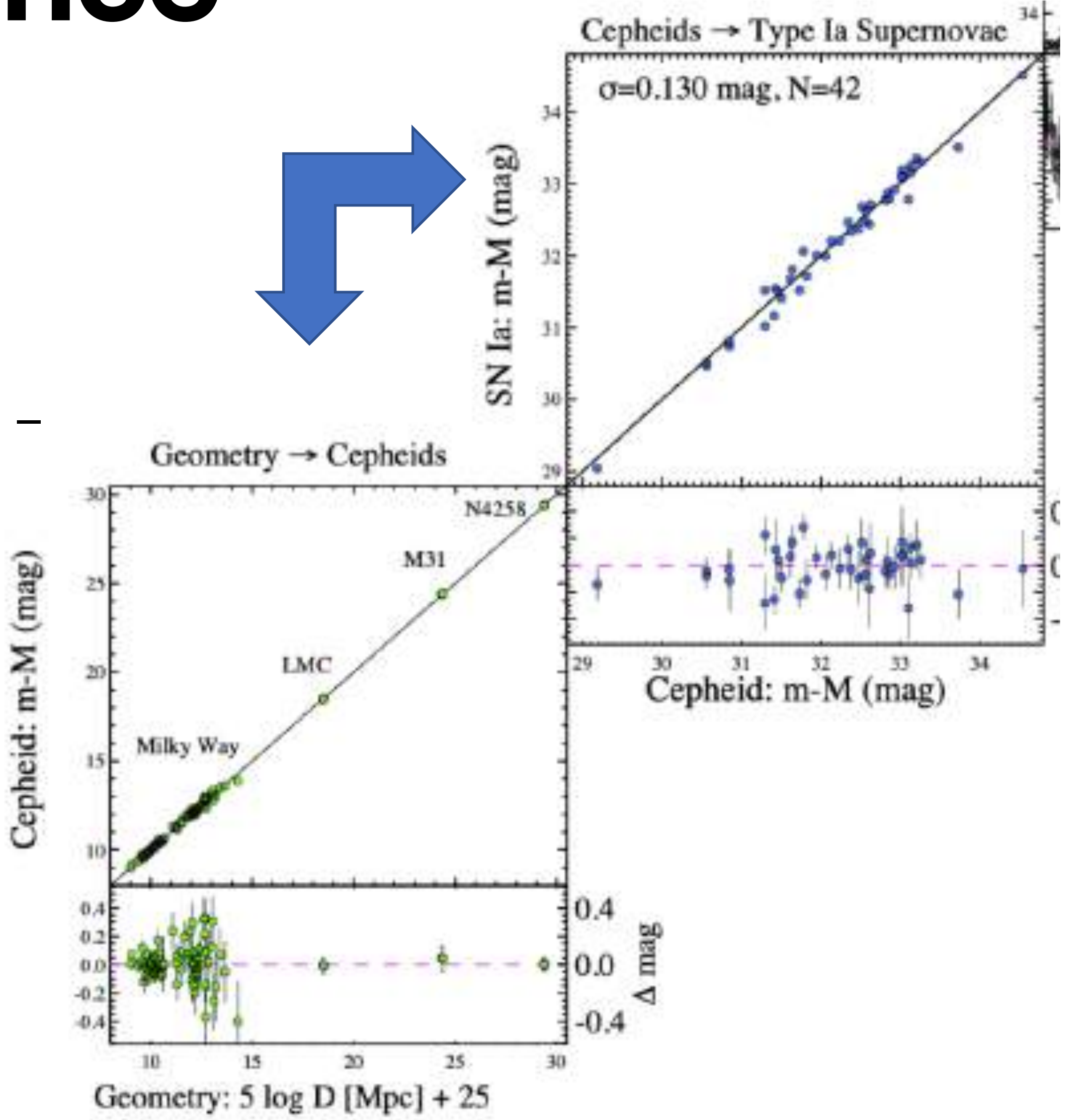


4.5σ difference between Aseq & Bseq!

Ensuring equivalence between rungs 1 and 2

Testing rung equivalence

- Dust mitigation by reddening-free Wesenheit formulation effective
  (Mörtsell+22, Riess+22, RIA 22)
- Quantified metallicity effect using high-res spectra – converges with model predictions (Romaniello+22, Breuval+22, RIA+16)
- Binaries ubiquitous = no problem
  (RIA & Riess 18, Karczmarek+22, Shetye+ in prep)
- **Stellar association bias (clusters)**
  (RIA & Riess 18, Spetsieri+ in prep)
- **Relativistic effects** (RIA 19,22)
- **TRGB standardization** (Wu+22, Scolnic+23)



Stellar association bias

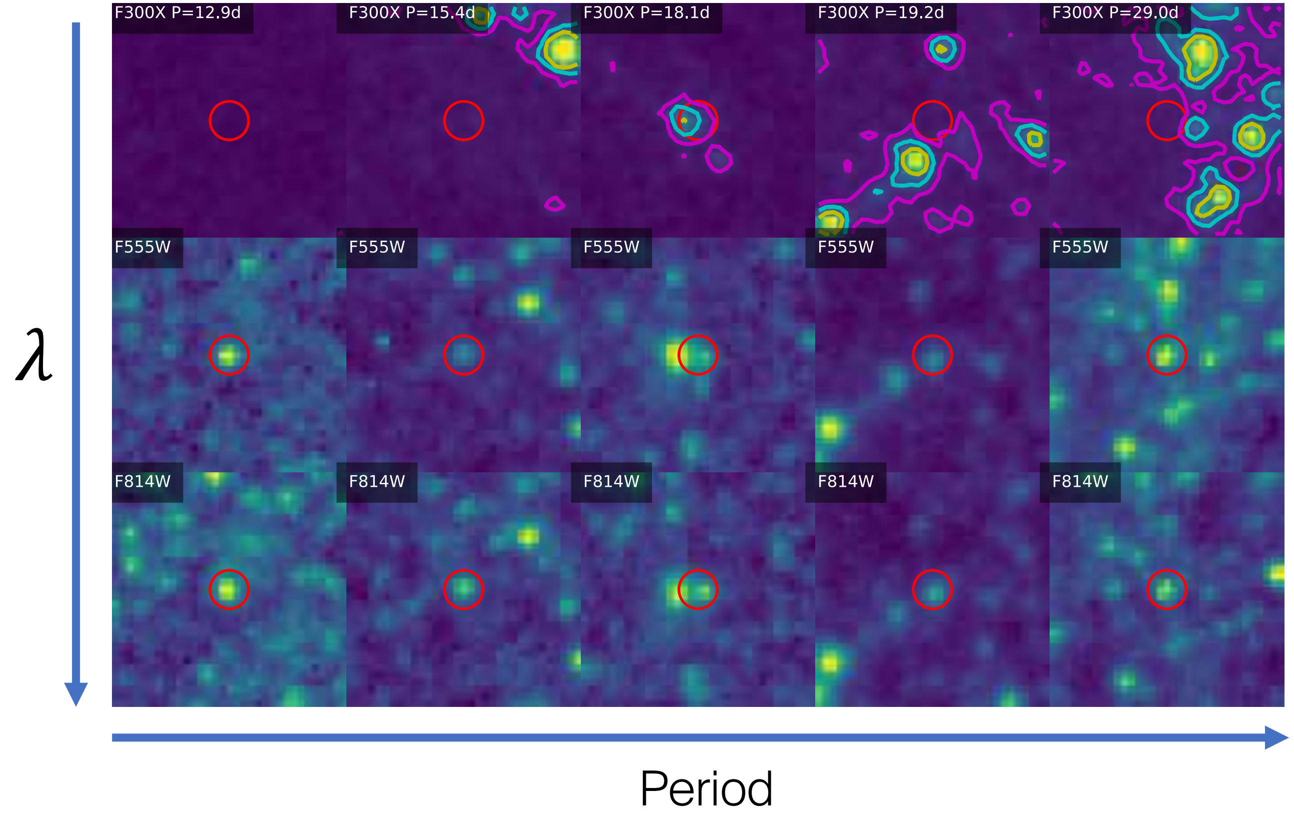
How does the physical association of stars with their birth clusters impact distance estimates?

HST UV observations identify Cepheid host clusters in M101 & NGC4258

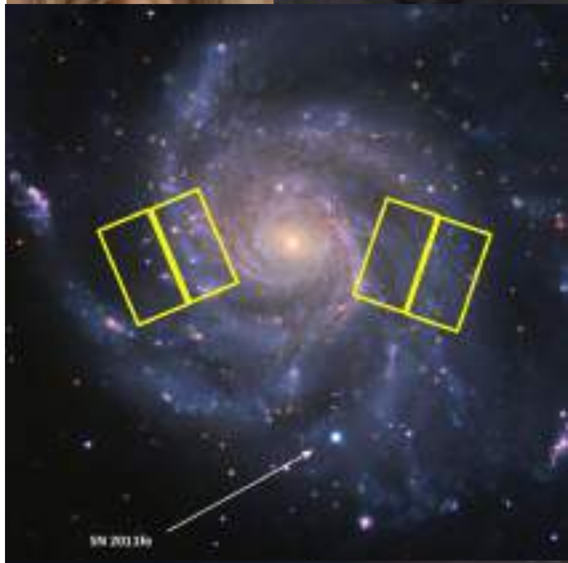
Spetsieri et al. in prep.; Anderson & Riess (2018)

$$\Delta\mu_\lambda \propto f_{cc,\mathrm{eff}} \cdot \langle \Delta\mu_{\lambda,cc} \rangle$$

M101 work in progress



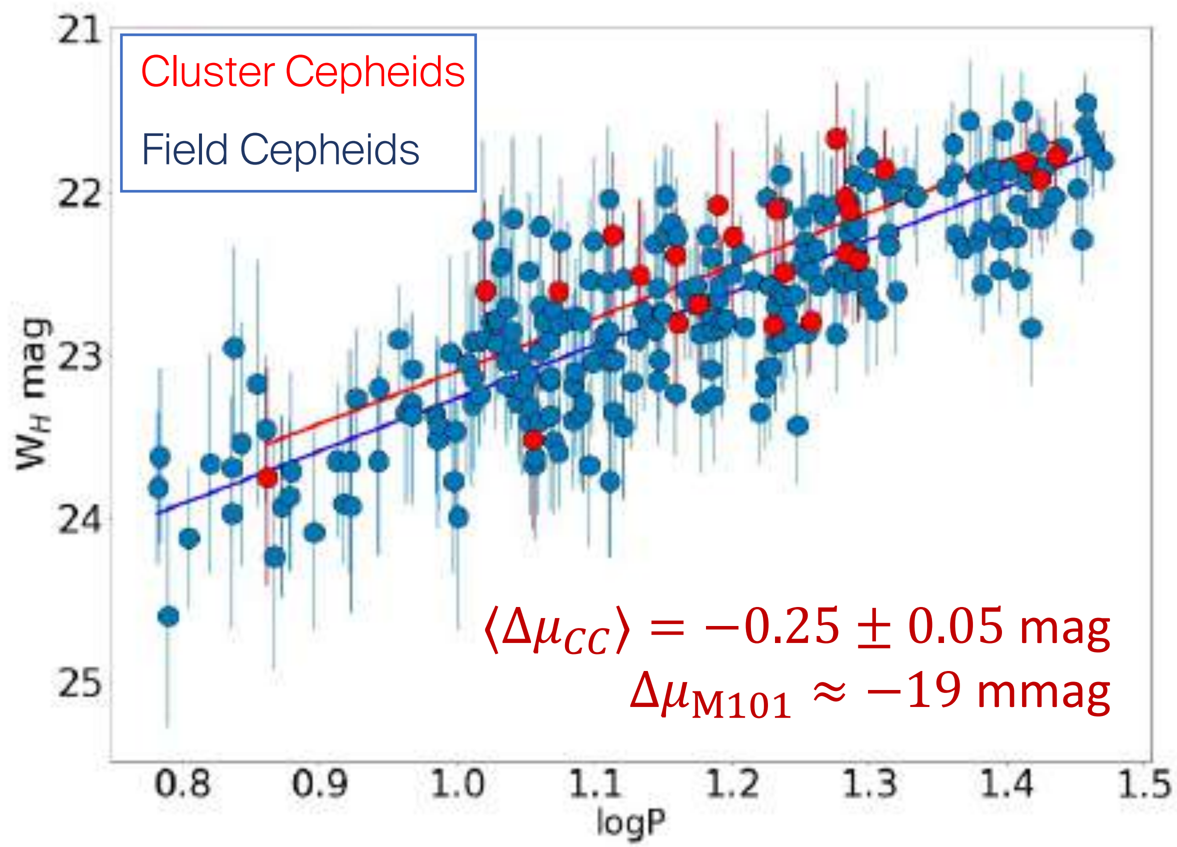
- $f_{\mathrm{CC,eff}} \approx 7.5\%$
- f_{CC} varies spatially
- M101 similar to MW sample
- M101 has more CCs than M31, M33
- NGC4258 is next!



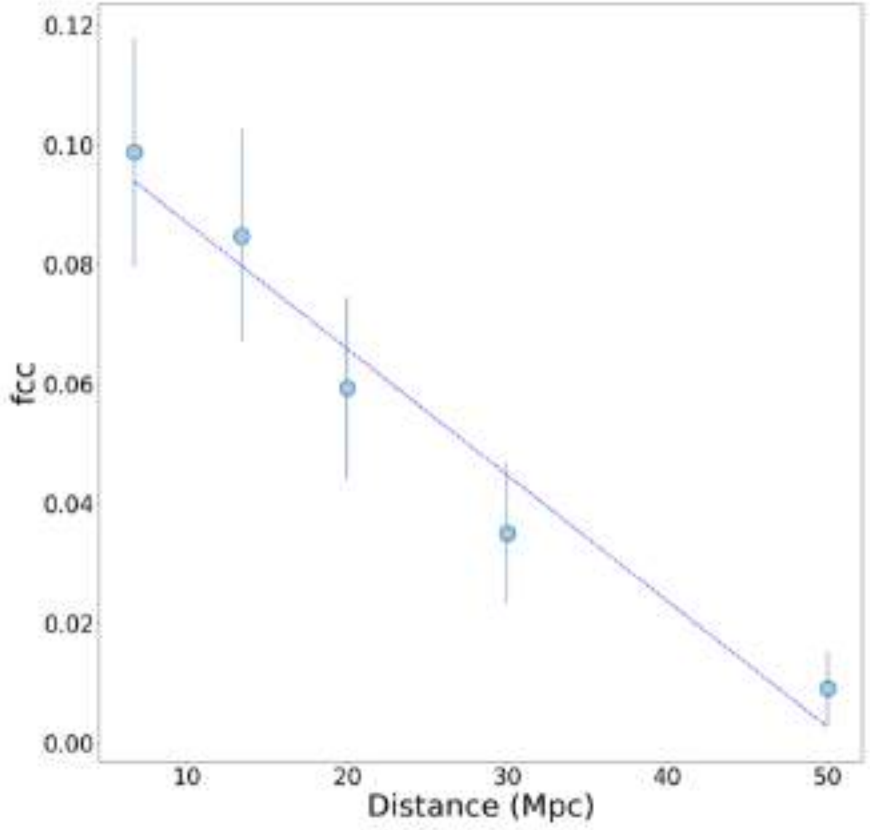
M101’s stellar association distance bias

Spetsieri, RIA et al. in prep.

$$\Delta\mu_\lambda \propto f_{CC,\mathrm{eff}} \cdot \langle \Delta\mu_{\lambda,CC} \rangle$$



$\mathrm{f}_{\mathrm{CC,eff}} \xrightarrow{\mathrm{d}} 0$ because Cepheids in clusters become unrecognizable at large distances



M101's stellar association distance bias

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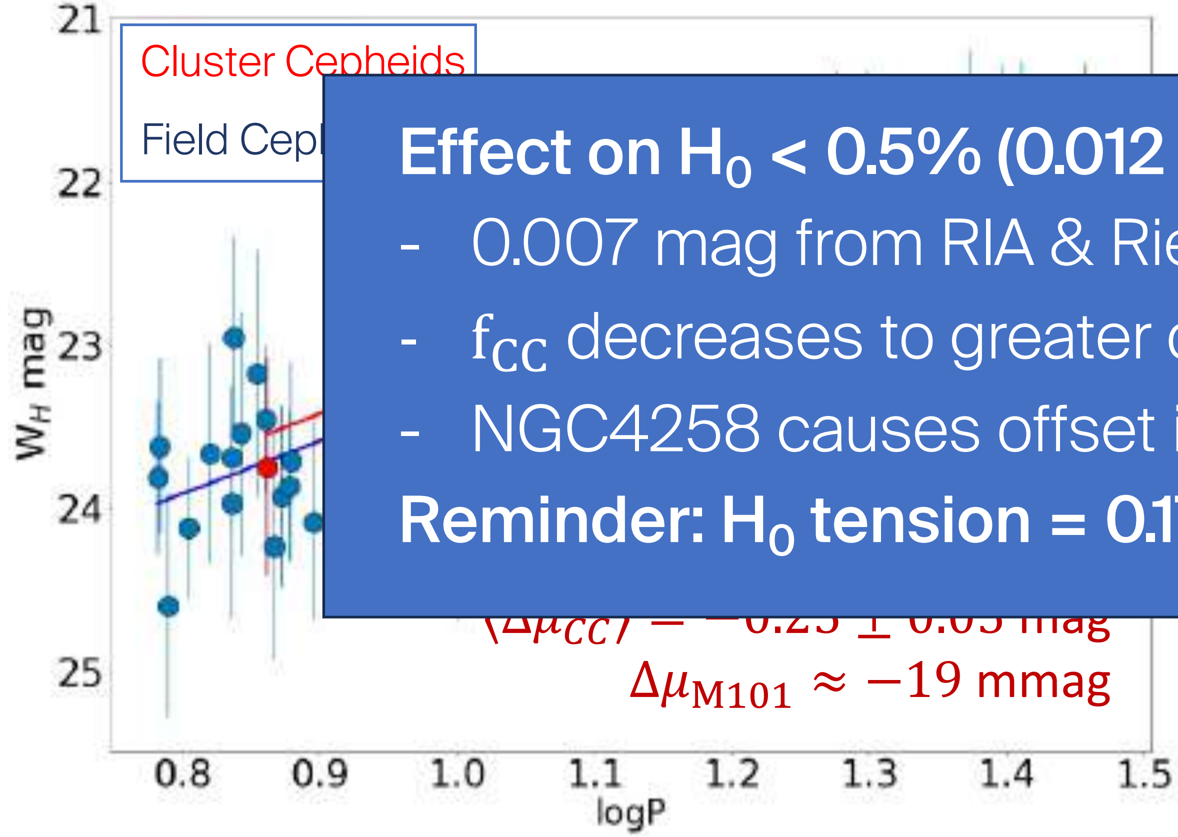
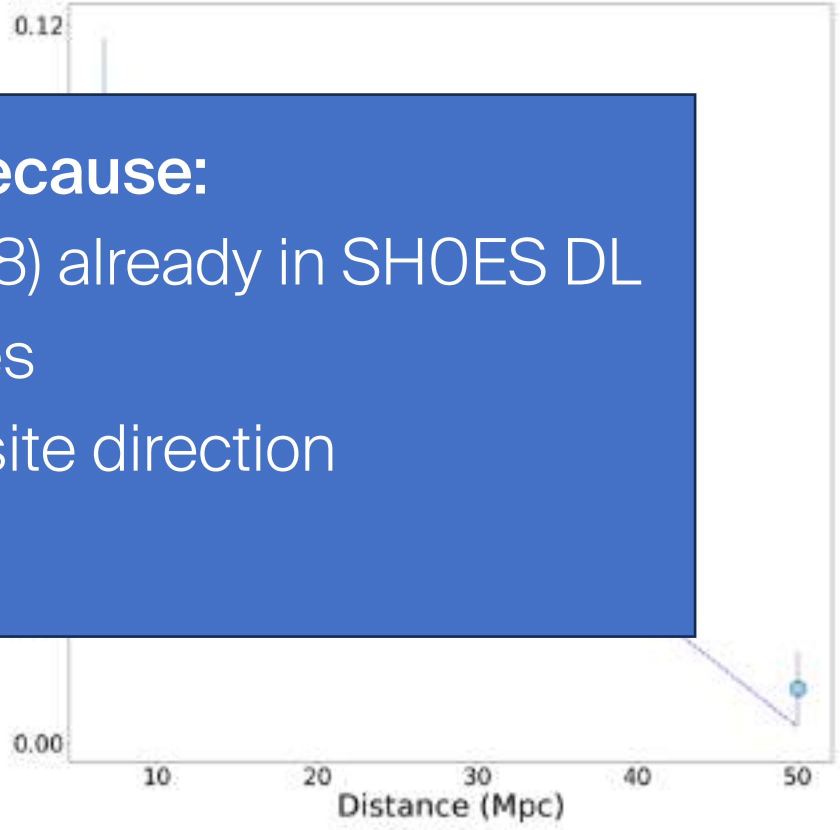




Effect on H_0 < 0.5% (0.012 mag) because:

- 0.007 mag from RIA & Riess (2018) already in SH0ES DL
- f_{CC} decreases to greater distances
- NGC4258 causes offset in opposite direction

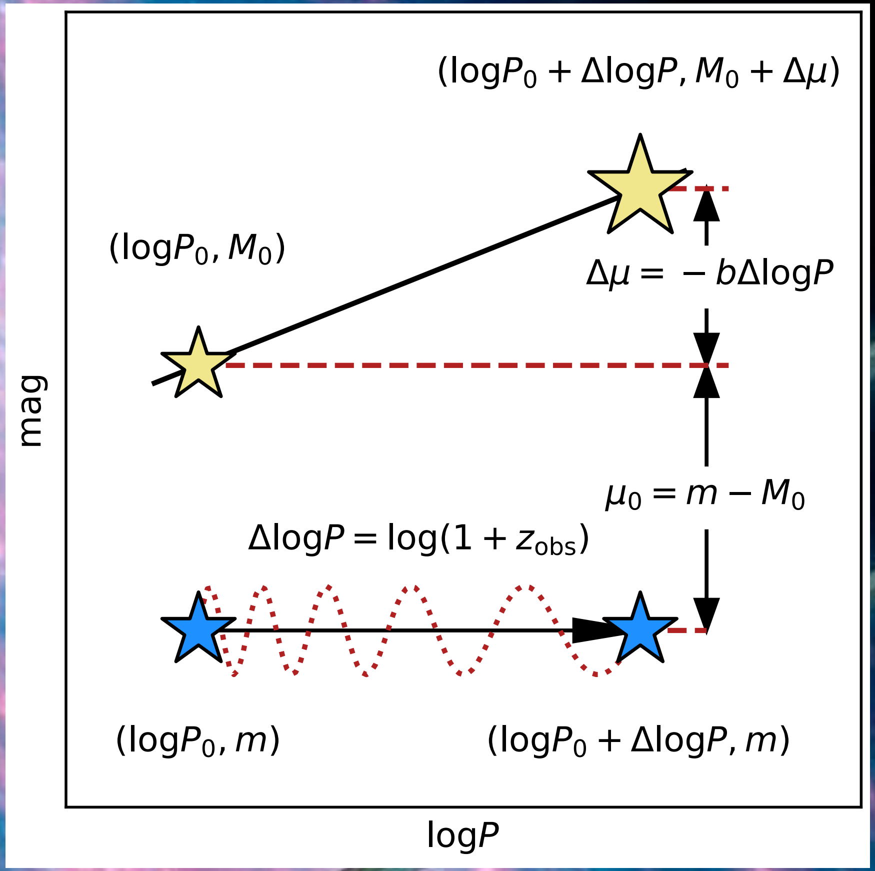
Reminder: H_0 tension = 0.17 mag

Relativistic corrections

Time dilation

RIA, A&A 631, A165 (2019)

Correction included in 2022 SHOES result



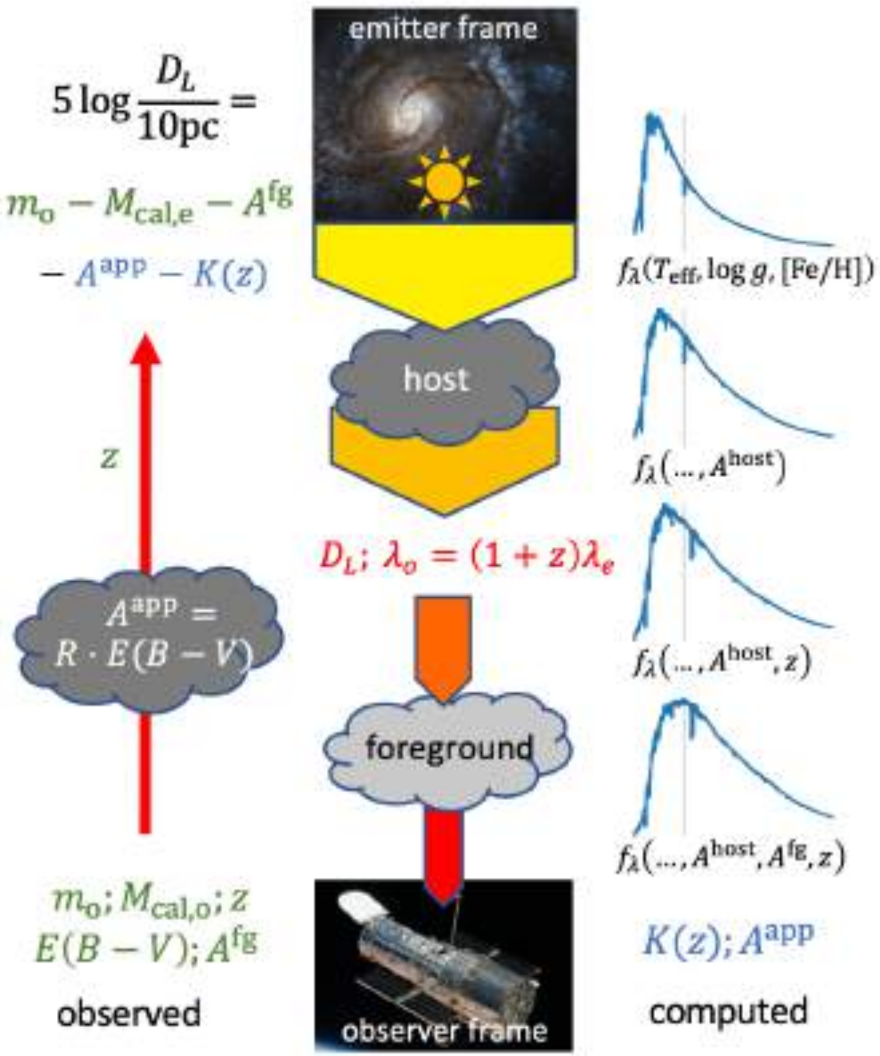
z_{obs}

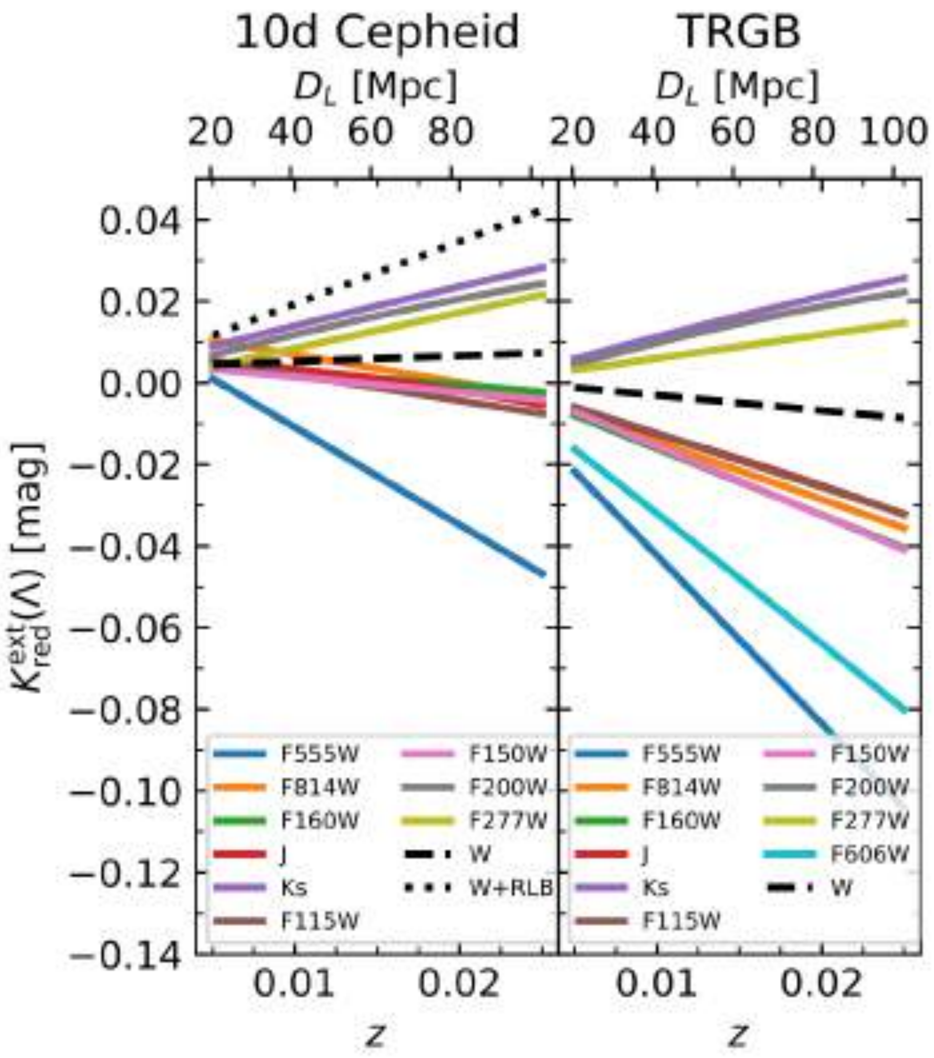
$z_{obs} \approx 0$

$$M = \alpha + \beta \log P$$

RIA (2022), A&A, 658, A148

K-corrections





JWST

Wesenheit

optical

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

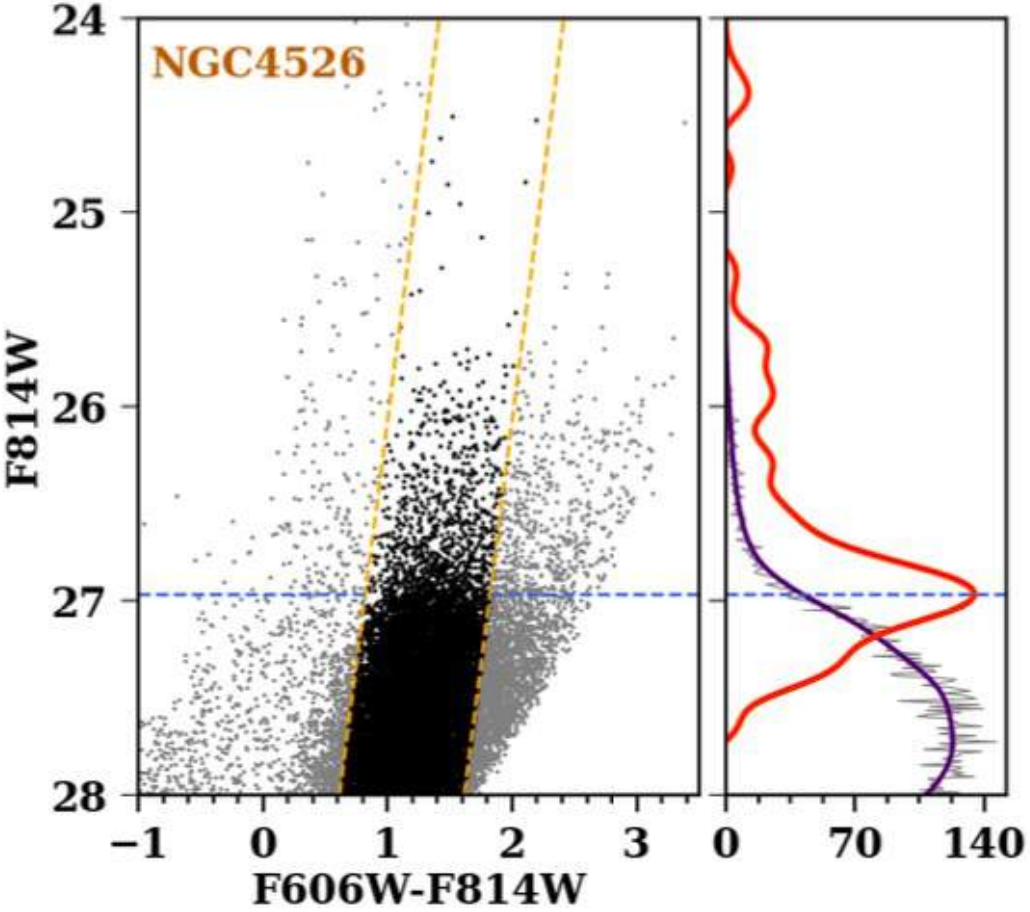
Relativistic corrections: impact on H_0

RIA (2019), A&A 631, A165, and RIA (2022), A&A, 658, A148

- Three corrections: all increase H0
- Dilated observed periods:
  largest impact & easy to correct

  SH0ES 2022
- K corrections small in SH0ES Wesenheit filters
- Reddening law slope effect is tiny
- More distant SN-hosts require larger corrections
- **TRGB using JWST@100Mpc: K-corrections are ~1%**

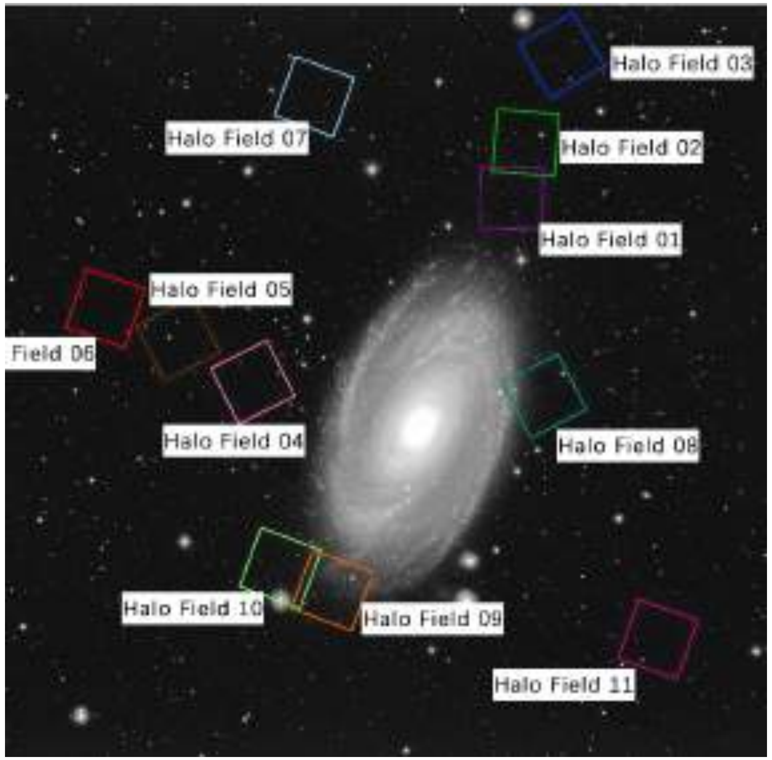
The TRGB as a standardizable Candle

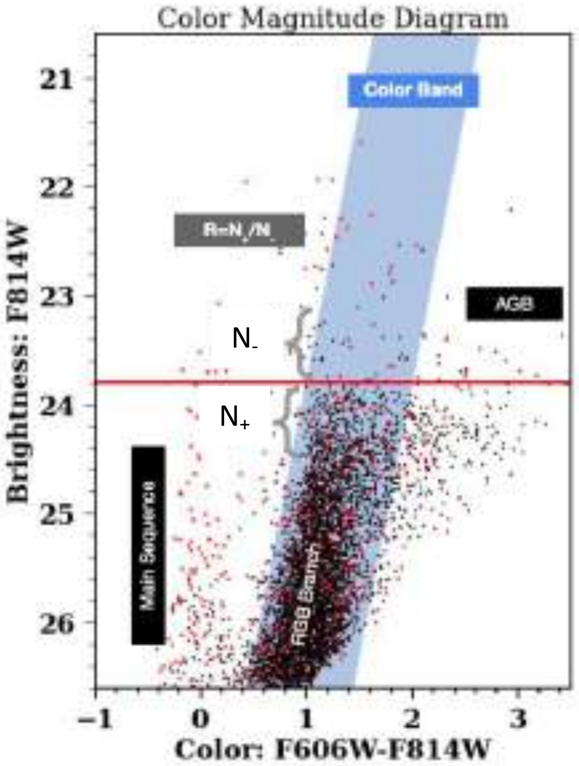


How to ensure TRGB features are the same in anchors & hosts?

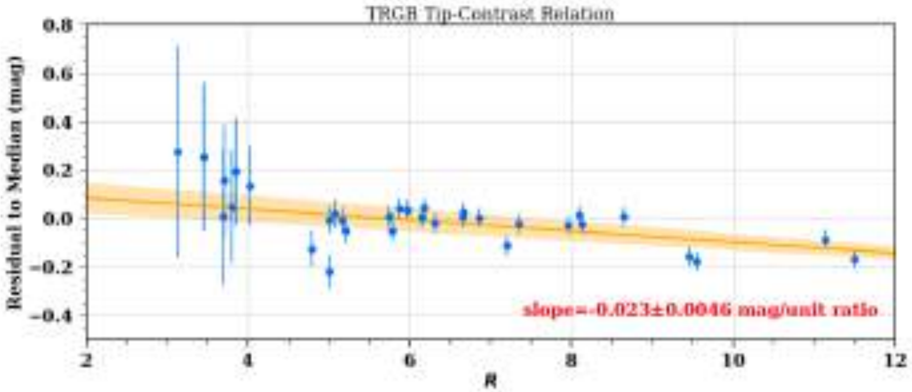
Standardizing m_{TRGB} using Tip Contrast Relation

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





$$R = N_+/N_-$$



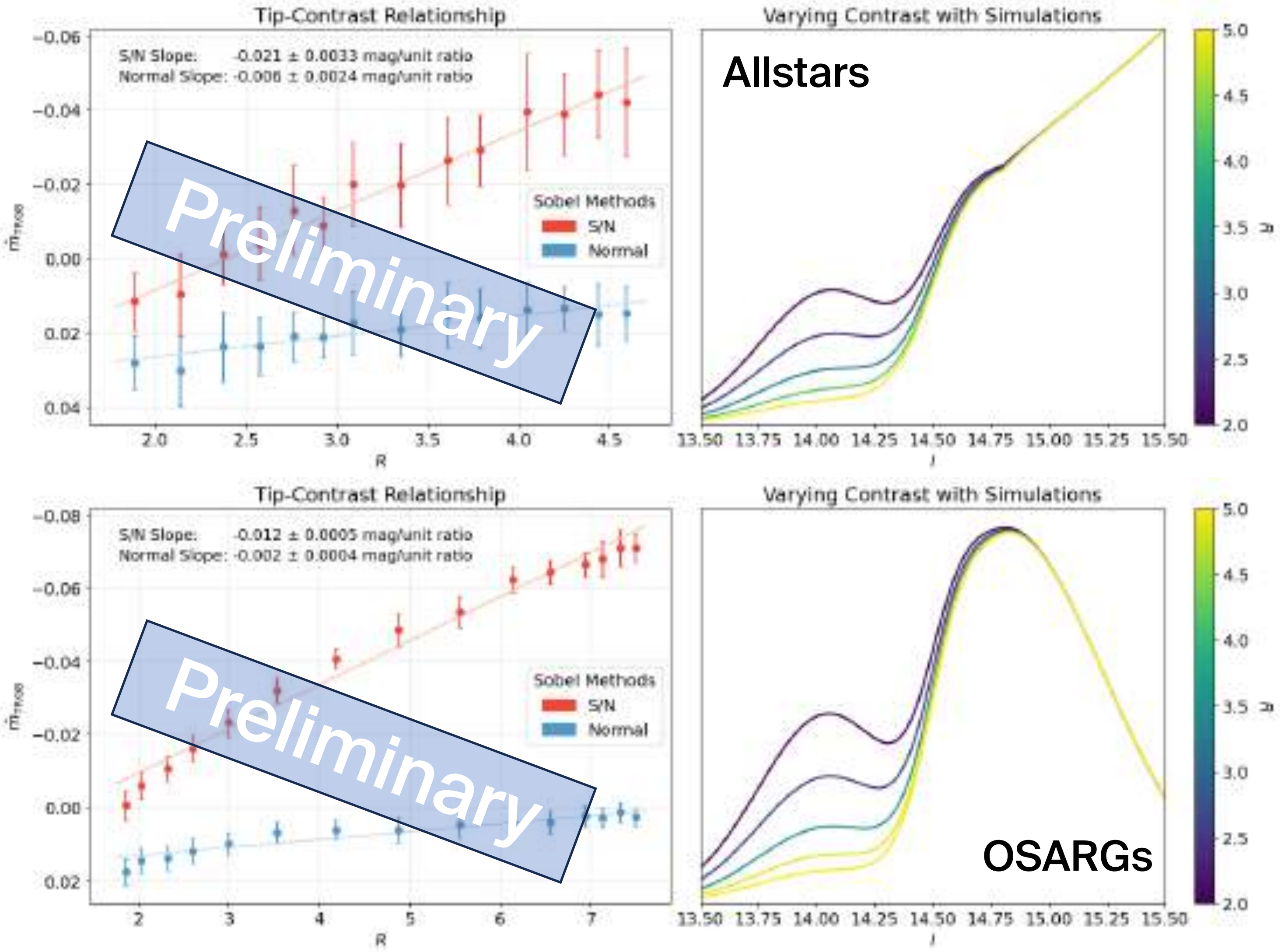
$$m_{I,\mathrm{TRGB}}^{R=4} = m_{I,\mathrm{TRGB}} - 0.021(R-4)$$

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

TCR depends on LF and Sobel filter

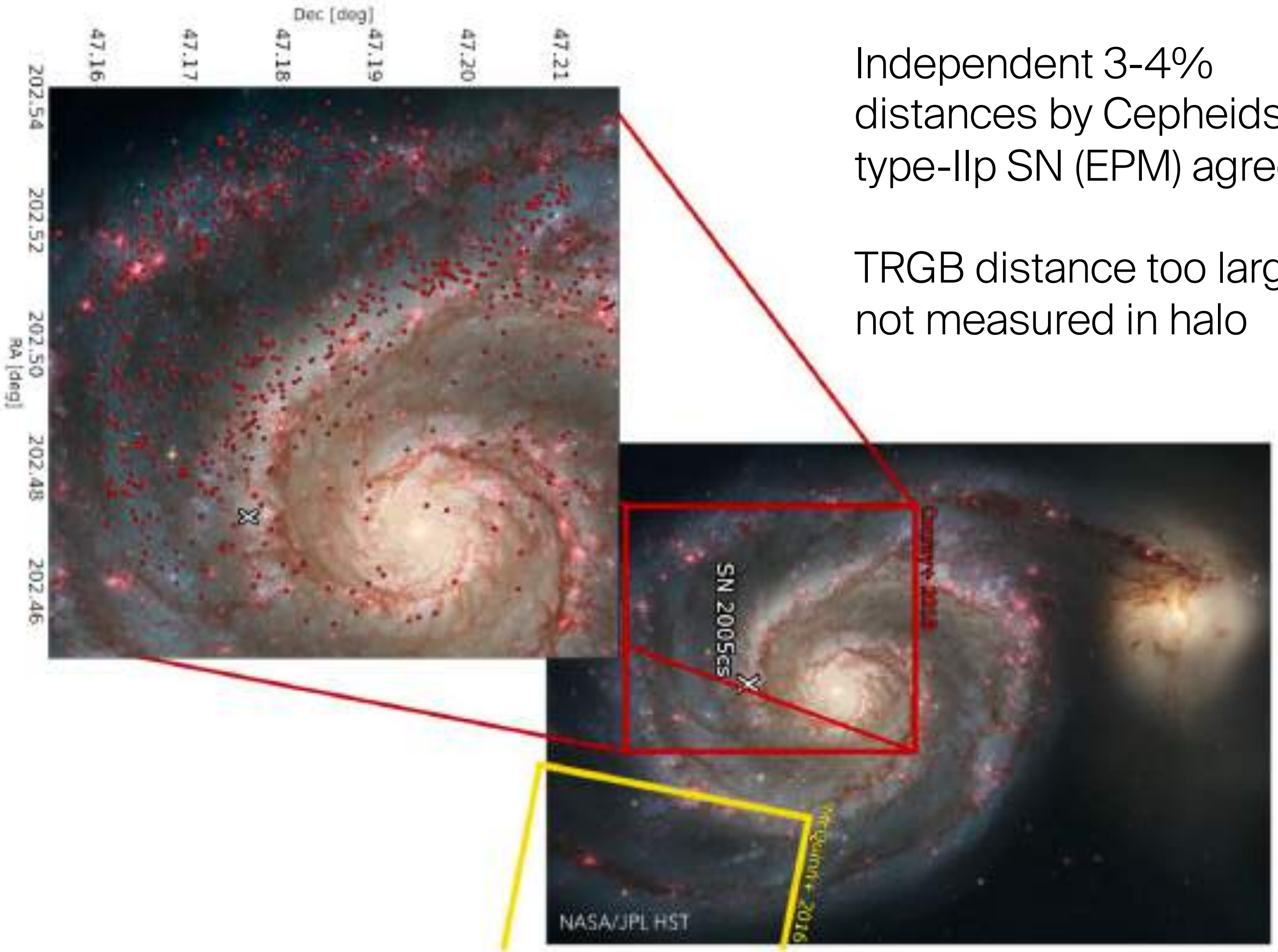
RIA et al. 2303.04790

- "S/N"-weighted EDR in CCHP (Hatt+2017) increases sensitivity to Tip contrast
- Simulations from RIA+23: $\Delta m = -0.021 \pm 0.003$ mag/R
- Observed tip-contrast ratio (Scolnic+23): $\Delta \mathrm{m} = -0.021 \pm 0.004$ mag/R
- Unweighted EDR is insensitive to tip contrast
- OSARG LF less sensitive for either Sobel filter



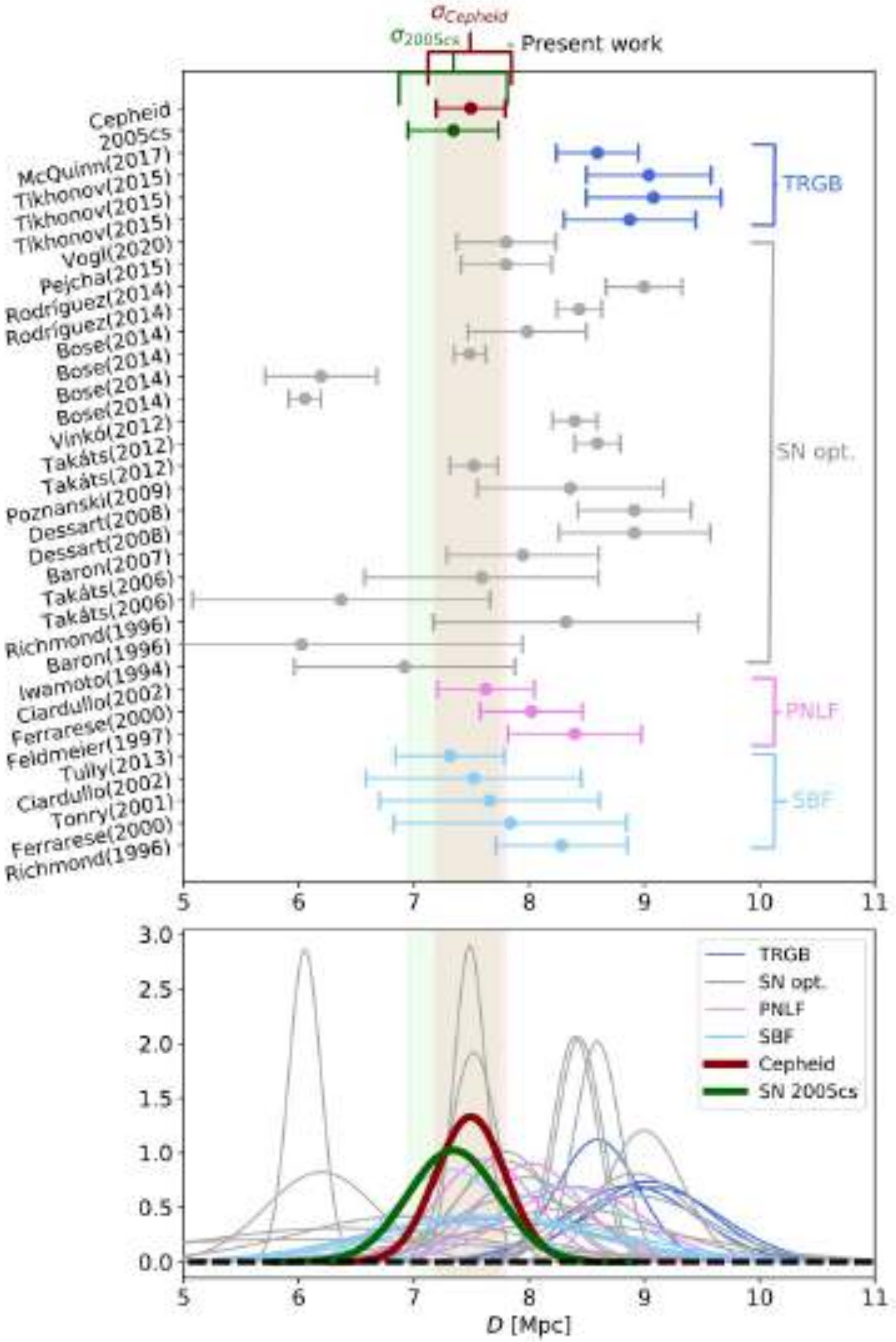
TRGB location matters

Csörnyei, RIA et al. 2305.13943



Independent 3-4% distances by Cepheids & type-IIp SN (EPM) agree

TRGB distance too large & not measured in halo

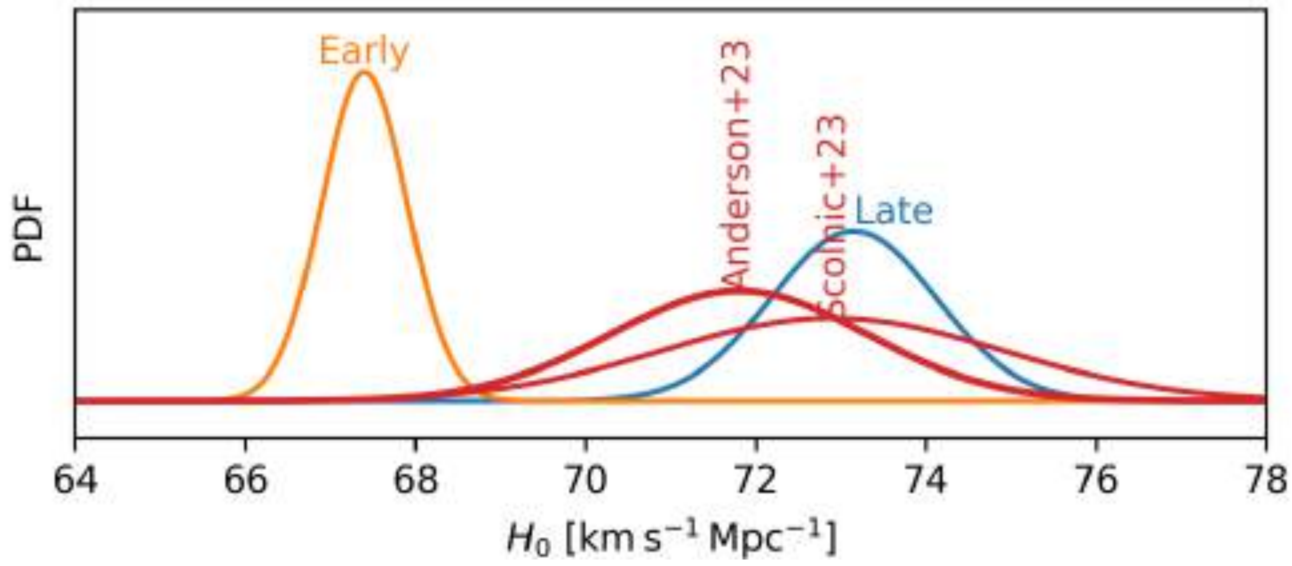


Summary of systematics

- Cepheids systematics best understood, at ~1% level
  - Extensive work to sharpen H0 accuracy & mitigate even small biases
  - 1% H0 measurement attainable
- TRGB systematics complex at the < 2-3% level
  - TRGB is a **statistical** feature, stars not individual standard candles
  - Diversity of populations identified by variability (RIA+23)
    - unfortunately too small for use in SN hosts (0.02 mag)
  - Location where TRGB is measured counts: cross-checks vital
  - Shape of the luminosity function
  - Details of Edge Detection Algorithm (smoothing, weighting, etc.)
- Further cross-checks important

Where does this leave H0?

- Cluster Cepheids provide best parallax calibration (Cruz Reyes + RIA 23)
- Cepheid systematics enable refinements to get to 1% (Spetsieri, RIA+ in prep)
- TRGB: ignore population diversity at your own peril (RIA+23)
- TRGB: empirical standardization & Pantheon+ SNeIa: 72.9 ± 2.0 km/s/Mpc (Scolnic+23)
- TRGB & Cepheids reconciled
- No disagreement among late-Universe probes
- K-corrections relevant for 1% using single filter JWST (RIA22)



The end