Anomalies in Cosmology

H_0 (Cepheids, TRGB)

https://indico.in2p3.fr/event/30622/timetable/#20231129

Anomalies in Cosmology

29–30 nov. 2023
Annecy
Fuseau horaire Europe/Paris

Entrer le texte à rechercher

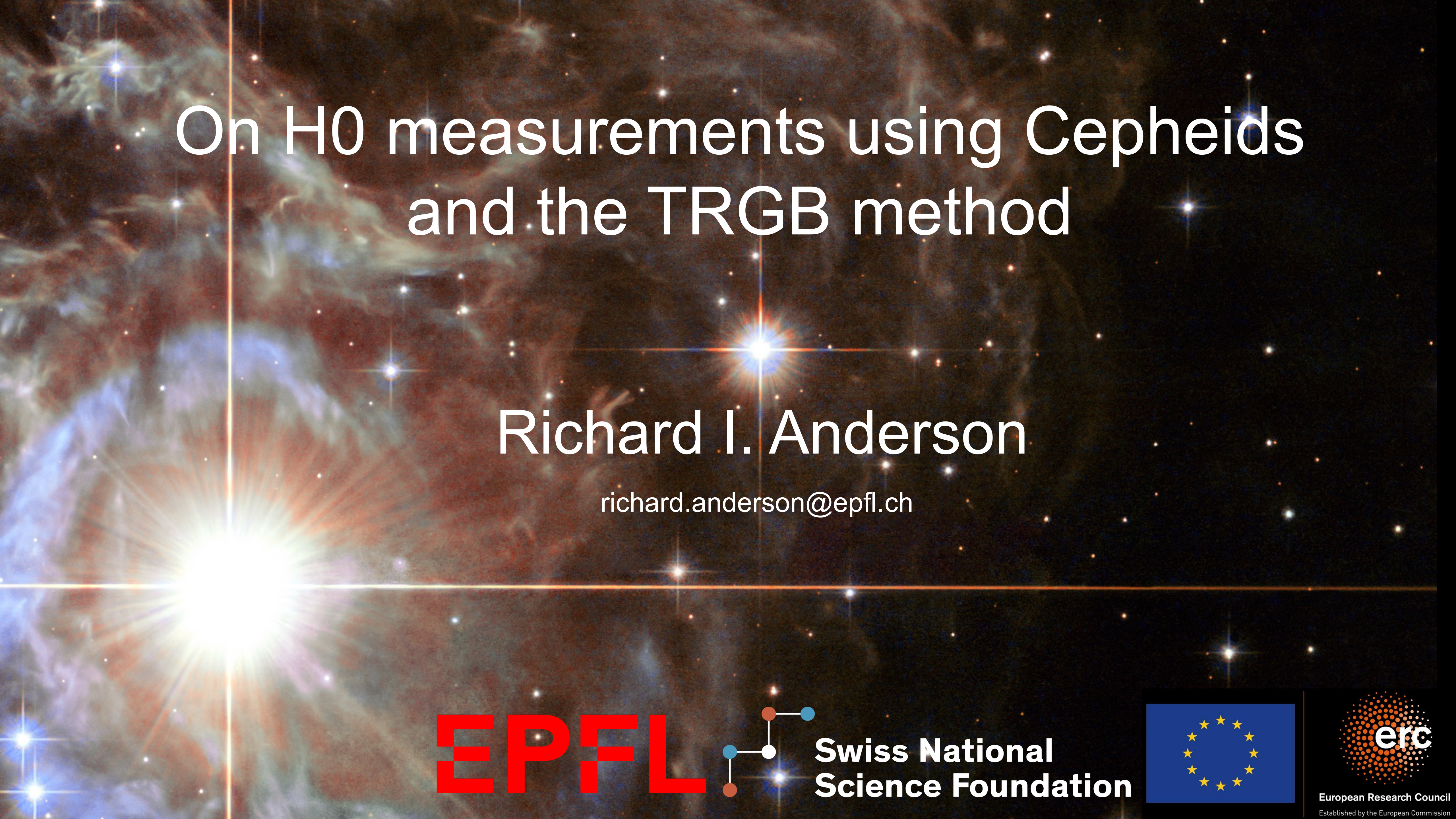
Rationale:
With the advent of "precision cosmology", a number of anomalies of diverse statistical significance has emerged. These include, but are not limited to: the "Hubble tension" between measurements of the Hubble parameter with a variety of late-universe probes (cepheid-calibrated supernovae in particular) and its prediction from the LCDM model fit to early-universe data (Planck CMB data in particular); the "S8 tension" between the amplitude of the clustering measured via weak-lensing surveys and that predicted by the Planck/LCDM cosmology; a recent "growth factor" tension which reminds of the S8 tension; as well as older long-standing "cosmic dipole" anomalies, the famous "lithium problem", and even some intriguing anomalies within Planck data. As of yet, it is not clear whether these anomalies are connected to each other, or even that they are cosmological in origins. The workshop “anomalies in cosmology” aims to gather the efforts of cosmologists interested in these growing (potential) issues of the LCDM model, in order to foster works to better characterize what sorts of systematic effects could be at play, or conversely, what sorts of new physics would be responsible for these anomalies. This will also serve as a platform to discuss with astrophysicists and particle physicists interested in these topics, whose expertise could help the cosmology community in understanding the origin of these anomalies.

Focus of the first workshop:
The workshop "anomalies in cosmology" is organized in the context of the corresponding "transverse task force" of the GDR CoPhy.

The first meeting will take place on November 29th and 30th, and will be hosted by LAPTh, in Annecy-le-Vieux. It will focus on "cepheids", a key part of the distance ladder. The program includes:

	welcome coffee		*petit amphitéatre, Annecy*	10:30 - 11:00
11:00	**Review: The SH0ES measurement of H0**	*Prof. Richard Anderson*	*petit amphitéatre, Annecy*	11:00 - 12:00
12:00	**Discussions/Questions**		*petit amphitéatre, Annecy*	12:00 - 12:30
	Lunch		*petit amphitéatre, Annecy*	12:30 - 14:00
13:00				
14:00	**Cepheids near and far**	*Pierre Kervella*	*petit amphitéatre, Annecy*	14:00 - 15:00
15:00	**Discussions/Questions: Discussion around cepheids**		*petit amphitéatre, Annecy*	15:00 - 16:00
16:00	**Coffee break**		*petit amphitéatre, Annecy*	16:00 - 16:30
	A critical view of the SH0ES measurement	*Pierre Astier*	*petit amphitéatre, Annecy*	16:30 - 17:30
17:00				
	Discussions/Questions		*petit amphitéatre, Annecy*	17:30 - 18:30
18:00				

	Welcome coffee		*petit amphitéatre, Annecy*	09:30 - 10:00
10:00	**Critical view on SH0ES (continued)**	*Pierre Astier*	*petit amphitéatre, Annecy*	10:00 - 12:00
11:00				
12:00	**Lunch break**		*petit amphitéatre, Annecy*	12:00 - 13:30
13:00				
	Tip of the Red Giant Branch	*Richard Anderson*	*petit amphitéatre, Annecy*	13:30 - 15:30
14:00				
15:00				
	Farewell coffee		*petit amphitéatre, Annecy*	15:30 - 16:00



On H0 measurements using Cepheids and the TRGB method

Richard I. Anderson

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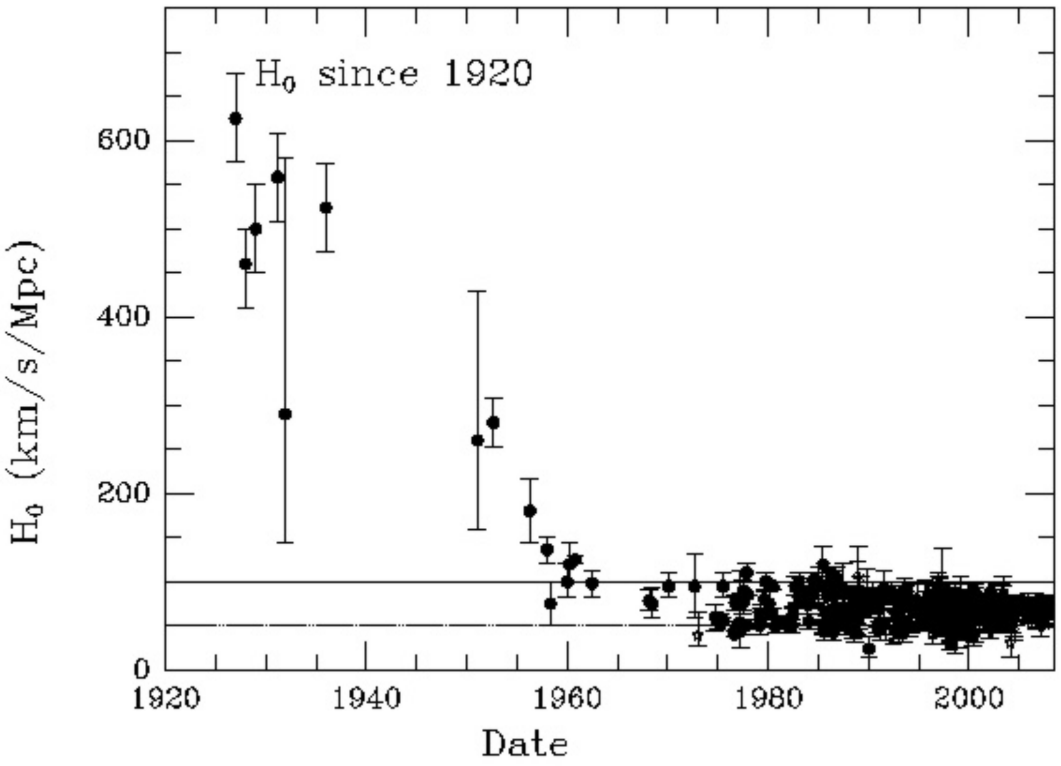
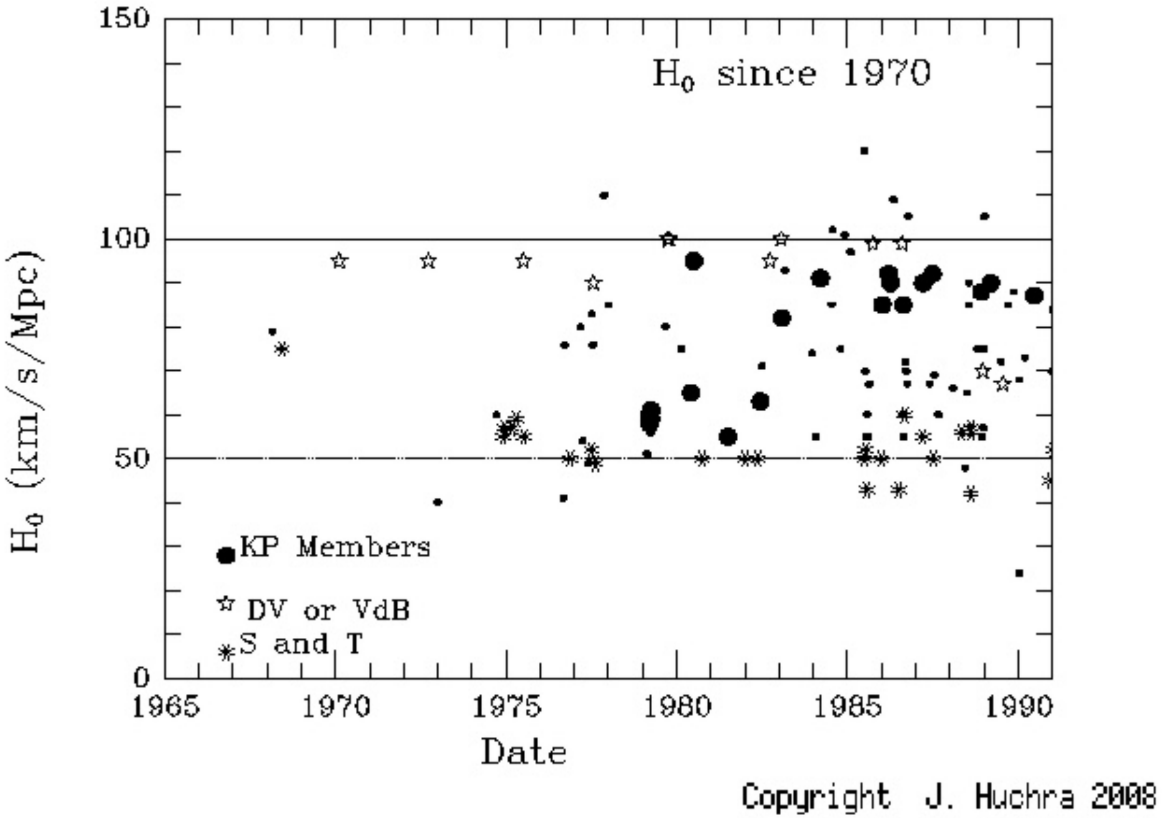
EPFL

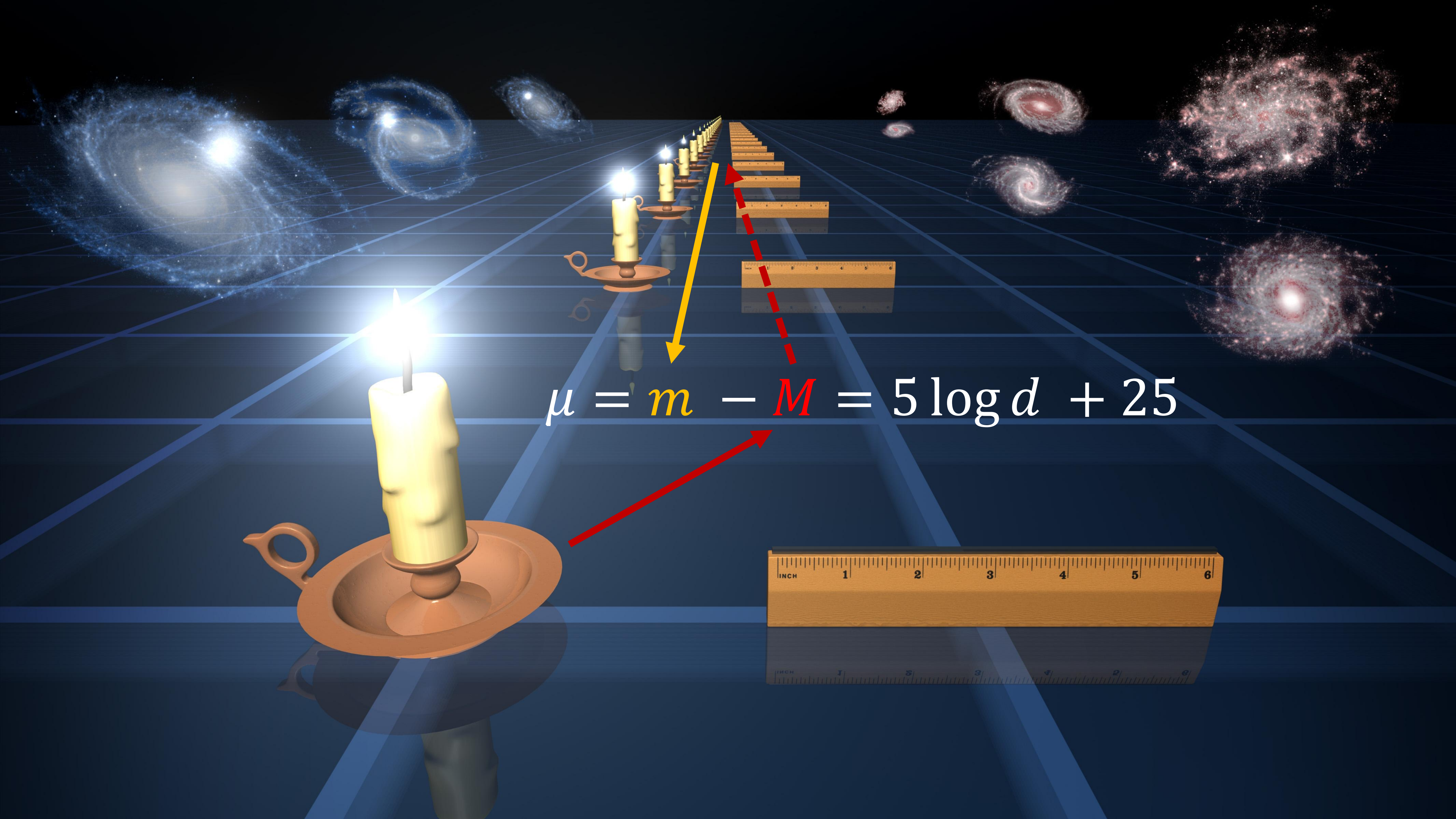
Swiss National Science Foundation

European Research Council
Established by the European Commission

The chequered history of Hubble's constant





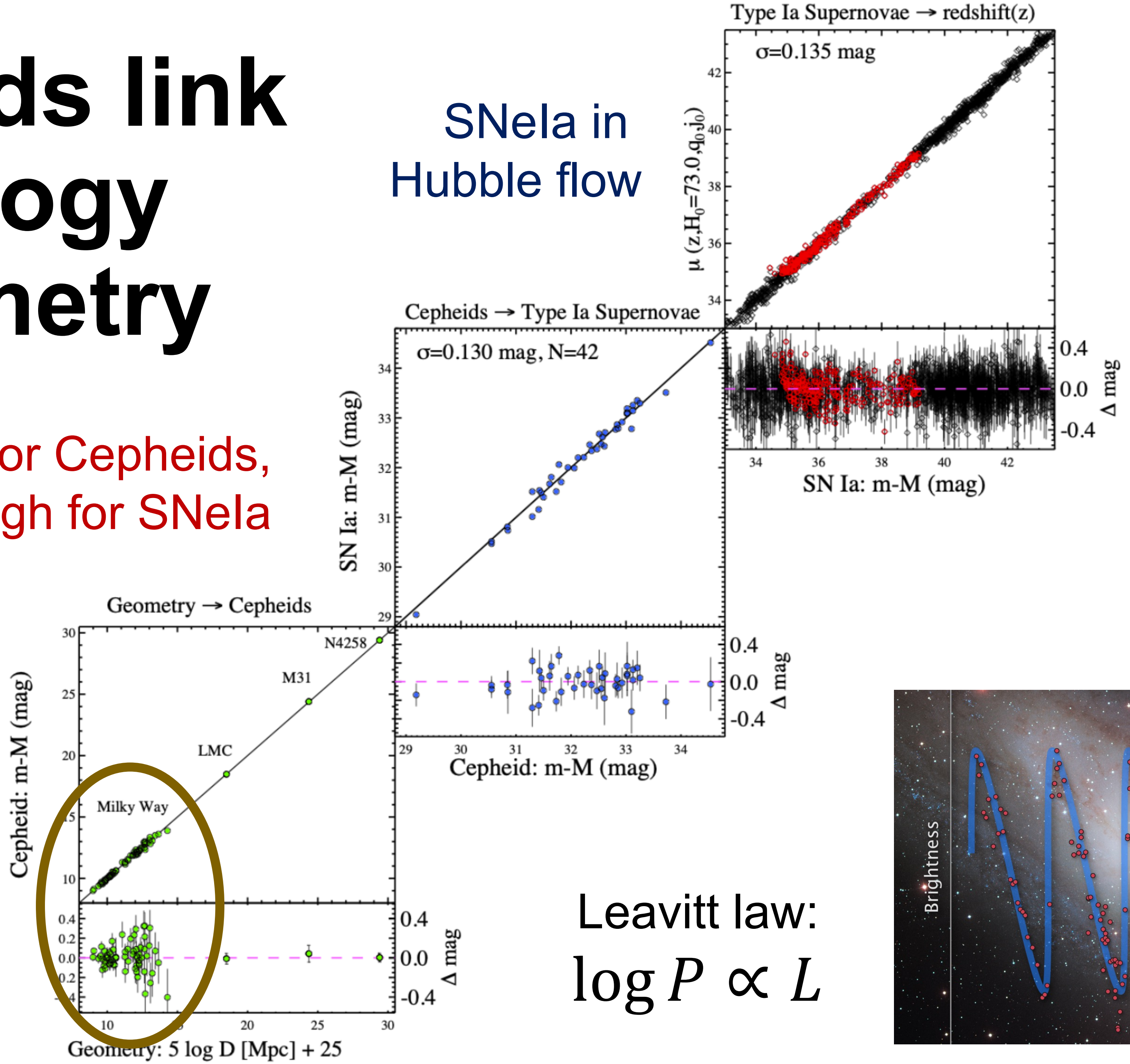

$\mu = m - M = 5 \log d + 25$
INCH 1 2 3 4 5 6

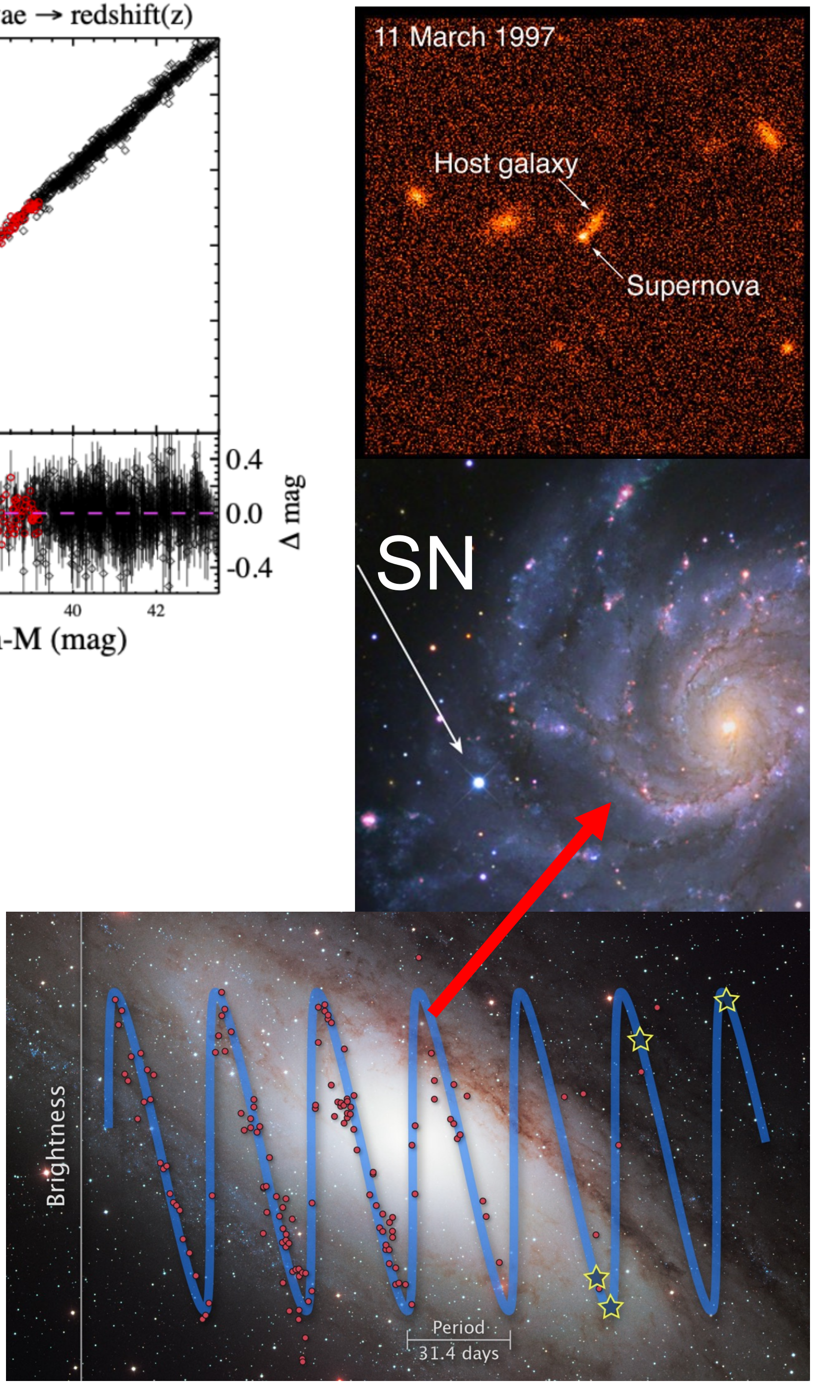
Cepheids link cosmology to geometry

SNeIa in Hubble flow

Close enough for Cepheids, far enough for SNeIa

Gaia Parallaxes

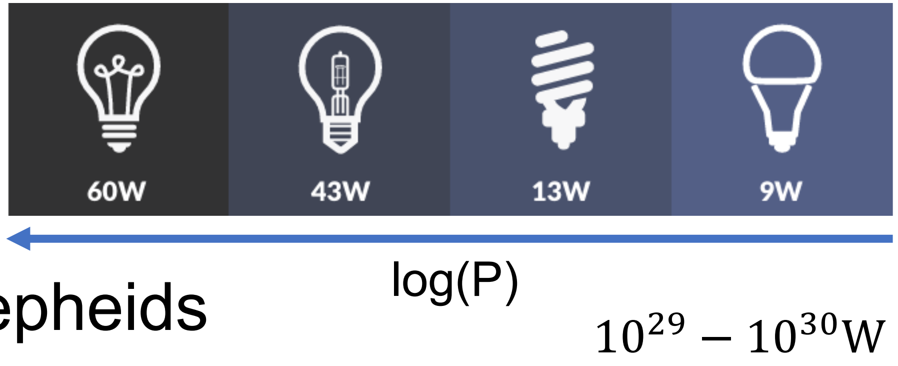




Leavitt law:

$$\log P \propto L$$

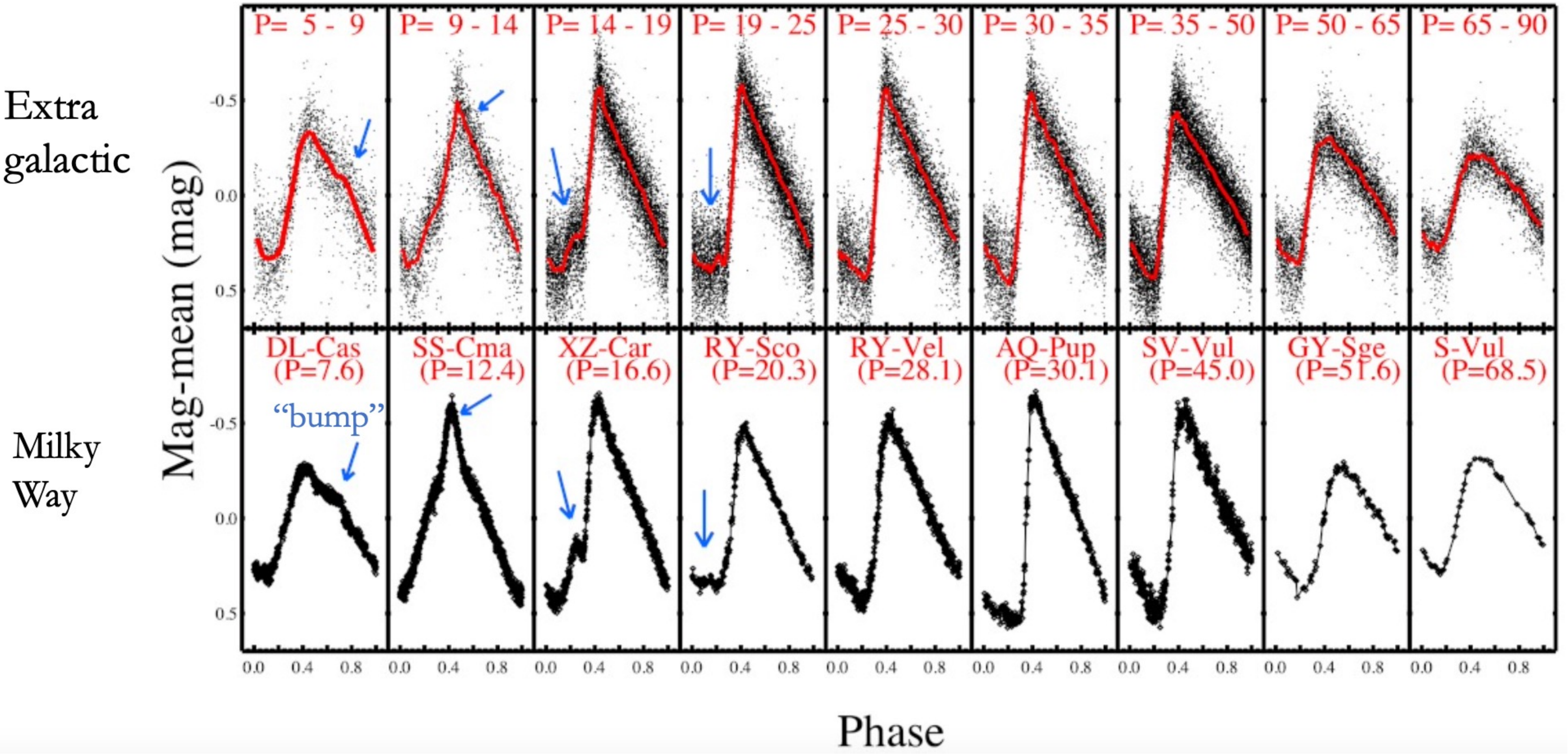
Classical Cepheids are great for this!



- Each Cepheid a standard candle
- Characteristic variability identifies individual Cepheids
- Minimal contamination of PL-sequences by non-Cepheids
- Tight scatter in PL relation constrains uncertainties
- Exciting modulated variability no challenge to accuracy (e.g. Smolec 2017)
- Comparatively well understood by stellar evolution

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

Hertzsprung progression in MW and SN-hosts



Distance Ladder Equations

Reddening-free "Wesenheit"

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

observed fiducial Period slope Metallicity

$$m_{H,i,j}^W = \mu_{0,i} + M_{H,1}^W + b_W (\log P_{i,j} - 1) + Z_W [\mathrm{O/H}]_{i,j},$$

Leavitt law

$$M_{H,j}^W = m_{H,\mathrm{N4258},j}^W - \mu_{0,\mathrm{N4258}} + \Delta\mu_{\mathrm{N4258}},$$

$$m_{B,i}^0 = \mu_{0,i} + M_B^0,$$

SNeIa standardized

$$a_B = \log cz \left\{1 + \frac{1}{2}[1 - q_0]z - \frac{1}{6}[1 - q_0 - 3q_0^2 + j_0]z^2 + O(z^3)\right\} - 0.2m_B^0,$$

$$\log H_0 = 0.2M_B^0 + a_B + 5.$$

A simultaneous analytical LS fit

$$y = \begin{pmatrix} m^W_{H,1} \\ \cdot\cdot \\ m^W_{H,\mathrm{nh}} \\ \hline m^W_{H,\mathrm{N4258}} - \mu_{0,\mathrm{N4258}} \\ m^W_{H,\mathrm{M31}} \\ m^W_{H,\mathrm{LMC}} - \mu_{0,\mathrm{LMC}} \\ \hline m^0_{B,1} \\ \cdot\cdot \\ m^0_{B,\mathrm{ncc}} \\ \hline M^W_{H,1,\mathrm{HST}} \\ M^W_{H,1,\mathrm{Gaia}} \\ 0 \\ 0 \\ 0 \\ \hline m^0_{B,1} - 5\log cz_1\{\} - 25 \\ \cdot\cdot \\ m_{B,\mathrm{nhf}} - 5\log cz_{\mathrm{nhf}}\{\} - 25 \end{pmatrix}$$

observations

Covariance Matrix

$$\chi^2 = (y - Lq)^T C^{-1} (y - Lq)$$

Model = equations * parameters

$$q = \begin{pmatrix} \mu_{0,1} \\ \cdot\cdot \\ \mu_{0,\mathrm{nh}} \\ \Delta\mu_{\mathrm{N4258}} \\ M^W_{H,1} \\ \Delta\mu_{\mathrm{LMC}} \\ \mu_{M31} \\ b_W \\ M^0_B \\ Z_W \\ \Delta\mathrm{zp} \\ 5\log \mathrm{H}_0 \end{pmatrix}.$$

$$q_{\mathrm{best}} = (L^T C^{-1} L)^{-1} L^T C^{-1} y, \qquad cq = (L^T C^{-1} L)^{-1}$$

Covariance

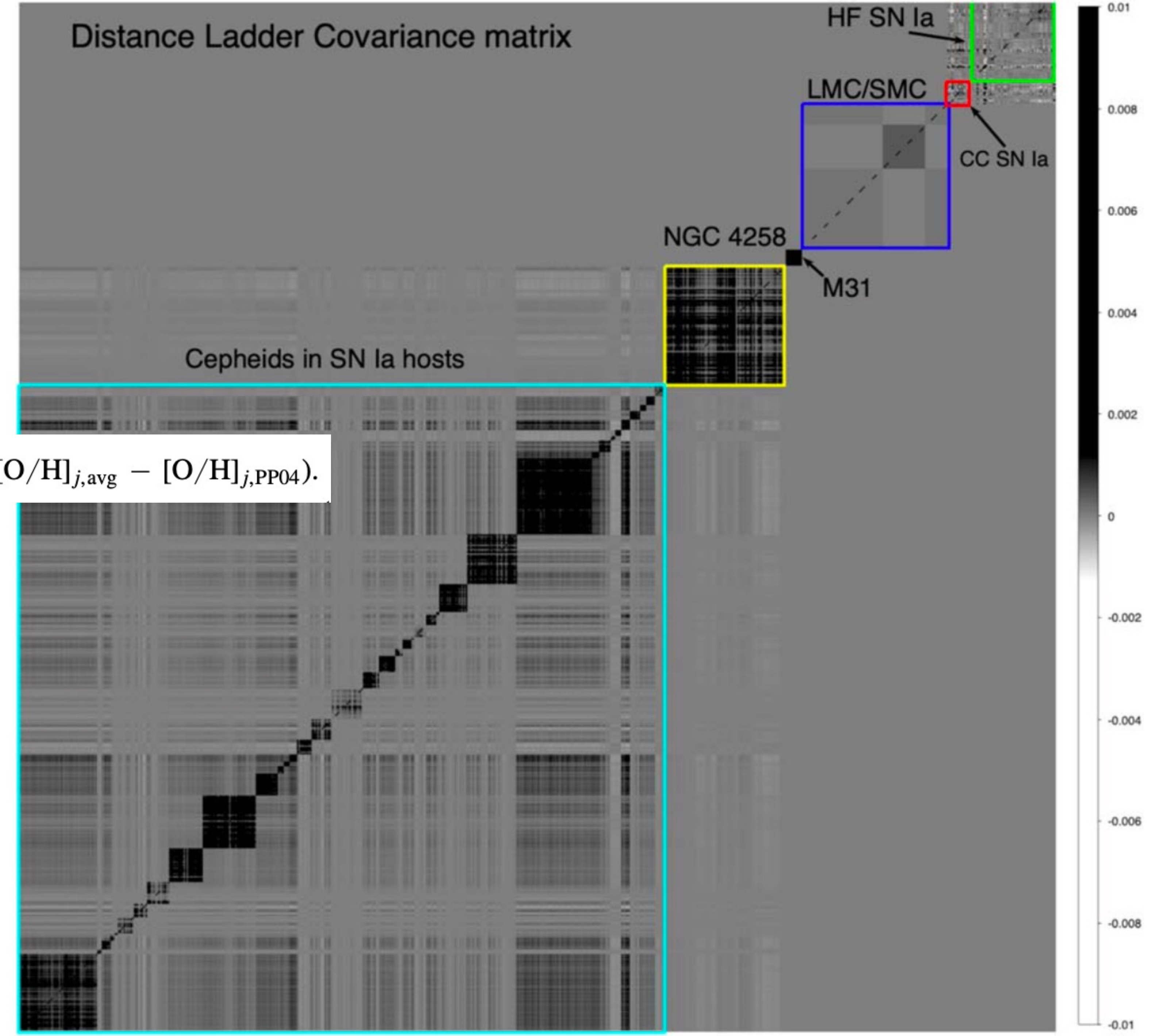
- Explicitly propagated
- Metallicity!

$$C_{i,j,\mathrm{syst}} = Z_W^2([\mathrm{O/H}]_{i,\mathrm{avg}} - [\mathrm{O/H}]_{i,\mathrm{PP04}})([\mathrm{O/H}]_{j,\mathrm{avg}} - [\mathrm{O/H}]_{j,\mathrm{PP04}}).$$

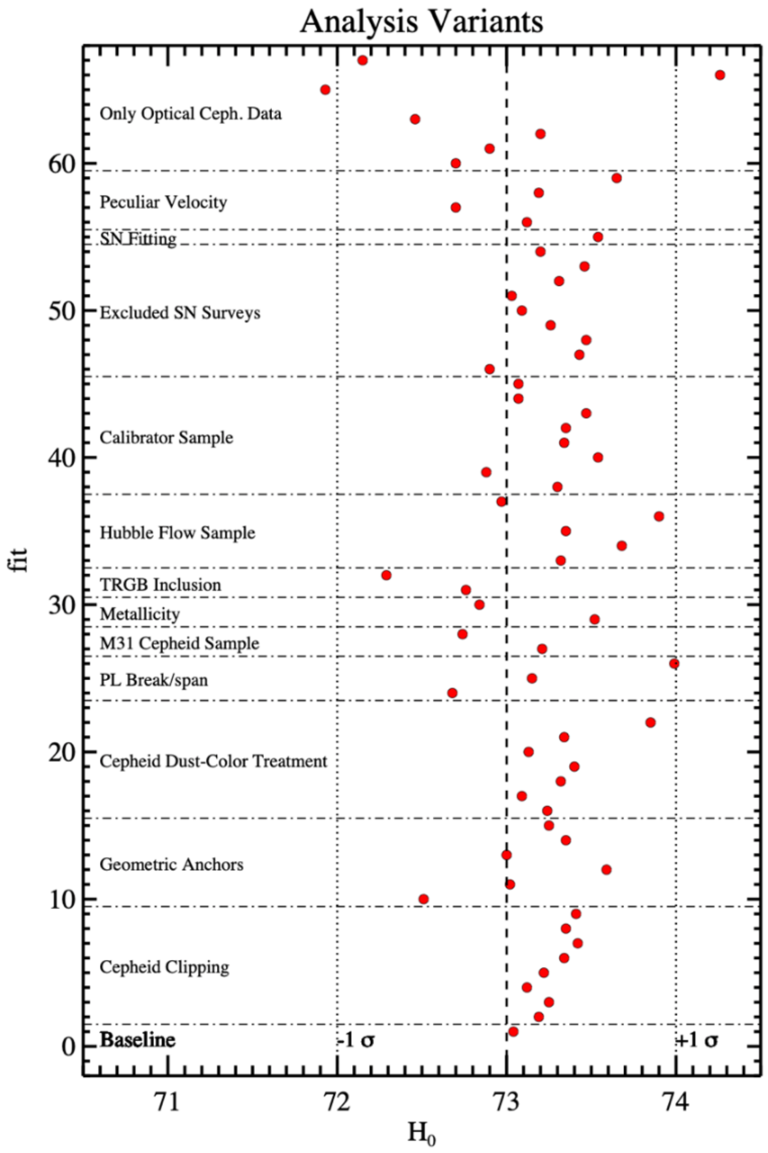
- Background

$$C_{i,j,k,\mathrm{bkgd}} = 0.2^2(\mathrm{bkgd}_{i,j})(\mathrm{bkgd}_{i,k}).$$

- SN-SN (Pantheon+)



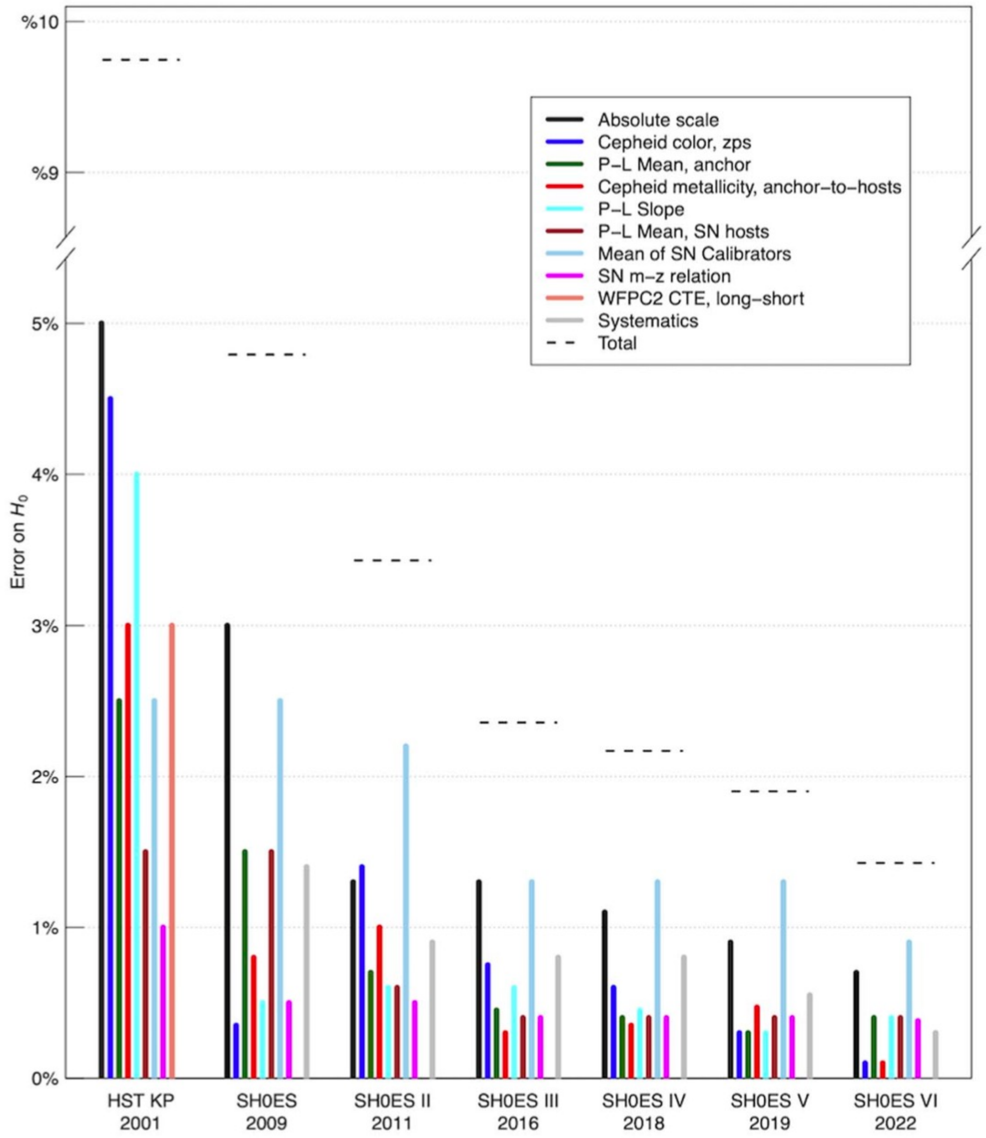
Analysis Variants: 12 categories, 67 variants, bifurcations, extensions, etc



- Optical Cepheid data only (72.7)
- Different pec. vel map or none (73.1,72.7)
- SN scatter ind. wave+mass step (73.5)
- No pre-2000 SNe (73.2)
- closest half hosts (73.1)
- most crowded half (73.4)
- least crowded half (73.3)
- Skip "local hole" z>0.06 (73.4)
- All host types (73.3)
- include TRGB (consistent) jointly (72.5)
- No metallicity term (73.5)
- Break in PL at P=10 days (72.7)
- No dust correction (74.8)
- Individual host dust law (73.9)
- Free param dust law (73.3)
- Low R_V=2.5 dust law (73.2)
- Two of three anchors (73.0,73.4,73.2)
- No outlier rejection (73.4)

Bottom line: hard to get below 72.5, above 73.5, propagate dispersion as extra systematic

Uncertainties improve, tension grows



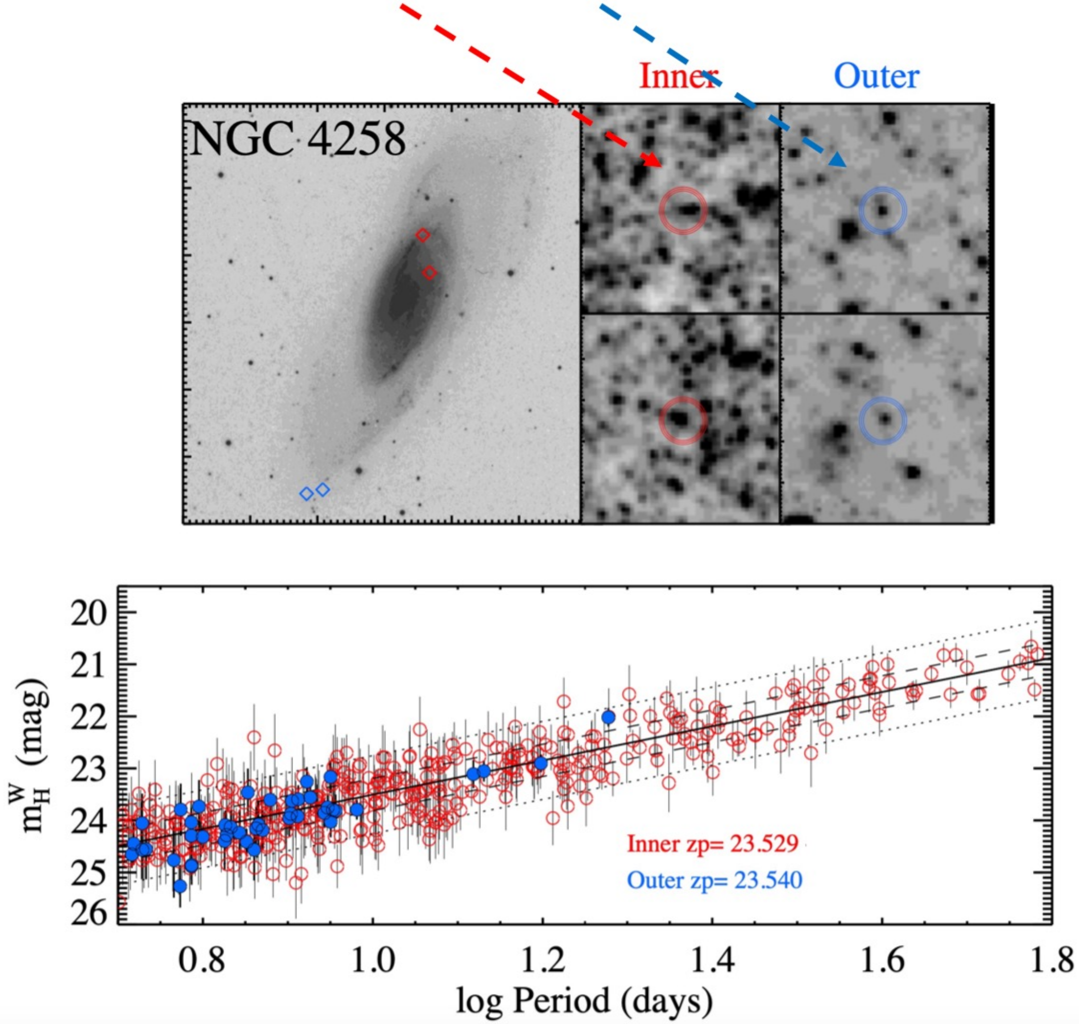
Crowding

Corrections already applied in SH0ES DL (artificial star tests)
Null tests imply no crowding problem
Amplitude-based tests performed
Quality cuts (amplitude ratios, colors, etc.) protect against this

Do Cepheid crowded backgrounds compromise accuracy?

- Six validation tests of backgrounds/crowding, here is one:

Compare Cepheids in high and low background/crowding, same distance



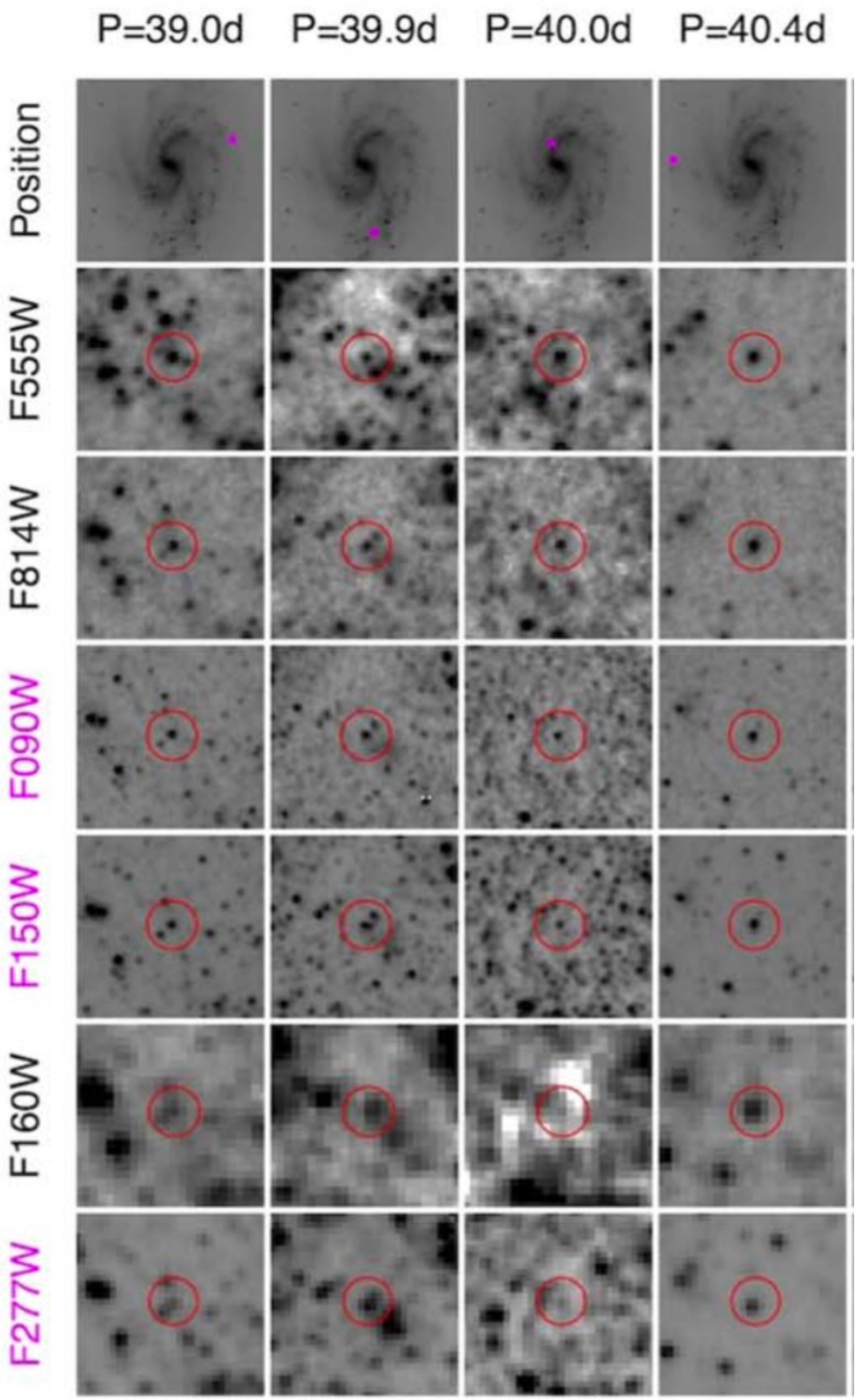
Difference in distance,
Between inner
and outer ~0.01 mag

Riess+2022

JWST uncrowds distant Cepheids

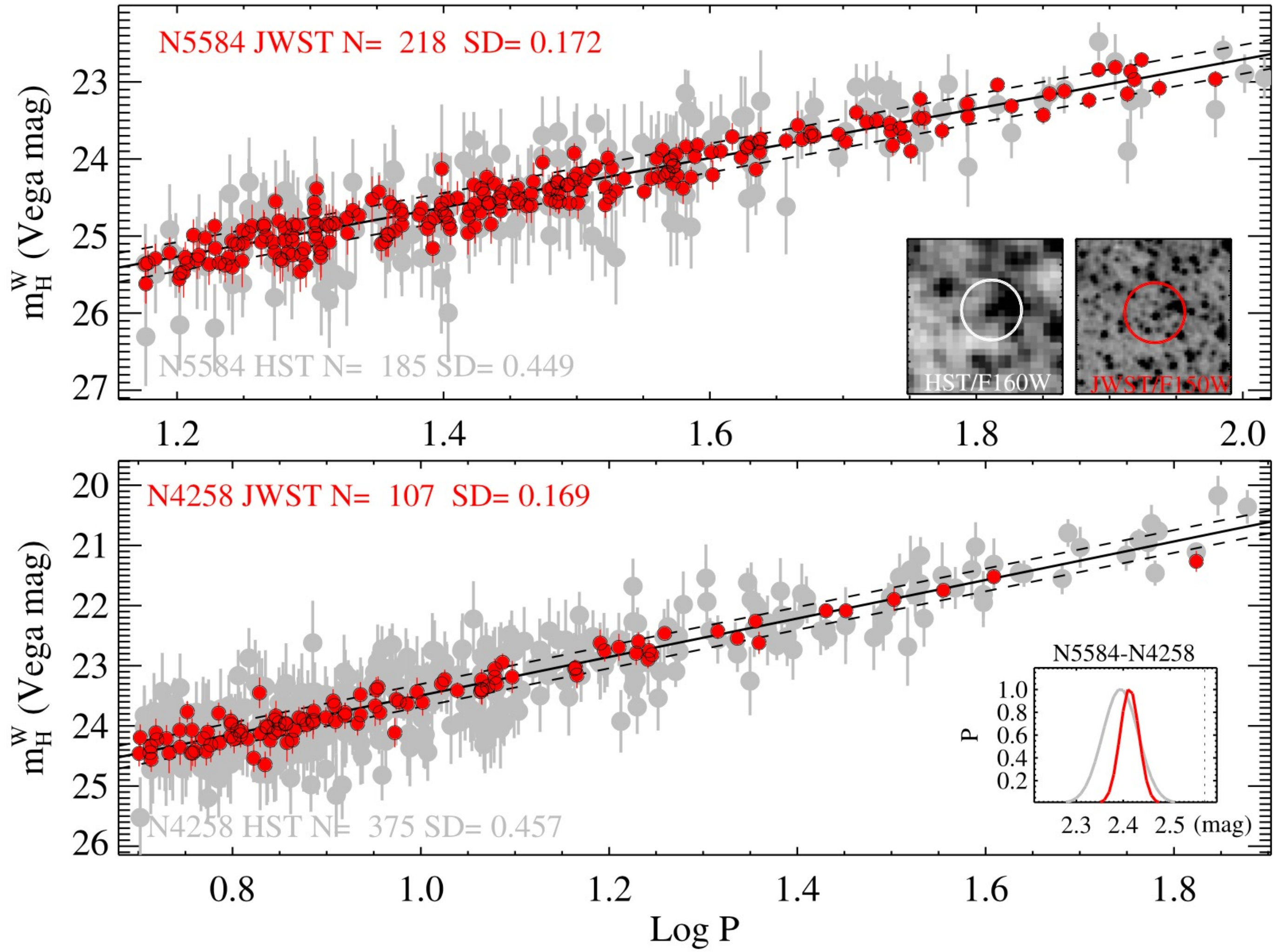
Riess et al., incl RIA (2023), ApJL 956, L18

- 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



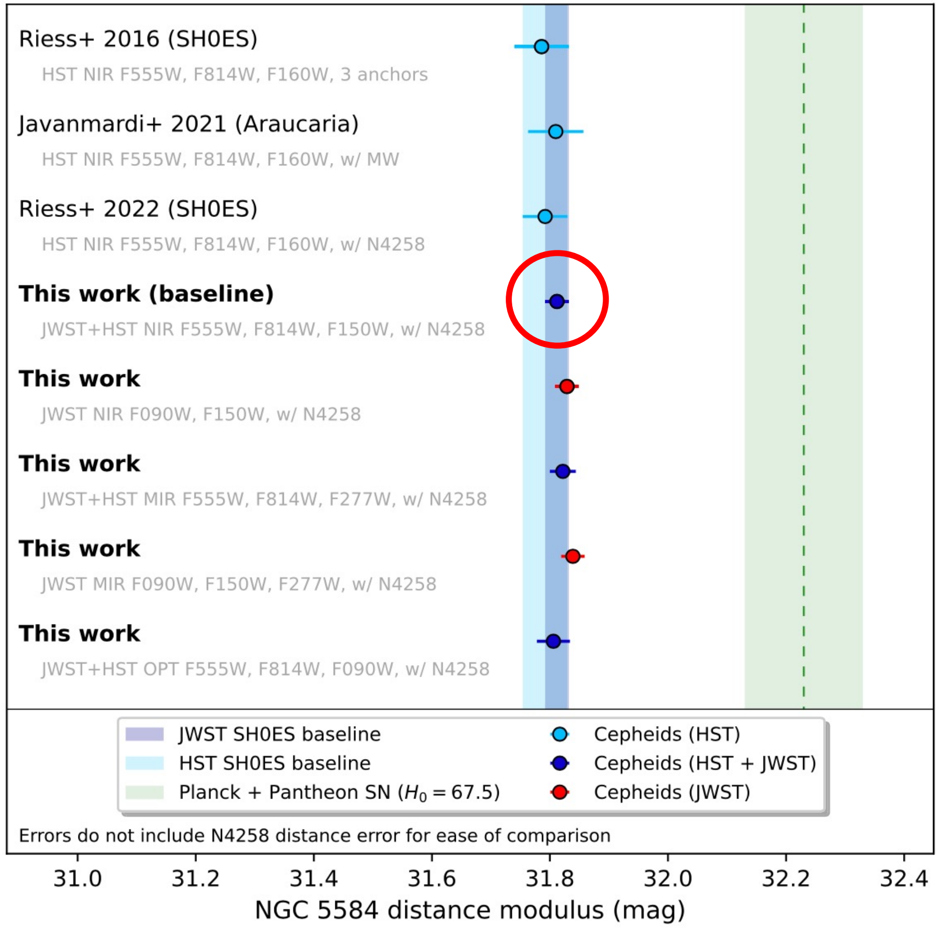
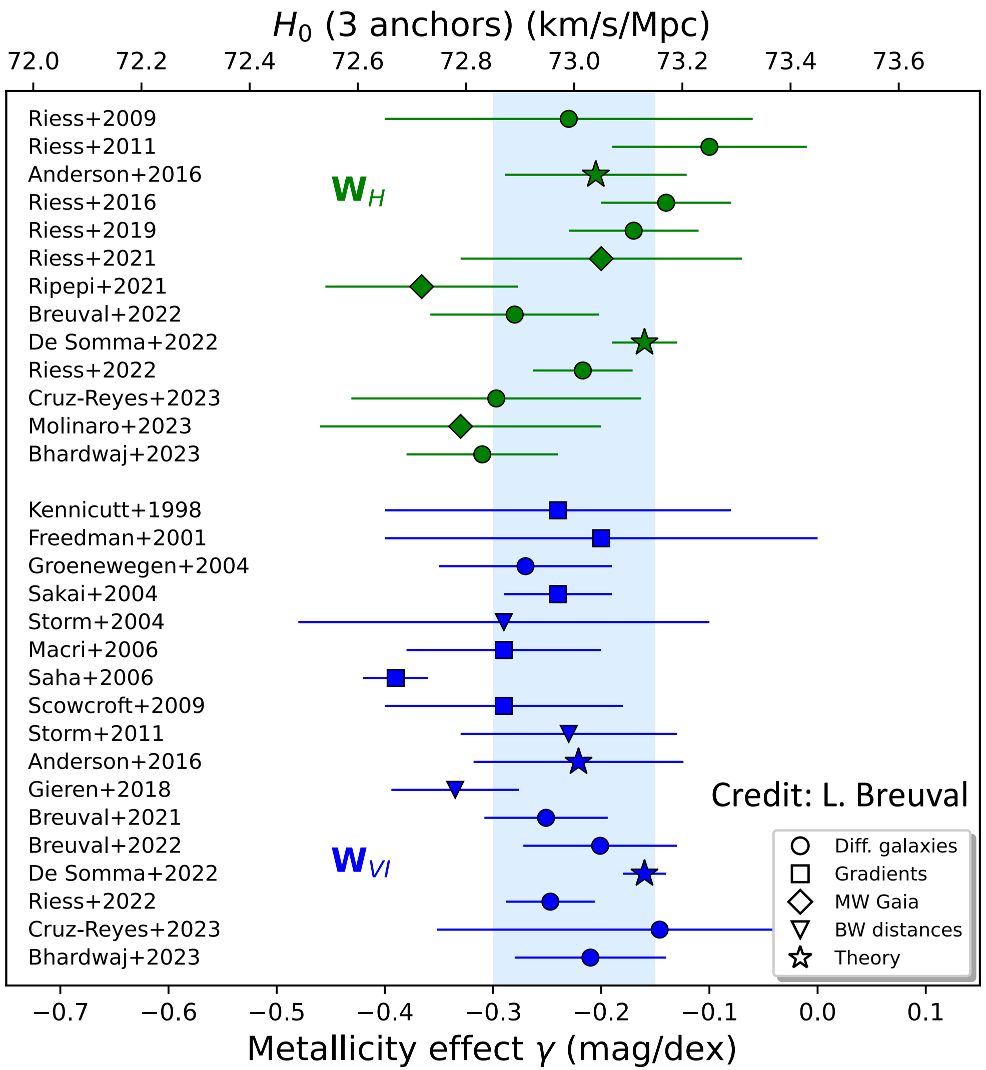


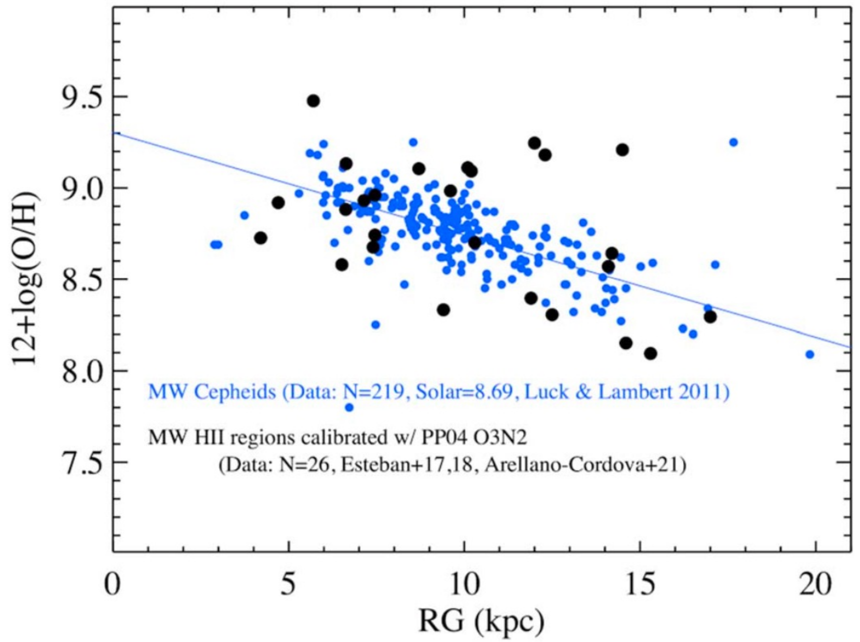
Figure 15. A comparison of Cepheid distance measures to NGC 5584.

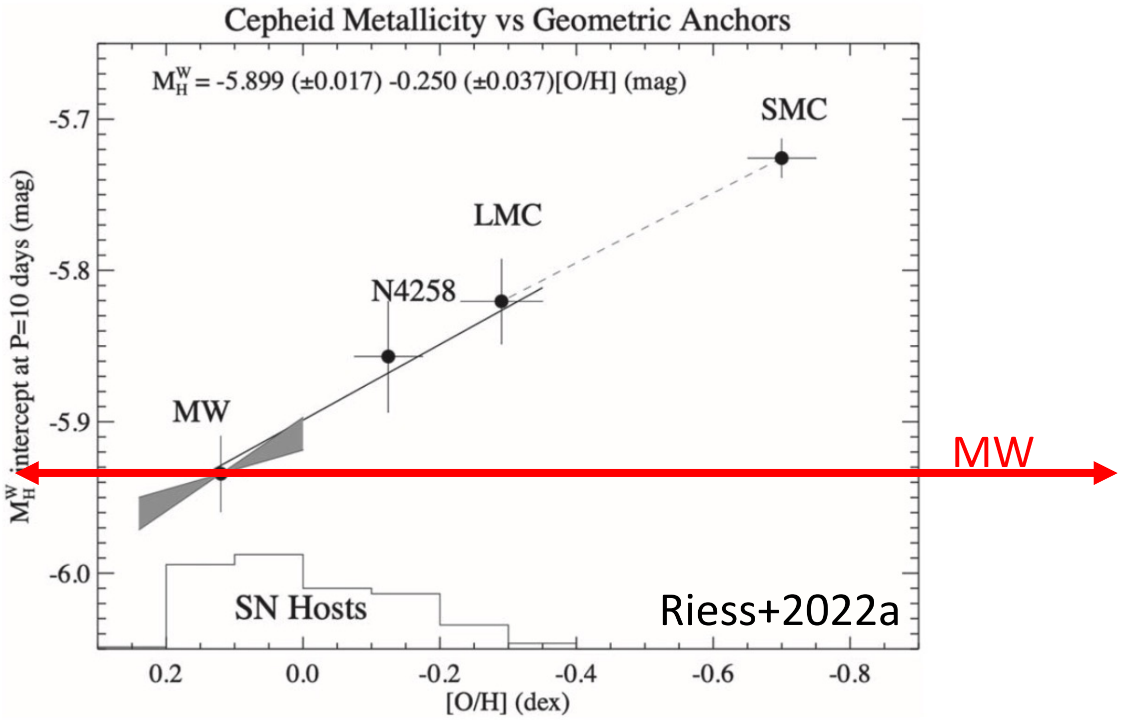
Metallicity

See Louise’s talk?

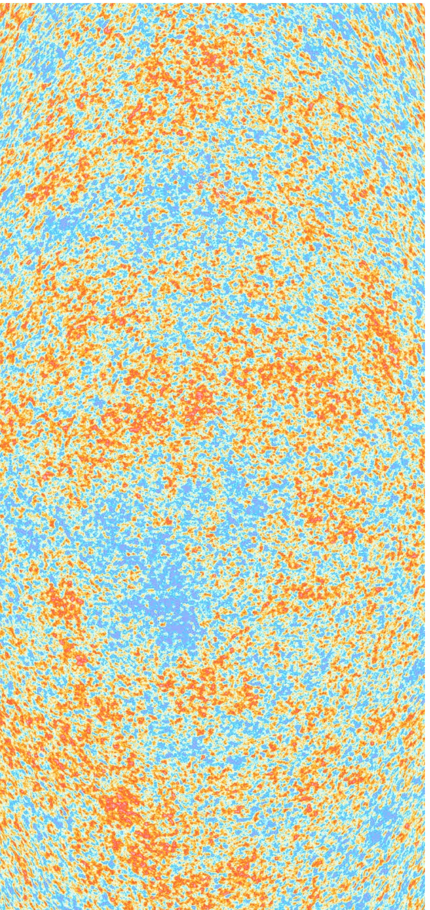
Metallicity

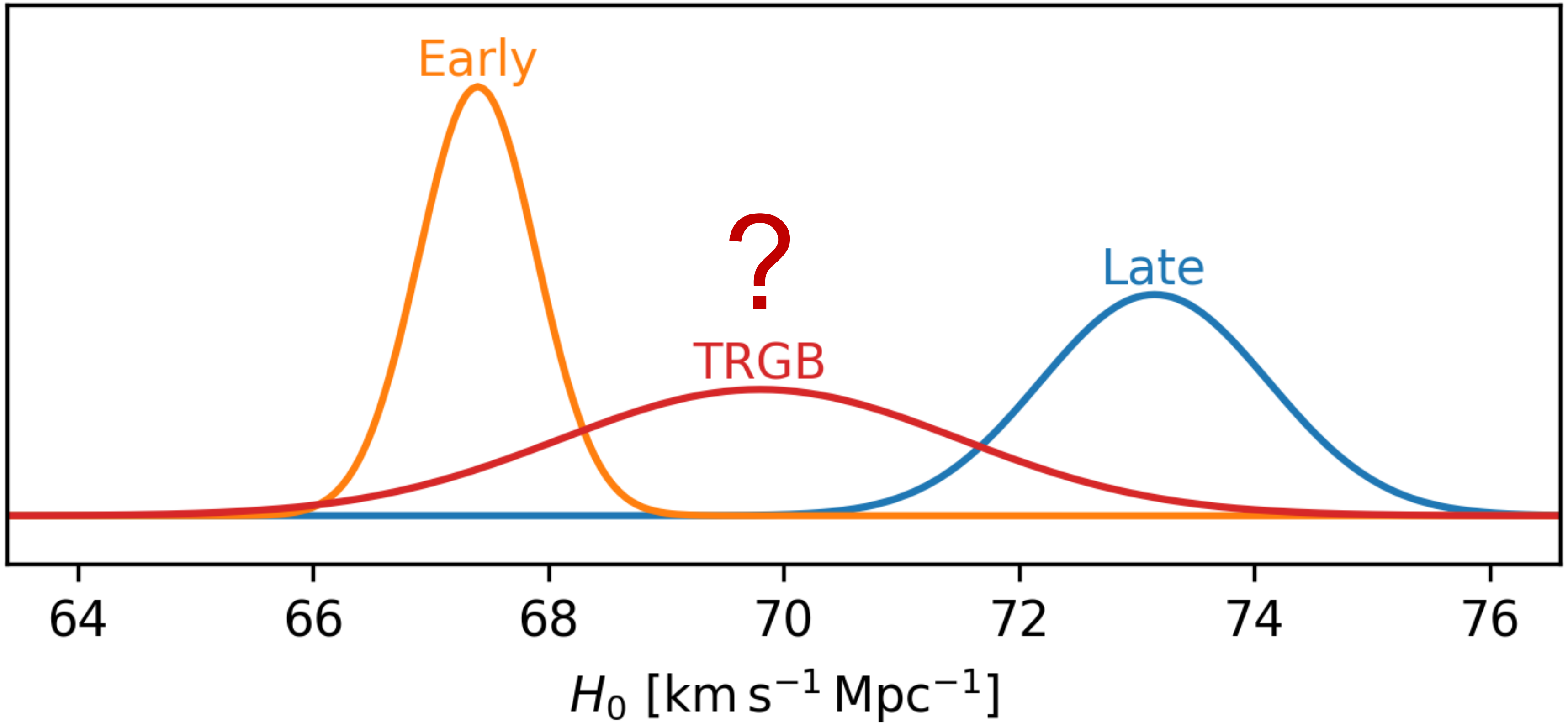




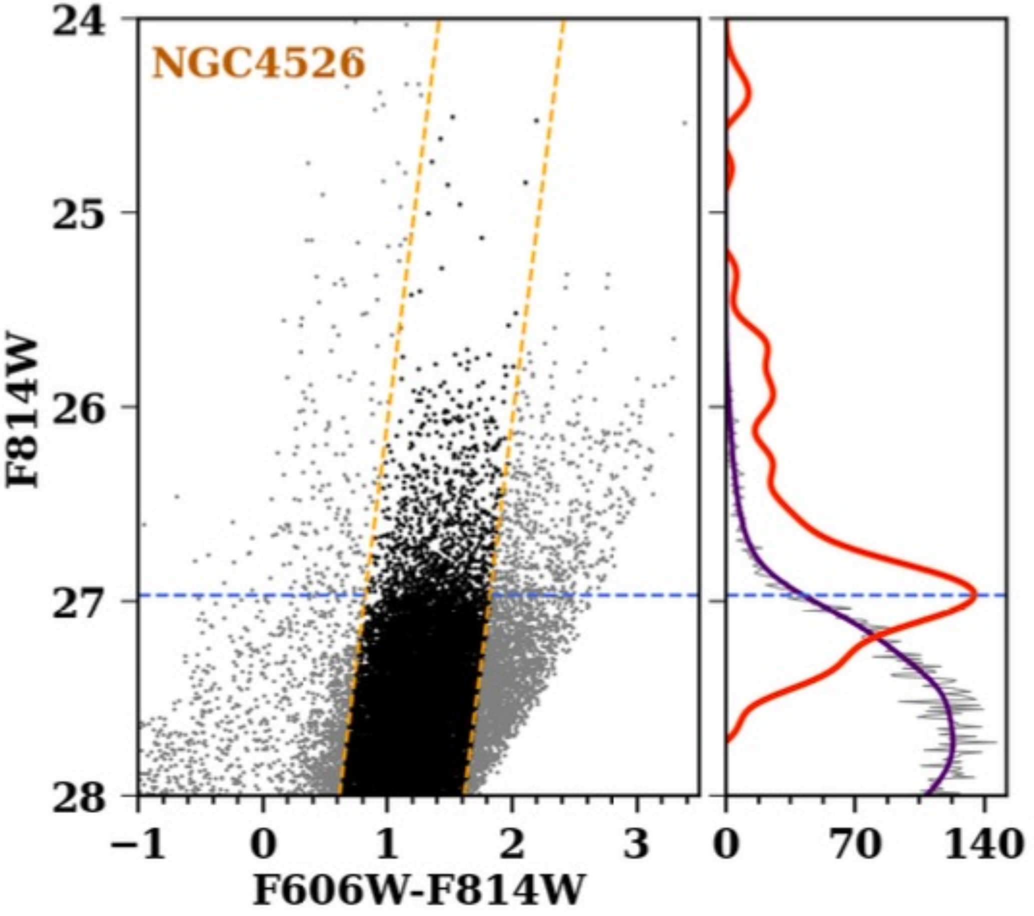


Reconciling standard candles?





New insights on TRGB calibration and standardization



CCHP mainly disagrees with SH0ES because of SNeIa!

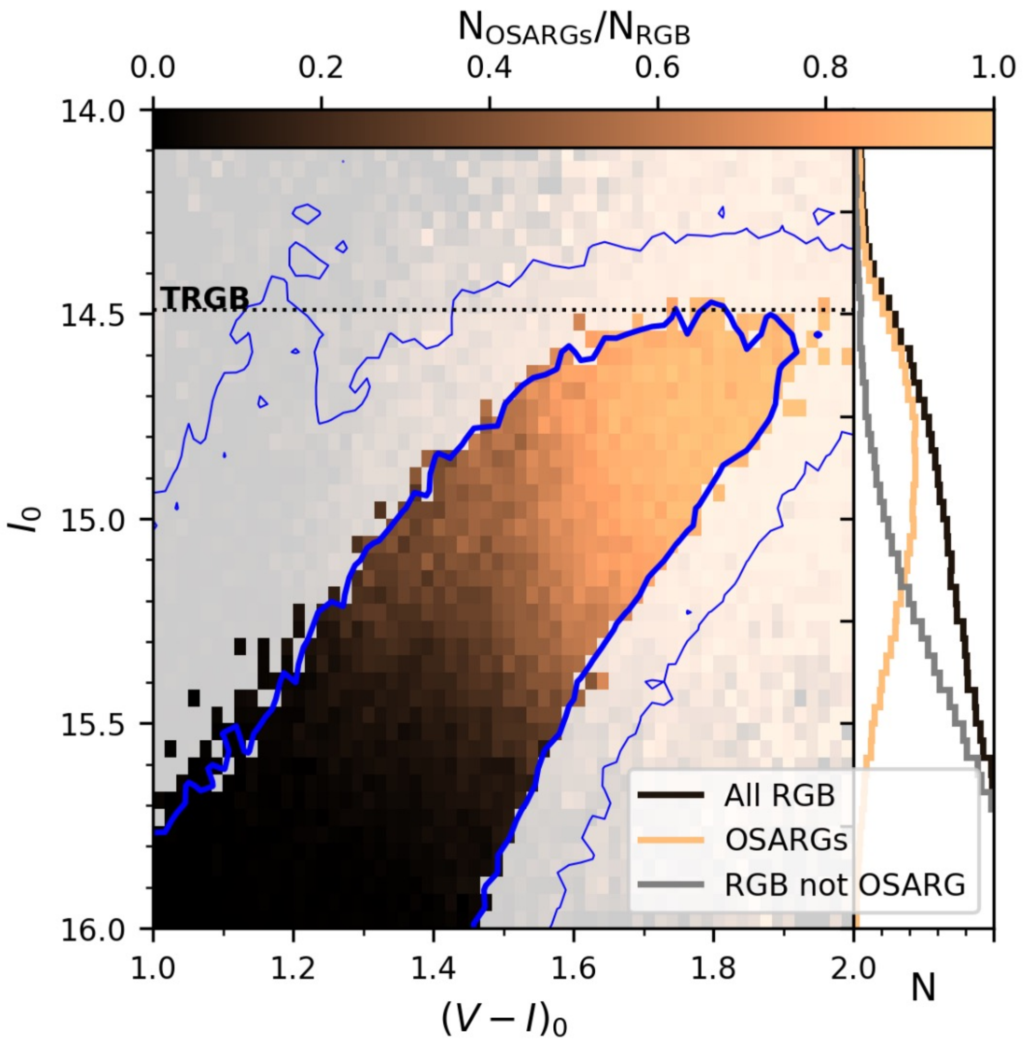
Scolnic et al. (2023)

Table 5
Sources of Differences in H_0 between TRGB Analysis by CATS (Here), CCHP, and EDD (in H_0)

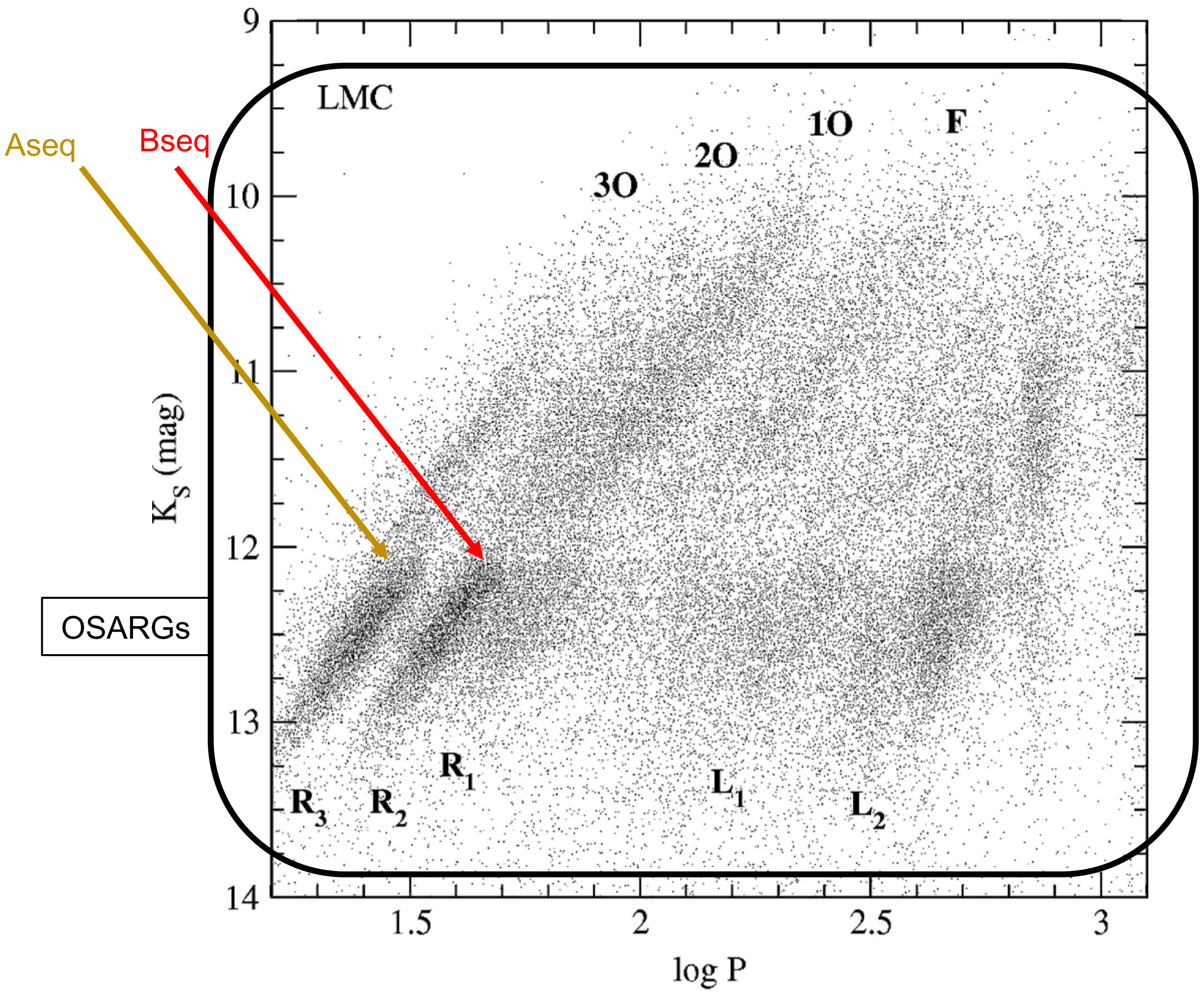
Term	ΔCCHP ($km\ s^{-1}\ Mpc^{-1}$)	ΔEDD ($km\ s^{-1}\ Mpc^{-1}$)
SN-related		
(1) Include SNe 2021pit, 2021rhu, 2007on	0.6	1.3
(2) No TRGB detected in N5584, N3021, N1309, N3370	0.0	0.0
(3) Peculiar flows (Pantheon+)	0.4	0.0
(4) Hubble flow surveys (Pantheon+)	1.1	0.0
SN subtotal	2.0	1.3
TRGB-related		
(5) Fiducial TRGB calibration/tip-contrast relation	1.4	–0.3
Total	3.4	1.0

The TRGB is chock-full of variable stars

RIA et al. 2303.04790 (to be updated)



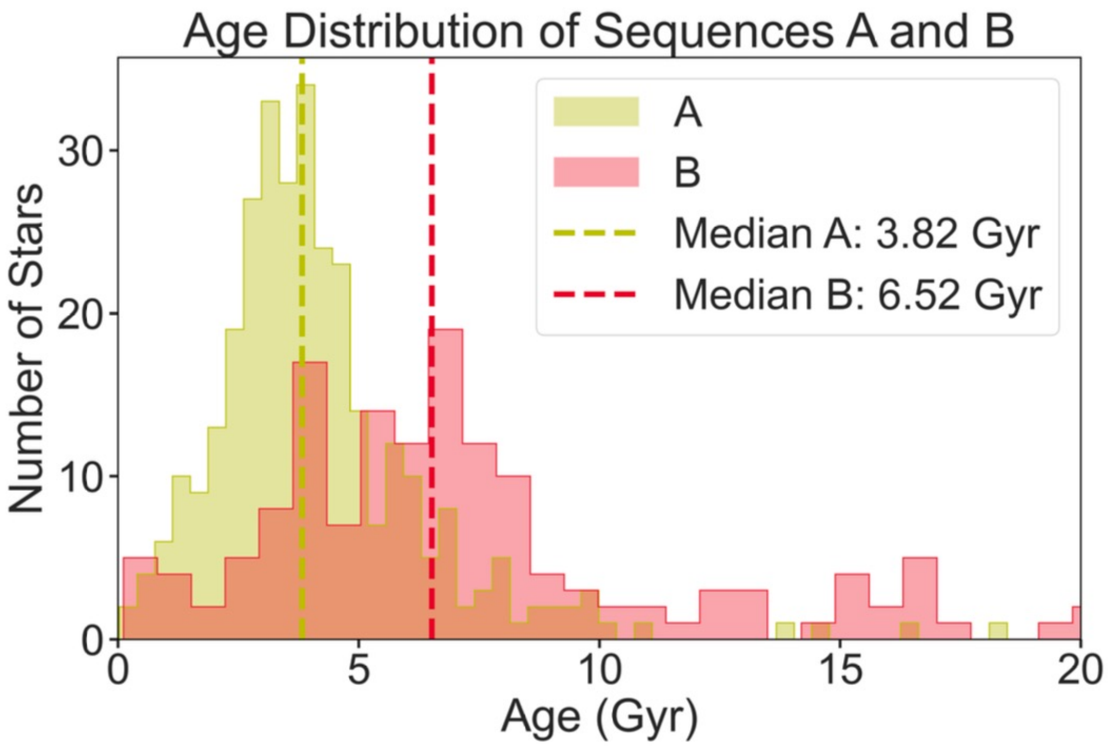
79'200 Small Amplitude Red Giants in OGLE-III

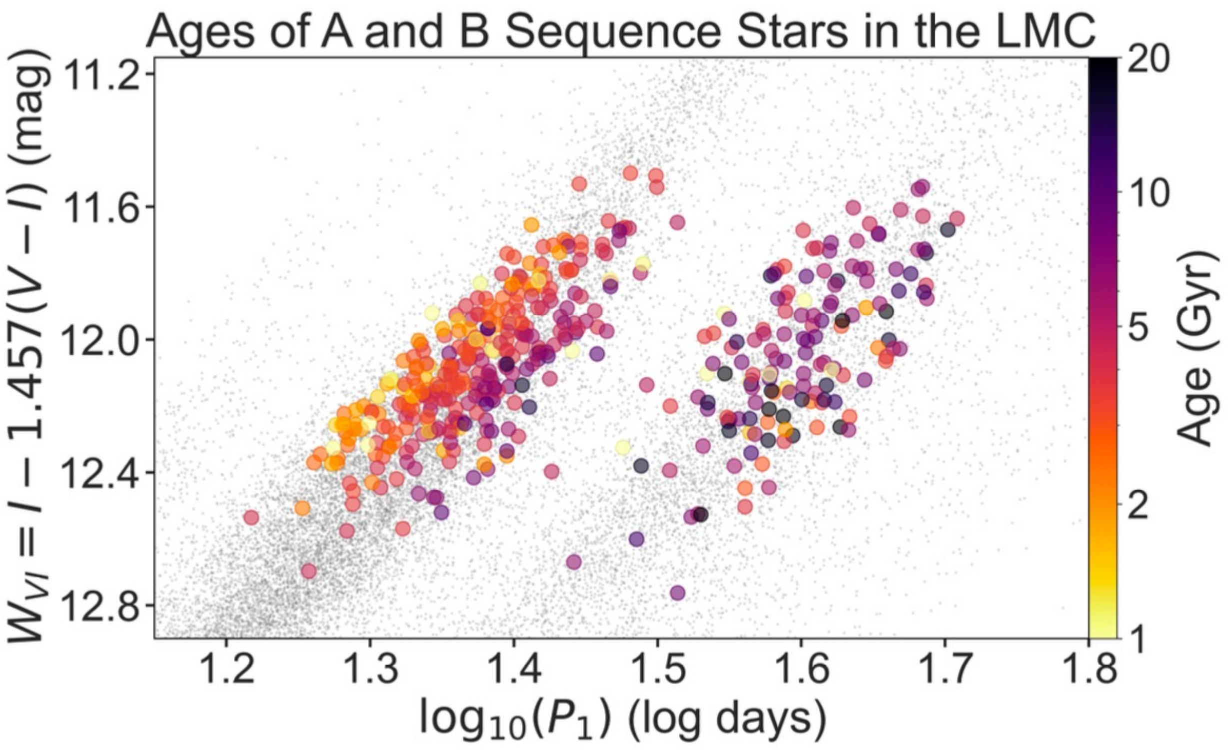


Ita et al. (2002); Kiss & Bedding (2003)

Variability elucidates RG diversity and allows standardization

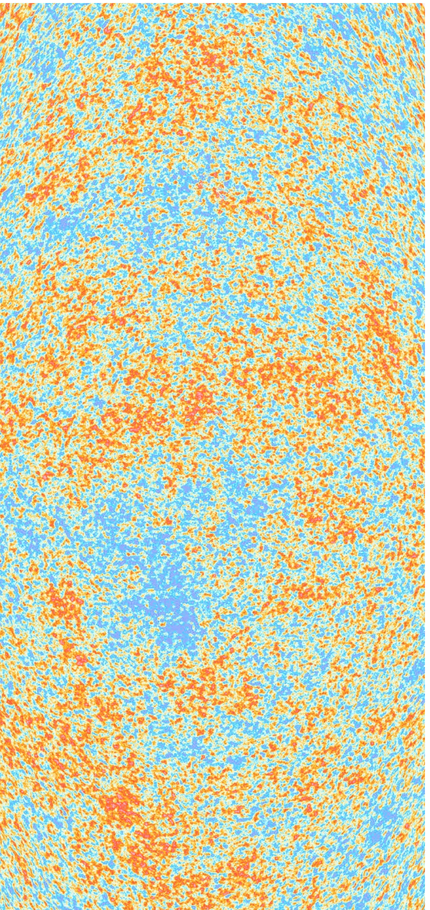
RIA et al. 2303.04790 (to be updated)

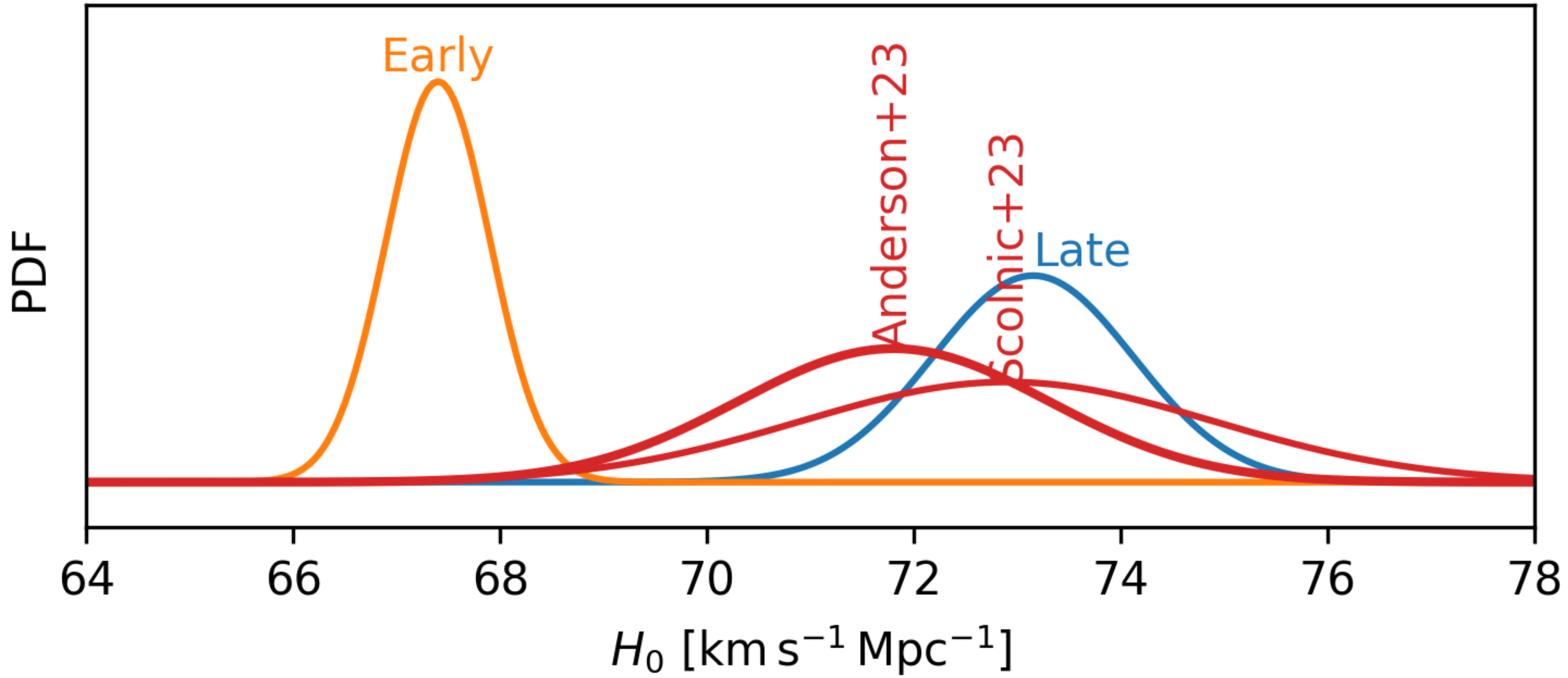




Ages from Povick et al. (2306.06348)

Improved systematics increase TRGB-calibrated H0!





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

Cepheids Near and Far

Pierre Kervella
Behnam Javanmardi
Antoine Mérand
Louise Breuval
Alexandre Gallenne
Nicolas Nardetto
Boris Trahin
Anton Afanasyev
Wolfgang Gieren
Grzegorz Pietrzyński
Vincent Hocdé
Simon Borgniet

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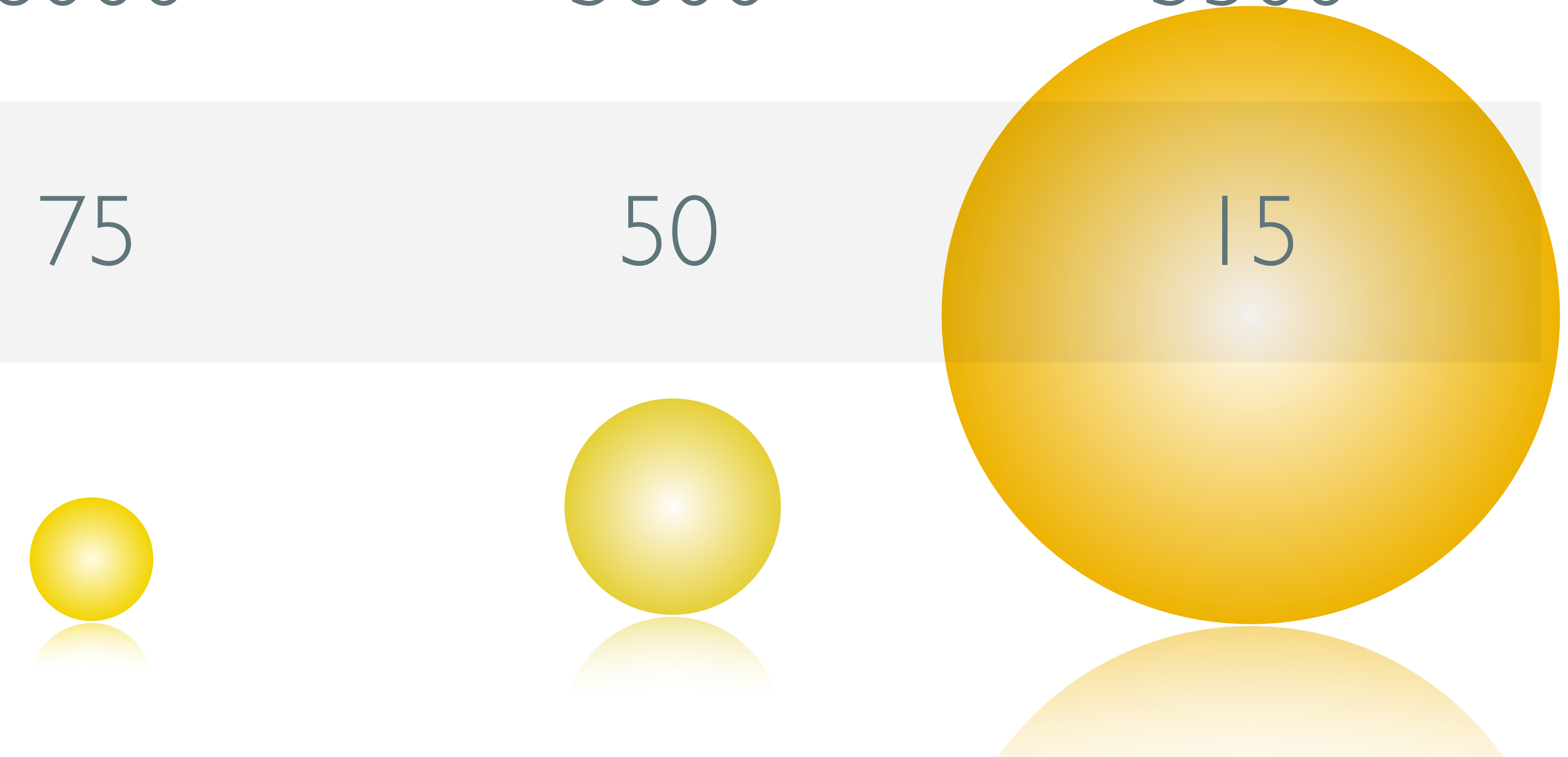
Overview of the presentation

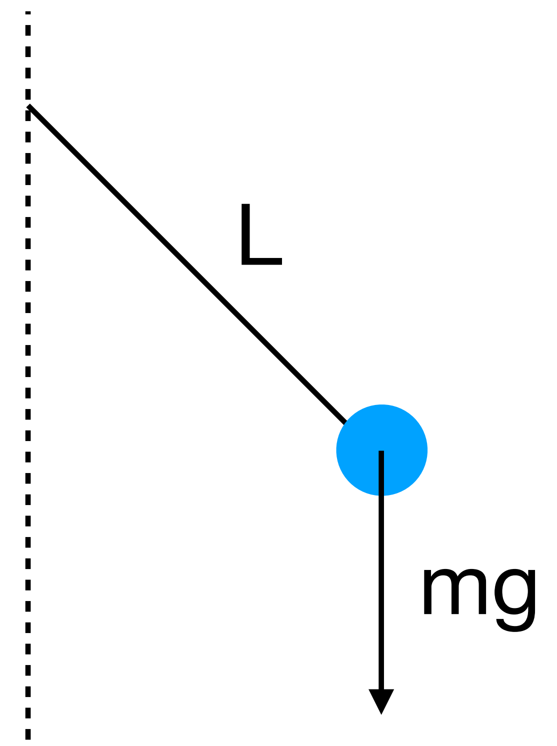
1. **Cepheids as stars and standard candles**
   - Modeling Cepheid pulsation, projection factor
   - Period-Luminosity calibration, effect of metallicity
   - Binarity, envelopes, reddening
2. **The distance to galaxy NGC 5584 from Cepheids**
   - The Cepheid+SNIa distance scale, HST data on NGC 5584
   - Photometric measurement methodology, corrections
   - Resulting distance, comparison with existing estimate

Period	5 days	10 days	40 days
Mass (Msun)	6	7	13
Radius (Rsun)	40	70	200
Density (g/m^3)	100	25	2
Luminosity (sol)	1000	2000	10 000
Temperature (K)	6000	5600	5300
Age (Ma)	75	50	15

Sun: 1 T/m^3
Air: 1300 g/m^3



Oscillation



- For an oscillating pendulum: $P = 2\pi\sqrt{\frac{L}{g}}$
- For an oscillating star:

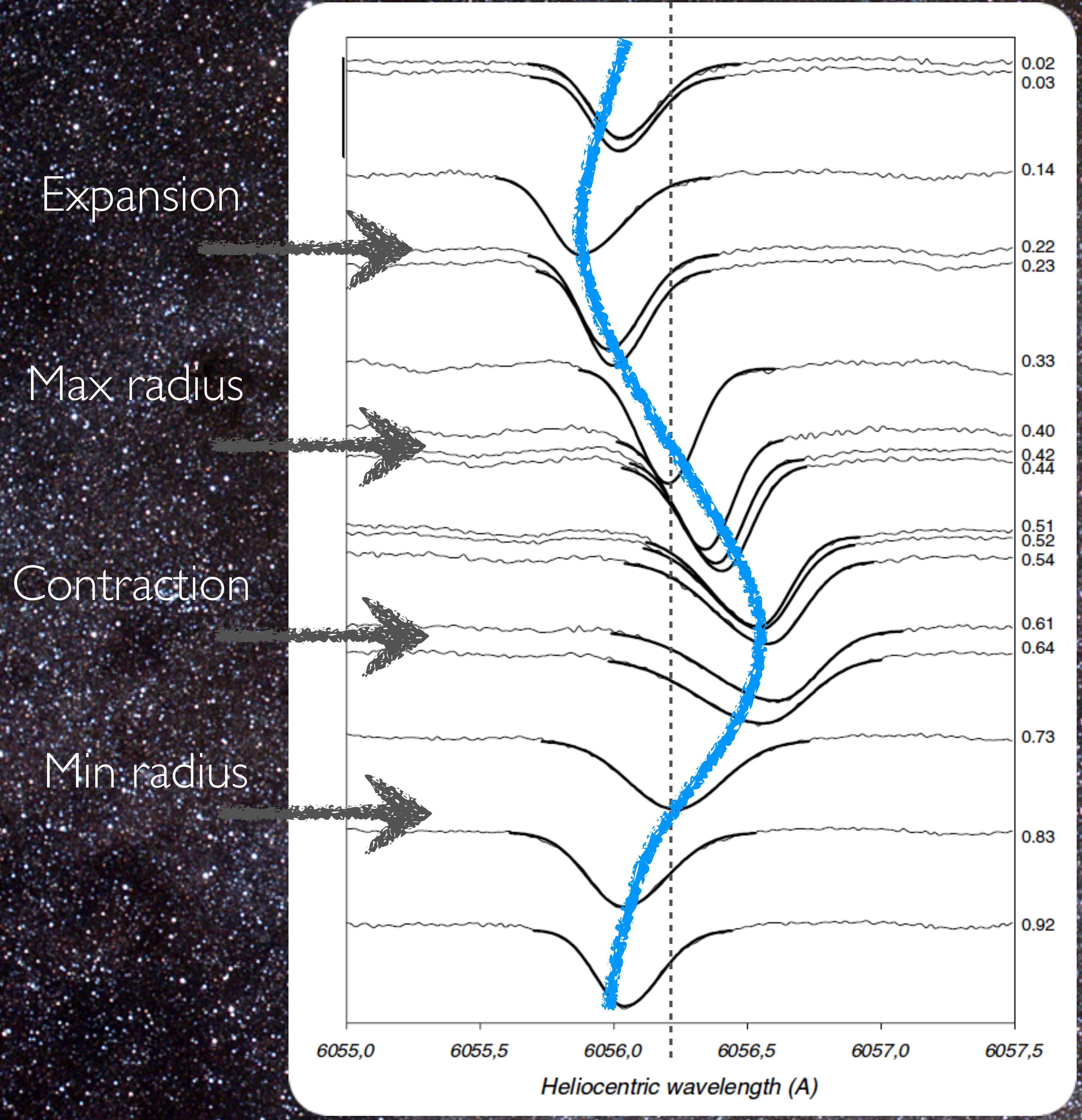
$$P \approx \sqrt{\frac{R}{GM/R^2}} \approx \sqrt{\frac{R^3}{M}} \approx \sqrt{\frac{1}{\mathrm{density}}}$$

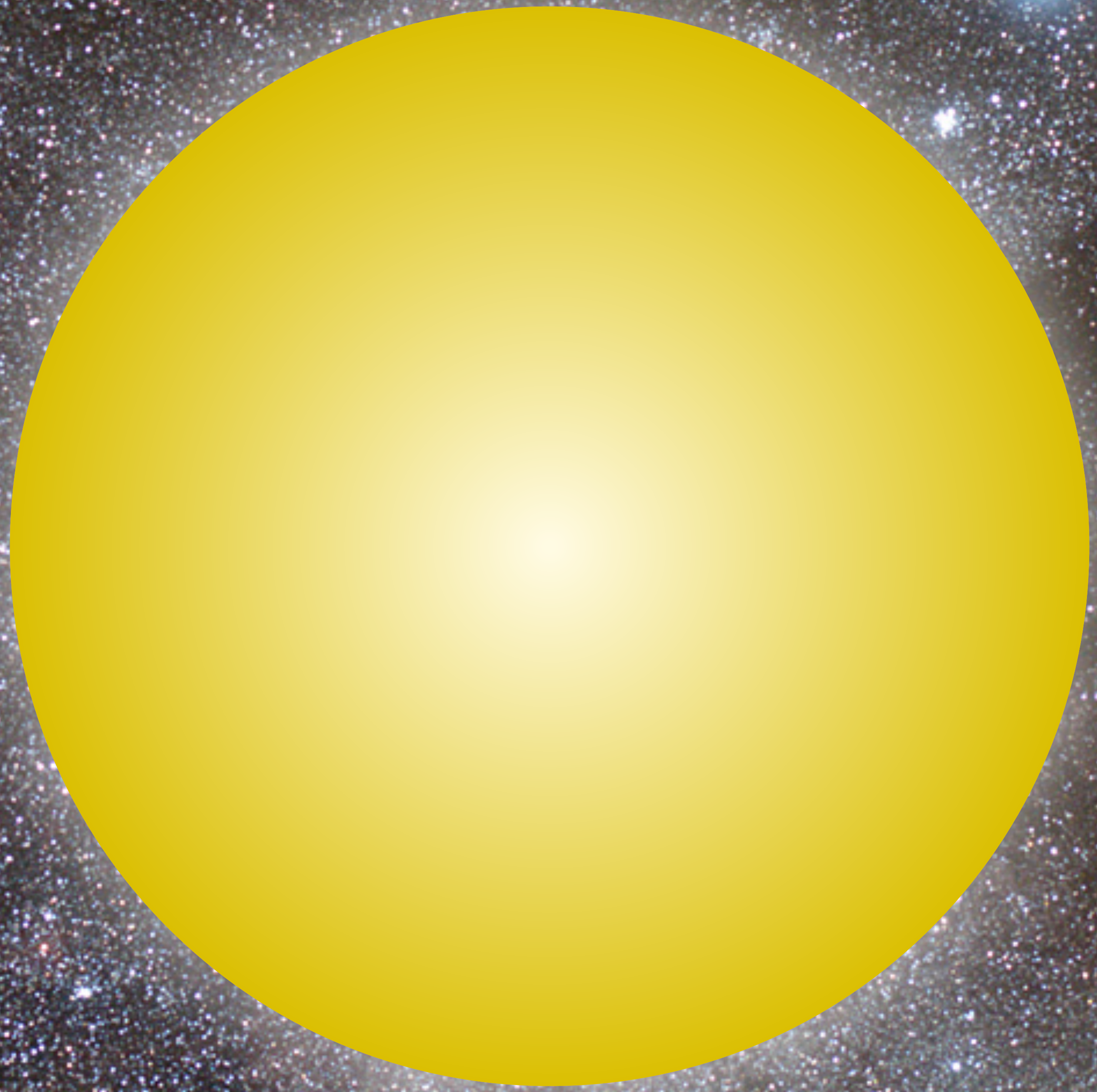
- For Cepheids

$$P[\mathrm{days}] \approx 0.0425 \times \sqrt{\frac{1}{\mathrm{density}[\mathrm{kg\,m}^{-3}]}}$$

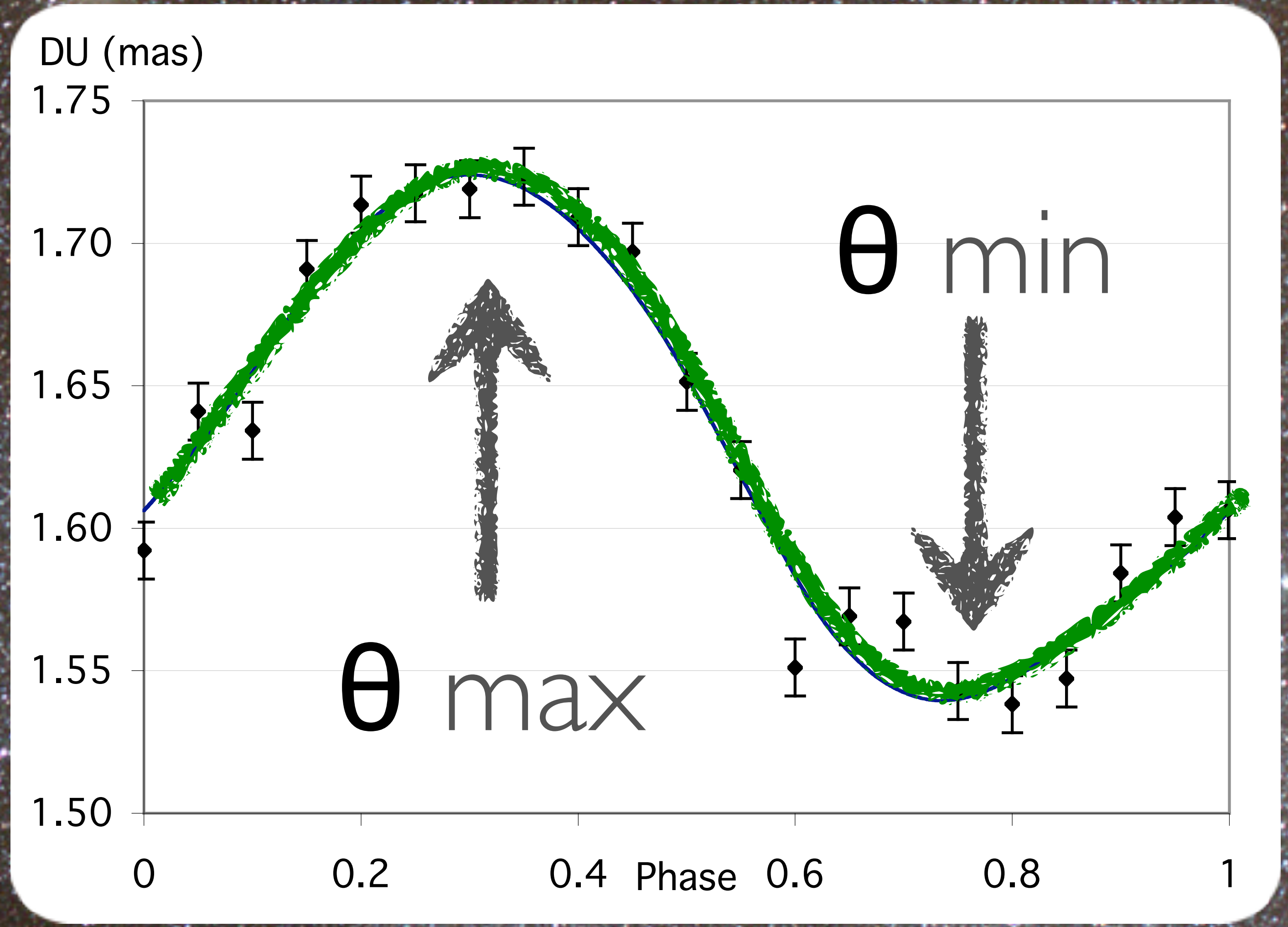
Measuring the pulsation

Radial velocity (spectroscopy)

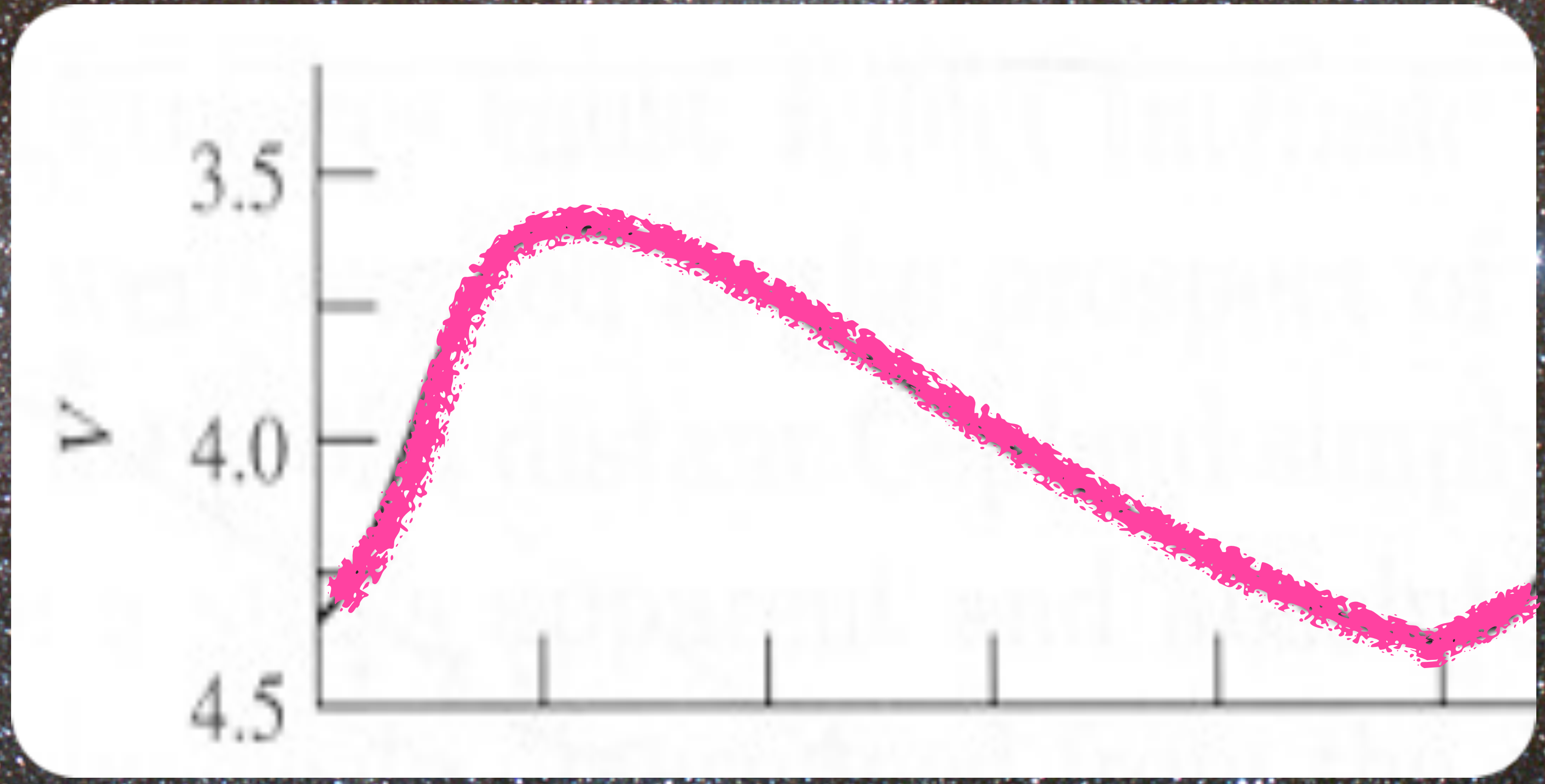




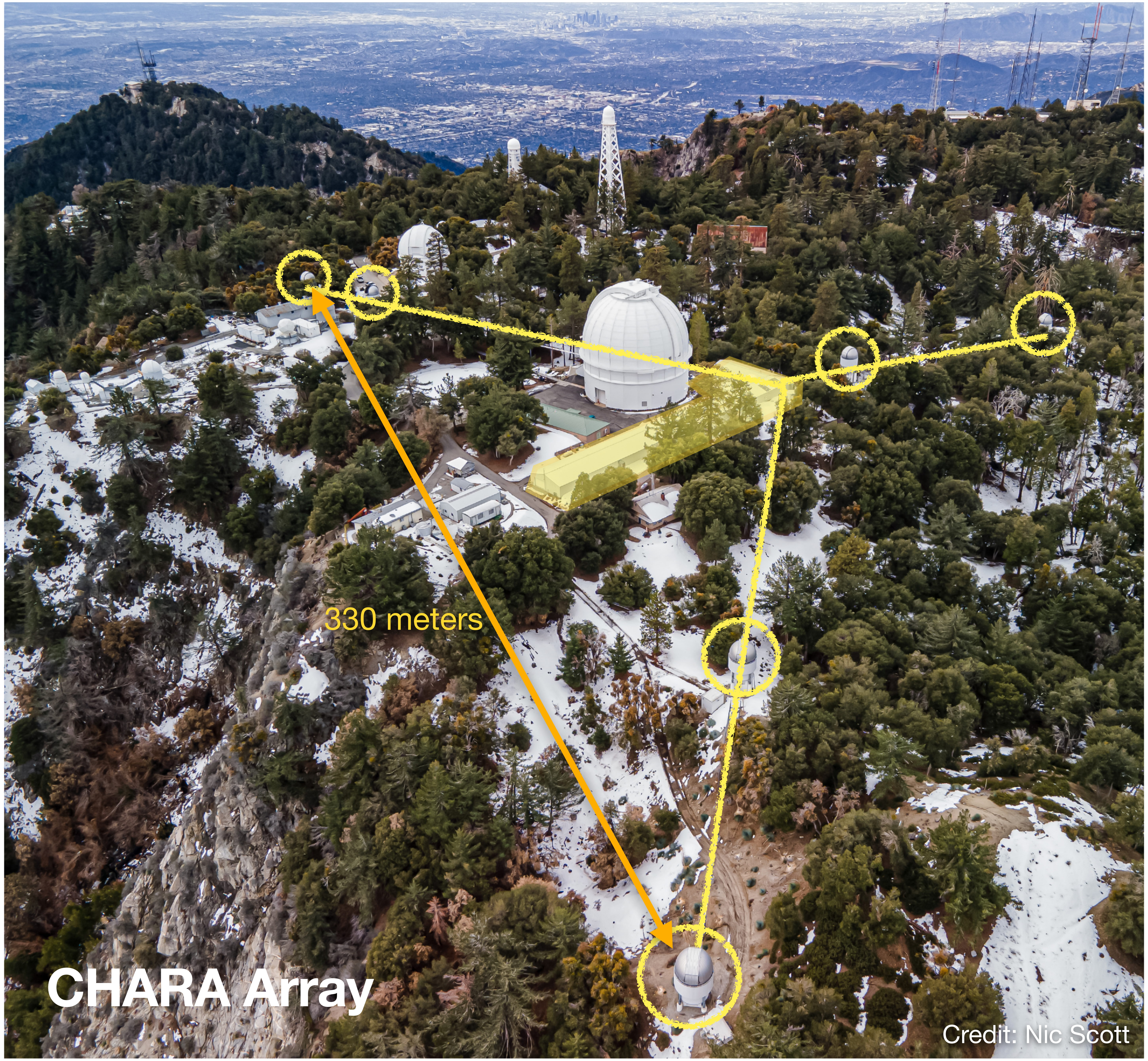
Angular diameter



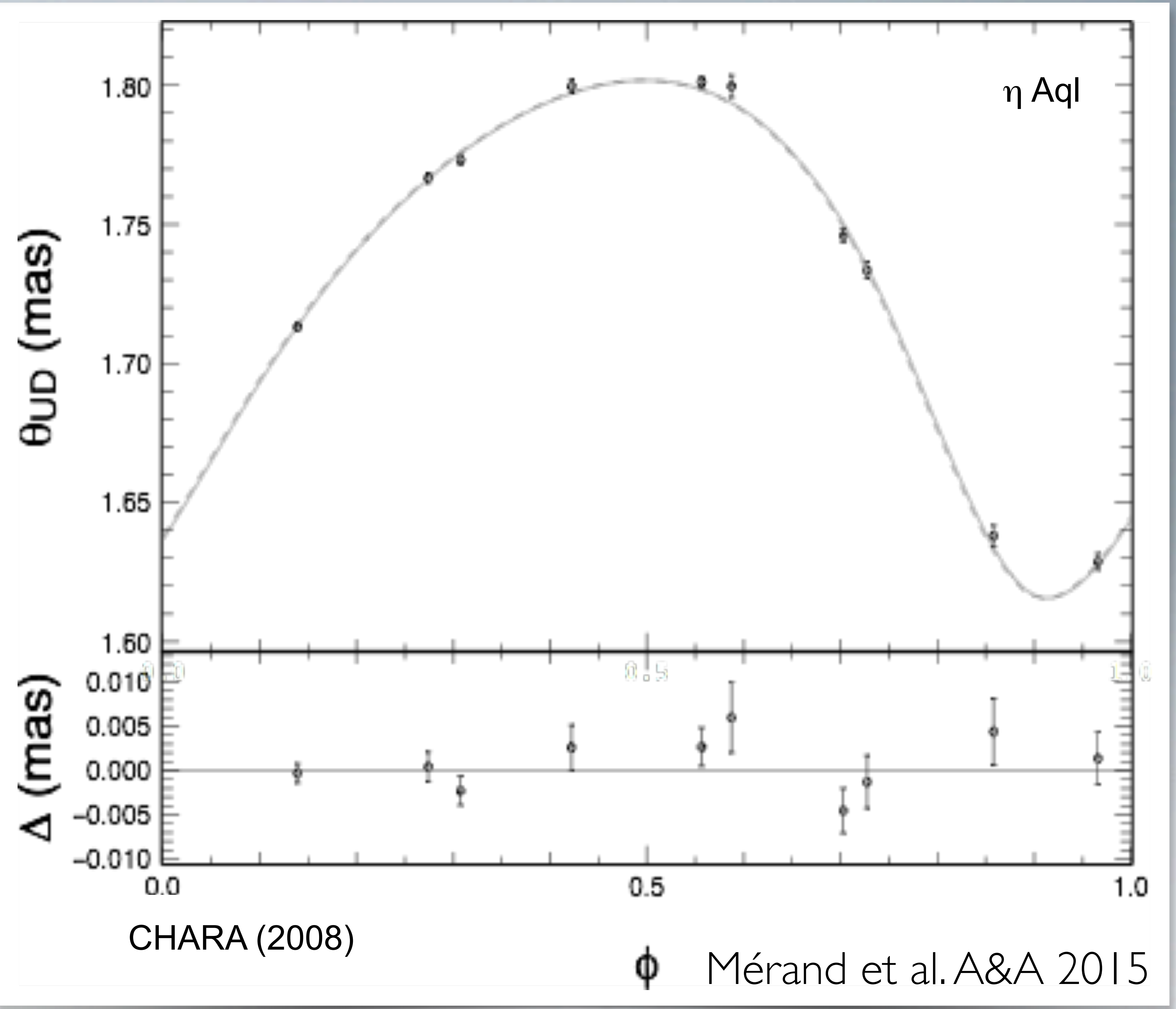
Photometry



Interferometry



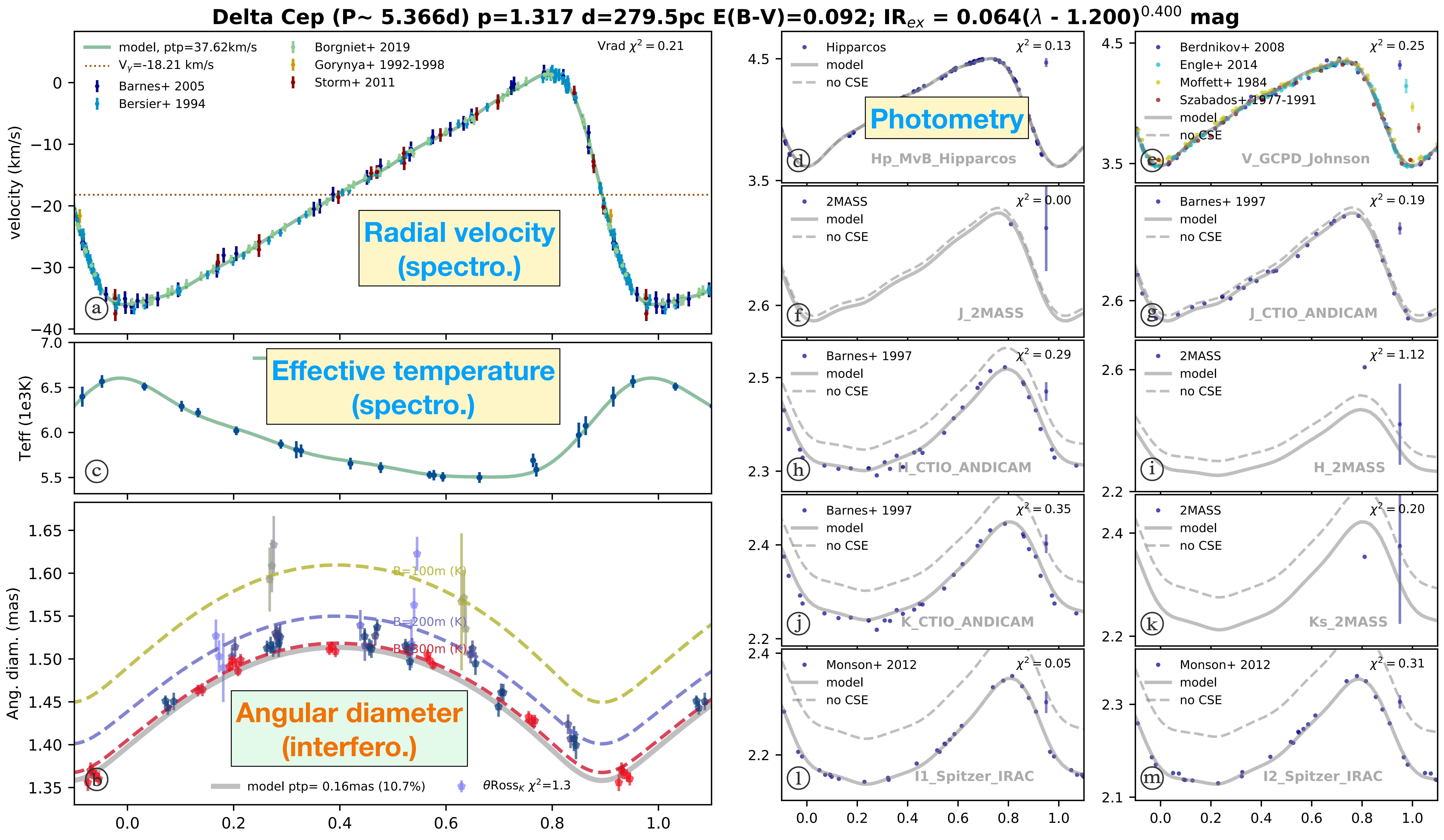
- Changing angular diameter of Cepheid η Aql



Modeling of Cepheid pulsation

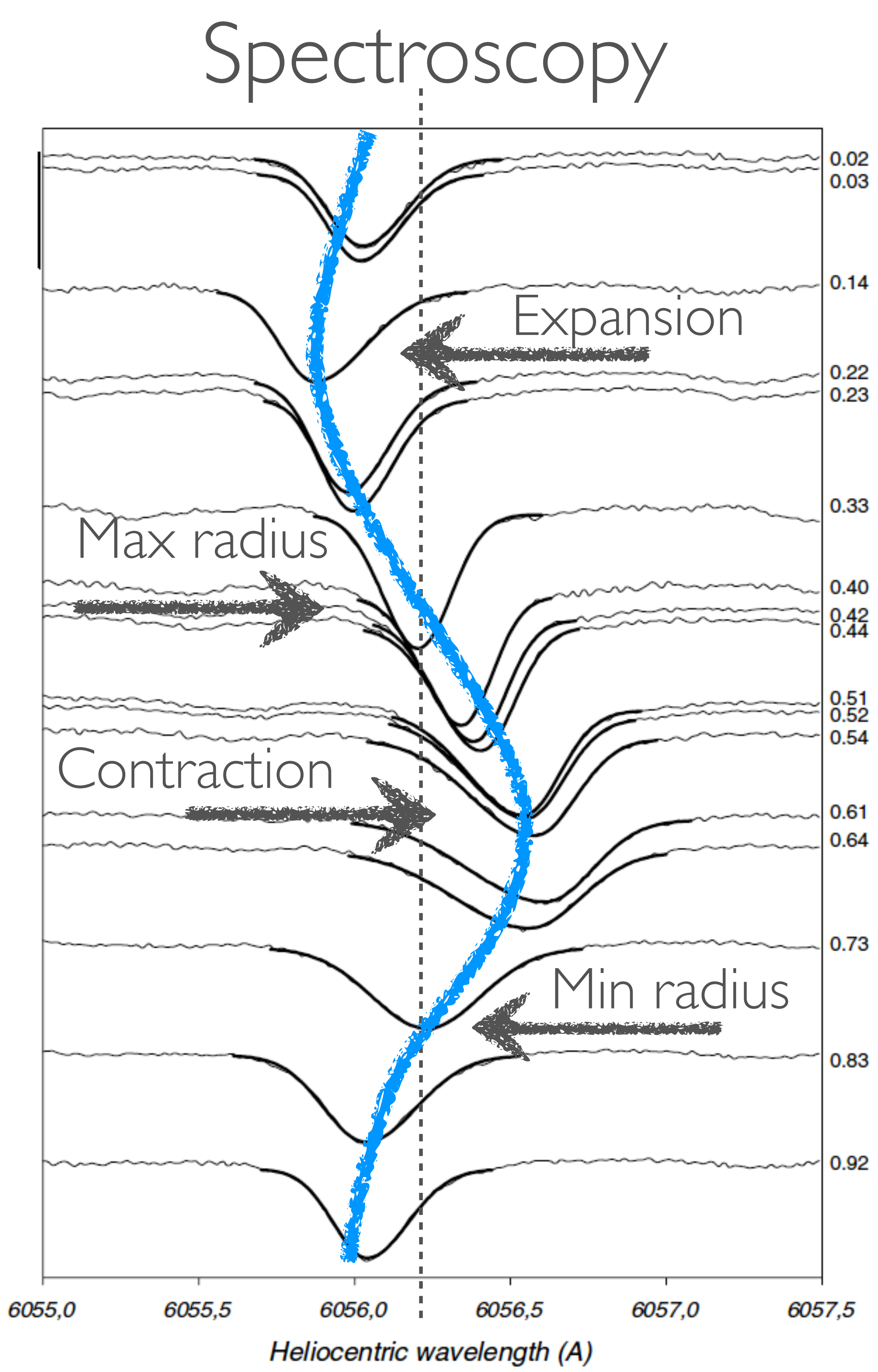
- Multi-observable modeling of the pulsation of **Galactic Cepheids**
- **Simultaneous fit** of multi-band photometry, radial velocity and interferometry
- Objectives: **better understand their pulsation and calibrate their properties**
- **T**aking advantage of ESA's Gaia astrometric distances

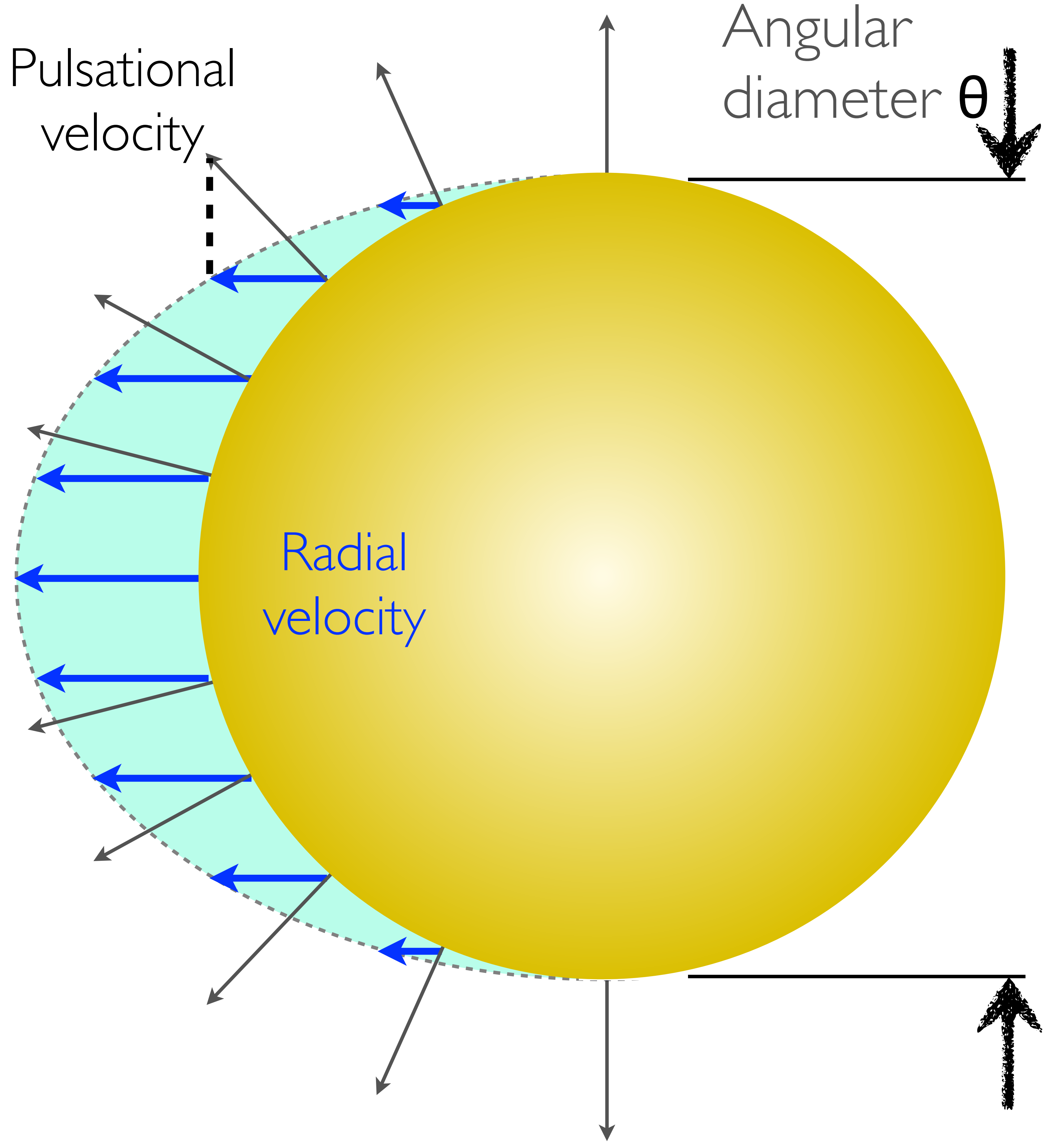
Modeling of Galactic Cepheids

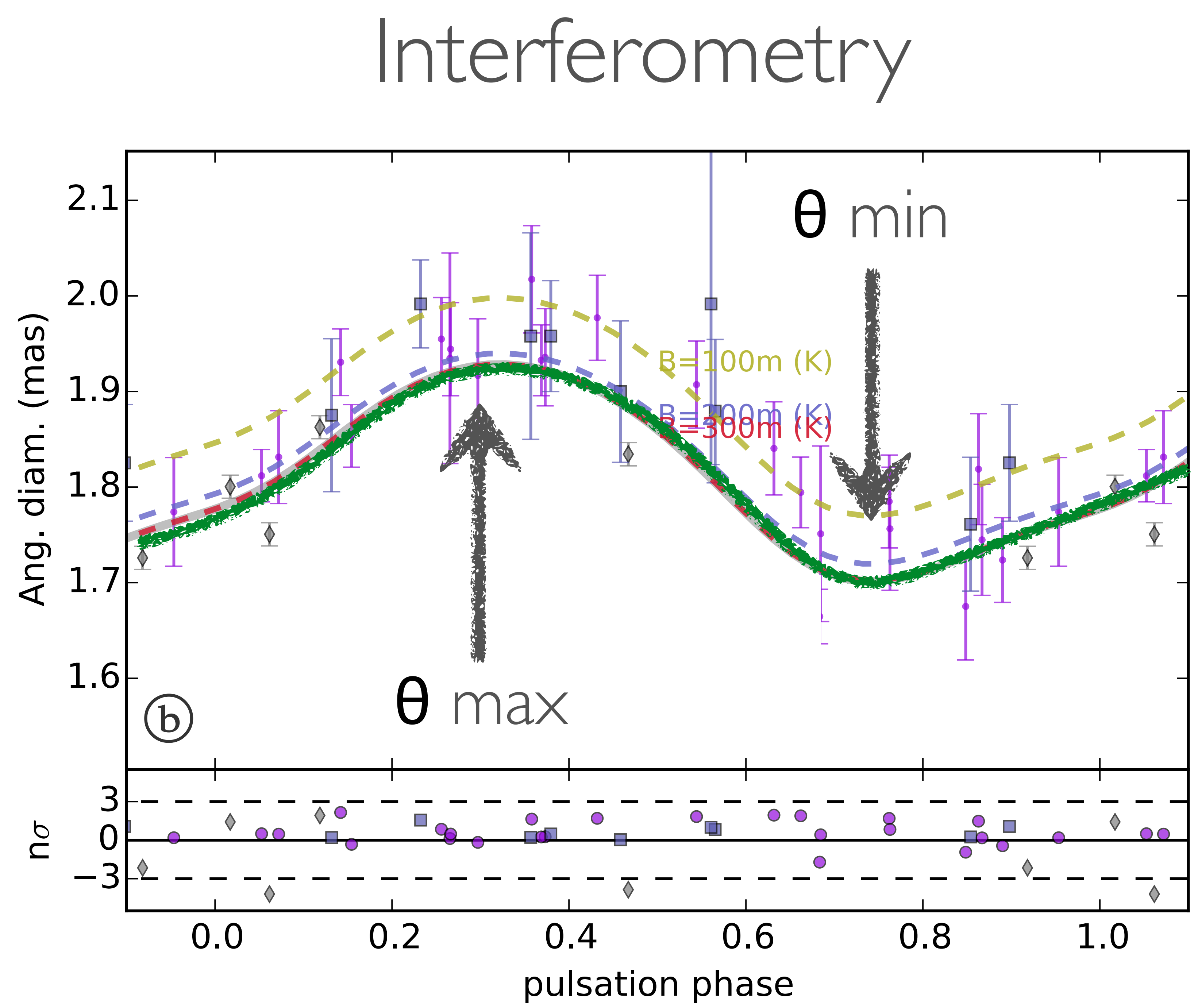


Trahin et al. (2021, A&A, 656, A102)

The Baade-Wesselink projection factor

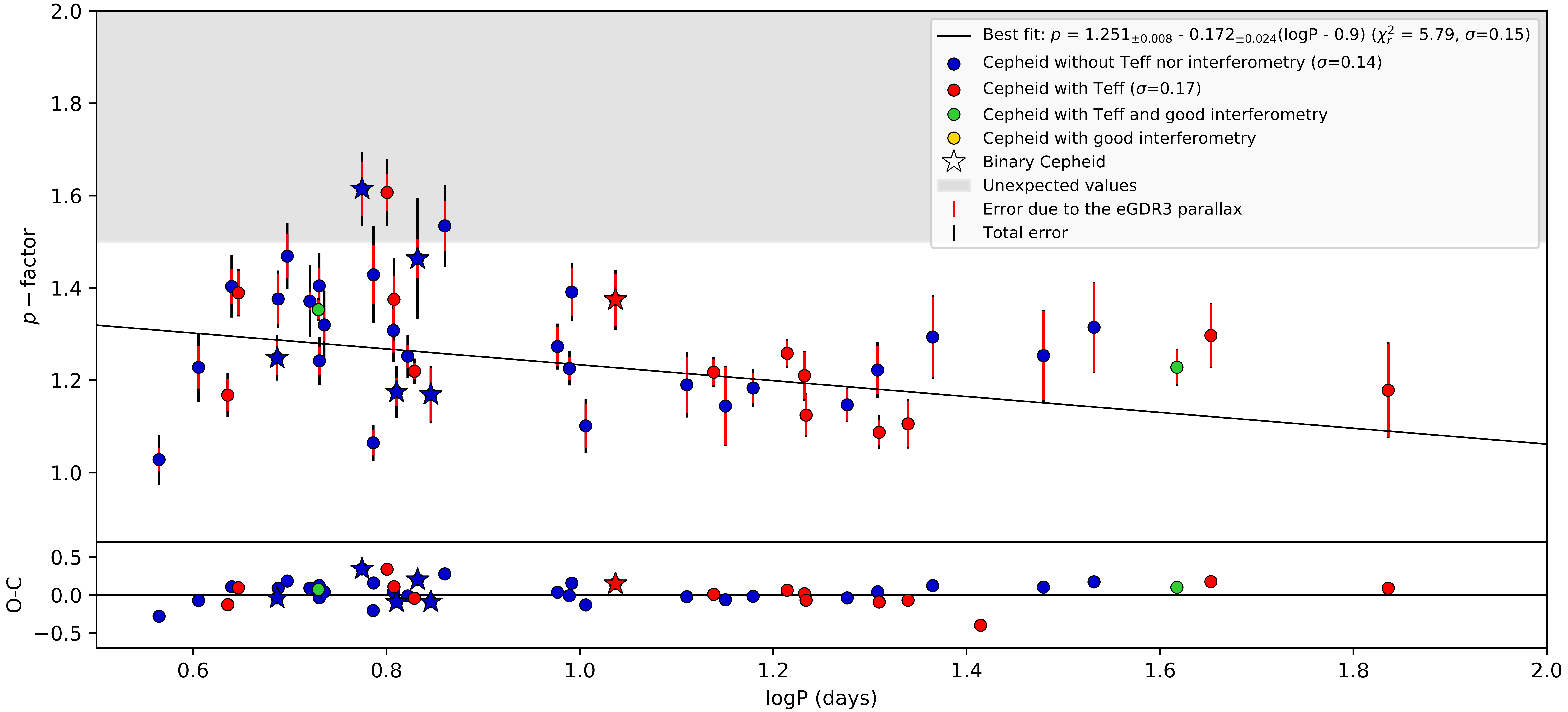






The Baade-Wesselink projection factor

- Significant scattering between Cepheids (σ = 0.15)
- No clear function of specific physical parameters of the stars

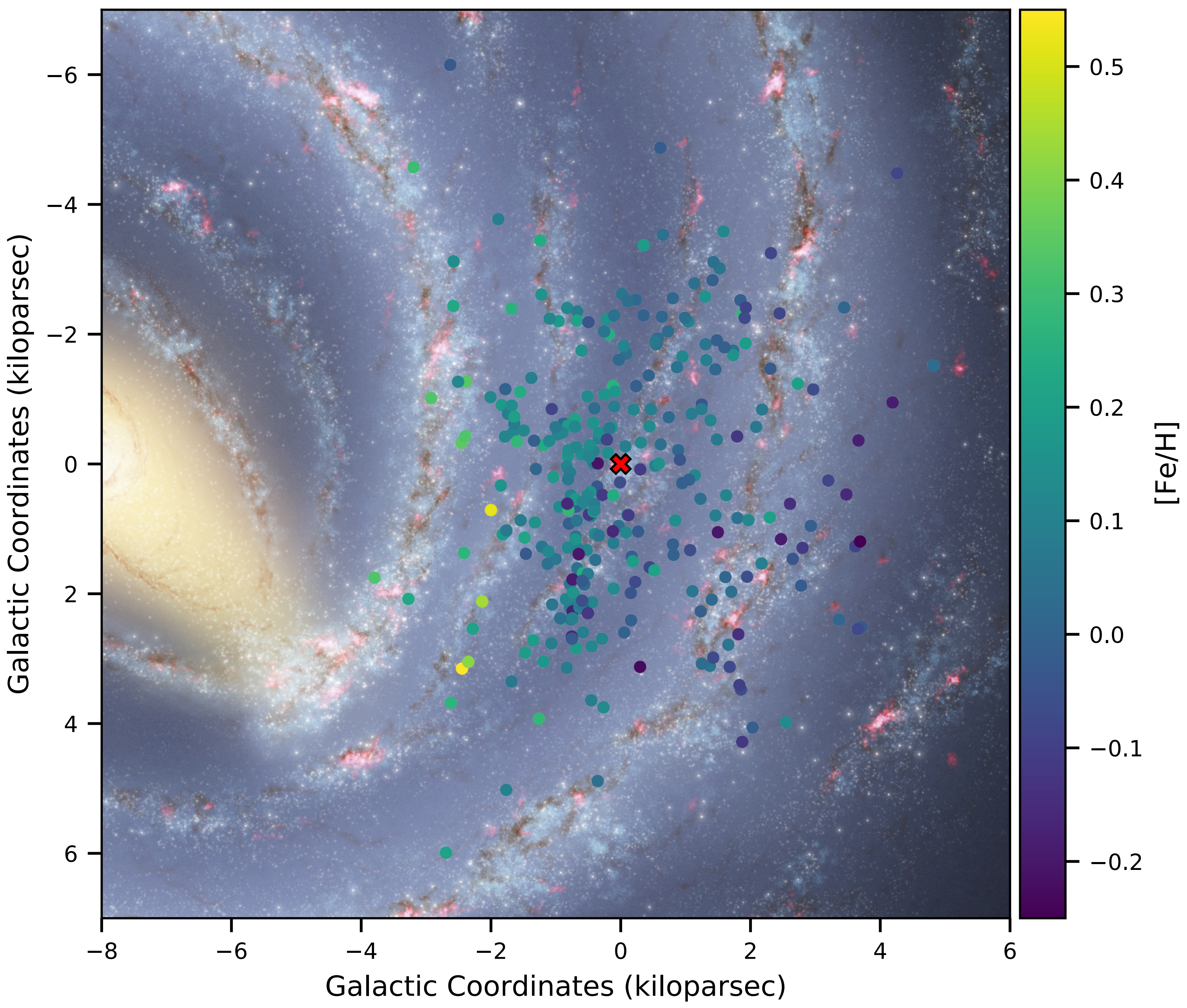


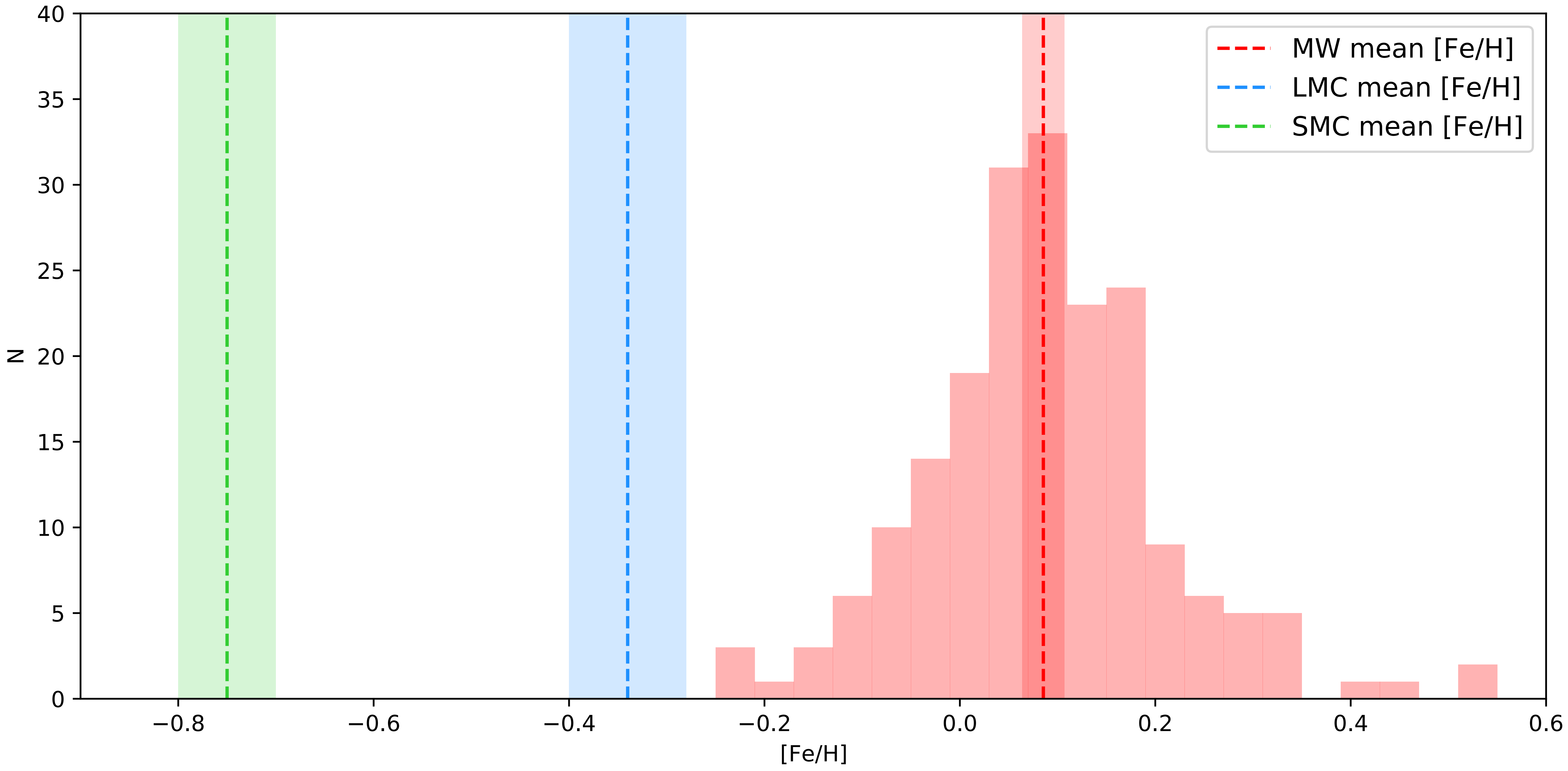
Trahin et al. (2021, A&A, 656, A102)

Period-Luminosity-Metallicity relation

Gaia EDR3 Galactic - LMC - SMC

- Calibration based on on DR2 Cepheid companion parallaxes, then on EDR3 parallaxes of Galactic Cepheids, together with LMC and SMC EB distances





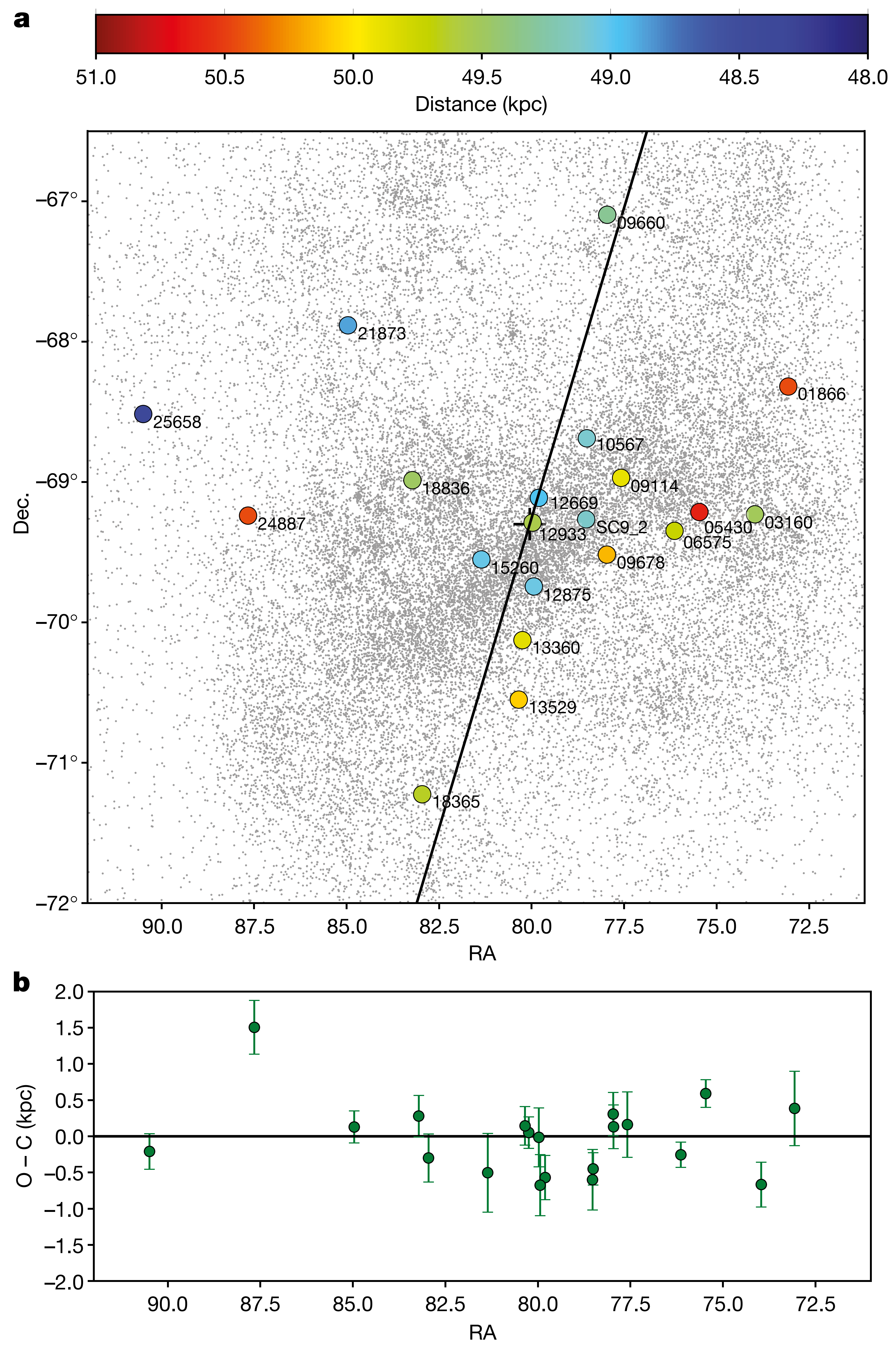
Breuval et al. 2021, ApJ, 913, 38
Breuval 10/2021, PhD thesis, Obs. De Paris

The LMC and the SMC

- The LMC is at present the **main anchor** of the Cepheid distance scale
- **Metallicity** has an effect on the absolute luminosity of Cepheids. At the moment, this effect is **uncertain**
- Metallicity of LMC [Fe/H] ~ -0.4 dex, SMC [Fe/H] ~ -1.0 dex
- Independent 1% distance modulus to the LMC using eclipsing binaries:

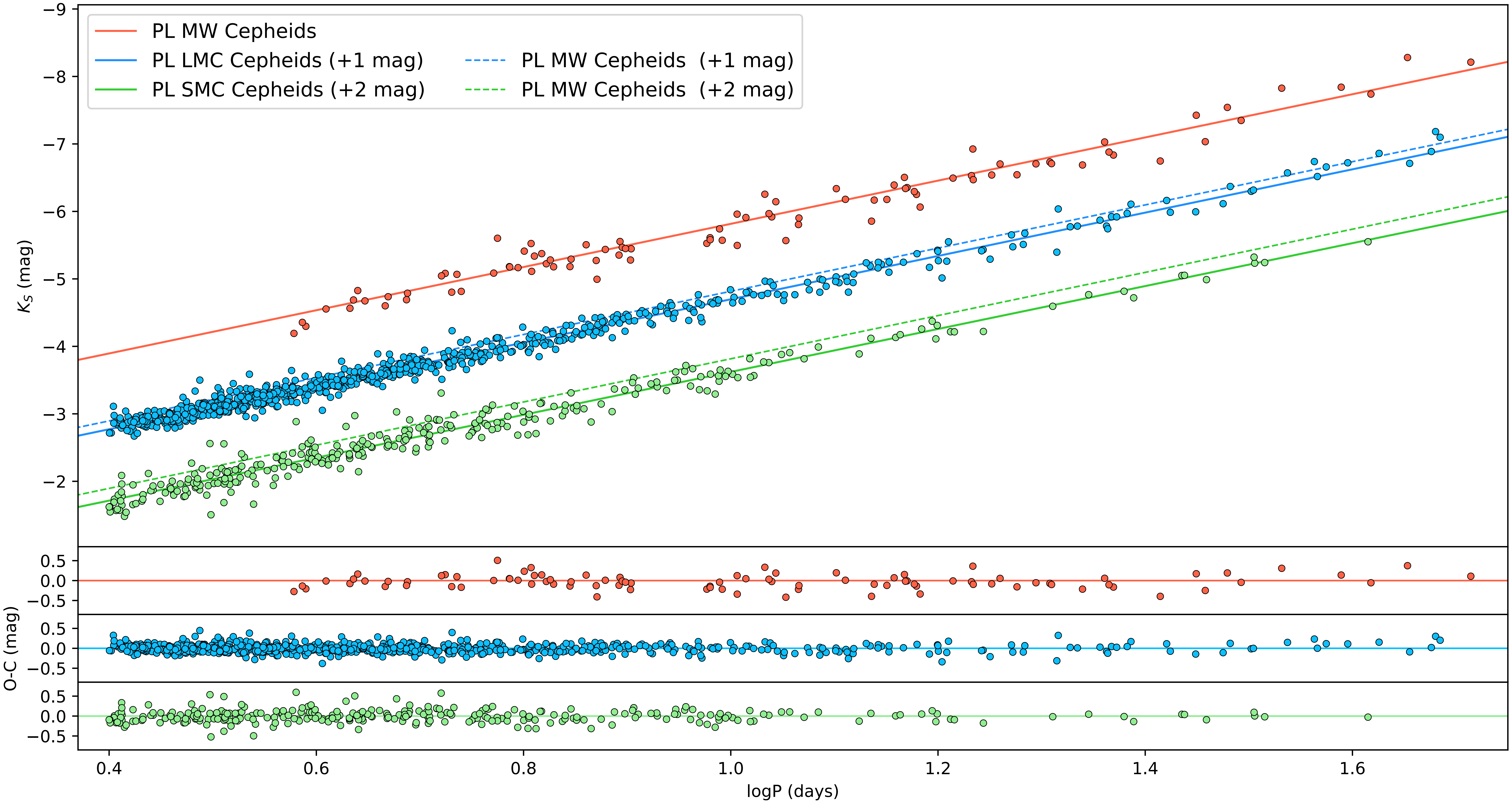
$$\mu = 18.477 \pm 0.004\ (\text{stat}) \pm 0.026\ (\text{syst})$$

- Relies on SBC calibrated by **VLTI angular diameter** measurements of red clump giants



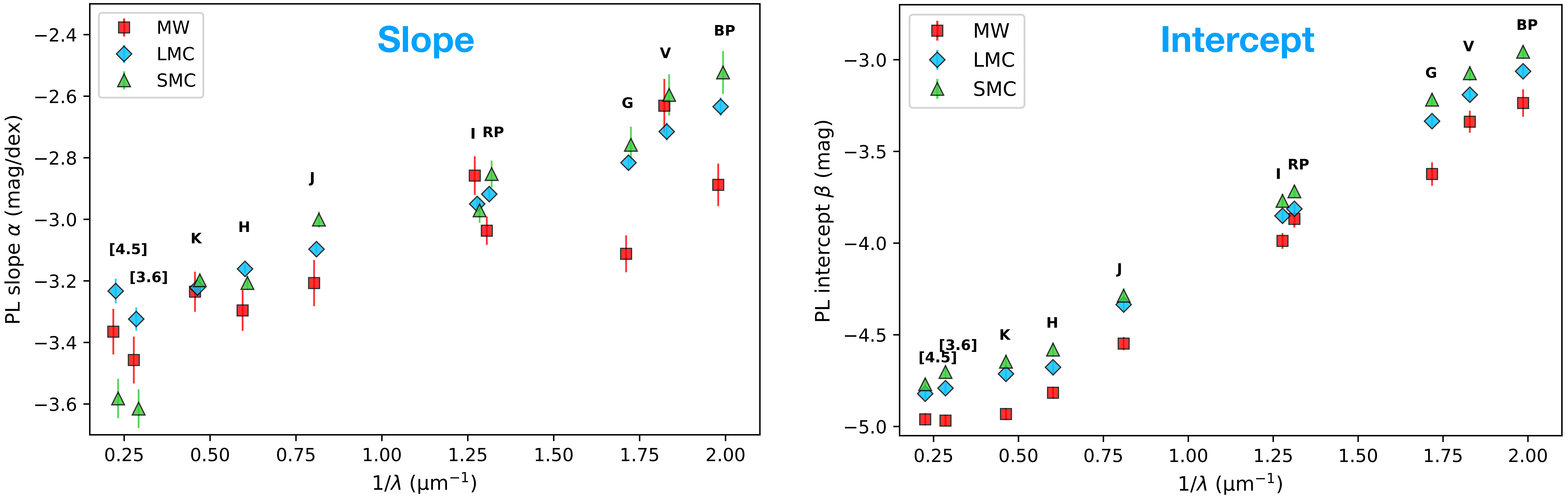
Pietrzynski et al. (2019, Nature, 567, 200)

Gallenne et al. (2018, A&A, 616, A68)



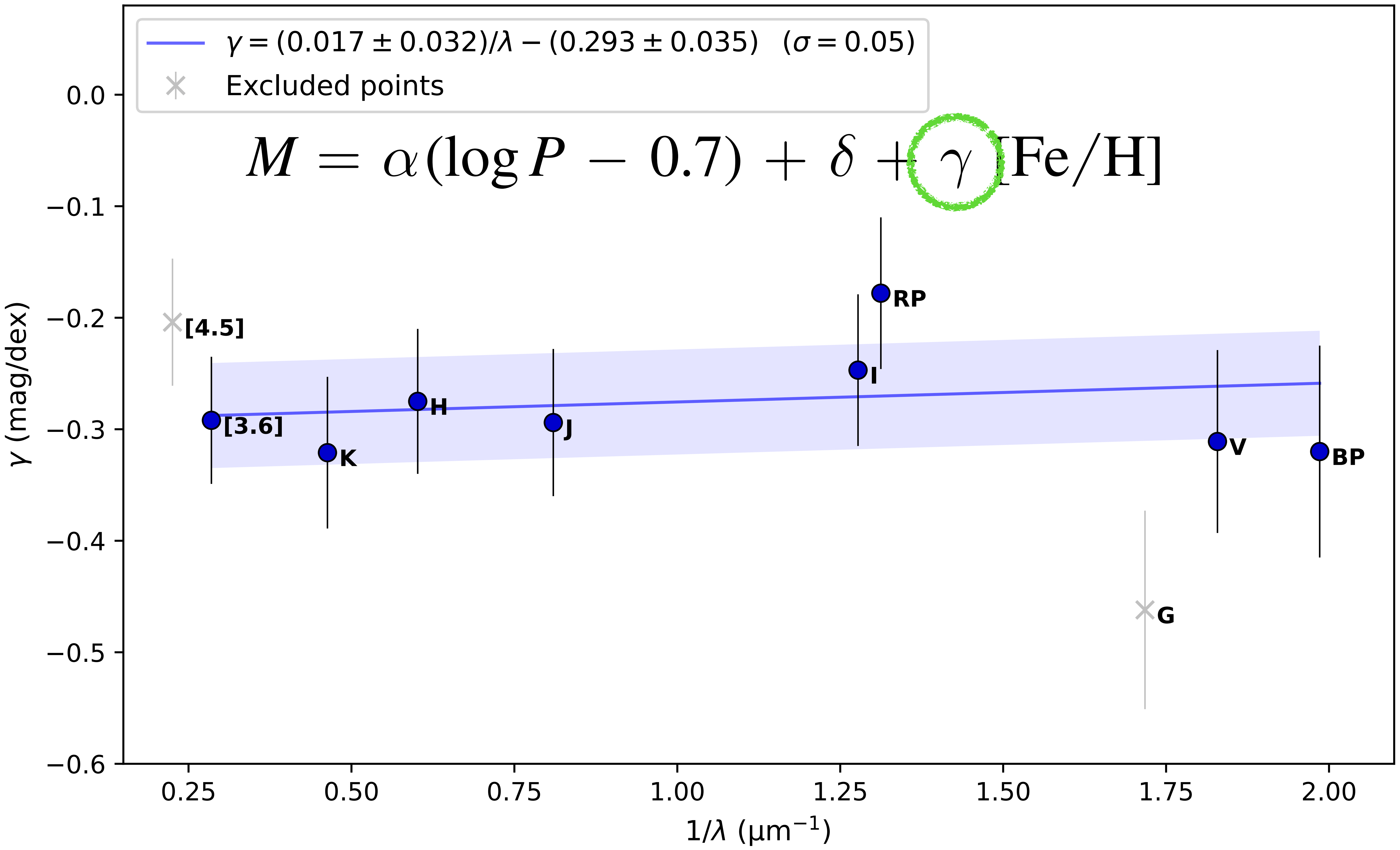
Breuval et al. 2021, ApJ, 913, 38
Breuval 2021, PhD thesis

Metallicity dependence of the PL relation



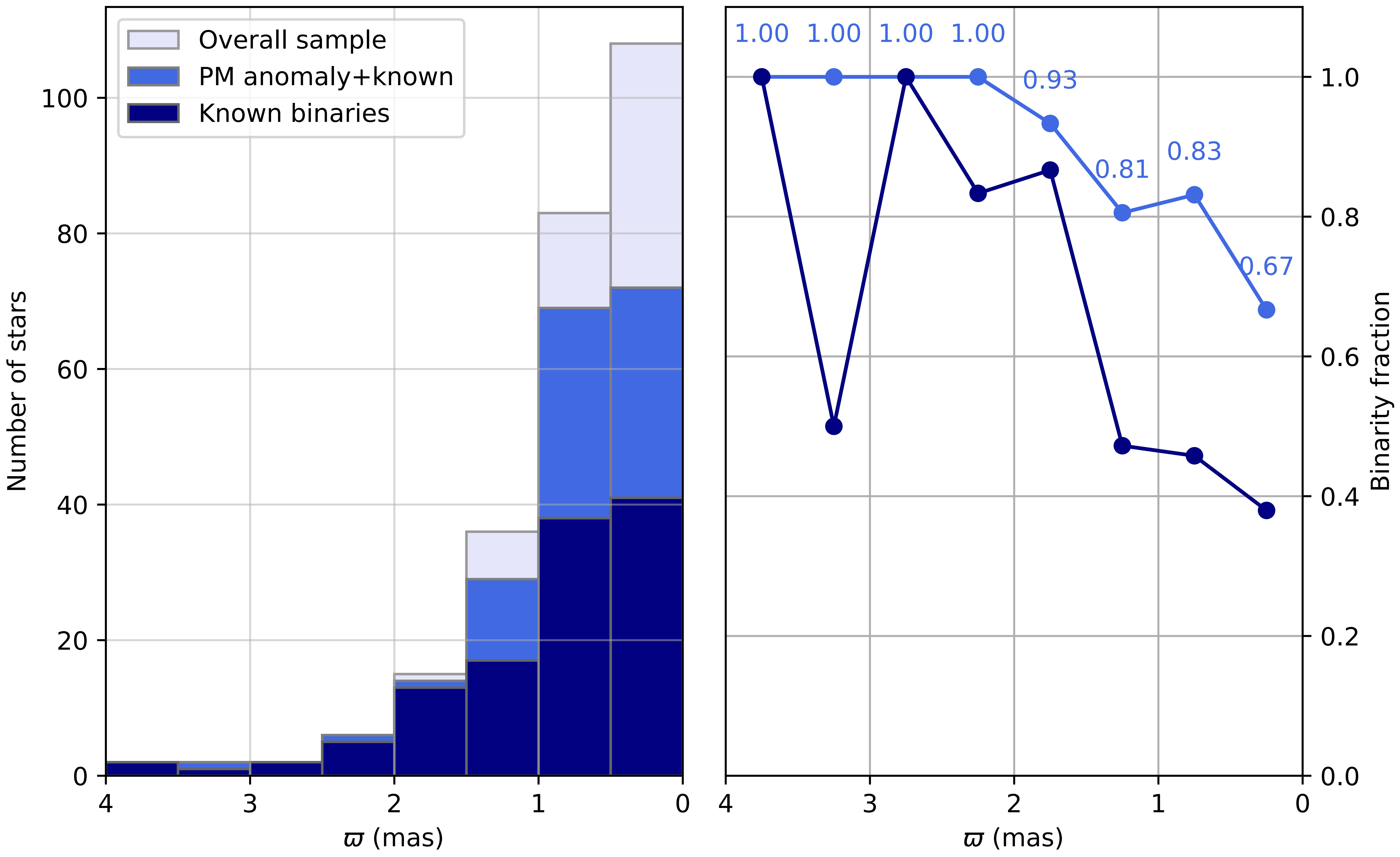
Breuval et al. 2022, ApJ, 939, 89

Metallicity term of PL relation



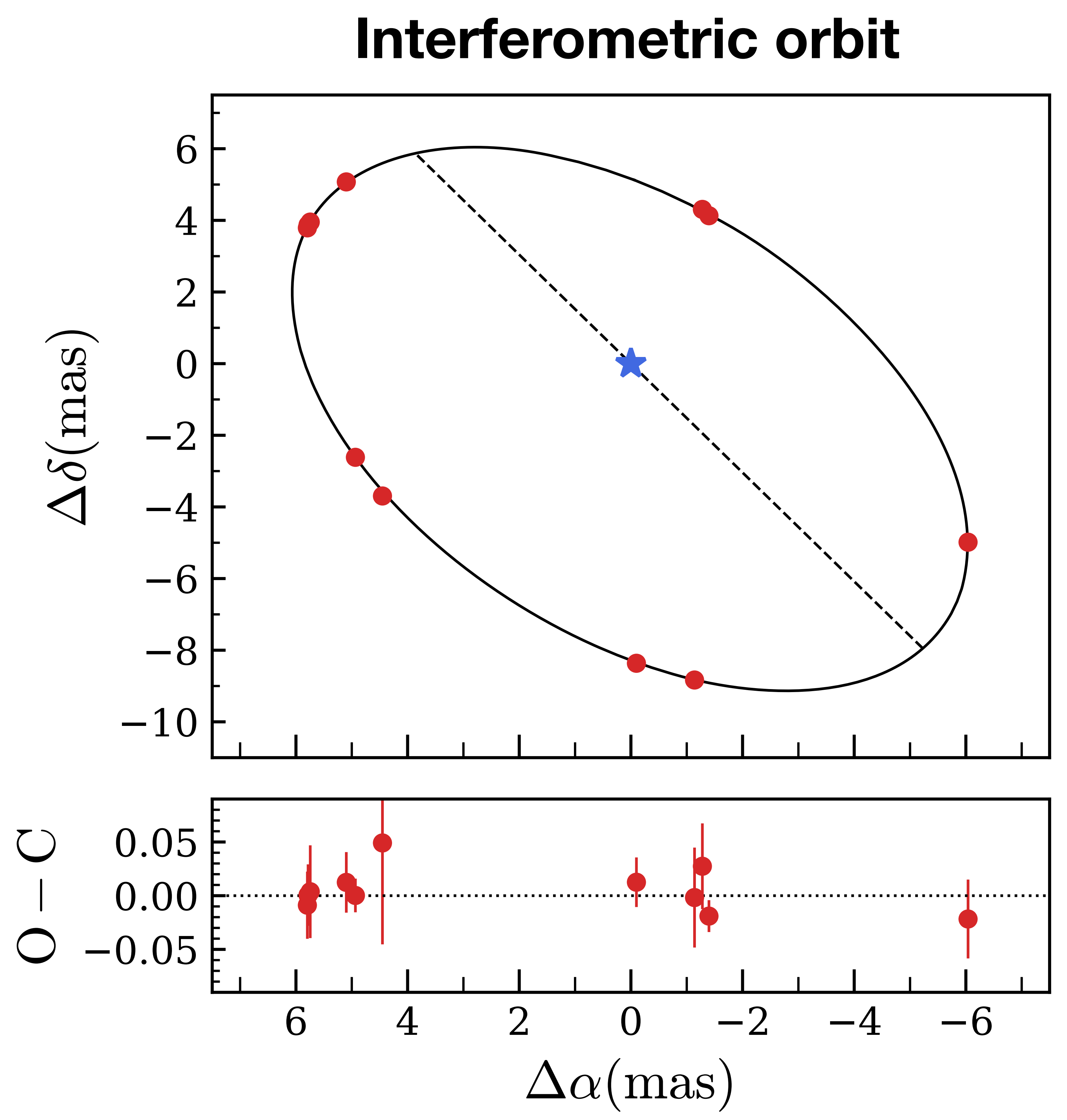
Breuval et al. 2022, ApJ, 939, 89

Cepheid binary fraction

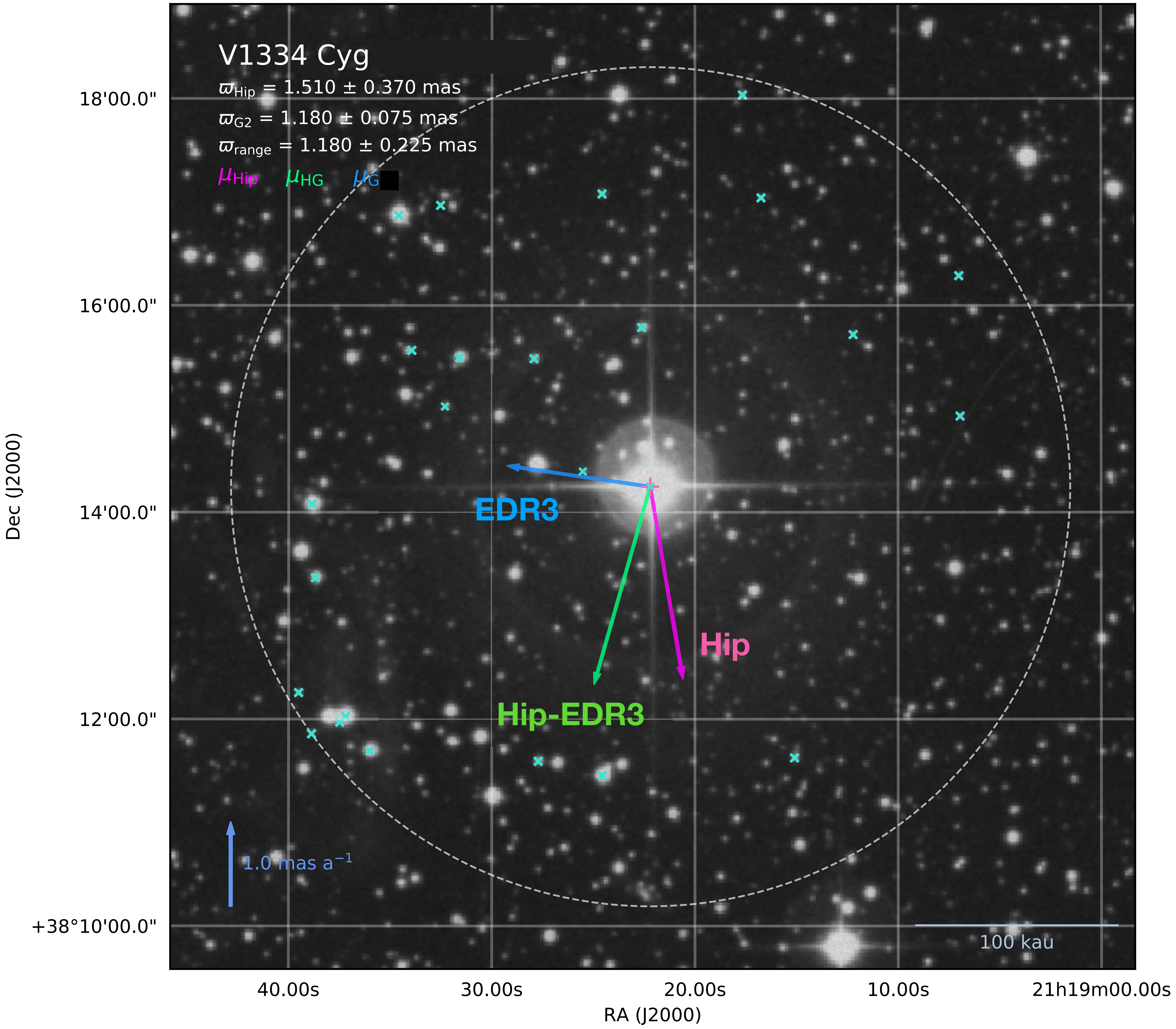


Kervella et al. 2019, A&A, 623, A116

V1334 Cyg

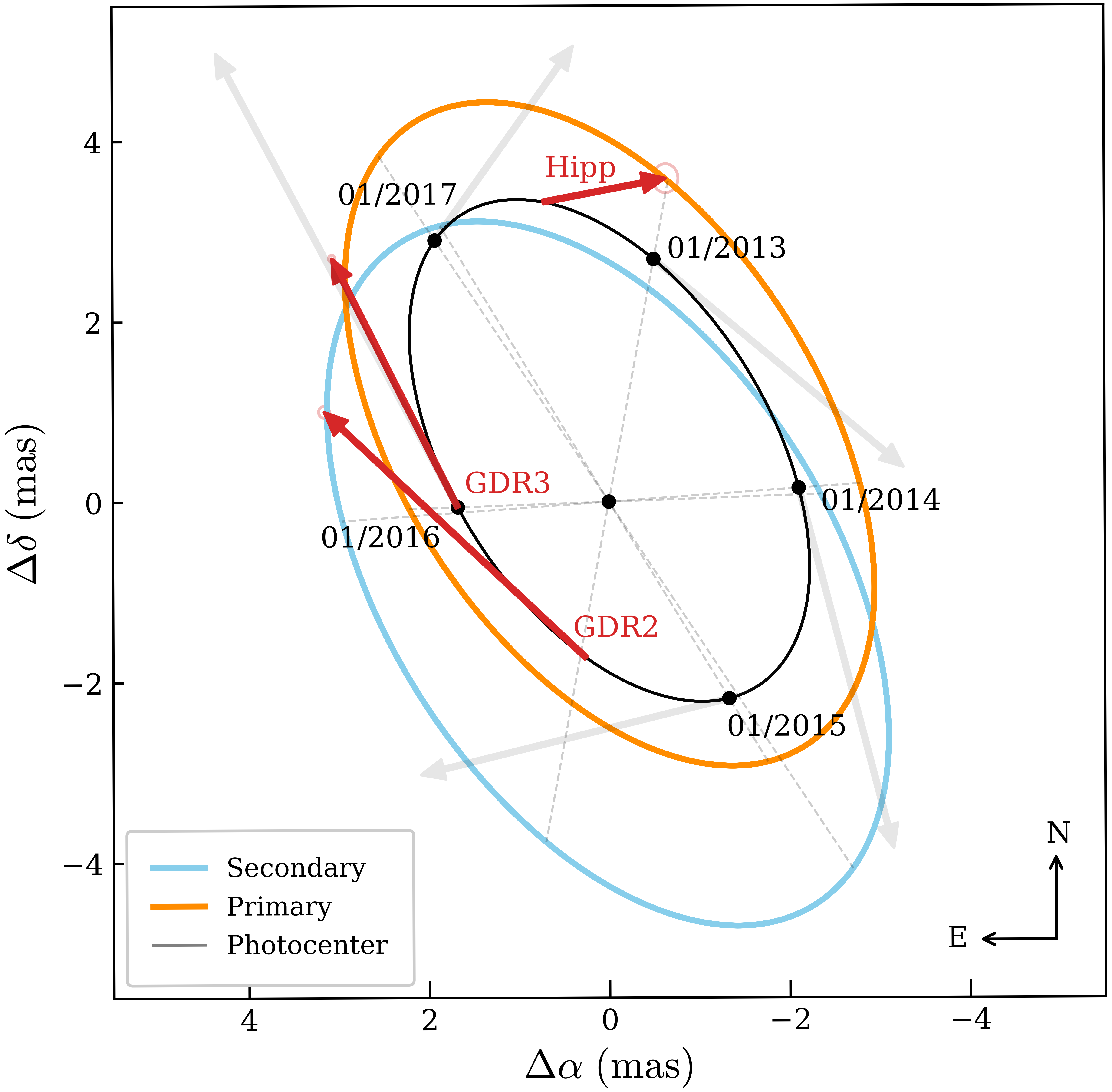


Gallenne et al. 2018, ApJ, 623, A116



V1334 Cyg

Gallenne et al. 2018, ApJ, 623, A116



Adopted parameters	
Parallax from GDR2 ϖ	$1.180_{\pm 0.066}$ mas $(1.388_{\pm 0.015}$ mas)
Mass from P-M m_1	$4.6_{\pm 0.7}\ M_\odot$ $(4.29_{\pm 0.13}\ M_\odot)$
Parameters from Evans (2000)	
Orbital period P	$1937.5_{\pm 2.1}$ d $(1932.8_{\pm 1.8}$ d)
Eccentricity e	$0.197_{\pm 0.009}$ $(0.233_{\pm 0.001})$
Arg. of periastron ω	$226.4_{\pm 2.9}$ deg $(229.8_{\pm 0.3}$ deg)
v_r amplitude K_1	$14.1_{0.1}$ km s^{-1} $(14.168_{0.014}$ km s^{-1})
v_r at Hip epoch	$+9.86 \pm 0.41$ km s^{-1}
v_r at GDR2 epoch	-9.66 ± 1.33 km s^{-1}
PMa vectors	
μ_{Hip}	$[-1.36_{\pm 0.29}, +0.26_{\pm 0.33}]$ mas a^{-1}
μ_{G2}	$[+2.90_{\pm 0.12}, +2.73_{\pm 0.14}]$ mas a^{-1}
Parameters from present analysis	
Inclination i	$118_{\pm 6}$ deg $(124.94_{\pm 0.09}$ deg)
Semimajor axis a	$6.18_{\pm 0.21}$ au $(6.16_{\pm 0.07}$ au)
Ang. semimajor axis θ	$7.3_{\pm 0.5}$ mas $(8.54_{\pm 0.04}$ mas)
Long. of asc. node Ω	$208_{\pm 6}$ deg $(213.17_{\pm 0.35}$ deg)
Mass of secondary m_2	$3.80_{\pm 0.57}\ M_\odot$ $(4.04_{\pm 0.05}\ M_\odot)$

ϖ(orbit) = 1.388 ± 0.015 mas

ϖ(Hip2) = 1.51 ± 0.37 mas (+0.3σ)

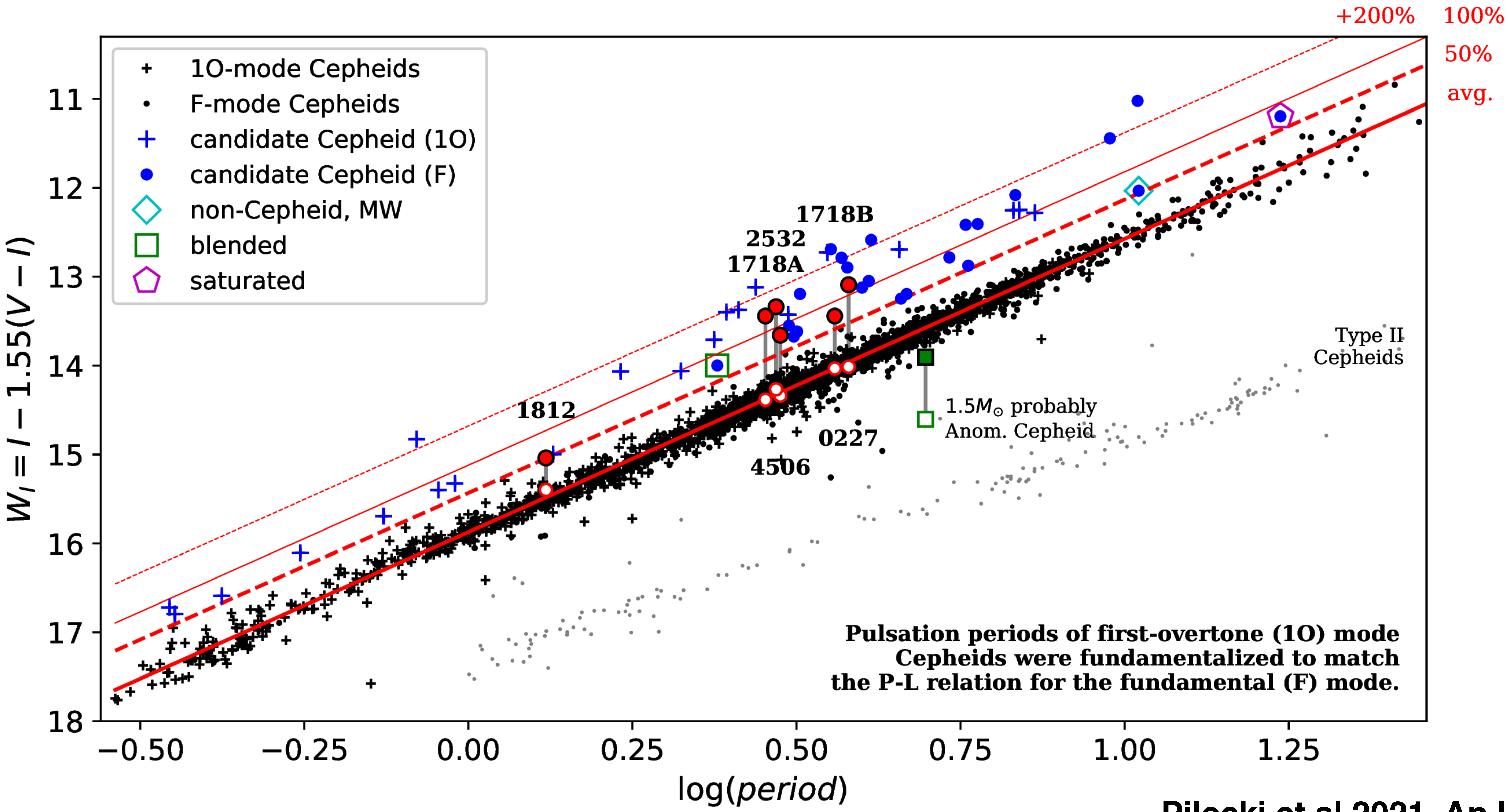
ϖ(DR2) = 1.180 ± 0.075 mas (RUWE =1.2; -3.3σ)

ϖ(EDR3) = 1.113 ± 0.084 mas (RUWE = 2.8; -3.2σ)

Kervella et al. 2019, A&A, 623, A116

Effect of binarity in the LMC

– 41 LMC Cepheids brighter > 50% (OGLE-3 catalog)



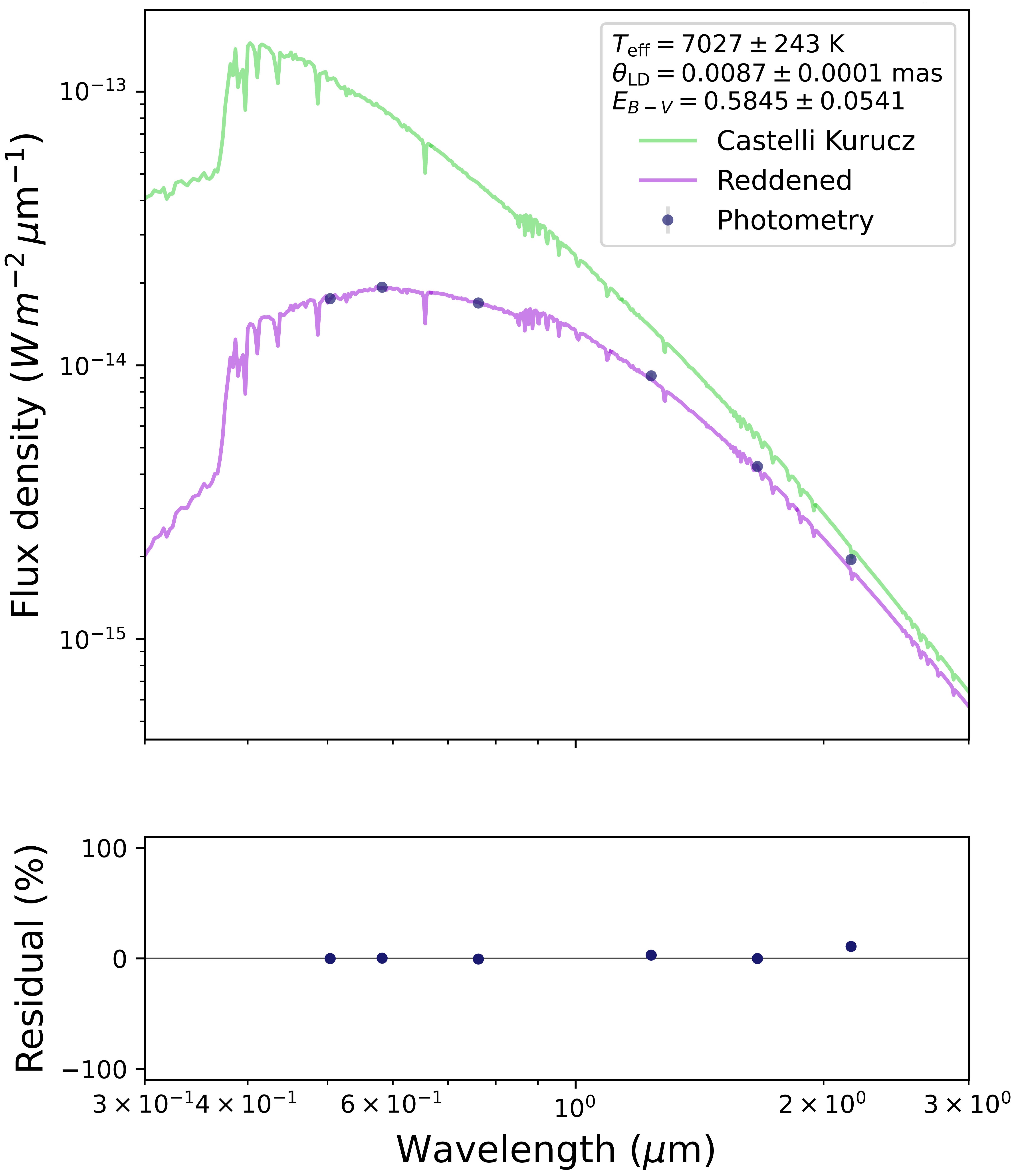
Pilecki et al 2021, ApJ 910, 118

Reddening

- The interstellar dust absorption/scattering modifies the apparent spectral energy distribution of stars
- It is possible to use Wesenheit indices to obtain « reddening insensitive » magnitudes (Madore 1982), for instance:

$$W_{VI} = I - 1.526\,(V - I)$$

- The chosen reddening law has an influence.



Reddening law

Extinction:

$$A_\lambda \equiv 2.5 \log_{10}(F_\lambda^0 / F_\lambda)$$

Slope of reddening law A_λ in the visible:

$$R_V = \frac{A_V}{A_B - A_V}$$

~1.2 for very small grains (Rayleigh scattering)

→∞ for very large grains (grey extinction)

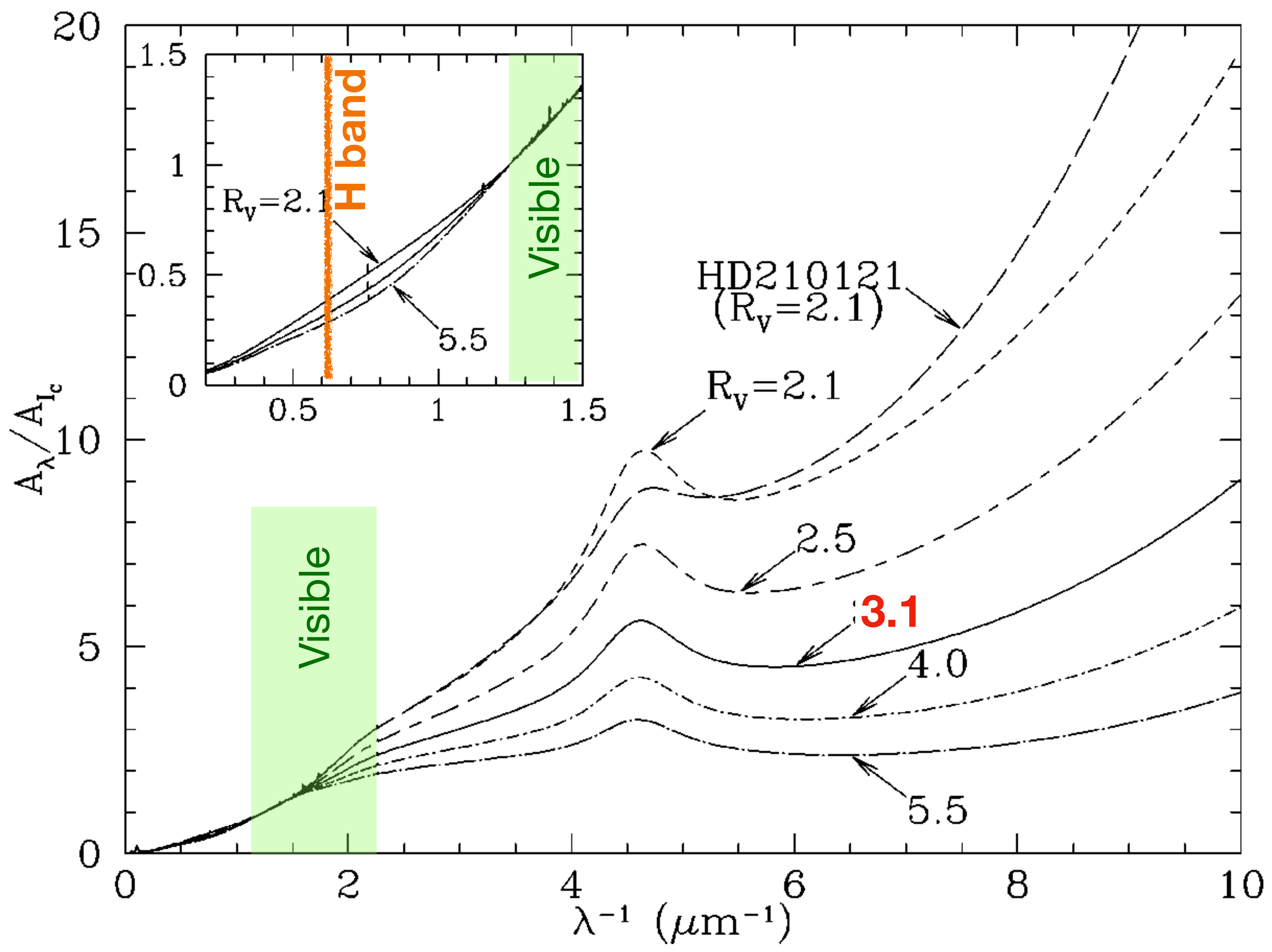
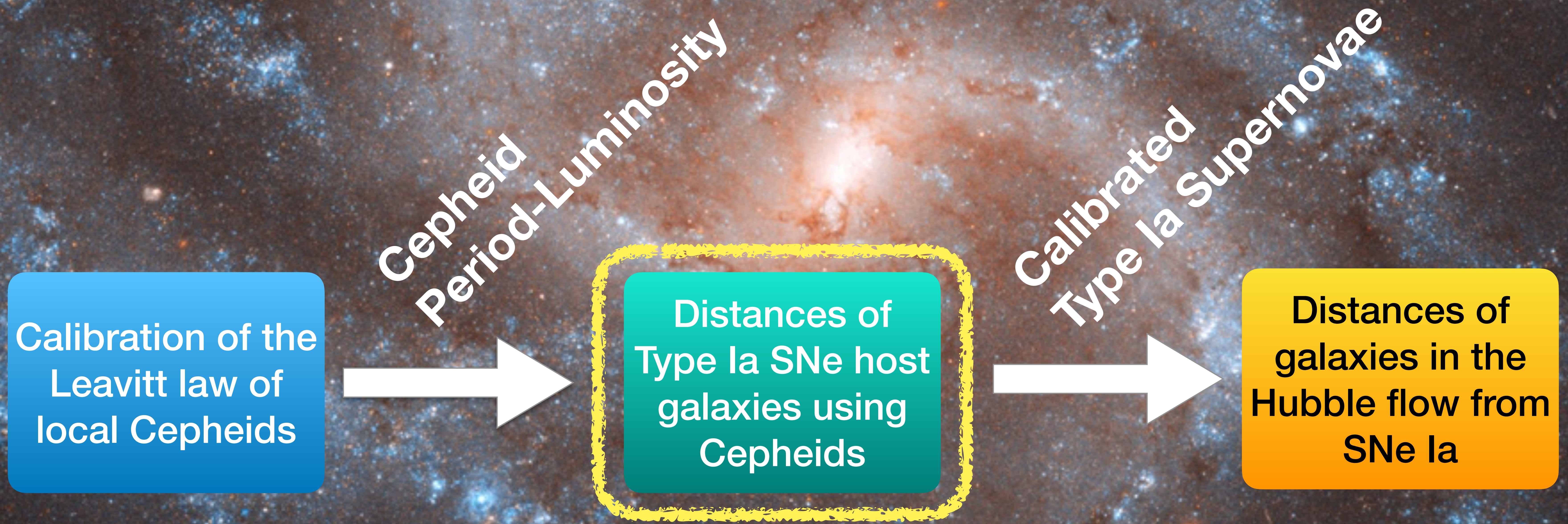


Figure 1 Extinction curves from prescription of Fitzpatrick (1999), with diffuse interstellar bands (DIBs) added as described in Section 3.3. The DIBs are barely visible on this plot.

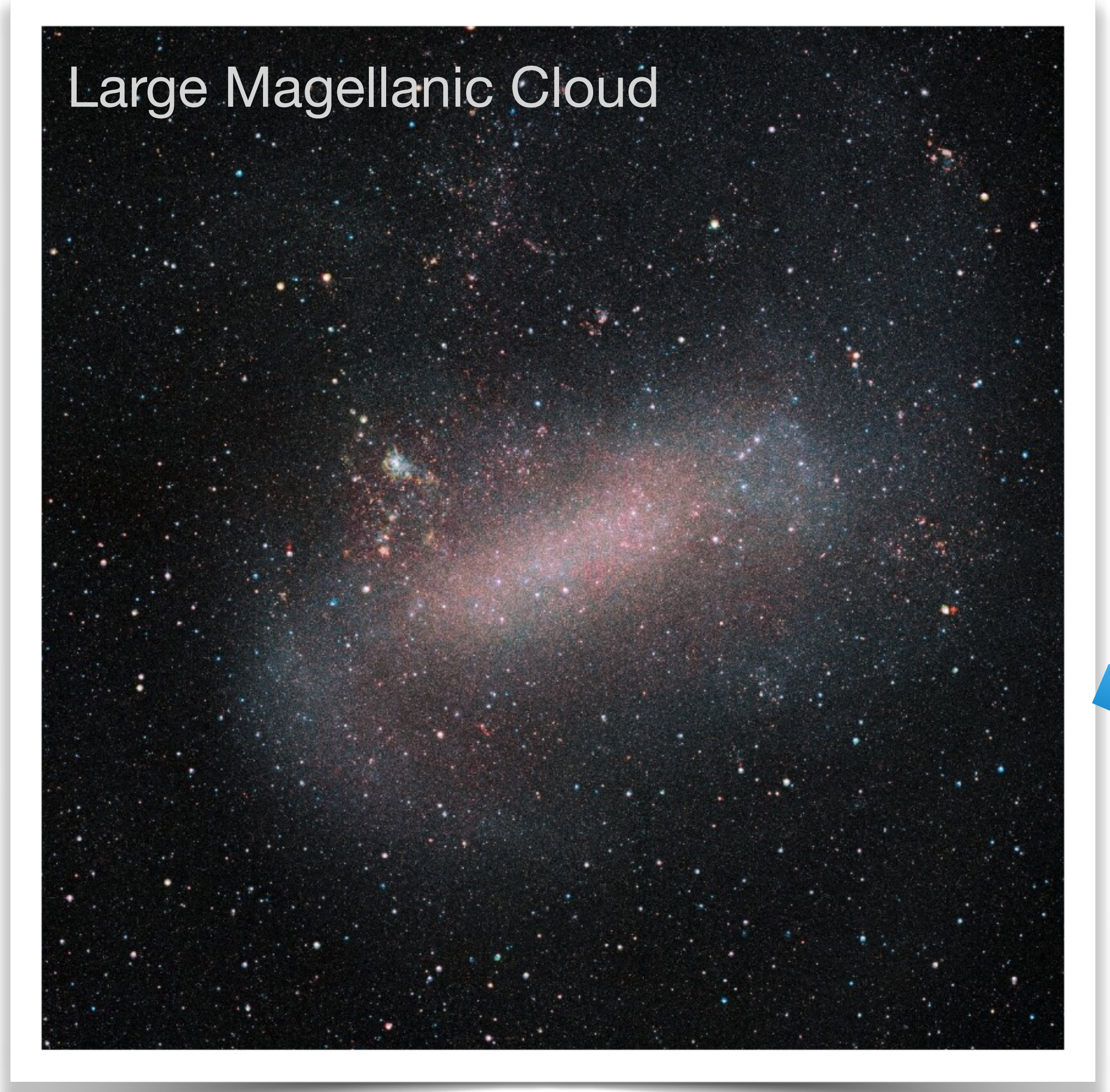
Draine 2003, ARA&A 41, 241

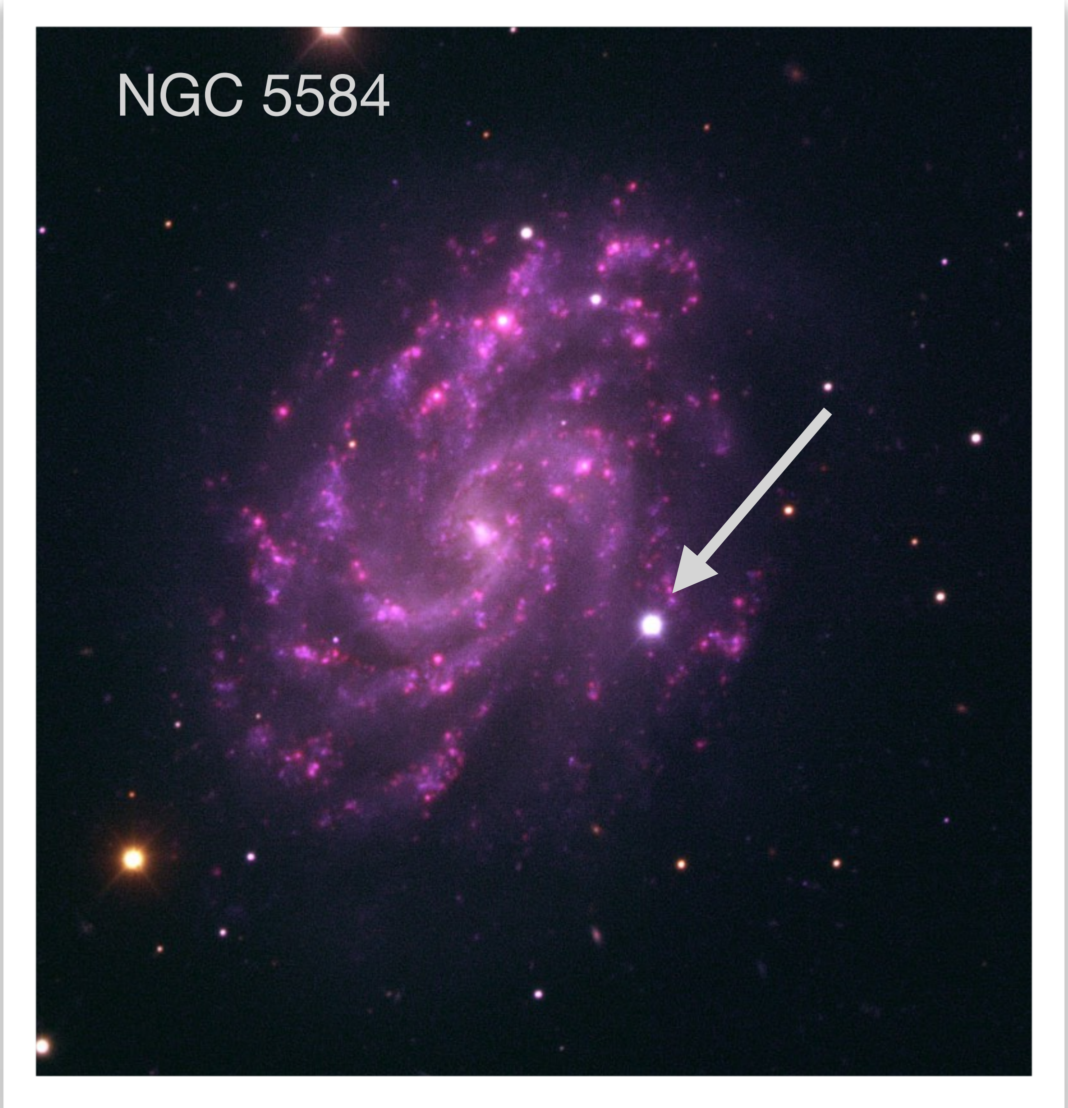
Cepheids in distant galaxies

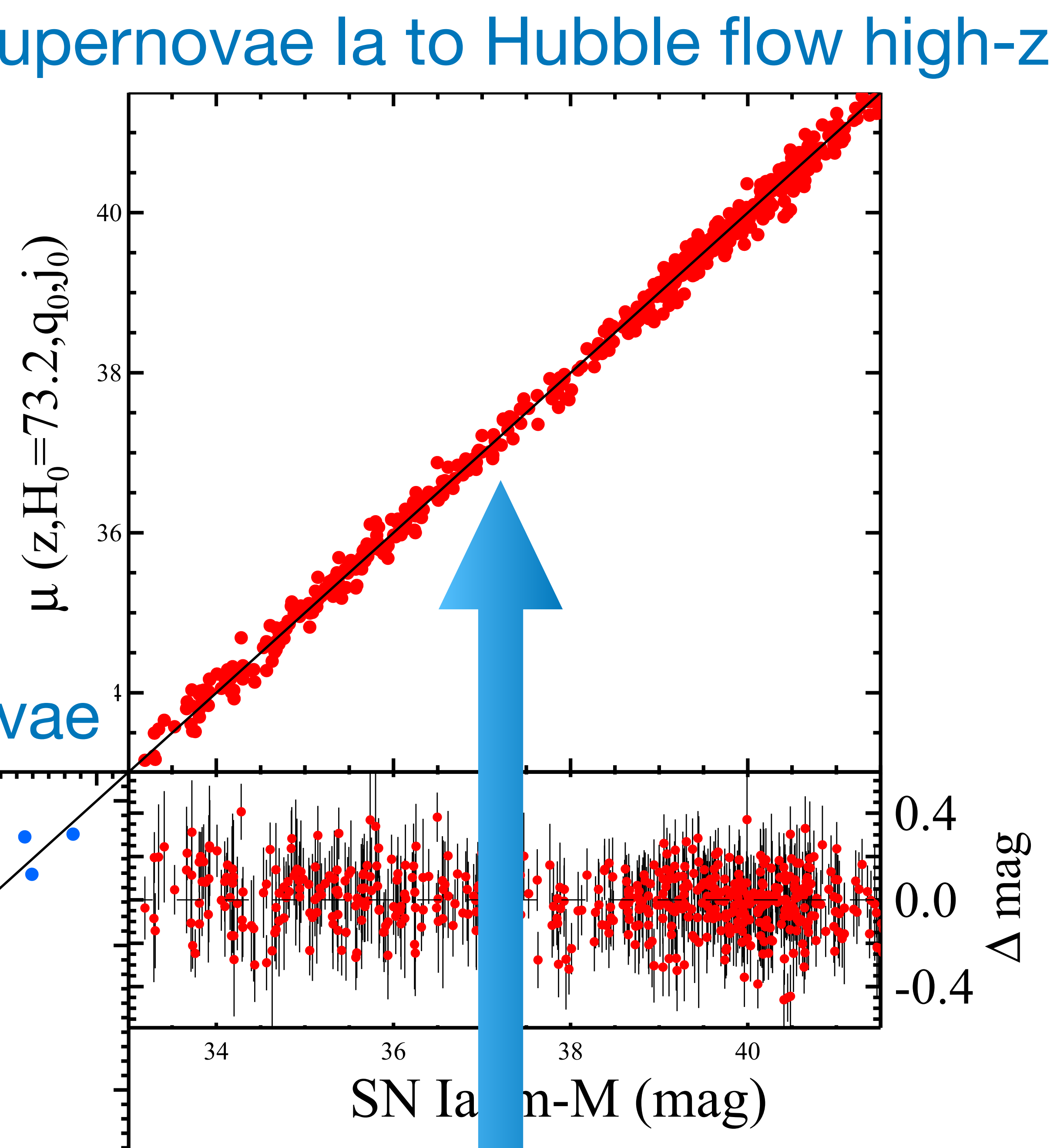


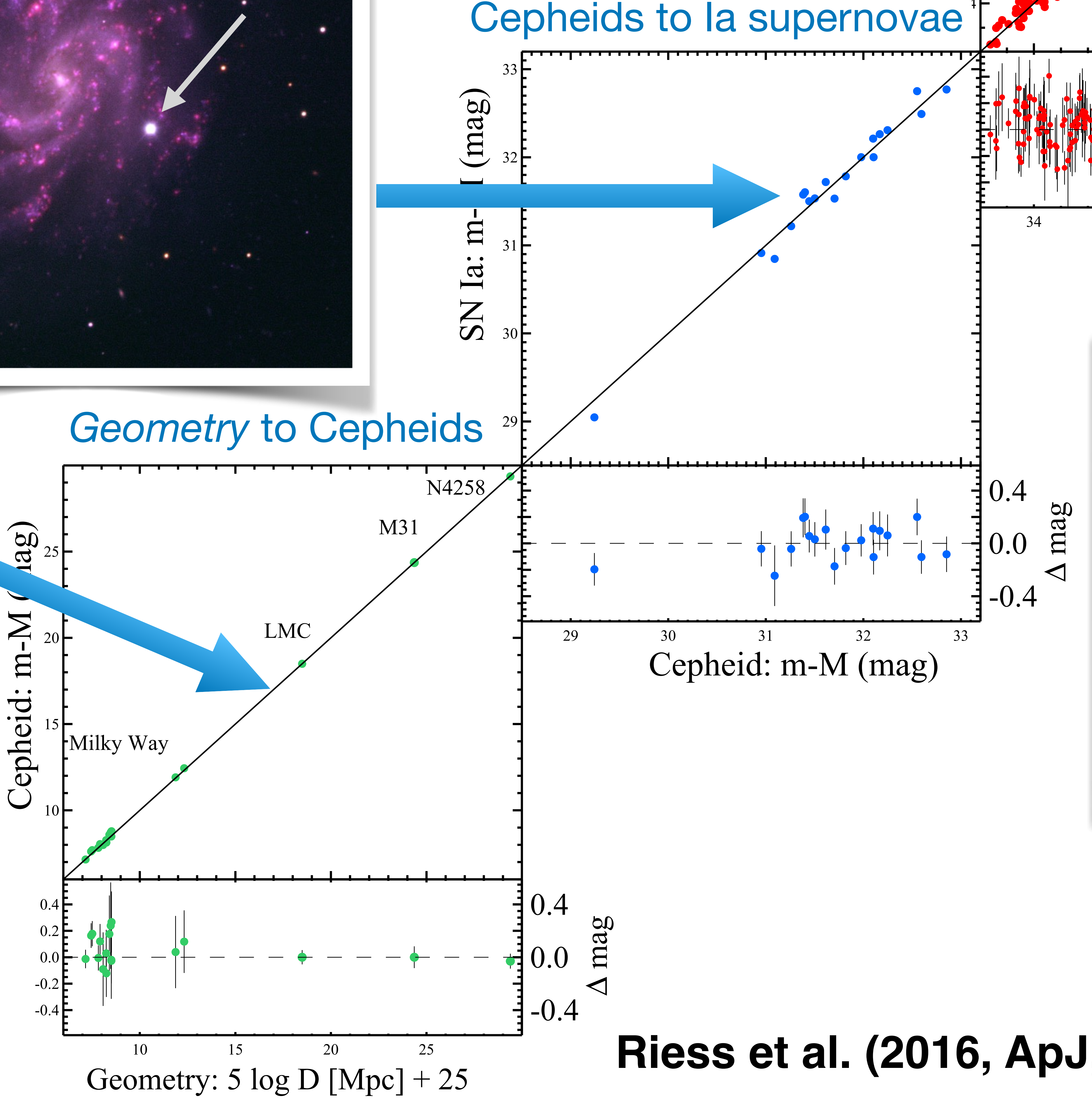
1. Scope of our project, data set
2. Photometry, crowding bias
3. Period-luminosity relation, distance modulus

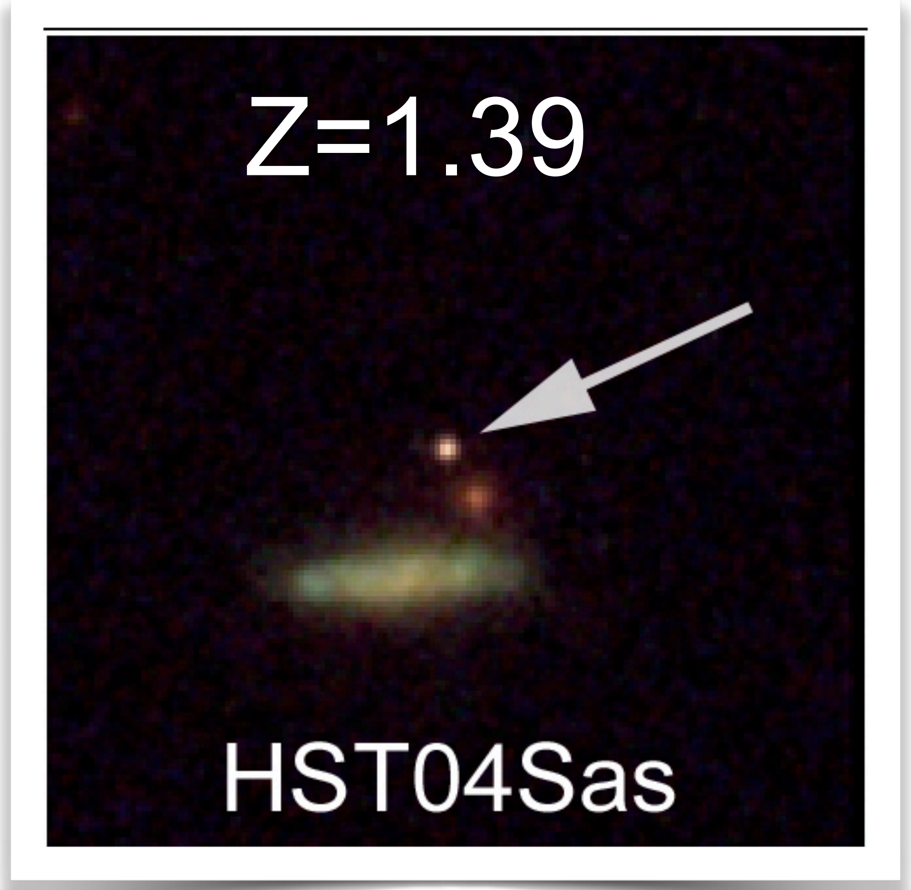
The empirical distance scale









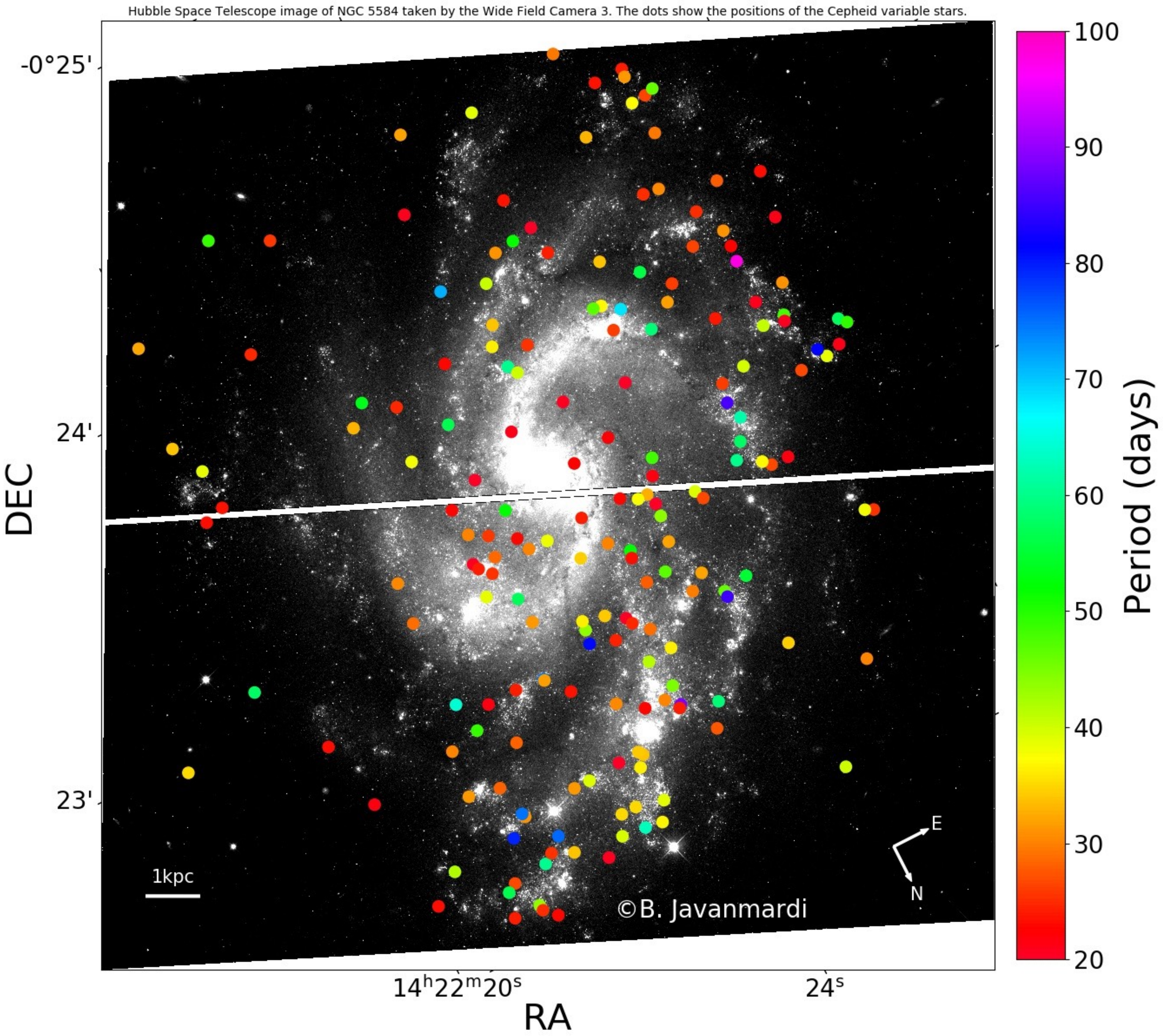


- **Other distance calibrators:** eclipsing binaries, megamaser, TRGB,…

Riess et al. (2007, ApJ, 659, 98)

Riess et al. (2016, ApJ, 826, 56)

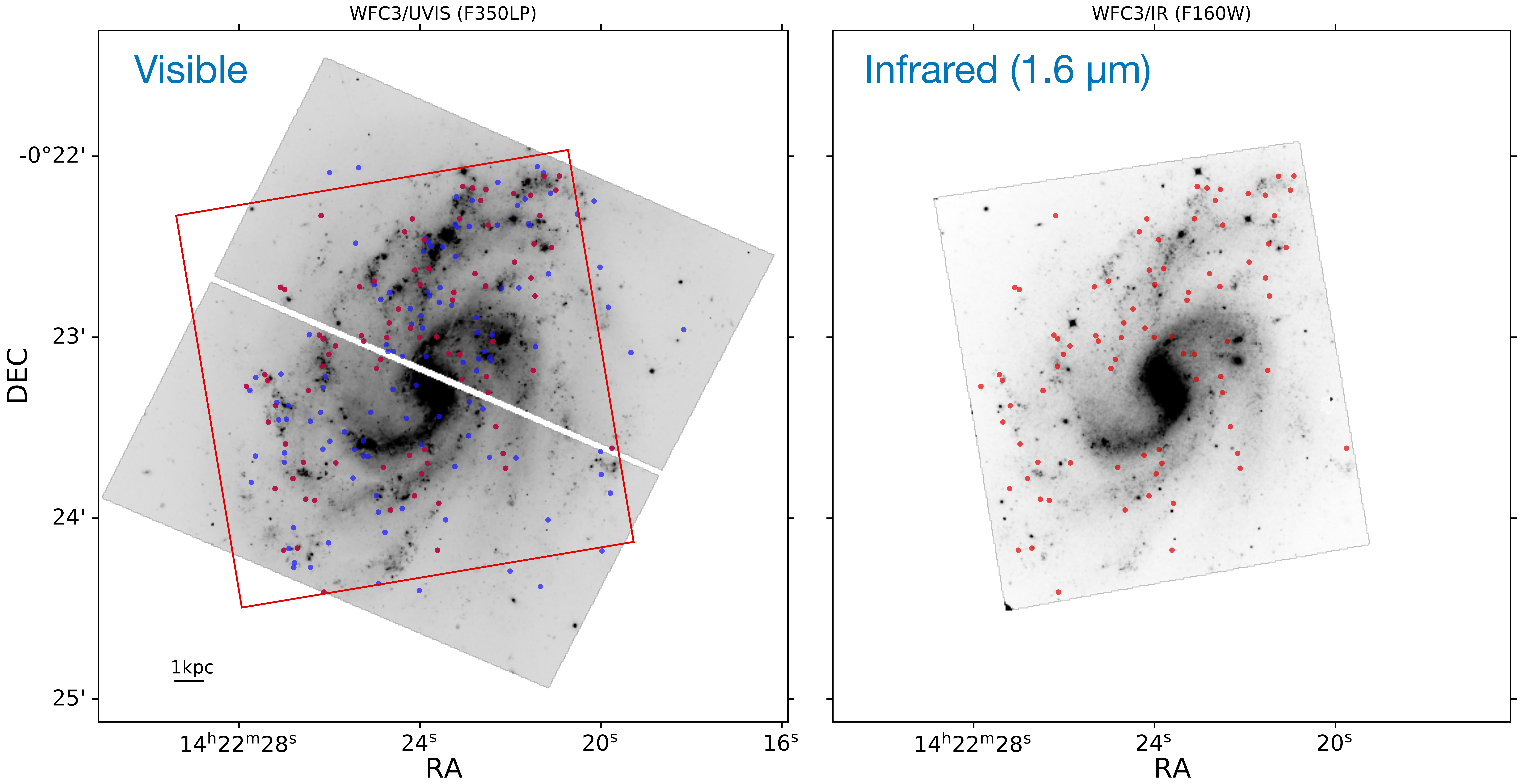
Inspecting the HST/SH0ES distance to NGC 5584

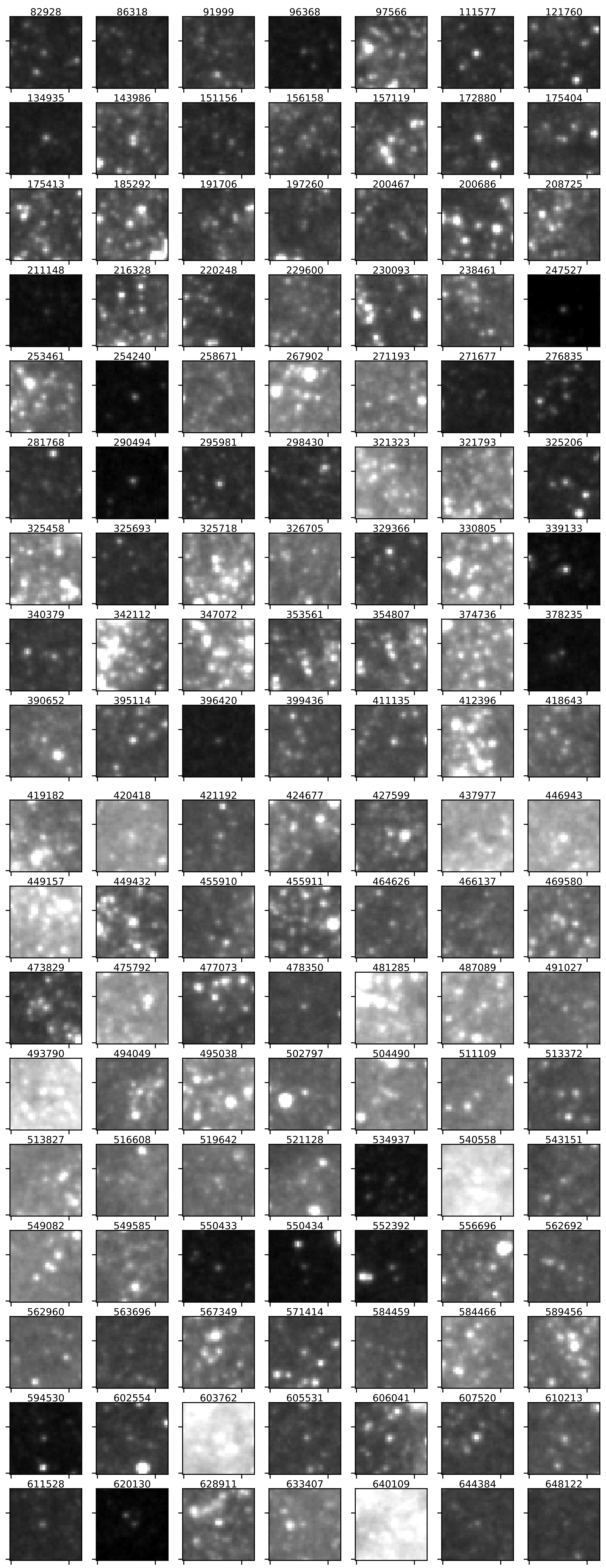


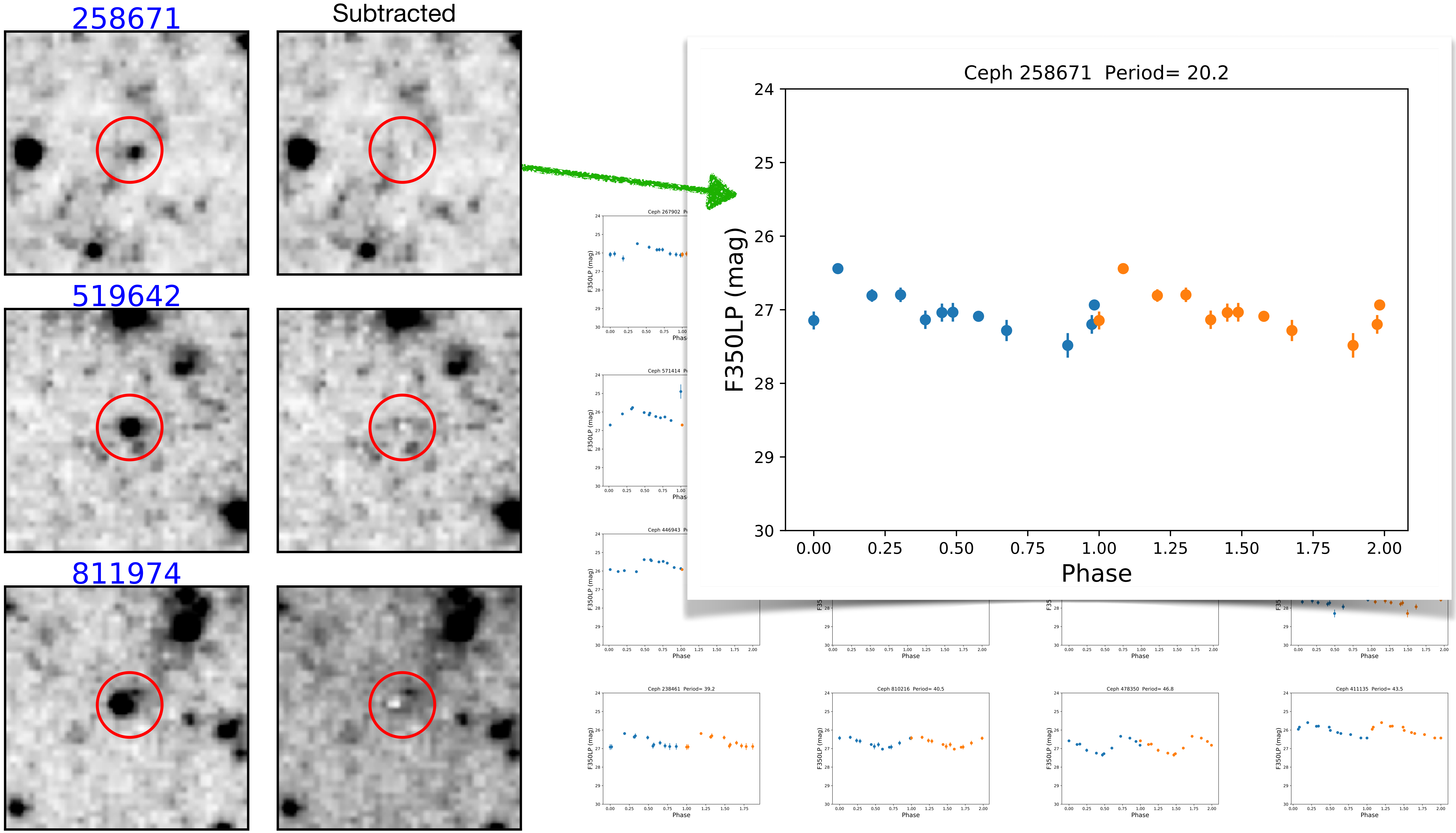
- Most intensively observed SN Ia host galaxy of the 2016 SH0ES sample
- This is not a re-analysis of SH0ES results or metadata
- **Independent reanalysis from raw HST data to distance measurement**

Javanmardi et al. 2021, ApJ, 911, 12

The Cepheids of NGC 5584





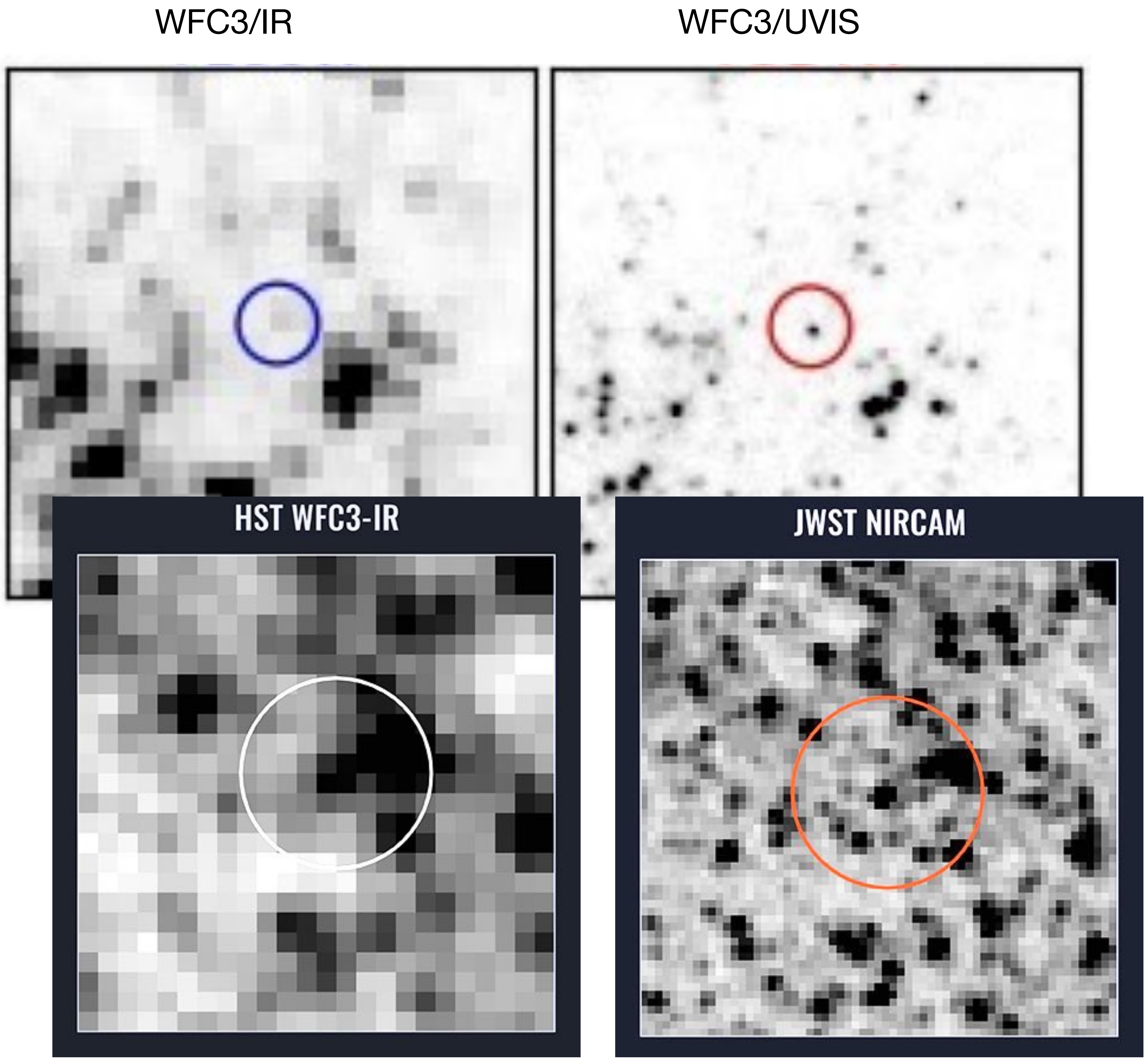


Same sample (82 Cepheids) as the SH0ES study

Our study: PSF fitting with **`astropy/photutils`**

SH0ES: PSF fitting with **`DAOPHOT`** (Stetson 1987)

Crowding Bias

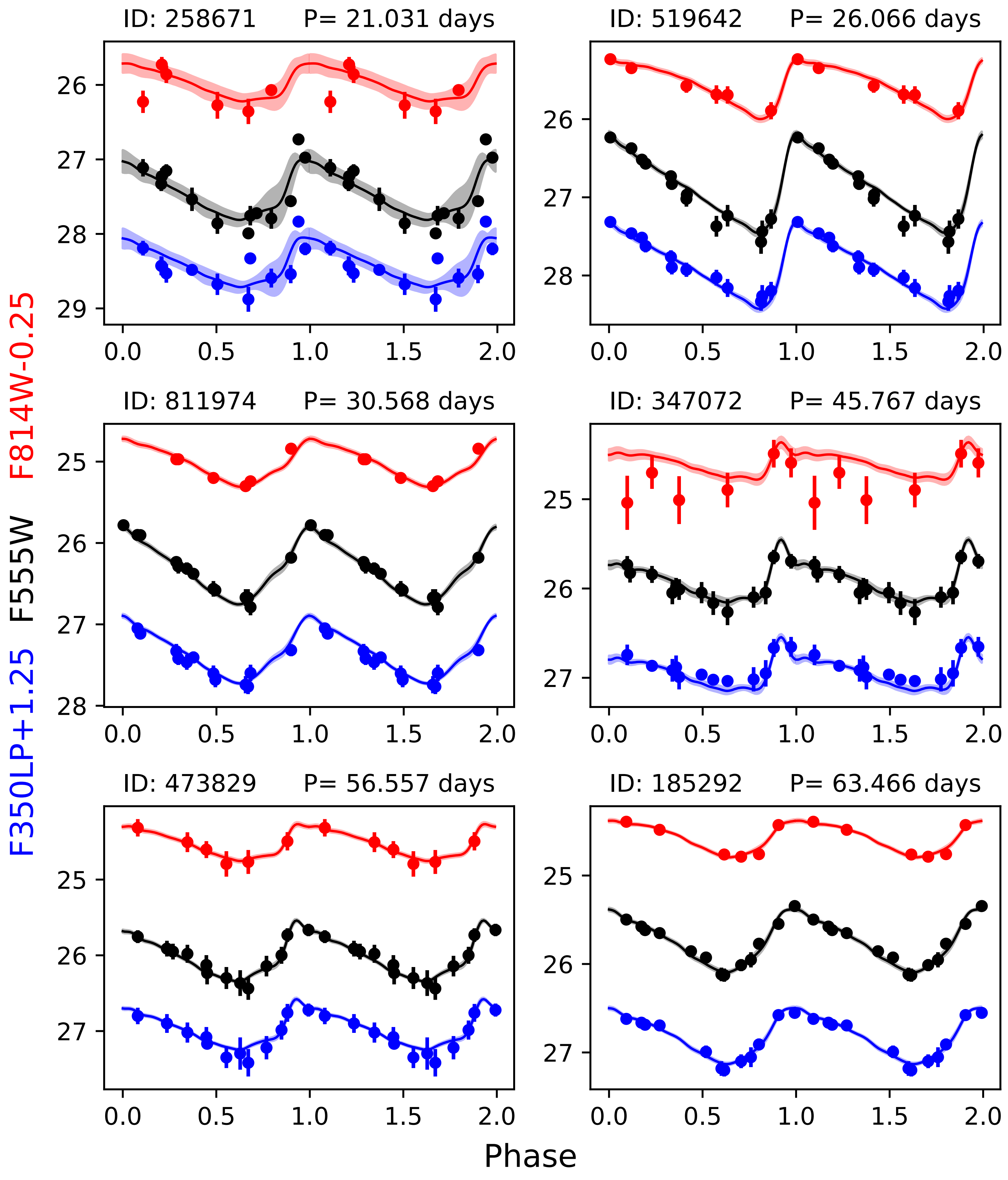


- Photometric bias caused by the **superposition** of sources and the limited pixel sampling
- Determined by randomly injecting **artificial stars** and checking the effect of field stars on their photometry
- Crowding effect on measured Cepheid magnitudes is limited (**Riess et al. 2023, arXiv:2307.1580**)

Light curve fitting using templates

Our study:

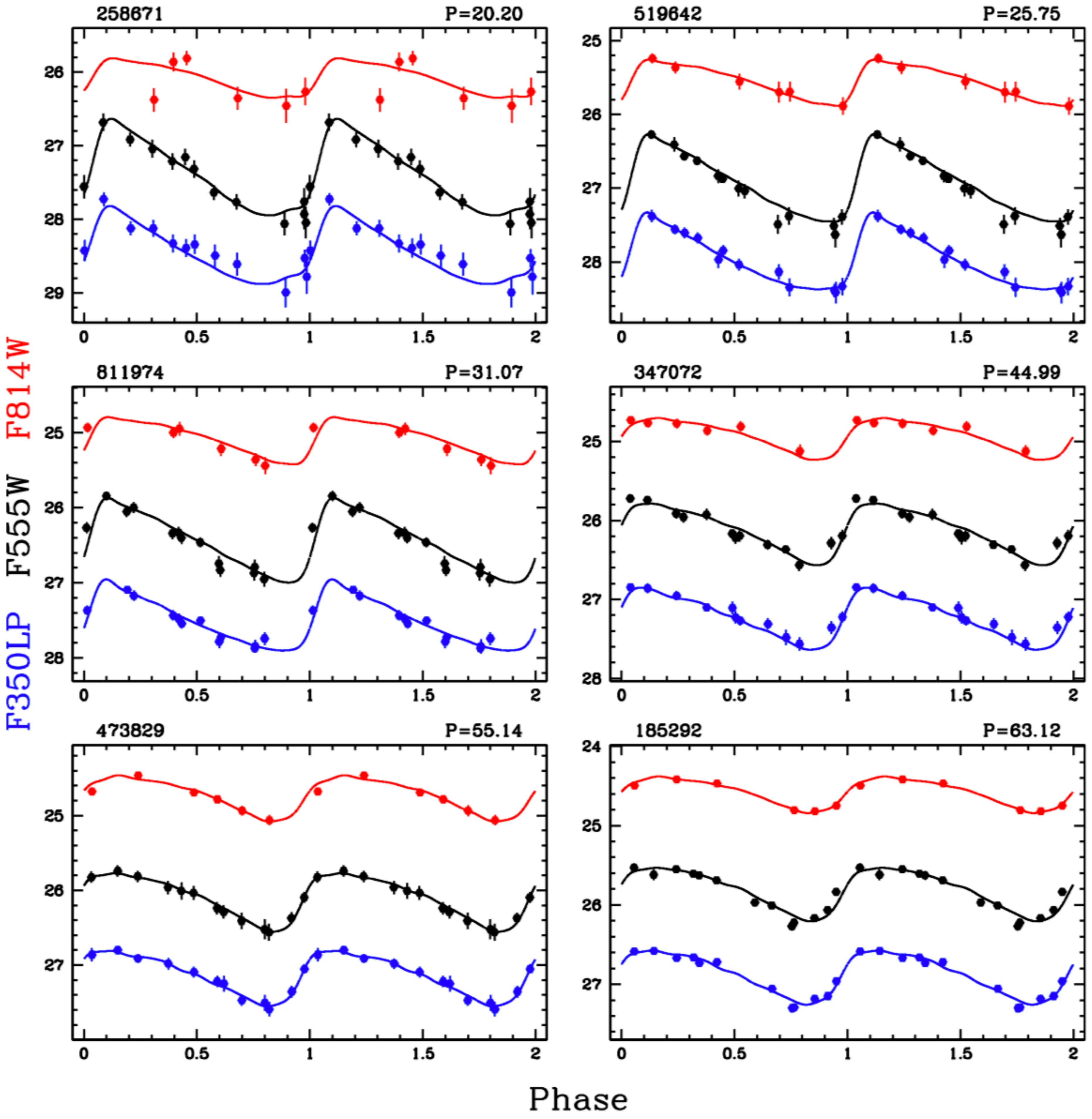
SpectroPhoto-Interferometry of Pulsating Stars (**SPIPS**), Mérand et al. (2015)



Javanmardi et al. (2021)

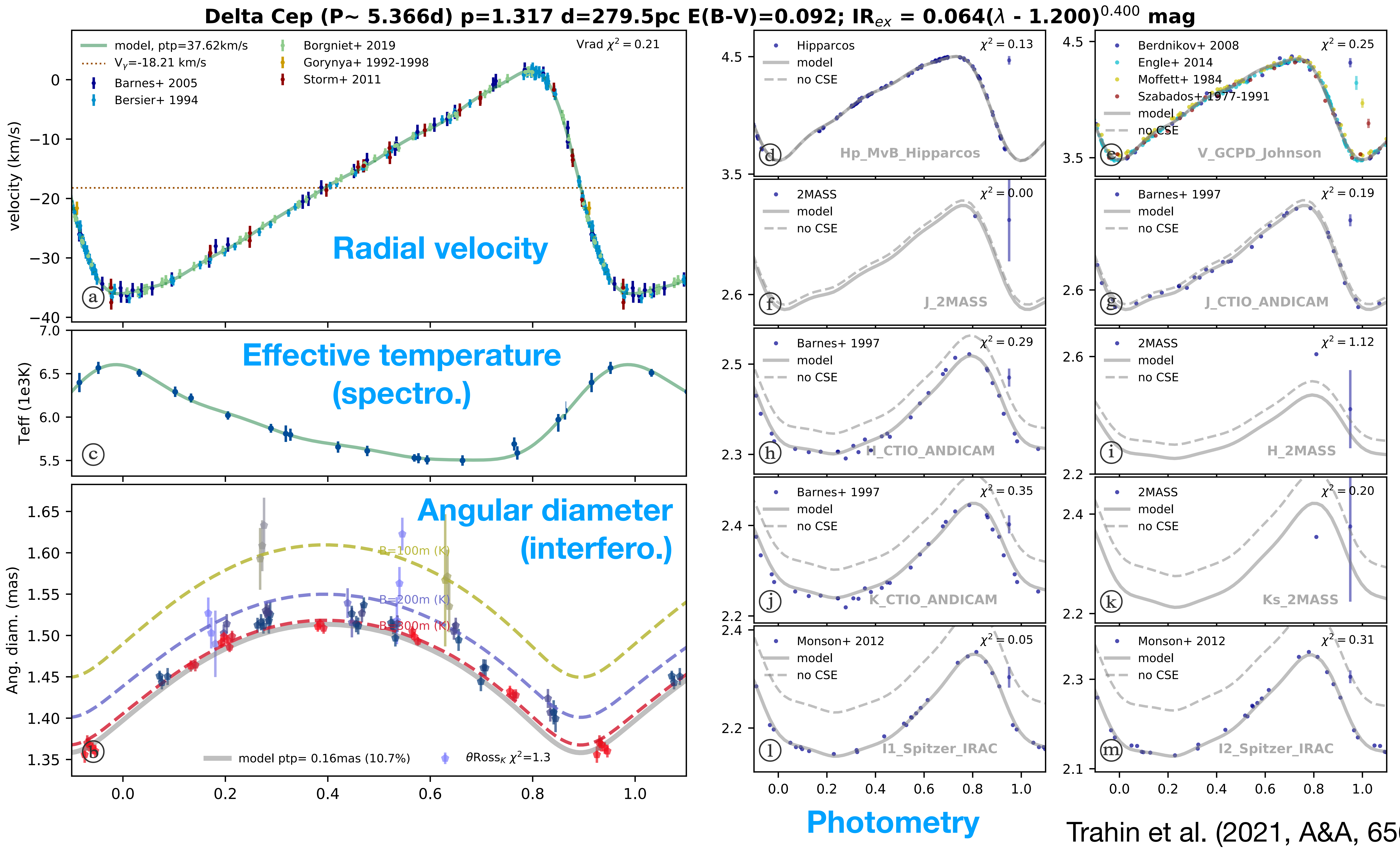
SH0ES:

Yoachim et al. (2009) templates



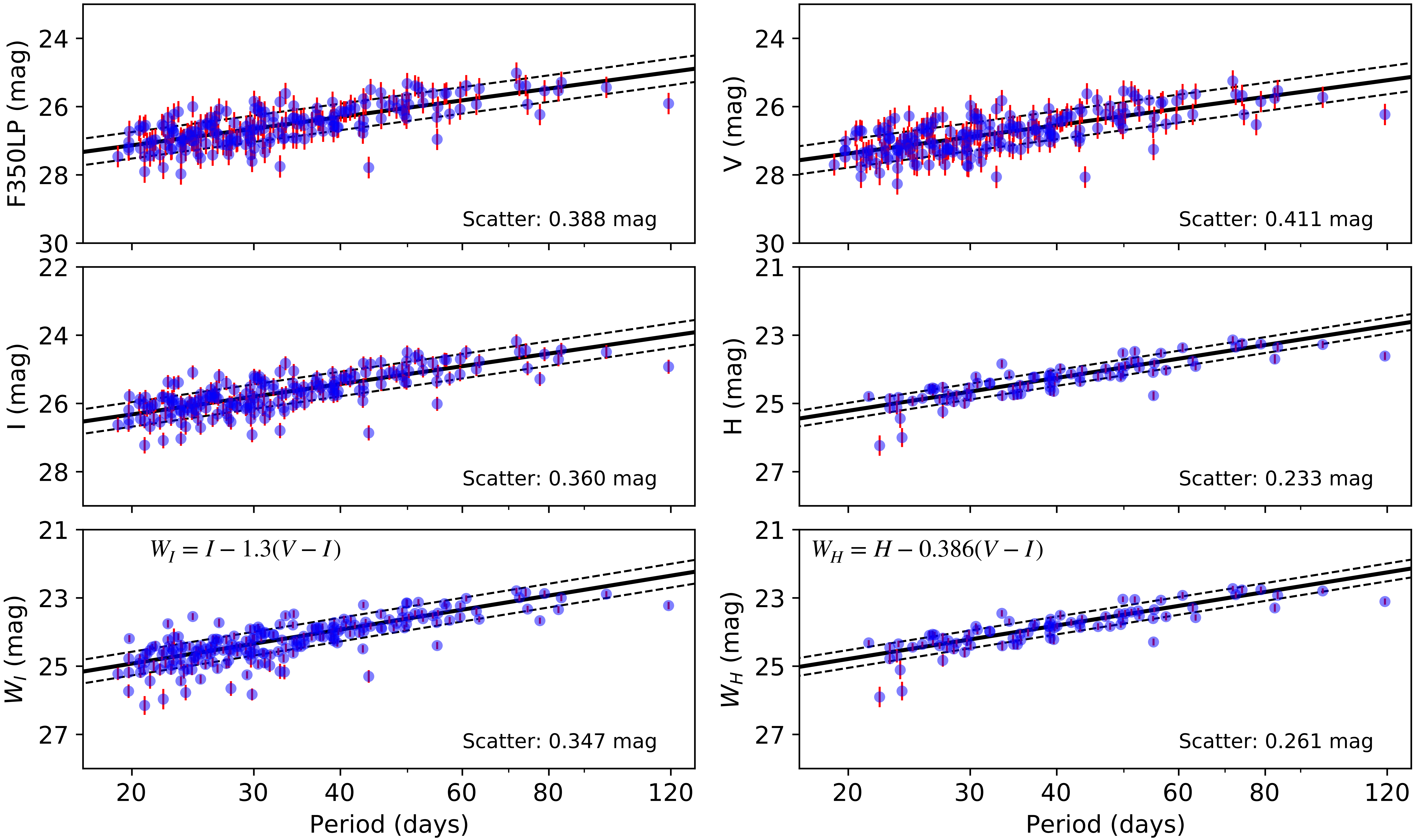
Hoffmann et al. (2016)

SPIPS models of Galactic Cepheids



Trahin et al. (2021, A&A, 656, A102)

Period-Luminosity diagrams for NGC 5584



Javanmardi et al. (2021)

Distance modulus of NGC 5584

- Using two Period-Luminosity relations:
  - LMC relation (Riess et al. 2019) with no metallicity correction

$$M_H^W = 15.898 - 3.26 \log P$$

  - Milky Way relation based on Gaia DR2 (Breuval et al. 2020)

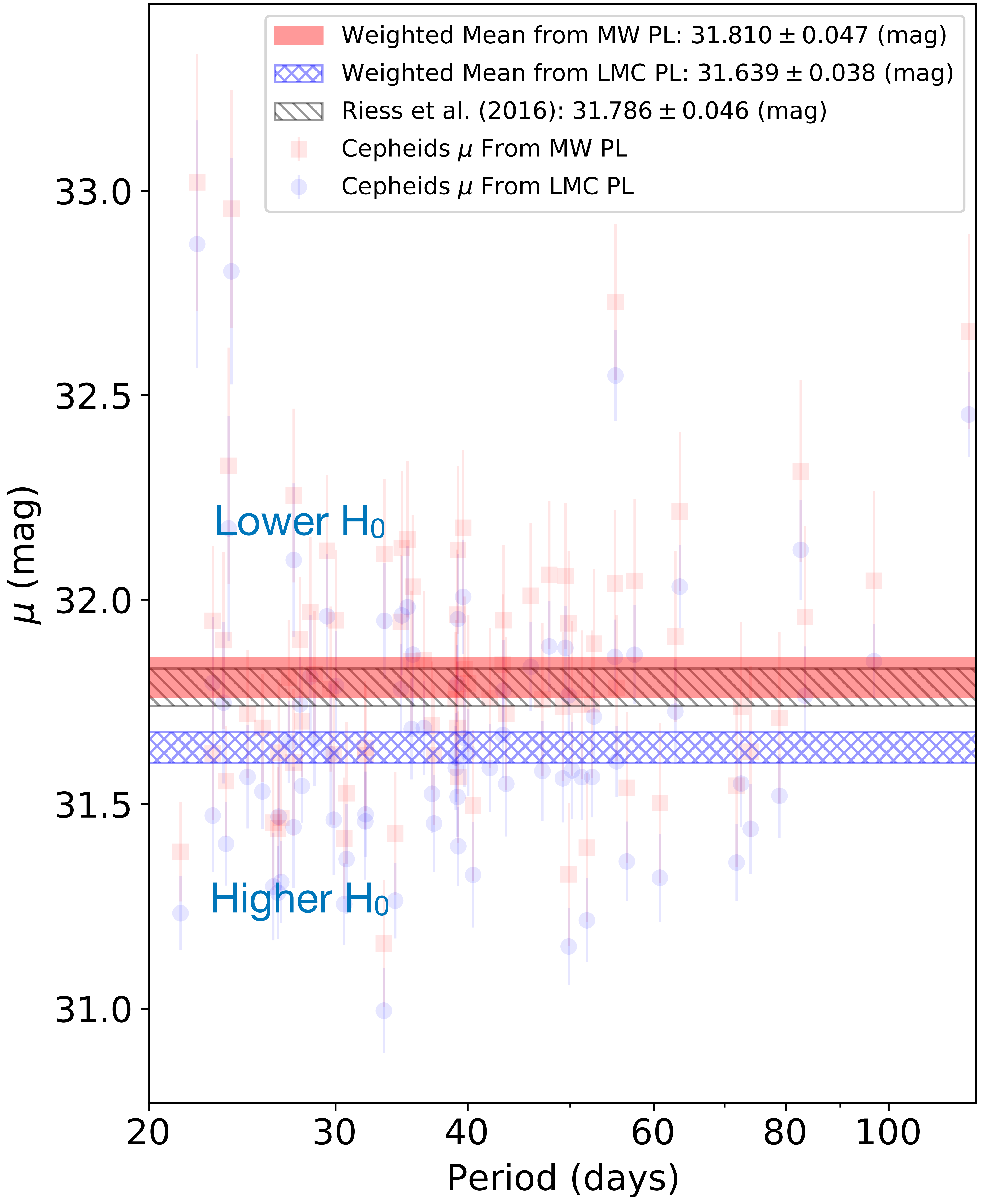
$$M_H^W = -5.432\ (\pm 0.029) - 3.332\ (\pm 0.177)[\log P - 0.84]$$

Our work:
μ = 31.810 ±0.047

SH0ES:
μ = 31.786 ±0.046

Agreement within 0.5σ

Small metallicity shift between NGC 5584 and MW
ΔW_{VI} ~ +0.01 mag, ΔW_H ~ +0.02 mag



Javanmardi et al. (2021)

Summary

- ✓ Different Tools for PSF photometry.
- ✓ Negligible influence of the choice of PSF modelling and background subtraction algorithms.
- ✓ Alternate approach to determine the crowding bias compared to SH0ES.
- ✓ Different template light curves fitting approach.
- ✓ Analysis done independently from the SH0ES team.

↓

On NGC 5584, we found no direct hint towards a resolution of the H_0 tension

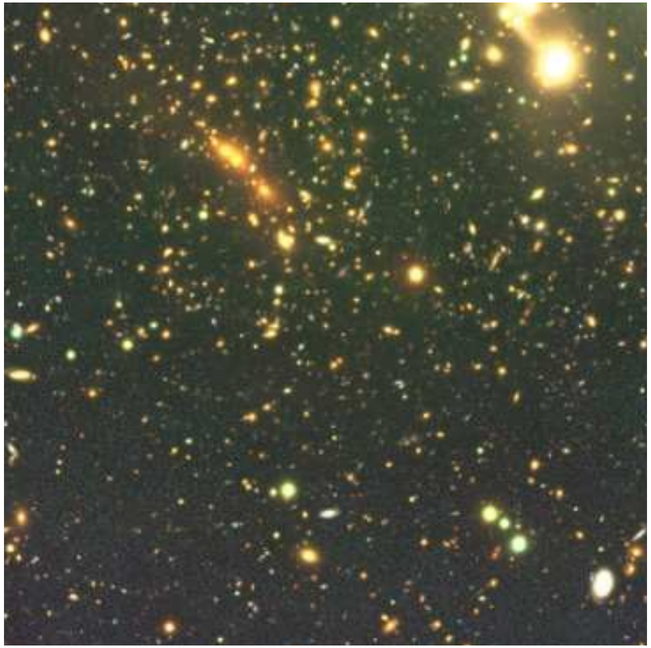
Perspectives

- However the **Leavitt law** still has a remarkably low dispersion and remains a cornerstone to measure cosmic distances.
- Cepheids are (still) **surprising stars !** The Baade-Wesselink projection factor does not behave so nicely as expected.
- **Metallicity** is important. Additional calibrating galaxies with independent distances beyond the SMC and LMC would be desirable.
- Using Cepheids in distant galaxies is delicate, as corrections are needed for crowding, extinction, metallicity… **should be checked !**
- Within the framework of our ERC SyG UniverScale:
  - **PhD thesis** to be announced in 2024 focusing on the study of interstellar reddening.
  - **Post-doctoral position** to work on JWST observations.

Gaia Trigonometric parallaxes
Surface brightness-color
Classical Cepheids Leavitt law
SNe Ia
AGNs reverb. mapping
Eclipsing binaries
T2Cep Miras, RRL, TRGB...
1
2
3
4
5
6
7
UniverScale

Cepheids, Distances, H_0

Pierre Astier
(LPNHE/IN2P3/CNRS, SU, Paris)



Anomalies ?
Really ?

Annecy, November 2023

P. Astier (2101.05463)

The local H0 measurement(s), as of today

- Requires (absolute) distances and redshifts.
- In the Hubble flow, z>~0.02 or ~80 Mpc
- Distances are obtained via a 3 rung ladder:
  - Supernovae (Ia) in the Hubble flow
  - Local supernovae in galaxies with observable Cepheids (<80 Mpc)
  - Cepheids at known distances (Milky Way, LMC)
- "Local" calibrators :
  - LMC: (detached) eclipsing binaries (DEBs)
  - Milky Way : parallaxes
  - NGC4258 : Hydrogen Maser

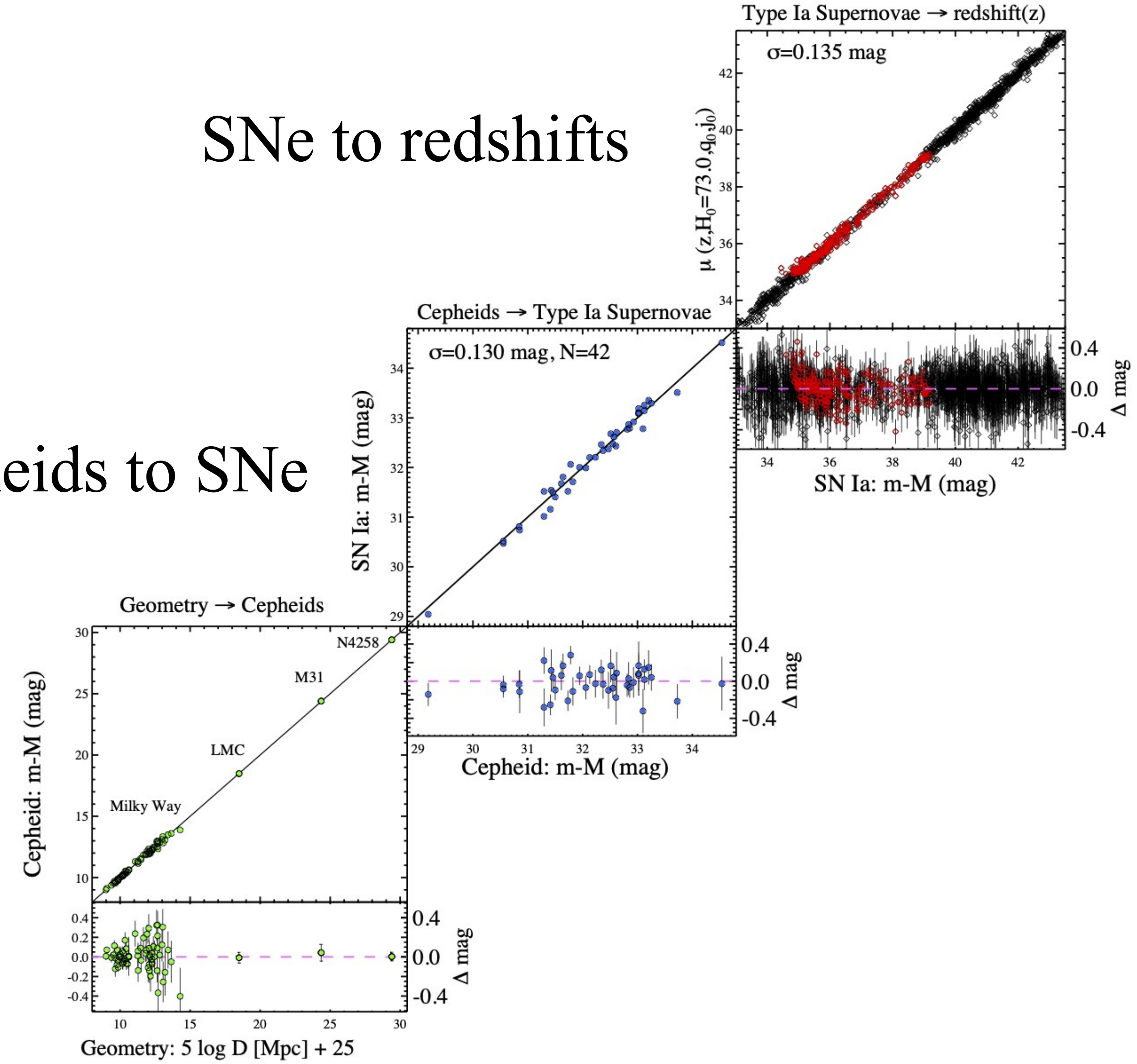
You can replace "cepheid" by any other (bright) distance indicator (e.g. TRGB)

SNe to redshifts

R22, fig12.

Cepheids to SNe

Actual distances to Cepheids



P. Astier

Supernovae statistics (1)

- The scatter of SNe is typically 0.14 mag (i.e. ~7% in distance)
- In order to get 1% precision, one needs ~50 events (2^{nd} rung)
  - Current statistics is 42.
- Usable SN events (nearby galaxy with observable cepheids, moderate extinction) occur at $\sim 1 y^{-1}$ rate.
- This is the core limitation for H_0 statistical precision.
- We already have more SNe in the Hubble flow than we need.
- Selecting SNe in galaxies with cepheids actually selects late type SN hosts : galaxies still forming stars.

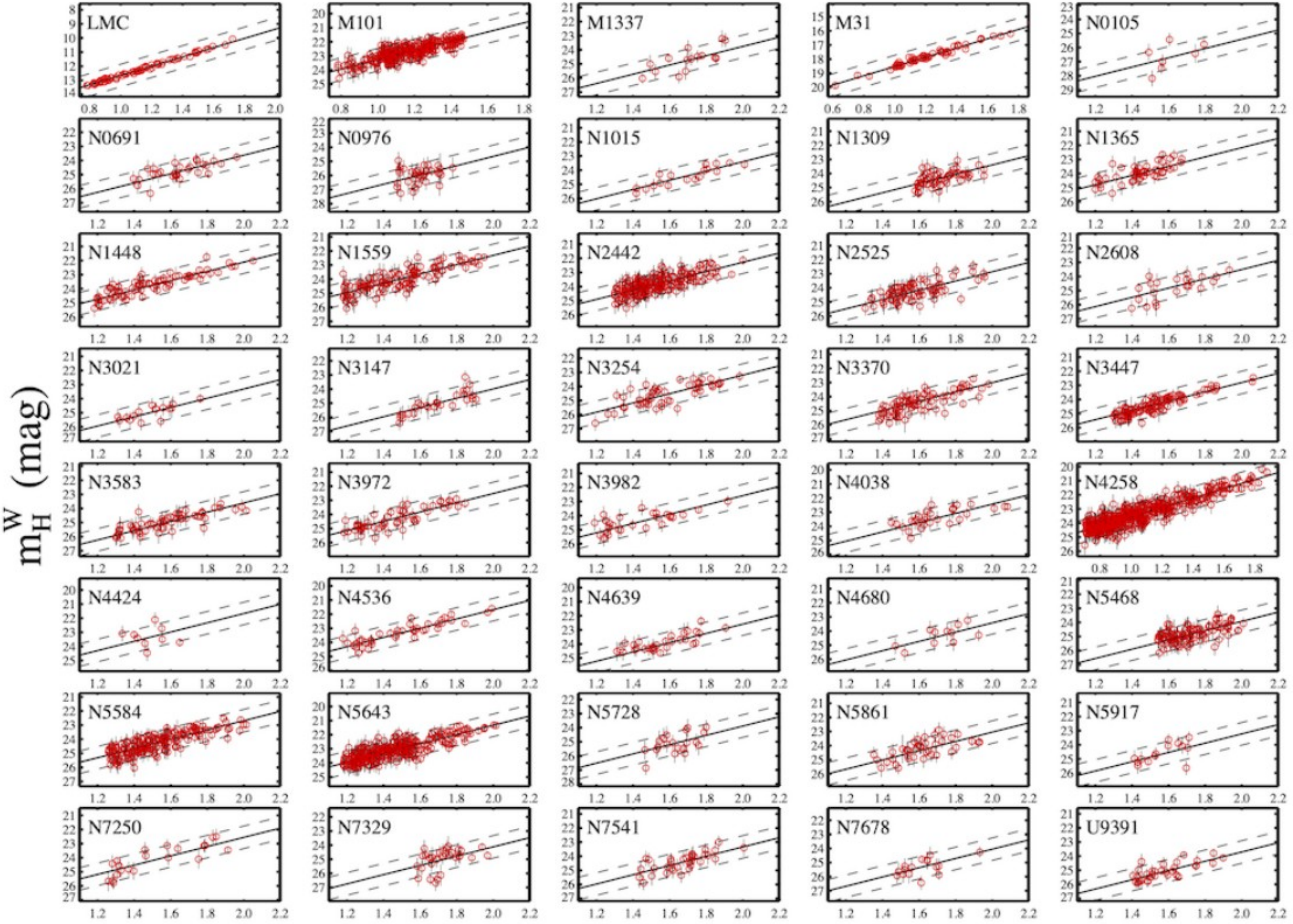
Cepheids (in a single slide !)

- These are bright (super) giants variables. Luminosity : 10^{3-4} Sun
- Variability: from a few tenths to ~1 mag.
- Henrietta Leavitt + (1908) : the period-luminosity relation discovered in the LMC
- Since then, many refinements: two populations, extinction, metallicity corrections, color terms, precise photometry, etc...
- Are we at the end of refinements ?
- However, further refinements are confined within the empirical dispersion around the PL relation, ~0.08 mag rms in the NIR

Cepheids from R22

NIR Extinction-corrected magnitudes vs log(Period)

In distant hosts m~25 for P~10 d.



P. Astier

The use of cepheids

- They are used to bridge the local distance calibrations with the nearby SN host galaxies.
  - The farthest SN/cepheids galaxies are at the limit of HST capabilities
- So there are basically two kinds of potential problems:
  - The quality of calibrators
  - The photometry of cepheids in SN host galaxies
- Then, there could be problems in the comparison
  - Different populations
  - systematics which do not cancel out (metallicity !)
  - ….

Cepheid calibrators in R22

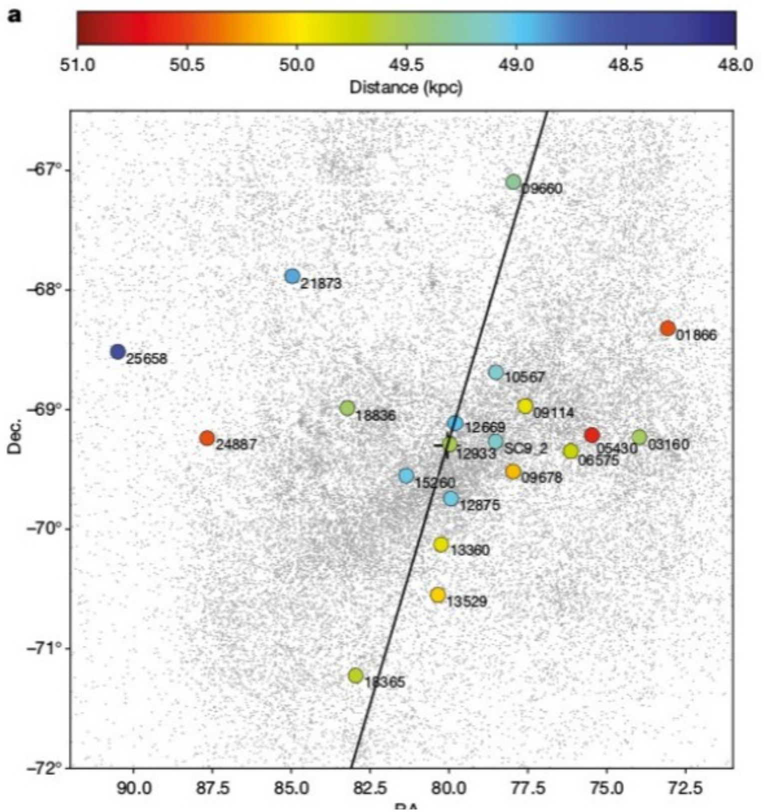
- Milky Way: (mostly) Gaia early DR3 (EDR3) :
  - 0.9% systematics (in distance) related to parallax offset, 1% with statistics.
- LMC : detached eclipsing binaries:
  - 0.0263 mag or 1.2%   (49.5 kpc)
- NGC4258: Water maser:
  - 1.5% in distance (7.6 Mpc)
- Added complexity: M31 is used (without a geometrical anchor) to constrain the P-L slope of cepheids.

Parallaxes of Cepheids in the Milky Way

- R22 mostly uses Gaia Early Data Release 3
- In Gaia EDR3 parallaxes have issues (5.2 of F23):
  - Underestimated uncertainties
  - Global offset (discussed by the Gaia team)
  - Color and magnitude dependent corrections (idem)
  - Leads to about 4% distance uncertainties for Cepheids rather than 1% as assumed in R22
  - Requires a new assessment with DR3 (out since June 22)
- For both Cepheids and TRGB, Gaia is anyway expected to provide the ultimate calibration.

Distance to the LMC : 1903.08096 (2)

- The reported distance uncertainty is 1.1%
- My sense is that the accuracy of geometric star radii (from occultation in lighcurves) deserves a more detailed discussion
- I don't understand what secures the linearity of V mag measurements between V~5 (MW) and V~21 (LMC)
- I don't understand why the interferometric radius scale uncertainty (2.7%) is not propagated into the final error budget.



Measuring Cepheids

- One has to observe from space in order to resolve stars in distant galaxies (HST scientific rationale).
- In order to reduce systematics, all cepheids involved in H_0 measurements should be observed with the same instrument and bands, i.e. the HST (or JWST).
- NIR observations are obviously favored in order to reduce extinction corrections, significant in late type galaxies. However, angular resolution is degraded as compared to visible.
- One needs to measure apparent brightnesses, which is difficult in crowded stellar fields.

Cepheids "standardization"

$$m_H^W = m_H - R\,(m_V - m_I),$$

R is modest, ~0.4
because it refers to H band

$$m_{H,i,j}^W = \mu_{0,i} + M_{H,1}^W + b_W\,(\log\,P_{i,j} - 1) + Z_W\,[\mathrm{O/H}]_{i,j},$$

Expected mag.

Abs. Mag.
of a P=10d
Cepheid

PL slope

Metallicity correction

Metallicities

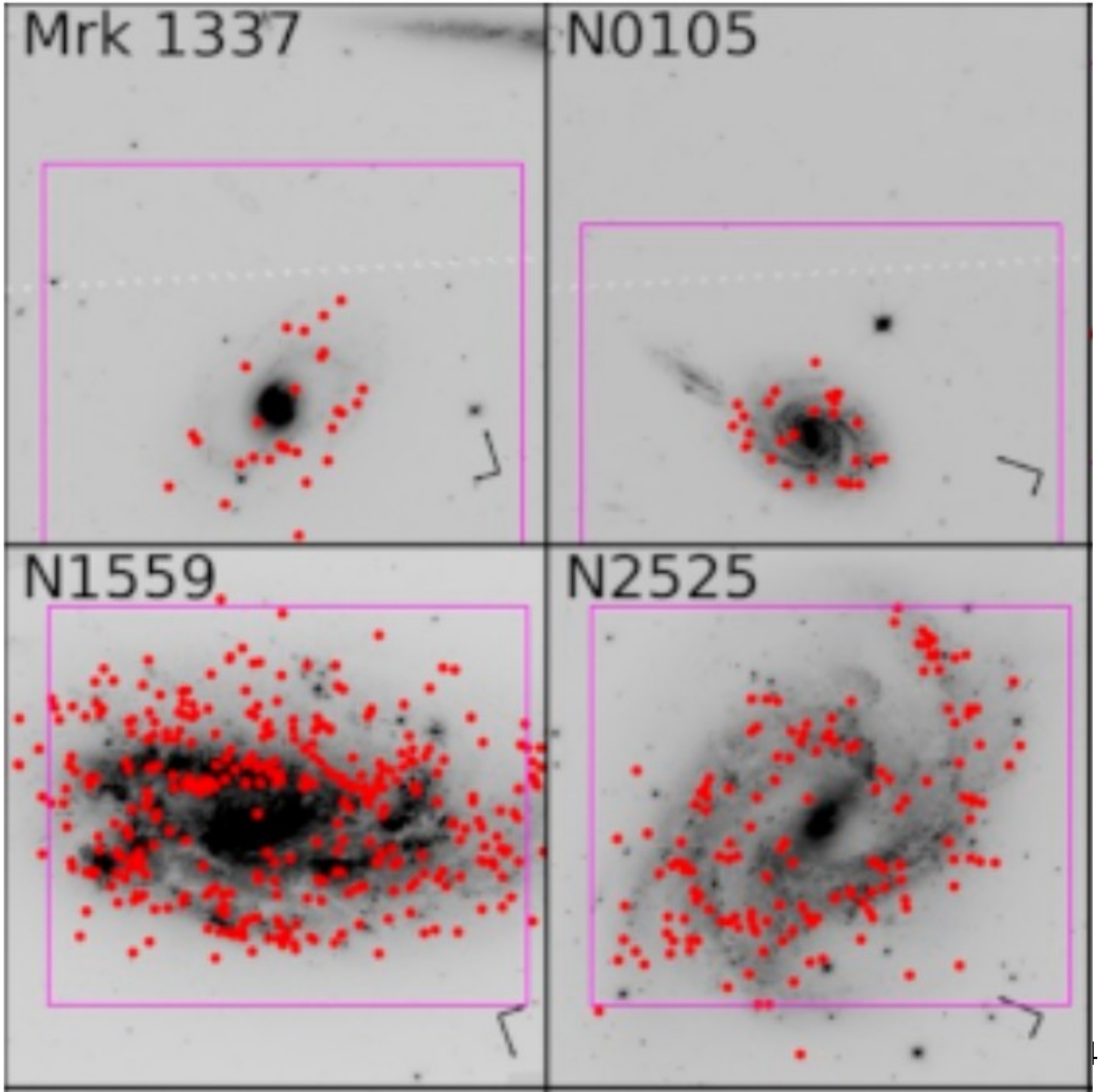
- The dependence of Cepheids P-L (or P-L-C) relation with metallicity was uncovered in the 50's (?) and led to a revision of the distance to the LMC (because MW and LMC have a different average metallicity).
- In R22, the metallicity is assessed by spectroscopy and some spatial gradient across galaxies is fitted.
- For SN host galaxies (2nd rung), I do not imagine a mechanism that biases distances.
- For the first rung, uncertainties in metallicities translate to potential shifts of the other parameters of the P-L-C relation

A few SN host galaxies with the location of selected cepheids.

For each host, a period cut is defined in order to avoid a magnitude bias due to missing detections.

Distant galaxies deliver a small number of eligible cepheids

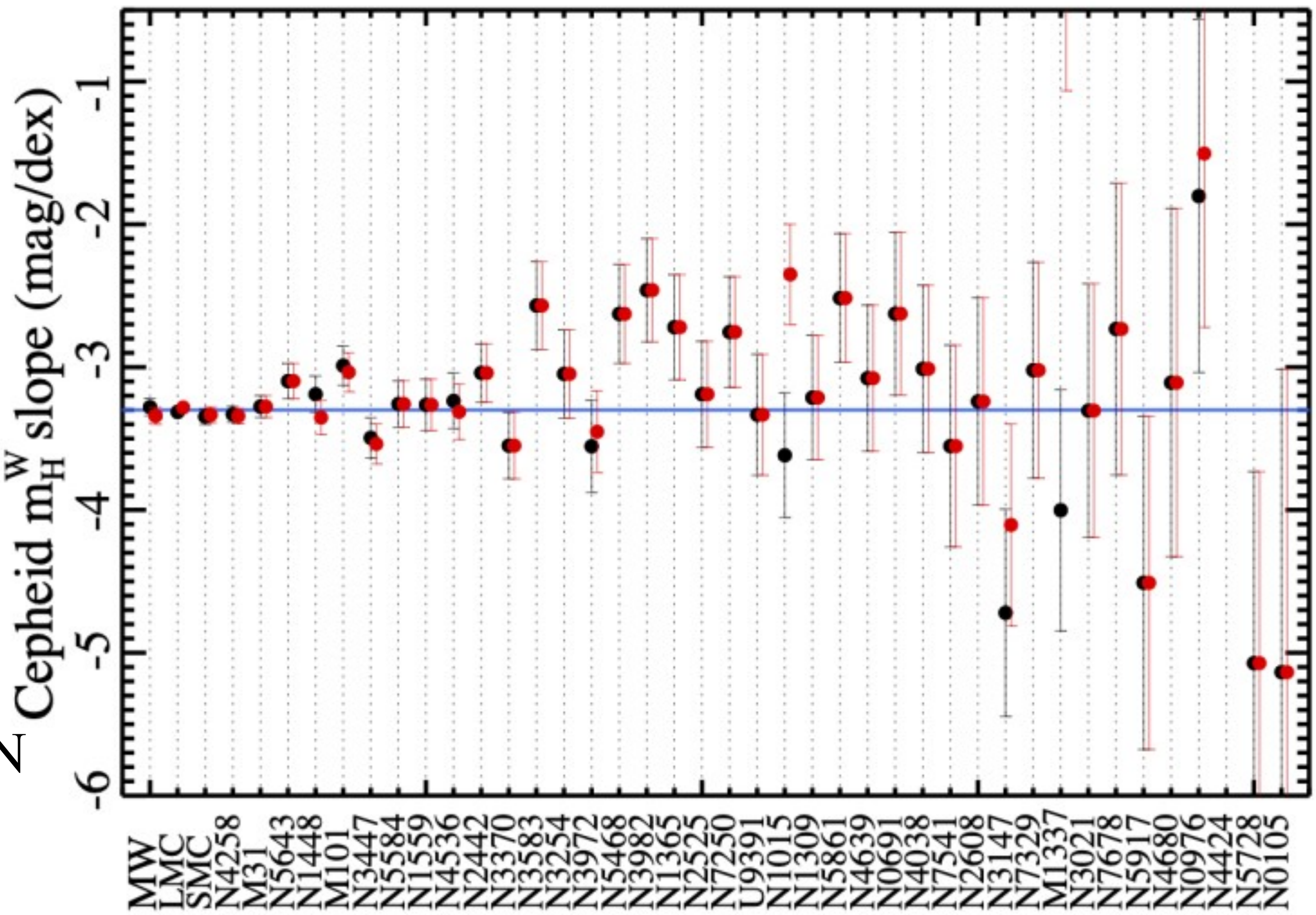
The distribution of periods varies with distance



R22 PL slopes

This is a test.
In the end,
a single slope
is fitted across
all cepheids.

The range of S/N
is huge.



Log-normal photometry error distributions

- Definition : X is log-normal if Y=log(X) is normal
- There are then 2 parameters, E[Y] and Var[Y]
- R22 (and before) argue that measured *magnitudes* have Gaussian errors, because the background (undetected stars) is log-normal.
- I don’t understand how that can be valid at all distances, because the relative contributions of background stars (deemed log-normal) and sky (Gaussian) vary a lot with distance.
- Gaussian distributions in magnitudes seem to describe the observed distributions, but I could not find a detailed test of sensitivity of the distance to the assumed error distribution.

A small difference between median and mean?

- For a perfect log-normal flux distributions, magnitudes are Gaussian (by definition)
- Is med-mean=0.03 small ?
- If measured fluxes are Gaussian then M=log(F) :
  - Median(M) = log(median(F))) = log(E[F])
- E[M] = log(E[F]) -1/2 Var[F]/E[F]^2+ ….
- So that, for the log of a Gaussian, the difference between median and mean is a proxy for S/N

For a difference of 0.03, $\mu \sim 4\,\sigma$

$$\frac{\sigma_X^2}{\mu_X^2} = 2(med[Y] - E[Y])$$

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Crowded No More: The Accuracy of the Hubble Constant Tested with High-resolution Observations of Cepheids by JWST

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- Bottom line: remeasuring ~300 Cepheids in 2 galaxies reduces the scatter (by about a factor of 2) but does not change the average (distance)
- The quality of the test (1 σ) is 0.03 which is marginal, especially because the chosen Cepheid galaxies are one calibrator and one "average", while the largest bias is expected at the largest distances.
- Reminder: TRGB is essentially immune to confusion (and much less to extinction)

Photometry...

$$\hat{f} = \frac{\sum_{\text{pixels}} \psi_p (I_p - s) w_p}{\sum_{\text{pixels}} \psi_p^2 w_p}$$

low | high

$w_p \to s^{-1} \equiv w$

$$\hat{f} = \frac{\sum_{\text{pixels}} \psi_p (I_p - s)}{\sum_{\text{pixels}} \psi_p^2}$$

$w_p \to (f \psi_p)^{-1}$

$$\hat{f} = \sum_{\text{pixels}} (I_p - s)$$

For this science (and many others) we are interested in accurate flux ratios
The simplest way for that is to impose the low-flux weighting scheme at all fluxes: then even an approximate PSF delivers correct flux ratios.
R22 relies on DAOphot which does **not** use this weighting scheme (at least by default).

Summary: photometry of cepheids, potential issues

- Average of numerous poor measurements:
  - Average of fluxes or distance moduli
  - Accuracy of background subtraction might depend on flux
  - Outlier rejection
  - Position variance (and associated flux bias) certainly depends on flux.
- PSF photometry of bright vs faint objects: brighter-fatter and accuracy of the PSF model.
- Linearity of the device.

Supernovae Ia (1)

- The 42 “calibrators” happen in galaxies hosting Cepheids, which eliminates SNe Ia in late type hosts.
- We know that the intrinsic brightness of SNe Ia depends on the host galaxy type, presumably of the stellar age or the star formation rate.
- In cosmological analyses, this is handled through the “mass step”, an offset applied to all supernovae of a given host type (indexed originally by host stellar mass (e.g. Sullivan+ 2010))
- Rather than correcting distances of Hubble diagram events, R22 selects those in galaxies that may host Cepheids.

Supernovae Ia (2)

- Selecting the same SN demography seems totally reasonable.
- There were tensed exchanges on this subject because initially, the SH0ES team argued that they did not see any effect related to SFR, at variance with all other actors in the field.
- Assuming (very unlikely) that R22 misses the whole "mass step effect", the average brightness correction is at most 0.05 mag
- Regarding more general SN selection, the used cuts are at about 2 sigma in the standard variables x1 and c:
  - $|x1|<2$, $|c|<0.2$
- Replicating the analysis with NIR SN data (less events…) gives the same results 72.3 +/- 2 (Galbany+ 23, 2308.01875)

Supernovae Ia (3)

- I my opinion, there is no significant gain to expect at collecting new SN samples for improving SH0ES.
- It would be better to collect all events (calibrators and HD) with the same instrument, but it is very unlikely that some part of the current data is grossly wrong.
- Switching from Cepheids/HST to TRGB/JWST, the rate of SN calibrators increases from ~1/y to more than 5. This is the only practical way to replace/enlarge the calibrator sample rapidly, if there is a good reason to do that.
- ZTF can do (and has partially done) the SN part, but the JWST proposals did not fare well (?!).

The result (R22)

$H_0 = 73.04 \pm 1.01 \text{ km s}^{-1} \text{ Mpc}^{-1}$

The difference with 67 km s^{-1} Mpc^{-1} is 0.185 mag.

The uncertainty from the fit, accounts for: uncertainty of the anchors
shot noise, dispersion of Cepheids and SNe, uncertainties on standardizations,
There is not much room for improvement with 42 calibrator SNe

Is there any point at reducing this formal uncertainty ?
Introducing more redundancy is the way to go.

R22: systematics/ variants

- Systematics are evaluated by studying "variants", which consist in changing some point of the analysis (but one at a time):
  - Cepheid clipping, selecting anchors, color correction, PL relation M31 handling, Metallicity handling, SNe handling,…
- The rms of H_0 over variants is 0.3
- R22 add 0.3 to 1.01 (in quadrature) and find 1.04. I find 1.05.
- I don't understand why the **rms** over variants is a measure of systematic uncertainty: the potential sources seem to add up, because all are potentially active.
- If adding up the changes measured on variants, the uncertainty becomes ~1.4 .

Internal consistency: are anchors compatible ? (1)

- As shown before, M31, introduced to nail the cepheid PL slope has a different slope than the other hosts.
- One key aspect to reduce uncertainty is to average three anchors, but the average only makes sense if they are compatible
- G. Efstathiou claims that it is not the case: LMC and N4258 both host cepheids and both have geometrical distances. This allows a null test, failed at >3σ :

$$\Delta\mu_{\rm N4258} = (\mu_{\rm N4258} - \mu^{P}_{\rm N4258}) = 0.177 \pm 0.051,$$

2007.10716

- In 2007.10716, SH0ES replies that the residual is closer to 2 σ (0.1 mag), but they seemingly had not carried out the test.

Internal consistency: are anchors compatible ? (2)

- So, two geometrical anchors are questionable
- The third one, the Milky Way is also questionable (2309.05618, 5.2)
  - Quality of "zero point" of Gaia parallaxes (which dominate the sample)
  - Position-dependent offsets, "color terms"
  - Linearity of cepheid photometry
- It is clear that more anchors would be welcome.
- It is not clear if Gaia can deliver a (statistical) parallax of the LMC, because of "zero point" parallax uncertainty.

Comments/conclusions (1)

- There have been other analyses of the SH0ES data, that usually find the same result (see references in R22).
- Reproducing the photometry of cepheids is difficult and tedious. I am not sure it is useless, given the scatter in the Javanmardi+ (2021) comparison. Instrumental aspects may deserve a critical look. Brighter-fatter was not corrected, non-linearity may be trickier than a power law.
- There are potentially serious issues when comparing (very) bright and (very) faint cepheids.
- The quality of anchors is arguable: they could be more consistent and the published uncertainties are propagated as such, while they are likely optimistic: uncertainties are uncertain.

Summary/conclusions(2)

- The handling of systematics in R22 (and before) is arguable, and mostly does not address many photometry potential issues. The analysis relies on averaging (how?) a lot of (very) poor measurements, a bad situation in general.
- I think we need more redundancy, as opposed to more cepheids or new SNe in the second rung.
- TRGB (in the SN hosts that already have cepheid data) is probably the natural next step, underway in fact.
- HST/JWST is the bottleneck for this science. The standard time allocation scheme is probably not the best way to cook up an observing program.

If I had to bet (I wish I didn’t)

- I cannot imagine how the SN part of the analysis could be wrong. I don’t know about CSP from Freedman et al.
- I have suspicions about the photometry of cepheids, but I doubt that it could reconcile with Planck. But it is worth investigating, even if crowding seems settled.
- If I had to bet, I would first question the anchors.