Gaia and the distance ladder

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Overview

- Importance of distance determination
- Standard candles
- Distance ladder in three steps
- Gaia contribution and open problems
- Future perspectives

Distances in astronomy

- Distances are a central problem in astronomy.

- Allow us to measure the intrinsic energy emitted by a source → constraints on the theoretical models

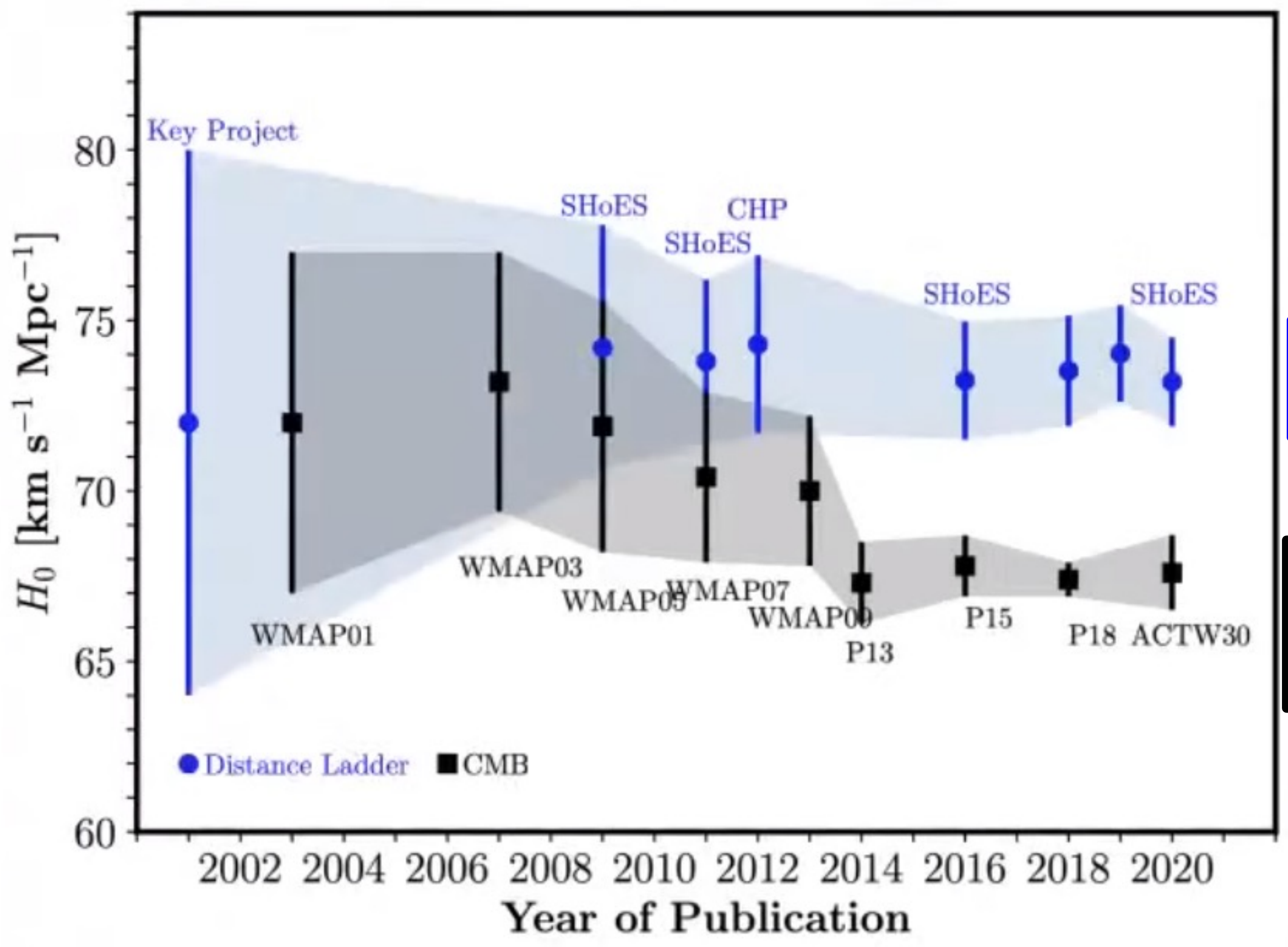
- Measure the dimensions of each celestial objects

- Measure the dimension of the local and distant universe → at the base of measure of H_0

- In the ΛCDM model, H_0 is a crucial ingredient, like the speed of light. H_0 enters in everything we know about the universe: how old it is, how big it is, what it's made of...

- If H_0 changes even slightly, we get a different age of the universe, different relative amounts of matter, dark matter, dark energy, and so on.

Hubble tension



Distance scale

Cosmic microwave background

Credit: W. Freedman

Distances and Standard Candles

- Distances in astronomy are correlated with the concept of **standard candles** (term coniated by H. Leavitt according to Fernie, 1969)

- **Standard candles**: a class of astrophysical objects which have known luminosity due to some characteristic quality possessed by the entire class of objects. → if an extremely distant object can be identified as a standard candle then the absolute magnitude *M* (luminosity) of that object is known → from the apparent magnitude *m* the distance comes from $m\text{-}M=-5+5log_{10}(D)$.

- The characteristics that a good standard candle must have:

  - Physics-based (i.e., based on a well-understood, theoretically solid physical principle) Examples: Cepheids; Miras (stellar equilibrium equations); Detached binaries, Megamasers (Kepler's law); TRGB (well-understood stellar evolution theory).

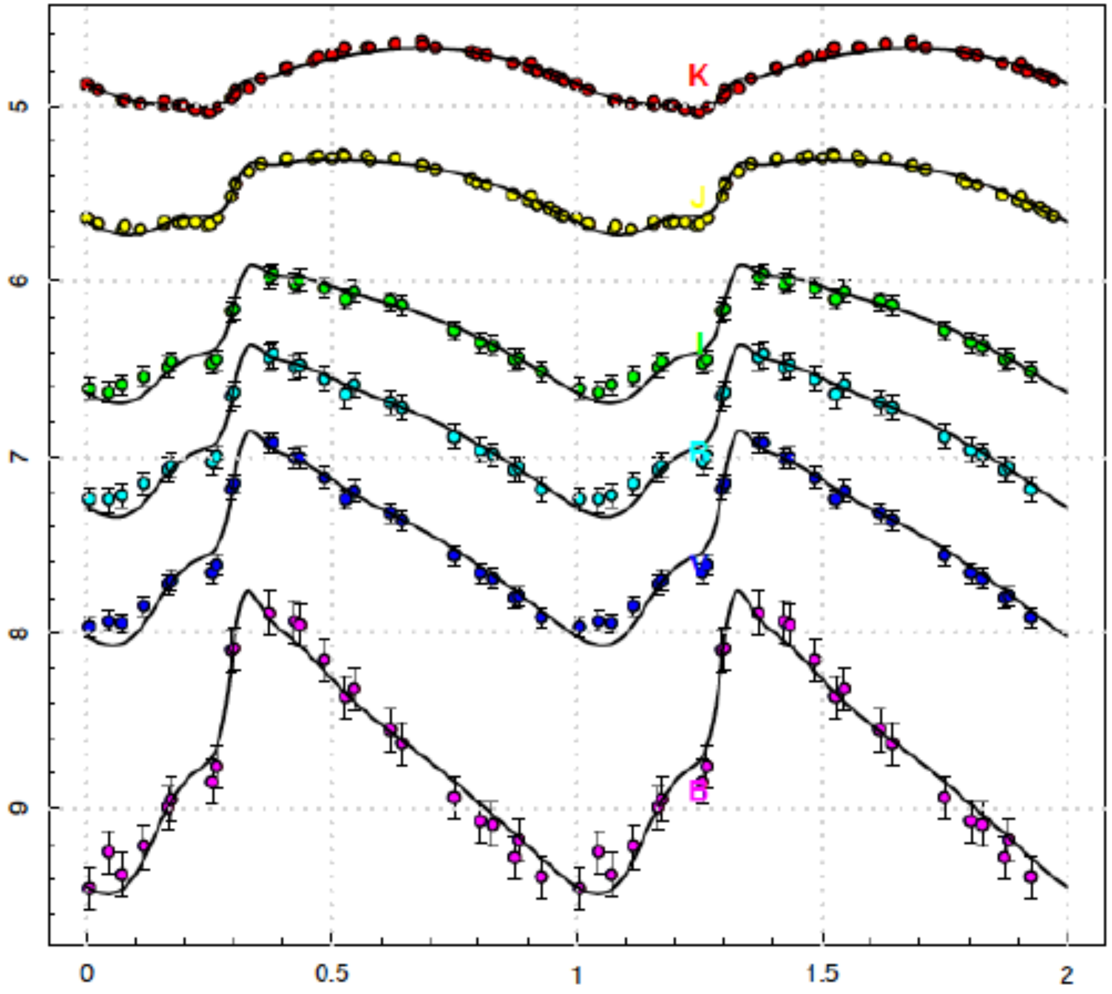
  - Low dispersion of the instrinsic luminosity;

  - Bright enough and easy to individuate at long distances;

  - Small observational uncertainties

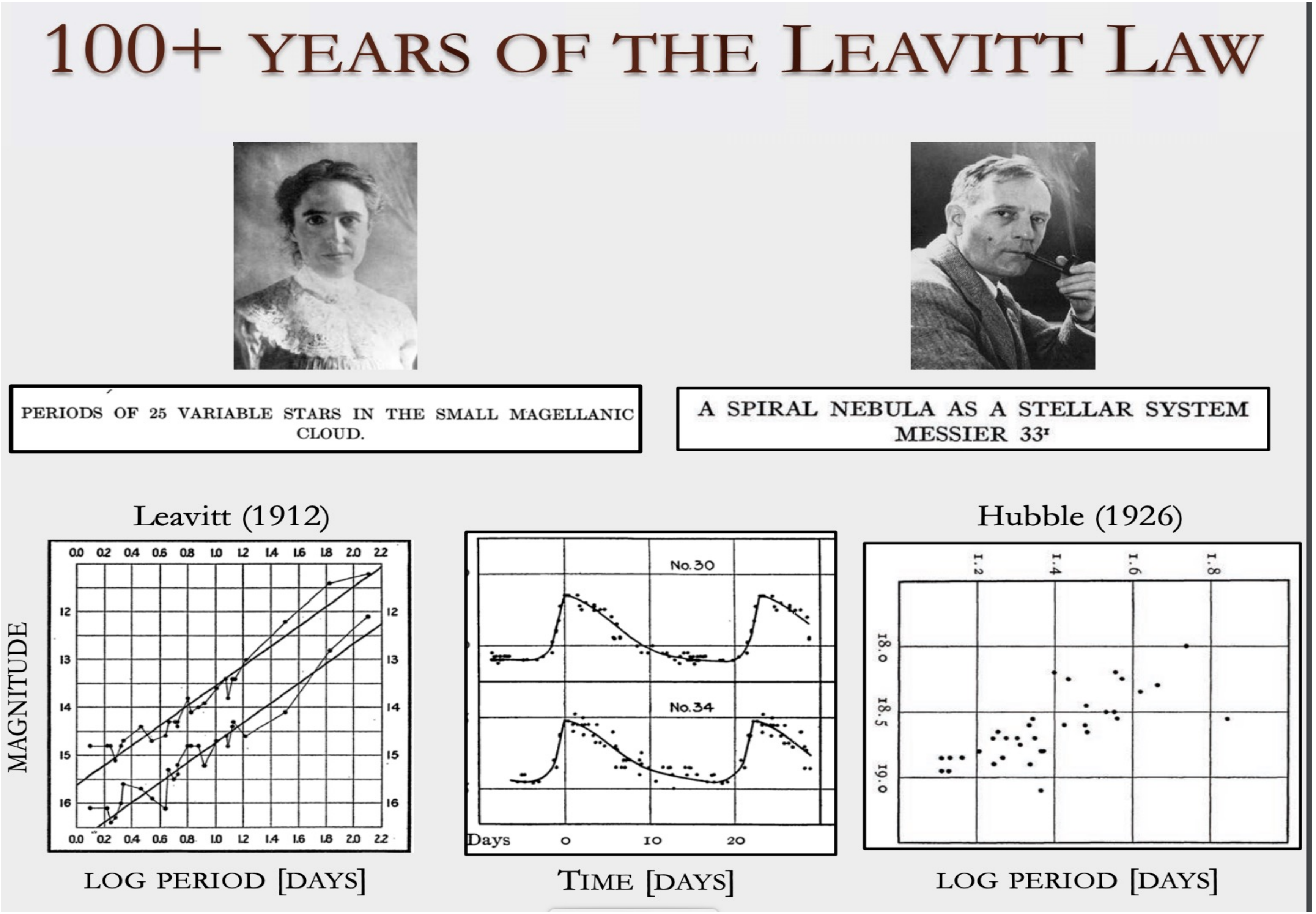
  - Control of systematics

Standard candles: Classical Cepheids



- **Classical Cepheids:** central helium burning stars ($M=3\div13M_{\odot}$, $M_V=$ -2÷- 7 mag, P=1÷100 d; 50÷500 Myrs). Pulsate in F, 1O, 2O, Multiple modes.
- High amplitudes of variations in the optical (~ 1 mag) → easy to identify even at long distances.
- Sufficiently bright to be visible up to 40-50 Mpc with HST

Classical Cepheids Period-Luminosity



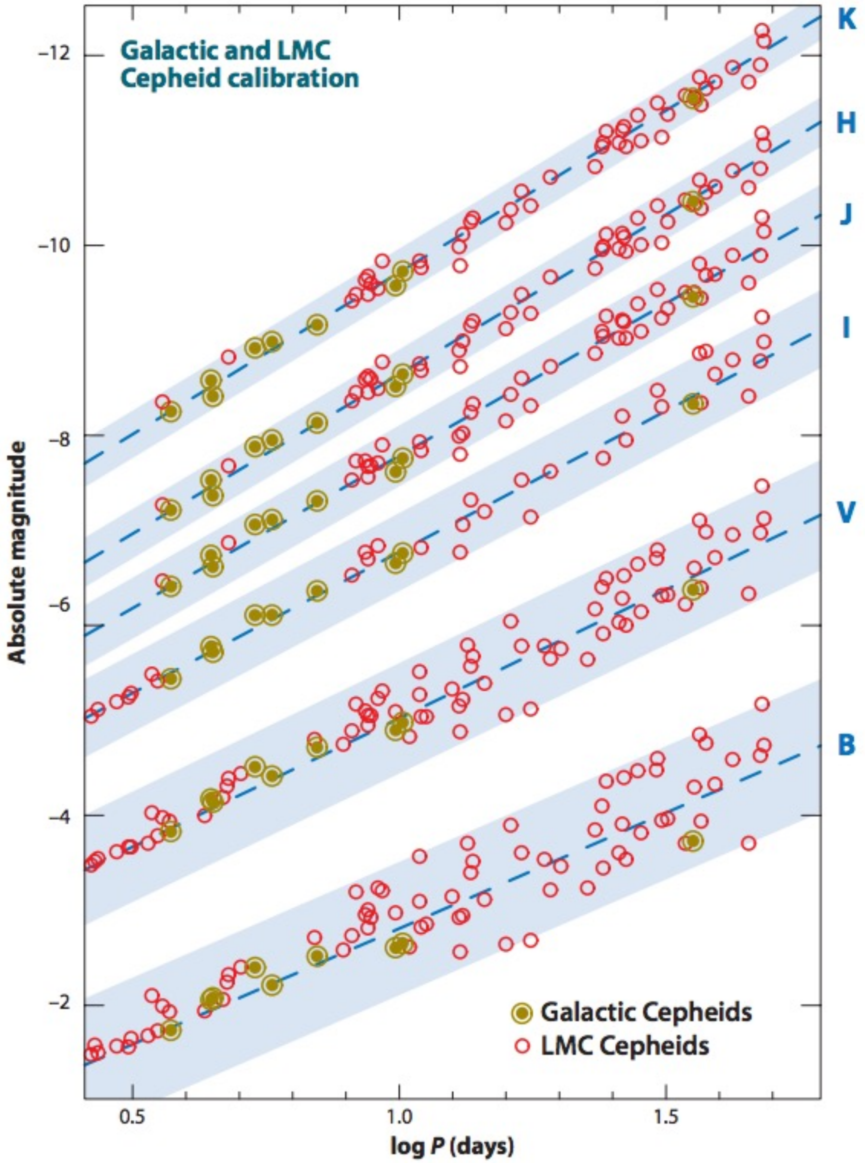
From Lucas Macri: https://www.eso.org/sci/meetings/2019/magellanic_clouds/program.html

Cepheids as distance indicators

- In the NIR low amplitude light curves.
- Absorption in Ks ~10% that in V.
- PL linear, with low dispersion and metallicity dependence.
- <u>Wesenheit magnitudes: reddening free</u>

$$W(\lambda_2, \lambda_1) = m_{\lambda_1} - \left[\frac{A(\lambda_1)}{E(m_{\lambda_2} - m_{\lambda_1})} \right] \times (m_{\lambda_2} - m_{\lambda_1});$$

- PWs have low dispersion: also takes partially into account the width of instability strip



Freedman & Madore, 2010

SNe Ia as Standard Candles

A good standard candle has the smallest possible range in luminosity

SNe Ia exhibit $\Delta M_B^{\mathrm{peak}} \sim 1.5$ ($\times 4$ in L)

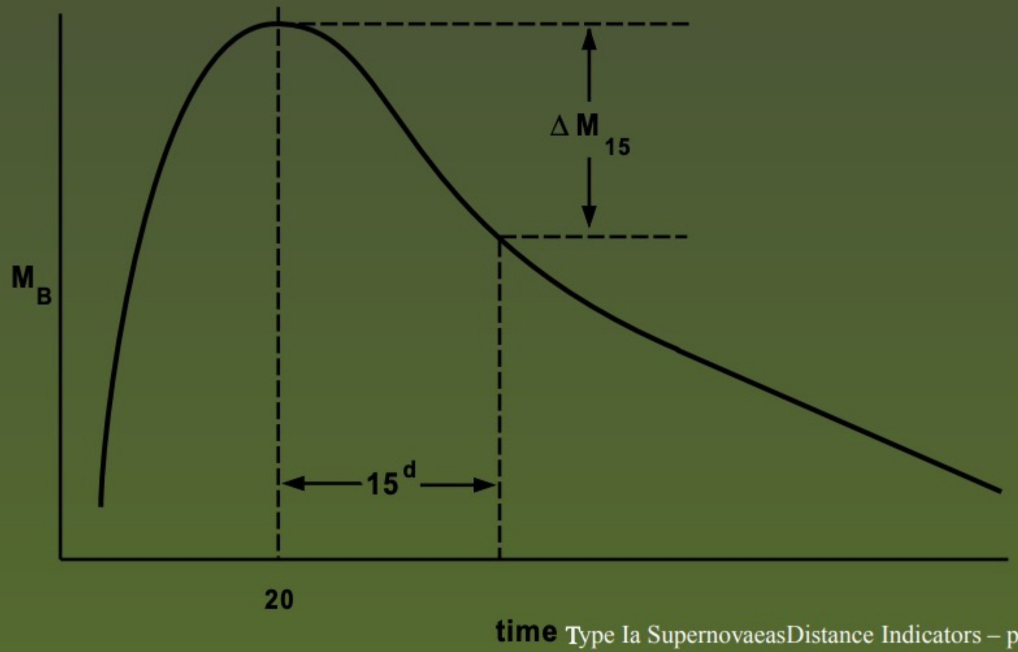
$\rightarrow$ too large for precision cosmology

Phillips ('93) discovered that the width of the lightcurve peak is correlated with the peak luminosity:

Brighter = Broader

Larger $M \leftrightarrow$ smaller Δm_{15}

Can use the $\Delta m_{15}/L$ relation to "standardize" the candle to $\sigma \sim 0.1$ mag



SNe Ia explode at approximately the same mass (Chandrasekar limit) → approximately the same luminosity

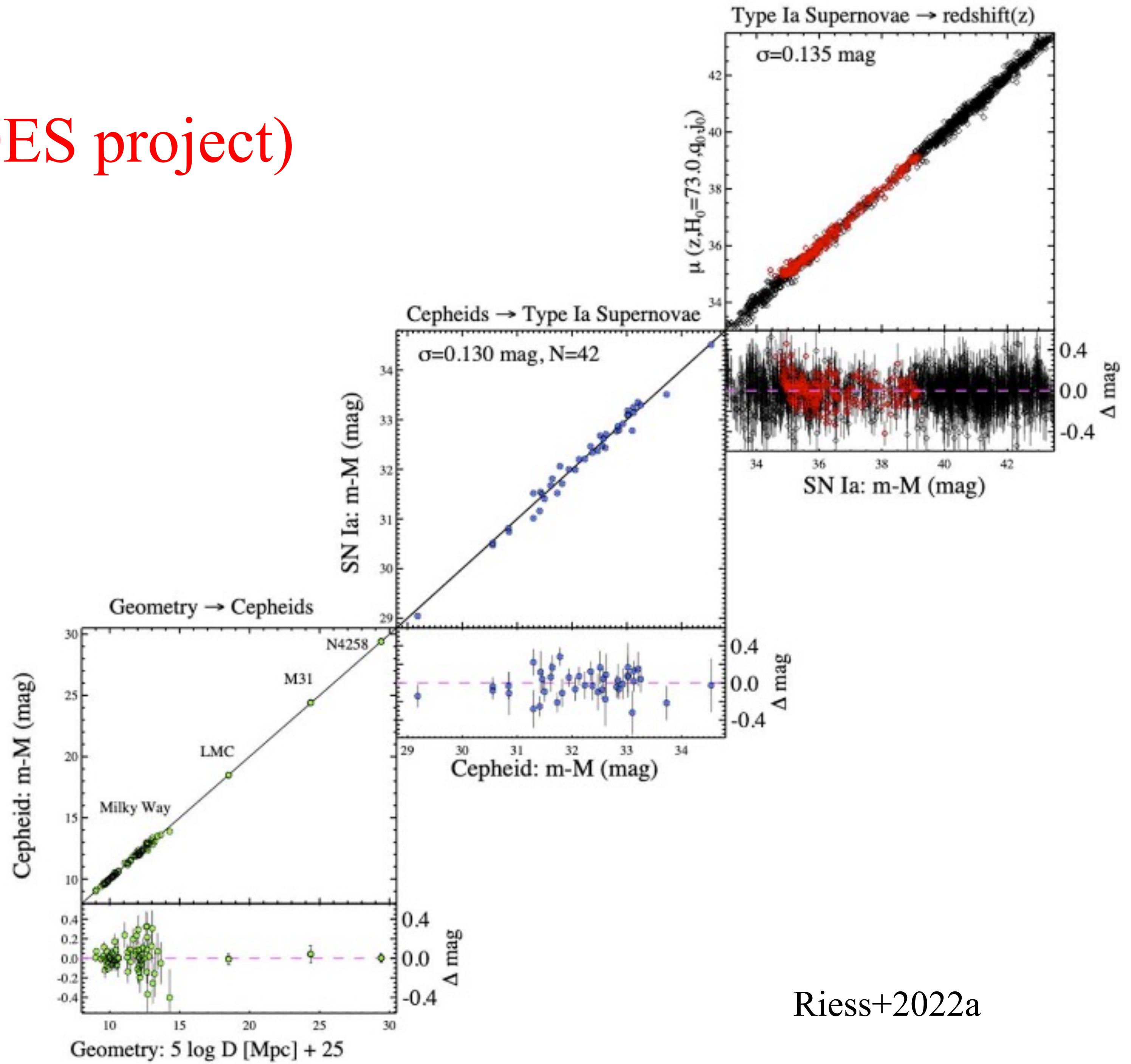
Maximum light $M_B \sim -19.3$ mag → visible well in the Hubble flow.

Credit: P. Pinto

Cosmic distance ladder:
a three step process (SH0ES project)

STEP 1: Geometric distances to calibrate the PL relation of Cepheids:

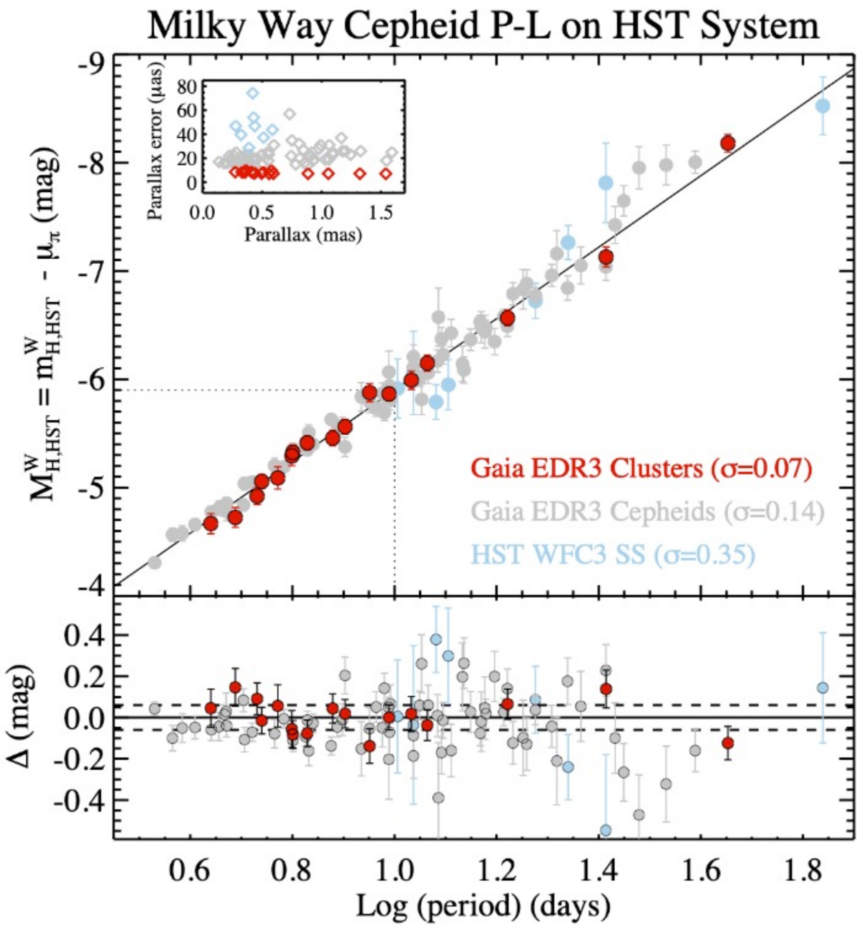
- Parallaxes in the MW (HST, Gaia)
- EB in the LMC
- Masers orbiting central supermassive black hole in NGC4258



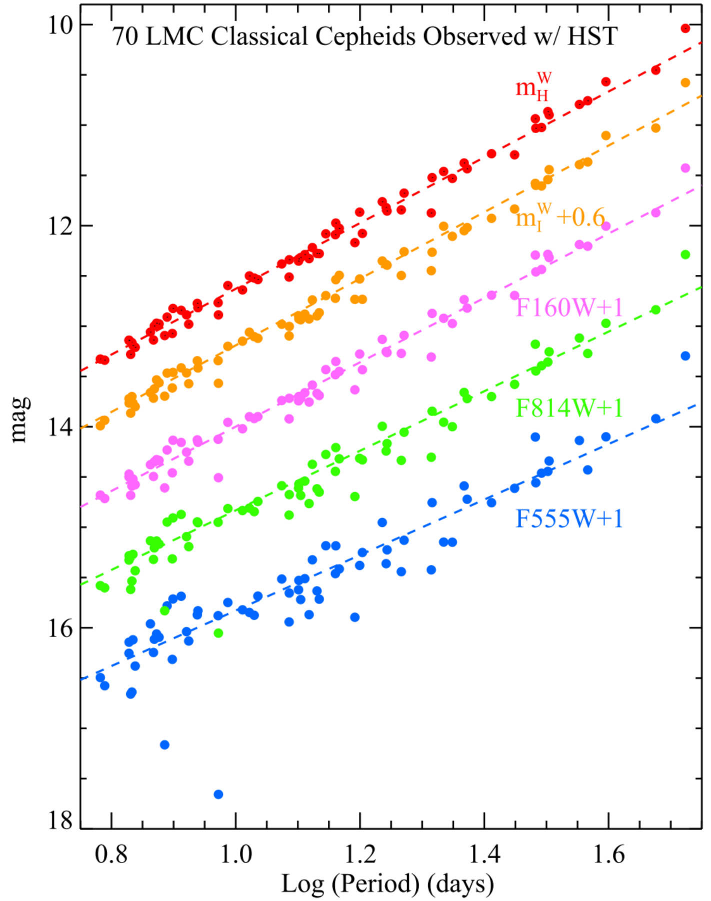
Riess+2022a

Step 1: Geometry → Cepheids, 3 anchors

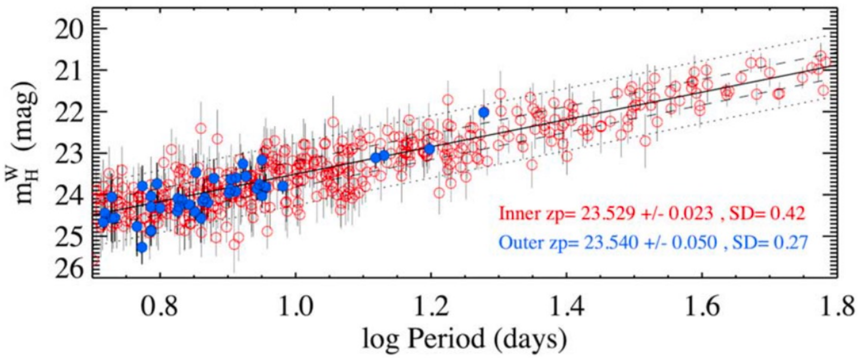
Gaia (and HST) Parallaxes to calibrate the PL of Cepheids in the MW (Riess+2022b)



Eclipsing binaries distances to LMC (Pietrzyński+2019) to calibrate the Cepheid PL in this galaxy

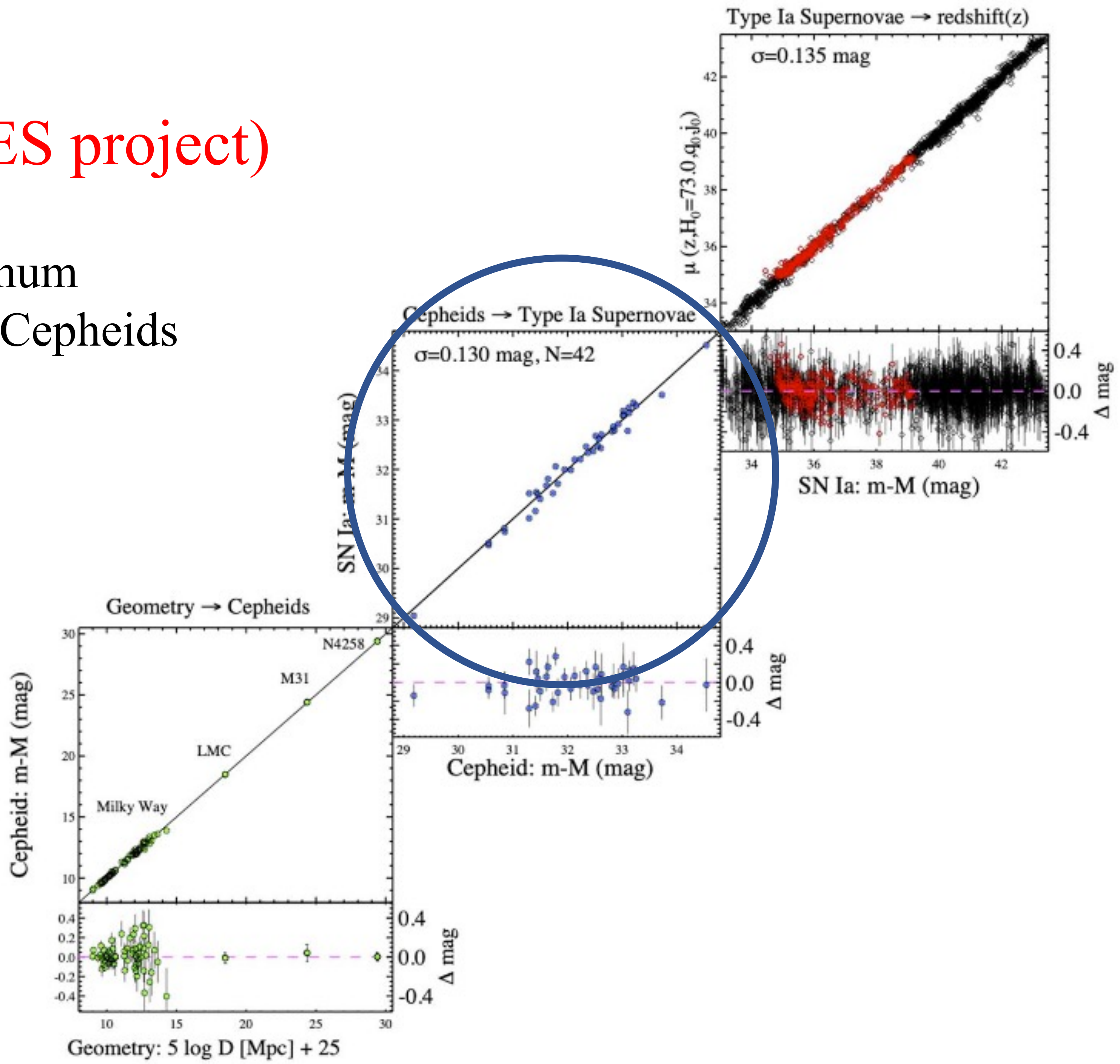


Water maser distances in NGC4258 (Reid+2019) to calibrate the PL in this galaxy.



Cosmic distance ladder:
a three step process (SH0ES project)

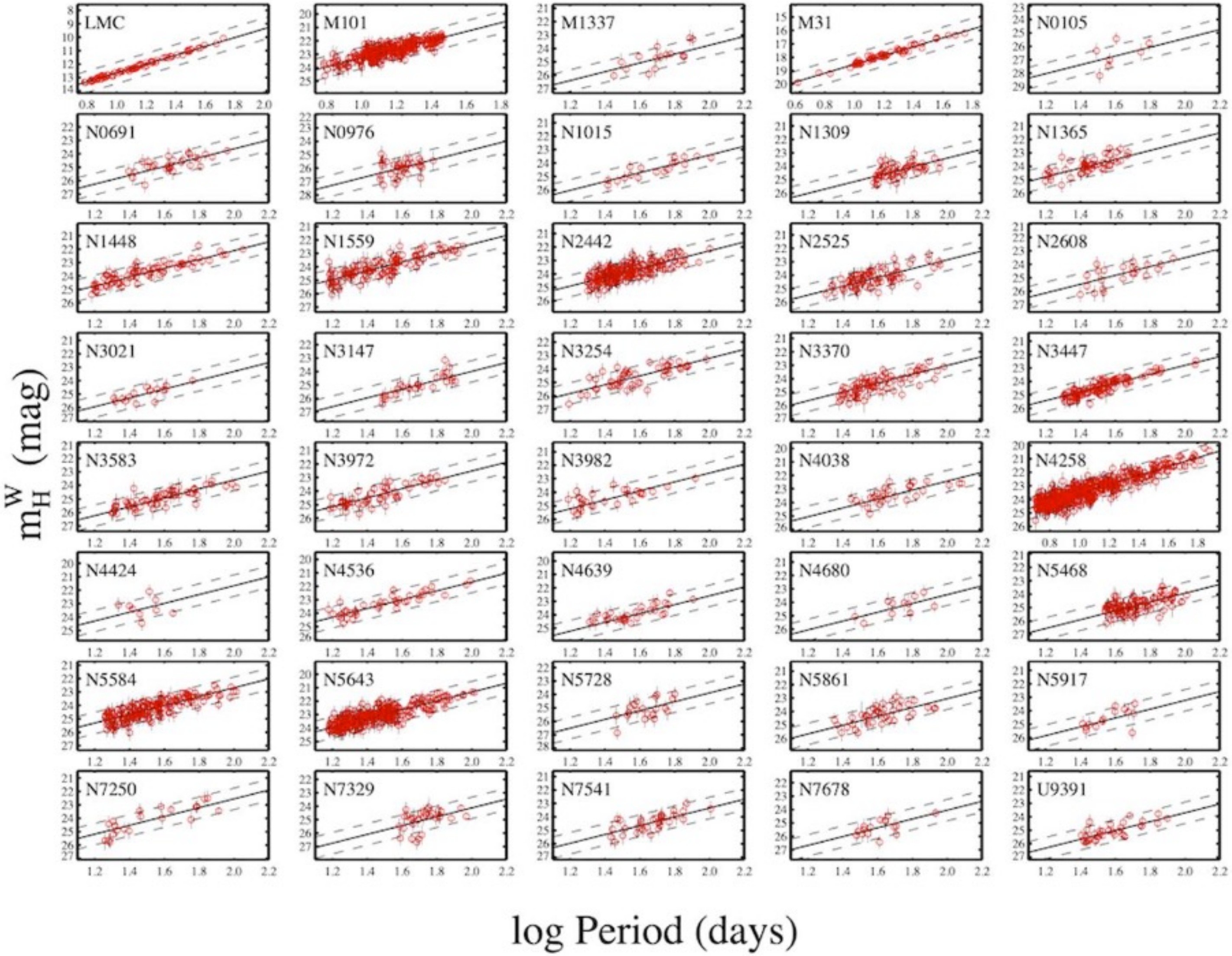
Step 2: Calibration of SNa Ia maximum luminosity in galaxies hosting both Cepheids and SNa Ia



Riess+2022

Step 2: Cepheids → SNe Ia, 3 anchors

Measure PL zero points in distant galaxies hostig SNe Ia (assuming the same slope) – comparison with the zero point calibrated geometrically gives the distance of each SNe Ia host.



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

SNe Ia maximum-light apparent magnitude (corrected for variations around the fiducial color, luminosity, and any host dependence).

Distance modulum from Cepheids

SNe Ia Fiducial magnitude (what we want to calibrate)

Riess+2022

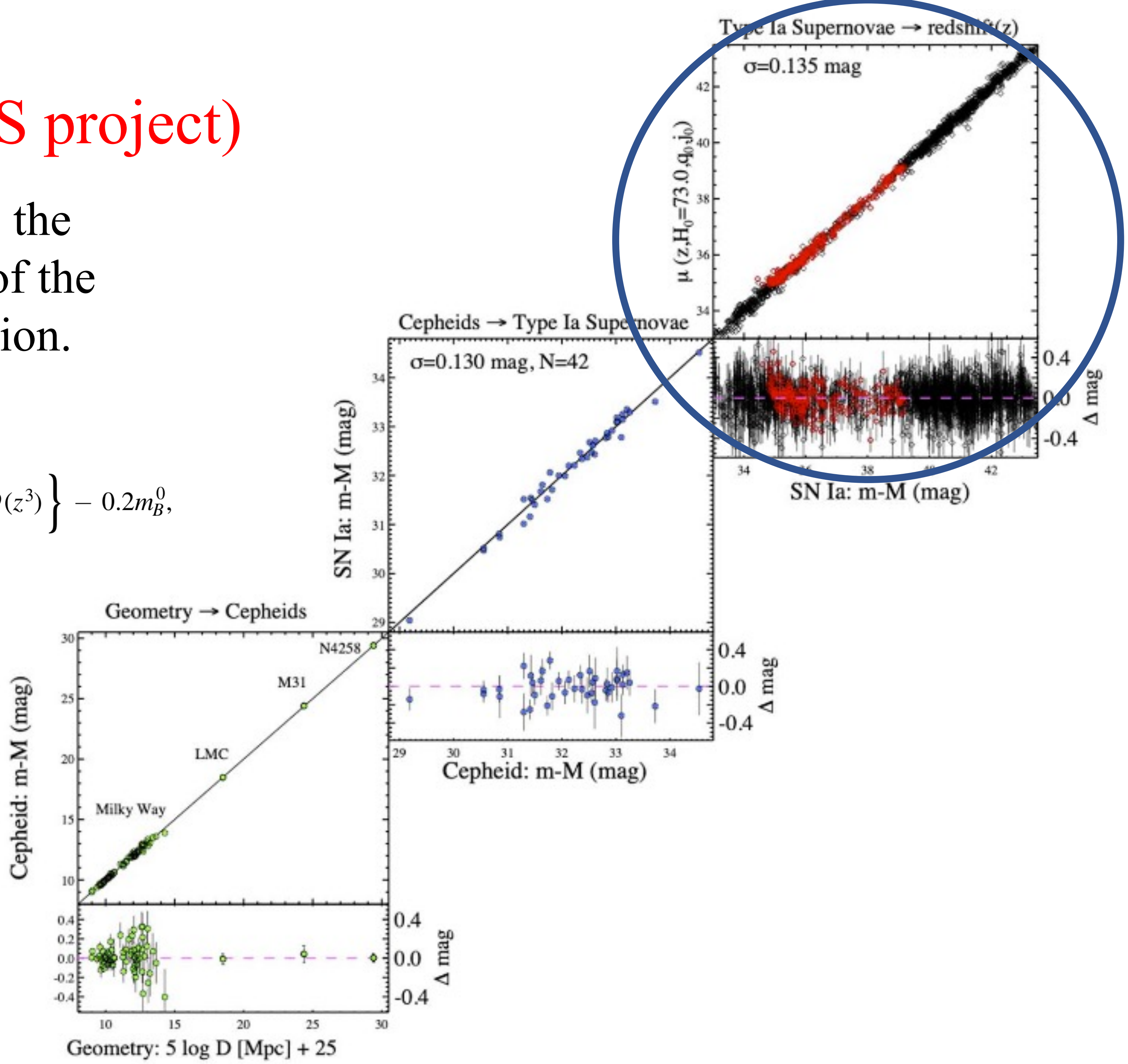
Cosmic distance ladder: a three step process (SH0ES project)

Step 3: A set of SNe Ia that measure the expansion rate, a_B i.e. the intercept of the distance or magnitude–redshift relation.

$$a_B = \log cz - 0.2m_B^0$$

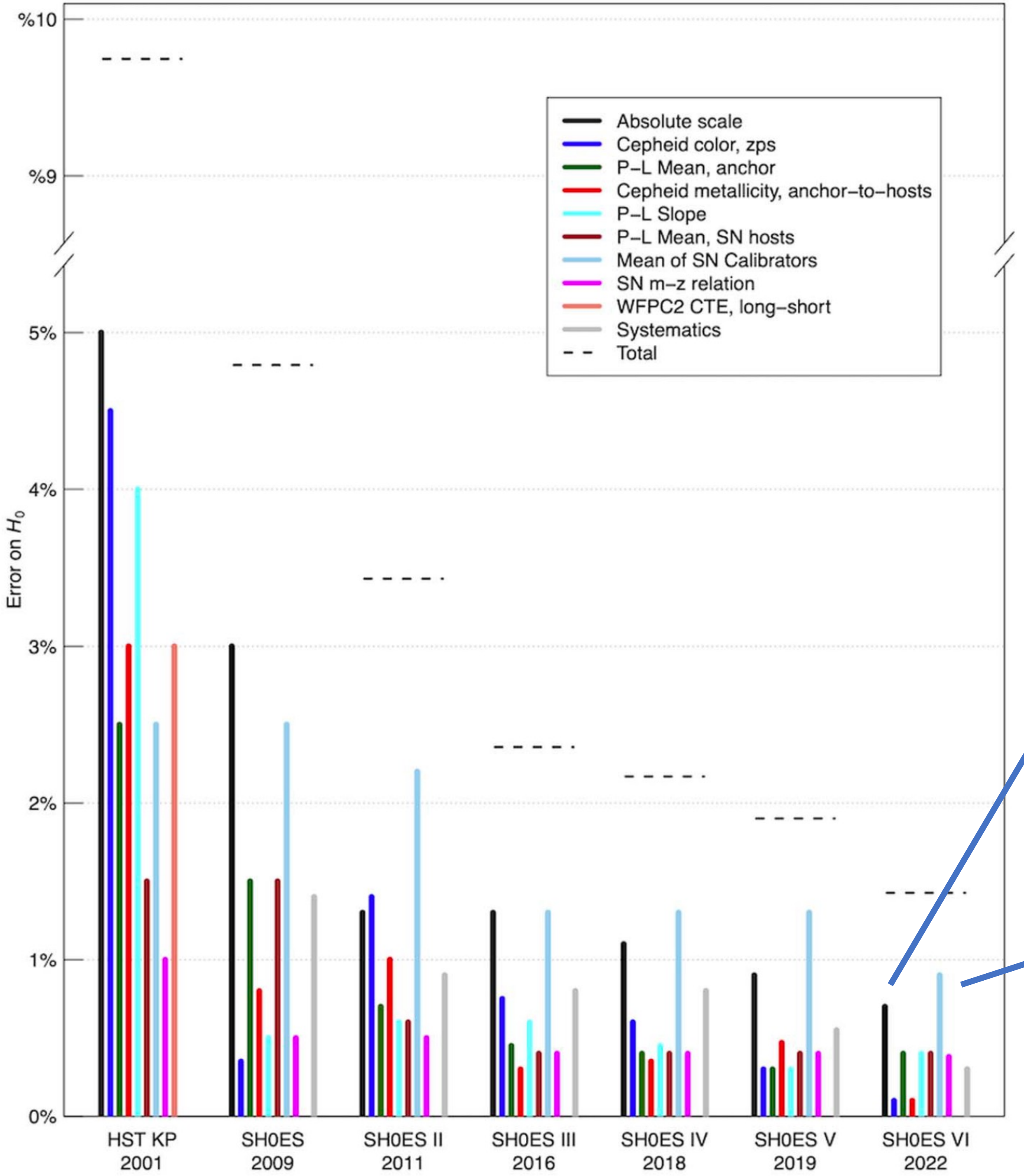
$$a_B = \log cz\left\{1 + \frac{1}{2}[1 - q_0]z - \frac{1}{6}[1 - q_0 - 3q_0^2 + j_0]z^2 + O(z^3)\right\} - 0.2m_B^0,$$

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



Riess+2022

Error budget

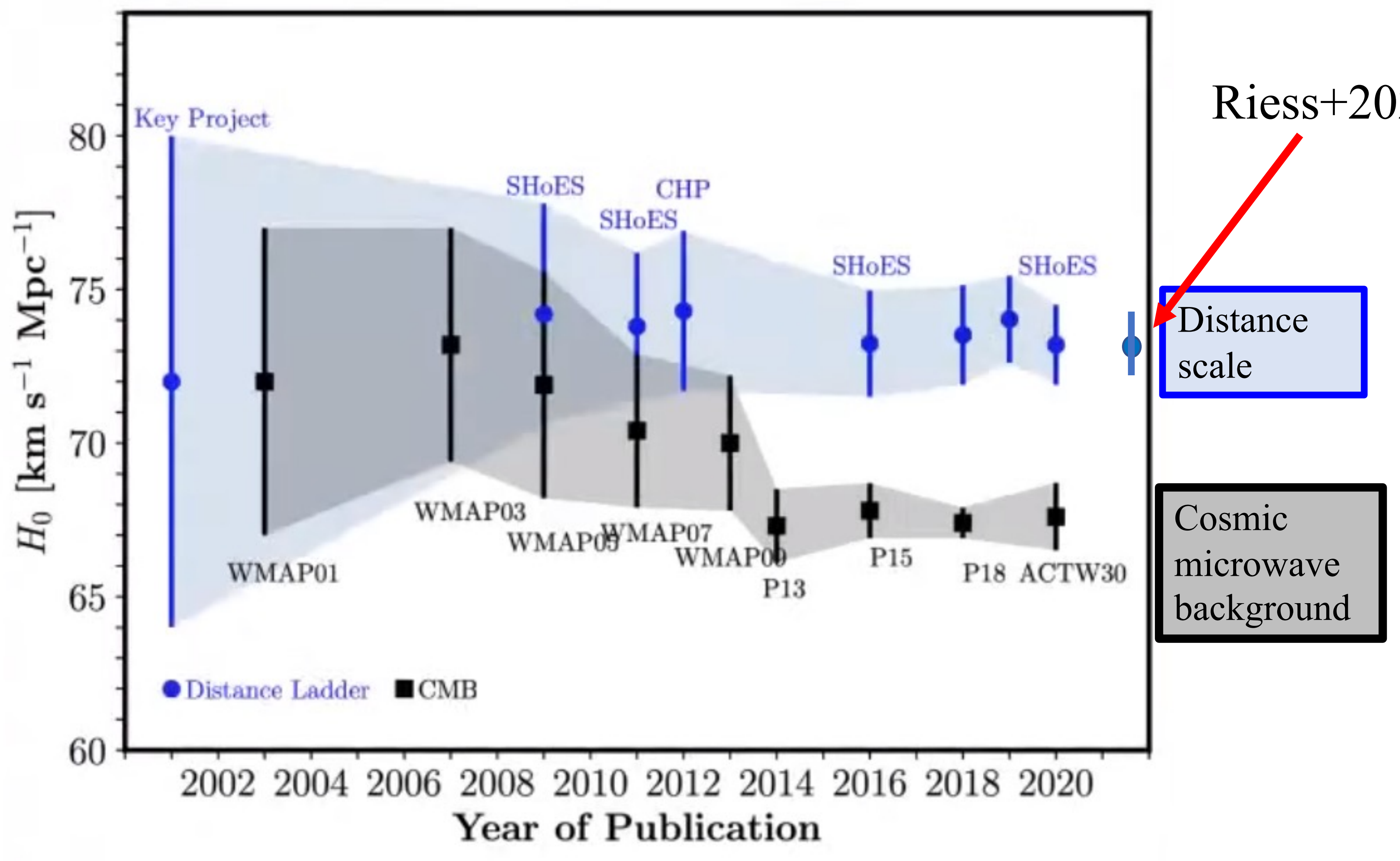


Step 1: Geometric calibration of the Cepheid PL

Step 2: Cepheid calibration of the SNe Ia peak luminosity

Riess+2022

Hubble tension



Credit: W. Freedman

Tip of the Red Giant Branch as standard candles

Classical Cepheids as standard candles have some drawbacks:

1) Young objects → observable only in late type galaxies

2) Typical disc objects:

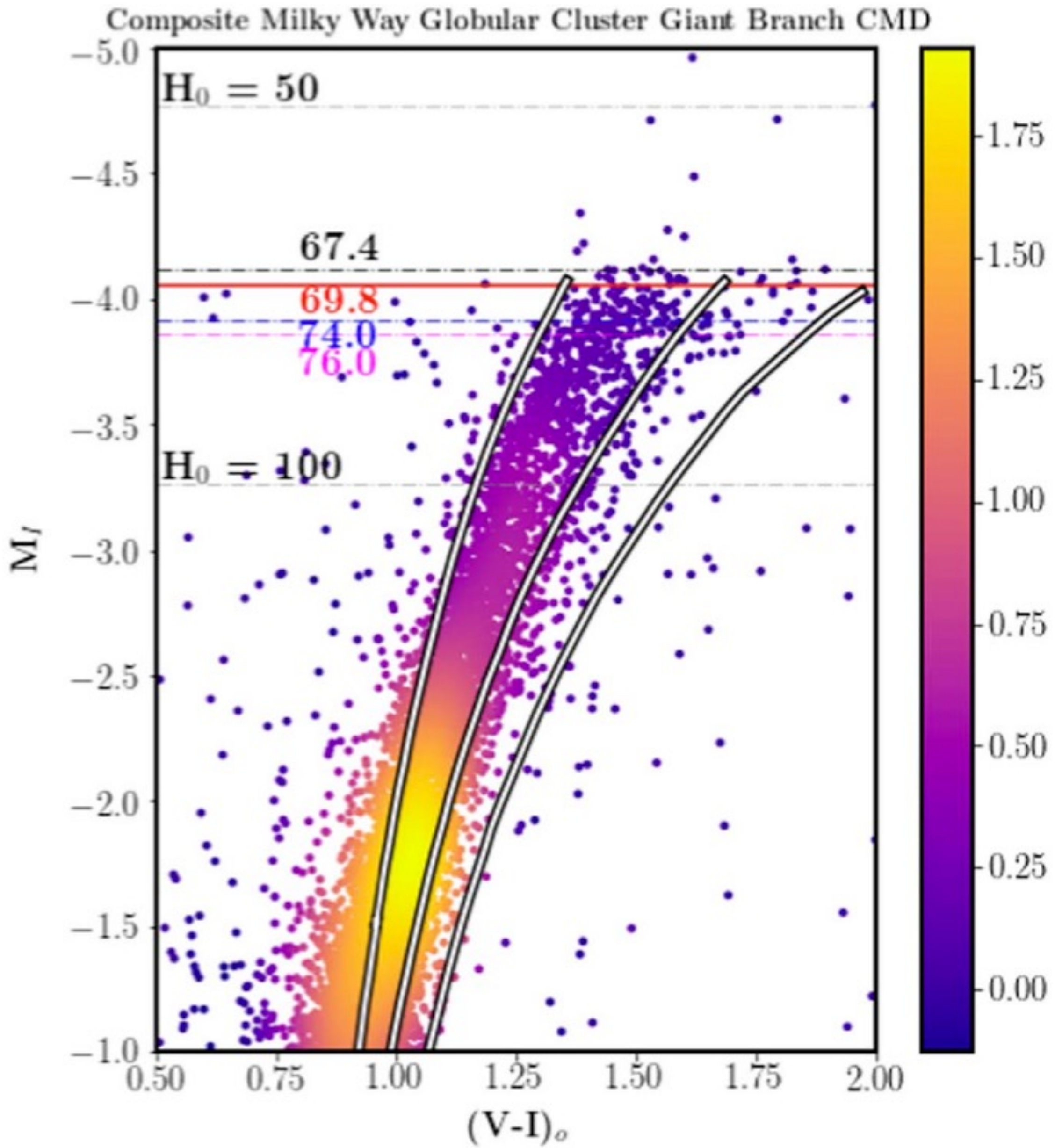
    1) crowding effects can be severe a large distances;

    2) High reddening regions: the extinction law can be different from the Fitzpatrick 1999 adopted by the SH0ES group.

↓

Search for an alternative: Tip of the RGB

Tip of the Red Giant Branch as standard candles



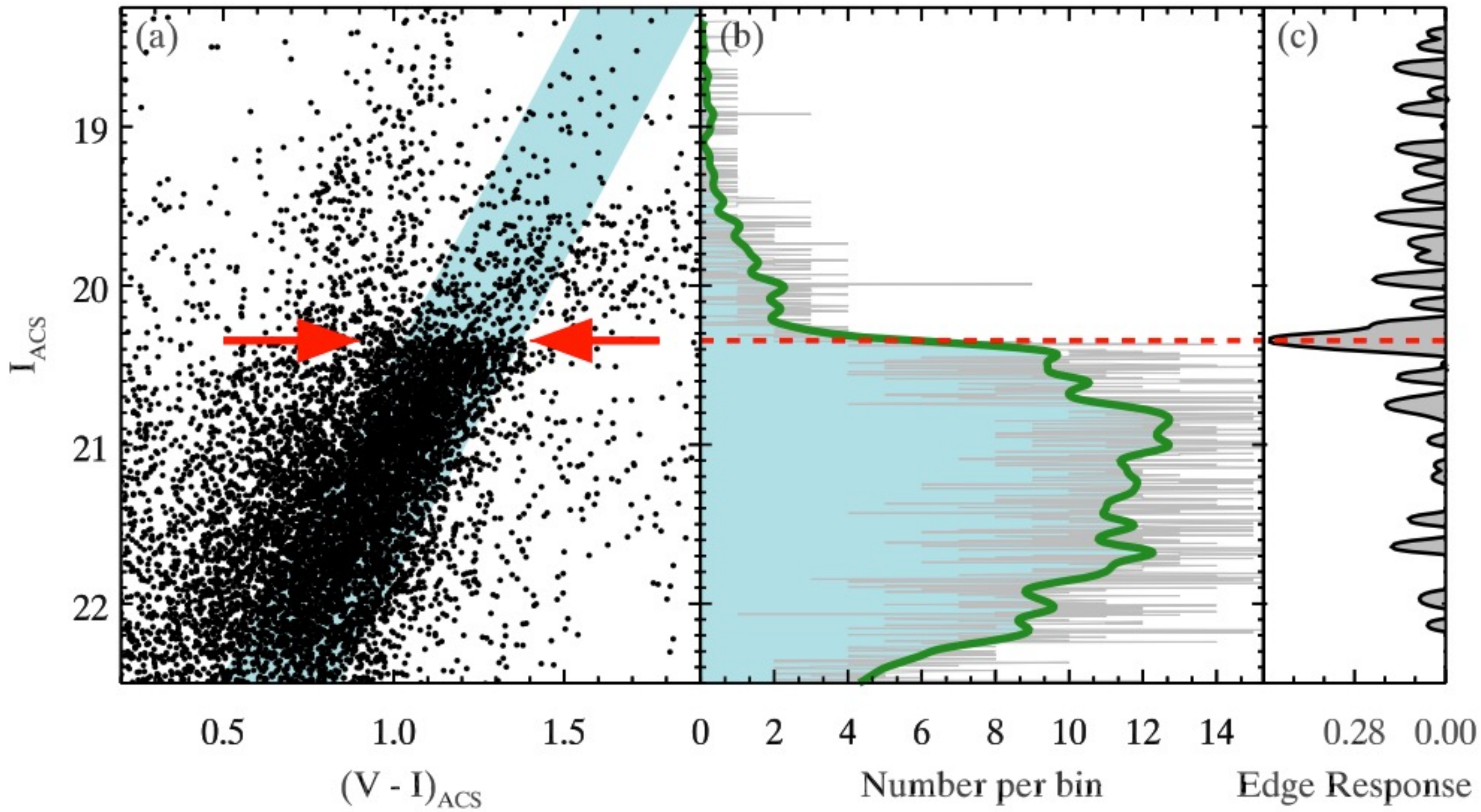
The TRGB is an excellent standard candle due to the an unambiguous location of the core helium flash luminosity at the end phase of red giant branch (RGB) evolution for low-mass stars.

TRGB stars are present in all the galaxies and can be measured in their outskirts, thus mitigating the crowding and reddening effects.

In the I band the TRGB stars have stable absolute magnitude ~ -4 mag. Not depending on age, metallicity or colour.

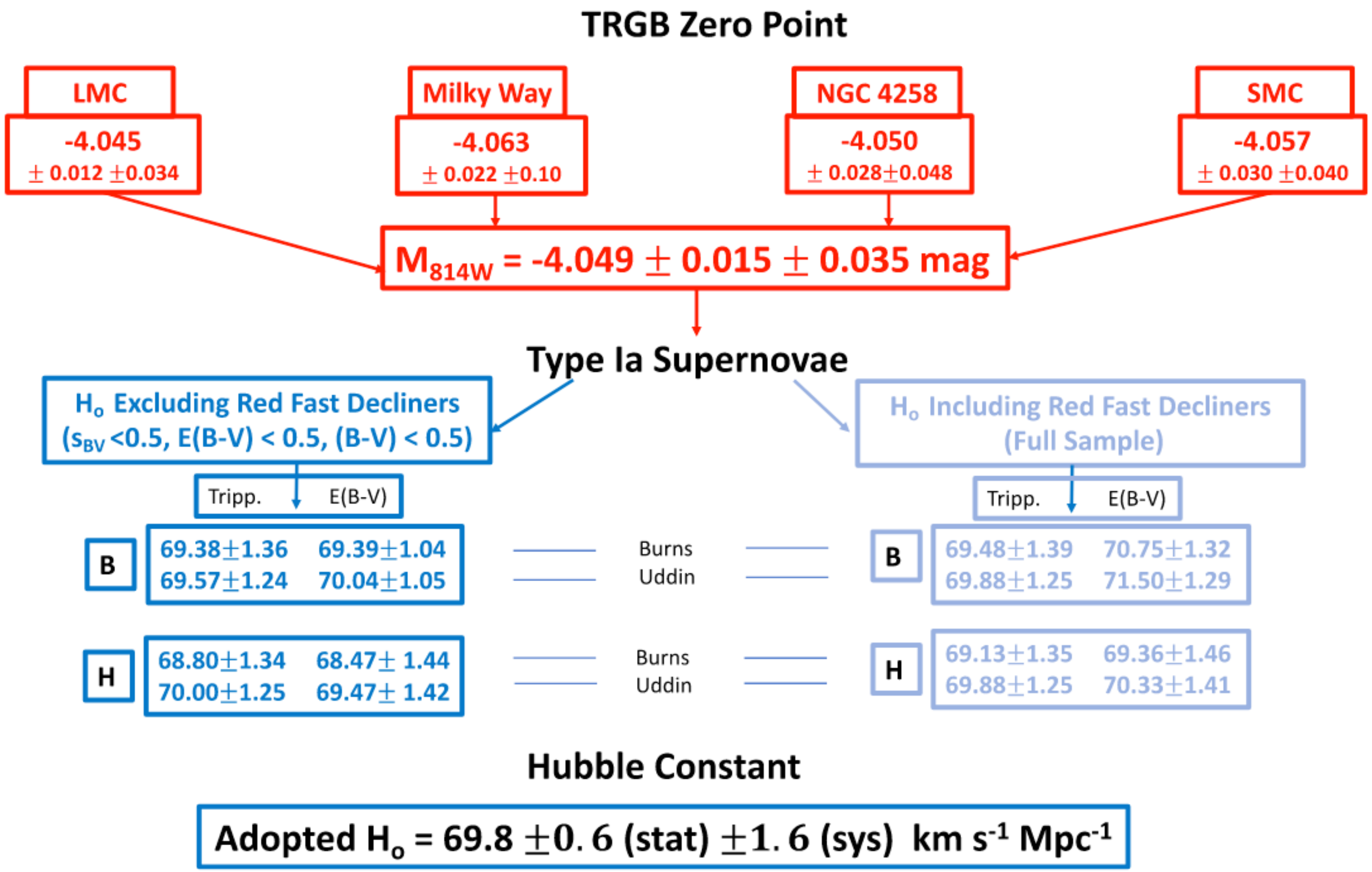
Fainter than Cepheids, improvements with future facilities (e.g. JWST, ELT)

Determination of TRGB peak



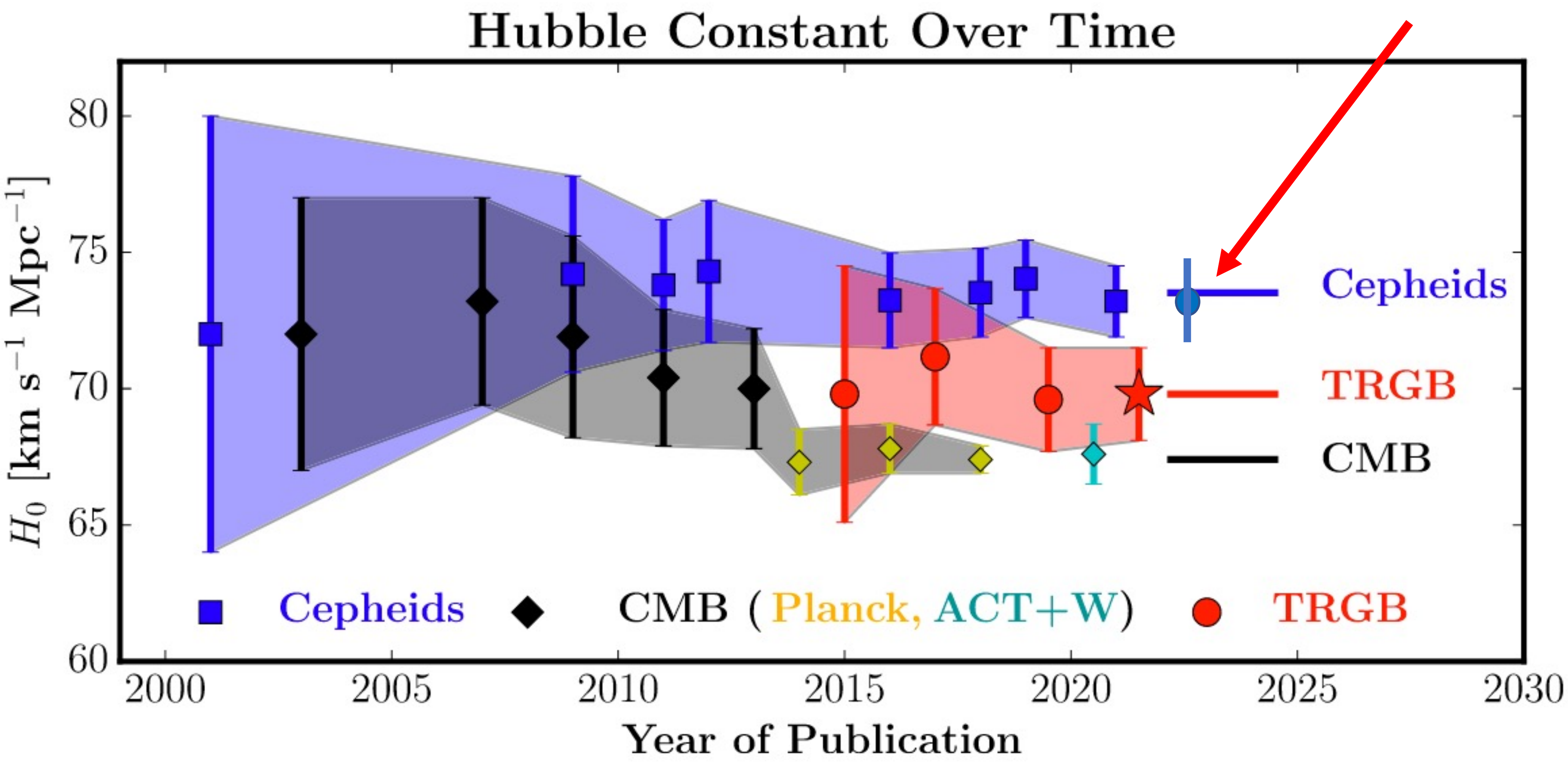
Hatt et al. 2017

Determination of H_0 with TRGB as primary distance indicators



Hubble tension: ”old” route

Riess+2022



Credit: W. Freedman

Residual source of uncertainty in the use of Cepheids as standard candles

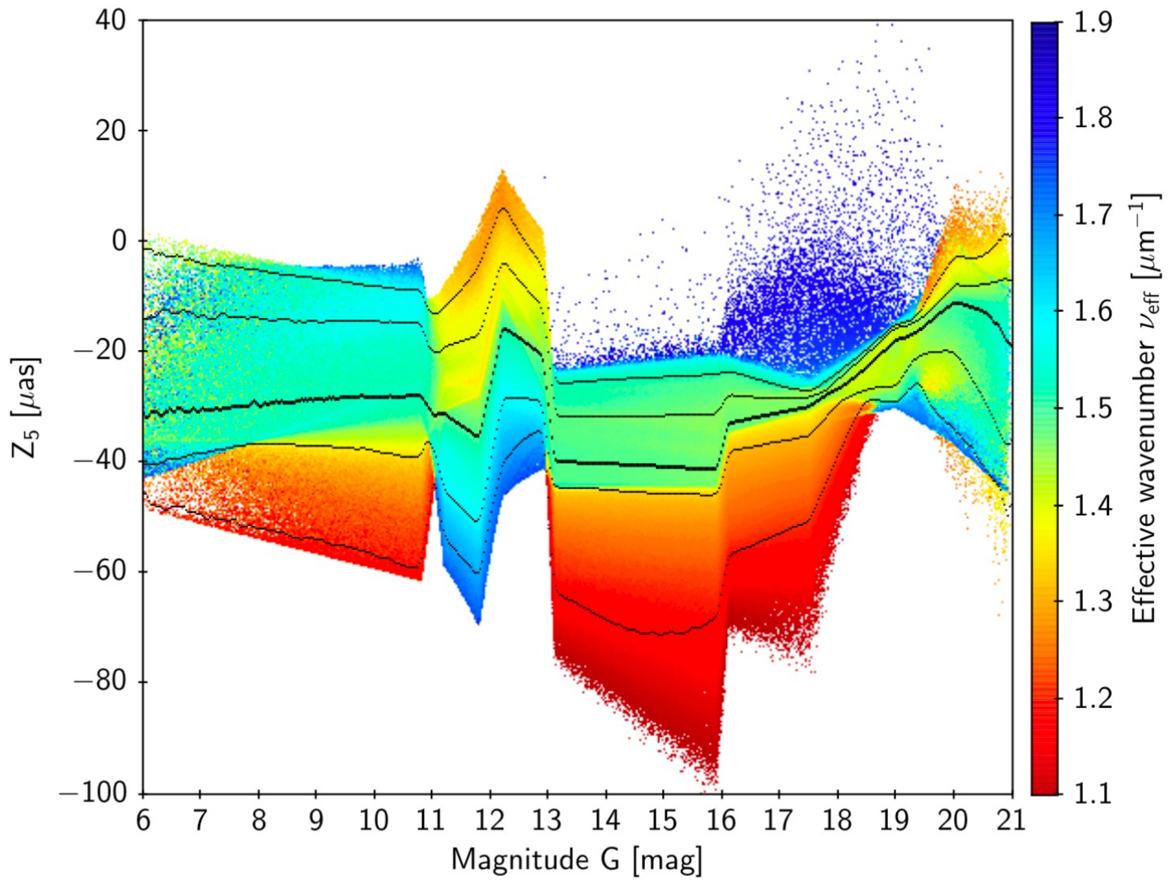
- Zero point offset of the Gaia parallaxes
- Metallicity dependence of the PL relations: *"As we enter an era where 1%–2% accuracies are required to resolve whether there is an H0 tension, it is critical that the long-standing uncertainties due to metallicity be better understood and calibrated."* (Freedman, 2021)
- The two quantities can be correlated

Zero point offset of the Gaia parallaxes

- The parallax solution is degenerate with respect to certain variations of the 'basic angle' between the viewing directions of Gaia's two telescopes (Butkevich et al. 2017). This means that one cannot, purely from Gaia's own astrometric observations, simultaneously determine absolute parallaxes and calibrate this particular perturbation of the instrument (Lindegren+2021).

- A correction to the Gaia zero point (ZP) parallaxes **for each star in DR3** was calculated by Lindegren+2020 using QSO, binary stars, LMC stars, RC stars.

- This ZP correction depends on the positioning the sky, G magnitude and colour of the source.



Lindegren+2021

Zero point offset of the Gaia parallaxes

Individual ZP offsets published by Lindegren+2021 were found to overcorrect Gaia parallaxes by a variety of Authors:

- Riess+2021 → -14±6 μas from DCEPs
- Zinn+2021→ -15 ± 3 μas for G ≳ 10.8 mag from asteroseismology
- Gilliland+2021→ -10 ± 7 μas from RR Lyrae
- Groenewegen 2021 → individual ZPOs
- ….
- ….

Knowing the accuracy of these correction is critical. The measure of H_0 with a 1% error requires that we calibrate the Cepheids PL relations with an accuracy better than 2%.
To this aim, the ZP offset of Gaia parallaxes must be known with an accuracy of 2-3 μas.

Estimating the ZP parallax offset directly from Cepheids

The ZP offset can be calculated directly from the Cepheid data, constraining directly the coefficients of the PL relation (Riess+2021)

$$m_H^W = m_{F160W} - 0.386(m_{F555W} - m_{F814W}).$$

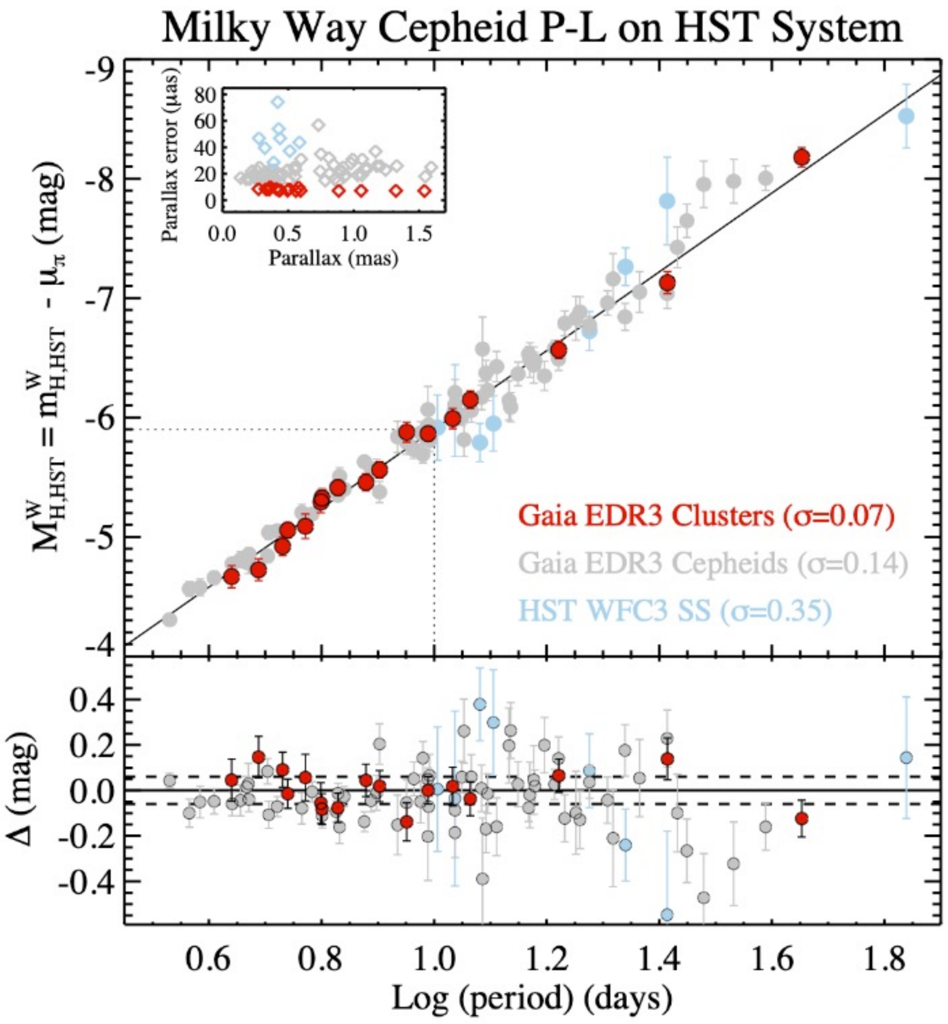
$$\mu_{0,i} = m_{i,H}^W - (M_{H,1}^W + b_W\,(\log\,P_i - 1) + Z_W\,\,\Delta[\mathrm{O/H}]_i)$$

$$\pi_{phot,i} = 10^{-0.2(\mu_{0,i}-10)}$$

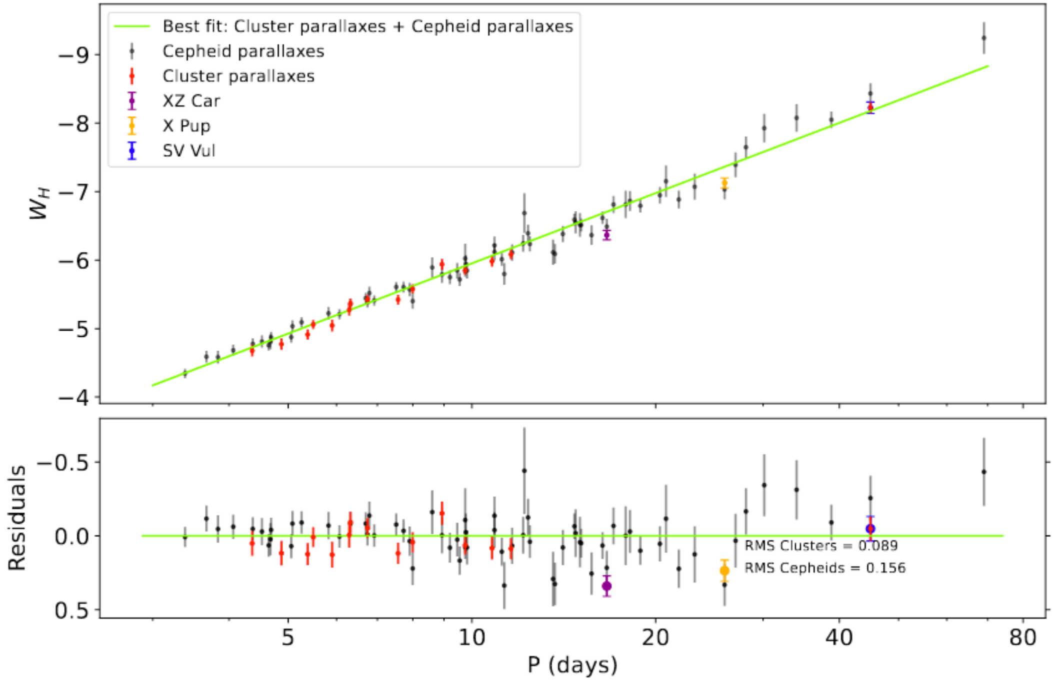
$$\chi^2 = \sum (\pi_{\mathrm{EDR3},i} - \pi_{\mathrm{phot},i} + zp)^2 \sigma_i^{-2},$$

Riess+2021 found an average overcorrection of the Lindegren+2021 equal to 14±6 µas. This 6 µas represent about 0.9% uncertainty on the value of H

Cepheids in open clusters (Riess+2022, Reyes & Anderson 2022)

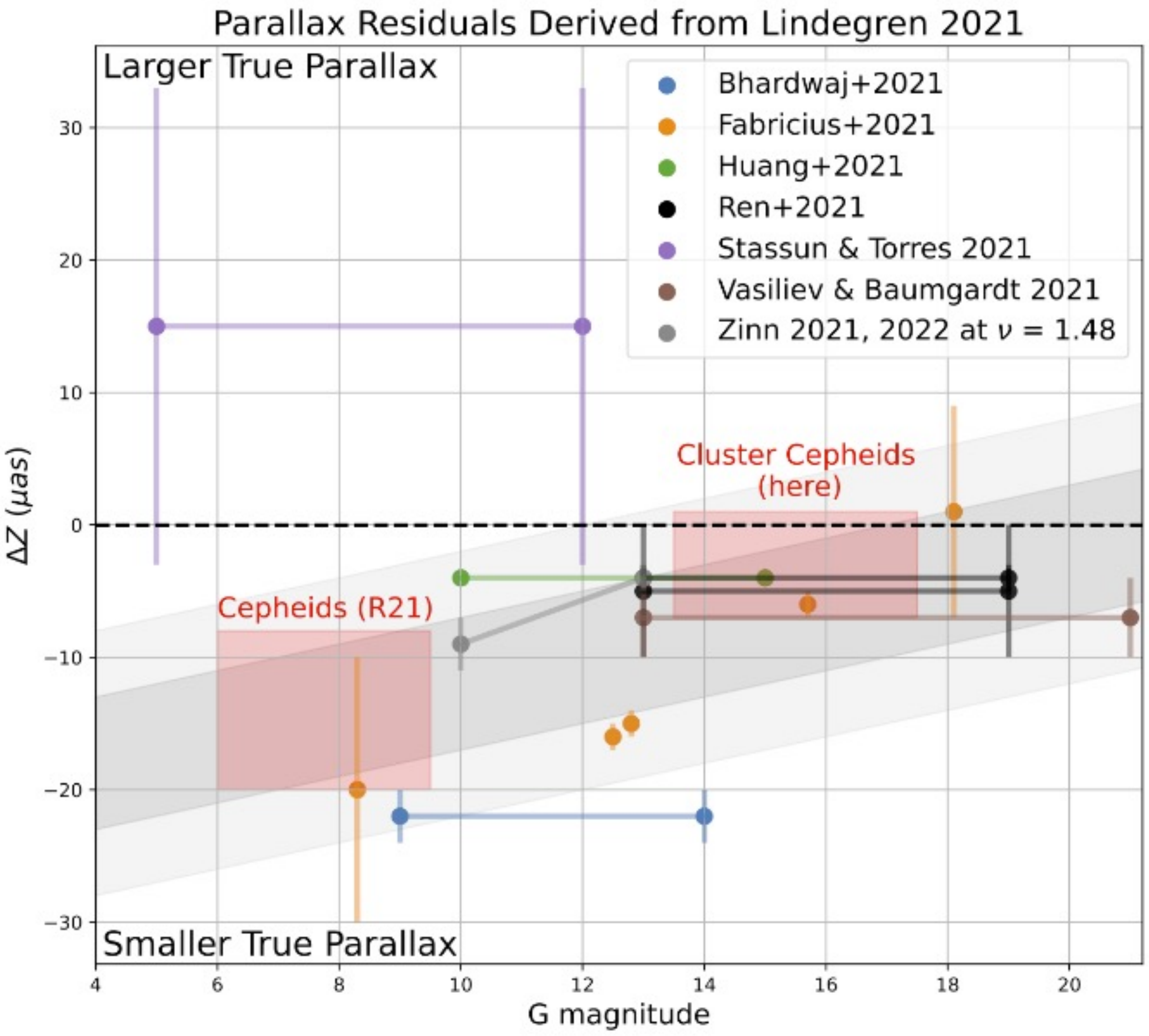


Riess et al. 2022



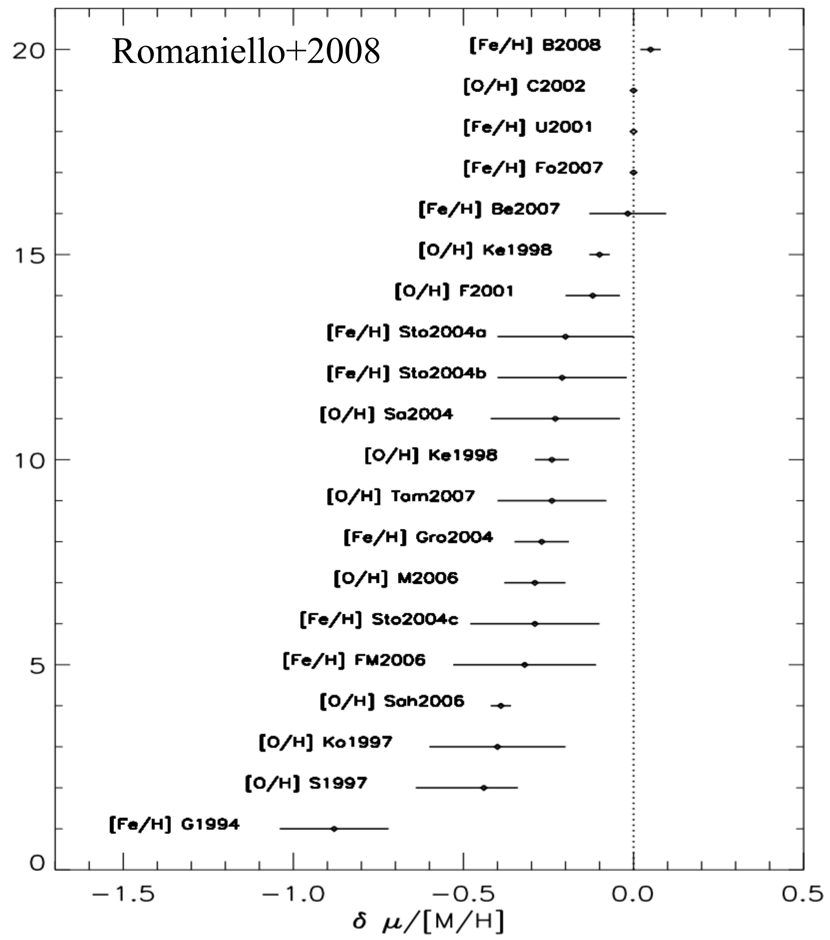
Reyes & Anderson et al. 2022

Zero point



Riess et al. 2022

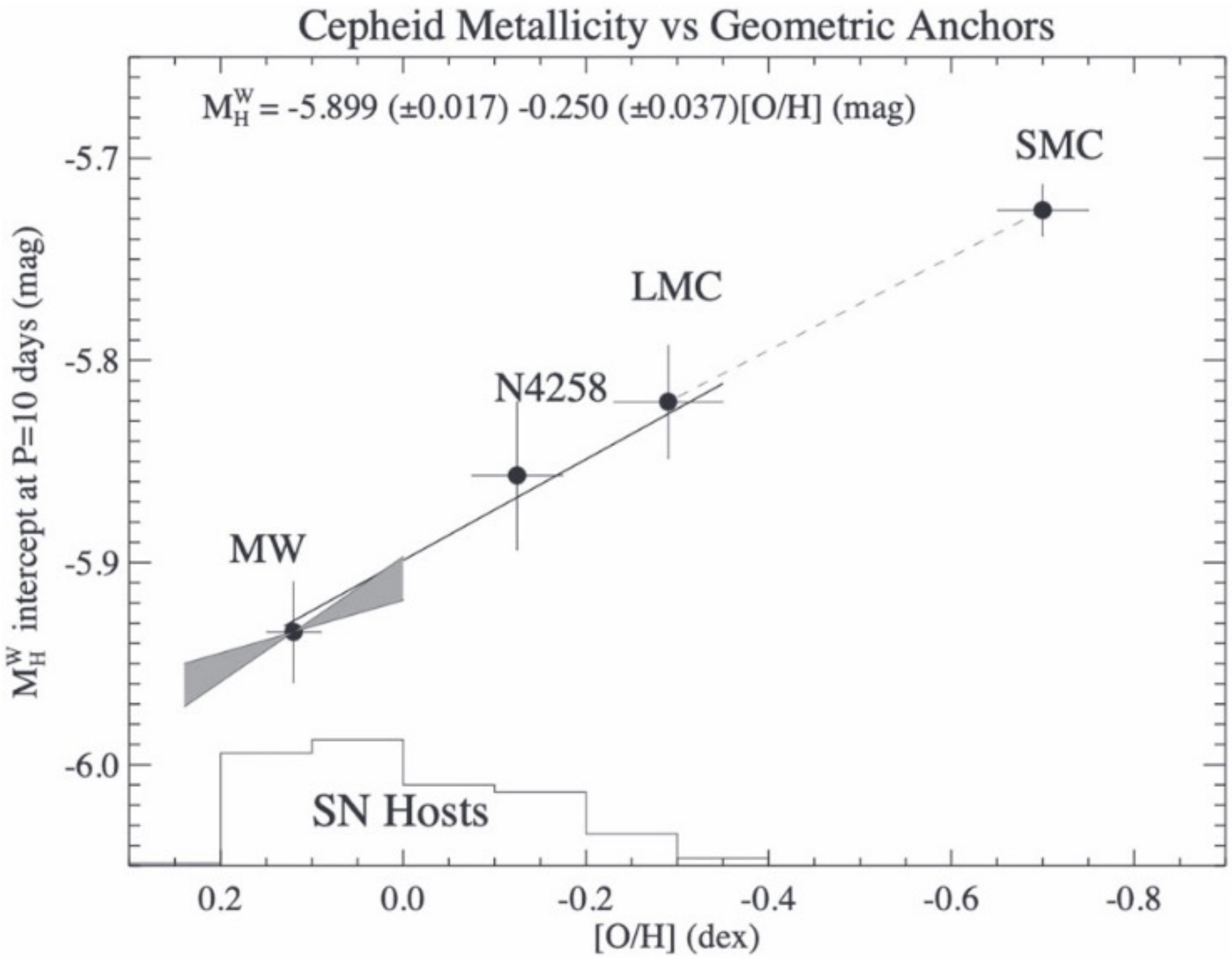
Metal dependence of DCEP PL/PW uncertain



- +0.27 ± 0.30 mag/dex (V-band) Groenewegen 2008
- −0.11 ± 0.24 mag/dex (K-band) Groenewegen 2008
- −0.29 ± 0.11 mag/dex (WVI) Scowcroft+2009
- ~−0.8± ~ 0.2(WVI) Shappee & Stanek 2011
- −0.23± 0.10 mag/dex (WVI) Storm+2011
- +0.09 ± 0.10 mag/dex (V-band) Storm+2011
- −0.10 ± 0.10 mag/dex (K-band) Storm+2011
- −0.23± 0.06 mag/dex (K-band) Gieren+2018
- −0.34 ± 0.06 mag/dex (WVI) non linear at low metallicities Gieren+2018
- −0.237 ± 0.199 mag/dex (Gaia DR2) Ripepi_2019
- −0.20 ± 0.13 mag/dex. (MW DCEPs, but <70 objects and very narrow range of [Fe/H]) Riess+2021
- −0.21 ± 0.05 mag/dex (use MC with distances from EBs to enlarge the [Fe/H] range.) Breuval+2021
- -0.3, -0.4 (Gaia DR3) Ripepi+2021
- -0.52 ±0.09 mag/dex (Gaia DR3) Ripepi+2022

- The imetallicity dependence of PL/PW relations is one of the remaining possible sources of systematic uncertainties in the application of the PL/PW relations to the distance scale.
- The effect is estimated to only deemed to be a few 0.**1**% on a total uncertainty of 1.3% in the determination of the Hubble constant - Riess et al. 2022).
- But estimates in the literature for its actual value and uncertainty vary significantly also with wavelenght $\Longrightarrow$ more efforts needed to reach a 1% accurate H_0.

Metallicity dependence of PLs



$\langle[Fe/H]\rangle \sim \langle[O/H]\rangle - 0.06$ (Romaniello 2022)

75 MW Cepheids calibrators with HST photometry

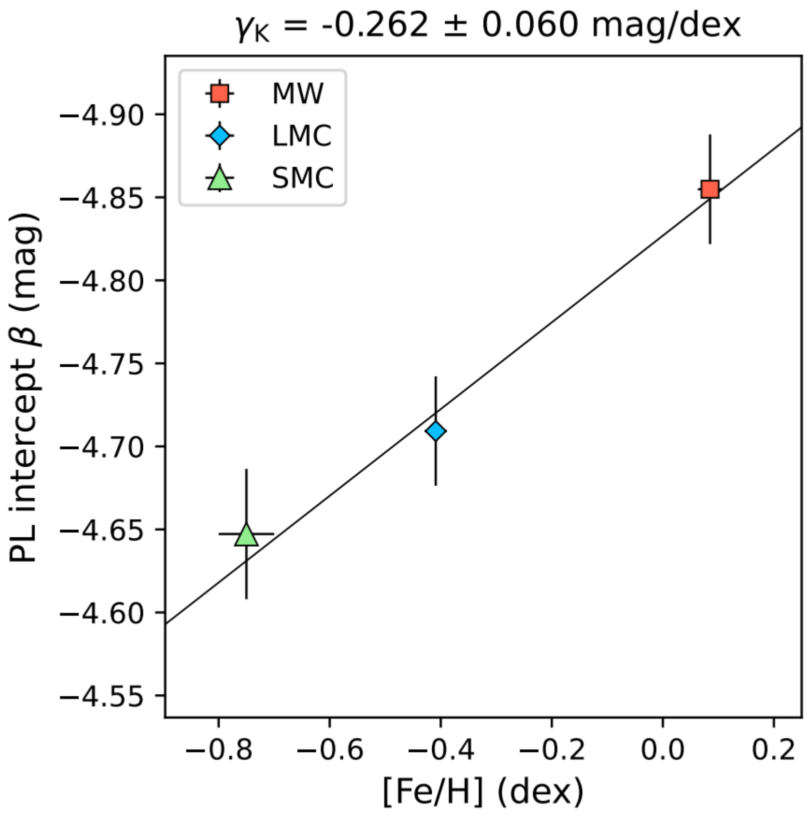
Riess+2022

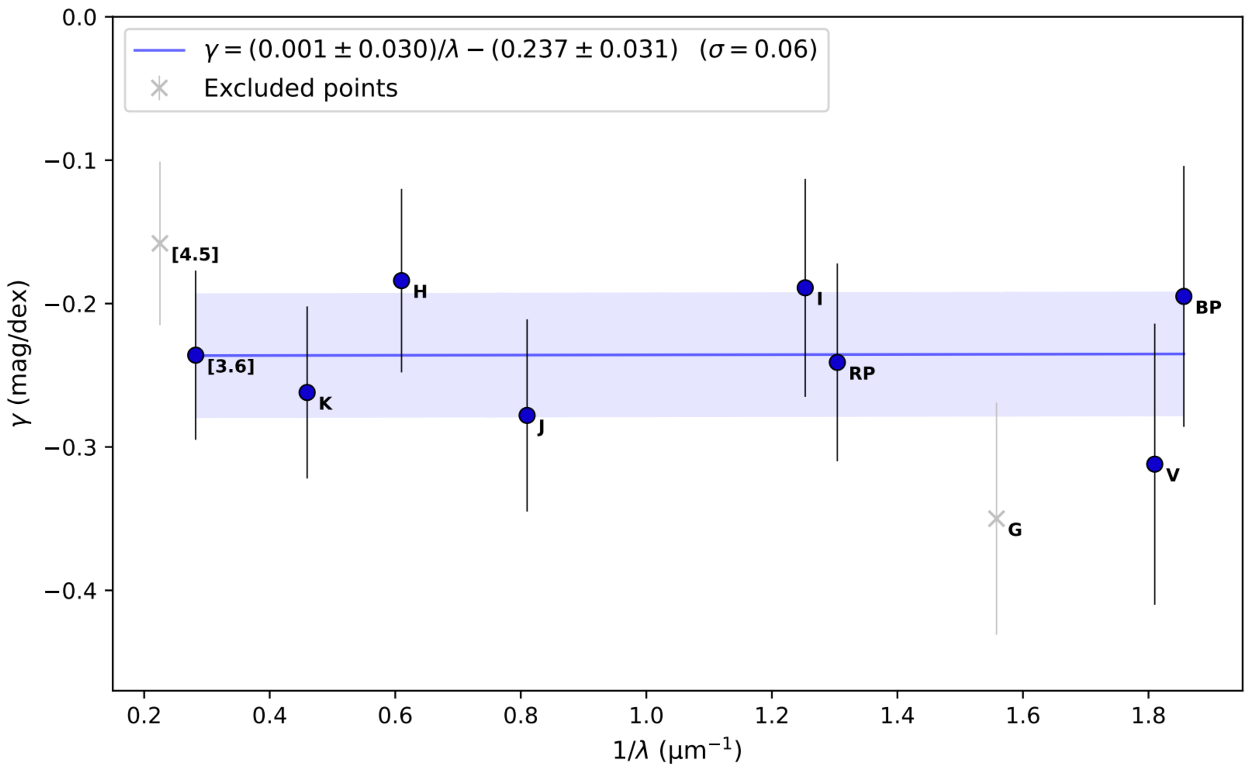
Metallicity dependence of the Cepheid PL relation (Breuval+2022)

MW, LMC and SMC used as single metallicity hosts of Cepheids.

MW ZP calibrated with a sample of > 200 Cepheids with Gaia parallaxes.

LMC and SMC ZP using the distances from EBs (Pietrzyński+2019 and Graczyk+2020)





The C-MetaLL project

- Use Galactic Cepheids in conjunction with Gaia parallaxes to constrain the PLZ/PWZ relations but: i) too narrow range in [Fe/H]; ii) not enough stars with accurate NIR photometry, reddening estimates.

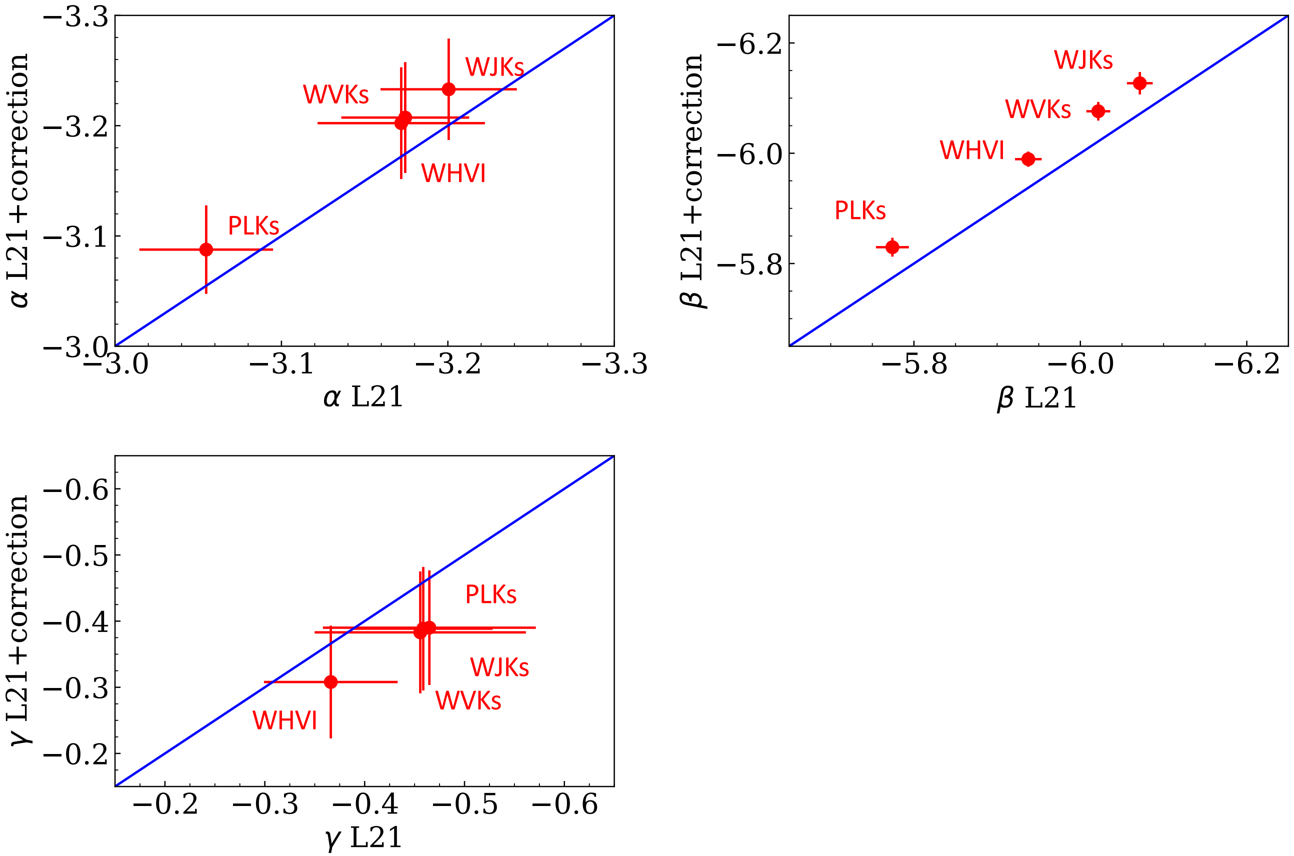
1. Significantly enlarge (+~300 objects) the sample of Cepheids with metallicity measured from high-resolution spectroscopy.

2. Enlarge the range of [Fe/H] adopted in the determination of the PLZ/PWZ relations up to values typical of the SMC or more metal poor.

3. Obtain multiband g,r,i,z,J,H,Ks photometry for a large sample of Cepheids to obtain precise average magnitudes and individual reddening measurements.

C-MetaLL-I (Ripepi+2021)

$$\mathrm{ABL} = 10^{0.2W} = 10^{0.2(\alpha+\beta\log P+\gamma[Fe/H])} = \varpi 10^{0.2w-2},$$



The inclusion of a 11 μas shift:

- Increases the slope of the PL/PW relations by ~1%
- increases the intercept of the PL/PW relations by ~5%
- Decreases the metallicity term by ~10%

- The effect of ZPO correction and metallicity are degenerate → important to fix correction independently.

- In all the cases our metallicity term is larger than what found in the recent literature.

C-MetaLL-II Trentin et al. 2022 (in prep.)

Literature plus Gaia sample

Literature sample:

- 633 stars with metallicity from high-resolution spectroscopy (Gaia Collaboration+2017,Groenewegen 2018, Catanzaro+2020, Ripepi+2021, Kovtyukh+2022) → 114 from C-MetaLL project.

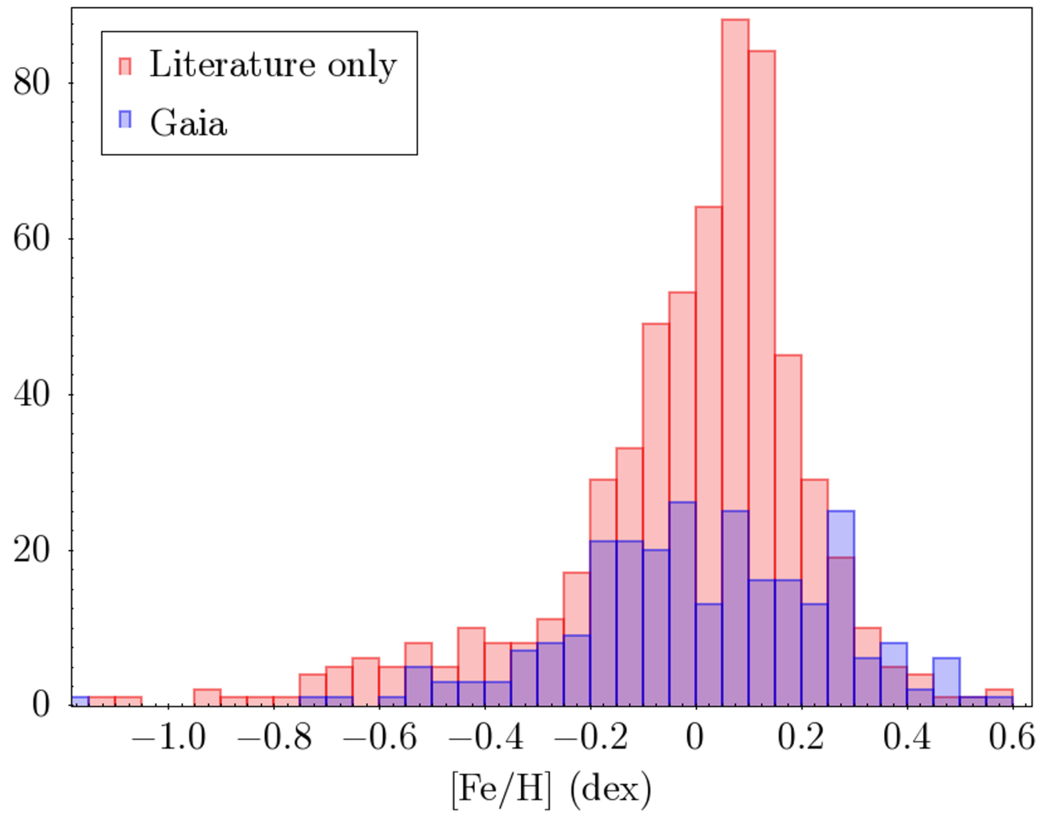
- About 480 photometry (V,I,J,H,Ks and G,Gbp,Grp) from literature.
  1. From Gaia bands→V, I magnitudes (Pancino+2022) transformations
  2. From JHK 2MASS single epoch→Mean magnitudes with template fittings (Soszynki+2005).

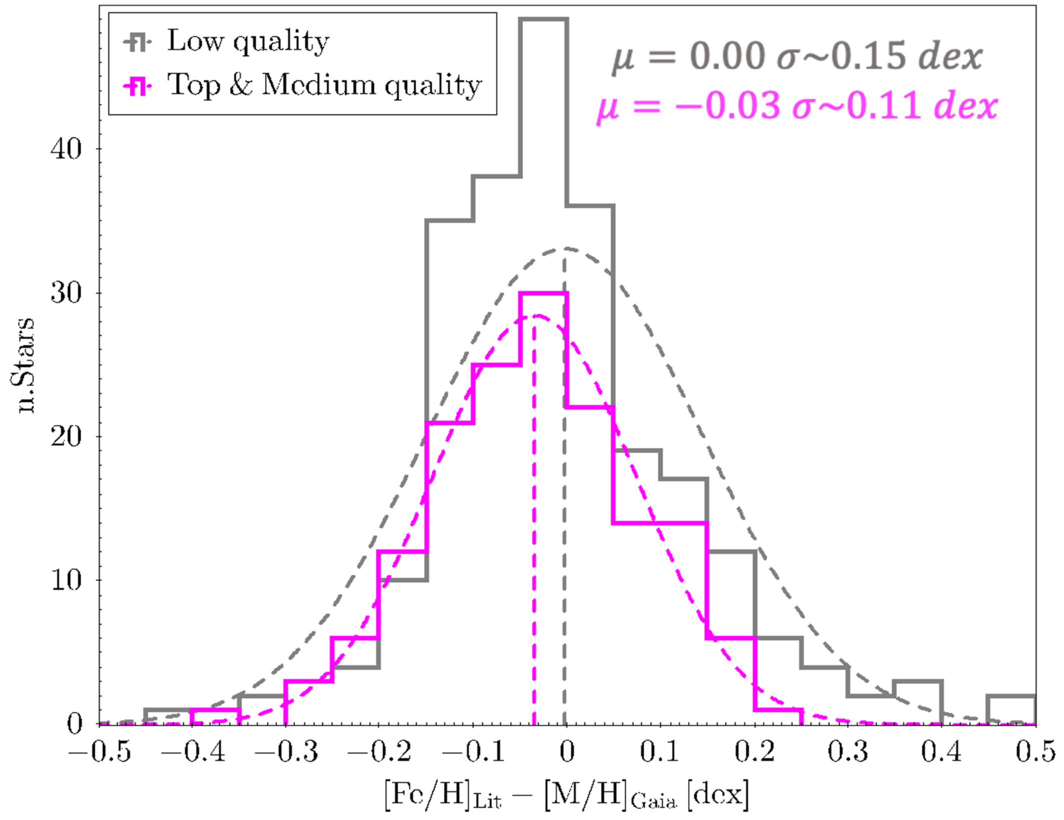
- Total sample, including Gaia and after the fidelity_v2>0.5 filtering (Rybizki+2022) and the filtering for the quality flags (by Recio-Blanco+2022): 873 in total: 297 DCEP_1O (among these 22 are 1O/2O) and 576 DCEP_F (among these 24 F/1O).

Trentin et al.2022b (in prep)

Spectroscopic metallicities and photometry

Literature vs Gaia sample





Trentin et al.2022b (in prep)

Astrometry-based luminosity (ABL)

Calibration of the PL/PW using the ABL

To avoid bias problems, the **Astrometry-Based Luminosity (ABL)** method (Arenou & Luri 1999; Gaia Collaboration+2017): **linear in parallax; <u>no selection on parallax (negative parallaxes are included) nor on its relative uncertainty is needed</u>**

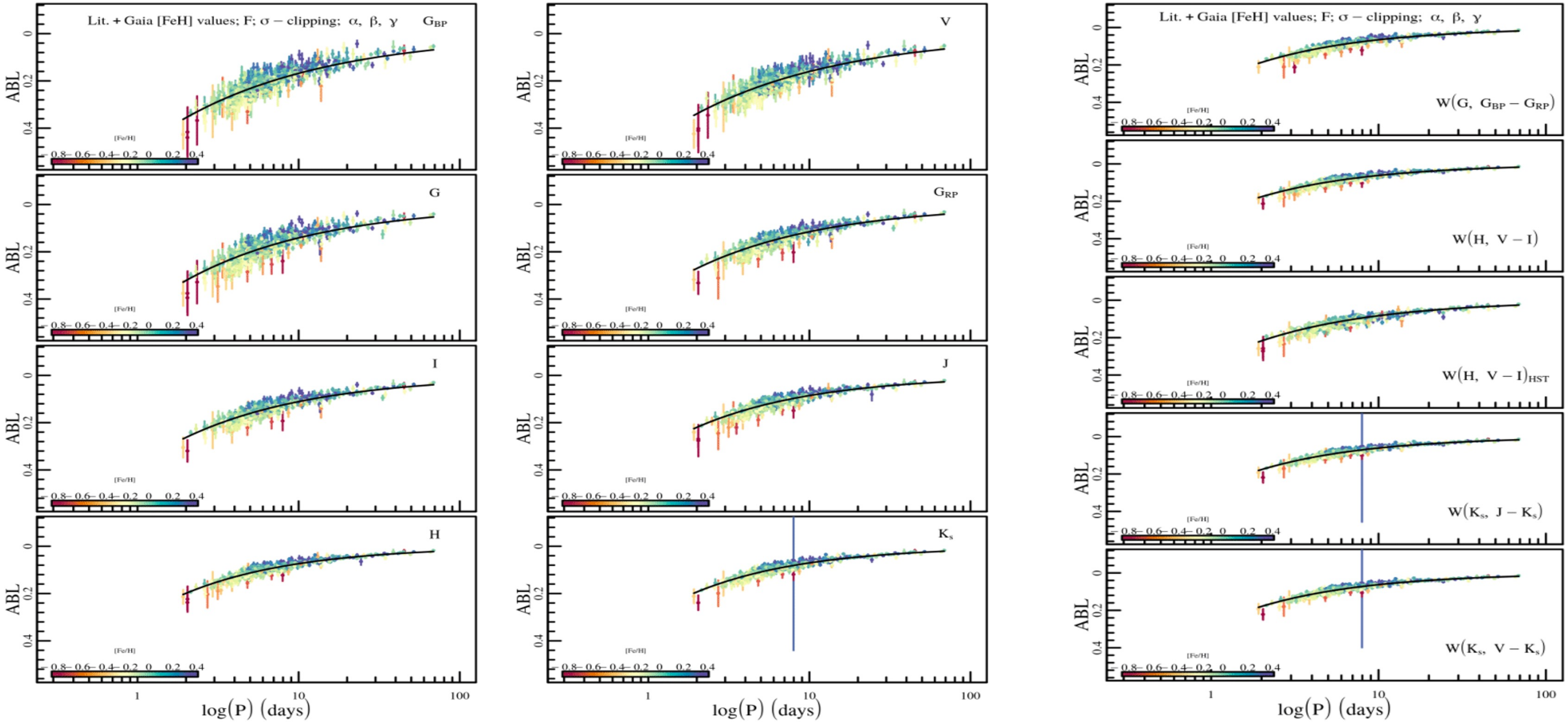
$$M = \alpha + (\beta + \delta[\mathrm{Fe/H}])(\log P - \log P_0) + \gamma[\mathrm{Fe/H}],$$

$$\mathrm{ABL} = \varpi 10^{0.2m-2} = 10^{0.2(\alpha+(\beta+\delta[\mathrm{Fe/H}])(\log P - \log P_0)+\gamma[\mathrm{Fe/H}])},$$

- PLZ/PWZ relations obtained with NLR (weighting on the ABL).
- Metallicity dependence on the slope, not only on the intercept.
- ZP corrected according to Lindegren+2021.

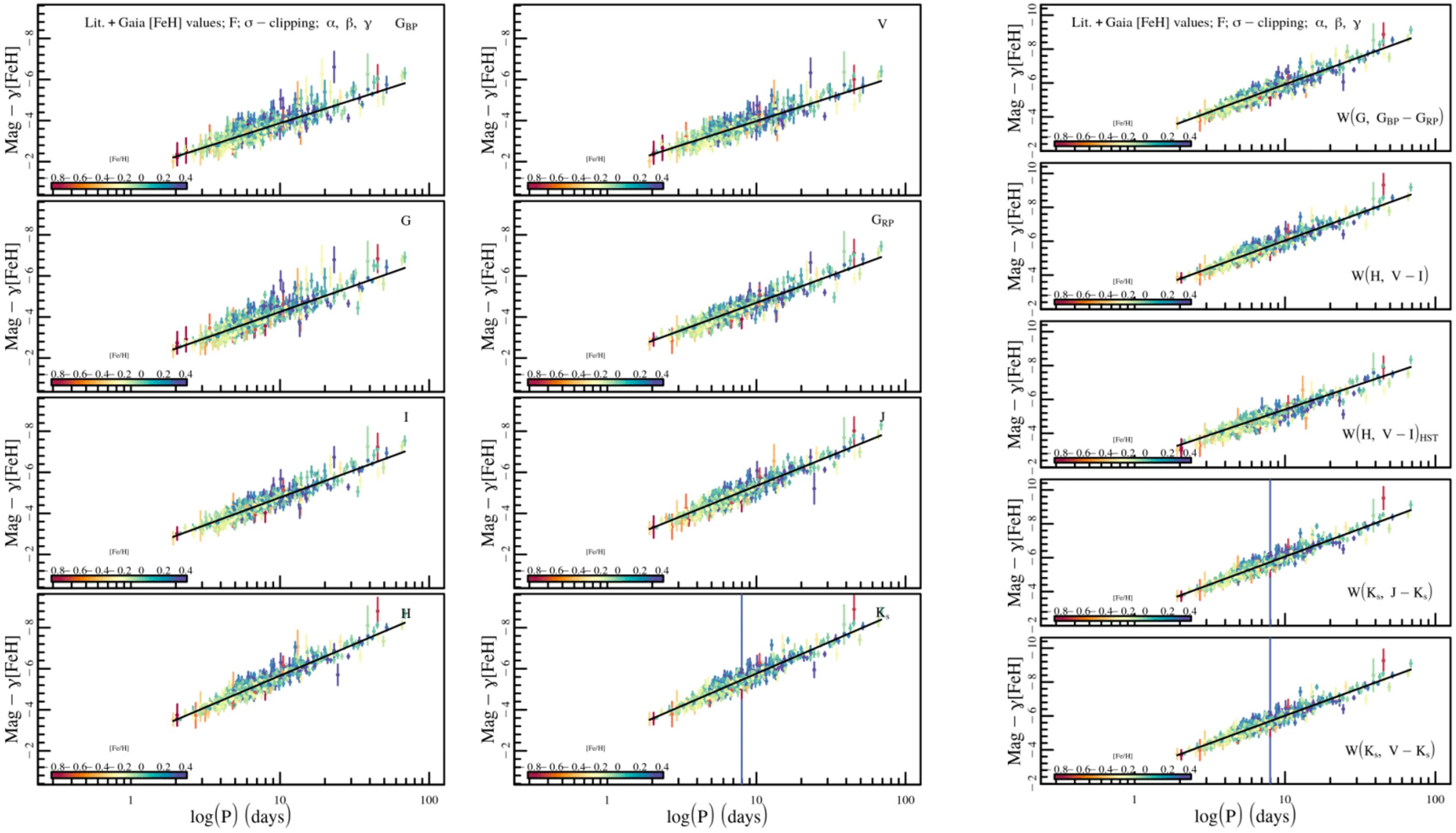
Astrometry-based luminosity (ABL)

Calibration of the PL/PW using the ABL



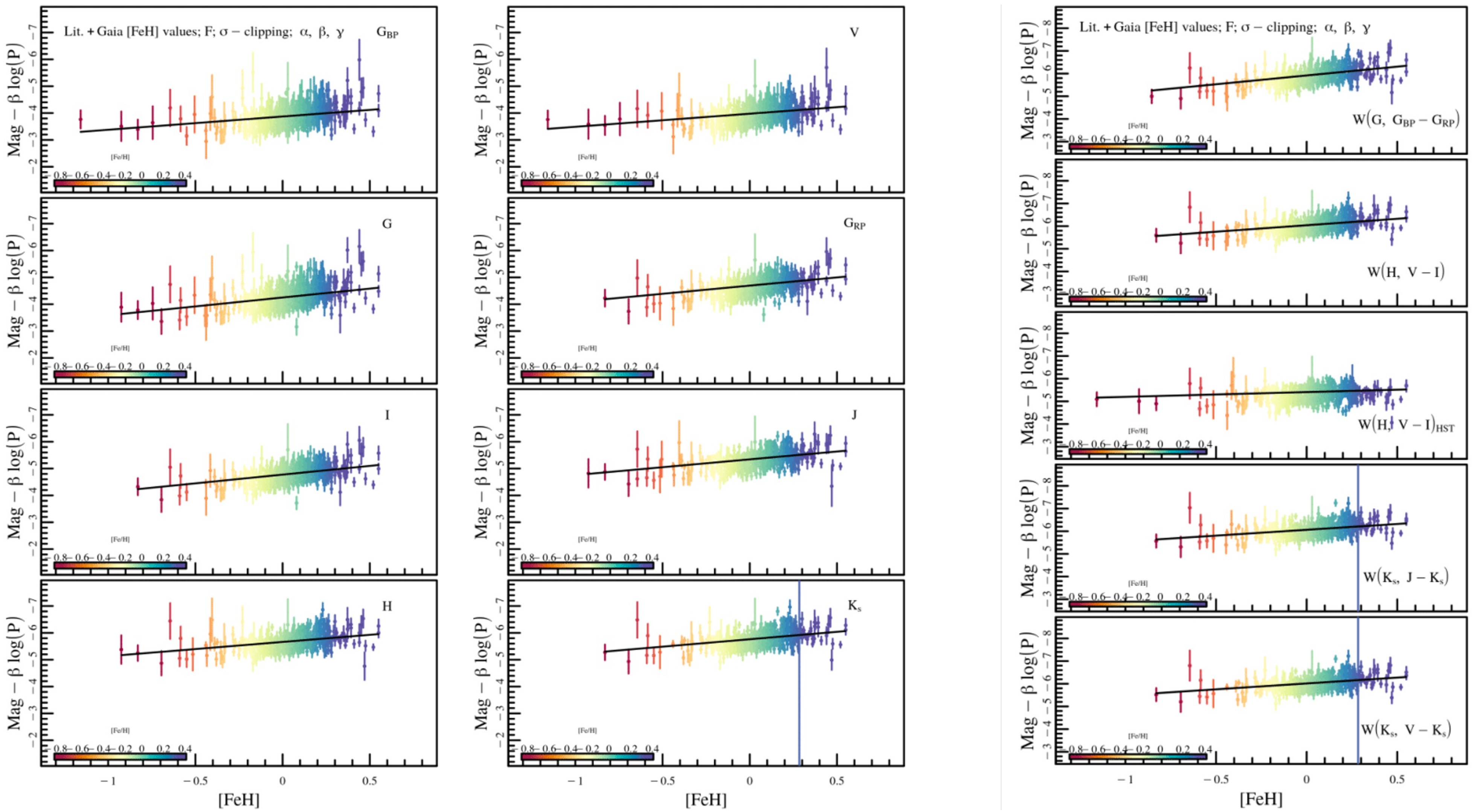
PLZ/PWZ projections

$$M = \alpha + (\beta + \delta[Fe/H])(\log P - \log P_0) + \gamma[Fe/H]),$$

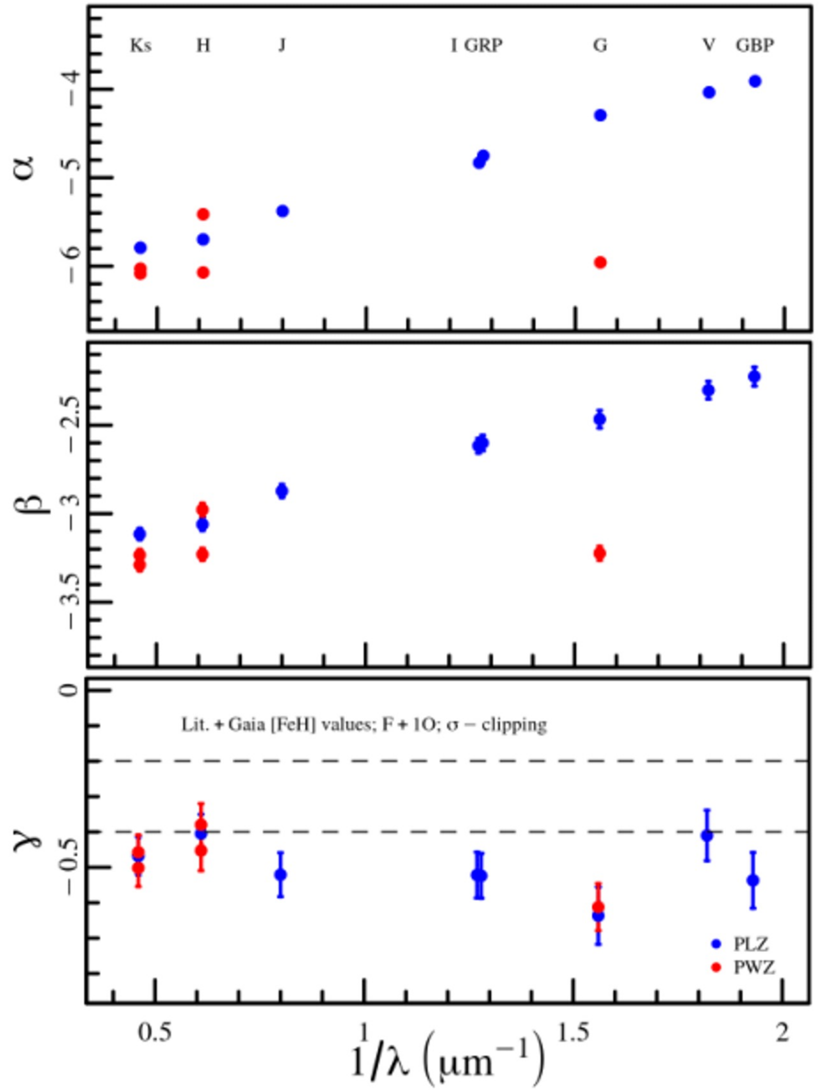


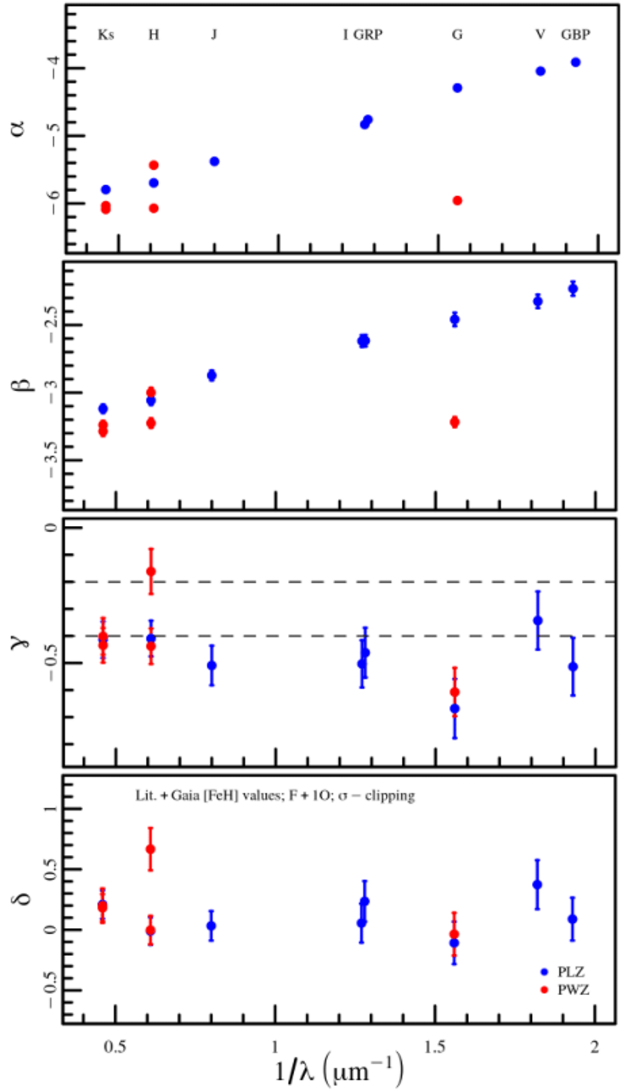
PLZ/PWZ projections

$$M = \alpha + (\beta + \delta[\mathrm{Fe/H}])(\log P - \log P_0) + \gamma[\mathrm{Fe/H}]),$$



PLZ/PWZ coefficients





We confirm a larger metallicity dependence of Cepheids PLs than that adopted by the SH0ES group

Conclusions and future perspectives

- The extra-galactic distance ladder and the measure of H_0 are a hot topic due to the tension with the measurements with the Cosmic Microwave Background.

- The role of Gaia in this context is to fix the zero point of the absolute distance scale, through the calibration of the PL relation of classical Cepheids.

- Some residual problems remain for what concerns the metallicity dependence of the PL relations and the correction of the Gaia parallaxes.

- Gaia DR4 will probably allow us to reduce all the remaining uncertainties to negligible values.