The Cepheid period-luminosity relation and its calibration

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In collaboration with:

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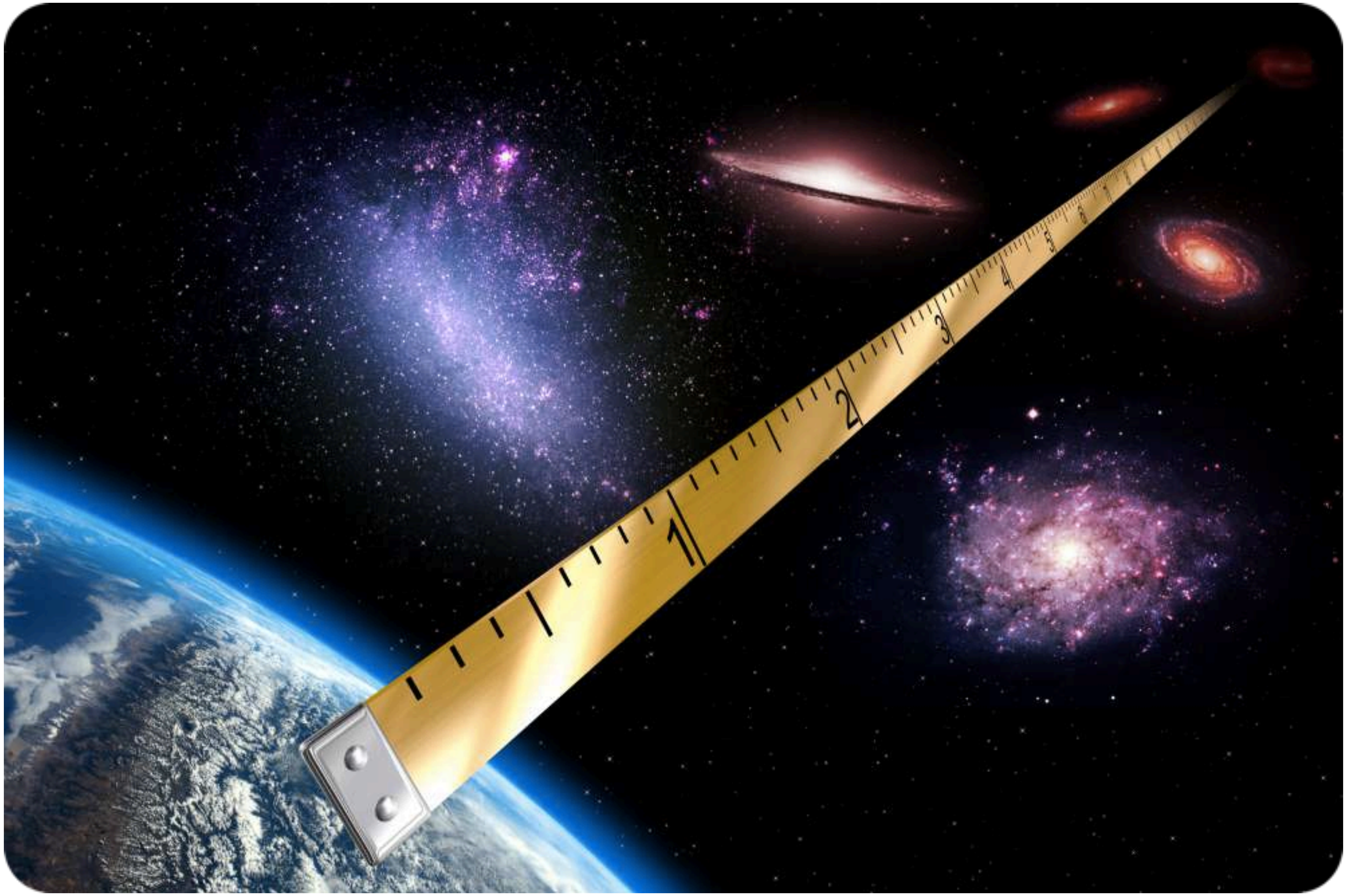
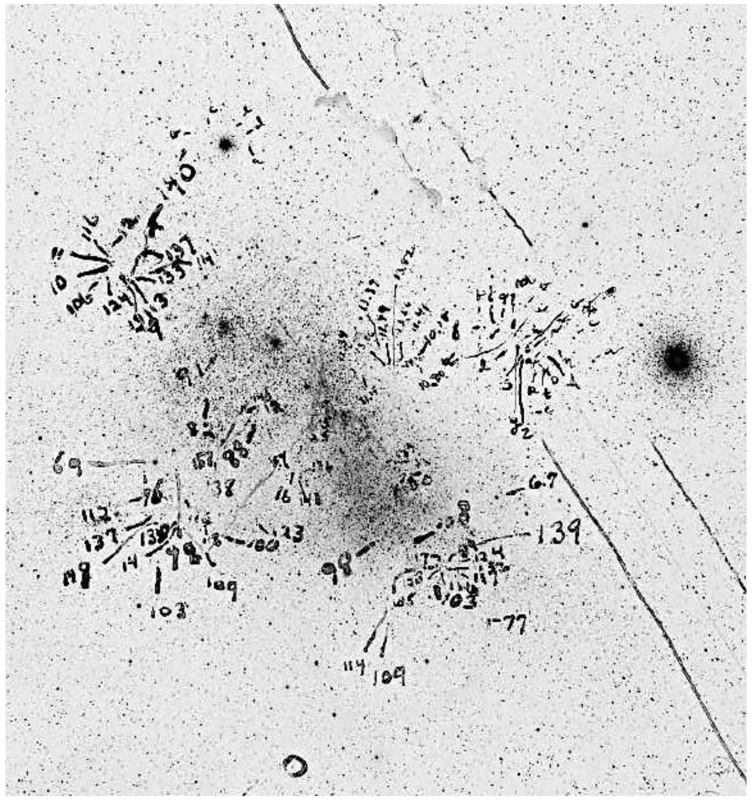
MIAPP workshop - The Hubble tension
27 Sept. - 1 Oct. 2021

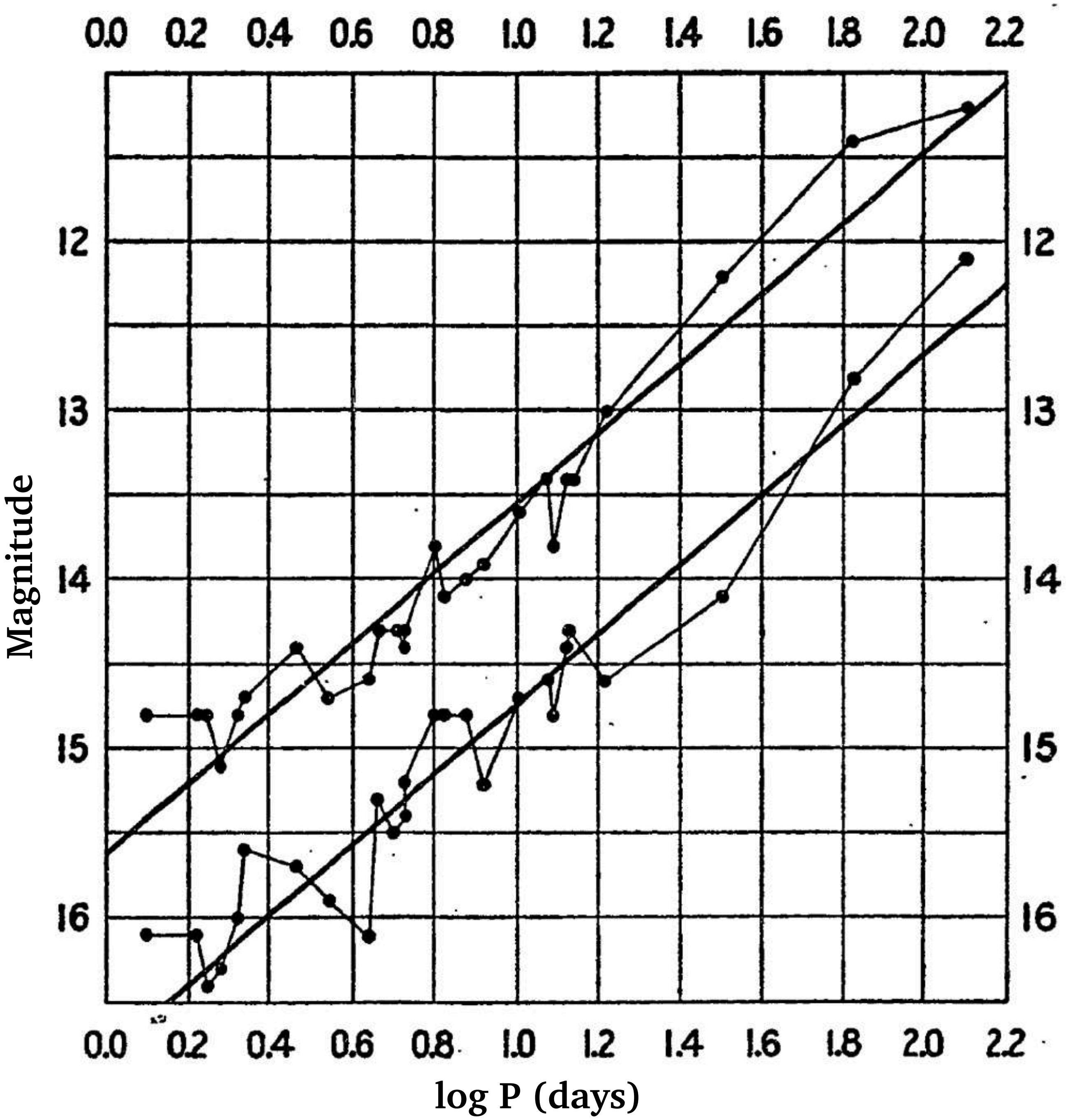
1. Measuring distances in the Universe



Henrietta Leavitt (1908)



Photographic plate of the SMC studied by Henrietta Leavitt



First Period-Luminosity relation calibrated by Henrietta Leavitt in the SMC (Leavitt & Pickering 1912)

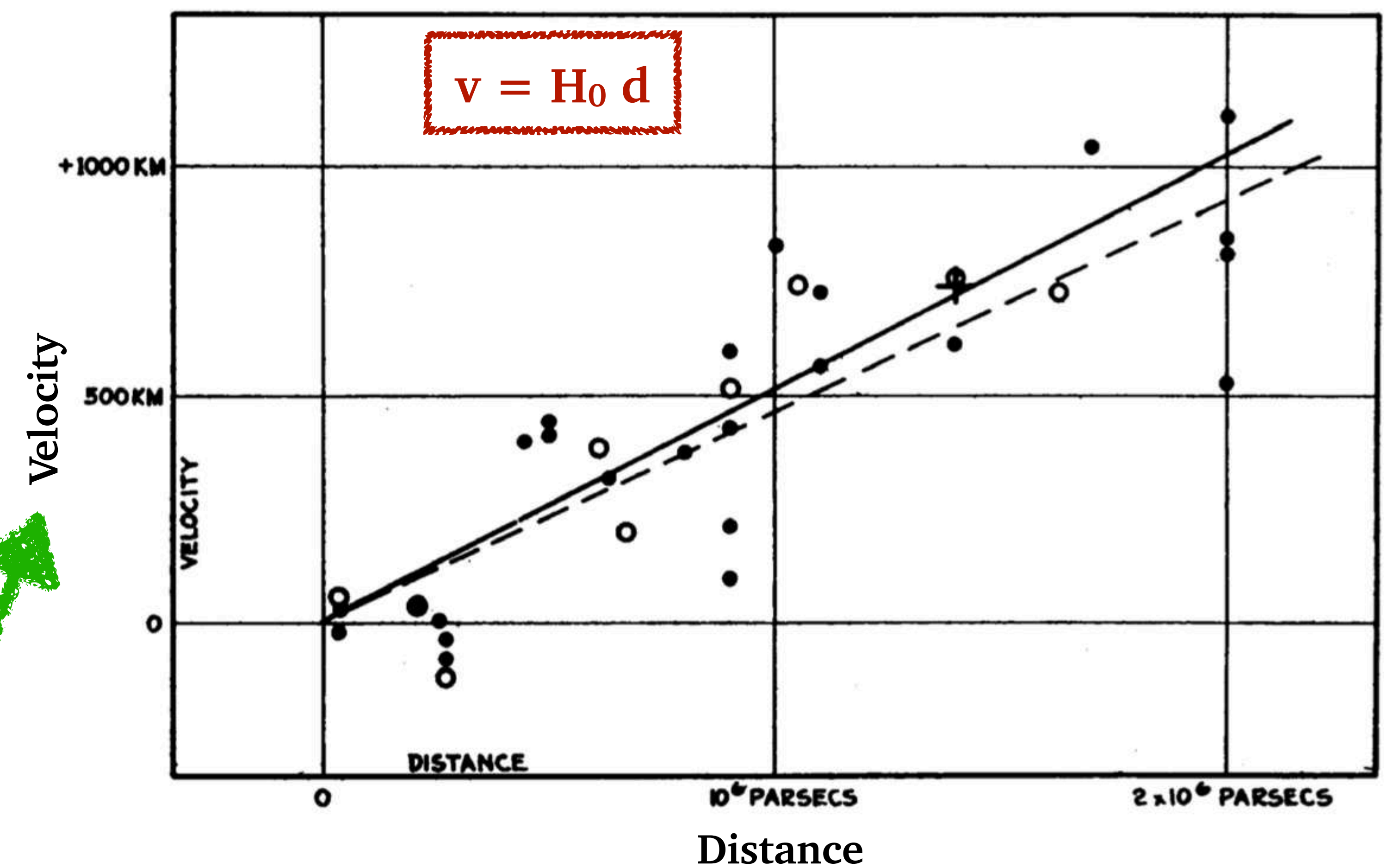
"It is worthy of notice that the brighter variables have the longer periods." (H. Leavitt)

1. Measuring distances in the Universe

Edwin Hubble and the 2.5m telescope at Mount Wilson Observatory

- 1920: "The Great Debate" between Harlow Shapley and Heber Curtis.

Relation between galaxies distance and velocity (Hubble 1929)

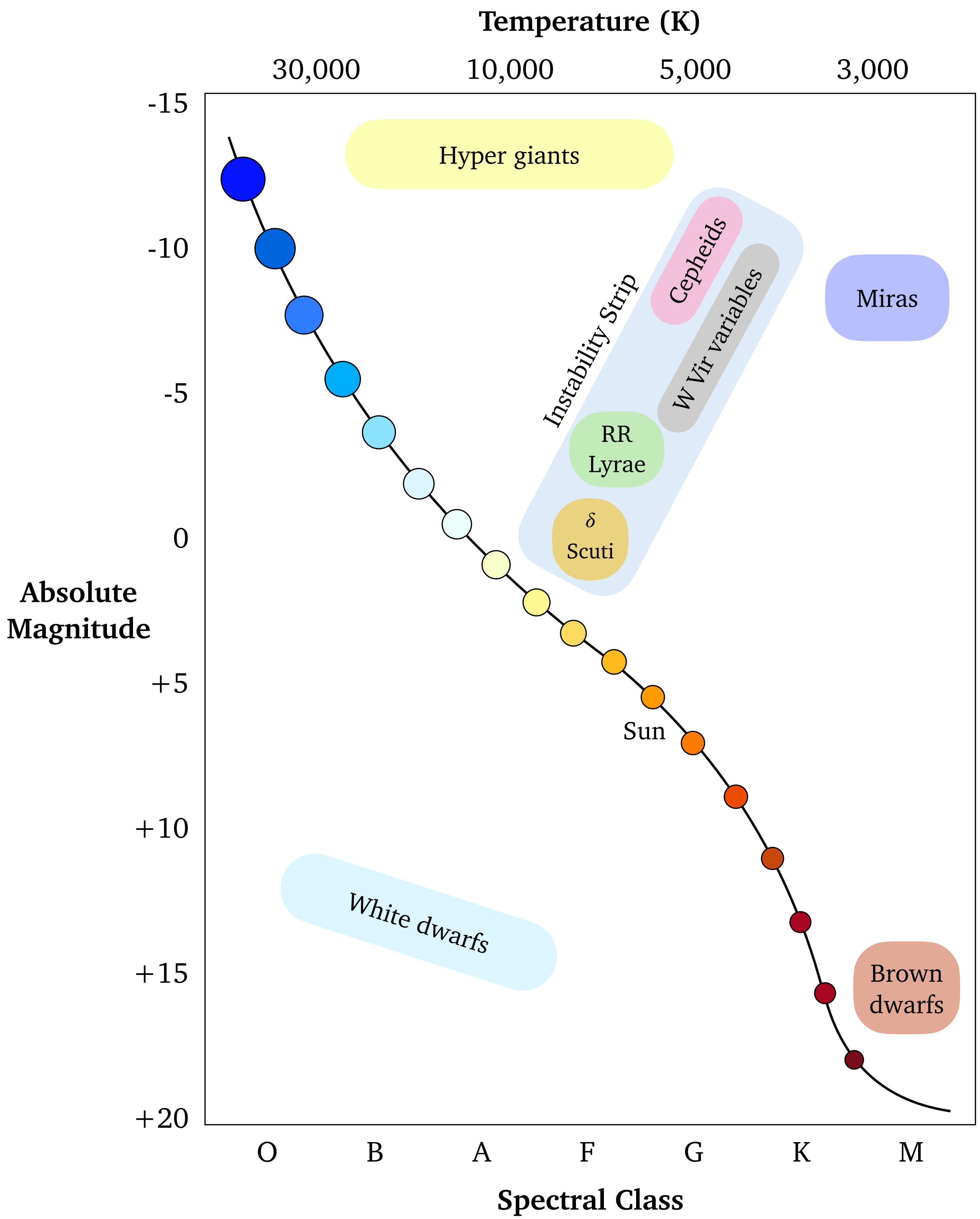


from spectroscopy

from Cepheids

- 1929: Edwin Hubble discovered that the velocity of galaxies increases with their distance. The Universe is expanding!

1. Measuring distances in the Universe



Hertzsprung-Russell diagram (Breuval 2021, PhD thesis)

CLASSICAL CEPHEIDS

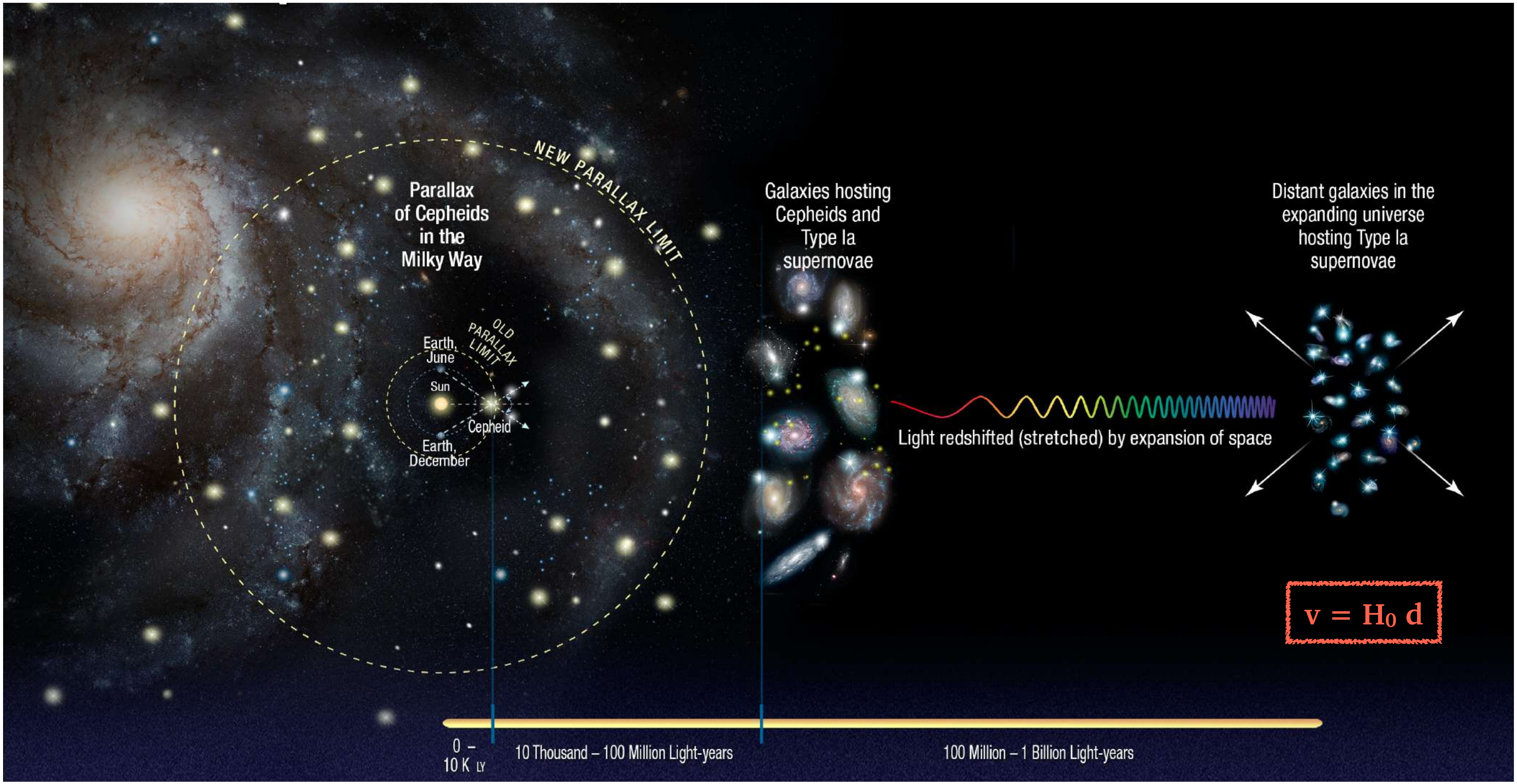
Pulsation period	2 - 100 days
Mass	4 - 15 $M_\odot$
Luminosity	10,000 - 100,000 $L_\odot$
Radius	10 - 100 $R_\odot$
Type	giant, supergiant
Class	F, G, K
Temperature	4,000 - 8,000 K
Metallicity	Metal rich
Luminosity variation	0.5 - 2 mag

1. Measuring distances in the Universe

Step 1: calibration of the P-L relation with nearby Cepheids (e.g. parallaxes of Milky Way Cepheids, eclipsing binaries distances in the Magellanic Clouds...)

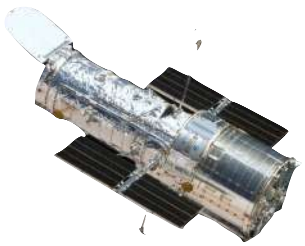
Step 2: use Cepheids to calibrate type Ia supernovae (SN-Ia) in nearby galaxies

Step 3: For distant galaxies in the Hubble flow, measure the redshift to obtain the velocity and measure the distance using SN-Ia.

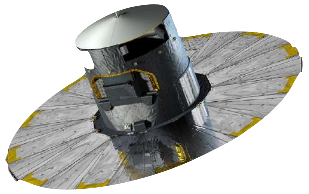


The distance scale (Credit: NASA, ESA, A. Field, STScI and A. Riess, STScI/JHU).

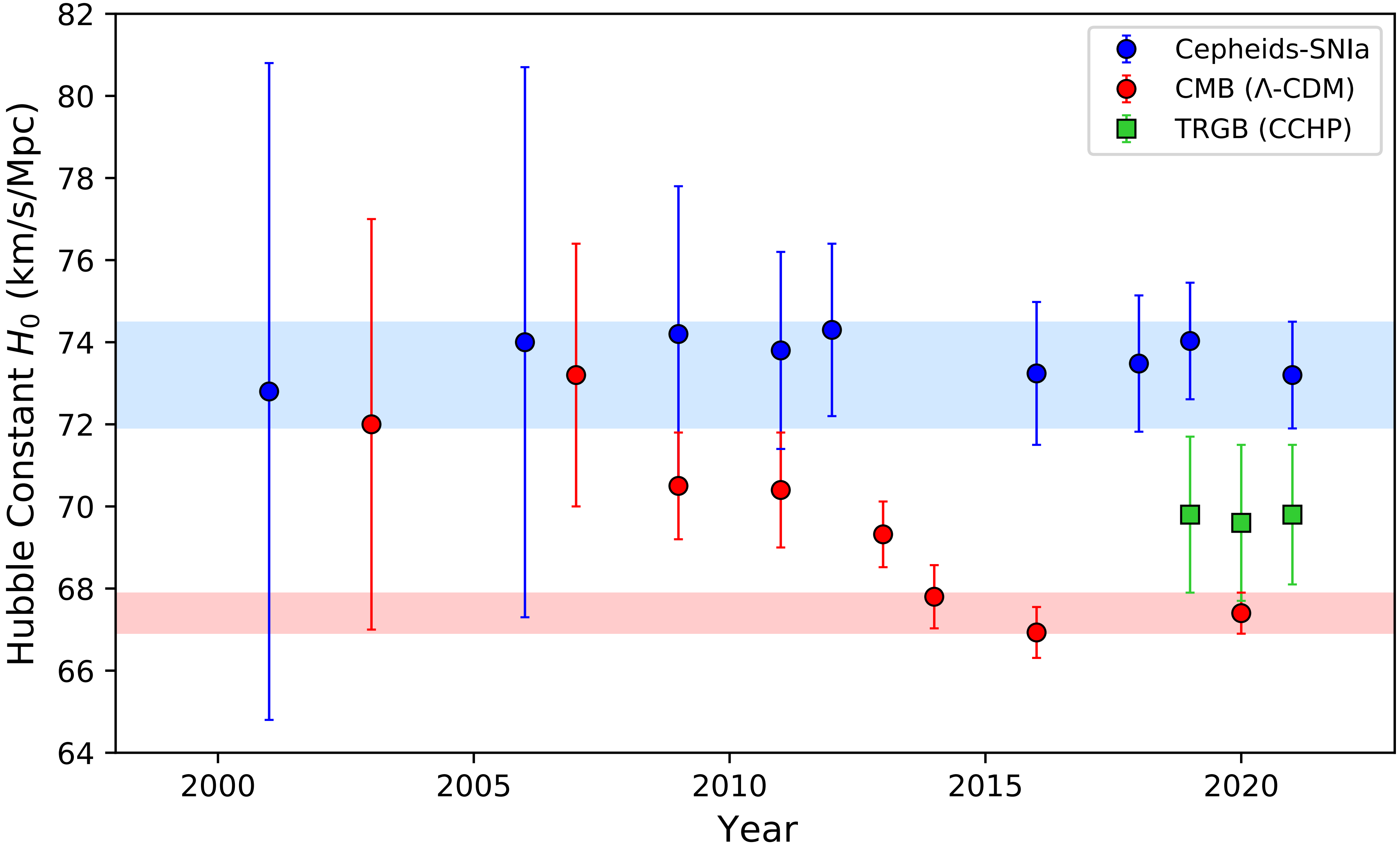
1. Measuring distances in the Universe



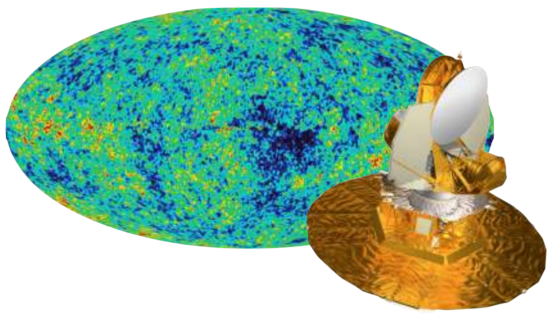
Hubble Space Telescope



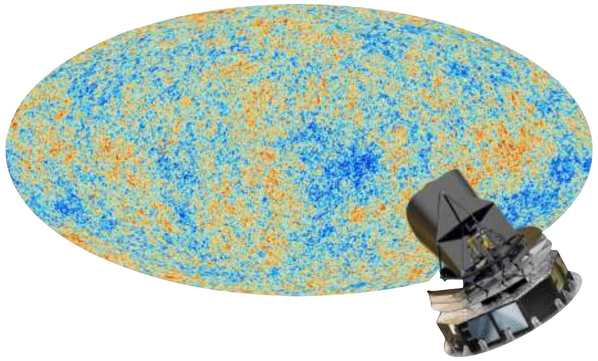
Gaia



The tension on the Hubble constant (Breuval 2021, PhD thesis)



WMAP



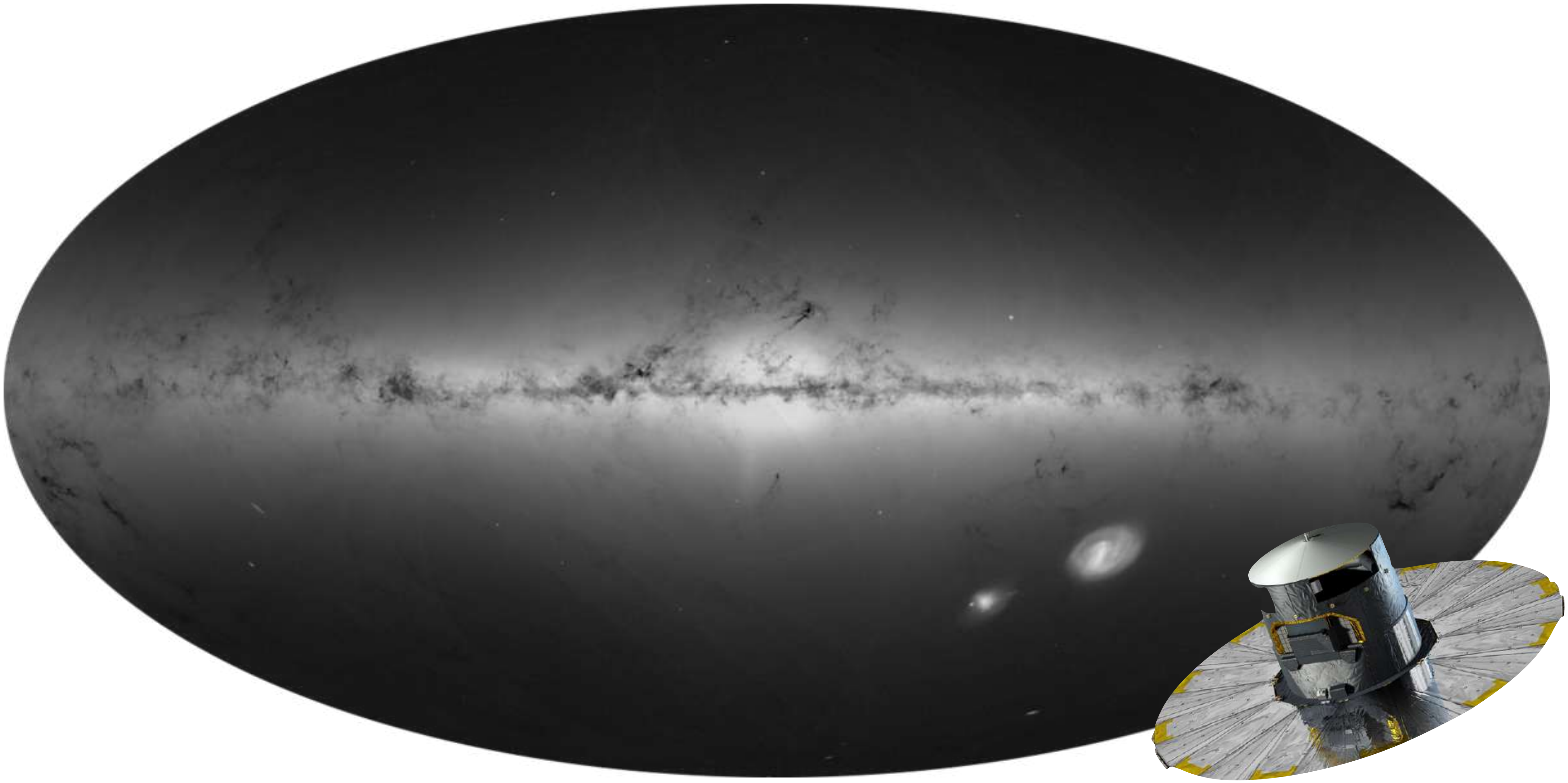
Planck

1. Measuring distances in the Universe

- The calibration of the Cepheid PL relation requires **very precise** distance measurements, since it has strong consequences on the distance scale and the Hubble constant.
- **Systematic effects** on the physics of Cepheids, on distance measurements, photometry or on the PL calibration itself, must be understood and taken into account in the determination of SN Ia distances.

Outline of the presentation

2. Calibration of the Cepheid Leavitt law in the Milky Way



2. Calibration of the Cepheid Leavitt law in the Milky Way

Cepheids before the *Gaia* era:

- ***Hipparcos* satellite:** large number of stars but low precision parallaxes. (Van Leeuwen+ 2007)
- ***Hubble* Space Telescope:** good precision parallaxes (spatial scanning) but small number of stars. (Benedict+2007, Riess+2018)

Gaia before launch (Credit: ESA, Astrium France)

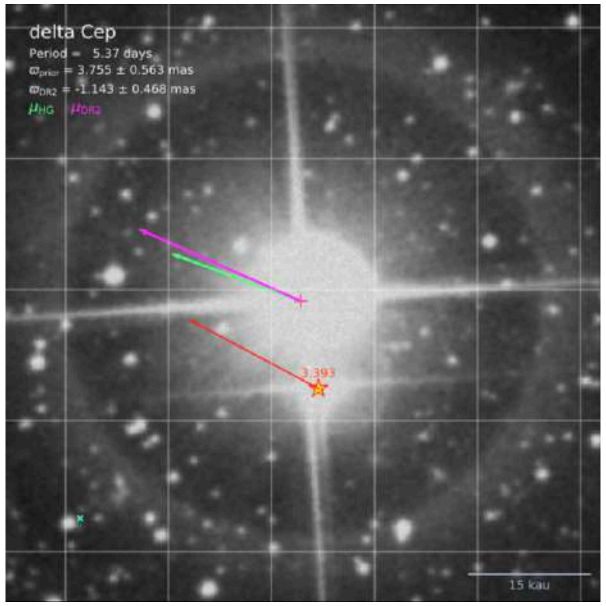
Cepheids with *Gaia*:

- ~10,000 Cepheids with high-precision astrometry!
- Radial velocities (DR3)
- *G*, *BP*, *RP* multi-epoch photometry (broad optical bands)

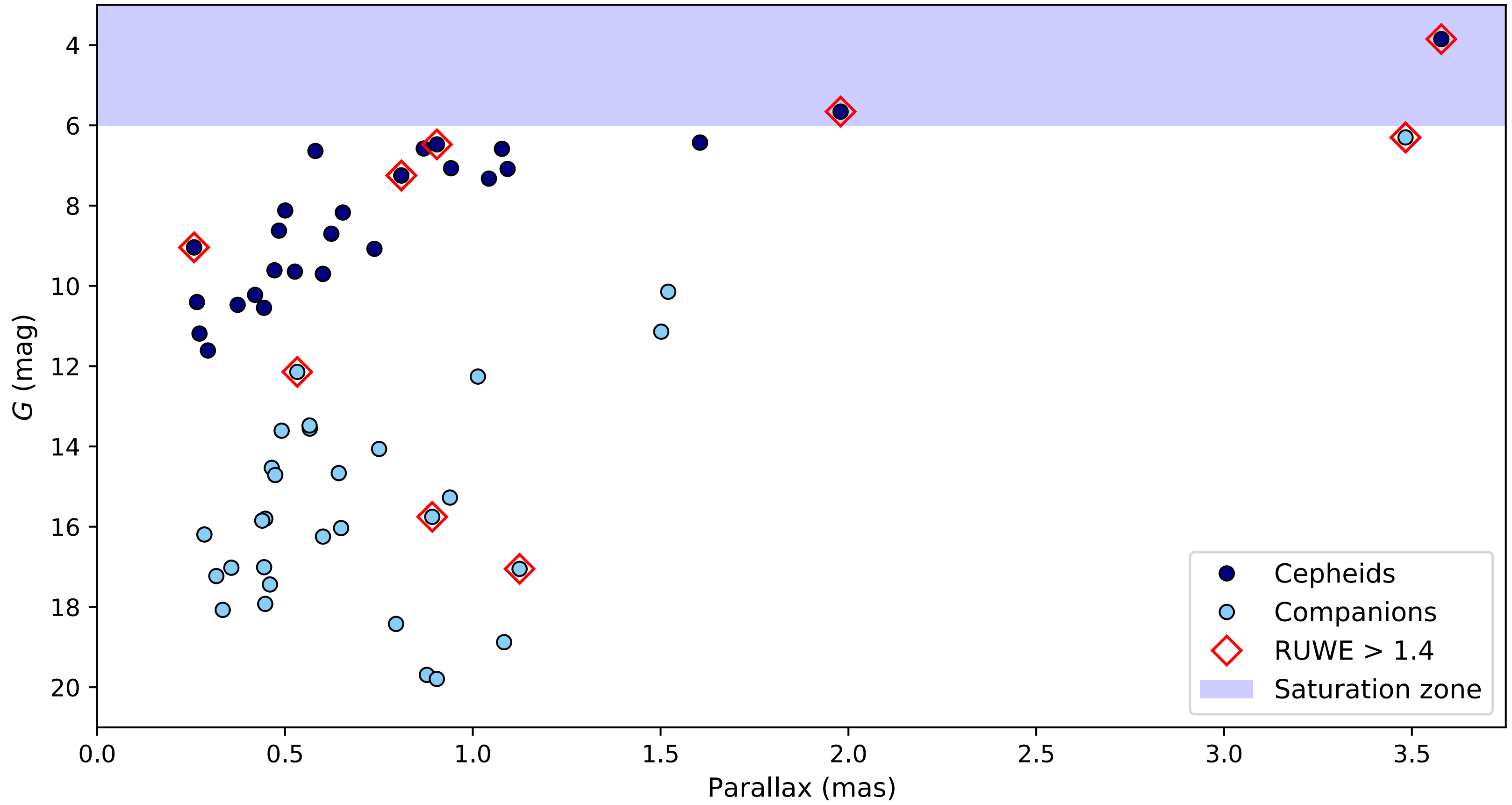
Main issues with *Gaia* parallaxes		Solutions
‣ Parallaxes are subject to a **zero-point** offset	→	Zero-point correction proposed by Lindegren+ 2021: takes into account the magnitude, color and position of the sources. (Other correction proposed by Groenewegen 2021)
‣ **Saturation**: Cepheids are very bright stars ($3 < G < 10$ mag)	→	Adopt the RUWE < 1.4 criterion to eliminate unreliable parallaxes.
	→	Find faint companion stars in the close neighbourhood of Cepheids, adopt their parallaxes.
‣ **Color variation** during a pulsation cycle (Δ *BP-RP* up to 0.5 mag)	→	Find non-variable stars in the close neighbourhood of Cepheids, adopt their parallaxes.

Cepheids with close companions

- Kervella et al. (2019b): 22 Cepheids with resolved companions
- not variable, unsaturated (∼6 mag fainter than Cepheids)
- not sensitive to flux contamination by the Cepheid

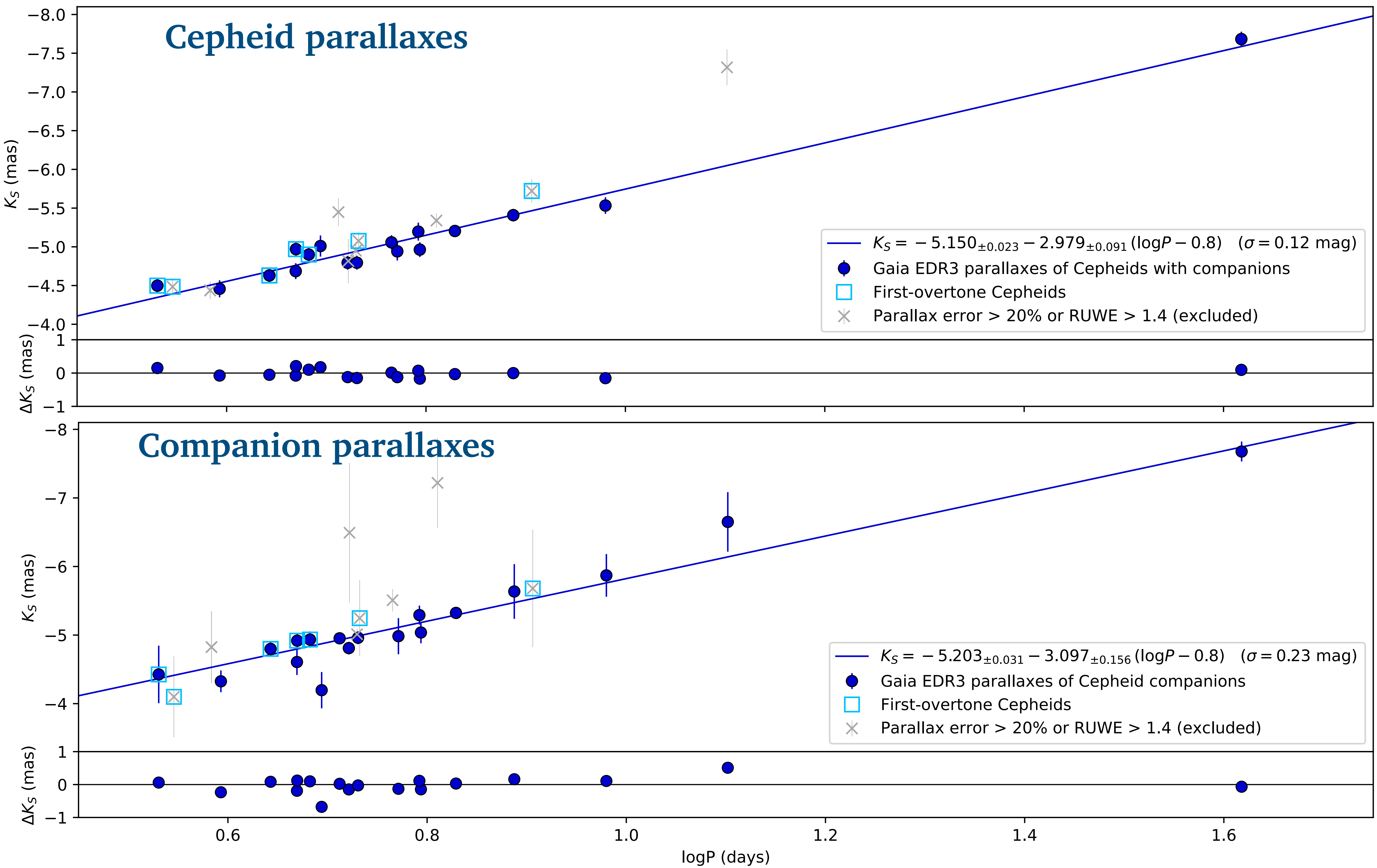


Proper motion of δ Cep and its companion (Kervella et al. 2019b)

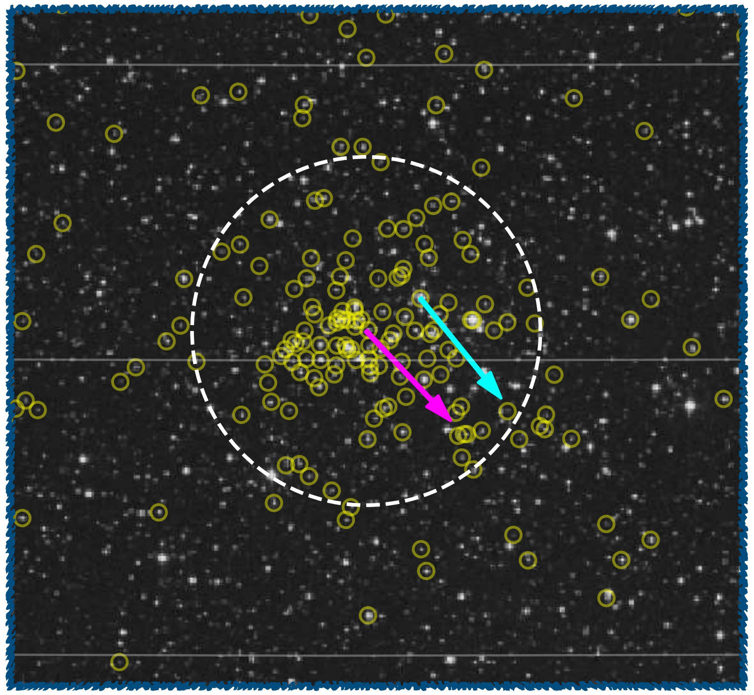


G-band apparent magnitude of Cepheids and their companions as a function of Gaia EDR3 parallax (Breuval 2021, PhD thesis)

2. Calibration of the Cepheid Leavitt law in the Milky Way



P-L relation in the K-band for Gaia EDR3 parallaxes of Cepheids (top) and of companions (bottom)
(Breuval 2021, PhD thesis)

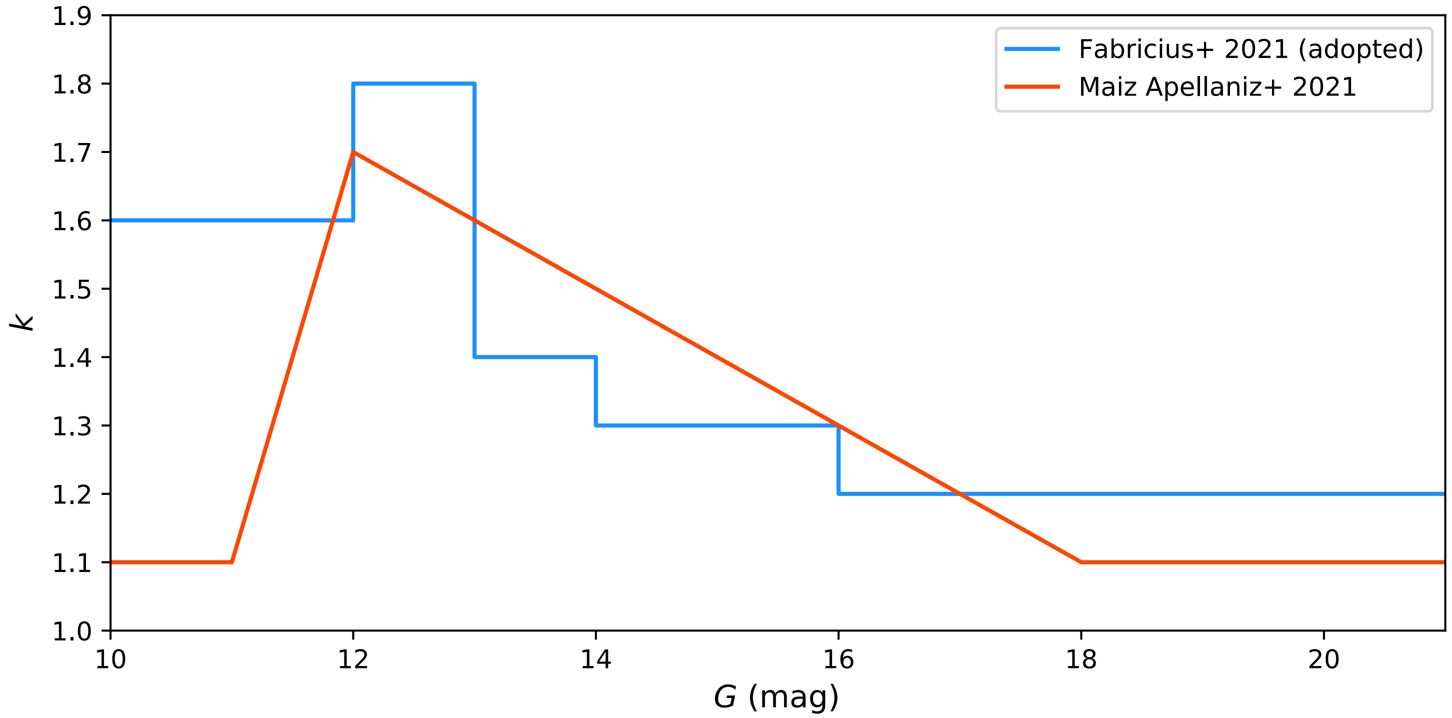


Proper motion of the Cepheid CF Cas and its host open cluster NGC 7790 (Breuval et al. 2020)

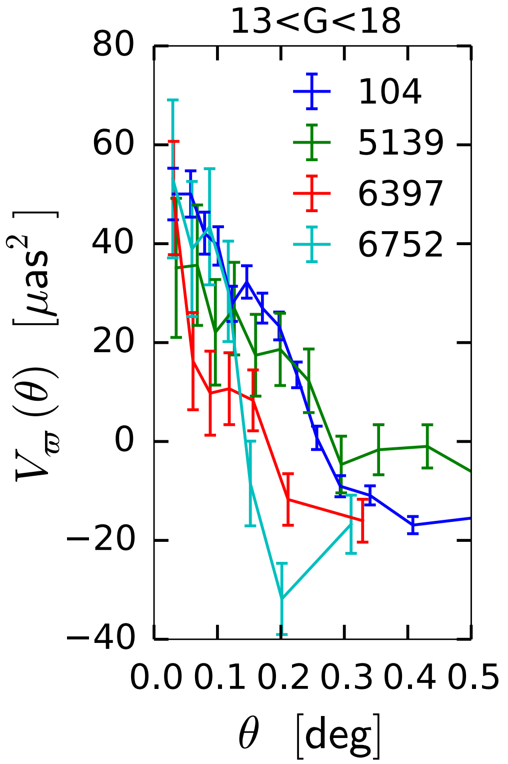
Cepheids in open clusters

- Cross-match (ϖ, α, δ, μ_α, μ_δ) between the open clusters from Cantat-Gaudin et al. (2018) and MW Cepheids: 20 candidates.
- Cluster members are not variable and are fainter than Cepheids.
- Gain in precision by averaging over the cluster members.

$$\sigma^2_{\text{total}} = \frac{1}{N}\left[k^2\langle\sigma_i^2\rangle + V_\varpi(0)\right] + \frac{N-1}{N}\langle\langle V_\varpi(\theta_{ij})\rangle\rangle$$

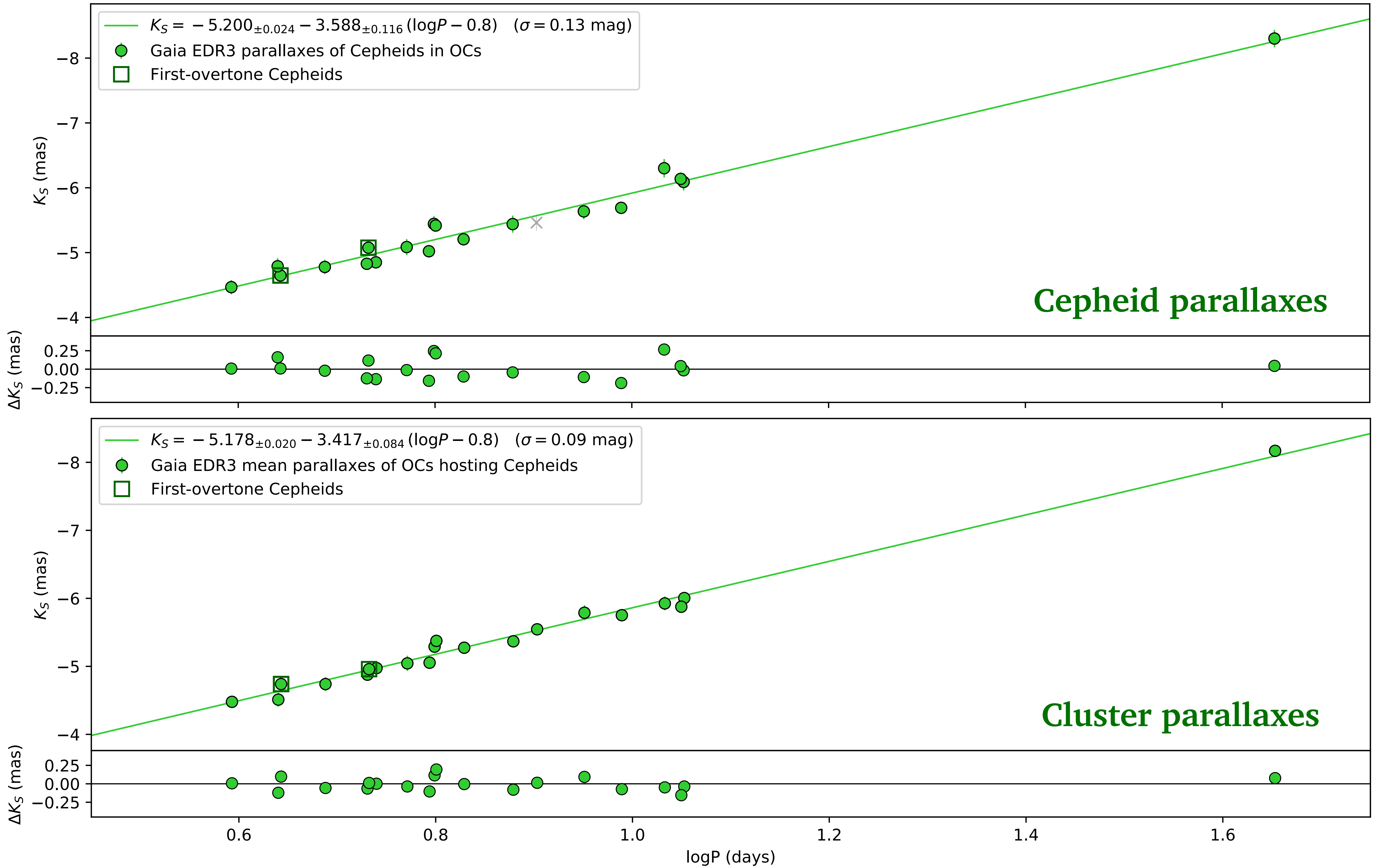


Breuval (2021, PhD thesis)



Vasiliev & Baumgardt (2021)

2. Calibration of the Cepheid Leavitt law in the Milky Way



P-L relation in the K-band for Gaia EDR3 parallaxes of Cepheids (top) and of clusters (bottom)
(Breuval 2021, PhD thesis)

Anchor(s)	Value (km s^{-1} Mpc^{-1})
One Anchor	
NGC 4258: Masers	72.25 ± 2.51
MW: 15 Cepheid Parallaxes	76.18 ± 2.37
LMC: 8 Late-type DEBs	72.04 ± 2.67
M31: 2 Early-type DEBs	74.50 ± 3.27
Three Anchors (**Preferred**)	
NGC 4258 + MW + LMC	**73.24** ± **1.74**

H_0 estimates from different distance indicators (Riess et al. 2016)

Re-evaluation of the Hubble constant in the Milky Way

$$H_{0,\,\mathrm{Gaia}} = \frac{\varpi_{\mathrm{Gaia}}}{\varpi_{\mathrm{predicted}}} H_{0,\,\mathrm{init.}}$$

$$5 \log \varpi_{\mathrm{predicted}} = M_H^W\,(\mathrm{MW\ Cepheids}) - \mathrm{m_H^W} + 10$$

$$M_H^W\,(\mathrm{MW\ Cepheids}) = -3.26\,(\log \mathrm{P} - 1) - 5.85$$

(Riess et al. 2018)

NGC 4258: Masers	72.25 ± 2.51
MW: 32 Gaia EDR3 parallaxes (Breuval 2021, PhD thesis)	**73.47 ± 1.77**
LMC: 8 Late-type DEBs	72.04 ± 2.67
M31: 2 Early-type DEBs	74.50 ± 3.27

- More consistent with other estimates from different distance indicators.
- Still in 3.3σ tension with the Planck prediction.
- Need to include systematics due to Gaia EDR3 parallax zero-point (< 1.5 km/s/Mpc).

Summary

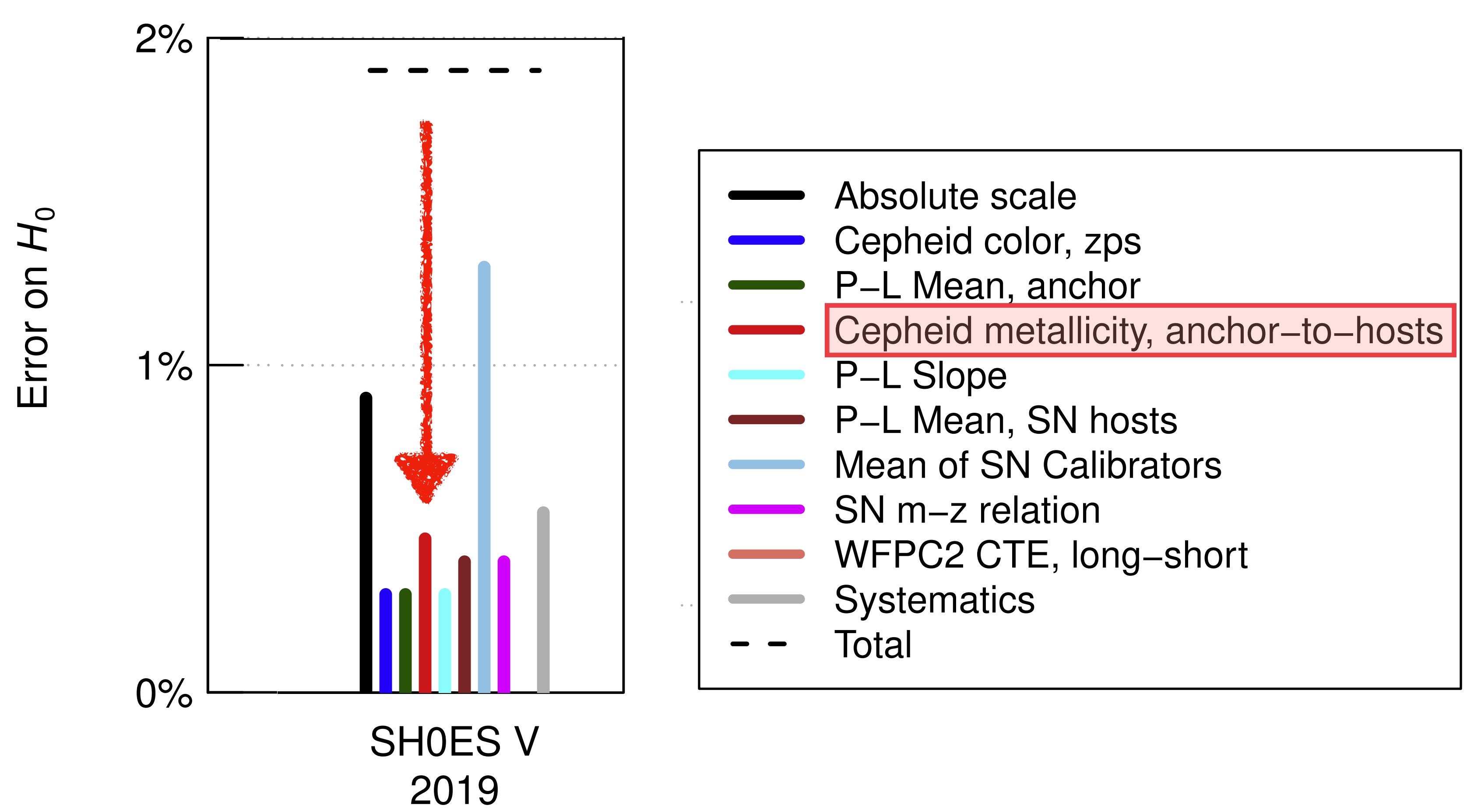
- Calibration of the PL relation with companions stars and host open clusters.
- Avoid issues due to saturation and color variation.
- Results: low dispersion of the PL relation ($\sim$ instability strip).
- Re-evaluation of the Hubble constant: consistent with other distance indicators, still 3.3σ from Planck.

Limitations

- Companions are often too faint for precise parallax measurements.
- Open clusters are limited by angular correlations.
- Photometry from ground-based telescopes: need consistency with extragalactic Cepheids (HST)
- Reddening corrections: NIR is less sensitive (or use Wesenheit indices).
- *Gaia* EDR3 zero-point systematic, although better estimated now.
- Other systematics: the effect of metallicity.

3. The effect of metallicity on the Leavitt Law

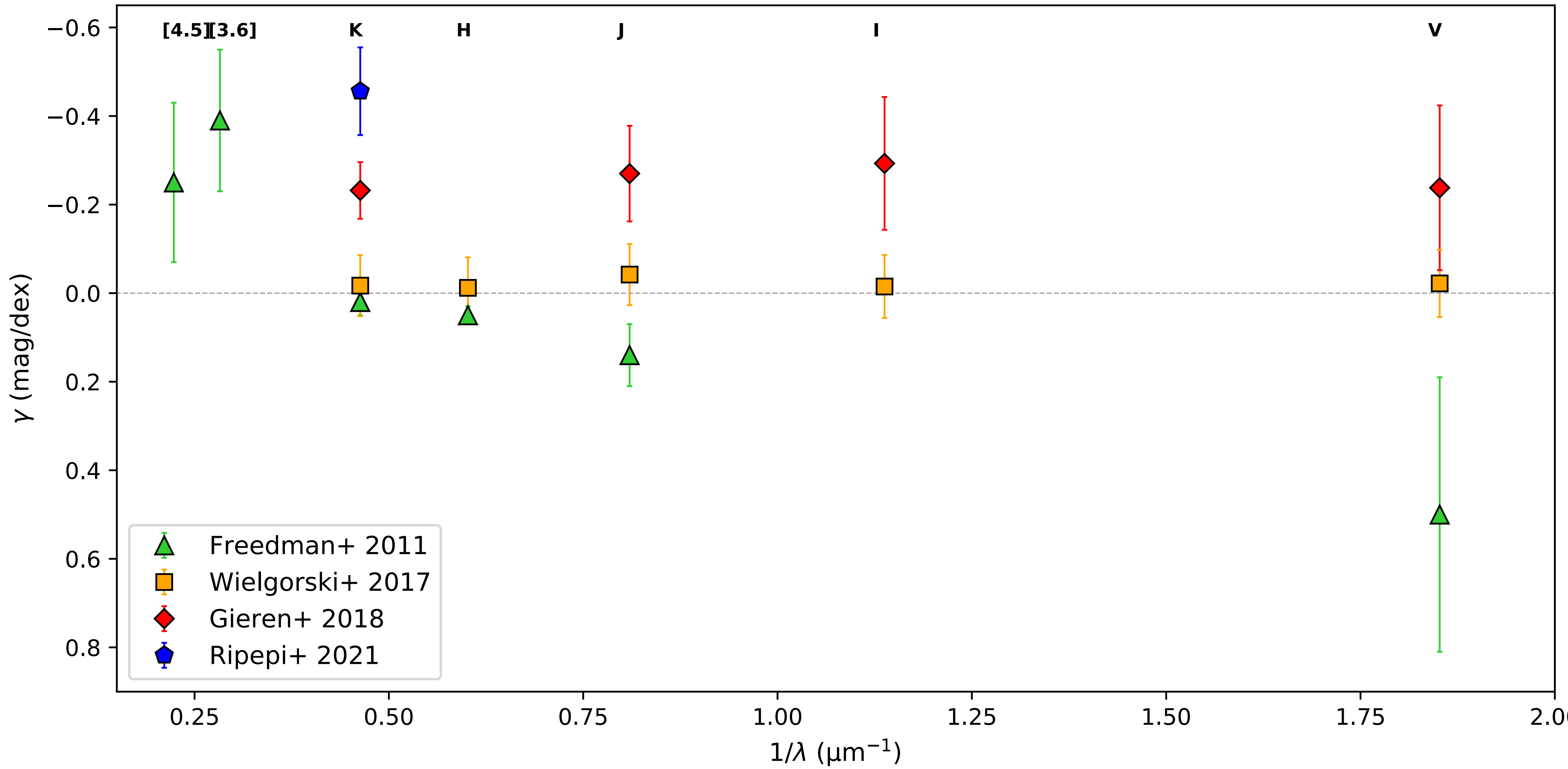
Error budget on the Hubble constant (Riess et al. 2019)



In the literature

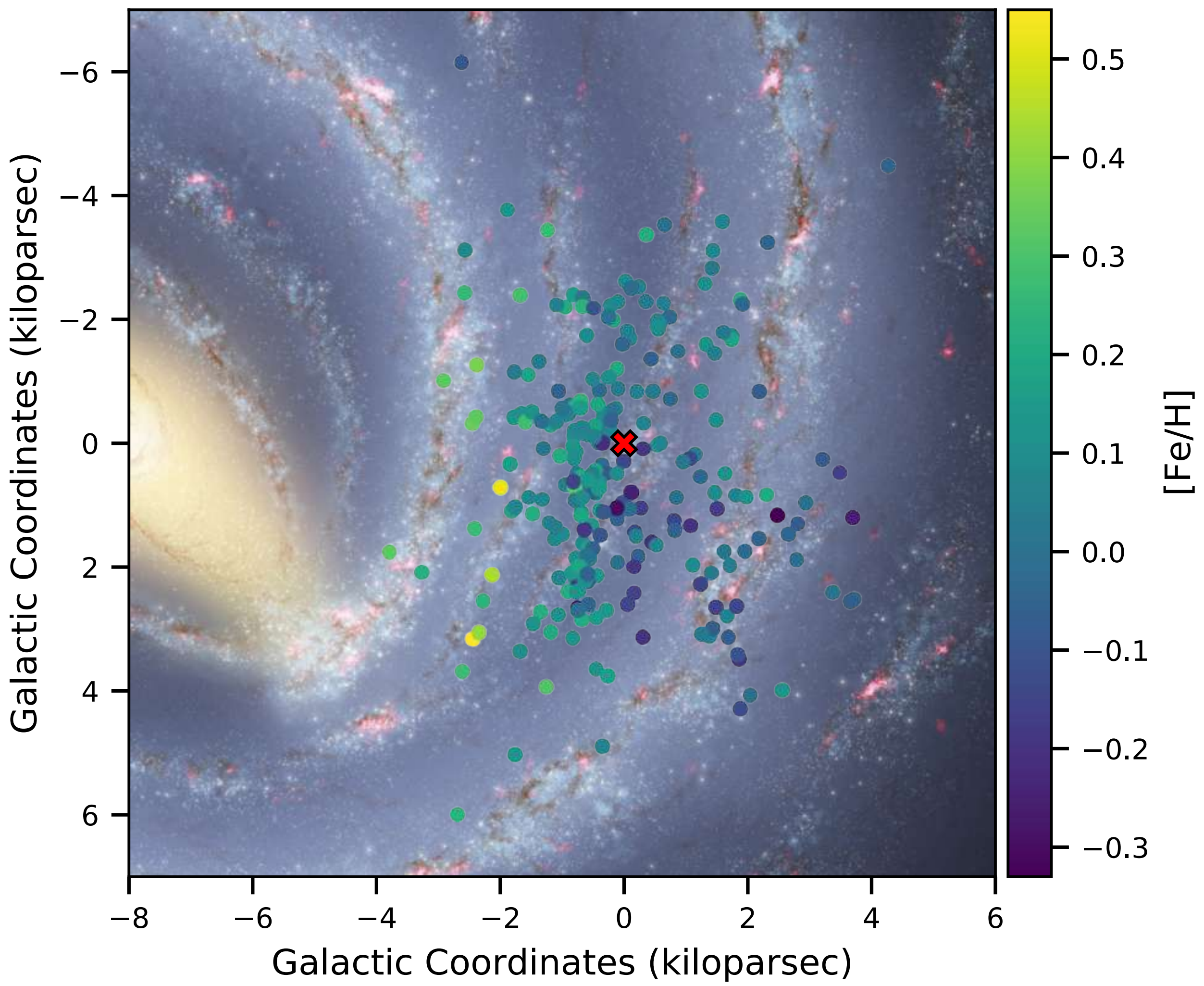
$$M = \alpha\,(\log P - \log P_0) + \beta + \gamma\,[\mathrm{Fe/H}]$$

- Empirically: mostly $\gamma \lesssim 0$ from recent studies.



- Theoretical studies: mostly $\gamma \gtrsim 0$

Milky Way:



Milky Way Cepheids and their metallicity (Breuval+ 2021)

Metallicity

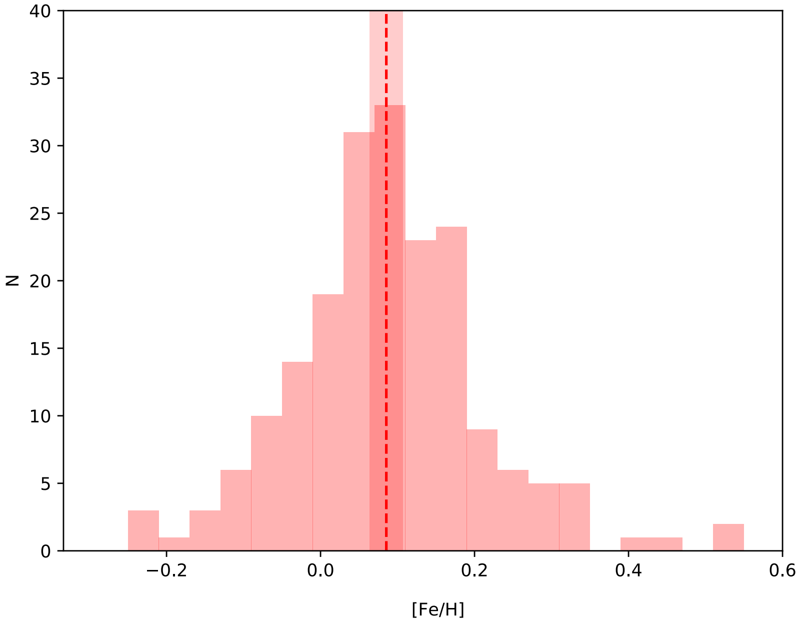
- Several catalogs with low precision.
- Mean value of +0.085 ± 0.022 dex.

Distances

- *Gaia* EDR3 parallaxes of Cepheids.
- Zero-point correction (Lindegren+2021).
- Exclude stars with RUWE > 1.4.

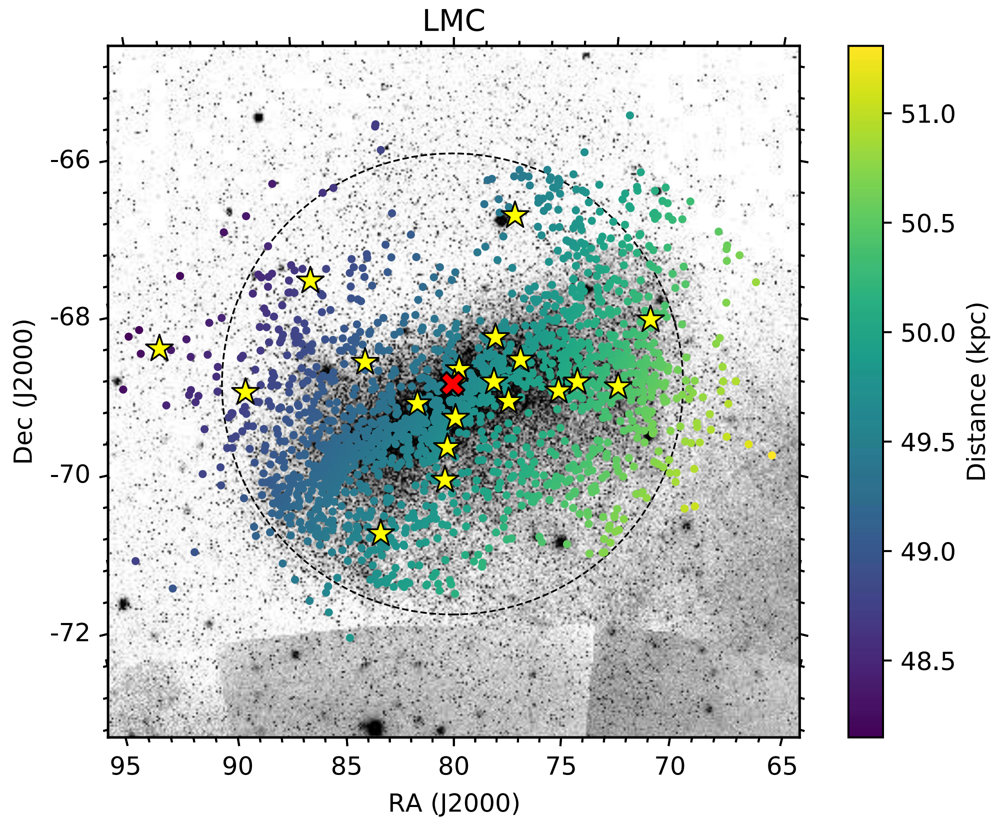
Photometry

- V, I, J, H, K light-curves from ground-based telescopes.
- G, BP, RP light-curves from *Gaia*.
- [3.6 μm], [4.5 μm] light-curves from *Spitzer*.



Metallicity of MW Cepheids (Breuval+ 2021)

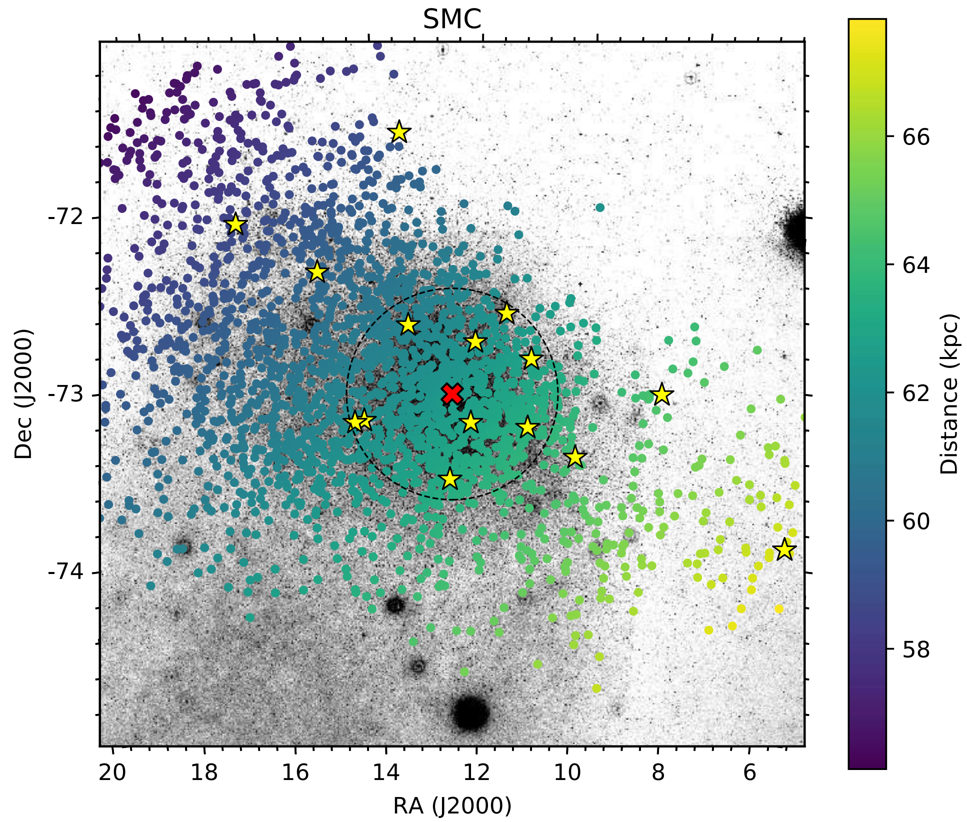
Large Magellanic Cloud:



LMC Cepheids and their distance. Yellow stars are eclipsing binaries (Breuval+ 2021)

- LMC distance from Pietrzynski+ (2019): d = 49.59 ± 0.09 ± 0.54 kpc, measured with eclipsing binaries + geometry correction (Jacyszyn-Dobrzeniecka+ 2016).
- Select a radius of 3° around LMC center.
- Metallicity: -0.34 ± 0.03 dex

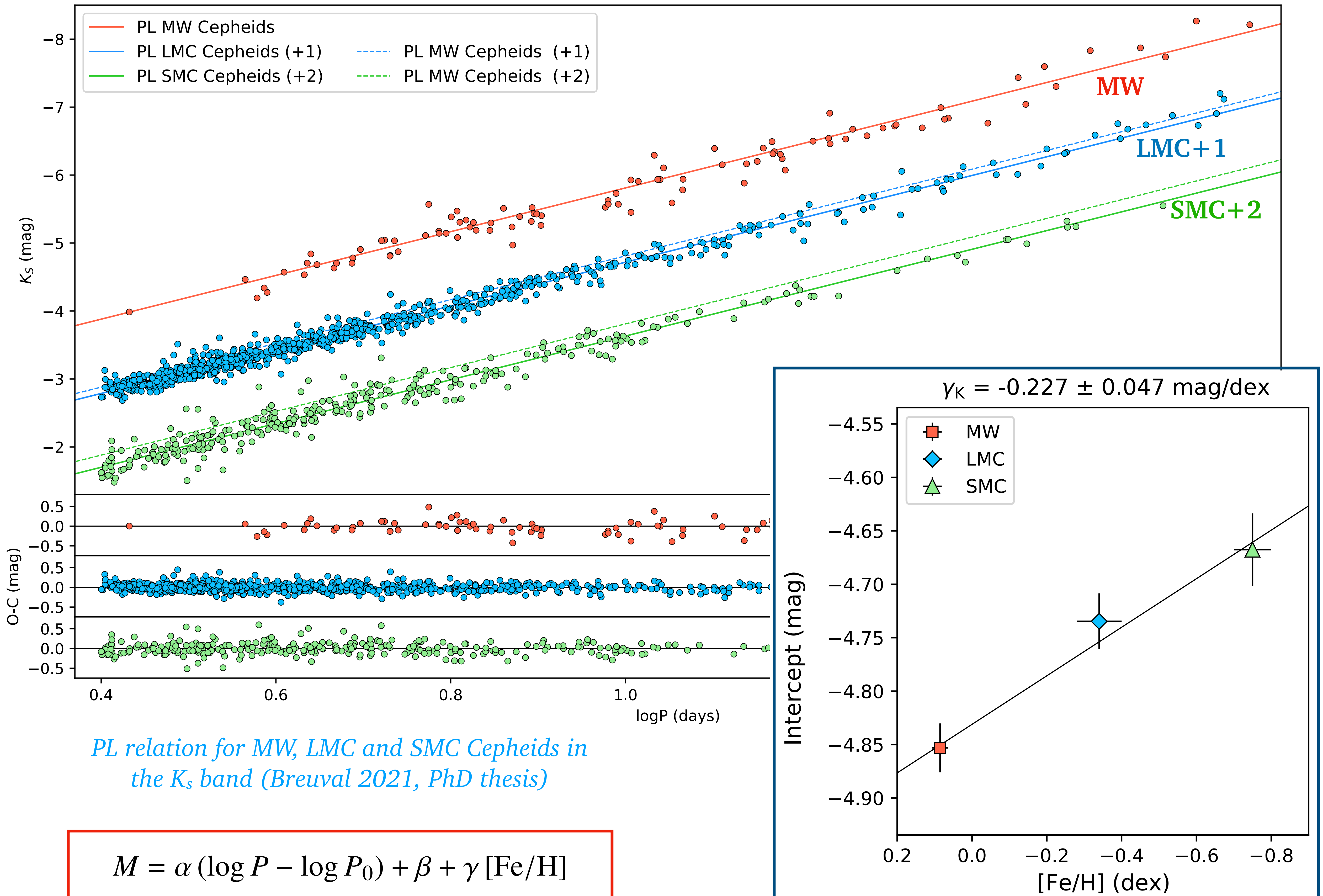
Small Magellanic Cloud:



SMC Cepheids and their distance. Yellow stars are eclipsing binaries (Breuval+ 2021)

- SMC distance from Graczyk+ (2020): d = 62.44 ± 0.47 ± 0.81 kpc, measured with eclipsing binaries + geometry correction (Graczyk+ 2020).
- Select a radius of 0°6 around SMC center.
- Metallicity: -0.75 ± 0.02 dex

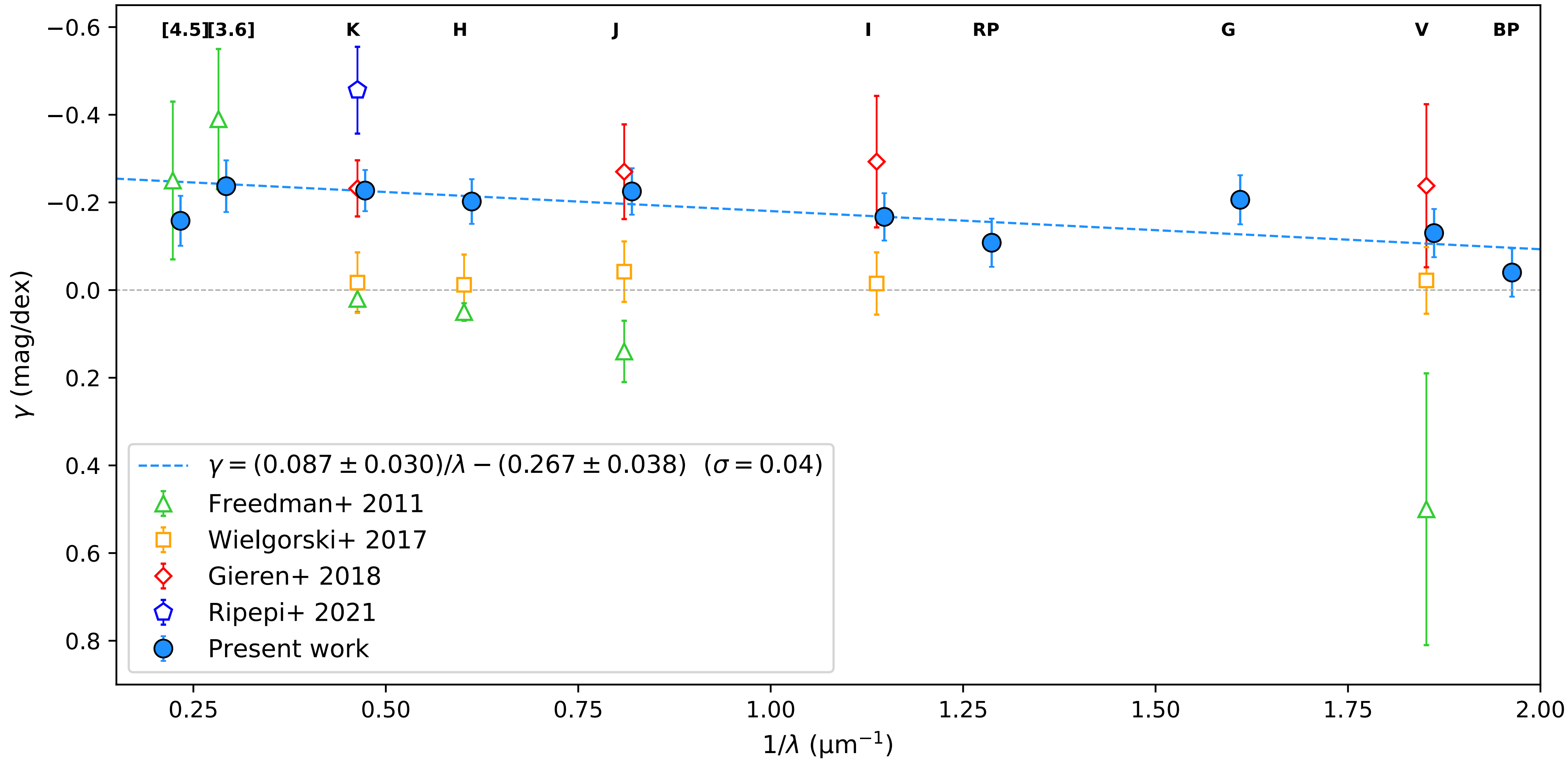
3. The effect of metallicity on the Leavitt Law



PL relation for MW, LMC and SMC Cepheids in the K_s band (Breuval 2021, PhD thesis)

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

3. The effect of metallicity on the Leavitt Law



Metallicity effect as a function of the wavelength (Breuval 2021, PhD thesis)

- $\gamma < 0$: metal-rich Cepheids are brighter than metal-poor ones.
- Wide CO absorption bands aligned with the [4.5 μm] filter.
- NIR seems more sensitive to metallicity than optical bands.

Summary

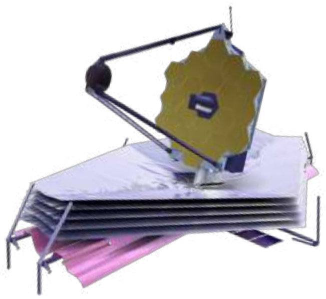
- We have used the best distances available for Milky Way and Magellanic Cloud Cepheids.
- Wide range of metallicities covered by the three galaxies ($\sim$1 dex).
- We confirm that $\gamma<0$, consistent with other empirical studies.
- Our results suggest that NIR bands are more sensitive to the metallicity effect than the optical.
- We obtain the best precision so far for the γ term: will reduce H_0 error budget.

Limitations

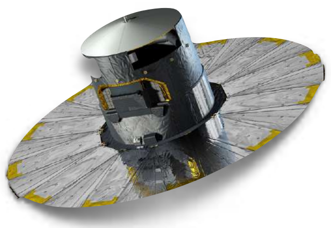
- Large systematics because of the combination of different photometric systems.
- LMC and SMC Cepheid samples are required for a precise determination of the metallicity effect.
- Few individual metallicity measurements $\rightarrow$ use average values only.
- Distance to the SMC: difficult to measure because of its elongated shape.

4. Perspectives

- 2022: **Hubble Space Telescope**
  → HST photometry by spatial scanning for Cepheids in Open Clusters for consistency with extragalactic Cepheids (same system).



- 2022-2023: **James Webb Space Telescope / NIRCam**
  → Uncrowding the Cepheids for an improved determination of the Hubble constant (co-PI Proposal GO #1685 Cycle 1, PI: A. Riess)



- 2023-2024: **Gaia DR4**
  → Precise parallaxes for Cepheids, better estimate of the ZP offset
  → Improve the calibration of the P-L relation in the Milky Way

- 2025: **Extremely Large Telescope**
  → High resolution spectra for MW/LMC/SMC Cepheids
  → Precise calibration of the metallicity effect

H_0 to 1%

Thank you !

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Breuval et al. 2020, A&A, 643, A115
Breuval et al. 2021, ApJ, 913, 38