Measuring Astronomical Distances with Pulsating Stars: From Cepheids in the Milky Way to the Hubble Constant

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1. Cepheids and the Period-Luminosity relation

Cepheid stars play a considerable role as astronomical distances indicators, thanks to the simple relation between their pulsation period and intrinsic luminosity (PL relation) **[1]**. By comparing their apparent luminosity to the brightness predicted by the PL relation, it is possible to derive their distance. The uncertainty on this relation is currently the main source of error in the determination of the Hubble constant (H_0), a quantity that describes how fast the Universe is expanding. Therefore, the empirical calibration of the PL relation still needs to be improved using known distances of Cepheids.

The 2^{nd} data release of the Gaia satellite (Gaia DR2), published in 2018, provided parallaxes (~1/distance) for 1.3 billion stars with an unprecendented precision and was expected to improve the accuracy of the PL calibration. However, Cepheids are bright stars and are often saturated in detectors. Their parallaxes are also affected by systematics due to their photometric variability **[2]**. For these reasons, using Gaia DR2 parallaxes of Cepheids may not be the finest method to calibrate the PL relation.

We propose an original and alternative method in order to avoid the direct use of potentially unreliable Cepheid parallaxes. We adopt a combination of 2 samples:

1) Gaia DR2 parallaxes of **22 companions** of Cepheids
2) Average Gaia DR2 parallaxes of **14 open clusters** hosting Cepheids

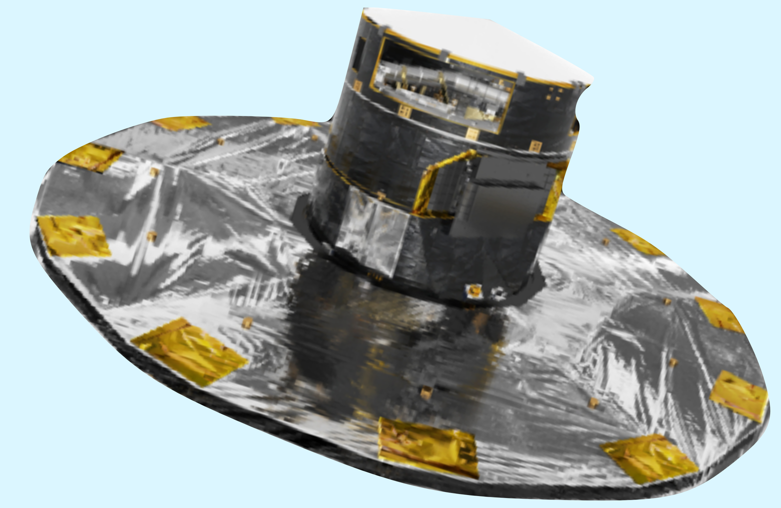


Fig. 1: Gaia Satellite (credit: ESA)

Fig. 2: The Cepheid RS Puppis (credit: HST)

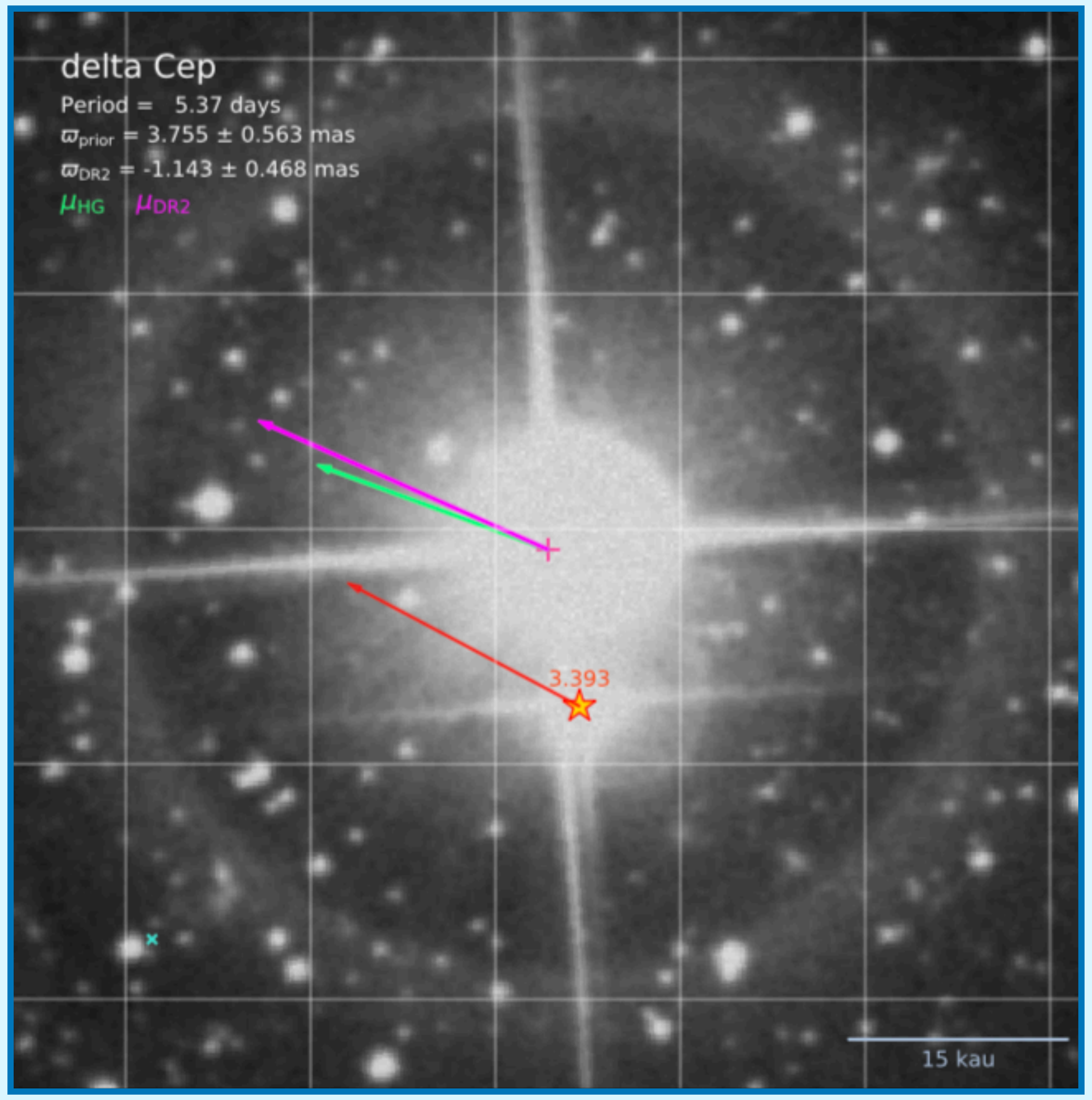


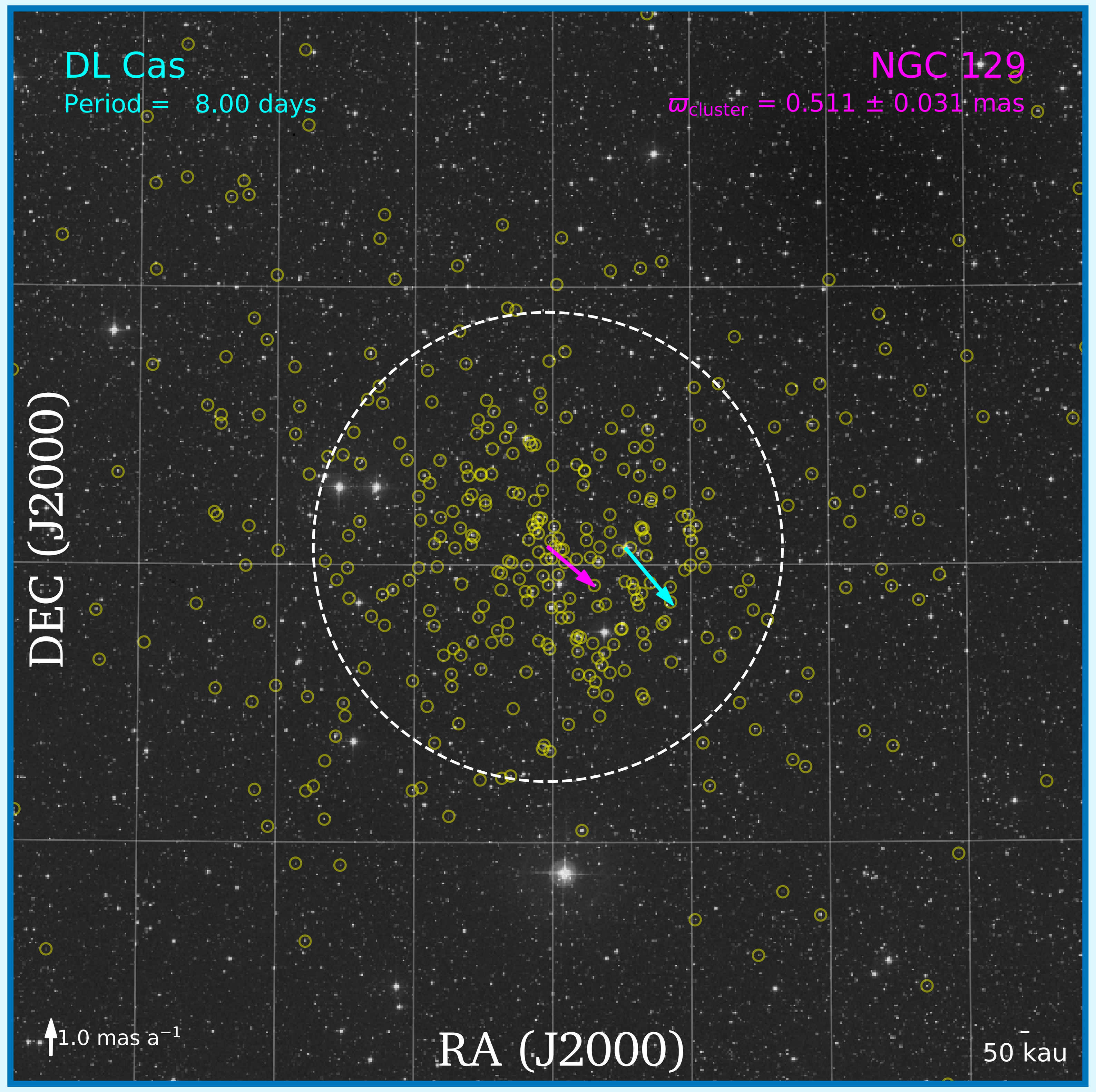
Fig. 3: Proper motion of Delta Cep and of its companion ***[3]***.

2. The sample of Cepheids companions

Kervella et al. (2019) **[3]** provides a sample of 28 Cepheids with resolved companions (see Fig. 3). Assuming the companions are located at the same distance as Cepheids, they provide an indirect measurement for the Cepheid distance. The advantage of these companions is that unlike some Cepheids, they are not variable, unsaturated and all of them have a valid Gaia DR2 parallax.

The angular separation between Cepheids and their companion is large enough to prevent from flux contamination. Given the separation and orbital period of these systems, parallaxes are insensitive to binarity. After a quality check based on various indicators **[4]**, we obtain a final sample of 22 companions.

Fig. 4: Proper motion of DL Cas and of its host open cluster NGC 129 ***[2]***.



3. The sample of Open Clusters hosting Cepheids

Open clusters contain a large number of stars, so the average parallax of their members provides a precise estimate for the distance to the Cepheids they host (see Fig. 4 for example). We performed a cross-match between Gaia DR2 Cepheids and a catalogue of Milky Way open clusters with average Gaia DR2 parallaxes **[5]**. We compared their positions, proper motions, ages, and parallaxes and we complemented our sample by a few additional couples found in the literature. We obtain 14 Cepheids being very likely members of open clusters with average parallaxes based on Gaia DR2.

4. Method and results

Gaia DR2 parallax zero-point

Gaia DR2 parallaxes (ϖ) are subject to a zero-point (ZP) offset. We corrected our parallaxes by applying a ZP of -0.046 ± 0.015 mas, to account for the diverse values found for this parameter in the literature.

First overtone pulsators

Our sample contains a few Cepheids pulsating in the first overtone mode. These particular Cepheids obey to a PL relation slightly different from fundamental ones. Their period of pulsation was converted into the fundamental mode so they can still be used in the PL calibration.

Deriving absolute magnitudes (M)

We used well sampled light-curves in order to obtain apparent mean magnitudes (m) and corrected them for the extinction A_λ E(B-V) using the equation:

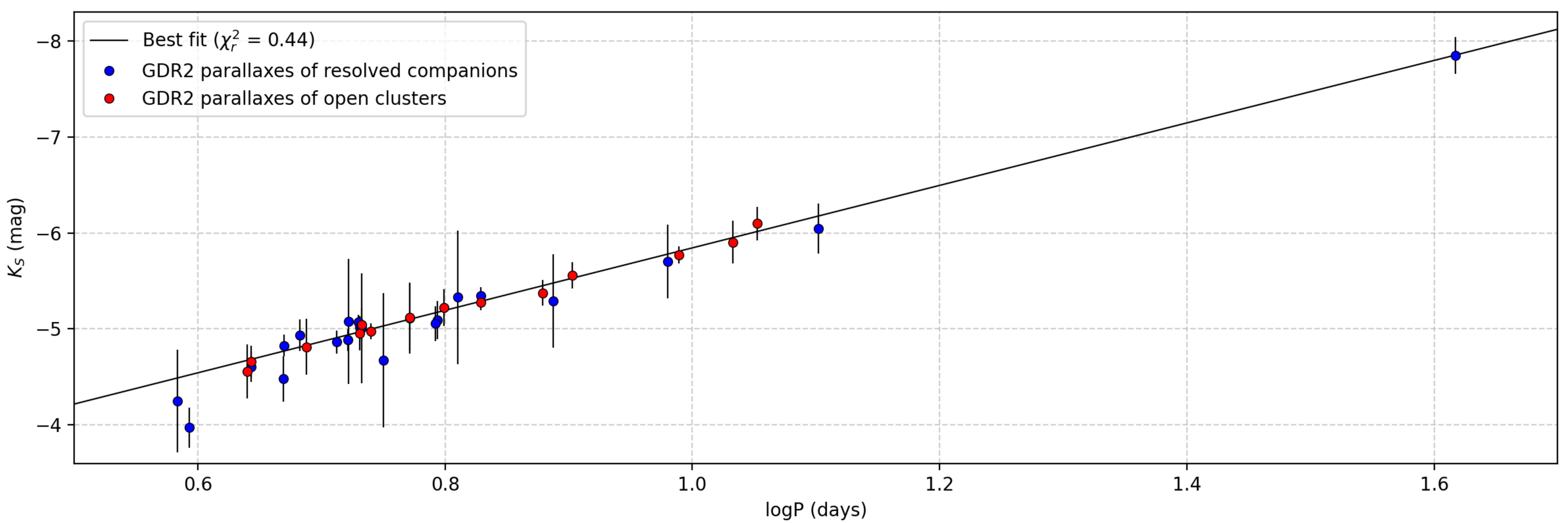
$$M_\lambda = m_\lambda + 5 \log \varpi_{(mas)} - 10 - A_\lambda E(B-V)$$

We perform a Monte-Carlo algorithm to fit the data.

The resulting PL relation in the K_S band is:

$$K_S = -3.257_{\pm 0.163} (\log P - 1) - 5.844_{\pm 0.037}$$

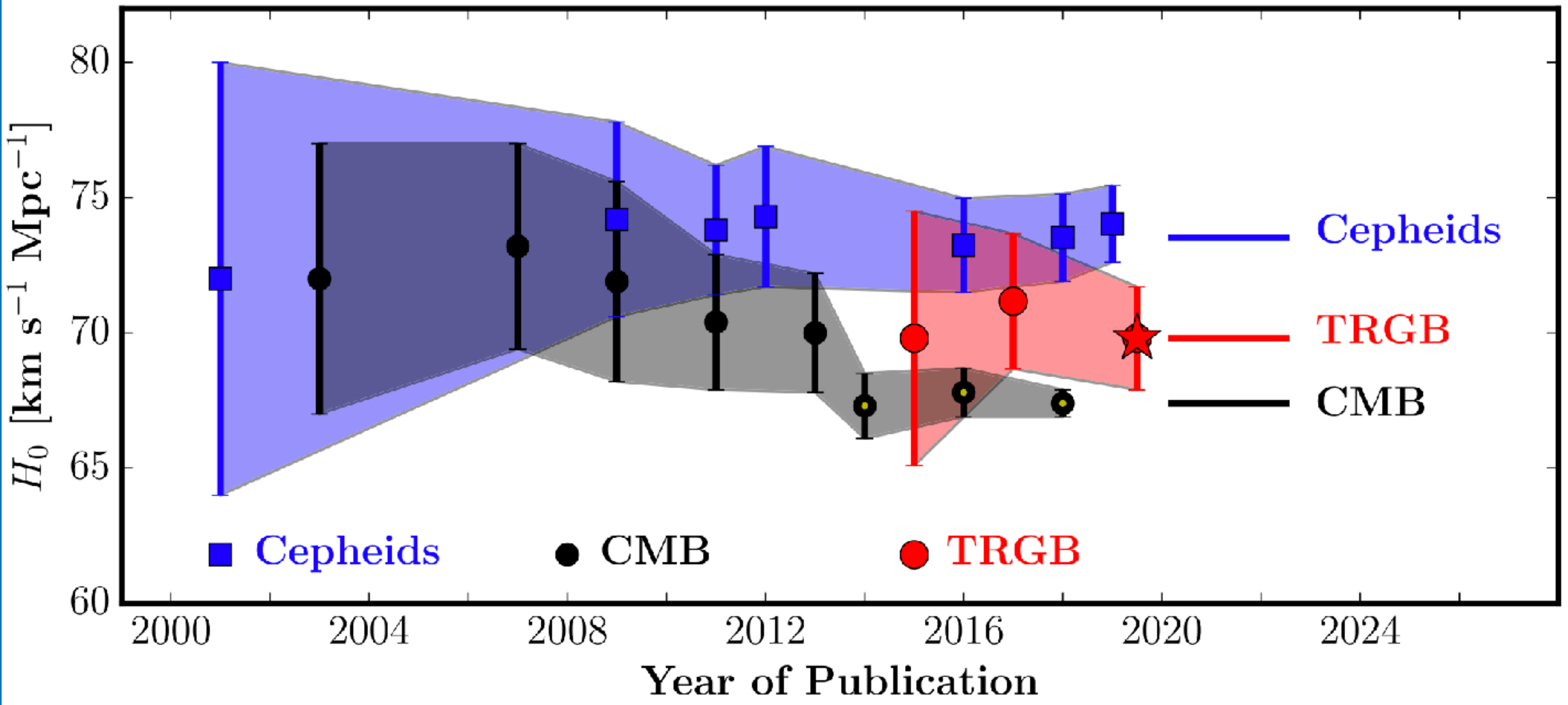
Fig. 5: Period-Luminosity relation in the K_S band based on Gaia distances for Cepheids companions (blue points) and open clusters hosting Cepheids (red points) **[2]**.



5. Implications on the Hubble constant H_0

Cepheids are used to calibrate the cosmic distance ladder, which provides a measurement of the Hubble constant H_0. This parameter represents the Universe's expansion rate. It is currently at the center of a major scientific controversy (see Fig. 6): while it is estimated at 67.4 ± 0.5 km/s/Mpc by the Planck satellite [7], the local measurement based on Cepheids is larger by more than 4σ, with a value of 74.0 ± 1.4 km/s/Mpc [8]. This discrepancy may provide evidence for physics beyond the standard model. Precise and accurate distance measurements of Cepheids are therefore crucial to solve the Hubble constant tension.

Fig. 6: H_0 values as a function of time, from different methods [6].



Riess et al. (2016) [9] derived a Hubble constant of 76.18 ± 2.37 km/s/Mpc using the Milky Way anchor alone, made of Hubble Space Telescope (HST) parallax measurements of Galactic Cepheids. Combining this galactic estimate with other extragalactic anchors leads to a final average value of 73.24 ± 1.74 km/s/Mpc.

We revise the Milky Way H_0 value by adopting our sample of companions and clusters parallax measurements from Gaia DR2 in place of the previous HST parallaxes and we obtain $H_0 = 72.8 \pm 2.7$ km/s/Mpc. This result does not solve the tension, mostly because of the uncertainty on the Gaia DR2 offset. However, adopting our sample of parallaxes allows to bring the Milky Way estimate in excellent agreement with the values based on extragalactic anchors. The next Gaia data releases are expected to provide more precise and accurate parallaxes of Cepheids in the near future, hopefully leading to a sub-percent measurement of H_0.

References

[1] Leavitt & Pickering 1912 (Harvard College Observatory Circular, 173, 1)
[2] Breuval et al. 2020 (arXiv: 2006.08763)
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[7] Planck Collaboration et al. 2018 (arXiv: 1807.06209)
[8] Riess et al. 2019 (ApJ, 876, 85)
[9] Riess et al. 2016 (ApJ, 826, 56)

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