The Cepheid distance ladder: from the local Gaia calibration to distant galaxies

Recent results: Breuval et al. 2020
Accepted in A&A, arXiv:2006.08763

1. Measuring distances in the Universe

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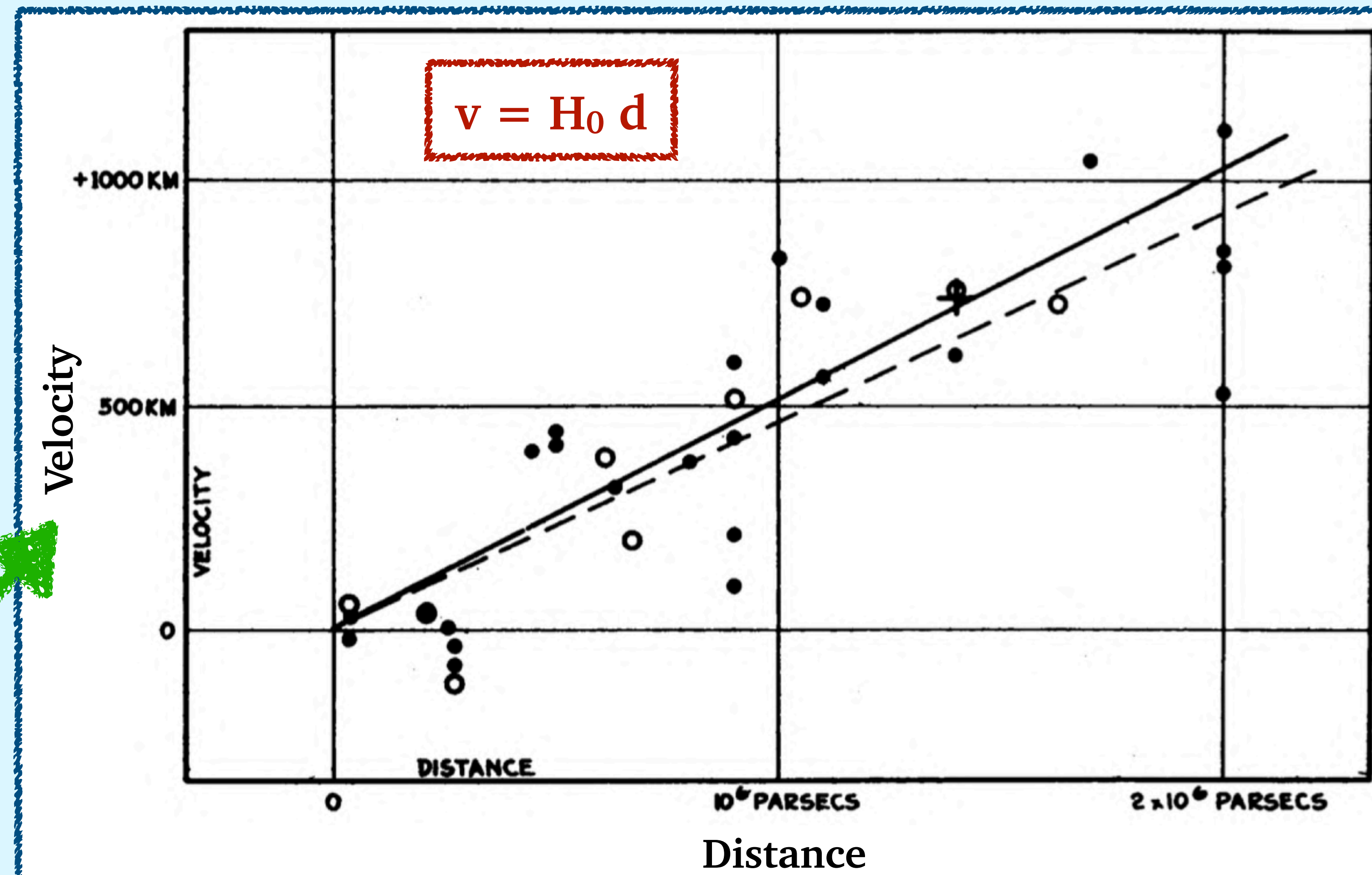
Edwin Hubble and the 2.5m telescope
at Mount Wilson Observatory

- 1920: "The Great Debate" between Harlow Shapley and Heber Curtis.
- 1929: Edwin Hubble discovers that the velocity of galaxies increases with their distance.

Relation between galaxies distance and velocity (Hubble 1929)

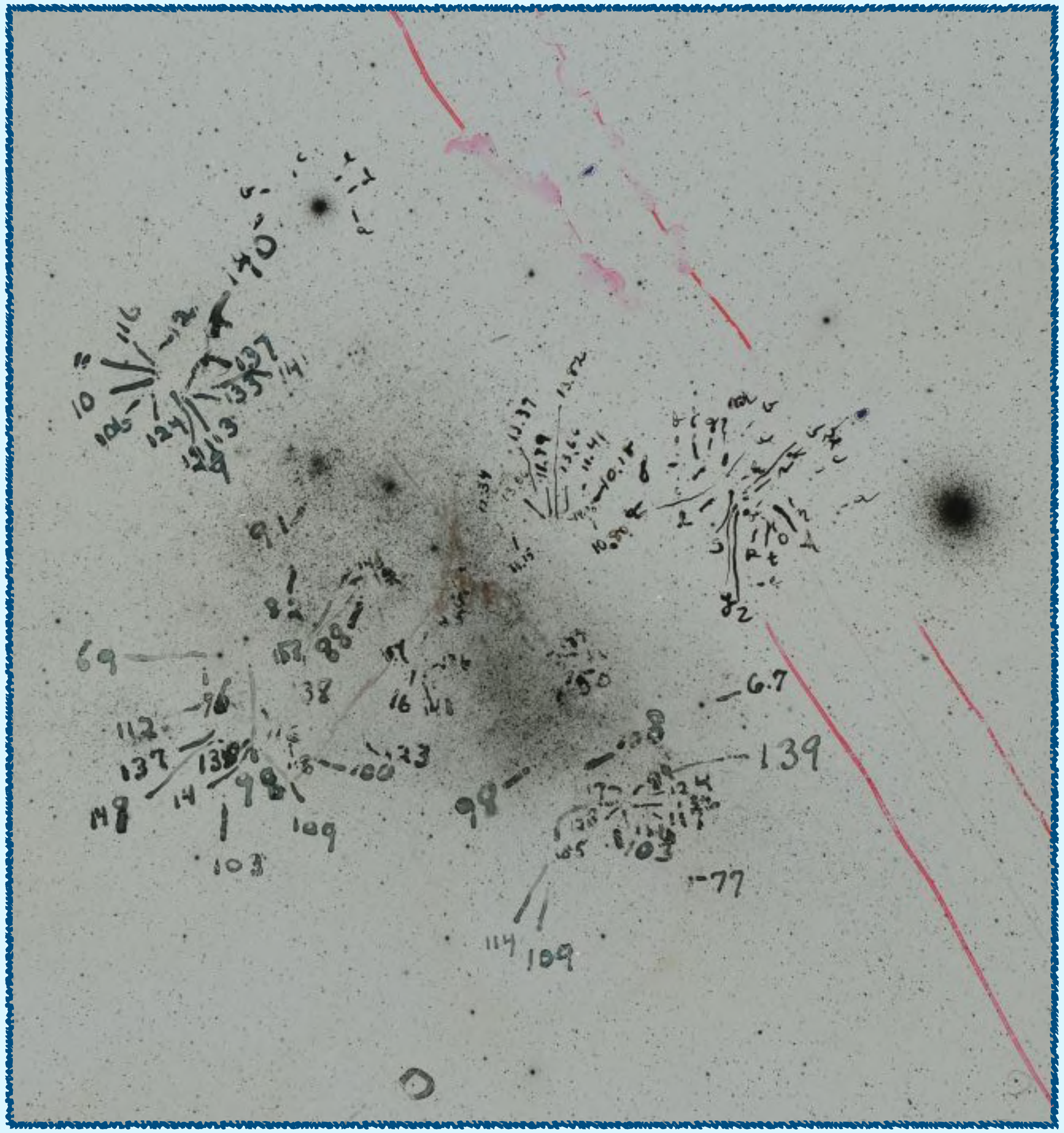


spectroscopy

Cepheids

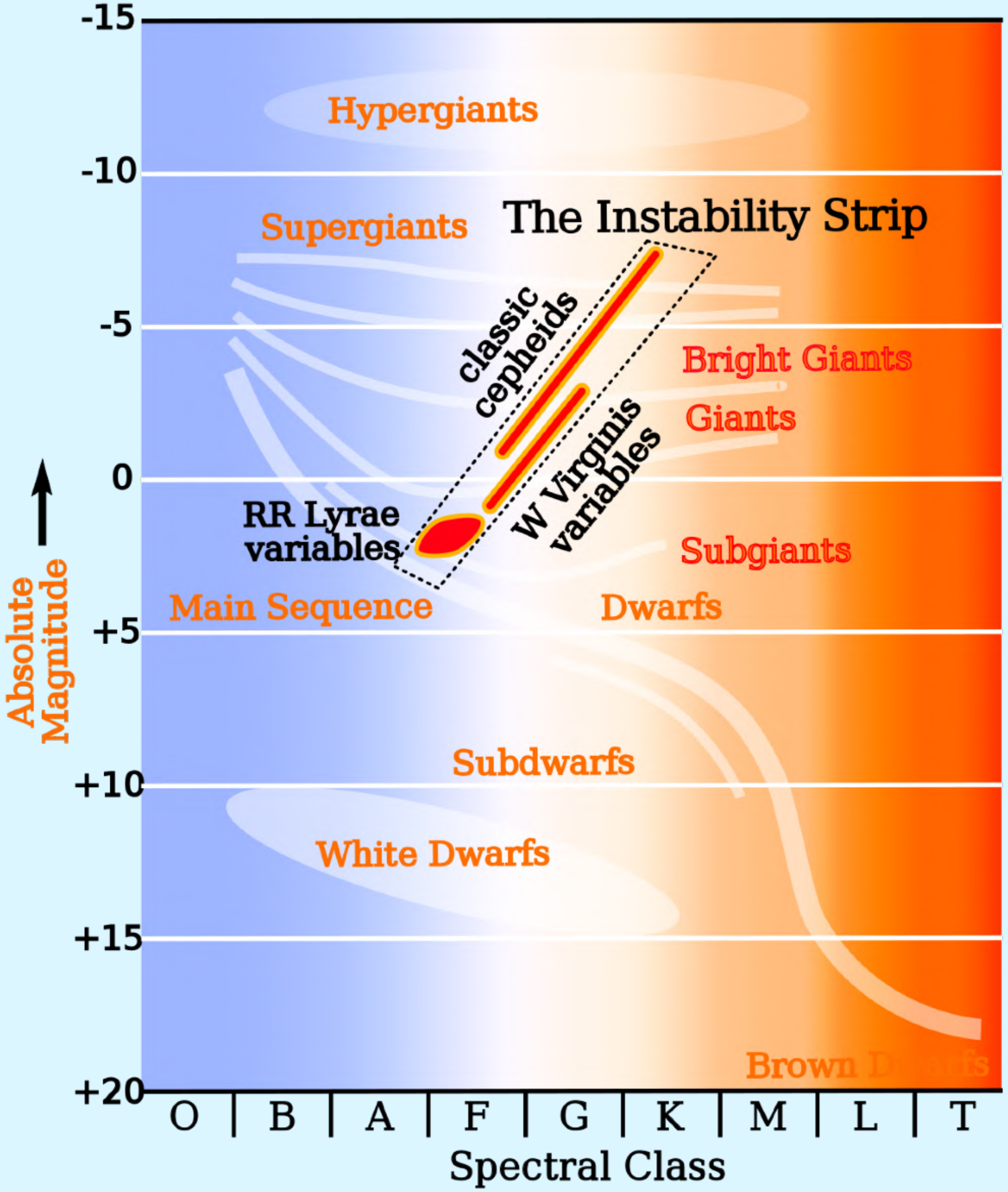
1. Measuring distances in the Universe

Henrietta Leavitt (1908)



Photographic plate of the Small Magellanic Cloud studied by Henrietta Leavitt

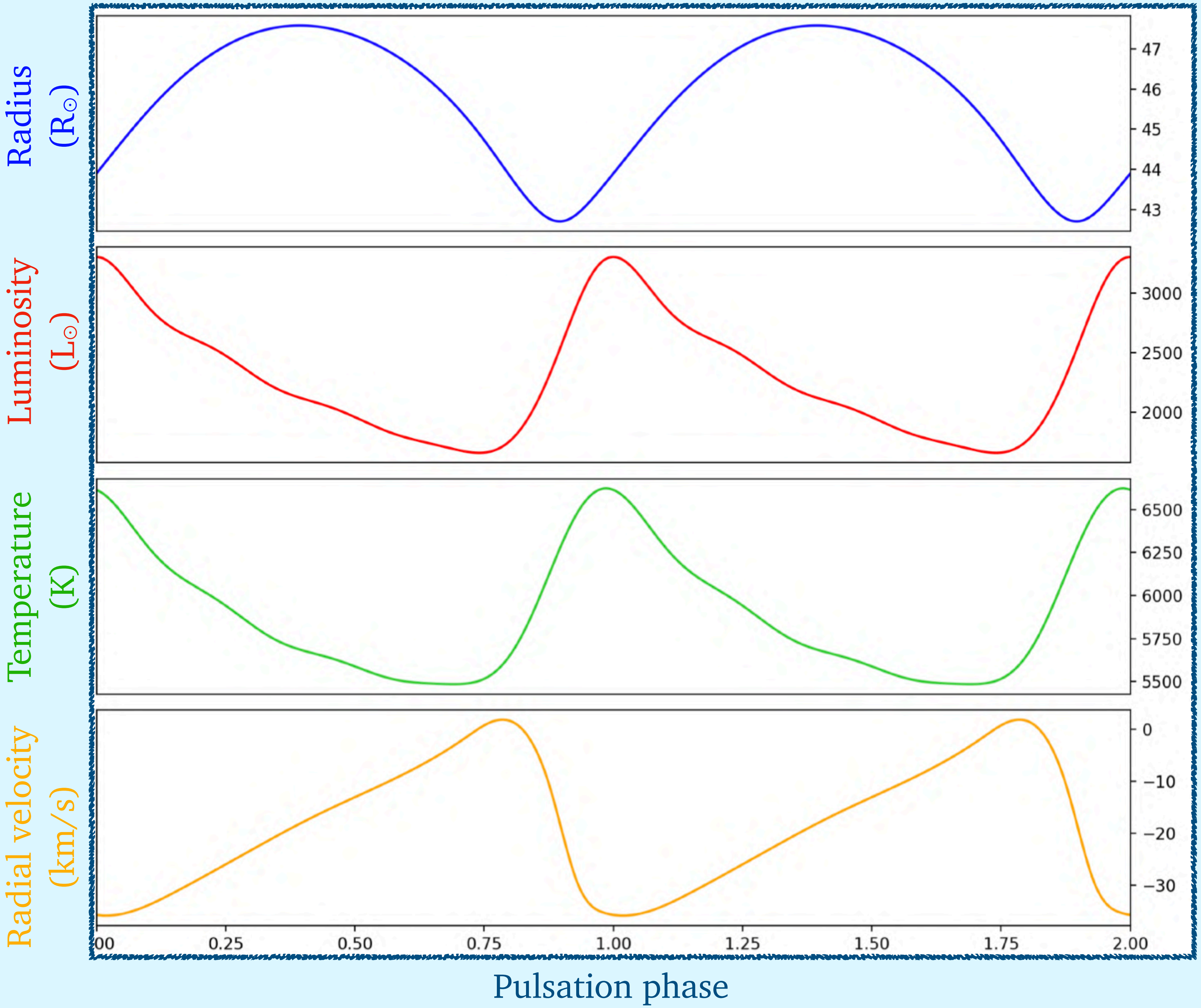
Cepheids in the HR diagram



CLASSICAL CEPHEIDS

Pulsation period	from 2 to 100 days
Position in HR diagram	instability strip
Mass	4 - 20 $M_\odot$
Luminosity	10 000 - 100 000 $L_\odot$
Radius	10 - 100 $R_\odot$
Type	giant, supergiant
Class	F, G, K
Temperature	4000 - 8000 K
Metallicity	Metal rich
Luminosity variation	0.5 - 2 mag

1. Measuring distances in the Universe



1. Measuring distances in the Universe

Pulsation mecanism (κ-mecanism):

Contraction

Heating

Pressure rises

Helium ionisation in outer layers

Opacity rises

Contraction continues

Pressure becomes sufficient to balance gravity

Expansion begins

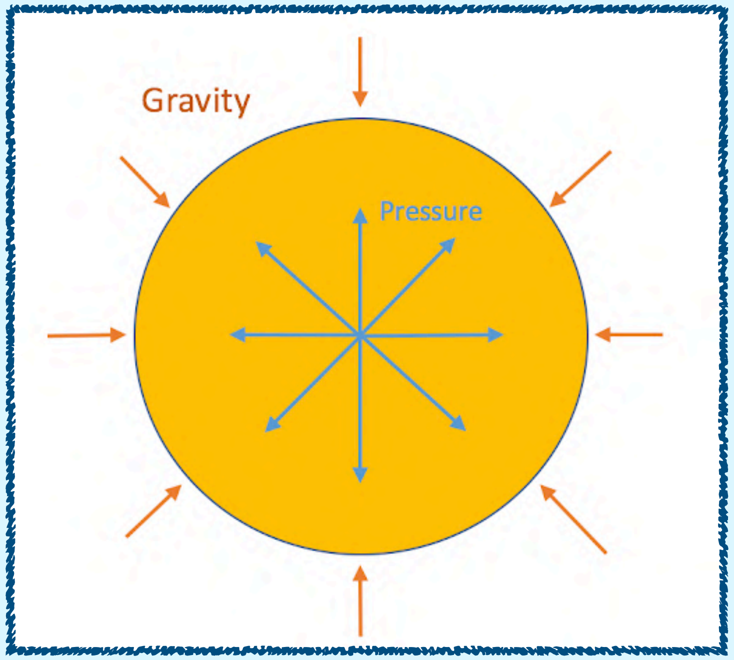
Cooling

Opacity decreases

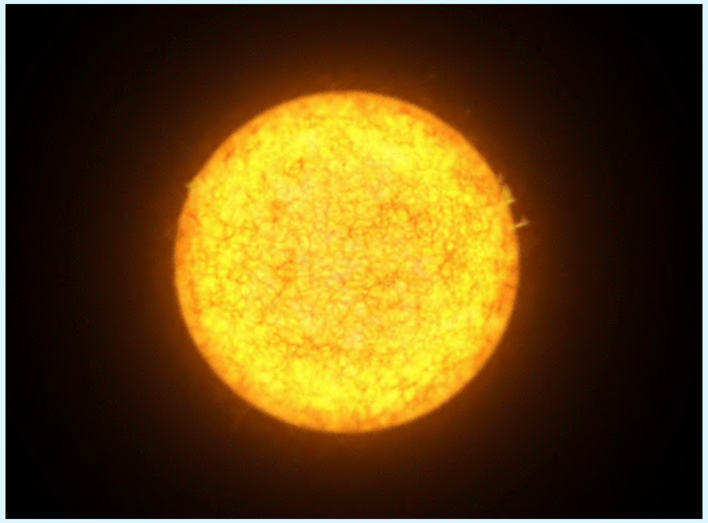
Pressure decreases

Gravitation becomes dominant again

Hydrostatic equilibrium between pressure and gravitation



Hydrostatic equilibrium in stars

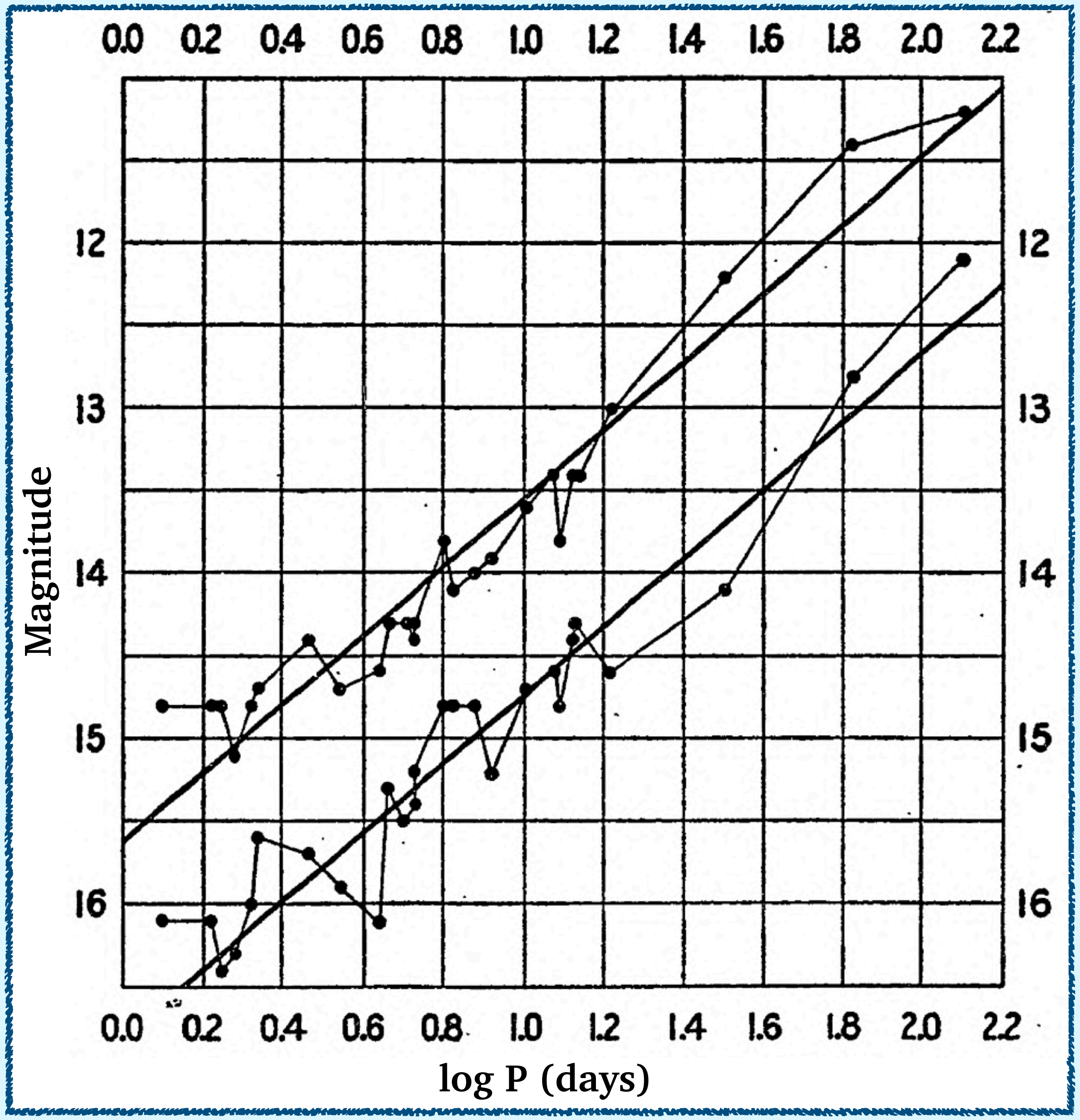


1. Measuring distances in the Universe

Henrietta Leavitt (1908)

Henrietta Leavitt discovered that the brightest Cepheids have the longest periods ! The relation between the absolute magnitude **M** and the period **P** is now called the **Leavitt law** or **Period-Luminosity** (PL) relation:

$$\boxed{M = a \log P + b}$$



PL relation calibrated by Henrietta Leavitt

→ **How does this relation allow to measure distances ?**

1. Measuring distances in the Universe

$$\boxed{(\text{absolute mag } M) - (\text{apparent mag } m) = 5 - 5 \log d_{[pc]}}$$

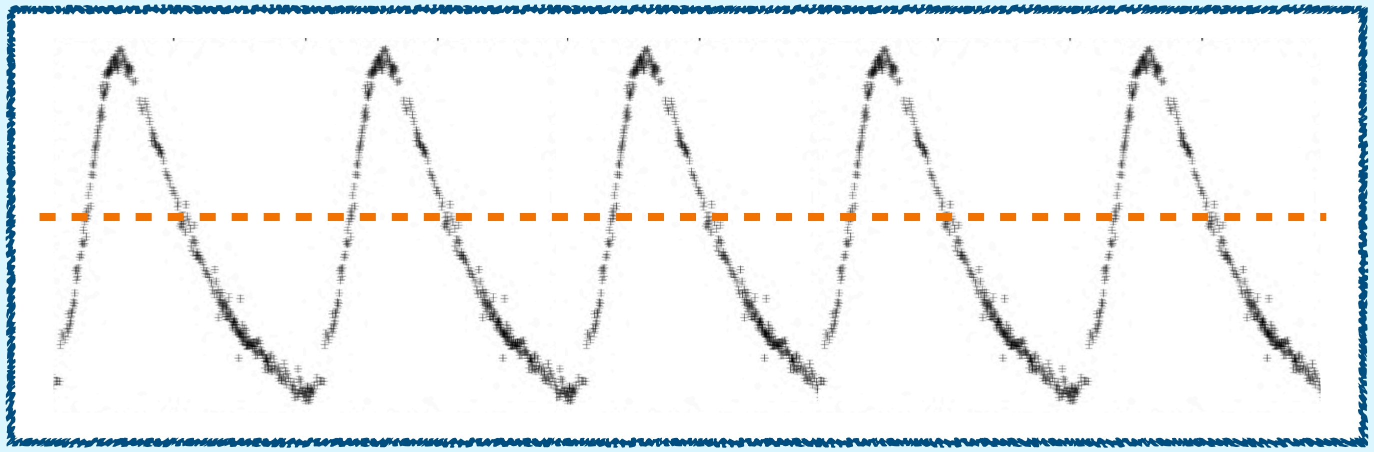
- Observe the light curve of the Cepheid and measure its period ***P***.

- Use the PL relation to compute the absolute (intrinsic) magnitude M.

$$\boxed{M = a \log P + b}$$

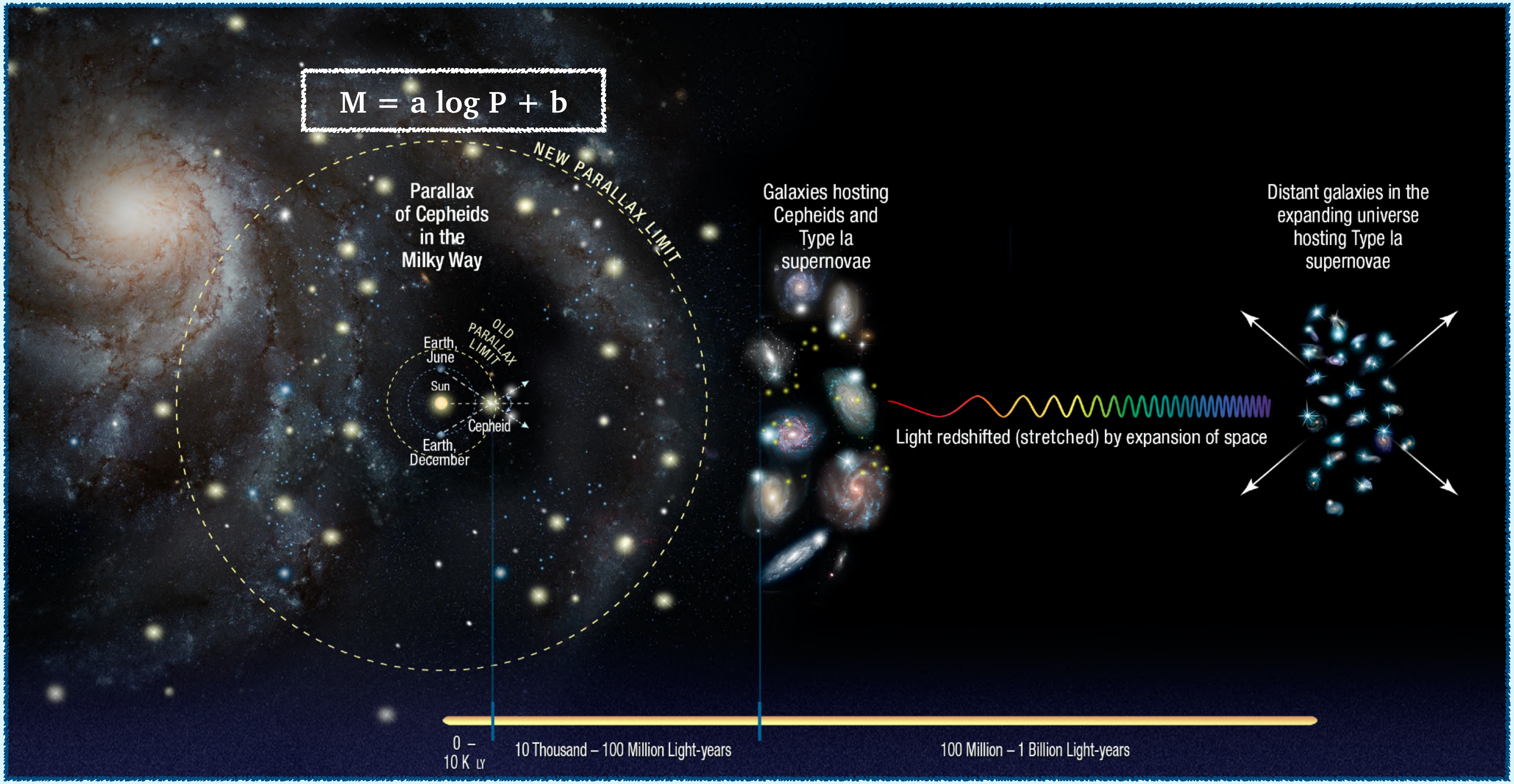
- On the light curve, measure the apparent mean magnitude ***m***.

m



P

1. Measuring distances in the Universe



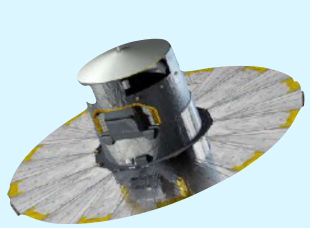
→ Calibrating the PL relation (finding the precise value for a and b) is essential for the calibration of the extragalactic distance scale.

→ To calibrate the PL relation, we need to know a-priori distances of some Cepheids.

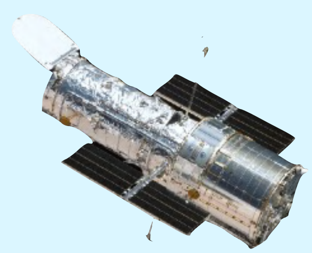
1. Measuring distances in the Universe

Empirical ("local") determination

Cepheids + SN1a + other indicators
Gaia, Hubble Space Telescope
Riess et al. 2019



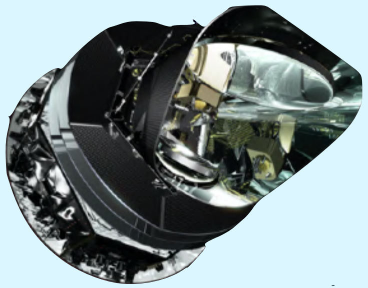
Gaia



HST

Planck measurement

Cosmic Microwave Background
assuming a Λ-CDM cosmological model
Planck Collaboration et al. 2018

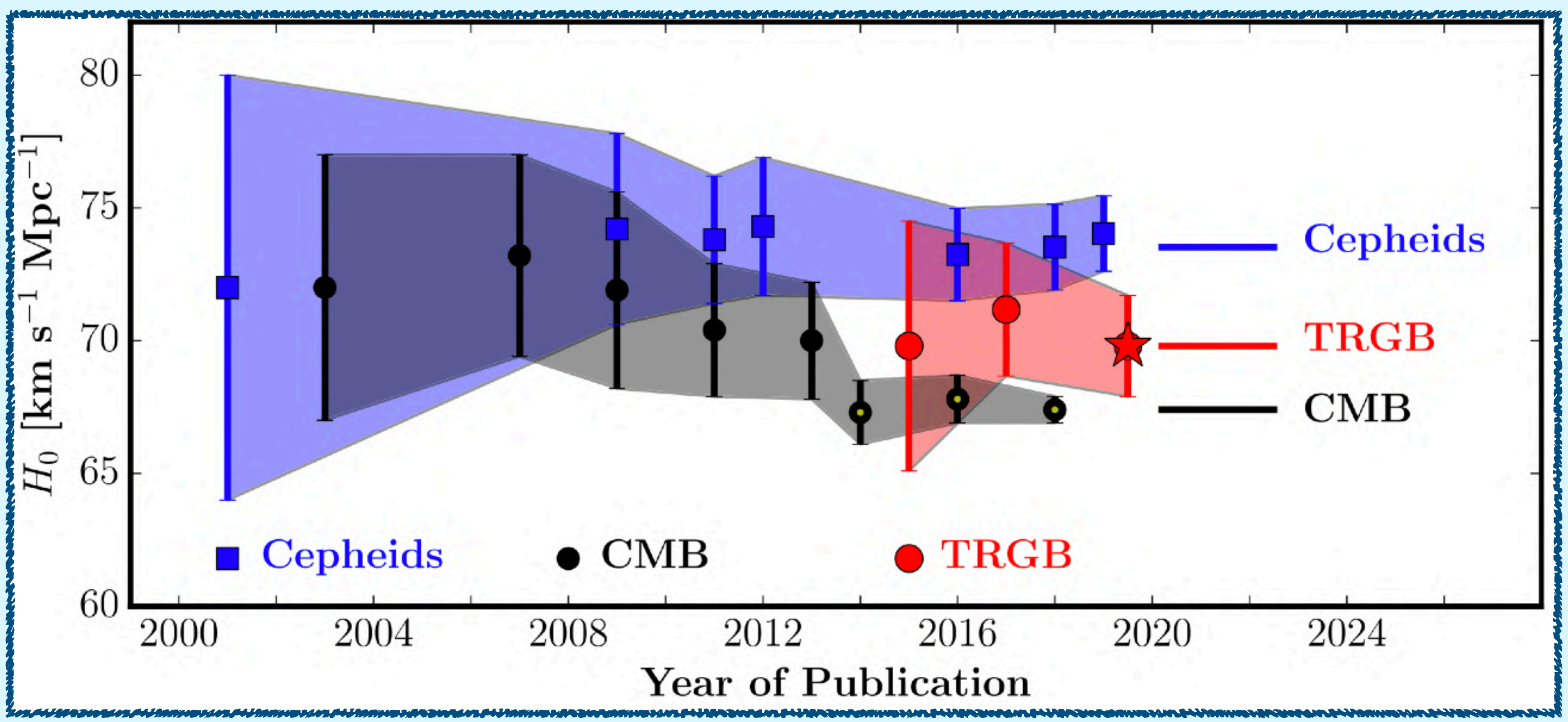


Planck

H_0 = 74.03 ± 1.42 km/s/Mpc

⚡ **Tension** ⚡

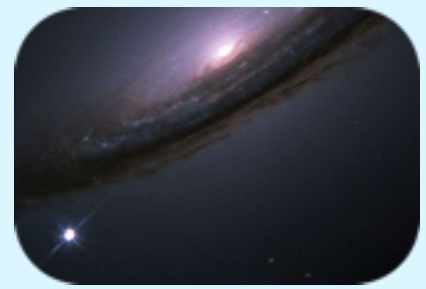
H_0 = 67.4 ± 0.5 km/s/Mpc



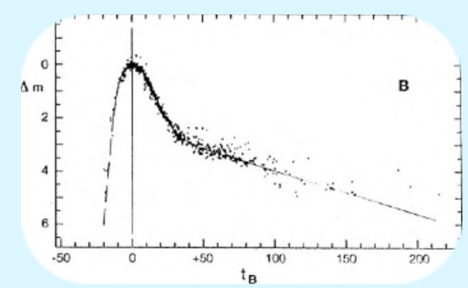
1. Measuring distances in the Universe

precise Cepheids distances

precise calibration of the PL relation



precise distance measurements for Cepheids located in galaxies hosting supernovae



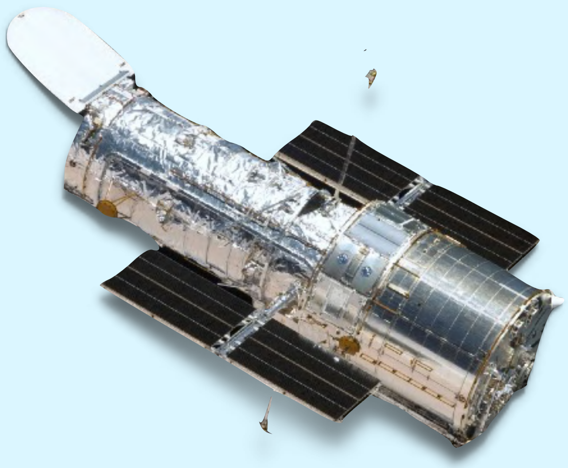
precise calibration of SN1a distances

precise measurement of the Hubble constant H_0

2. Parallaxes and the Gaia satellite

2. Parallaxes and the Gaia satellite

- We **need very precise distances** to calibrate the PL relation.

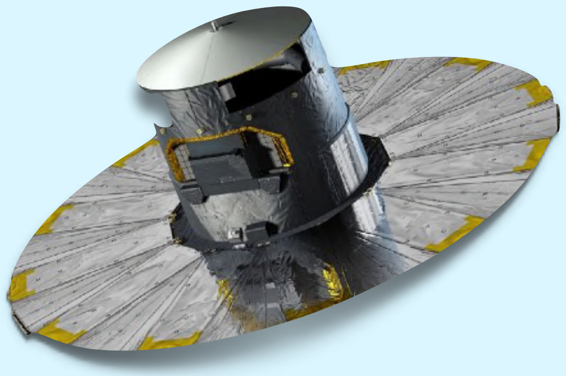


Hubble Space Telescope
(NASA, ESA)

- Over the past 20 years, only the Hubble Space Telescope (HST) provided precise geometrical paxallaxes of Cepheids :

  → Freedman et al. (2001)
  → Sandage et al. (2006)
  → Benedict et al. (2002, 2007)
  → Riess et al. (2011, 2014, 2016, 2018, 2019)

- GAIA satellite : first alternative to HST parallaxes.

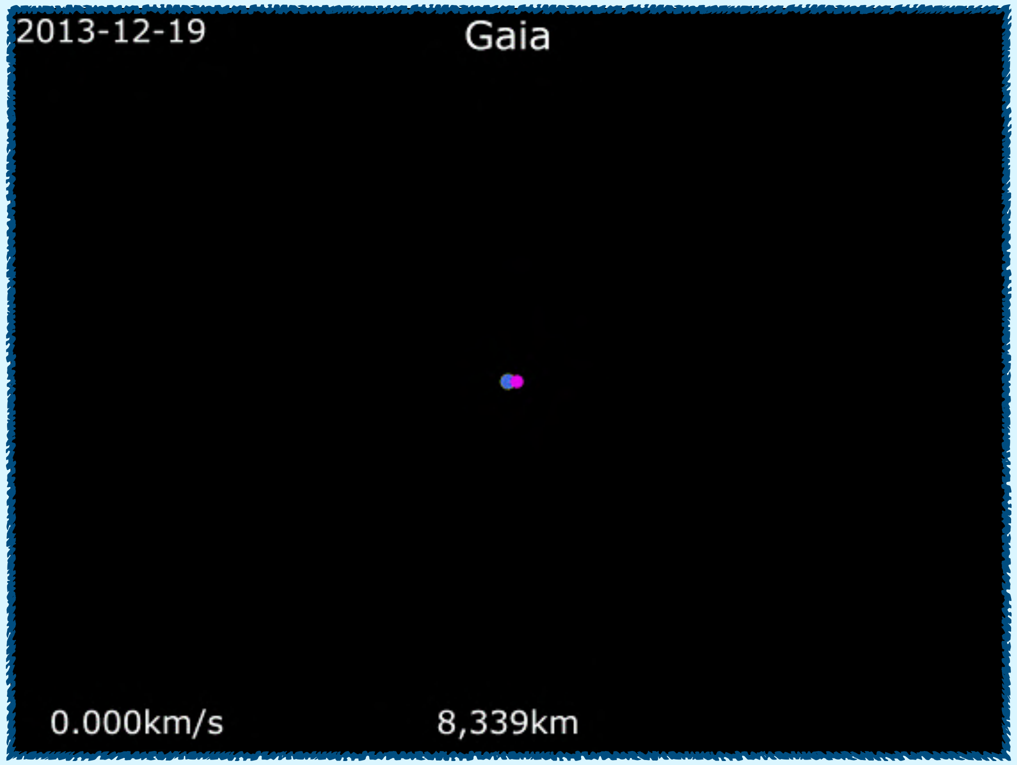


GAIA satellite (ESA)

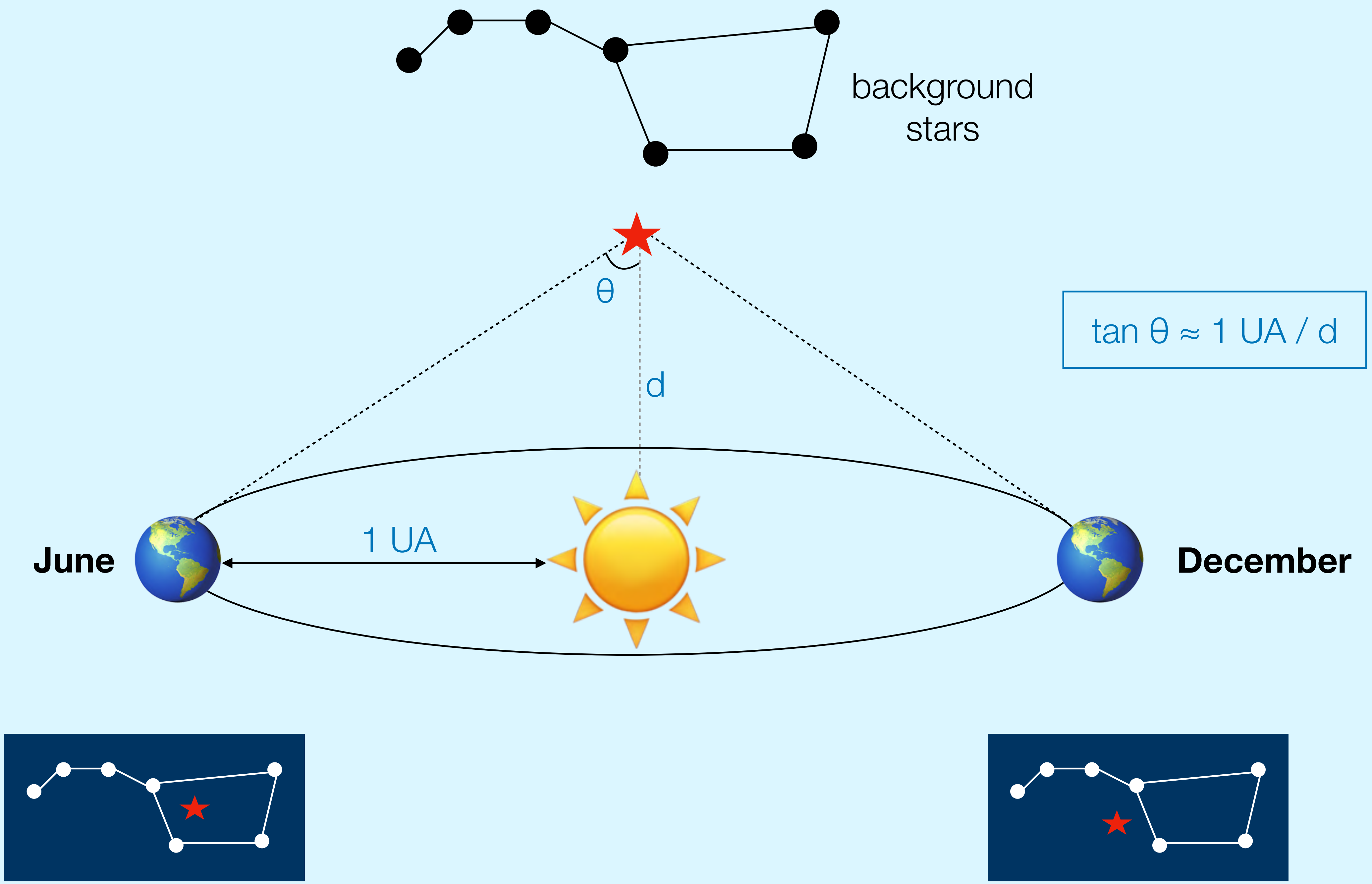
Gaia is a European mission (ESA). The satellite was launched in 2013. It is dedicated to the study of our galaxy, its structure, its composition and our close environment.

- Gaia Data Release 1 (Gaia DR1): September 2016
- Gaia Data Release 2 (Gaia DR2): April 2018
- Early Gaia Data Release 3 (Gaia e-DR3): **3 December 2020 !**

Gaia under construction at ESA



Gaia's trajectory viewed from the Sun



Parallax method

2. Parallaxes and the Gaia satellite

Issue 1:

The value of the Gaia DR2 parallax zero-point (ZP_{GDR2}) is still uncertain.

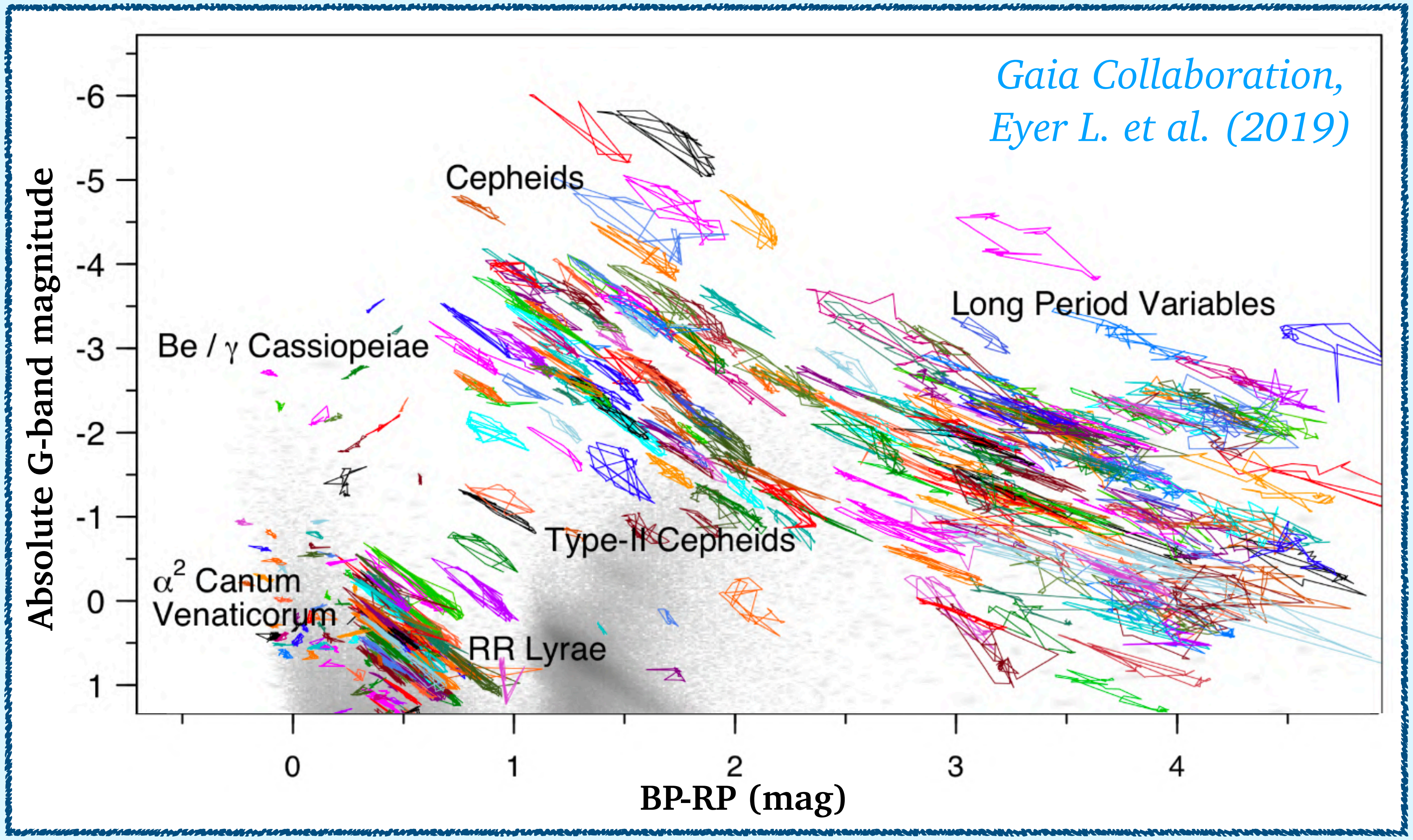
Recent estimates of the Gaia DR2 parallax zero-point

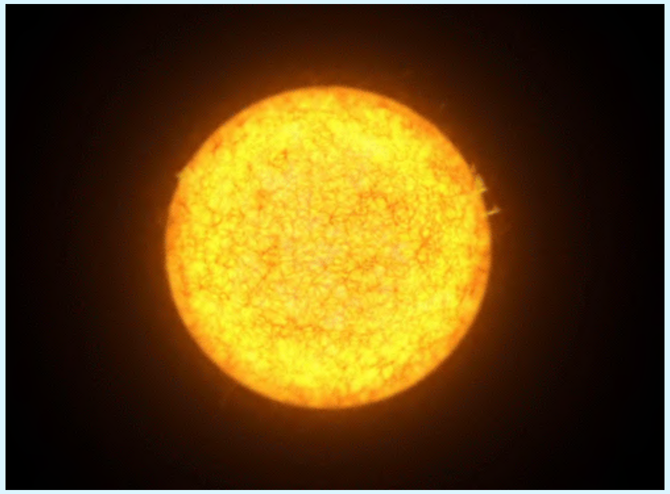
ZP_{GDR2} (mas)	Reference	Type of sources	Typical G (mag)
-0.029	Lindegren et al. (2018)	Quasars	19
$-0.031_{\pm 0.011}$	Graczyk et al. (2019)	Eclipsing binaries	9
$-0.0319_{\pm 0.0008}$	Arenou et al. (2018)	MW Cepheids	8
$-0.035_{\pm 0.016}$	Sahlholdt & Silva Aguirre (2018)	Dwarf stars	9
$-0.041_{\pm 0.010}$	Hall et al. (2019)	Red giants	13
$\boxed{-0.046_{\pm 0.013}}$	Riess et al. (2018b)	MW Cepheids	9
$-0.049_{\pm 0.018}$	Groenewegen (2018)	MW Cepheids (HST)	8
$-0.053_{\pm 0.003}$	Zinn et al. (2019)	Red giants	13
$-0.054_{\pm 0.006}$	Schönrich et al. (2019)	GDR2 RV	12
$-0.057_{\pm 0.003}$	Muraveva et al. (2018)	RR Lyrae	12
$-0.070_{\pm 0.010}$	Ripepi et al. (2019)	LMC Cepheids	15
$-0.082_{\pm 0.033}$	Stassun & Torres (2018)	Eclipsing binaries	9

We adopt ZP_{GDR2} = -0.046 ± 0.015 mas

Issue 2:

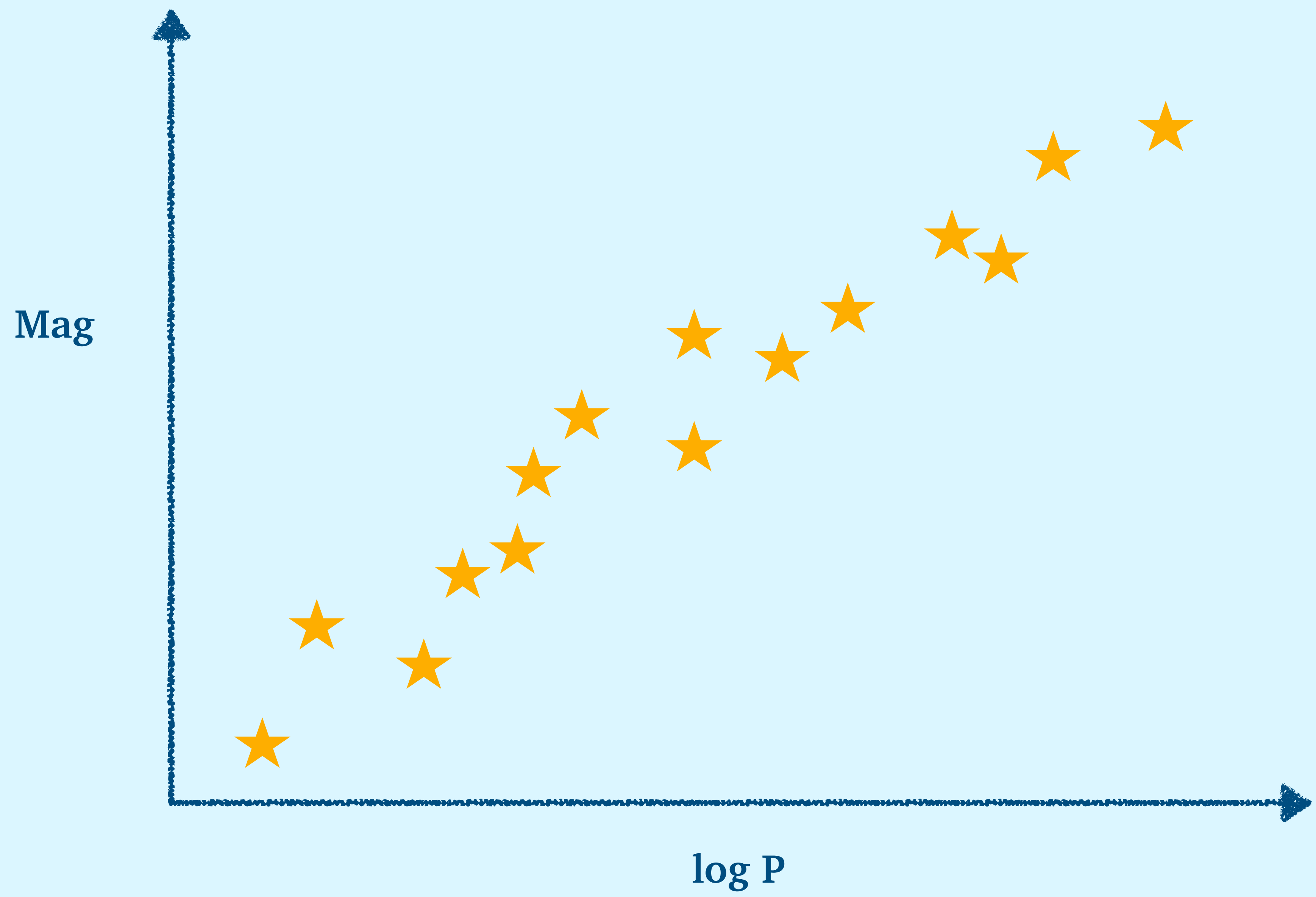
Gaia DR2 parallaxes are derived assuming that the stars have a constant color and a constant brightness.
(Lindegren et al. 2018, Mowlavi et al. 2018)





No chromaticity correction: data reduction **not adapted to variable stars !**
→ Parallaxes of Cepheids are affected by **systematics** and may be **potentially unreliable**.

3. Calibration of the PL relation

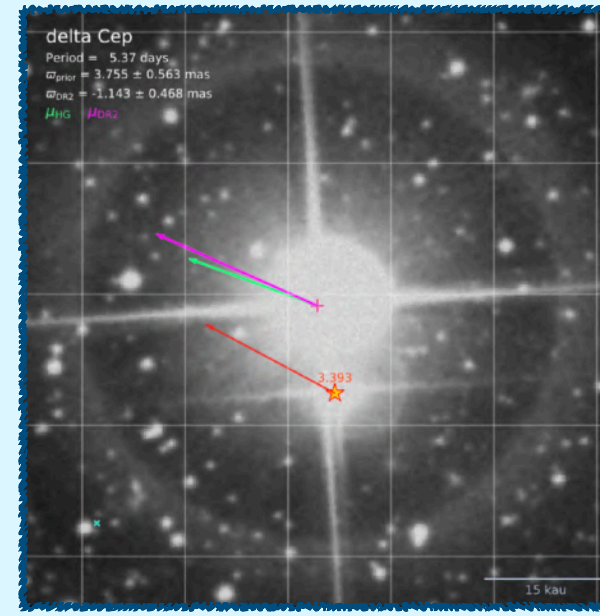


3. Calibration of the PL relation

Gaia DR2 parallaxes of Cepheids are affected by **systematics** and may be **potentially unreliable**.
→ We look for **stable** (non-variable) and **faint** stars in the close neighbourhood of Cepheids.

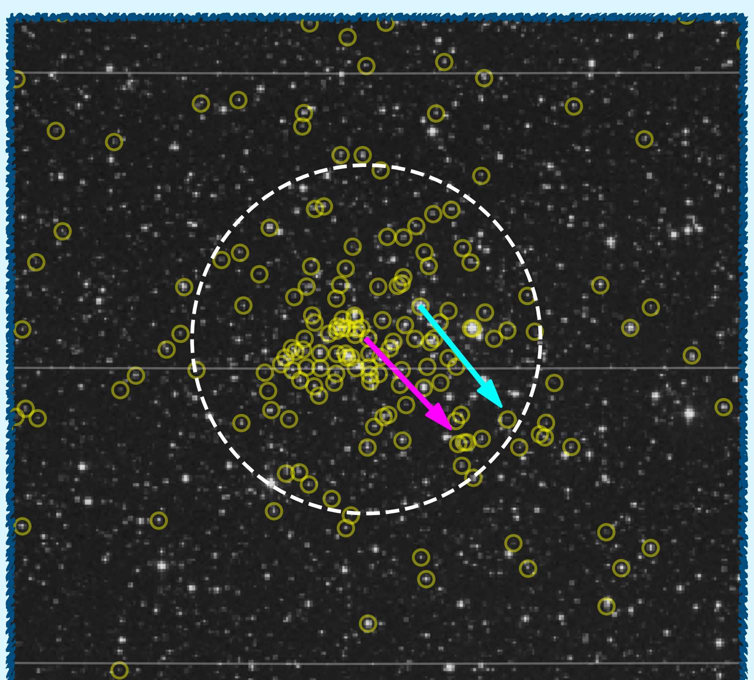
Cepheids with close companions

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



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

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

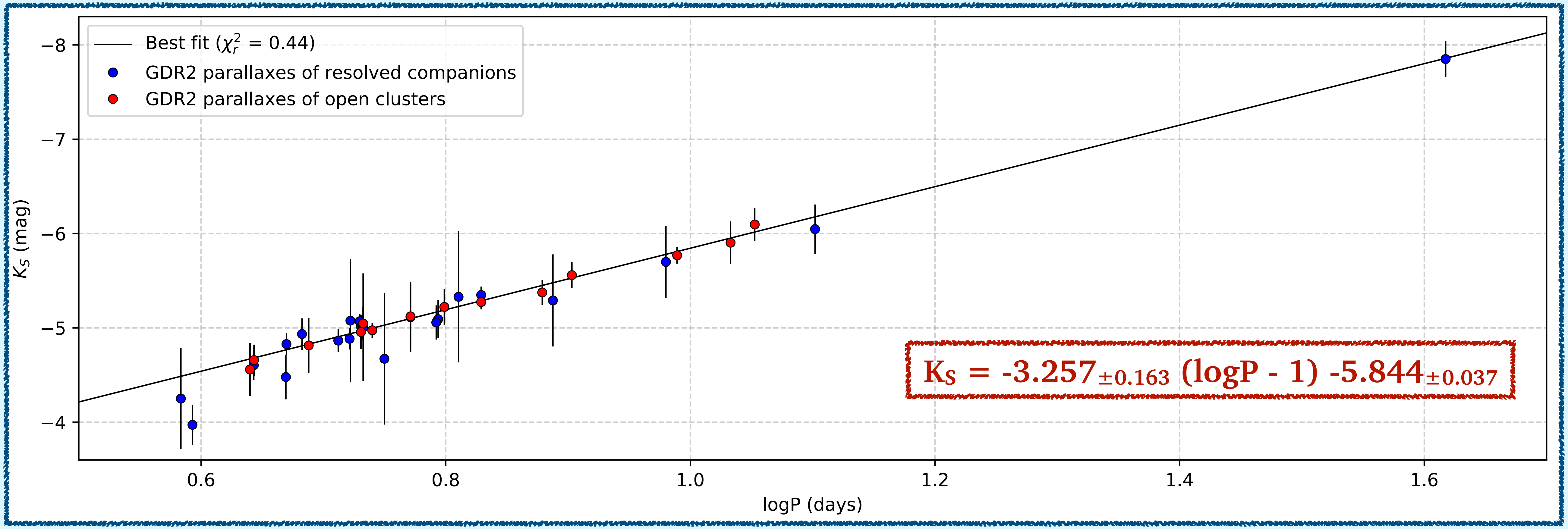


Cepheids in open clusters

- comparison between a catalog of open clusters (Cantat-Gaudin et al. 2018) and Milky Way Cepheids. Cross-match of parallaxes, proper motions and coordinates: **14 candidates**.
- gain in precision by averaging over the cluster members
- members are not variable stars and fainter than Cepheids

3. Calibration of the PL relation

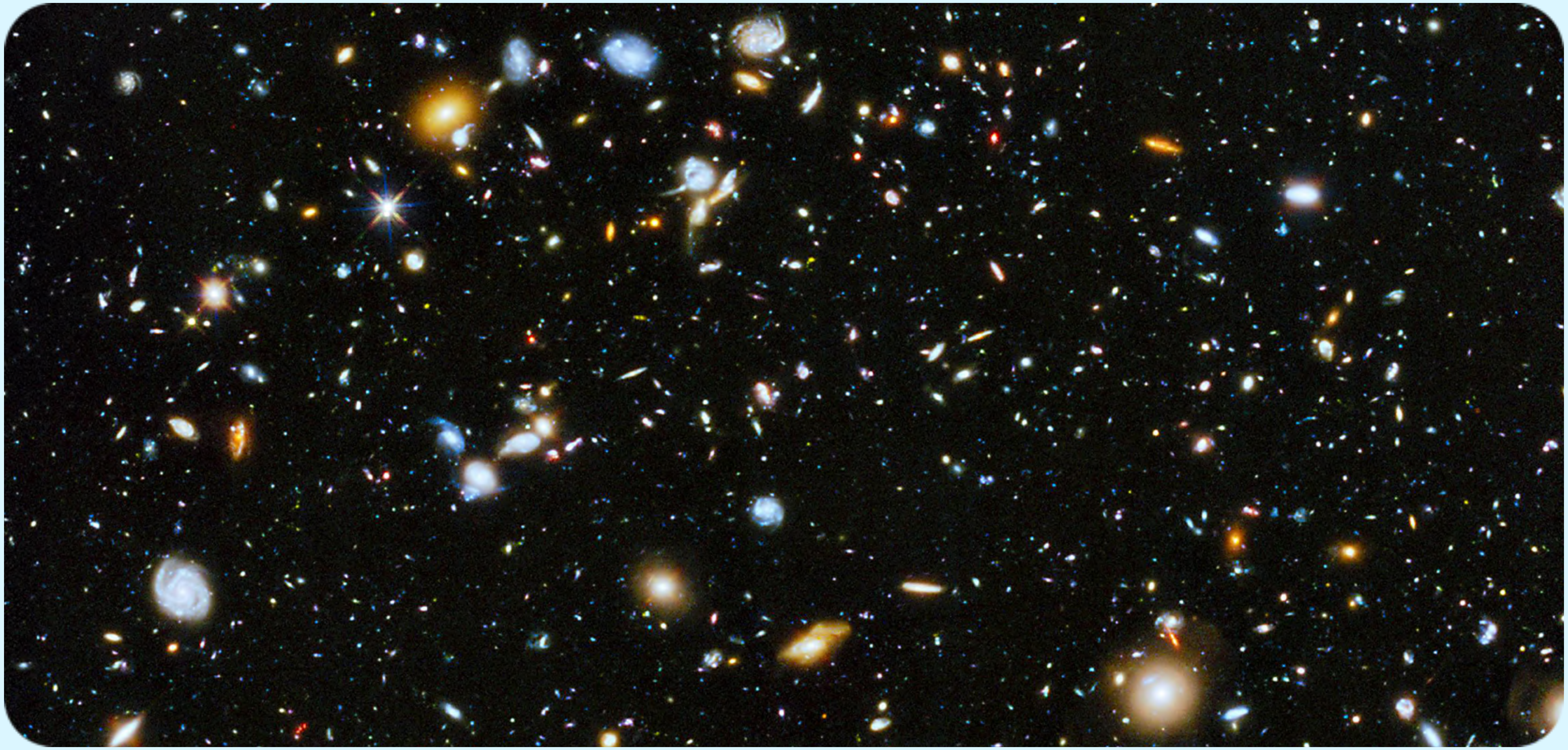
- Mean apparent magnitudes from well-sampled light curves
- Reddening corrections on apparent magnitudes
- Check of pulsation modes and conversion in the fundamental mode
- Gaia DR2 parallaxes of companions and open clusters: application of the Gaia DR2 parallax zero-point (-0.046 ± 0.015 mas)



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

Period-Luminosity relation in the Ks band derived from Gaia DR2 parallaxes of companion stars and open clusters hosting Cepheids (Breuval et al. 2020)

4. Implications on the Hubble constant H_0



4. Implications on the Hubble constant H_0

Anchor(s)	Value ($\mathrm{km\ s^{-1}\ Mpc^{-1}}$)
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
Two Anchors	
NGC 4258 + MW	74.04 ± 1.93
NGC 4258 + LMC	71.62 ± 1.78
Three Anchors (**Preferred**)	
NGC 4258 + MW + LMC	$\mathbf{73.24 \pm 1.74}$

Best estimates of H_0 from Riess et al. (2016), based on several anchors

4. Implications on the Hubble constant H_0

Riess et al. (2016)

15 parallaxes of Milky Way Cepheids
HST/FGS, HST/WFC3, *Hipparcos*

$\mathbf{H_{0,\,R16} = 76.18 \pm 2.37}$ **km/s/Mpc**

Breuval et al. (2020)

22 parallaxes of Cepheids companions
14 parallaxes of open clusters hosting Cepheids
Gaia DR2

$\mathbf{H_{0,\,B20} = ???}$

Rescale of the Milky Way Hubble constant: $H_{0,\,B20} = (\pi_{B20} / \pi_{R16})\, H_{0,\,R16}$

$$\boxed{H_{0,\,B20} = 72.76 \pm 1.86_{\text{(statistics, systematics)}} \pm 1.89_{\text{(ZP)}}\ \text{km/s/Mpc}}$$

→ Still large error because of the uncertainty on the Gaia DR2 parallax zero-point.
→ New value in better agreement with the other anchors estimations from R16

NGC 4258: Masers	72.25 ± 2.51
MW: 34 Gaia DR2 parallaxes (Breuval+ 2020)	72.76 ± 2.65
LMC: 8 Late-type DEBs	72.04 ± 2.67
M31: 2 Early-type DEBs	74.50 ± 3.27

4. Implications on the Hubble constant H_0

- Using Gaia DR2 parallaxes of **companions** and **open clusters** instead of Cepheids parallaxes allows us to :

  → bypass the systematics on GDR2 Cepheids parallaxes
  → calibrate the PL relations with non-HST parallaxes

- We revise the Milky Way value of the Hubble constant by using our sample of Gaia DR2 parallaxes instead of previous non-Gaia parallaxes (mostly HST). From an initial value of **76.18** km/s/Mpc (Riess et al. 2016), we obtain **72.8** km/s/Mpc.

- We need to investigate the metallicity effect on PL relations !

- We expect the Gaia DR3 to :

  → provide a precise (and smaller) value of the parallax zero-point
  → provide more accurate parallaxes for Cepheids (but still no chromaticity corrections)


Thank you !
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Breuval et al. (2020), Accepted in A&A, arXiv:2006.08763