The Hubble constant tension: The Cepheids' point of view

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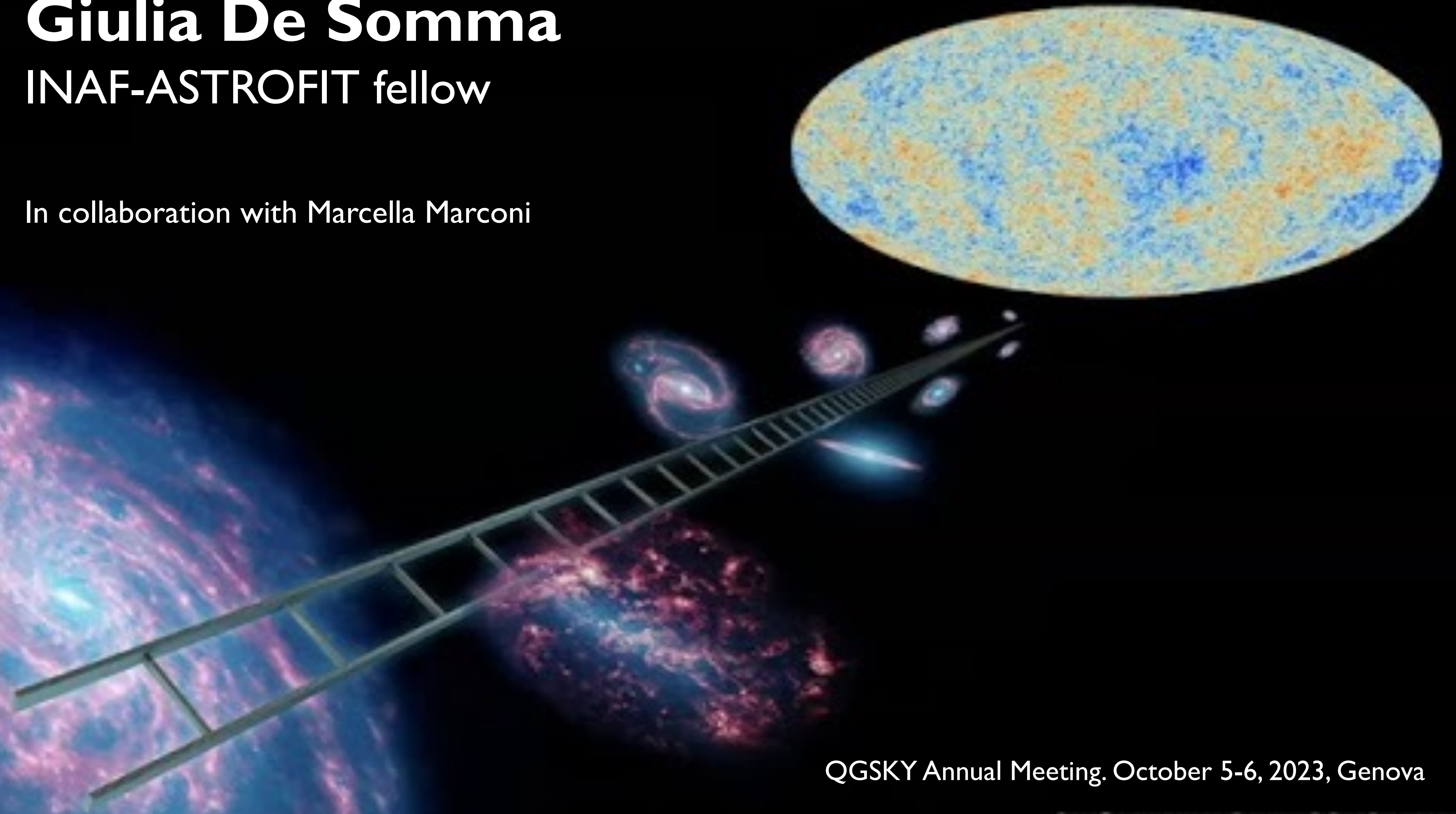
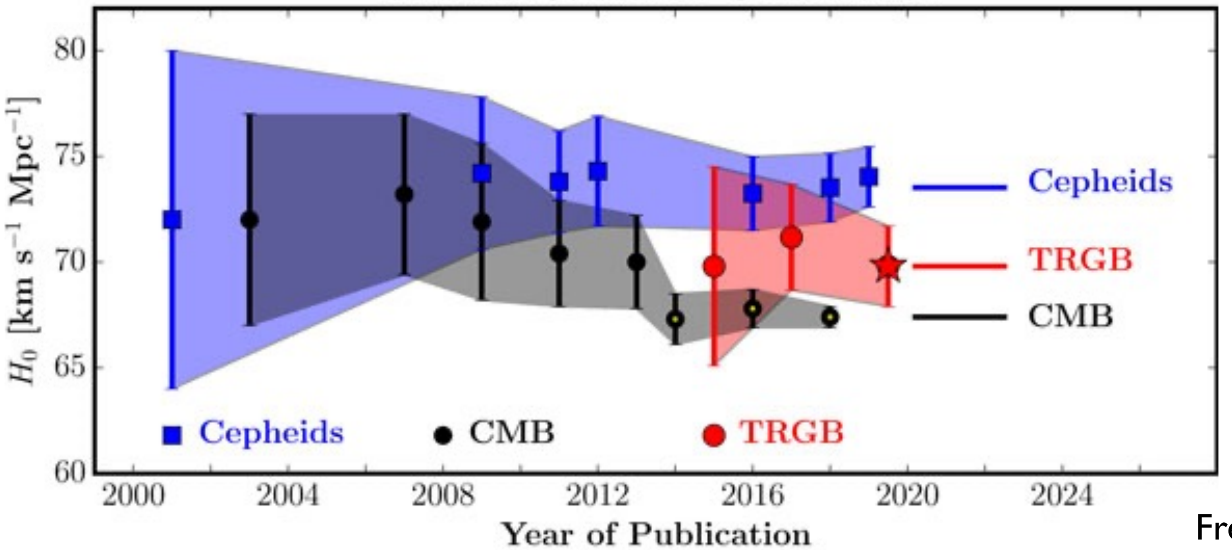


QGSKY Annual Meeting. October 5-6, 2023, Genova

The Hubble Constant Tension



Freedman et al., 2020

$\mathbf{H_0}$ = 73.04 ± 1.4 km s^{-1} Mpc^{-1} (Riess et al. 2022)

vs

$\mathbf{H_0}$ = 67.7 ± 0.4 km s^{-1} Mpc^{-1} (Planck collaboration, 2020)

↓

5σ tension between the early and late Universe H_0 measurements

↓

Systematic uncertainties

in the calibration of the extragalactic distance scale based on CCs

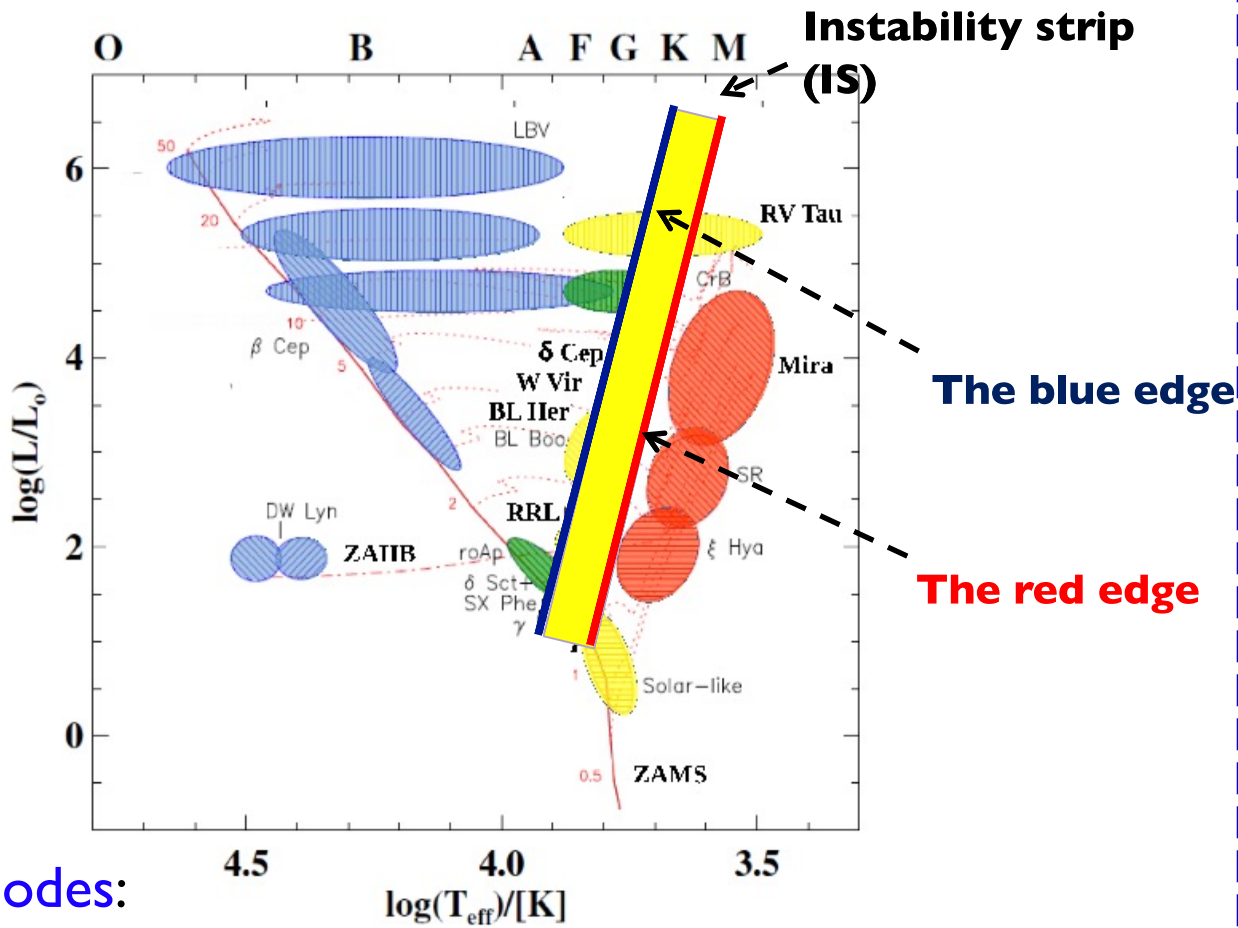
or

new physics?

Classical Cepheids (I)

Classical Cepheids (CCs) are young and intermediate-mass stars

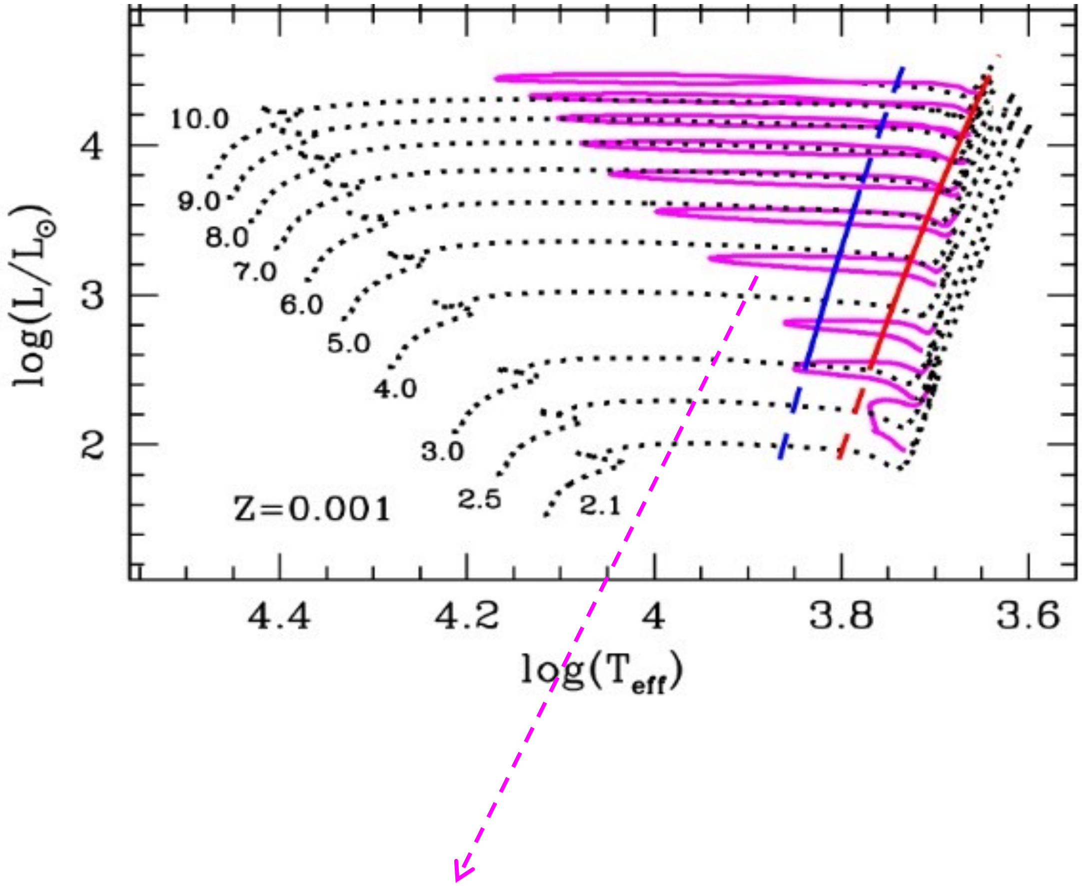
- $1d \leq P \leq 100d$
- $-2mag \leq M_V \leq -7mag$
- $3.0 \leq M/M_{\odot} \leq 13.0$
- t < hundreds of Myr



Pulsation in three radial modes:
Fundamental (**F**),
First Overtone (**FO**)
and Second Overtone (**SO**)

Classical Cepheids (II)

CCs cross the IS three times called FIRST, SECOND, and THIRD CROSSING



Associated with the so-called ***'blue loop'*** evolutionary phase of massive and intermediate-mass stars during the central Helium burning phase.

The Pulsation Relations

Pulsating stars → $P\sqrt{\rho}$= constant + Stefan-Boltzmann law →

P is a function of M, L, and T_{eff} (and chemical composition)

$$\log P = a + b \log T_{eff} + c \log(M/M_{\odot}) + d \log(L/L_{\odot})$$

Classical Cepheid Relations

For the blue loop phase, a **Mass-Luminosity relation** is predicted by stellar evolution

$\log L = a + b \log M + c \log Z + d \log Y$

By inserting the ML relation in the previous PMLT$_{eff}$ → PLC relation

CCs obey a Period-Luminosity-Color (PLC) relations → distances

By averaging over the color extension of the instability strip → PL relation

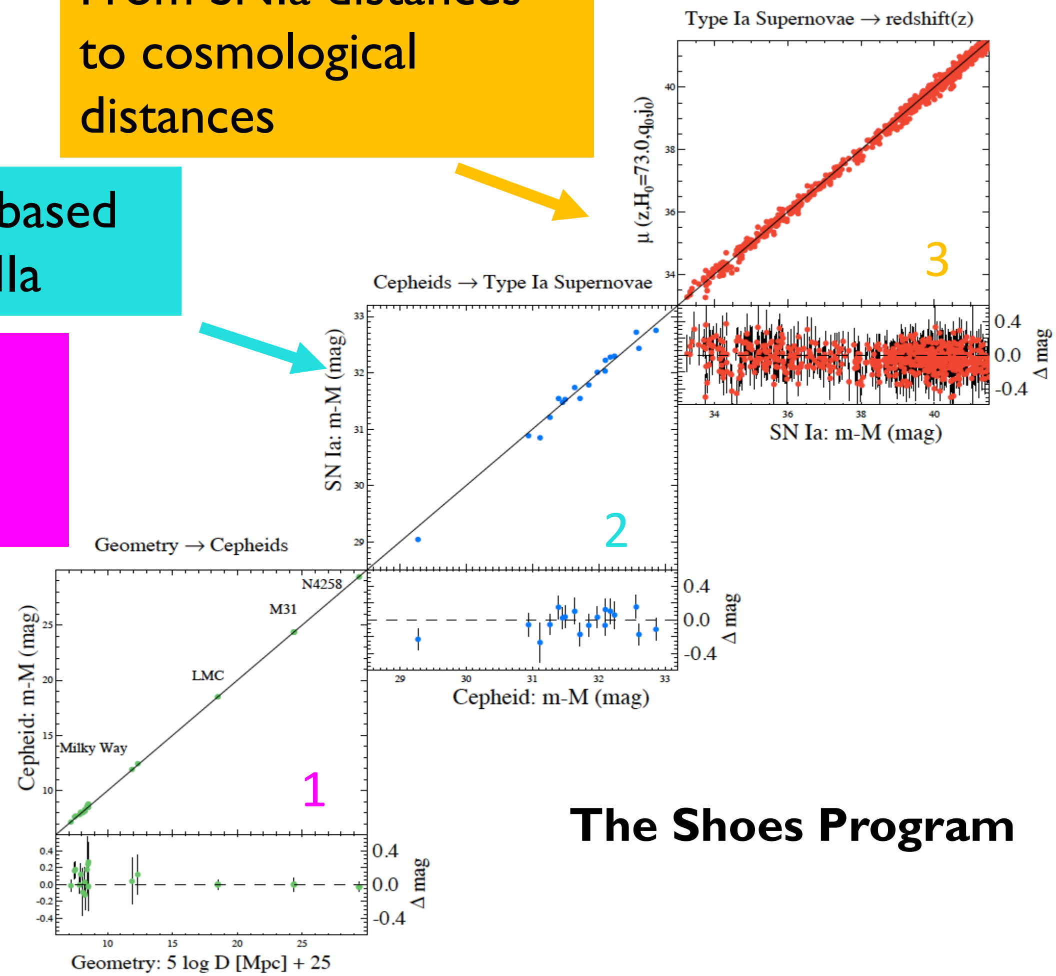
PL and PLC relations make CCs the most used primary distance indicators in the extragalactic distance scale calibration

The Local Universe Measurement of H_0

From SNIa distances to cosmological distances

From Cepheid-based distances to SNIa

From geometric distance to Cepheids

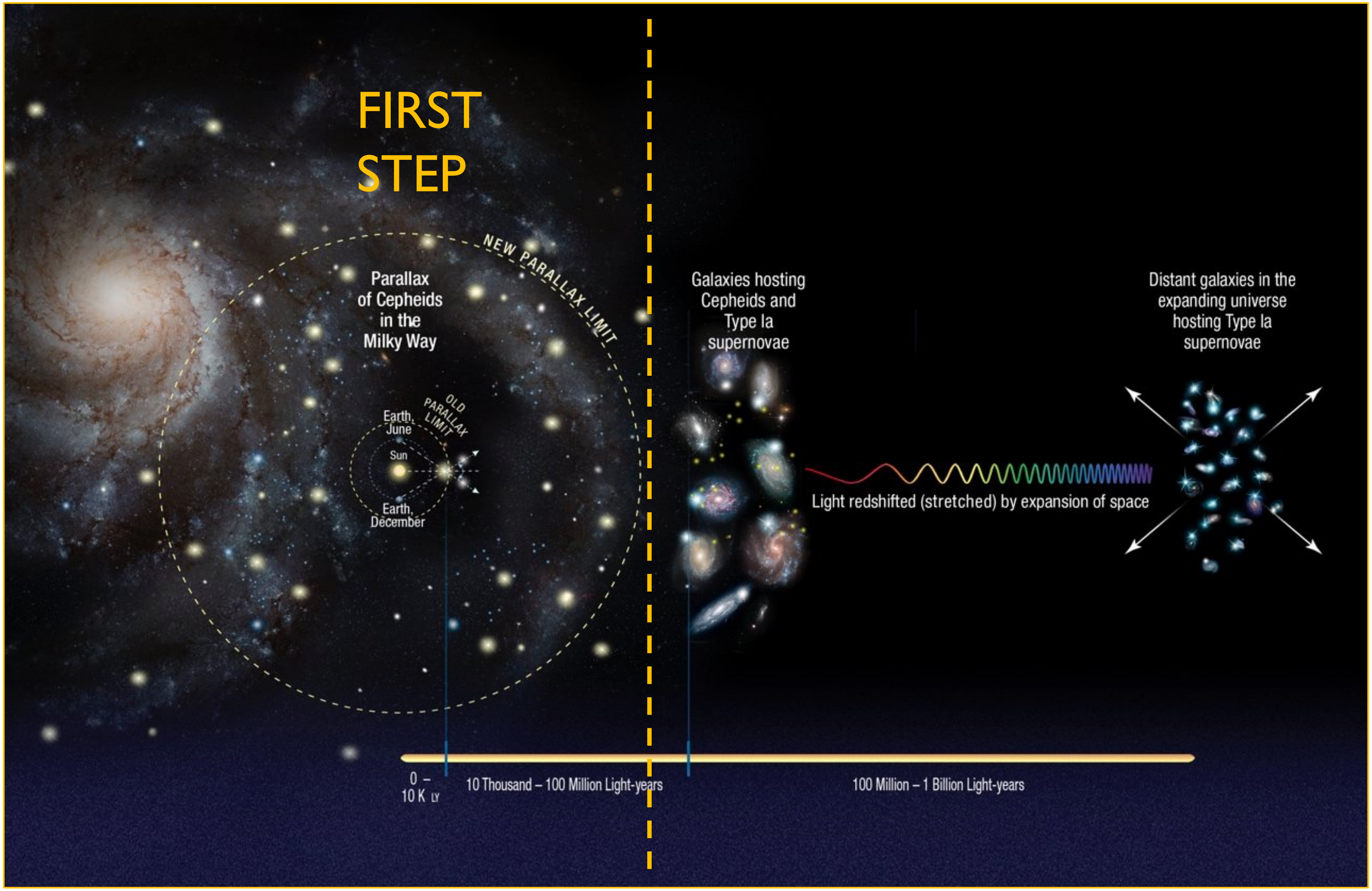


The Shoes Program

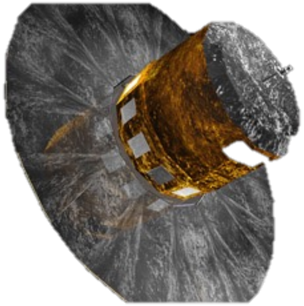
$\mathbf{H_0} = 73.04 \pm 1.4$ km s^{-1} Mpc^{-1} (Riess et al. 2022)

To resolve the tension, studying and removing the systematics affecting each step is fundamental

First Step: The Geometric Calibration of the Cepheid Distance Scale:



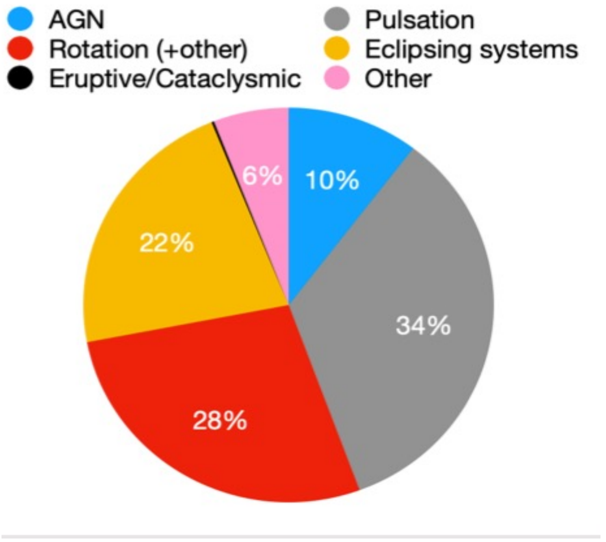
The impact of the ESA Gaia Mission on the first step:



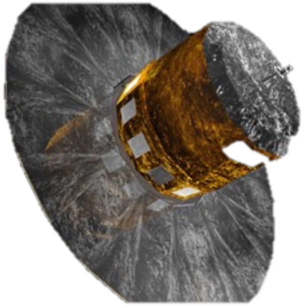
Gaia summary

- Launch December 2013
- Operational at L2 since July 2014
- Astrometry and spectrophotometry (G, G_{BP} , G_{RP}) for > 1 billion objects
- Radial velocities (BP, RP, RVS) for > 100 million objects
- Gaia's end-of-life is estimated at early 2025

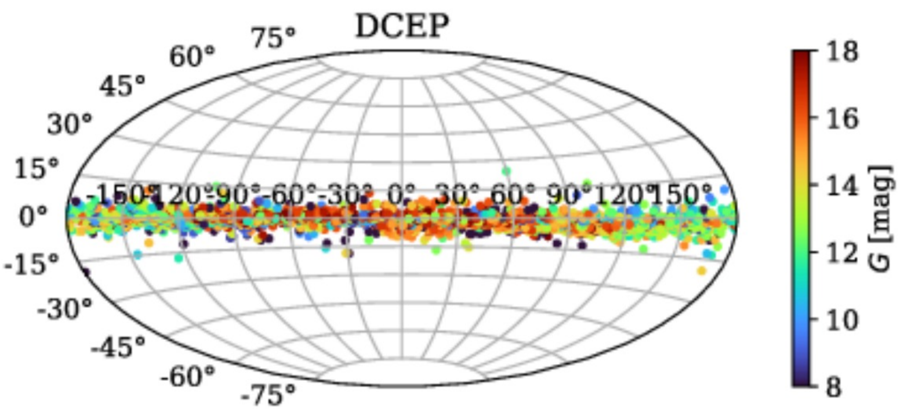
10.5 million variable sources with light curves
24 variable types

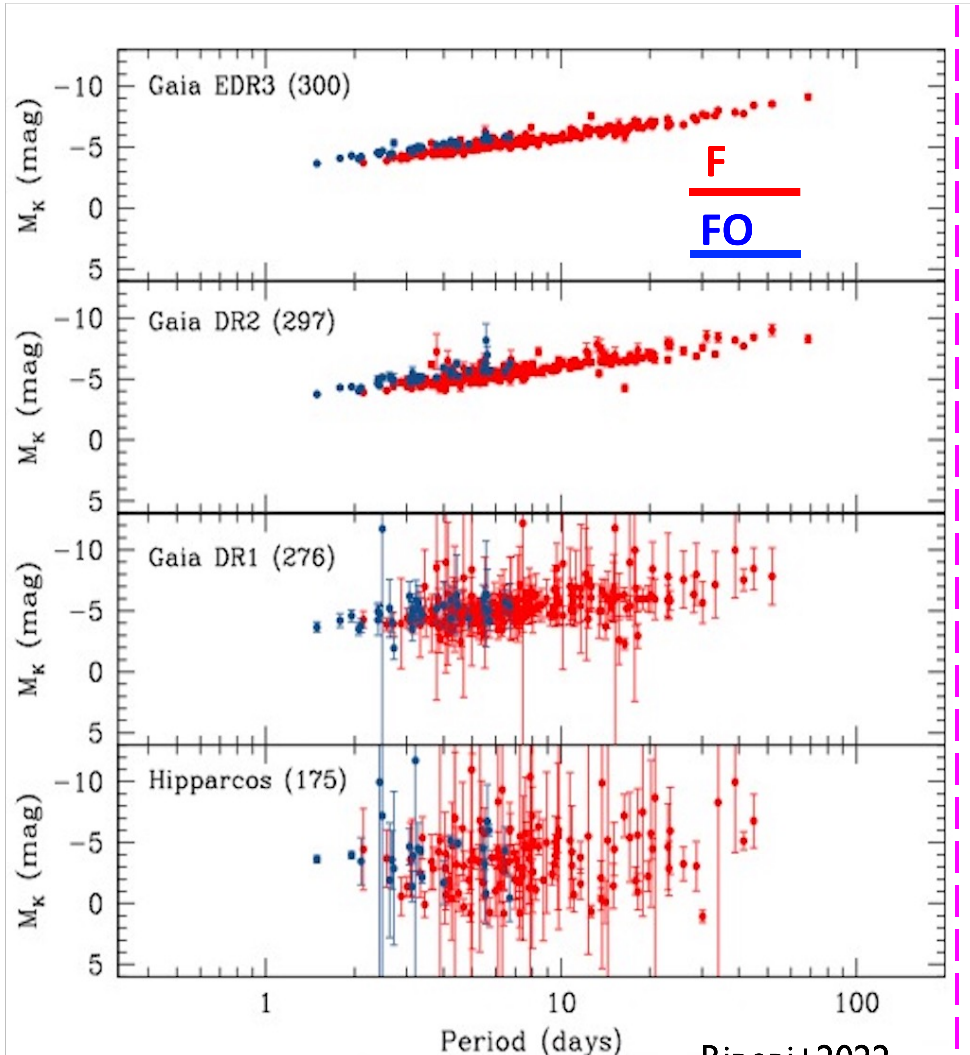


The ESA Gaia Mission Contribution



3,434 MW CCs in Gaia DR3 → largest homogeneous dataset published so far.





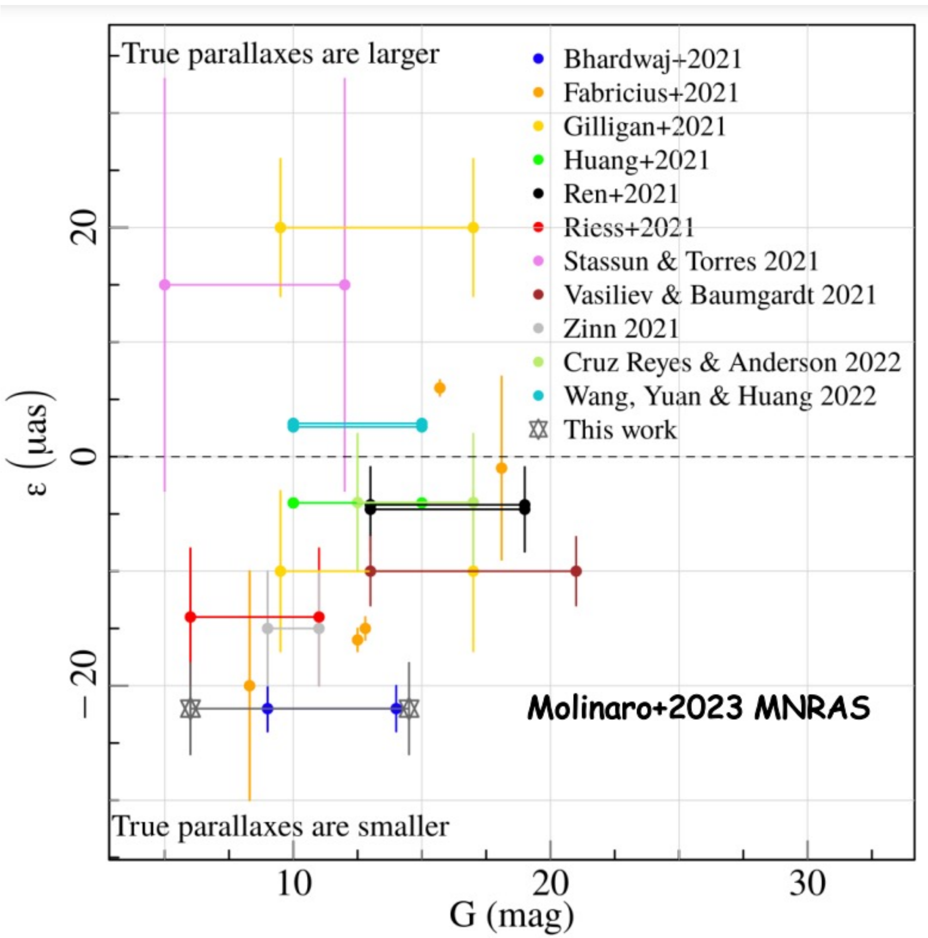
Ripepi+2022

The dispersion of the PL strongly reduces from Hipparcos to Gaia DR1 to Gaia EDR3

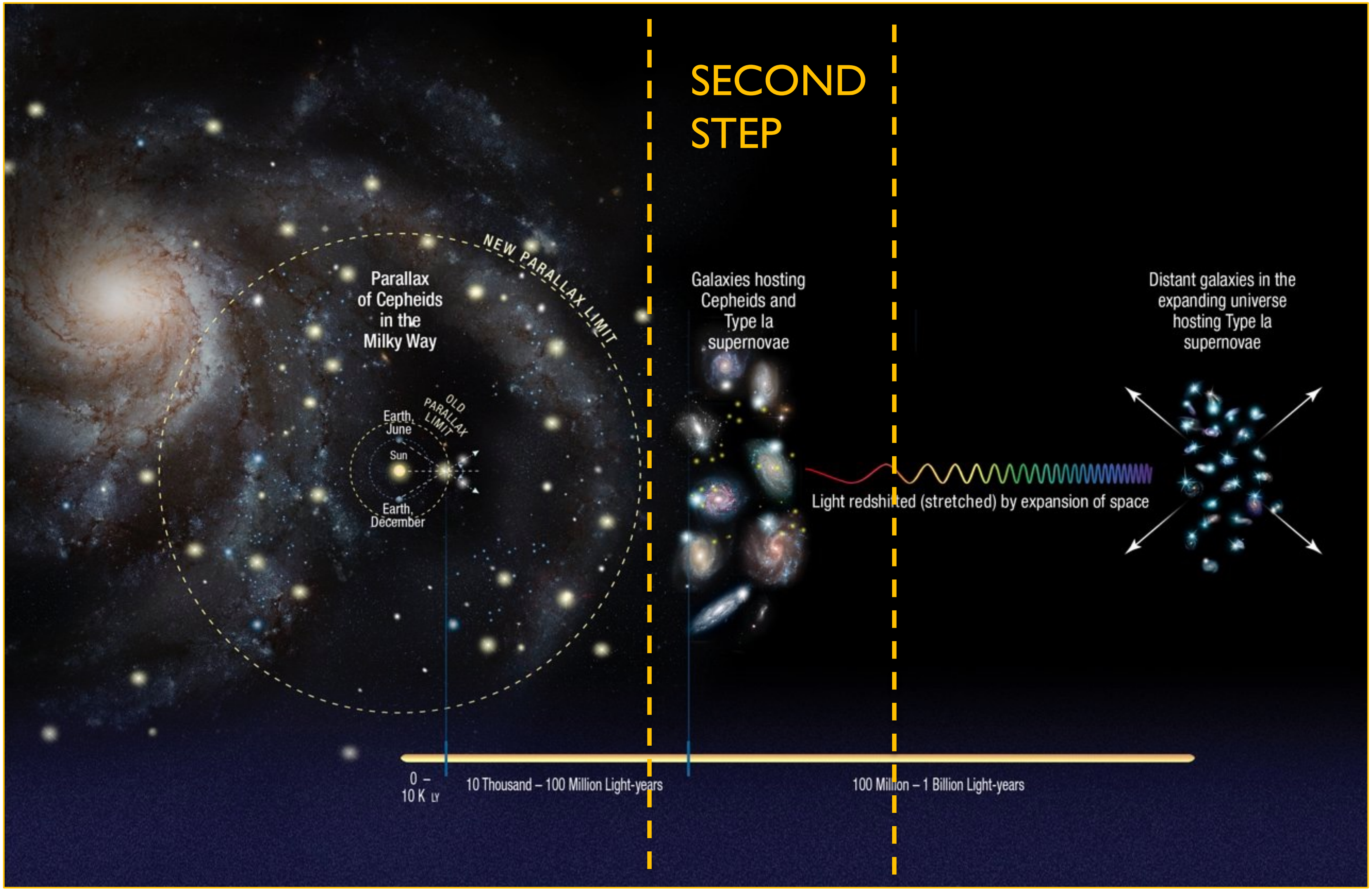
The Gaia Parallax Zero Point Offset

The Gaia parallaxes show an offset of their zero point that depends on source color, magnitude, and position.

This effect will hopefully be reduced in future Gaia data releases.



Second Step: The Calibration of SN1A in Galaxies Containing both CCs and SN1A



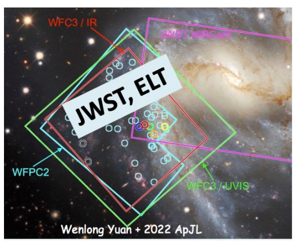
The Systematic Uncertainties Affecting the PL, PLC and PW Relations

- PL intrinsic dispersion
- PL metallicity dependence
- PL nonlinearity

To reduce

↙ ↘

Work into near or mid-infrared filters



Use the PW relation

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

In the B-V color → $W(B-V) = V - \gamma(B-V)$ $\quad \gamma = \dfrac{A_V}{E(B-V)}$

- Dependence of PW on the assumed extinction law (e.g. in PW relations) on the environment

There are systematic uncertainties affecting the Cepheid distance scale related to the hydrodynamical modelling of pulsating stars

Theoretical Approaches to Create a Pulsation Model

❑ 1D pulsation models

○ Linear:

- adiabatic → oscillation period
- nonadiabatic → oscillation period and the blue edge (Anderson et al. 2016, Kovacs&Karamiqucham 2021)

○ Nonlinear:

- radiative → oscillation period, amplitude, blue edge
- convective → period, amplitude, blue edge, red edge, light curves. radius curves, velocity curves
  (e.g. Gehmeyr et al.1990, Bono, Stellingwerf et al. 1994, Yeco 1998, Bono, Marconi, Stellingwerf 1999, Szabo et al. 2000, 2004)

❑ Multidimensional pulsation models

(e.g. *Mundprecht et al. 2013, 2015)*

New Dataset of Nonlinear Convective Cepheid Pulsation Models

By using a nonlinear and convective hydrodynamical code (Stellingwer,1994), I built the most detailed dataset of CC pulsation models

- Wide range of masses and effective temperatures
- 4 chemical compositions
- 3 assumptions about the Mass-Luminosity relation
- 3 values for the efficiency of super adiabatic convection

Low metallicity	**Z=0.004**	**Y=0.25** →	**696 stable F-mode 110 stable FO-mode 3 stable SO-mode**
	Z=0.008	**Y=0.25** →	**639 stable F-mode 126 stable FO-mode 3 stable SO-mode**
Solar metallicity	**Z=0.02**	**Y=0.28** →	**360 stable F-mode 44 stable FO-mode**
Oversolar metallicity	**Z=0.03**	**Y=0.28** →	**127 stable F-mode 4 stable FO-mode**

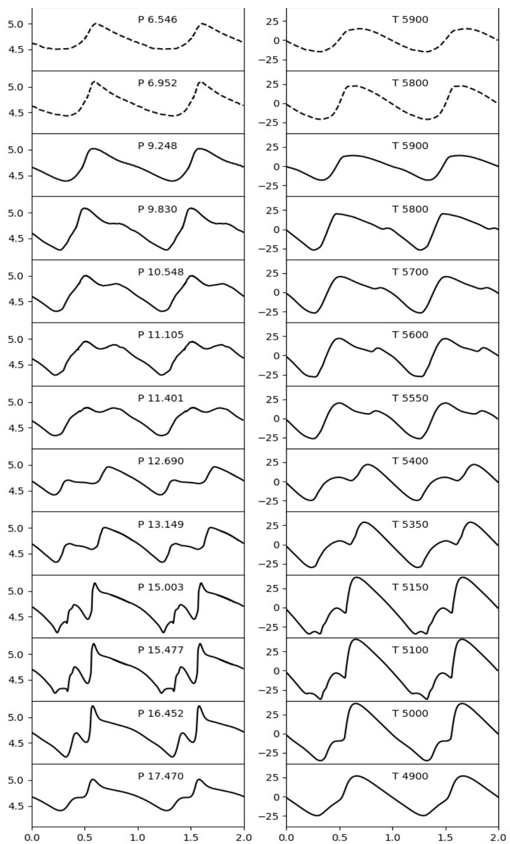
The Atlas of Bolometric Light and Radial Velocity Curves

Canonical ML α=1.5

Z=0.004 Y=0.25

7 $M_\odot$

$-M_{bol}$ (mag) Velocity (Km/sec)

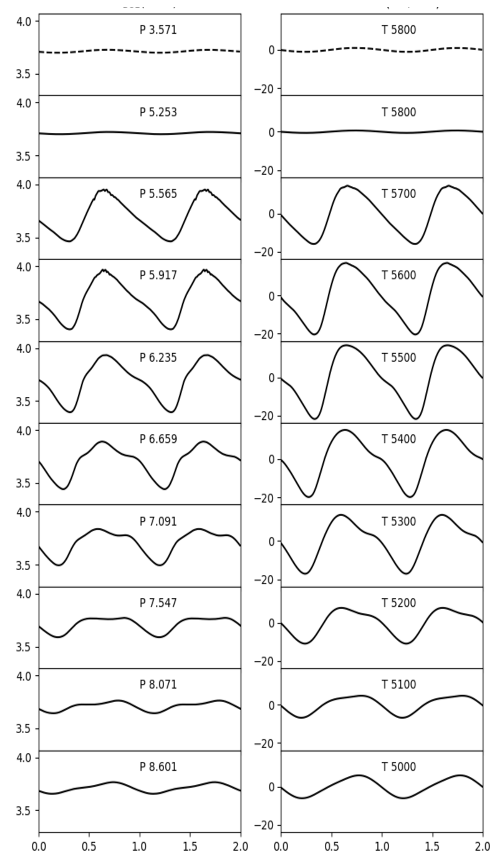


Phase Phase

Z=0.03 Y=0.28

6 $M_\odot$

$-M_{bol}$ (mag) Velocity (Km/sec)



Phase Phase

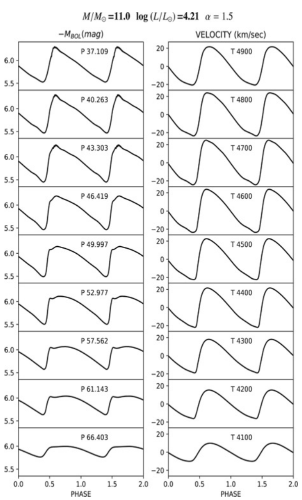
From Bolometric to Gaia, HST-WFC3, Johnson and Rubin-LSST Filter Light Curves

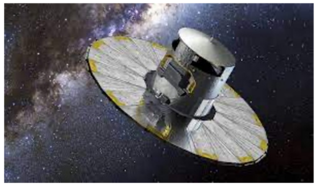
By using bolometric corrections (Chen, Girardi et al. 2019 A&A), the bolometric light curves can be transferred into various photometric system passbands.

Filters:

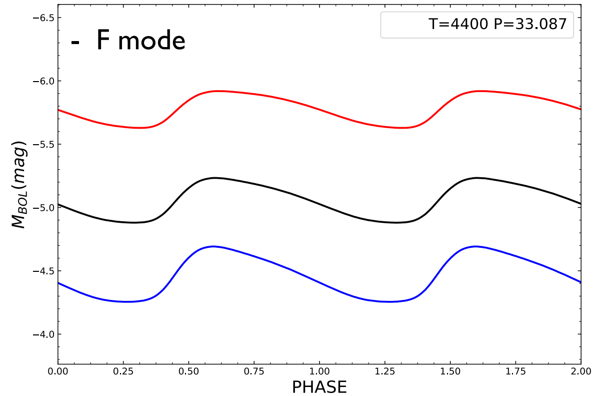
GAIA → G_{BP} (blue line), G (black line), G_{RP} (red line)

RUBIN-LSST → g (blue line) r (green line) i (yellow line) z (orange line) Y (red line)



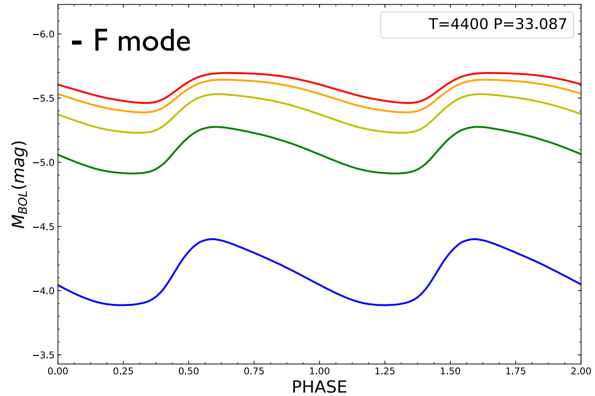


$M=3M_{\odot}$ $\log(L/L_{\odot})=2.32$ $\alpha=1.5$



De Somma et al., 2020, ApJS

$M=9M_{\odot}$ $\log(L/L_{\odot})=3.92$ $\alpha=1.5$



De Somma et al. in preparation

The first theoretical atlas of Gaia and Rubin-LSST light curves

From Gaia, HST-WFC3, Johnson and Rubin-LSST Filter Light Curves to Individual Distances

Nonlinear models

↓

Converted light curves

↓

The intensity weighted mean magnitudes, the pulsation amplitudes, and colors

↓

The theoretical PLC, PW, and PWZ relations

↓

Theoretical distances and parallaxes

The theoretical PLC and PW in the HST and Johnson filters, and

the first PLC and PW in Gaia

PLC →

$$< G >= a + b \log P + c \, (< G_{BP} > - < G_{RP} >)$$

For instance for Z=0.004 ML can and α = 1.5 → <G> = -3.143 – 3.741 + 3.107 (<G_{BP}> - <G_{RP}>)

For instance for Z=0.02 ML can and α = 1.5 → <G> = -3.451 – 3.854 + 3.223 (<G_{BP}> - <G_{RP}>)

PW →

$$< W >=< G > -1.9 < G_{BP} - G_{RP} >= a + b \log P$$

For instance for Z=0.008 ML can and α = 1.5 → <W> = -2.670 – 3.341 logP

For instance for Z=0.03 ML can and α = 1.5 → <W> = -2.779 – 3.264 logP

From De Somma et al., 2020, 2022 ApJS

The metal-Dependent Period-Wasenheit relations

$W = a + b \log P + c\,[Fe/H]$

α_{ml}	ML	a	b	c	σ_a	σ_b	σ_c	σ	R^2
F									
1.5	A	−6.018	−3.314	−0.189	0.009	0.016	0.021	0.118	0.993
1.7	A	−6.072	−3.379	−0.129	0.010	0.016	0.021	0.090	0.996
1.9	A	−6.170	−3.472	−0.245	0.023	0.018	0.040	0.072	0.998
1.5	B	−5.853	−3.234	−0.190	0.011	0.016	0.022	0.139	0.991
1.7	B	−5.871	−3.262	−0.260					
1.9	B	−5.968	−3.370	−0.189					
1.5	C	−5.694	−3.270	−0.105					
1.7	C	−5.722	−3.274	−0.140					
1.9	C	−5.800	−3.327	−0.167					
FO									
1.5	A	−6.676	−3.450	−0.221					
1.7	A	−6.818	−3.627	−0.243					
1.9	A	−6.933	−3.688	−0.349					
1.5	B	−6.634	−3.566	−0.304					
1.7	B	−6.616	−3.533	−0.303					
1.9	B	−6.719	−3.627	−0.304	0.066	0.050	0.068	0.030	0.998
1.5	C	−6.473	−3.510	−0.235	0.043	0.051	0.038	0.038	0.996
1.7	C	−6.486	−3.506	−0.261	0.049	0.056	0.051	0.030	0.998

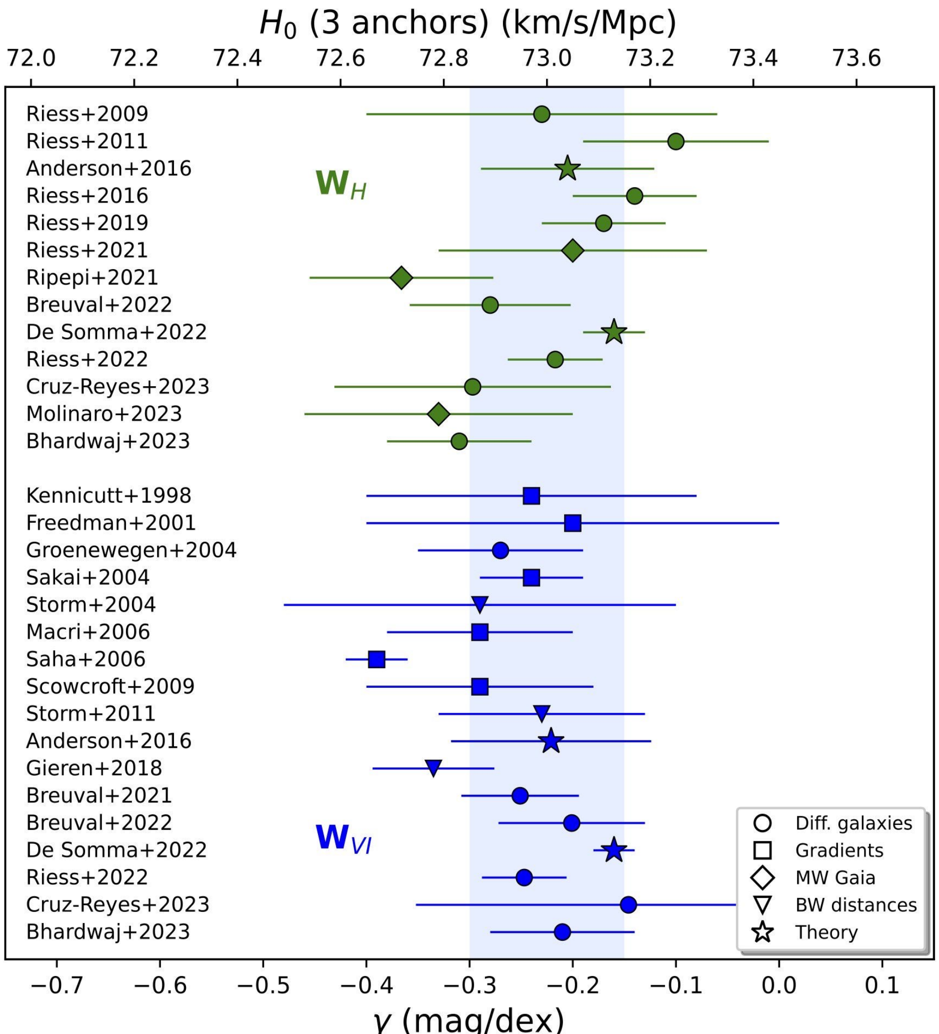
Metal-dependent PW relations point towards a metallicity effect on the zero point varying from ~-0.1 dex to ~-0.2 dex for the F-mode relations and from ~-0.1 dex to ~-0.3 dex for the FO-mode relations.

De Somma et al. 2022 ApJS

At fixed period and color, models predict that more metallic Cepheids are brighter → effect on the distance scale!

The Debated Metallicity Effects of PL and PW Relations

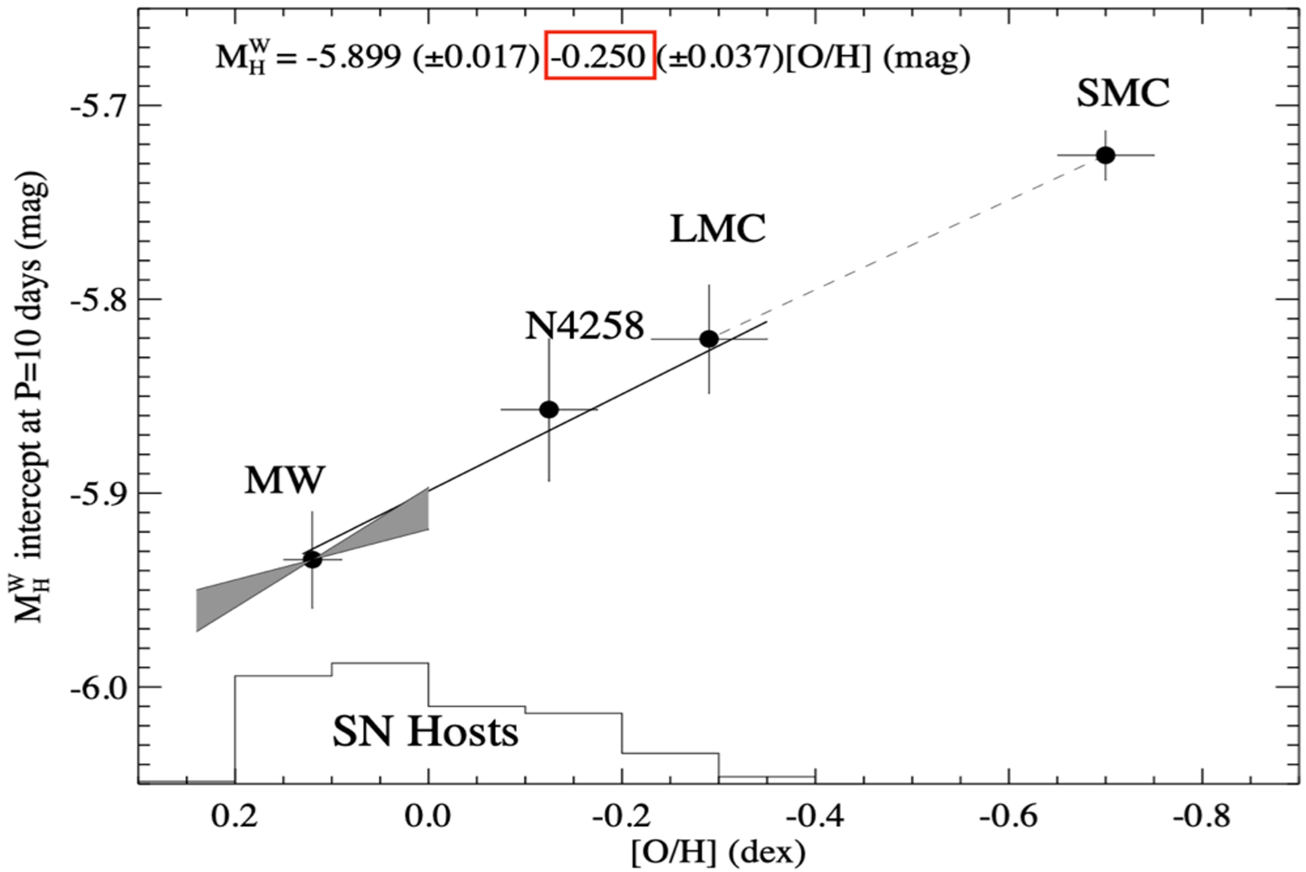
Theoretical vs Empirical metallicity corrections



Credit: L.Breuval

Theoretical and empirical results are in good agreement!!

Metallicity Correction: Small Effect on H_0



Overall, Cepheids in anchor galaxies (MW, LMC, NGC 4258) and in SNIa host galaxies have approximately the same metallicity → according to Riess et al. → no impact on H0

The Role of the Mass Luminosity Relation

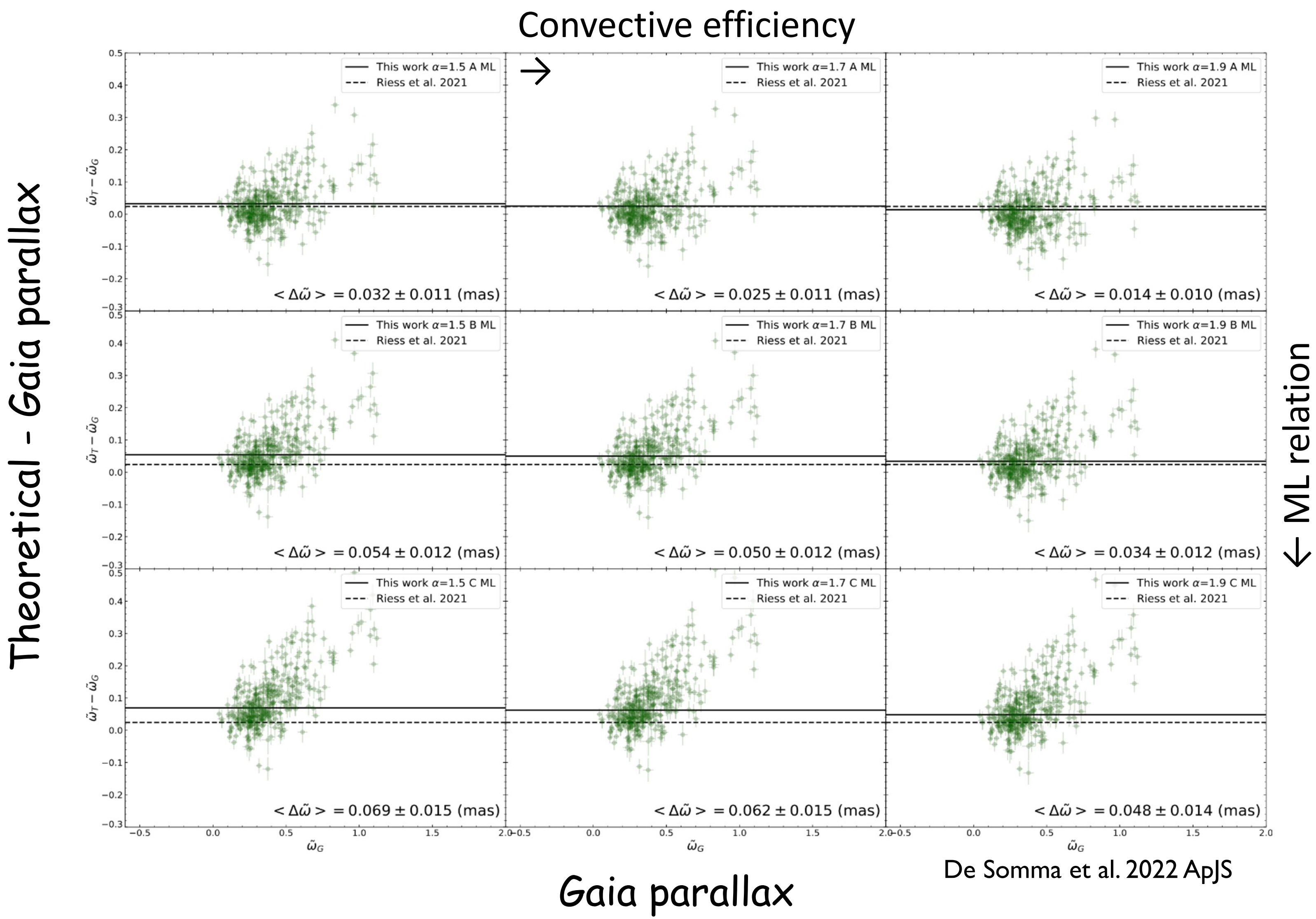
The ML relation theoretically determines the coefficients of the PLC and in turn, PL and PW relations → impact on CC distance determinations → impact on H_0 estimation

Predicted Distance to the Large Magellanic Cloud

Standard ML	μ_{LMC} = 18.67 (0.05) mag
SML + ΔLogL=0.2 dex	μ_{LMC} = 18.56 (0.05) mag
SML + ΔLogL=0.4 dex	μ_{LMC} = 18.40 (0.05) mag

Theoretical versus Gaia parallaxes for Galactic Cepheids (I)

Theoretical parallaxes were obtained by applying the PWZ: W= a + b logP + c [Fe/H]



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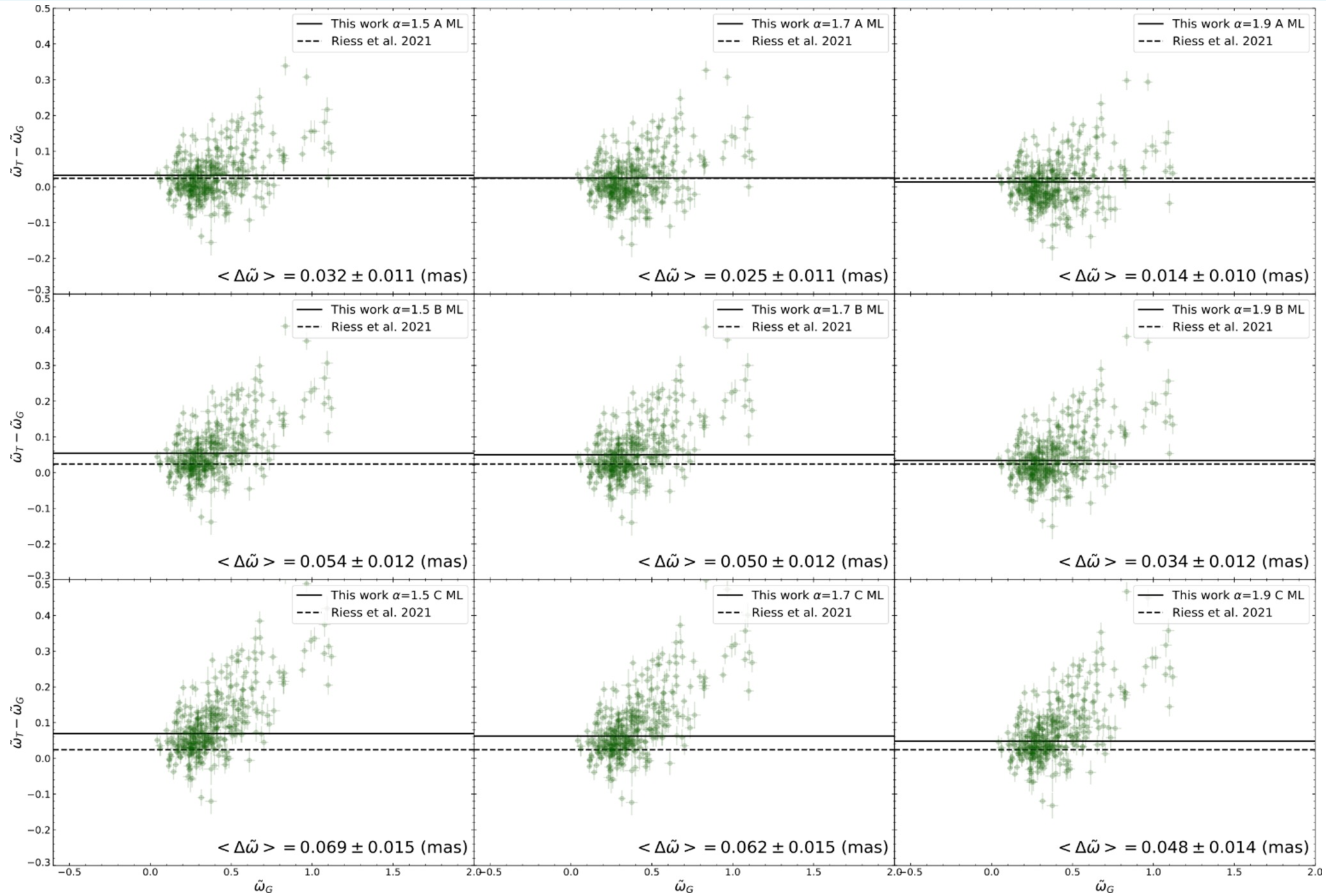
Theoretical versus Gaia parallaxes for Galactic Cepheids (II)

The effect of the ML relation

$$\frac{\Delta\varpi}{\varpi} \sim \frac{\Delta H_0}{H_0}$$

Theoretical - Gaia parallax



← ML relation

Gaia parallax

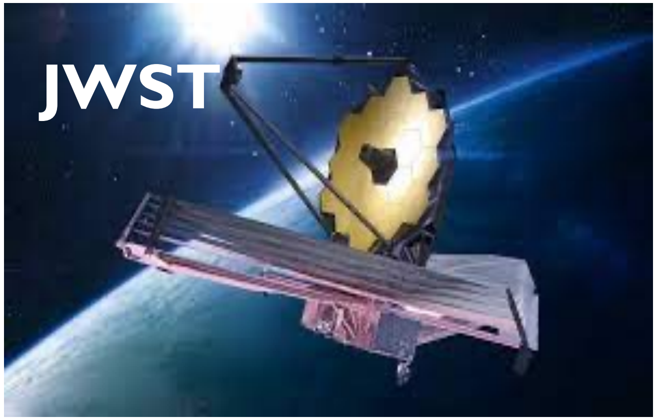
De Somma et al. 2022 ApJS

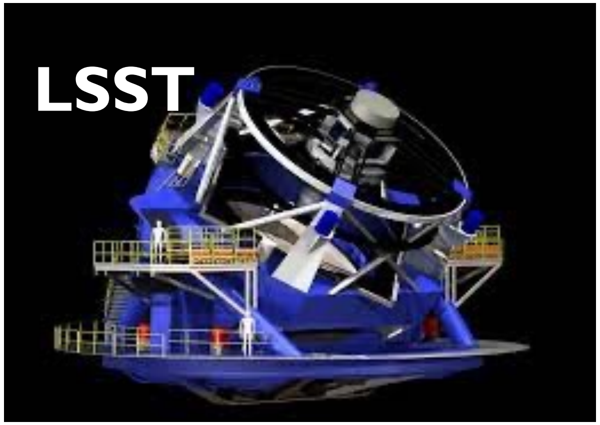
Brighter/fainter ML relation implies a shorter/longer distance scale
→ increase/decrease of H_0

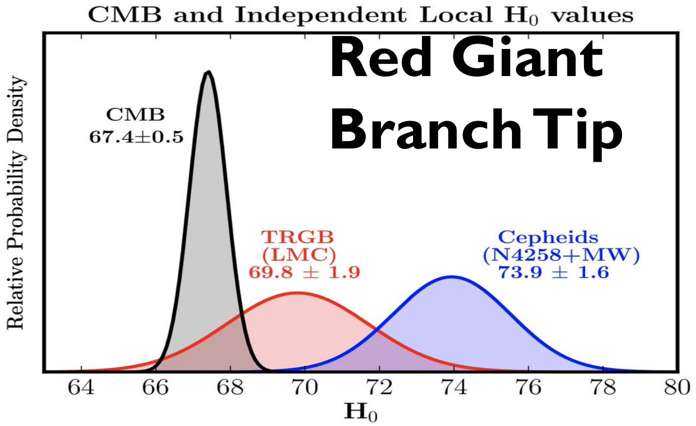
Conclusion

- The Hubble constant tension is one of the most debated topics in both cosmology and astrophysics
- The stellar route is largely based on Classical Cepheids
- Modeling these pulsating stars through nonlinear convective hydrodynamical computations is useful for constraining the residual systematics
- Models predict a dependence of the Cepheid distance scale on metallicity that is consistent with empirical evaluations
- Models suggest that a non-universal ML relationship can have a significant role

Future Perspectives







Any questions, comments, and requests to collaborate are welcome!!!!

Thank you

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