Cosmoverse Workshop@Naples

Type II and Anomalous Cepheids: an alternative route to the Hubble constant

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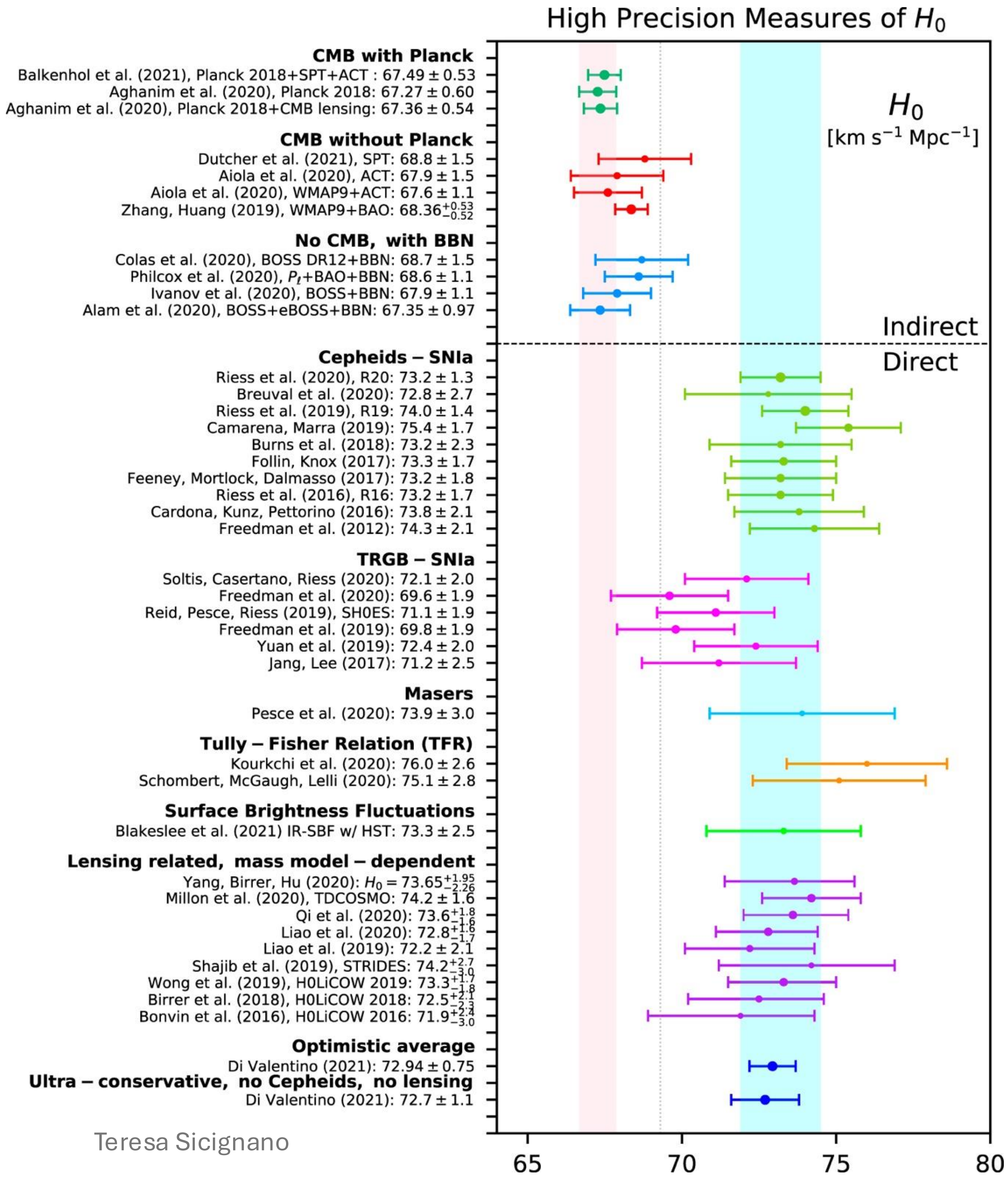
Hubble tension



Di Valentino+2021

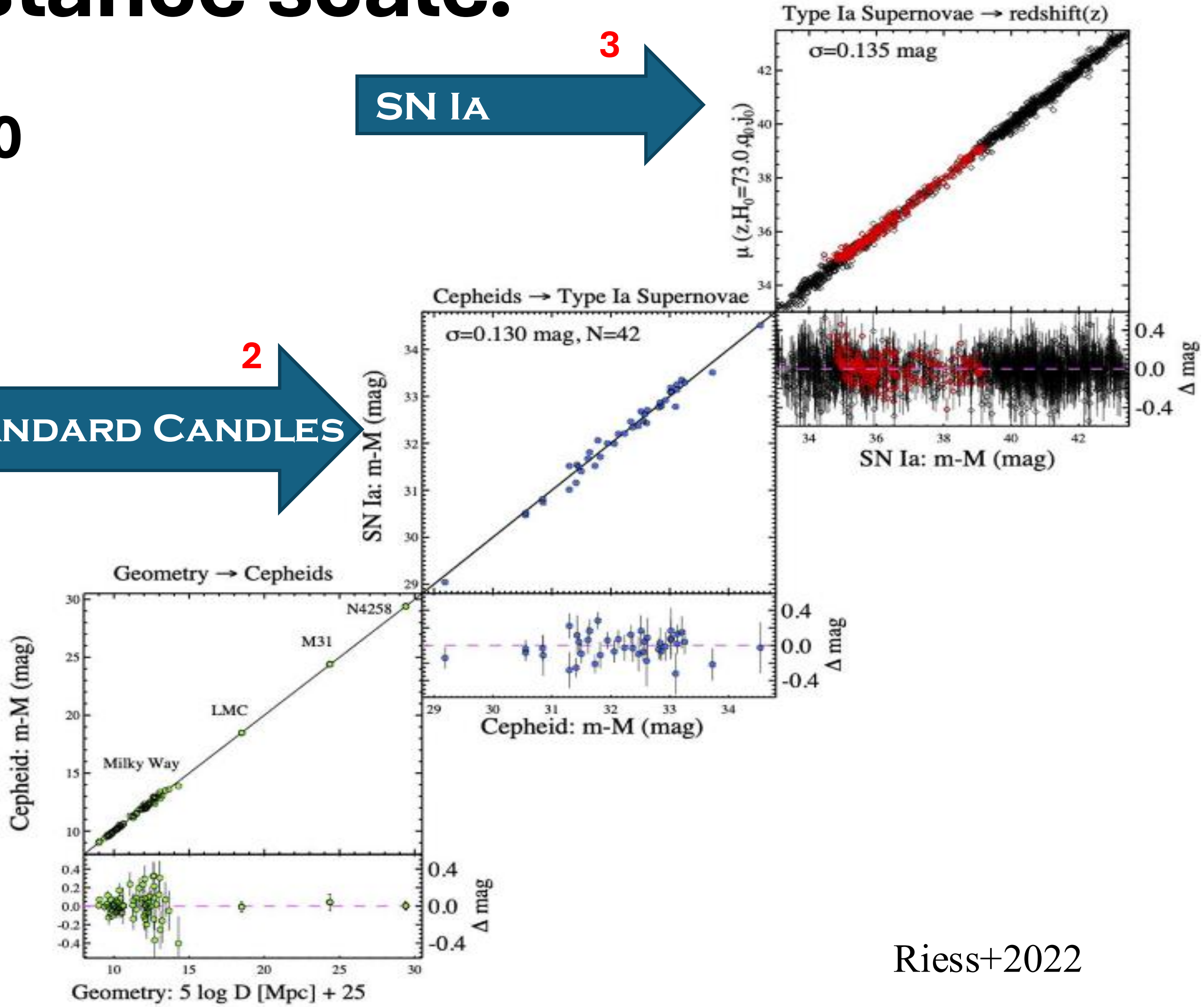
The extragalactic distance scale.
The three steps to H_0

1. Geometric indicators to calibrate the Period-Luminosity (PL) relations of Cepheids
2. PL relations to calibrate the absolute magnitude of the peak luminosity of SN Ia
3. SN Ia distance + recession velocity → H_0

1 GEOMETRY

2 STANDARD CANDLES

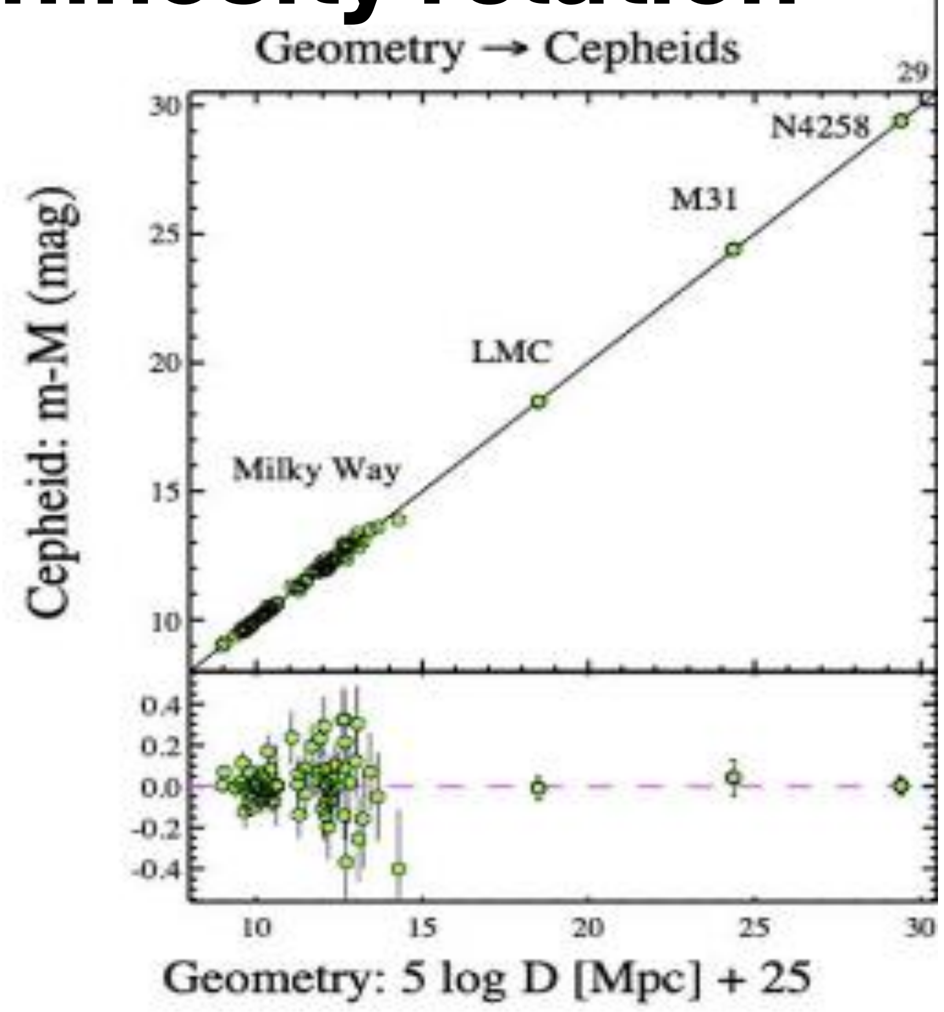
3 SN IA



Riess+2022

The first step to H_0
Period Luminosity relation

1. Geometric indicators to calibrate the Period-Luminosity (PL) relations of Classical **Cepheids**



Riess+2022

Period Luminosity relation

HARVARD COLLEGE OBSERVATORY.

CIRCULAR 173.

PERIODS OF 25 VARIABLE STARS IN THE SMALL MAGELLANIC CLOUD.

The following statement regarding the periods of 25 variable stars in the Small Magellanic Cloud has been prepared by Miss Leavitt.

A Catalogue of 1777 variable stars in the two Magellanic Clouds is given in H.A. 60, No. 4. The measurement and discussion of these objects present problems of unusual difficulty, on account of the large area covered by the two regions, the extremely crowded distribution of the stars contained in them, the faintness of the variables, and the shortness of their periods. As

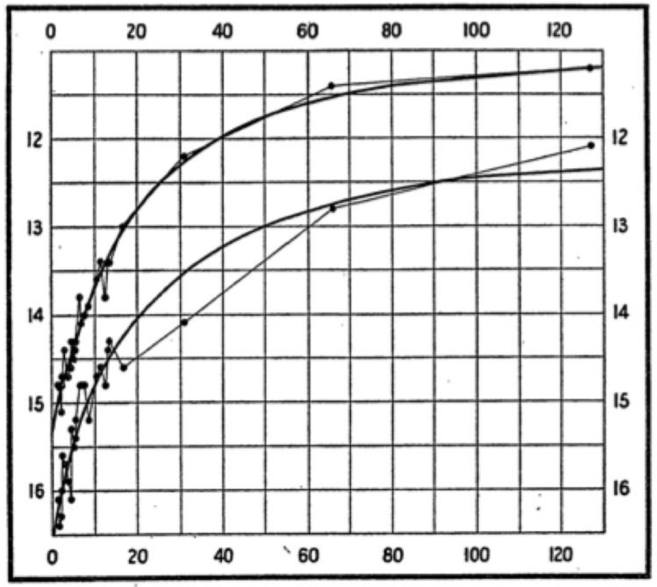


FIG. 1.

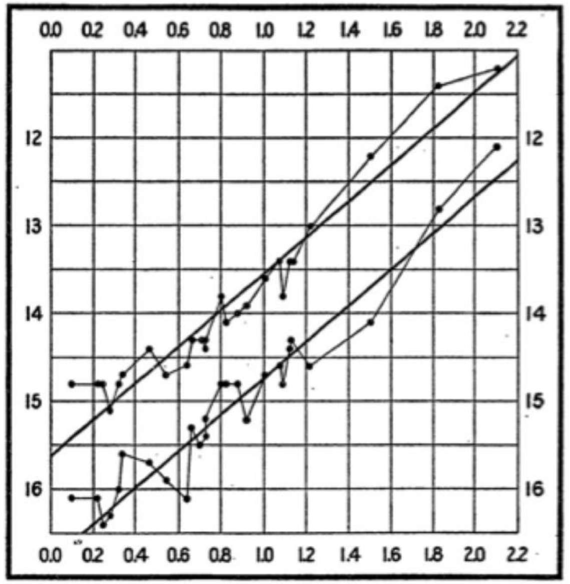


FIG. 2.

has not been published hitherto. A remarkable relation between the brightness of these variables and the length of their periods will be noticed. In

variables alike, is about 1.2 magnitudes. Since the variables are probably at nearly the same distance from the Earth, their periods are apparently associated with their actual emission of light, as determined by their mass, density, and surface brightness.

Leavitt 1912

Period Luminosity in the Great Debate

*Cepheids in Spiral Nebulæ**.

MESSIER 31 † and 33, the only spirals that can be seen with the naked eye, have recently been made the subject of detailed investigations with the 100-inch and 60-inch reflectors of the Mount Wilson Observatory. Novæ are a common phenomenon in M 31, and Duncan has reported three variables within the area covered by M 33 ‡. With these exceptions there seems to have been no

* Abstract of paper read at the Thirty-Third Meeting of the American Astronomical Society. From *Popular Astronomy*, vol. xxxiii. No. 4, April 1925.
† Messier 31 is the Andromeda Nebula.
‡ *Publications of the Astronomical Society of the Pacific*, xxxv. p. 290 (1922).

Tables I. and II. give the data for the Cepheids in M 33 and M 31 respectively. No magnitudes fainter than 19·5 are recorded, because of the uncertainty involved in their precise determinations. The now familiar period-luminosity relation is conspicuously present.

For more detailed investigation of the relation, the magnitudes at maxima have been plotted against the logarithm of the period in days. This procedure is necessary, not only because of the

minations. When this is done, the resulting values of $M - m$ are —21.8 and —21.9 for M 31 and M 33, respectively. These must be corrected by half the average ranges of the Cepheids in the two spirals, and the final values are then on the order of —22.3 for both nebulae. The corresponding distance is about 285,000 parsecs. The greatest uncertainty is probably in the zero point of Shapley's curve.

Hubble 1925

Period Luminosity in the Great Debate

"The Galactic System, of which our Sun is a member, is a flattened swarm of stars. It is quite isolated in space, but men have long supposed that beyond its borders there must be other systems of the same general order of size, separated from one another by immense distances. The spirals and other small symmetrical nebulae were seized upon as visible evidence, and upon them was constructed the grand theory of 'island universes.'

"Recently the great telescopes of modern astronomy have established the reality of this theory. Several of the most conspicuous spirals and irregular nebulae have been partially resolved into swarms of actual stars. Among these stars various types have been recognized which are well known in our own system, such as Novae, Cepheid variables, and Blue Helium stars, all brilliant giants. Assuming that their actual brightness is the same as stars of the same type in our own system, we are able to determine how far they are away by comparing their apparent brightness with what we believe to be their actual brightness."

Hubble, Washington, 1927

A second important method of determining the actual brightness and consequently the distances of far-away stars turns upon an observation made by Miss Leavitt of the Harvard Observatory, developed and applied by Doctor Harlow Shapley, Director of the same Observatory, and hence called the Leavitt-Shapley law. This method is restricted to stars of a certain class, known as Cepheid variables.

These stars pass through definite periods of variation during which the luminosity of each gradually becomes more intense and then gradually weakens. The periods range from less than one day to 100 days, depending upon the individual star. It was observed that among these stars, which are all giant suns much larger than our own, a definite relationship exists between their actual brightness and the period of their variation. That is to say, the brighter the star, the longer it takes to complete its cycle. While astronomers are not clear as to the causes of this remarkable relationship between luminosity and period-variation, they believe that it holds good for all Cepheid variables wherever found. Inasmuch as Doctor Hubble has definitely

Only Period Luminosity?

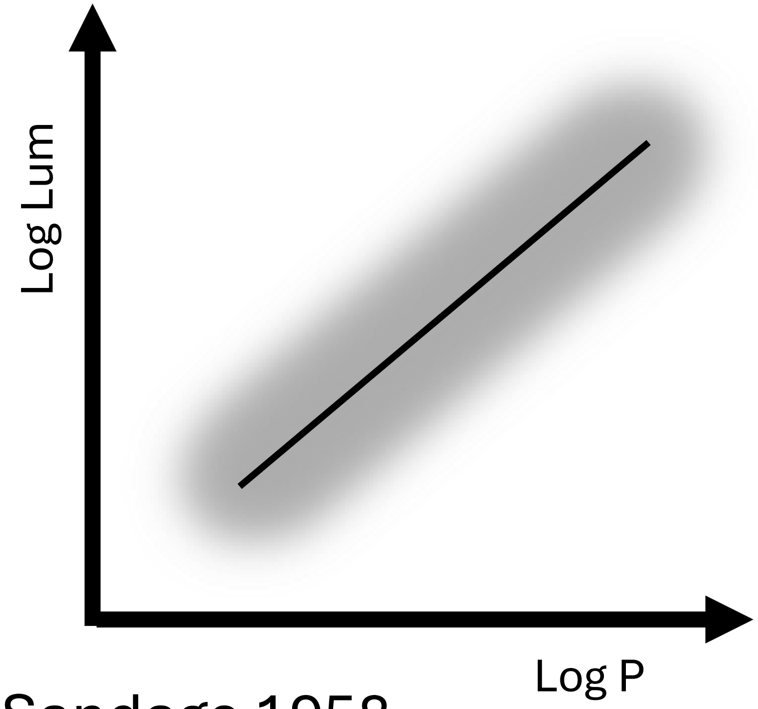
The curve for M 33 appears to be very definite. The average deviation is about 0.1 magnitude, although a considerable systematic error is allowable in the slope. For M 31 the slope is very closely the same but the dispersion is much greater, averaging about 0.2 magnitude. This is probably greater than the accidental errors of measurement.

Hubble 1925

From 1925 to the present day, the period-luminosity (P-L) relation for cepheid variables has been almost exclusively used to find distances to galaxies in the local group (Hubble 1925, 1926, 1929*b*). Justification for its use has always come from the empirical data rather than from theoretical considerations, even though the extensive investigations in the Magellanic Clouds by Shapley, Nail, and collaborators have shown that a large scatter exists in the relation. Most investigators, following Shapley, have usually assumed that the true P-L relation is narrow and that the observed scatter is the result of photometric uncertainties together with the presence of internal absorption in the Clouds. But the possibility exists that the P-L relation is not unique and the scatter real. The first observational data bearing on this point were the precise photometry of

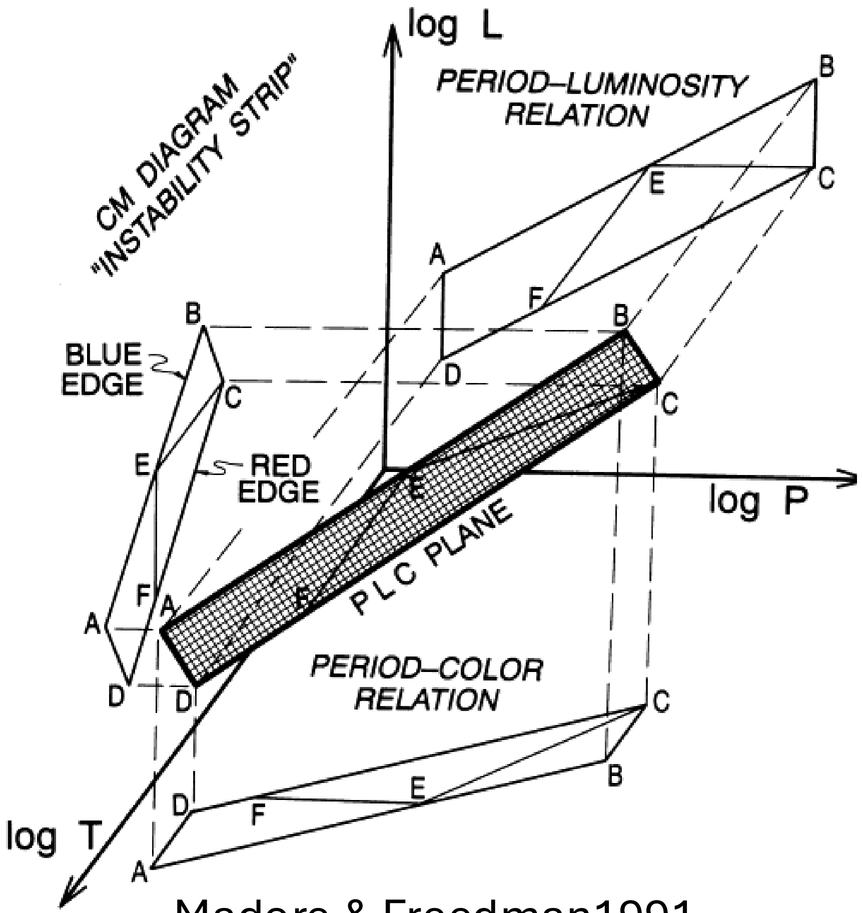
high. The existence of intrinsic scatter in $P = f(L)$ suggests that a third parameter is involved.

In what follows, a semitheoretical relation is found which indeed does involve three parameters. These are P, M_v, and the color $B-V$. The intrinsic scatter predicted by this treatment makes the use of cepheids for distance determinations more difficult than was previously believed.



Sandage 1958

The Period-Luminosity-Color relation



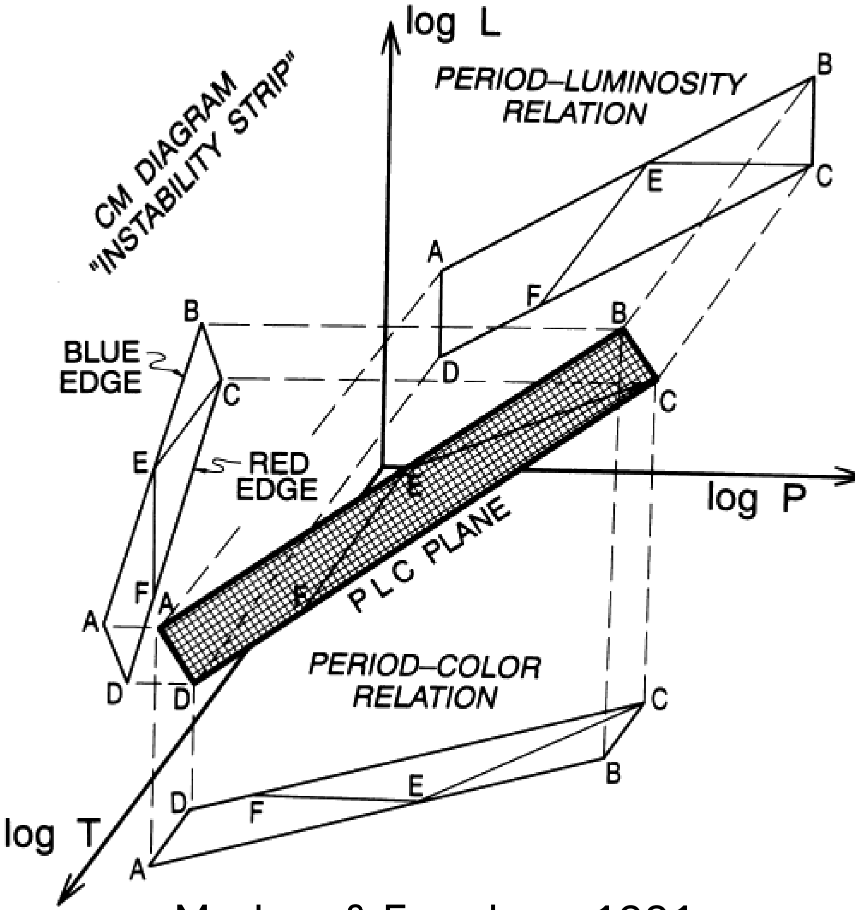
Madore & Freedman1991

- Pulsating star $P\sqrt{\rho} = const$
- Stefan-Boltzmann law $L = 4\pi\sigma R^2 T_e^4$

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

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

The Period-Luminosity-Color relation



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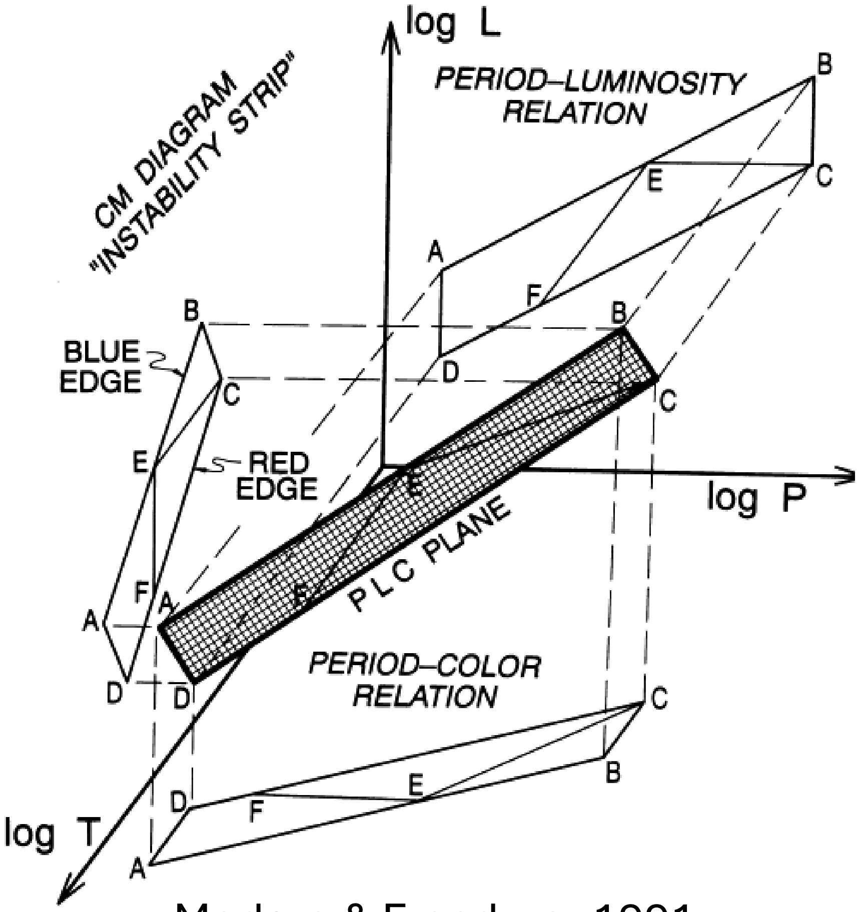
M is not independent

The Period-Luminosity-Color relation



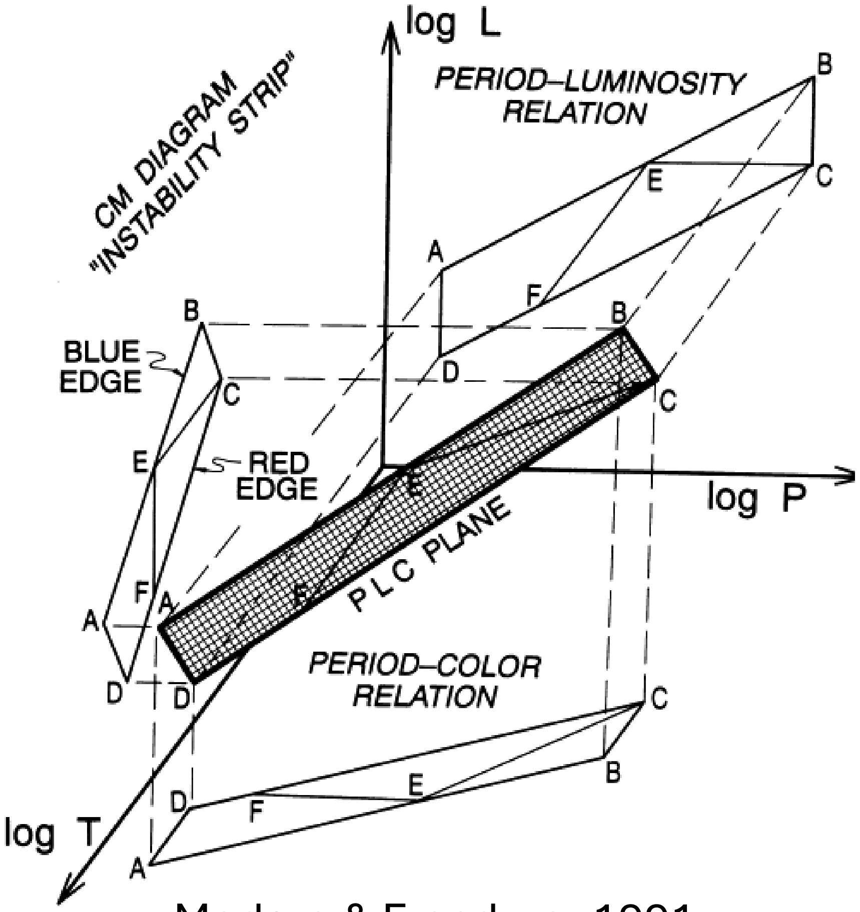
Madore & Freedman1991

$$\log P = a + b \log L/L_{\odot} + d \log T_{eff}$$

With observable quantities:

$$\log P = \alpha' + \beta' M_{\lambda_1} + \delta'\left(M_{\lambda_2} - M_{\lambda_1}\right)$$

The Period-Luminosity-Color relation



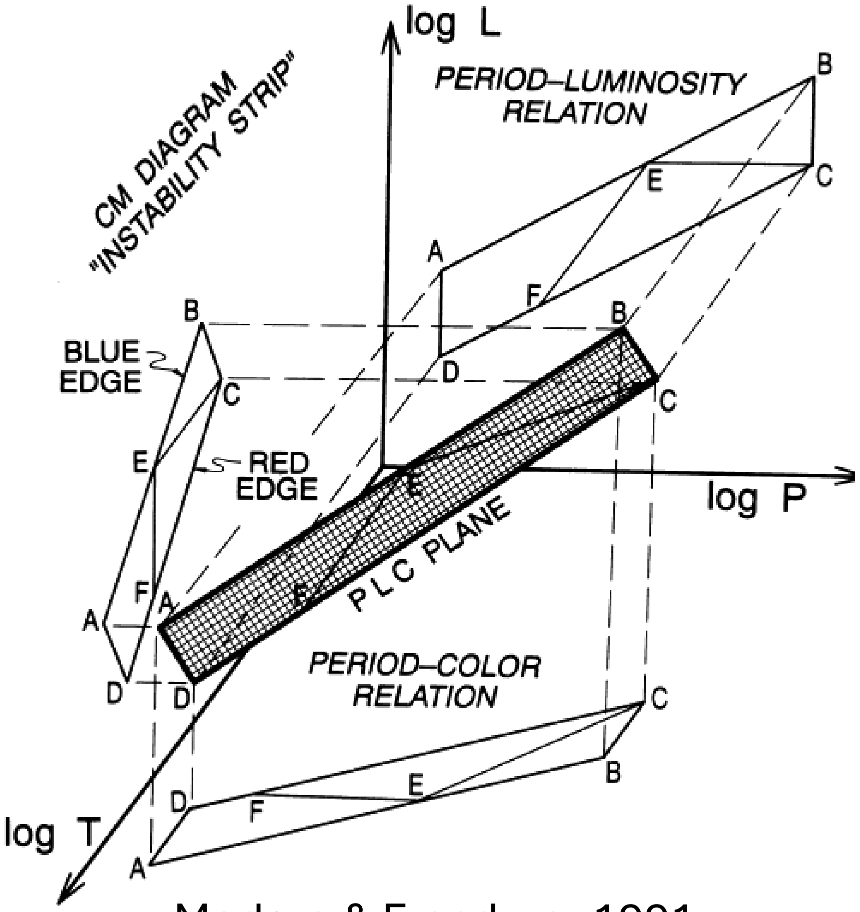
Madore & Freedman1991

$$\log P = a + b \log L/L_{\odot} + d \log T_{eff}$$

With observable quantities:

$$M_{\lambda_1} = \alpha + \beta \log P + \delta\left(M_{\lambda_2} - M_{\lambda_1}\right)$$

The PLC relation and its projections



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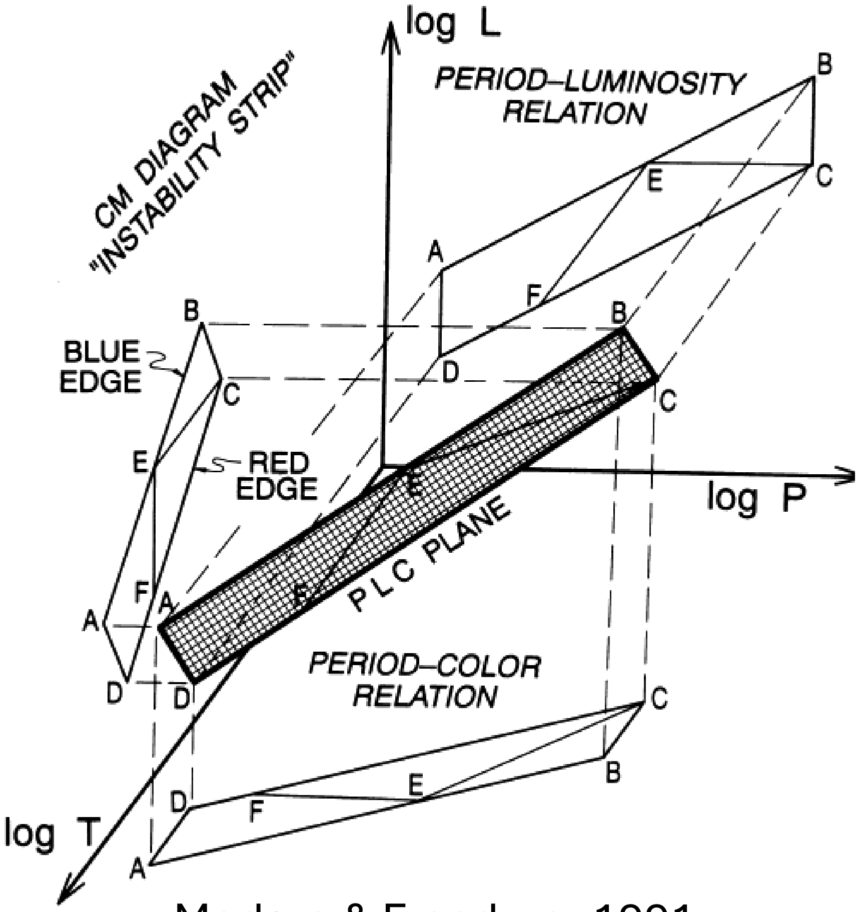
- **The PLC relation holds for each individual Cepheid**: period + color → absolute magnitude → distance

- **The PL relation is obtained by averaging over the color extension of the instability strip**

The PLC relation and its projections



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Standard(izable) Candle

- **The PL relation is obtained by averaging over the color extension of the instability strip**

$$M_{\lambda_1} = \alpha + \beta \log P$$

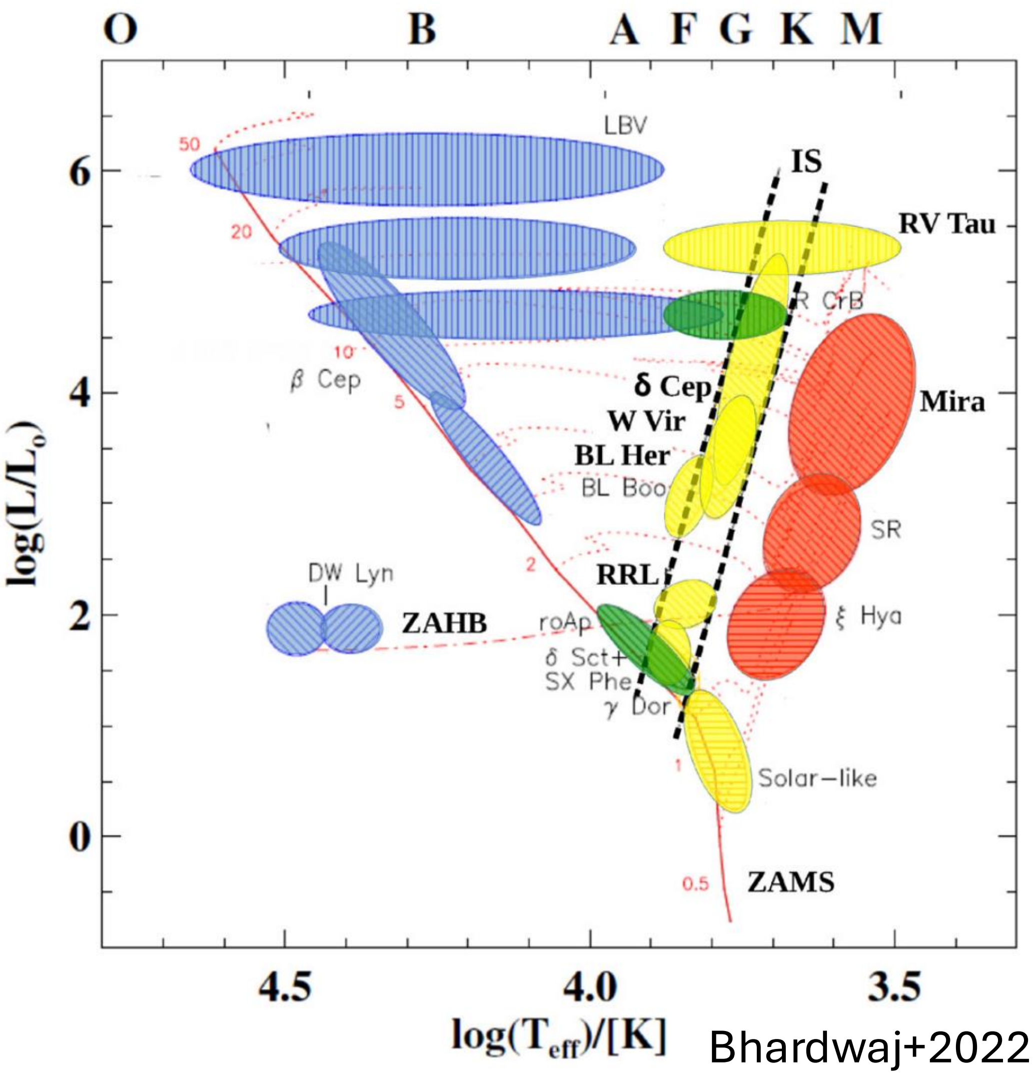
The Instability Strip

- The conditions for radial pulsation define a locus in the Temperature-Luminosity plane known as the “Instability Strip”.

- When stars cross it in their evolution, they become radial pulsators.

- The finite width in temperature of the Strip causes the pulsational period to depend both on luminosity and temperature.

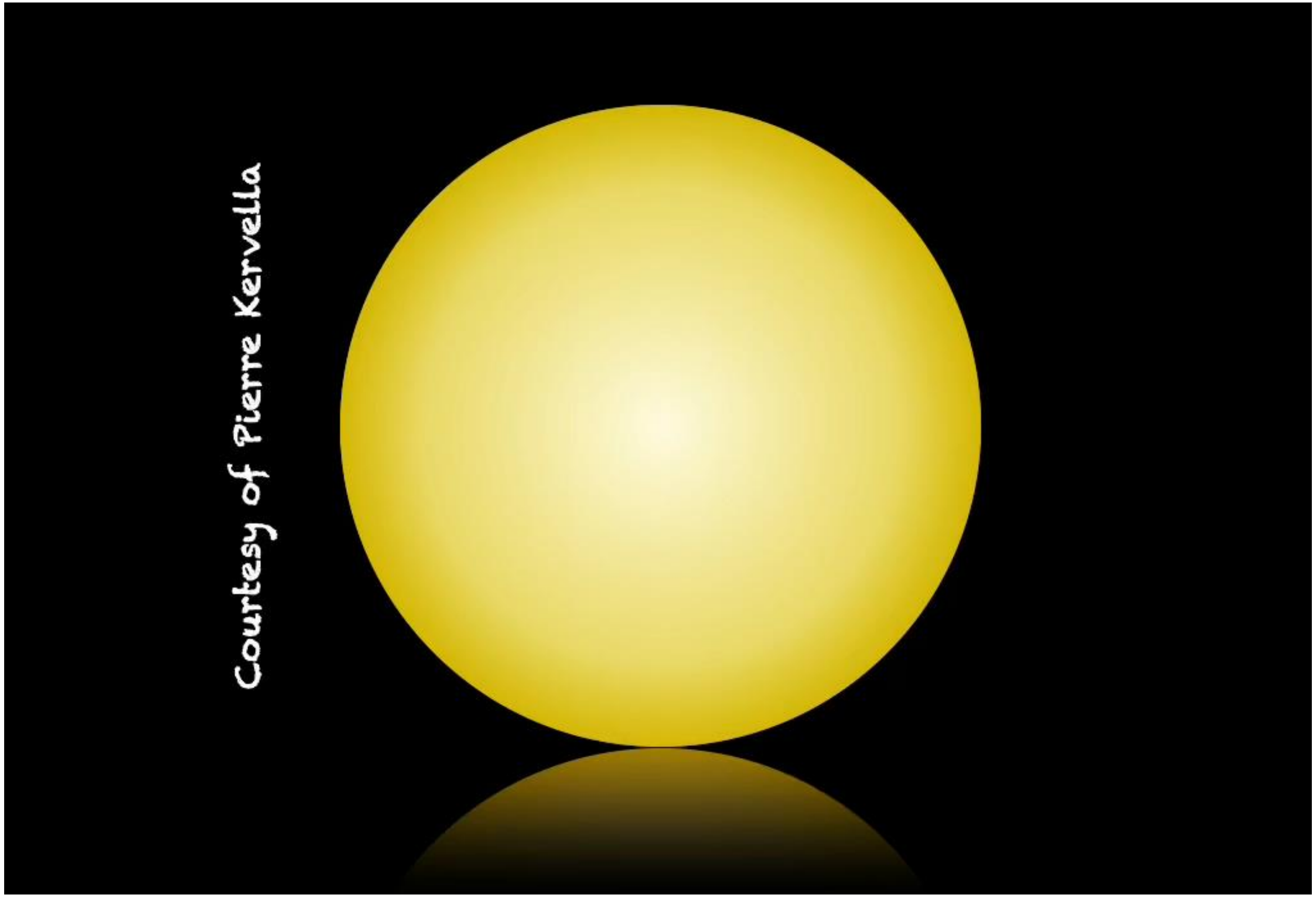
→ **Pulsating variables** provide extra observables (periods, amplitudes) that correlate with fundamental stellar properties (L, T_{eff}, M).



Bhardwaj+2022

The physics behind the scenes…

The Pulsation mechanism



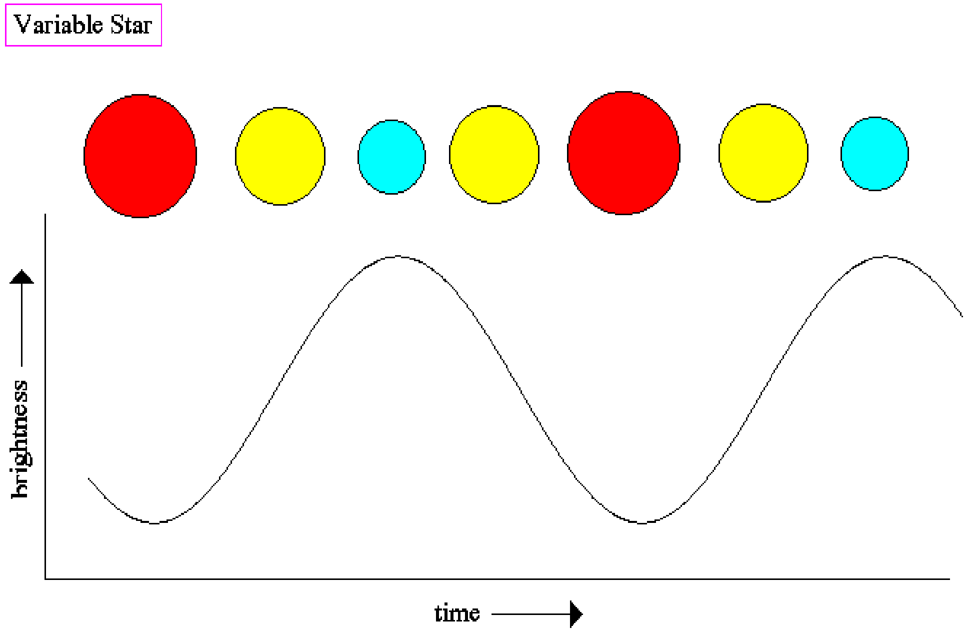
Pulsating variable stars

Pulsating stars are intrinsic variables showing periodic variations.
In the simplest case they are <u>radial</u> pulsators.

The basic driver of pulsation are changes to opacity:

κ mechanism: effect of κ (ρT^{-s}) variations on L variations

γ mechanism: effect of T variations on L variations ($\mathrm{L} \propto T^4$)

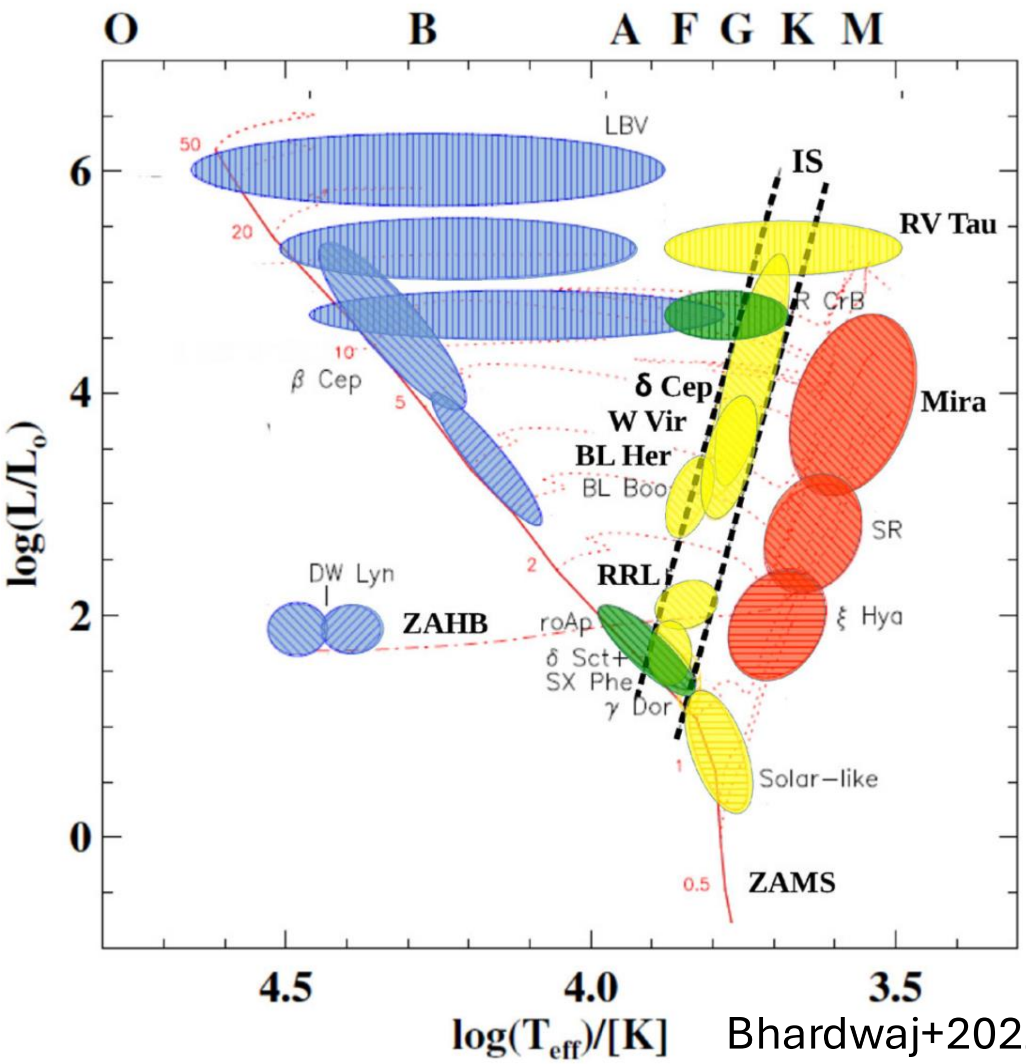


Initial contraction phase → density increases → Small increase of T → Small L variation → Energy is trapped → Energy excess during the subsequent expansion phase → **PULSATION**

Path to the Instability Strip

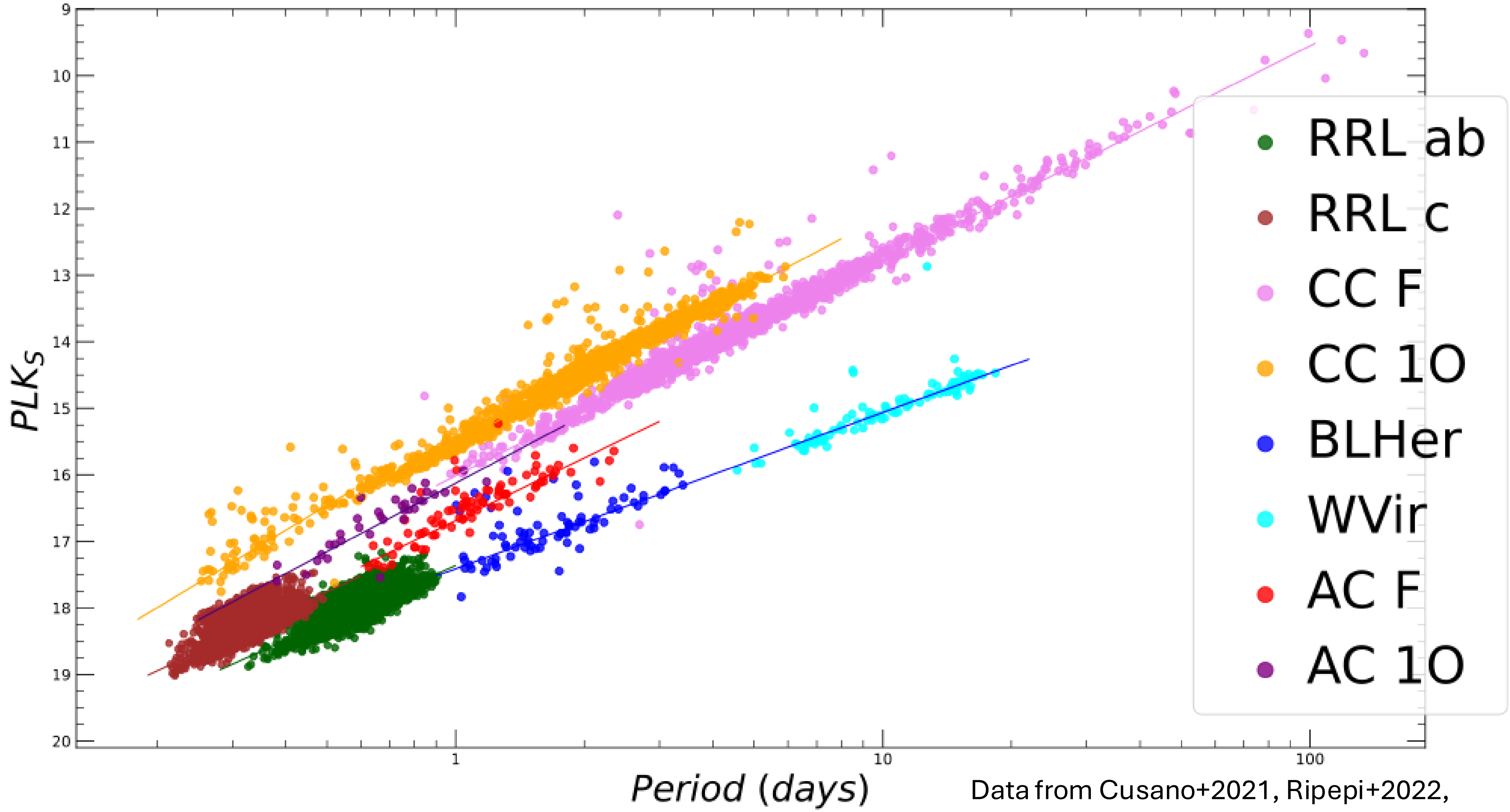
- Classical Cepheids: Pop I; 3-13 $M_{\odot}$; 0.2-100 days; fundamental, first, and second overtone modes.
- RR Lyrae: Pop II, 0.5-0.8 $M_{\odot}$; 0.2 – 1 day, fundamental and first overtone modes.
- Type II Cepheids: **BLHer** & **WVir** Pop II; low mass; 1-4 & 4-20 days.

  RVTau t > 2 Gyr; intermediate mass; 20-100 days.
- Anomalous Cepheids : intermediate age; 1.3-2.3 $M_{\odot}$; 0.5-2.5 / 0.4-1 d; fundamental and first overtone modes.



Bhardwaj+2022

Period Luminosity relations of pulsating stars in the LMC



Data from Cusano+2021, Ripepi+2022, Sicignano+2024,2025 under review

Limitations of the PL relation

→ Astronomers have used PL, but… if we want 1% precision on the Hubble constant, we must investigate every source of dispersion and systematics.

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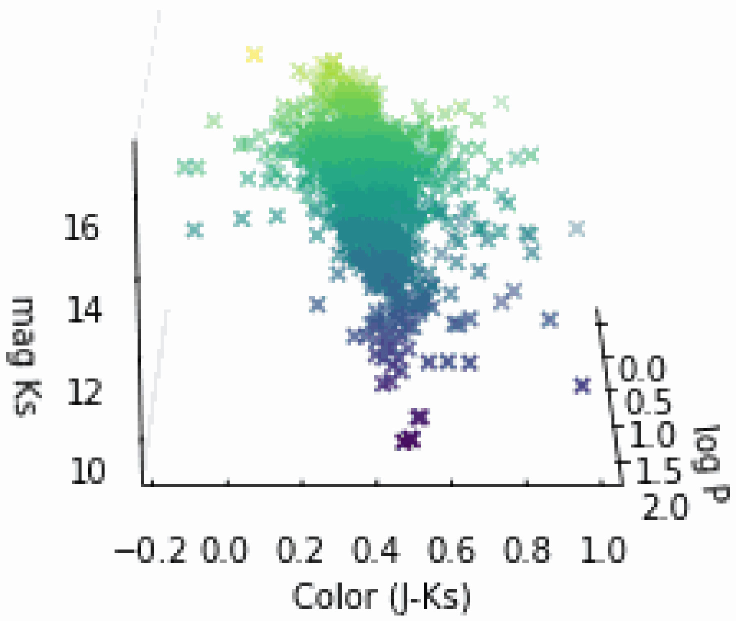
→ Astronomers have used PL, but... if we want 1% precision on the Hubble constant, we must investigate every source of dispersion and systematics.

❑Width of the PL
❑Extinction
❑Metallicity

❑ Width of the PL



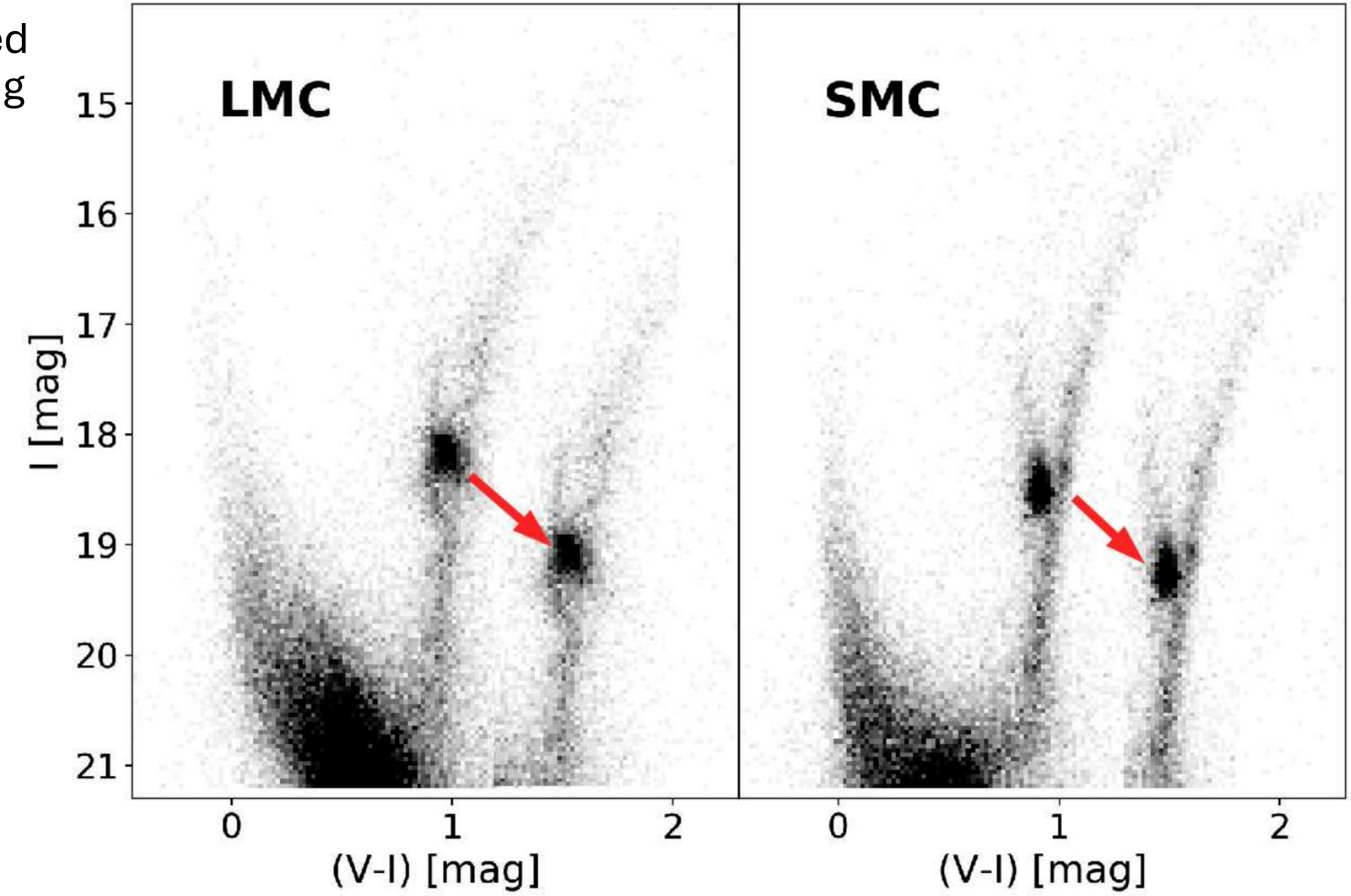
- PL has a finite width → average goes with ~ square root of N.
- PL is a projection of the Period-Luminosity-Color.

❑ Extinction

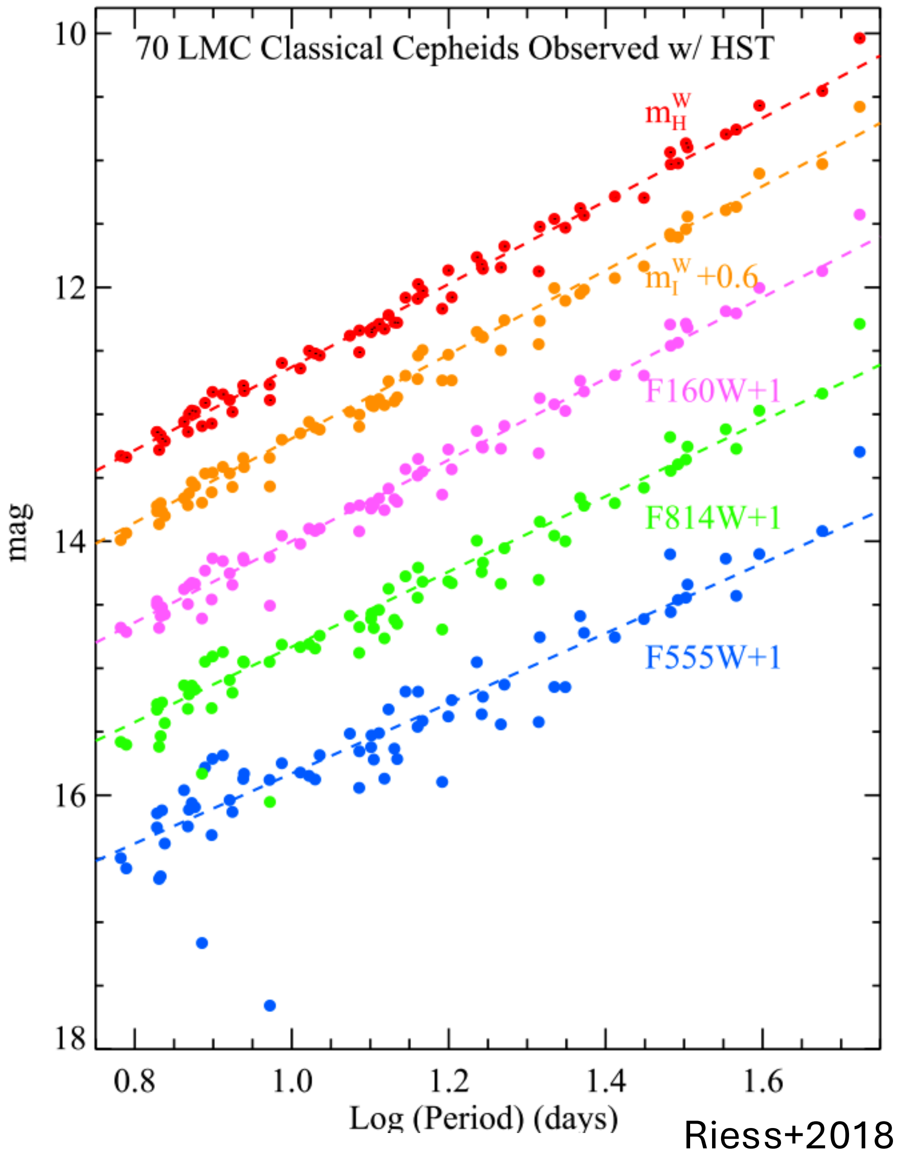
The blue light is strongly absorbed and scattered by the dust, making the objects appear redder.

- ❑Stellar atmosphere
- ❑Extinction law
- ❑Instrumental filter response

Skowron 2022



From the PLC to the Period Wesenheit



Riess+2018

$$M_{\lambda_1} = \alpha + \beta \log P + \delta\left(M_{\lambda_2} - M_{\lambda_1}\right)$$

Wesenheit function introduced by Madore in 1982.

Defined to be a reddening-free quantity:

$$W \equiv M_{\lambda_1} - R_{M_{\lambda_1}}\left(M_{\lambda_2} - M_{\lambda_1}\right) \equiv M_{\lambda_1} - \frac{A_{M_{\lambda_1}}}{E\left(M_{\lambda_2} - M_{\lambda_1}\right)}\left(M_{\lambda_2} - M_{\lambda_1}\right)$$

$$W = M_{\lambda_{1}0} + A_{M_{\lambda_1}} - R\left[\left(M_{\lambda_2} - M_{\lambda_1}\right)_0 + E\left(M_{\lambda_2} - M_{\lambda_1}\right)\right]$$

$$W = M_{\lambda_{1}0} + R_{M_{\lambda_1}}\left(M_{\lambda_2} - M_{\lambda_1}\right) - R\left[\left(M_{\lambda_2} - M_{\lambda_1}\right)_0 + E\left(M_{\lambda_2} - M_{\lambda_1}\right)\right]$$

$$W = M_{\lambda_{1}0} - R\left(M_{\lambda_2} - M_{\lambda_1}\right)_0 = W_0$$

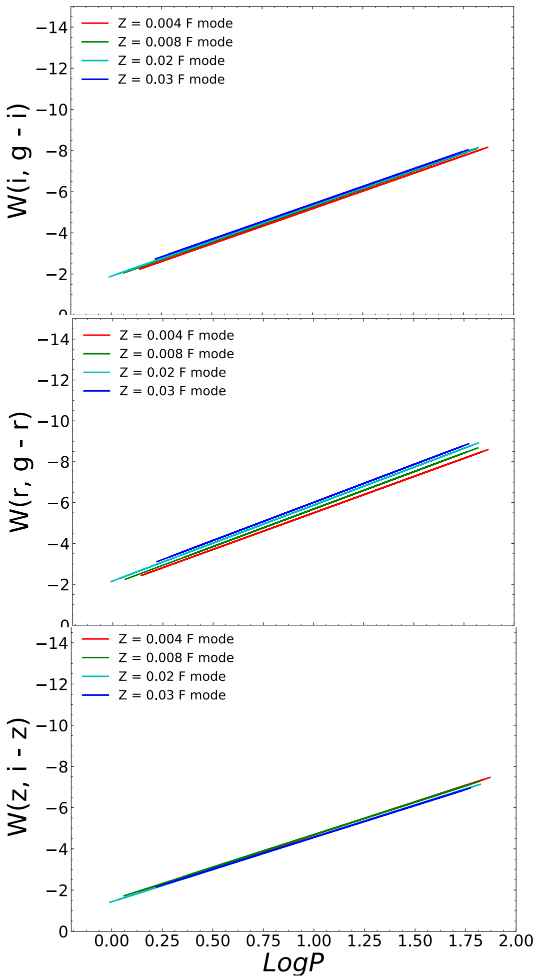
$$W = \alpha + \beta \log P$$

❑ Metallicity

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

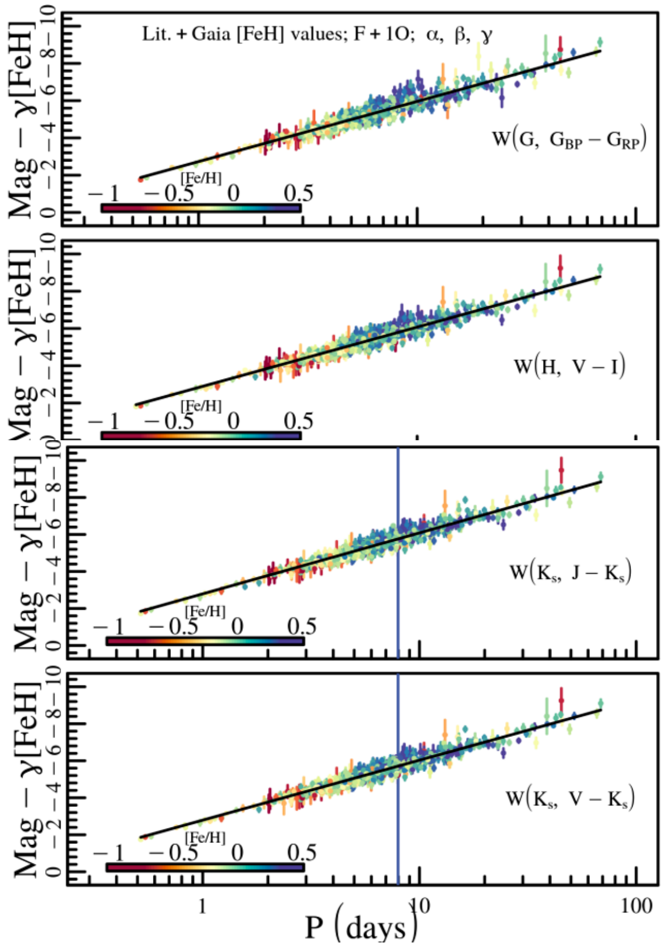
$$\log P = \alpha + \beta W + \gamma Z$$

Theory



Adapted from De Somma+2024

Observations



Adapted from Trentin+2024

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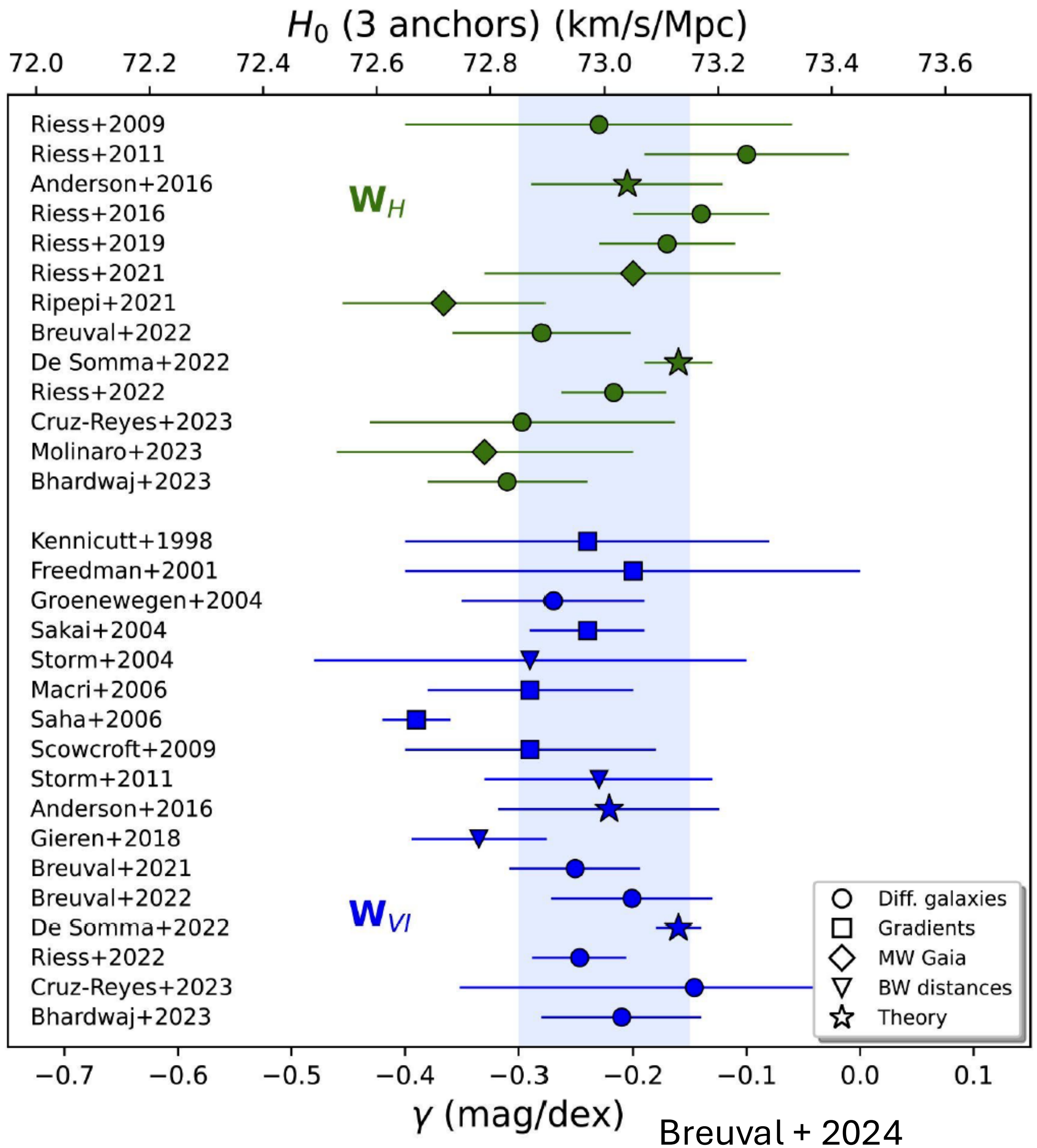
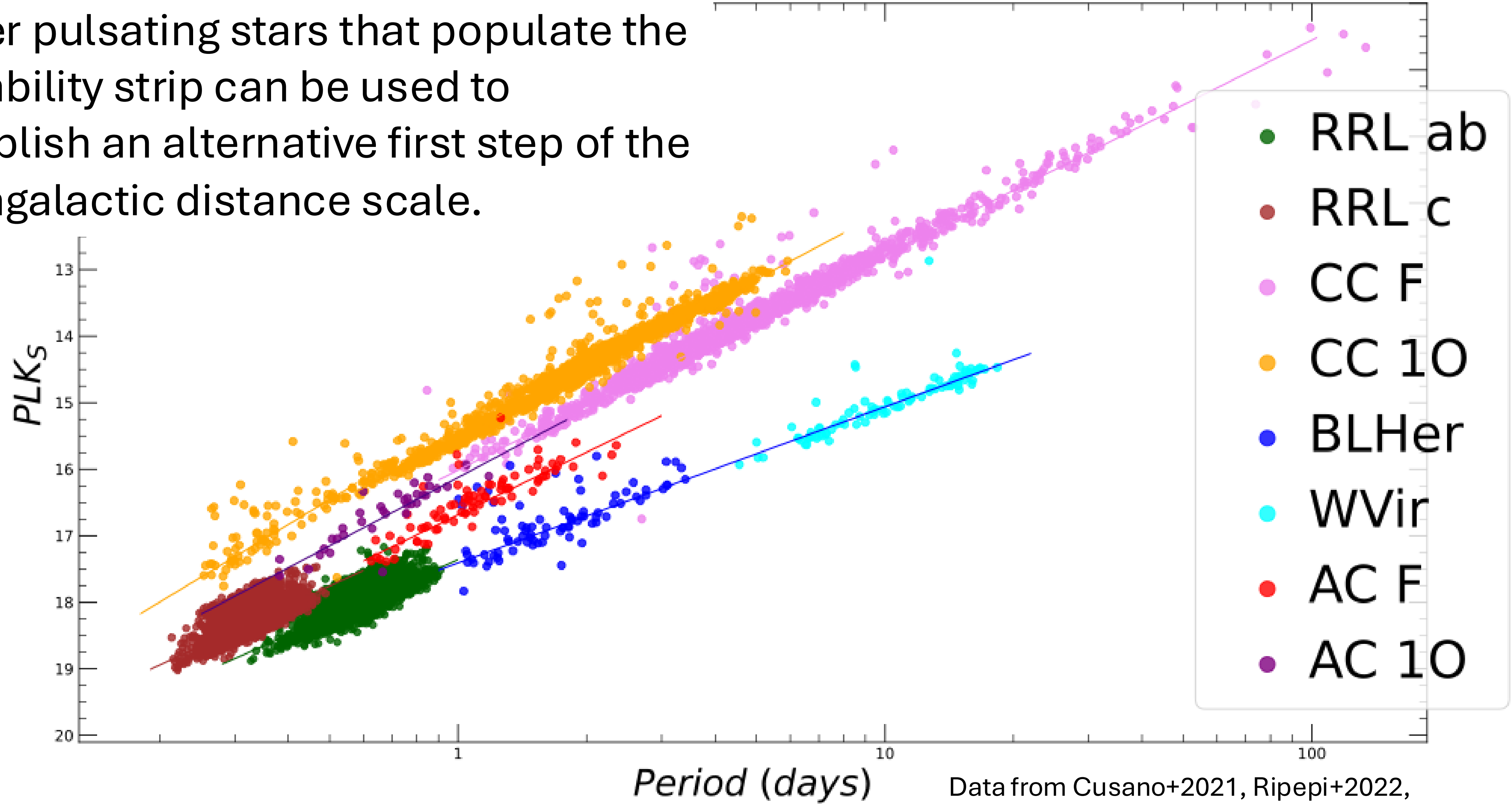


Breuval + 2024

Not only Classical Cepheids...

Other pulsating stars that populate the instability strip can be used to establish an alternative first step of the extragalactic distance scale.



Data from Cusano+2021, Ripepi+2022, Sicignano+2024,2025 under review

An alternative self-consistent stellar route to the Hubble constant

- Exploitation of the VMC-Deep and TNG-REM photometry for Type II and Anomalous Cepheids.

- Quantify the effect of metallicity on the zero point and slope of PL relation through high-resolution spectroscopic abundances from the 4MOST 1001MC survey and UVES spectra.

- Calibration through Gaia DR4 parallaxes.

- Compare the distance scales produced for different kinds of pulsating stars and look into the reasons for any discrepancies.

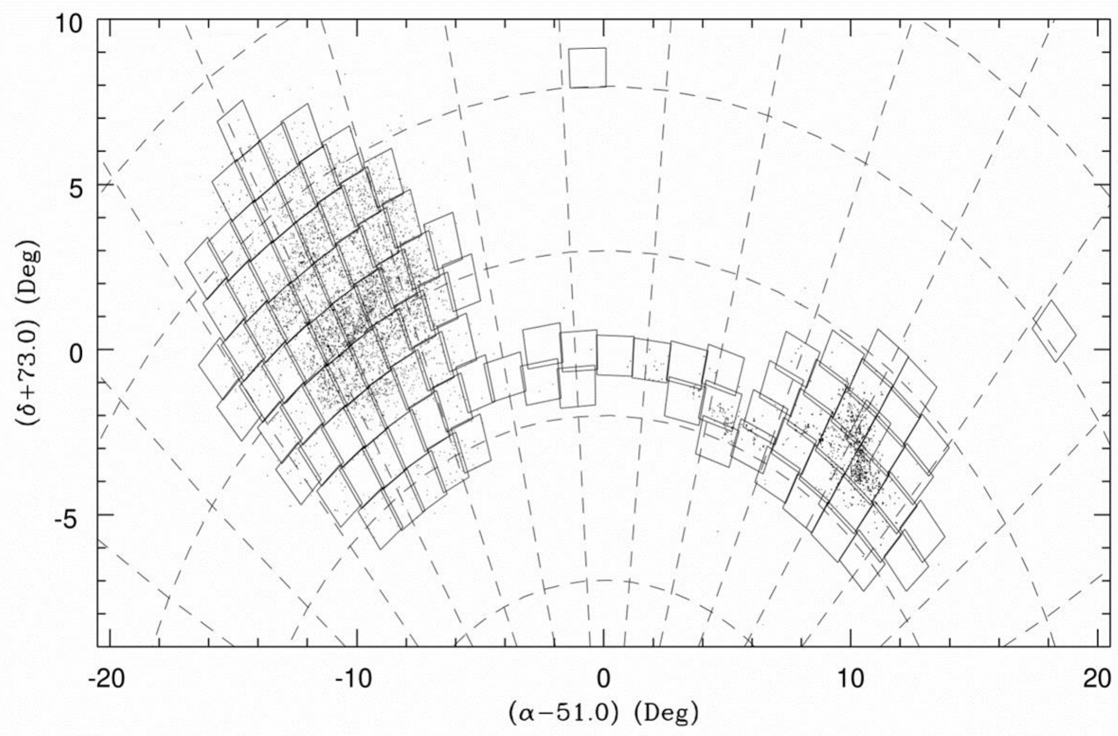
↓

Provide a common self-consistent calibration of secondary distance indicators.

TYPE II AND ANOMALOUS CEPHEIDS IN THE MAGELLANIC CLOUDS

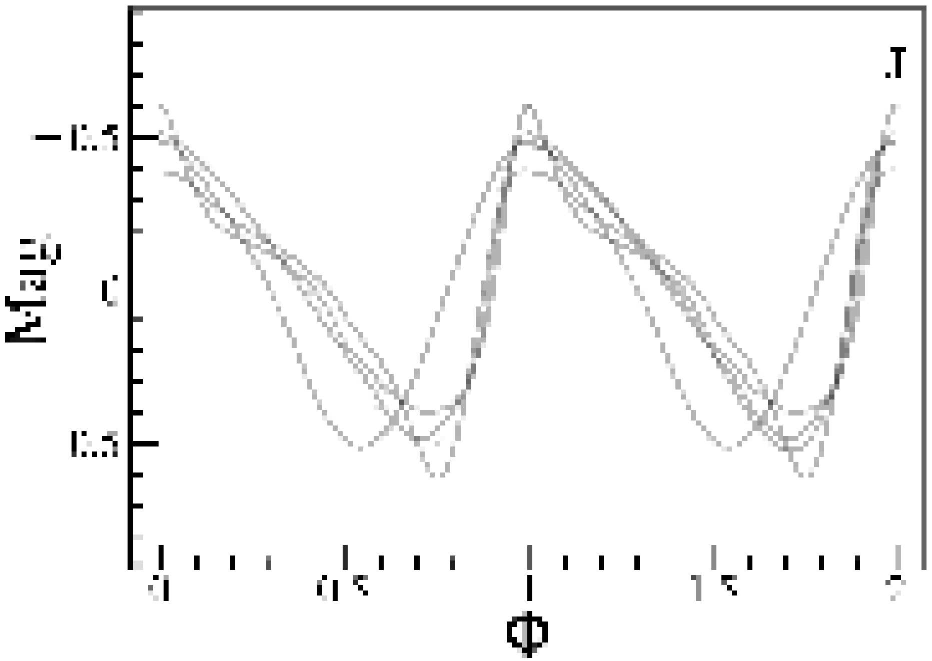
- VMC is an ESO public survey (P.I. M.-R. Cioni)
- Observations in YJKs with VIRCAM@VISTA 4 m (Paranal, Chile)
- Data reduction with the VISTA Data Flow System (VDFS) pipeline at CASU (Cambridge Astronomical Survey Unit)
- Catalogues handling through the Vista Science Archive (VSA)

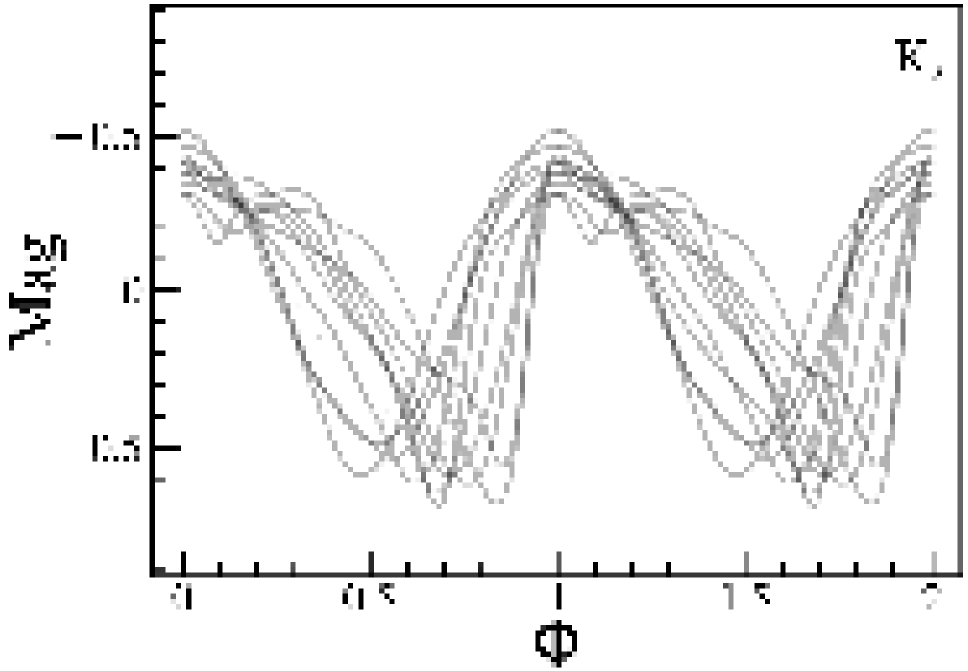
339 T2Cs and 198 ACs with VMC photometry in the Magellanic Clouds



TEMPLATE FITTING TO THE DATA

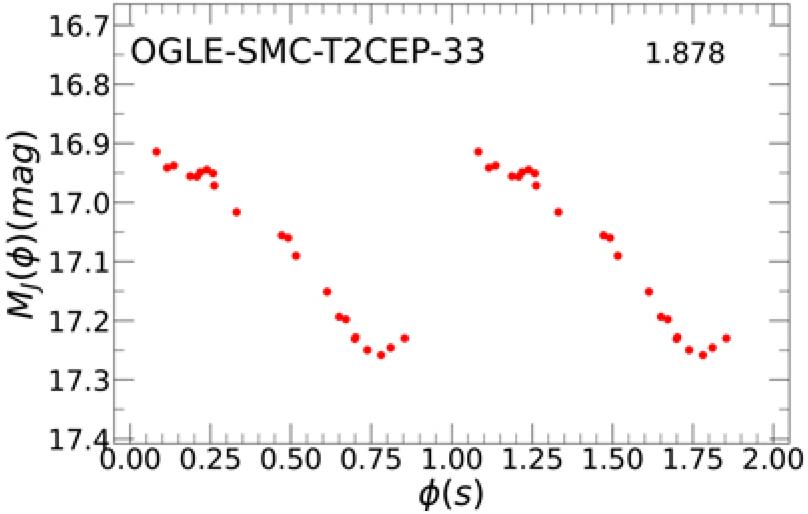
To construct the PL/PW it is necessary to calculate the intensity-averaged magnitudes, using the tecnique of templetes.

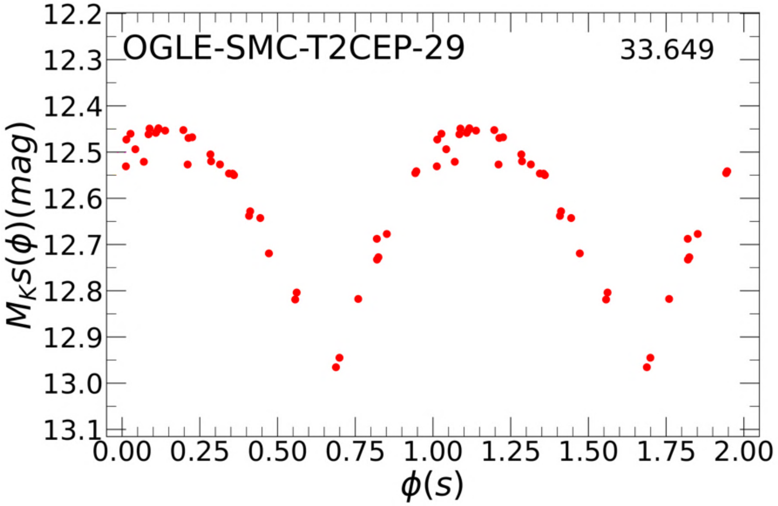




TYPE II CEPHEIDS

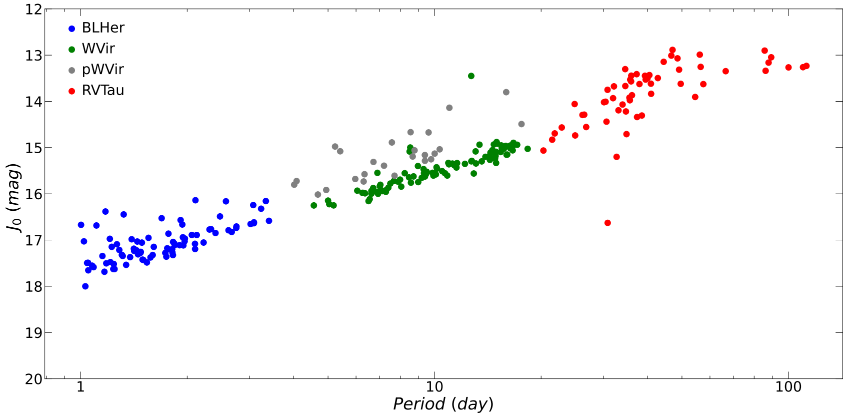
LIGHT CURVES

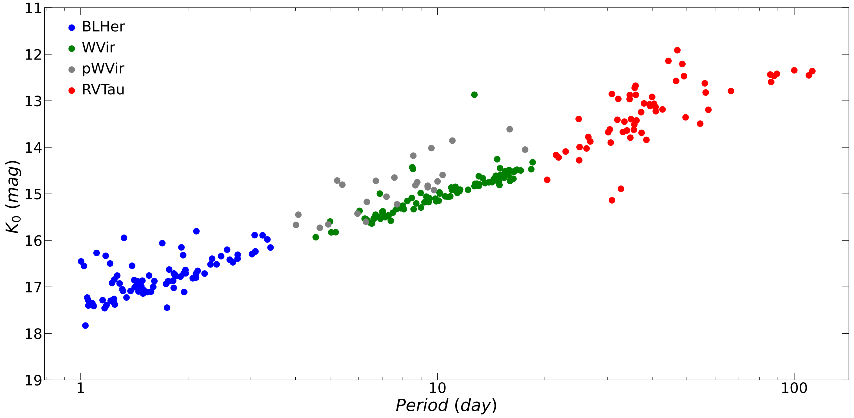




Sicignano+2024, A&A, 685, A41.

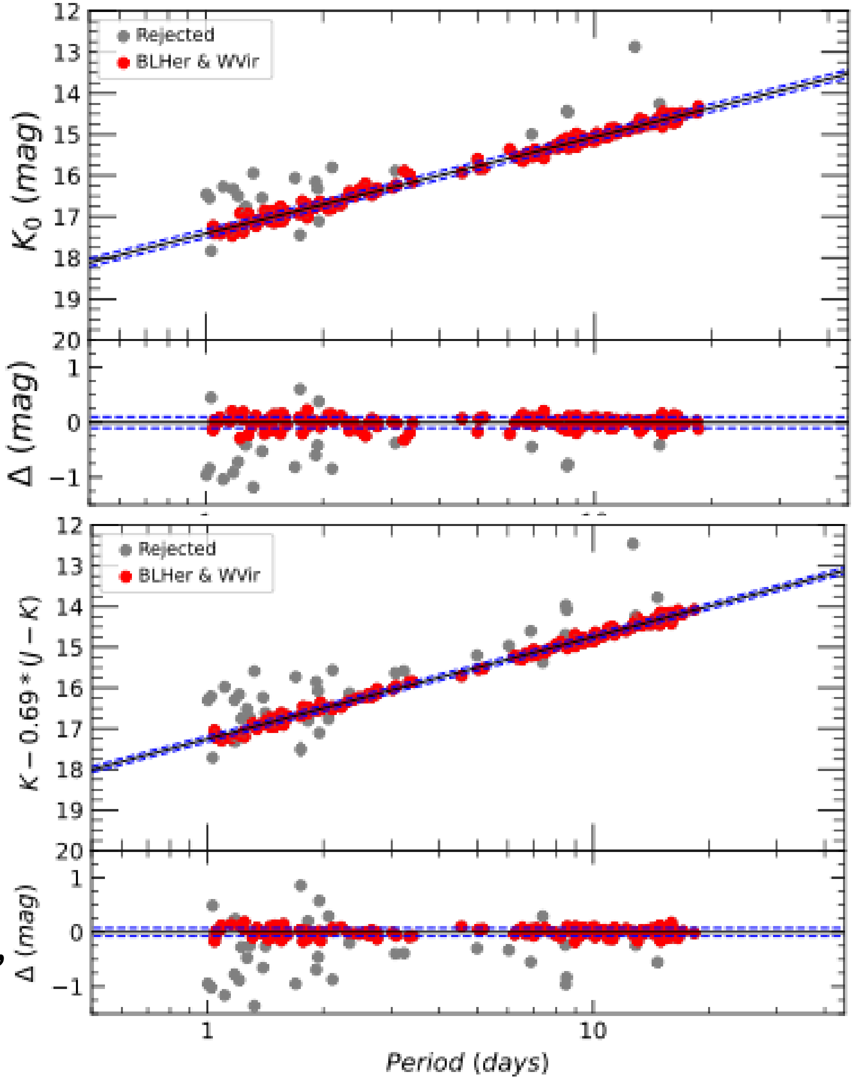
OBSERVED PERIOD – LUMINOSITY RELATIONS





TYPE II CEPHEIDS

FITTED PERIOD – LUMINOSITY AND PERIOD - WESENHEIT RELATIONS

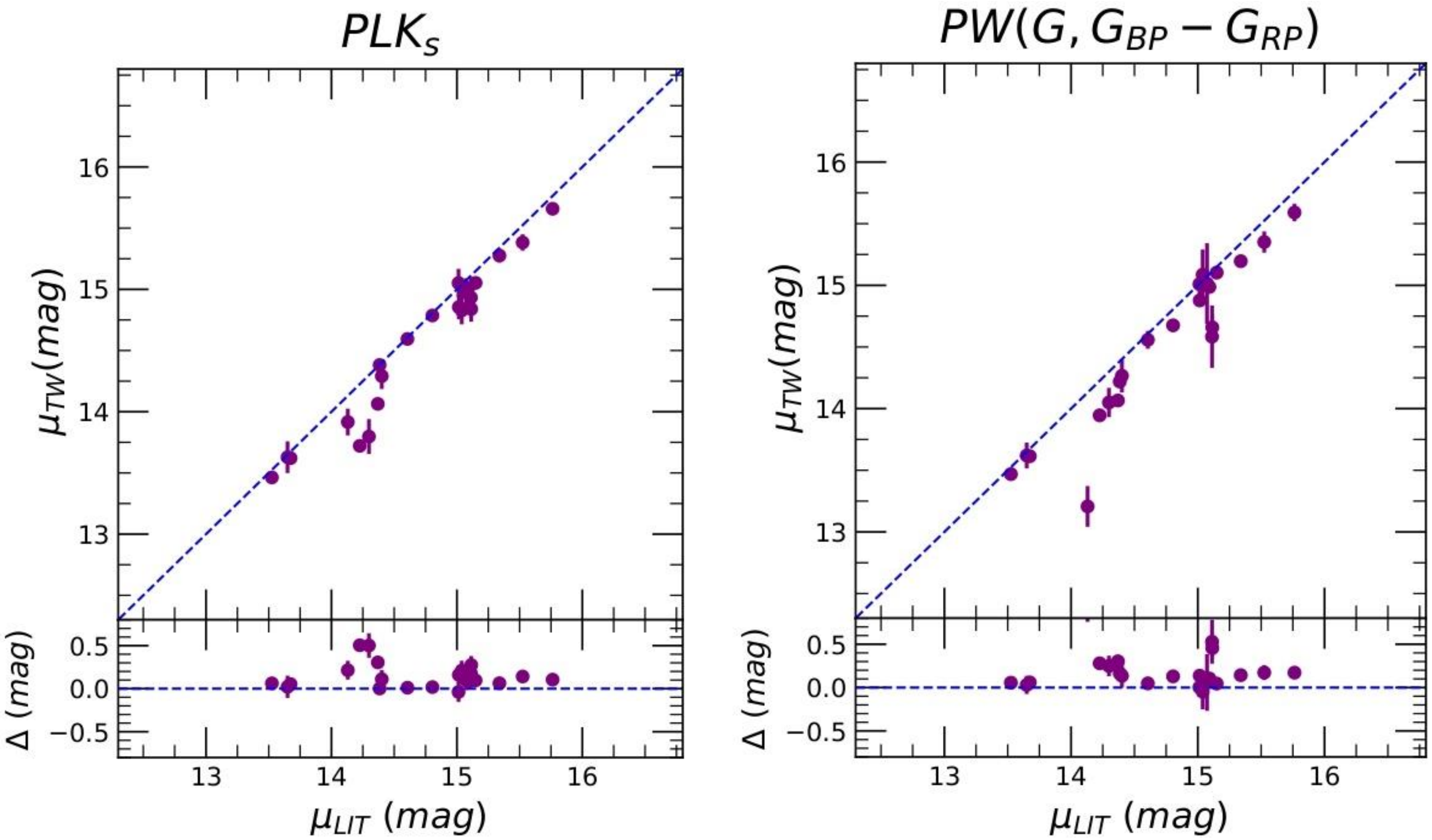


Relation	Group	α mag	σ_α mag	β mag/dex	σ_β mag/dex	γ	σ_γ	RMS mag	Used stars	Total stars
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
PLBP	BLHer	18.348	0.130	−0.840	0.250			0.29	74	83
PLBP	WVir	19.266	0.039	−2.190	0.110			0.18	98	103
PLBP	BLH&WVir	18.505	0.020	−1.439	0.047			0.27	175	186
PLG	BLHer	18.382	0.082	−1.450	0.160			0.20	78	85
PLG	WVir	19.019	0.029	−2.270	0.082			0.13	93	103
PLG	BLH&WVir	18.454	0.014	−1.722	0.034			0.19	178	188
PLRP	BLHer	17.945	0.097	−1.670	0.200			0.25	72	83
PLRP	WVir	18.538	0.033	−2.363	0.092			0.14	100	103
PLRP	BLH&WVir	18.092	0.012	−1.943	0.030			0.17	160	186
PLV	BLHer	18.432	0.079	−1.250	0.160			0.18	73	85
PLV	WVir	19.066	0.039	−2.150	0.110			0.17	99	104
PLV	BLH&WVir	18.520	0.016	−1.618	0.037			0.21	178	189
PLI	BLHer	17.973	0.067	−1.800	0.140			0.16	79	85
PLI	WVir	18.483	0.036	−2.370	0.100			0.16	102	104
PLI	BLH&WVir	18.028	0.012	−1.940	0.029			0.17	182	189
PLY	BLHer	17.711	0.082	−1.680	0.170			0.19	68	77
PLY	WVir	18.266	0.028	−2.473	0.080			0.13	97	100
PLY	BLH&WVir	17.823	0.012	−2.048	0.029			0.16	162	177
PLJ	BLHer	17.657	0.069	−2.250	0.140			0.17	73	83
PLJ	WVir	17.919	0.024	−2.400	0.068			0.10	94	98
PLJ	BLH&WVir	17.664	0.010	−2.156	0.024			0.12	162	181
PLK	BLHer	17.444	0.066	−2.560	0.140			0.16	73	84
PLK	WVir	17.508	0.019	−2.439	0.053			0.08	98	103
PLK	BLH&WVir	17.410	0.009	−2.348	0.019			0.10	165	187
PWG	BLH&WVir	17.445	0.009	−2.436	0.022			0.14	170	186
PWVI	BLH&WVir	17.337	0.010	−2.491	0.022			0.12	177	189
PWVK	BLH&WVir	17.282	0.007	−2.475	0.017			0.09	160	187
PWYK	BLH&WVir	17.226	0.007	−2.516	0.017			0.09	151	177
PWJK	BLH&WVir	17.251	0.006	−2.501	0.016			0.08	146	181
PLCG	BLH&WVir	17.334	0.009	−2.501	0.033	2.070	0.062	0.15	170	186
PLCVI	BLH&WVir	17.143	0.013	−2.604	0.036	2.912	0.092	0.10	168	189
PLCVK	BLH&WVir	17.295	0.007	−2.447	0.029	0.118	0.030	0.09	162	187
PLCYK	BLH&WVir	17.325	0.008	−2.421	0.026	0.223	0.059	0.09	157	177
PLCJK	BLH&WVir	17.252	0.007	−2.493	0.025	0.691	0.099	0.075	145	181

Sicignano+2024, A&A, 685, A41.

IMPACT ON THE DISTANCE SCALE

Comparison between our distance moduli and those by Baumbgardt & Vasiliev 21

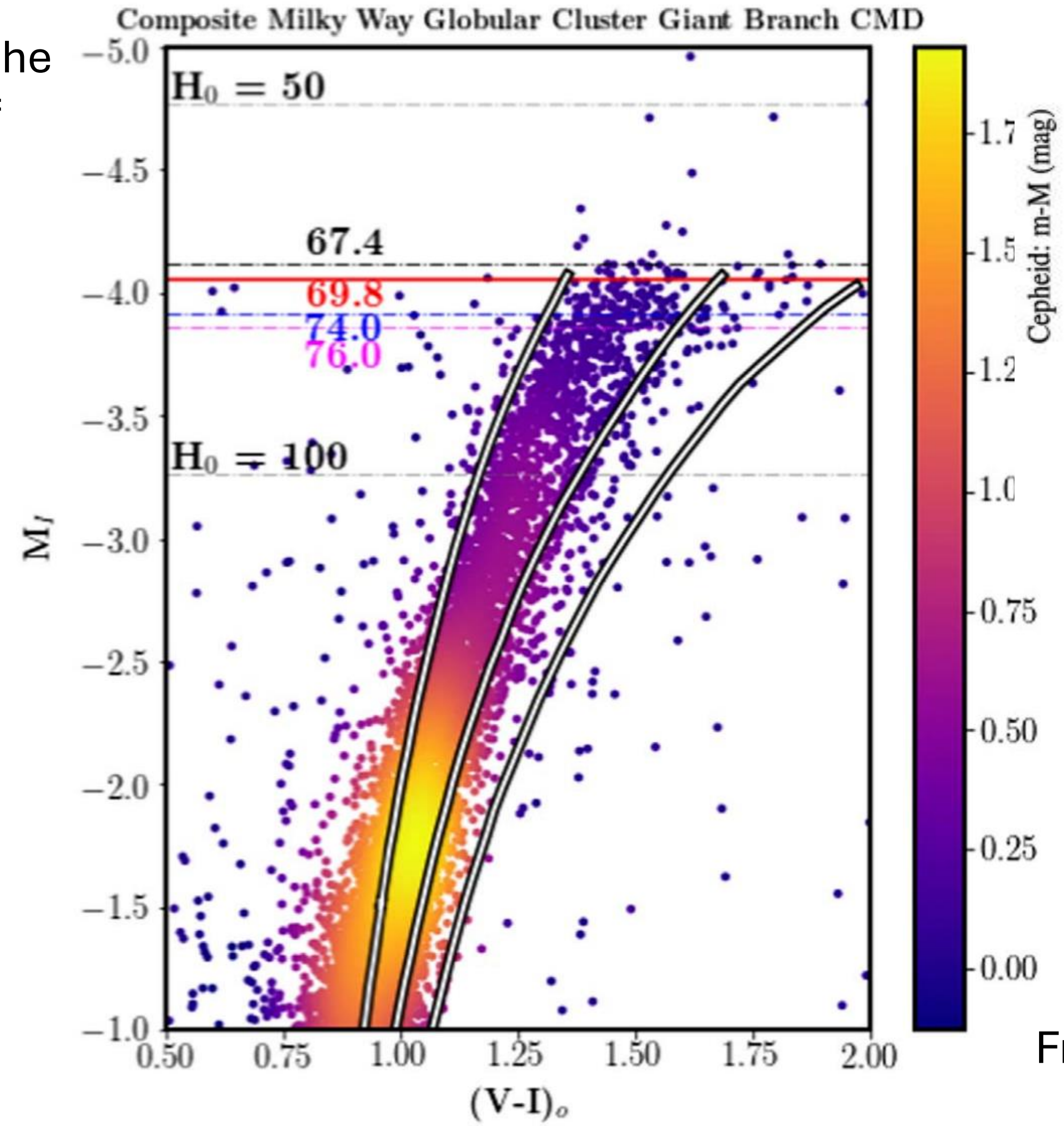


Sicignano+2024,
A&A, 685, A41.

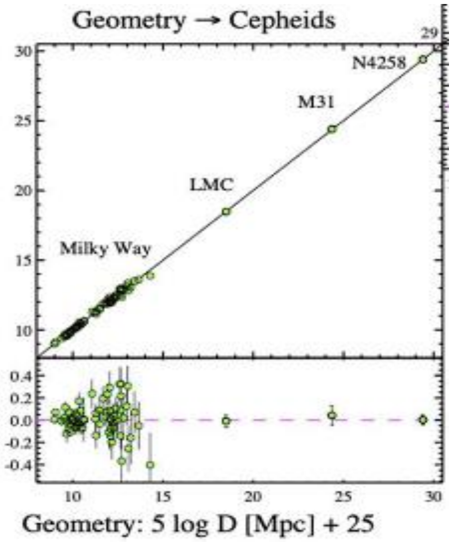
The distance moduli of GGCs appear **overestimated** up to **3%**.

IMPACT ON THE DISTANCE SCALE

1. Geometric indicators to calibrate the Period-Luminosity (PL) relations of Cepheids



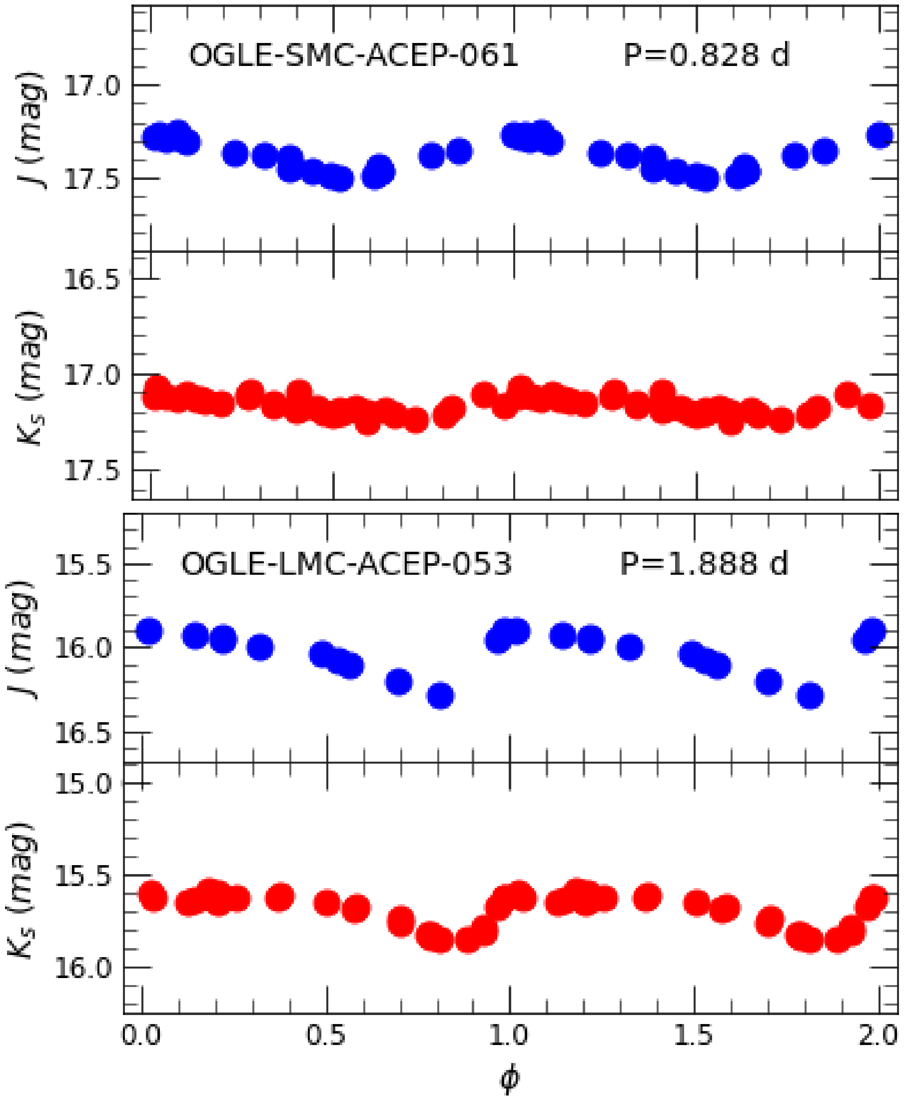
Freedman+ 2021



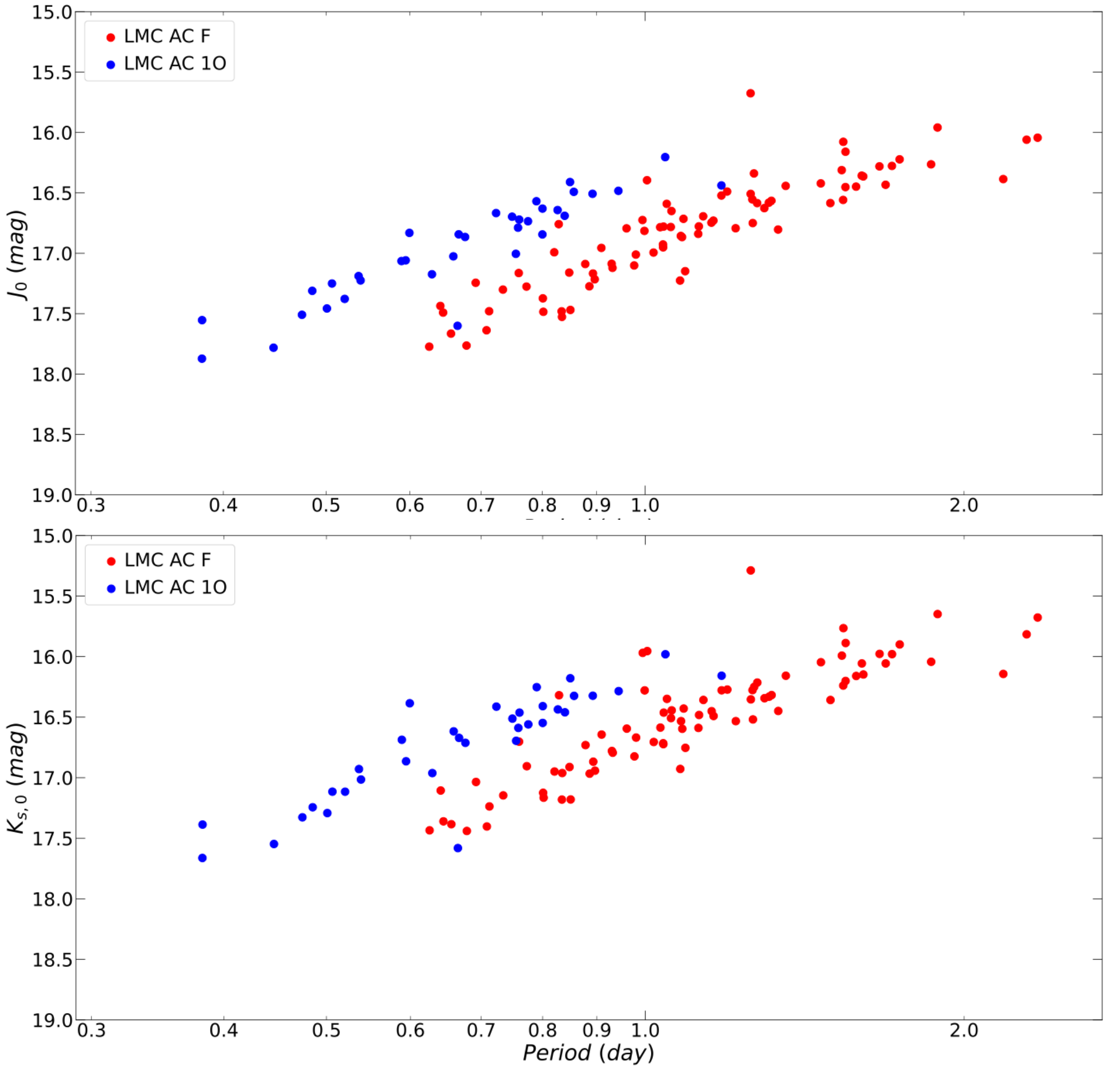
Riess+2022

ANOMALOUS CEPHEIDS

LIGHT CURVES



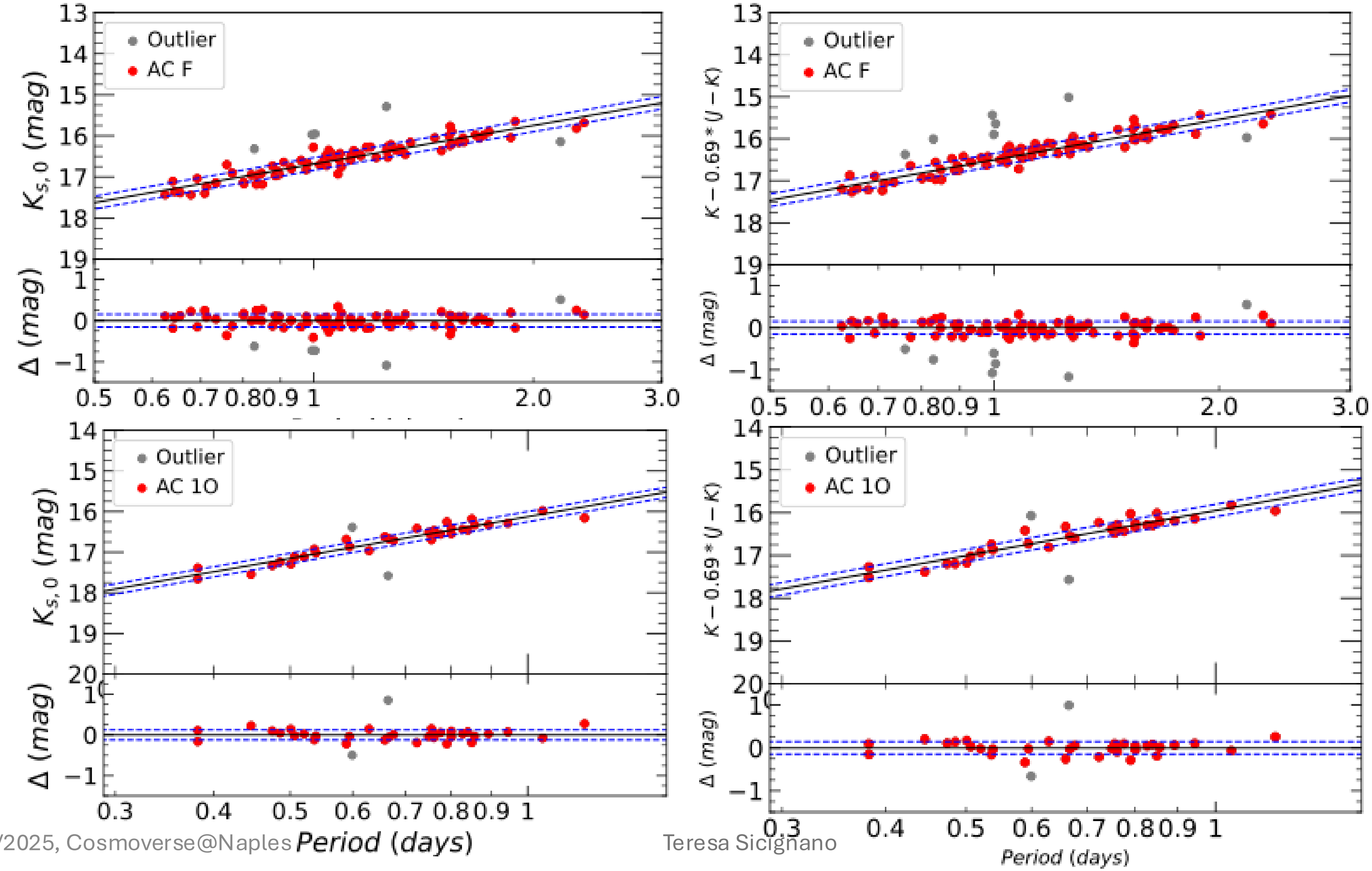
OBSERVED PERIOD – LUMINOSITY RELATIONS



Sicignano +2025, A&A, under revision.

ANOMALOUS CEPHEIDS

FITTED PERIOD – LUMINOSITY AND PERIOD WESENHEIT RELATIONS

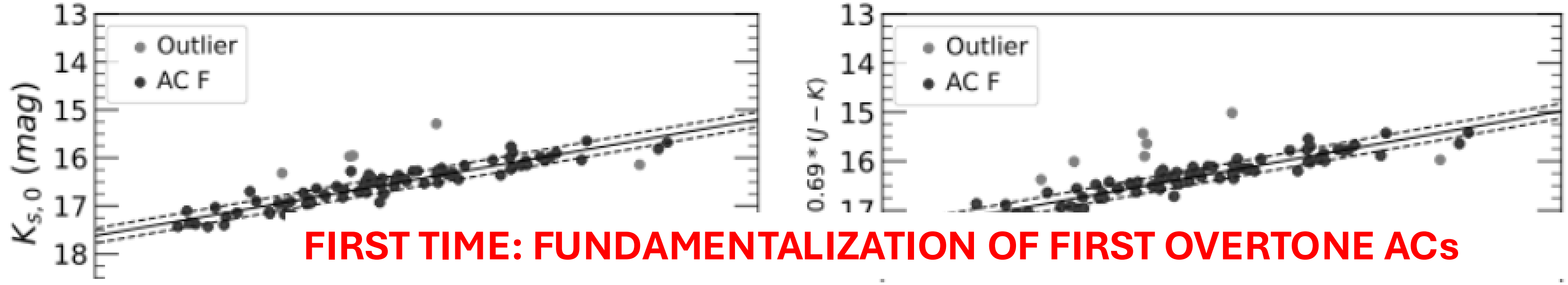


Sicignano +2025, A&A, under revision.

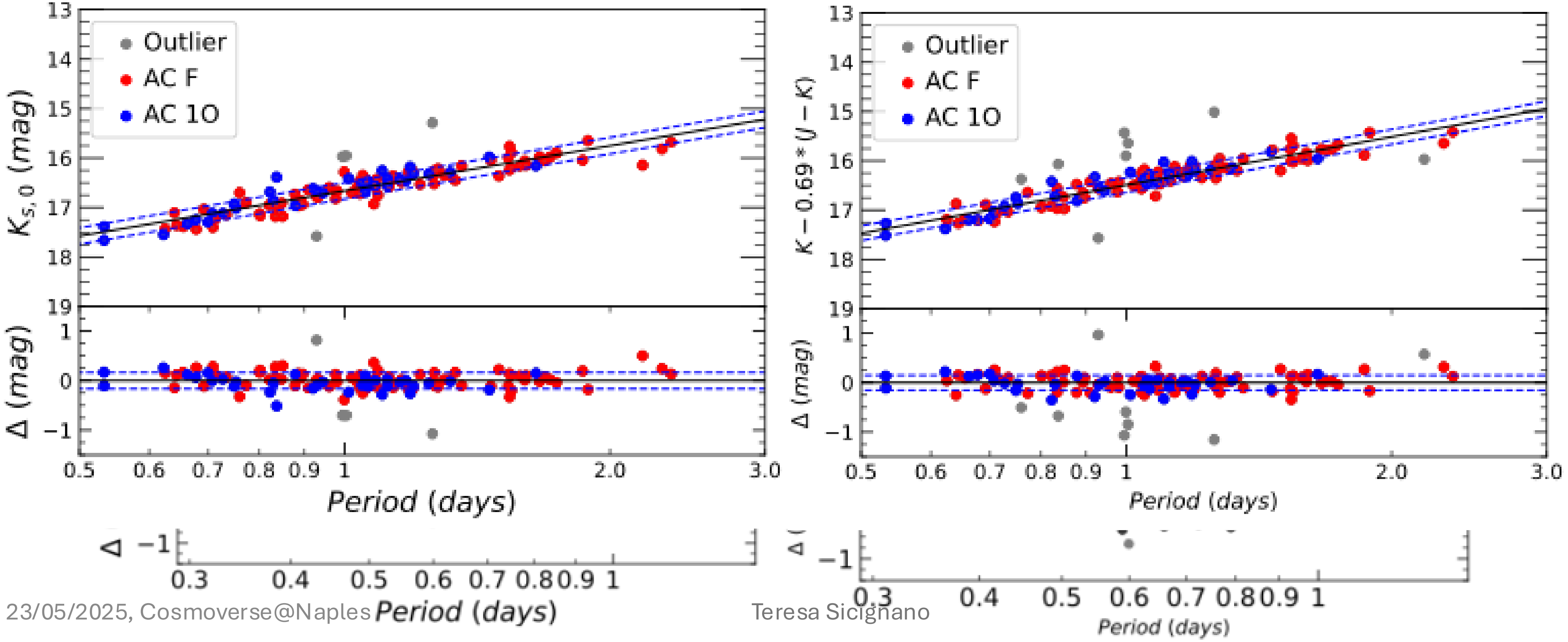
ANOMALOUS CEPHEIDS

FITTED PERIOD – LUMINOSITY AND PERIOD WESENHEIT RELATIONS

Sicignano +2025, A&A, under revision.



FIRST TIME: FUNDAMENTALIZATION OF FIRST OVERTONE ACs



ANOMALOUS CEPHEIDS

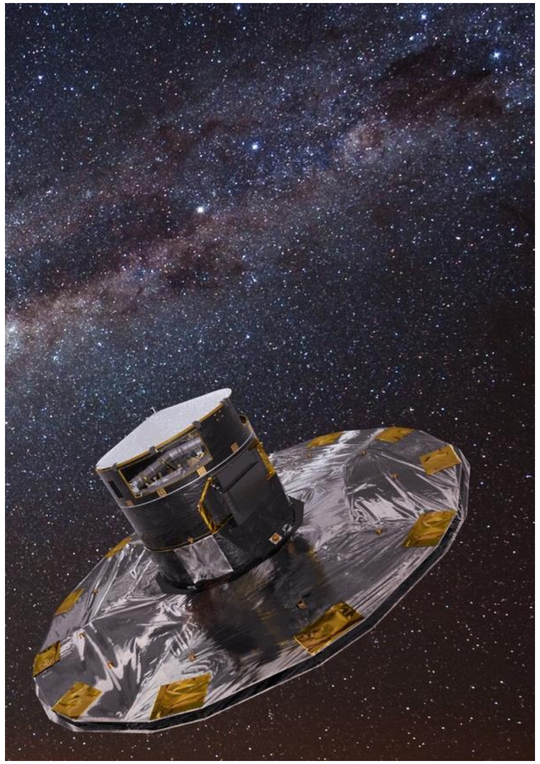
FITTED PERIOD – LUMINOSITY AND PERIOD-WESENHEIT RELATIONS

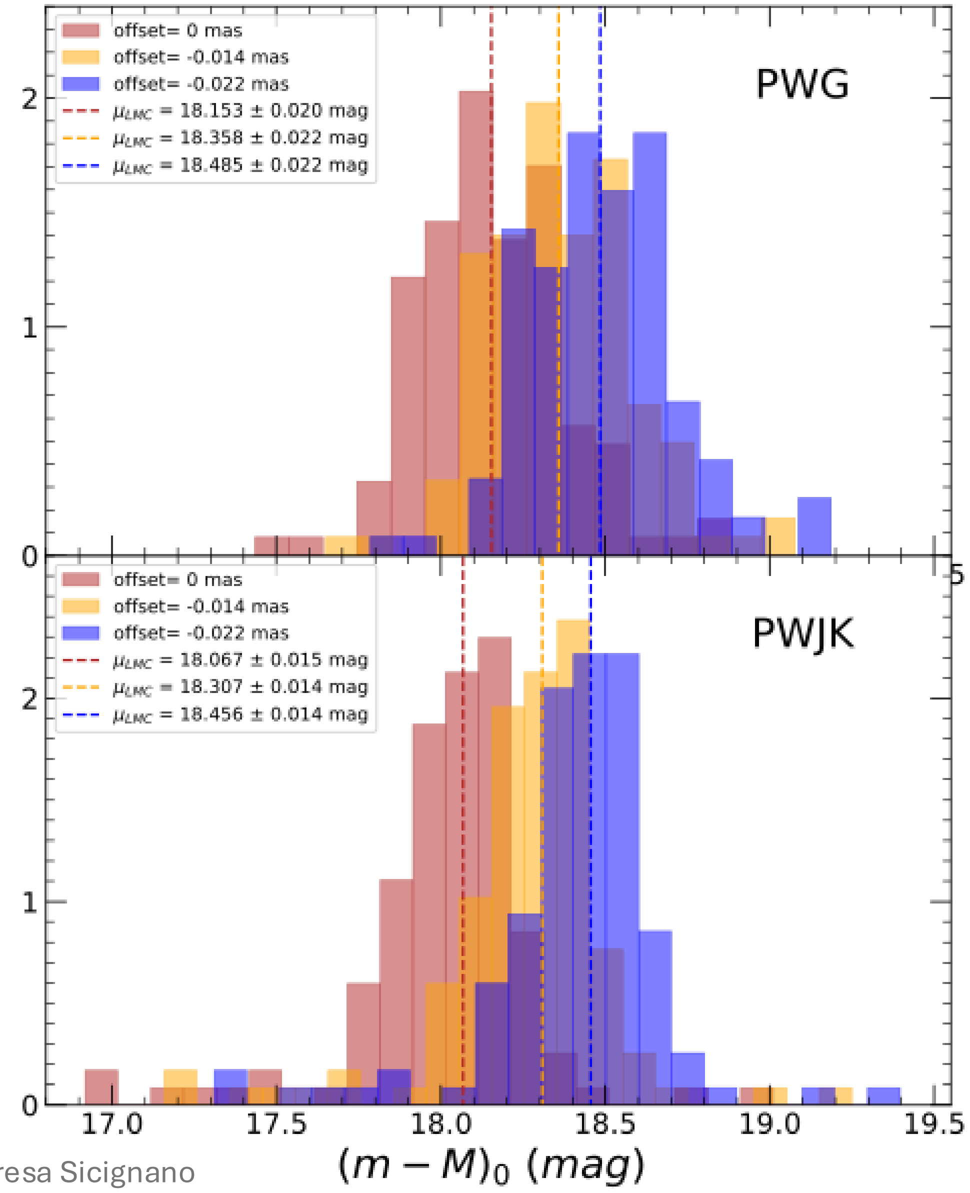
Rel. (1)	Mode (2)	α mag (3)	σ_α mag (4)	β mag/dex (5)	σ_β mag/dex (6)	RMS mag (7)	n.stars (8)	α mag (9)	σ_α mag (10)	β mag/dex (11)	σ_β mag/dex (12)	RMS mag (13)	n.stars (14)
		LMC						SMC					
PLY	F	17.109	0.036	−2.80	0.19	0.226	81/1	17.475	0.037	−2.62	0.23	0.192	48/0
PLY	1O	16.415	0.026	−3.61	0.20	0.133	32/3	16.962	0.043	−3.55	0.44	0.210	26/0
PLY	All	17.074	0.030	−2.82	0.15	0.21	115/2	17.487	0.035	−2.84	0.20	0.201	74/0
PLJ	F	16.962	0.028	−2.98	0.14	0.176	81/2	17.357	0.03	−2.75	0.20	0.159	47/1
PLJ	1O	16.370	0.025	−3.25	0.20	0.134	34/1	16.839	0.041	−3.70	0.42	0.201	26/0
PLJ	All	16.924	0.025	−2.95	0.12	0.174	116/2	17.380	0.031	−3.01	0.18	0.178	73/1
PLK	F	16.686	0.025	−3.12	0.13	0.155	78/5	17.073	0.032	−2.92	0.21	0.171	47/1
PLK	1O	16.126	0.024	−3.41	0.18	0.127	33/2	16.590	0.046	−3.75	0.44	0.223	27/0
PLK	All	16.667	0.022	−3.14	0.11	0.152	112/6	17.09	0.03	−3.08	0.17	0.174	72/3
PWVI	F	16.601	0.024	−3.14	0.13	0.148	80/4	16.942	0.026	−3.04	0.17	0.121	44/4
PWVI	1O	16.240	0.015	−2.61	0.11	0.041	19/16	16.379	0.023	−4.29	0.23	0.079	22/6
PWVI	All	16.589	0.021	−3.07	0.11	0.117	112/7	17.02	0.032	−3.41	0.18	0.164	75/1
PWG	F	16.768	0.031	−2.98	0.16	0.202	82/2	17.144	0.033	−3.18	0.21	0.158	46/2
PWG	1O	16.238	0.027	−3.23	0.22	0.143	33/2	16.664	0.045	−3.84	0.45	0.213	26/0
PWG	All	16.759	0.027	−3.05	0.13	0.175	116/3	17.161	0.030	−3.28	0.18	0.161	69/5
PWVK	F	16.541	0.022	−3.17	0.12	0.136	75/8	16.950	0.024	−3.14	0.16	0.126	42/6
PWVK	1O	15.991	0.026	−3.42	0.20	0.136	33/2	16.452	0.050	−3.77	0.48	0.243	27/0
PWVK	All	16.537	0.021	−3.21	0.10	0.136	109/9	16.962	0.037	−3.25	0.21	0.216	75/0
PWYK	F	16.484	0.023	−3.30	0.12	0.141	76/6	16.888	0.026	−3.14	0.17	0.134	43/5
PWYK	1O	15.944	0.027	−3.41	0.21	0.140	33/2	16.307	0.023	−3.78	0.26	0.093	19/7
PWYK	All	16.470	0.021	−3.29	0.10	0.139	109/8	16.915	0.038	−3.40	0.22	0.222	74/0
PWJK	F	16.504	0.025	−3.21	0.13	0.152	76/7	16.874	0.029	−3.04	0.19	0.1478	44/4
PWJK	1O	15.951	0.028	−3.50	0.21	0.146	33/2	16.386	0.048	−4.12	0.49	0.235	26/0
PWJK	All	16.494	0.022	−3.25	0.11	0.148	109/9	16.892	0.035	−3.21	0.20	0.200	72/2

Sicignano +2025, A&A, under revision.

IMPACT ON THE DISTANCE SCALE

Comparison between our LMC distance moduli based on Gaia DR3 parallaxes of Galactic ACs and the geometric one based on eclipsing binaries ($\mu_{LMC} = 18.477 \pm 0.003 \pm 0.027\ mag$)

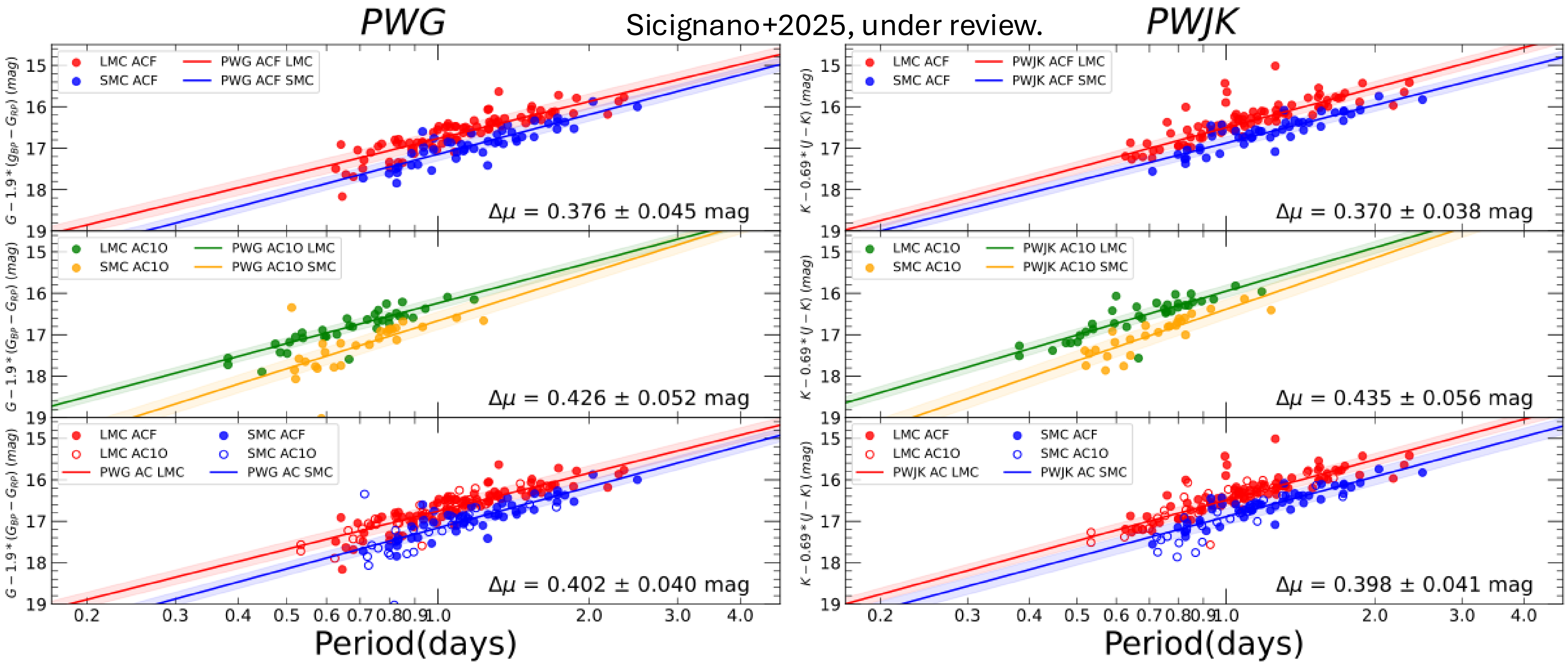




Sicignano +2025,A&A, in press.

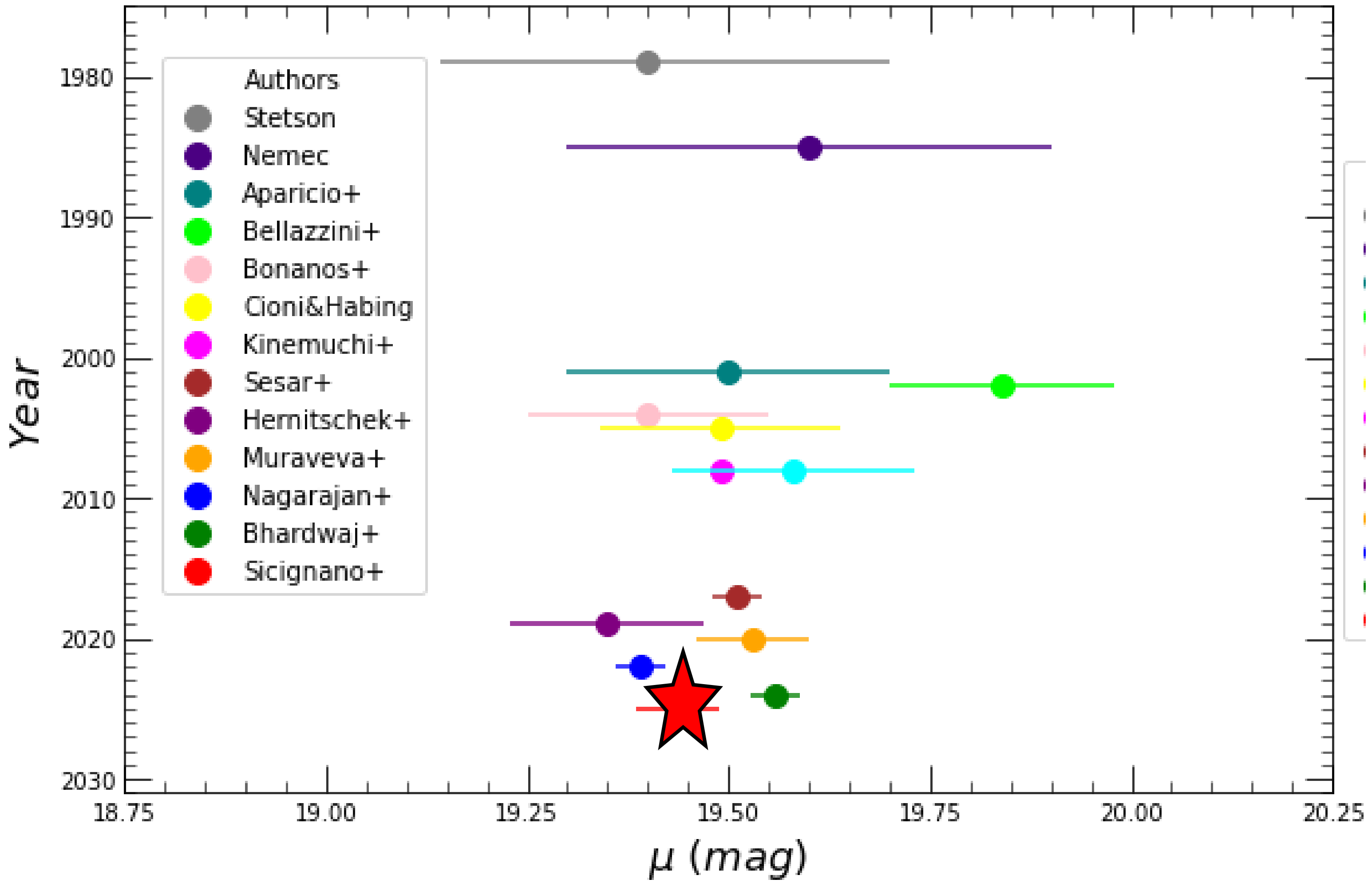
LMC/SMC RELATIVE DISTANCE

Sicignano+2025, under review.



DRACO

To calibrate the zero points of our relations we used the distance modulus of the LMC as measured by Pietrzynski et al. (2019) based on eclipsing binaries ($\mu_{LMC} = 18.477 \pm 0.003 \pm 0.027\ mag$)



Sicignano +2025,A&A, under review.

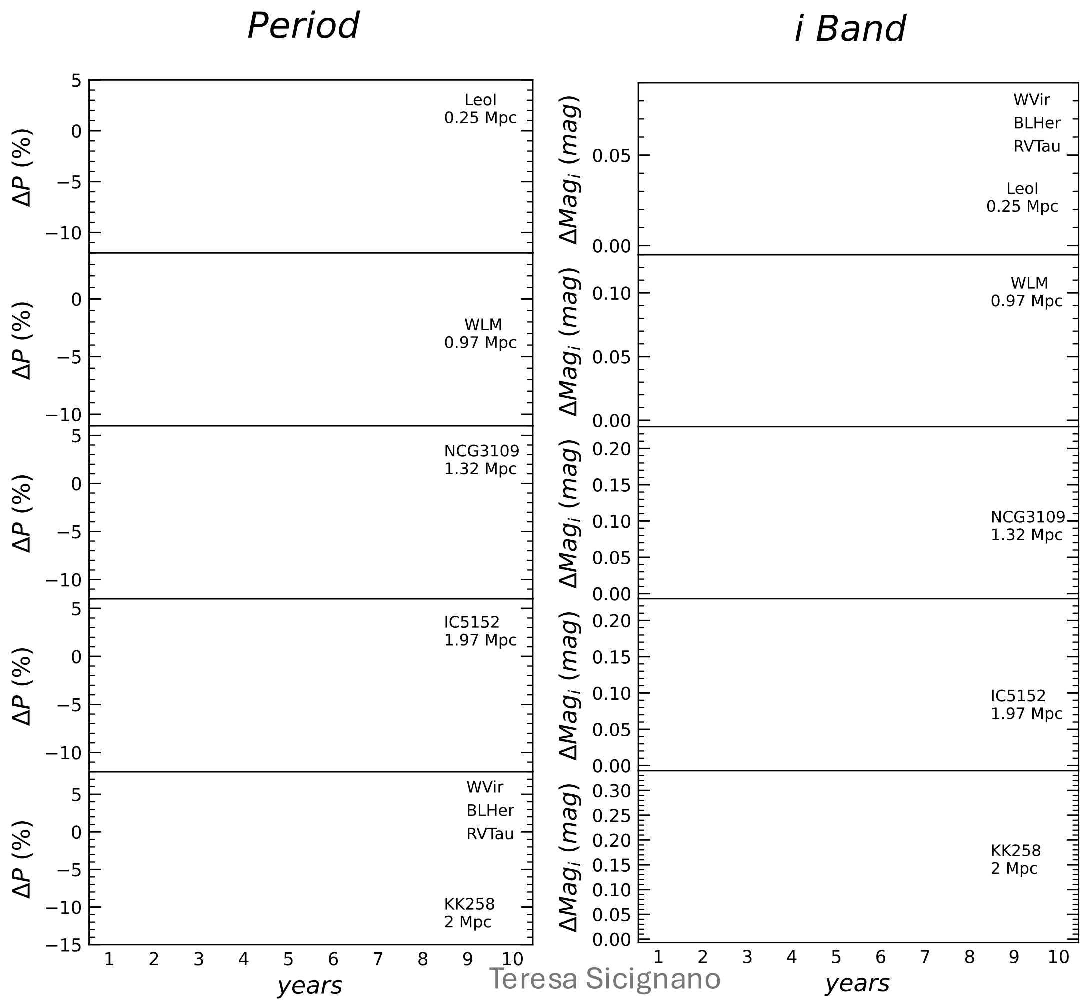
Conclusions

- The most accurate H_0 coming from the Late Universe is based on CC+SN Ia 3 run distance scale.
- We are pursuing an alternative to it based on T2Cs and Acs.
- Same base physics but sample completely independent so we can check systematics and improve statistics.

Future prospectives

TYPE II CEPHEIDS DIRECTLY IN SN Ia HOST

LSST VERA RUBIN AND NANCY GRACE ROMAN SPACE TELESCOPES.



- PERIOD – LUMINOSITY RELATION
- PRESENCE IN ANCHORS
- ZERO POINT CALIBRATION
- SN Ia HOST

Sicignano+, in prep.

Thank you for your attention!

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DI CAPODIMONTE

VMC

C-MetaL L

ANOMALIES & TENSIONS IN COSMOLOGY
COSMOVERSE

MOST 4

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