ESO

SSM Scuola Superiore Meridionale

INAF OSSERVATORIO ASTRONOMICO DI CAPODIMONTE

WST the Wide-field Spectroscopic Telescope

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

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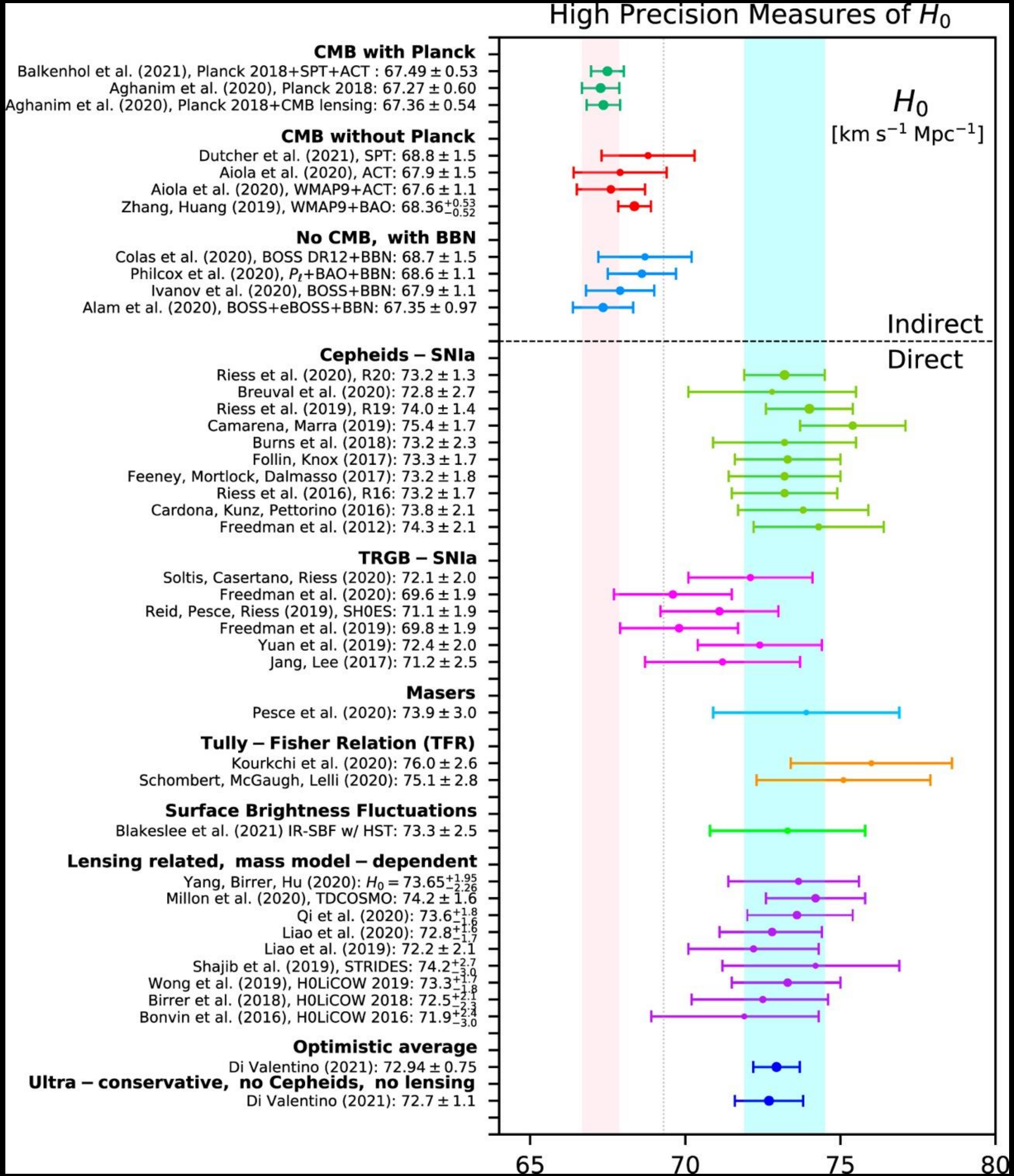
In collaboration with Vincenzo Ripepi, Marina Rejkuba, Martino Romaniello, Marcella Marconi, Giulia De Somma and the stellar variability group of Naples

Italian Workshop in memory of Bianca Garilli

Naples, March 12, 2025

Hubble tension



Di Valentino 2021

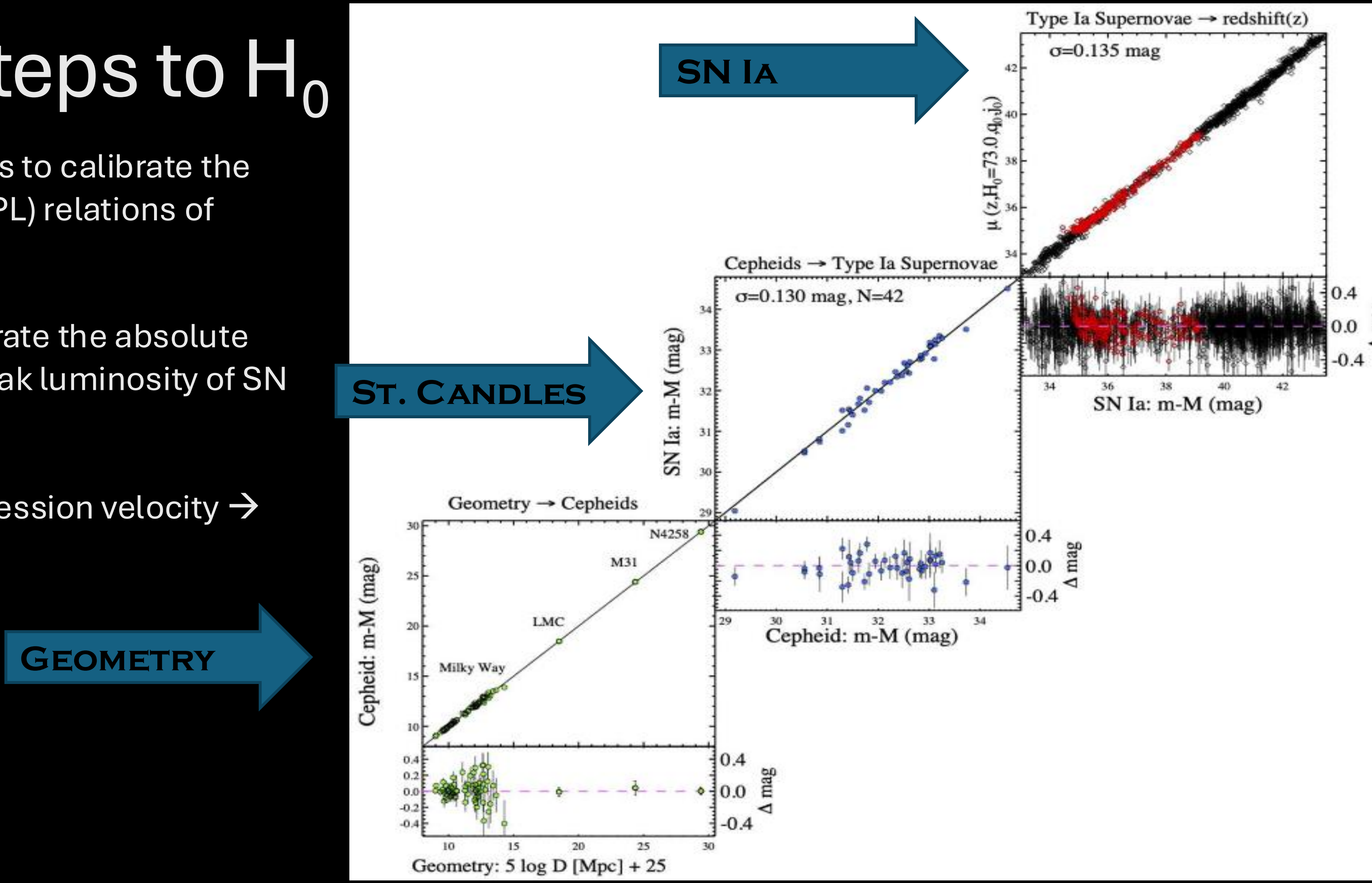
The extragalactic distance scale.

The three steps to H_0

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

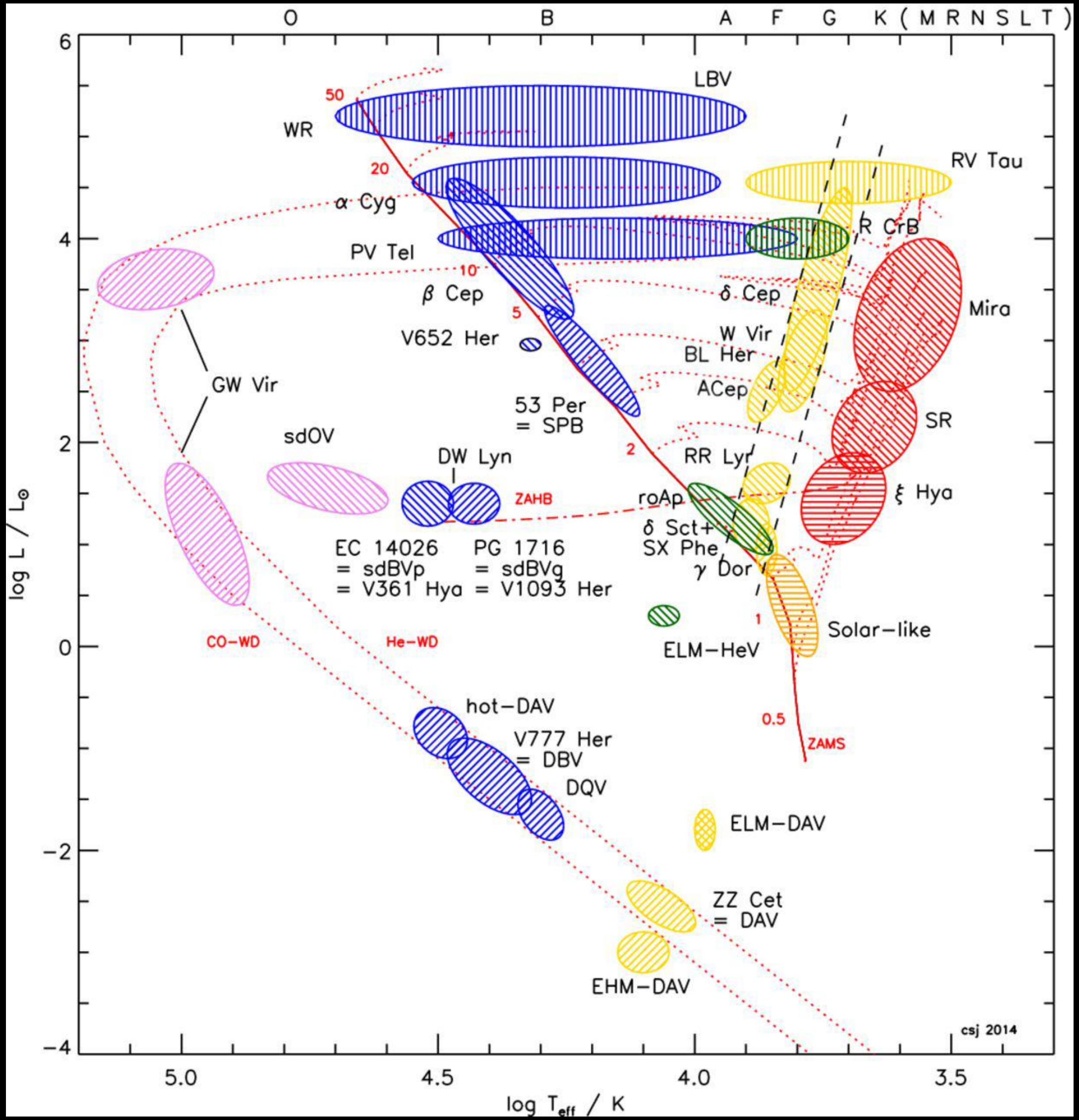
2. PL relations to calibrate the absolute magnitude of the peak luminosity of SN Ia

3. SN Ia distance + recession velocity → H_0



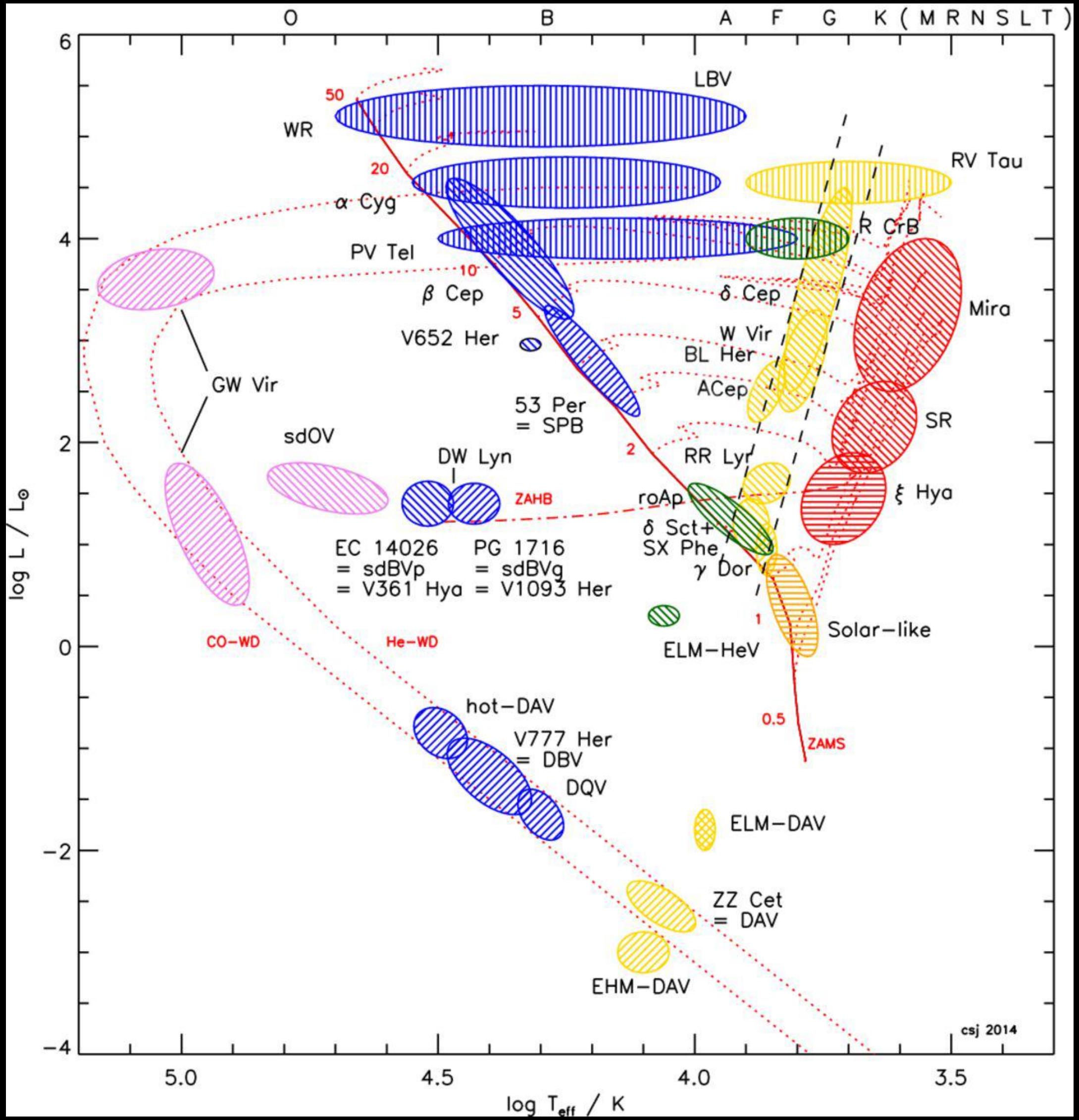
Type II Cepheids

BL Herculis	W Virginis	RV Tauri
Low mass	Low mass	Intermediate-mass
t>10 Gyrs	t>10 Gyrs	t>1-2 Gyrs
Post-HB	AGB stars	Post AGB stars
1-4 days	4-20 days	20-150 days
L > RRLyrae	L> BLHer	L> WVir
	* pWVir	



Anomalous Cepheids

≈1.3-2.3 $M_\odot$
Giants with partially He-degenerate core
0.5-2.5 days/ 0.4 – 1 day
F, 1O
L(T2Cs)<L(Acep)<L(CCs)
$Z<10^{-4}$



Distance indicators

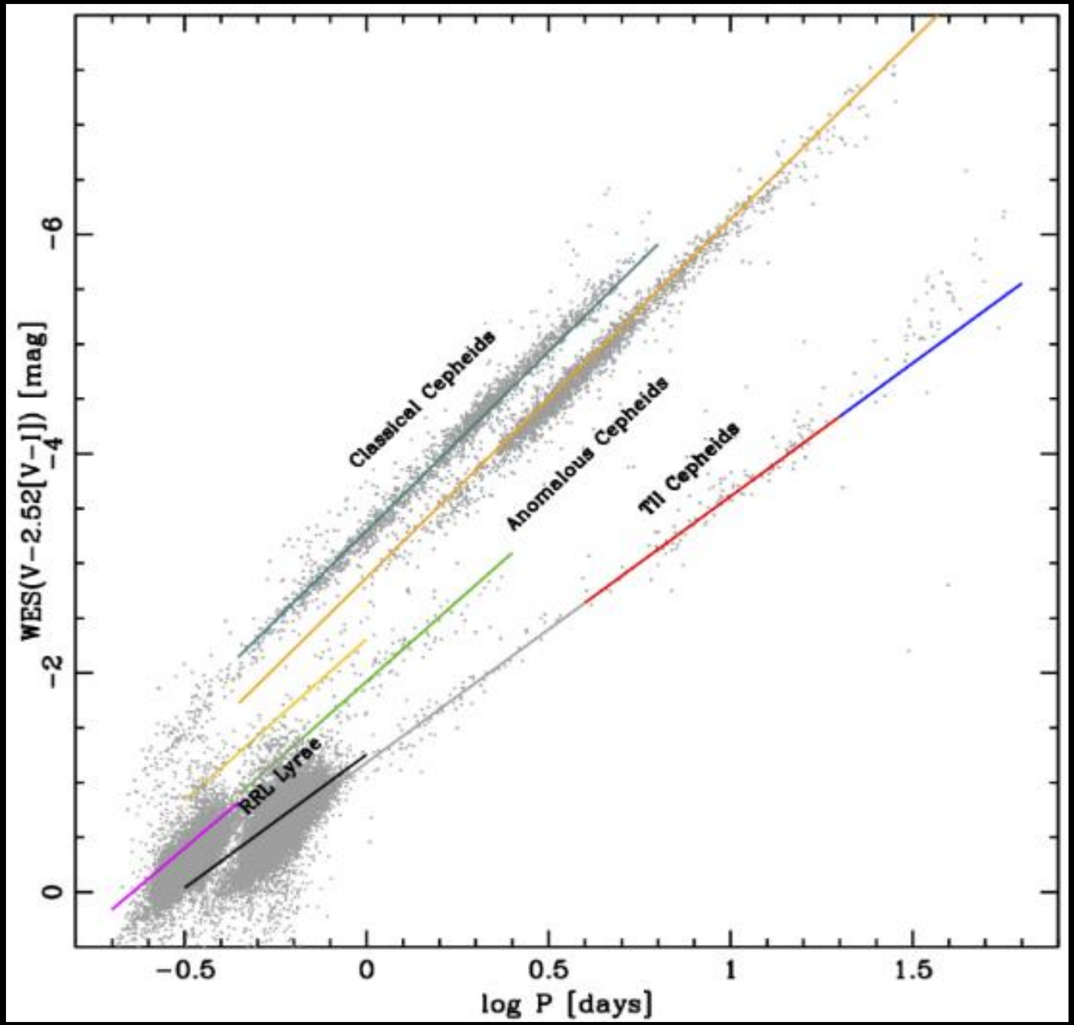
Period Wesenheit (*PW*)

Defined to be a reddening-free quantity:

$$W \equiv V - R_V \cdot (B - V)$$

$$W = V_0 - R(B - V)_0$$

(Madore+1982)

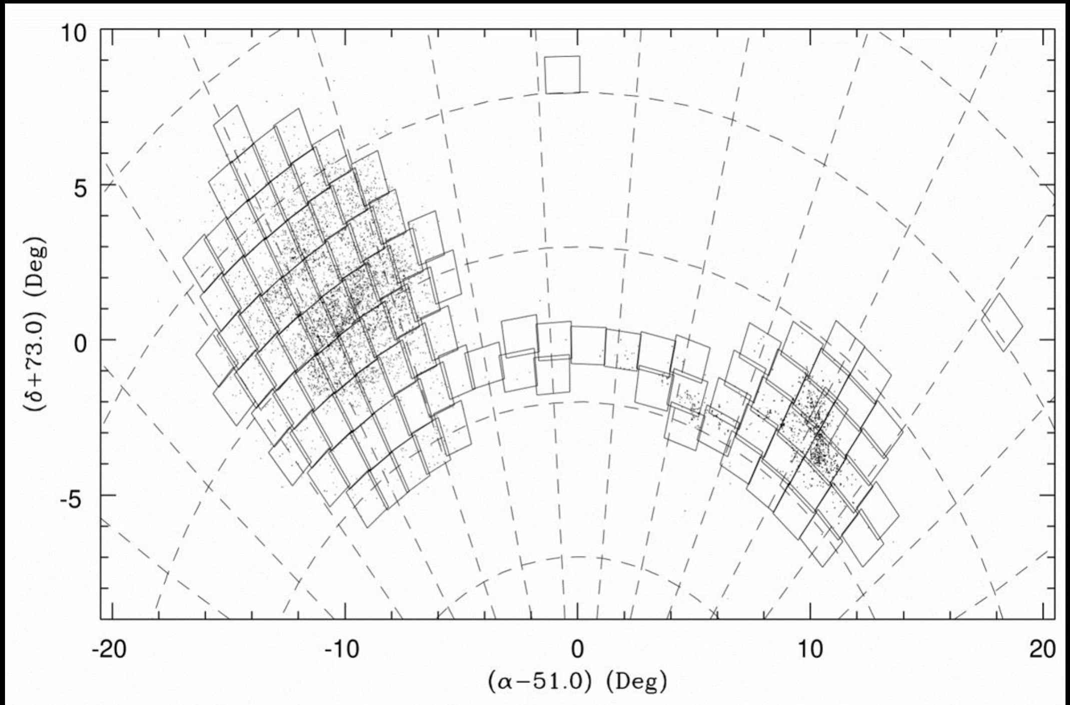


📍PERIOD–LUMINOSITY RELATION

📍PRESENCE IN ANCHORS

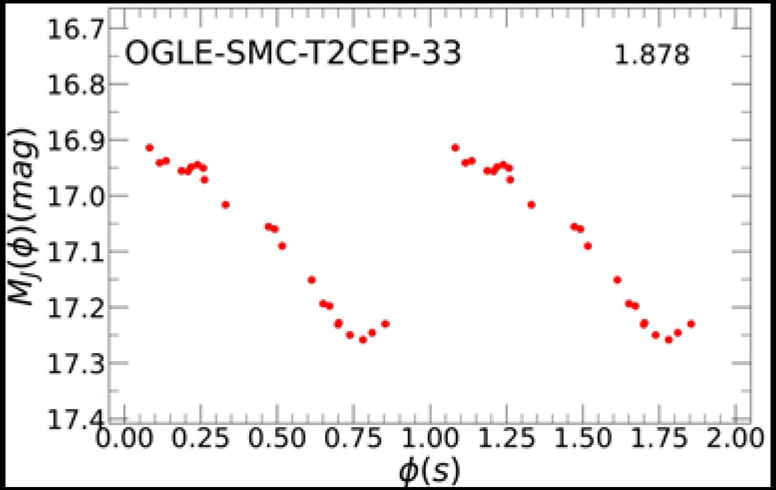
- VMC is an ESO public survey (P.I. M.-R. Cioni)
- Observations in YJKs with VIRCAM@VISTA 4 m (Paranal, Chile)
- Data reduction with the VISTA Data Flow System (VDFS) pipeline at CASU (Cambridge Astronomical Survey Unit)
- Catalogues handling through the Vista Science Archive (VSA)

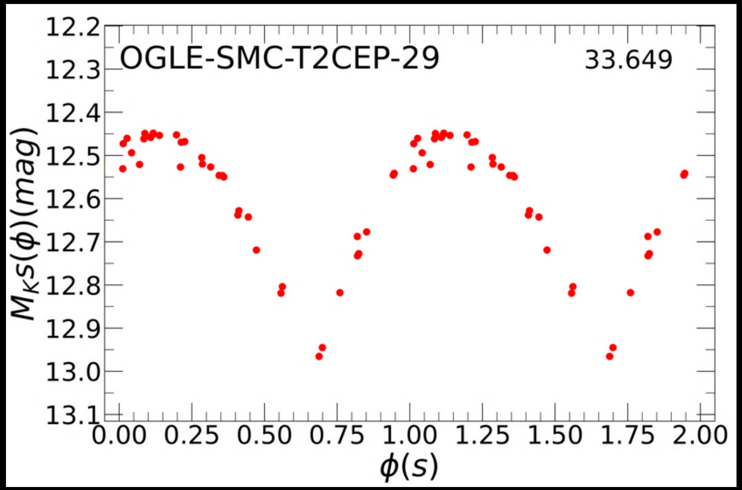
339 T2Cs and 198 ACs with VMC photometry in the Magellanic Clouds



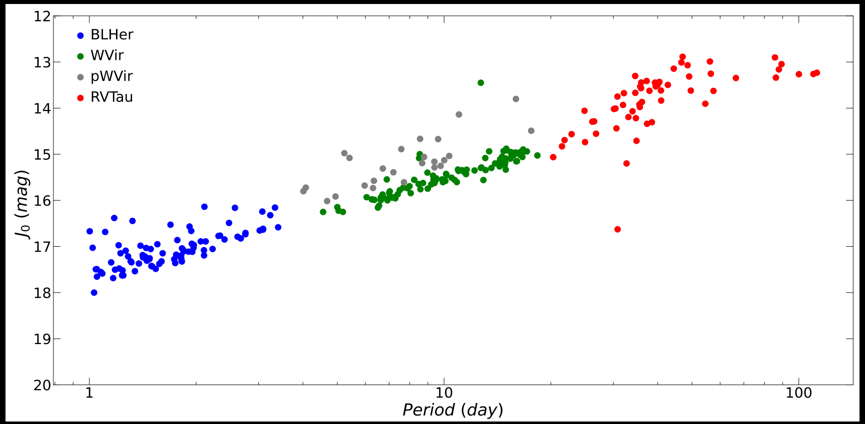
TYPE II CEPHEIDS

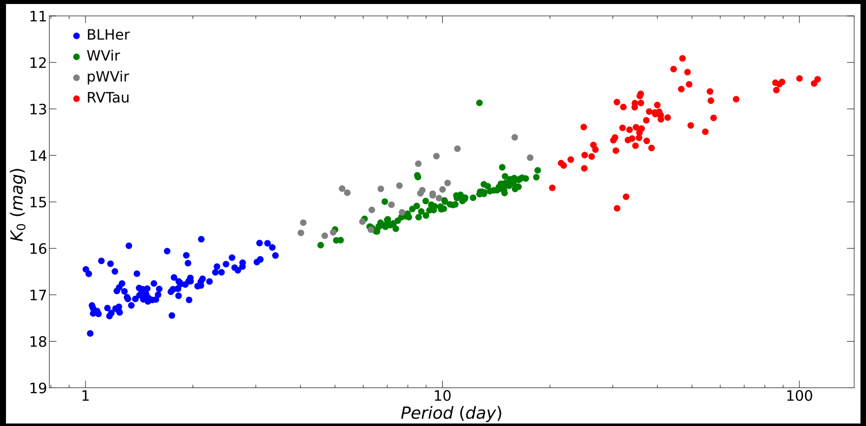
LIGHT CURVES





OBSERVED PERIOD – LUMINOSITY RELATIONS

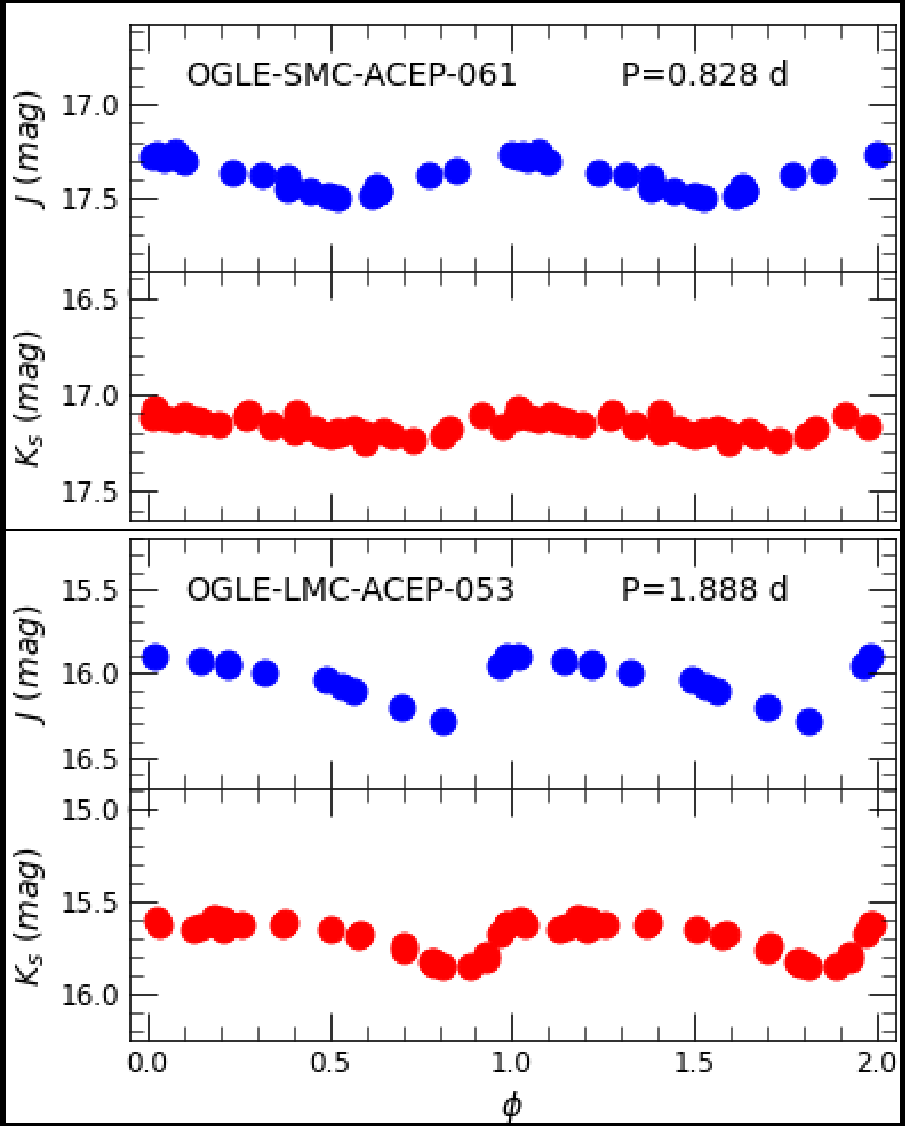




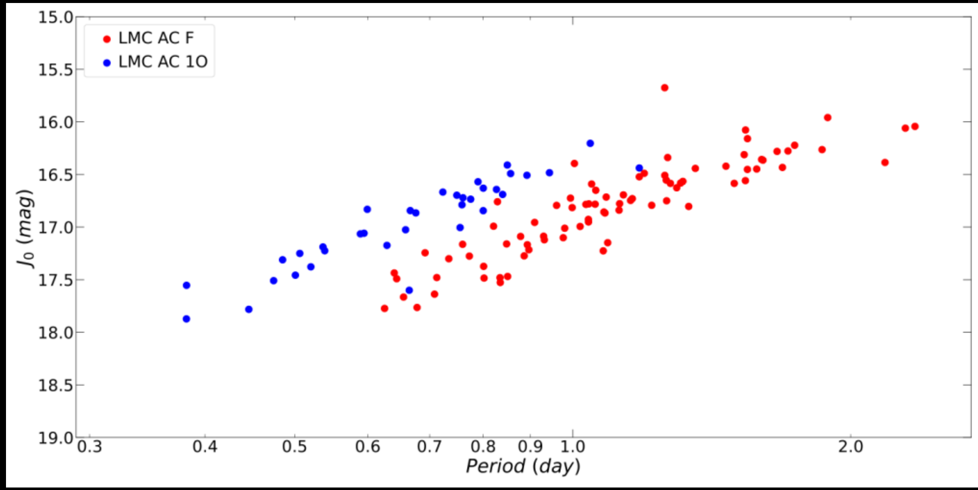
Sicignano+2024, A&A, 685, A41.

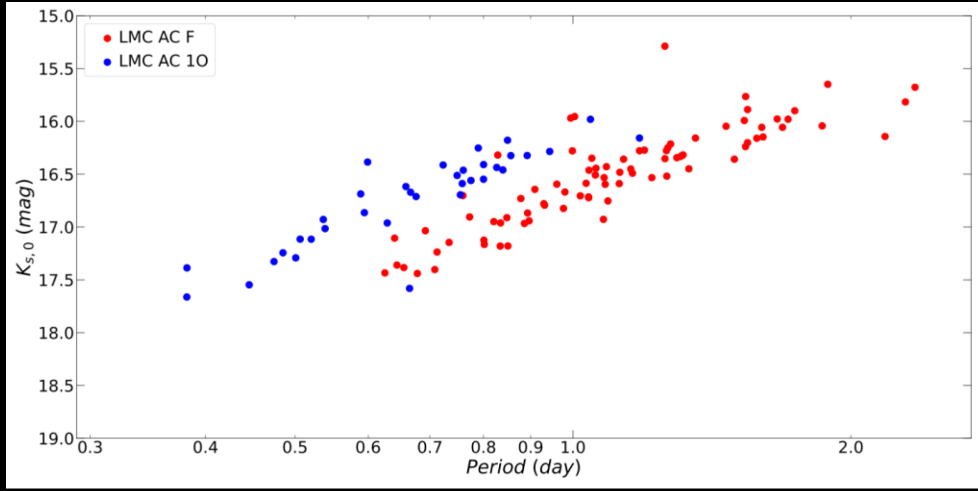
ANOMALOUS CEPHEIDS

LIGHT CURVES



OBSERVED PERIOD – LUMINOSITY RELATIONS

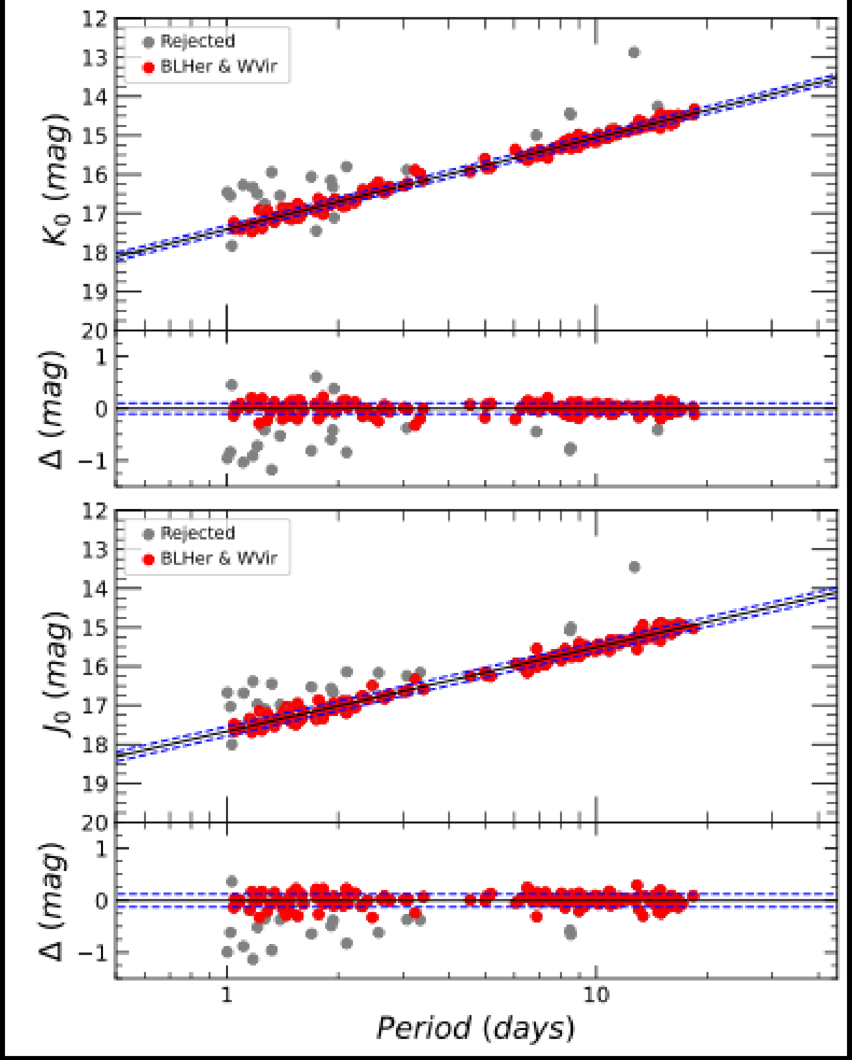




Sicignano+2025, A&A, in submission.

TYPE II CEPHEIDS

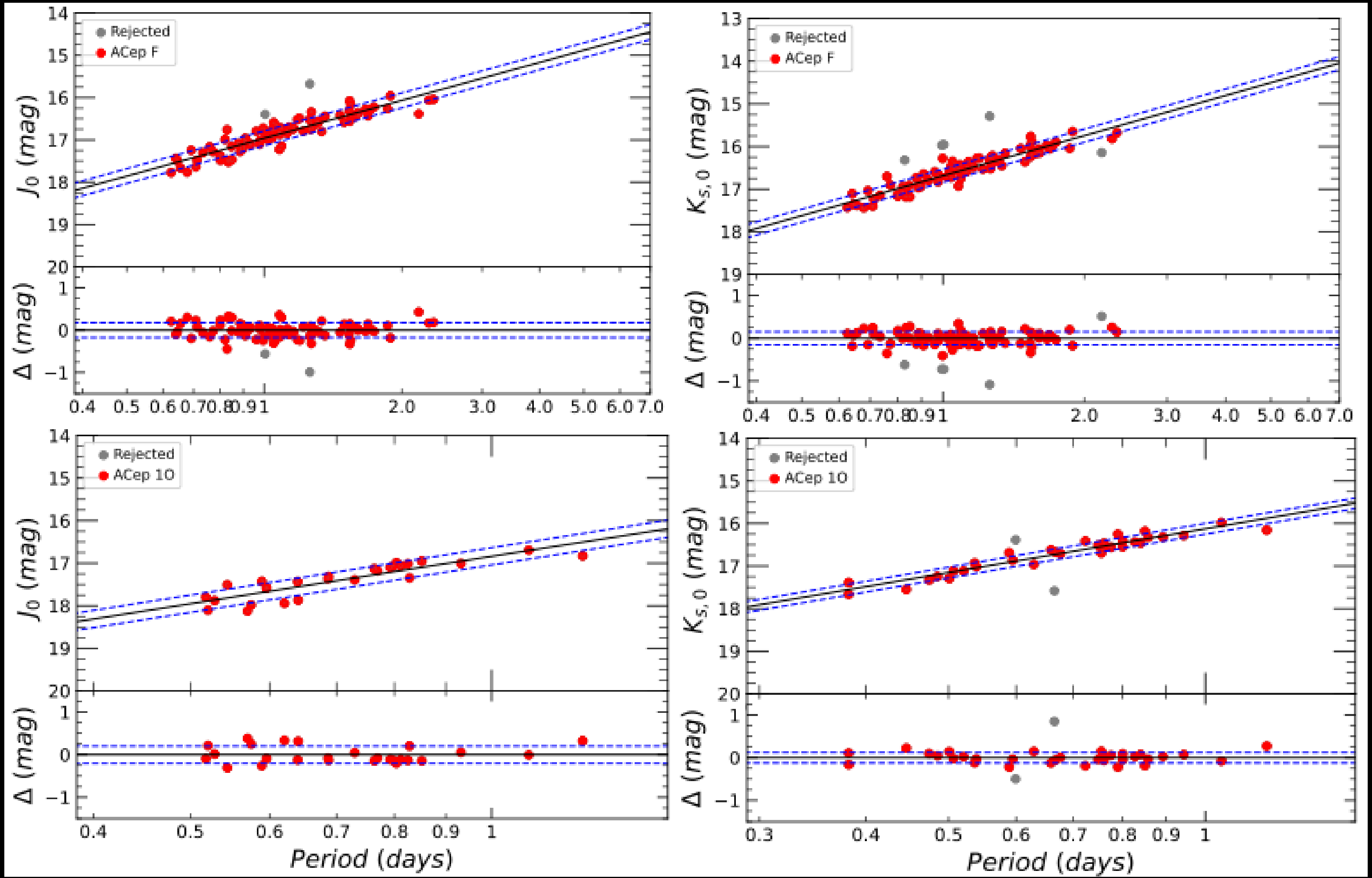
FITTED PERIOD – LUMINOSITY RELATIONS



Relation (1)	Group (2)	α mag (3)	σ_α mag (4)	β mag/dex (5)	σ_β mag/dex (6)	γ (7)	σ_γ (8)	RMS mag (9)	Used stars (10)	Total stars (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

ANOMALOUS CEPHEIDS

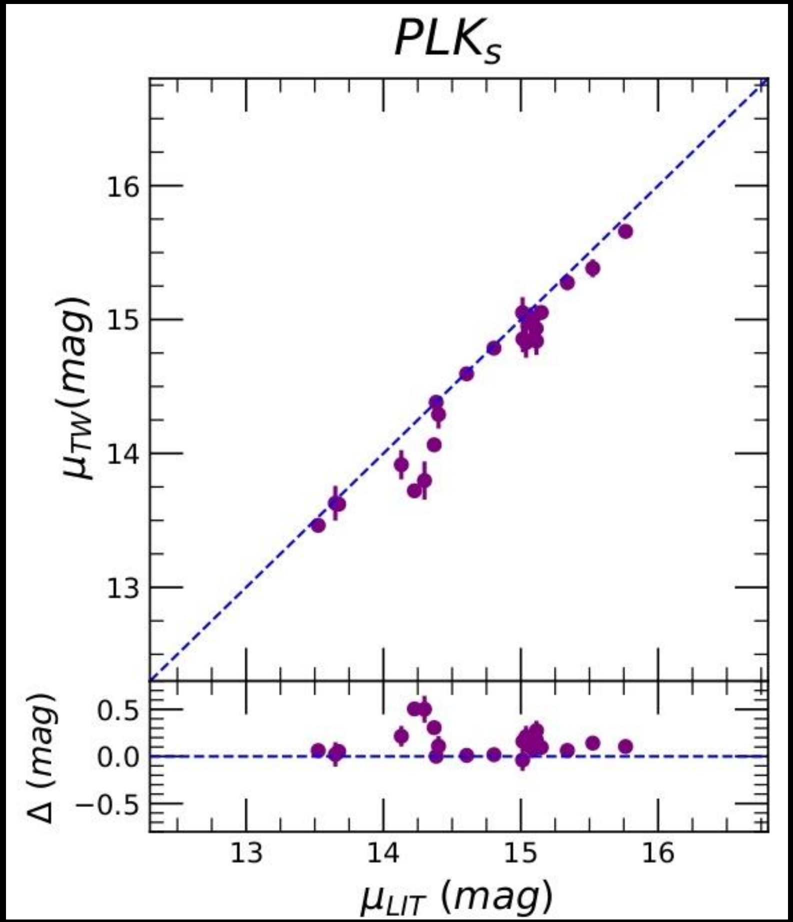
FITTED PERIOD – LUMINOSITY RELATIONS

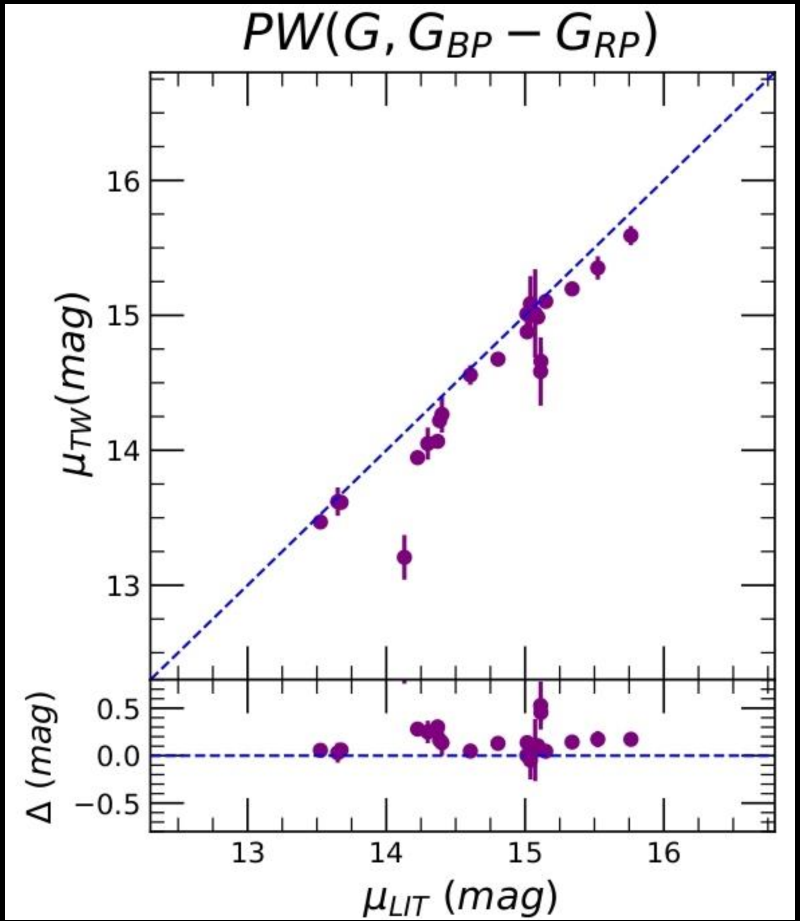


Rel. (1)	Mode (2)	α mag (3)	σ_α mag (4)	β mag/dex (5)	σ_β mag/dex (6)	RMS mag (7)	n.stars (8)
		LMC					
PLI	F	17.330	0.028	−3.01	0.15	0.171	79/5
PLI	1O	16.706	0.032	−3.28	0.24	0.166	34/1
PLI	All	17.287	0.026	−2.95	0.13	0.179	113/6
PLV	F	17.801	0.035	−2.82	0.19	0.223	80/4
PLV	1O	17.096	0.041	−3.31	0.32	0.221	35/0
PLV	All	17.735	0.035	−2.74	0.17	0.242	115/4
PLG	F	17.784	0.037	−2.99	0.20	0.238	83/1
PLG	1O	17.054	0.038	−3.27	0.29	0.202	34/1
PLG	All	17.708	0.036	−2.85	0.18	0.253	117/2
PLBP	F	17.871	0.041	−2.75	0.22	0.266	82/2
PLBP	1O	17.201	0.048	−3.05	0.38	0.258	35/0
PLBP	All	17.812	0.041	−2.62	0.20	0.288	118/1
PLRP	F	17.356	0.034	−2.78	0.18	0.214	81/3
PLRP	1O	16.758	0.036	−3.13	0.29	0.195	35/0
PLRP	All	17.313	0.030	−2.76	0.15	0.208	115/4
PLY	F	17.109	0.036	−2.80	0.19	0.226	81/1
PLY	1O	16.415	0.026	−3.61	0.20	0.133	32/3
PLY	All	17.074	0.030	−2.82	0.15	0.21	115/2
PLJ	F	16.962	0.028	−2.98	0.14	0.176	81/2
PLJ	1O	16.370	0.025	−3.25	0.20	0.134	34/1
PLJ	All	16.924	0.025	−2.95	0.12	0.174	116/2
PLK	F	16.686	0.025	−3.12	0.13	0.155	78/5
PLK	1O	16.126	0.024	−3.41	0.18	0.127	33/2
PLK	All	16.667	0.022	−3.14	0.11	0.152	112/6
PWVI	F	16.601	0.024	−3.14	0.13	0.148	80/4
PWVI	1O	16.240	0.015	−2.61	0.11	0.041	19/16
PWVI	All	16.589	0.021	−3.07	0.11	0.117	112/7
PWG	F	16.768	0.031	−2.98	0.16	0.202	82/2
PWG	1O	16.238	0.027	−3.23	0.22	0.143	33/2
PWG	All	16.759	0.027	−3.05	0.13	0.175	116/3
PWVK	F	16.541	0.022	−3.17	0.12	0.136	75/8
PWVK	1O	15.991	0.026	−3.42	0.20	0.136	33/2
PWVK	All	16.537	0.021	−3.21	0.10	0.136	109/9
PWYK	F	16.484	0.023	−3.30	0.12	0.141	76/6
PWYK	1O	15.944	0.027	−3.41	0.21	0.140	33/2
PWYK	All	16.470	0.021	−3.29	0.10	0.139	109/8
PWJK	F	16.504	0.025	−3.21	0.13	0.152	76/7
PWJK	1O	15.951	0.028	−3.50	0.21	0.146	33/2
PWJK	All	16.494	0.022	−3.25	0.11	0.148	109/9

IMPACT ON THE DISTANCE SCALE

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

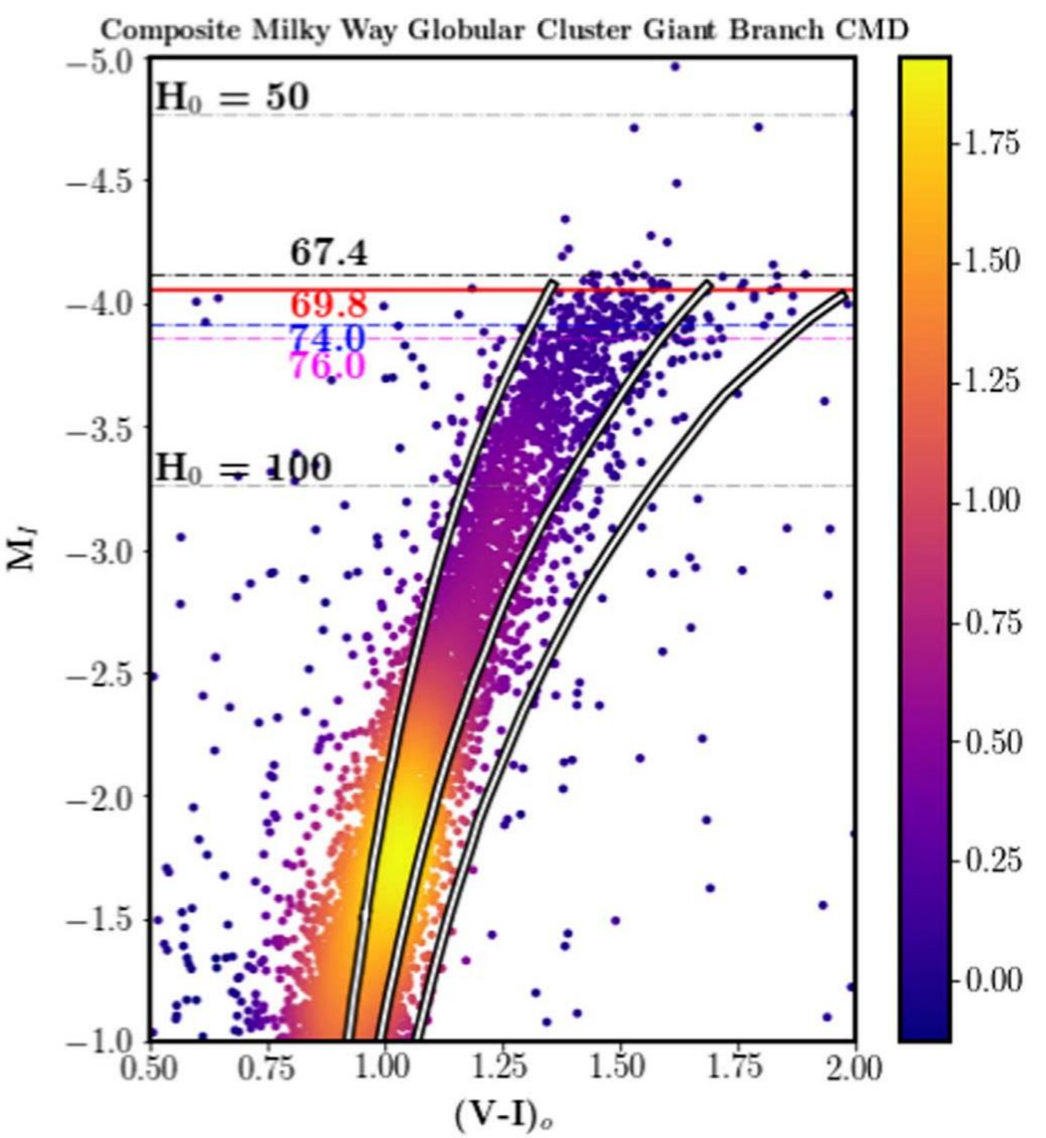


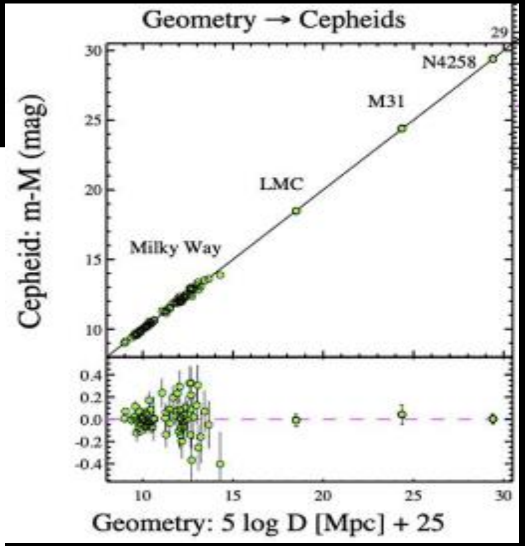


The distance moduli of GGCs appear **overestimated** up to **3%**.

The first step to H_0

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



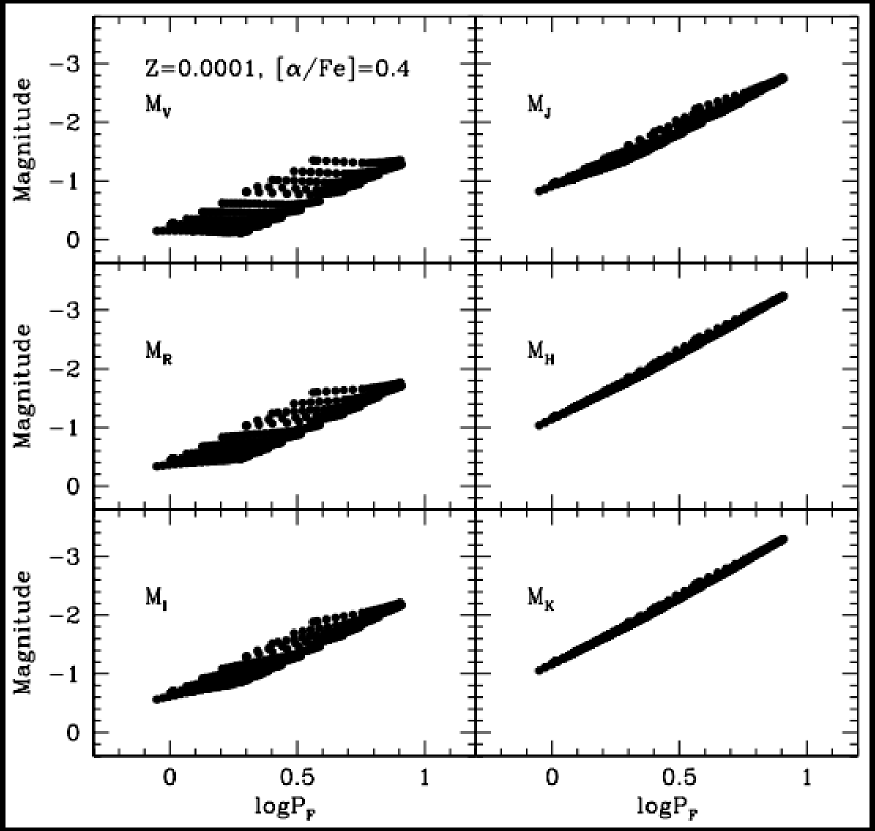


Riess+2022

Freedman+ 2021

📍UNCERTAINTES: TO BE OR NOT TO BE PLZ?

TYPE II CEPHEIDS:
THEORY? OBSERVATIONS?



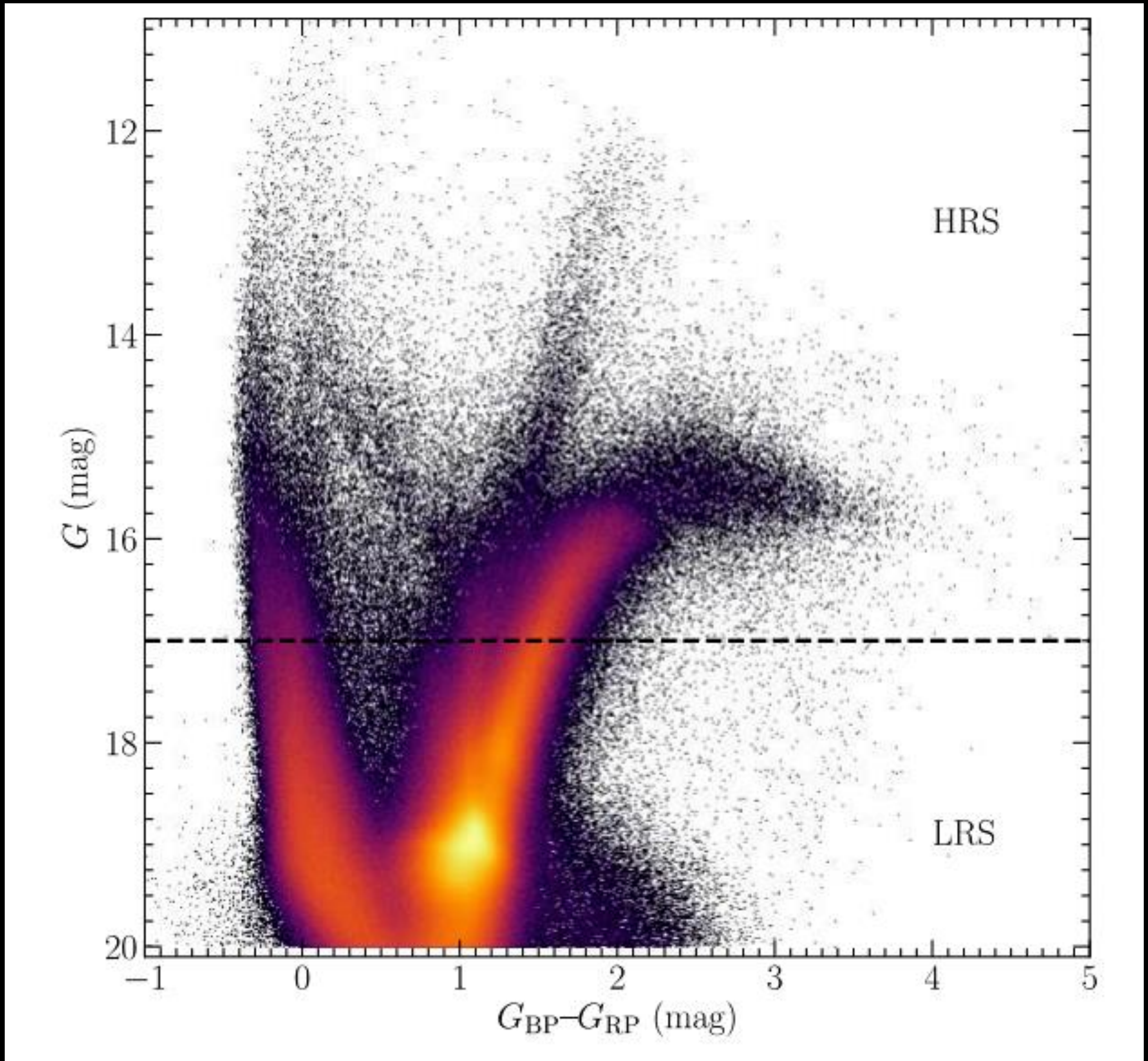
Di Criscienzo+2007

- Metallicity spanning of Pop II stars in the LMC.
- Predicted PL dependence on metallicity.
- 7 Galactic T2C show a dependence
  & No dependence in GGCs.

4MOST

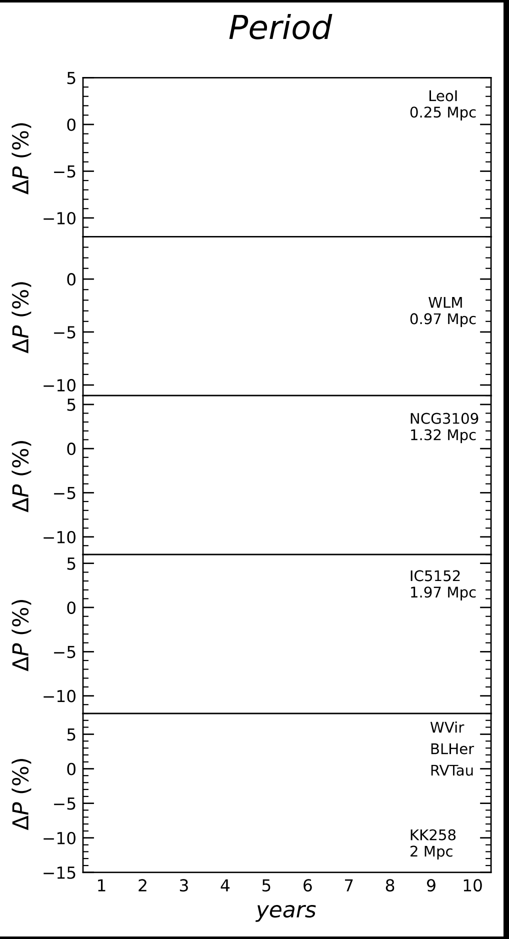
High resolution limit in the G band ~ 17 mag

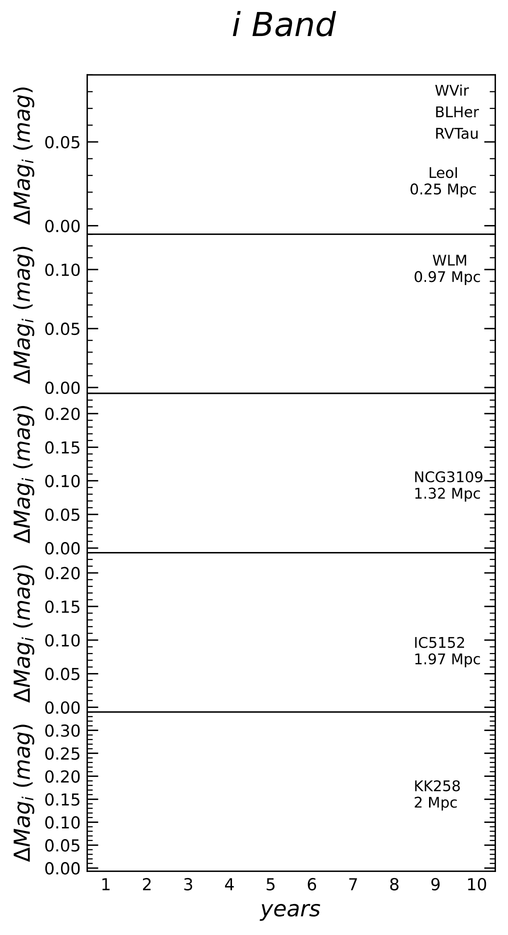
Low resolution limit in the G band ~ 20 mag



Synergies:
GAIA DR5 2030
LSST starting from 2026

Reclassification and discoveries for variable stars





Sicigano+,in prep.

WST MOS

High resolution mode up to mag V= 20 mag

Low resolution mode up to mag V= 22.5 mag

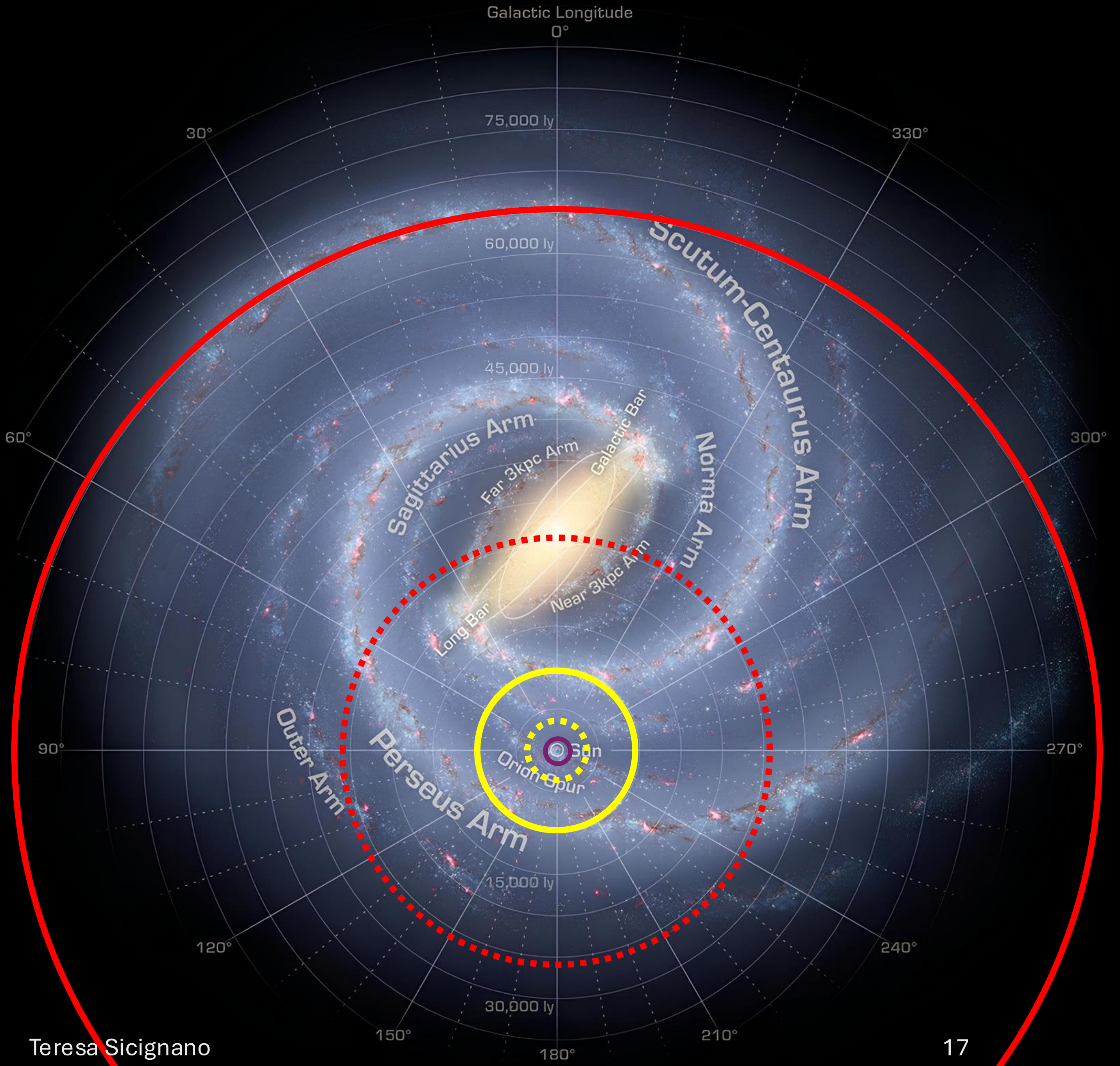
Gaia DR3 Spectroscopy

4MOST MS Sun-like 1 kpc

WST MS Sun-like 3 kpc

4MOST Red Giant 8 kpc

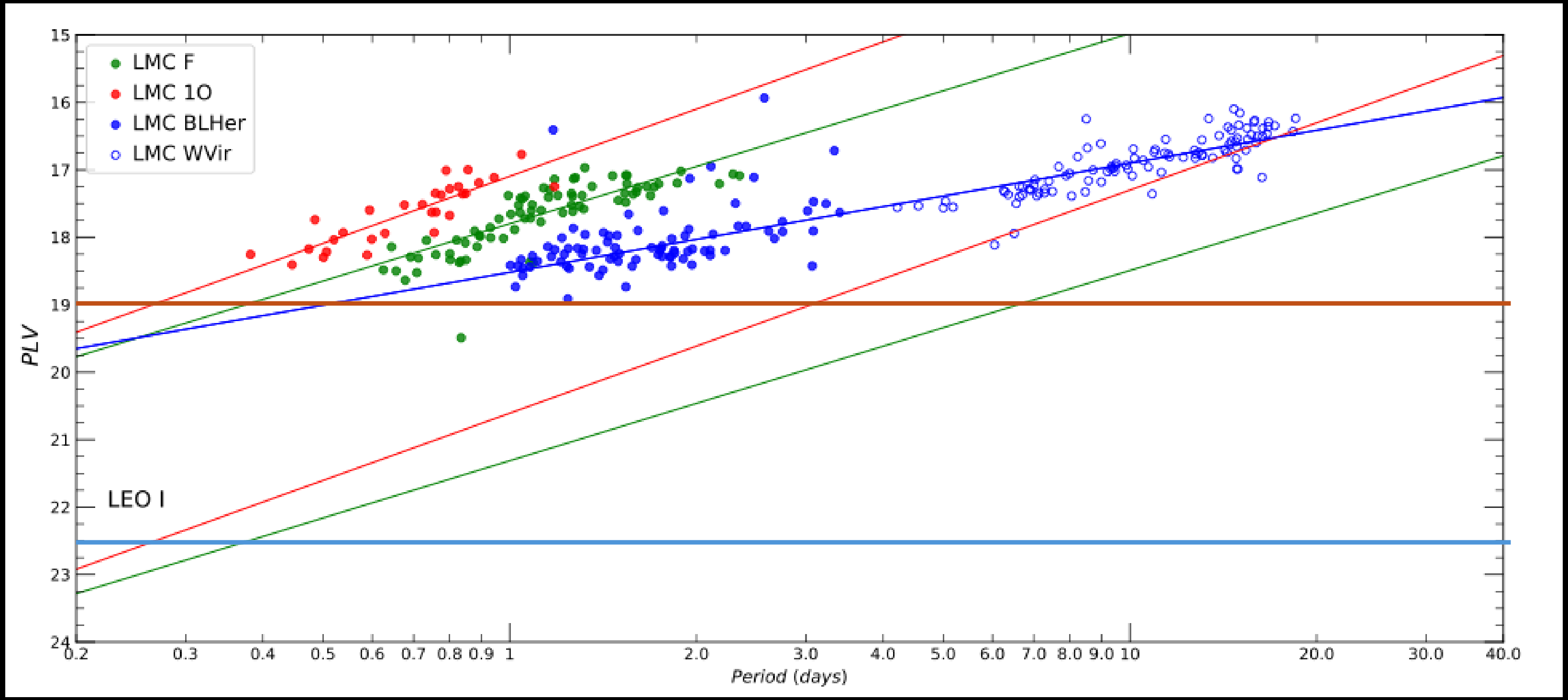
WST Red Giant 20 kpc



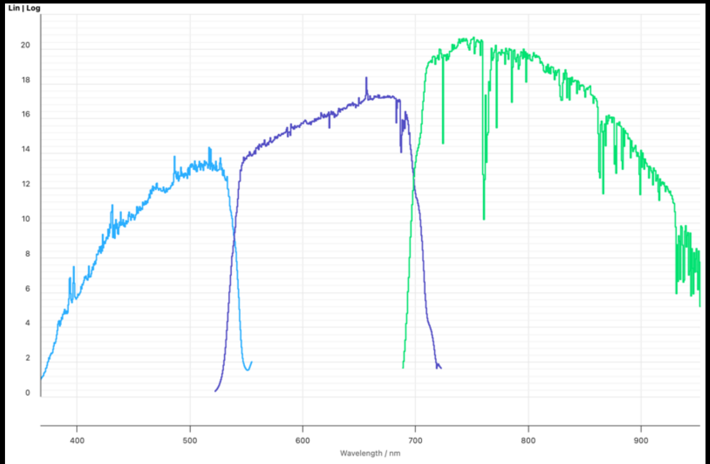
Thanks to F.Ficara

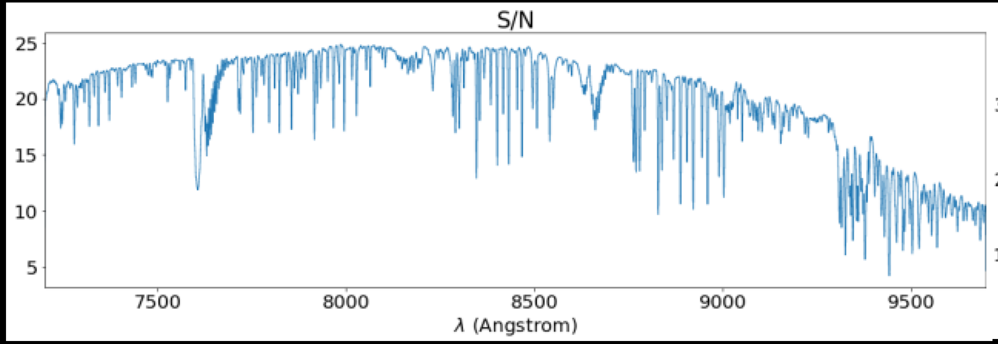
Low resolution

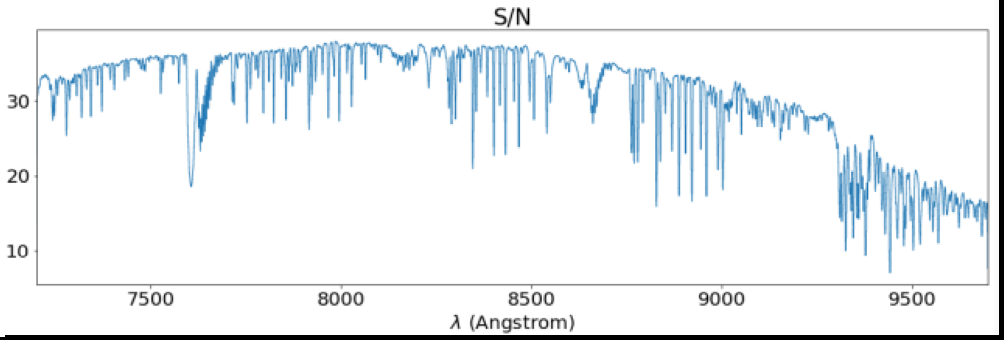
4 hours of observation (1800s*8),



4MOST up to magV~19 mag





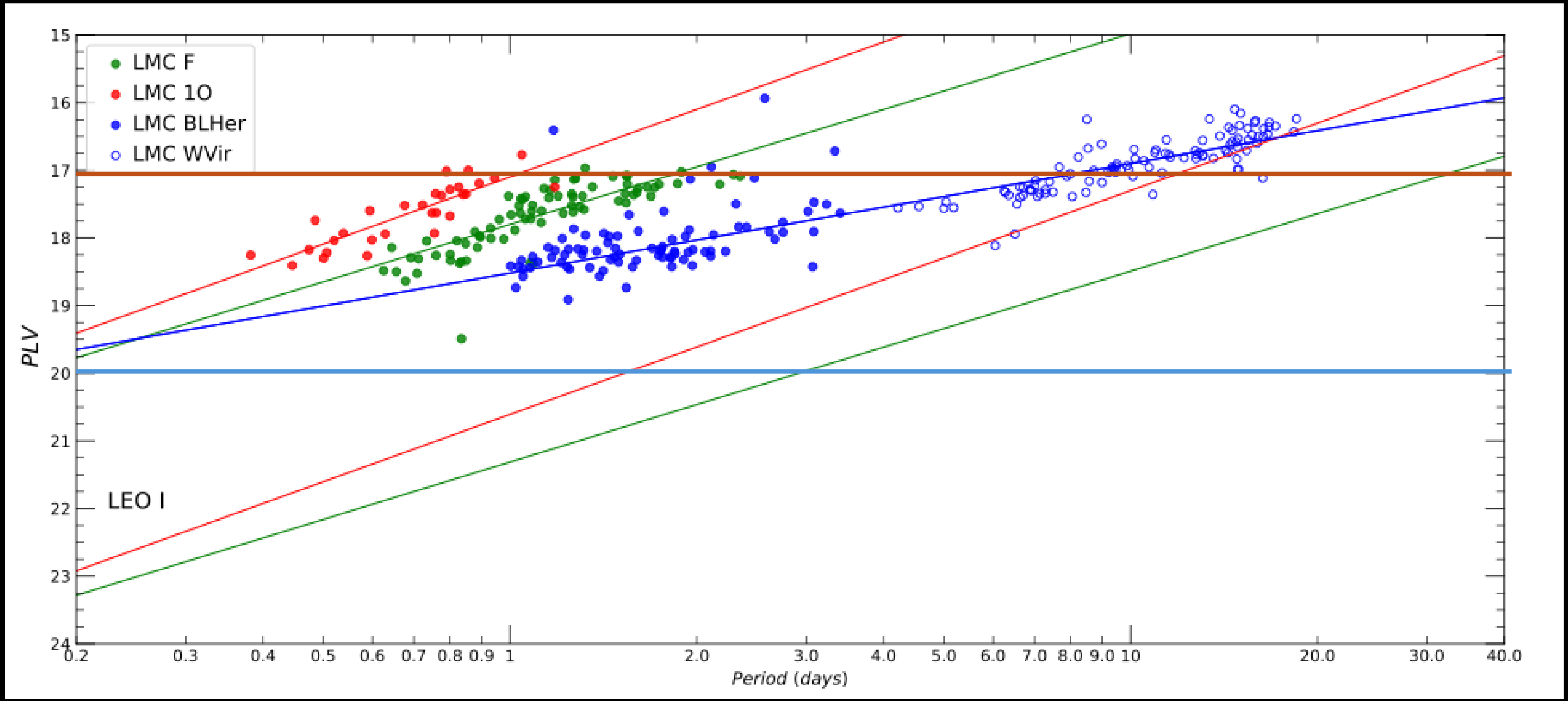


WST up to magV~22.5 mag

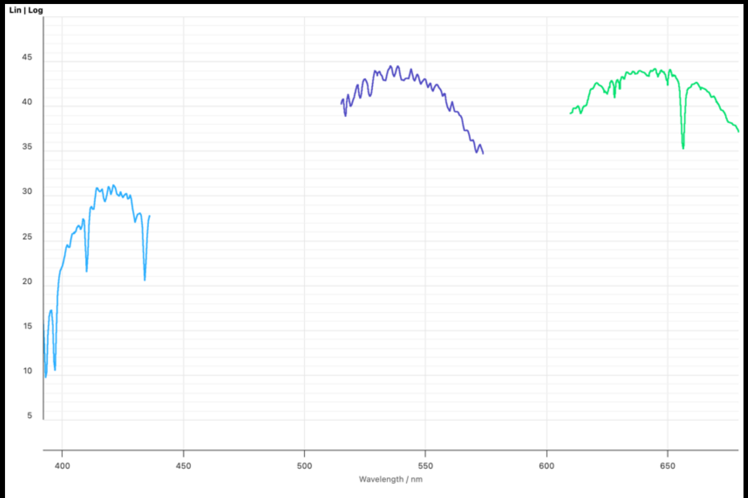
Carina, Fornax , Sextans, Leo I

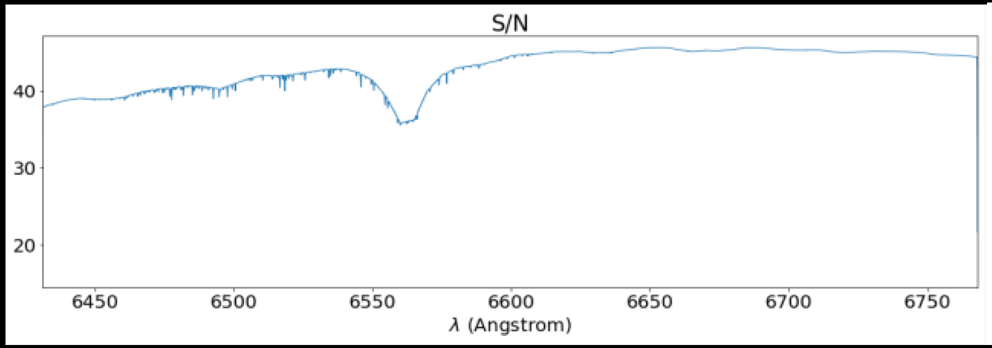
High resolution

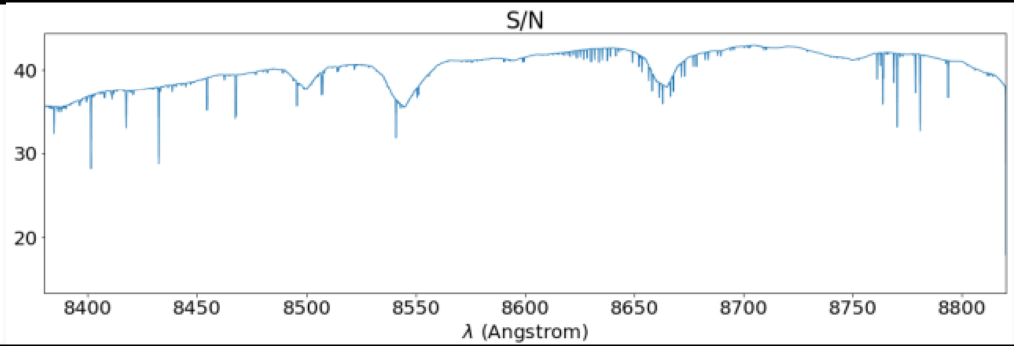
4 hours of observation (1800s*8),



4MOST up to magV~17 mag



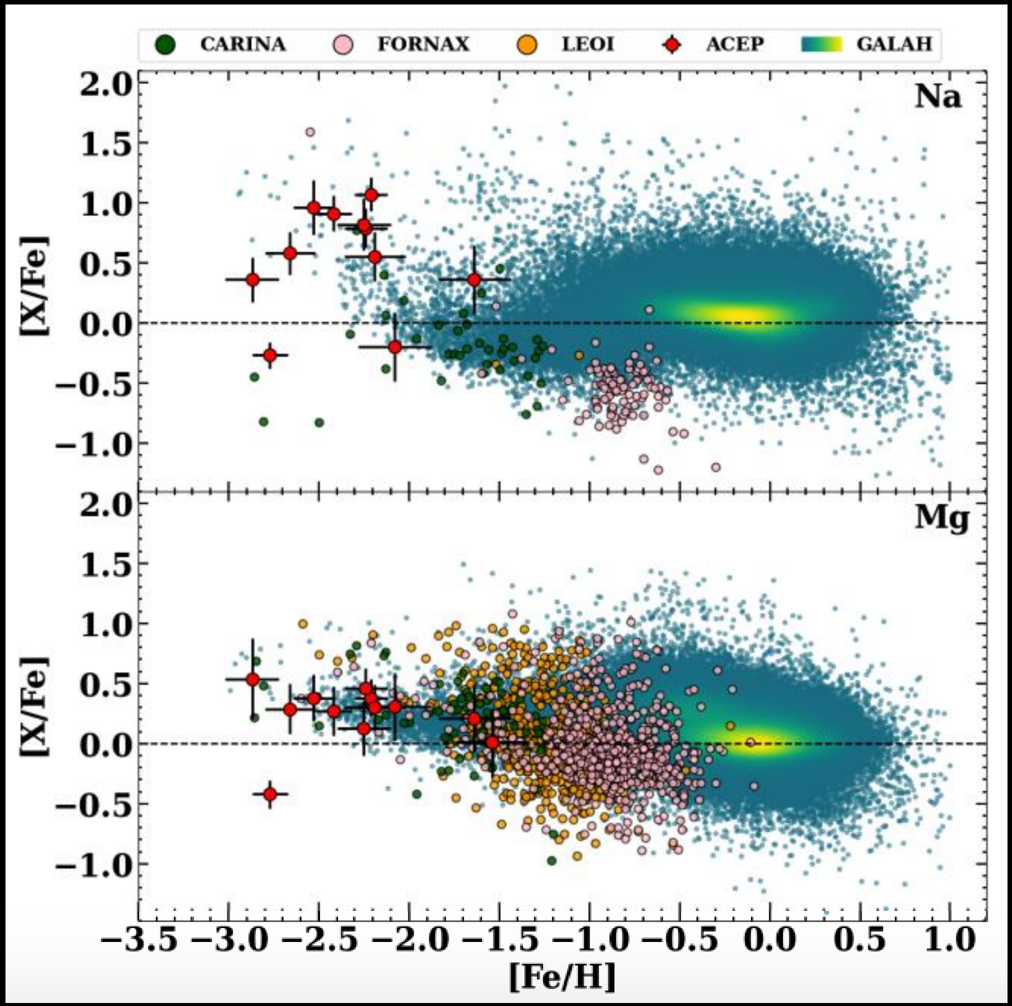


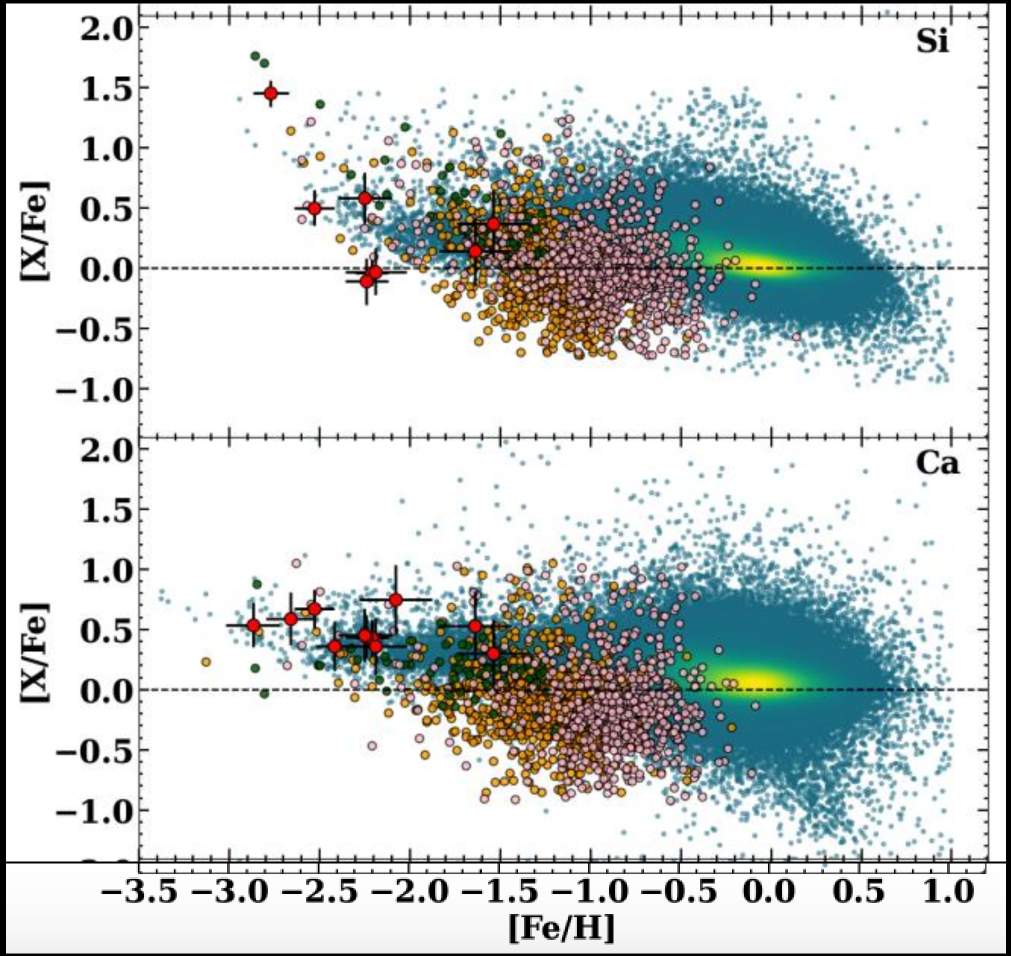


WST up to magV~20 mag

Not only distance indicators
Stellar formation:

Adapted from Ripepi+2024





Summary:

- 4MOST, LSST AND GAIA DR5 ARE CRUCIAL STARTING POINTS FOR WST.

- LOW RESOLUTION
  - 4MOST WILL ALLOW US TO DERIVE PLZ UP TO THE LMC
  - WST UP TO LEO I (250 kpc)

- HIGH RESOLUTION:
  - 4MOST WILL ALLOW US TO OBTAIN GALACTIC SPECTRA OF T2CS AND ACS
  - WST UP TO THE LMC

Thank you for your attention!

ESO SSM Scuola Superiore Meridionale
European Southern Observatory

INAF OSSERVATORIO ASTRONOMICO DI CAPODIMONTE

VMC

C-MetaLL

ANOMALIES & TENSIONS IN COSMOLOGY · COSMOVERSE

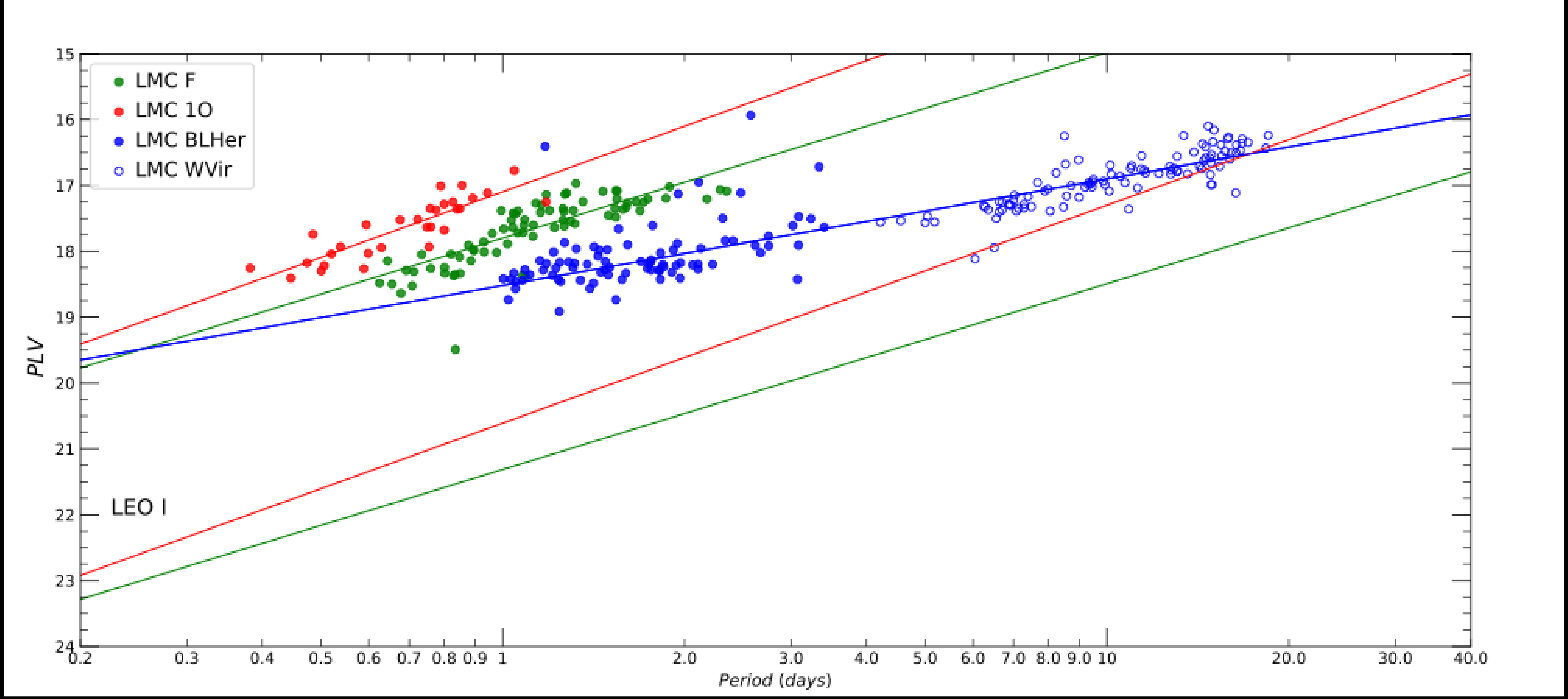
4MOST

VERA C. RUBIN OBSERVATORY

INFN NAPOLI

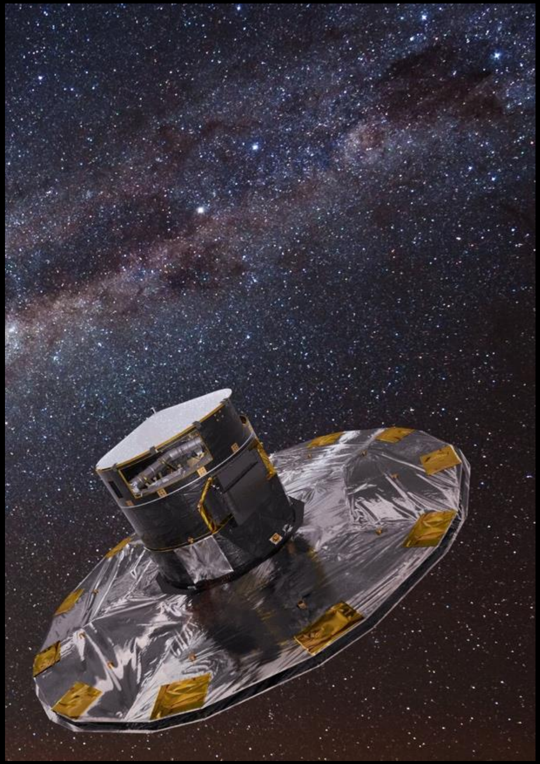
teresa.sicignano@inaf.it

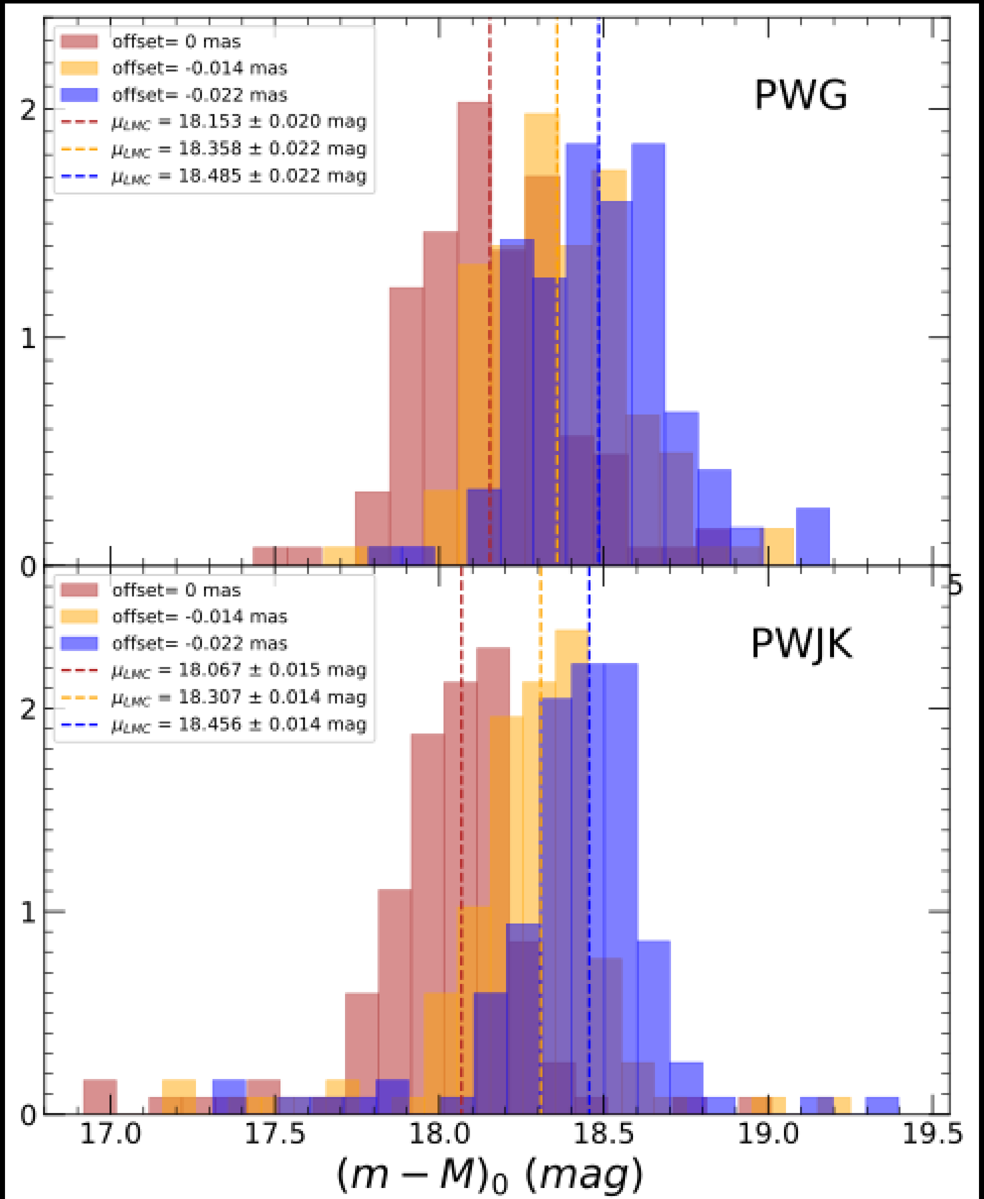
Low resolution



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 ($\mu_{LMC} = 18.477 \pm 0.003 \pm 0.027\ mag$)

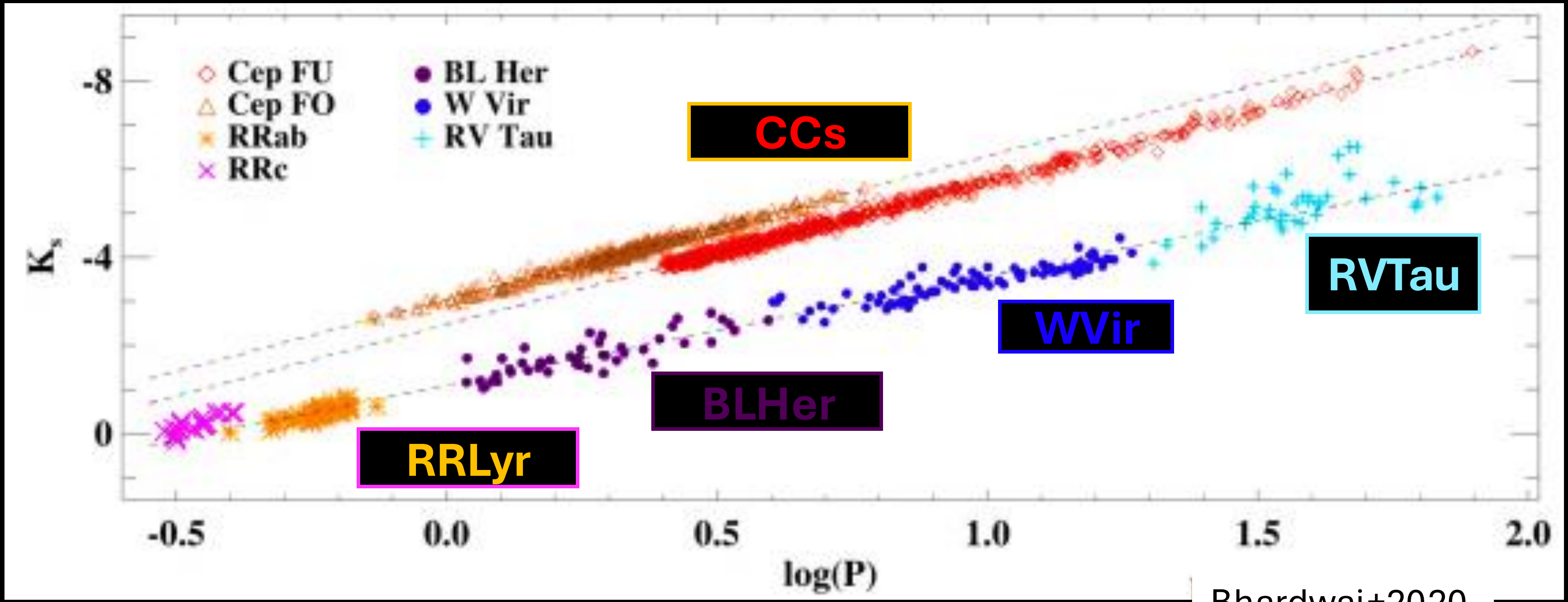




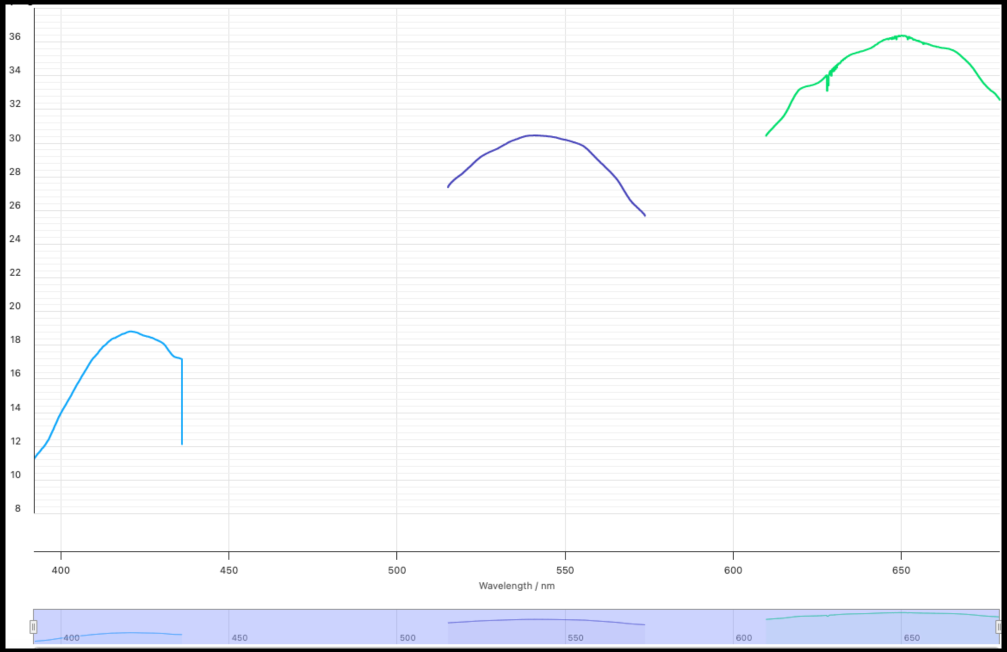
T2Ceps as distance indicators:

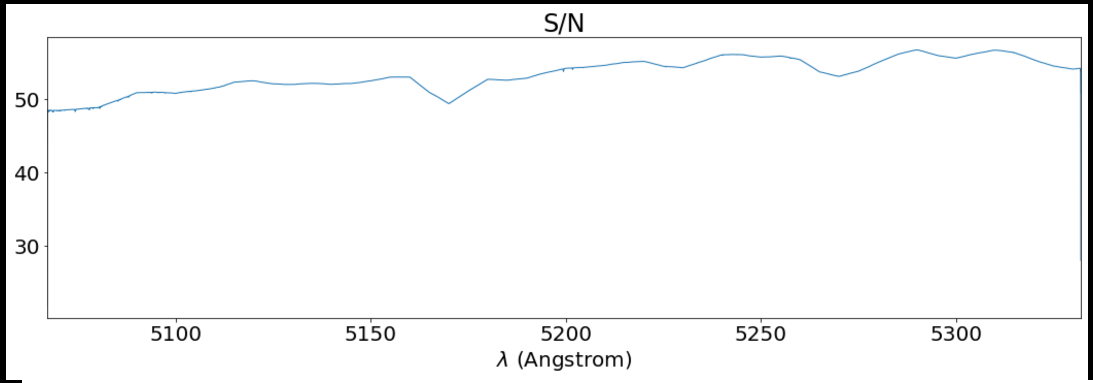
- Obey to a tight Period Luminosity relation with small dependence on metallicity (Ngeow+2022).

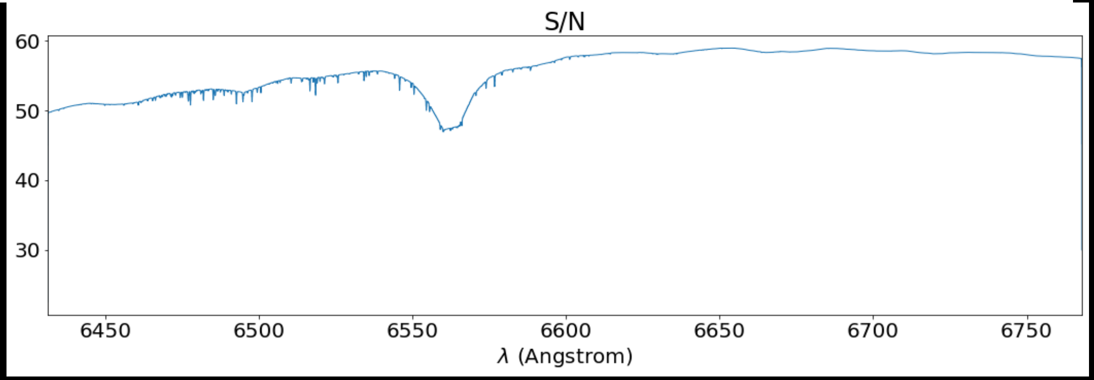
- Brighter than RRLyrae; 1-1.5 mag fainter than the TRGB.

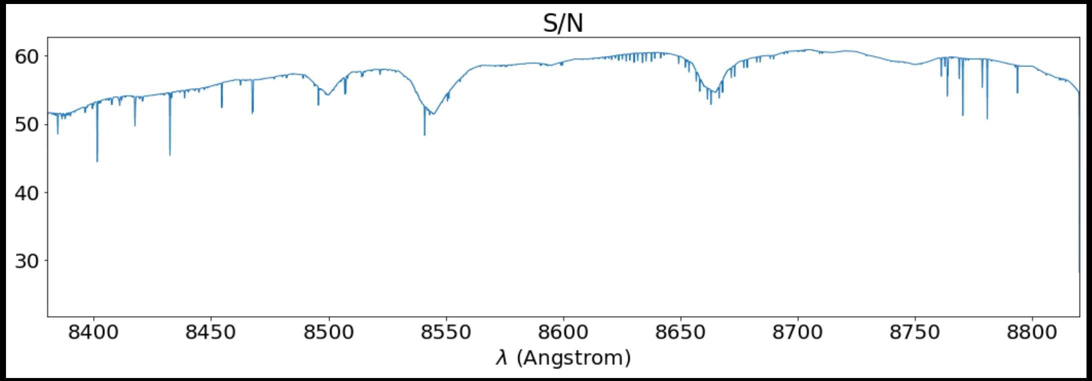


Bhardwaj+2020





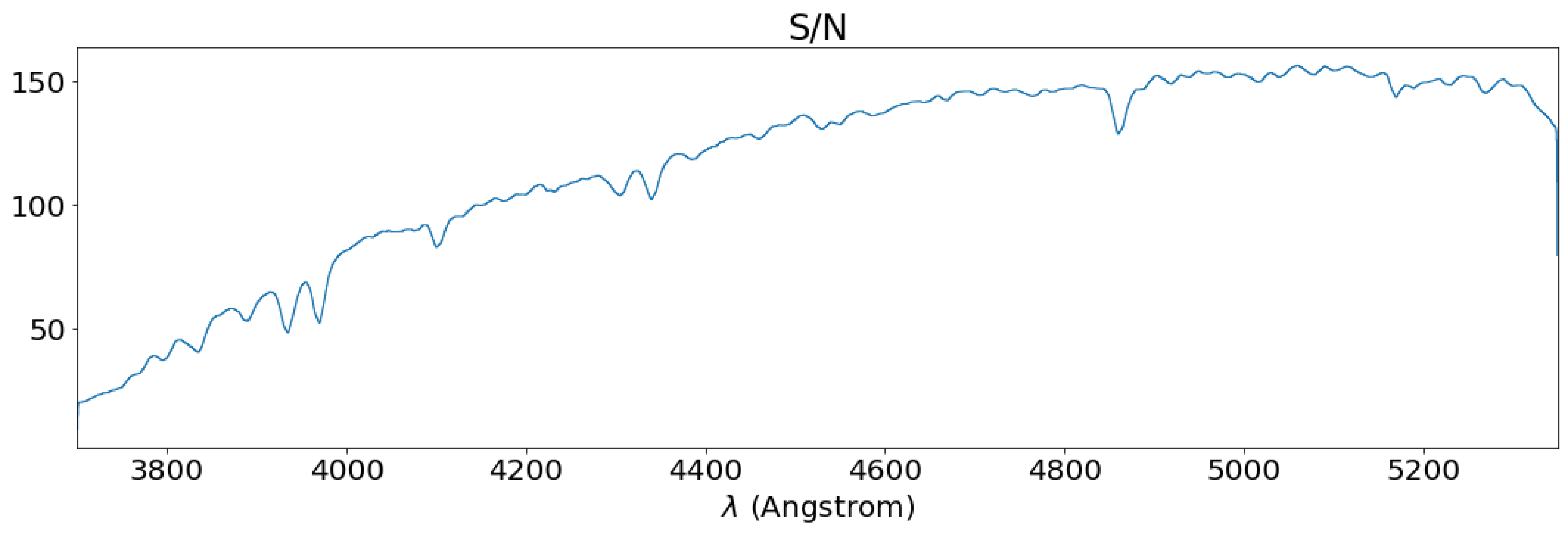


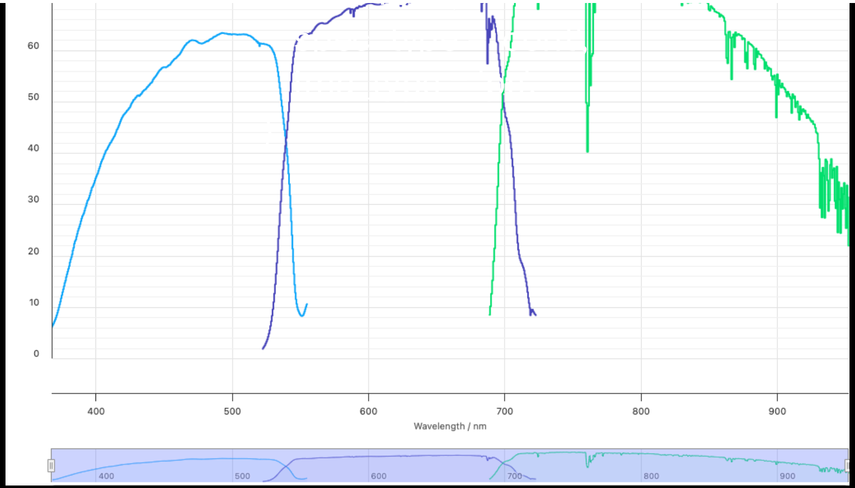


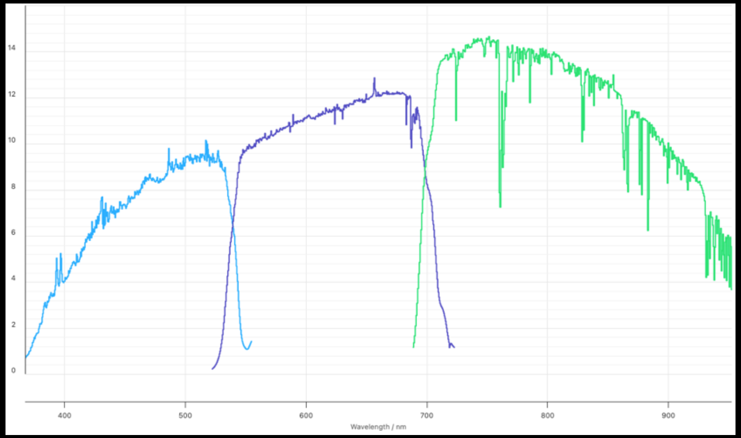

```
mos = ws
dspec =
name='p
     wa
mag = 17
obs = dic
  moon =
  seeing
  airmas
  ndit = 6
  dit = 18
spec_typ
```

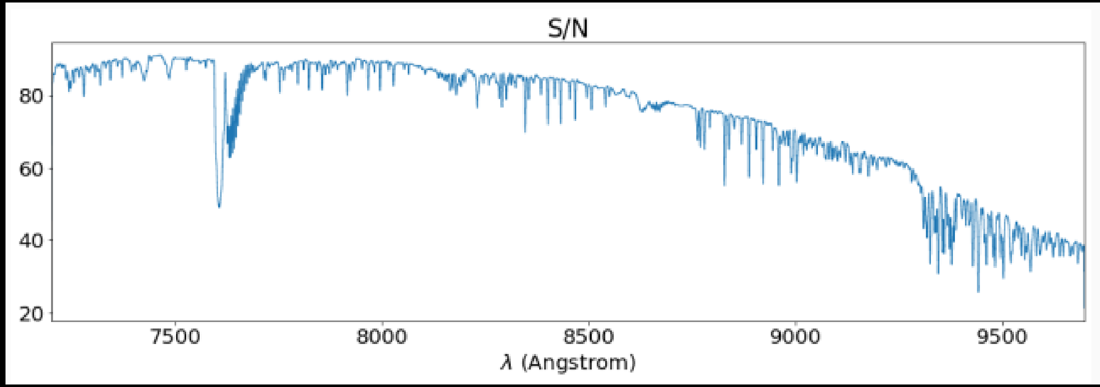
```
mos = wst
wave,dw  =
mag = 17
obs = dict(
  moon =
  seeing =
  airmass
  ndit = 6,
  dit = 180
  spec_typ
  ima_typ
```

```
mos = wst
wave,dw =
spec = ws
  moon =
  seeing =
  airmass
  ndit = 6,
```


S/N
150
100
50
3800
4000
4200
4400
4600
4800
5000
5200
λ (Angstrom)


60
50
40
30
20
10
0
400
500
600
700
800
900
Wavelength / nm




S/N
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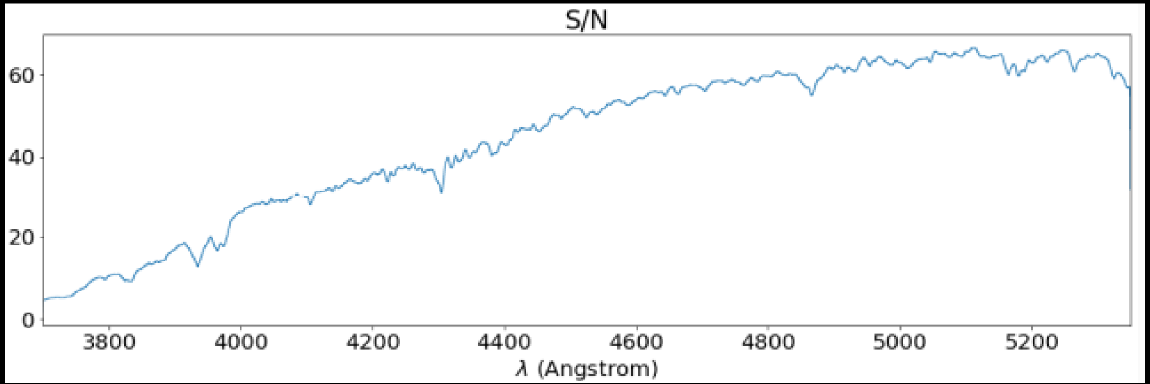
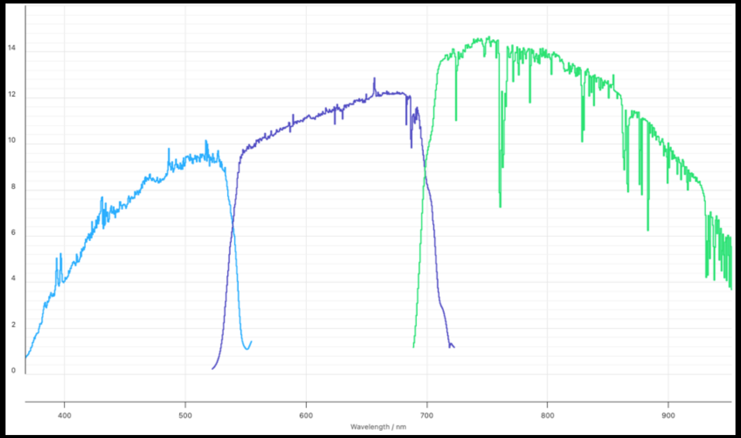
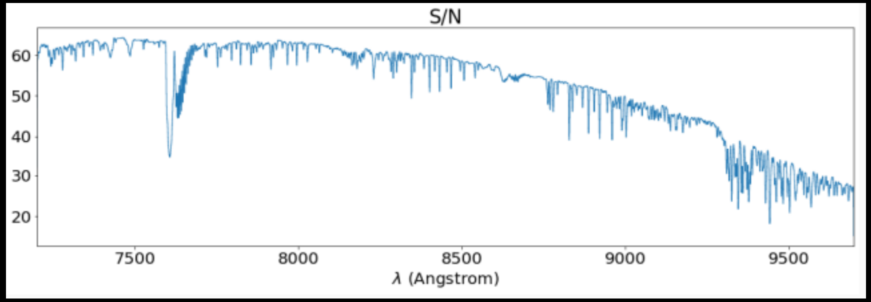
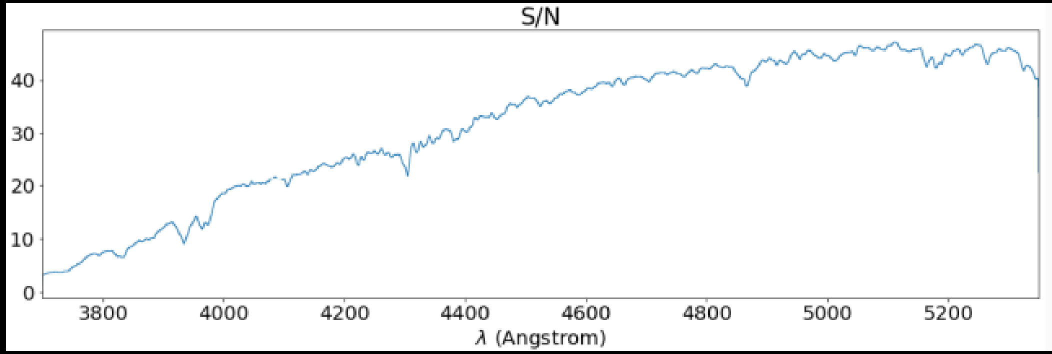
60
40
20
7500
8000
8500
9000
9500
λ (Angstrom)


S/N
60
40
20
0
3800
4000
4200
4400
4600
4800
5000
5200
λ (Angstrom)


Wavelength / nm


S/N
λ (Angstrom)


S/N
λ (Angstrom)

- **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.**

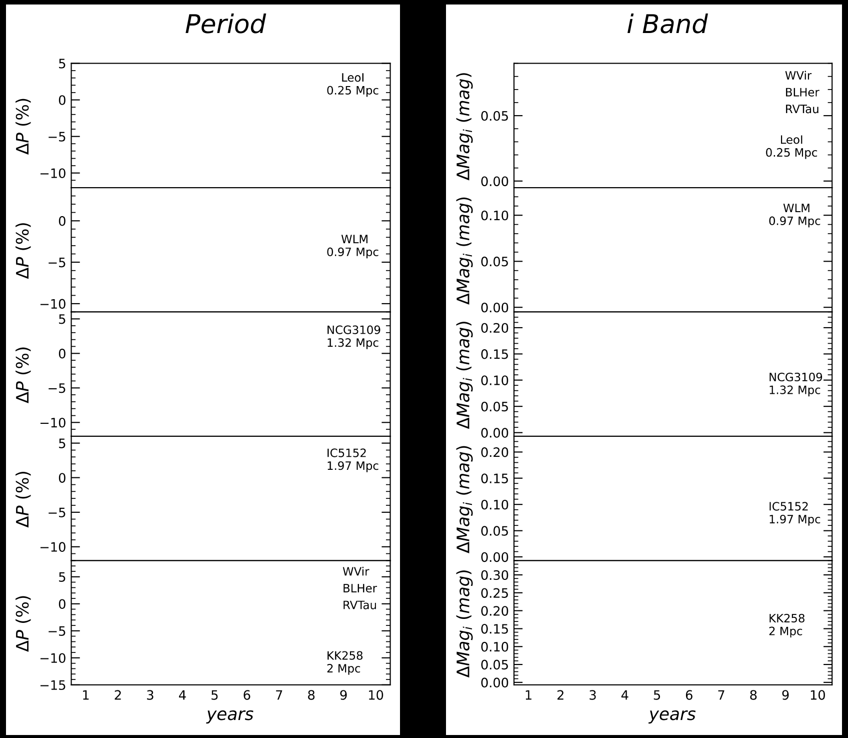
↓

Provide a common self-consistent calibration of secondary distance indicators, resulting in a new Hubble constant evaluation.

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

📍SN Ia HOST

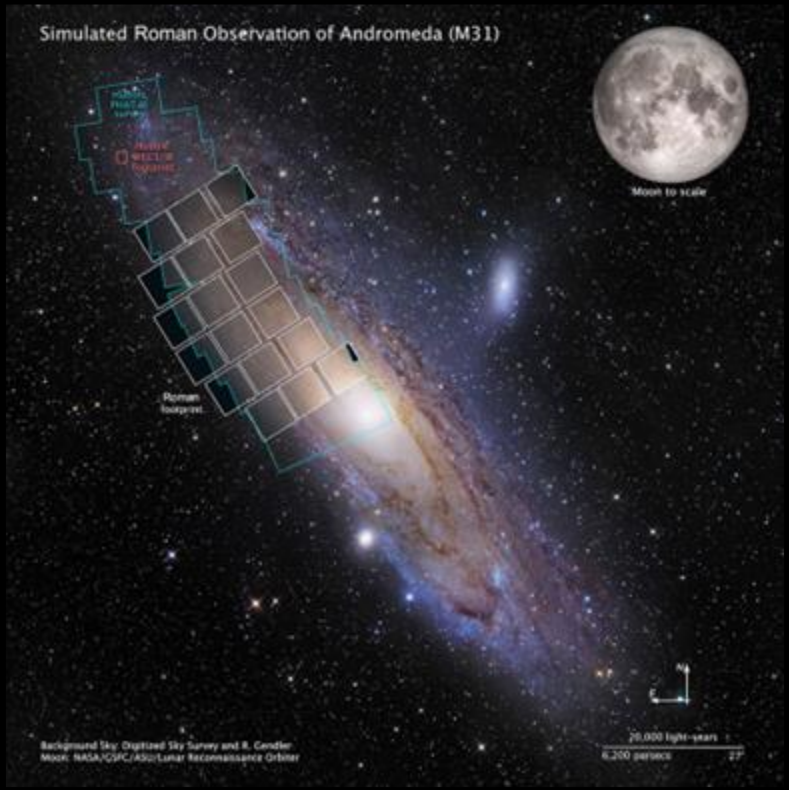
LSST



Sicignano+, in prep.

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

📍SN Ia HOST
NANCY GRACE ROMAN SPACE TELESCOPE



Beaton's lesson,
Budapest Spring School 2023

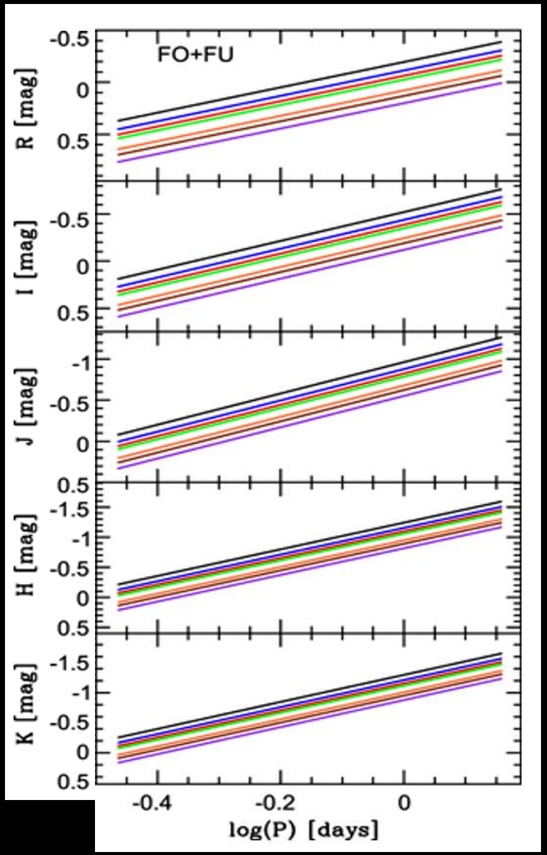
MASTER THESIS
- 📍 PERIOD – LUMINOSITY
- 📍 PRESENCE IN ANCHORS

PHD PROJECT
- 📍 ZERO POINT CALIBRATION
- 📍 SN Ia HOST

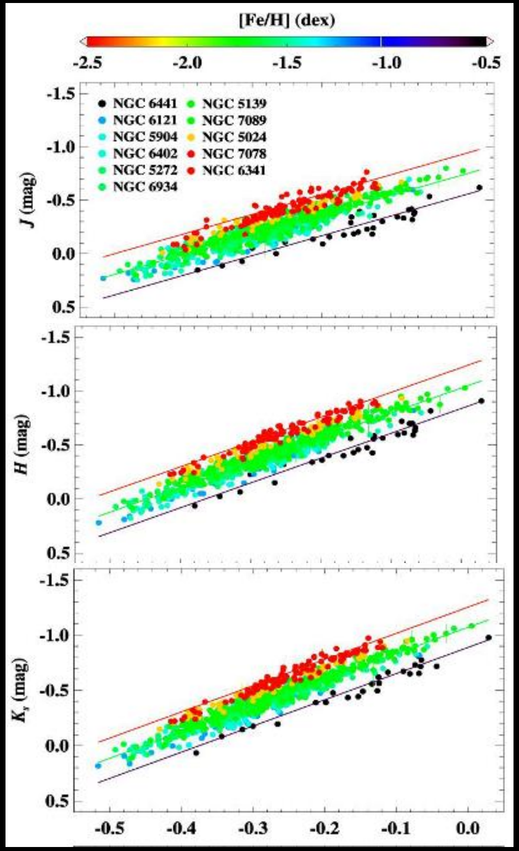
BACKUP SLIDES

📍 ZERO POINT CALIBRATION

RRLYRAE THEORY AND OBSERVATIONS

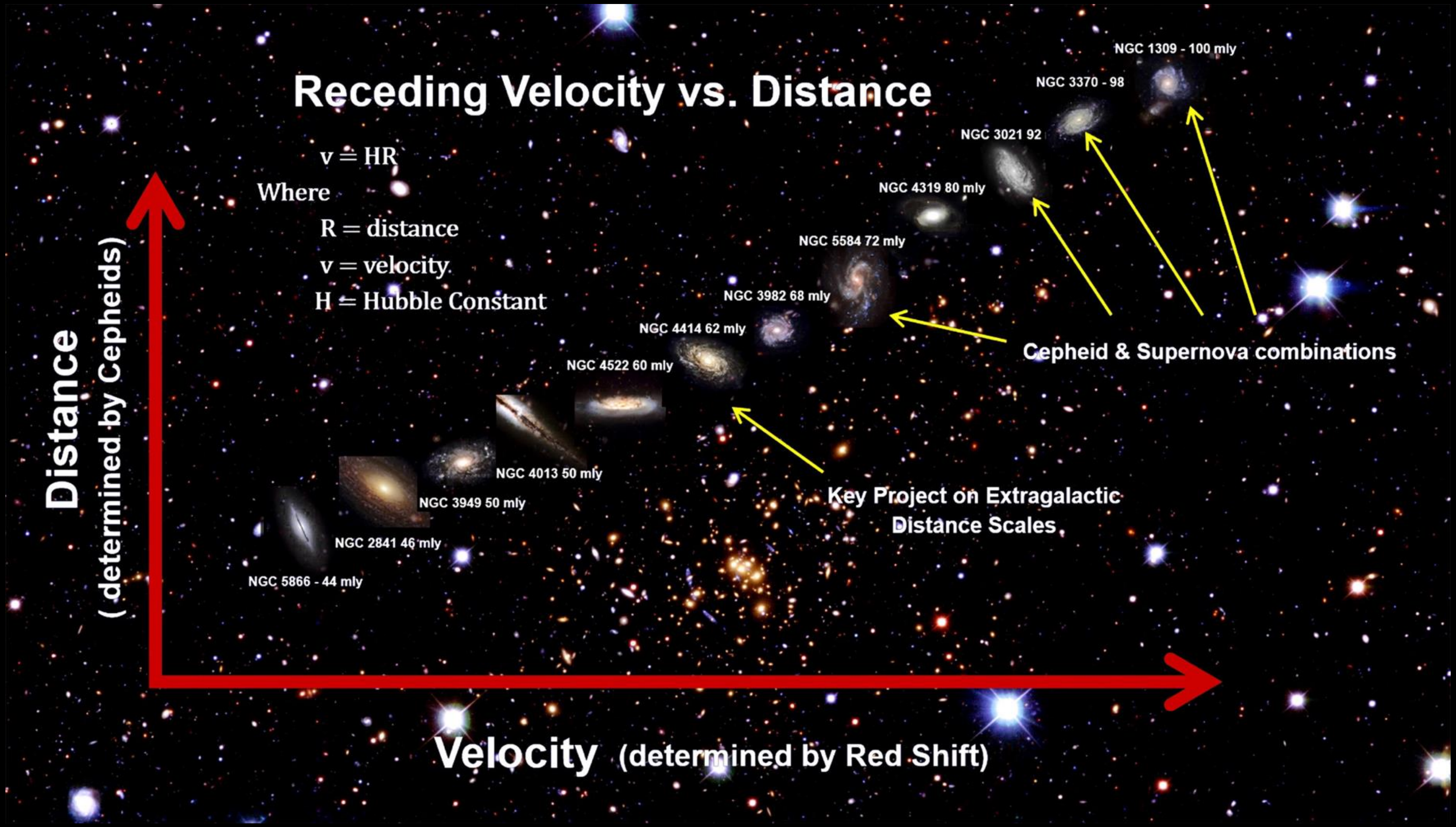


Adapted from Marconi+2015

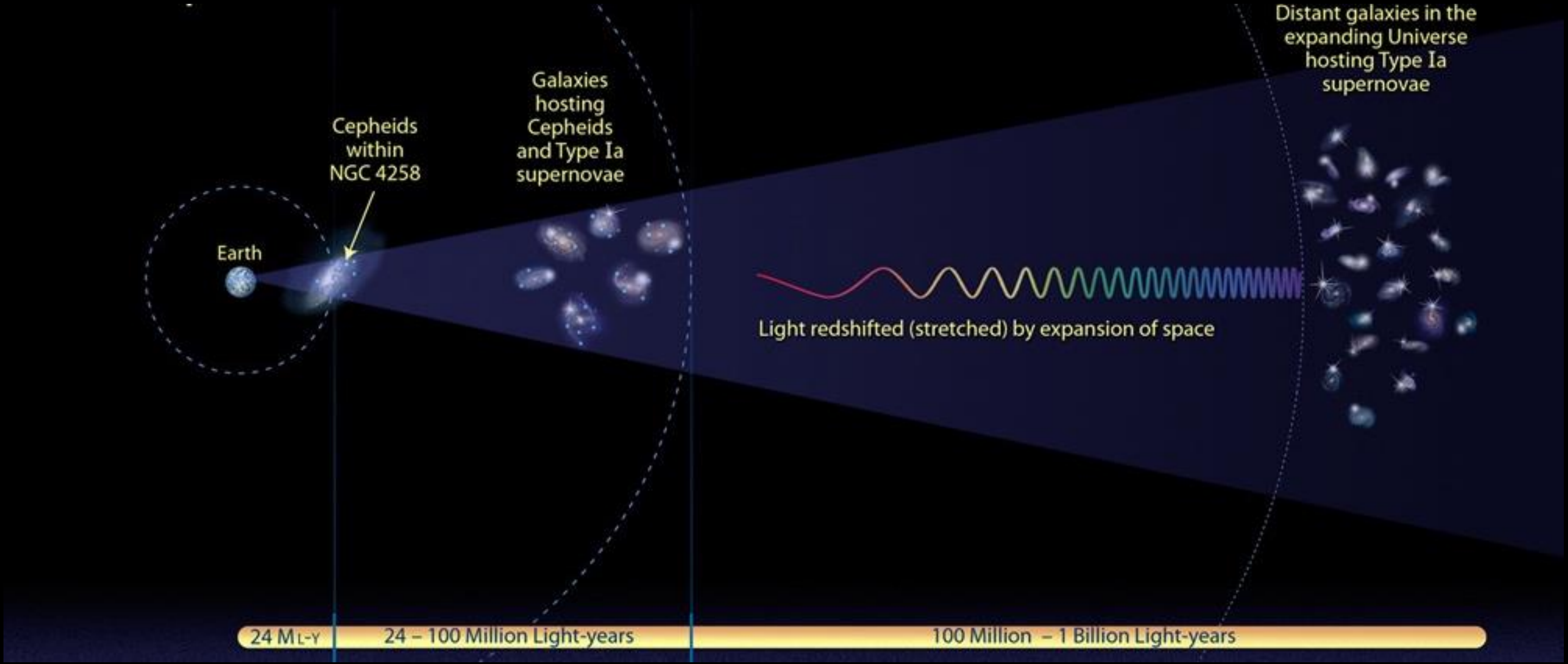


Adapted from Bhardwaj+2023

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

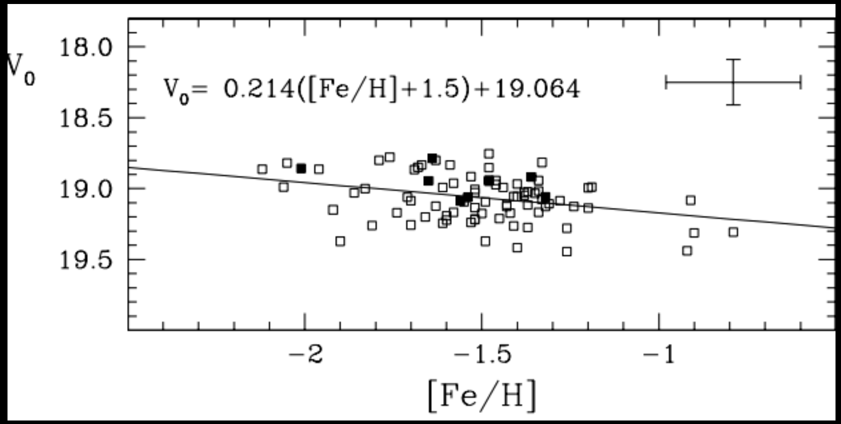

Receding Velocity vs. Distance
v = HR
Where
R = distance
v = velocity
H = Hubble Constant
Distance
(determined by Cepheids)
Velocity (determined by Red Shift)
NGC 1309 - 100 mly
NGC 3370 - 98
NGC 3021 92
NGC 4319 80 mly
NGC 5584 72 mly
NGC 3982 68 mly
NGC 4414 62 mly
NGC 4522 60 mly
NGC 4013 50 mly
NGC 3949 50 mly
NGC 2841 46 mly
NGC 5866 - 44 mly
Cepheid & Supernova combinations
Key Project on Extragalactic
Distance Scales

The extragalactic distance scale.
The three steps to H_0



📍ZERO POINT CALIBRATION

TYPE II CEPHEIDS:
THEORY? OBSERVATIONS?



Gratton+2004

- Metallicity spanning of RRLyrae (Pop II) in LMC.

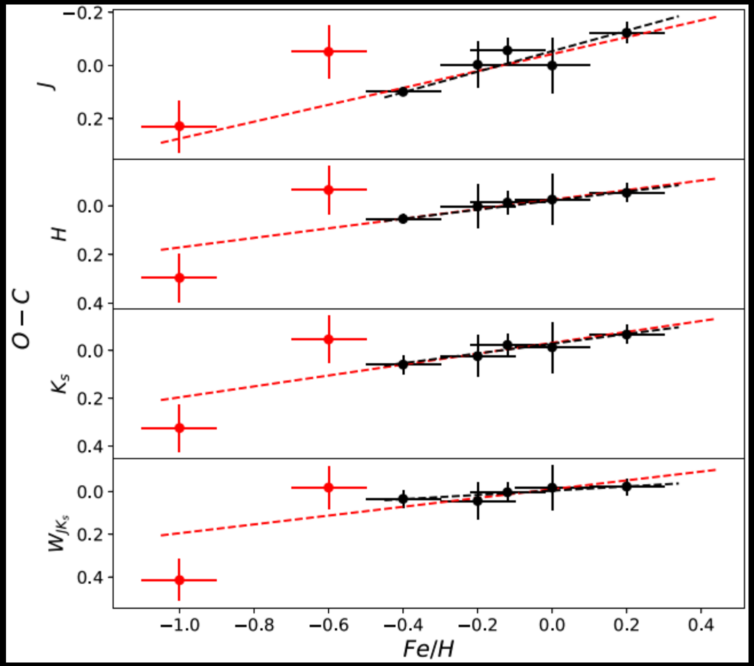
MASTER THESIS { 📍**PERIOD – LUMINOSITY RELATION**

PHD PROJECT { 📍**PRESENCE IN ANCHORS**, 📍**ZERO POINT CALIBRATION**

📍**SN Ia HOST**

📍 ZERO POINT CALIBRATION

TYPE II CEPHEIDS:
THEORY? OBSERVATIONS?



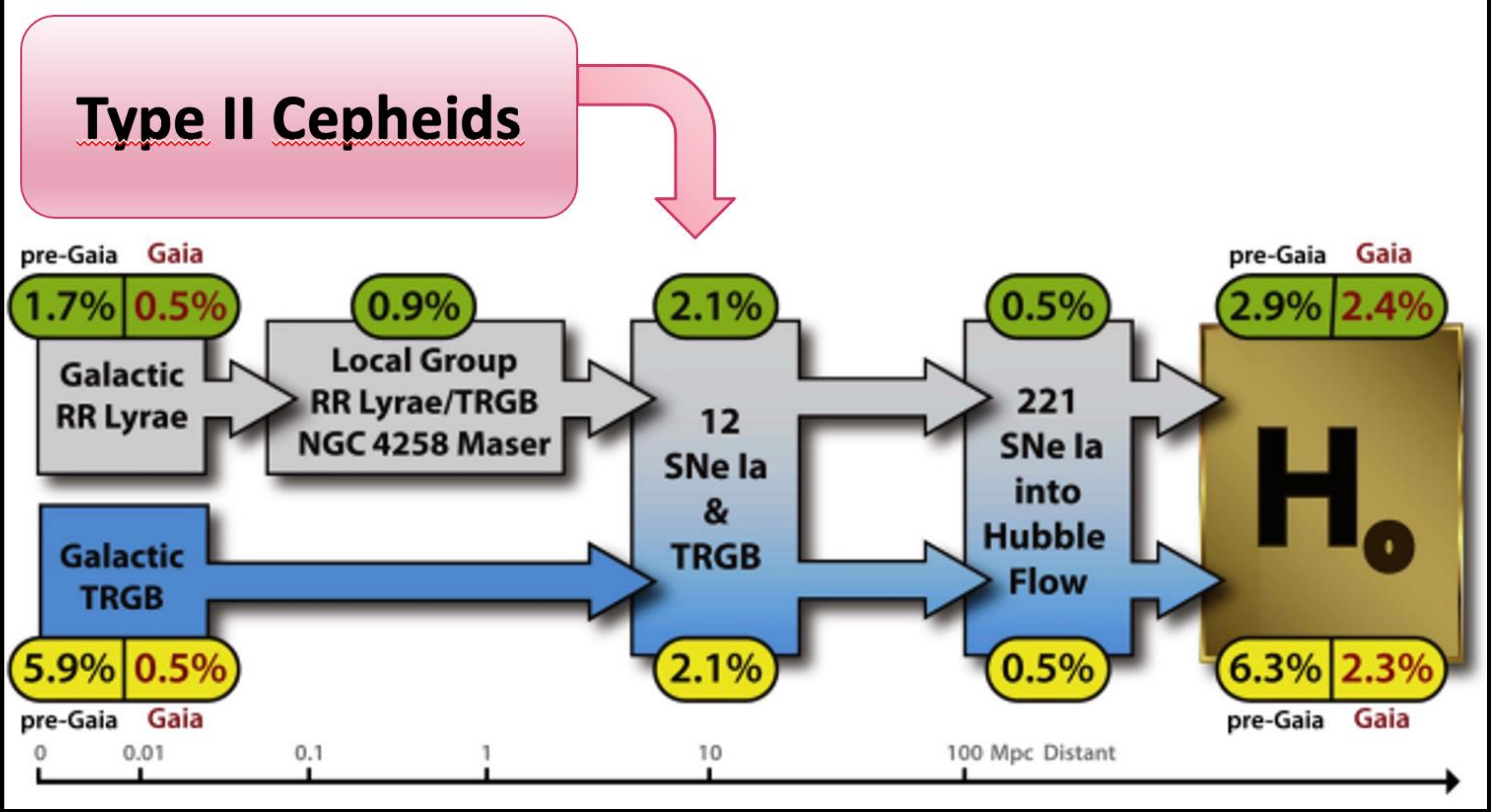
Wielgorski+2022

- Metallicity spanning of RRLyrae (Pop II) in LMC.
- Predicted PL dependence on metallicity for BLHer.
- 7 Galactic T2C show a dependence & No dependence in GGCs.

MASTER THESIS

PHD PROJECT

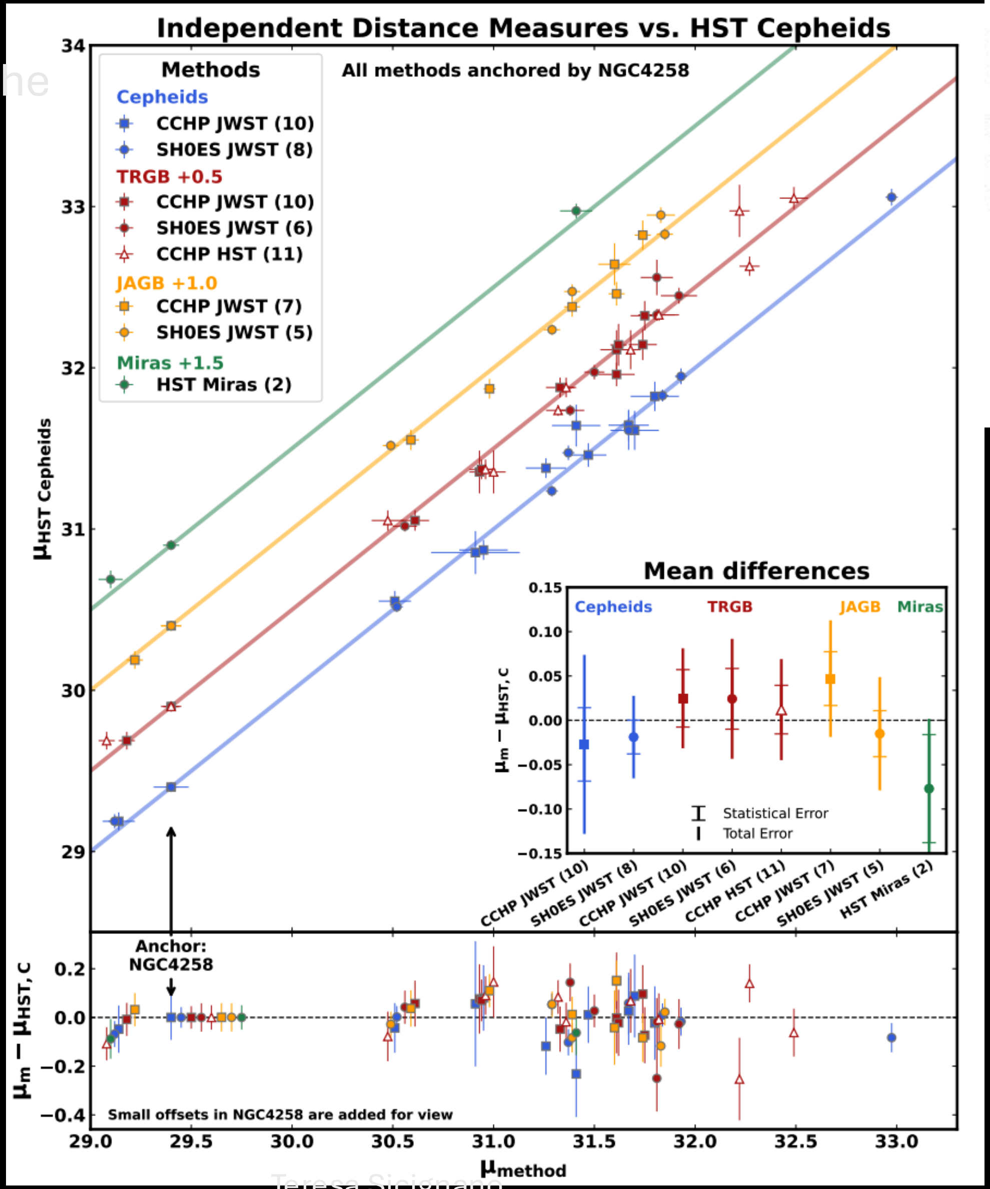
- 📍 **PERIOD – LUMINOSITY RELATION**
- 📍 **PRESENCE IN ANCHORS**
- 📍 **ZERO POINT CALIBRATION**
- 📍 **SN Ia HOST**



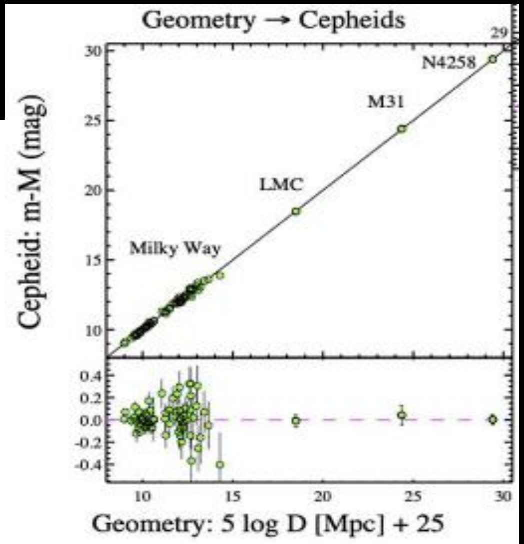
Adapted from Beaton+2016

The first step to H_0

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

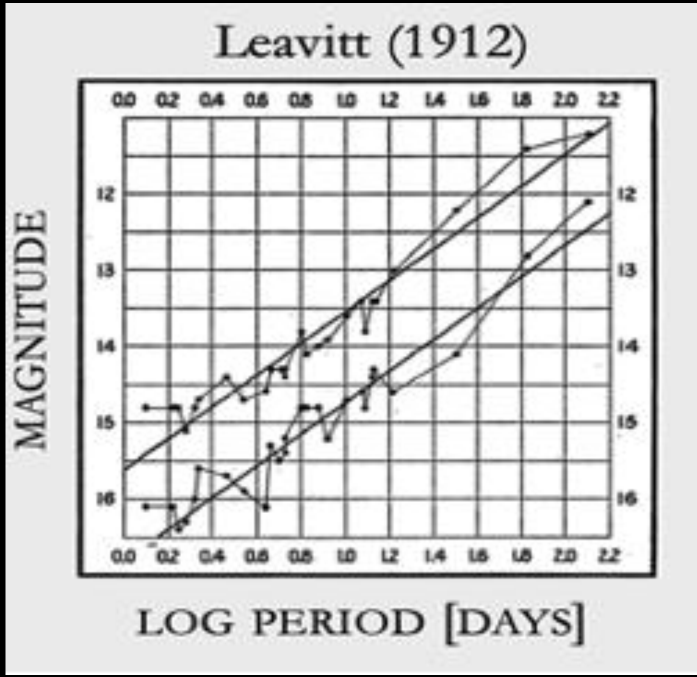


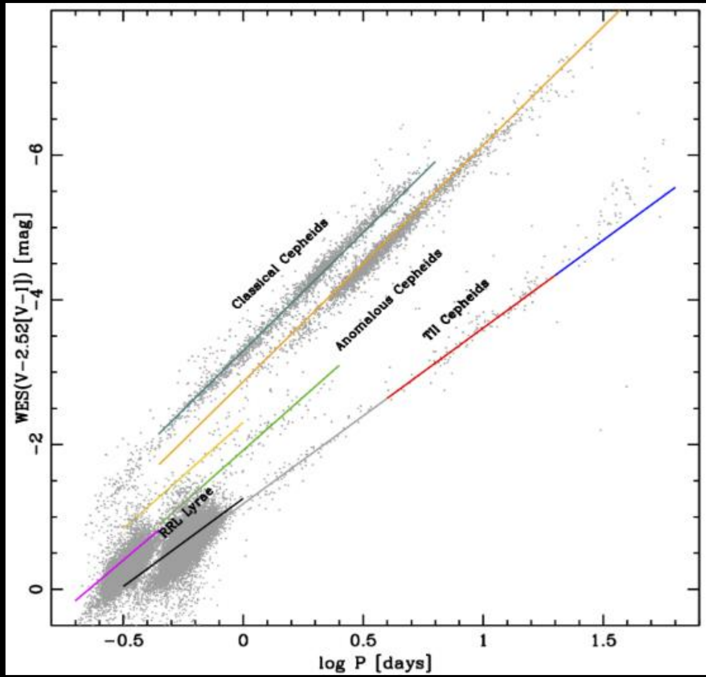
Riess+2024



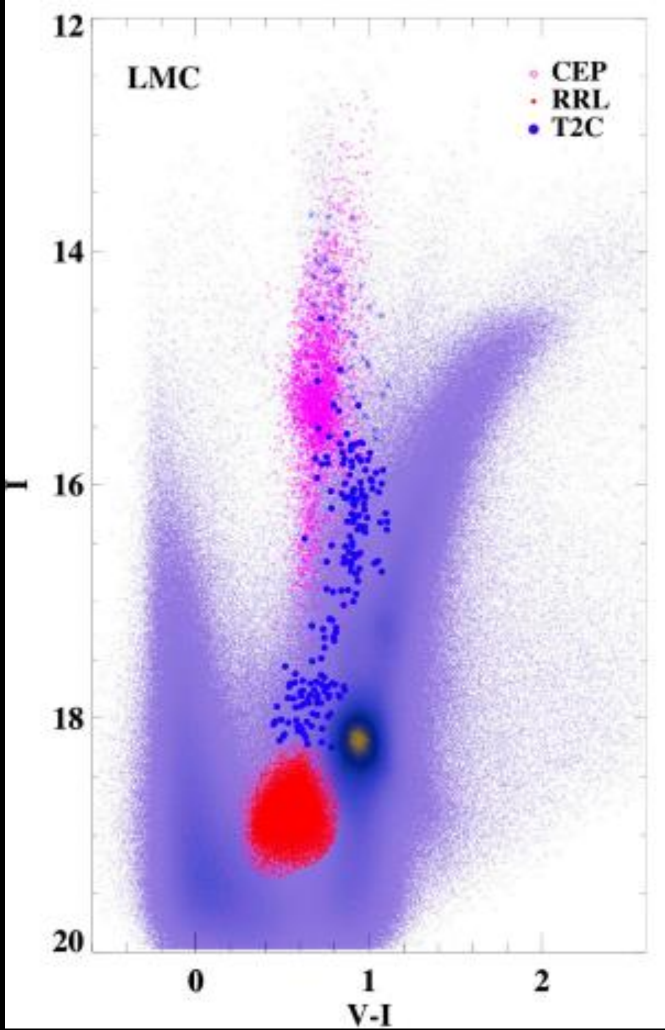
Riess+2022

+ Period Luminosity (***PL***)
+ Period Luminosity Colour (***PLC***)
+ Period Wesenheit (***PW***) - Defined to be a reddening-free quantity:

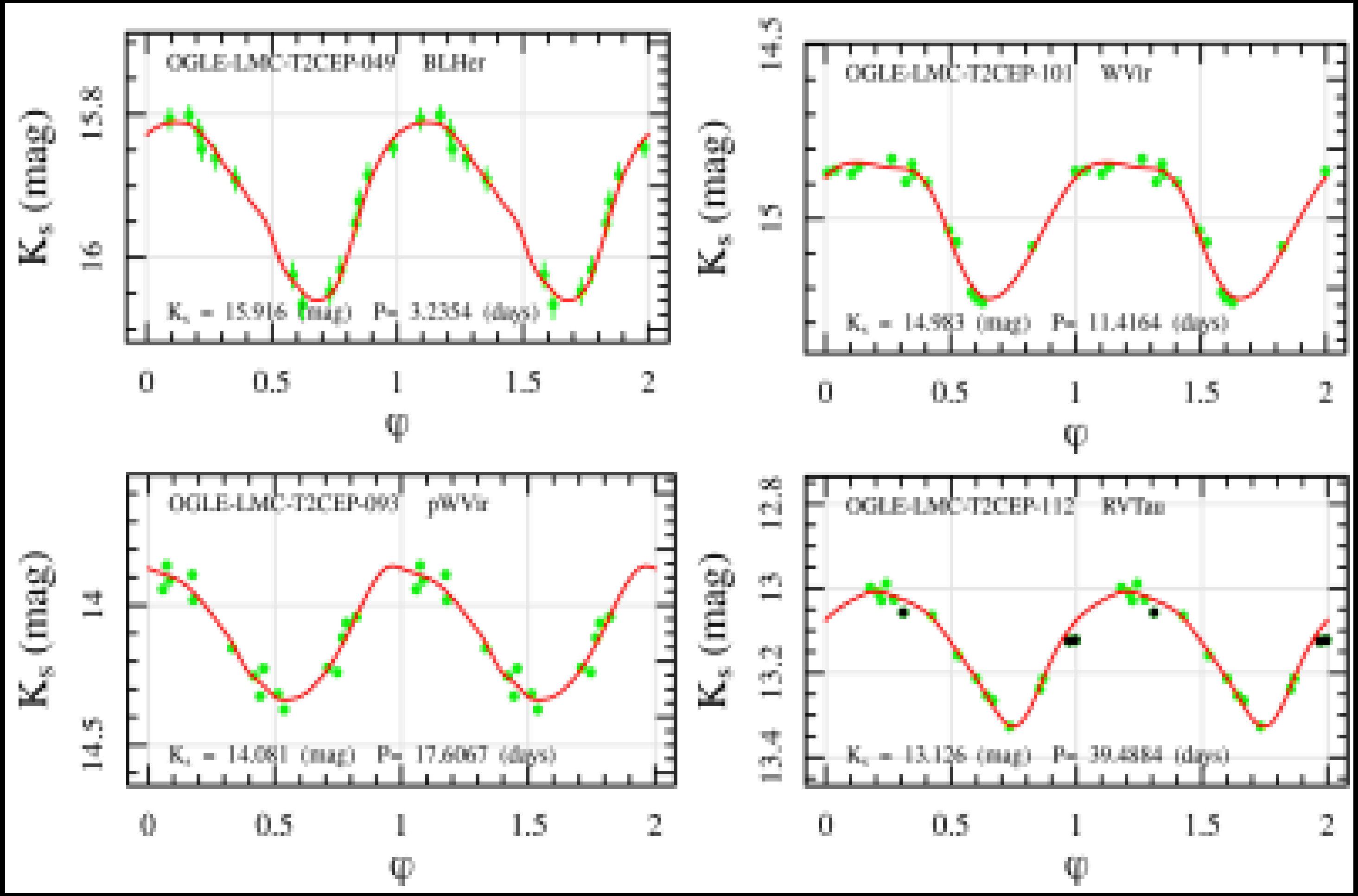




- **PERIOD – LUMINOSITY**
- **PRESENCE IN ANCHORS**
- **ZERO POINT CALIBRATION**
- **SN Ia HOST**



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



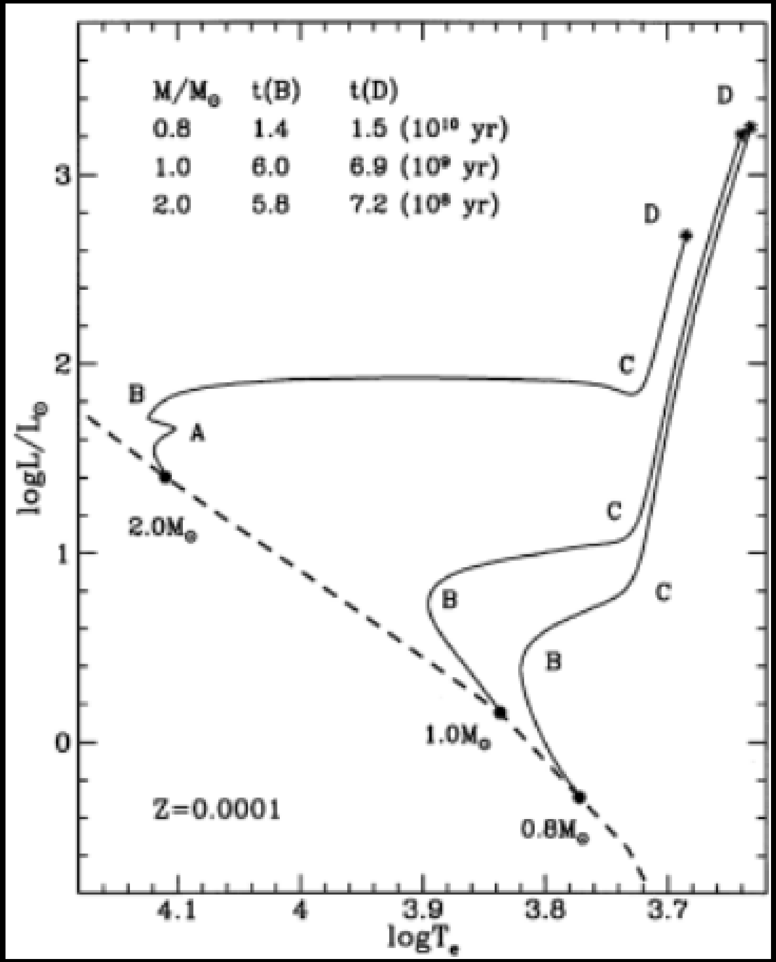
MASTER THESIS

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

Evolution of Population II stars

Z ~ 10^{-4} to Z ~ 10^{-3}

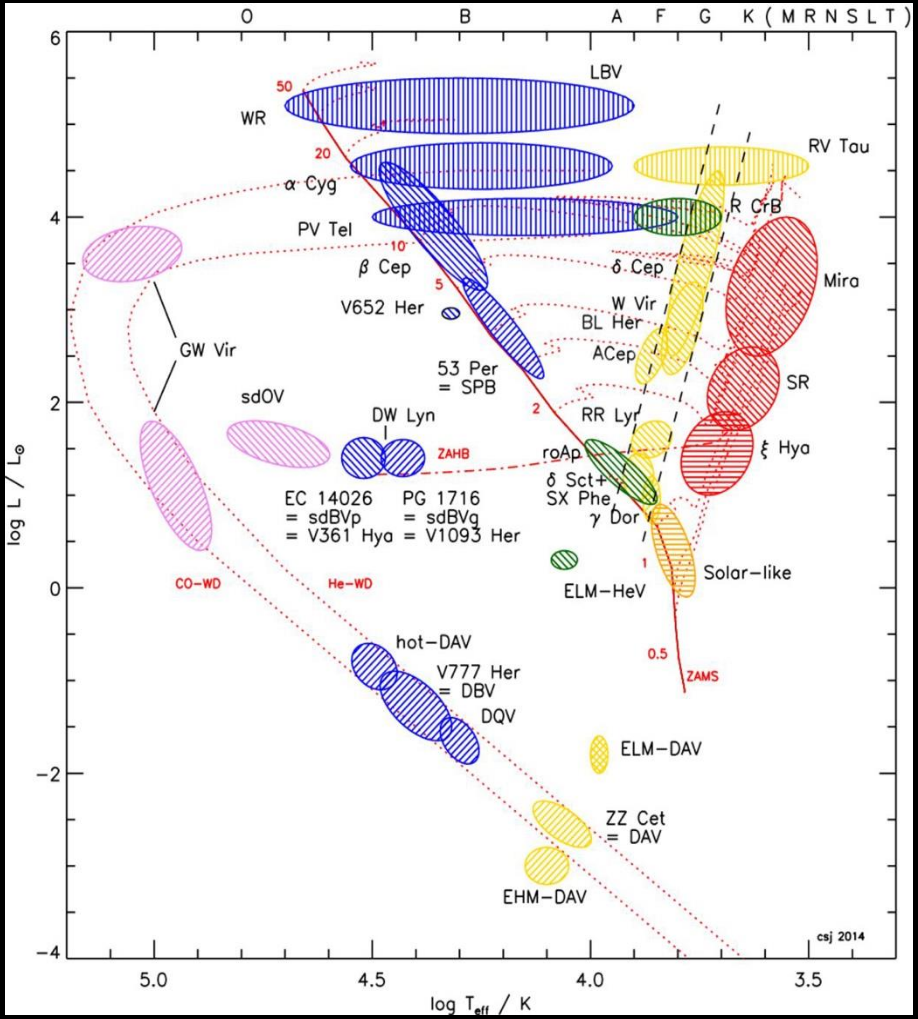
- Zero Age Main Sequence
- Main Sequence
- Red Giant Branch
- Horizontal Branch
- Asymptotic Giant Branch
- CO White Dwarf



Pulsation mechanism

Trapped energy becomes pulsational work.

- **γ Mechanism**: an initial (stochastic) contraction of the star leads to an increase in density. In the ionization regions, at the same time, there is a temperature increase, but less than the same scenario without ionization. Since the luminosity L goes as T 4 , its variation will also be smaller: there is an energy entrapment. The excess energy, during the next expansion phase, goes into pulsational work.
- **K Mechanism**: In a stellar interior, normally the opacity decreases during a contraction, according to Kramer’s law (κ ~ ρT −3.5) producing a loss of heat. In the ionization regions, due to the interaction of radiation with matter, small increases in temperature cause a large increase in opacity (the temperature exponent in Kramer’s law becomes positive). This again means trapping of energy, which will be converted into pulsational work.



Properties of the PL relations

The cause is the fact that at longer *wavelenght* λ the instability strip become steeper and narrower.

The physical explanation of this is the different dependence of the surface brightness from Te at different λ.

Rewriting the Stephan-Boltzman law as: $M_\lambda = -2.5 \log R^2 - 2.5 \times a_\lambda \log T_e + b_\lambda,$

Surface brightness

$|M_\lambda| = 2.5 \times a_\lambda |f_{\text{blue}} - f_{\text{red}}|.$ → ~ width of the PL

$\Delta M_\lambda / \Delta \log P = A_\lambda = -5c + 2.5 e a_\lambda.$ ~slope of the PL (c ~ 0.7 and e ~ 0.08)

$a_\lambda = 4$ in the optical

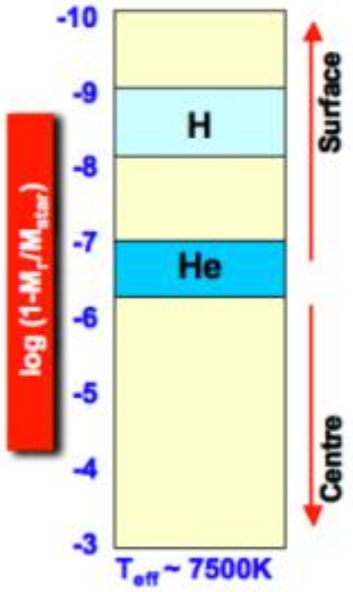
$a_\lambda \sim 1.5$ in the K band

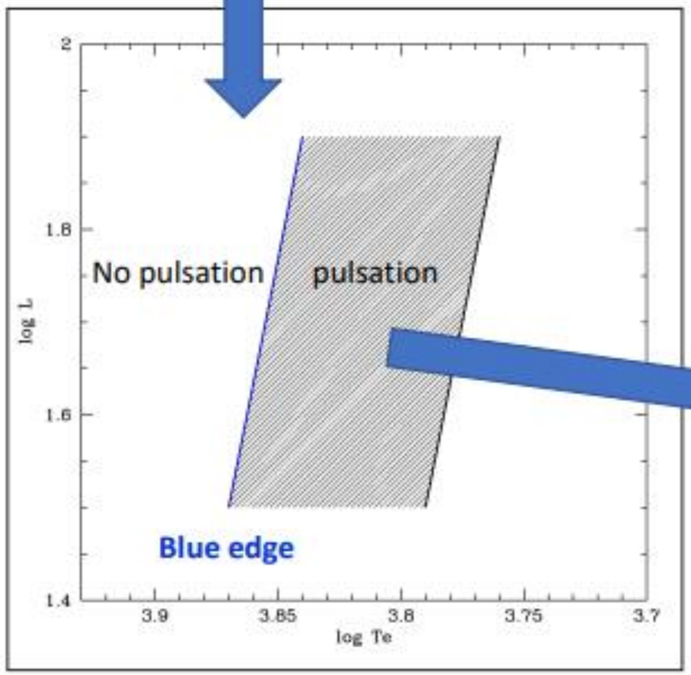
→ Explains the observed behaviour of Slope and dispersion of the PL.

Madore & Freedman 2012

*Why the instability strip has a **BLUE** boundary?*

If the model effective temperature is too high (e.g. Teff>7500 K) the H and He ionization regions are very external ⇒ low density, small mass takes part in the pulsation driving through the κ and γ-mechanisms ⇒ damping prevails ⇒ no pulsation





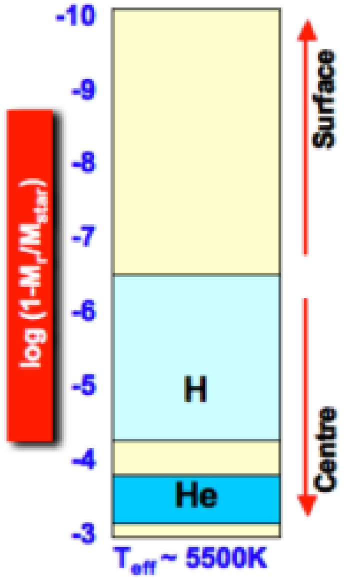
Only when the ionization regions are deep enough the mass involved in the pulsation driving mechanisms prevails ⇒ pulsation

Erice International PhD school – October 14-15, 2015

Why the instability strip has a RED boundary?

Moving toward lower effective temperature (e.g. 6500 K) the depth of the driving ionization regions increases and the mass taking part in the phenomenon is larger ⇒ increasing pulsation efficiency.

At even lower Teff (~5500K) the ionization zones Are deep in the star's interior.

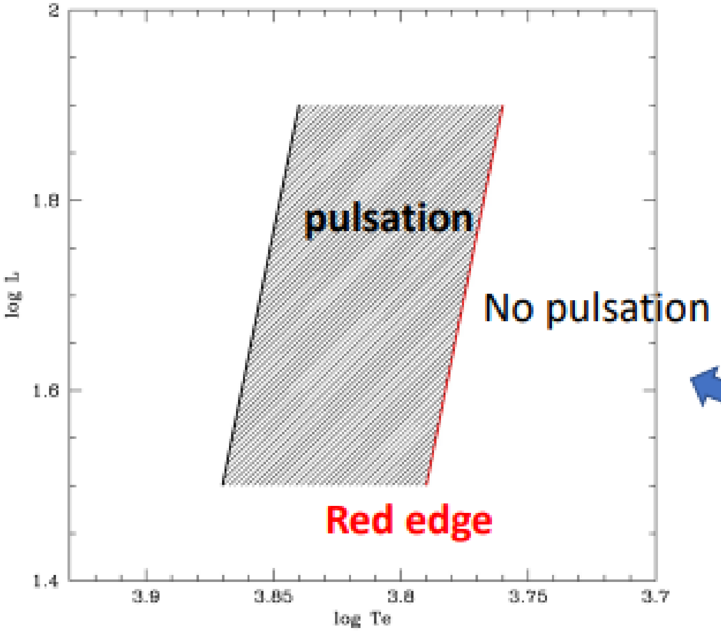


But convection also starts to become more efficient at lower effective temperatures:

⇒ κ and γ gradients are reduced

⇒ quenching of pulsation

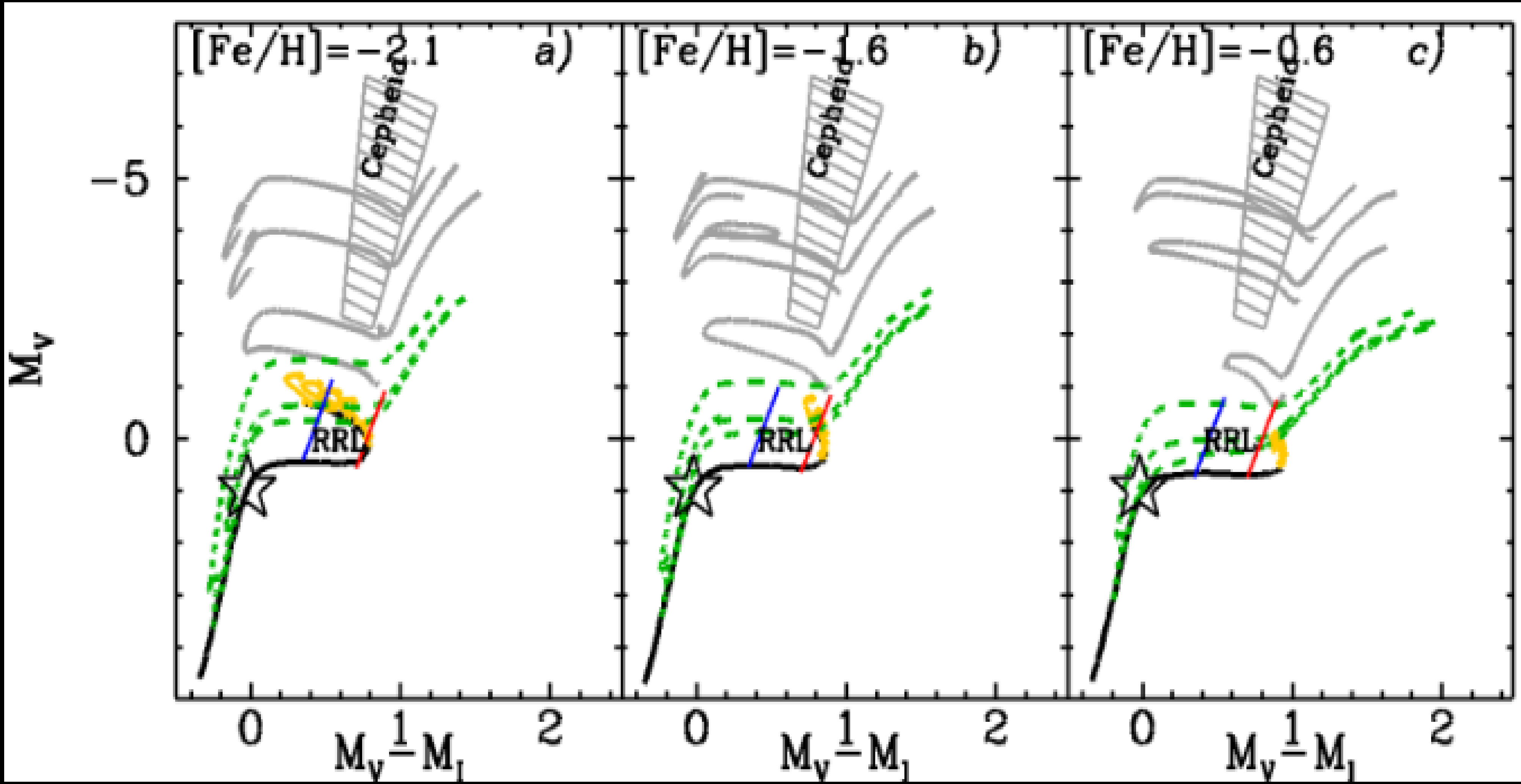
When the quenching effect due to convection prevails pulsation is no more efficient



⇒ **red boundary** of the instability strip

Erice International PhD school – October 14-15, 2015

Type II and Anomalous Cepheids

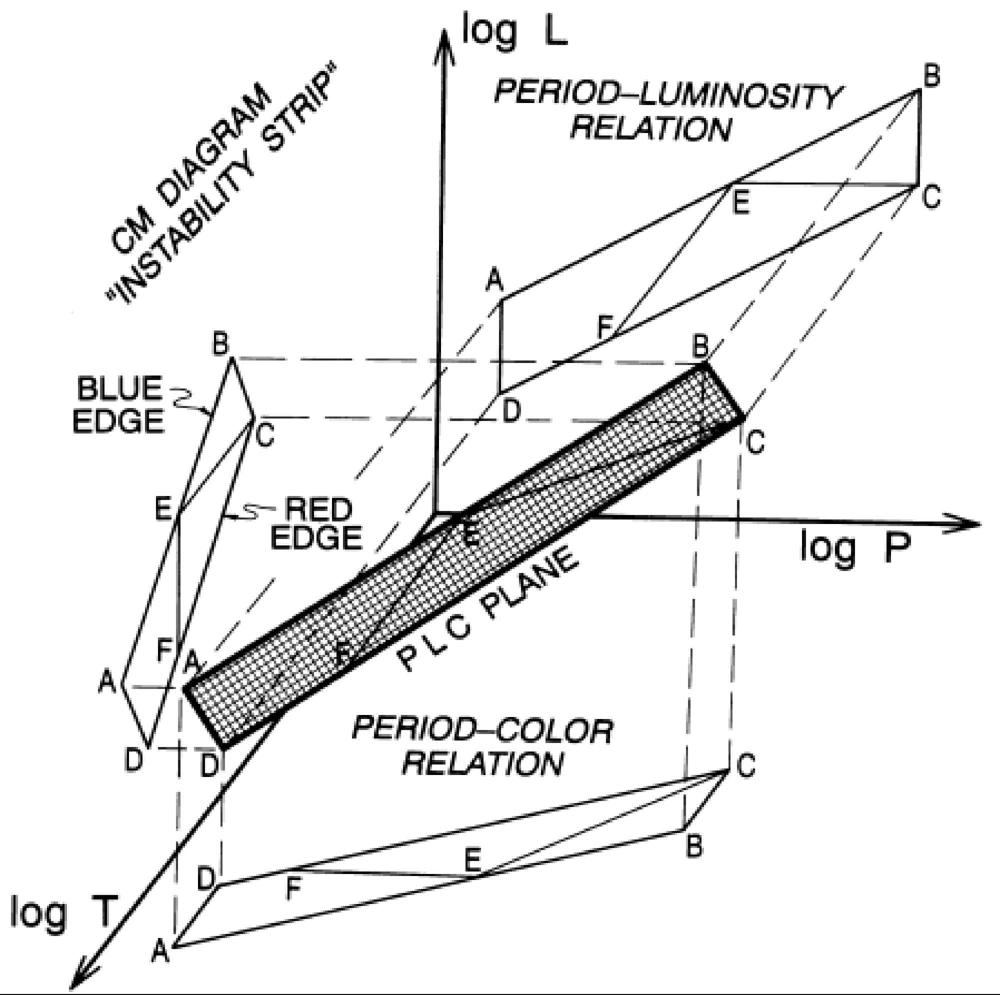


Period-luminosity-colour and period-luminosity

$$P \simeq M^{-1\backslash 2} \cdot L^{3\backslash 4} \cdot T_e^{-3}$$

PLC exists for every star;

PL and PC are statistical relations.



Observationally:

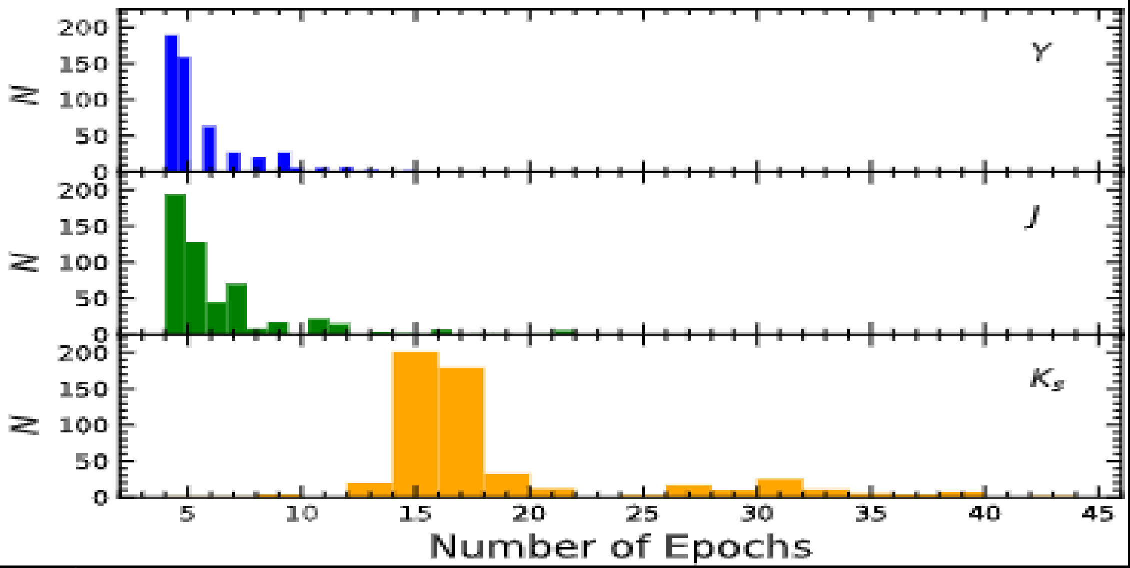
$$M_{\lambda_1} = \alpha + \beta \cdot \log P + \gamma (m_{\lambda_1} - m_{\lambda_2})_0$$

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

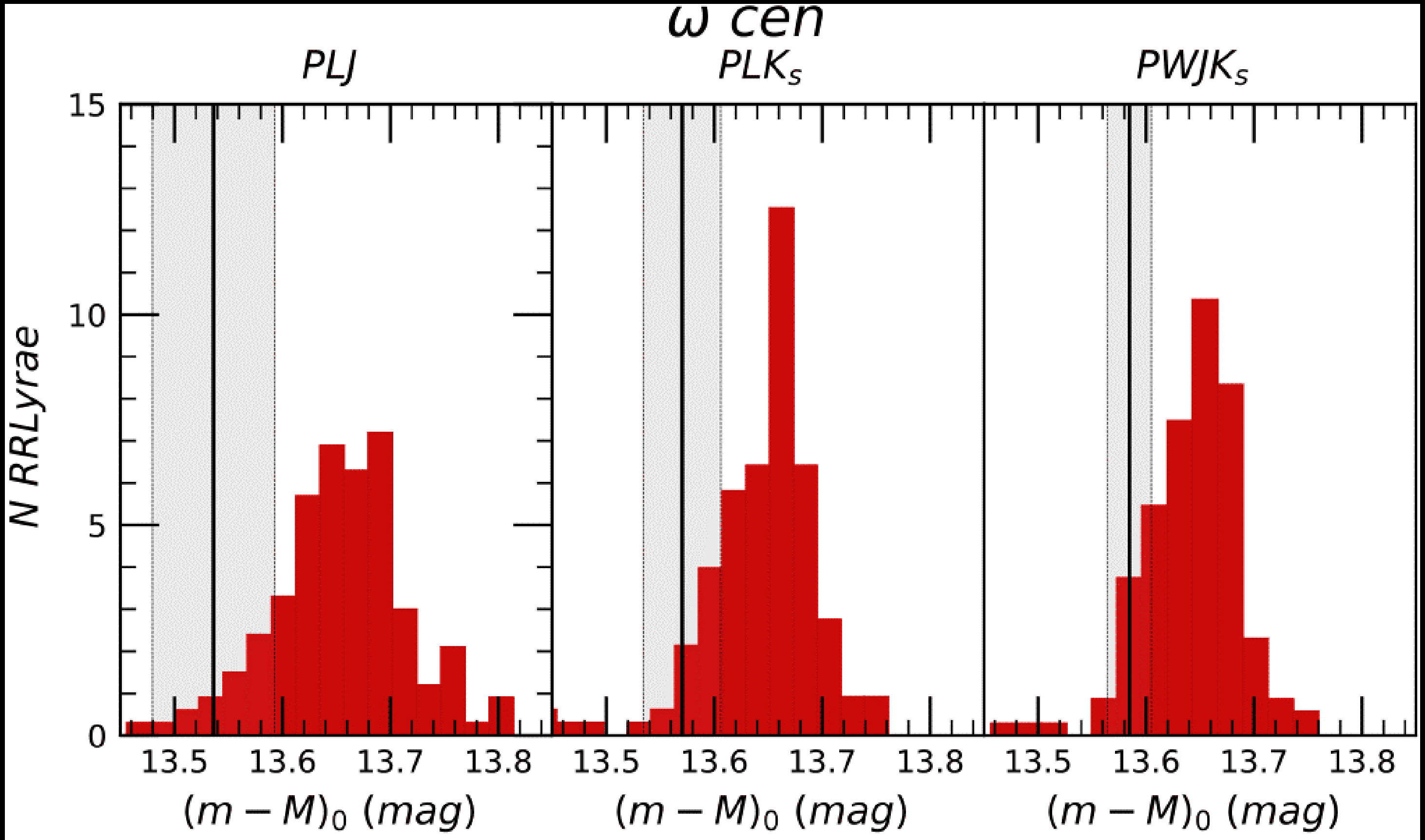
Template derivation

2. Calculate the average magnitude in each band:
   A. Fitting the light curve with some analytical functions.
   B. Transforming it into intensities.
   C. Calculate the average in intensity.
   D. Transforming the average intensity in average magnitude.

But can all observed light curves be fitted?



Comparison between ω cen distance calculated with T2Cs and RRLyrae (photometry from Navarrete+2017 and relations from Bhardwaj+ 2023)

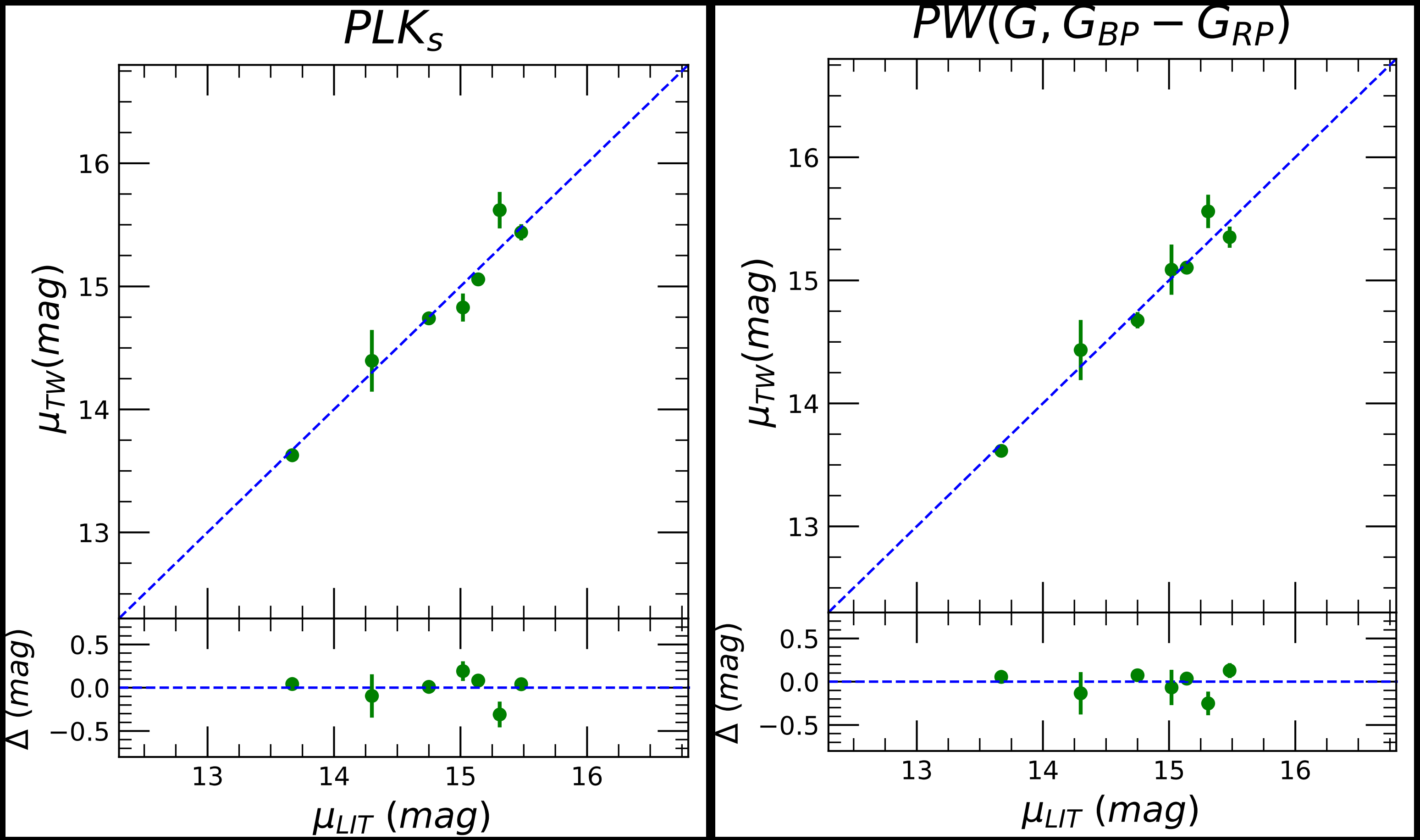


MASTER THESIS

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

IMPACT ON THE DISTANCE SCALE

Comparison between our distances and those by Bhardwaj 2023



MASTER THESIS

- **PERIOD – LUMINOSITY RELATION**
- **PRESENCE IN ANCHORS**
- **ZERO POINT CALIBRATION**
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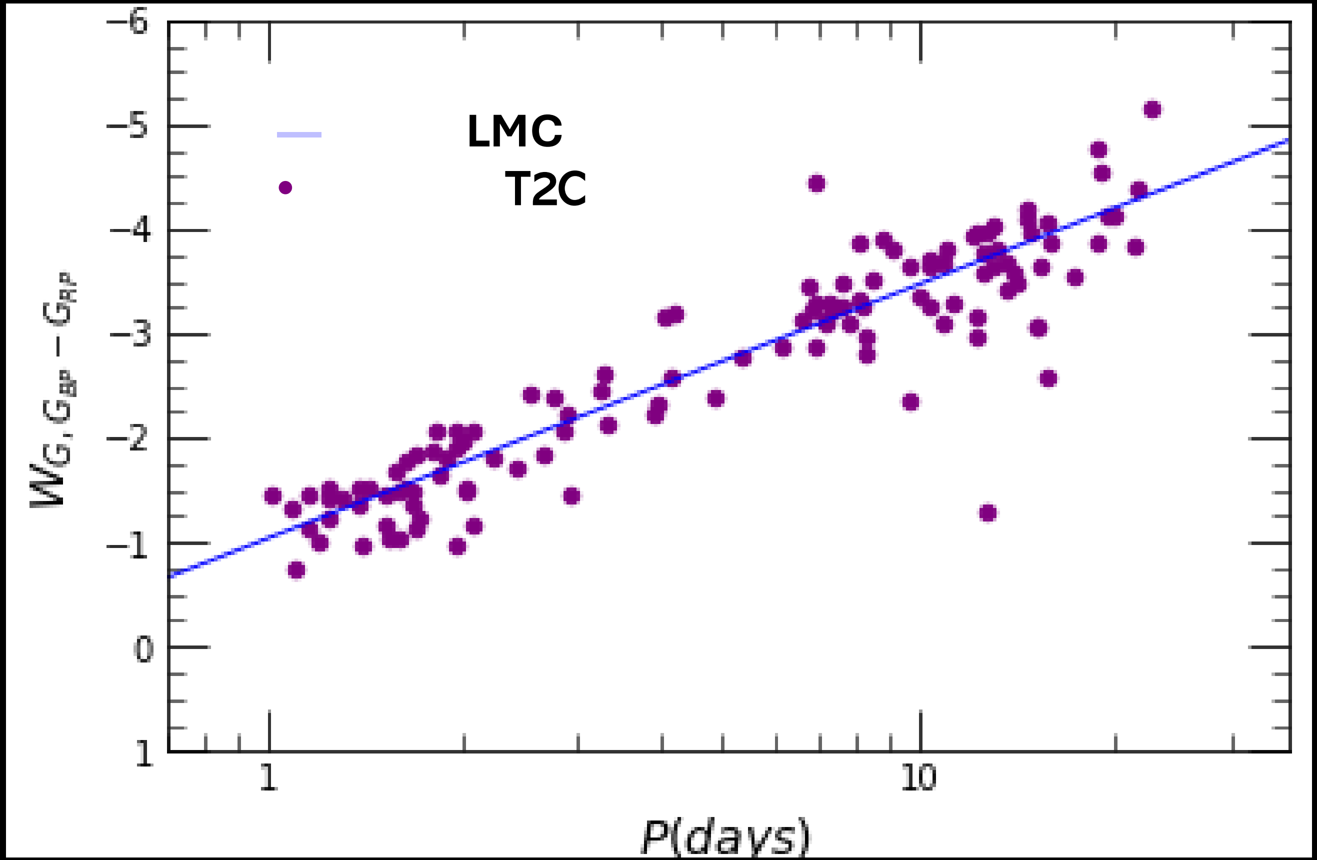
The distance moduli of GGCs appear **overestimated** up to **2%**.

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

IMPACT ON THE DISTANCE SCALE



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

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

$$W_{G,G_{BP}-G_{RP}} = m_G - 1.90 \cdot \left(m_{G_{BP}} - m_{G_{RP}}\right) + 5\log\pi - 10$$