Unlocking Cosmic Distances with AGB Stars: the Potential of Miras as Precision Distance Indicators

Massimo Marengo
Florida State University - mmarengo@fsu.edu

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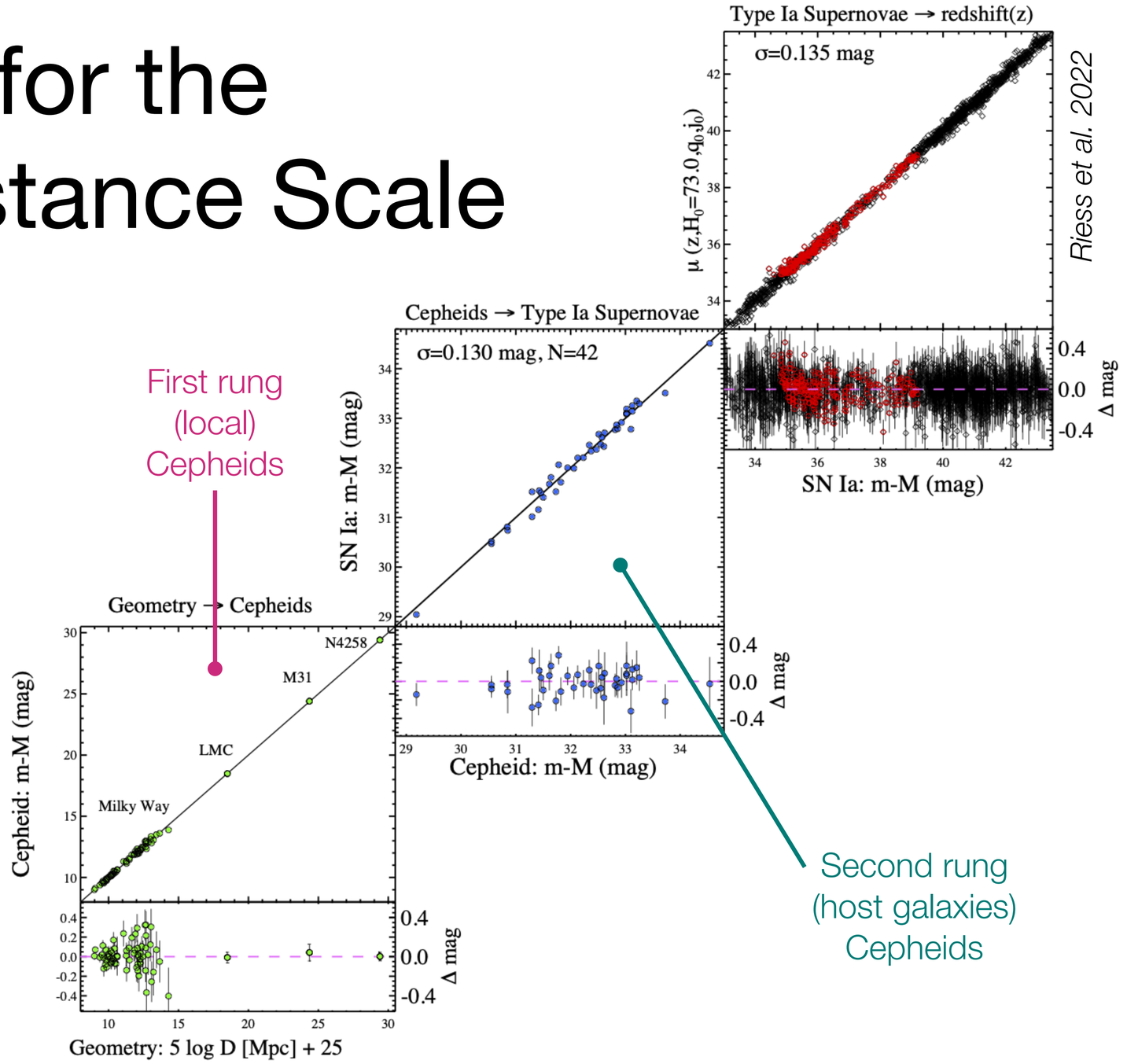
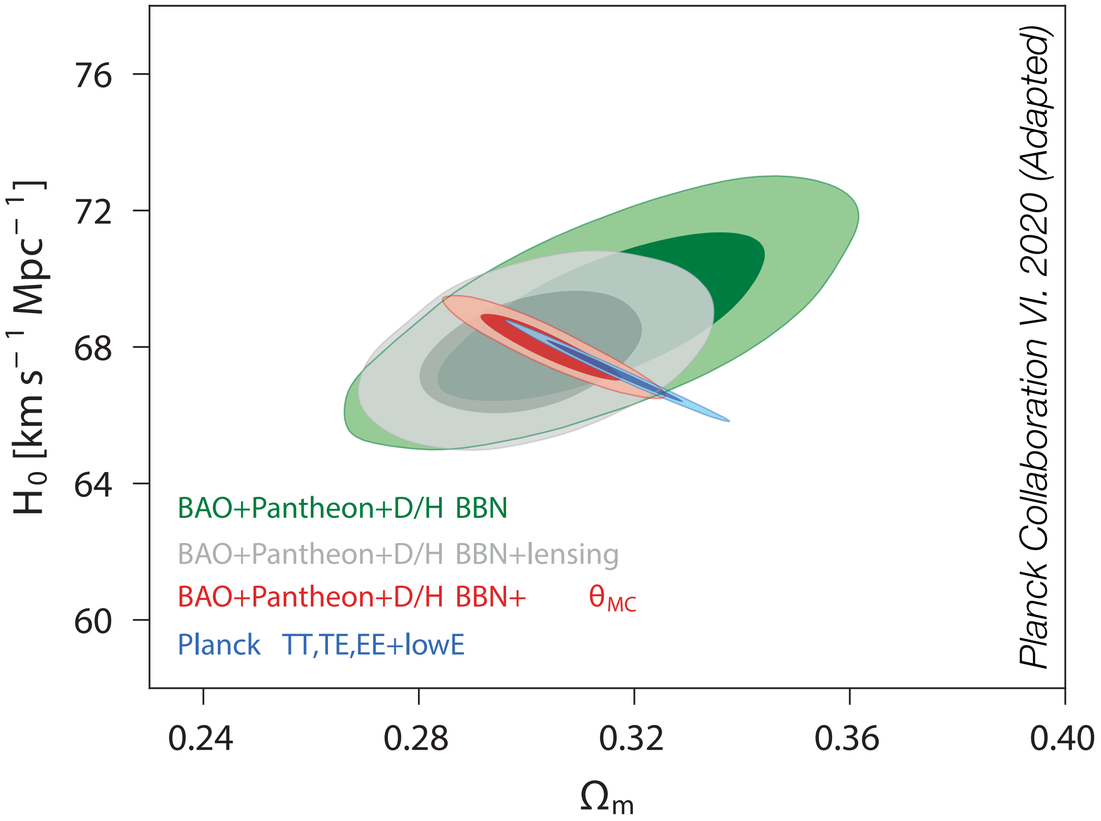
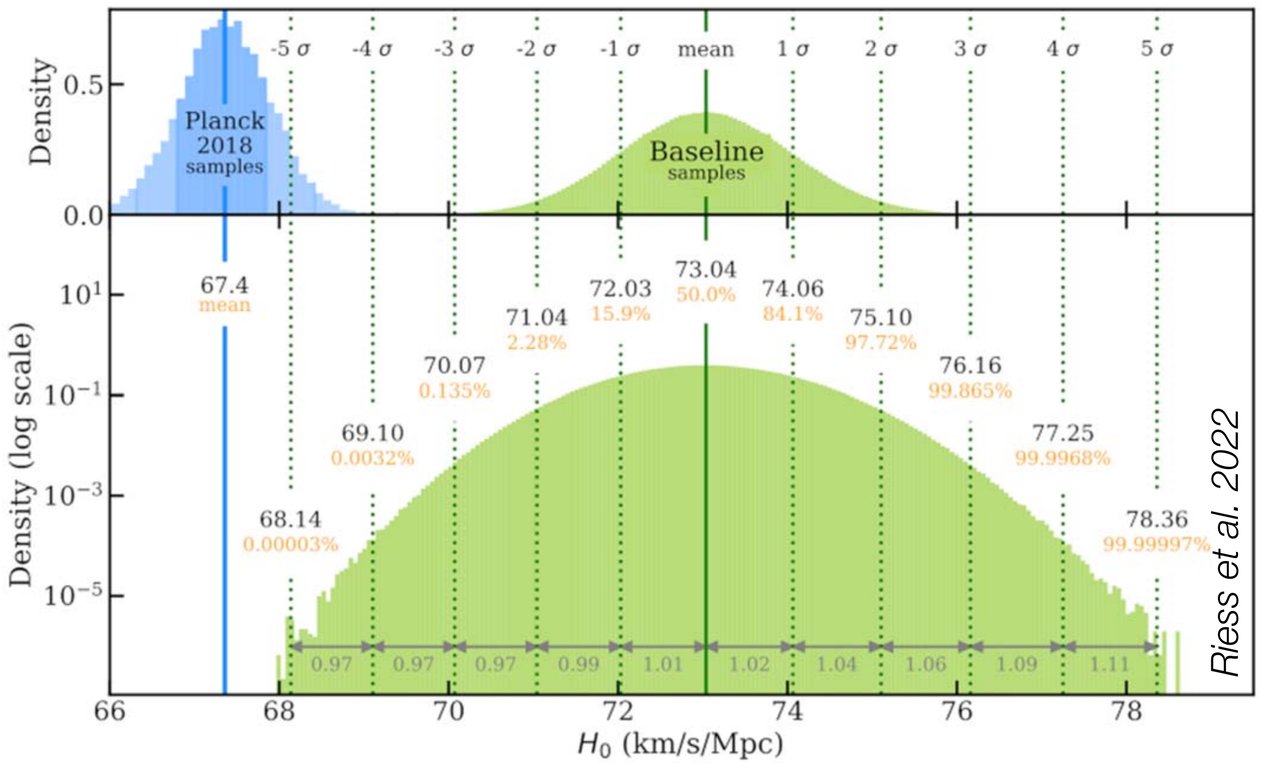
Calibrators for the Cosmological Distance Scale

- Most precise distance scale ladder relies on **Cepheids** and **SNIa**.
- Cepheids calibrated mainly on the basis of 2 primary anchors: **LMC** and **NGC 4258** (+ SMC, M31 and MW Cepheids with Gaia DR3 parallaxes).
- SNIa calibrated in host galaxies with Cepheids (⇒ with young populations).
- There are alternatives (**J-AGB**, RGB, Tully-Fisher, Surface Brightness Fluctuations), but not (yet?) as accurate.



The H_0 tension

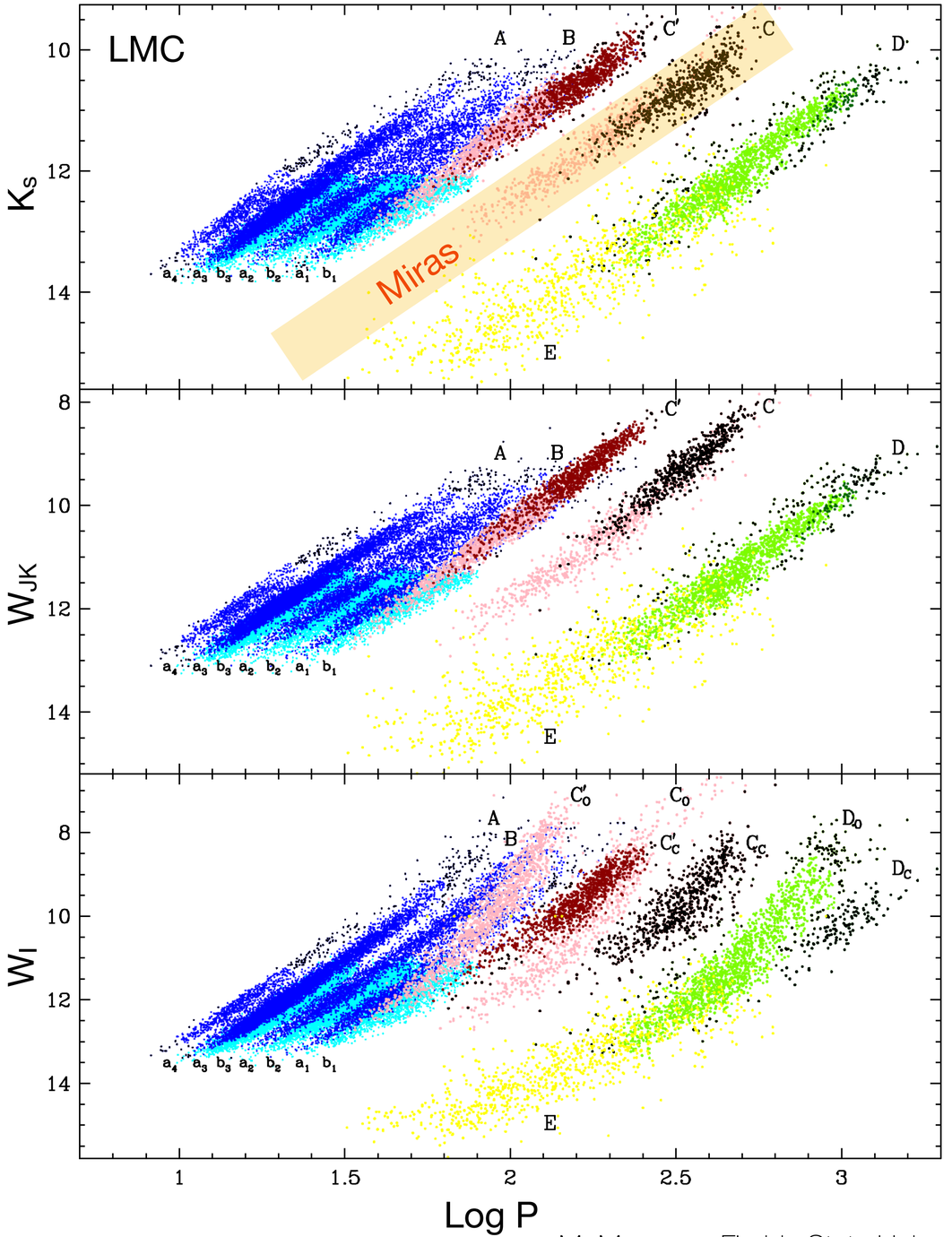




- Mounting evidence of **tension at > 5σ level** between cosmological parameters determined by fitting ΛCDM model with Planck CMBR+BAO data (H_0 = 67.4 ± 0.5 km s^{-1} Mpc^{-1}) vs. *direct* determination with *cosmological distance scale* (H_0 = 73.04 ± 1.04 km s^{-1} Mpc^{-1}, e.g. *Riess et al., 2022*).
- SH0ES results appear convincing, but <u>not a settled issue</u> (see e.g. Carnegie-Chicago upcoming results).

Miras to the rescue?

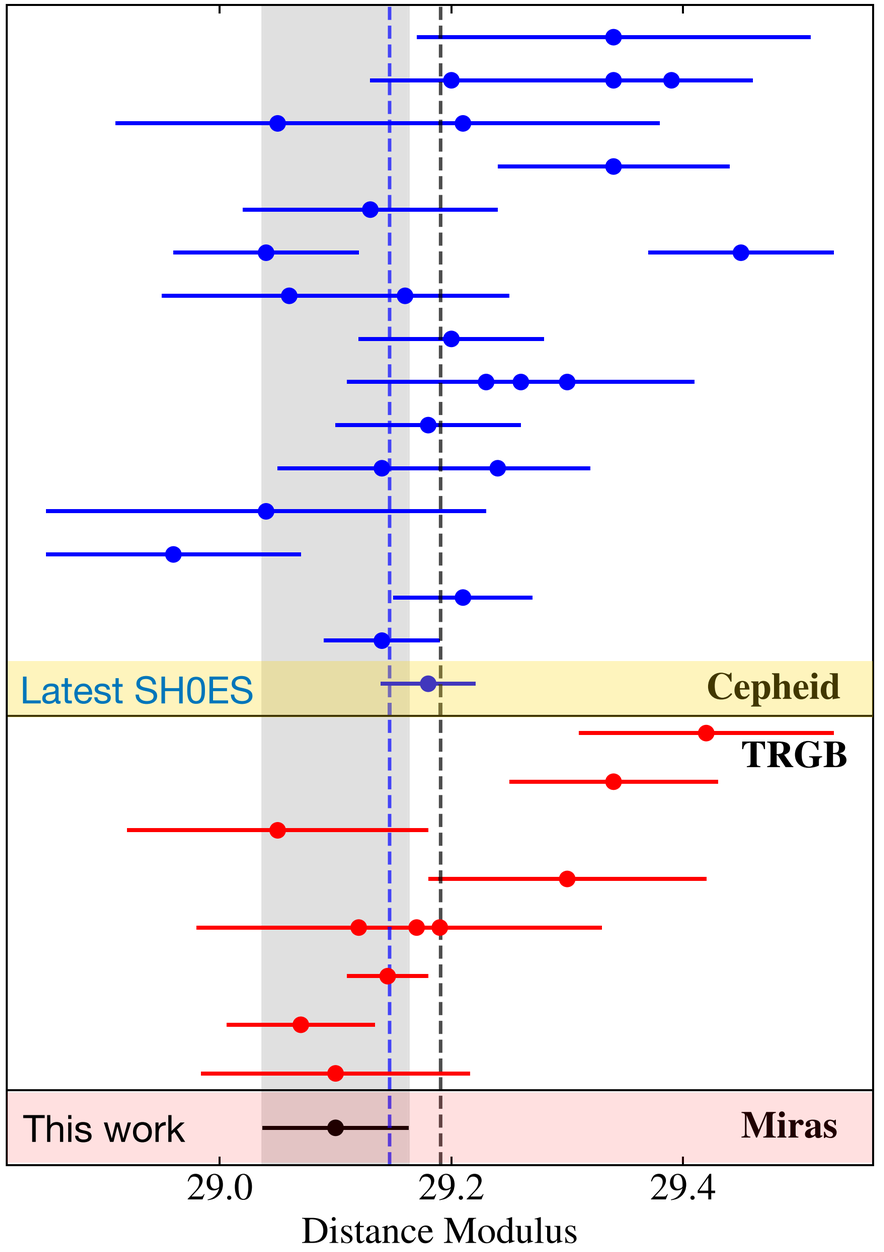
- *Miras are (on paper) astronomers' best friends:*
  - They follow well characterized PL relations (see Wood et al., 1991, OGLE papers)
  - They are bright (long period Miras are brighter than Cepheids) ⇒ can potentially replace Cepheids entirely
- *… until we have to actually use them:*
  - Their light curves are not very regular
  - They come in different chemical flavors (C/O ratio)
  - They have a complex evolutionary history (TP-AGB)
  - So much dust!



Testing Mira distances in the real world

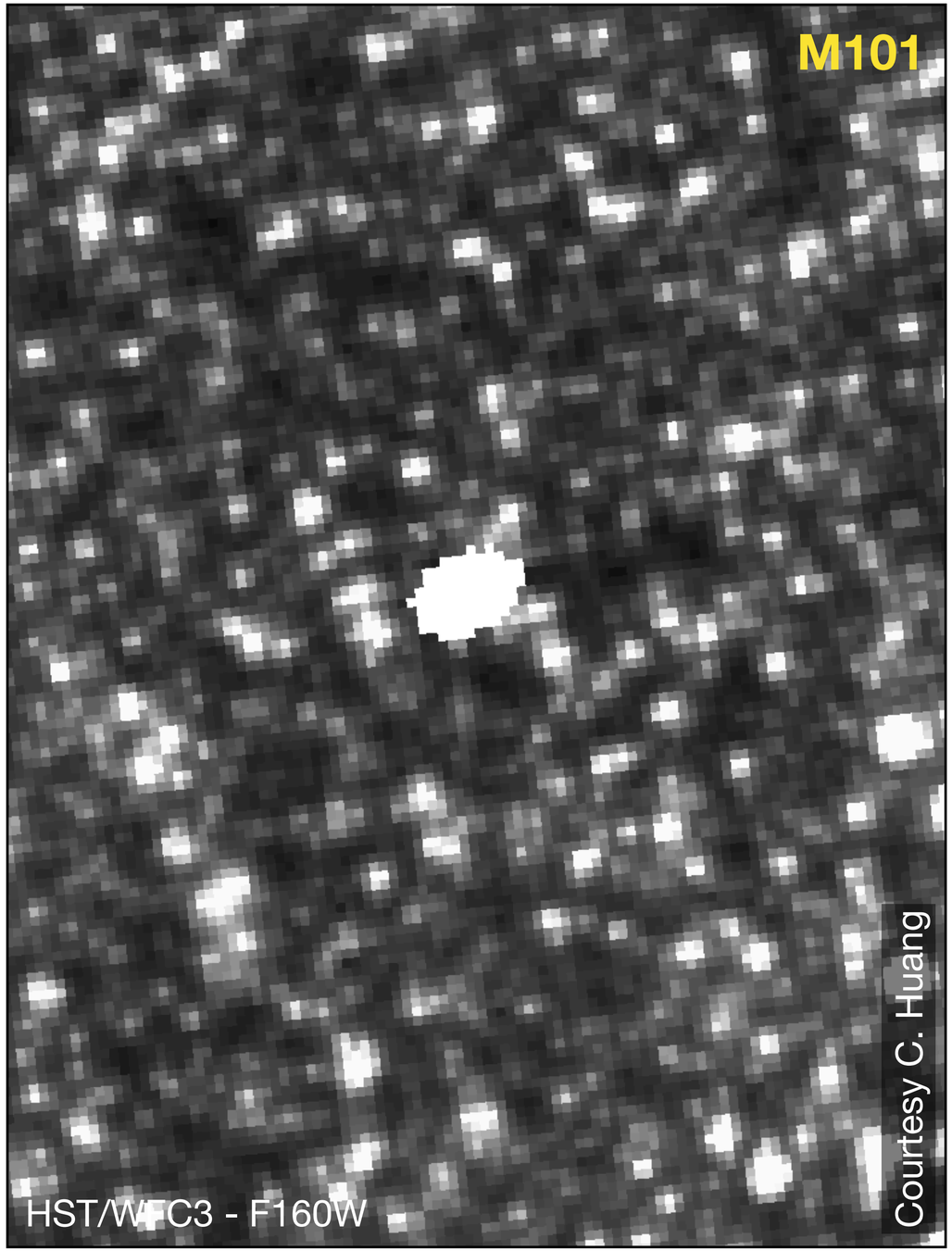
- An HST/JWST program to calibrate Miras P-L relation to be competitive for the Cosmological Distance Scale (PI *Caroline Huang*).
- Preliminary results obtained with HST WFC3/NIR data (primarily F160W), based on Miras in the LMC and NGC 4258 (anchors, *Huang et al. 2018*, *2020*), NGC 1559 and M101 (SNIa hosts, *Huang et al. 2020*, *2024*).
- Current result: $H_0 = 72.37 \pm 2.97$ km/s/Mpc (cfr. e.g. $H_0 = 73.04 \pm 1.04$ km/s/Mpc, SH0ES).
- Challenges to reach ~1% accuracy (~Cepheids):
  - Observational challenges (e.g. crowding)
  - Intrinsic challenges (complex AGB physics)

M101 distance moduli (from *Huang et al. 2024*)



JWST to the rescue!

- Miras are cool sources with very red colors: better observed with IR telescopes from space.
- Observing Miras in SNIa host galaxies requires to beat crowding (while they are among the brightest stars, a crowded field still induce bias).
- C-rich and O-rich Miras have different PL relations: IR wavelengths help separating AGB surface chemistry.
- IR excess due to circumstellar dust can be characterized in suitable MIR bands.
- **JWST/NIRCam MIR observations of M101** testing Mira distances accuracy, and refine the Mira distance ladder.
- **How accurate can we potentially get?**



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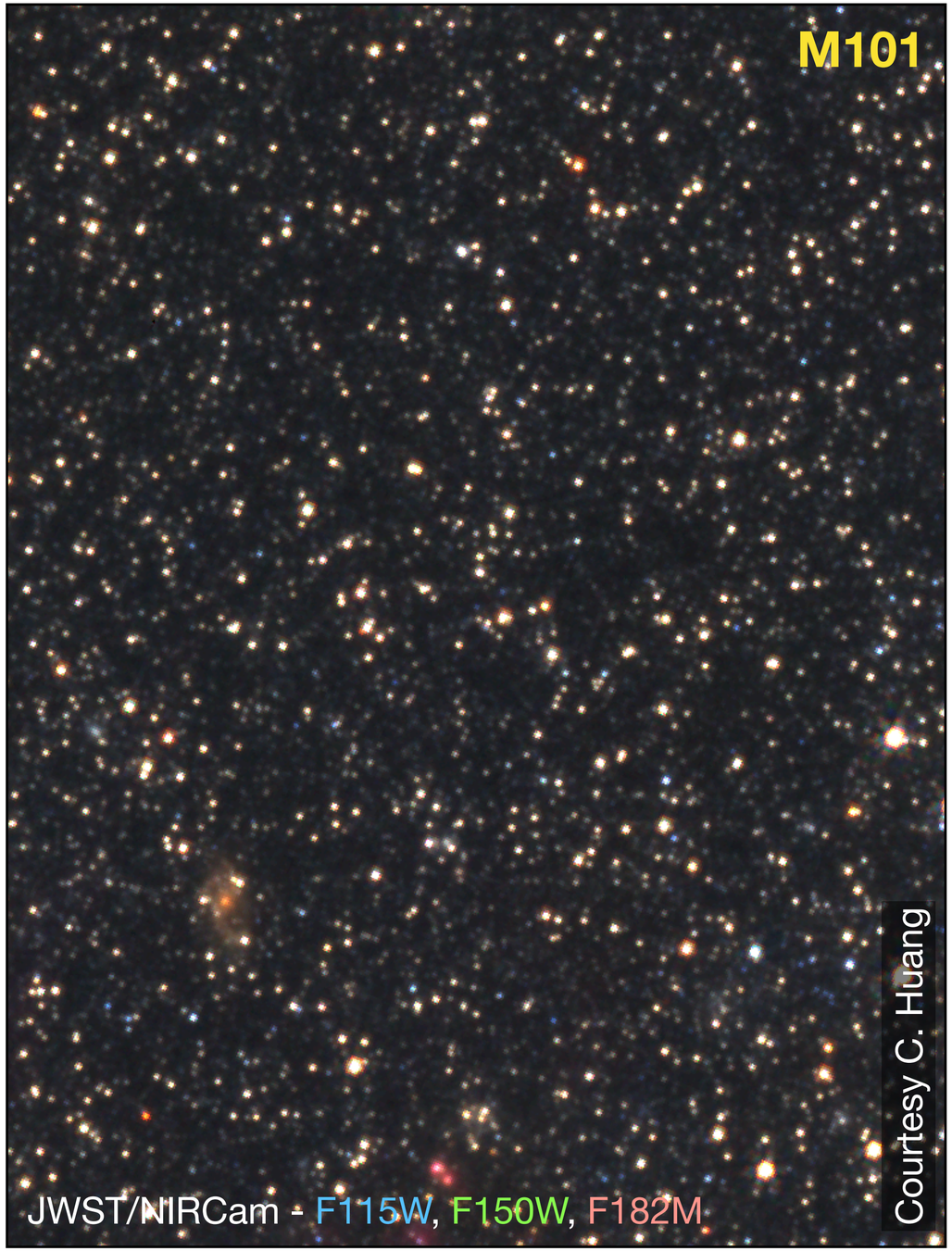
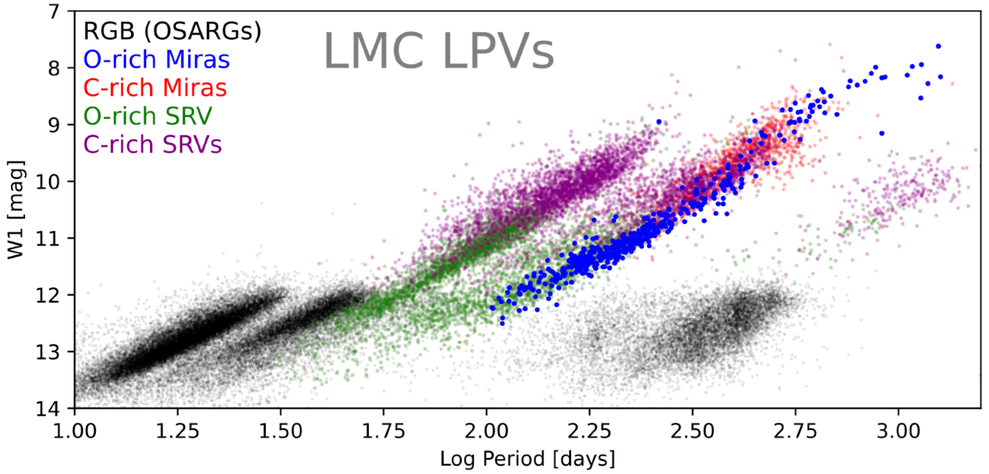
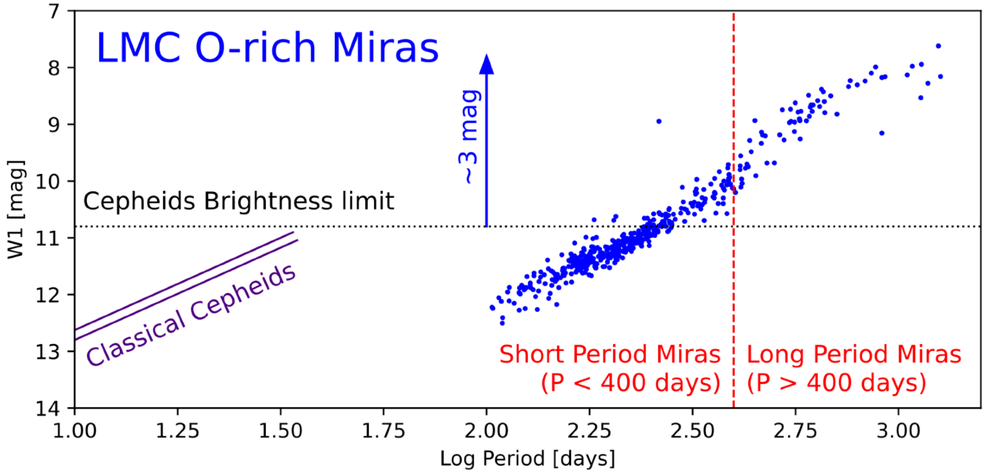
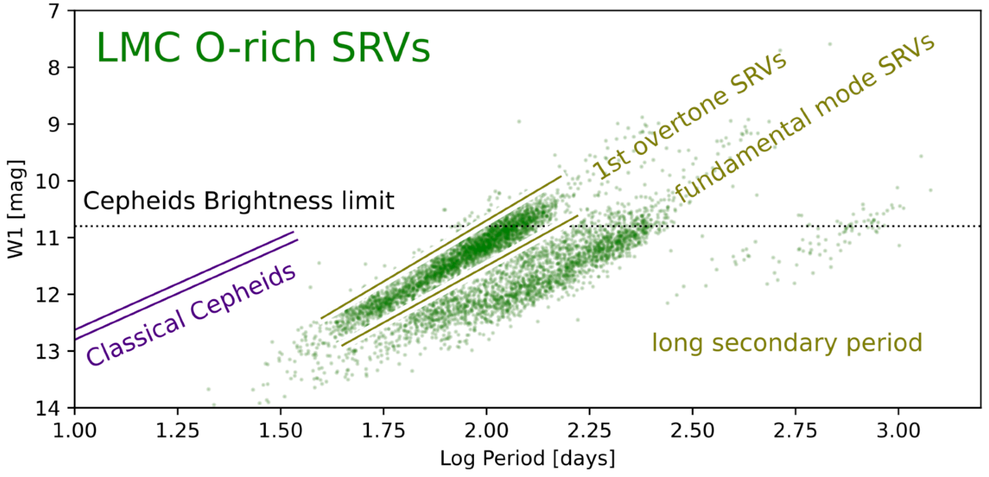


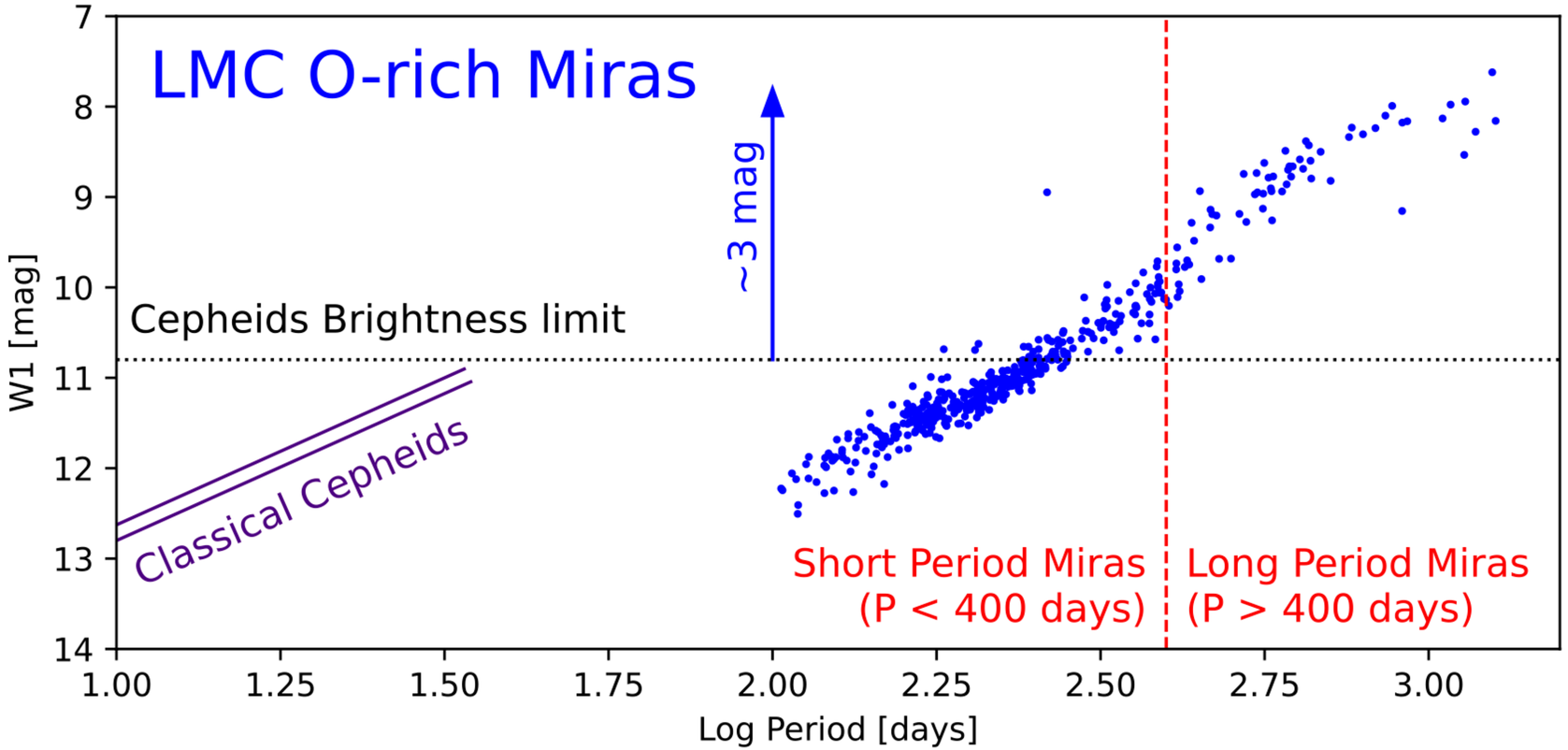
MIR PL Relations

- **JWST NIRCam F356W & F444W passbands** (equivalent to WISE W1 & W2 bands and Spitzer/IRAC 3.6 & 4.5 μm bands) show well defined and narrow PL sequences.
- No existing native calibration of PL relation in NIRCam bands: however rich dataset exists for LMC/SMC (and MW, but caution with Gaia parallaxes) in Spitzer/IRAC and WISE bands.
- **NEOWISE** (WISE extension mission) provides light curves for LMC/SMC OGLE LPVs (~750 epochs over 12 years).
- **CatWISE** provides flux average photometry (from resampled coadded images) over entire NEOWISE database: provides *average magnitudes without the need of fitting light curves*.
- **O-rich AGBs**, fundamental mode (Miras) and 1st overtone PL relations present least amount of scatter. **C-rich AGBs** show largest amount of scatter (both modes).

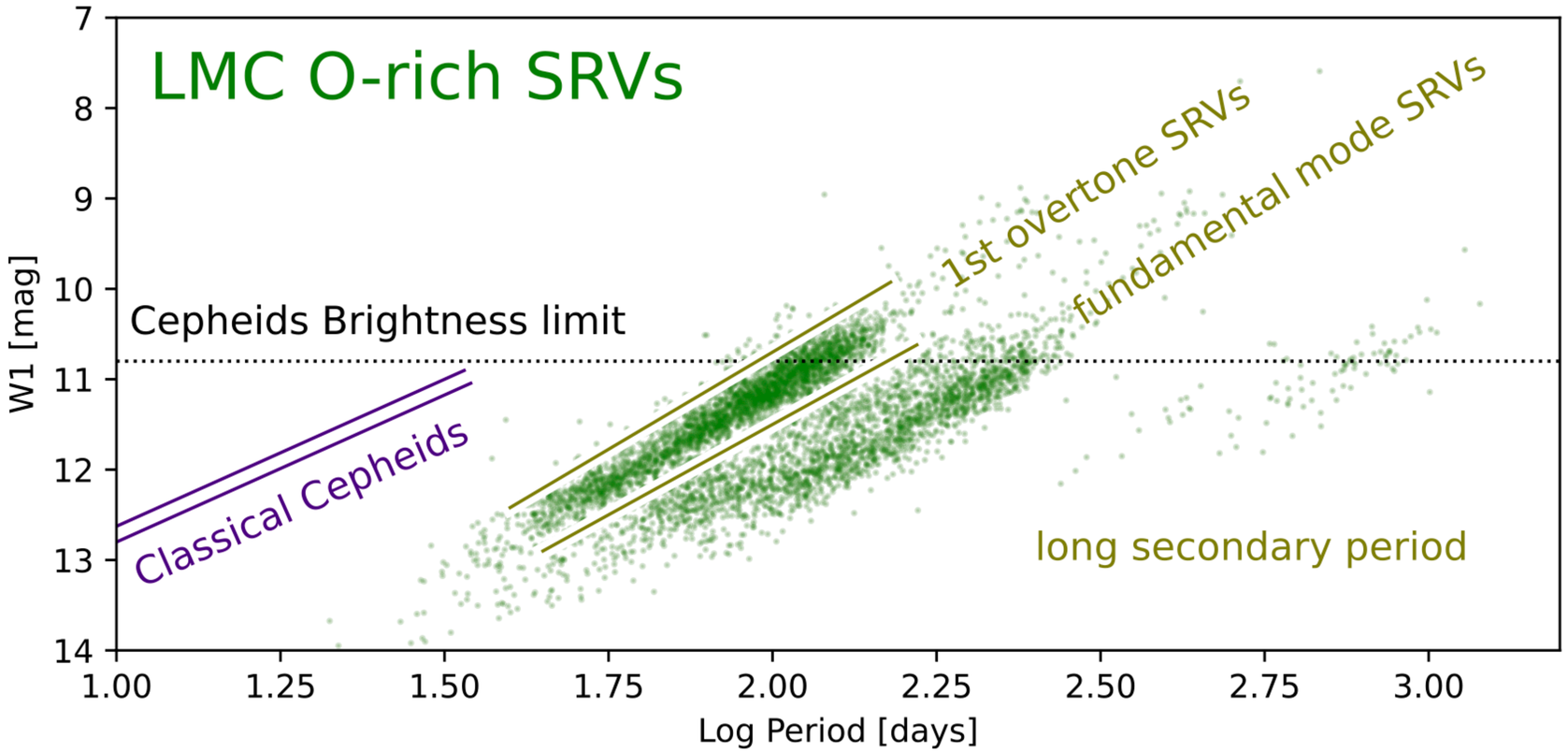








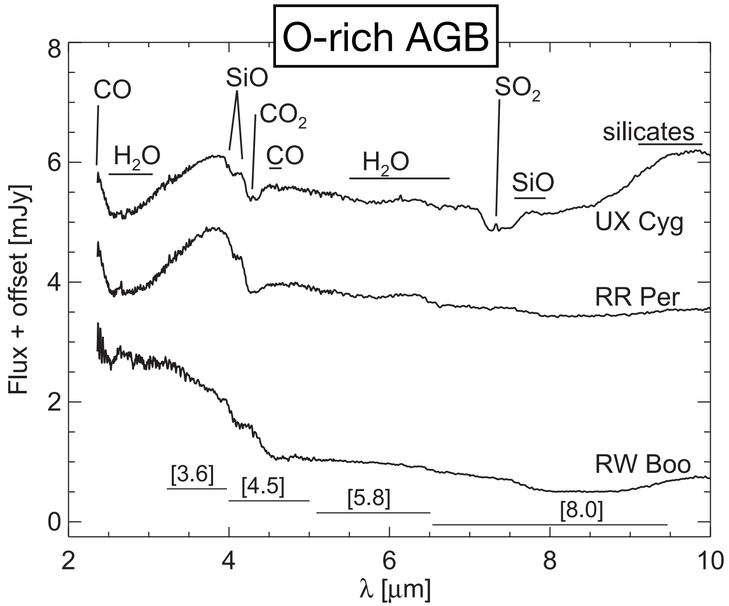
- O-rich Miras: Homogeneous set of fundamental mode LPVs (selection based on Bailey diagram).
- Linear PL for **short period Miras** (P < 400 days); quadratic fit (NIR, see *Yuan et al. 2017*) not required. Up to ~ 1 mag brighter than Cepheids. In W1 (and W2) bands do not show significant IR excess.
- **Long period Miras** (P > 400 days): intermediate-mass AGB stars. Different PL slope and departure from linearity. Larger scatter. Up to ~3 mag brighter than Cepheids (in W2 and W2 bands), extending the range of PL distances from z ~ 0.02 (SH0ES Cepheids) to z ~ 0.08 (middle of SNIa range).
  Potential for a 2-step (Miras to redshift) cosmological distance scale? (see Caroline Huang work)

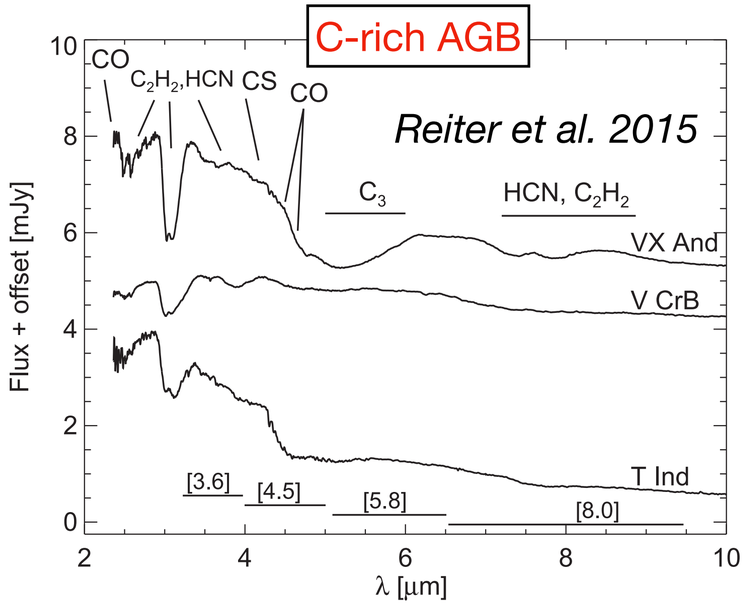


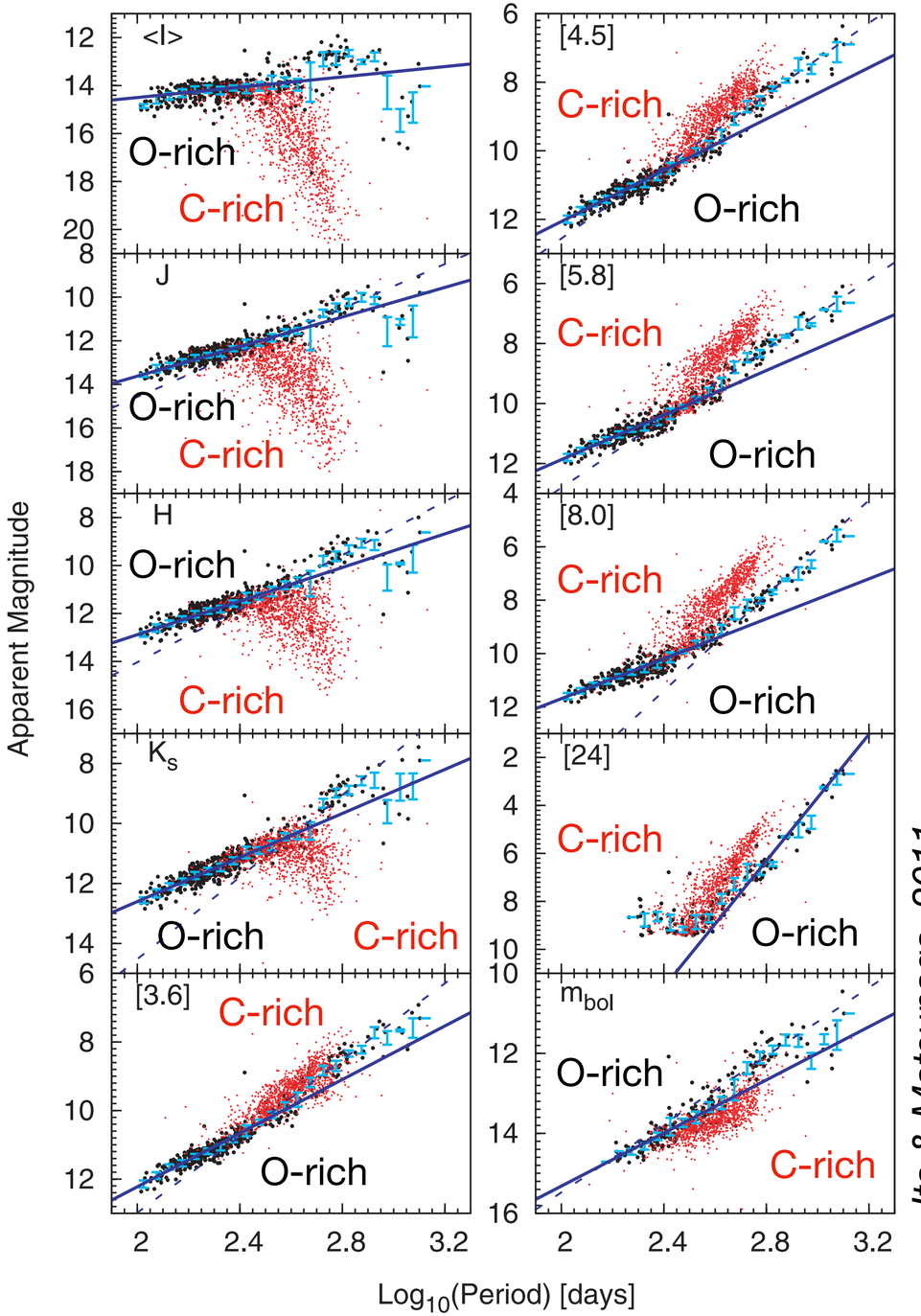
- Shoutout for **1st overtone O-rich AGBs**: low scatter linear PL relation (W1 and W2 bands). Seemingly unaffected by molecular extinction / dust emission. Low mass stars: more numerous than Miras $\Longrightarrow$ higher statistics. Older stellar population (may allow adopting SNIa hosts with older populations). Low amplitude: smaller uncertainty when observed with low phase coverage. As bright as Cepheids.

- Difficult to select: Bailey diagram selects for SRVs: mixed fundamental mode - 1st overtone population. Smaller amplitude $\Longrightarrow$ more difficult to identify as variables.

Molecular absorption and dust infrared excess

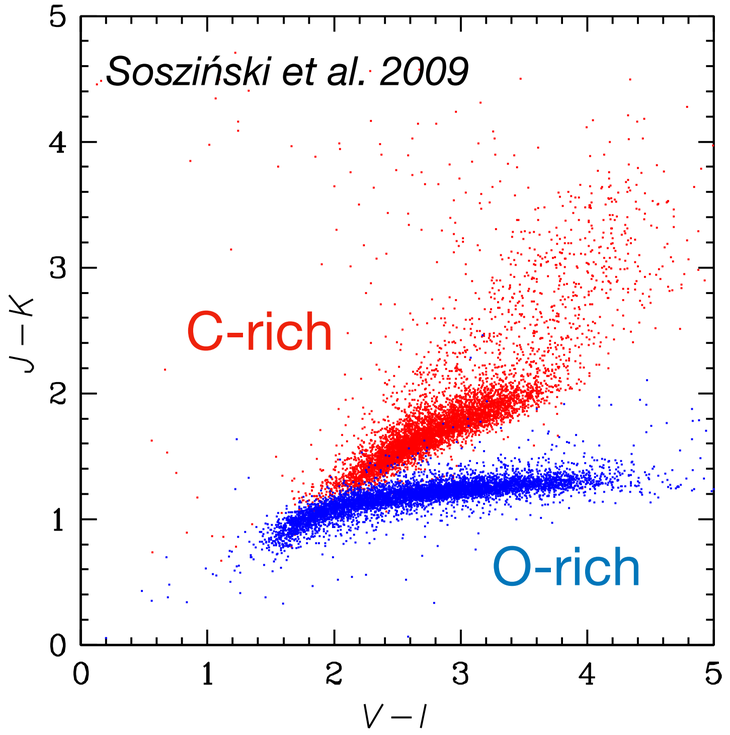


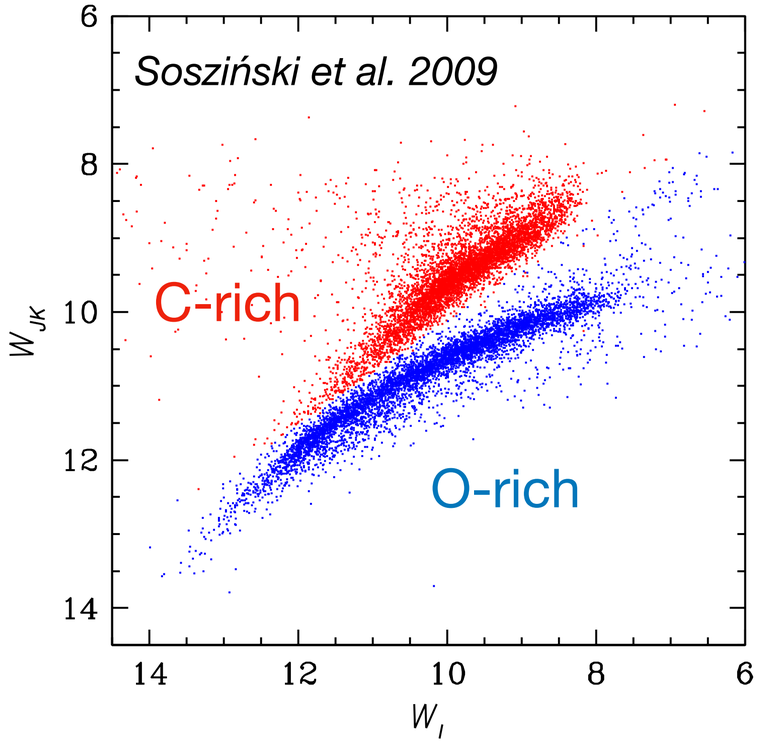


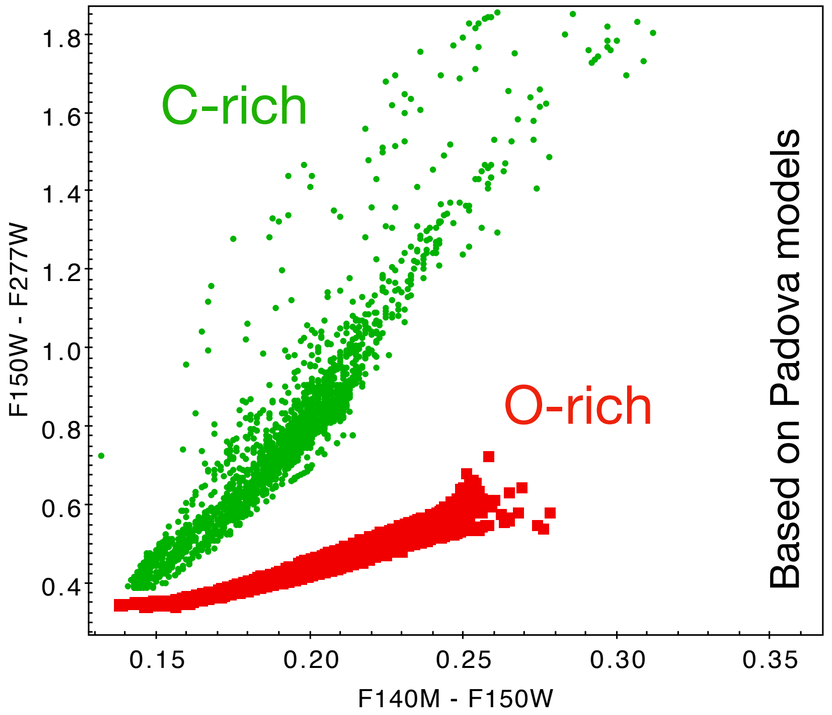


- C-rich Miras more affected by molecular absorption (C_2H_2, HCN, CS, CO, C_3) and dust infrared excess (in the MIR). **Tighter PL relations can be obtained by adding color term.**
- **O-rich Miras** less affected by molecular absorption (NIR); only **long period Miras** have significant dust MIR excess (but less than C-rich Miras.

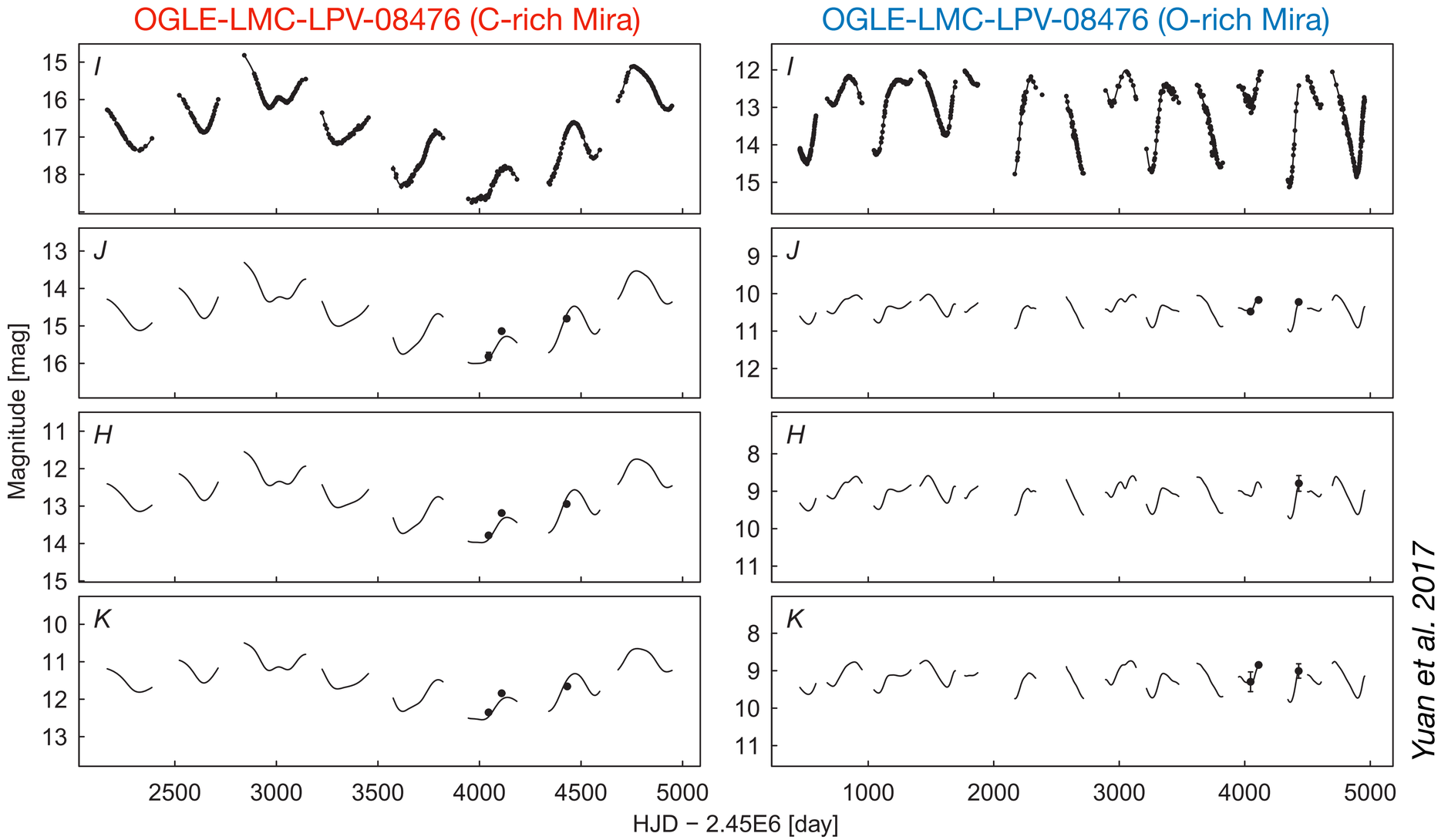
Chemical type separation (C/O)



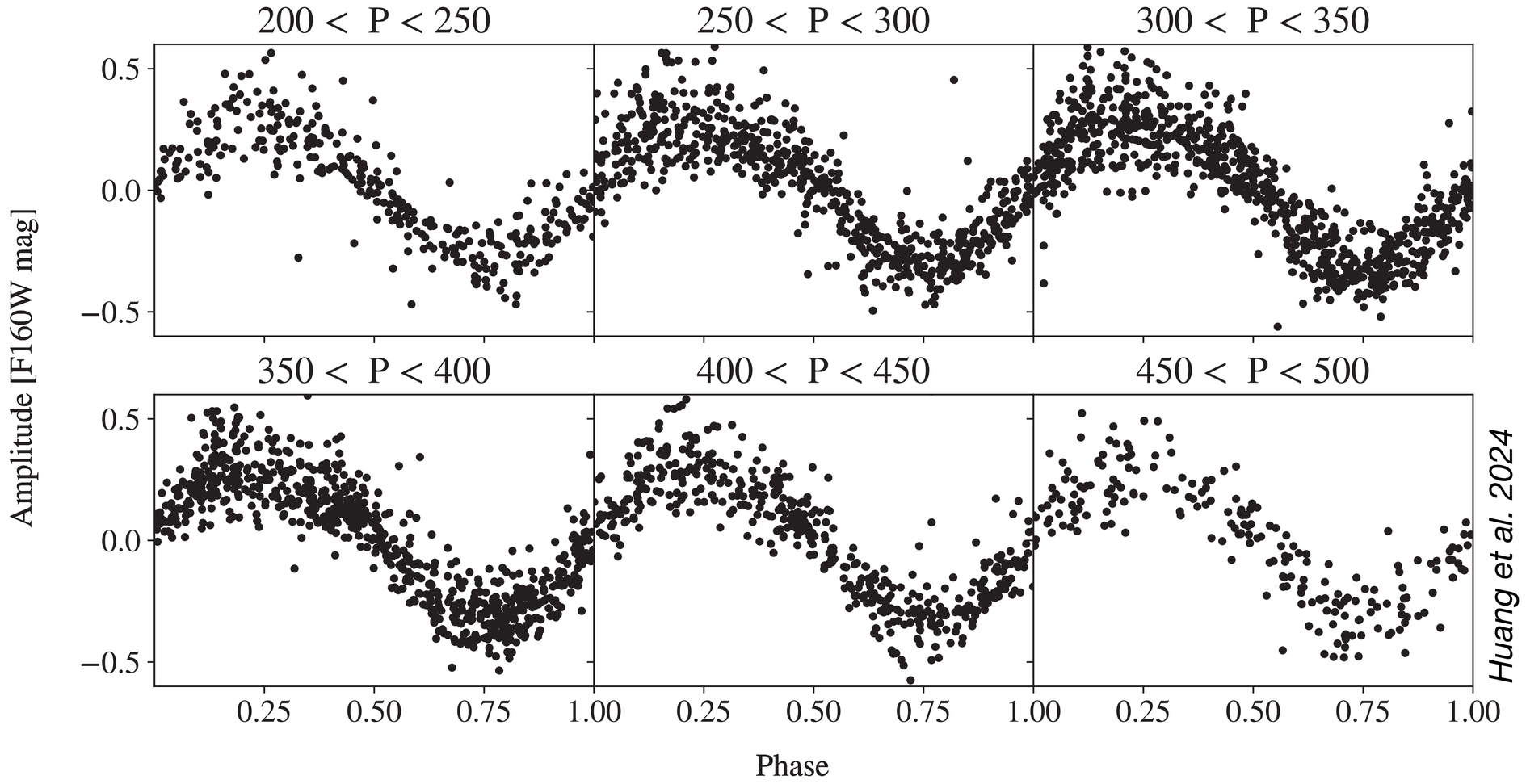




- A number of IR bands sample molecule absorption and dust emission in AGB stars. Discrimination more efficient for stars with larger amount of circumstellar dust.
- NIRCam medium width filters potentially sensitive to molecular band absorption in C and O-rich AGBs.

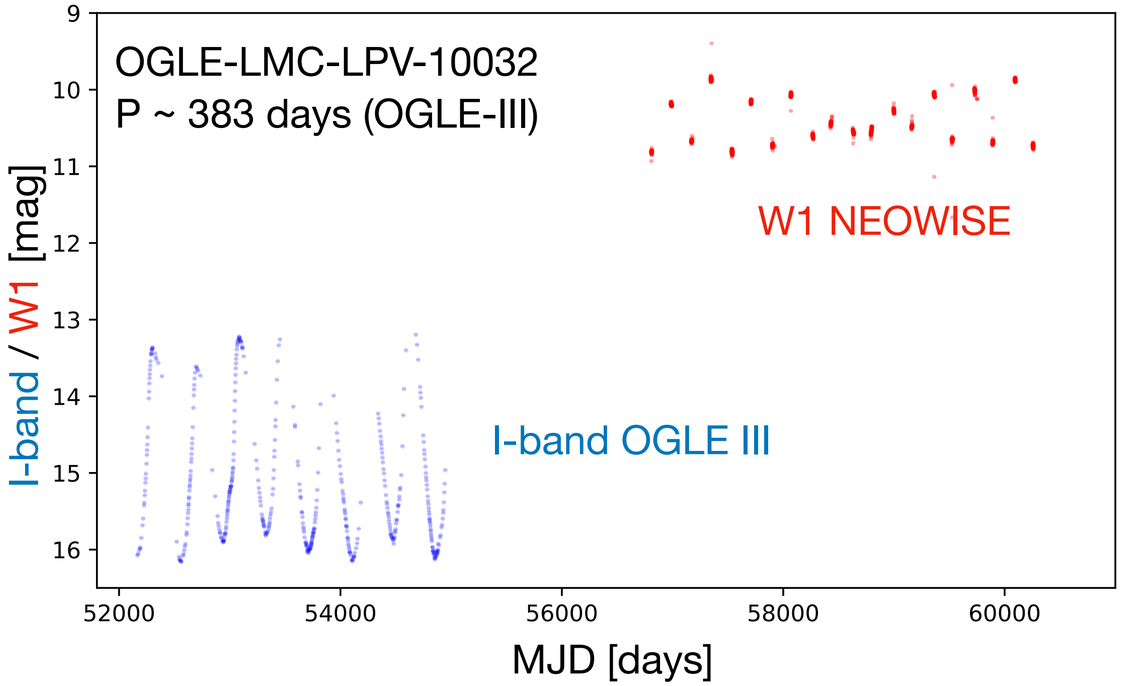


- **Period-to-period light curve variations** more pronounced in C-rich Miras (O-rich Miras more regular).
- <u>No NIR universal template</u>: variations can be corrected by rescaling a well sample template (e.g. I-band OGLE templates to derive more precise NIR average magnitudes). Needs simultaneous observations.

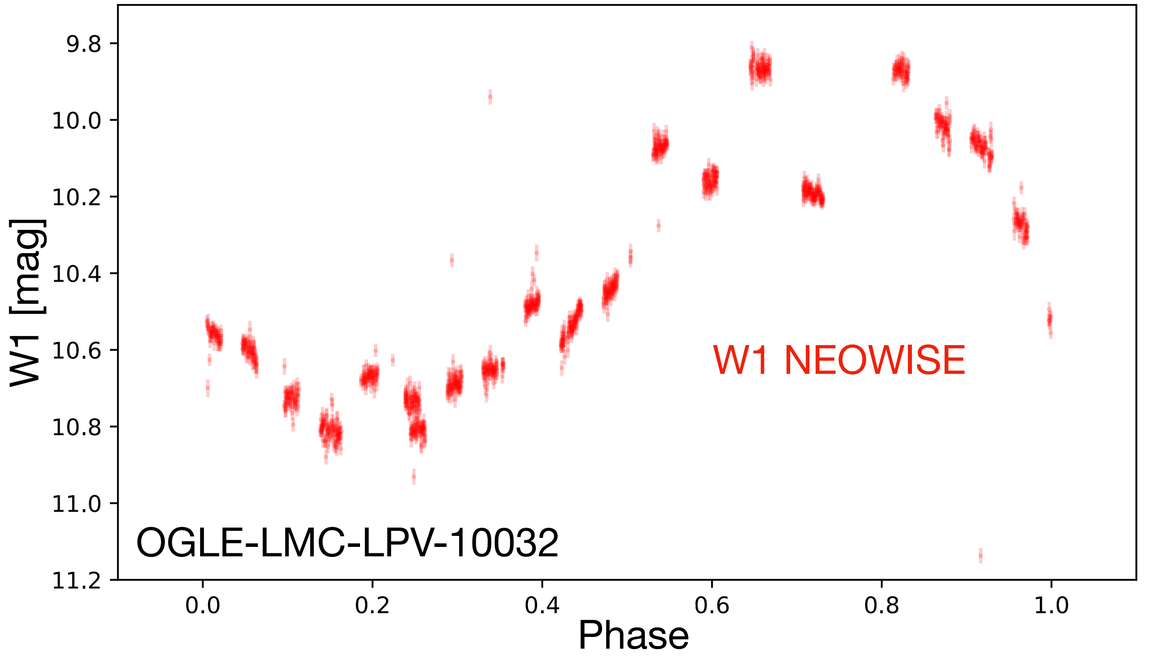


- Are light curve variations a problem in the infrared?
- Composite light curves of O-rich Miras appear sinusoidal; residual variations from star to star and period-to-period result in scatter ~ 0.2 mag (HST WFC3 F160W band, see *Huang et al. 2024*).
- Effect of light curve variations can be mitigated statistically (larger samples of Miras).

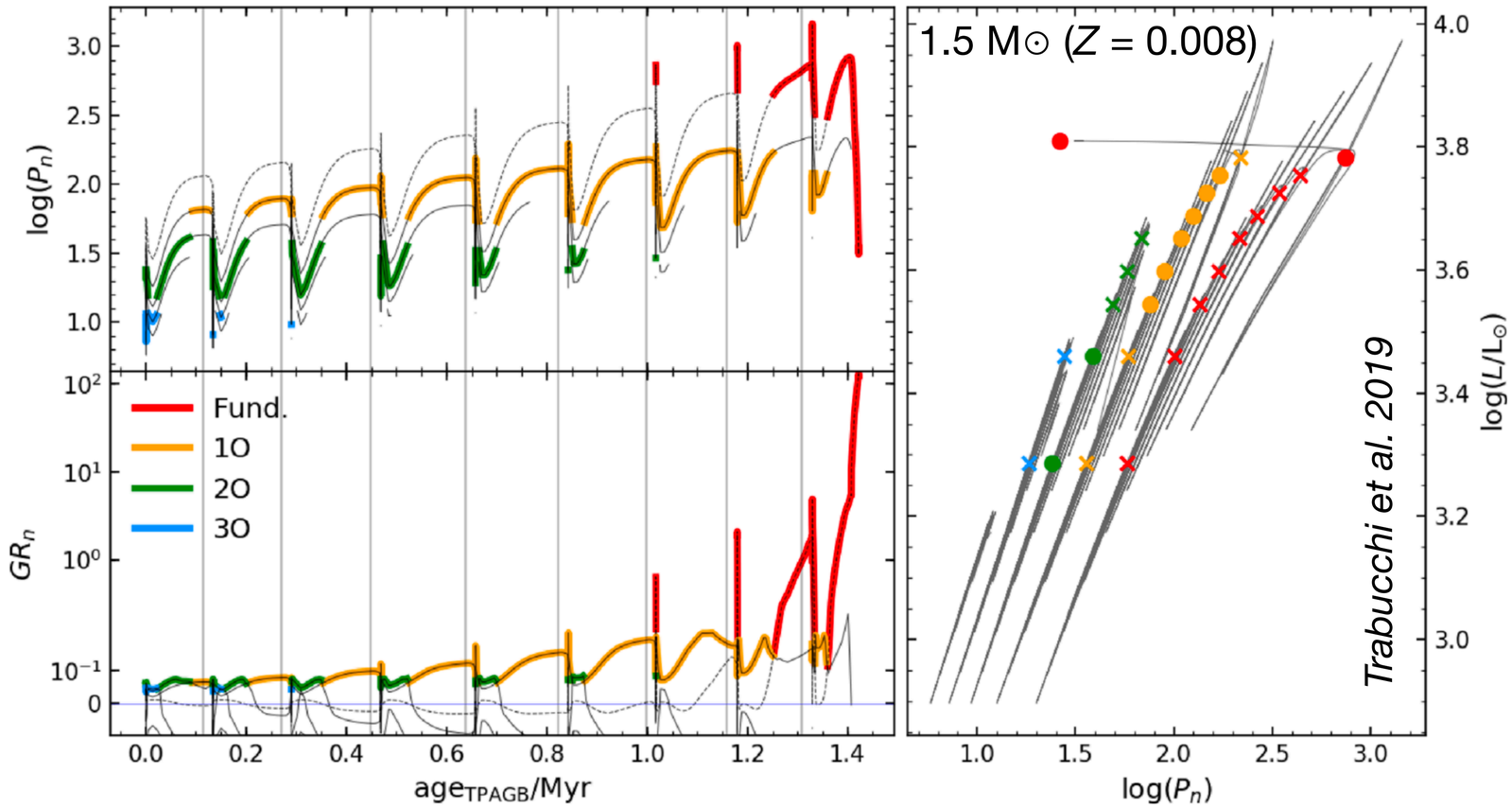
MIR light curve variations (O-rich Miras)



- In the MIR (W1 and W2 bands) the light curve variations are comparable to NIR
- Light curve are sinusoidal, with amplitude ~0.5 mag
- Period-to-period variations ⟹ scatter ≲0.2 mag.
- Scatter can be somewhat reduced by fitting new period (best fit period of IR data within 2 - 3 days of OGLE P_1 period.



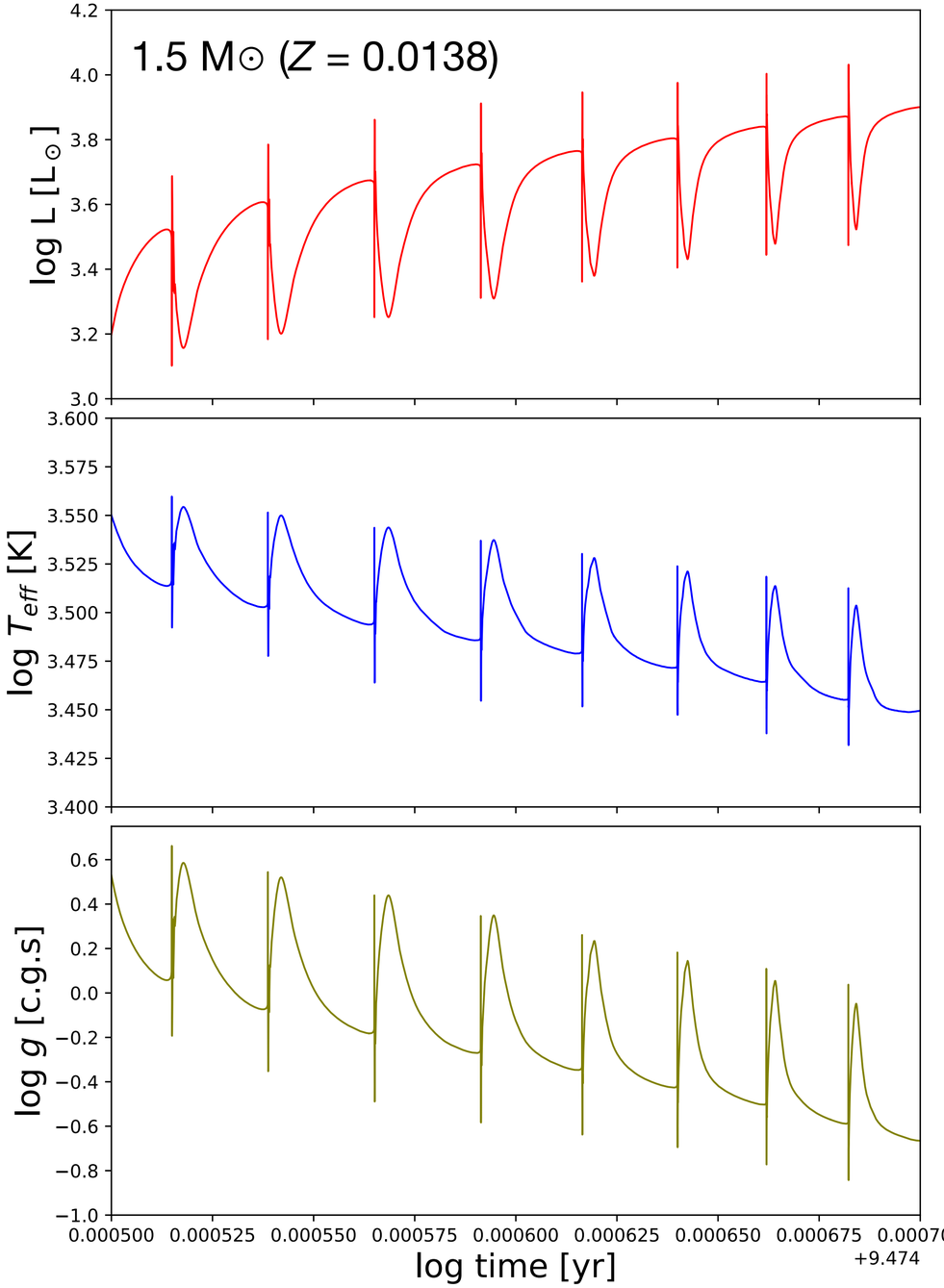
Evolutionary effects: TP and PL relation

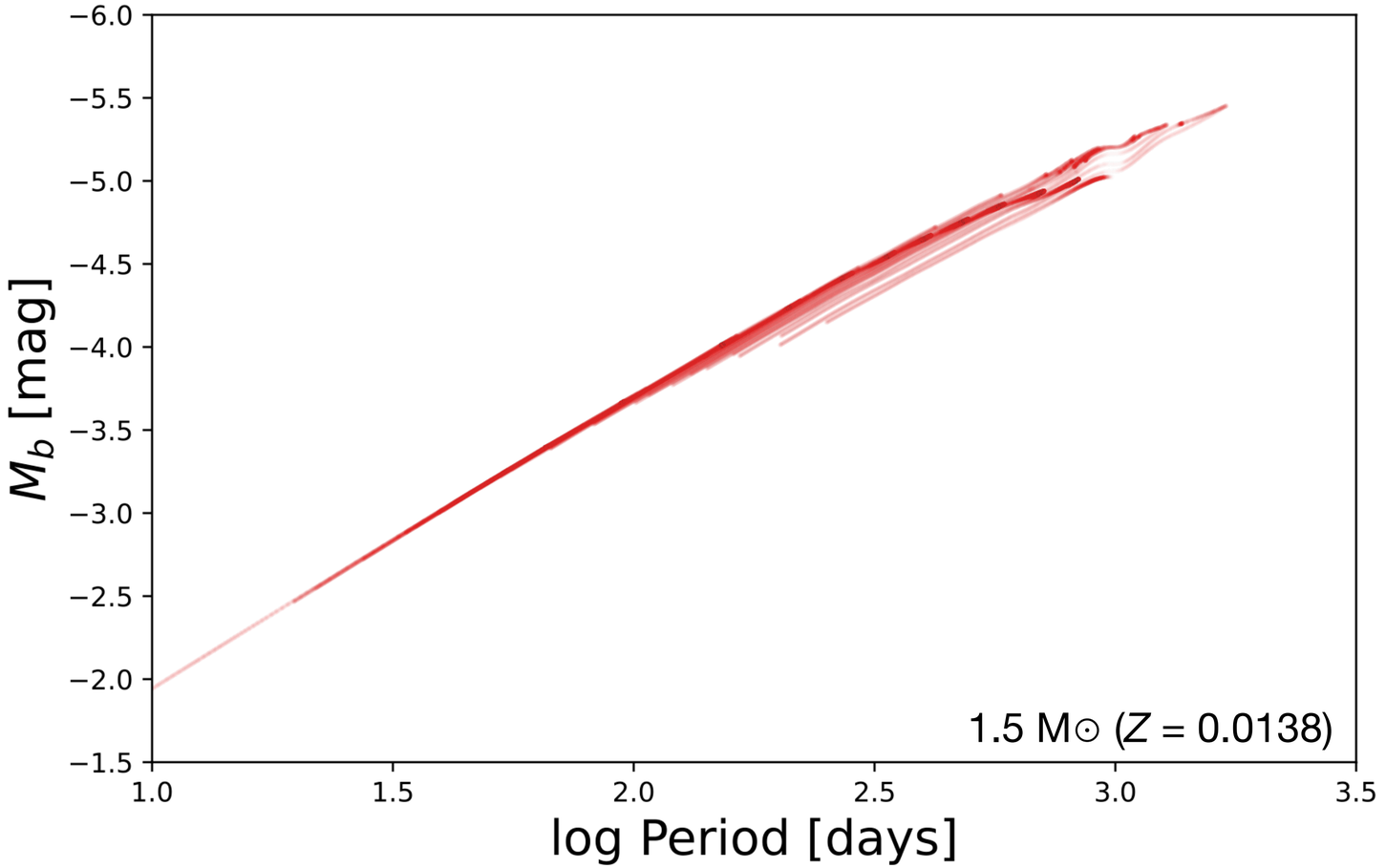


- As an AGB stars goes through a number of TP, different modes and periods will be excited.
- A low-mass AGB will settle on Mira-like pulsations (fundamental mode) after a number of TP (see *Trabucchi et al. 2019*). How will this process affect the PL relation?

Effects of TP on PL

- The changes in L, $T_{\rm eff}$ (and R) due to the occurrence in thermal pulses may affect both log P and log L for a TP-AGB star with a given mass M.
- In general the pulsation period is a function (in log space) of M and $R \Longrightarrow$ log g, as well as the atmosphere composition (Z, C/O, etc, see e.g. *Trabucchi et al. 2019*).
- Simultaneous change of log L and log $g \Longrightarrow$ change in both log P and $M_{\rm bol} \Longrightarrow$ potential source of scatter in PL relation.





- Log P estimated with simplified linear relation from Prager et al. 2022 (for illustrative purposes only).
- Maximum scatter in PL relation ~ 0.3 mag (in M_{bol}), for log P > 2.4, but only for a short part of the overall TP. Variation negligible in the interpulse phase.
- It remains to be verified the magnitude of the effect in the observable plane (especially IR bands).

Summary

- LPVs are an important tool to check for systematics in the traditional Cepheids+SNIa cosmological distance scale.
- Among LPVs, O-rich short-period Miras currently provide the best alternative to Cepheids (but O-rich 1st overtone variables are an interesting possibility, if they can be properly identified and characterized).
- Long period O-rich Miras (if they can be “domesticated”) are bright enough to directly connect to the Hubble flow, skipping SNIa.
- IR wavelengths minimize cycle-to-cycle variations and can be fitted with low amplitude sinusoidal light curves. Residual scatter can be reduced with enough statistics.
- Importance to have clean samples (e.g. separate pulsation modes and chemical signatures). Evolutionary effects (e.g. TP) do not appear to be insurmountable issues (more work needed).
- Program to develop a precision Mira distance scale with JWST/NIRCam. Current effort (HST/WFC3 IR) provides H_0 within 4%; JWST data analysis in progress.