Mira Variables as Distance Indicators

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Miras: identification and evolutionary status

Miras in the Galaxy and LMC

- PL relation (JHK_S [3.6] [4.5] M_{bol})

The Local Group and beyond

- NGC6822, NGC4258, NGC1559

Collaborators: Feast, Menzies, Matsunaga …

Work by: Yuan, Huang, Macri, Riess ...

AGB (Mira) Variables

Definition:

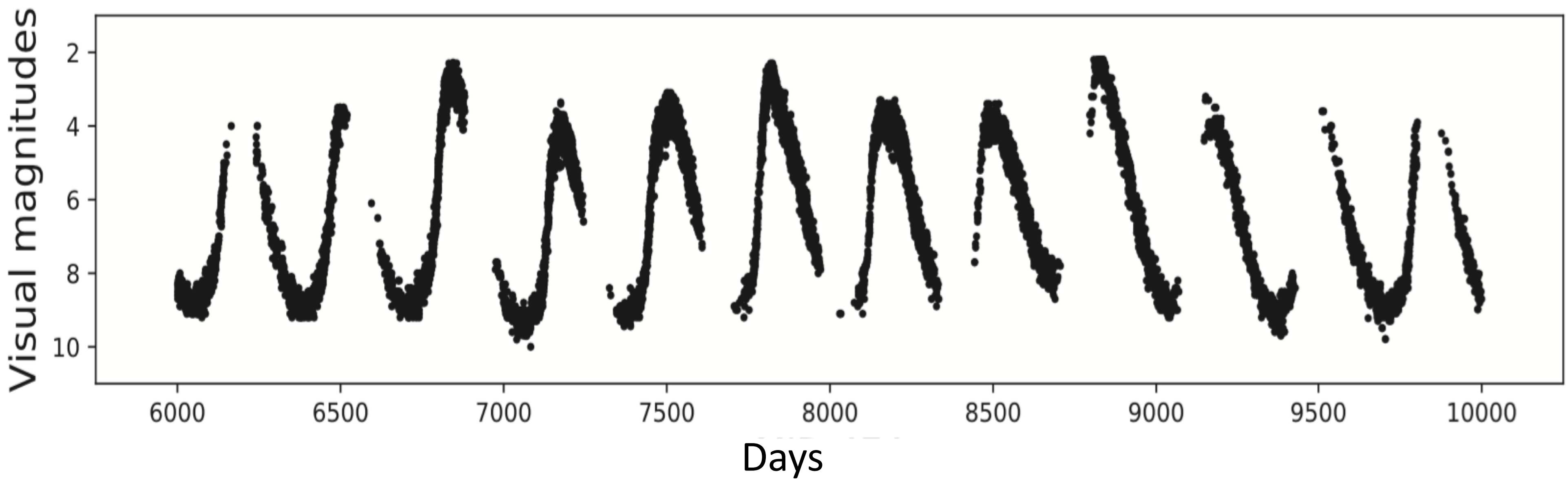
Large amplitude: $\Delta m_P \geq 2.5$ mag ($\Delta I \geq 0.8$; $\Delta K \geq 0.4$)

Spectrum: Late type with emission lines: Me, Ce (few Se, Ke)

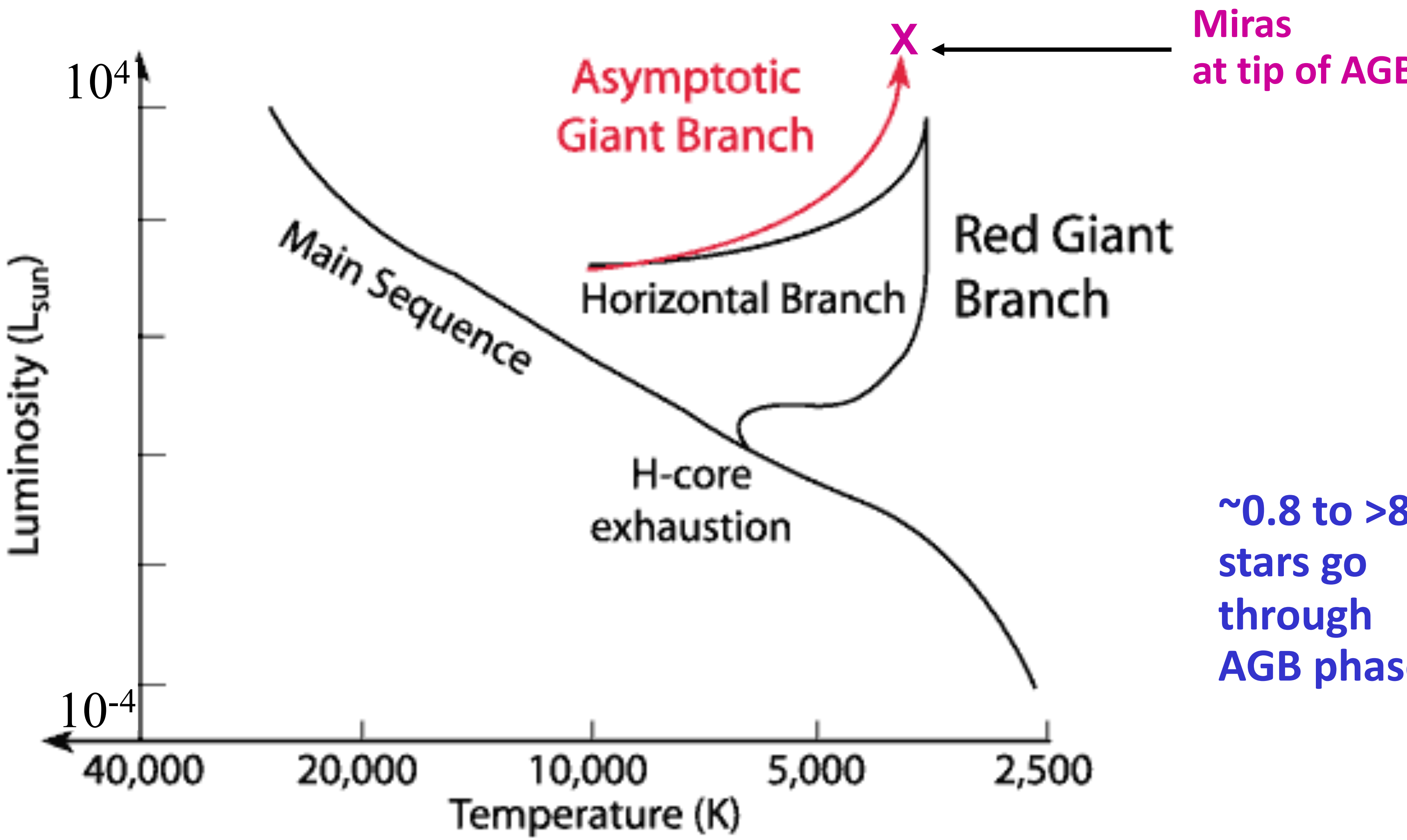
Long Period: $90<P<3000$ days (very few $P>900$) func(M_i, M)

Many similar, but lower amplitude variables – "semi-regular"

o Ceti (AAVSO) ΔV>6mag



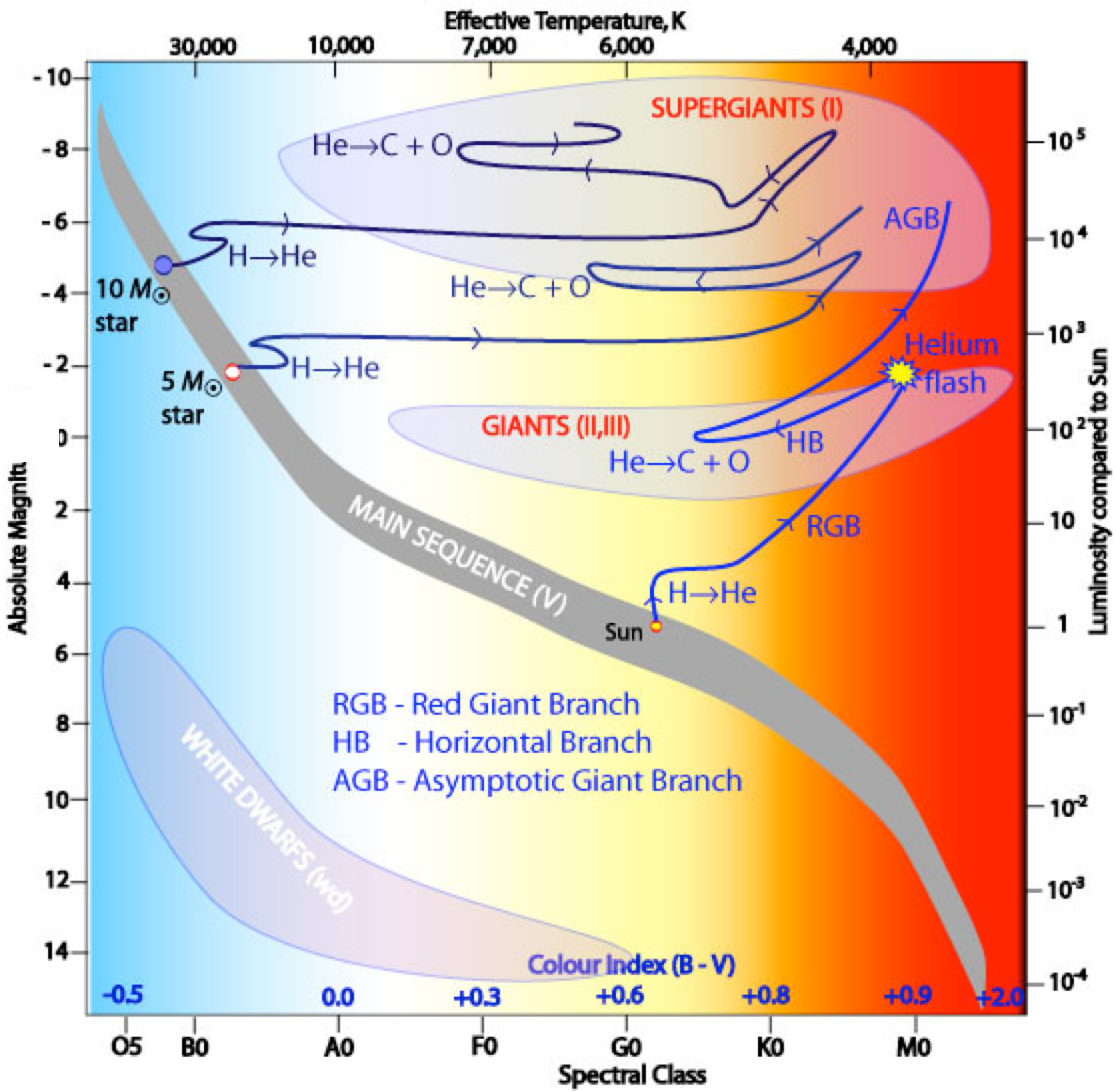
AGB Evolution



~0.8 to >8 $M_\odot$ stars go through AGB phase

www.noao.edu/outreach/press/pr03/sb0307.html

Intermediate Mass AGB

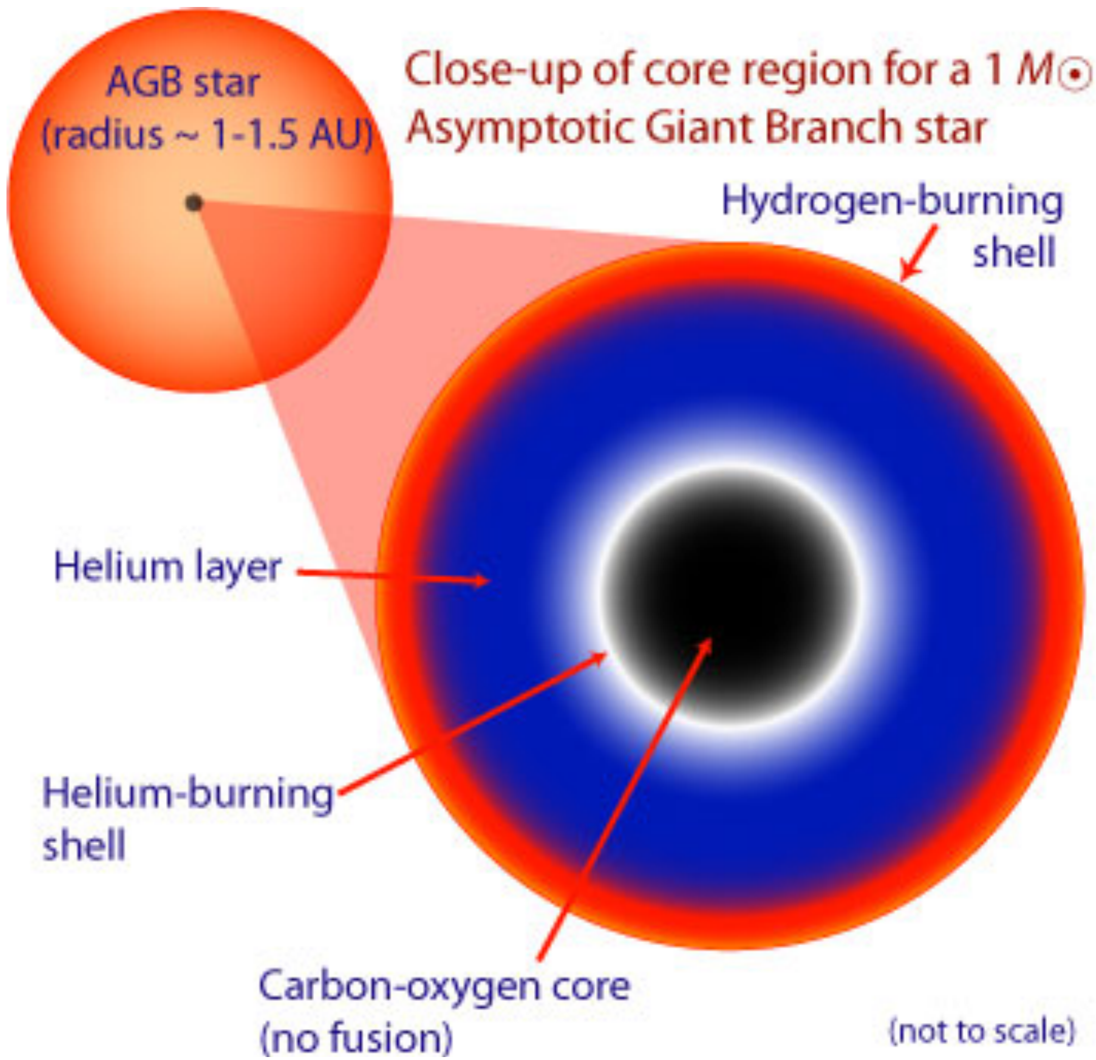


8 to 12 $M_{\odot}$ may also reach the AGB: "Super AGB stars"

Star at tip of AGB is brighter (M_{bol}) than Cepheid with same initial mass and *much* brighter at infrared wavelengths

http://www.atnf.csiro.au

Structure of a Mira



www.atnf.csiro.au/outreach/education/senior/astrophysics/stellarevolution_postmain.html

Surface composition
C/O<1 O-rich stars
C/O>1 C-rich stars

Luminosity at which
star becomes C-rich
depends on:
1. Initial mass
2. Initial O abundance

High mass-loss rates

M_i>3-4 $M_\odot$
Hot Bottom Burning
may occur:
    increased luminosity
    abundance changes

L α M_{Core}
(except: He-shell flash, HBB)

Pulsation & Convection

- Convection dominates energy transport in very cool stars
- Pulsation driven by convection

(Freytag+ 2017; Xiong+2018)

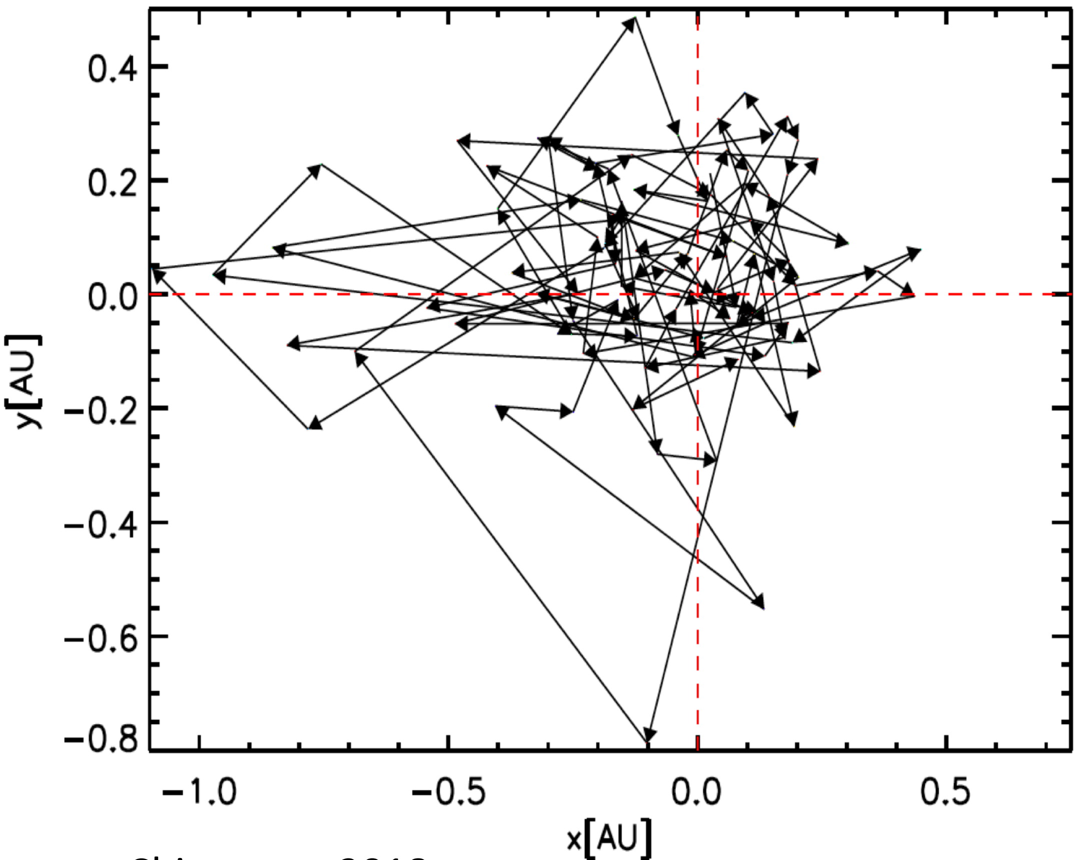
Mira Simulation
(Freytag 2018)

Miras (angular diameters)

Early optical interferometry: non-uniform (spotted) surface
(HST: Lattanzi+1997)
Confirmed IR VLT VLBI
(Wittkowski+2016)

Angular diameter of
Mira larger than parallax
e.g. o Ceti **π=11** mas (Hipparcos)
Φ=24 mas(*K*) – larger @ shorter λ

Gaia **π** ~5-10% uncertainty
 photocentre movement for SRs
 will be more for Miras



Chiavassa+ 2018
Photocentre movement simulated SR-variable

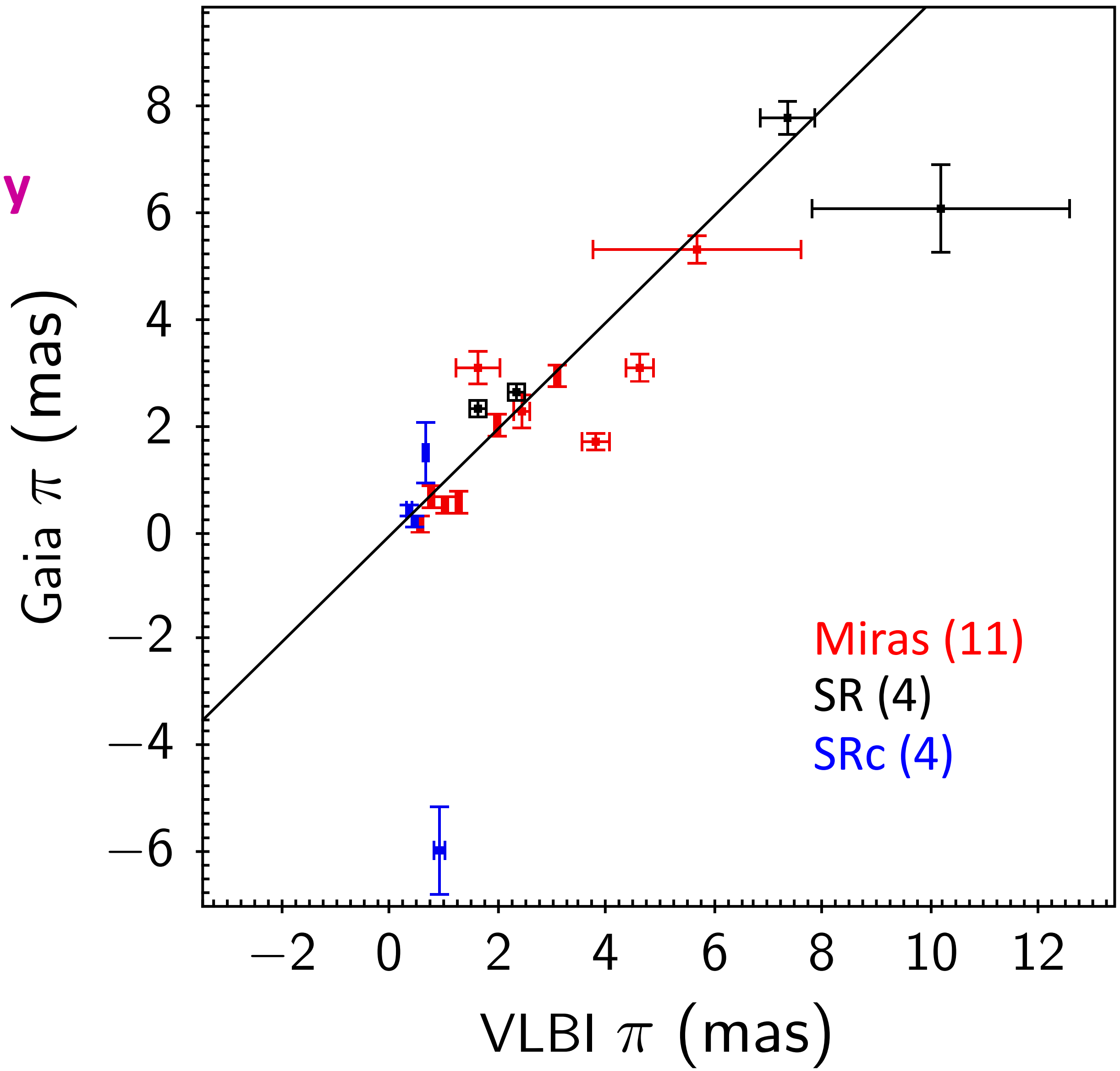
Dusty Miras more problematic
Gaia data may (eventually) be sufficent to better understand above
<u>and </u>obtain good ZP for the PL relation

Mira Parallaxes (VLBI – Gaia DR2)

VLBI parallaxes from
Masers: H_2O, OH, SiO
i.e. O-rich with CS shells only
- mostly VERA

Asymmetries:

- **Convection**
- **Non-uniform mass loss**
- **Non-radial pulsation?**



Gaia (DR2)
VLBI (Subramanian+ 2017)

So – why bother? Miras and Cepheids

K(2.2μm): Cepheid P=50d M_K ~-7.9

Mira P=380d M_K ~-7.9

8μm: Cepheid P=50d M_8 ~-8.3

Mira P=230d M_8 ~-8.3

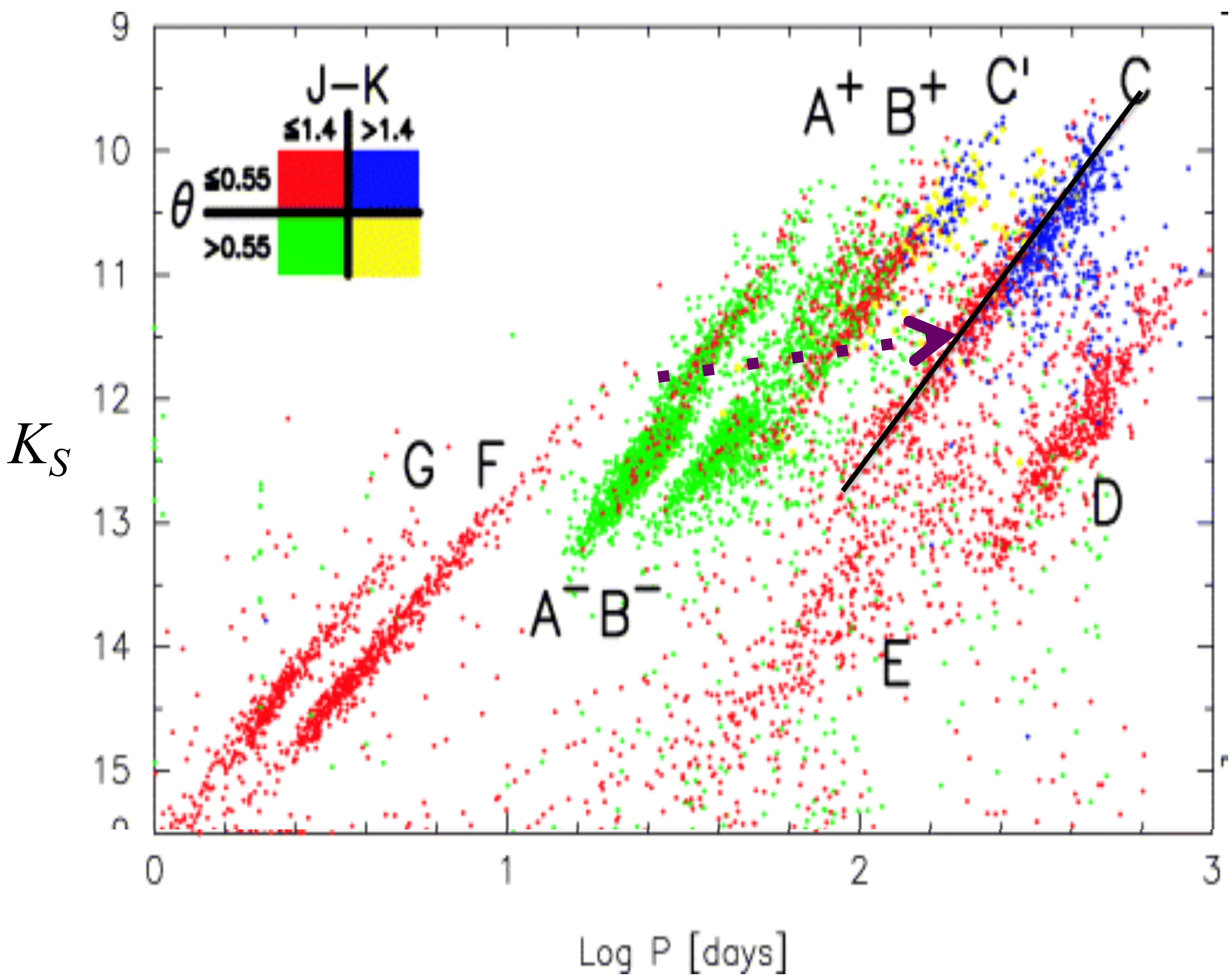
Mira P=380d M_8 ~-9.2

- Miras will be present in older populations, e.g. elliptical galaxies and haloes of spiral galaxies, i.e. easier to resolve at large distances
- Miras in galaxies with SNe Ia but no Cepheids
- JWST ideal for these infrared sources

Miras often better distance indicators than Cepheids

Feast (2010)

Period Luminosity Relations in the LMC



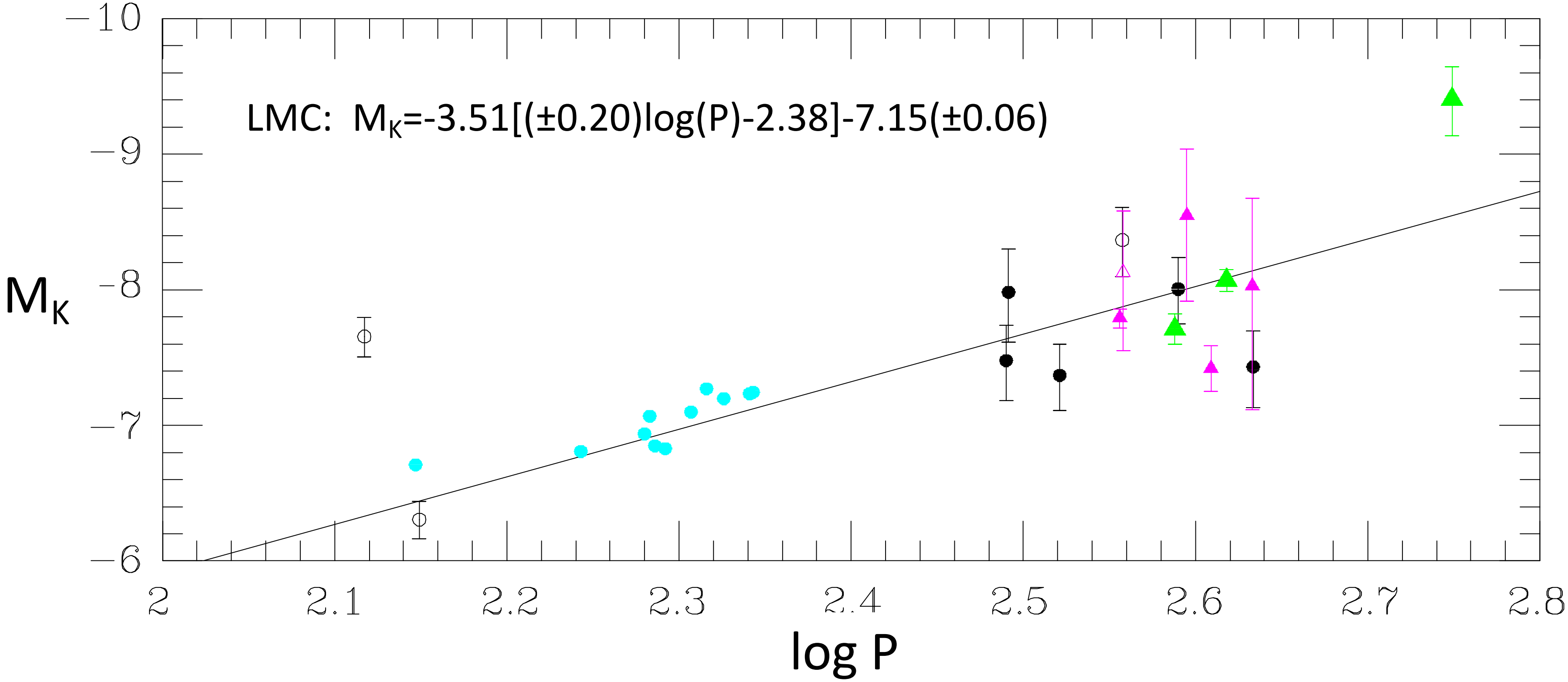
Variables from OGLE & IRSF (Ita et al. 2004) single K_S (2.2 μm) observations (scatter)

Wood (2000)

Does NOT show highly obscured stars

Galactic PL(*K*) O-rich

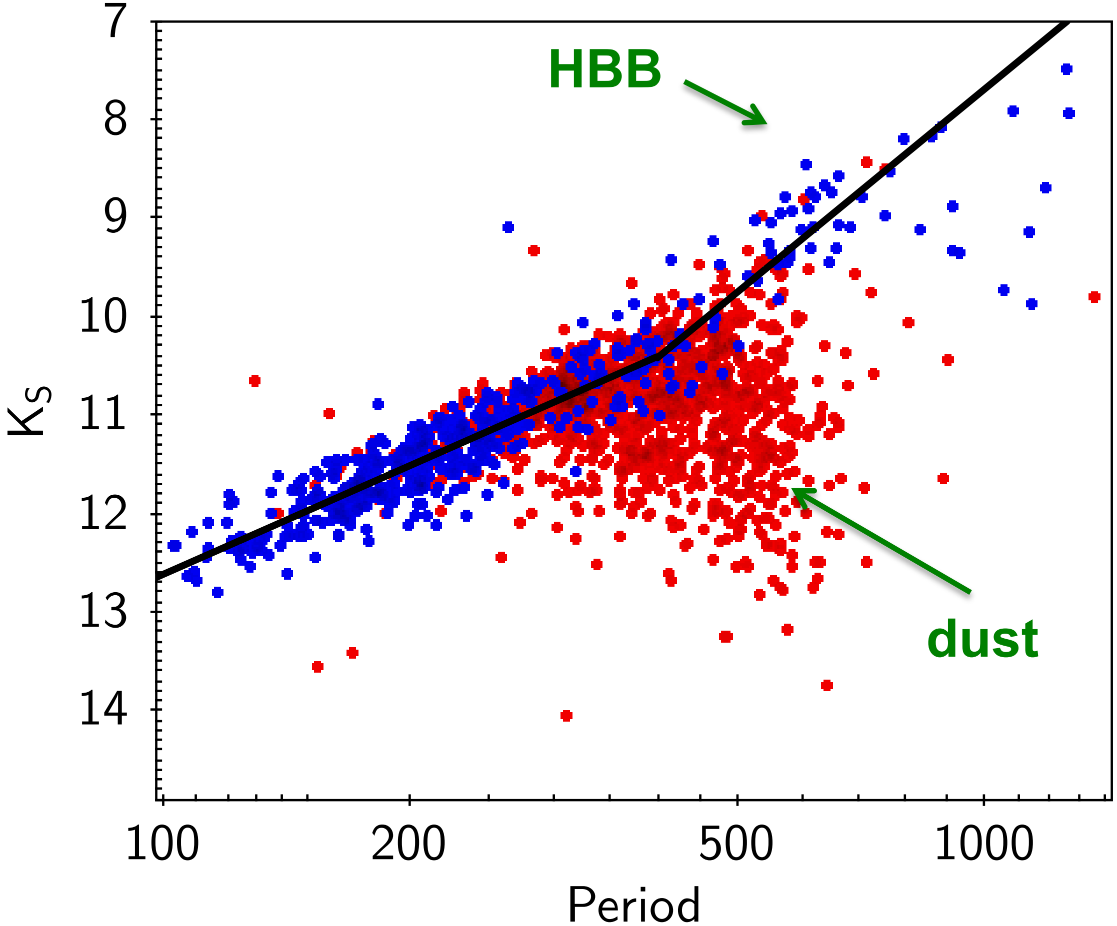
Blue circles: Globular cluster
Black circles Hipparcos π ($\sigma_\pi/\pi<0.16$)
Magenta triangles VLBI π
Green H_2O/SiO VLBI π
(VERA: Kurayama et al. 2005; Nyu et al. 2011, Min et al. 2014)



Open symbols: SR variables
Closed symbols: Miras

(Whitelock, Feast, Van Leeuwen 2008
LMC $(M\text{-}M)_0$=18.39)

LMC Miras



Ita & Matsunaga (2011)
Red carbon-rich
Blue oxygen-rich

JHK from 2MASS
P from OGLEIII:
-very thick shells missing

P>400 days spread in *K*

Many C-stars faint
due to CS reddening
(*J-K* tells you if *K* will fit PL)

LMC Miras

Yuan+2017

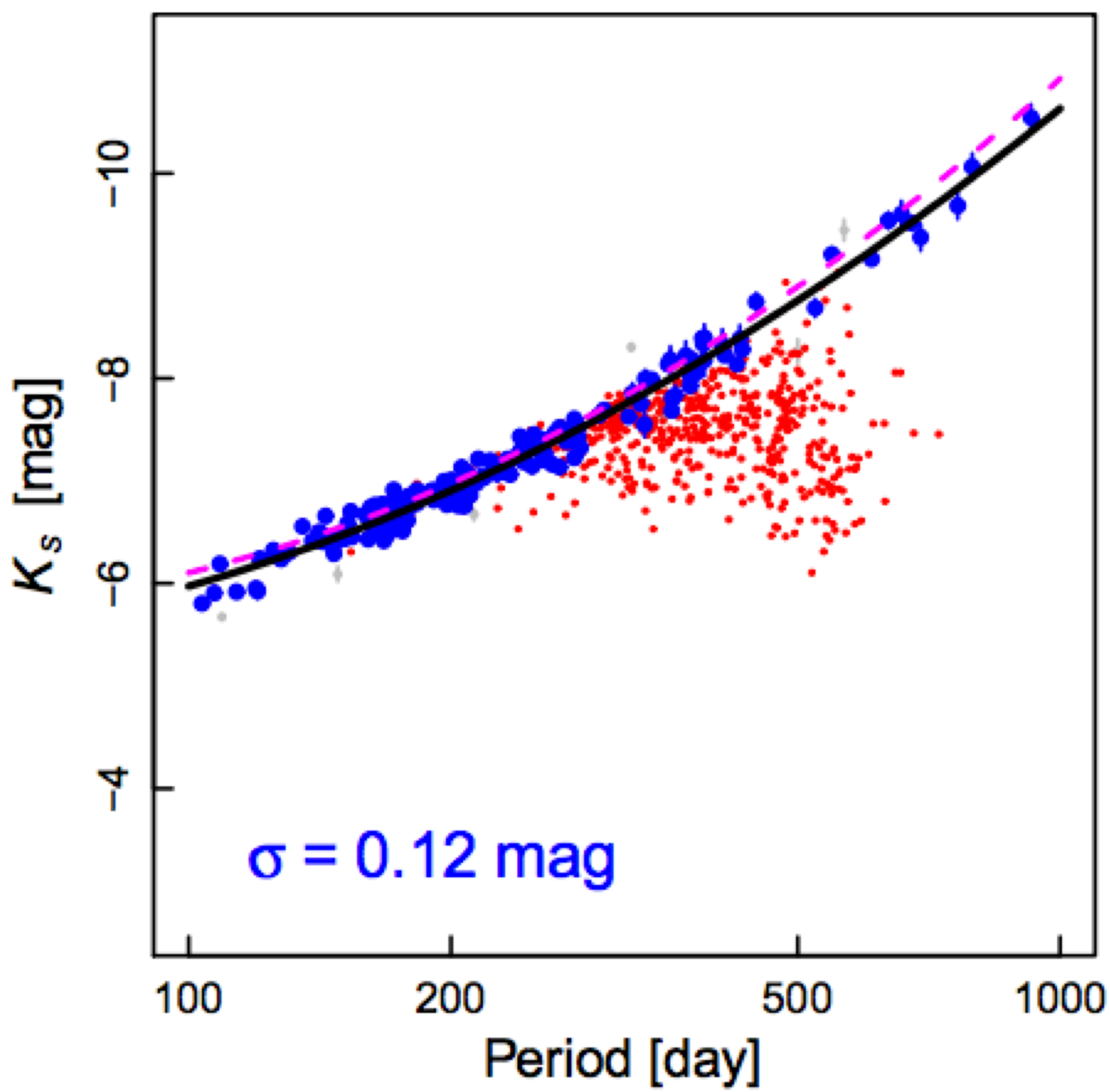
“Mean” JHK_S from LMCNISS+OGLE (*I*) to correct the data (He+2016)

Blue: oxygen rich

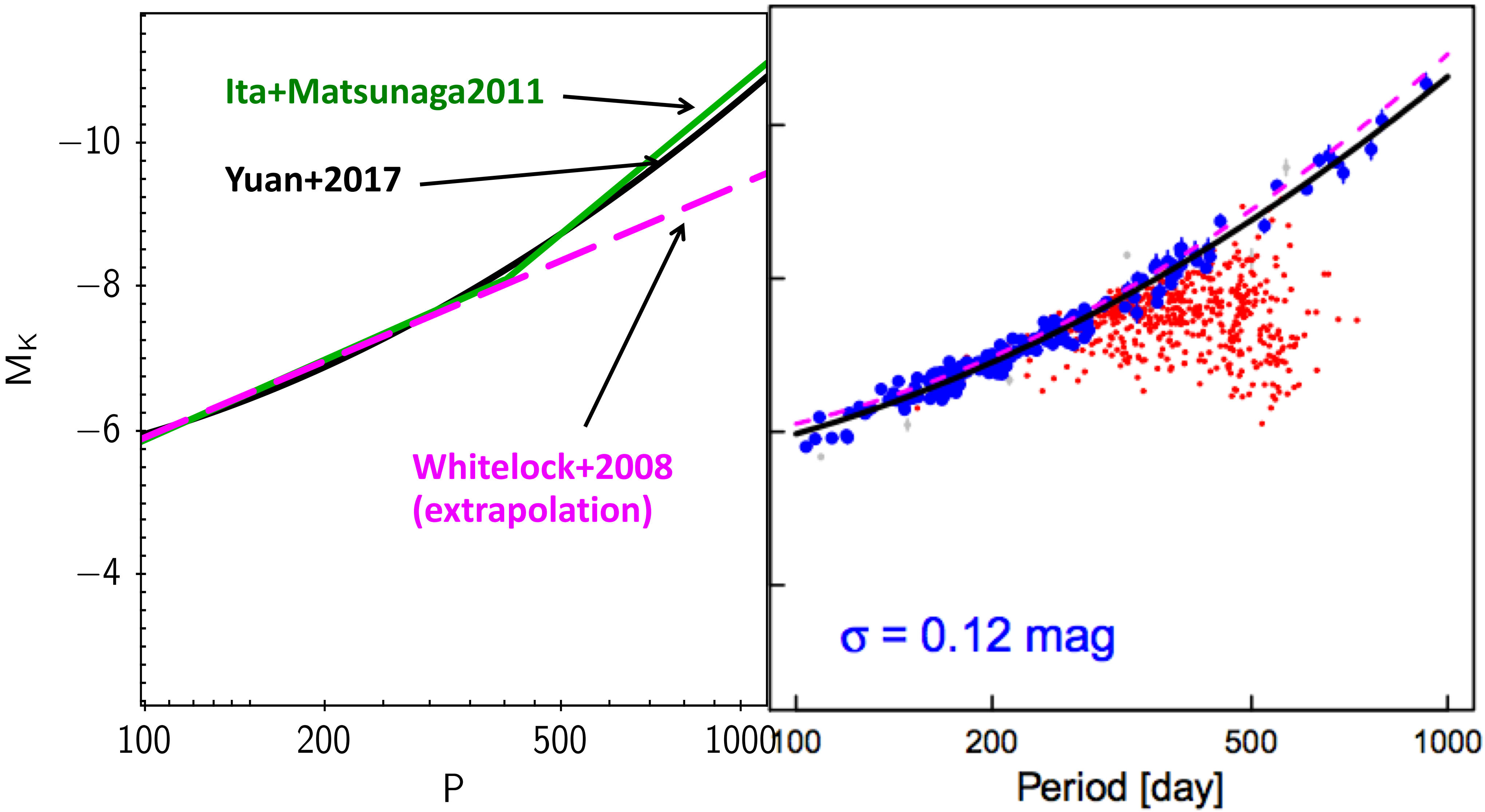
Red: carbon rich

much reduced scatter

nonlinear PLR for O-rich Miras



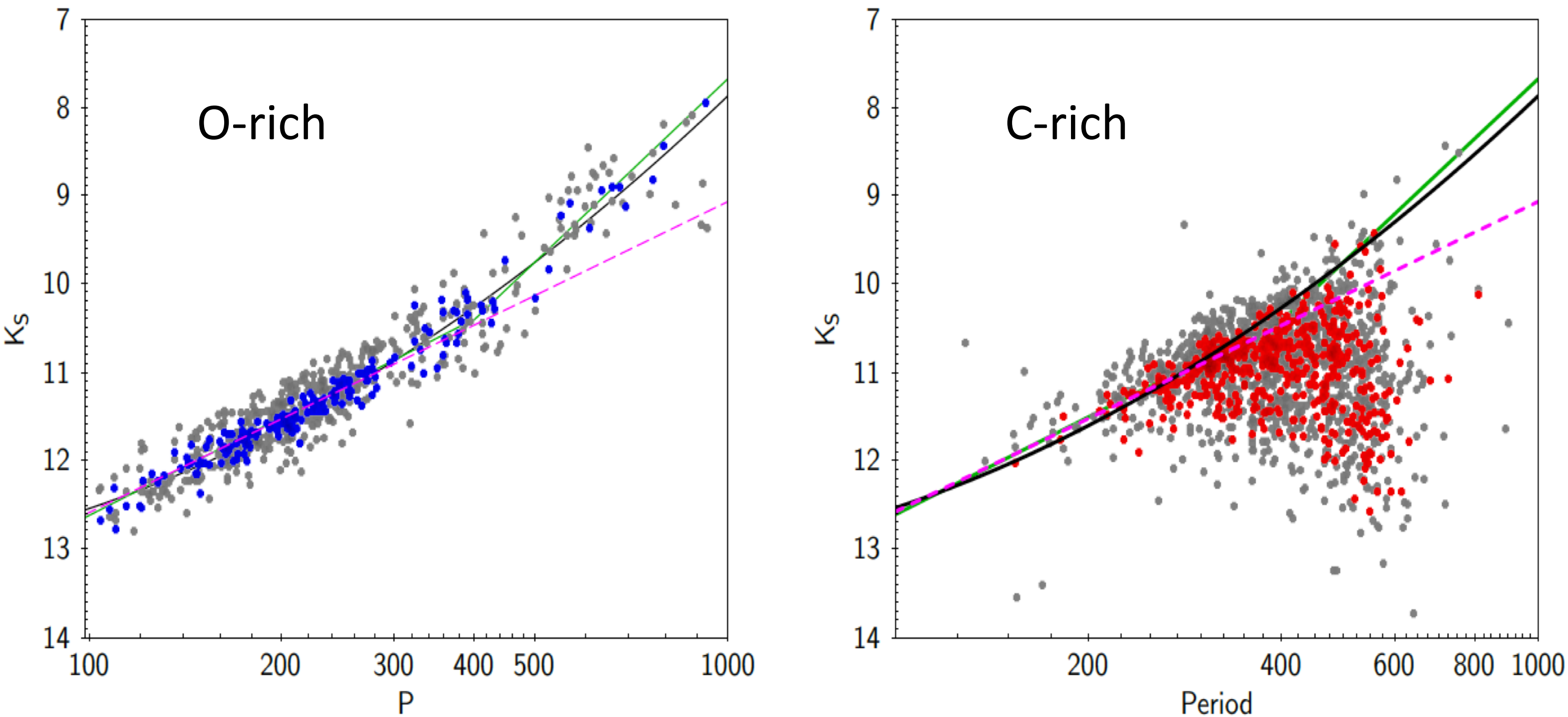
LMC Miras



Ita+Matsunaga2011
Yuan+2017
Whitelock+2008
(extrapolation)
−10
−8
−6
−4
M_K
100
200
500
1000
P
σ = 0.12 mag
100
200
500
1000
Period [day]

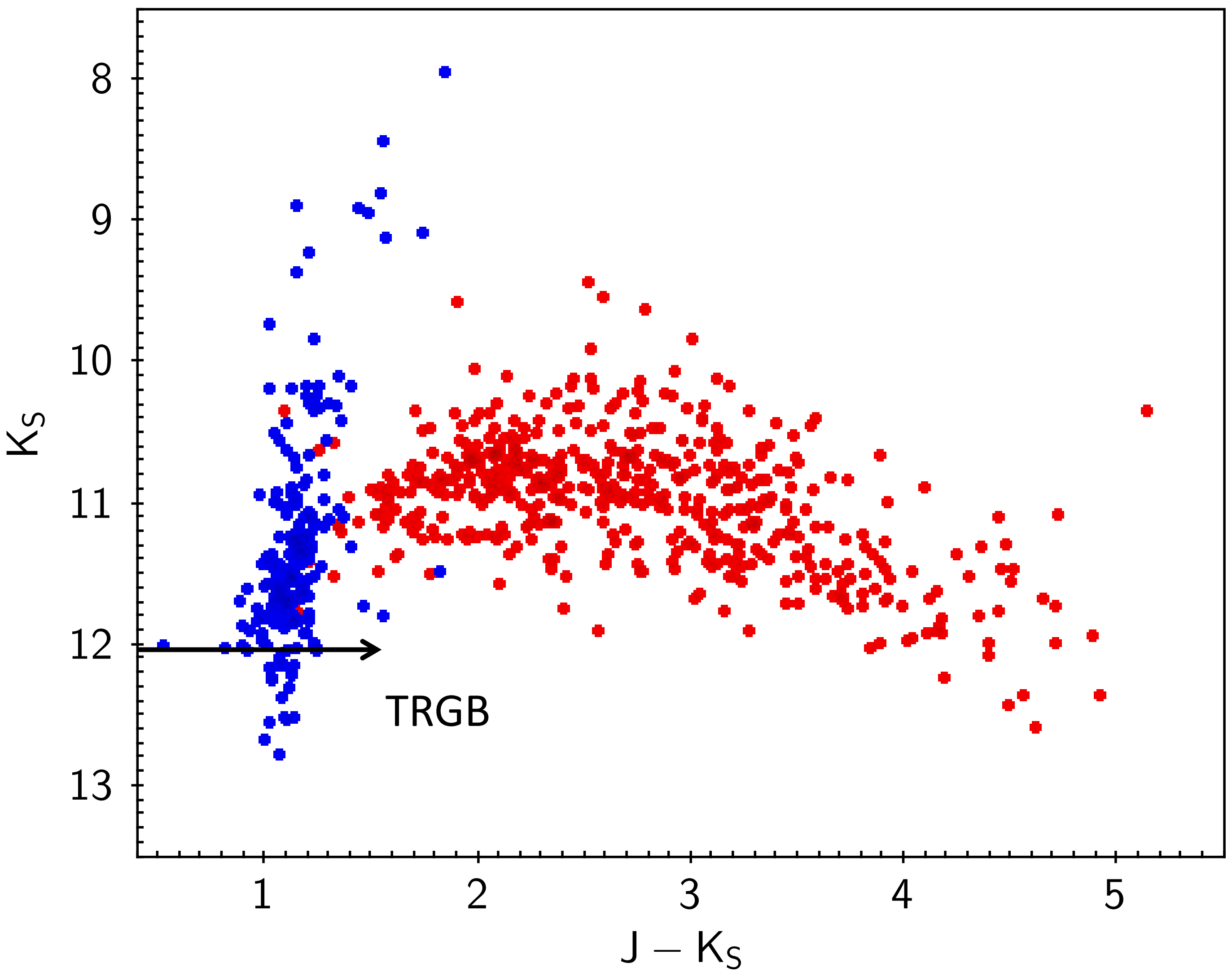
LMC Miras

Data from Yuan+2017 and 2MASS (P from OGLE)
Curves PLR: Whitelock+2008, Ita_Matsunaga2011 Yuan+2017
O- C-rich division from OGLE (Soszyński+2009)



Selecting Miras for Distance Determination

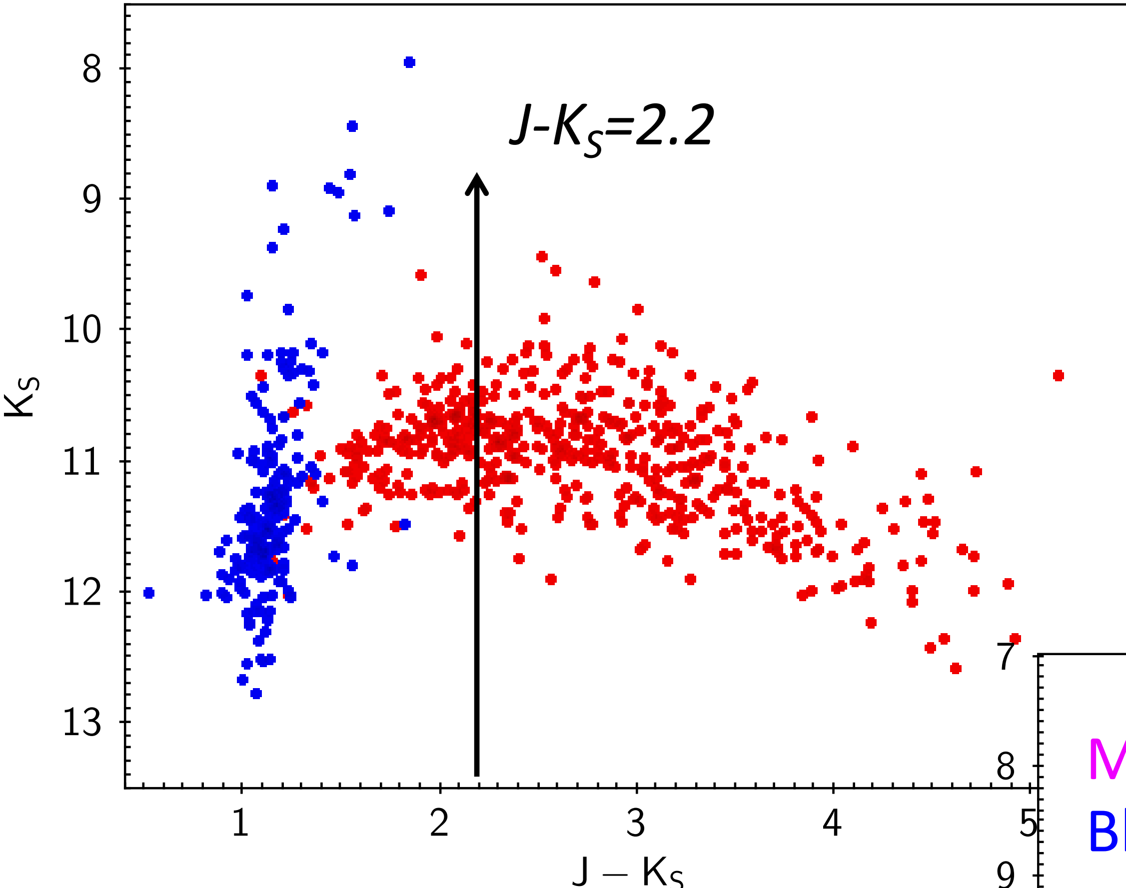
Yuan+2017 C- and O-rich Miras in LMC

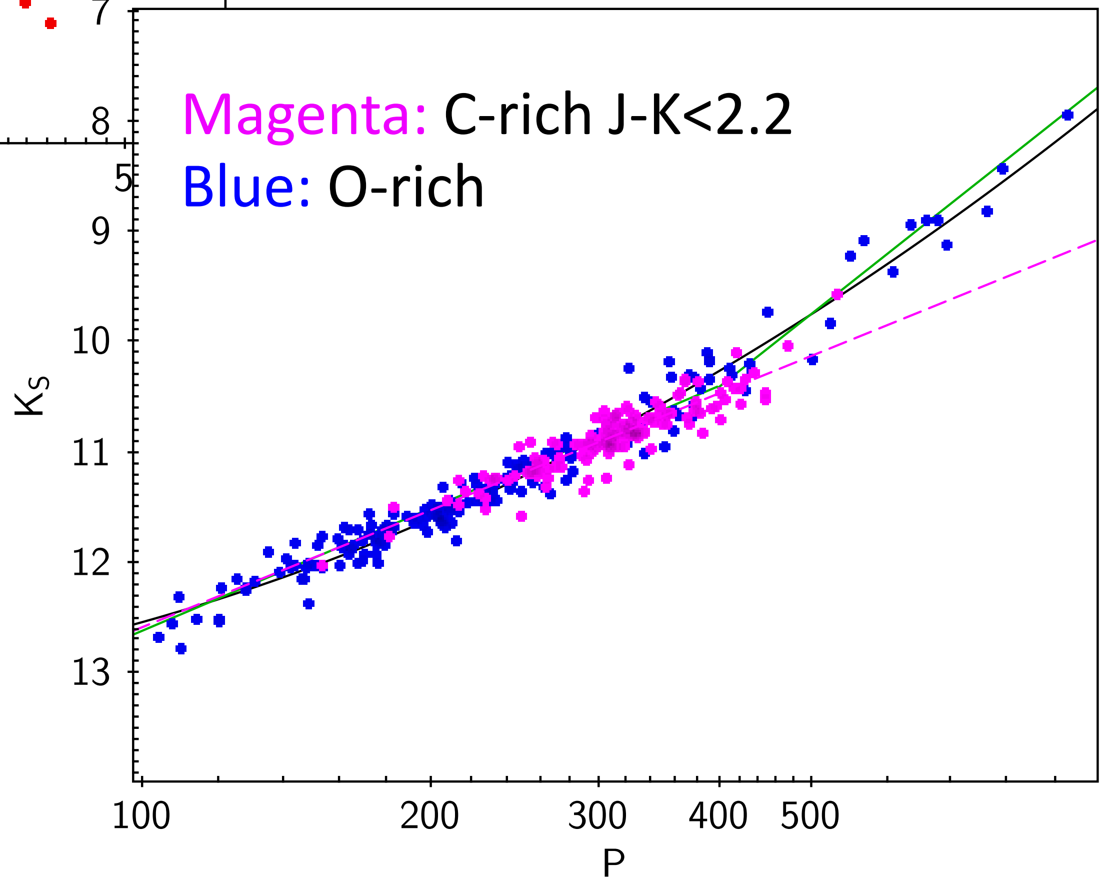


Red: C-rich
Blue: O-rich

O-rich larger range of initial mass than C-rich

Selecting Miras for Distance Determination





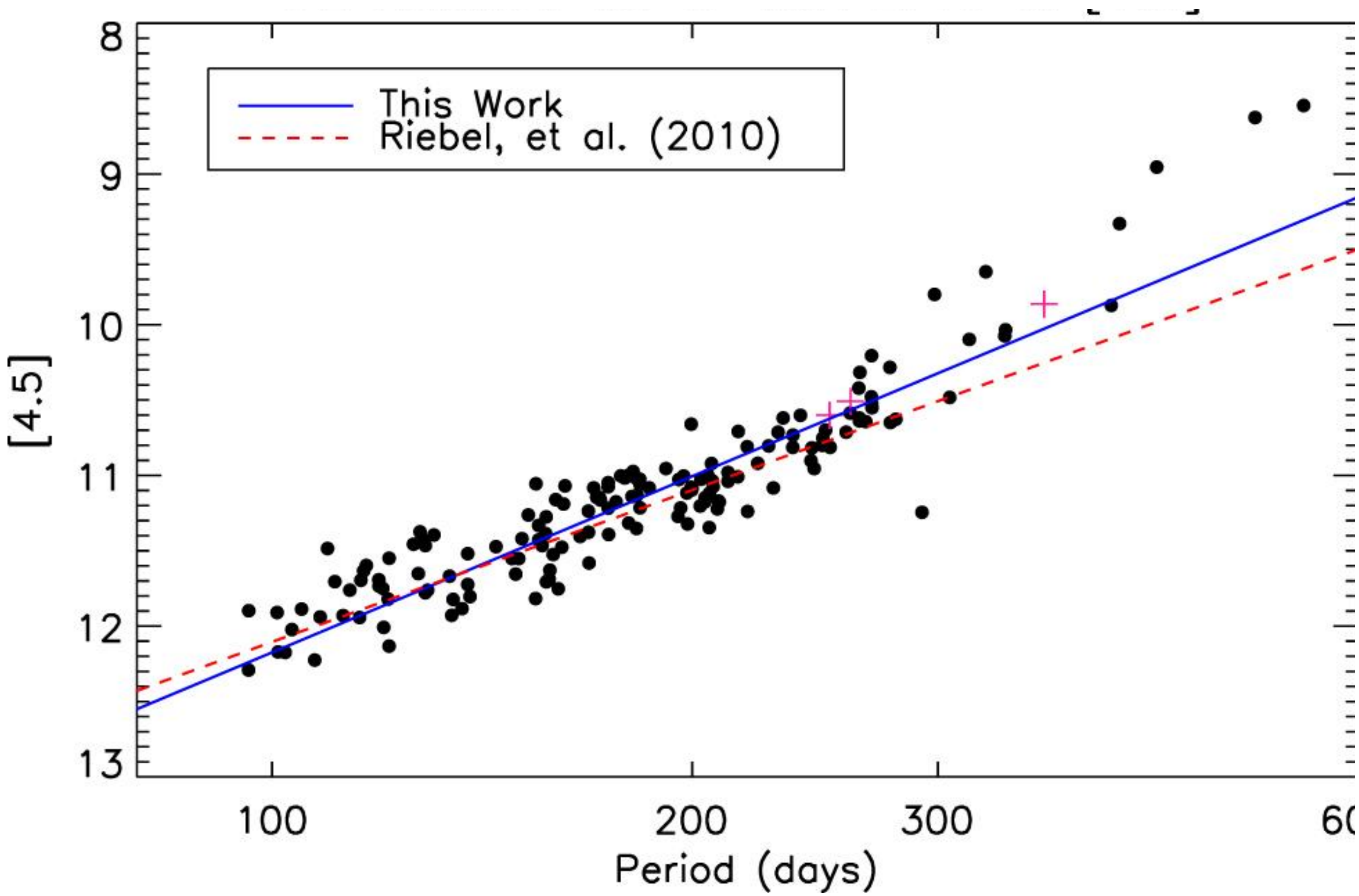
O-rich and C-rich stars **without** circumstellar reddening fall on same K_S PLR

select $J\text{-}K<2.2$

Or correct for CS extinction (Ita & Matsunaga 2011)

P>420?

Mira Period-Luminosity [4.5] Relations LMC



Spitzer Spacecraft:
mid-infrared
3.6, 4.5, µm
Riebel+2015
SAGE survey data

Excluding Mira with obvious shells (X-AGB stars)
Mean [4.5] luminosity
- Considerable spread despite mean mags

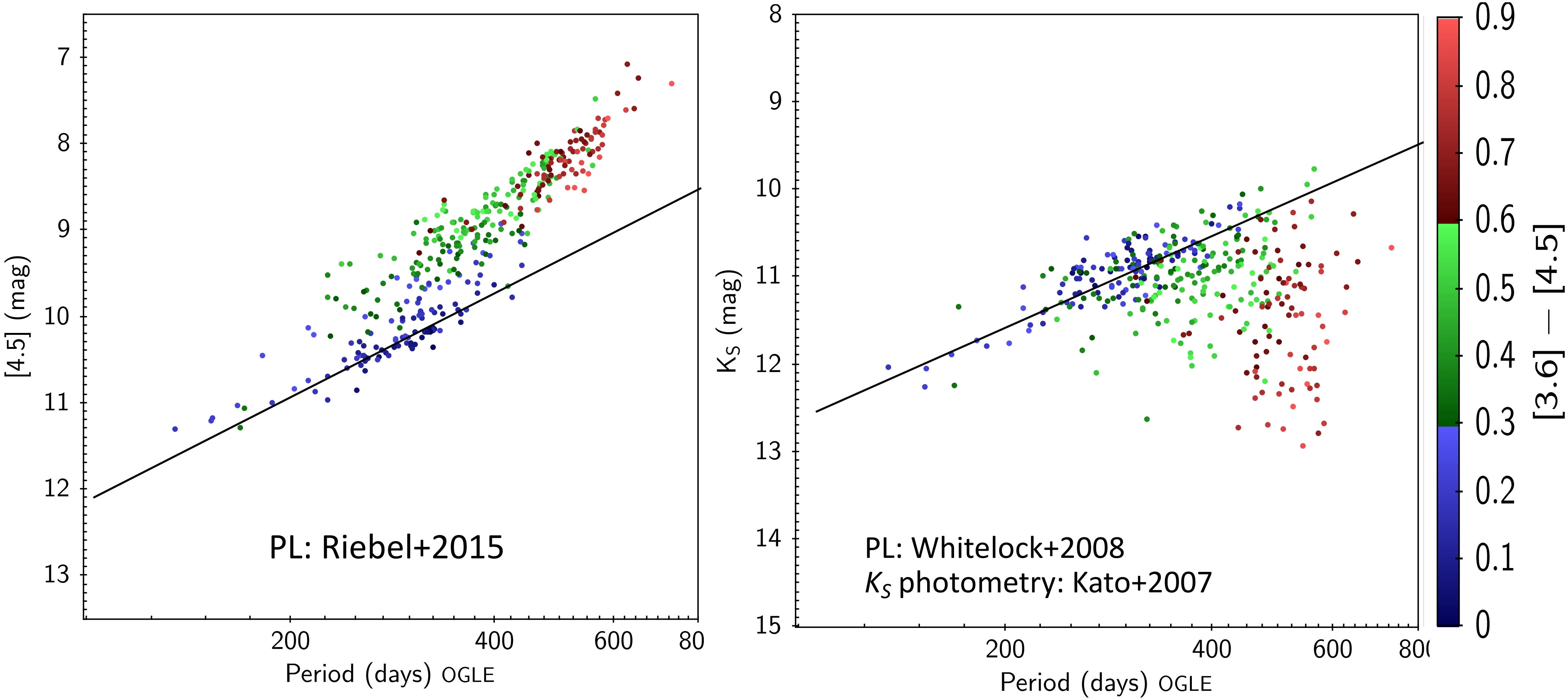
Period-Luminosity ([4.5] and K_S) C-rich Miras

Effect of thick dust at different wavelengths

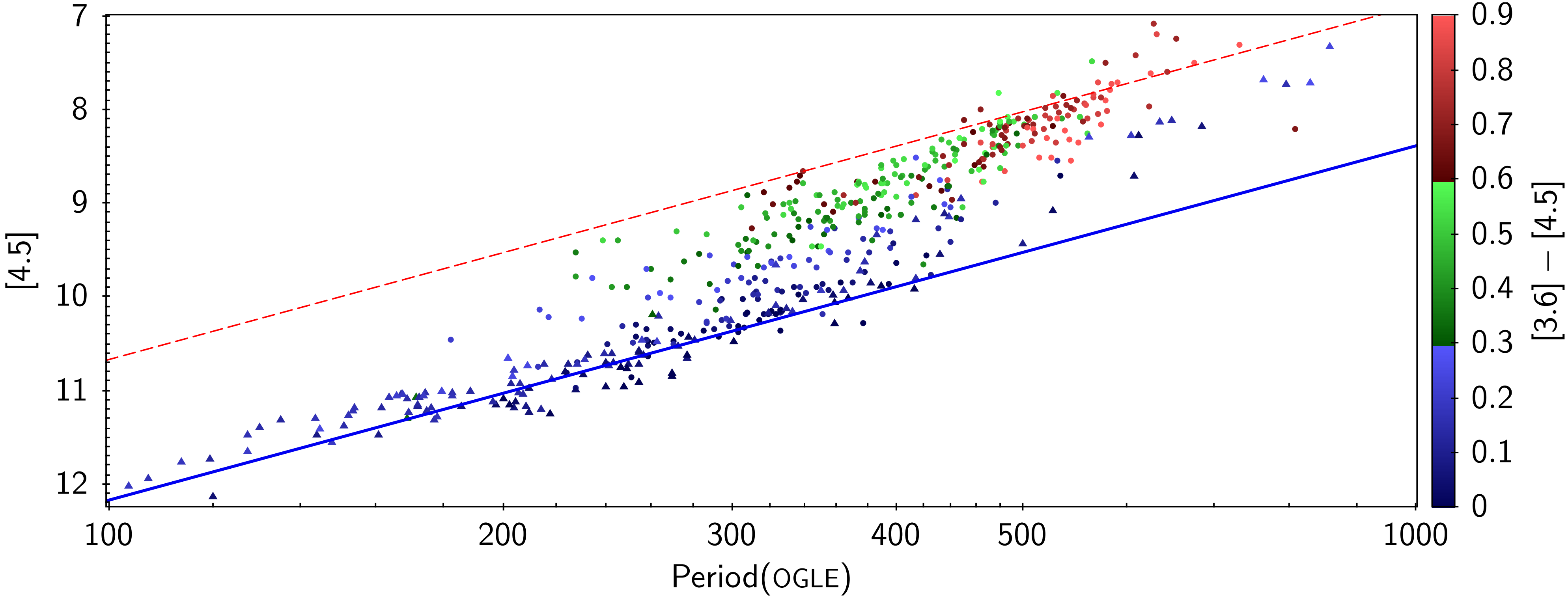
Emission at [4.5], absorption at K_S (2.2µm)

Red stars may be more evolved or more massive (or both)

most massive stars will not become C-rich (HBB)



Mira Period-Luminosity [4.5] Relations



Miras in other Local Group dIGs: NGC6822, IC1613 & Sgr dIG, NGC3109

name	$(m\text{-}M)_0$	Stellar Mass	[Fe/H]	AGB Vars
NGC 6822	23.5	$100\ 10^6$	-1.0	Whitelock+2013
IC 1613	24.4	$100\ 10^6$	-1.6	Menzies+2015
Sgr dIG	25.2	$3.5\ 10^6$	-1.9	Whitelock+2018
NGC 3109	25.6	$76\ 10^6$	-1.8	Menzies+2019

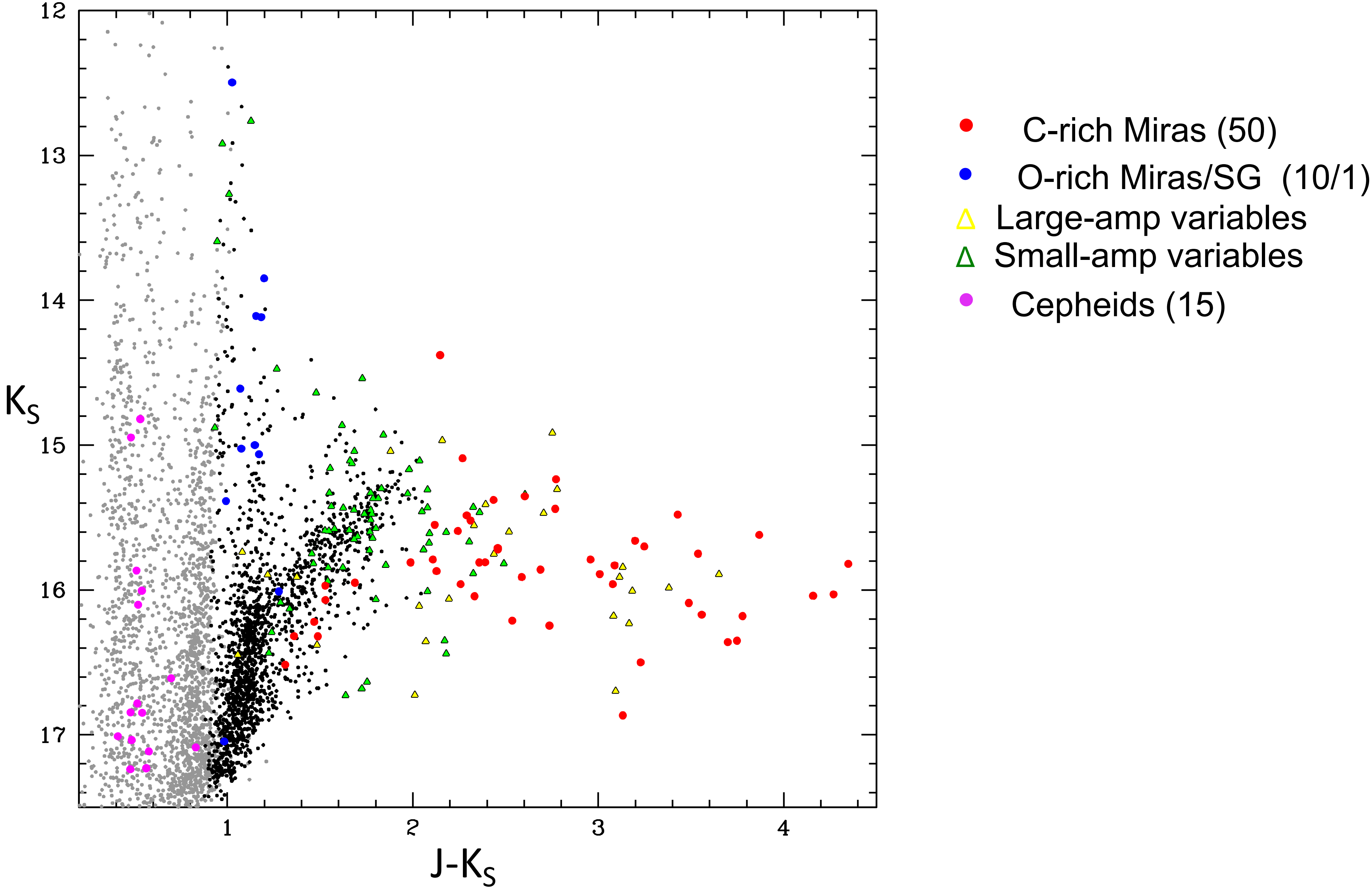
All have had star formation over long periods.

All have C- and O-rich Mira variables, with a range of periods

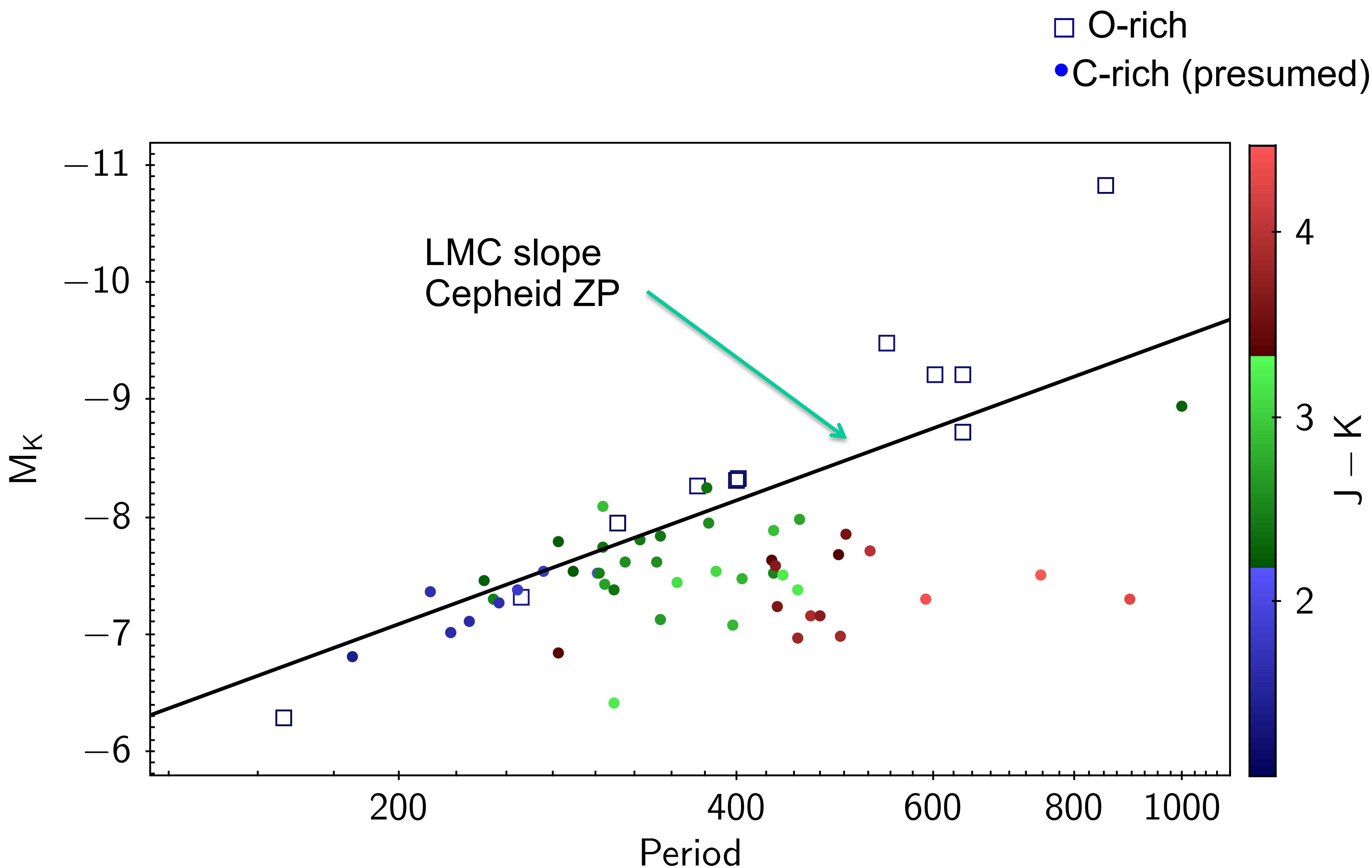
IC1613 has Li-rich star, presumed hot bottom burning

- **similar stars in the other dIGs**

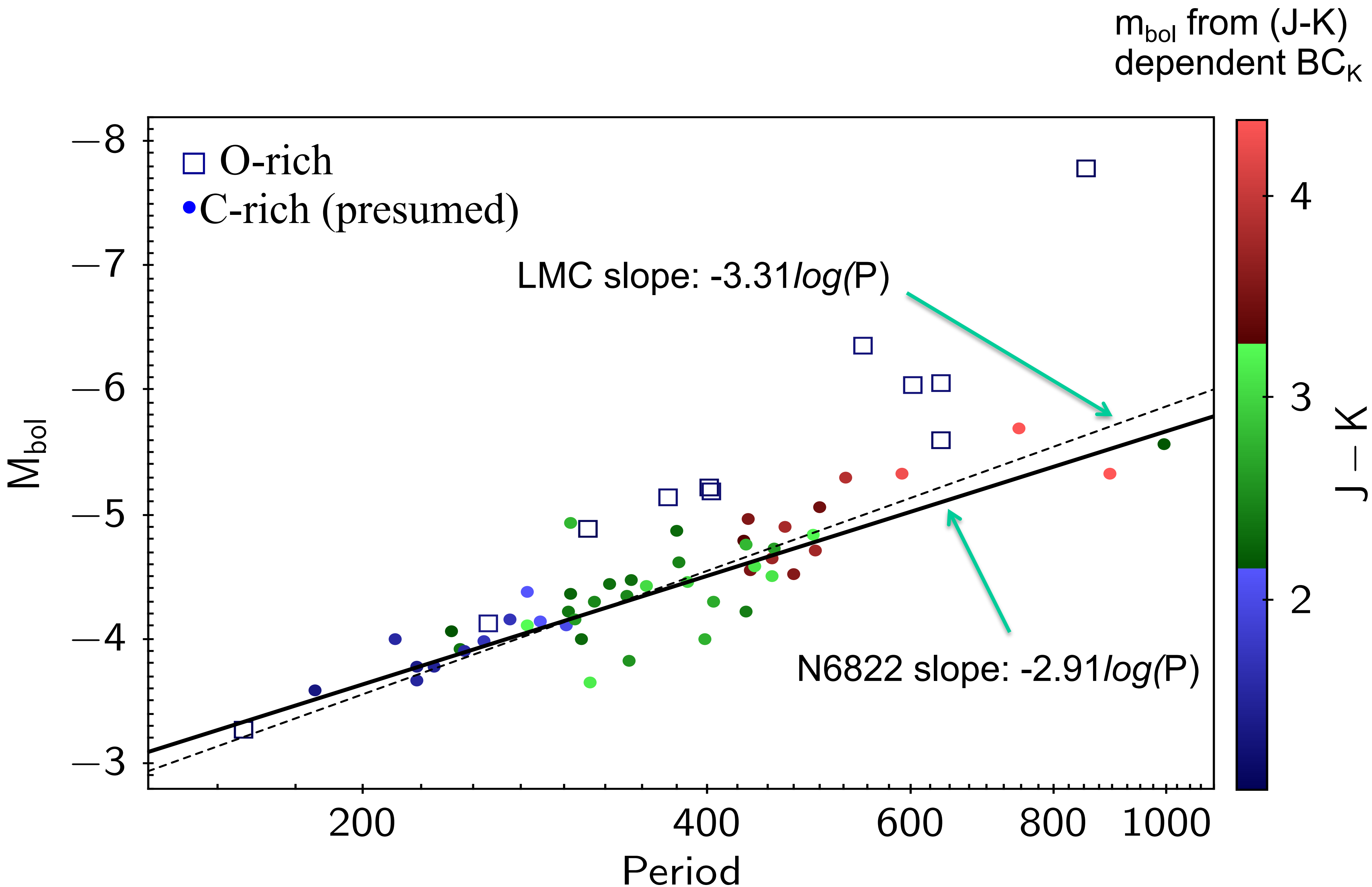
NGC 6822 Variables



NGC6822: PL(*K*) for Miras



C-star PL compared to LMC



NGC6822 Distance

Assume the LMC slope for the PL relations

LMC: [$(m-M)_0$=18.5]

K PL 4 O-rich stars with P<400days

$(m-M)_0=23.38\pm0.16$

Bolometric PL

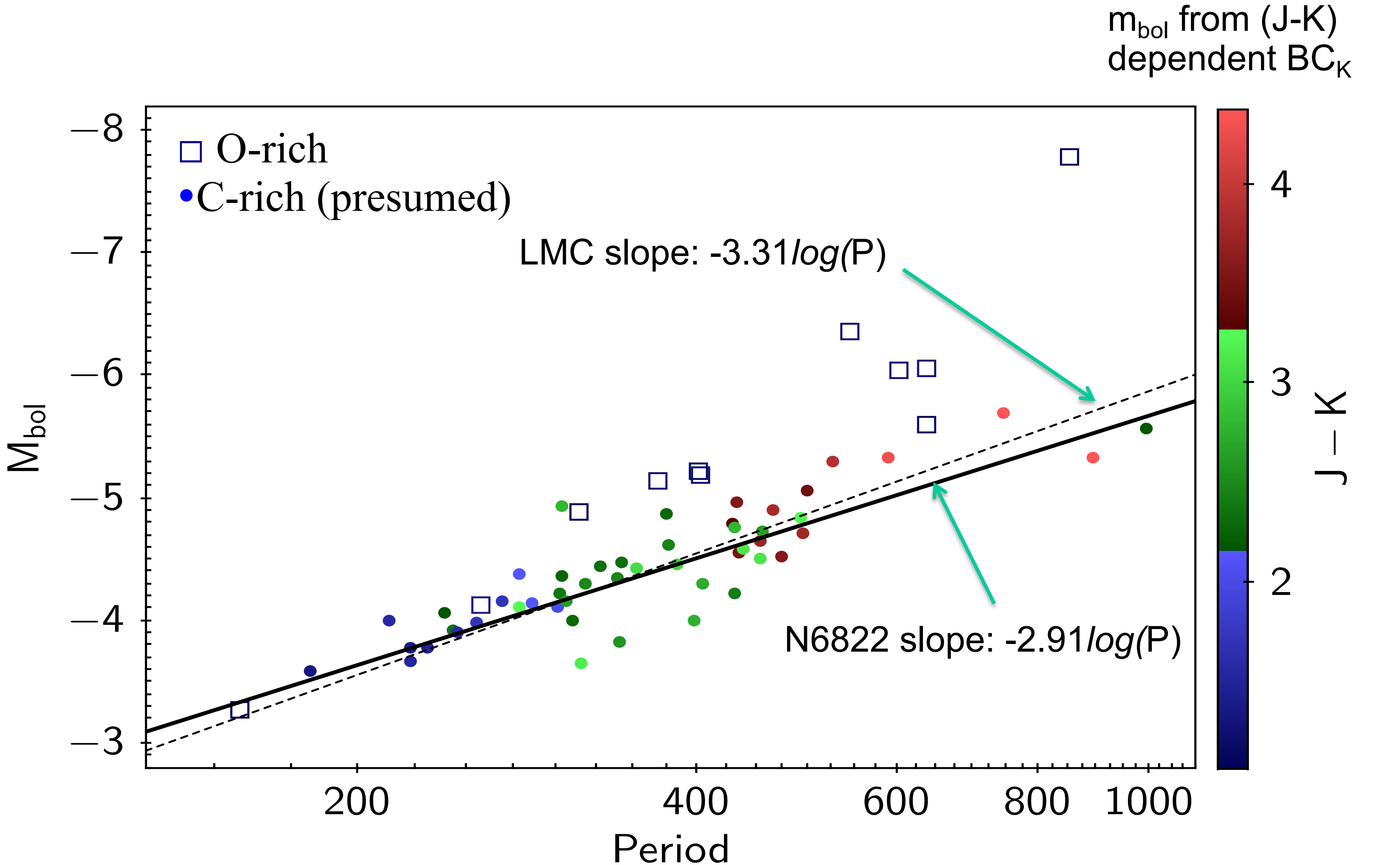
$(m-M)_0=23.56\pm0.03$ (internal error) C-rich Miras

$(m-M)_0=23.40\pm0.05$ Cepheids (Feast et al. 2012)

$(m-M)_0=23.49\pm0.03$ RR Lyr (Clementini et al. 2003/Benedict et al. 2011)

NB there are systematic errors in all of these

M_{bol} of C stars with log P >2.6 fall on extrapolated linear PL relation!

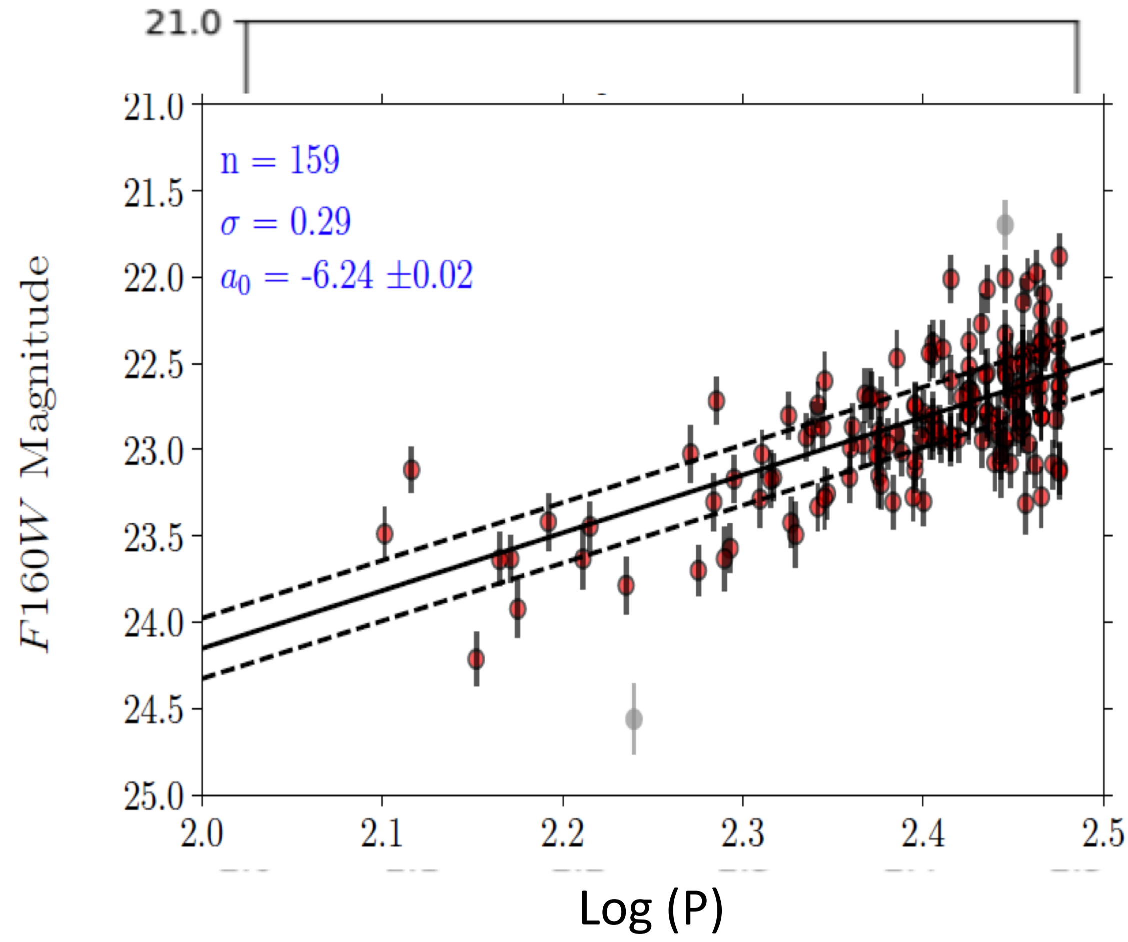


NGC 4258 (Huang+2018, 2019)

HST WFPC3 observations
F160W only
438 Miras – 1 field
Comparison wrt LMC PLR (Δμ)
Amplitudes: O-rich P<300 d

Δμ = 10.95 ± 0.01 ± 0.06 (Miras)
Δμ = 10.92 ± 0.02 (Cepheids)
(Riess+2016)

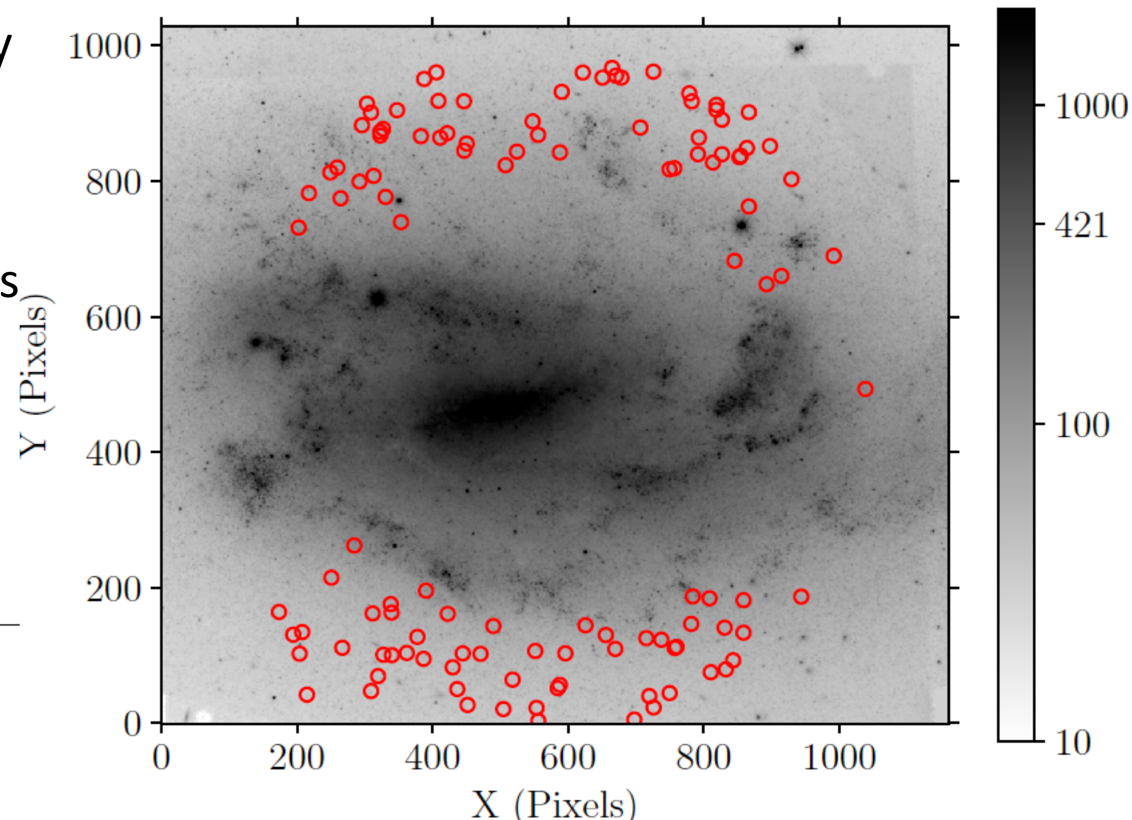
Megamaser 29.40 ± 0.03
Δμ~10.90 (Reid 2019)

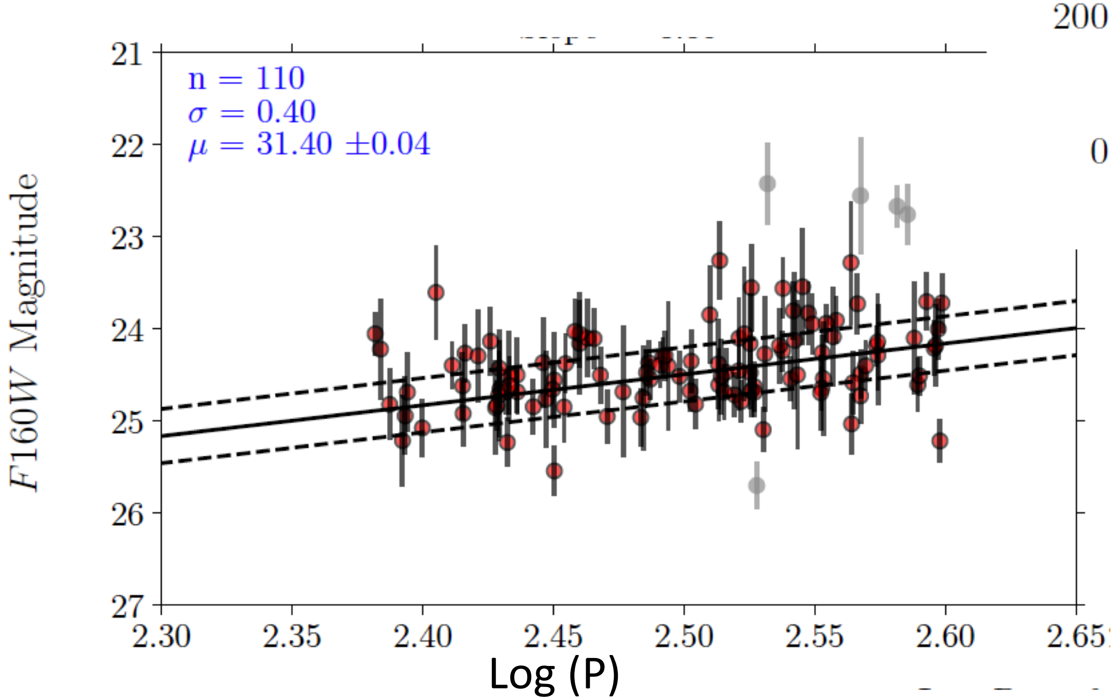


NGC 1559 (Huang+2019)

First Mira in SNIa (SN2005df) host galaxy

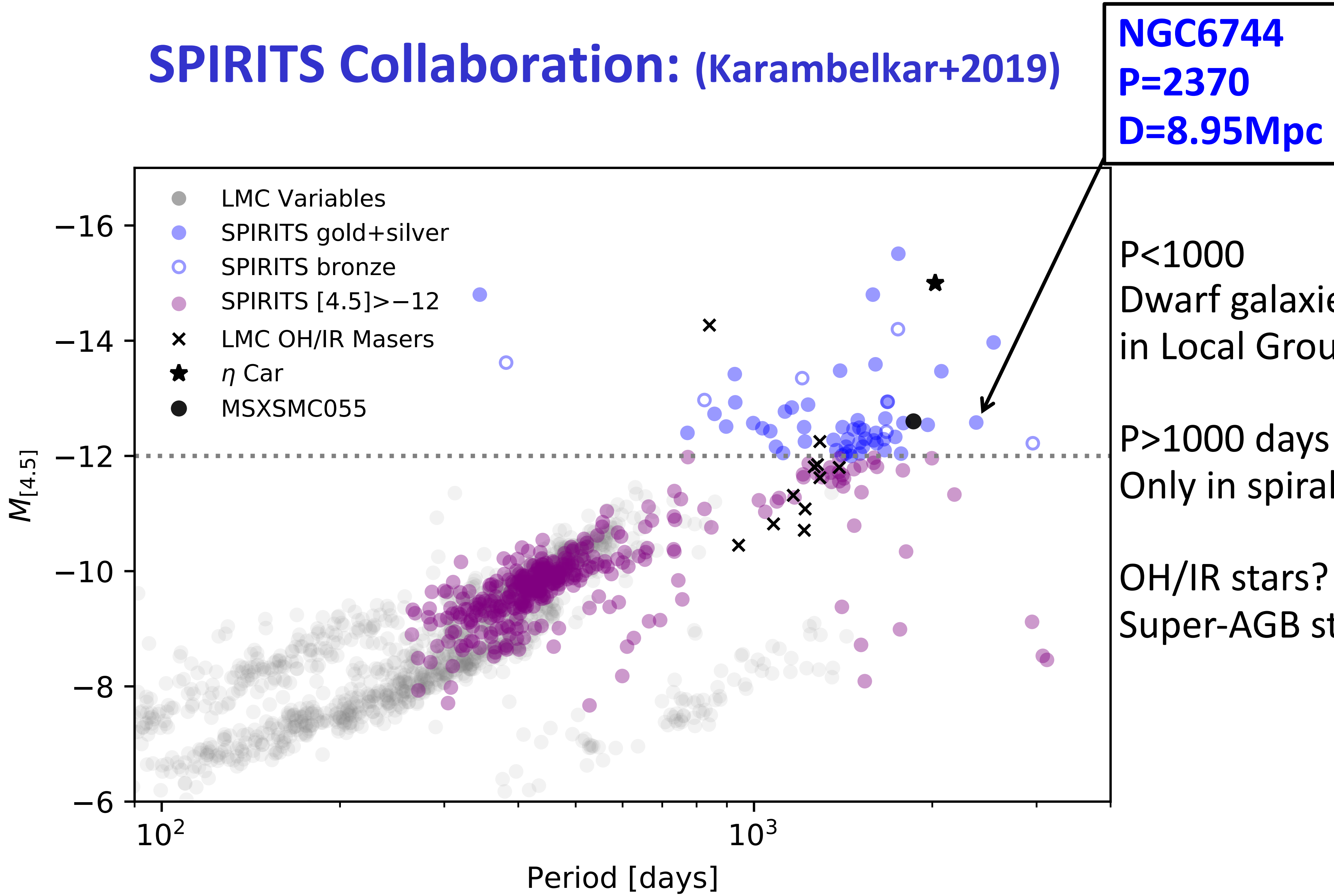
Calibrated wrt megamaser in NGC4258
HST F160W
10 observations 370 days, 3000 variables
110 Miras $0.4<A<0.8$; $240<P<400$
$\mu=31.41 \pm 0.05 \pm 0.04$
in agreement with Cepheid/SN





$H_0 = 73.20 \pm 4.68$ (all Miras) km s^{-1} Mpc^{-1}
74.96 ± 4.73 (P range)
73.92 ± 4.23 (same P LMC)
73.64 ± 3.85 (same P LMC+N4258)

SPIRITS Collaboration: (Karambelkar+2019)



P<1000
Dwarf galaxies
in Local Group

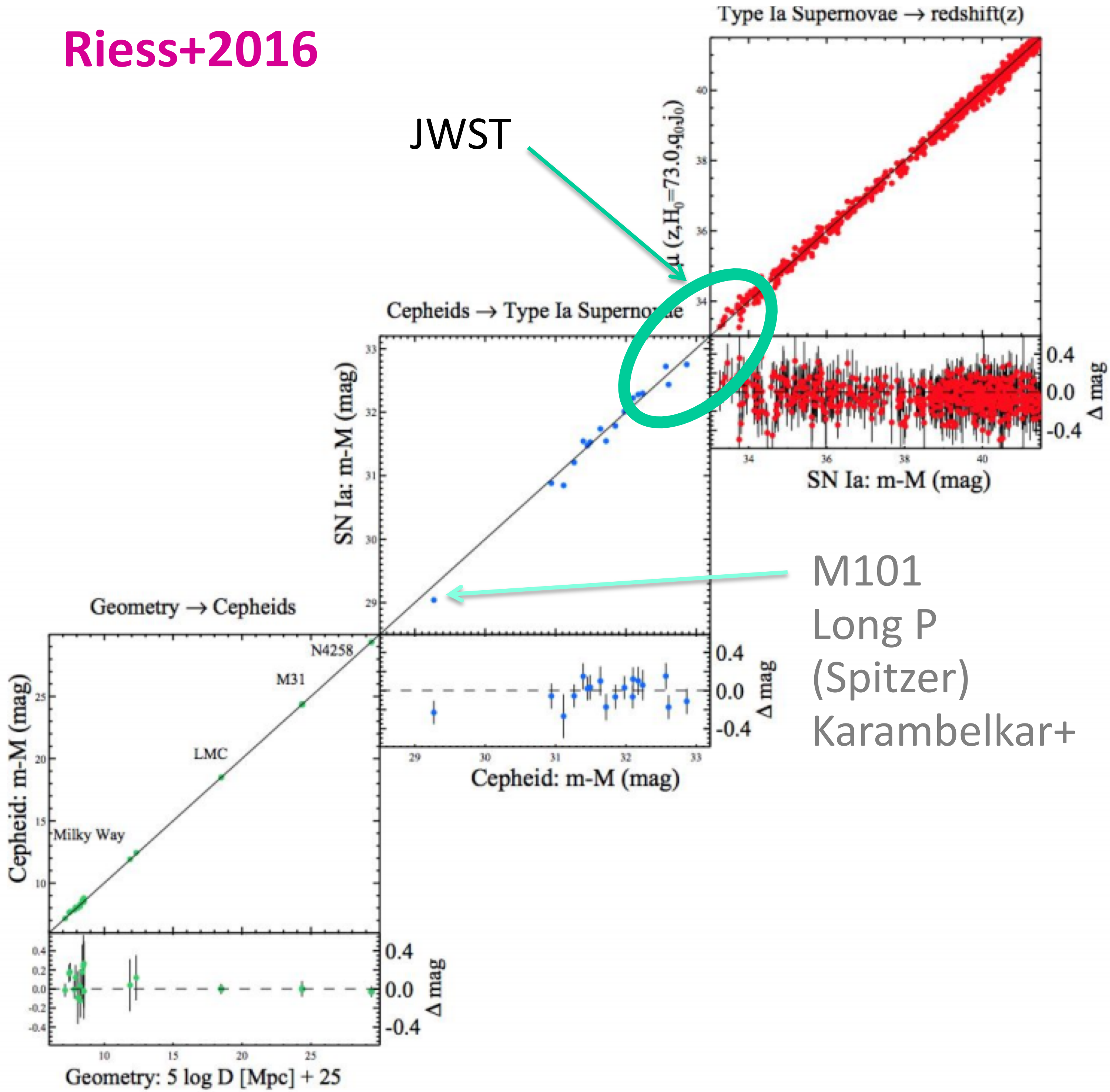
P>1000 days
Only in spirals (8)

OH/IR stars?
Super-AGB stars?

Miras as Standard Candles

- Miras (O & C rich) great potential
- P<400 days or C-stars
  - corrected for circumstellar extinction (2 colours)
  - selected to have thin shells
- M_K=-7.9: for a Cepheid P=50 or a Mira P=380
- Use linear period-luminosity
- P>400day astrophysically interesting, not well understood
- SPIRITS collaboration (Kasliwal+) P >1000day [3.6] [4.5]
- Future: LSST light curves + JWST/ELT luminosities?

Riess+2016



JWST
M101
Long P
(Spitzer)
Karambelkar+
Type Ia Supernovae → redshift(z)
Cepheids → Type Ia Supernovae
Geometry → Cepheids
SN Ia: m-M (mag)
Cepheid: m-M (mag)
Geometry: 5 log D [Mpc] + 25
Δ mag
Milky Way
LMC
M31
N4258