

# Long-Period Variables

## Pulsating AGB stars in the Gaia Era



Dipartimento  
di Fisica  
e Astronomia  
Galileo Galilei



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May 2019 - Uppsala Universitet

(super)giants: large radii

100 - 1000 days

# Long-Period Variables

stellar pulsation

# Long-Period Variables

Periods: ~10 days --- ~1000 days

Amplitudes: 0.001 mag --- 10 mag

Multi-periodicity, non-radial modes

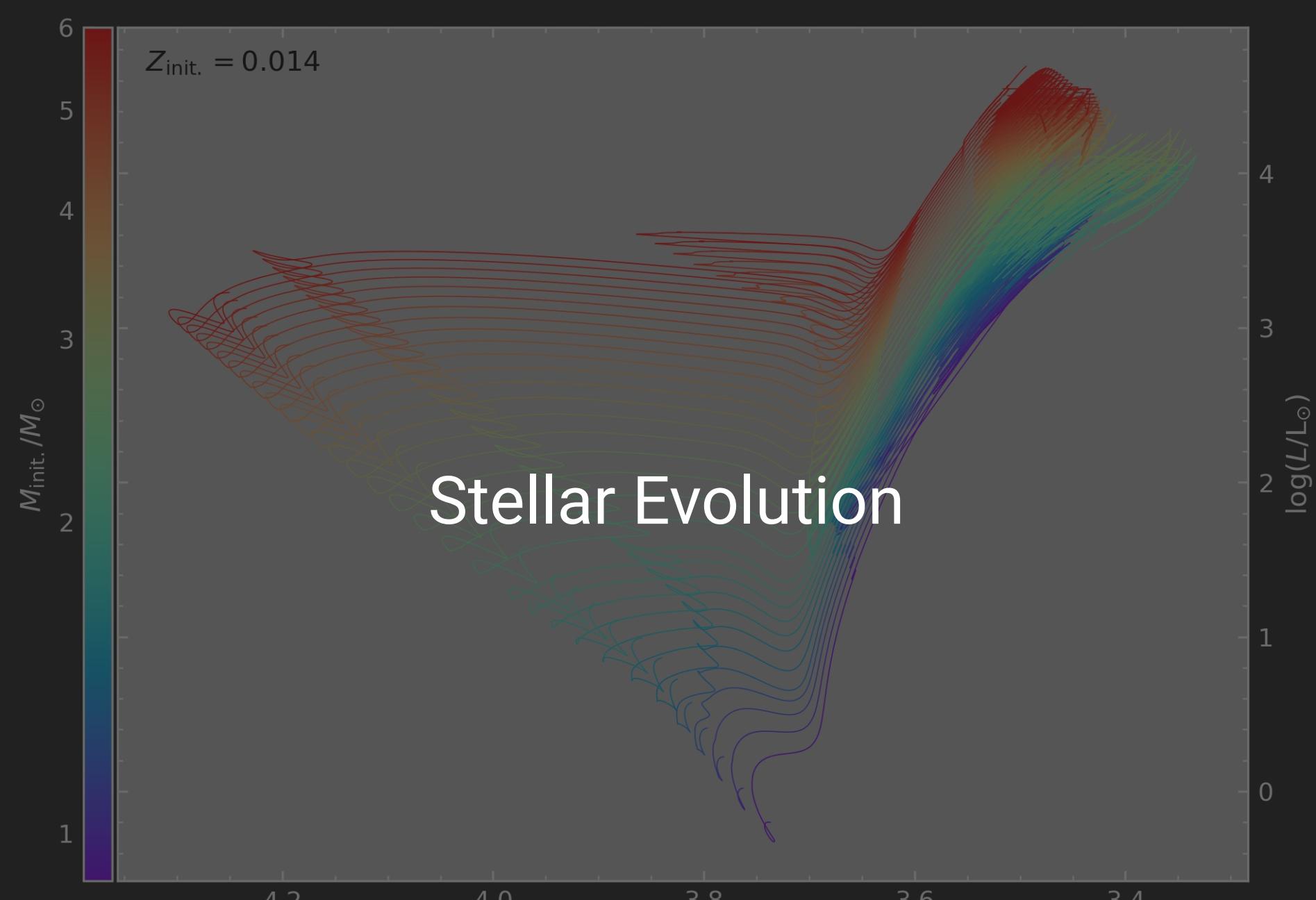
~ intermediate age populations

Low- and intermediate-mass stars

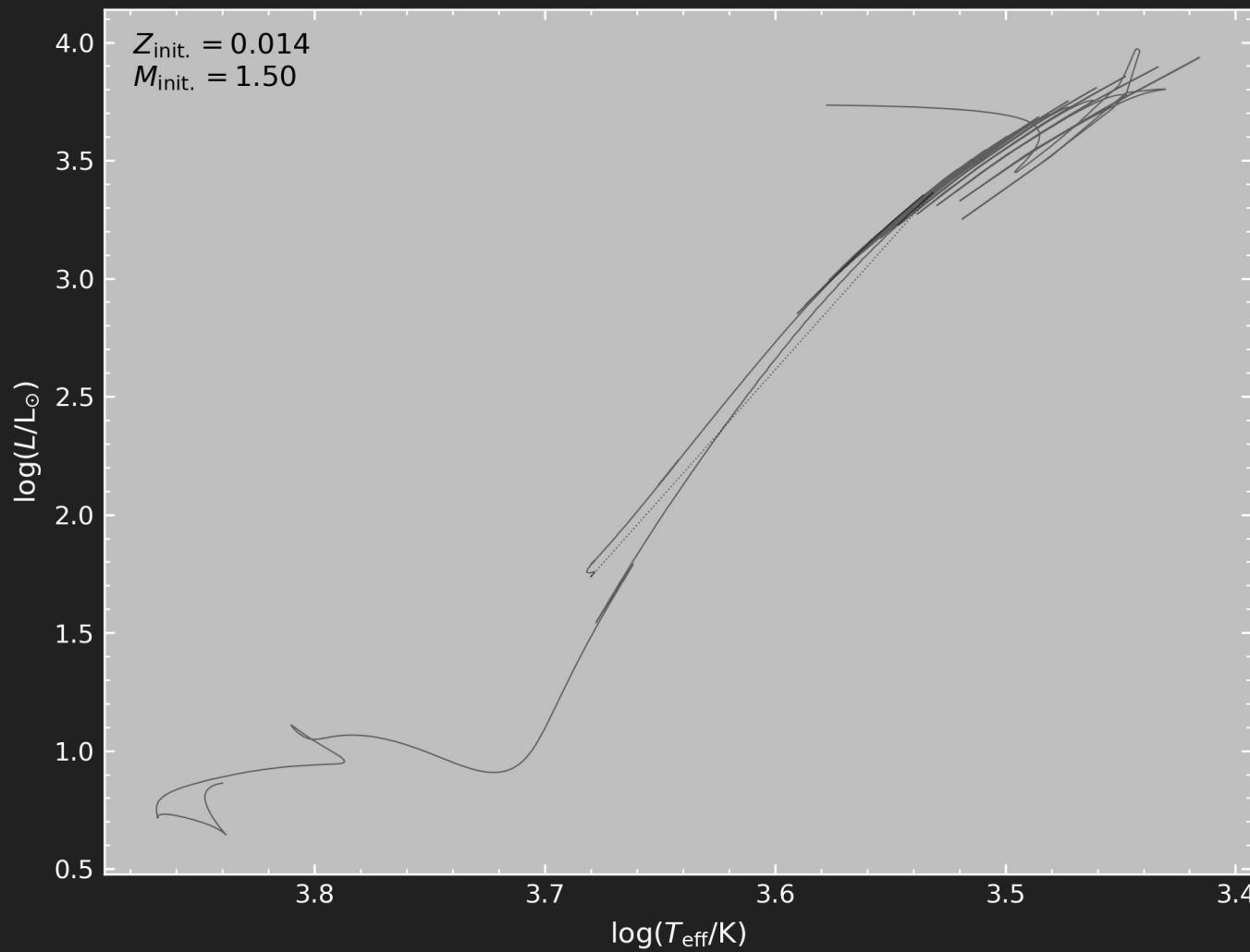
# OUTLINE

# Long-Period Variables

- Quick summary
  - Stellar evolution
  - Stellar pulsation
- Observed variability
- Ensemble properties
- Current research
- Some future prospects

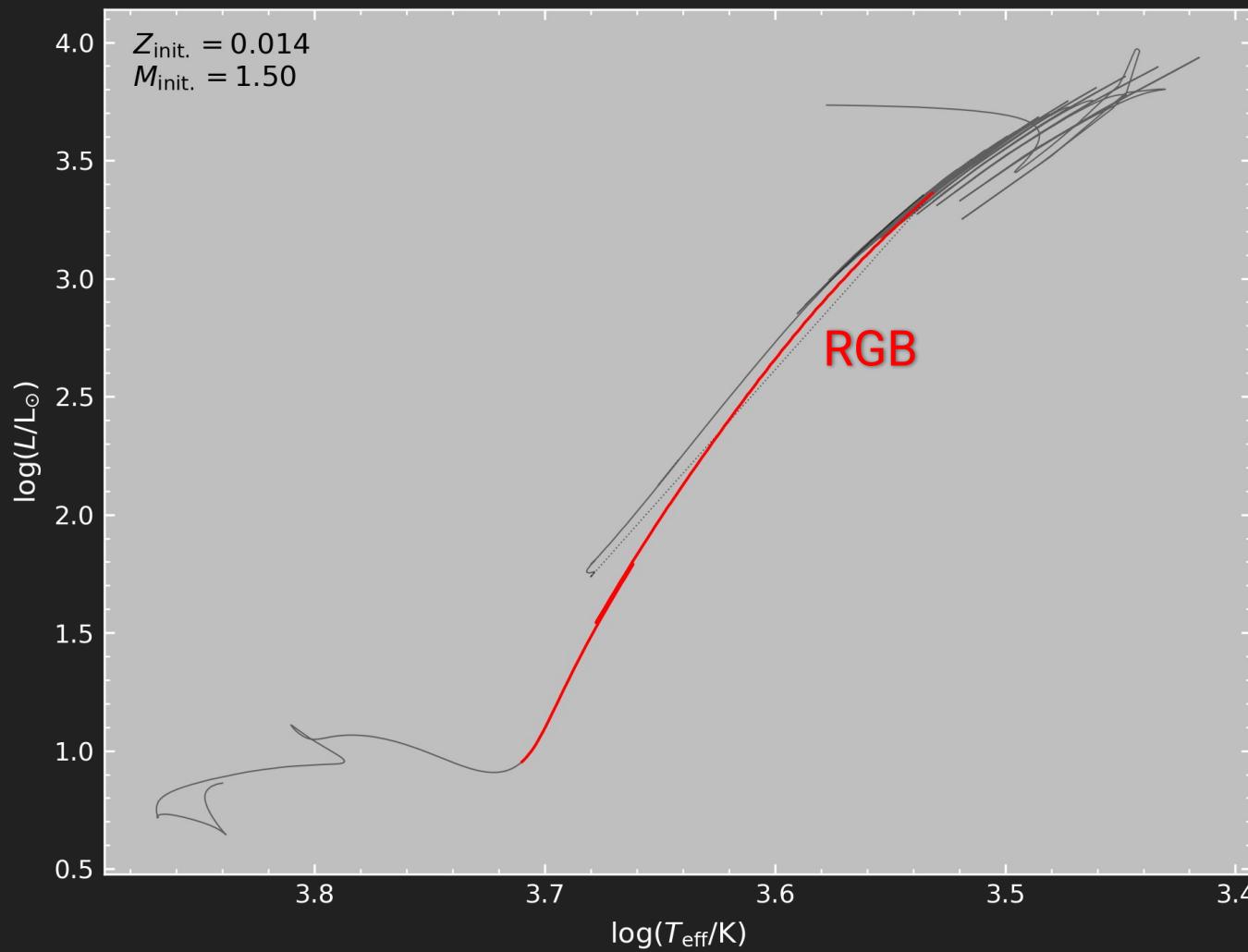


# Stellar evolution - Quick summary



PARSEC+COLIBRI evo-tracks  
[Bressan+ 2012, Marigo+ 2017, Pastorelli+ 2019]

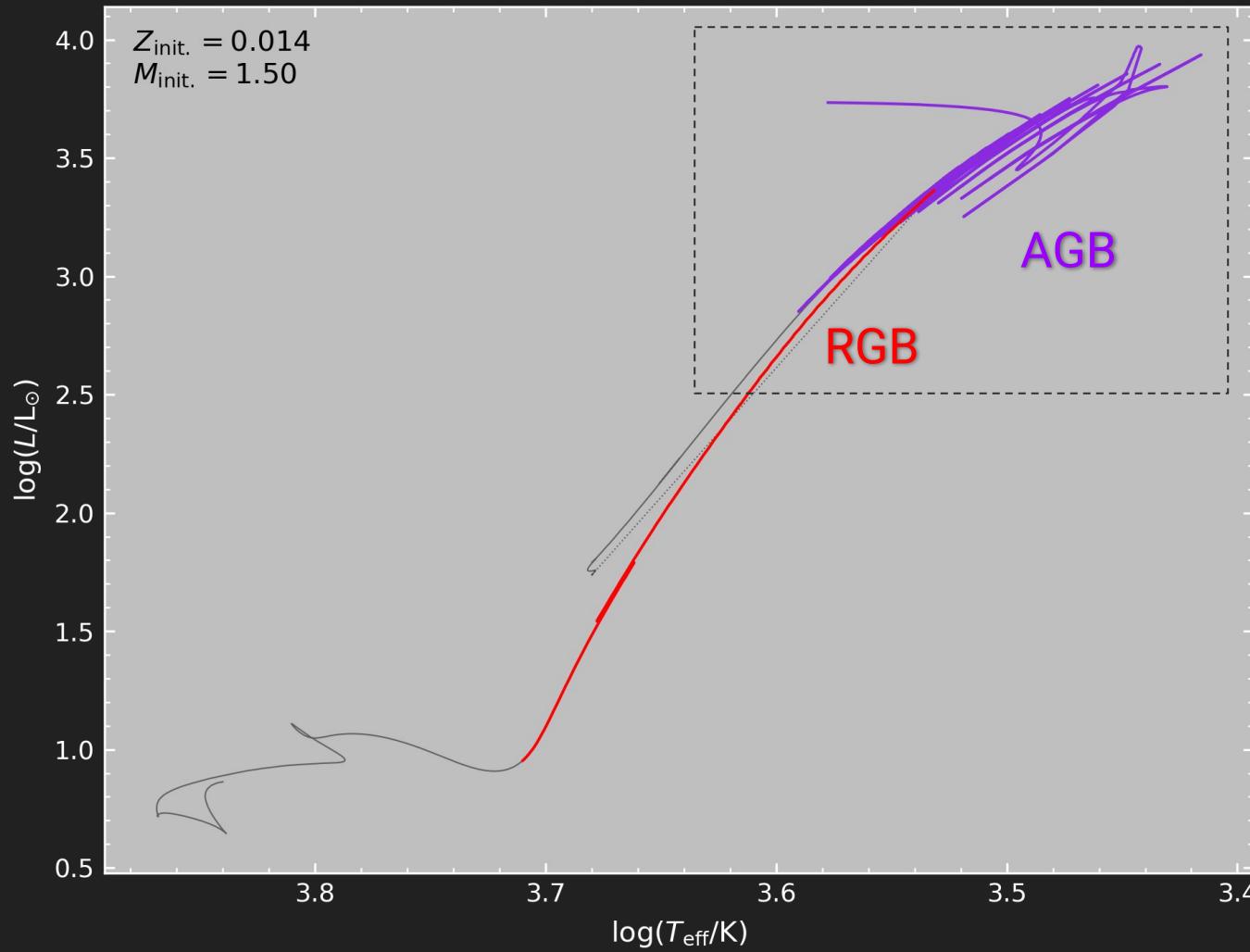
# Stellar evolution - Red Giant Branch



PARSEC+COLIBRI evo-tracks

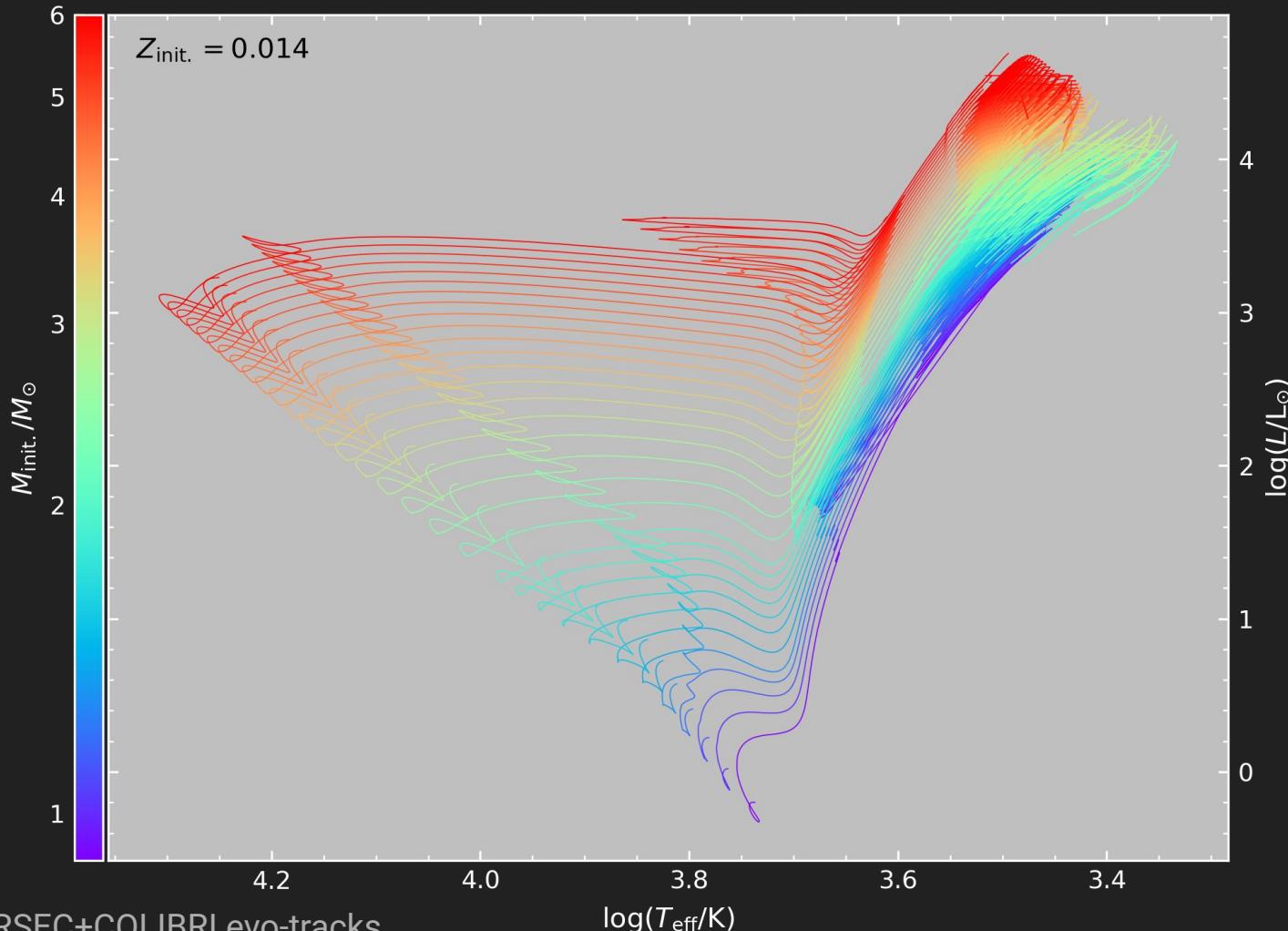
[Bressan+ 2012, Marigo+ 2017, Pastorelli+ 2019]

# Stellar evolution - Asymptotic Giant Branch



PARSEC+COLIBRI evo-tracks  
[Bressan+ 2012, Marigo+ 2017, Pastorelli+ 2019]

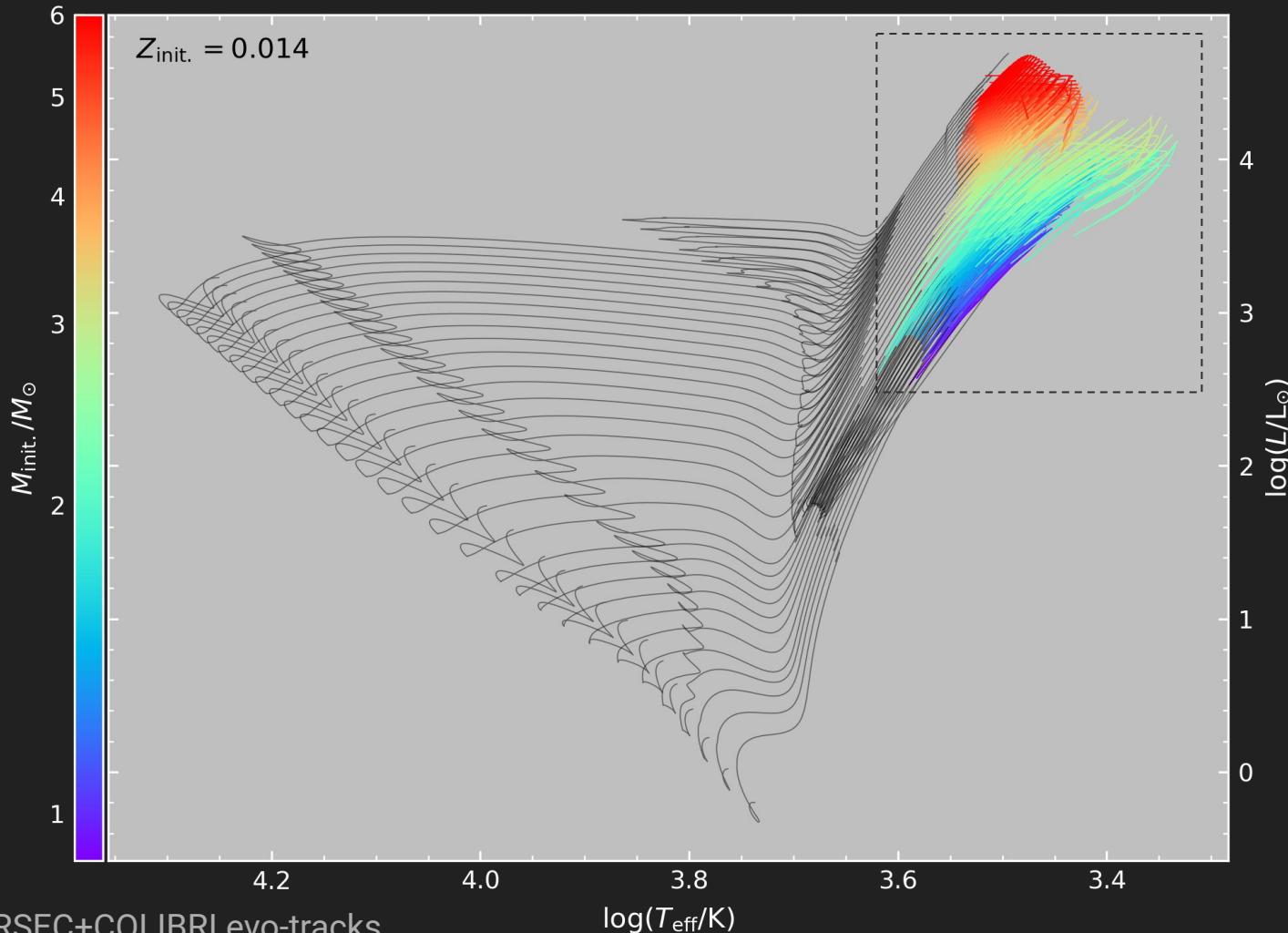
# Asymptotic Giant Branch - Evolution



PARSEC+COLIBRI evo-tracks  
[Bressan+ 2012, Marigo+ 2017, Pastorelli+ 2019]

$\log(T_{\text{eff}}/\text{K})$

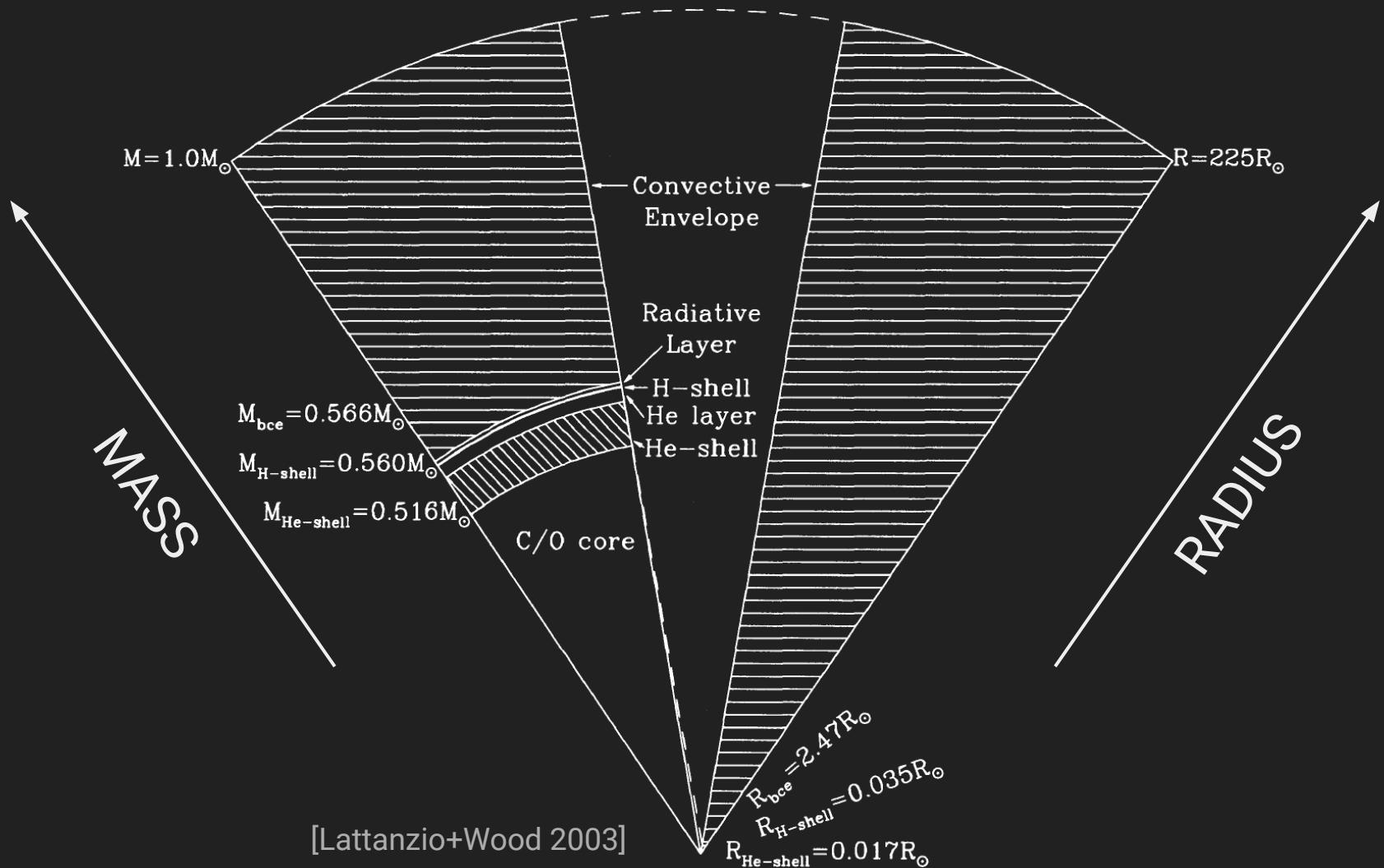
# Asymptotic Giant Branch - Evolution



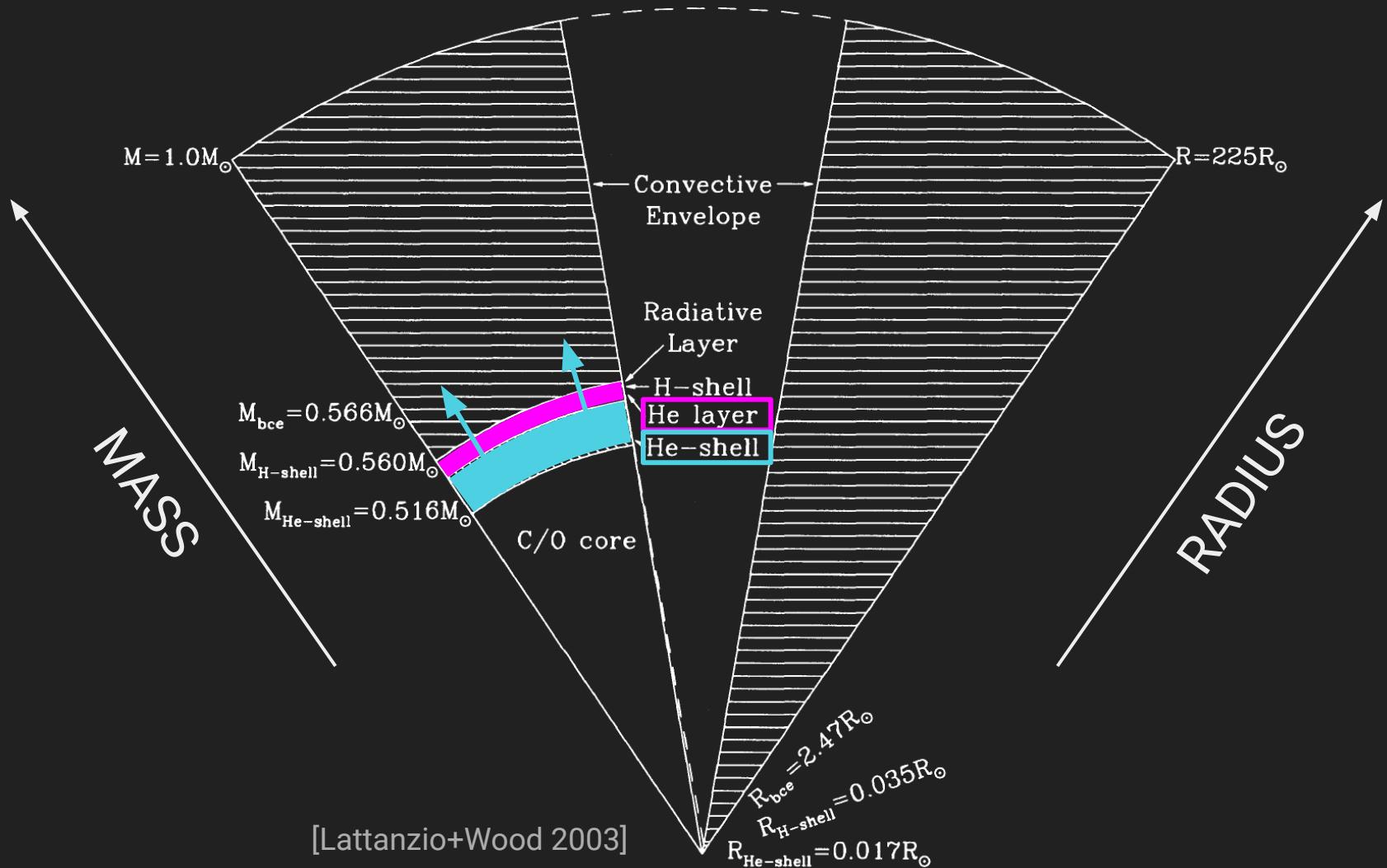
PARSEC+COLIBRI evo-tracks  
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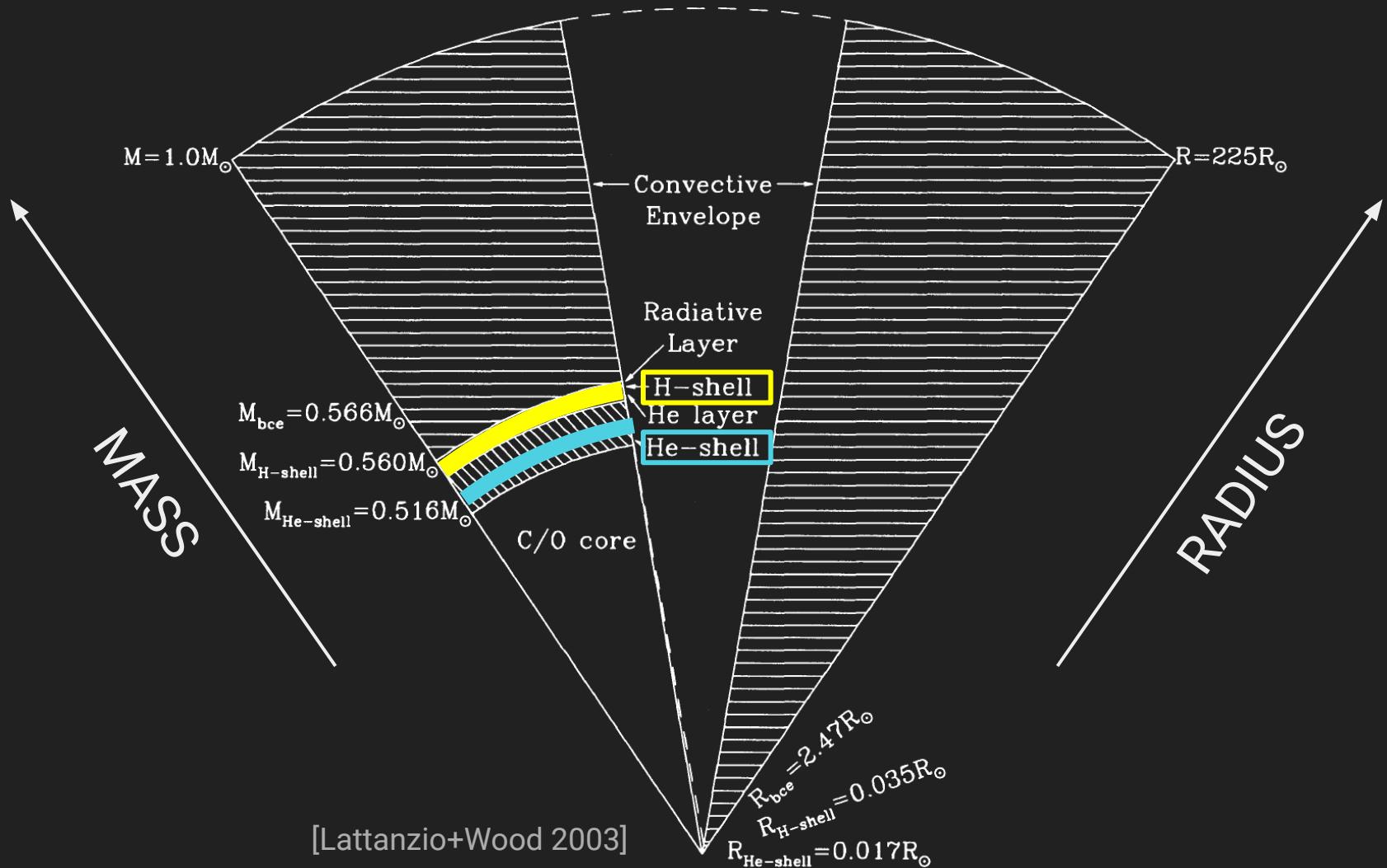
# Asymptotic Giant Branch - Structure



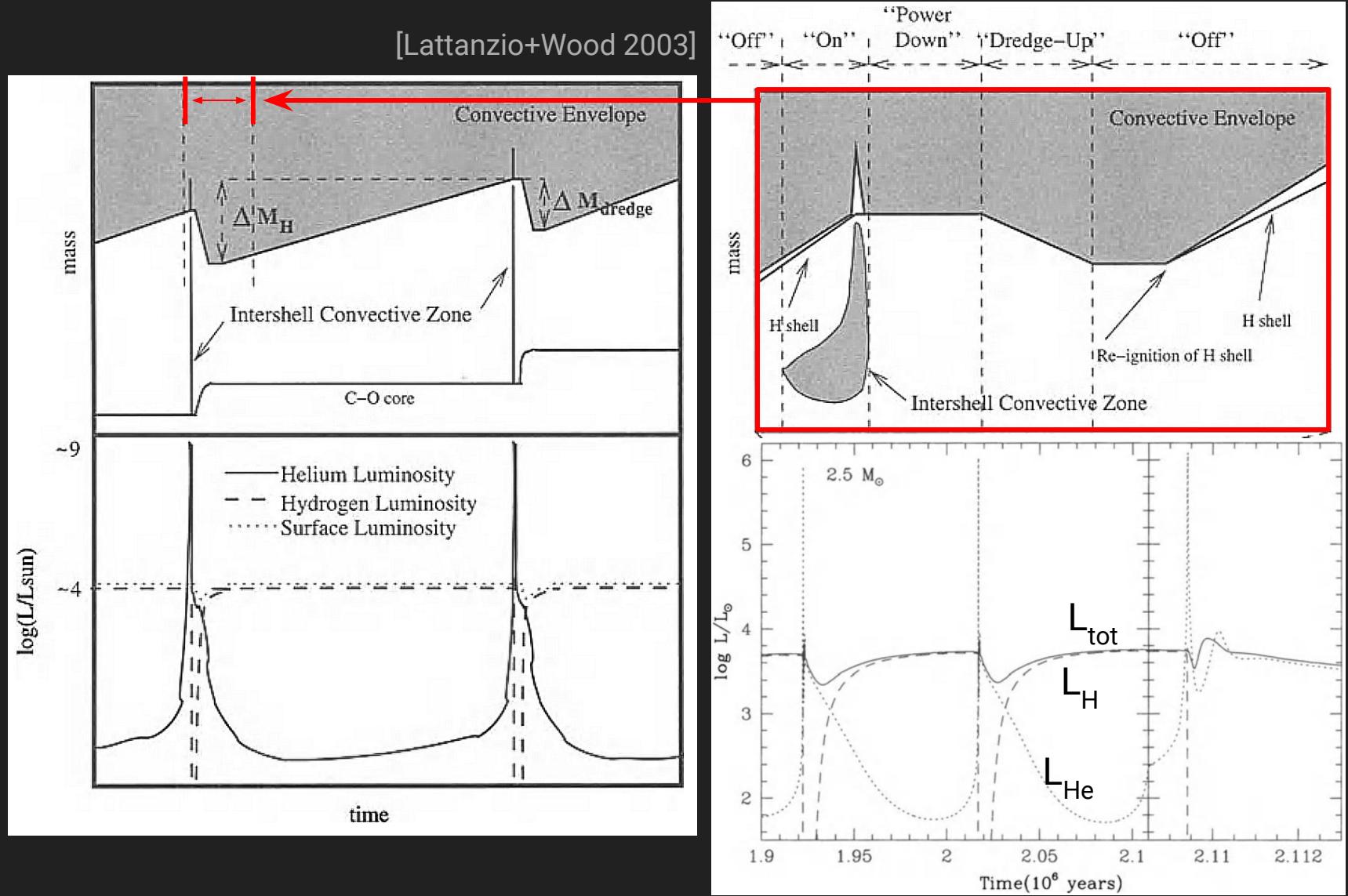
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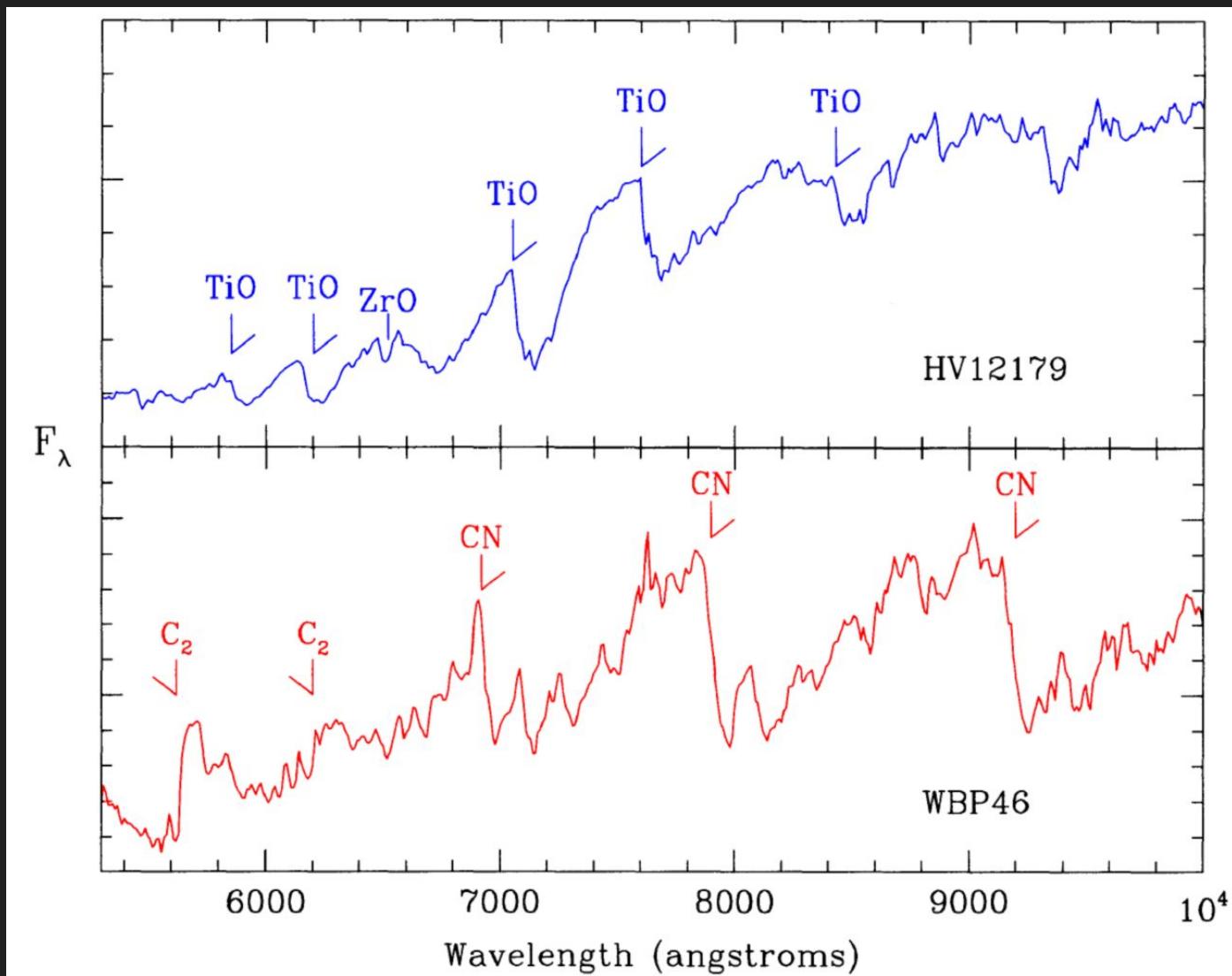
# Asymptotic Giant Branch - Structure



# Stellar evolution - Asymptotic Giant Branch

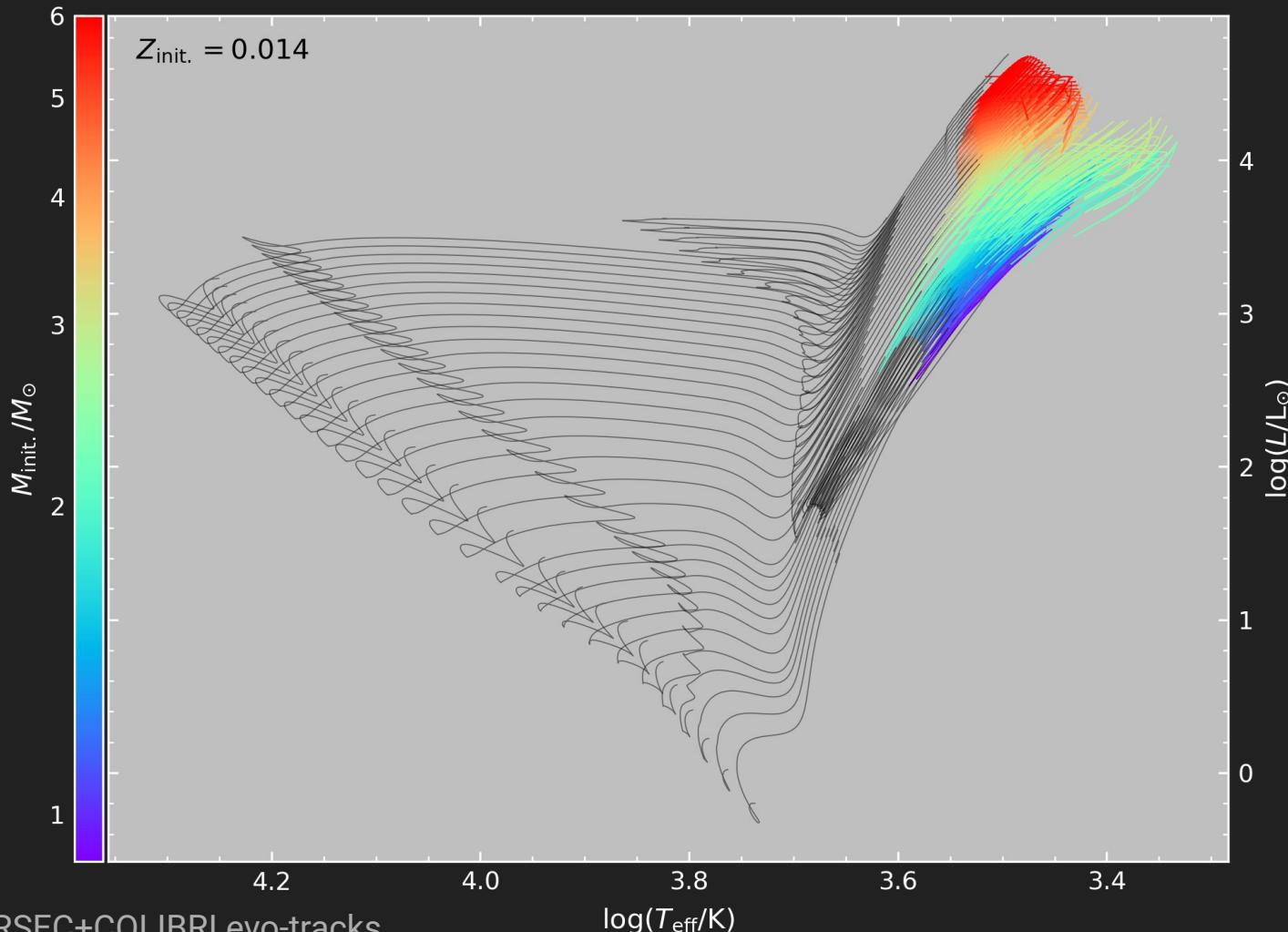


# Stellar evolution - Asymptotic Giant Branch



[Lattanzio+Wood 2003]

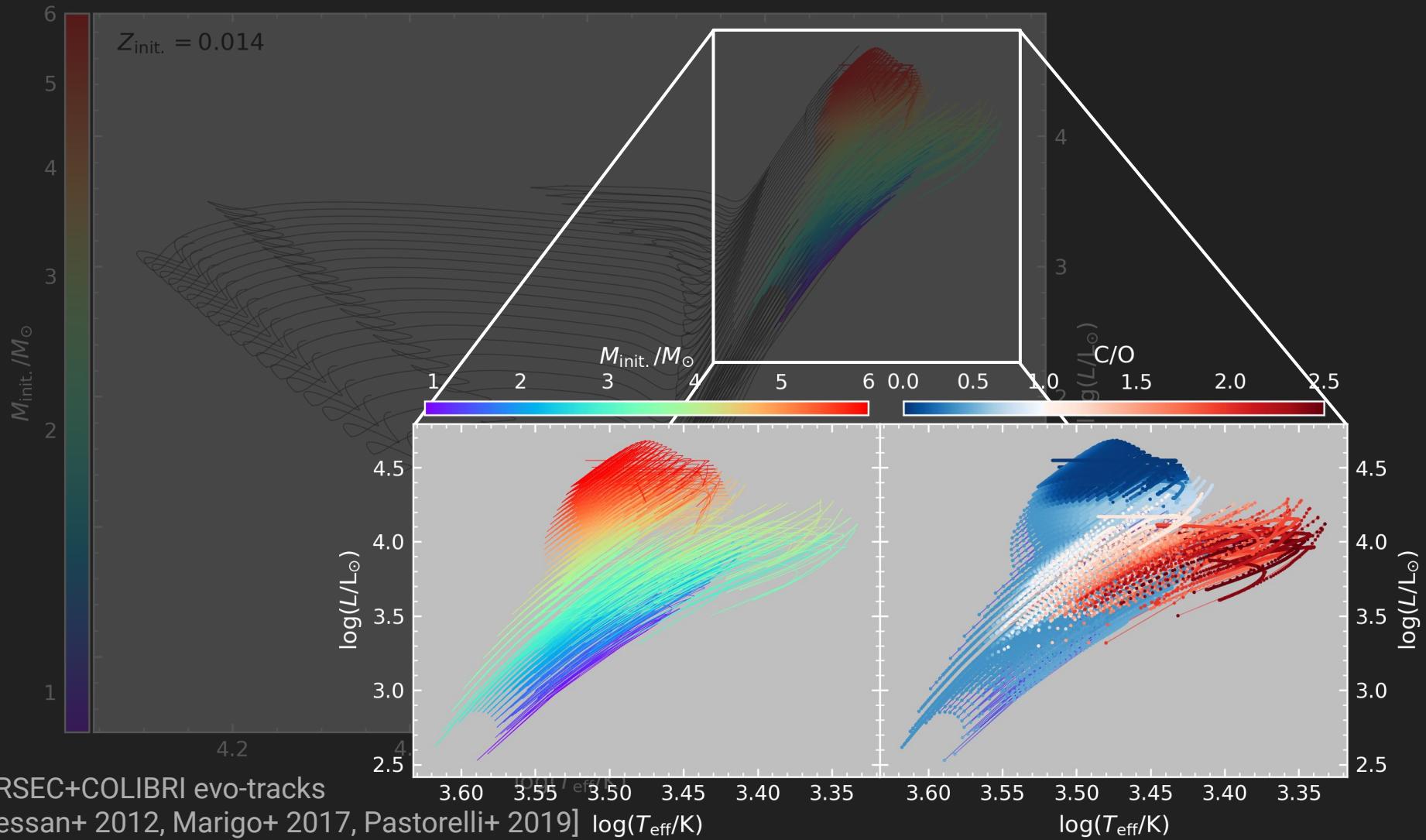
# Asymptotic Giant Branch - Evolution



PARSEC+COLIBRI evo-tracks  
[Bressan+ 2012, Marigo+ 2017, Pastorelli+ 2019]

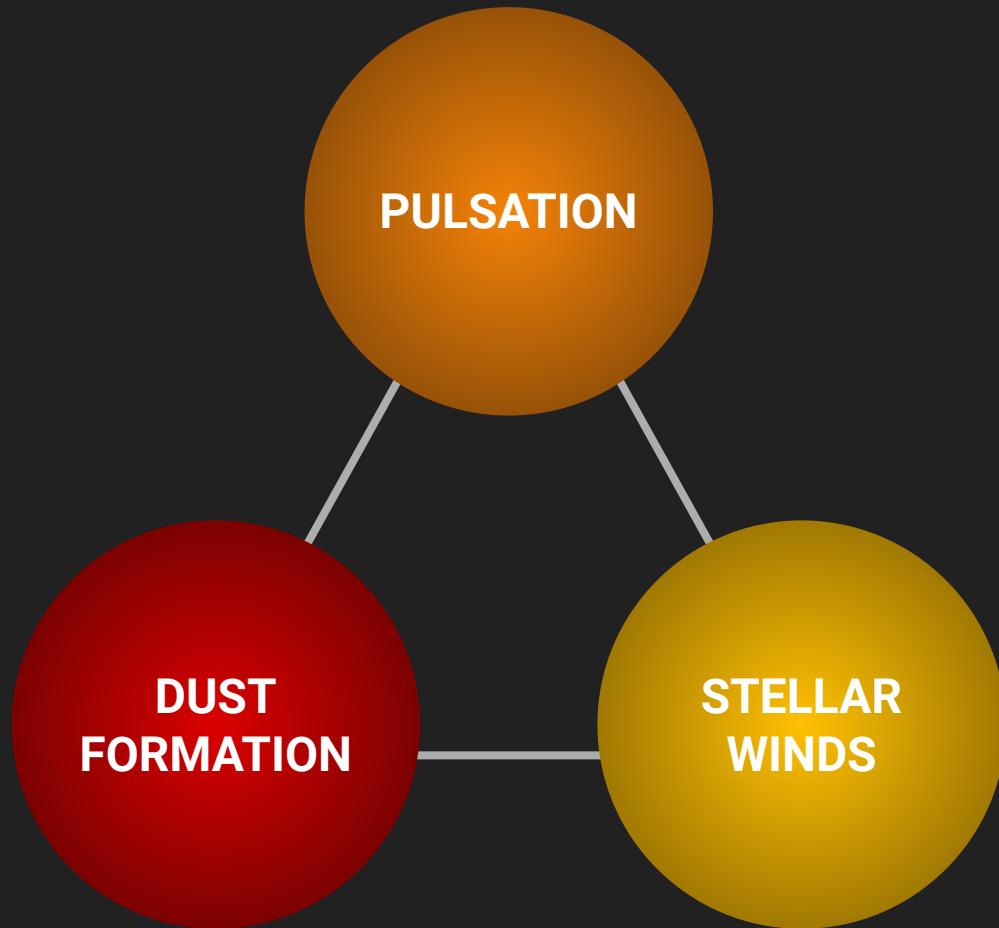
$\log(T_{\text{eff}}/\text{K})$

# Asymptotic Giant Branch - Thermally-Pulsing stage



# TP-AGB processes

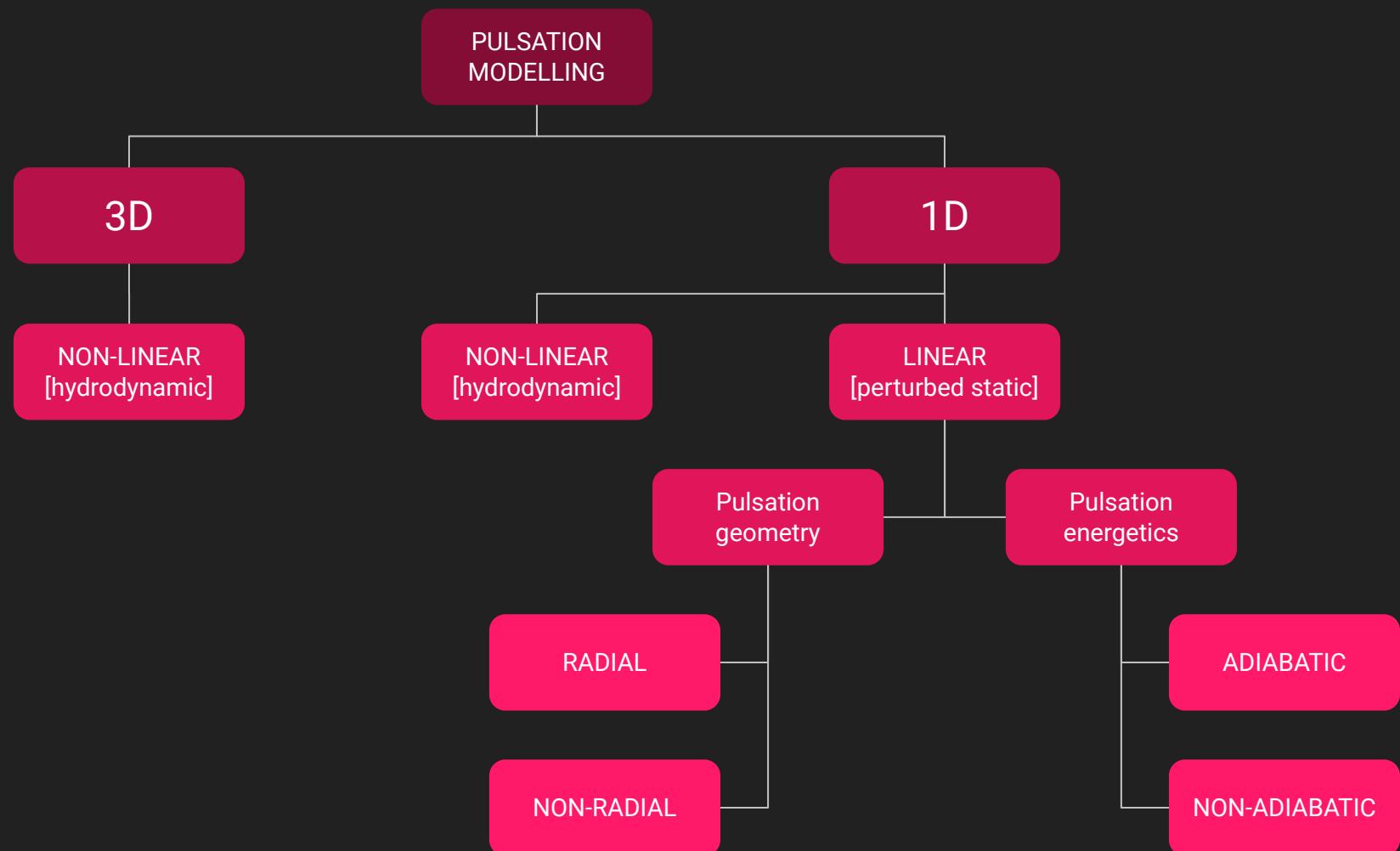
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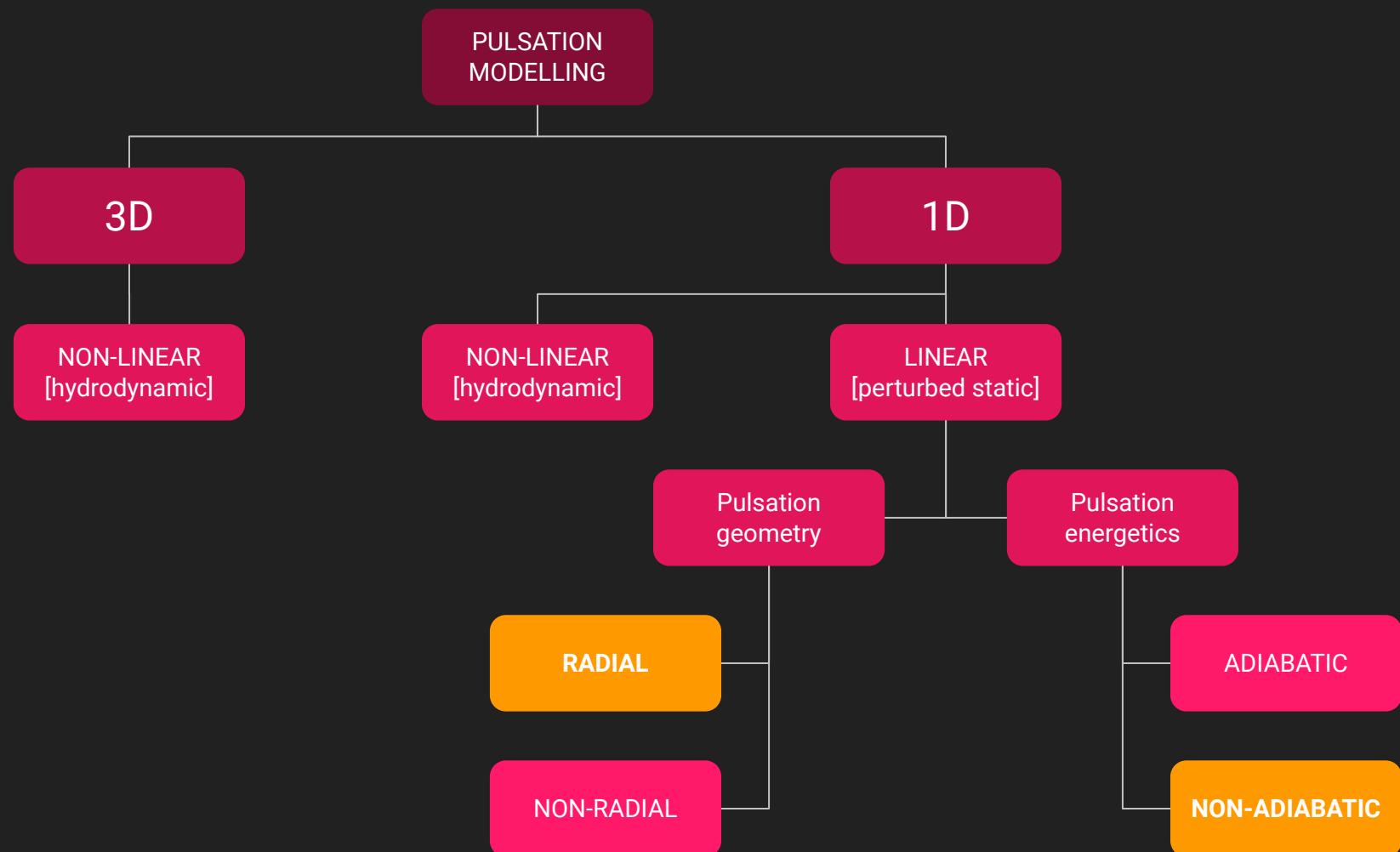
# Stellar Pulsation

# Pulsation modelling

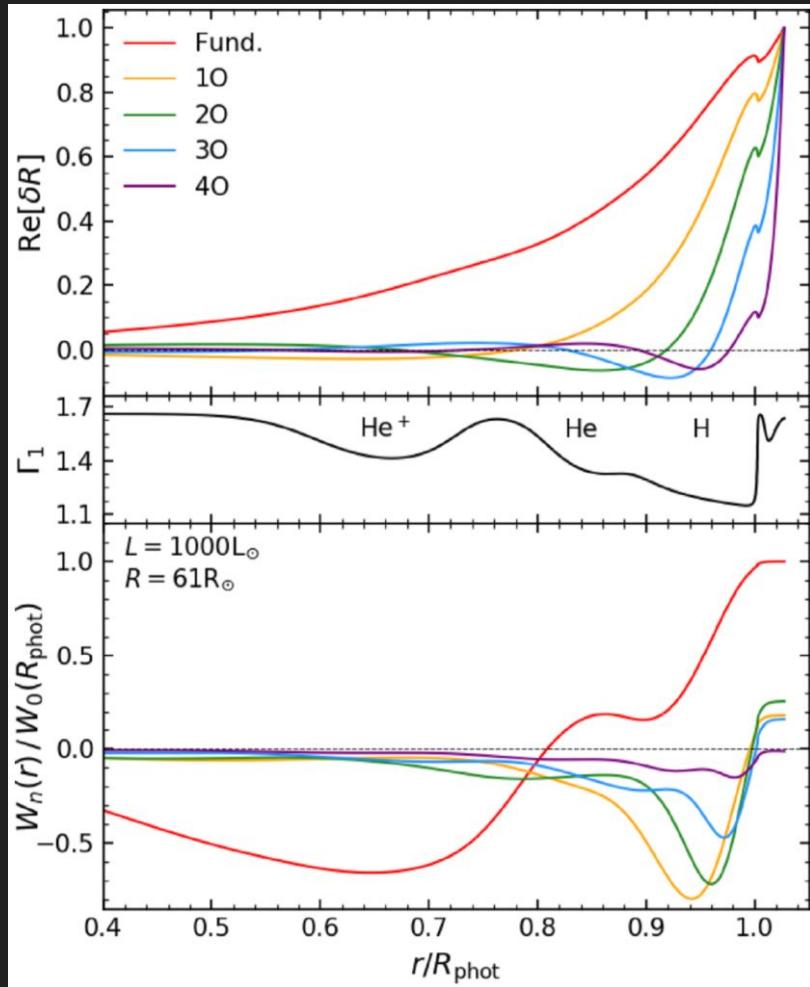
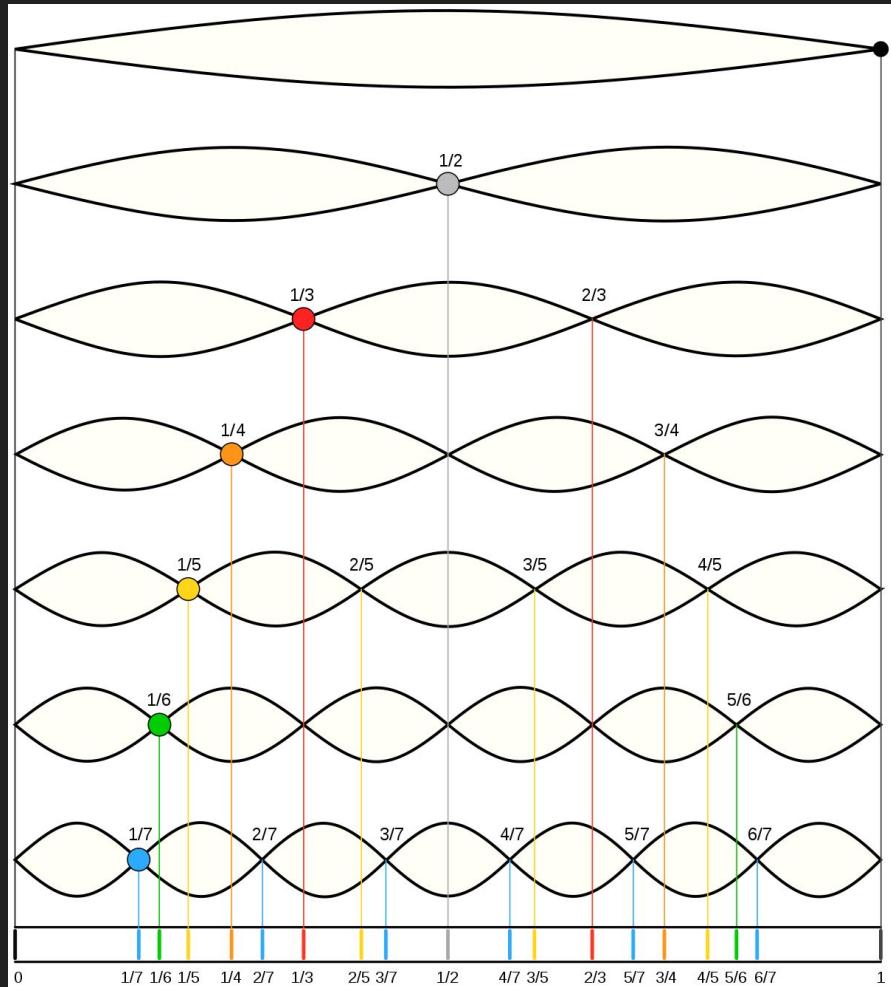
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# Pulsation modelling



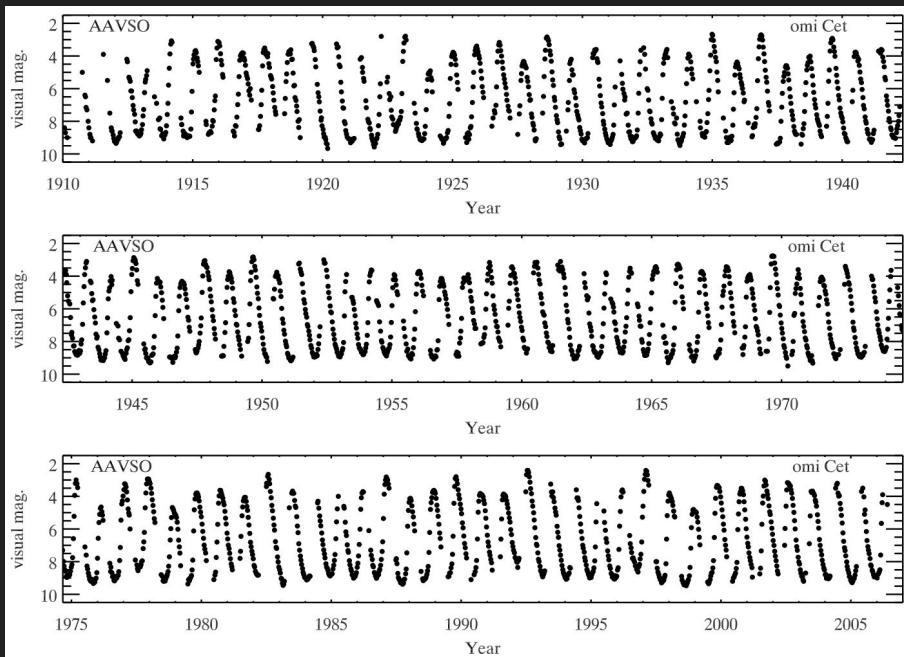
# Linear, non-adiabatic pulsation



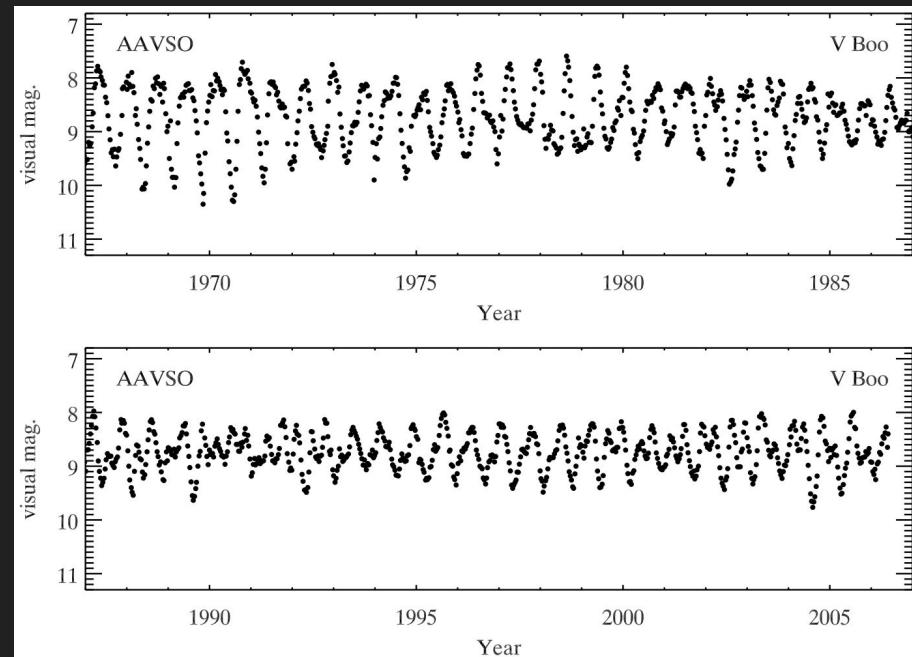
[Trabucchi+ 2019]

# Miras and Semiregulars: light curves

The AAVSO historical visual light curve of Mira



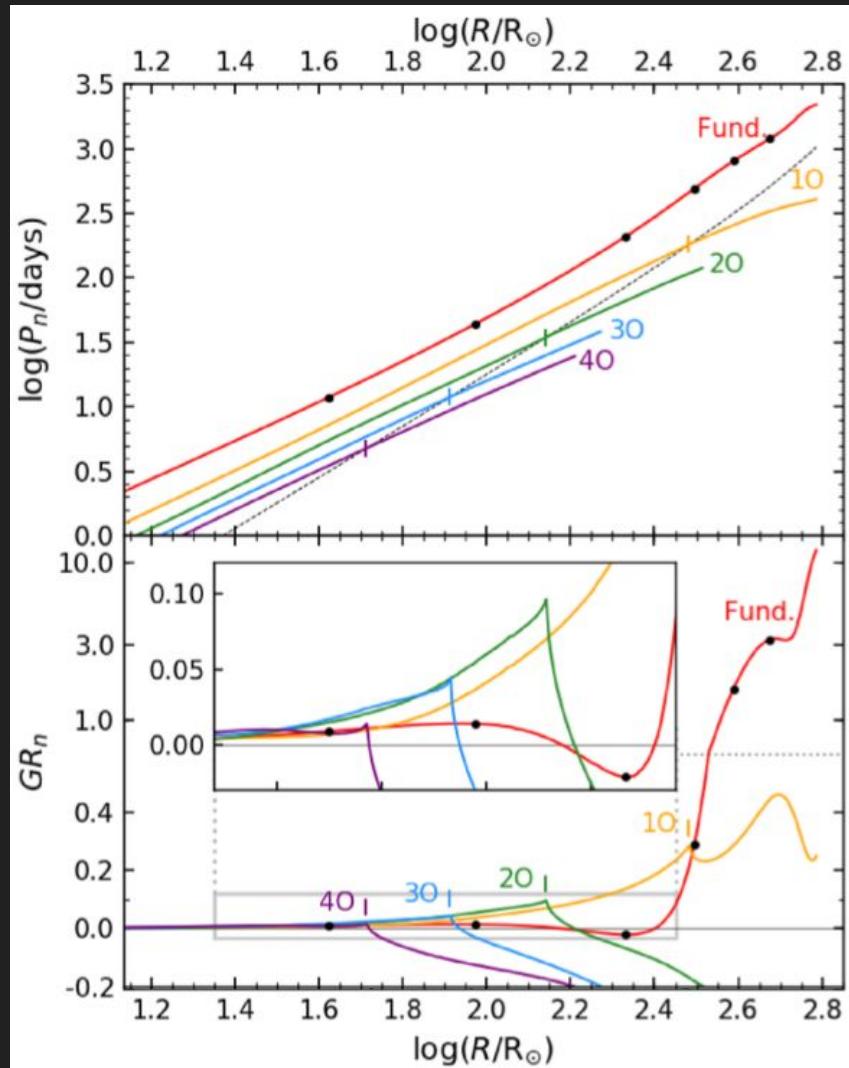
Visual light curve of SRa star V Boo



[Aerts+ 2015, credit: Matthew Templeton]

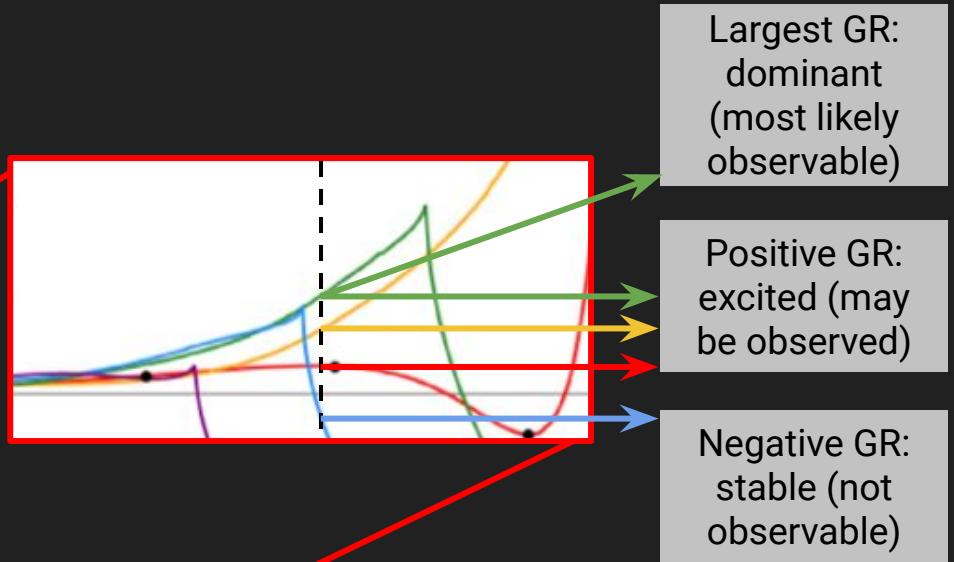
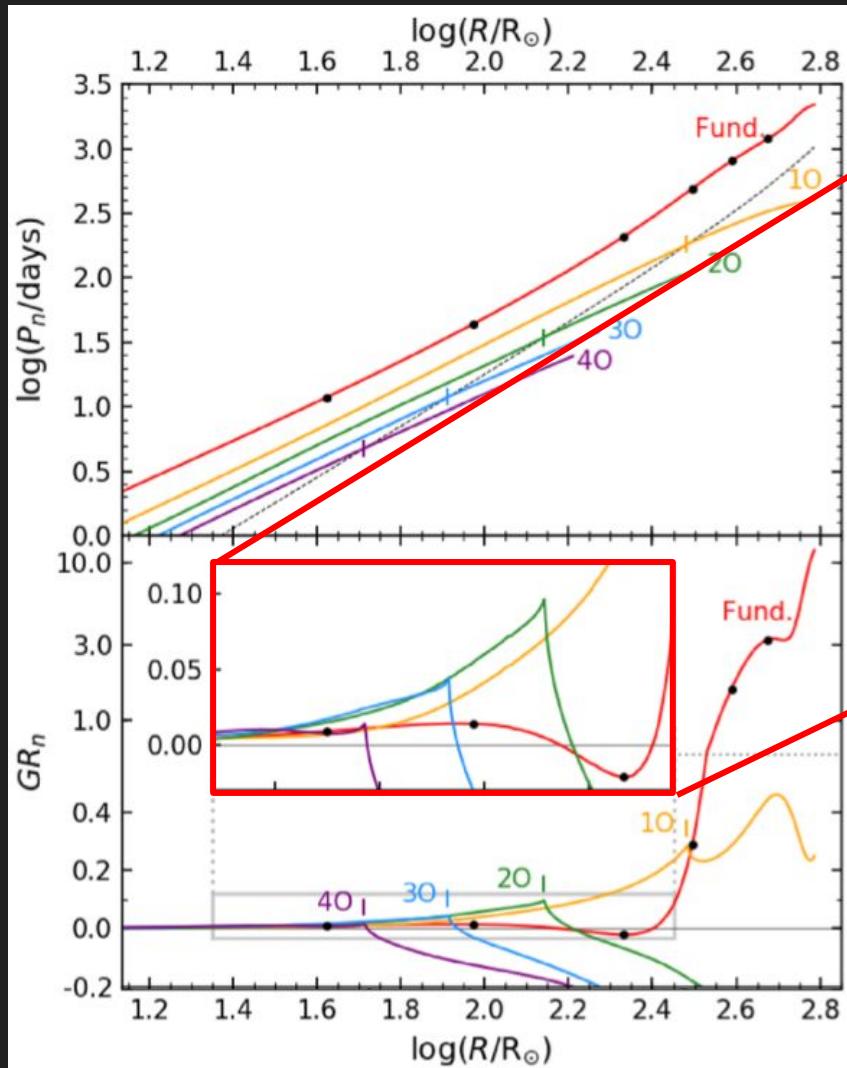
From the definition of the SRa type in the General Catalogue of Variable Stars:  
" [...] Many of these stars differ from Miras only by showing smaller light amplitudes."

# Models of pulsating AGB star



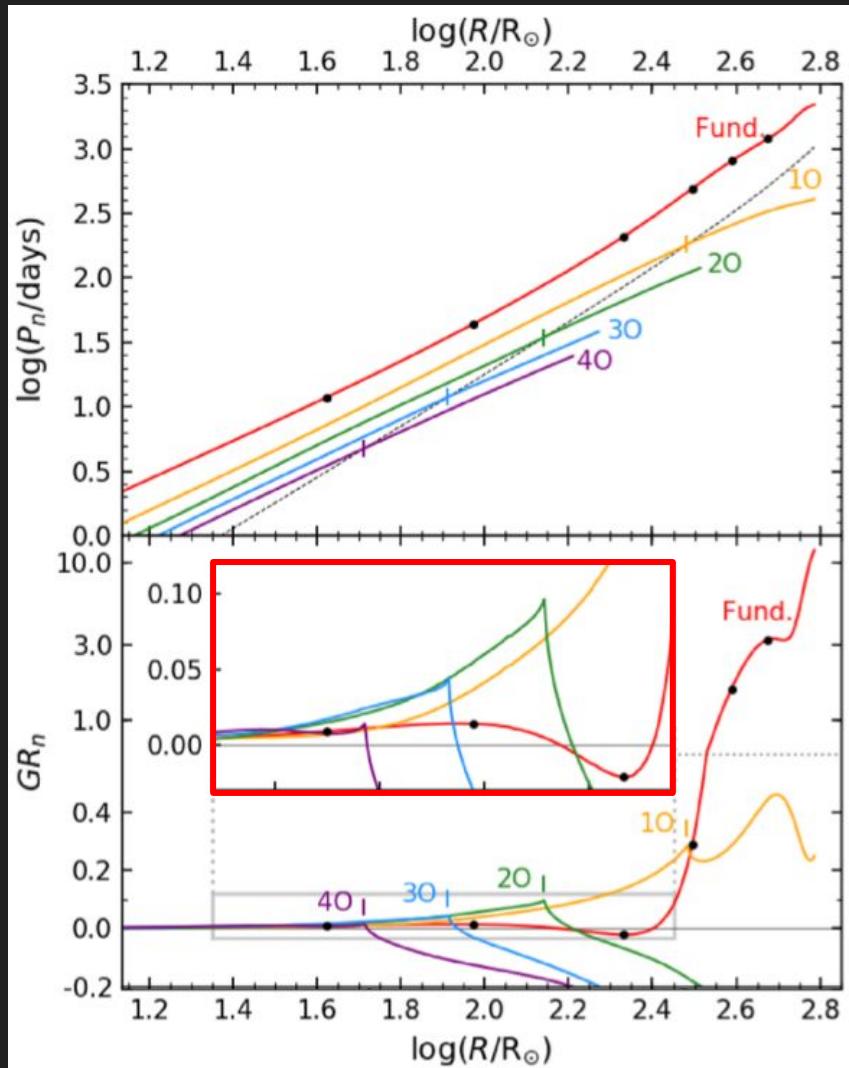
[Trabucchi 2019]

# Models of pulsating AGB star

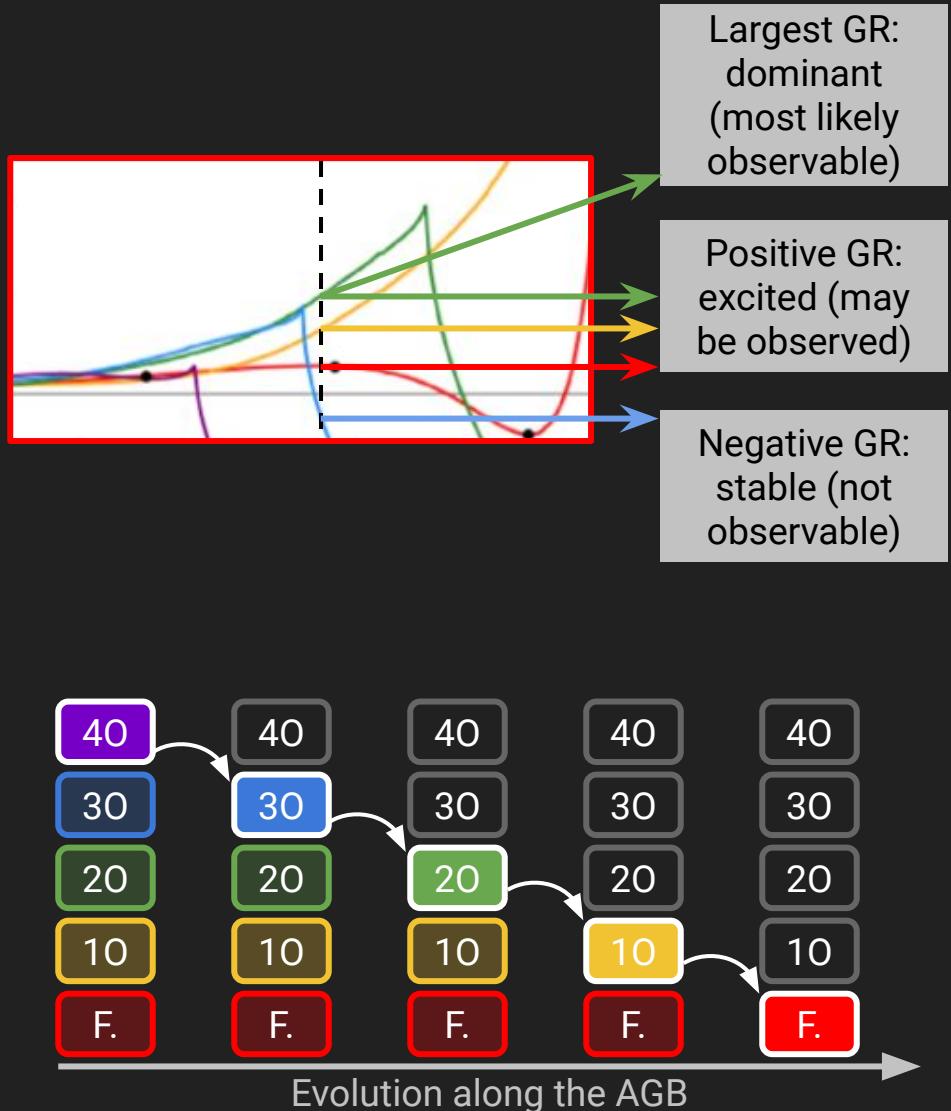


[Trabucchi+ 2019]

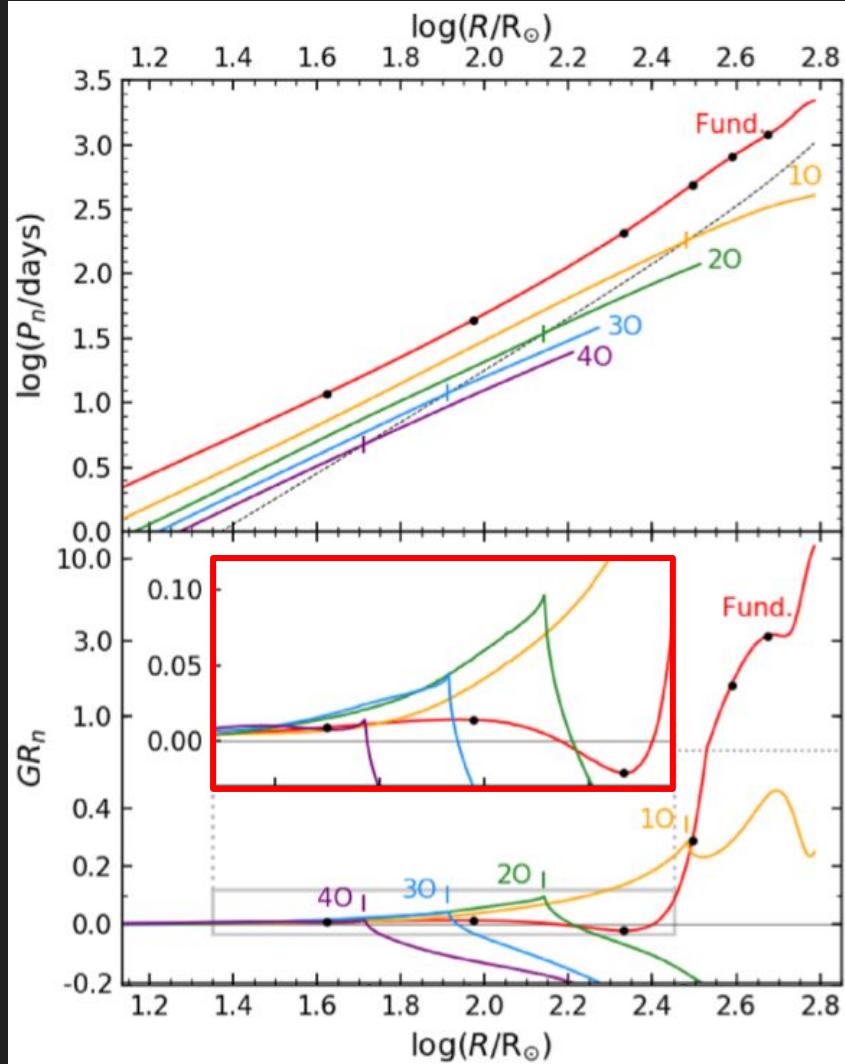
# Models of pulsating AGB star



[Trabucchi+ 2019]

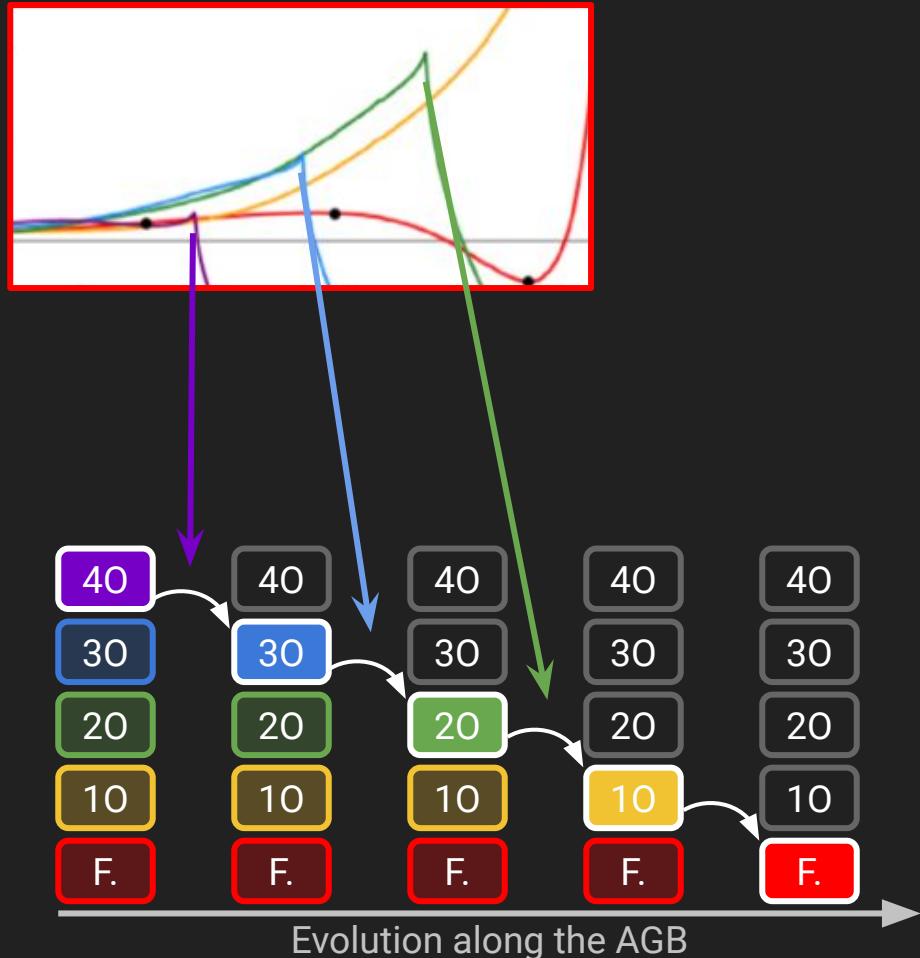


# Models of pulsating AGB star



[Trabucchi+ 2019]

GR “peak”: mode reaches acoustic cut-off  
no surface reflection



# LPVs variability properties

# Variability sub-types

"RED VARIABLES",  
by amplitude

LARV

MARV

SARV

LPV

by variability  
properties

M (Mira)

SR (semiregular)

L (slow irregular)

SRa

SRb

SRc

SRd

SRS

Lb

Lc

by P-L relation  
(Magellanic Clouds)

SRV  
(Semi-Regular Var.)

OSARG  
(OGLE Small Amp. RG)

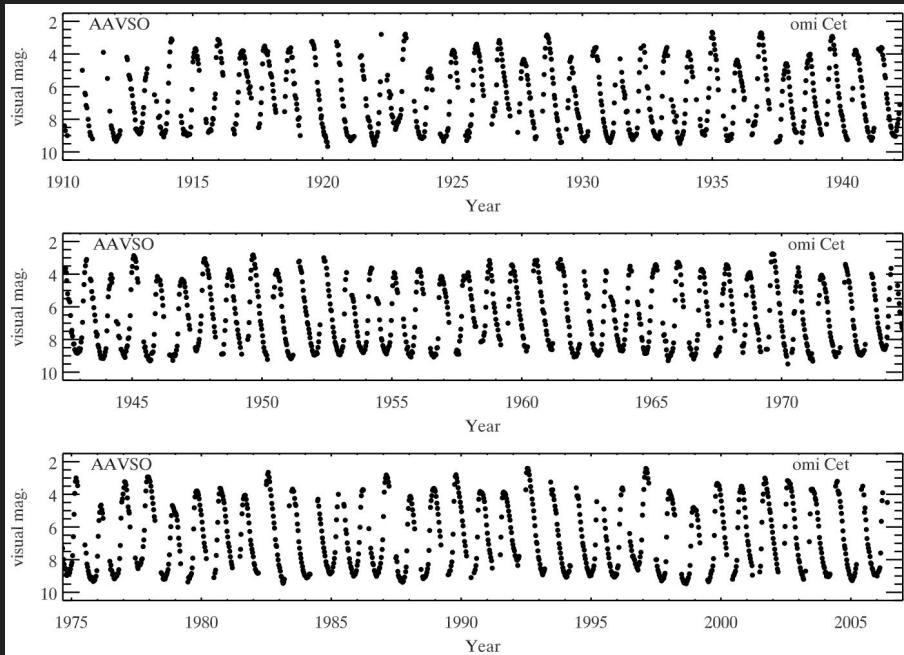
Mira

RGB

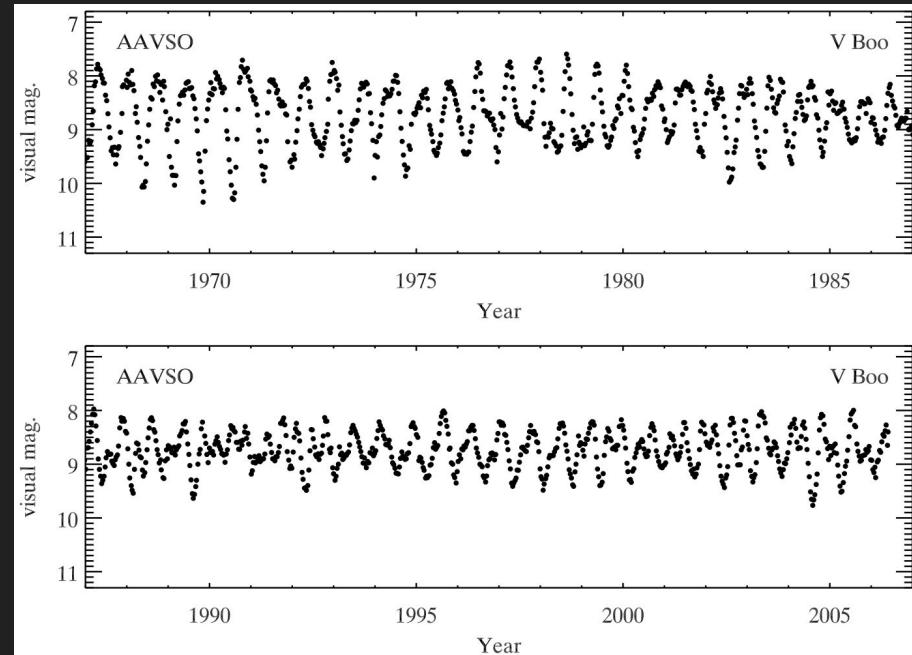
Late-type giants  
Late-type supergiants

# Miras and Semiregulars: light curves

The AAVSO historical visual light curve of Mira



Visual light curve of SRa star V Boo

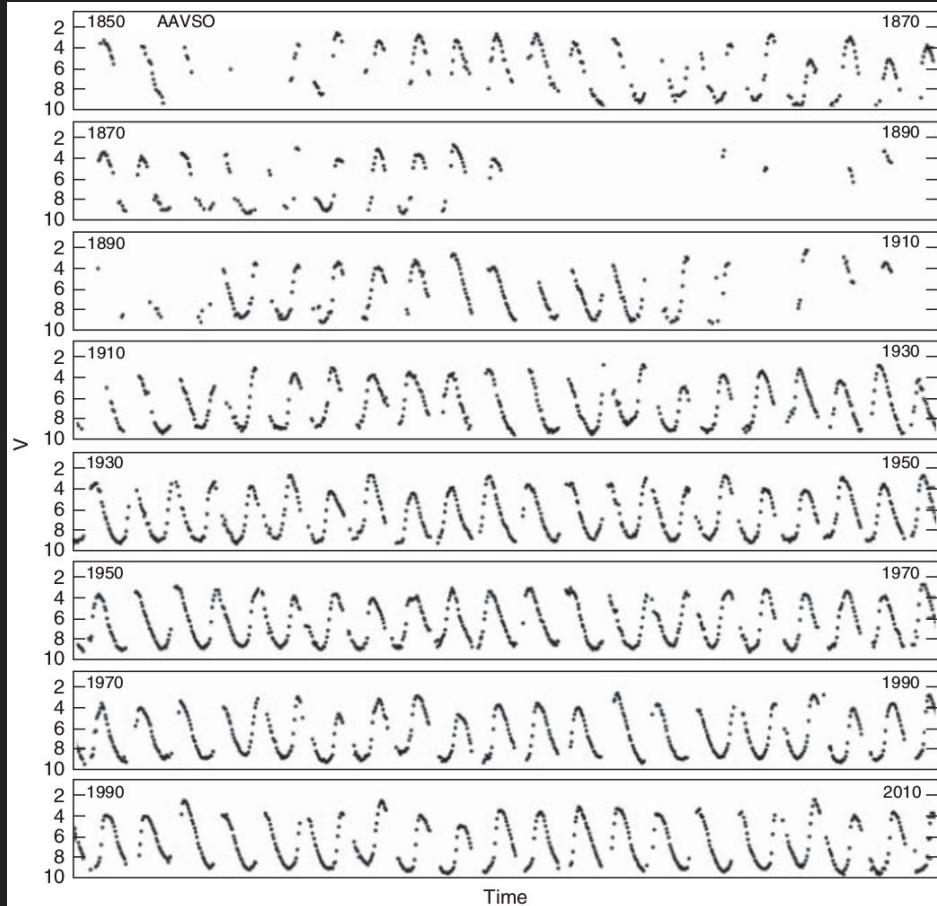


[Aerts+ 2015, credit: Matthew Templeton]

From the definition of the SRa type in the General Catalogue of Variable Stars:  
" [...] Many of these stars differ from Miras only by showing smaller light amplitudes."

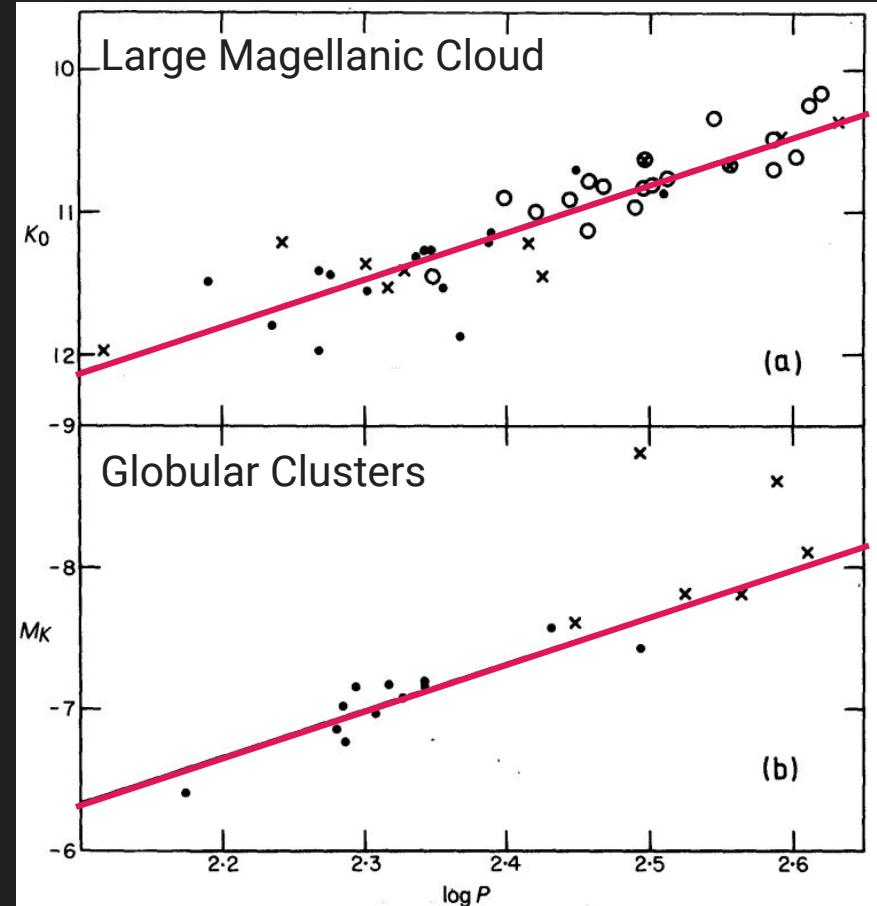
# Period-Luminosity relations - Mira variables

The AAVSO historical visual light curve of Mira



[Catelan+Smith 2015, data: Henden 2013]

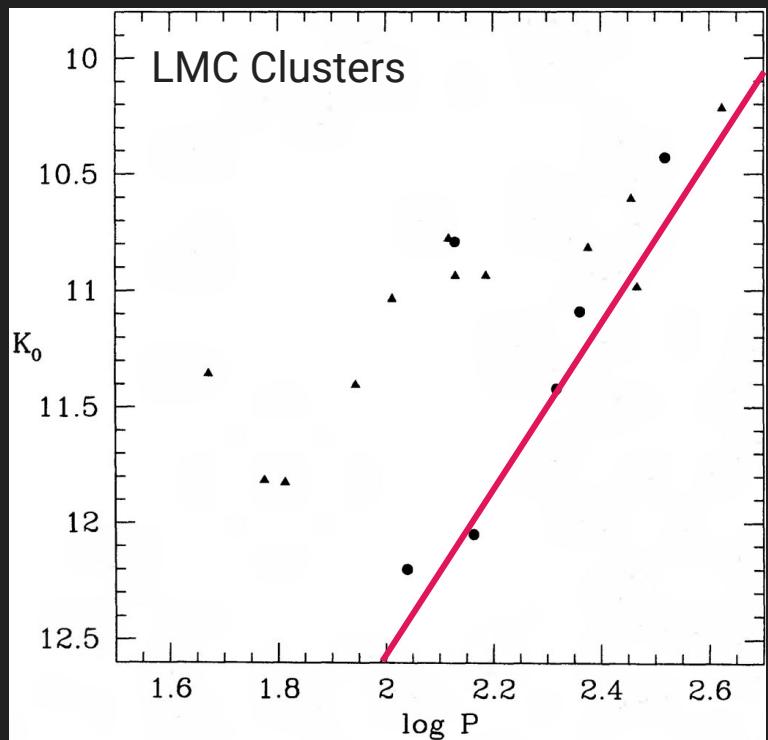
NIR Period-Luminosity relation of Miras



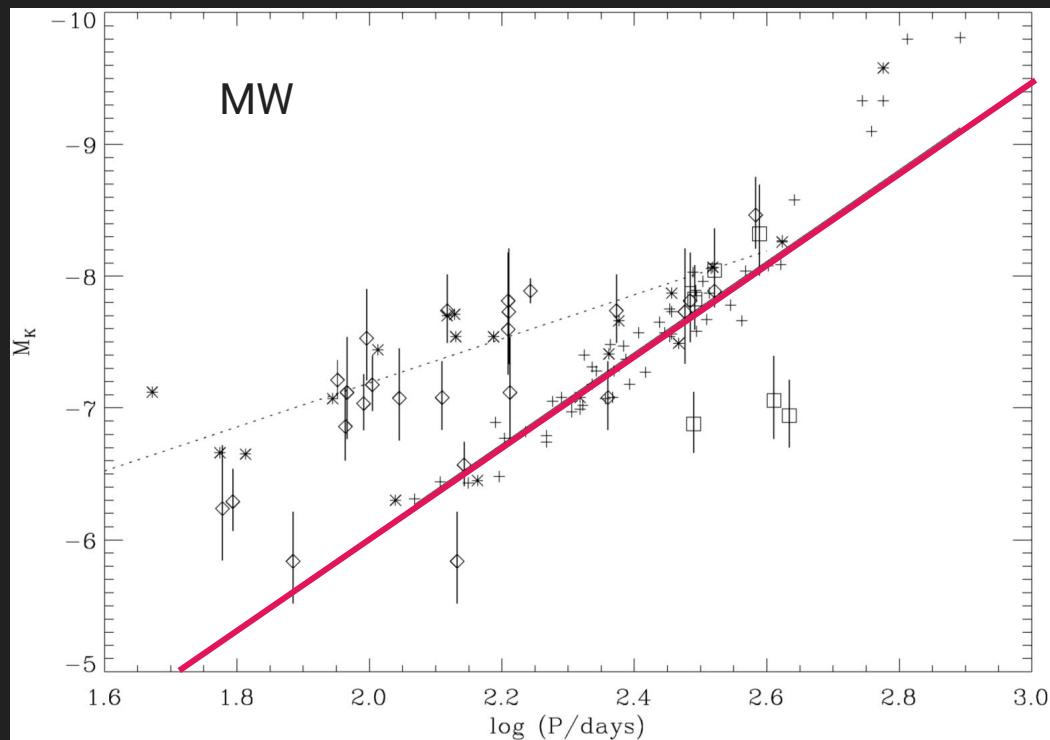
[Feast 1984]

# Period-Luminosity relations - SRa variables

Evidence of a second P-L relation formed by semiregular variables



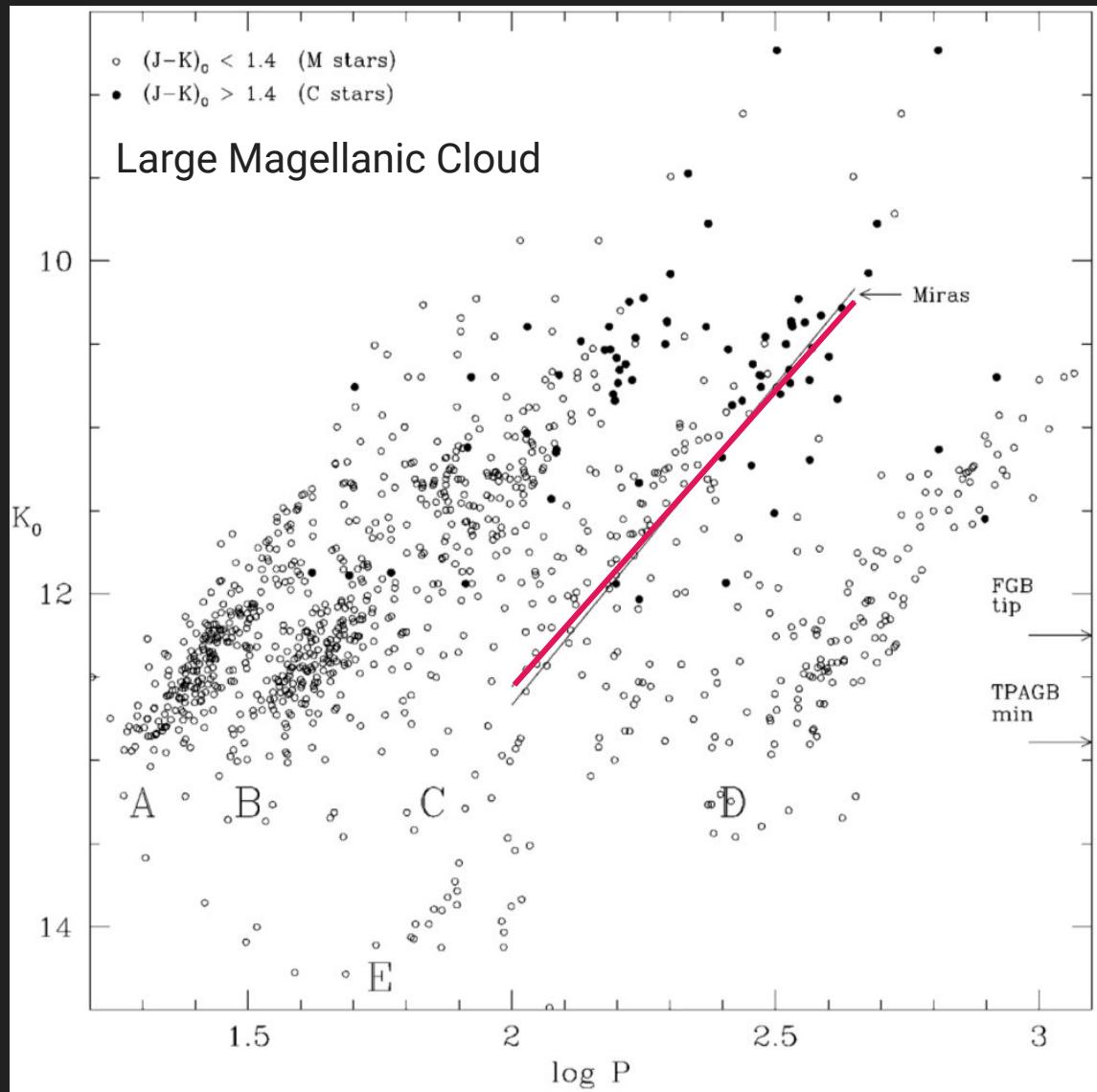
[Wood+Sebo 1996]



[Bedding+Zijlstra 1998]

Additional P-L relation  $\rightarrow$  constraint on the pulsation mode of Mira and SR variables.

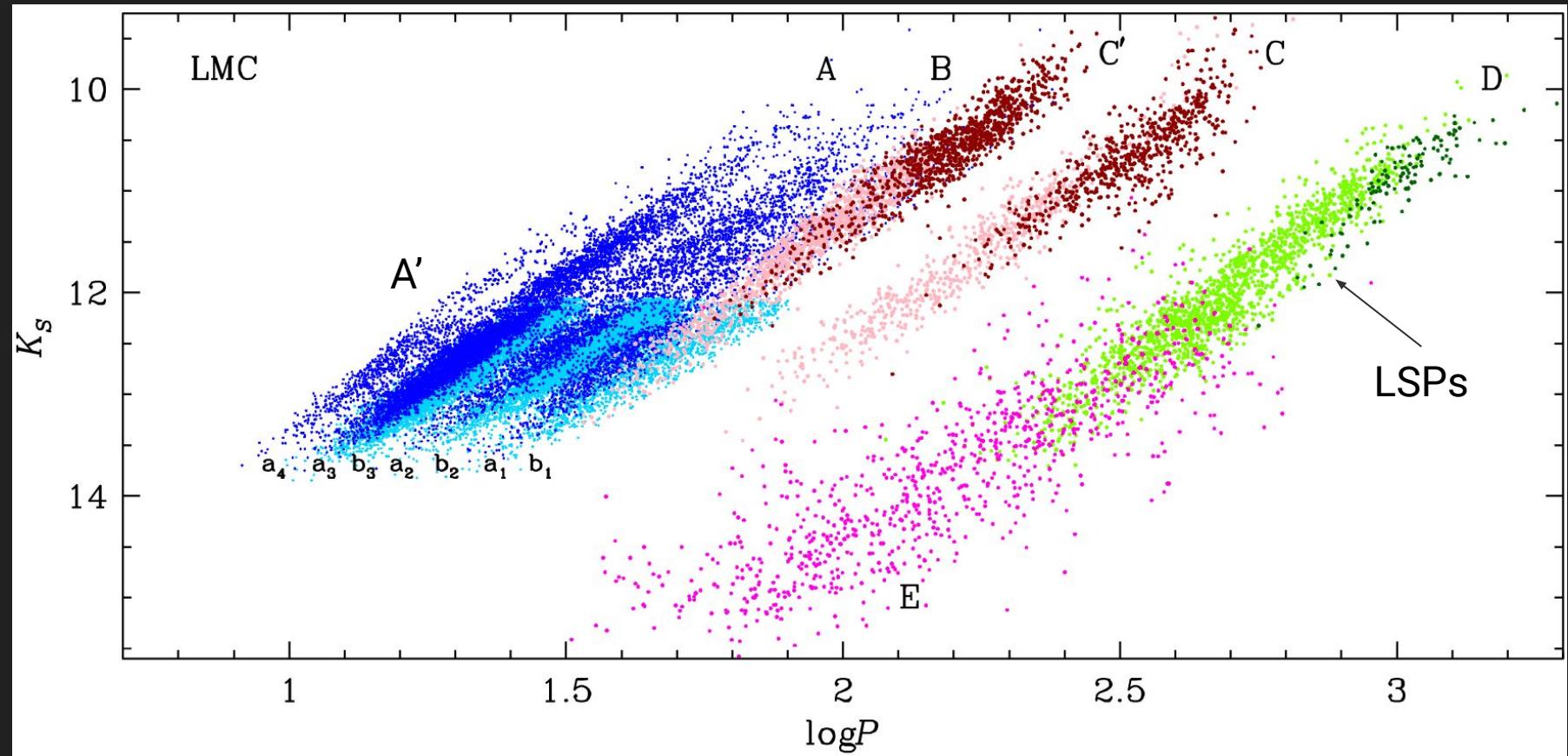
# Period-Luminosity relations - SR variables



MACHO program:  
discovery of multiple P-L  
relations of SR variables in the  
Large Magellanic Cloud

- multi-periodic LPVs  
(constraint on pulsation modes)
- overtone-mode sequences
- P-L relation of long secondary periods (LSPs)
- P-L relation of ellipsoidal variables

# Period-Luminosity relations



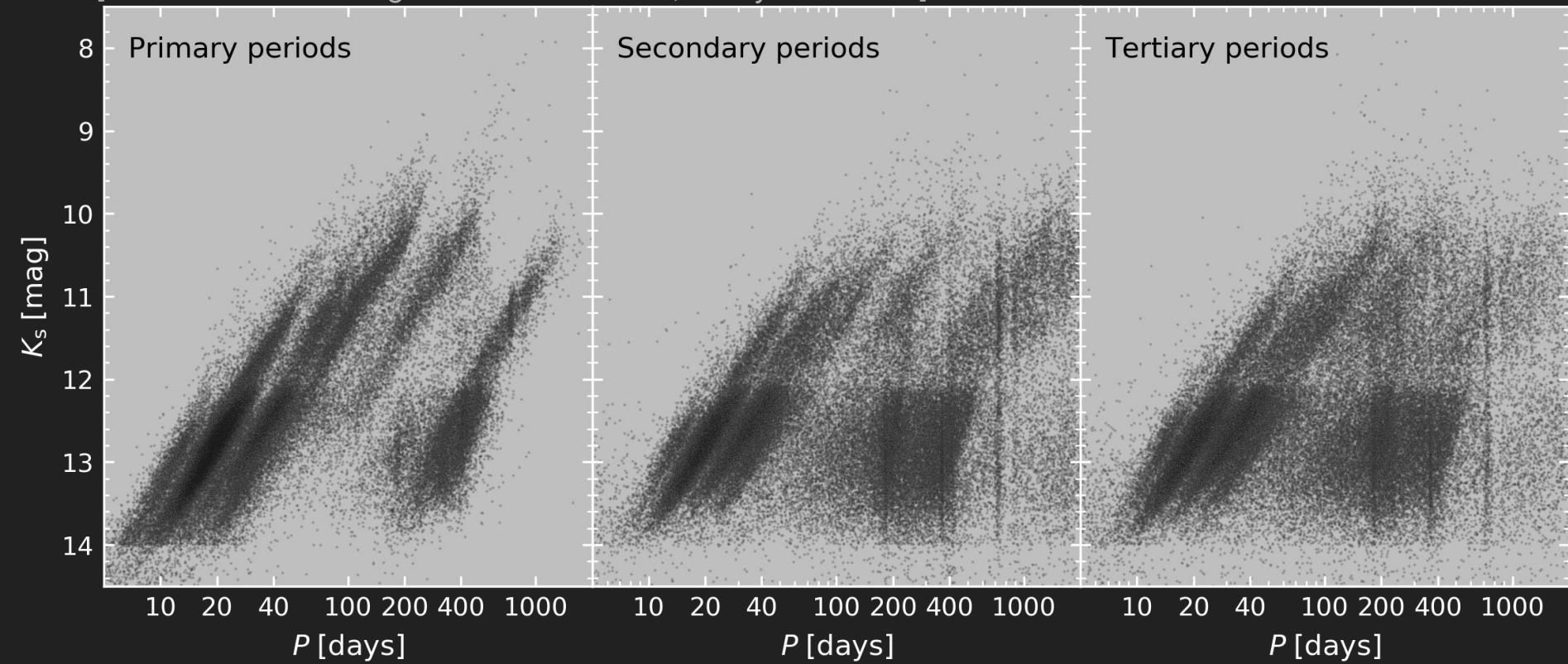
[Soszynski+ 2007]

OGLE program: faint, short-period sequences and fine structure

- secondary sequences of RGB stars
- period ratios and introduction of OSARG type

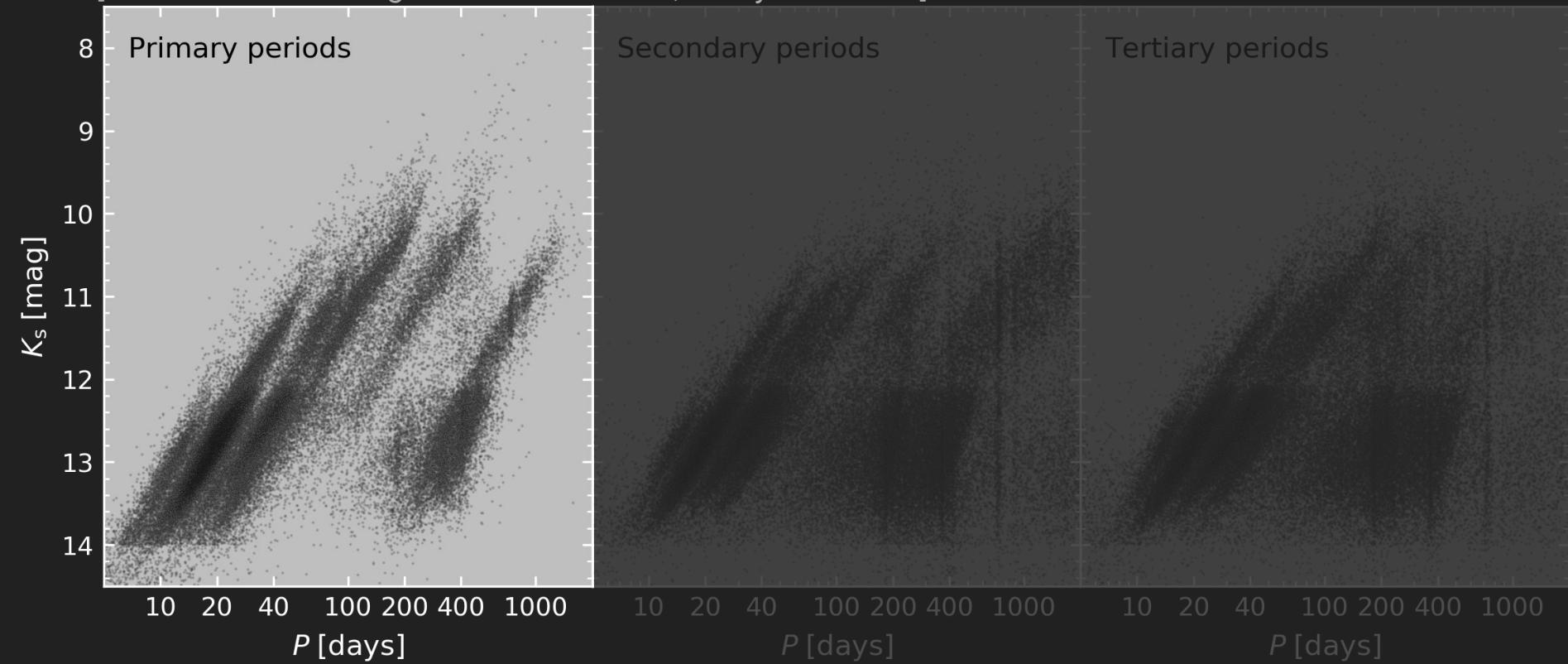
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[data: OGLE-III Catalog of LPVs in the LMC, Soszynski+ 2009]



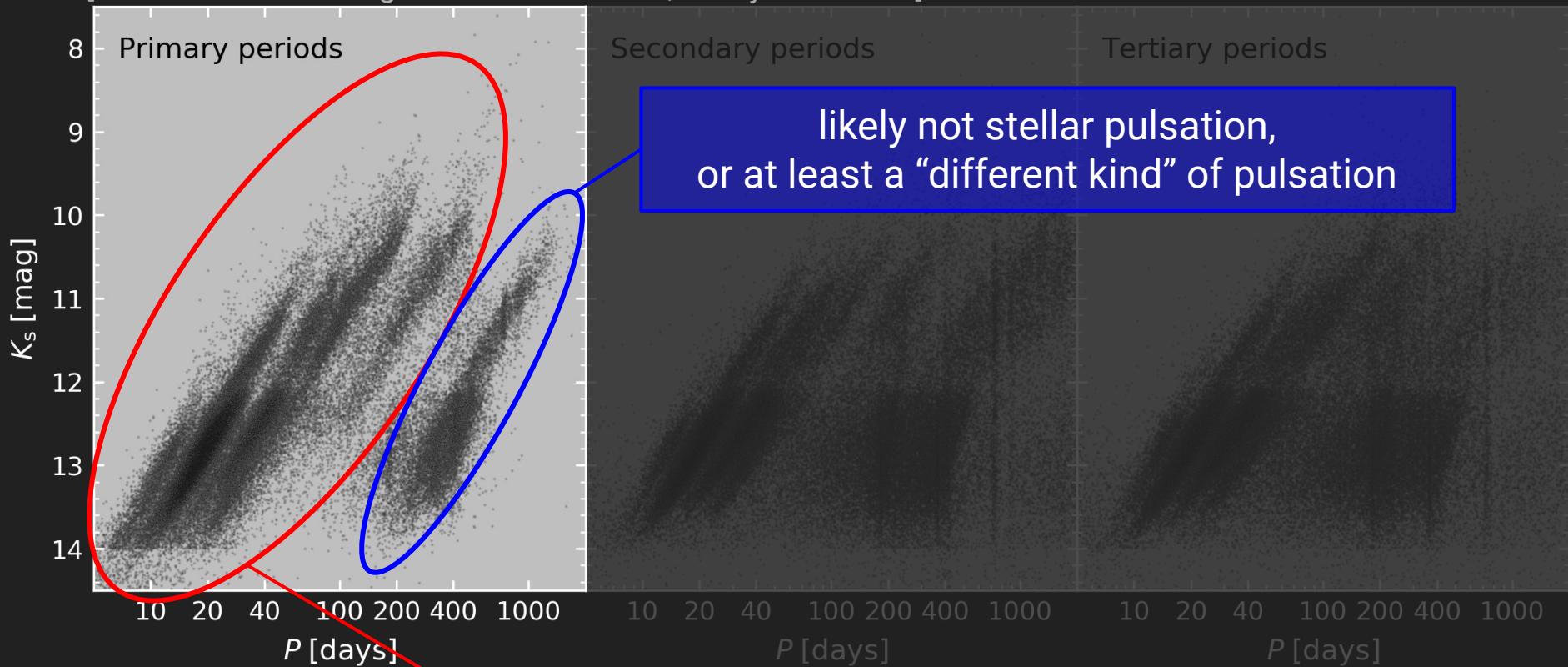
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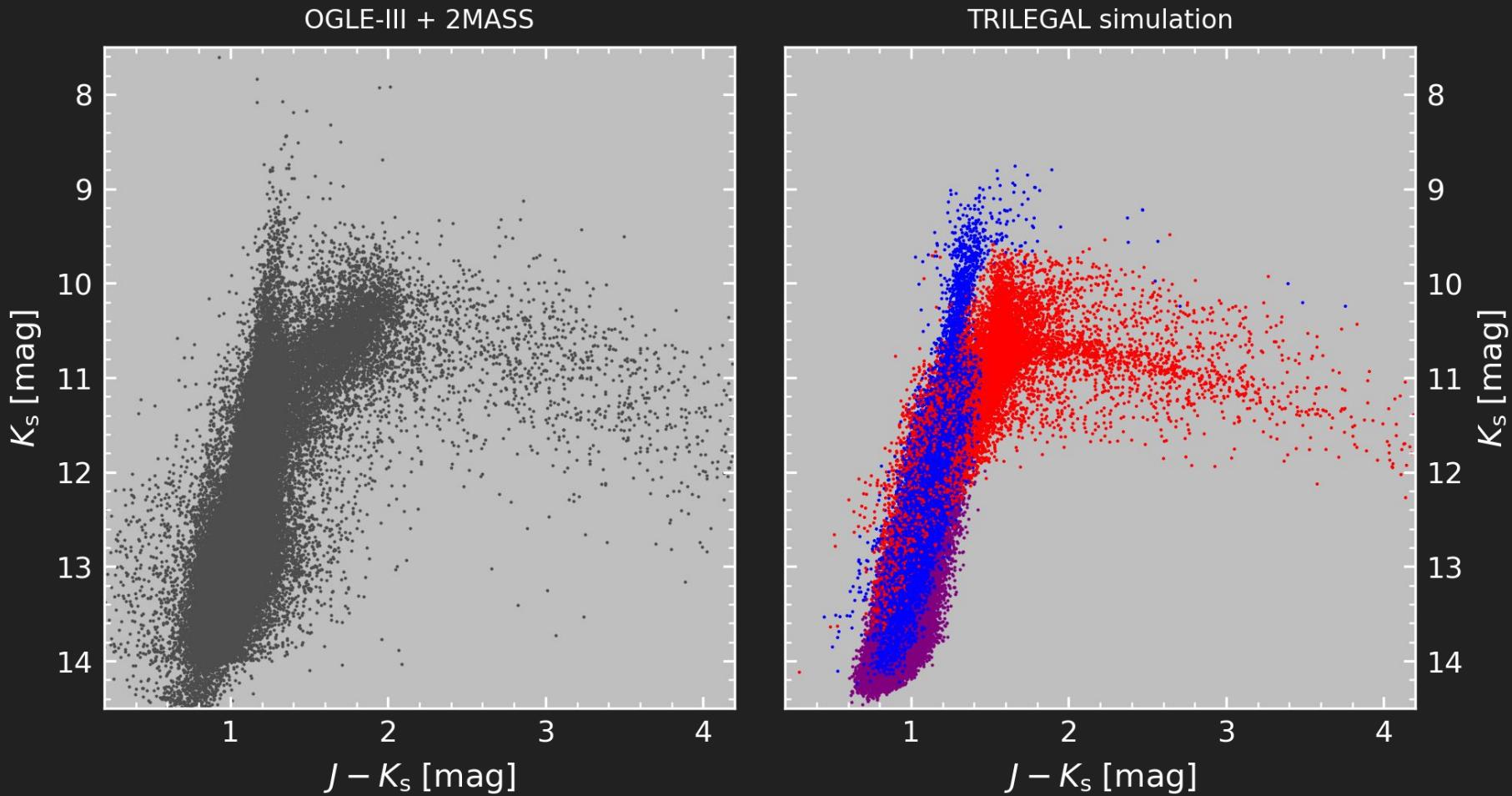


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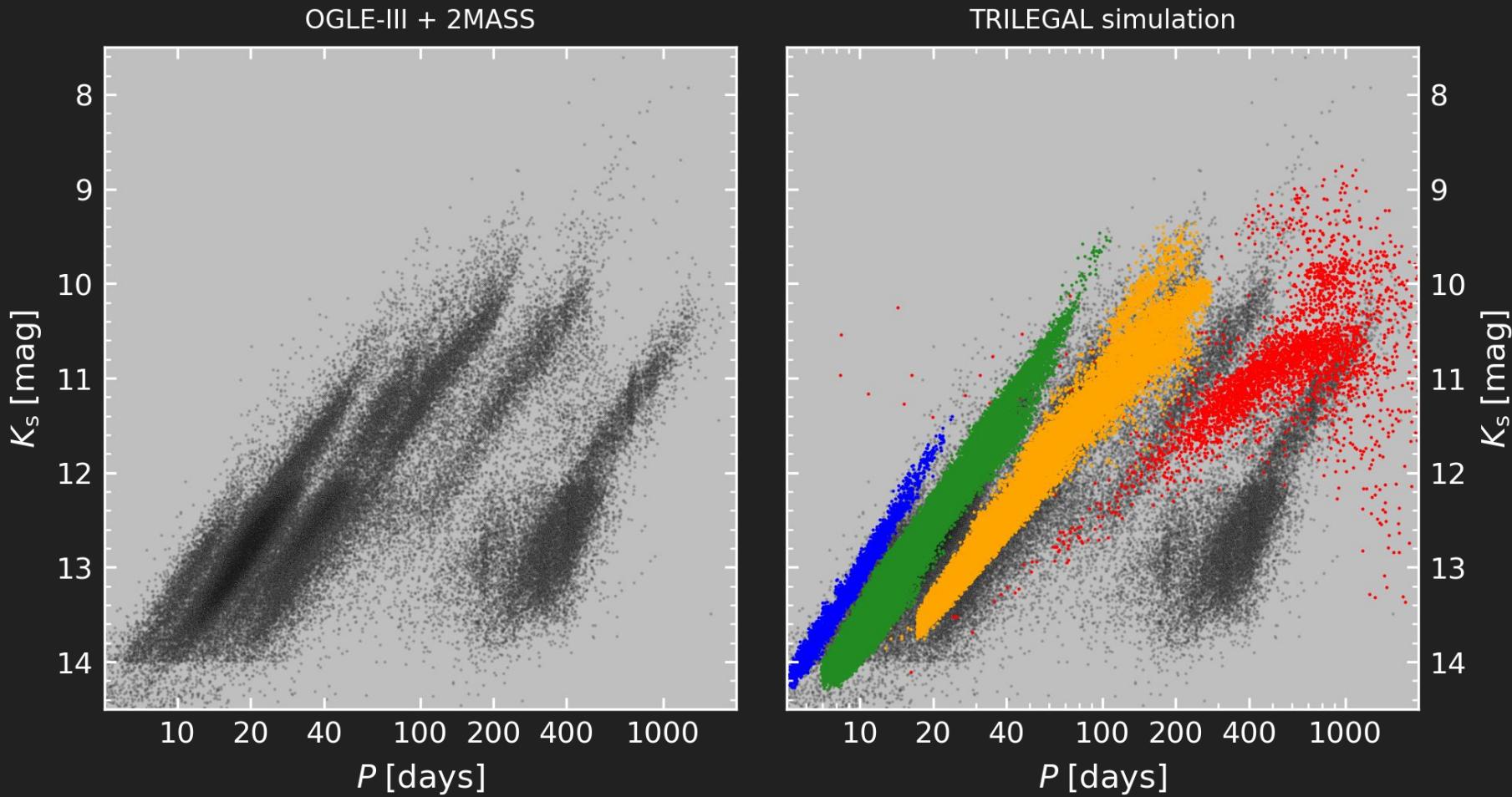


# Synthetic PL relations



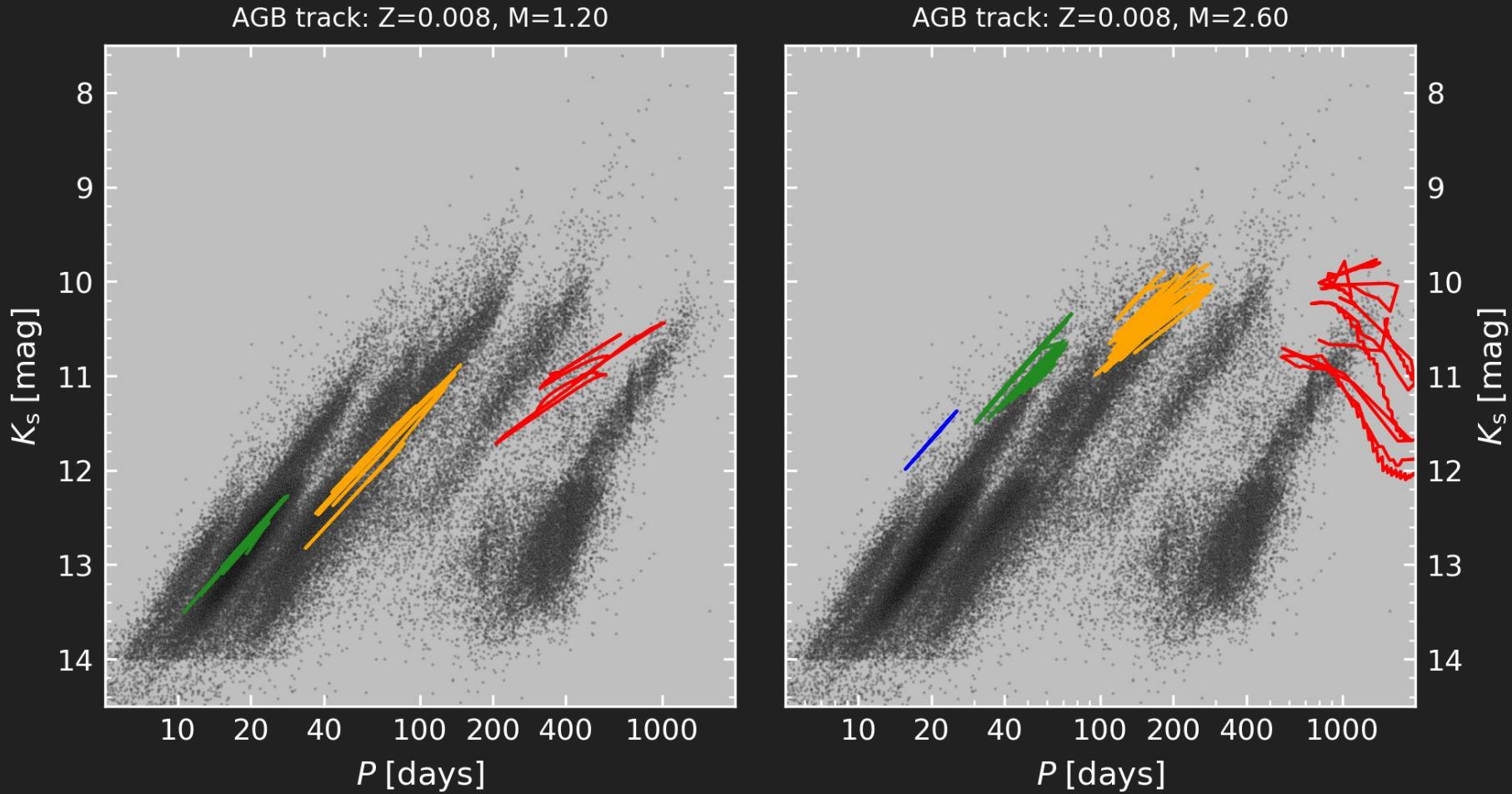
[models: Pastorelli+ 2019, Trabucchi+ 2019]

# Synthetic PL relations



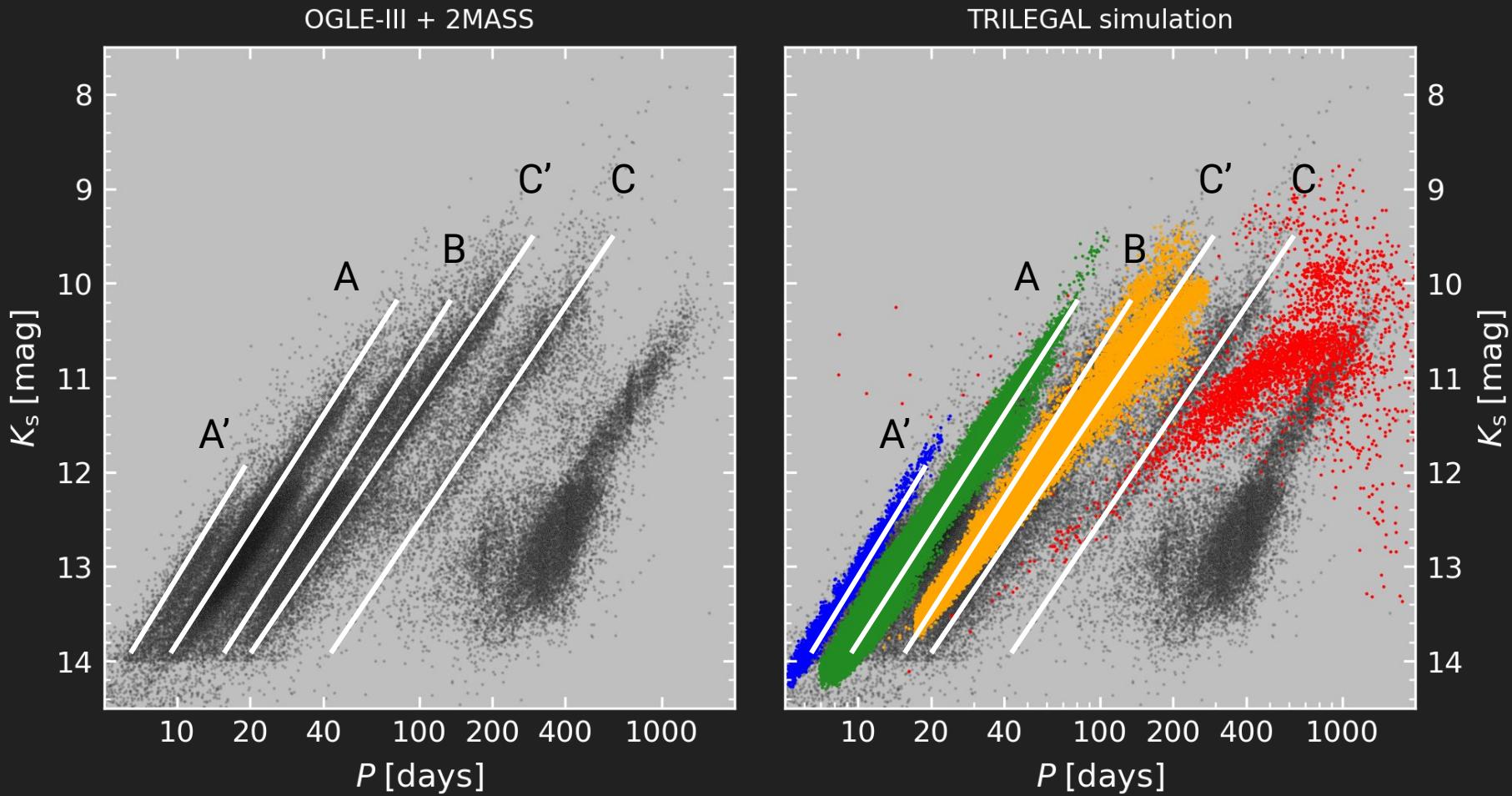
[models: Pastorelli+ 2019, Trabucchi+ 2019]

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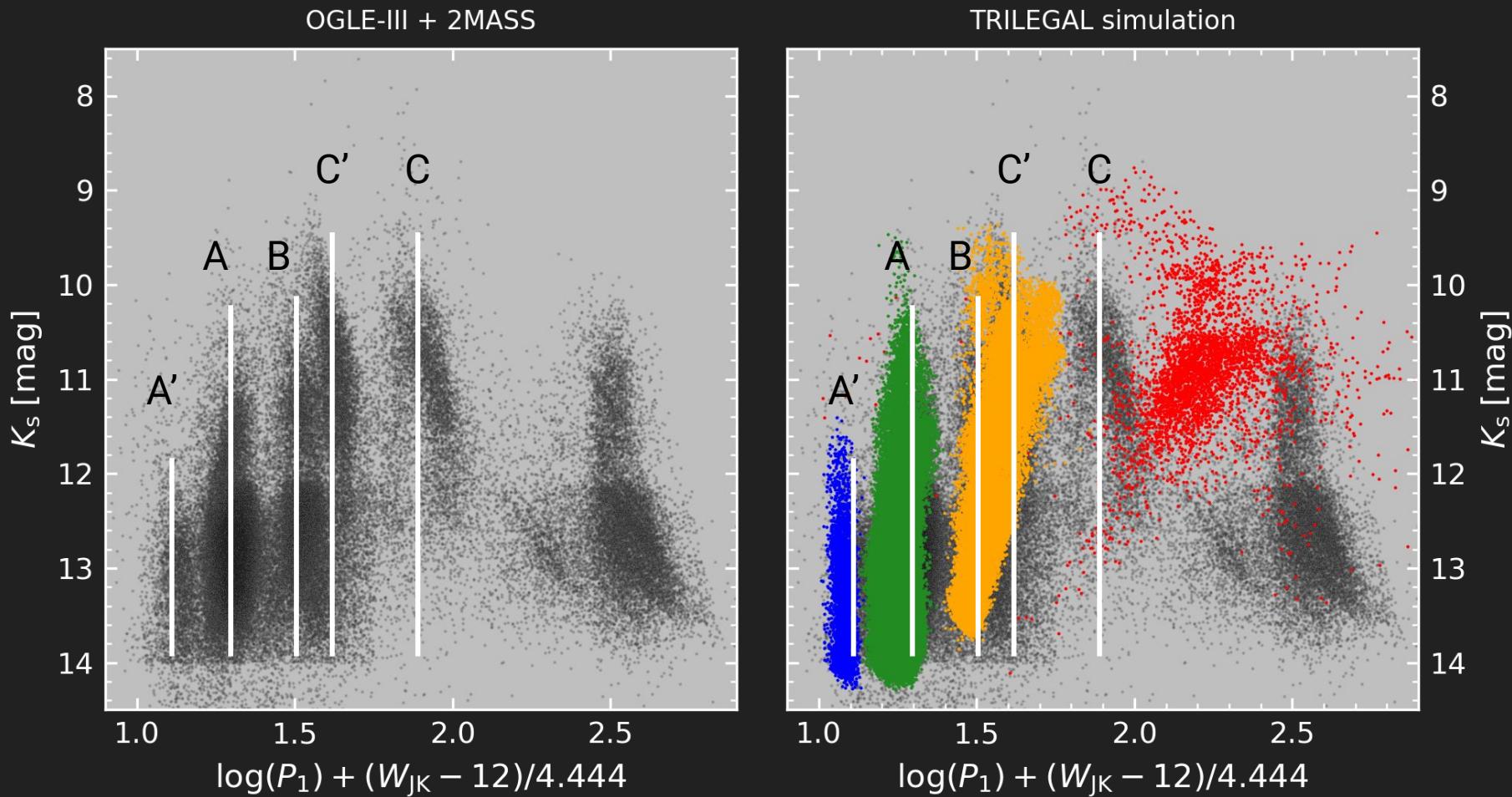
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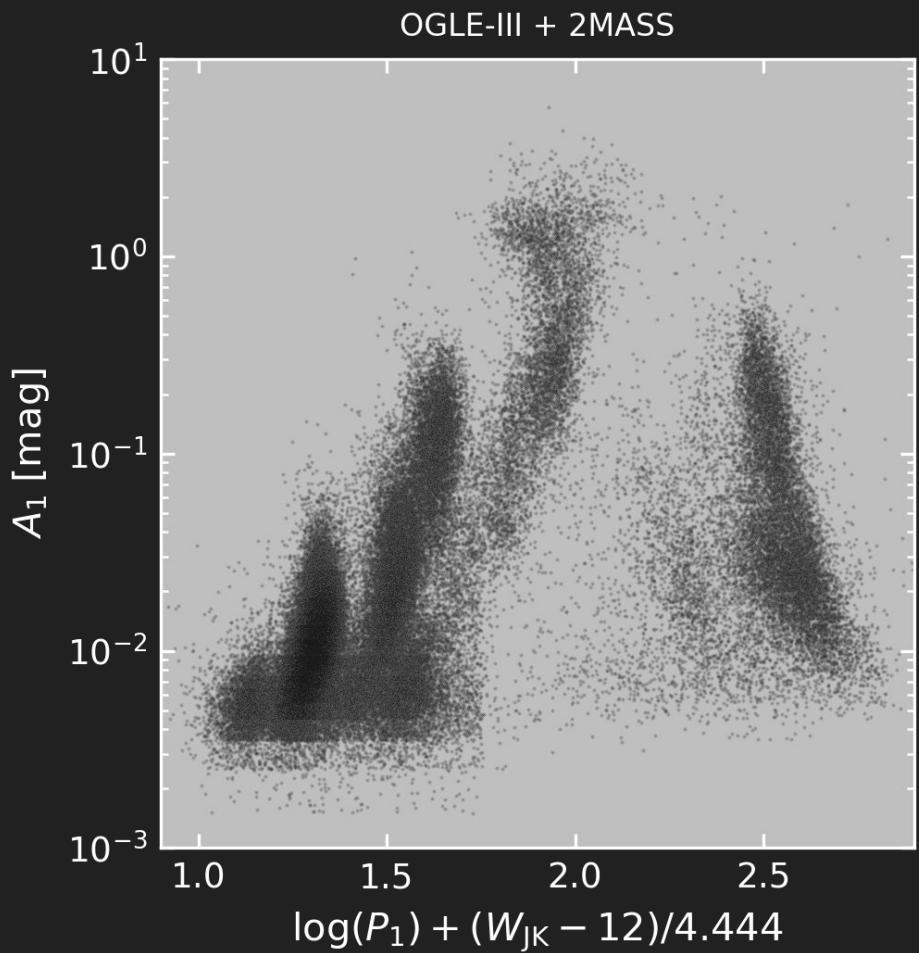
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[models: Pastorelli+ 2019, Trabucchi+ 2019]

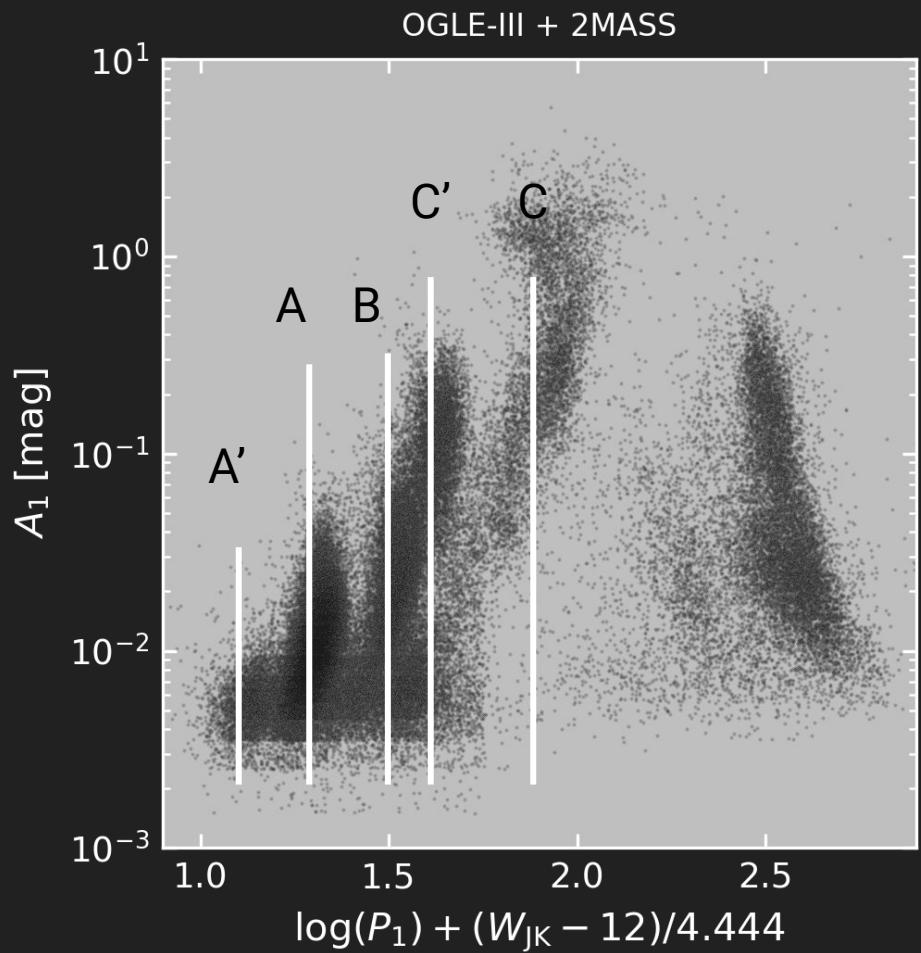
# Synthetic PL relations

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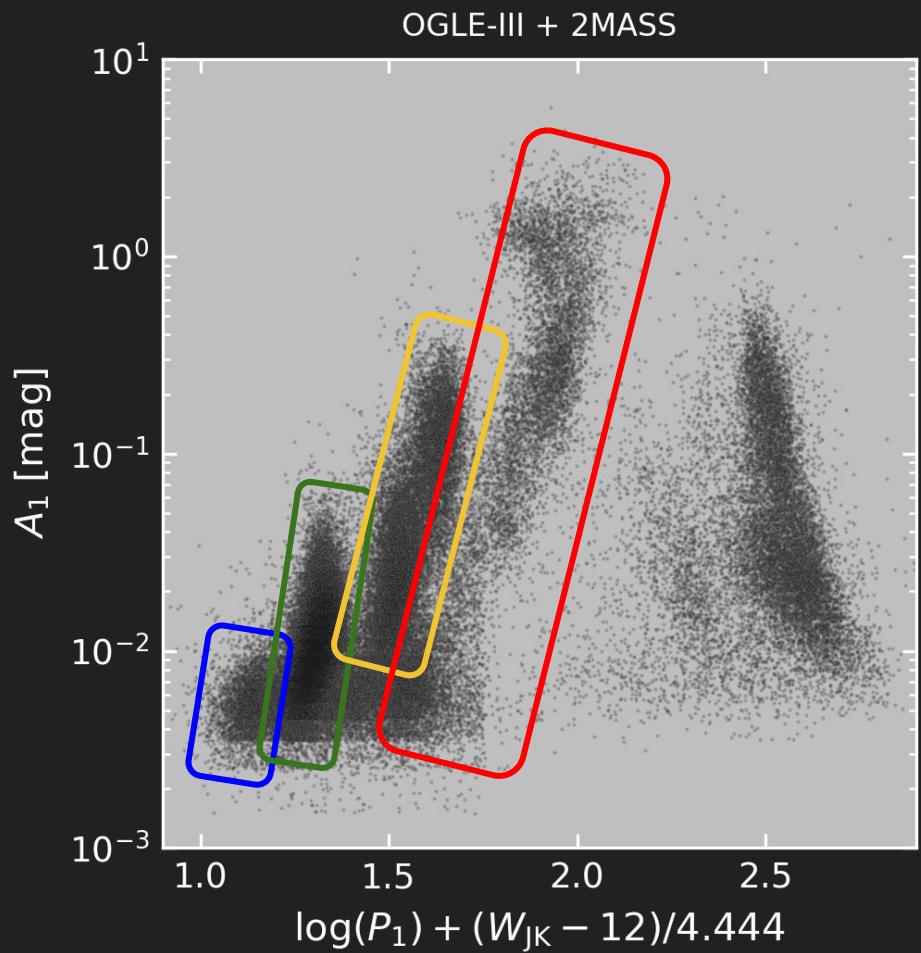
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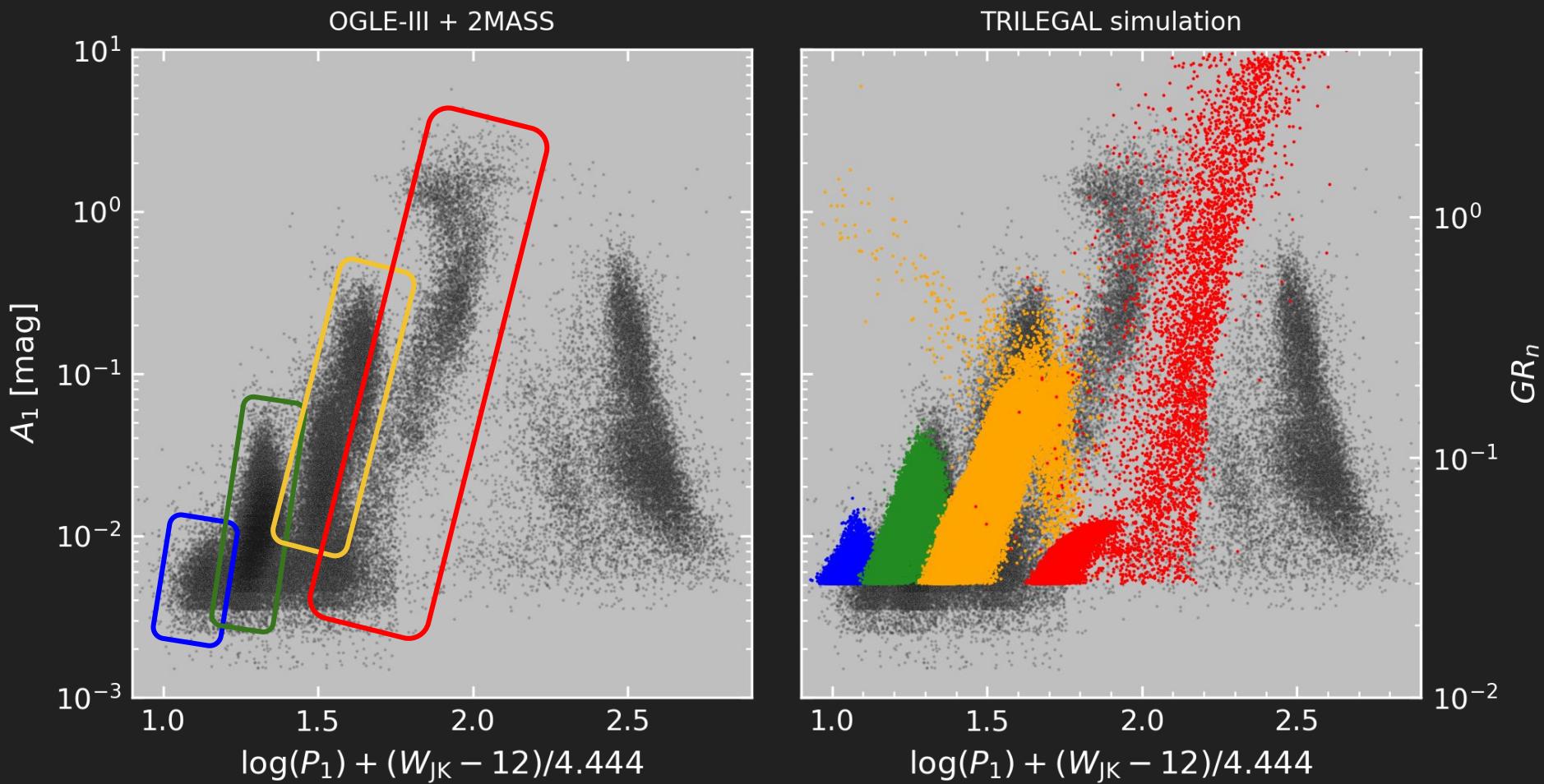
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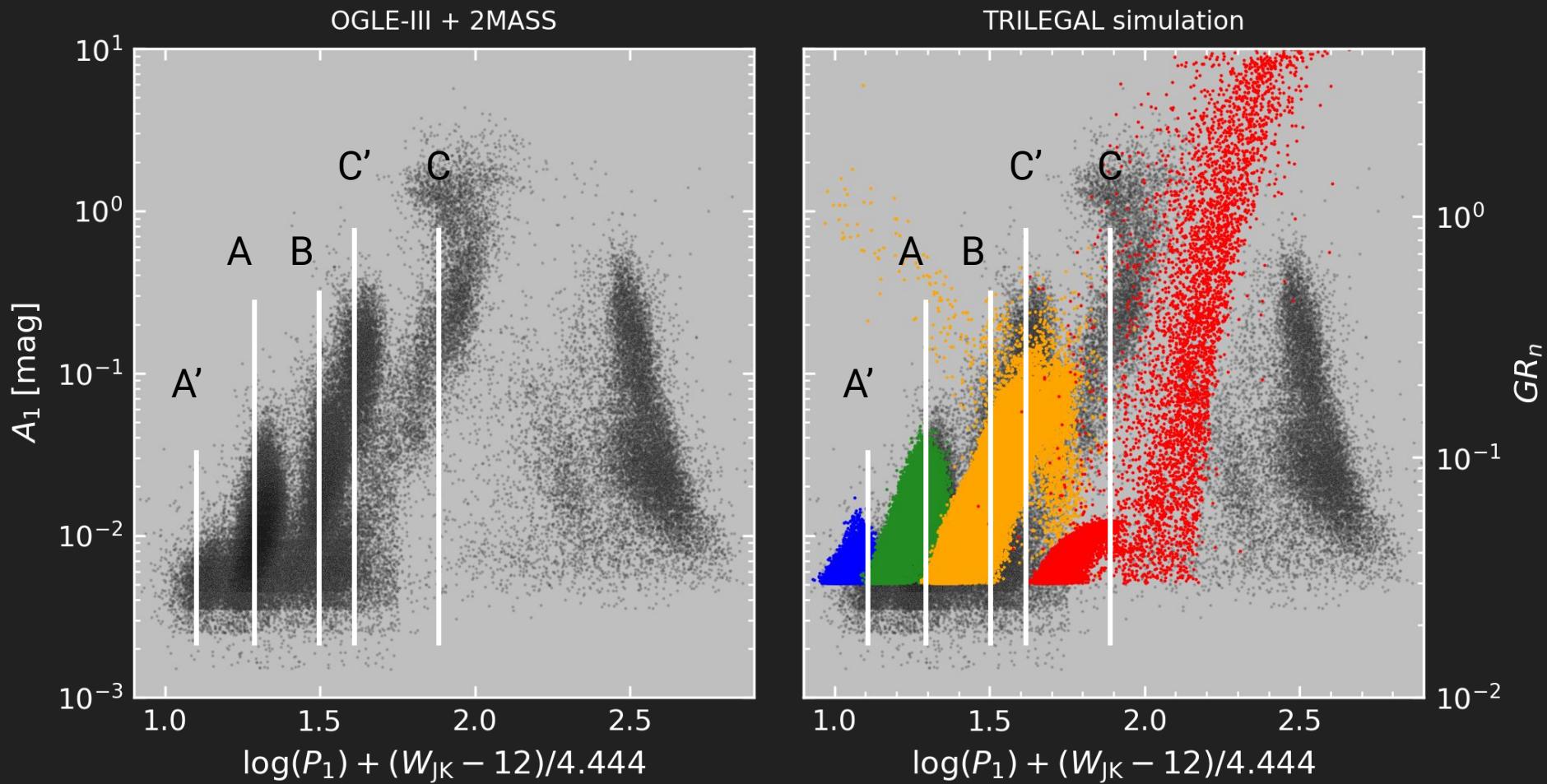
[models: Pastorelli+ 2019, Trabucchi+ 2019]

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[models: Pastorelli+ 2019, Trabucchi+ 2019]

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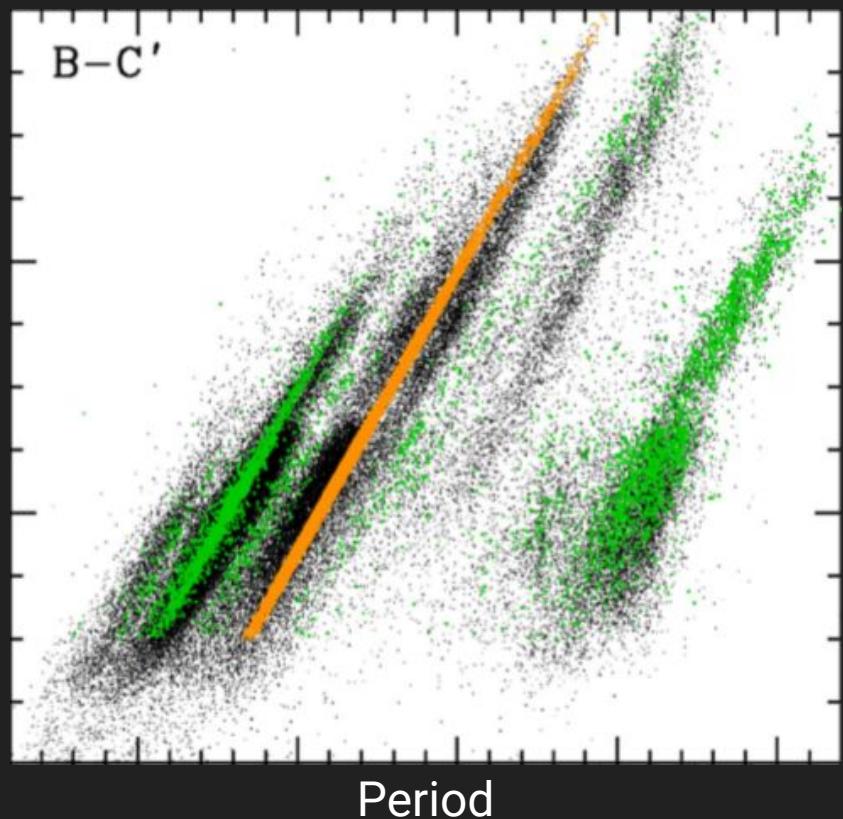
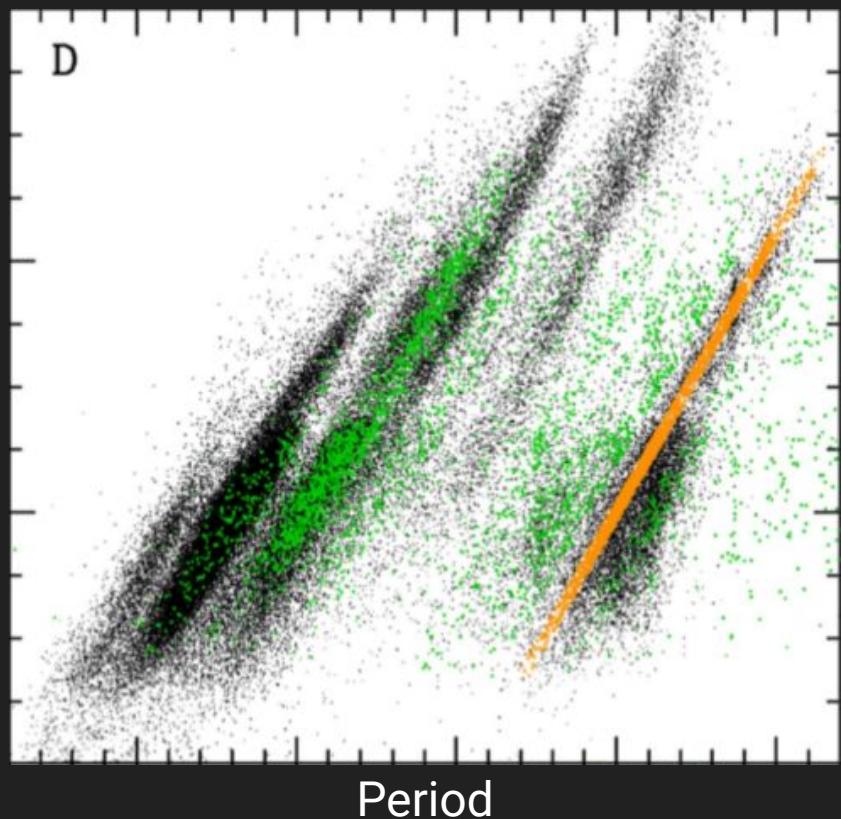


[models: Pastorelli+ 2019, Trabucchi+ 2019]

# Sequences B and C'

Stars with a **primary period** on seq. D  
usually have a **secondary (tertiary)**  
**period between** seq. B and C'

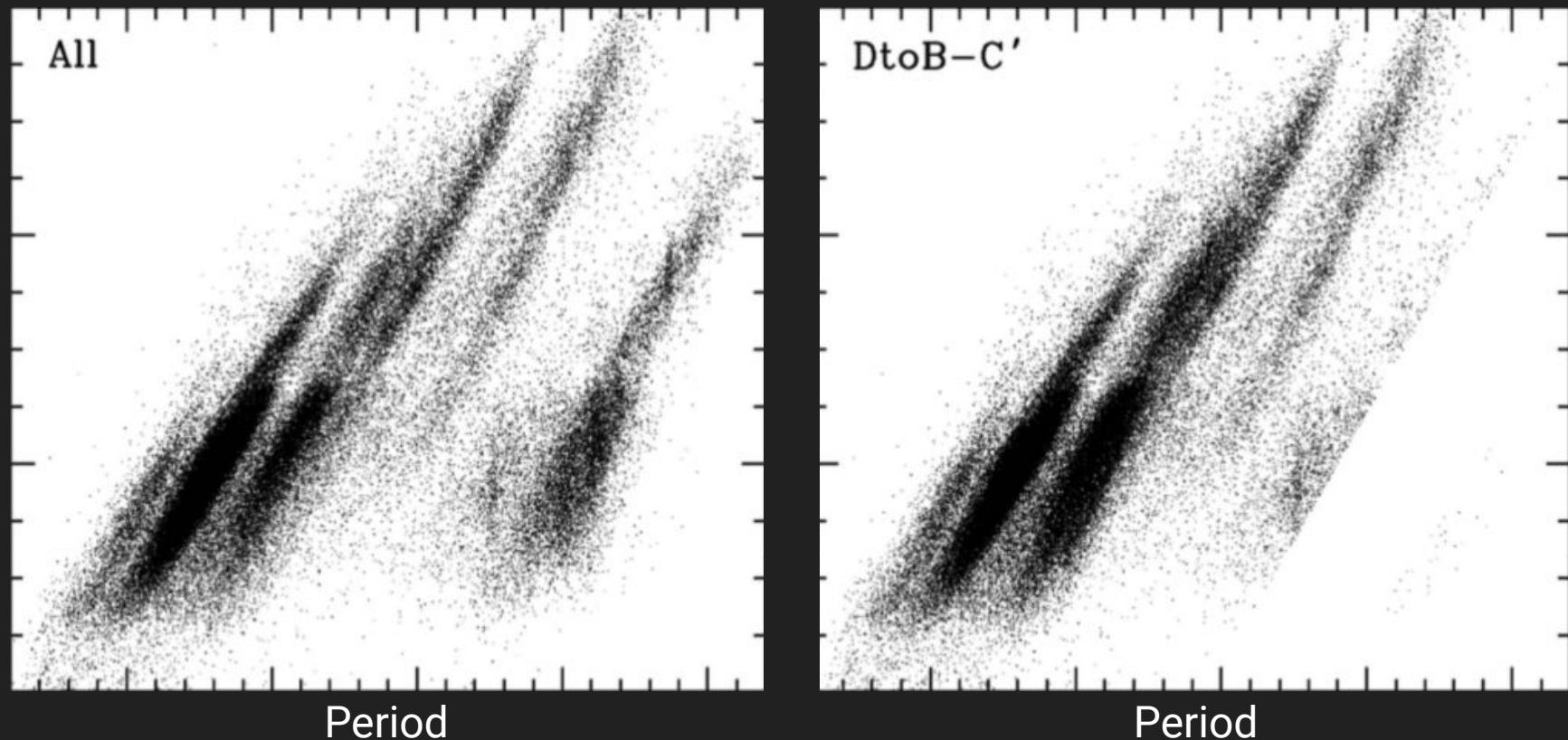
Stars with a **secondary (tertiary) period**  
**between** seq. B and C' usually have a  
**their primary period between** on seq. D



[Trabucchi 2017]

# Sequences B and C'

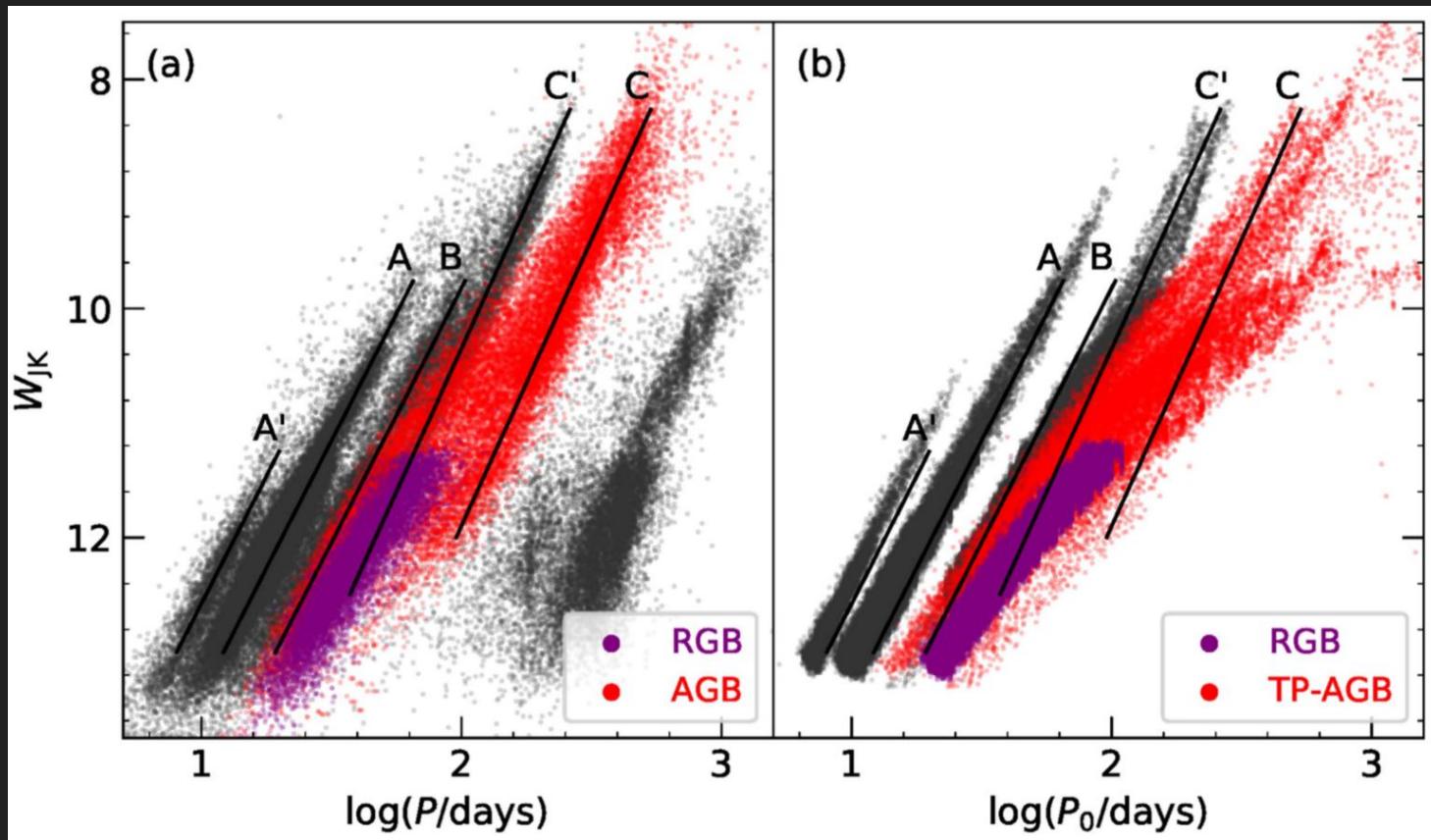
The classification into primary, secondary, and tertiary periods is based on amplitudes.  
If LSPs are excluded, there is no evident gap between sequences B and C'.  
It is an observational bias.



[Trabucchi 2017]

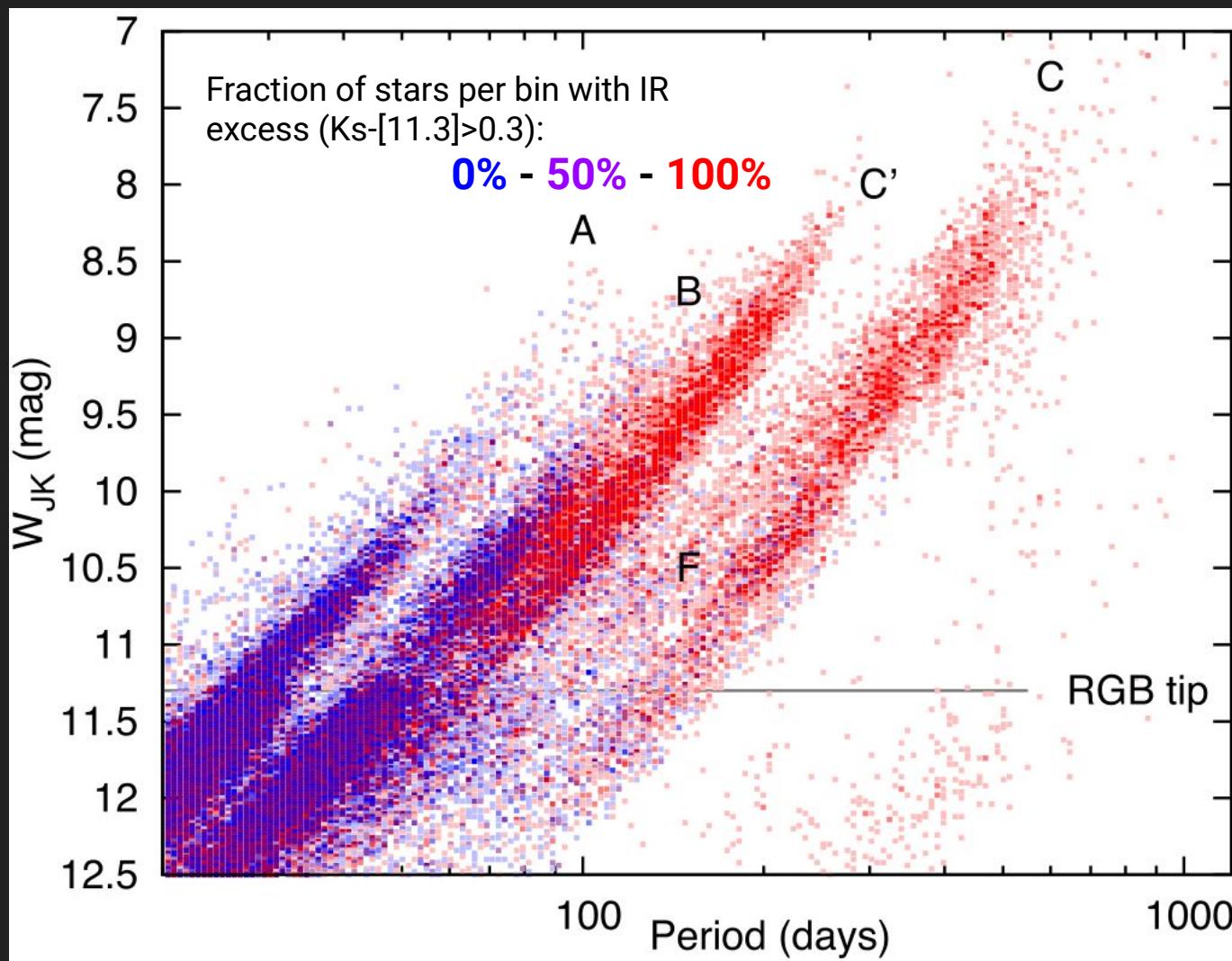
# Complexity in the PL diagram

The interpretation of the PL relations is not a straightforward as we thought: there is no one-to-one correspondence between PL relations and pulsation modes



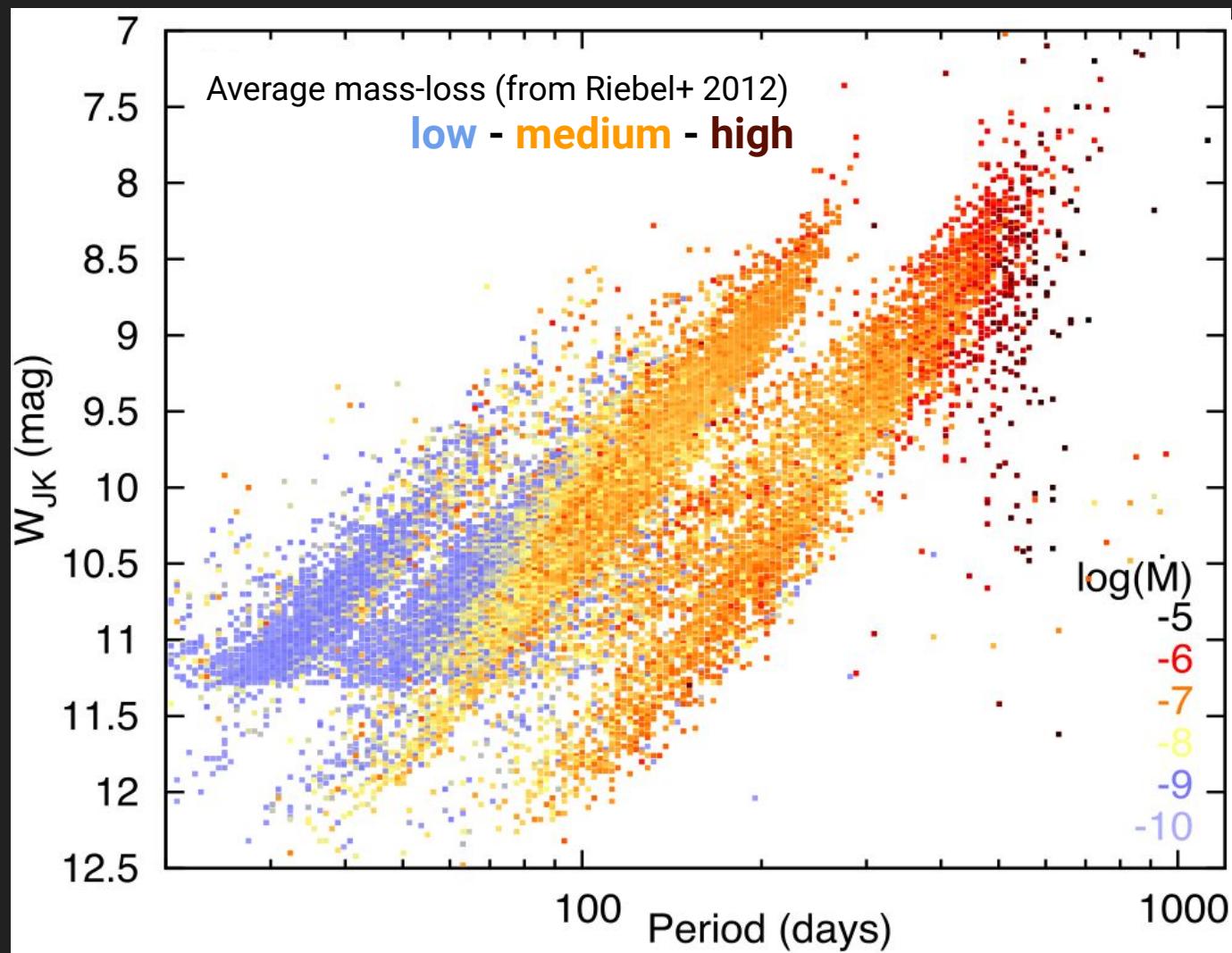
[Trabucchi+ 2017]

# Dust, mass-loss, and the PL sequences



[McDonald+Trabucchi 2019]

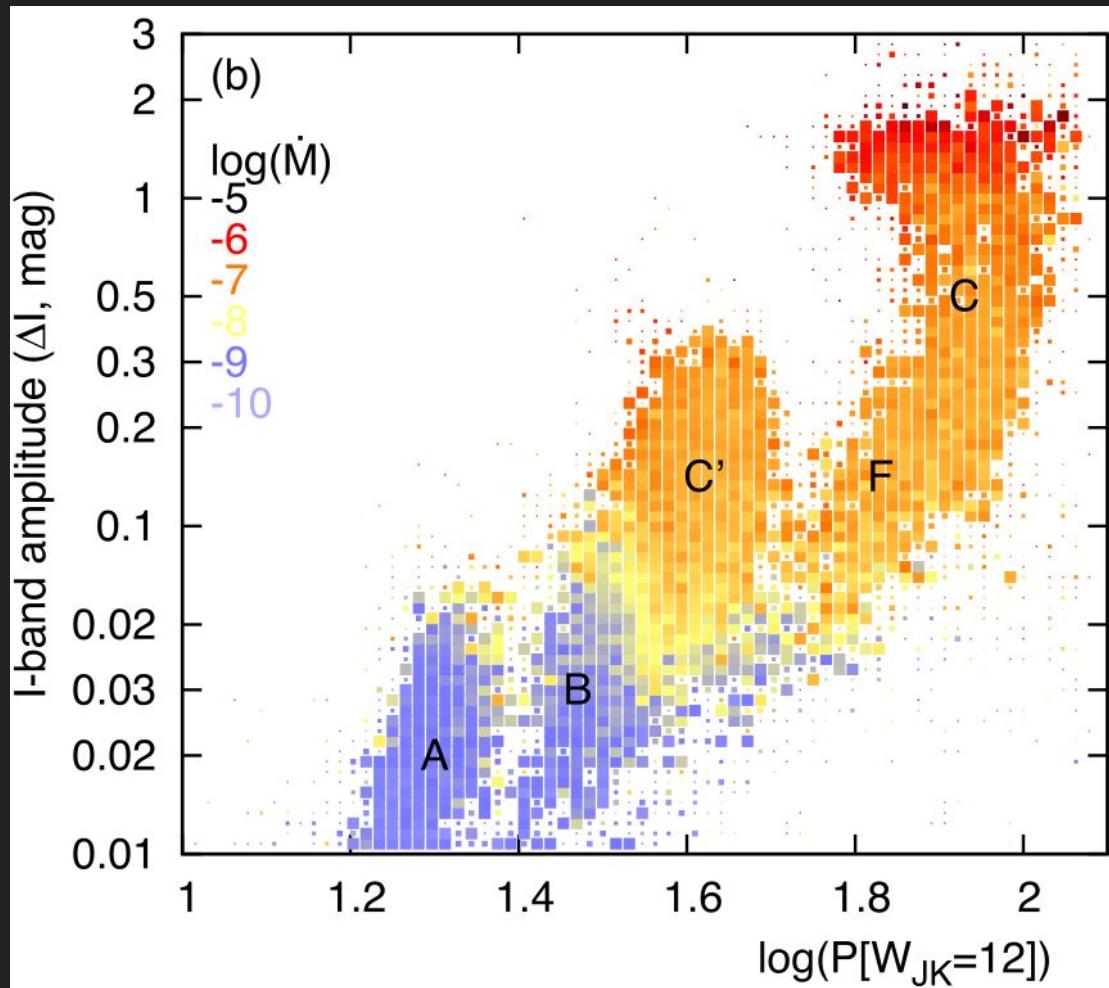
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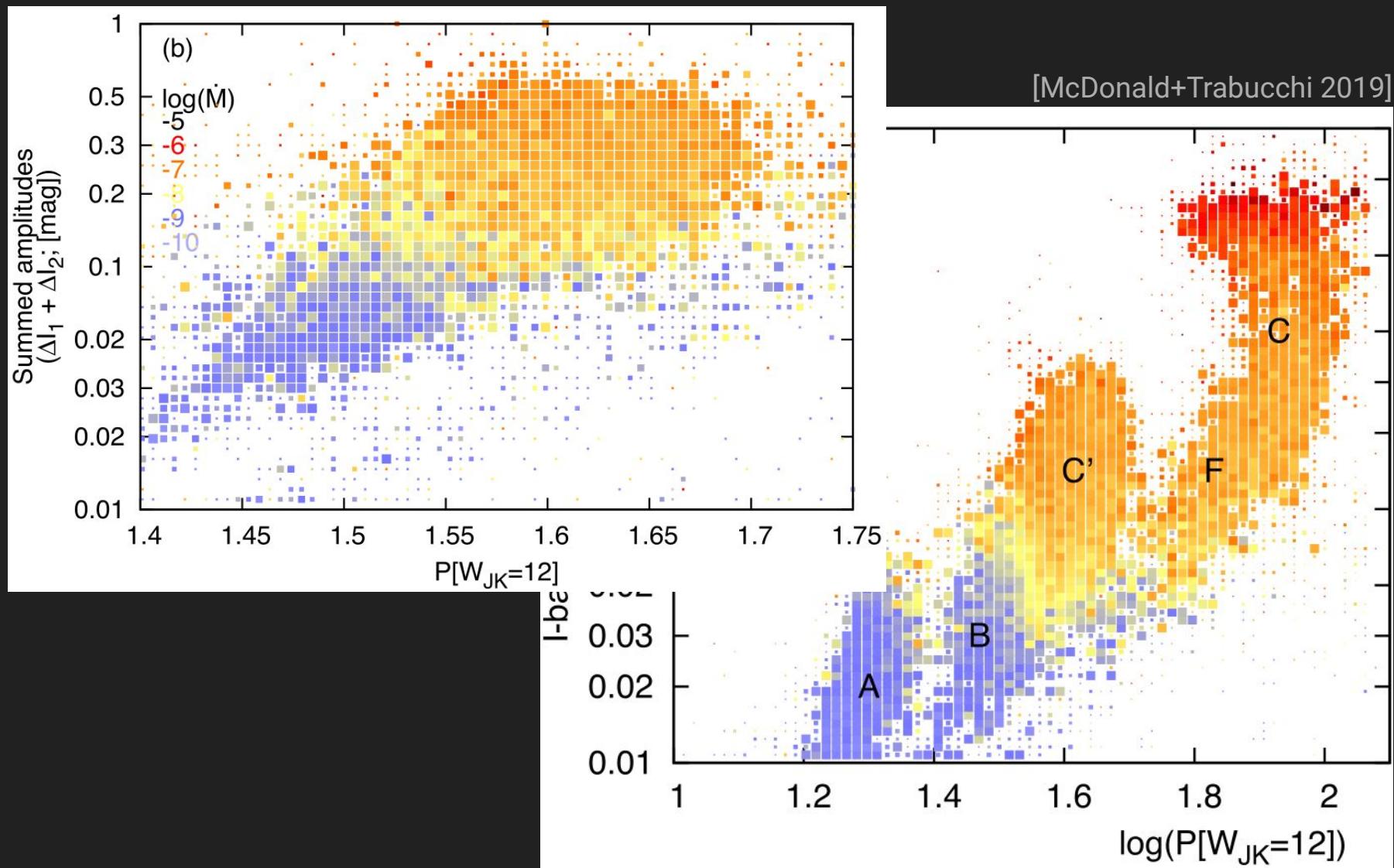
[McDonald+Trabucchi 2019]

# Dust, mass-loss, and the PL sequences

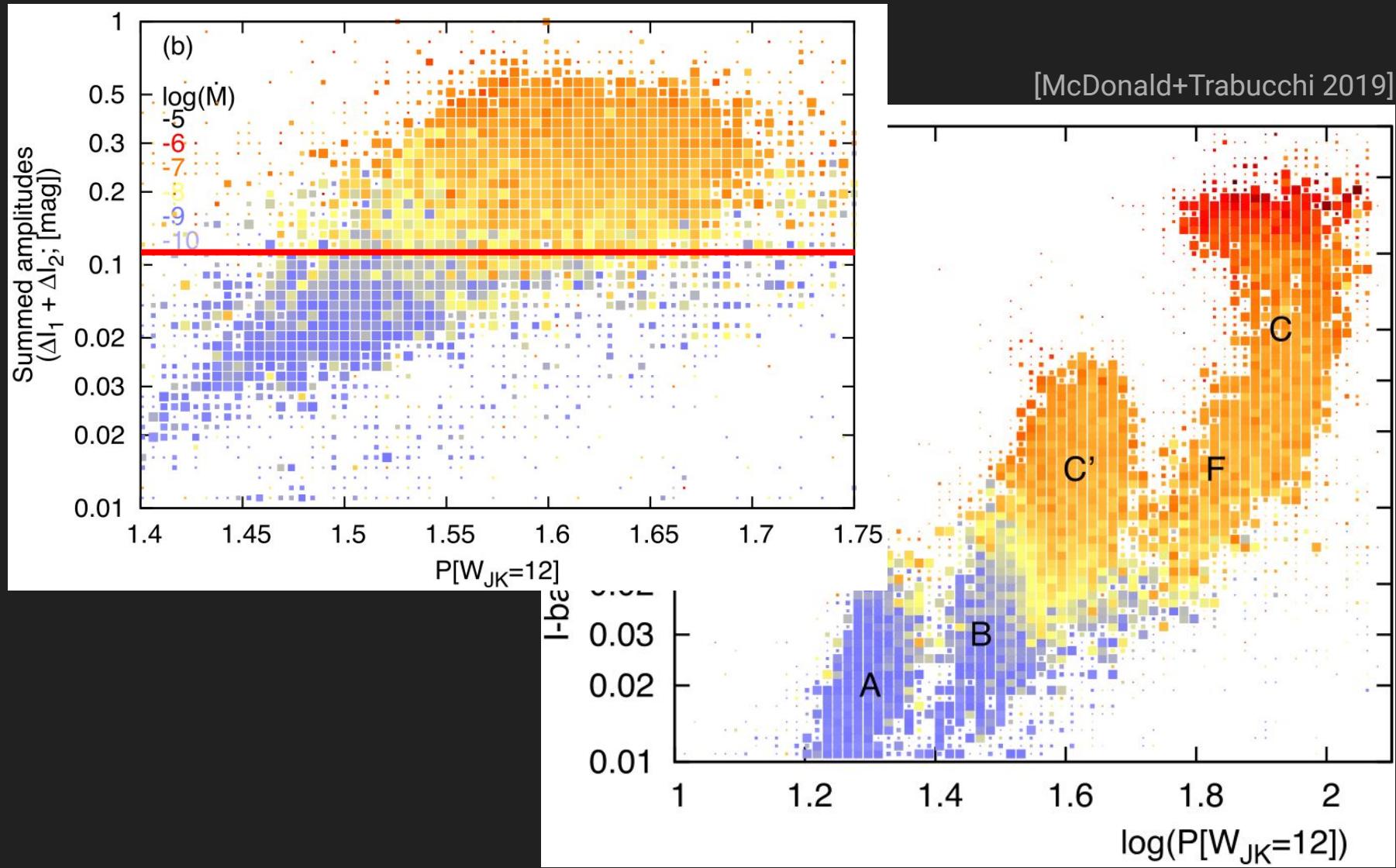
[McDonald+Trabucchi 2019]



# Dust, mass-loss, and the PL sequences

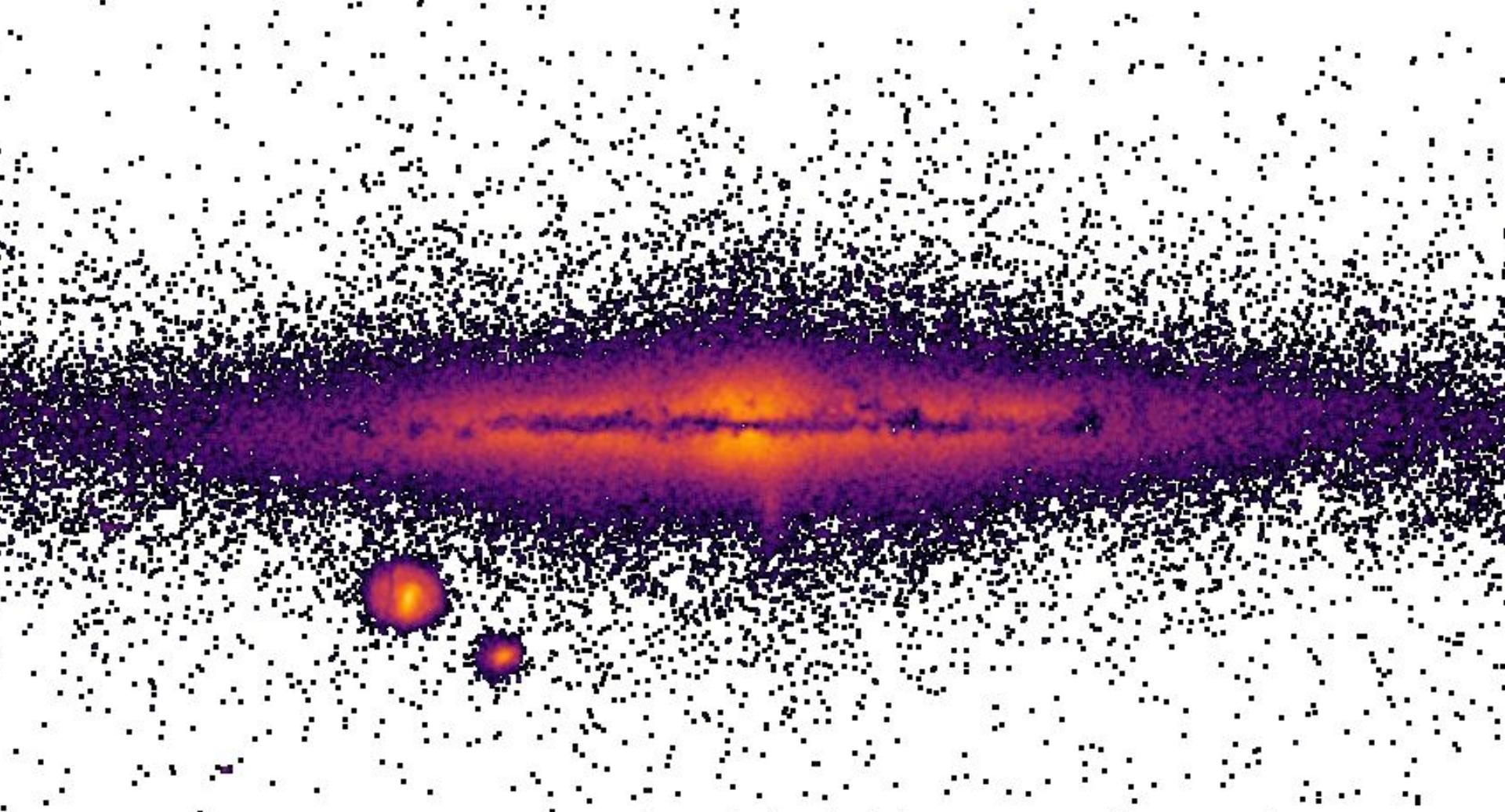


# Dust, mass-loss, and the PL sequences



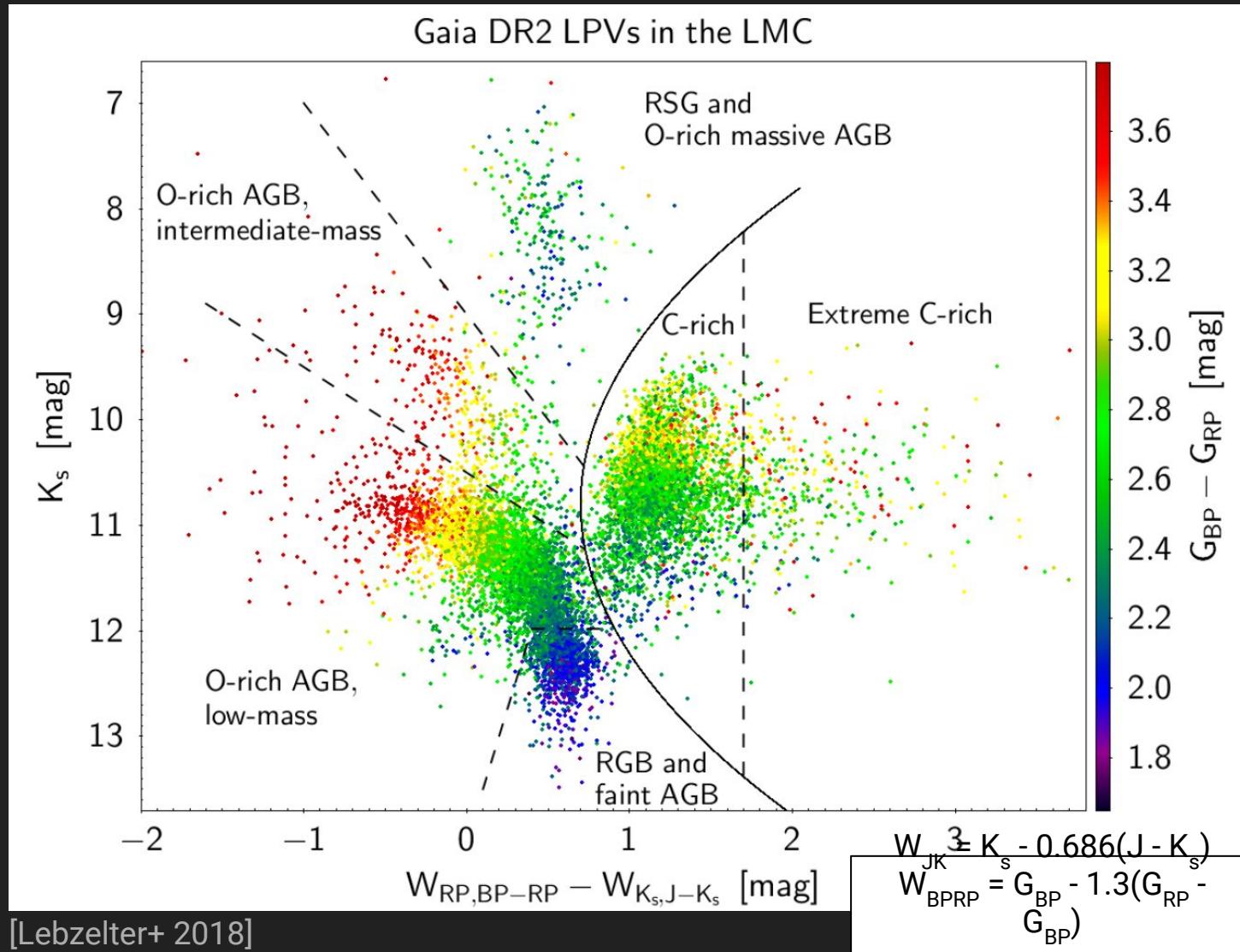
# LPVs and Gaia

Catalogue of LPV candidates from the Gaia DR2 ~150000 stars [Mowlavi+ 2018]



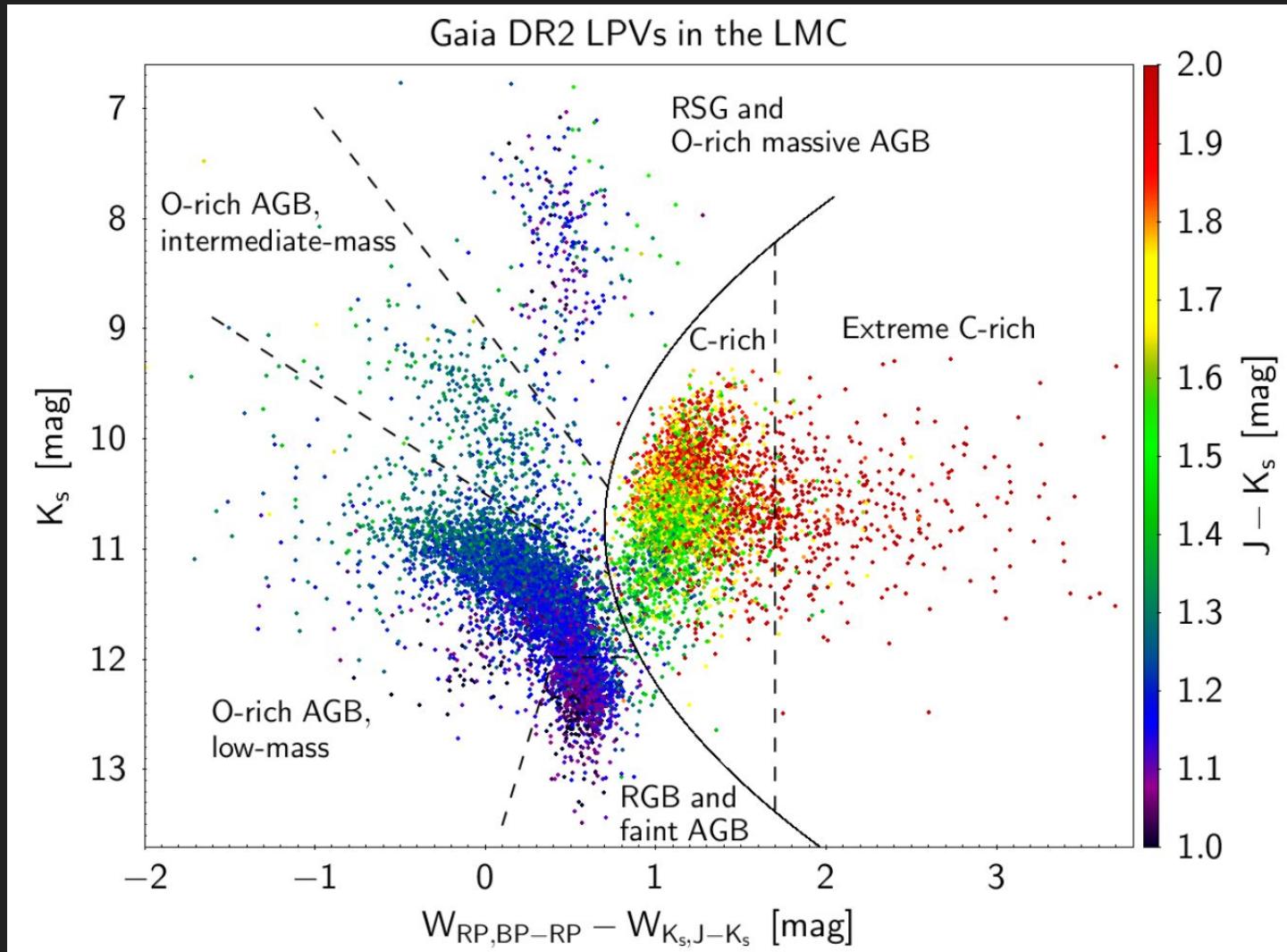
# LPVs and Gaia

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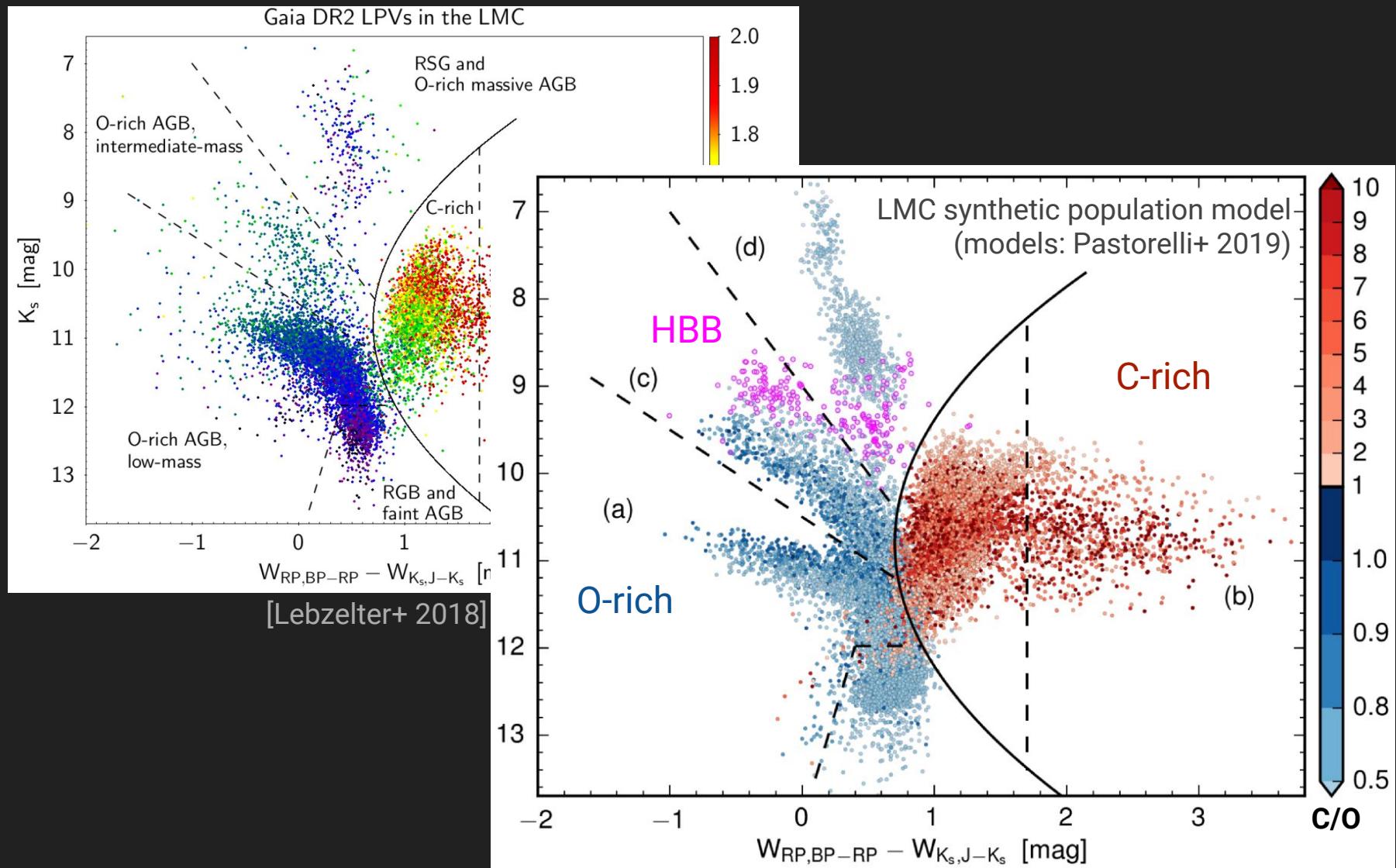
# LPVs and Gaia

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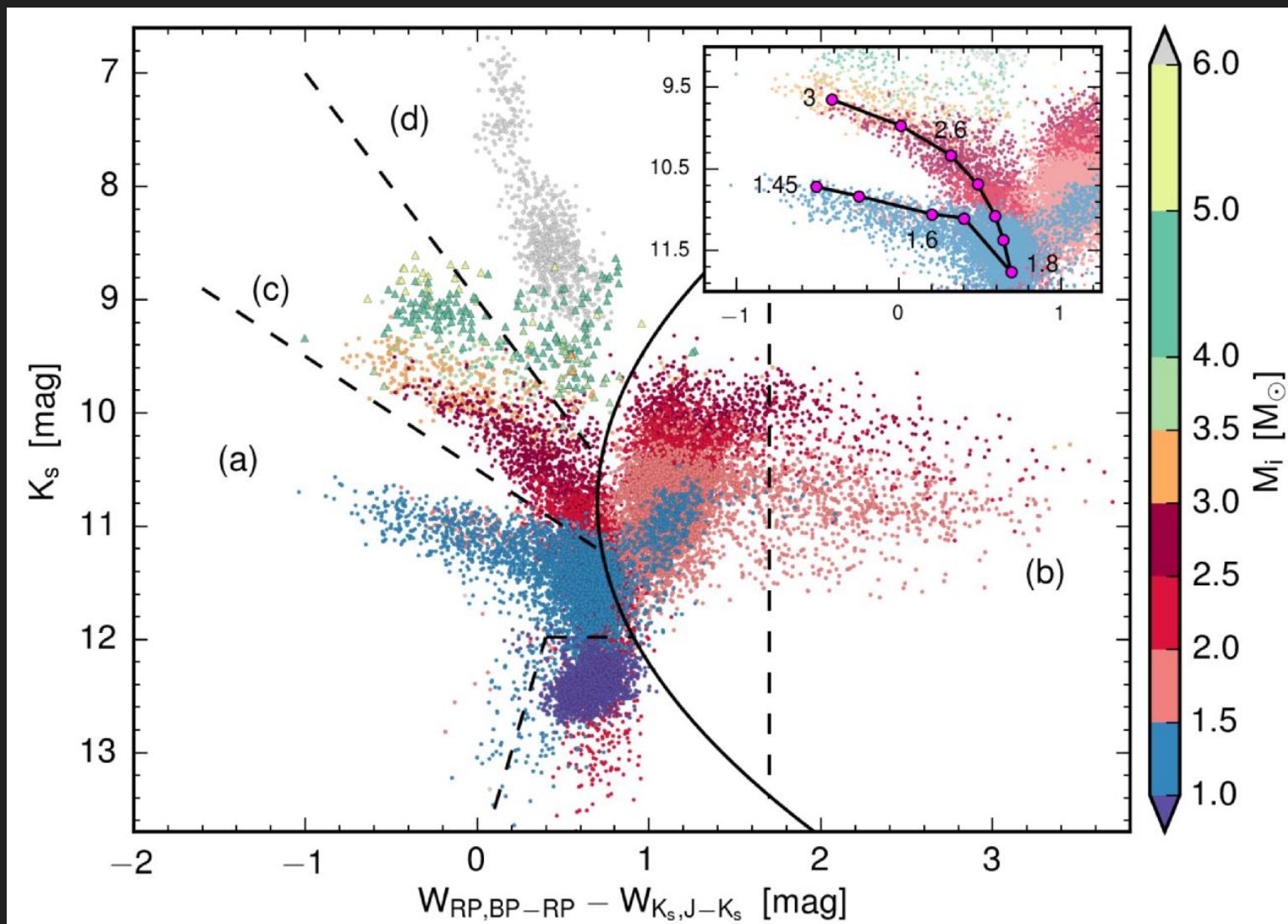


[Lebzelter+ 2018]

# LPVs and Gaia



# LPVs and Gaia



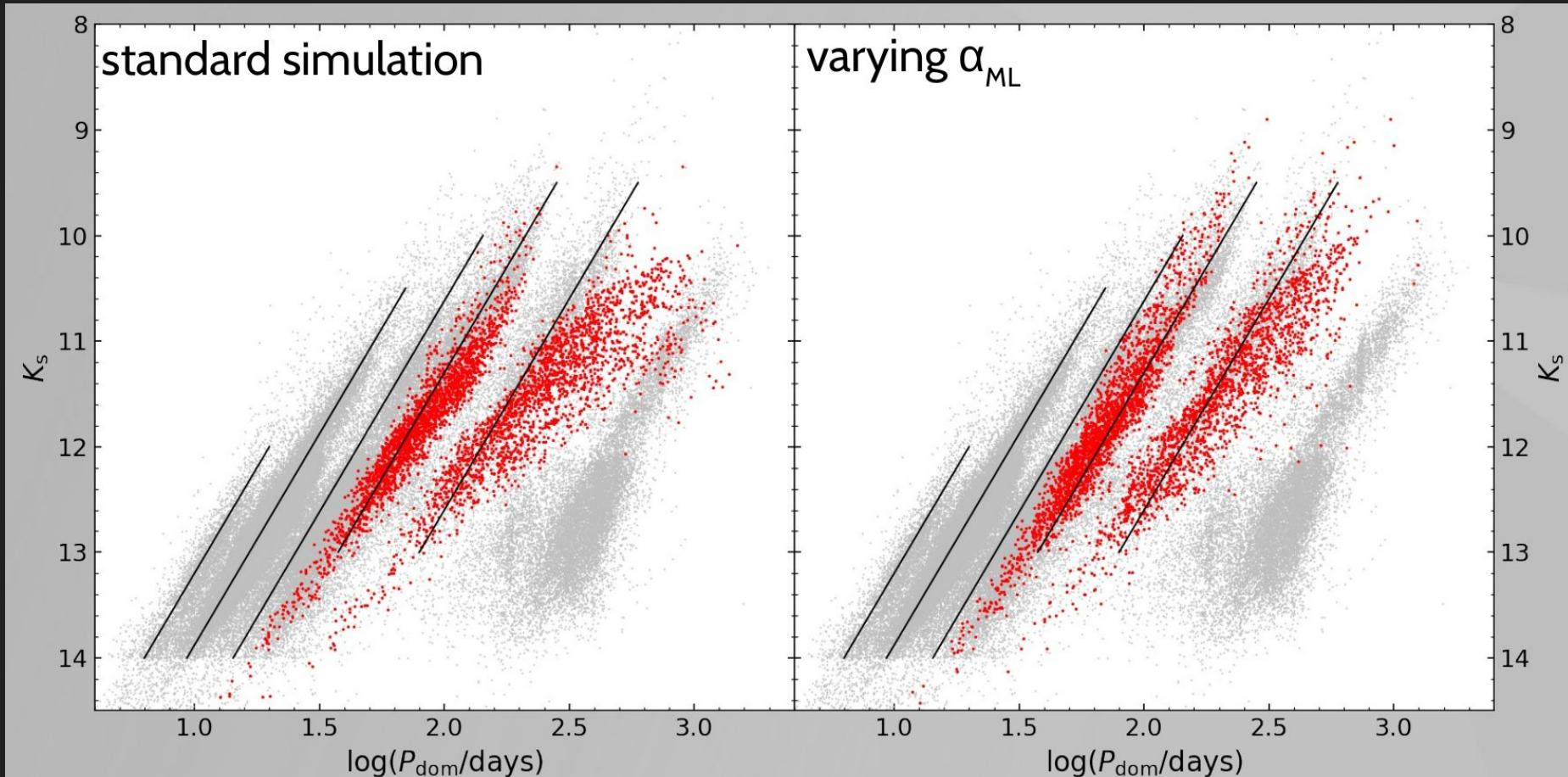
# The fundamental mode

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- Systematic period overestimate where dominant - issue may affect growth rates
- Theoretical period-mass-radius (PMR) relation underestimate masses by up a factor of 10 (provided accurate independent radius estimate)
- Most likely cause: description of convection-pulsation interaction
- Stellar models' structure unrealistic? Pulsation as a probe of stellar interiors
- Temperature scale offset: models become “too cold too fast”

# The fundamental mode

Temperature scale offset: models become “too cold too fast”.  
Tests with “variable mixing length” provide encouraging results.



# What to expect from the future

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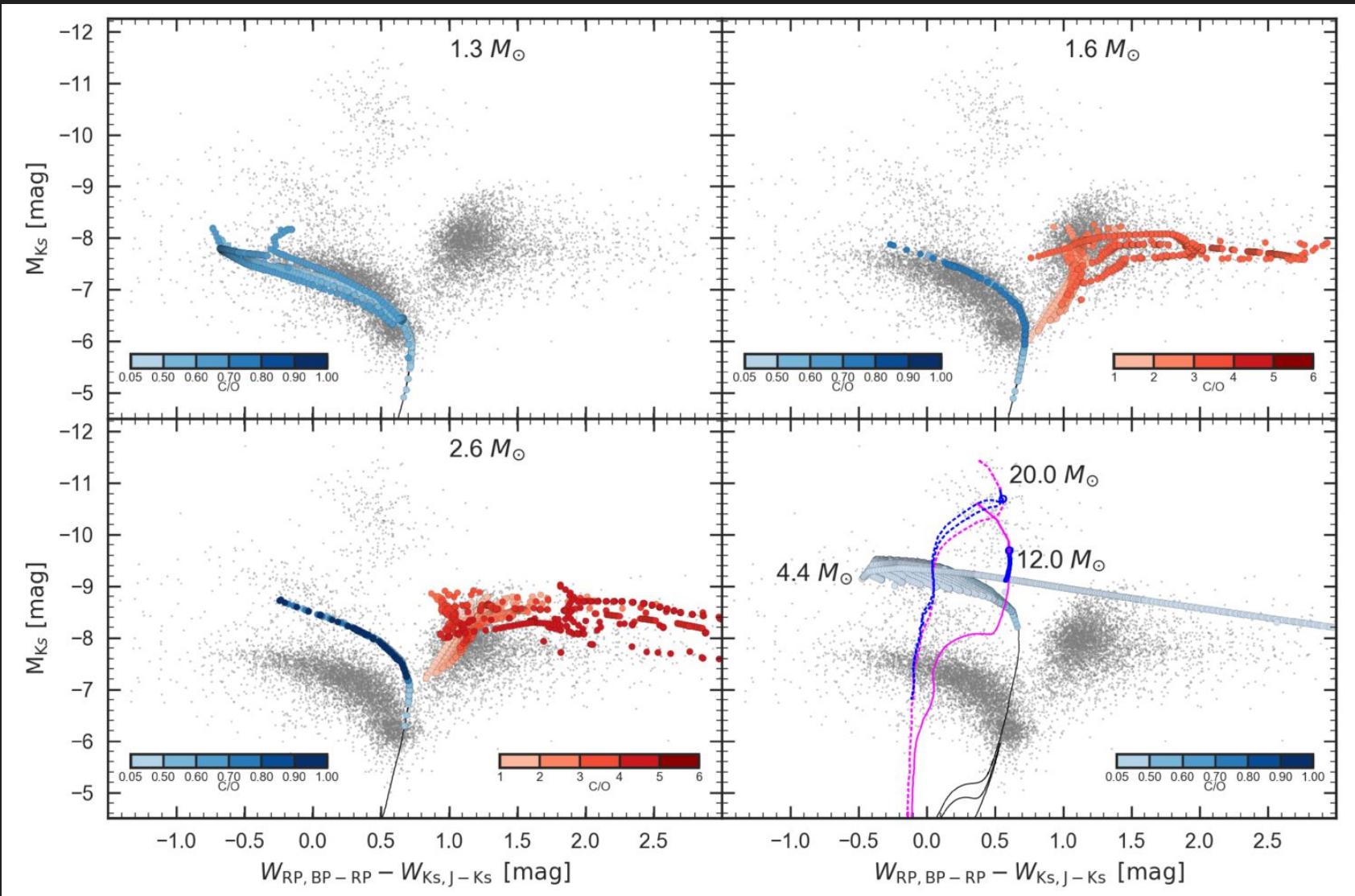
- **Gaia DR3:** Better parallaxes and longer light curves - more accurate periods and amplitudes, and better detection of multiple modes
- **LSST:** continuous, high-cadence optical monitoring of southern sky
- **OGLE IV?** Combined with OGLE-I-II-III: more than 20 years of observational baseline, exceptional quality light curves
- **JWST?**



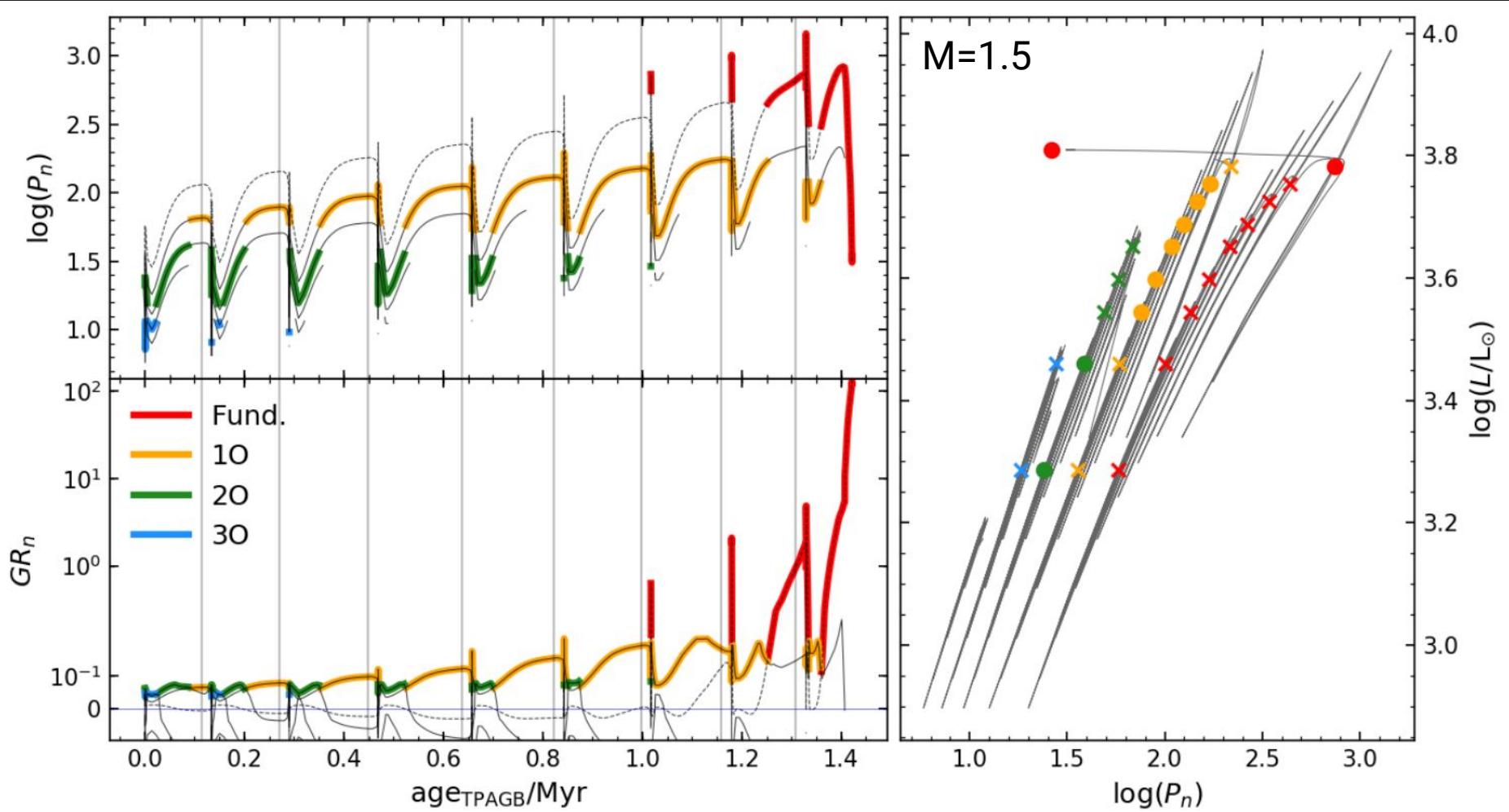
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Thanks!

# LPVs and Gaia

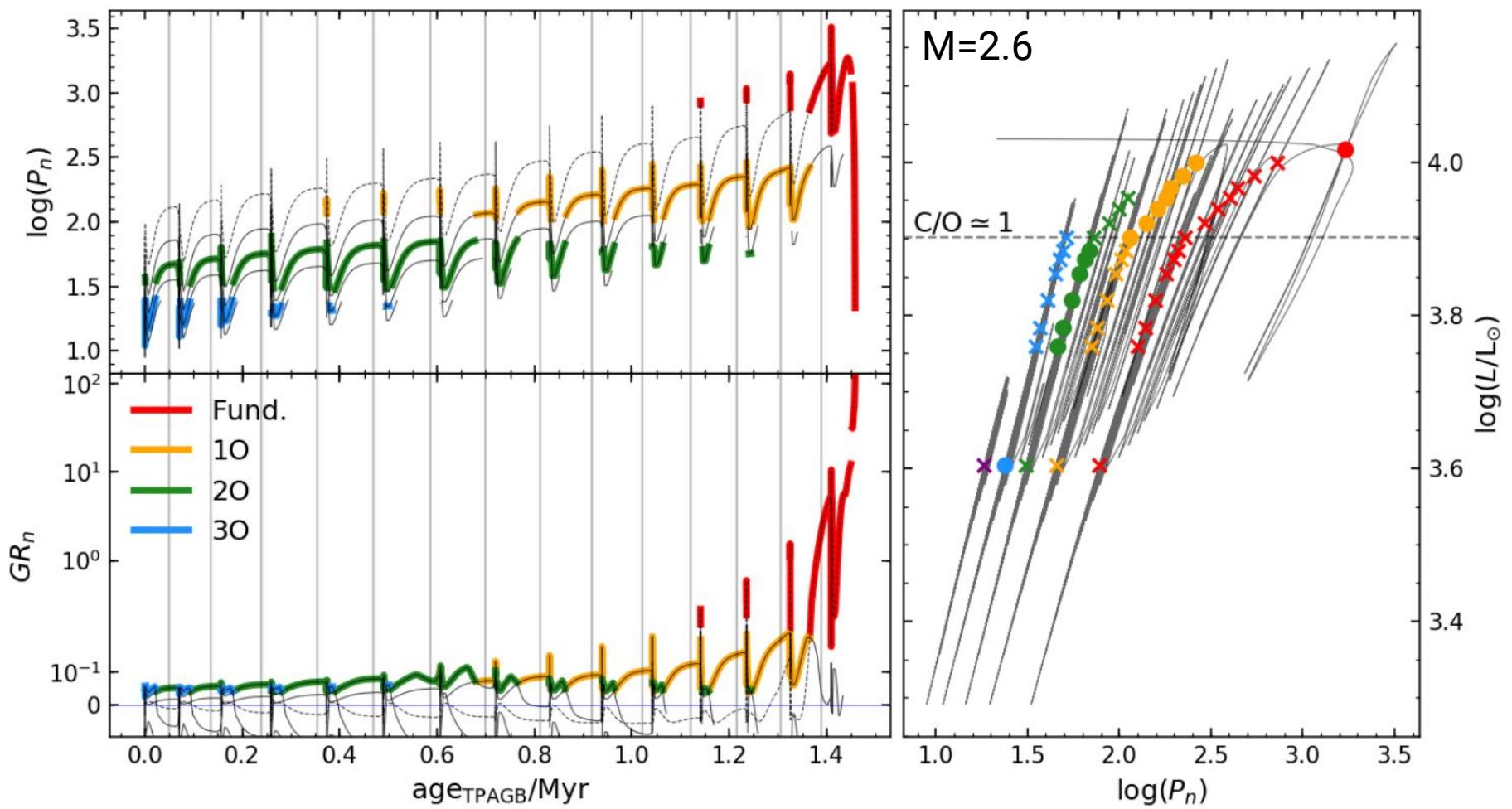


# Pulsation on the TP-AGB



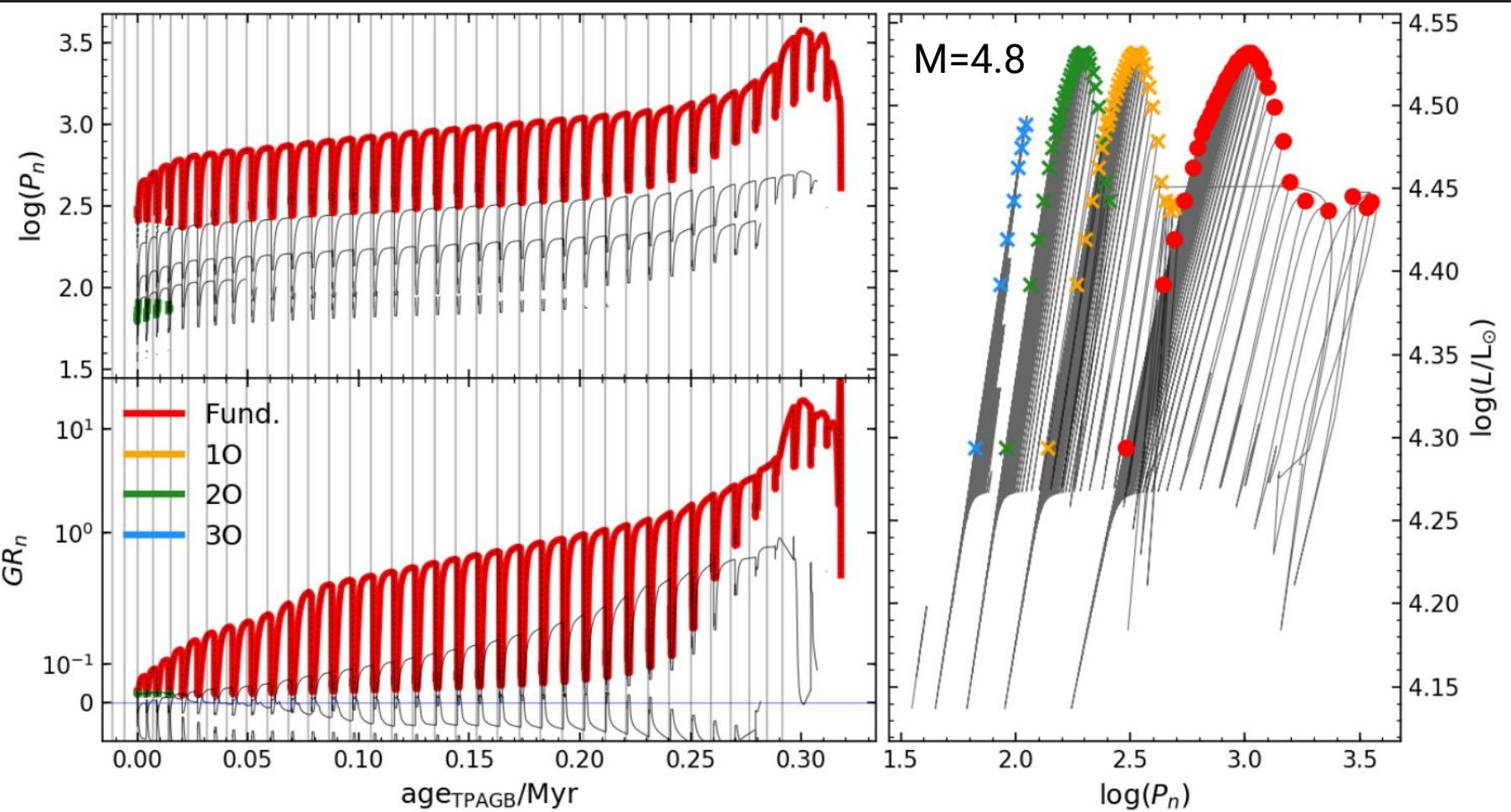
[Trabucchi+ 2019]

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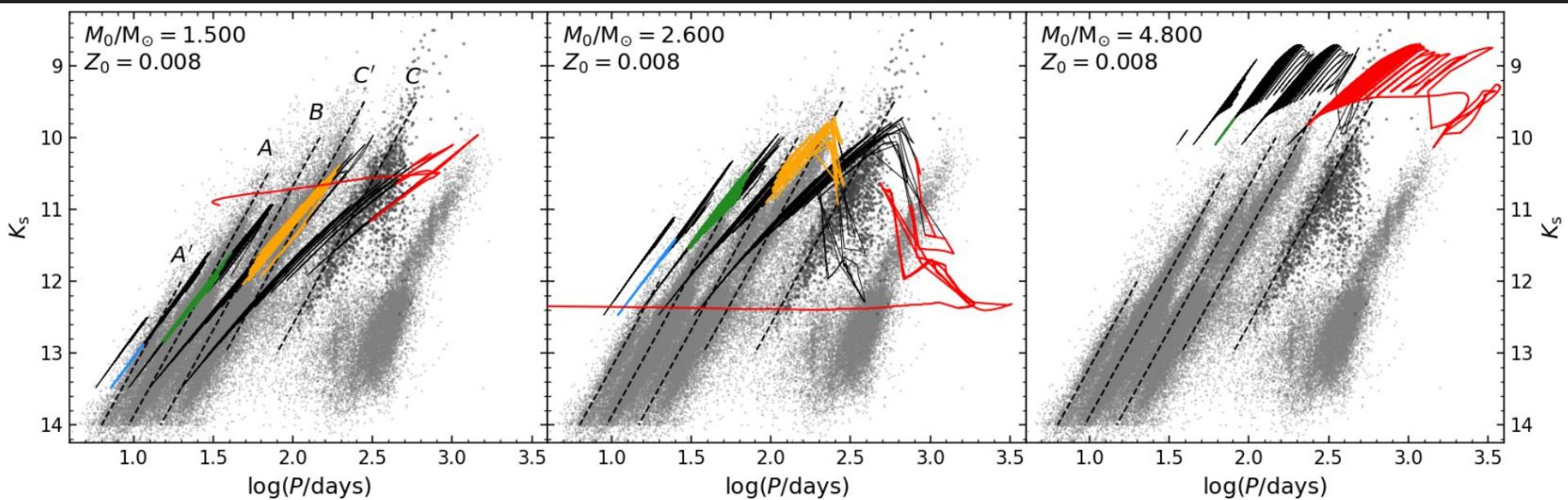
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# Definitions from the GCVS

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- **M:** Mira (Omicron) Ceti-type variables. These are long-period variable giants with characteristic late-type emission spectra (Me, Ce, Se) and light amplitudes from 2.5 to 11 mag in V. Their periodicity is well pronounced, and the periods lie in the range between 80 and 1000 days. Infrared amplitudes are usually less than in the visible and may be <2.5 mag. For example, in the K band they usually do not exceed 0.9 mag. [...]
- **SR:** Semiregular variables, which are giants or supergiants of intermediate and late spectral types showing noticeable periodicity in their light changes, accompanied or sometimes interrupted by various irregularities. Period lie in the range from 20 to >2000 days, while the shapes of the light curves are rather different and variable, and the amplitudes may be from several hundredths to several magnitudes (usually 1-2 mag in V).
  - **SRa:** Semiregular late-type (M, C, S or Me, Ce, Se) giants displaying persistent periodicity and usually small (<2.5 mag in V) light amplitudes (Z Aqr). Amplitudes and light-curve shapes generally vary and periods are in the range 35-1200 days. Many of these stars differ from Miras only by showing smaller light amplitudes.
  - **SRb:** Semiregular late-type (M, C, S or Me, Ce, Se) giants with poorly defined periodicity (mean cycles in the range of 20 to 2300 days) or with alternating intervals of periodic and slow irregular changes, and even with light constancy intervals (RR CrB, AF Cyg). [...] In a number of cases, the simultaneous presence of two or more periods of light variation is observed.
  - **SRc:** Semiregular late-type (M, C, S or Me, Ce, Se) giants (Mu Cep) with amplitudes of about 1 mag and periods of light variation from 30 days to several thousand days.
  - **SRd:** Semiregular variable giants and supergiants of F, G, or K spectral types, sometimes with emission lines in their spectra. Amplitudes of light variation are in the range from 0.1 to 4 mag, and the range of periods is from 30 to 1100 days (SX Her, SV UMa).
  - **SRS:** Semiregular pulsating red giants with short period (several days to a month), probably high-overtone pulsators. Prototype: AU Ari.

# Asymptotic Giant Branch - Structure

