

Long-Period Variables

“Recent” developments in the modelling and interpretation

Michele Trabucchi

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e Astronomia
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DE GENÈVE

Outline

0. Intro / motivation
1. Pulsation models of Long-Period Variables
2. An application: the period-age relation
3. Ongoing work and next steps...

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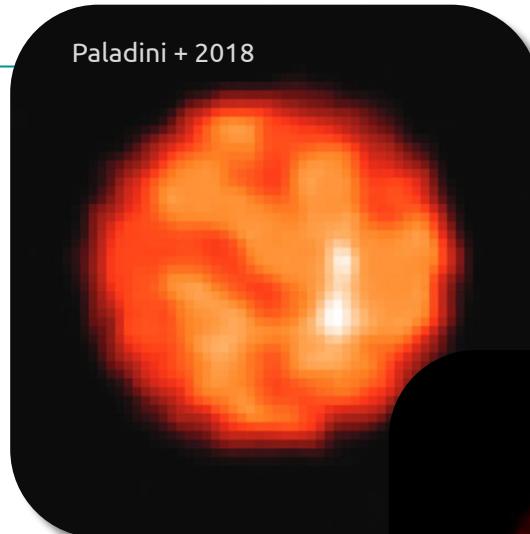
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Long-Period Variables

- Evolved stars: AGB, RSG
- Radial pulsation (and more)
- Possibly multiperiodic
- Period: days to months
- Amplitude: $0.001 \leq \Delta V / \text{mag} \leq 10$

Paladini + 2018



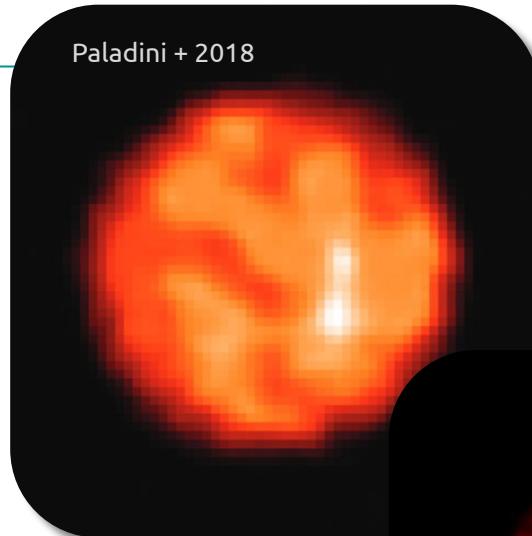
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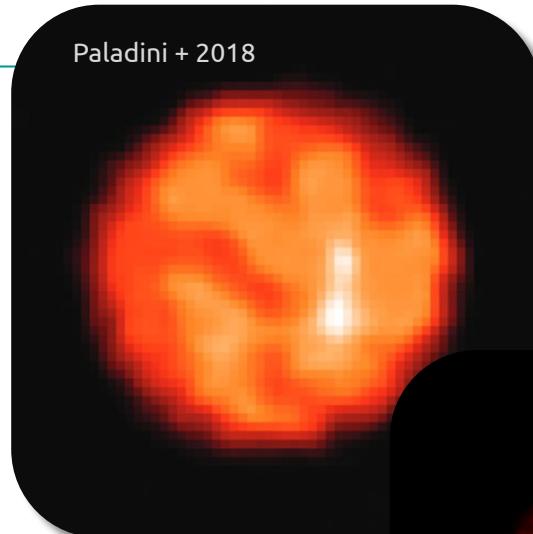
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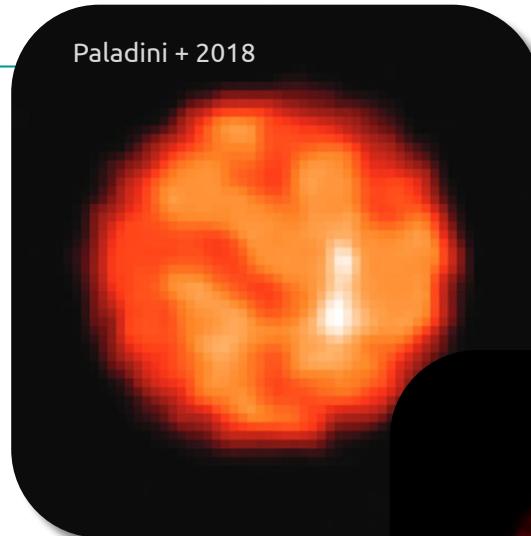
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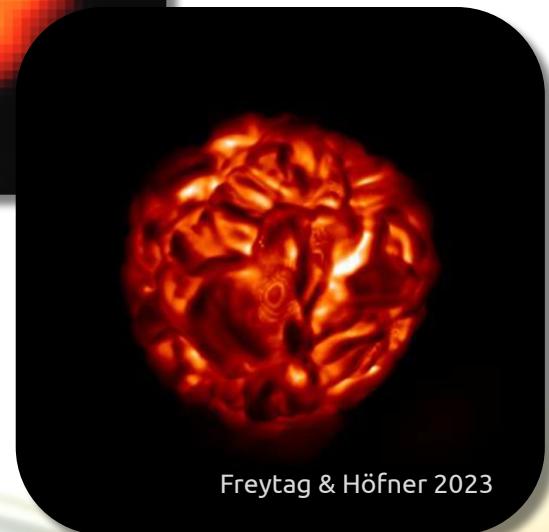
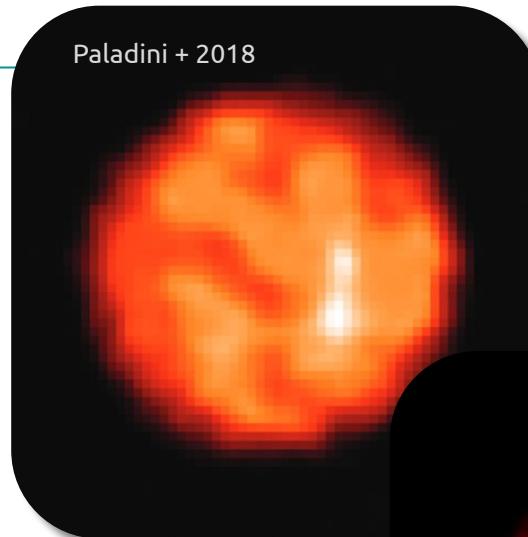


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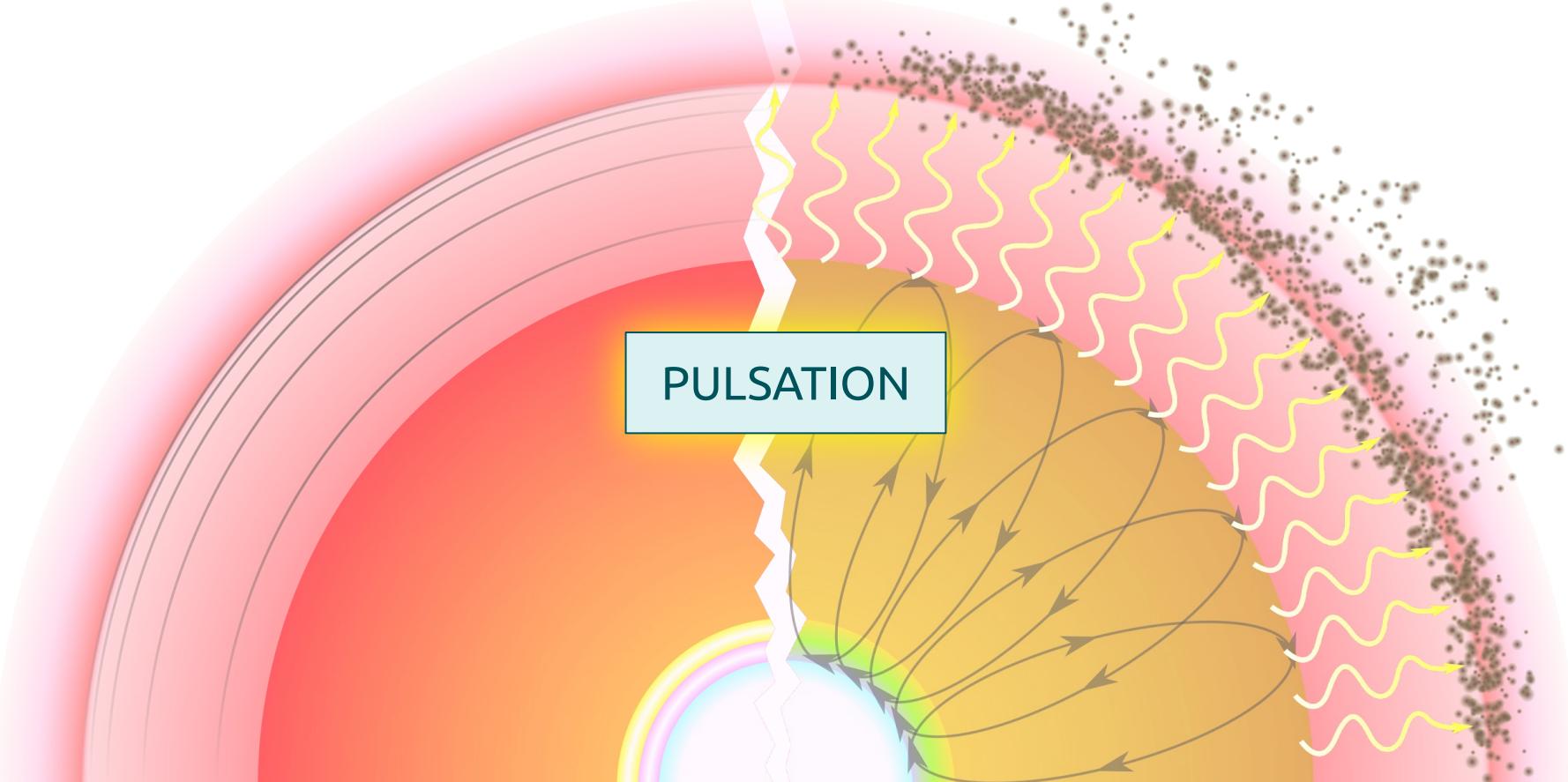


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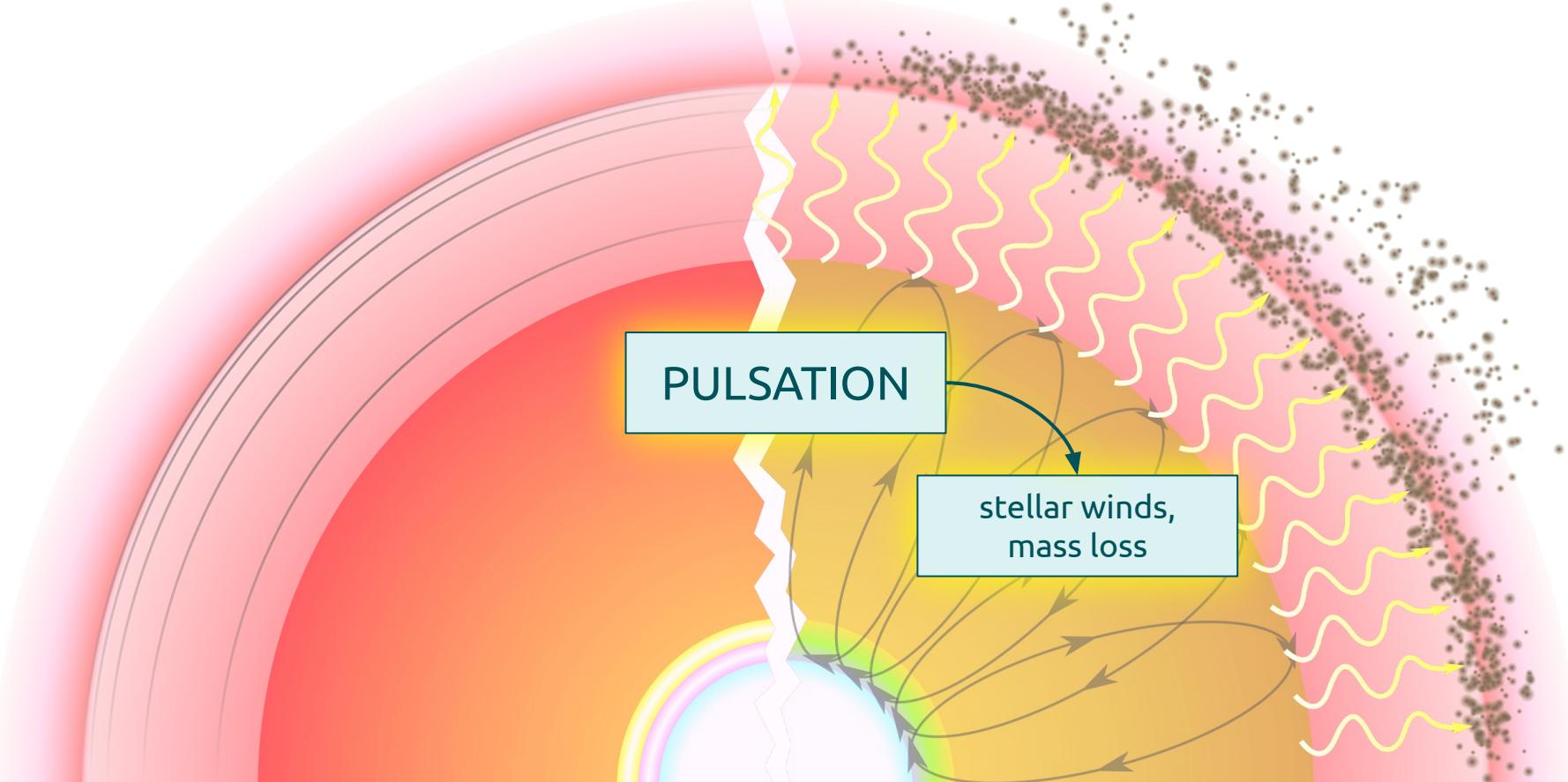
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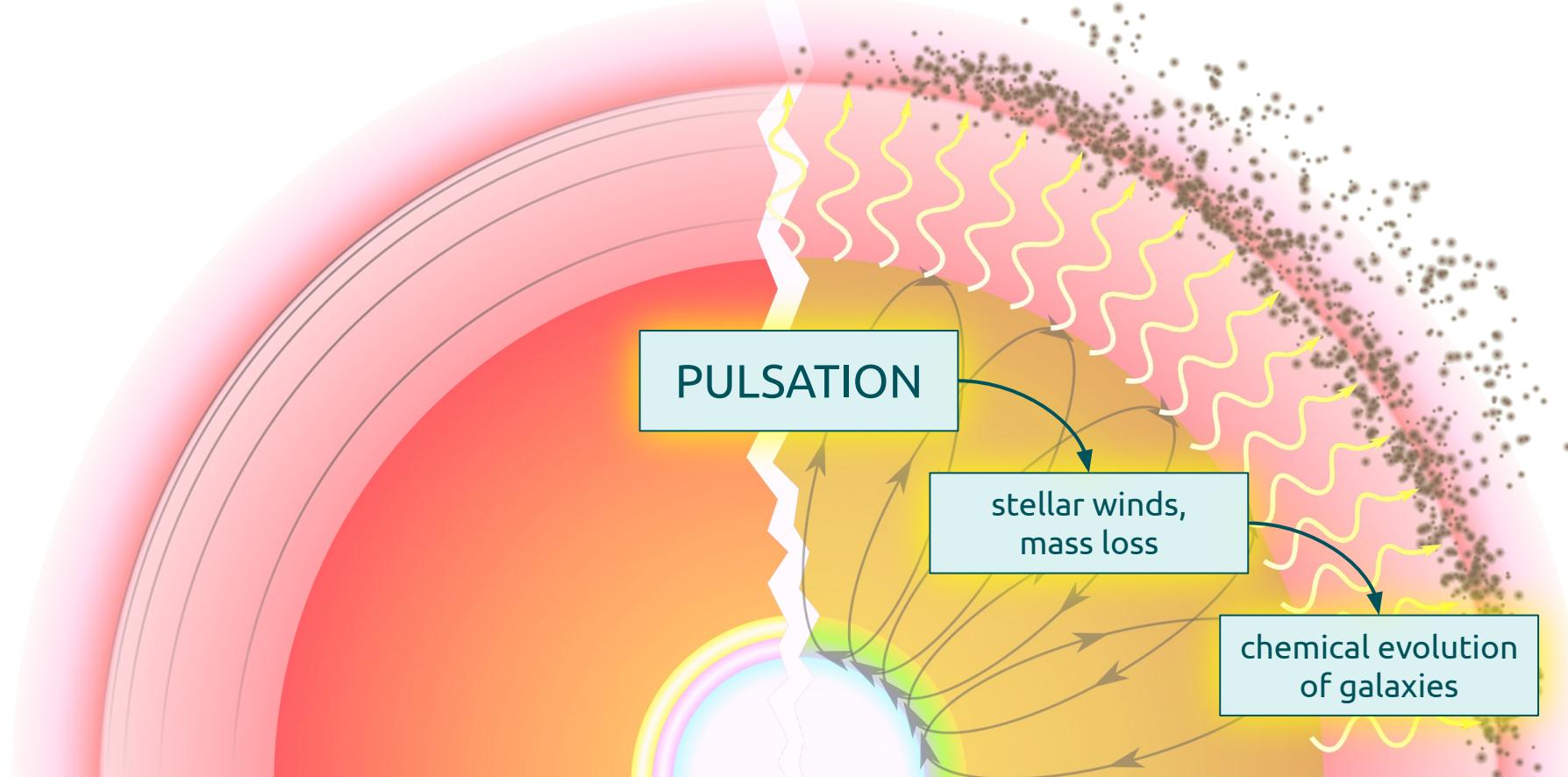
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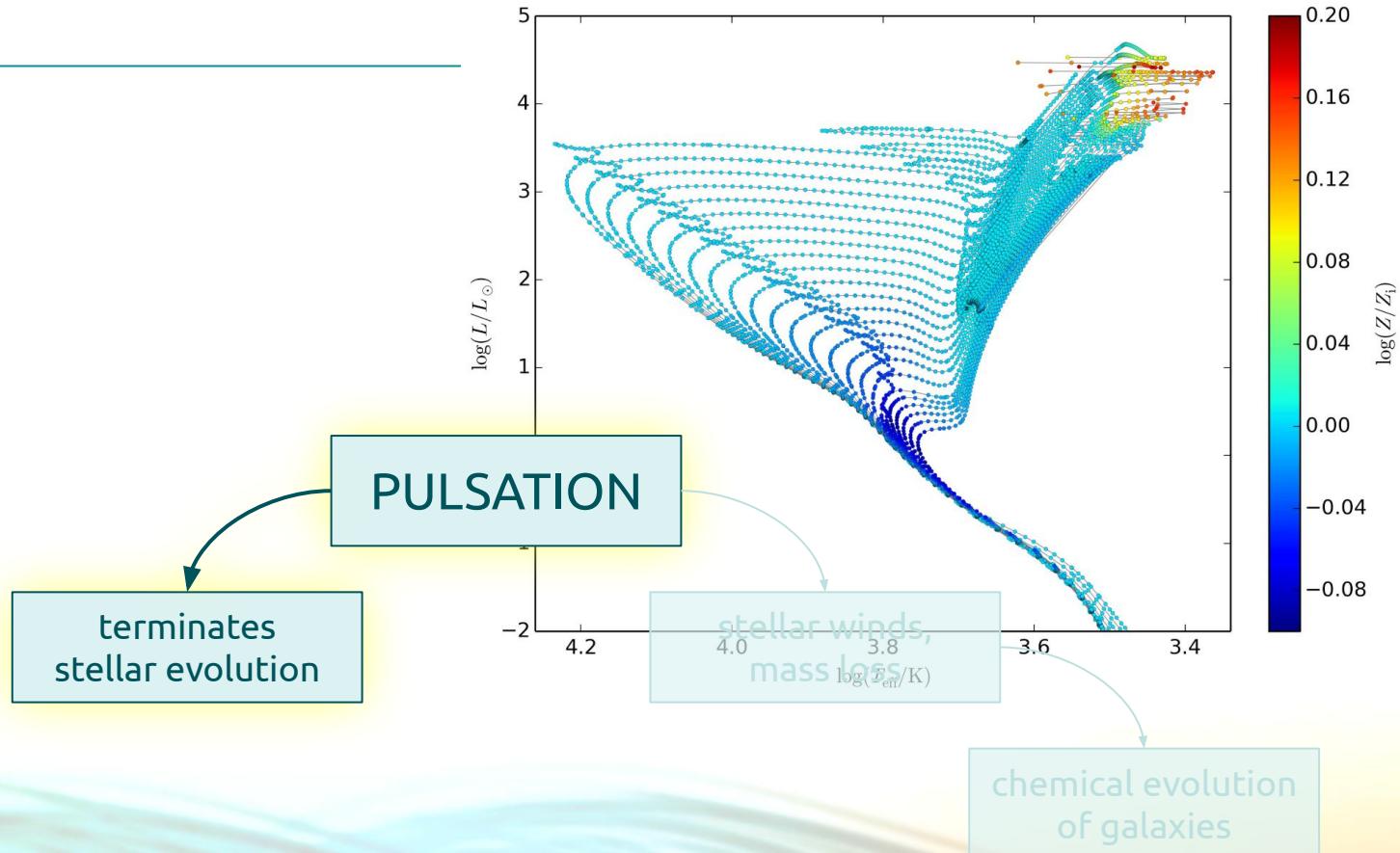
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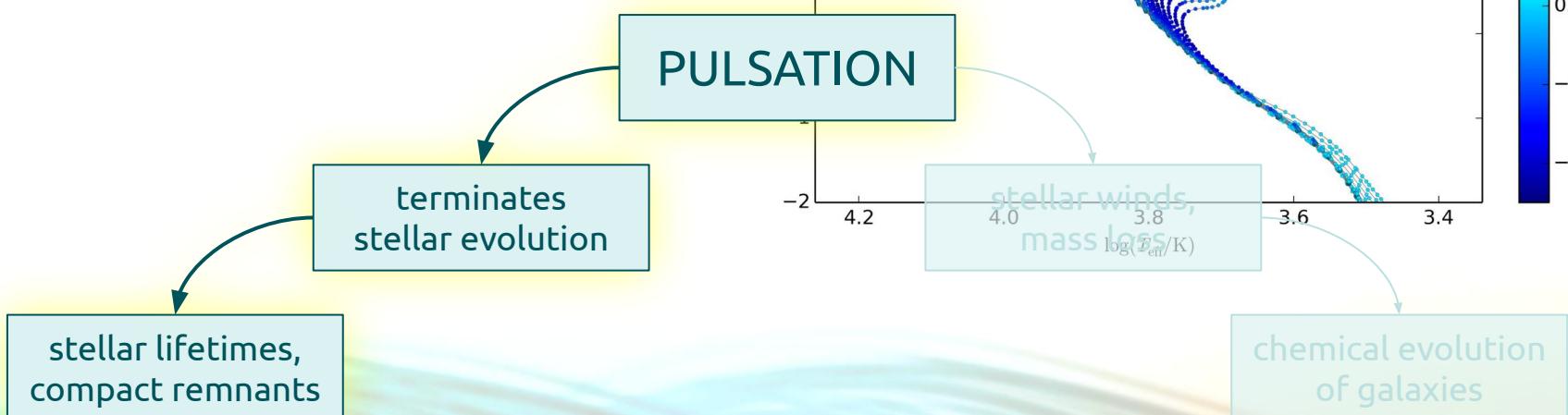
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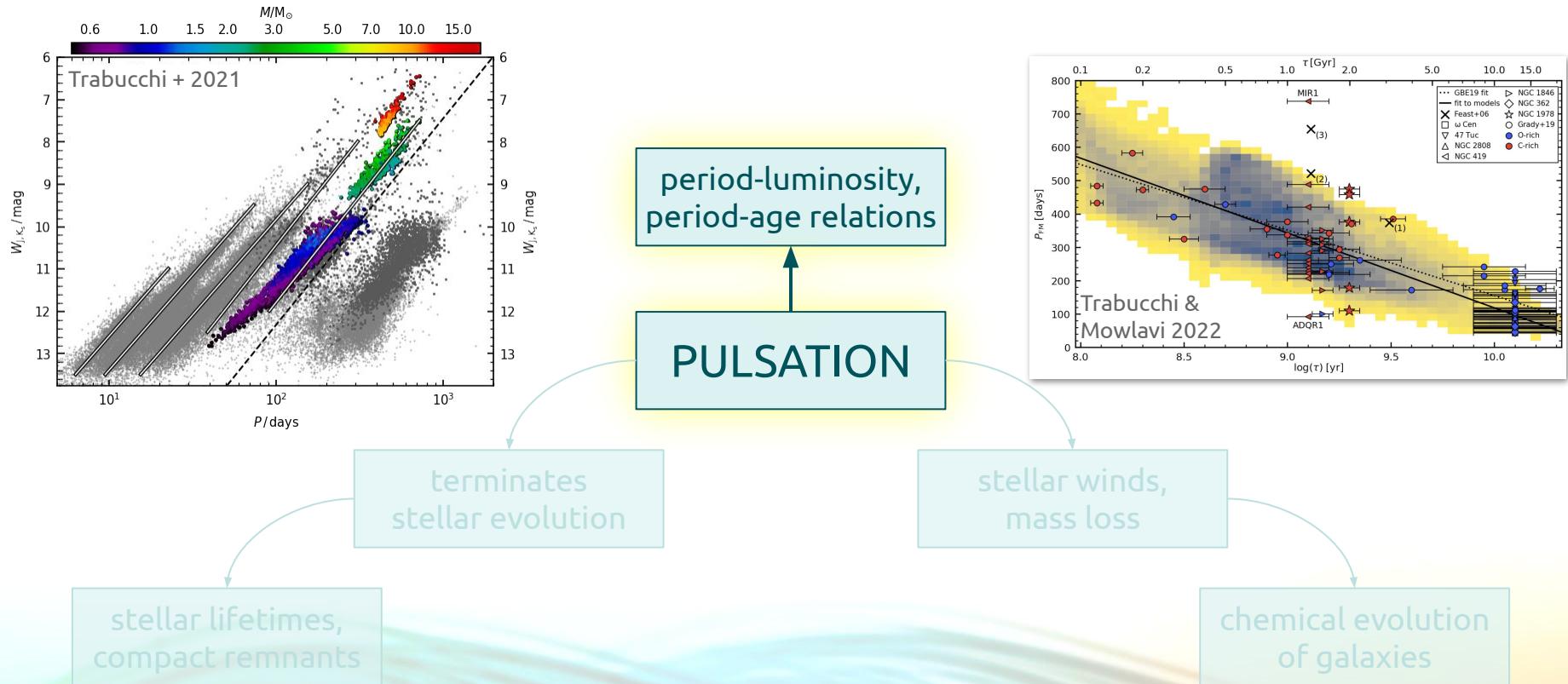
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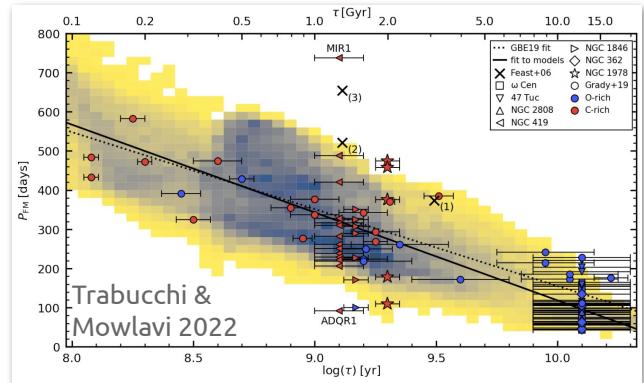
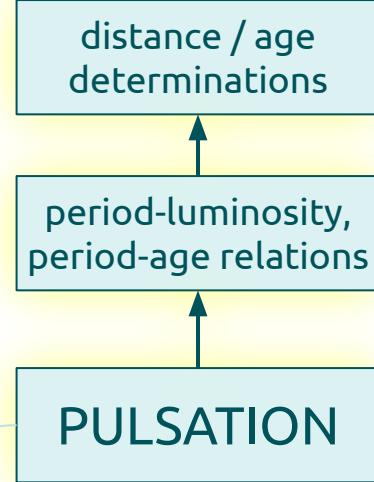
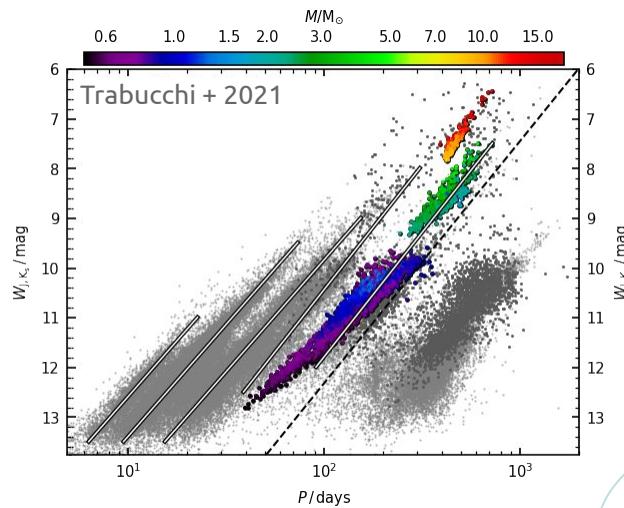
Motivation



Motivation



Motivation



stellar lifetimes,
compact remnants

chemical evolution
of galaxies

1. Pulsation models of LPVs

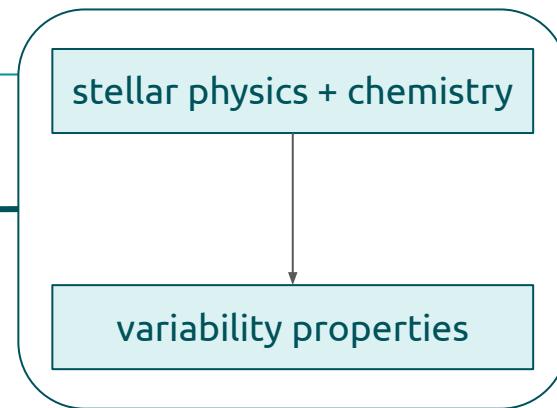
LPV Pulsation Models

calibration of TP-AGB evolutionary models



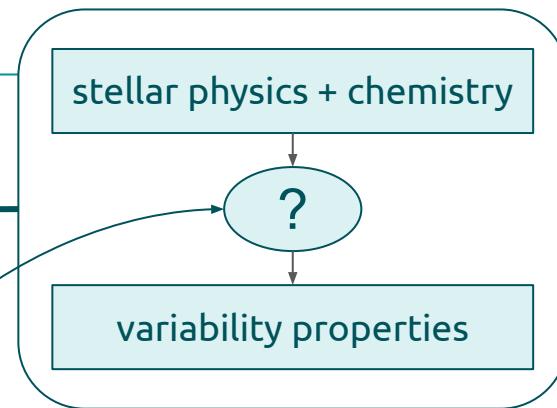
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LPV Pulsation Models

calibration of TP-AGB evolutionary models



Literature:

- fragmented/inhomogeneous
- incomplete/poor coverage of space of stellar parameters
- only 1 or 2 pulsation modes

LPV Pulsation Models

Pulsation code Fox & Wood 1982; Wood & Olivier 2014

- 1D (spherically symmetric star)
- radial (spherically symmetric oscillation)
- non-adiabatic
- *linear*

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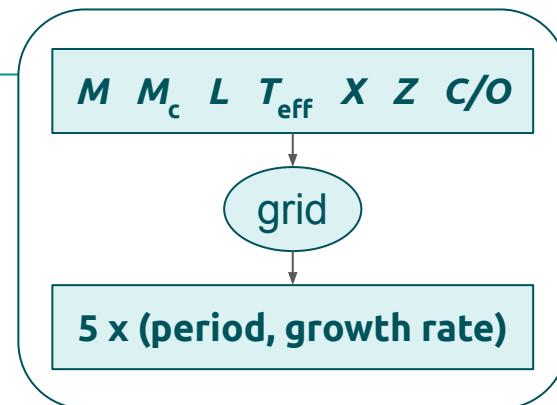
decoupled from evolution code!

1. envelope integration
2. linear stability analysis
(small-amplitude perturbation approximation)

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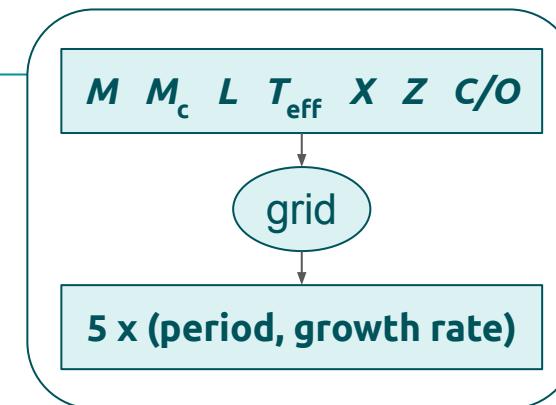
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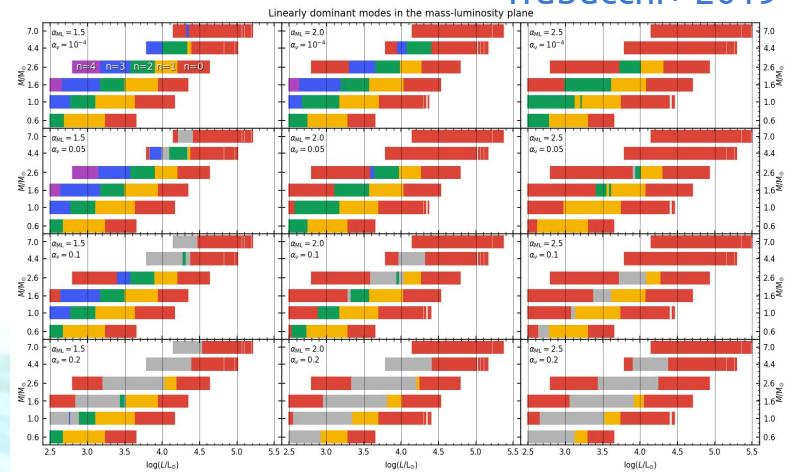
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Grid: several million different combinations of parameters.

- Widest, most densely sampled grid of LPV models.
- First systematic investigation of:
 - chemistry-pulsation connection
 - pulsating C-rich giants



Trabucchi+ 2019



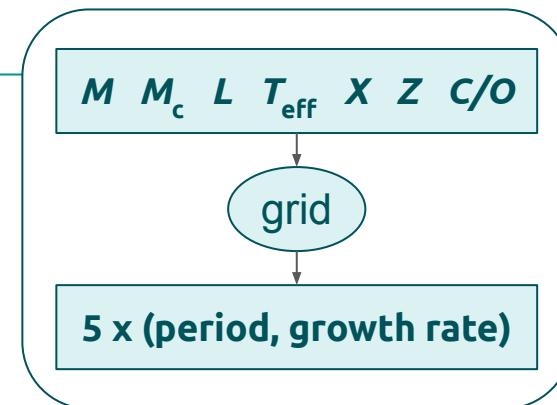
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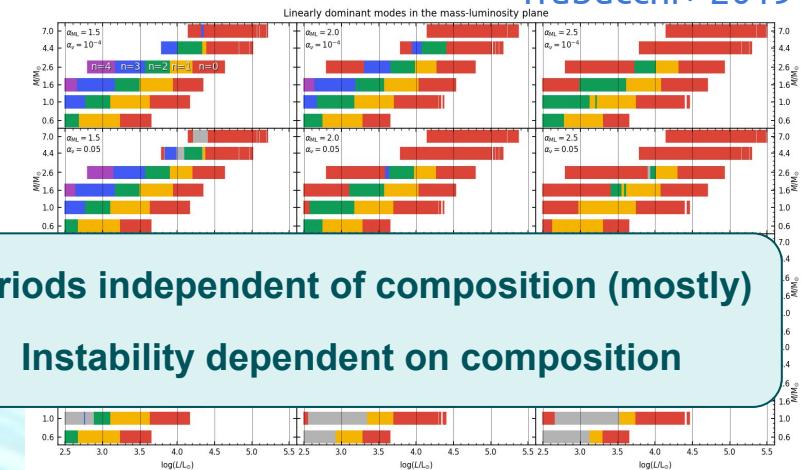
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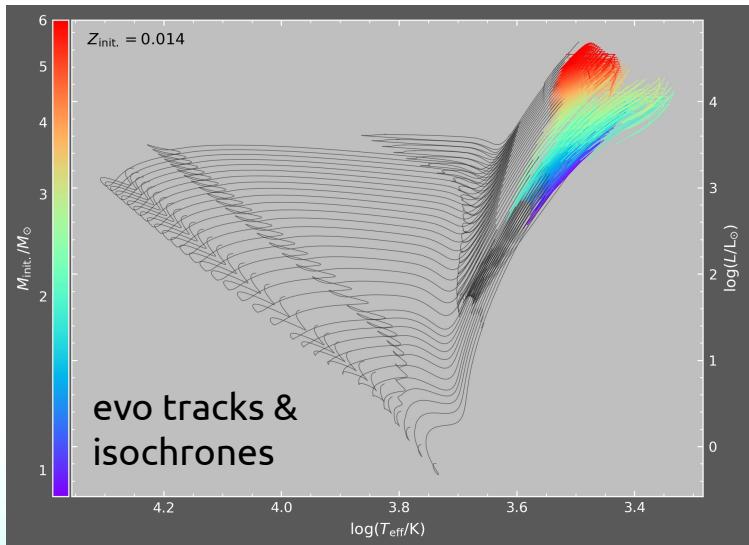


LPV Pulsation Models

Grid *fully compatible*
and *easily interfaceable*
with evolutionary models

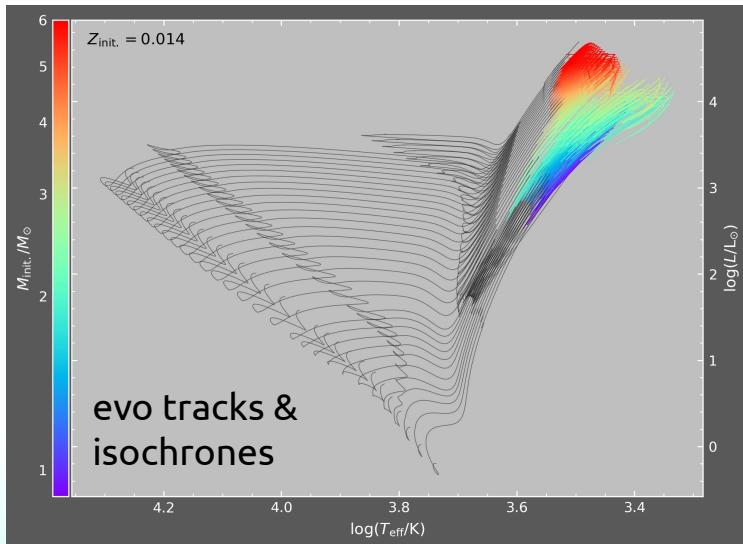
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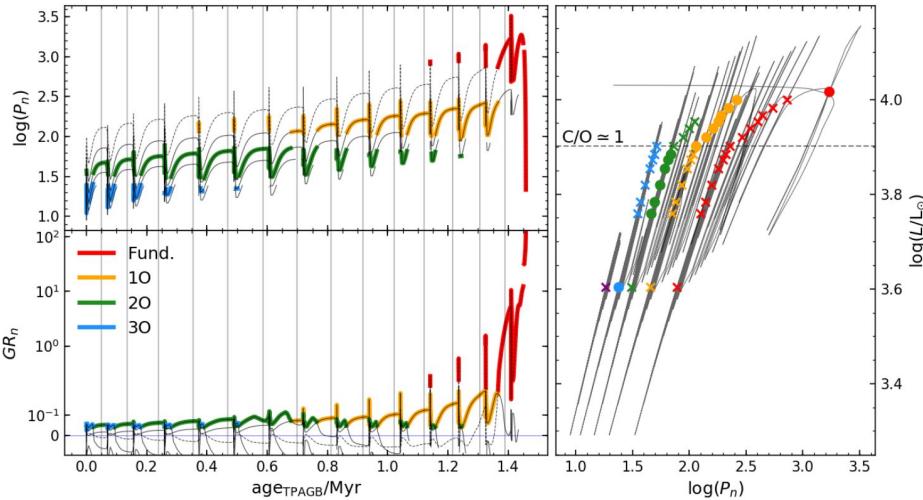
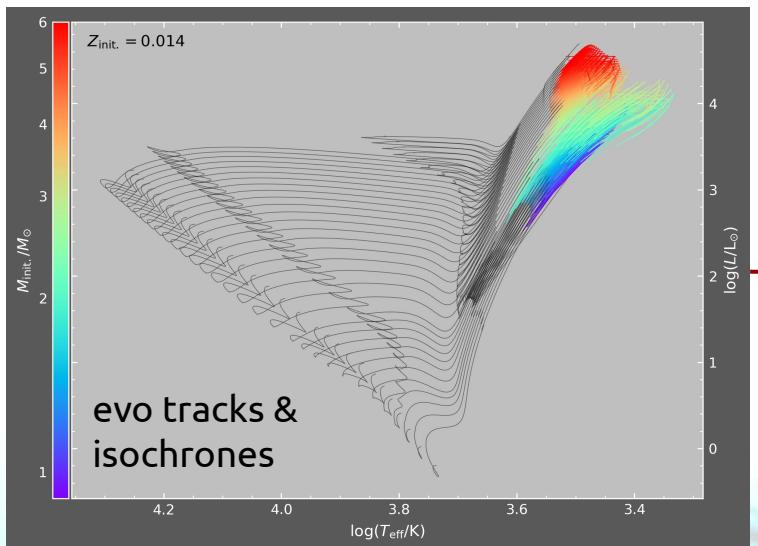


grid of LPV
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models

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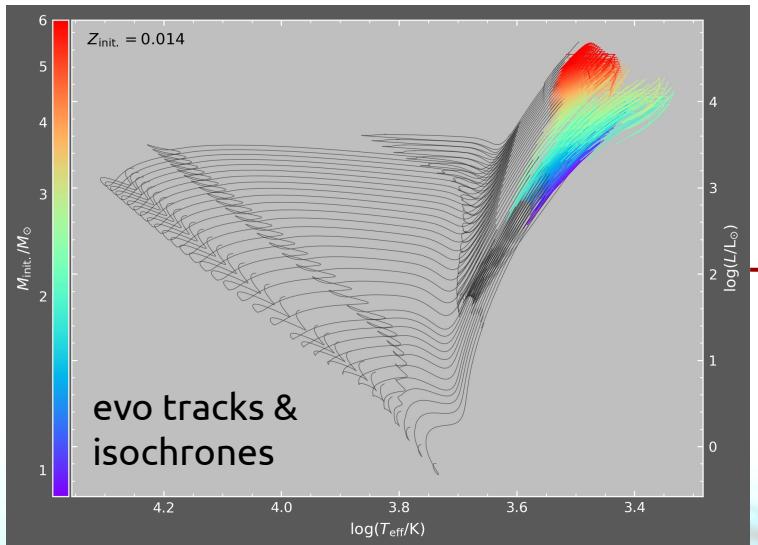


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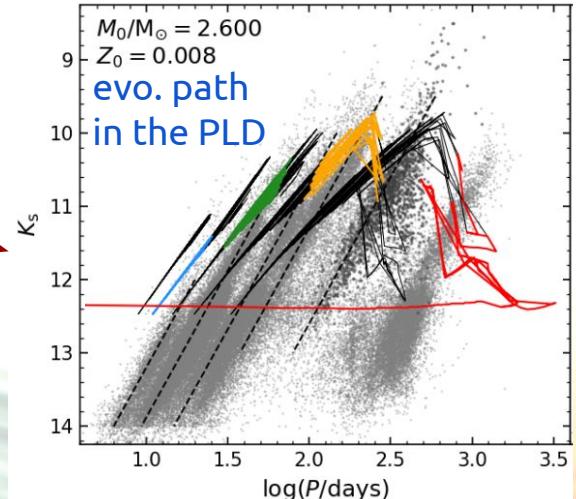
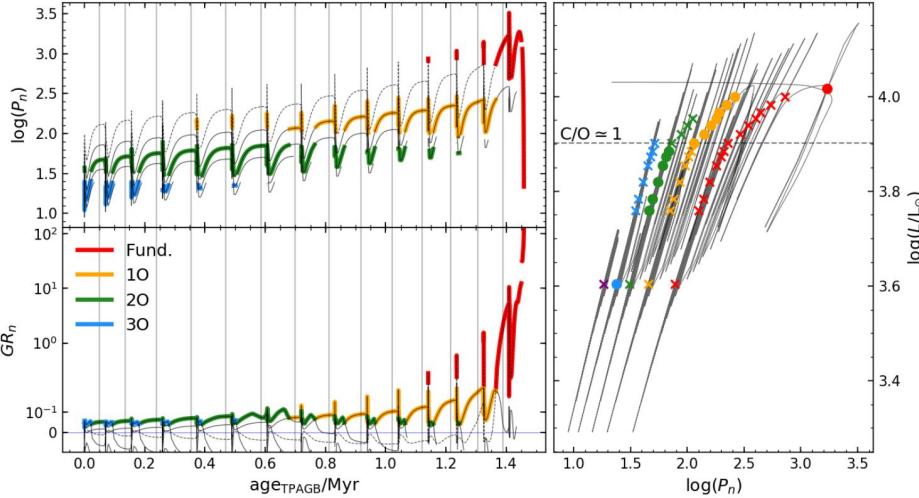
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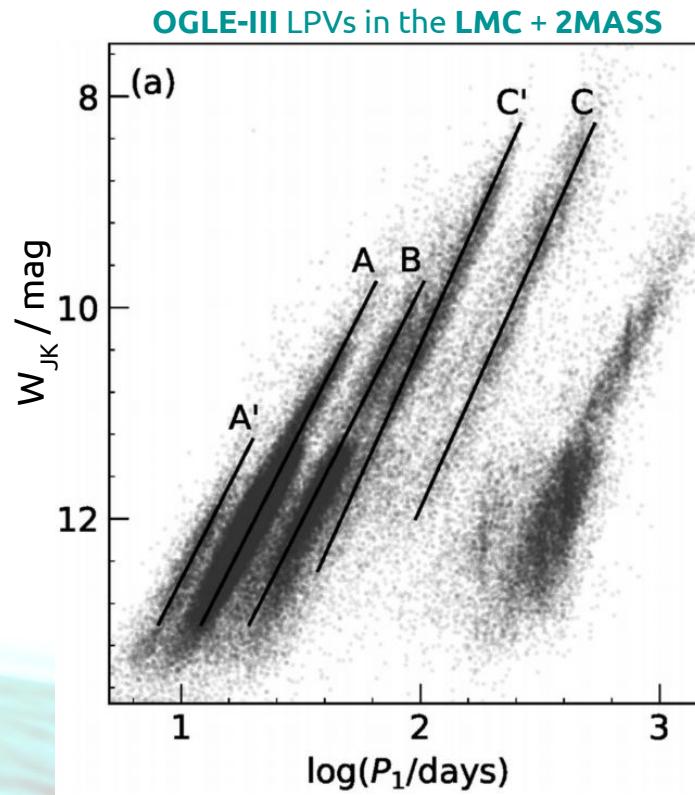
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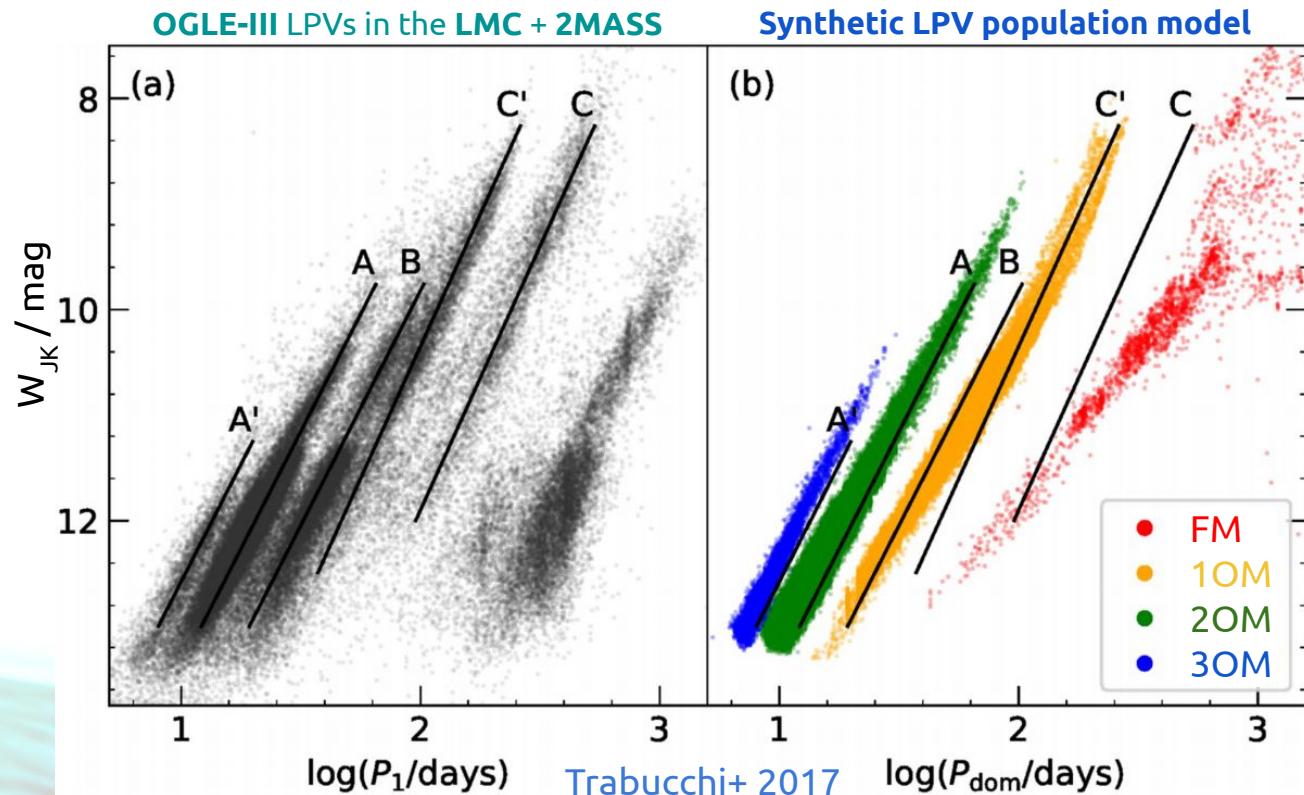


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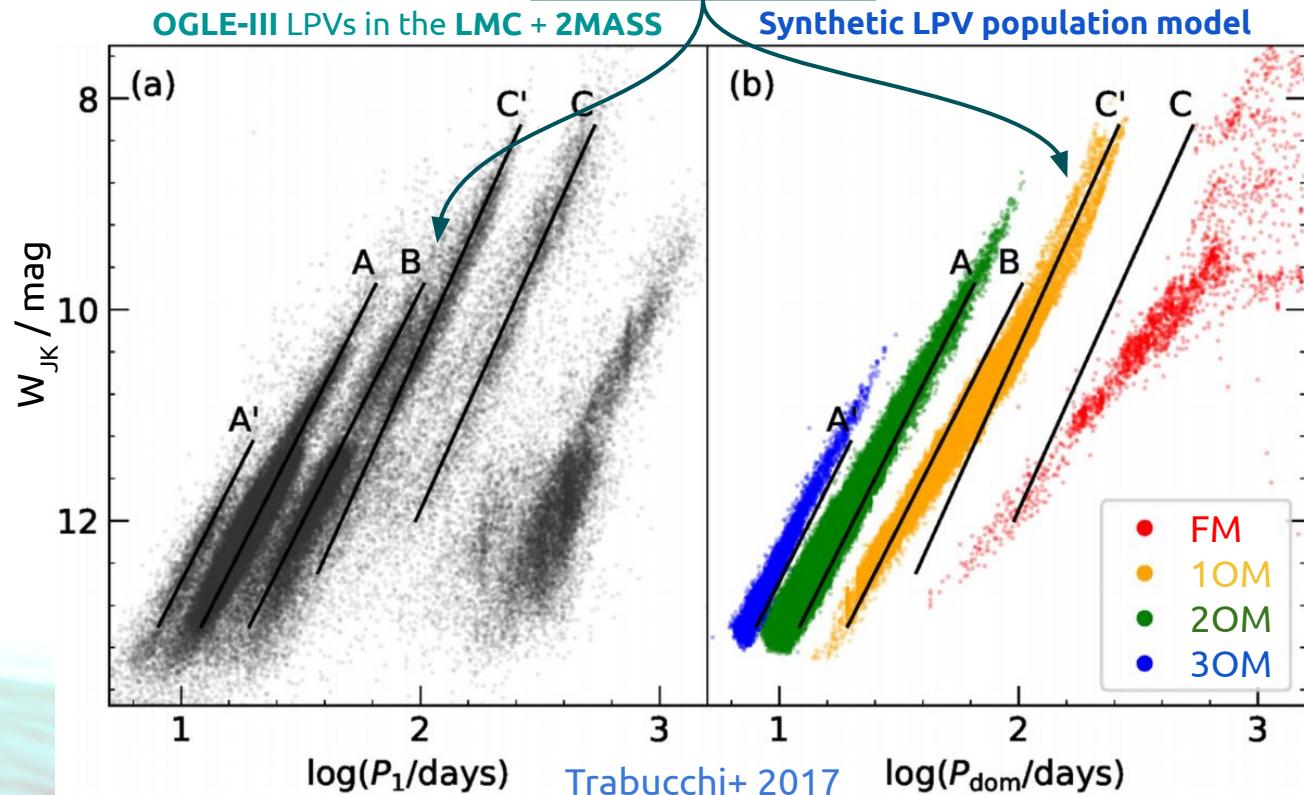
LPV Pulsation Models

2 PL relations
for 1 pulsation mode:
observational
selection bias

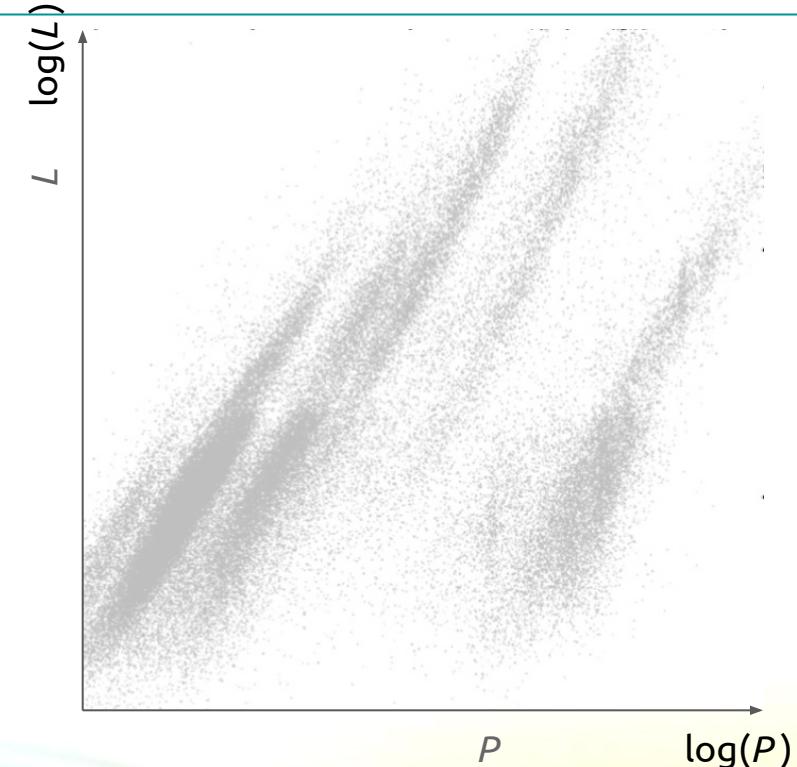
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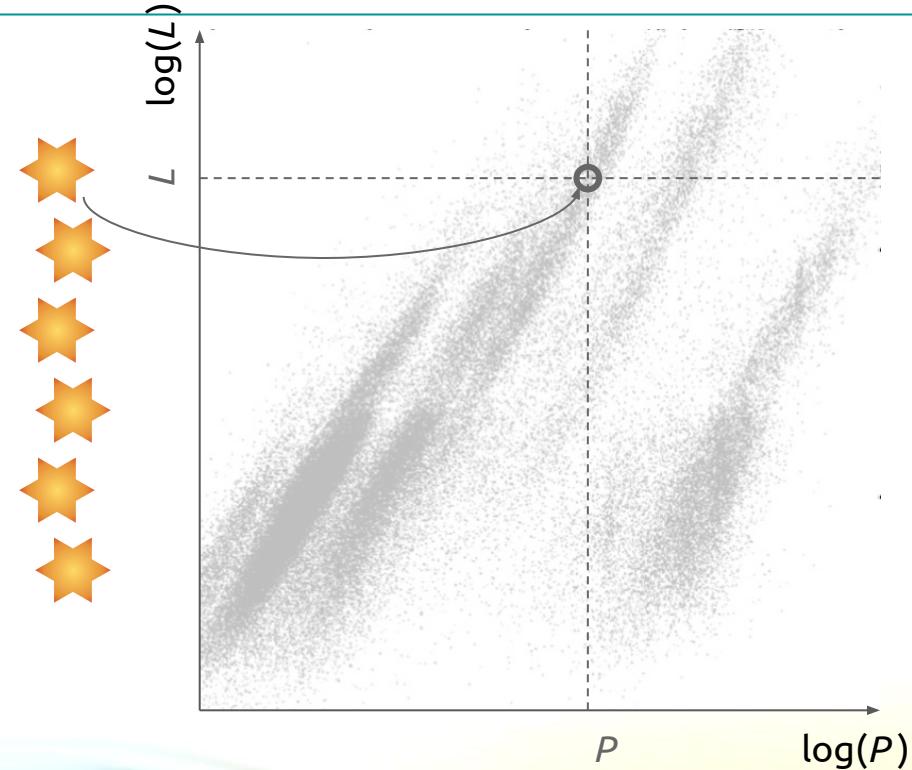


Period-Luminosity Diagram 101



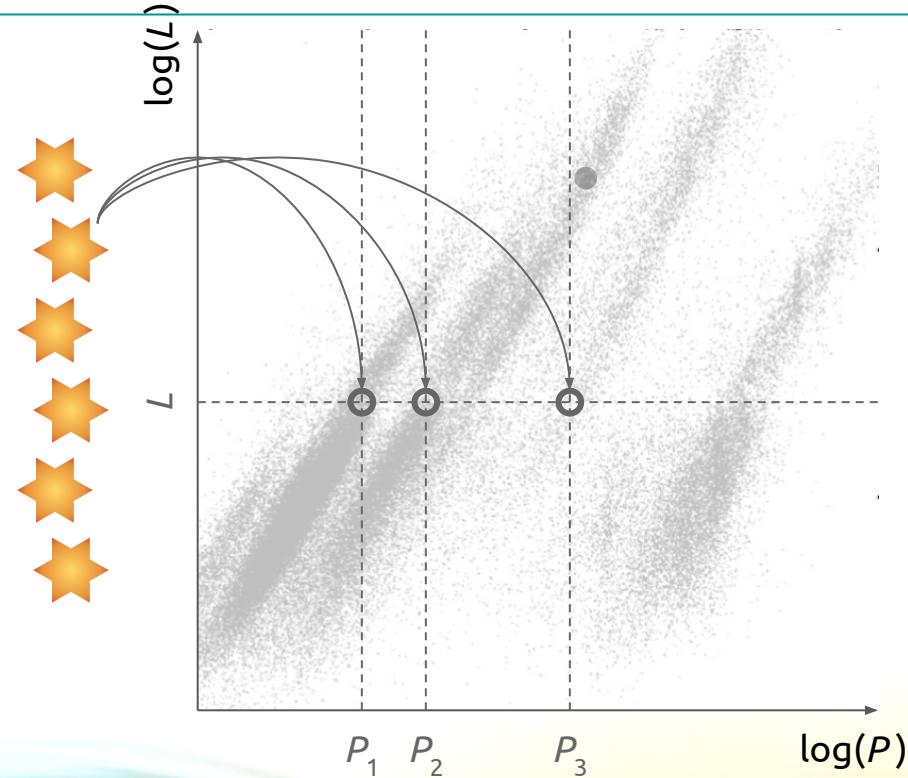
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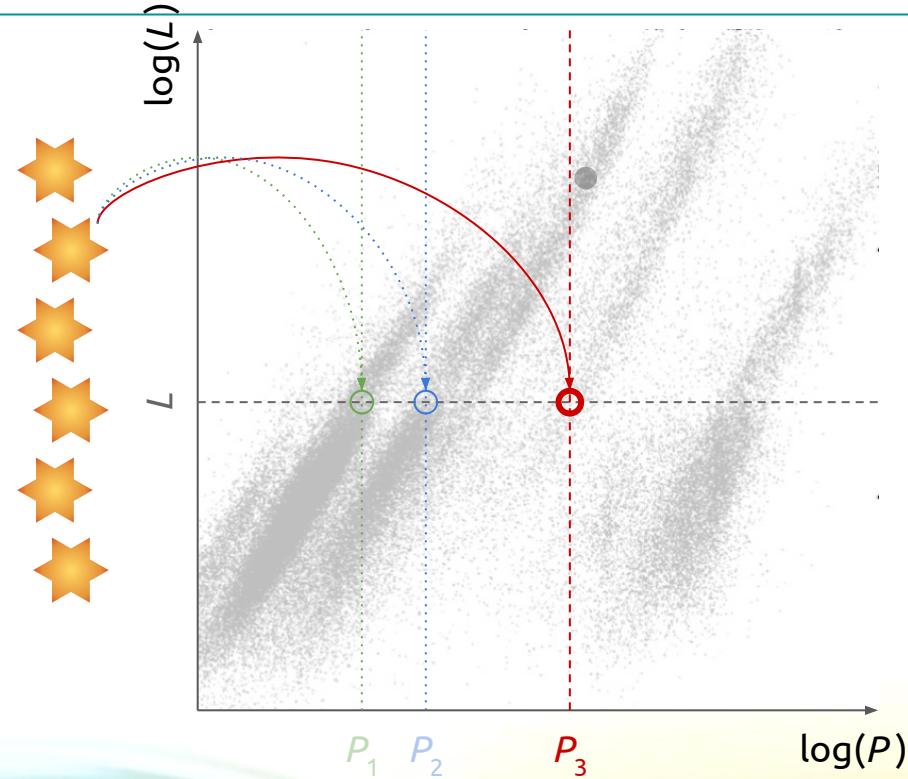
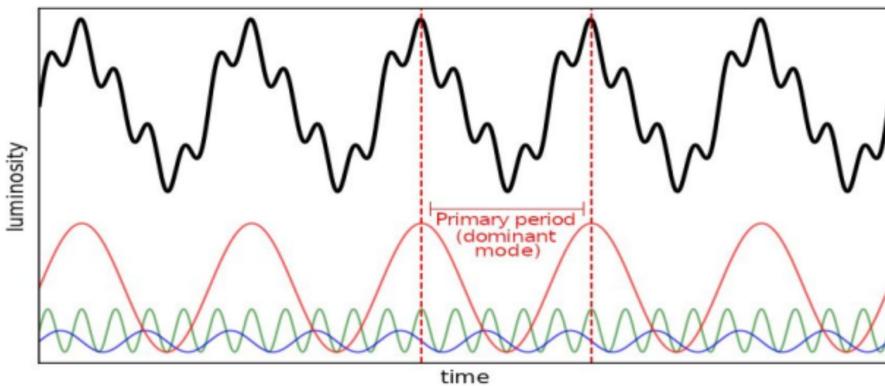
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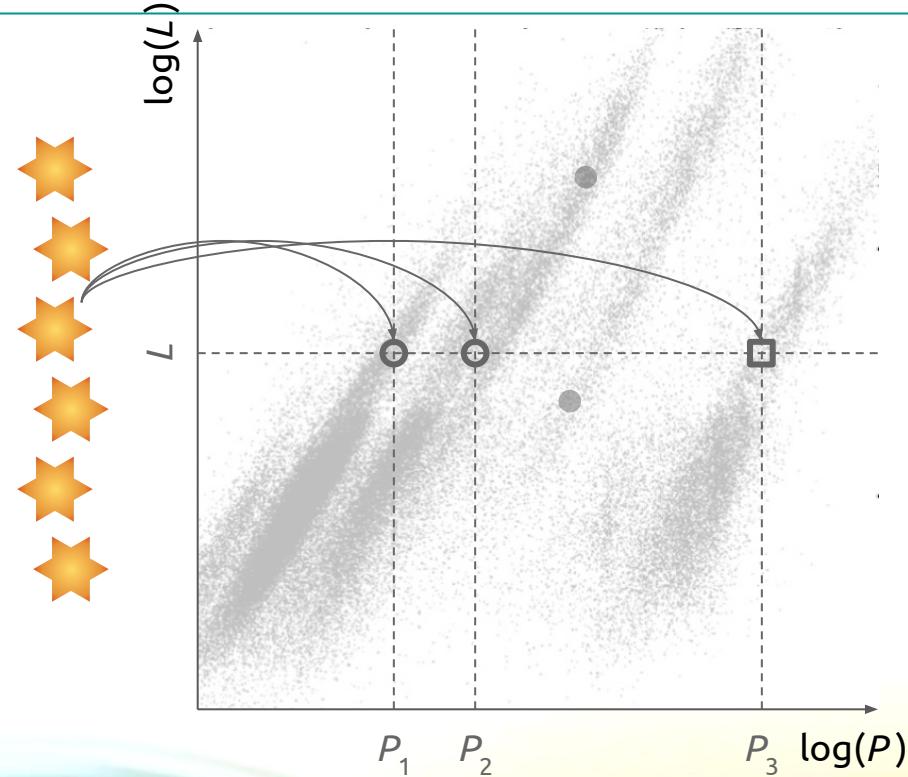
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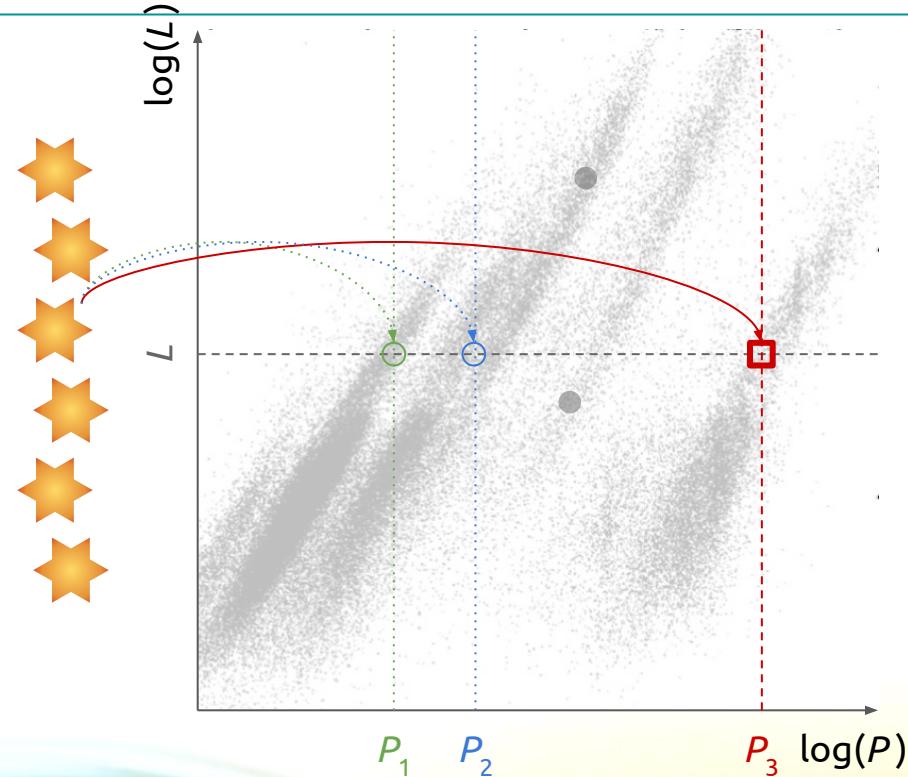
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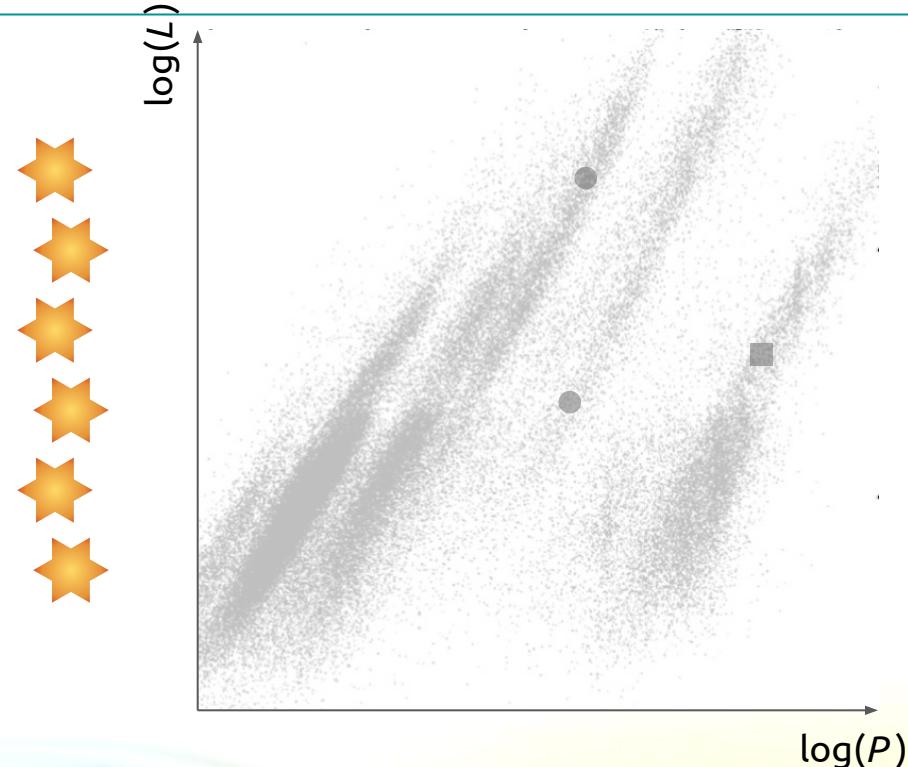
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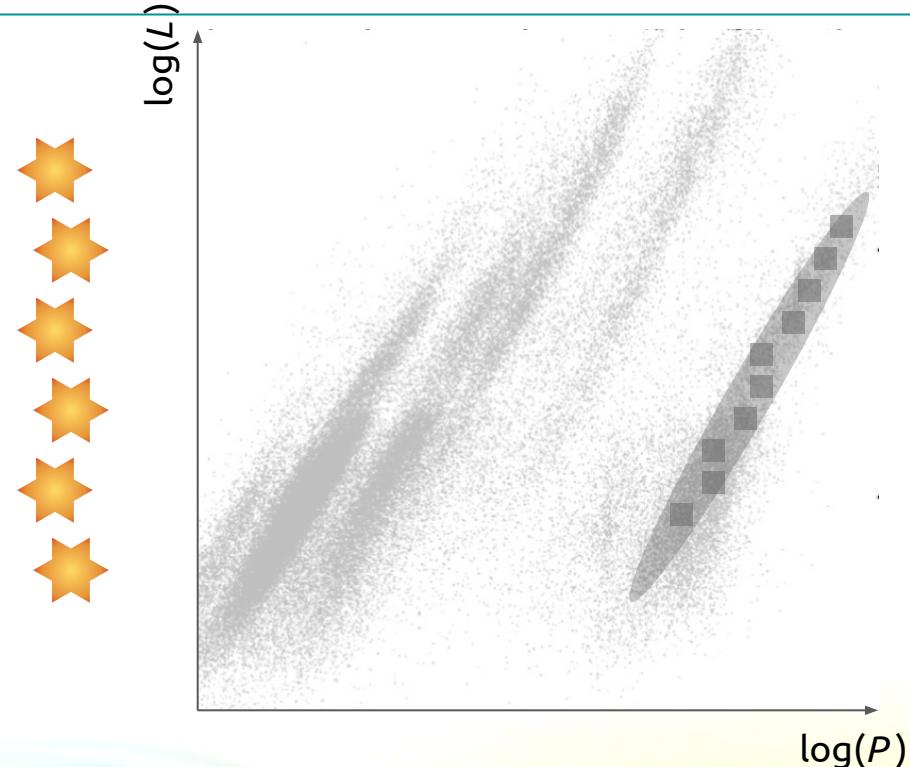
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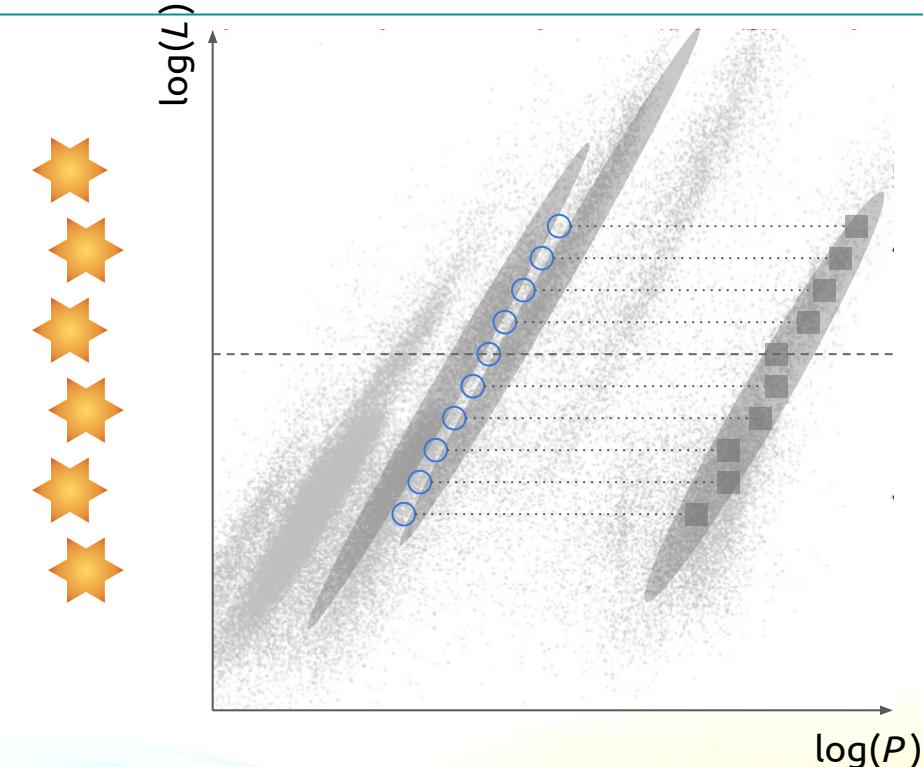
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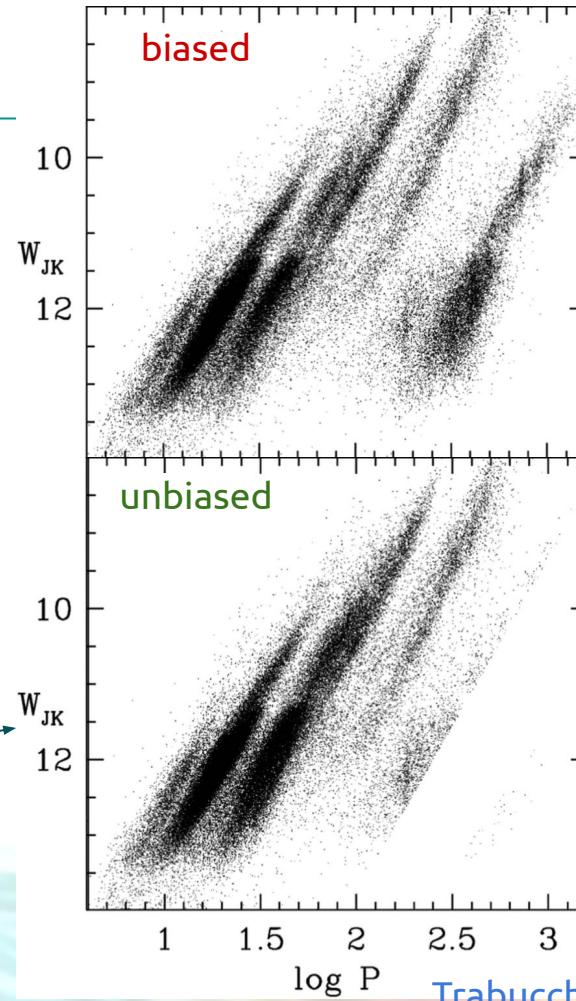
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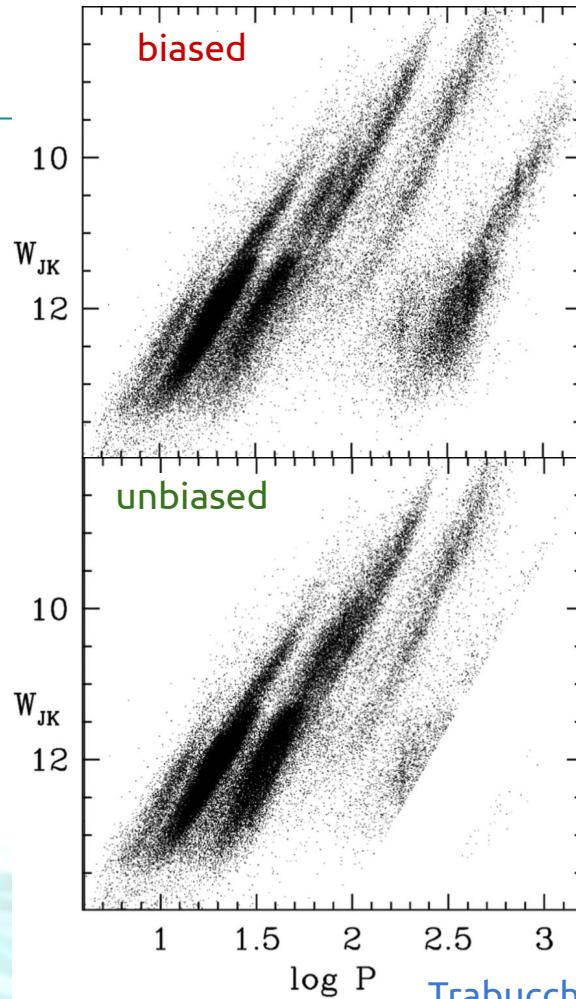
Trabucchi+ 2017

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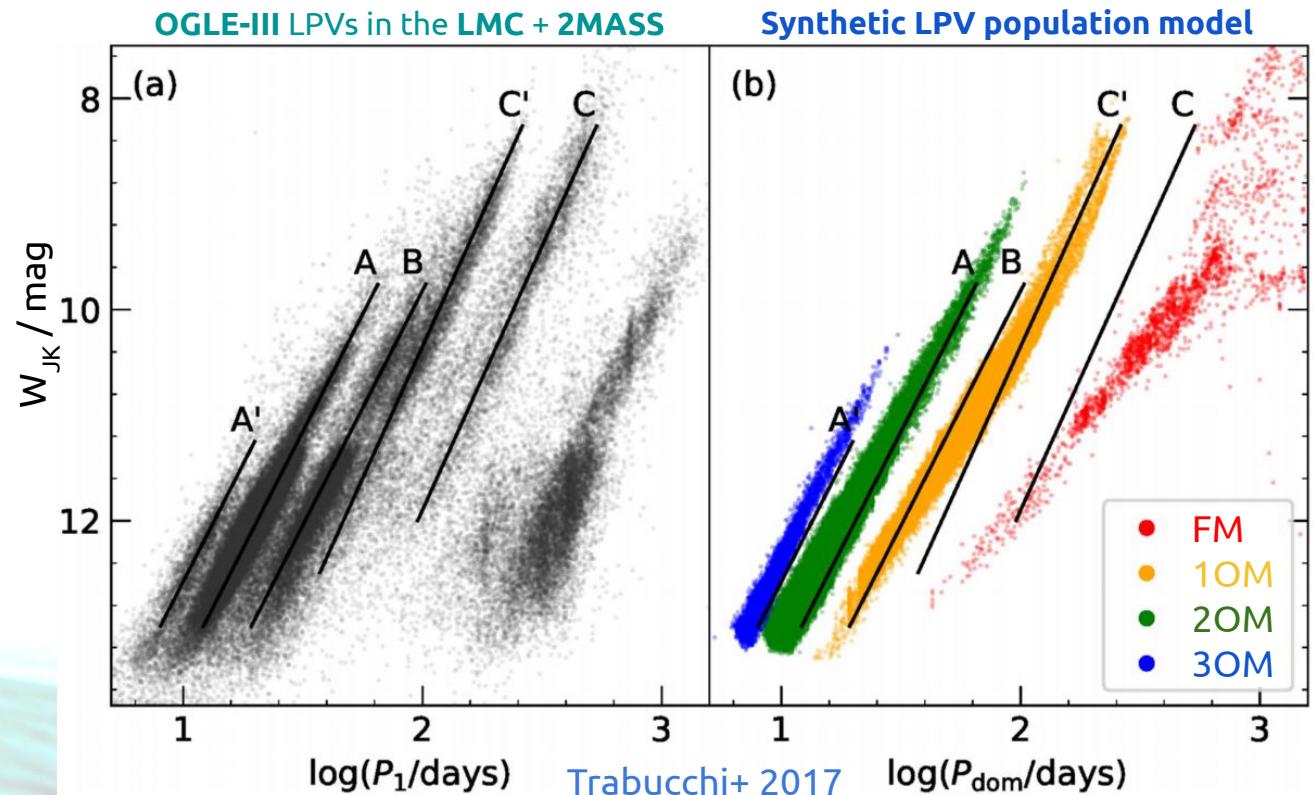
- High complexity of the PLD of LPVs
(multi-periodicity, non-pulsation periods, ...)
- Pulsation models + synthetic pop. model =
powerful approach for understanding LPVs

- canceled: gap between sequences B and C'
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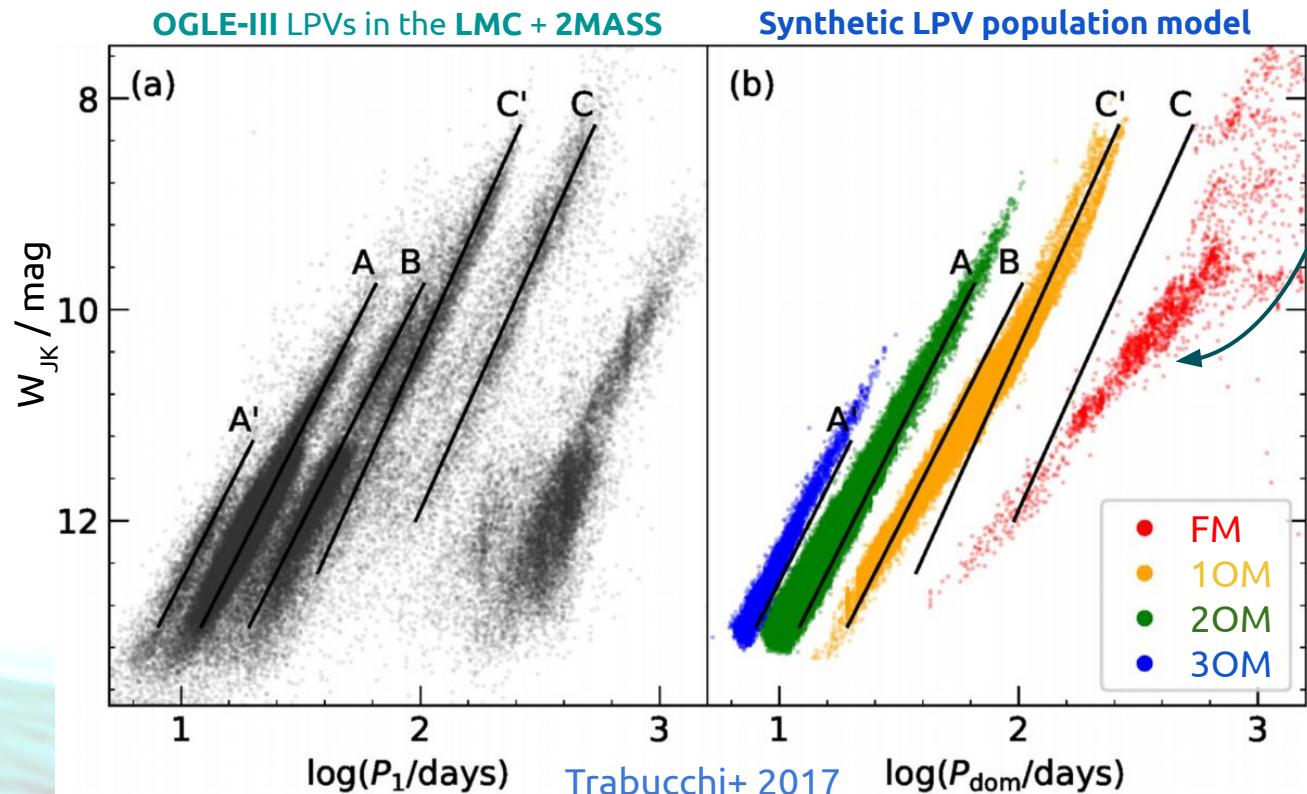
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LPV Pulsation Models



LPV Pulsation Models

linear approx.
breaks down



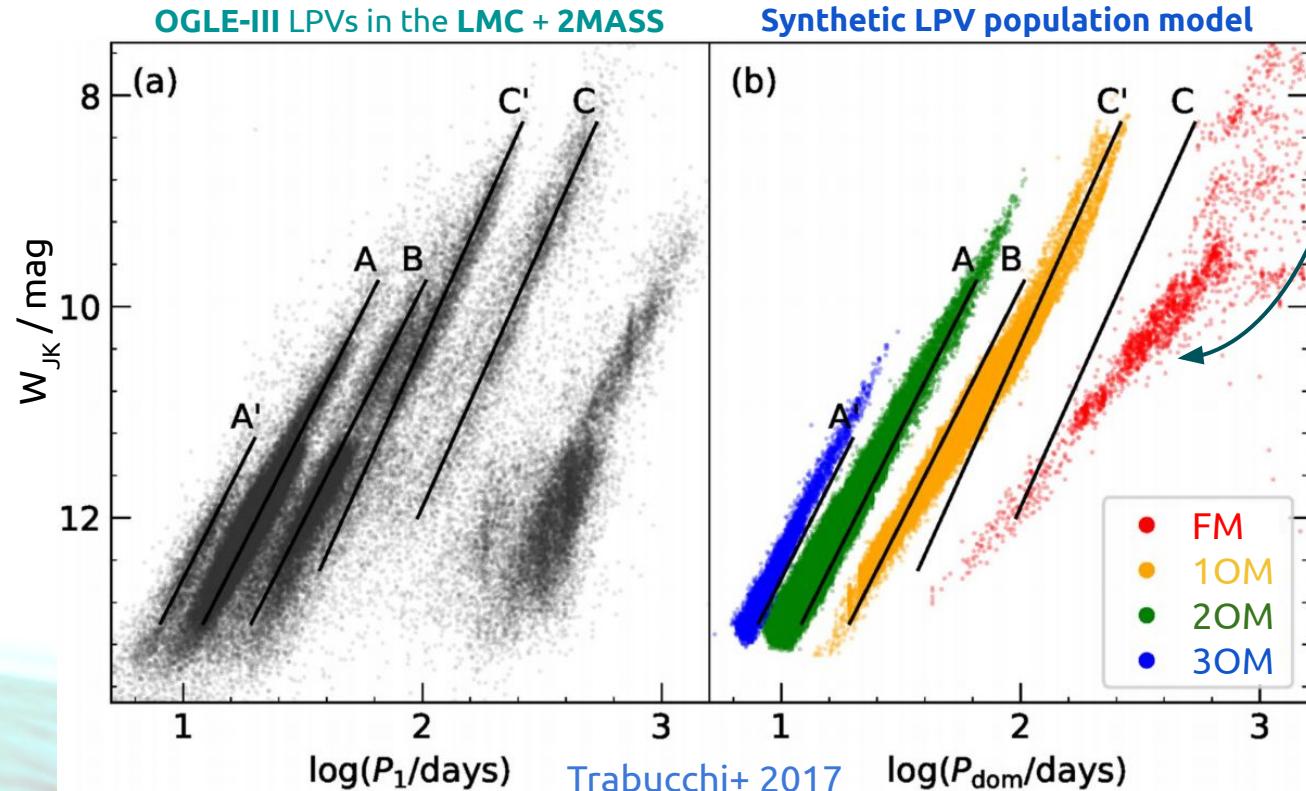
LPV Pulsation Models

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FM pulsators
large amplitude

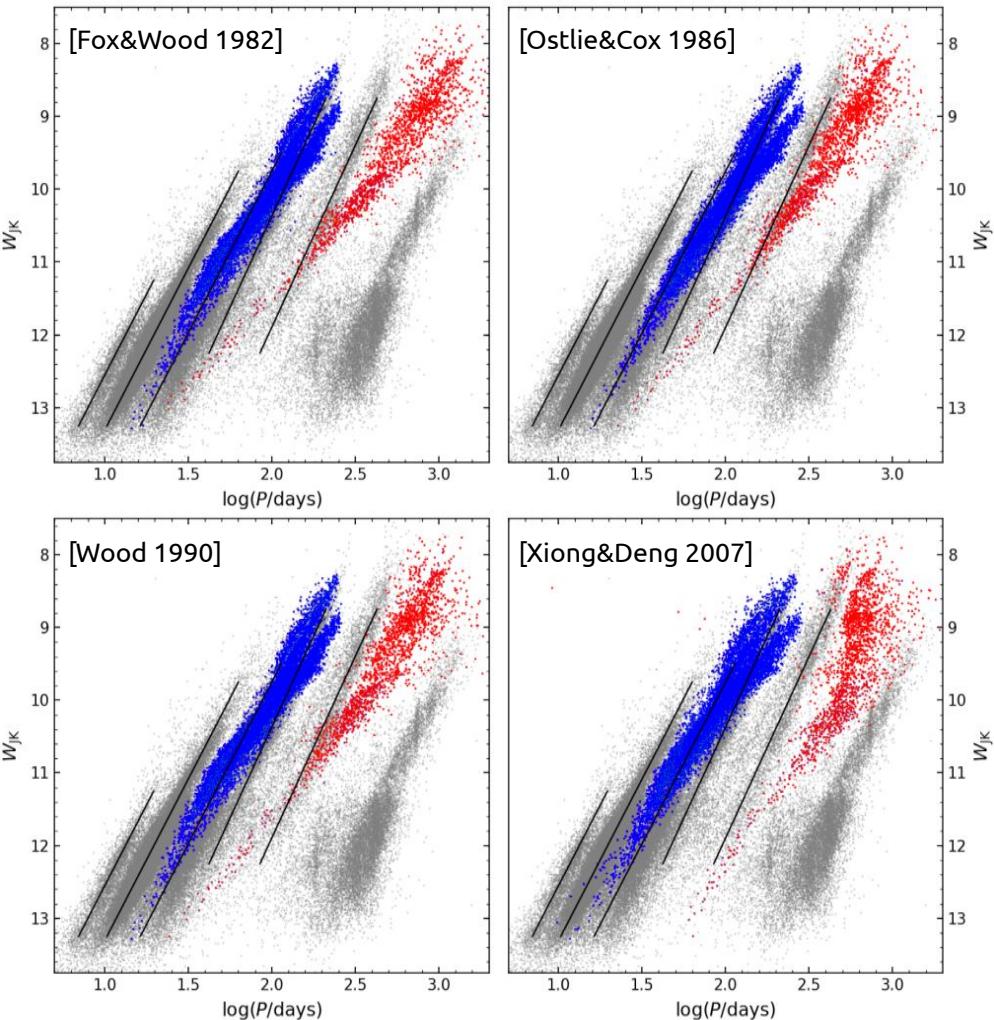


**intrinsically
non-linear:**



LPV Pulsation Models

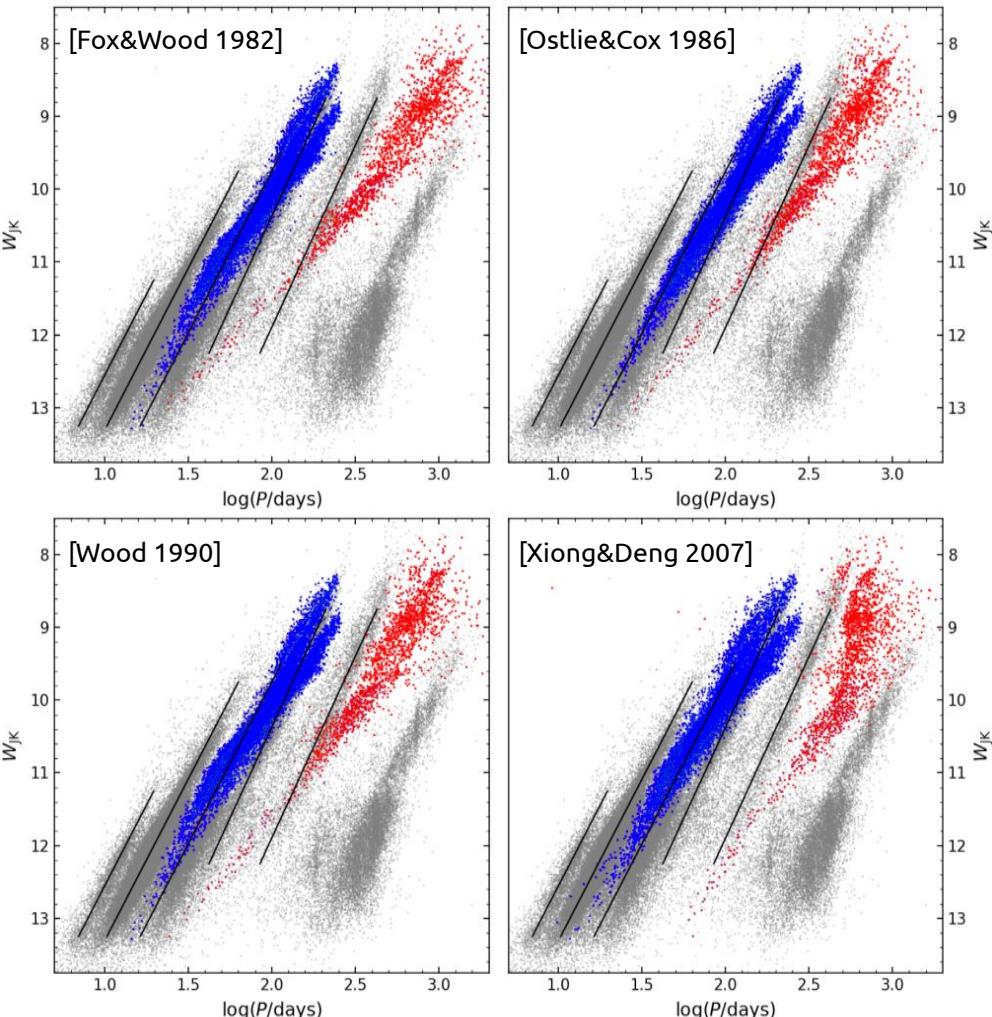
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LPV Pulsation Models

Trabucchi+ 2020

The vast majority of prescriptions from literature that are most commonly adopted to link pulsation and stellar structure/evolution are based on linear models, and **overestimate the FM period**.



LPV Pulsation Models

Pulsation code [Wood 1974, Keller & Wood 2006](#)

- 1D (spherically symmetric star)
- radial (spherically symmetric oscillation)
- non-adiabatic
- *hydrodynamic (non-linear)*

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1. envelope integration
2. hydrodynamic evolution
3. synthetic time series
4. post-processing!

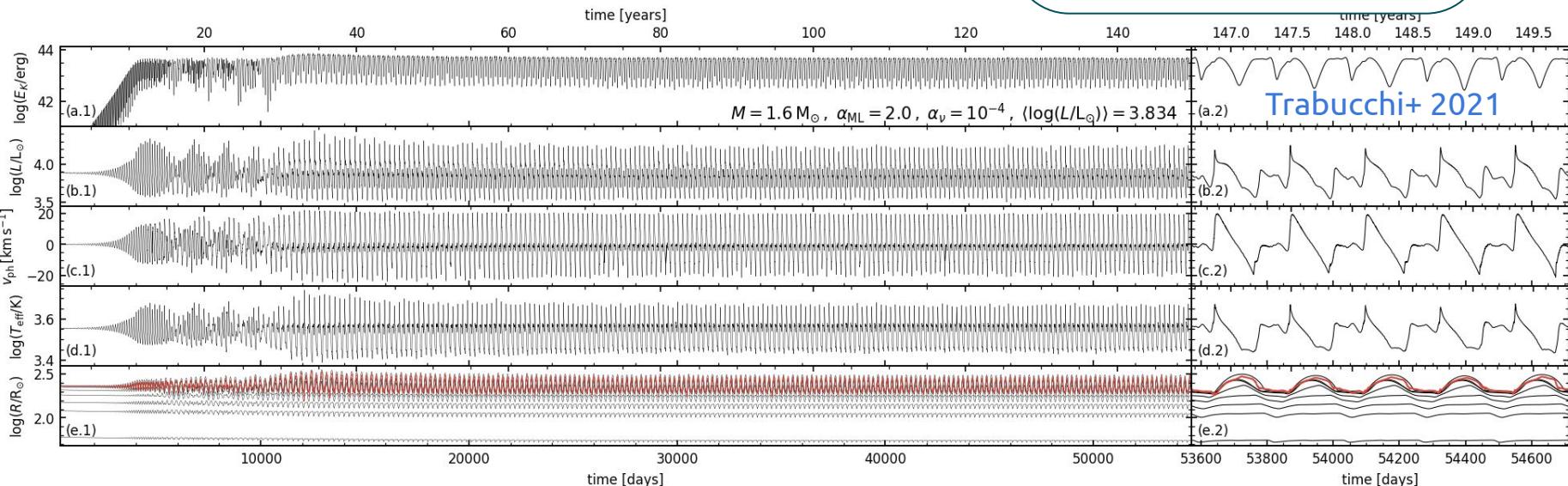
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Limited portion of the grid (fixed chemistry).

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- First systematic investigation of LPV pulsation in the non-linear regime
- Confirmed pulsation-induced readjustment of envelope structure, causing shorter FM period
(Ya'ari & Tuchman 1996, Lebzelter & Wood 2015)

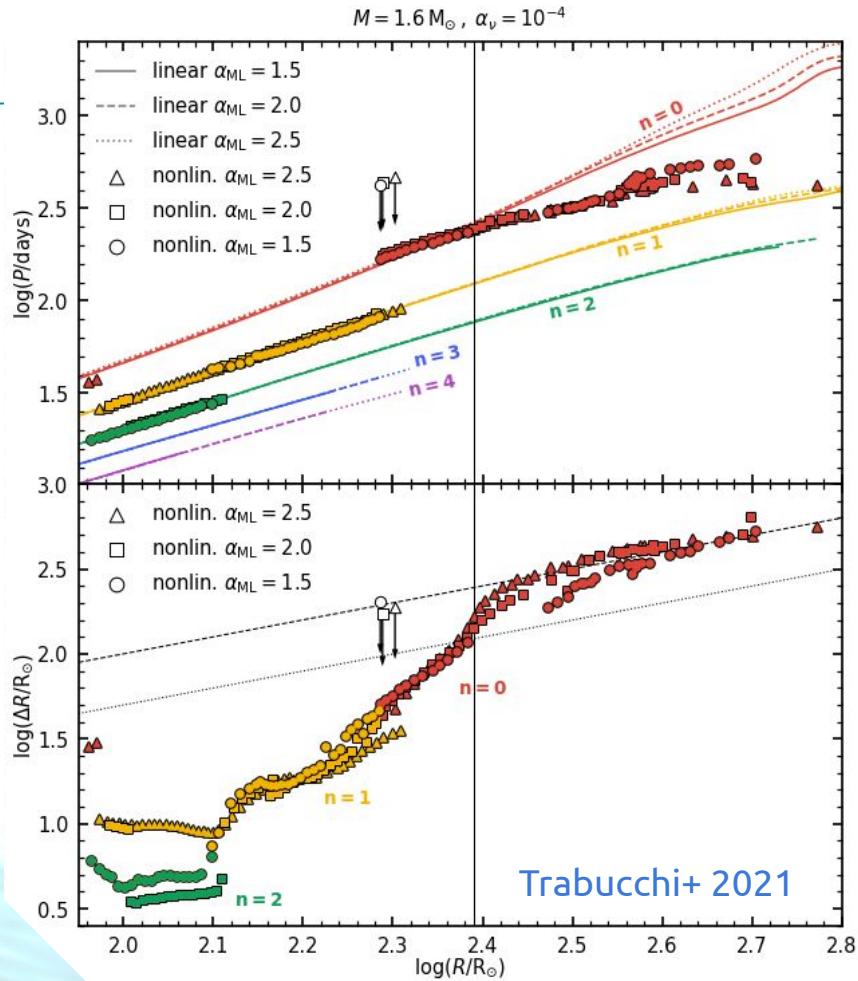
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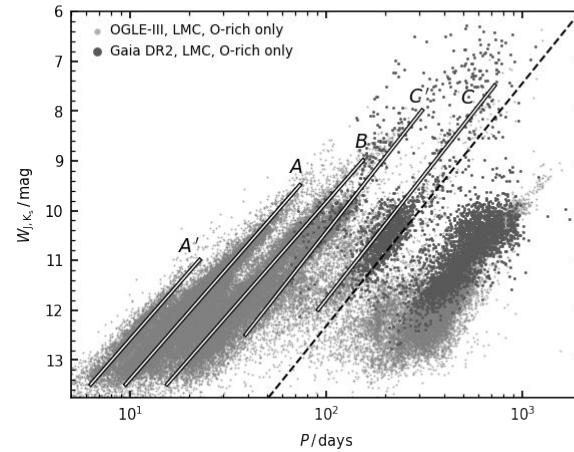
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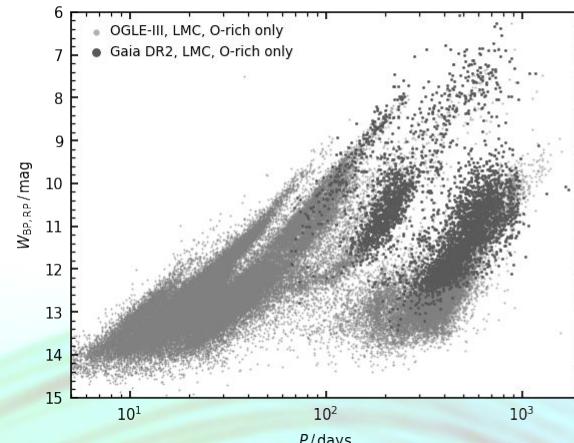
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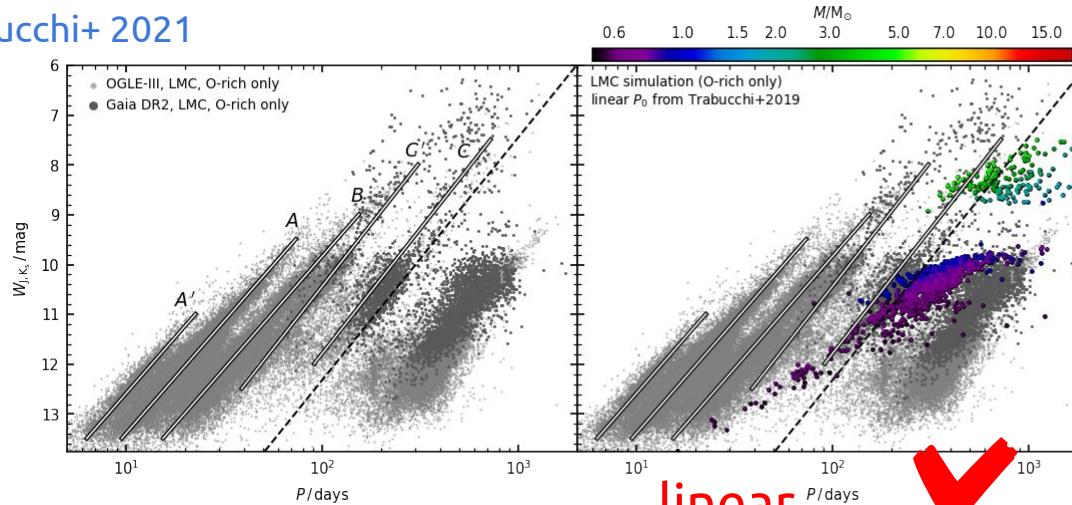
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- Confirmed pulsation-induced readjustment of envelope structure, causing shorter FM period ([Ya'ari & Tuchman 1996](#), [Lebzelter & Wood 2015](#))



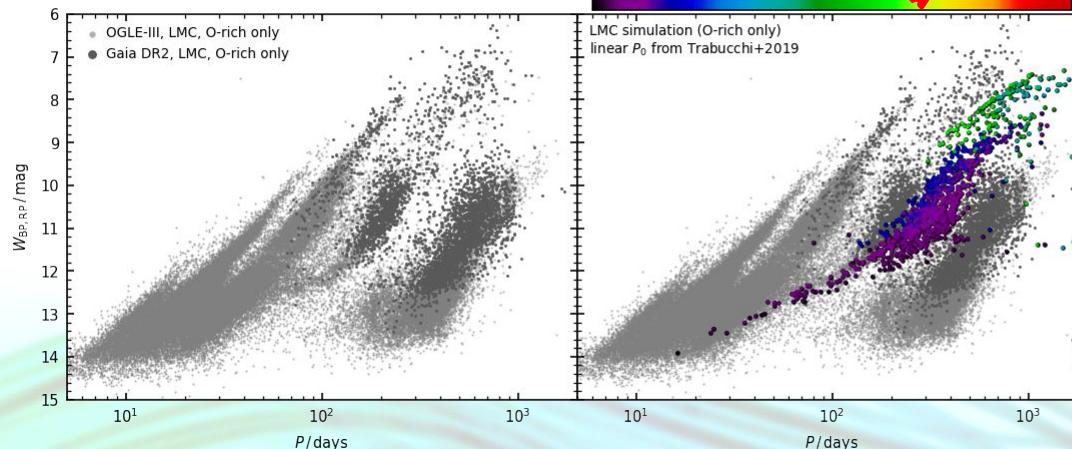


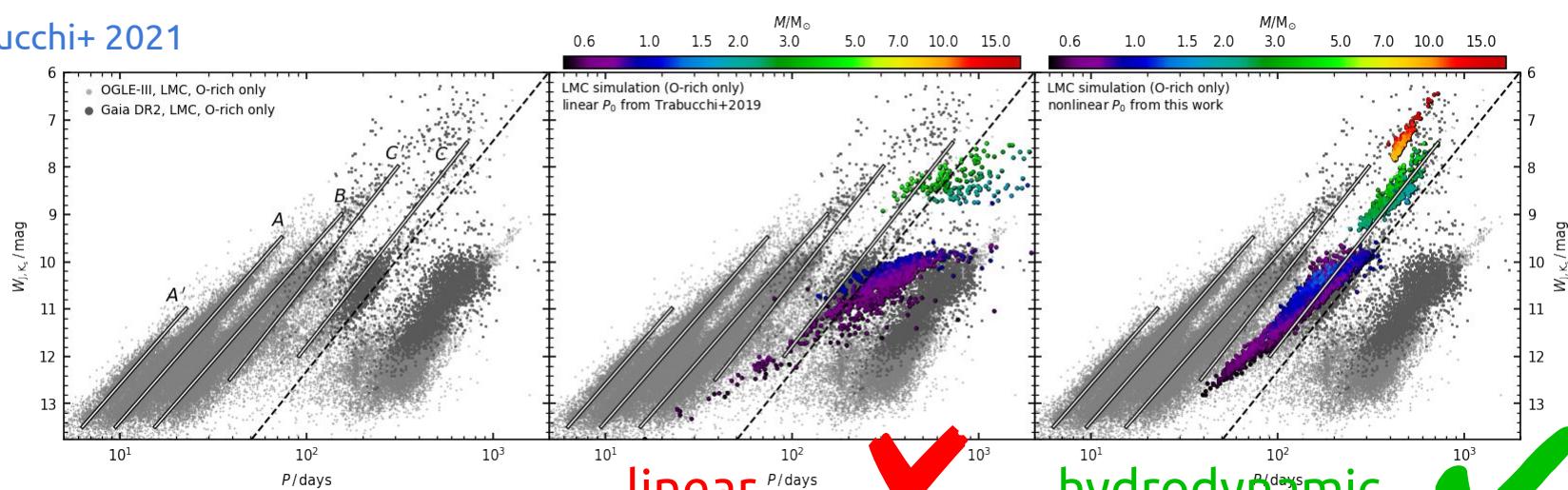
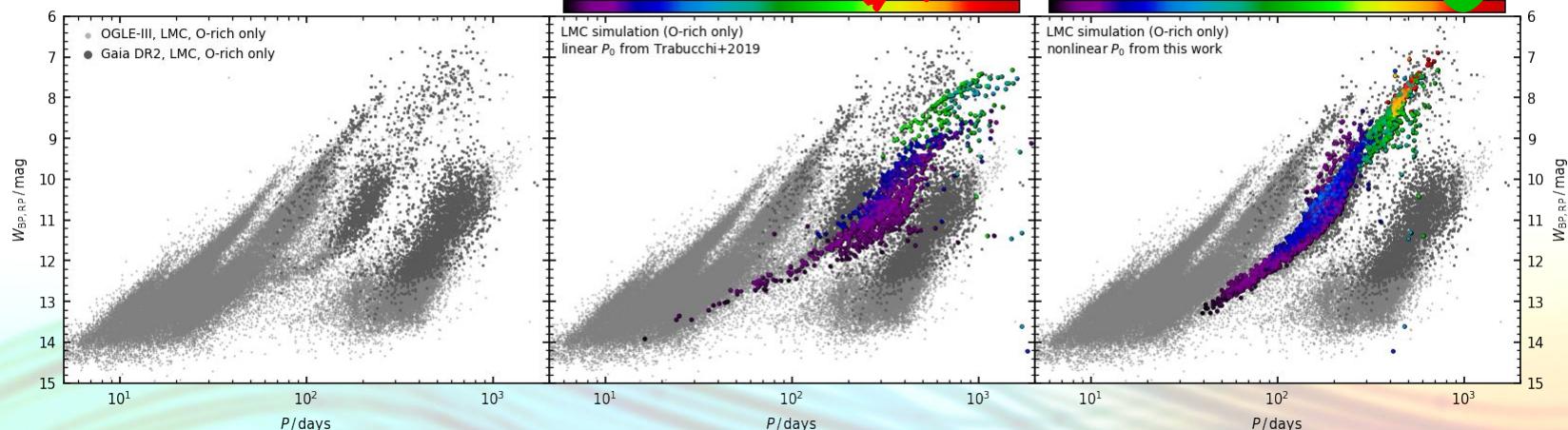
observations only





observations only

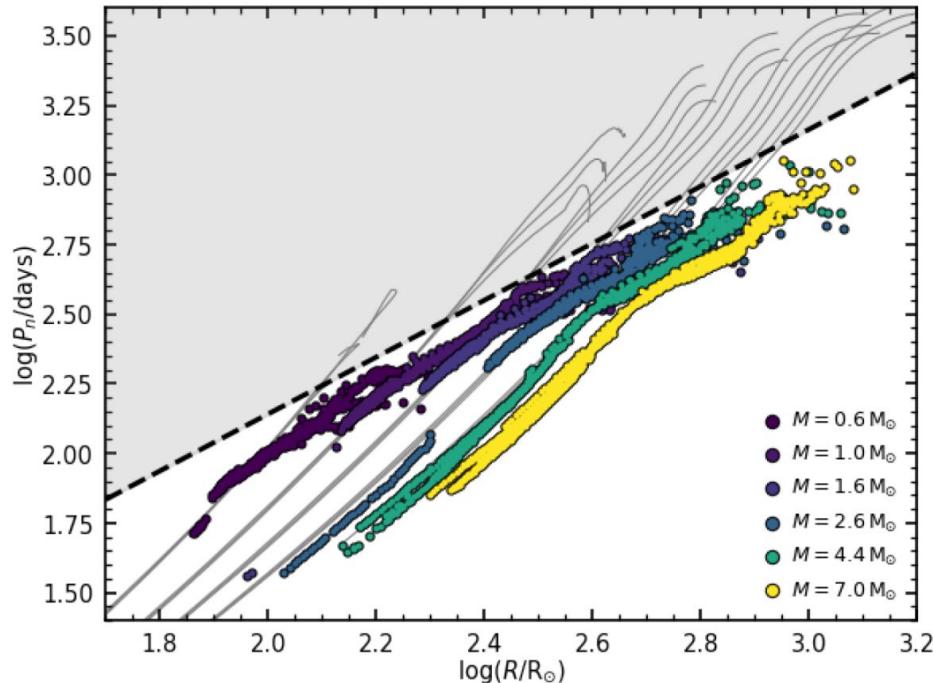


**observations only****linear****hydrodynamic**

LPV Pulsation Models

Main difference between linear & hydrodynamic models:

- linear: period increase indefinitely with radius
- hydrodynamic: period saturates

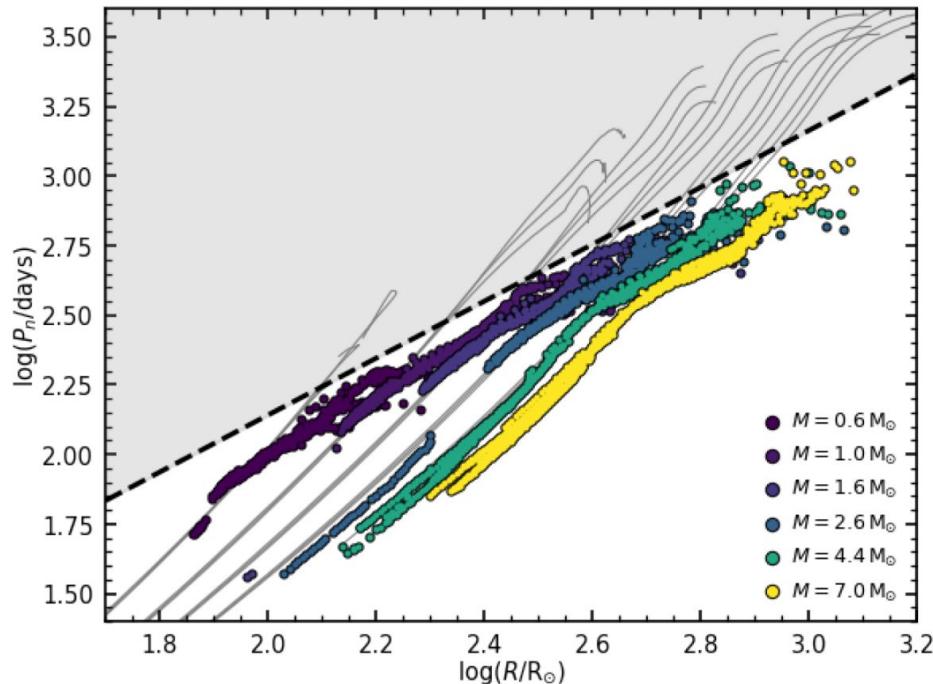


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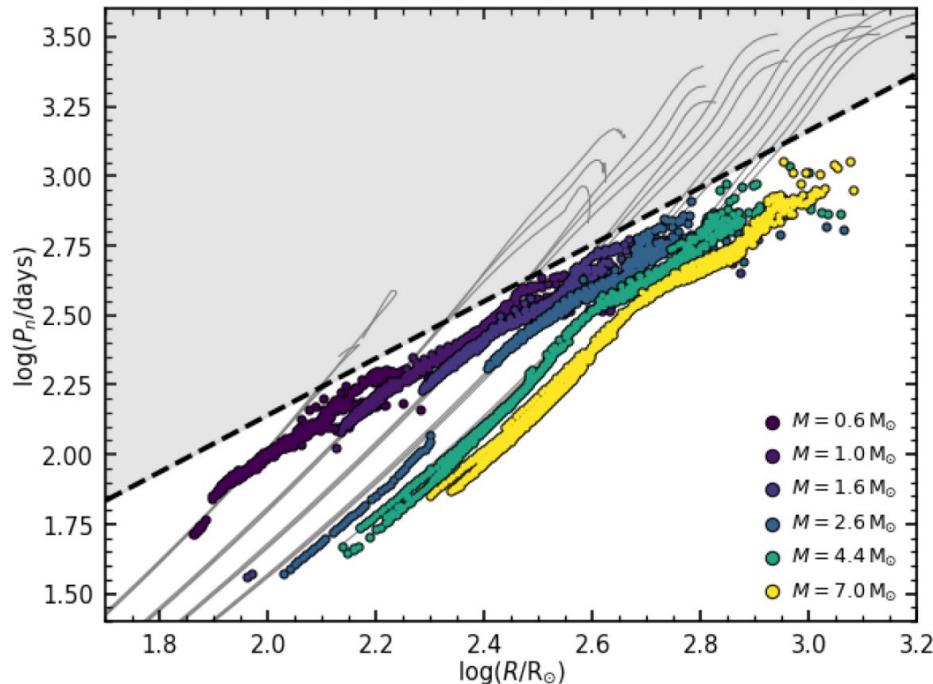


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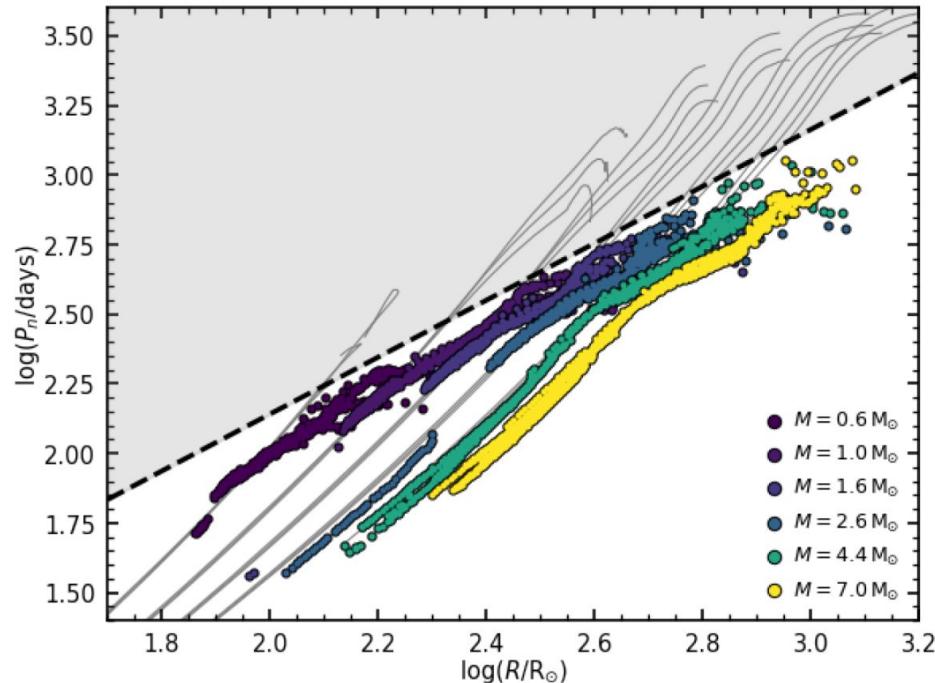
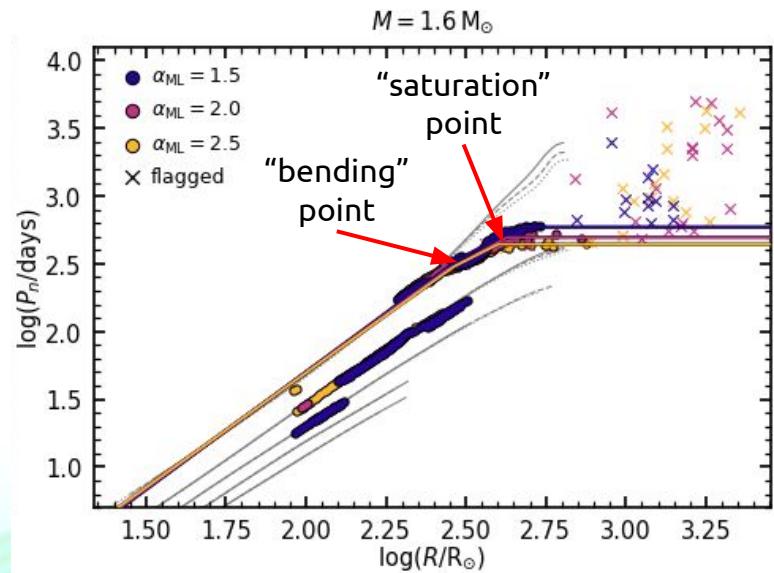


Trabucchi+ 2021

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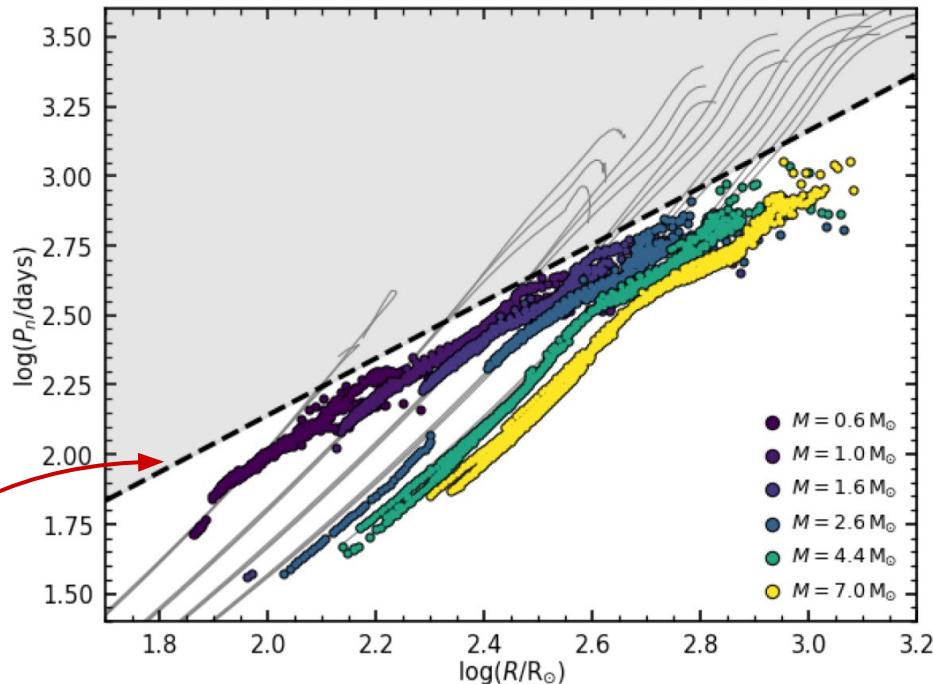
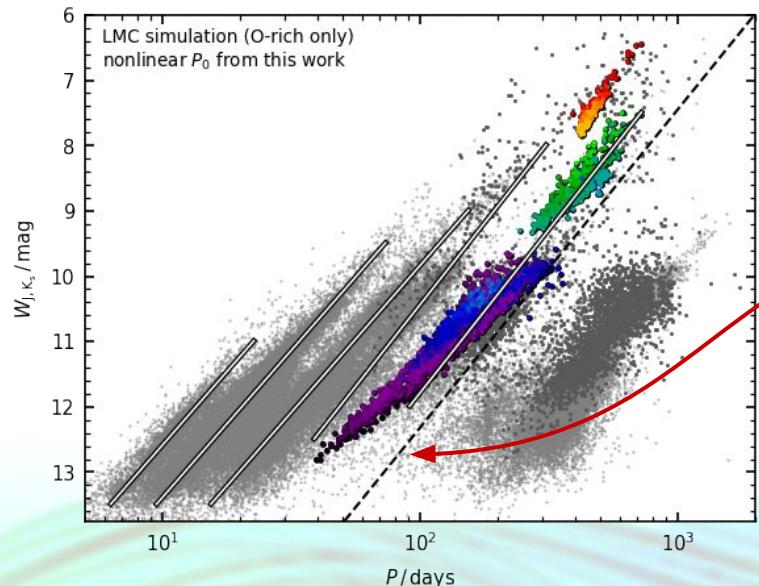
Trabucchi+ 2021

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Non-linear behaviour determines **right edge of FM PLR**



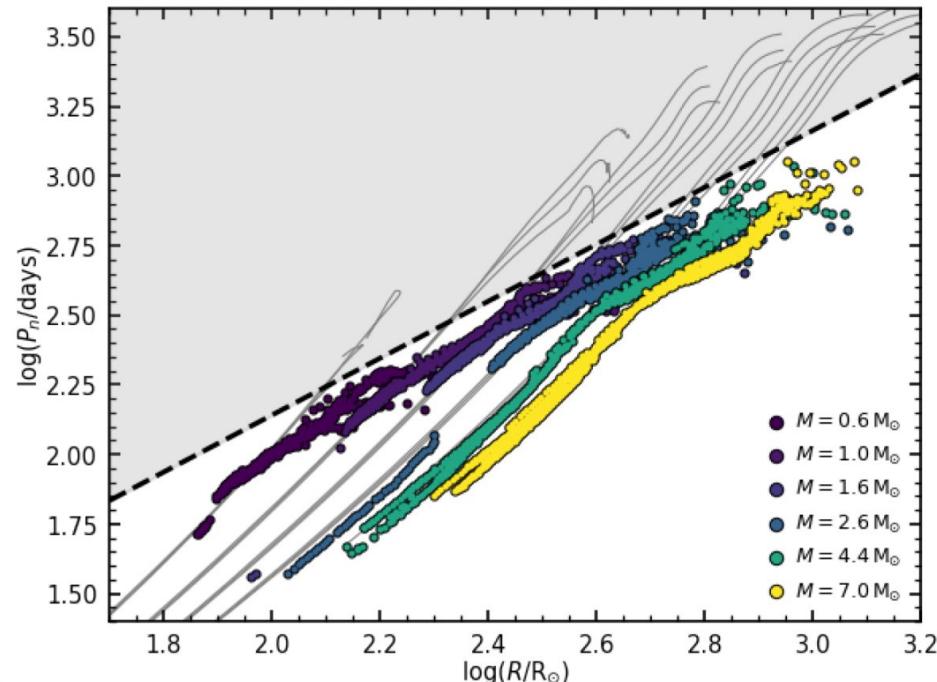
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Example: impact on mass estimate (roughly...)



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LPV Pulsation Models

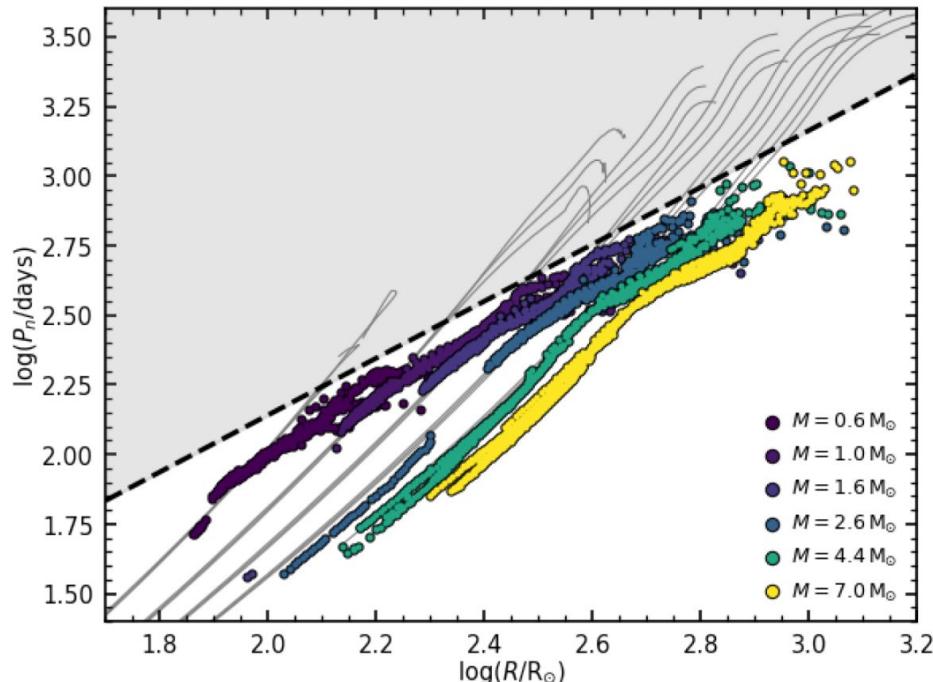
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- for long-period, relatively massive AGB stars, linear prescriptions cause to underestimate the mass by ~50% to ~100%
- for low-mass AGB stars, linear prescriptions cause to overestimate the mass by a factor ~2-4 at short periods, and twice as much for long periods



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LPV Pulsation Models

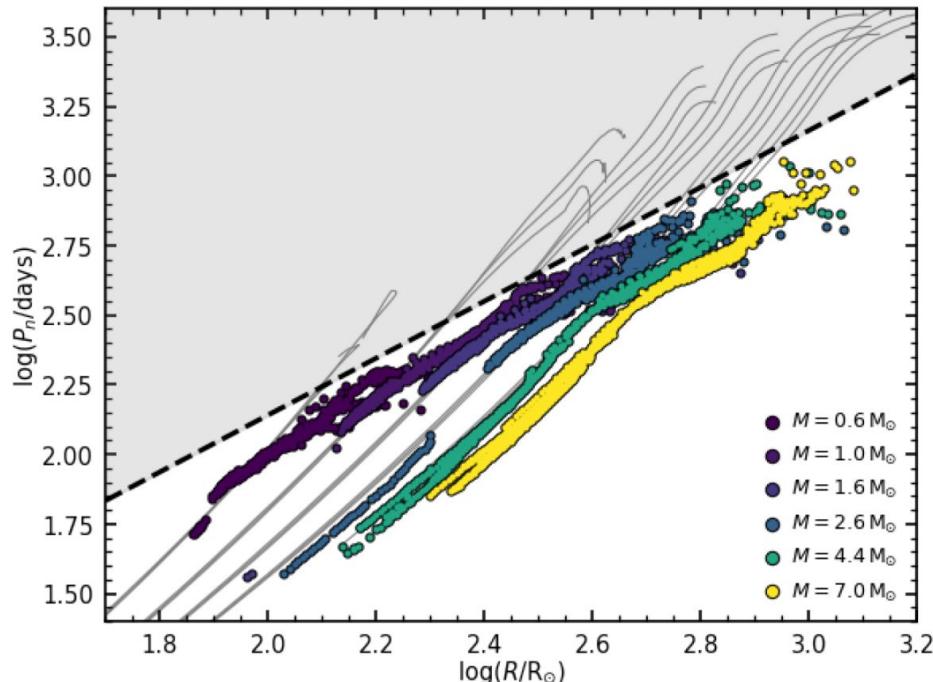
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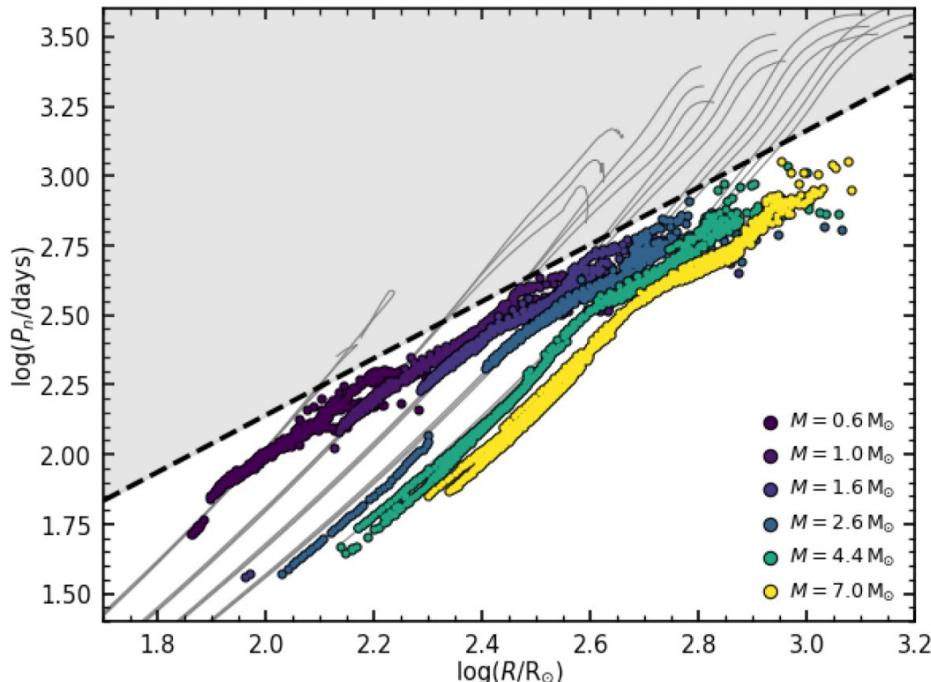
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Always use non-linear prescriptions for the FM period!



Trabucchi+ 2021

2. An application: the period-age relation

Period-Age Relation of LPVs

Historically known from kinematic studies
(Merrill 1923; Wilson & Merrill 1942; Feast 1963)

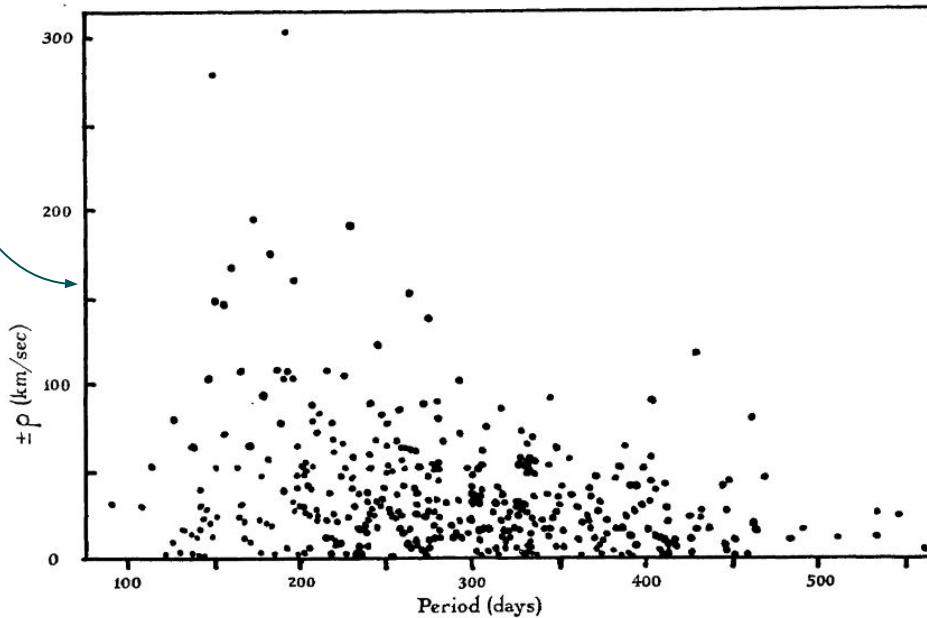


FIG. 4.—Relation of residual velocity (ρ) to period for Me variables.

Period-Age Relation of LPVs

Historically known from kinematic studies
(Merrill 1923; Wilson & Merrill 1942; Feast 1963)

Shorter-period LPVs = hotter kinematics = older

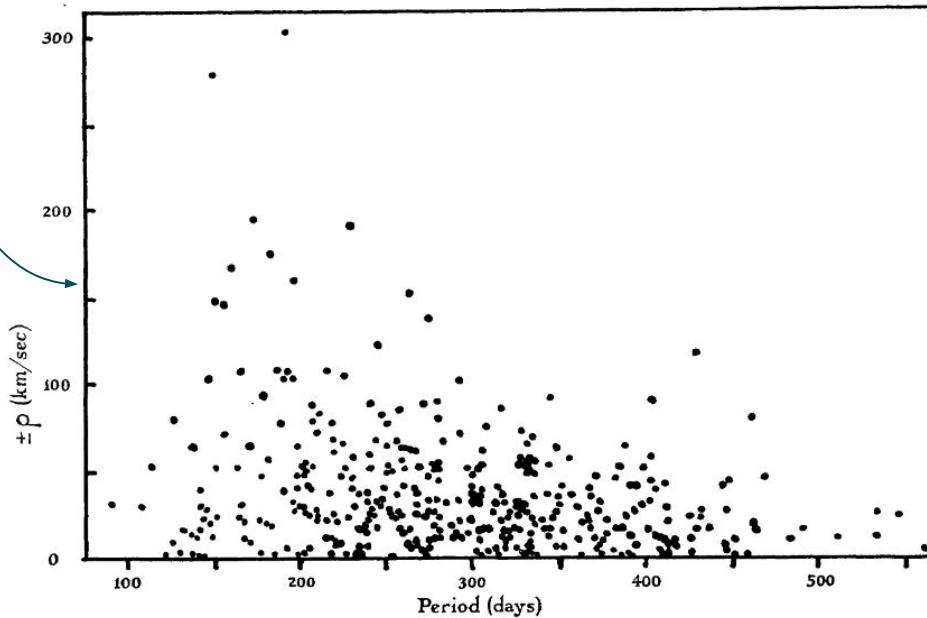


FIG. 4.—Relation of residual velocity (ρ) to period for Me variables.

Period-Age Relation of LPVs

Historically known from kinematic studies
(Merrill 1923; Wilson & Merrill 1942; Feast 1963)

Shorter-period LPVs = hotter kinematics = older

Basic explanation:

- PLR: longer period = brighter
- more luminous = more massive
- massive stars evolve faster, the ones we see are young
- thus: the longer the period, the younger the star

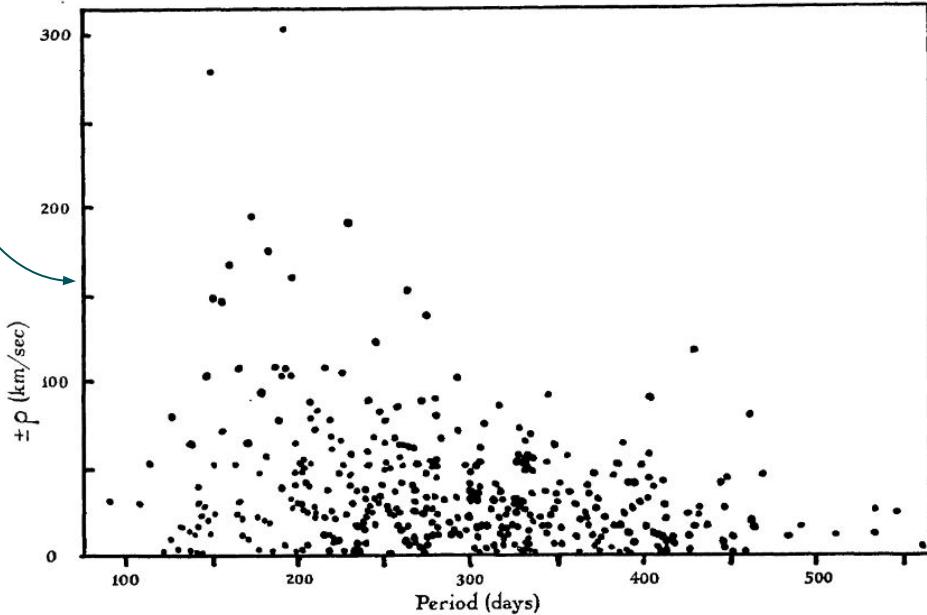


FIG. 4.—Relation of residual velocity (ρ) to period for Me variables.

Period-Age Relation of LPVs

Monthly Notices
of the
ROYAL ASTRONOMICAL SOCIETY

MNRAS 483, 3022–3035 (2019)
Advance Access publication 2018 December 4

doi:10.1093/mnras/sty

Age gradients throughout the Galaxy with long-period variables

J. Grady,¹ V. Belokurov^{1,2} and N. W. Evans^{1*}

¹Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK

²Center for Computational Astrophysics, Flatiron Institute, 162 5th Avenue, New York, NY 10010, USA

Monthly Notices
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ROYAL ASTRONOMICAL SOCIETY

MNRAS 492, 3128–3142 (2020)
Advance Access publication 2020 January 7

Age demographics of the Milky Way disc and bulge

J. Grady, V. Belokurov¹ and N. W. Evans^{1*}

Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA

JOURNAL ARTICLE

Mira variables in the Milky Way's nuclear stellar disc: discovery and classification

[Get access >](#)

Jason L Sanders, Noriyuki Matsunaga, Daisuke Kawata, Leigh C Smith, Dante Minniti, Philip W Lucas

Monthly Notices of the Royal Astronomical Society, Volume 517, Issue 1, November 2022,
Pages 257–280, <https://doi.org/10.1093/mnras/stac2274>

Published: 18 August 2022 Article history ▾

Astronomy
&
Astrophysics

A&A 660, A35 (2022)
<https://doi.org/10.1051/0004-6361/202141805>
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The VVV survey: Long-period variable stars

I. Photometric catalog of ten VVV/OGLE tiles*

F. Nikzat^{1,2}, C. E. Ferreira Lopes³, M. Catelan^{1,2,4}, R. Contreras Ramos^{1,2}, M. Zoccali^{1,2}, A. Rojas-Arriagada^{1,2}, V. F. Braga^{5,6}, D. Minniti^{7,8}, J. Borissova^{2,9}, and I. Becker^{1,10}

THE ASTROPHYSICAL JOURNAL, 836:218 (5pp), 2017 February 20

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<https://doi.org/10.3847/1538-4357/836/2/218>



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Absence of an X-shaped Structure in the Milky Way Bulge Using Mira Variable Stars

Martín López-Corredoira^{1,2}

¹ Instituto de Astrofísica de Canarias, E-38205 La Laguna, Tenerife, Spain; martinlc@iac.es

² Departamento de Astrofísica, Universidad de La Laguna, E-38206 La Laguna, Tenerife, Spain

Received 2016 October 25; revised 2016 December 12; accepted 2016 December 12; published 2017 February 23

Period-Age Relation of LPVs

Few theoretical studies

(Wyatt & Cahn 1983; Feast & Whitelock
1987; Eggen 1998)

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New non-linear FM prescription
enables first accurate and systematic
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Compared with Miras/SRVs in clusters

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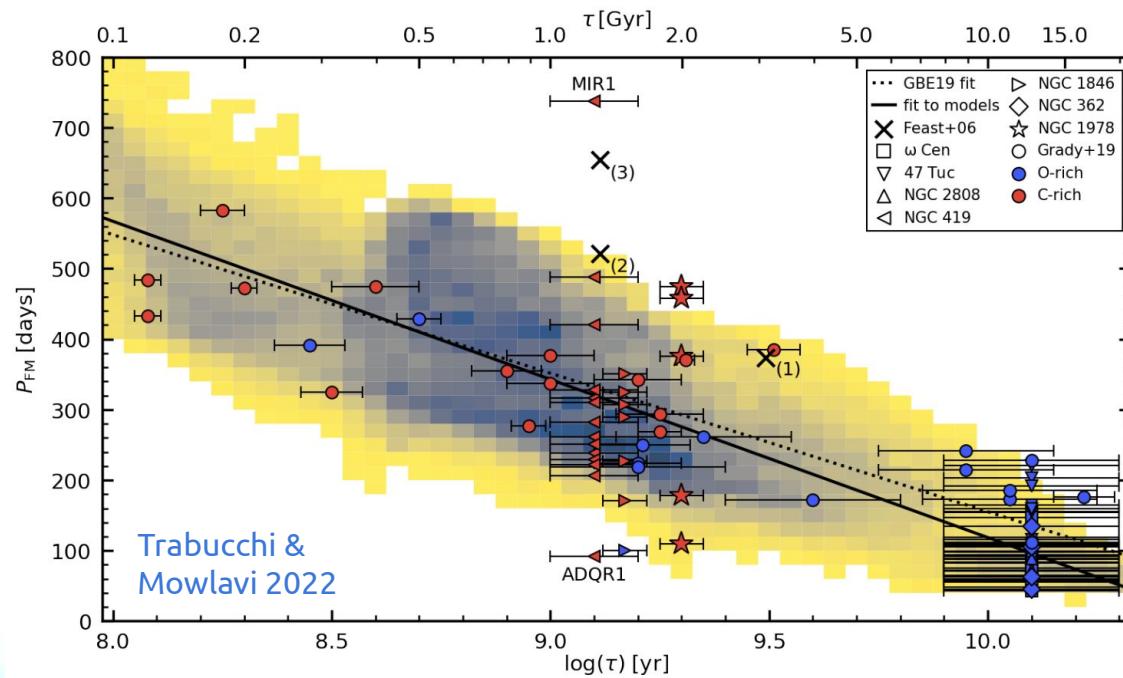
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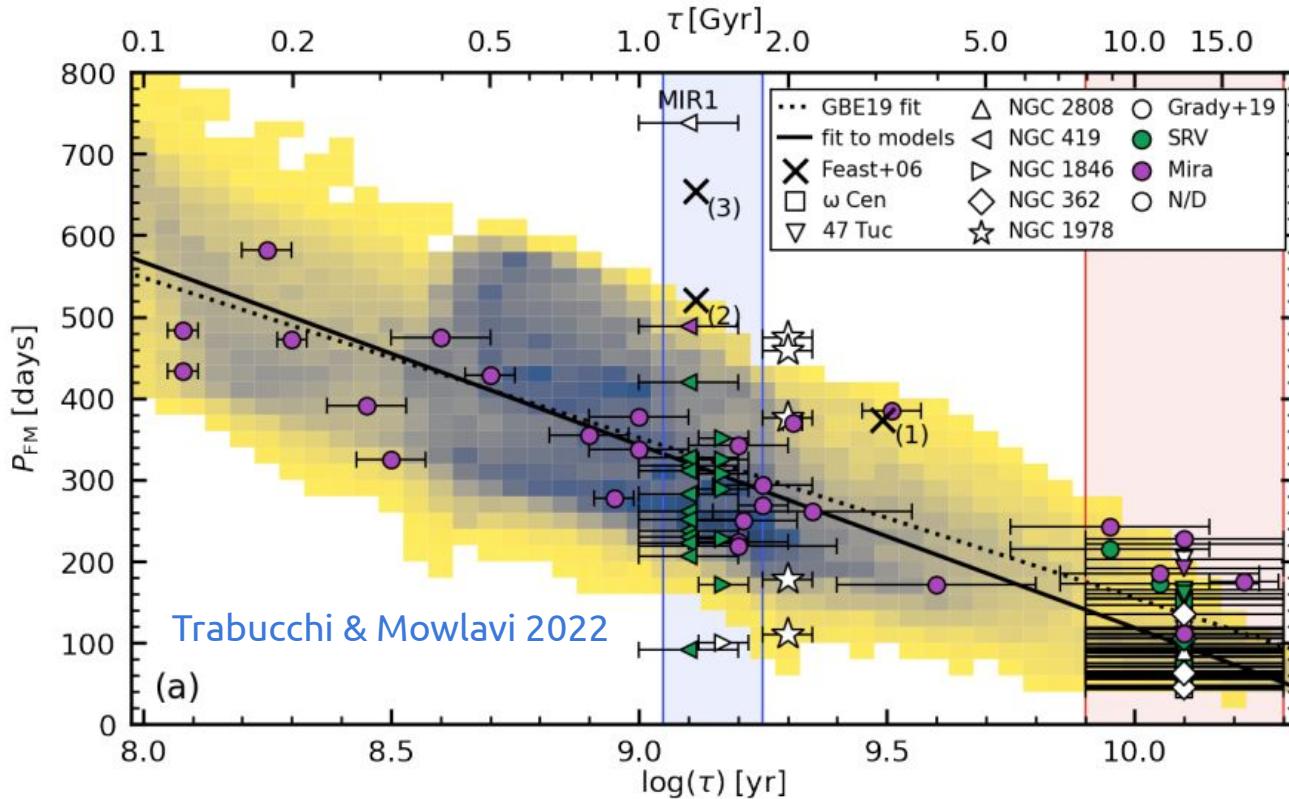
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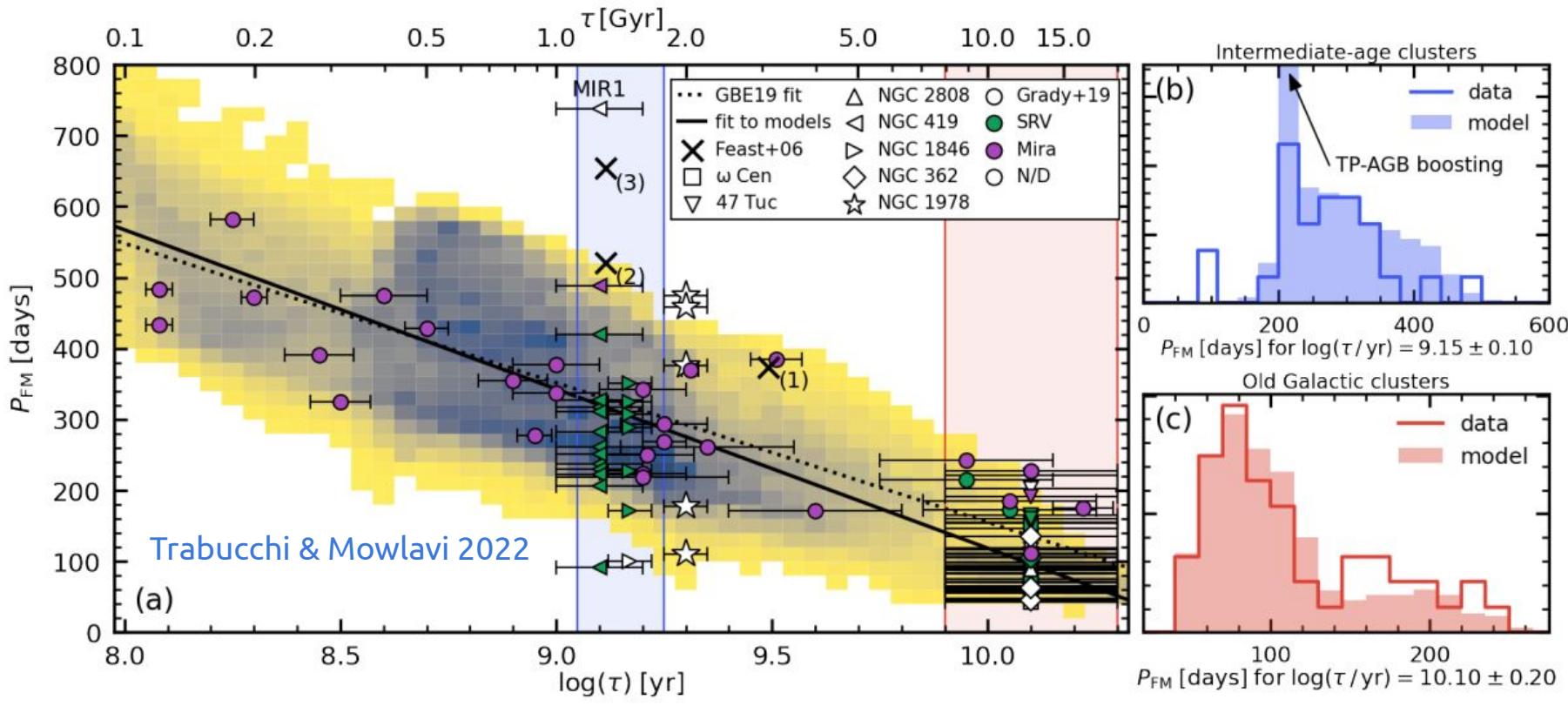
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Period-Age Relation of LPVs



Period-Age Relation of LPVs



Period-Age Relation of LPVs

Several uncertainties...

Sensitivity of period-age distribution on metal content

Selection effects:
inclusion/exclusion of SRVs and
completeness of Mira sample

Sensitivity of photometric amplitude on metal content and impact on source selection

Sensitivity of pulsation instability on metal content

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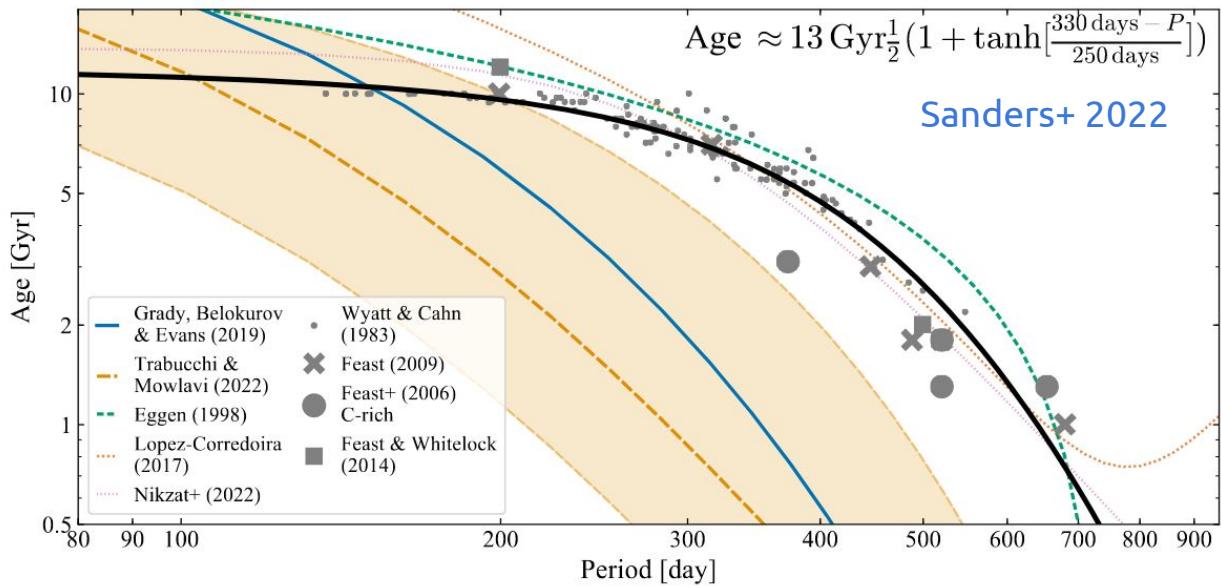
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Sensitivity of pulsation instability on metal content



3. Ongoing work and next steps

Composition effects...

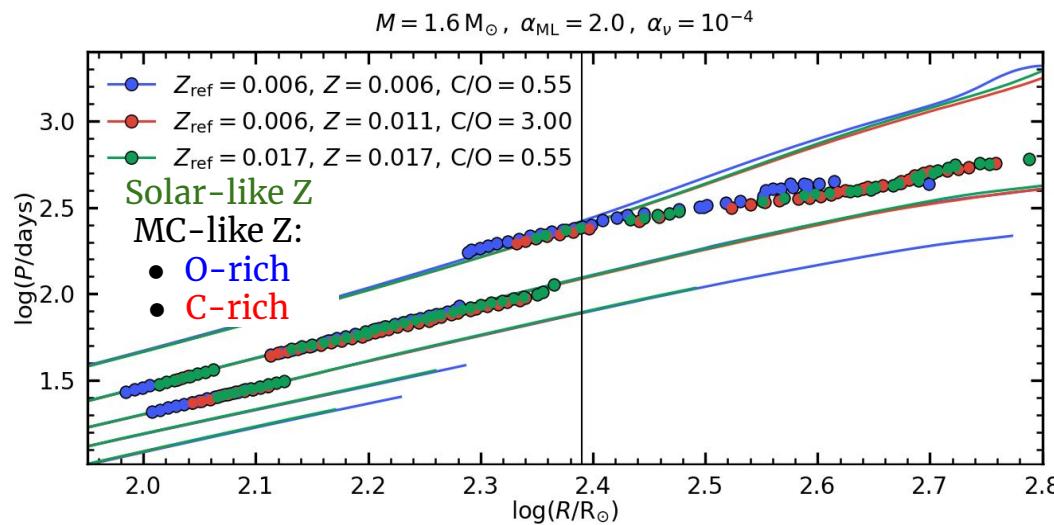
No (non-linear) models!

Only minimal analysis:
higher Z or C-star

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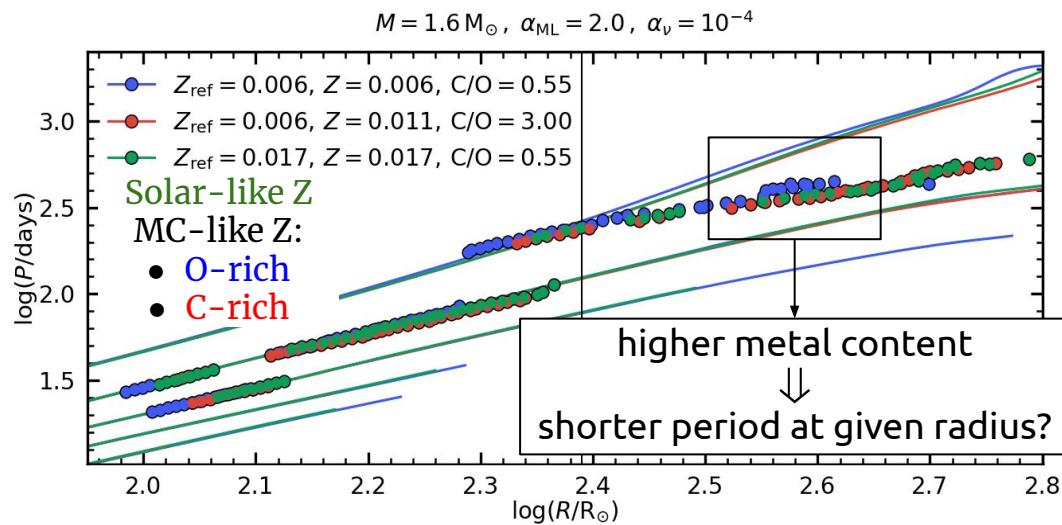
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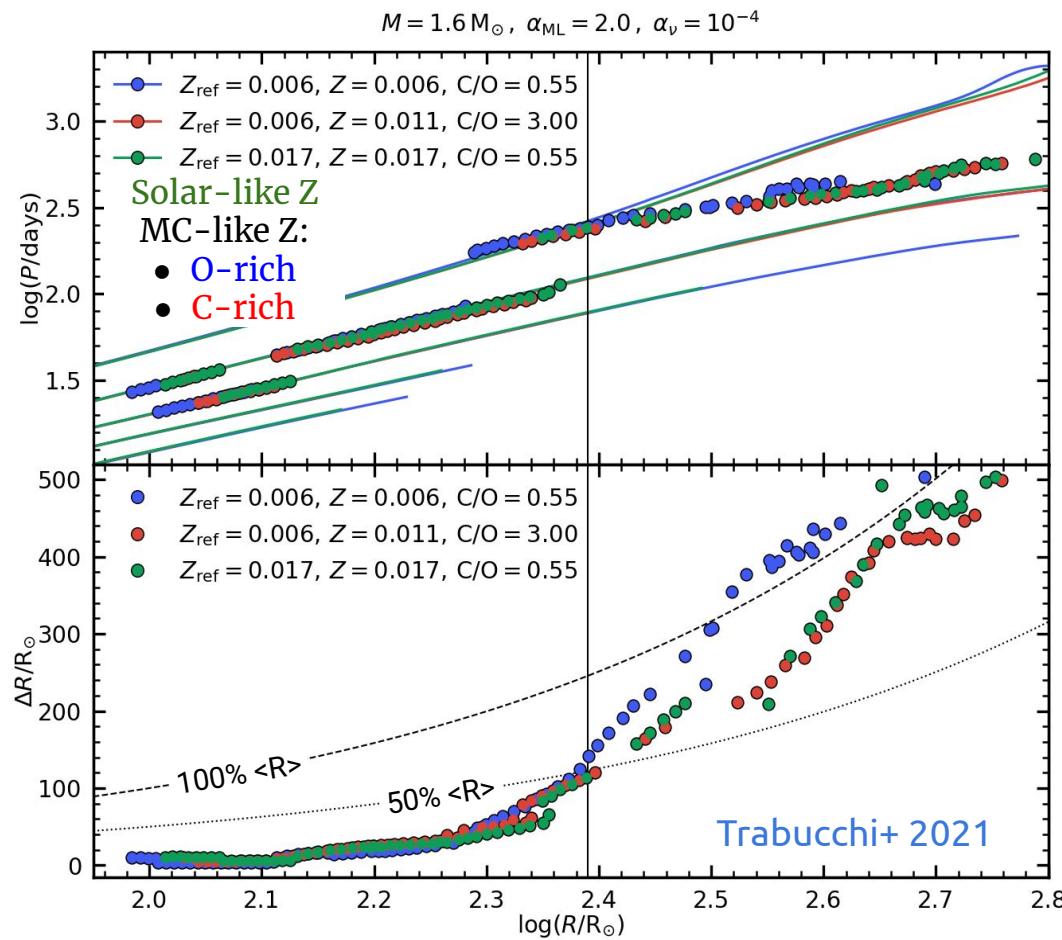
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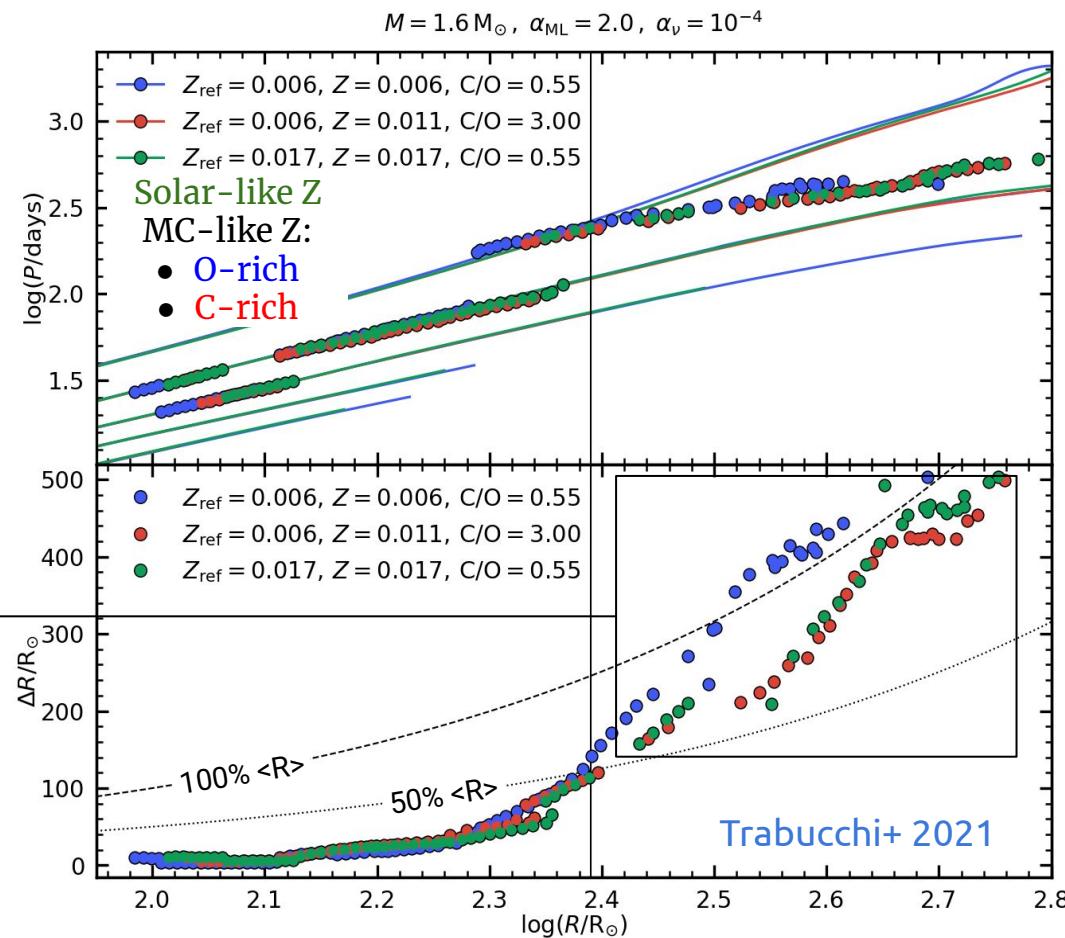


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Different amplitude
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shape of the PR relation?
selection of Miras?



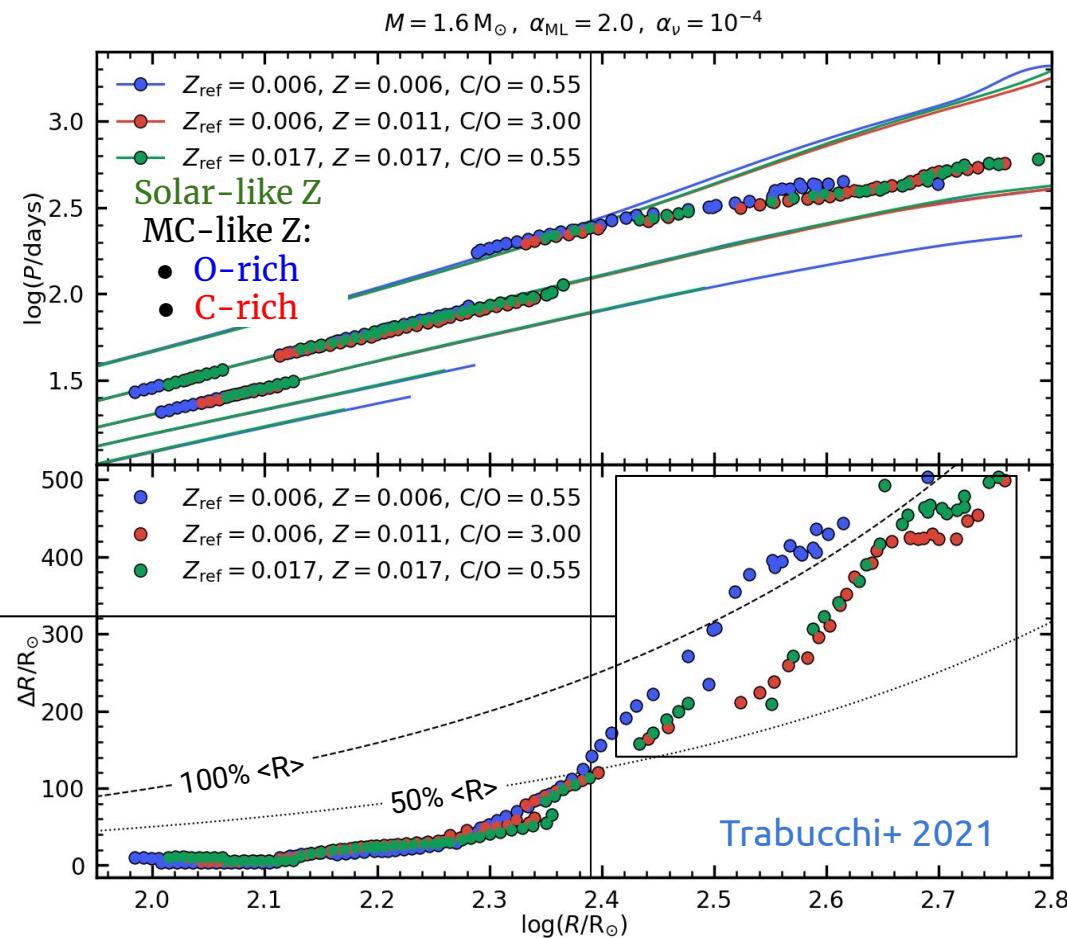
Composition effects...

No (non-linear) models!

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Further investigation needed!

Different amplitude
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New models



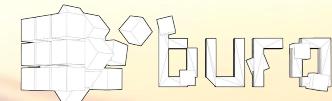
New calculations ongoing, preparatory for VRO-LSST



New models



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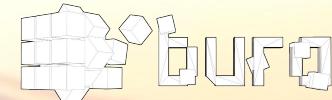


New models



New calculations ongoing, preparatory for VRO-LSST

- Grid upgrade: full hydrodynamic
- Extension to other chemical parameters (Z, C/O, ...)
- Multi-periodicity properties
- Template folded curves of surface parameters (L , T_{eff} , R_{phot})
- Envelope structure throughout pulsation cycle
- Preliminary light curve templates

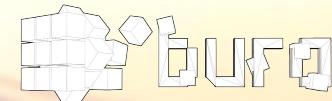


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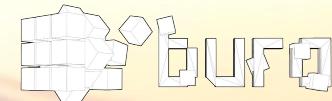
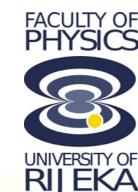


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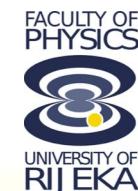


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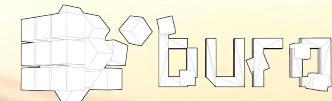
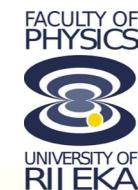


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New opacity

National Grant Project
P.I. Paola Marigo



ÆSOPUS 2.0 input form

Low-temperature Rosseland mean opacities on demand

See the paper [Marigo & Aringer \(2009\)](#) for code details,
and [Marigo et al. \(2022\)](#) for the latest novelties.

The former ÆSOPUS 1.0 interface is [here](#).

Note added on 14.02.2023: The accuracy of the EoS solution has been improved, and there may be minor changes
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Astronomy
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Astrophysics

Low-temperature gas opacity
ÆSOPUS: a versatile and quick computational tool

P. Marigo¹ and B. Aringer^{2,3}

New opacity

National Grant Project
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Astronomy
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Astrophysics

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THE ASTROPHYSICAL JOURNAL, 940:129 (15pp), 2022 December 1

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Updated Low-temperature Gas Opacities with ÆSOPUS 2.0

<https://doi.org/10.3847/1538-4357/ac9b40>



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THE ASTROPHYSICAL JOURNAL, 960:18 (9pp), 2024 January 1

<https://doi.org/10.3847/1538-4357/ad0898>

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ÆSOPUS 2.0: Low-temperature Opacities with Solid Grains



Paola Marigo¹ , Peter Woitke² , Emanuele Tognelli³ , Léo Girardi⁴ , Bernhard Aringer⁵ , and Alessandro Bressan⁶

¹ Department of Physics and Astronomy G. Galilei, University of Padova, Vico del dell'Osservatorio 3, I-35122, Padova, Italy; paola.marigo@unipd.it

² Space Research Institute, Austrian Academy of Sciences, Schmiedlstr. 6, 8042, Graz, Austria

³ CEICO, Institute of Physics of the Czech Academy of Sciences, Na Slovance 2, 182 21 Praha 8, Czech Republic

⁴ INAF-Osservatorio Astronomico di Padova, Vico del dell'Osservatorio 5, I-35122 Padova, Italy

⁵ Department of Astrophysics, University of Vienna, Türkenschanzstrasse 17, A-1180 Vienna, Austria

⁶ SISSA, via Bonomea 265, I-34136 Trieste, Italy

Received 2023 August 2; revised 2023 October 9; accepted 2023 October 30; published 2023 December 19

Next steps...



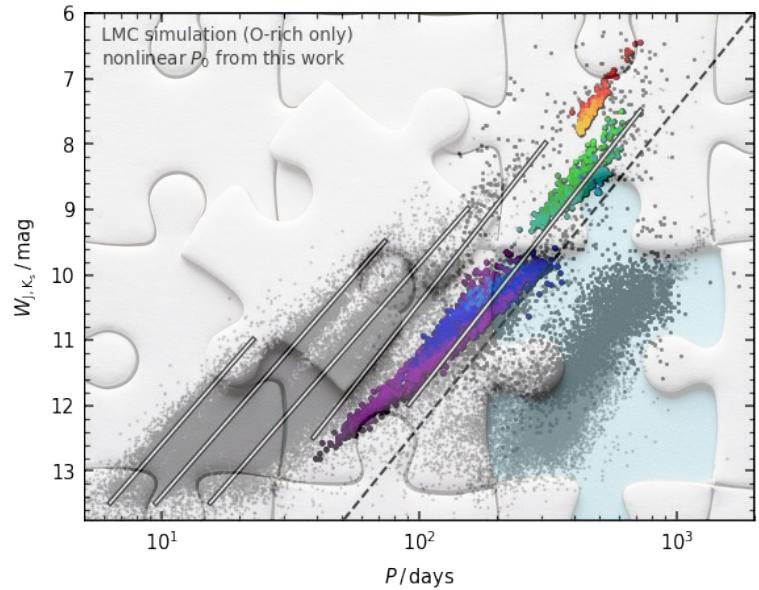
CONVERGENCE

CONstraining the Variability of Evolved Red Giants
for ENhancing the Comprehension of Exoplanets

Next steps...



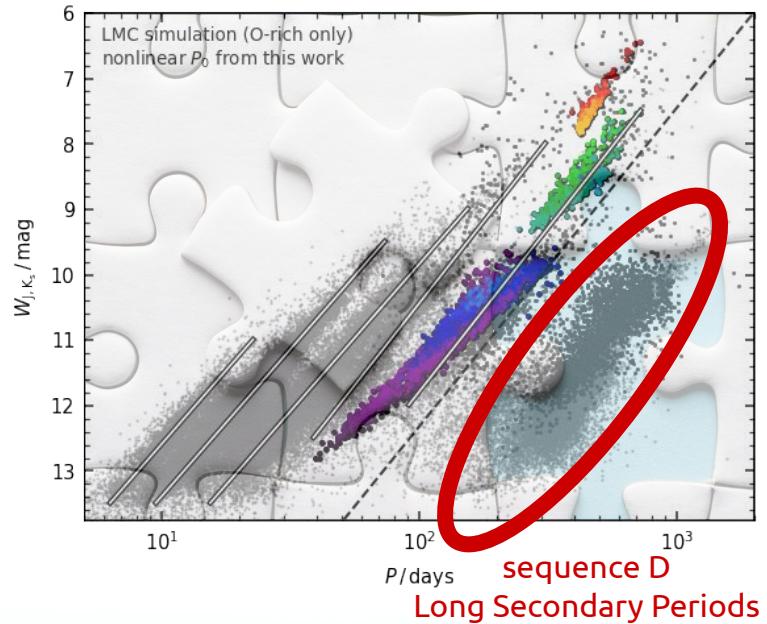
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Next steps...



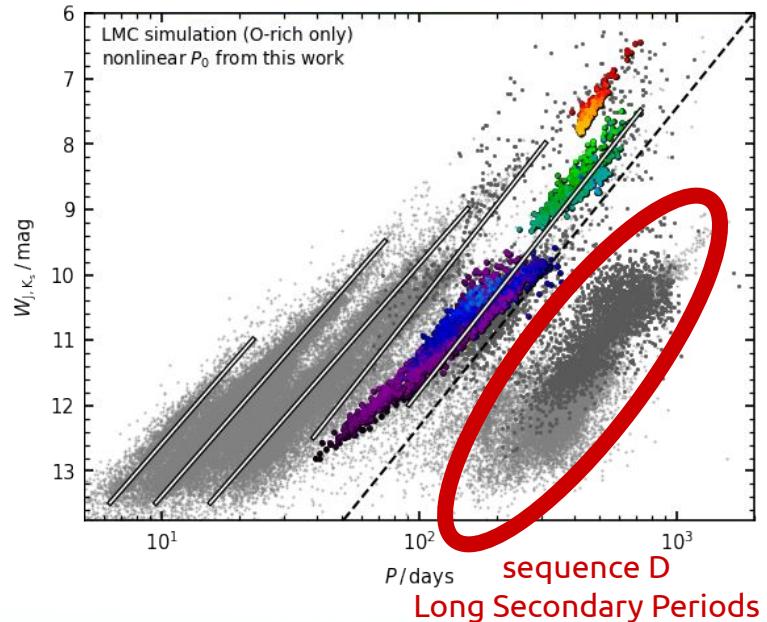
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Next steps...



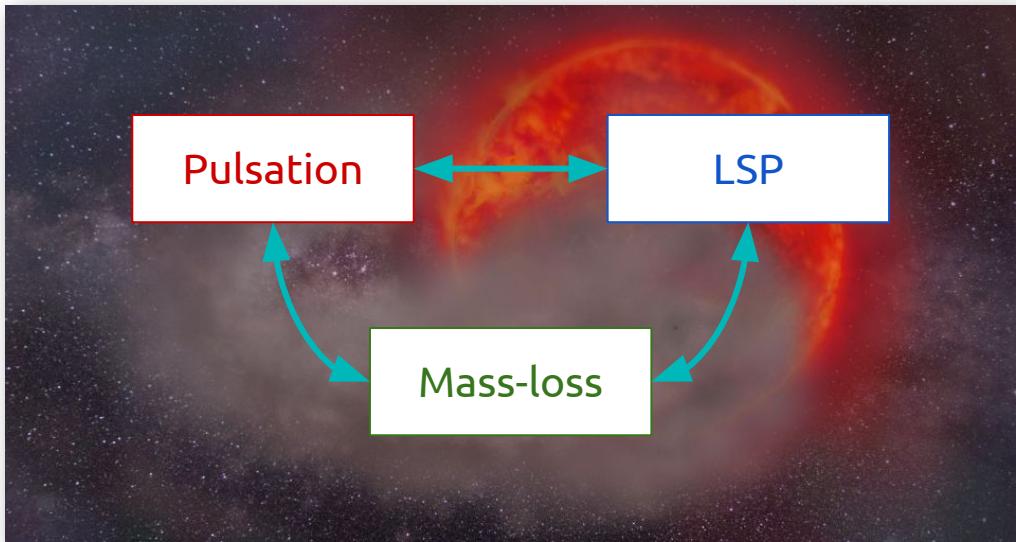
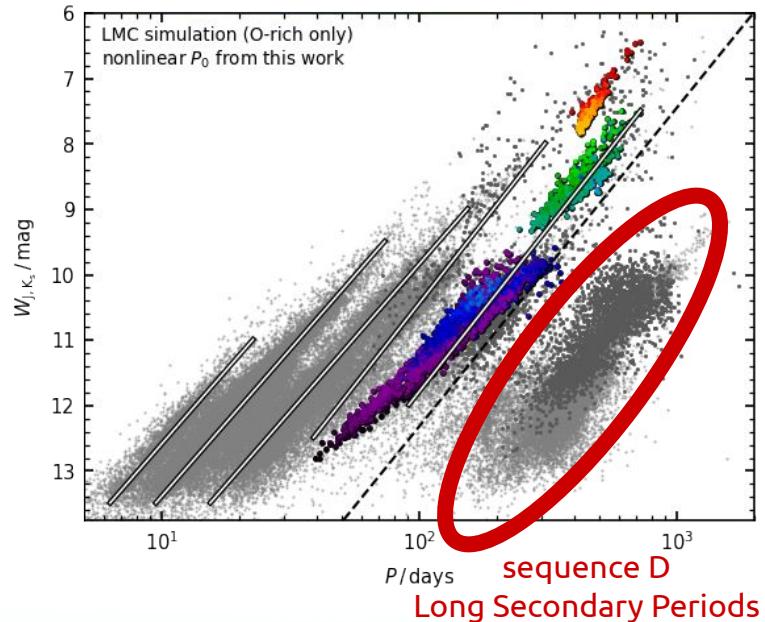
CONVERGENCE



Artistic impression of the LSP dust cloud interpretation

Credits: Matylda Soszyńska
(Soszyński 2022, XL Polish Astronomical Society Meeting, 12, 154)

Next steps...



Artistic impression of the LSP dust cloud interpretation

Credits: Matylda Soszyńska
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Next steps...

A&A, 680, A36 (2023)
<https://doi.org/10.1051/0004-6361/202347287>
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**Astronomy
&
Astrophysics**



Gaia Focused Product Release: Radial velocity time series of long-period variables

OCT 2023

Gaia Collaboration: M. Trabucchi^{1,2,*}, N. Mowlavi², T. Lebzelter³, I. Lecoeur-Taibi⁴, M. Audard^{2,4}, L. Eyer², P. García-Lario⁵, P. Gavras⁶, B. Holl^{2,4}, G. Jevardat de Fombelle², K. Nienartowicz^{7,4}, L. Rimoldini⁴, P. Sartoretti⁸, R. Blomme⁹, Y. Frémat⁹, O. Marchal¹⁰, Y. Damerdji^{11,12}, A. G. A. Brown¹³, A. Guerrier¹⁴, P. Panuzzo⁸, D. Katz⁸, G. M. Seabroke¹⁵, K. Benson¹⁵, R. Haigron⁸, M. Smith¹⁵, A. Lobel⁹, A. Vallenari¹⁶, T. Prusti¹⁷, J. H. J. de Bruijne¹⁷, F. Arenou⁸, C. Babusiaux¹⁸, A. Barbier¹⁴,

Next steps...

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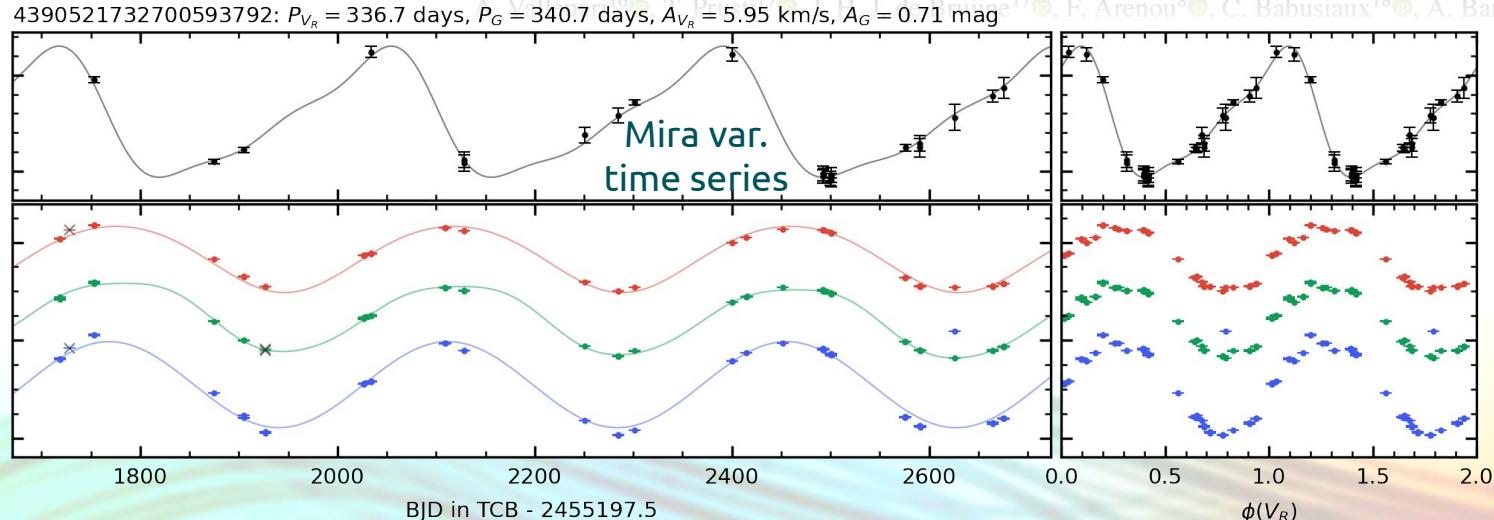
Astronomy
&
Astrophysics



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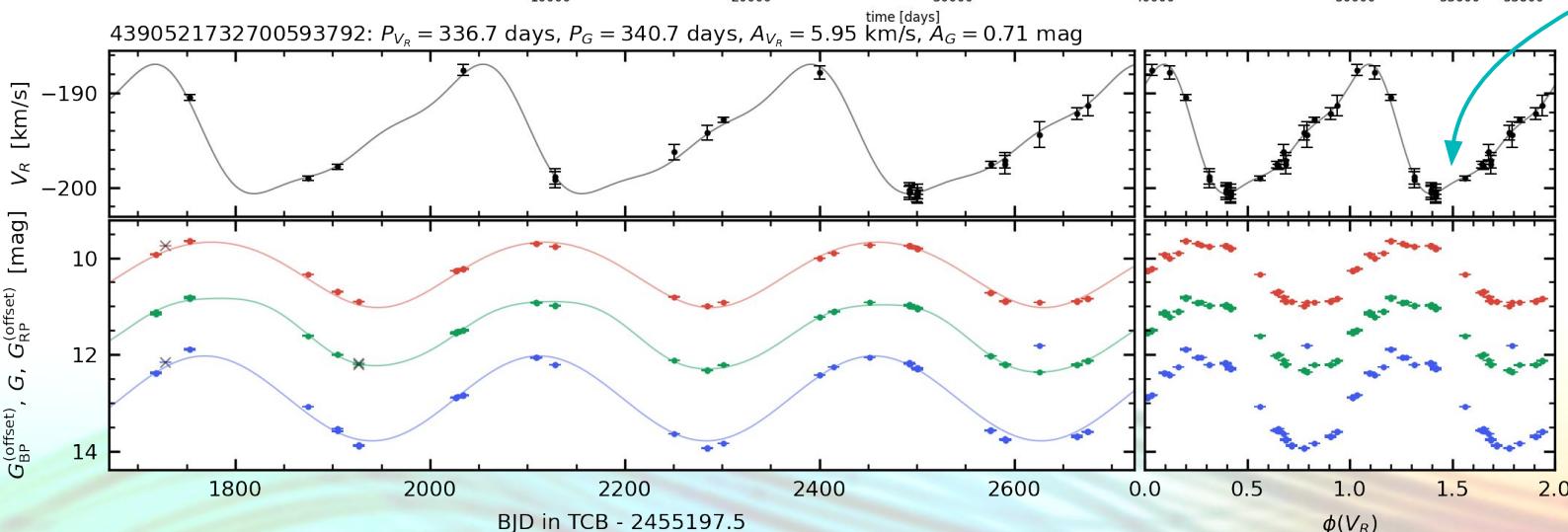
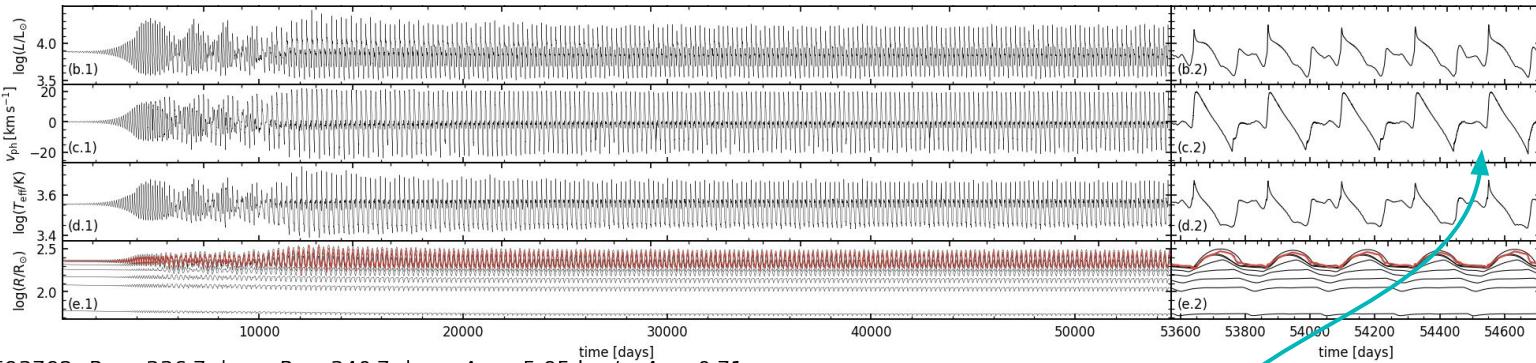
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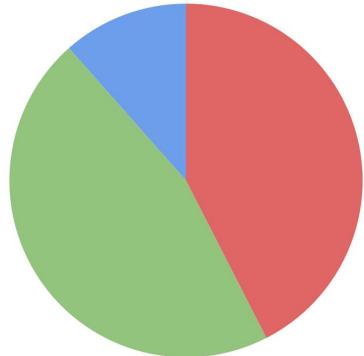


Next steps...

Model
calibration
with
RV
observations



Next steps...

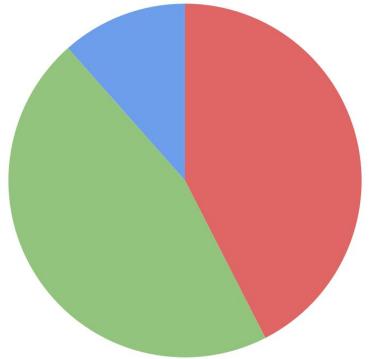


LPV pulsators ~42.5%

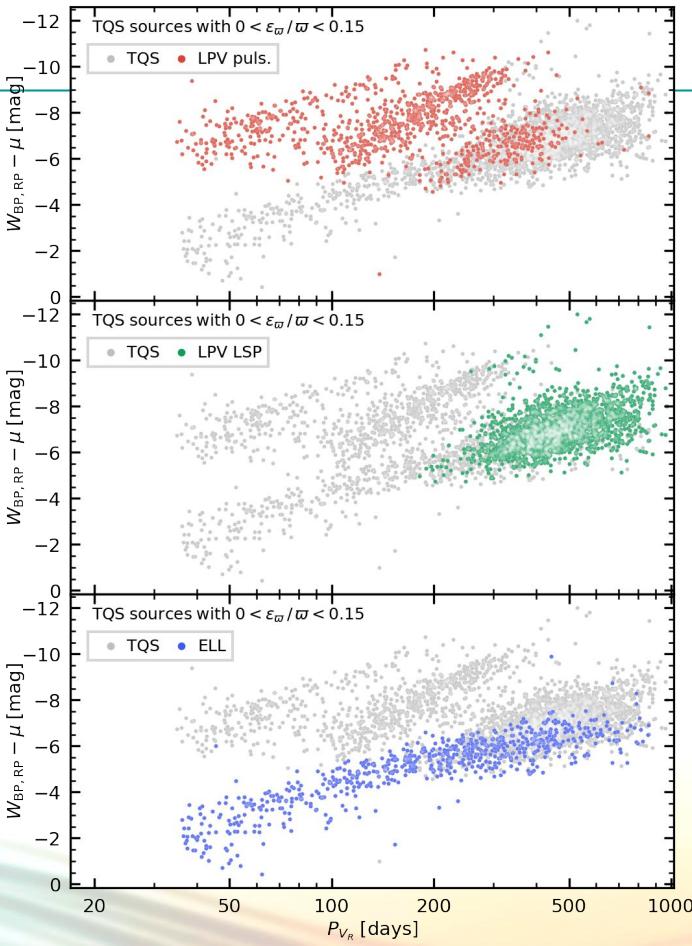
LPV LSPs ~46.0%

Ellipsoidal RGs ~11.5%

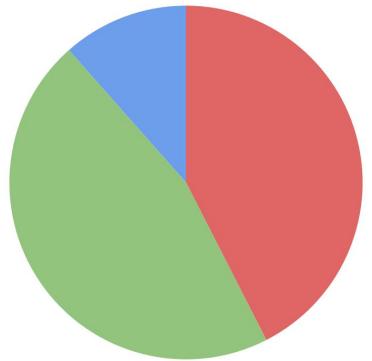
Next steps...



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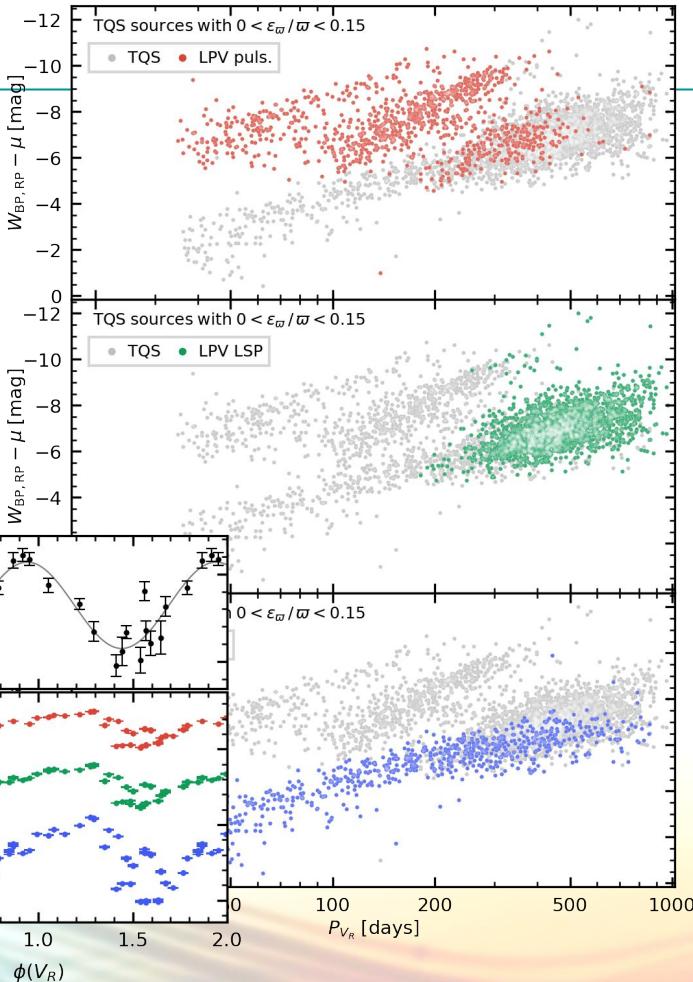
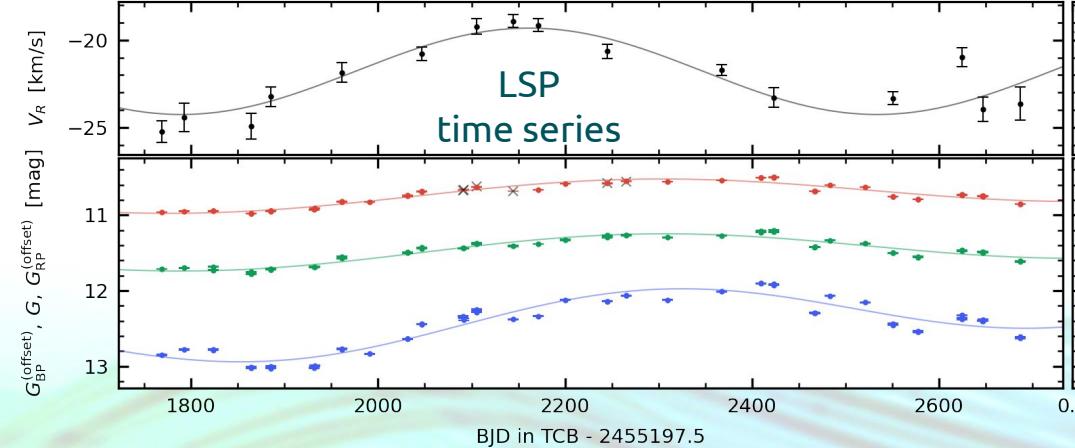


Next steps...



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1968599531437522176: $P_{V_R} = 743.9$ days, $P_G = 955.8$ days, $A_{V_R} = 2.47$ km/s, $A_G = 0.20$ mag



Conclusions

- A. Always use non-linear FM period prescriptions for LPVs!
- B. Age estimates with LPVs - now theory-based!*
- C. Coming soon:
 - a. CONVERGENCE - a step closer to the LSPs?
 - b. New grid of hydrodynamic pulsation models
- D. Already out: epoch RVs of LPVs - take a look at the *Gaia* FPRs!

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