OAPD days - INAF Padova
27-28 June 2024

Stellar modeling: evolution with PARSEC and COLIBRI, including variability, asteroseismology, and opacities

Guglielmo Costa on behalf of stellar astrophysics group:

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People

INAF-OAPd


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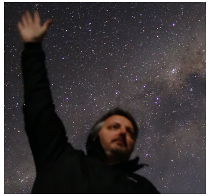
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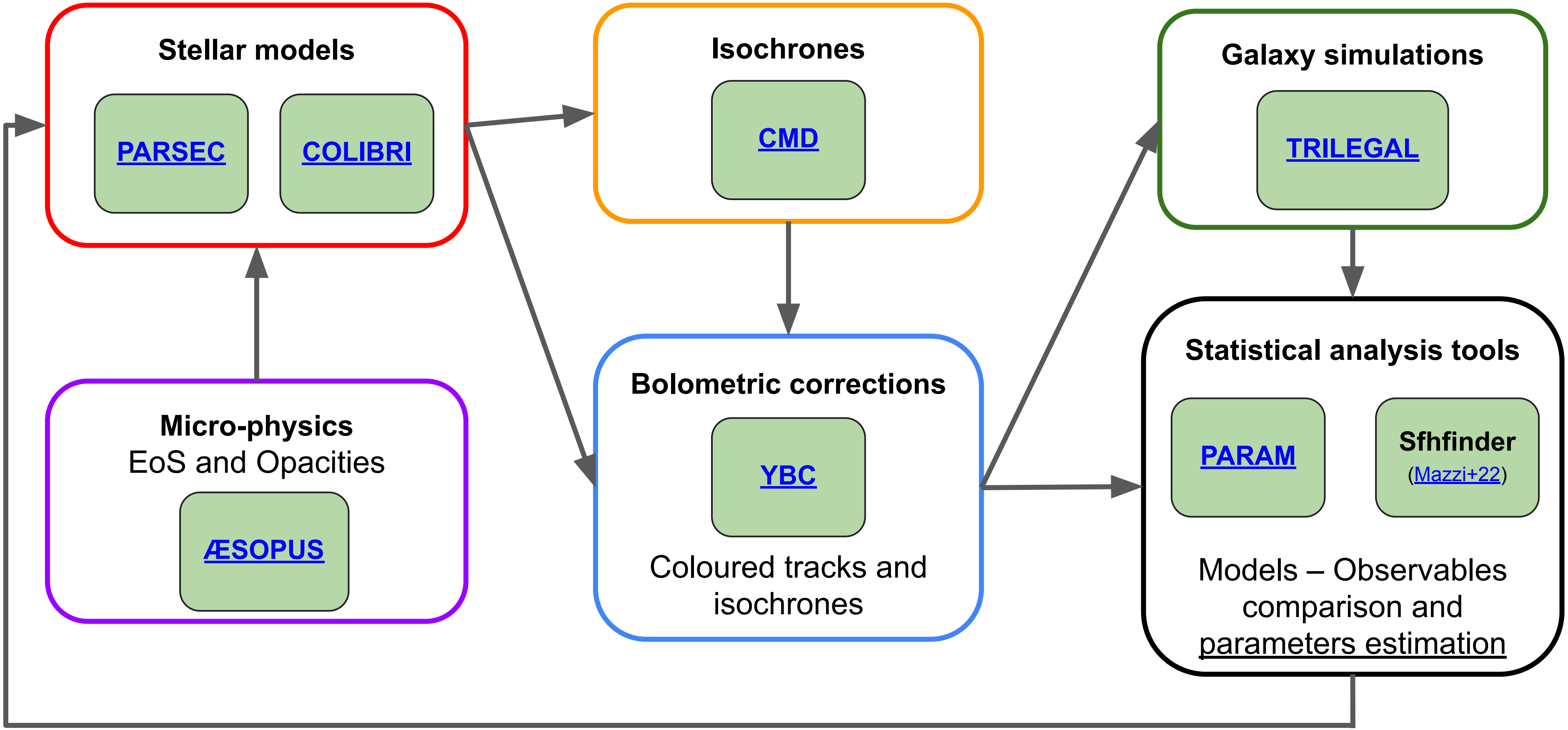
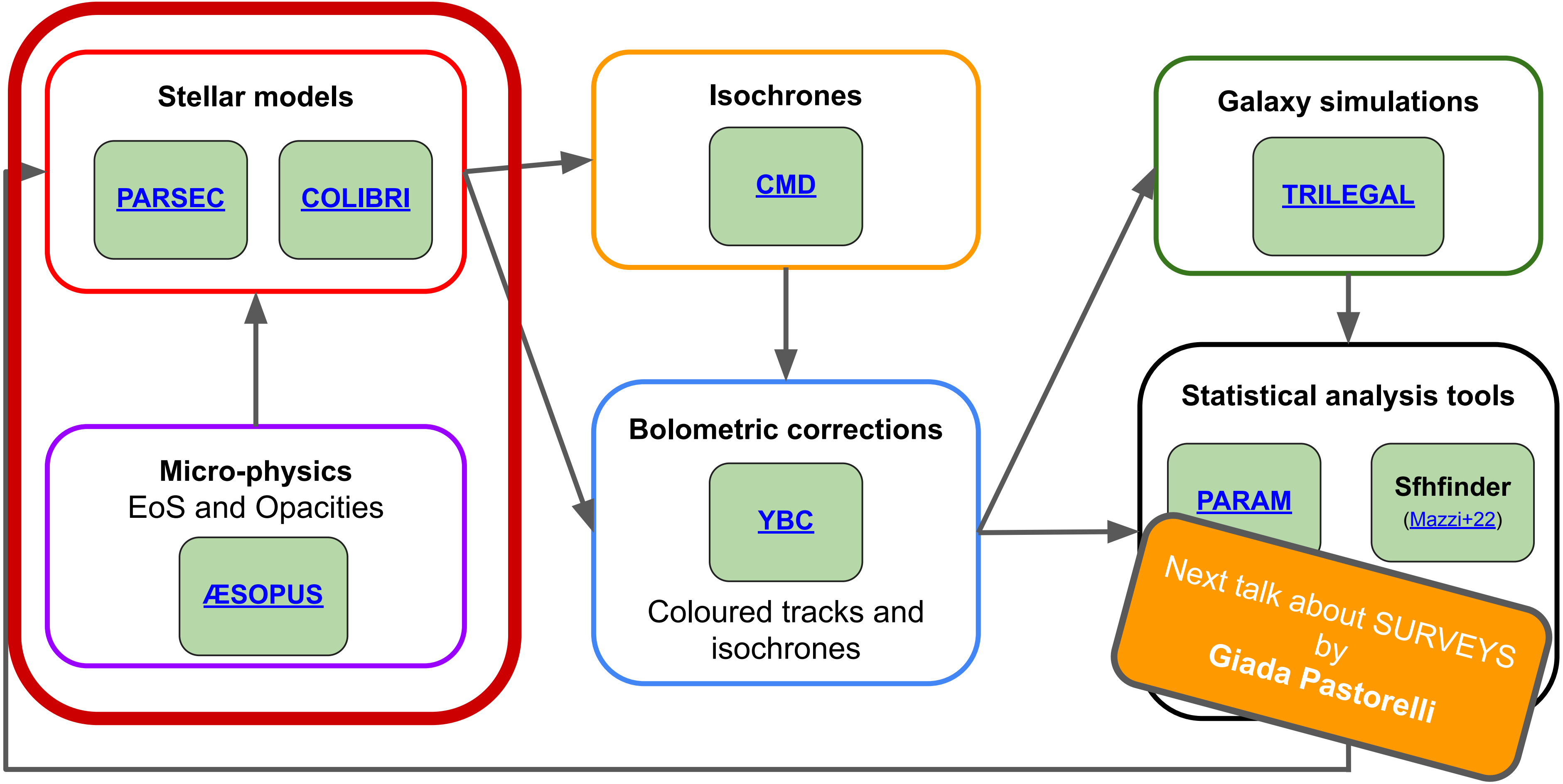
Stellar tools environment



Stellar tools environment



Stellar evolution – PARSEC

PARSEC (**PA**dova t**R**ieste **S**tellar **E**volutionary **C**ode)

It is an updated version of the Padova's stellar evolution code

Padova Tracks

- Bressan et al., 1993
- Bertelli et al., 1994
- Salasnich et al., 2000
- Girardi et al., 2000
- Marigo et al., 2001
- Marigo et al., 2003
- Bertelli et al., 2008
- Bertelli et al., 2009

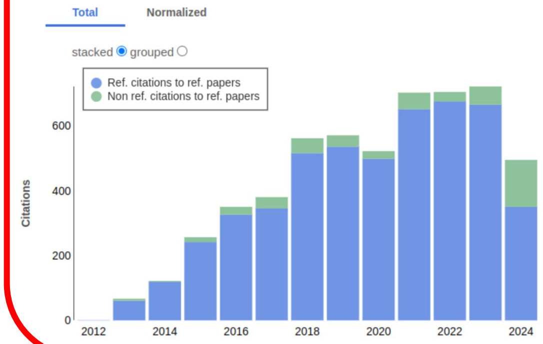
PARSEC v1.x

- Bressan et al., 2012
- Bressan et al., 2013
- Chen et al., 2014
- Tang et al., 2014
- Chen et al., 2015
- Fu et al., 2015
- Chen et al., 2015
- Tang et al., 2016
- Marigo et al., 2017
- Fu et al., 2018

PARSEC v2.x

- Costa et al., 2019a, b
- Girardi et al., 2019
- Costa et al., 2021
- Goswami et al., 2021
- Costa et al., 2022
- Goswami et al., 2022
- Nguyen et al., 2022
- Volpato et al., 2023
- Volpato et al., 2024
- Addari et al., 2024

Since 2012, more than 30 papers, with more than 5800 citations.



PARSEC tracks and isochrones are widely used by the community

Stellar physics, **Exoplanets**, **Dust Formation**, **Stellar Cluster, Galaxy populations**, **Yields**, **Compact Objects**, **Gravitational Waves**

Stellar evolution – New PARSEC v2.0

New updates and physical processes

Nuclear reactions coupled with mixing, and solved with a diffusive scheme.

New prescriptions for **Mass loss**:

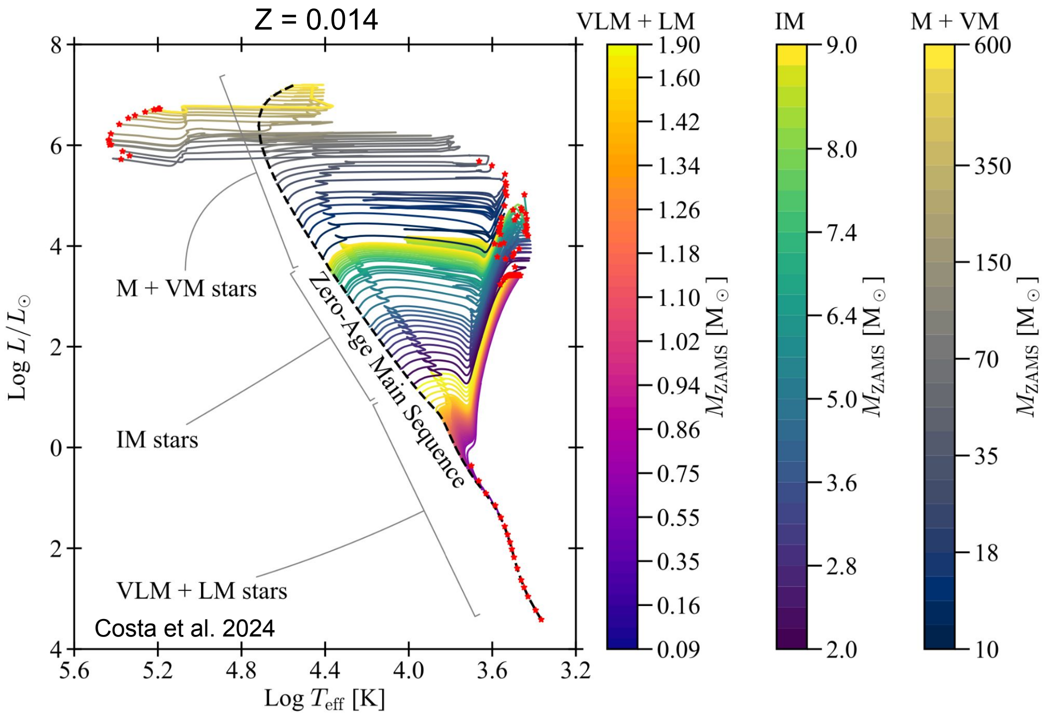
- Massive stars
- Wolf-Rayet
- Pure-He stars
- Pulsation driven mass loss

Inclusion of **Rotation** main effects:

- Geometrical distortion
- Rotational instabilities
- Gravitational darkening

Updated **EOS**, with the inclusion of electron-positron **pairs creation**.

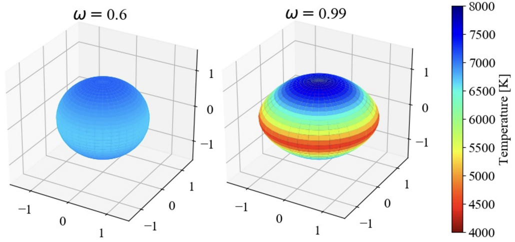
Expansion of the **nuclear reaction network**, with now **72 reactions** that follow the evolution of **32 isotopes** from Hydrogen to Zinc. Updated screening factors.



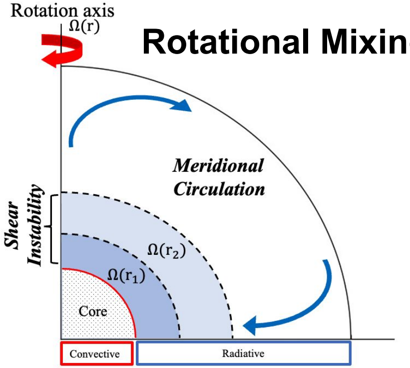
PARSEC can follow the evolution of **any star**, ranging from **very-low-mass** (VLM) to **very-massive** (VM) stars, throughout the entire lifespan within the same framework!

Stellar evolution – Rotation

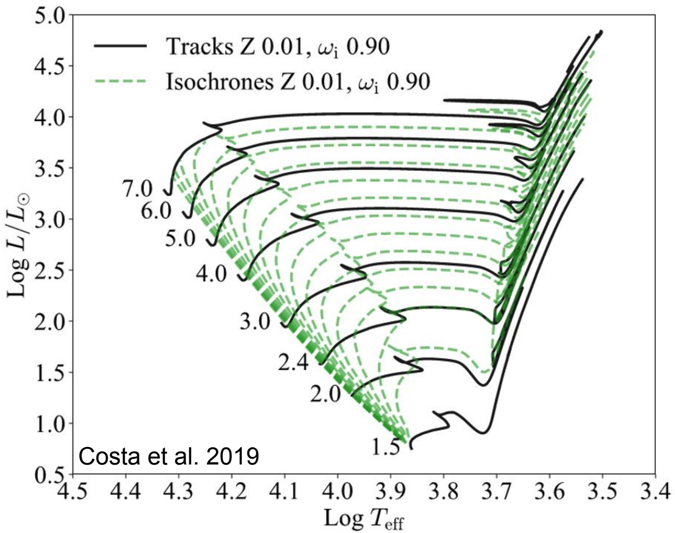
Stellar geometry



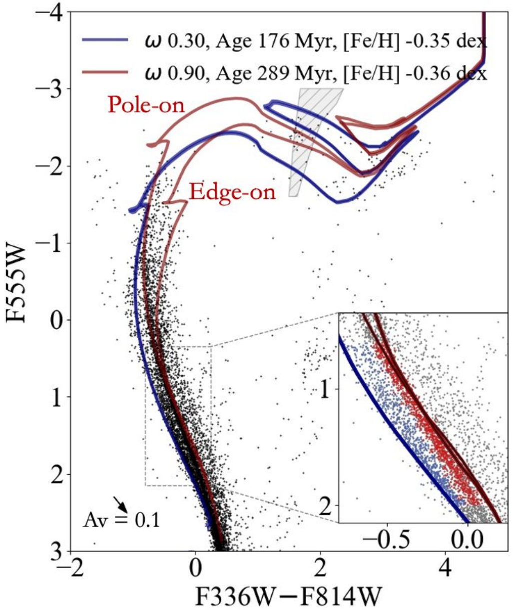
Rotational Mixing



Tracks and Isochrones

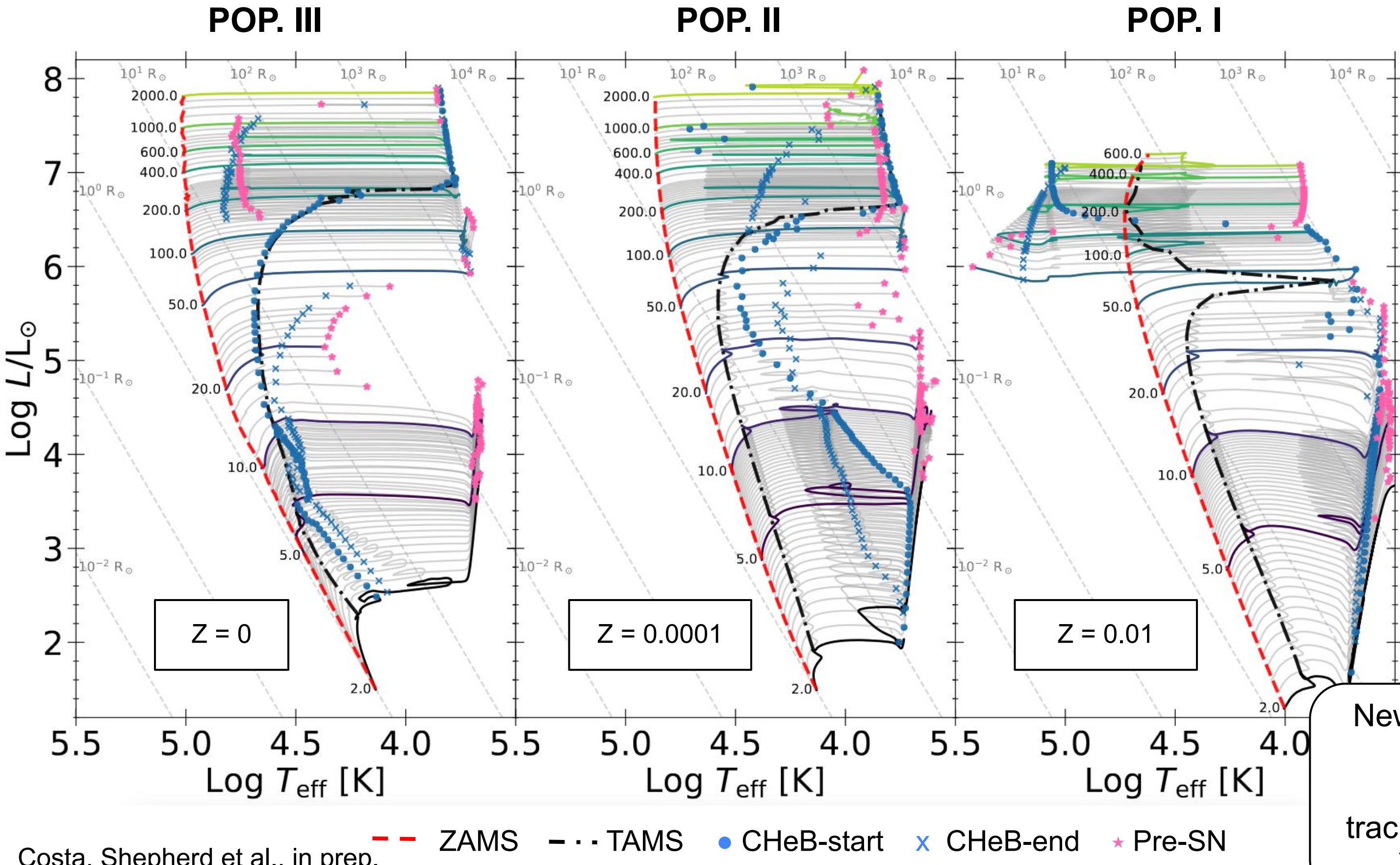


Cluster analysis



- New catalogues of rotating tracks and isochrones released in Nguyen et al. 2022 (2022A&A...665A.126N). Check the PARSEC Database (for tracks) and CMD WebApp (for isochrones)!
- Database expansion and a systematic analysis of star clusters is ongoing, see Ettorre et al. (submitted).

Stellar evolution – Massive stars



Costa, Shepherd et al., in prep.

Recently, we studied:

- The role of pulsating driven winds (Volpato et al. 2023);
- The impact of rotation (Volpato et al., 2024);
- Stellar yields (Goswami et al., 2021, 2022, Volpato et al., 2023, 2024)
- Stellar winds (Shepherd et al., in prep.).
- Final remnants (Volpato et al., 2023, 2024, Costa et al., in prep.);

New tracks will be released soon!!

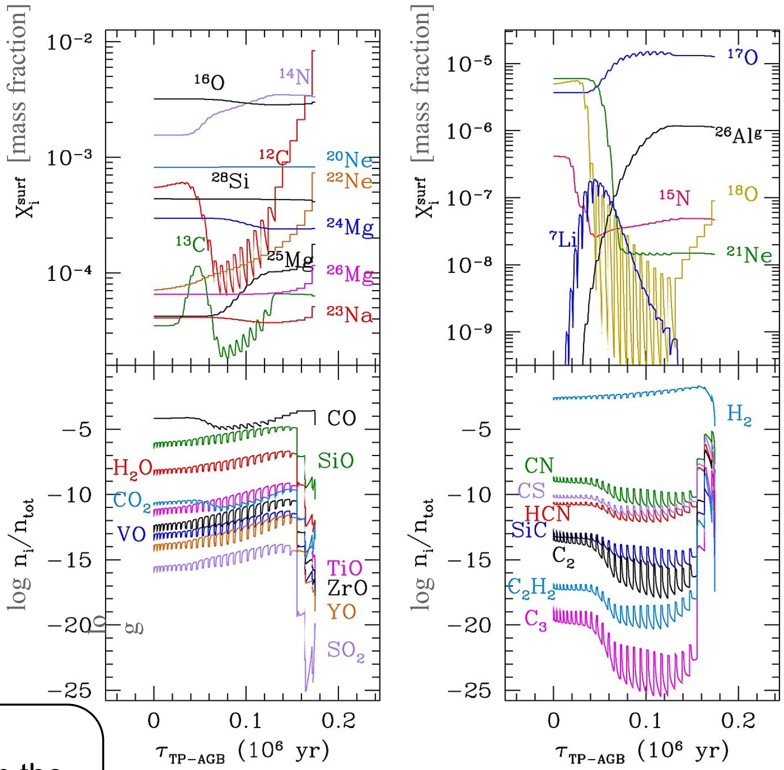
14 Zs – from Z = 0 to 0.04
tracks – from 2 to 600 (2000) Msun
Yields and Ionizing photons

Stellar evolution – COLIBRI

COLIBRI is a hybrid ‘envelope-based’ stellar evolutionary code. Which greatly supersedes the so-called ‘synthetic’ codes.

- **Physical Accuracy:**
  - ➔ On-the-fly computation of molecular chemistry and opacities (Marigo & Aringer+09)
  - ➔ HBB nucleosynthesis: CNO cycle, NeNa, MgAl chains
- **Quick** calculations of large grids of models:
  - ➔ 11 Z for ~ 70 Mi values: **770 TP-AGB tracks**
  - ➔ **100X faster** than full TP-AGB models
- **Parametrized description of:**
  - ➔ **Third dredge-up**
  - ➔ **Mass loss**

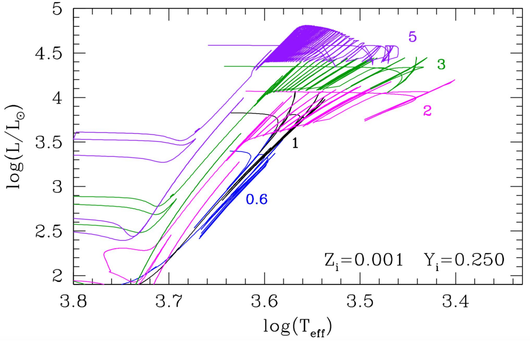
COLIBRI computes the AGB evolution from the early-AGB to the complete ejection of the envelope by winds.



Marigo et al., 2013

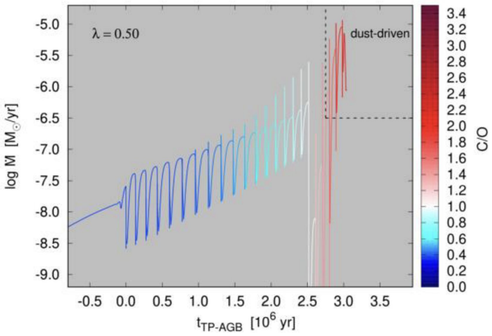
Stellar evolution – AGB

Stellar tracks (Marigo et al., 2013)



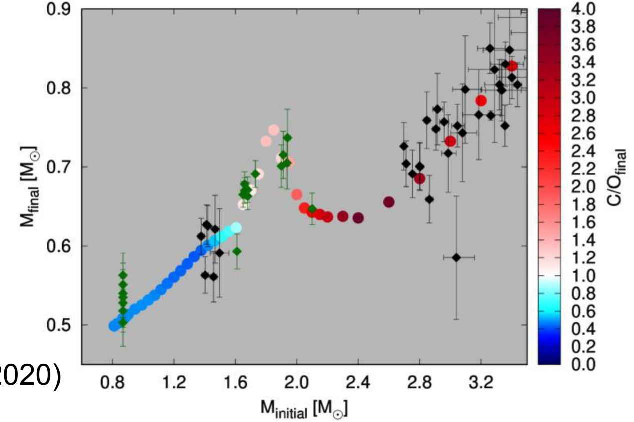
Isochrones with TP-AGB (Marigo et al., 2017)

TP-AGB **new mass-loss** recipe (Marigo et al., 2020)



Initial Final Mass Relation

Fit of the WD kink at ~ 1.9 Msun



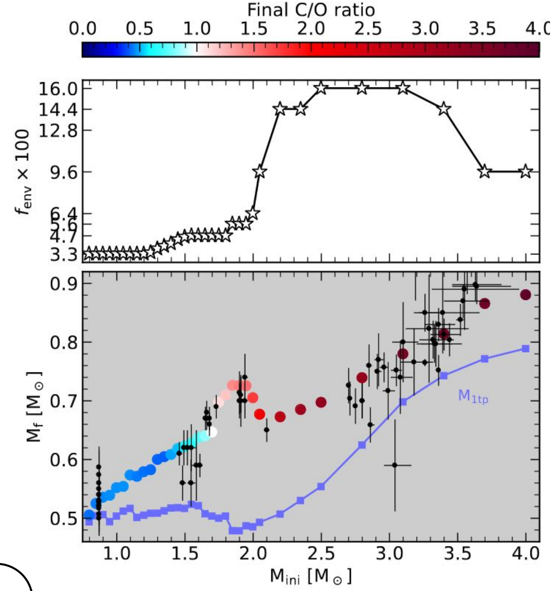
Marigo et al., 2020

COLIBRI let us study the properties of the final TP-AGB phases in detail.

COLIBRI findings also help us in the PARSEC development!

PARSEC-FULL AGB

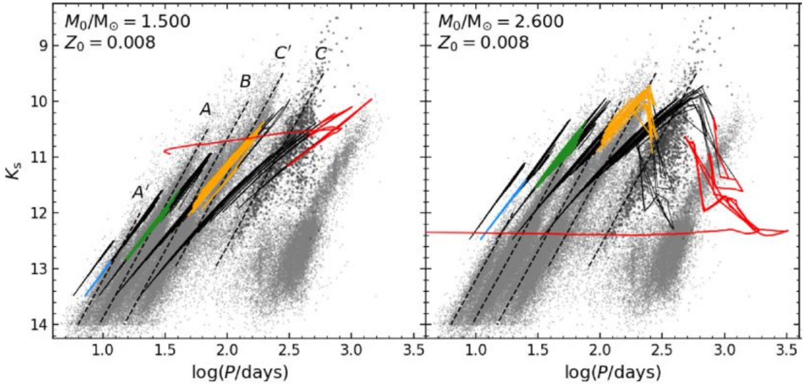
Envelope overshooting calibration



Addari et al., 2024

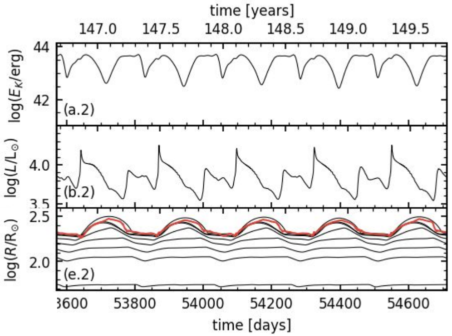
Stellar evolution – Ongoing work

Linear + hydrodynamic pulsation models for evolved giant stars (AGB, late RGB)

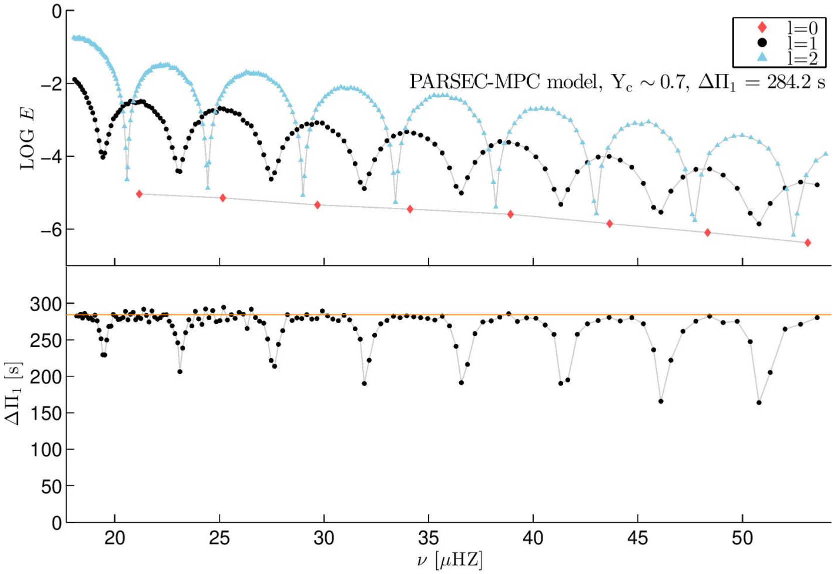


Trabucchi+19 - Period-luminosity plane of long period variables (LPV) + COLIBRI tracks + pulsation models

Trabucchi+21 - Hydrodynamic pulsation models and feedback on stellar structure and evolution to study Mira-like variables.



Inclusion of physical quantities for asteroseismic computation



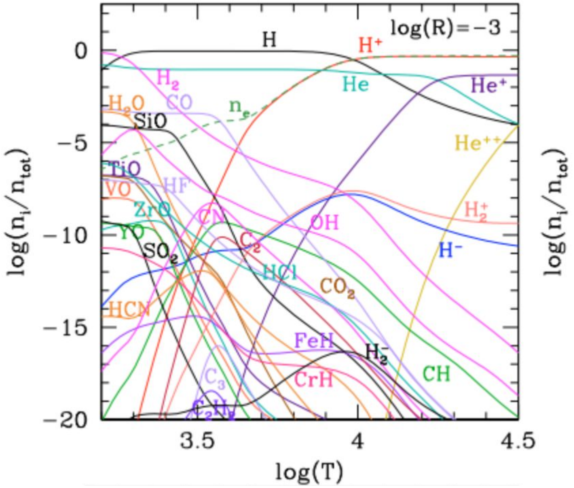
From Bossini+15
Preview of oscillation modes properties of a RC model.
(Upper panel) Mode inertia as a function of the frequency for different angular degree l=0,1,2.
(Lower panel) Period spacing $\Delta\Pi_1$ as a function of the frequency (in orange the asymptotic value).

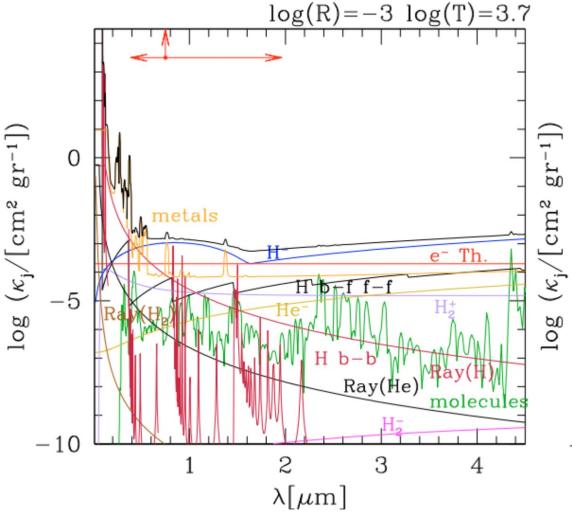
Micro-physics – ÆSOPUS

ÆSOPUS (**A**ccurate **E**quation of **S**tate and **OP**acity **U**tility **S**oftware)

Computation of **equation of state** and the **Rosseland mean opacities** of matter in the ideal gas phase.

ÆSOPUS solves the equation of state for more than **800 species** in the gas phase.
It accounts for continuum processes and line processes.





[ÆSOPUS](#) web App.
Versatile: users can change the composition
Quick: tables in a question of minutes, not days

Under continuous development:

v1: Temperature range 1500 < T/K < 30000 (Marigo+2009);

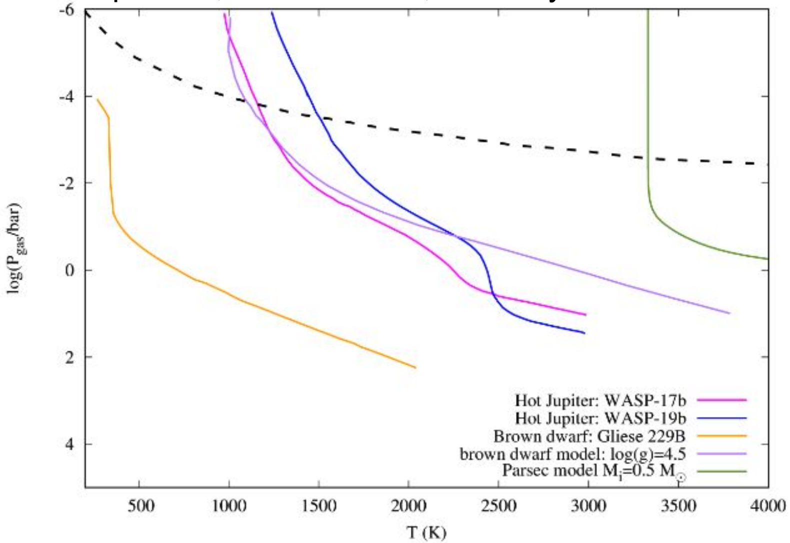
v2.0: expanded molecular absorption of 80 species (Marigo+2022);

v2.0+: Temperature down to 400K, inclusion of dust grains opacities (Marigo+2024);

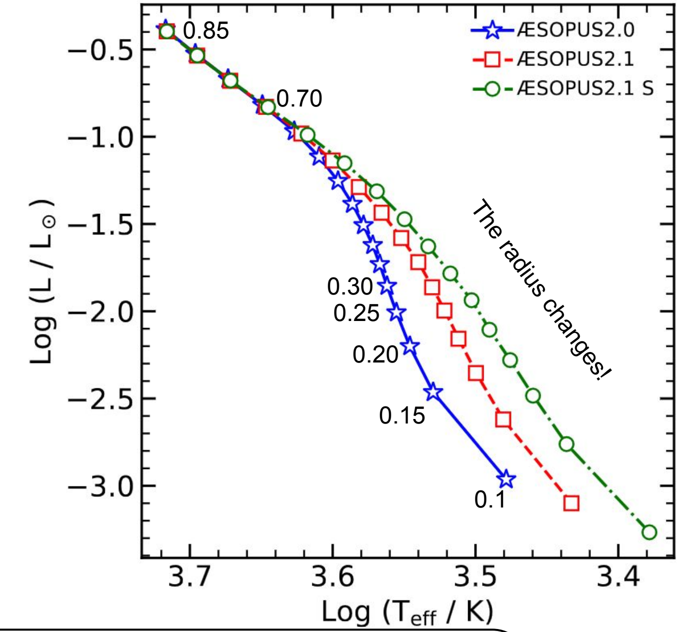
v2.1: Temperature down to 100K, density range extended (Marigo+submitted).

Stellar evolution – VLM stars and Brown Dwarfs

Atmospheric pressure-temperature profiles for exoplanets, brown dwarfs, and very low mass stars.



Marigo et al., submitted



Opacities are fundamental for studying several astrophysical objects, i.e.,

AGB and **super-AGB** stars, **long-period variables**, **supernova light curves**, **white dwarfs**, **brown dwarfs** and **planets**.

Take home messages

- Publicly available databases and tools (check links in slide 3!);
- Database of PARSEC rotating tracks and isochrones already available;
- New grids from Pop III to supra-solar metallicity with stars from 2 to 600 Msun are coming soon;
- Better models every year (TP-AGB, Pulsating variables, Red giants with asteroseismology, Brown dwarfs with updated opacities, etc..). Stay tuned!!!