"la Caixa" Foundation

ICCUB

Institut de Ciències del Cosmos
UNIVERSITAT DE BARCELONA

EXCELENCIA MARÍA DE MAEZTU 2020–2023

UNIVERSITAT DE BARCELONA

A new tool on the workbench:
the rapid population synthesis code SEVN
for gravitational wave astronomy

Giuliano Iorio

La Caixa Junior Leader fellow

LISA Spain meeting 2024

15th-16th October, Barcelona

A (LISA) Spain newcomer

Postdoc/Staff @ Unipd. (Demoblack group)

Developing of a **population synthesis code** for the study of **Gravitational Wave progenitors** (binary compact objects)

Part of LVK, Einstein Telescope and LISA collaborations

Since yesterday

La Caixa Junior leader fellow @ ICCUB

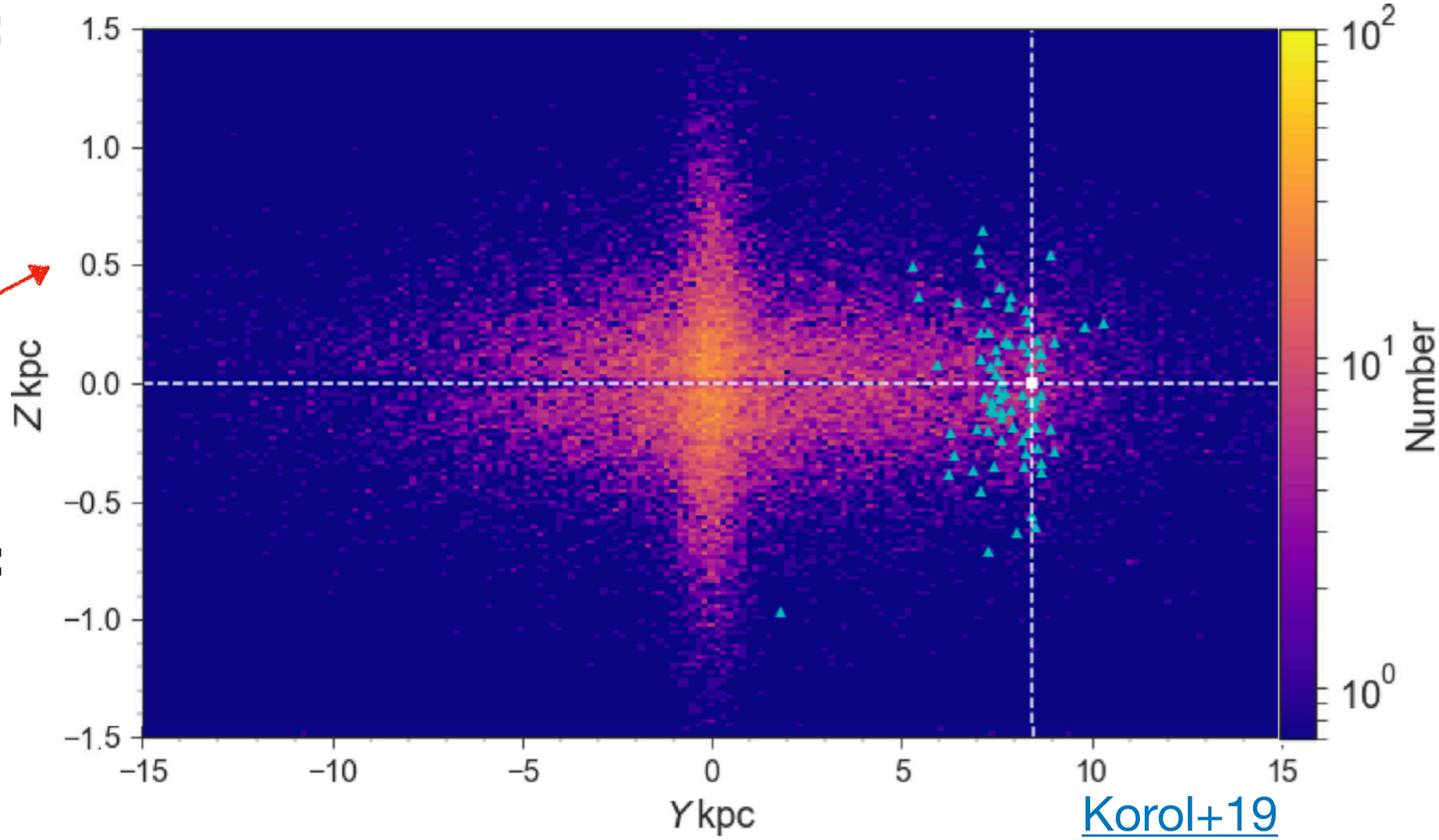
Focusing on the formation of metal-rich RR Lyrae through binary evolution

(Possible double WD progenitors)

Interested in being involved in the LISA Spain community!

Why populations studied are import for LISA? (and for GW detectors in general)

- **Before the mission:**
  - Scientific cases
  - Instrument development
  - Predictions
- **During the mission:**
  - Astrophysical interpretation



Korol+19

Predictions of source count of DWD detected by LISA

How can we account for stellar and binary evolution in population studies?

Hydrostatic stellar evolution codes

(e.g. PARSEC, MESA)

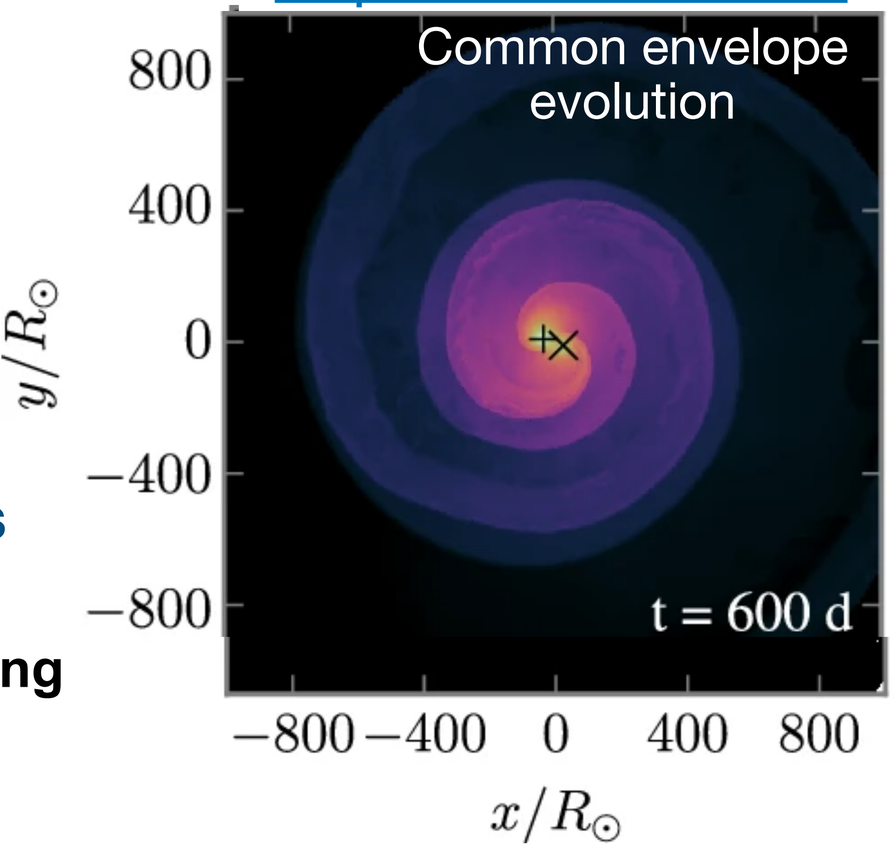
From minute to hours for a single model

Hydrodynamical simulations

(e.g. Starsmasher, Phantom, Arepo)

Millions of CPU hours for simulating a binary process

Röpke&De Marco 23



Rapid population synthesis codes

Analytic, semianalytic formalisms for:

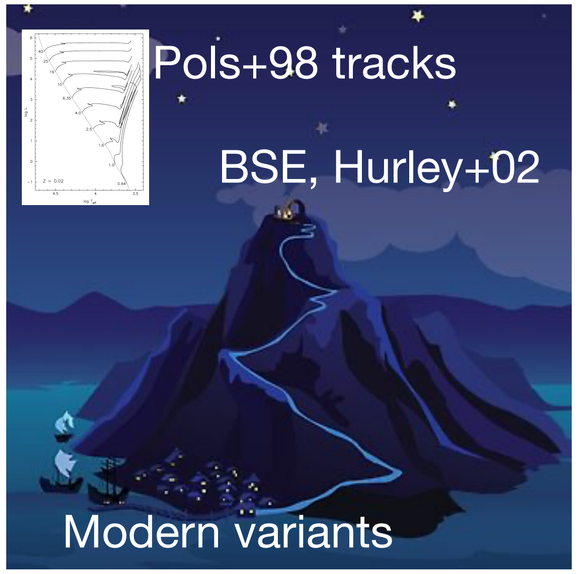
- Stellar evolution
- Binary processes

<< second for a complete binary evolution

Millions binaries in hours!

Finding our way in the rapid population synthesis codes World

Finding our way in the rapid population synthesis codes World

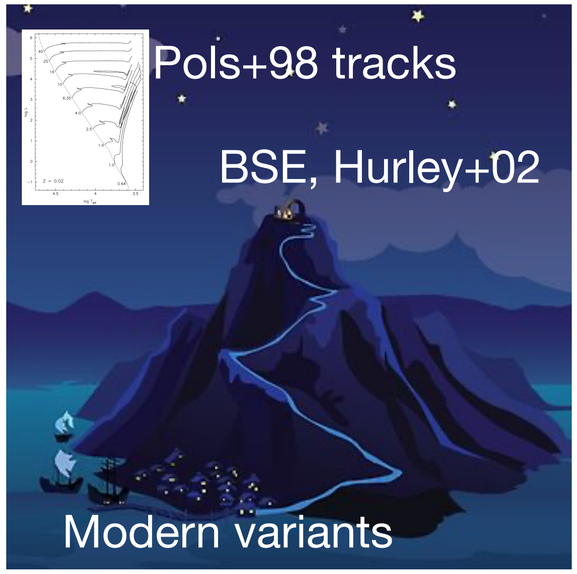


“BSE island”

Stellar evolution through fitting equations of Pols+98 tracks.

(Almost) Fixed stellar evolution

Finding our way in the rapid population synthesis codes World



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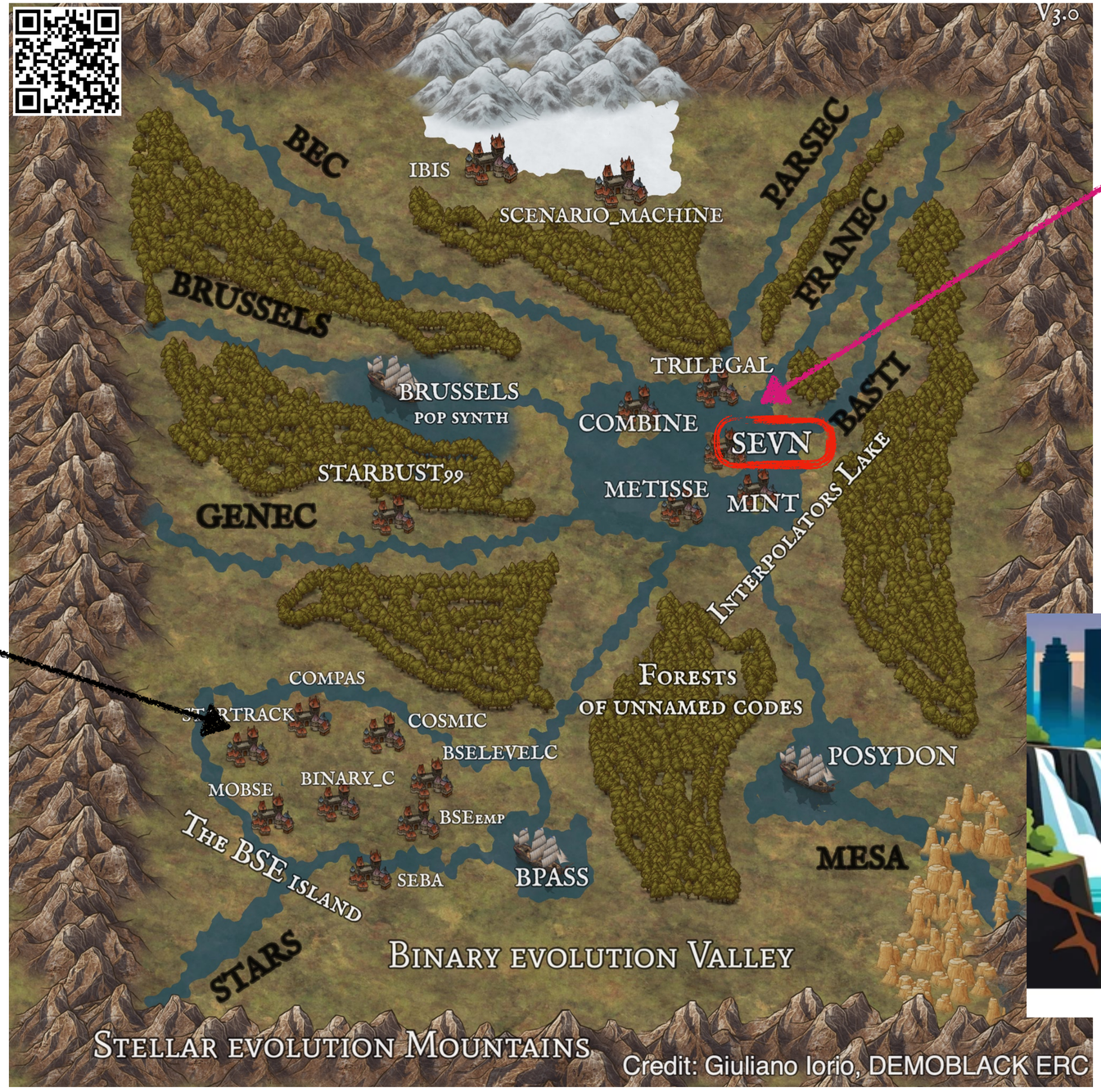
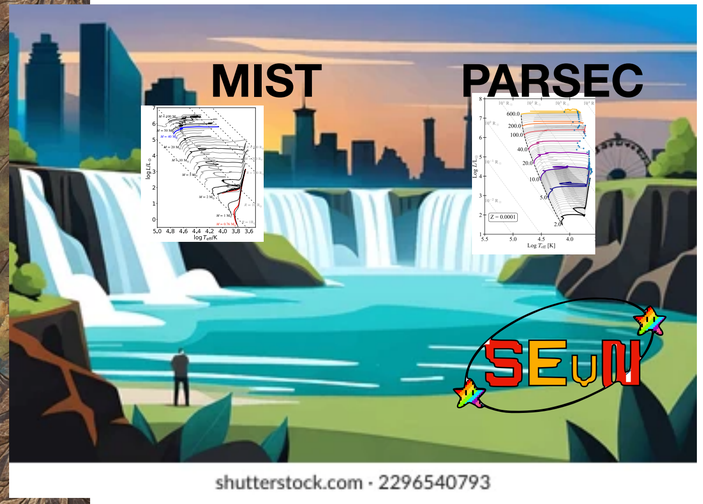


Interpolators “lake”

Stellar evolution through interpolation of stellar evolution tracks.

Allow exploration of stellar evolution models/uncertainties



Stellar EVolution *N*-body

Iorio+23 (Based on the original idea by Spera+19)

Gitalb Public repository: https://gitlab.com/sevncodes/sevn

Single Stellar Evolution

- Stellar evolution through **interpolation of precomputed stellar tracks**
- Precomputed stellar tracks can be easily added to use the **most updated stellar evolution models**

```
./sevnB.x  -tables tables/SEVNtracks_parsec_AGB
```

Enable the explorations of different stellar evolution models

Binary evolution

- **Analytic/Semi-analytic prescriptions:**
  - Wind mass accretion
  - Roche-Lobe overflow
  - Stellar tides
  - Common Envelope
  - GW orbital decay
  - Hardening

>4 SN models and variations

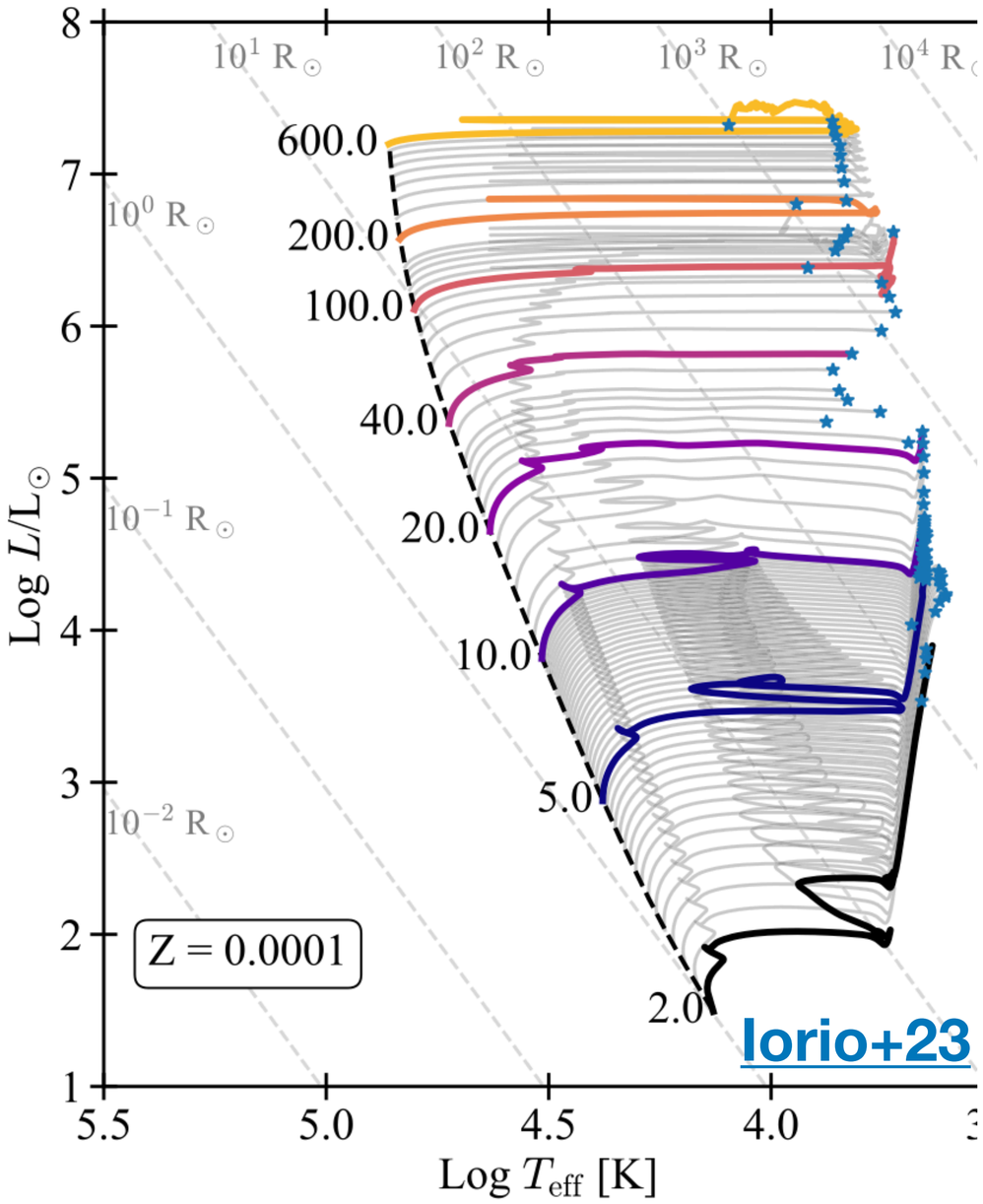
(Fryer+12, Wooesly+19, Mapelli+20, Patton&Sukhbold+20,Woosley+20)

2 PISN models

(Farmer+19,Mapelli+20)

SEVN

Stellar evolution tables



- **7 mandatory properties + optionals**
- **New properties are easy to add**

PARSEC models:
(Iorio+23,Costa+21,Nguyen+22)
- Masses: 2-600 Msun
- Z: 1E-11 - 4E-2
- Two overshoot models

PARSEC PureHe models:
(Iorio+23,Costa+21,Nguyen+22)
- Masses: 0.3-350 Msun
- Z: 1E-11 - 5E-2

MIST models:
(Choi+16)
- Masses: 0.7-150 Msun
- Z: 1.4E-5 - 4.5E-2

SEVN

The code philosophy

Easy to use/install

Documented GitLab repo
(Incudine userguides/tutorials)

Public docker image

Custom python bindings
(no external packages)

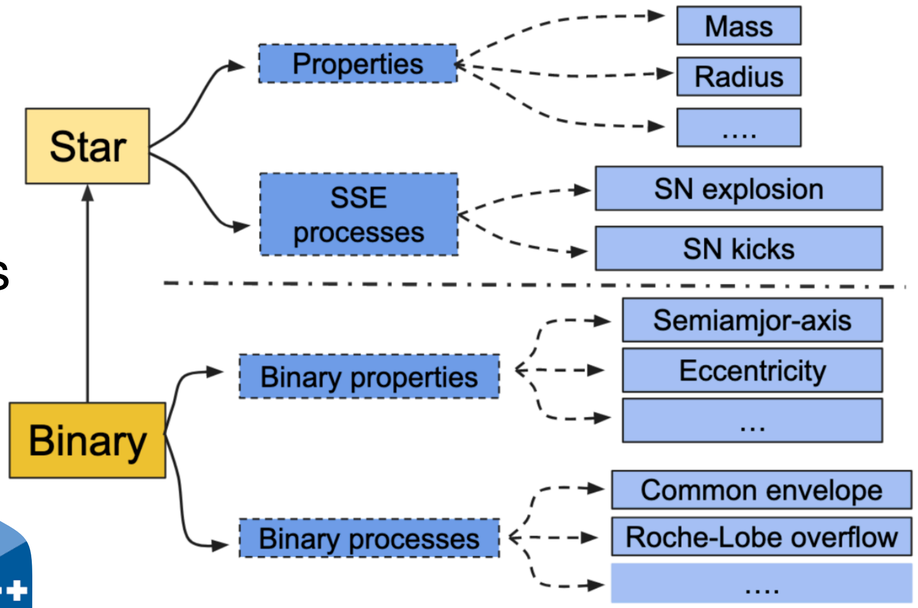
Ready python/bash scripts
To simplify installation, run,
data analysis

Library/Executable

Scalable

from laptop to clusters

Easy to extend



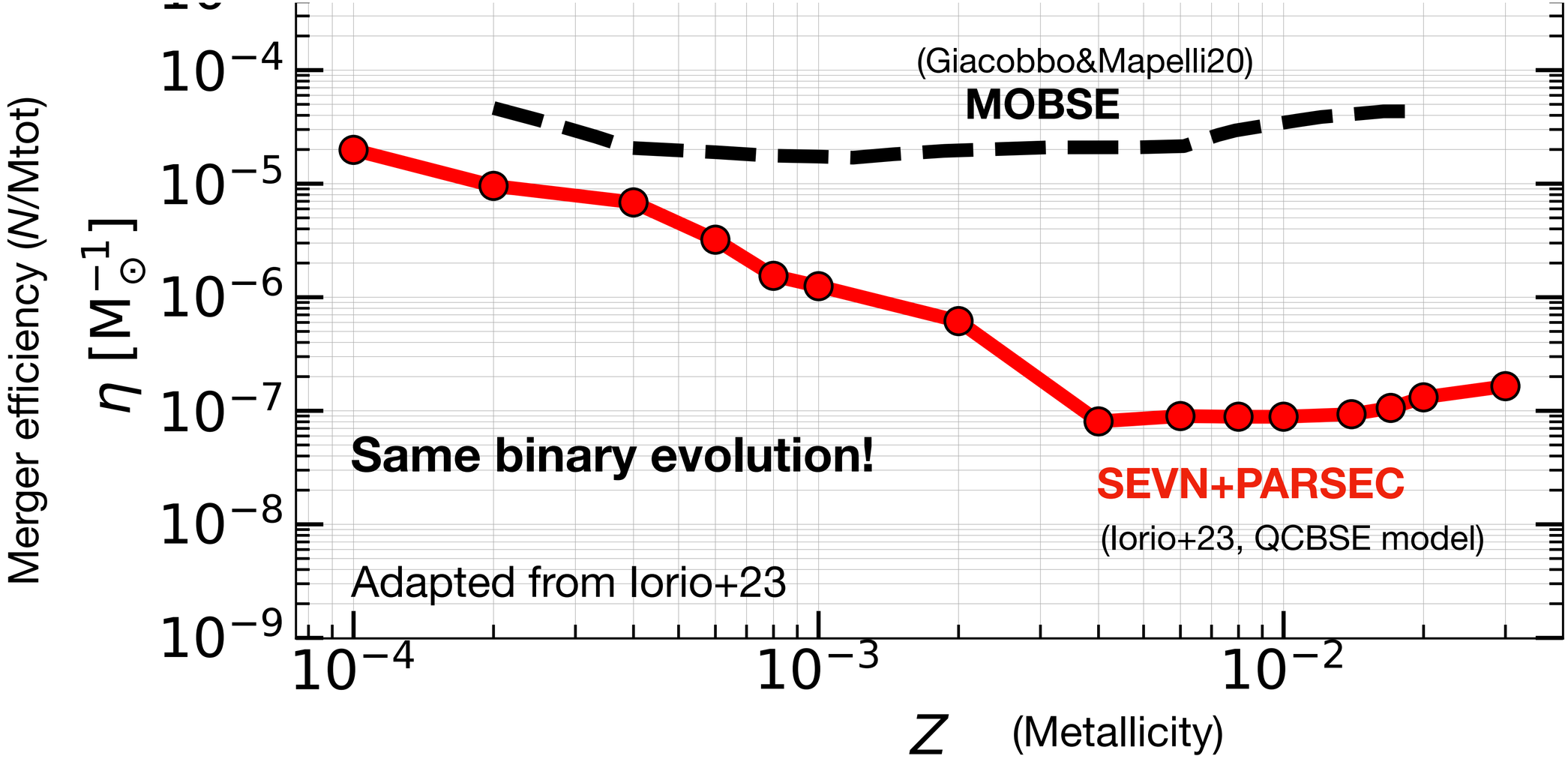
Modular and object oriented:
(Factory method pattern)

- Chose models at runtime
- Add processes/properties easily by just adding classes

Enable the explorations of different stellar evolution models

Does Stellar Evolution Matter?

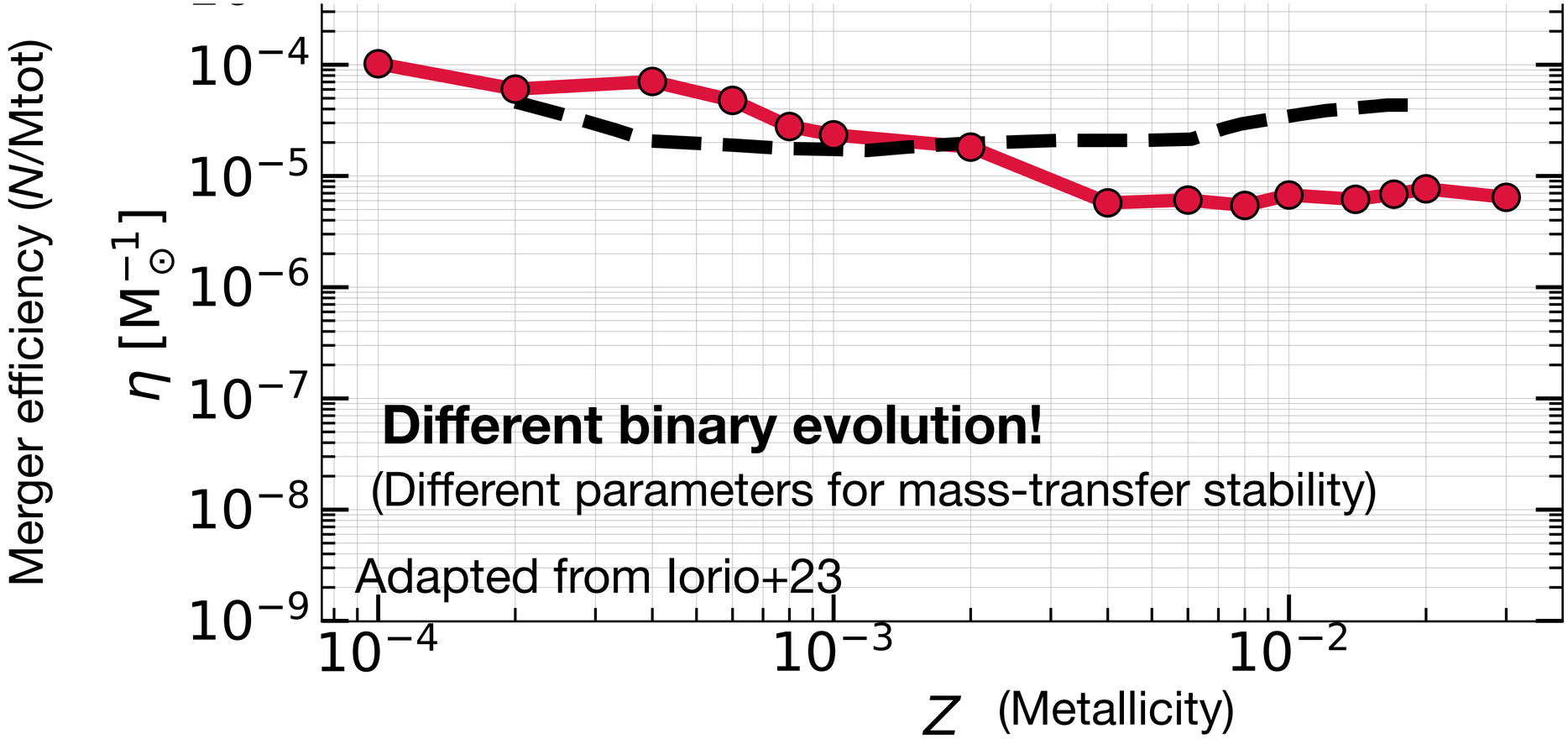
What is the impact on merging neutron stars?



Significant impact!

Does Stellar Evolution Matter?

What is the impact on merging neutron stars?

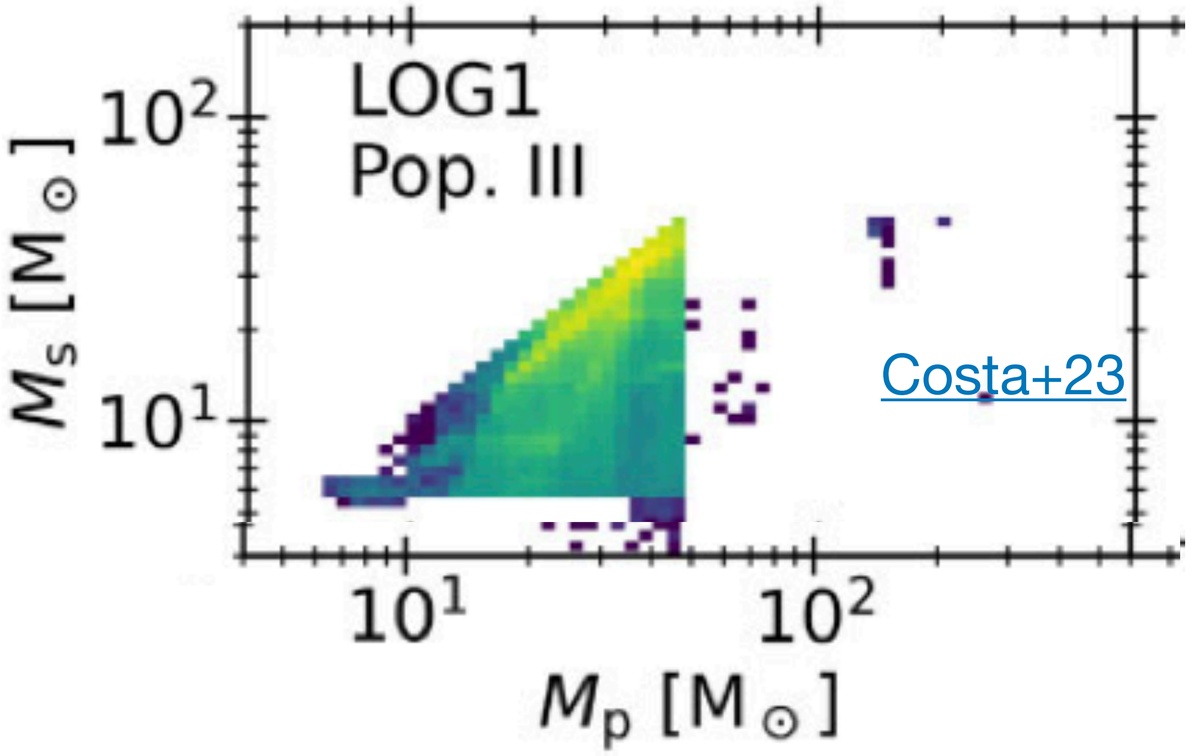


Binary evolution parameter and stellar models are correlated!

Does Stellar Evolution Matter?

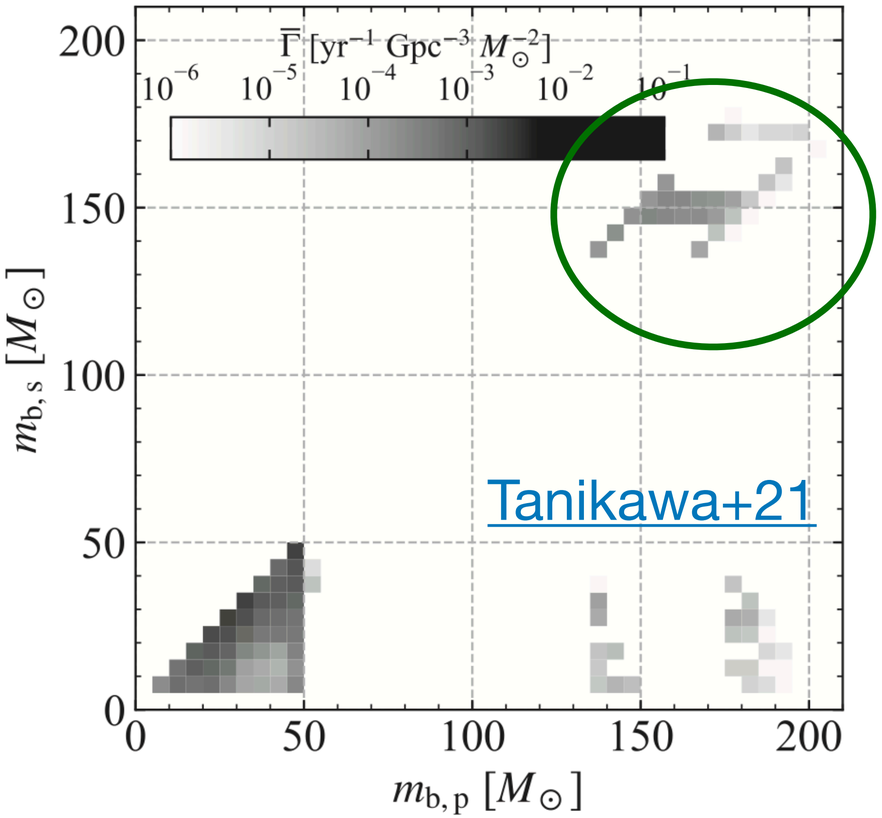
Population III stars

SEVN+Parsec popIII



No very massive BBH merges

BSE + popIII update



Very massive BBH mergers!

Depends on the the different evolutions of massive progenitors

Implications for LISA

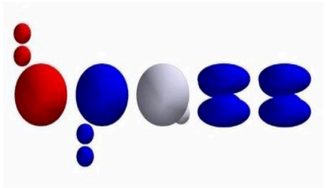
LISA Synthetic Ultra Compact Binaries Catalogs Project

- Dominated by double white dwarfs
- Uncertainties from implementation
- Uncertainties from our knowledge
- Community-scale effort

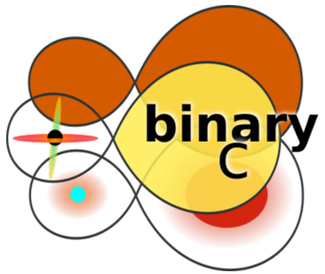
A Large Community Effort!

POSYDON

BSE



ComBinE



SEBA

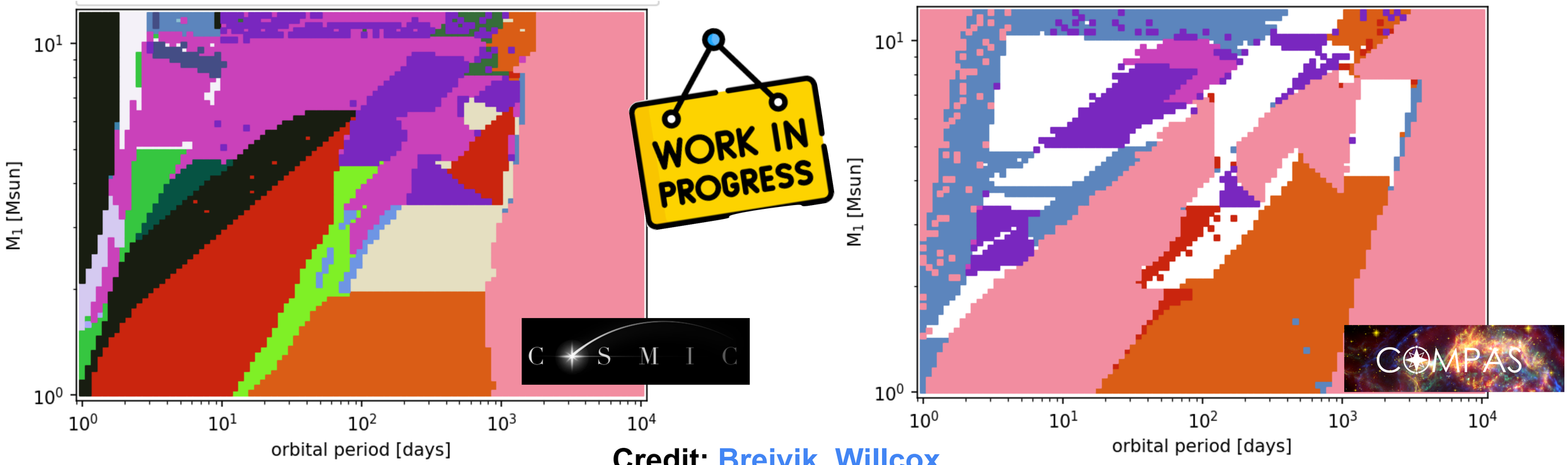
METISSE

Over 70 members; 10 code coordinators; 10 core analysis team members

Implications for LISA

LISA Synthetic Ultra Compact Binaries Catalogs Project

Example of variations



Credit: Breivik, Willcox

- 10 codes
- 6 parameter variations

Take away messages

- **Stellar evolution matters!** (Including pop. studies for LISA)
- **Binary parameters and stellar evolution models are correlated**

to include stellar evolution models and explore stellar evolution uncertainties in population studies

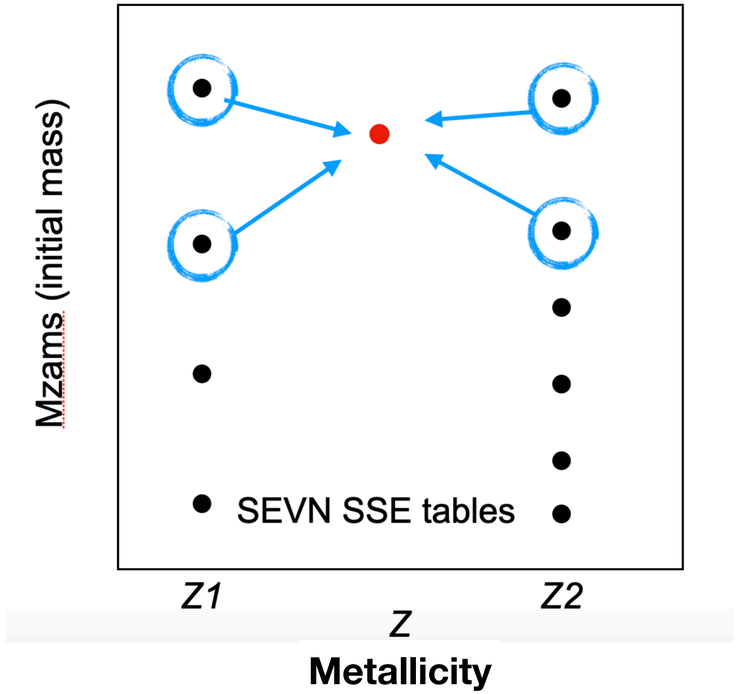
I am happy to help and be involved in population synthesis studies within the LISA (Spain) community

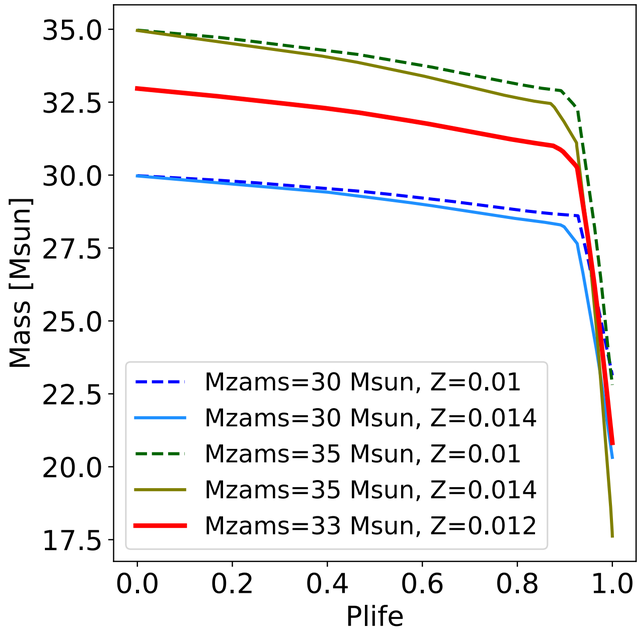
giuliano.iorio.astro@gmail.com

BACKUP

SEVN

Stellar evolution interpolation





- 4 Interpolating tracks for each (Mzams, Z)
- Interpolate properties through a weighted mean (depenging on Mzams, Z) of the tracks at the same plife

$$\mathrm{plife} = \frac{\tilde{t} - t_{0,\mathrm{phase}}}{\Delta t_{\mathrm{phase}}}$$

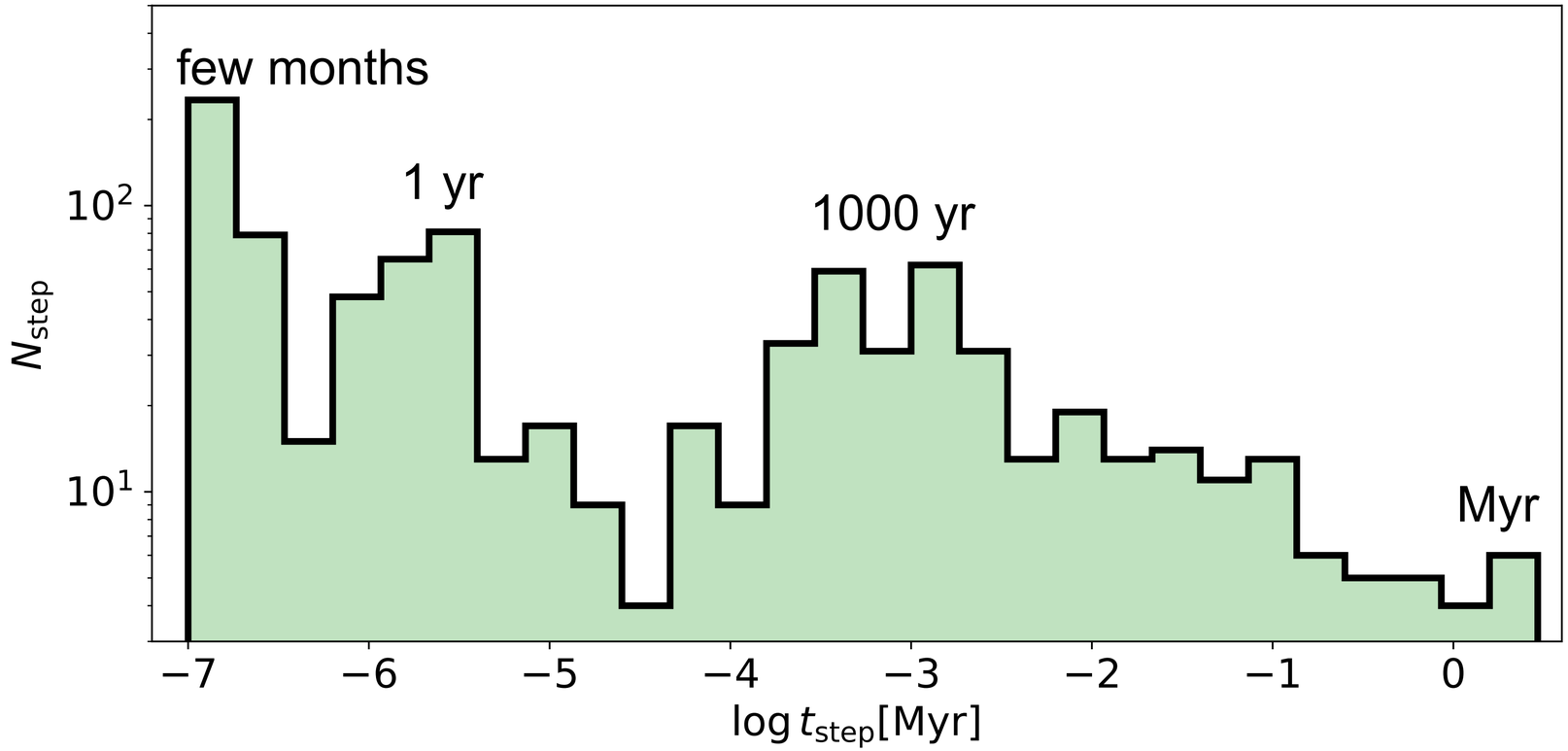
- Jump to new tracks when deviate from tracks (binary interactions)

SEVN

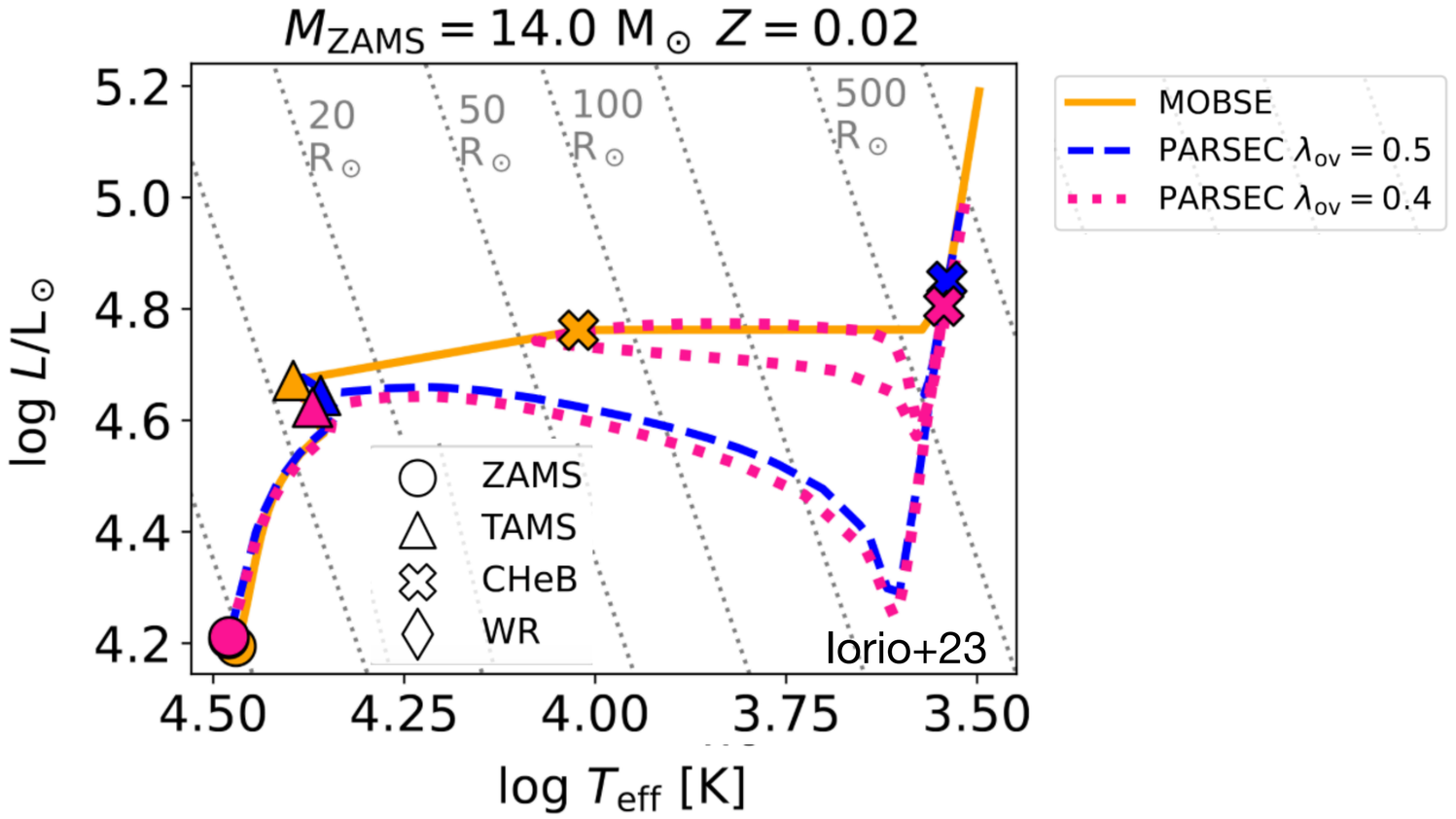
Adaptive timestep

- **repeat if properties change to much (e.g. >5%)**
- **predict next time step based on current variations**

Distribution of time steps for a complete massive binary evolution (25 Myr)



The impact of stellar evolution on binary compact object



BSE-like: NS progenitors ignite **He-burning in the "blue"**

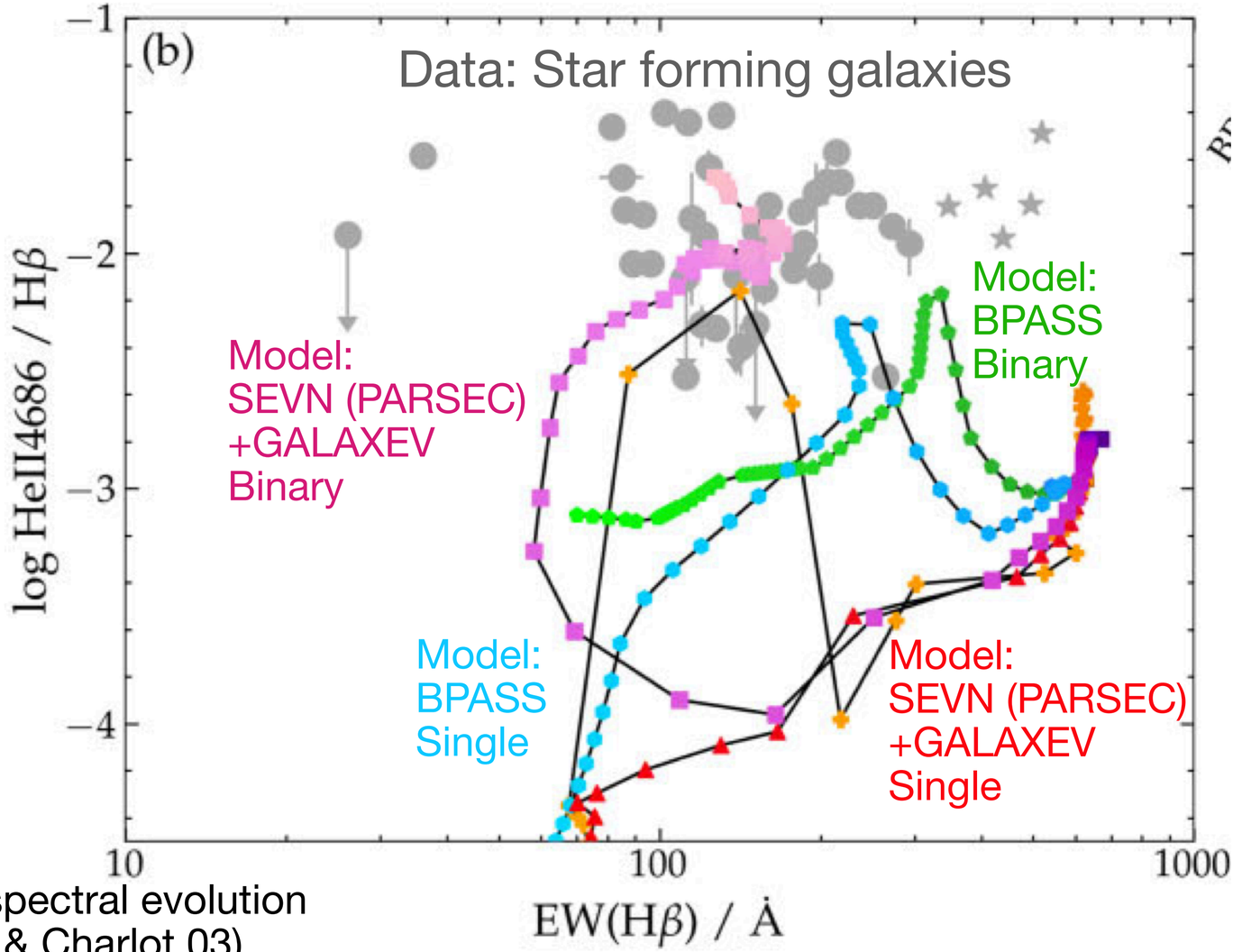
PARSEC: NS progenitors ignite **He-burning in the "red"**

What is the effect for merging BNS?

Not only BCOs:

SEVN + GALAXEV nebular emission from young populations

Lecroq+24



GALAXEV: spectral evolution
(Bruzual & Charlot 03)