POSYDON

a general-purpose binary population synthesis code employing detailed stellar structure and binary evolution calculation

Simone Bavera

POSYDON collaboration: Tassos Fragos, Jeff Andrews, Christopher Berry, Scott Coughlin, Aaron Dotter, Prabin Giri, Vicky Kalogera, Aggelos Katsaggelos, Konstantinos Kovlakas, Shamal Lalvani, Devina Misra, Philipp Shrivastava, Ying Qin, Jaime Román-Garza, Kyle Rocha, Juan Gabriel Serra Pérez, Petter Alexander Stahle, Meng Sung, Xu Teng, Goce Trajcevski, Zepei Xing, Manos Zapartas, Zevin Michael

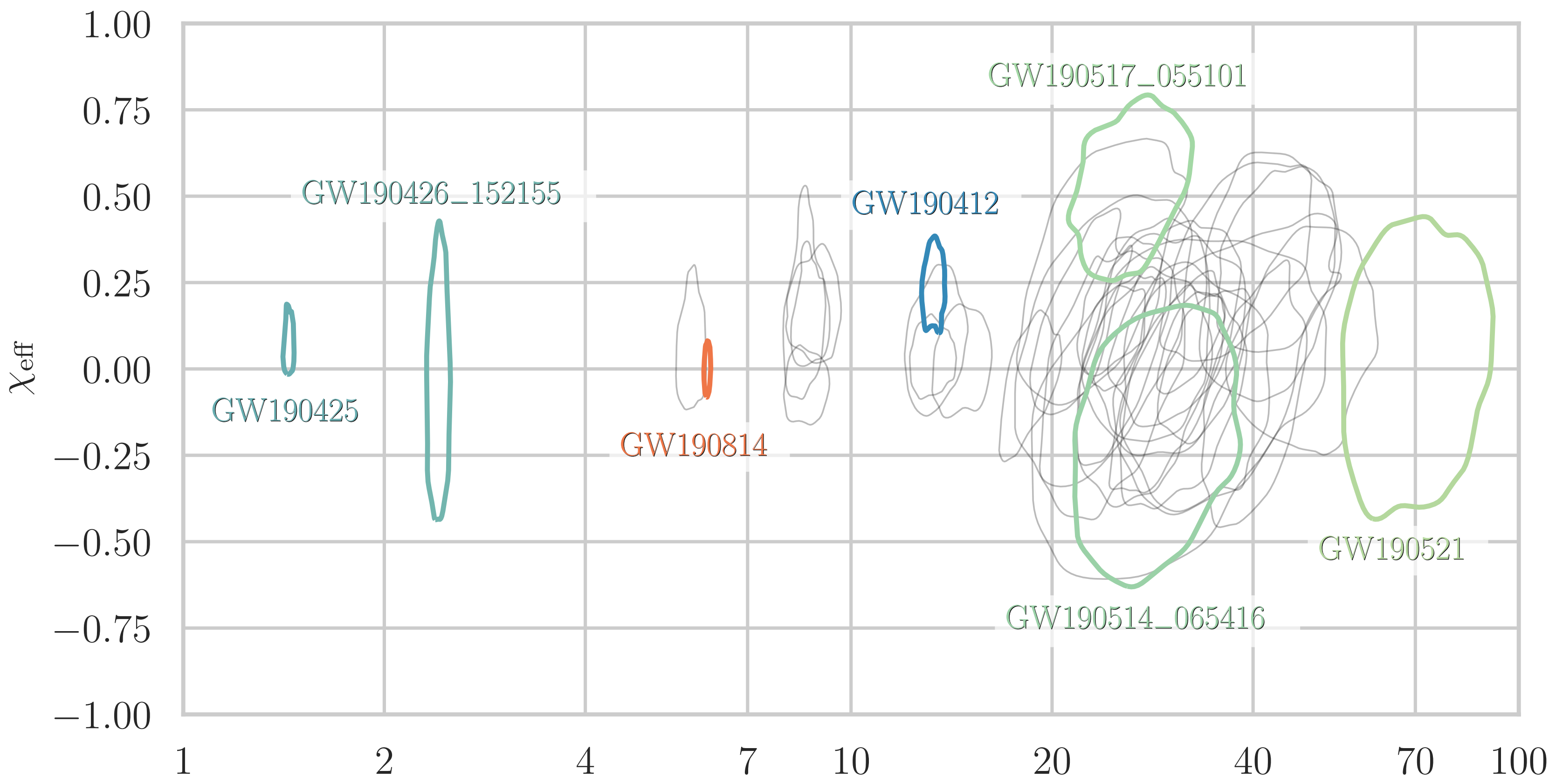
UNIVERSITÉ DE GENÈVE
FACULTÉ DES SCIENCES
Département d'astronomie

Institut d'astrophysique de Paris, 14 April 2022

FNSNF
FONDS NATIONAL SUISSE
SCHWEIZERISCHER NATIONALFONDS
FONDO NAZIONALE SVIZZERO
SWISS NATIONAL SCIENCE FOUNDATION

A wealth of observational data challenging our theories of binary evolution and compact object formation

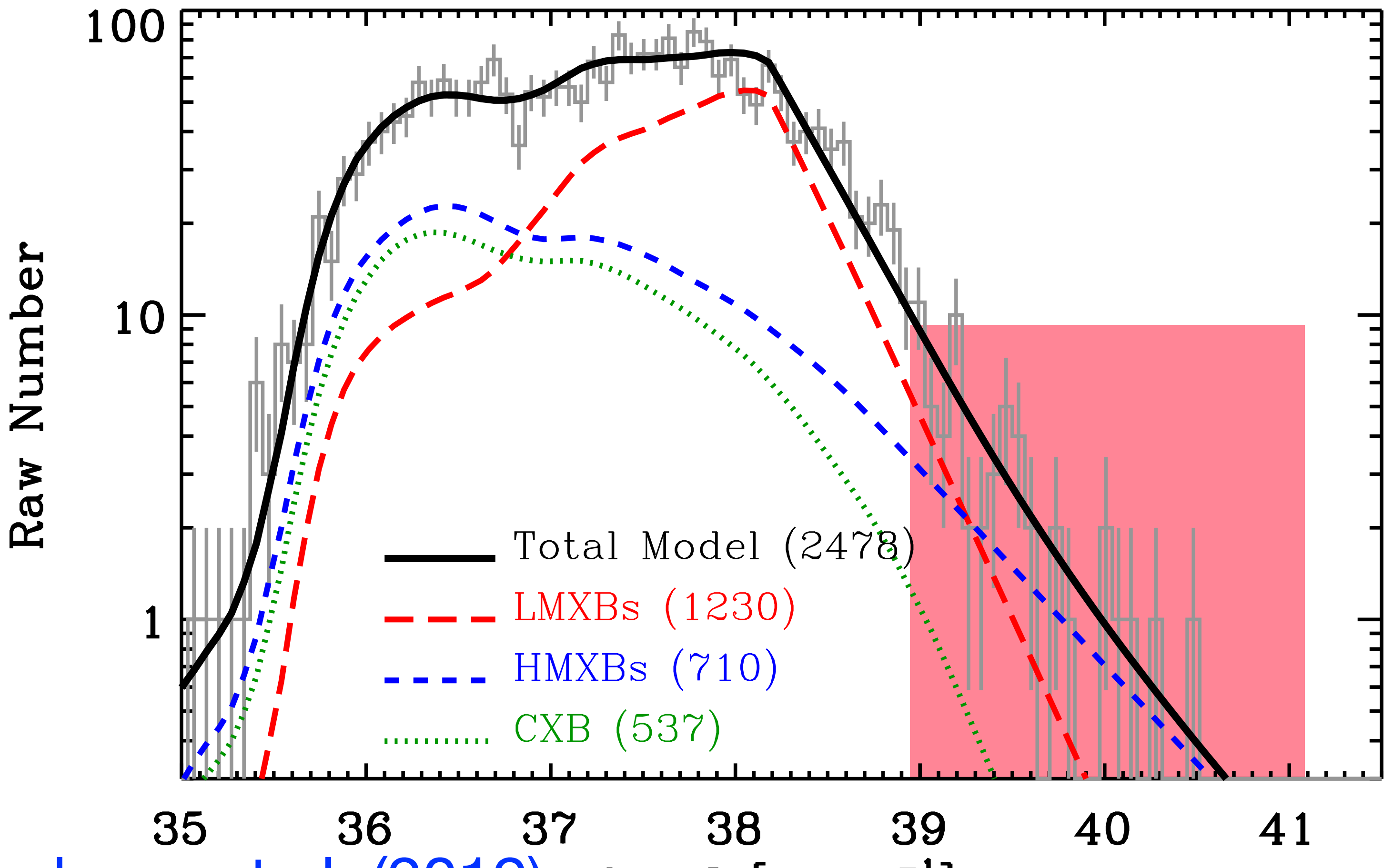
Coalescing double compact objects



Abbott et al. (2021) $\mathcal{M}/M_\odot$

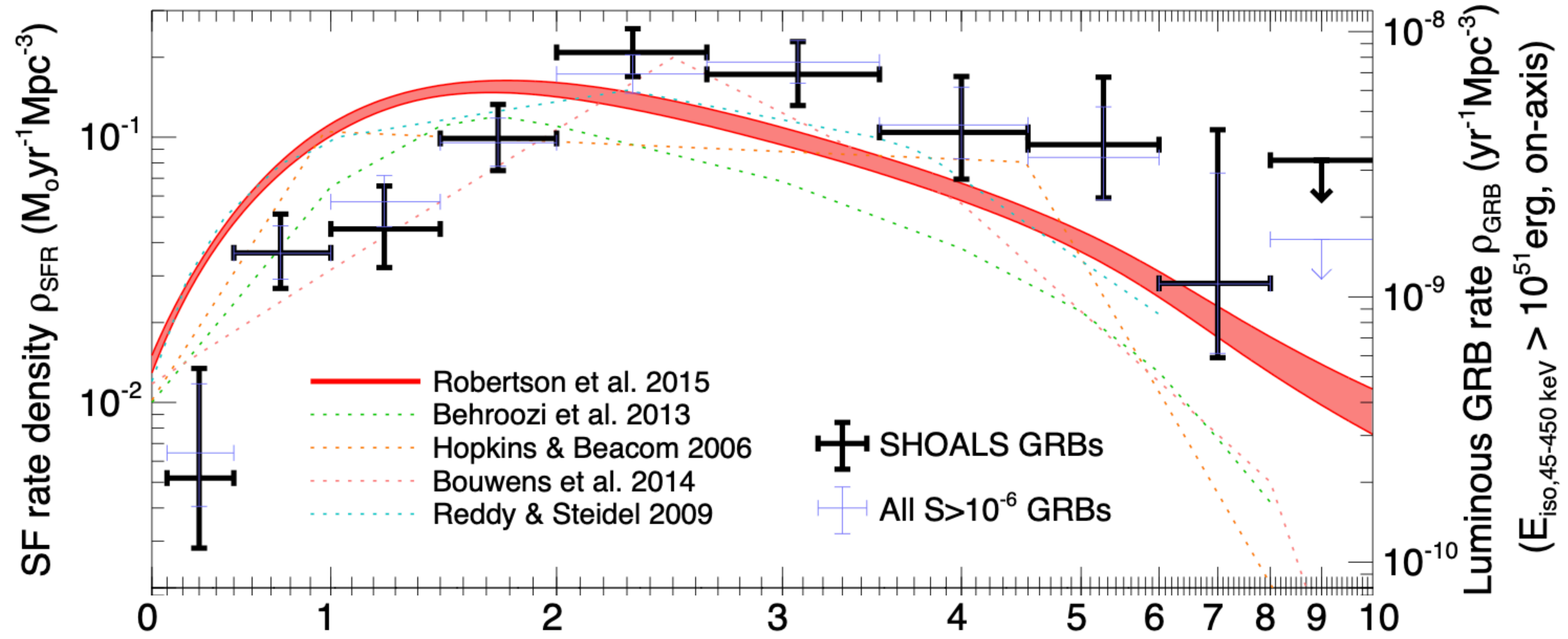
Most information is carried by the statistical properties of the whole population of sources

Ultraluminous X-ray sources



Lehmer et al. (2019) log L [erg s^{-1}]

Long-duration Gamma-ray bursts

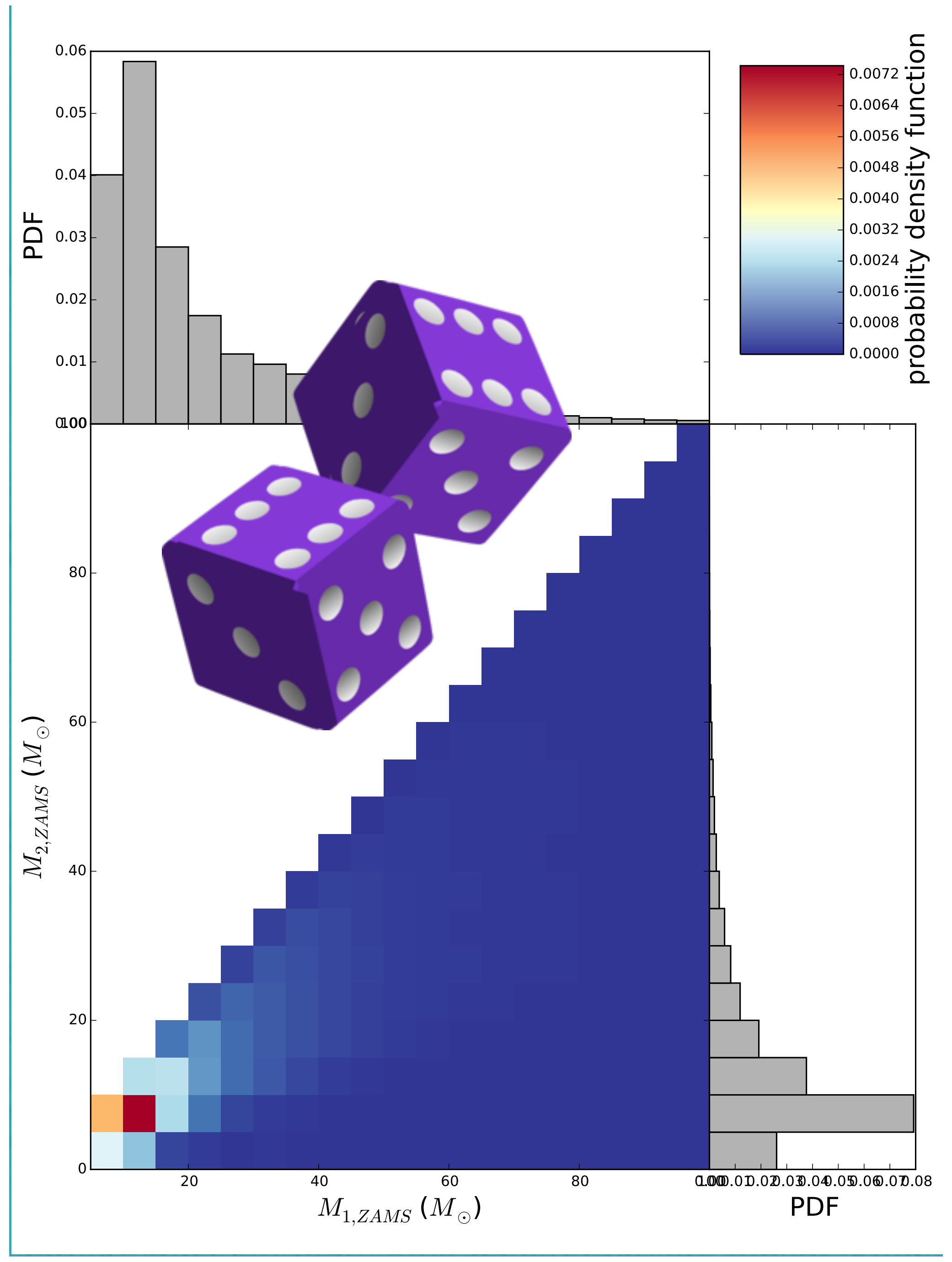


Perley et al. (2016) Redshift (z)

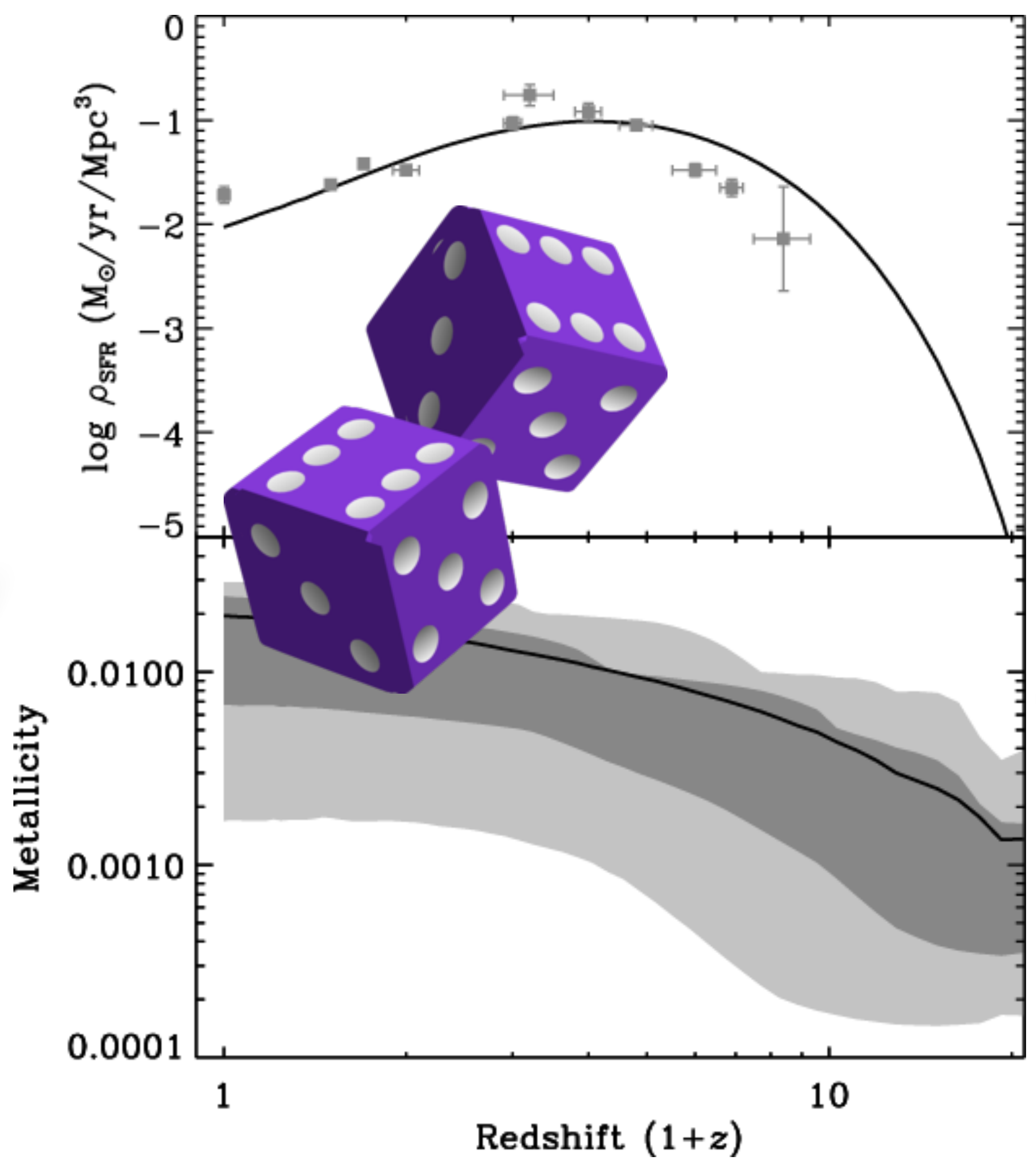
Observable properties are determined by the interplay of binary interaction & stellar interior physics

Binary Population Synthesis

Initial binary population



Star-formation history

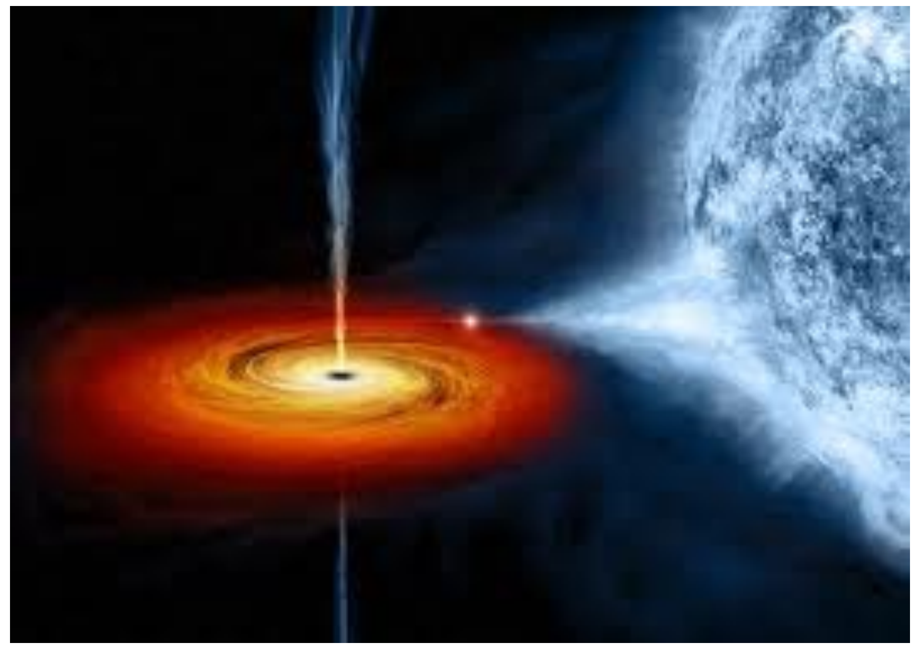


Rapid binary evolution

binary_c

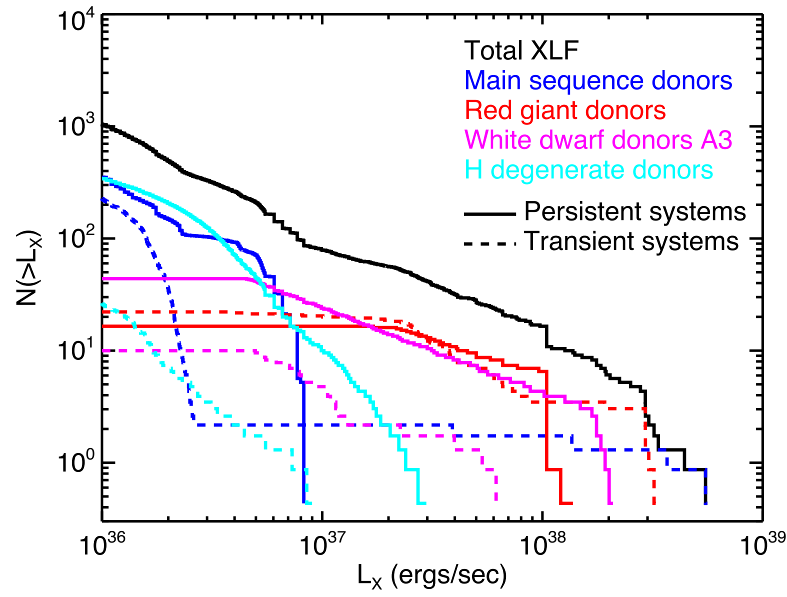
COMPAS

Properties of binary



Repeat $10^{6\text{-}7}$

Synthetic population



Binary Population Synthesis

Current Generation
Binary Population Synthesis Codes

BSE (Hurley et al. 2002)
StarTrack (Belczynski et al. 2002, 2008)
MOBSE (Giacobbo et al. 2018)
BPASS (Eldridge et al. 2017)
binary_c (Izzard et al. 2004, 2006, 2009)
Brussels' code (Vanbeveren et al. 1998)
ComBinE (Kruckow et al. 2018)
COMPAS (Stevenson t al. 2017)
COSMIC (Breivik et al. 2020)
SEVN (Spera et al. 2015)
The Scenario Machine (Lipunov et al. 1996, 2009)
SeBa (Portegies Zwart & Verbunt 1996, Toonen et al. 2012)

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Current Generation Binary Evolution Codes

BEC (Heger et al. 2000, Heger & Langer 2000)
BINSTAR (Seiss et al. 2013)
Cambridge STARS (Eldridge & Tout 2004)
MESA (Paxton et al. 2013)
TWIN (Nelson & Eggleton 2001, Eggleton & Kiseleva-Eggleton 2002)

Binary Population Synthesis

Current Generation Binary Population Synthesis Codes

Current Generation Binary Evolution Codes

BEC (Heger et al. 2000, Heger & Langer

What’s the difference?

Binary population synthesis codes don’t self-consistently evolve each stars’ structure with the orbit.

Current-Generation Binary Population Synthesis

Stellar properties of binary components are derived from fitting formulae or look up tables based on **single, constant mass, non-rotating stars, at thermal equilibrium.**

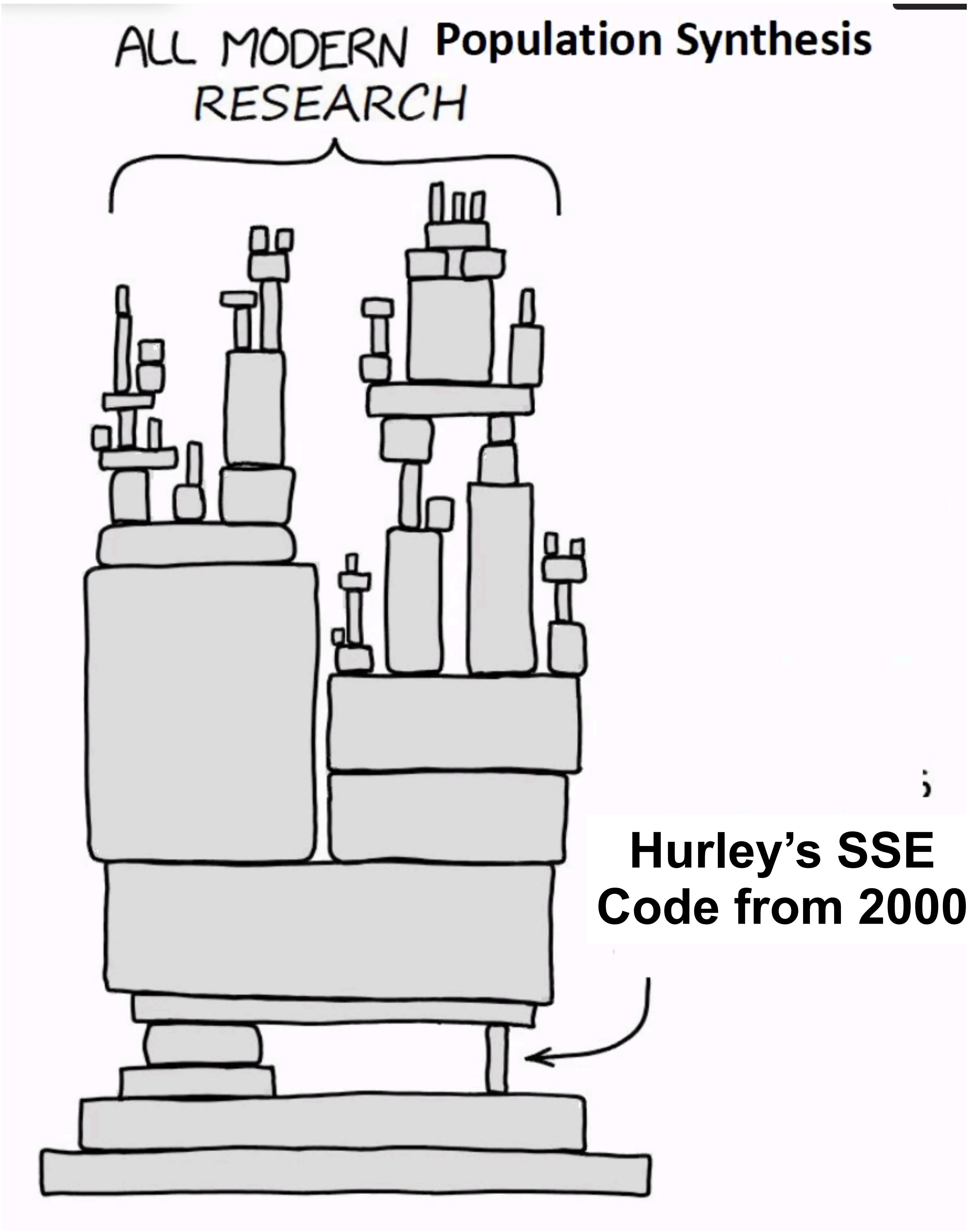
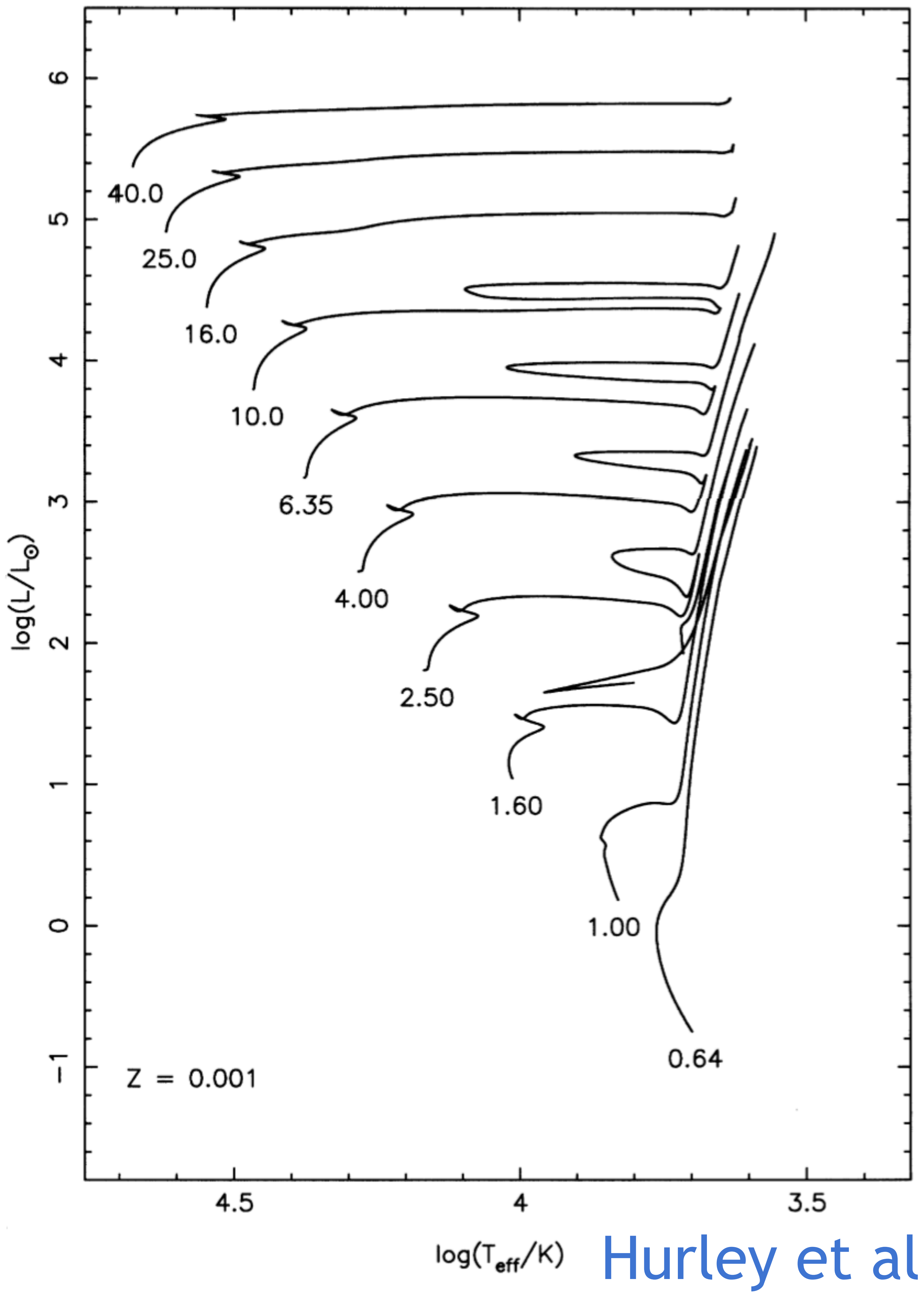


Figure Credit: Floor Broekgaarden



Hurley et al.(2000)

Current-Generation Binary Population Synthesis

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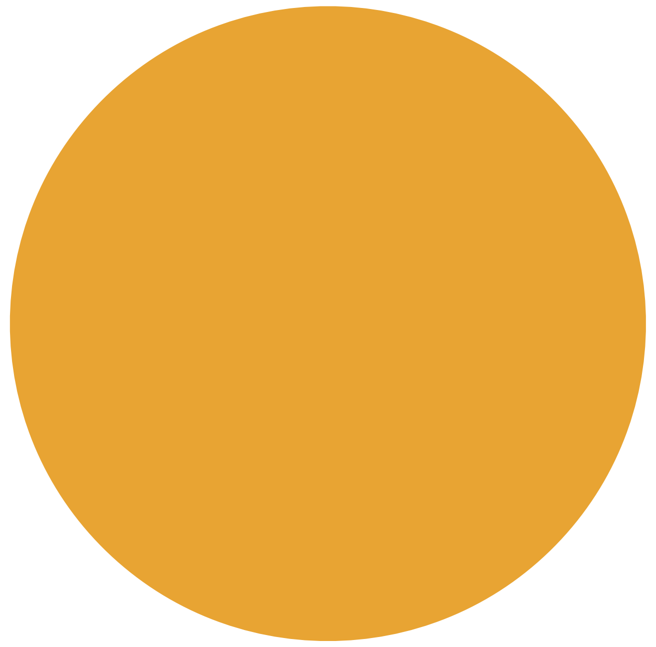
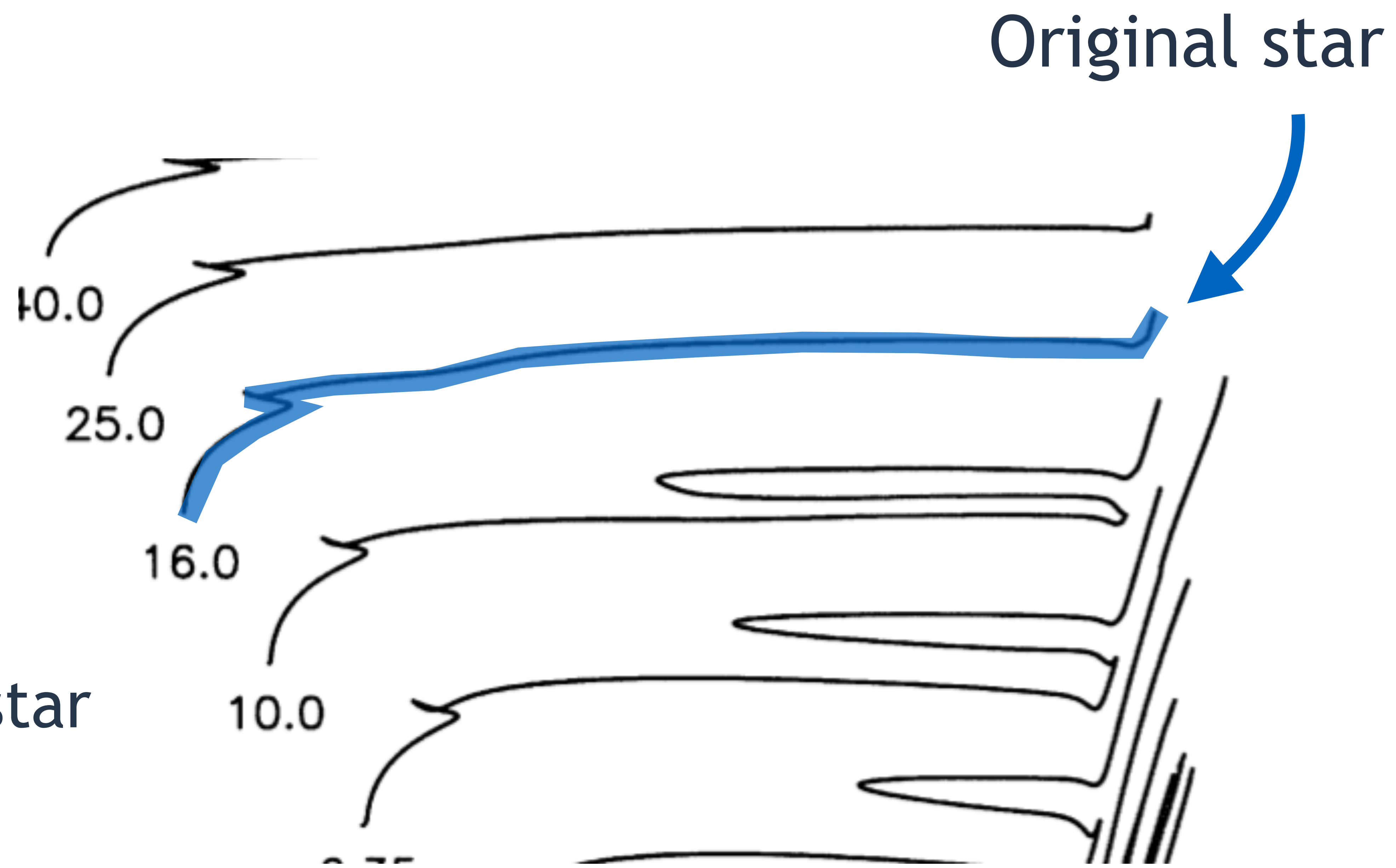
This affects the:

- assessment of mass-transfer stability
- estimate of mass-transfer rate
- structure of the pre-core-collapse stars and the resulting compact object
- transport of angular momentum between and within the binary components
- its effects on the structure of the star (e.g., rotational mixing)



Remove mass from a star
$M = 16\ M_\odot$



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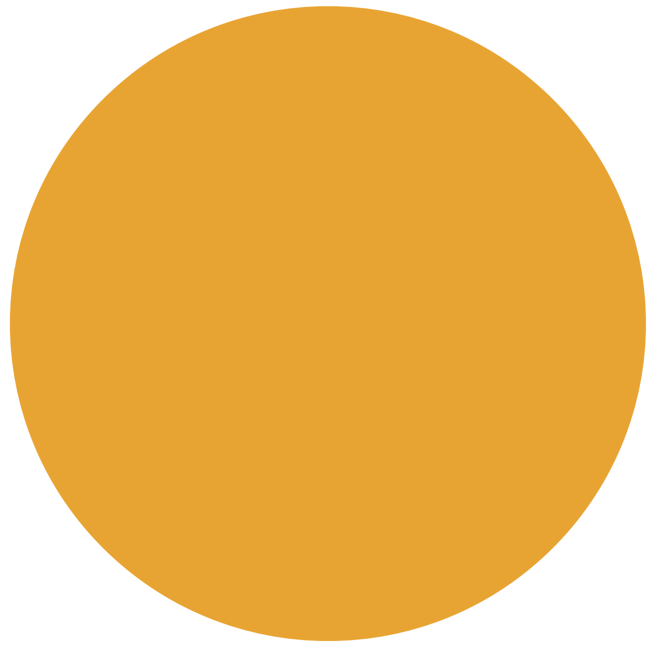
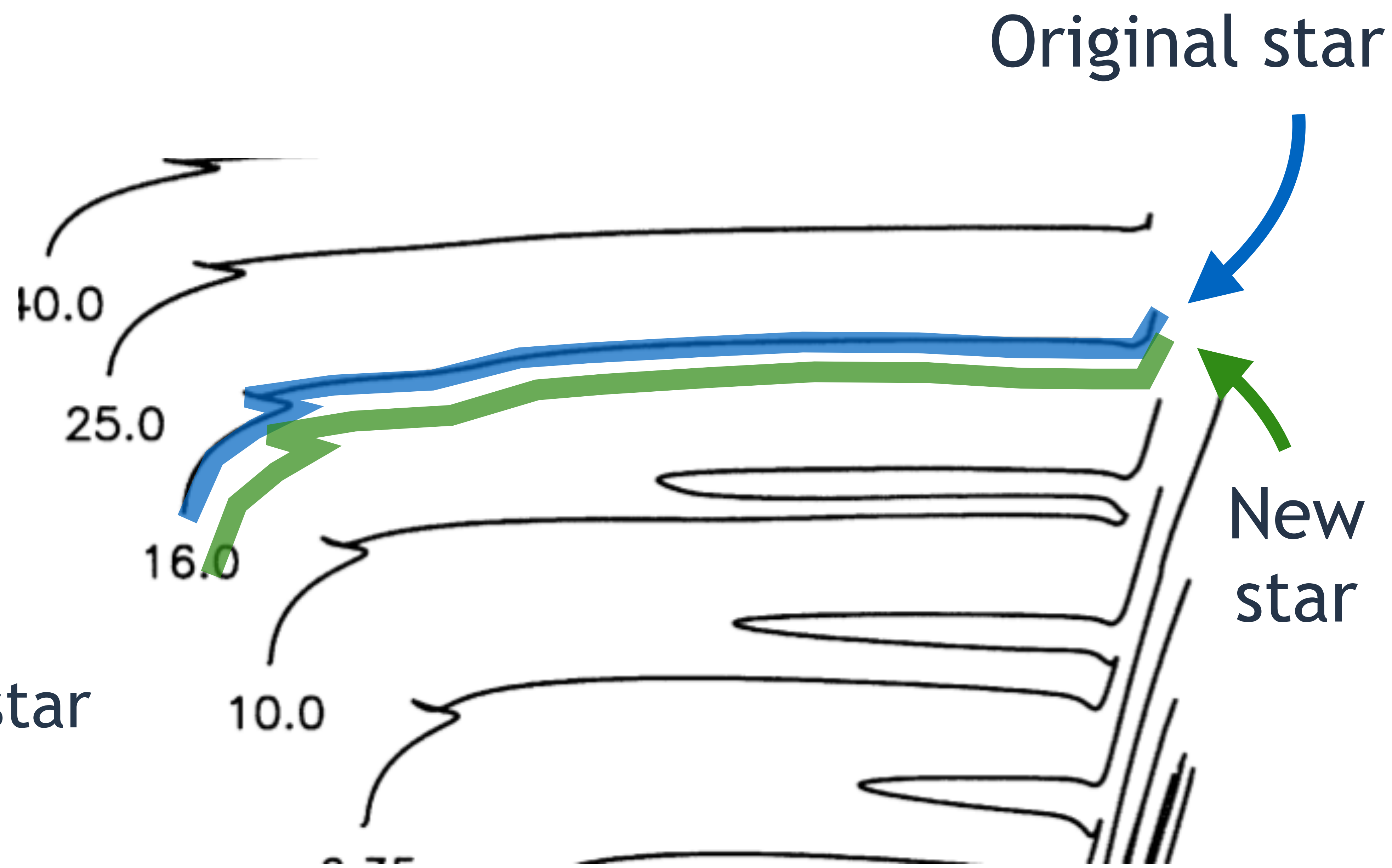


Remove mass from a star
$M = 16\ M_\odot - \Delta M$



Move between stellar models

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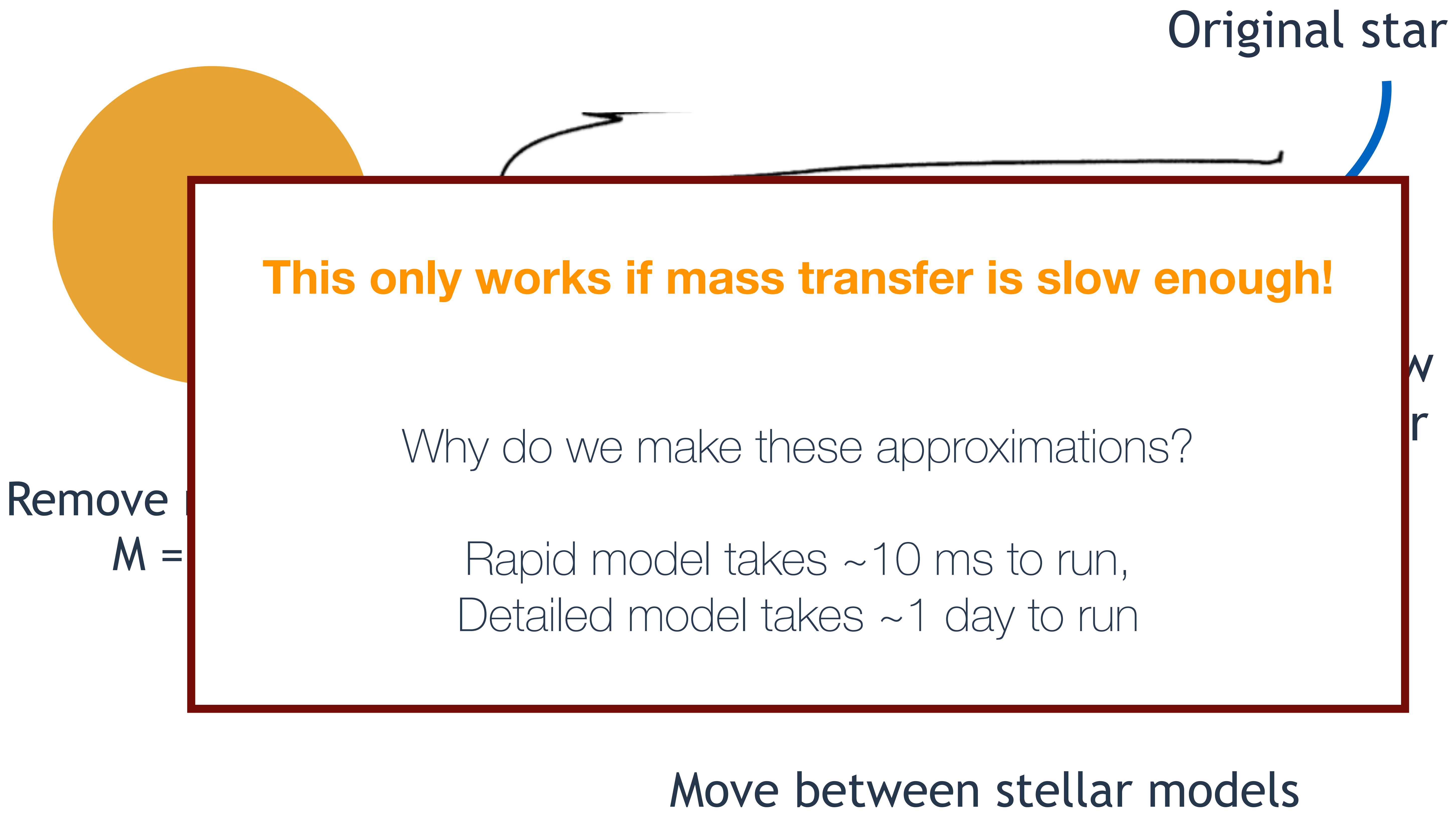

This only works if mass transfer is slow enough!

Why do we make these approximations?

Rapid model takes ~10 ms to run,
Detailed model takes ~1 day to run

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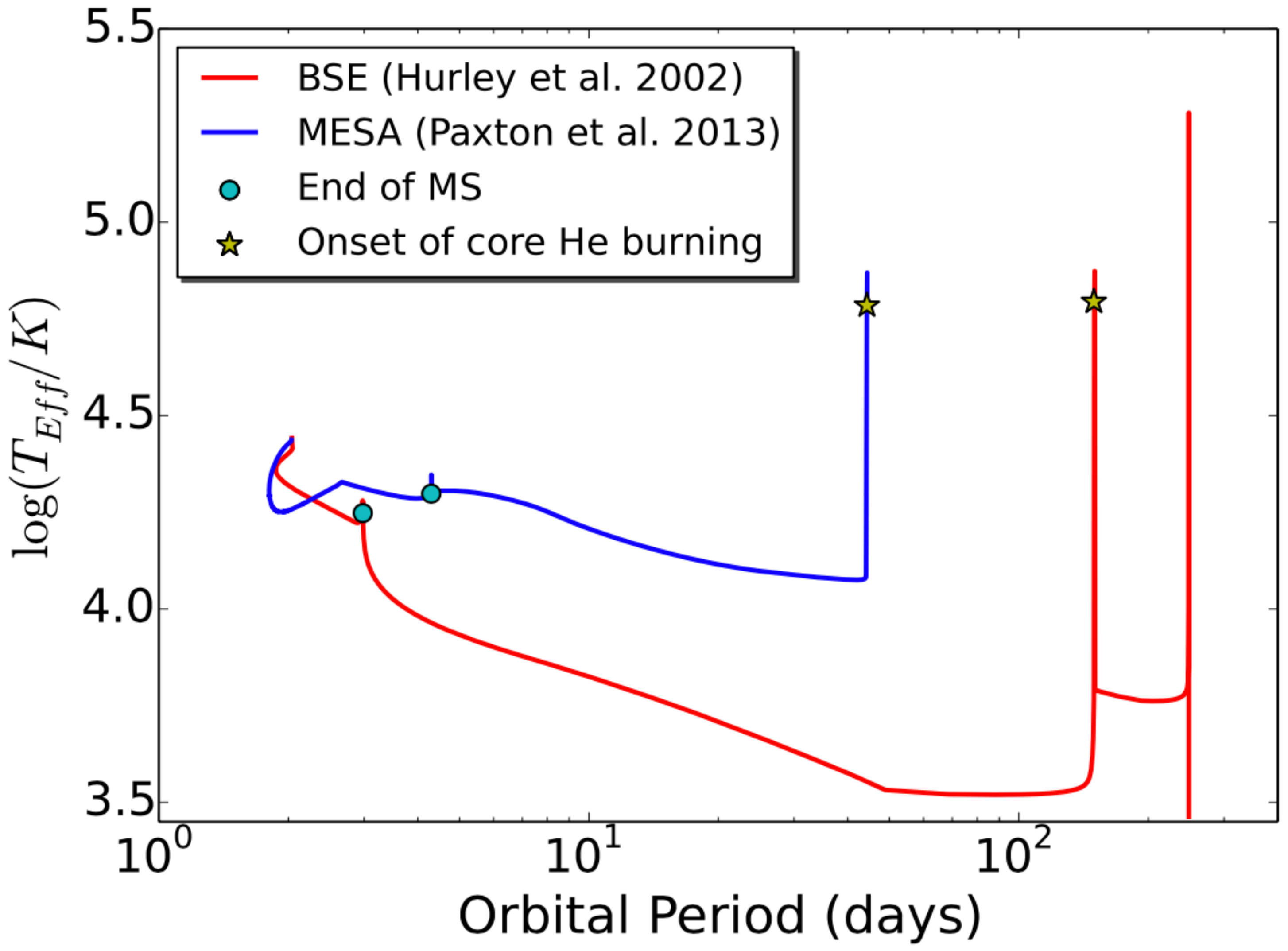

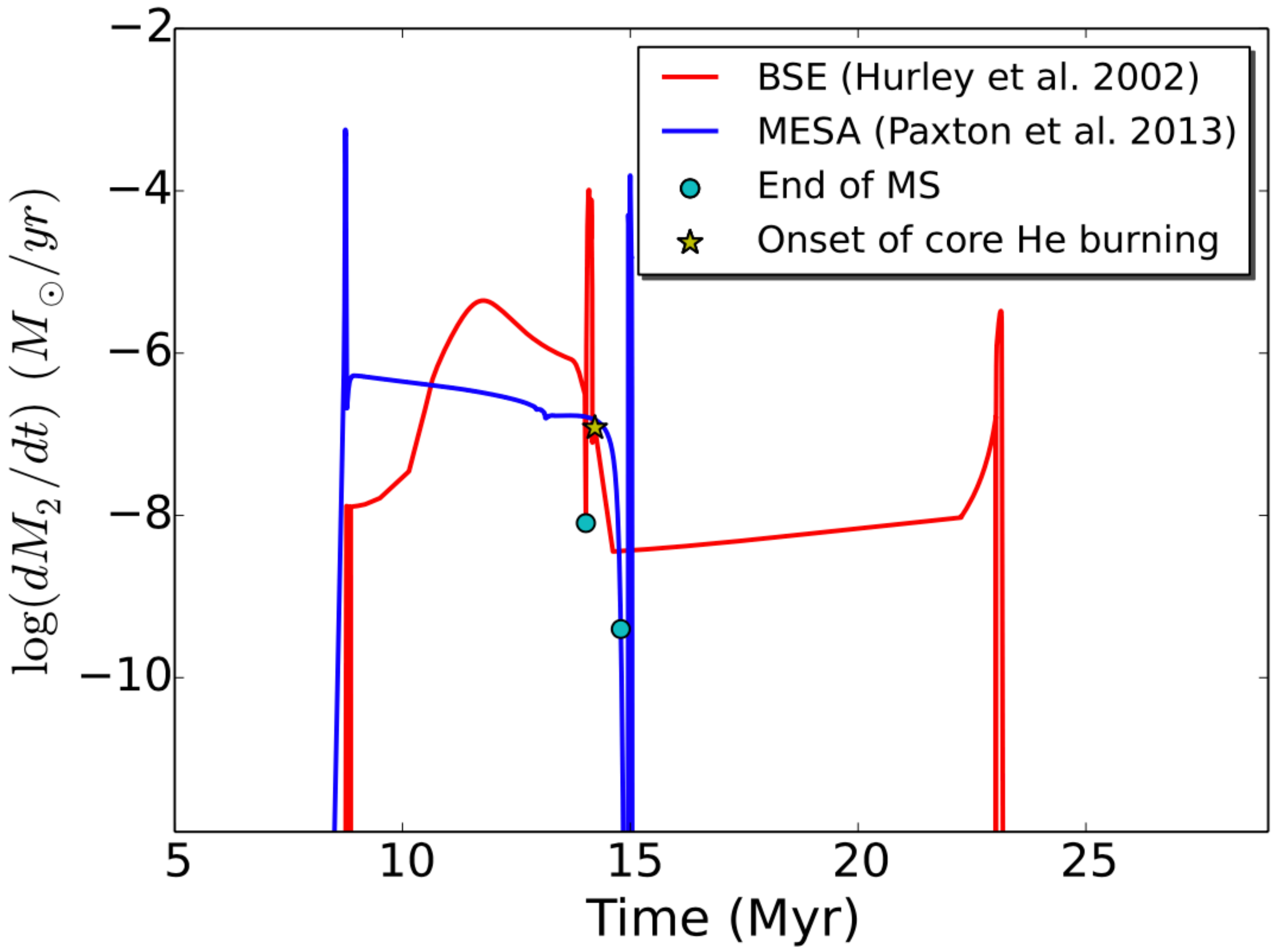

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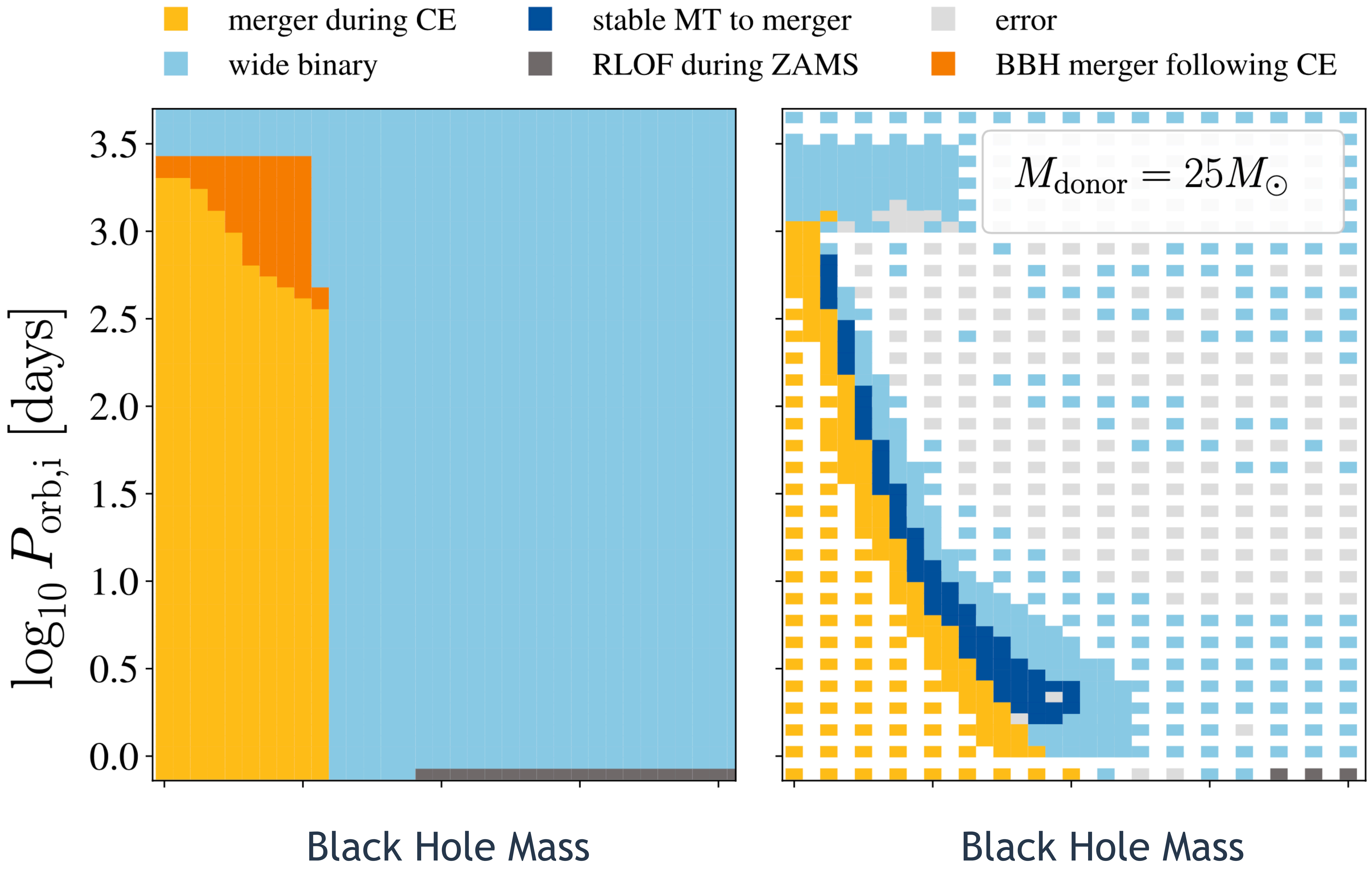
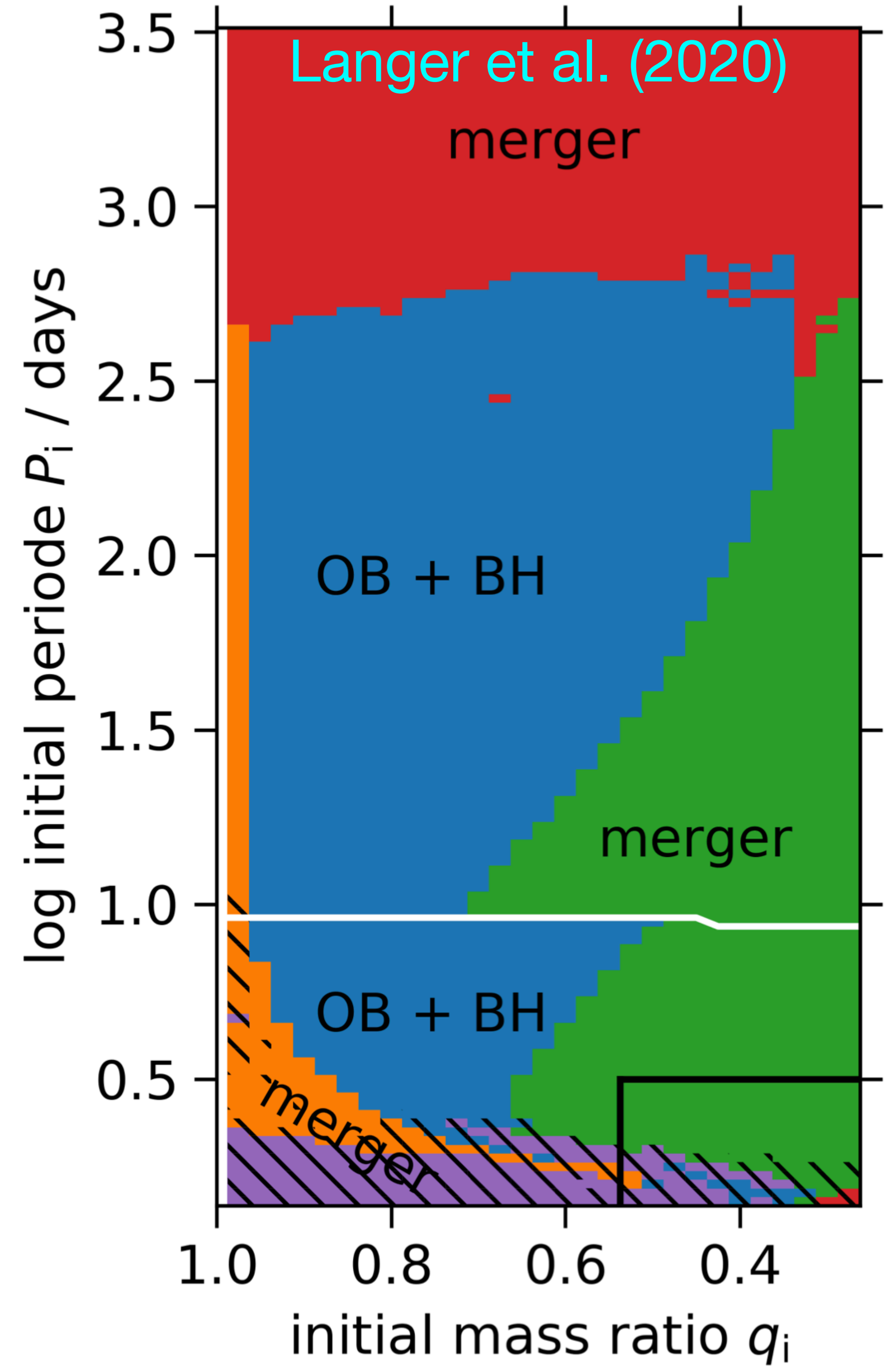
Gallegos-Garcia (2021)



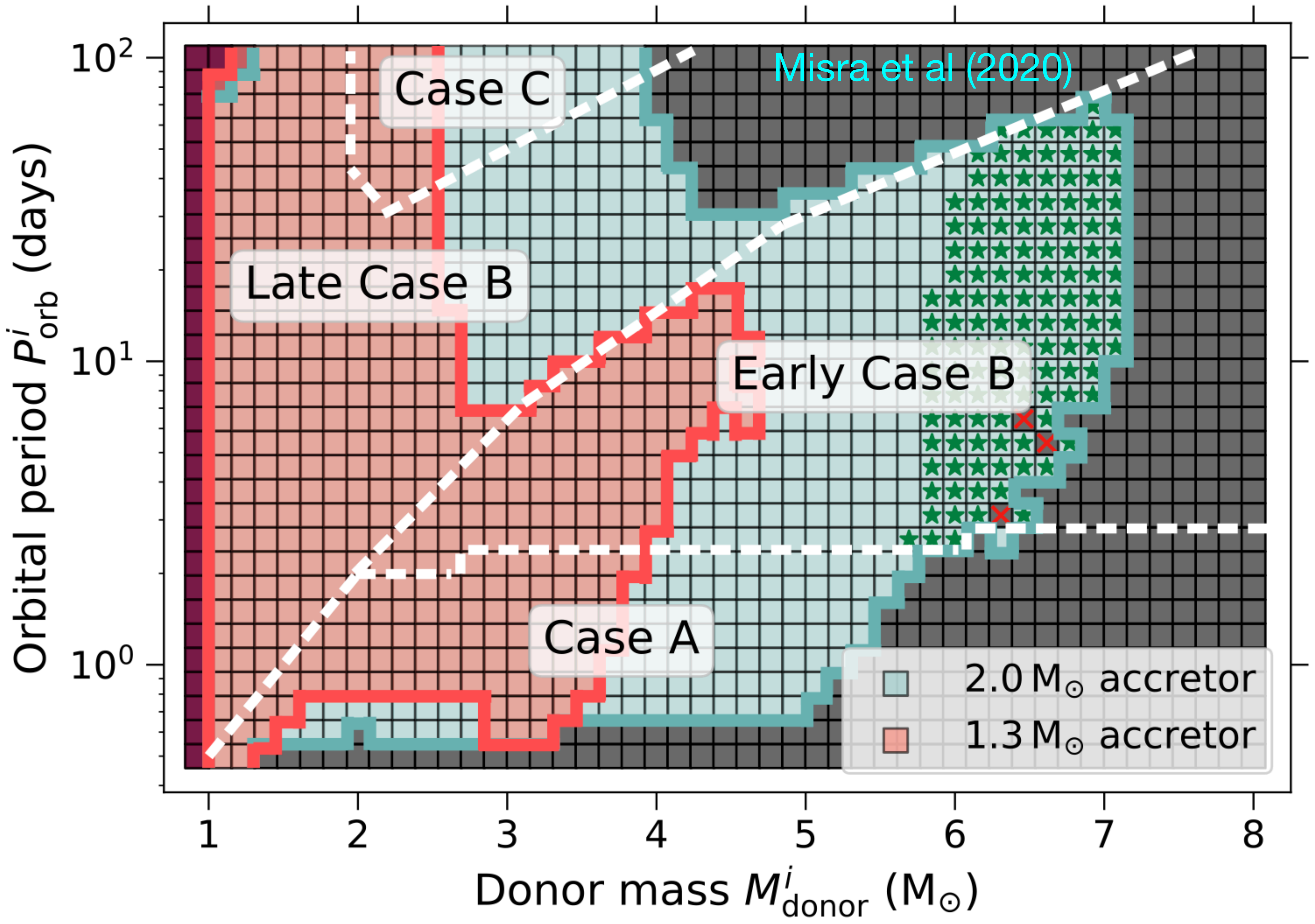
Detailed stellar structure and binary evolution models

Detailed stellar structure and binary evolution models can alleviate many of these weaknesses

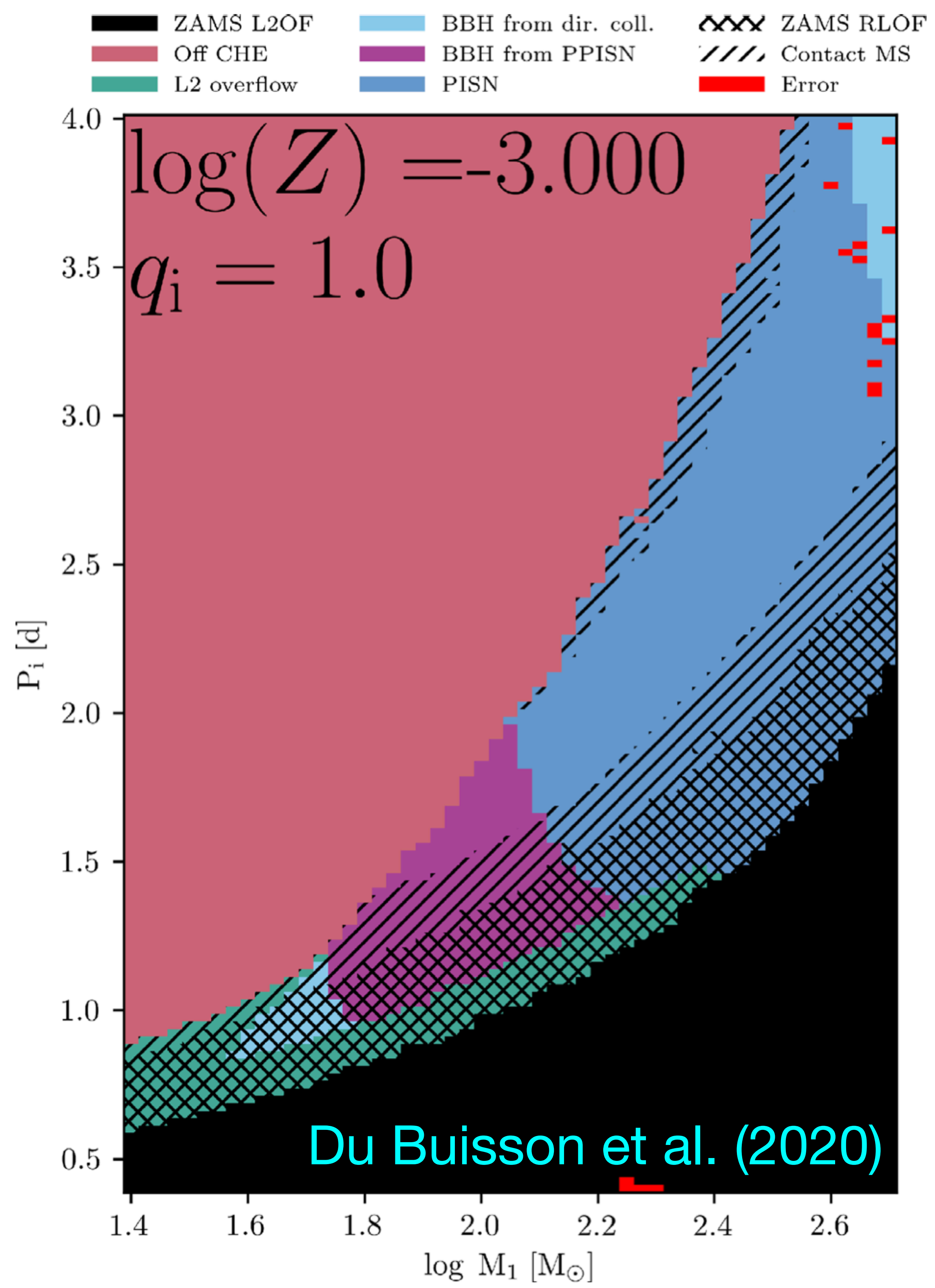
O/B-star—black hole binaries



Ultralouminous X-ray sources with neutron-star accretors



Chemically homogeneous evolution



10^4-10^6 times more computationally expensive — Usually target on a limited parameter space

POSYDON is a new framework for binary population synthesis studies that uses detailed stellar structure and binary evolution simulations (Fragos et al. 2022).

The core developer team

The **POSYDON collaboration**: Jeff Andrews, Simone Bavera, Christopher Berry, Scott Coughlin, Aaron Dotter, Tassos Fragos, Prabin Giri, Vicky Kalogera, Aggelos Katsaggelos, Konstantinos Kovlakas, Shamal Lalvani, Devina Misra, Philipp Shrivastava, Ying Qin, Jaime Román-Garza, Kyle Rocha, Juan Gabriel Serra Pérez, Petter Alexander Stahle, Meng Sung, Xu Teng, Goce Trajcevski, Zepei Xing, Manos Zapartas

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Fondo nazionale svizzero
Swiss National Science Foundation

GORDON AND BETTY MOORE FOUNDATION

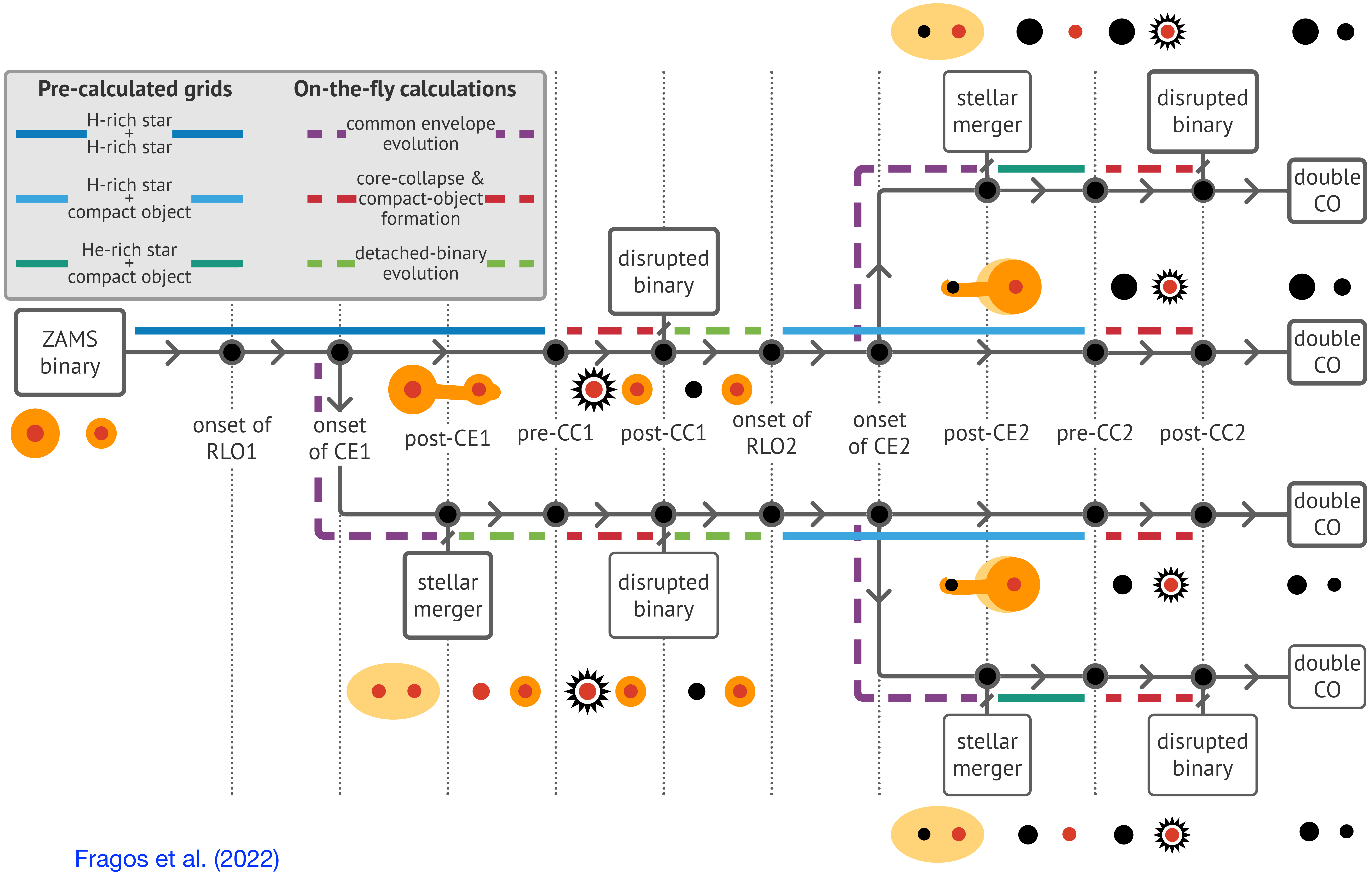
NORTHWESTERN UNIVERSITY

CIERA
Center for Interdisciplinary Exploration and Research in Astrophysics

An overview of POSYDON

POSYDON v1 only at Solar metallicity

- Following the detailed structure of both binary components
- Taking into account stella rotation (inc. rotational mixing) and tides
- Includes detailed stellar structure profiles at key evolutionary stages
- Modular and extendable
- Use of Machine Learning to tackle computational challenges.



Fragos et al. (2022)

Single hydrogen- and helium-rich stars

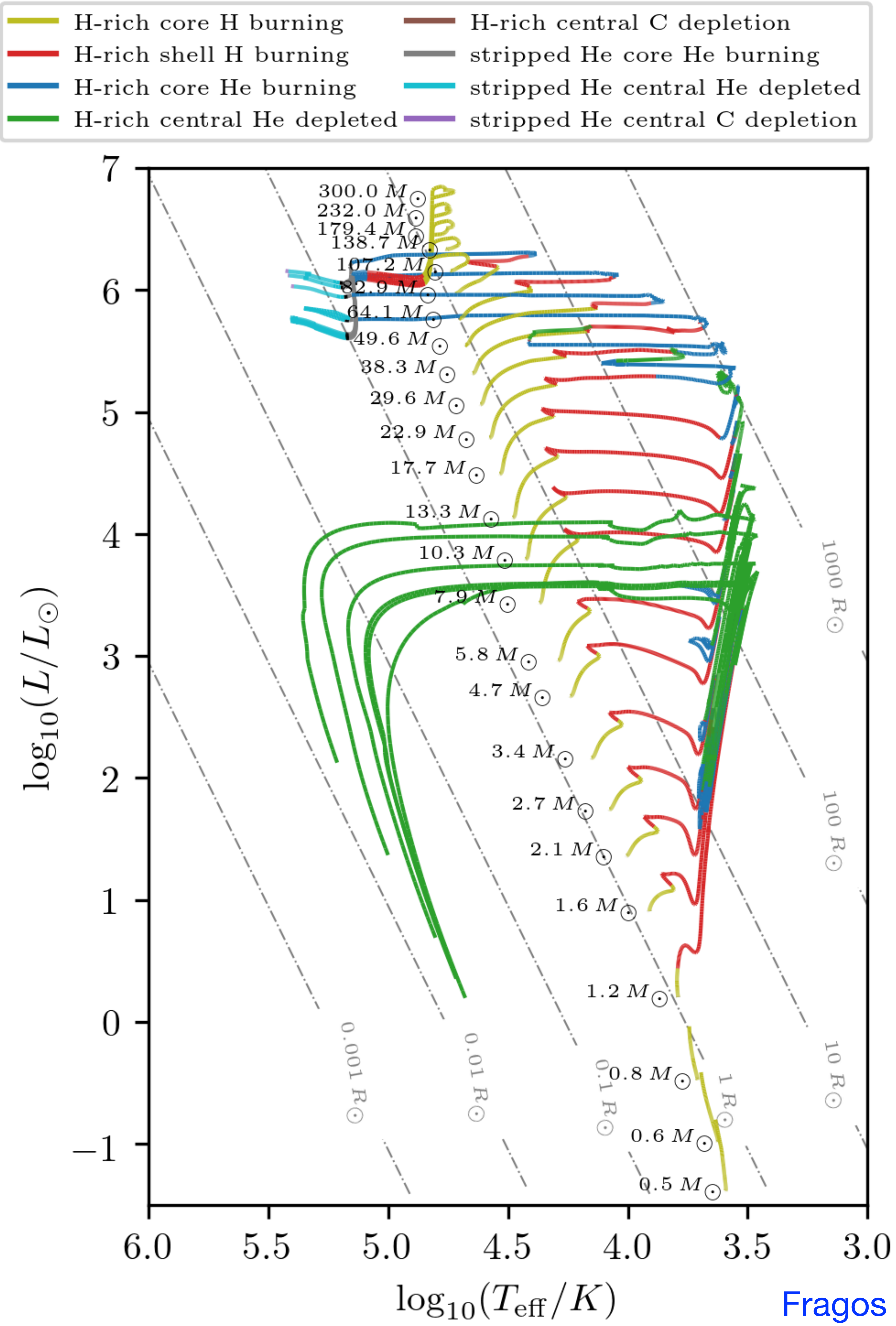
- **Stellar winds**
  Hot winds: Vink et al. 2001
  Cool winds: De Jager et al. 1988
  WR winds: Nugis & Lamers 2000
  Rotationally enhanced winds

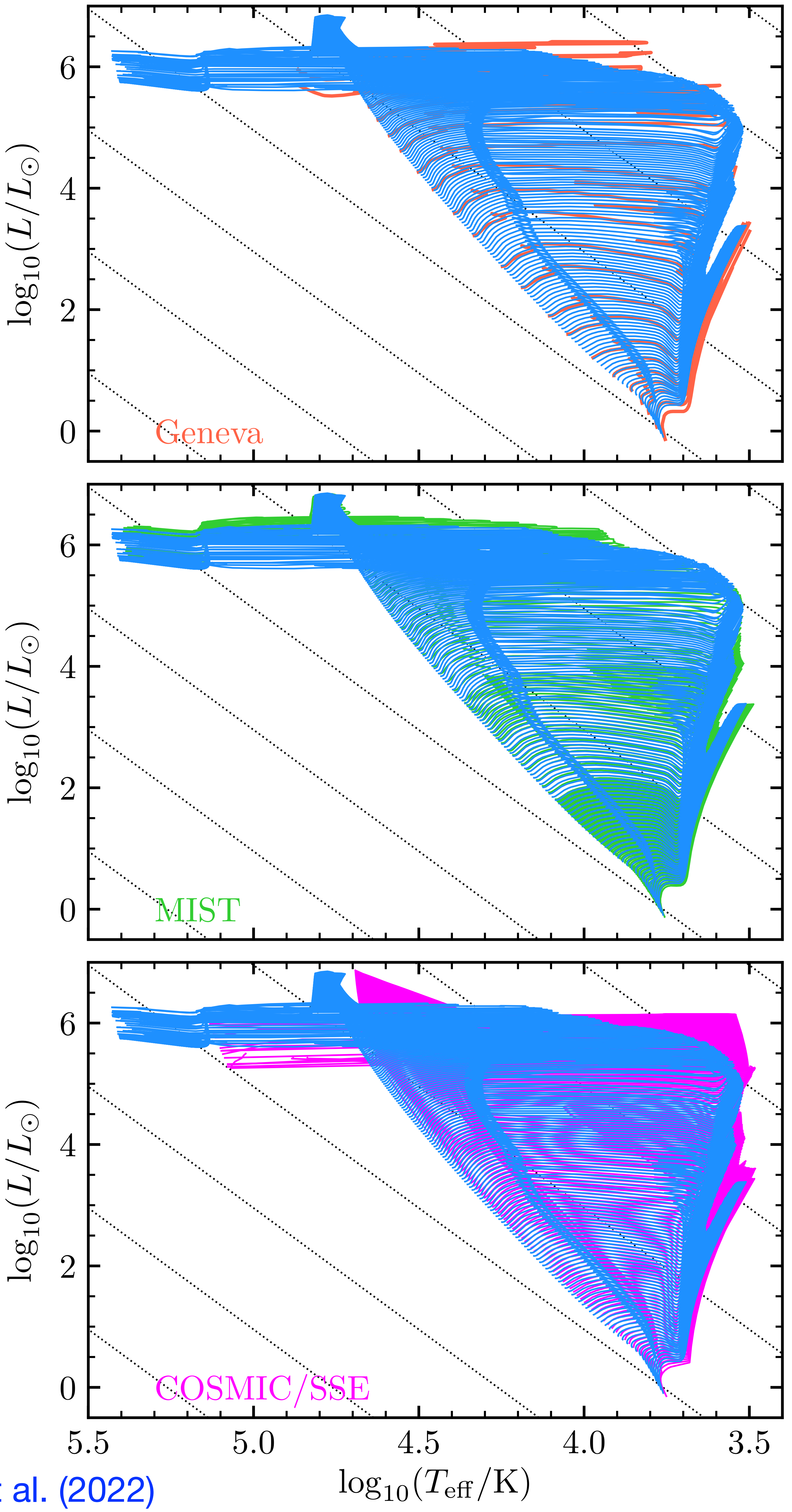
- **Overshooting**
  low-mass stars: f_{OV}=0.016 (Choi et al. 2016)
  high-mass stars: f_{OV}=0.0415 (Brott et al. 2011)

- MLT++ (Paxton et al. 2013)

- Efficient angular momentum transport (Spruit 2002) (but single stars non-rotating!)

- Interpolation between single stellar tracks using the EEP method (Dotter 2016)





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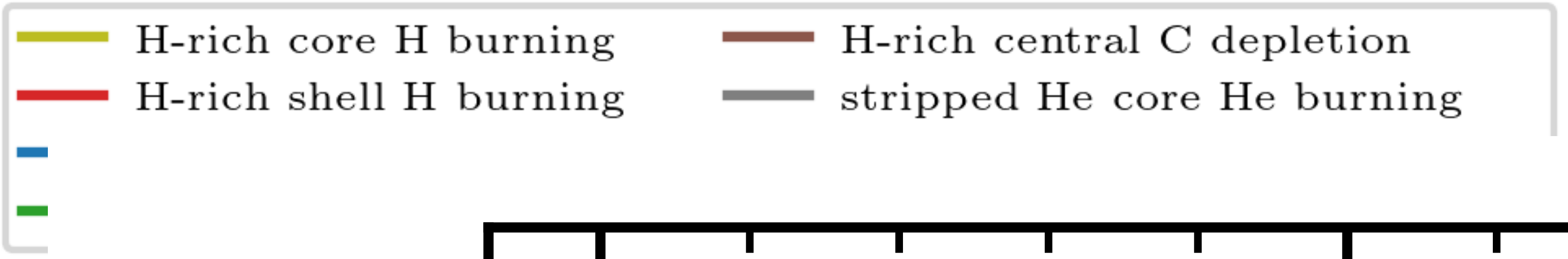
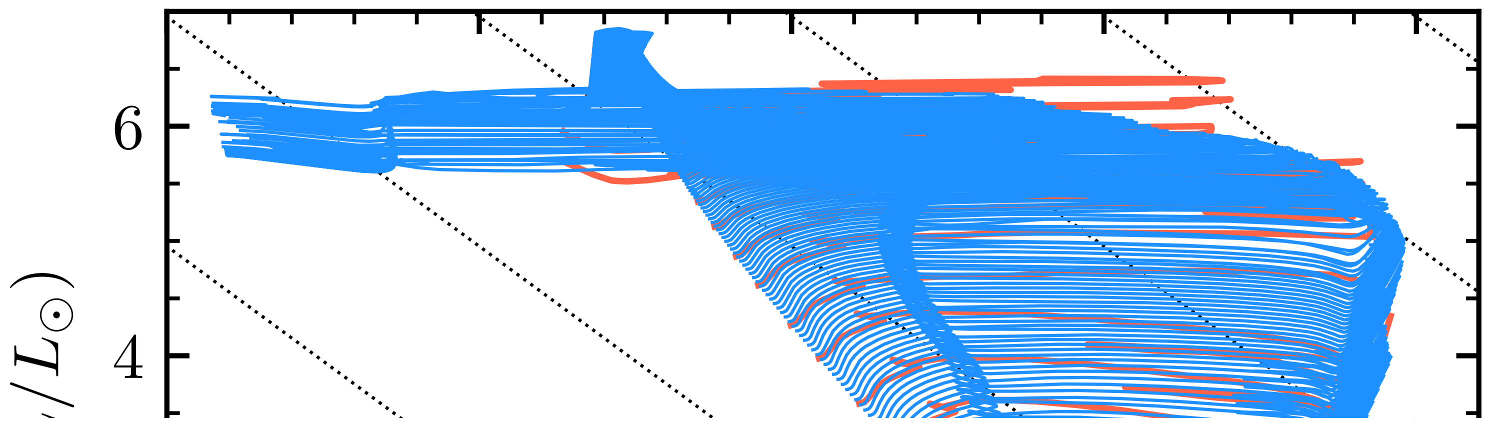
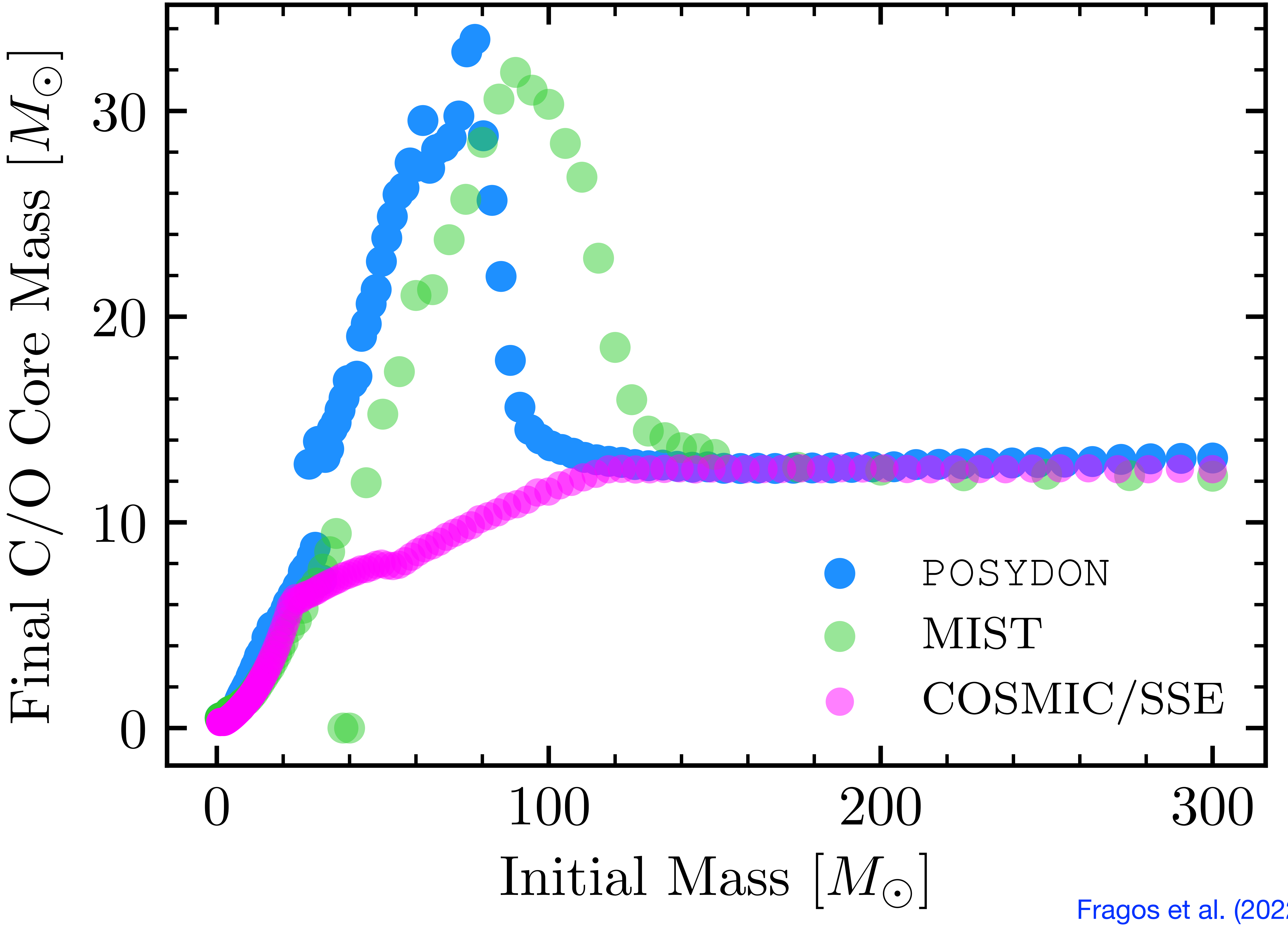






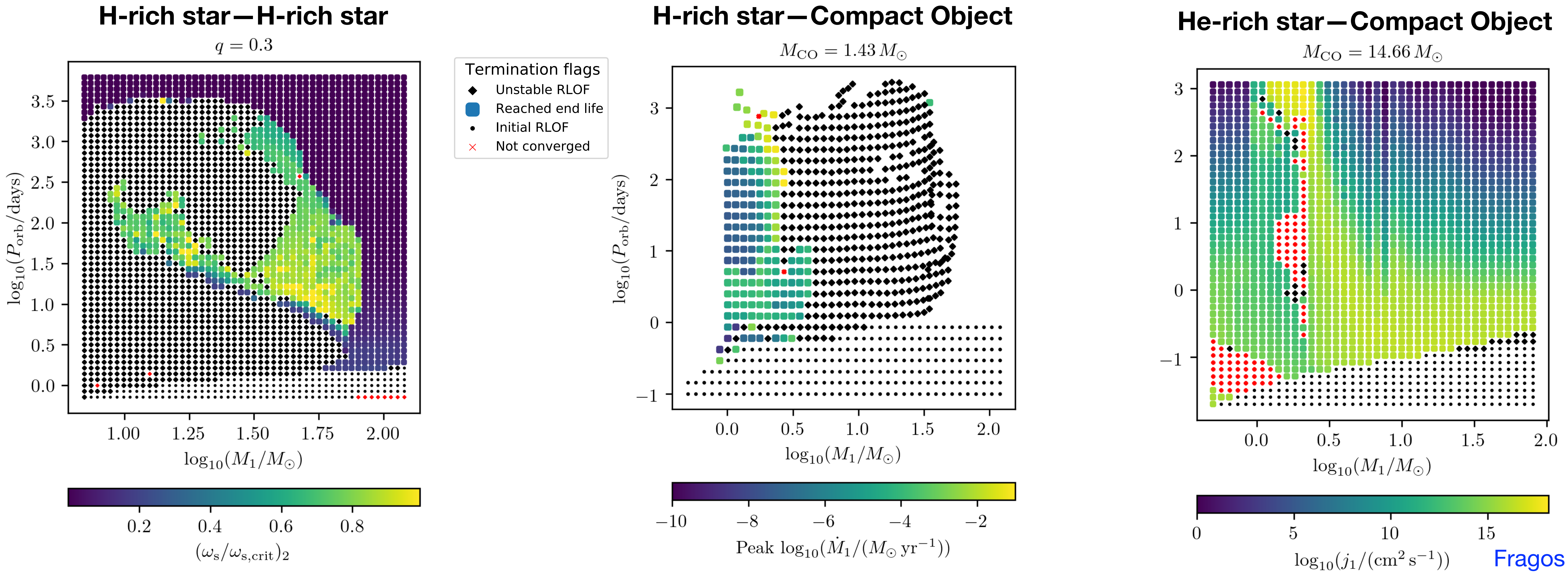
Fragos et al. (2022)

Three binary-star models

MESA

Paxton et al. (2011, 2013, 2015, 2018, 2019)

● Differential rotation ● tidal interactions ● thermal-timescale mass-transfer ● physically-motivated mass-transfer efficiency ● contact binaries ● chemically homogeneous evolution ● POSYDON v1 only at Solar metallicity



Fragos et al. (2022)

>150’000 binary tracks; >2M CPU hours; >2TB or raw data; non-convergence rate <2%

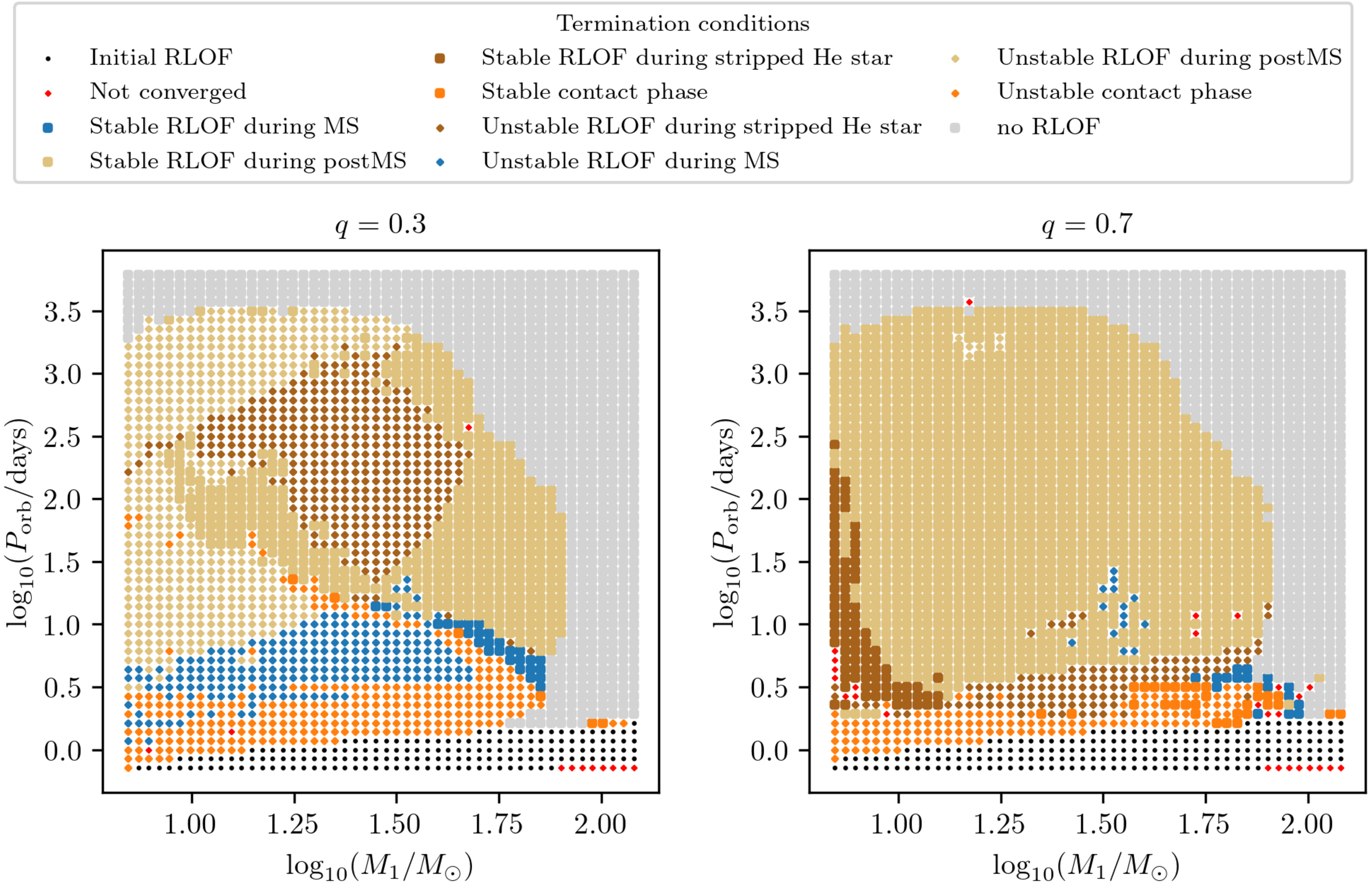
H-rich star + H-rich star grid

- **Mass-transfer efficiency**
  Assume that accreted material carries the Keplerian specific angular momentum of the star's surface (de Mink et al. 2009)

- **Tides - L/S coupling**
  Consider both radiative and convective tides

- **Mass-transfer stability**
  L2 overflow
  MT rate > 0.1Msun/yr
  Trapping radius > RL radius

- **Eddington limited accretion**



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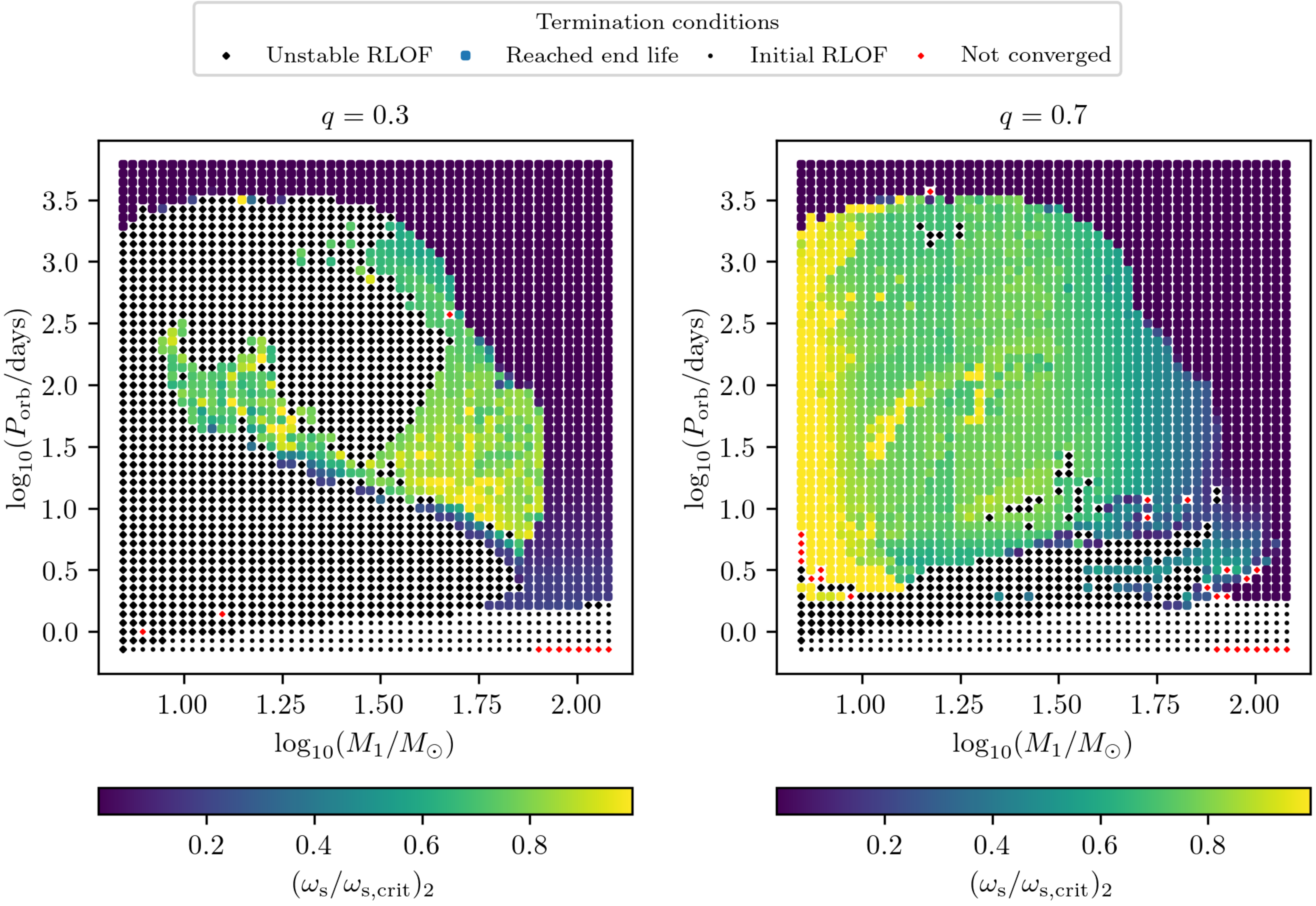

Fragos et al. (2022)

H-rich star + Compact Object (at the onset of RLO) grid

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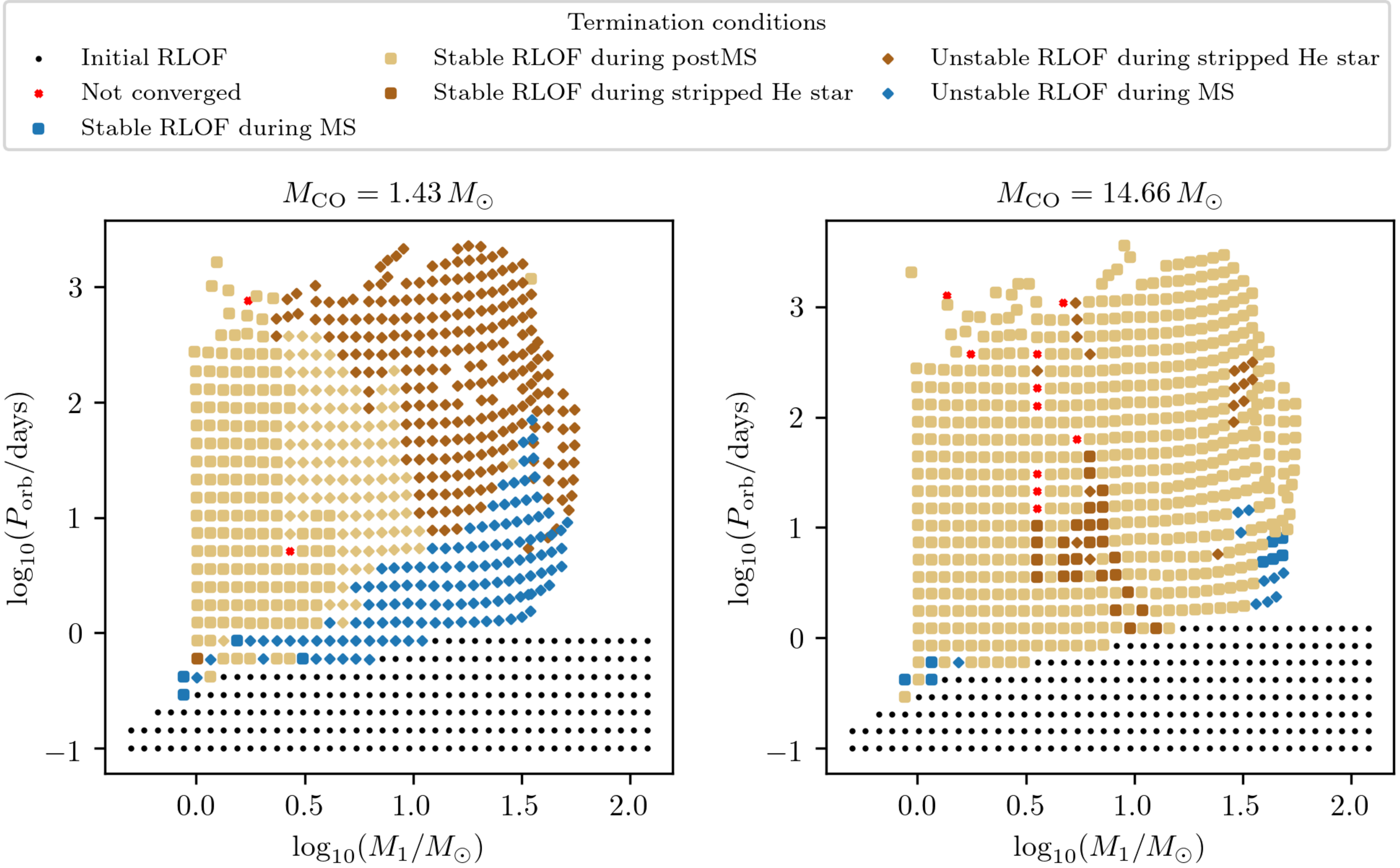

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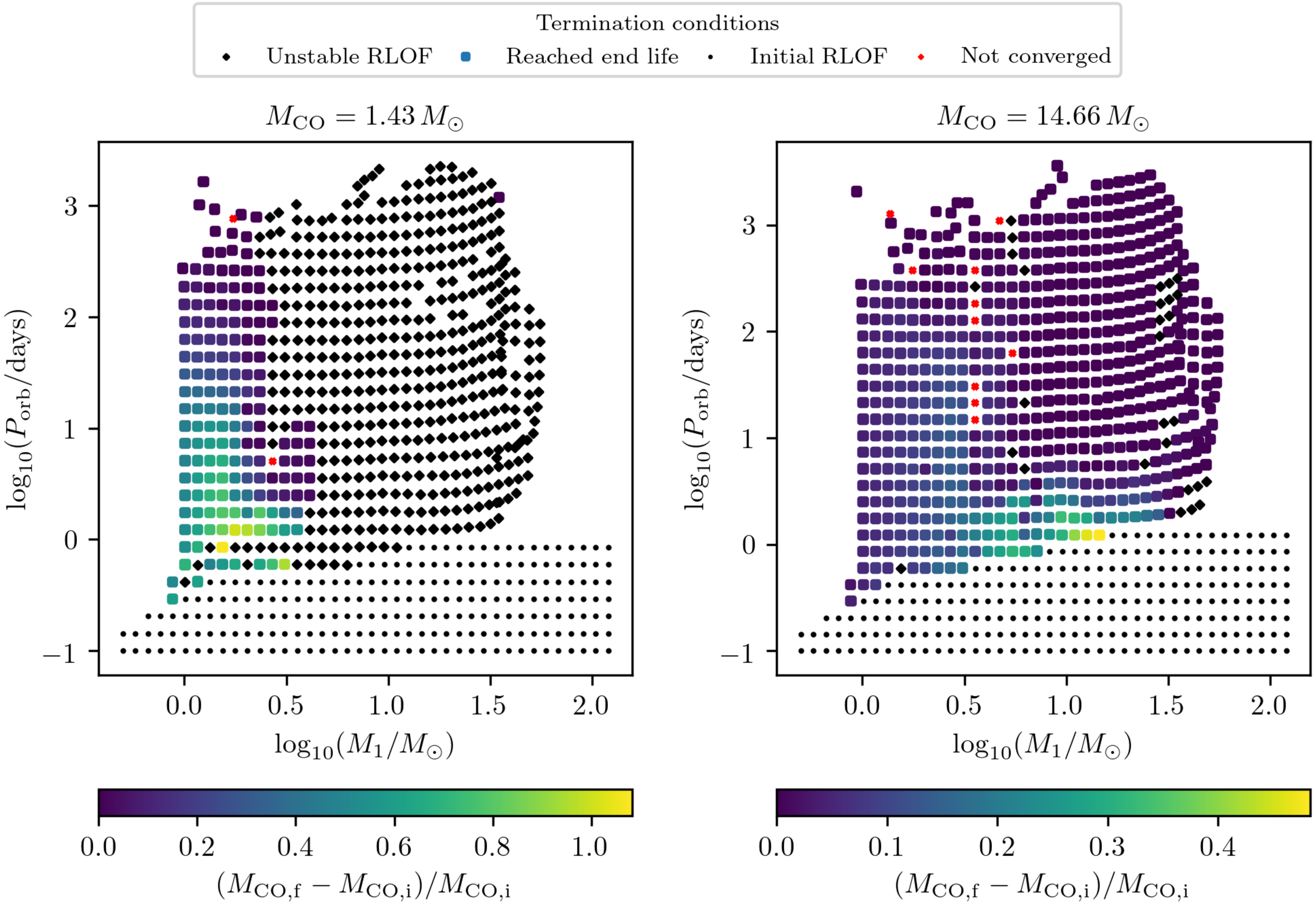

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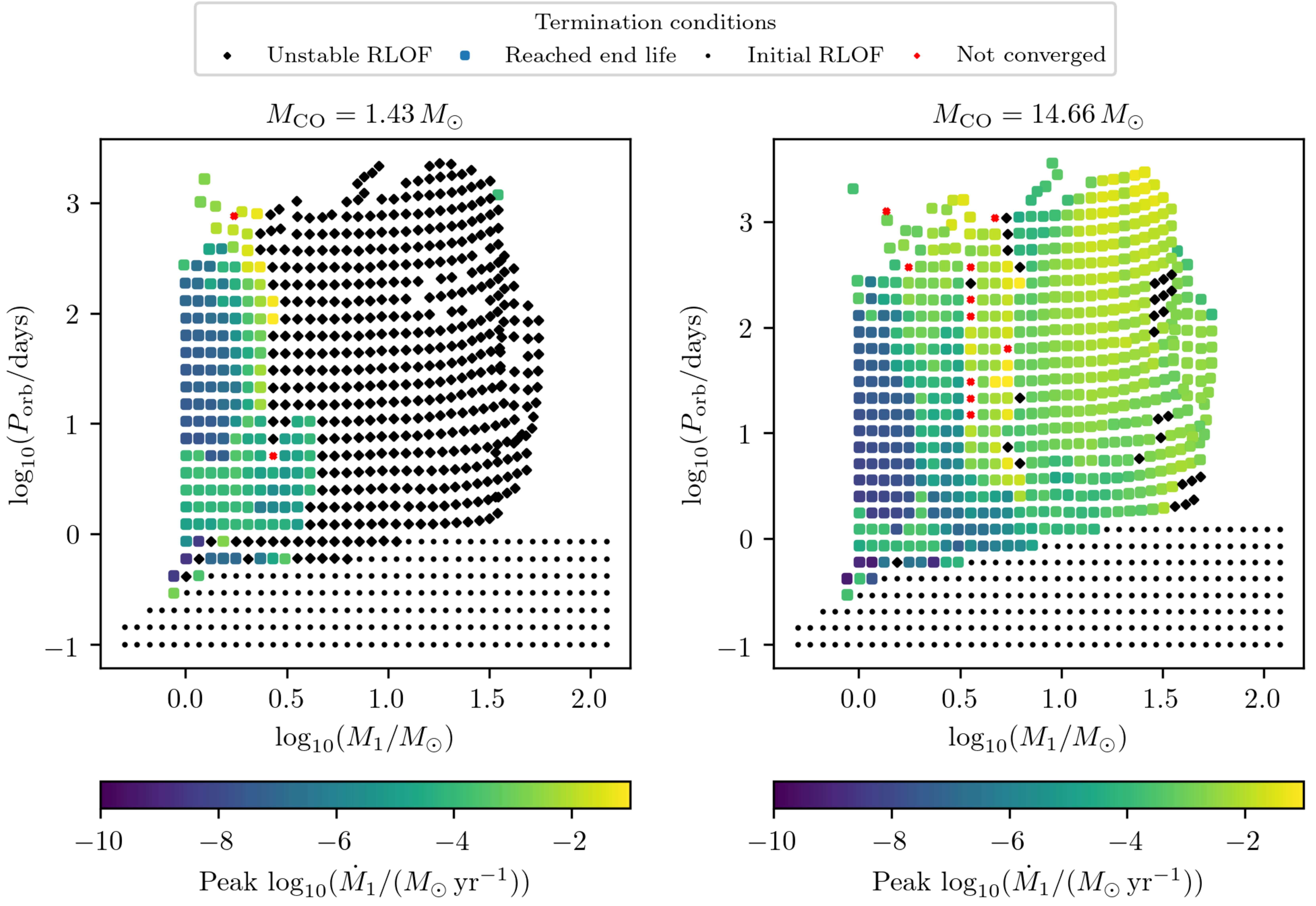

Fragos et al. (2022)

He-rich star + Compact Object Grid

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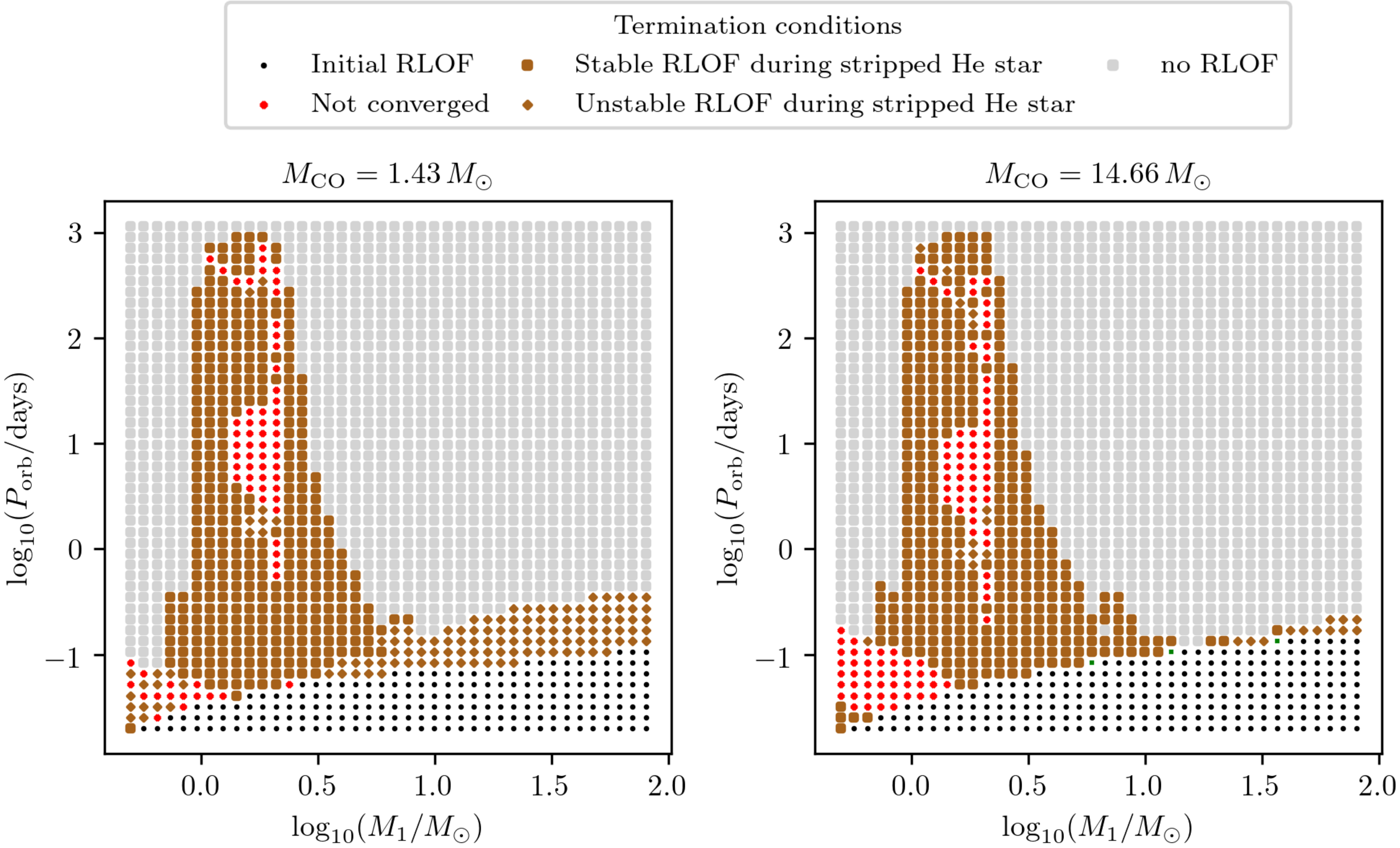

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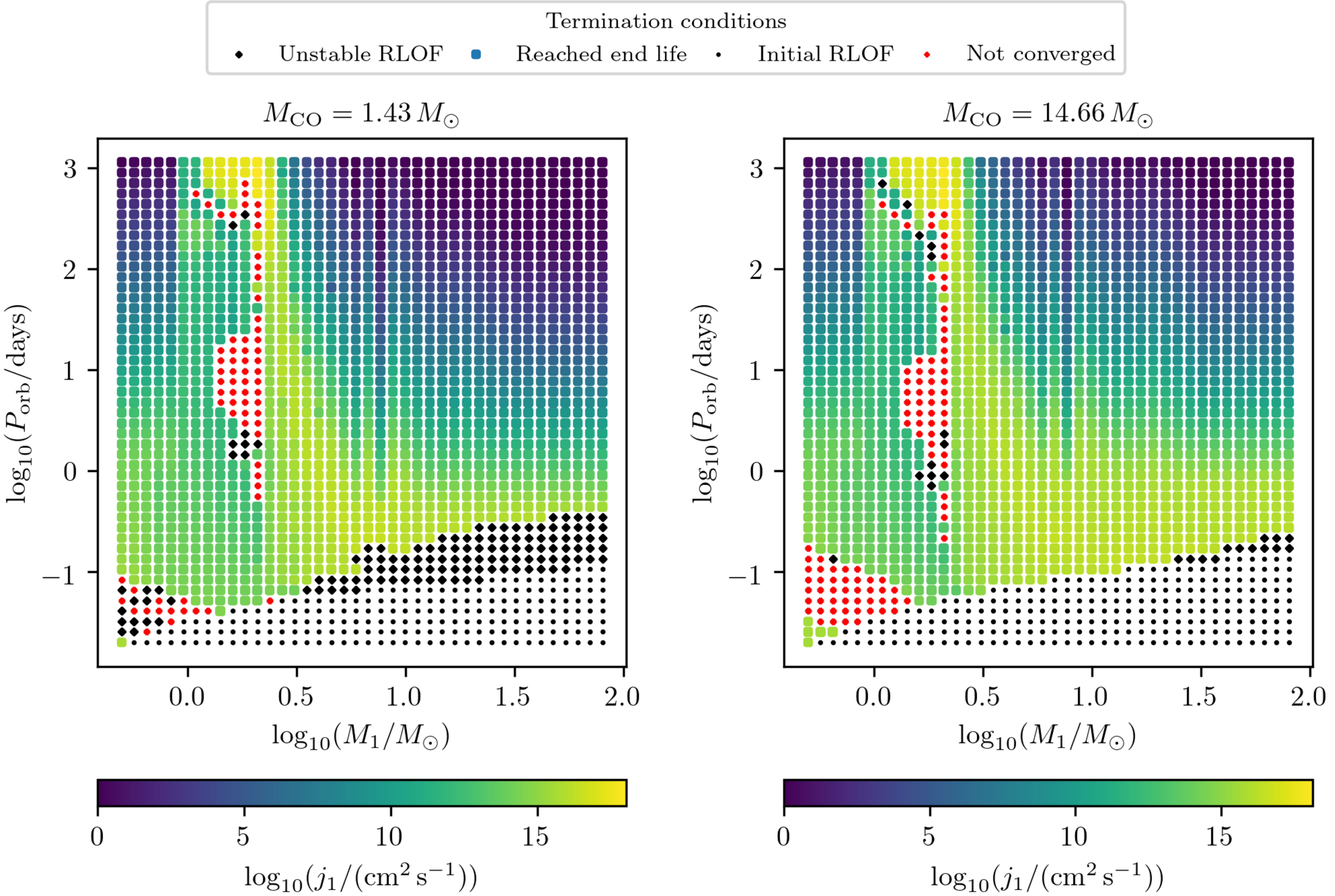
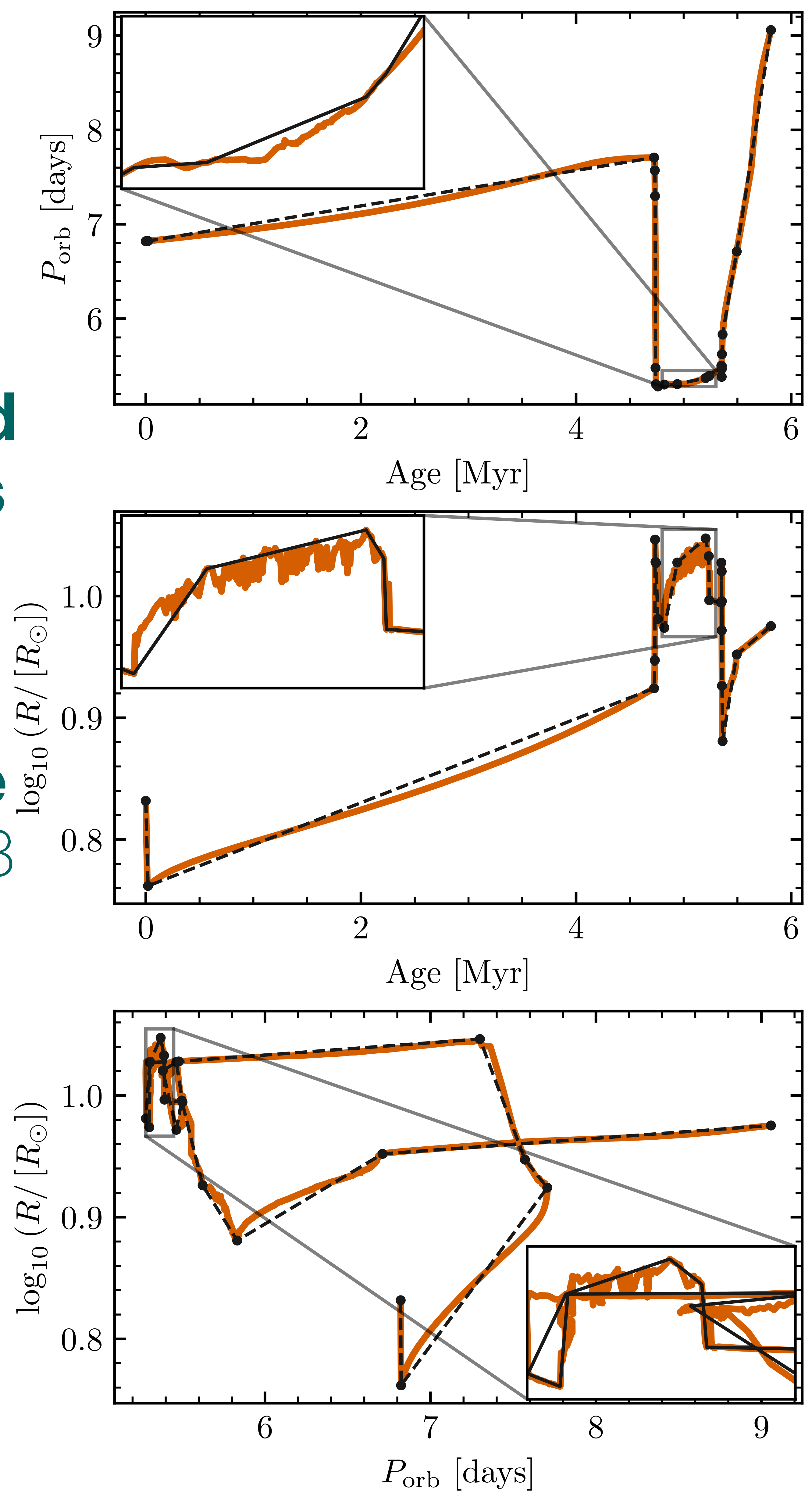
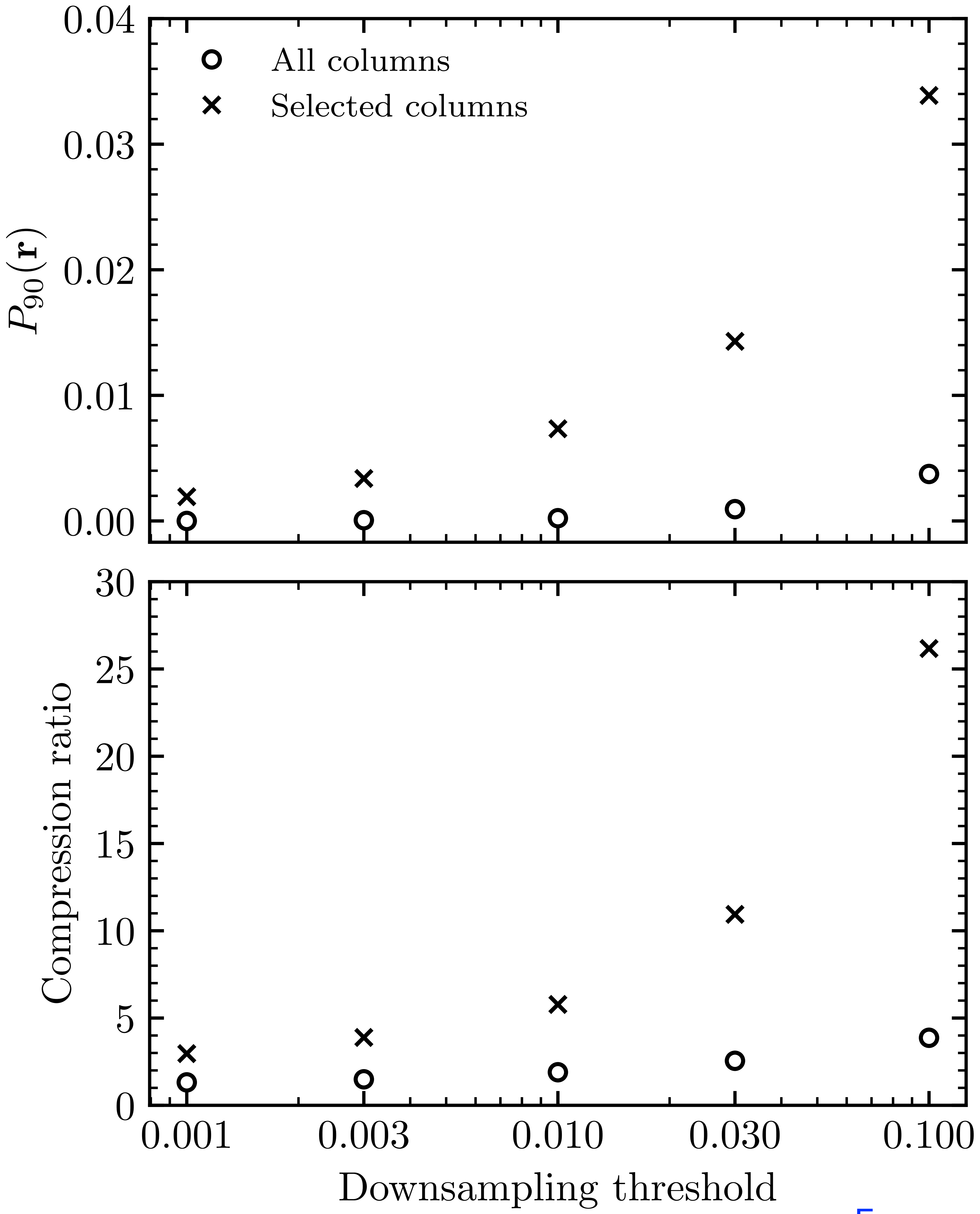


Fragos et al. (2022)

Initial-final interpolation: **post-processing**, classification & regression

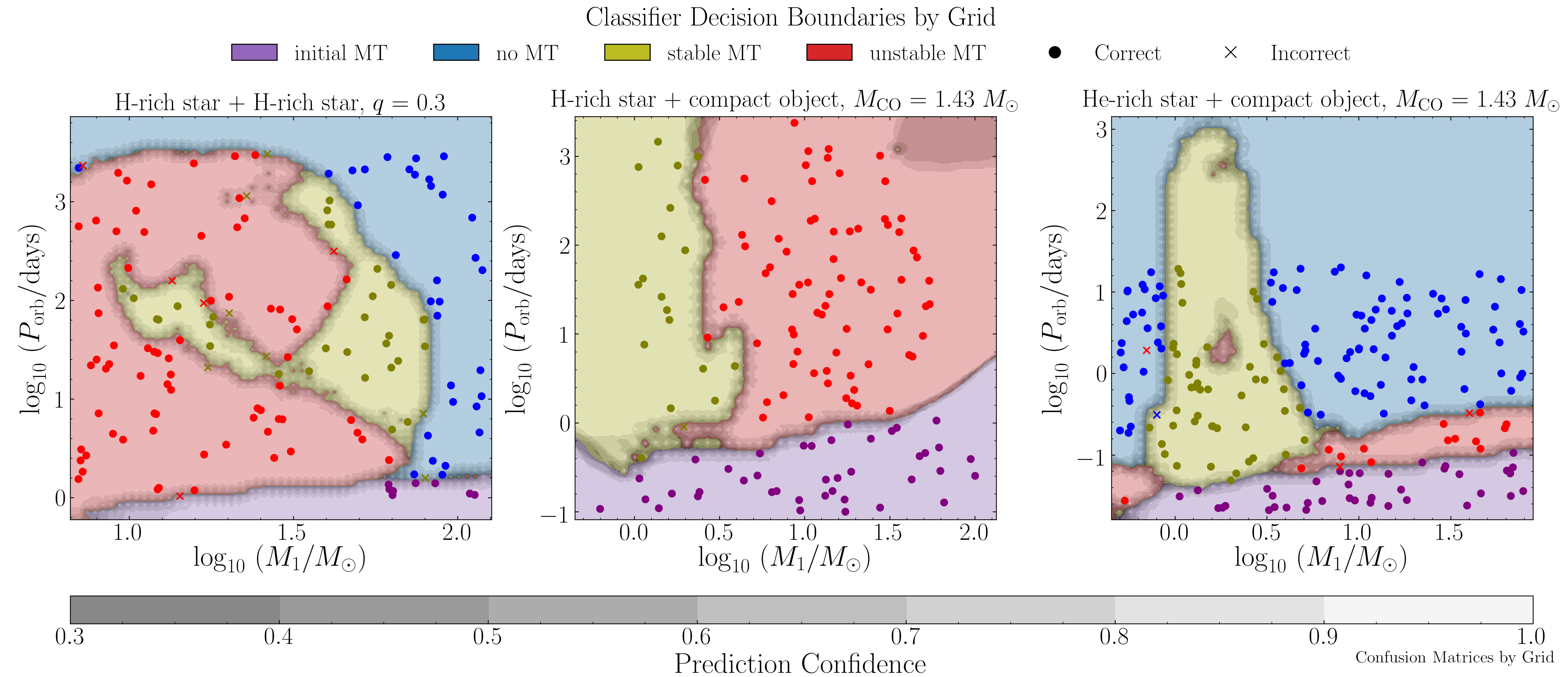
- **Calculate post processed quantities of final models** e.g. λ_{CE}, compact object parameters, etc
- **Reduce model grids' size** by a factor of ~26 to ~5.5GB





Fragos et al. (2022)

Initial-final interpolation: post-processing, **classification** & regression



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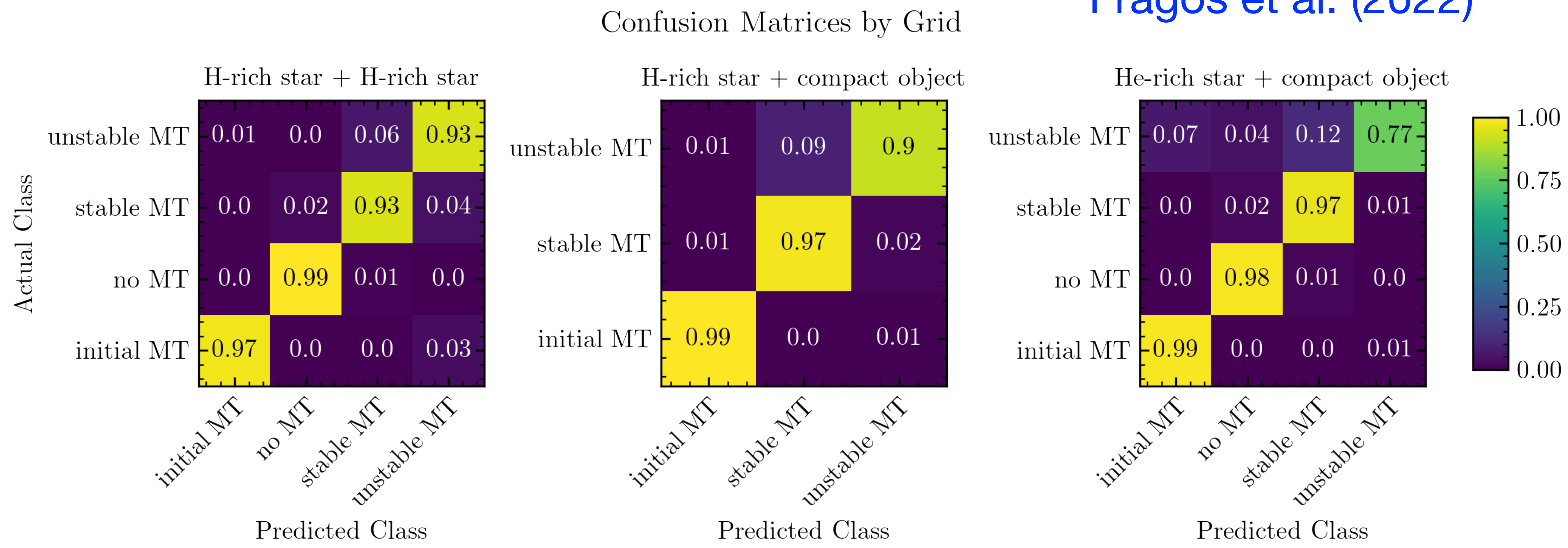
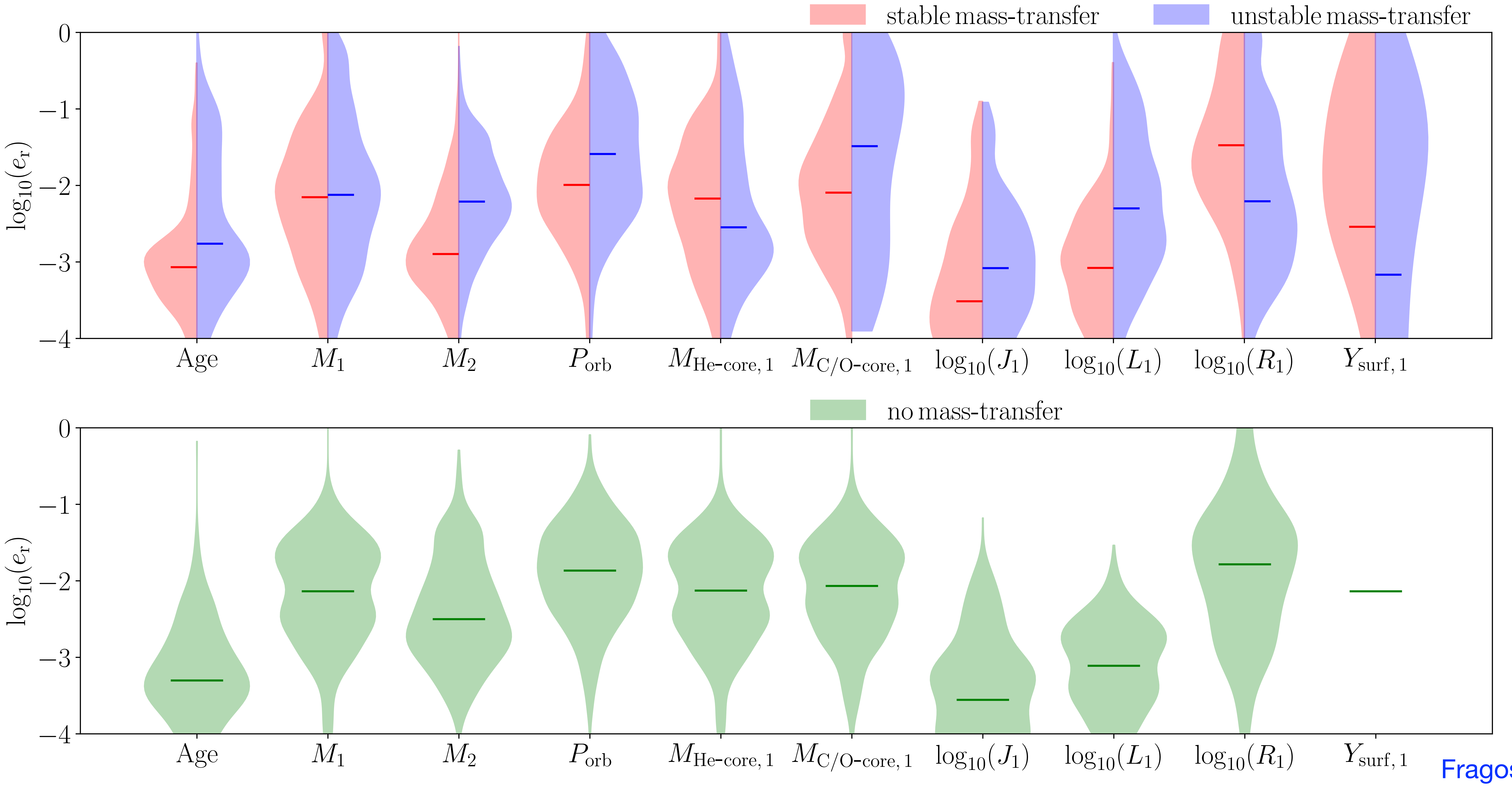


We use **k-Nearest Neighbors** classification as default in **POSYDON** v1.0, but other methods exist using Gaussian Processes, Radial-basis functions, and Neural Networks.

Initial-final interpolation: post-processing, classification & **regression**

Interpolation performance of 10 indicative quantities for the H-rich star + H-rich star grid

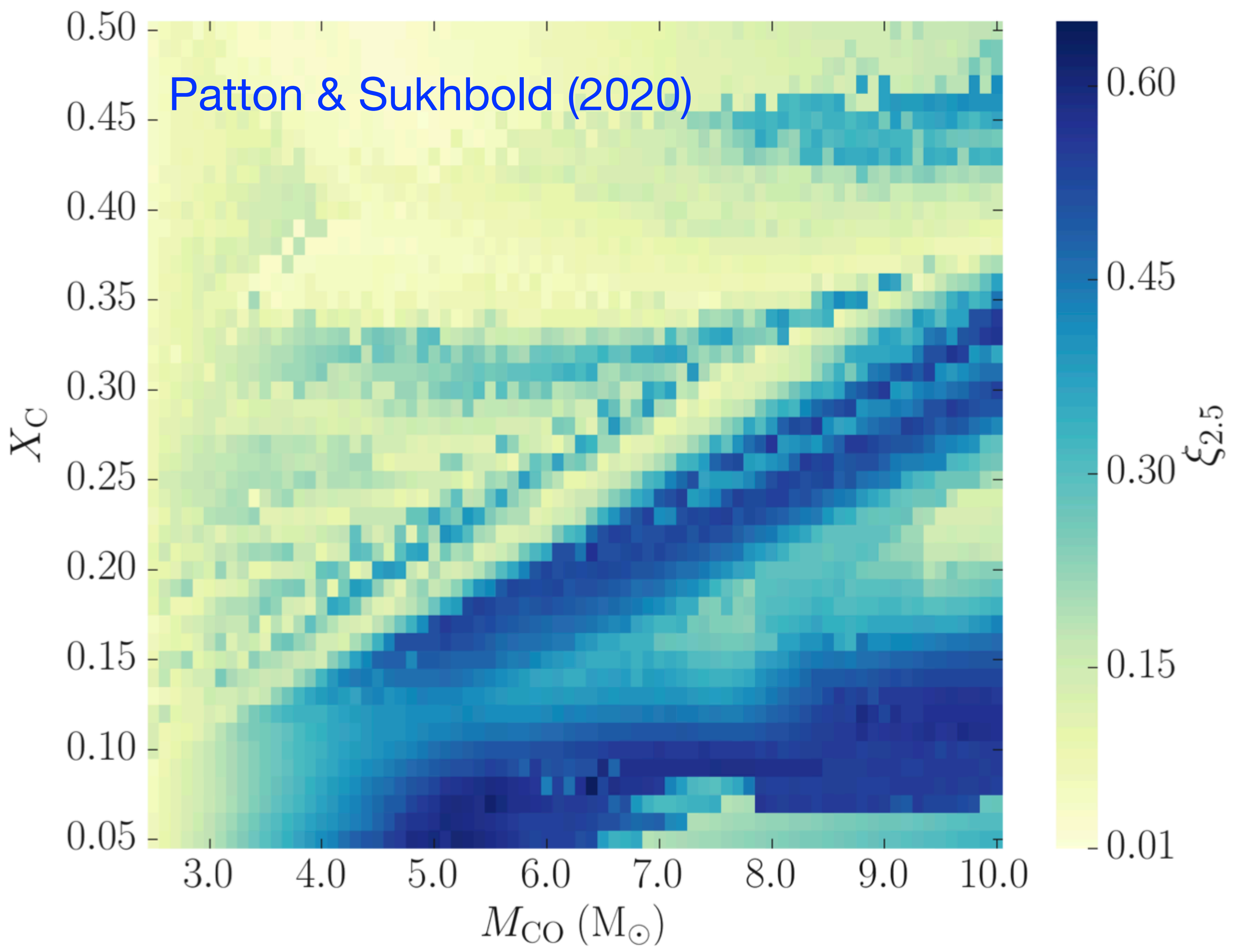


Fragos et al. (2022)

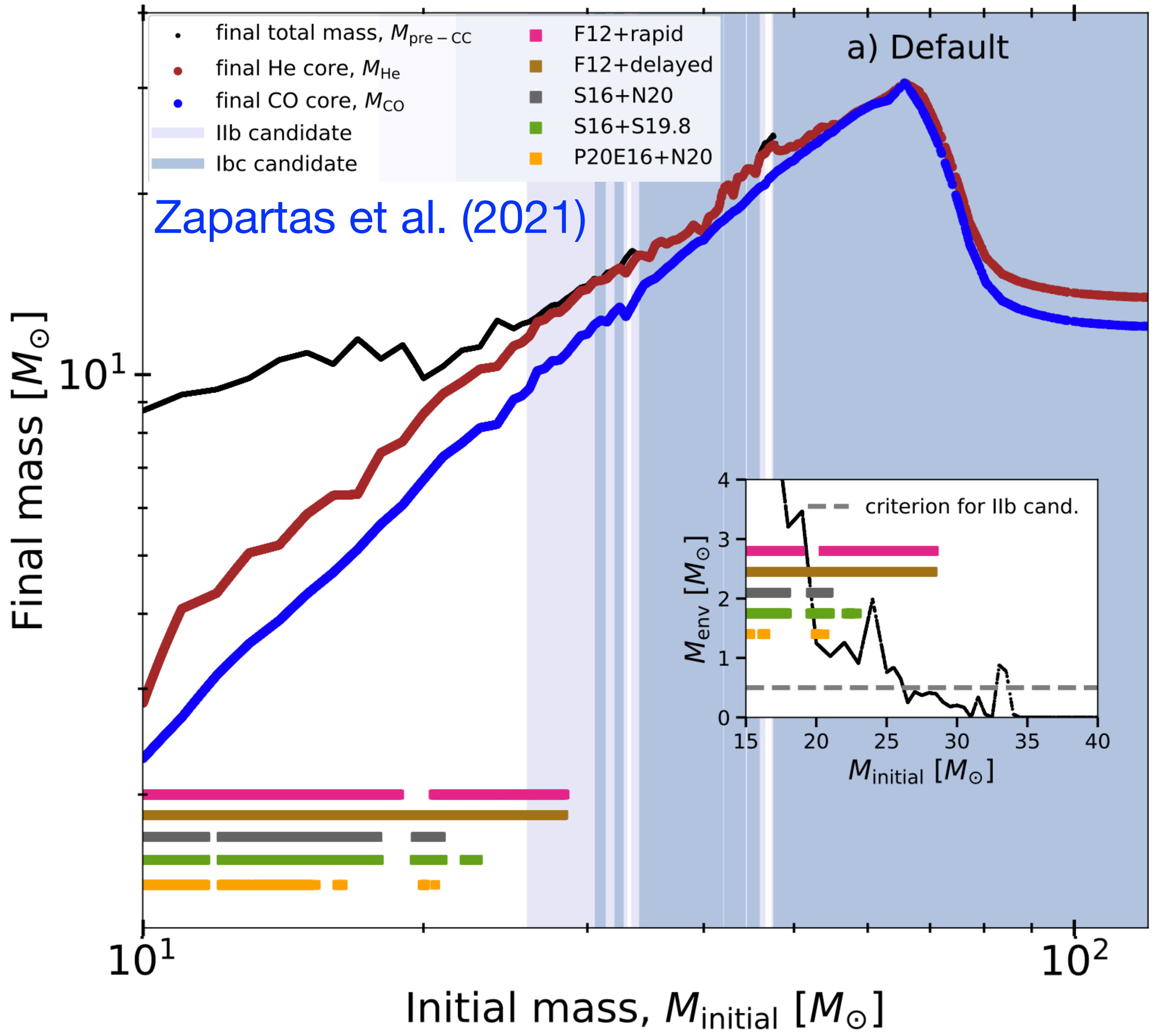
We use **N-dimentional linear interpolation** as default in POSYDON v1.0, but other methods exist using Gaussian Processes, Radial-basis functions, and Neural Networks

Compact-Object Formation

We retain the stellar structure profile information at key evolutionary stages, including at **carbon exhaustion.**



Mapping of structure to explodability parameters



Flexibility in the compact object formation prescription

Fryer et al. (2012); Sukhbold et al (2016); Patton & Sukhbold (2020); Couch et al. (2020)

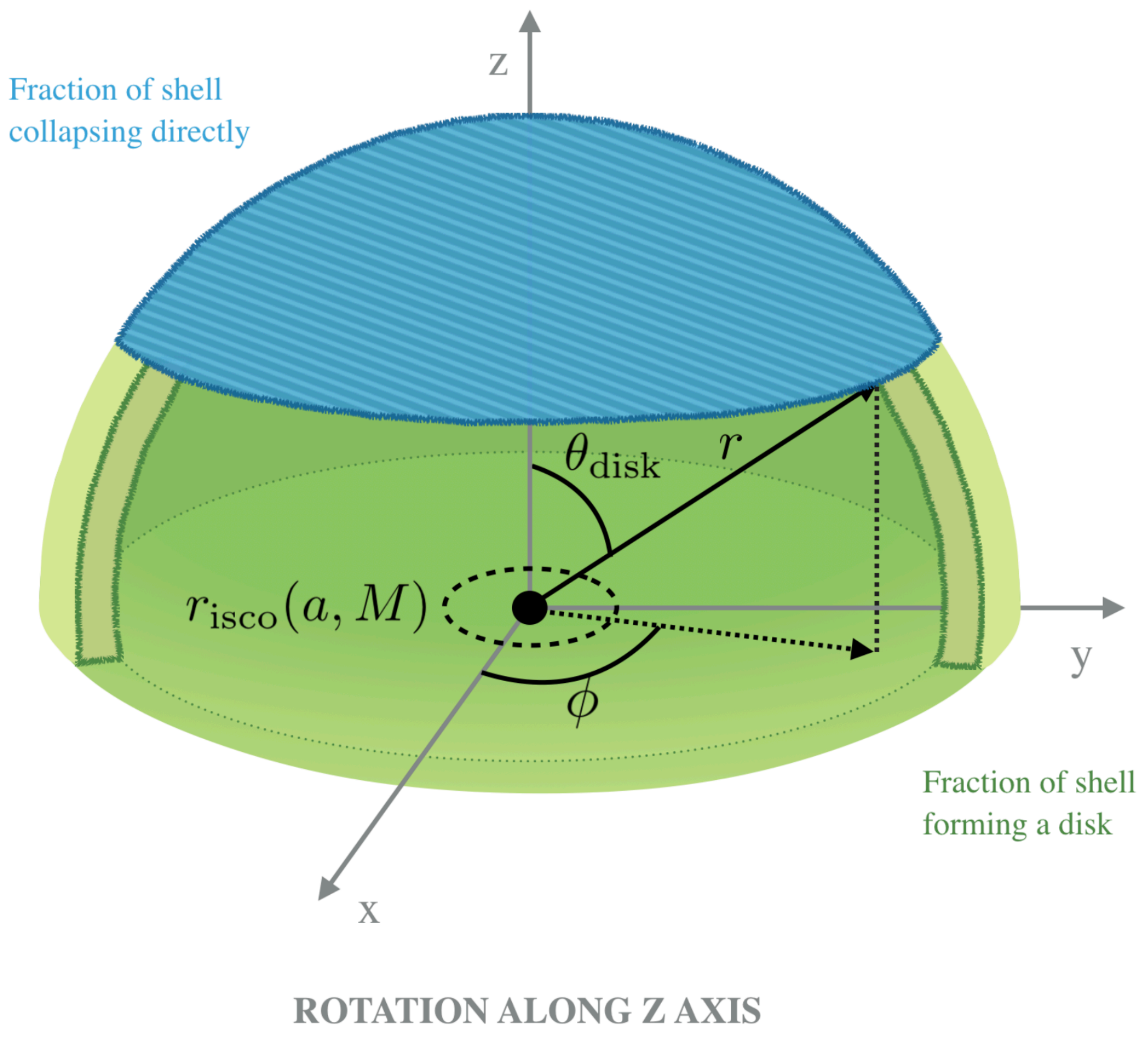
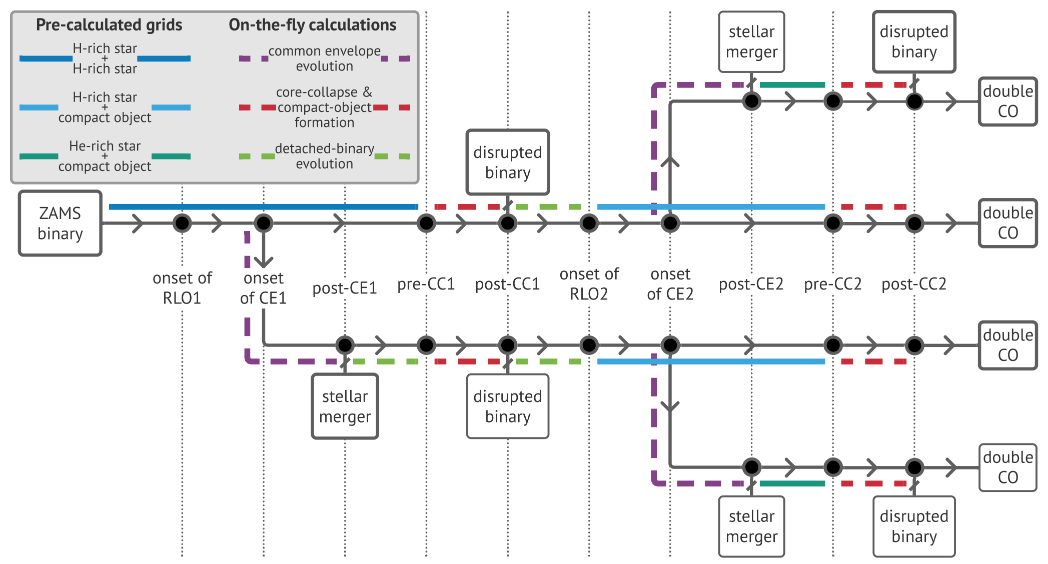


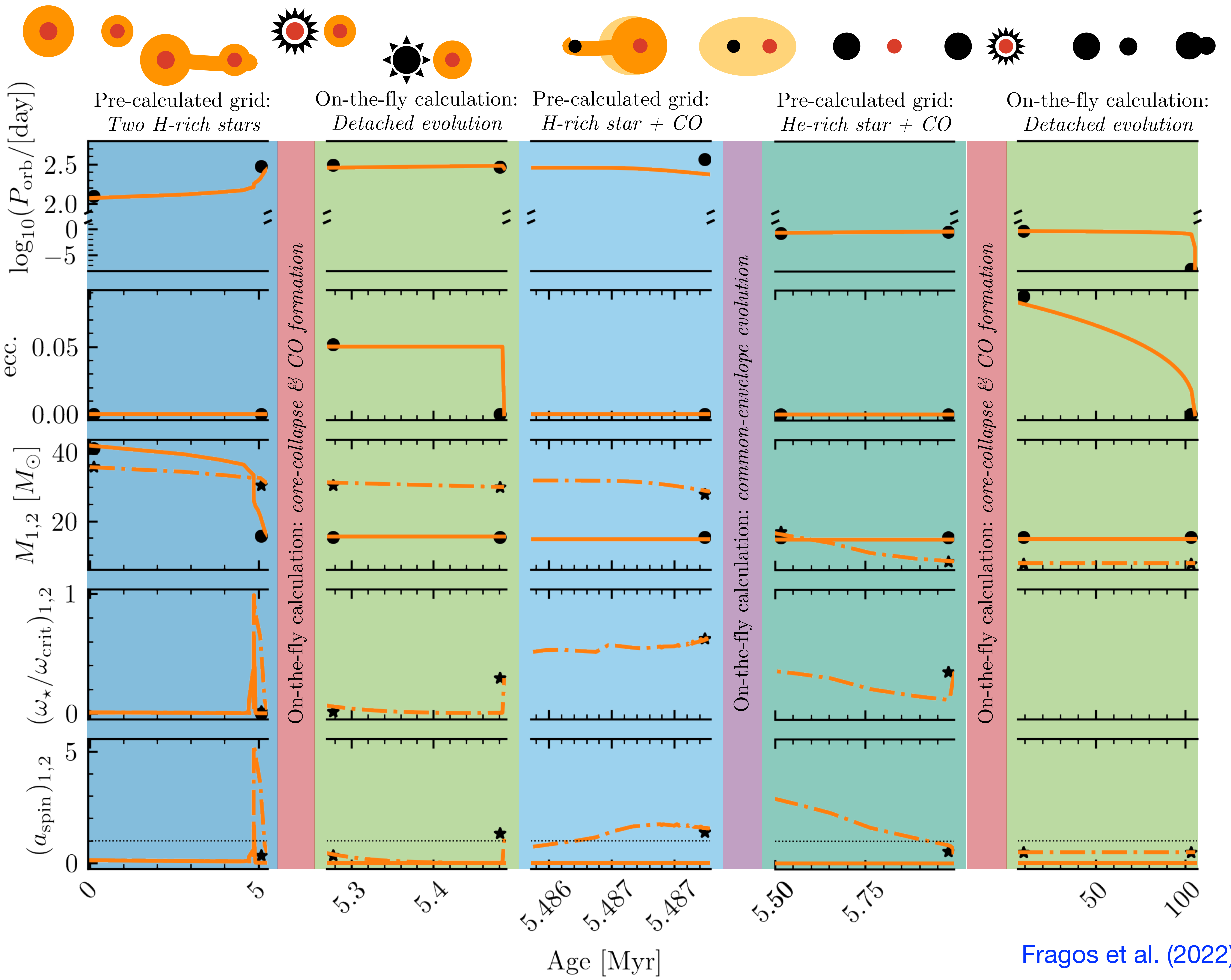
Image credit: Batta et al. (2020)

Robust estimates of compact object spins

Bavera et al. (2020,2021a,2022a,2022b)

Putting it all together to evolve a binary from ZAMS to double compact object



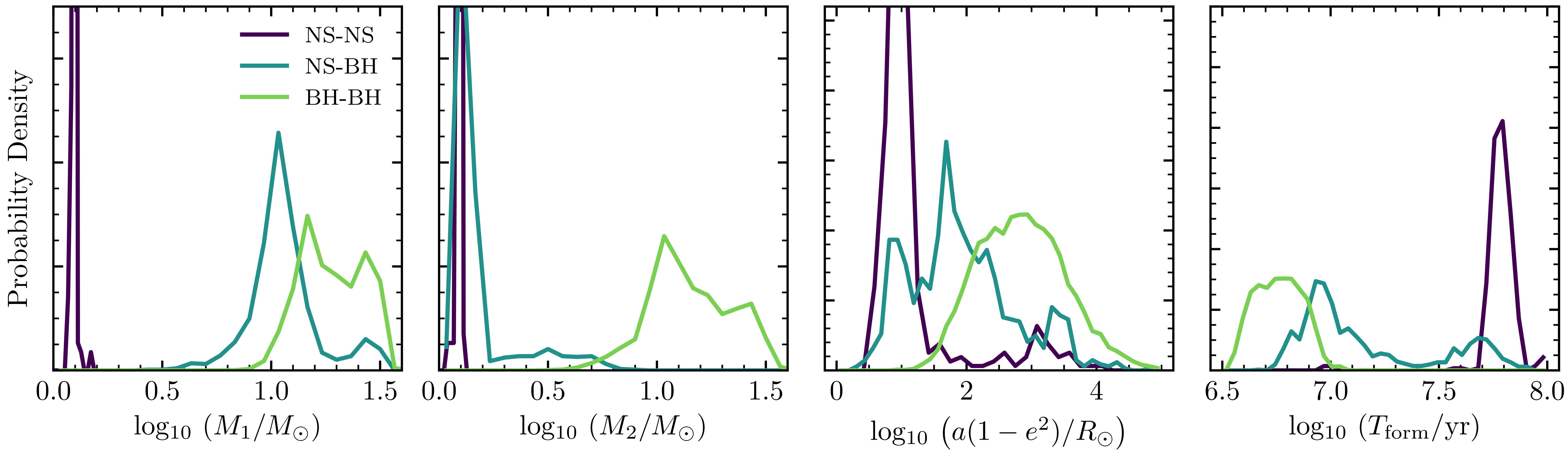


Fragos et al. (2022)

Evolving a whole population of binaries

Example population of 10^6 binaries, looking at the formation of binary compact objects.

Fragos et al. (2022)

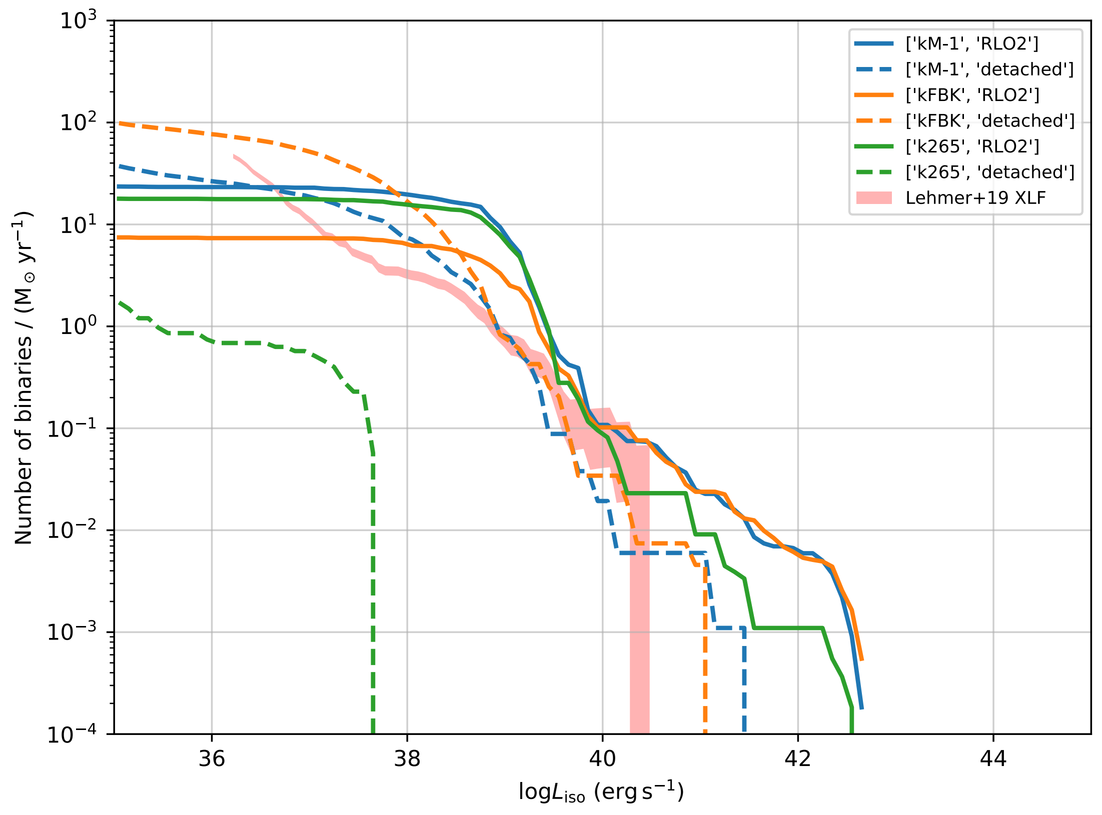


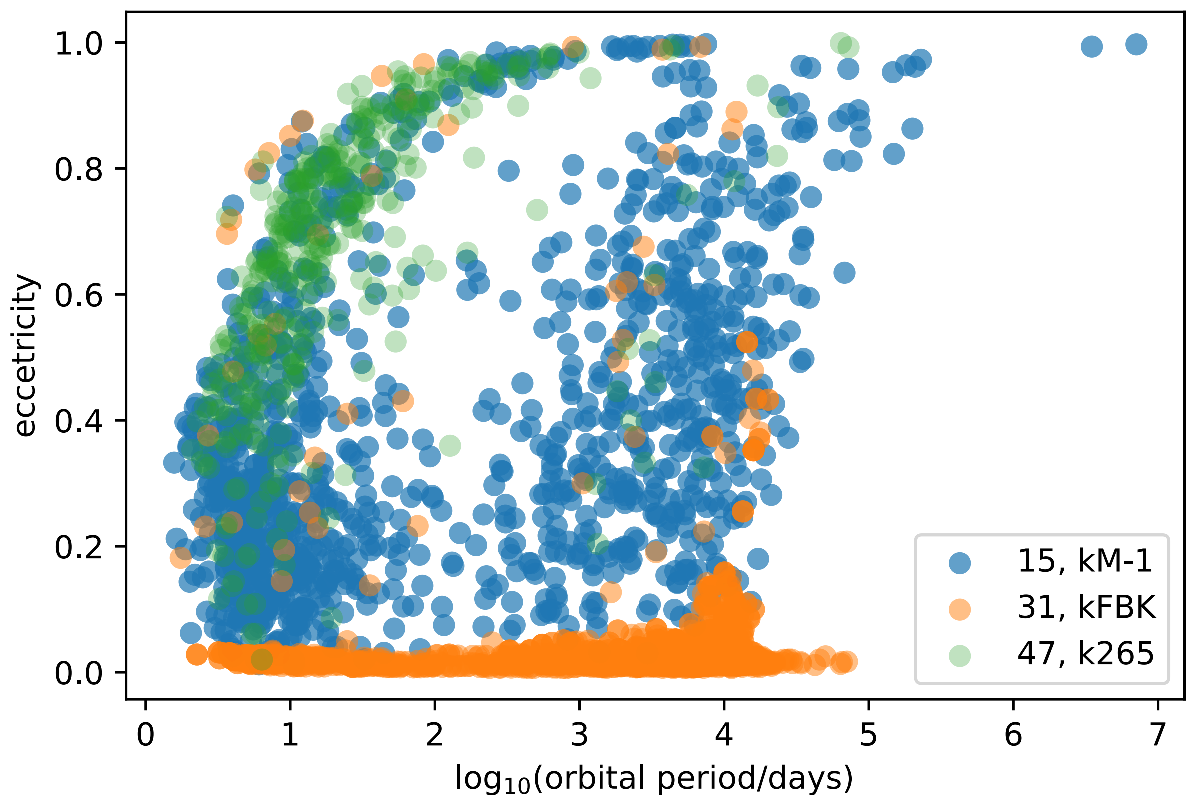
Computational cost ~1s per binary, infrastructure to use in HPC environment, parallelization with MPI, output in PANDAS data frames using HDF5 files.

Science applications ongoing…

X-ray binaries & ultra luminous X-ray sources

Devina Misra, Konstantinos Kovlakas

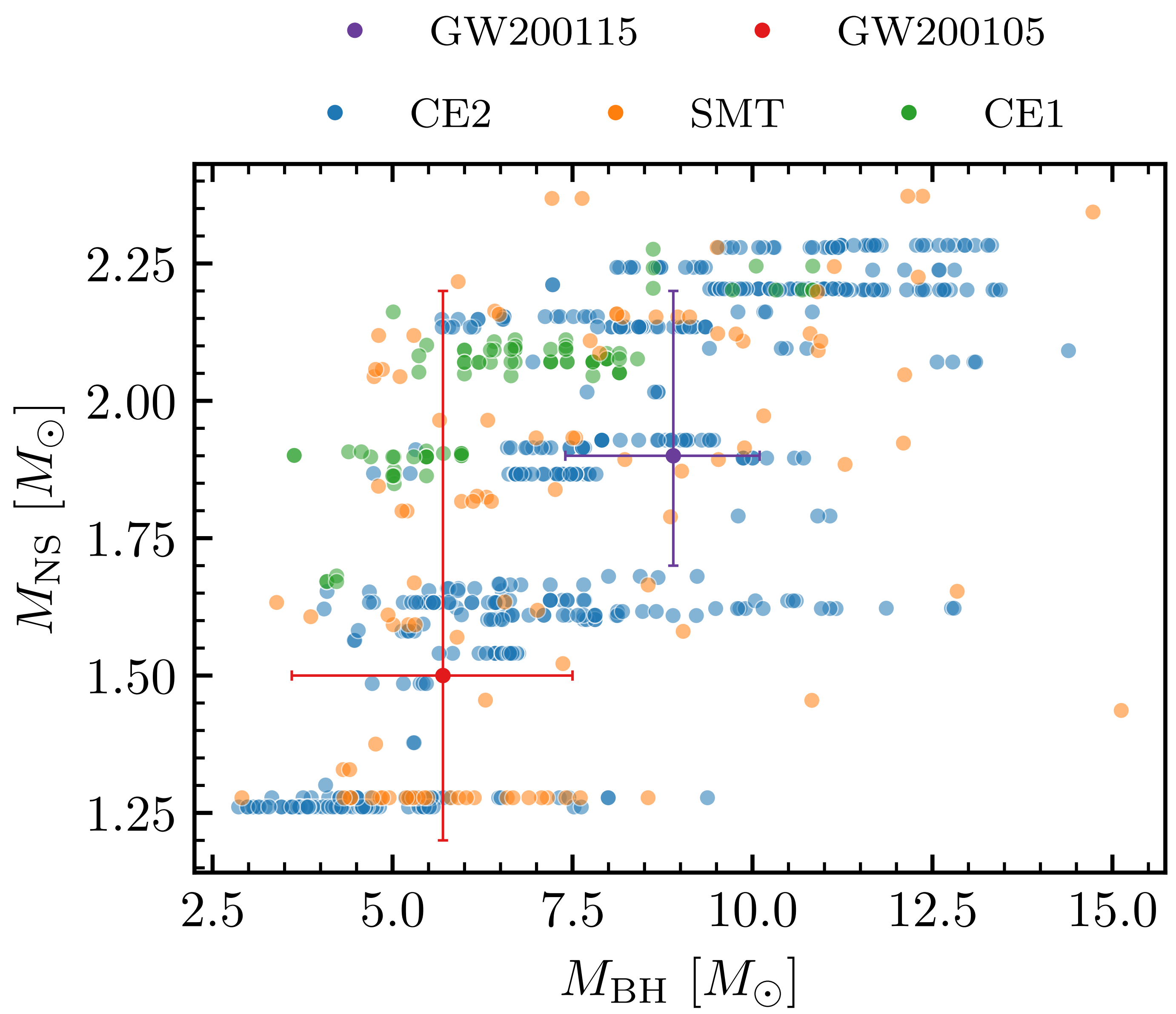




Misra et al. (in prep.)

Gravitational-wave sources

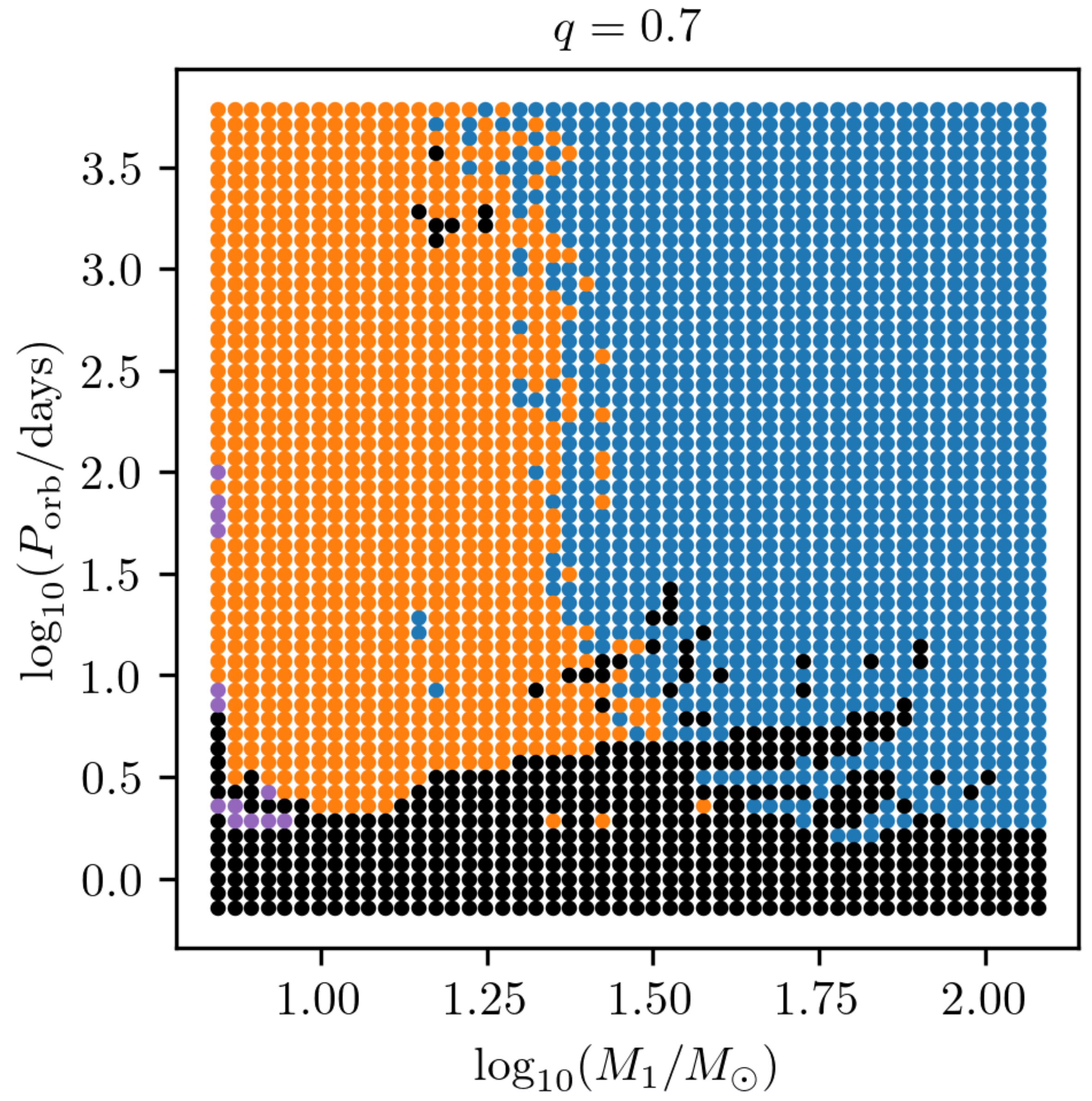
Zepei Xing, Simone Bavera



Xing et al. (in prep.)

Core-collapse supernovae

Manos Zapartas



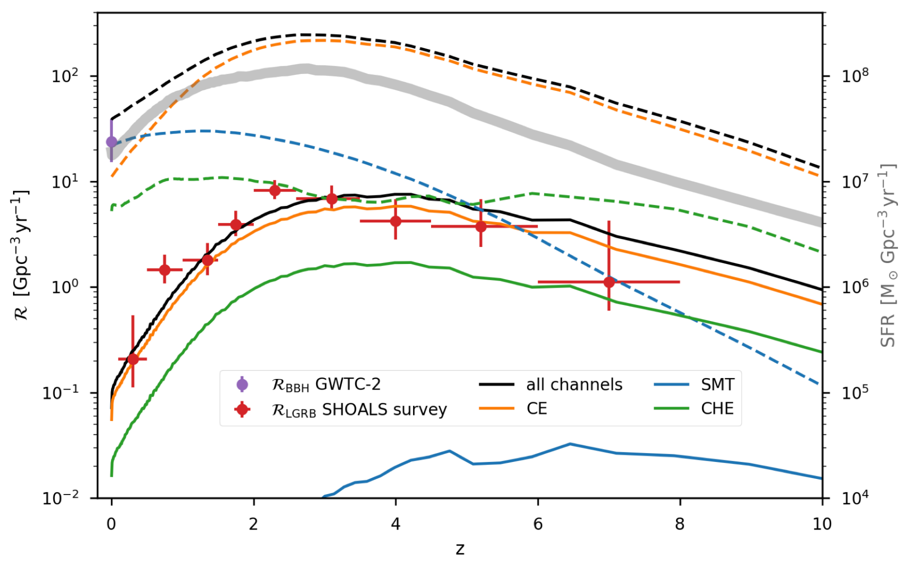
Zapartas et al. (in prep.)

POSYDON is modular!

- Use the extensive single and binary star grids of simulations
- Infrastructure for creating, post processing, and visualizing large grids of simulations.
- Data-driven tools for simulation grid classification and interpolation.
- Use POSYDON for to model a specific evolutionary phase
- Combine POSYDON with other model grids or codes

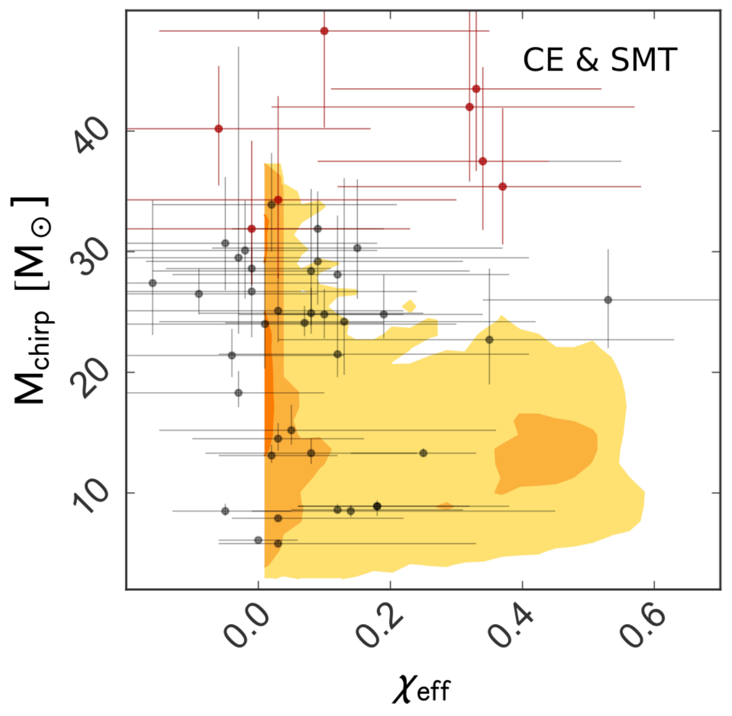
Breivik et al. 2020

Long-Gamma-ray bursts



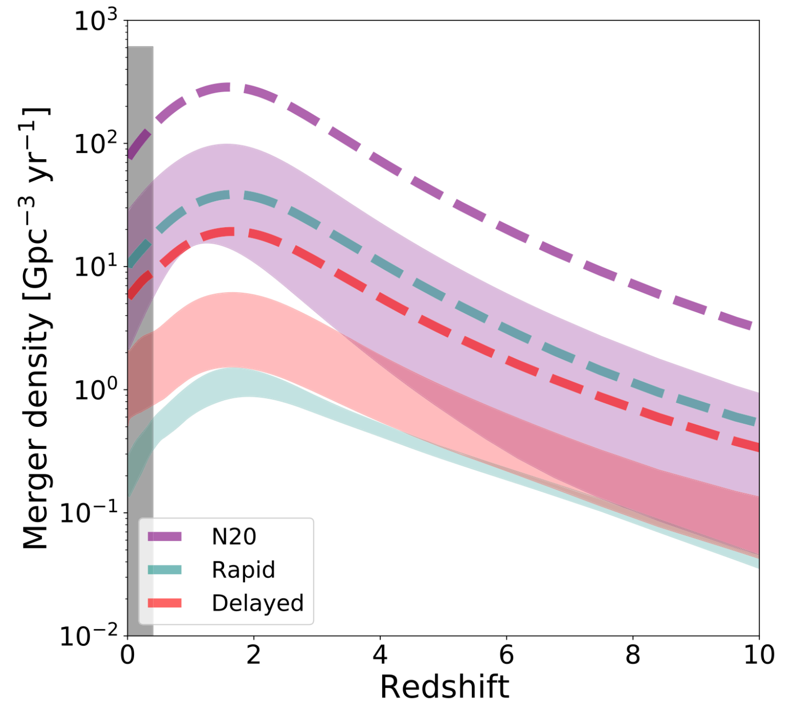
Bavera et al. (2022a)

Binary black holes



Bavera et al. (2021)

Black hole - Neutron star binaries



Roman-Garza et al. (2021)

POSYDON is a community tool

Public release in spring **2022**

• Code • single & binary star grids • simulation results
• documentation • web-POSYDON • mineable database with all data products

Stay tuned at https://posydon.org