A new(ish) tool on the workbench: the population synthesis code SEVN

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&

SEVN core team: Michela Mapelli, Mario Spera, Gaston J. Escobar, Guglielmo Costa, Cecilia Sgalletta, Erika Korb, Alessandro Trani

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What is a rapid pop synth code

Rapid pop synth codes evolve million-billion of stars/binaries to study the properties of stellar populations*

(*Hydrostatic/hydrodynamic codes too slow,
but necessary to tune rapid pop synth parameters)

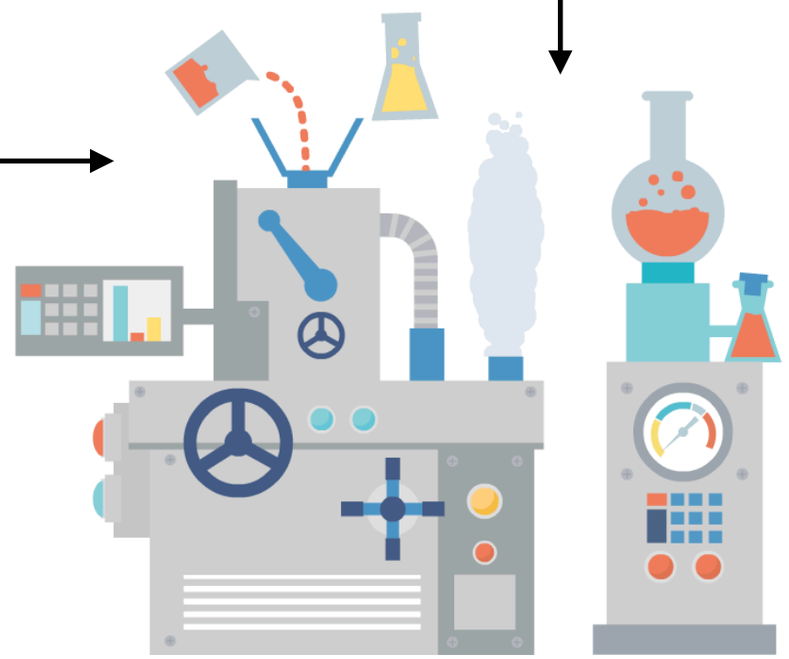
What is a rapid pop synth code

Rapid pop synth codes evolve million-billion of stars/binaries to study the properties of stellar populations*

Initial stellar populations:
Masses, Metallicity,
Binary parameters

Analytic/Semianalytic stellar and binary evolution

Parameters, Presciptions (e.g. SN)



Star/Binary properties

Population statistic

across time

(*Hydrostatic/hydrodynamic codes too slow,
but necessary to tune rapid pop synth parameters)

Why SEVN

Most rapid pop synth codes* evolve stars using fitting equations based on old stellar tracks (Pols+98): **difficult to adapt to new stellar evolution models**

*E.g. BSE (Hurley+02), MOBSE (Giacobbo+18), COSMIC (Brevik+19), COMPAS (Riley+21)

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Stellar EVolution *N*-body

Based on the idea developed
by Mario Spera, Alessandro Trani, Michela Mapelli
(Spera+17,Spera+19)

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
```

Binary evolution

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

4 SN models

2 PISN models

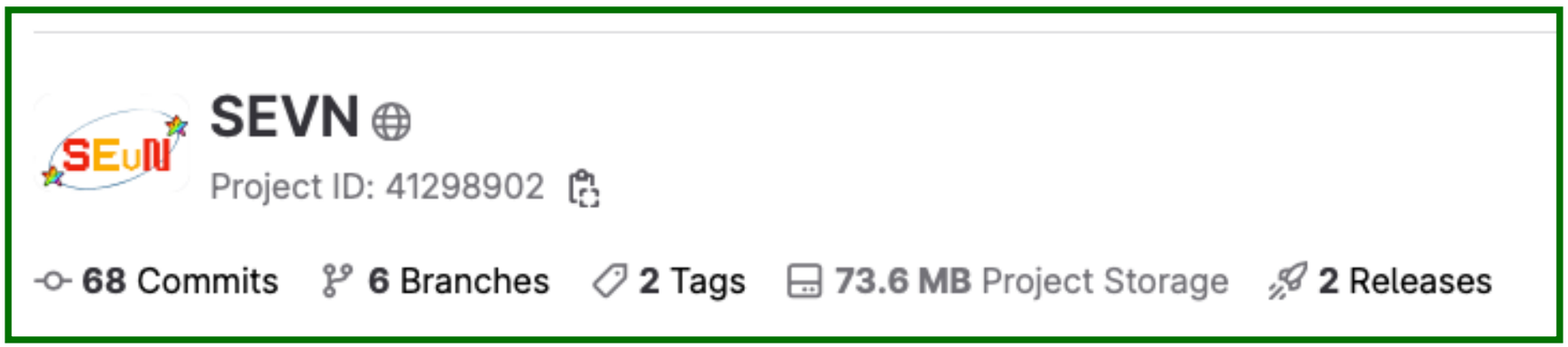
*E.g. BSE (Hurley+02), MOBSE (Giacobbo+18), COSMIC (Brevik+19), COMPAS (Riley+21)

SEVN “in production”

Only rapid pop synth based on tracks interpolation publicly available*

https://gitlab.com/sevncodes/sevn

- **Userguide**
- **Wiki with FAQ and examples of SEVN output analysis**
- **Python and bash scripts for compilation and execution**
- **Available stellar tracks from PARSEC (Bressan+12, Costa+21,Nguyen+22) and MIST (Choi+16)**



*Other Pop synth implementing similar strategies are

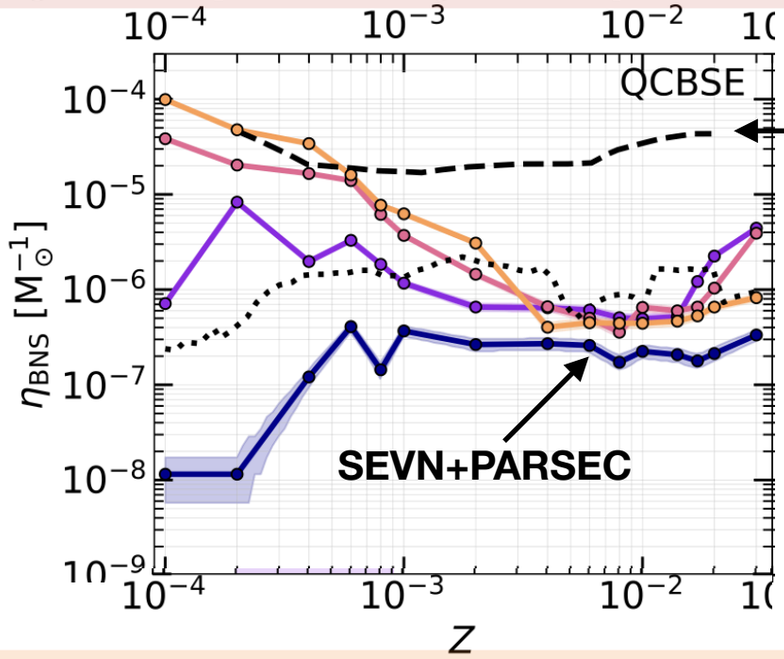
COMBINE (Kruckow+18),
METISSE (Agrawal+22, Agrawal+20)

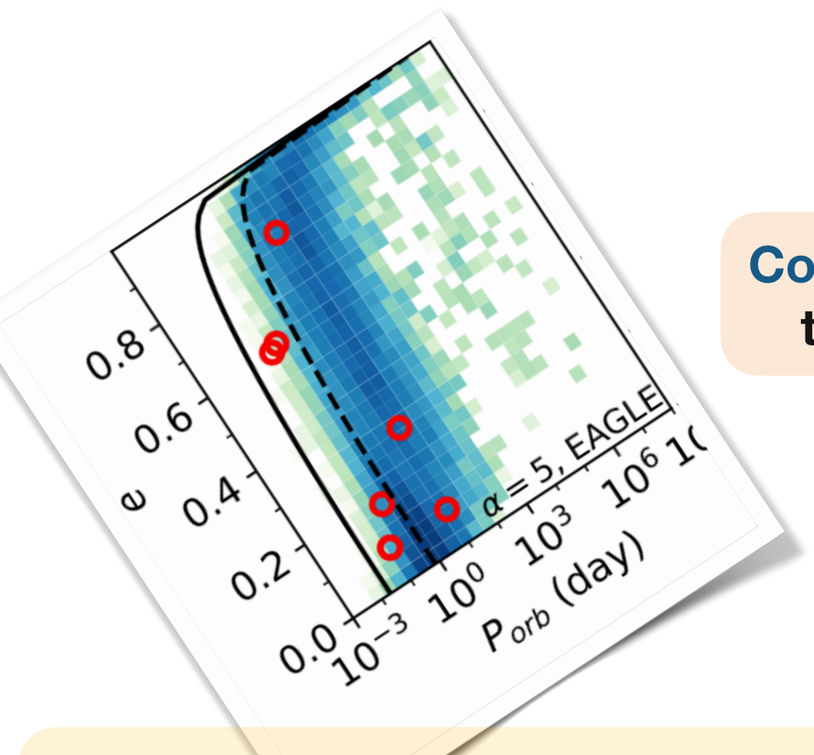
*Poseidon (Fragos+23),
is available but strongly based on MESA tracks

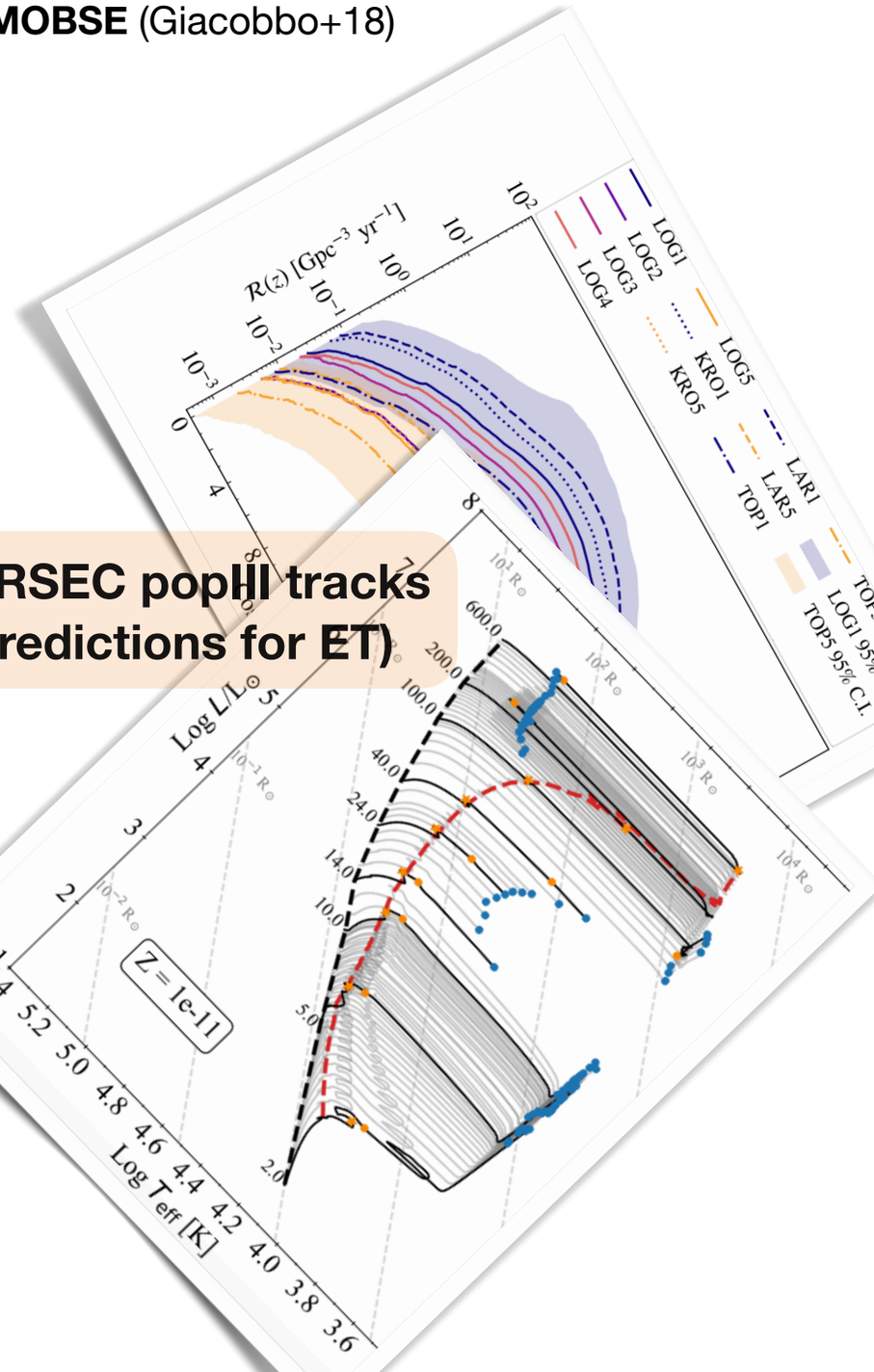
SEVN “in production”

Only rapid pop synth based on tracks interpolation publicly available*

Iorio+23*: SEVN presentation and study of merging of binary compact objects (BCOs) with PARSEC tracks







Costa+23,Santoliquido+23: SEVN + PARSEC popIII tracks to study BCOs from the first stars (predictions for ET)

Sgalletta+23: SEVN + PARSEC to study the population of Galactic BNS (predictions for SKA)

*https://gitlab.com/sevncodes/sevn

**Iorio et al., 2023, MNRAS in print, arXiv: arXiv:2211.11774

SEVN structure & algorithms

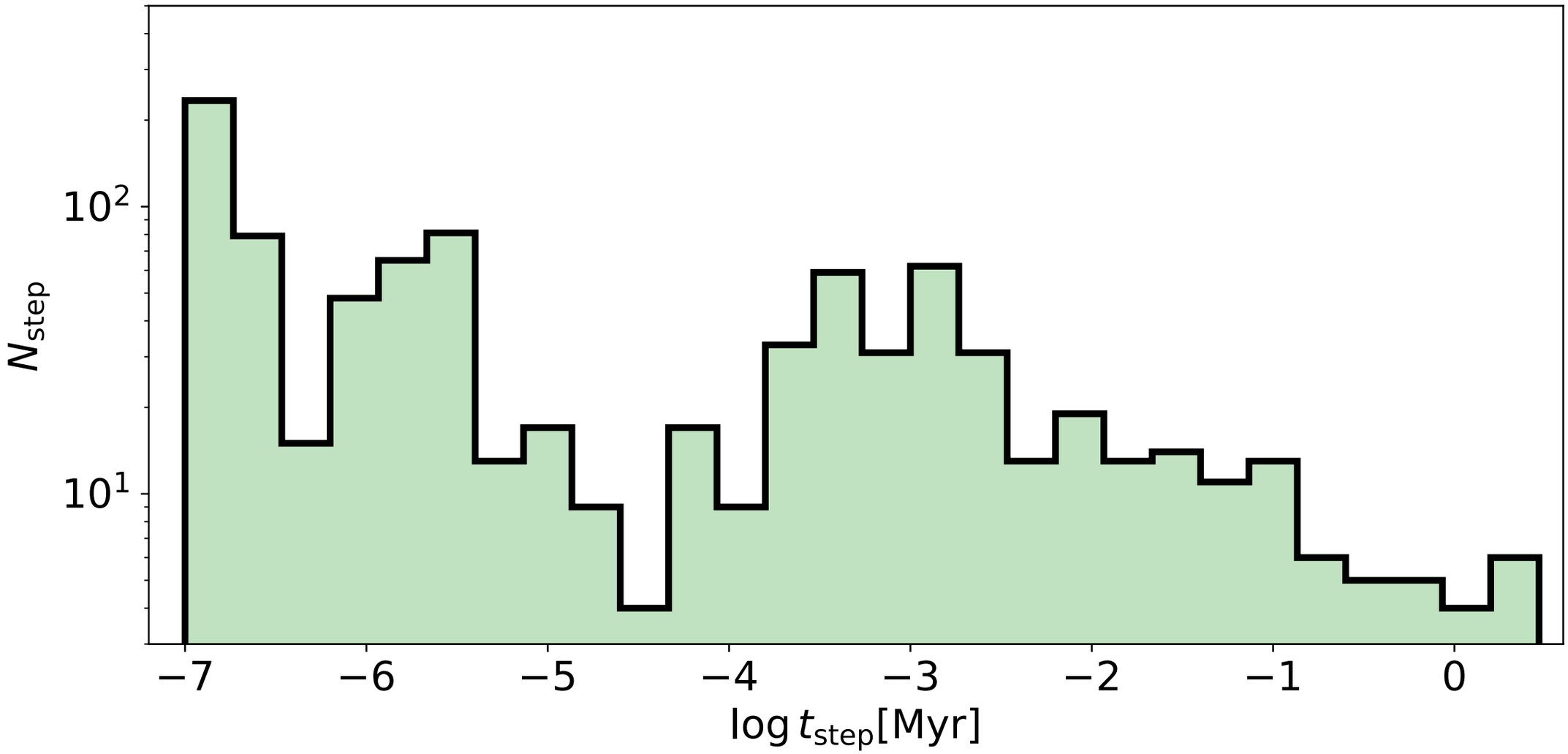
- **Written in C++ (std C++11)**
- **Object-oriented for flexibility and maintainability**
- **Stand-alone code: no external libraries**
- **Executables + Library (dynamic and/or static)**
  (Ongoing pairing with *N*-body codes)
- **Cmake for compilation and library linking**

```
find_package(SEVN)

if(SEVN_FOUND)
    message("SEVN found!")
else()
    message( FATAL_ERROR "SEVN not found" )
endif()

add_executable(binary_evol.exe binary_evol.cpp)

#Check if static lib are present, otherwise link to shared
if(SEVN_STATICLIB)
    message("Executable will be linked to the SEVN static lib")
    target_link_libraries(binary_evol.exe PRIVATE SEVNLIBS::sevn_lib_static)
```

SEVN structure & algorithms

Adaptive timestep

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

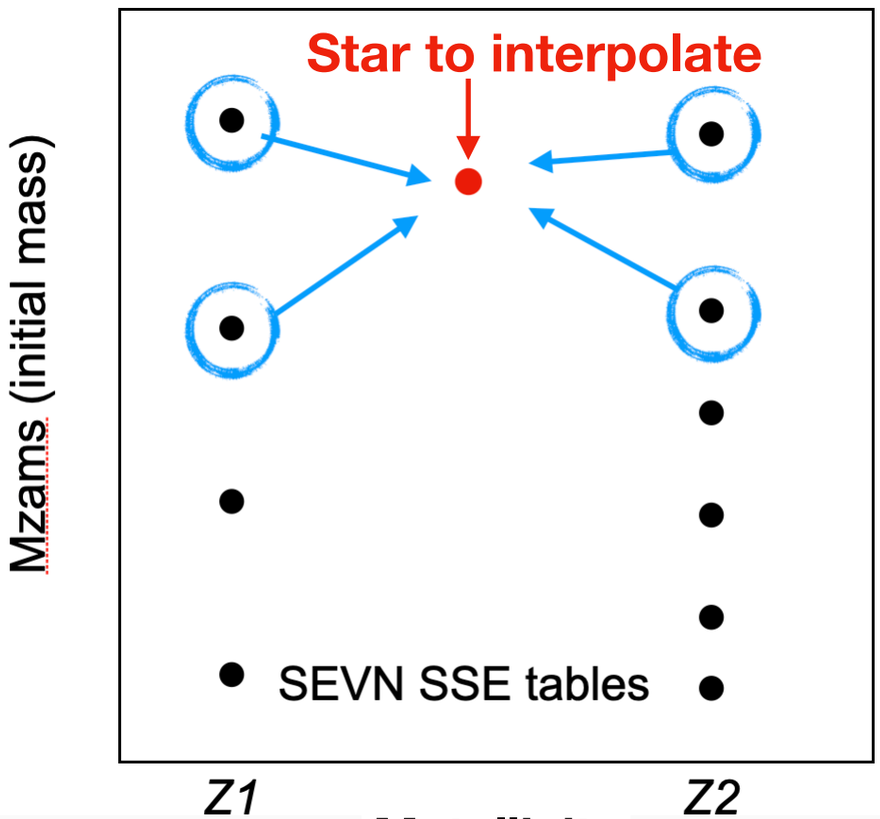


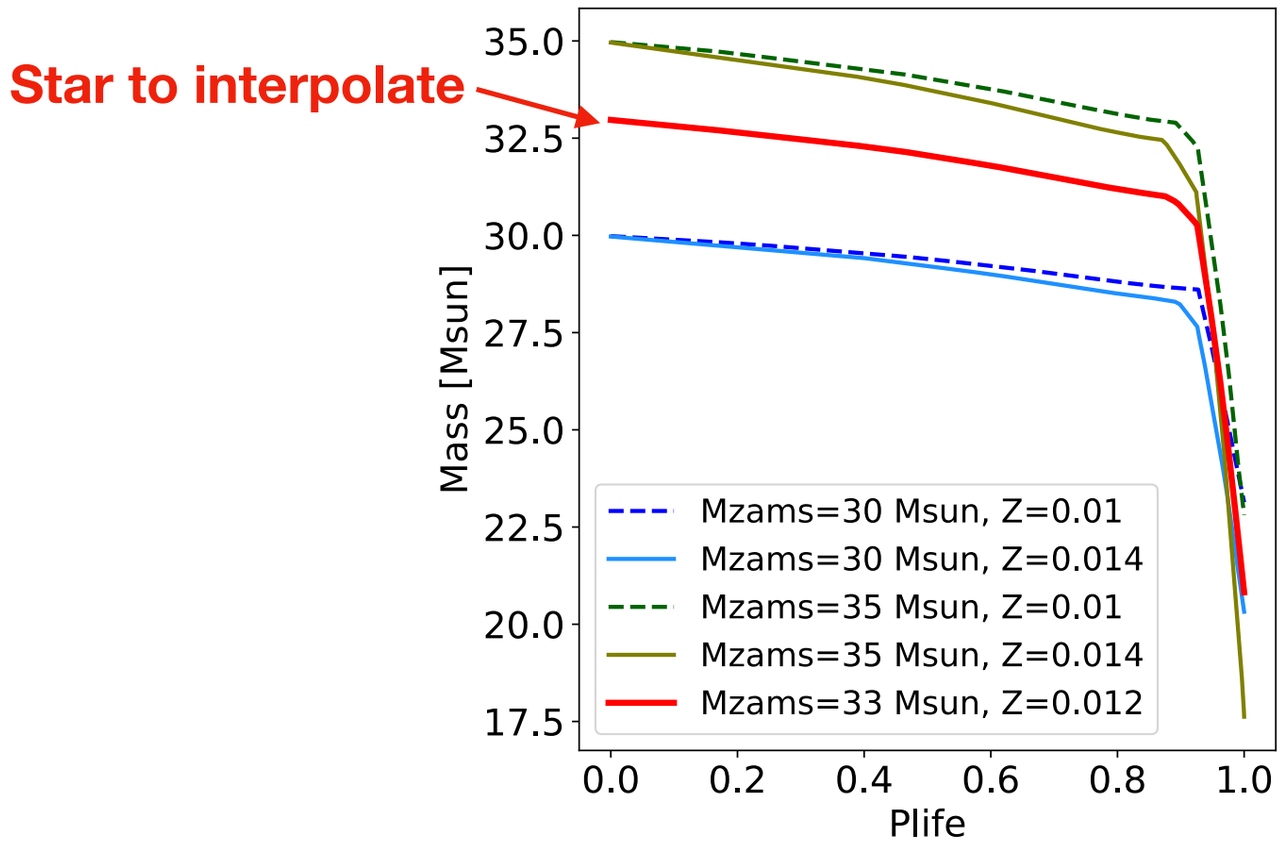
SEVN structure & algorithms

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**

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

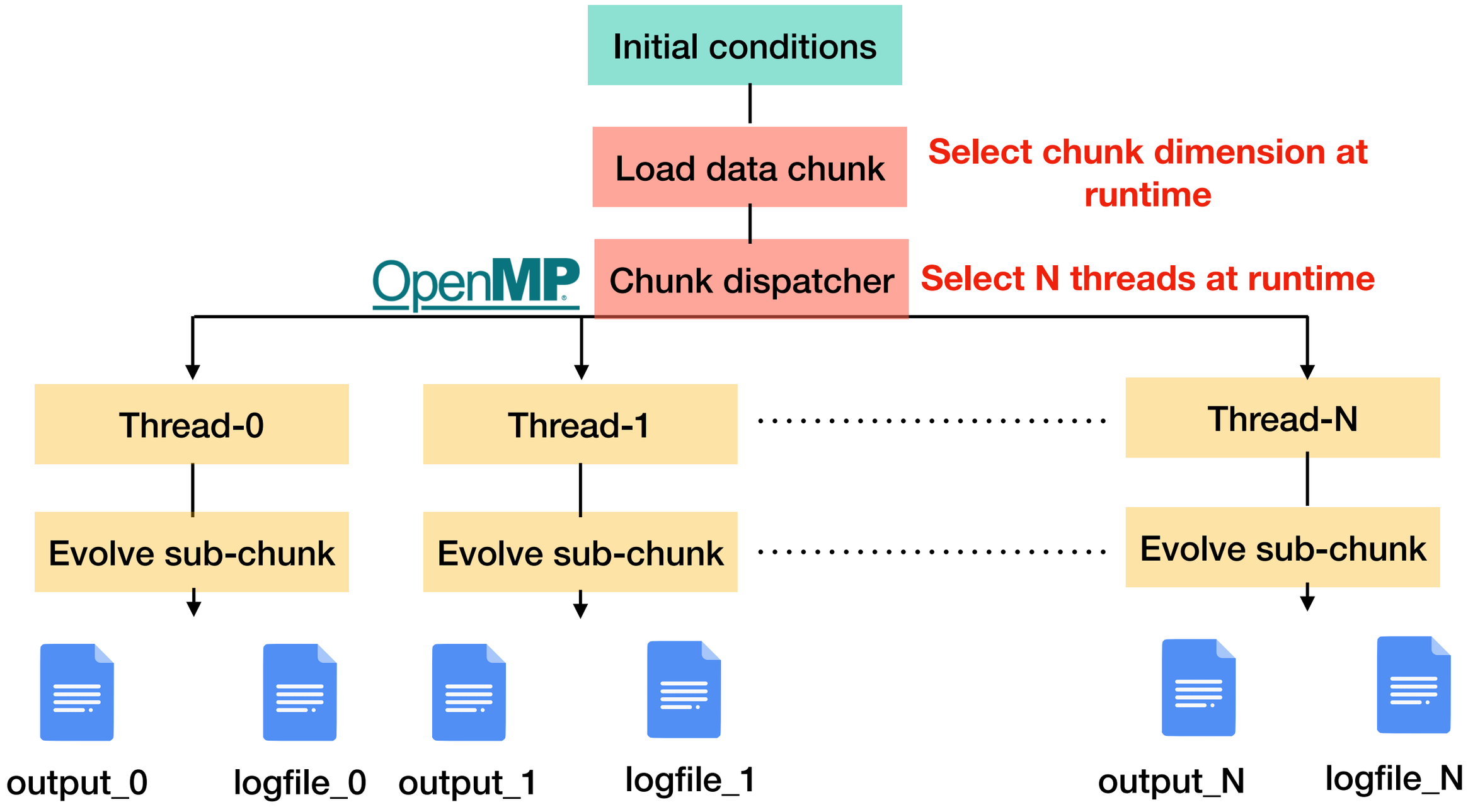




ATM, the track interpolation is not parallelised (but some compilers seems to exploit AVX vectorisation)

SEVN parallelisation

- **OpenMP to evolve in parallel chunk of initial conditions**
- **Each thread produce its own outputs**
- **"Splitted" output files make easier to analyse the simulations in "distributed environments" (e.g. using dask, spark)**



SEVN future needs

Not really accelerators…

- **SEVN does not really require accelerators (true for rapid pop synths in general)**
- **Ideally: Nodes with efficient I/O, high performance cpus (avx?)**

… but solutions for storage and services

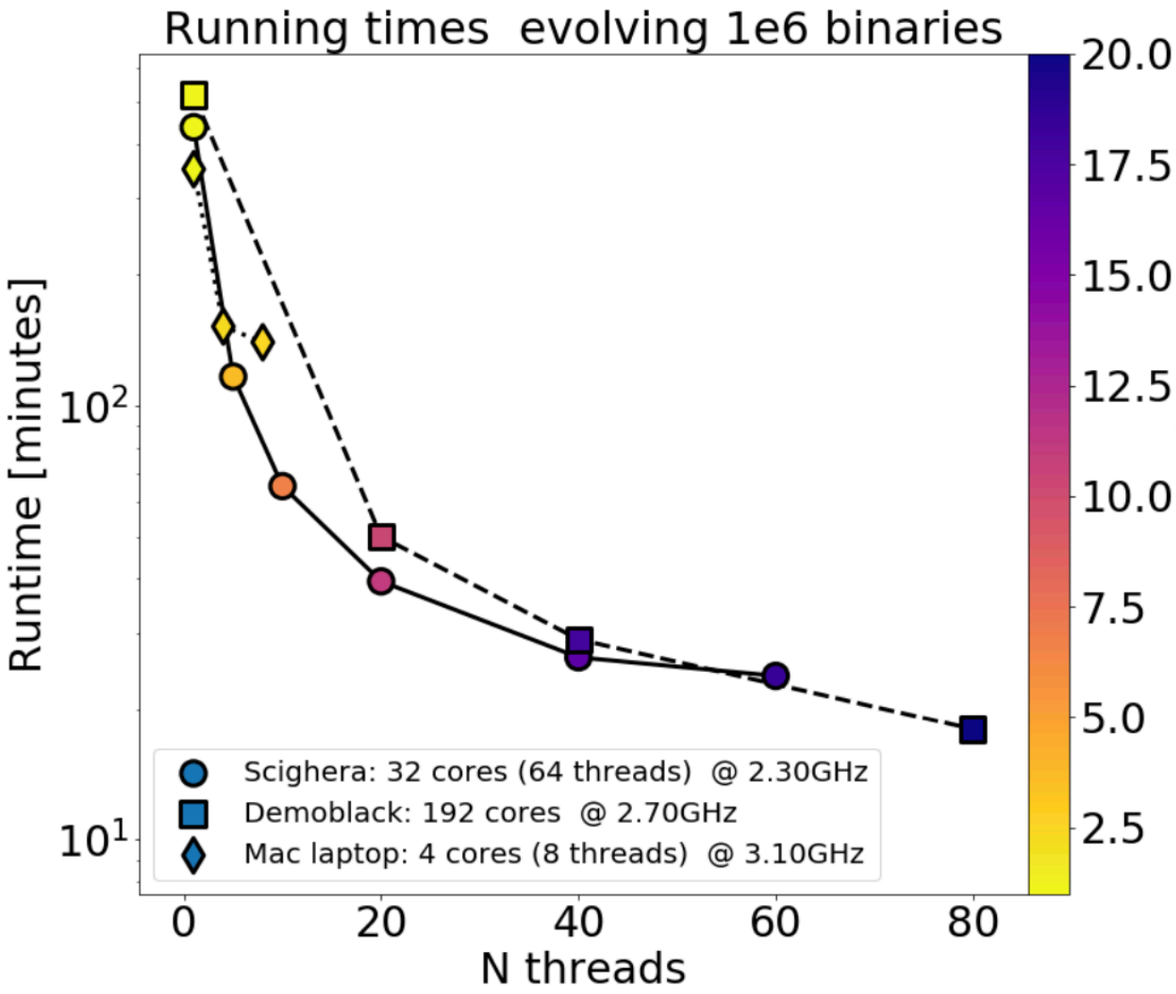
- **Large and efficient memory storages (~1-100 T)**
- **Resources to develop databases, query system, distributed data analysis**
- **Servers to run SEVN as a service and use API (something similar to Amazon elastic)**

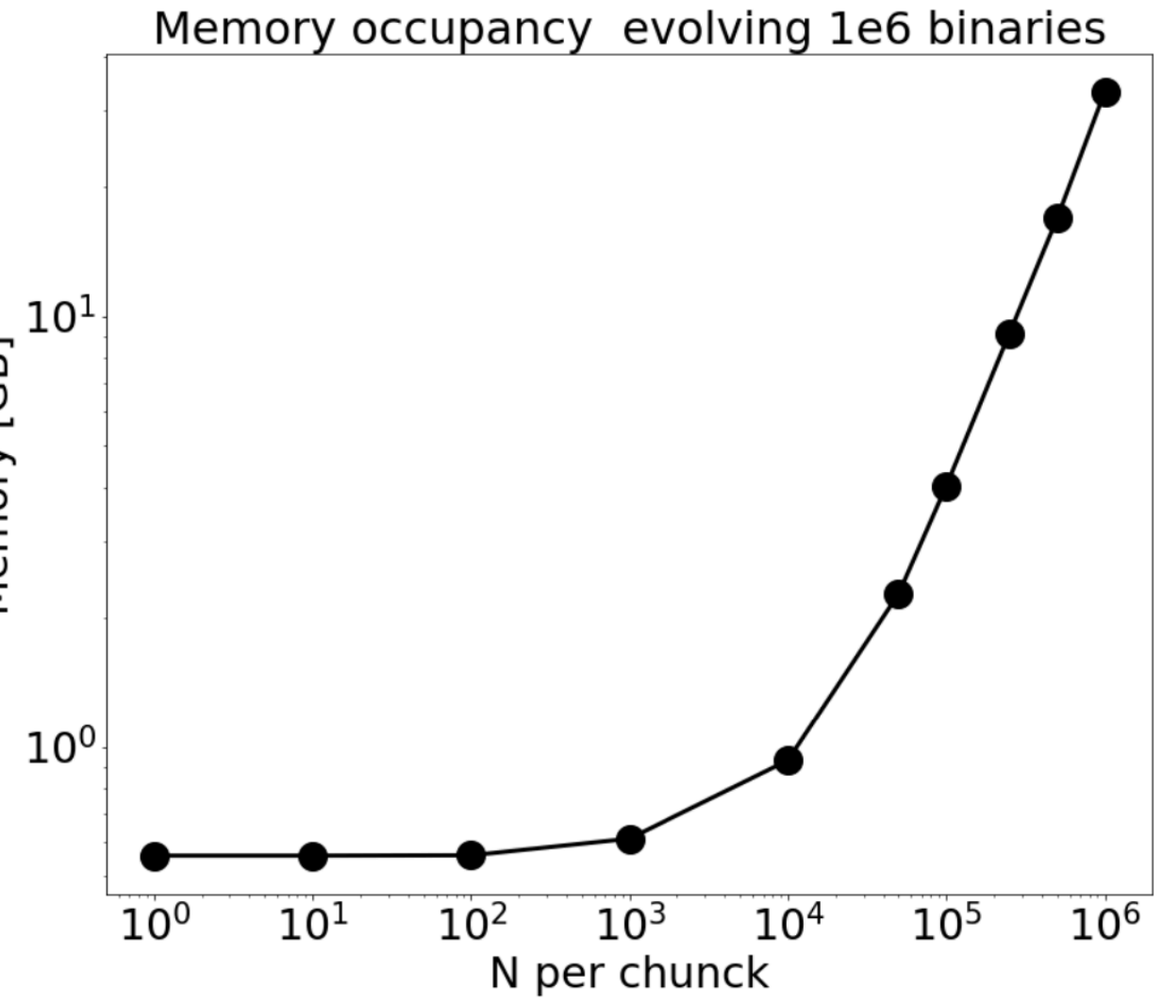
Thank you!

https://gitlab.com/sevncodes/sevn

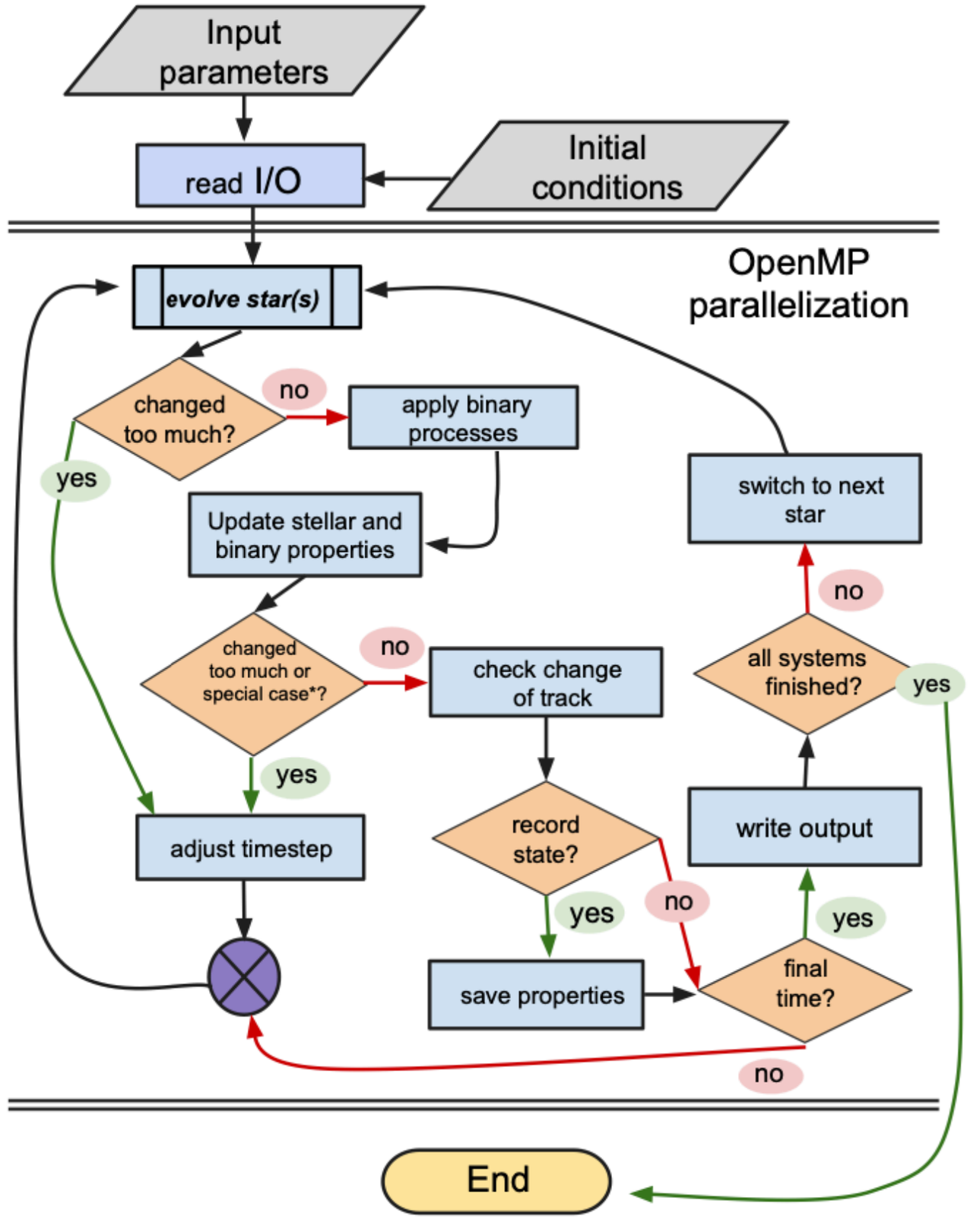
Backup

Performance





SEVN structure & algorithms



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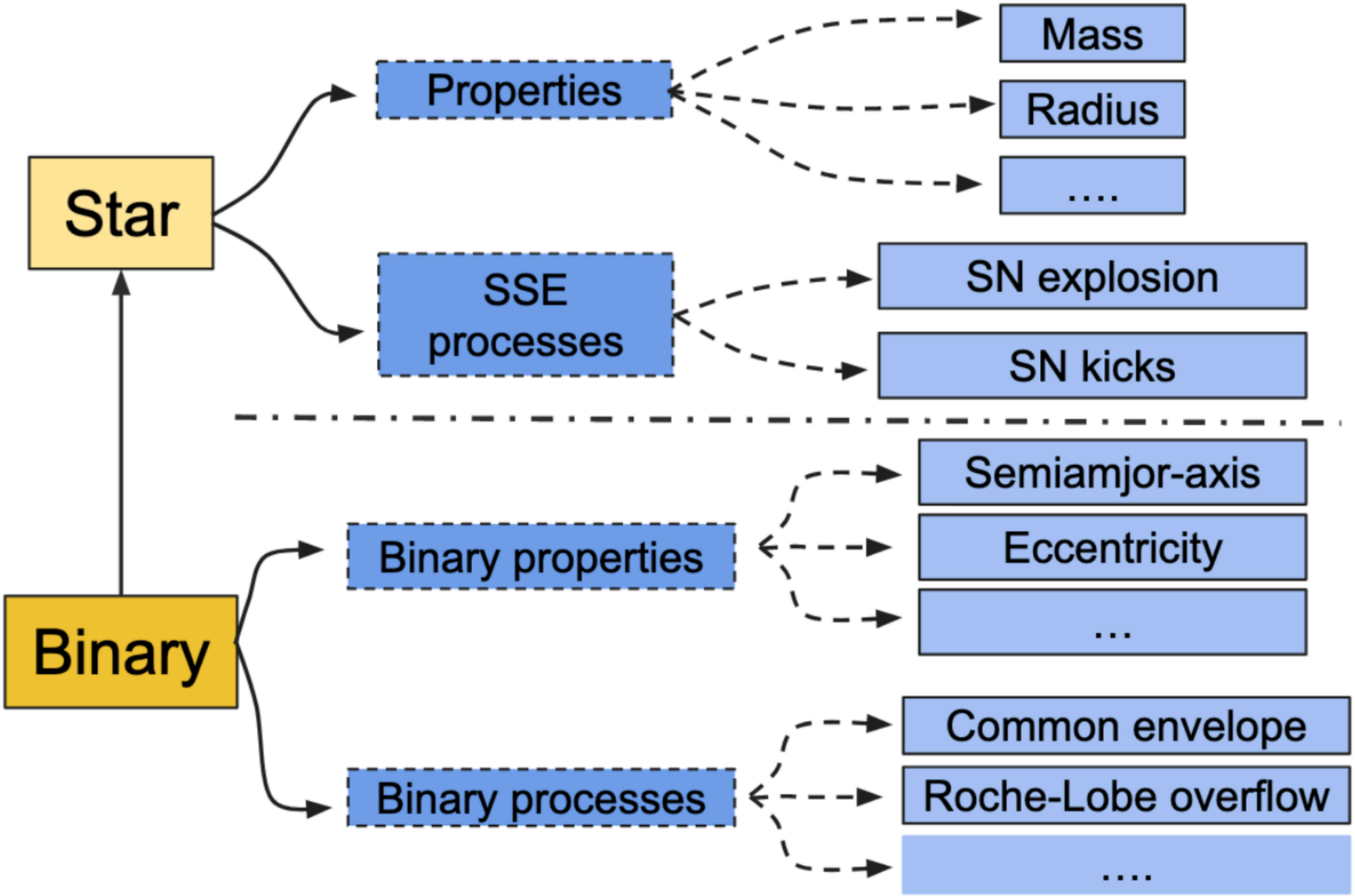
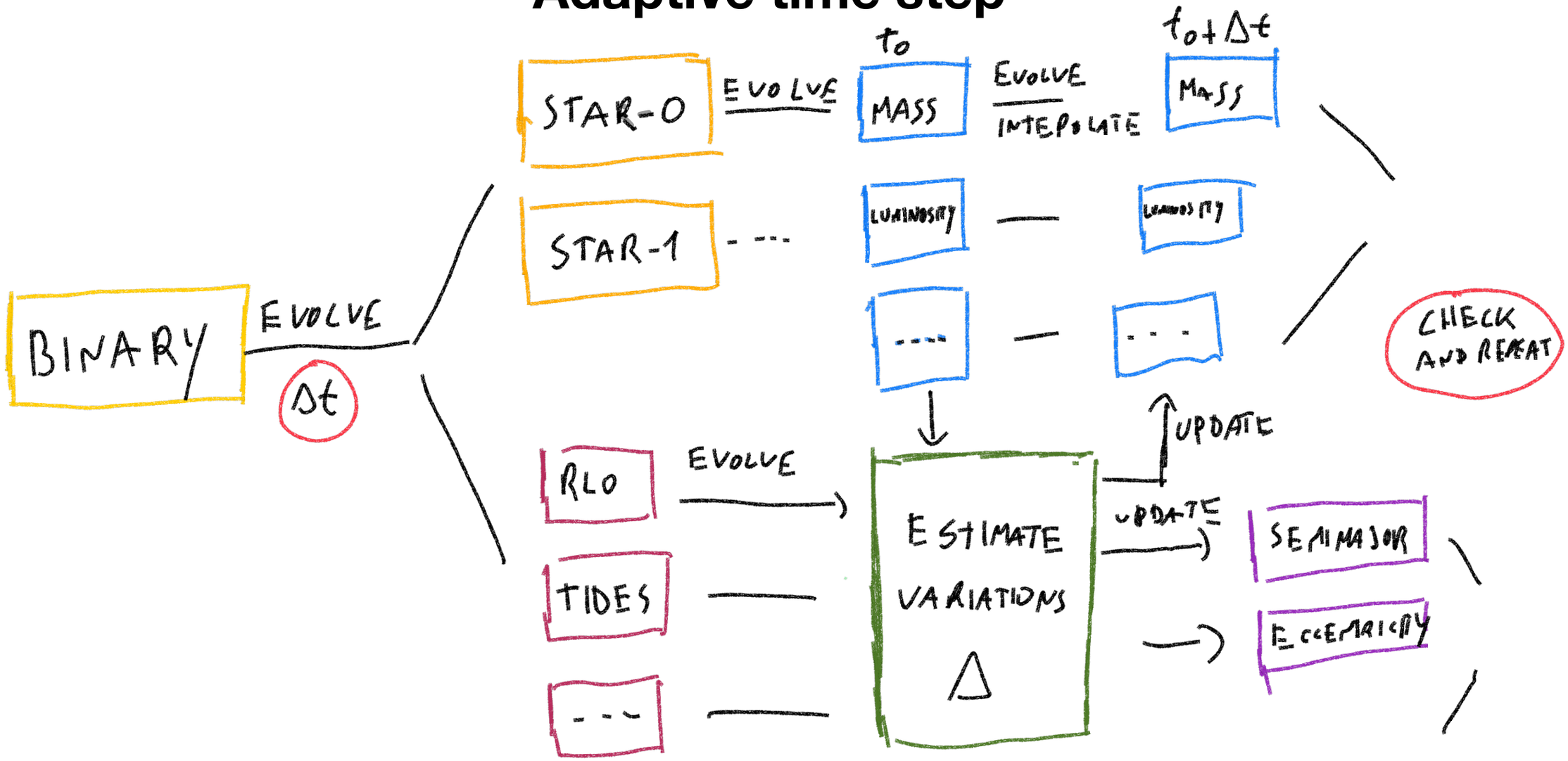


SEVN structure & algorithms

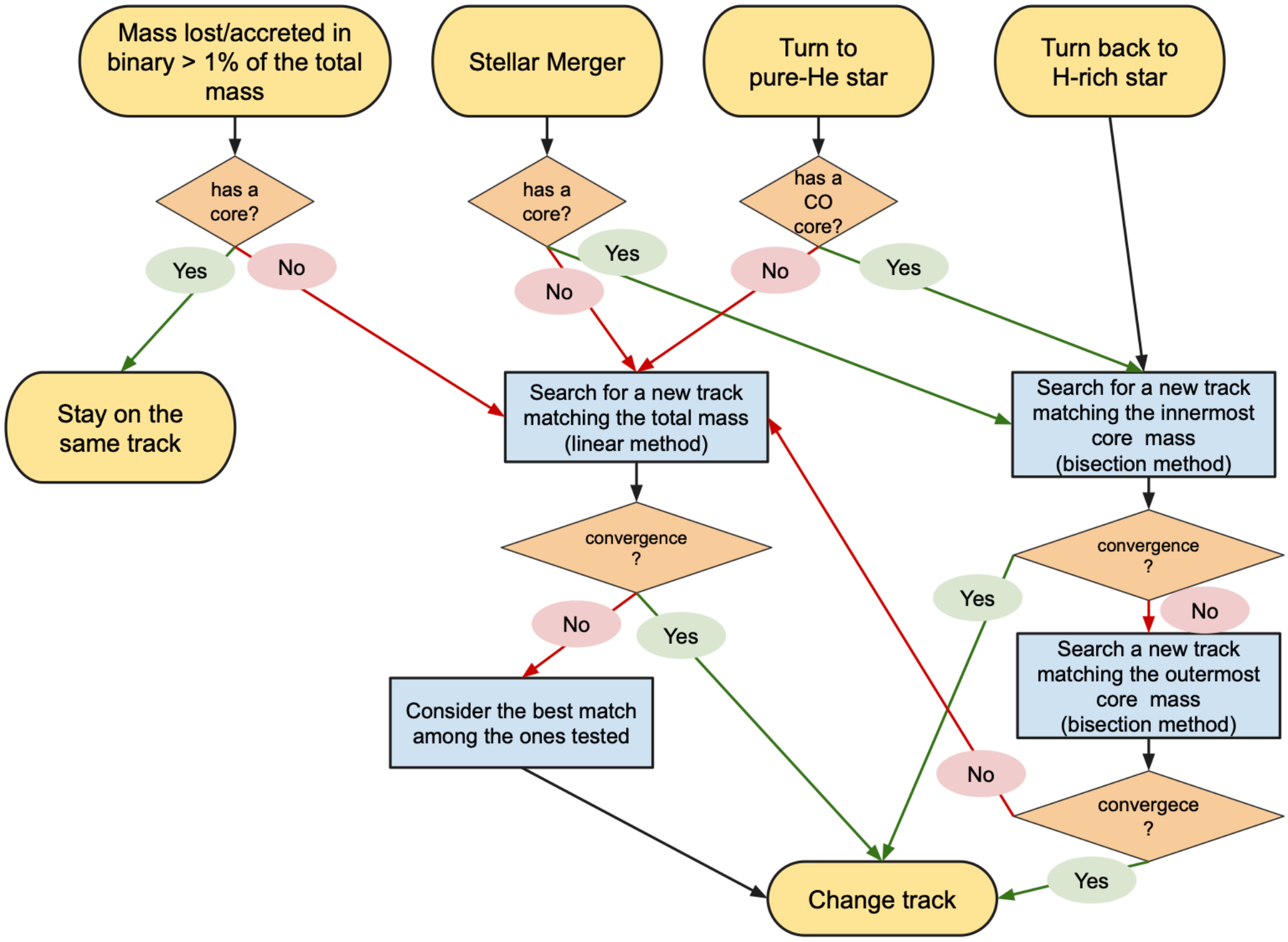
- **Synchronous evolution**
- **Adaptive time step**



- **Repeat if properties change to much (e.g. >5%)**
- **Predict next time step based on current variations**
- **ATM, the evolution step is not parallelised**

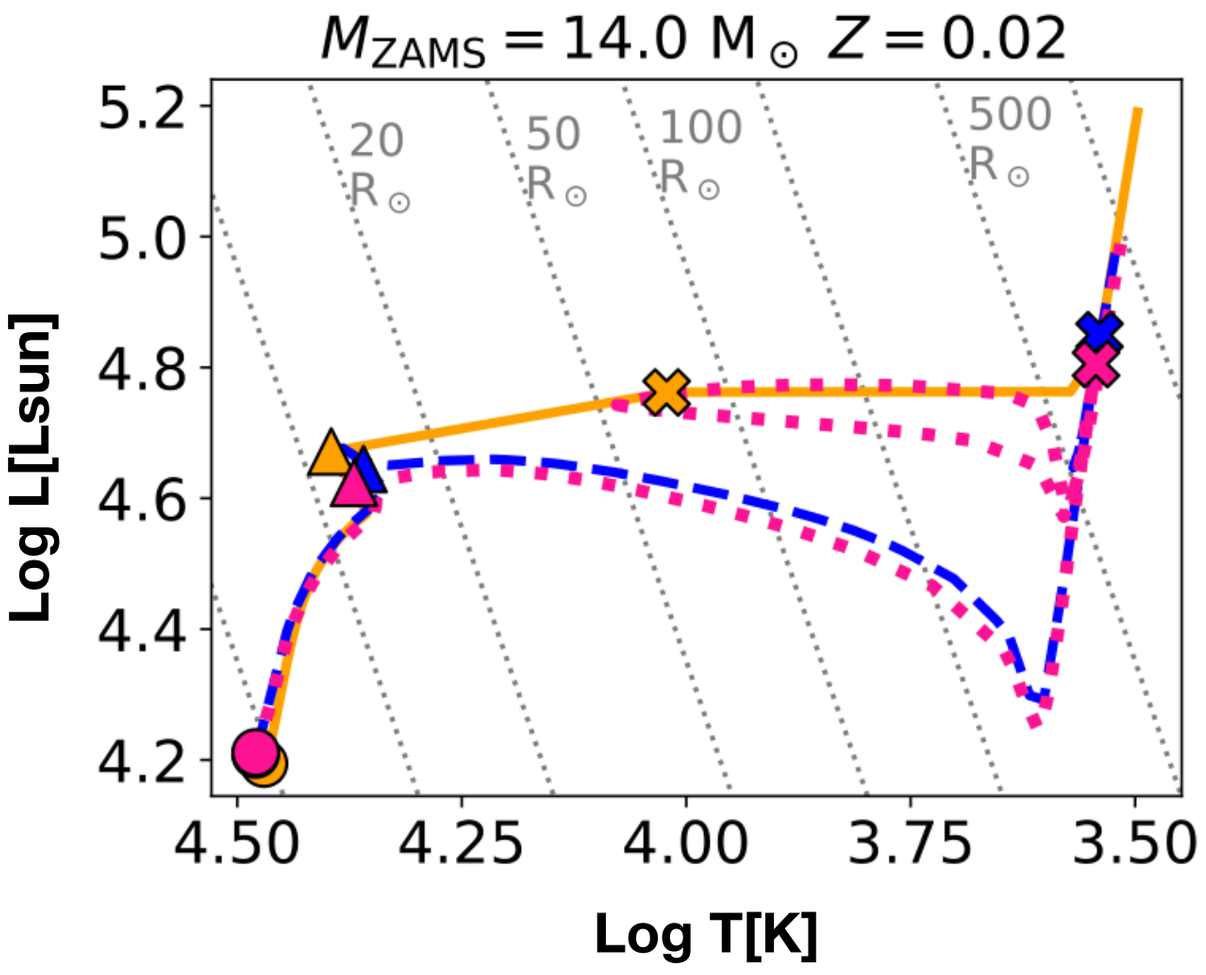
- **(but some compilers seems to exploit AVX vectorisation)**

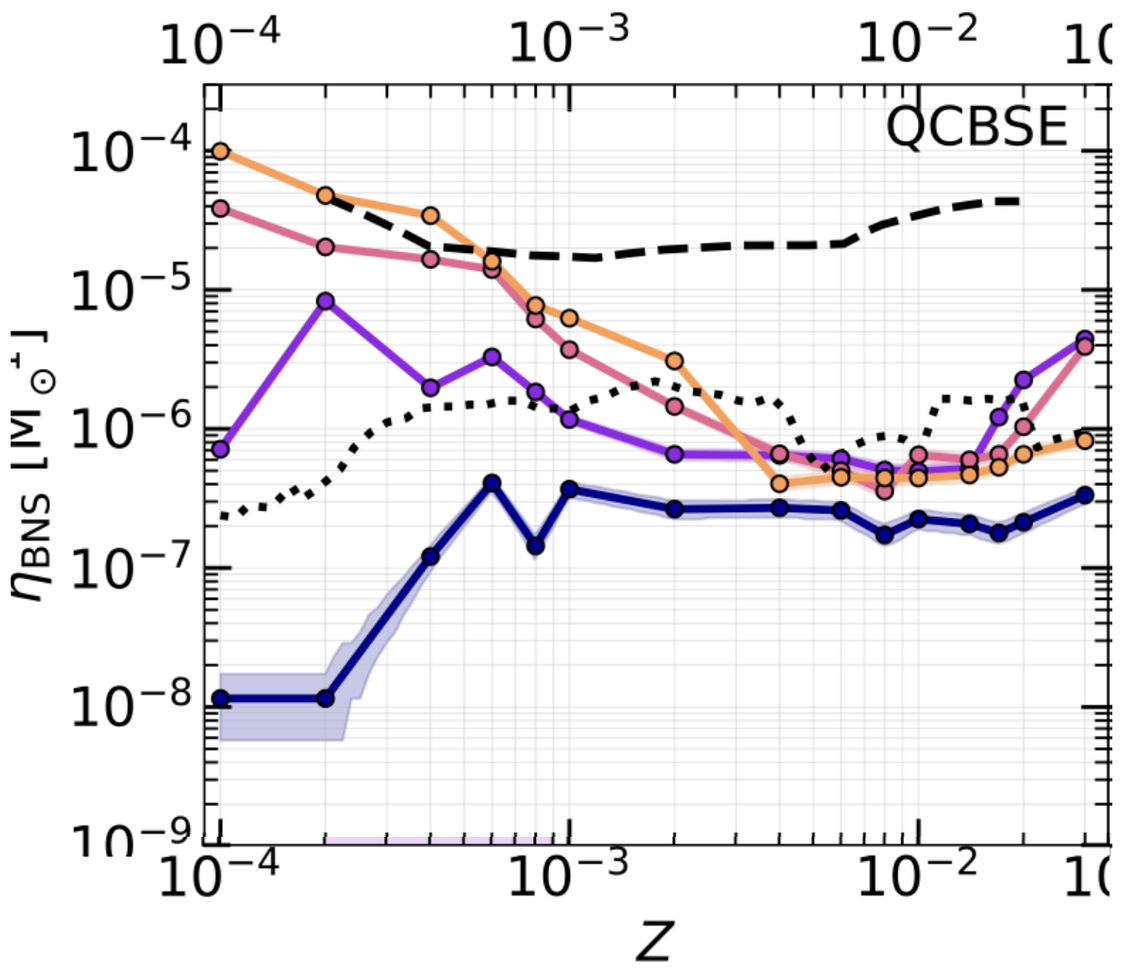
SEVN change of tracks



SEVN results

Iorio+23*: SEVN presentation and study of merging of binary compact objects (BCOs) with PARSEC tracks



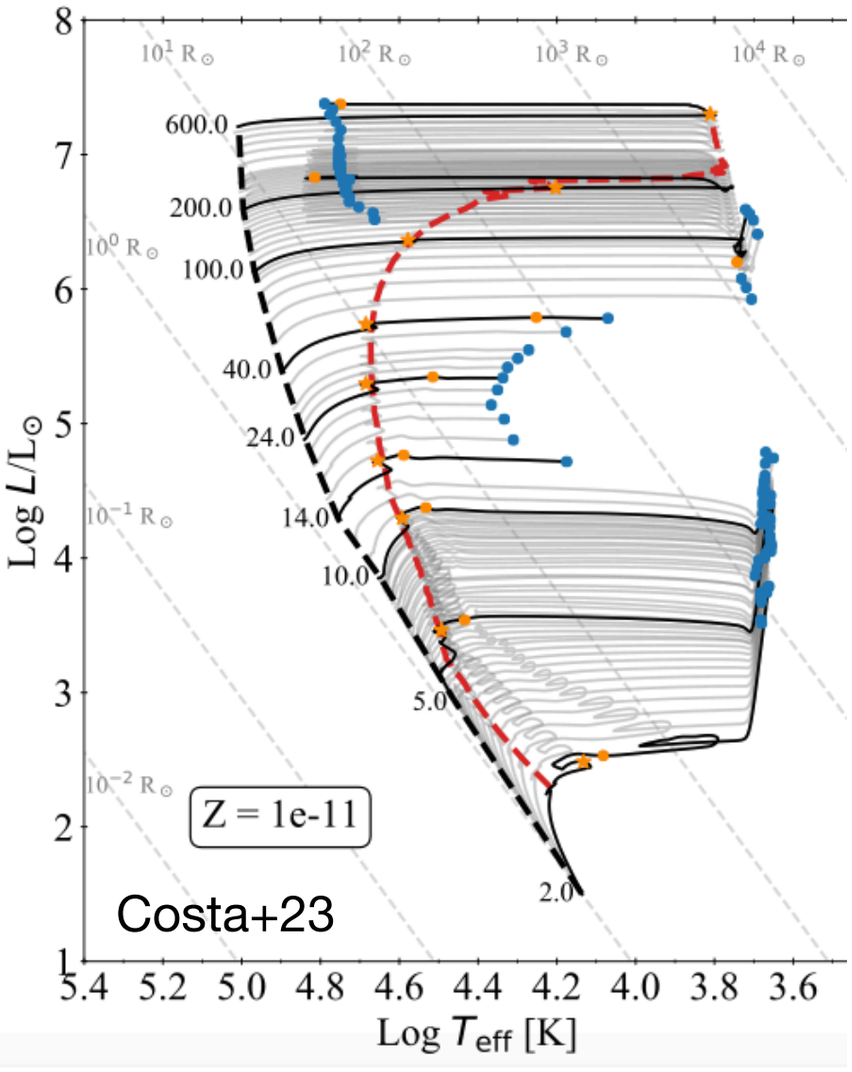


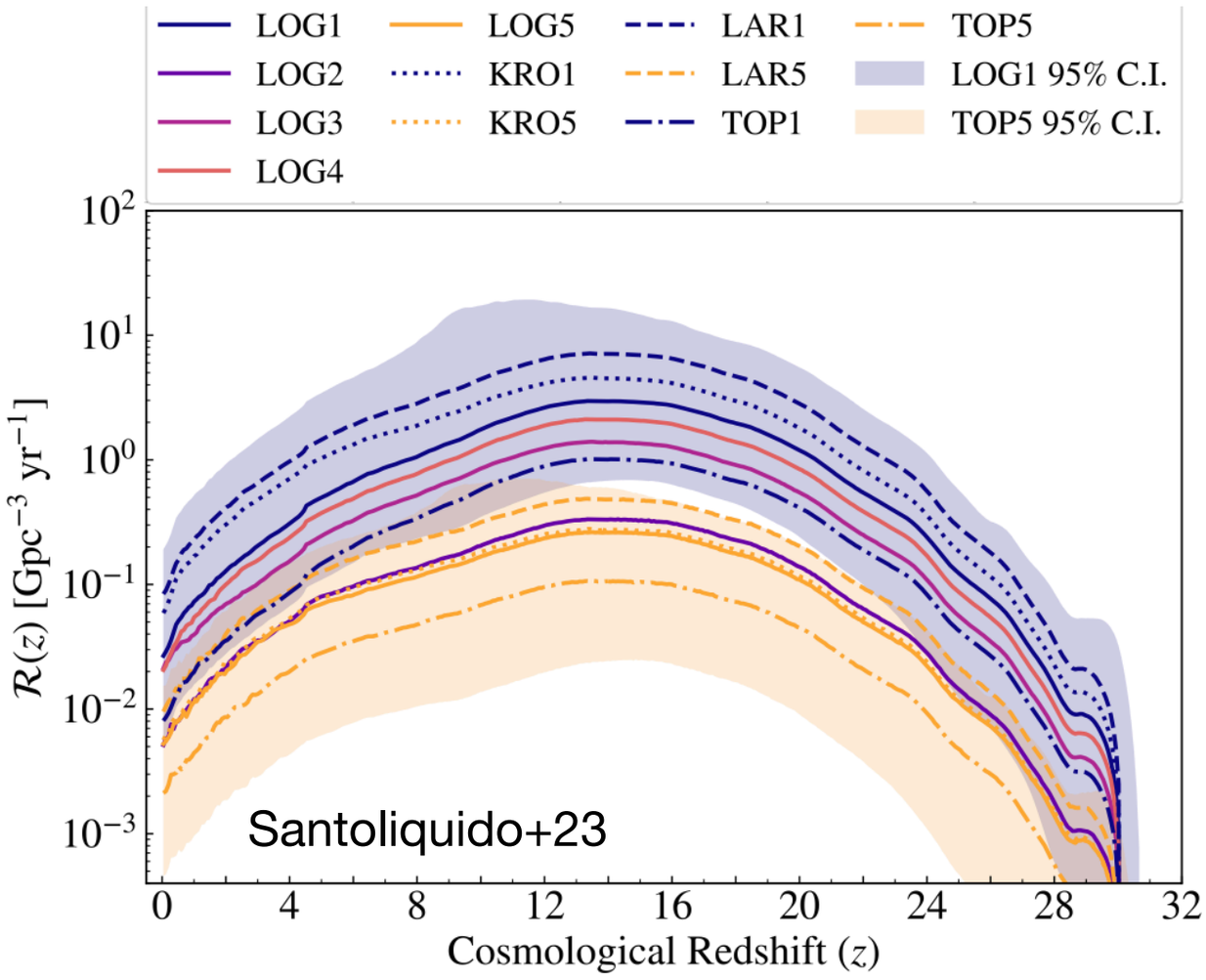
- First comprensive study of BCOs using PARSEC tracks
- Difference in SSE can have a dramatic impact of the BCO populations
- Parameter of the Binary evolution and SSE models are correlated

*Iorio et al., 2023, MNRAS in print, arXiv: arXiv:2211.11774

SEVN results

Costa+23*, Santoliquido+23**: Use SEVN and PARSEC tracks of popIII stars to study merger of binary black hole (BBH) from popIII populations





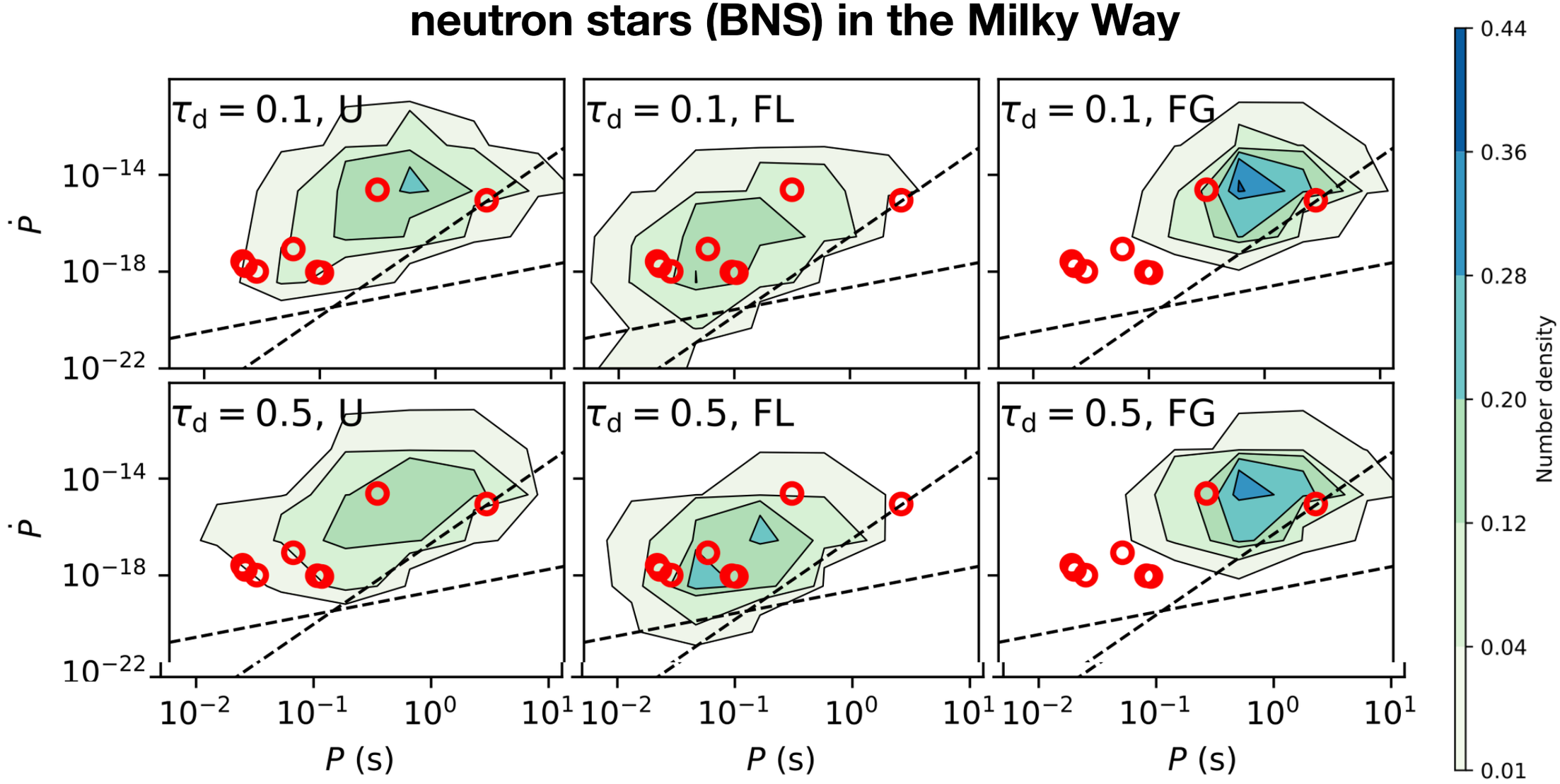
- **Mild difference between popIII and popII concerning merging BBHs**
- **Only 3.3% of BBH mergers have primary mass above 100 Msun**
- **Prediction for Einstein Telescope: 10-10000 pop III BBH mergers per year**

*Costa et al., 2023, arXiv:2303.15511

**Santoliquido et al., 2023, arXiv:2303.15515

SEVN results

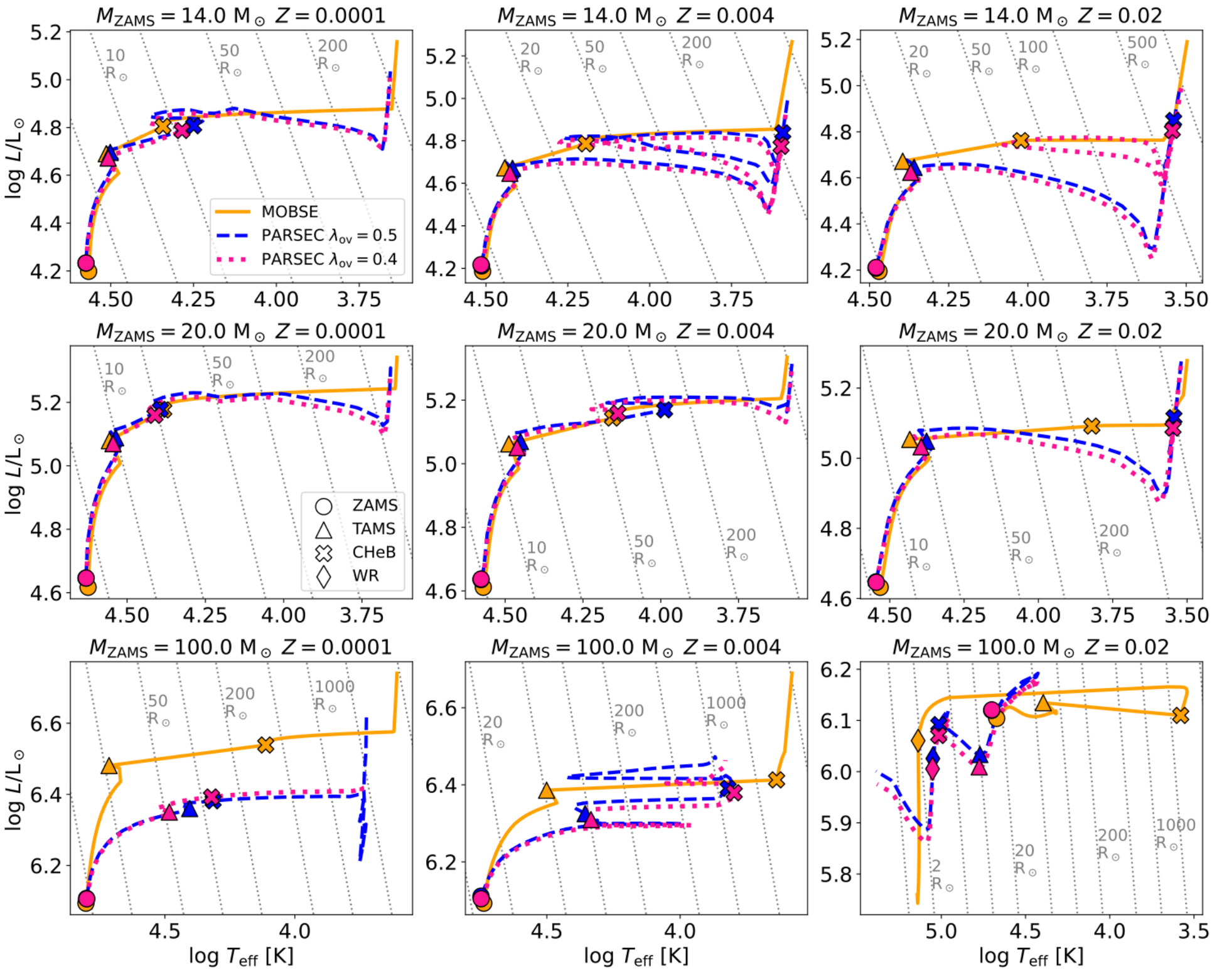
Sgalletta+23*: Use SEVN and PARSEC tracks to investigate the population of binary neutron stars (BNS) in the Milky Way



- **Properties of Galactic BNSs are reproduced**
- **Constrain on initial distribution of magnetic field and spin (both uniform)**
- **Prediction for SKA: ~20 new BNS detections in the MW**

*Sgalletta et al., 2023, arXiv:2305.04955

PARSEC - MOBSE



Available Tables

Tables in SEVN

H-rich stars:

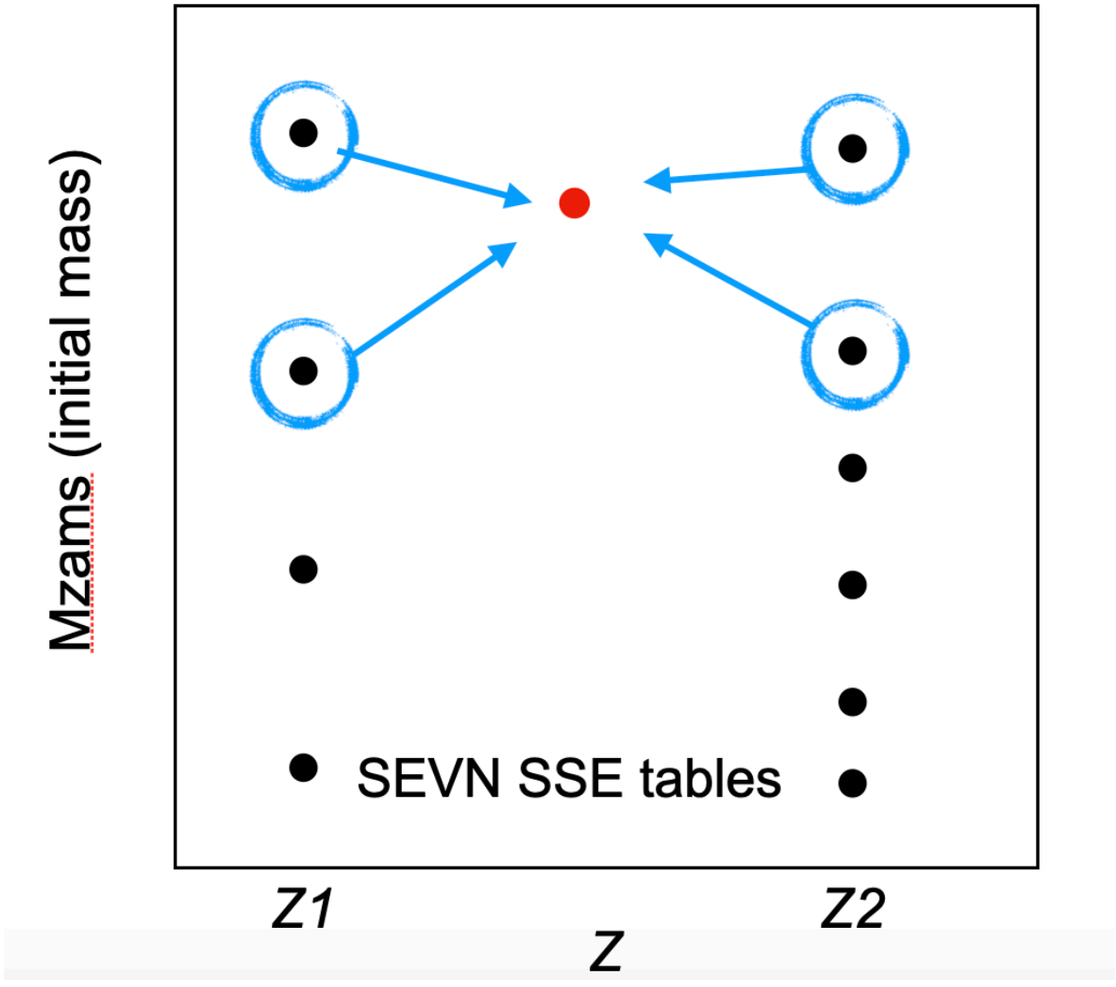
Name	Mass range [Msun]	Z range	Notes
SEVNtracks_parsec_ov05_AGB	2.2 - 450*	1E-11 - 0.04	Most updated tracks from PARSEC with overshooting parameter = 0.5
SEVNtracks_parsec_ov04_AGB	2.2 - 600	1E-4 - 0.04	Most updated tracks from PARSEC with overshooting parameter = 0.4
SEVNtracks_MIST_AGB	0.7 - 150	1.4E-5 - 0.045	MIST tracks (made with MESA)

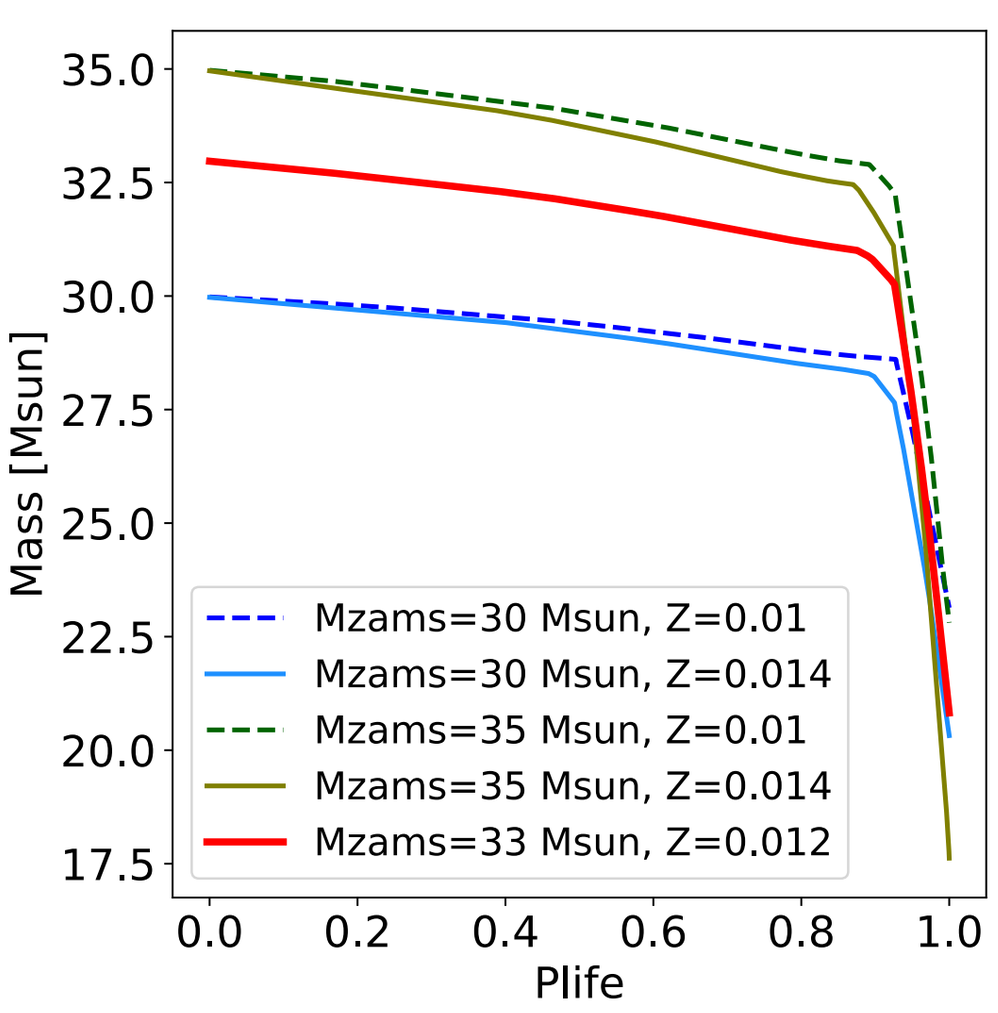
*Some specific metallicities have Mzams up to 600 Msun

Interpolation

Stellar evolution through **interpolation of precomputed stellar tracks**

- **SSE mostly depends on** initial Mass, **Mzams**, and metallicity ***Z*** (fraction of non H/He elements
- Each couple of Mzams,*Z* **identifies a stellar track** in the tables
- Stellar tracks contain the **temporal evolution of stellar parameters** (e.g. Mass, Radius etc.)
- If (Mzams,*Z*) not in the tables interpolate using **four interpolating tracks**





Interpolation