Constraining occurrence rates of short-period post-common envelope binaries

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Common Envelope evolution

- ~50% to 85% of stars are predicted to be in binaries.
- For short-period binaries that have a compact object:
  - White dwarfs, neutron stars, black holes, etc. come from larger stars.

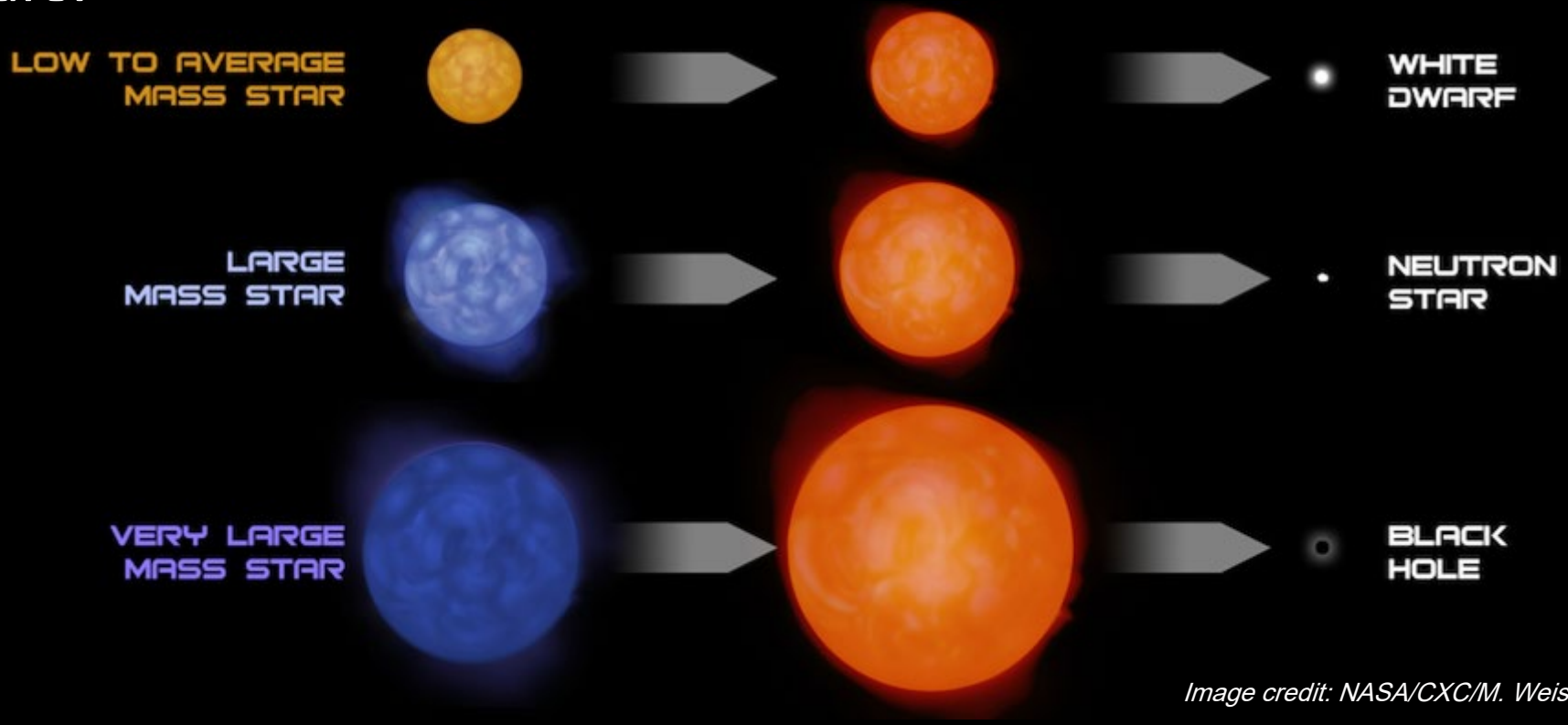


Image credit: NASA/CXC/M. Weiss

1. The primary star undergoes a radius expansion into the asymptotic giant branch (AGB).
2. The primary star fills its Roche Lobe and wraps the companion into a common envelope.
   - The exchange of angular momentum will cause the orbit to shrink.
3. Eventually, the envelope gets ejected or stars merge.

- **Goal: model close-in binaries to study this process and predict occurrence rates for future observations.**

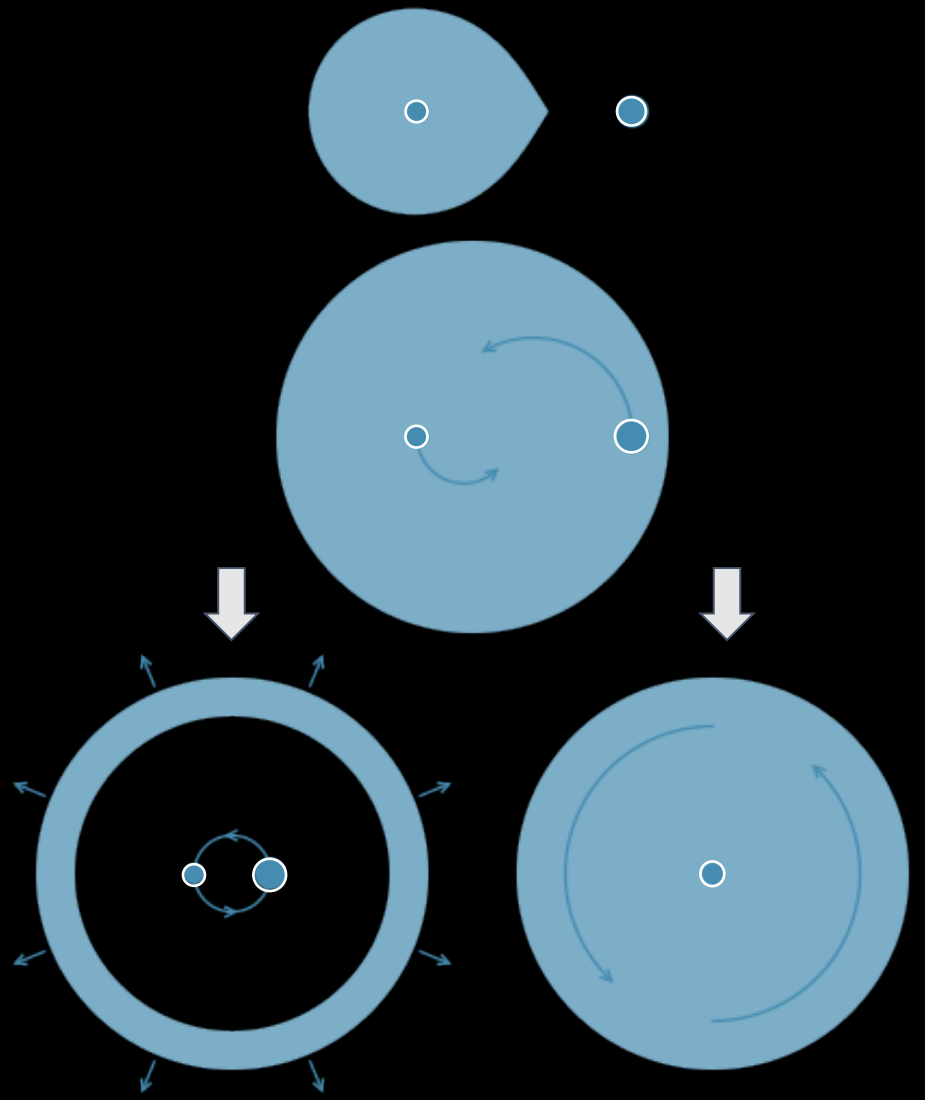


Image credit: Phillip D. Hall

Stellar evolution at a glance

- Main sequence until core H depletion.
- Star will undergo radius expansion into giant branch (GB), and He fusion.
- After He fusion => CO core. More expansion, asymptotic giant branch.
  - AGB: stars become brighter and larger radii.
- Can lose outer layers due to stellar winds.
- Compact remnants: white dwarfs, neutron stars, or black holes.

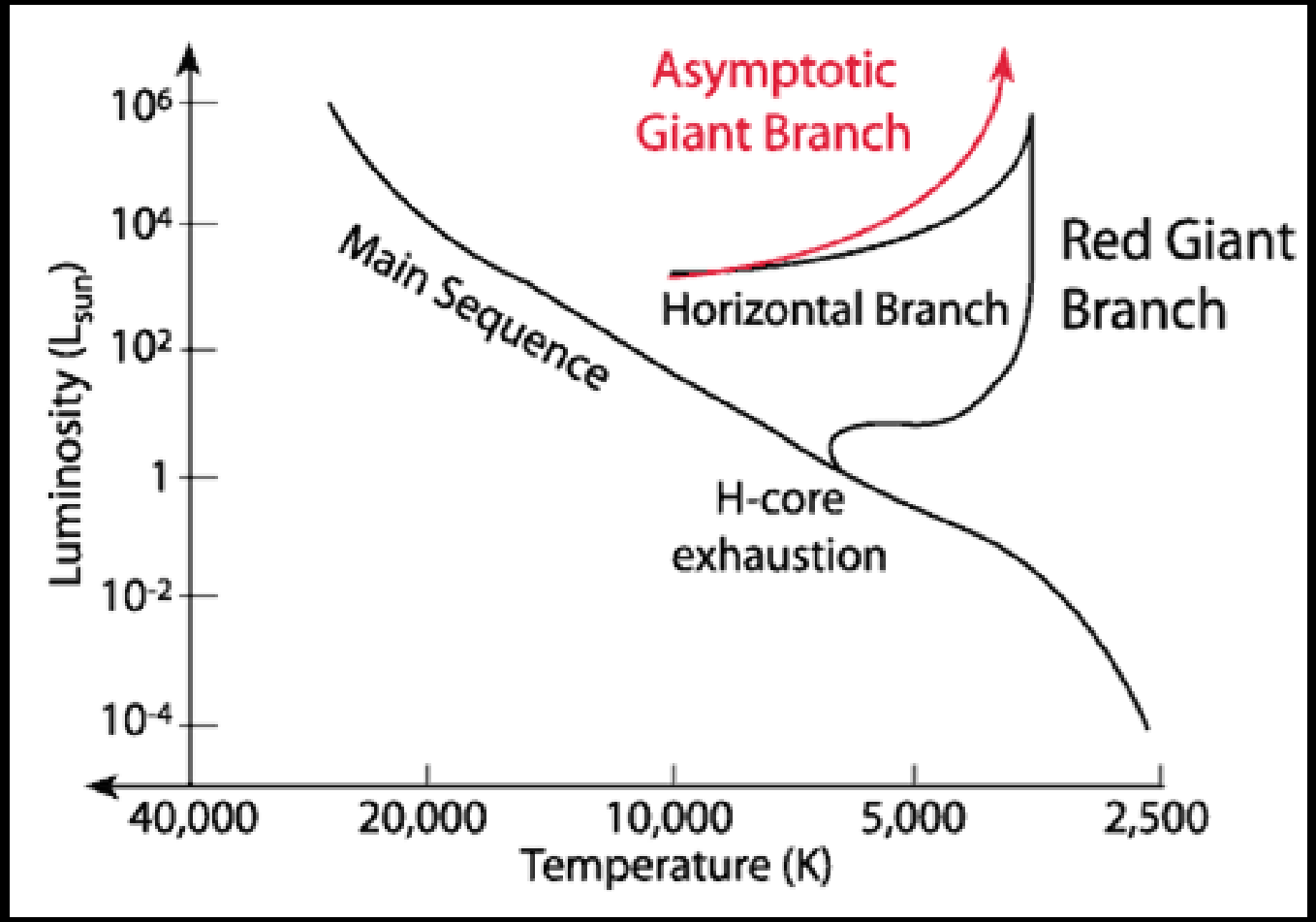
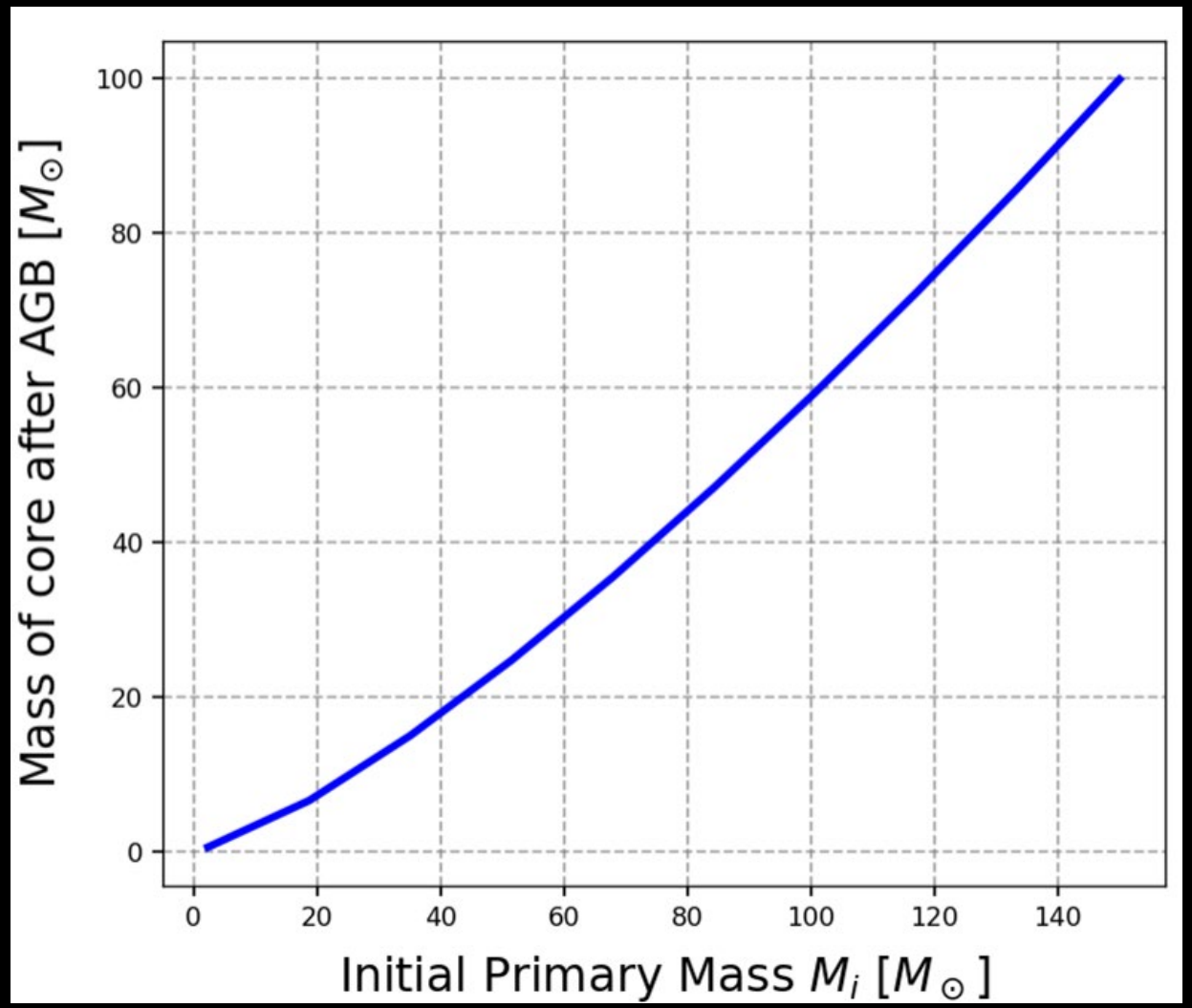


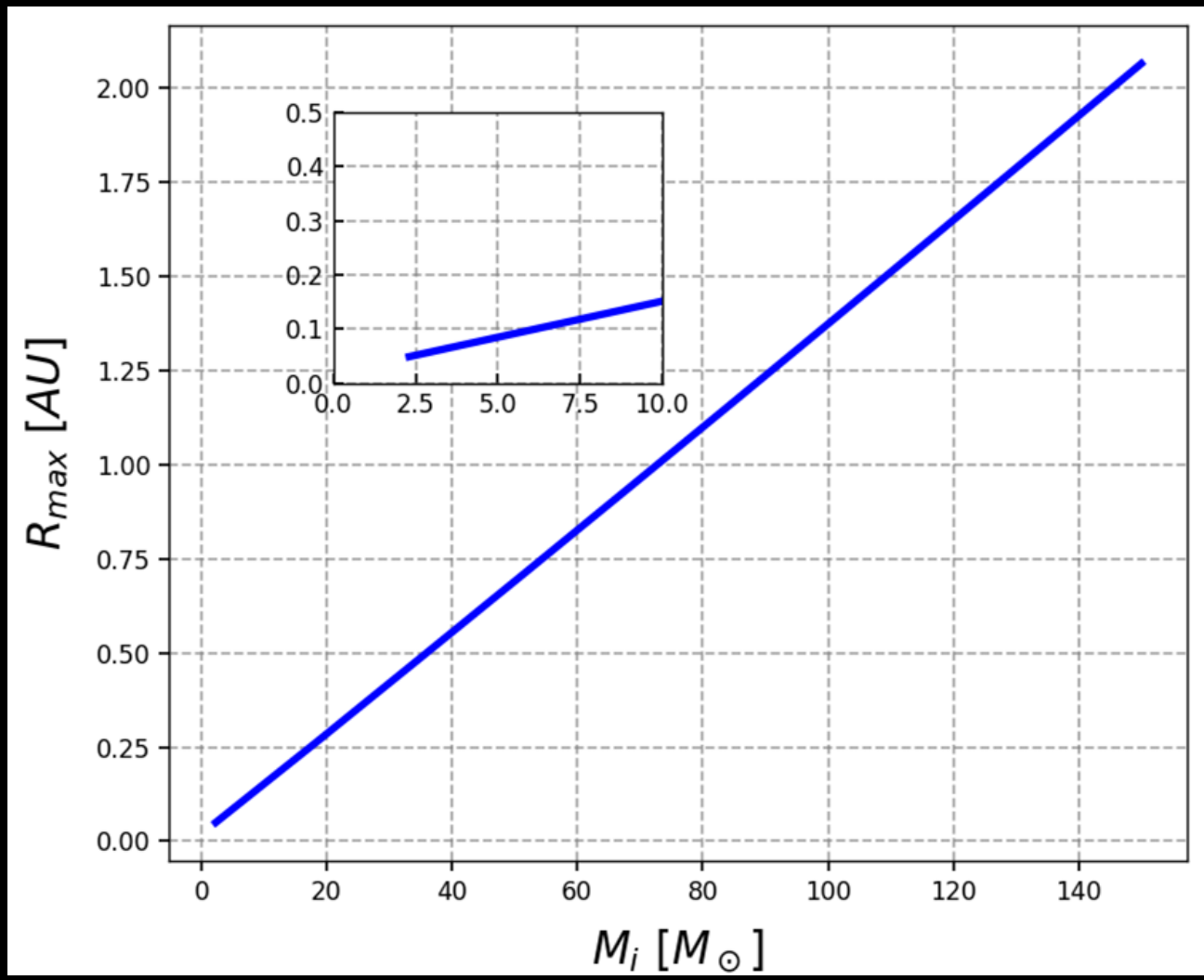
Image credit: NOAO

Our process

- Synthetic population of binaries (N=10 million)
  - Progenitor mass: IMF $\propto M^{-2.35}$ (2 to 150 M⊙)
  - Mass ratio, $q = \frac{M_2}{M_1}$: linear (0.1 to 1)
  - Orbital period: lognormal distribution (0.1 to 10^6 days)
    - Mean= 4.8, St. Dev.= 2.3 (Kroupa et al. 2011)
- Circular orbit (for now)
- Metallicity: 0.02 (for now constant)

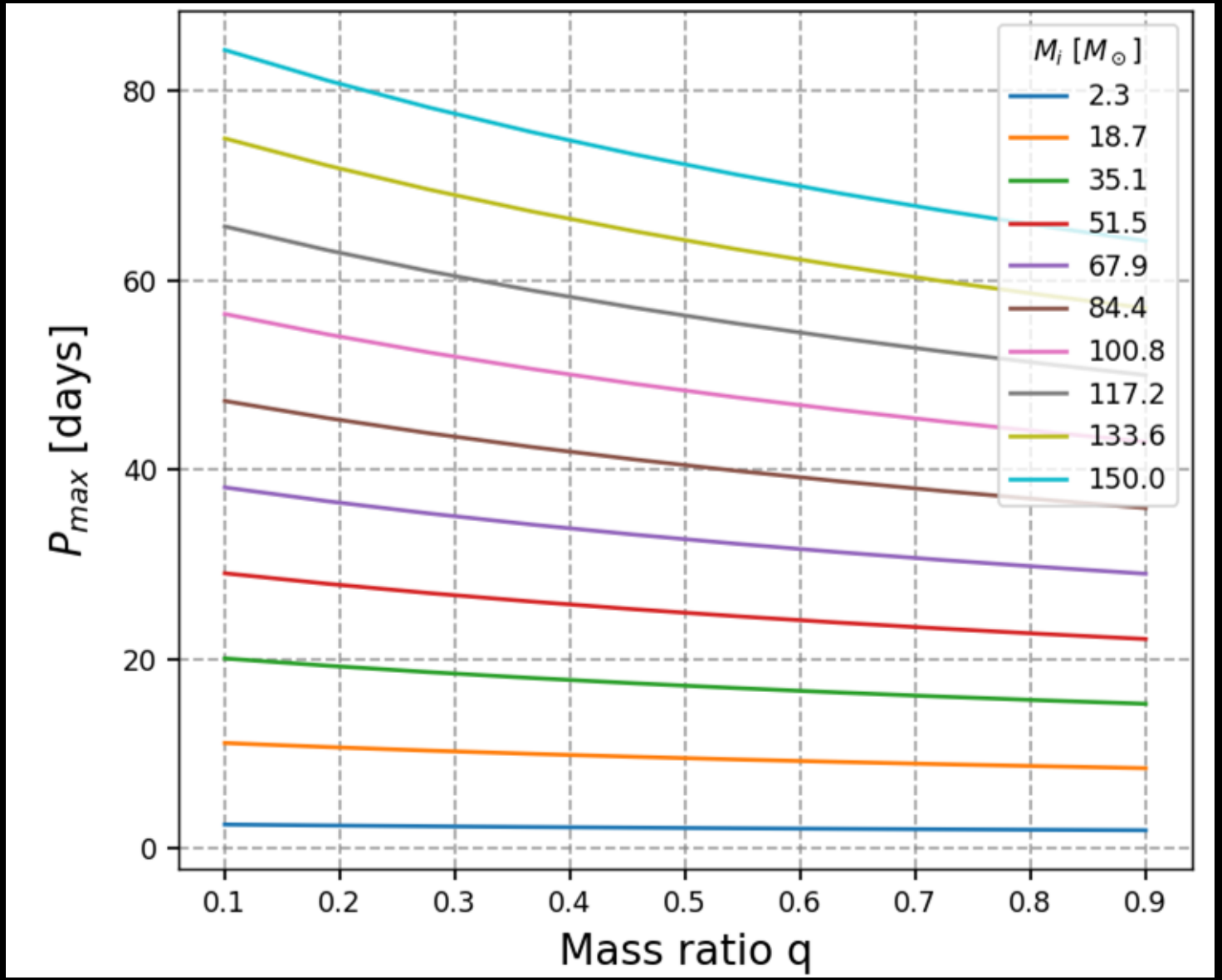
- R_{max} reached during evolution (limit at the base of AGB).
- Mass at the end of AGB (core remaining after CE).


Mass of core after AGB [$M_\odot$]
Initial Primary Mass M_i [$M_\odot$]
0
20
40
60
80
100
120
140


R_{max} [AU]
M_i [$M_\odot$]
0.00
0.25
0.50
0.75
1.00
1.25
1.50
1.75
2.00
0.0
0.1
0.2
0.3
0.4
0.5
2.5
5.0
7.5
10.0

- If initial orbital period P_i is less than P_{max} (the corresponding period to separation R_{max}), then system undergoes CE.

- Orbital separation will shrink
  - So, an observed system with orbital period less than this could have gone through CE.



Common envelope

- Change in semi-major axis: *(Webbink, 1984)*

$$\left(\frac{GM_cM_*}{2a_{f_{CE}}} - \frac{GM_iM_*}{2a_i}\right) = \frac{G(M_i - M_c)M_i}{\alpha\lambda R_{Roche}}$$

Where:

$\alpha\lambda$ = efficiency and concentration coefficients *

M_c=Mass of core after AGB

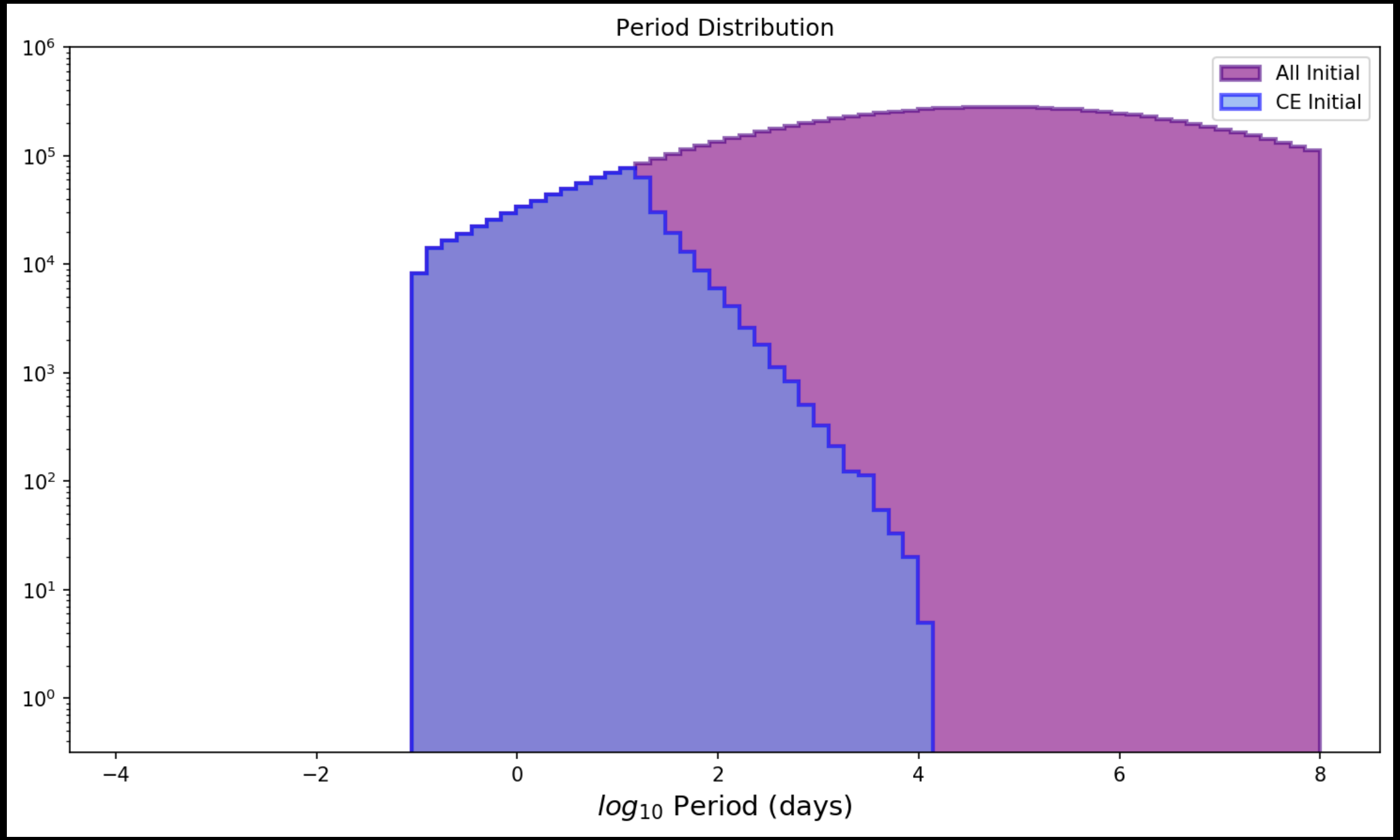
M_*=Mass of companion (found with mass ratio q)

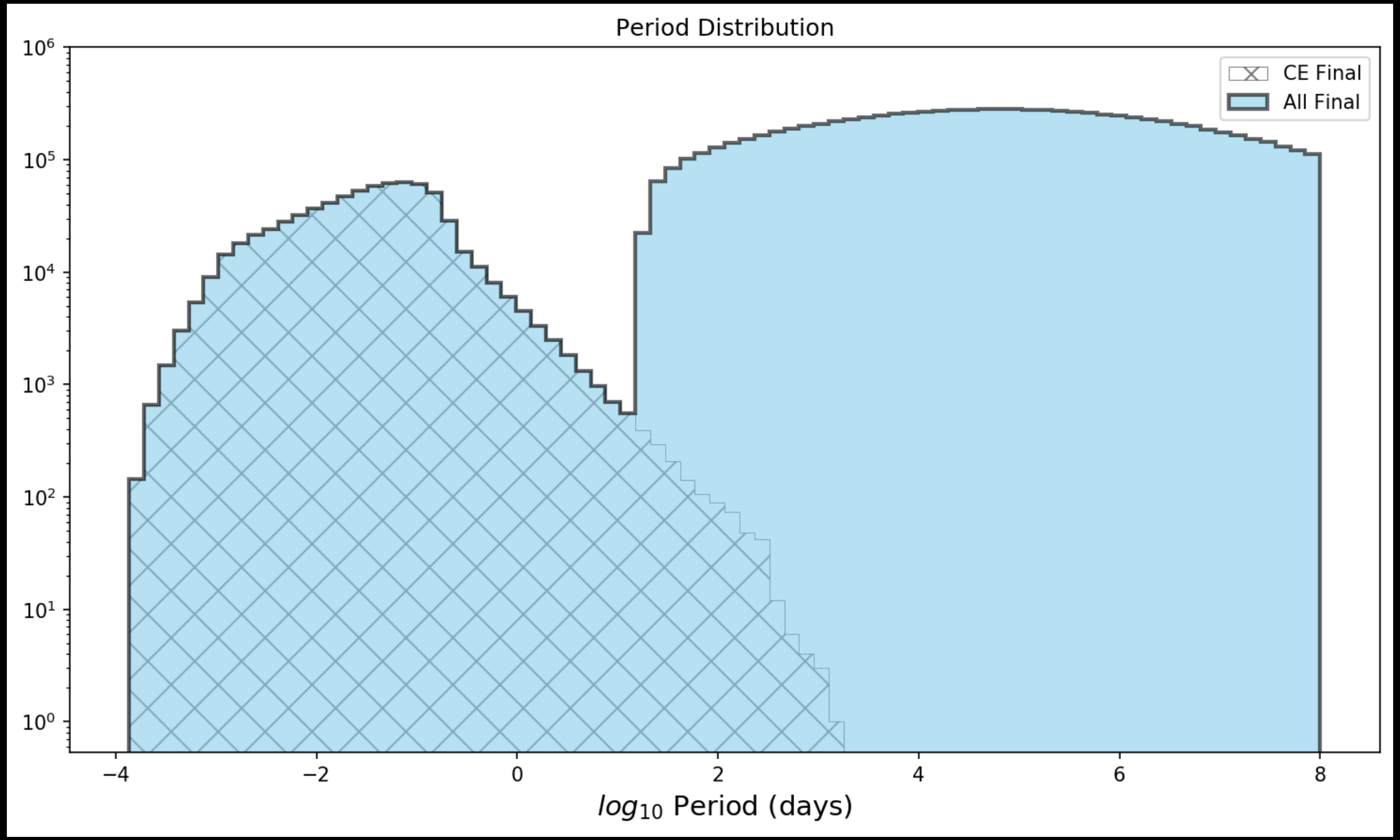
M_i=Initial mass of primary

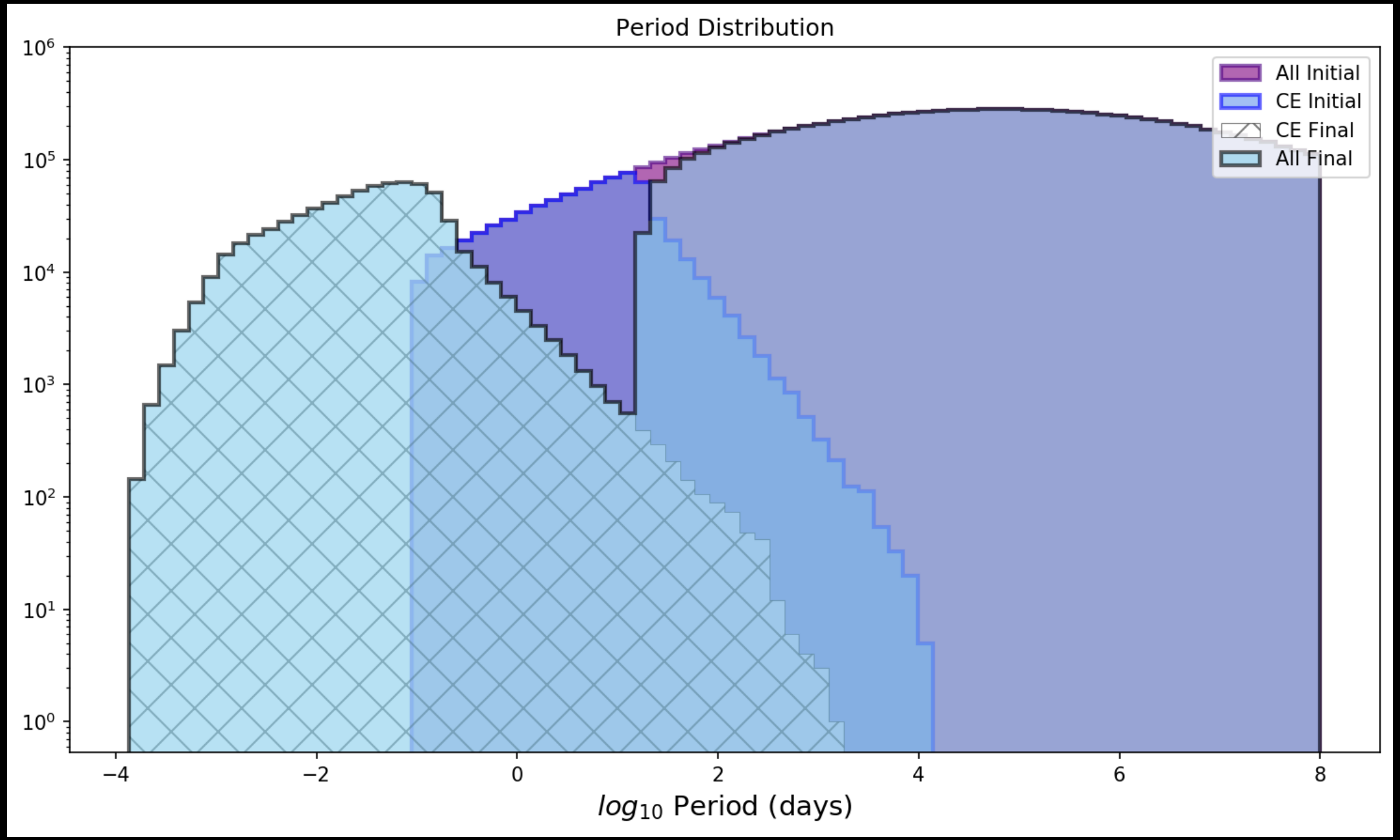
a_i=Initial semi-major axis

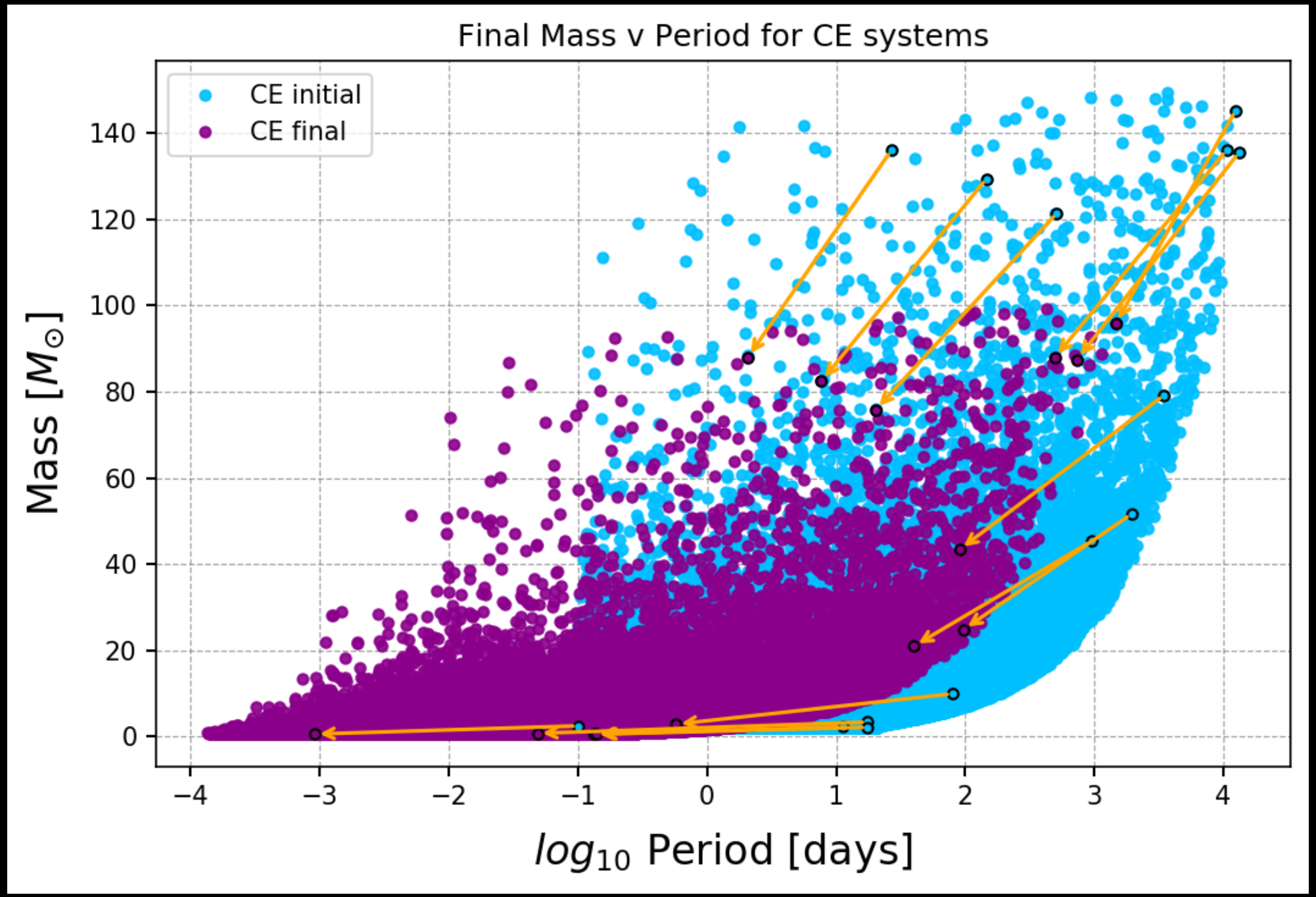
R_{Roche}=Roche radius

*We will vary to explore parameter space


Period Distribution
All Initial
CE Initial
10^6
10^5
10^4
10^3
10^2
10^1
10^0
−4
−2
0
2
4
6
8
log_{10} Period (days)


Period Distribution
CE Final
All Final
10^6
10^5
10^4
10^3
10^2
10^1
10^0
−4
−2
0
2
4
6
8
log_{10} Period (days)


Period Distribution
All Initial
CE Initial
CE Final
All Final
10^6
10^5
10^4
10^3
10^2
10^1
10^0
−4
−2
0
2
4
6
8
log_{10} Period (days)


Final Mass v Period for CE systems
CE initial
CE final
Mass [$M_\odot$]
log_{10} Period [days]
140
120
100
80
60
40
20
0
−4
−3
−2
−1
0
1
2
3
4

Occurrence rate

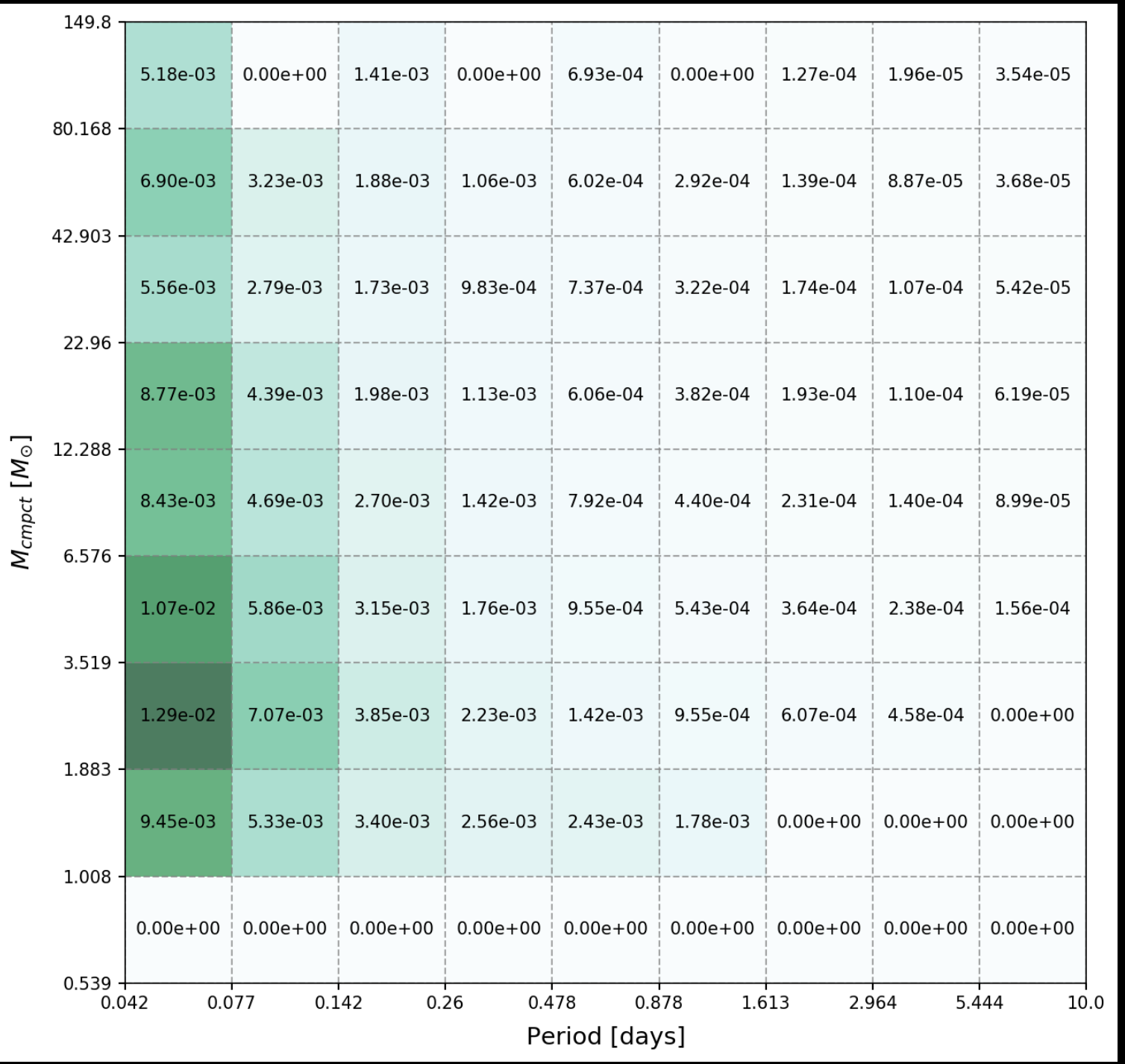
- We follow a procedure similar to Masuda & Hotokezaka (2019), using field binary model.
- For a given stellar companion of mass M_*, the distribution of a range of orbital period P, and black hole (or compact object) mass M_{BH}

$$p_{field}(P, M_{BH}|M_*) = \frac{C}{M_{BH}} \frac{H(M_{BH} - 5M_\odot) I_{BH} M_{BH}}{I(M_*)} \frac{1}{P}$$

- C is constant so that binary mass fraction: 0.5 (will be a free parameter)
- $I(M_*) \propto M_*^{-2.3}$

- Occurrence rate:

$$p_{CE}(P, M_{BH}|M_*) = \left| \frac{\partial(P_i, M_i)}{\partial(P_f, M_{BH})} \right| p_{field}(P_i, M_i|M_*)$$



Occurrence rates immediately after CE

Note:
This includes mergers

TESS and CE evolution

- We need a sufficiently large observational baseline to inform our theoretical models of binary formation and evolution.

- TESS is good for observing binaries:
  - Bright targets, all-sky, 2-min cadence, 10-min FFI.
  - TESS Eclipsing Binaries catalog (available online)

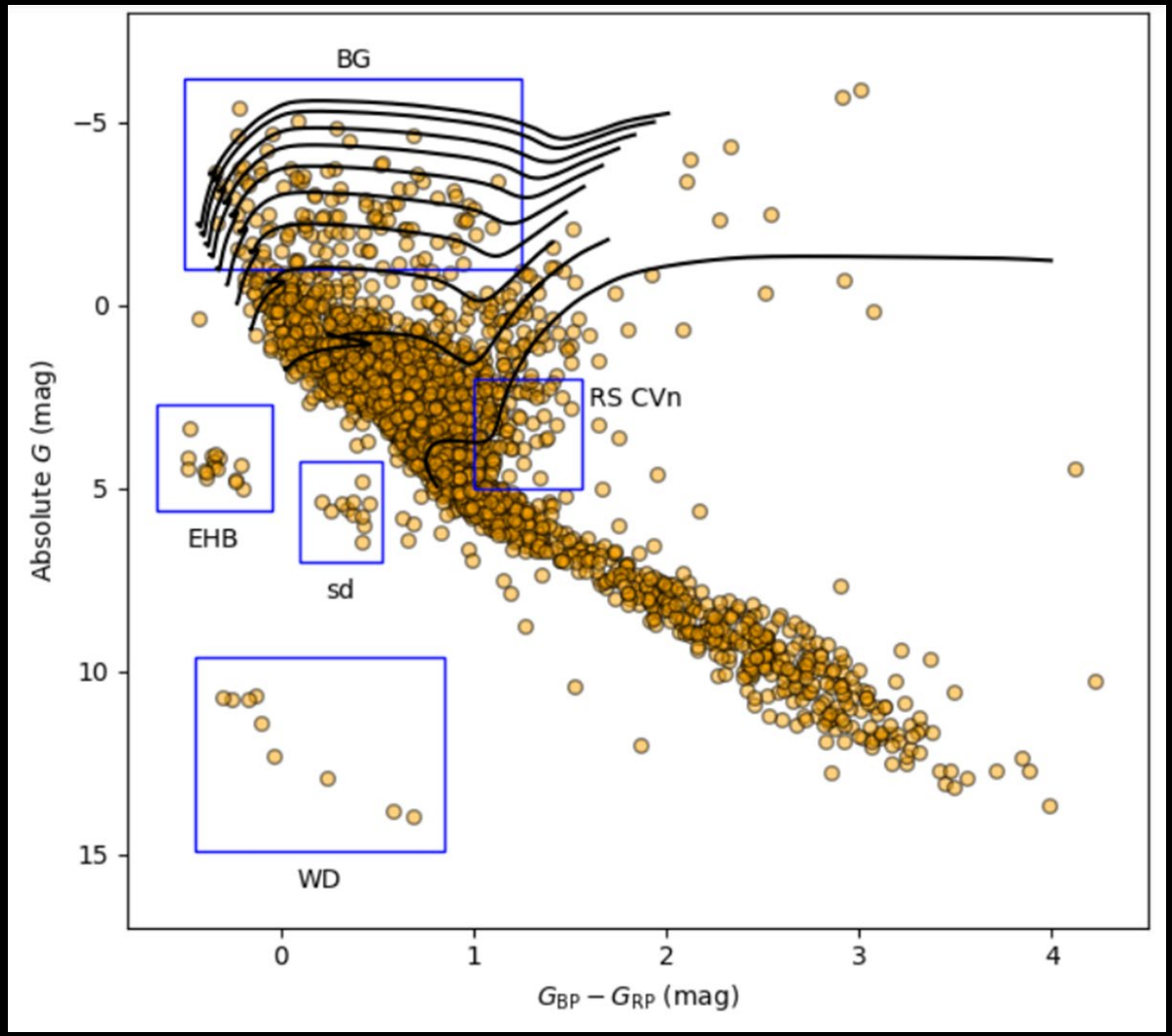


Fig. 20 (Prša et al. 2022)

Next steps in our project

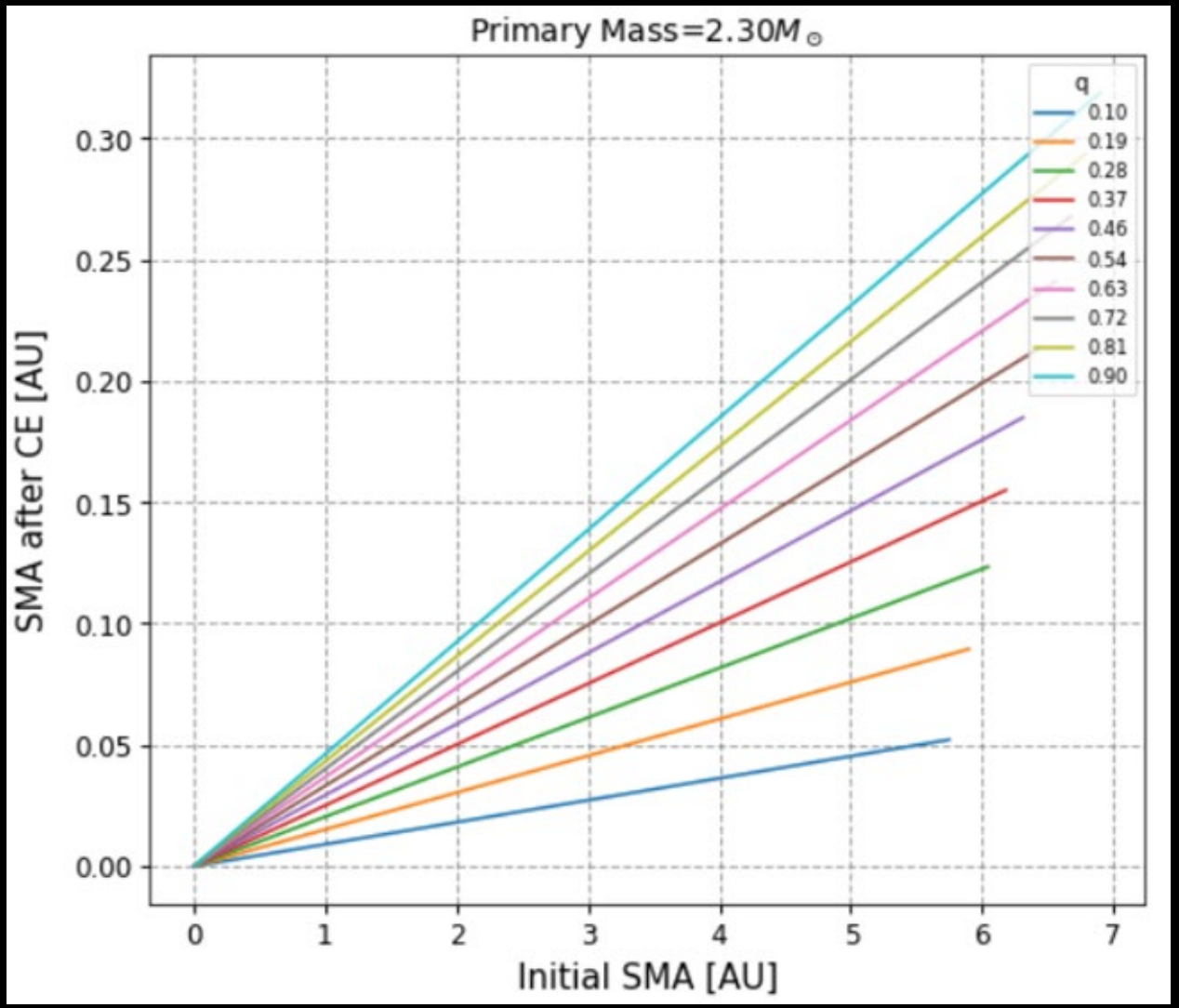
- MCMC analysis and explore free parameters space.
- Potentially use available data to help train/test our models.
- Run simulations (hydro+N-body) and compare to final observed state of binary systems.

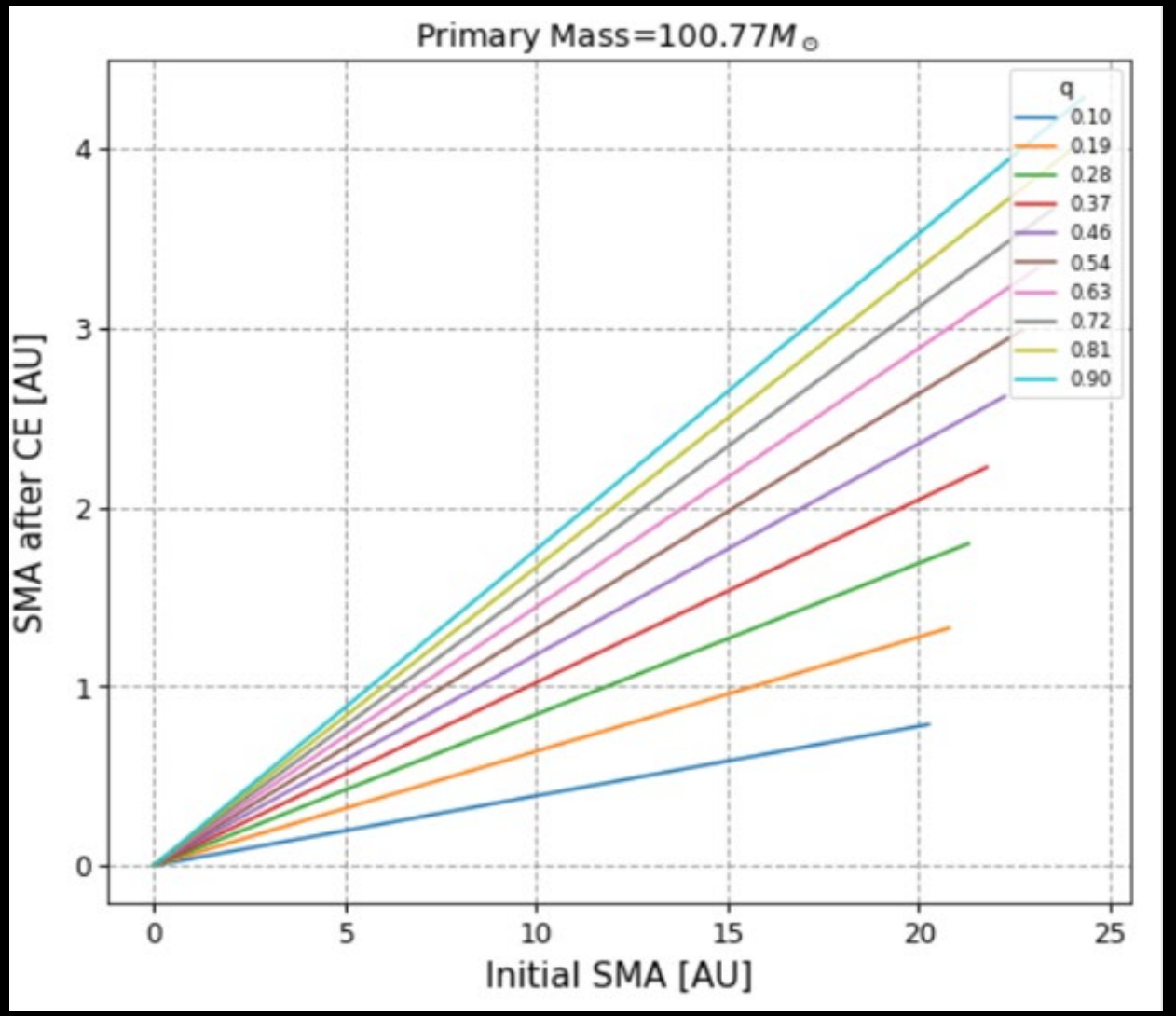
- Could be extended to the formation and evolution of other stellar objects and companions like brown dwarfs and exoplanets.

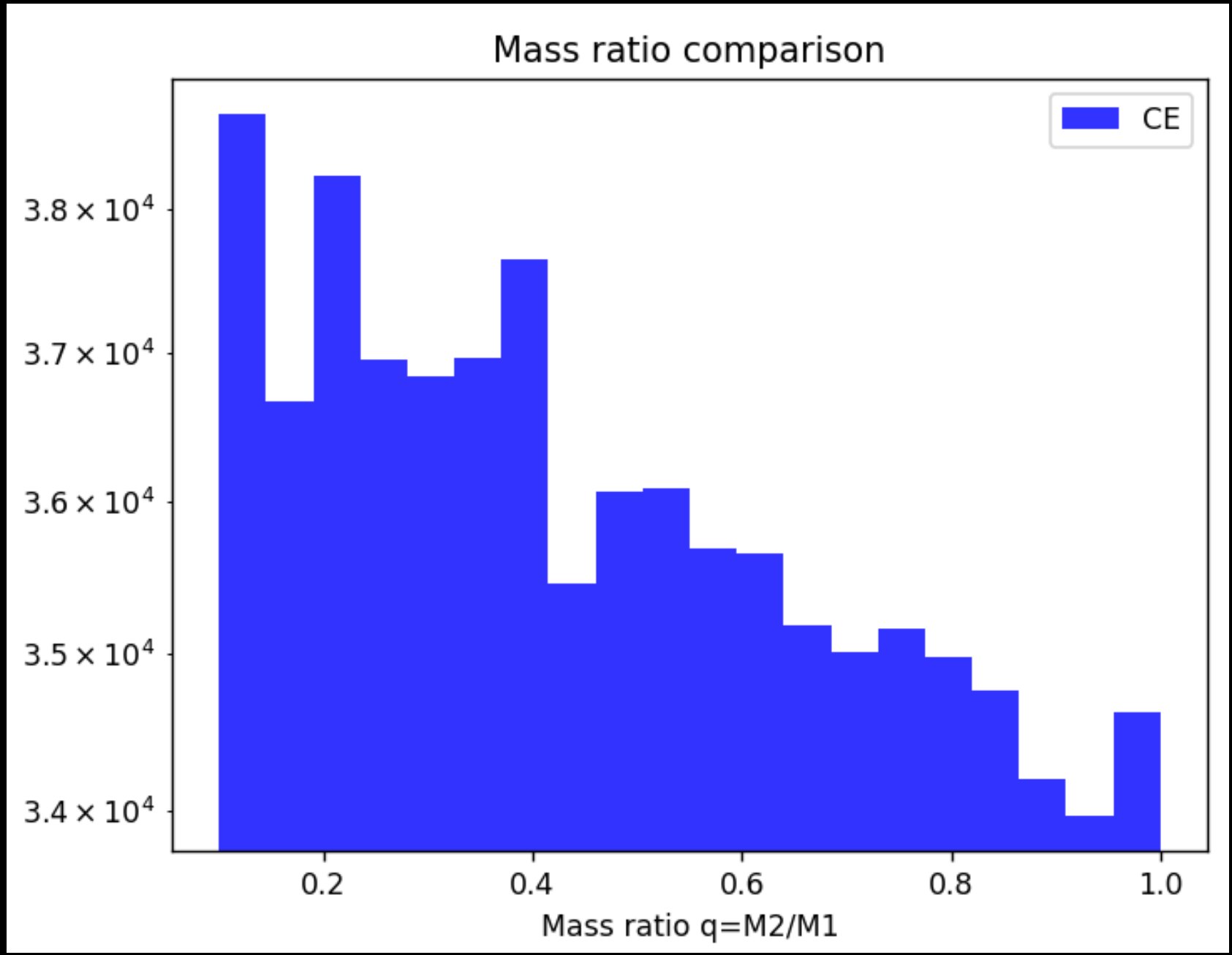
What do we need?

- Further observations of post-CE systems could shed light on the history of these binary and merger populations based on orbital morphology and spectroscopy for mass ratios.

- Moreover, time-domain observations of planetary nebulae and supernova remnants can help guide the existing theoretical models for ejected material during and after CE.


Primary Mass=2.30$M_\odot$
SMA after CE [AU]
Initial SMA [AU]
q
0.10
0.19
0.28
0.37
0.46
0.54
0.63
0.72
0.81
0.90
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0
1
2
3
4
5
6
7


Primary Mass=100.77$M_\odot$
SMA after CE [AU]
Initial SMA [AU]
q
0.10
0.19
0.28
0.37
0.46
0.54
0.63
0.72
0.81
0.90
0
1
2
3
4
0
5
10
15
20
25


Mass ratio comparison
CE
3.8×10^4
3.7×10^4
3.6×10^4
3.5×10^4
3.4×10^4
0.2
0.4
0.6
0.8
1.0
Mass ratio q=M2/M1