

Binary Pathways to Fast-Rotating Core-Collapse Supernova Progenitors

through Chemically Homogeneous Evolution and Common Envelope Tidal Spin-Up

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Why Fast-Rotating Core-Collapse Supernovae?

Why in Binary Systems?

Why Fast-Rotating Core-Collapse Supernovae?

- ◆ In recent years, gamma-ray bursts (GRBs) and fast radio bursts (FRBs) have become important topics in high-energy astrophysics, but their origins remain unclear.
- ◆ Magnetar is a possible source of FRBs (Bochenek et al., 2020) or GRBs (Metzger et al., 2011).
- ◆ Magnetar is one kind of fast-rotating neutron star with a powerful magnetic field.

Why Fast-Rotating Core-Collapse Supernovae?

Tracing the origin of FRBs and GRBs

Why in Binary Systems?

Why in Binary Systems?

- ◆ A magnetar may originate from a binary system. (Hu & Zhang 2026)
- ◆ In a binary system, the accretor star can increase its rotational speed through mass transfer, which also transfers angular momentum.
- ◆ The majority of massive stars reside in close binaries.

Chemically Homogeneous Evolution (CHE)

- ◆ Fast rotation drives efficient global mixing.
- ◆ Suppresses standard chemical stratification (no onion structure).
- ◆ Surface hydrogen and helium are depleted at the end of core helium burning.

Why in Binary Systems?

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Why Fast-Rotating Core-Collapse Supernovae?

Solving the Angular Momentum Crisis for Magnetars

Why in Binary Systems?

Spin-up via Binary Mass Transfer

Method

Method

- ◆ Using MESA (Modules for Experiments in Stellar Astrophysics) to simulate single stars and binary stars evolution. (Paxton et al. 2011, 2013, 2015, 2018, 2019; Jermyn et al. 2023)
- ◆ MESA is a 1D stellar evolution code
- ◆ Our simulation set up follow Renzo (2021) and Wang (2024).

Initial Configurations

Binary Systems

◆ Metallicity : $Z = 0.001$

◆ Donor Mass ($M_{d,0}$) : $25 - 65 M_{\odot}$

◆ Period (P_i) : $8 - 18$ days

◆ Mass ratio (q) : $0.5 - 0.8$

Single Stars

◆ Metallicity : $Z = 0.001$

◆ Star Mass : $10 - 50 M_{\odot}$

◆ Rotation : $0.1, 0.5 \omega_{\text{crit}}$

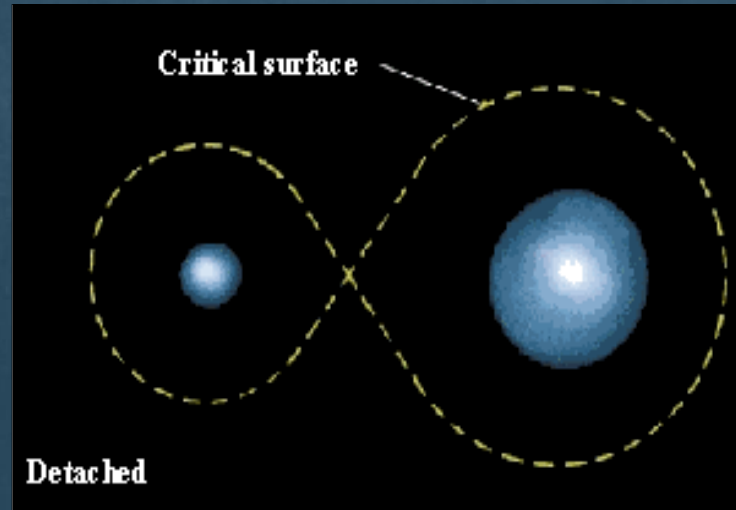
ω_{crit} is the critical rotation

Accretor Evolutionary Pathways

Binary Systems

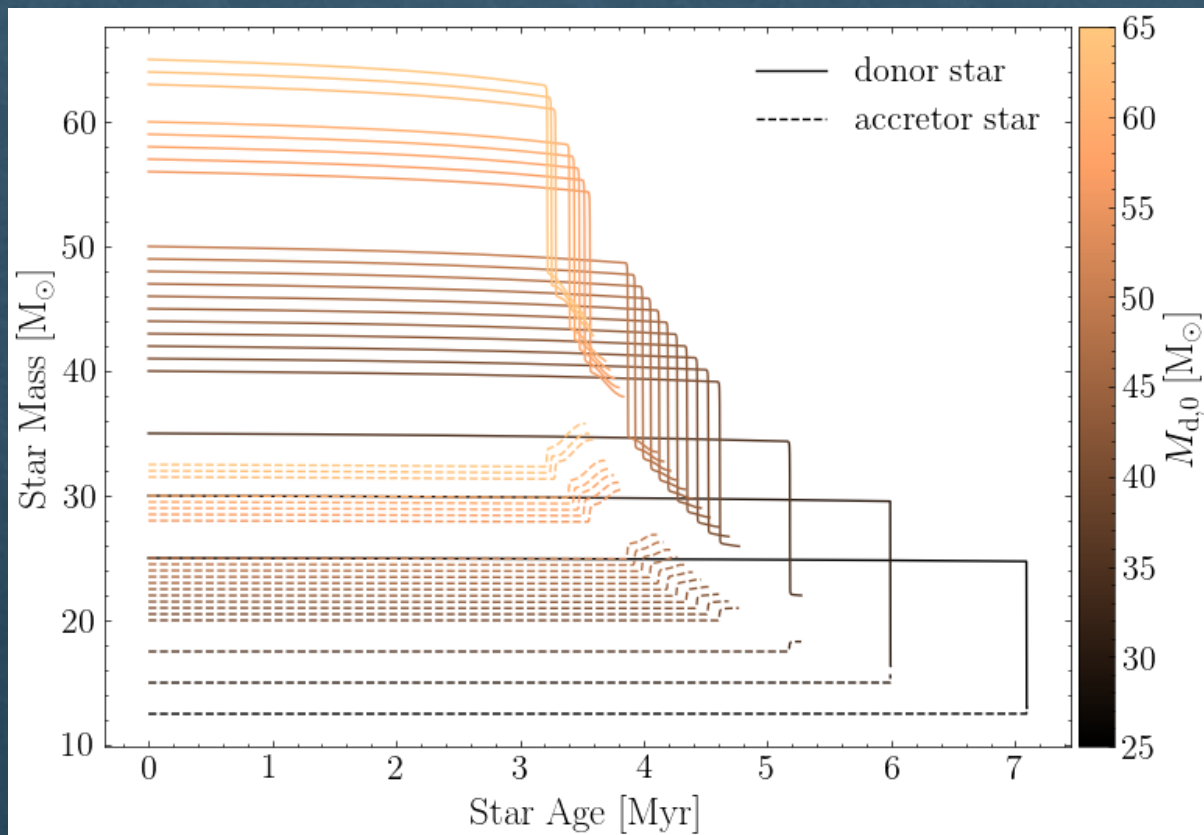


Evolve to Detachment



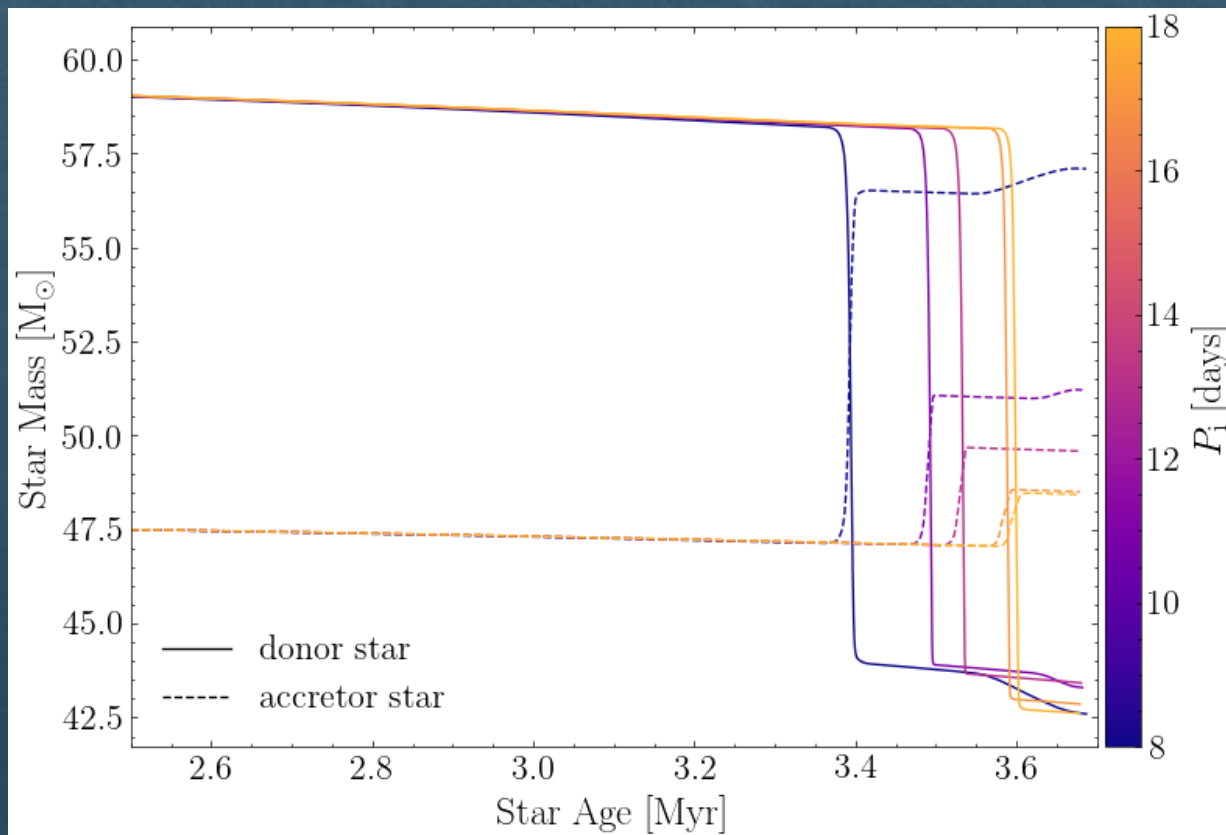
Binary Evolution to Detachment

Accretor Star Mass vs Star Age



$q = 0.5$ and $P_i = 8$ days

Accretor Star Mass vs Star Age



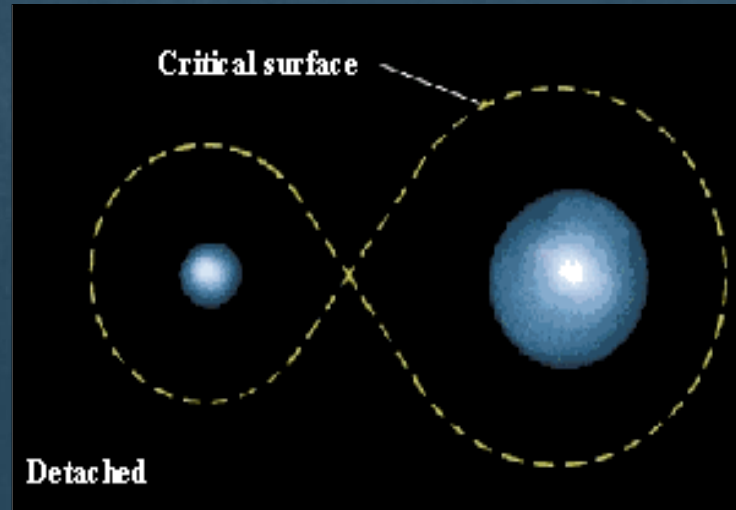
$q = 0.8$ and $M_{d,0} = 60 M_\odot$

Accretor Evolutionary Pathways

Binary Systems



Evolve to Detachment



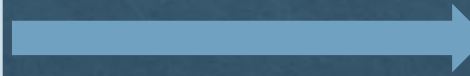
Accretor Evolutionary Pathways

Binary Systems

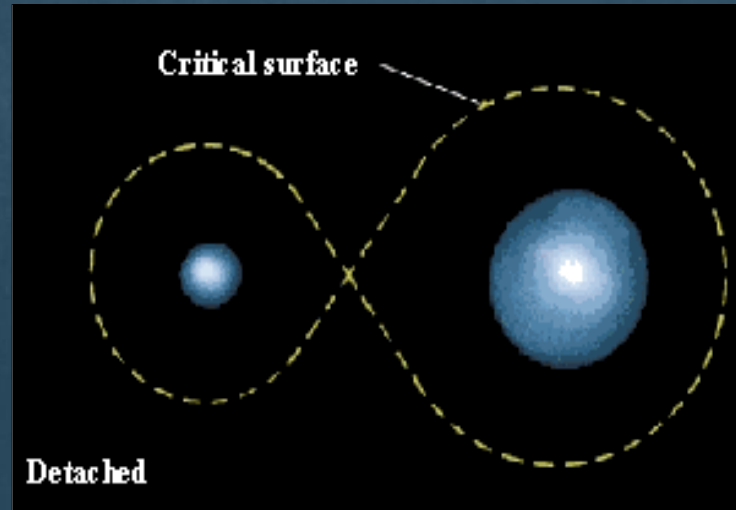


Evolve to Detachment

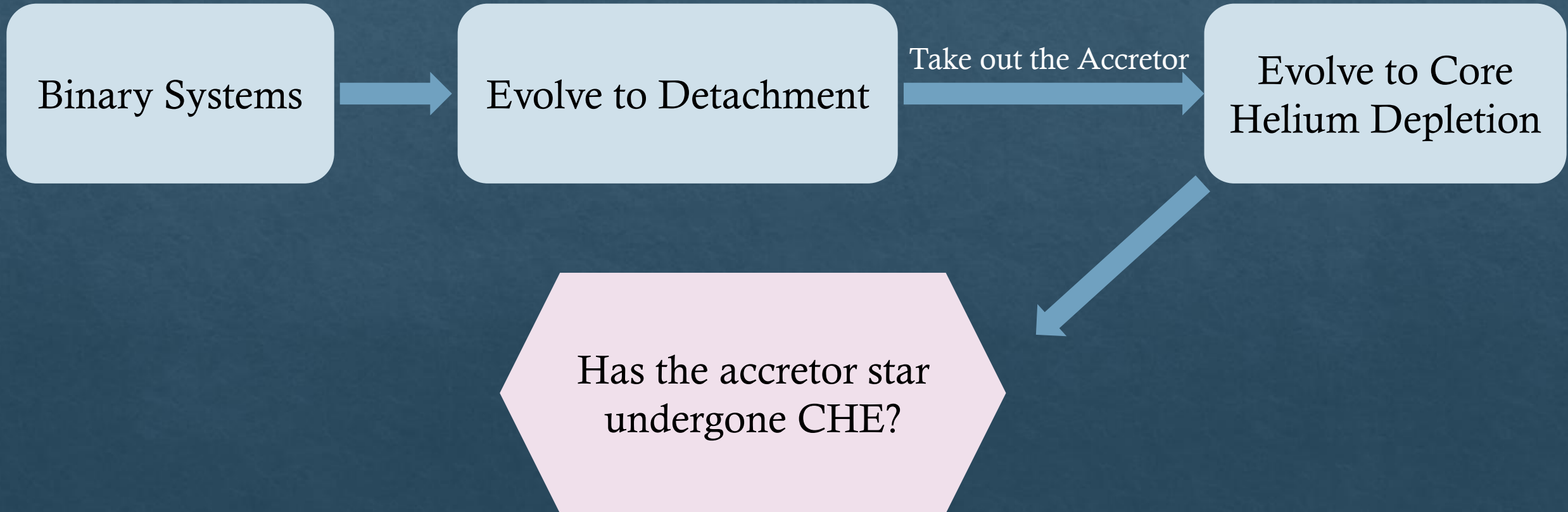
Take out the Accretor



Evolve to Core Helium Depletion

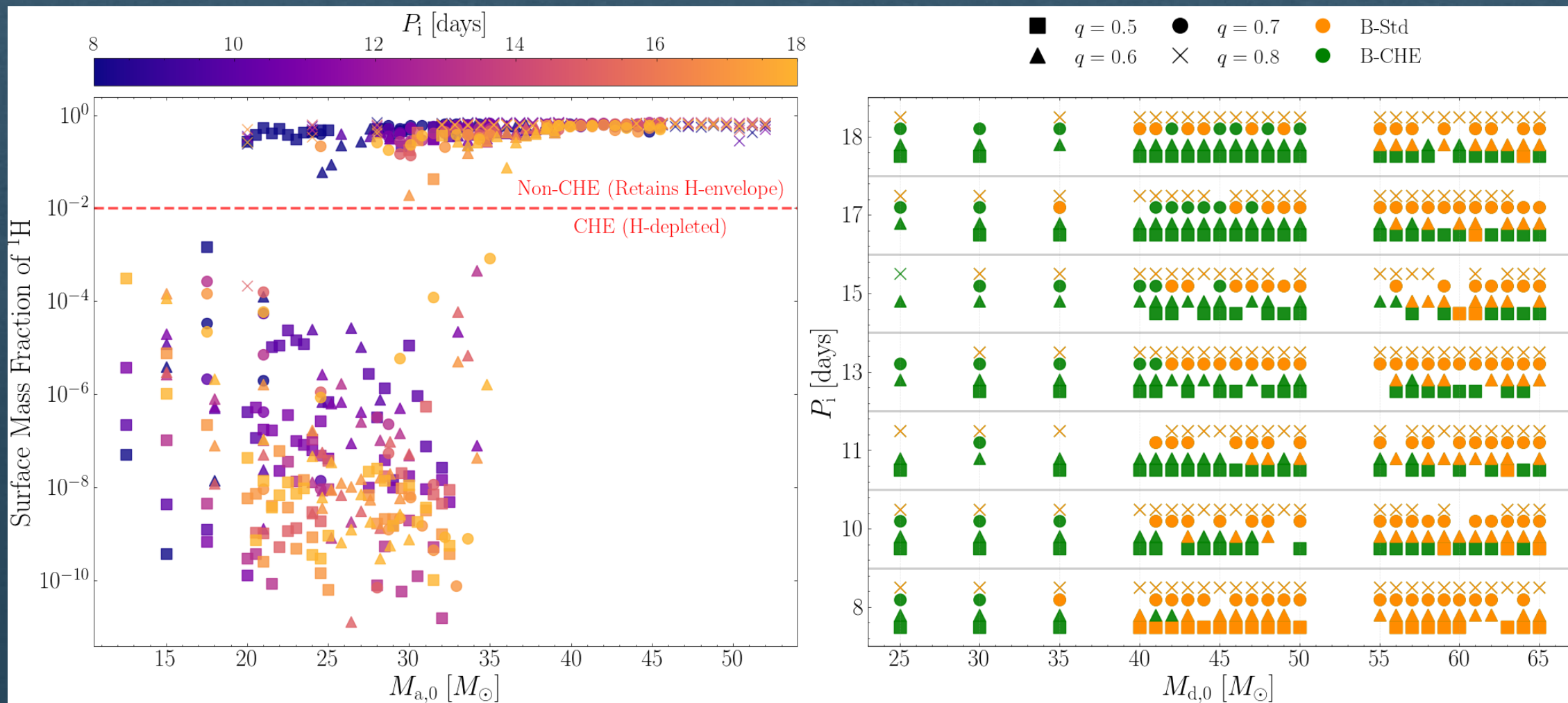


Accretor Evolutionary Pathways



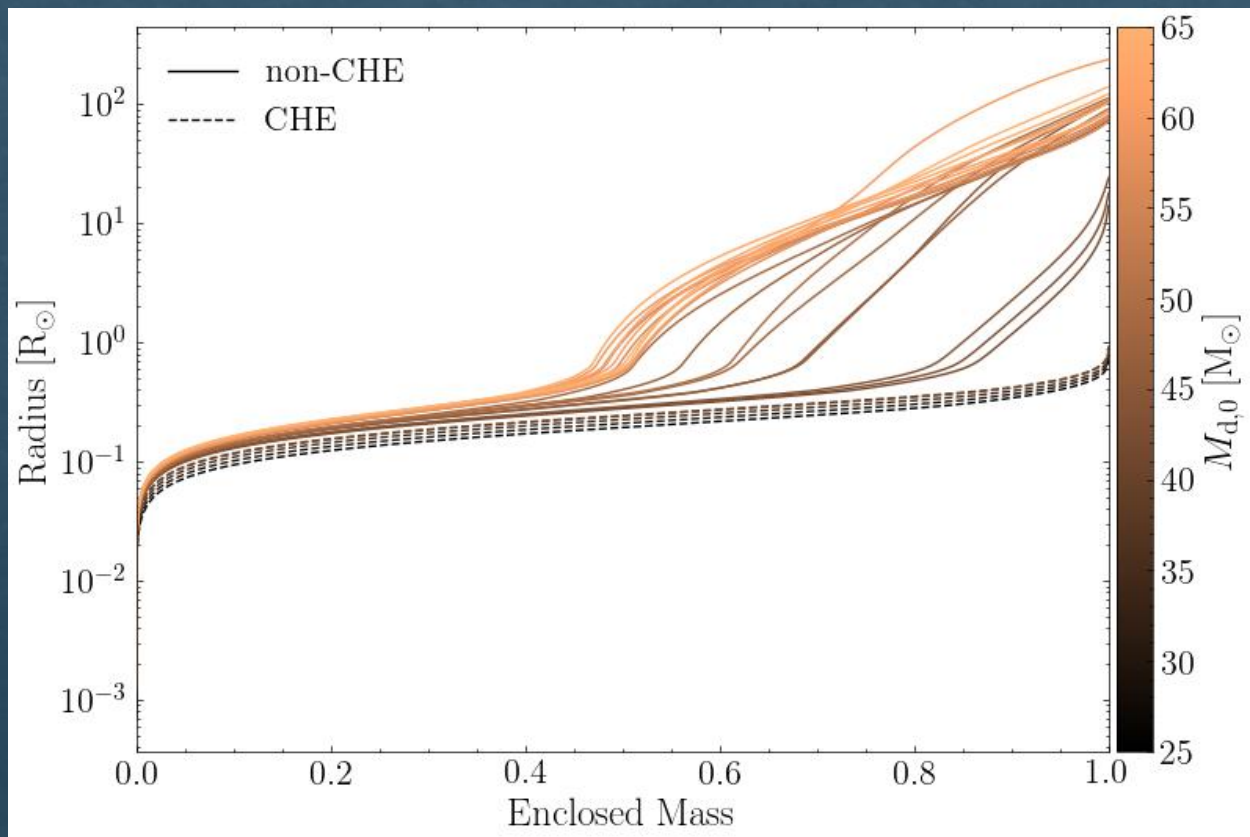
End of helium core burning

Triggering Chemically Homogeneous Evolution in Binaries



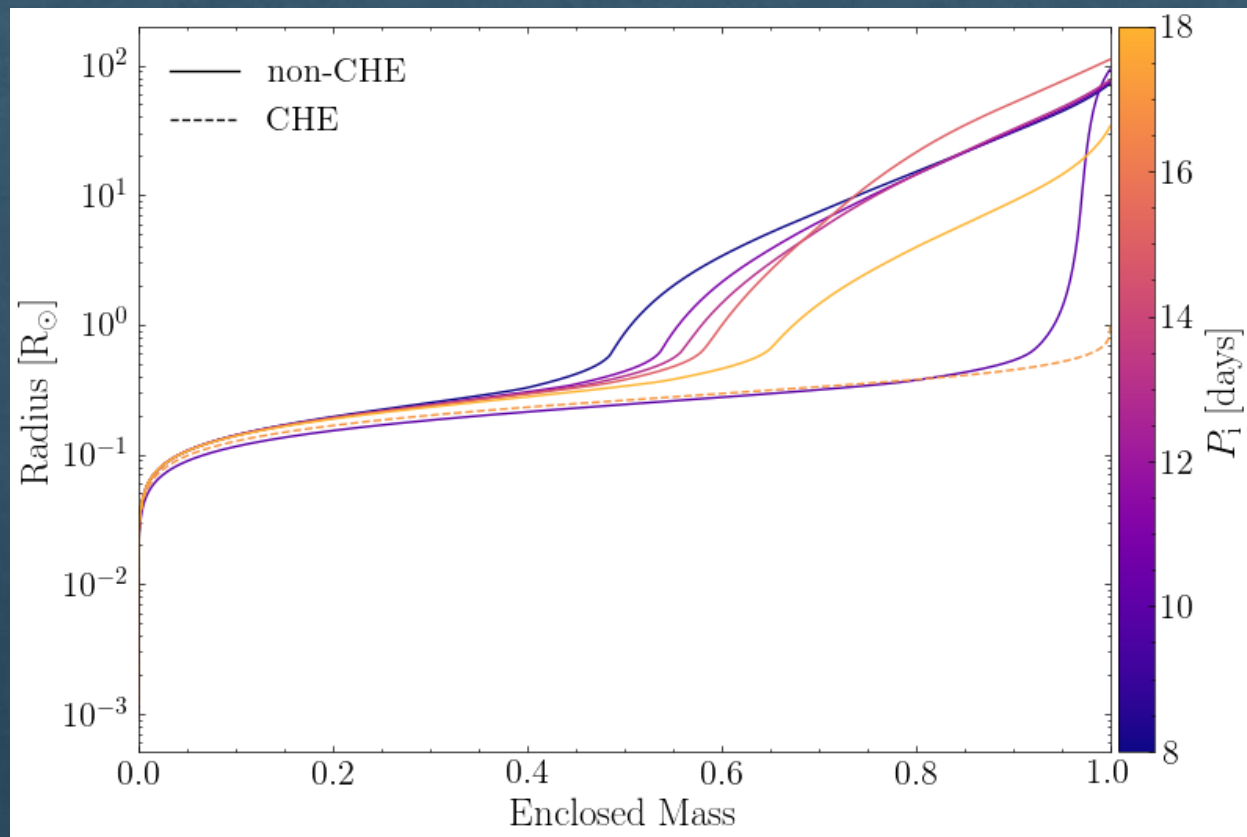
End of helium core burning

Accretor Star Radius



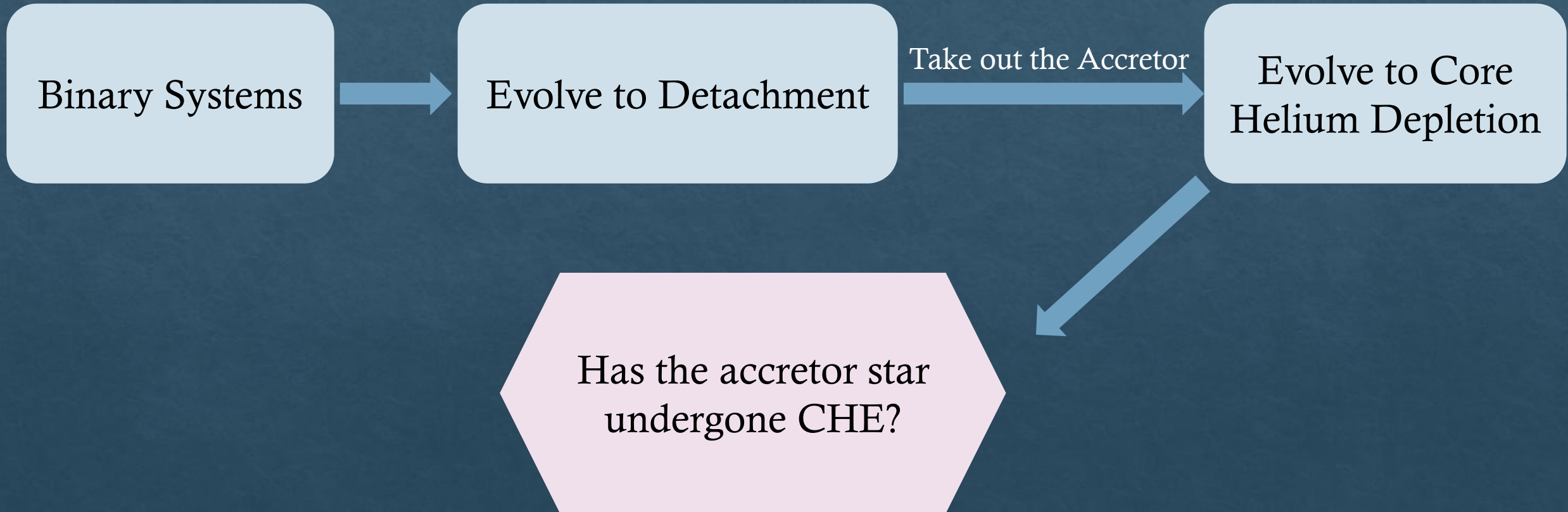
$q = 0.7$ and $P_i = 13$ days

Accretor Star Radius



$q = 0.7$ and $M_{d,0} = 47M_{\odot}$

Accretor Evolutionary Pathways

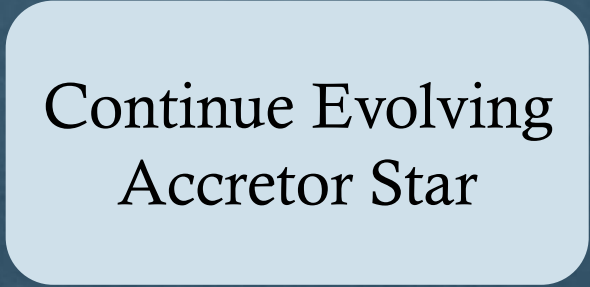


Accretor Evolutionary Pathways

Has the accretor star
undergone CHE?

Yes

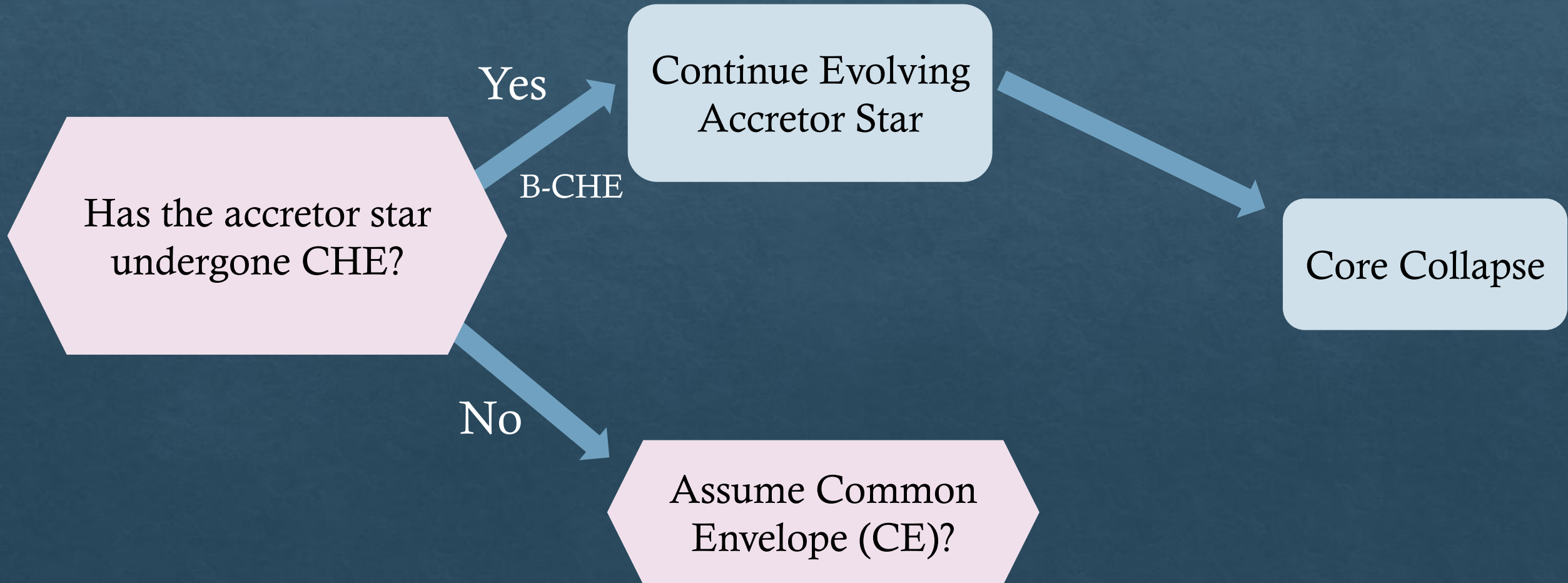
Continue Evolving
Accretor Star



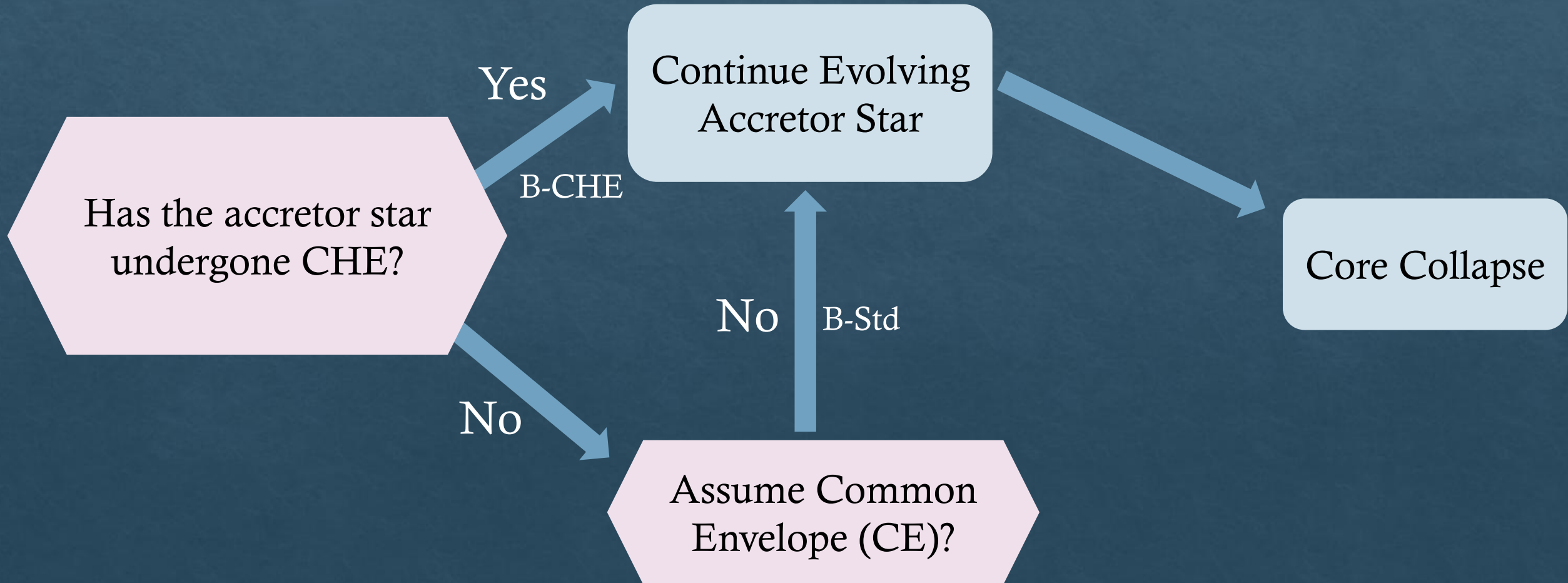
Accretor Evolutionary Pathways



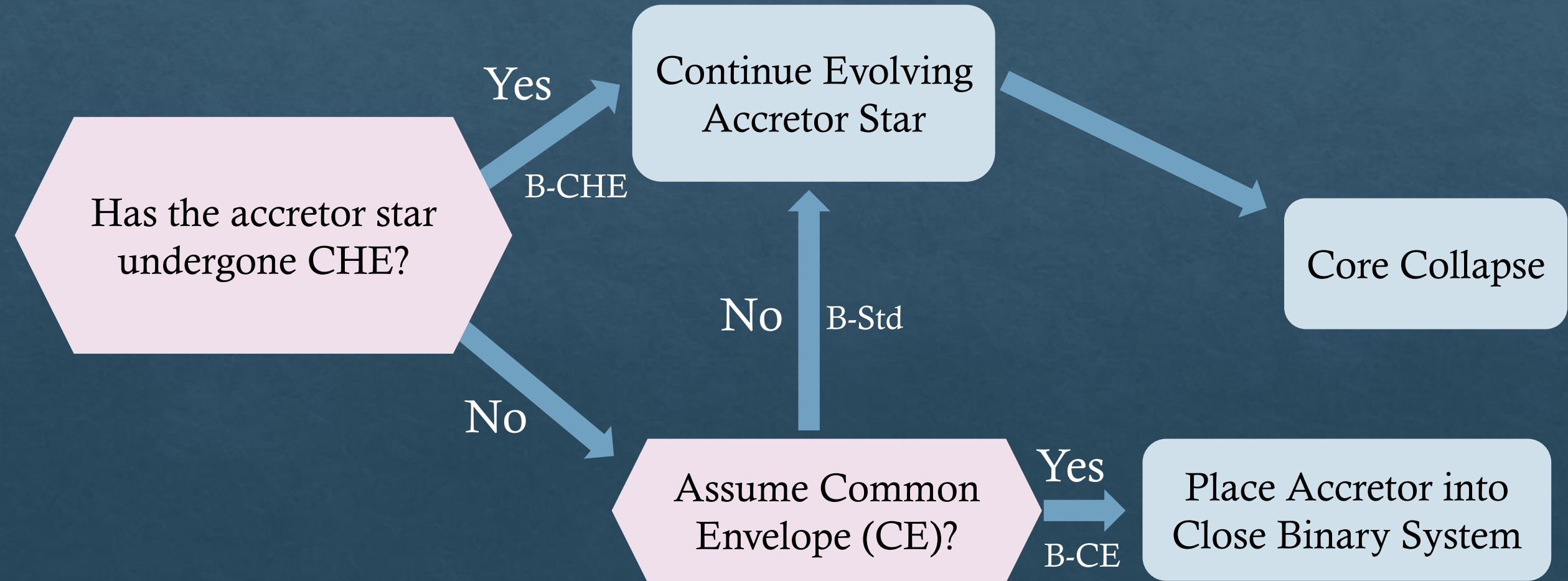
Accretor Evolutionary Pathways



Accretor Evolutionary Pathways



Accretor Evolutionary Pathways



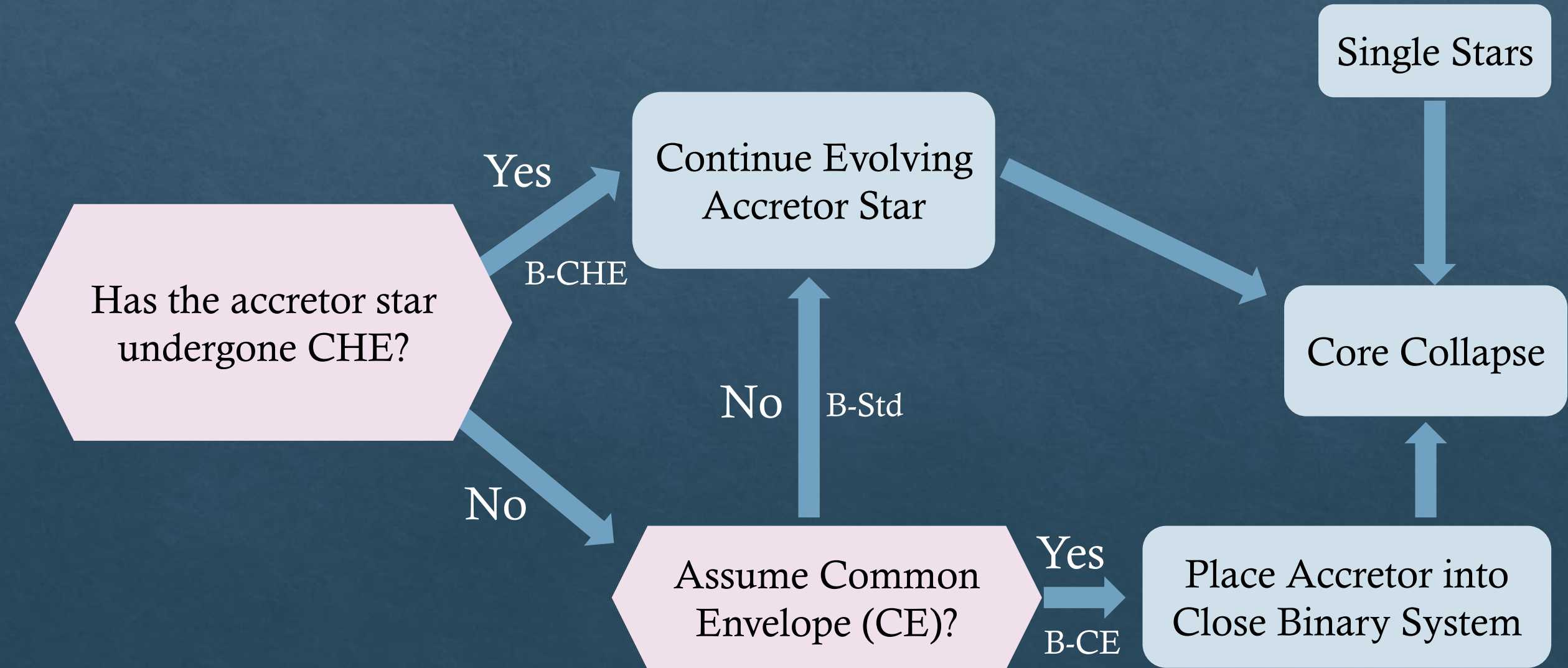
Accretor Evolutionary Pathways

Close Binary Systems

- ◆ Period (P_{CE}) : 0.3, 0.4, 0.5 & 1 days
- ◆ Companion Mass (M_c) : $3 - 5M_{\odot}$
- ◆ B-CE-P0.3d-M3 indicates $P_{\text{CE}} = 0.3$ days
and $M_c = 3M_{\odot}$

Place Accretor into
Close Binary System

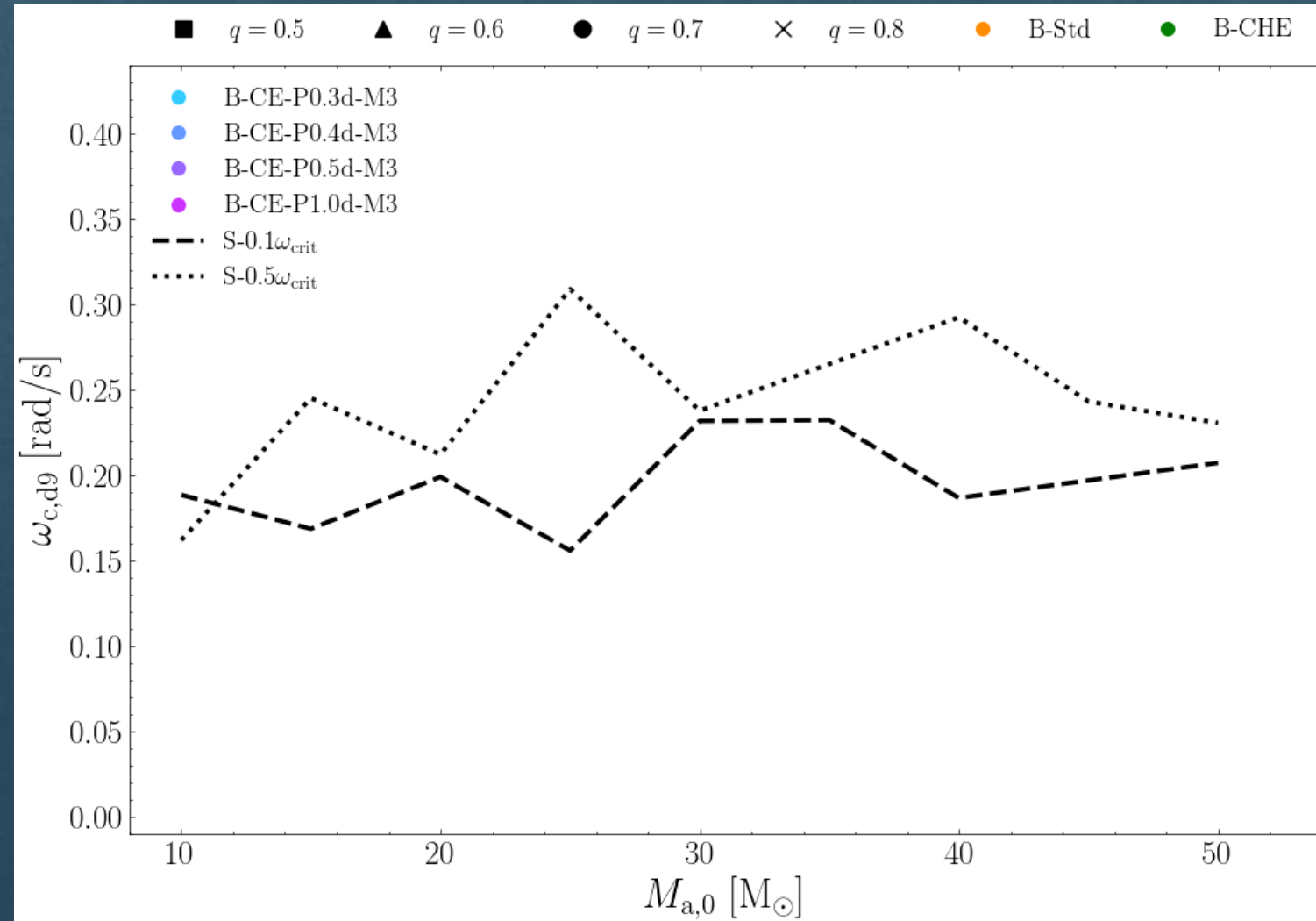
Accretor Evolutionary Pathways



Result and Discussion

Around Core Collapse

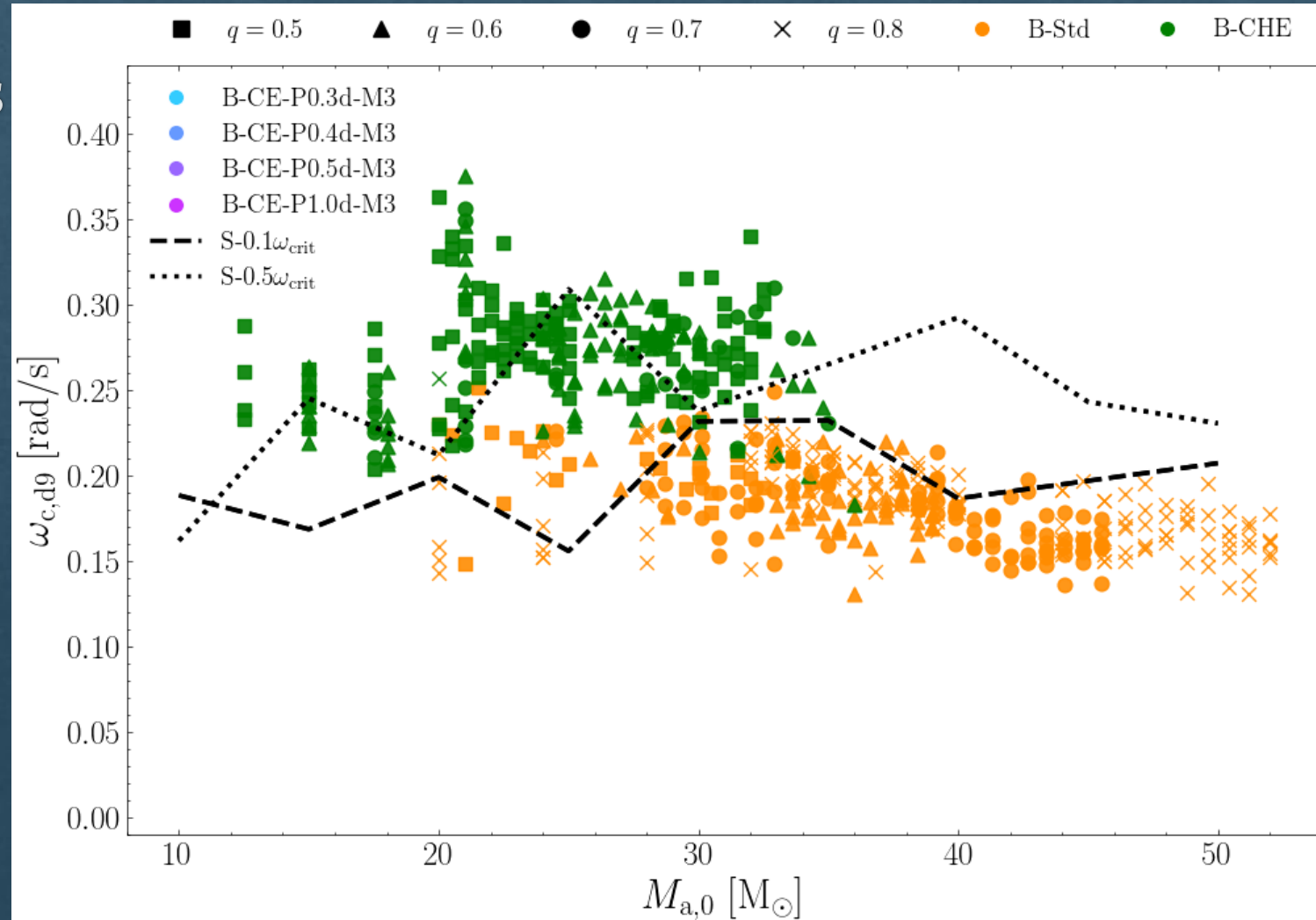
Central Angular Velocity at Central Density of 10^9 g/cm^3



Around Core Collapse

◇ B-CHE vs B-Std: B-CHE has faster core rotation.

Central Angular Velocity at Central Density of 10^9 g/cm^3

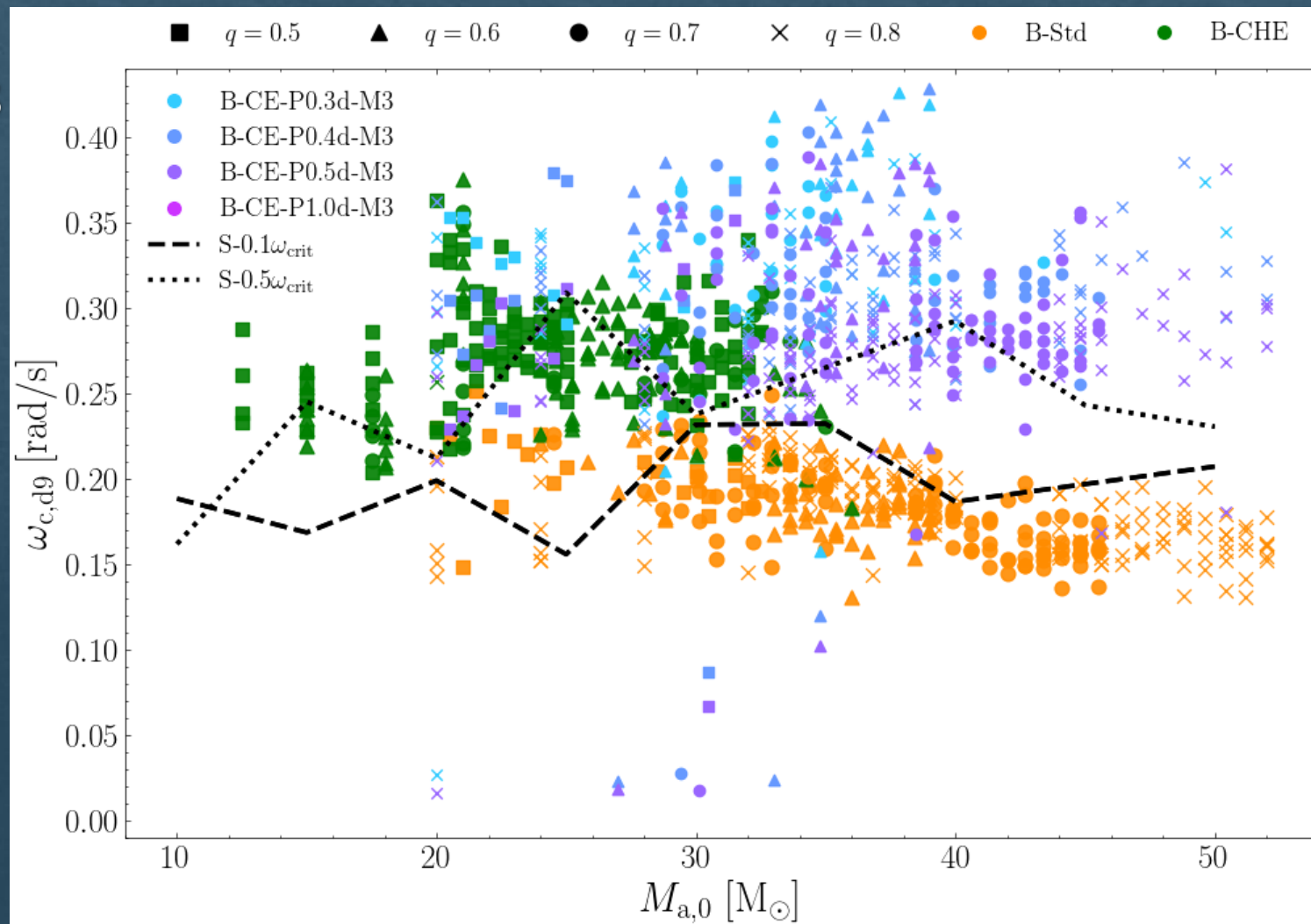


Around Core Collapse

◇ **B-CHE vs B-Std:** B-CHE has faster core rotation.

◇ $P_{\text{CE}} < 0.5$ d: Core spun up (Faster than B-CHE & single stars).

Central Angular Velocity at Central Density of 10^9 g/cm^3



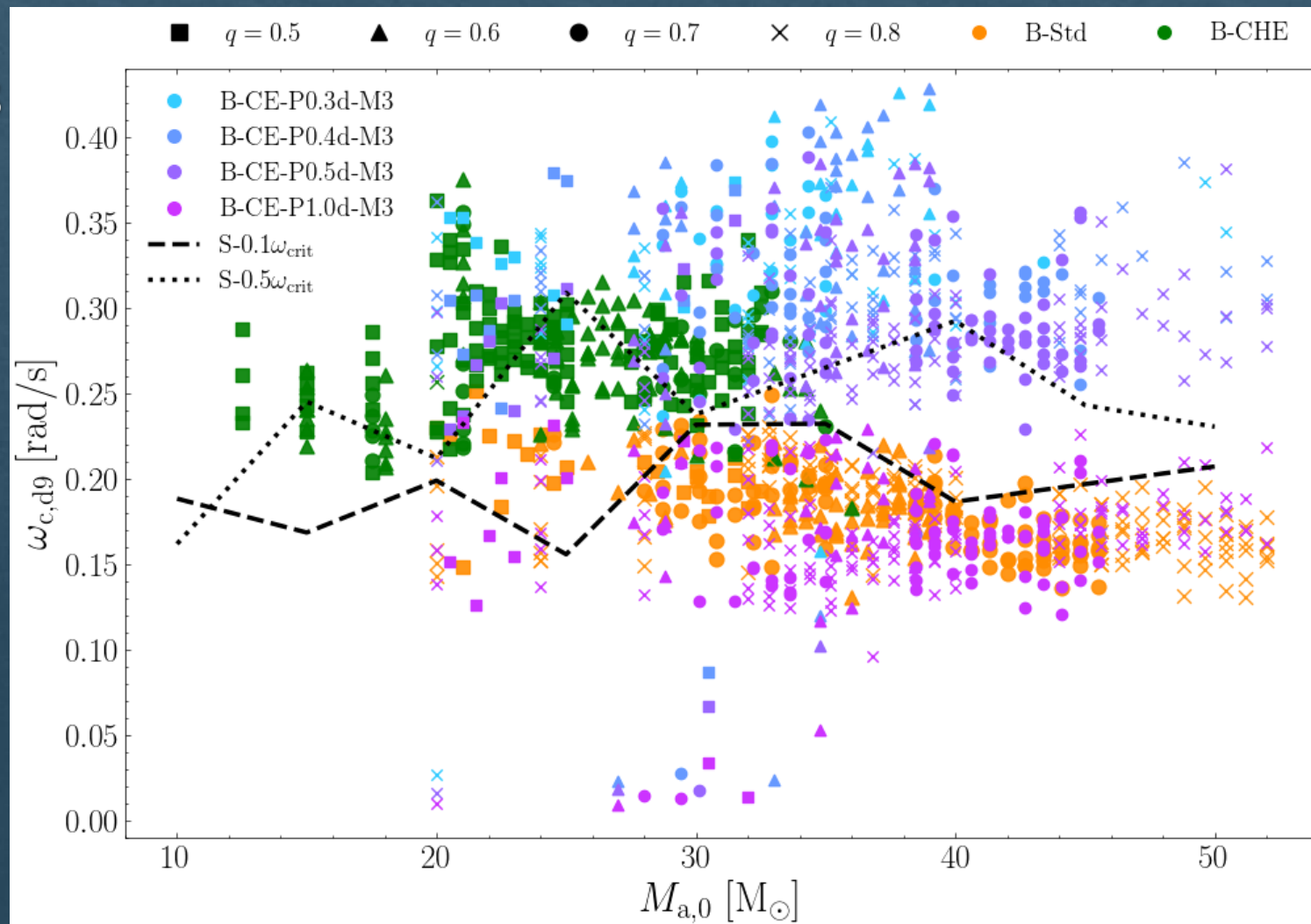
Around Core Collapse

◇ **B-CHE vs B-Std**: B-CHE has faster core rotation.

◇ $P_{\text{CE}} < 0.5 \text{ d}$: Core spun up (Faster than B-CHE & single stars).

◇ $P_{\text{CE}} = 1 \text{ d}$: No core spin-up.

Central Angular Velocity at Central Density of 10^9 g/cm^3



Around Core Collapse

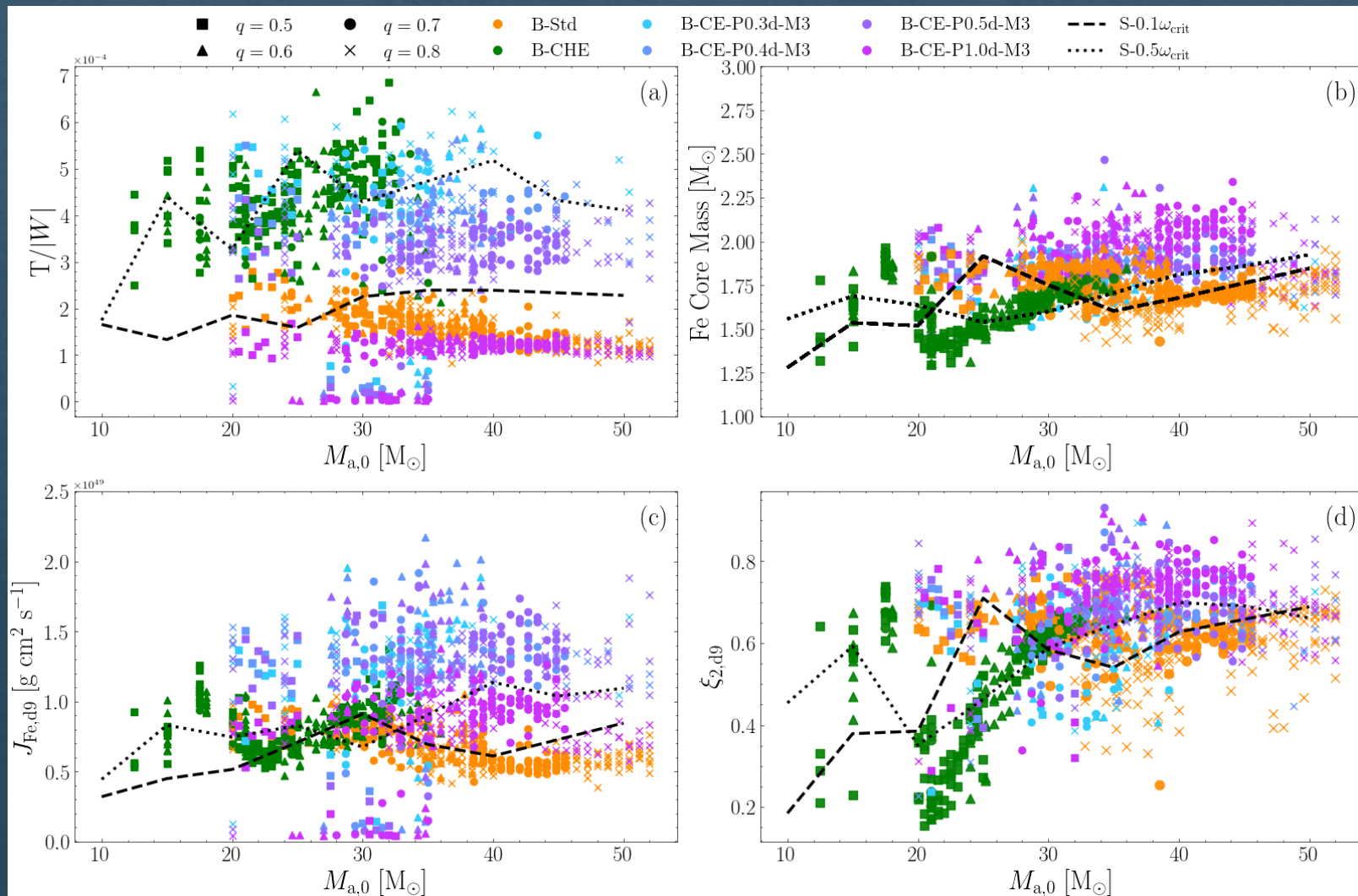
(a) Ratio of rotational kinetic to gravitational potential energy. ($T/|W|$)

(b) Iron core mass.

(c) Angular momentum of the iron core. ($J_{\text{Fe,d9}}$)

(d) Compactness parameter for $2M_{\odot}$ enclosed mass.

$$\xi_M = \frac{M/M_{\odot}}{R(M)/1000\text{km}}$$



Summary

Summary

- ◇ Mass transfer drives two pathways:
 - ◇ **B-CHE**: Surface is H-depleted at the end of He-core burning.
 - ◇ **Non-CHE (B-Std & B-CE)**: Retains surface Hydrogen.
- ◇ B-CHE has higher $\omega_{c,d9}$ and $T/|W|$ than B-Std.
- ◇ Post-CE Tidal Spin-up: Tight orbits ($P_{CE} < 0.5\text{days}$) further spin up the core. $\omega_{c,d9}$ and $J_{Fe,d9}$ become larger than those of single stars and B-CHE.

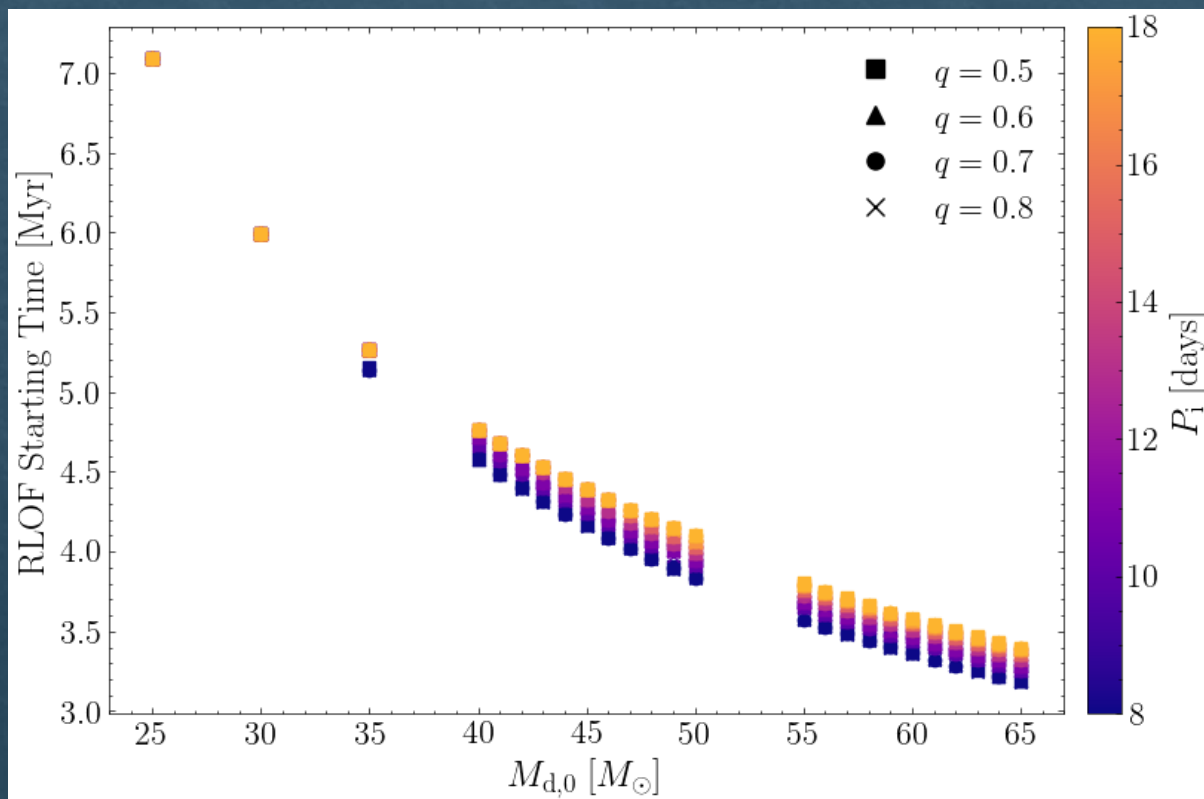
Reference

- ◇ Bochenek et al. (2020), *Nature*, 587, 59
- ◇ Duncan & Thompson (1992), *ApJ*, 392, L9
- ◇ Heger et al. (2000), *ApJ*, 528, 368
- ◇ Paxton et al. (2011-2019), *ApJS*
- ◇ Renzo & Götberg (2021), *ApJ*, 923, 277
- ◇ Sana et al. (2012), *Science*, 337, 444
- ◇ Spruit (2002), *A&A*, 381, 923
- ◇ Metzger et al. (2011), *MNRAS*, 413, 2031
- ◇ Wang & Pan (2024), *ApJ*, 964, 23
- ◇ Hu & Zhang (2026), *ApJ*, 999, 102

The simulations and data analysis were conducted on the CICA Cluster at National Tsing Hua University

Detachment Stage

RLOF Starting Time



Accreted Mass Fraction of $M_{a,0}$

