Binary formation channels of stripped-envelope supernovae

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MoCA
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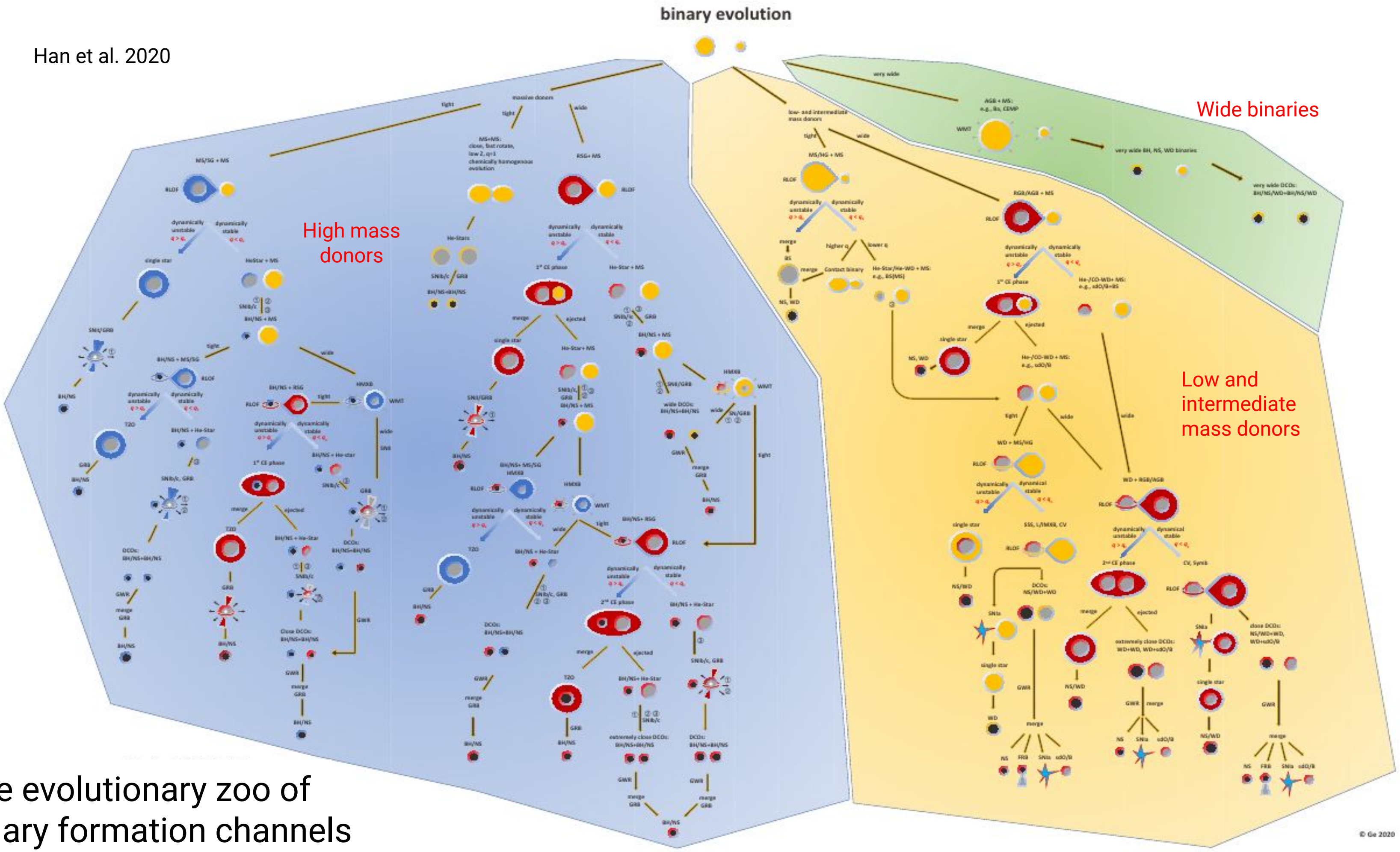
COMPAS

CENTER FOR ASTROPHYSICS
HARVARD & SMITHSONIAN

What are binary formation channels?

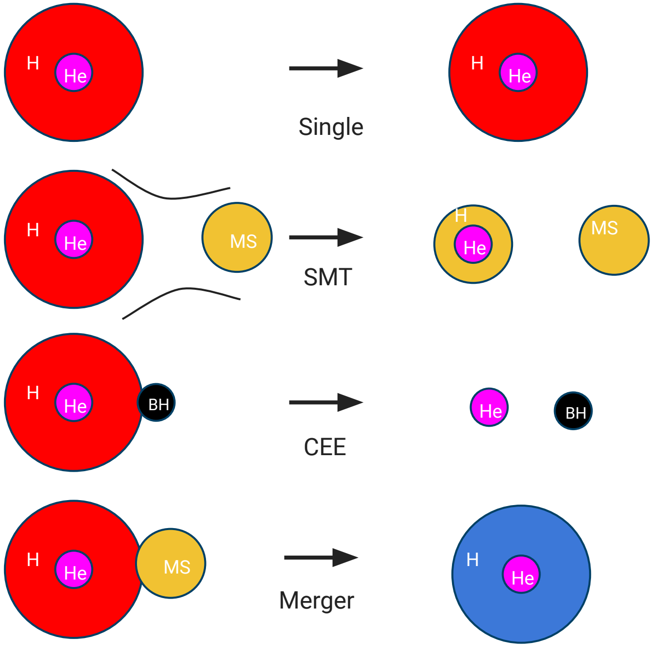
Han et al. 2020



The evolutionary zoo of binary formation channels

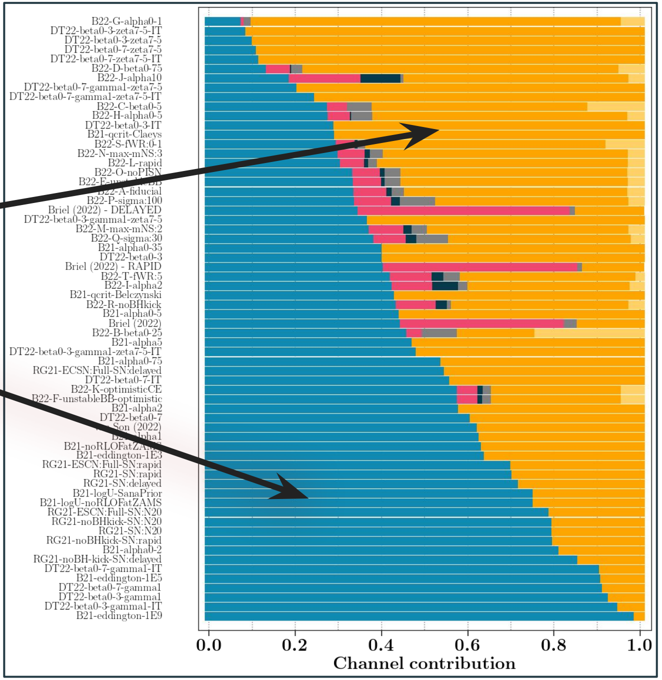
Focus on very broad formation channels

- Single (also, effectively single, wide binaries)
- Stable Mass Transfer (SMT)
  - Mass transfer proceeds in smooth, stable manner
  - Orbital evolution is predictable
  - **Leaves small envelope**
- Common Envelope Evolution (CEE)
  - Rapid spiral in on dynamical timescale
  - Requires 3D hydro - still unsolved problem
  - **Removes entire envelope**
- Stellar merger
  - “Failed” Common Envelope
  - Also requires 3D hydro



Connection to GWs

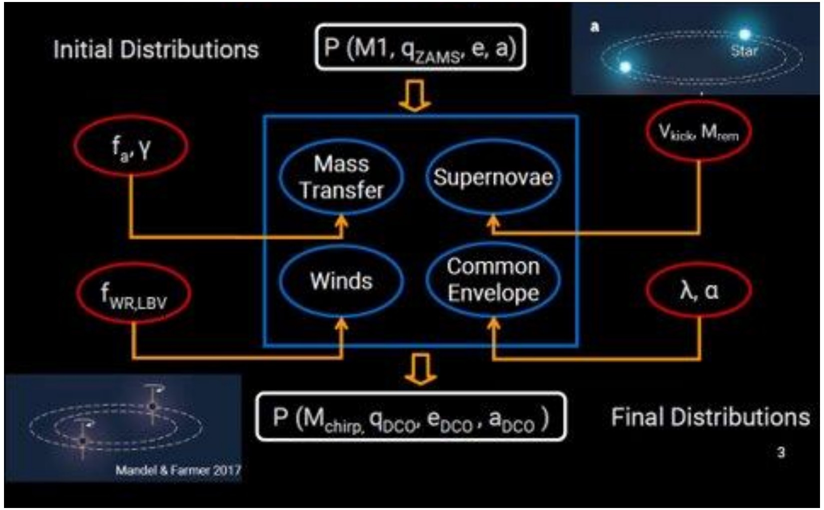
- How do GW progenitors evolve?
  - Some studies say mostly SMT
  - Others say mostly CEE
- The solution requires an **improved understanding of mass transfer stability**
- Difficult modelling problem
  - Compact binaries are a rare outcome
  - Detailed simulations (MESA) are slow



Formation channel ratios for BBHs, according to population synthesis studies.
Broekgaarden et al. (in prep)

Population synthesis

open source: https://github.com/TeamCOMPAS/COMPAS



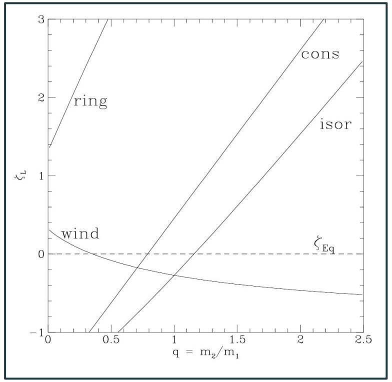
Use many simple parameters and prescriptions to do rapid evolution
A. Vigna-Gomez

- Approximate evolution tracks with polynomials
- Physics is treated with **simple, modular prescriptions**
- ~0.1s / binary !
  - ~few hours for MESA
- Useful for:
  - Rare events (BBHs)
  - Quickly testing new models
- Caveat: low detail, cannot update tracks

What determines if a binary experiences stable or unstable mass transfer?

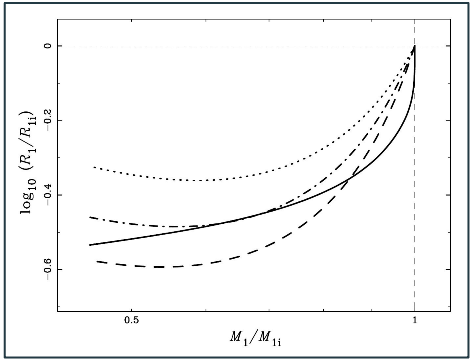
Instability boundary

- Old method (Soberman et al. 1997):
  - Compares the donor's initial radial response to mass loss to the change in Roche lobe
  - **Allows variable accretion efficiency and angular momentum (AM) loss**
  - Stellar response is over-simplified



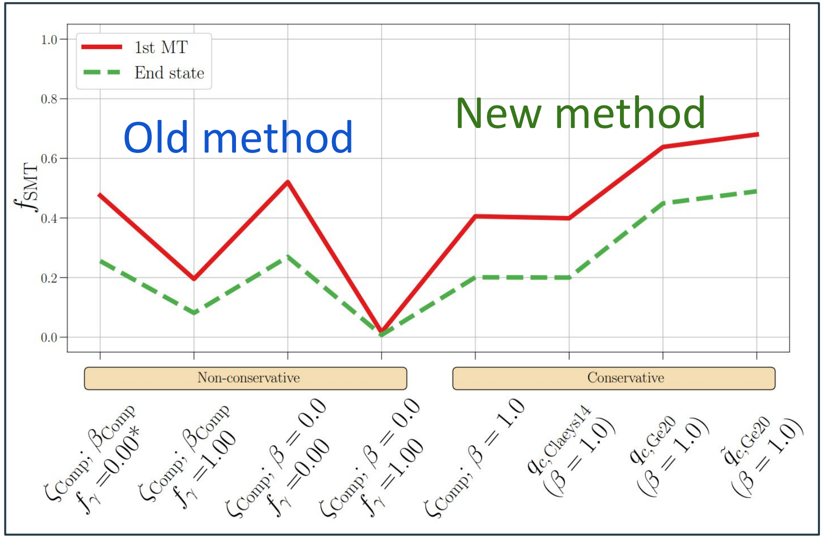
Roche-lobe response, varying efficiency and AM loss
Soberman et al. 1997

- New method (Ge et al. 2010, 2015, 2020):
  - Uses detailed models to allow for *delayed dynamical instability*
  - Better represents stellar structure
  - **Requires that mass transfer is fully conservative - no AM loss** 🚩



Donor response (solid), vs Roche-lobe response (dotted/dashed)
Ge et al. 2010

Evolutionary outcomes

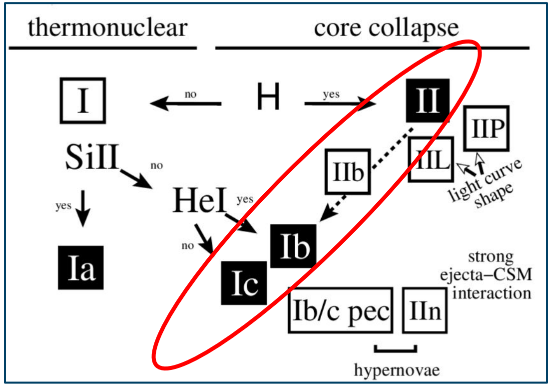


Fraction of systems that experience only stable mass transfer (f_{SMT})
RW et al. (2023)

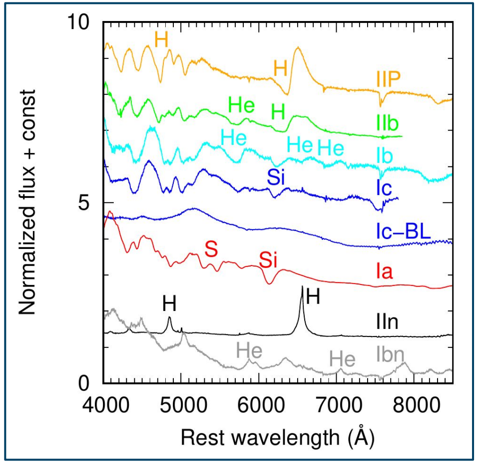
- The Stable Mass Transfer fraction (f_{SMT})
  - Compare 1st interaction (red) to end of simulation (green)
  - Depends on mass transfer stability models (x-axis) - the boundary between SMT and CEE
- Old method: simple response, **flexible AM loss**
- New method: detailed response, but **no AM loss**
- Takeaway:
  - New method ignores AM losses to simplify computation, but this parameter is critical for determining f_{SMT}
  - **2 steps forward, 1 step back**

Can we apply observational constraints?

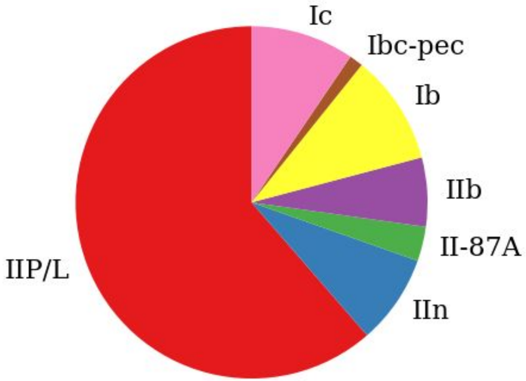
Yes! Core-collapse supernovae



SN type classification
Bersten et al. (2013)



Prototypical spectra.
Maeda et al. (2022)

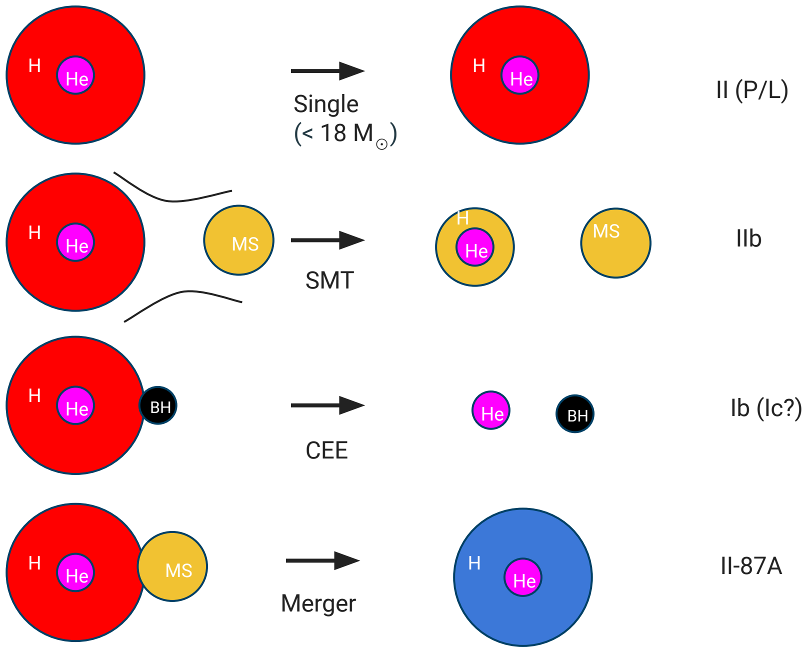


Intrinsic observational rates ≲100 Mpc.
RW & Hirai (in prep)
(adapted from Aleo et al. (2023))

Connecting branching ratios to SN types

- Single stars (< 18 $M_\odot$) retain H-envelopes ➪ SN II (P/L)
  - higher mass = more winds
- SMT likely leaves a thin H-envelope ➪ SN IIb
- CEE should remove the entire envelope ➪ SN Ib
- Mergers should be H-rich, or similar to 1987A (unusual, blue supergiant progenitor)

Warning: *very* speculative



Relative fractions of all supernova types

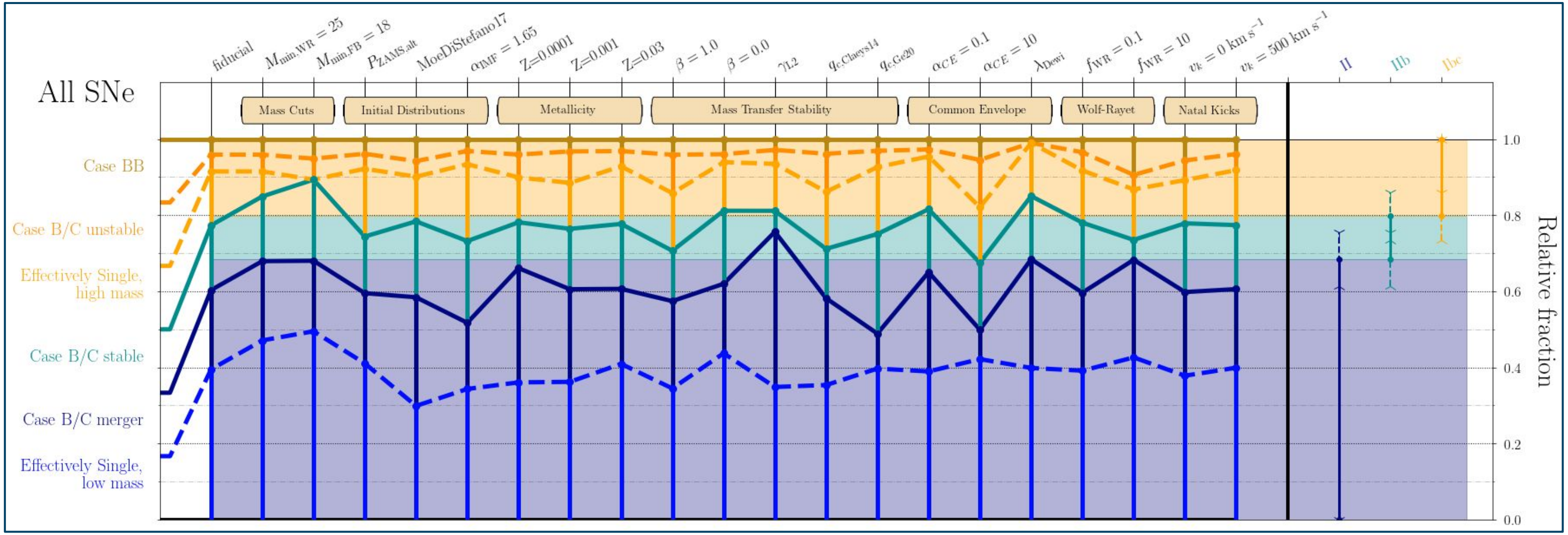
Common population synthesis variations

Observations

H-absent

H-low

H-rich



Takeaway 1: none of the models are *terrible*

Compare branching ratios: H-rich - H-low - H-absent

RW & Hirai (in prep)

Takeaway 2: mergers with an evolved star are ubiquitous

Conclusions

- Binary population synthesis **roughly reproduces** observed SESN branching ratios
  - Despite notoriously many uncertainties and variations
- Stellar mergers compose a large fraction of “single” SN progenitors
  - Does this pollution bias single star models?
- Direct 1:1 mapping between channels and SN types likely doesn’t exist
  - **Stripped stars likely continue self-stripping**
- Next steps: construct a mass transfer model that includes detailed stellar structure and AM loss
  - Implement in population synthesis

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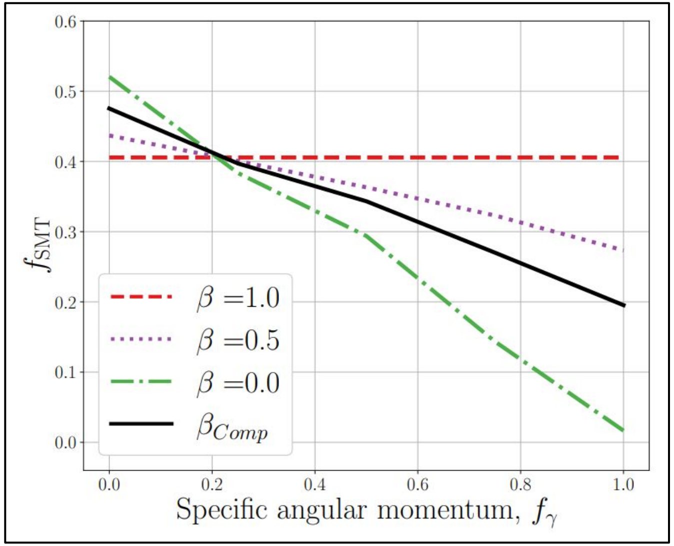
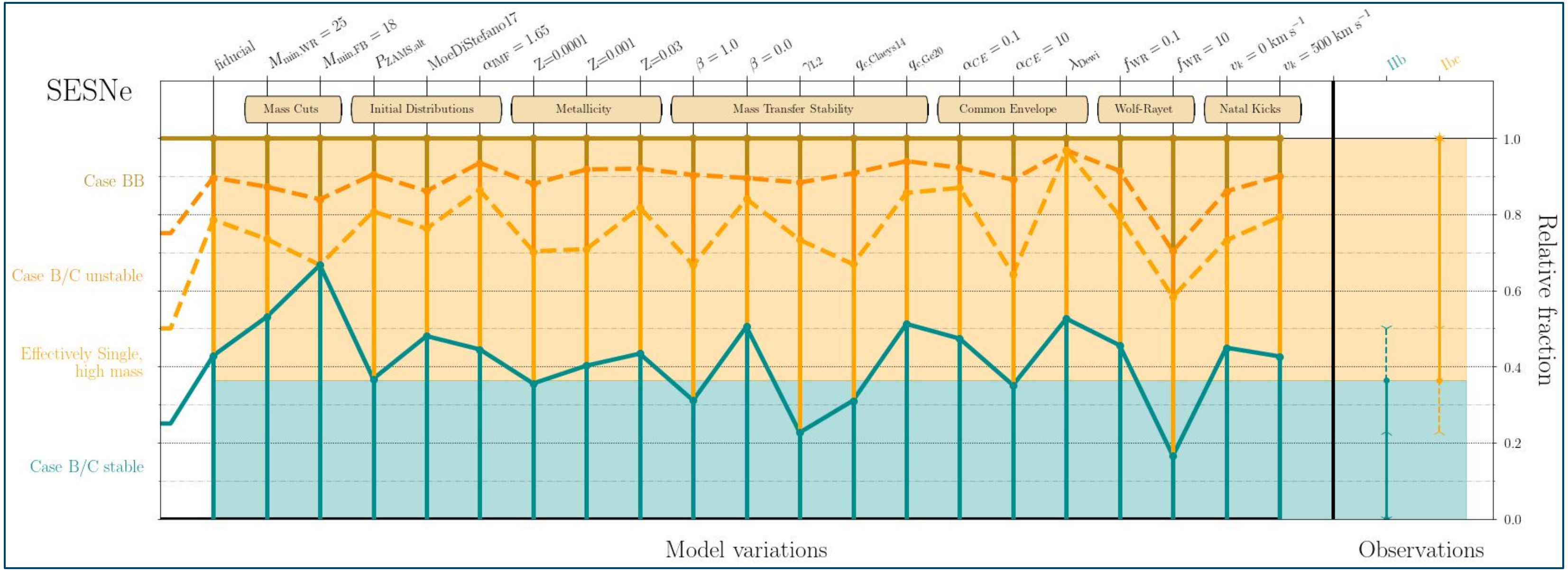
Evolutionary outcomes



Fraction of systems that experience stable mass transfer (f_{SMT}) during the first interaction depends strongly on efficiency and AM loss
RW et al. (2023)

- The isolated star (or *binary*) fraction depends primarily on the initial conditions.
- The fraction which experience *stable mass transfer* (SMT), depends on the adopted physical model.
  - How efficient is mass transfer? (β)
  - How much angular momentum (AM) is removed during mass transfer? (f_γ)

Relative fractions of stripped supernova types

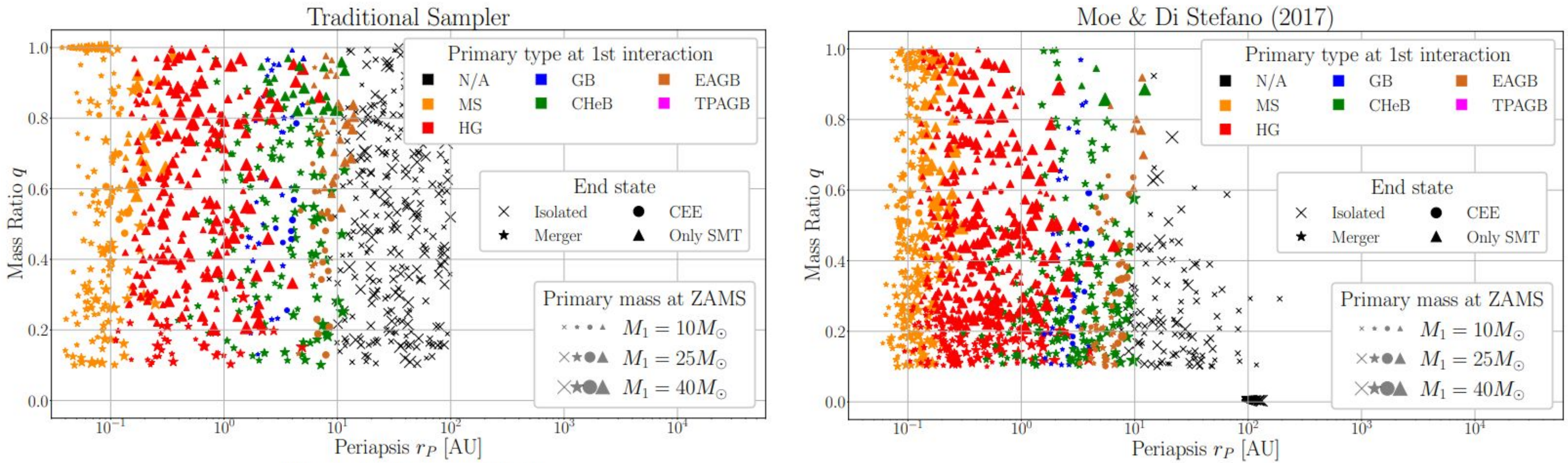


Compare branching ratios: H-low - H-absent

RW & Hirai (in prep)

What does population synthesis science look like?

Evolutionary outcomes



Visualizing the outcomes of binary evolution: Single - SMT - CEE - Merger
while **varying the birth distributions**
RW et al. (2023)