Birthrates of accretion-induced collapse neutron stars from binary evolution models

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Some previous studies of accretion-induced collapse of WD -> NS

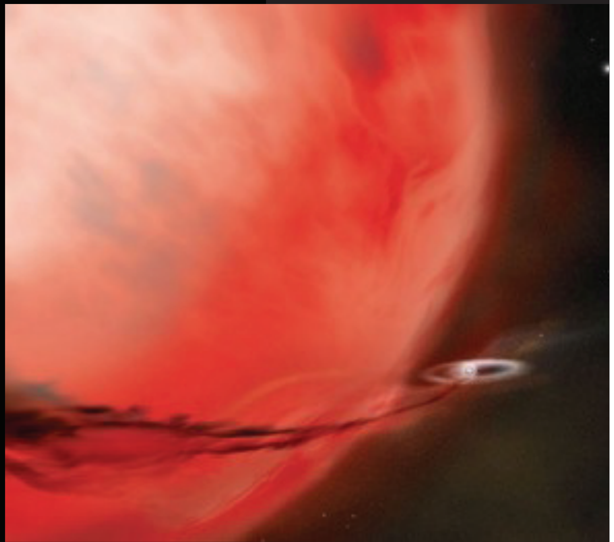
- Miyaji; Nomoto, Saio, Kondo (e.g. accretion in merging CO WDs)
- Colgate, Fryer (rate estimates, explosion models, NS EOS)
- Ivanova+ (formation mechanisms; globular clusters)
- Dessart (radiation-hydro collapse models of massive WDs)
- Darbha, Metzger+ (using Dessart collapse models; post-collapse nucleosynthesis and light curves)
- Wickramasinghe+ (rates, properties)
- Bhattacharya, Yoon, Janka, Woosley, Abdikamalov, Schwab, & others.

Motivation: why learn about neutron stars formed via collapse of a WD?

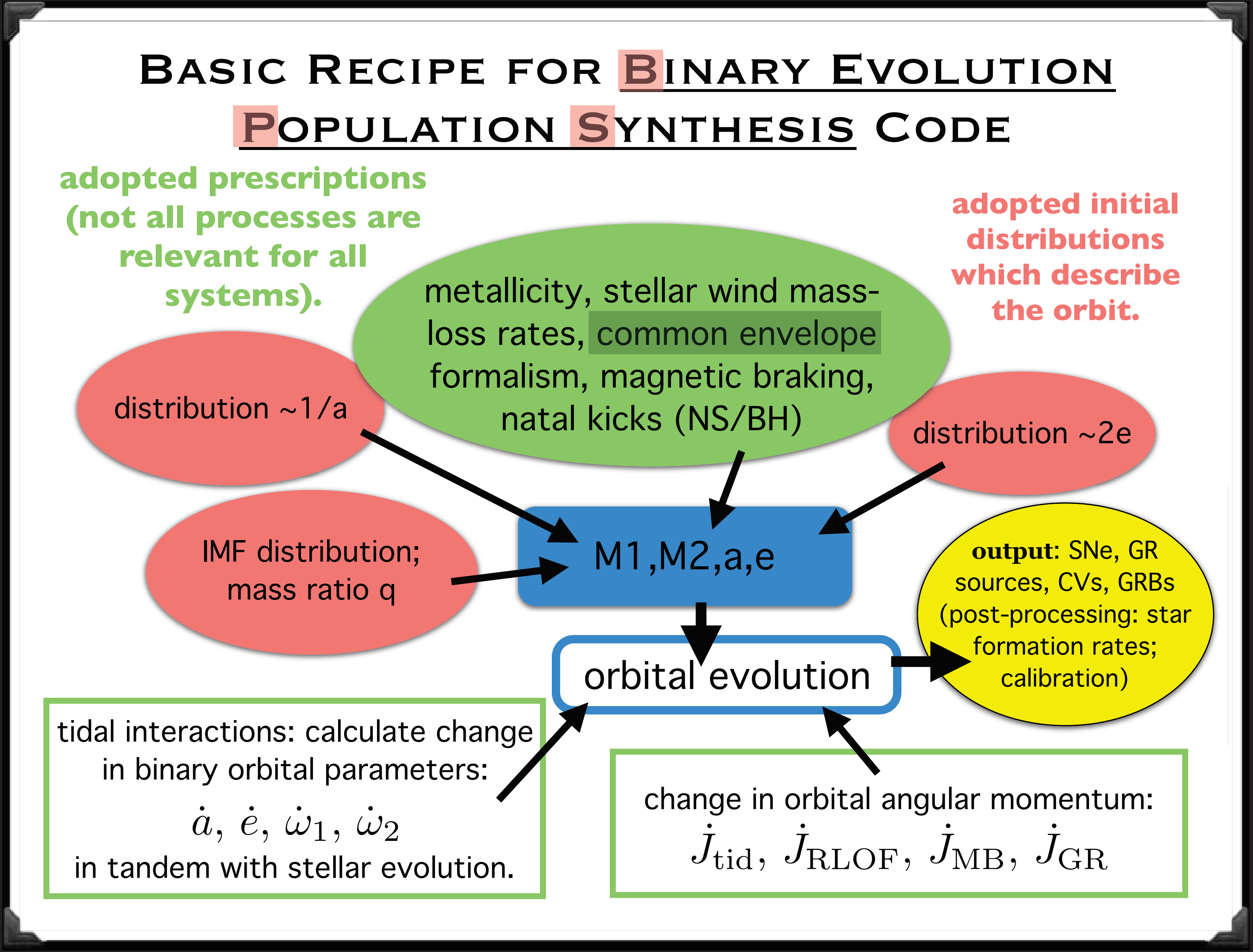
- If we can predict rates, delay time distribution (DTD) & physical properties (e.g. donor star type), **detection probability** is higher.

- Rates (vs. SNe Ia) <-> effect on **chemical evolution**: How much synthesized material is locked up in the remnant? How much is expelled into the ISM? The **r-process**, neutron-rich isotopes.

- Rates are estimated to be higher than was previously assumed (e.g. Hurley et al. 2010; binary MSPs).



StarTrack BPS code (e.g. Belczynski et al. 2008).
Orbital equations evolved in tandem with stellar evolution.



BASIC RECIPE FOR BINARY EVOLUTION POPULATION SYNTHESIS CODE

adopted prescriptions (not all processes are relevant for all systems).

adopted initial distributions which describe the orbit.

metallicity, stellar wind mass-loss rates, common envelope formalism, magnetic braking, natal kicks (NS/BH)

distribution ~1/a

distribution ~2e

IMF distribution; mass ratio q

M1,M2,a,e

orbital evolution

output: SNe, GR sources, CVs, GRBs (post-processing: star formation rates; calibration)

tidal interactions: calculate change in binary orbital parameters:

$$\dot{a},\ \dot{e},\ \dot{\omega}_1,\ \dot{\omega}_2$$

in tandem with stellar evolution.

change in orbital angular momentum:

$$\dot{J}_{\rm tid},\ \dot{J}_{\rm RLOF},\ \dot{J}_{\rm MB},\ \dot{J}_{\rm GR}$$

Orbital separation ‘a’, eccentricity ‘e’, Initial Mass Function (IMF) of stars: chosen via Monte Carlo from probability distribution functions that are based on observational data.

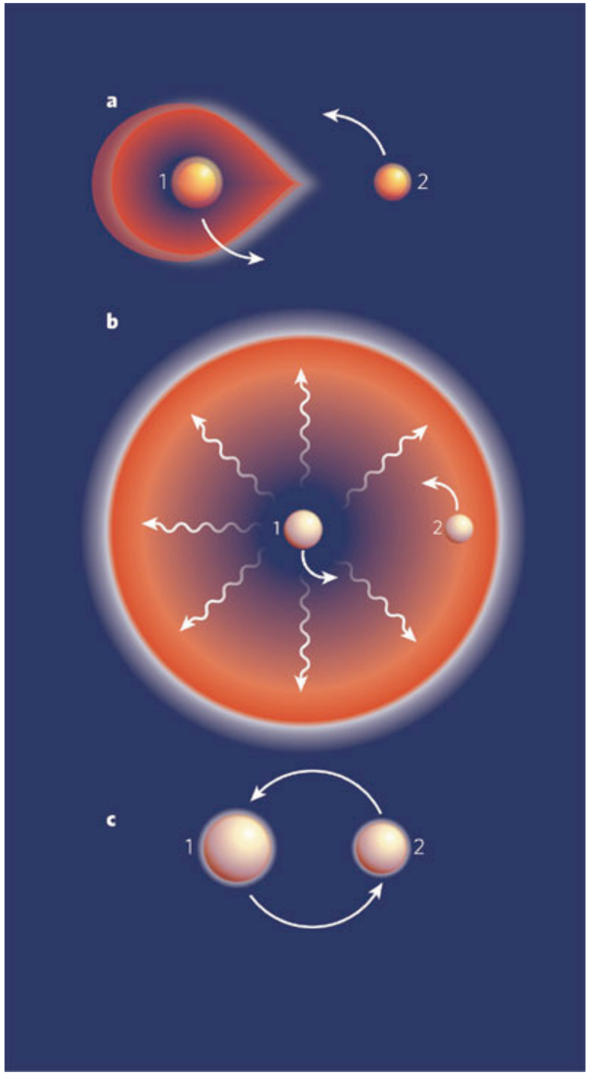
Biggest uncertainty in population synthesis: mass transfer/accretion and common envelope.

- Angular Momentum Loss (AML) through Roche-lobe overflow (RLOF), Common Envelope (CE), magnetic braking, gravitational radiation → $\dot{J}_{\rm orb}$
- On what timescale does mass transfer proceed? → $\dot{M}_{\rm nuc}$ or $\dot{M}_{\rm th}$,? Non-degenerate vs. degenerate? CE: $\dot{M}_{\rm dyn}$, **two formalisms** we use in BPS: Webbink (α); Nelemans (γ):

$$\alpha\left(\frac{-G M_{\rm rem} M_2}{2a_{\rm f}} + \frac{G M_{\rm giant} M_2}{2a_{\rm i}}\right) = -\frac{G M_{\rm giant} M_{\rm env}}{\lambda R_{\rm giant}}$$

$$\gamma \frac{J_{\rm i}}{M_{\rm giant}+M_2} = \frac{J_{\rm i}-J_{\rm f}}{M_{\rm env}}$$

Binding energy parameter “λ” may have *metallicity dependence* (Xu & Li, 2010).



Nature

Adopt two CE models

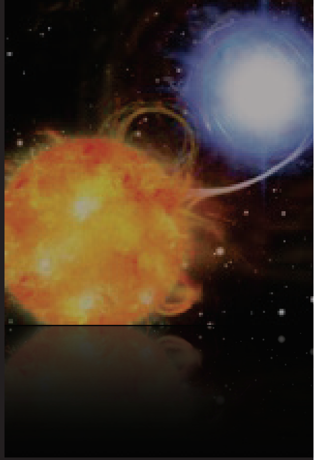
lower value of “α x λ” -> closer post-CE orbits

- `Classic’ Webbink (1984) prescription where binding energy parameter λ is constant for all H-rich stars: α x λ = 1.

- ‘New’ prescription with variable λ based on Xu & Li (2010) employs evolutionary stage-dependent λ, and α=1. *Example*:, λ is ~1 for sub-giants, can be ~3-10+ for AGB.

- Run BPS model (burst of SF at t=0, 40,000 binaries each) *for each* CE prescription: ‘old’ & ‘new’.

Neutron stars formed from intermediate-mass stars



- **In a binary**: either via *(i)* merger (runaway accretion), **or** through *(ii)* non-dynamical Roche-lobe overflow or wind accretion.

- Specific nomenclature for different evolutionary scenarios (see Ivanova et al. 2008). If NS is formed:

Through **merger** of WD binary: **merger-induced** collapse (**MIC**).

Through **stable accretion** in a binary: **accretion-induced** collapse (**AIC**).
Here I include this in wind-accretion scenarios.

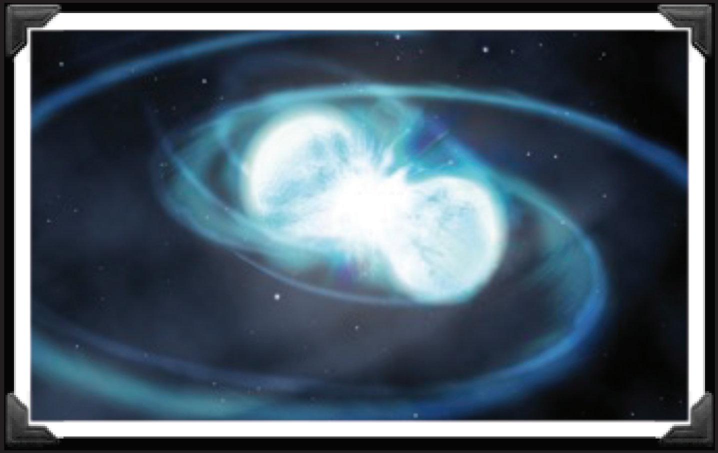
Through **single star evolution**: **evolutionary-induced** collapse (**EIC**).
I will not discuss these in this talk.

Modelling **Progenitors**: overlap between SNe Ia and AIC/MIC

AIC cf. SDS

- We assume if **ONe WD accretes to MCh** -> AIC (but see Marquardt et al. 2015).
- Donors can be MS stars, giants (including AGB), stripped helium-burning stars, or WD (rare).

- As for **WD mergers**: How do we delineate between "SN Ia" and "collapse to NS"? This is unclear.
- Previously it was thought MOST mergers of two CO WDs would form a neutron star. This is no longer the standard assumption (SN Ia gained favour).
- We assume any double **WD merger with ONE OR MORE ONe WD** -> MIC.



MIC cf. DDS

Results: AIC for ‘old’ CE model

- Events with delay times **> 1000 Myr** have red giant or sub-giant donors. ZAMS mass range of donor 1.3 - 1.8 M_{sun}.
- Events with delay times **< 1000 Myr** have a **variety** of donors: main sequence, giants, AGB, and helium-burning stars.
- Most prompt delay time events (**< 100 Myr**) all have AGB donors (via *wind accretion*, not RLOF).

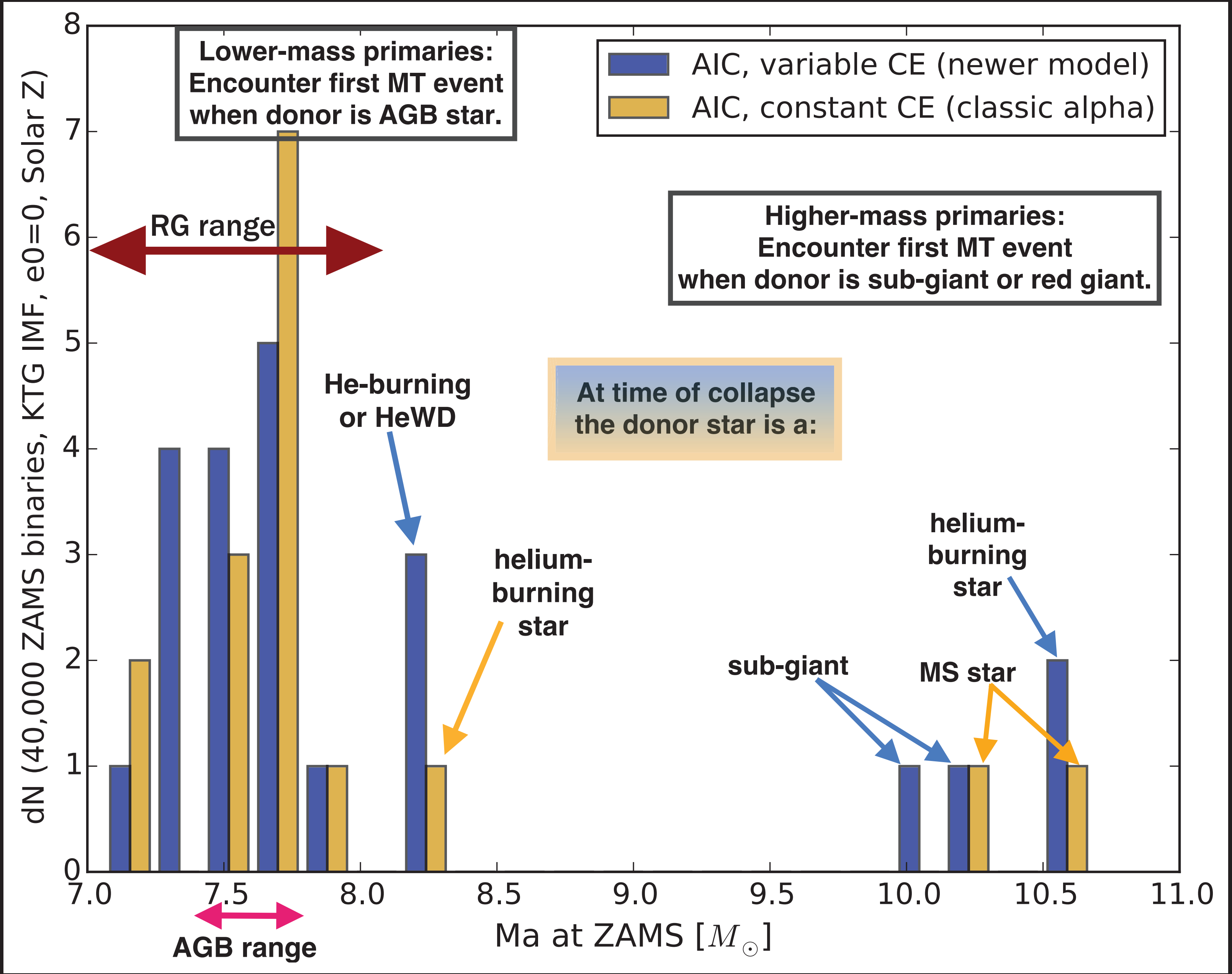
Results: AIC for ‘new’ CE model (main differences in *mauve*)

- Events with delay times **> 1000 Myr** have red giant, sub-giant, or *white dwarf* donors. Thus mostly similar to old CE model.

- Events with delay times **< 1000 Myr** have mostly helium-burning star donors. Some AGB donors, but **no** *sub-giants or red giants*. Very *different results from old CE model!*

- Most prompt delay time events (**< 100 Myr**) have AGB or *helium-burning* star donors.

Progenitor properties for **AIC** from StarTrack: x-axis: ZAMS mass of collapsing star (primary)



Results: MIC for both CE models (WD mergers)

- Delay times **span wider range for mergers**; more likely in older populations compared to AIC.
- Merger most often between **ONe + CO WD**. Rarely double ONe WD.
- Shorter delay time events (<1000 Myr) tend to involve two CE phases, whereas >1000 Myr systems typically have encounter 1 CE.

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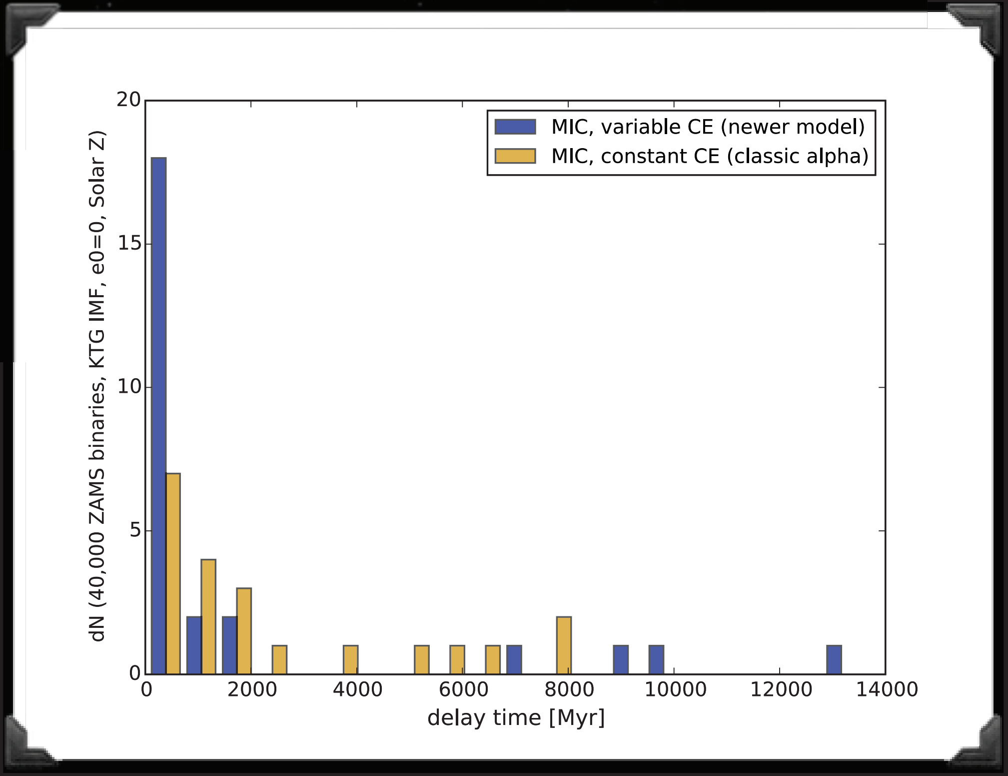
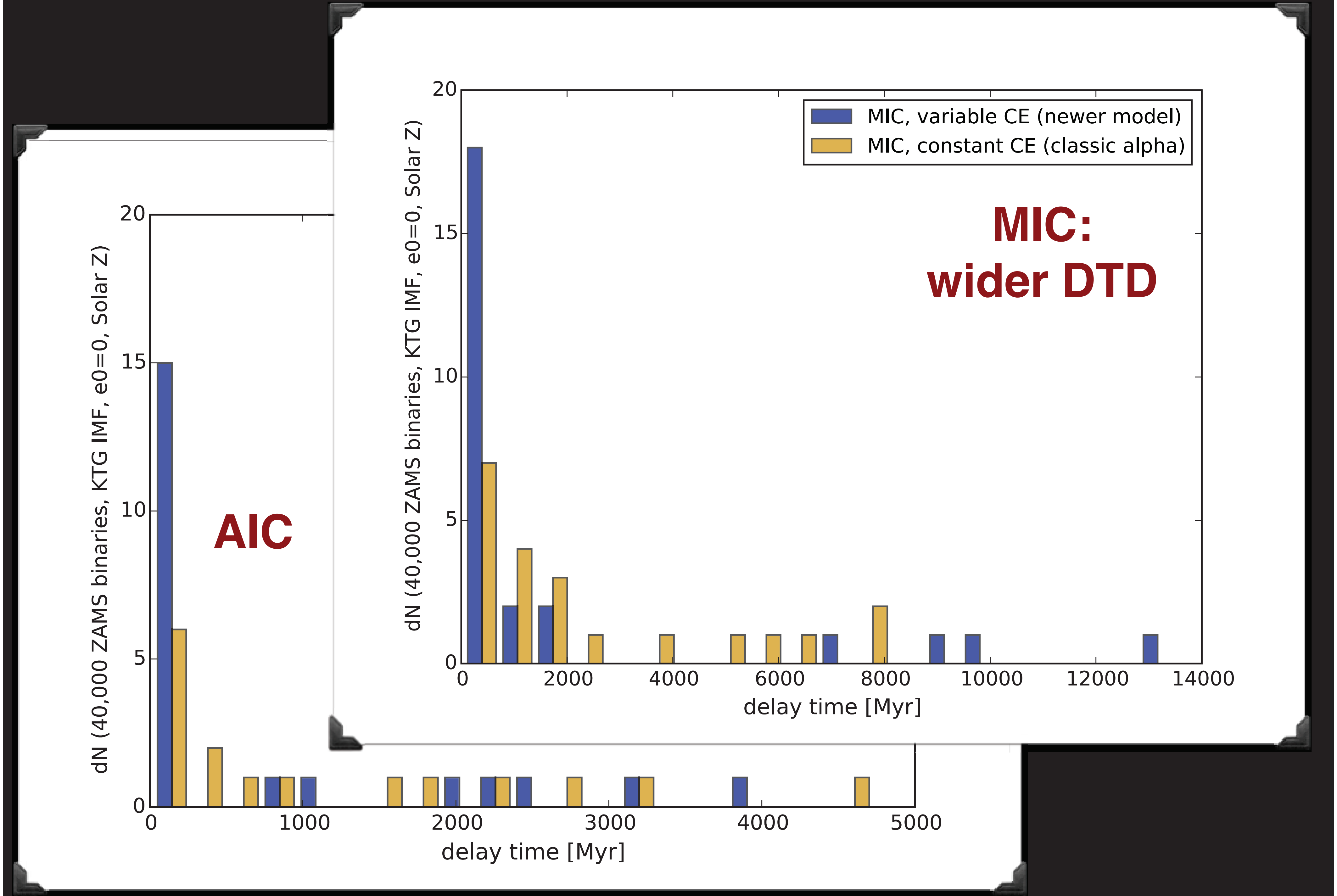


Delay times for AIC vs. MIC



AIC

MIC: wider DTD

Summary

Galactic rate estimates

- Assume Galaxy has stellar mass 6.4×10^{10} M_{sun}.
- Remember: we assume all *CO+CO mergers make SNe Ia* or something else; not MIC.
- Actual rate for MW including AIC & MIC together: **5×10^{-5} < AIC+MIC < ~10^{-4} per year**.

Summary

delay times (ages), donors

- Most AIC/MIC occur **shortly after star formation** (delay times < 300 Myr). **Components** are either:
  -ONeWD + COWD (MIC)
  -ONeWD + AGB star donor (AIC)

- MIC systems predicted to be born out to t_Hubble. AIC extremely rare >5000 Myr (for field evolution).

- So what about young radio pulsars observed in (old) globular clusters? (e.g. Boyles et al. 2011).

Binaries can explain **young** radio pulsars in Galactic globular clusters

- At least 3 isolated, 1 binary pulsar seen in Galactic globular clusters (metal-rich).
- EIC have low natal kicks, but unlikely progenitors in **old globular clusters**.
- The **3 isolated pulsars** could be formed via **MIC** (long enough delay times) without invoking N-body interactions. **AIC** could explain the pulsars if stellar dynamics are invoked.

NGC 6624: metal-rich GC.
Known to host at least 3 YOUNG pulsars.
http://www.naic.edu/~pfreire/GCpsr.html

Conclusions

- Notable differences (donor star type) in AIC progenitor properties depending on adopted common envelope formalism. (Reason: different evolution due to wider post-CE orbit in 'new' model).
- MIC can occur at very long delay times; both MIC & AIC produce prompt progenitors. Rates ~1-2 orders of mag below SNe Ia.
- We see many AIC events with delay times < 100 Myr (AGB donors) **only** if we allow for **wind** RLOF in BPS model (Abate et al. 2013).
- Can we draw a line between ***thermonuclear SNe*** and ***AIC*** production? This will set limits on event rates, thus **nucleosynthesis yield** estimates, including r-process site investigations (e.g. Qian & Wasserburg 2007).