The evolution of Hierarchical Triples

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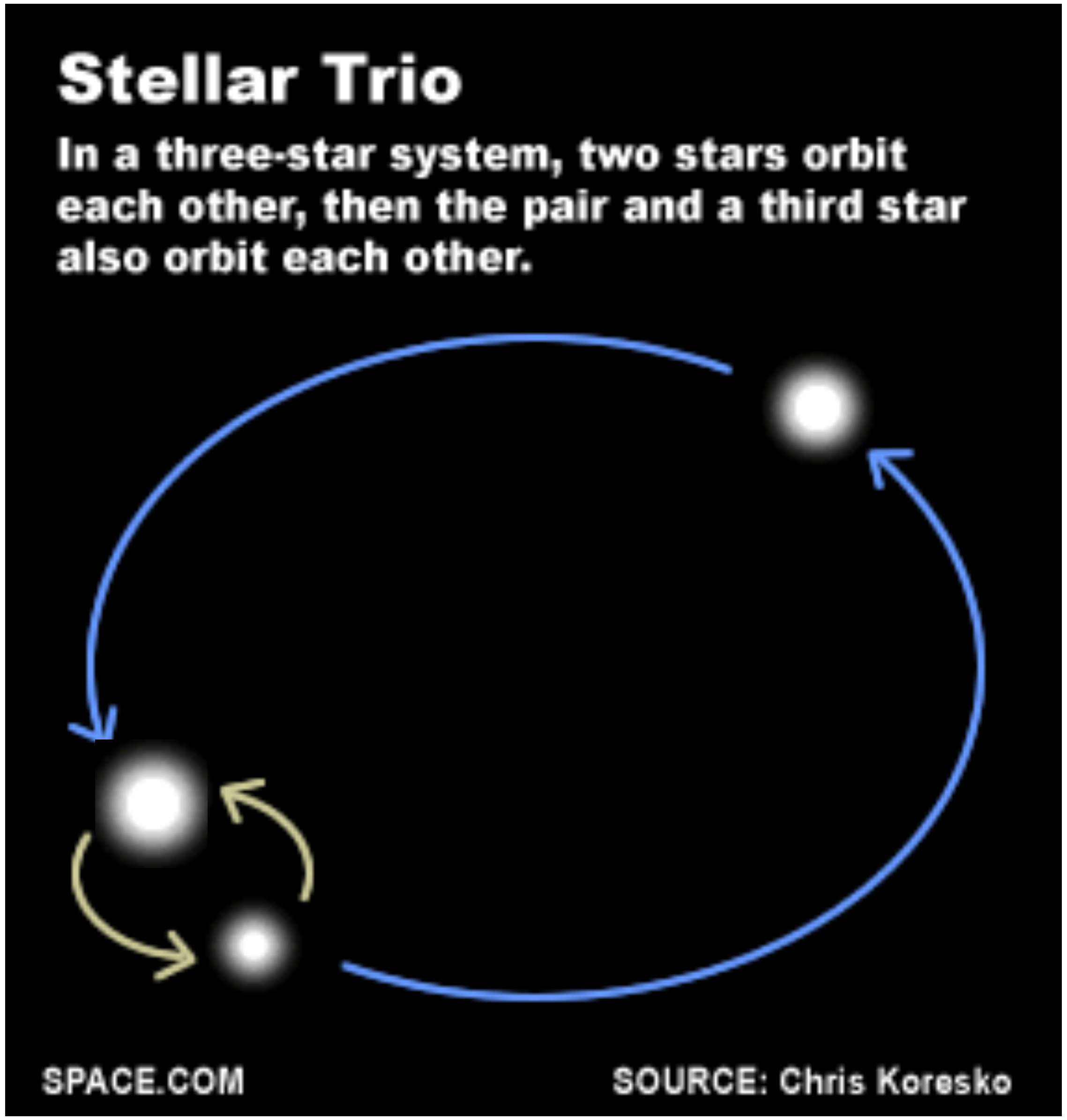
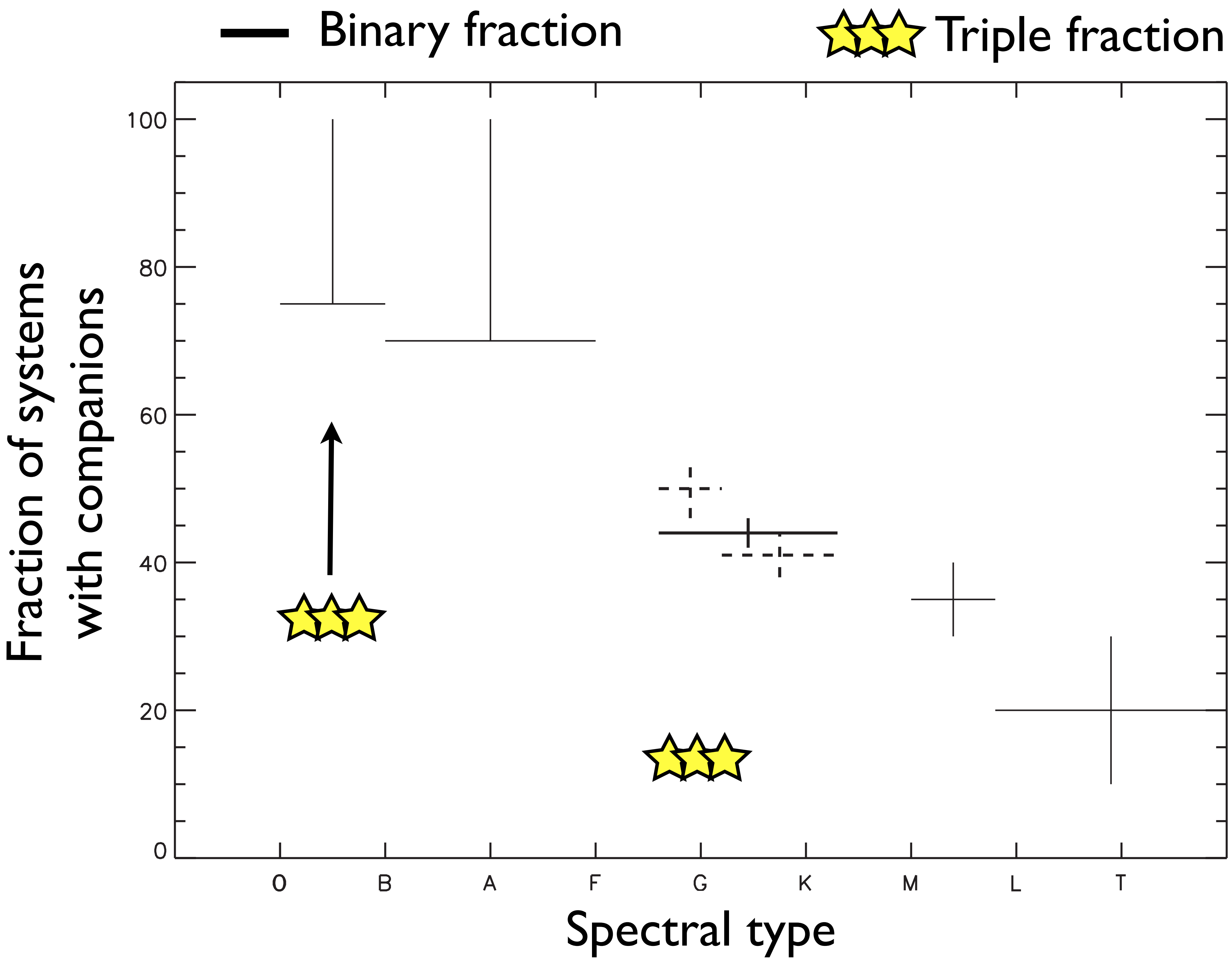
Stellar triples



- Isolated
- Stable $P_{\mathrm{outer}} \gtrsim 5P_{\mathrm{inner}}$
  - inner & outer orbit
- Abundant

Triples are abundant

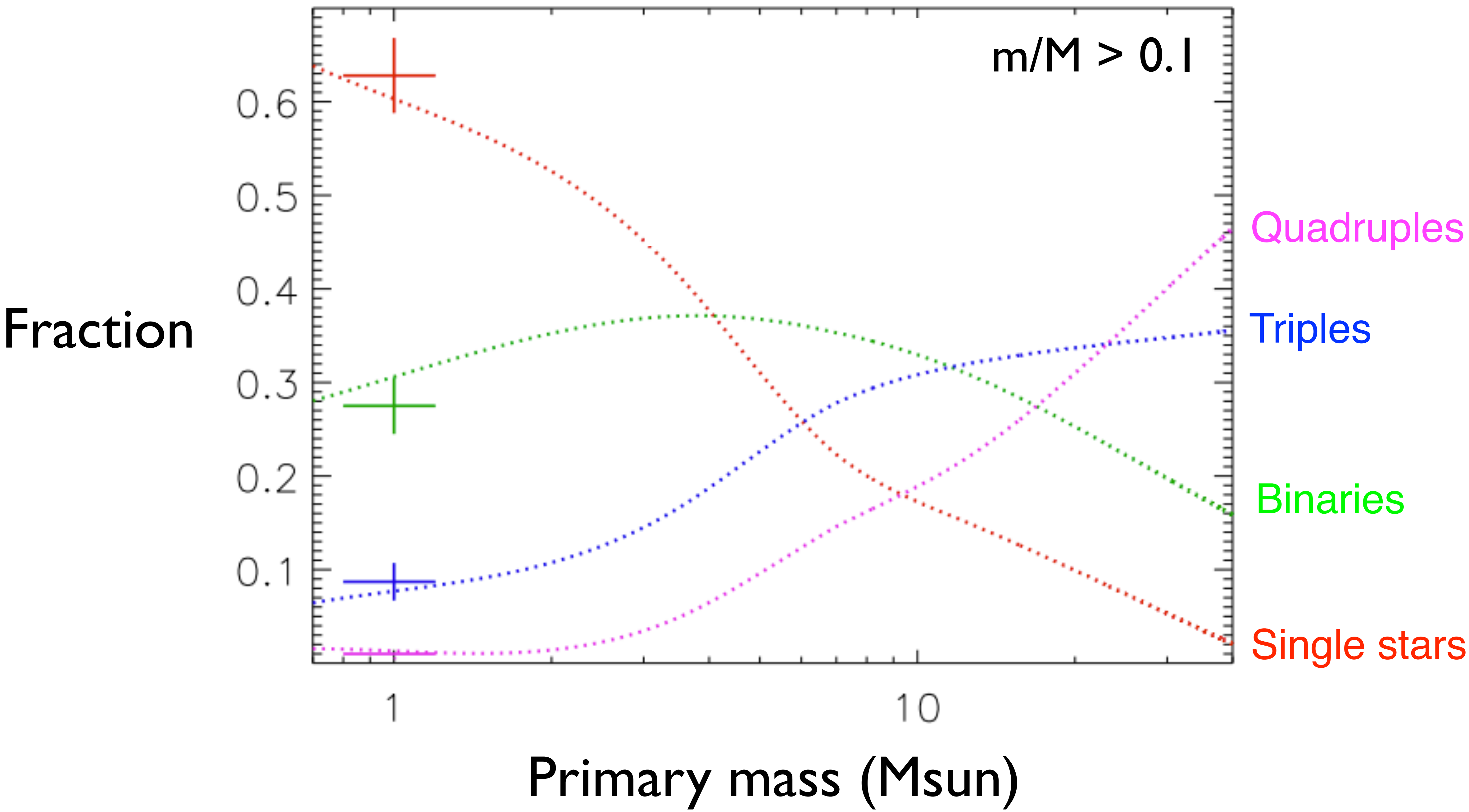


Initial distribution - young systems

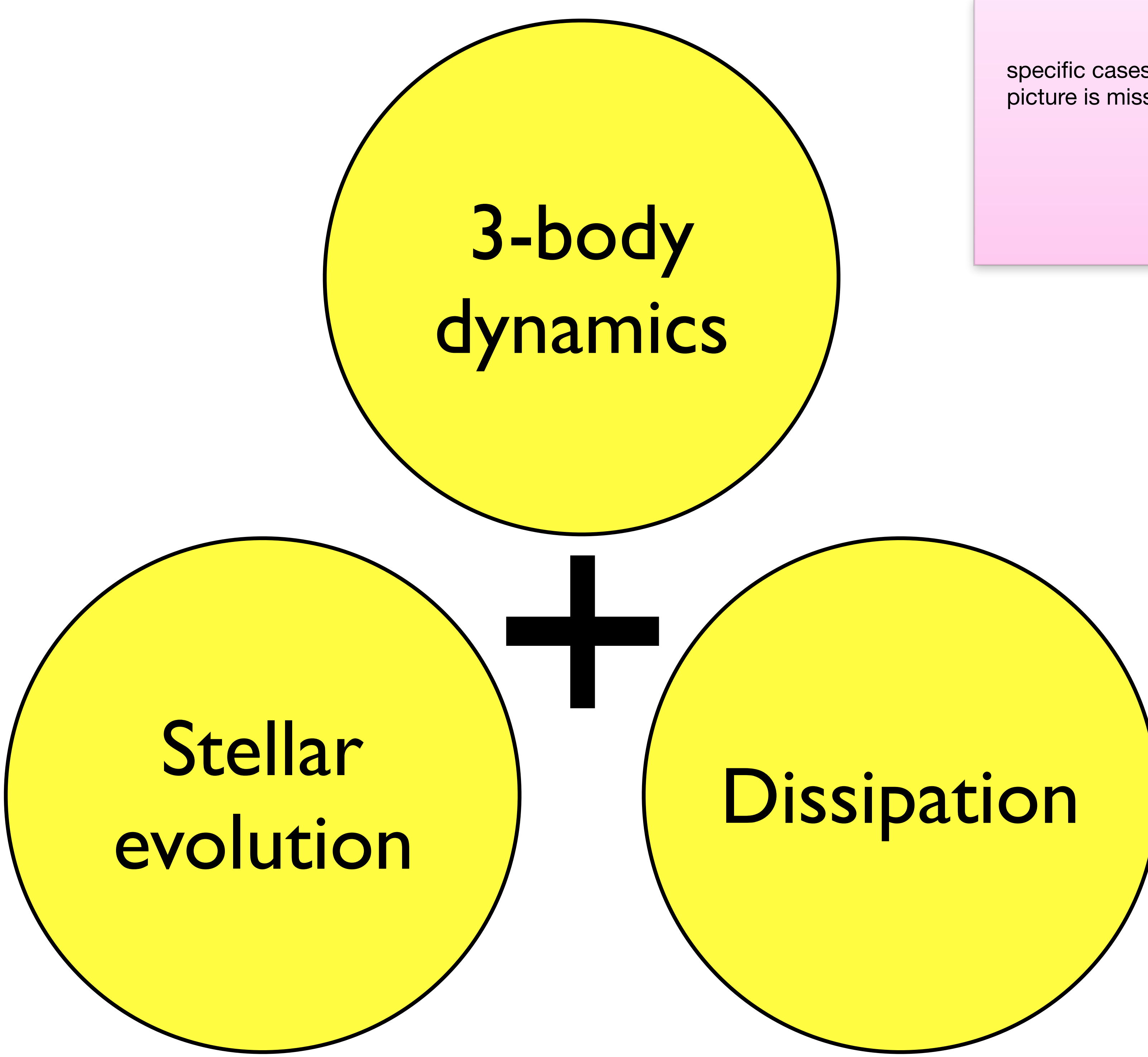
Raghavan+ ’10, Tokovinin ‘08, ‘14, Evans ’05, Duchene & Kraus ’13, Sana+ ’14, Moe+ ’17

Triples are abundant

Moe+ '17



Triple evolution



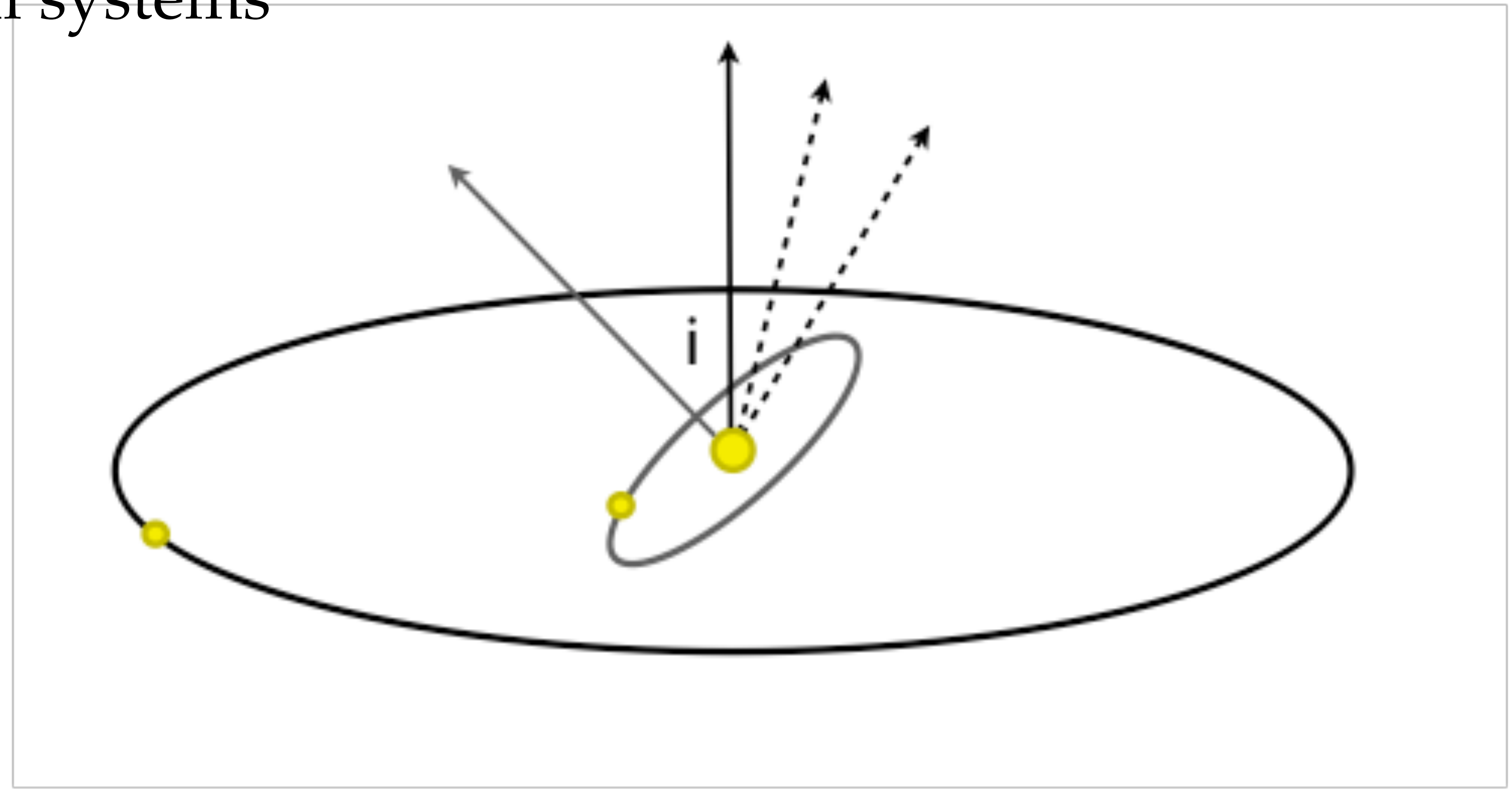
specific cases investigated, overall picture is missing

- Evolution of radius & core
- Mass loss & accretion

- Tides
- Gravitational waves

3-Body dynamics

Hierarchical systems



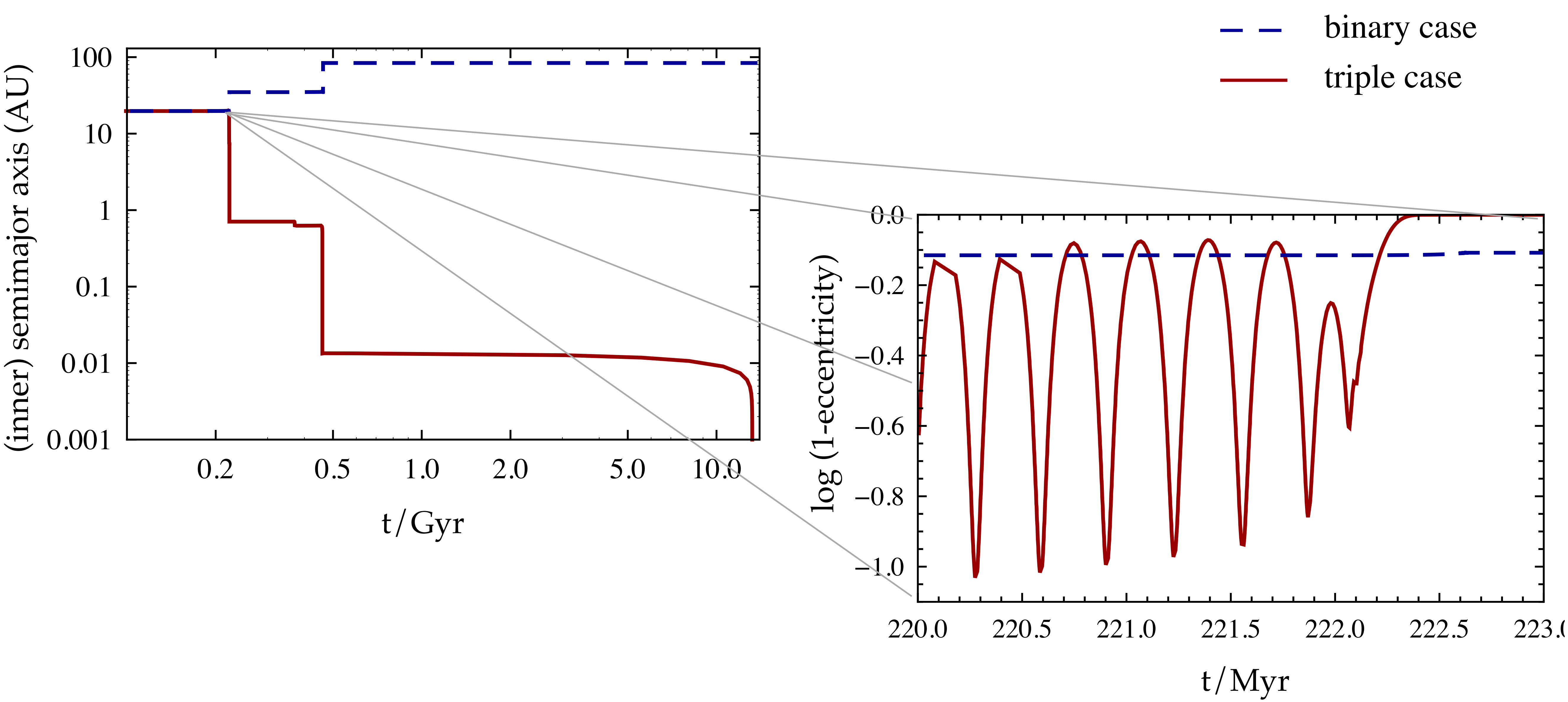
- Kozai-Lidov cycles (Lidov '62 , Kozai '62)

$$P_{\rm KL} \sim \frac{P^2_{\rm outer}}{P_{\rm inner}} \frac{m_1 + m_2 + m_3}{m_3} (1 - e^2_{\rm outer})^{3/2}$$

- Higher-order effects: more extreme eccentricities, orbital flips (see review of Naoz+ 16)

Long-term effect

example: M1=3.95, M2=3.03, M3=2.73MSun, a1=19.7, a2 =636AU, e1=0.23, e2 =0.82, i=116



courtesy of Adrian Hamers

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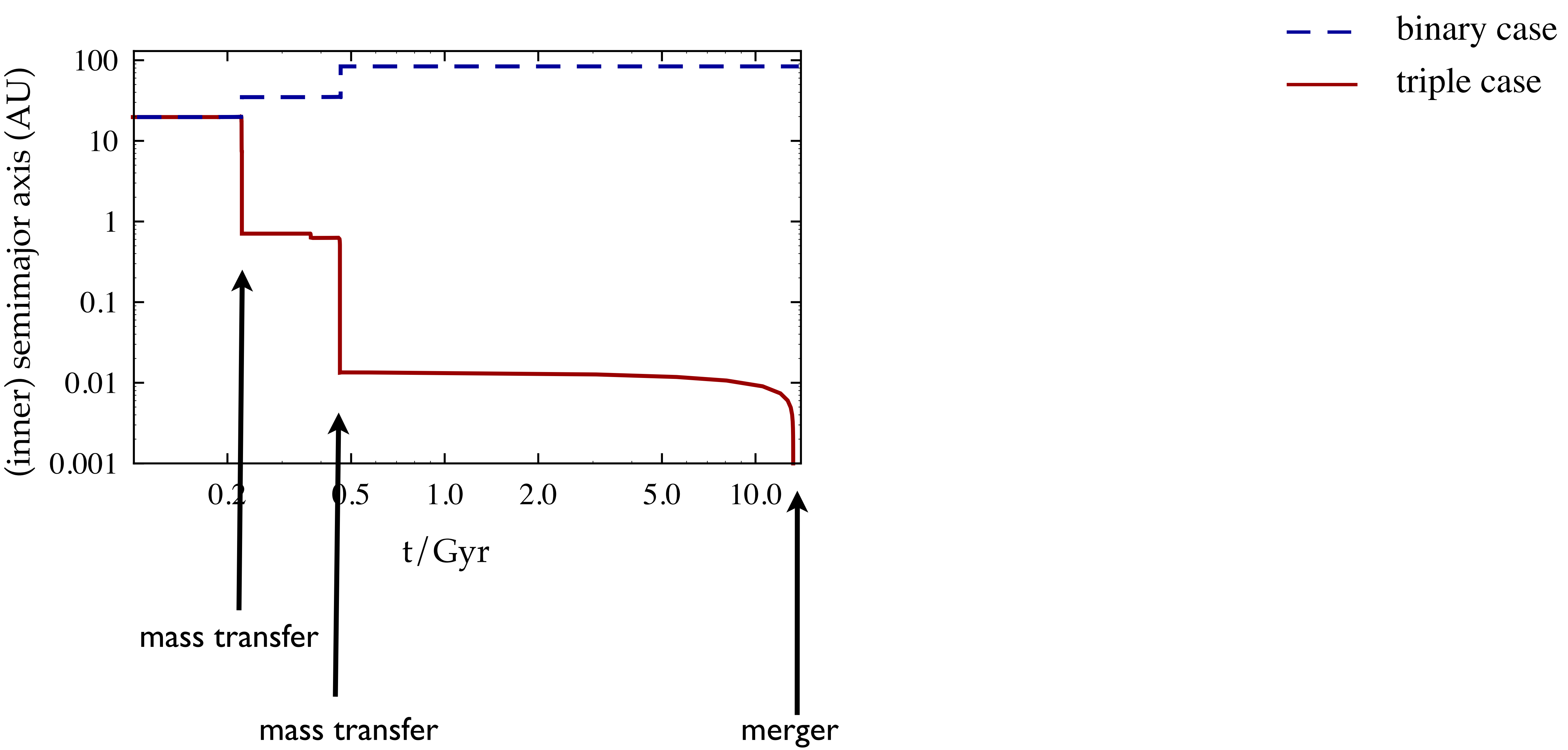
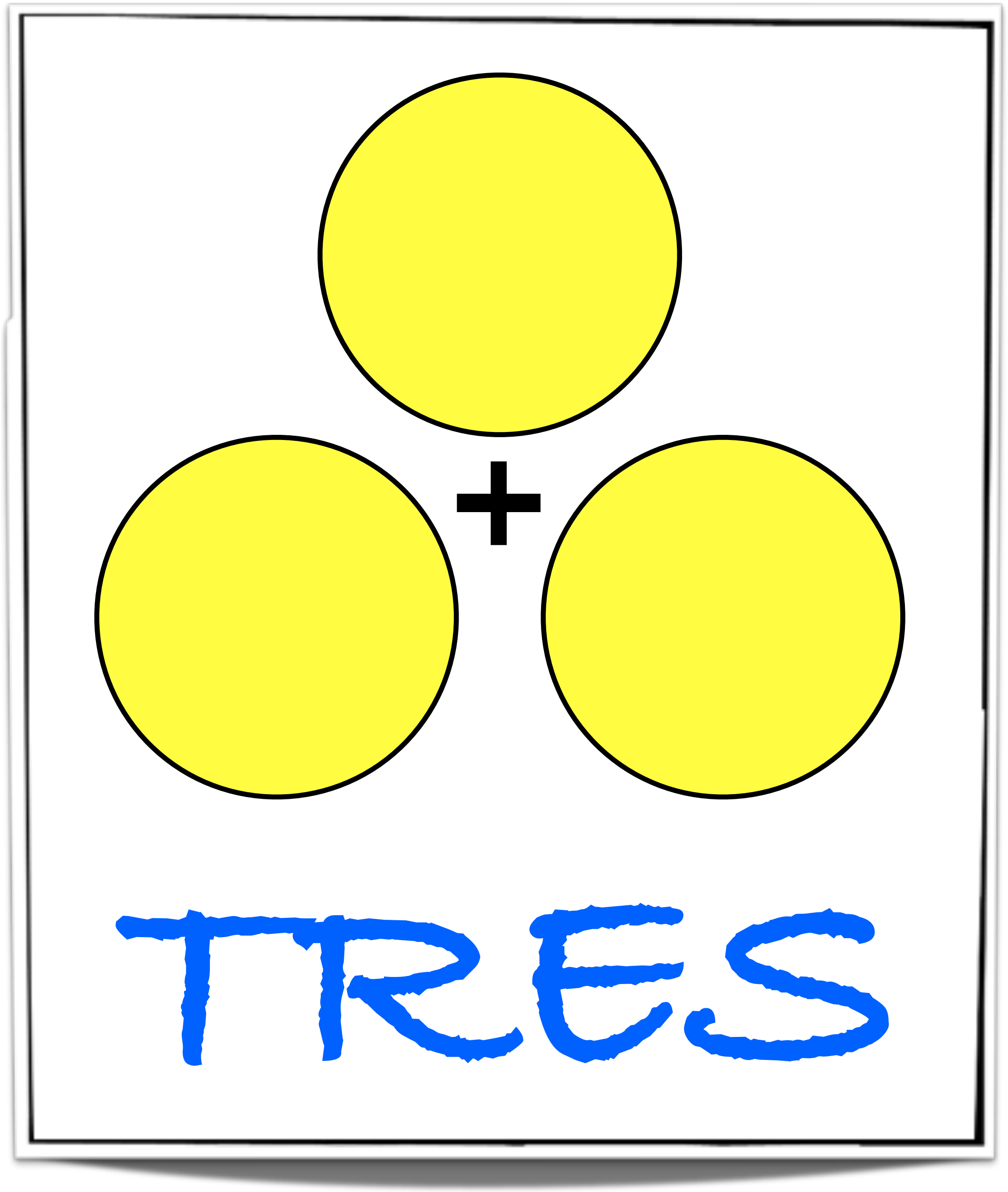


courtesy of Adrian Hamers

Code: TRES

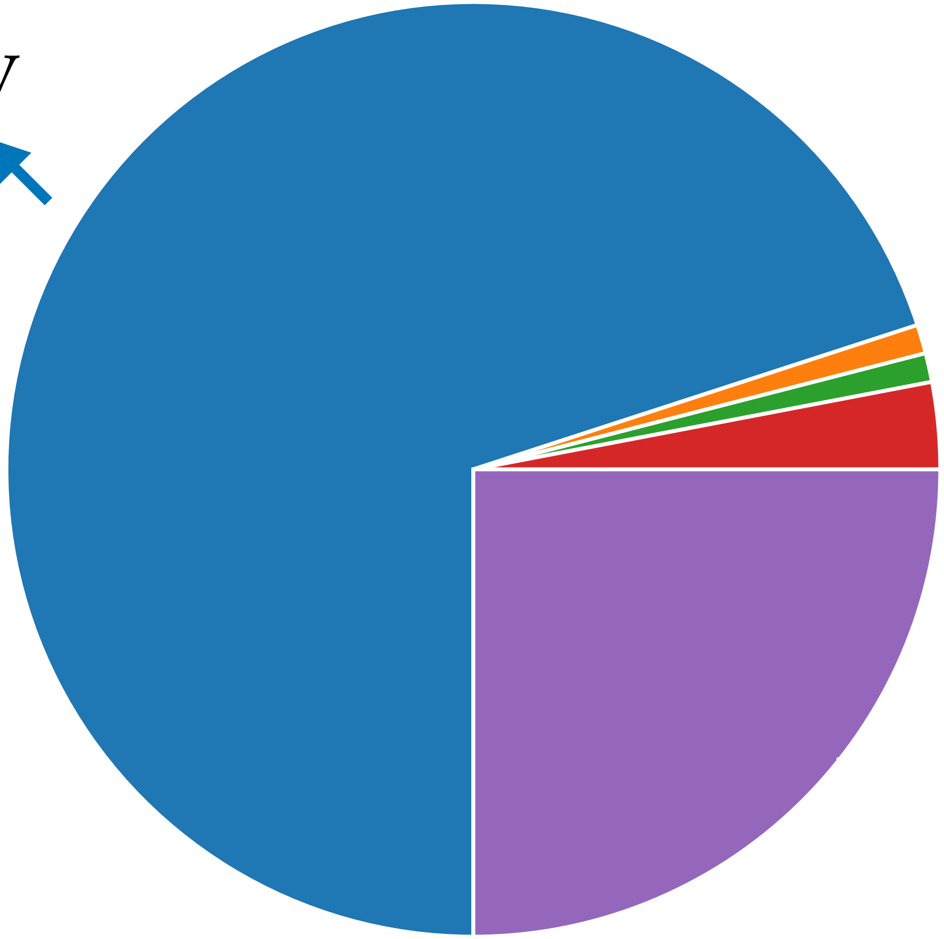


- Triple review and code publication (Toonen+ '16)
- BH-BH mergers (Antonini, Toonen+ '17)
- Supernova type Ia (Toonen+ '18)
- Common evolution (Toonen+ in prep.)

Typical evolution of triples

- low & intermediate mass primaries (1-7.5$M_\odot$)

Mass transfer by primary ~64-75%



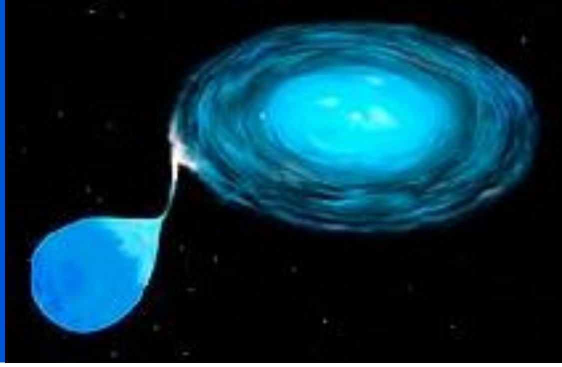
In binaries:

only ~28-39%

- N(P) ∝ 1/P
- N(P) ∝ log-normal(P)

ref: Toonen+ in prep.

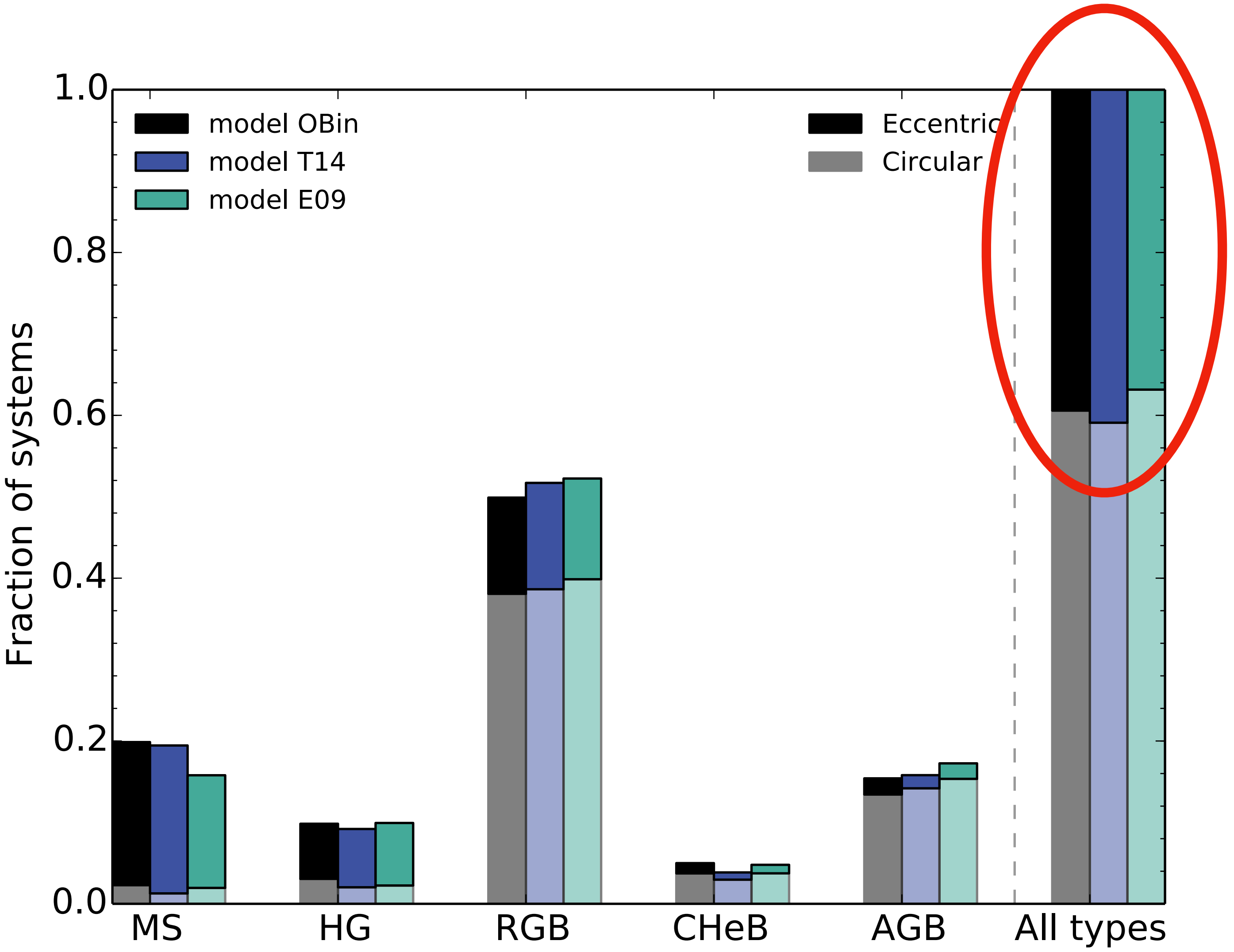
Mass transfer



- Mass transfer common in triples
- Other differences with binaries?
  - Mass transfer occurs earlier
  - Orbit still eccentric upon onset of mass transfer
    ➡ Observed sources

    (e.g. Petrova & Orlov 1999, Nicholls & Wood 2012)

~40% still eccentric

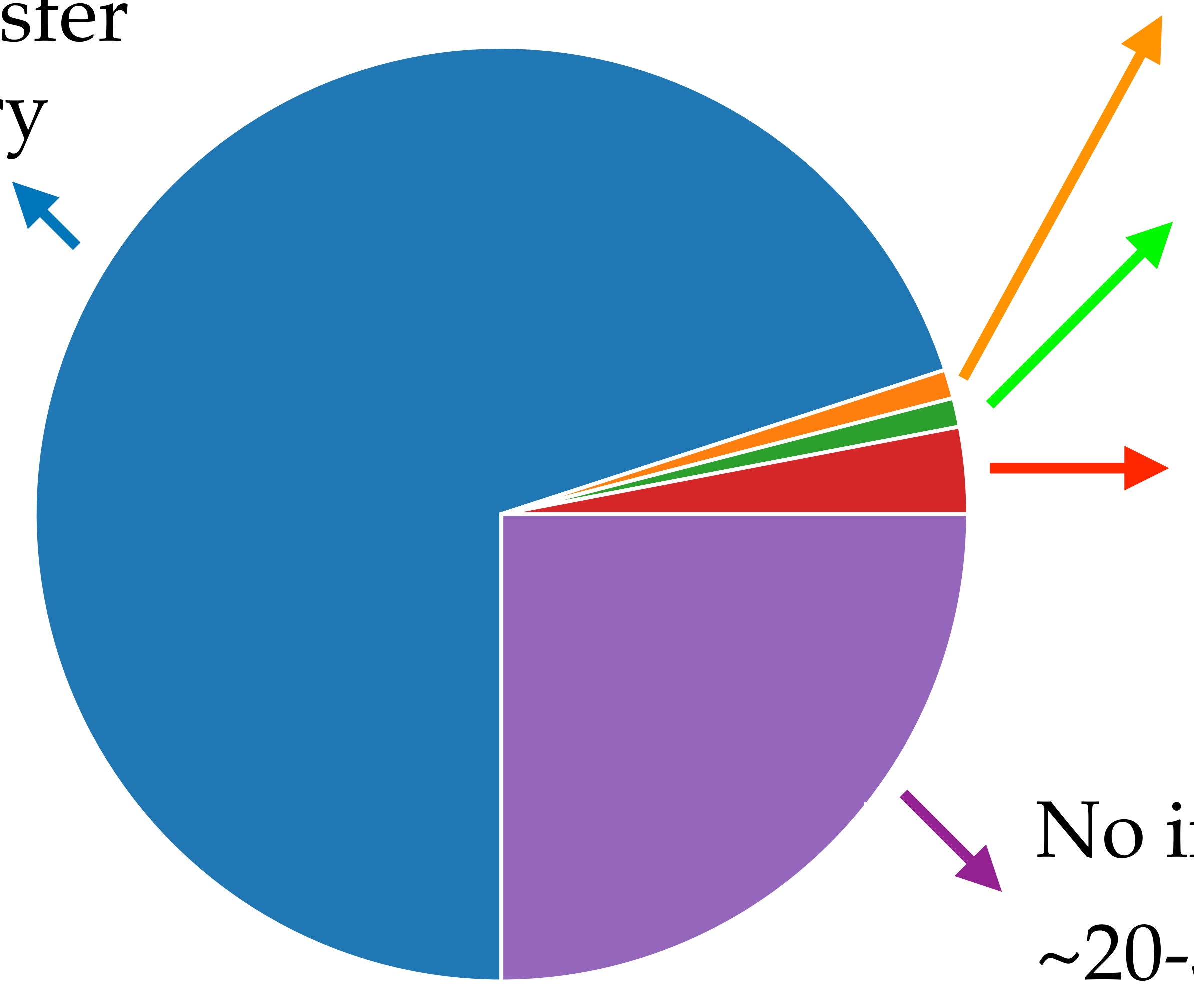


Type of donor star in triple

Typical evolution of triples

- low & intermediate mass primaries (1-7.5$M_\odot$)

Mass transfer by primary ~64-75%



Secondary donates mass (~0.75%)

Tertiary donates mass (~0.5-1%)

Dynamically unstable (~2-4.5%)

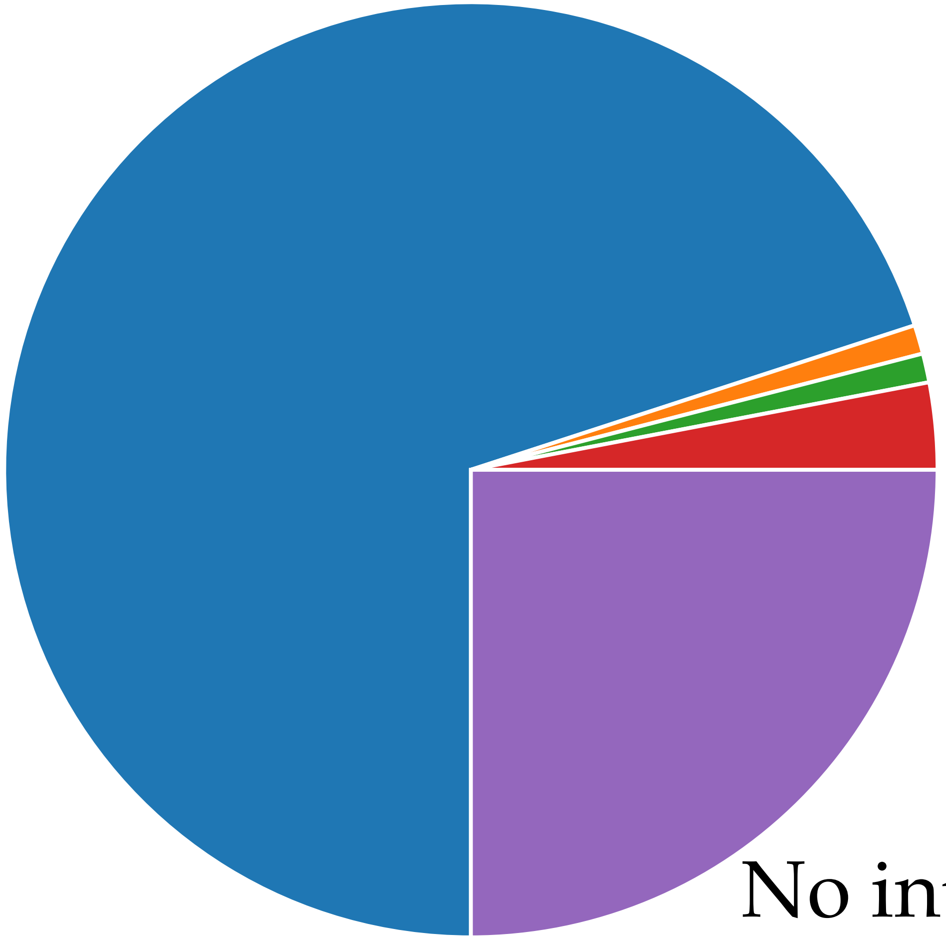
No interaction ~20-30%

In binaries: only ~28-39%

- $N(P) \propto 1/P$
- $N(P) \propto$ log-normal(P)

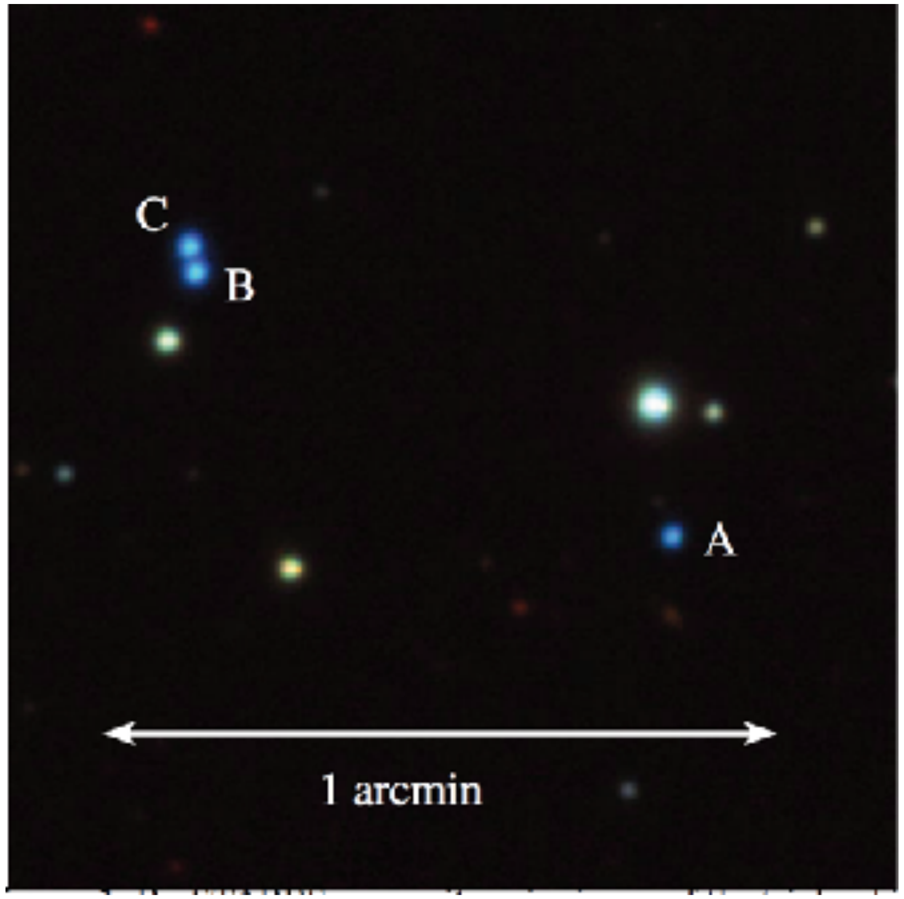
ref: Toonen+ in prep.

Typical evolution of triples



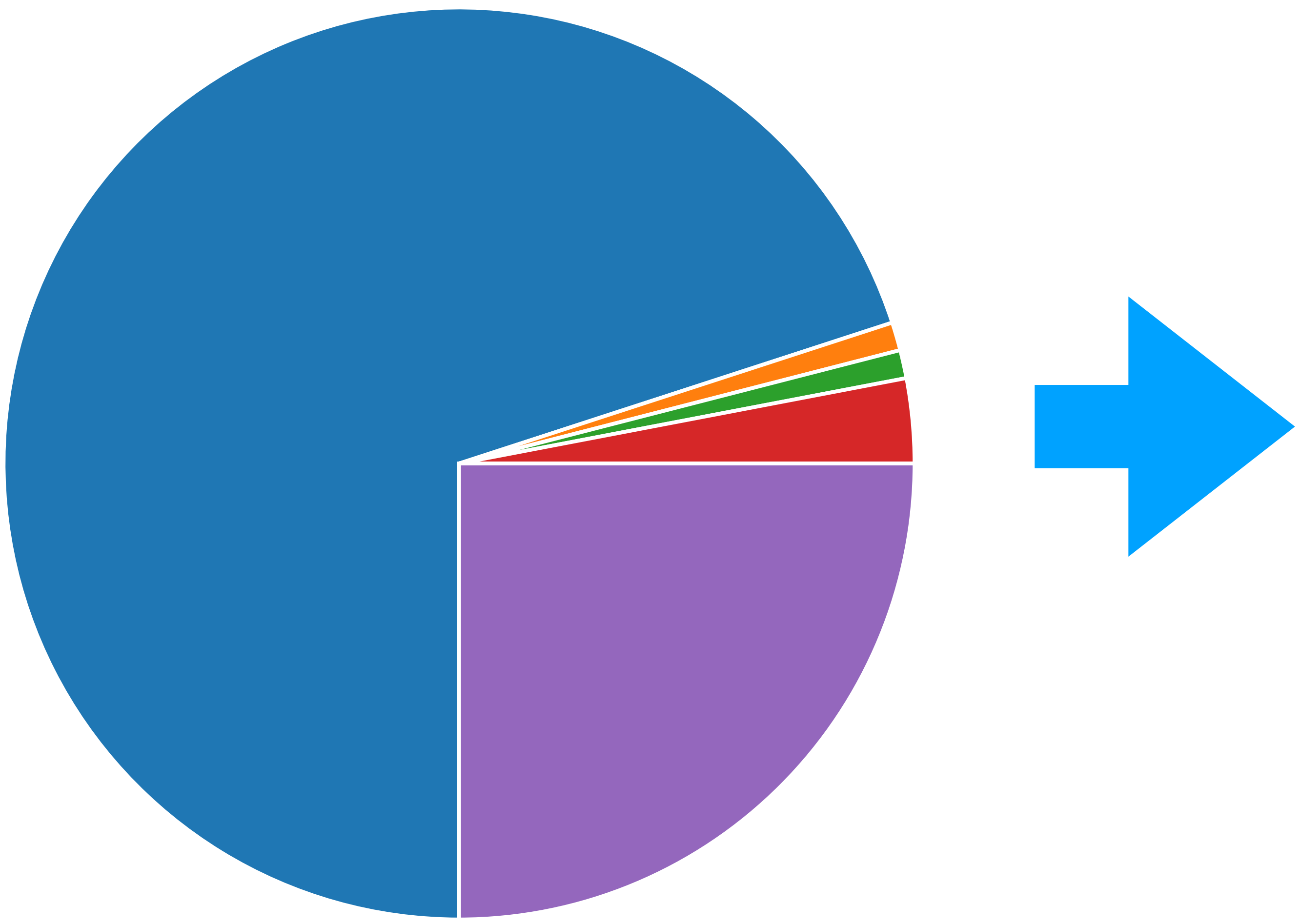
No interaction
~20-30%

Gaia DR2 discovery:

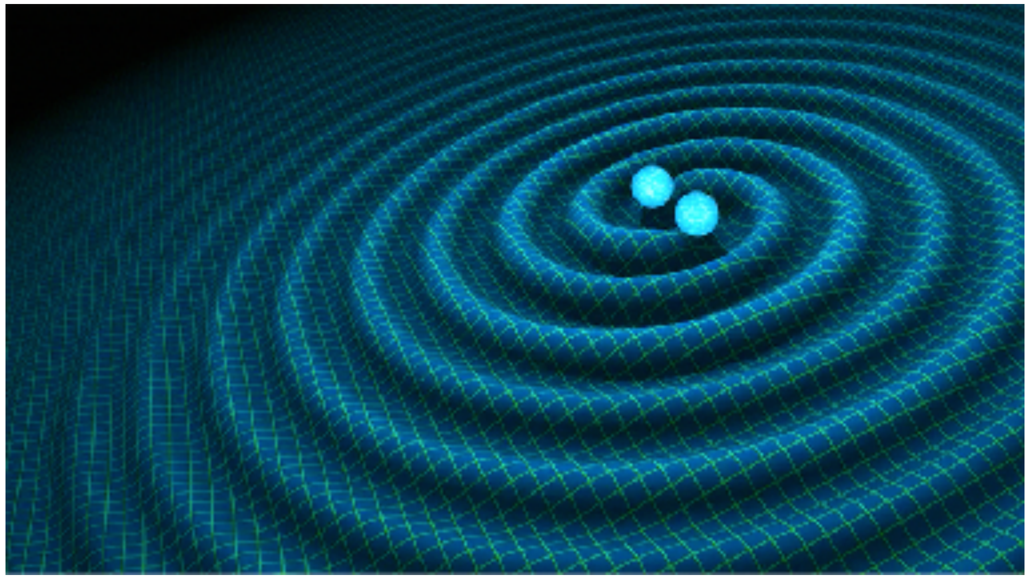


Triple compact objects:
(Perpinya-Valles w/ Toonen 19)

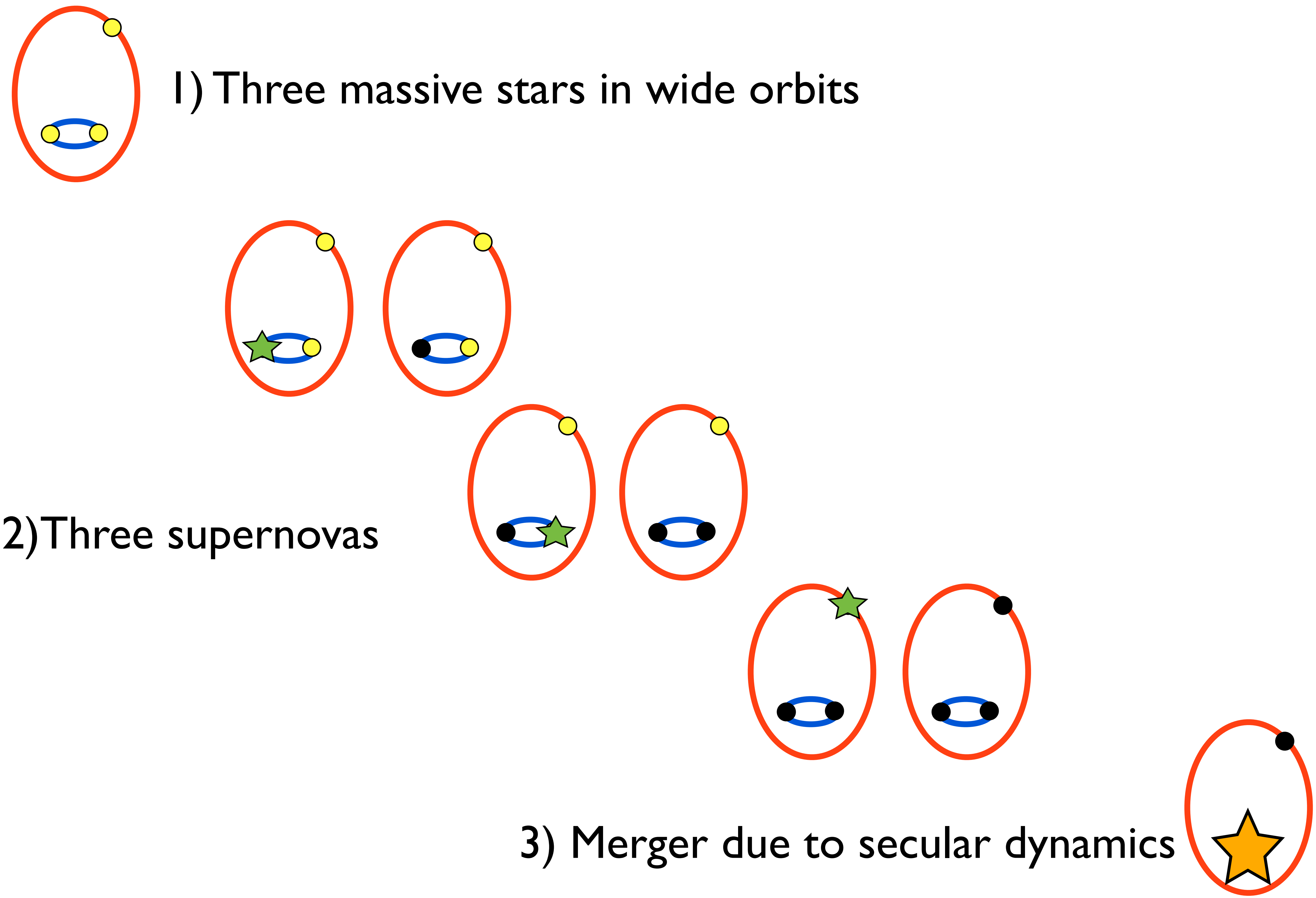
Triple evolution towards GWs



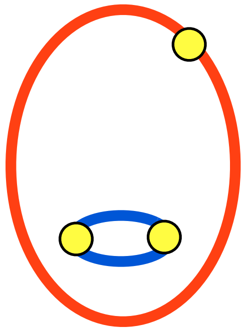
Gravitational wave sources



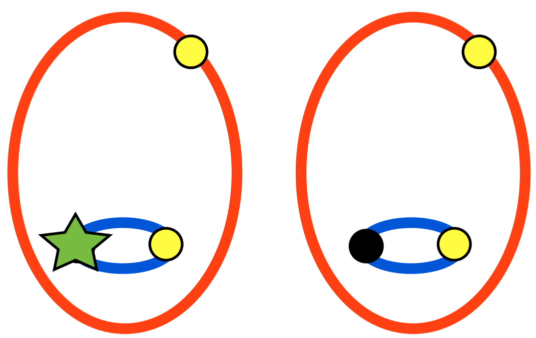
Evolutionary channel

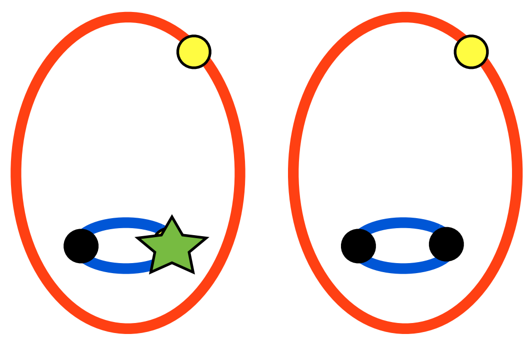


Difficulties



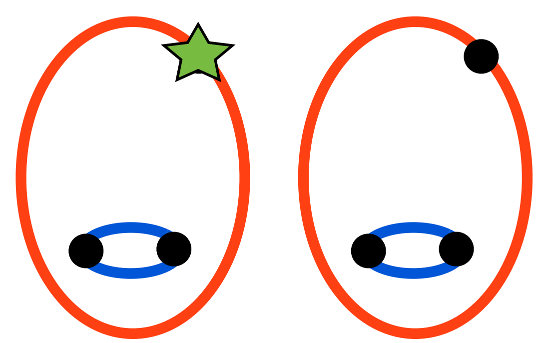
1) Three massive stars in wide orbits





2)Three supernovas

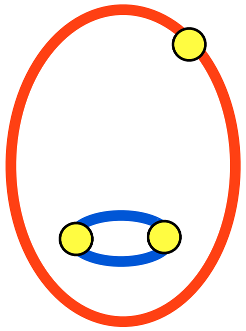
Avoids: a)Mass transfer
b)Dynamical instabilities
c)Dissolution



3) Merger due to secular dynamics

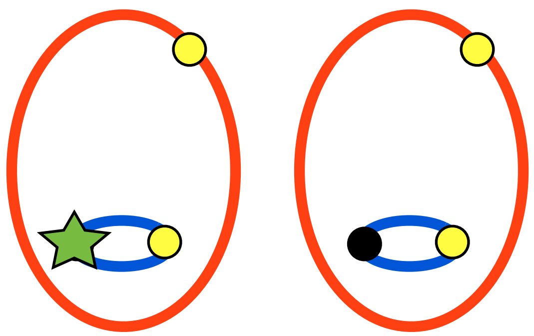
Get a merger, but not at earlier stage

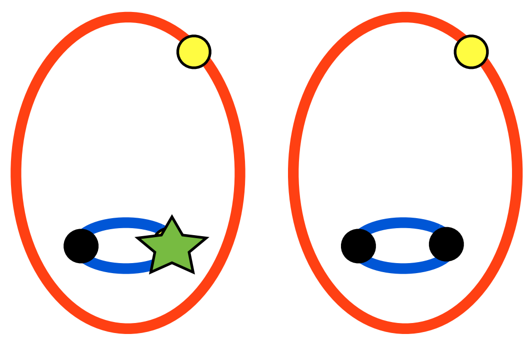
Difficulties & advantage



1) Three massive stars in wide orbits

But no mass transfer or common-envelope needed!





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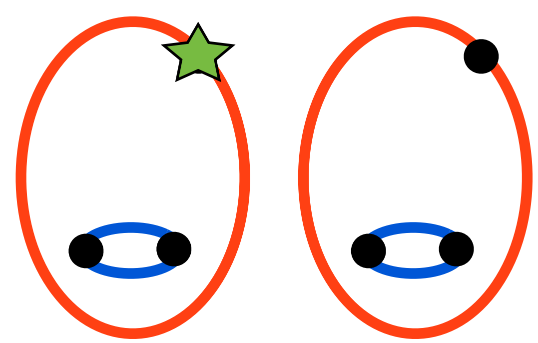


3) Merger due to secular dynamics

Get a merger, but not at earlier stage

Gravitational wave sources

nsns
3 orders of magnitude lower

8-22Msun

Black hole - black hole merger rate:

- LIGO O1+O2 rate: 9.7-101 per year per Gpc^3 (LSC 18)

Triples:

- With natal-kick: ~0.4 per year per Gpc^3
- Only Blaauw-kick: ~1.2 per year per Gpc^3

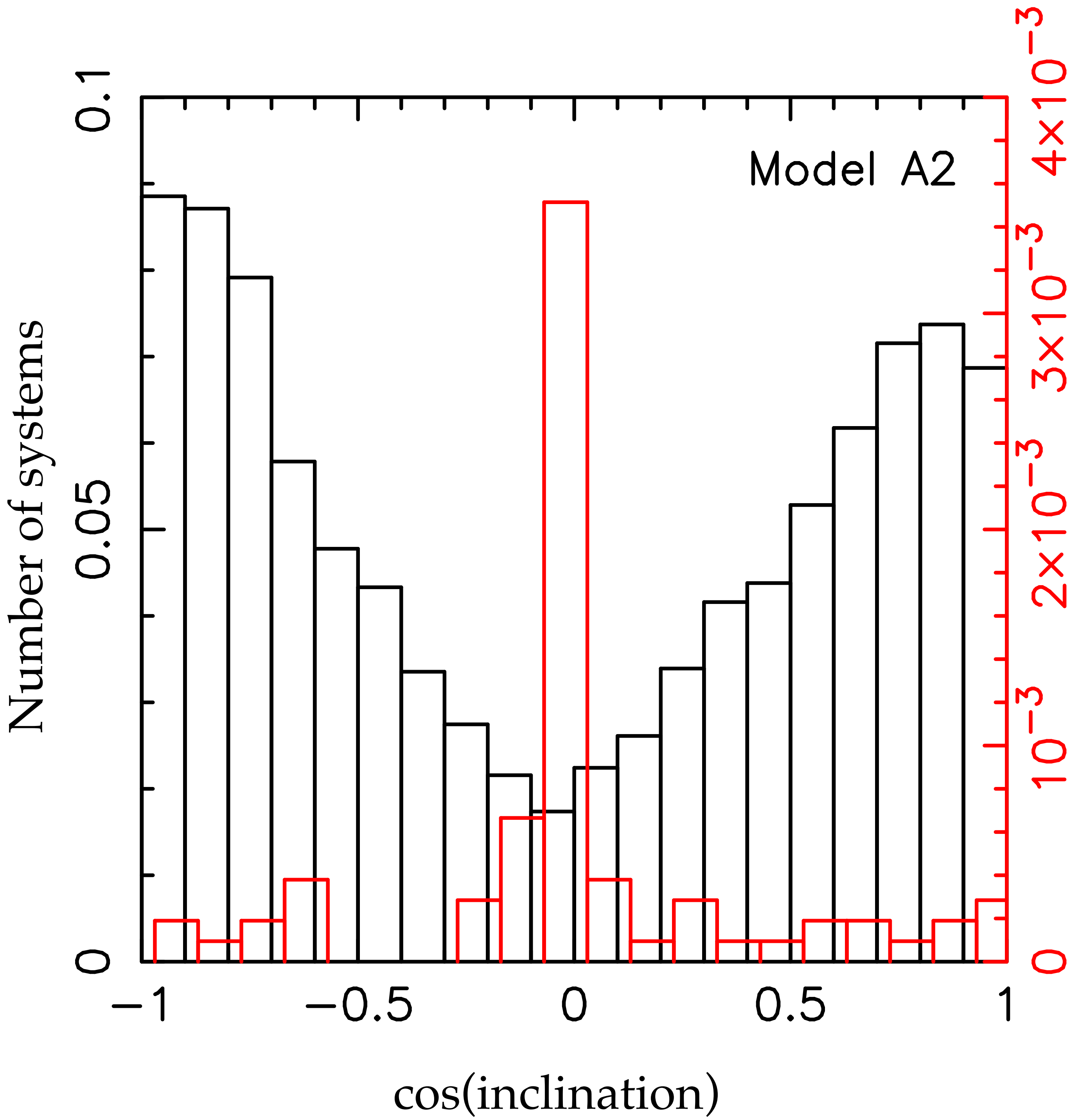
  Hobbs / Arzoumanian, momentum-conserving kicks, direct collapse for M>40Msun,

ref: Antonini, Toonen+ 17

- At low metallicity: ~2-25 per year per Gpc^3

  (Rodriguez & Antonini 18)

BH-BH mergers



- ➡ Triple BHs formed
- ➡ Merging BHs

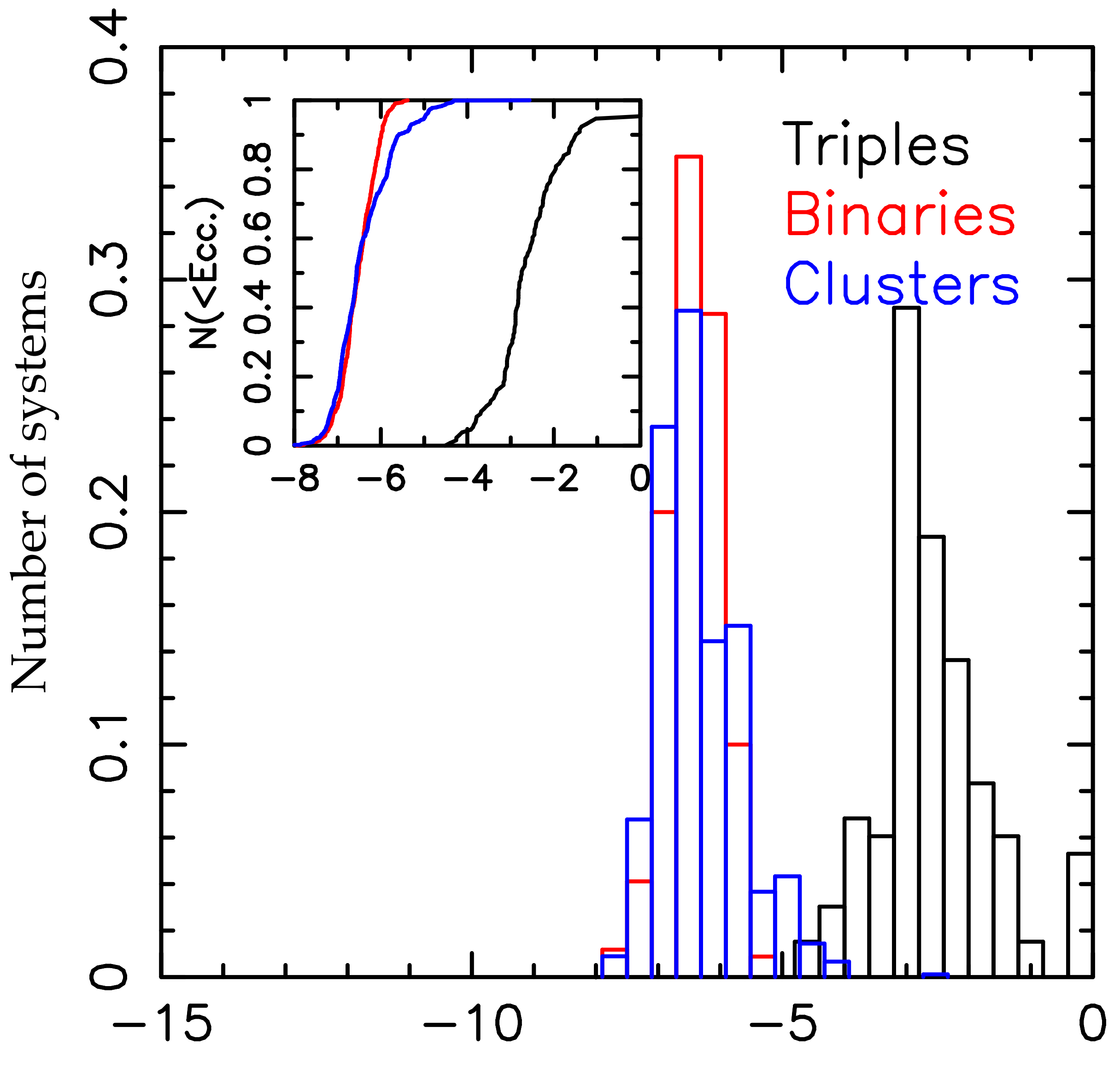
- Important to model formation of BH-BH in triples consistently

ref: Antonini, Toonen+ 17

Eccentricity

Taken from Breivik+ '16

- Distinct eccentricities
- Measurable in the LISA band
  - Hard to detect ~40% with ecc >5e-3 (Chen & Amaro-Seoane+17)
  - Eccentricity oscillations measurable out to few Mpc (Hoang+ 19)

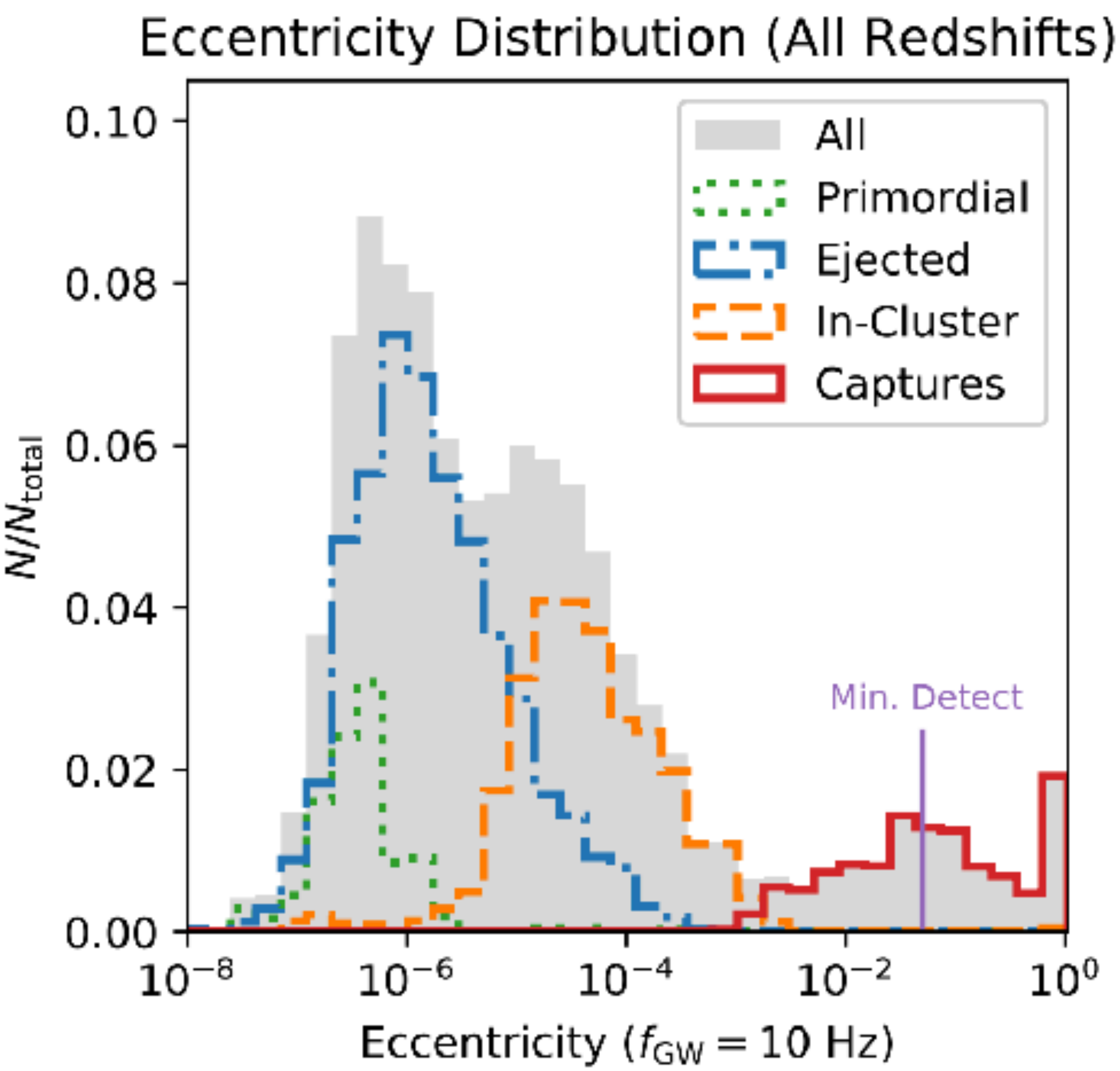


log(eccentricity)
upon entering LIGO band

Eccentricity

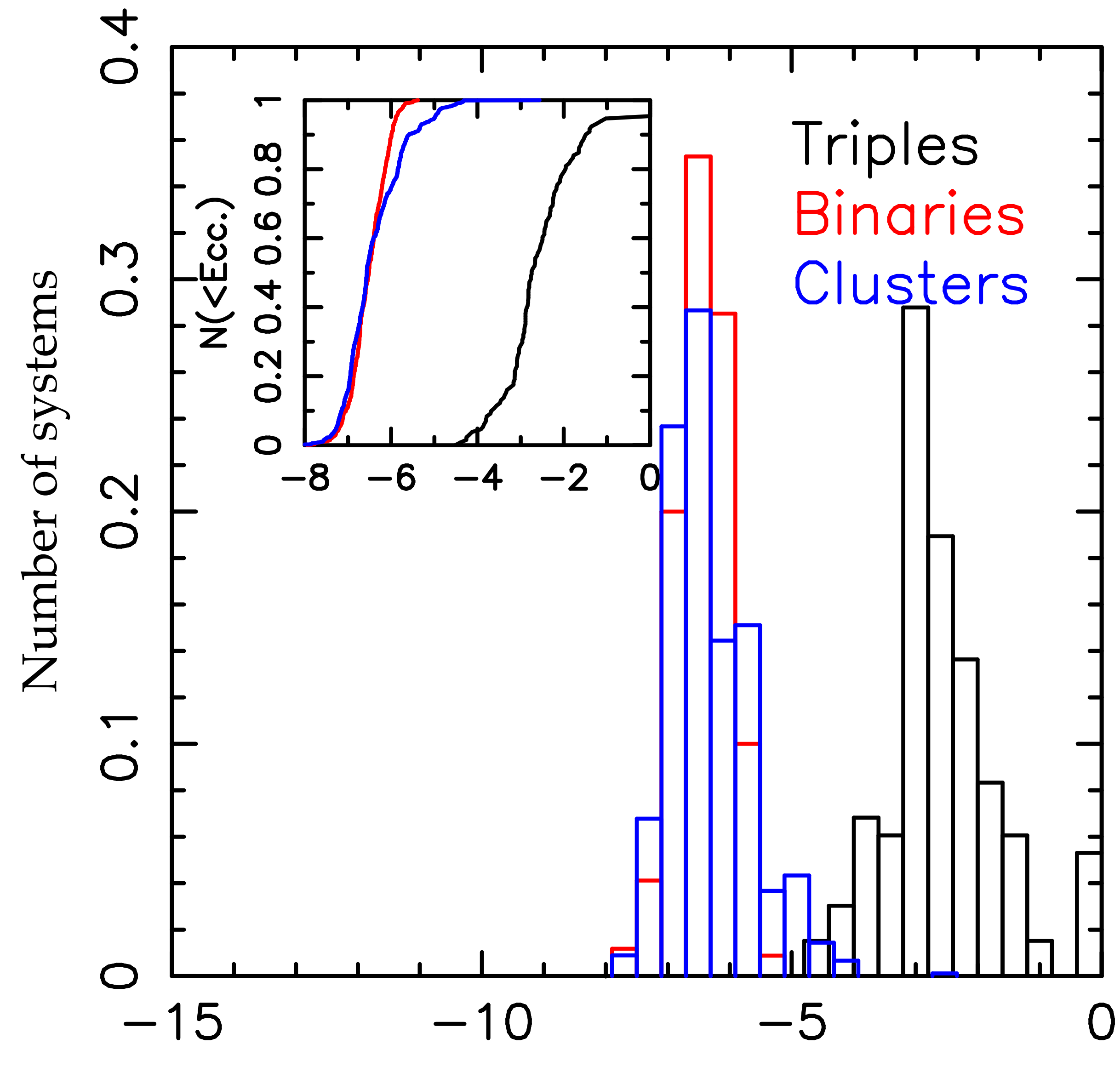
Taken from

Rodriguez+ ’18



Taken from

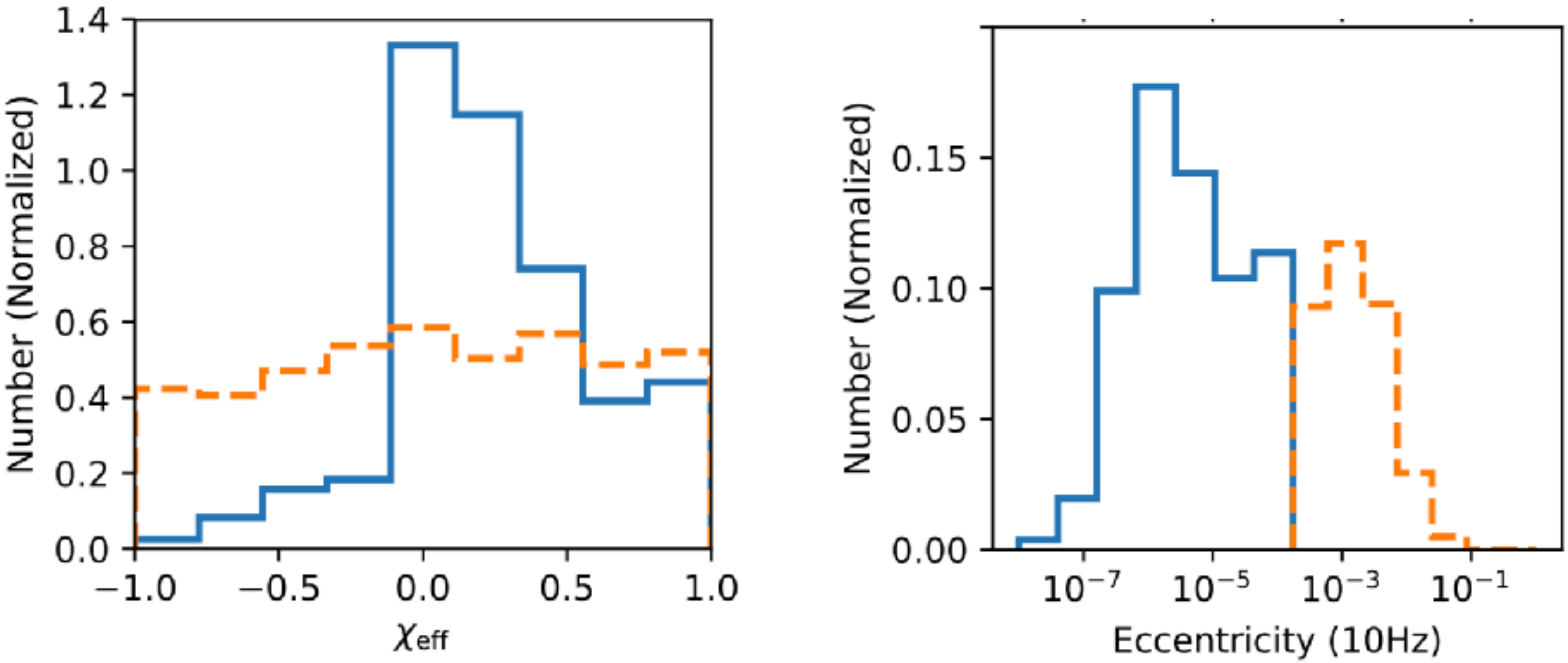
Breivik+ ’16



log(eccentricity)
upon entering LIGO band

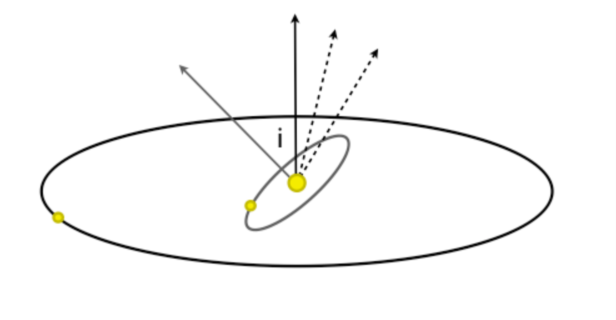
Spins

- Two regimes (Liu & Lai 17, 18, Antonini+ 17, Rodriguez & Antonini 18, Liu+ 19)
  - Plunge-in (from 3-body dyn., followed by: 2.5pN damps LK)
  - Freeze-out (spin precession damps LK-cycles gradually)



Taken from Rodriguez & Antonini '18

Summary



- Triple evolution
  - Triples are abundant
  - Code **TRES** to simulate triple evolution consistently (Toonen+ 2016)

- Leads to e.g.
  - Enhanced occurrence rate of mass transfer
  - Mass transfer in eccentric orbits
  - Stellar collisions, supernova Type Ia
  - Gravitational wave sources
    - 3-body interactions in wide triples
    - Rate: ~1 to several 10 per year per Gpc^3
    - High eccentricities, specific spin distribution