Evolution of stellar triples

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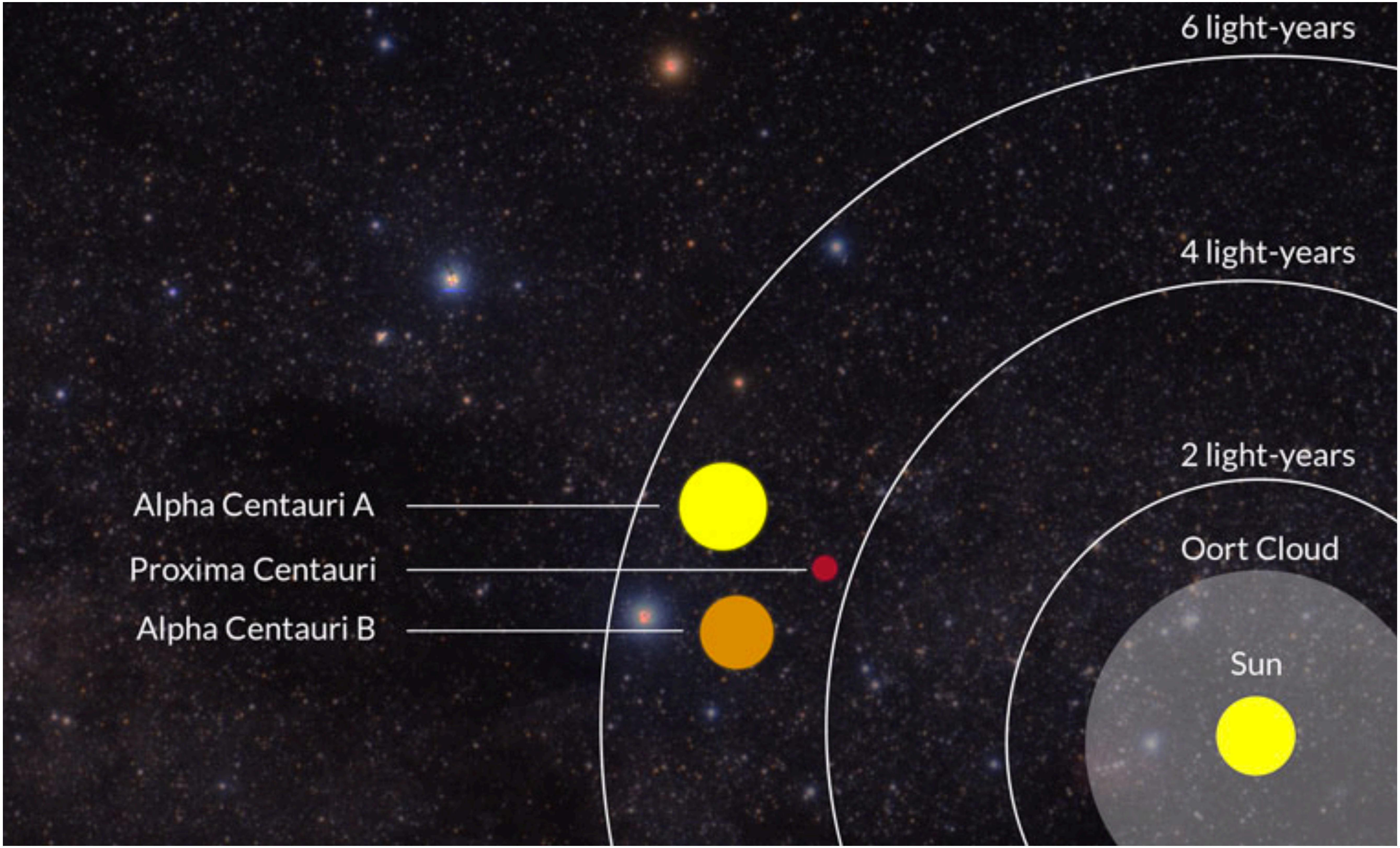
Simon Portegies Zwart (Leiden), Christian Knigge (Southampton)

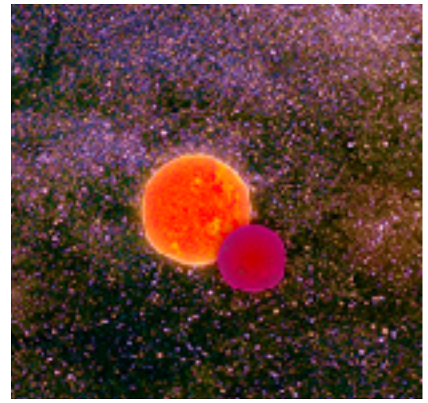
Our nearest neighbour…



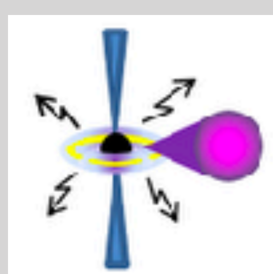
Single stars

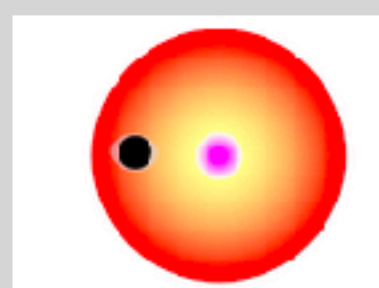
Binaries

Triples



Stellar interactions, e.g.:





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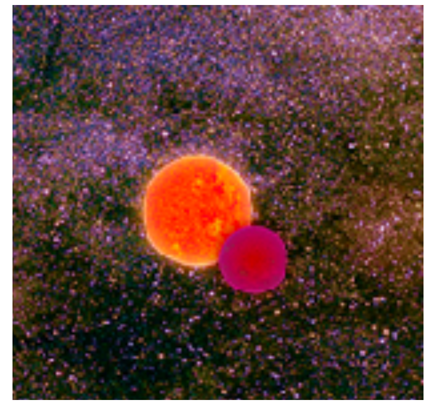

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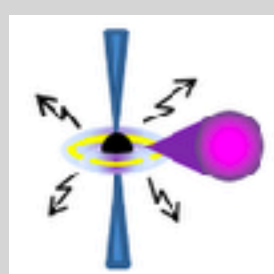
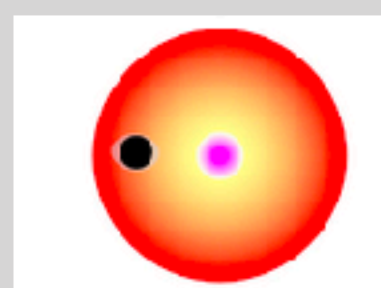
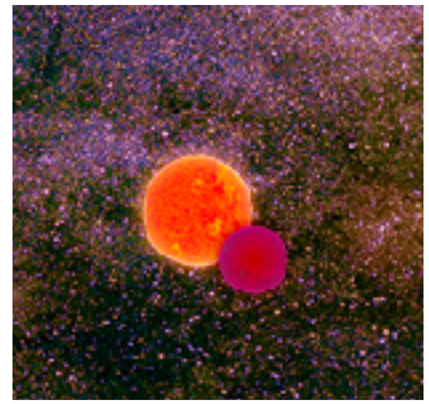




Single stars | Binaries | Triples



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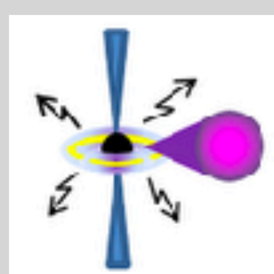
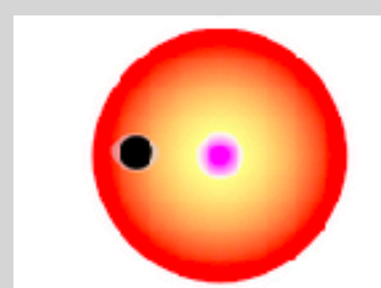
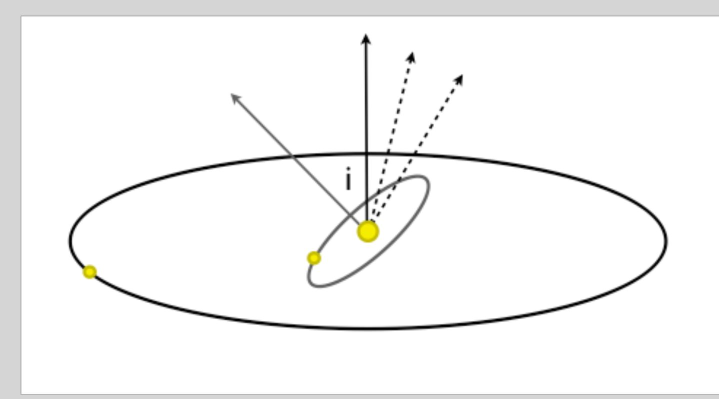




Orbital interactions:



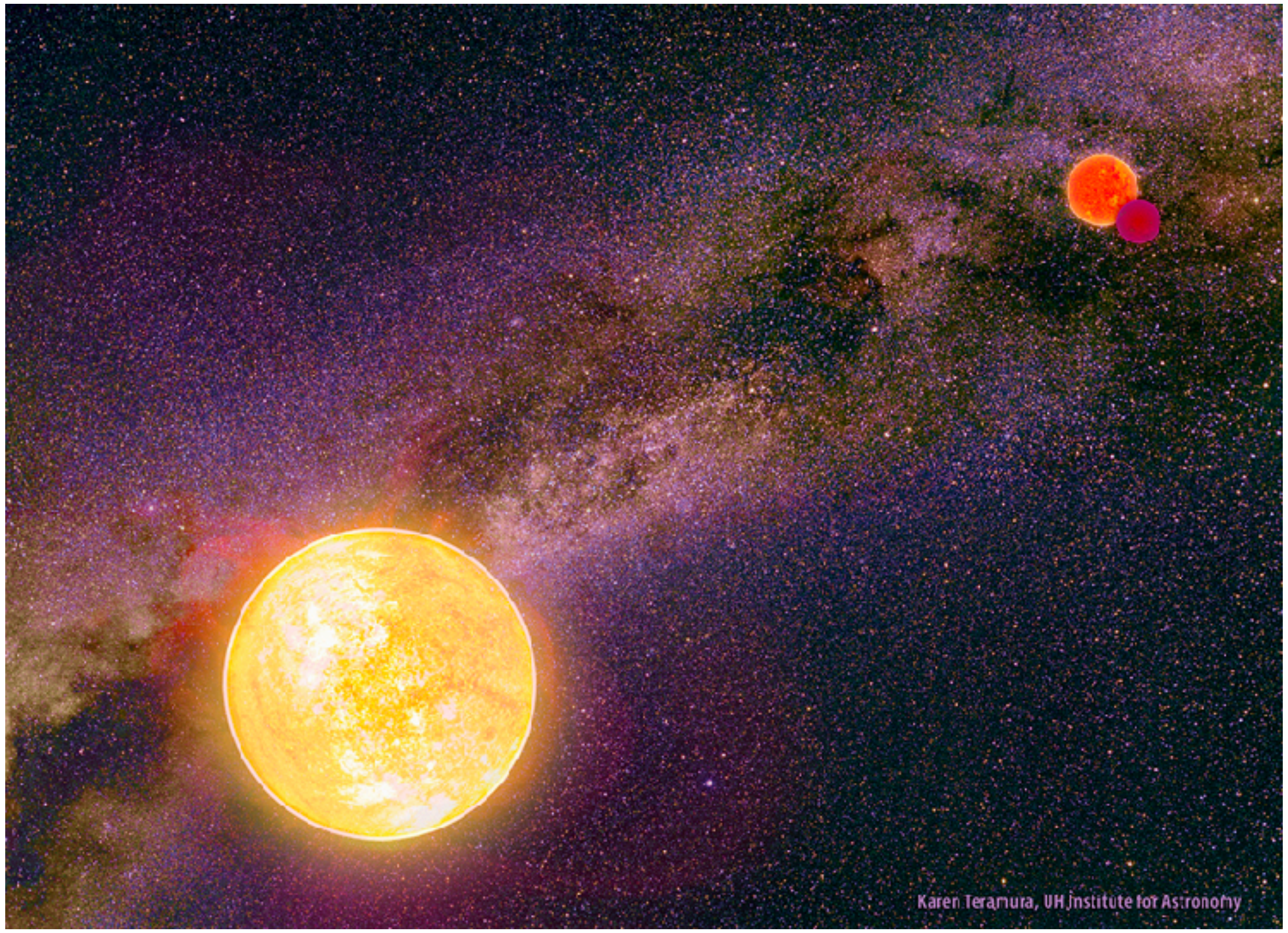
3-body dynamics

➡ The observational revolution calls for a higher accuracy in theoretical astronomy

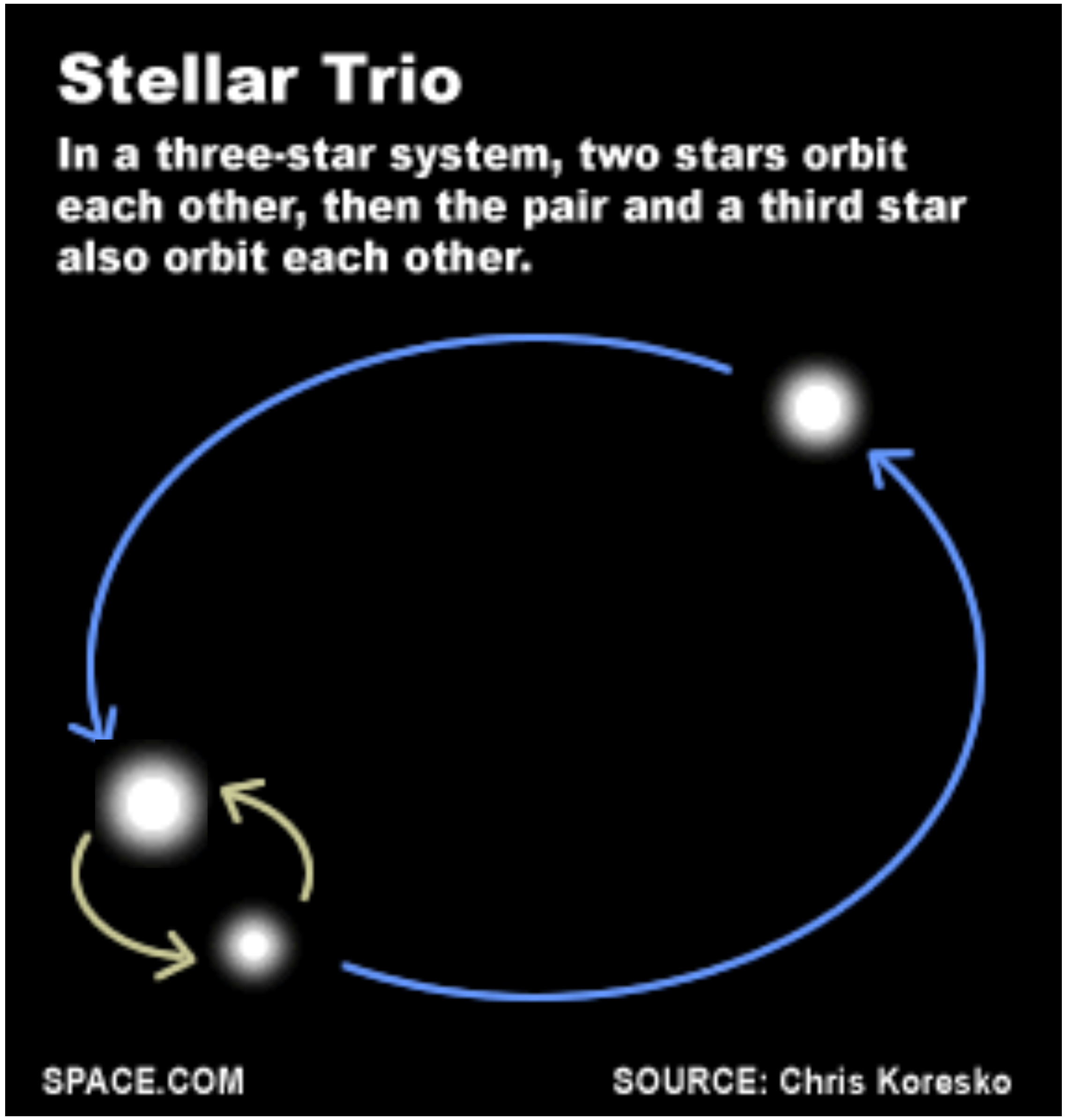
Outline

1. Triple intro
   - Why care about stellar triples
   - How do triples evolve differently than binaries?

2. Typical evolution of triples & applications of triple evolution
   - Cataclysmic variables, barium stars, gravitational wave sources etc.



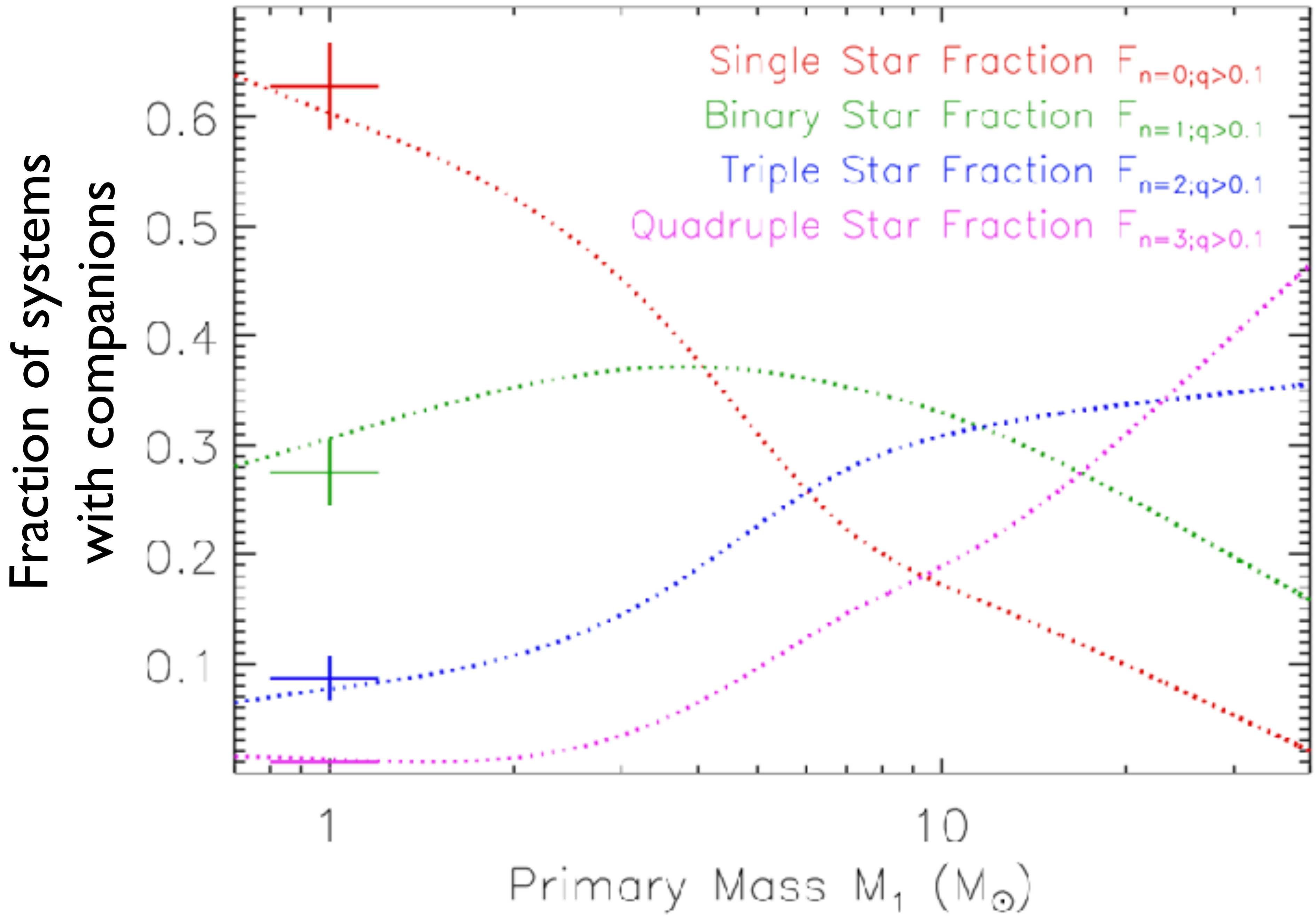
Stellar triples



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

Abundance

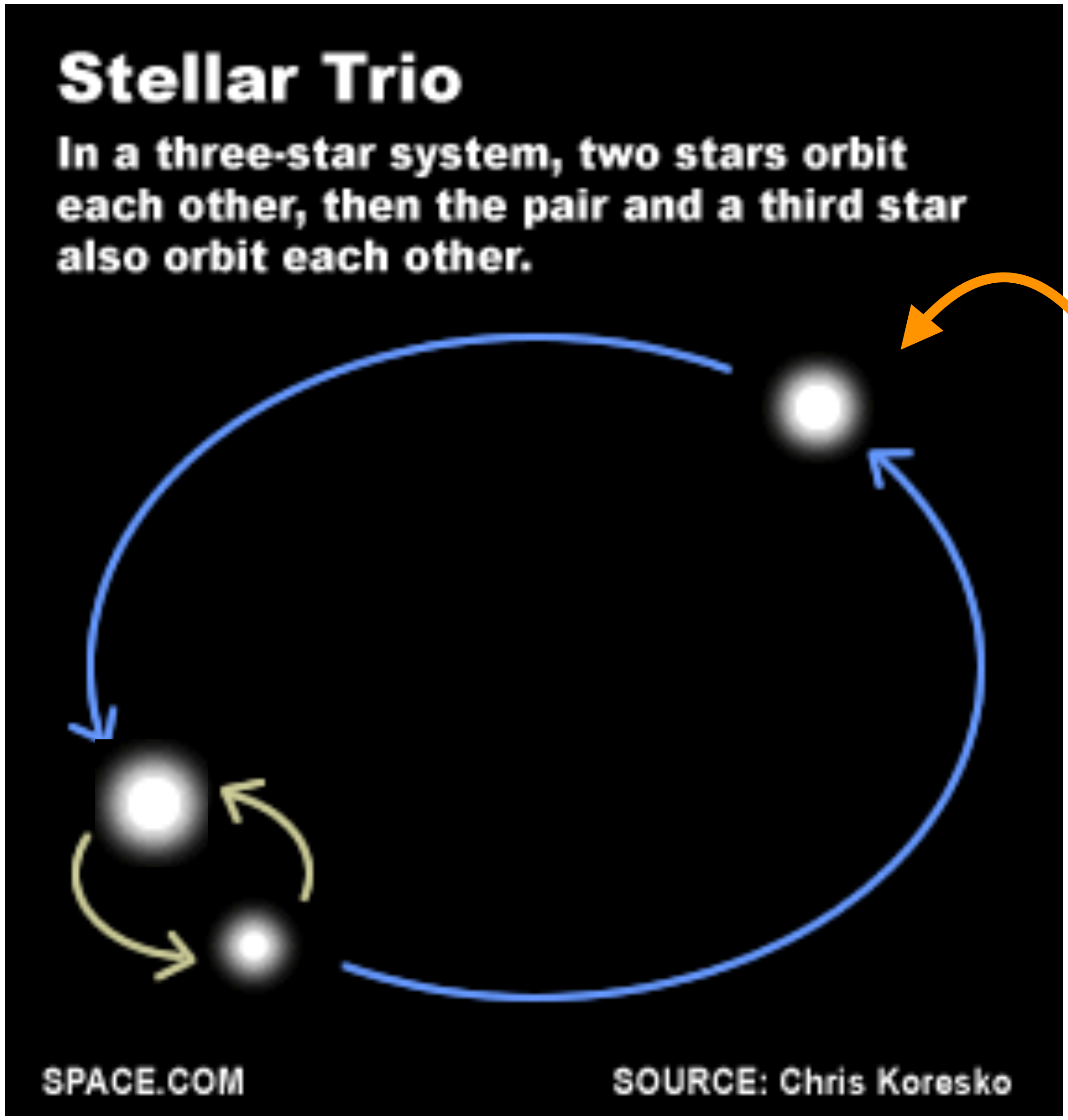
Moe+ '17



Initial distribution - young systems

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

Stellar triples

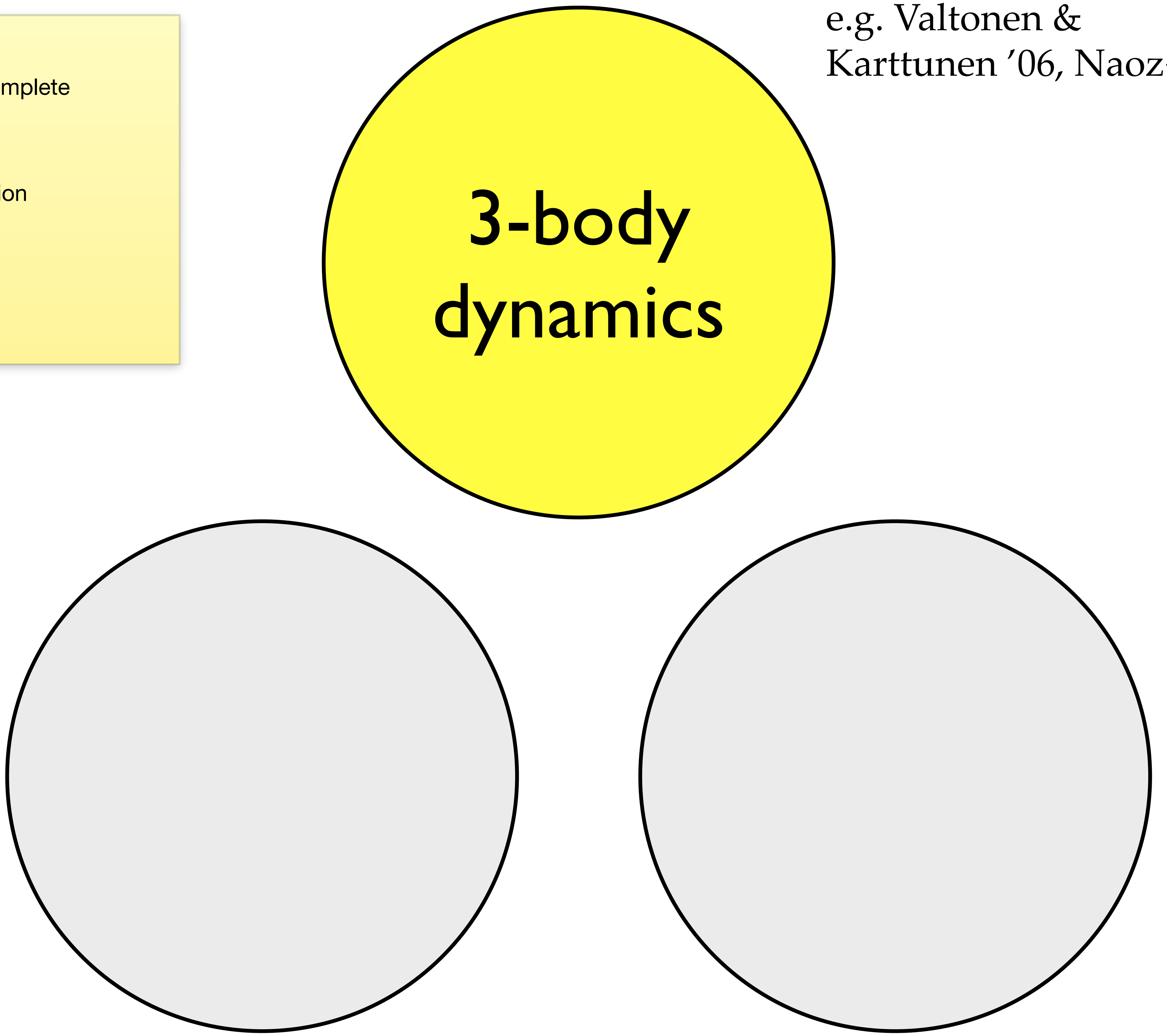


- Triple evolution poorly understood, but recent progress
- Not only physical interactions play a role, but first level where orbital interactions play a role.
- Strong effect on inner binary. How? When?

Triple evolution

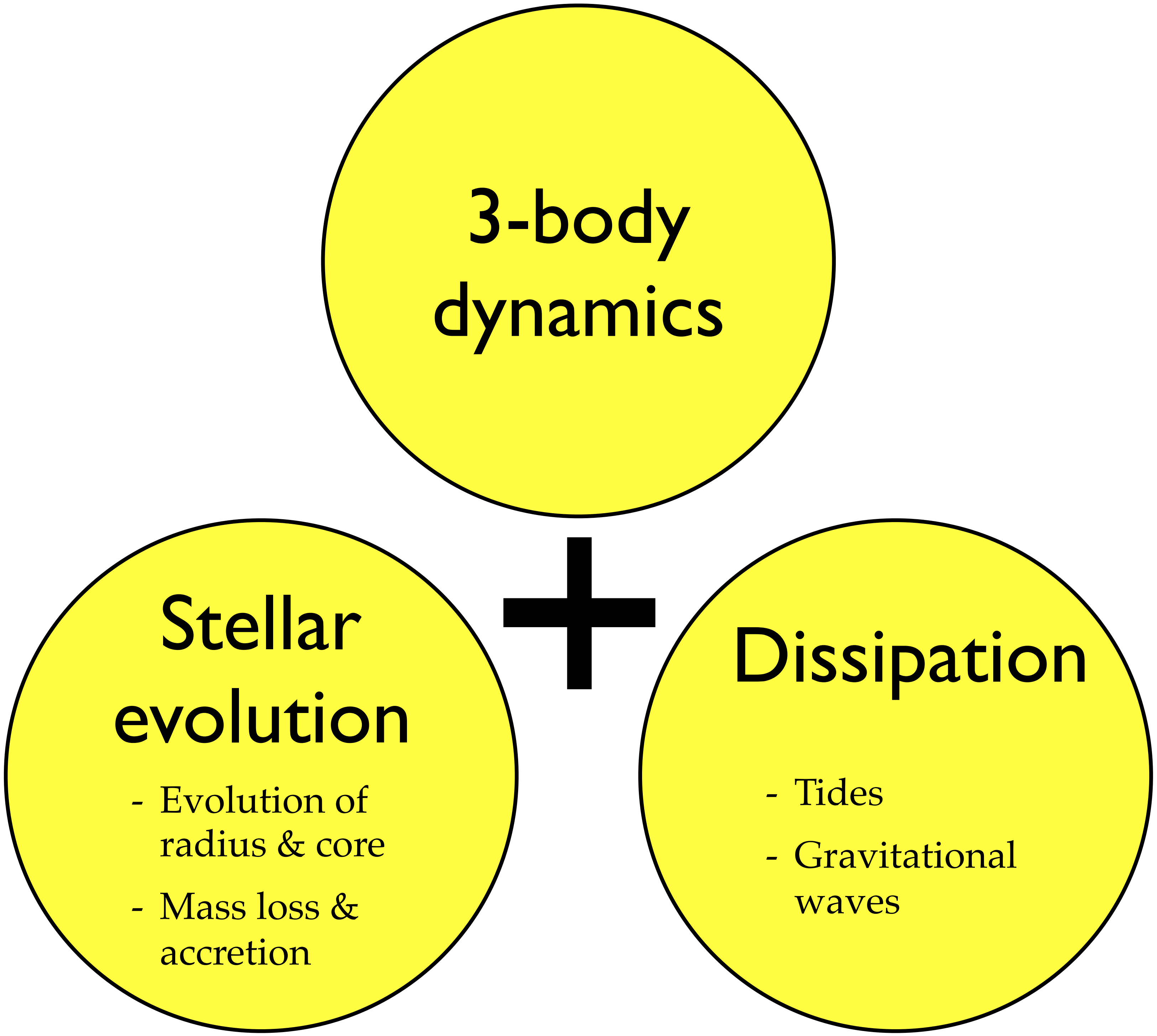
fragmented & incomplete

3-body problem
no analytical solution

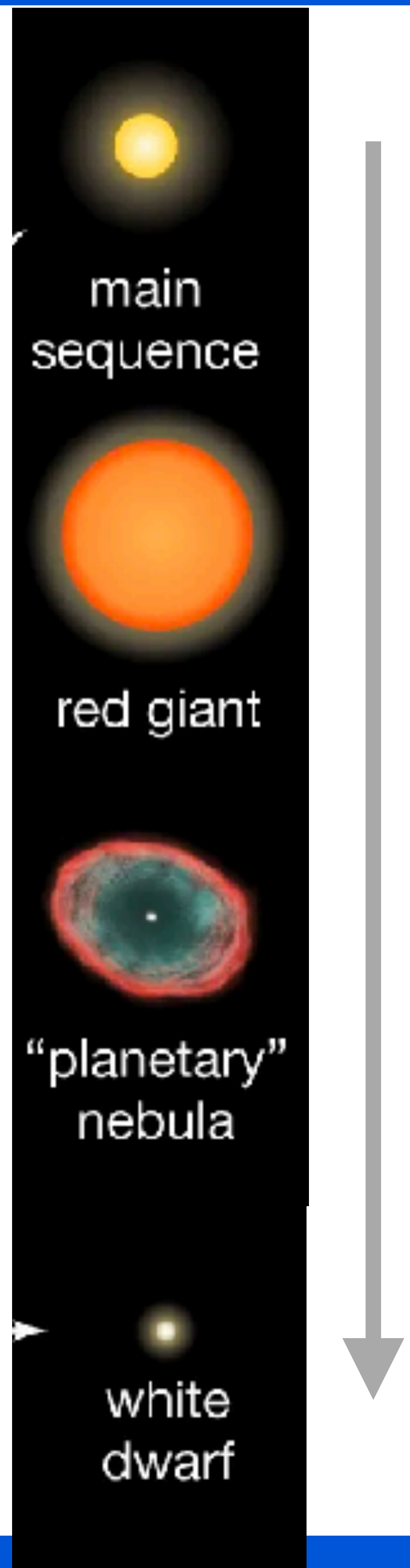


e.g. Valtonen & Karttunen '06, Naoz+ 16

Triple evolution



Triple evolution



3-body dynamics

+

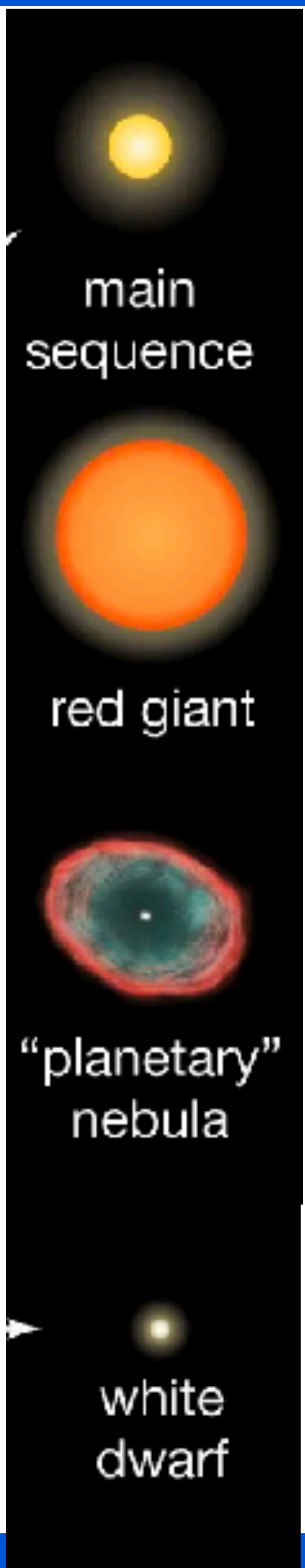
Stellar evolution

- Evolution of radius & core
- Mass loss & accretion

Dissipation

- Tides
- Gravitational waves

Triple evolution



3-body dynamics

+

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Dissipation

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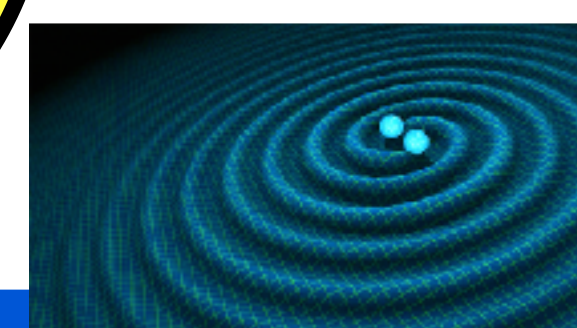
Tides effective when:
radius ~ orbit

Gravitational waves
effective when:
orbit small



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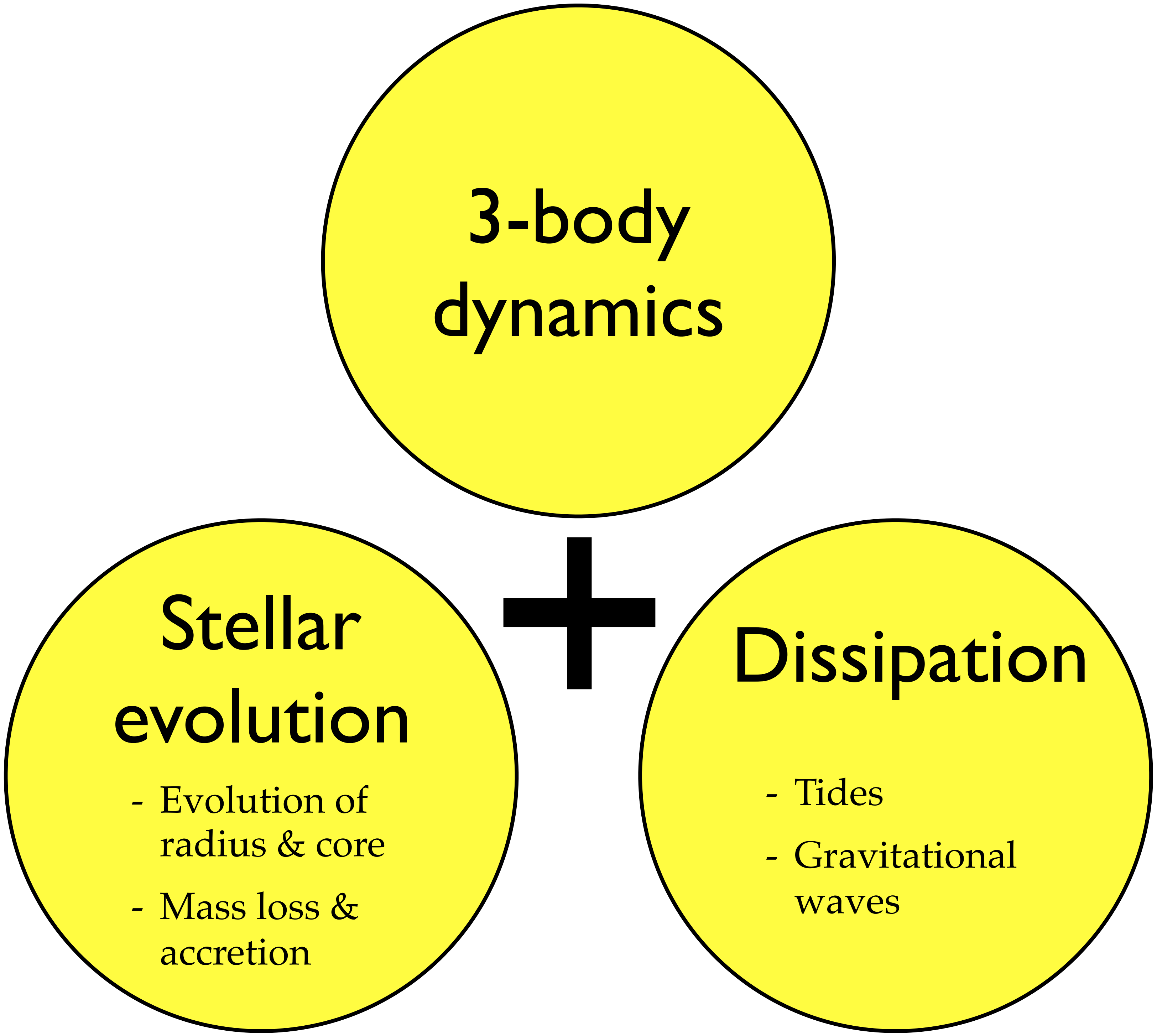


Triple code TRES

- Common evolution (Toonen+ '20)
- Supernova type Ia (Toonen+ '18)
- BH-BH mergers (Antonini, Toonen+ '17)
- Sequential mergers (Vigna-Gomez+ '20)
- Circumbinary planets (Columba+ '23)
- Unstable triples (Toonen+ 2022)
- Formation of cataclysmic variables (Knigge+ 2022)
- Formation of Barium stars (Gao+ '23)
- Massive stars (Kummer+ subm)

TRES core team

Tjarda Boekholt

Floris Kummer

Silvia Toonen, PI

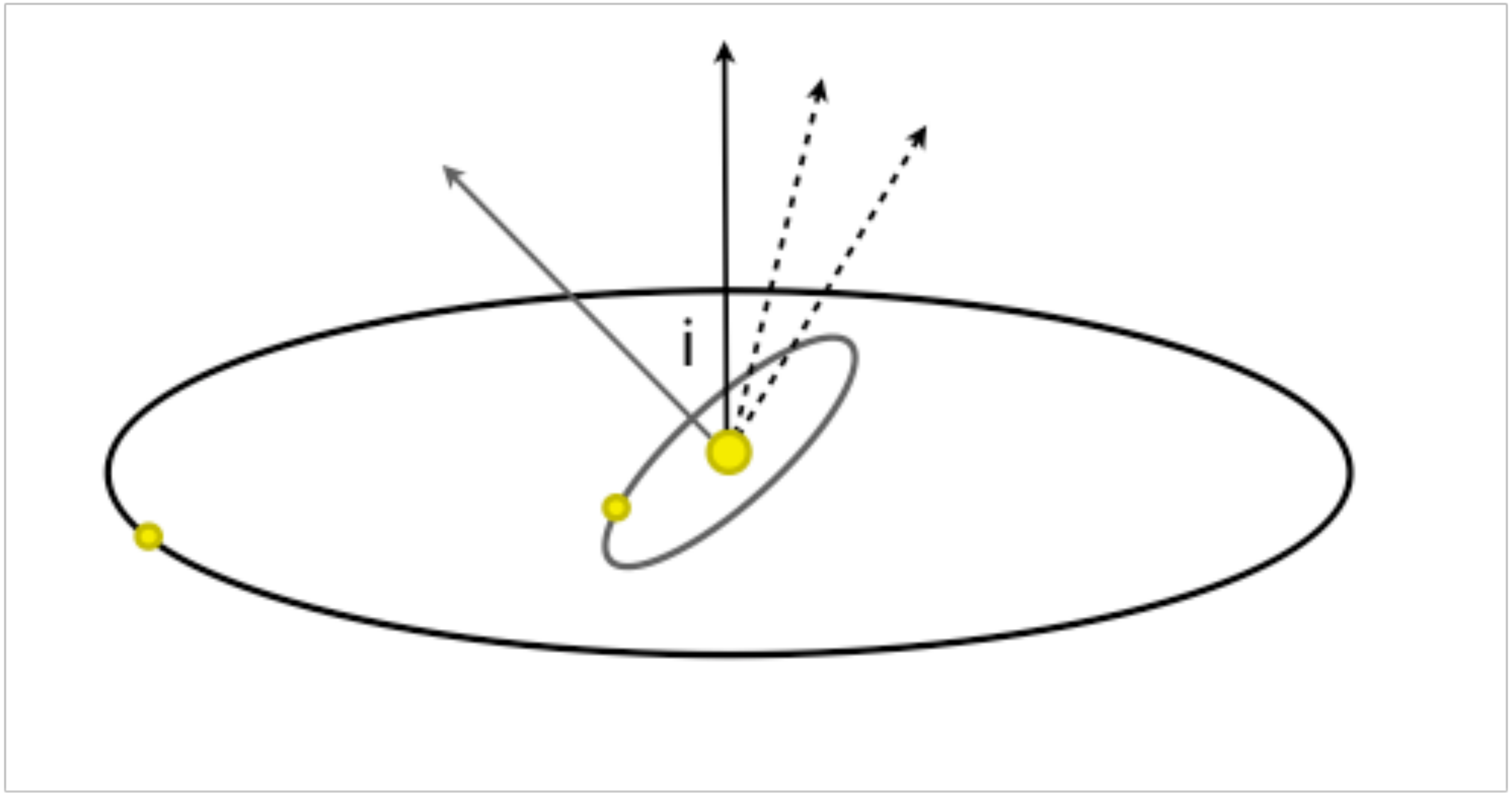
Andris Dorozsmai

Simon Portegies Zwart

Caspar Bruenech

github.com/amusecode/TRES

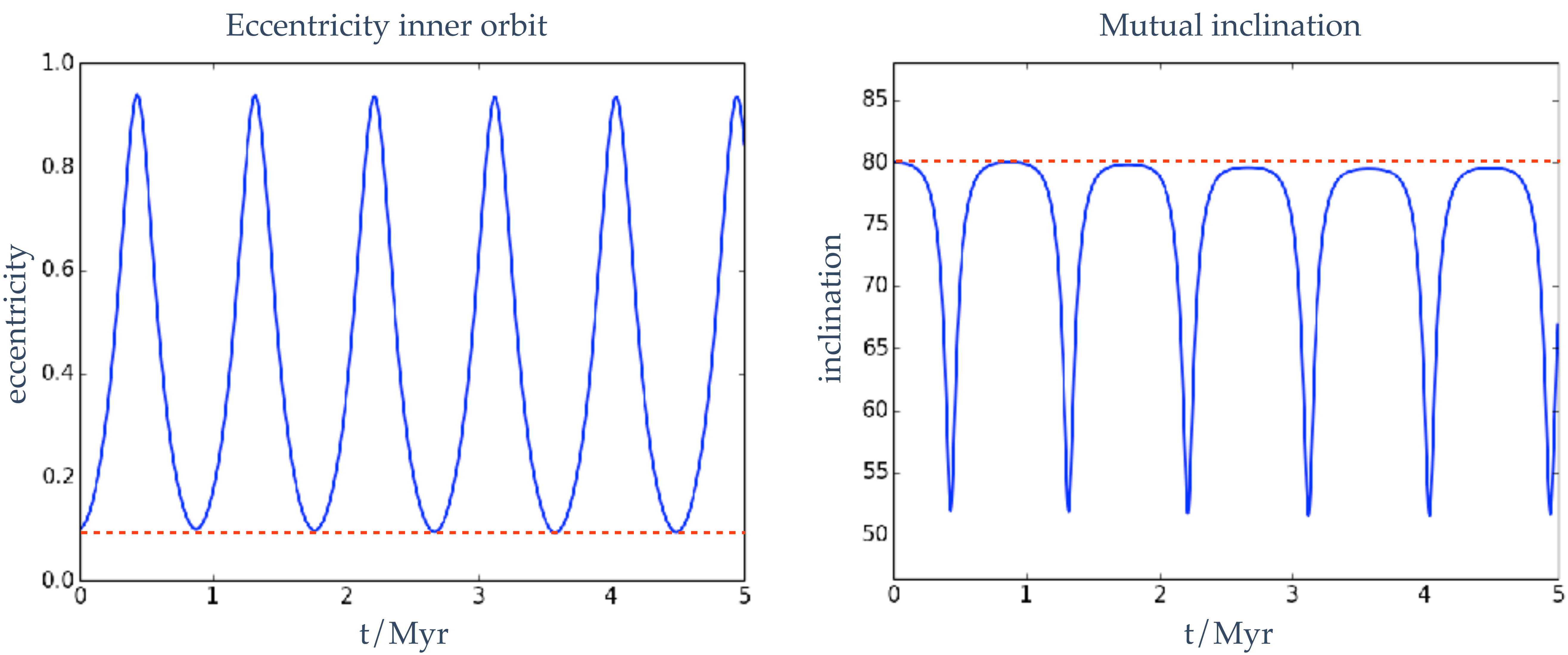
3-Body dynamics



- Kozai-Lidov cycles (Lidov '62 , Kozai '62) $P_{\mathrm{KL}} \sim \frac{P_{\mathrm{outer}}^2}{P_{\mathrm{inner}}} \frac{m_1 + m_2 + m_3}{m_3} (1 - e_{\mathrm{outer}}^2)^{3/2}$
- Higher-order effects: more extreme eccentricities, orbital flips (see review of Naoz+ 16)

Kozai-Lidov cycles

example: M1=1.3, M2=0.5, M3=0.5MSun, a1=200, a2 =20000RSun, e1=0.1, e2 =0.5, i=80, g1=0.1, g2=0.5

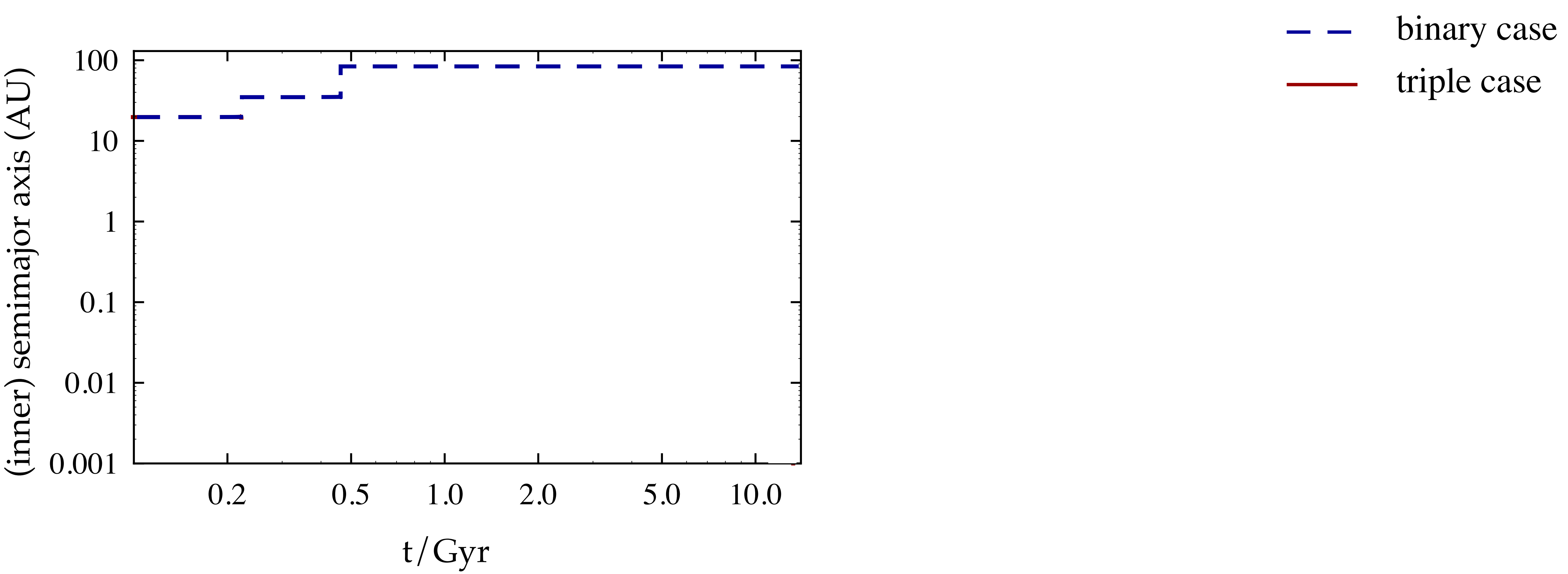


Binary case
Triple case

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

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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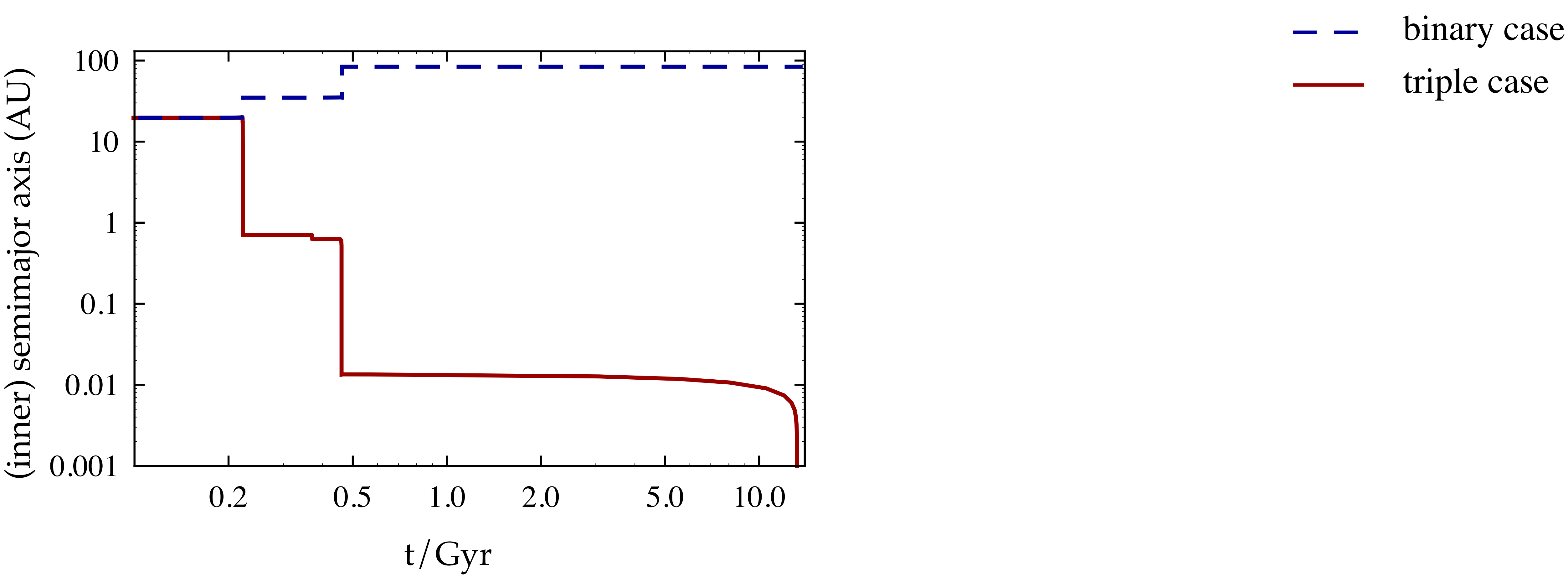

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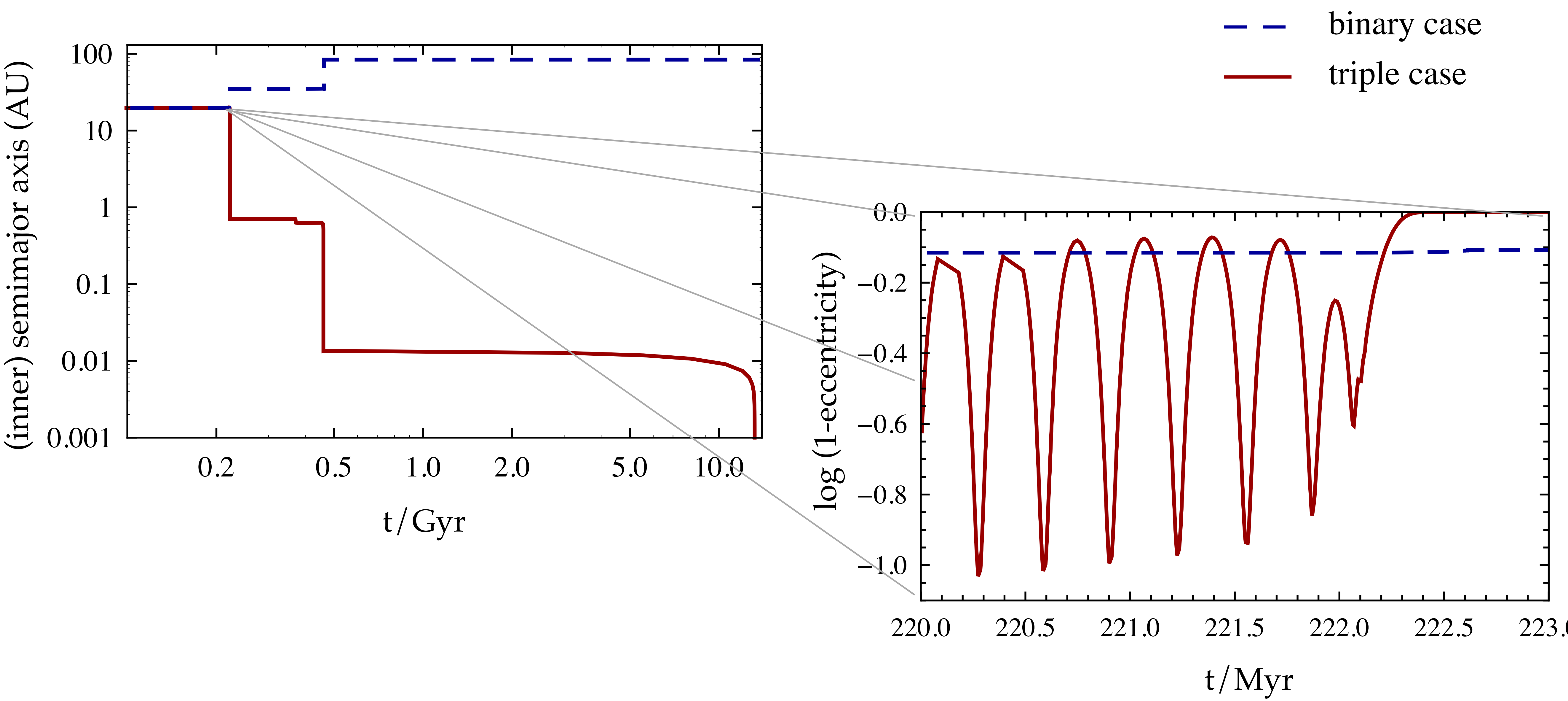

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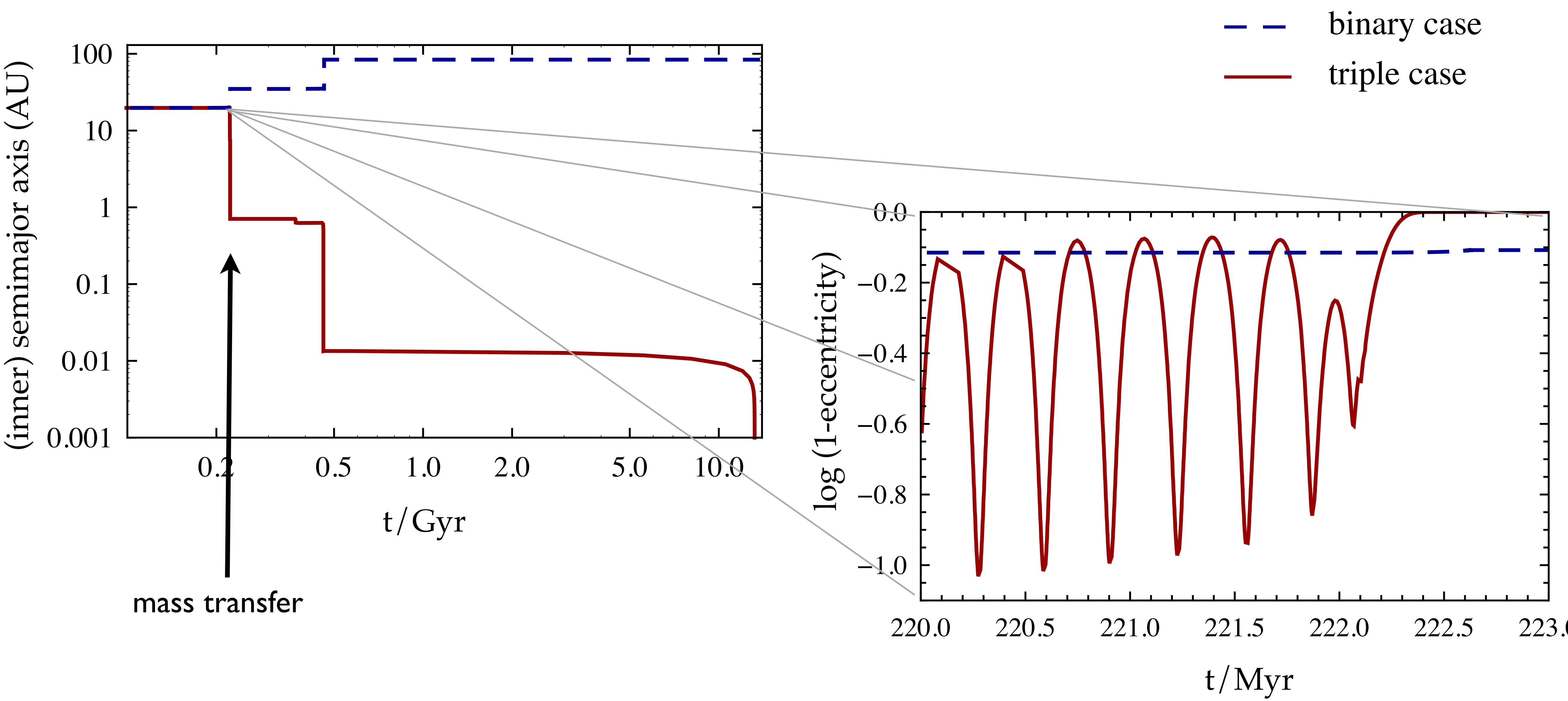

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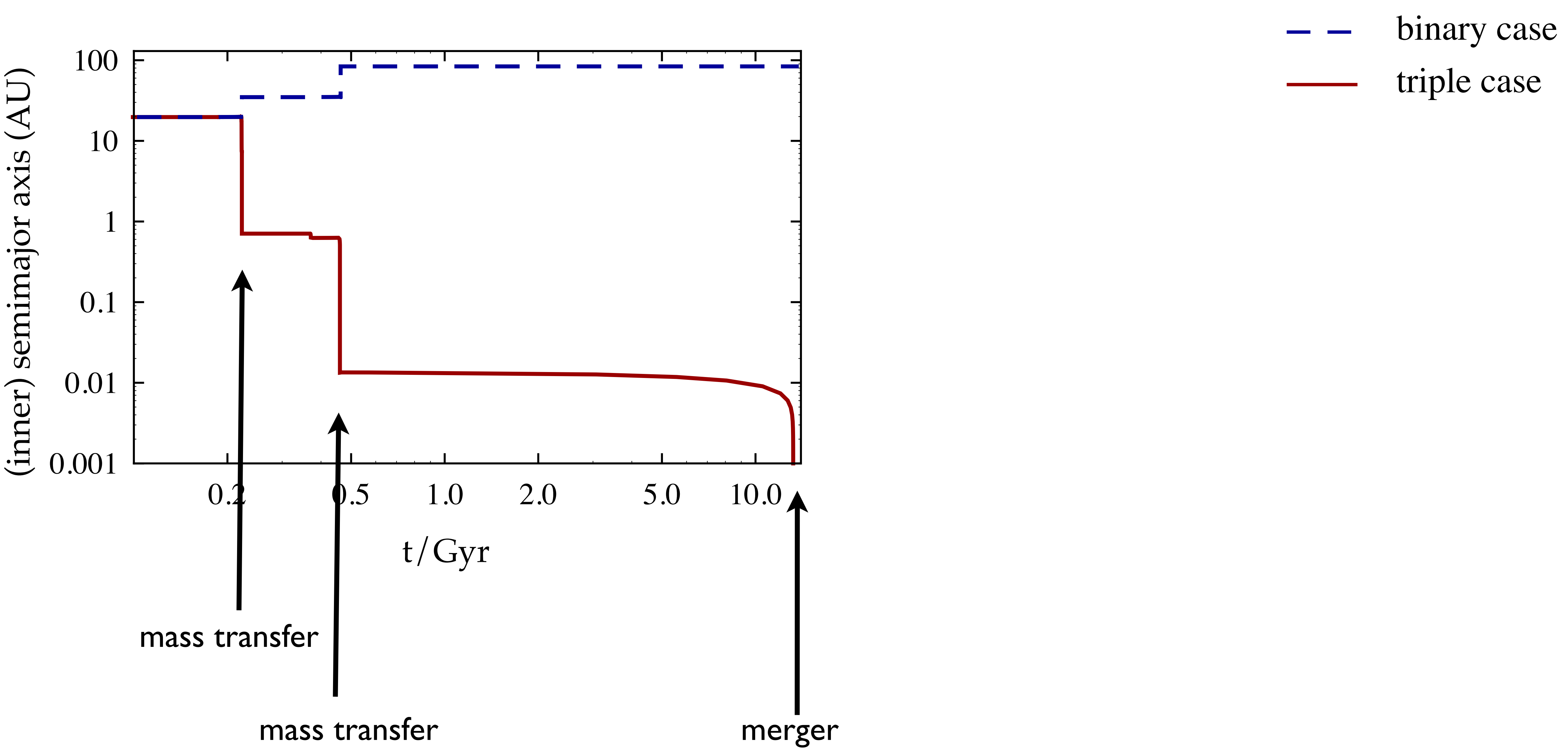

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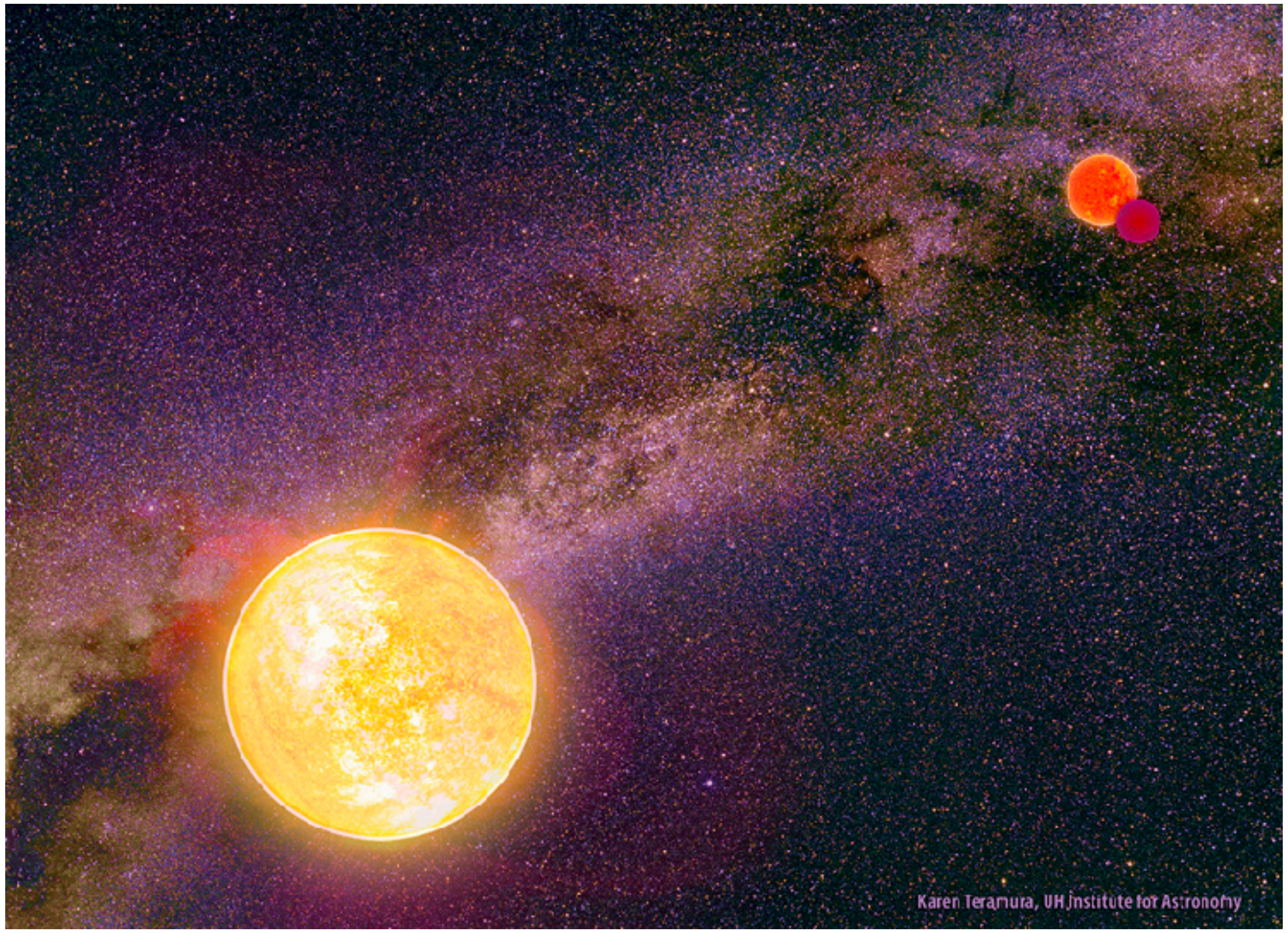

Typical evolution of triples

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

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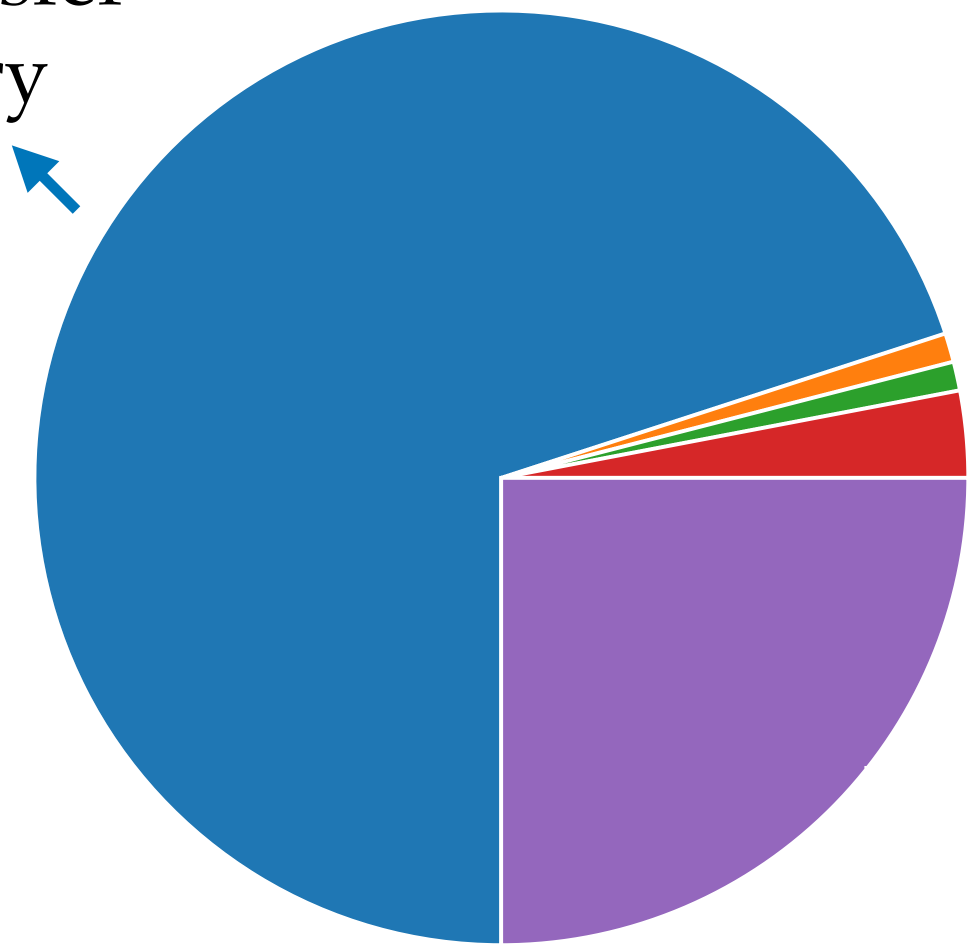
Mass transfer
by primary
~64-75%



In binaries:

only ~28-39%

- N(P) ∝ 1/P
- N(P) ∝ log-normal(P)

Take-home message

For every 3 binaries formed, at least one triple is born
(Tokovinin+ '14, Moe+ '17)

Triples interact more often than binaries!
(Toonen+ '20)

Triples on even footing with binaries

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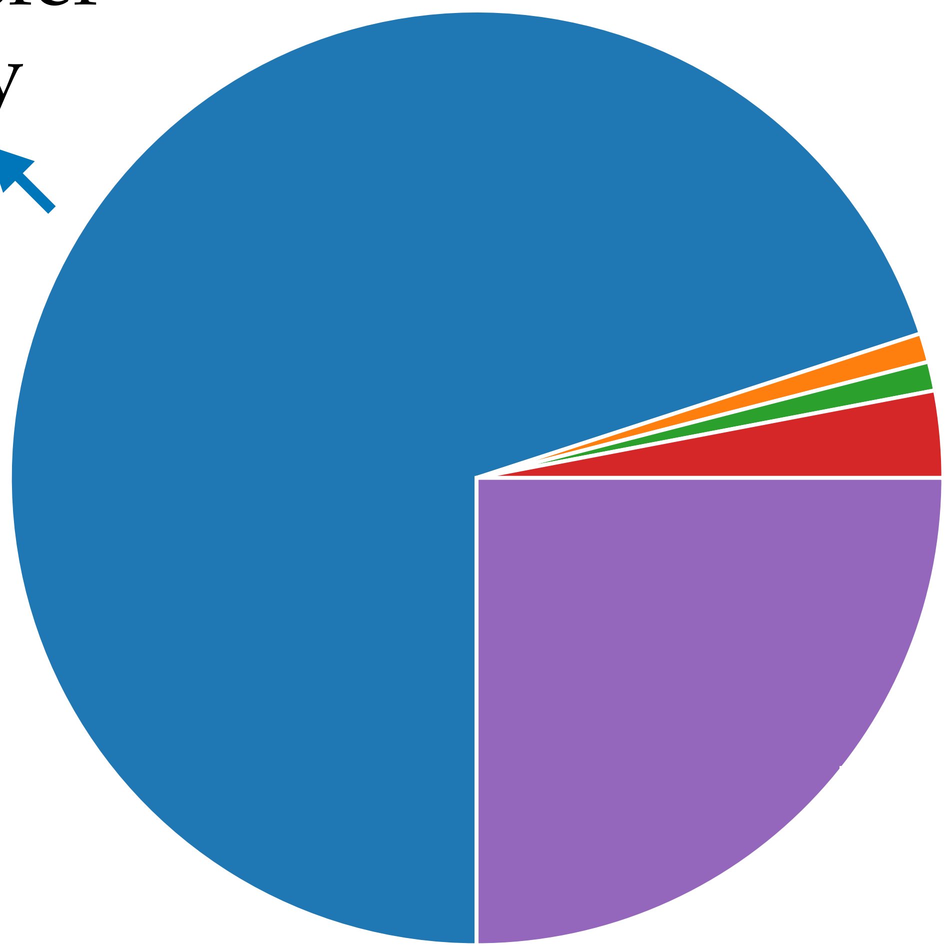

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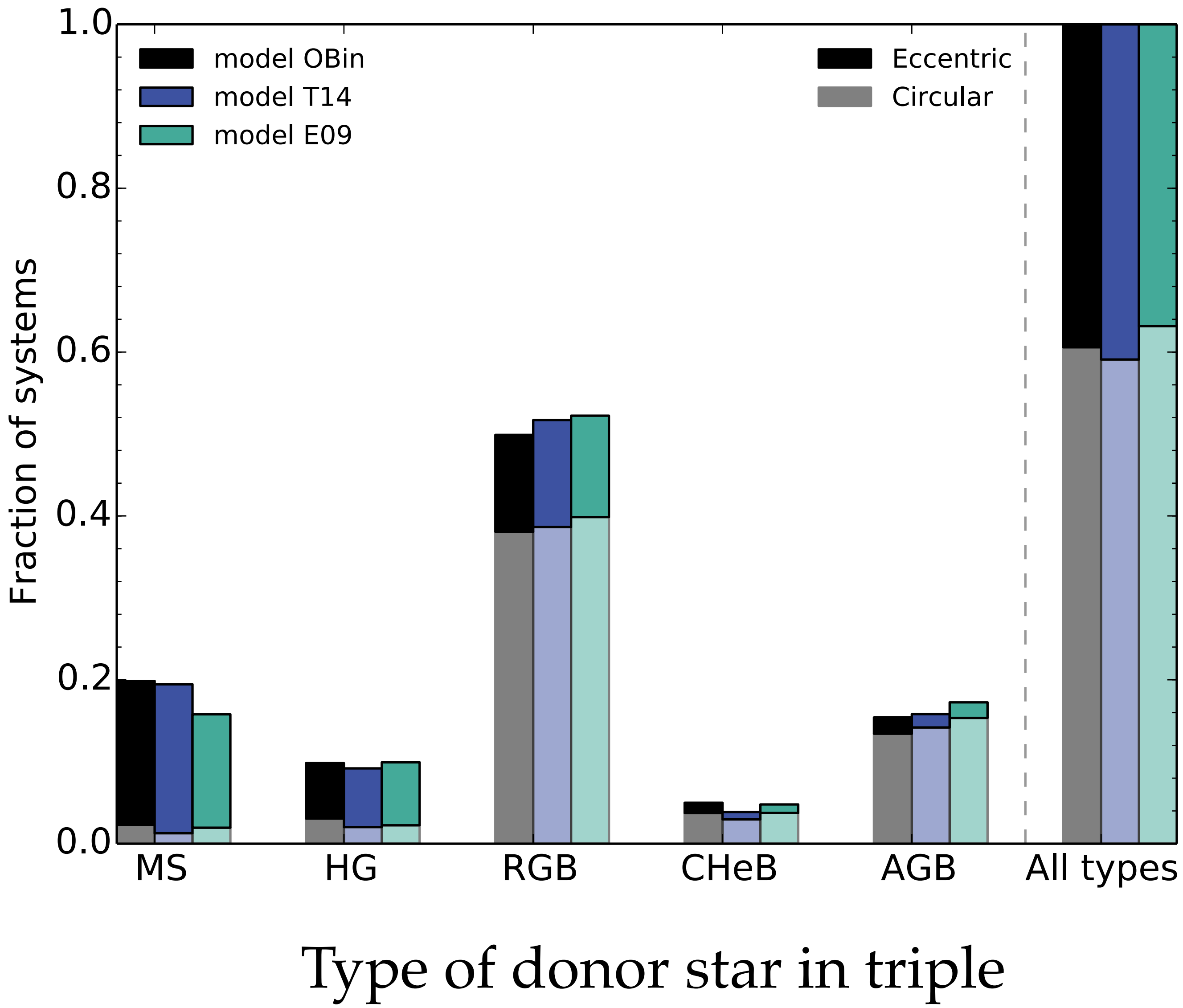
Mass transfer

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



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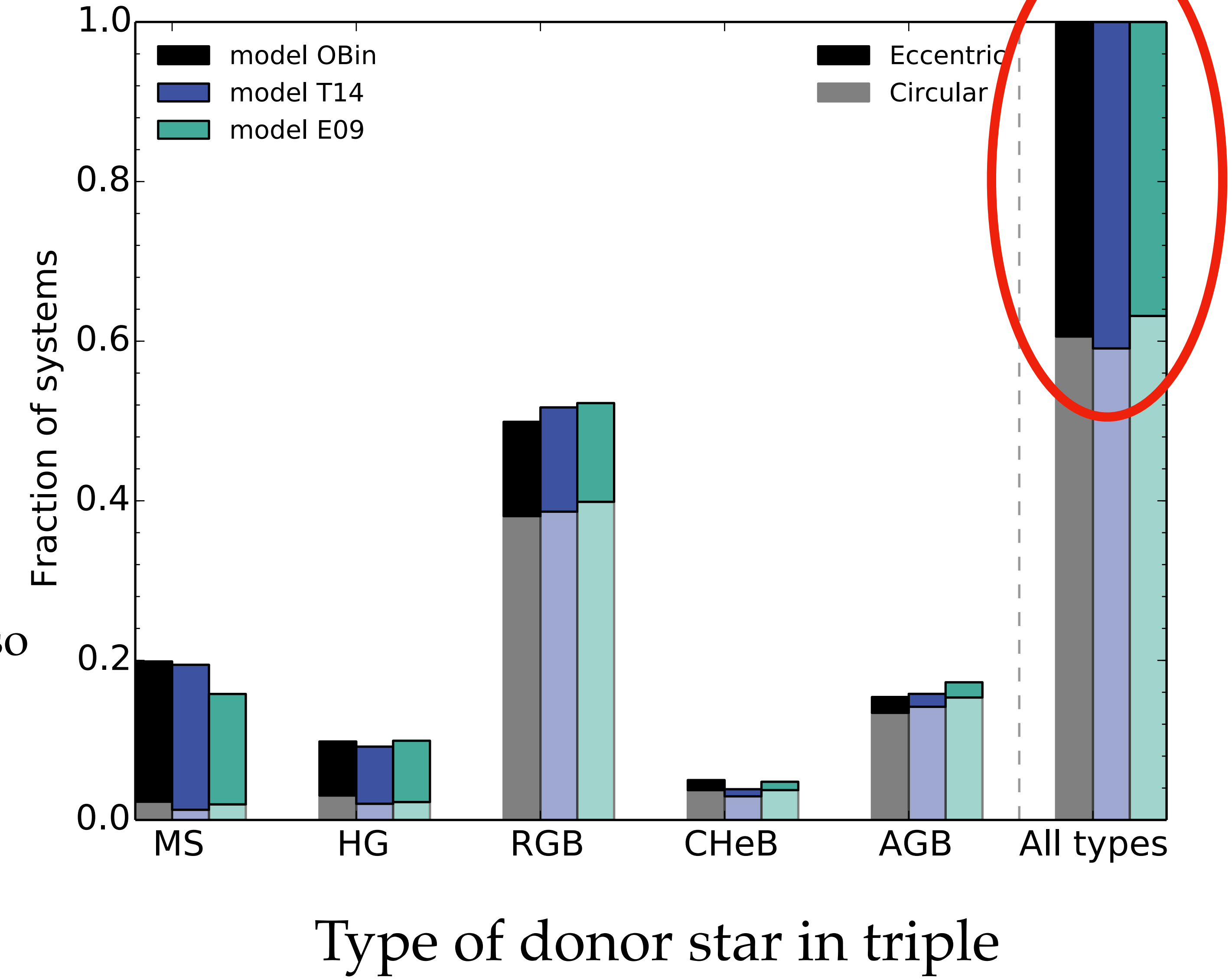
    ➡ Observed sources

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

➡ Tides crucially important (see also Preece+ 22)

➡ New framework needed for modelling eccentric mass transfer (Sepinsky+ '07, '09, '11, Dosopoulou+ '16, Hamers & Dosopoulou '19)

~40% still eccentric



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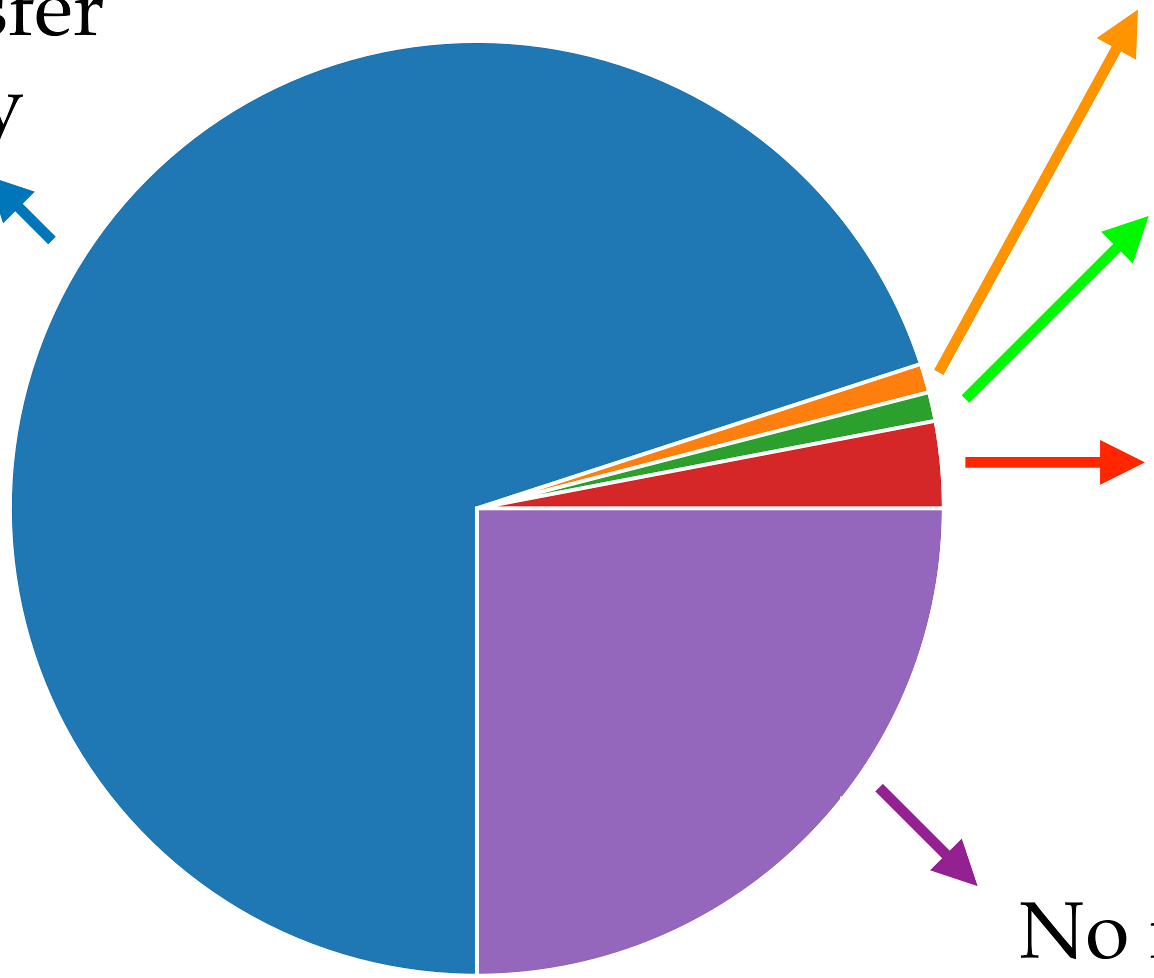

Secondary donates mass (~0.75%)

Tertiary donates mass (~0.5-1%)

Dynamically unstable (~2-4.5%)

No interaction ~20-30%

In binaries: only ~28-39%

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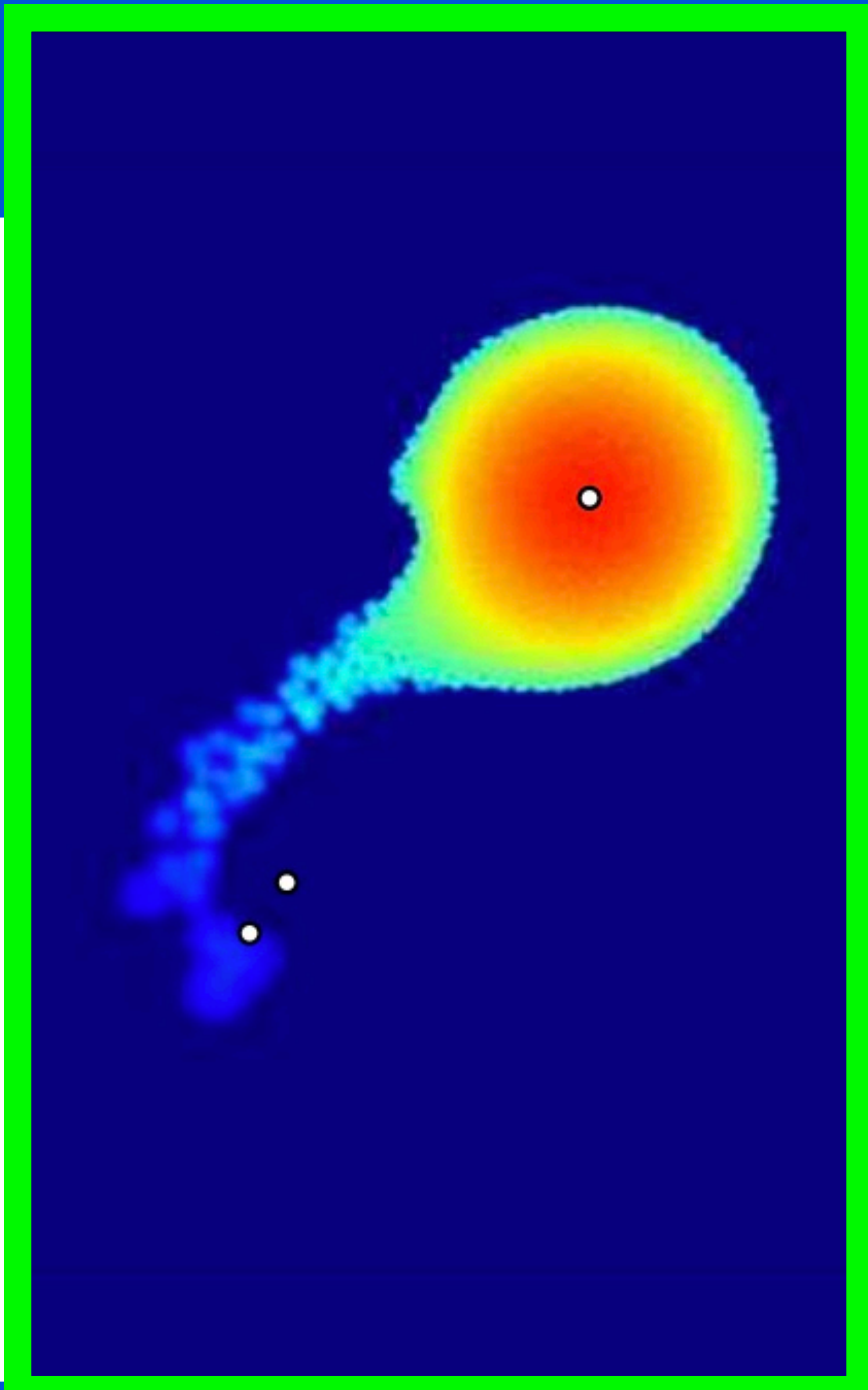

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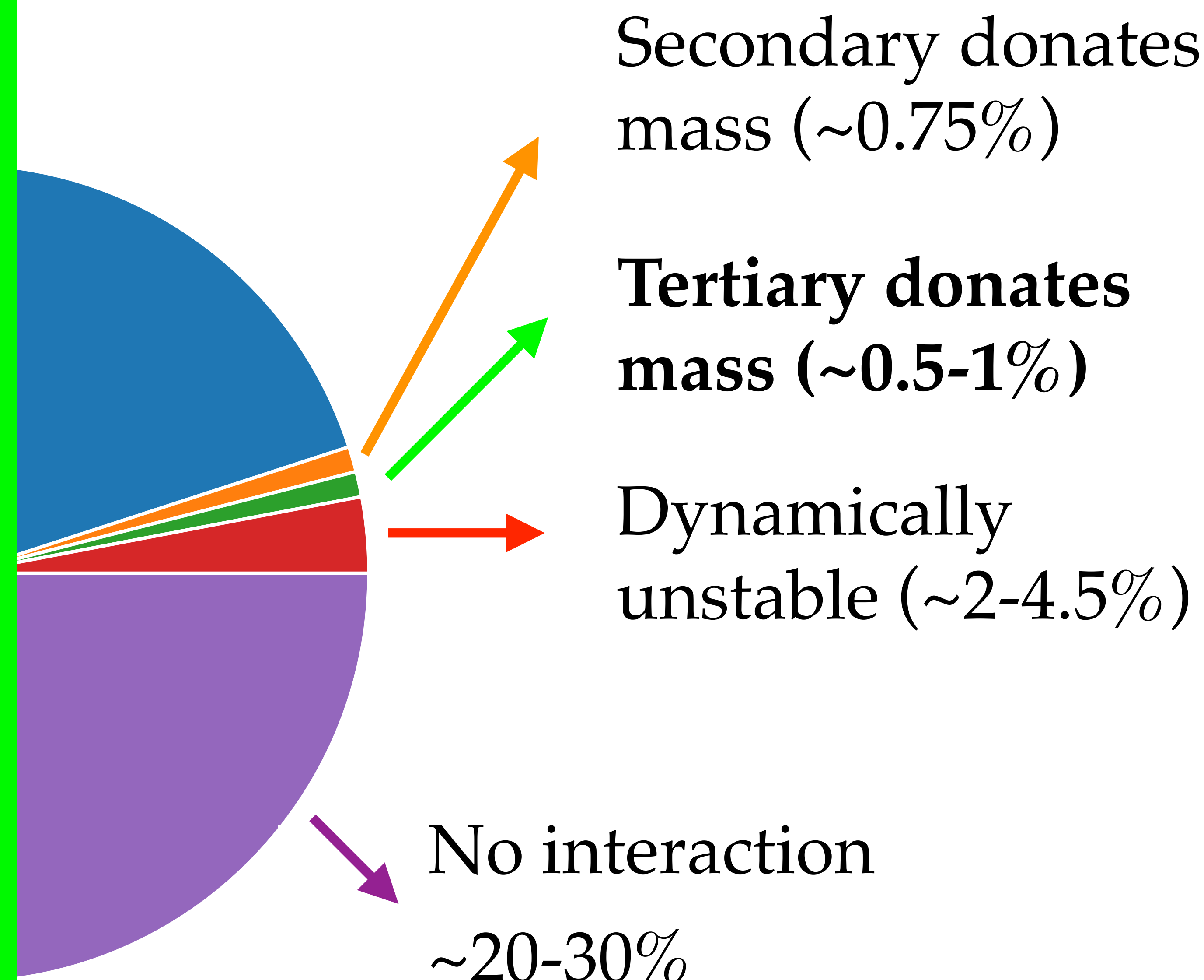
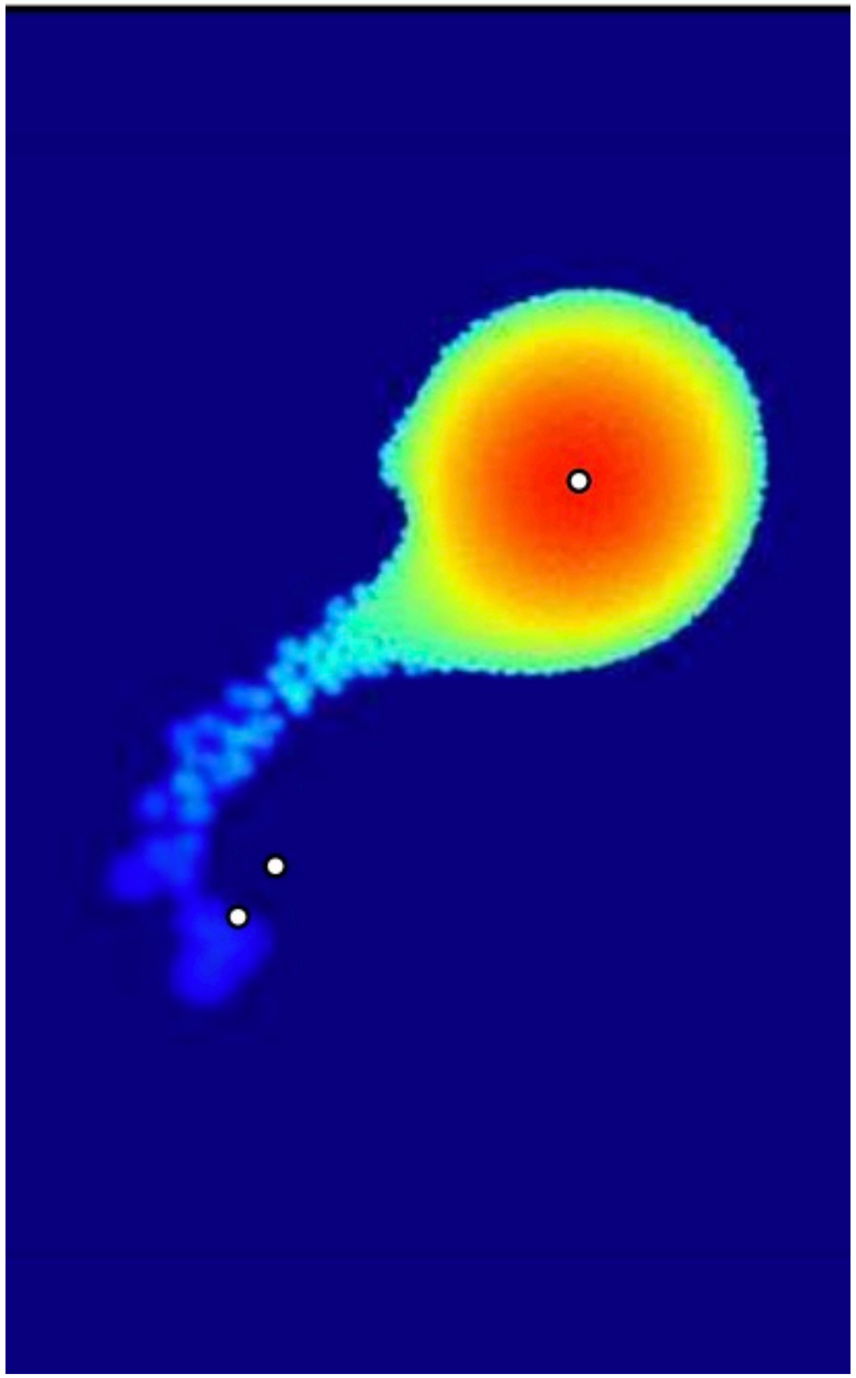


Tertiary donates mass

- Frequency (~0.5-1%) consistent with observations of Tokovinin catalogue (De Vries+ '14)
- Creates twin blue stragglers through circum-binary disks
  (Portegies Zwart & Leigh '19)
- For other systems: based on binary modelling (Leigh+ w/Toonen '20):
  ~1% of MS-MS
  ~ 1-5% of WD-MS
  ~5-10% of WD-WD

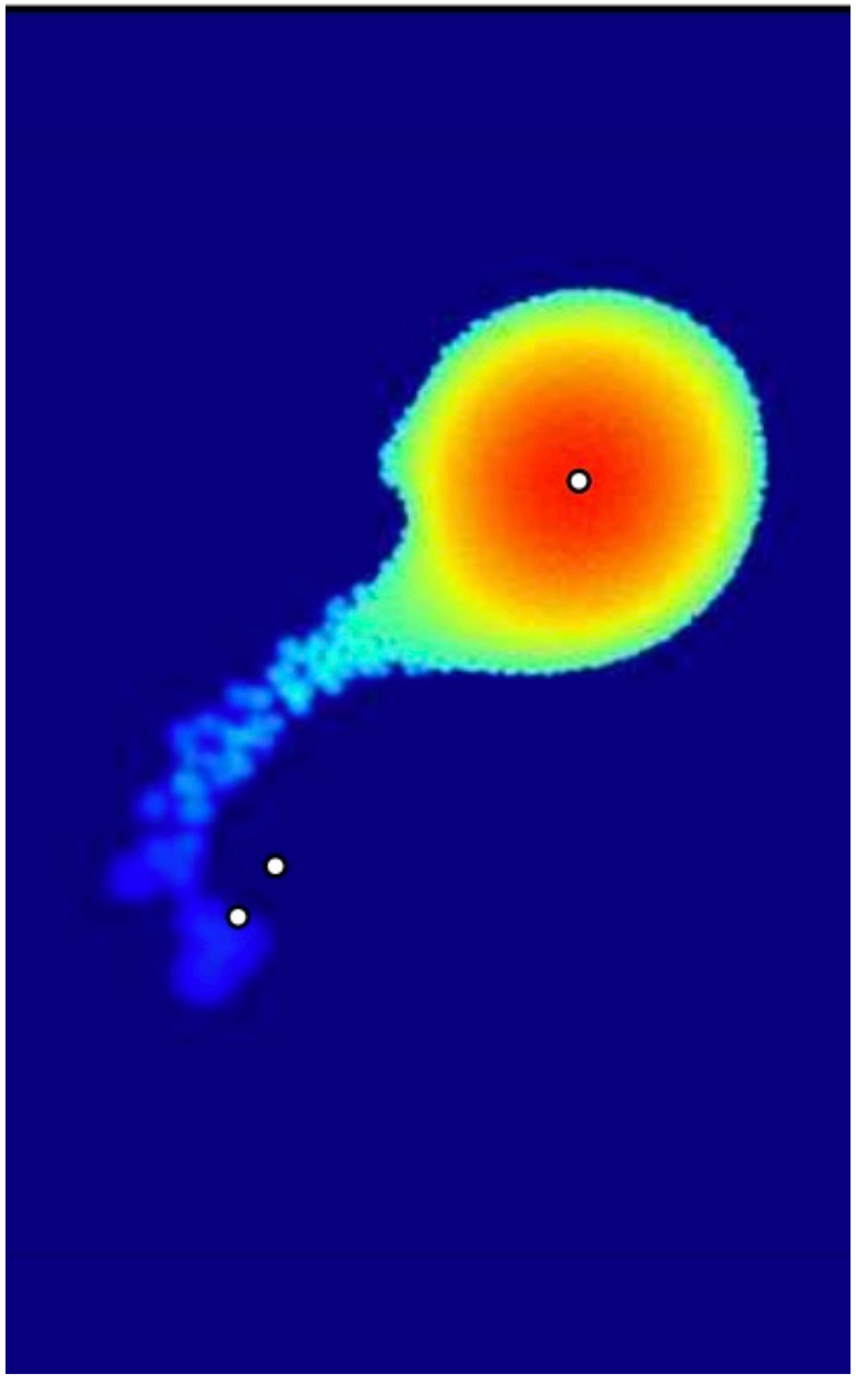


See also: Gao+ '18, Comerford+ '19,DiStefano+ '20, Glanz+ '21

Tertiary donates mass

Formation of barium stars
(Gao, Toonen, Leigh 2023)

- Direct impact accretion onto inner binary leads to orbital shrinkage, eventually merger (De Vries+ '14)
- Tertiary donor in triples is typically an AGB star (~75-90%, Toonen+ '20)
- Mass transfer more likely stable because commonly $M_1, M_2 < M_3 < M_1 + M_2$
- Eccentric orbits of barium stars explained by eccentric mass transfer?



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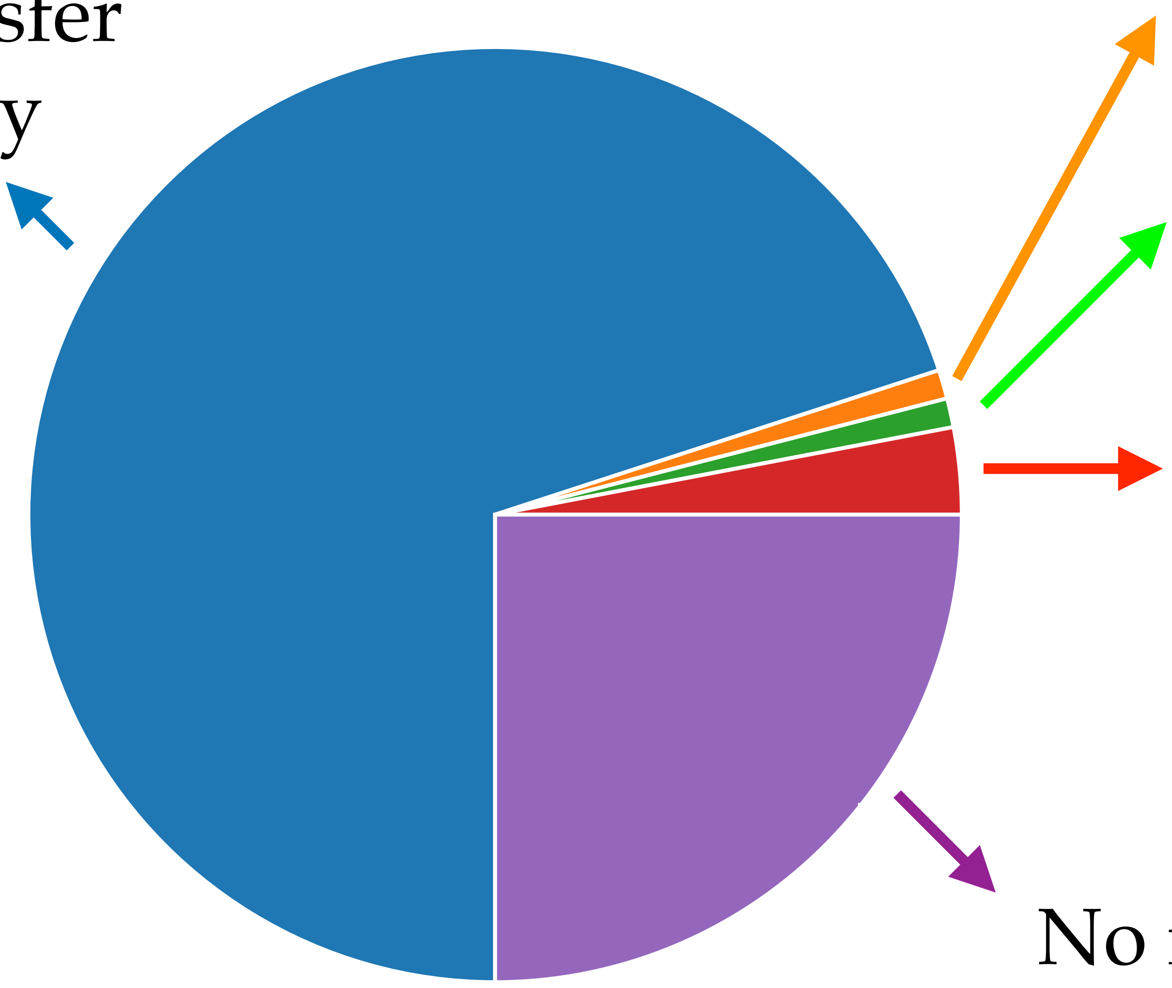

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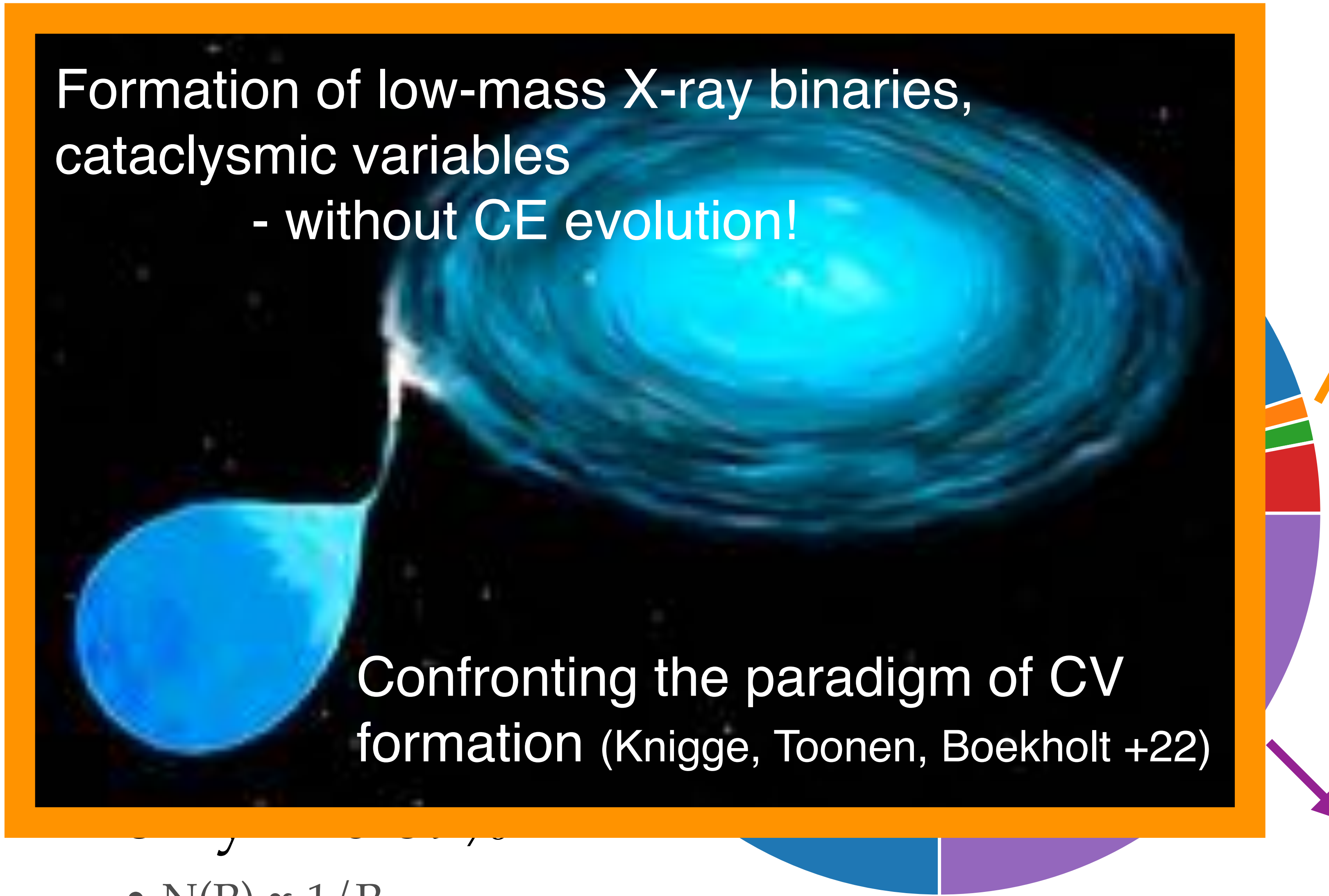

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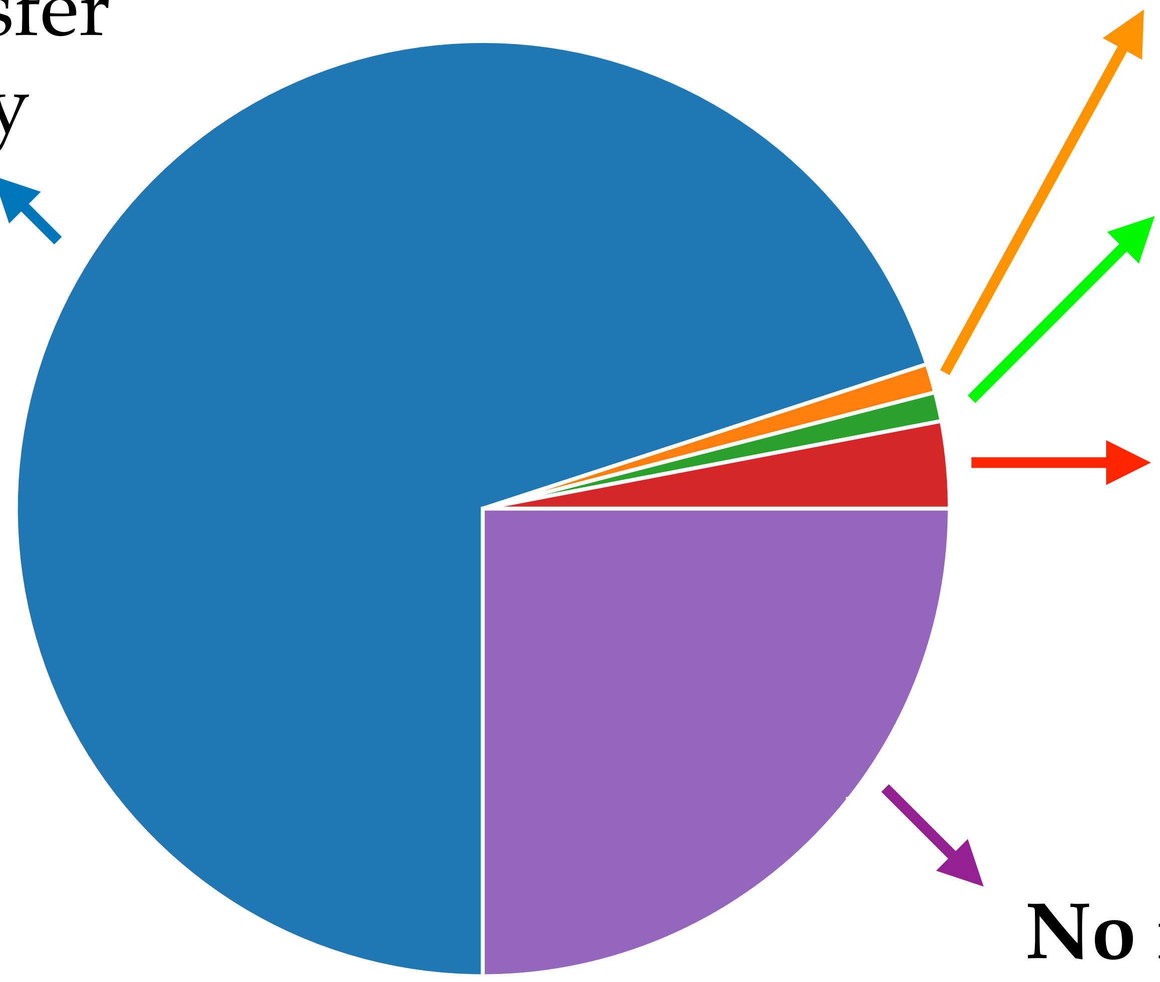

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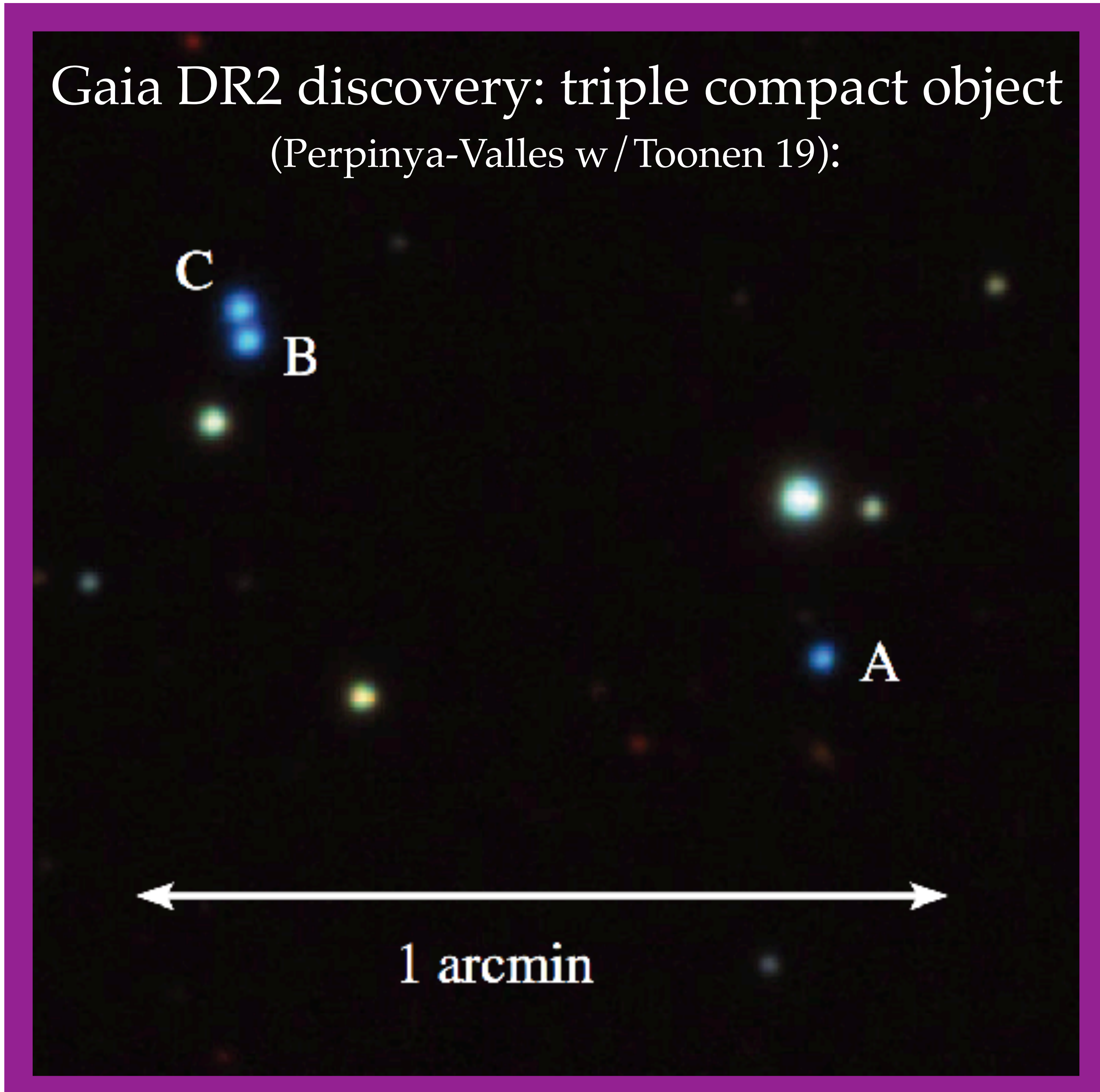
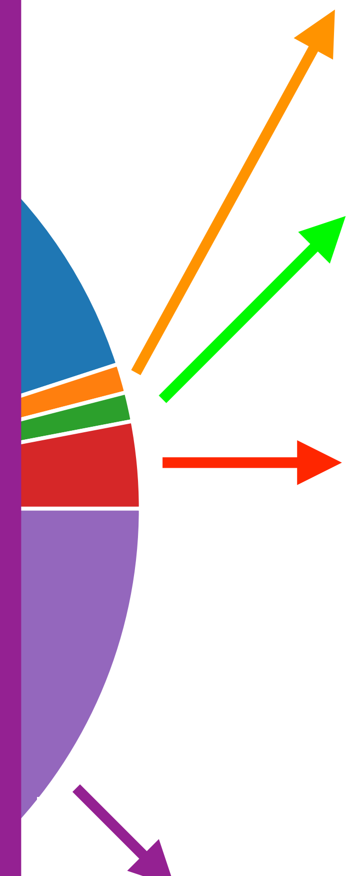


$(1\text{-}7.5M_{\odot})$



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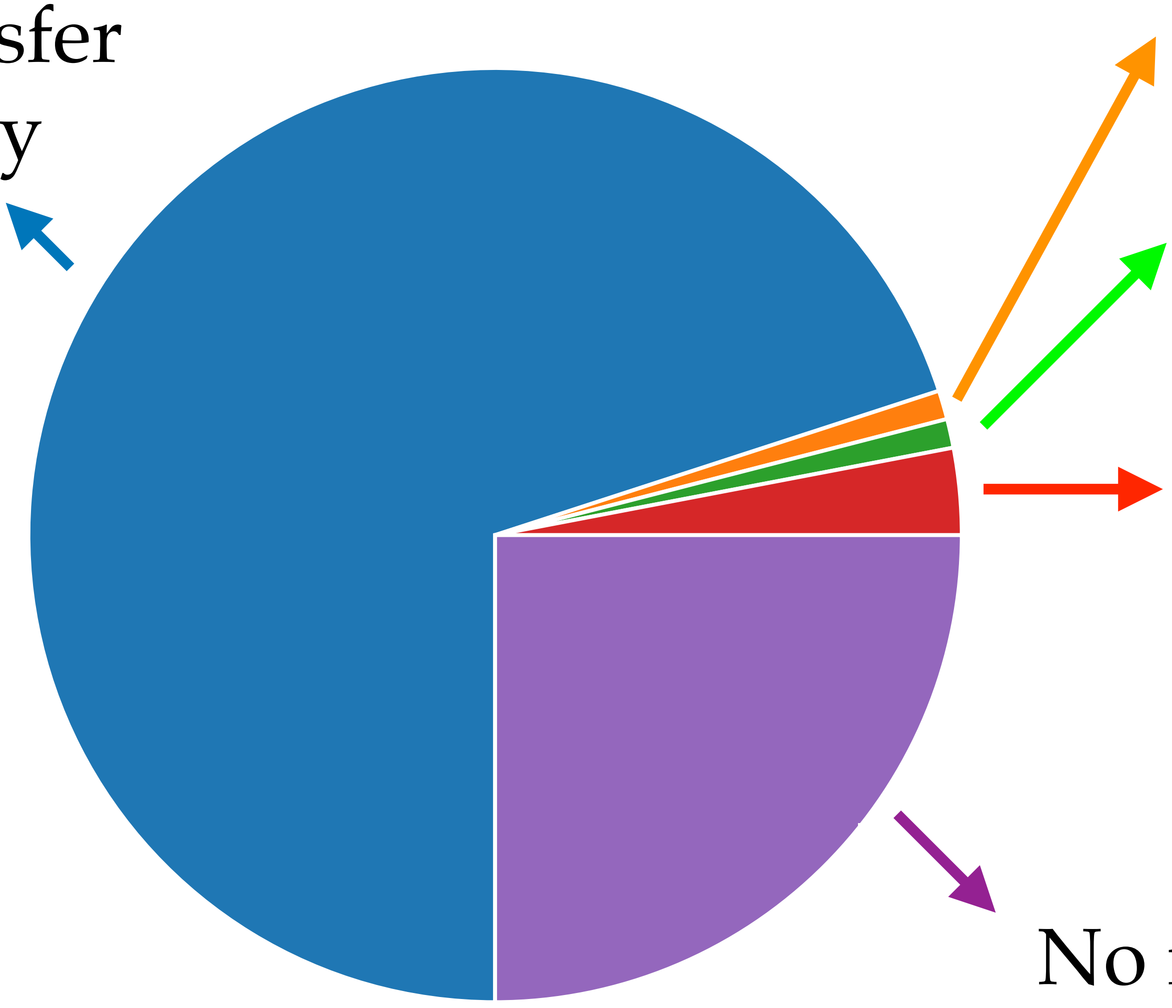

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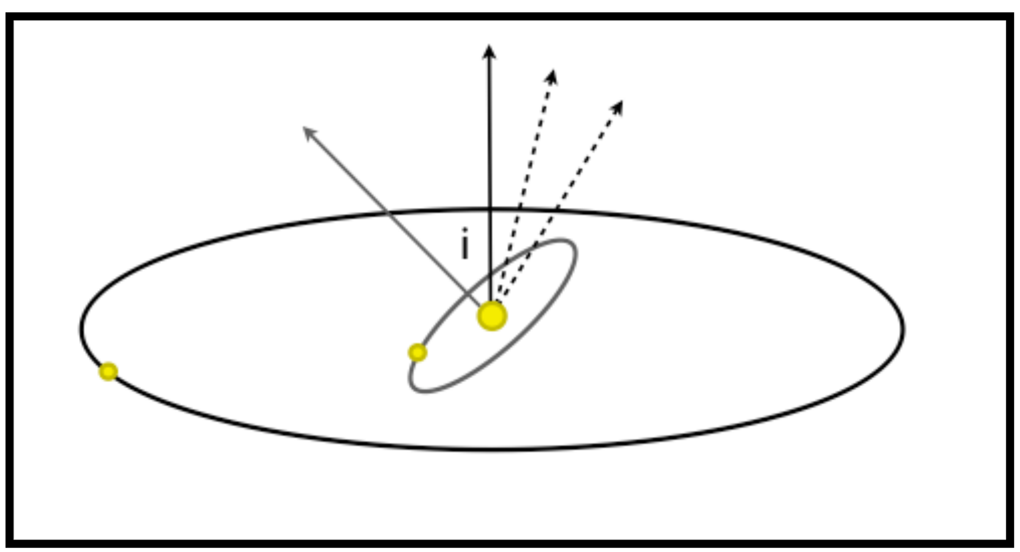
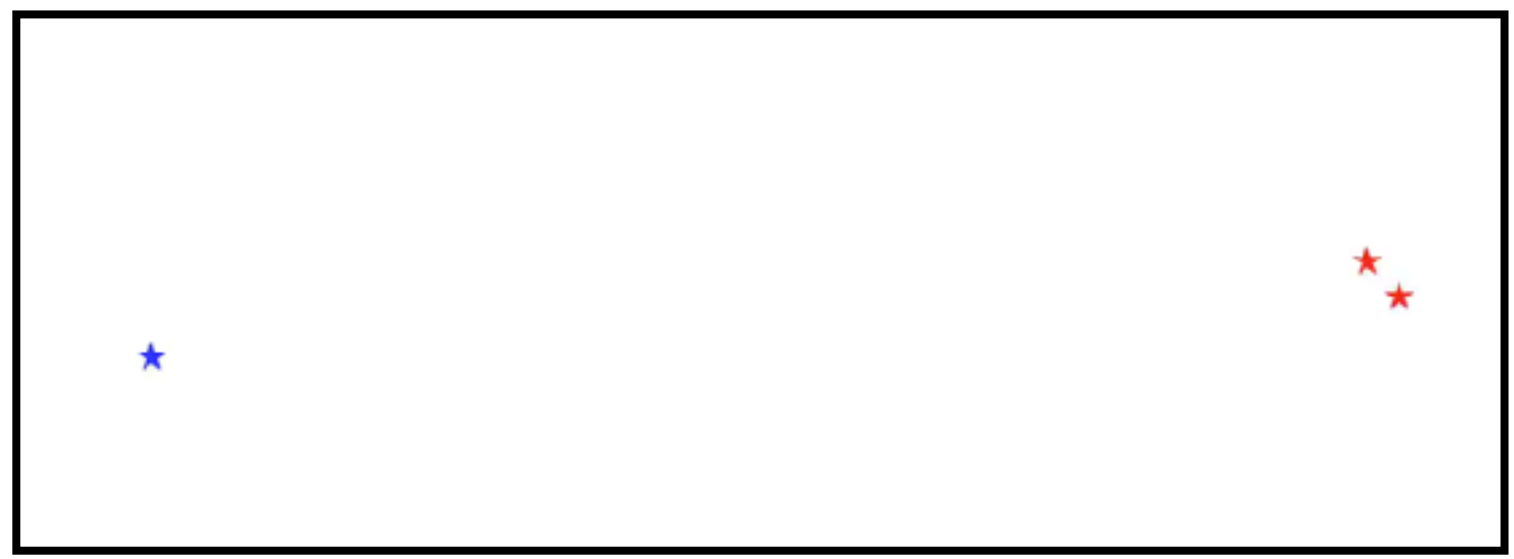
Dynamically unstable triples

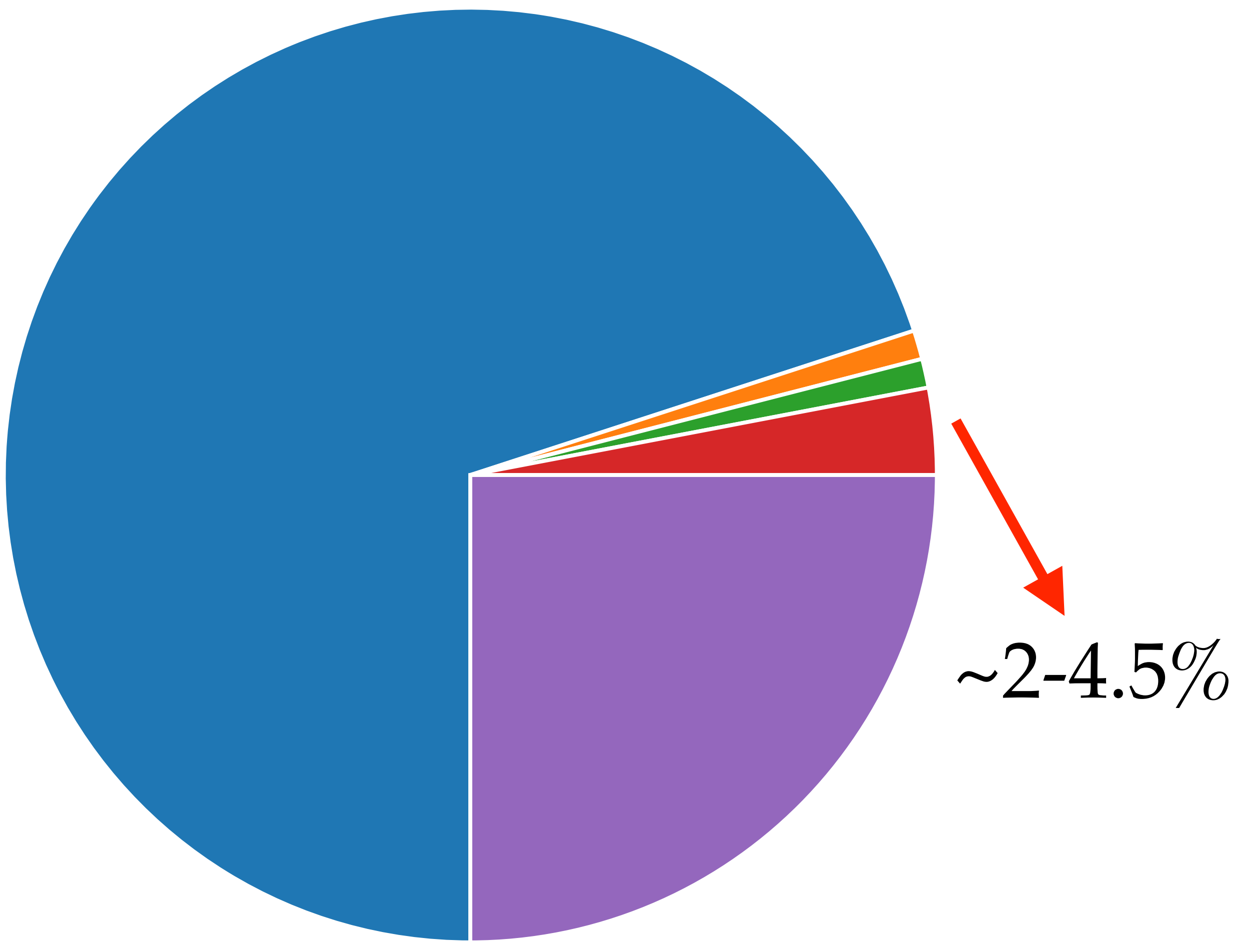
Evolution: from secular → to dynamical timescale





Dynamically unstable triples

➡Dynamical instability (e.g. Kiseleva+ ’94, Iben & Tutukov ’99, Toonen+’20 ~1-2 per kyr)



Outcomes

Toonen, Boekholt & Portegies Zwart 2022

- Ejections (50-70%)
  - Velocities up to several 10km/s
  - Origin of runaway stars?
- Collisions (10-25%)
  - MW rate of ~0.1 per kyr (consistent with Perets & Kratter ’12, Hamers+ ’22)
- Remain on the edge (10-20%)

Triples with compact objects

Collisions of white dwarfs

- Collision rate ~ 5e-4 - 2e-2 per 10000 Msun (Toonen+ '17)
- Rates enhanced by fly by's (~1.5) or WD kicks (~2) (Michaely & Perets '15, Hamers & Thompson '19, Michaely '21)

Supernova Type Ia

(Benz+ 89, Katz & Dong '12, Kushnir+ 13):

- Observed rate: 11.3 ± 2.4 per 10000 Msun (Maoz & Graur '17, Maoz '10, 12)

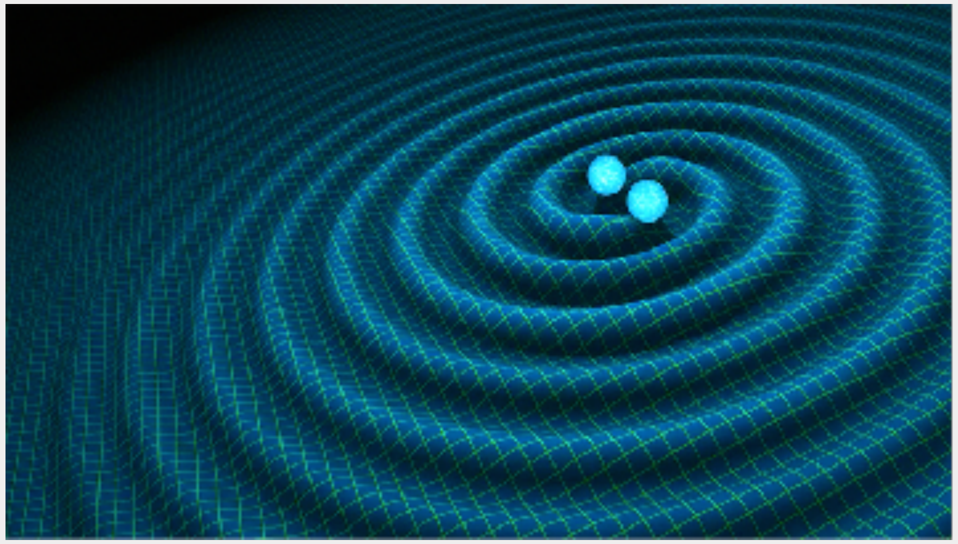
May lea
more c
eventu

Triples with compact objects

Mergers of black holes

- Merger rate ~ 0.4-6/yr/Gpc^3 (Silsbee & Tremaine '17, Antonini, Toonen, Hamers+ 17, Fragione & Kocsis '20, Martinez+ ' 22)
- @ low metallicity ~ 2-25 /yr/ Gpc^3 (Rodriguez & Antonini '18)

Gravitational wave sources



- Observed rate: LIGO O1-3a: ~ 23.9 (+14.9,-8.6) /yr/Gpc^3 (LSC 20)

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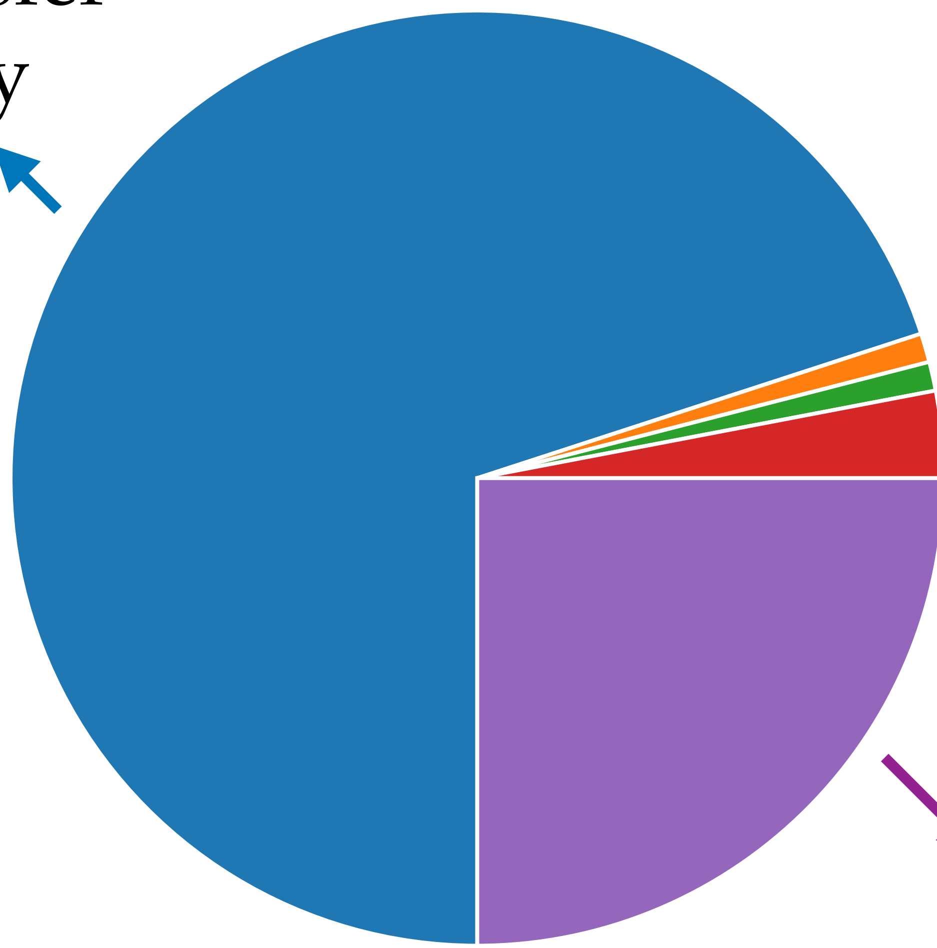
more co
eventua

➡ for NS mergers, see Hamers & Thompson 2019, Fragione & Loeb 2019 (2x)

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%

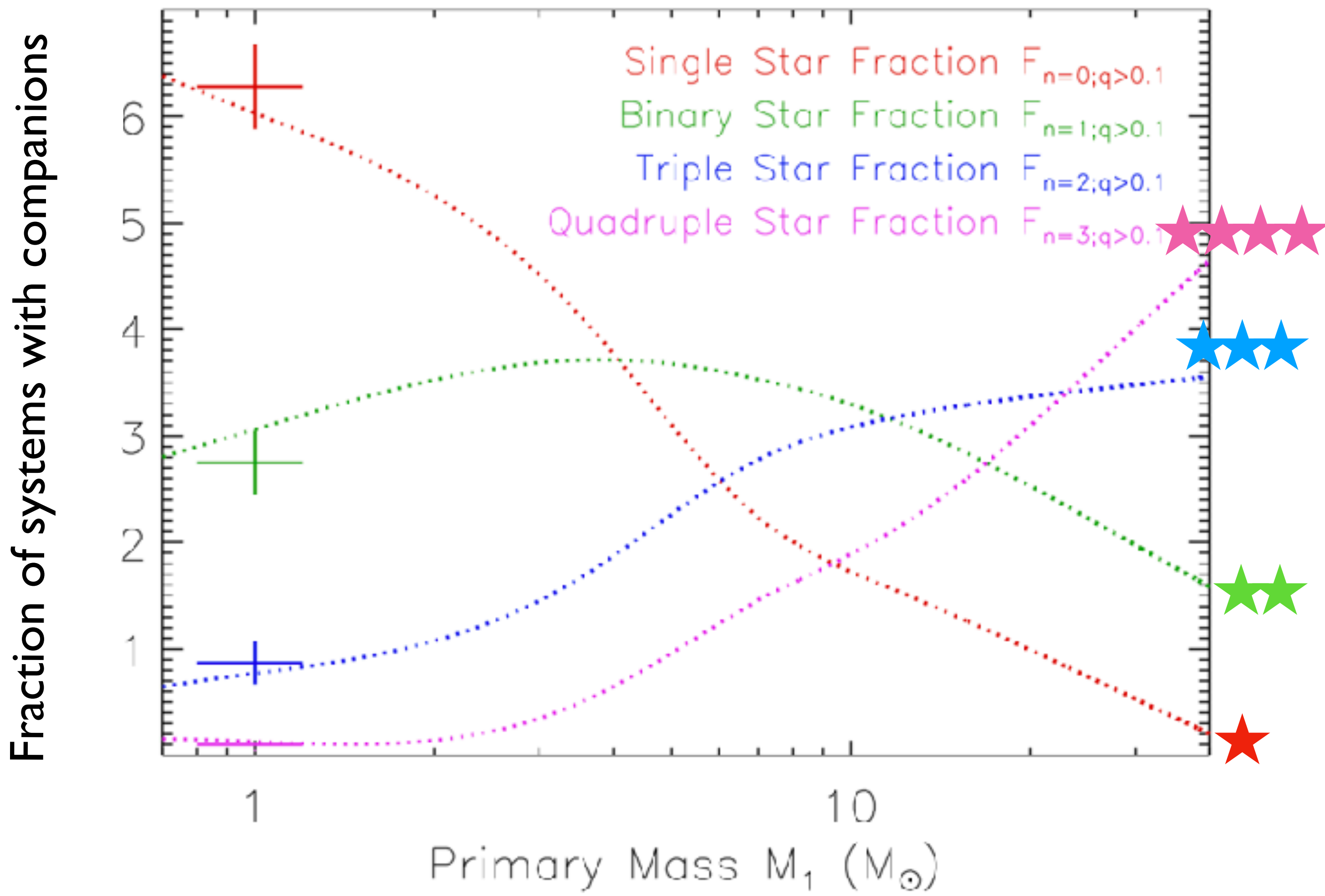
- $N(P) \propto 1/P$
- $N(P) \propto$ log-normal(P)

Summary

Stellar interactions & transients

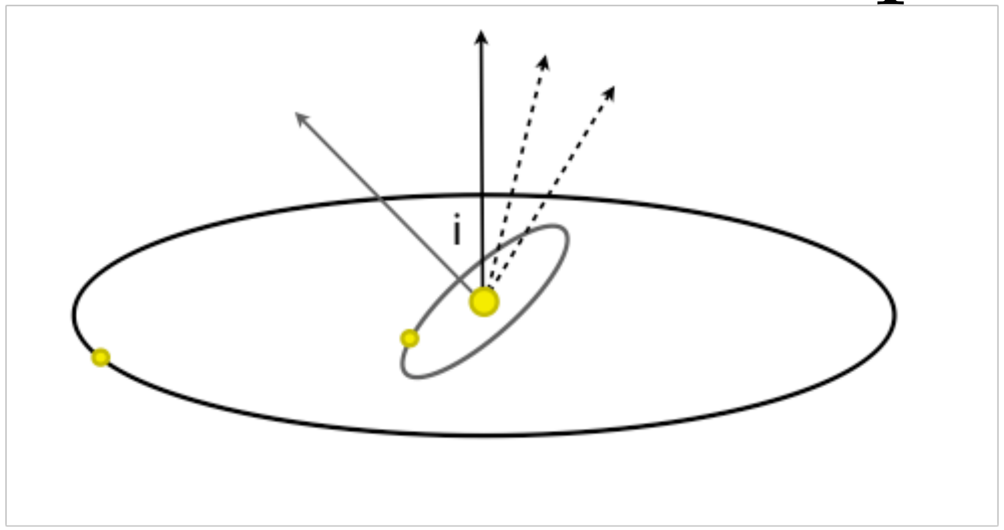
- Future is bright!
  - Gaia, SDSS, LSST, ZTF, Panstars,
  - LIGO, LISA etc etc
- Binaries & triple are abundant
  - Even dominating for massive stars

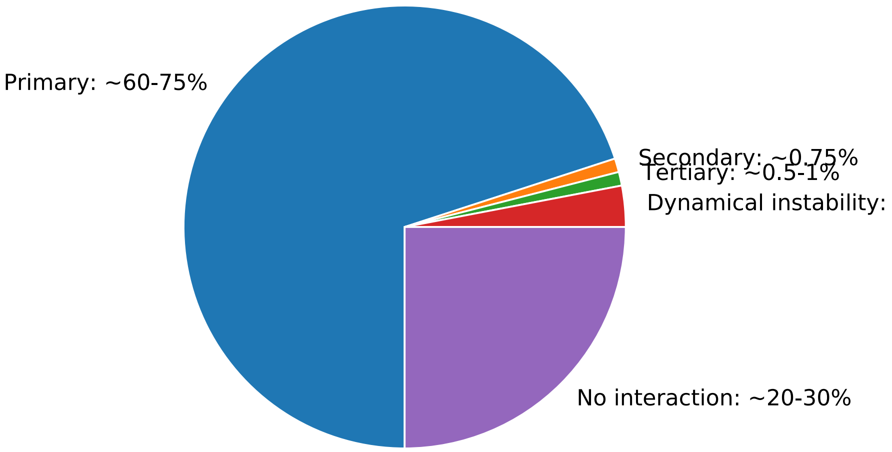
Moe+ '17



Summary

Triple evolution





- Triples are abundant
- Public code TRES to simulate triple evolution consistently (Toonen+ '16)
- Enhanced occurrence rate of mass transfer (Toonen+ '20)
  - Triples on even footing compared to binary
- Novel channels: e.g. compact binaries without common-envelope evolution, tertiary mass transfer etc

Summary

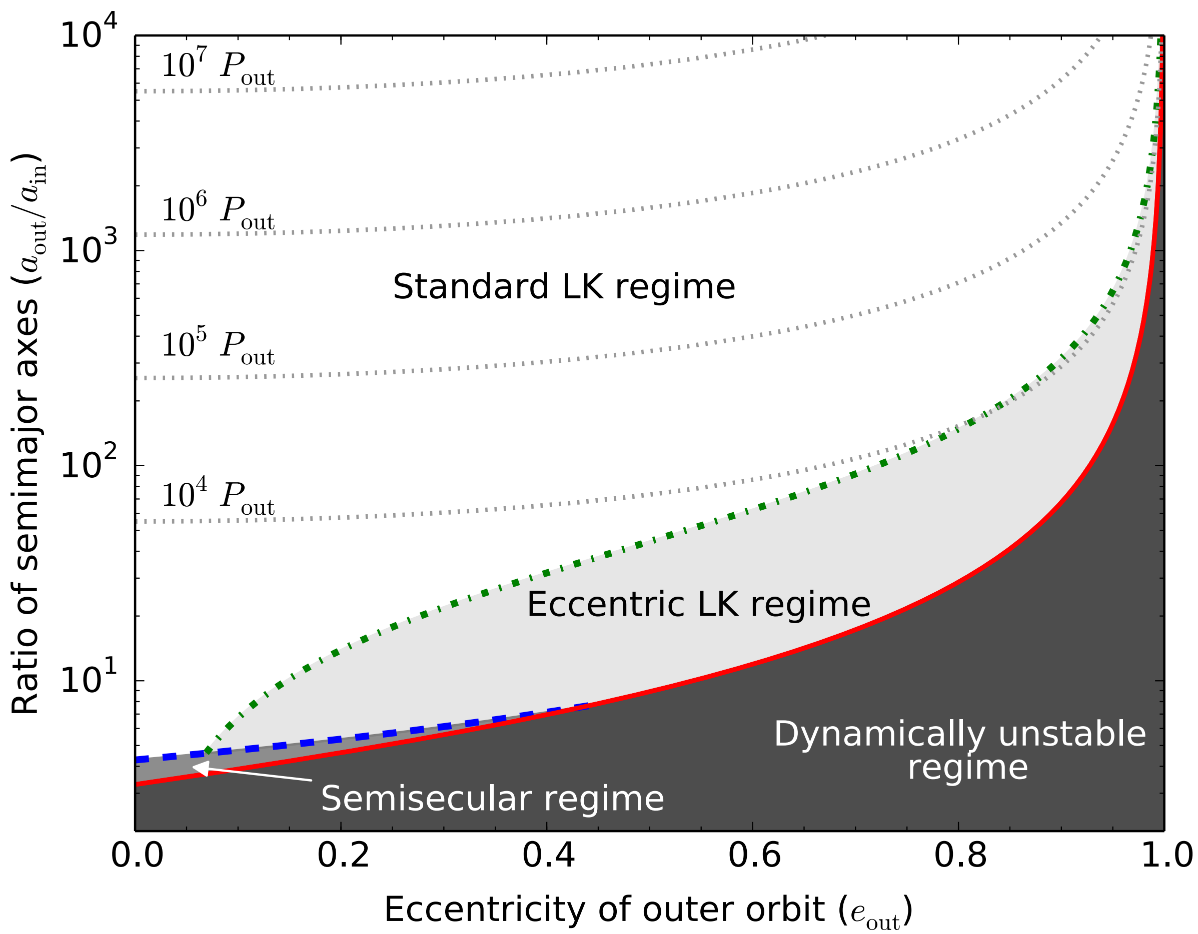
Triple evolution major (or even dominant) player for:

- Gravitational wave sources (Silsbee & Tremaine '17, Antonini, Toonen, Hamers+ 17, Fragione & Kocsis '20, Martinez+ ' 22)
- Stellar collisions in the field (Toonen, Boekholt, Portegies Zwart 2022)
- Formation of cataclysmic variables
    - Eccentricity from triple evolution to kickstart the enhanced mass transfer rates observed (Knigge, Toonen, Boekholt 2022)
- Elegant formation channel for barium stars (Gao, Toonen, Leigh 2023)

Checkout:

- Facebook group: triple evolution & dynamics

- Webinterface:
  - https://bndr.it/wr64f
  - when you find a triple… plug it into this Jupyter notebook to asses its dynamics



- Or find the links on my website:
  - staff.fnwi.uva.nl/s.g.m.toonen

Summary