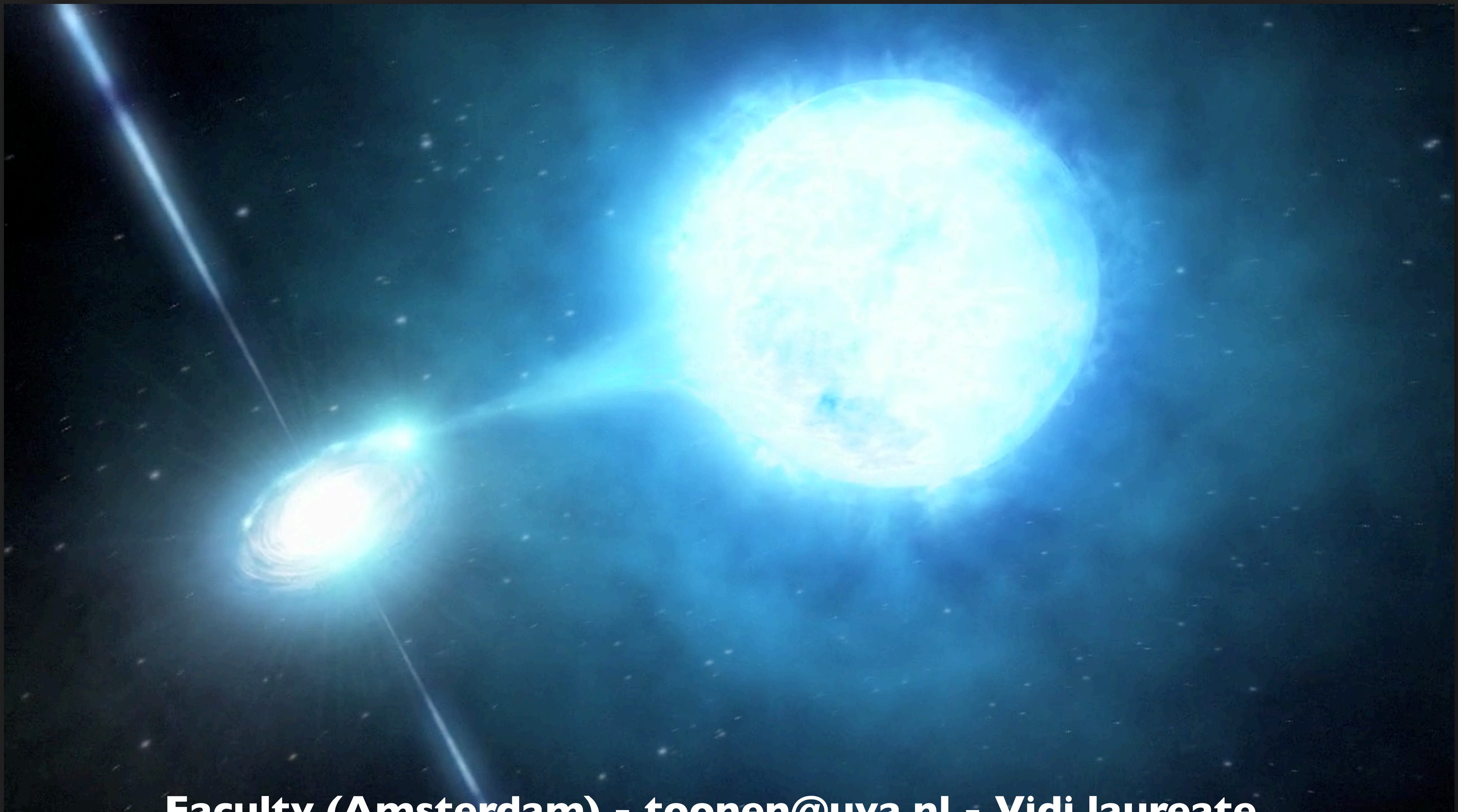
REVIEW OF SNIA PROGENITORS

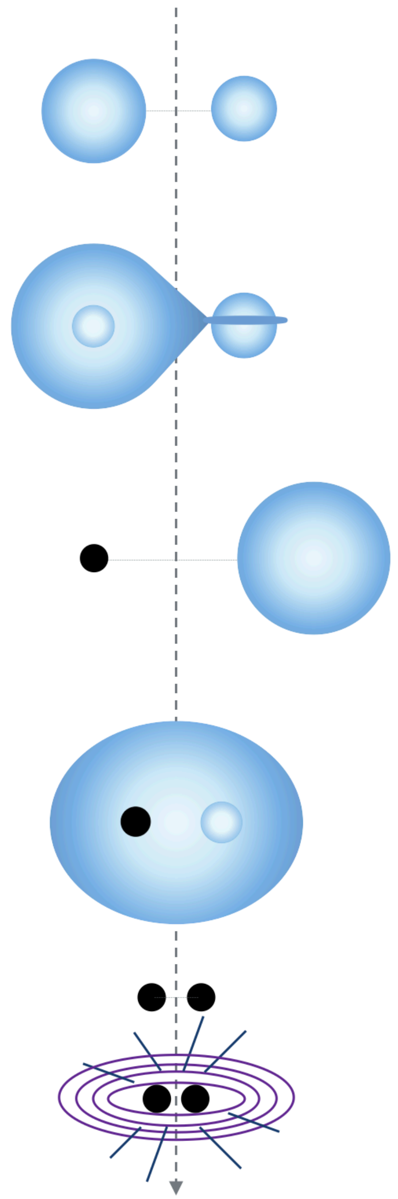


Faculty (Amsterdam) - toonen@uva.nl - Vidi laureate

Floris Kummer, Andris Dorozsmai, Caspar Bruenech, Adam Parkosidis, Karel Temmink, Yan Gao,
Tjarda Boekholt (Oxford), Nathan Leigh (Conception), Alejandro Vigna-Gomez (Garching), Simon Portegies Zwart (Leiden), Boris Gaensicke (Warwick), Mark Hollands (Sheffield)

Binary population synthesis

Model Binary evolution



Including:

Stellar evolution

- Stellar winds

Stellar dynamics

- Physics of mass transfer
- Stability of mass transfer
- Mass loss and accretion
- Angular momentum loss
- Mass loss
- Gravitational waves
- Magnetic braking
- Tidal effects

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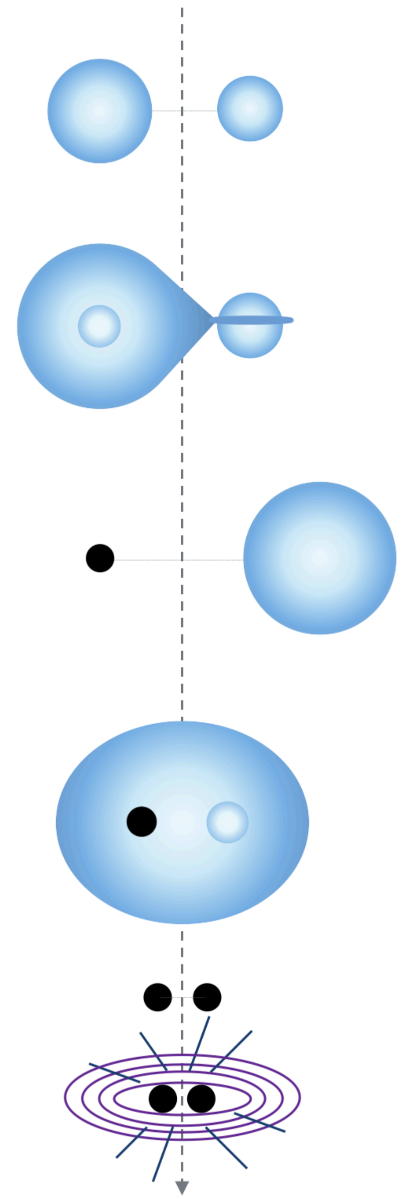

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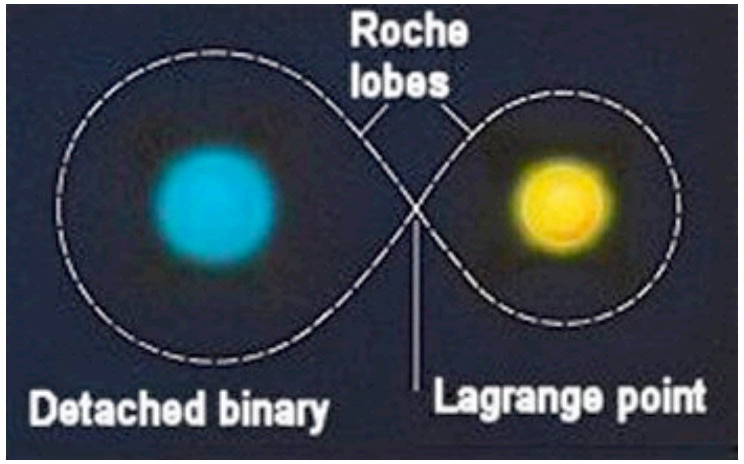

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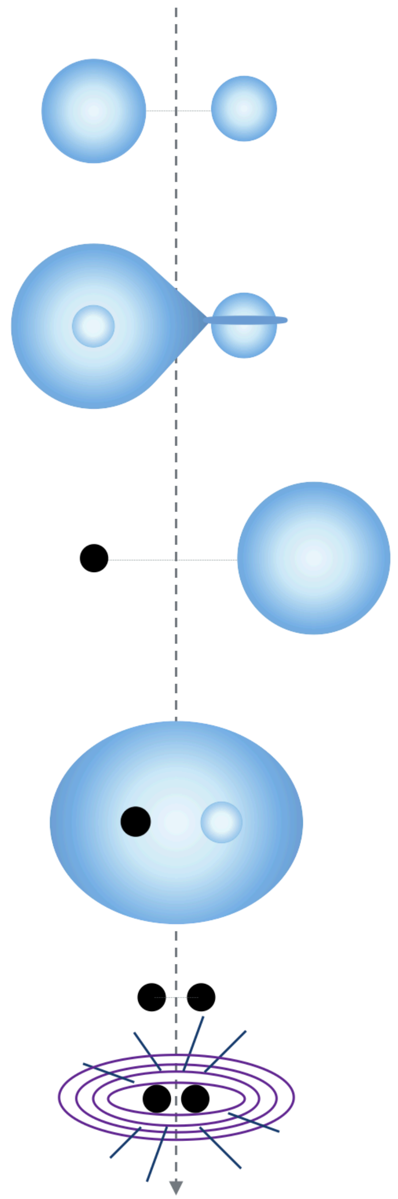

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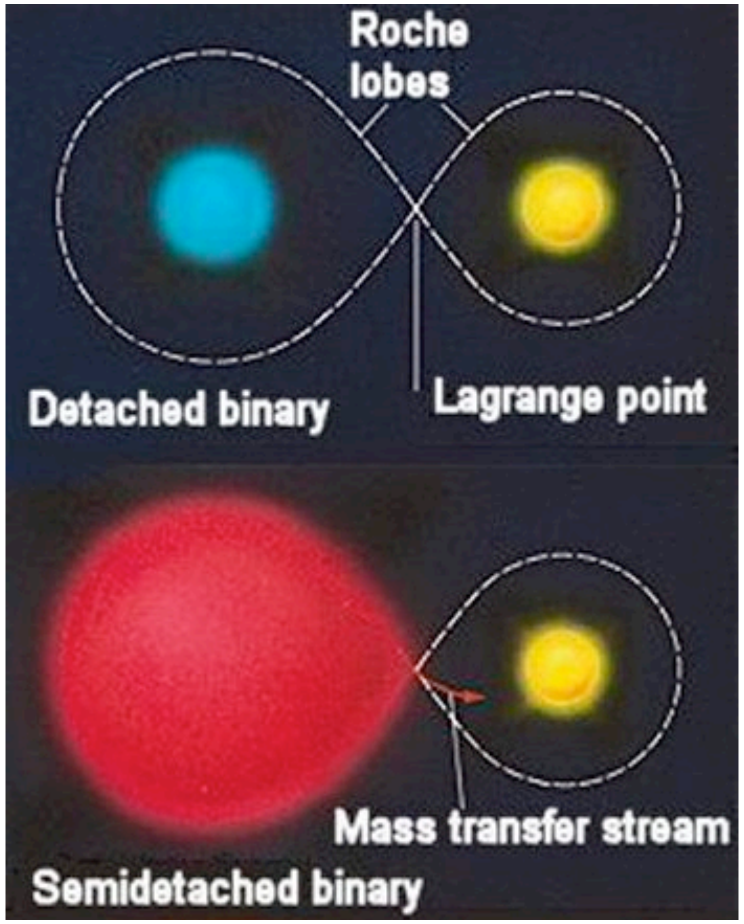

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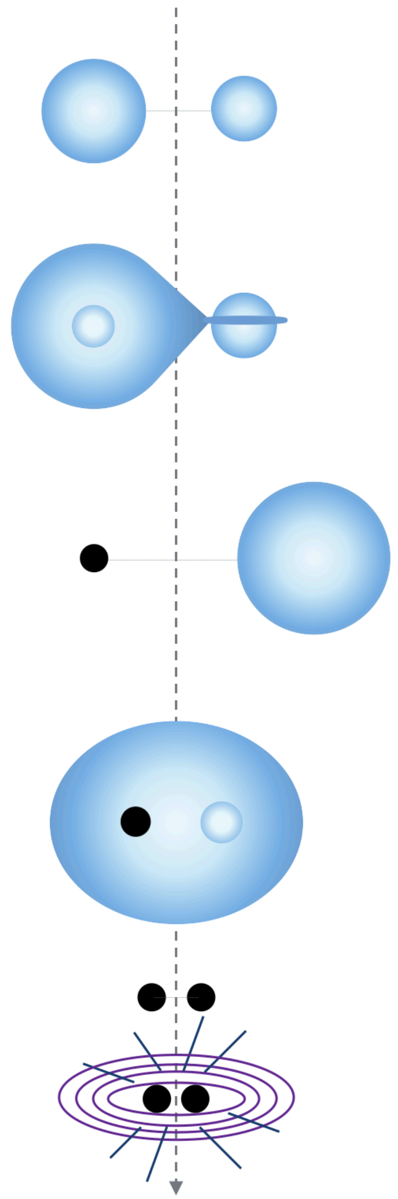

Including:

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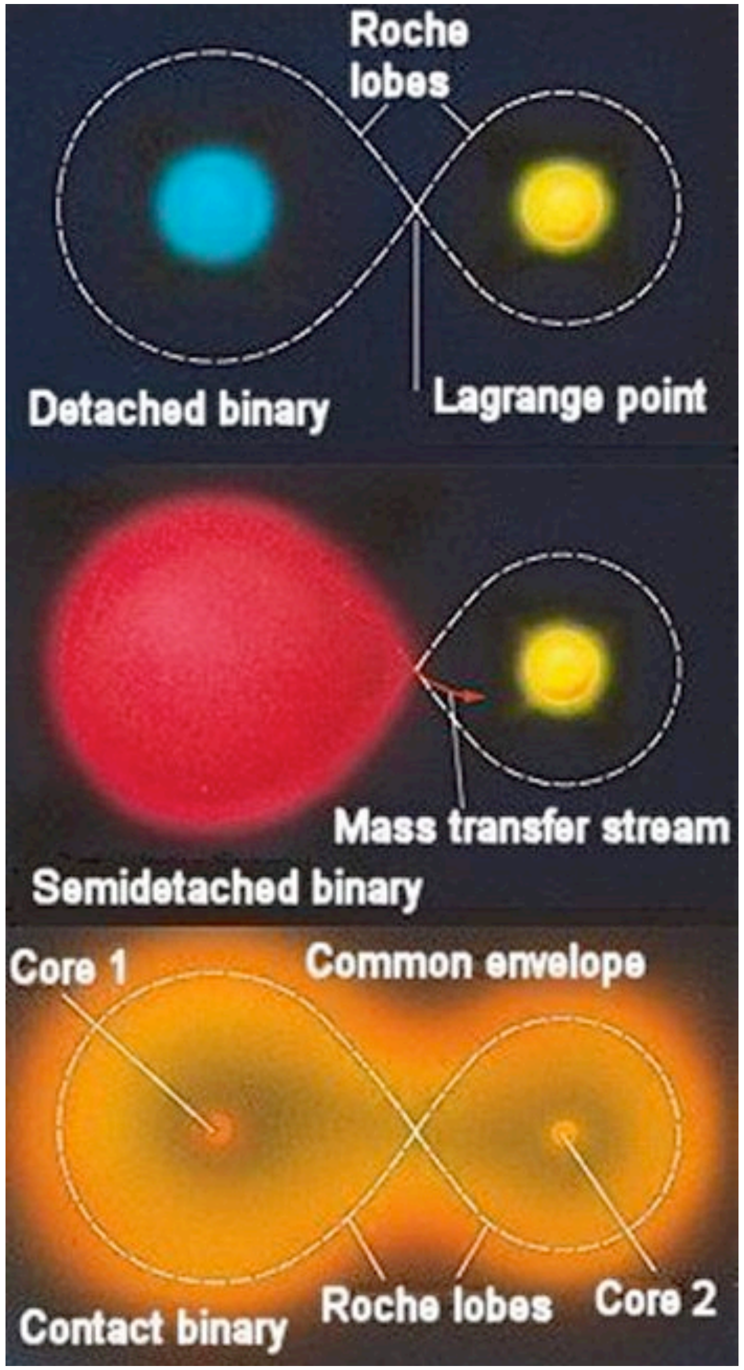
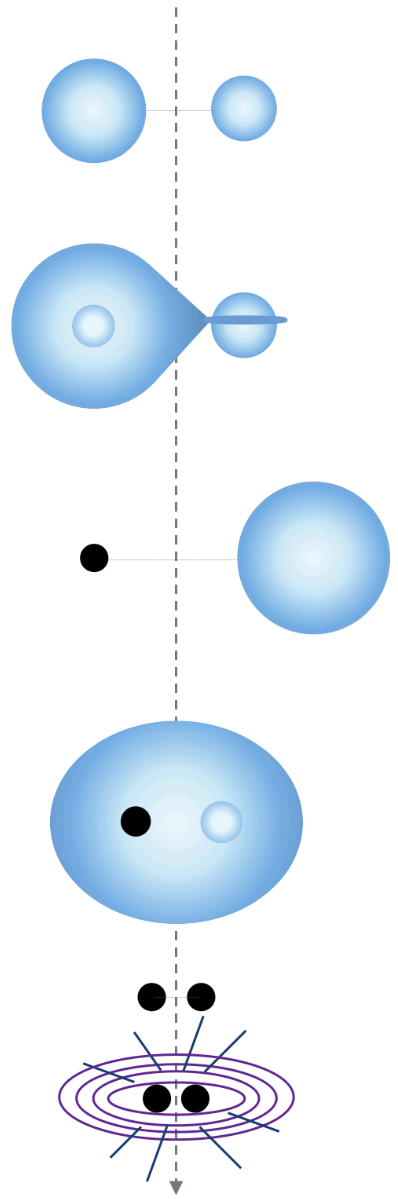
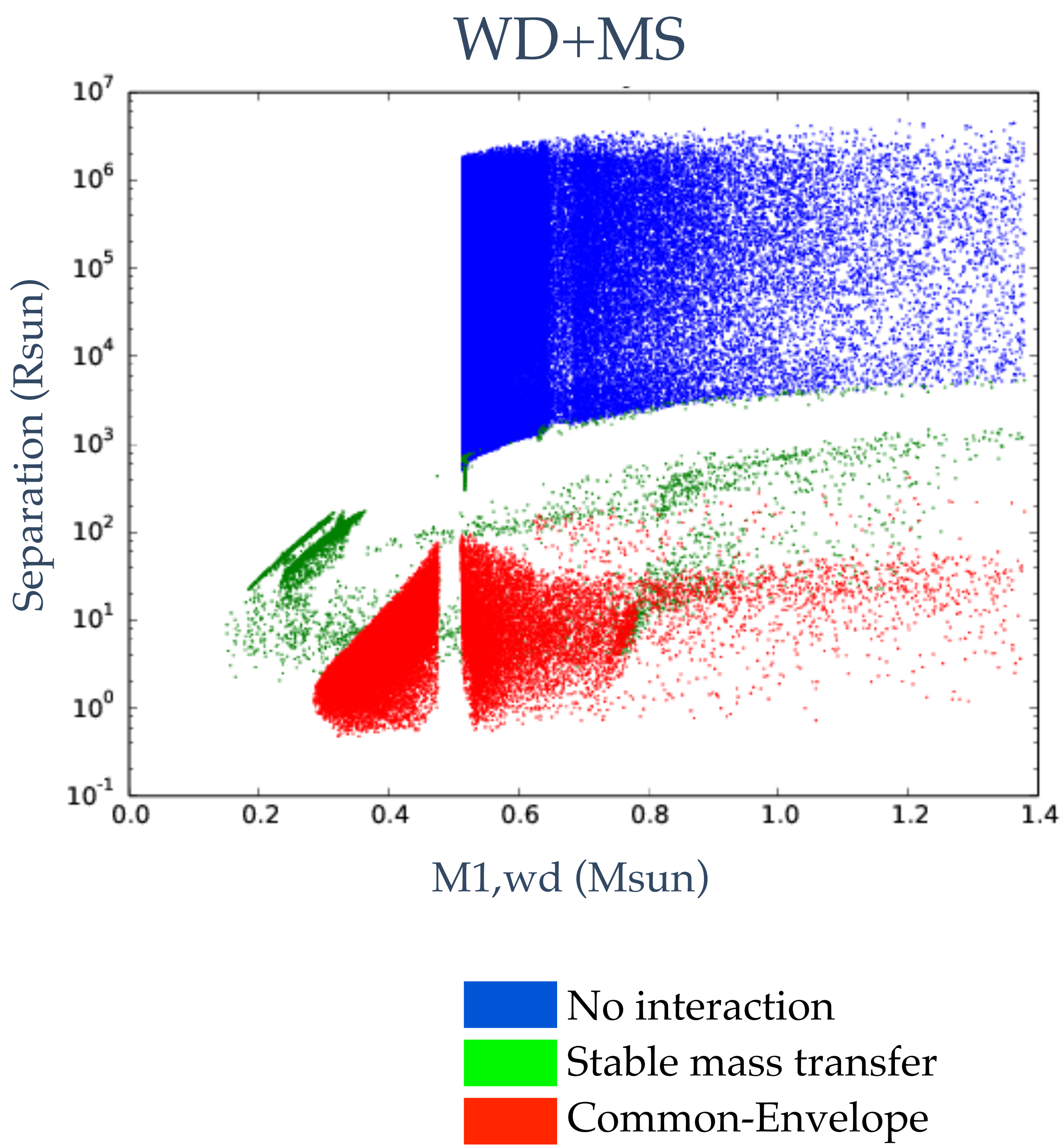


Binary population synthesis

Model Binary evolution



Make synthetic population

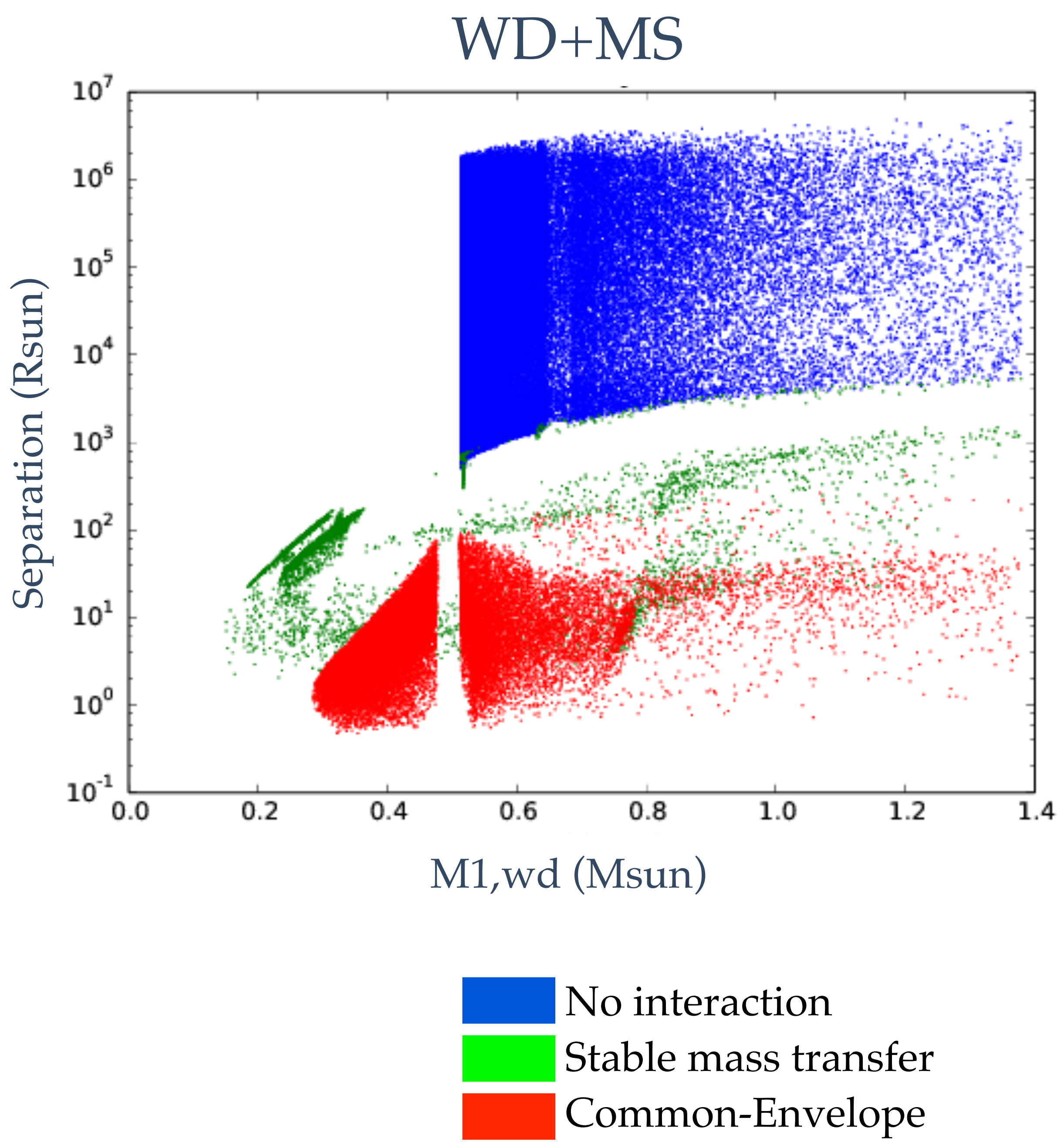


Binary population synthesis

Study e.g.

- characteristics of a binary population (e.g. mass ratio distribution, period distribution)
- frequency of an astrophysical event
- chemical enrichment of a region

Make synthetic population



Binary population synthesis

Regarding transients:

- Pick your favourite progenitor channel & study e.g.:
- Rates, delay time distribution
- Typical age of progenitor

Example 1:

- Channel: Helium star transfer mass onto a white dwarf
- Typically young environment (e.g. Wang+ 09, Ruiter+ 11)
- Matches well with SNIax (Lyman+ 13, 18, Takaro+ 20, Maguire+ 23)

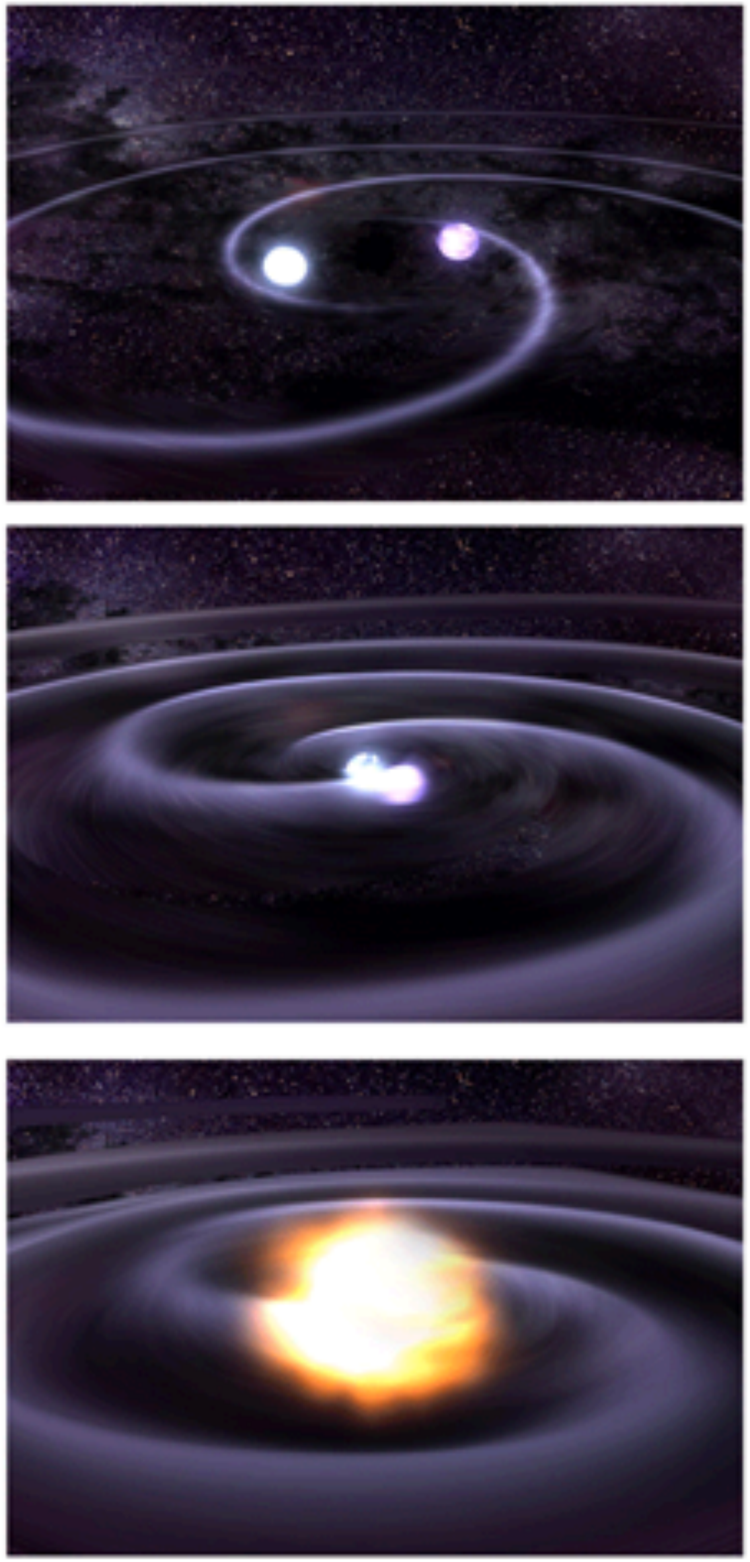
Example 2:

- How many high-velocity surviving companions?
- Some WD candidates found (Shen+ 18, Raddi+19, Igoshev+ 23), but small amount of candidates might elude to channels without surviving companions, but see El Badry+ 23

BPS studies for SNIa progenitors:

- Yungelson et al. 1994
- Han et al. 1995
- Jorgensen et al. 1997
- Yungelson & Livio 2000
- Nelemans et al. 2001
- DeDonder & Vanbeveren 2004
- Han & Podsiadlowski 2004
- Belczynski et al. 2005
- Yungelson 2005
- Bogomazov & Tutukov 2009
- Meng et al. 2009
- Ruiter et al. 2009
- Wang et al. 2009 (2x)
- Claeys et al. 2010
- Meng & Yang 2010 (3x)
- Mennekens et al. 2010
- Wang et al. 2010
- Wang & Han 2010 (2x)
- Yungelson 2010
- Bogomazov & Tutukov 2011
- Meng et al. 2011
- Ruiter et al. 2011
- Chen et al. 2012
- Meng & Yang 2012
- Toonen et al. 2012
- Bours et al. 2013
- Claeys et al. 2013
- Mennekens et al. 2013
- Ruiter et al. 2013
- Wang et al. 2013
- Ruiter et al. 2014
- >2014 not even included yet…

Double white dwarfs



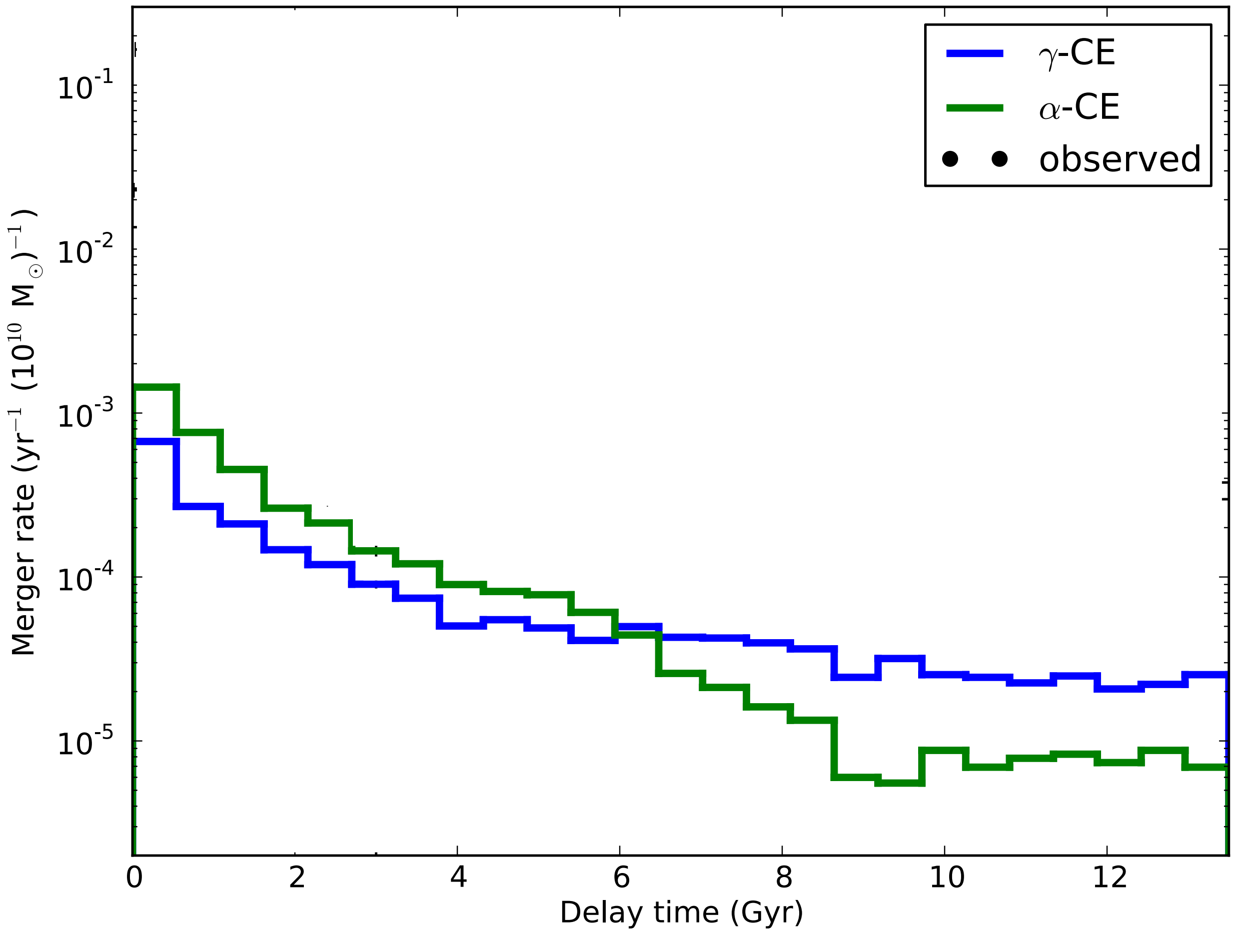
Suggested formation channels

- Classically: Chandrasekhar mergers (Iben & Tutukov '84, Webbink '84)
- Also: Sub-Chandrasekhar mergers
  - Violent mergers (e.g. Pakmor ea '10, '11, '12, van Kerkwijk ea '10, Sato ea '15)
  - Surface He detonations (Guillochon ea '10, Pakmor ea '13, Shen & Bildsten '14)
  - White dwarf collisions (Dense environments: Benz ea '89, Triples: Katz & Dong '12, Hamers+ ' 13, Toonen+, Abinaya)

Chandrasekhar mergers

Chandrasekhar mergers

ref: Toonen, Nelemans, Portegies Zwart 2012



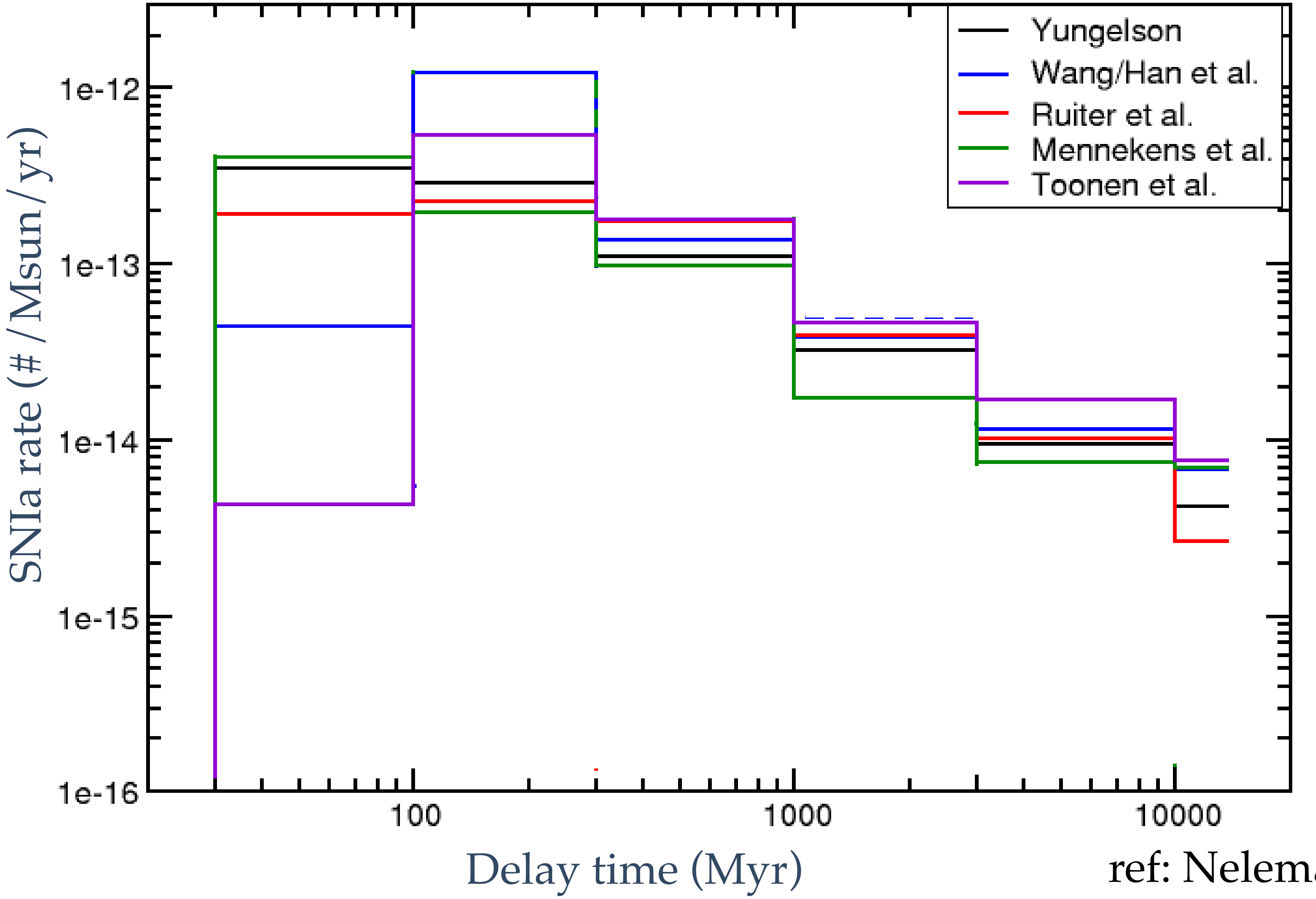
Using the code:

Portegies Zwart+ '96,
Nelemans+ 01,
Toonen+ '12

- Delay time distribution =
  SNIa rate per unit mass of created stars as a function of time since a hypothetical instantaneous starburst

Chandrasekhar mergers

- Giving robust shape for delay time distribution $\propto t^{-1}$
- Driven by gravitational wave inspiral (rather than population properties)

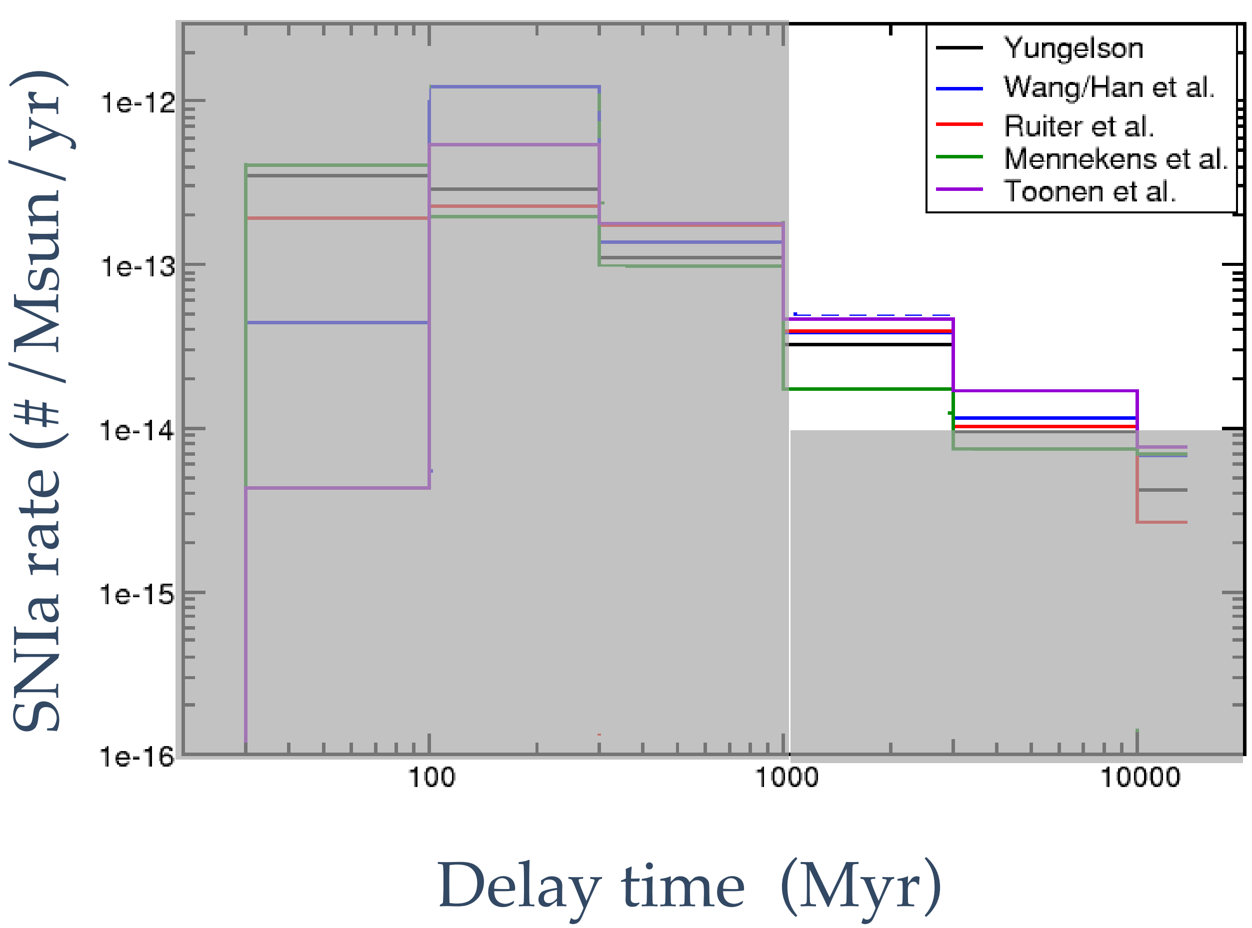


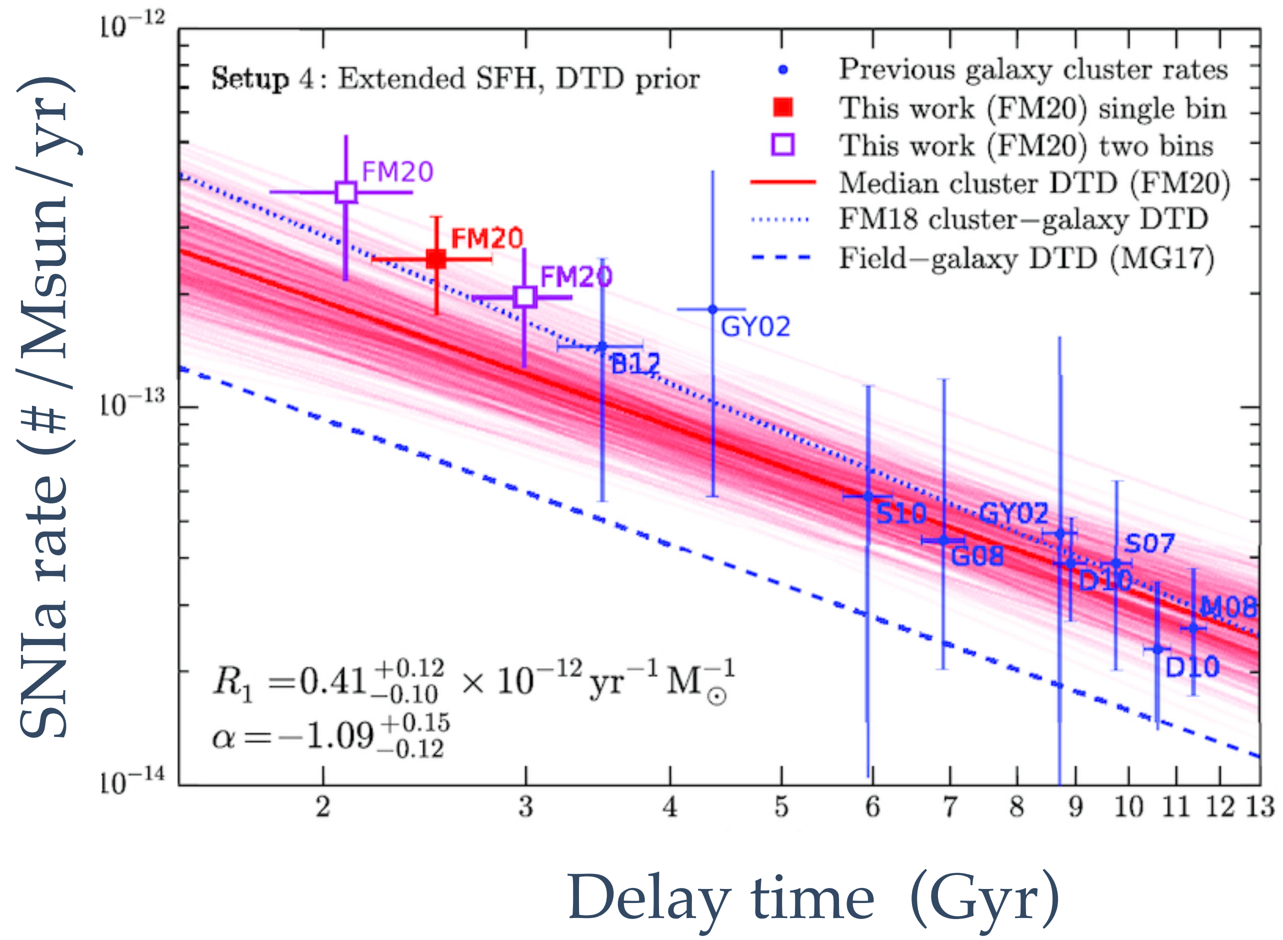
Different BPS codes

ref: Nelemans, Toonen, Bours 2011

Chandrasekhar mergers

- Giving robust shape for delay time distribution $\propto$ t^{-1}
- In line with observations (Maoz & Graur 17, Freundlich & Maoz '21, Castrillo+ '21)
- Driven by gravitational wave inspiral - rather than population properties





Taken from: Freundlich & Maoz '21

But see Toy+ 23 for lower rates in clusters at lower redshifts. Metallicity effect (Ruiter & Seitenzahl 25)?

Integrated rate

Integrated rate (1e-4/Msun)		BPS - SeBa
Observations (field)	Graur+ '14, Maoz & Graur '17	16±0.3, 13±0.1
Observations (clusters)	Maoz & Graur '17, Freundlich & Maoz ' 21	54±3, 31±11
Chandrasekhar mergers	M1+M2 >1.38	4.2-5.5
All DWD mergers	All masses & flavours	31-32

Sub-chandrasekhar mergers

Integrated rate (1e-4/Msun)		BPS - SeBa
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All DWD mergers	All masses & flavours	31-32
Sub-chandrasekhar models ?		

Advantage of sub-Ch mergers

- Generally more common
- More massive mergers early on -> if peak luminosity set by primary mass -> diversity & evolution of luminosity function (Shen+ 17, 21)

Sub-chandrasekhar mergers

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Sub-chandrasekhar models:			
v. Kerkwijk+ ’10	Accretion of thick disk + compressional heating	q>0.8	
		q>0.9	
Pakmor+ ’10,’11,’12	WD structure distorted in merger	q>0.8, M1>0.8	
		q>0.9, M1>0.8	
Sato+ ’15	Total		
	Merger phase	0.9<M1<1.1, 0.9<M2<1.1	
	Merger remnant phase	0.7<M1<0.9, M1+M2>1.38	
D6: Shen	Shen, Toonen, Graur ’17 <—	M2> -10.2041(m1-0.85)^2+0.805	

Sub-chandrasekhar mergers

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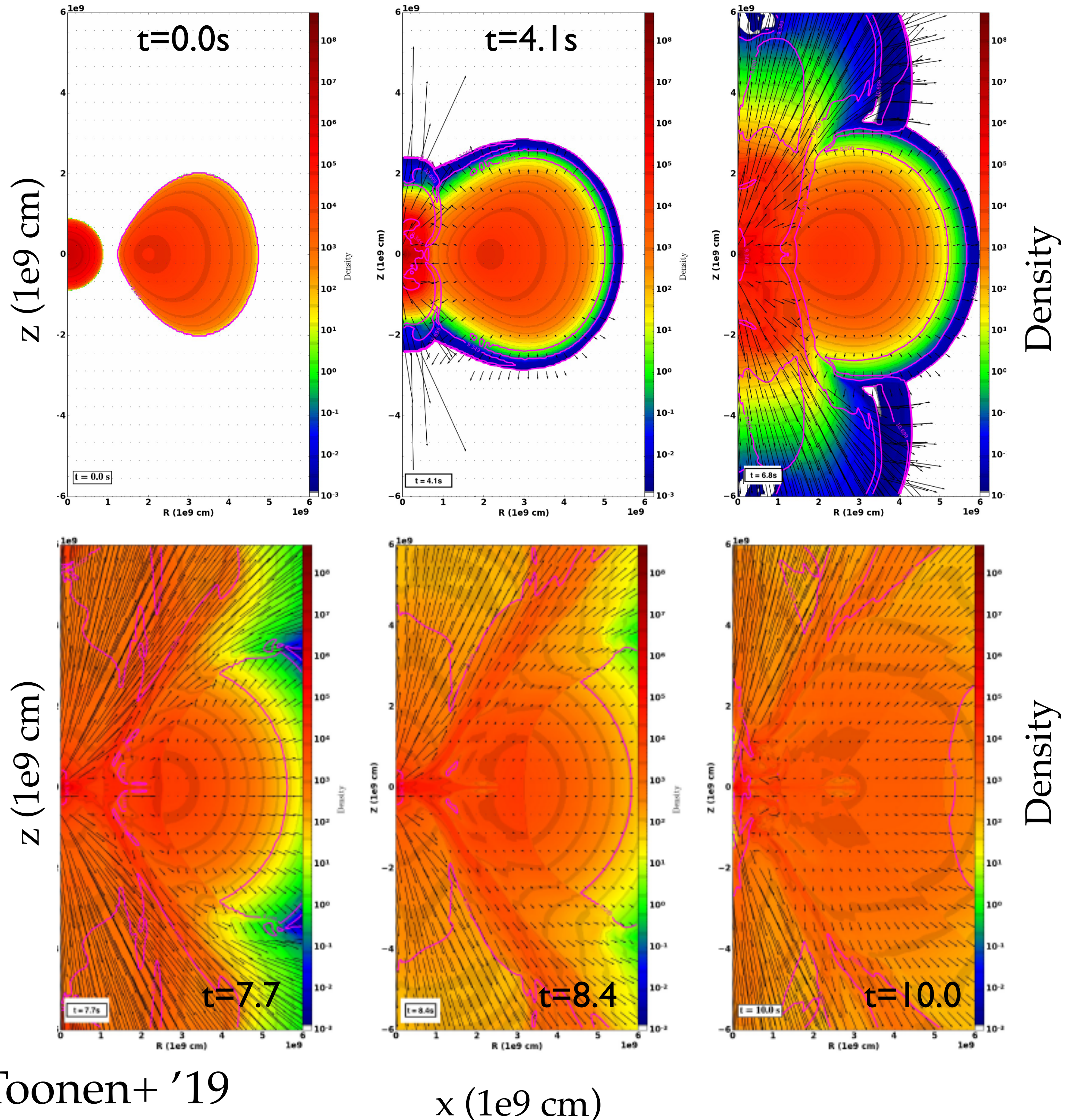
Sub-chandrasekhar models:			
v. Kerkwijk+ ’10	Accretion of thick disk + compressional heating	q>0.8	4.8-5.3
		q>0.9	2.3-2.6
Pakmor+ ’10,’11,’12	WD structure distorted in merger	q>0.8, M1>0.8	1.1-1.3
		q>0.9, M1>0.8	0.3-0.4
Sato+ ’15	Total		1.5-2.5
	Merger phase	0.9<M1<1.1, 0.9<M2<1.1	0.02-0.09
	Merger remnant phase	0.7<M1<0.9, M1+M2>1.38	1.4-2.4
D6: Shen	Shen, Toonen, Graur ’17 <—	M2> -10.2041(m1-0.85)^2+0.805	1.7-2.9

Helium as a facilitator

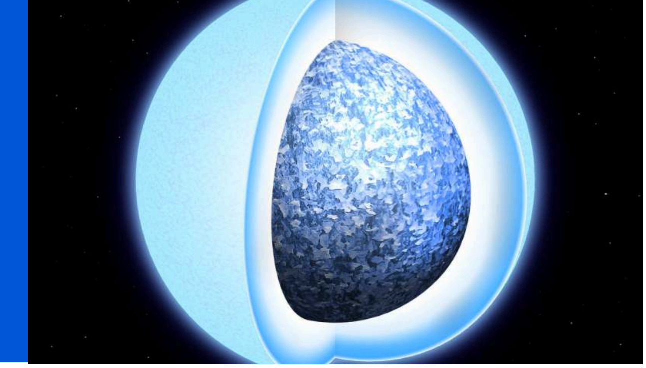


MESA + Flash

- Helium assists nuclear burning
- Need modestly enriched layer
- (e.g. Guillochon+ 10, Kromer+ 10, Woosley+ 11, Pakmor+ 13, Shen+ 14, Townsley+ 19, Pakmor+ w/ Toonen '21, Zenati+ w/Toonen

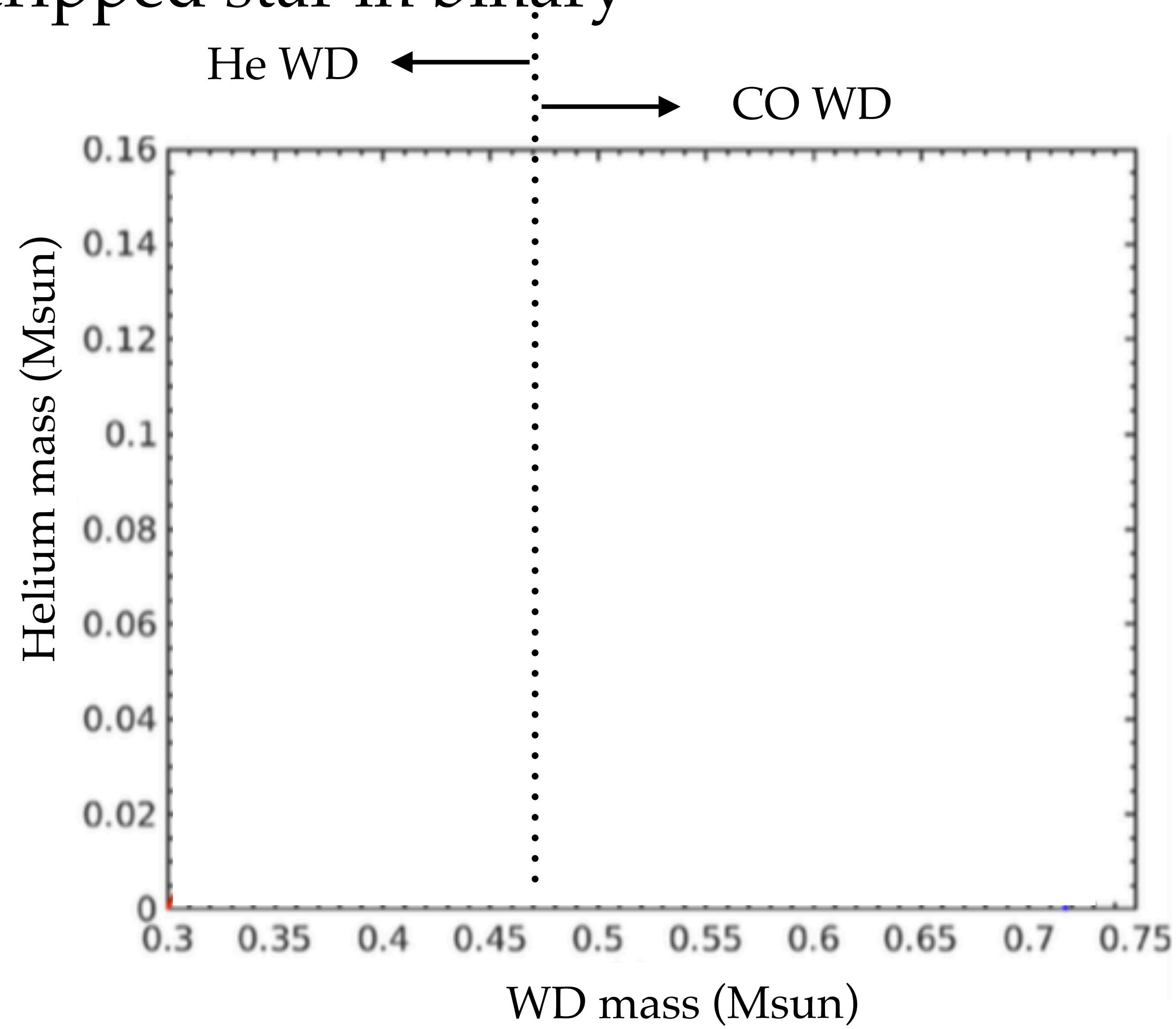
Perets+ w/Toonen+ '19

Hybrid white dwarfs



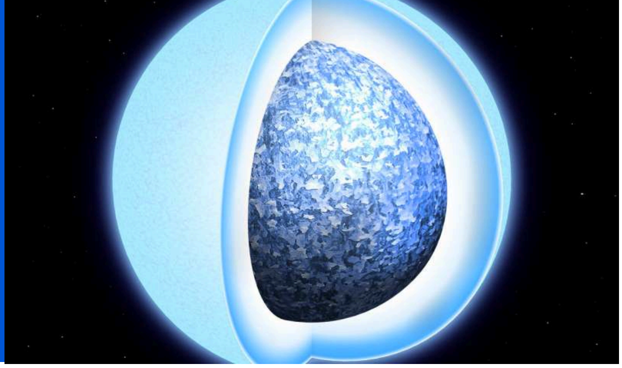
Hybrid white dwarfs

- CO core + He envelope (Iben & Tutukov ’85, Yungelson+ ’17, Zenati, Toonen+ ’18)
- Stripped star in binary



Zenati, Toonen+ ’19

Hybrid white dwarfs



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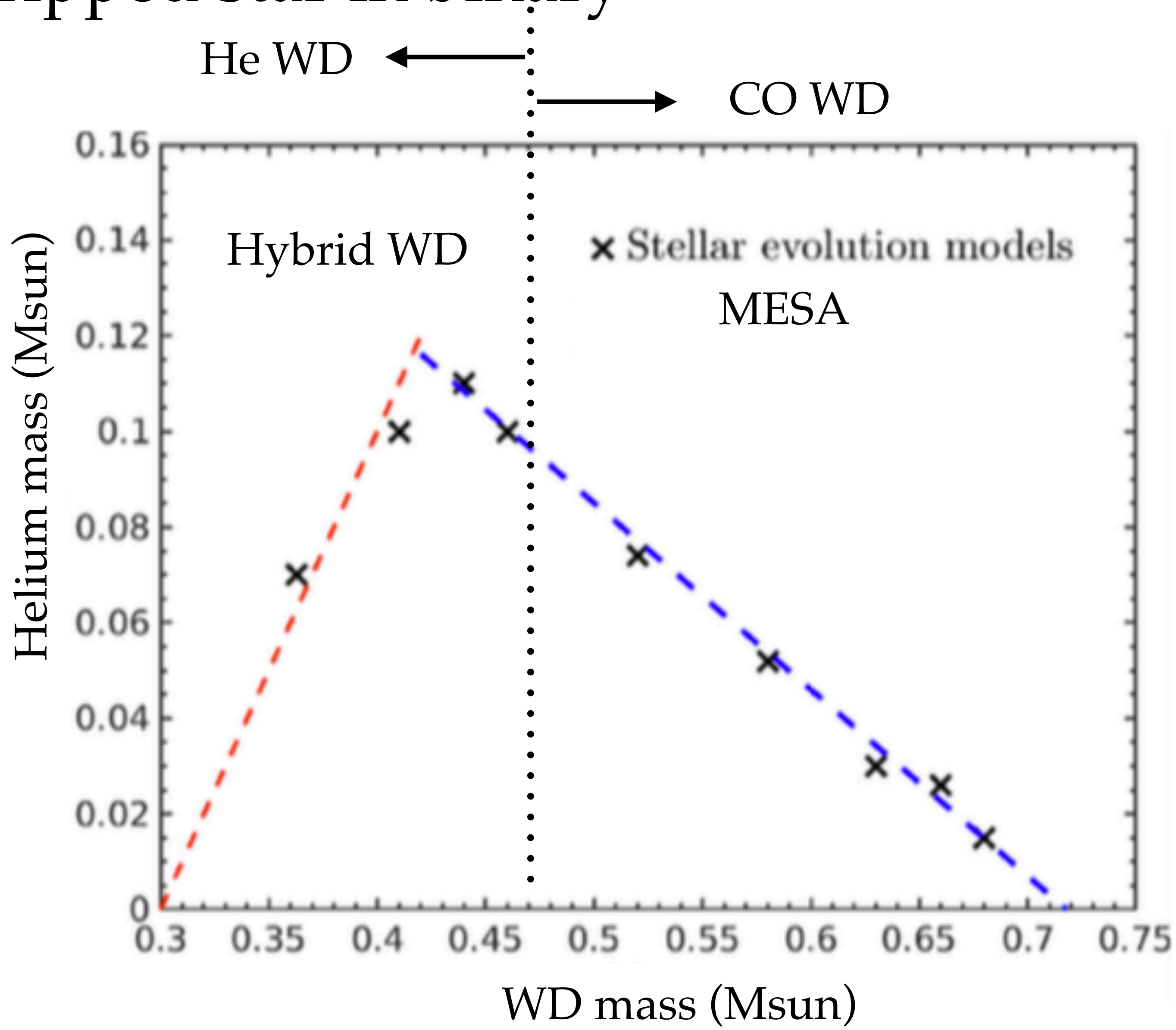

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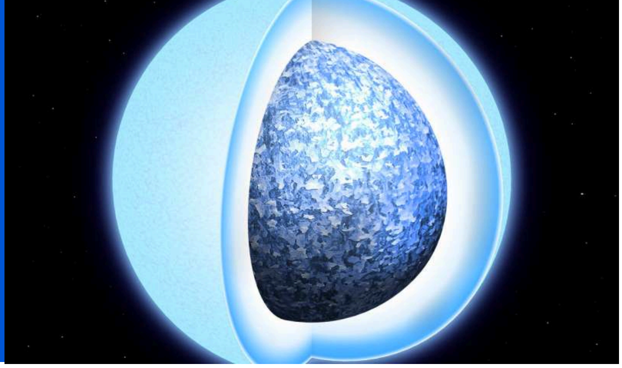

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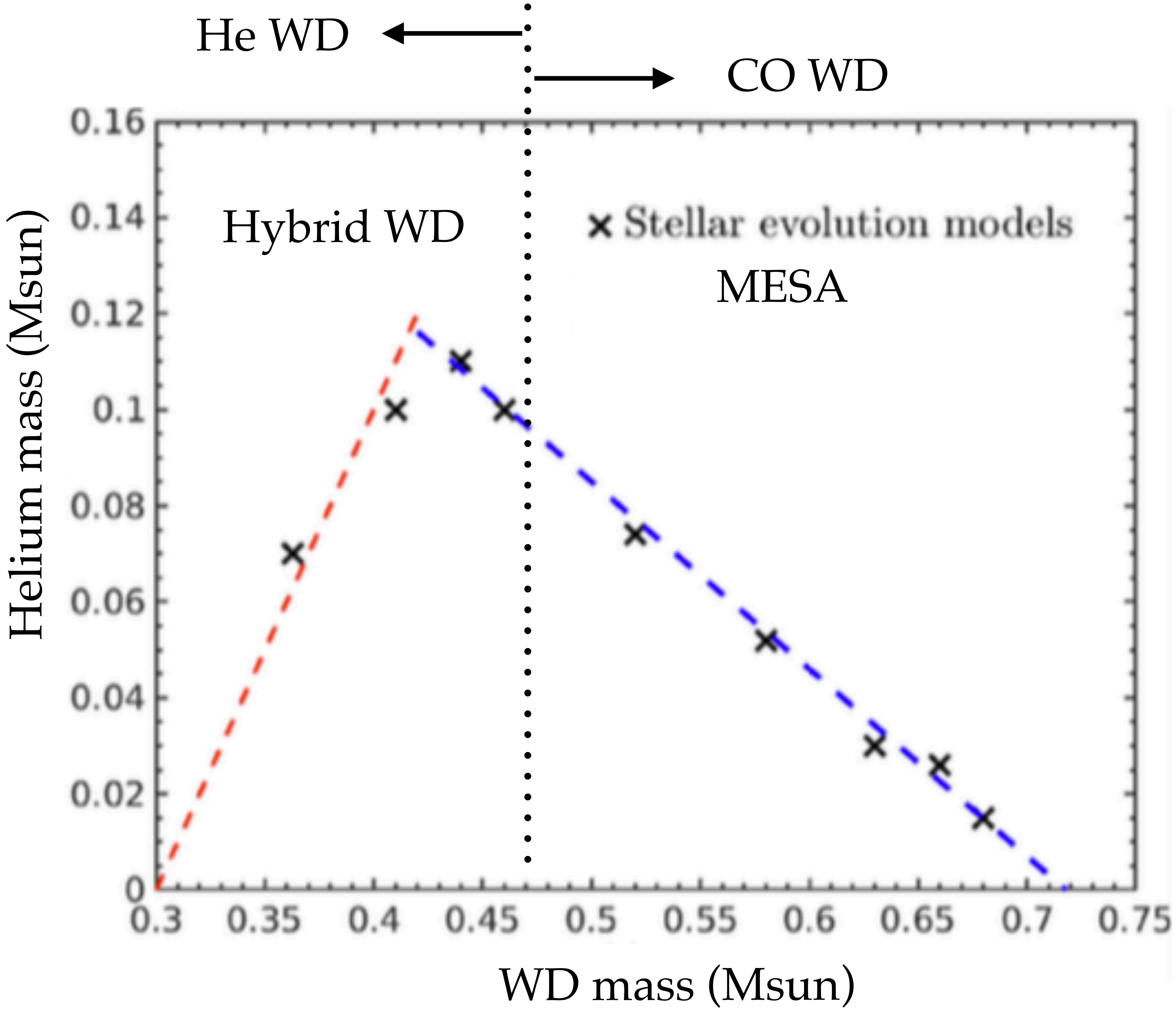


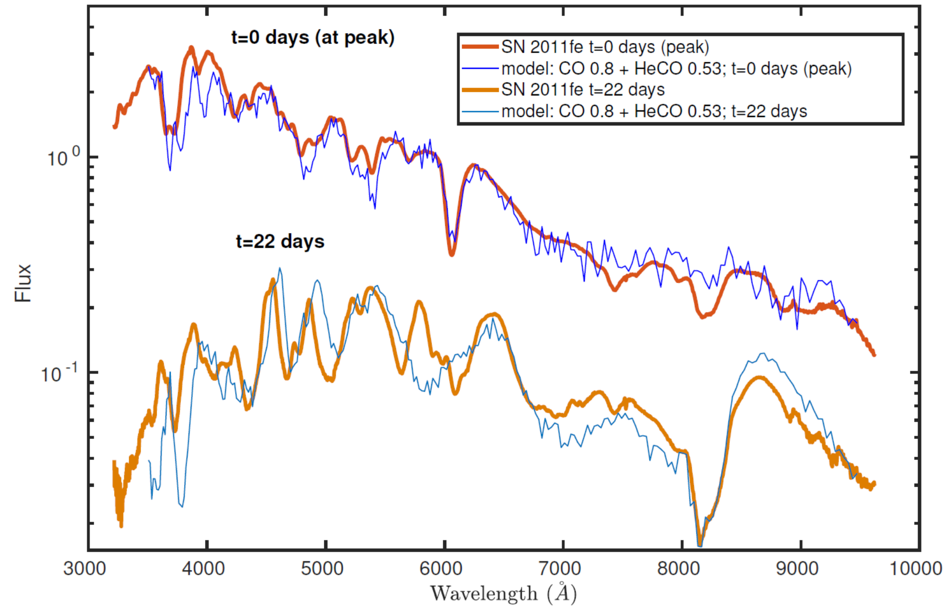
- Hybrid involved in ~25-30% of all WD-WD mergers
- Need ~15% to match SNIa rate (Maoz+ 18)

Zenati, Toonen+ '19

Diversity

Disruption of hybrid WD onto CO WD

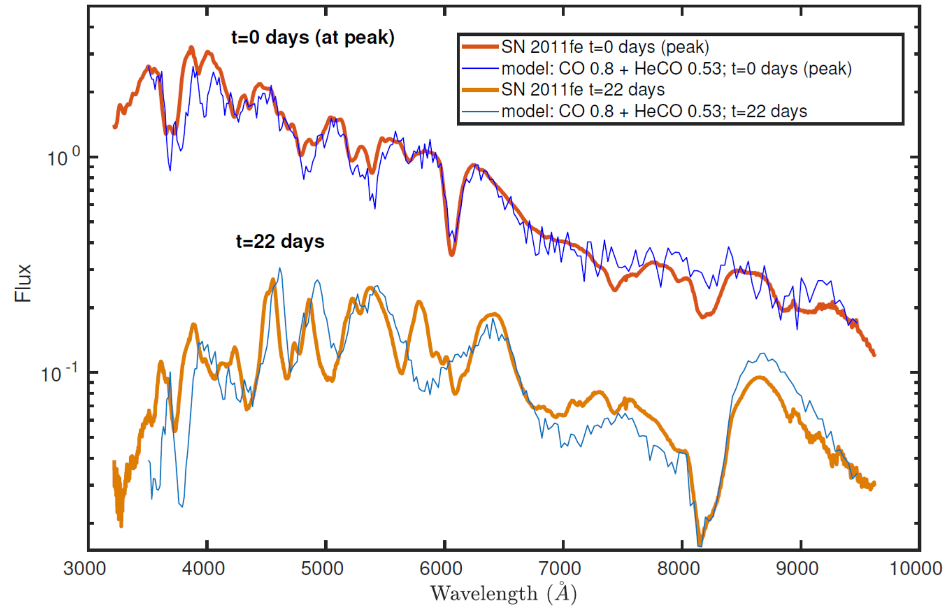
Disruption of CO WD through double detonation



Spectra alike SNIa - Perets+ w/ Toonen+ '19

Diversity

Disruption of hybrid WD onto CO WD
Disruption of CO WD through double detonation



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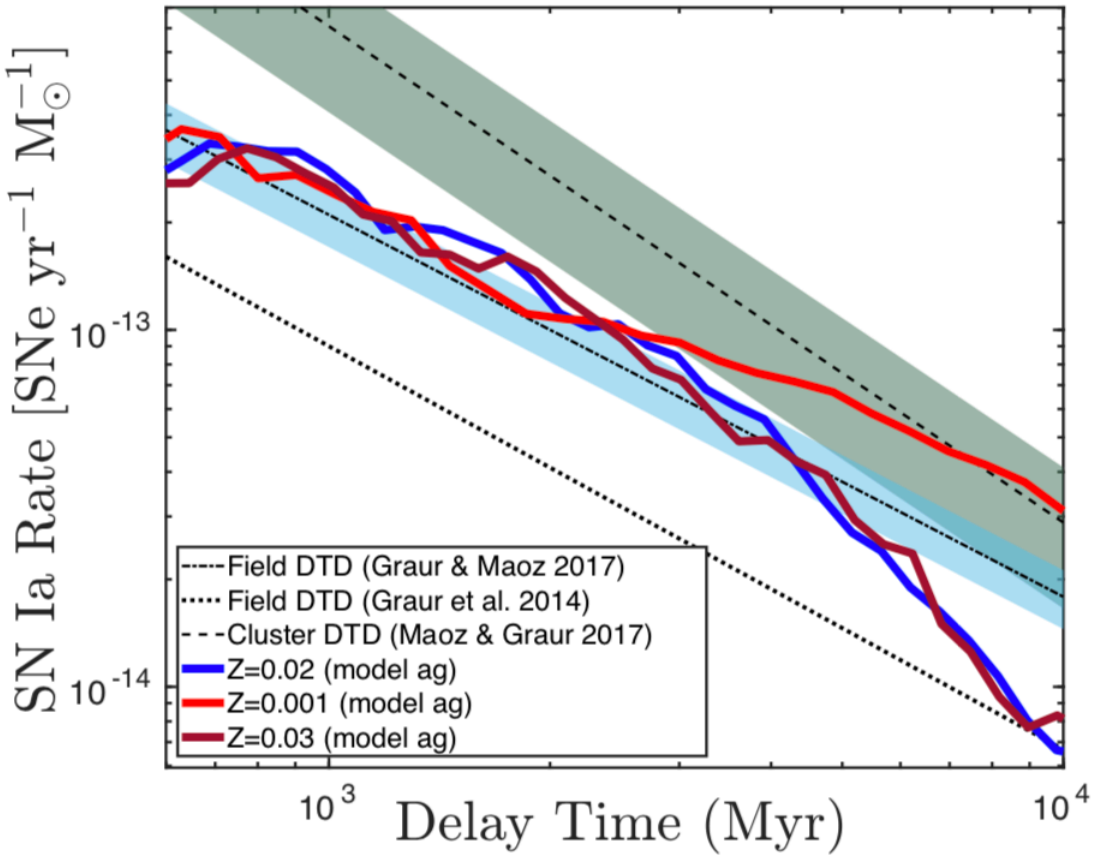
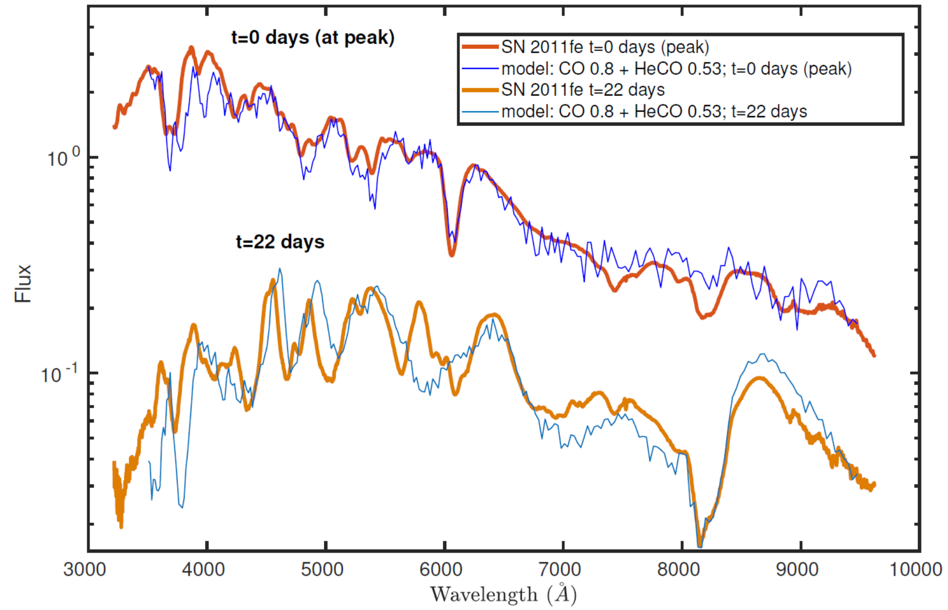


- ~60-70% from hybrid mergers (Mco>Mhybrid, Mtot>1.15Msun)
- ~30-40% from massive CO+CO WD mergers (M1,M2>0.9Msun)

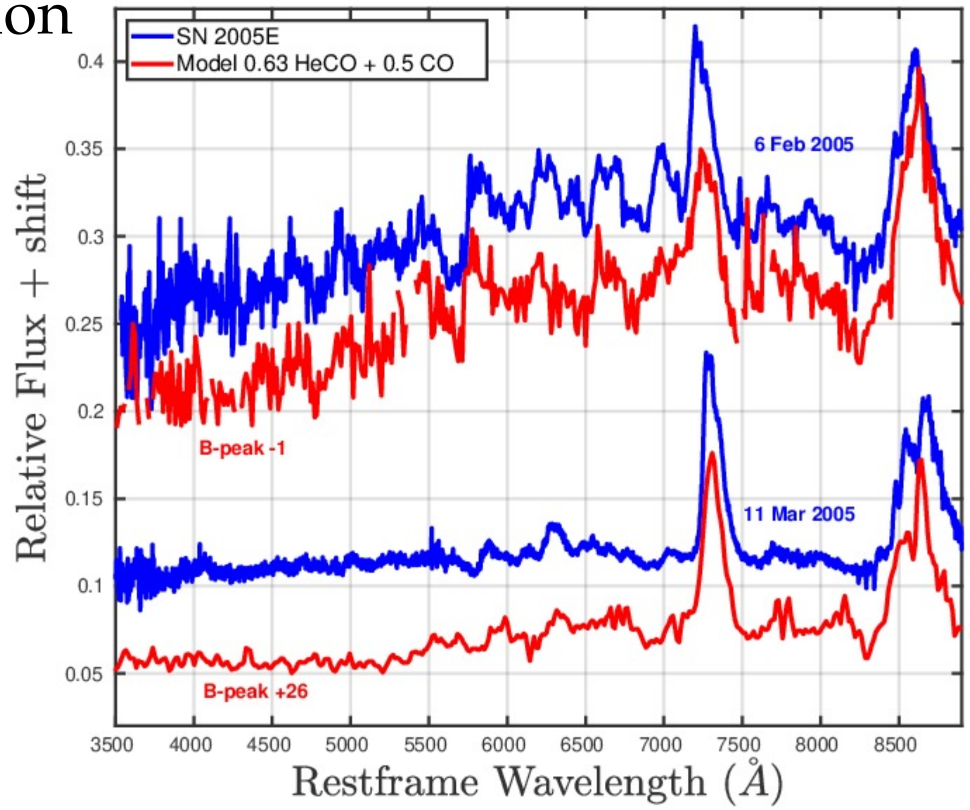
Diversity

Disruption of hybrid WD onto CO WD
Disruption of CO WD through double detonation



Spectra alike SNIa - Perets+ w/Toonen+ '19

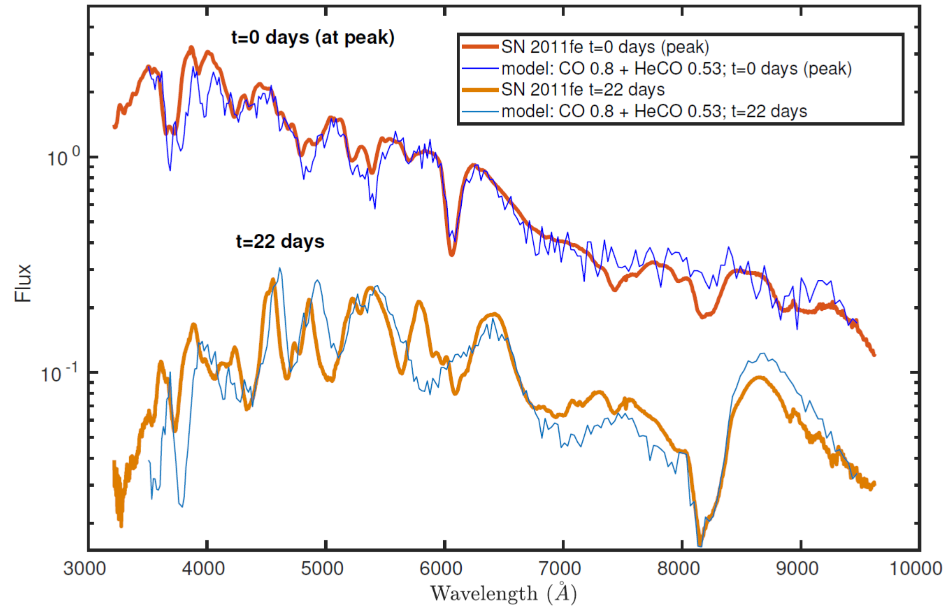
Disruption of a low-mass CO WD by a higher mass hybrid WD
Disruption of hybrid WD through double detonation



Spectra alike Calcium-strong transients - Zenati+ w/Toonen+ '23
Old environments -> in line with Kasliwal+12, De+20

Diversity

Disruption of hybrid WD onto CO WD
Disruption of CO WD through double detonation



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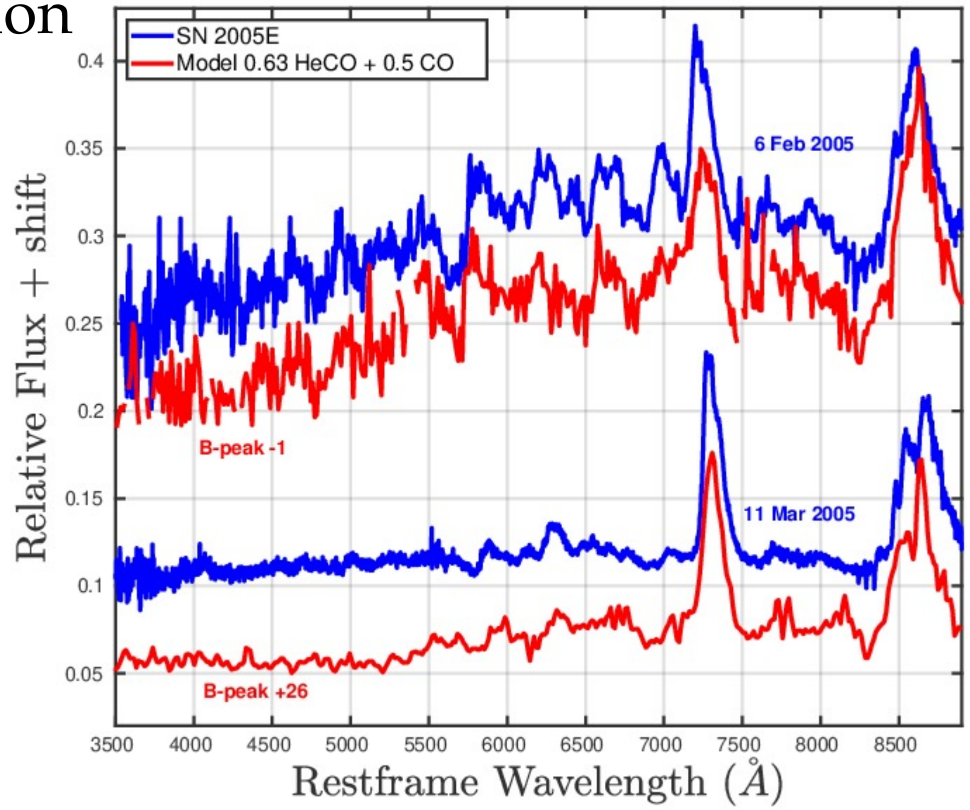
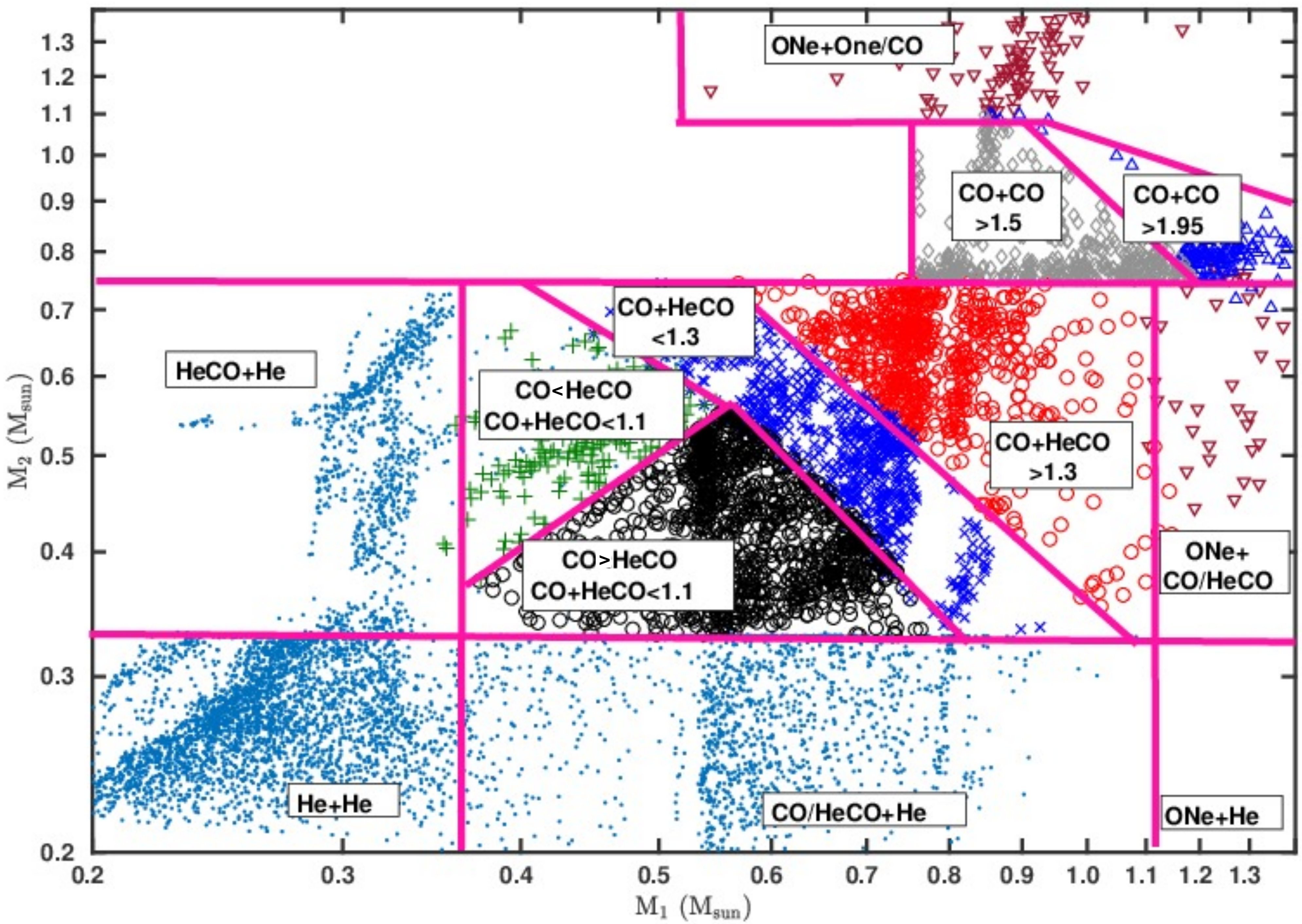


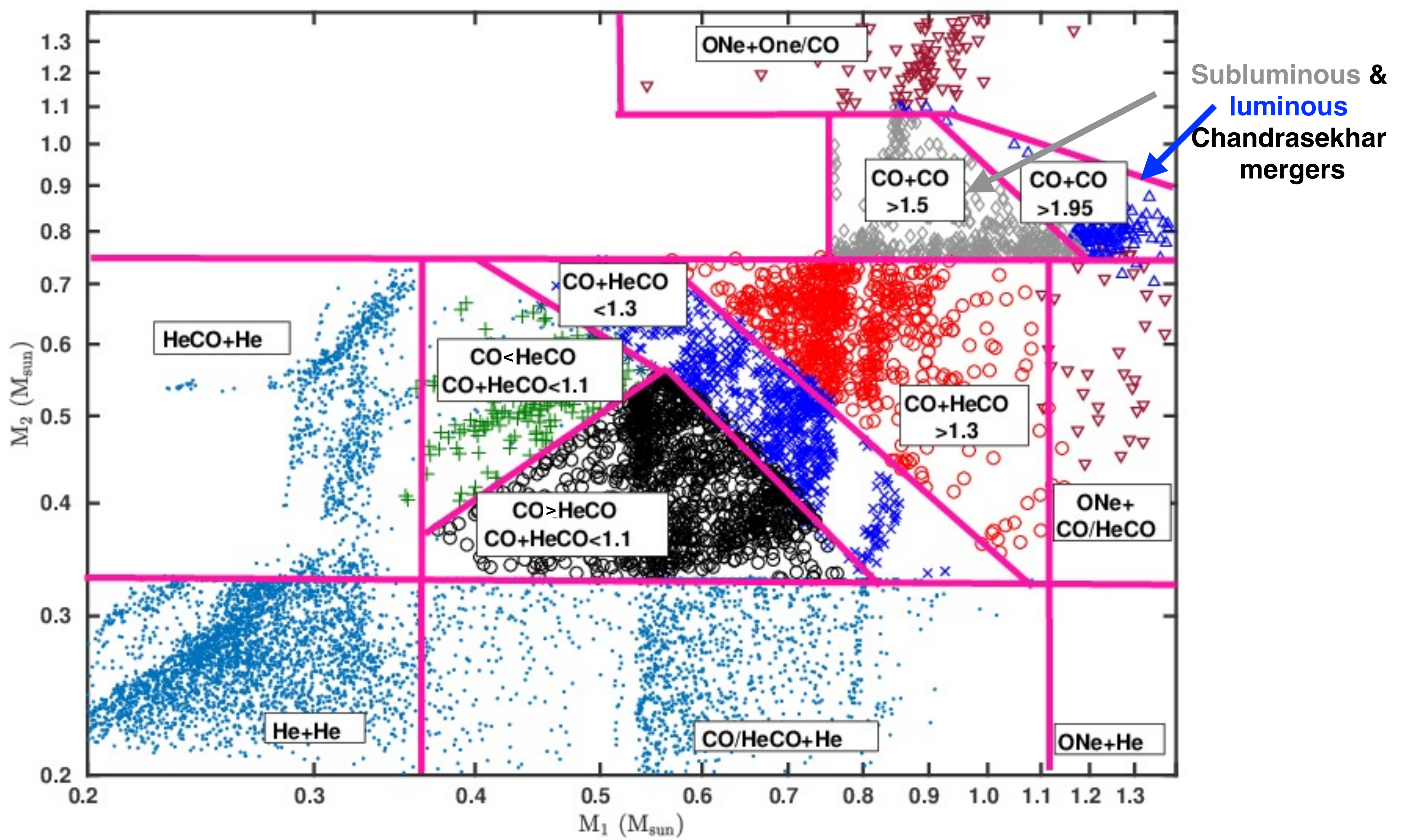
Spectra alike Calcium-strong transients - Zenati+ w/Toonen+ '23
Old environments -> in line with Kasliwal+12, De+20

Disruption of massive He-rich hybrid WD onto CO WD
Helium detonation travels upstream triggering a double detonation of the hybrid WD - Pakmor+ w/Toonen '21

Population


ONe+One/CO
CO+CO
>1.5
CO+CO
>1.95
CO+HeCO
<1.3
HeCO+He
CO<HeCO
CO+HeCO<1.1
CO+HeCO
>1.3
CO>HeCO
CO+HeCO<1.1
ONe+
CO/HeCO
He+He
CO/HeCO+He
ONe+He
M_2 (M_{sun})
M_1 (M_{sun})

Population



ONe+One/CO
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CO+HeCO<1.1
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>1.3
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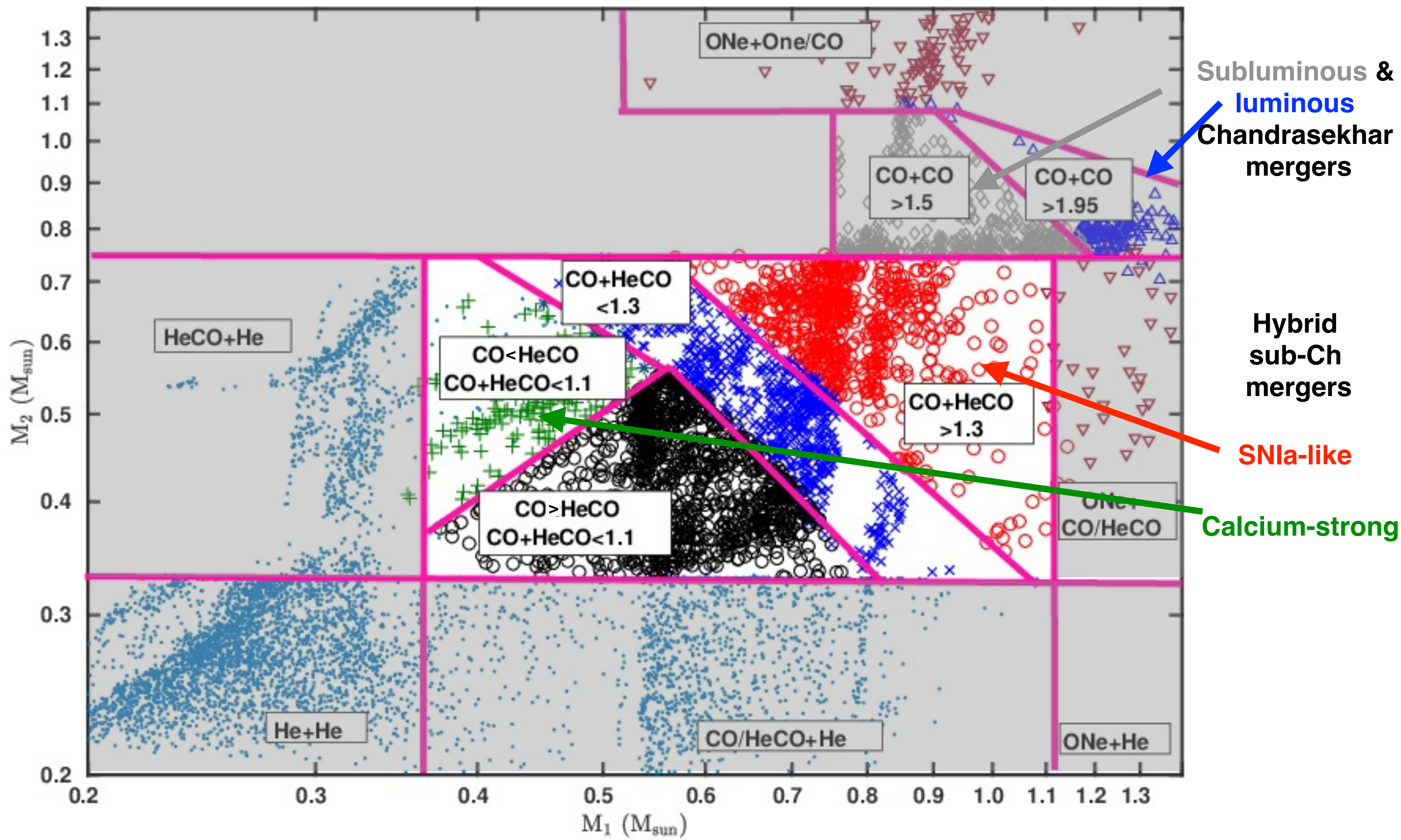
CO+HeCO<1.1
ONe+
CO/HeCO
He+He
CO/HeCO+He
ONe+He
M_2 (M_{sun})
M_1 (M_{sun})
Subluminous & luminous Chandrasekhar mergers

Population



ONe+One/CO
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CO+HeCO<1.1
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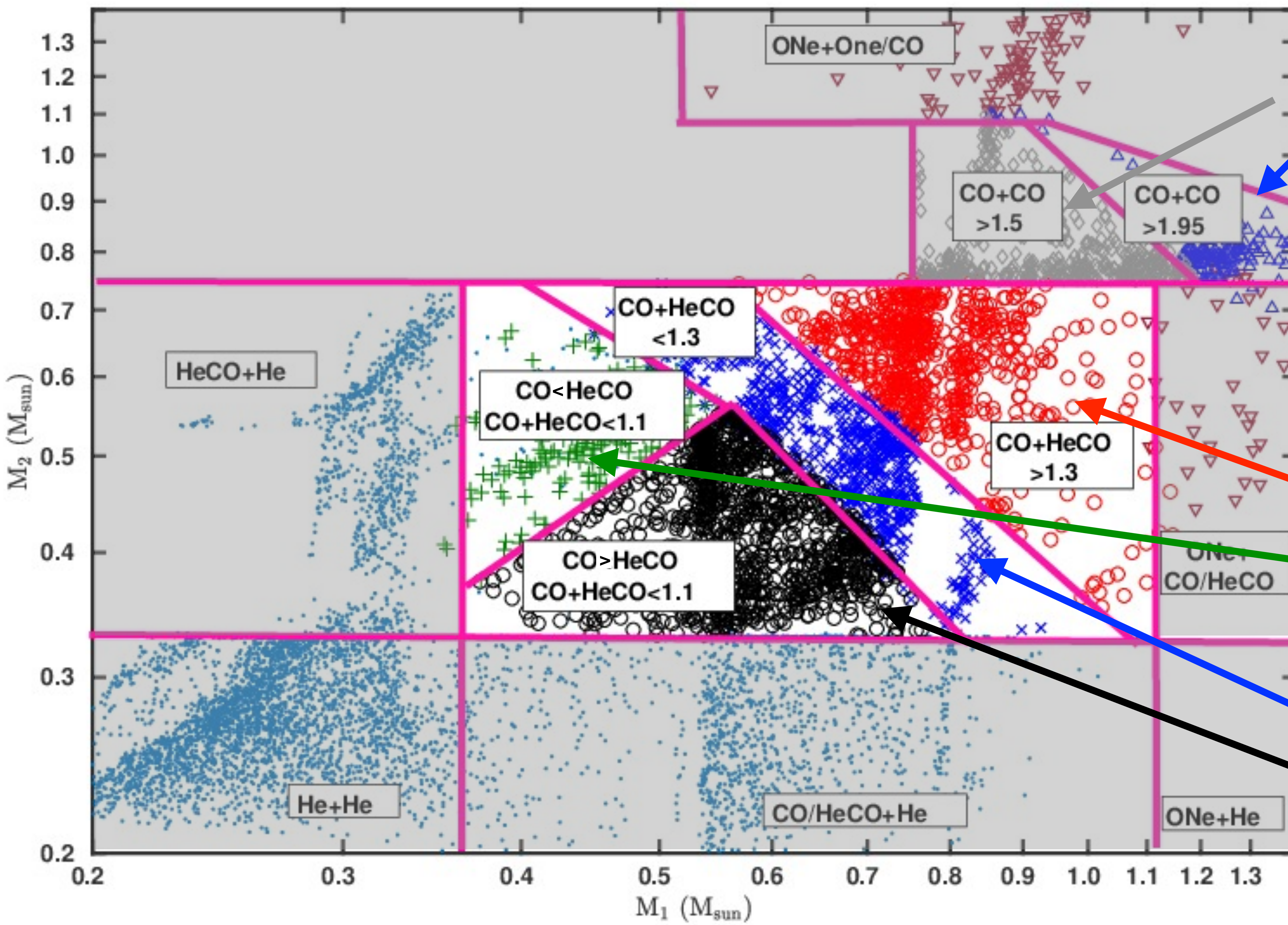
CO+HeCO
>1.3
ONe+
CO/HeCO
He+He
CO/HeCO+He
ONe+He
M_2 (M_{sun})
M_1 (M_{sun})
Subluminous & luminous Chandrasekhar mergers
Hybrid sub-Ch mergers
SNIa-like
Calcium-strong

Population



Integrated rate 10^{-4} per Msun

Subluminous & luminous Chandrasekhar mergers

2-4 & 0.2-0.4

Hybrid sub-Ch mergers

SNIa-like
2-4

Calcium-strong
~0.01-0.4
Old environment

1-3

0.4-1

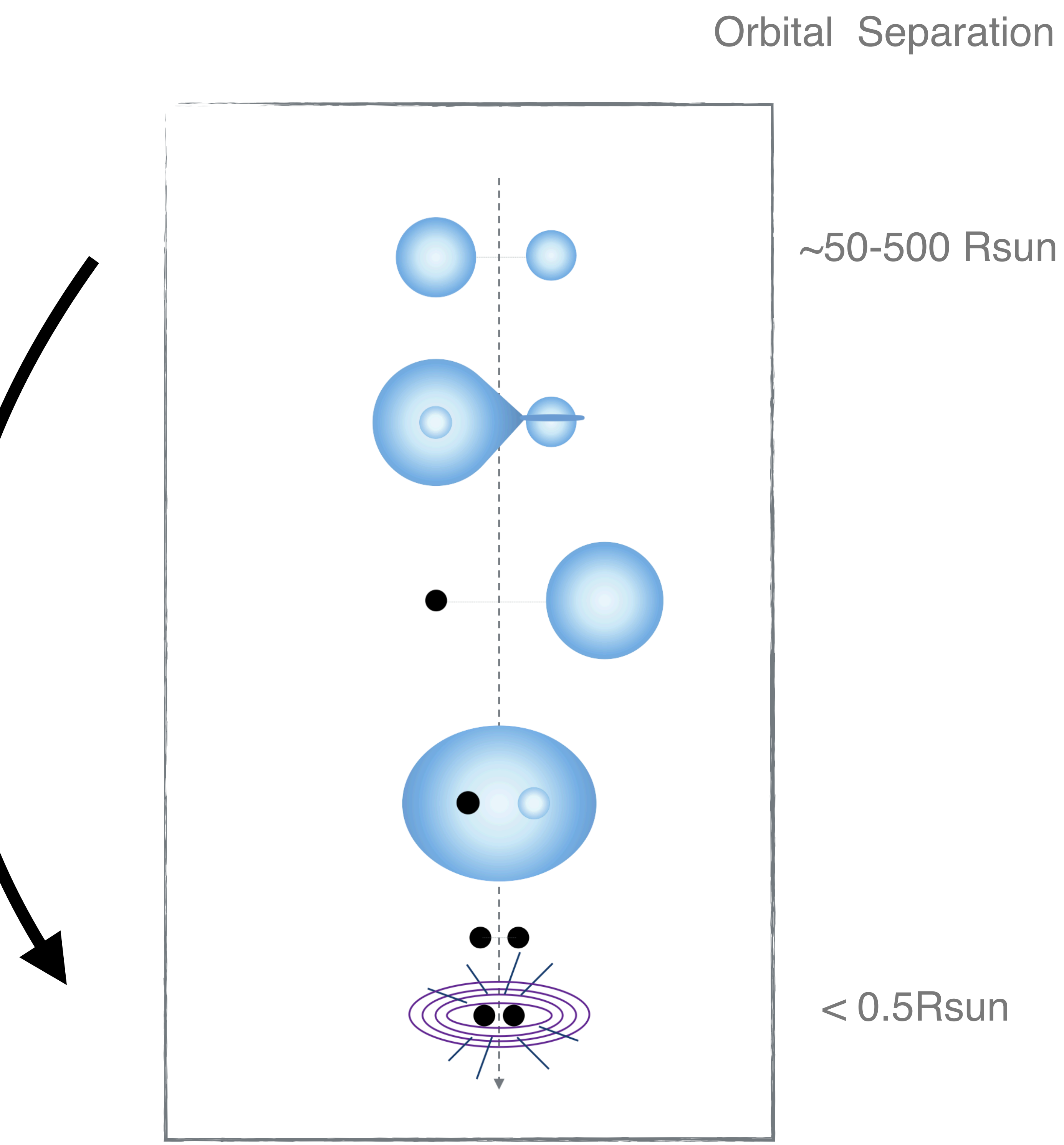
Other pathways?

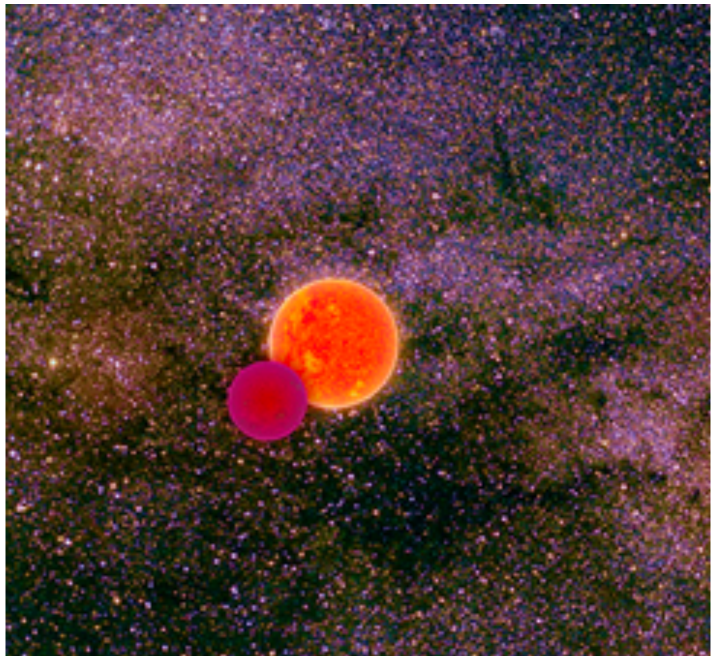
Strong orbital shrinkage!

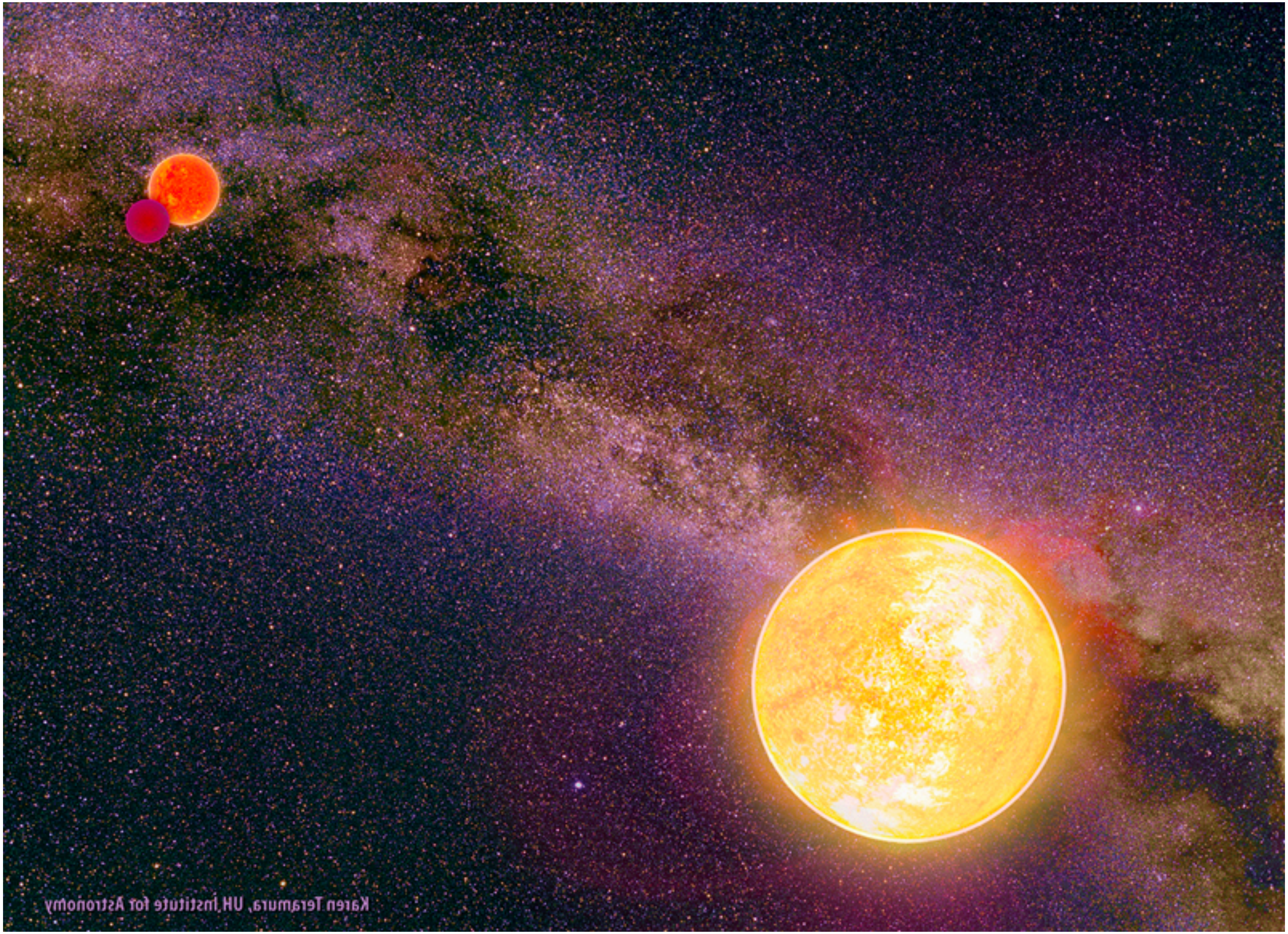
Need interactions for that

Finetuning to end with compact orbit

Can we think of other processes that shrink the binary or drive interactions?

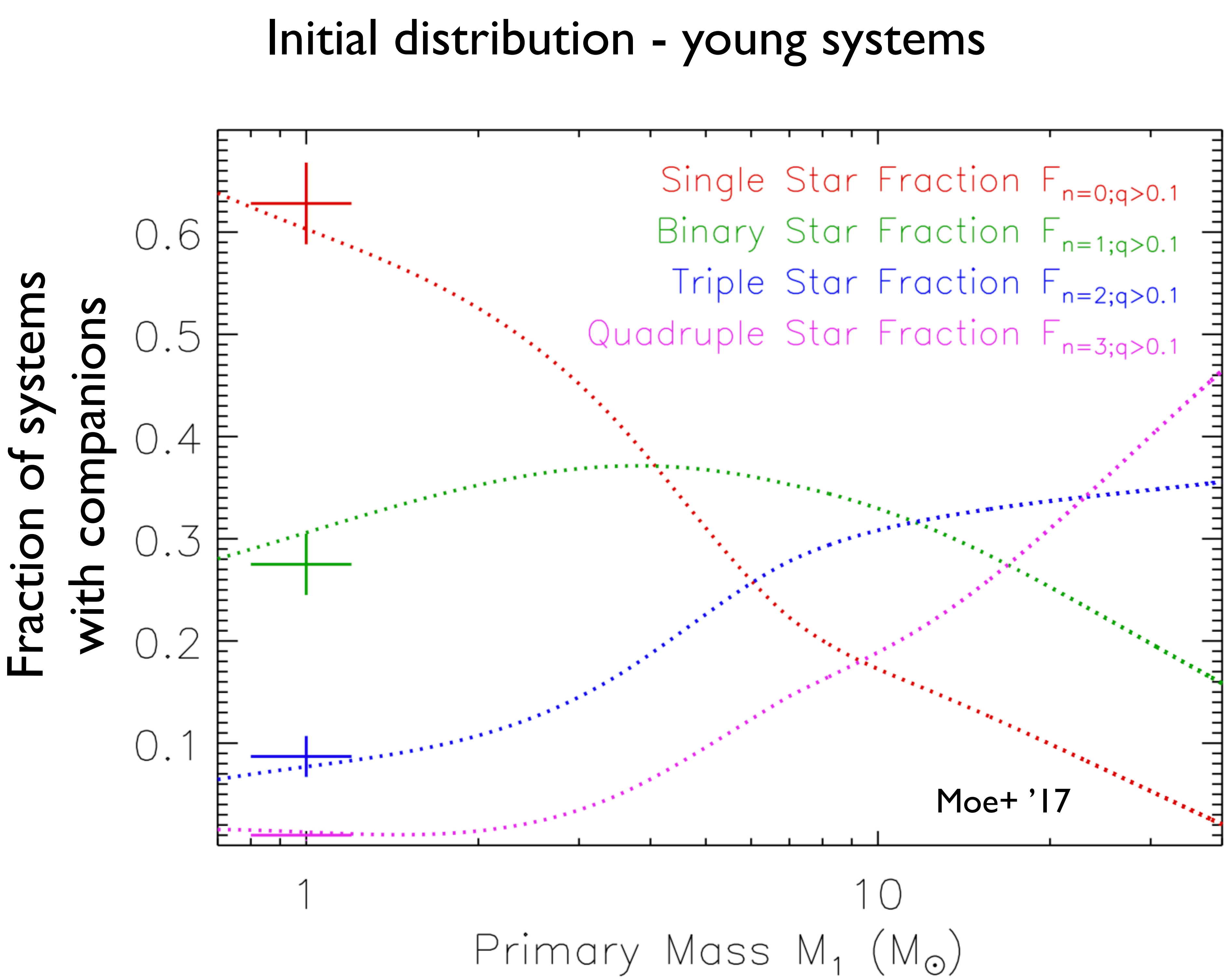






Dynamically stable if $P_{\mathrm{outer}} \gtrsim 5 P_{\mathrm{inner}}$ -> long-lived

Many stars have several stellar companions

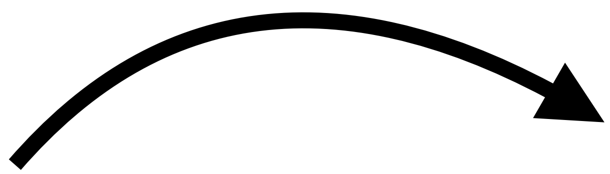


Mostly low mass triples: Raghavan+ '10, Tokovinin '08, '14, Duchene & Kraus '13

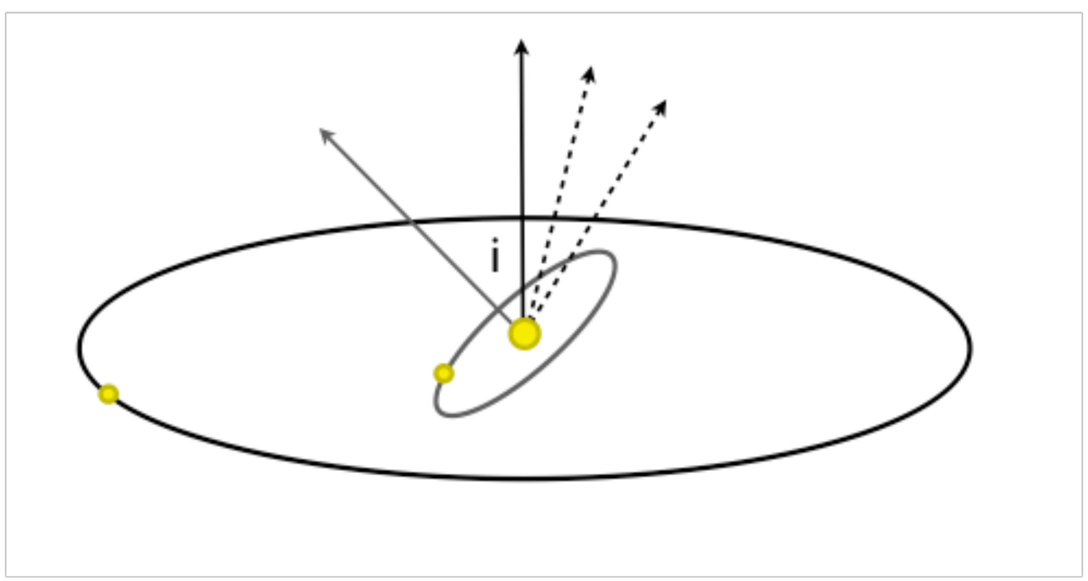
High mass triples (non-bias corrected):

- 33% within <200mas (Sana+ '14)
- 16% (Kobulnicky+ '14)
- 44% for Cepheids (Evans+'05, '11)
- 50% Bordier+ 22
- 60% for Massive contact systems (Abdul-Masih)
- 35% for B-type stars (Frost in prep.)

Triple pathways

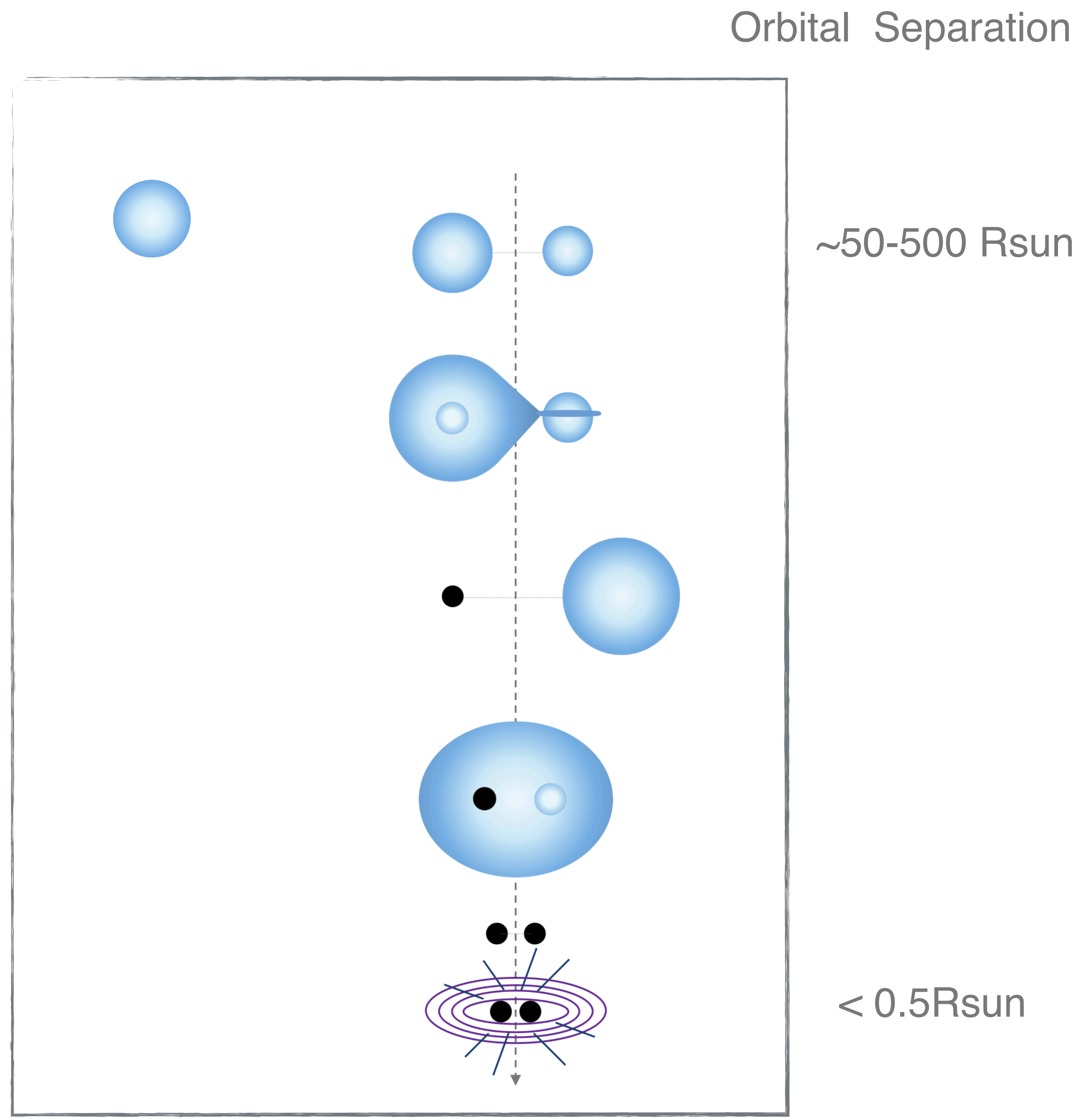


What happens if I add a third star?



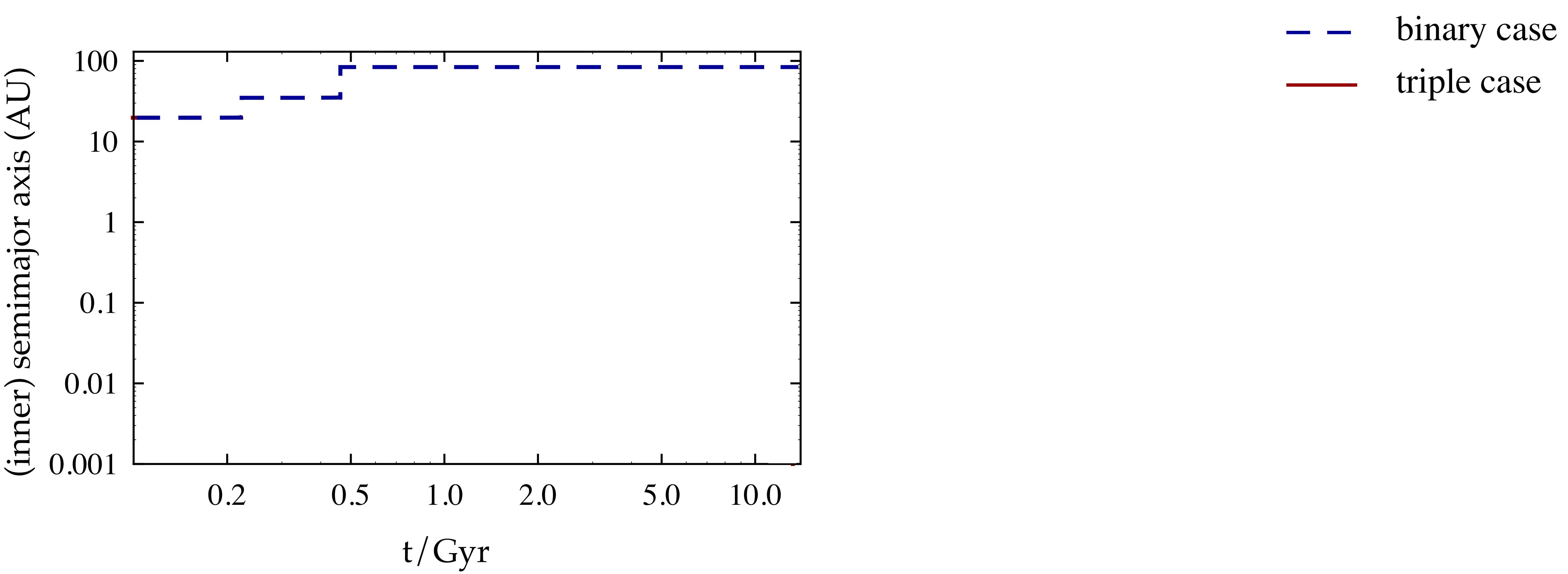
Three-body dynamics:

- von-Zeipel-Lidov-Kozai cycles (Von Zeipel '10, Lidov '62, Kozai '62) in eccentricity & inclination
- 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

Long-term effect

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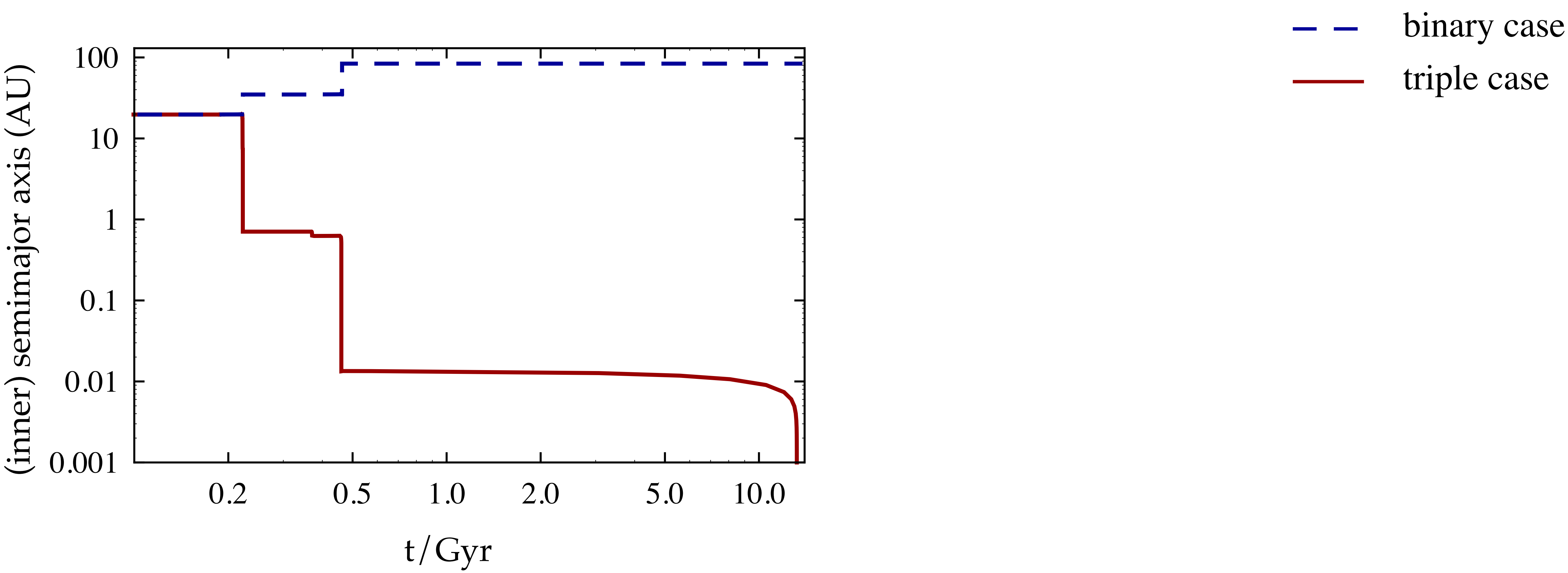

courtesy of Adrian Hamers

Long-term effect

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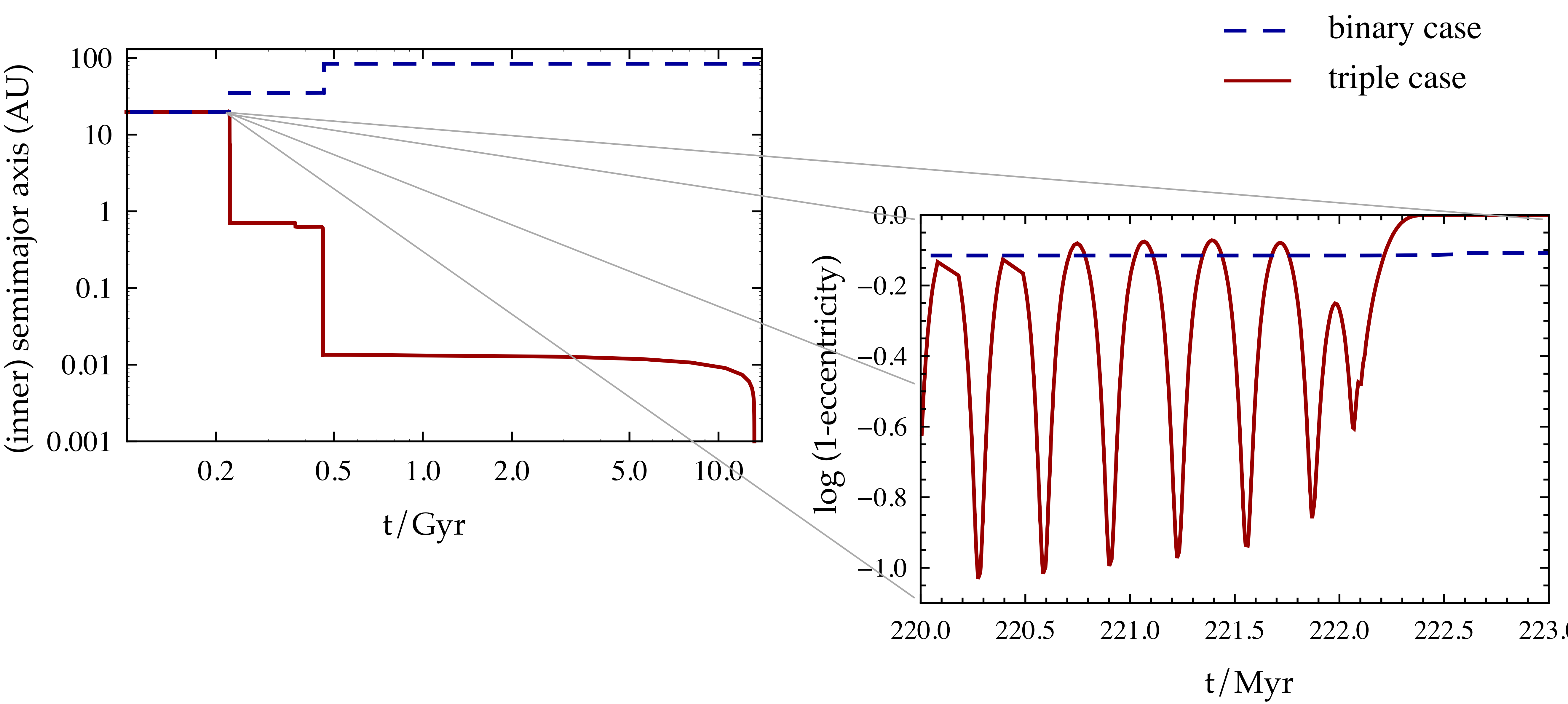
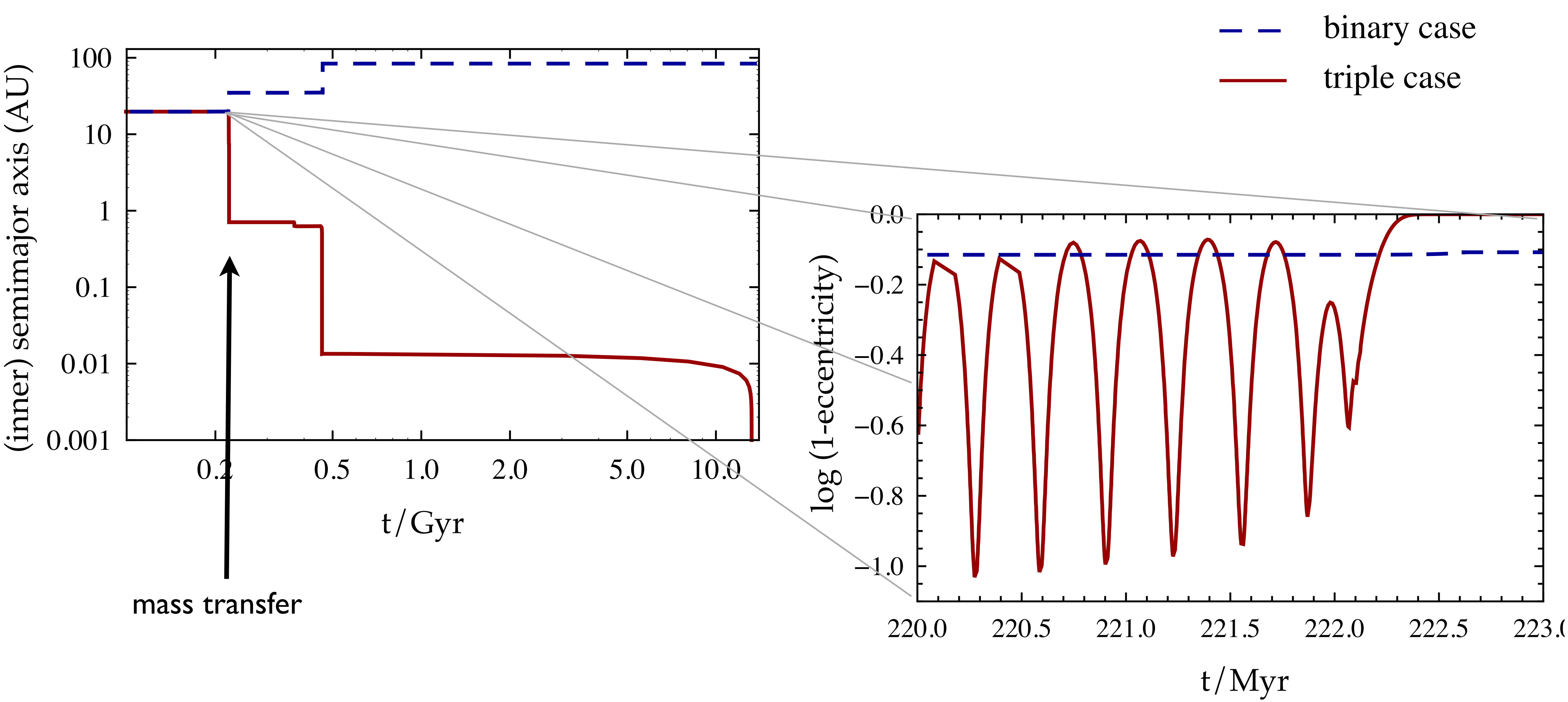


courtesy of Adrian Hamers

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

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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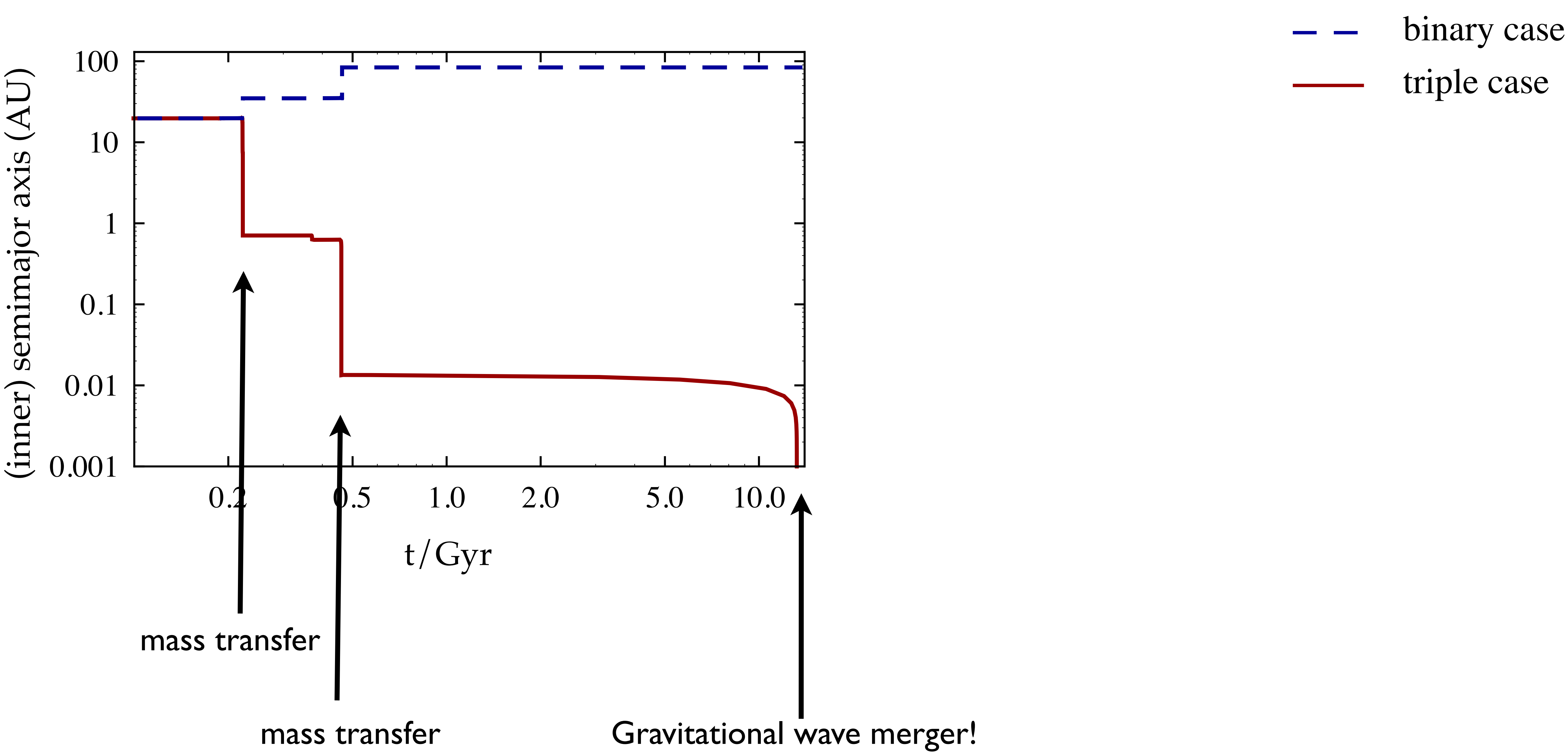
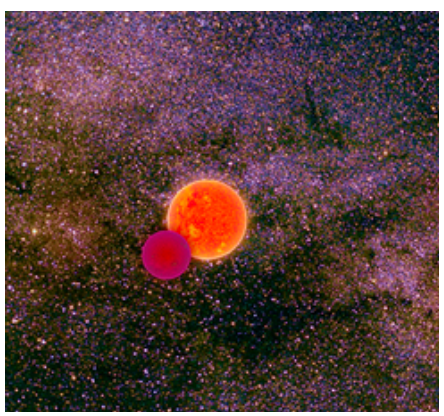


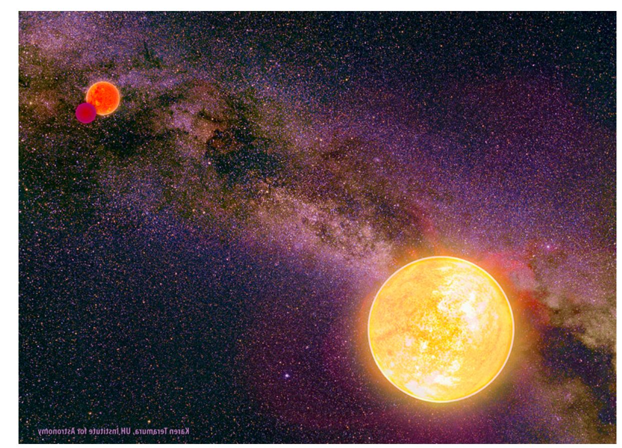
courtesy of Adrian Hamers

refs: Toonen+ ’20, Kummer+ ‘24

What happens if I add a third star?

Three-body dynamics leads to high eccentricities and close passages:
- close binaries due to enhanced tides & GW emission
- katalyse stellar interactions
    - In systems that would otherwise not interact
    - Earlier in the evolution -> changes the finetuning





(Typical) Binaries
- ~1/4-1/3 of systems interact

Triples
- ~2/3-3/4 of systems interact

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

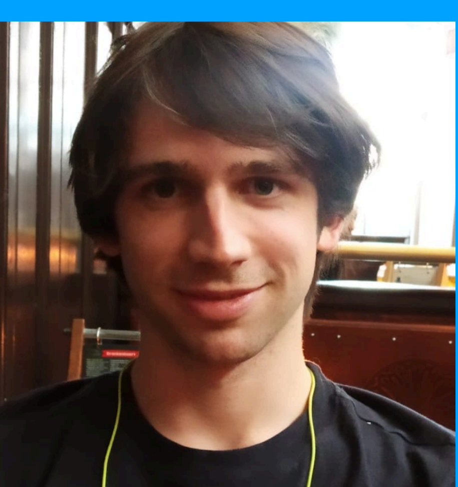
Triple code TRES

- 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+ '23)
- CHE triples (Dorozsmai+ '24, Kummer+ '24)

TRES core team

github.com/amusecode/TRES

Andris Dorozsmai



Adam Parkosidis

Silvia Toonen, PI

Floris Kummer

Simon Portegies Zwart

Caspar Bruenech

Triple SNIa progenitors

Mergers

- (interactions with one set of simplified assumptions)
- Similar rate between triples & binaries
- Triple rate of 0.9-3.7 per 10000 Msun compared to a binary rate of 3.2 per 10000 Msun (Rajamuthukumar + '23)
- Most models >97% from He WD + CO WD mergers
- Rest from CO WD + CO WD with M1>0.9Msun.

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)
- Rate of ~1.5-4e-2 when combinating with mass transfer (Rajamuthukumar + '23)

Binary population synthesis

How good are the binary population synthesis models??

How good are the number estimates?
e.g. rates or space densities?

Binary population synthesis

- Space density of WD+WDs - as fraction of single WDs

Observationally

BPS models

Binary population synthesis

- Space density of WD+WDs - as fraction of single WDs

<u>Observationally</u>

- 0.017–0.19 (Maxted & Marsh 99)
- 0.01-0.04 (20-pc sample of WDs, Toonen+ 17, Hollands, Toonen +19)
- 0.095 ± 0.020 ± 0.010 (SDSS statistics, Badenez & Maoz 12, Maoz & Hallakoun '17, Maoz+18)

<u>BPS models</u>

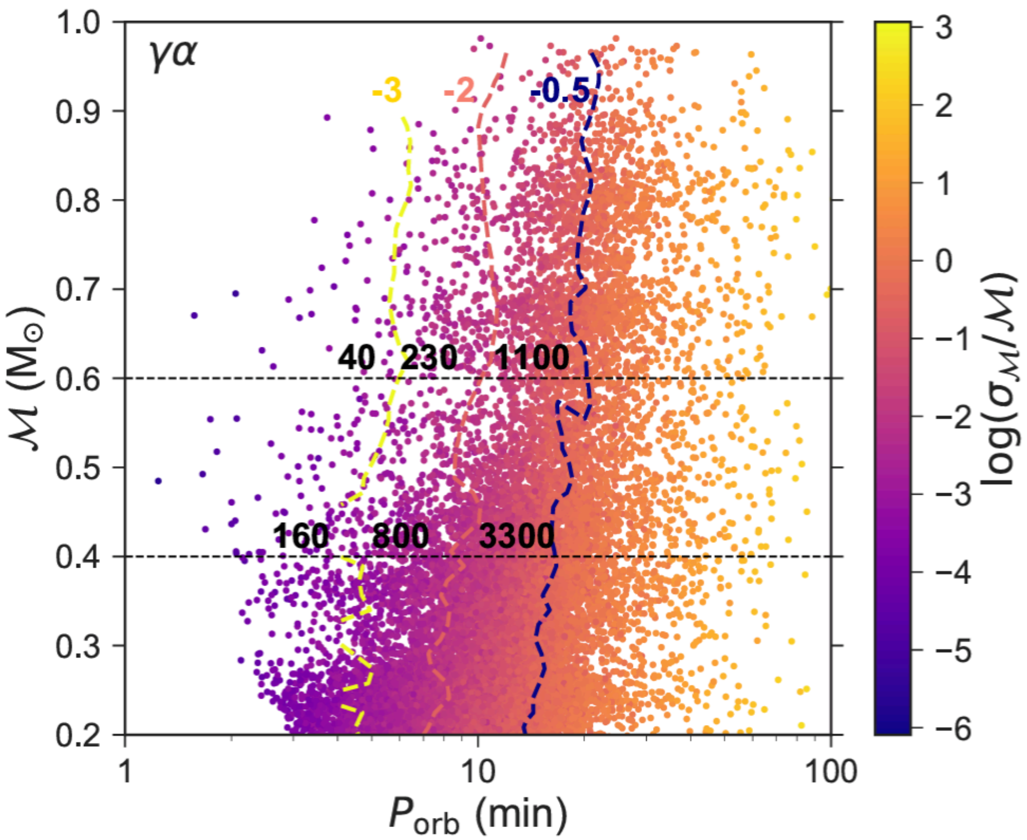
- 0.02-0.04

➡ Helps to relieve tention for SNIa progenitors

➡ More LISA gravitational wave sources

LISA double WDs

- The SDSS statistics imply 60.000 sources! (Korol+ w/Toonen 22)
- Typically BPS codes predict 10.000-30.000 LISA observable DWDs
  - SeBa: ~25.000 (Korol+ w/Toonen '17)
  - Most recent BPS estimate: ~700 sources (van Zeist+ 24, Tang+ 24)
- Best WD+WD sample to date (ZTF eclipsing & DBL sources) imply minimum of ~7000 sources (van Zeist+ w/Toonen subm.)



- Periods from the GW frequency
- Chirp mass only for inspiring sources

$$\mathcal{M} = \frac{(m_1 m_2)^{3/5}}{(m_1 + m_2)^{1/5}}$$

  - ~1000 WD+WD with accurate chirp masses
  - ~100 massive WD+WD with accurate chirp masses

Past, present & future

Past:

- ~10 yrs ago : ~50 WD+WDs known, detected with variety of methods

Present: ~300 WD+WDs

- Mostly from: SDSS ELM survey (Brown+ '10, '22) & SPY survey (Napiwotzki et al. '20)
- But few (~77) with well measured properties for both stars
  - 31 discovered in 2024 by the DBL survey (Munday+ incl. Toonen '24)
  - ZTF: ~30 eclipsing WD+WDs (van Roestel in prep.)

Future:

- Gaia satellite: ~30 eclipsing WD+WDs (mid 2026), thousands non-eclipsing need EM followup (Korol+ 17, priv. comm. Roestel)
- Vera Rubin Observatory: ~200 eclipsing WD+WDs (Korol+ 17, priv. comm. Roestel)
- DBL survey : ~200 more by completion of survey

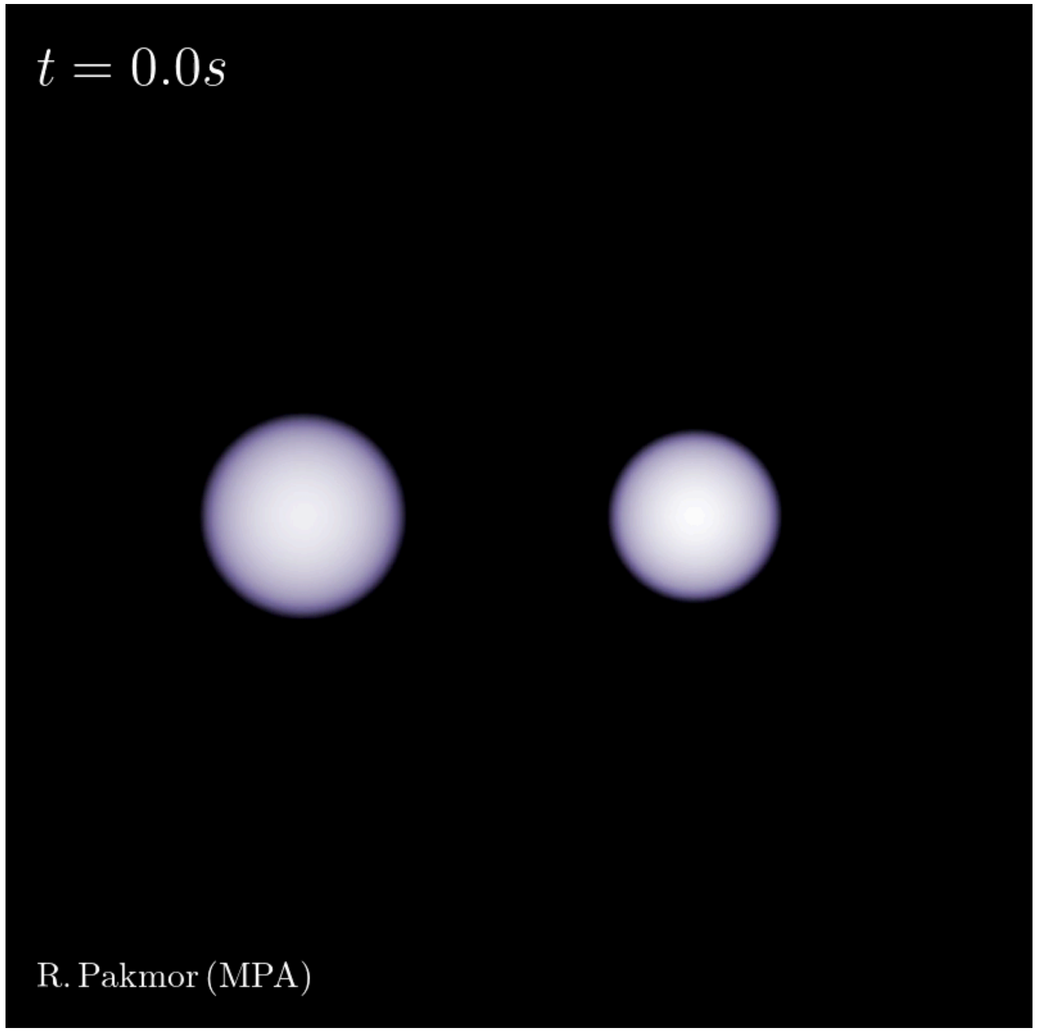
Finding SNIa progenitors?

- Rebassa-Mansergas, Toonen+ 19: chance of finding a (Ch or sub-Ch) WD+WD progenitor low (~0.00001- 0.00002)

Finding SNIa progenitors!

- Rebassa-Mansergas, Toonen+ 19: chance of finding a (Ch or sub-Ch) WD+WD progenitor low (~0.00001- 0.00002)
- To be published tomorrow in Nature astronomy (Munday+ w/ Toonen)

WDJ181058.67+311940.94



First SNIa progenitor

- 0.83+0.72Msun @ 14.24 hr
- Merger in 22Gyr
- Close by: 49pc

- Subluminous SNIa from a double detonation based on Arepo simulations

https://youtu.be/jRk5lYE0Y78

Summary

WD+WD mergers as progenitors of SNIa

- Delay time distribution typically in agreement with observations
- Absolute rate?
    - Glass half full: Ch-channel in agreement with observations - within the BPS uncertainties
    - Glass half empty: sub-Ch channels typically lower rates

Improving the BPS models:

- Taking into account triple evolution
- Constraints from WD+WD observations
    - DBL survey already doubled the number of WD+WD systems with well measured properties
    - And found the first SNIa progenitor