Gravitational waves from quadruple stars - quadruple the fun! (?)

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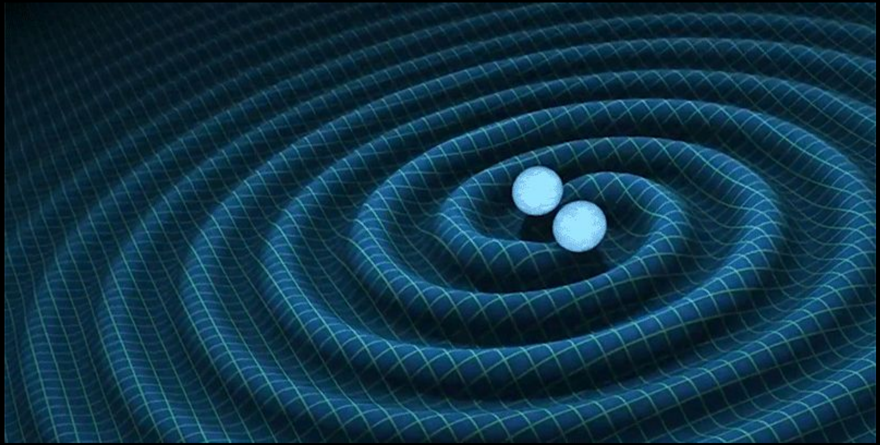
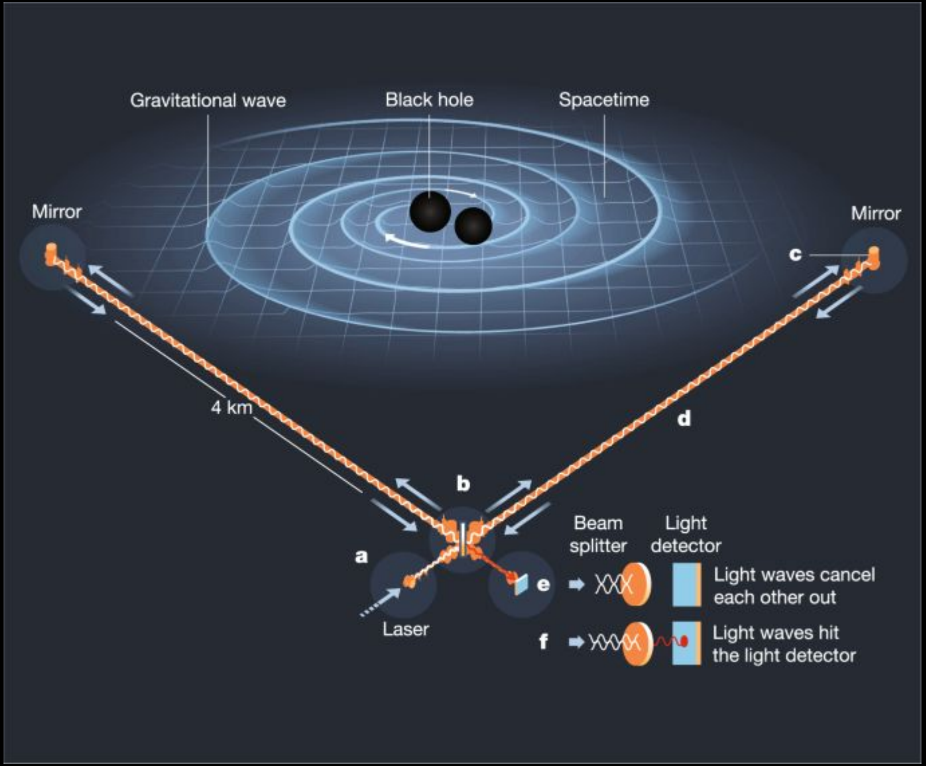
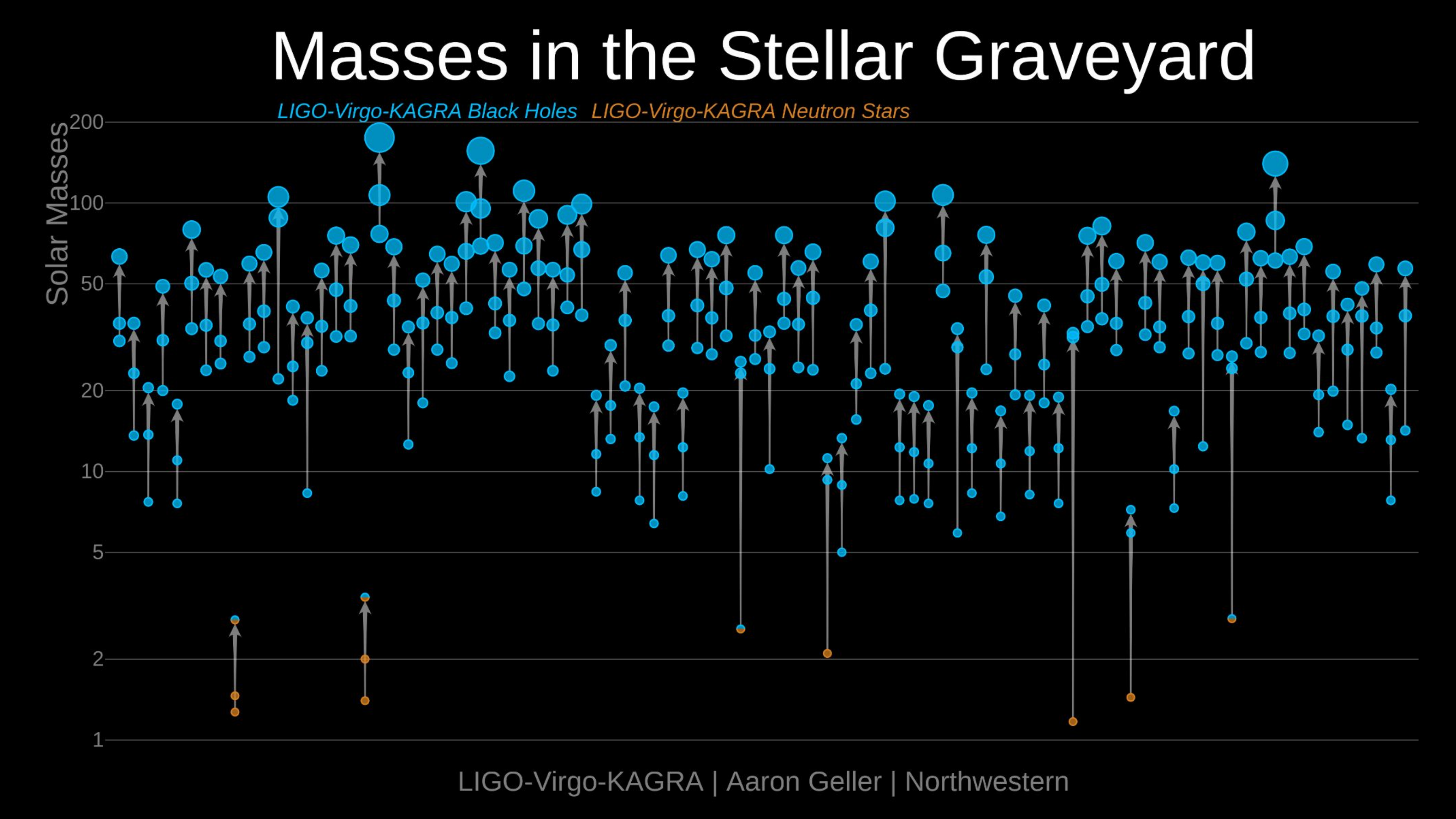
Gravitational waves (GWs)

- Ripples in spacetime
- Inspiral of **compact objects**
- Compact objects - black holes (BH), neutron stars (NS) are **remnants of massive stars**






Masses in the Stellar Graveyard
LIGO-Virgo-KAGRA Black Holes
LIGO-Virgo-KAGRA Neutron Stars
Solar Masses
200
100
50
20
10
5
2
1
LIGO-Virgo-KAGRA | Aaron Geller | Northwestern

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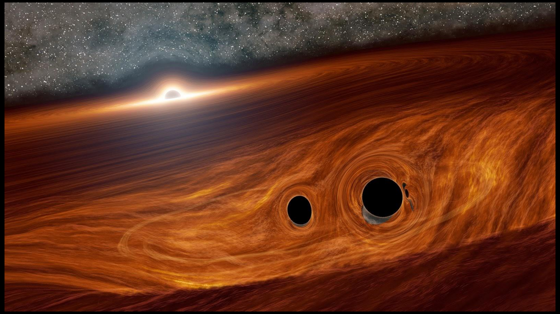
Compact object merger channels

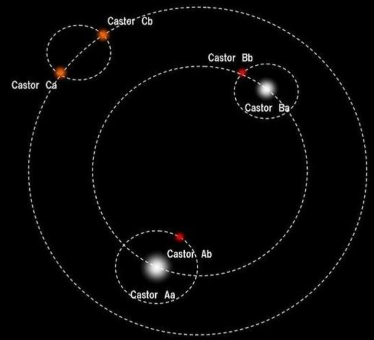
Isolated binaries



AGN disks

Dynamical formation

Clusters and stuff



Multiple systems

Why multiple-star systems (quadruples specifically)?

1. Massive stars are found mostly in multiple systems (triples and quadruples)

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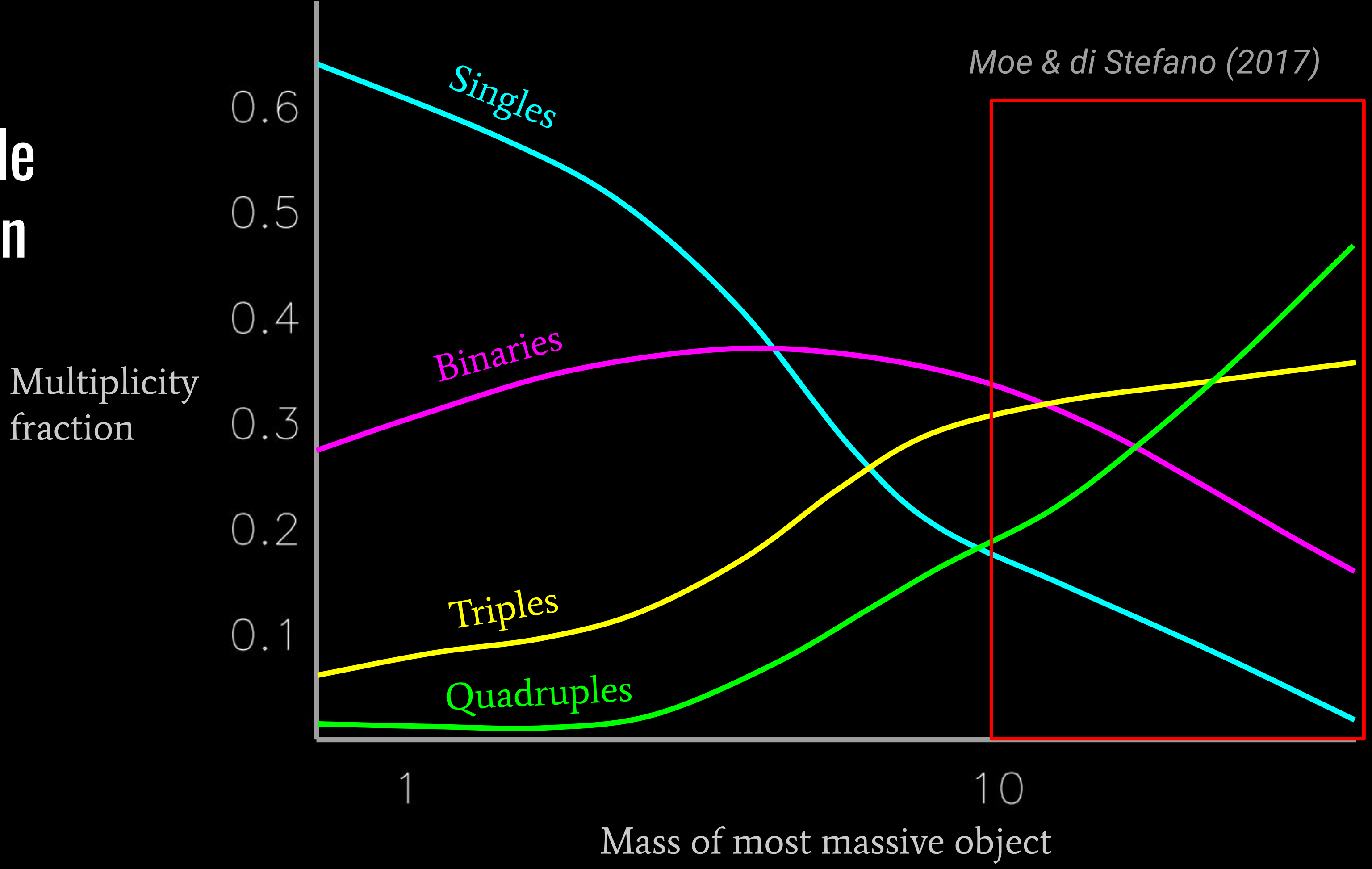
1. High multiple fraction



Why multiple-star systems (quadruples specifically)?

1. Massive stars are found mostly in multiple systems (triples and quadruples)
2. Possible eccentricity enhancements due to interactions → closer approaches for mergers

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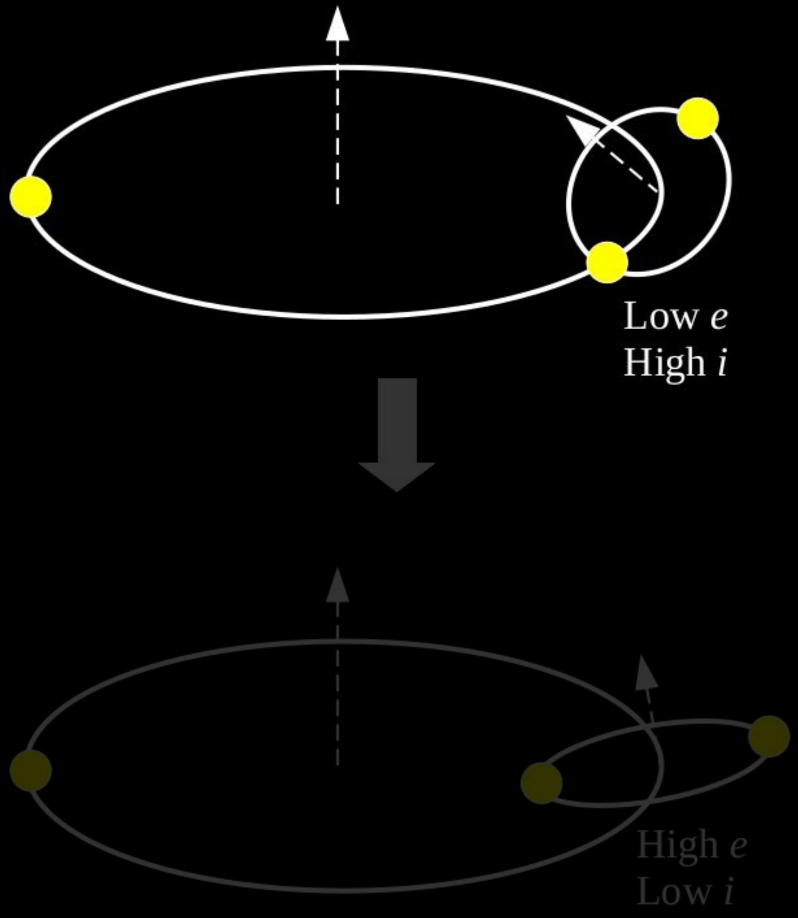
2. Eccentricity enhancement

- **Secular evolution**
- **von Zeipel-Lidov-Kozai (ZLK) oscillations**
- Maximum eccentricity depends on initial mutual inclination
- Larger parameter space for secular effects in quadruples (*Hamers & Lai 2018*)



Why multiple-star systems (quadruples specifically)?

1. Massive stars are found mostly in multiple systems (triples and quadruples)
2. Possible eccentricity enhancements due to interactions → closer approaches for mergers
3. Binary evolution plays an important role as well

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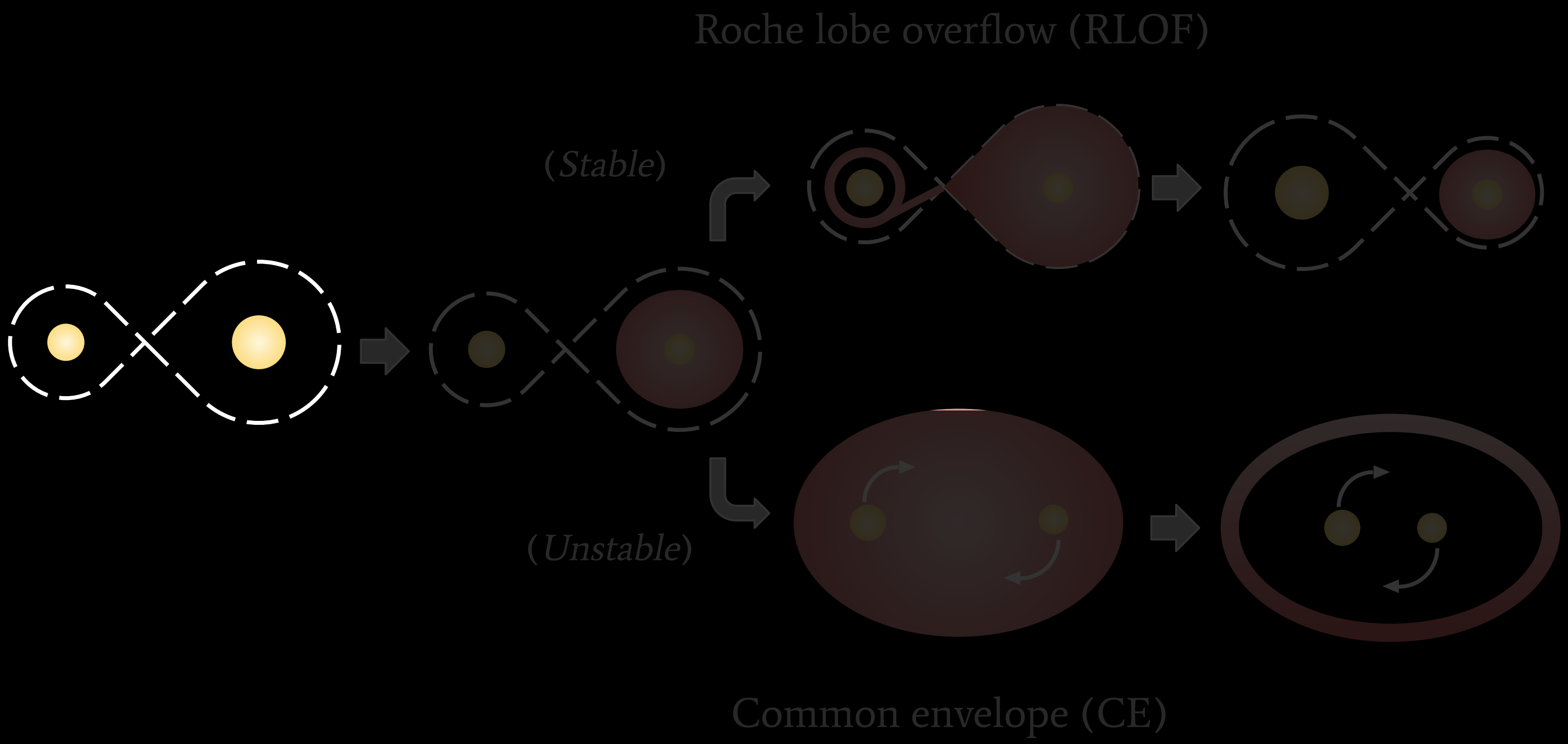
3. Binary evolution



Why multiple-star systems (quadruples specifically)?

1. Massive stars are found mostly in multiple systems (triples and quadruples)
2. Possible eccentricity enhancements due to interactions → closer approaches for mergers
3. Binary evolution plays an important role as well
4. The more, the merrier!

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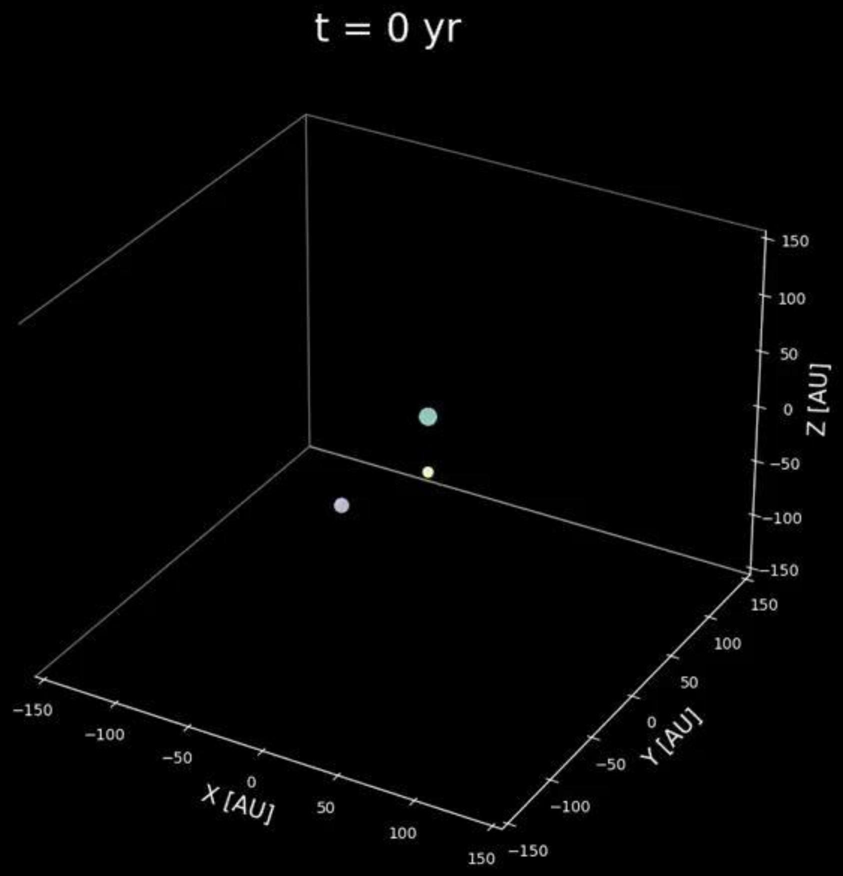
Non-hierarchical Triple (unstable)



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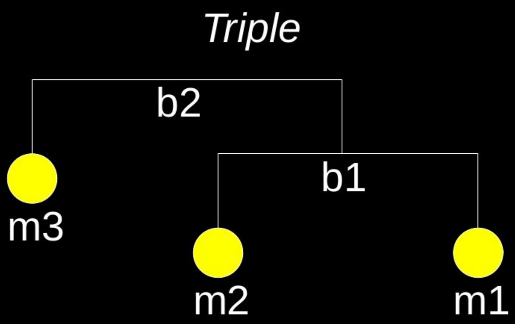

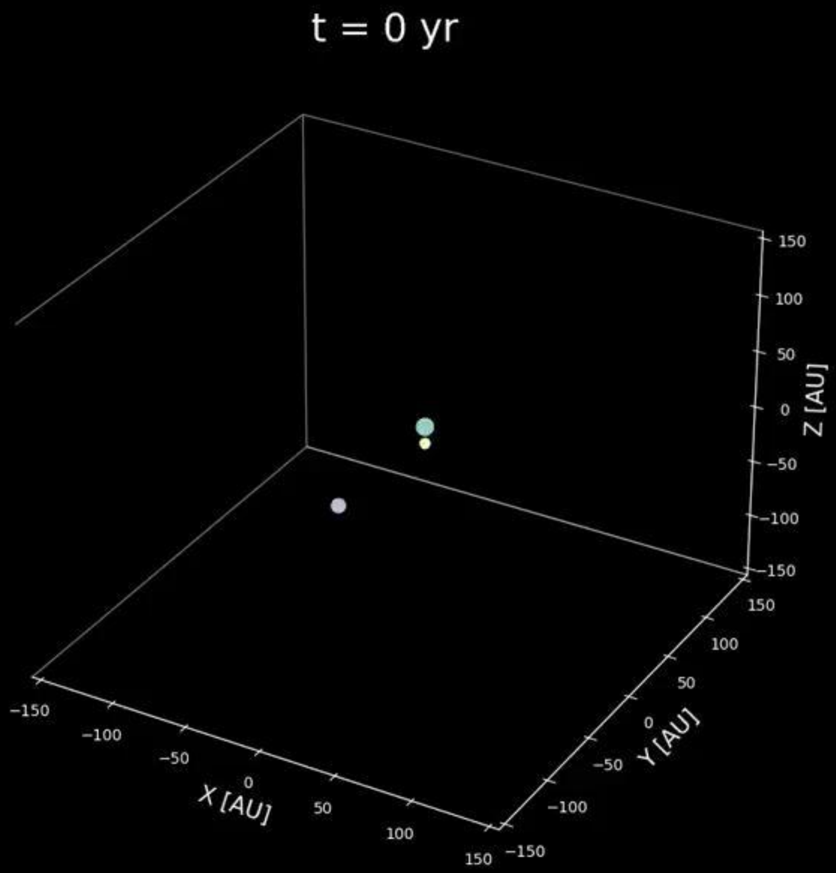

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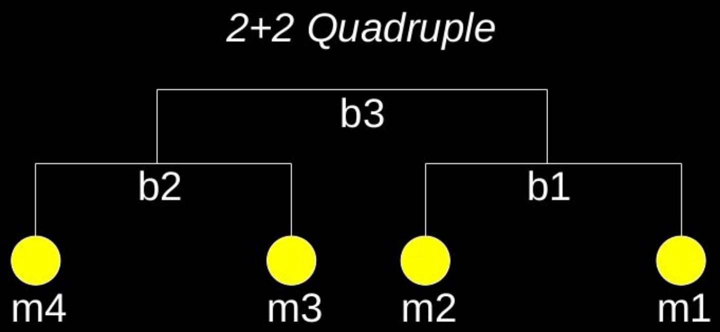

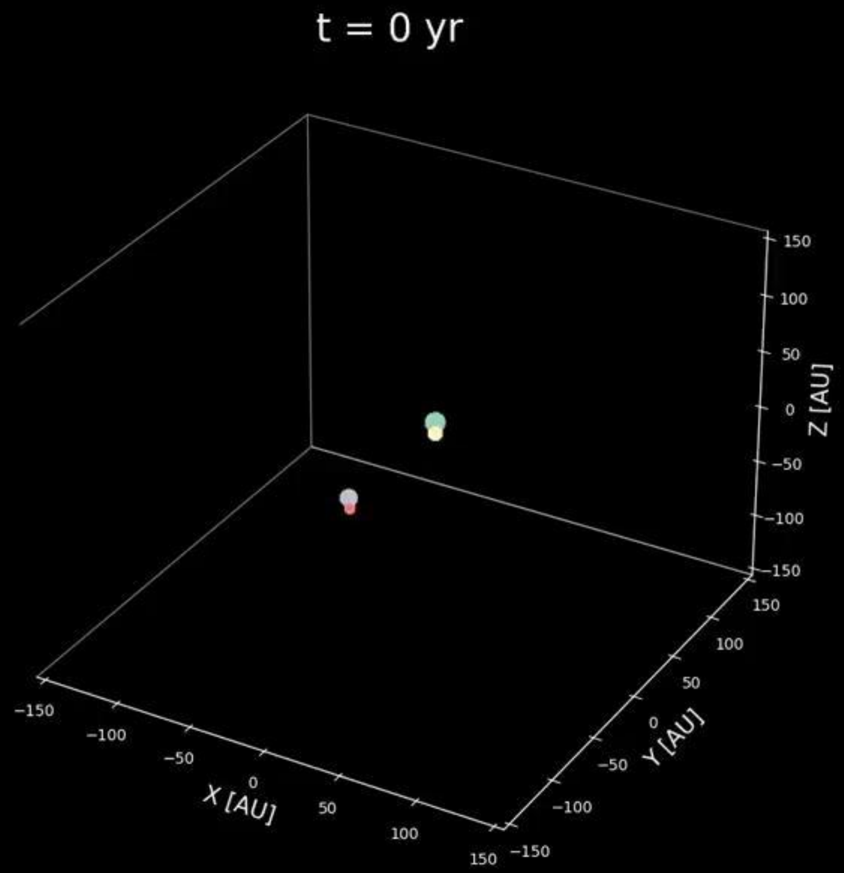

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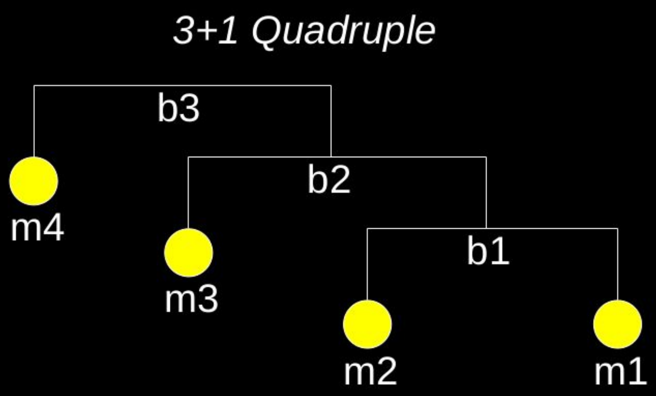
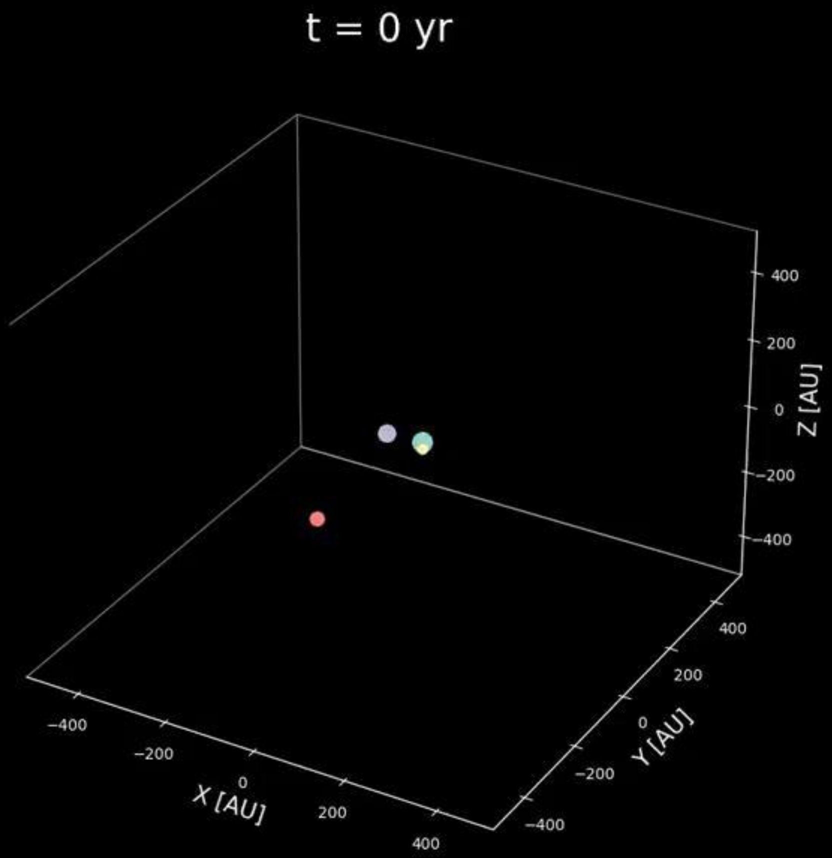


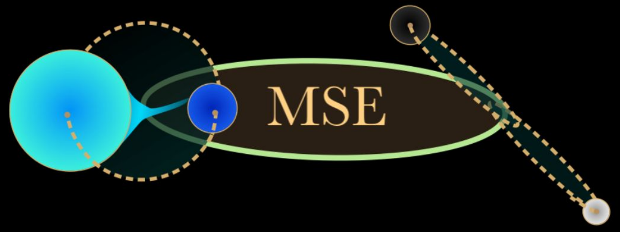


Project outline

Refer to *Vynatheya & Hamers (2022)*
(ApJ, 926, 195V)

- Population synthesis using MSE code *(next slide)*
- (2+2) quadruples compared with isolated binaries (same initial conditions)
- (3+1) quadruples
- Look for BH-BH, BH-NS or NS-NS 'mergers'

Population synthesis : MSE code



- **'Multiple Stellar Evolution'** by *Hamers et al. (2021)*
- **Stellar evolution + dynamics**
- Two modes - **secular** (orbit averaged) and **direct *N*-body** integration
- Uses SSE *(Hurley et al. 2000)* for **stellar evolution tracks**, and improves upon BSE *(Hurley et al. 2002)* for **binary events**
- Features – eccentric mass transfer, effect of flybys, triple mass transfer/CE evolution, equilibrium tides, supernova kicks

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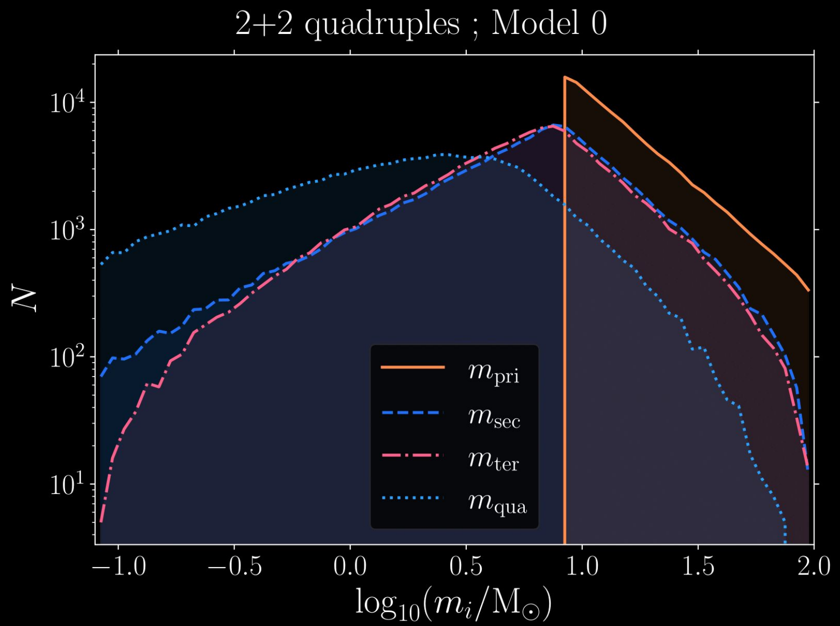
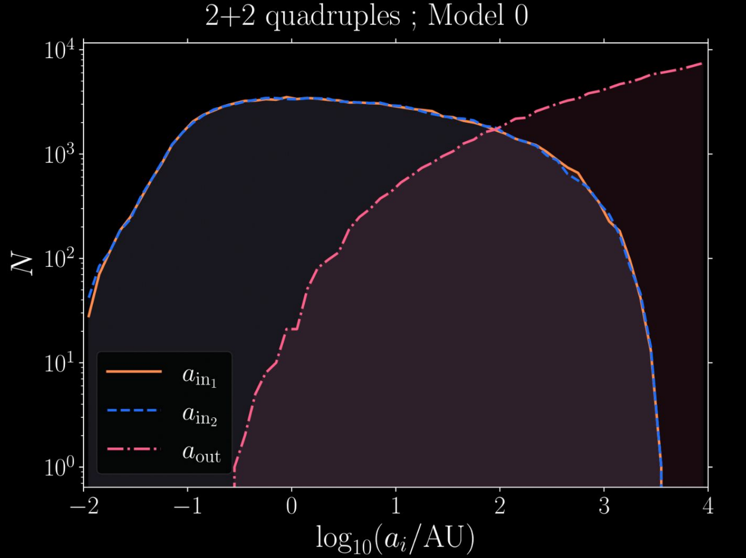
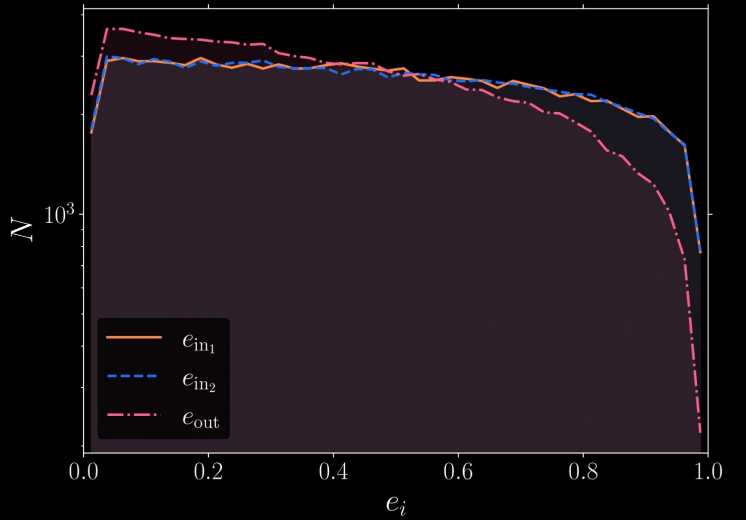
Initial conditions: 2+2 quadruples

- 100,000 **2+2 quadruples &** 200,000 **isolated binaries**
- ***m* - Kroupa (2001); *a* - log flat; *e* - flat; isotropic**







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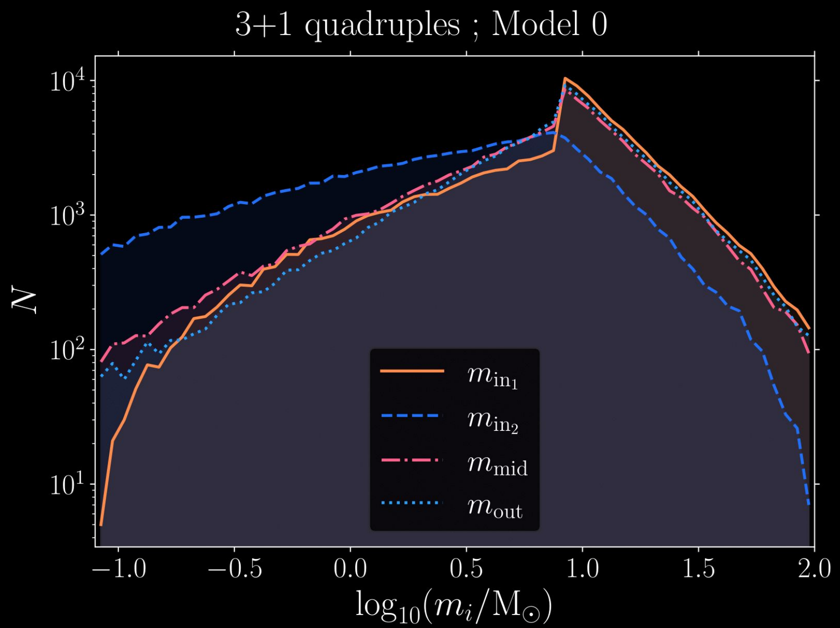
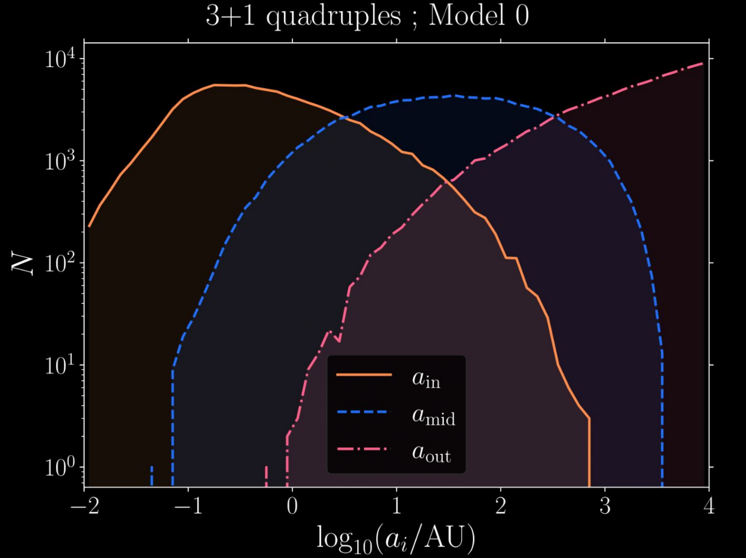
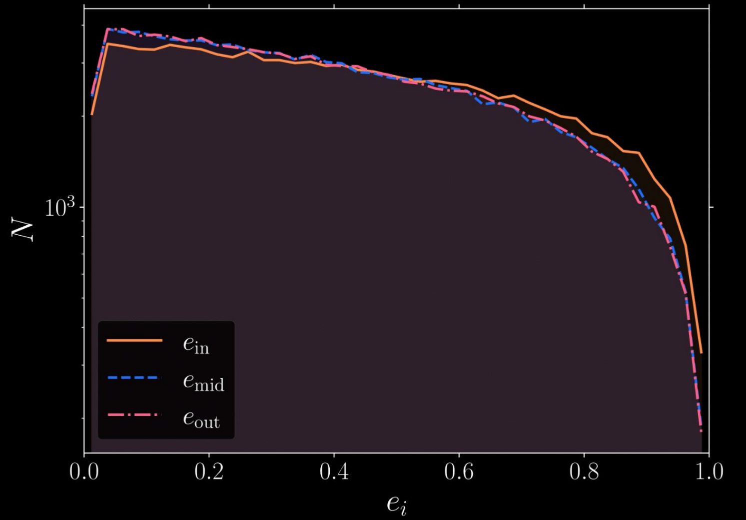
Initial conditions: 3+1 quadruples

- 100,000 **3+1 quadruples**
- ***m*** **- Kroupa (2001);** ***a*** **- log flat;** ***e*** **- flat; isotropic**







Different models

Model	SNe kicks	fly-bys	Metallicity Z	CE timescale t_{CE}
0	non-zero	included	2×10^{-2}	10^3 yr
1	**zero**	included	2×10^{-2}	10^3 yr
2	non-zero	**excluded**	2×10^{-2}	10^3 yr
3a	non-zero	included	$\mathbf{2 \times 10^{-3}}$	10^3 yr
3b	non-zero	included	$\mathbf{2 \times 10^{-4}}$	10^3 yr
4a	non-zero	included	2×10^{-2}	$\mathbf{10^2}$ **yr**
4b	non-zero	included	2×10^{-2}	$\mathbf{10^4}$ **yr**

Vynatheya & Hamers (2022)

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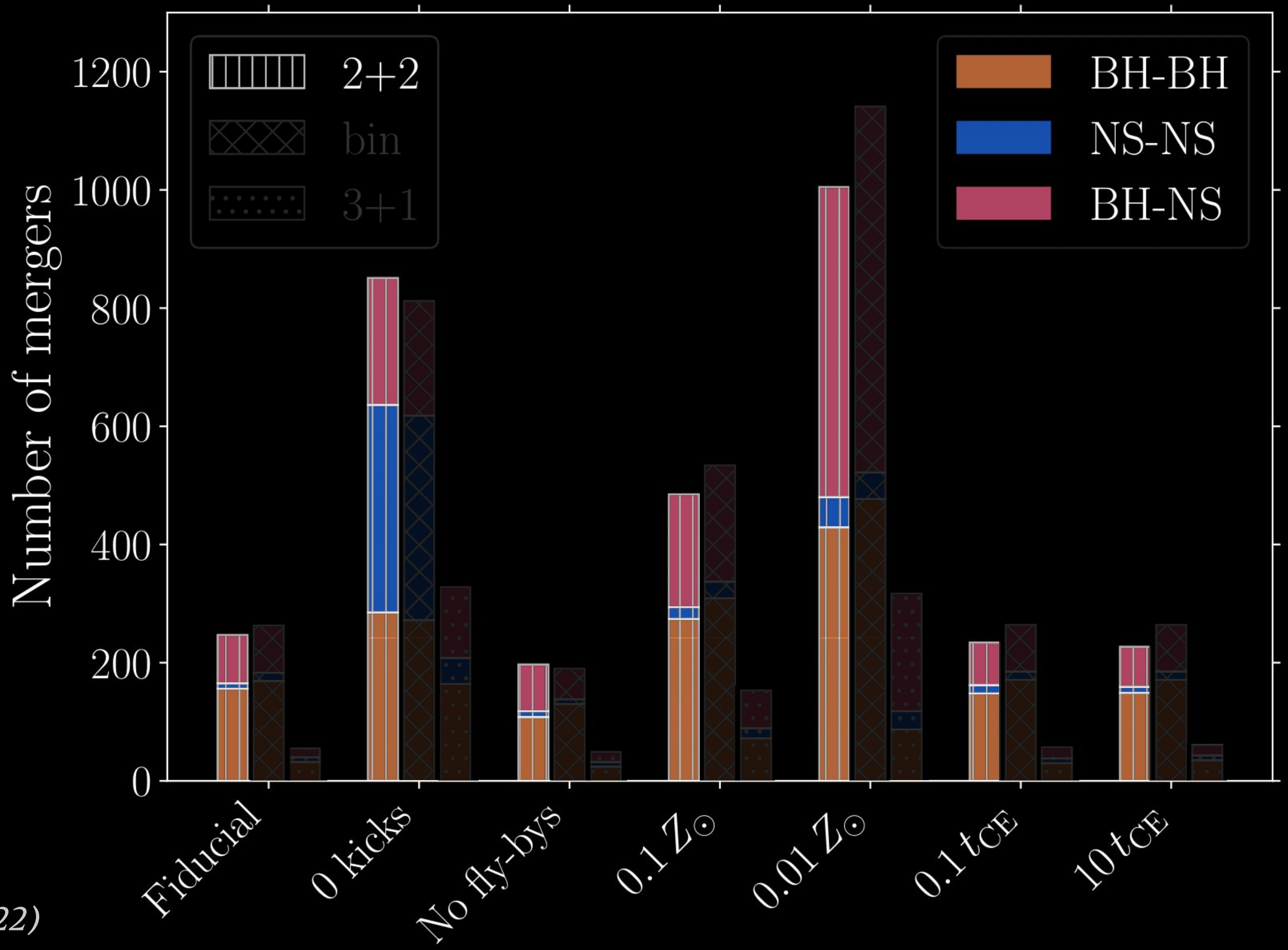
Merger numbers



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Merger rates

For our fiducial model (in units of $Gpc^{-3}yr^{-1}$)

Merger type	2+2 quadruples	3+1 quadruples	LIGO (GWTC-3)
BH-BH	10.8 ± 0.9	2.9 ± 0.5	17.3 – 45
BH-NS	5.7 ± 0.6	1.4 ± 0.4	7.4 – 320
NS-NS	0.6 ± 0.2	0.7 ± 0.3	13 – 1900

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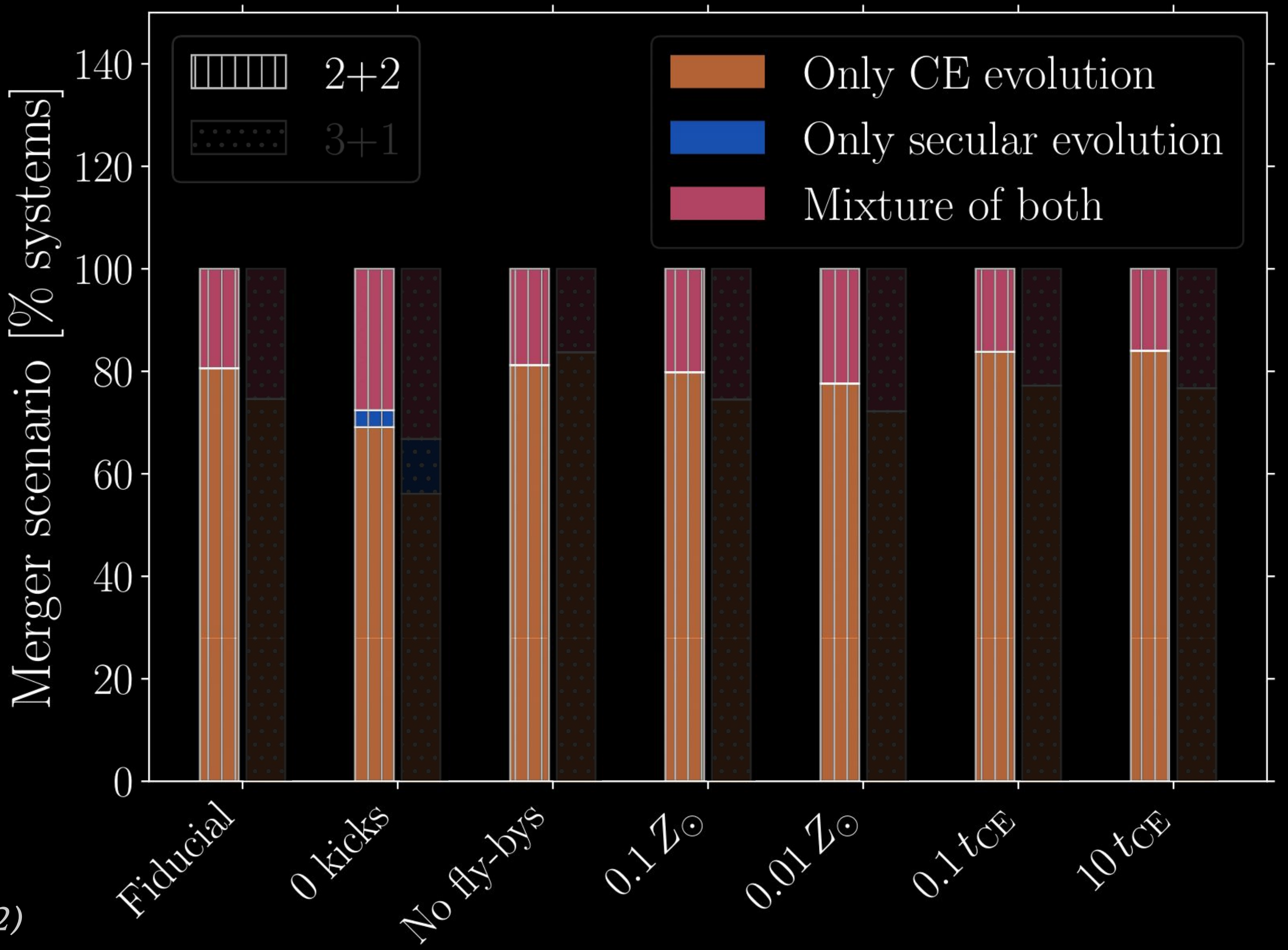
Merger scenarios



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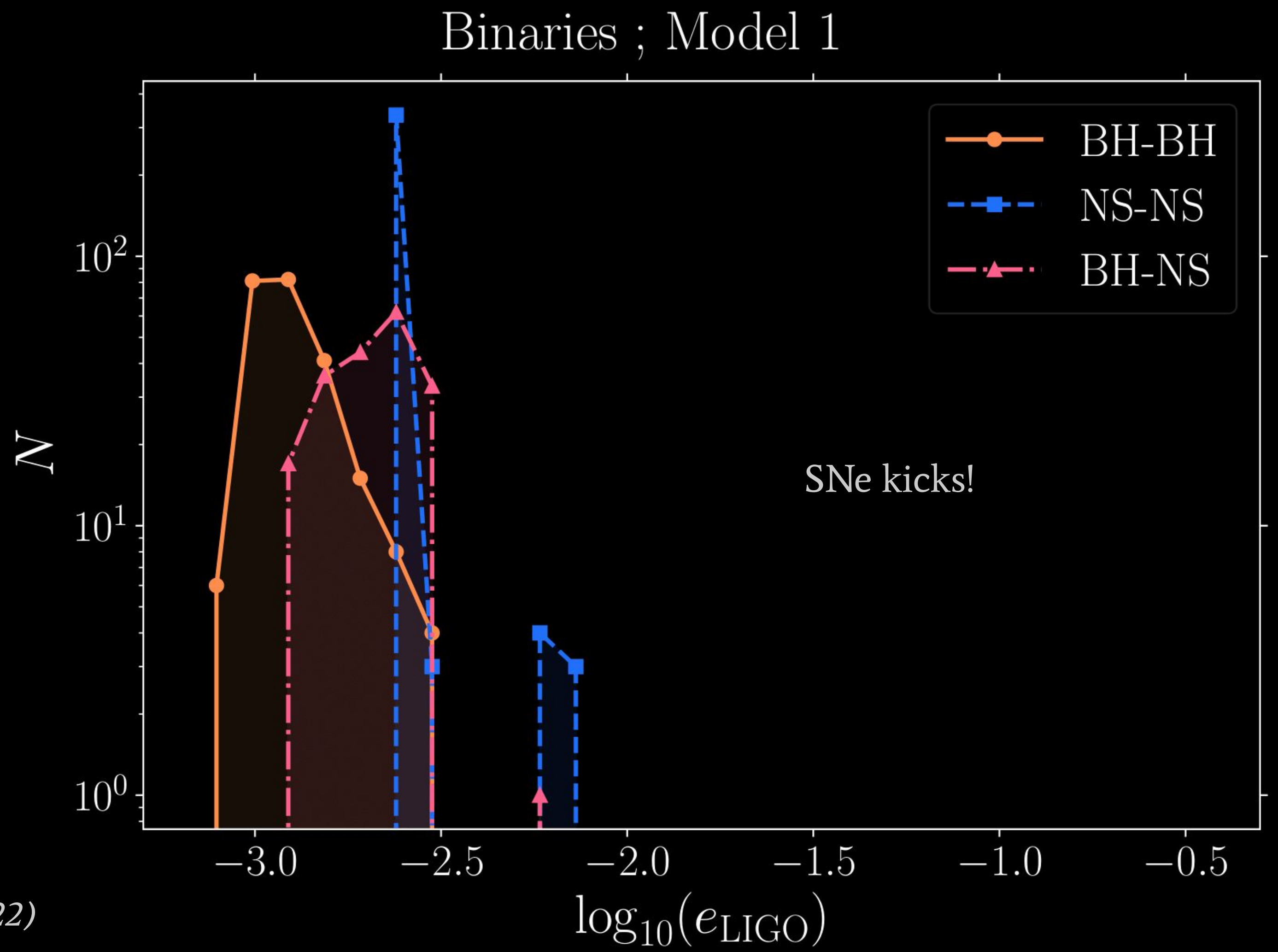
e_{LIGO} dist.

(LIGO band eccentricities)



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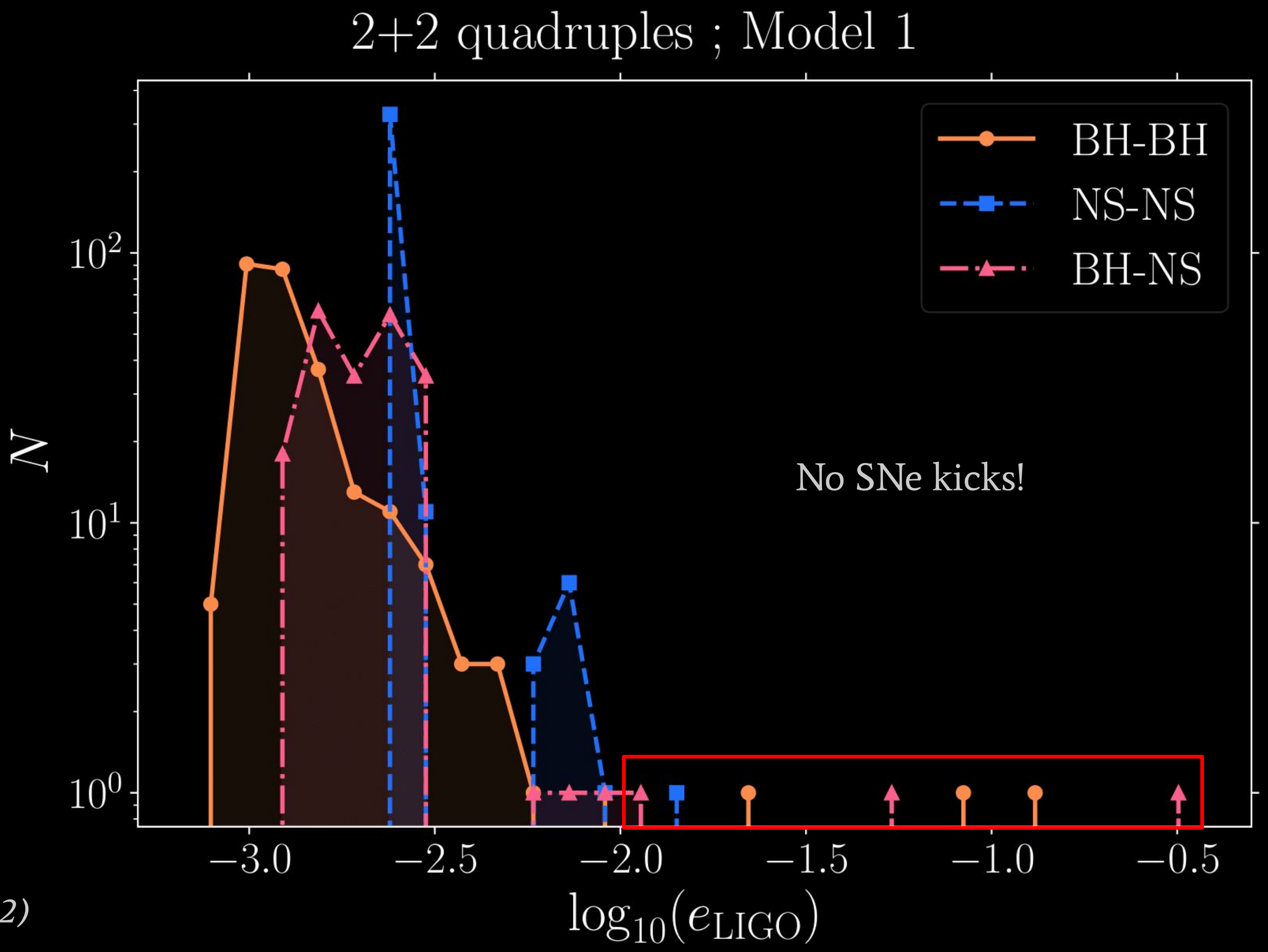

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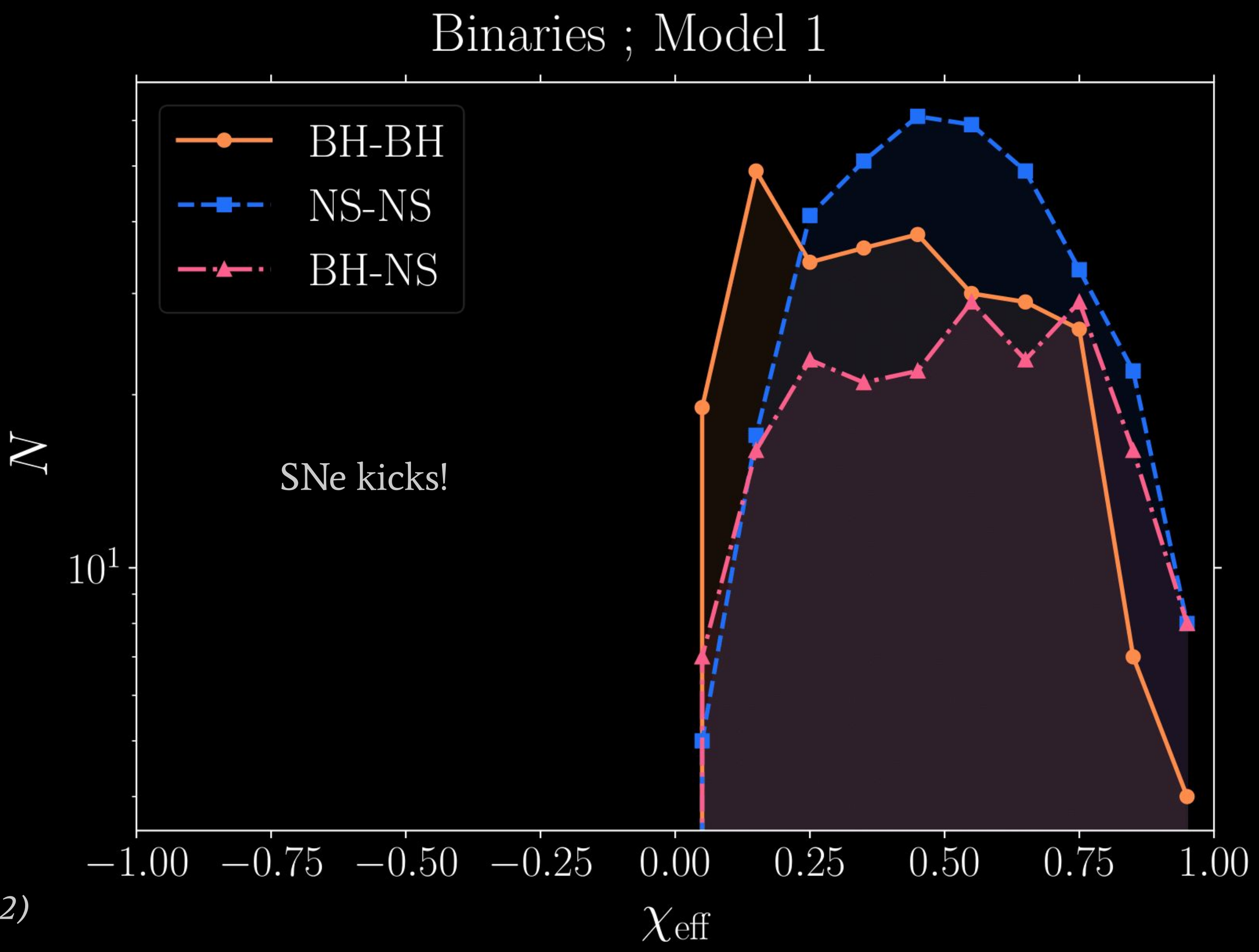
χ_{eff} dist.

(effective spin parameters)



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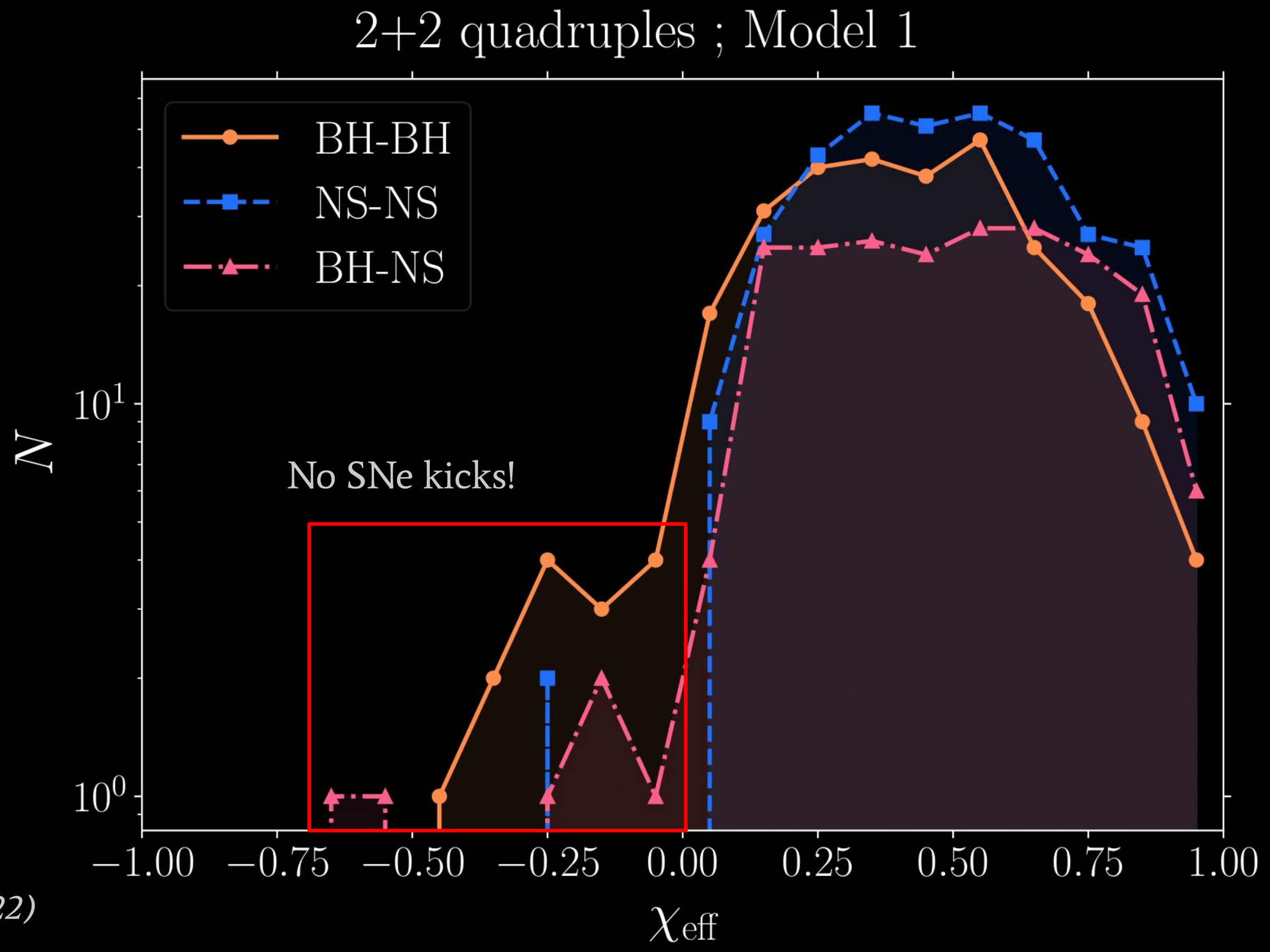

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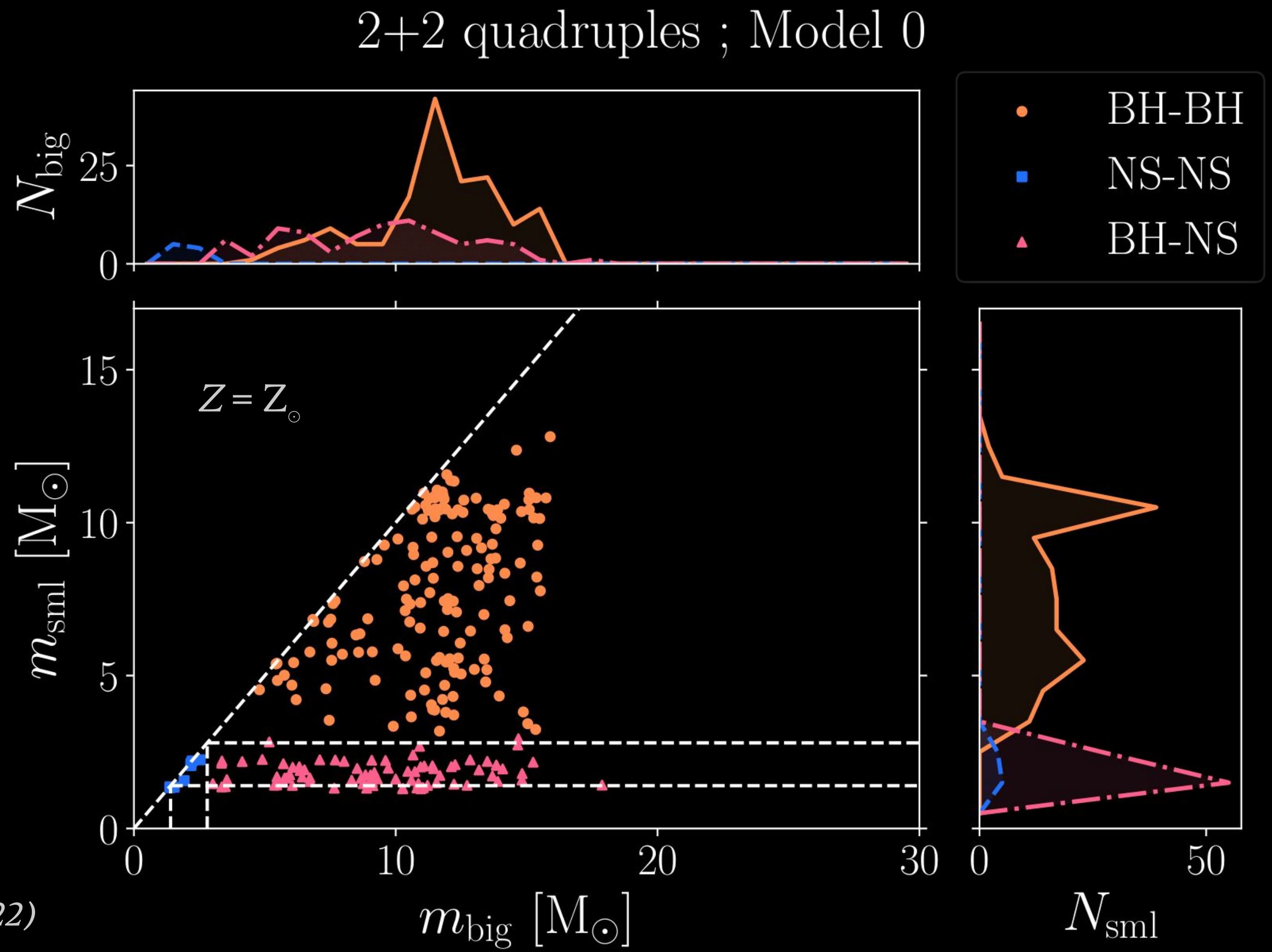
m_{pri} vs. m_{sec}

(pre-merger masses)



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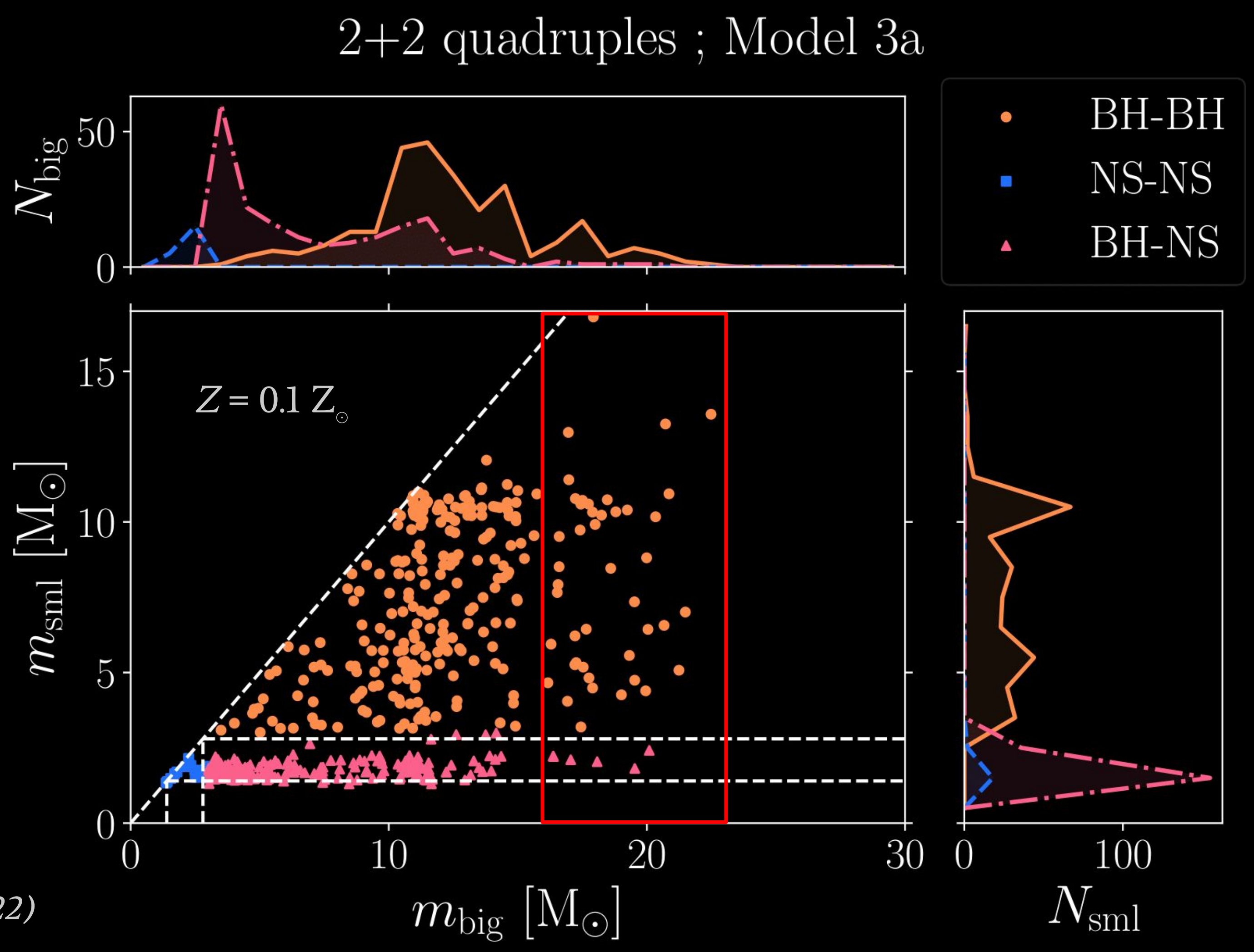

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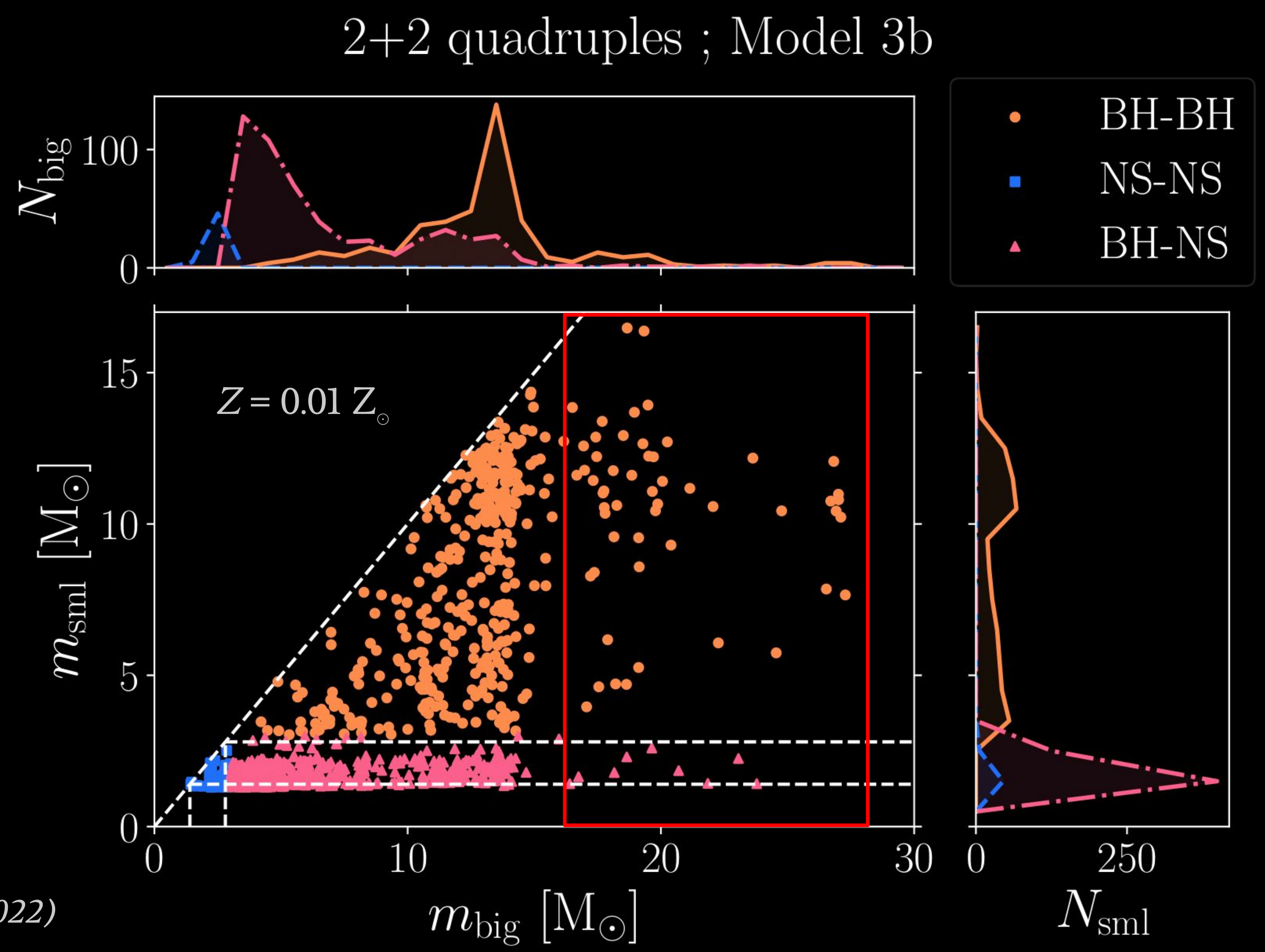

Vynatheya & Hamers (2022)

Summary

Refer to *Vynatheya & Hamers (2022)* (ApJ, 926, 195V)

- BH-BH rates agree with LIGO, others fall short
- CE evolution more important than secular evolution
- 3+1 quadruples have lesser mergers than 2+2 quadruples
- Zero SNe kicks -> more mergers, possible high e_{LIGO} and negative χ_{eff}
- Low metallicities -> more mergers, higher BH masses

The End

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