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Orbital stability of circumbinary exoplanets orbiting double white dwarfs

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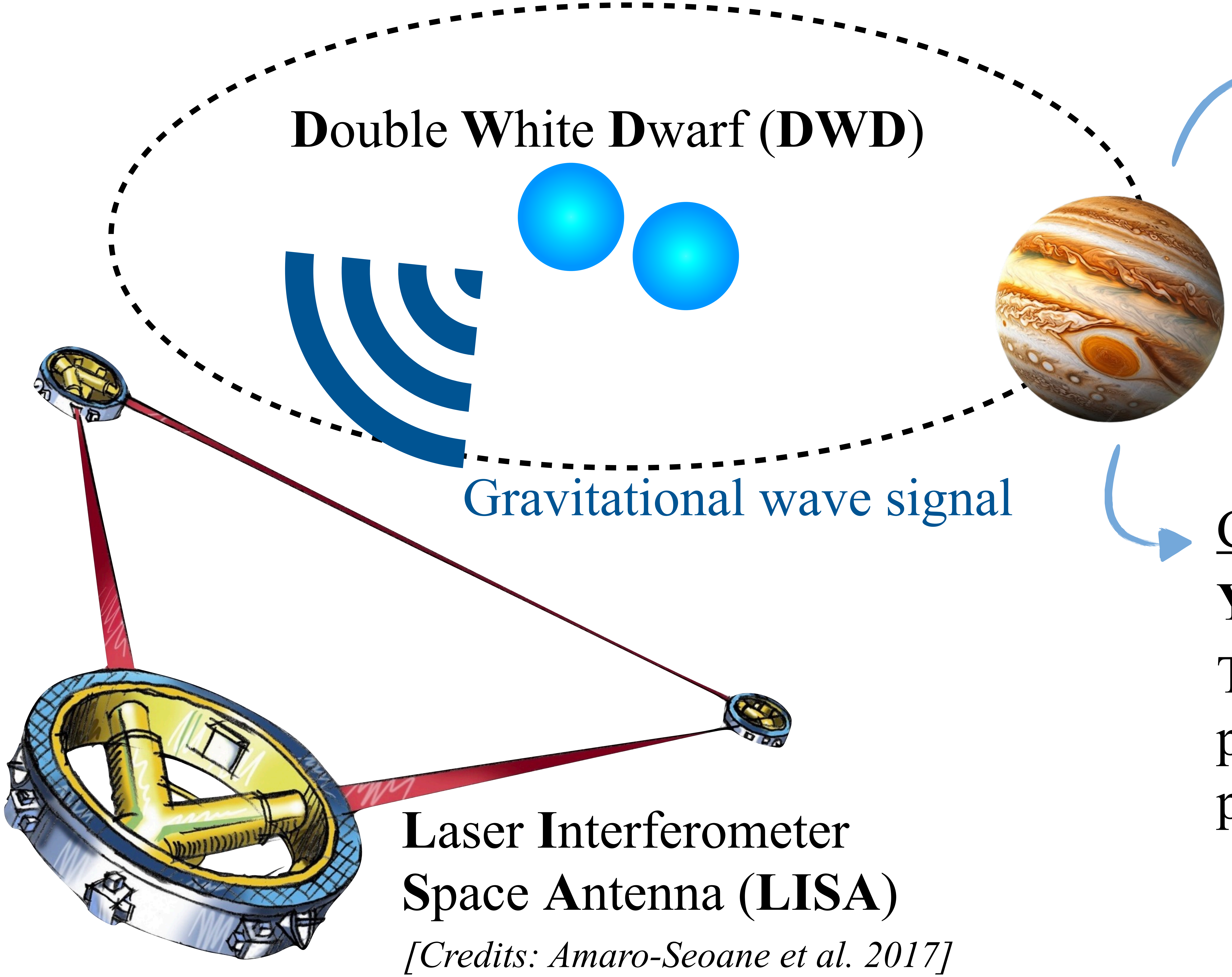
Science case



<u>Can we form them ?</u>

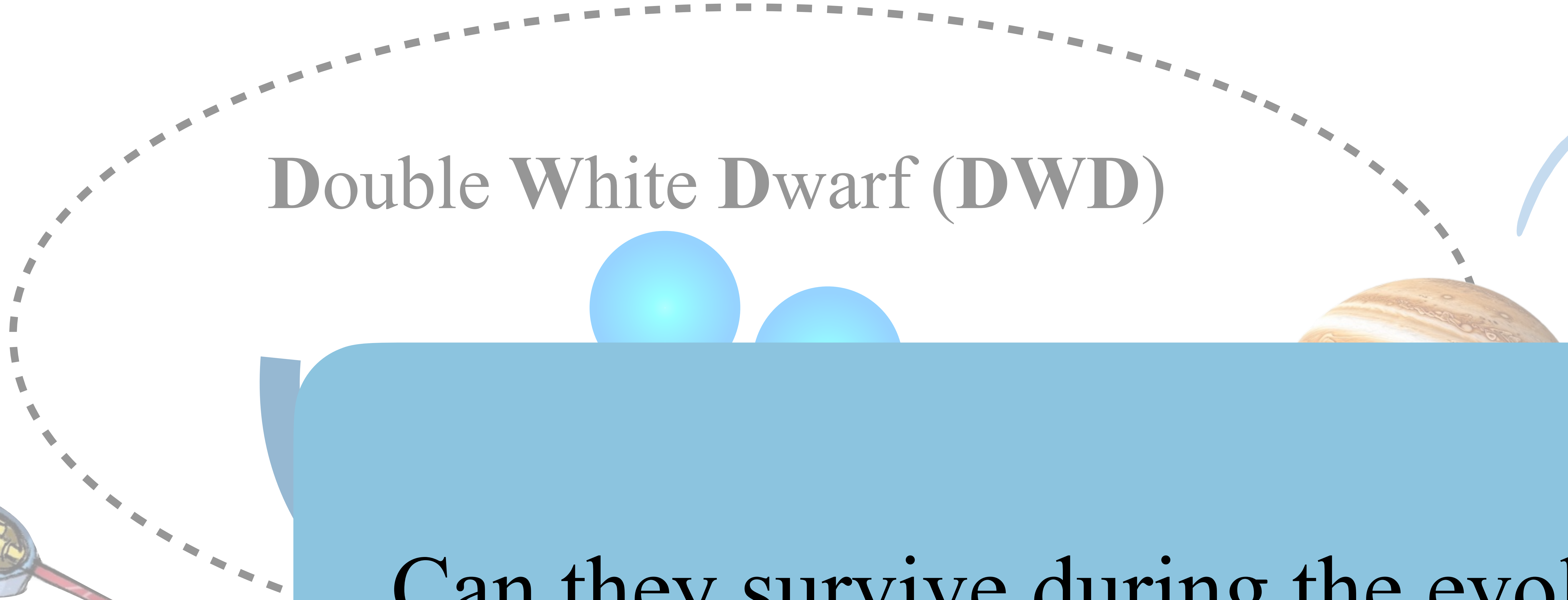
Yes ! *[Ledda et al. 2023]*

<u>Can we detect them ?</u>

Yes ! *[Tamanini & Danielski 2019]*

The gravitational wave signal is periodically modulated by the planet if $0.2\ M_J < M_p < 13\ M_J$

Science case



Double White Dwarf (DWD)

Can we form them ?

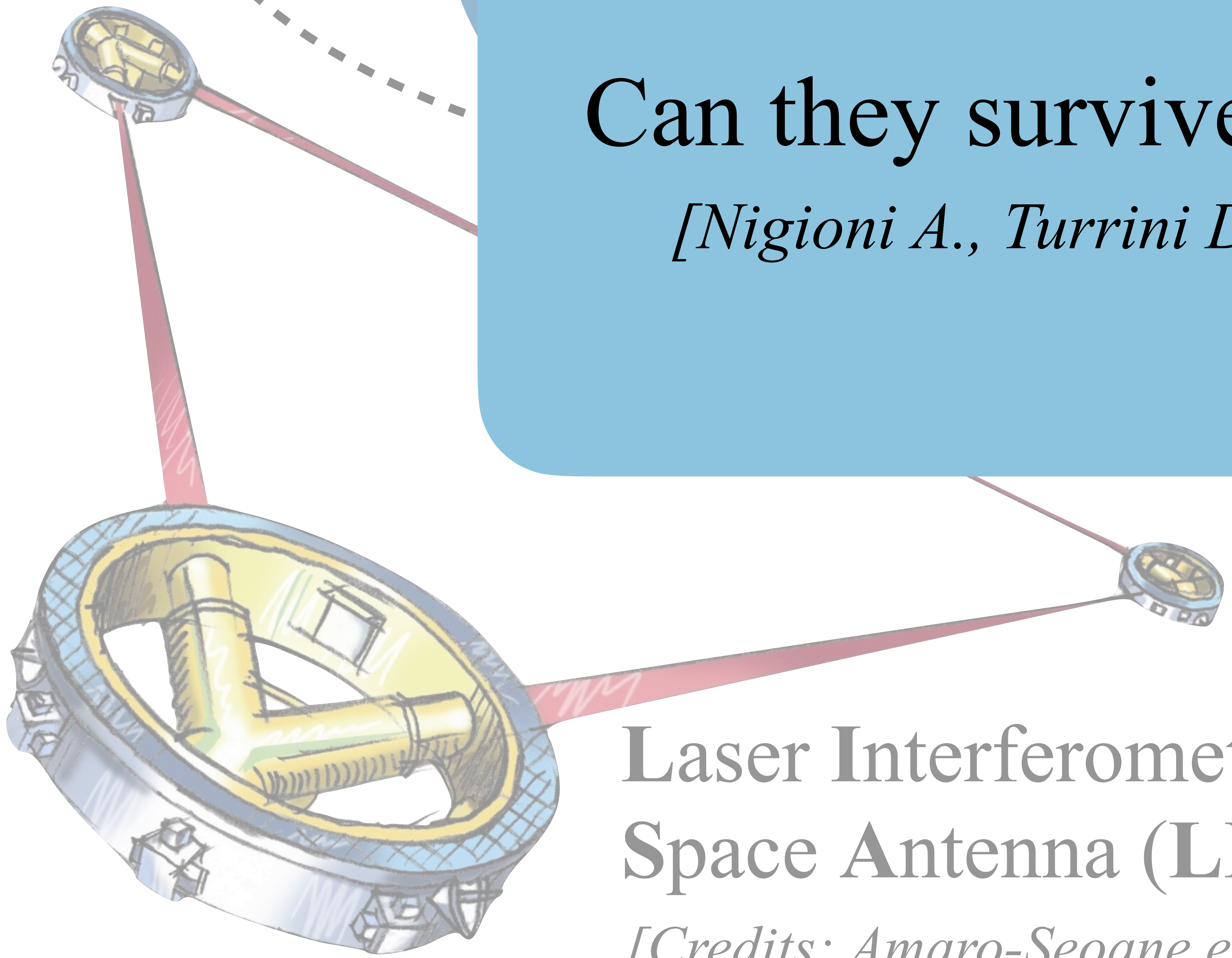
Yes ! *[Ledda et al. 2023]*

Can they survive during the evolutionary phase ?

[Nigioni A., Turrini D., Danielski C., Chambers J.E. under review]

...ielski 2019]

The gravitational wave signal is periodically modulated by the planet if $0.2\ M_J < M_p < 13\ M_J$



Laser Interferometer Space Antenna (LISA)

[Credits: Amaro-Seoane et al. 2017]

N-body problems in P-type binaries

Short execution times

+

Small energy variation

↓

Symplectic integrators

[Wisdom & Holman 1991]

↓

Adaptation to the possibility of having close-encounters (Hybrid symplectic integrator)

[Chambers 1999]

↓

Adaptation to presence of a secondary star (P-type binary coordinates)

[Chambers et al. 2002]

Our systems' Hamiltonian in P-type binary coordinates

$H =$ dominant term + perturbation term

dominant term → $H_{\rm Kep} = H_{\rm P,Kep} + H_{\rm B,Kep}$

perturbation term → $H_{\rm int} = H_{\rm P,int} + H_{\rm B,int}$ & $H_{\rm jump}$

Integration scheme

1. Advance $H_{\rm P,int}$ for $\tau/2$;
2. Repeat the following $N_{\rm bin}$ times:
   Advance $H_{\rm B,int}$ for $\tau/(2N_{\rm bin})$;
   Advance $H_{\rm B,Kep}$ for $\tau/(2N_{\rm bin})$;
3. Advance $H_{\rm jump}$ for $\tau/2$;
4. Advance $H_{\rm P,Kep}$ for τ;
5. Advance $H_{\rm jump}$ for $\tau/2$;
6. Repeat the following $N_{\rm bin}$ times:
   Advance $H_{\rm B,int}$ for $\tau/(2N_{\rm bin})$;
   Advance $H_{\rm B,Kep}$ for $\tau/(2N_{\rm bin})$;
7. Advance $H_{\rm P,int}$ for $\tau/2$.

$N_{\rm bin} \simeq T_{\rm innermost\ planet}/T_{\rm bin}$

Initial conditions

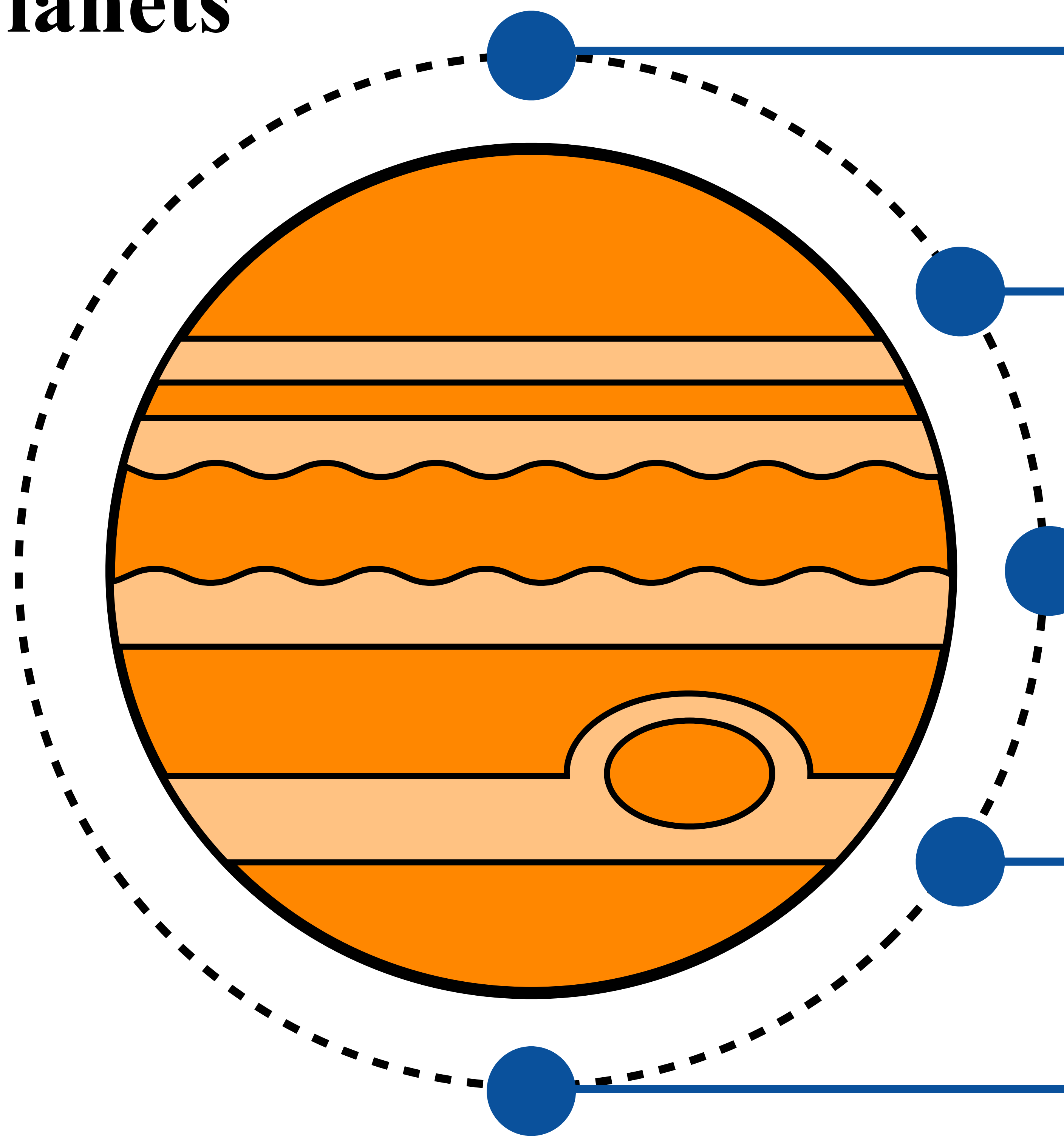
Binary

system	M_1 [$M_\odot$]	M_2 [$M_\odot$]	$P_{\rm bin}$ [h]	$a_{\rm bin}$ [au]
DWD_2	0.31	0.21	0.43	1.078×10^{-3}
DWD_3^*	0.75	0.26	1.51	3.106×10^{-3}
DWD_4^*	0.31	0.25	1.71	2.773×10^{-3}

Eccentricity is zero *[Ledda et al. 2023]*, inclination set to zero for simplicity, phase angles sampled randomly

The systems marked with the $*$ belong to the LISA DWD population presented in [*Korol et al. 2019*].

Planets



Number: $2 \leq N_s \leq 4$

Mass: $[0.4,0.5]\ M_J$ (DWD_2) — $[2.5,15]\ M_J$ (DWD_3^*) — $[0.12,1.2]\ M_J$ (DWD_4^*)

Semi-major axis: $a_{\rm crit} \leq a \leq a_{(P=8\ {\rm yr})}$

Eccentricity: $0 \leq e \leq 0.01$

Inclination: $1^\circ \leq i \leq 3^\circ$

- Mass ranges from [Ledda et al. 2023]
- Eccentricity and inclination ranges from *[Gong and Ji 2017; Turrini et al. 2019 & 2021]*
- **100 simulations for each DWD system**

Metrics to analyse and compare planetary systems

Normalized Angular Momentum Deficit

[Chambers 2001; Turrini et al. 2021]

$$\mathrm{NAMD} = \frac{\mathrm{AMD}}{\mathrm{CAM}} = \frac{\sum_k m_k \sqrt{a_k}\left(1 - \sqrt{1 - e_k^2}\cos i_k\right)}{\sum_k m_k \sqrt{a_k}}$$

Threshold value: 1.3×10^{-3} → Distinguish between dynamically COLD and HOT planetary system

Orbital Spacing Statistics

$$S_s = \frac{6}{N-1}\left(\frac{a_{\max} - a_{\min}}{a_{\max} + a_{\min}}\right)\left(\frac{3M_{\mathrm{bin}}}{2\bar{m}}\right)^{1/4} \quad \text{where} \quad N > 1$$

→ S_s^f / S_s^s

Fraction of total mass retained in the largest object

$$S_m = \frac{M_{\text{most massive}}}{\sum_i^N m_i}$$

→ S_m^f / S_m^s

Planetary centre of mass

$$\mathrm{COM} = \frac{\sum_i^N m_i a_i}{\sum_i^N m_i}$$

→ Δ_{COM}

Results (1/5)

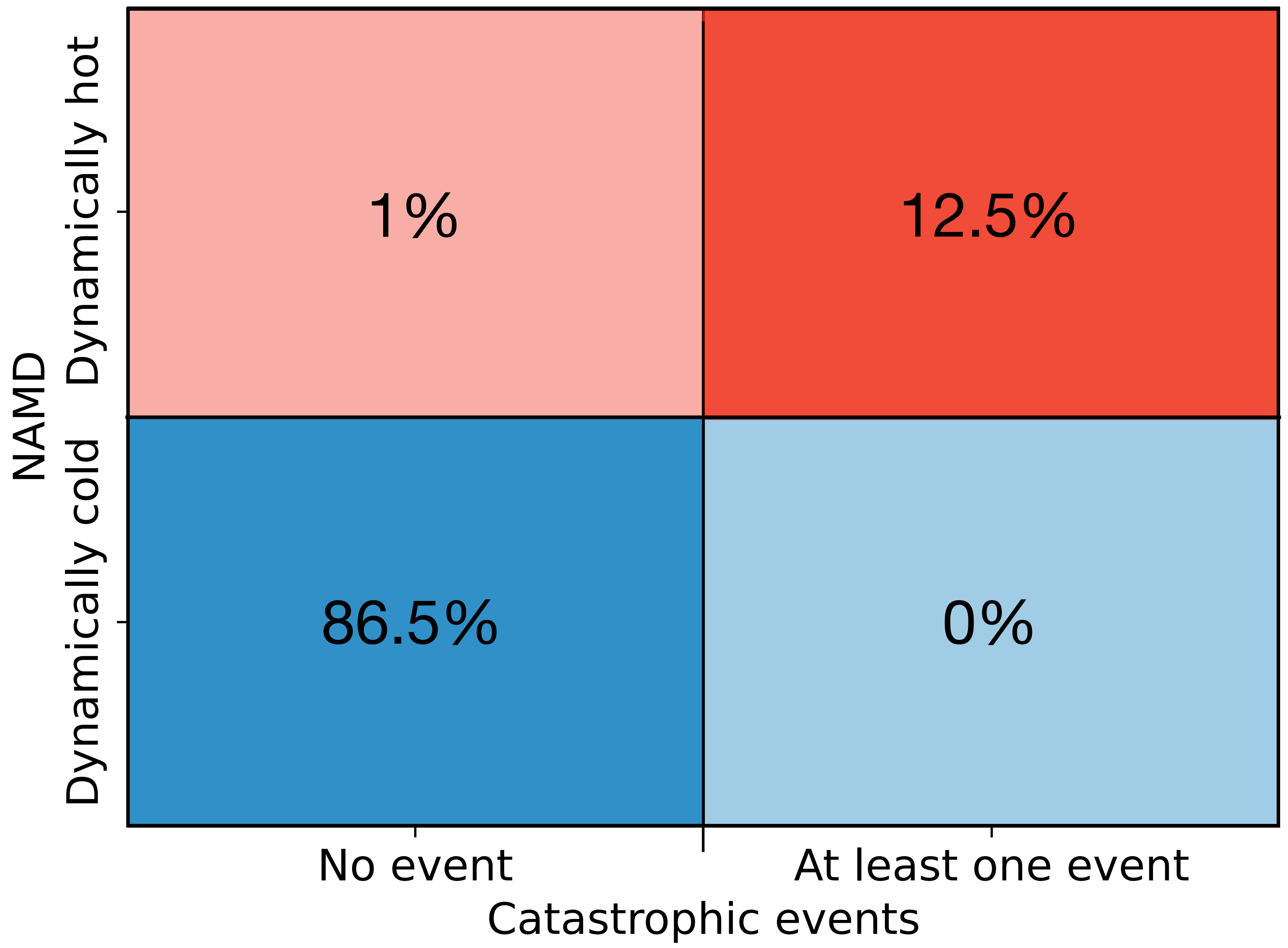
We identify two populations:

- Population A: $M_p^i \leq 1.2\ M_J$ and orbit a binary with mass $M_{\rm bin} < 0.6\ M_\odot$. Corresponds to DWD_2 and DWD_4^*
- Population B: $M_p^i \geq 2.5\ M_J$ and orbit a binary with mass $M_{\rm bin} \sim 1\ M_\odot$. Corresponds to DWD_3^*

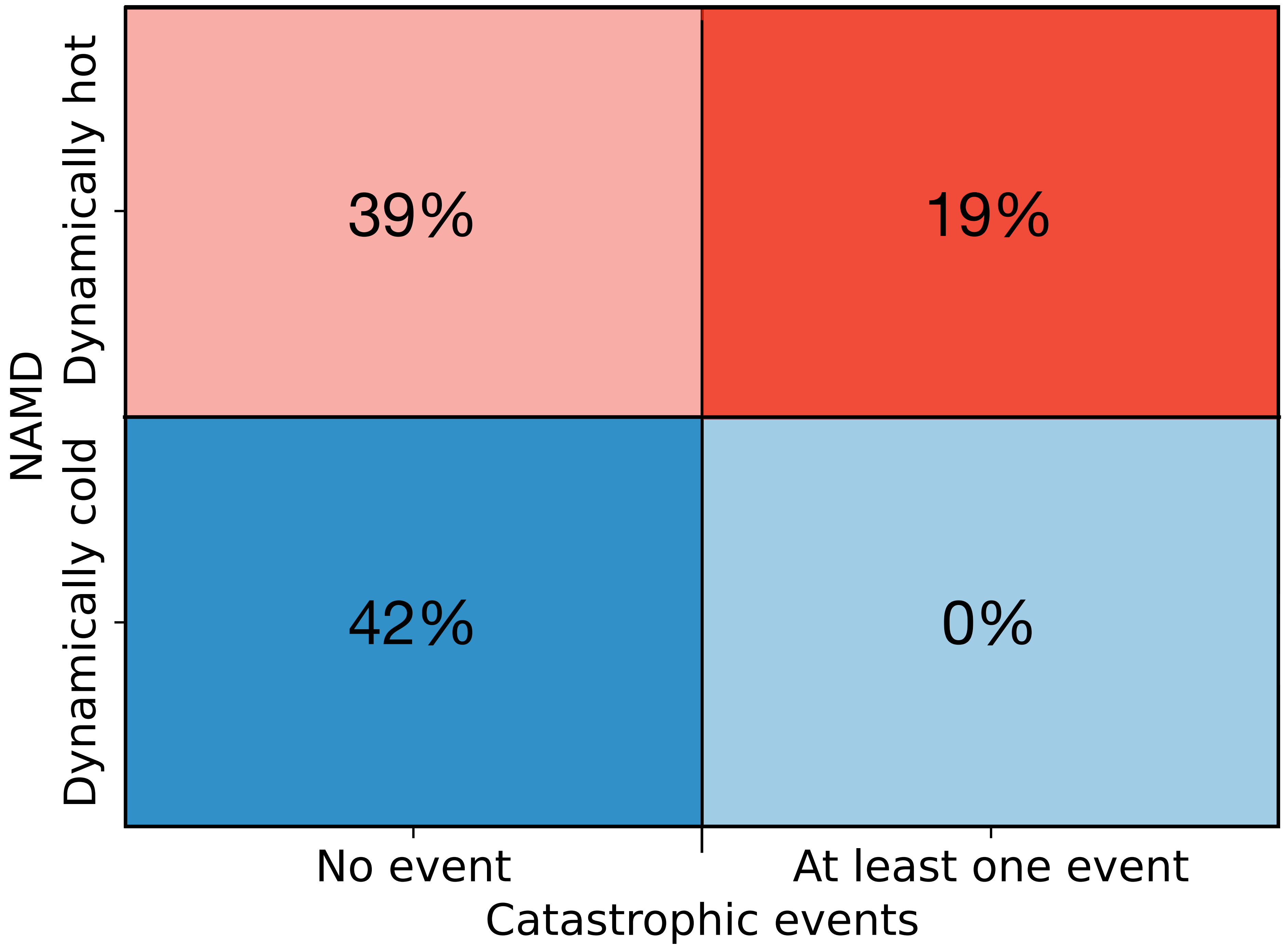
We define catastrophic events as:

- Single catastrophic events: ejections, planet-planet collisions, close approach to the binary
- Multiple catastrophic events: combination of the above

Population A



Population B



Does the dynamical evolution depend on the initial multiplicity N_s?

Population A	$N_s = 2$	$N_s = 3$	$N_s = 4$
NAMD<1.3×10^{-3}	100%	94%	58%
NAMD>1.3×10^{-3}	0%	6%	42%
Disrupted systems	0%	0%	0%

Population B	$N_s = 2$	$N_s = 3$	$N_s = 4$
NAMD<1.3×10^{-3}	79%	33%	13%
NAMD>1.3×10^{-3}	21%	61%	65%
Disrupted systems	0%	6%	22%

Population A	$N_s = 2$	$N_s = 3$	$N_s = 4$
No catastrophic events	100%	97%	59%
Ejections only	0%	2%	26%
Collisions$_{\text{p-p}}$ only	0%	1%	7.5%
Multiple catastrophic events	0%	0%	7.5%

Population B	$N_s = 2$	$N_s = 3$	$N_s = 4$
No catastrophic events	100%	81%	57%
Ejections only	0%	2%	13%
Collisions$_{\text{p-p}}$ only	0%	4%	4%
Multiple catastrophic events	0%	13%	26%

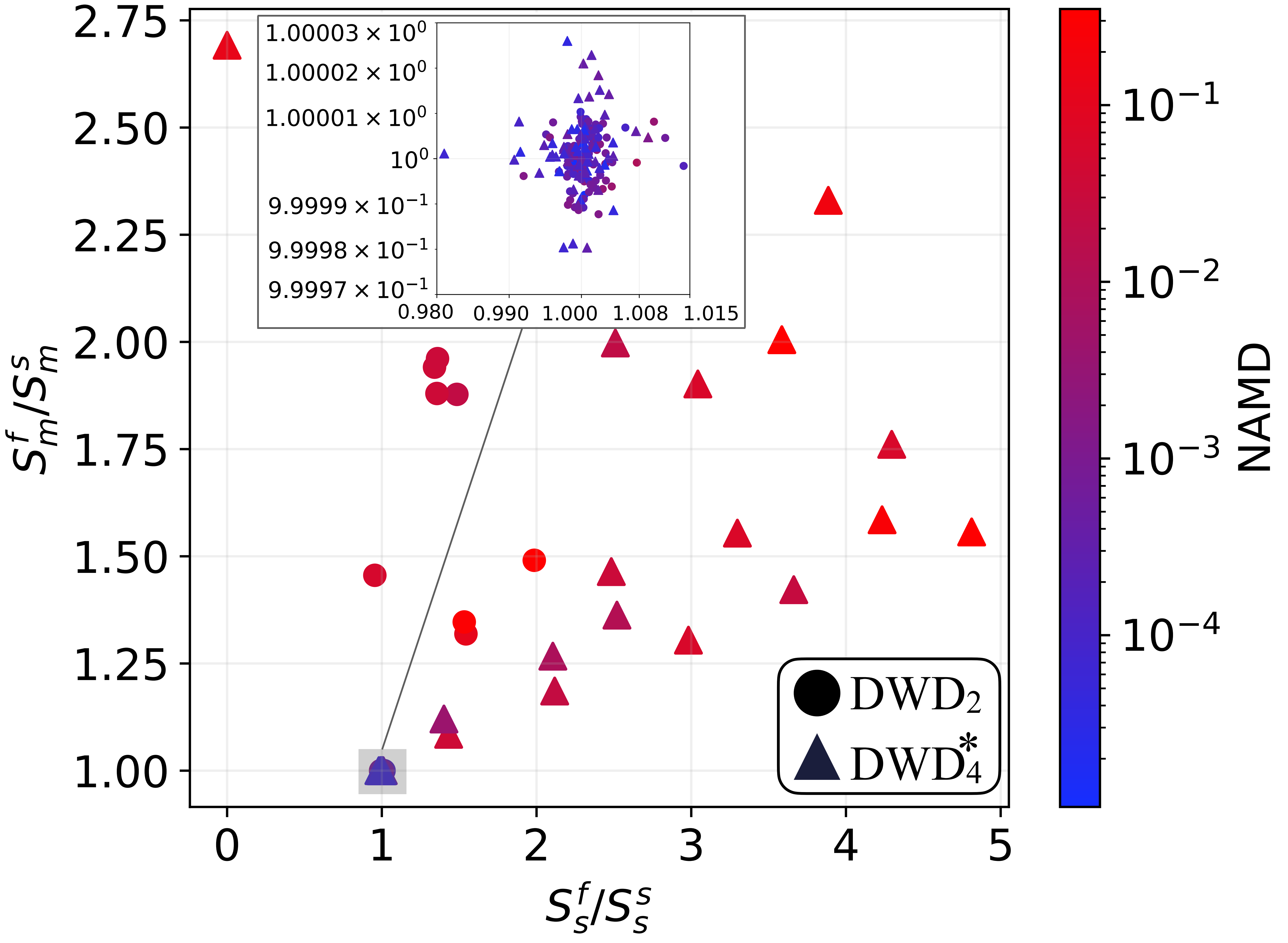
N_s is the initial number of planets

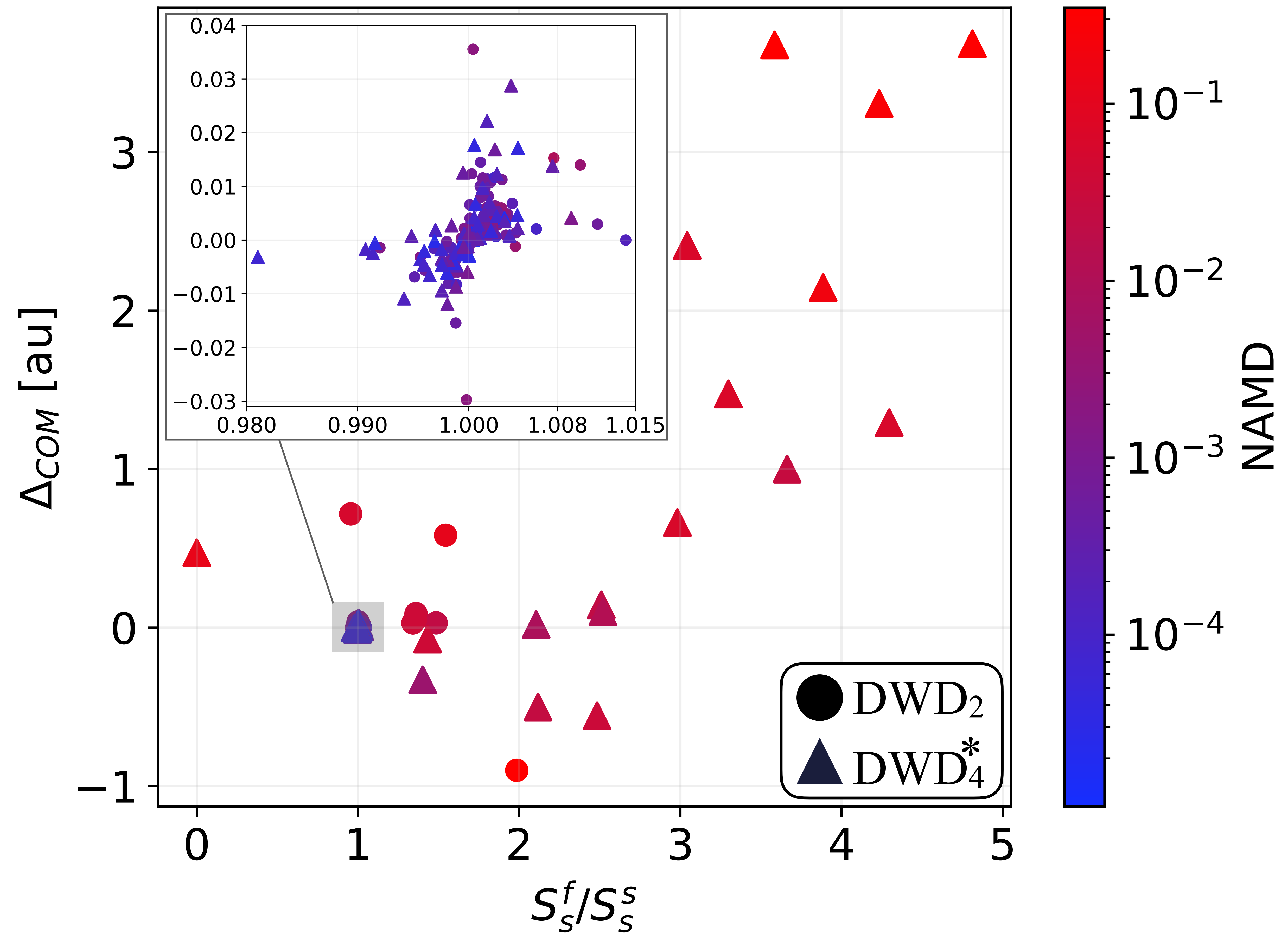
	$N_s = 2$	$N_s = 3$	$N_s = 4$
DWD_2	32%	48%	20%
DWD_3^*	29%	48%	23%
DWD_4^*	31%	36%	33%

- Population A corresponds to DWD_2 and DWD_4^*
- Population B corresponds to DWD_3^*

Results (3/5)

Population A

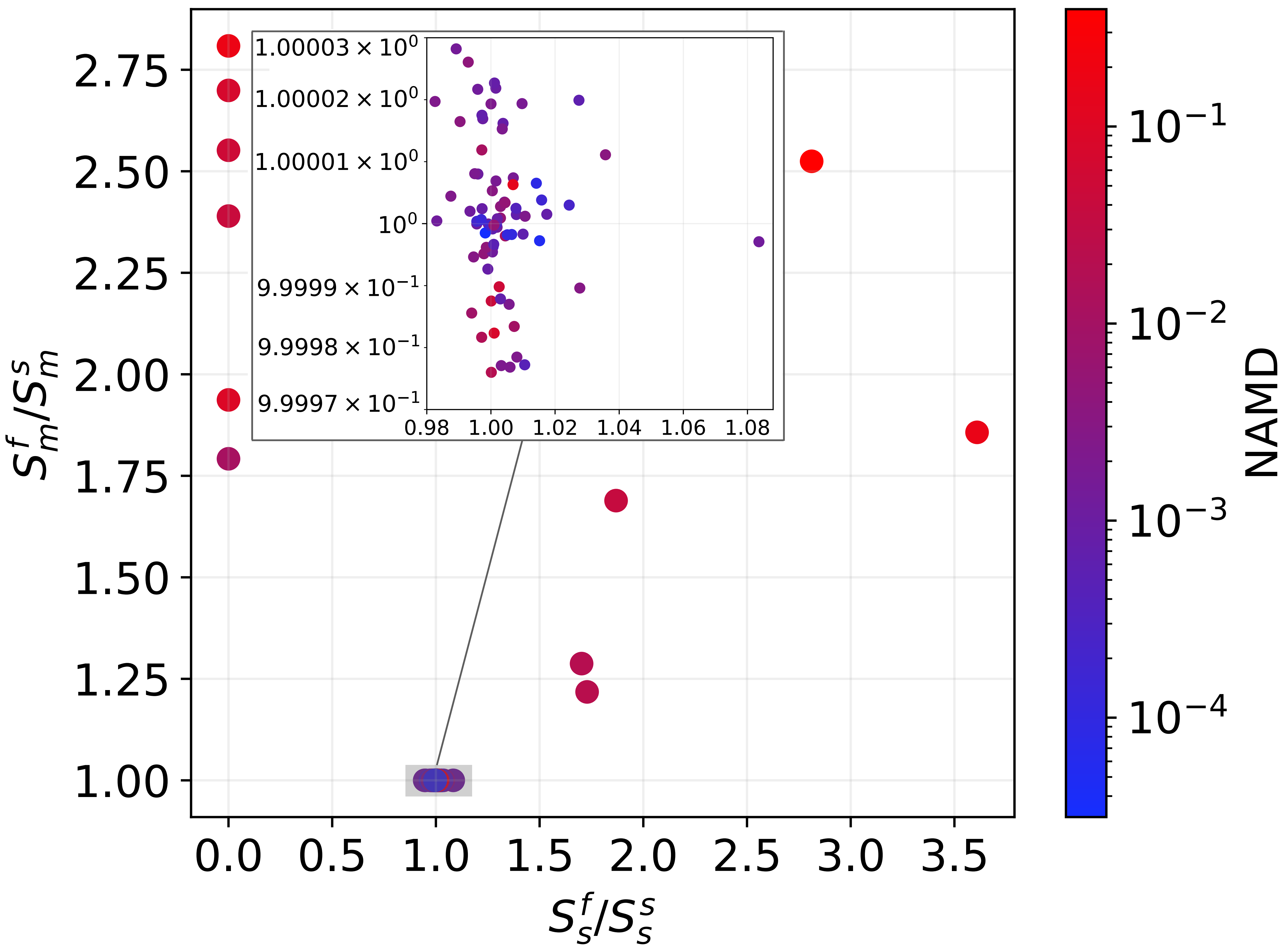


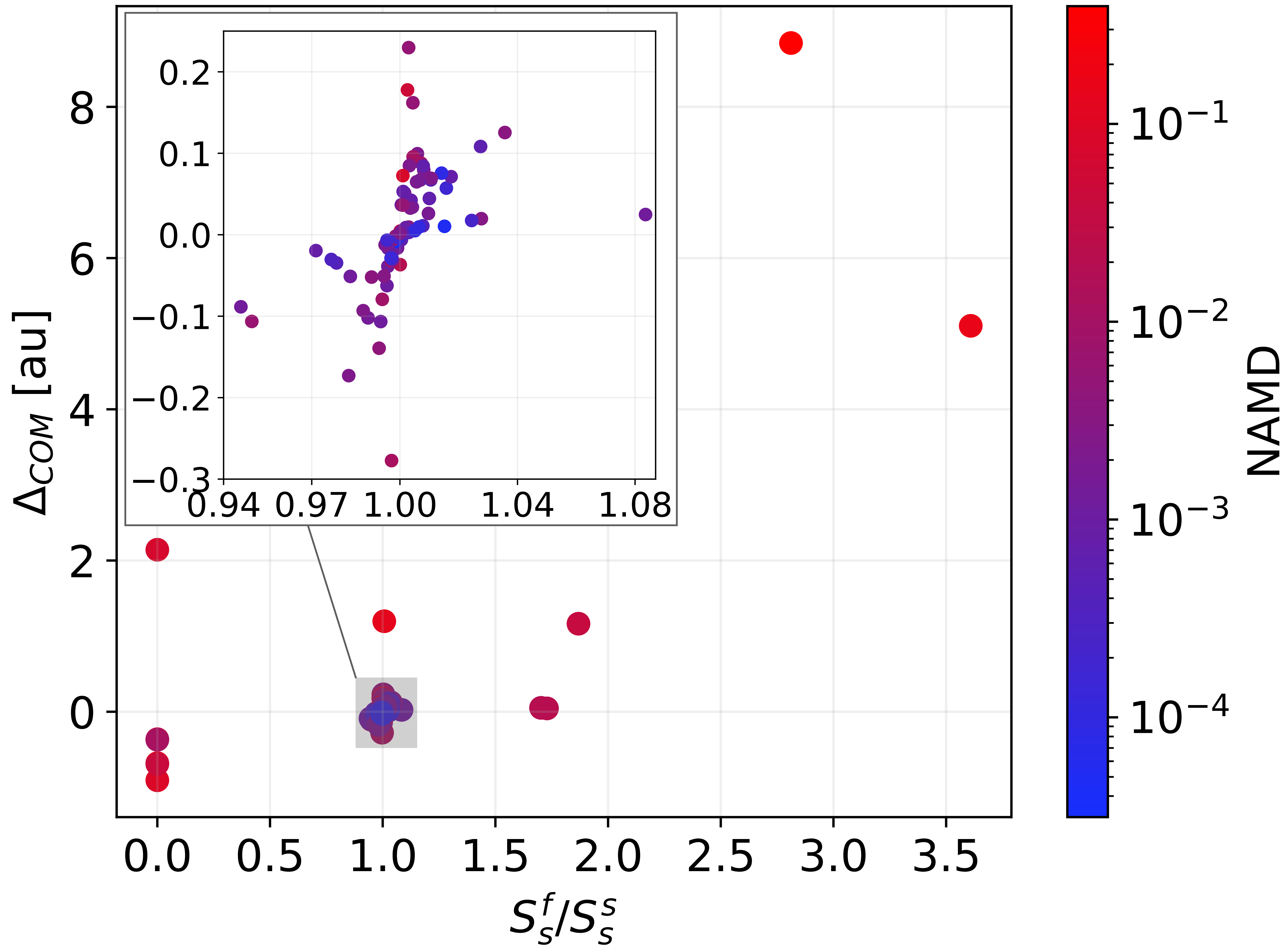


- Dynamically cold systems: <u>no</u> loss of planets, $S_s^f/S_s^s \sim 1$, $S_m^f/S_m^s \sim 1$, $|\Delta_{\mathrm{COM}}| < 0.04$
- Dynamically hot systems: loss of planets, $S_s^f/S_s^s > 1$, $S_m^f/S_m^s > 1$, $|\Delta_{\mathrm{COM}}| > 0.04$

Results (4/5)

Population B



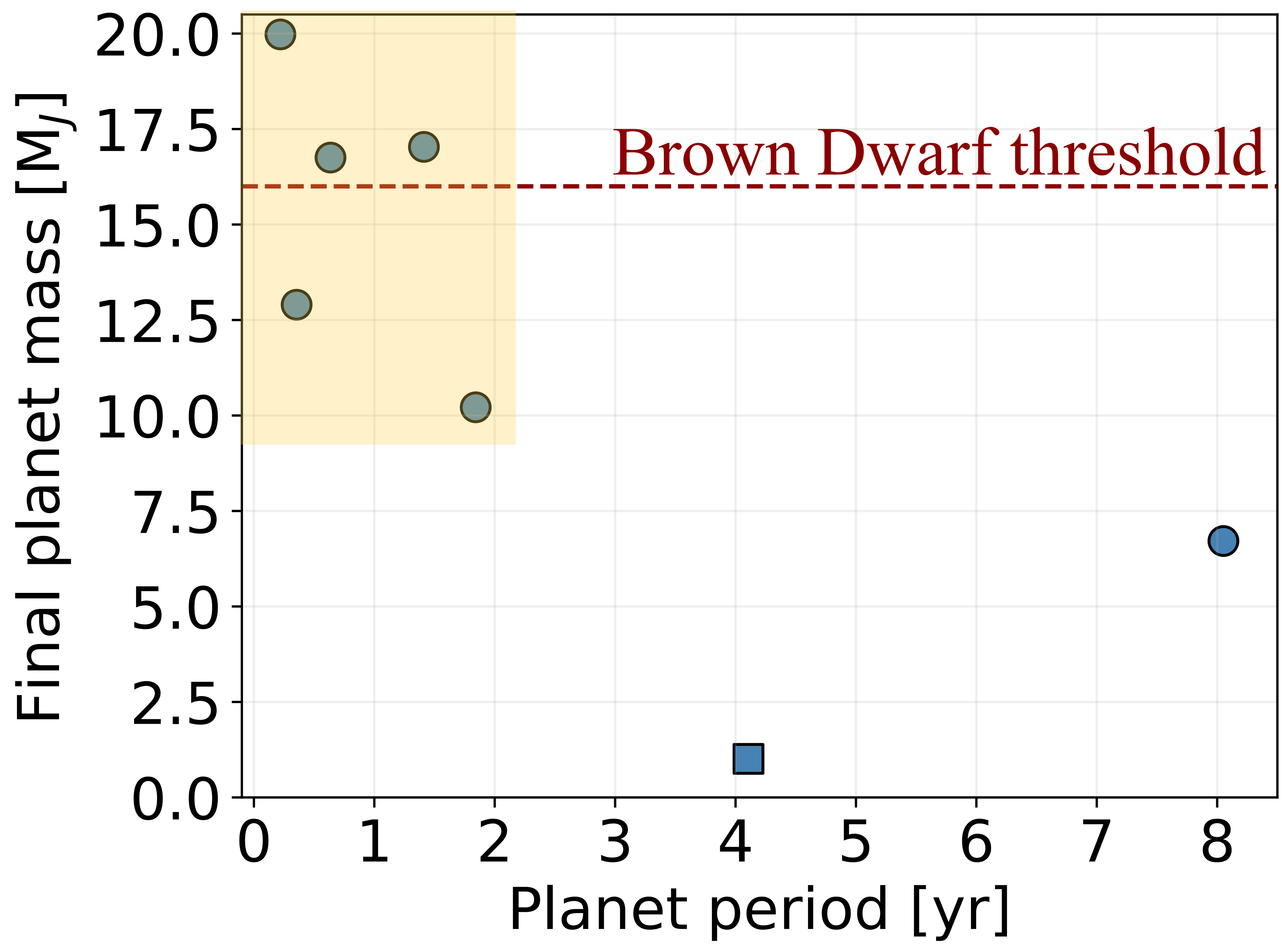


Same trends as population A but:

- More systems end up with one surviving planet (i.e., $S_s^f/S_s^s = 0$)
- Larger $|\Delta_{\mathrm{COM}}|$
- Some dynamically hot systems keep their initial orbital configuration

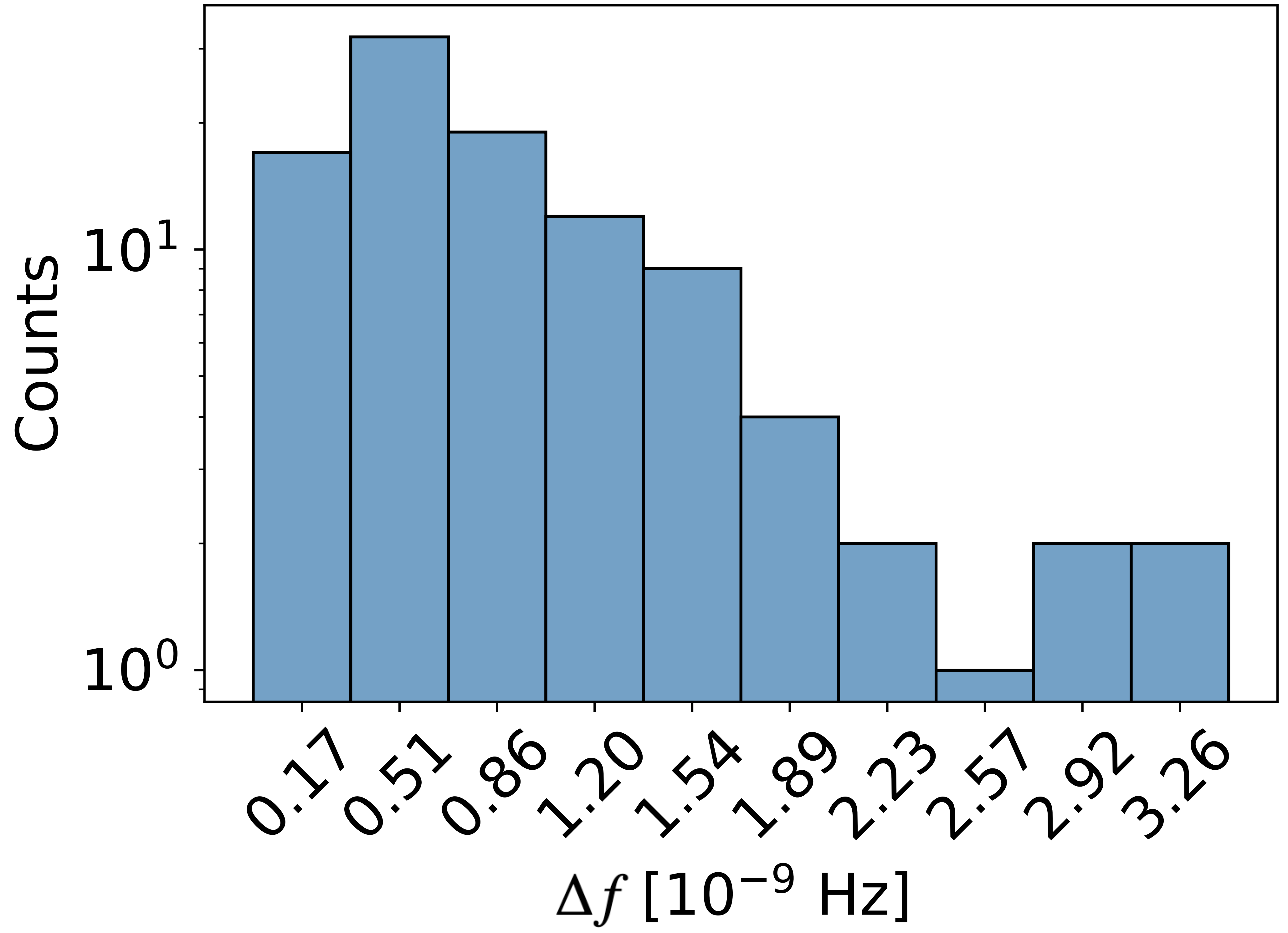
Detectability with LISA ?

One-planet population



Following the results by *Katz et al. (2022)* some of our single planet systems have the potential to be detected, pending though the distance of the systems, their sky-location, polarisation and inclination, which determine the GW signal-to-noise *[Robson et al. 2018]*.

DWD_3^* multi-planet population gravitational wave frequency shift



LISA frequency resolution:

$\sim 7.92 \times 10^{-9}$ Hz for a 4 years mission

$\sim 3.96 \times 10^{-9}$ Hz for a 8 years mission

Summary

- Multi-giant planet systems can survive around Double White Dwarf systems
  → 97% of all our simulated systems have at least one surviving planet
- More massive binaries hosting more massive planets are more likely to go through unstable phases compared to the less massive counterpart
- Dynamically hot systems tend to loose planets and evolve towards less compact architectures and can experience large shifts of the planetary centre of mass (up to ~ 8 au)
- Dynamically cold systems preserve their initial architecture
- Systems with initial higher multiplicity are more likely to undergo unstable phases and experience planet loss
  → Creation of a one-planet population (3%) and most of these planets have the potential of being detected by LISA
- Our multi-planet systems are unlikely to be detectable by LISA