LONG-TERM EVOLUTION OF CIRCUMBINARY PLANETS

AND ANALYSIS OF THEIR DISTRIBUTIONS

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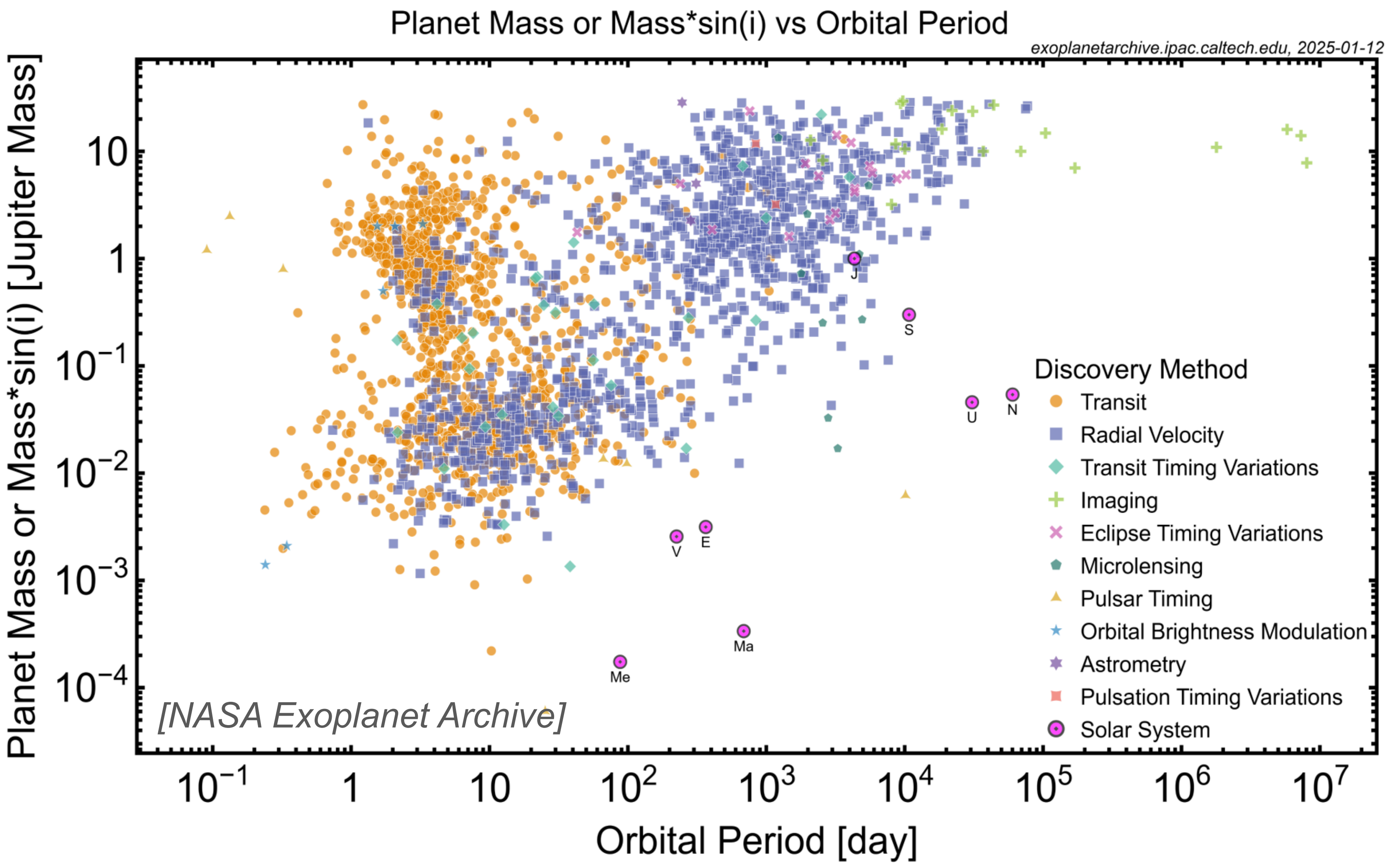
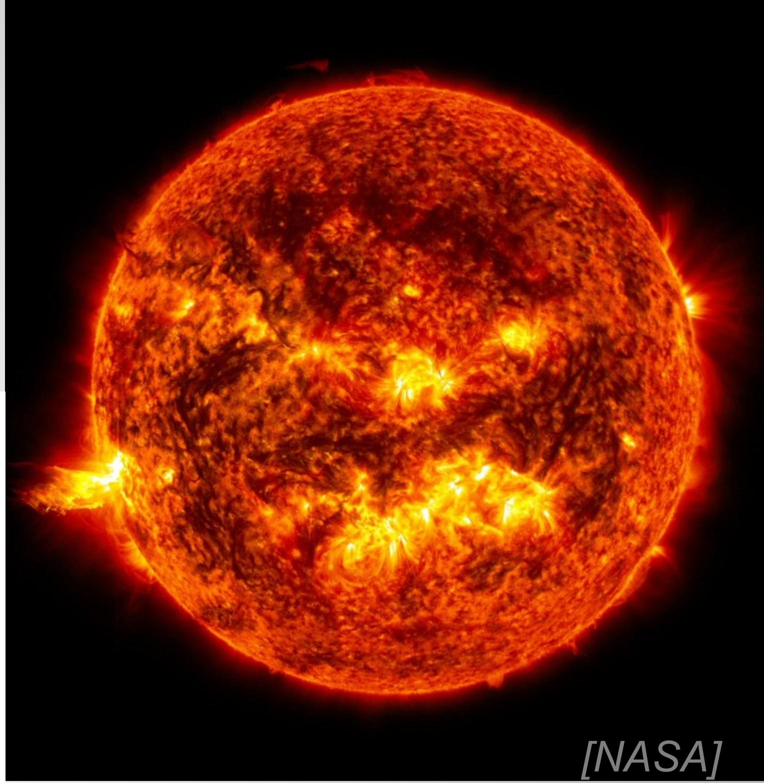
EXCELENCIA SEVERO OCHOA

CIRCUMBINARY PLANETS IN CONTEXT

Most of currently detected exoplanets revolve around **main sequence** (MS) and **single** stars.



[NASA Exoplanet Archive]



[NASA]

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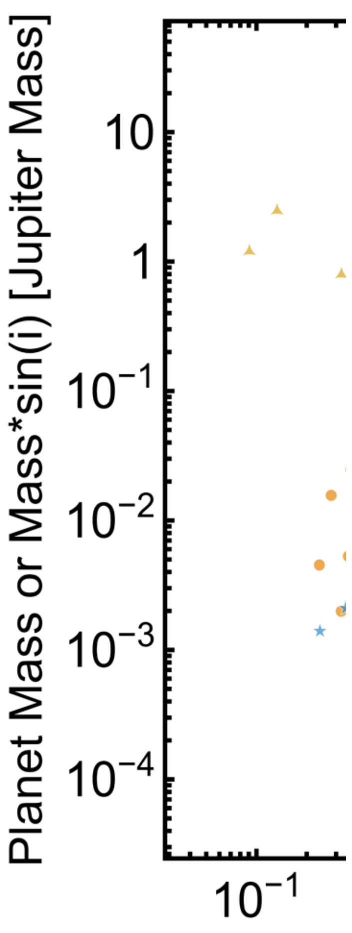

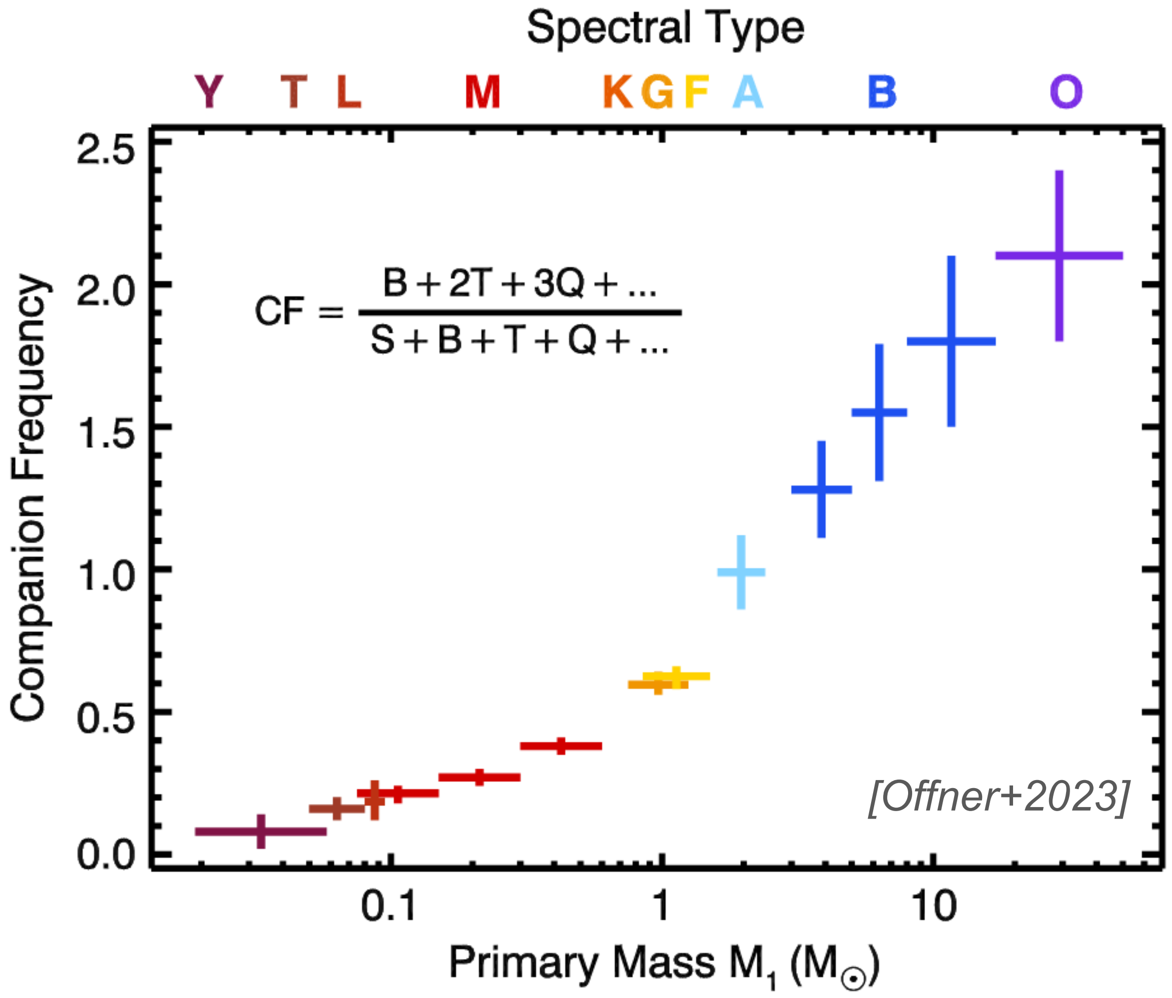

[Offner+2023]

[NASA]

Multiple stars are the rule, not the exception!

(Kouwenhoven et al. 2007; Raghavan et al. 2010; Duchene & Kraus 2013; Moe & Di Stefano 2017, and more)

CIRCUMBINARY PLANETS: NUMBERS

To date, over the 5800* exoplanets discovered, only around 48* are CBPs: **0.8%** !
(and 530 in total are part of multiple hosts, around 10%)

CBPs discovered through different <u>methods</u>:

Eclipse Timing Variations	Transits	Imaging	Microlensing	Radial Velocity
~ 35%	~ 30%	~ 19%	~ 10%	~ 4%

*according to the NASA Exoplanet Archive, other sources might have differing numbers.

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CBPs showcase intriguing binary host stars:

- 14 CBPs orbit at least one post-MS star (e.g. Kepler-451, Esmer et al. 2022, HW Vir, Beuermann et al. 2012, or NY Vir, Song et al. 2019)
- 7 of these 14 orbit a binary with a white dwarf (WD, for example RR Cae, Qian et al. 2012, UZ For, Potter et al. 2011, or NN Ser, Beuermann et al. 2010)

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CIRCUMBINARY PLANETS: LET'S GO?

If CBPs are not preferentially coplanar, they could be very abundant (Armstrong at al 2014)

Favourable environment for their long-term **survival**? (Kostov et al. 2016)

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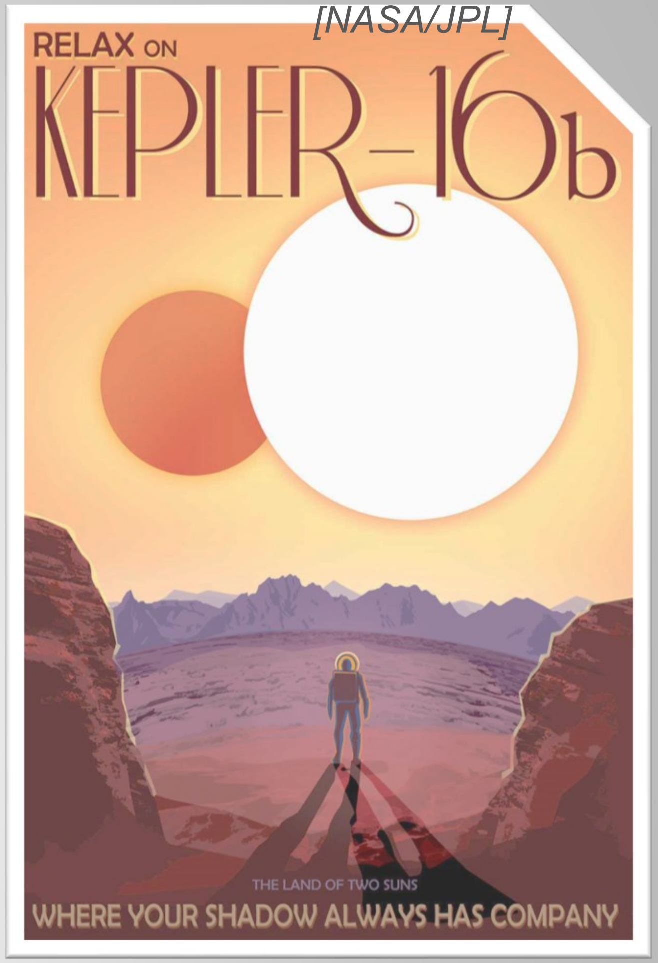
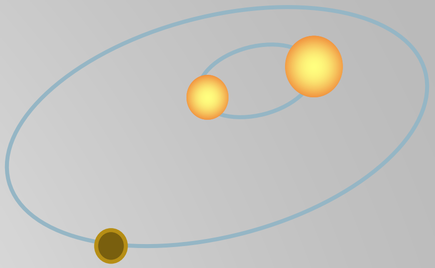

[NASA/JPL]

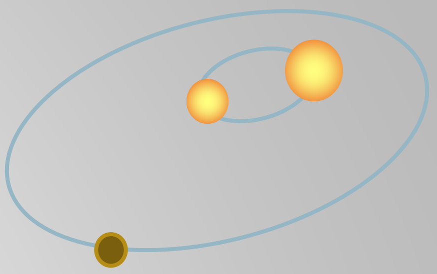
CIRCUMBINARY PLANETS EVOLUTION



Motivation:

- Limited sample size of detected CBPs
- Most planetary systems in general are around main sequence stars
- Possibility of CBPs detection with future LISA mission

CIRCUMBINARY PLANETS EVOLUTION



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Goals:

- Assess the **fate** of CBPs in the context of the binary host evolution
- Characterise the **parameter space** and properties of the CBPs population in time

→ **Project**: Numerical simulations of circumbinary giant planets long-term evolution

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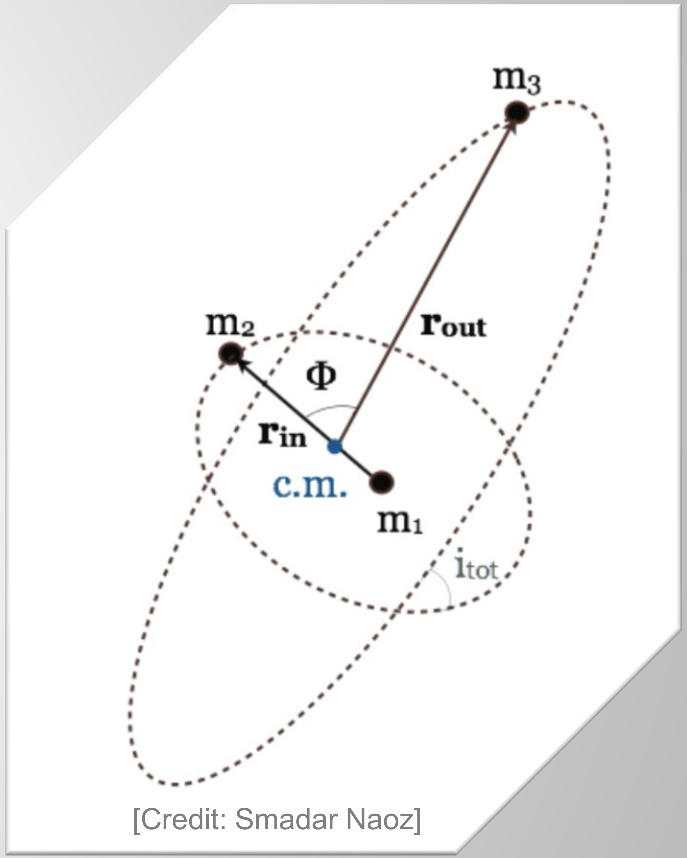
THE SIMULATION FRAMEWORK

Codes:

- **TRES** (Toonen 2016), to simulate three-body systems
- **SeBa** (Toonen & Nelemans 2013), to include stellar evolution

Numerical code for hierarchical triples, combining secular orbital evolution, with stellar evolution and interactions via heuristic recipes.



[Credit: Smadar Naoz]

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THE SIMULATION FRAMEWORK

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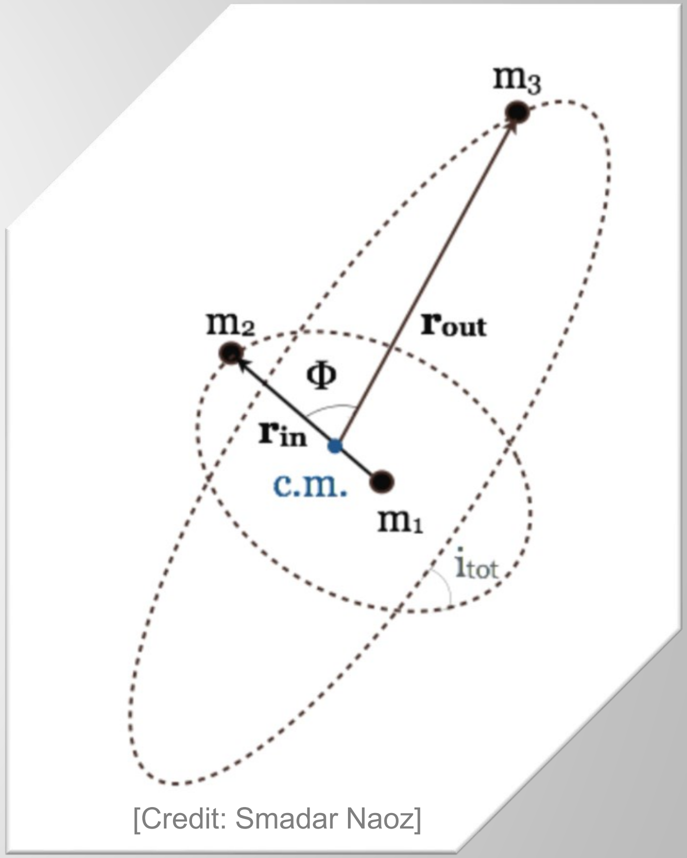
Methods:

- Review of planet-binary star <u>interactions</u>
- <u>Implementation</u> of new modules into TRES code New!
- Secular simulation of <u>CBPs populations</u> up to 13.5 Gyr



[Credit: Smadar Naoz]

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NEW IMPLEMENTATIONS

Mass-radius dependence for SSOs
(Chen&Kipping2017)

P-type orbit stability criterion
(Holman&Wiegert1999)

Planetary photoevaporation by XUV
(e.g. Sanz-Forcada+2011)

Planetary rotational velocity
(Bryan+2018)

Gyration radius and the *apsidal motion constant*,
evolving from ZAMS to WD (Claret+2019)

`TRES-exo` (Columba+2023)
included within the main TRES package

On GitHub!

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POPULATIONS SETUP

Inner binaries

$\boldsymbol{M_1}$: Kroupa IMF $[0.95 - 10]\ \mathrm{M}_\odot$

$\boldsymbol{M_2}$: uniform $\left(\frac{M_2}{M_1}\right)$ $[0.95 - 10]\ \mathrm{M}_\odot$

$\boldsymbol{a}_{\mathbf{bin}}$: log-uniform $[0.07 - 10]\ \mathrm{au}$

$\boldsymbol{e}_{\mathbf{bin}}$: thermal $[0 - 0.95]$

Progenitors to match the Milky Way DWDs population (Toonen+2012)

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Giant CBPs

Pop. A:

$\boldsymbol{M_{\mathrm{pl}}}$:	uniform	$[0.2 - 16]\ \mathrm{M_{Jup}}$
$\boldsymbol{a_{\mathrm{pl}}}$:	log-uniform	$[0.17 - 200]\ \mathrm{au}$
$\boldsymbol{i_{\mathrm{pl}}}$:	cos-uniform	$[-1\ ;\ 1]$
$\boldsymbol{e_{\mathrm{pl}}}$:	Beta (α=30,β=200) (Bowler+2020)	$[0 - 0.95]$

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Pop. B:

All simple **uniform** distributions, same ranges

(10500 systems per population)

$t_0 = ZAMS$

$t_{\mathrm{end}} \leq 13.5\ \mathrm{Gyr}$

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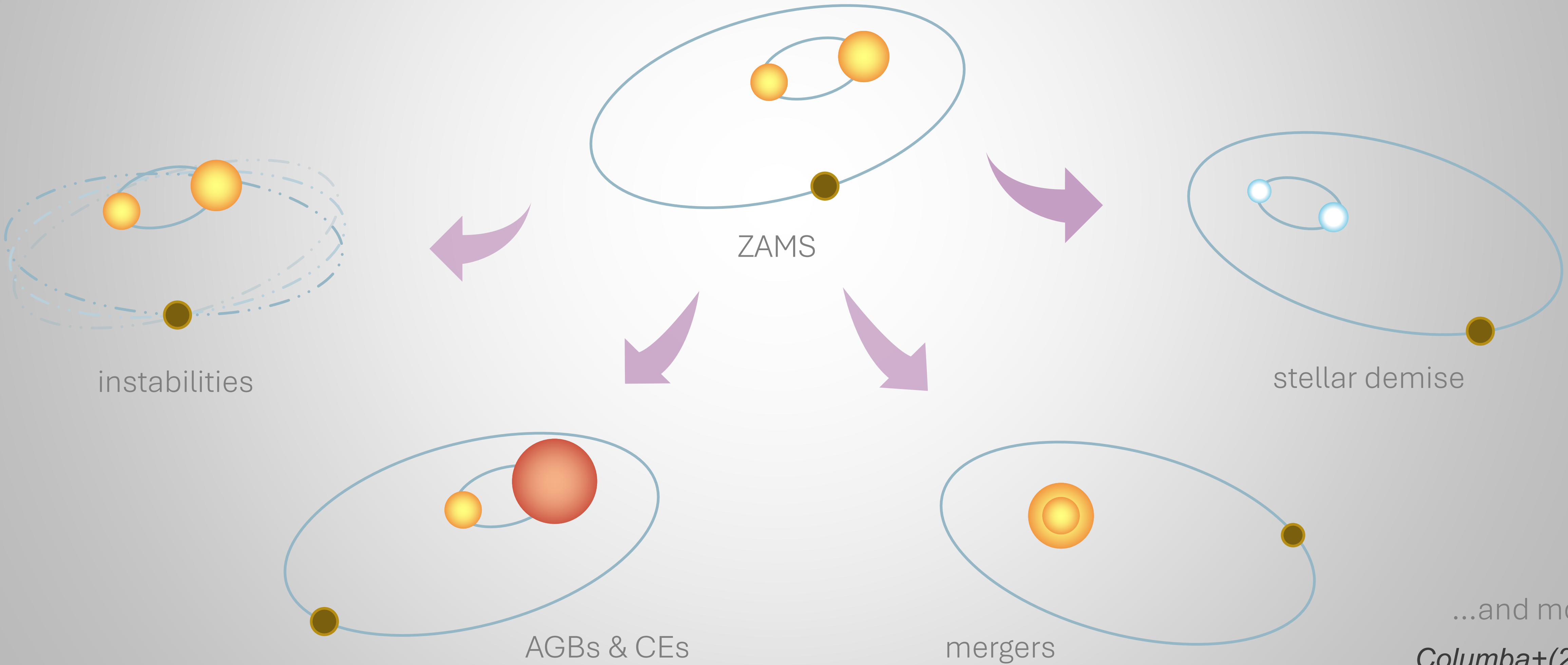
RESULTS

The simulated CBPs were grouped in different categories based on their final fate.



ZAMS

instabilities

AGBs & CEs

mergers

stellar demise

...and more!

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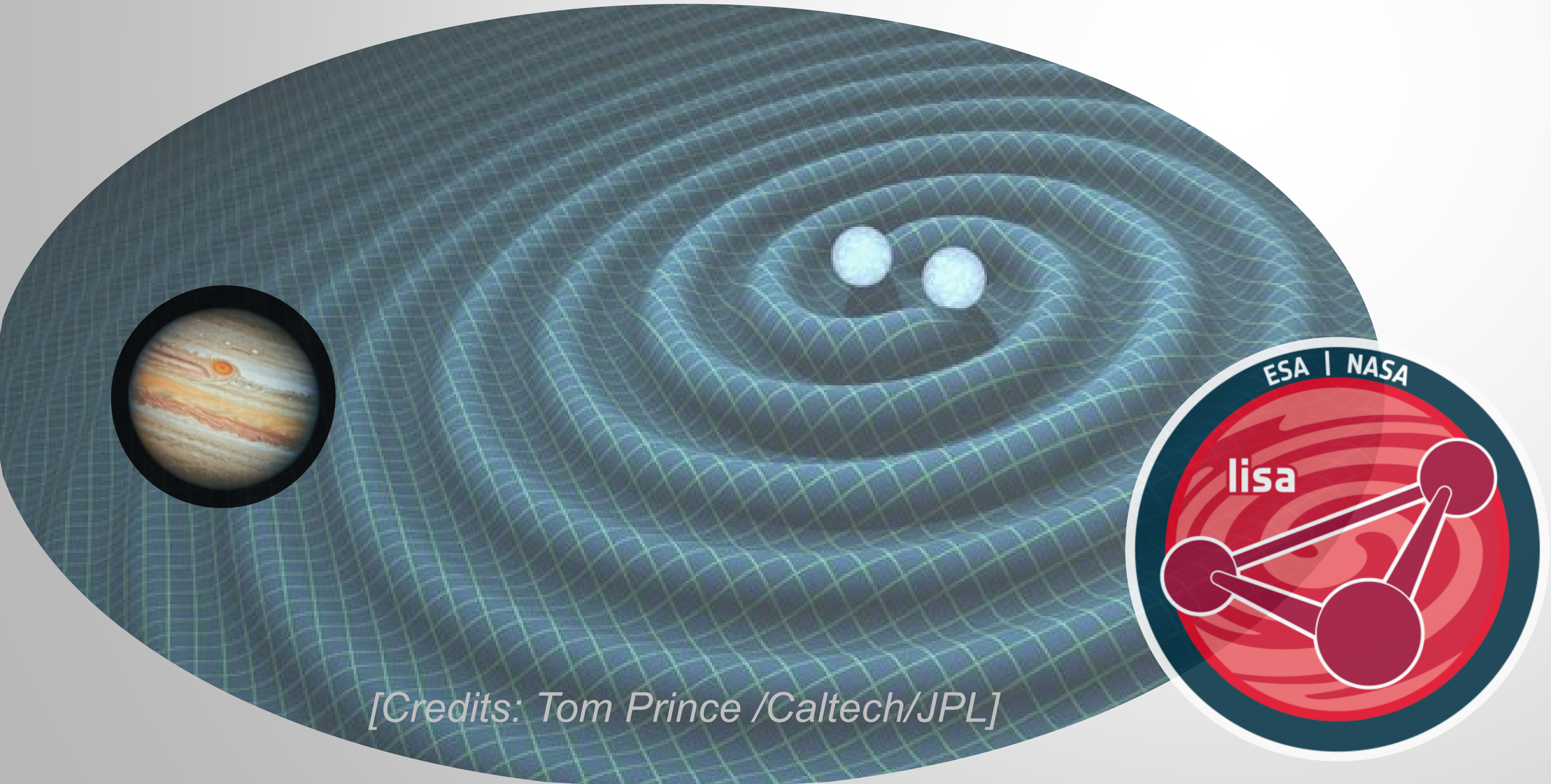
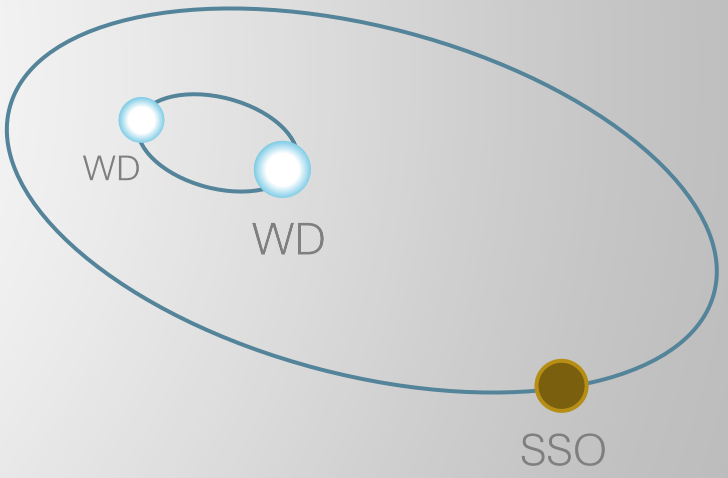
RESULTS: MAGRATHEA PLANETS

Special focus on CBPs surviving to the WD stage of both stars: “**Magrathea**”

LISA mission will have the sensitivity necessary to detect gas giants and brown dwarfs around DWDs *in the entire Milky Way* (Tamanini & Danielski 2019; Danielski et al. 2019)



[Credits: Tom Prince /Caltech/JPL]



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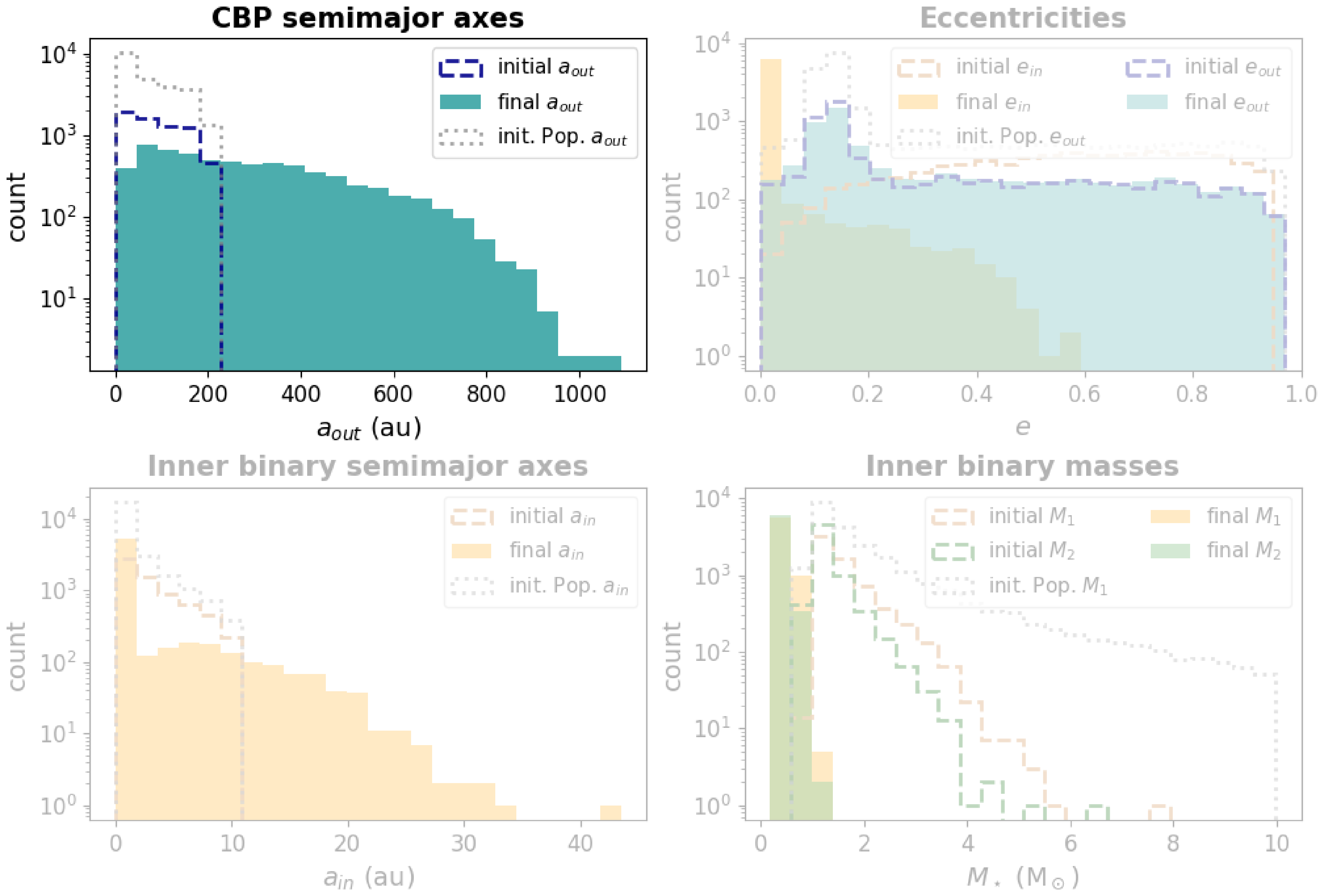

Pop A + B

Occurrence rate ~ 23 – 32%

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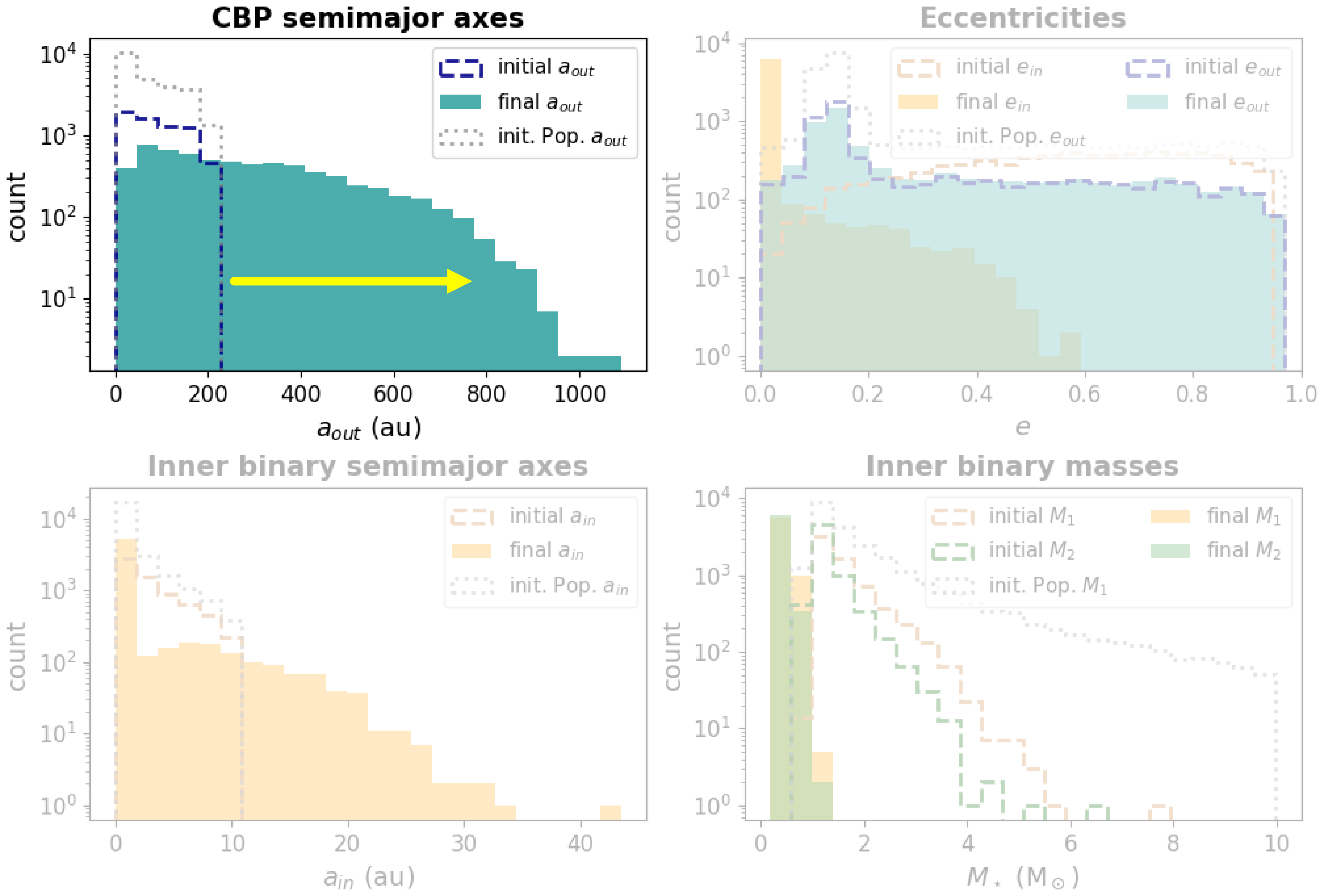
RESULTS: MAGRATHEA PLANETS



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Large CBP semimajor axes

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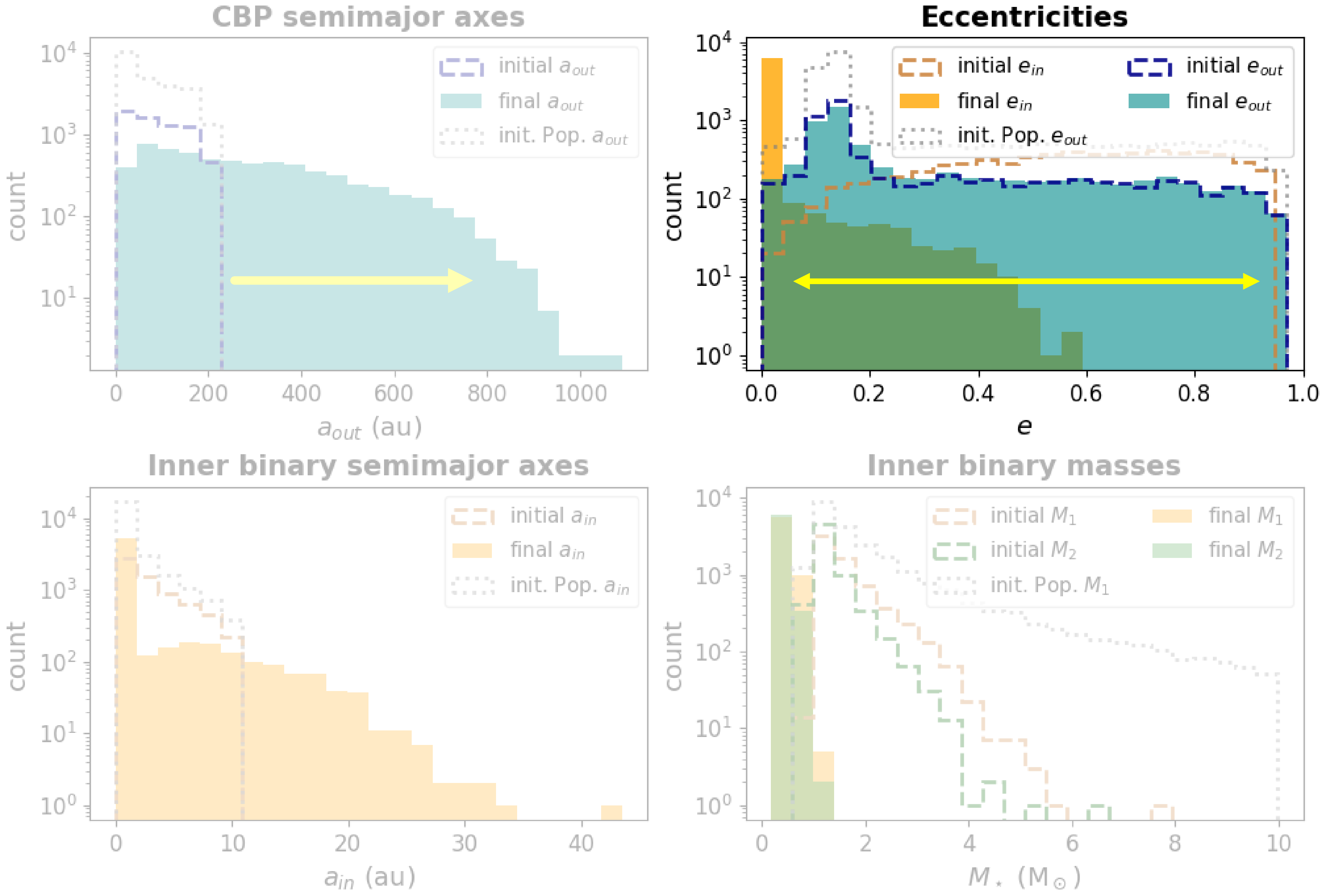

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CBP with any eccentricity

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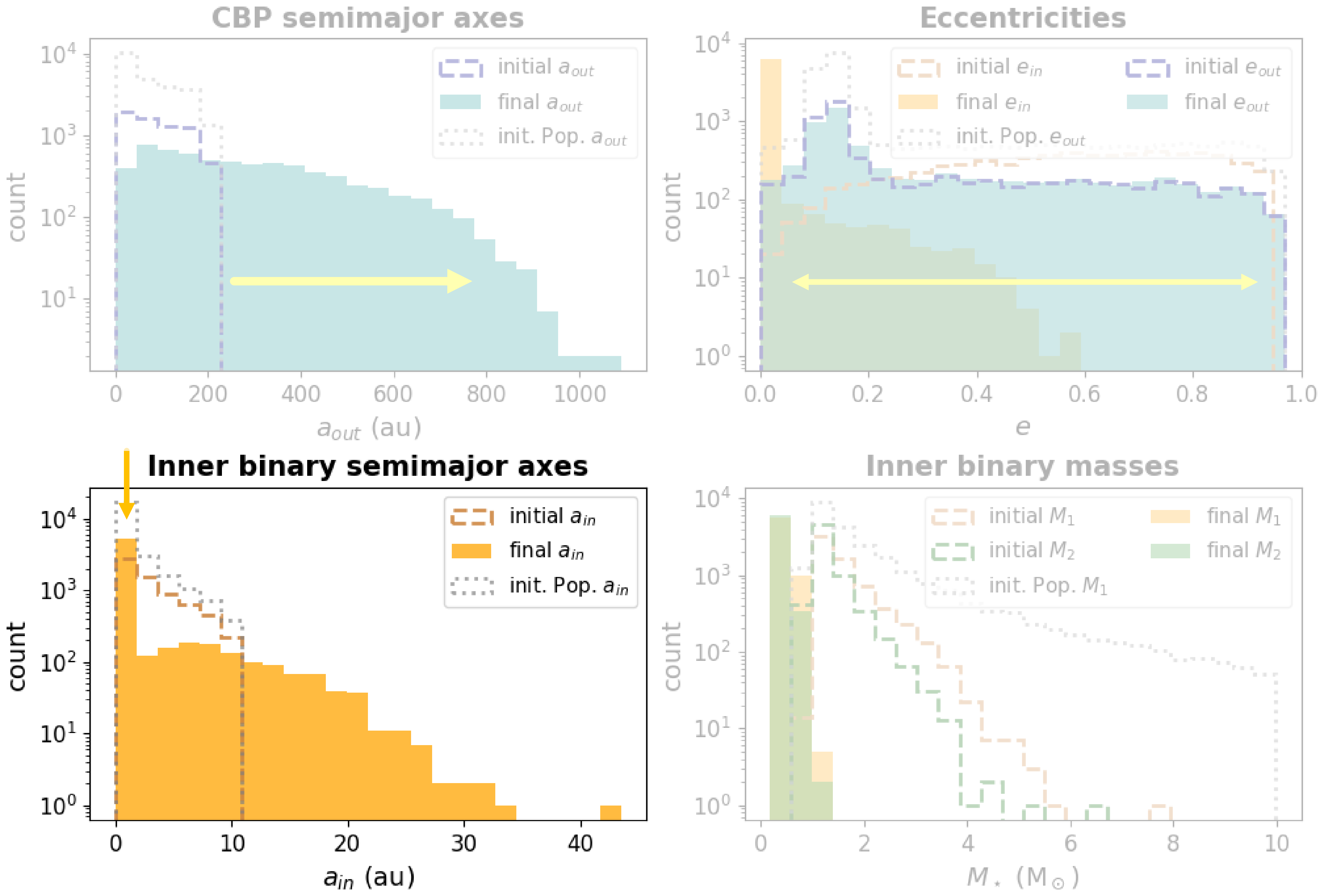

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Tight binary hosts

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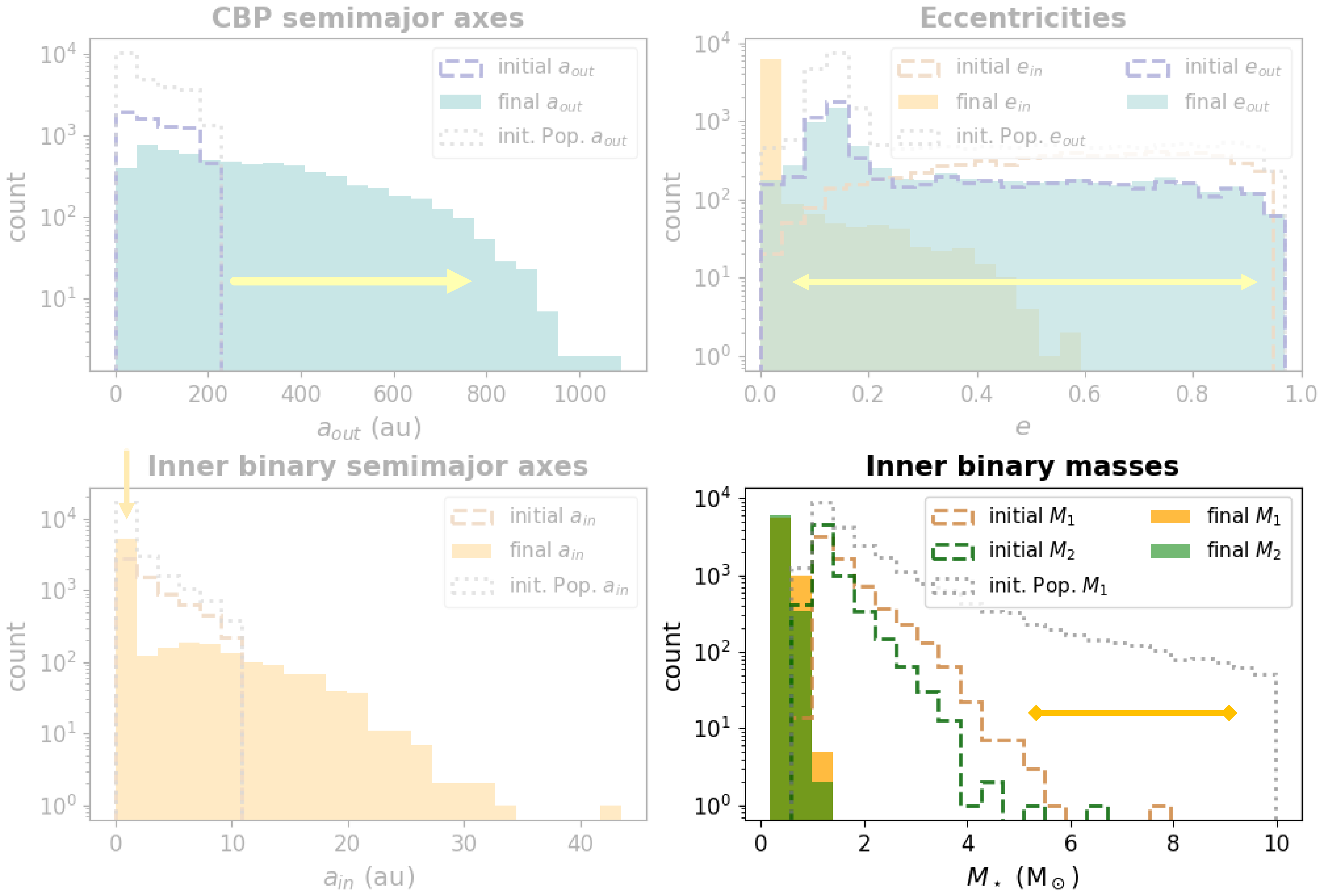

Pop A + B

Occurrence rate $\sim 23 - 32\%$

Large CBP semimajor axes

CBP with any eccentricity

Tight binary hosts

Lack of heavy progenitors

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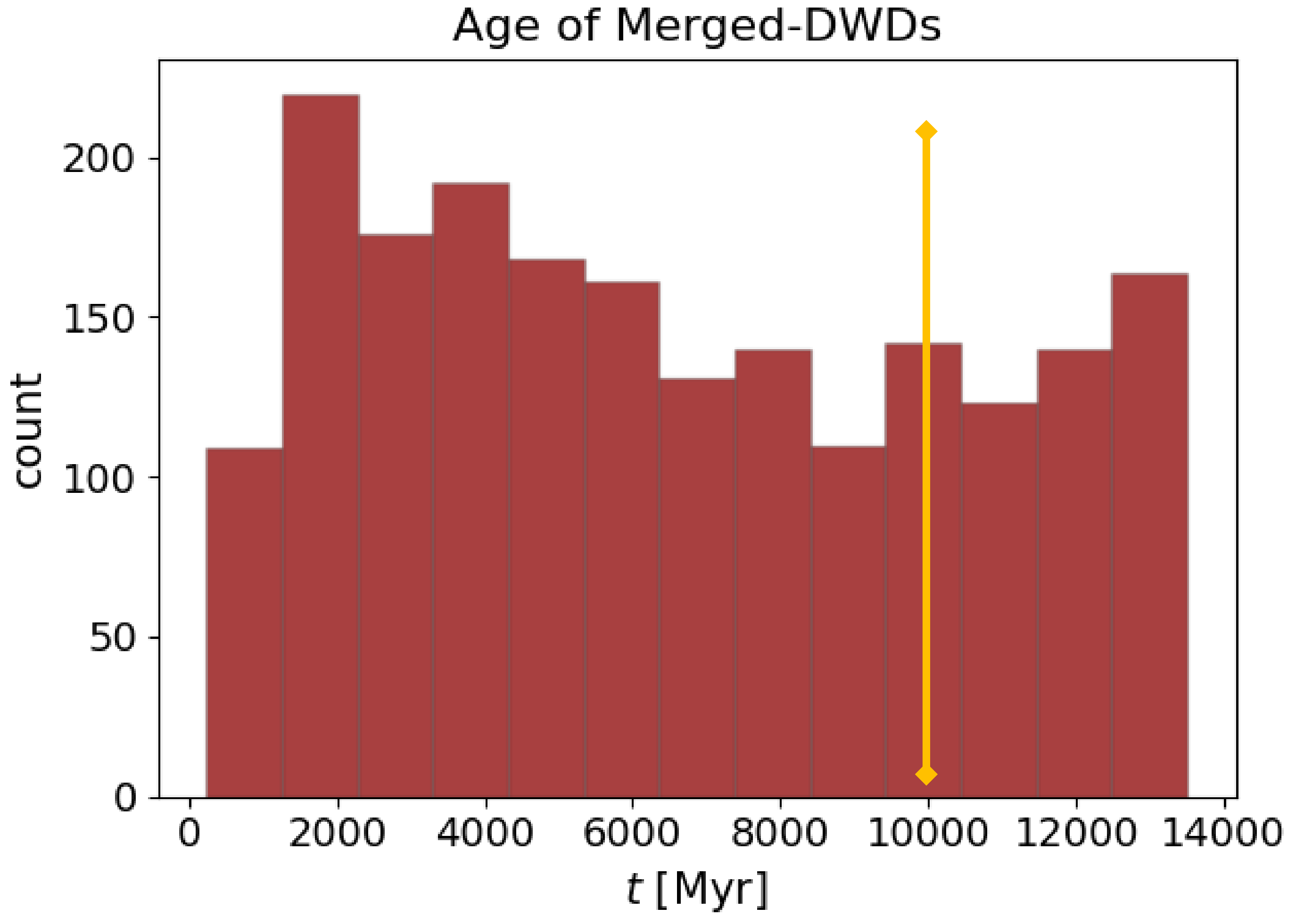
ROOM FOR WIGGLE

The Magratheas are selected after 13.5 Gyr exactly. DWD “survivors” can increase for shorter time limits.



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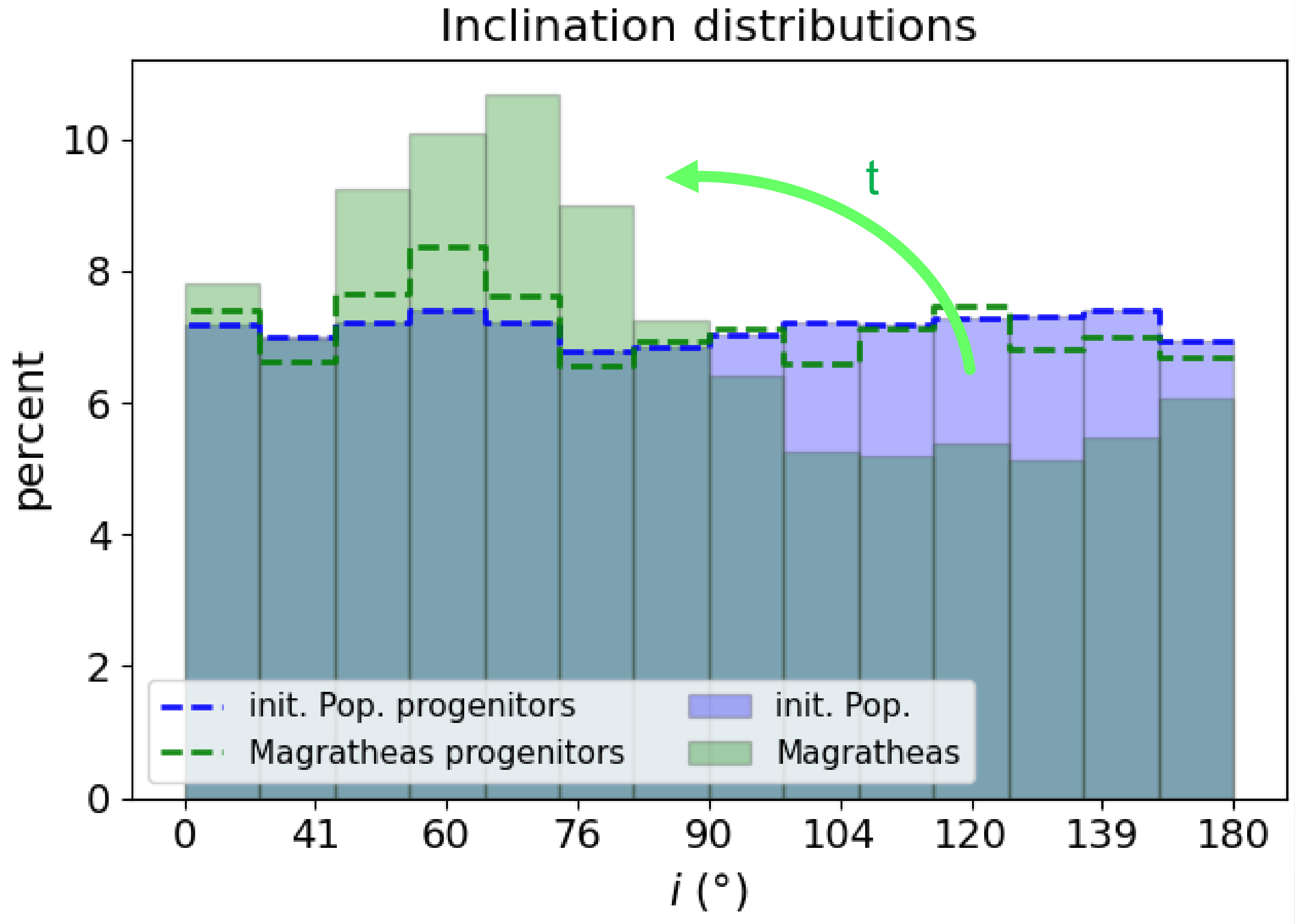
INCLINATION PREFERENCE

Surviving CBPs are preferentially found on **prograde** orbits, but **inclined**!



Surplus of around 7%

Neither coplanar, nor polar ?!

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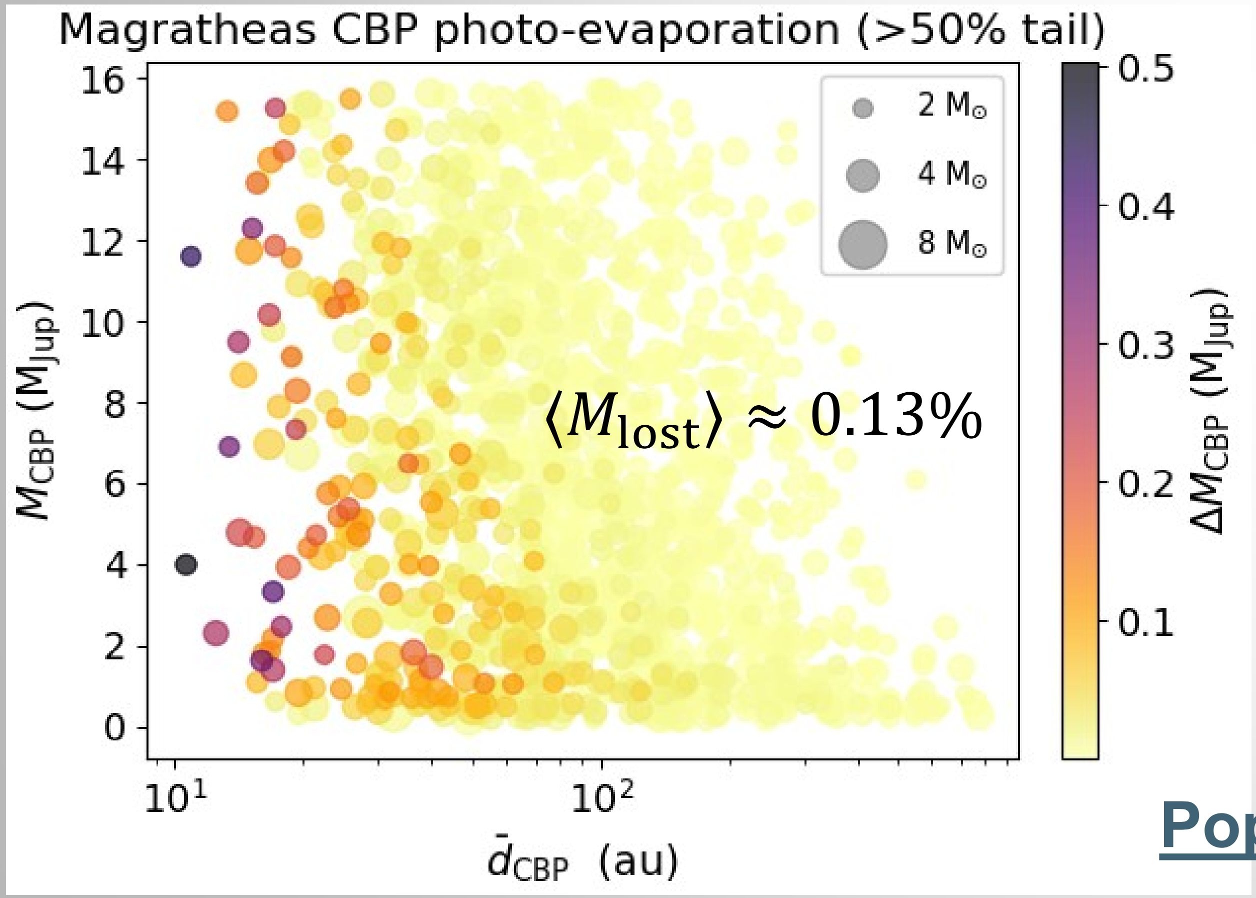
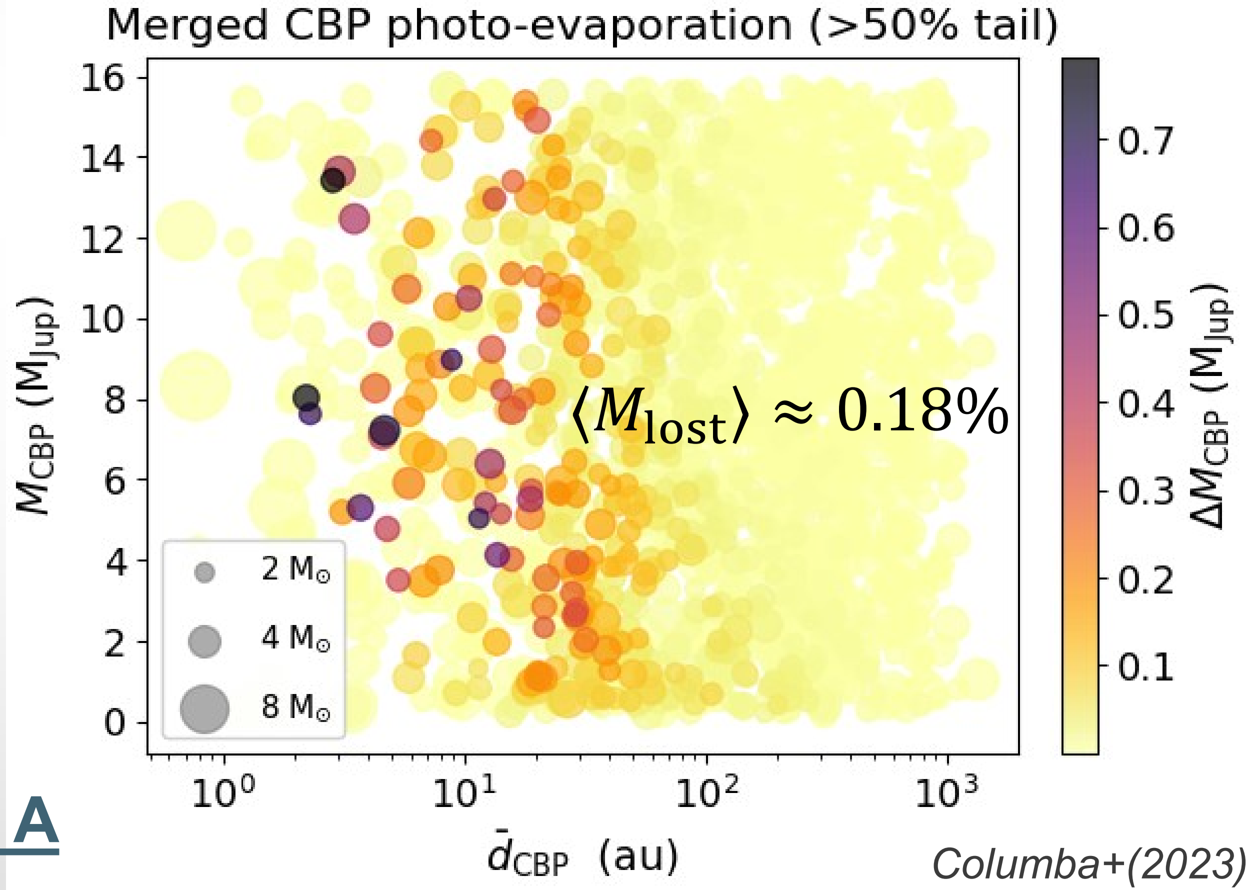
RESULTS: PHOTOEVAPORATION

- Photoevaporation significant for **a few** individual CBPs
- Stronger loss around low/intermediate mass binaries



$\langle M_{\mathrm{lost}} \rangle \approx 0.13\%$



$\langle M_{\mathrm{lost}} \rangle \approx 0.18\%$

Pop A

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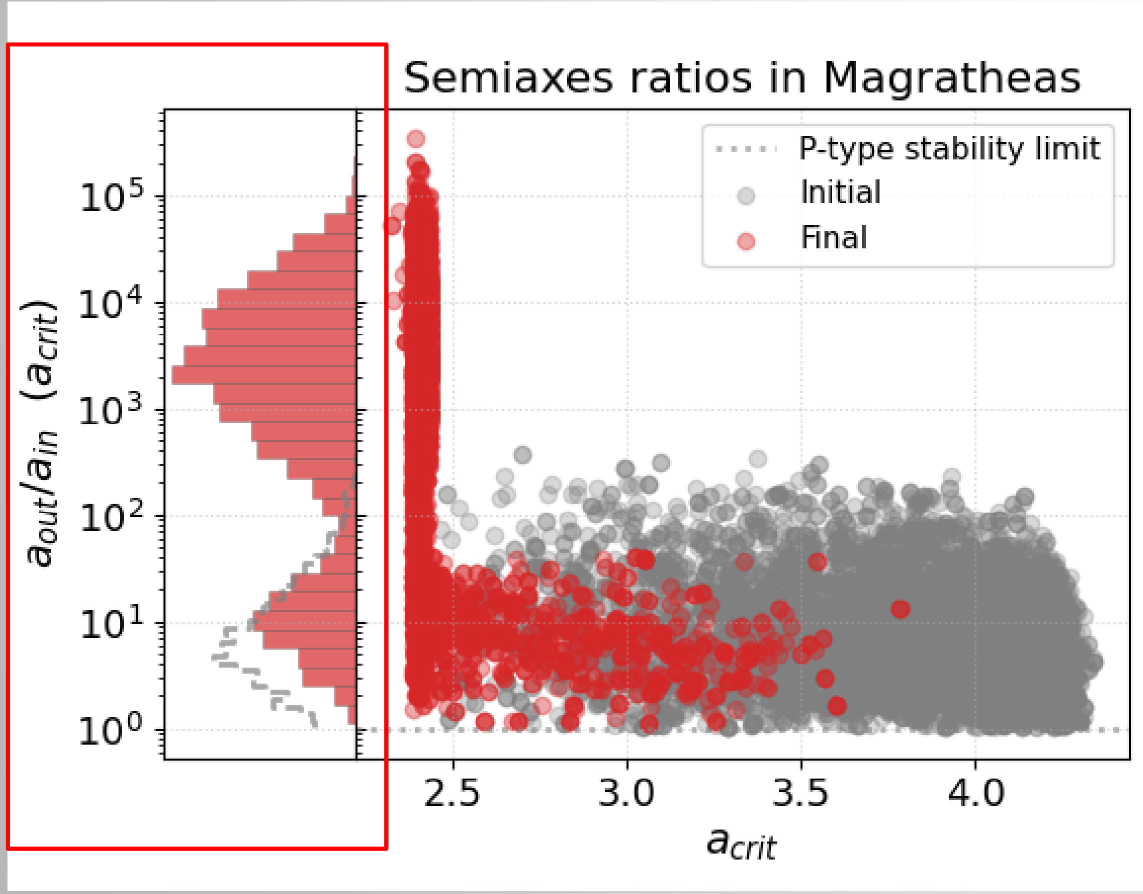
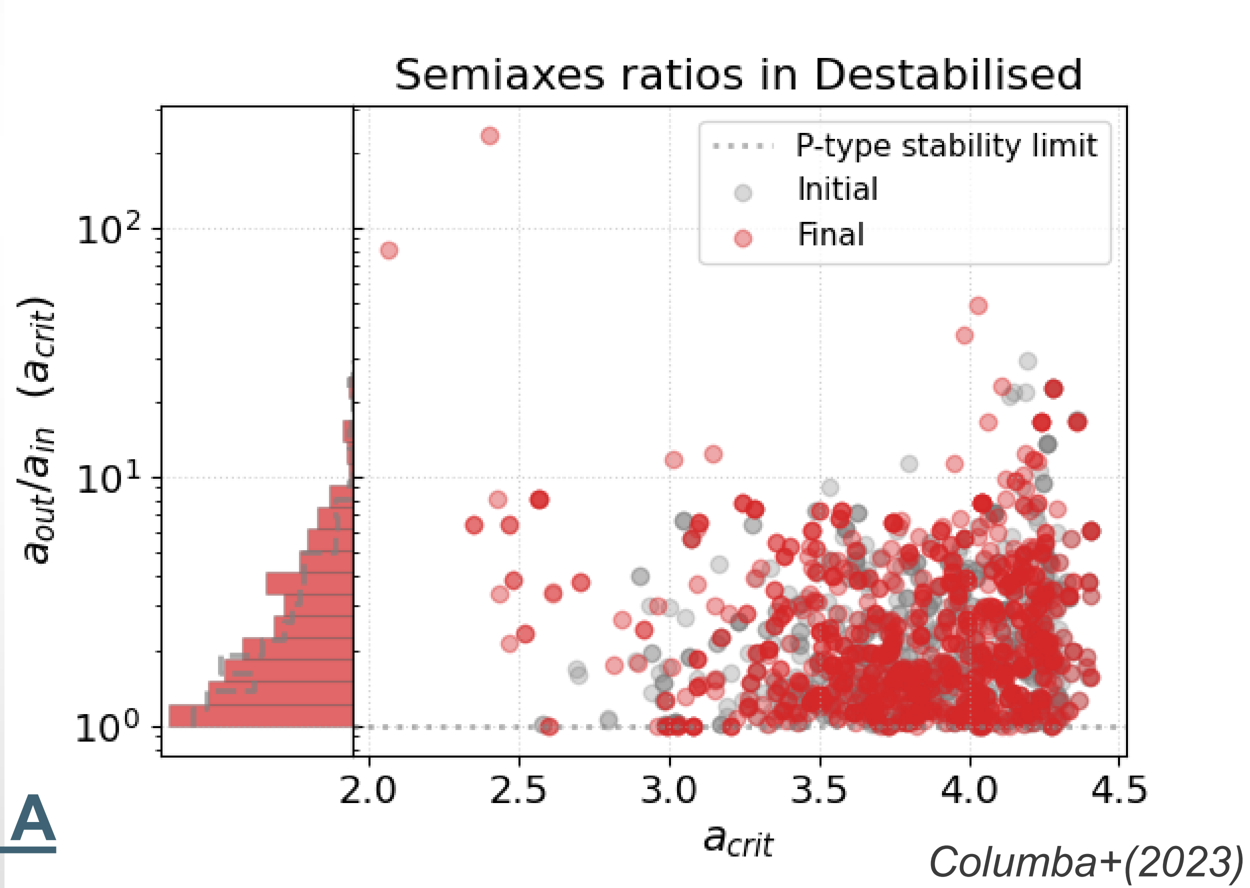
RESULTS: STABILITY

- No particular pile-up of CBPs at the stability limit, but two bumps in the log-distribution
- Destabilised systems have wider binaries and CBPs closer to the a_crit (= a_pl / a_bin)



Semiaxes ratios in Magratheas

Pop A



Semiaxes ratios in Destabilised

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RESULTS: TABLES

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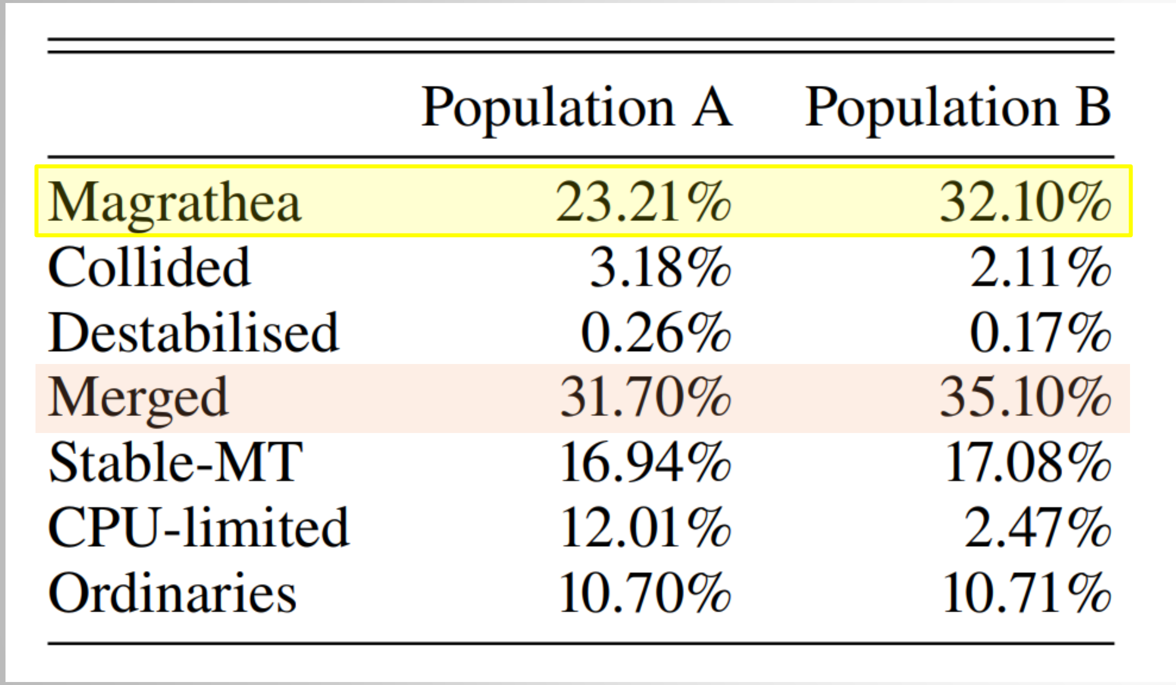

	Population A	Population B
Magrathea	23.21%	32.10%
Collided	3.18%	2.11%
Destabilised	0.26%	0.17%
Merged	31.70%	35.10%
Stable-MT	16.94%	17.08%
CPU-limited	12.01%	2.47%
Ordinaries	10.70%	10.71%

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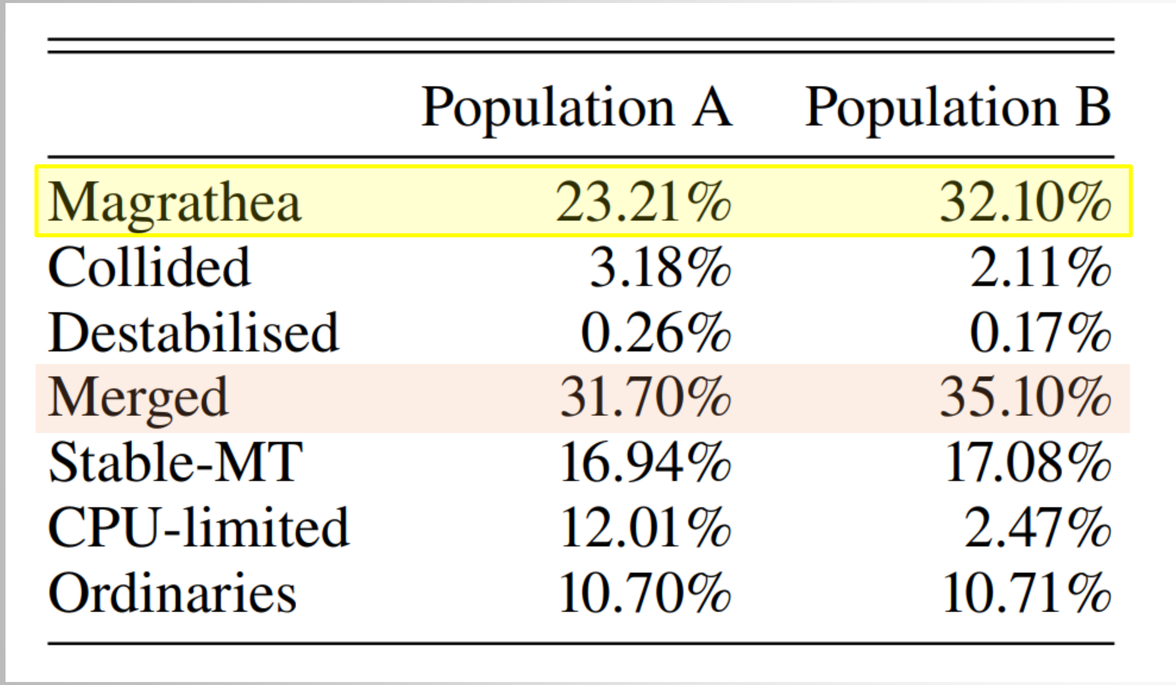

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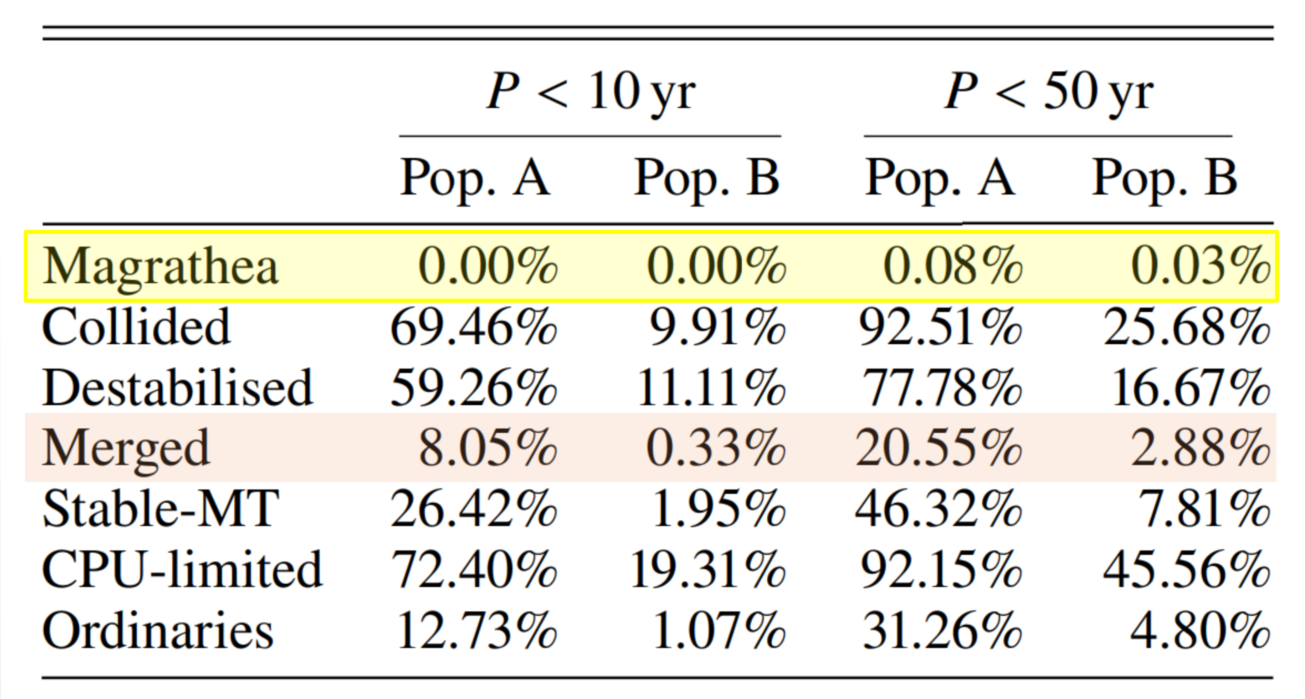

	$P < 10$ yr		$P < 50$ yr	
	Pop. A	Pop. B	Pop. A	Pop. B
Magrathea	0.00%	0.00%	0.08%	0.03%
Collided	69.46%	9.91%	92.51%	25.68%
Destabilised	59.26%	11.11%	77.78%	16.67%
Merged	8.05%	0.33%	20.55%	2.88%
Stable-MT	26.42%	1.95%	46.32%	7.81%
CPU-limited	72.40%	19.31%	92.15%	45.56%
Ordinaries	12.73%	1.07%	31.26%	4.80%

FINAL REMARKS


[Credits: Tom Prince /Caltech/JPL]

Our sample of Magrathea CBPs is currently *not ideal* for **LISA detection**:

- Generally large orbits + WD are lightweight = long CBP orbital **periods**
- Secular approach not allowing unstable orbital shrinking
- Only **one** CBPs per system ?

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N-body integration
[see talk by Nigioni!]

Instability during WD phase necessary to perturb objects on to the star (Debes & Sigurdsson 2002; Veras et al. 2013, Veras & Hinkley 2021)

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FINAL REMARKS

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N-body integration
[see talk by Nigioni!]

Multi-CBP systems and planet-planet scattering,
or even 3rd–gen (post-AGB) disks & planets ?
[See talk by Ledda!]

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CIRCUMBINARY PLANETS EVOLUTION: SUMMARY

Main takeaways:

- **23% - 32%** of all giant CBPs survive for one Hubble time to become ***Magrathea*** planets
- Single CBPs evolve towards larger and **larger orbits** as their hosts die
- Around 33% of the binary stars eventually **merge**
- **Photoevaporation** has a negligible impact on a population of giant CBPs
- **Eccentricity** alone does not prevent the long-term survival

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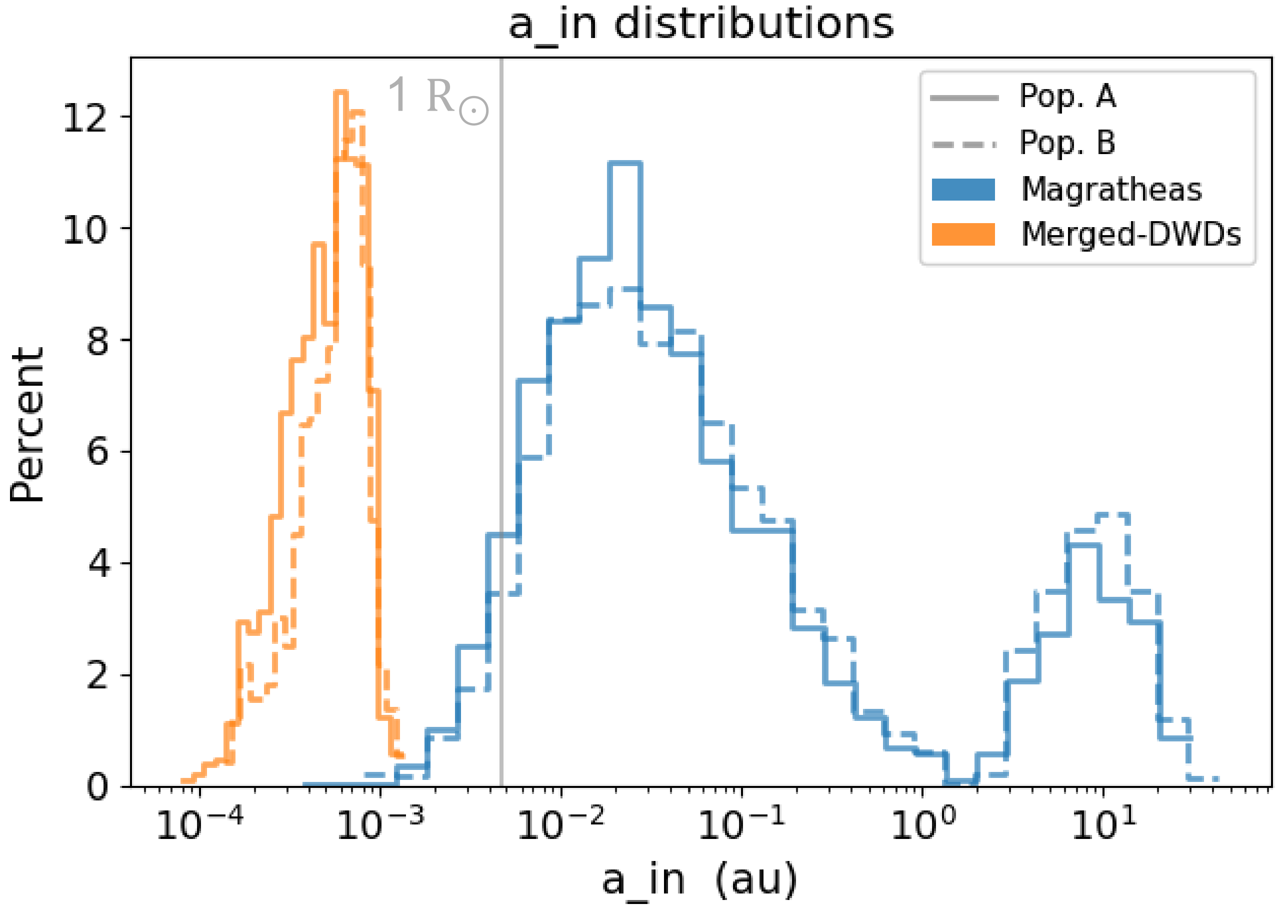
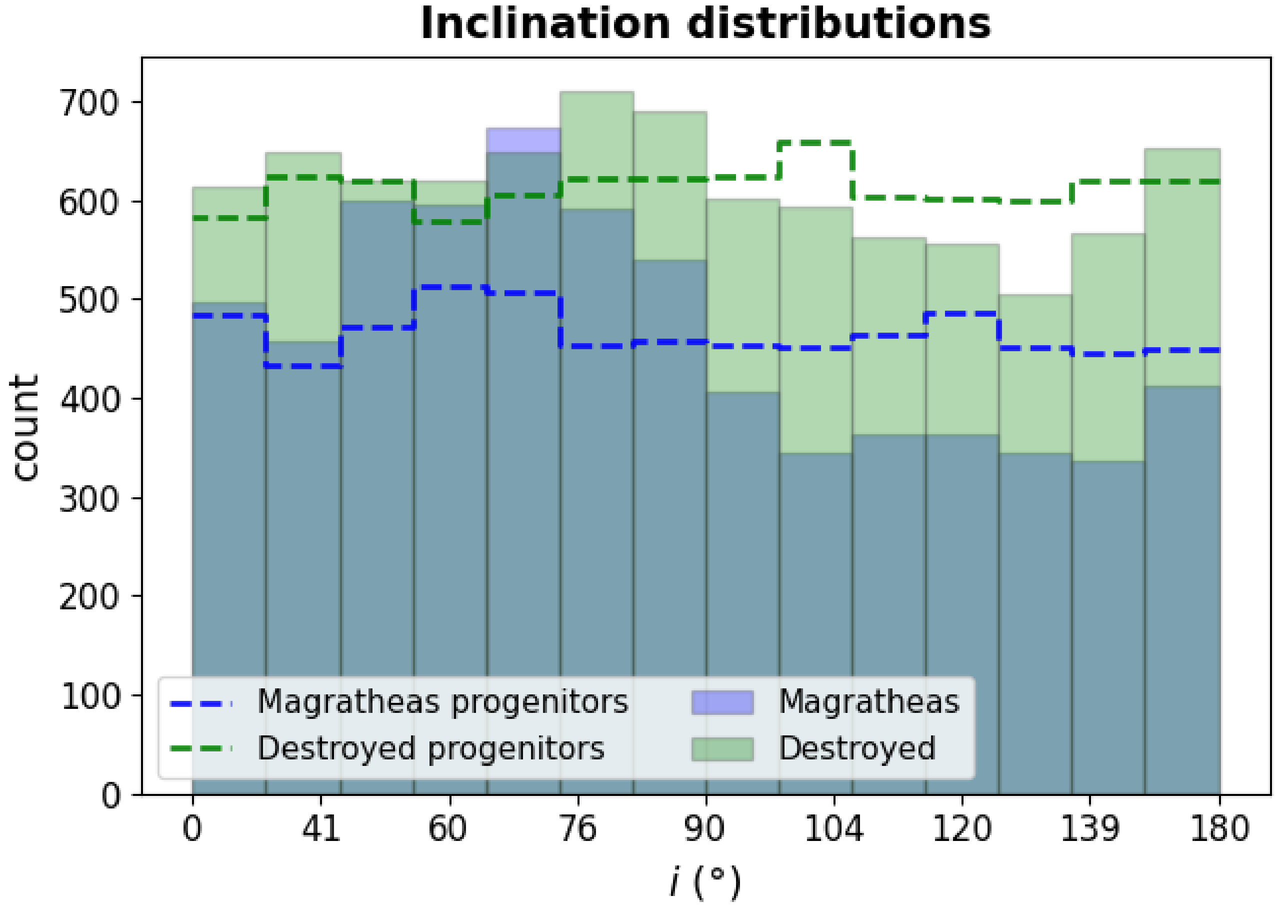
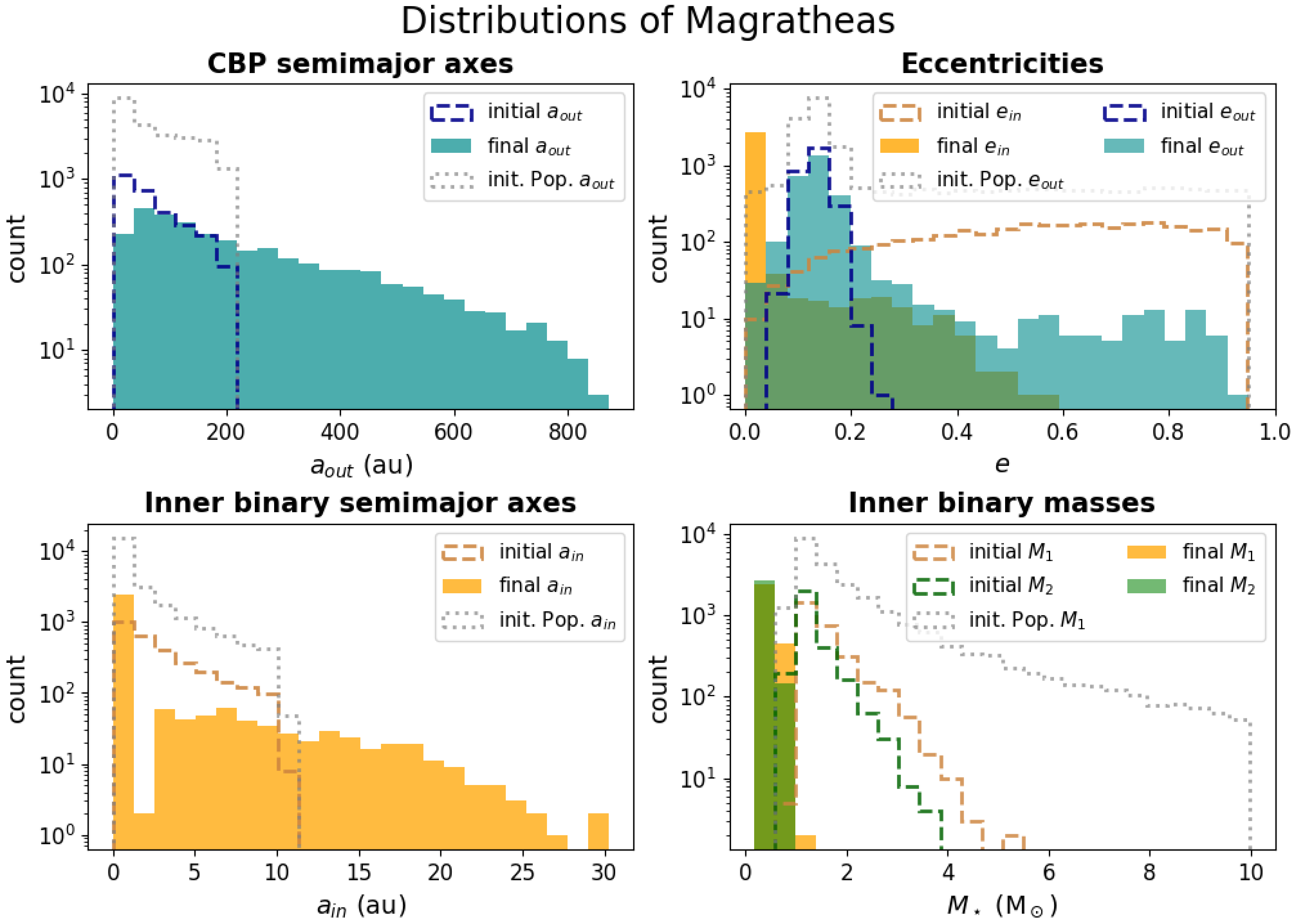
Back up slides

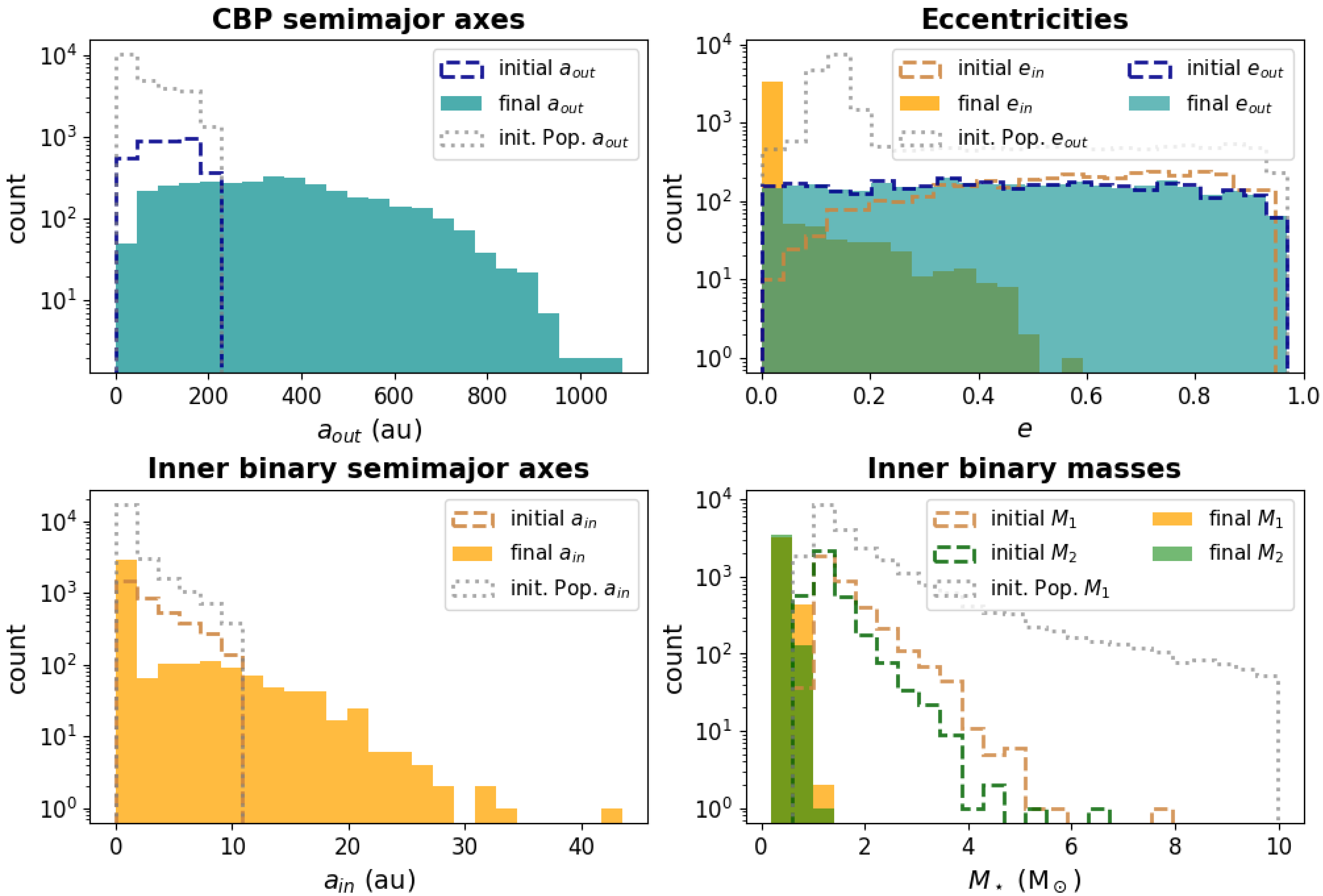

a_in distributions


Inclination distributions

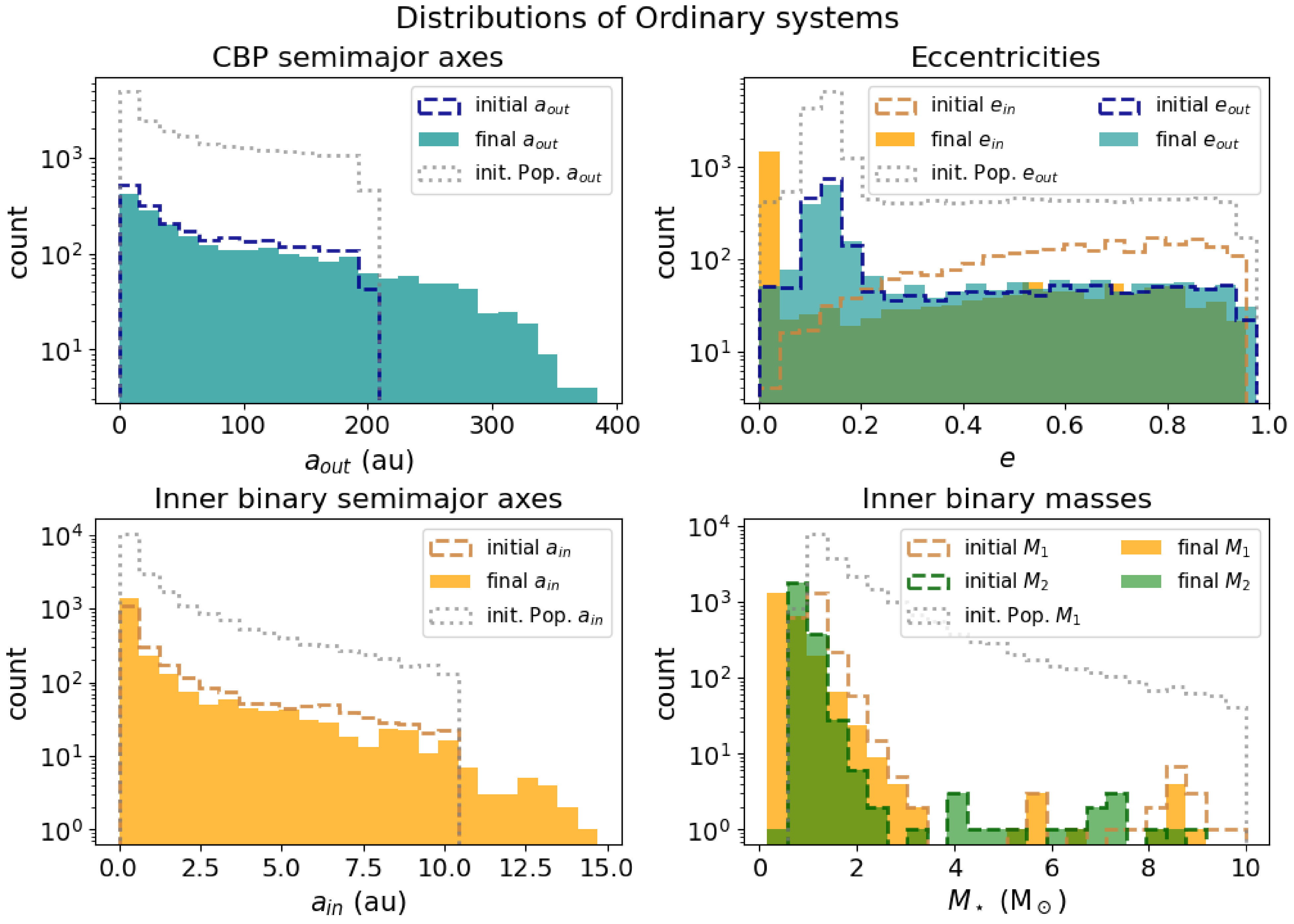

Distributions of Magratheas
CBP semimajor axes
initial a_{out}
final a_{out}
init. Pop. a_{out}
count
10^1
10^2
10^3
10^4
0
200
400
600
800
a_{out} (au)
Eccentricities
initial e_{in}
final e_{in}
init. Pop. e_{out}
initial e_{out}
final e_{out}
count
10^0
10^1
10^2
10^3
10^4
0.0
0.2
0.4
0.6
0.8
1.0
e
Inner binary semimajor axes
initial a_{in}
final a_{in}
init. Pop. a_{in}
count
10^0
10^1
10^2
10^3
10^4
0
5
10
15
20
25
30
a_{in} (au)
Inner binary masses
initial M_1
initial M_2
init. Pop. M_1
final M_1
final M_2
count
10^1
10^2
10^3
10^4
0
2
4
6
8
10
$M_\star$ ($M_\odot$)

Pop A only

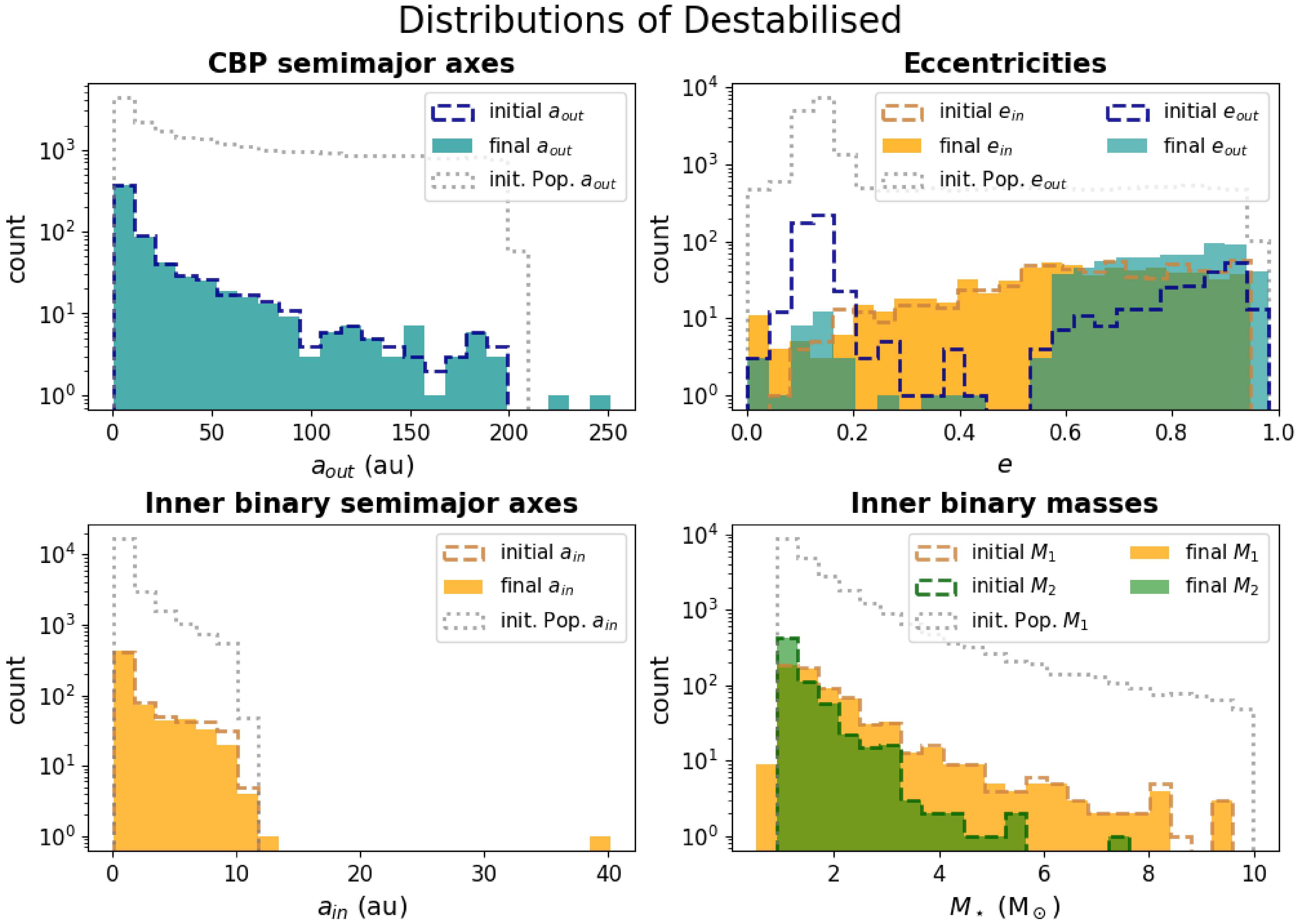
Distributions of Magratheas



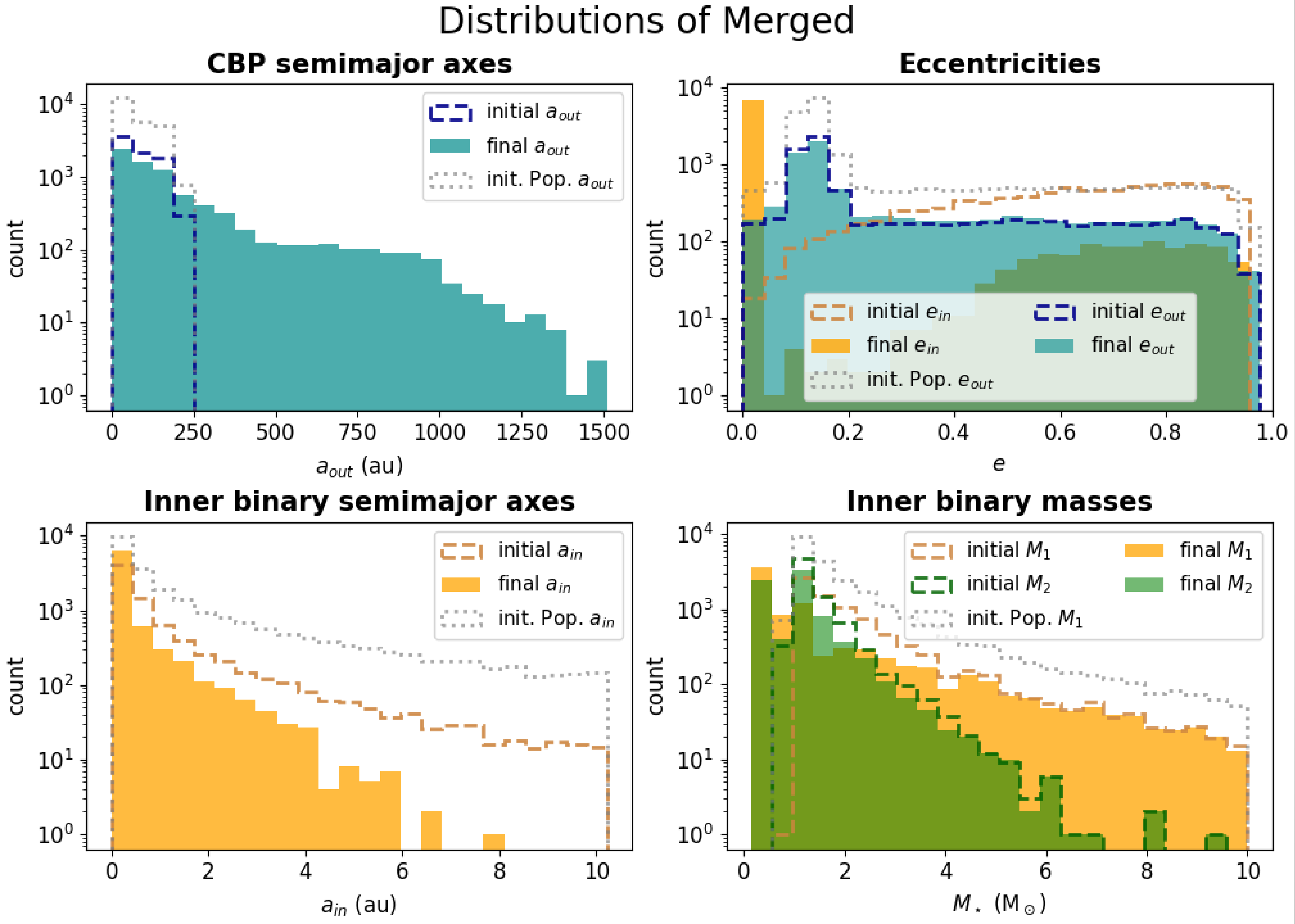
Pop B only


Distributions of Ordinary systems
CBP semimajor axes
count
10^1
10^2
10^3
0
100
200
300
400
a_{out} (au)
initial a_{out}
final a_{out}
init. Pop. a_{out}
Eccentricities
count
10^1
10^2
10^3
0.0
0.2
0.4
0.6
0.8
1.0
e
initial e_{in}
final e_{in}
init. Pop. e_{out}
initial e_{out}
final e_{out}
Inner binary semimajor axes
count
10^0
10^1
10^2
10^3
10^4
0.0
2.5
5.0
7.5
10.0
12.5
15.0
a_{in} (au)
initial a_{in}
final a_{in}
init. Pop. a_{in}
Inner binary masses
count
10^0
10^1
10^2
10^3
10^4
0
2
4
6
8
10
$M_\star$ ($M_\odot$)
initial M_1
initial M_2
init. Pop. M_1
final M_1
final M_2

Pop A + B

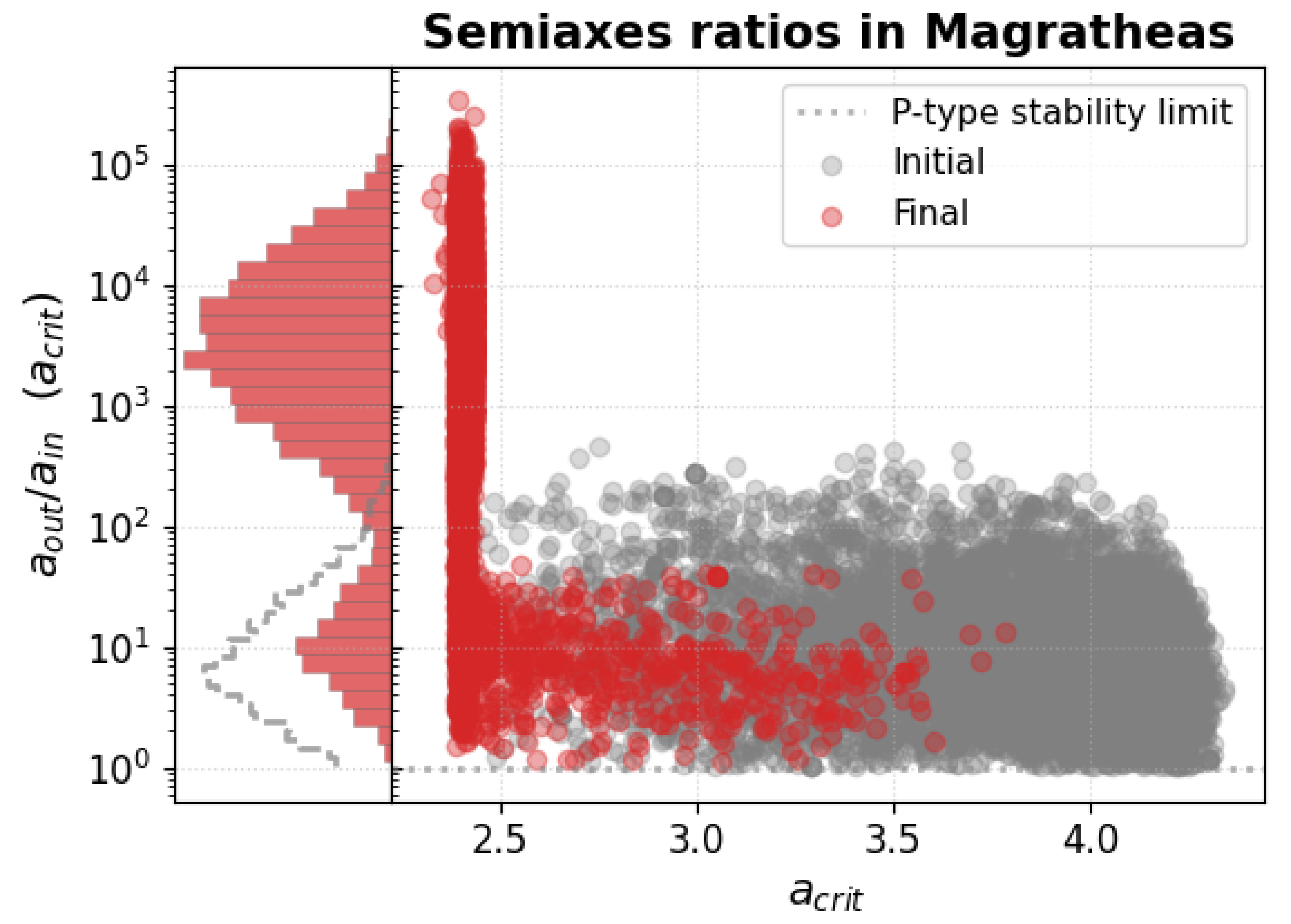

Distributions of Destabilised
CBP semimajor axes
initial a_{out}
final a_{out}
init. Pop. a_{out}
count
10^0
10^1
10^2
10^3
0
50
100
150
200
250
a_{out} (au)
Eccentricities
initial e_{in}
final e_{in}
init. Pop. e_{out}
initial e_{out}
final e_{out}
10^4
0.0
0.2
0.4
0.6
0.8
1.0
e
Inner binary semimajor axes
initial a_{in}
final a_{in}
init. Pop. a_{in}
0
10
20
30
40
a_{in} (au)
Inner binary masses
initial M_1
initial M_2
init. Pop. M_1
final M_1
final M_2
2
4
6
8
10
$M_\star$ ($M_\odot$)

Pop A + B

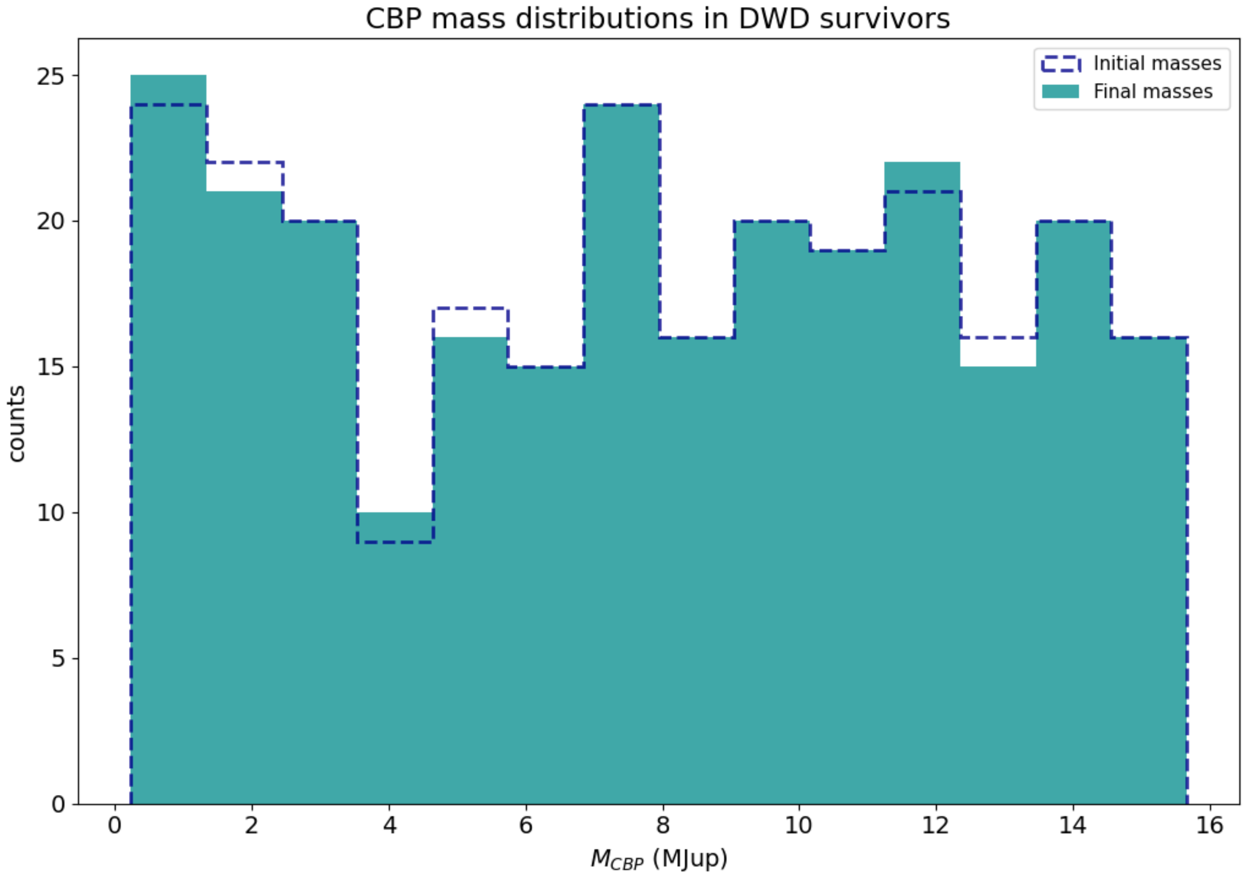

Distributions of Merged
CBP semimajor axes
count
10^0
10^1
10^2
10^3
10^4
0
250
500
750
1000
1250
1500
a_{out} (au)
initial a_{out}
final a_{out}
init. Pop. a_{out}
Eccentricities
count
0.0
0.2
0.4
0.6
0.8
1.0
e
initial e_{in}
final e_{in}
init. Pop. e_{out}
initial e_{out}
final e_{out}
Inner binary semimajor axes
count
0
2
4
6
8
10
a_{in} (au)
initial a_{in}
final a_{in}
init. Pop. a_{in}
Inner binary masses
count
0
2
4
6
8
10
$M_\star$ ($M_\odot$)
initial M_1
initial M_2
init. Pop. M_1
final M_1
final M_2

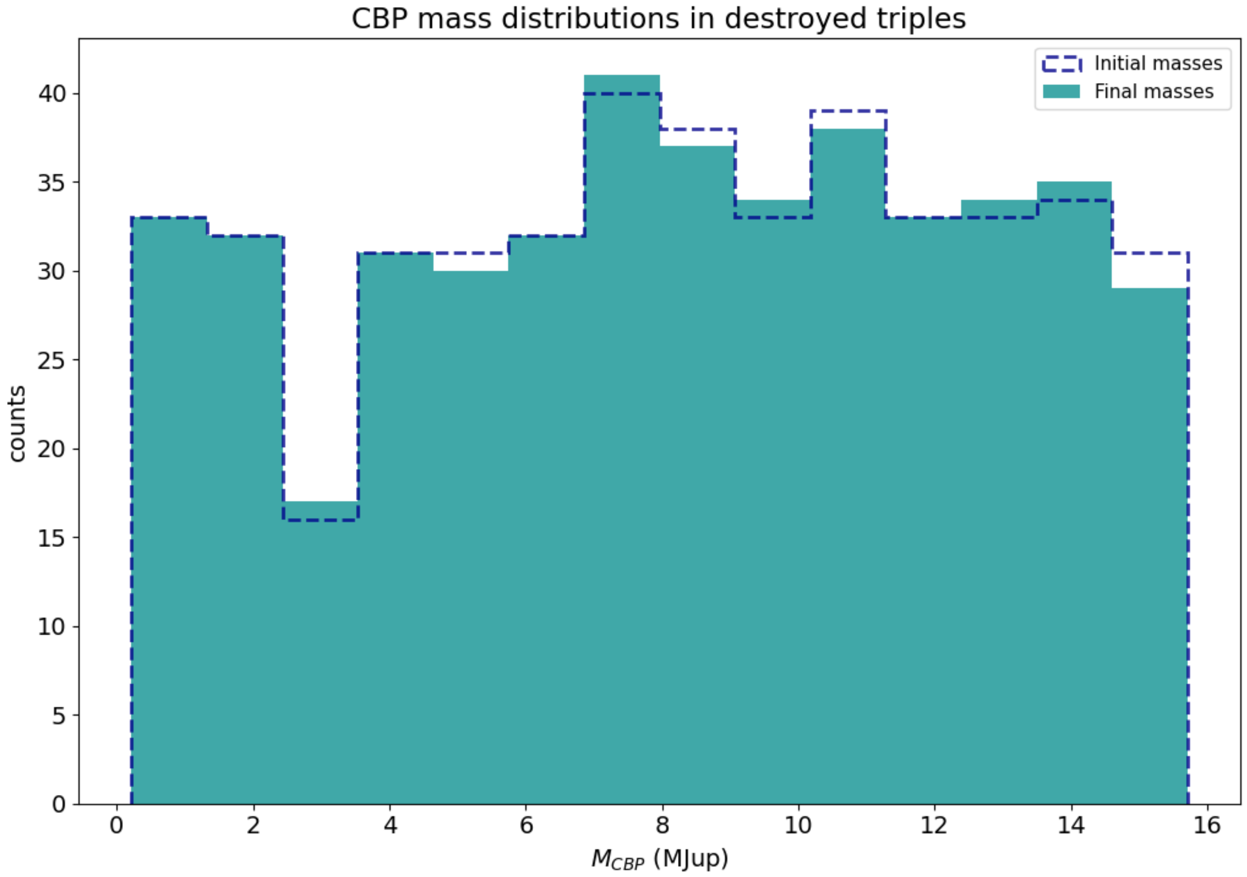
Pop A + B

CRITICAL SEMIMAJOR AXES



CBP MASSES


CBP mass distributions in DWD survivors
Initial masses
Final masses
counts
0
5
10
15
20
25
0
2
4
6
8
10
12
14
16
M_{CBP} (MJup)


CBP mass distributions in destroyed triples
Initial masses
Final masses
counts
0
5
10
15
20
25
30
35
40
0
2
4
6
8
10
12
14
16
M_{CBP} (MJup)