The Effects of Binary Companions on Planet Formation and Evolution

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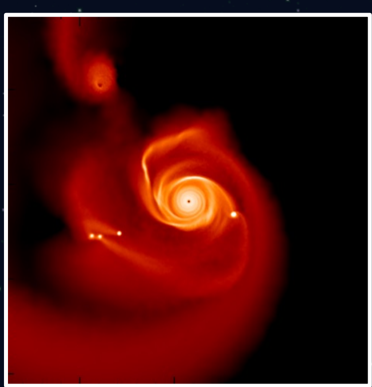
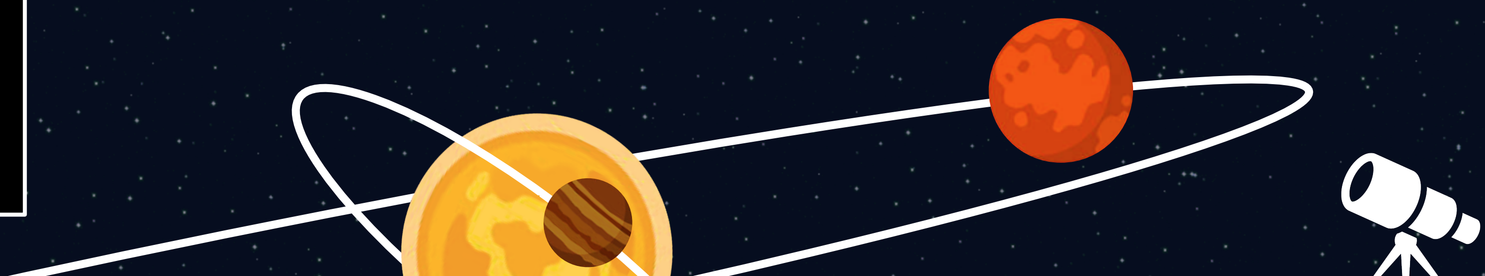
January 17, 2023





Stars, Brown Dwarfs and (Exo)planets

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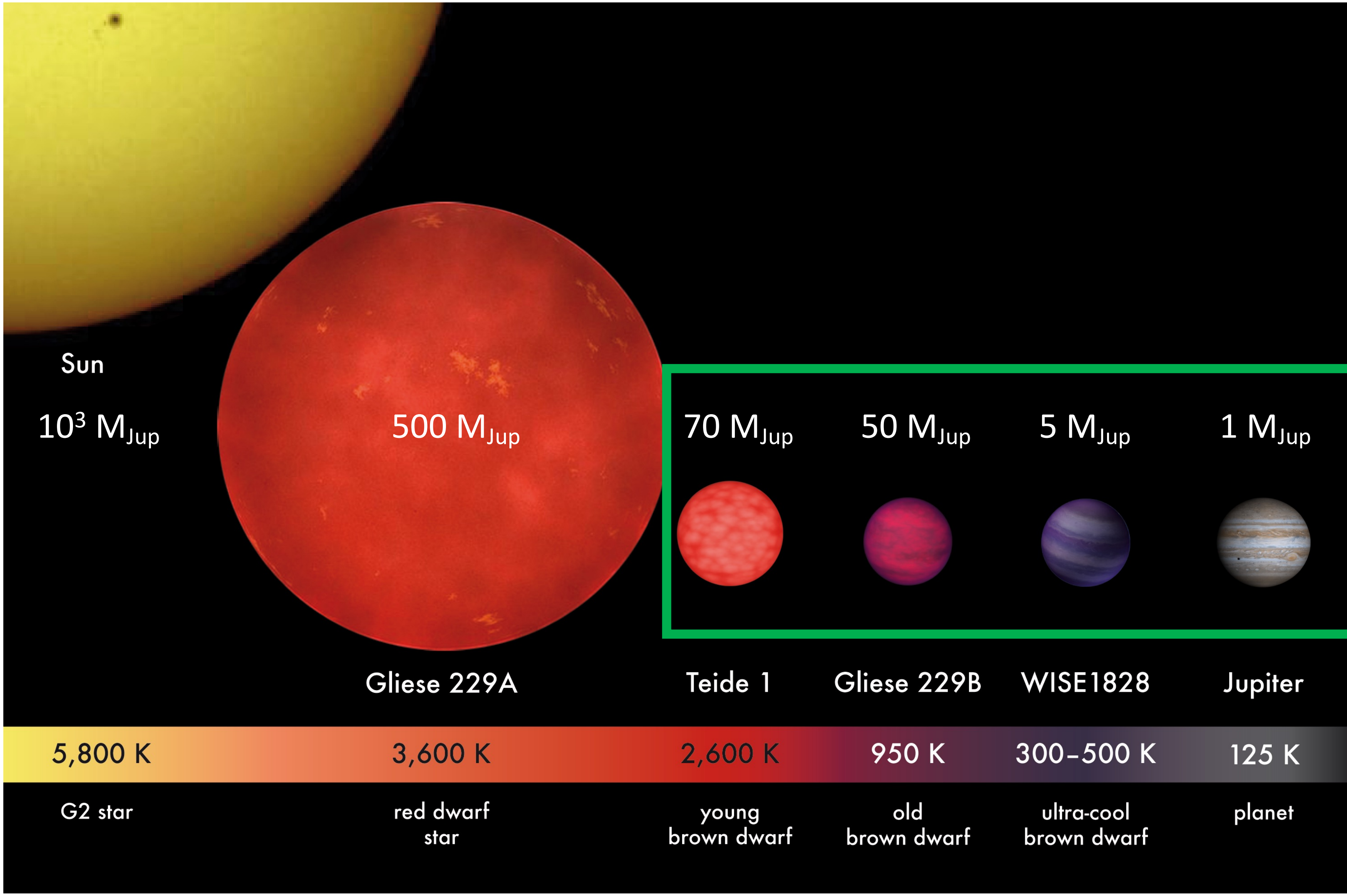

S-type Planets in Binaries

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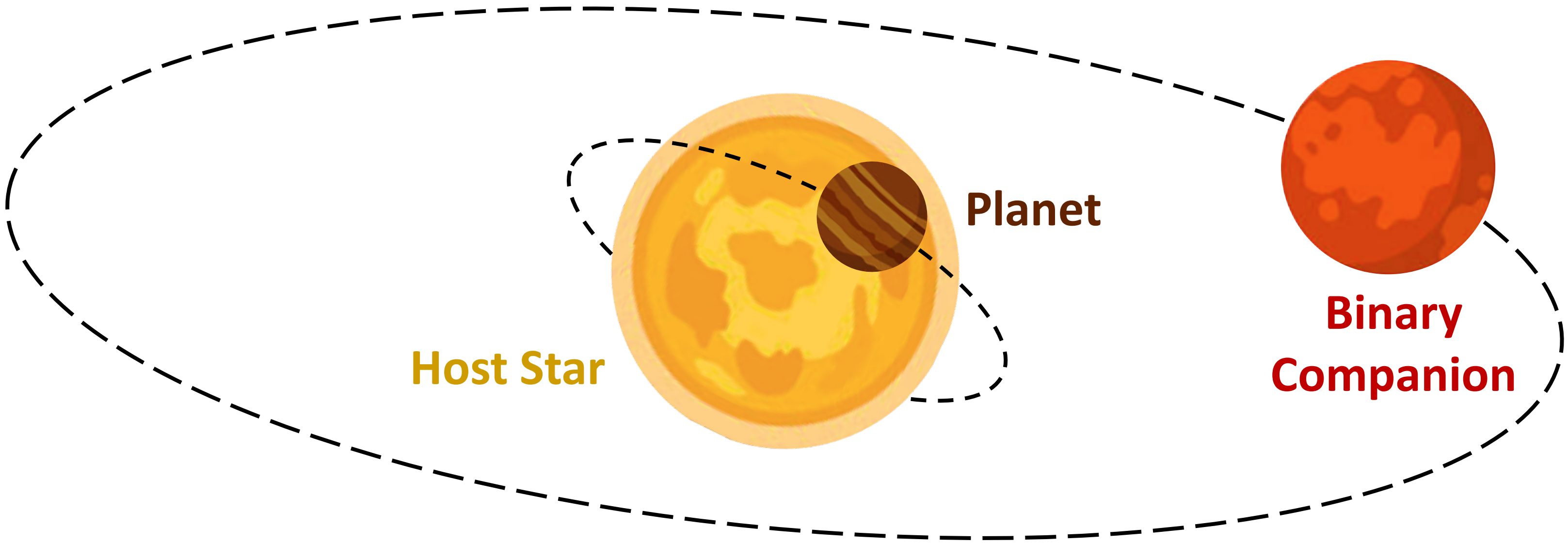

S-type = Orbiting one component from a multiple stellar system (circumstellar)

$\neq$

P-type = Orbiting two stars in a binary system (circumbinary)

Planets in Binaries: a Neglected Family

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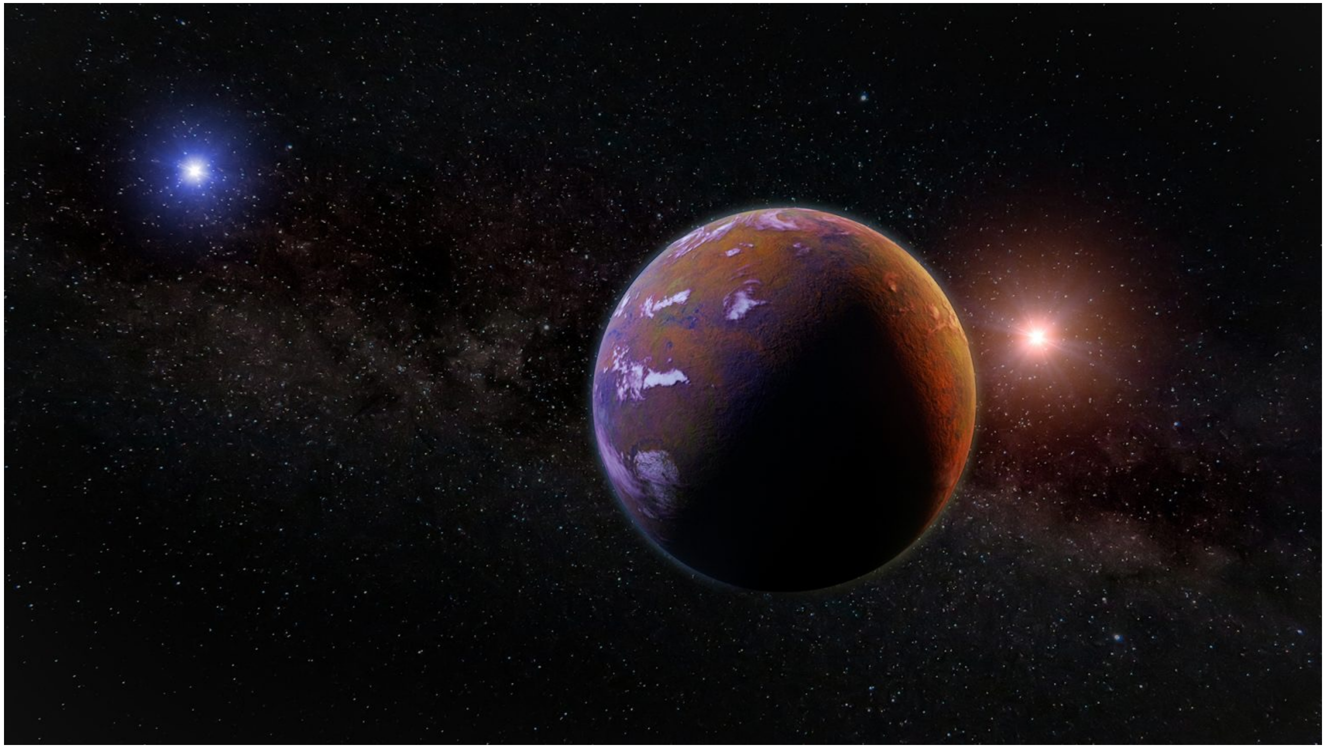
About 50% of Sun-like stars in binaries or higher-order multiples!

(Duquennoy & Mayor 1991, Raghavan+2010)



Binaries mostly ignored in exoplanet science until now…

Planets in Binaries: a Neglected Family

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Historically many biases against binaries in planet searches:

- known binaries excluded from surveys
- only searched for to validate planet nature
- wide companions and null detections not reported

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Mostly ignored in planet formation theories

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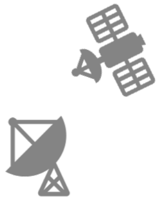


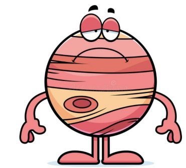
Mostly ignored in planet formation theories

Large disagreements between existing statistical studies:

- how to account for these biases?
- bound vs. optical companion?

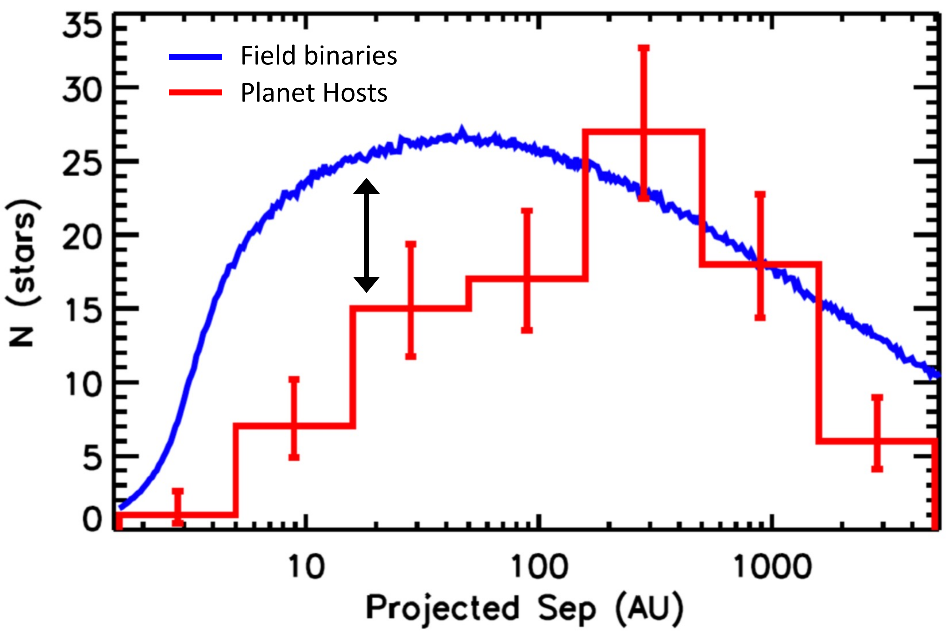
Effects of Binaries on Planet Formation

Some results:



– close binarity (<50–100 AU) inhibits planet formation (e.g. Pichardo+2005, Jang-Condell+2008, Kraus+2012,2016, Bergfors+2013, Wang+2014, Bonavita&Desidera2020)

Kraus+2016



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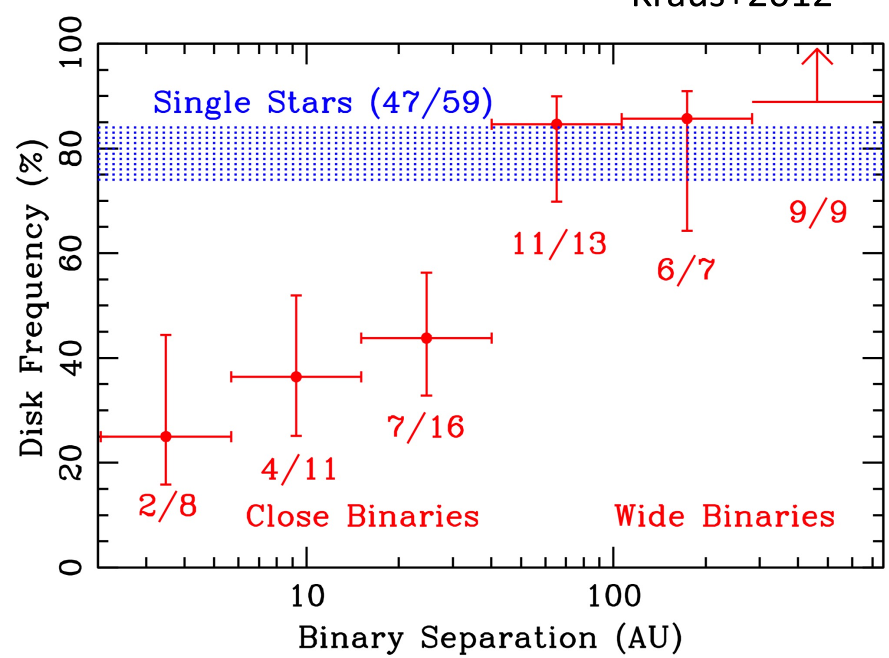

Effects of Binaries on Planet Formation

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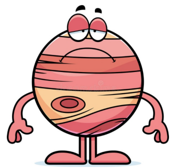

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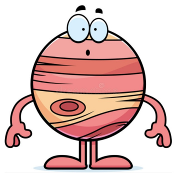
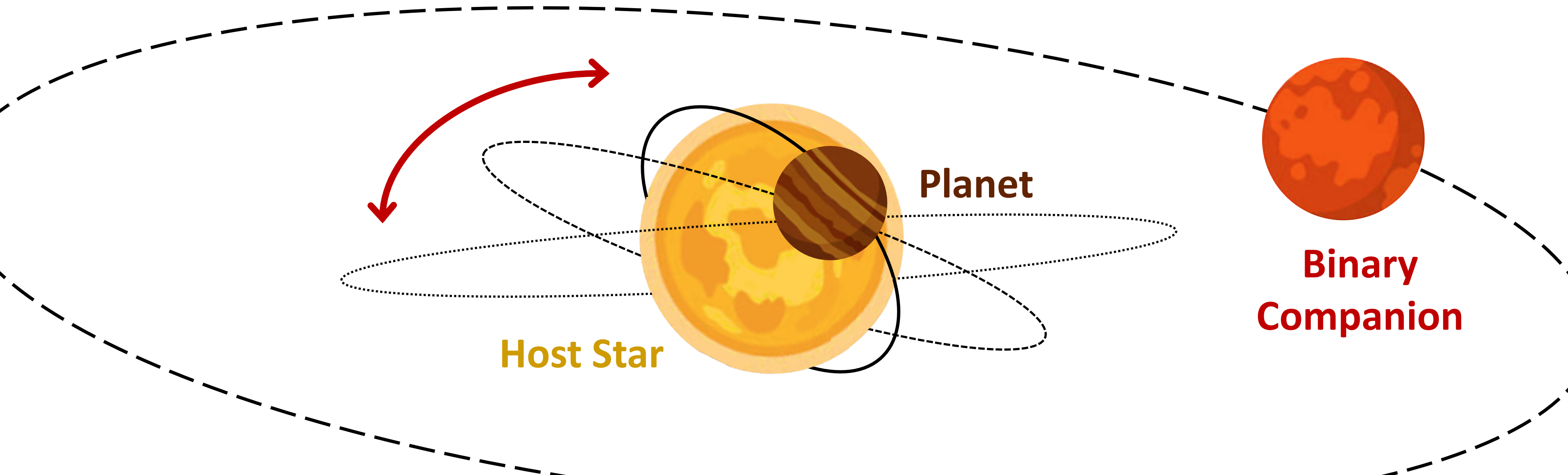


– wide binary systems (> 100 AU) may facilitate planet migration (e.g. Dong+2015, Fabrycky&Tremaine2007, Naoz+2012)



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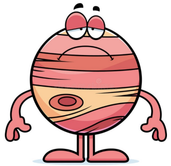

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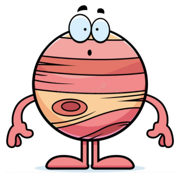

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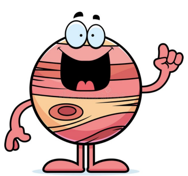

- excess of hot Jupiters in binaries and different planet demographics (Zucker&Mazeh2002, Eggenberger+2004, Desidera&Barbieri2007, Mugrauer+2007, Ngo+2016)

Outer Companions to HJs and BDs

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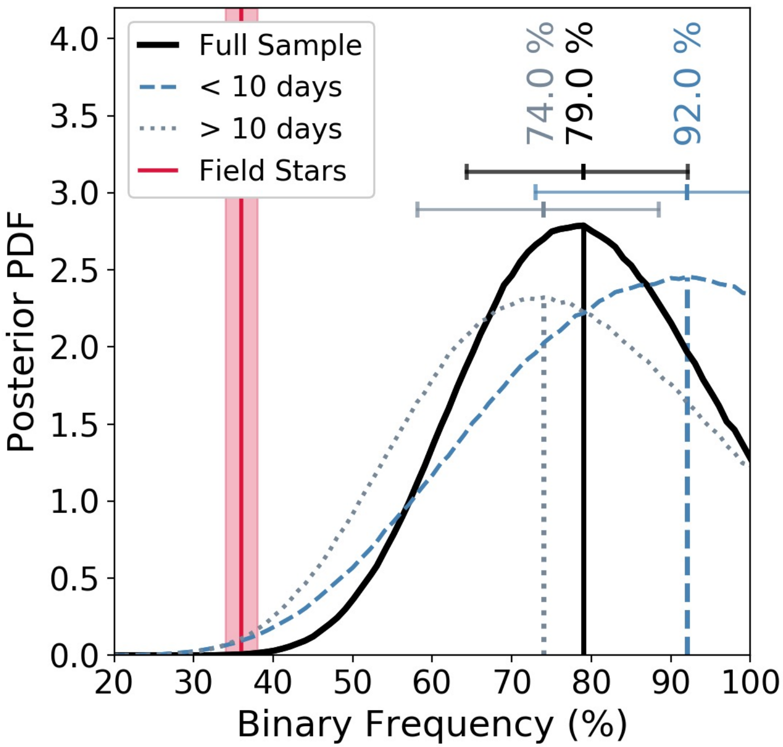
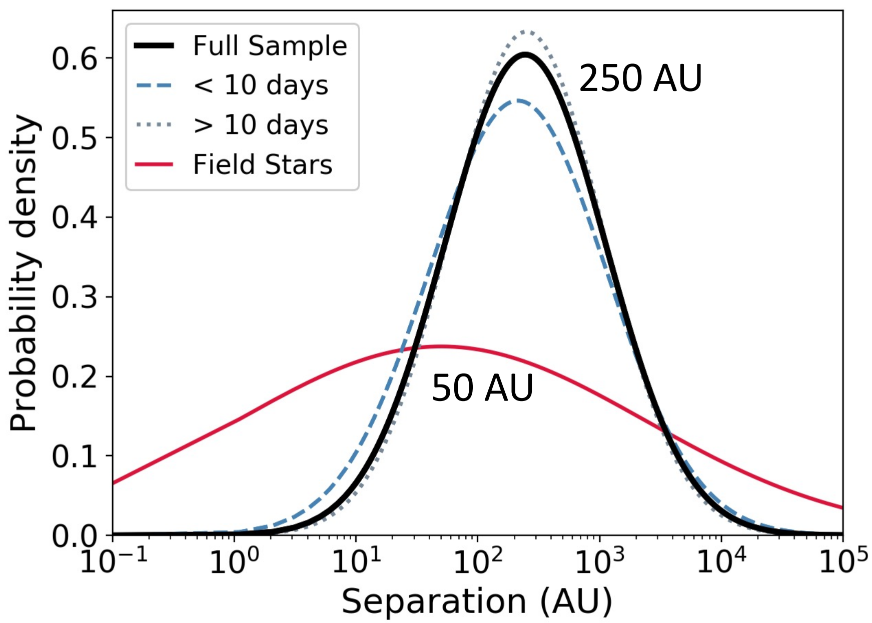
$> 7\ M_{Jup}$ & < 1 AU





Fontanive+2019

80% of stars hosting close-in giant planets and brown dwarfs have a wide stellar companion between 20–10,000 au, twice as field stars.

Compilation of Planets in Binaries

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Fontanive & Bardalez Gagliuffi 2021

Gathered Sample:

- 1326 exoplanets & brown dwarfs
- 938 host stars, from M dwarfs to A stars
- within 200 pc

Binary Companions:

- searched for visual comoving companions in Gaia + literature
- 218 hosts in multiple systems (186 binaries, 32 triples)
- ranging from 0.07–2.17 $M_{\odot}$ and < 1 to 20,000 AU

Raw Occurrence Rates

Planetary population	Total	Single-star systems		Multiple-star systems	
All Planets	1316	1030	$(78.3 \pm 2.4\,\%)$	286	$(21.7 \pm 1.3\,\%)$
All Planetary Systems	938	720	$(76.8 \pm 2.9\,\%)$	218	$(23.2 \pm 1.6\,\%)$
Single-Planet Systems	693	519	$(74.9 \pm 3.3\,\%)$	174	$(25.1 \pm 1.9\,\%)$
Multi-Planet Systems	245	201	$(82.0 \pm 5.8\,\%)$	44	$(18.0 \pm 2.7\,\%)$
$M_{pl} < 0.1\ M_{Jup}$	554	462	$(83.4 \pm 3.9\,\%)$	92	$(16.6 \pm 1.7\,\%)$
$M_{pl} = 0.1 - 7\ M_{Jup}$	597	444	$(74.4 \pm 3.5\,\%)$	153	$(25.6 \pm 2.1\,\%)$
$M_{pl} > 7\ M_{Jup}$	165	124	$(75.2 \pm 6.7\,\%)$	41	$(24.8 \pm 3.9\,\%)$
$a_{pl} < 0.5$ AU	766	603	$(78.7 \pm 3.2\,\%)$	163	$(21.3 \pm 1.7\,\%)$
$a_{pl} = 0.5 - 10$ AU	476	365	$(76.7 \pm 4.0\,\%)$	111	$(23.3 \pm 2.2\,\%)$
$a_{pl} > 10$ AU	74	62	$(83.8 \pm 10.6\,\%)$	12	$(16.2 \pm 4.7\,\%)$
$M_{pl} \geq 0.1\ M_{Jup}$, $a_{pl} \leq 10$ AU	688	506	$(73.5 \pm 3.3\,\%)$	182	$(26.5 \pm 2.0\,\%)$
$M_{pl} \geq 0.1\ M_{Jup}$, $a_{pl} \leq 0.5$ AU	236	164	$(69.5 \pm 5.4\,\%)$	72	$(30.5 \pm 3.6\,\%)$
$M_{pl} \geq 7\ M_{Jup}$, $a_{pl} \leq 10$ AU	106	73	$(68.9 \pm 8.1\,\%)$	33	$(31.1 \pm 5.4\,\%)$
$M_{pl} \geq 7\ M_{Jup}$, $a_{pl} \leq 0.5$ AU	28	19	$(66.9 \pm 15.6\,\%)$	9	$(32.1 \pm 10.7\,\%)$

2.2 σ

3.6 σ

Compilation from Fontanive & Bardalez Gagliuffi 2021

Planet Properties vs. Stellar Multiplicity

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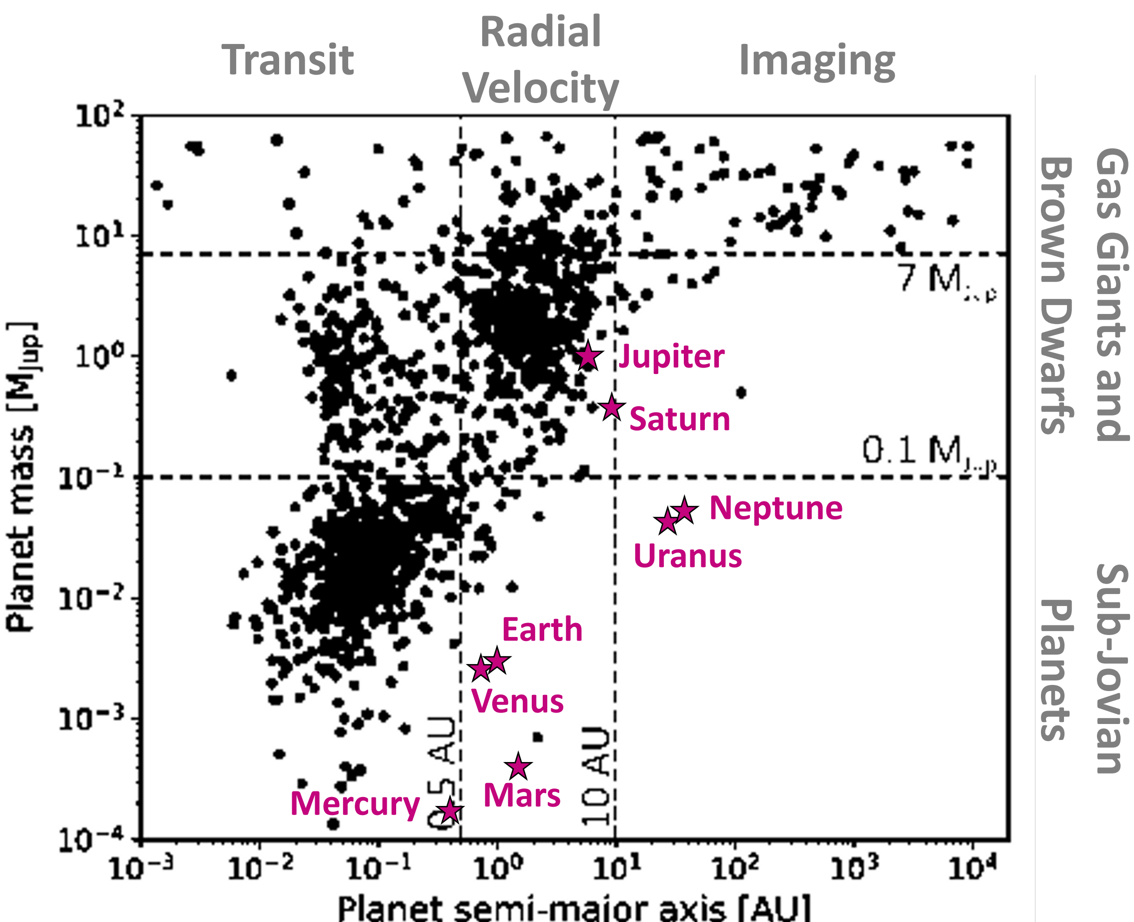

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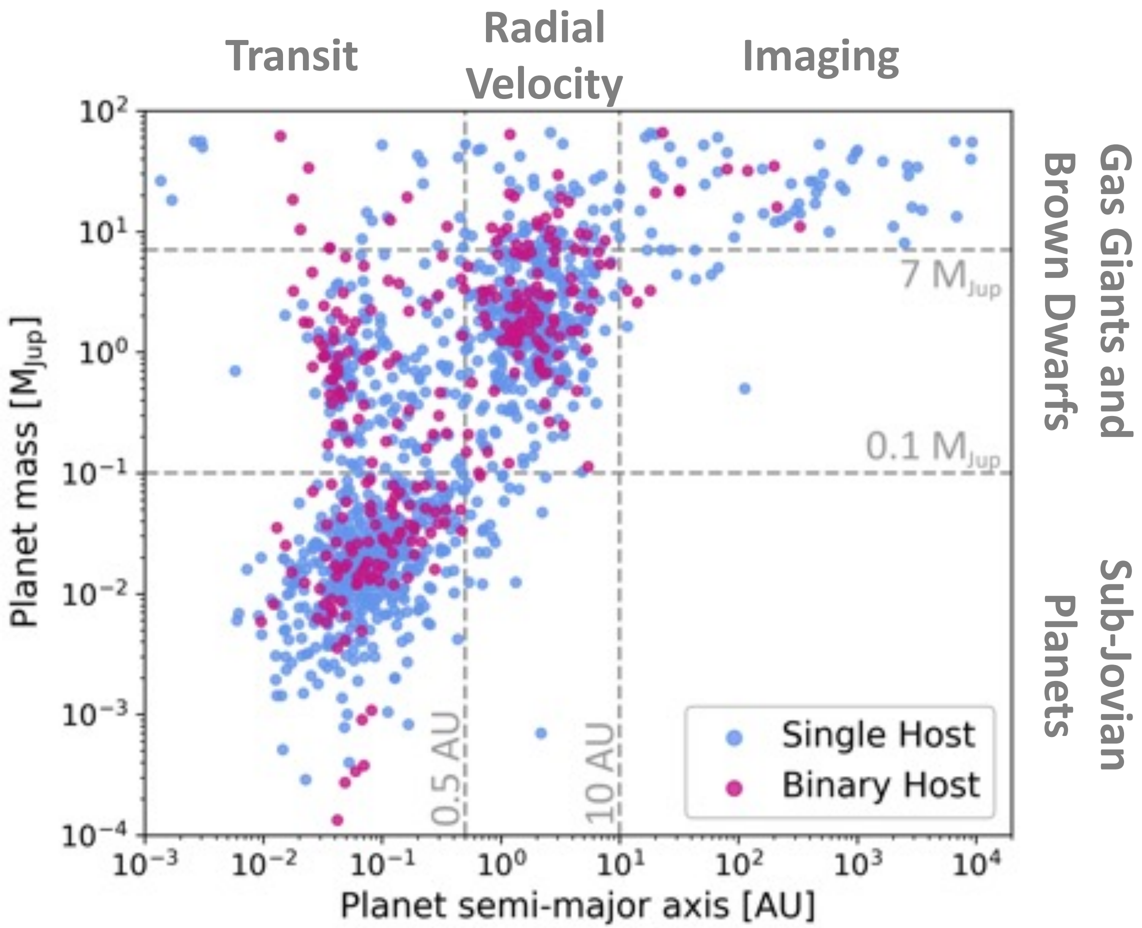

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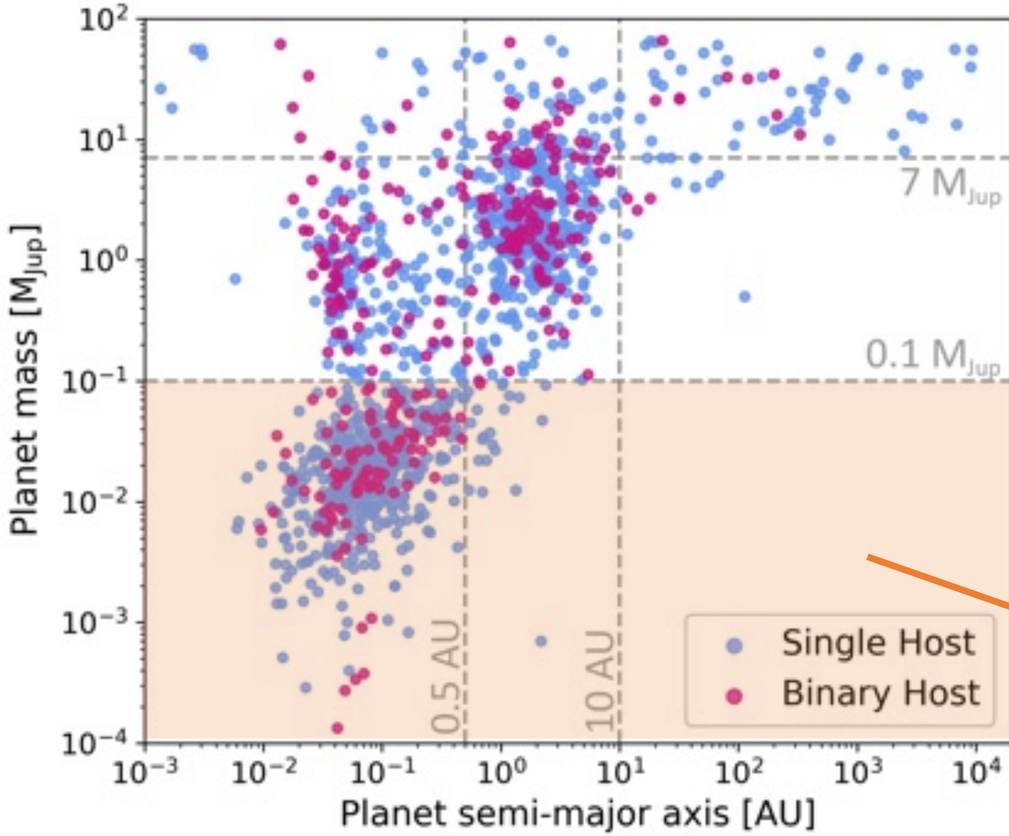
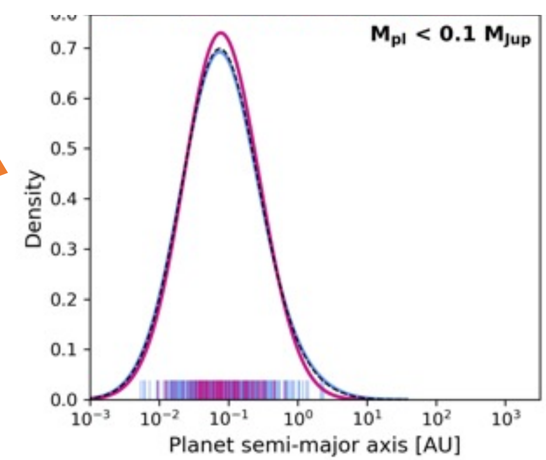
Mass slices:
Semi-major axis distributions





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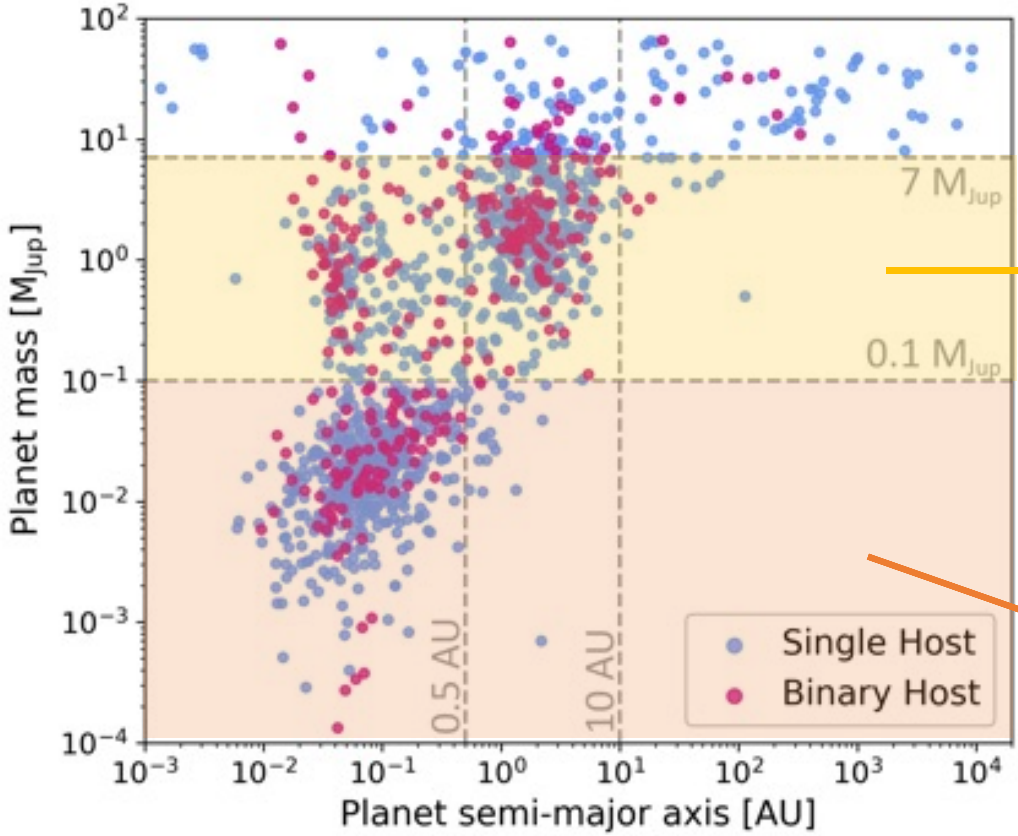

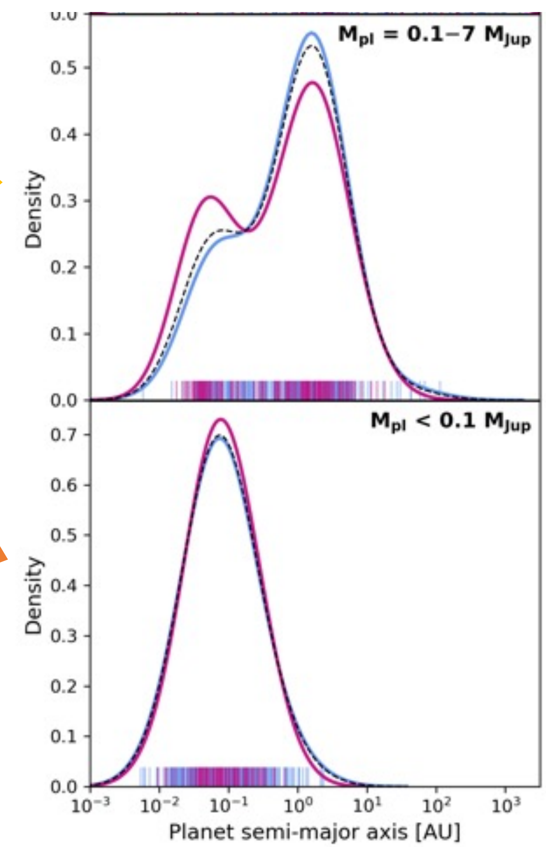

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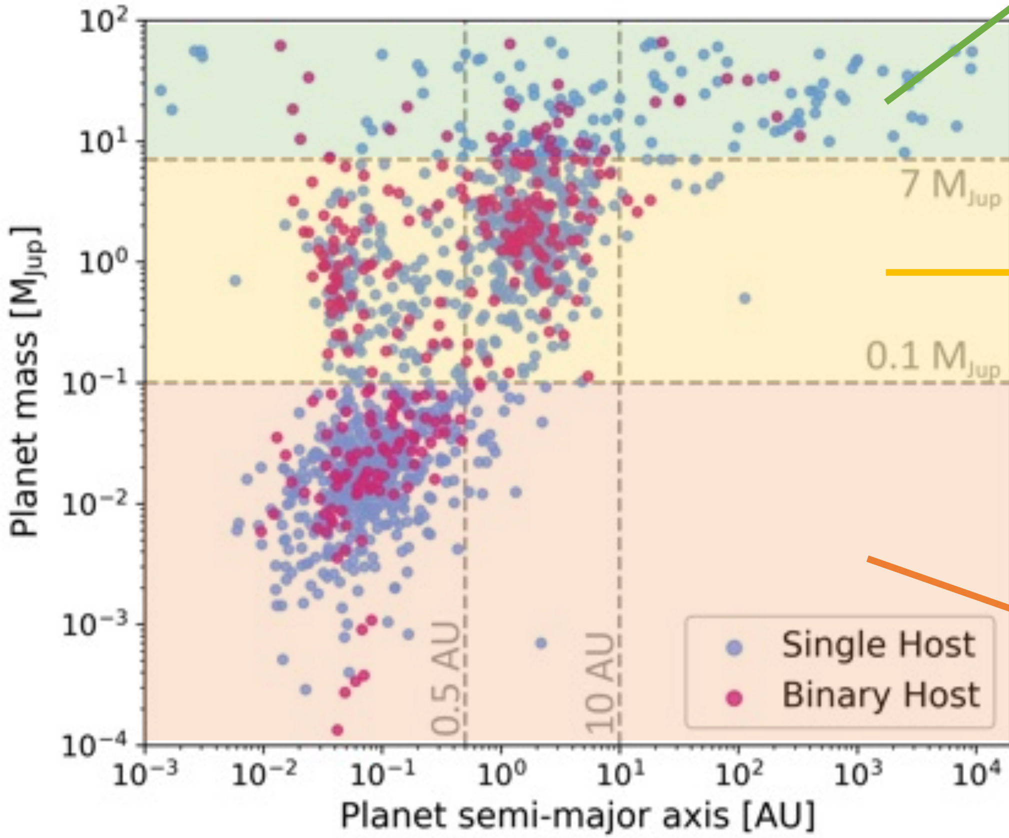

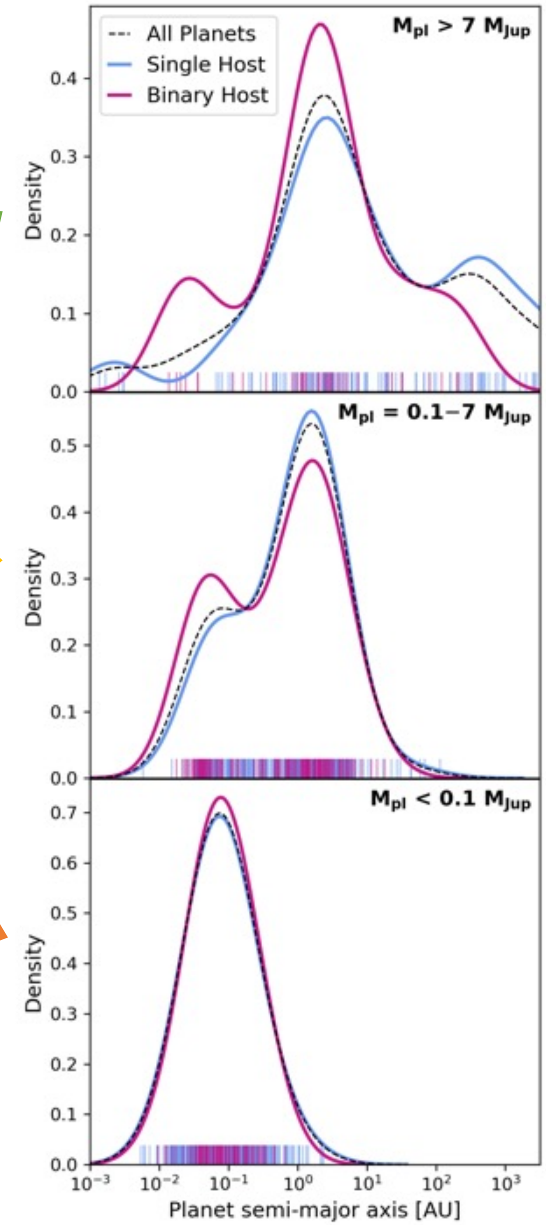

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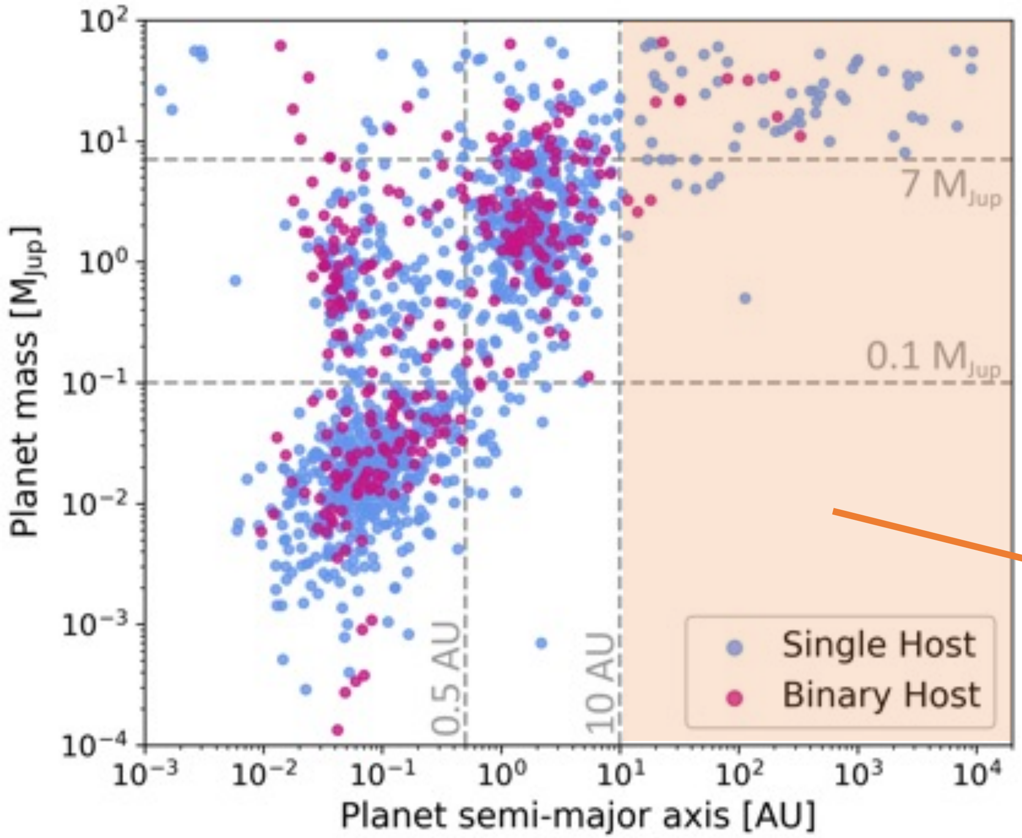

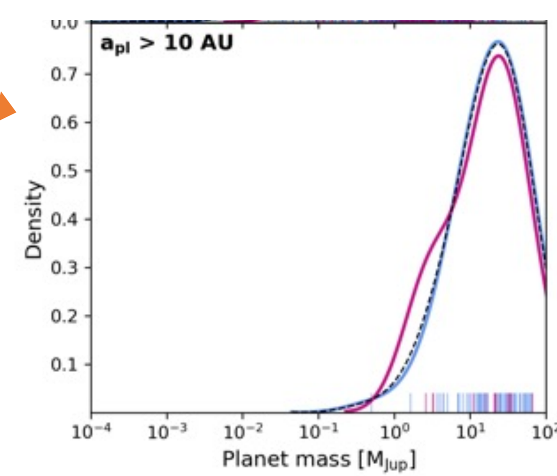

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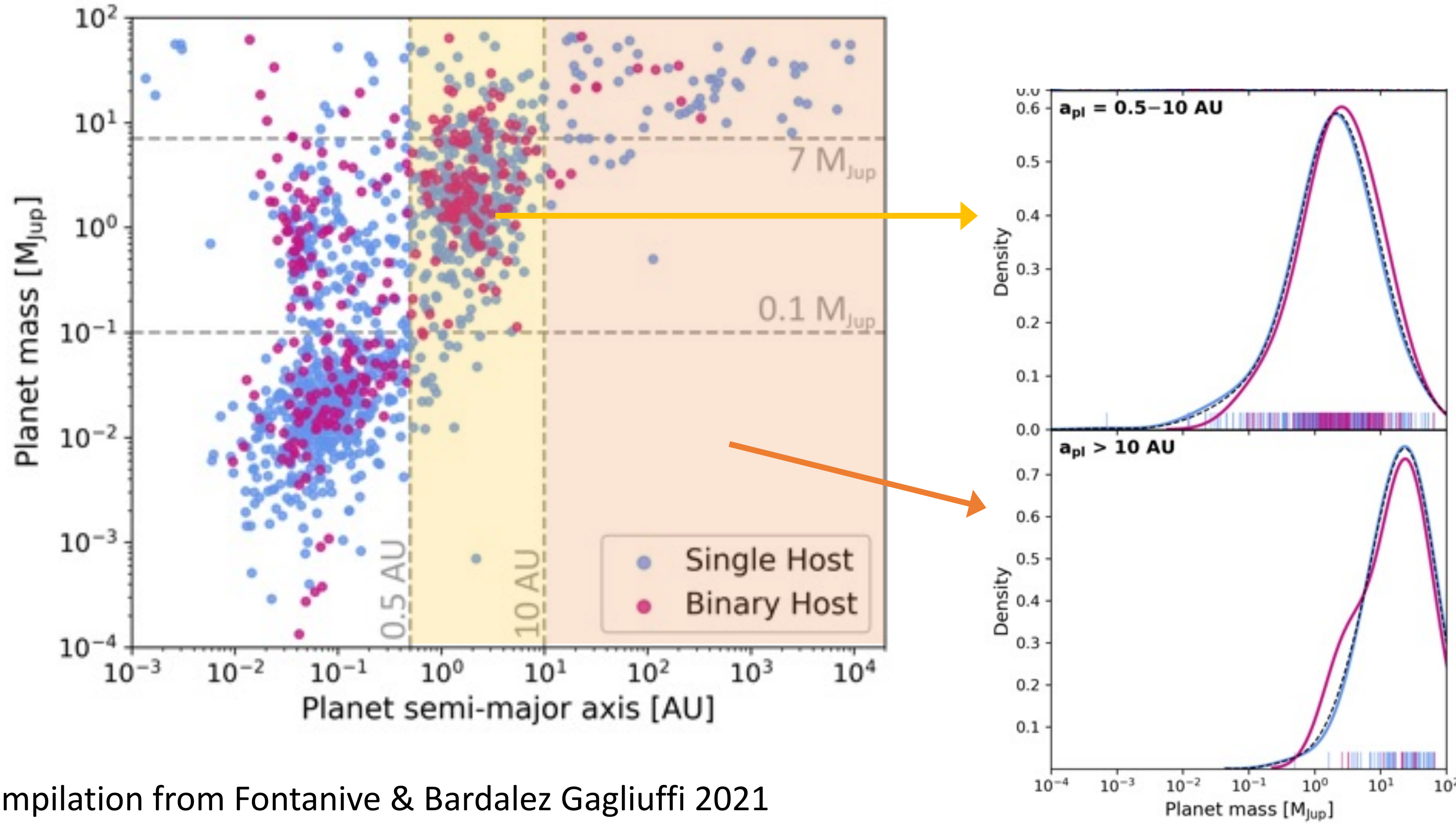

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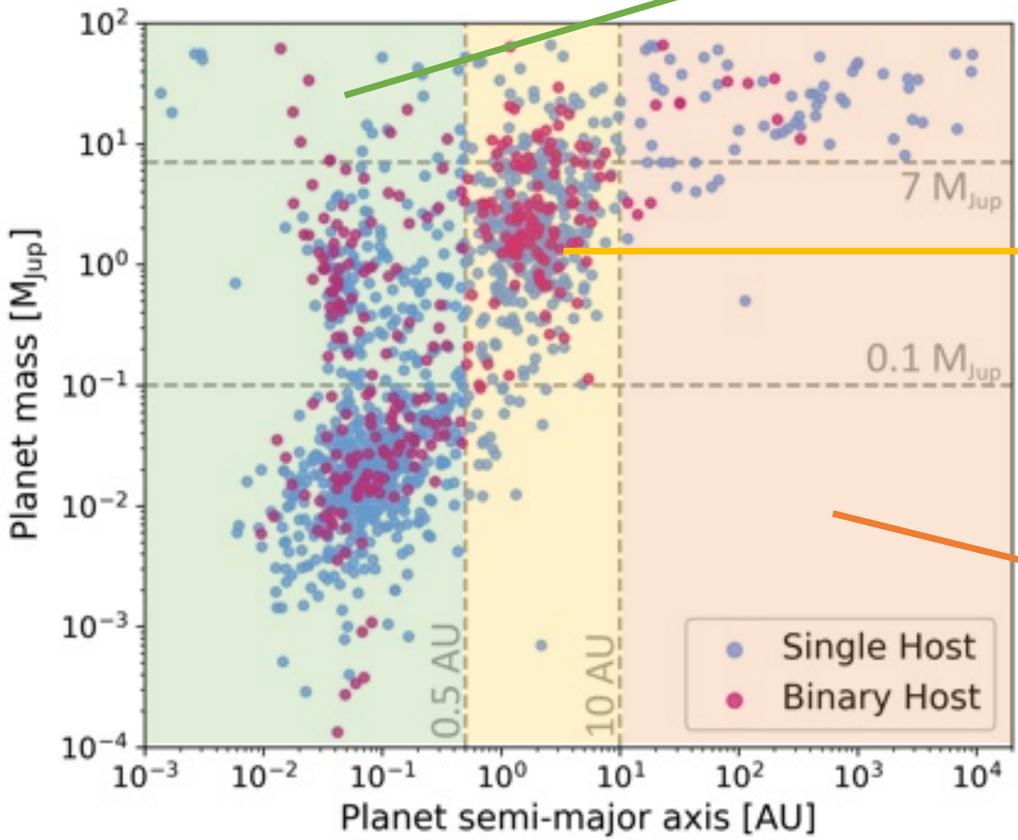

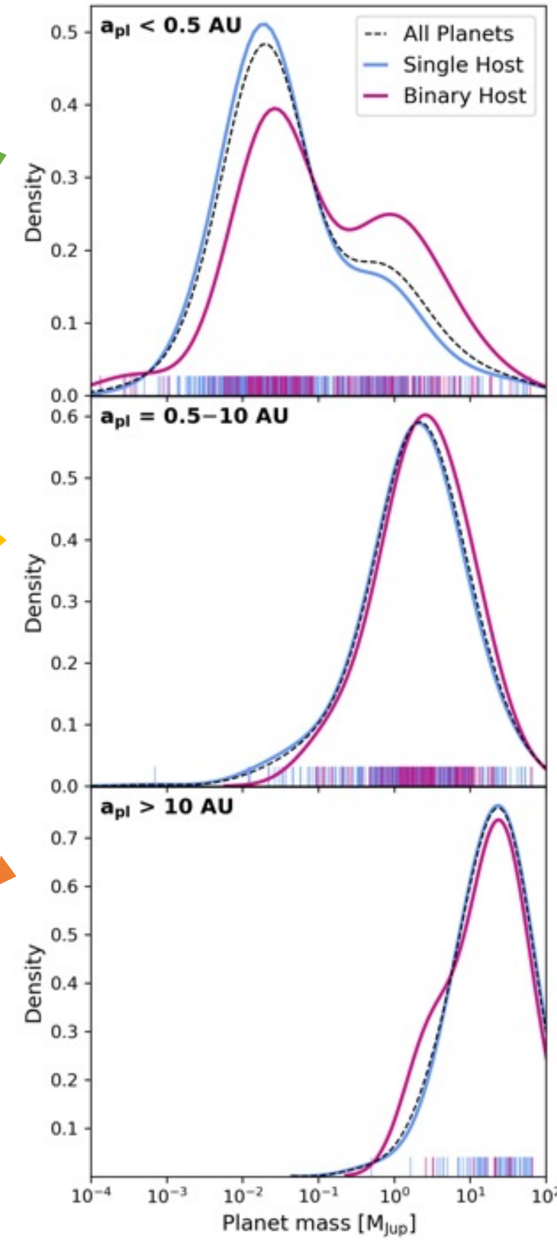

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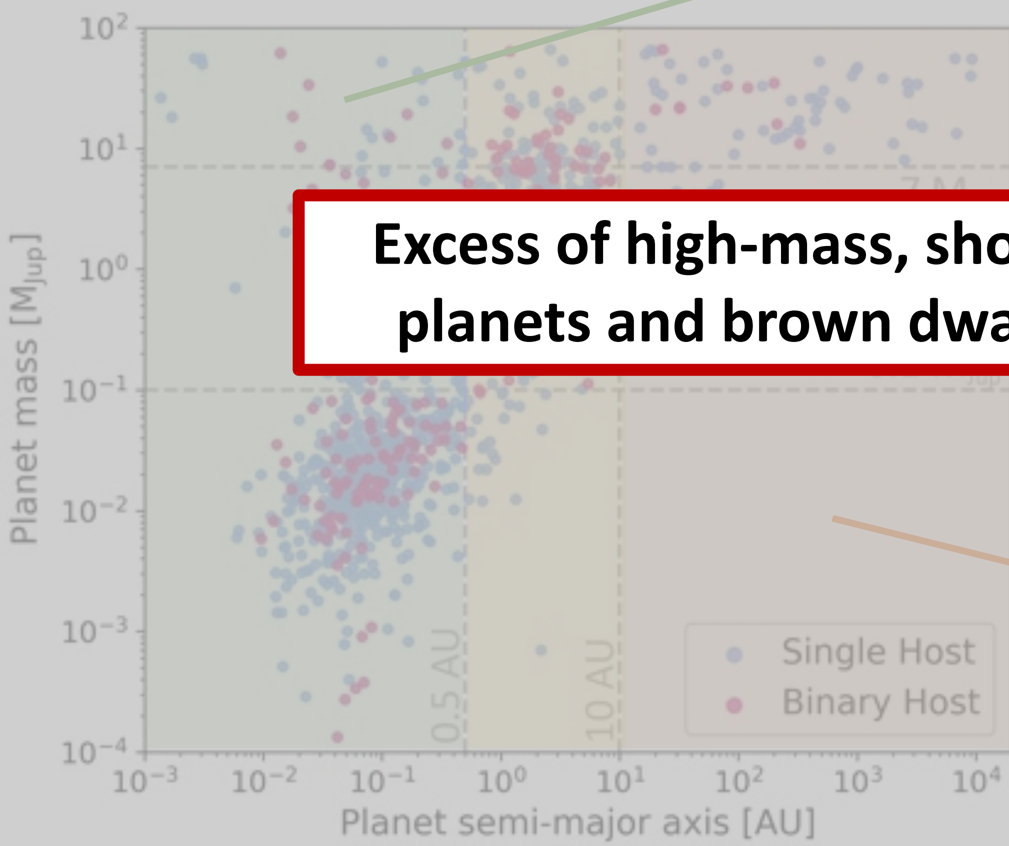
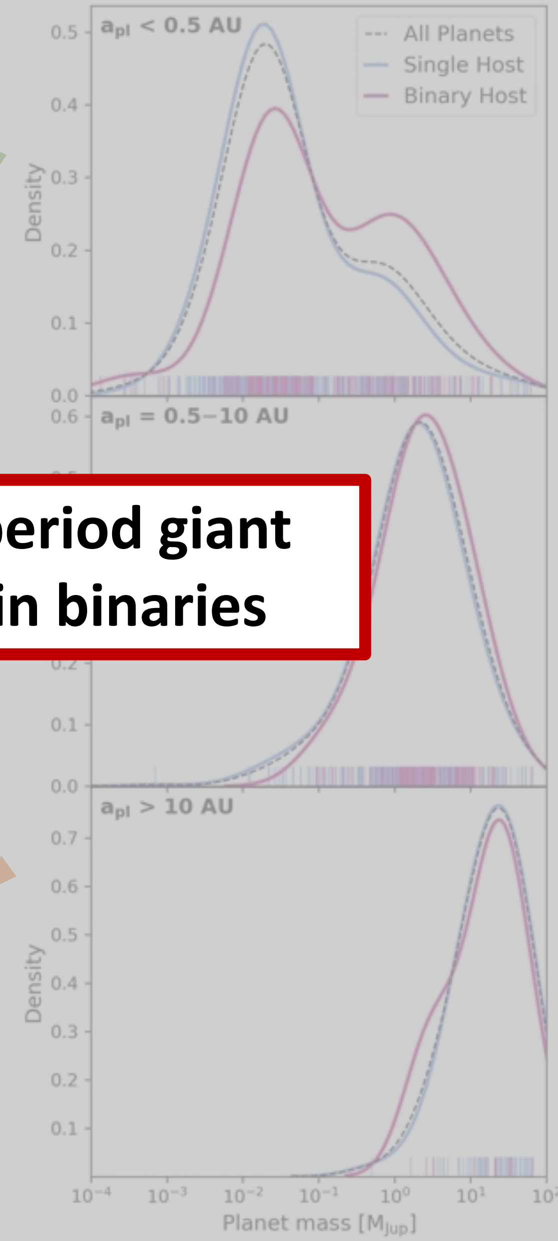


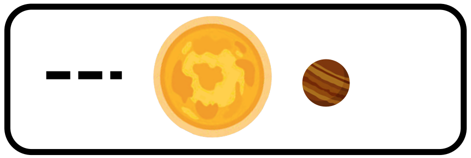


Excess of high-mass, short-period giant planets and brown dwarfs in binaries

Compilation from Fontanive & Bardalez Gagliuffi 2021

Effect of Binary Separation

Planets orbiting single stars:



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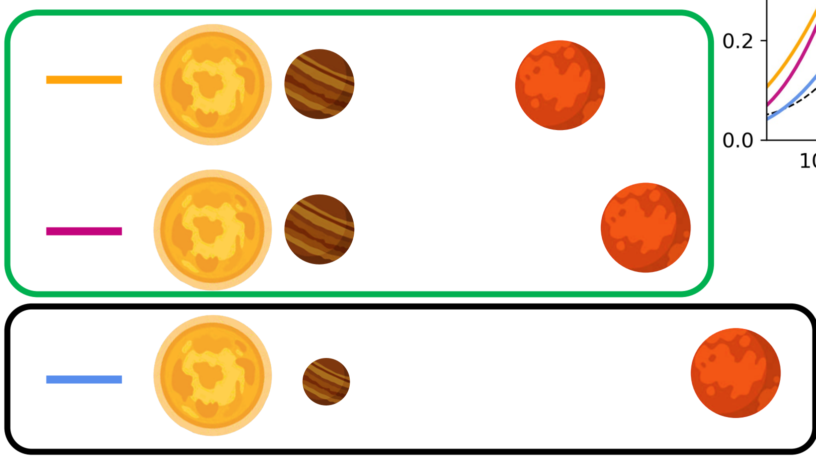

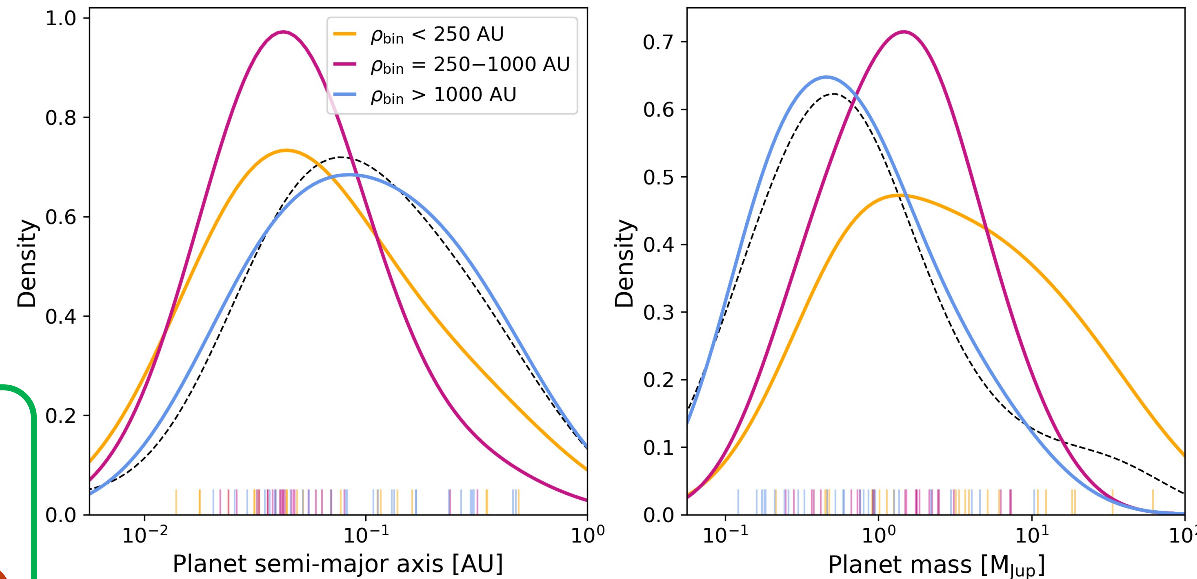

Fontanive & Bardalez Gagliuffi 2021

$M_{pl} > 0.1\ M_{Jup}$ & $a_{pl} < 0.5$ AU

—> Exoplanets in very wide binaries have the same properties as those around single stars

—> Giant planets in binaries on few hundred AU separations have larger masses and tighter orbital periods

Main Observational Results

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Binaries on few 100 AU separations play a role in the existence of high-mass short-period giant planets and brown dwarfs

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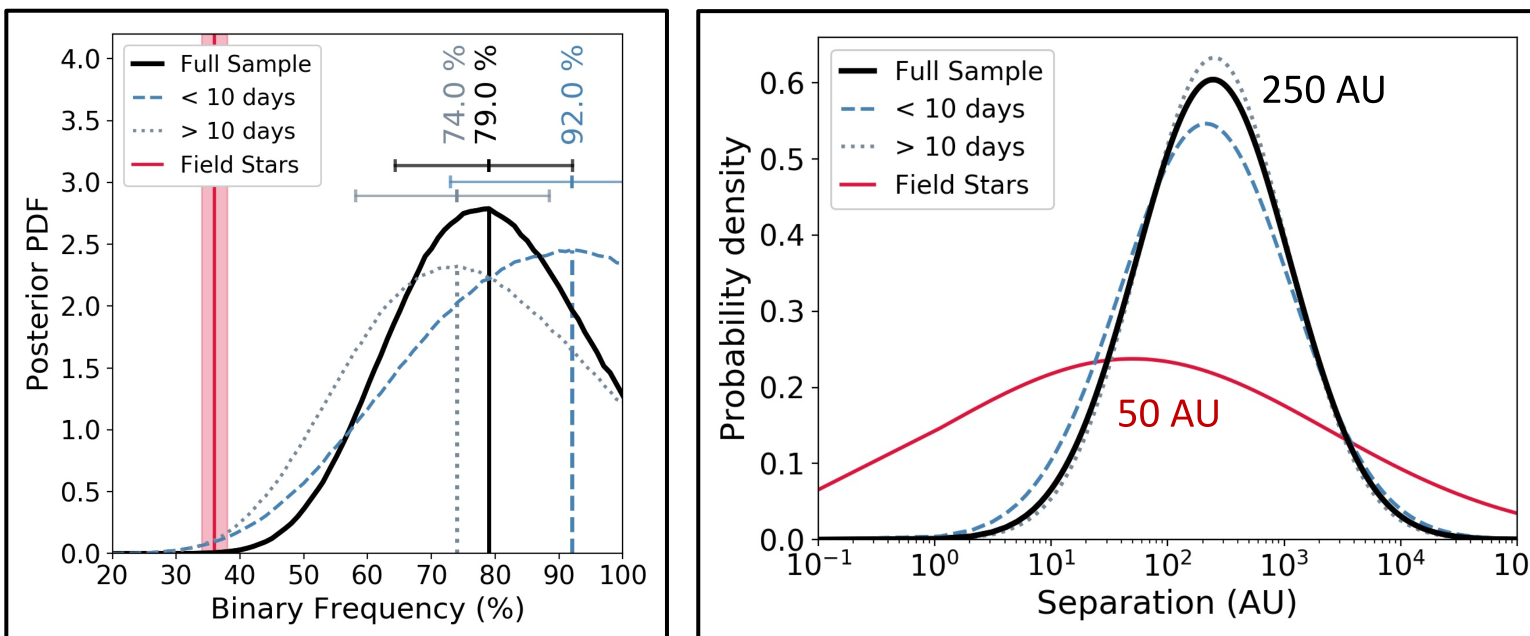
– <u>BINARY FRACTION</u>: 80% of stars hosting close-in giant planets and brown dwarfs > 7 M_{Jup} and < 1 AU have a wide stellar companion (Fontanive+2019)



Fontanive+2019

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- PLANET PERIOD: enhanced frequency of giant planets < 1 AU relative to wider planets in binaries > 100 AU, compared to planets in single stars (Hirsch+2021)

Main Observational Results

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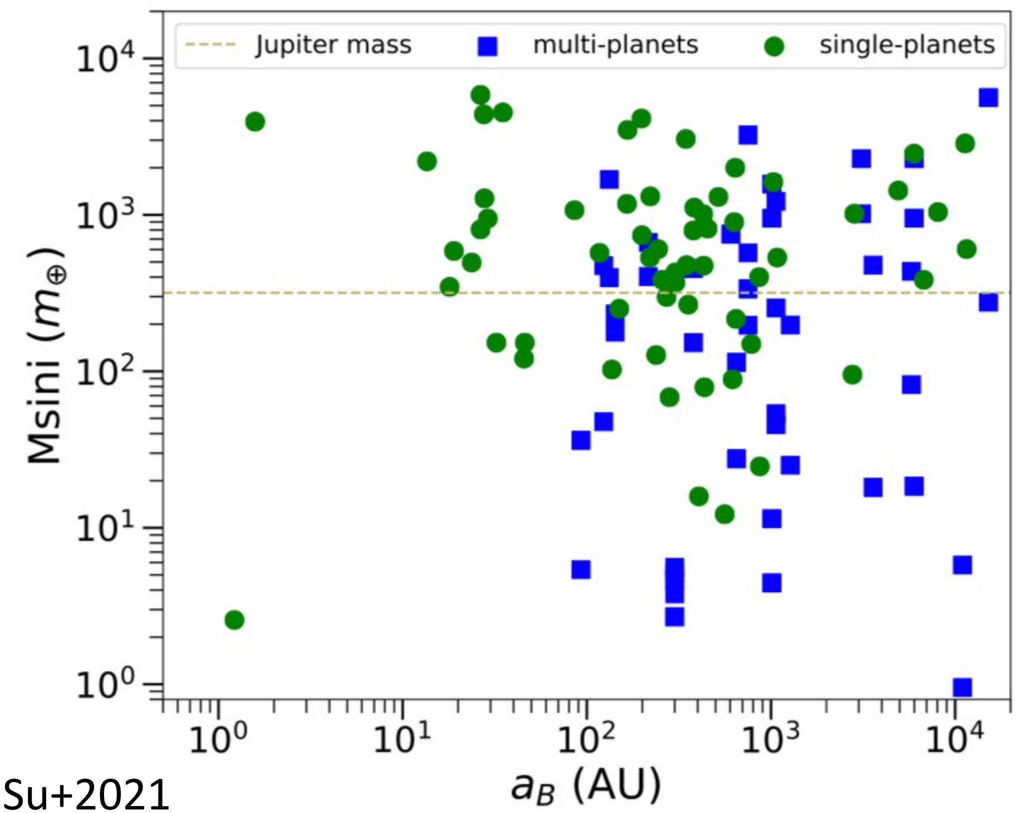
Binaries on ... e existence of high-m ... n dwarfs



Su+2021

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- PLANET MASS ... $_{Jup}$) and brown dwarfs ... i 2021)
- PLANET PERIO ... elative to wider planets for bi ... rs (Hirsch+2021)
- BINARY SEPARATIONS: tighter binaries predominantly host massive planets or brown dwarfs in single-planet systems (Su+2021)

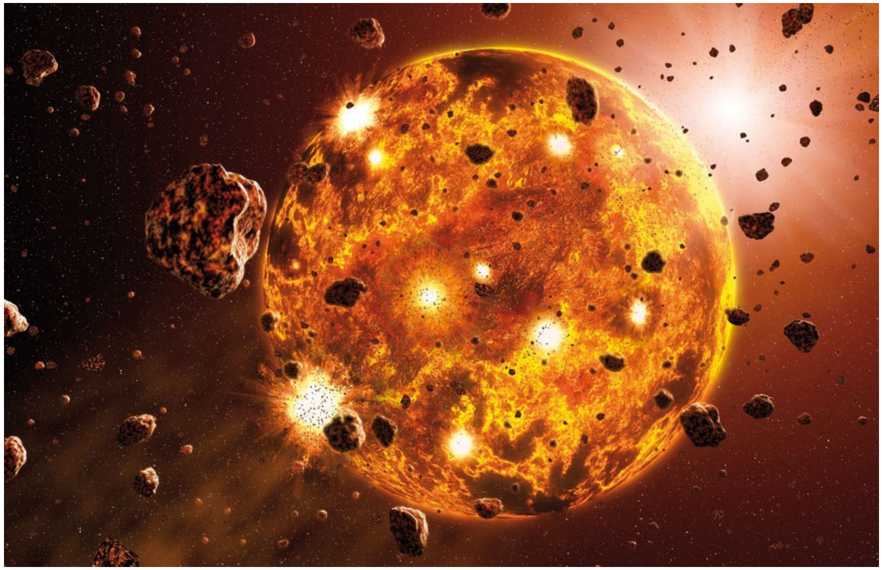
Planet Formation Channels

<u>Core Accretion</u> (CA)

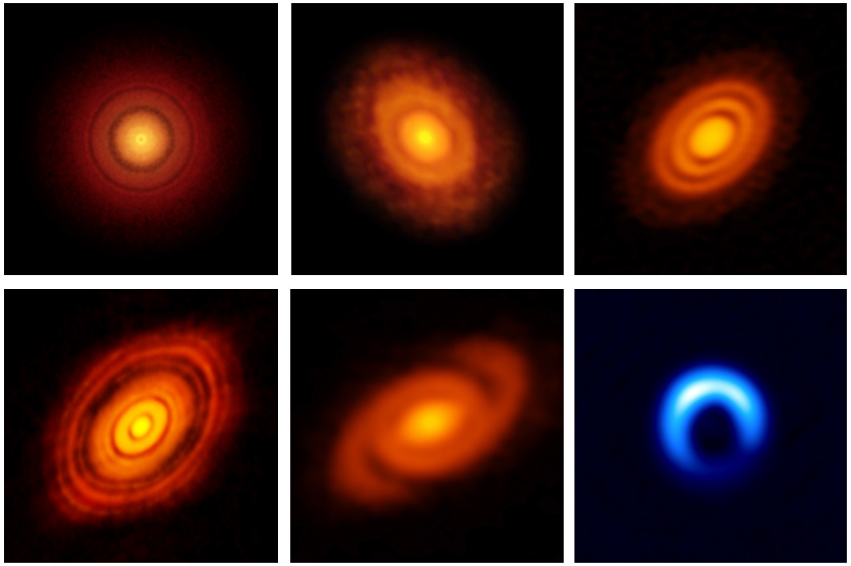
- “bottom-up”
- mostly smaller planets
- metallicity dependence for giant planets

<u>Gravitational Disk Instability</u> (GI)

- “top-down”
- massive planets & brown dwarfs
- no metallicity dependence



Alan Brandon/Nature



S. Andrews, L. Cieza, A. Isella, A. Kataoka
B. Saxton, ALMA (ESO/NAOJ/NRAO)

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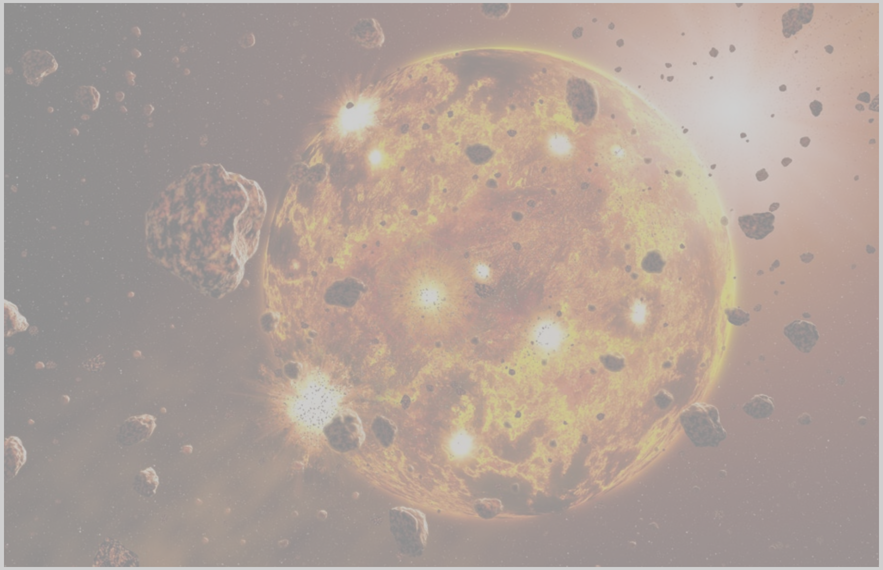

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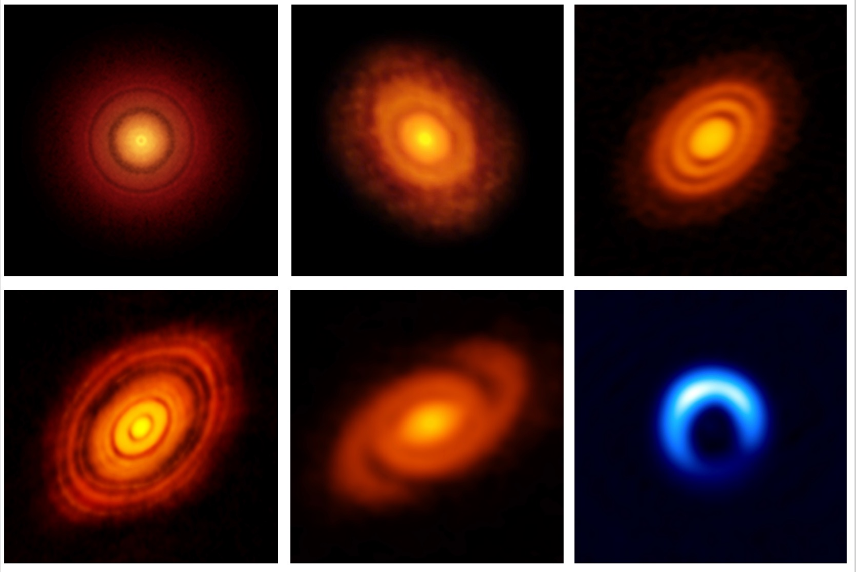

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GI Simulations in Binary Environments

Work done by James Cadman (PhD student, University of Edinburgh)

Cadman, Hall, Fontanive & Rice 2022

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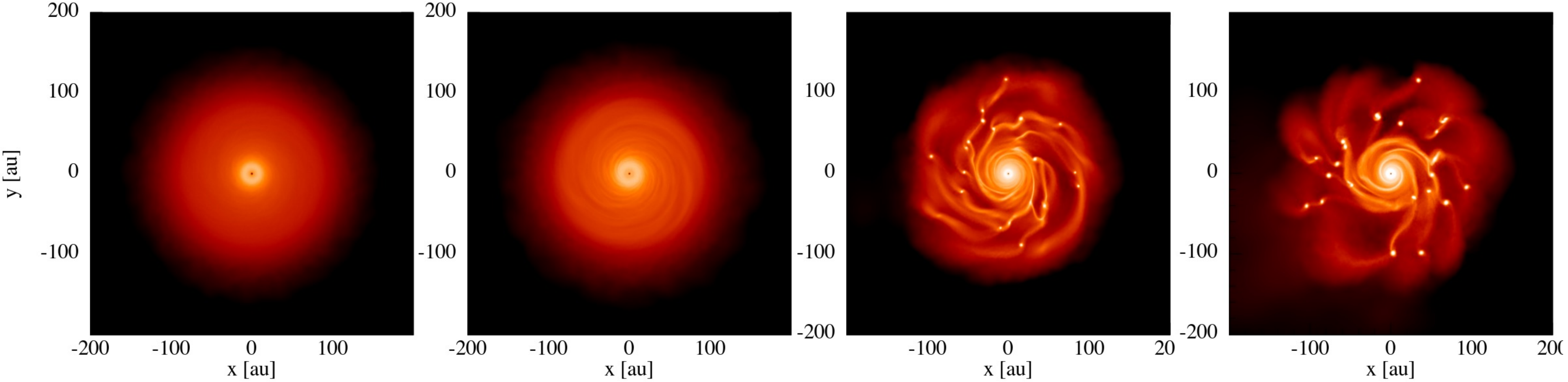
3D SPH simulations of self-gravitating discs around a 1 $M_\odot$ star

Disc mass: 0.1 $M_\odot$ 0.2 $M_\odot$ 0.3 $M_\odot$ 0.4 $M_\odot$



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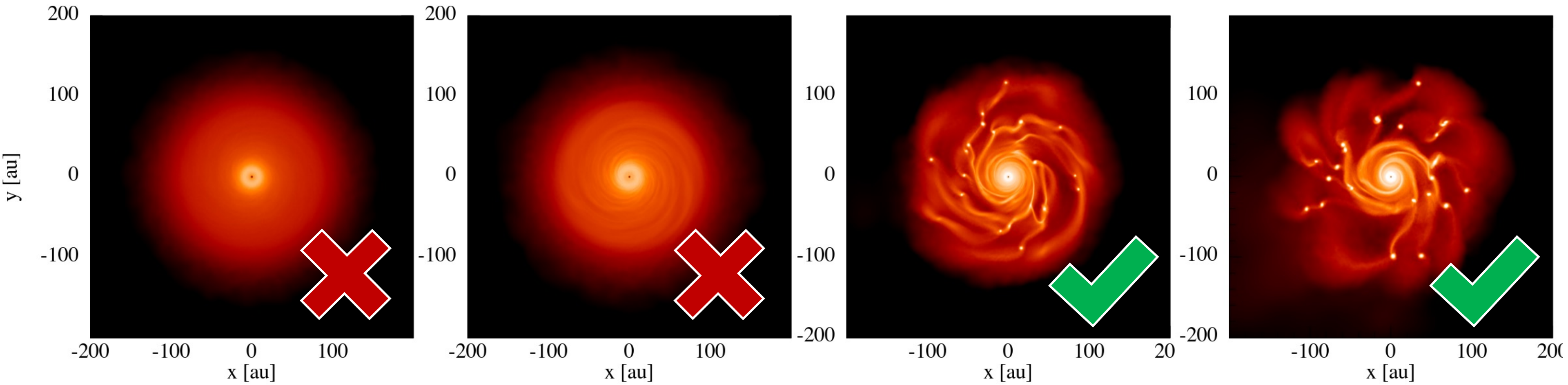

—> lower limit on disc mass for fragmentation around single star is between **0.2–0.3 $M_\odot$**

Effect of Binary Separation

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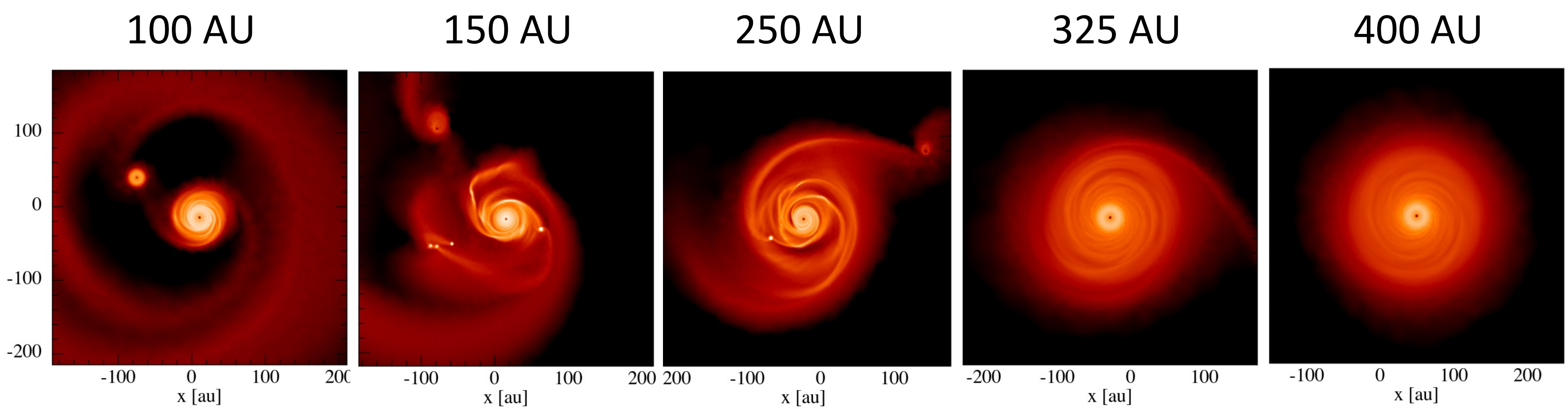
Add binary companions with varying semi-major axes around a 0.2 $M_\odot$ disc

Companion mass = 0.2 $M_\odot$, ecc=0, incl=0



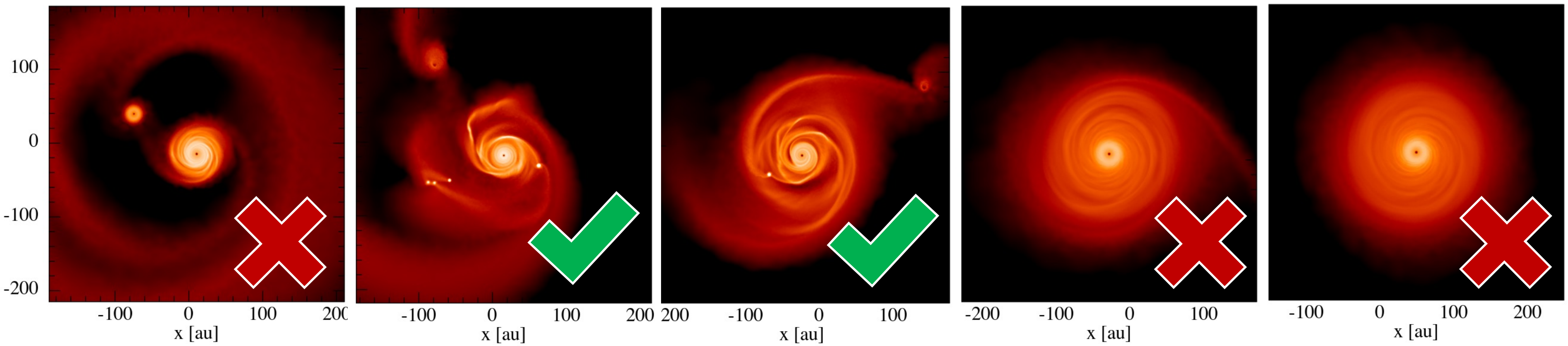
Effect of Binary Separation

Clémence Fontanive
Jan 17, 2023

Add binary companions with varying semi-major axes around a 0.2 $M_\odot$ disc

Companion mass = 0.2 $M_\odot$, ecc=0, incl=0

100 AU | 150 AU | 250 AU | 325 AU | 400 AU

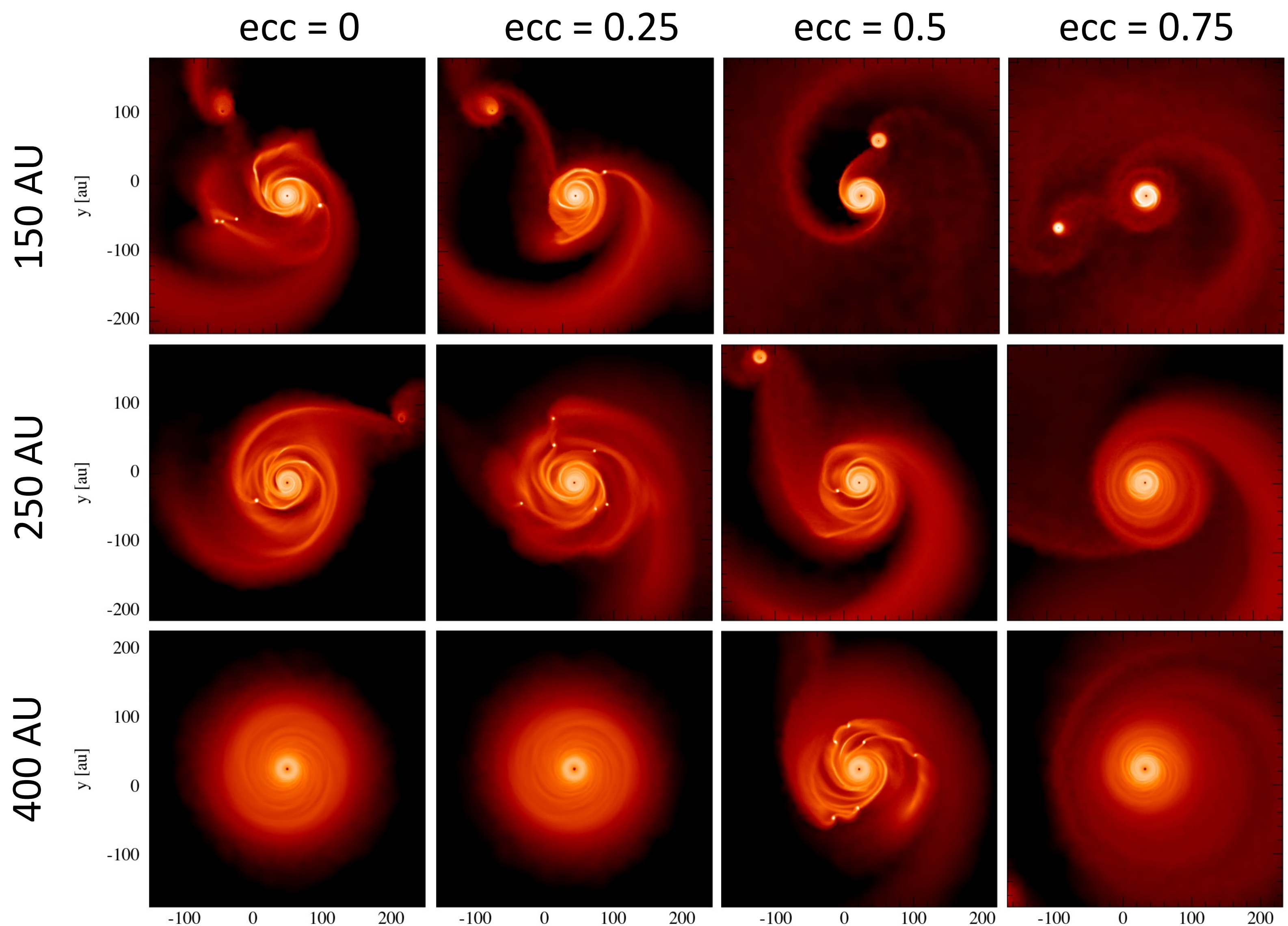


—> circular, aligned binary companions with **100 AU < separation < 300 AU** trigger fragmentation in discs that were stable around a single star

Effect of Binary Eccentricity

Clémence Fontanive
Jan 17, 2023

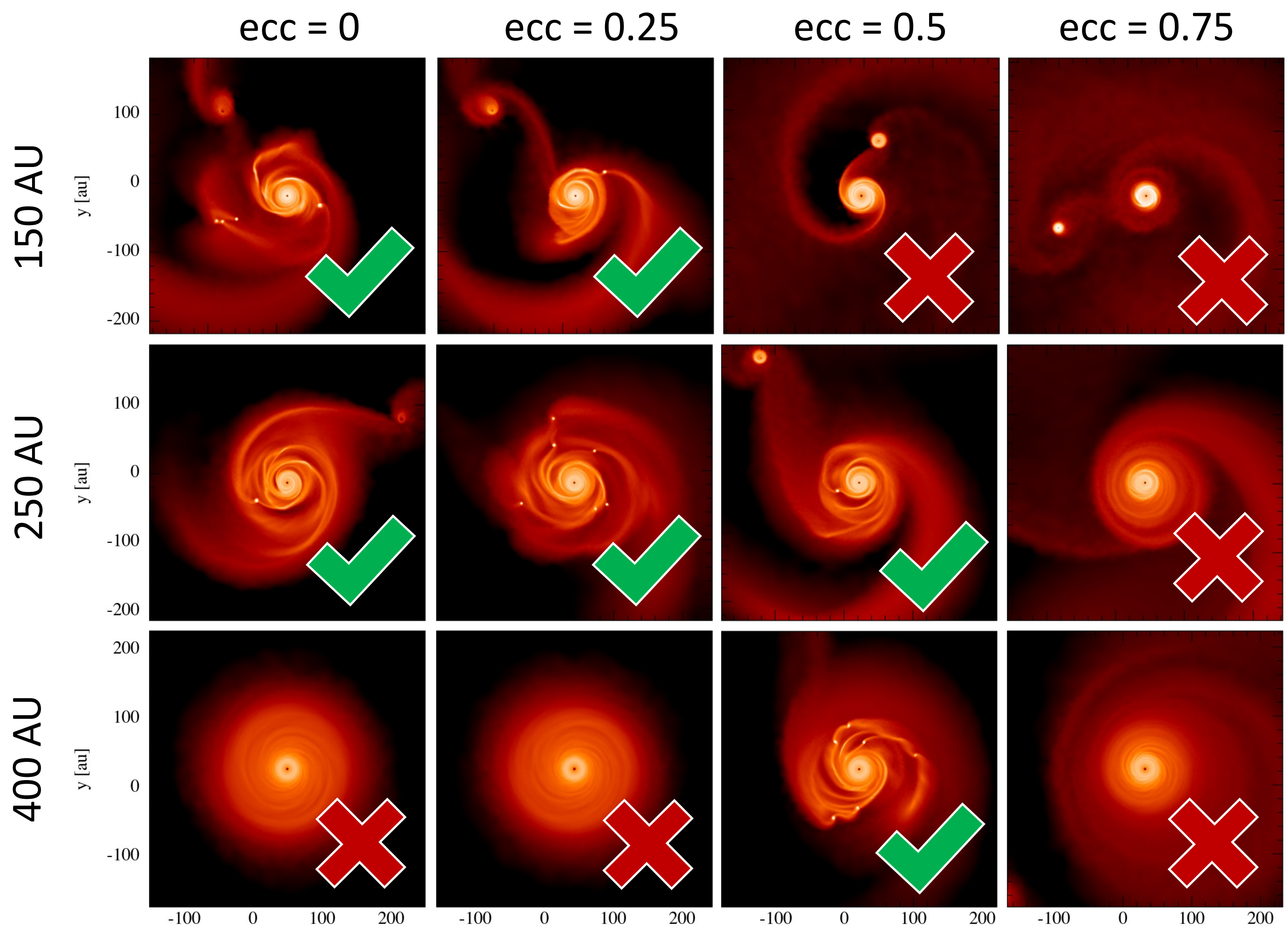
Varying eccentricities: companion mass = 0.2 $M_{\odot}$, incl=0 deg



Effect of Binary Eccentricity

Clémence Fontanive
Jan 17, 2023

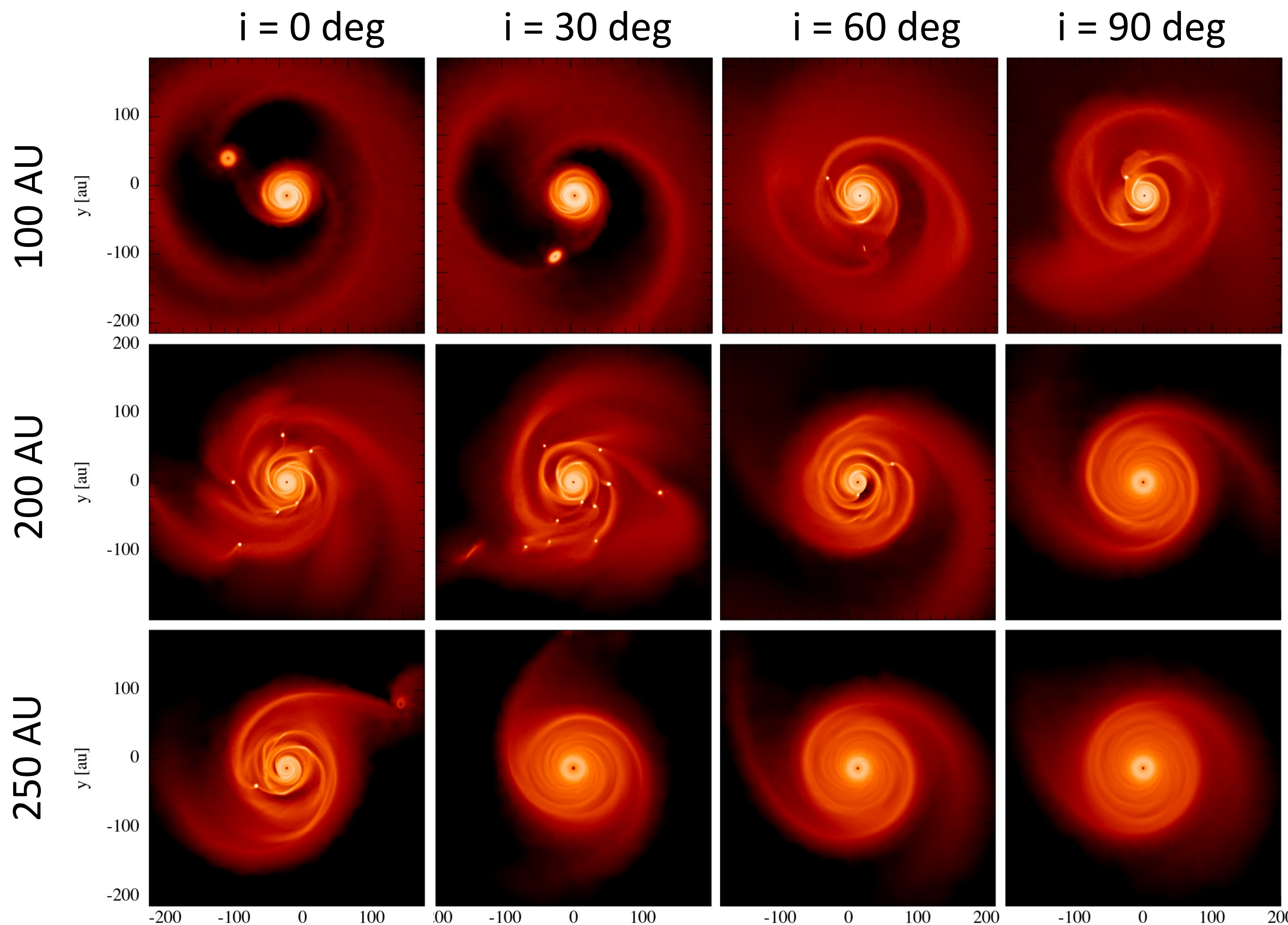
Varying eccentricities: companion mass = 0.2 $M_\odot$, incl=0 deg



Effect of Binary Inclination

Clémence Fontanive
Jan 17, 2023

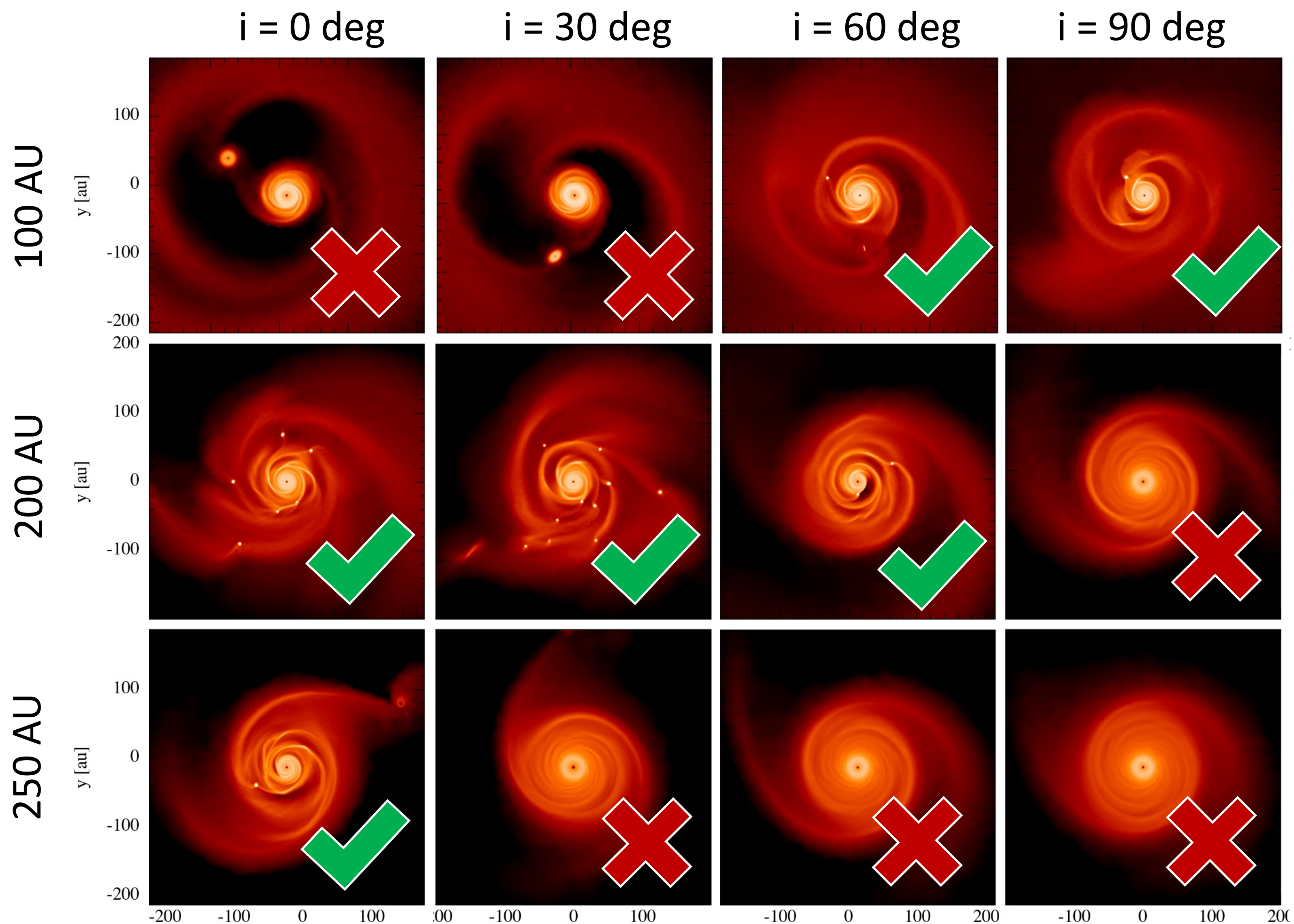
Varying inclinations: companion mass = 0.2 $M_{\odot}$, ecc=0



Effect of Binary Inclination

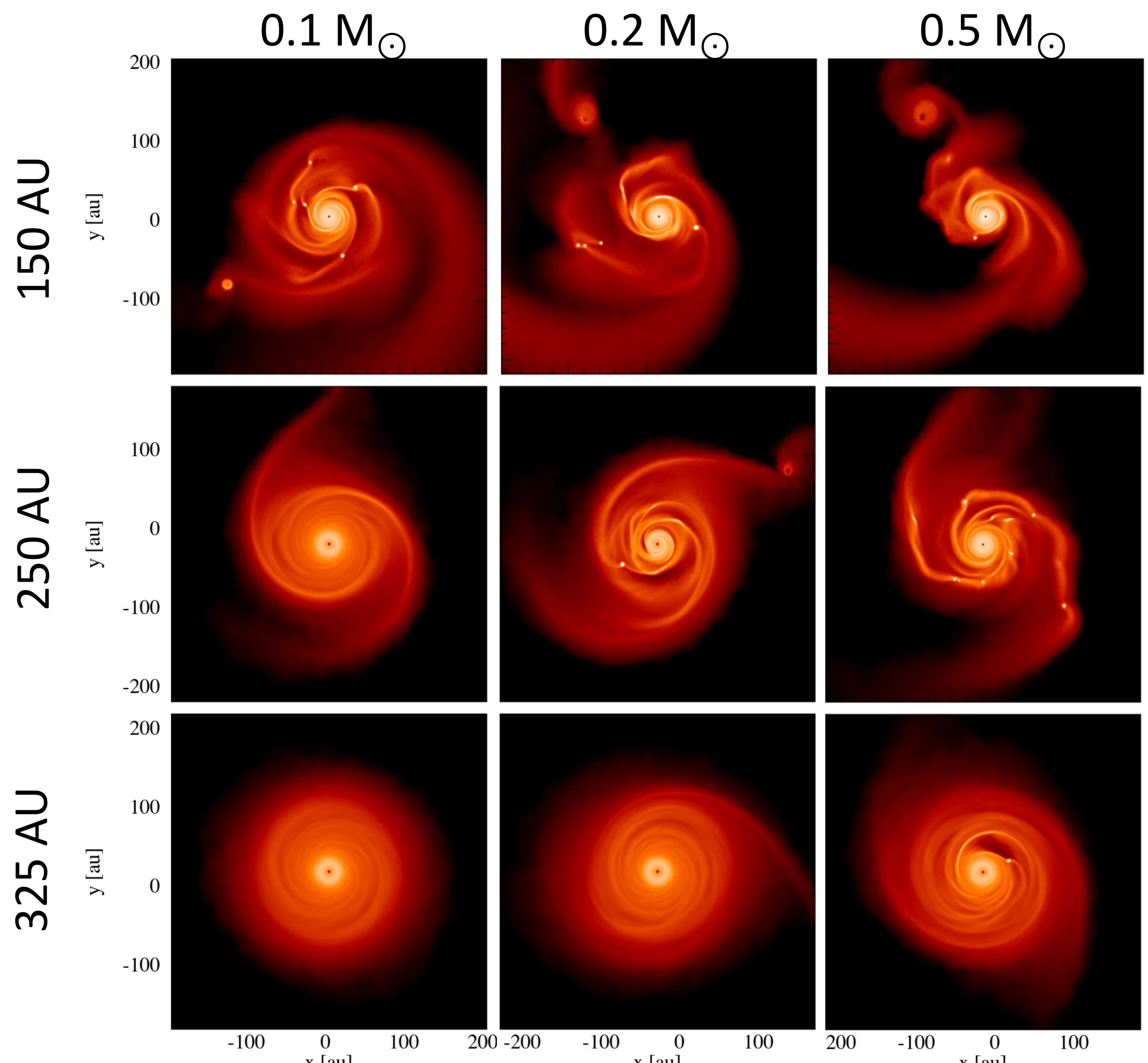
Clémence Fontanive
Jan 17, 2023

Varying inclinations: companion mass = 0.2 $M_{\odot}$, ecc=0



Effect of Companion Mass

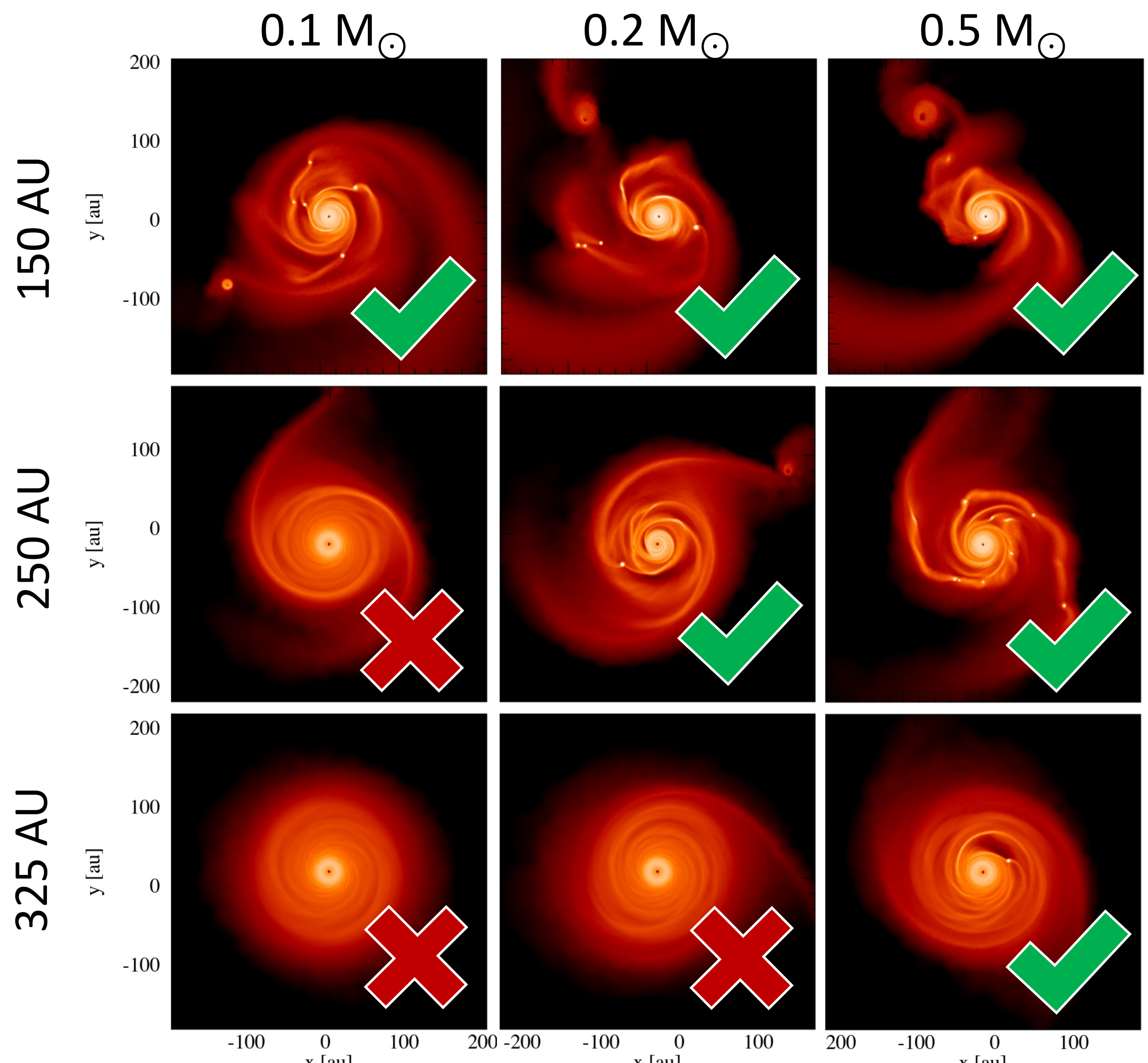
Varying companion masses: ecc = 0, incl = 0 deg



Effect of Companion Mass

Clémence Fontanive
Jan 17, 2023

Varying companion masses: ecc = 0, incl = 0 deg



Formation of GI Planets in Binaries

There is a "sweet spot" of binary parameters which can cause a stable disc to fragment and lead to the formation of giant planets!

– works for binaries with intermediate separations (~100–400 AU), with exact range function of binary eccentricity, inclination and companion mass

– short-separation and high-eccentricity disc-penetrating binary encounters are detrimental to fragmentation

– wide separation binary companions have little effect on the disc evolution

– consistent with the projected separations of binary systems around which an excess of massive planets and brown dwarfs is observed

Conclusions

– Tight binaries (<50–100 AU) typically detrimental to planet formation

– Very wide binaries (thousands AU scales) have little effect on the resulting planetary masses and separations

– High-mass giant planets and brown dwarfs often have an outer stellar companion on few hundred AU separations and show different demographics (higher masses, tigher orbits, single-planet systems)

– Binaries on these separations likely play a role in the formation and/or evolution of these inner companions

– GI triggered by stellar companions at few hundred AU may explain the formation of these giant planets and brown dwarfs observed in binaries

THANK YOU FOR LISTENING AND YAAAY FOR BINARIES