Formation of free-floating planets (FFPs) from circumbinary systems

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CBPs across the HR diagram, Florence 2025

Queen Mary
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What are FFPs

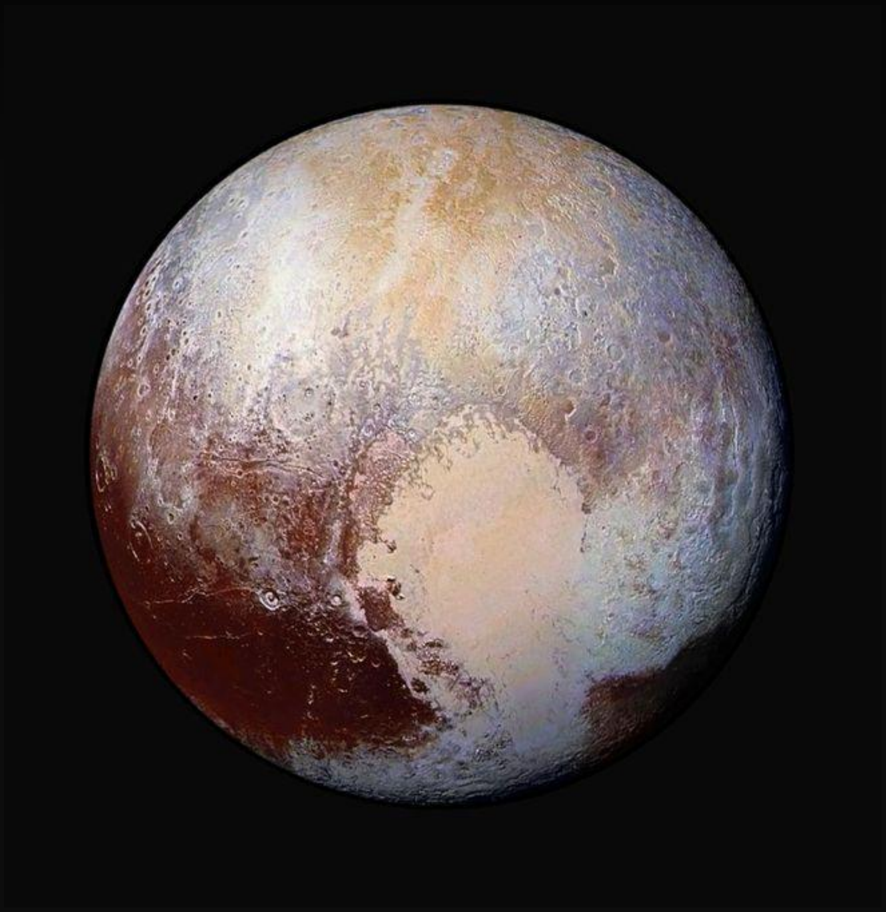
- Since the IAU have no definition, we made one up at recent conference (RogueWorlds2024)
- Follows the IAU definition:
    - Massive enough to maintain hydrostatic equilibrium (effectively spherical)
    - Is at most 13 Jupiter masses (not a Brown Dwarf)
- No definition based on dynamical clearing, or orbiting an object
- They should not be orbiting a known object

The important question of our time

The answer to everyone's burning question is

YES

Pluto would be a planet if it was ejected



What are FFPs

- Free floating planets (FFPs) are planetary sized objects that are not bound to any star or brown dwarf
- How they form is presently unknown
- Do they form through star formation processes? Or planet formation processes?
- Is there a wide diversity in FFPs? What is their underlying distribution?
- How well do they match bound populations?
- What do they have to do with Circumbinary Systems?

Observations of FFPs

- First discovered in 2000 with UKIRT observations of the Orion Nebula, where several objects found below the deuterium burning limit (Lucas+ 2000)
- Other direct imaging observations have pushed the mass of known FFPs down to ~Jupiter mass (Caballero 2018)
- Some surveys observed binarity in FFPs with JWST images, adding further complexity to their formation histories (Pearson+ 2023)

NASA/ESA/CSA JWST NIRCam (McCaughrean et al.)

Observations of FFPs

- FFPs have also been observed in microlensing data
- Smaller signatures than stars – hard to disentangle from other physical effects, e.g. flares
- Terrestrial (Mroz+ 2020), Neptunian (Mroz+ 2019) and Jovian (Sumi+ 2011) mass planets have been found

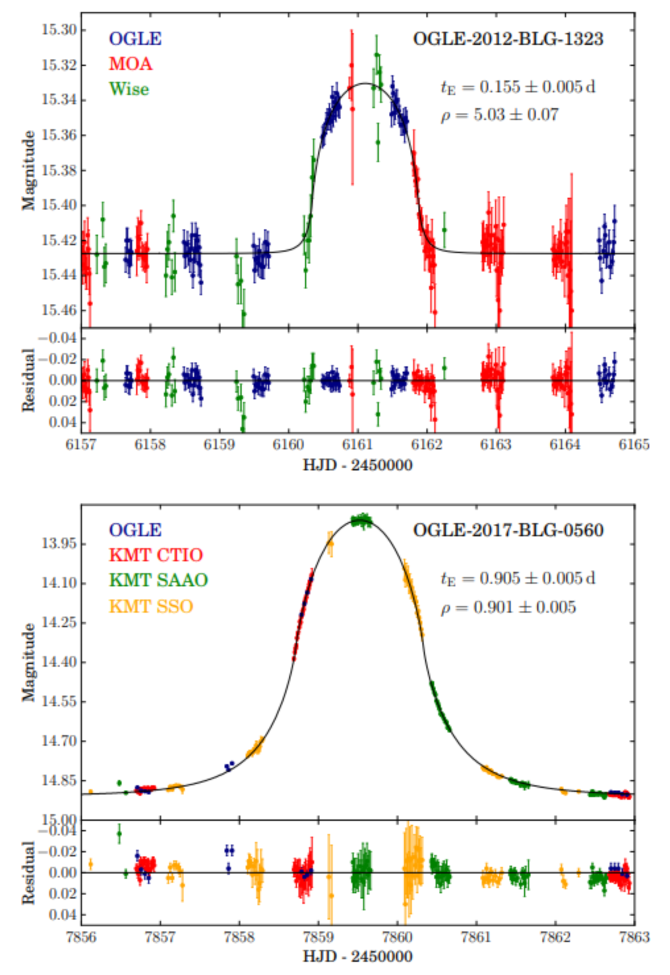


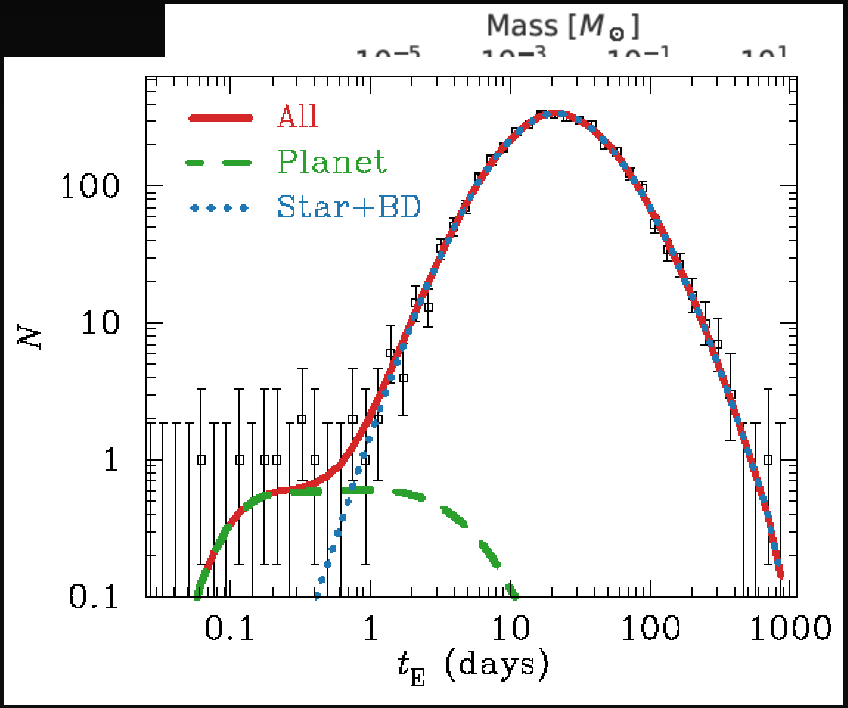
Fig. 1. Light curves of two ultrashort microlensing events. *Upper panel*: OGLE-2012-BLG-1323. *Lower panel*: OGLE-2017-BLG-0560. Both events show strong finite-source effects, which allows us to measure their angular Einstein radii.

Mroz+ 2019

Distributions from observations

- Handful of observations have allowed some initial estimations of the mass distribution (Sumi+ 2023)
- Extrapolate with a constant slope as mass decreases
- Follows a power law model:

$$\frac{dN}{d\log M} = \frac{2.18^{+0.52}_{-1.40}}{dex\ x\ star}\left(\frac{M}{8M_{\oplus}}\right)^{-0.96}$$



Sumi+ 2023

How to form FFPs

- More massive objects can form similar to stars:
  - Core collapse (Miret-Roig+ 2022)
  - Aborted stellar embryo injection (Reipurth+ 2001)
  - Photo-erosion of pre-stellar cores (Whitworth+ 2004)

- Terrestrial, Neptunian, Giant planets can form through planet formation processes, before being ejected from their parent system via:
  - Planet-planet scattering (Rasio+ 1996, Veras+ 2012)
  - Stellar flybys (Wang+ 2023)
  - Interactions with binary stars (Coleman+ 2023,2024, Chen+ 2024)

- Most planet formation scenarios include pre-defined distributions of planets – either initial embryos, or fully formed planets

- Focus on possibility of formation rather than occurrence rates / properties

What do we do?

- Explore the production rates of FFPs within circumbinary systems (Coleman 2024)
  - What masses of FFPs are produced?
  - To what frequency are they ejected from the systems?
  - Can their ejection location tell us anything?

- Include planet formation processes – no predefined distributions
  - Give a better representation of FFP production efficiencies
  - Allows us to test our understanding and effectiveness of planet formation processes/models when comparing with observations

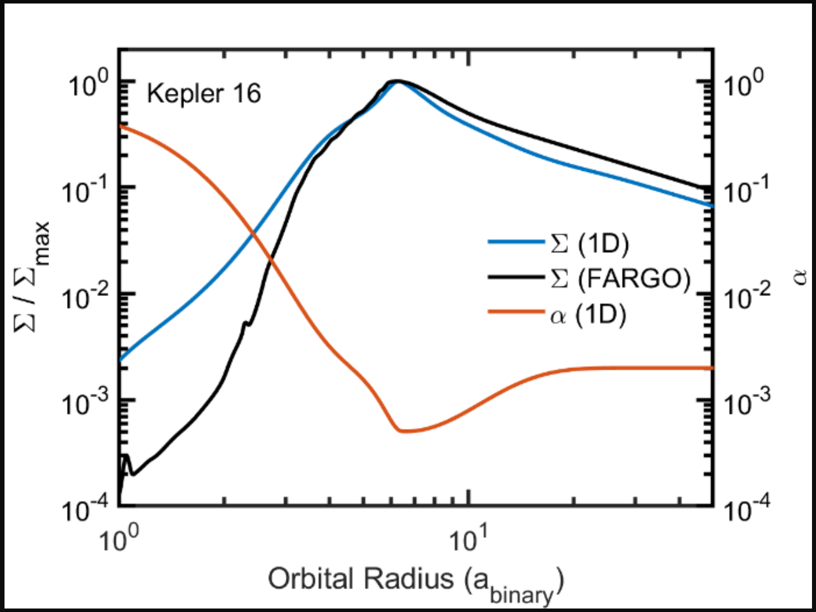
- Derive a galactic population using assumptions for planet formation in non-circumbinary systems (Coleman & DeRocco 2024)
  - Wide Binary Systems
  - Single star Systems

Basic Model

- Use Mercury 6, including effects of central binary (Chambers+ 1999,2003)
- Thermally evolving circumbinary viscous disc model including irradiation from both stars, and also a central circumbinary cavity
- Photo-evaporation due to high energy radiation from central stars (Picogna+ 2023) and from nearby stars (Haworth+ 2023)
- Planetesimal and Embryo formation models based on streaming instability (Coleman 2021)
- Pebble accretion model – Pebble production front expanding outwards forming pebbles that can be accreted by planets (Johansen+ 2017)
- Gas accretion onto embryos above 1 M_{Earth} using fits to 1D envelope structure models (Poon+ 2021)
- Planet migration for embedded planets (Paardekooper+ 2010,2011) and for gap opening planets (Lin+ 1986, Crida+ 2006)

Binary Cavity Inclusion

- Circumbinary stars form inner cavities devoid of gas
- Model this cavity through manipulating viscosity alpha parameter
- Match the 1D alpha models to 2D FARGO simulations assuming steady state accretion through the disc
- Allows buildup of material to form in 1D models similar to those seen in 2D models

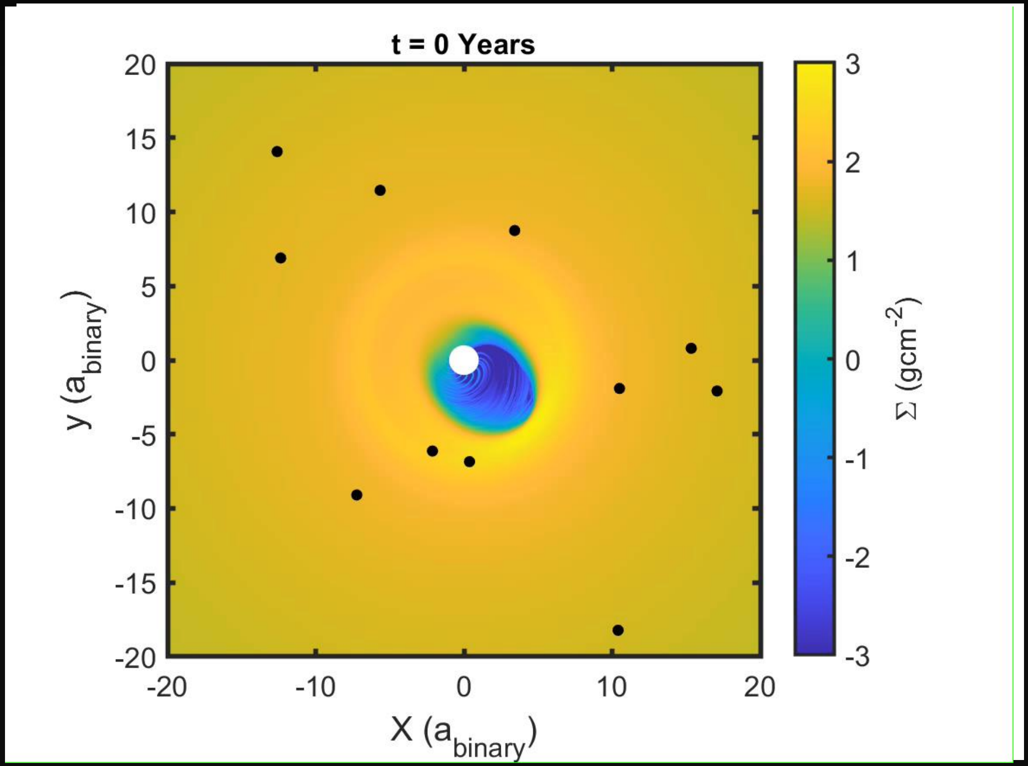


Incorporating a precessing 2D cavity

- Model a 2D surface density based on 1D azimuthally averaged value
- Matches FARGO simulations quite well, except in the cavity
- Not an issue for planet formation as low surface density, also inside the stability limit

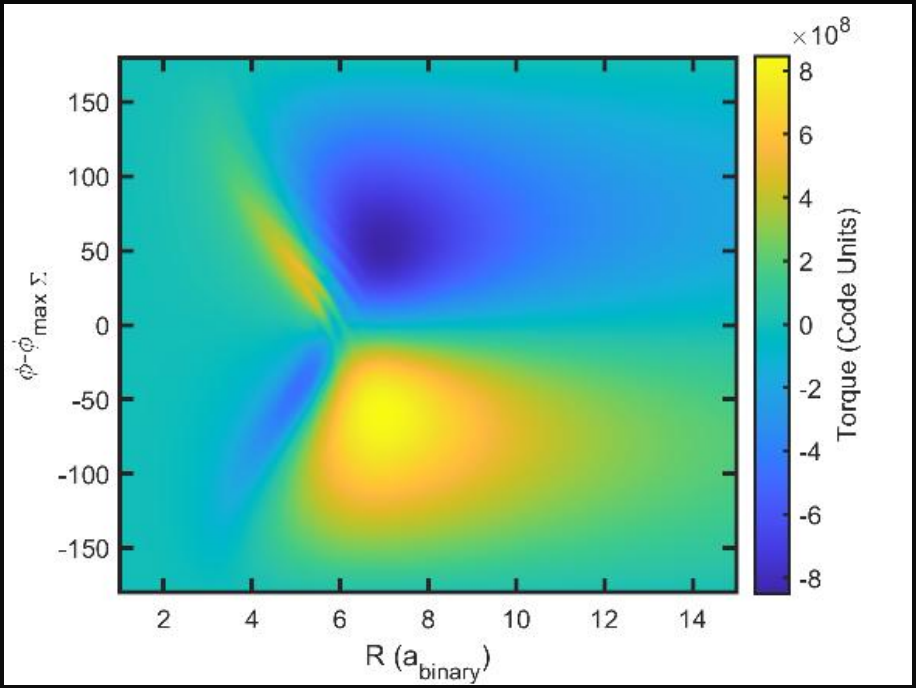
FARGO

1D Model



Apocentre Torques

- Buildup of material at the cavity apocentre can also impart a torque on to nearby planets
- Use FARGO to create torque maps in 2D to simulate this based on 1D profiles
- Acts to align planetary orbits with the eccentric circumbinary disc



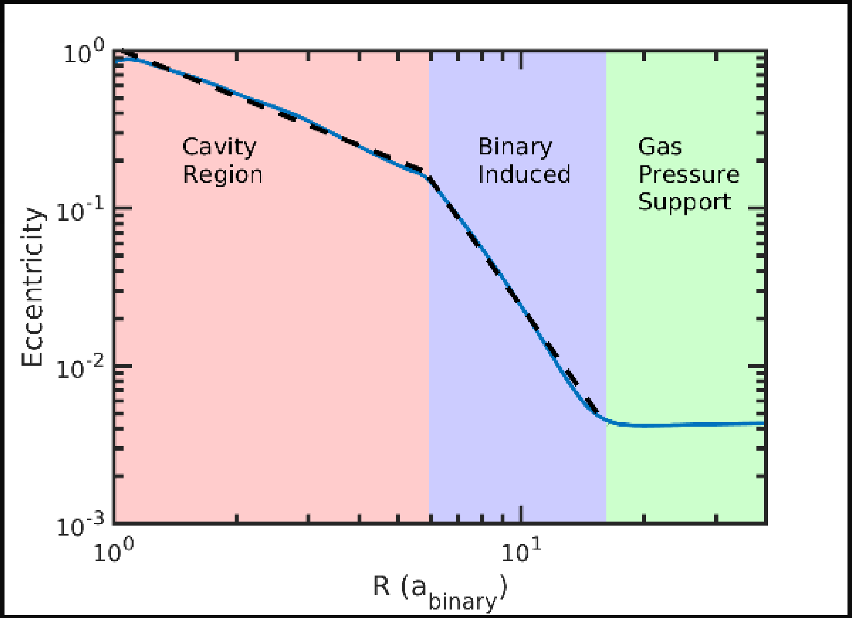
Eccentric disc

Eccentric disc in and around the cavity

Varying gas/pebble velocities around a planet's orbit

Fit profiles to disc eccentricity based on 2D hydro simulations

Calculate the gas and pebble velocity when determining accretion rates based on planets radial and azimuthal location



Coleman+ 2023

Setup

- Central stars based on those in the BEBOP-1 system
- Central circumbinary cavity properties calculated using hydrodynamic simulations with FARGO-3D
- Varied different parameters to explore their effect on the populations

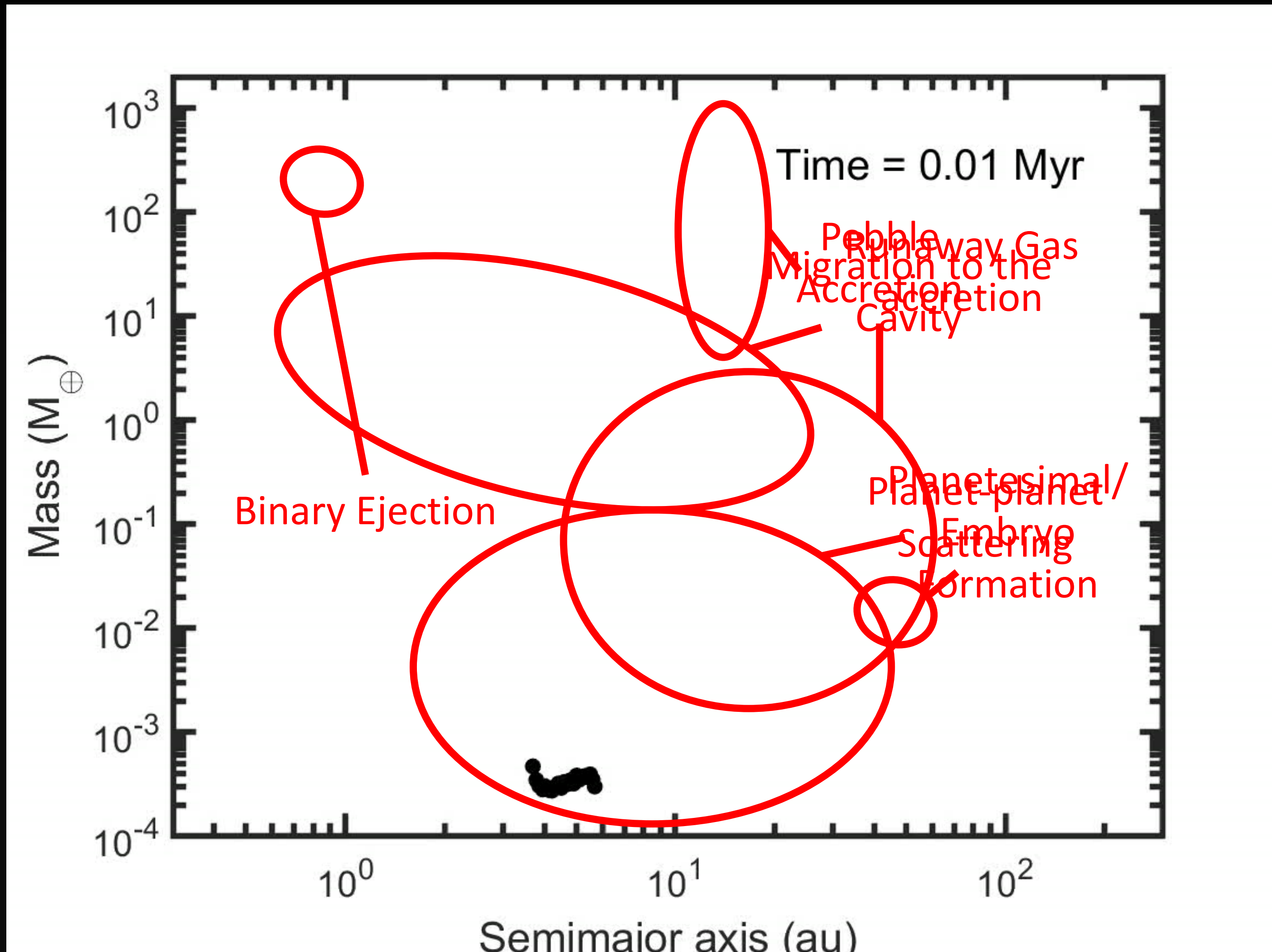
Parameter	Description	Value
$M_{\rm A}$ ($M_{\odot}$)	Primary Mass	1.0378
$M_{\rm B}$ ($M_{\odot}$)	Secondary Mass	0.2974
$T_{\rm A}$ (K)	Primary Temperature	4300
$T_{\rm B}$ (K)	Secondary Temperature	3300
$R_{\rm A}$ ($R_{\odot}$)	Primary Radius	2
$R_{\rm B}$ ($R_{\odot}$)	Secondary Radius	1.5
$e_{\rm bin}$	Binary Eccentricity	0.156
Metallicity (dex)	Stellar Metallicity	0
$r_{\rm cav}$ ($a_{\rm bin}$)	Cavity Radius	3.7377
$e_{\rm cav}$	Cavity Eccentricity	0.4162
$r_{\rm cav,a}$ ($a_{\rm bin}$)	Cavity Apocentre	5.2933
C_1	Cavity Parameter 1	1.1
C_2	Cavity Parameter 2	0.32
C_3	Cavity Parameter 3	4.5

Table 1. Simulation common parameters.

Parameter	Lower Value	Upper Value	Dimension
$a_{\rm bin}$ (au)	0.05	0.5	linear
$M_{\rm disc}$ ($M_{\rm bin}$)	0.05	0.15	linear
UV Field (G_0)	1	10^5	log
α	10^{-4}	$10^{-2.5}$	log

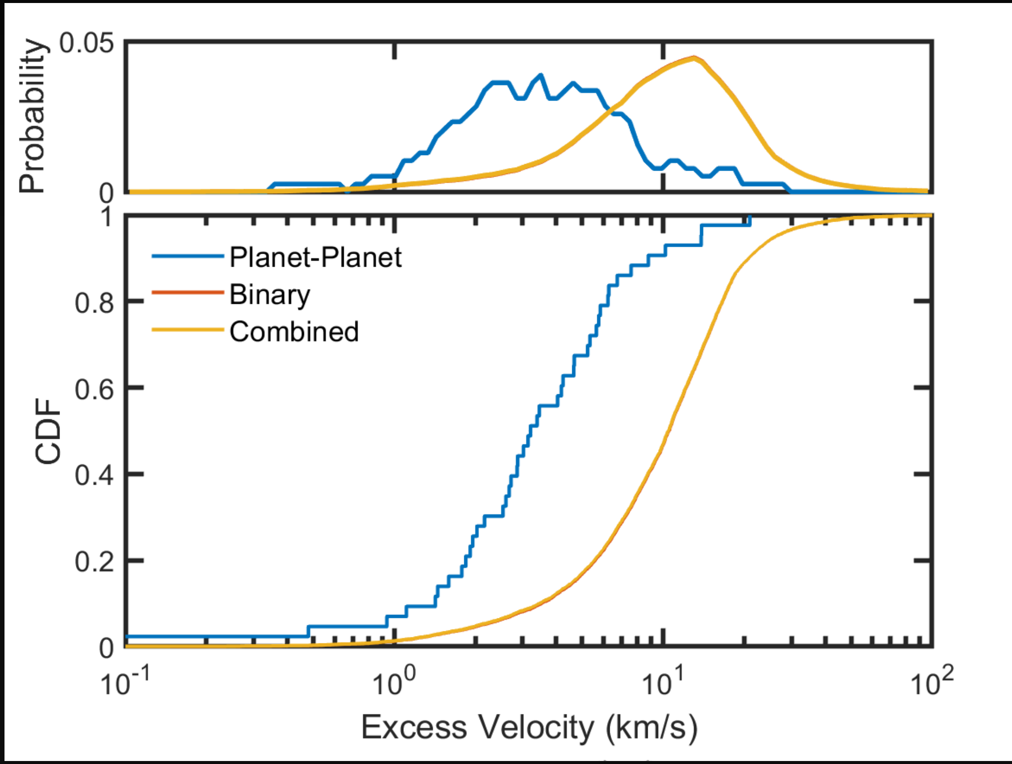
Table 2. Values for the parameters varied amongst the populations.

Forming FFPs in Circumbinary Discs



Where do FFPs come from?

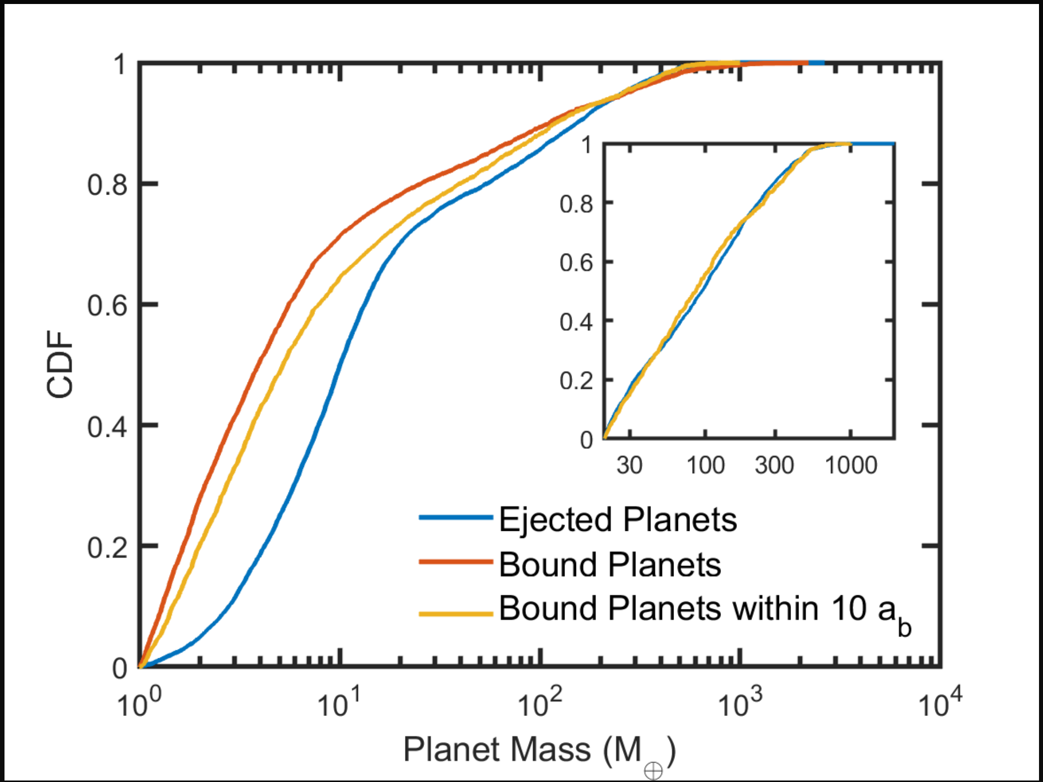
- Large range of planet masses undergo ejection
- Pericentre distance is a good proxy for ejection location
- Three distinct populations:
  - Binary – low mass
  - Binary – high mass
  - Planet-planet scatters
- Planet-planet scatters are a good proxy for those planets ejected in single star systems



Coleman 2024

Comparison with bound planets

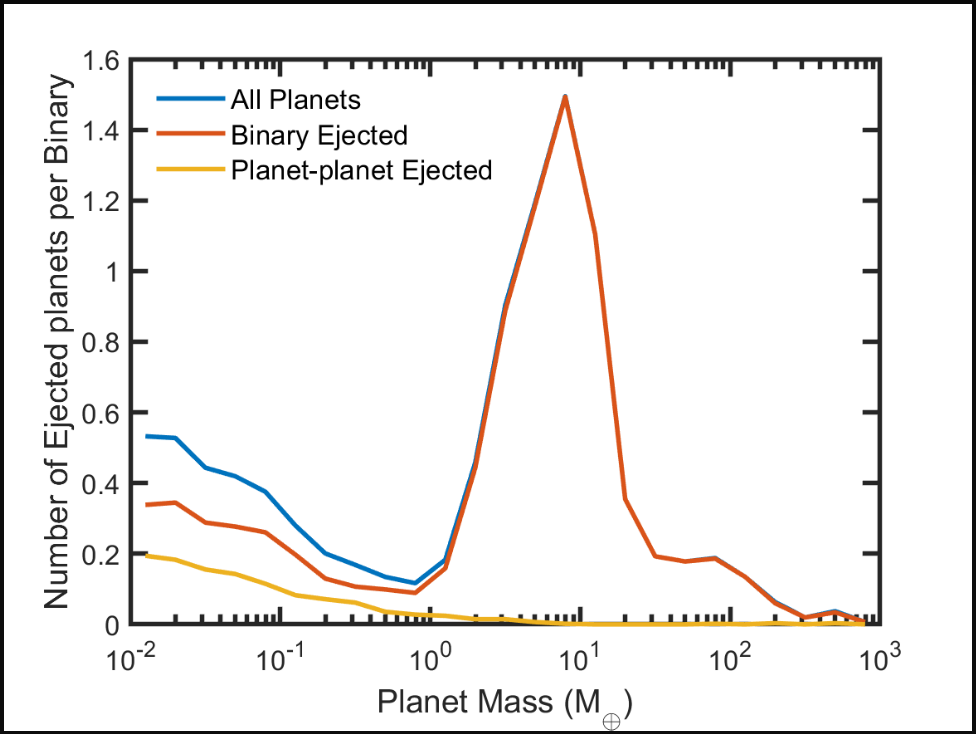
- Majority of planets ejected are in the super-Earth regime
- Good agreement in relative number distributions between ejected planets and bound planets seen close to the central binary
- Could provide a useful comparison point between Roman and other missions e.g. PLATO



Coleman 2024

Planet-planet or binary ejections?

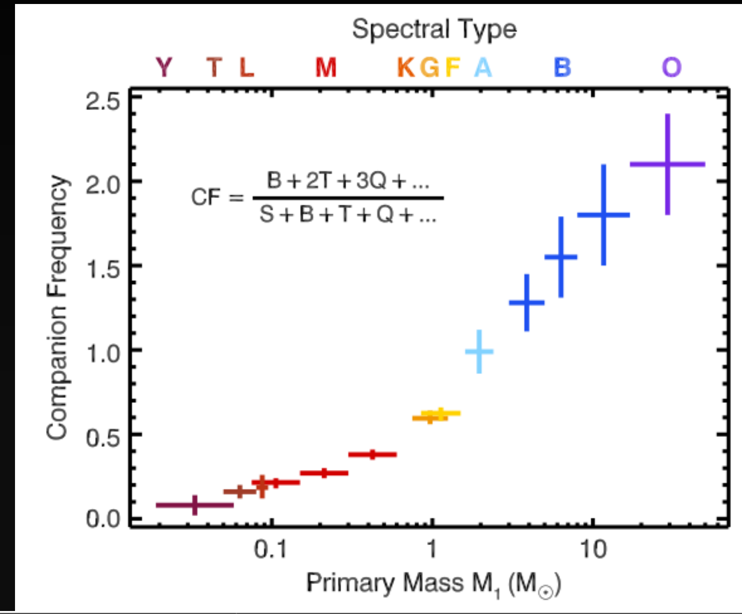
- Binary and planet-planet scattering eject different planets
- Planet-planet scatter – mainly low-mass sub-terrestrial planets
- Binary – more massive objects
- Peak seen around super-Earth masses
- Planet-planet scattering seen here used as proxy for single star ejections

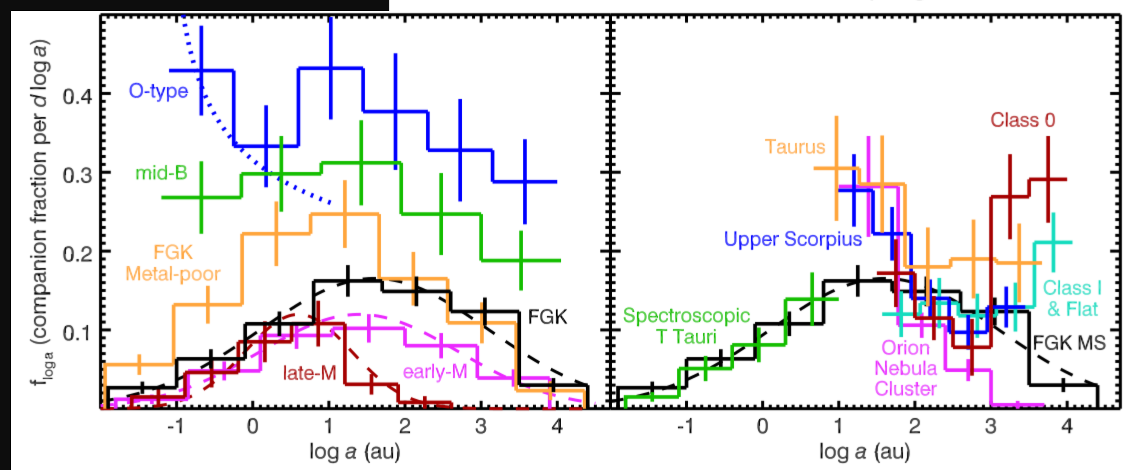


Coleman 2024

Building a galactic population

- For Solar type stars, 60% are found to be in binaries (Offner+ 2023)
- The distribution in binary separations is found to follow a lognormal distribution for FGK stars (Raghavan+ 2010)
- Varies for different stellar masses and with metallicity
- Follow the FGK trend found by Raghavan+ 2010





Offner+ 2023

Building a galactic population

- Circumbinaries – Similar to those presented in Coleman 2024 and make up 23% of all binaries
- Ultra wide binaries – assumed to form planets similar to single stars, make up 25% of all binaries
- Intermediate binaries – difficult to estimate their formation potential, due to either larger circumbinary cavities, or extreme truncation of the outer disc

Stellar Population	Semi-major Criteria	Stellar Percentage
Circumbinary	$a_{\mathrm{b}} < 3\,\mathrm{au}$	14%
Ultra Wide Binaries	$a_{\mathrm{b}} > 300\,\mathrm{au}$	15%
Intermediate Binaries	$3\,\mathrm{au} < a_{\mathrm{b}} < 300\,\mathrm{au}$	31%
Single Stars	-	40%
Total	-	69%

Coleman & DeRocco 2024

Building a galactic population

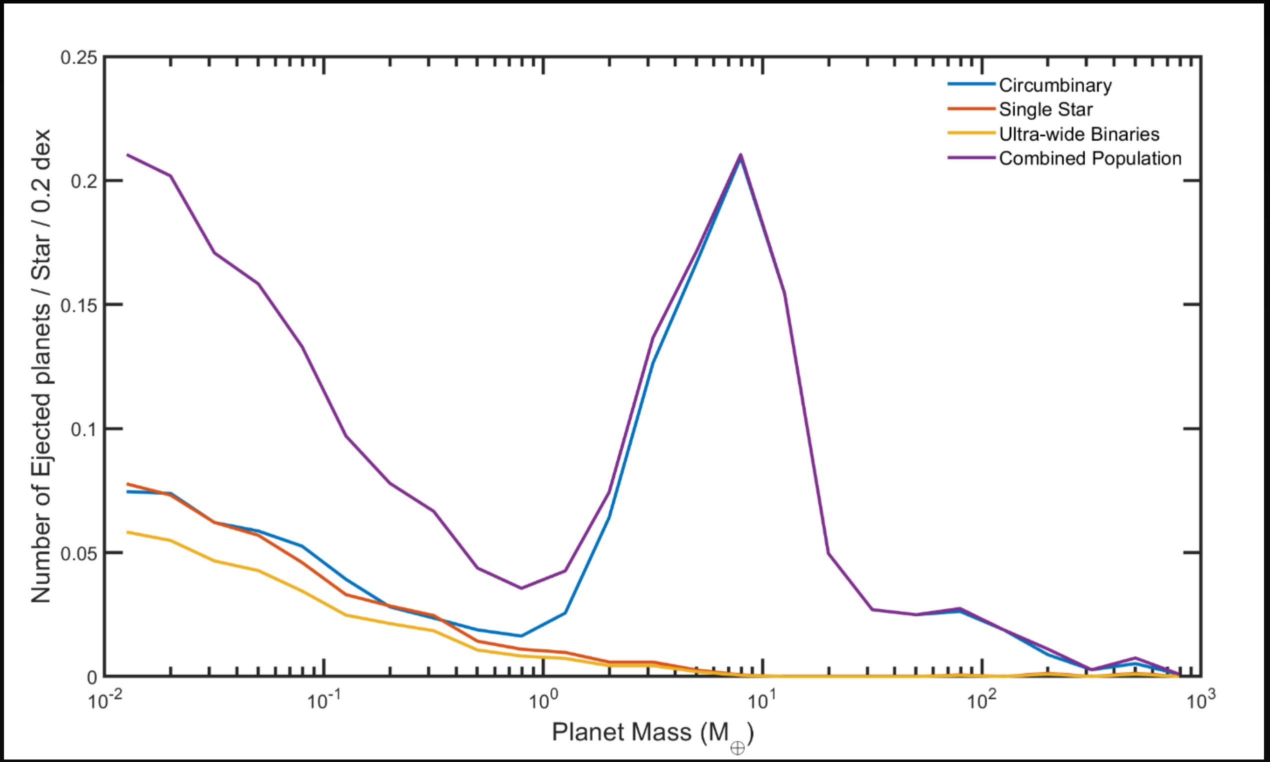
- Circumbinaries – provide the majority of FFPs when taking into account the whole population
- Ultra wide binaries and Singles – provide comparable contributions, but combined is only half that of circumbinaries
- Intermediate binaries – assumed to not provide any planets. However a conservative estimate could be similar to single stars / system

Stellar Population	Semi-major Criteria	Stellar Percentage	FFPs / system	FFP total / star
Circumbinary	$a_b < 3\,\mathrm{au}$	14%	9.7	1.36
Ultra Wide Binaries	$a_b > 300\,\mathrm{au}$	15%	2.28	0.34
Intermediate Binaries	$3\,\mathrm{au} < a_b < 300\,\mathrm{au}$	31%	0	0
Single Stars	-	40%	1.14	0.46
Total	-	69%	3.12	2.16

Coleman & DeRocco 2024

Galactic population of FFPs

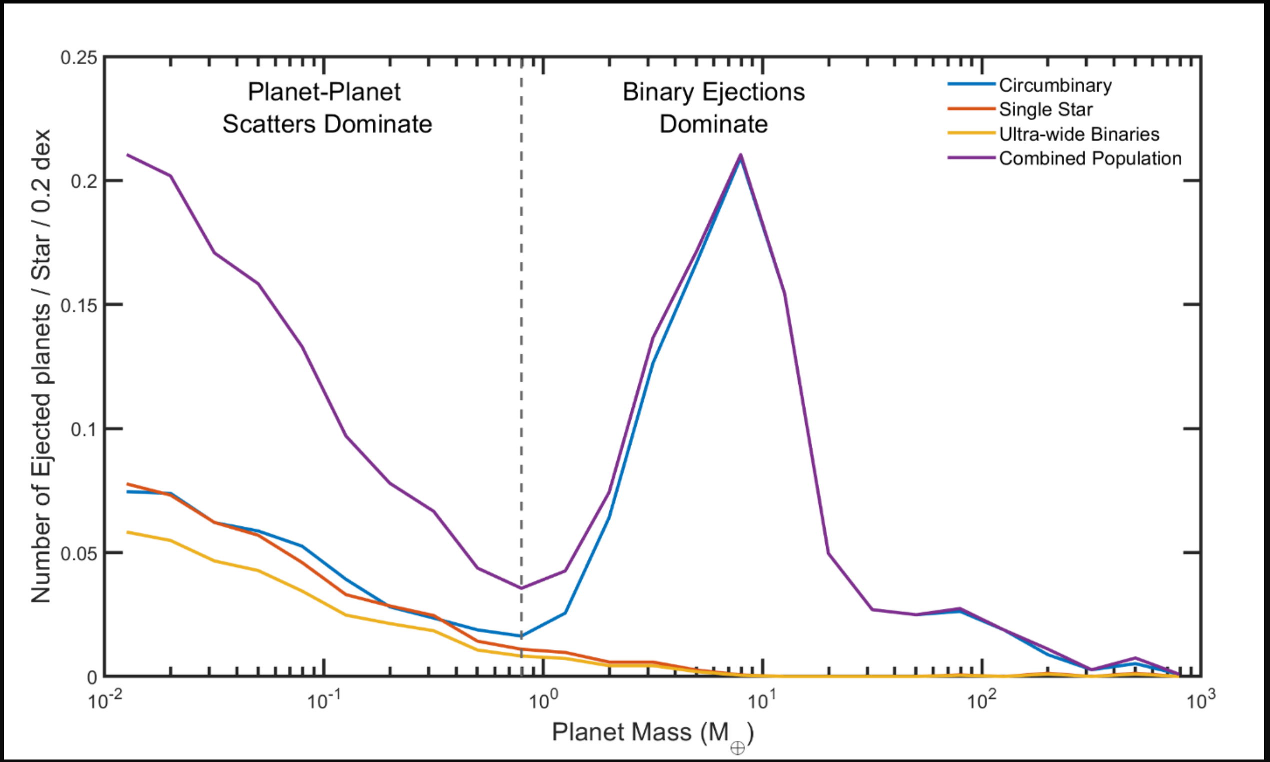
- Multiple features seen for the combined population
- Features can give insights into physical processes affecting planet formation
- Different stellar groups provide different planets



Coleman & DeRocco 2024

Galactic population of FFPs

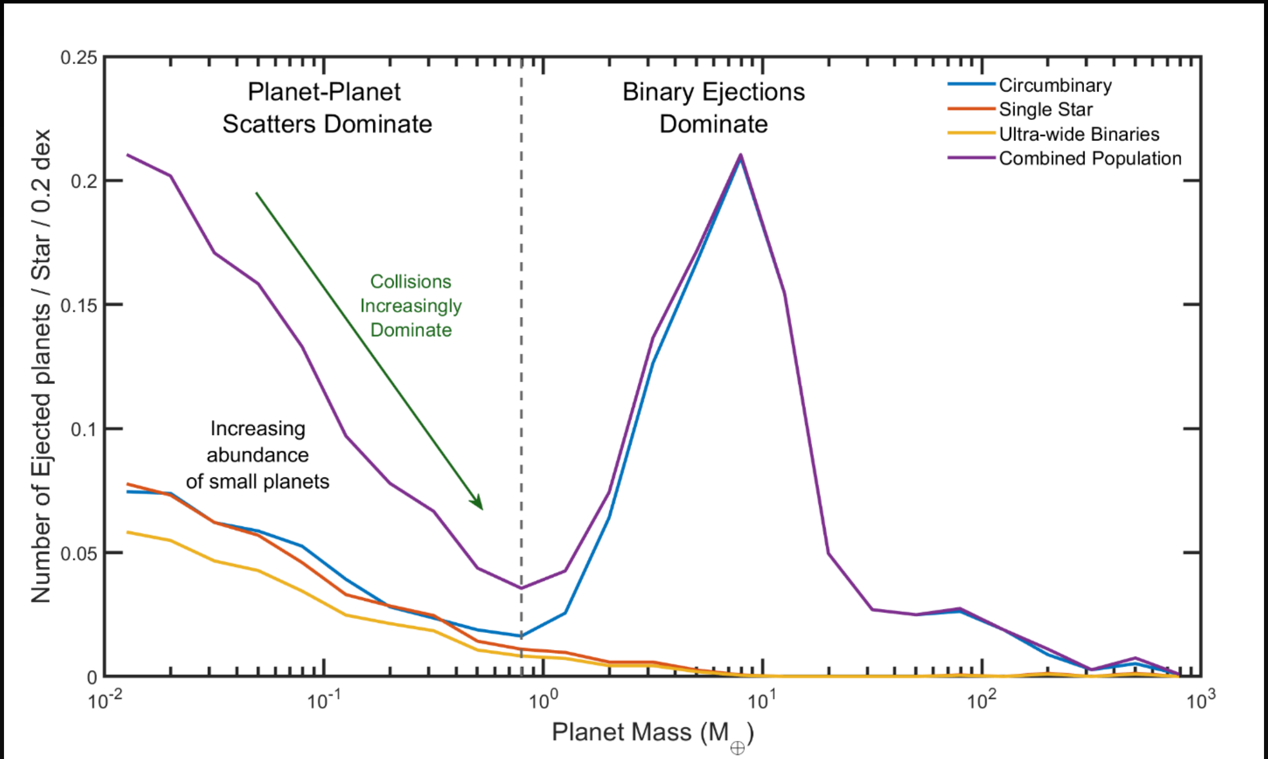
- Clearly separate planets ejected through binary interactions or through planet-planet scatters
- Single stars + UWBs supply low mass planets
- Circumbinaries provide super-Earths and giants as well



Coleman & DeRocco 2024

Galactic population of FFPs

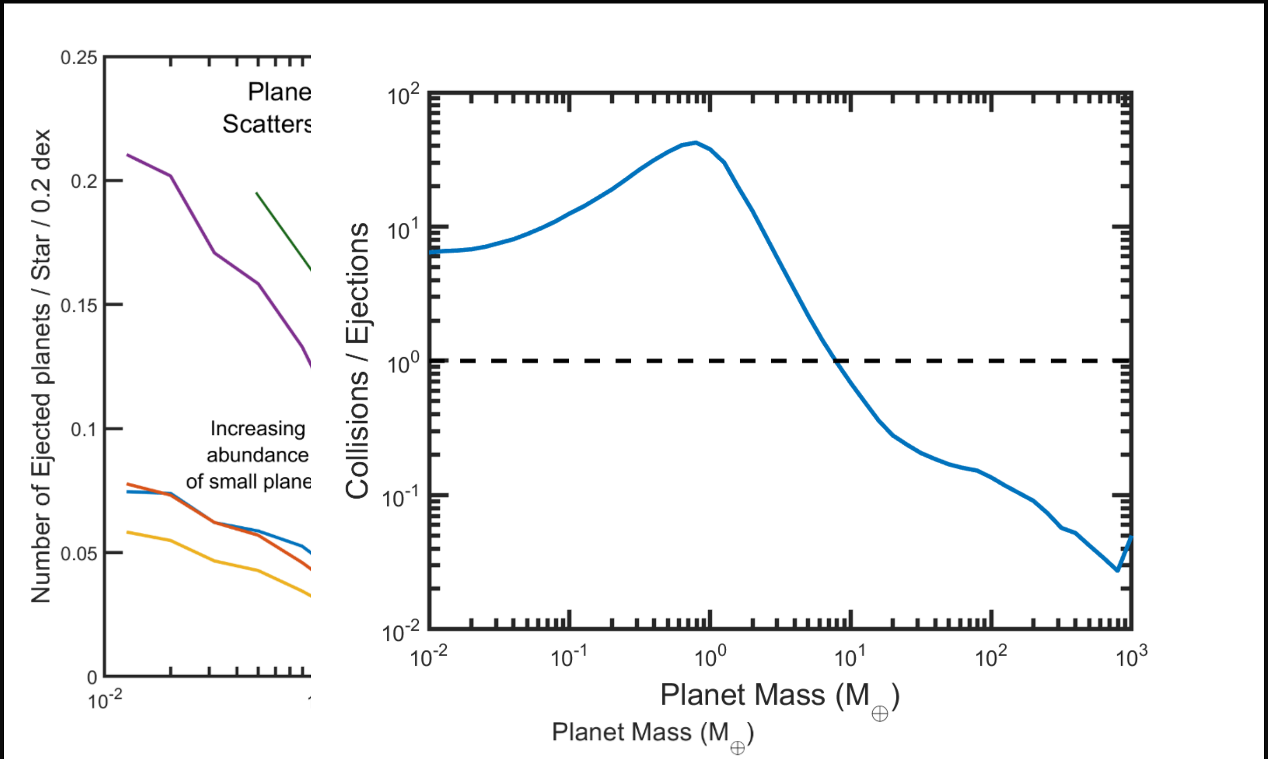
- Number frequency of low mass planets increase as mass decreases
- More Lunar mass planets than Earth mass
- Dearth of planets around an Earth mass



Coleman & DeRocco 2024

Galactic population of FFPs

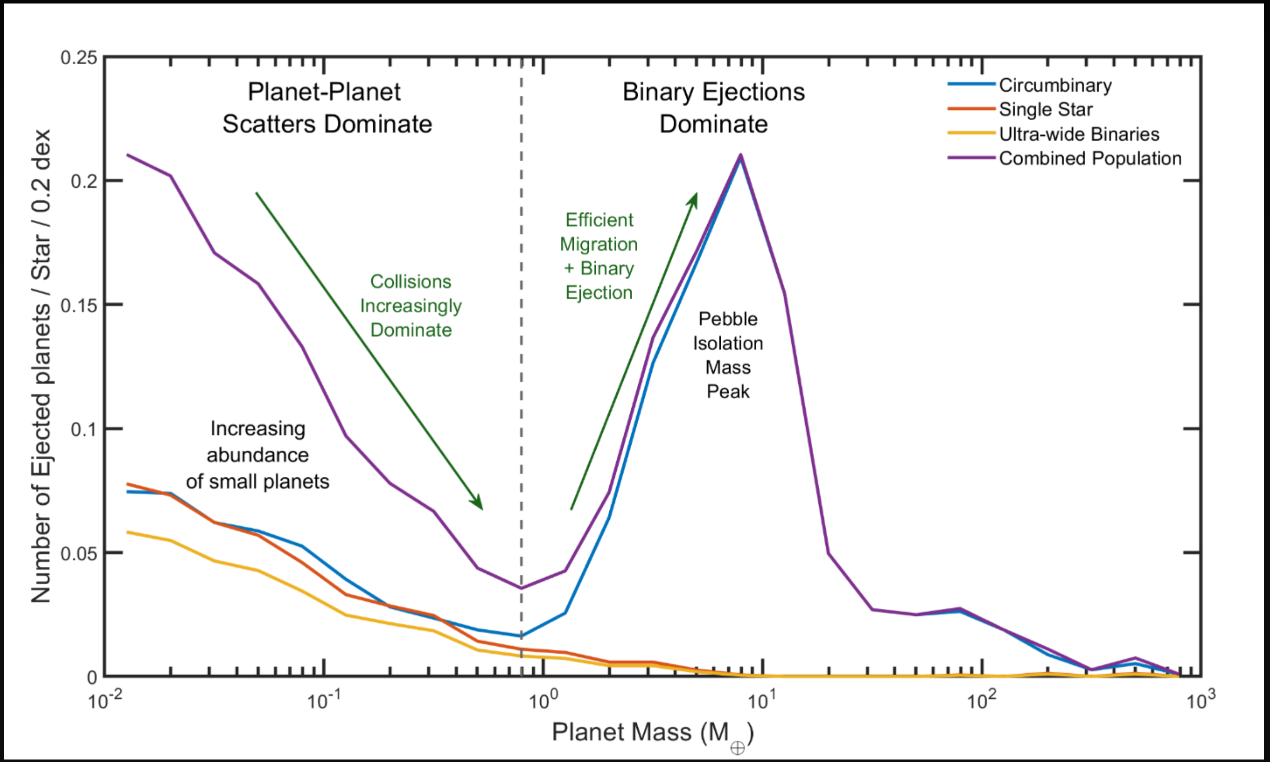
- Collisions between planets become more likely as mass increases
- Decreasing closest approach distances between mutually interacting planets
- Smaller delta-v between planets during interactions – more interactions required for ejection



Coleman & DeRocco 2024

Galactic population of FFPs

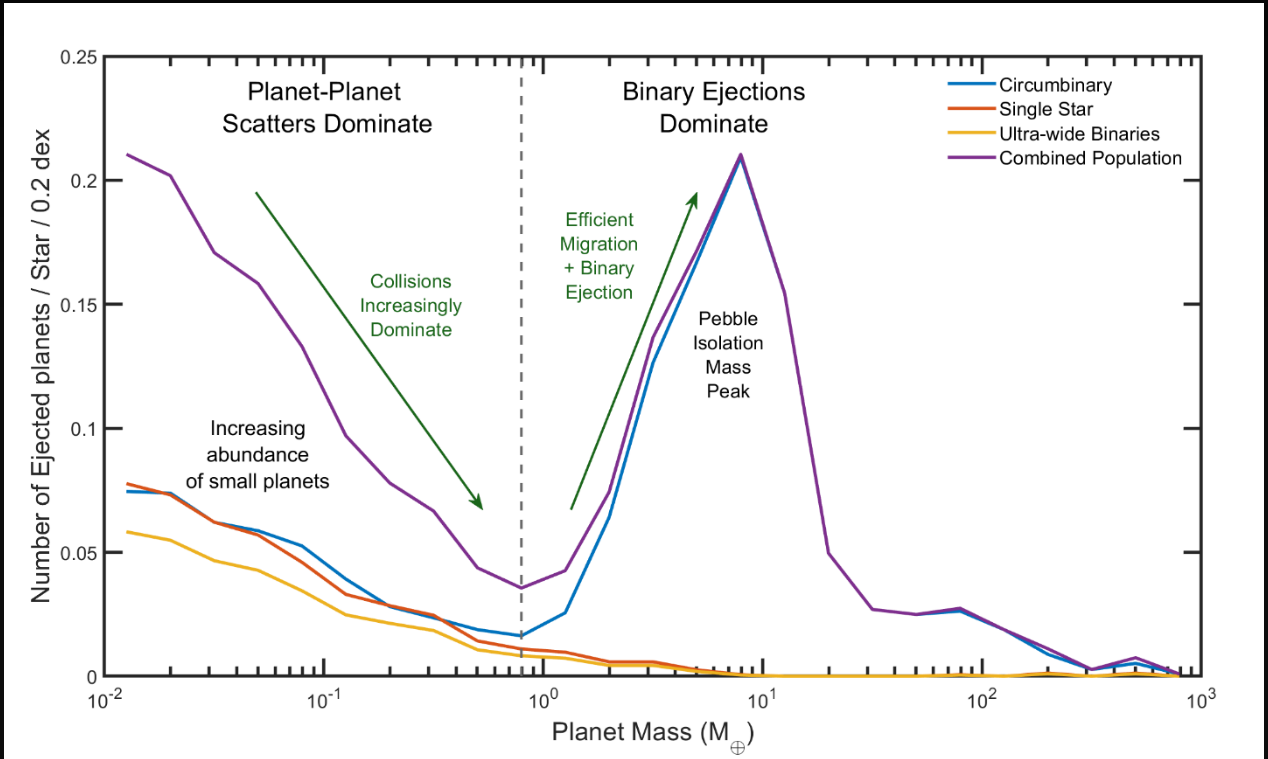
- As planets reach ~Mars mass, they begin migrating
- Efficient around an Earth mass – quickly reach the cavity near the central binary
- Interactions with one of the binary stars leads to their ejection



Coleman & DeRocco 2024

Galactic population of FFPs

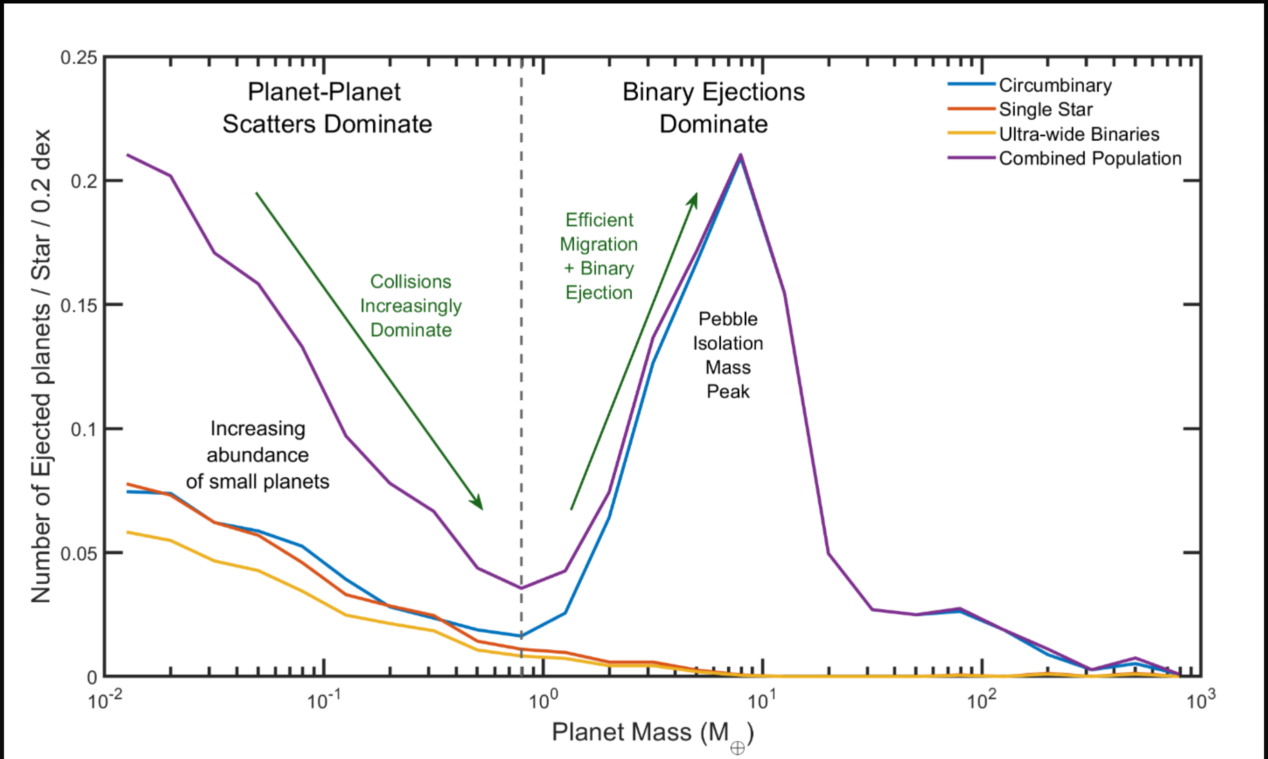
- Peak at super-Earth masses coincides with the Pebble Isolation Mass (PIM)
- Pressure bumps in the disc due to planets halts the supply of pebbles
- Planet growth transitions from fast pebble accretion to slow gas accretion



Coleman & DeRocco 2024

Galactic population of FFPs

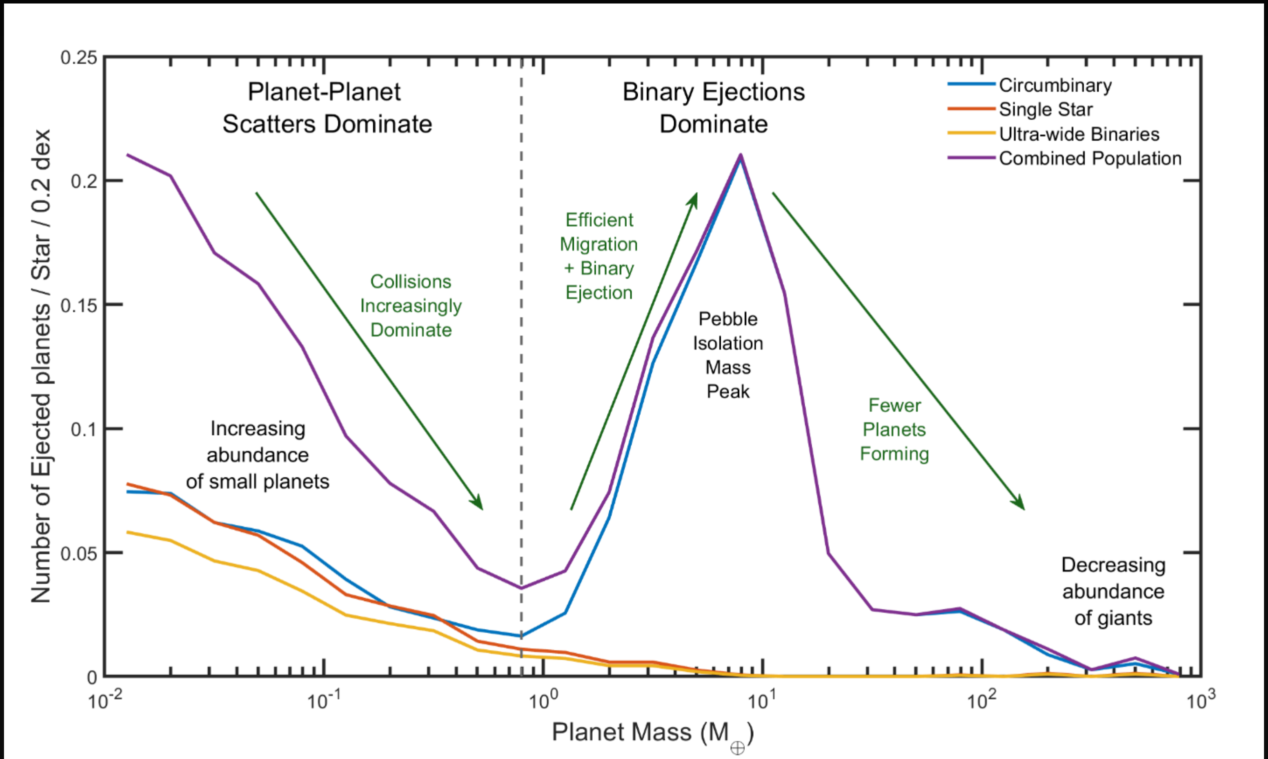
- Allows a large number of planets to occupy this mass range for a long time
- Increases their chances of ejection through binary interaction whilst they grow



Coleman & DeRocco 2024

Galactic population of FFPs

- Reduction in more massive planets being ejected due to lack of formation
- Lack of planets able to accrete significant gaseous envelopes and become giant planets
- Additionally, giant planets dynamically dominate their local area – less likely to be forced into ejection



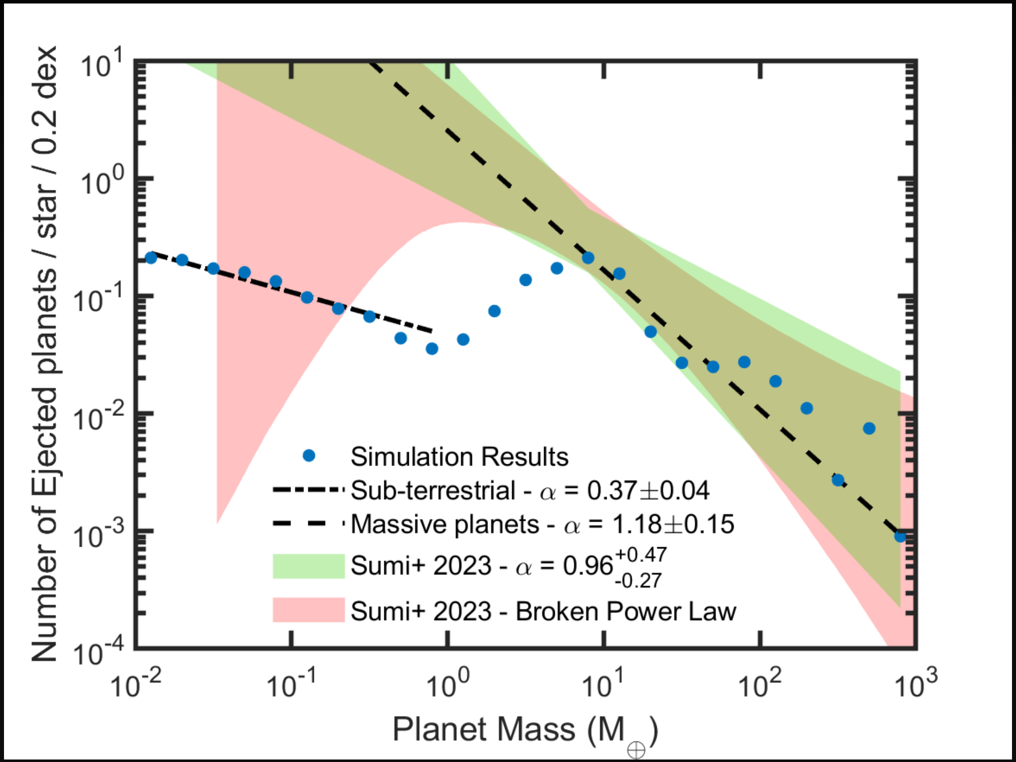
Coleman & DeRocco 2024

Match observations?

- Observations found a power law model fits the data well

$$\frac{dN}{d\log M} = \frac{2.18^{+0.52}_{-1.40}}{dex\ x\ star}\left(\frac{M}{8M_{\oplus}}\right)^{-0.96}$$

- Agreement for high mass planets above $8M_{\oplus}$
- Peak and trough not modelled in observations
- Seeing evidence of these peaks gives insights into the processes affecting planet formation



Coleman & DeRocco 2024

Conclusions

- Generated a galactic population of stars and FFPs using circumbinary planet formation simulations
- Mass distribution of FFPs does not follow a single power law – instead shows multiple features that give hints into planet formation processes:
  - Dearth of terrestrial mass planets – Collisions favoured over ejections
  - Peak at super-Earths – Migration and PIM
  - Lack of giant planets – gas accretion time-scales
- High mass planet distribution agrees with observed distributions
- Observed distribution extrapolates into low mass regime – poor agreement with models due to numerous features
- Galactic Population shows that circumbinary systems provide the majority of FFPs