Formation of second-generation exoplanets around double white dwarfs

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Reference paper
Ledda S., Danielski C., Turrini D. A&A 675, A184 (2023)

The formation and long-term evolution of circumbinary planetary systems across the H-R diagram
Florence,14-17 January 2025

Motivations

Circumbinary discs can form around double white dwarfs (DWD)

(e.g., Kashi & Soker 2011, Passy et al. 2012)

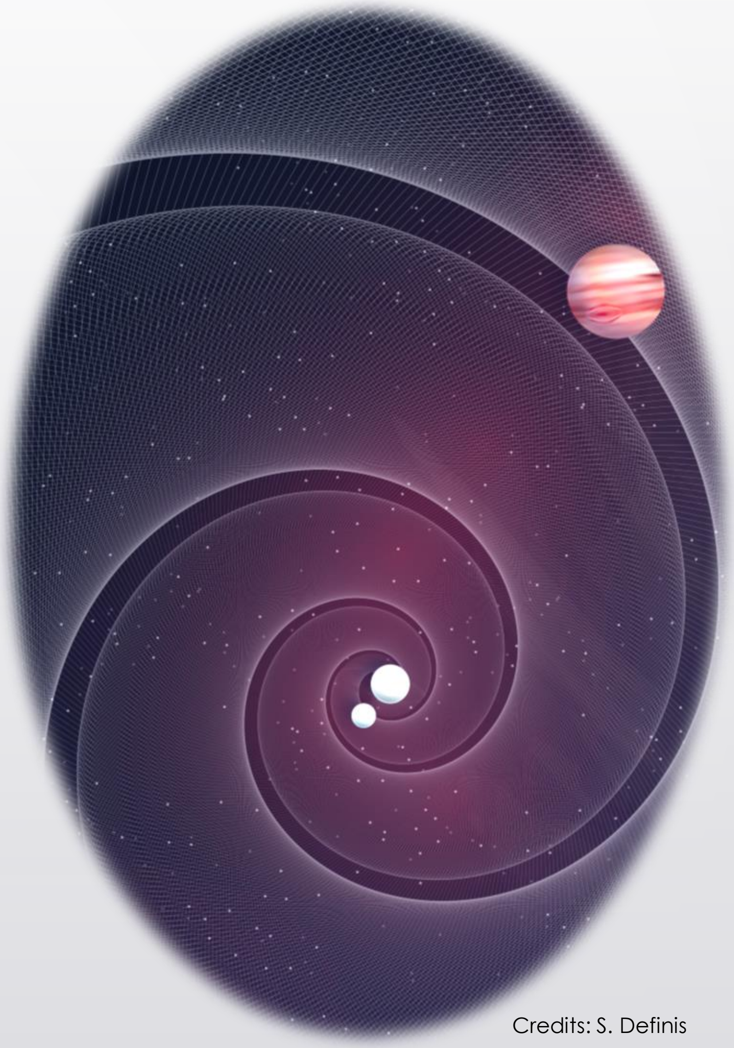
Unexplored testing ground for current planetary formation models

Constraining the population of potentially second-generation exoplanets

(e.g., Perets H. 2010, Zorotovic & Schreiber 2013, Volschow et al. 2014)

Supporting the planetary detection science case of the Laser Interferometer Space Antenna (LISA) mission

(e.g., Danielski et al. 2019)



Credits: S. Definis

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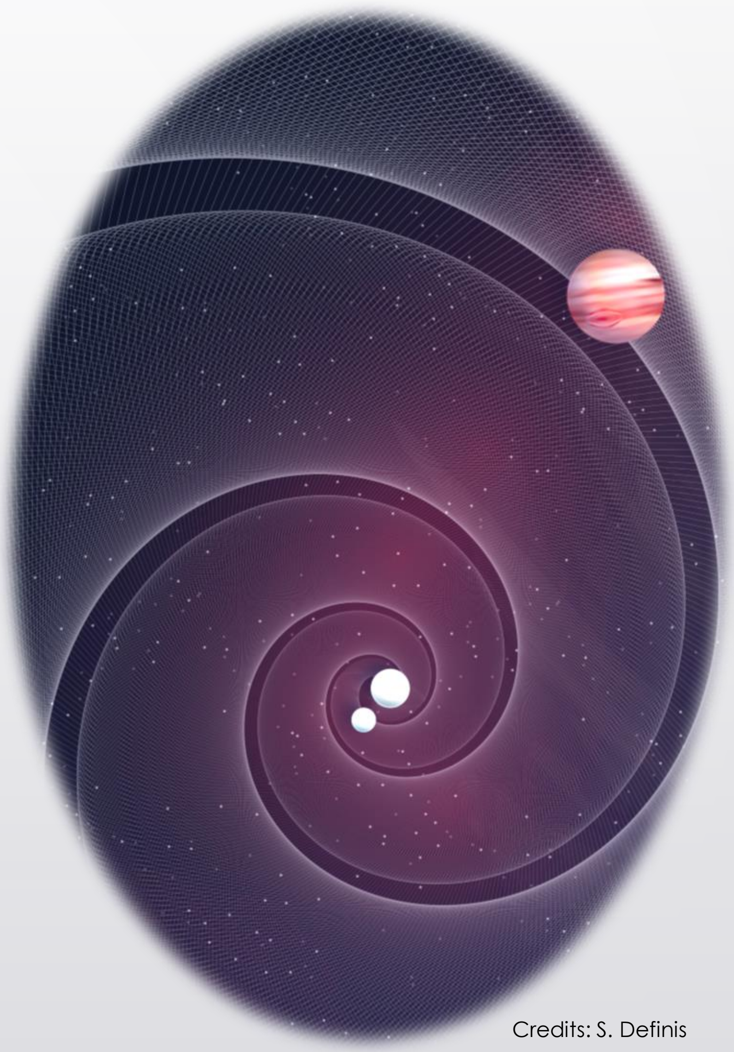
(e.g., Danielski et al. 2019)

What we found

- High metallicity and accretion rates are crucial to form gas giant (GG) planets
- Large population of sub-Neptunian (SN) and Neptunian (N) planets
- Final planet locations mostly within 5 au from the disc centre



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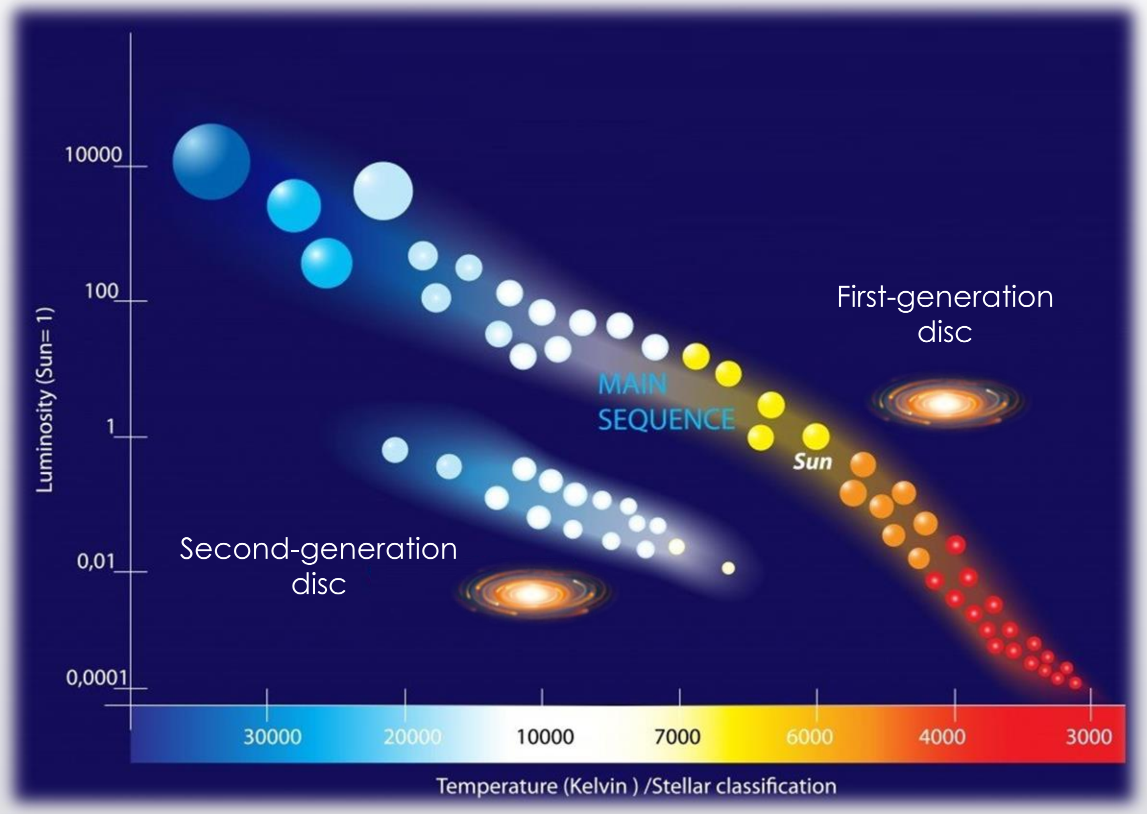
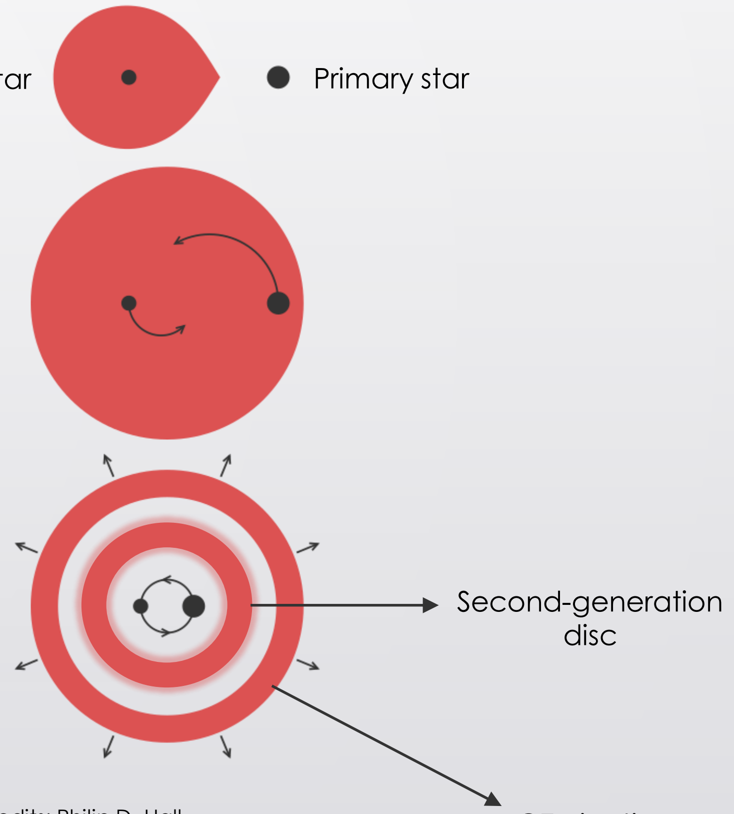
Binary evolution and disc formation



Credits: Designua/ Shutterstock

Case-study: common envelope (CE) evolution
(e.g., Ivanova 2011, Ivanova 2016)



Credits: Philip D. Hall

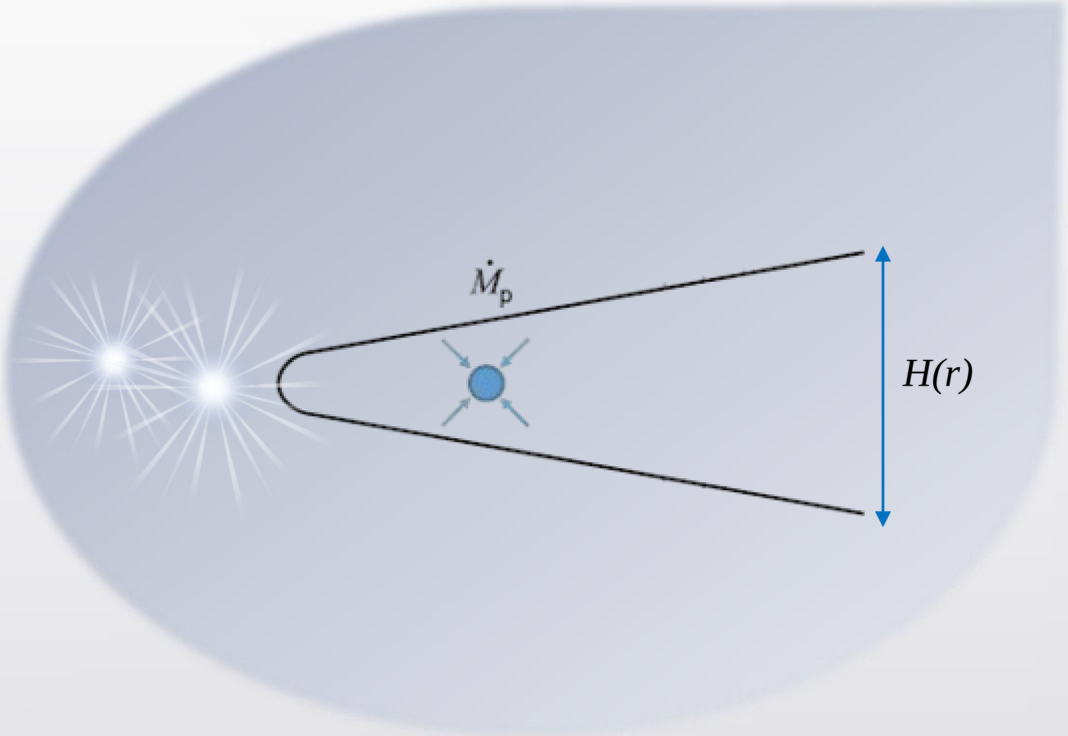
The disc models

- **Filling the gaps in our understanding working by analogy with pre-MS discs**

- **Time-independent**
  - Neglecting any evolution of the disc

Maximum planet-forming potential of the disc

Credits: Tanaka et al. 2020 ApJ 891, 143



The disc models

- **Filling the gaps in our understanding working by analogy with pre-MS discs**

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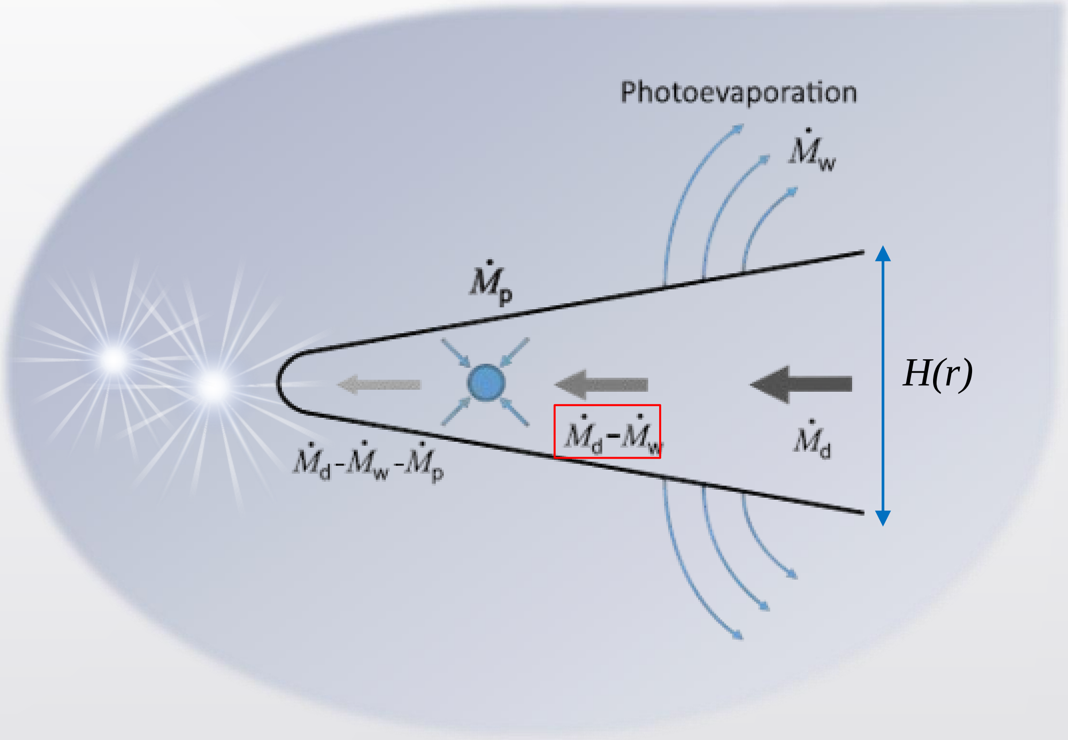
Maximum planet-forming potential of the disc

- **Time-dependent**
  - Viscosity-driven accretion rate onto the star ($\dot{M}_d$)
  - Photoevaporation rate ($\dot{M}_w = 10^{-8}\ M_\odot$/yr)

Limited disc lifetime

Time-dependent material supply to the planet-forming region

Credits: Tanaka et al. 2020 ApJ 891, 143



Planet formation processes

Runaway gas accretion

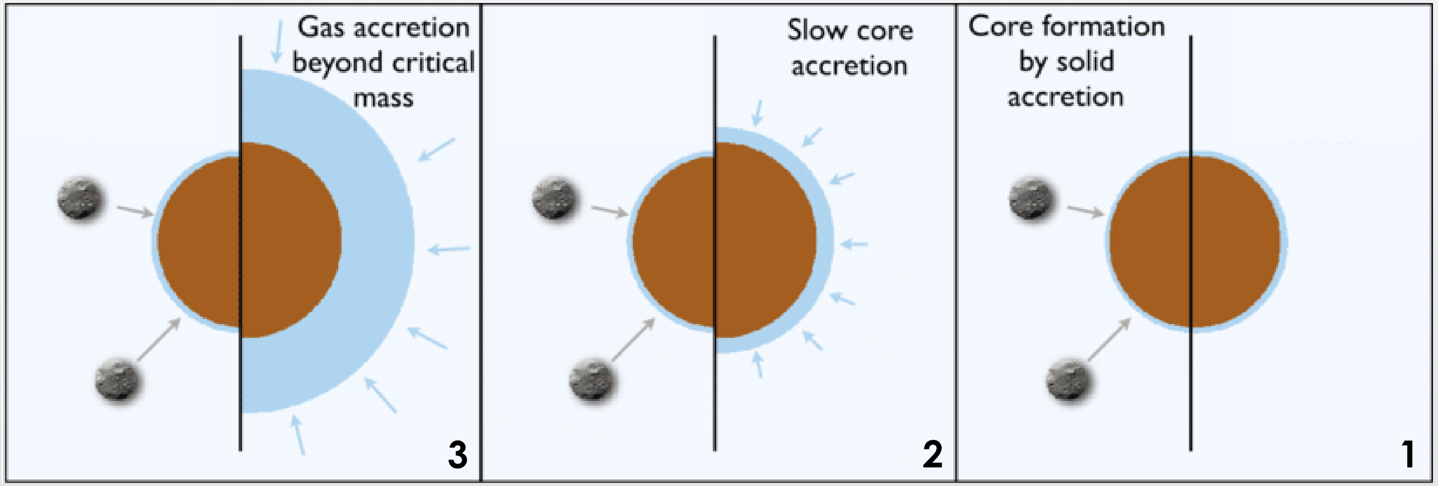
$$\frac{dM_p}{dt} \propto (\dot{M}_d - \dot{M}_w)$$

Gas contraction

$$\frac{dM_p}{dt} \propto M_p^{7/2}$$

Pebble accretion

$$\frac{dM_p}{dt} \propto \xi \dot{M}_d$$



Venturini, J., Ronco, M.P. & Guilera, O.M. *Space Sci Rev* **216**, 86 (2020)

Type II migration

$$\frac{dr}{dt} \propto -M_p \Sigma_{gap}$$

Type I migration

$$\frac{dr}{dt} \propto -M_p \Sigma_g (H/r)^{-2}$$

Simulations setup

Time before merging

DWD initial parameters

	M_1 [$M_\odot$]	M_2 [$M_\odot$]	P [h]	e	Δt	$T_{\rm eff\,1}$ [K]	$T_{\rm eff\,2}$ [K]
DWD_1	0.60	0.38	20.47	0	135 Gyr	8600	75 000
DWD_2	0.21	0.31	0.43	0	9 Myr	20 400	58 400
DWD_3	0.75	0.26	1.51	0	150 Myr	8800	52 000
DWD_4	0.31	0.25	1.71	0	430 Myr	8100	50 100

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Free parameters

Parameter	Values
t_0 [Myr]	$10\tau_c$, 0.1, 1
ξ	0.01, 0.015, 0.02
r_c [au]	50, 100, 150

First generation seeds

Second generation seeds

Simulations setup

DWD initial parameters

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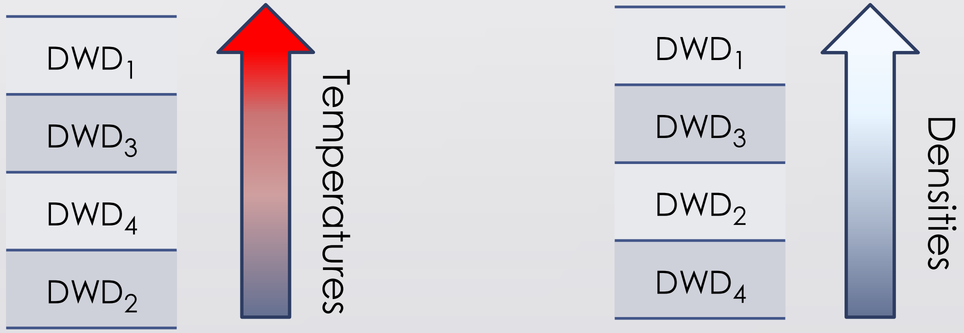
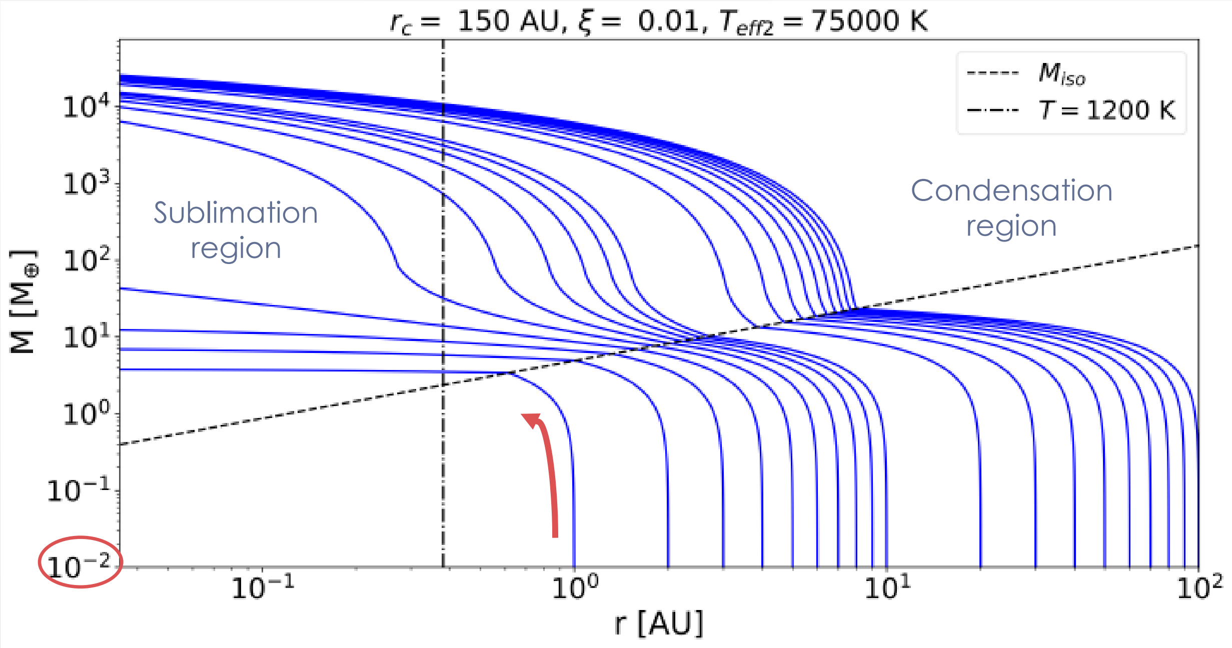
First generation seeds

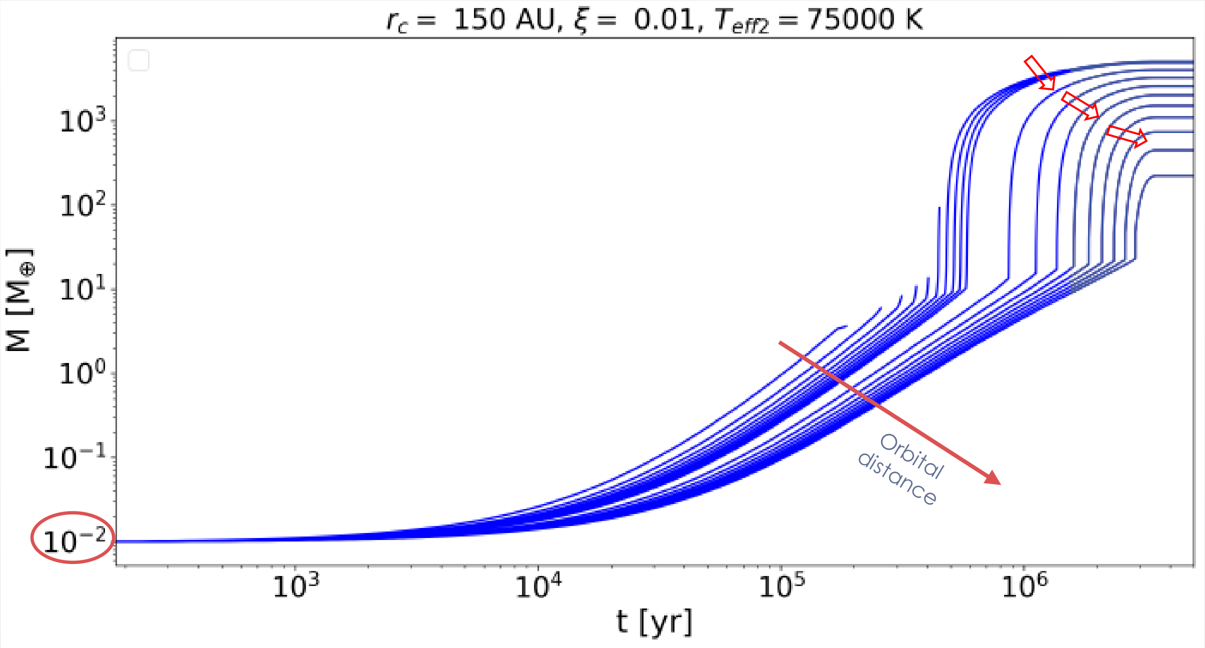
Second generation seeds

Initial formation environment



Results – Time-independent vs Time-dependent tracks





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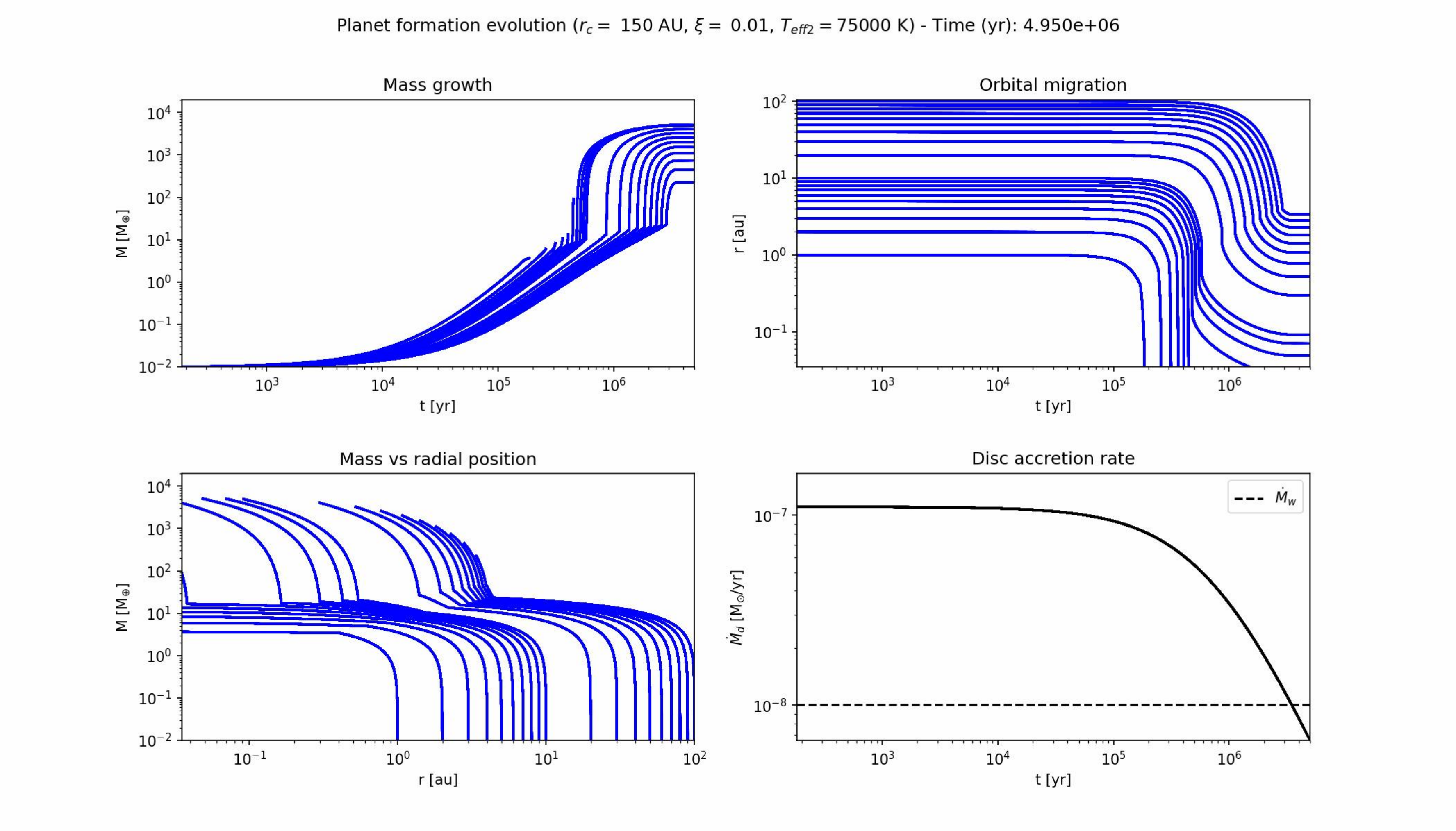
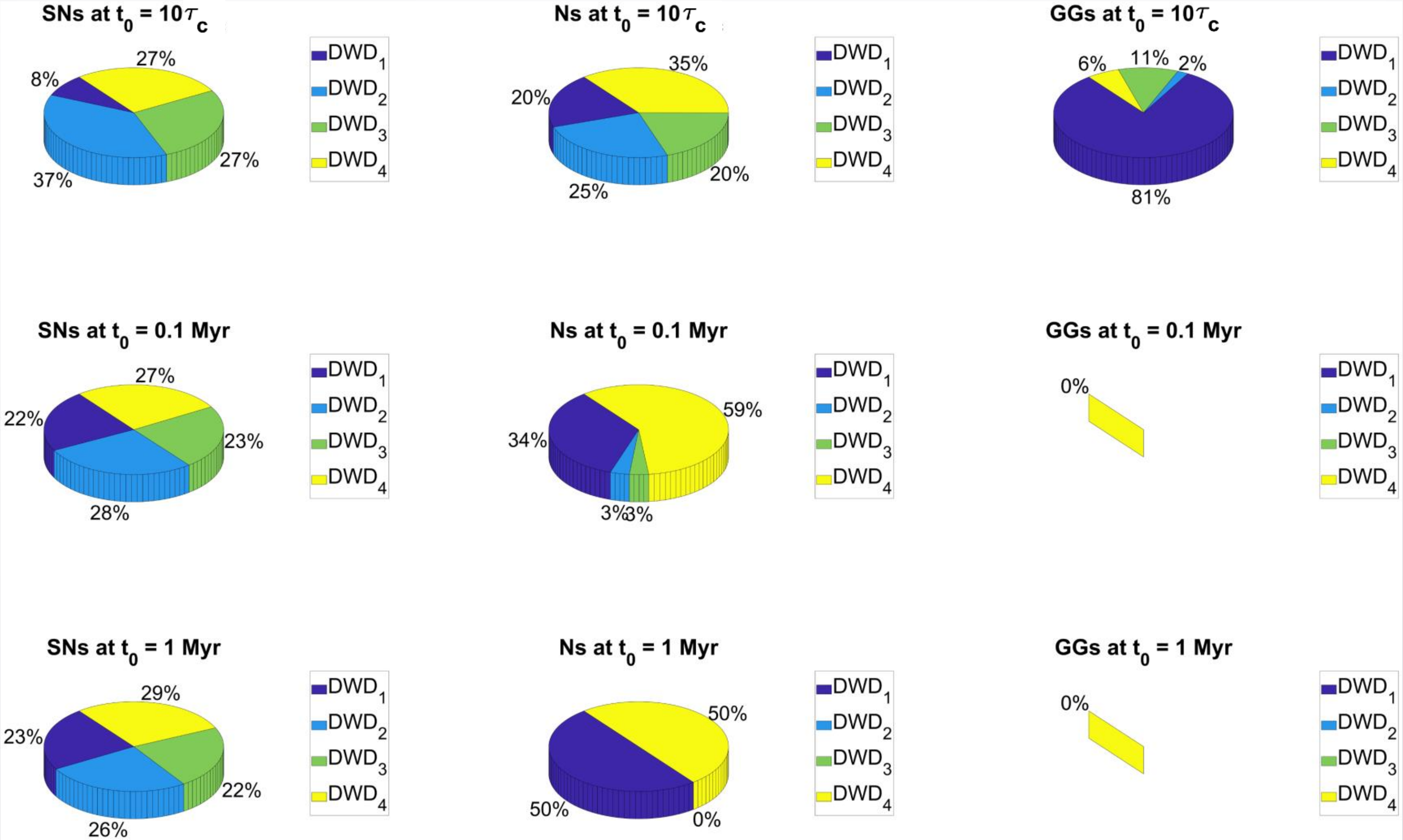


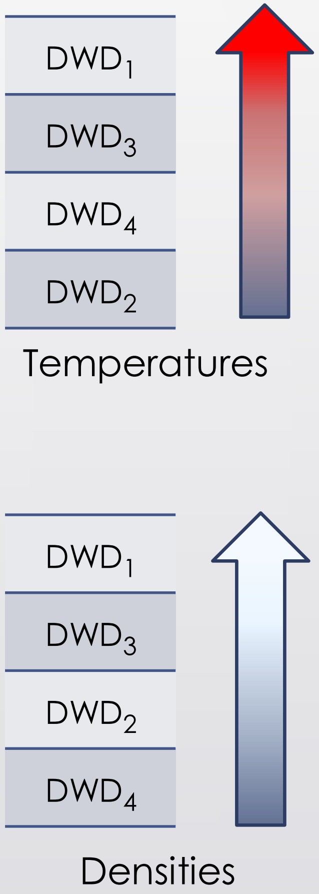
Results – Planets distribution

First-generation seeds

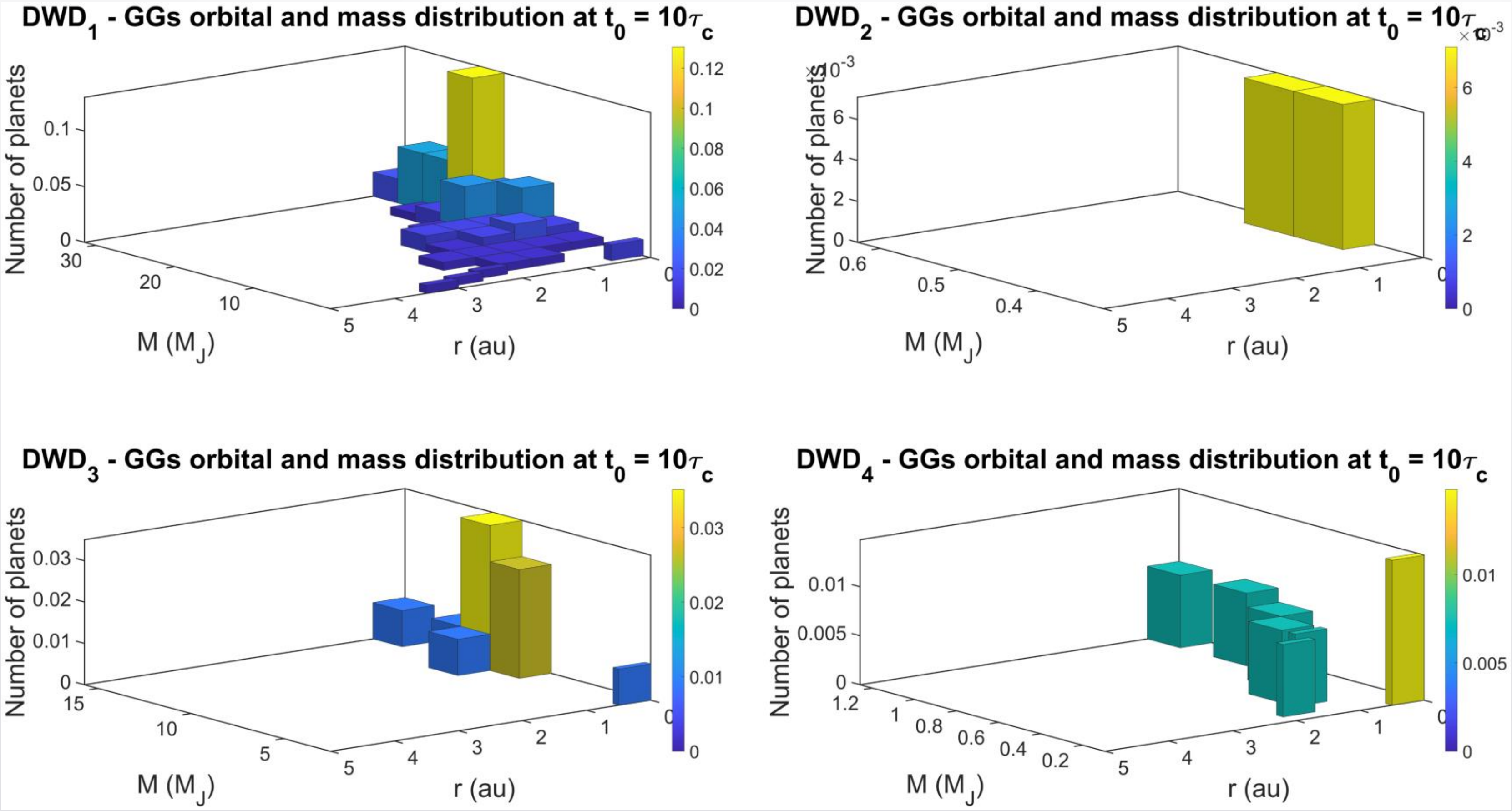
Second-generation seeds

Second-generation seeds



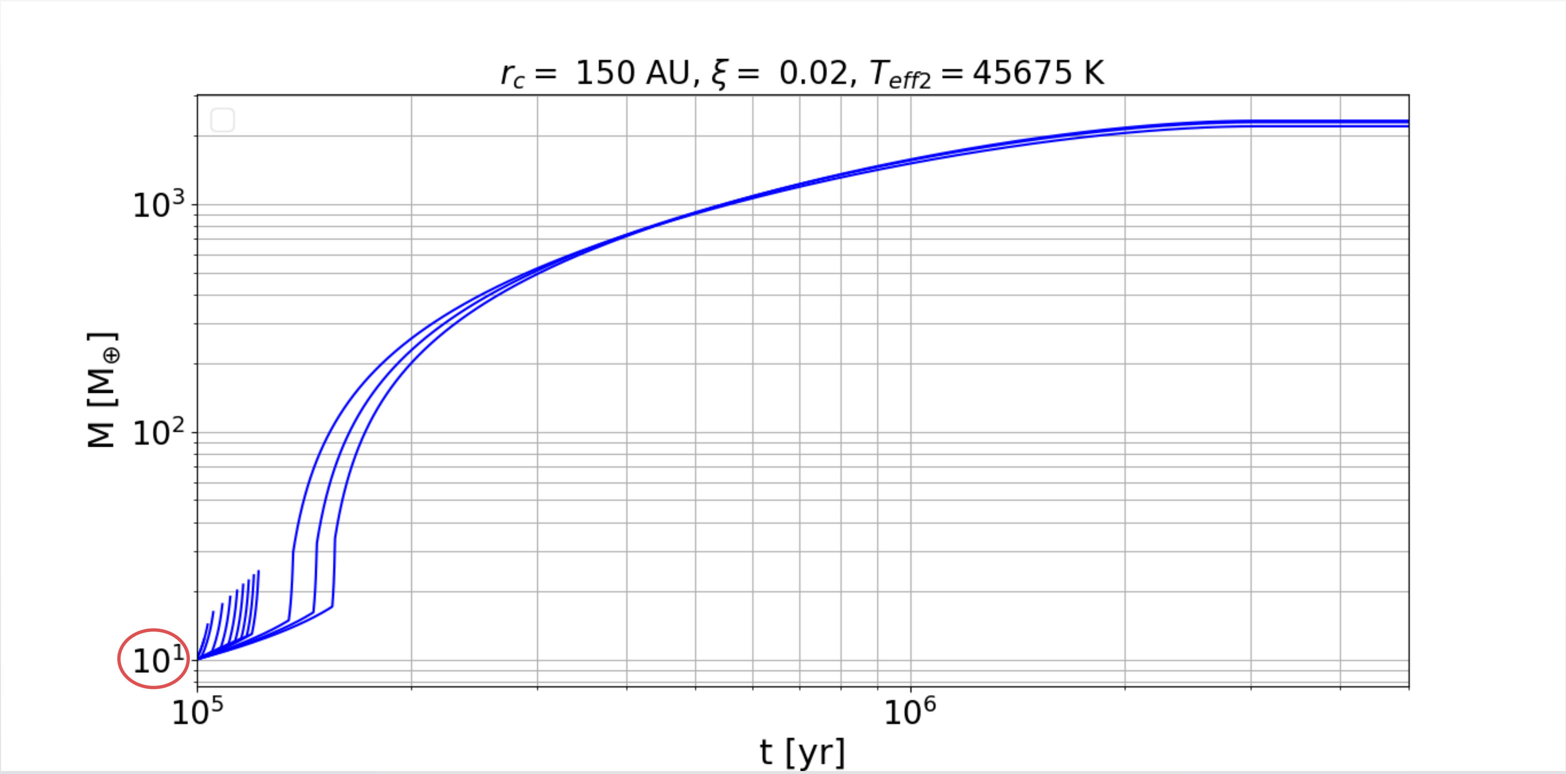


Results – Final masses and locations of GGs



Results – Body survived to the CE

t_0 = 0.1 Myr



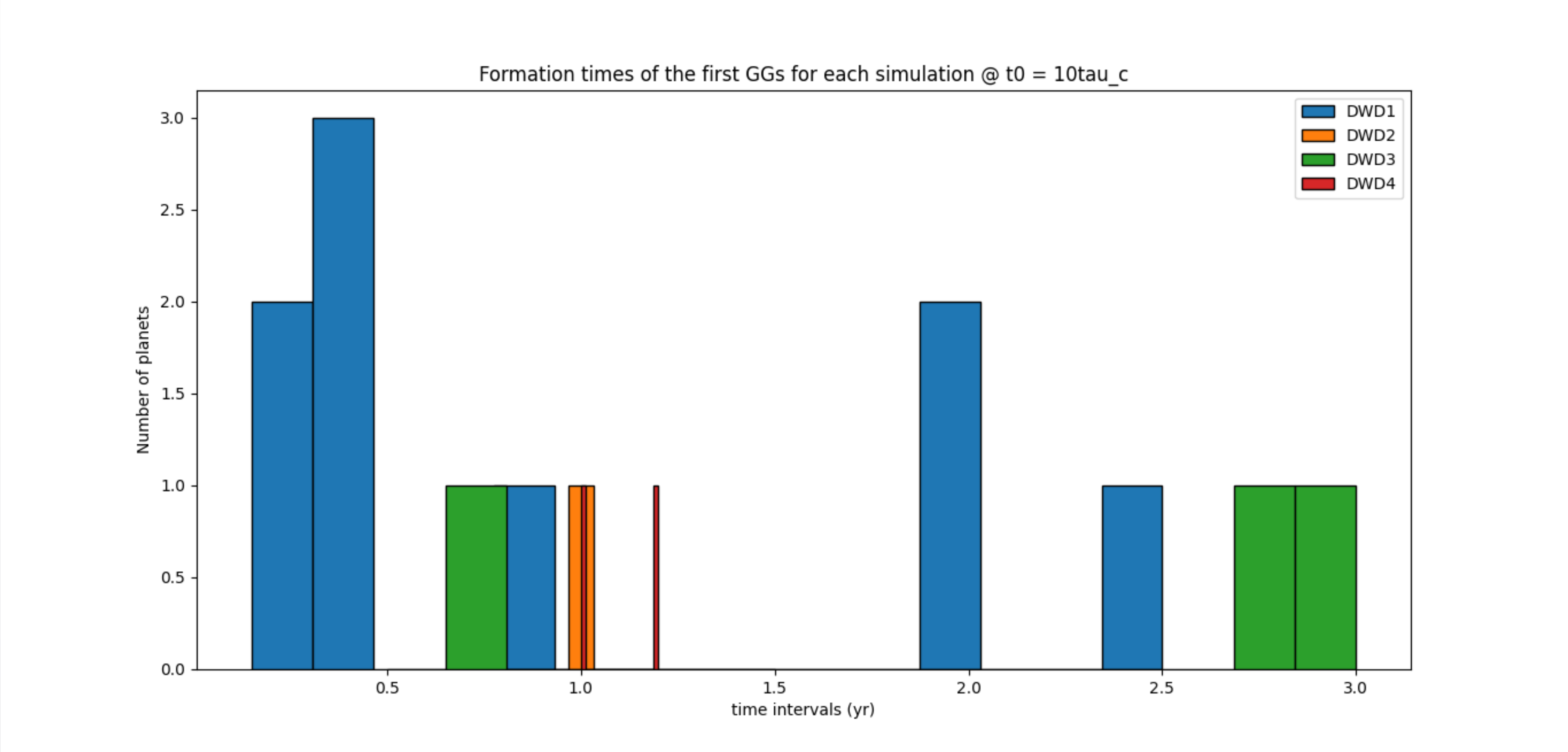
Conclusions

Planetary formation should be common in circumbinary discs around DWDs

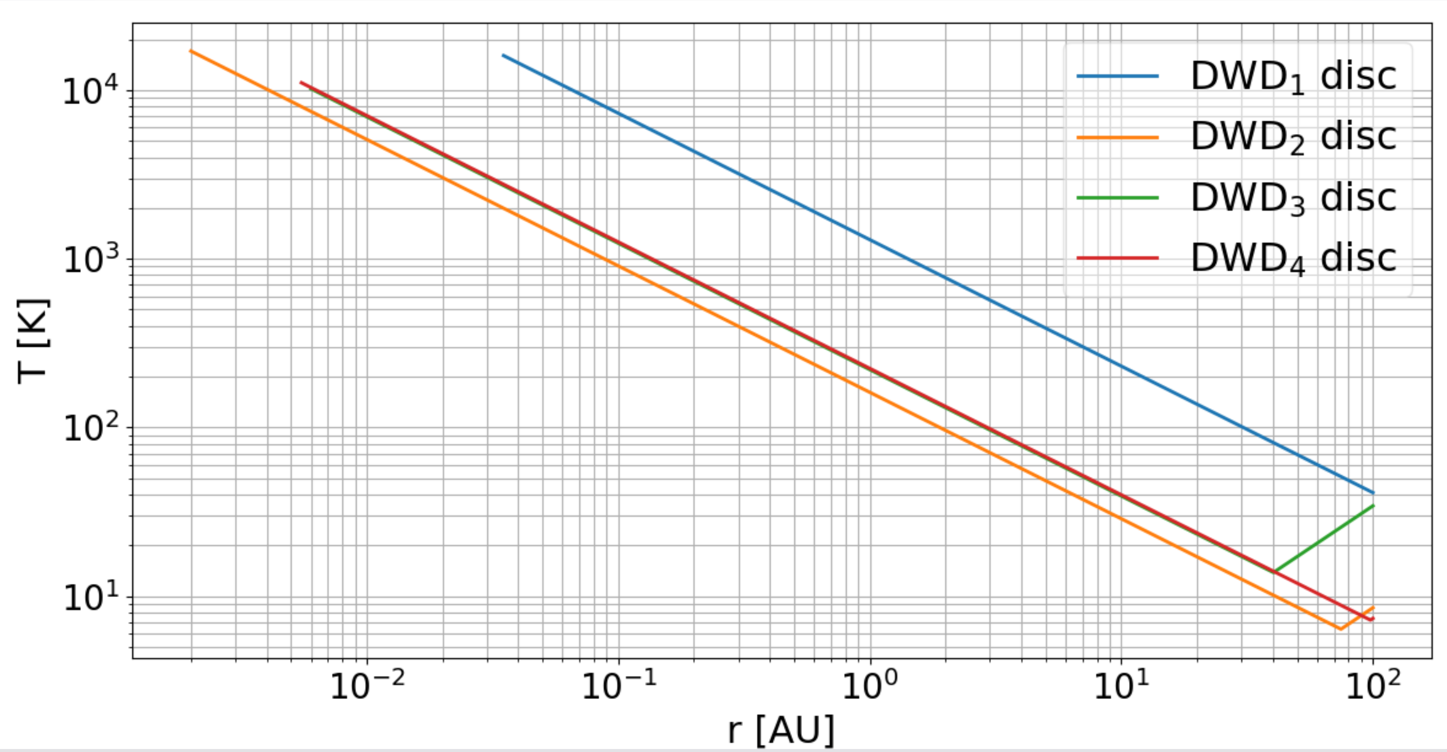
- High accretion rate and dust-to-gas ratio defines the best environment for planet formation, especially for GGs formation
- GGs can form only if the disc includes first-generation seeds with masses equal or larger than the Moon mass
- The higher the photoevaporation rate, the smaller the number and masses of the GGs, and the farther their final locations
- SNs and Ns can either be of first-generation or second-generation nature, and their evolution ends within 1 AU
- DWDs can host circumbinary planets detectable by LISA during the nominal time of the mission
  - Locations within 5 au
  - Masses larger than 1 M_J

Bakcup slides

Formation times of the first GGs

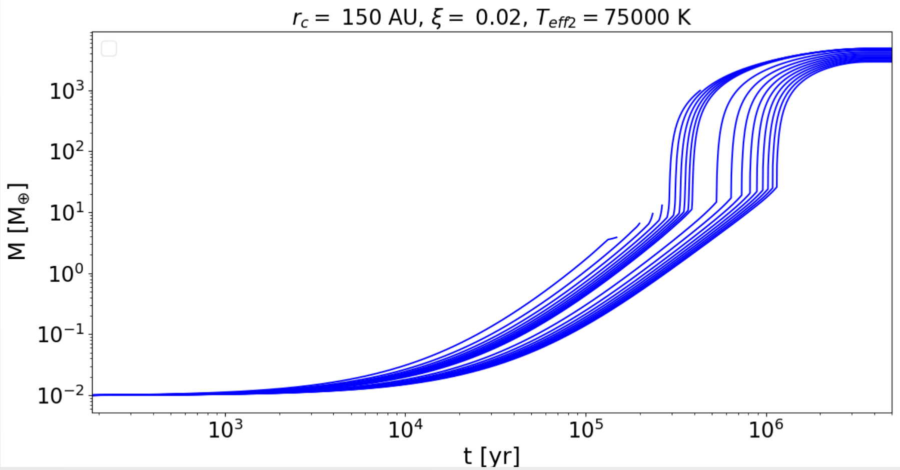


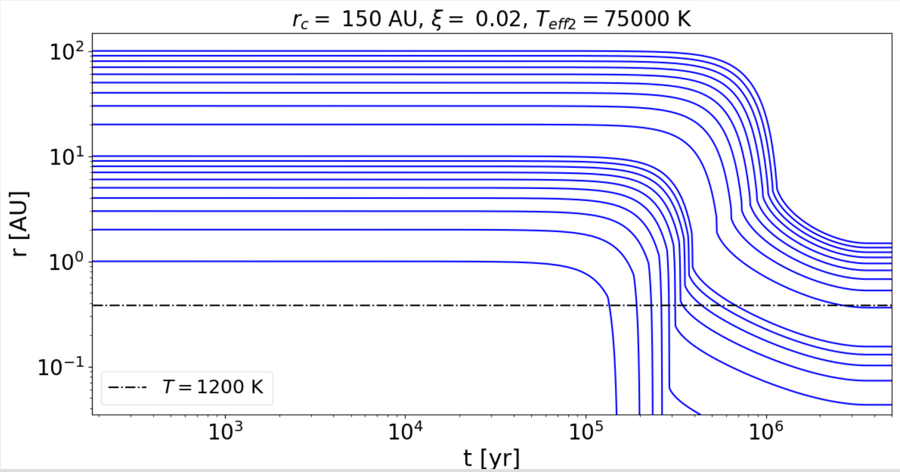
Initial temperature profiles



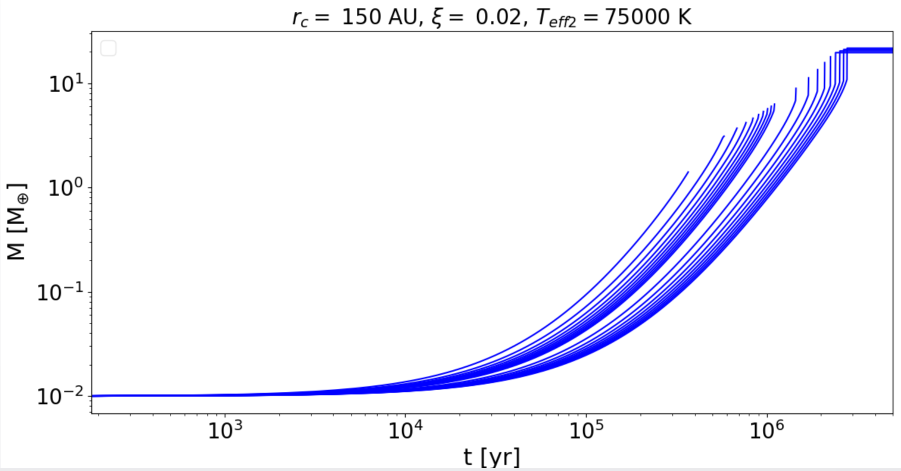
Growth tracks in the best case scenario with α < 0.01

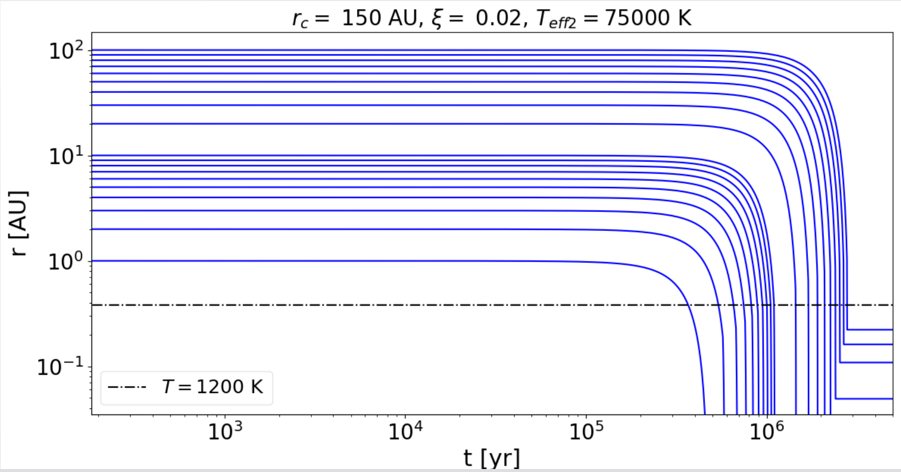
α = 0.005



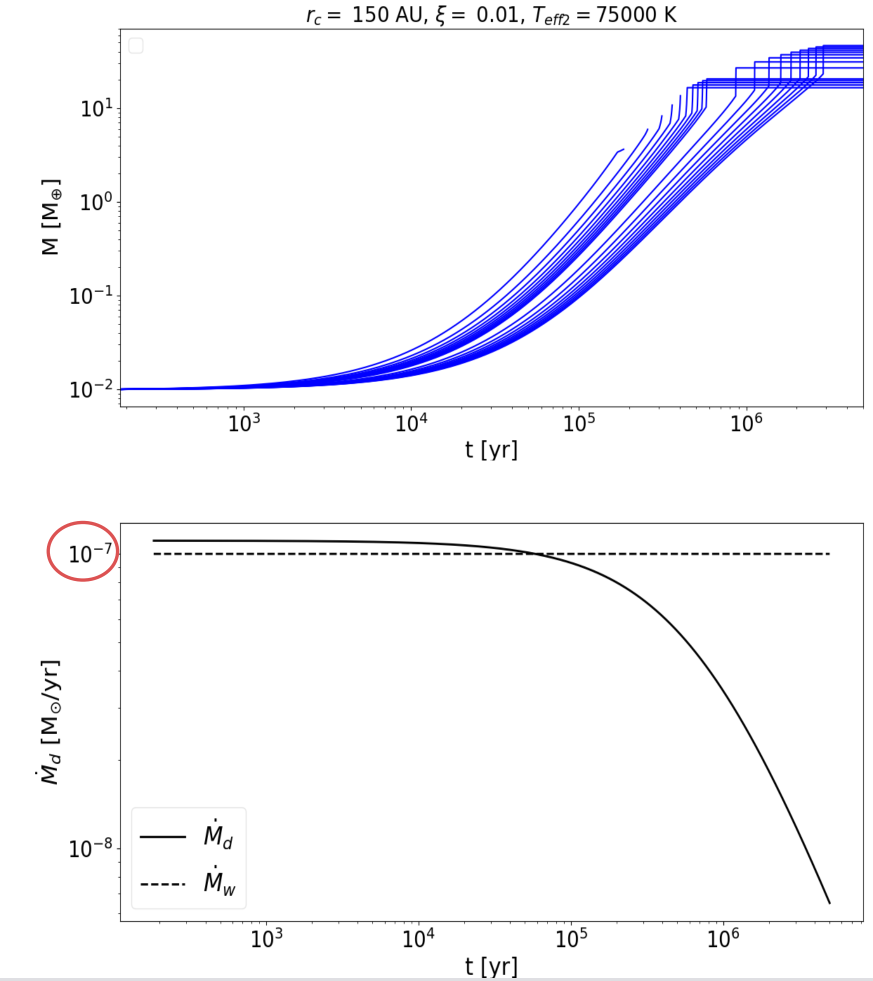


α = 0.001



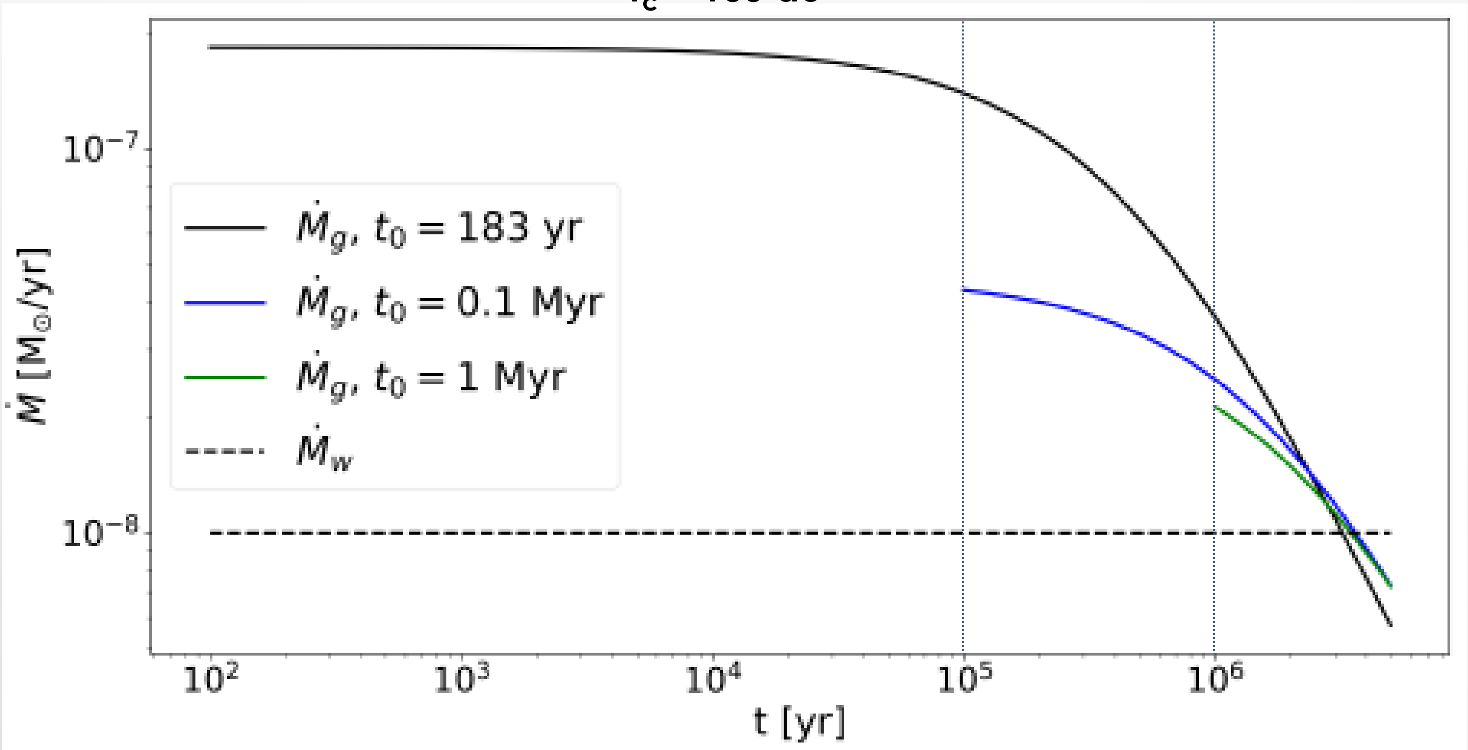


Results – Increased photoevaporation rate

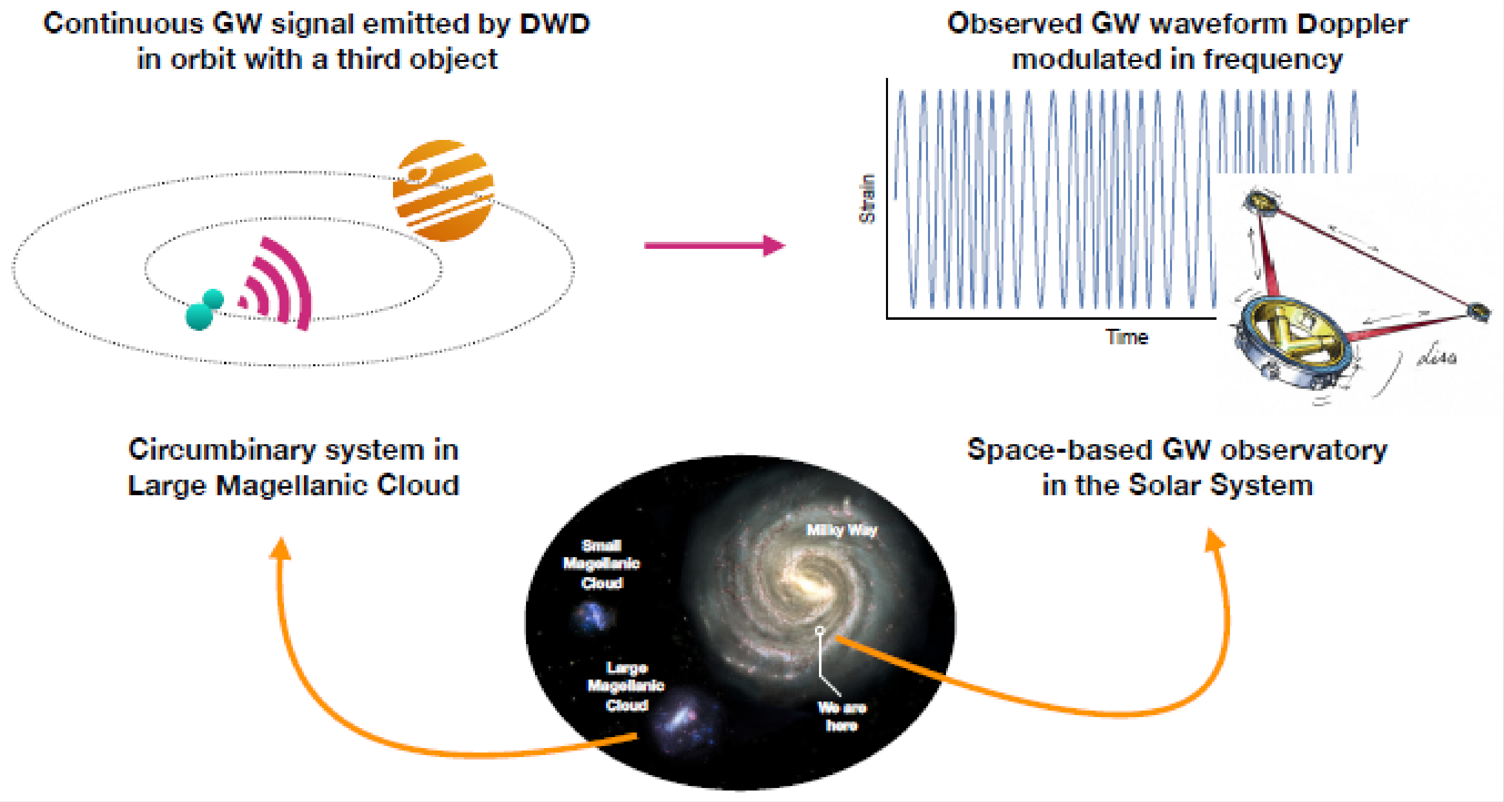


Accretion rates of the DWD_1 disc vs time

r_c = 100 au



Planet detection through gravitational waves



Tamanini N. & Danielski C. 2019 Nat. Astron. 3, 858