Where is the origin of giant planets?

Bertram Bitsch

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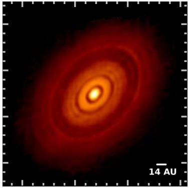
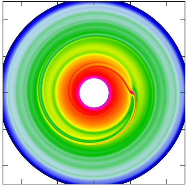
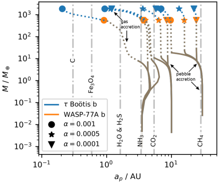
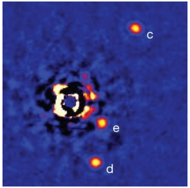
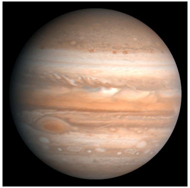


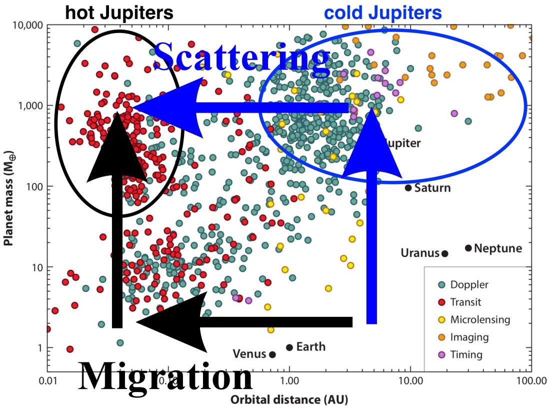








Where did the giant planets form?



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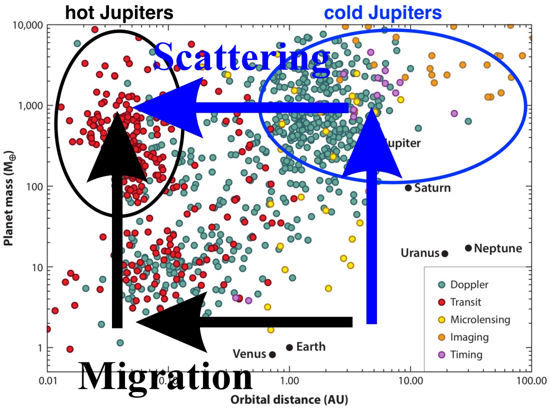

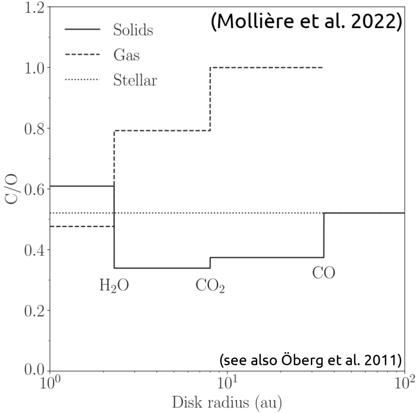

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⇒ The disc's C/O ratio changes with distance, potentially suggesting that we can constrain planet formation via atmospheric C/O ratios

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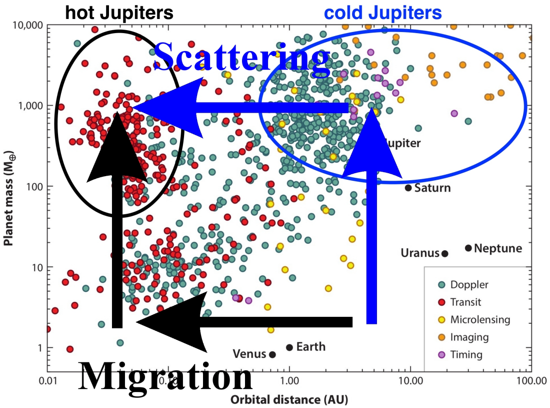
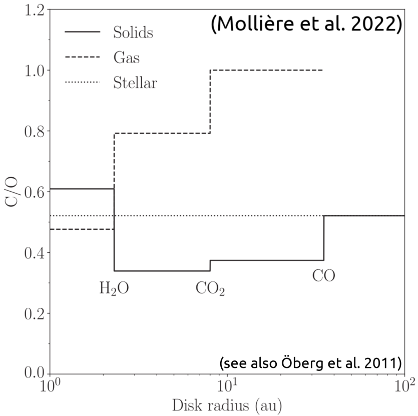




- Where did the giant planets form?

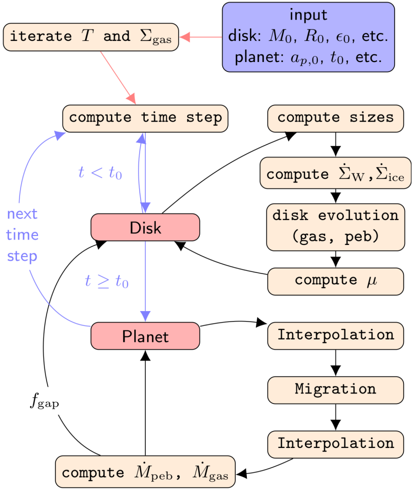
⇒ The disc's C/O ratio changes with distance, potentially suggesting that we can constrain planet formation via atmospheric C/O ratios

⇒ How complicated does this actually become?

Model: chemcomp

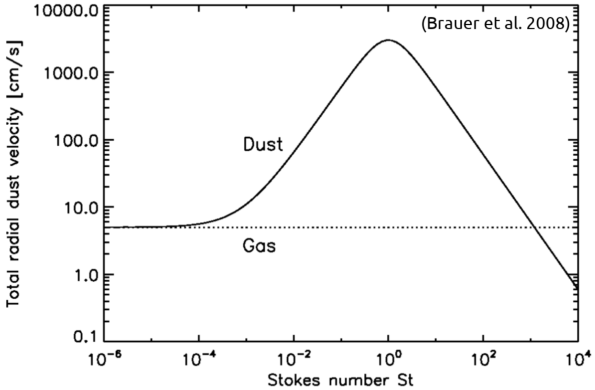
- Viscous disc evolution
- Pebble growth and drift
  (*Birnstiel et al. 2012*)
- Pebble evaporation and recondensation at ice lines
- Chemical partitioning model: No chemical evolution
  (Motivation: *Booth & Ilee 2019, Eistrup & Henning 2022*)
- Pebble accretion
  (*Johansen & Lambrechts 2017*)
- Gas accretion, limited by $\dot{M}_{\rm disc}$
  (*Ndugu et al. 2021*)
- Type-I migration
  (*Paardekooper et al. 2011*)
- Type-II migration
  (*Ndugu et al. 2021*)

$\Rightarrow$ Code is publicly available!
(*Schneider & Bitsch 2024*)



(*Schneider & Bitsch, 2021a*)

Effects of pebble drift and evolution



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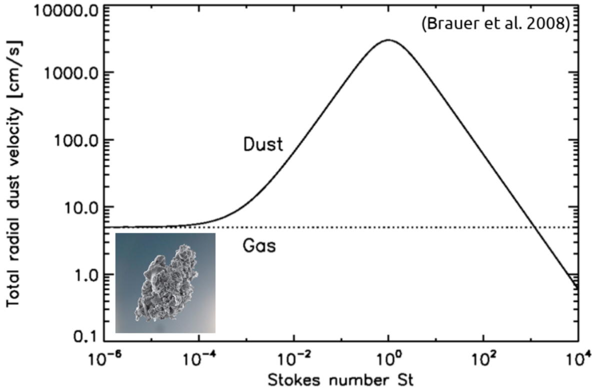

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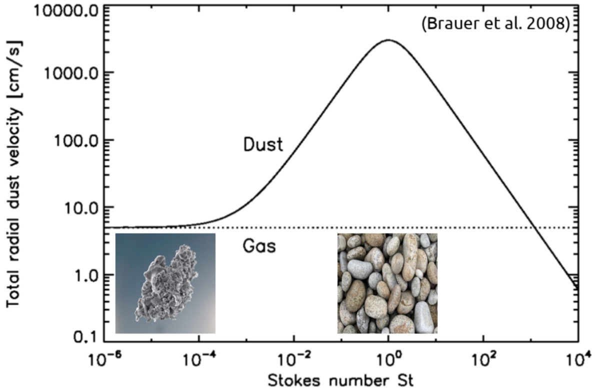

- Pebbles drift inwards faster than the gas moves!

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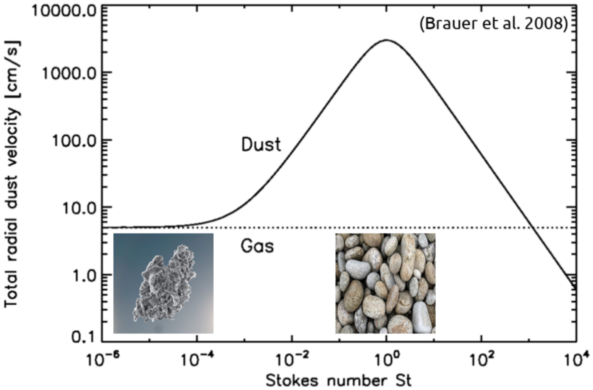

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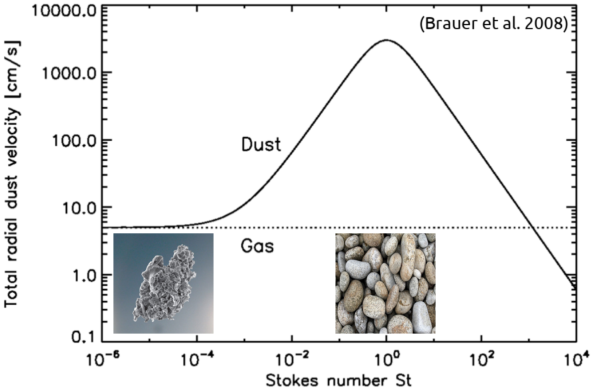

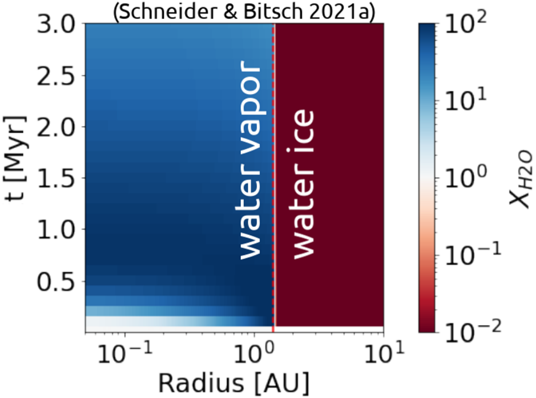

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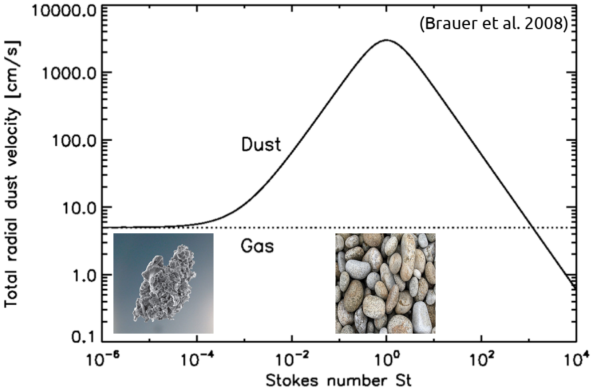

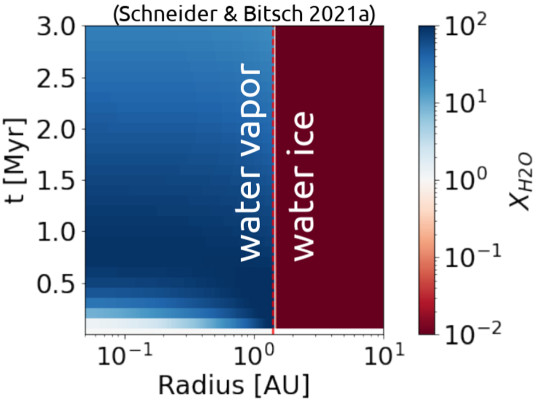

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$\Rightarrow$ Disc composition evolves with time!

What do you need to make a good pizza?

What do you need to make a good pizza?

⇒ It matters what you put in it!

⇒ But not all ingredients matter equally!

Assumptions vs. constraints
Initial Assumptions

- Disc mass/radius: M_{disc}, R_{disc}
- Viscosity: $\nu = \alpha c_{\mathrm{s}} H$
- Grain sizes: u_{f}
- Planetary growth model: $\dot{M}_{\mathrm{gas}}$
- Embryo starting time: t_0
- Embryo starting position: a_0
- Late infall? Stellar Fly-bys?
- ...

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Available Constraints

- Stellar mass/abundances: $M_{\rm star}$, X/H
- Planetary mass/radius; $M_{\rm P}$, $R_{\rm P}$
- Planetary atmospheric composition: C/H, O/H, S/H, ...
- Planetary heavy element content: $M_{\rm z}$
- Final planetary position: $a_{\rm P}$
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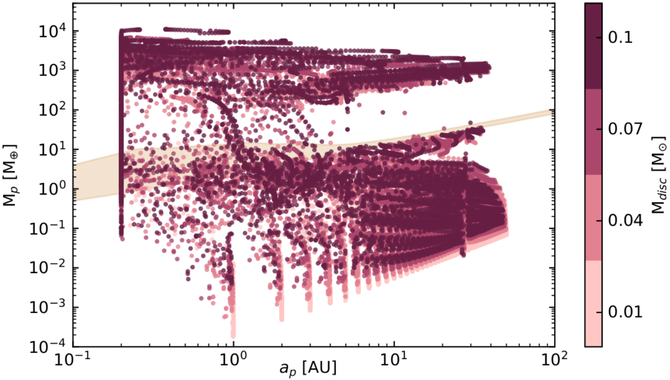
$\Rightarrow$ Want to determine the formation location of giant planets!

$\Rightarrow$ In most cases, not all constraints are available at the same time!

$\Rightarrow$ Not enough constraints to cover all initial assumptions...

$\Rightarrow$ But do all initial assumptions matter equally?

Formation of planets



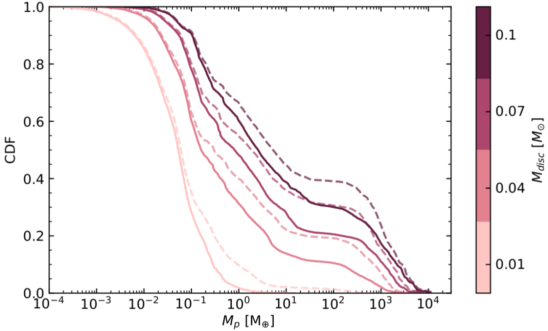
(*Savvidou & Bitsch 2023*)

$$M_{\rm disc} = 0.01, 0.04, 0.07, 0.1 M_\odot \qquad u_{\rm frag} = 1, 4, 7, 10 \mathrm{m/s}$$

$$t_0 = 0.1, 0.5, 0.9, 1.3 \mathrm{Myr} \qquad \alpha = 10^{-4}, 5 \times 10^{-4}, 10^{-3}$$

$$R_{\rm disc} = 50, 100, 150, 200 \mathrm{AU} \qquad f_{\rm DG} = 0.01, 0.015, 0.03$$

Planet growth: What disc conditions are needed to form giant planets?



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- Large disc mass beneficial for giant planet formation

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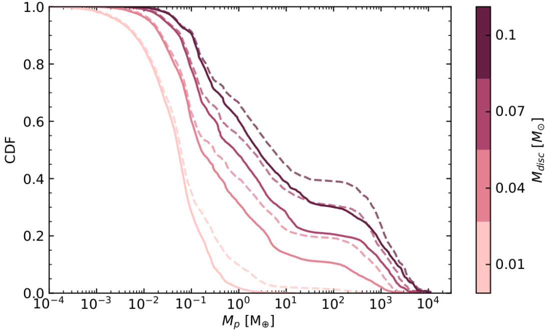

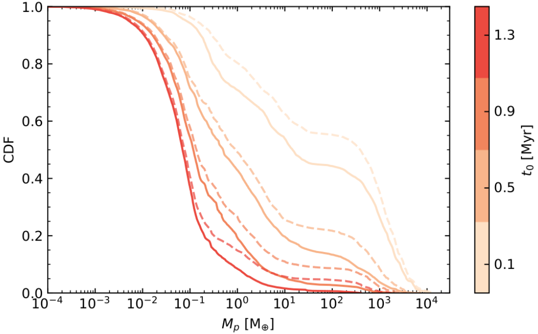

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- Large disc mass beneficial for giant planet formation
- Early starting time beneficial for giant planet formation

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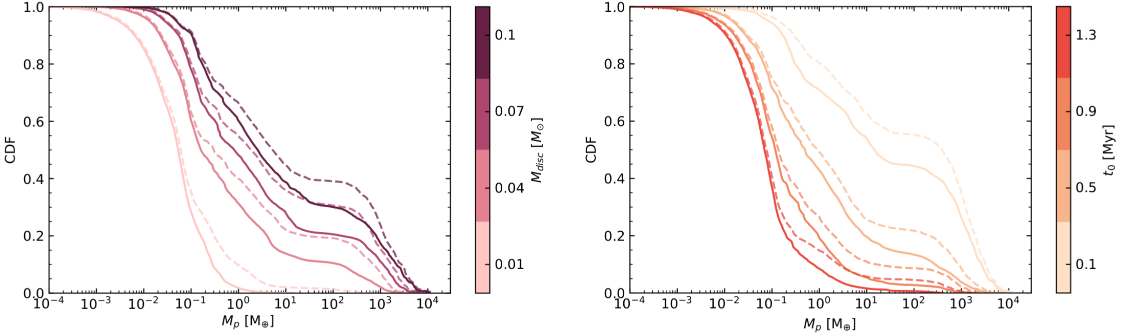

(*Savvidou & Bitsch 2023*)

- Large disc mass beneficial for giant planet formation
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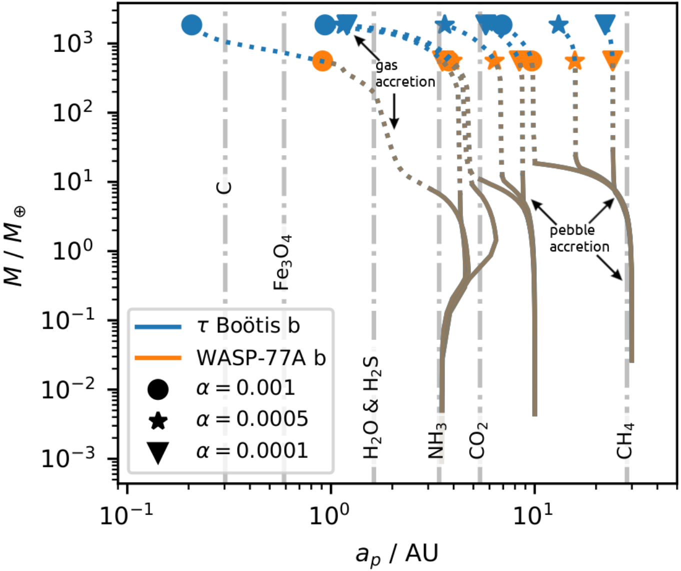
⇒ Multiple factors and their combination important to allow the formation of giant planets!

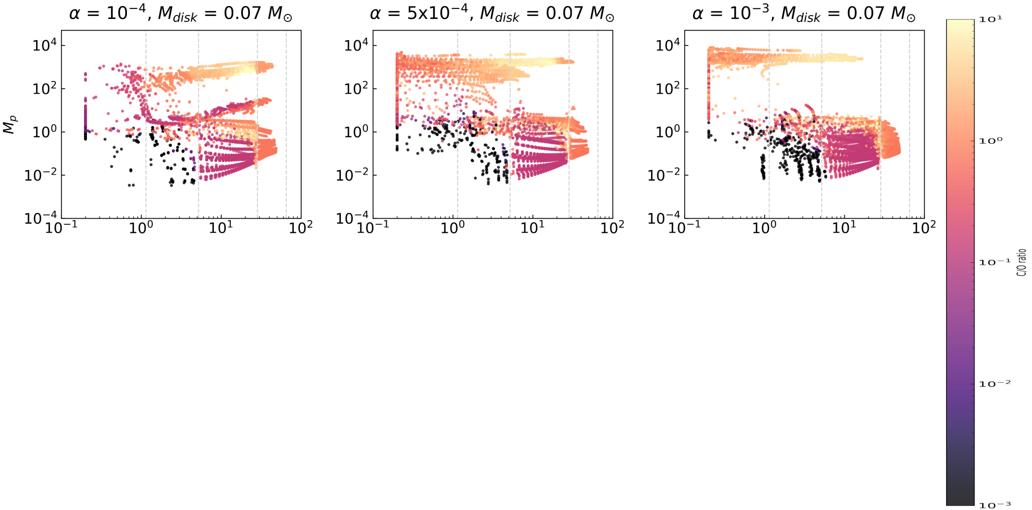
⇒ To make giant planets, one can chose larger disc masses and early starting times!

Growth Tracks



(*Bitsch et al. 2022*)

General trends for planetary compositions?



(*Guzman Franco, Savvidou & Bitsch, 2026*)

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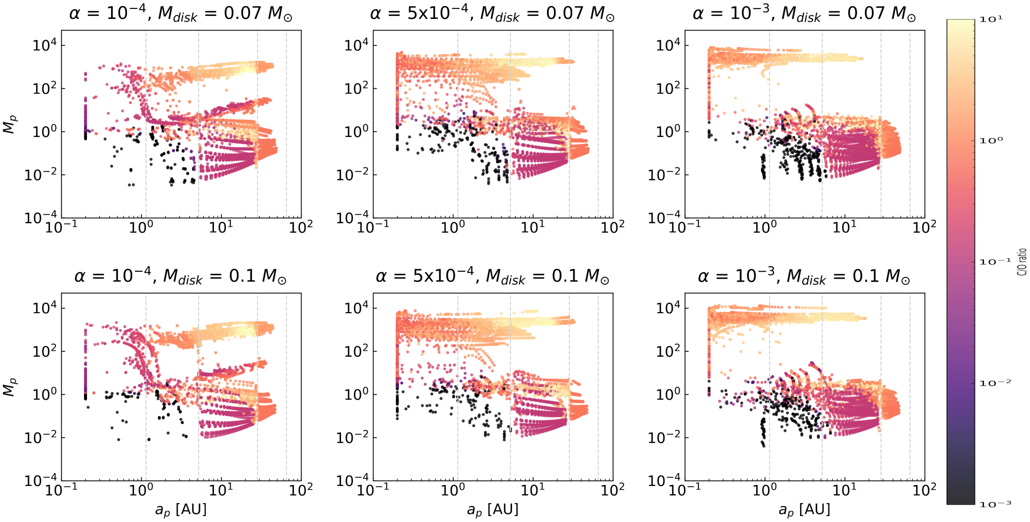
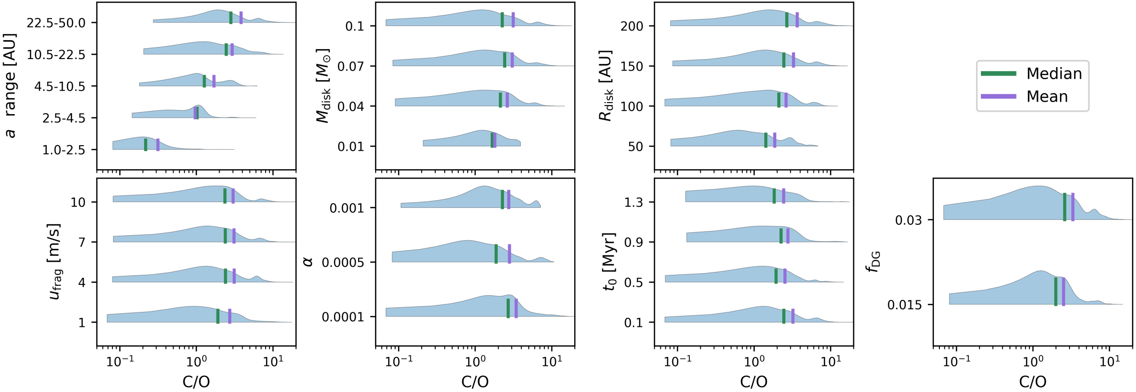


(*Guzman Franco, Savvidou & Bitsch, 2026*)

Full sample for planets above 100 Earth masses: C/O ratio



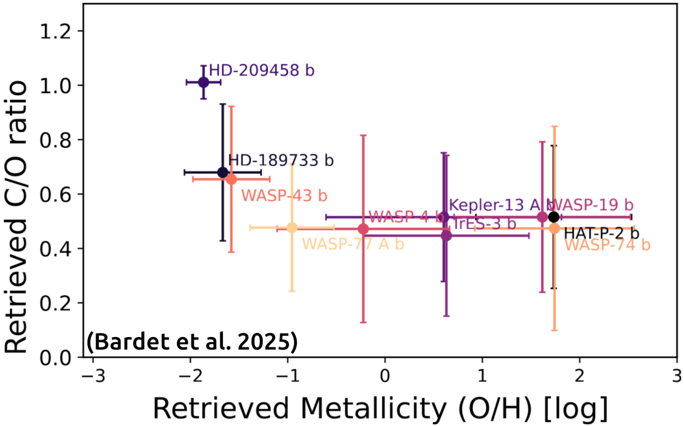
(*Guzman Franco, Savvidou & Bitsch, 2026*)

$\Rightarrow$ Most parameters are in the same range for the C/O ratio!

$\Rightarrow$ Clear trend with semi-major axis!

$\Rightarrow$ This indicates that the formation location matters most for the planetary composition!

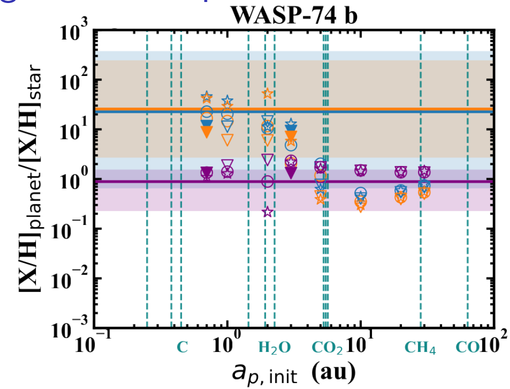
Atmospheric measurements of hot Jupiters



⇒ Large variations in the composition of hot Jupiters

⇒ Can we use these measurements to constrain the formation location of hot Jupiters?

Origin of hot Jupiters



(*He, Bitsch, et al. submitted*)

⇒ Observed planetary mass determines the end of the disc life time

⇒ We only vary the initial position of the planet and the disc viscosity!

⇒ Search for best fit of the C/H, O/H and C/O of the atmosphere!

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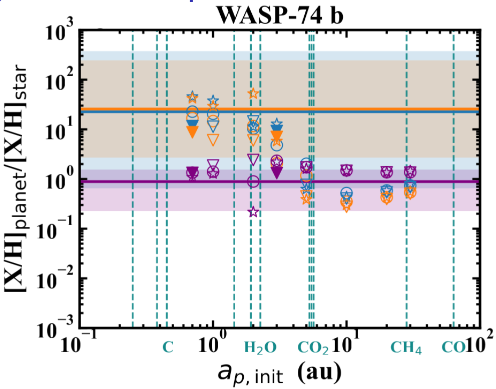

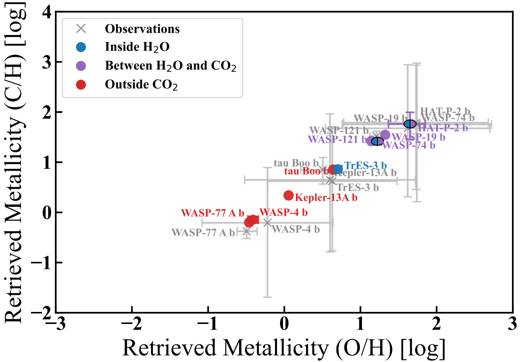

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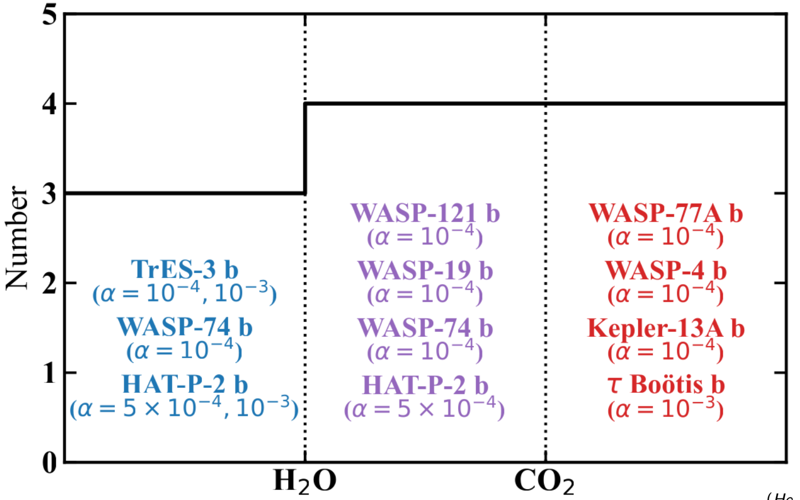
⇒ Search for best fit of the C/H, O/H and C/O of the atmosphere!

⇒ Hot Jupiters with largely super-solar abundances form in the inner disc regions!

Origin of hot Jupiters



(*He, Bitsch, et al., submitted*)

⇒ Majority of hot Jupiters originates from beyond the H_2O evaportion front!

Summary

⇒ Everything in the disc moves (gas, dust, pebbles, planets)

(e.g. *Brauer et al. 2008, Lambrechts & Johansen 2014, Paardekooper et al. 2022*)

- Inward drifting pebbles evaporate and enrich the disc

(e.g. *Booth et al. 2017, Banzatti et al. 2020, Aguichine et al. 2020, Schneider & Bitsch 2021a,b, Bitsch et al. 2022, Mah et al. 2023, 2024*)

⇒ Giant planets form early and in (massive?) discs and influence the disc's dust mass

(e.g. *Savvidou & Bitsch 2023, 2024*)

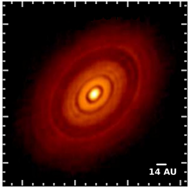
- Starting position and migration velocity matters more for planetary compositions than the disc properties (e.g. mass, radius)

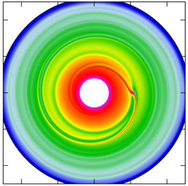
(e.g. *Guzman Franco et al., 2026*)

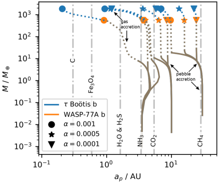
⇒ Hot Jupiters with super-solar abundances form in the inner discs, while giant planets with sub-solar abundances form in the outer disc and are then scattered inwards

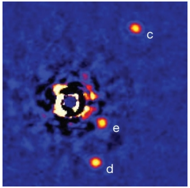
(e.g. *Schneider & Bitsch 2021a,b, O'Donovan & Bitsch, 2026, Guzman et al. 2026, He et al. submitted*)

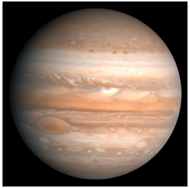
⇒ With more constraints (e.g. M_Z) we can probe more aspects of formation models!



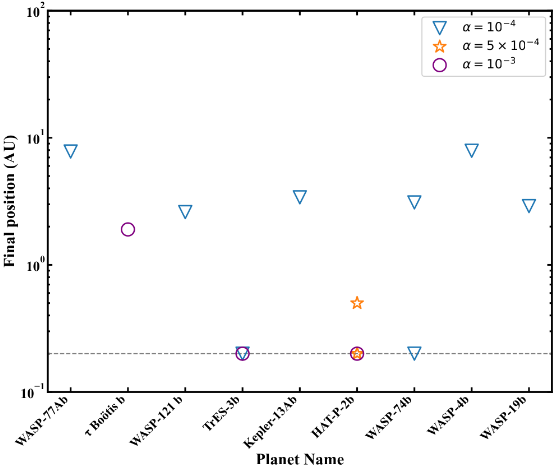








Origin of hot Jupiters



(*He, Bitsch, et al., submitted*)

⇒ Majority of hot Jupiters require scattering events to reach their final orbit!

Origin of hot Jupiters

Name	Prediction obliquity	Measurement obliquity	Prediction eccentricity	Measurement eccentricity	Obliquity outcome	Eccentricity outcome
WASP-77A b	misalign	align	$e \neq 0$	$e \approx 0$	$\tau_{\rm realign} \sim 0.3$–$3$ Gyr	$\tau_{\rm circ} \sim 8 \times 10^{-3}$ Gyr
τ Boötis b	misalign	unknown	$e \neq 0$	$e \approx 0$	($\tau_{\rm realign} \gtrsim 4$–$40$ Gyr[a])	$\tau_{\rm circ} \sim 2$ Gyr
WASP-121 b	misalign	misalign	$e \neq 0$	$e \approx 0$	($\tau_{\rm realign} \gtrsim 1$–$10$ Gyr[a])	$\tau_{\rm circ} \sim 10^{-3}$ Gyr
TrES-3 b	align	unknown	$e = 0$	$e \approx 0$	($\tau_{\rm realign} \sim 0.2$–$2$ Gyr)	($\tau_{\rm circ} \sim 4 \times 10^{-3}$ Gyr)
Kepler-13A b	misalign	misalign	$e \neq 0$	$e \approx 0$	($\tau_{\rm realign} \gg 5$ Gyr[b])	$\tau_{\rm circ} \sim 0.1$ Gyr
HAT-P-2 b	align/misalign	align	$e \neq 0$	$e = 0.5$	($\tau_{\rm realign} \gtrsim 8$–$80$ Gyr[a])	($\tau_{\rm circ} \sim 80$ Gyr)
WASP-74 b	align/misalign	align	$e = 0 \,/\, e \neq 0$	$e = 0$	($\tau_{\rm realign} \sim 6$–$60$ Gyr)	($\tau_{\rm circ} \sim 2 \times 10^{-2}$ Gyr)
WASP-4 b	misalign	align	$e \neq 0$	$e = 0$	$\tau_{\rm realign} \sim 0.4$–$4$ Gyr	$\tau_{\rm circ} \sim 3 \times 10^{-3}$ Gyr
WASP-19 b	misalign	align	$e \neq 0$	$e = 0$	$\tau_{\rm realign} \sim 0.1$–$1$ Gyr	$\tau_{\rm circ} \sim 2 \times 10^{-4}$ Gyr

(*He, Bitsch, et al., submitted*)

$\Rightarrow$ Model predictions are in general agreement with orbital constraints as well!