How to create giant planets 101

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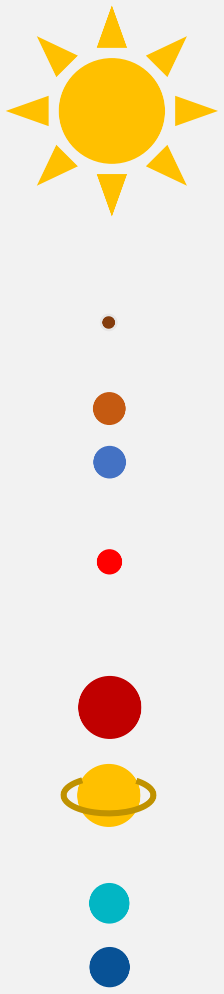
How to create giant planets ?

Overview:

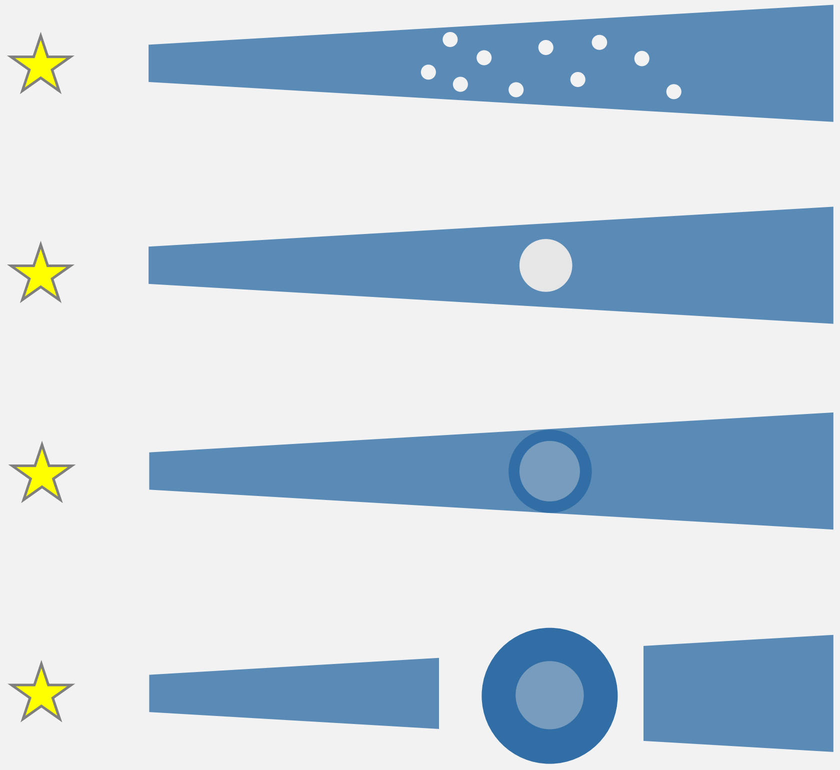
- Origins of giant planets: two possible formation scenarios
- Process of gas accretion and derived accretion rates
- How do we model gas accretion with Fargo2D1D
- Some results from my work



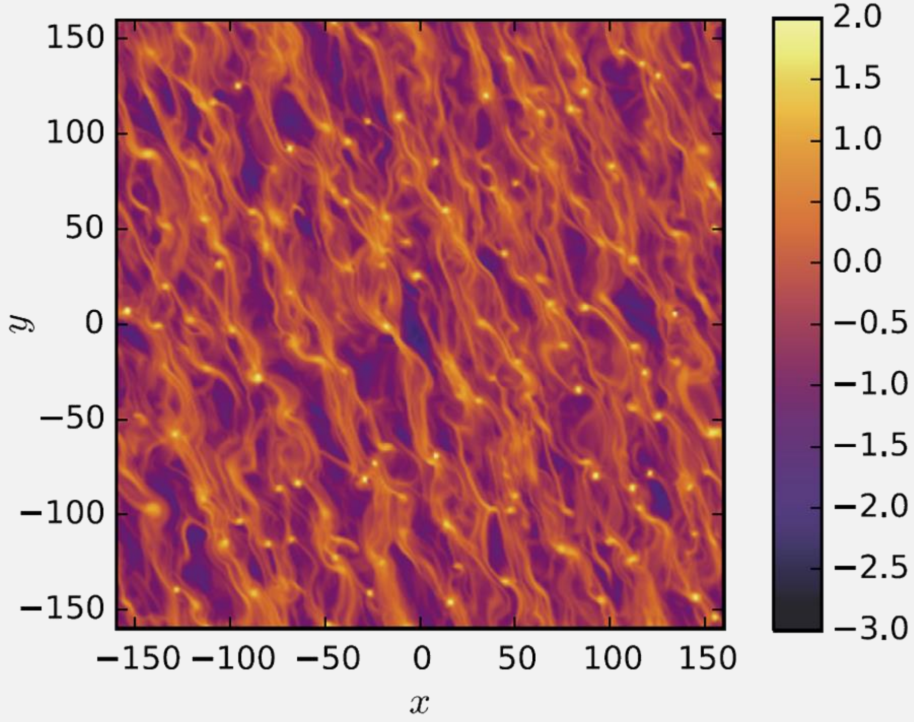
And please enjoy the macarons !

Origin of giant planets

Core accretion:
Pollack et al 1996



Gravitational Instability:
Adams et al 1989



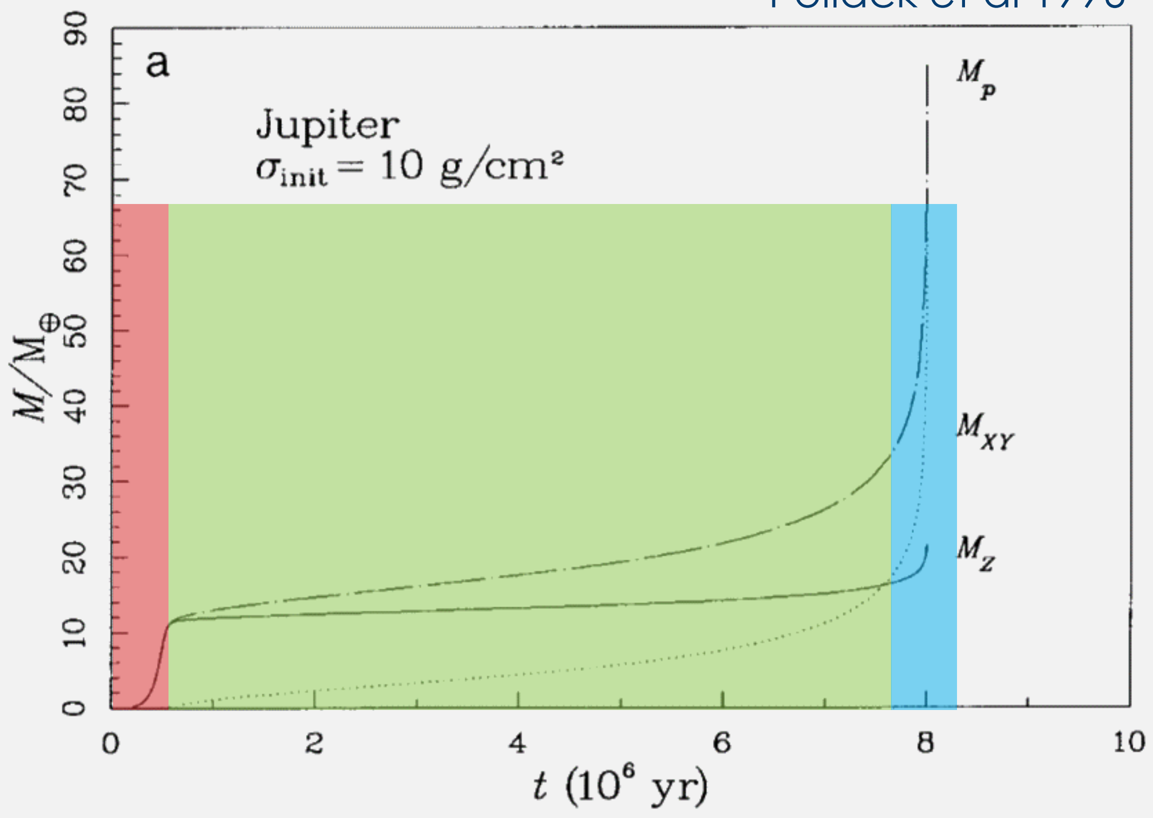
Paardekooper, SJ. & Johansen, A. (2018)

Origin of giant planets

Core accretion: Pollack et al 1996

- Step 1: Agglomeration of dust/pebbles to form a core
- Step 2: When massive enough, slow accretion of gas governed by Kelvin-Helmholtz cooling timescale
- Step 3: When $M_{core} \simeq M_{enveloppe} \simeq 10 M_\oplus$ outer layers of atmosphere collapse allowing more gas to be accreted: Runaway gas accretion

Pollack et al 1996



Origin of giant planets

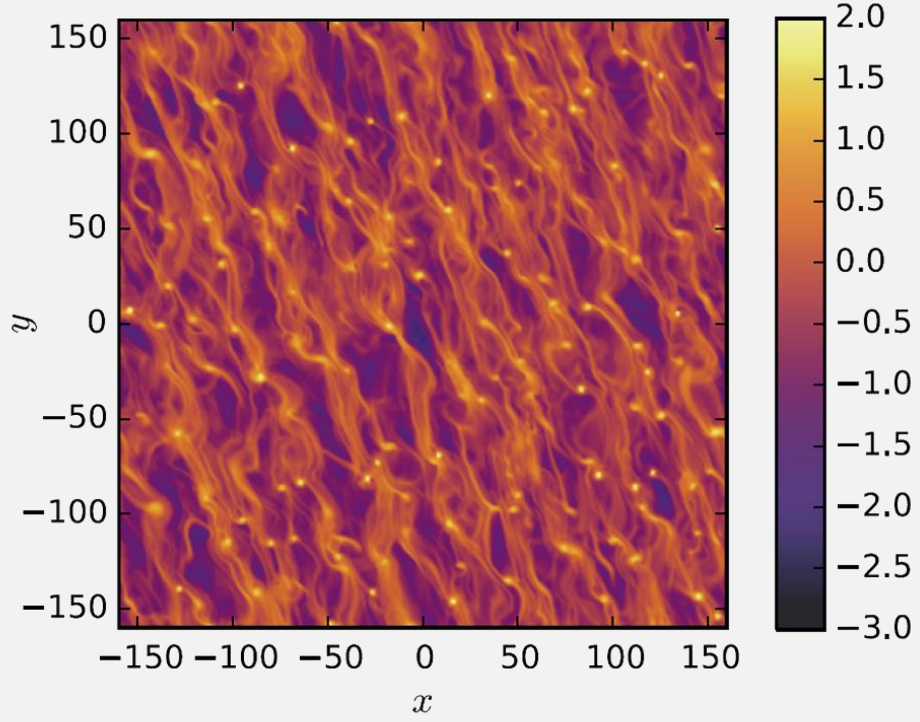
Gravitational Instability: Adams et al 1989

- Massive disks become unstable at large radii
  Toomre *stability* criterion $Q = \frac{c_s \Omega}{\pi G \Sigma} > 1$

- Instability causes initial over density, subject to self-gravity ➡ creating clumps

- If the clumps get rid of potential energy faster than pressure and differential rotation smooth them out ➡ collapse into a giant planet

Paardekooper & Johansen 2018



Origin of giant planets

Core accretion:
Pollack et al 1996

Produces:
- Gas giant and terrestrial planets

Pros:
- Can produce terrestrial and ice giants
- Composition can match

Cons:

- How to stop runaway gas accretion ?
- Many stages only partially understood yet

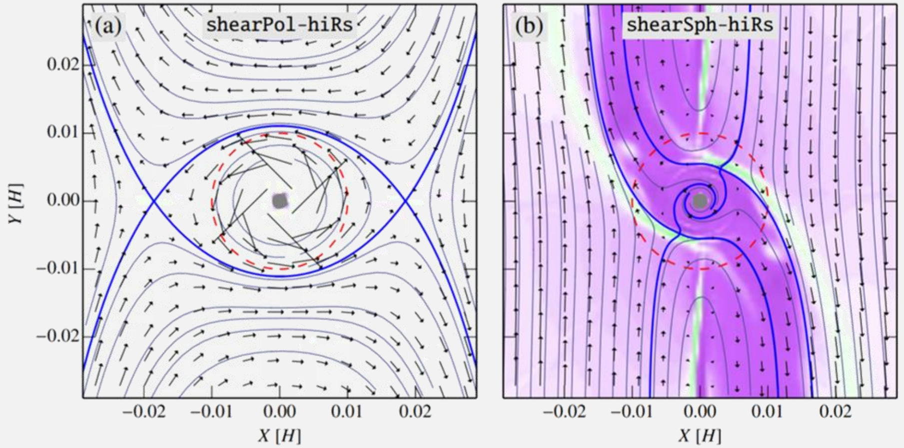
Gravitational Instability:
Adams et al 1989

Produces:
- Massive gas giant planets at large radii

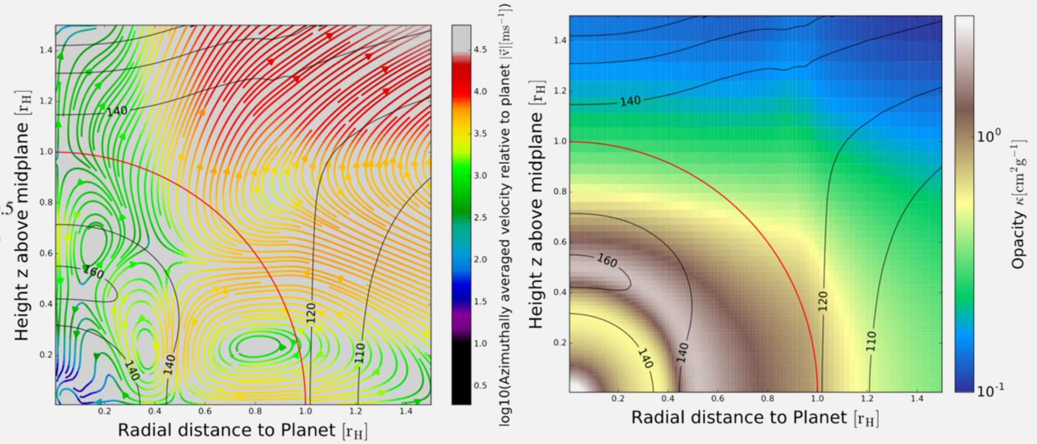
Pros:
- Can explain the formation of the massive cold giant planets observed
- Debated presence of core in Jupiter

Cons:
- Require a very massive disk
- Composition does not quite match
- Solar System planets are less massive

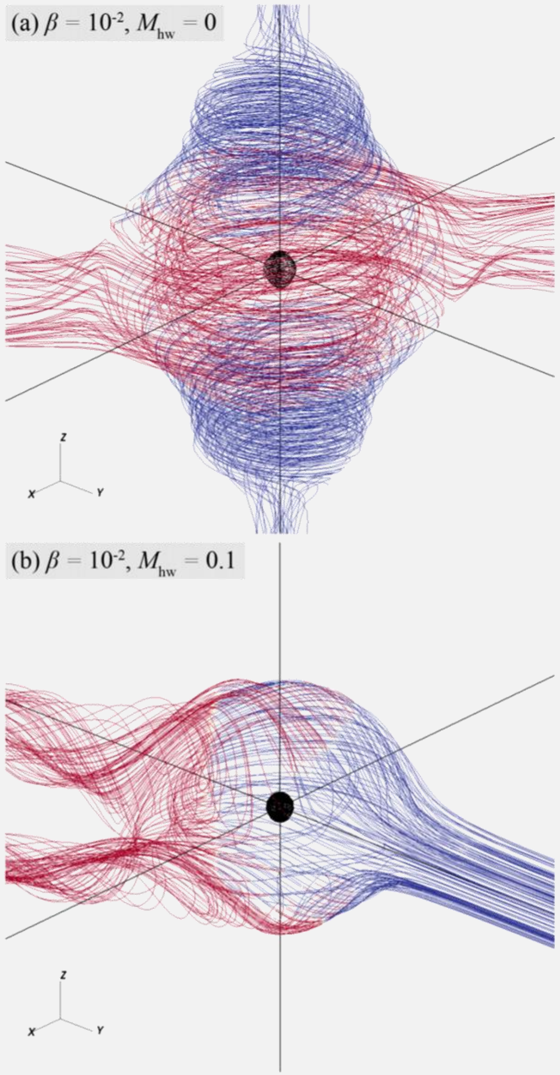
Gas accretion complicated ? Nooo ...

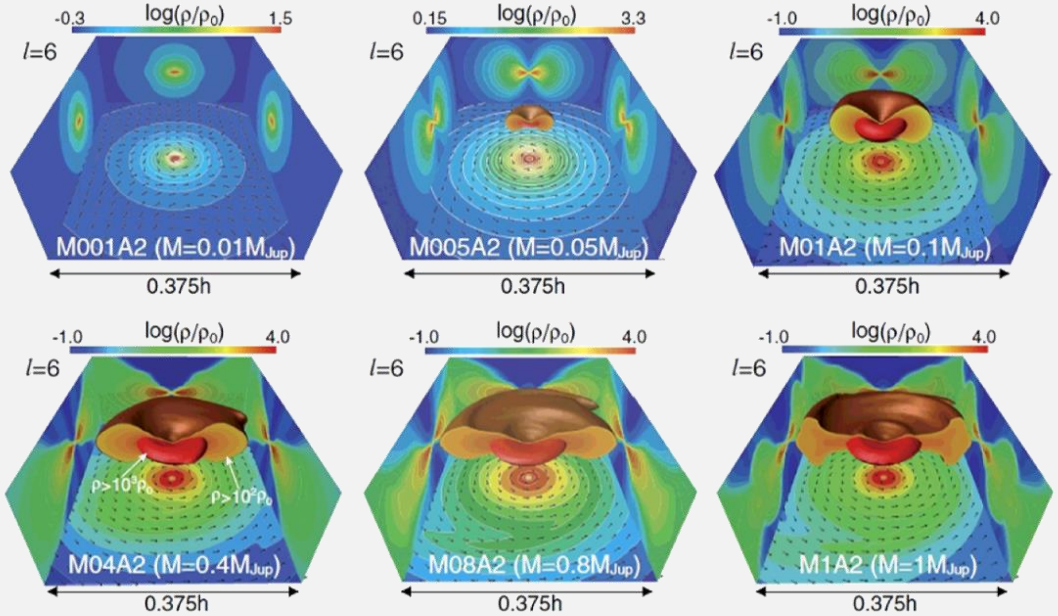


Ormel et al 2015

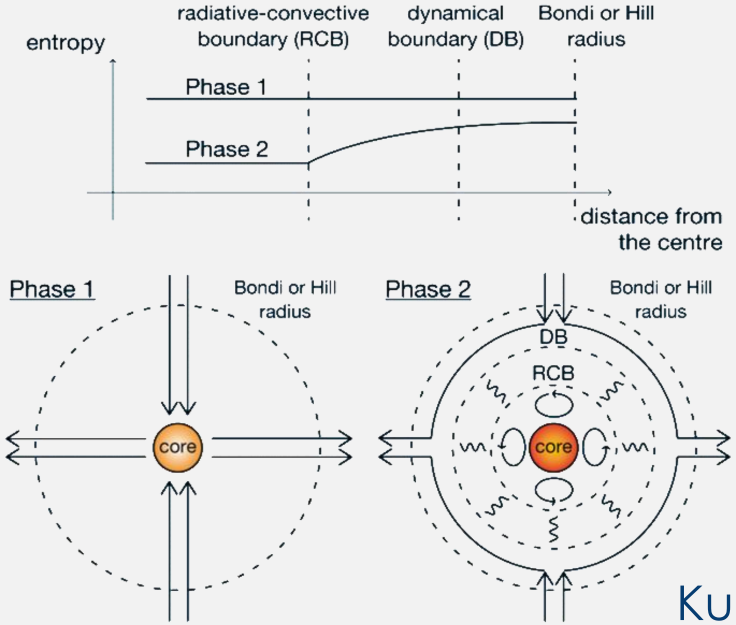


Schulik et al 2019



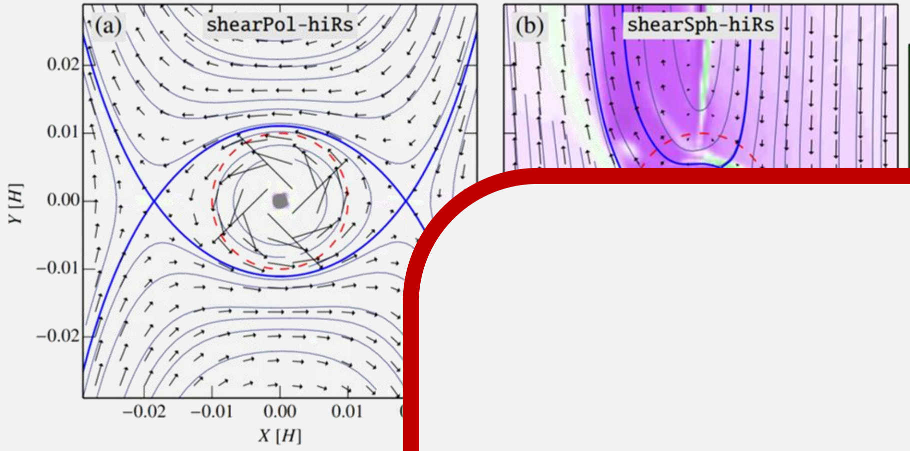


Machida et al 2010

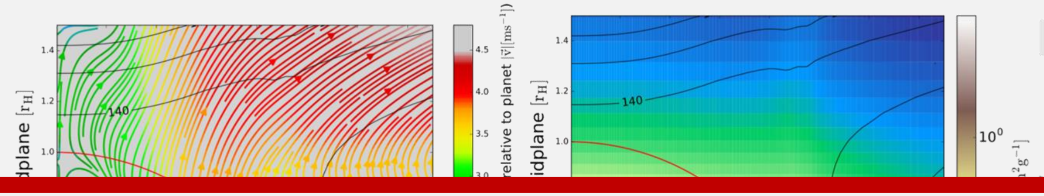


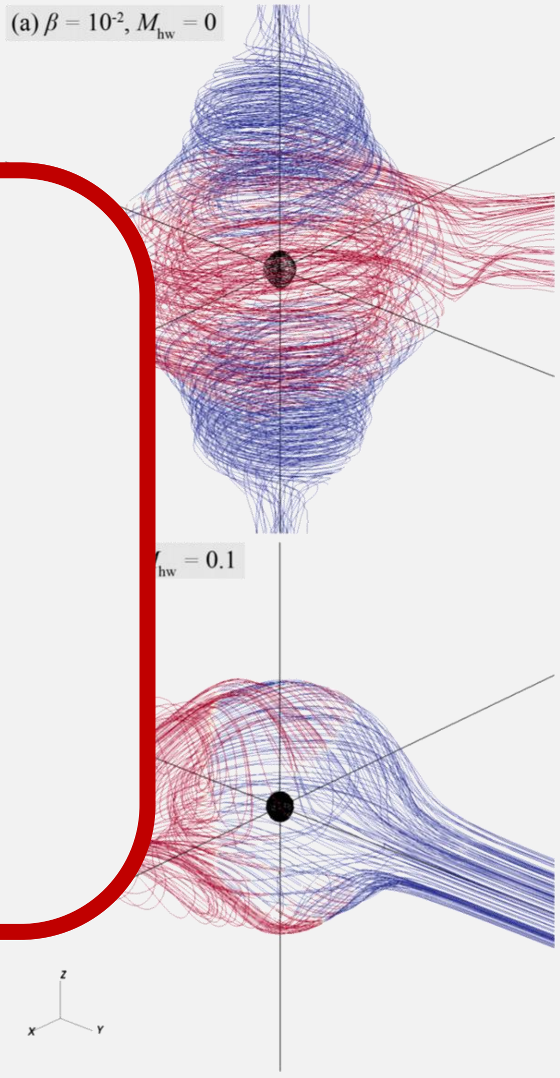
Kurokawa & Tanigawa 2018

Gas accretion complicated ? Nooo …



Ormel et al 20



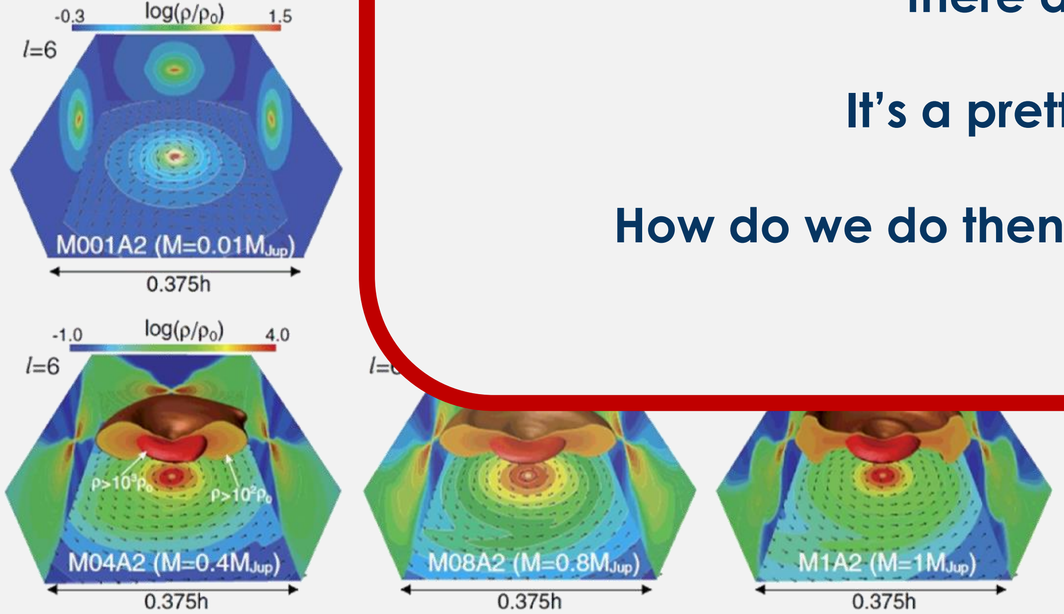


A lot of physics going on …

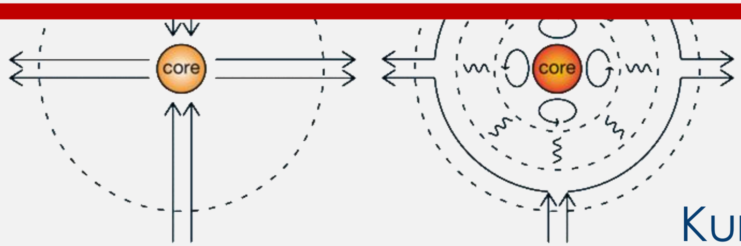
Therefore depending on different assumptions there are different results …

It's a pretty hard/messy subject !

How do we do then to know the gas accretion rate ?



Machida et al 2010



Kurokawa & Tanigawa 2018

Gas accretion rates ?

Paper	$\dot{M}_{runaway}$	Comment
D'Angelo et al 2003	$\sim 10^{-4}\ M_j/yr$	
Tanigawa & Ikoma 2007	$\sim 10^{-8}\ M_j/yr$	With photoevaporation
Machida et al 2010	$\sim (2-6).10^{-5}\ M_j/yr$	
Tanigawa & Tanaka 2016	$\sim 10^{-8}\ M_j/yr$	
Schulik et al 2019	$\sim 10^{-4}\ M_j/yr$	
Lambrechts et al 2019	$\sim \left(10^{-5}-10^{-6}\right) M_j/yr$	$\dot{M}_{flux\ atmosphere}$ $\sim 10^{-4}\ M_j/yr$

Modelling gas accretion

My work:

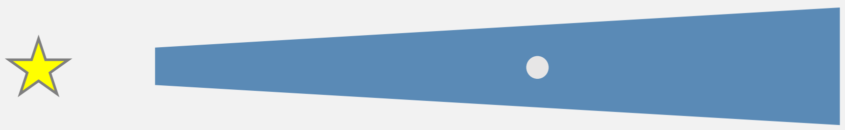
- Impact of gas accretion onto the protoplanetary disk
- Not resolving the process of gas accretion itself – different scale

➡ Value of accretion rate is one of my "input" parameters (see slide 11)

How gas accretion is modeled here ?

- 1 planet = 1 gravitational potential from a mass M_{planet}

dM ?



$$M_{disk}(t + dt) = M_{disk}(t) - dM$$

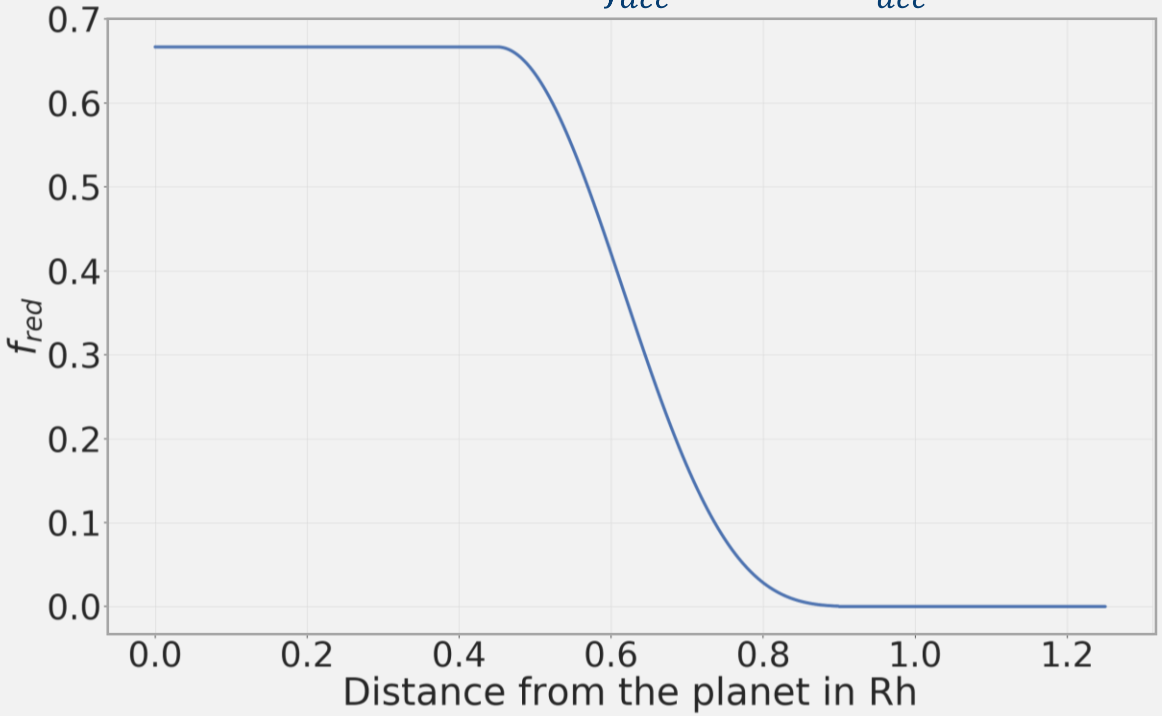
$$M_{planet}(t + dt) = M_{planet}(t) + dM$$

Accretion routine

Kley accretion principle (Kley 1999)

$$dM_K = f_{red}.S_{acc}.\Sigma(r,t).f_{acc}.dt$$

$f_{acc} = 1$ and $S_{acc} = \text{surface}$



$0.9r_H$

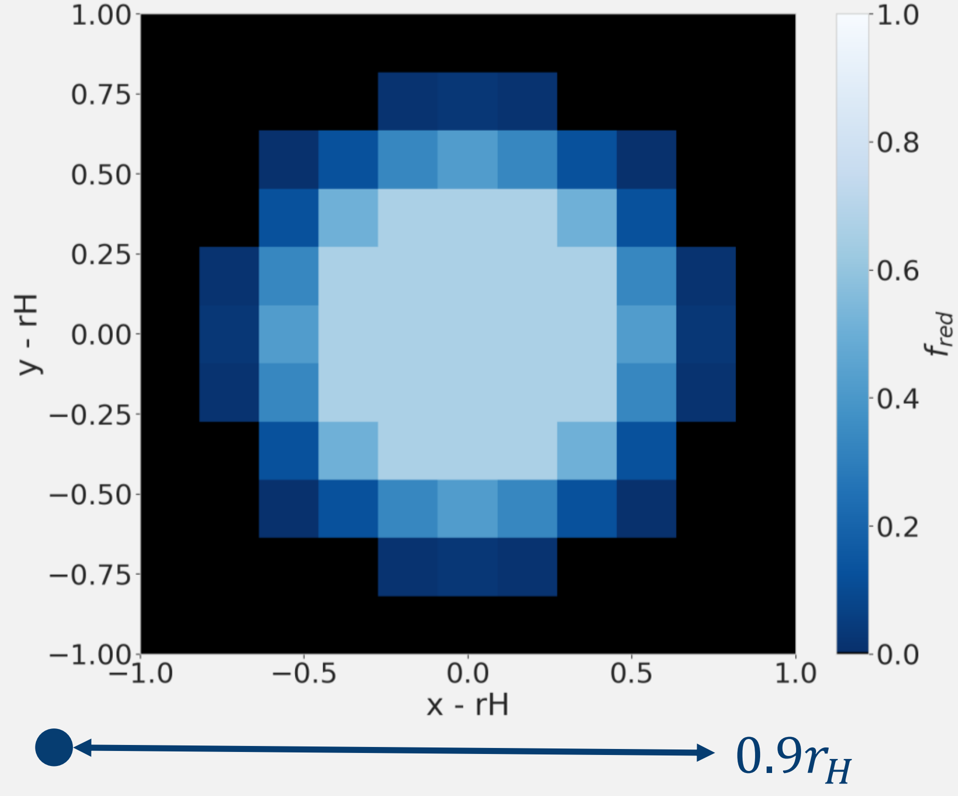
Machida accretion principle (Machida et al 2010)

Accretion routine

Kley accretion principle (Kley 1999)

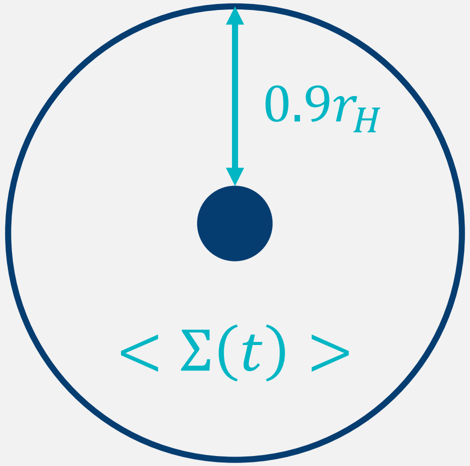
$$dM_K = f_{red}.S_{acc}.\Sigma(r,t).f_{acc}.dt$$

$f_{acc} = 1$ and S_{acc} = surface



Machida accretion principle (Machida et al 2010)

$$dM_M = \Sigma(r,t) \quad H^2\Omega \times \min\left(0.14\,;0.83.\,(r_H/H)^{9/2}\right).dt$$



$$r_H = r_p\left(\frac{m_p}{3M_\star}\right)^{1/3}$$

Machida+ 2010: Derived from 3D simulations without removing gas from the disk

Crida&Bitsch 2017: Used it in 2D simulations (migration + accretion) with $\Sigma(r,t) = \Sigma_0$

Accretion routine

Accretion routine at each dt:

- Step 1: Calculation of Kley accretion rate

- Step 2: Calculation of Machida accretion rate
  Tuning of Machida's accretion rate ➡ *Exploring different accretion rates*

- Step 3: Checking which accretion rate is the smaller ($dM = dM_{Machida}$ or dM_{Kley})

- Step 4: Removing the gas via Kley's principle with the smaller rate:

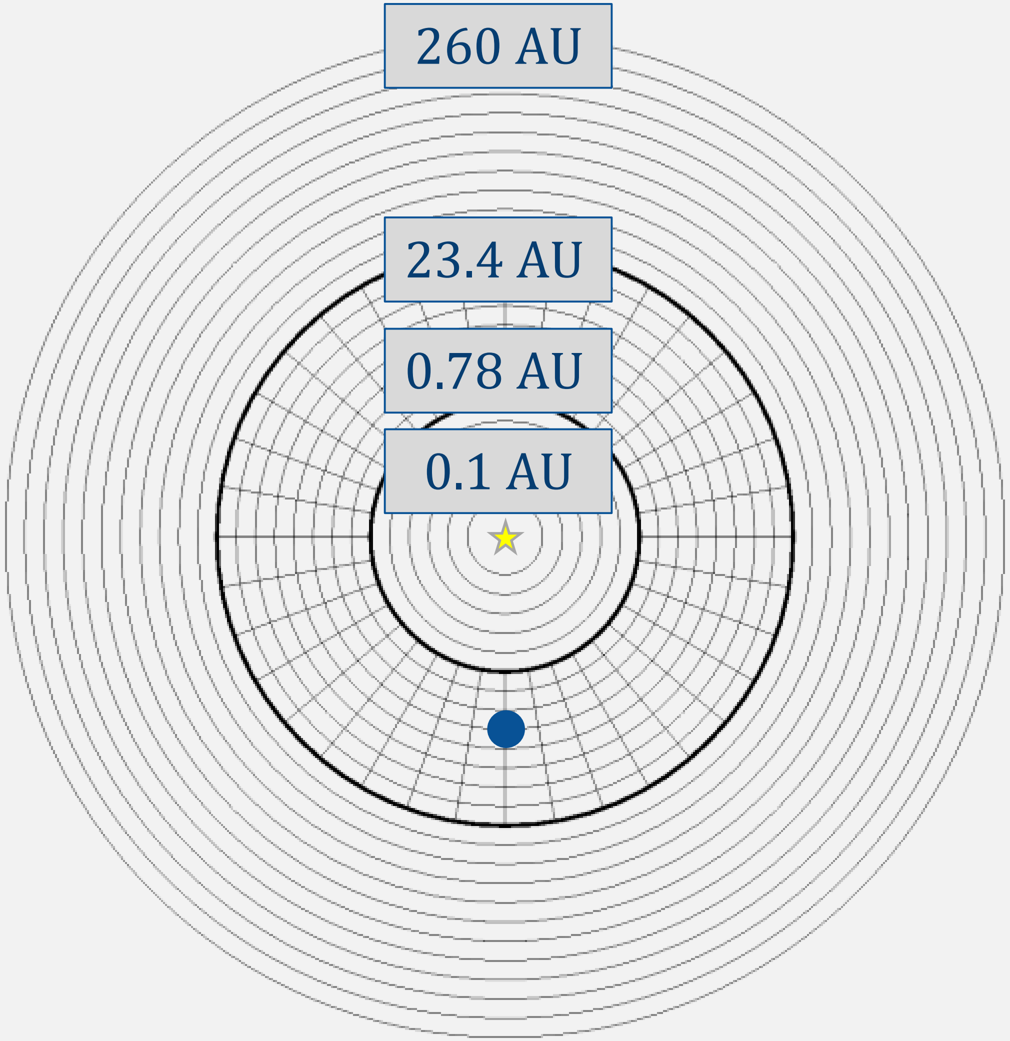
  if $dM_{Kley} > dM_{Machida}$:

$$f_{acc} = dM_{Machida}/dM_{Kley}$$

Simulations parameters

Fargo2D1D: locally isothermal

➡ Global viscous evolution of disc



Disc parameters:

$h = 0.03, 0.05, 0.07$ $\alpha = 10^{-2}, 5.10^{-3}, 10^{-3}, 10^{-4}$

$\Sigma \propto r^{-1}$ $\Sigma_0 = 3 \times 10^{-4} = 93.6\ g/cm^2$ $M_{disc} = 10\%\ M_\star$

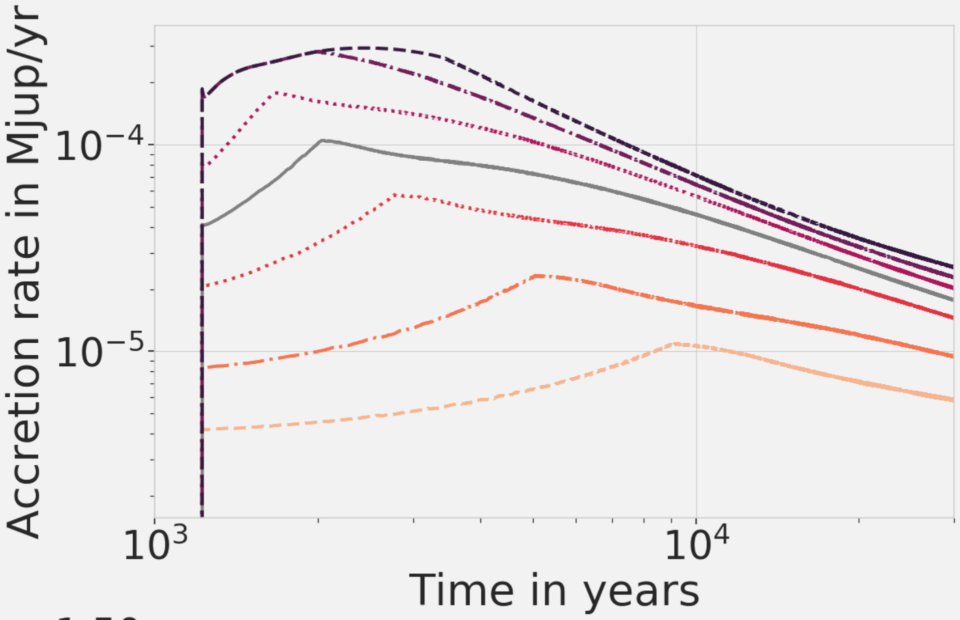
Planet initial parameters:

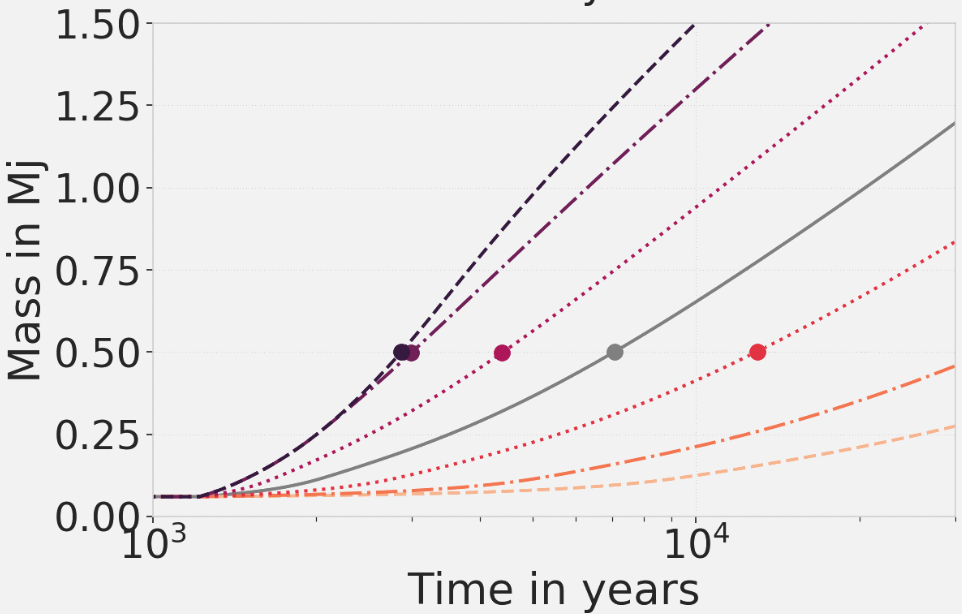
$M_{planet} = 20 M_\oplus$ $r = 5.2\ AU$ $\dot{M}_{Machida} = (0.1, 0.2, 0.5, 1, 2, 5, 10) \times \dot{M}_{Machida}$

Influence of accretion rate

Machida factor:

Reduced :10
Reduced :5
Reduced :2
Nominal
Enhanced x2
Enhanced x5
Enhanced x10





Range in accretion rates obtained:

From $\sim 2.10^{-4}\ M_j/yr$
to $\sim 6.10^{-6}\ M_j/yr$

Range in masses obtained:

From $\sim 3\ M_j$
to $\sim 0.5\ M_j$ in 6.10^4 yrs

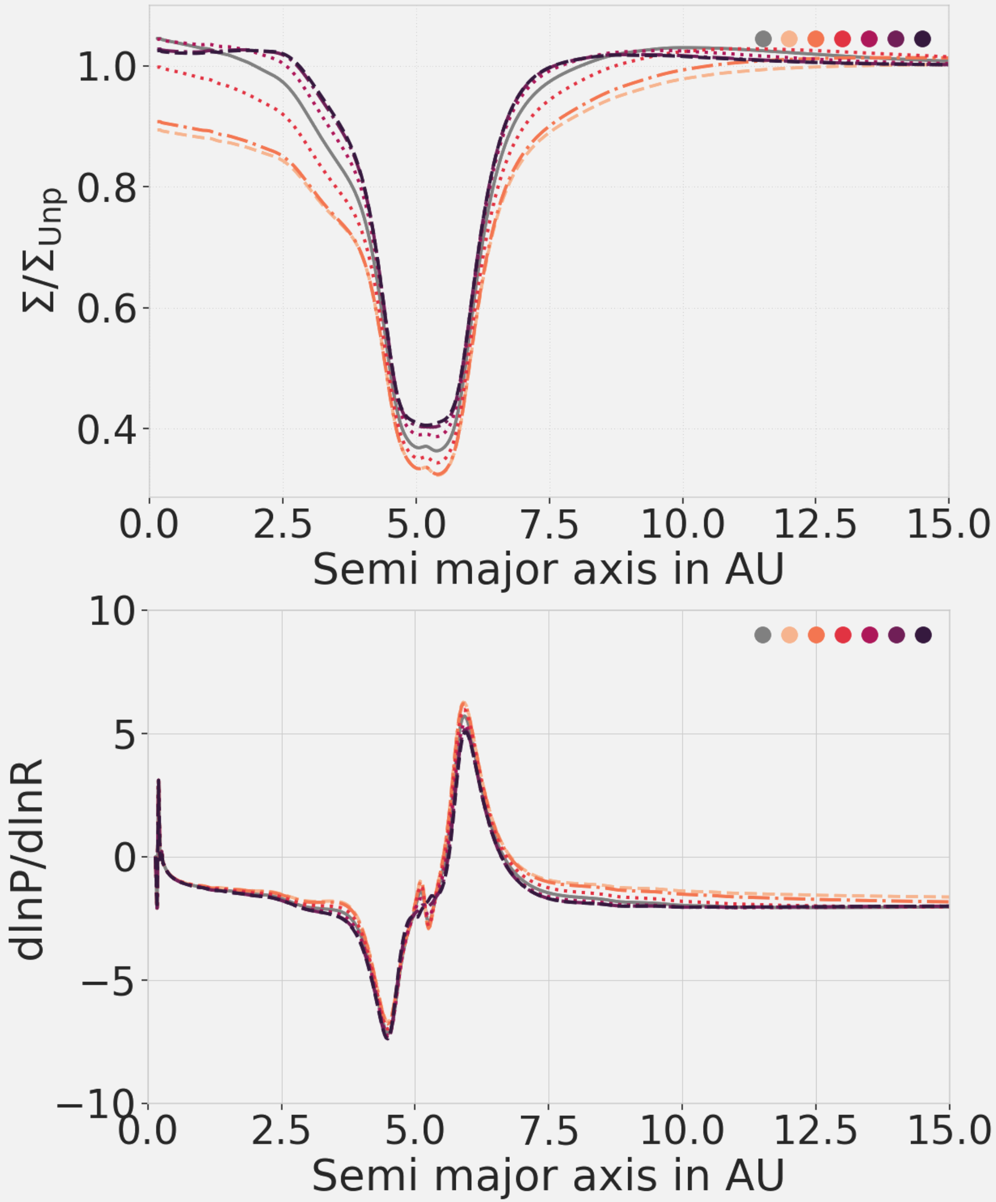
➡ Jupiter like planets

Bergez-Casalou et al (In prep)

Influence of accretion rate

Machida factor:

Reduced :10
Reduced :5
Reduced :2
Nominal
Enhanced x2
Enhanced x5
Enhanced x10



For $m_p = 0.5\,M_j$:

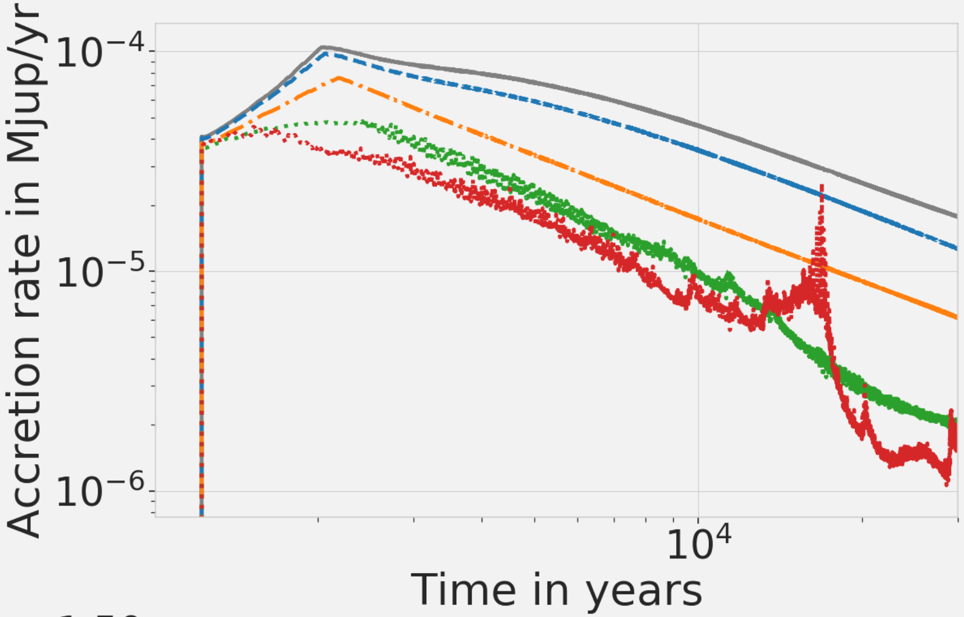
Only small differences in gap shape at the same mass **at this viscosity**

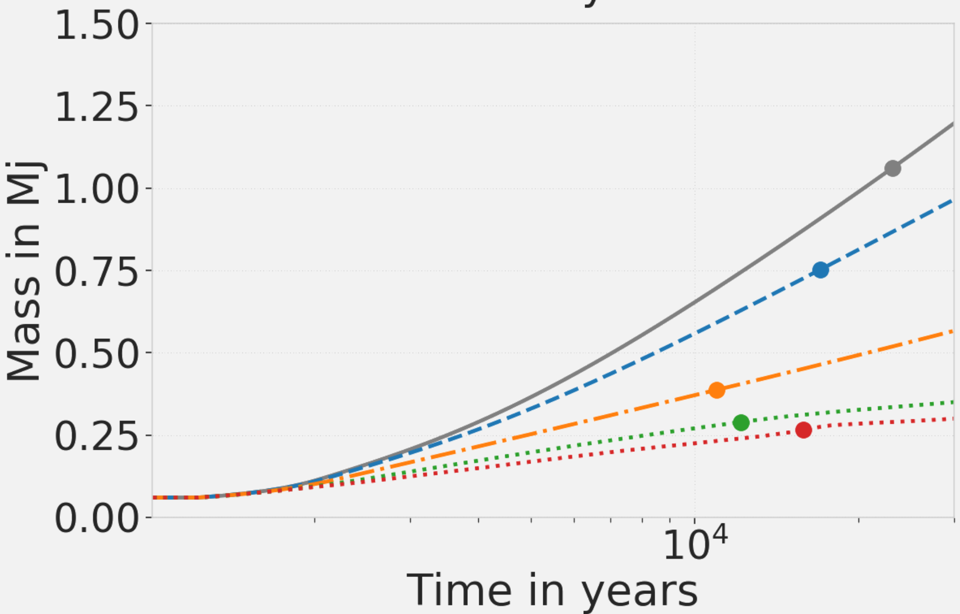
Bergez-Casalou et al (In prep)

Influence of viscosity

Alpha viscosity:

$\alpha = 10^{-2}$
$\alpha = 5.10^{-3}$
$\alpha = 10^{-3}$
$\alpha = 10^{-4}$
$\alpha = 10^{-5}$





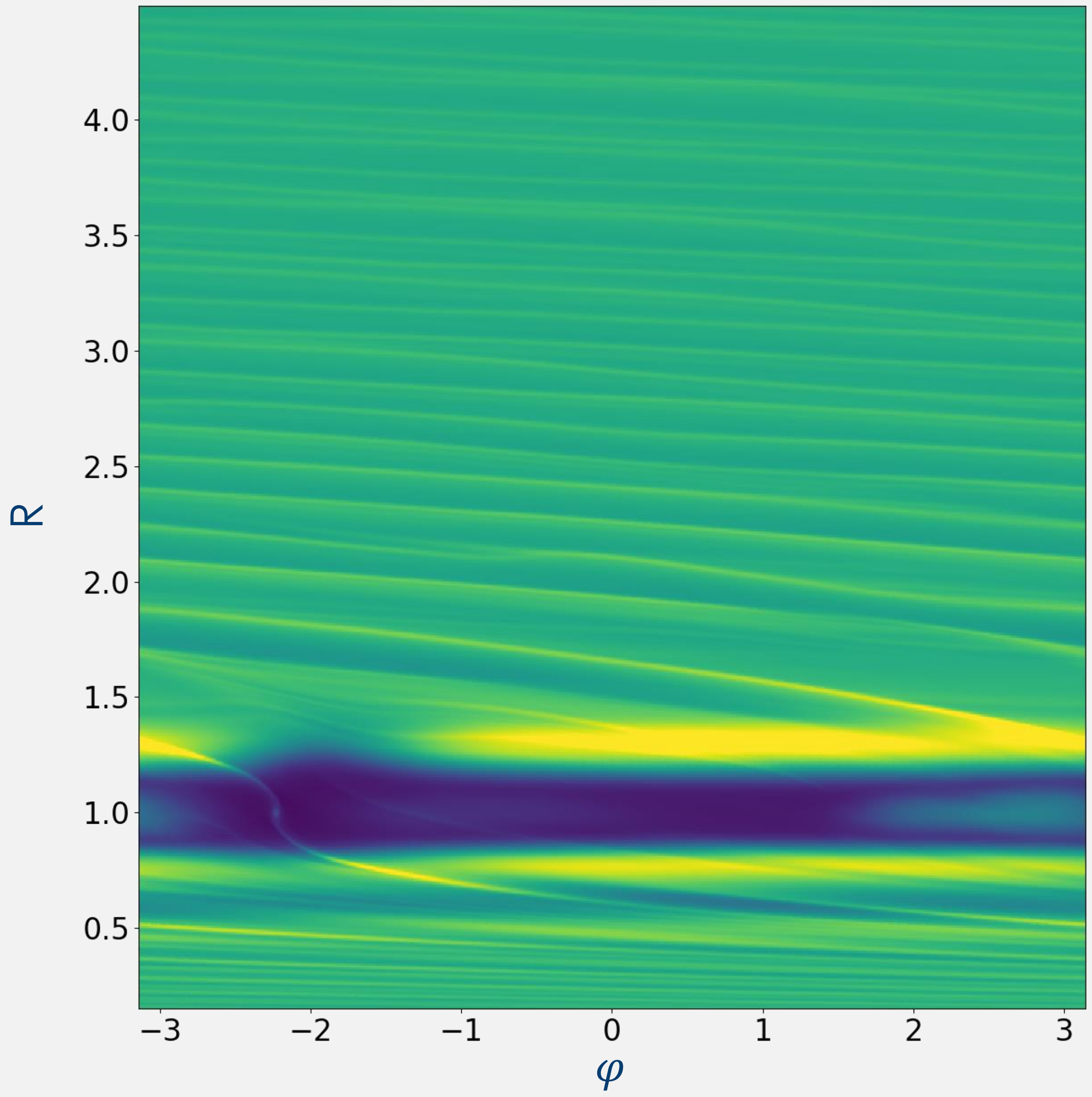
Viscosity has an influence on how the planet creates a gap via:
- Torques between the planet and the disc
- Refill of gas removed by accretion

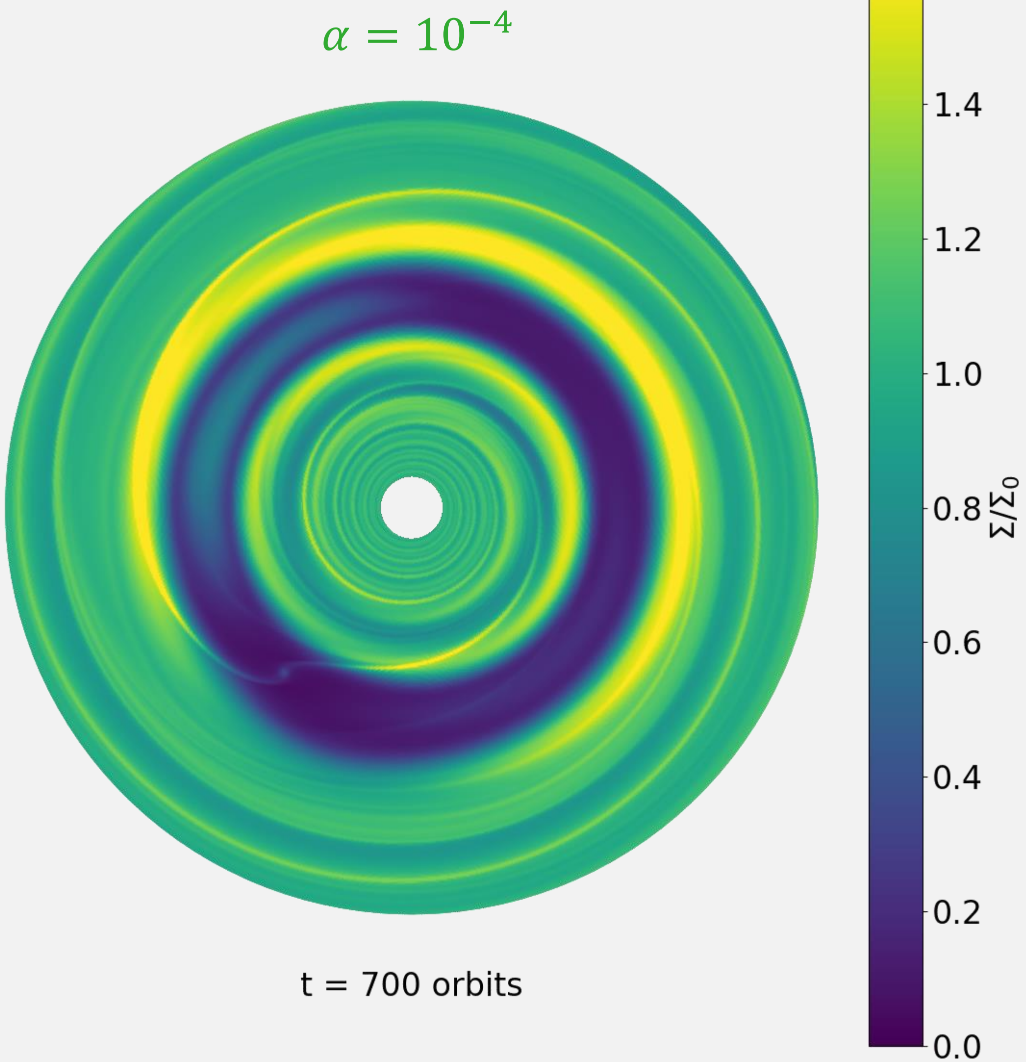
For $\alpha = 10^{-4}$ and $\alpha = 10^{-5}$ presence of vortices. They push material in the vicinity of the planet

➡ oscillations in the accretion rate

Bergez-Casalou et al (In prep)

Influence of viscosity





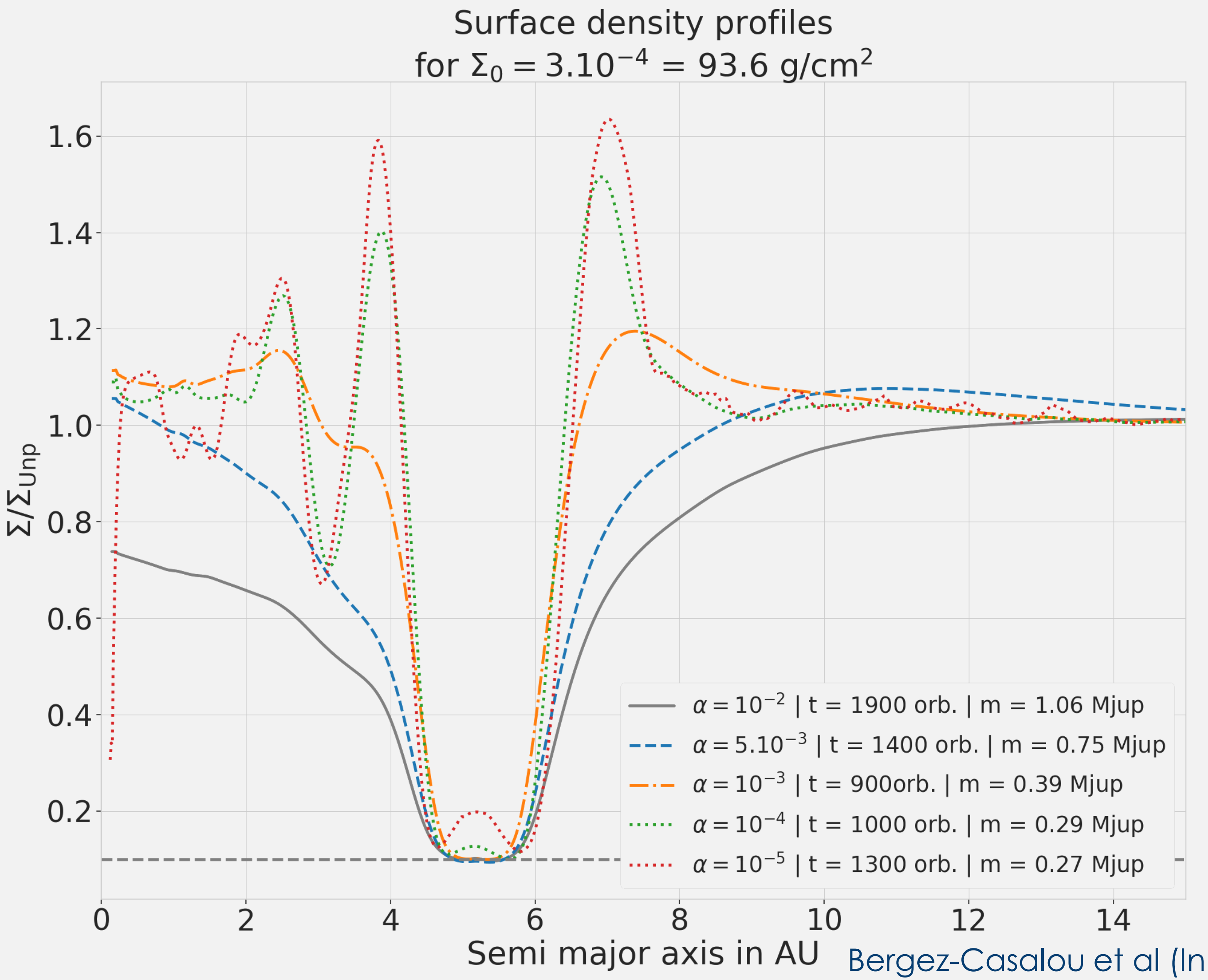
Gap opening mass

Alpha viscosity:

$\alpha = 10^{-2}$
$\alpha = 5.10^{-3}$
$\alpha = 10^{-3}$
$\alpha = 10^{-4}$
$\alpha = 10^{-5}$

Definition of a gap here:

$$\Sigma_{min} = 0.1 \frac{\Sigma}{\Sigma_{unp}}$$



Bergez-Casalou et al (In prep)

Gap opening mass

Timescale fight

When $\tau_{gap} > \tau_{acc}$:

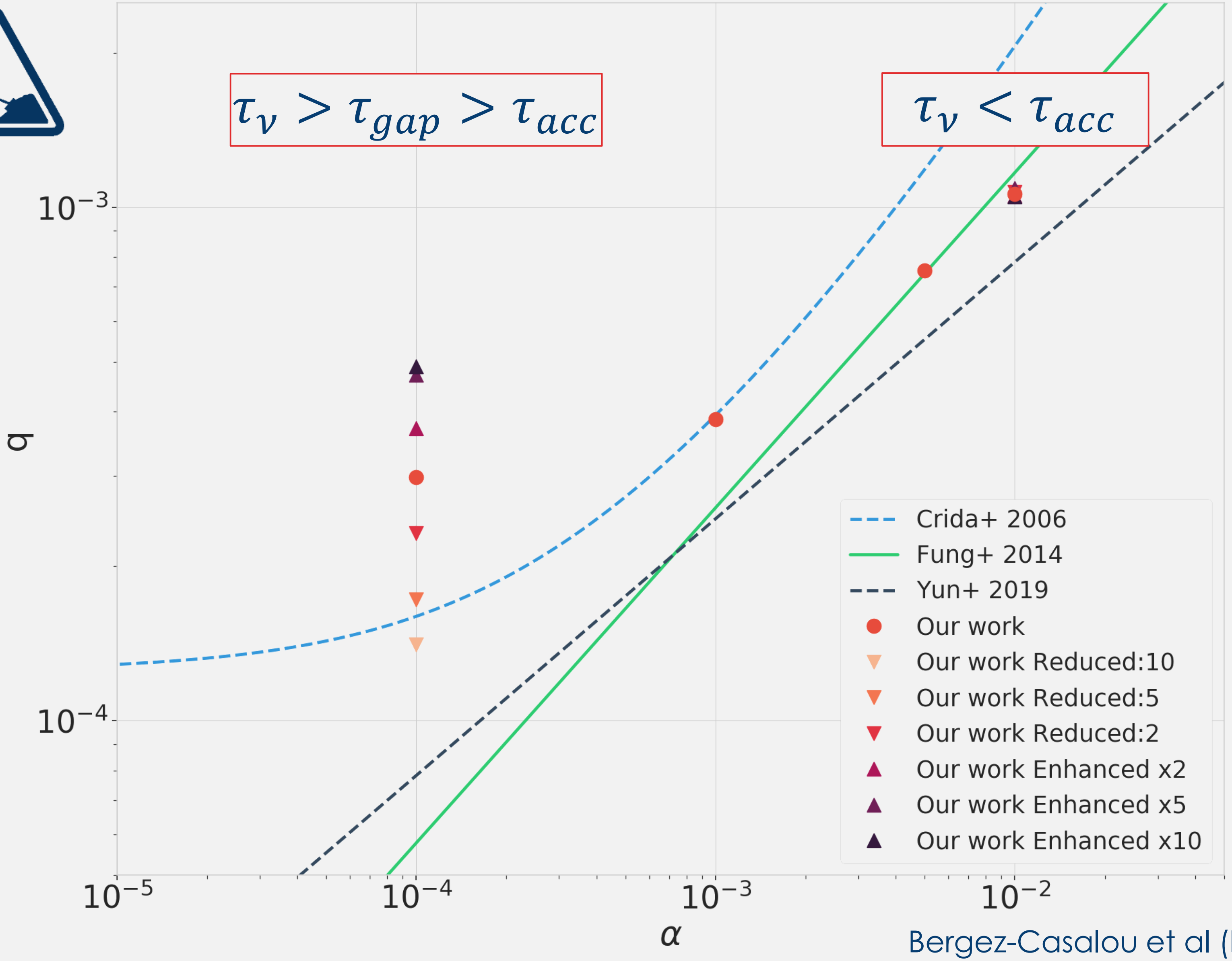
While planet is forming the gap, it is accreting

$$M_{acc,gap} > M_{non\ acc,gap}$$

When $\tau_{\nu} < \tau_{acc}$:

Everything that is accreted by the planet is replenished by viscosity

$$M_{acc,gap} \simeq M_{non\ acc,gap}$$



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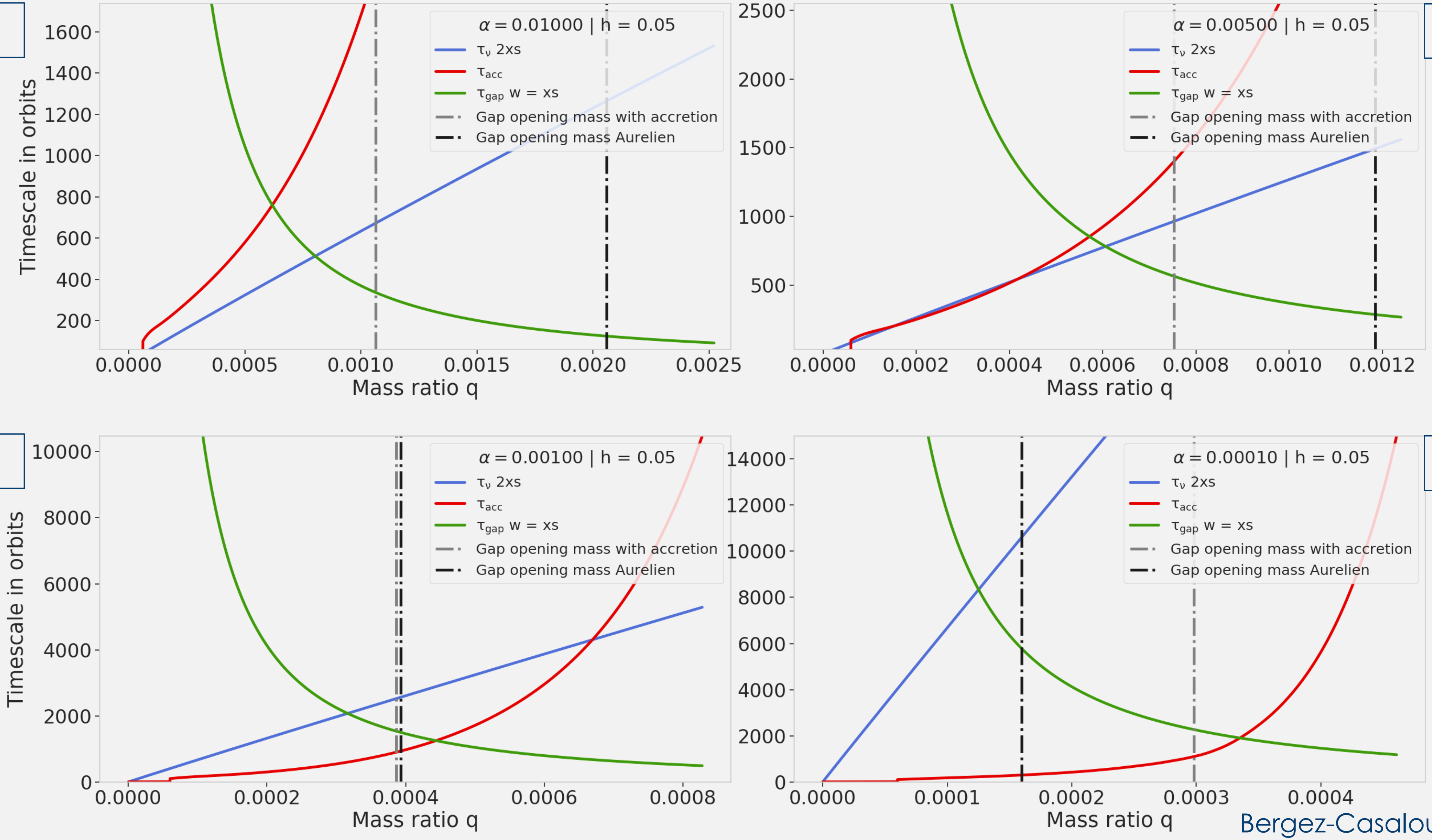
Gap opening mass

$\alpha = 10^{-2}$

$\alpha = 5.10^{-3}$

$\alpha = 10^{-3}$

$\alpha = 10^{-4}$



Bergez-Casalou et al (In prep)

Bibliography

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Core accretion and Gravitational instabilities:

Paardekooper, SJ. & Johansen, A. Space Sci Rev (2018) 214: 38.
https://doi.org/10.1007/s11214-018-0472-y

Gravitational instability in disks + planet formation:

K. Kratter, G. Lodato, Annu. Rev. Astron. Astrophys. **54** 271–311 (2016).
https://doi.org/10.1146/annurev-astro-081915-023307

Lecture notes:

Armitage, P. J. 2007
https://arxiv.org/pdf/astro-ph/0701485.pdf

This is a **chocolatine**

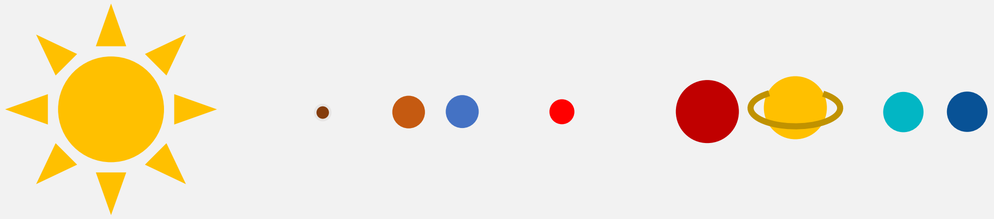
Take home messages

- Gas accretion is a complicated subject, not very well constrained yet. High resolution and complex physics simulations are starting to help us understand the details of gas accretion.

- The disc parameters have a strong impact on gas accretion: presence of vortices at low viscosity pushes material toward the planet.

- With respect to viscosity, gas accretion can change gap opening mass.

Thank you for your attention



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