Nordita Winter School 2017

PLANETARY MIGRATION

UNIVERSITÉ CÔTE D'AZUR

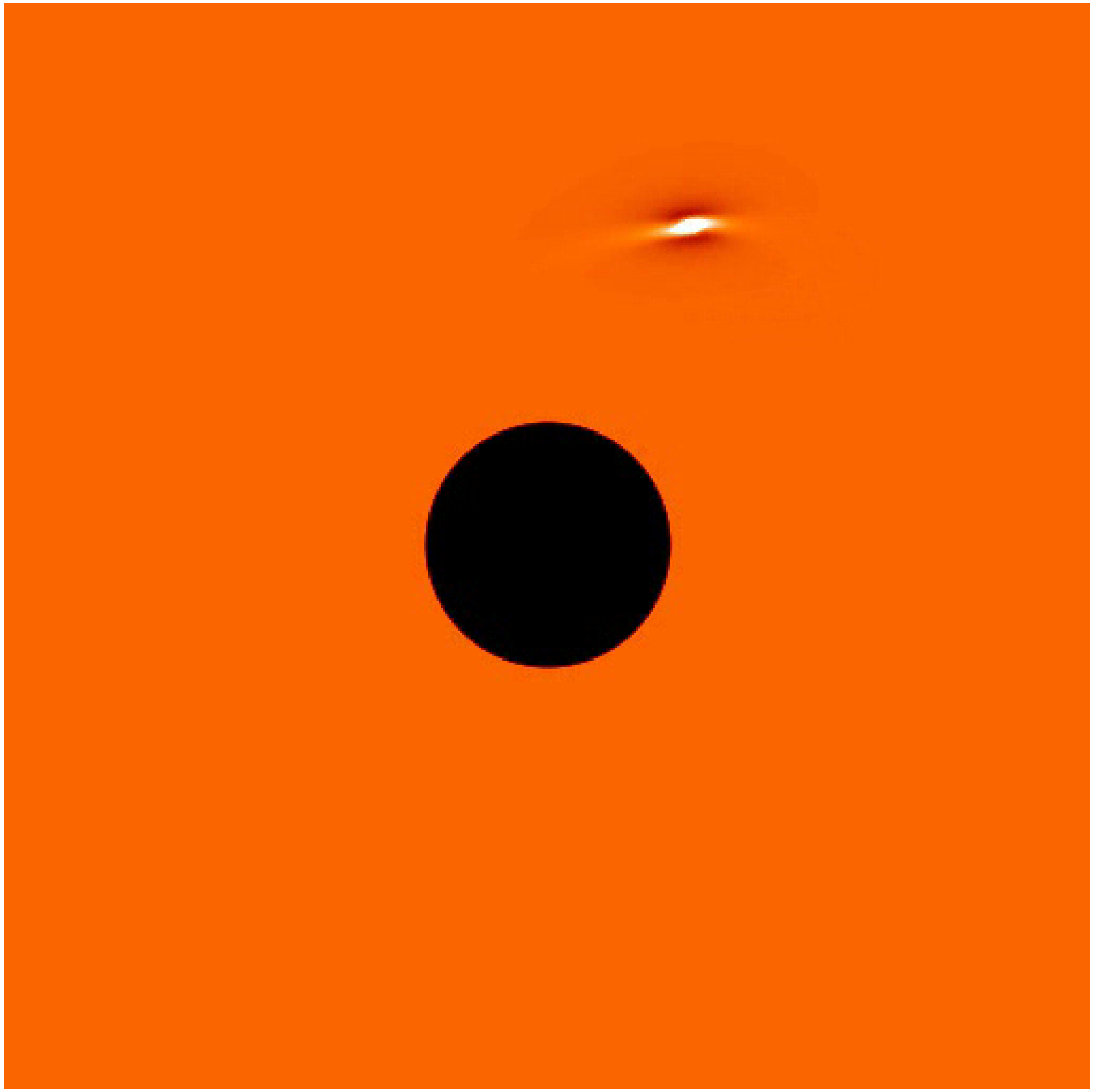
Observatoire de la CÔTE d'AZUR

Aurélien CRIDA

What is planetary migration ?

(the migration of Jupiter carrying its satellites. Alegory.)

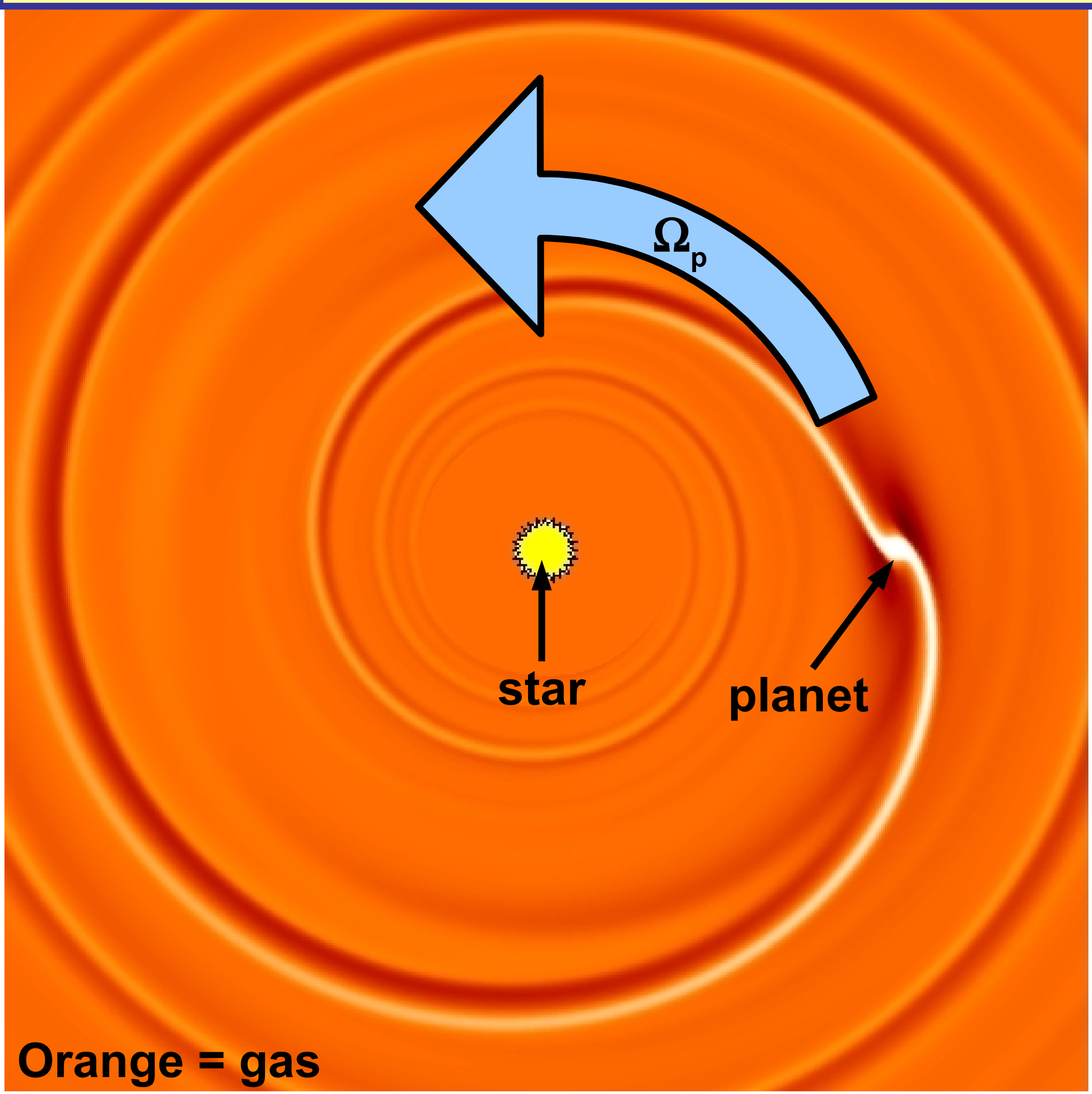
INTRODUCTION



A planet orbiting in a protoplanetary disk launches a one-armed, spiral wake.

Clear/white = over-density , Dark = underdensity. **Orange = gas**

INTRODUCTION



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This is a pressure-supported wave, caused by the planet's gravity perturbing the trajectories of the gas particles.

The wave corotates with the planet at the same angular velocity $\Omega_p = (GM_*/a_p^3)^{1/2}$.

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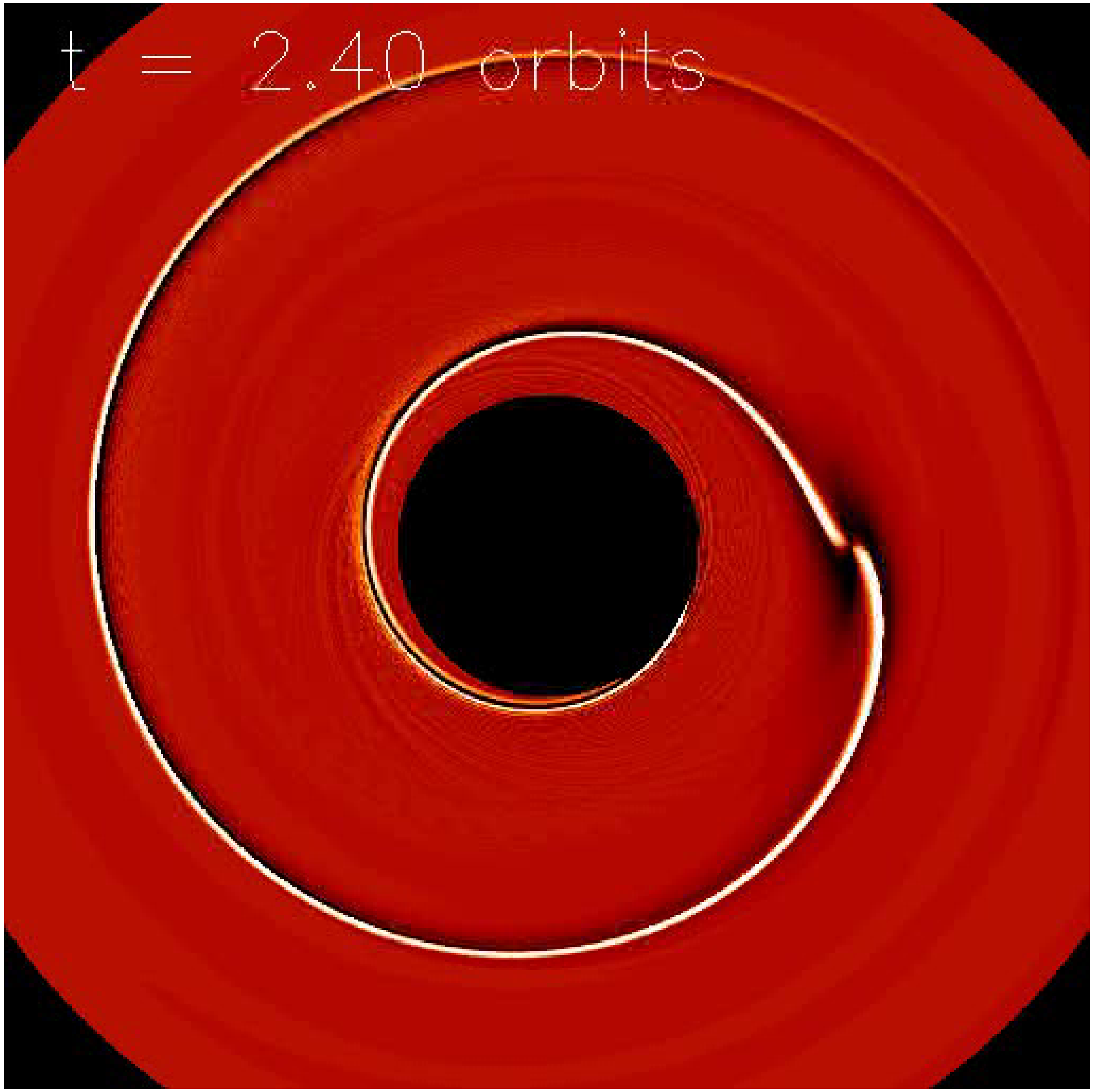

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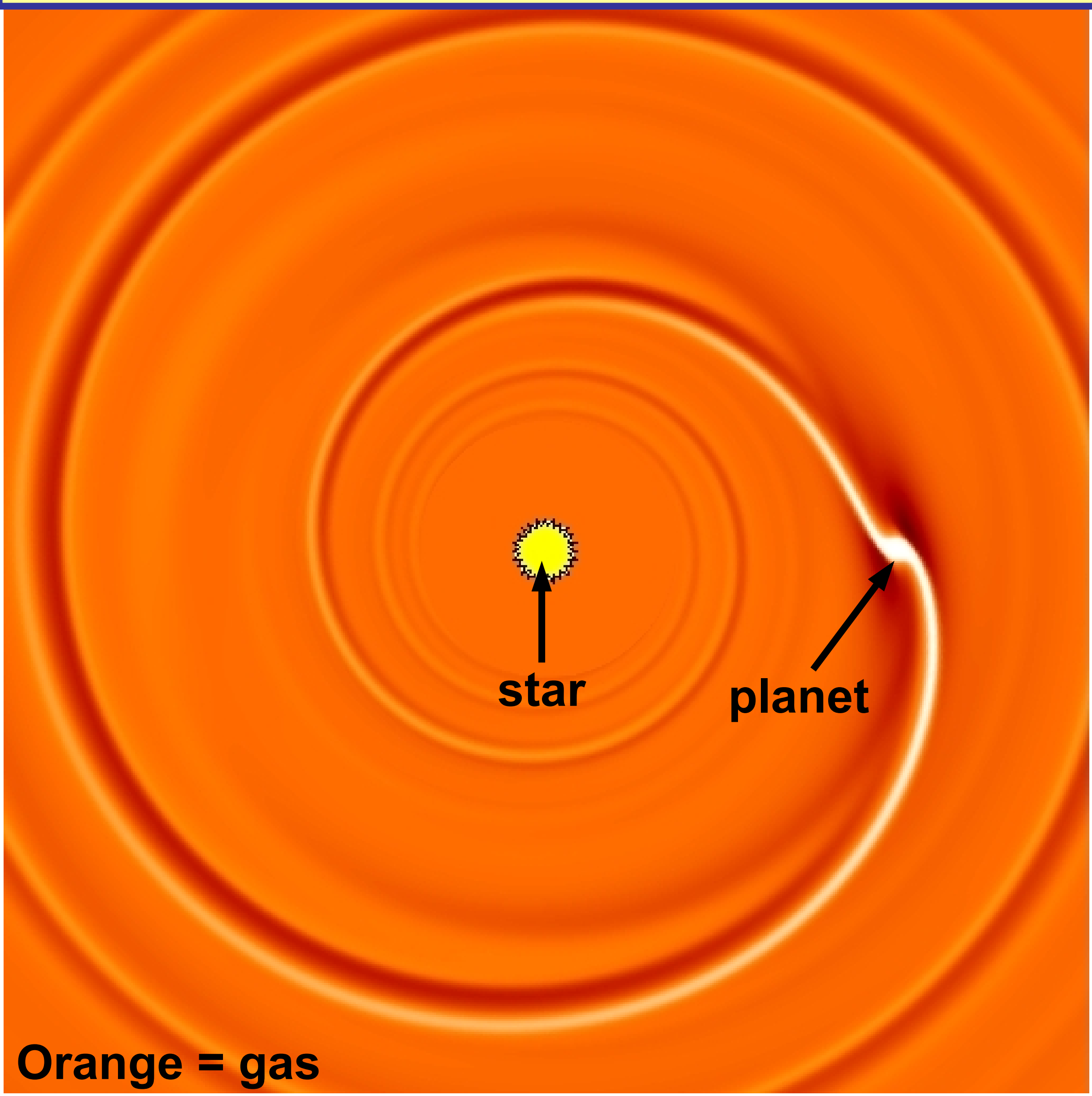


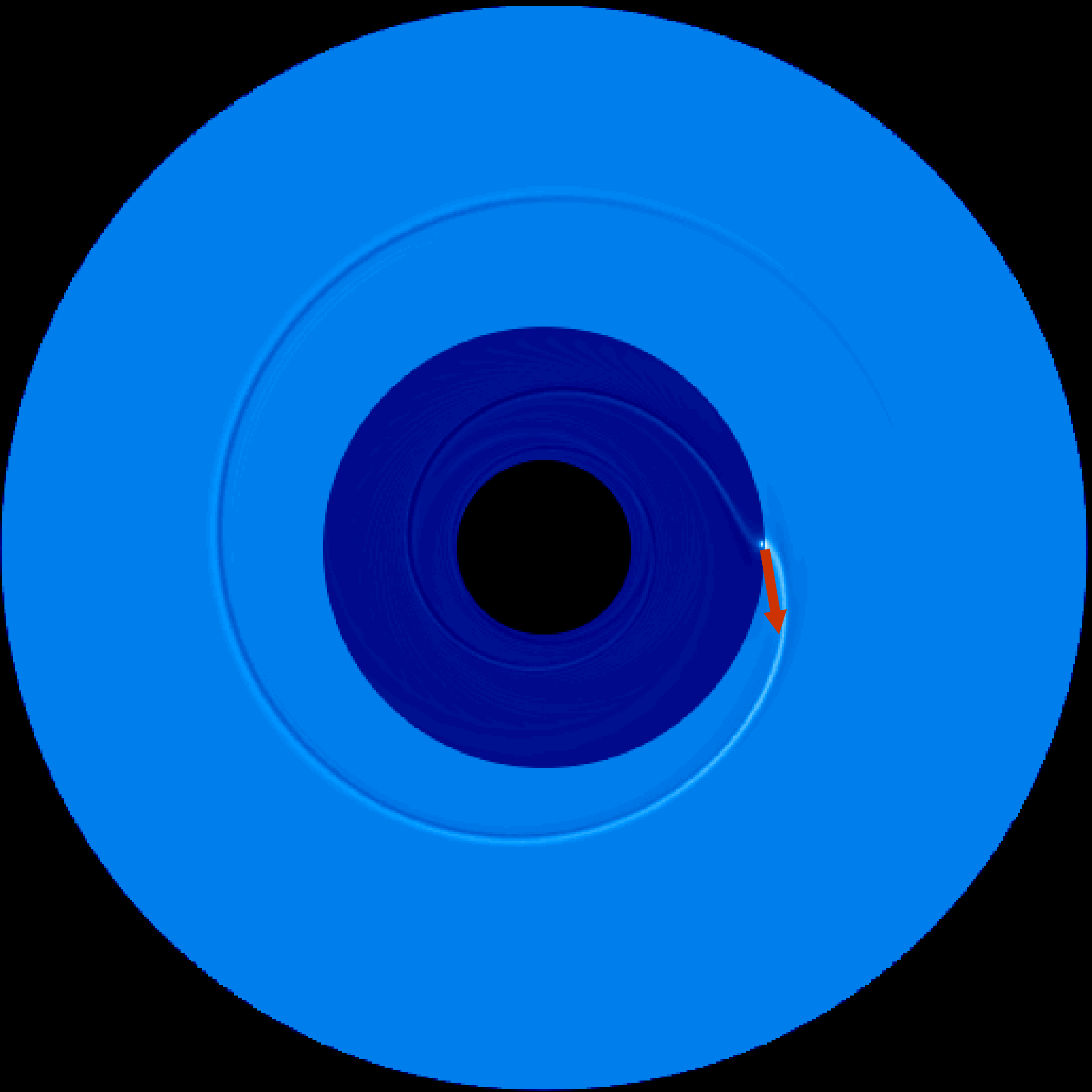
Clear/white = over-density , Dark = underdensity.

Wake = over-density.
This mass attracts the planet gravitationnally.

These forces exerted on the planet have a momentum with respect to the central star.

It leads to a torque, and thus a change in the planet's orbital angular momentum $L_p = M_p (G M_* a_p)^{1/2}$,
thus a change in a_p :
planetary migration.

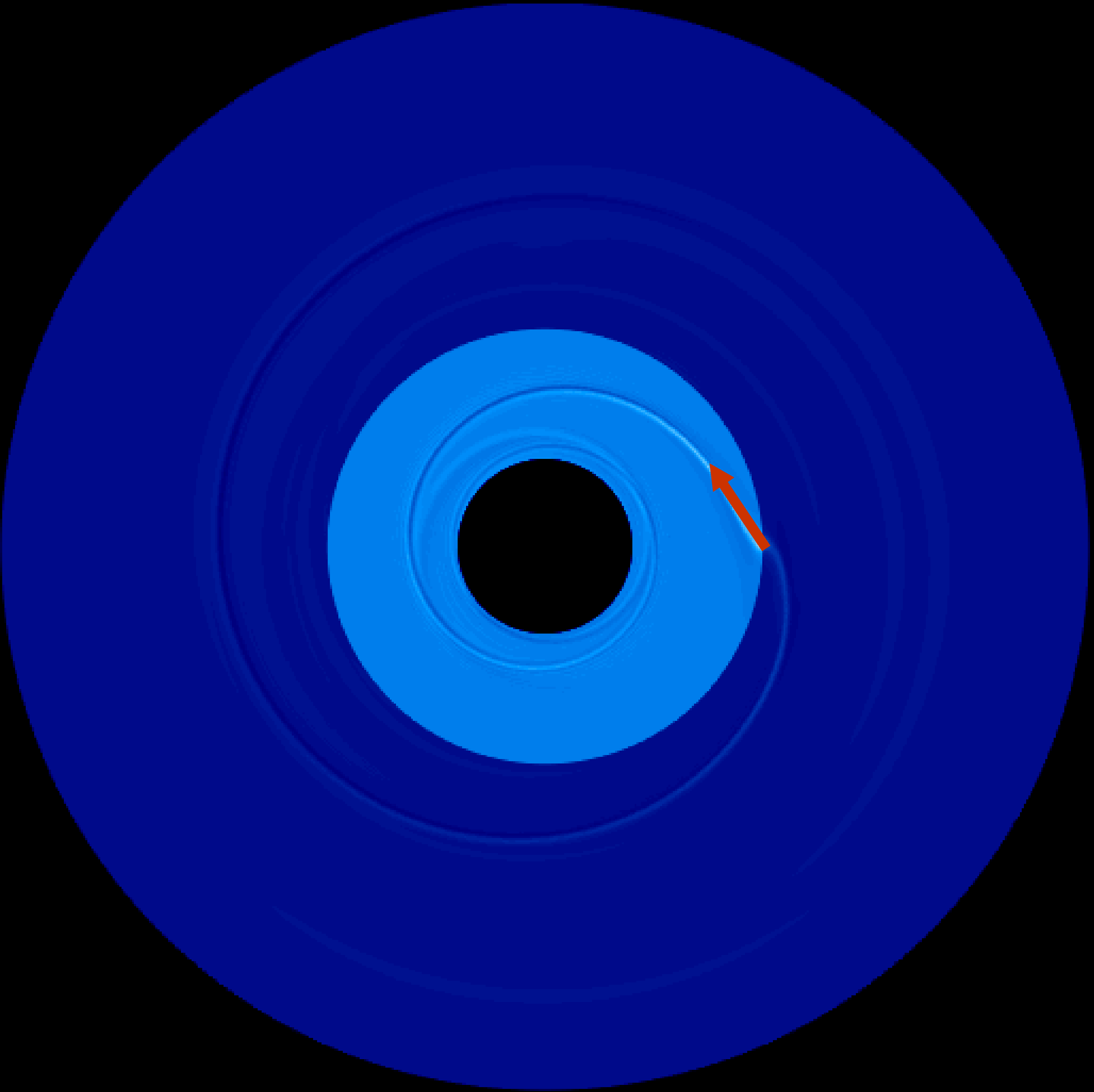
WAVE TORQUE



In the outer disk, the keplerian rotation is slower, so the wake trails behind the planet.

Thus, it exerts on the planet a <u>negative</u> torque.
It slows the planet down, and pushes it towards the central star.

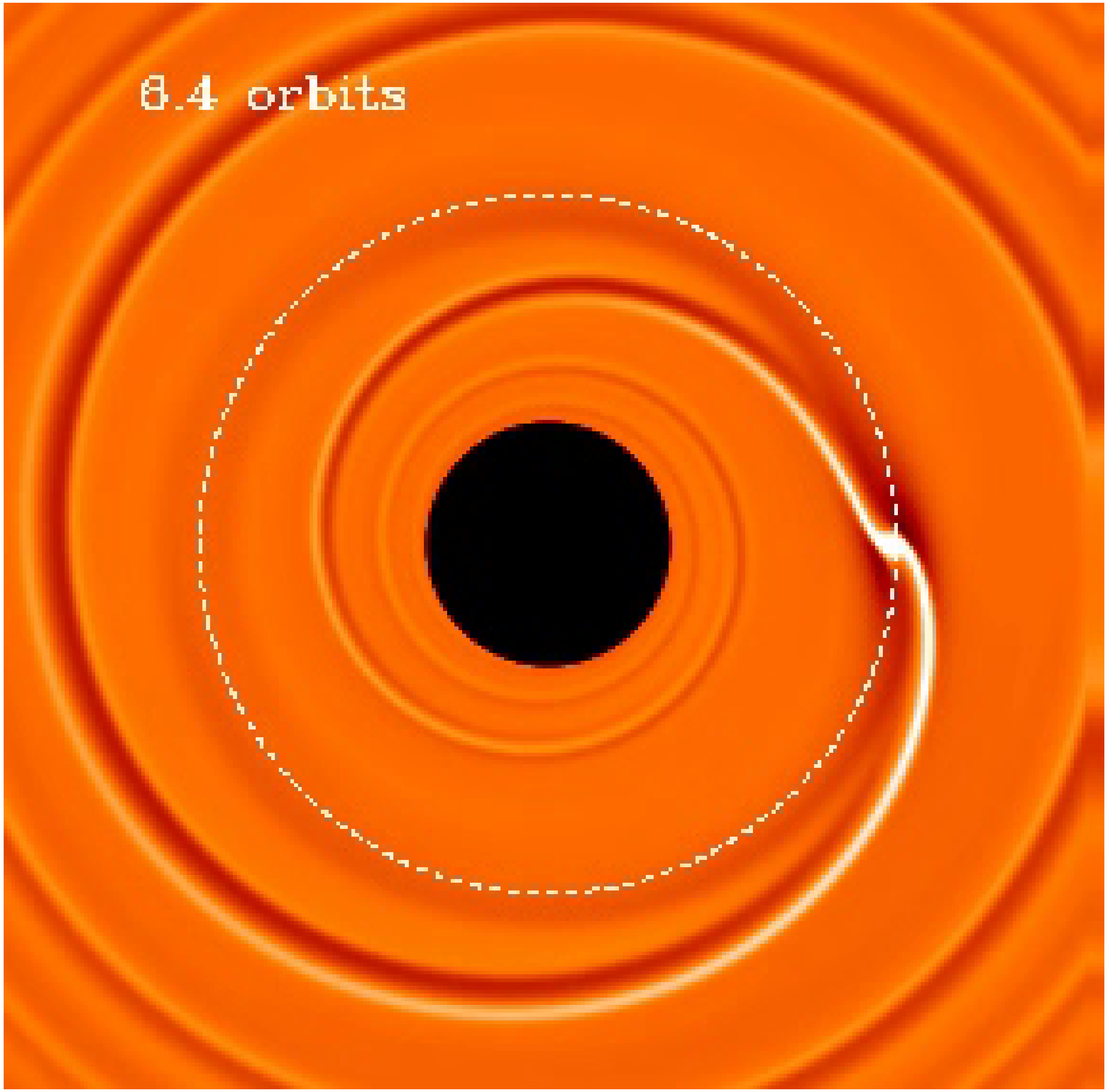
WAVE TORQUE



In the inner disk, the keplerian rotation is faster, so the wake leads the planet.

Thus, it exerts on the planet a <u>positive</u> torque.
It accelerates the planet, and pulls it outwards.

TYPE I MIGRATION



In general, the (negative) outer torque is larger (in magnitude) than the (positive) inner torque (Ward, 1997). The planet loses orbital angular momentum,
and its orbital radius a_p decreases.

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The inner / outer torque is called *one sided Lindblad torque*. The total is called the *differential Lindblad torque* and is :

$$\boxed{\gamma\Gamma_L / \Gamma_0 = -2.5 - 1.7\beta_T + 0.1\alpha_\Sigma}$$

where $\boxed{\Gamma_0 = q^2 \Sigma\, a_p^{\,4}\, \Omega_p^{\,2}\, (H/r)^{-2}}$,

$q=M_p/M_*$, Σ = surface density of the gas, $\Sigma \sim r^{-\alpha_\Sigma}$, $T \sim r^{-\beta_T}$,
H/r = aspect ratio of the disk, γ = adiabatic index.

(Paardekooper et al. 2010)

<u>Note:</u> in the linear regime, the amplitude of the wake is proportionnal to the planetary mass, and the force is proportionnal to the product of the planetary mass and that of the wake. Therefore, Γ_0 is proportionnal to q^2 .

TYPE I MIGRATION

Migration in the linear regime is often called *type I migration*.
It concerns small mass proto-planets (~ a few Earth masses).

The migration speed is proportionnal to the planet's mass.

Exer : Express $d\,r_p / d\,t$.

A.N. : Compute the migration time $t_{migr} = r_p / (dr_p/dt)$ associated to the Lindblad torque if :

M_p=1M_{Earth}, Σ=1700 g/cm^2, H/r=0.05

M_p=5M_{Earth}, Σ=5100 g/cm^2, H/r=0.1

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$M_p = 1 M_{Earth}$, $\Sigma = 1700$ g/cm^2, $H/r = 0.05$

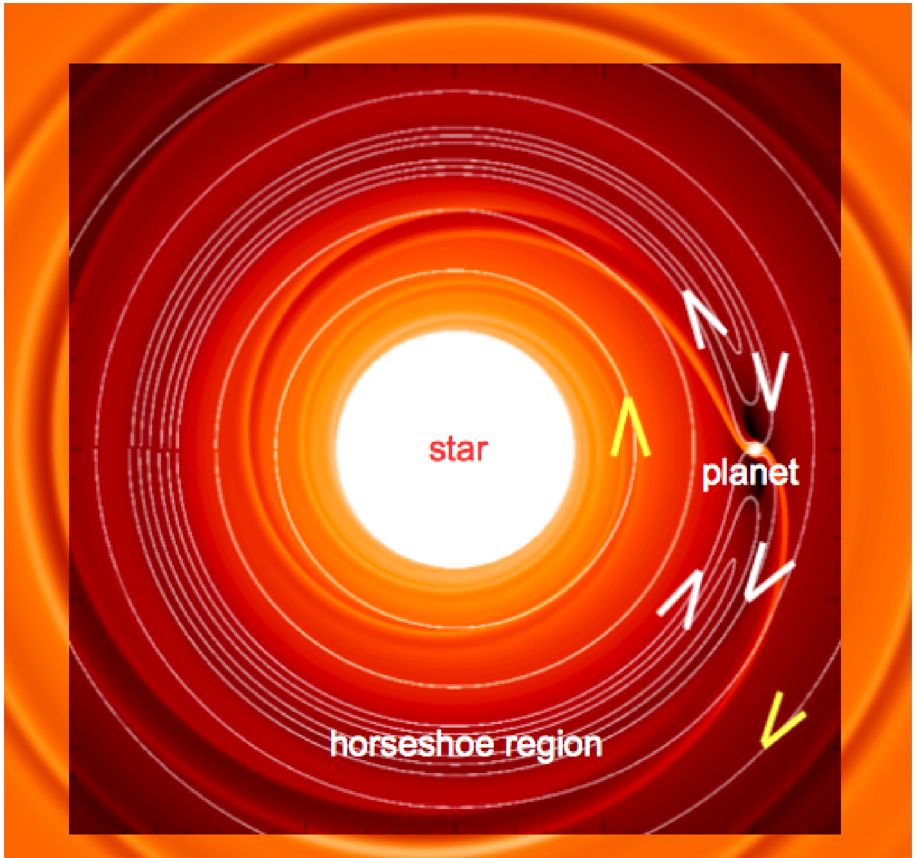
=> t_{migr} = 200000 years.

$M_p = 5 M_{Earth}$, $\Sigma = 5100$ g/cm^2, $H/r = 0.1$

=> t_{migr} = 53000 years.

COROTATION TORQUE

Around the planetary orbit, the gas corotates with the planet. The streamlines of the velocity field have horseshoe shapes.



Picture: C. Baruteau

COROTATION TORQUE

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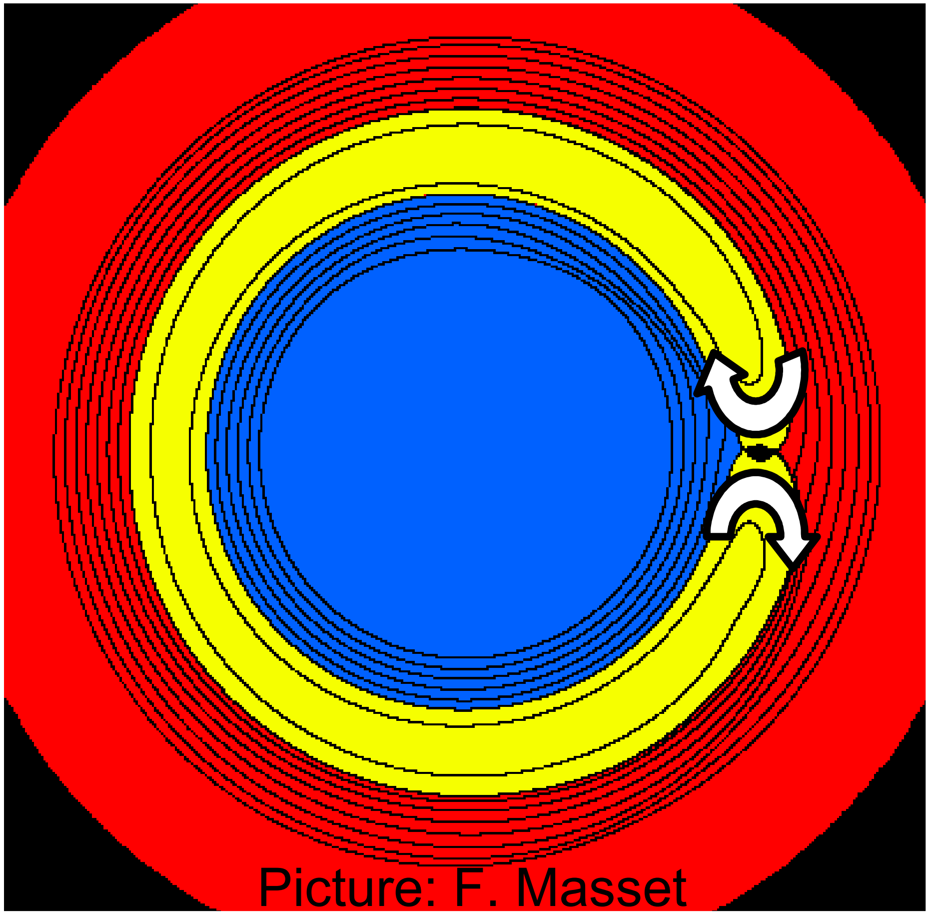
The torque arising from this «horseshoe region», the *corotation torque* Γ_c, has been widely studied in the last decade.

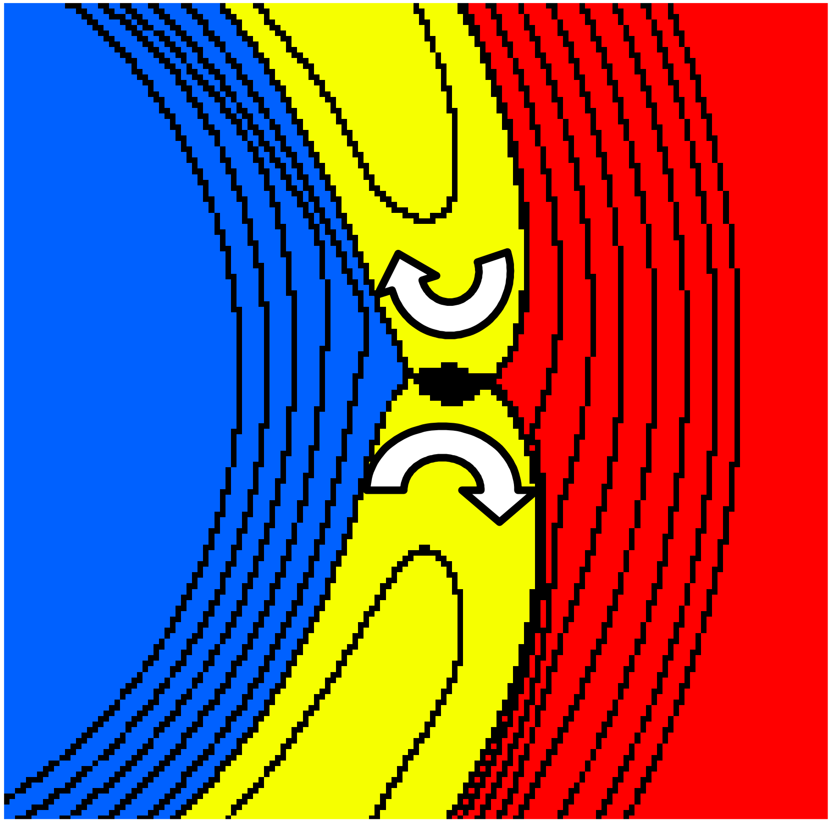


COROTATION TORQUE

$$\boxed{\gamma\Gamma_c / \Gamma_0 = 1.1\ (3/2 - \alpha_\Sigma) + 7.9\ \xi/\gamma}$$

$$\xi = \beta_T - (\gamma-1)\alpha_\Sigma$$

(Paardekooper et al. 2010)



<u>1st term :</u> barotropic part
(e.g.: Ward 1991, Masset 2001,
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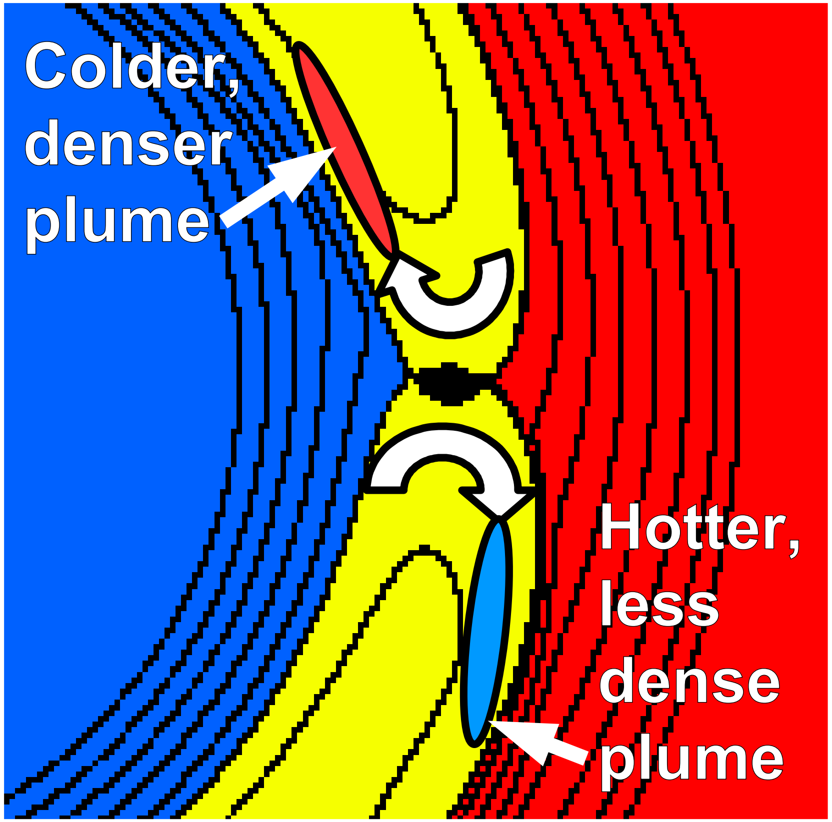


<u>1st term :</u> barotropic part

(e.g.: Ward 1991, Masset 2001, Paardekooper & Papaloizou 2009)

<u>2nd term :</u> thermal part, due to the advection of the entropy :

ξ = - dlog(entropy) / dlog(r)

(Paardekooper & Mellema 2008, Baruteau & Masset 2008)

TYPE I MIGRATION

$$\boxed{\gamma\Gamma_c / \Gamma_0 = 1.1 \left(3/2 - \alpha_\Sigma \right) + 7.9\, \xi/\gamma}$$

(Paardekooper et al. 2010)

As $\alpha_\Sigma < 3/2$ and $\xi > 0$, this torque is generally positive, and can overcome the negative Γ_L ,

→ outward migration !

Total torque (assuming γ=1.4) :

$$\boxed{(\Gamma_L+\Gamma_c) / \Gamma_0 = - 0.64 - 2.3\, \alpha_\Sigma + 2.8\, \beta_T}$$

TYPE I MIGRATION

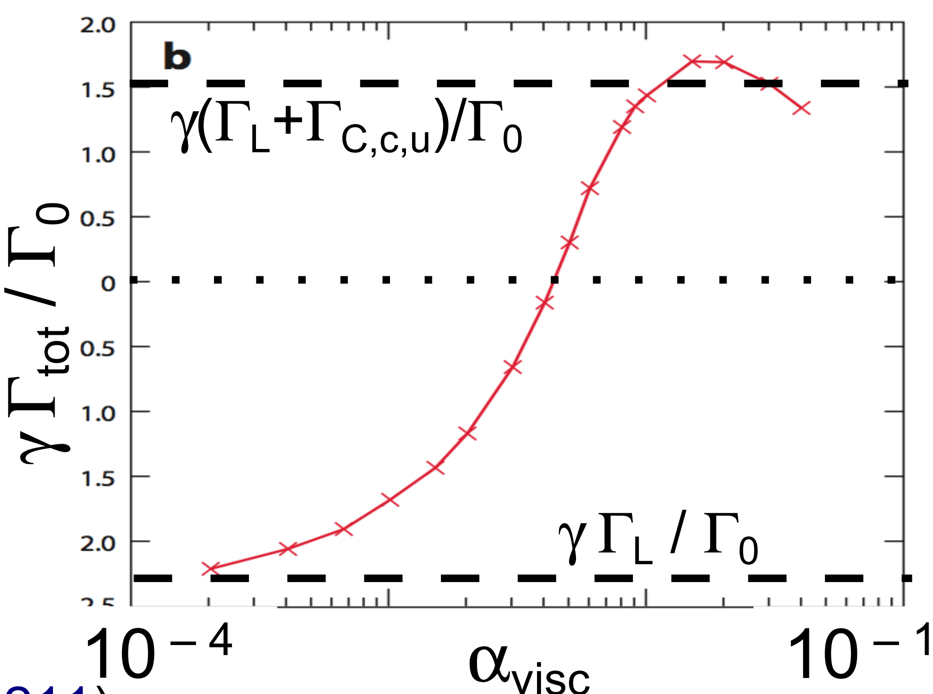
$$\gamma\Gamma_{c,\mathrm{circ,unsaturated}} / \Gamma_0 = 1.1\ (\ 3/2 - \alpha_\Sigma\ ) + 7.9\ \xi/\gamma$$

This is only true on circular orbits.
$\Gamma_c \rightarrow 0$ for large e . (Bitsch & Kley 2010, Fendyke & Nelson 2013)

The corotation torque is prone to *saturation*.

The horseshoe region only has a limited a.m. to exchange. Needs to be refreshed, through **viscosity**, otherwise $\Gamma_c \rightarrow 0$.

(see Masset & Casoli 2010,
Paardekooper et al. 2011,
Fig: Kley & Nelson 2012, ARAA, 52, 211).



TYPE I MIGRATION

The total torque depends on α_Σ and β_T, thus on the disc structure, + on saturation, thus on the planet mass → migration maps.

Viscous heating >< radiative cooling :
large β_T, non flared disks, easy outward migration.

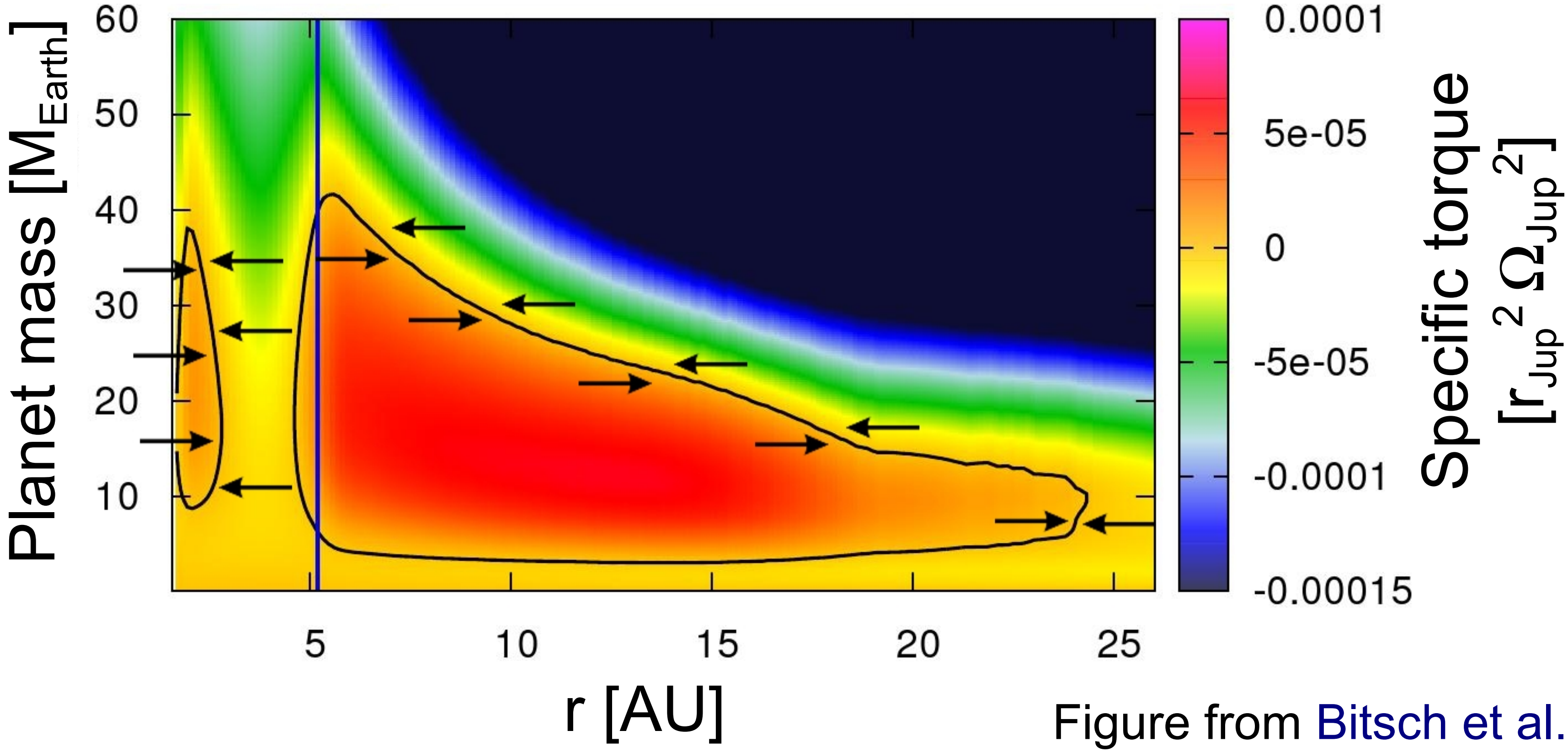
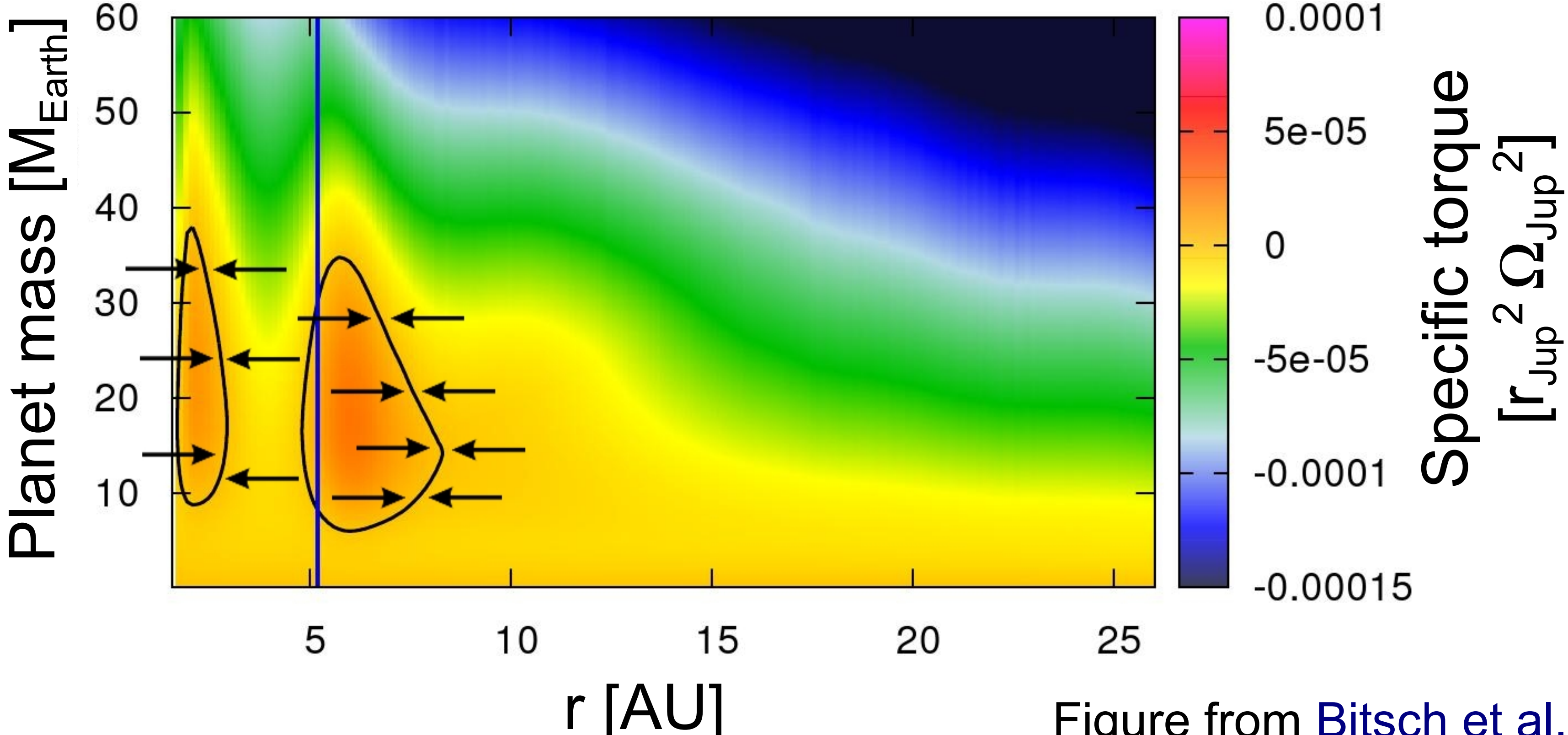


Figure from Bitsch et al. 2013

TYPE I MIGRATION

The total torque depends on α_Σ and β_T, thus on the disc structure, + on saturation, thus on the planet mass → migration maps.

Stellar irradiation + Viscous heating >< radiative cooling : smaller β_T, flared disks, smaller outward migration zone.



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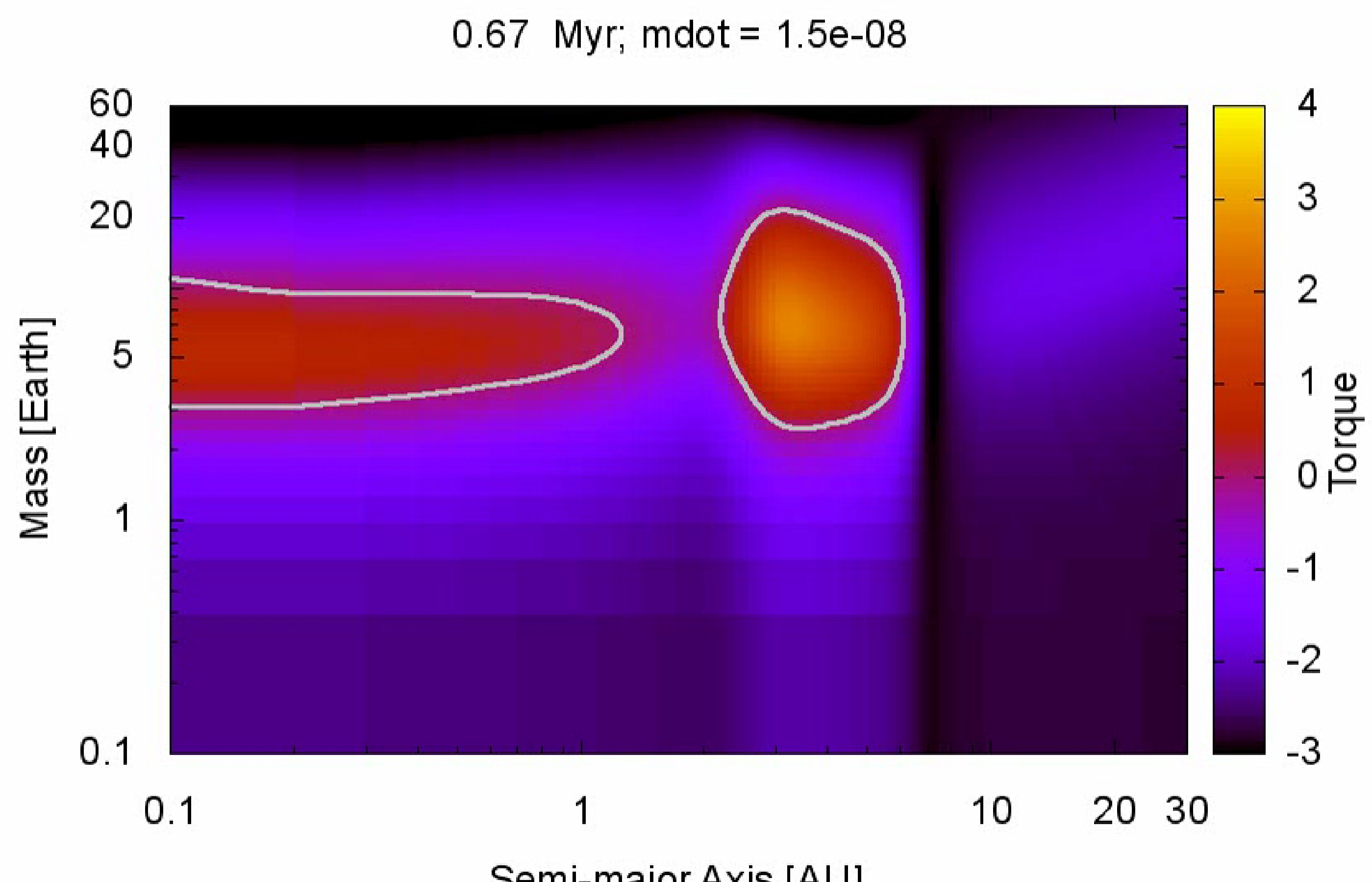
Disk evolution => migration map evolution.



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Disk evolution => migration map evolution.

→ movies by Cossou & Izidoro.

TYPE I MIGRATION

The slow inwards migration of a Super-Earth of mini-Neptune can prevent the formation of classical terrestrial planets.

A fast migration could leave embryos behind.

(Izidoro et al. 2014)

→ see movies Izodoro_SE_lente.avi ; Izodoro_SE_rapide.avi

TYPE I MIGRATION

<u>Summary :</u>

Small mass planets launch a spiral wake (*sillage*).

They feel a torque from the disk, prop to $\Gamma_0 = (q/h)^2 \Sigma\, a_p^4\, \Omega_p^2$, which changes their orbital angular momentum, hence radius: migration !

- the Differential Lindblad Torque promotes (too fast) inwards migration

- the Corotation Torque can promote outward migration

- the total torque depends on the planet mass, and on disk local properties.

→ zero torque radius, where embryos converge ?

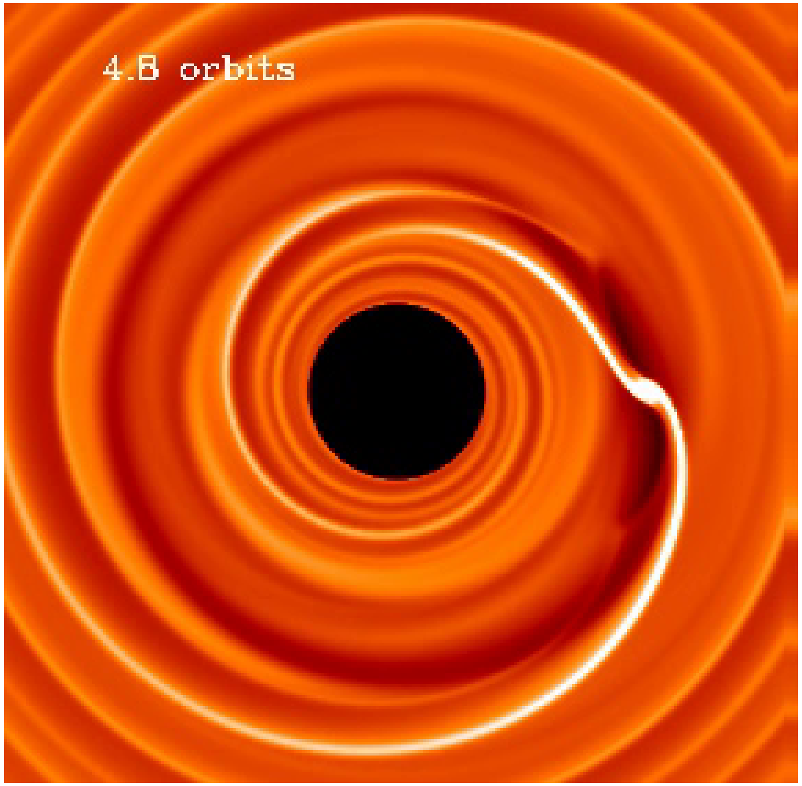
GIANT PLANETS

In the case of giant planets, the linear regime in not valid anymore. The wake shocks, and deposits angular momentum. Thus, giant planets perturb the density profile of the disk.

The outer disk is taking angular momentum from the planet, and is accelerated by the planet. Therefore, it shifts outwards.

The inner disk is giving angular momentum to the planet, and it is slowed down by the planet, because the wake is leading in front of the planet. Therefore, the inner disk loses orbital angular momentum, and shifts towards the star.

GAP OPENING



The outer wake has a larger angular velocity than the local gas ($\Omega_p > \Omega_{gas}$).

It accelerates the gas, gives angular momentum to the gas.

In contrast, the inner wake carries a negative angular momentum flux, given to the gas.
So, the gas moves inwards.

In the end, the planet tends to open a gap around its orbit, and to split the disk into an inner disk and an outer disk, separated by an empty region (Lin & Papaloizou, 1986).

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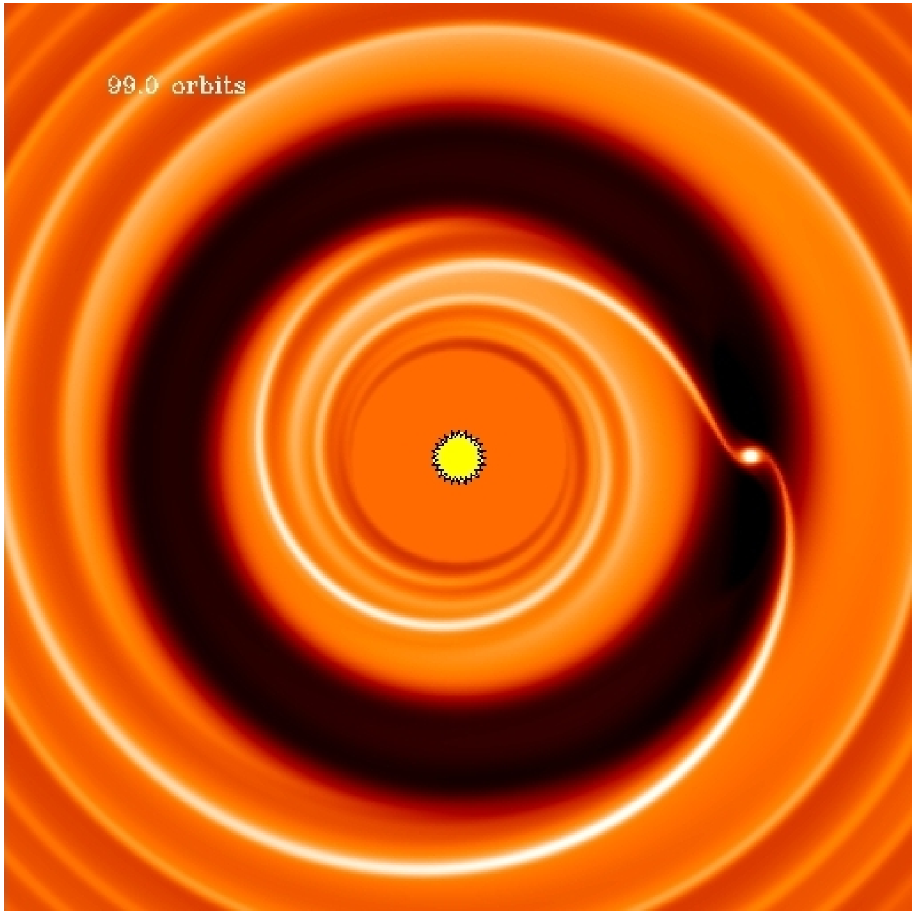

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GAP OPENING

The amount of gas remaining in the gap depends on the competition between the torques from the planet, wihch repel the gas, and the effects of the viscosity and pressure in the gap, which tend to make the profile smooth.

The more viscous or thick the disk is, the highest the planetary mass must be. Therefore, there is an opening criterion (Crida et al. 2006) for the density in the gap to be less than 10% of the unperturbed density :

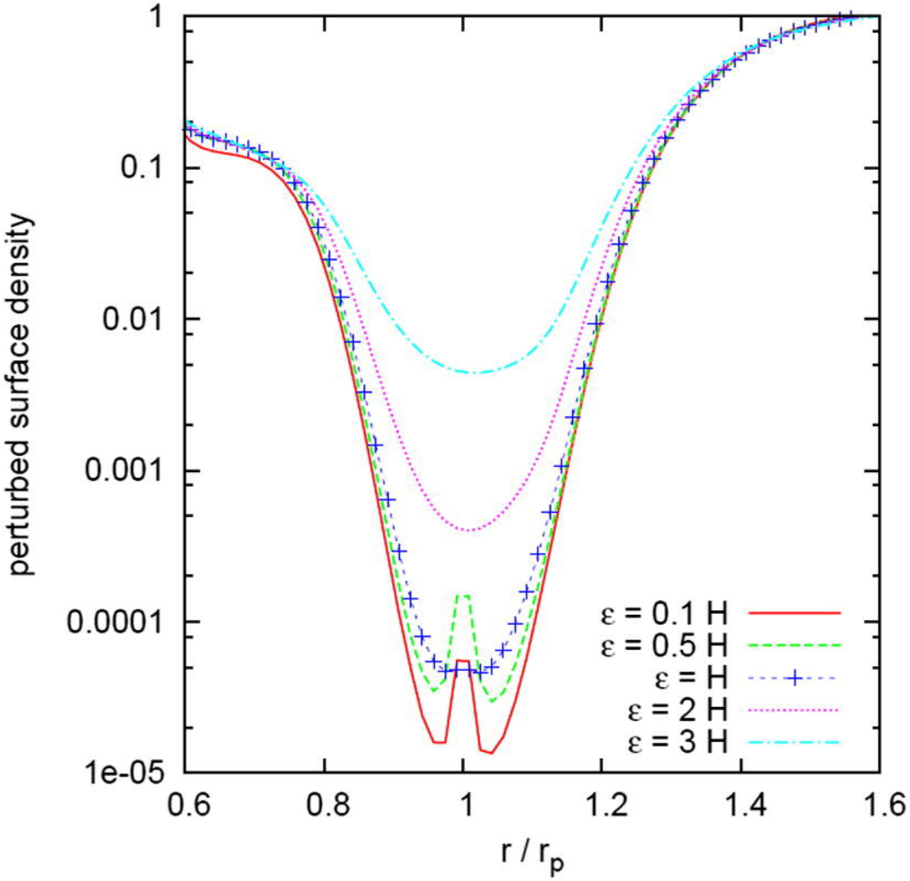
$$\boxed{\mathbf{3H / [4r_p(M_p/3)^{1/3}] + 50\nu / [r_p^2\Omega_p M_p] < 1}}$$

<u>Application</u> : In a standard disk, $H = \sim 0.05\, r_p$, $\nu = \sim 10^{-5}\, r_p^{\,2}\, \Omega_p$, and $M_p > M_{Saturn}$ is enough.

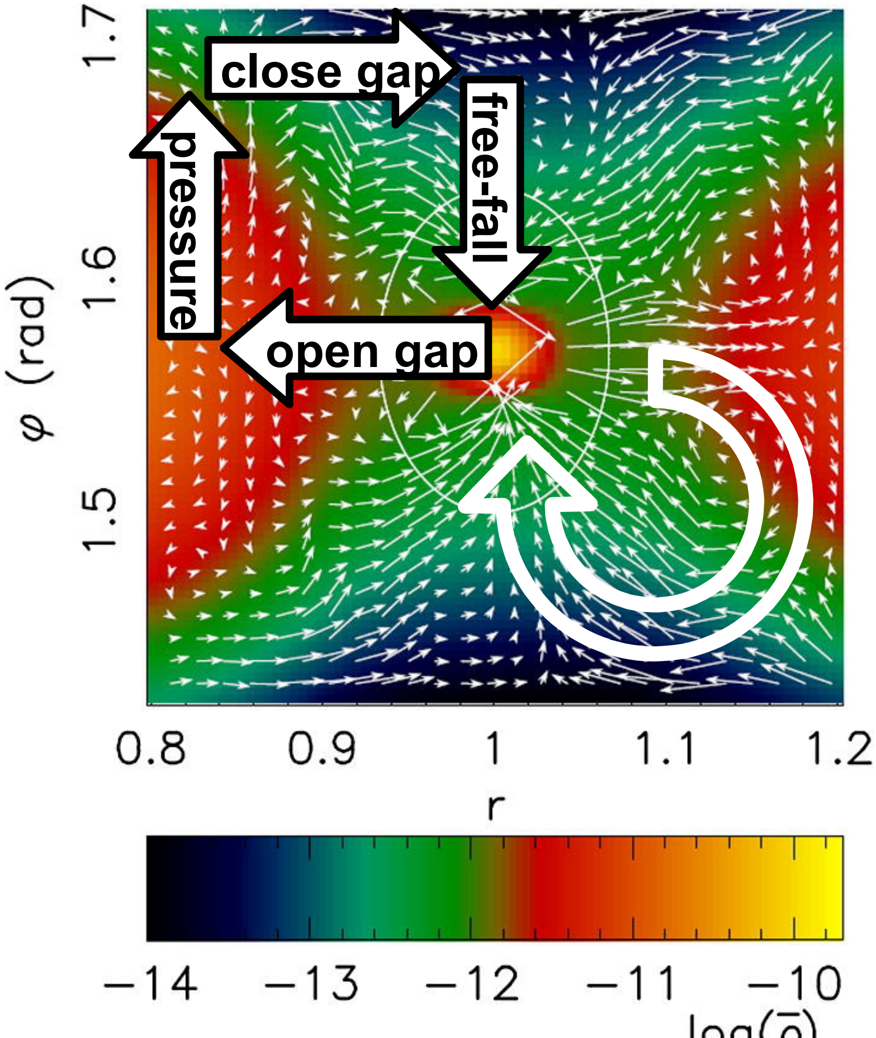
BACK to GAS ACCRETION

Consequences of gap opening on gas accretion.

1) A 3D structure of gas accretion



2D simulations, isothermal, M_{Jup} , various smoothing length = various planes = various gap profiles.



Meridional circulation (Morbidelli et al. 2014).

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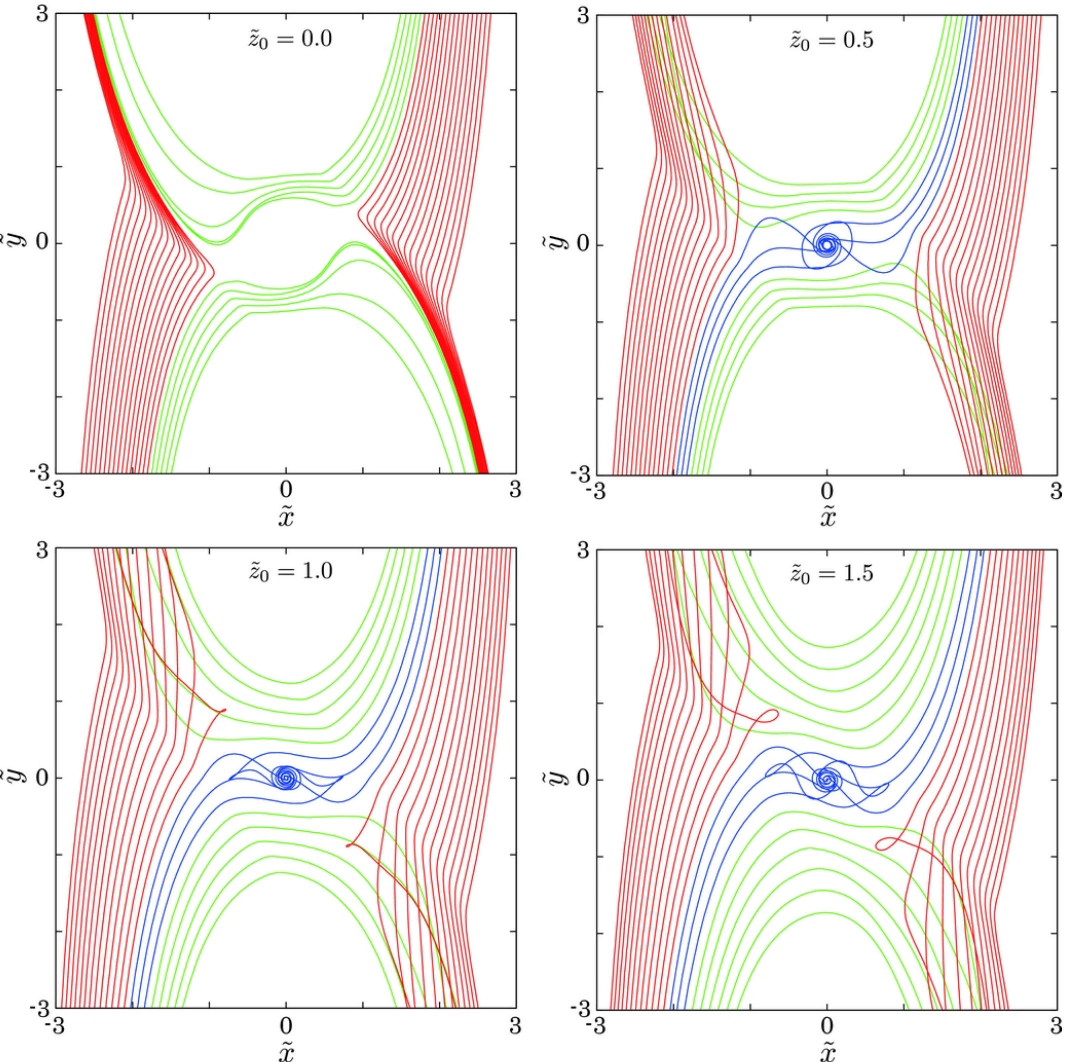
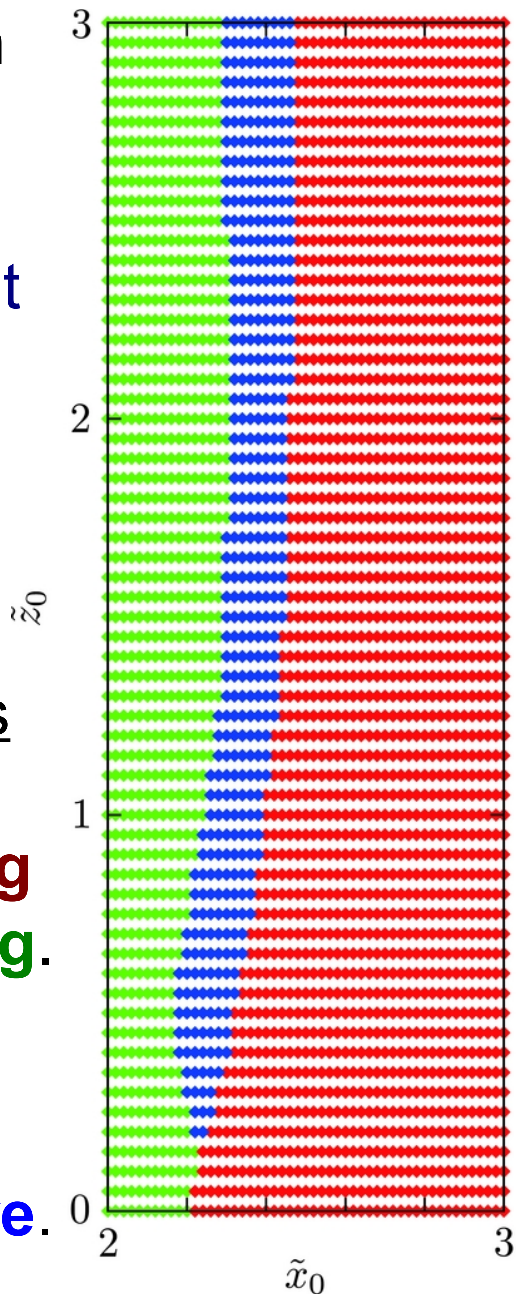


Tanigawa et al. (2012) : 3D simuls, isothermal, $M_p = M_{jup}$,

<u>Streamlines</u>
midplane :
circulating
or **librating**.

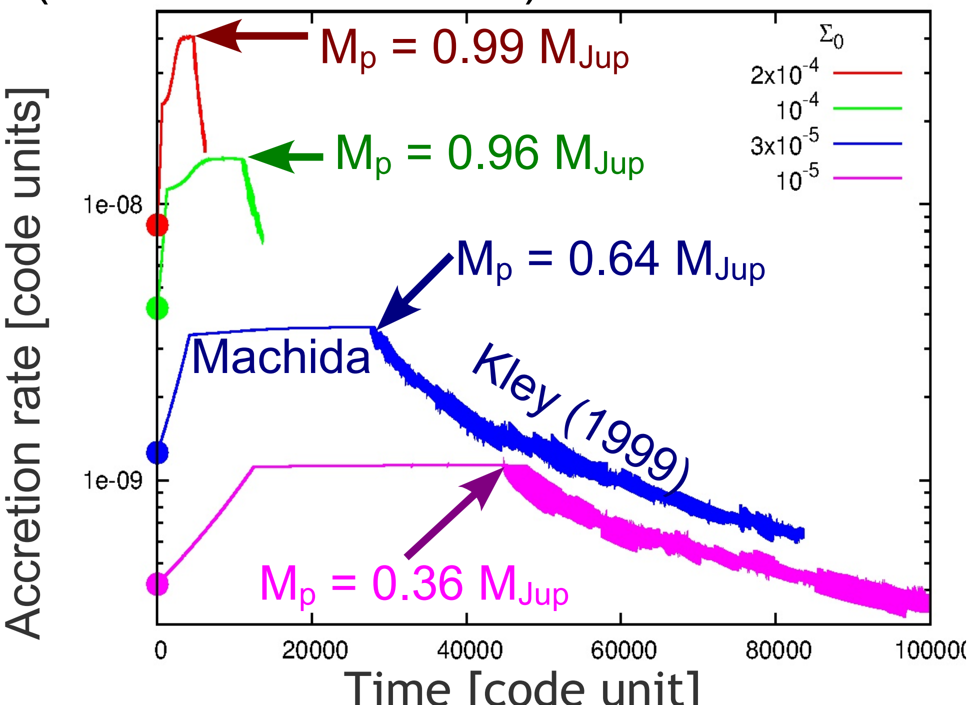
z>~0.2 H :
enter the Hill sphere.



BACK to GAS ACCRETION

Consequences of gap opening on gas accretion.
2) a possible decrease of the accretion rate.

When the planet opens a gap, or has accreted all its horseshoe region, the accretion rate drops (Crida & Bitsch 2016).



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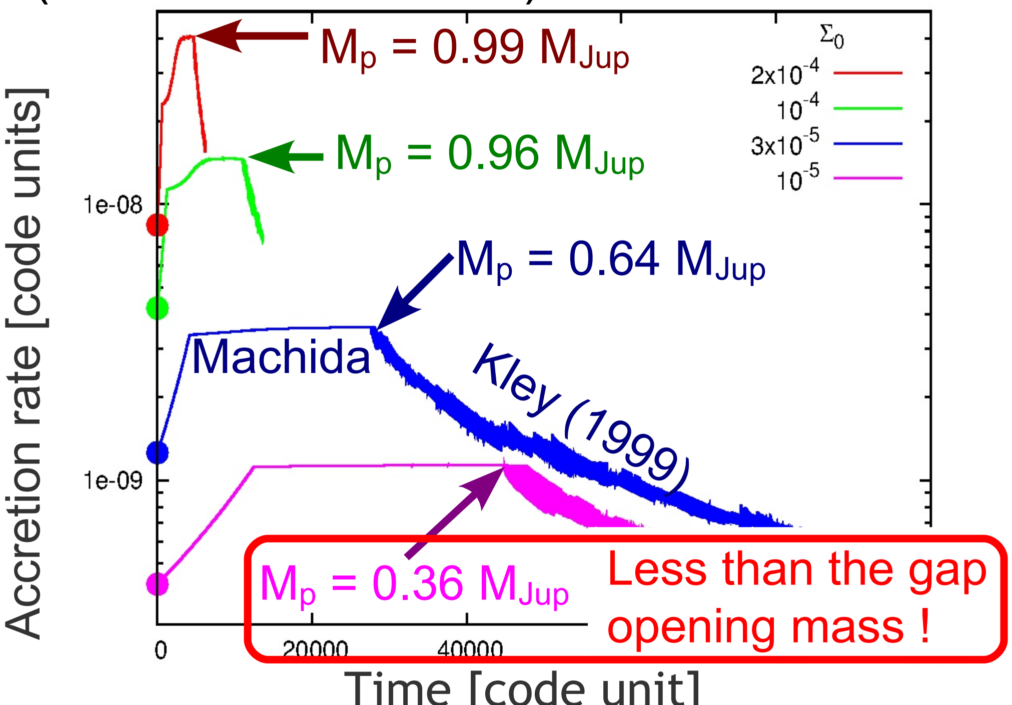


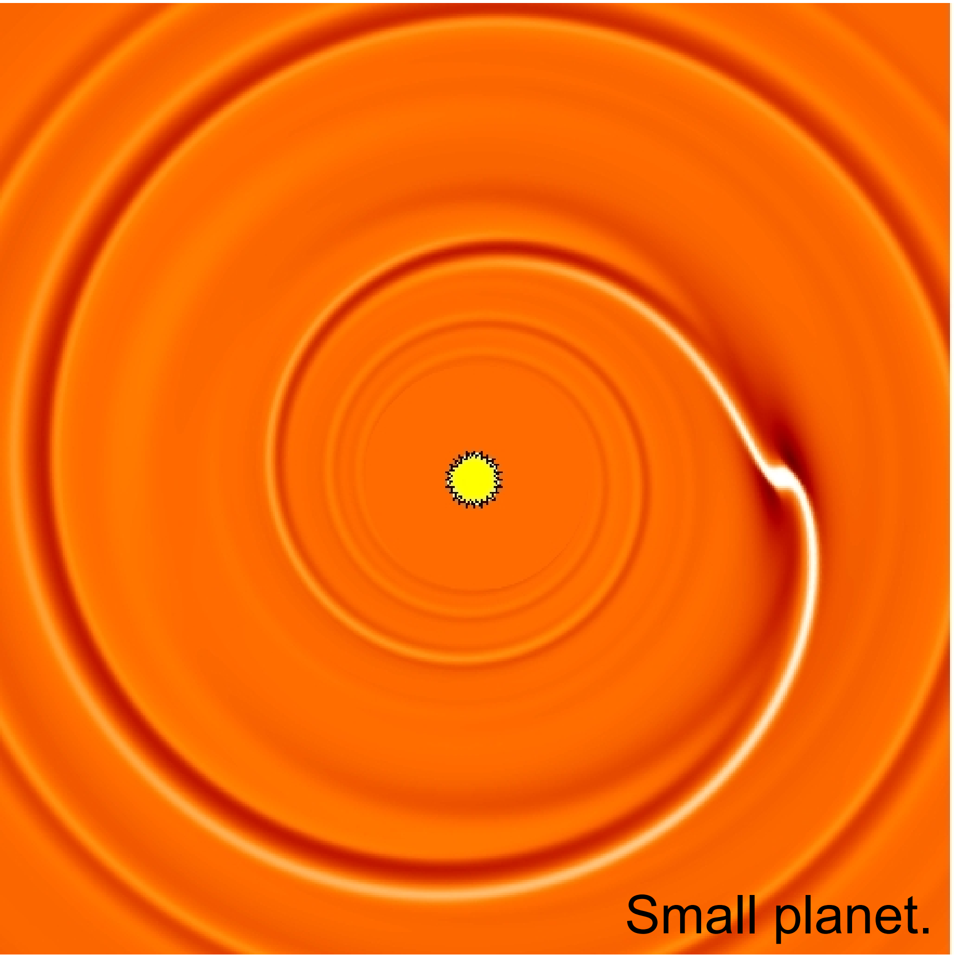
Actually, a planet can open a gap by accreting gas faster than the disk refills its horseshoe region.

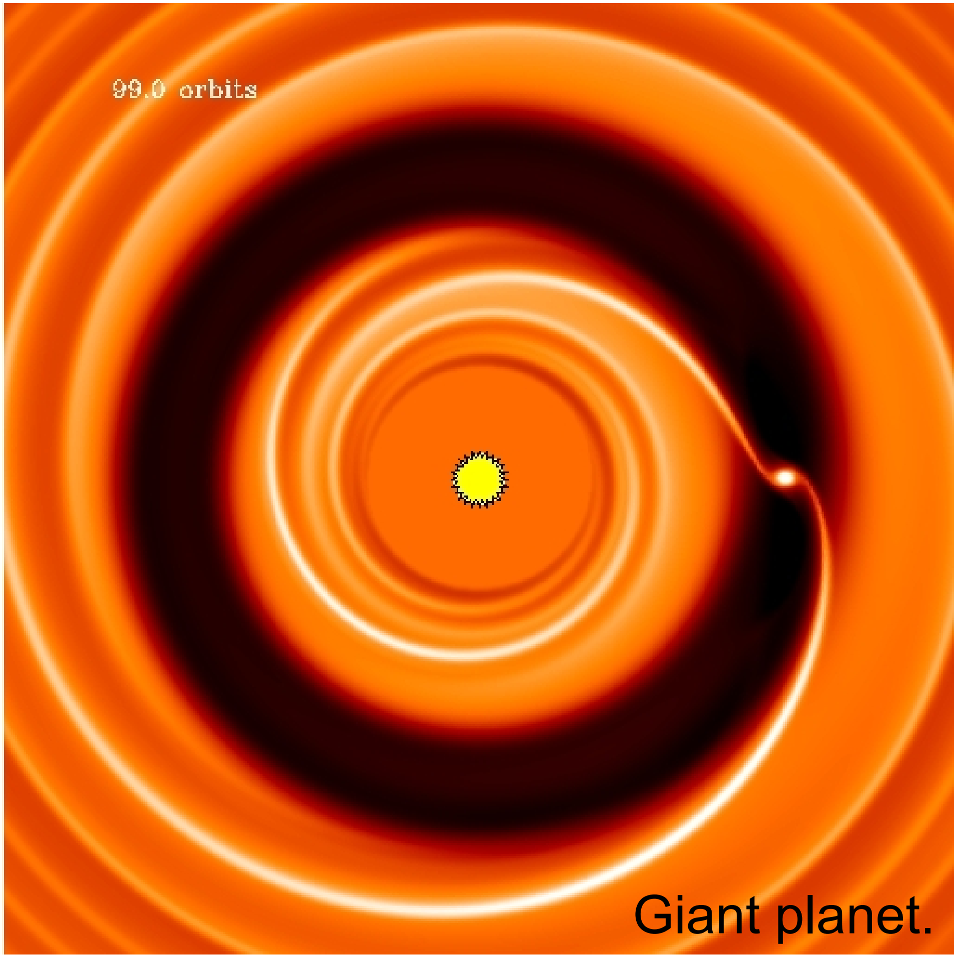
Indeed, the gas is accreted from the separatrix between the horseshoe and the disk. The horseshoe region spreads viscously into this void, until empty.

The accretion rate **then** becomes that of the disk.

GAP OPENING

In ~100 orbits, a giant planet of a Jupiter mass repels the disk around its orbit, and opens a gap.

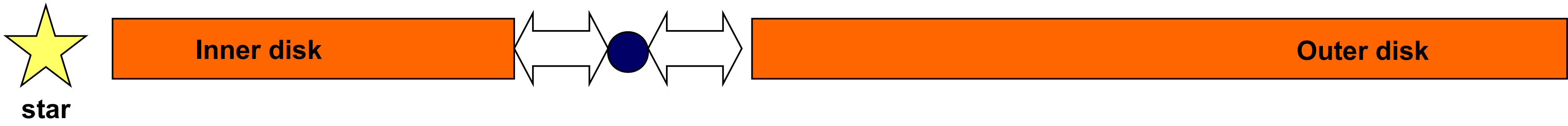




TYPE II MIGRATION

The planet is repelled
→ outwards by the inner disk
→ inwards by the outer disk.

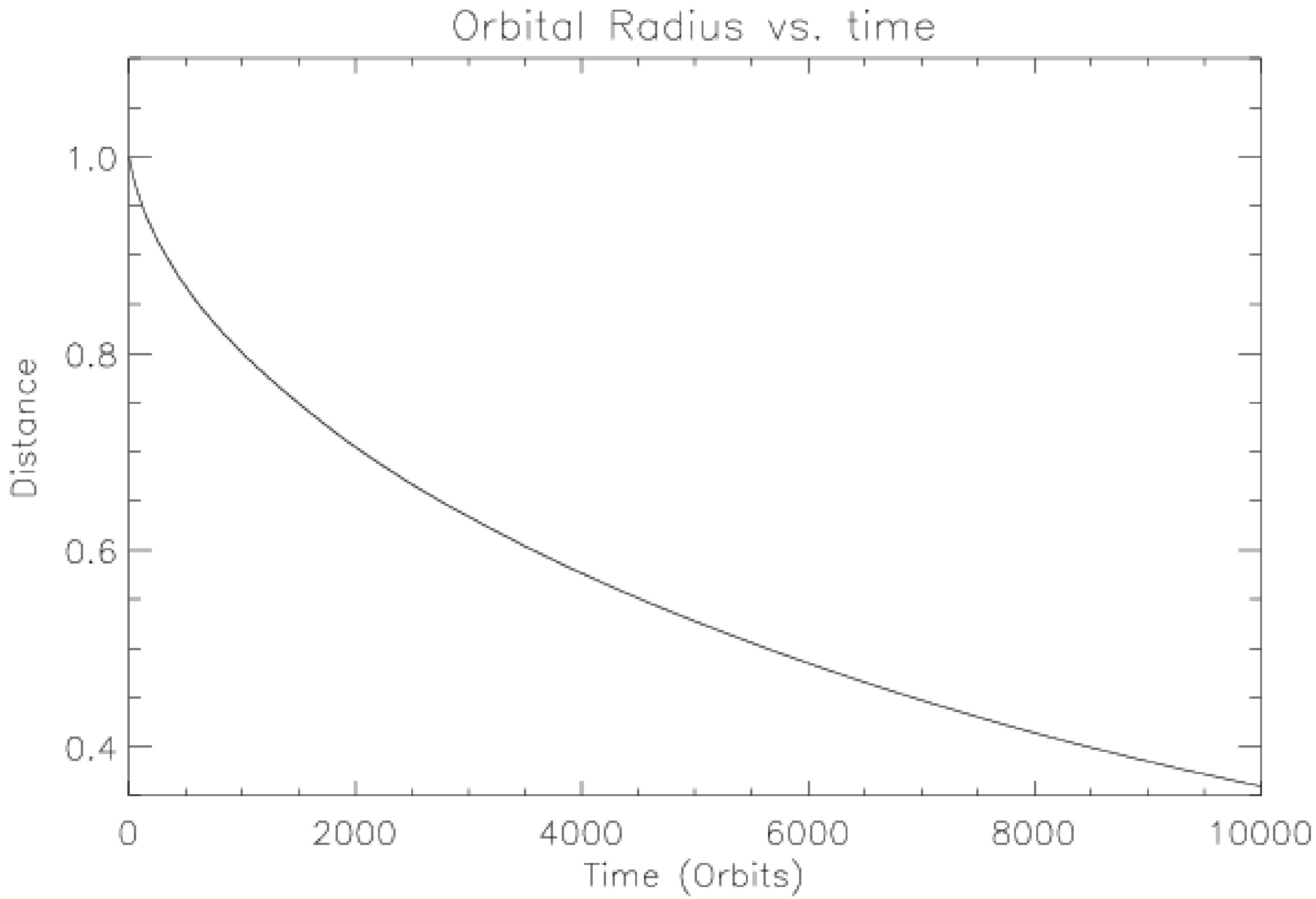
It is locked in the middle of the gap, and can not migrate **with respect to** the gas of the disk anymore.



But the disk falls onto the star (accretion), driving the planet inwards.

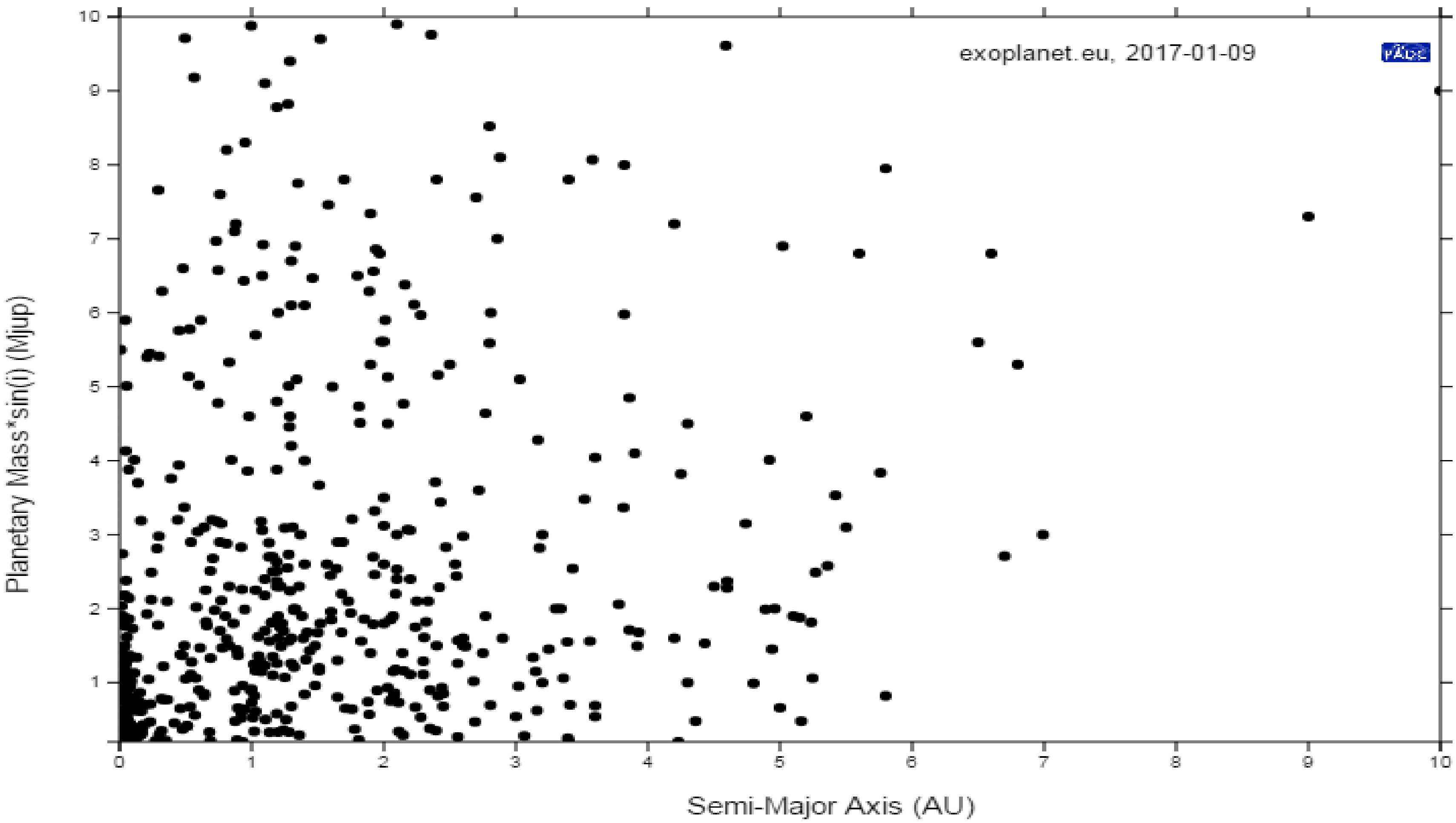
TYPE II MIGRATION

The planet follows the viscous accretion
of the disk towards the star



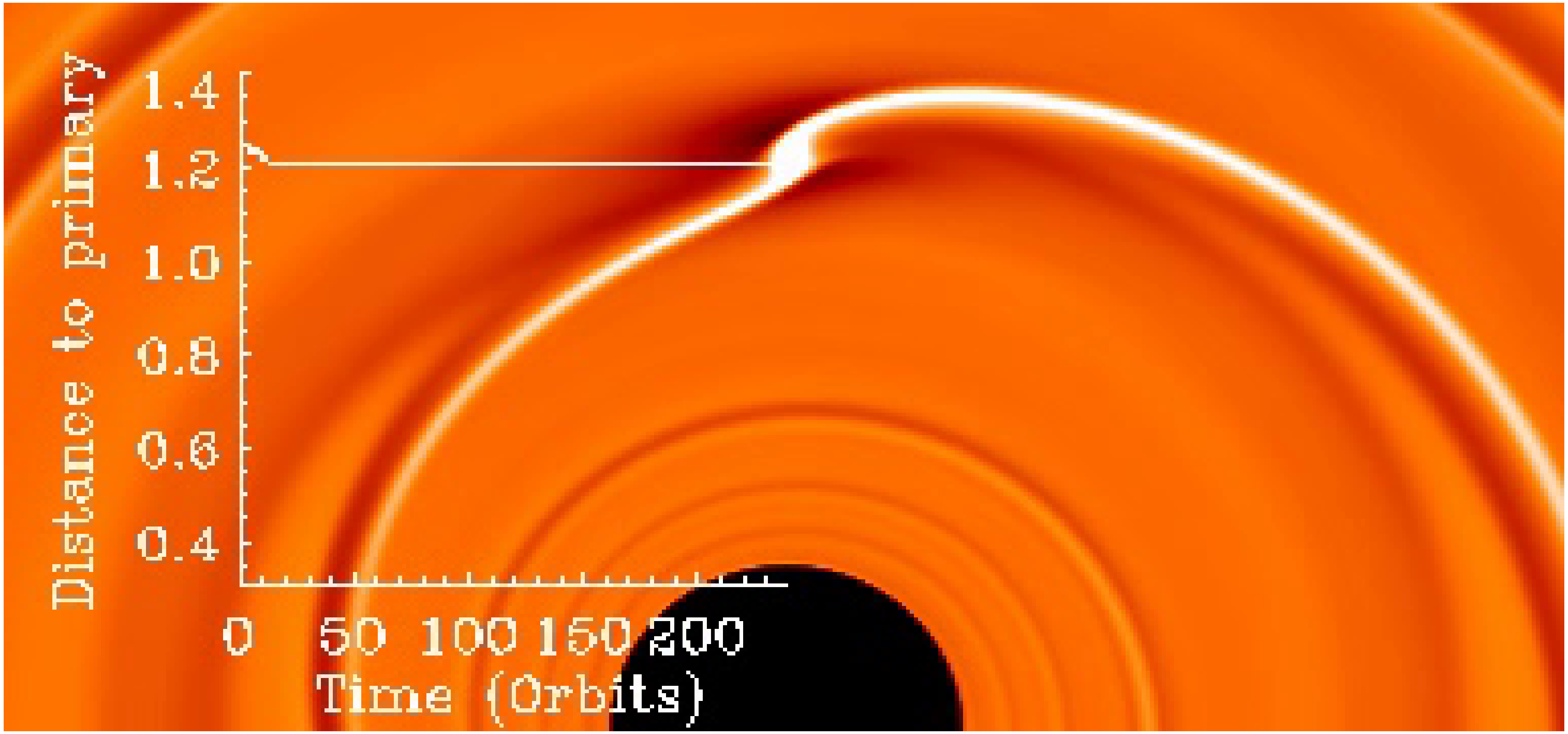
TYPE II MIGRATION

Many exoplanets are giant planets, close to their host star, where in principle they couldn't form : the *hot Jupiters*. This is a strong indication of type II migration....



TYPE II MIGRATION

Type I to type II transition by growth of the planet :



HISTORY OF JUPITER

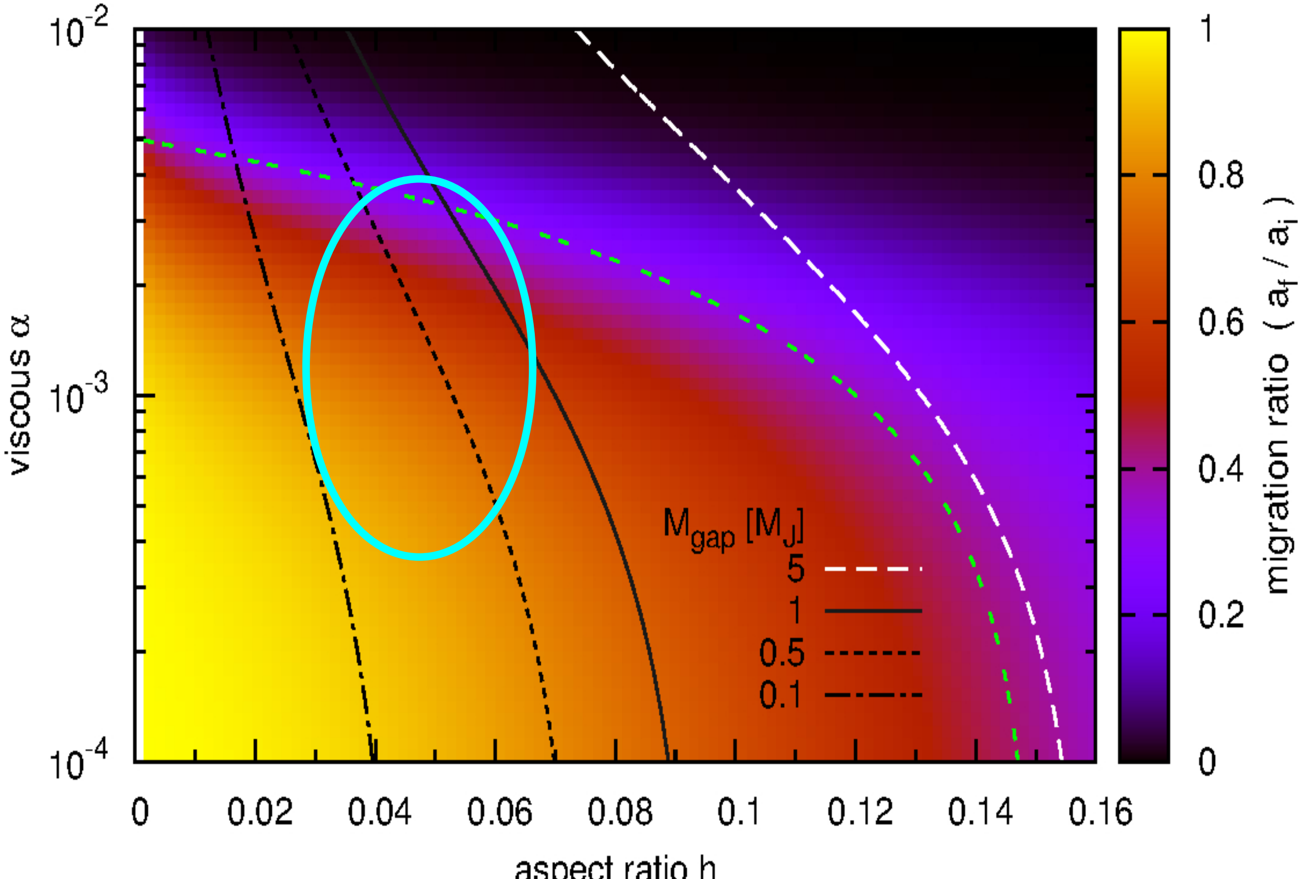
Type I to type II transition by growth of the planet.

How much type I migration (assuming isothermal EOS) during accretion until a gap opens (assuming Machida et al.'s rate) ?

Crida & Bitsch (in press) :

Analytic calculations + simulations of planets growing while migrating.

Color = a_f / a_i , where M_i = 10 M_{Earth} and M_f = gap opening mass.



Green line : $30\alpha = 0.15 - h$ ~(a_f / a_i=0.4)

HISTORY OF JUPITER

1) Jupiter's core probably grew fast by pebble accretion,

2) entered in the « egg » of outwards type I migration,

3) accreted gas in phase 2 at the zero torque radius (6-8 AU),

4) sarted to open a little gap (a dip) that blocked the pebble flux,

5) entered in runaway growth, left the « egg »,
and migrated to ~4 AU,

6) opened a real gap and transitioned to type II migration.

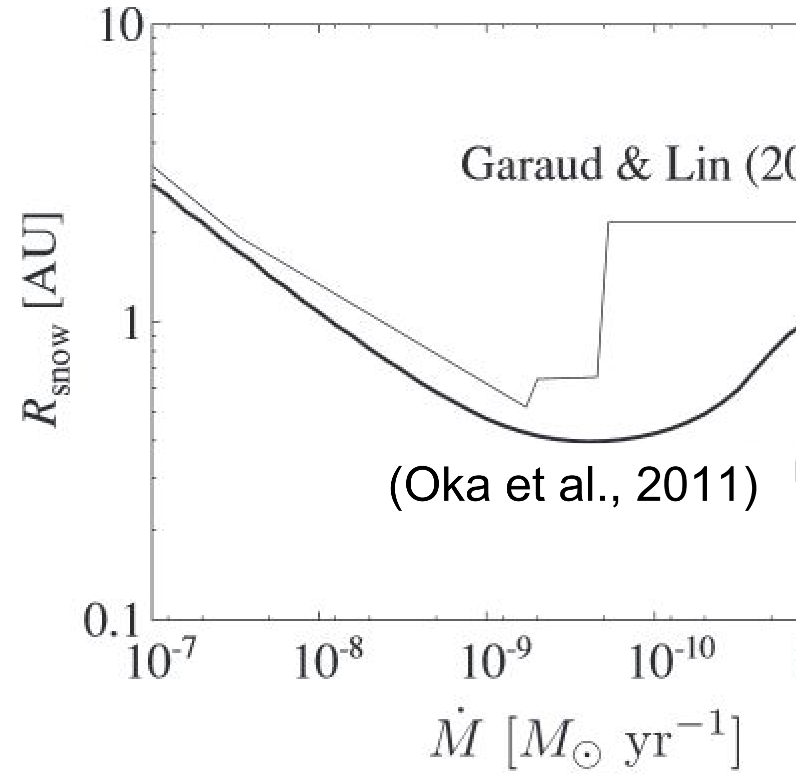
Consequences :

Jupiter acted as a barrier
- for drifting pebbles as soon as (4) happened,
- for migrating cores / proto-planets at (6).

FOSSILIZATION OF THE SNOWLINE

Reminder :

The snowline moves in, the Earth should be covered with ice.



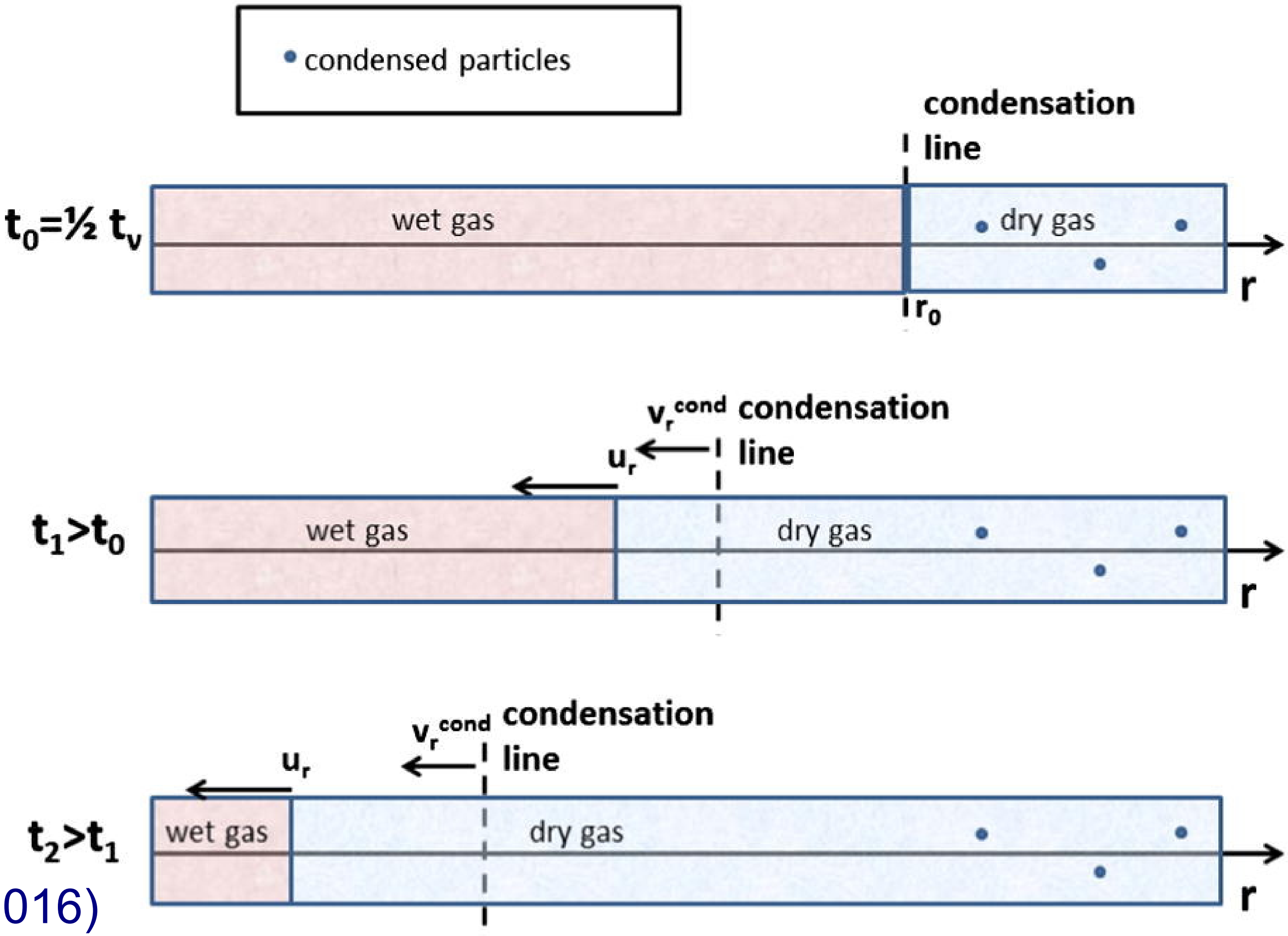
FOSSILIZATION OF THE SNOWLINE

Reminder :

The snowline moves in, the Earth should be covered with ice.

Or shoud it ?

Gas drifts faster than the snowline. Hence, only gas devoid of H_20 surrounds Earth when the snowline arrives.



(Morbidelli et al. 2016)

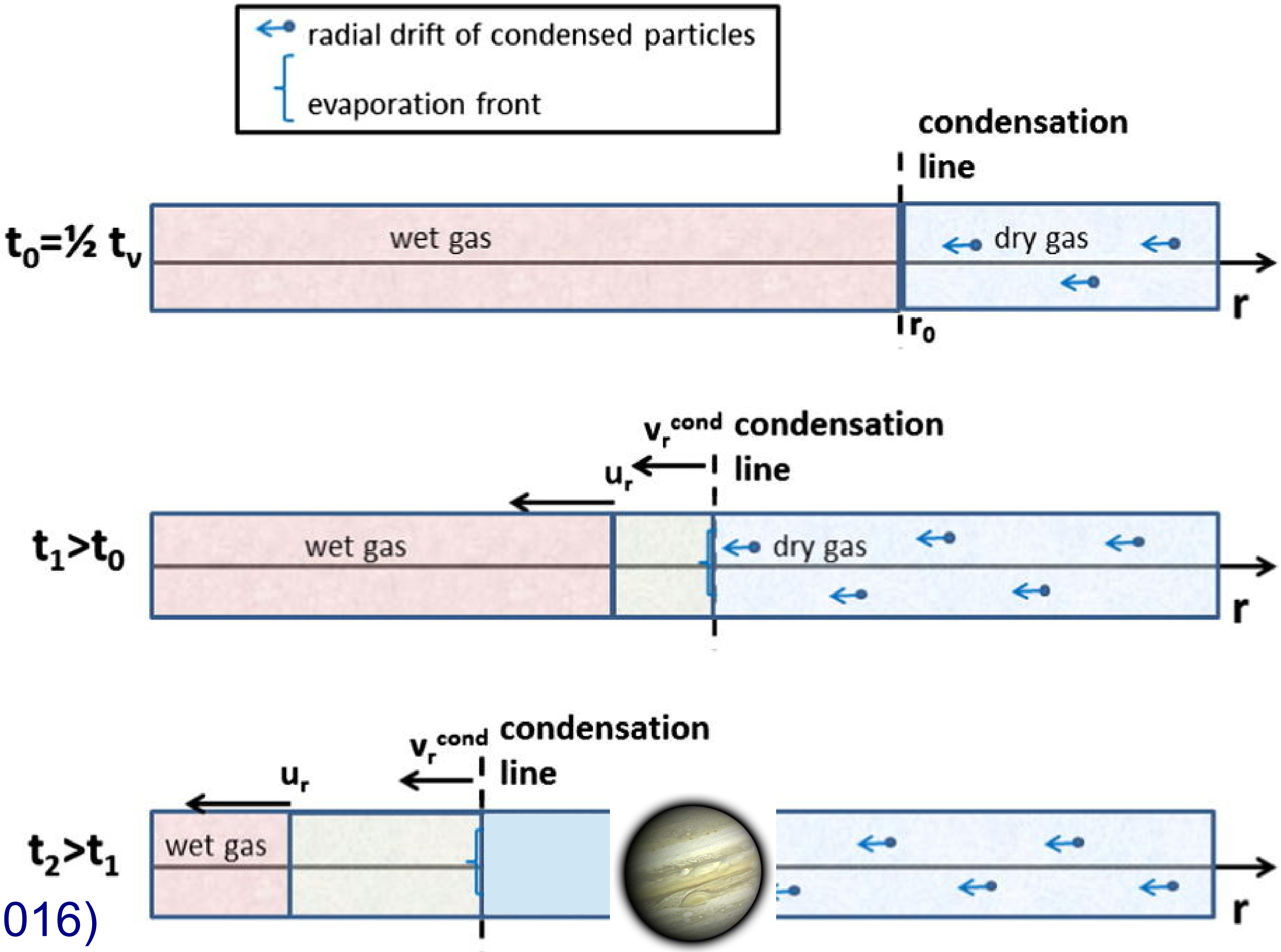
FOSSILIZATION OF THE SNOWLINE

Reminder :

The snowline moves in, the Earth should be covered with ice.

The key is the drift of solids.

When Jupiter blocs the drift of pebbles by opening a gap (or a dip), the snowline is fossilized !



(Morbidelli et al. 2016)

BLOC OF INCOMING SENs

If a Super Earth or a mini Neptune forms beyond / after Jupiter, and migrates inwards in type I migration,

It is caught in resonance by Jupiter, which is migrating slowlier.

(see movies Izodoro_Jup*)

This is why there is no hot SEN in the Solar System !

Jupiter saved the terrestrial planets !

HISTORY OF JUPITER'S MIGRATION

The rapid growth of Jupiter froze the snowline,
and blocked incoming SENs,
key events in shaping our Solar System.

Why did not Jupiter migrate all the way down to the Sun ?

It would have become a hot Jupiter, and scattered or destroyed the terrestrial embryos, shacked the main asteroid belt...

See Grand tack model tomorrow...