PLANETARY MIGRATION

Review presented at the Protostars & Planets VI conference in Heidelberg, september 2013 (updated).

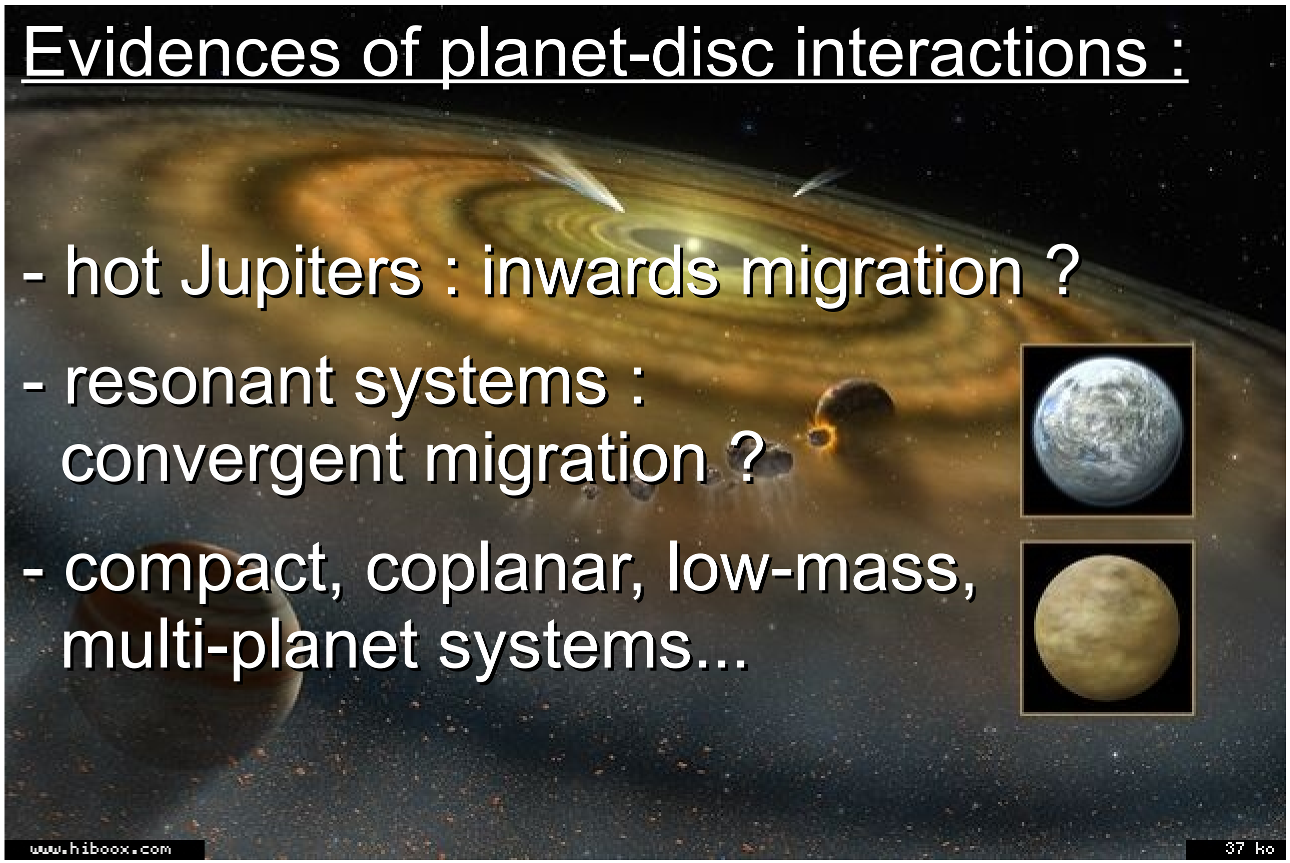
Reference : Baruteau et al. (2014) (arXiv:1312.4293)
see also : https://www.youtube.com/watch?v=_HMw4Lh7IOo

C. Baruteau, A. Crida,
B. Bitsch, J. Guilet, W. Kley, F. Masset,
S-J. Paardekooper, R. Nelson, J. Papaloizou

UNIVERSITY OF CAMBRIDGE
Queen Mary University of London
Universidad Nacional Autónoma de México
Eberhard Karls Universität Tübingen
Université Nice Sophia Antipolis
Observatoire de la Côte d'Azur

Planets form in proto-planetary discs.

Thus, there **must** be planet-disc interactions.



INTRODUCTION

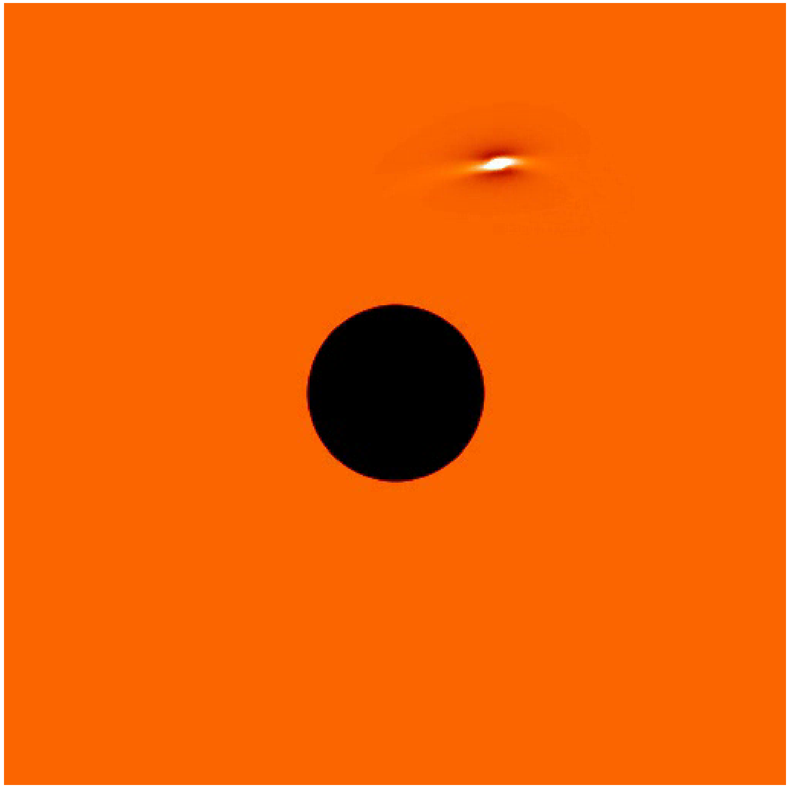
The gravity of the planet perturbs the fluid.

Spiral pressure wave : the wake, corotating with the planet.

Planet on a fixed, circular orbit.

White = over density, Dark = under density.

Movie by F. Masset



INTRODUCTION

<u>Effect of the disc on the planet :</u>

Overdensity => Force from the disc => Torque : $\Gamma = dJ_p / dt$

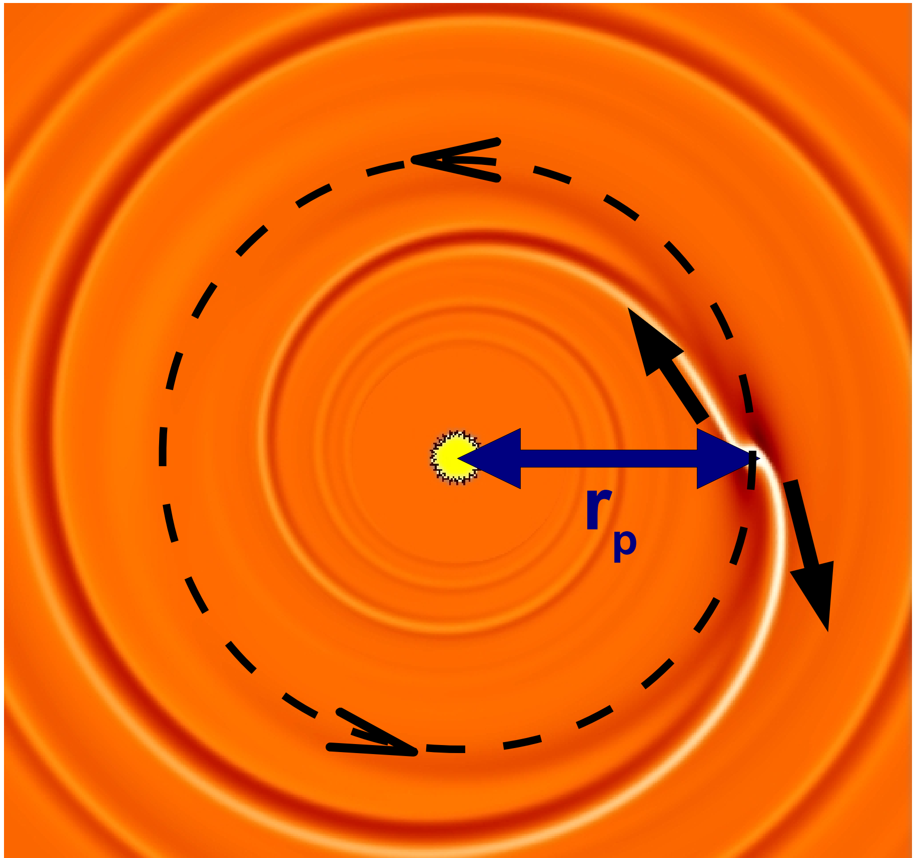
where $J_p = M_p (G M_* r_p)^{1/2}$
(orbital angular momentum for a circular orbit, r_p=orbital radius)

$\rightarrow \; d r_p / dt \sim \Gamma / M_p$

The planet feels a force from the disc, its orbit changes.

This is *planetary migration*.

Rate ? Direction ?
What is the value of Γ ?



Picture: F. Masset & A. Crida

INTRODUCTION

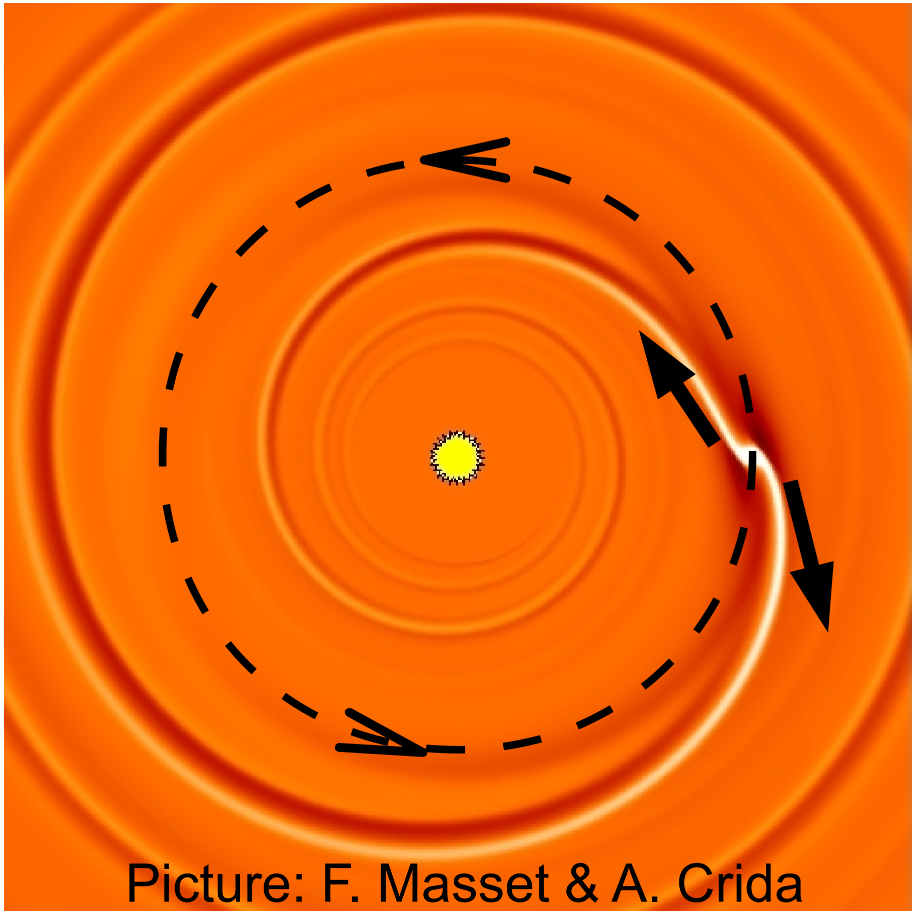
<u>Effects of the planet on the disc :</u>

→ gap opening ?

→ cavity opening ?

→ feedback on migration ?

→ link with observations ?



TYPE I MIGRATION

The torque scales with $\Gamma_0 = (q/h)^2 \Sigma_p r_p^4 \Omega_p^2$ (Lin & Papaloizou 1980, Goldreich & Tremaine 1979)

q = M_p / M_* planet/star mass ratio

Σ = gas surface density

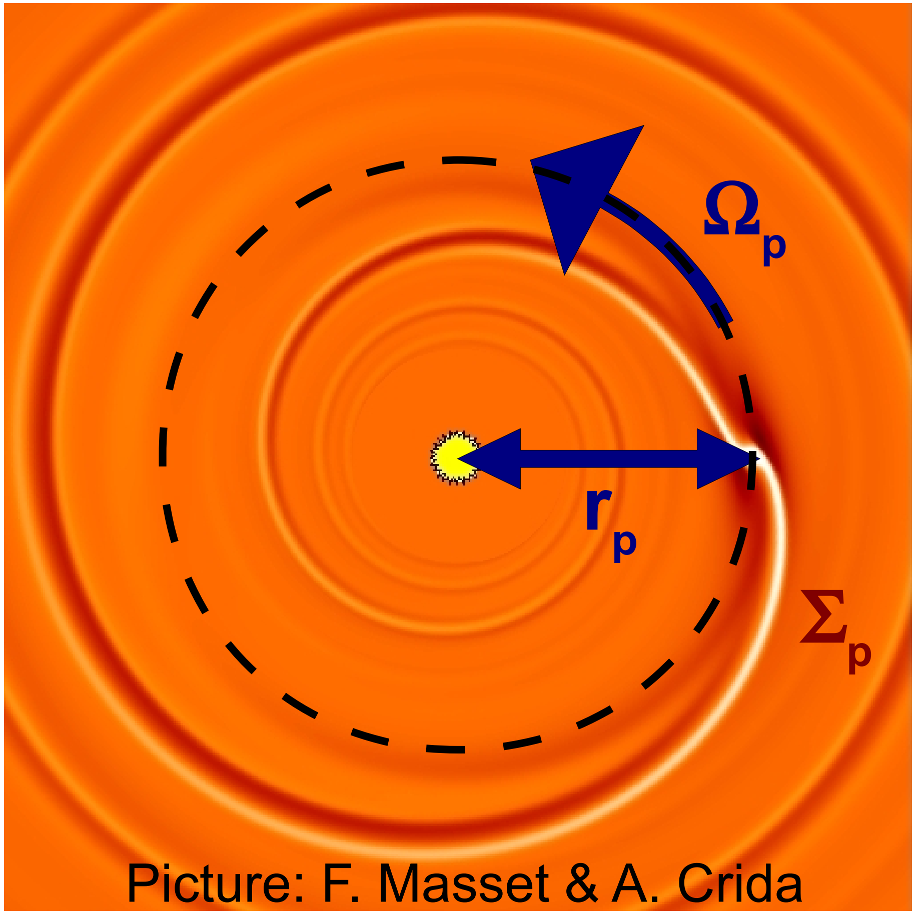
Ω = angular velocity

h = aspect ratio H/r

X_p = X at the planet location.

Σ(MMSN @1AU) =>
migration time [years] ≈ 1/q

→ 300000 yrs for an Earth ,
→ 20000 yrs for a Neptune !



Picture: F. Masset & A. Crida

TYPE I MIGRATION

The torque scales with $\Gamma_0 = (q/h)^2 \Sigma_p r_p^4 \Omega_p^2$ (Lin & Papaloizou 1980, Goldreich & Tremaine 1979)

The torque due to the wave is, in a 2D adiabatic disc :

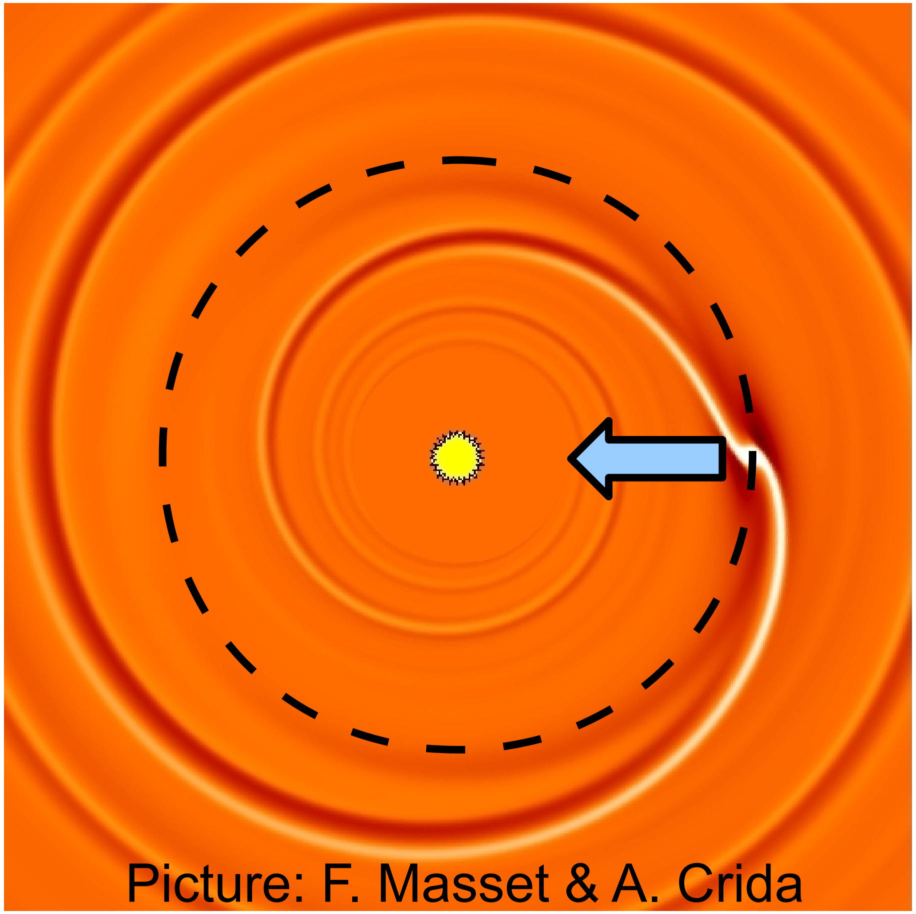
$$\gamma\Gamma_L / \Gamma_0 = -2.5 - 1.7\beta_T + 0.1\alpha_\Sigma$$

where γ = adiabatic index,

$$\Sigma \sim r^{-\alpha_\Sigma}, \quad T \sim r^{-\beta_T}.$$

(Paardekooper et al. 2010)

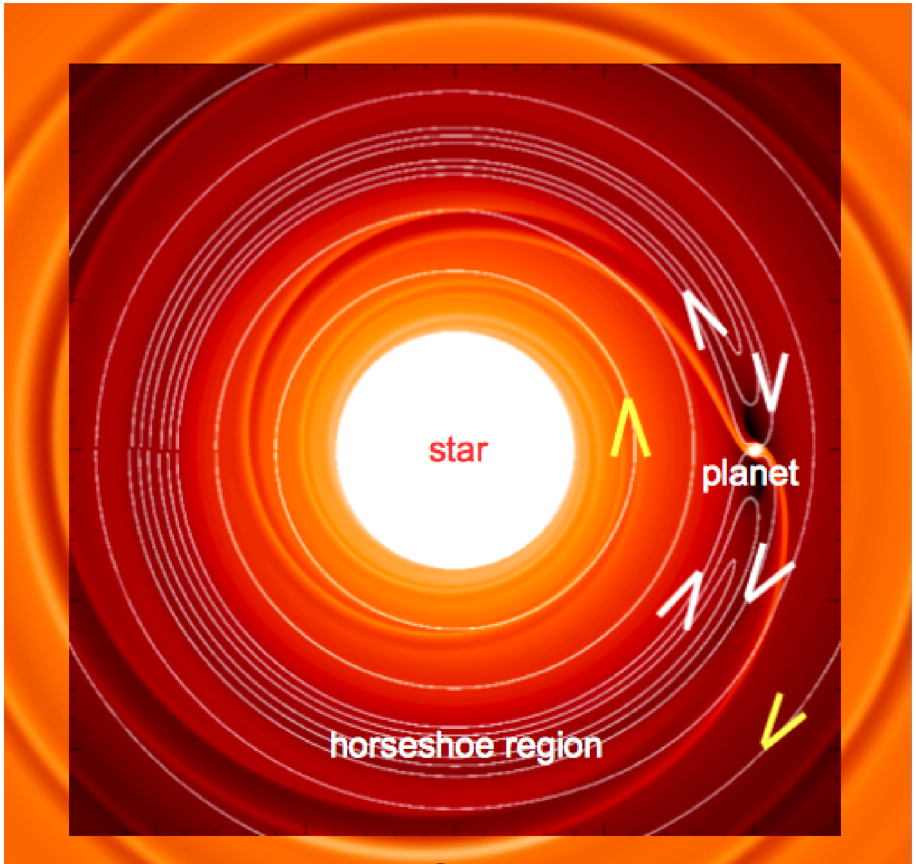
In general, $0.5<\alpha_\Sigma<1.5$ and $\beta_T \approx 1$
→ negative torque,
fast inward migration.



Picture: F. Masset & A. Crida

TYPE I MIGRATION

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

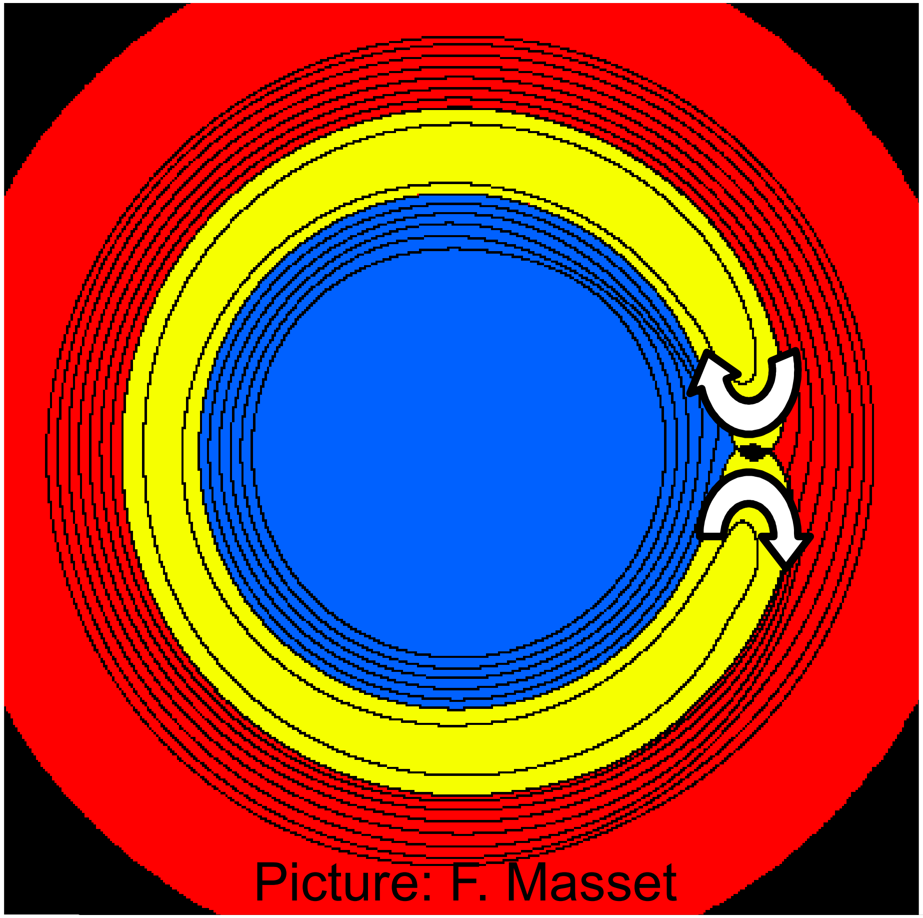


Picture: C. Baruteau

TYPE I MIGRATION

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

The torque arising from this «horseshoe region», the *corotation torque* Γ_c, has been widely studied in the last 10 years.



TYPE I MIGRATION

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

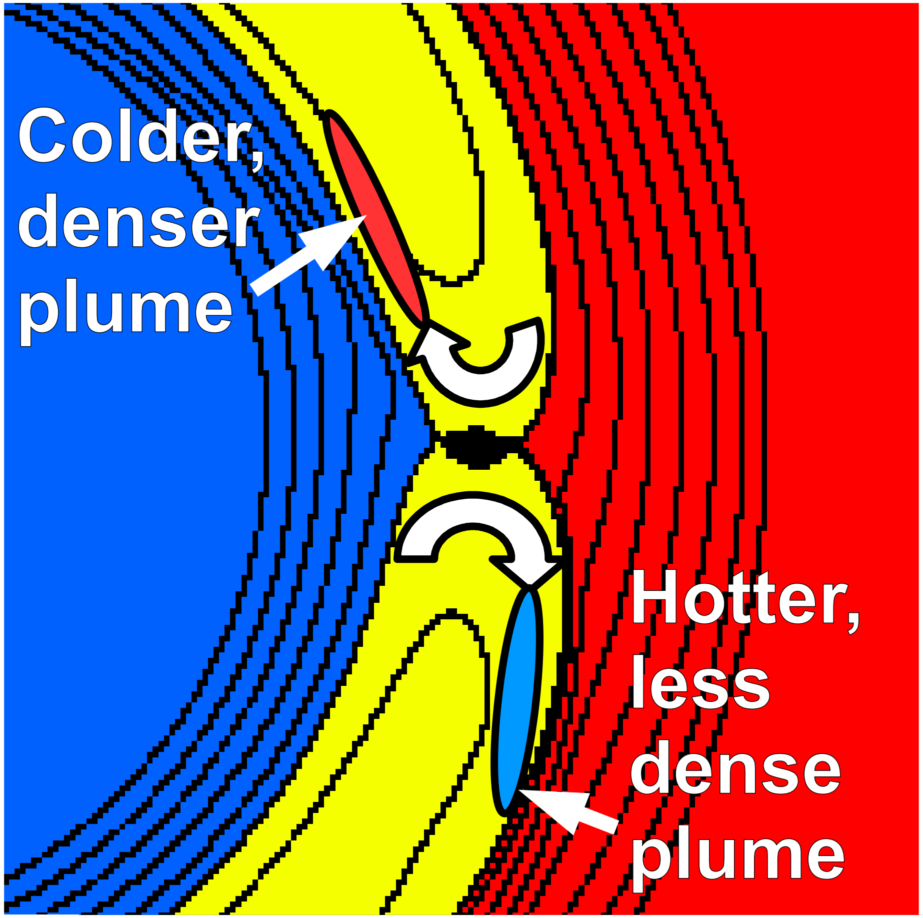
$$\xi = \beta_T - (\gamma-1)\alpha_\Sigma$$

(Paardekooper et al. 2010)

1st term : barotropic part
(e.g.: Ward 1991, Masset 2001, Paardekooper & Papaloizou 2009)

2nd term : thermal part, due to the advection of the entropy :
ξ = - dlog(entropy) / dlog(r)

(Paardekooper & Mellema 2008, Baruteau & Masset 2008)



TYPE I MIGRATION

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

(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) :

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

TYPE I MIGRATION

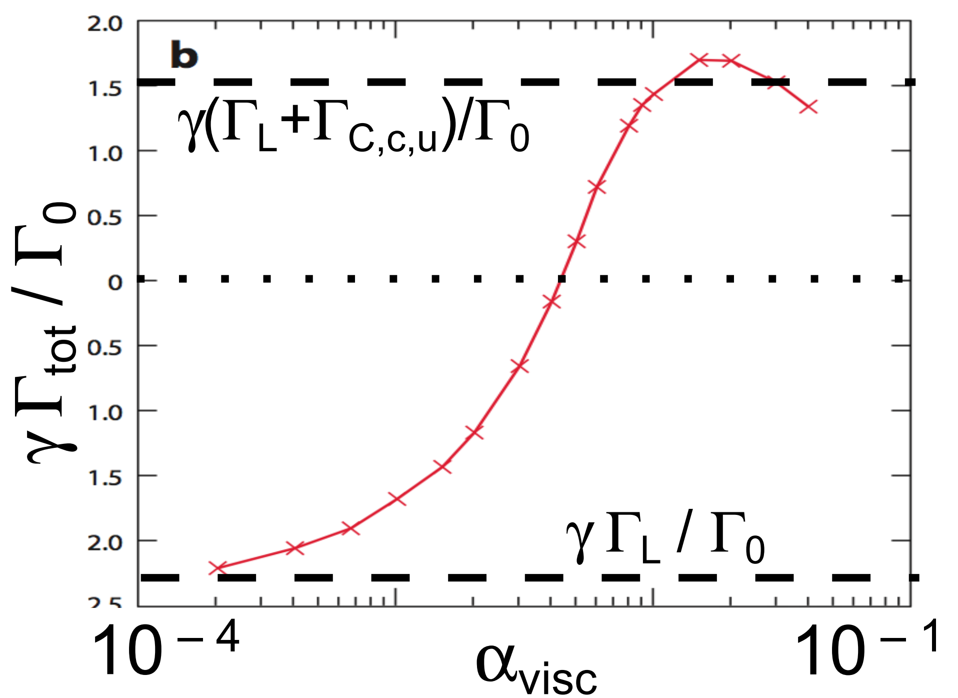
$$\gamma\Gamma_{c,circ,unsaturated} / \Gamma_0 = 1.1 \, (\, 3/2 - \alpha_\Sigma \,) + 7.9 \, \xi/\gamma$$

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.

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

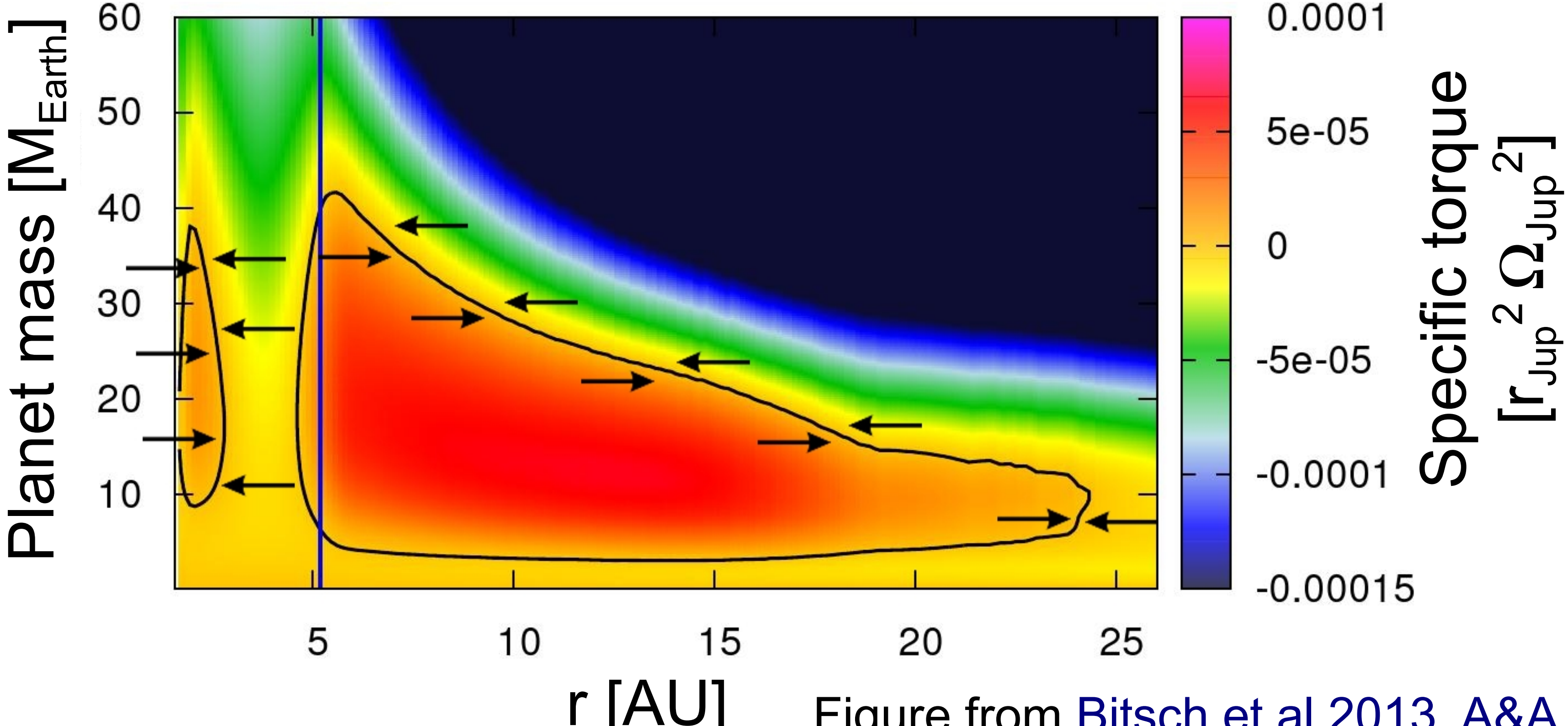


Figure from Bitsch et al 2013, A&A, 549, A124

TYPE I MIGRATION

The total torque depends on α_Σ and β_T,
thus on the disc structure.

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

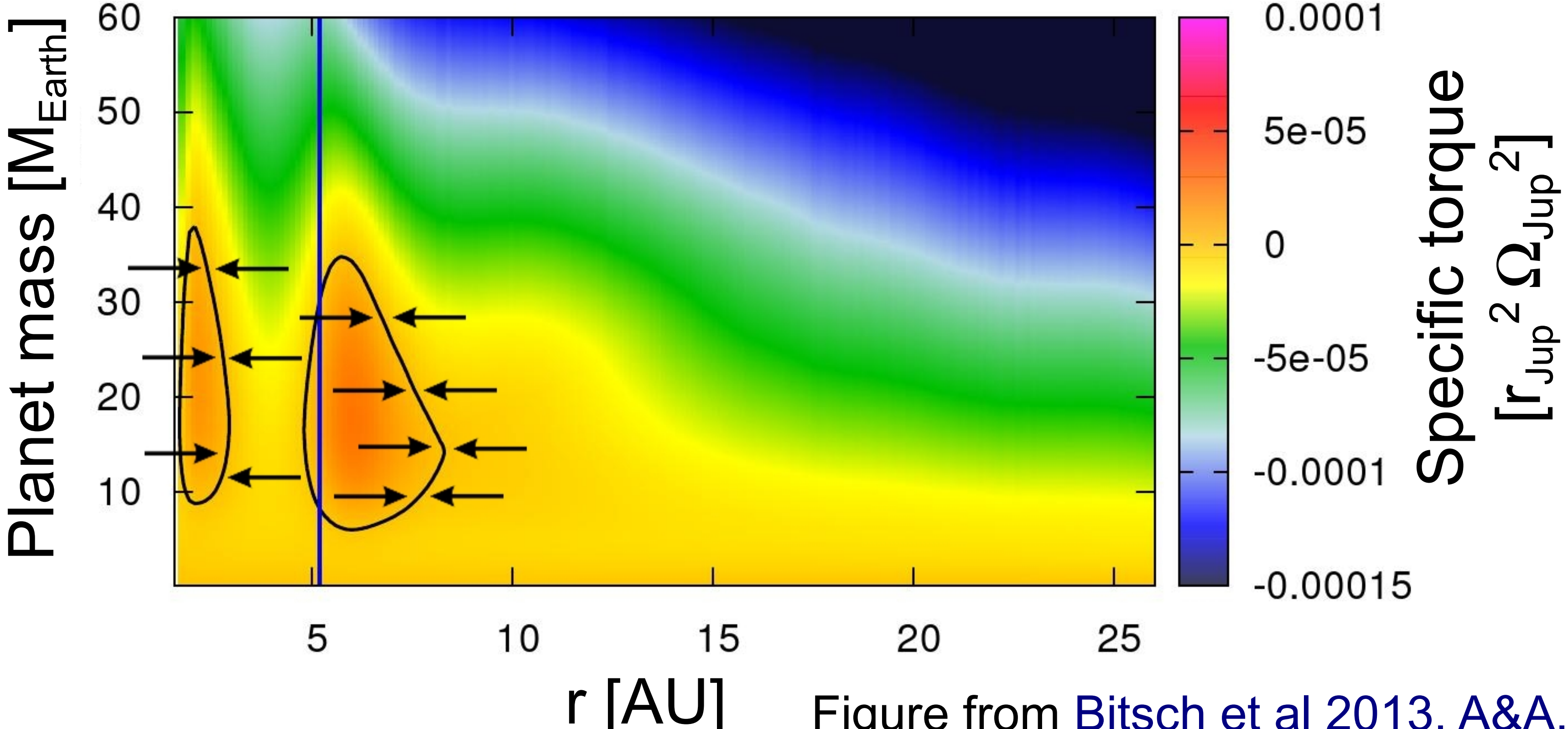


Figure from Bitsch et al 2013, A&A, 549, A124

TYPE I MIGRATION

Conclusion on type I migration :

Huge theoretical progresses have been made.

Well known The wave torque induces fast inwards migration.

NEW! The horseshoe drag (mostly its thermal part), enables outwards migration, but may saturate.

Still open Turbulence.
Magnetic fields.

Amplitude and direction depend on the disc properties...
Difficult to provide an *a priori*, universal scenario.

GAP OPENING

The planet exerts also
a negative torque on the inner disc → promotes its accretion,
a positive torque on the outer disc → repels it away from the star.

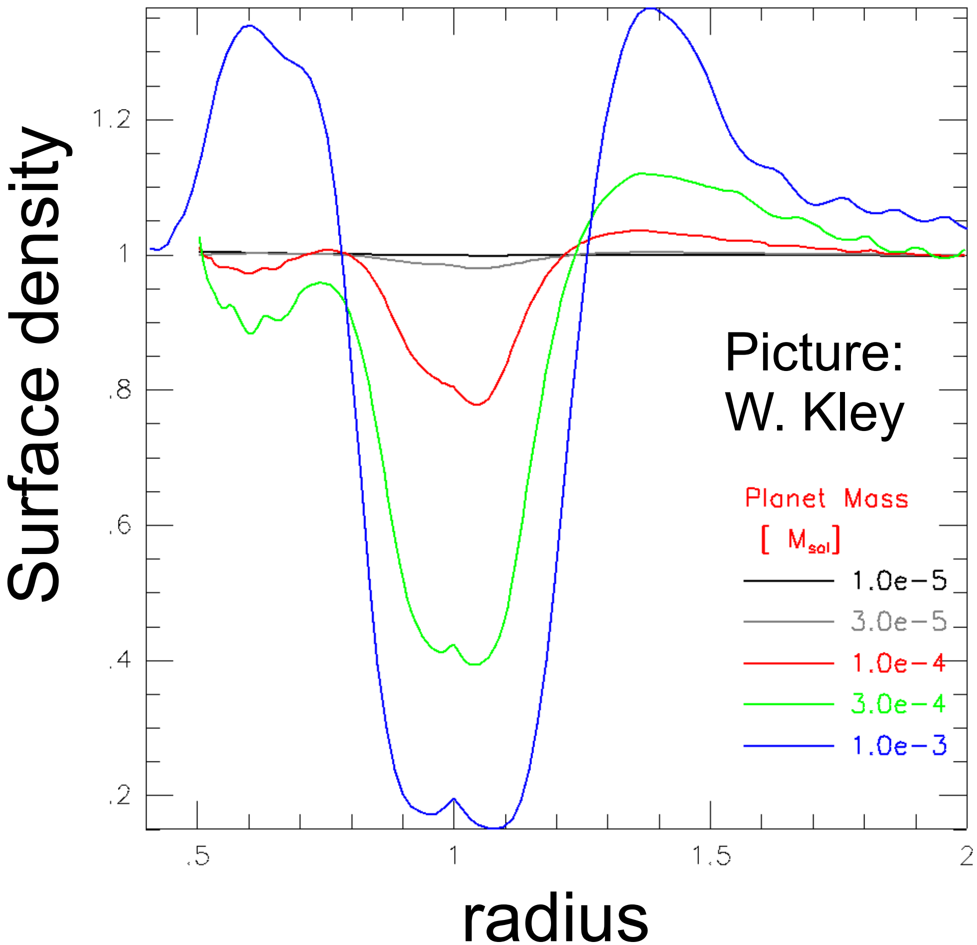
Competition with pressure and viscosity, who tend to smooth the gas profile.

A gap opens if :

$$\mathcal{P} = h/q^{1/3} + 50\alpha_{visc}/qh^2 < \sim 1$$

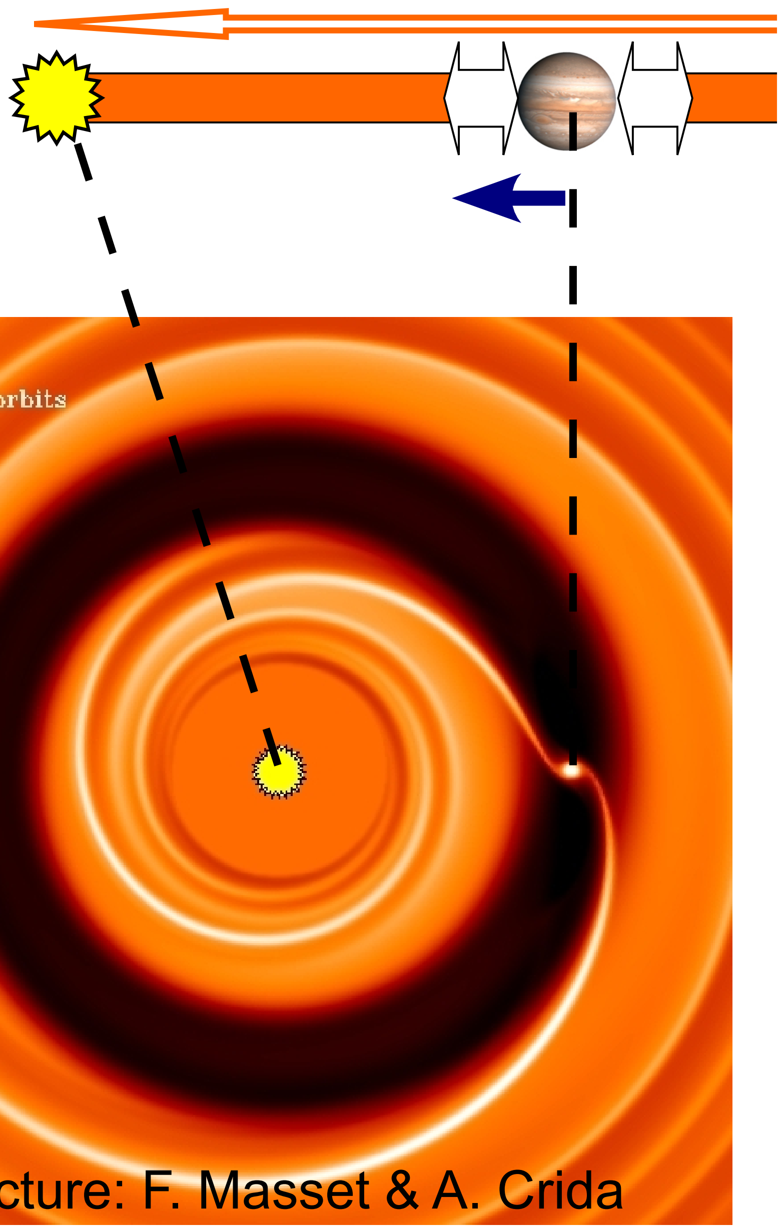
(Crida et al. 2006)

$h = 0.05$, $\alpha_{visc} = 0.004$
→ gap if $q>10^{-3}$.



TYPE II MIGRATION

Locked inside its gap, the planet must follow the disc accretion onto the star.

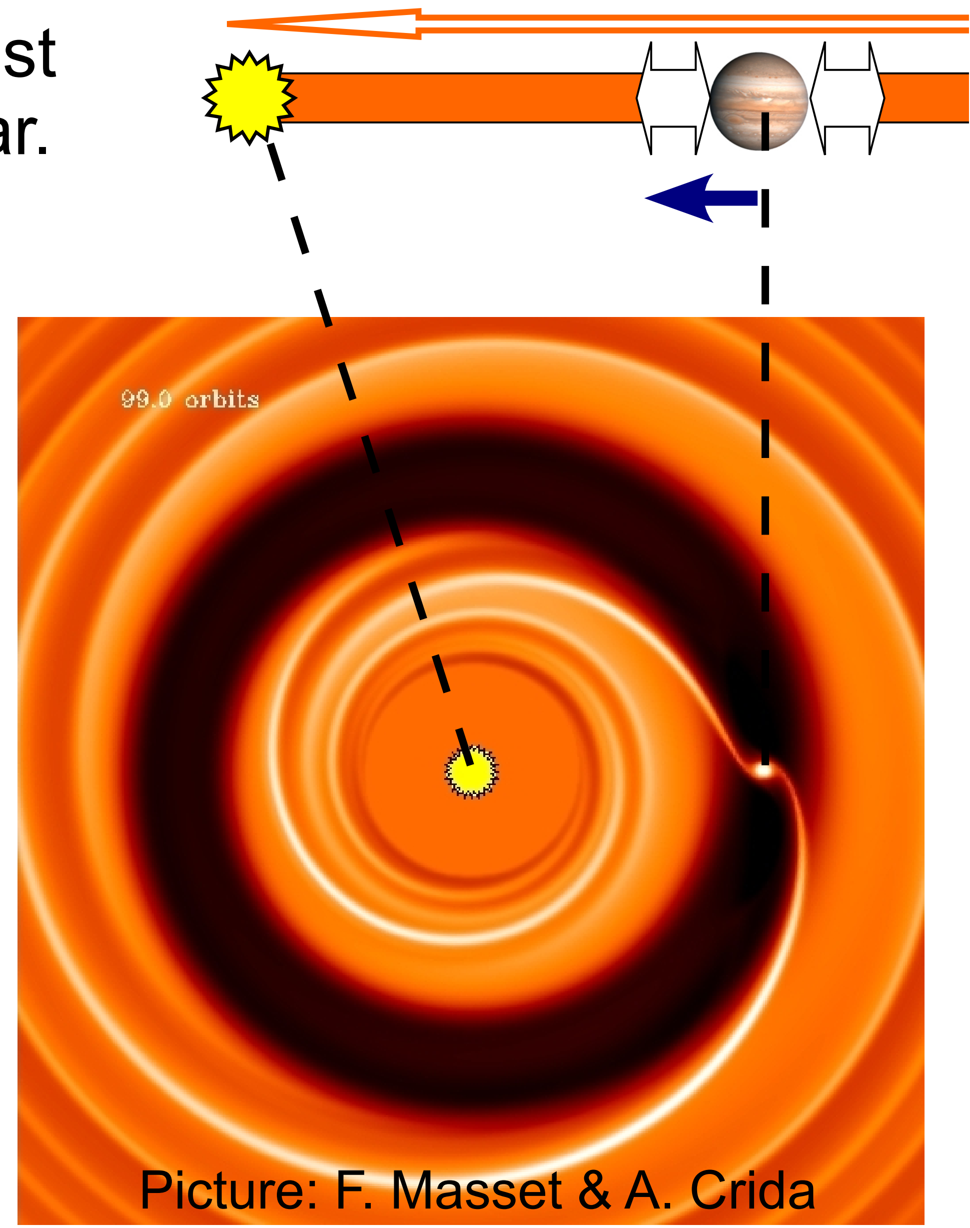


Migration with viscous time-scale $\tau_\nu = r_p^2 / \nu$.

(Lin & Papaloizou 1986)

TYPE II MIGRATION

Locked inside its gap, the planet must follow the disc accretion onto the star.



Migration with viscous time-scale $\tau_\nu = r_p^2 / \nu$ …

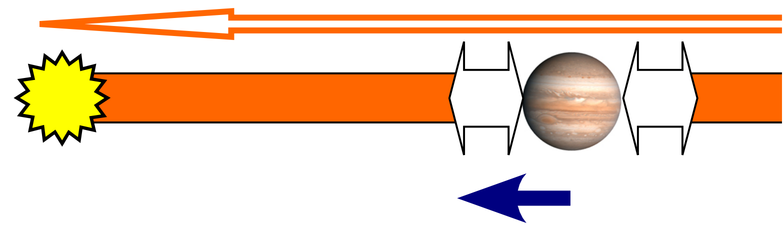
as long as the planet is not too massive, otherwise it slows down the disc. In fact,

$\tau_{II} = \tau_\nu$	disc dominated
$\tau_{II} = \tau_\nu \times M_p/M_{disc}$	planet dominated

(e.g.: Crida & Morbidelli 2007)

TYPE II MIGRATION

Locked inside its gap, the planet must follow the disc accretion onto the star.



Migration with viscous time-scale $\tau_\nu = r_p^2 / \nu$ …

as long as the planet is not too massive, otherwise it slows down the disc. In fact,

$\tau_{II} = \tau_\nu$ disc dominated

$\tau_{II} = \tau_\nu \times M_p/M_{disc}$ planet dominated

(e.g.: Crida & Morbidelli 2007)

Note :
This simplified picture is questionned by Dürmann & Kley (2015). Some gas can cross the gap, and the planets may decouple from the disc evolution.

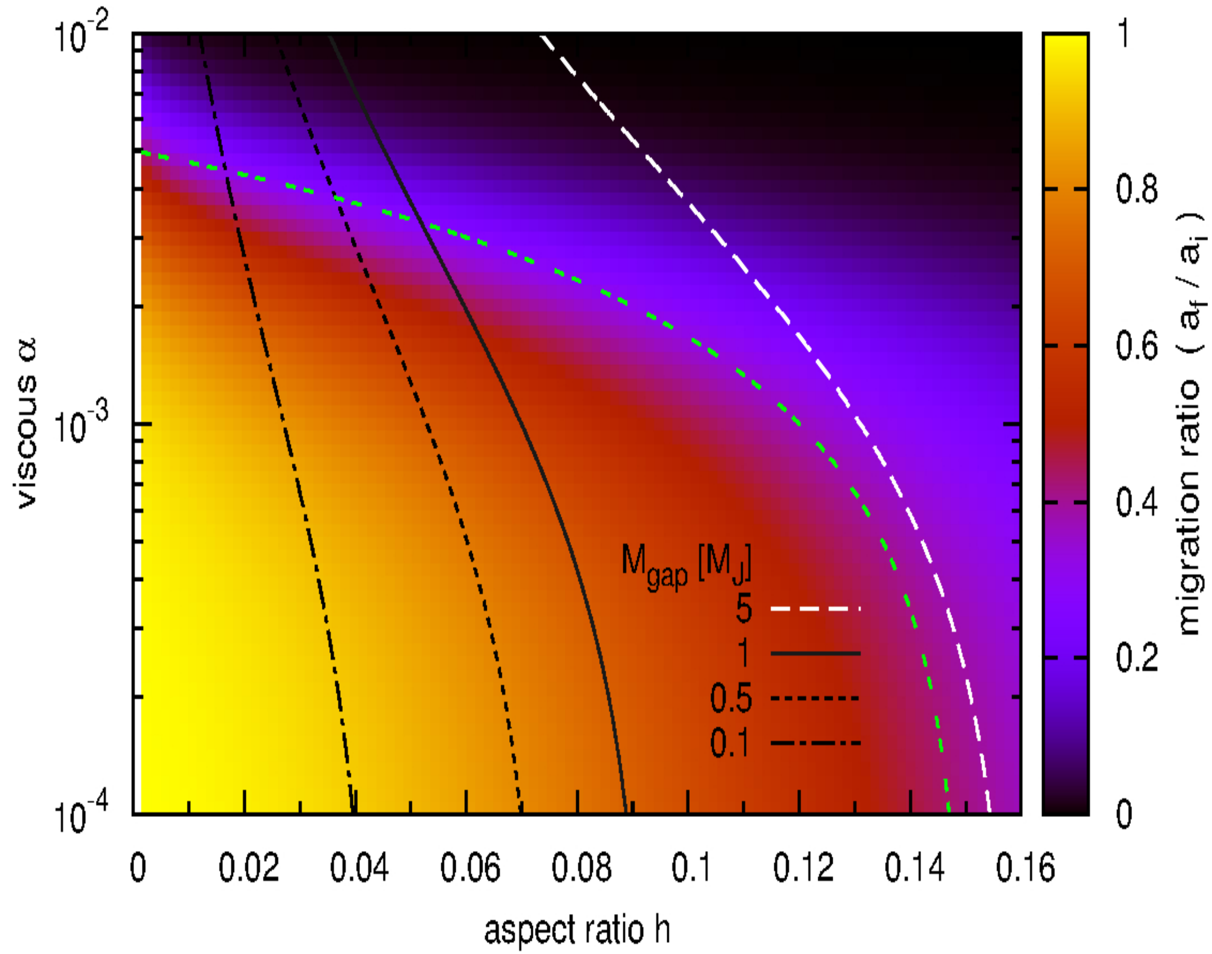
Stay tuned...

TYPE I – TYPE II TRANSITION

Type I migration can be stopped by the corotation torque up to ~30 M_{Earth} at most. A gap is opened beyond 100 M_{Earth} at least. In between ?

Given an accretion rate, and assuming a type I migration rate, one can compute the amount of migration a planet suffers while growing to a gap opening mass.

In thin discs with low viscosity, it survives...
(Crida & Bitsch 2016)



CAVITY OPENING ?

If the planet stops the outer disc,
the inner disk still accretes into the star
$\rightarrow$ depletion.

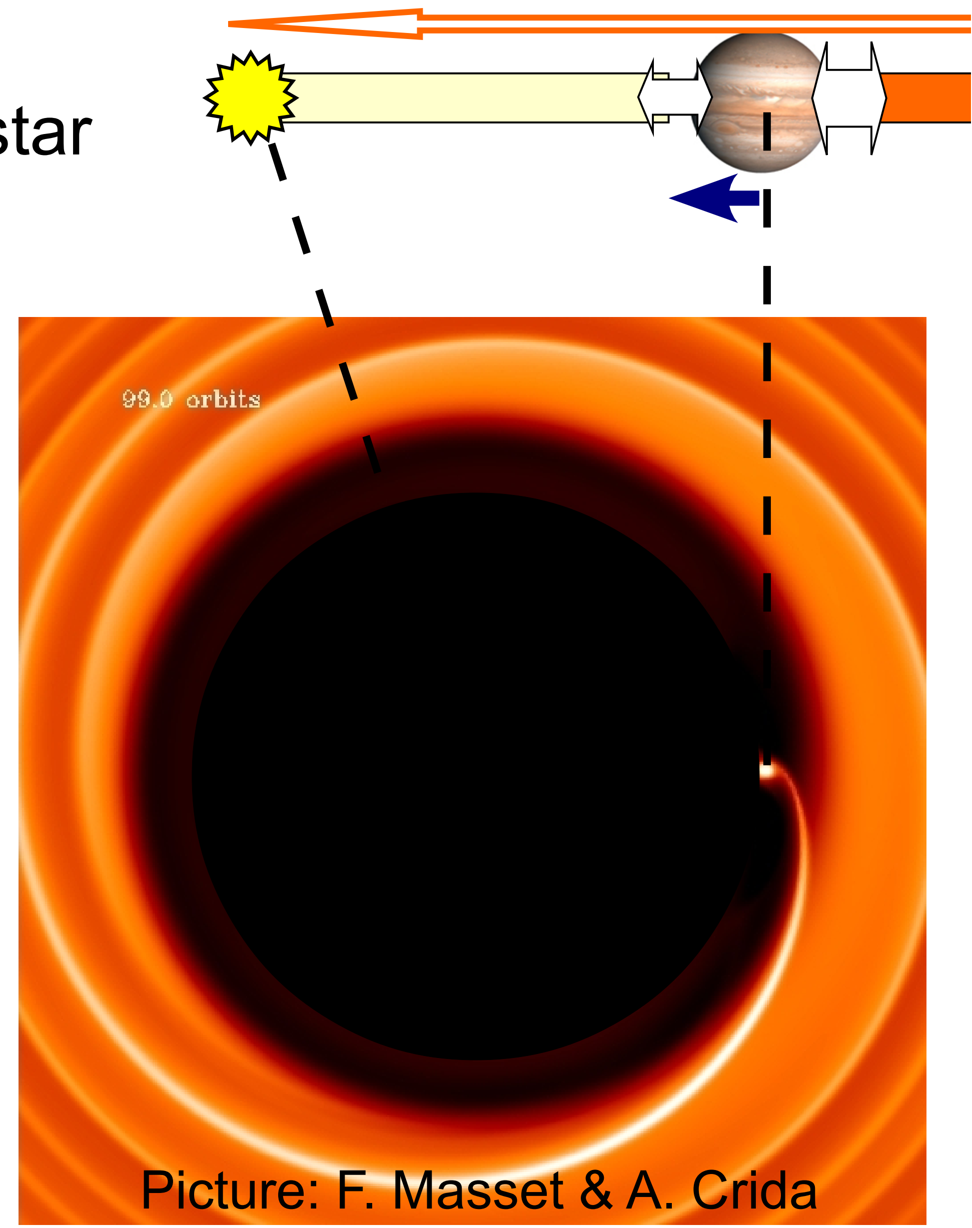
Assuming the inner disc disappears, one gets a *cavity* : nothing in the range $0 < r < r_o$.

Very different from a *gap* : nothing in $r_i<r<r_o$ with $r_o/r_i<2$

In numerical simulations, there is always gas in the inner disc, and gaps are always narrow.

Gas cavities are hard to make !

(Crida 2016, SF2A proceeding)

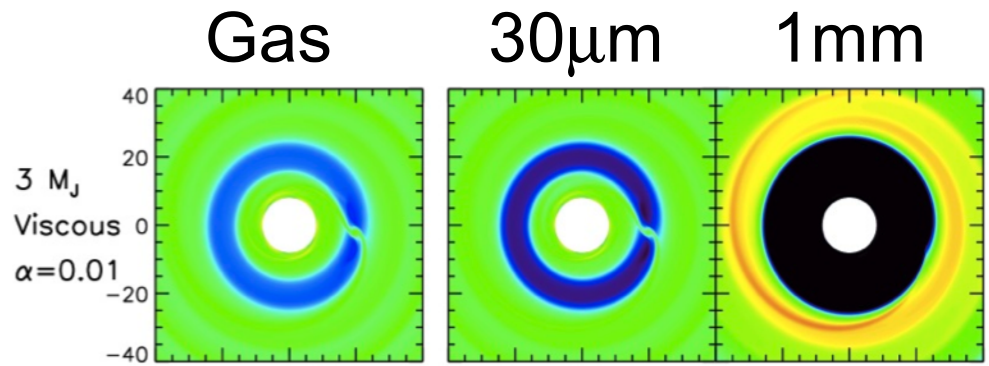


Picture: F. Masset & A. Crida

OBSERVATIONS

⚠ Observations of cavities <≠> presence of planet(s)

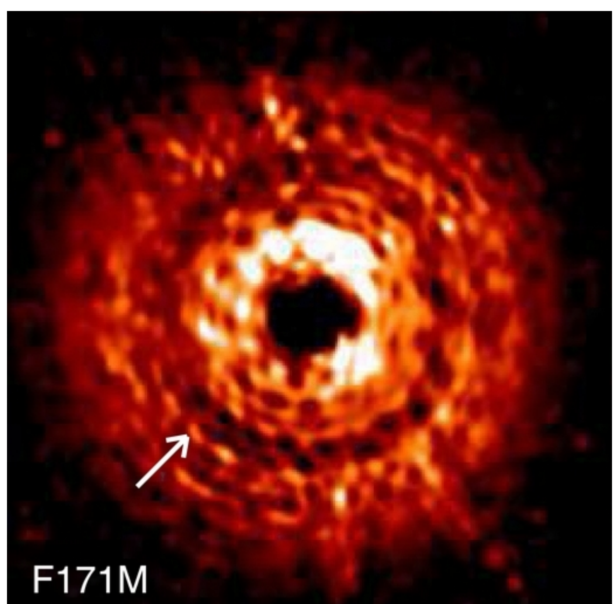
Dust (de)coupled from the gas.
Accumulates at pressure bumps,
ex: outer edge of a gap.
(Zhu et al. 2012 ApJ, 455, 6)

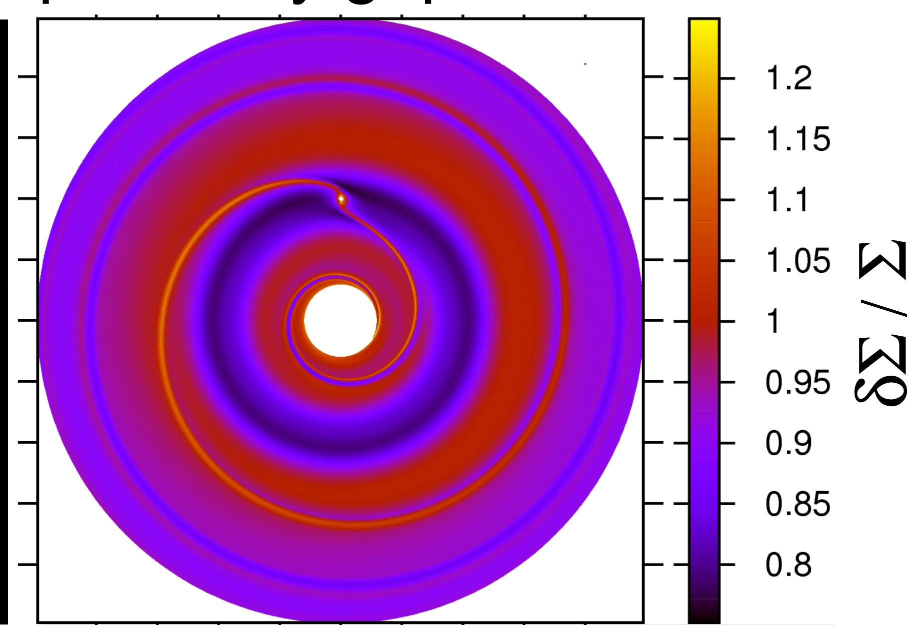


First observation that really looks like a planetary gap:

Debes et al 2013
ApJ 471, 988

$q = 1.18 \times 10^{-4}$
$h = 0.081$
$\alpha_{visc} = 5 \times 10^{-4}$
$r_p = 80$ AU

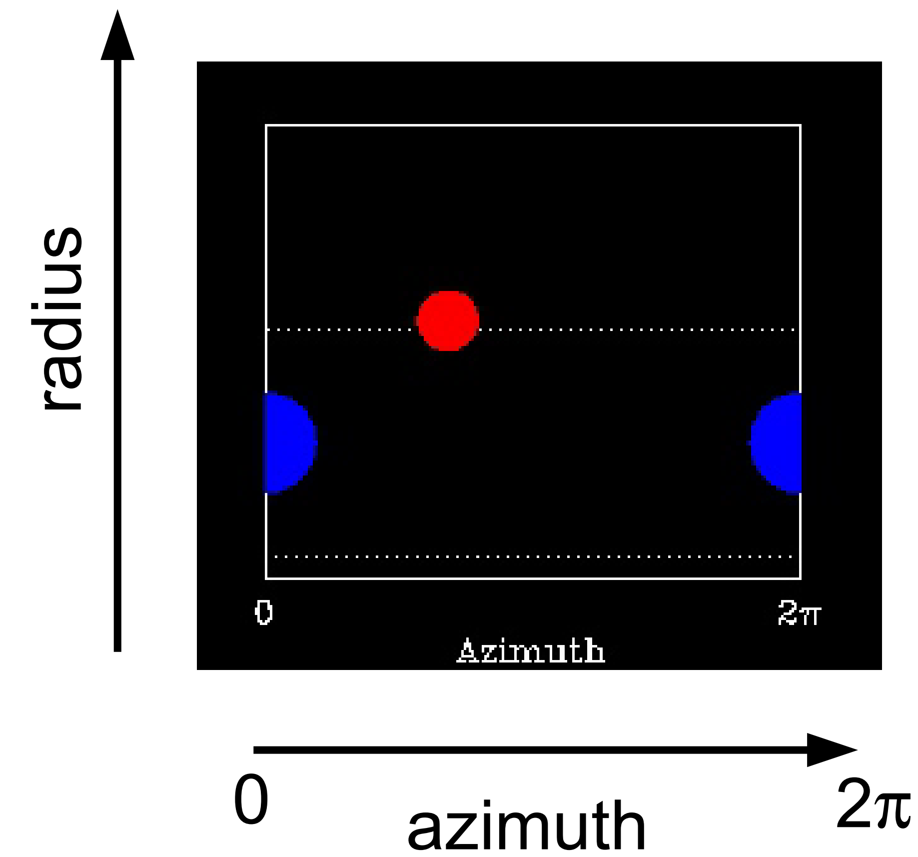




TYPE III MIGRATION

Intermediate mass planets,
with a partial gap

→ positive feedback on
the drift of the planet.



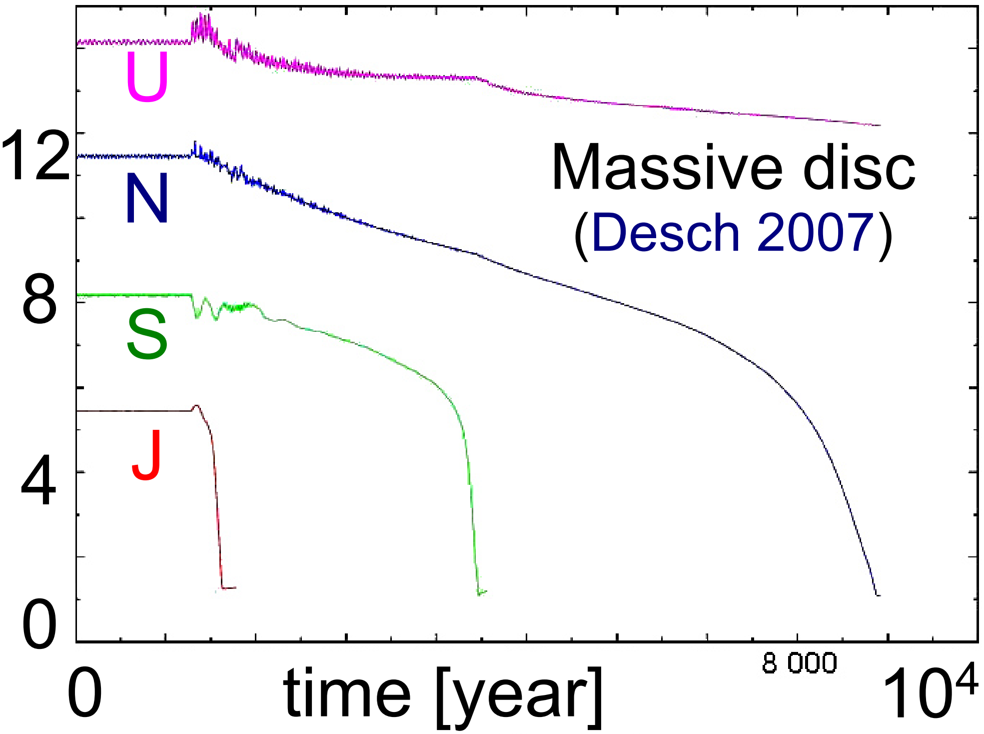
If the disc is massive enough,
runaway of the migration,
in either direction :
type III migration.

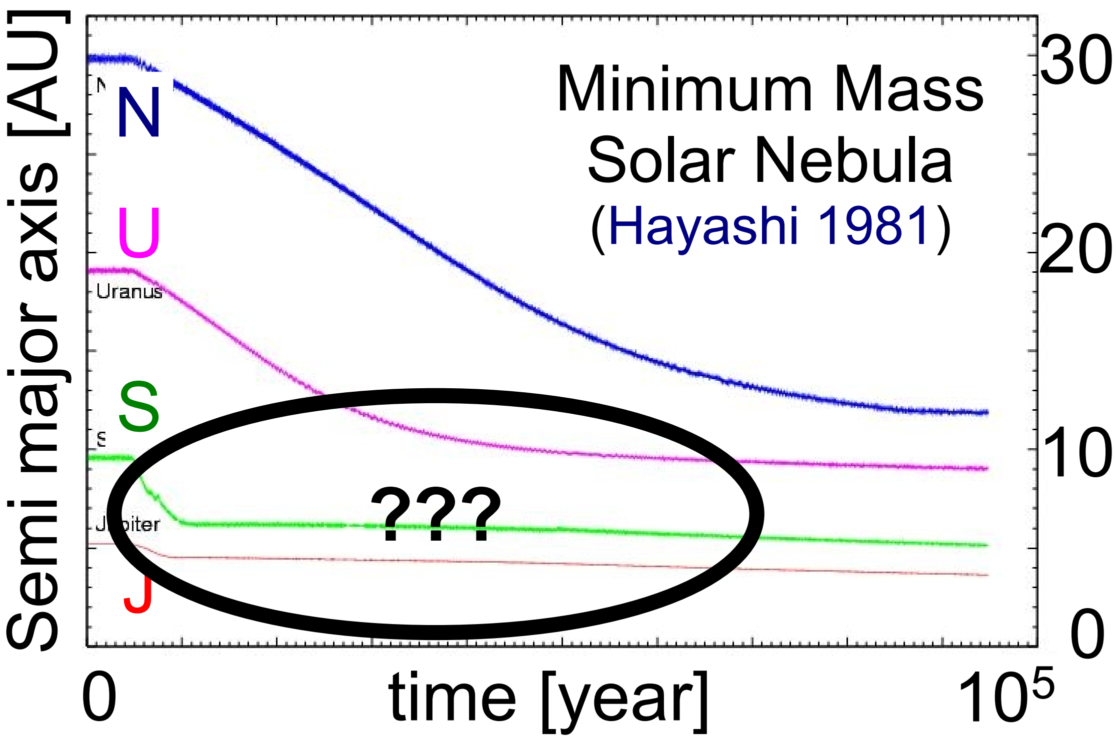
Planets of Neptune ~Jupiter mass can change their orbit,
inwards or outwards, dramatically in a few orbits !

TYPE III MIGRATION

Application:

Too massive proto-solar nebula → Jupiter lost.
(Crida 2009, ApJ, 698, 606-614).





PAIRS OF PLANETS

Two planets migrate at a different rate.

Their period ratio varies, and crosses simple fractions.

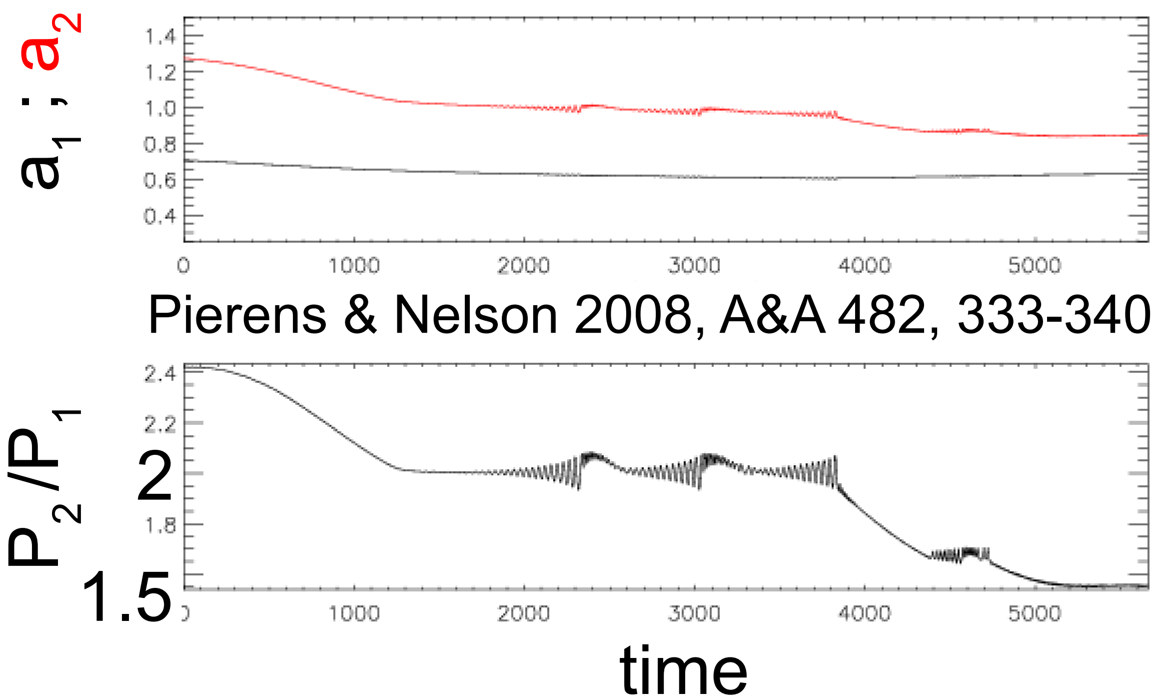
If they approach each other slowly enough,
they get captured in *Mean Motion Resonance* :

$$(p+q)\Omega_2 - p\Omega_1 = 0$$

$$P_2/P_1 = (p+q)/p$$

where p,q are integers.

Then, what happens ?



Pierens & Nelson 2008, A&A 482, 333-340

PAIRS OF PLANETS

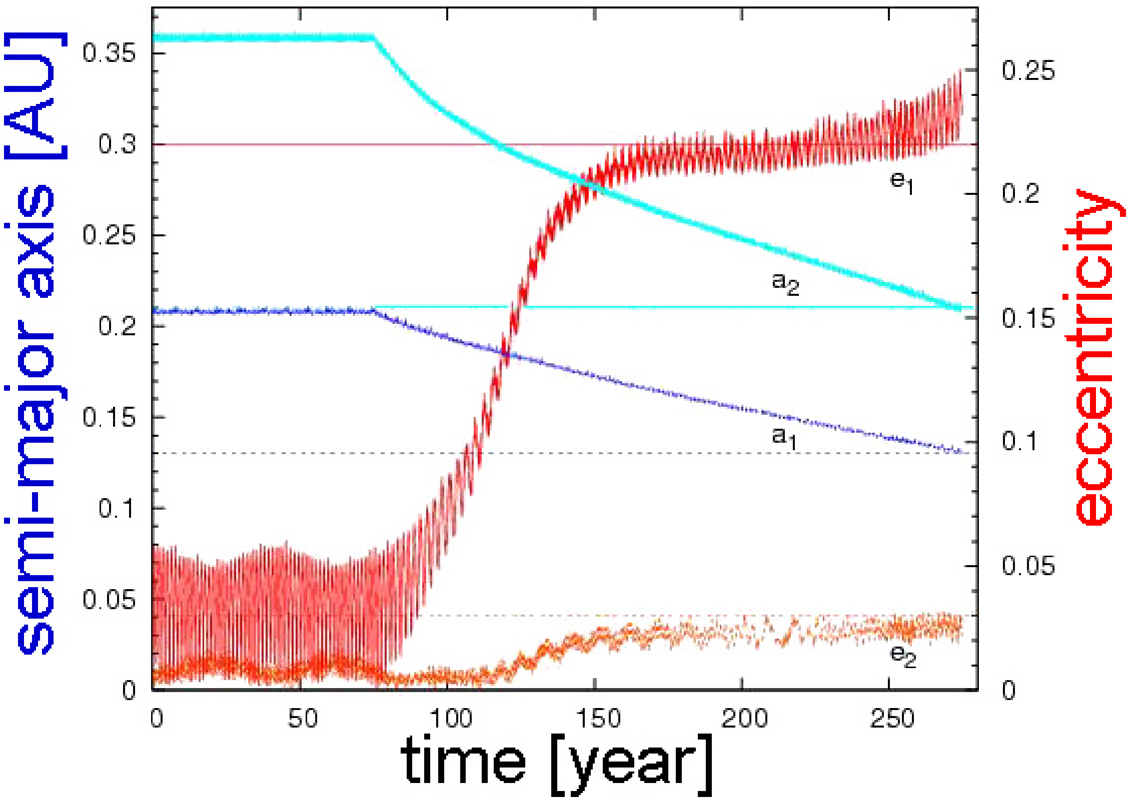
Eccentricities are excited by the resonance forcing, and damped by the gas disc.

→ reach non zero equilibrium value.

<u>Ex:</u> reproduction of the observed orbital parameters of the GJ876 system

(Lee & Peale 2002,
Kley et al. 2005,

Figure from:
Crida et al. 2008,
A&A 483, 325-327).



PAIRS OF PLANETS

Eccentricities are excited by the resonance forcing,
and damped by the gas disc.

→ reach non zero equilibrium value.

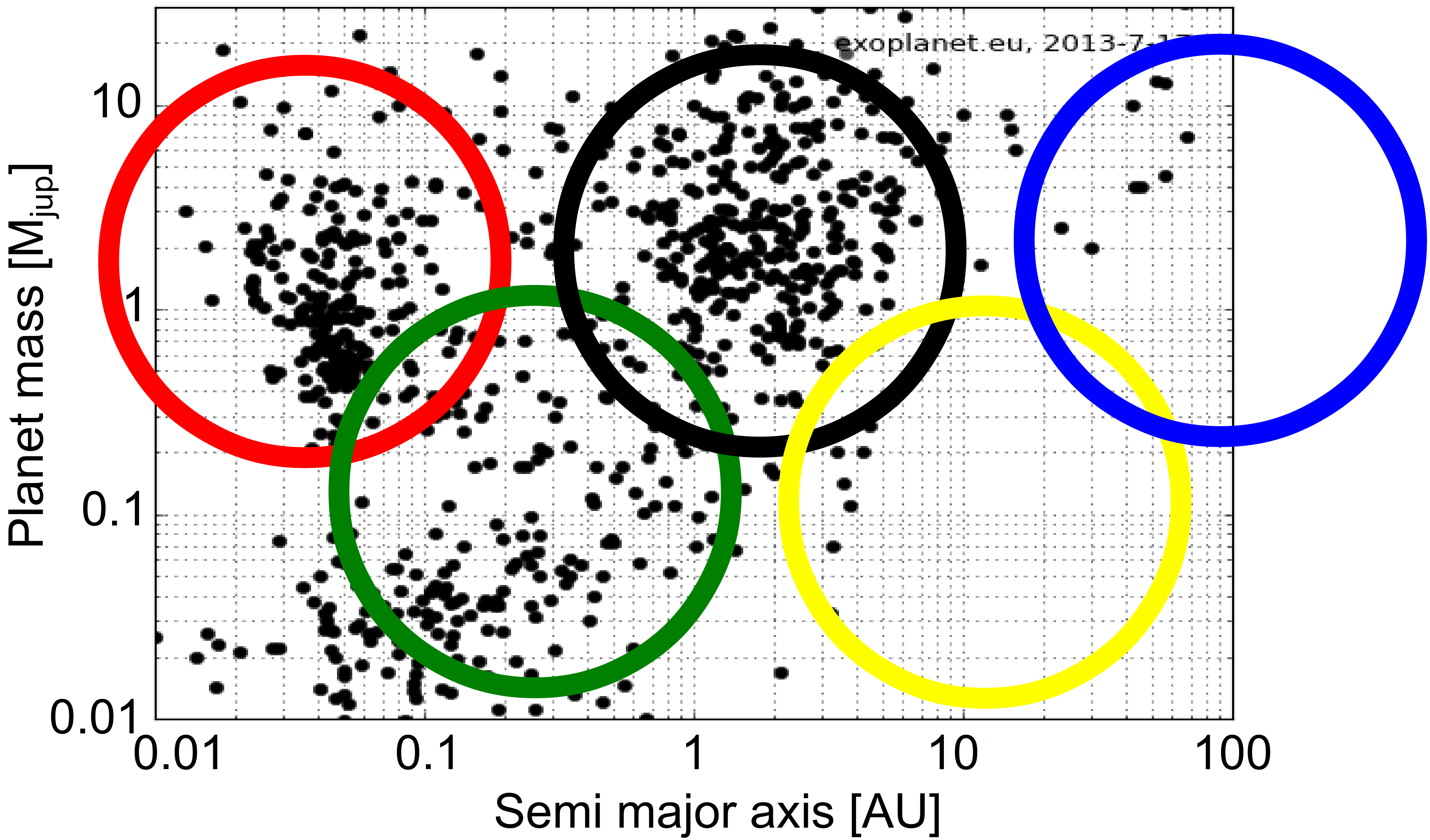
Possibility of close encounters, in particular if 3 planets.

Then, scattering and *e* and *i* increase.
(Marzari et al. 2010, Juric & Tremaine 2008, Chatterjee et al. 2008, Lega et al. 2013)

But the disc damps *e* and *i* of an isolated planet.
(Xiang-Gruess & Papaloizou 2013, Bitsch et al. 2013)

→ Scattering should take place as the disc dissipates
in order to explain the observed high *e* of exoplanets.
Unikely fine tuning of the timing (Lega et al. 2013).

EXO-PLANETS



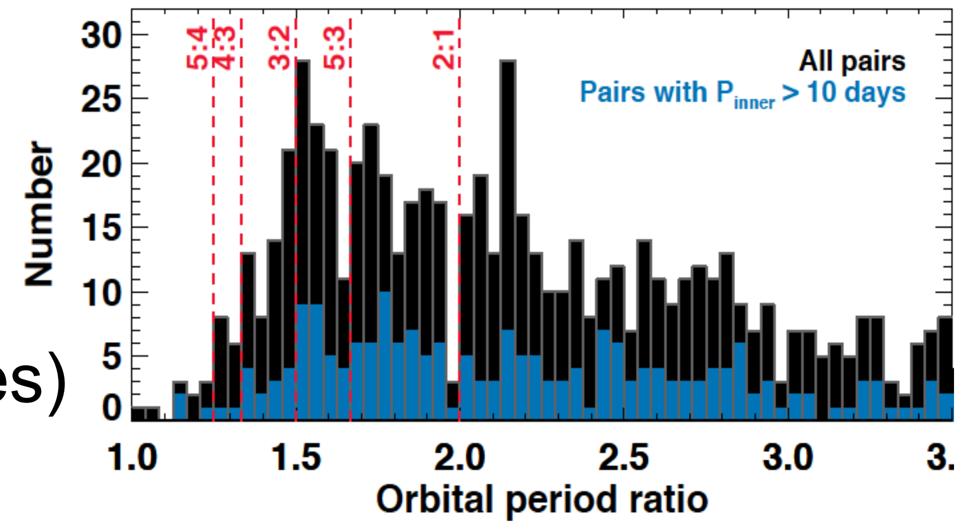
exoplanet.eu, 2013-7-17
10
1
0.1
0.01
Planet mass [M_jup]
0.01
0.1
1
10
100
Semi major axis [AU]

SYSTEMS

Resonant systems → smoking gun of convergent migration !

Coplanar, multi-resonant systems (Kepler 50, 55...) : even better.

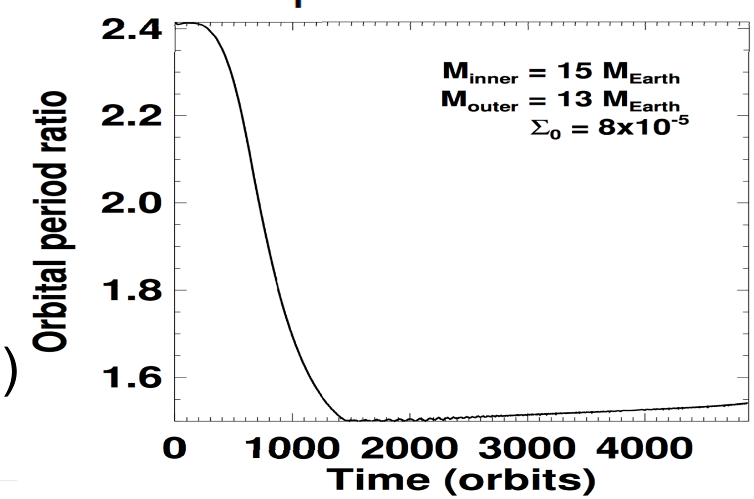
But there are non resonant, or close to resonant systems...
Does migration fail ? No.



Resonances can be broken after the disc dissipates (stellar tides) or due to planet-disc interactions:

- stochastic torques due to turbulence (Rein 2012, Pierens et al. 2012)

- interaction between a planet and the wake of a companion (Podlewska-Gaca et al. 12, Baruteau & Papaloizou '13)



Figures from our chapter in PPVI.

SYNTHESIS

Any statistic relies on the distribution of the parameters.

Planet Population Synthesis (see next talk...)

Past results concerning migration:

- only wave torque → loss of all planets.
- need of a small cavity to stop type II migration of hot Jupiters.

Possible improvements of the models:

- Effects of the corotation torque (implemented).
- Planet-planet interactions during migration (in progress).
- Disc structure and evolution.

THE FUTURE

Theory of Migration :

- role of magnetic fields
- effect of turbulence

Disc properties :

- Turbulence : which nature, which properties ?
- Density and temperature profiles … ALMA, ALMA, ALMA, AL

Observations :

- Disc structures: decouple gas and dust.
- Exo-planets statistics: understand the observed distribution.

CONCLUSION

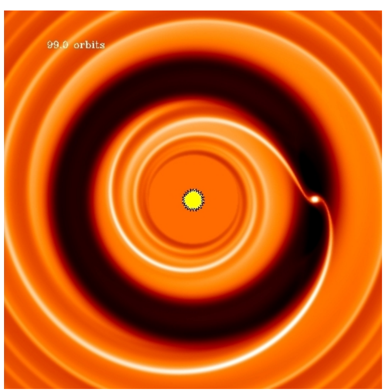
Planets do migrate.

It's a fact.

<u>Type I migration</u>
(small mass planets) :

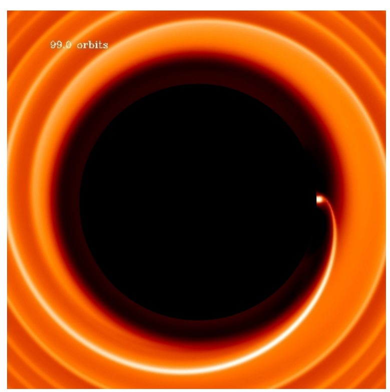
Can be outwards, depends on the disc's *local* properties α_Σ, β_T, γ, ν, h.

Gap



≠

Cavity



Not all structures are created by 1 planet.

Migration = a key ingredient of planet formation and evolution.

→ resonant or not systems
→ hot Jupiters (not all of them)
→ possibly cold Jupiters