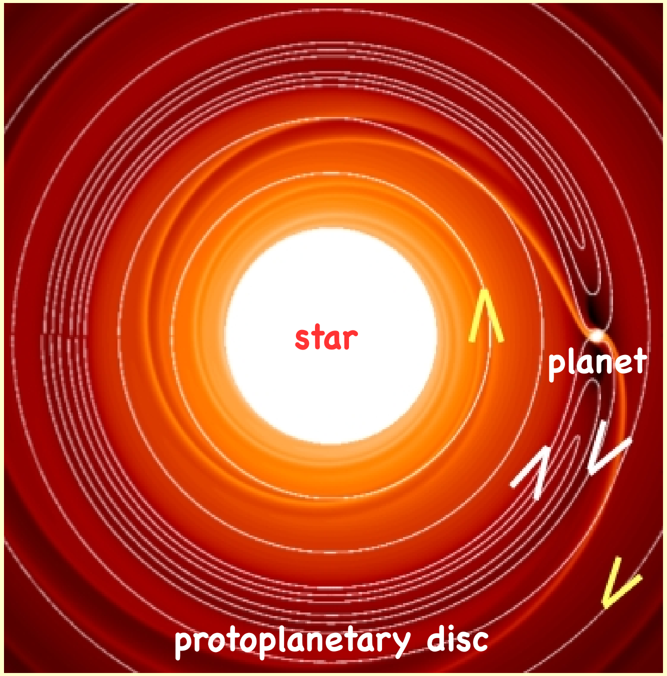
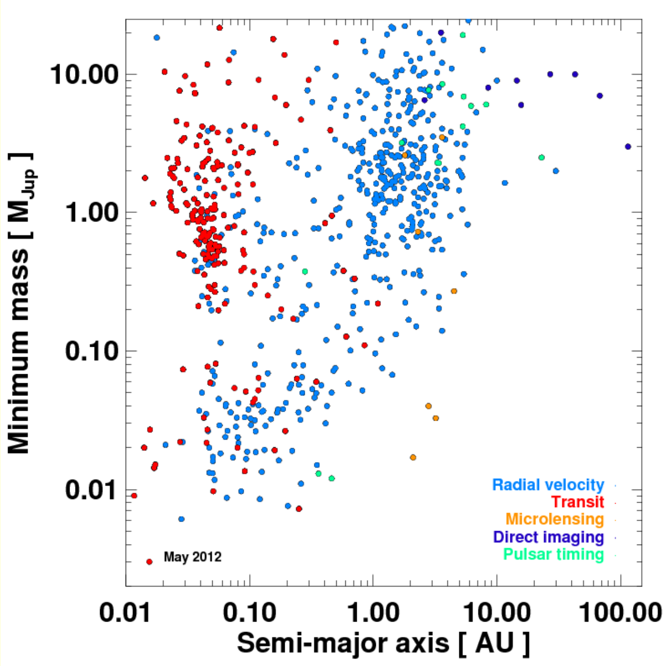
Recent developments in planet migration theory



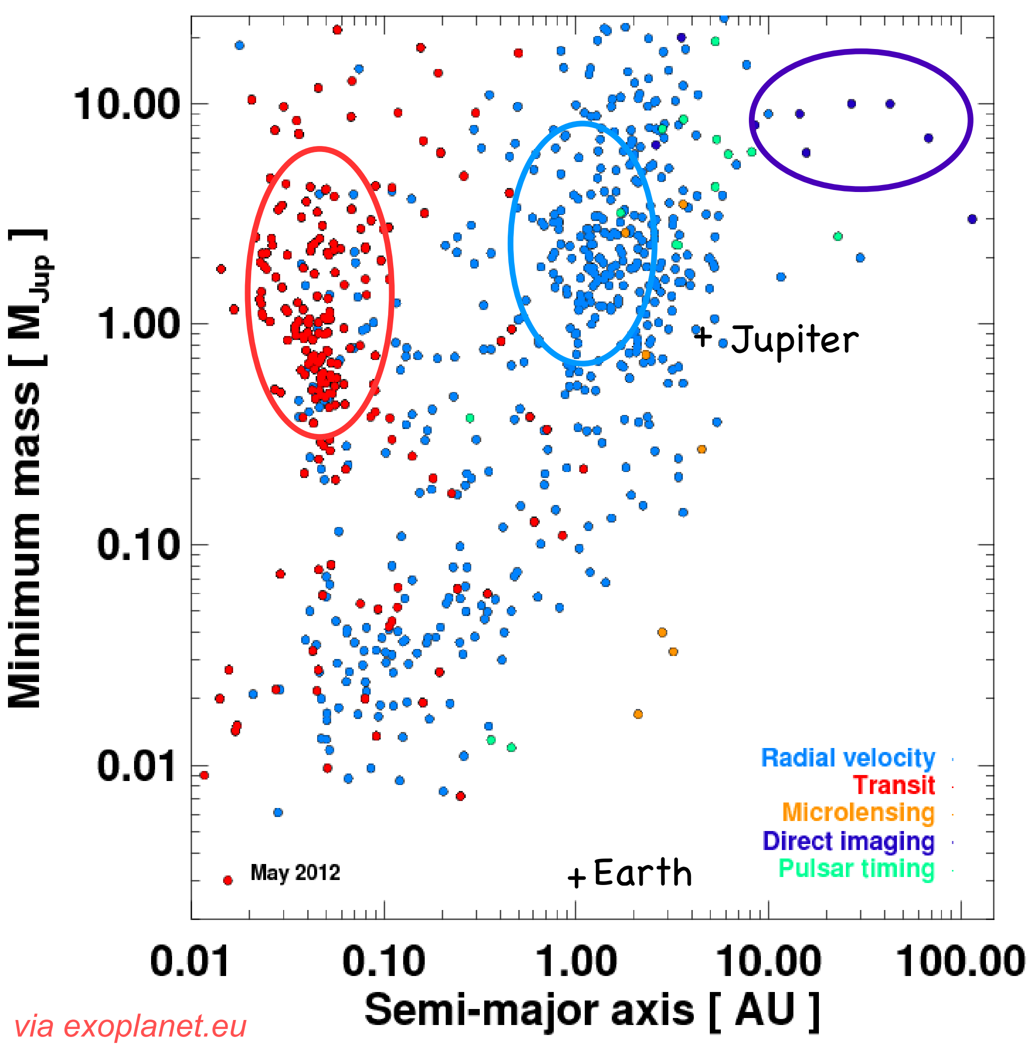


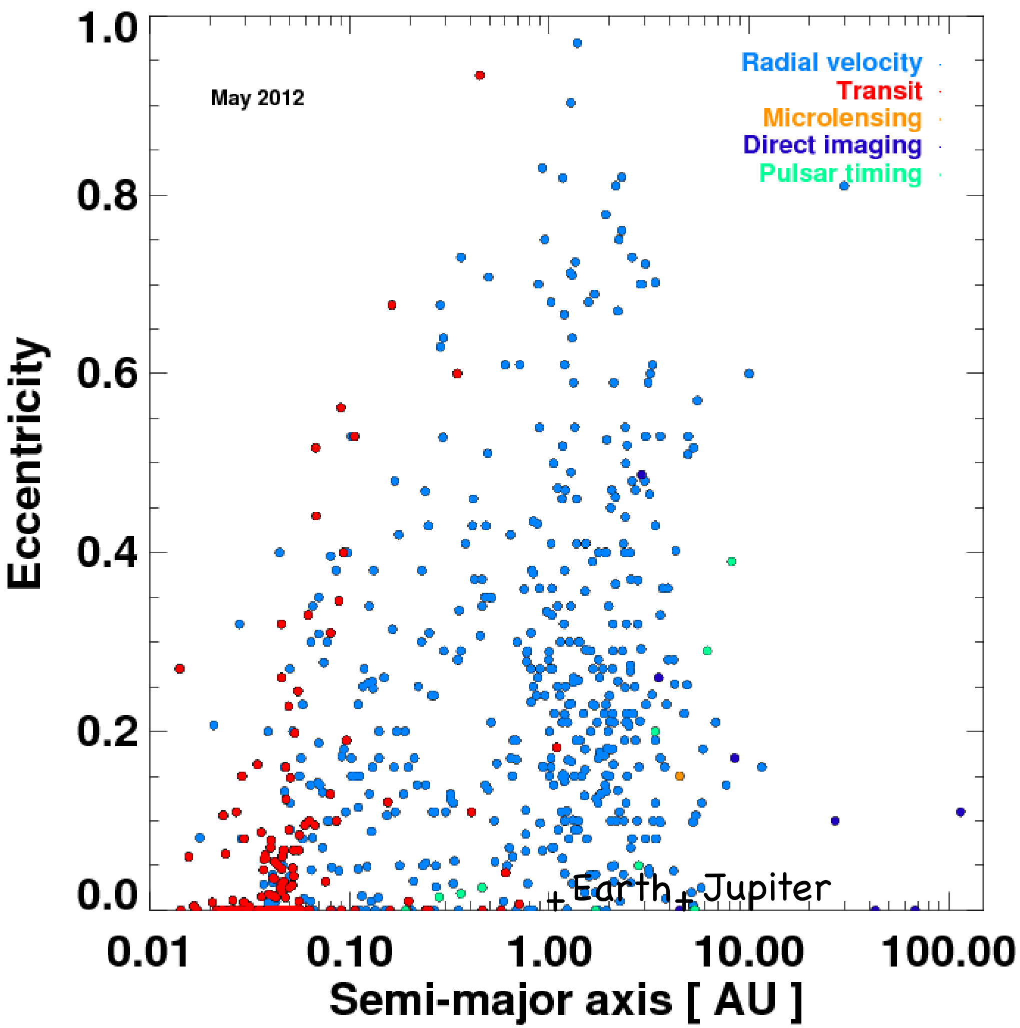
Clément Baruteau

DAMTP, University of Cambridge

<u>collaborators</u>: F. Masset, S.-J. Paardekooper, A. Crida, W. Kley, S. Fromang, R. Nelson, A. Pierens, J. Guilet and J. Papaloizou

About 800 exoplanets to date... and a fascinating diversity





via exoplanet.eu

→ Can we understand the statistical properties of the exoplanets?

→ How to explain the hot, warm and cold Jupiters?

→ Why is our Solar System different? ....

Formation and evolution of planetary systems

Key ingredients and main issues

disc evolution

. disc **properties?**
(density, temperature, magnetic field, **turbulence**...)

. **dispersal** after 1 to 10 Myr: what happens next?
*(planet-planet and **star-planet interactions**)*

planet migration

*(drift of planet's semi-major axis caused by **disc-planet interactions**)*

. **inwards or outwards**?

. **timescale**?

. ***planet-planet* interactions** may also dramatically change planets orbital properties

planet formation

. where? timescale?

. how to form km-sized **planetesimals**?

. **critical mass** to form a gas giant planet?

Formation and evolution of planetary systems

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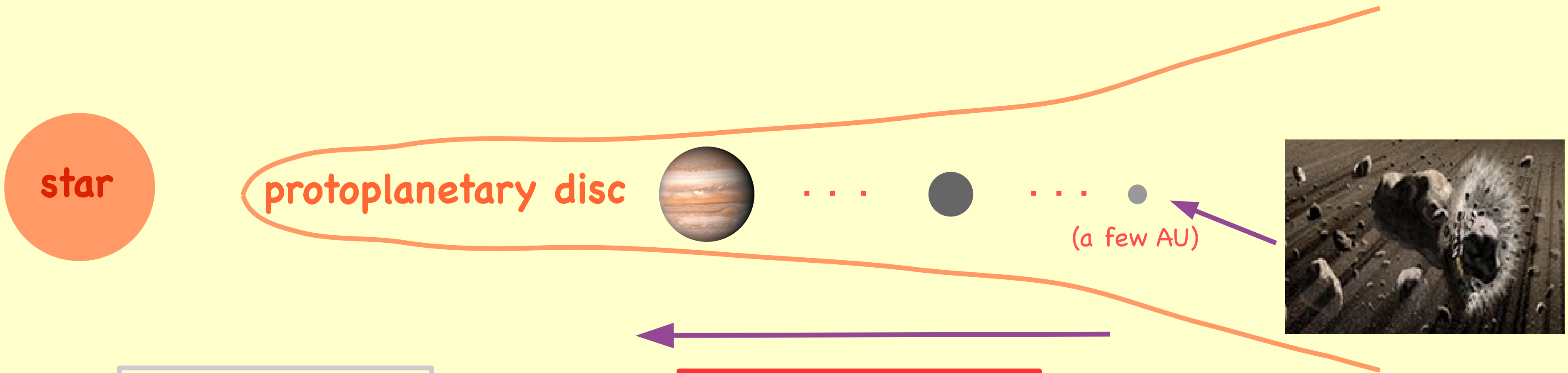

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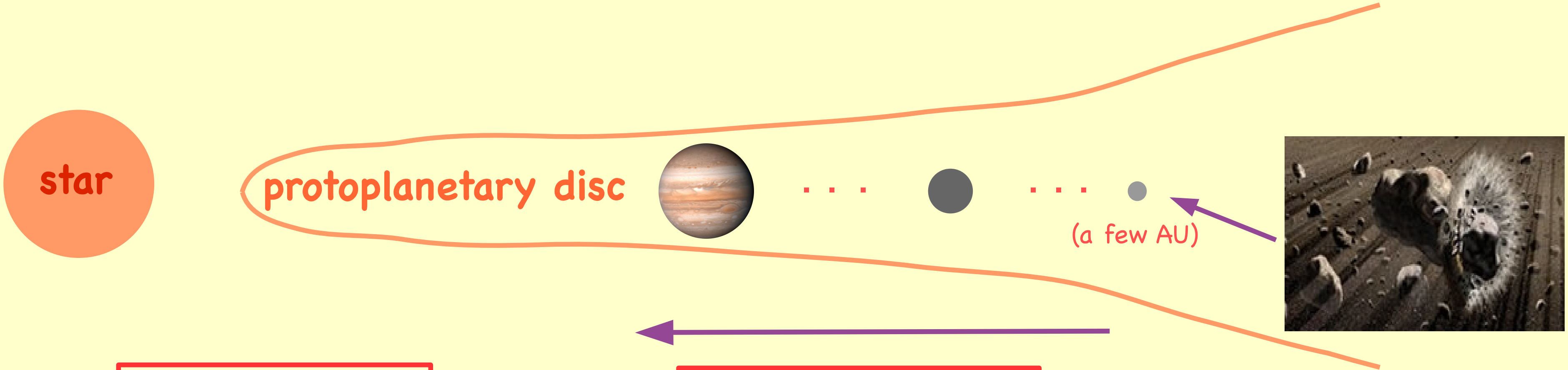

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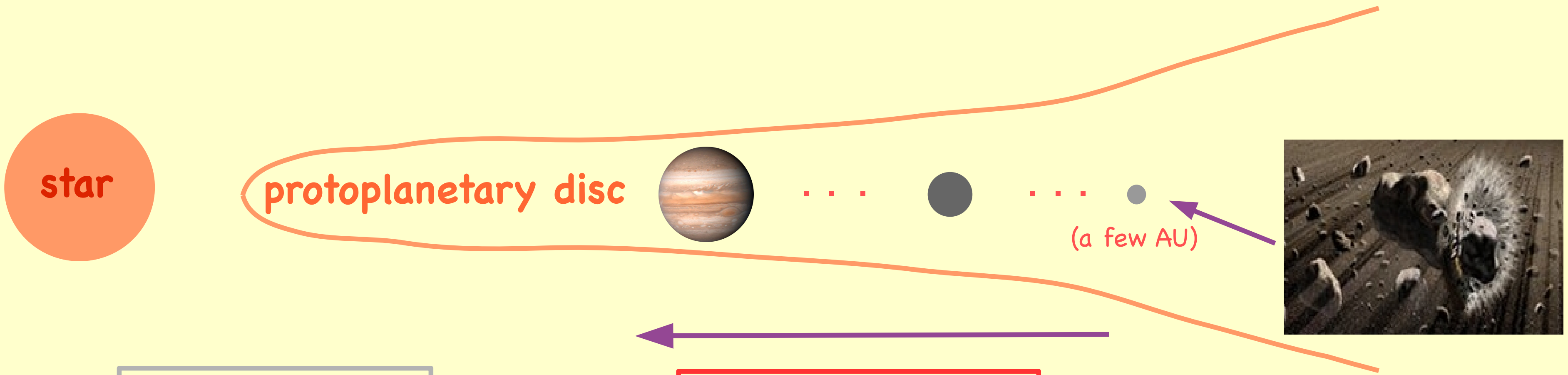

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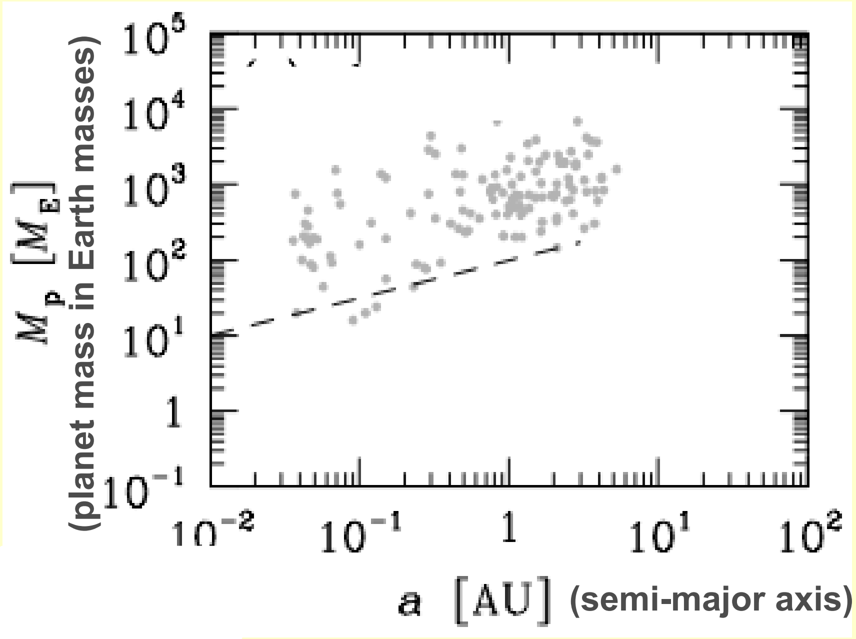
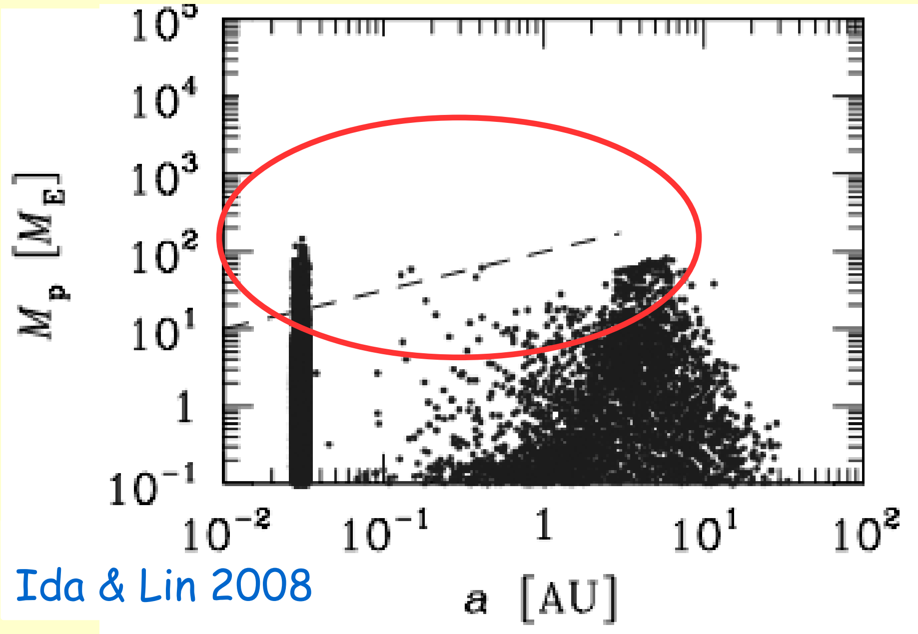
Confronting theory and observations

Need to slow down the migration of forming protoplanets

OBSERVATIONS



POPULATION SYNTHESIS



Ida & Lin 2008

Confronting theory and observations

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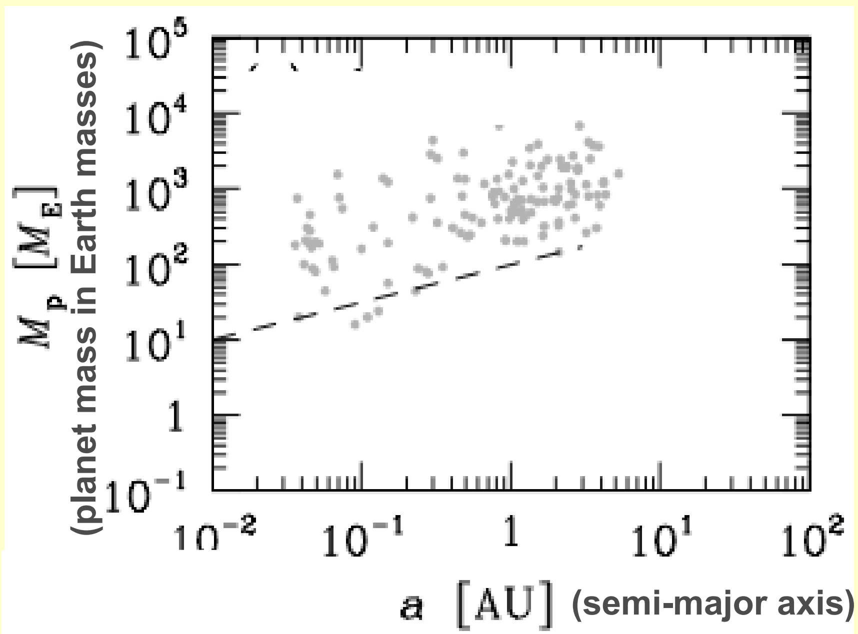

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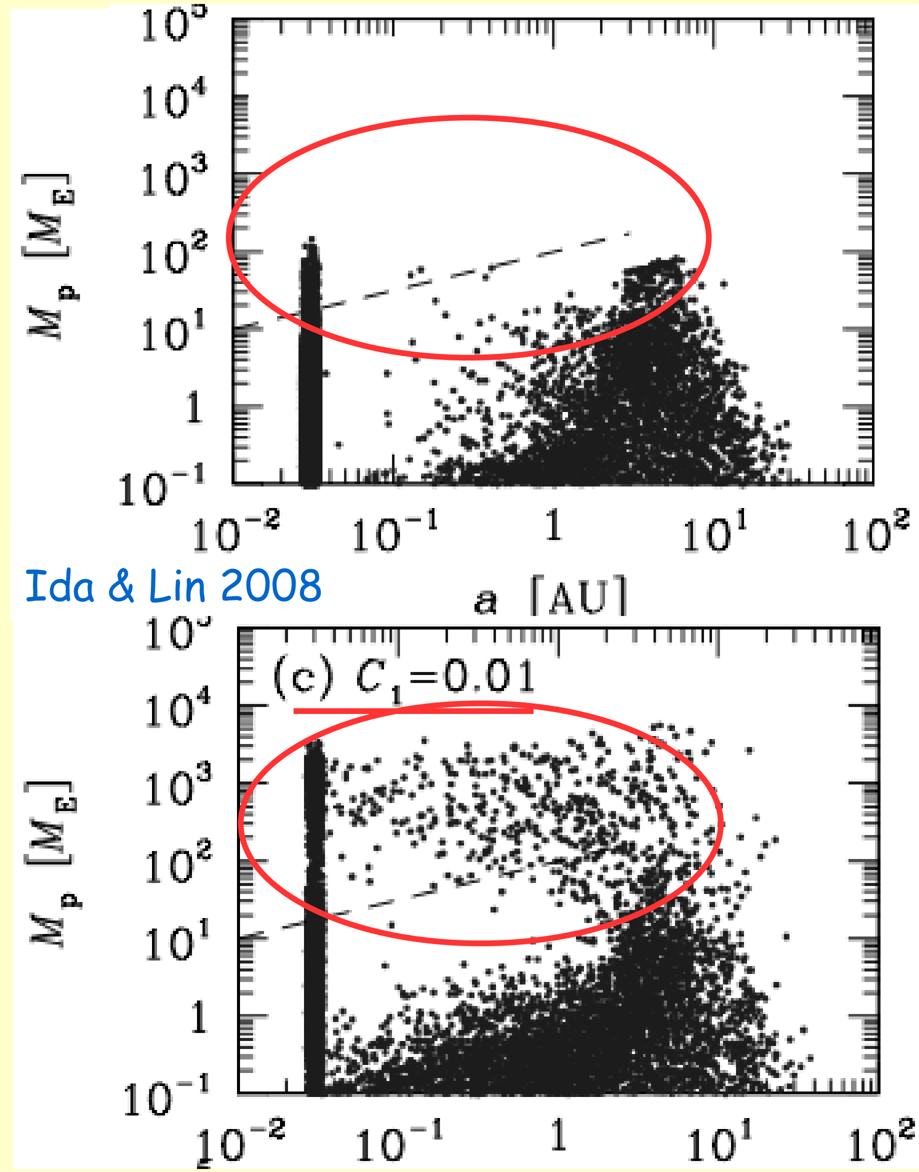
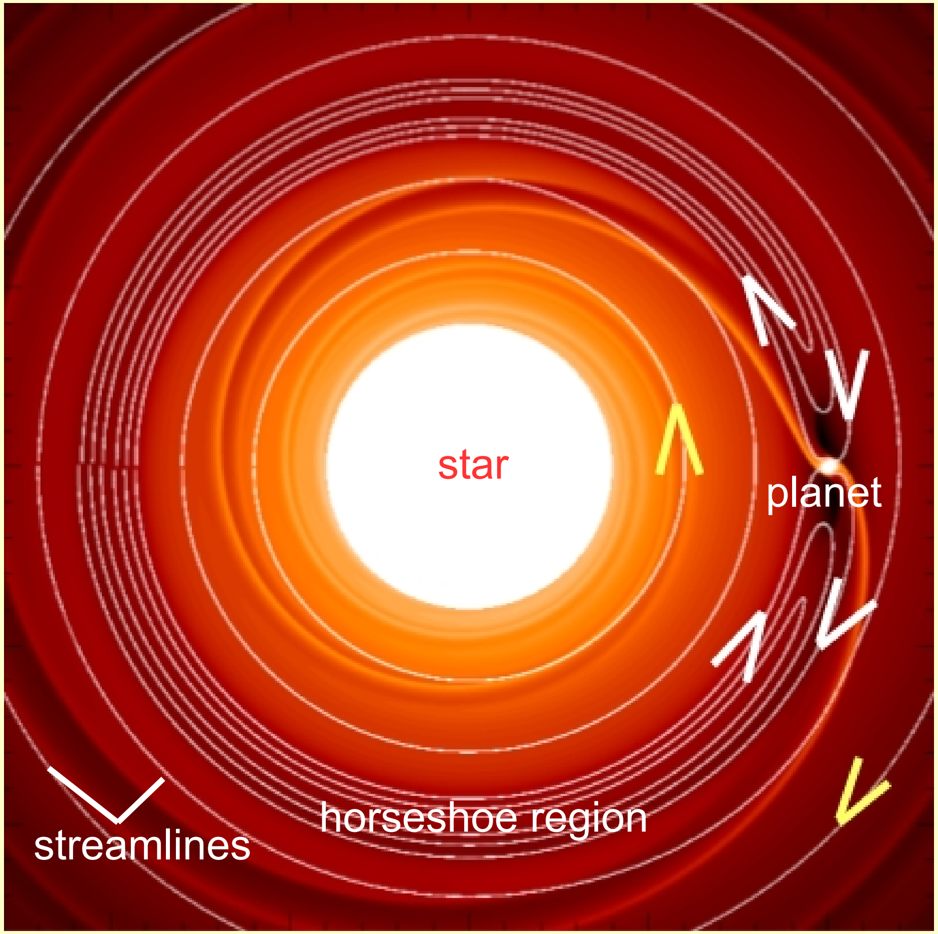


<u>Until recently</u>, the migration timescale of protoplanets had to be **arbitrarilly** increased by a factor of ~100 to make theory ~ match observations!

Migration of protoplanets

(typically a few Earth masses)

Recent reviews: Kley & Nelson (2012), Baruteau & Masset (2012)



Disc density perturbed by a 10 Earth-mass planet

Torque exerted by the disc on a planet:

1. Differential Lindblad torque
(angular momentum carried away by spiral density waves)

→ drives migration inwards

Ward 1997, Tanaka et al. 2002

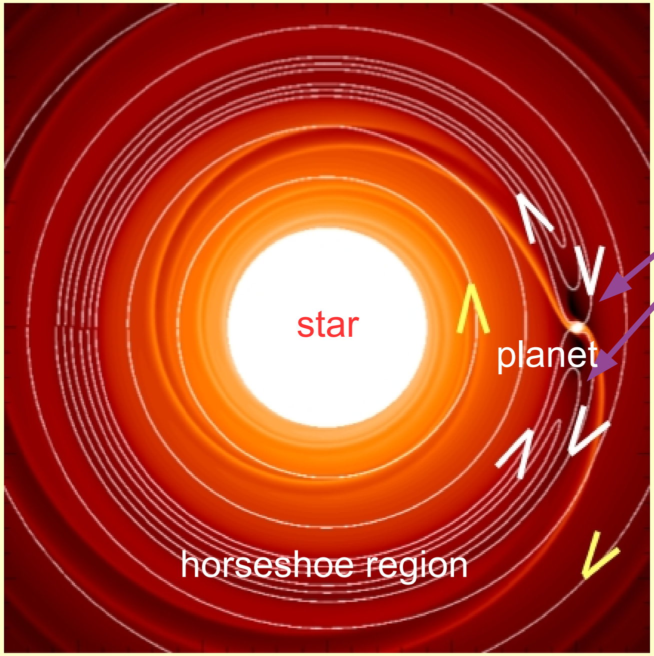
2. Corotation torque
(exchange of angular momentum with the planet's horseshoe region) – driven by *advection-diffusion* of **potential vorticity** within this region

→ drives migration inwards or *outwards*

Ward 1991, Masset 2001

Opt. thin / radiatively efficient disc parts: |corotation torque| < |Lindblad torque|

Slowing down protoplanetary migration



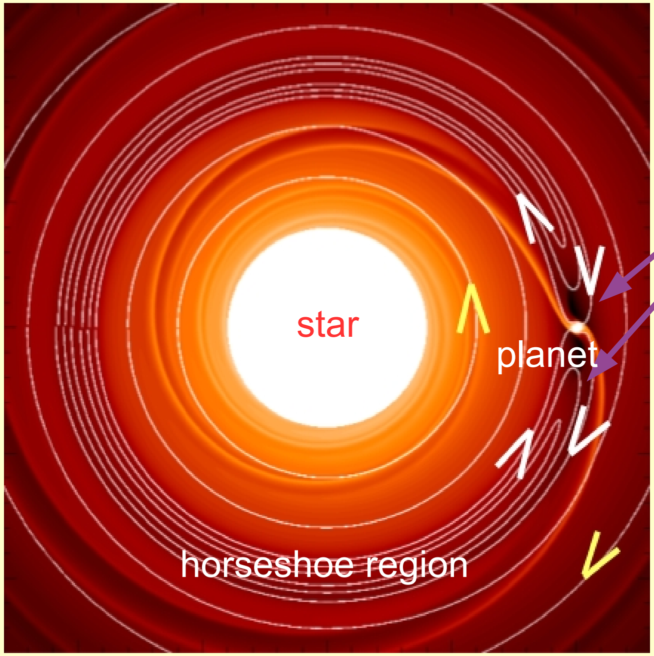
□ **Additional corotation torque in opt. thick disc parts**

(due to advection-diffusion of gas entropy within the horseshoe region)

→ may **slow down, stall, or even reverse** migration

Baruteau & Masset (2008), Paardekooper & Papaloizou (2008), Kley & Crida (2008) ...

Slowing down protoplanetary migration



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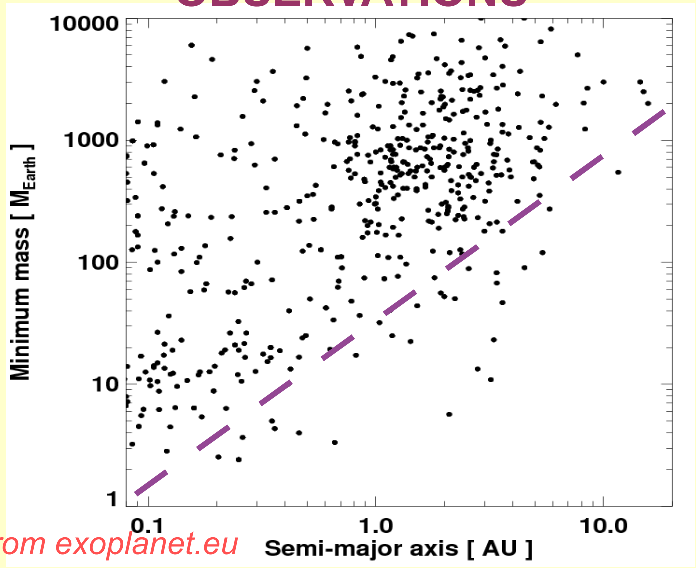
□ Semi-analytic estimates of the migration speed for models of planet population synthesis ↔ **observations**

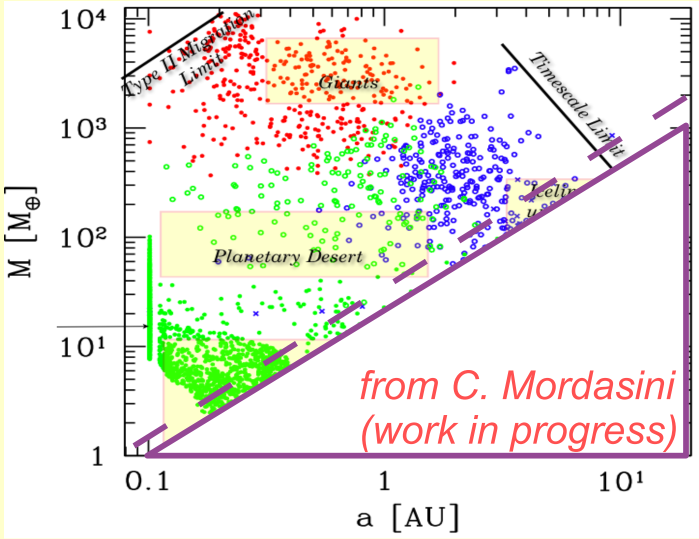
Masset & Casoli (2010), Paardekooper, Baruteau & Kley (2011)

OBSERVATIONS



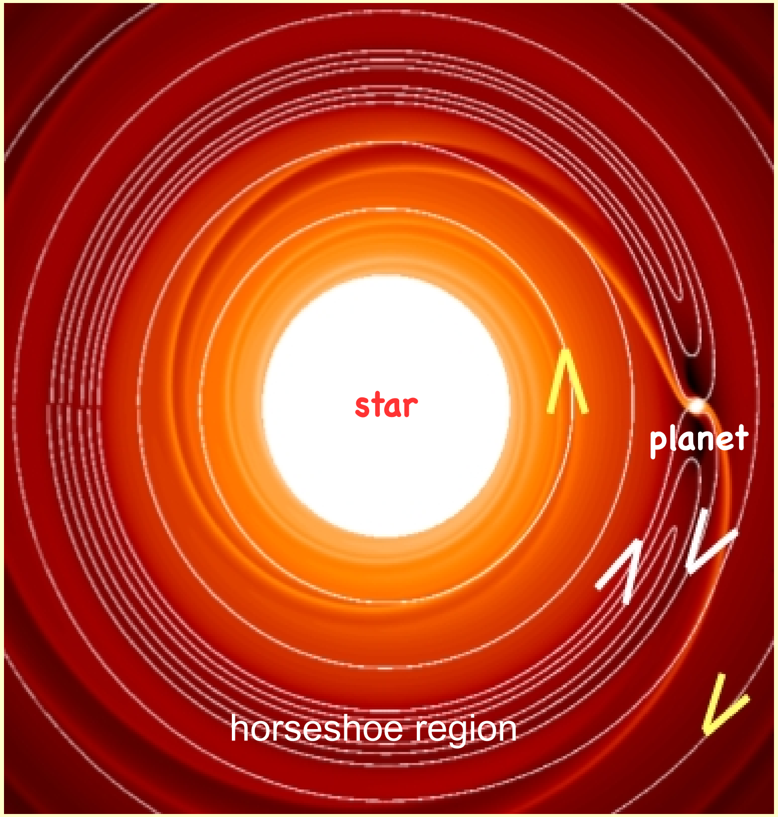
from exoplanet.eu

POPULATION SYNTHESIS



from C. Mordasini (work in progress)

A key question about the corotation torque



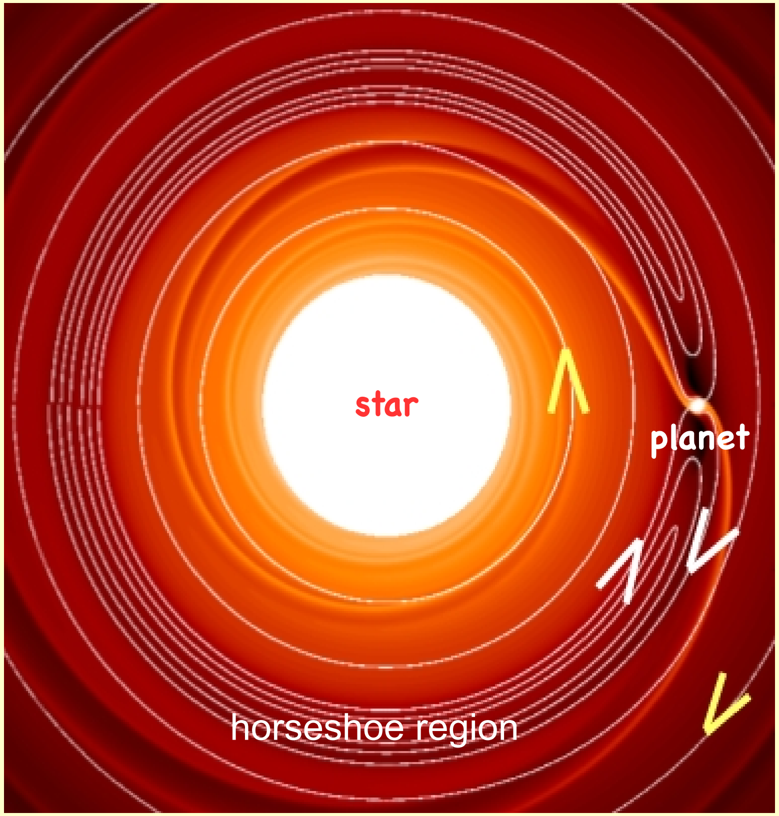
The corotation torque requires
<u>viscous and thermal diffusion</u>
acting over the horseshoe region

Its radial extent is a **<u>small fraction</u>**
of the disc's pressure scale-height
(typical size of turbulent eddies)

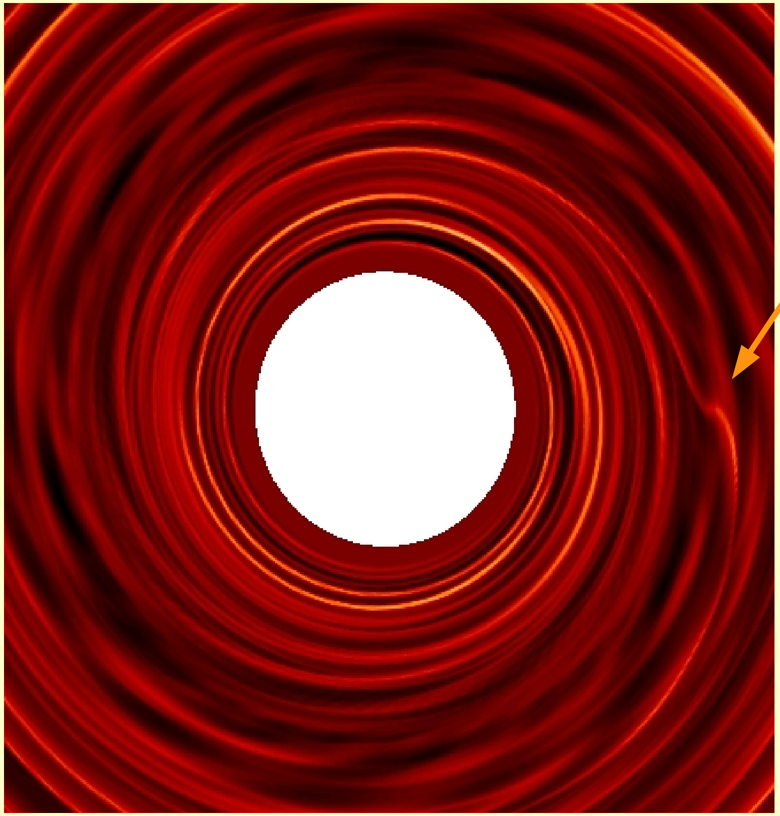
→ how does the corotation torque behave in **turbulent** disc models?

Protoplanetary migration in turbulent discs

Laminar **viscous** disc



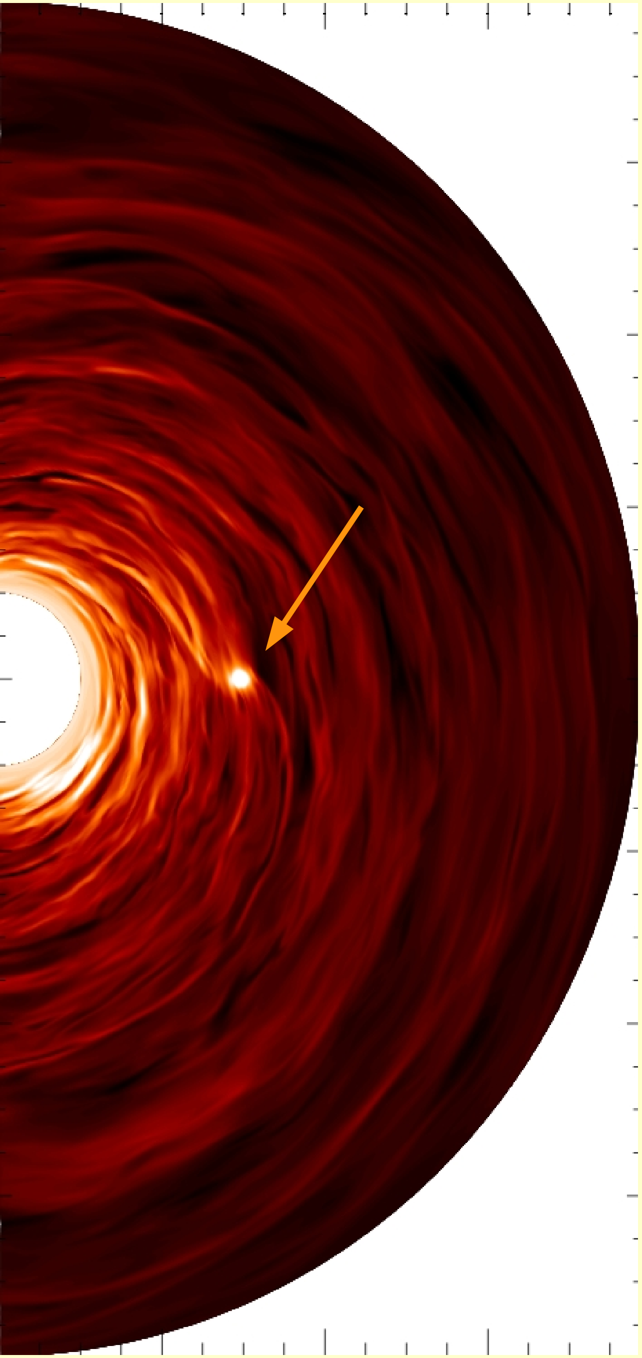
Hydro. turbulence induced by stochastic forcing (2D)



→ Time-averaged Lindblad **and** corotation torques **agree well** with predictions of 'equivalent' viscous disc models

Baruteau & Lin (2010)
Pierens, Baruteau & Hersant, accepted → **poster #66 by A. Pierens**

Protoplanetary migration in turbulent discs



MHD turbulence driven by the **Magneto-Rotational Instability**

(3D unstratified isothermal disc model, with non-ideal MHD, and mean toroidal B field)

Uribe, Klahr, Flock & Henning (2011)
Baruteau, Fromang, Nelson & Masset (2011)

→ Lindblad torque basically unchanged

→ **Still existence** of horseshoe dynamics with MHD turbulence

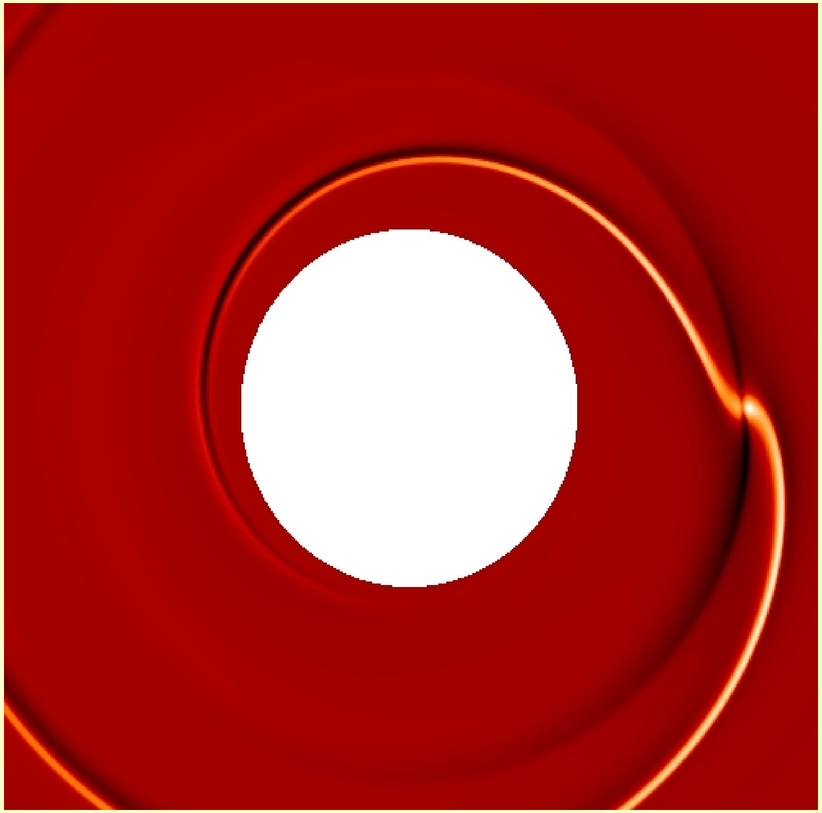
→ **<u>Additional</u>** corotation torque in the presence of a mean **toroidal magnetic field**

Protoplanetary migration in turbulent discs

Laminar disc model with a weak toroidal B field

(2D isothermal, viscosity, resistivity)

Guilet, Baruteau & Papaloizou (subm.)

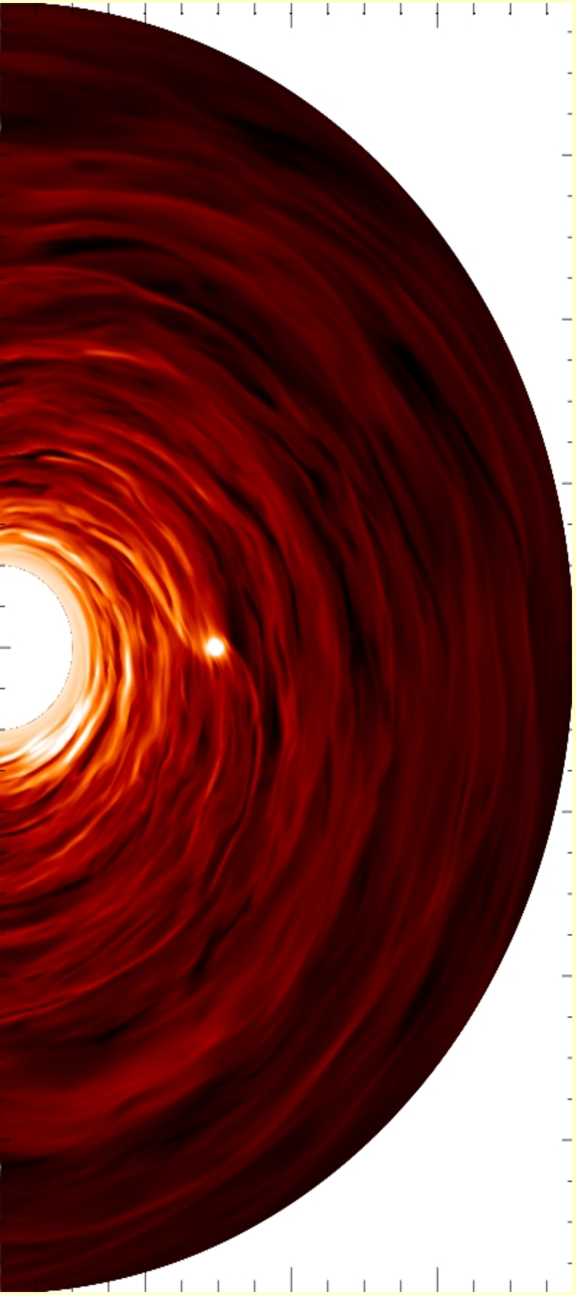


→ Additional corotation torque **confirmed**

→ **Sign** depends on the local density and temperature gradients. Usually positive: new way to **slow down or reverse migration**!

→ **Amplitude** does not depend on any disc gradients. Sensitive to the local viscosity, resistivity, and magnetic field

Take-away messages



□ The **corotation torque** appears to be an **efficient** and **robust** mechanism to slow down / reverse the migration of *low-eccentricity* protoplanets:

→ additional 'entropy-related' corotation torque in optically thick inner disc parts

→ new MHD corotation torque

But still a lot to be done!

□ It may help **reduce the discrepancies** between observations and theoretical models

□ Although planet migration is important (and inevitable), it is certainly **not the whole story**: star-planet & planet-planet interactions are also needed!