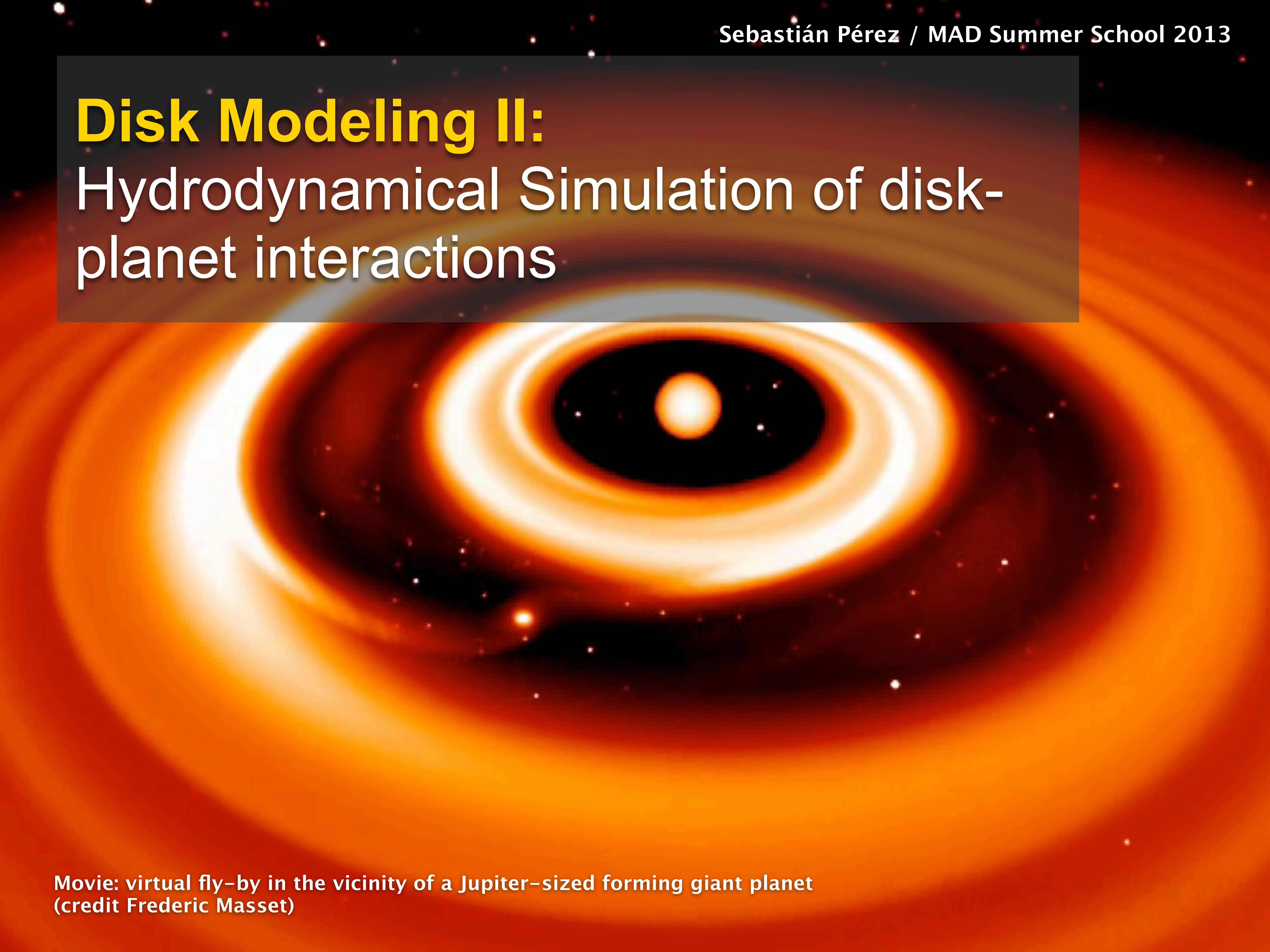
Sebastián Pérez / MAD Summer School 2013

Disk Modeling II:
Hydrodynamical Simulation of disk-planet interactions



Movie: virtual fly-by in the vicinity of a Jupiter-sized forming giant planet (credit Frederic Masset)

Lecture Overview

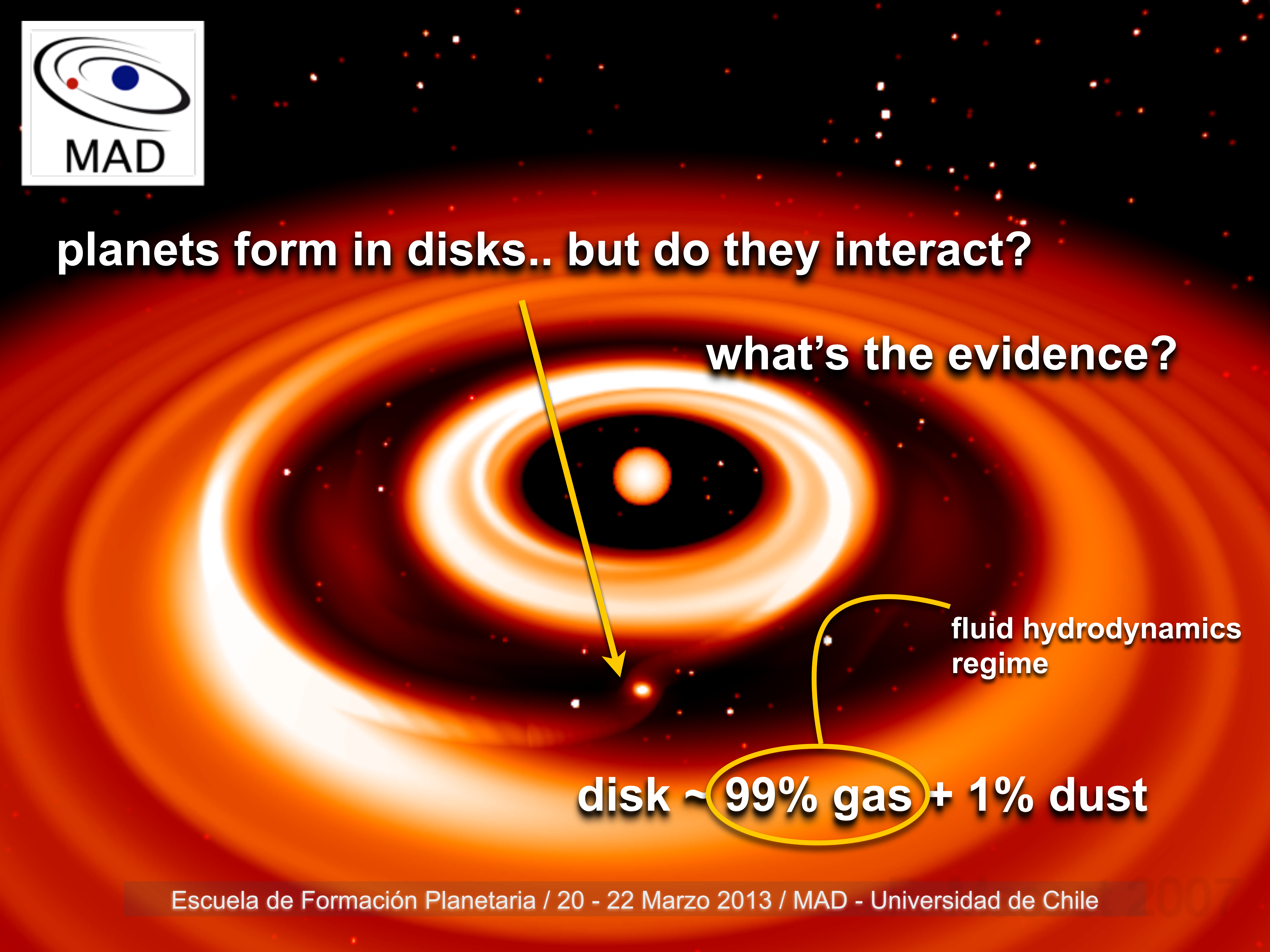
intro / planet-disk interaction evidence

basic notions of hydrodynamics and physical model [equations]

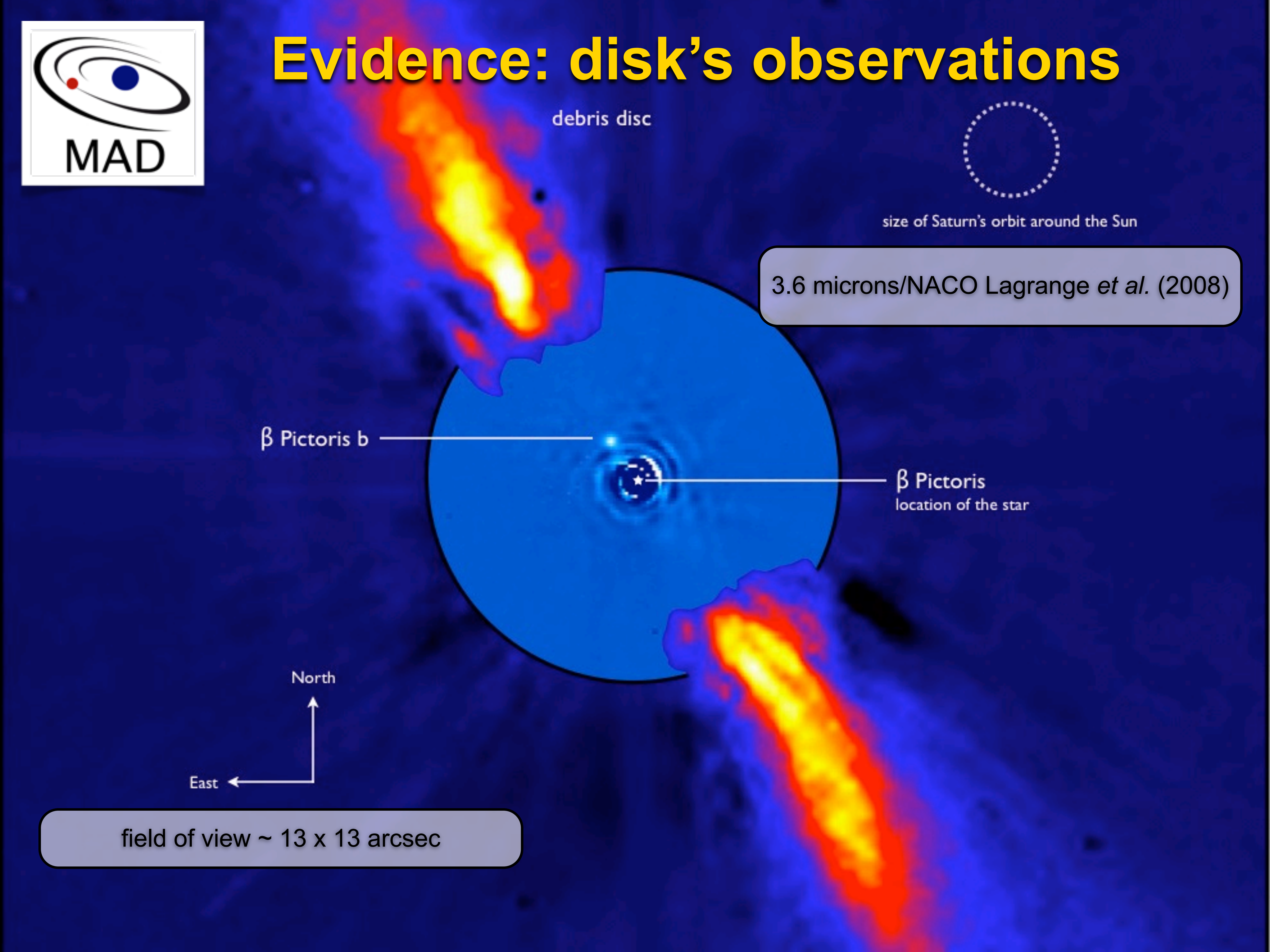
hydrodynamic codes [coding - fargo]

Real life examples:

- planetary migration and gap opening!
- vorticity and adding dust!
- multiple planets!

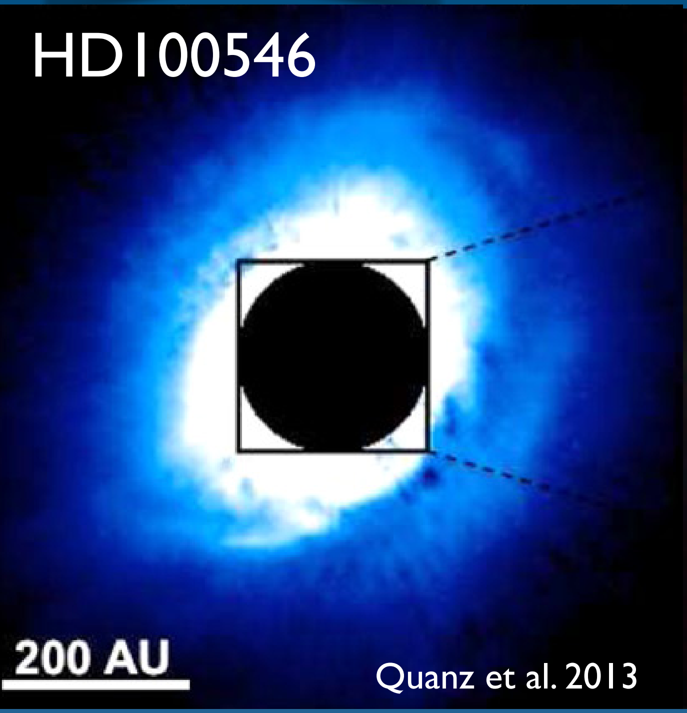

MAD
planets form in disks.. but do they interact?
what's the evidence?
fluid hydrodynamics
regime
disk ~ 99% gas + 1% dust

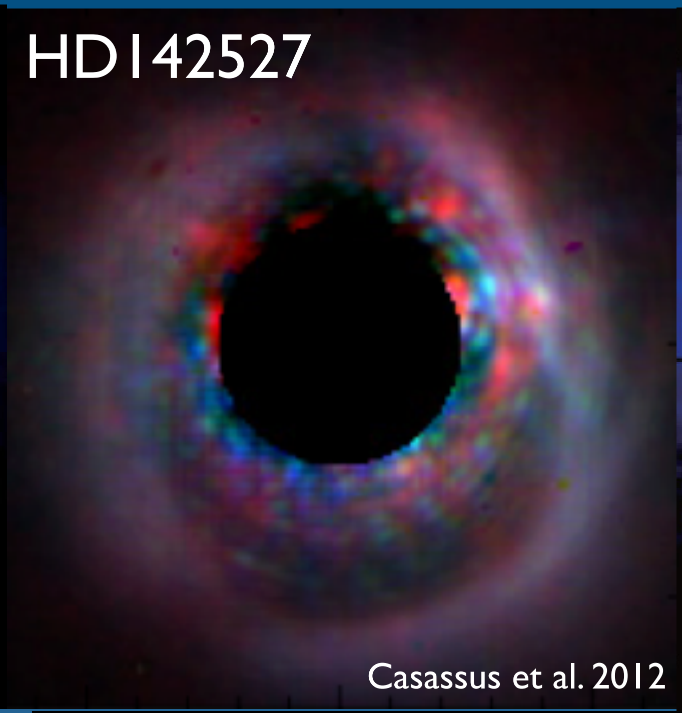
Evidence: disk’s observations

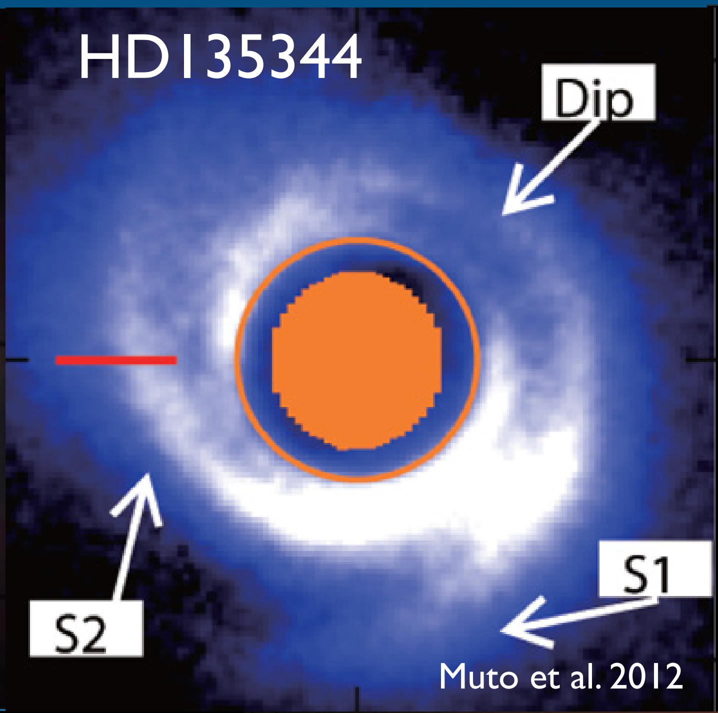


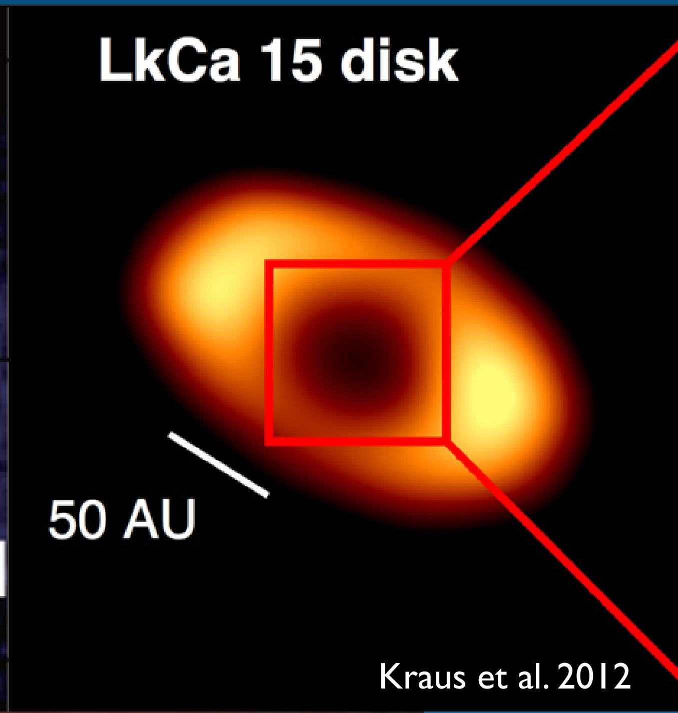
Transition disk's observations

In scattered light (optical, infrared):

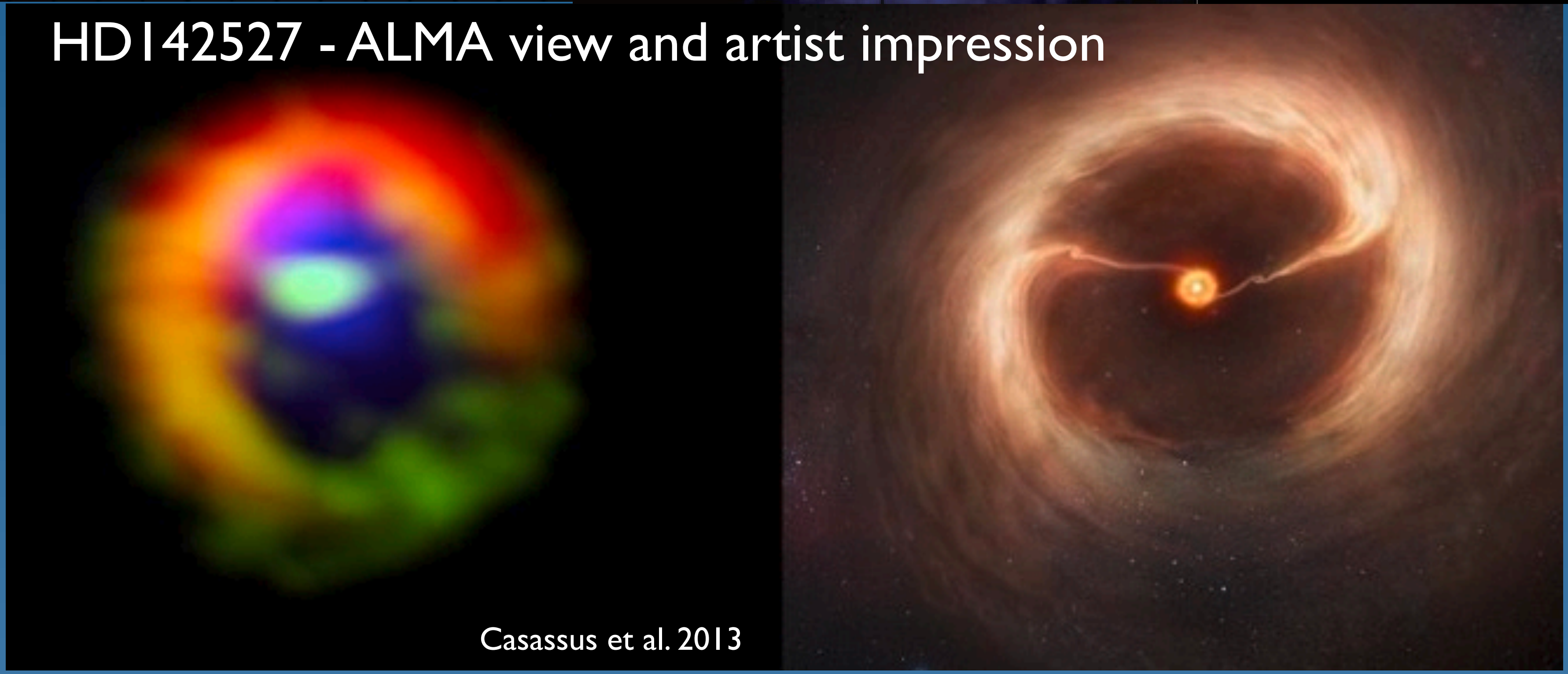








Gas line emission, Dust continuum emission (sub-mm).



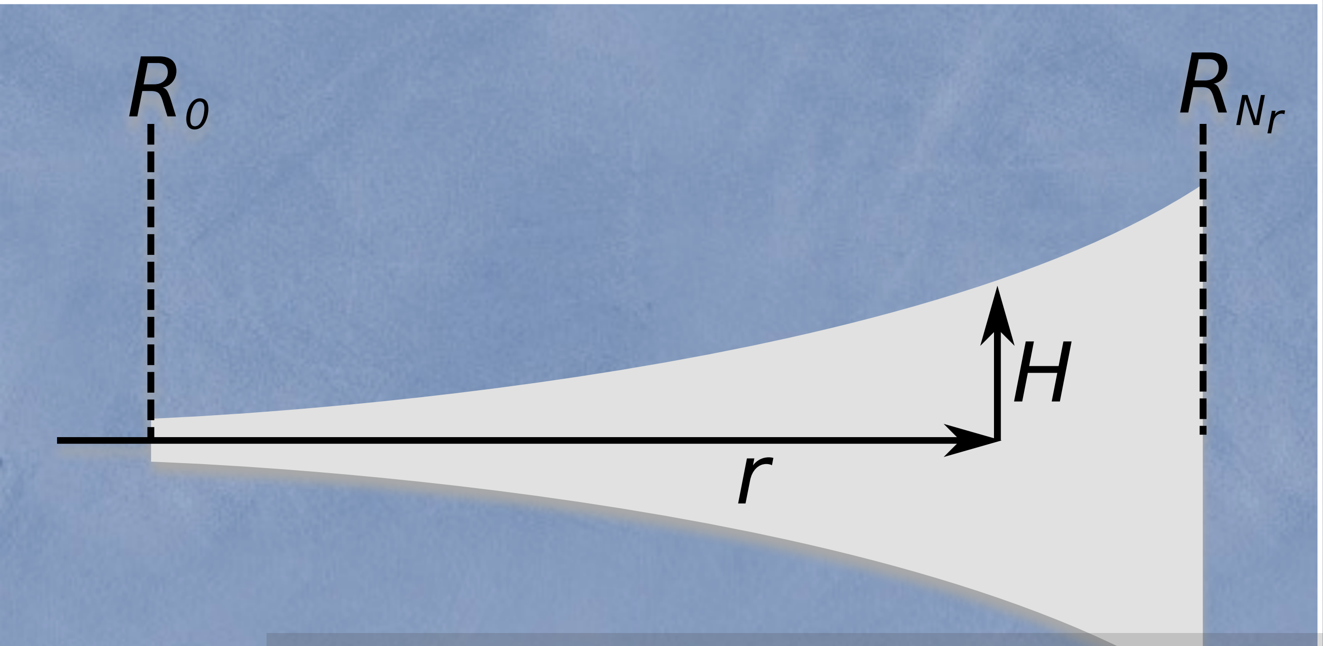
How to model a protoplanetary disk

1- define the problem you want to tackle

2- write down the equations / Physical Model

3- state your assumptions: geometry? thin? viscid? inviscid? 2D, 3D?

4- write a code that can do it for you



Mass, momentum and energy need to be conserved, etc

Disk physical model / Hydrodynamics Navier-Stokes

Sir George Stokes,
1st Baronet
Irish

Mass conservation

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0$$

Momentum conservation

$$\rho \left(\frac{\partial \vec{v}}{\partial t} + (\vec{v} \cdot \nabla)\vec{v} \right) = -\nabla p + \rho \vec{f} + \nabla \cdot \sigma$$

external forces: gravitation, Coriolis, centrifugal, etc.

viscosity!

Energy conservation

$$\frac{\partial (\rho \epsilon)}{\partial t} + \nabla \cdot (\rho \epsilon \vec{v}) = -p \nabla \cdot \vec{v} + \ldots$$

here we add heat generated by viscosity and heat lost by conduction!

Disk physical model / Gravity

Next we need to set boundary conditions and ADD A PLANET... but where? how?

in the momentum conservation equation.

+ add the gravity of the central star
+ plus that of an embedded planet
+ [optional] if the disk is massive enough, add self-gravity

Star's potential

$$\Phi_\star(r) = -\frac{GM}{r}$$

Plummer's potential

$$\Phi_P(r) = -\frac{GM}{\sqrt{(r-r_P)^2 + a^2}}$$

Self-gravitating disk potential

$$\Phi_{\rm disk}(r) = -G\int_{\rm disk} \frac{\rho(r')}{|r-r'|}dr'$$

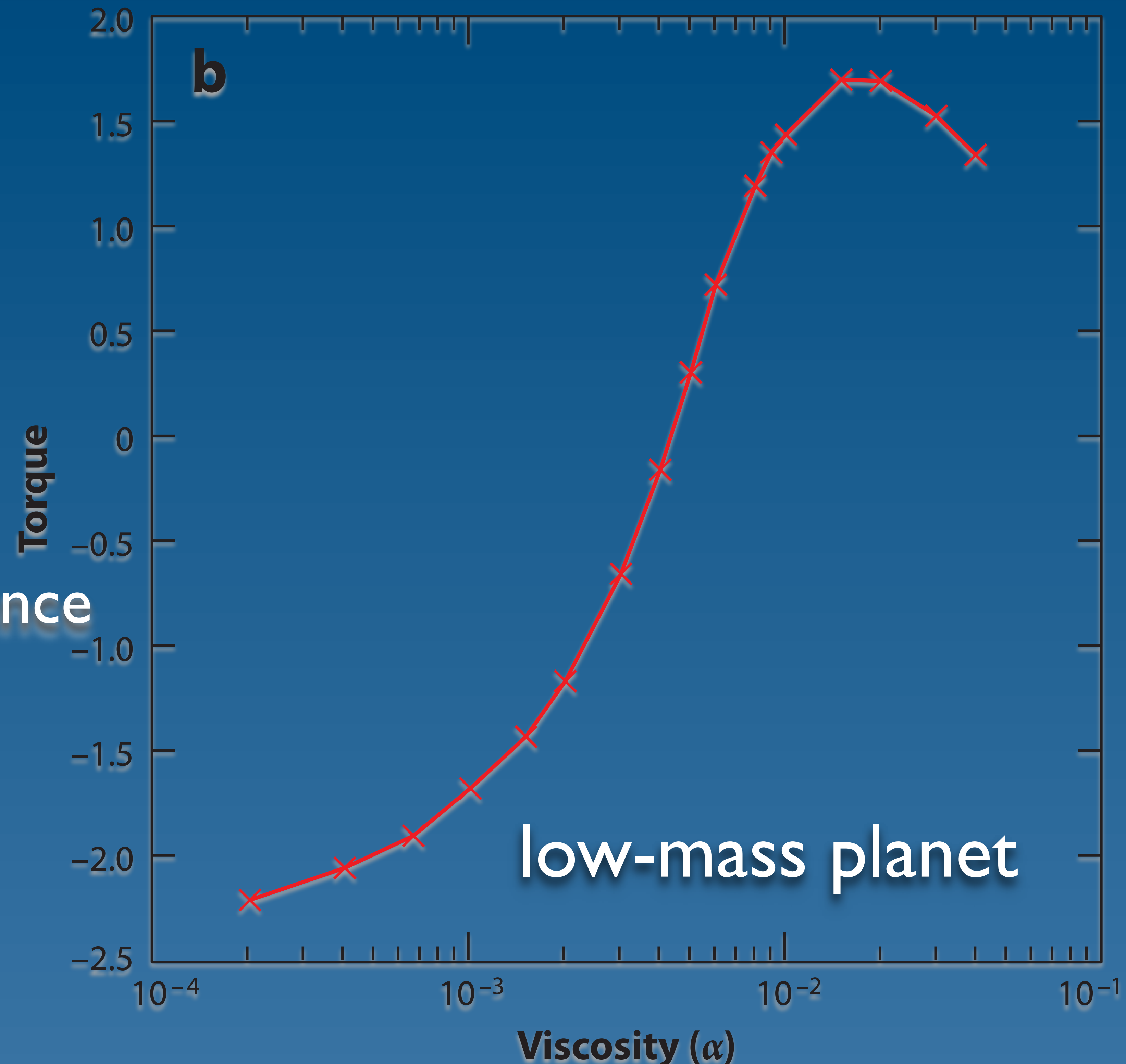
Disk physical model / viscosity

way of dissipating energy

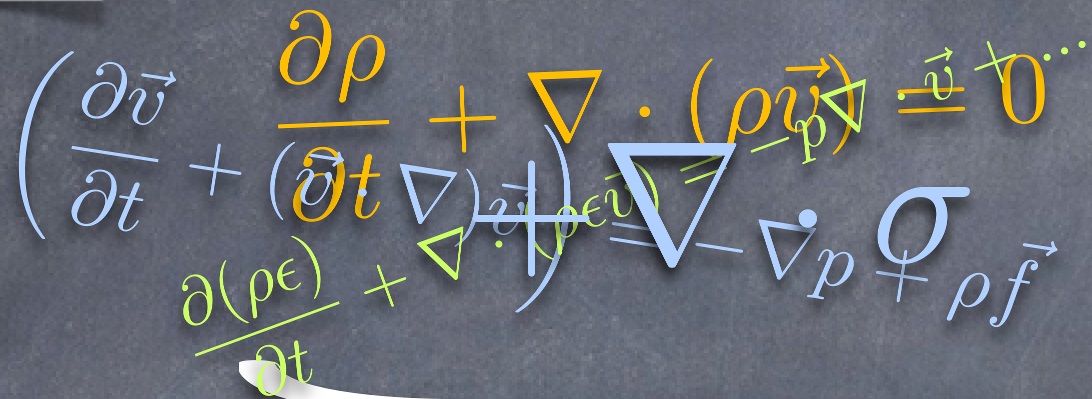
alpha-disk prescription (Shakura & Sunyaev 1973) based on subsonic turbulence

$$\nu = \alpha c_s H$$

actually driven by MHD turbulence



Disk physical model / Basic calculation



$$+ \frac{GM}{r} + \ldots + \quad p \propto \rho T$$

(gravity) (thermodynamics)

$$\int dz$$ ← Reduce to 2D!

↓

Set PHYSICAL MODEL and geometric grid

↓

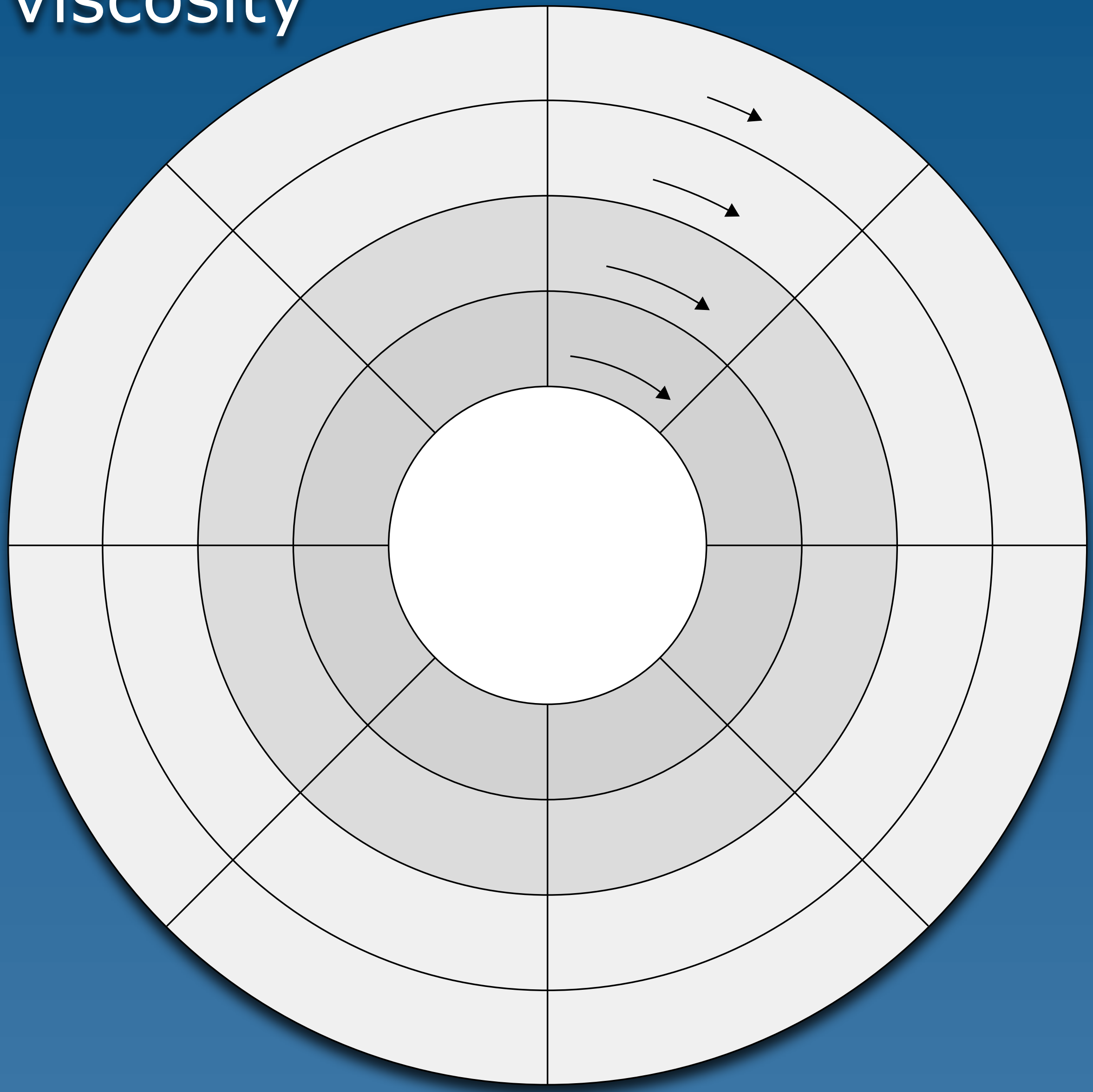
Solve it! with finite-differences with a time-explicit step solution

Code example: Fargo

developed by Frederic Masset et al. http://fargo.in2p3.fr

✓2D polar mesh hydrocode to represent a Keplerian disk
✓it uses alpha-disk prescription for viscosity
✓self-gravity can be switched on
✓very fast (clever at choosing dt)
✓open source
✓parallelized (mpi and openmpi)
✓widely used and tested

- no 3D
- can't evolve some parameters during a run (viscosity, H/r, ..)
- one fluid only (no dust)
- planet accretion is simplified



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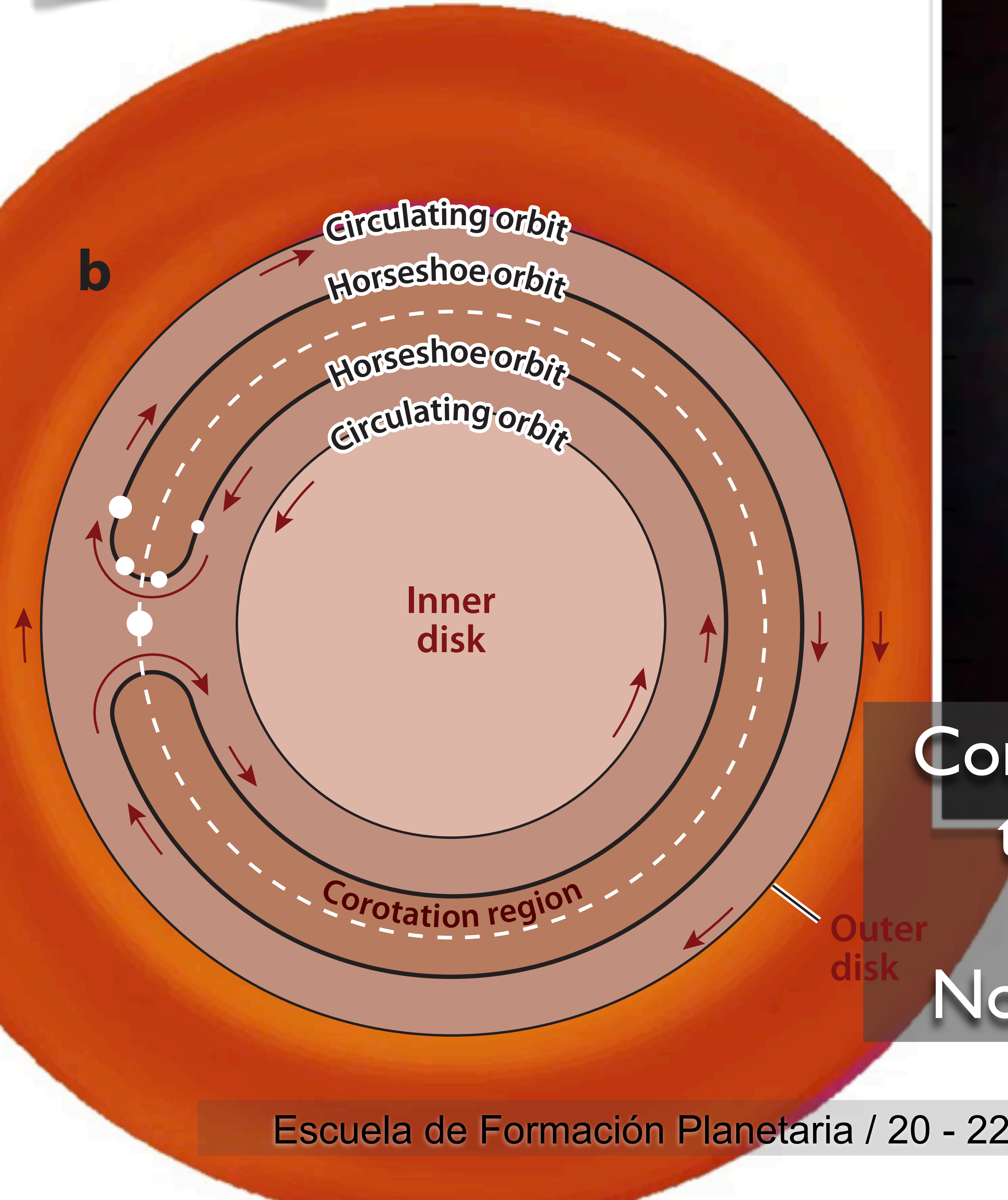
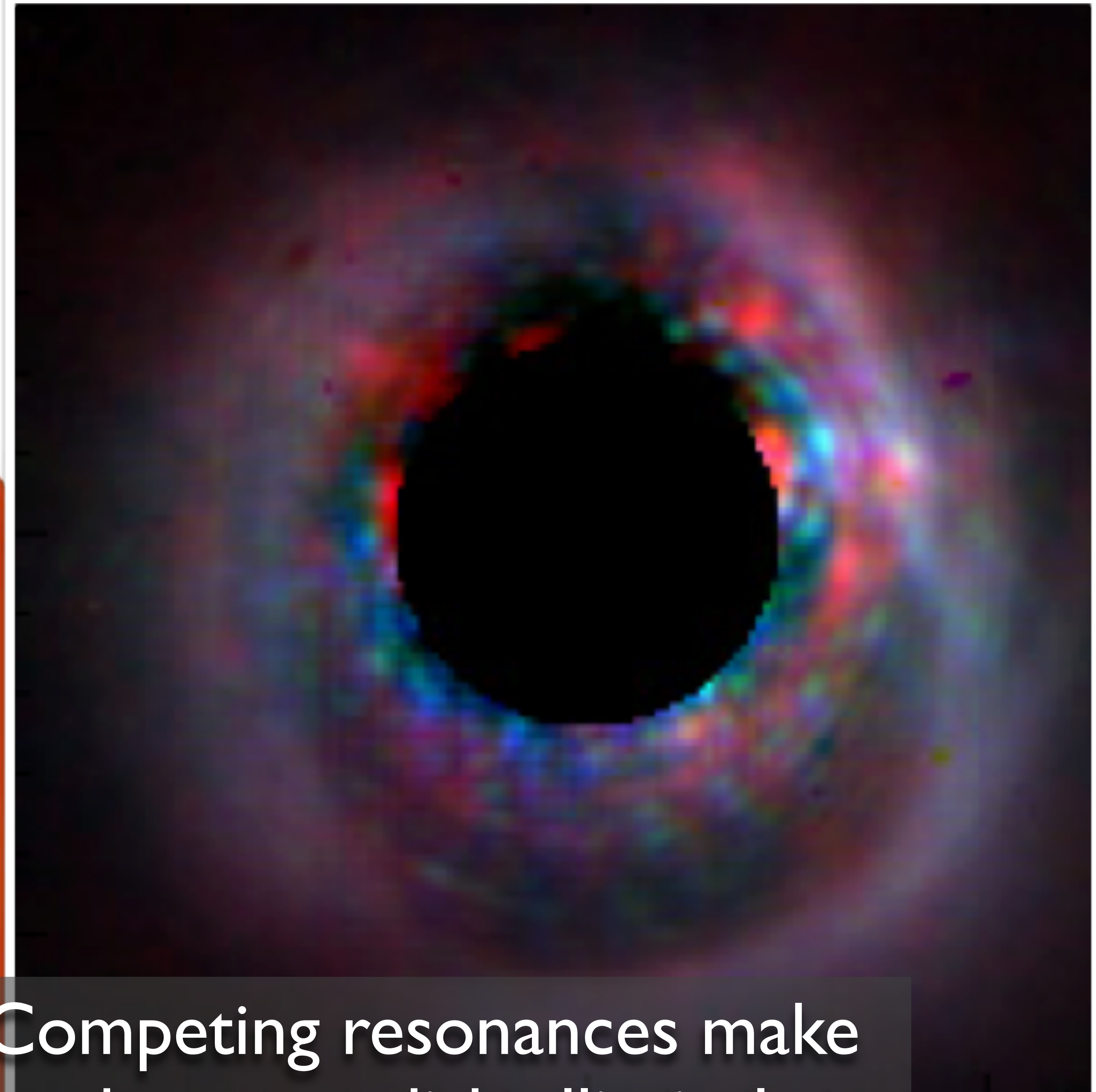




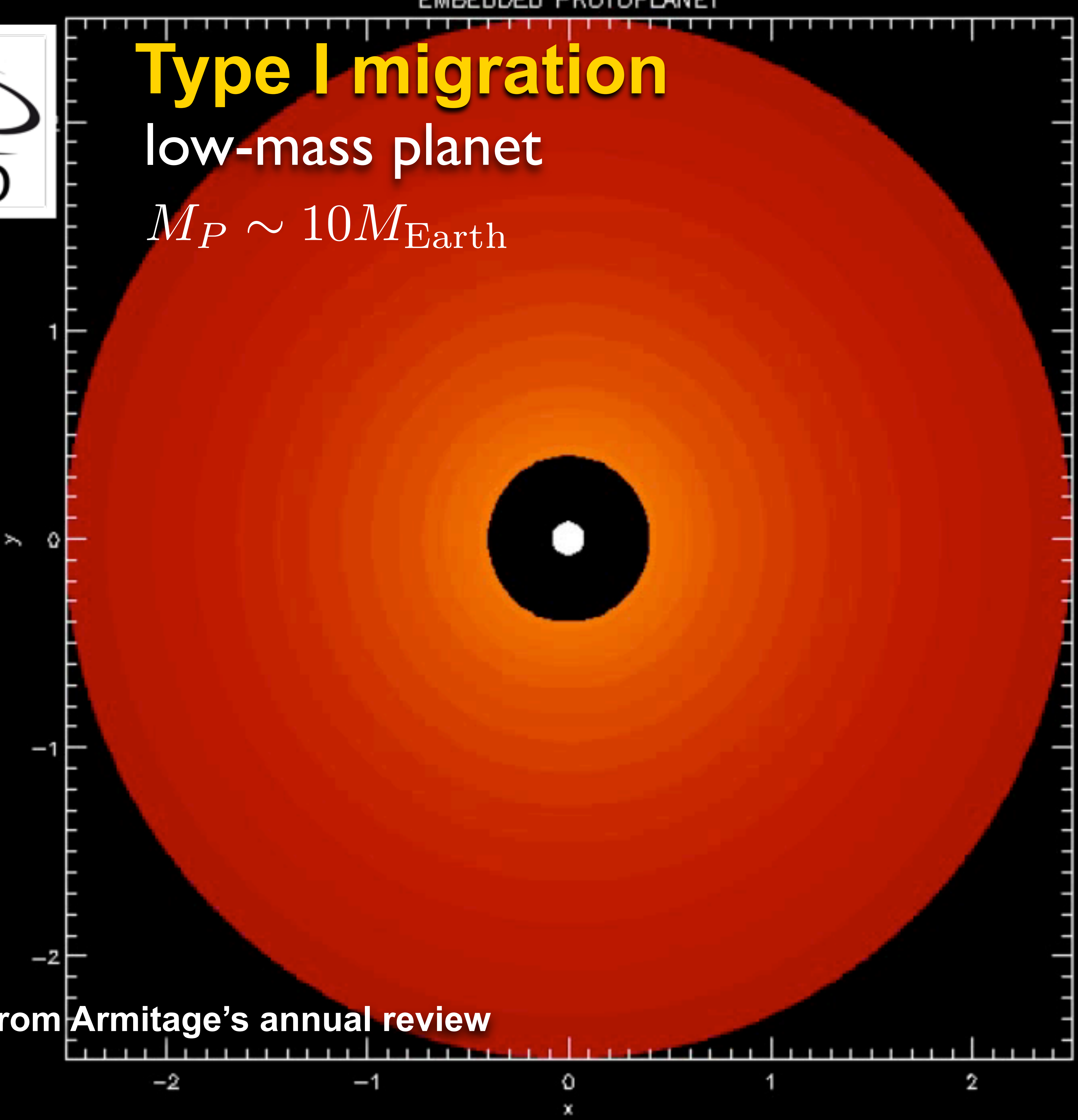
Competing resonances make the outer disk elliptical

Notice the corotation zone

Type I migration

low-mass planet

$M_P \sim 10 M_{\mathrm{Earth}}$



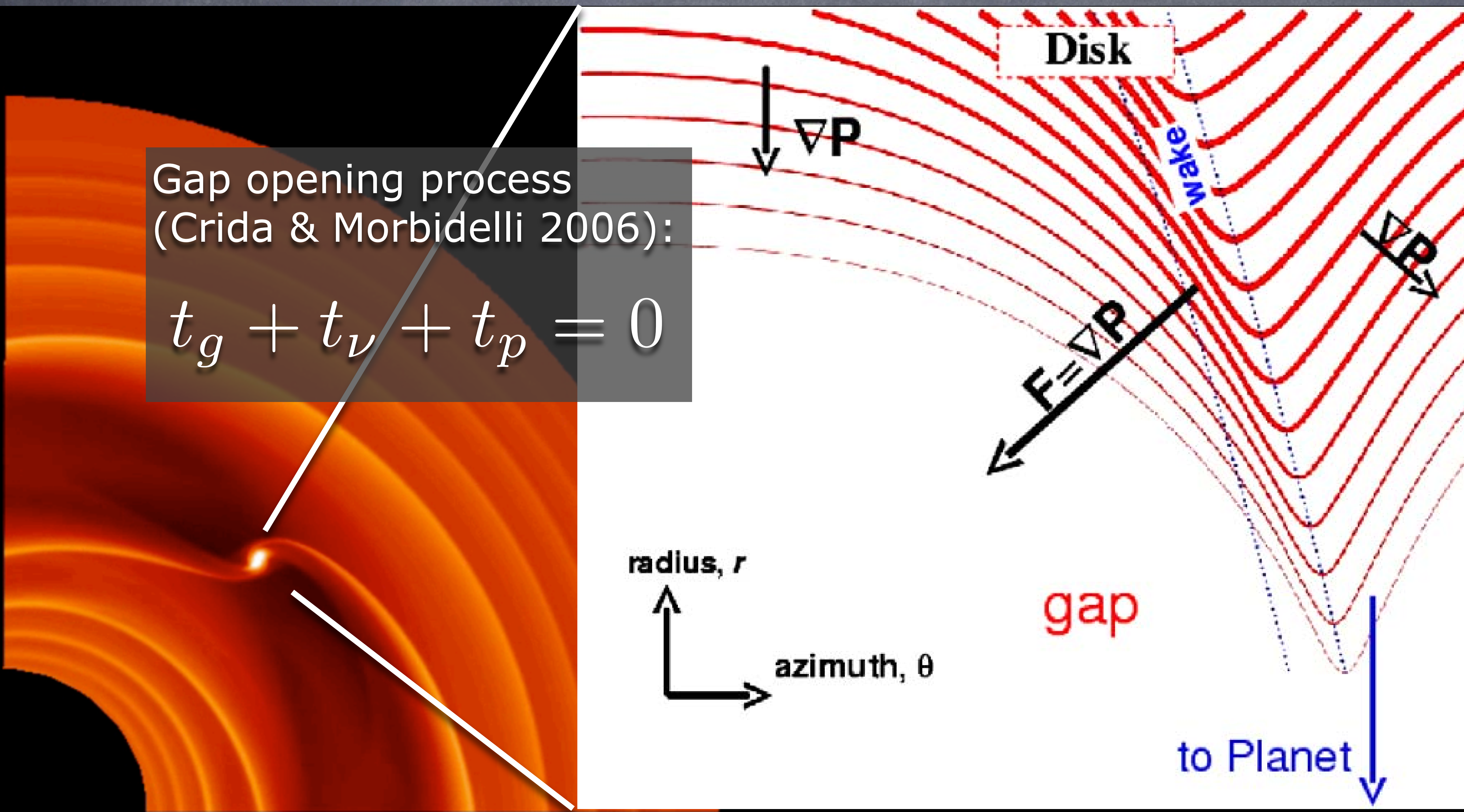
movie from Armitage's annual review

Type II migration

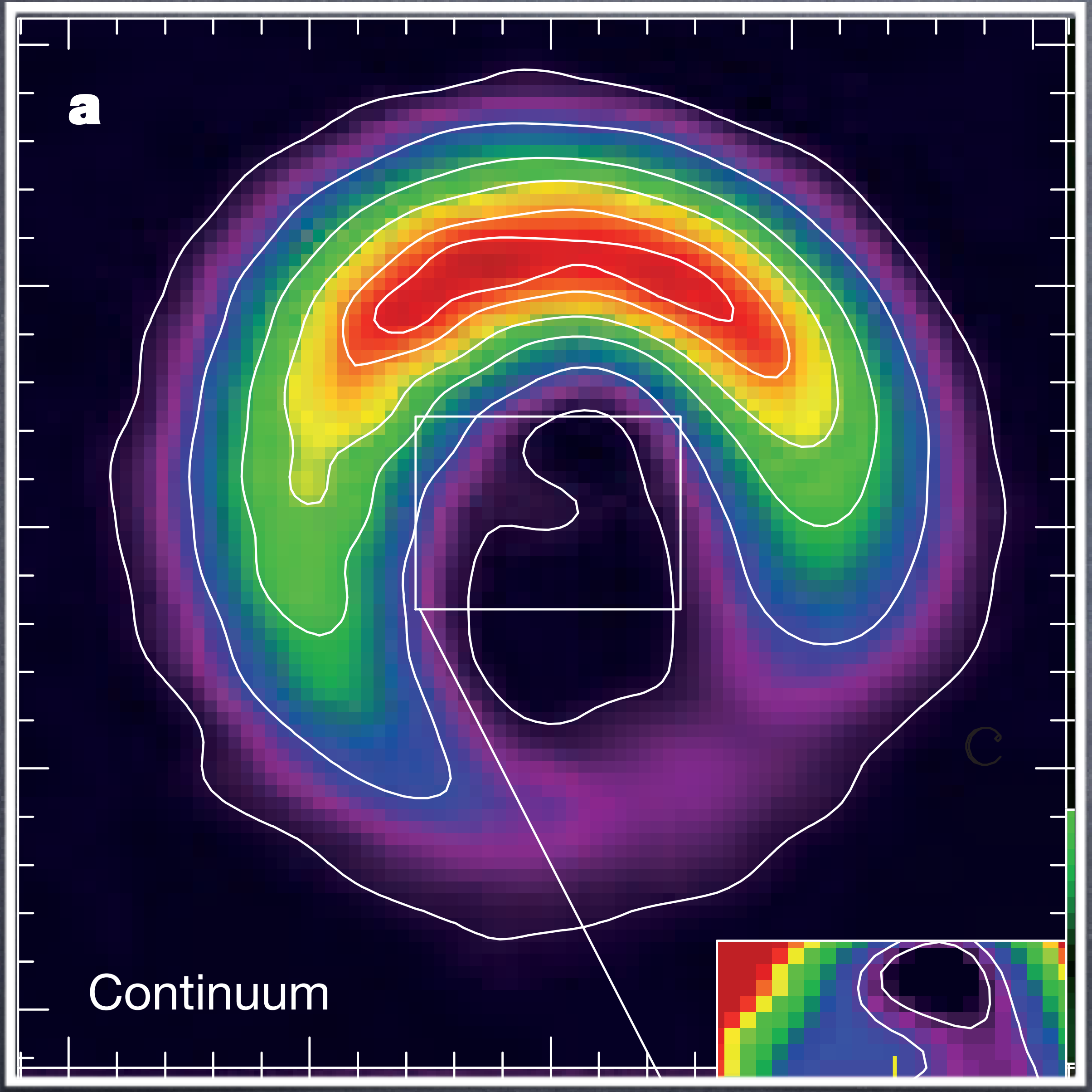
high-mass planet

Gap opening process (Crida & Morbidelli 2006):

$$t_g + t_\nu + t_p = 0$$

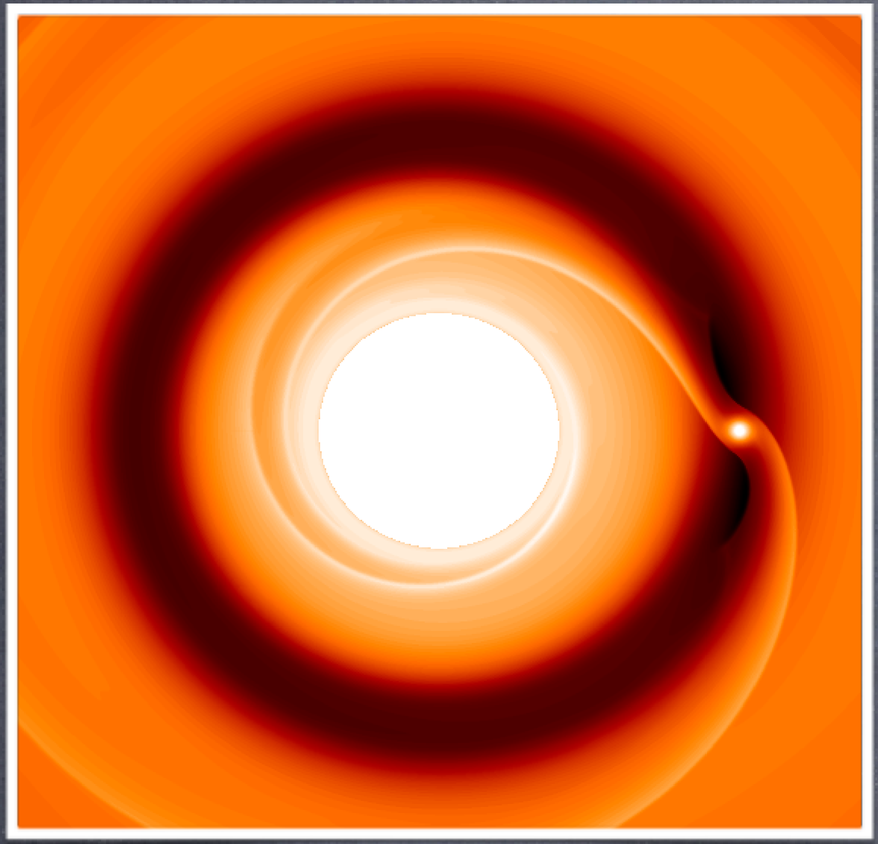


how do we get a horseshoe?



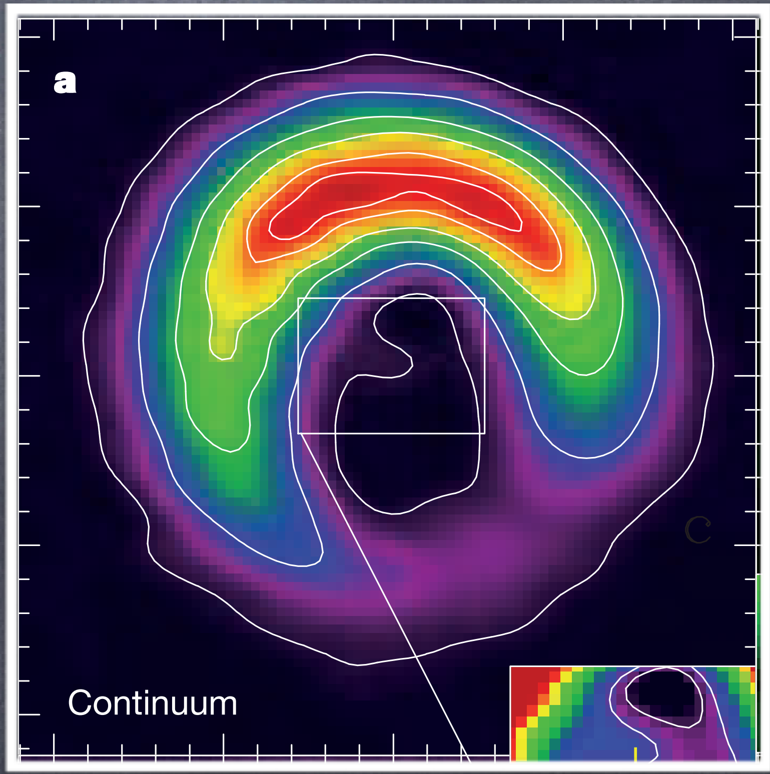
Look at Pinilla et al. 2012 and her modeling of particle traps.

vortices and 2-fluids (adding dust)



+ Vortex / Instability + dust particles that get trapped by pressure bump

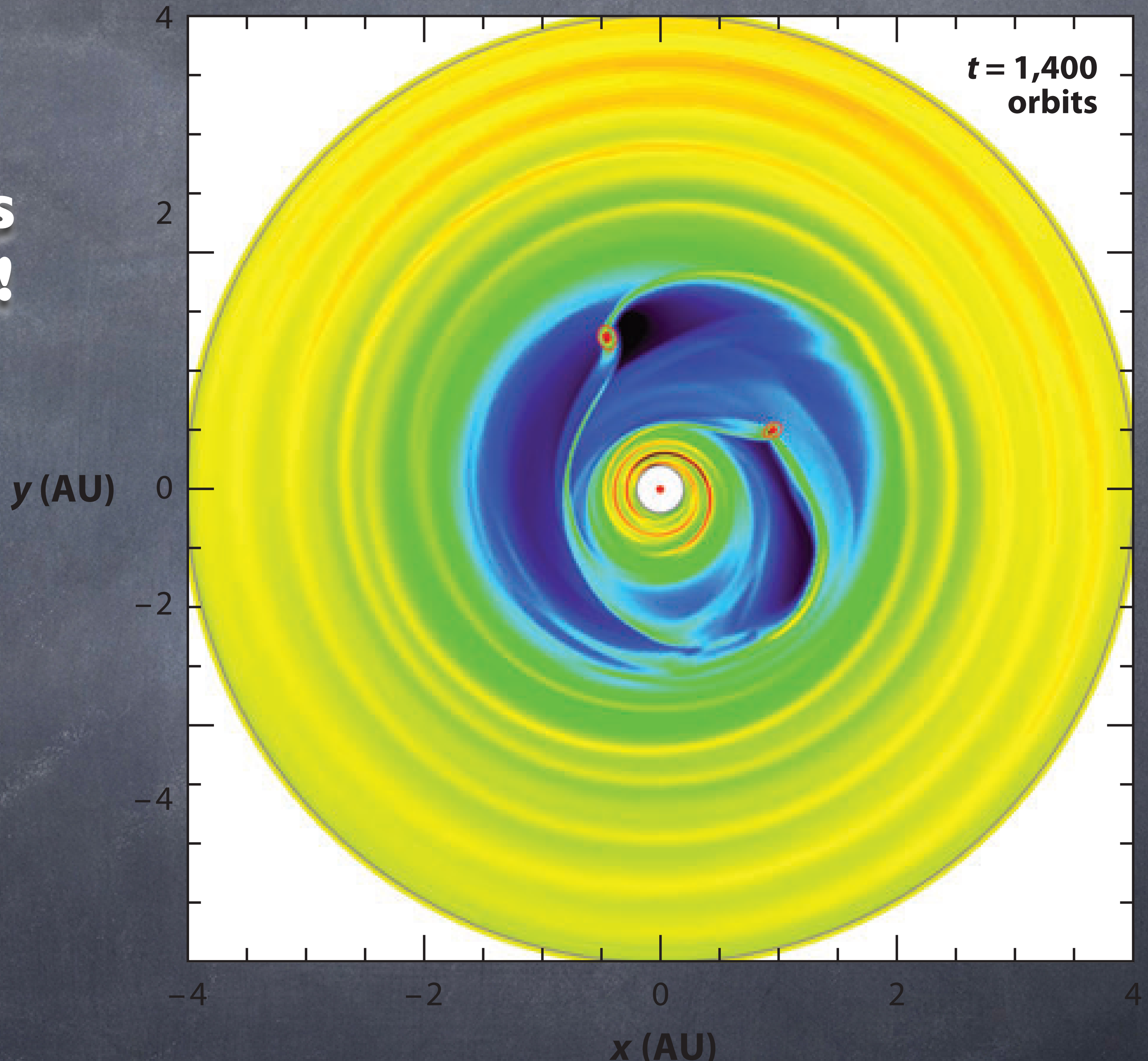
= (maybe..)



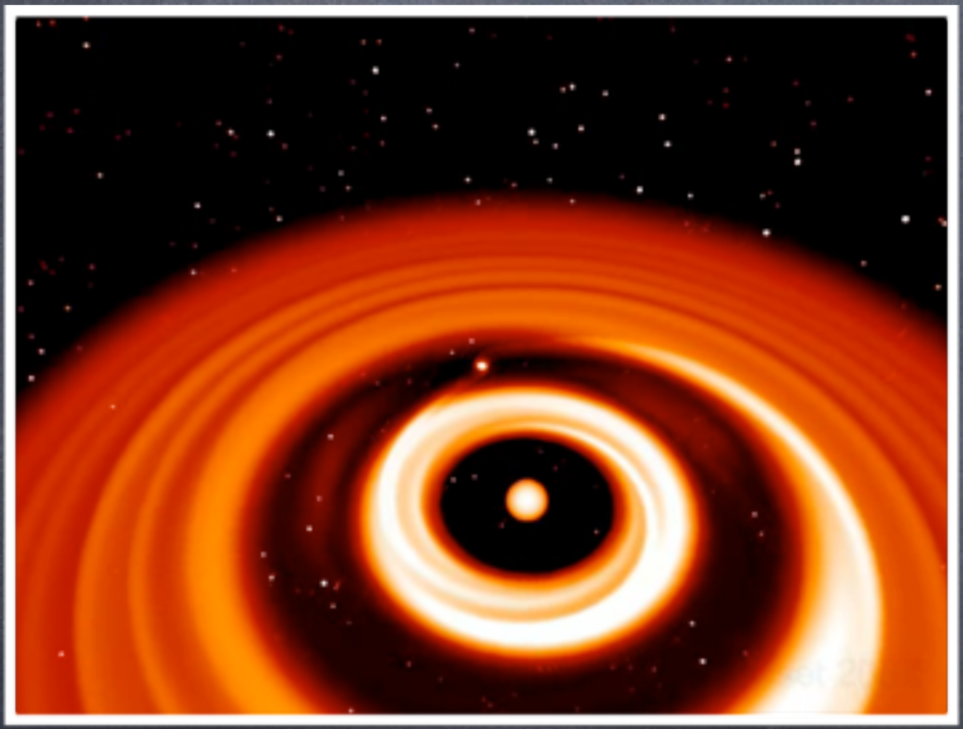
Multiple planets

Solar System has ~8 planets... duh!

Dodson-robinson & Salyk 2012 work



State of the art



something like Fargo plus..

+ multifluid
+ adaptive-mesh (refinement)
+ full 3D
+ more realistic MHD turbulence and radiative transfer

Summary

Disk-planet interaction is a natural process operating when young planets are still embedded in the protoplanetary disk.

It's intrinsically 3D.

Thanks to simulations we've been able to study migration and the possibility of outward migration (radiative disk)

Theoretical and computational developments are required to improve models of the planet formation environment, with particular emphasis on their structural evolution over time. Important ingredients are the disk's self-gravity, irradiation from the central star, chemistry, and nonideal MHD processes.

hydro codes

AMRA code (Pawel Ciecielag & Tomasz Plewa)
FLASH code
NIRVANA code
RH2D code (Willy Kley, Tübingen)
RODEO code (Sijme-Jan Paardekoper & Garrelt Mellema, Leiden)
ParaSPH code (Christoph Schäfer & Roland Speith, Tübingen)

and many more..