Migration and growth of giant planets in self-gravitating disks with varied thermodynamics

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Planetary formation

- 2 scenarii:
  - Core accretion
  - Gravitational instability
- In both cases, impossible to form planets very close to the star (few AU)
- Observations:
  - Hot Jupiters (at a few fractions of AU)
  - Potential signatures of planets at large distances (100 AU) that create structures in the debris disks.
- => Planets migrate

Migration of a Jovian planet (standard hypotheses)

- M_P = 1 M_J, a_{P0} = 5 AU, circular orbit
- 2D, locally isothermal disk
- Simulations: fixed orbit, migration rate computed thanks to the torques exerted by the disk.
- Result: Type II Migration not as fast as type I but still shorter timescale than disk lifetime.
- Question: How comes we observe planets, then ?????

Our Simulations
Parameters

- 3D SPH Code (GASOLINE, Wadsley et al. 2004), Standard Monaghan (most commonly used and most stable) α_{SPH}=1, β_{SPH} = 2, mean alpha_SS =0.01 (see MRI predictions and observations)
- 1MJ Planet initially at 5 AU
- 2 different sets of GLOBAL DISK sims:
  - 0.004 Msol Disk between 2 and 20 AU (MMSN)
  - 0.01 Msol Disk between 1 and 25 AU
- initially $\Sigma=\Sigma_0\ r^{-3/2}$, $T=T_0\ r^{-1/2}$; 10^5 to 10^6 gas particles
- 2 collisionless particles : Planet and star. Fully dynamical: Move freely under the action of the disk and of each other.
- Planet already formed at the beginning but no gap initially.
- No "sinks" => mass accumulates in the Hill radius

Our Simulations
Originality

- 3D
- Different equations of state
  - locally isothermal (extreme: very efficient cooling)
  - adiabatic with shock heating (extreme: no radiative cooling)
  - radiative transfer in the diffusion approximation with flux limiter (more realistic)
- Planet moves really, Star also not fixed.
- Self-gravity of the disk included

Our Simulations
Limits

- SPH not ideal to capture gap formation
  - explicit numerical viscosity (to prevent particles interpenetration), but we use the Balsara switch to decrease the viscosity in shear flows.
  - poor resolution in low density regions because few particles
- ➔ Correct shape but shallower gap as compared to grid code simulations (De Val-Borro et al. 2006)
- Same bias for different equations of state

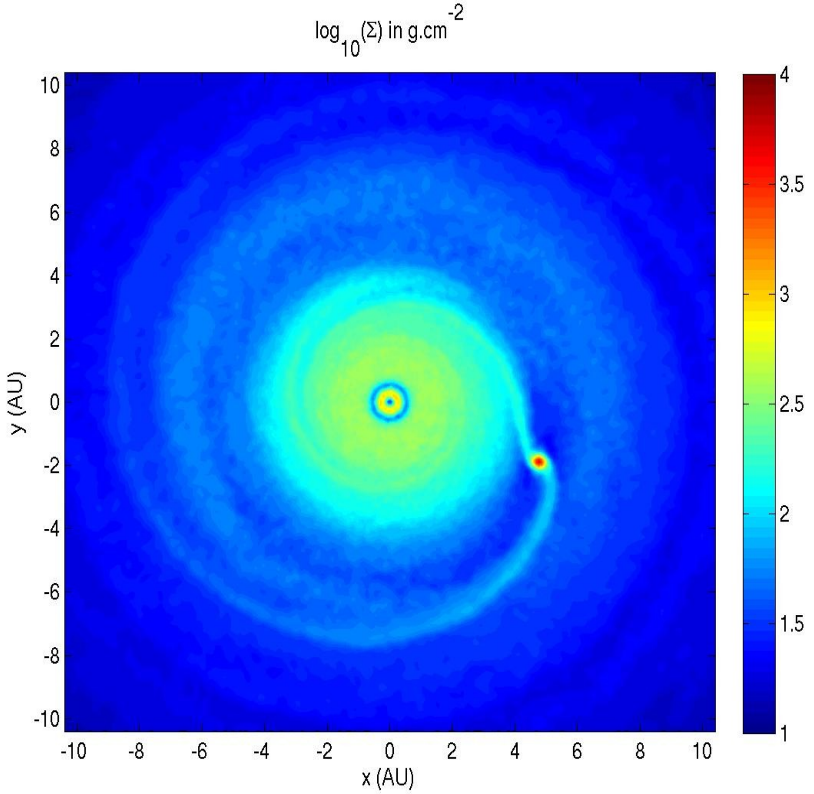
Our Simulations
Why Tree-SPH then????

- Tree-SPH is known to properly handle self-gravity thanks to the accuracy of the tree-based gravity solver (GASOLINE: up to hexadecapole term in the multipole expansion).
- SPH has no problems with advection and is galilean invariant (see Springel 2009).
- Lagrangian nature of SPH => suited to global simulations. No issues with preferential geometry, no need for specific boundary conditions.

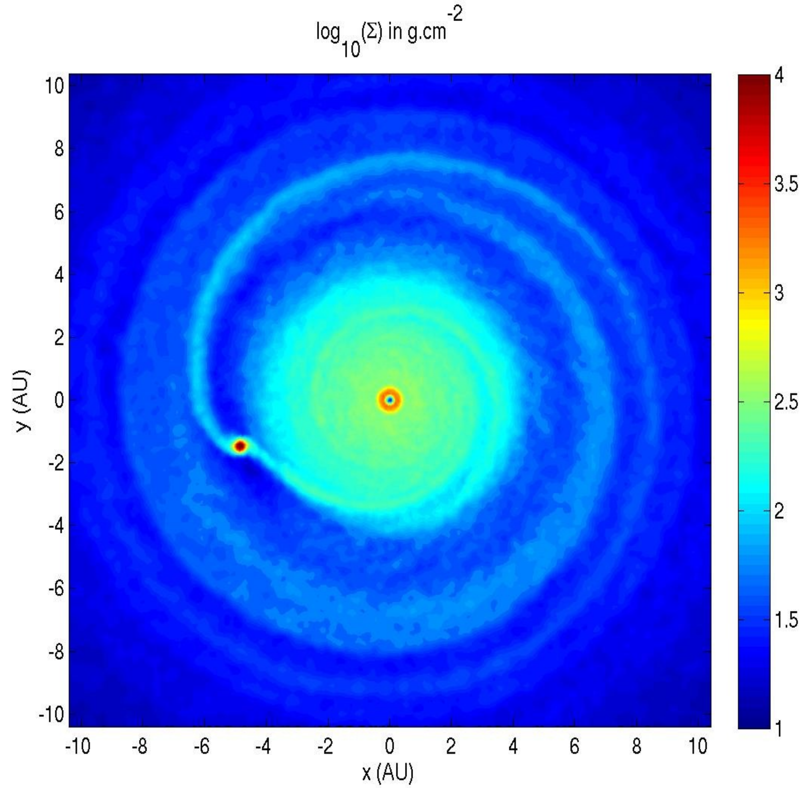
Results

Comparison transfer/isothermal (density)

Transfer, 17.5 orbits



Isothermal, 20 orbits

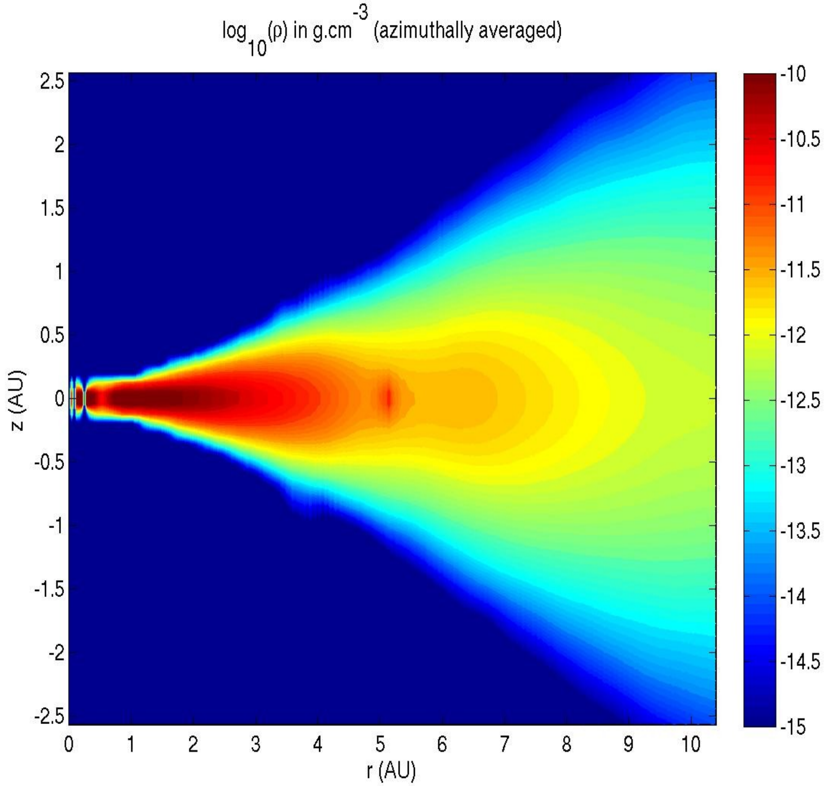


- Deeper gap in the isothermal case

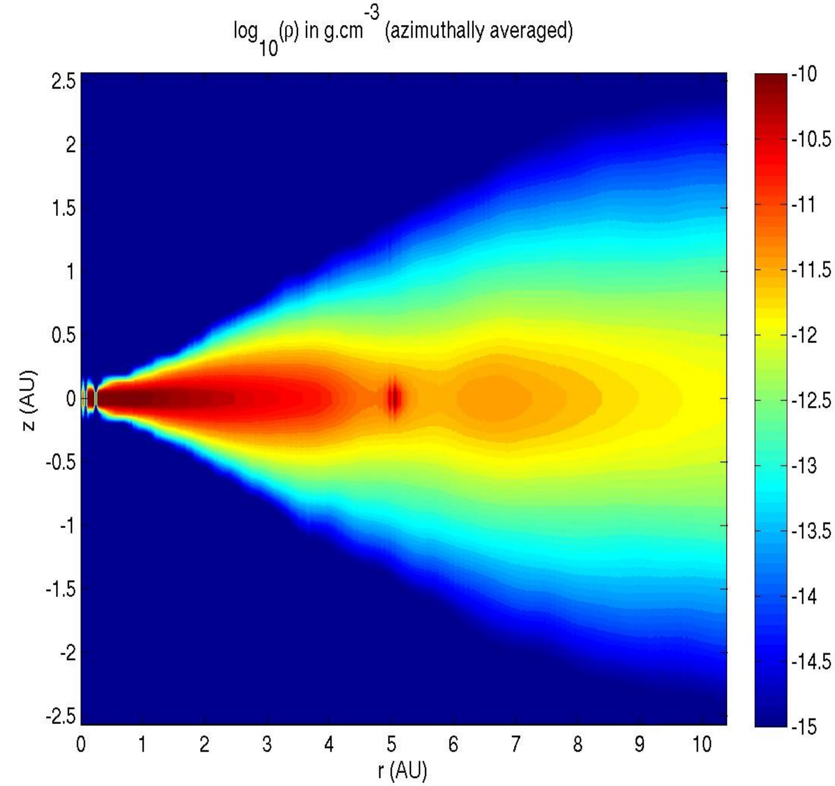
Results

Comparison transfer/isothermal (density)

Transfer, 17.5 orbits



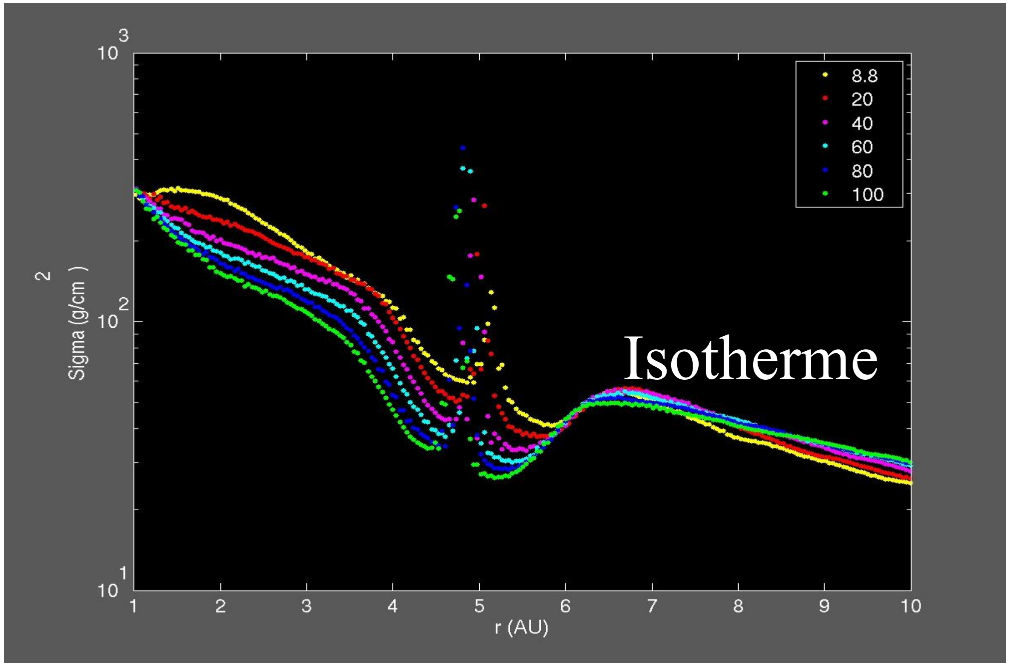
Isothermal, 20 orbits



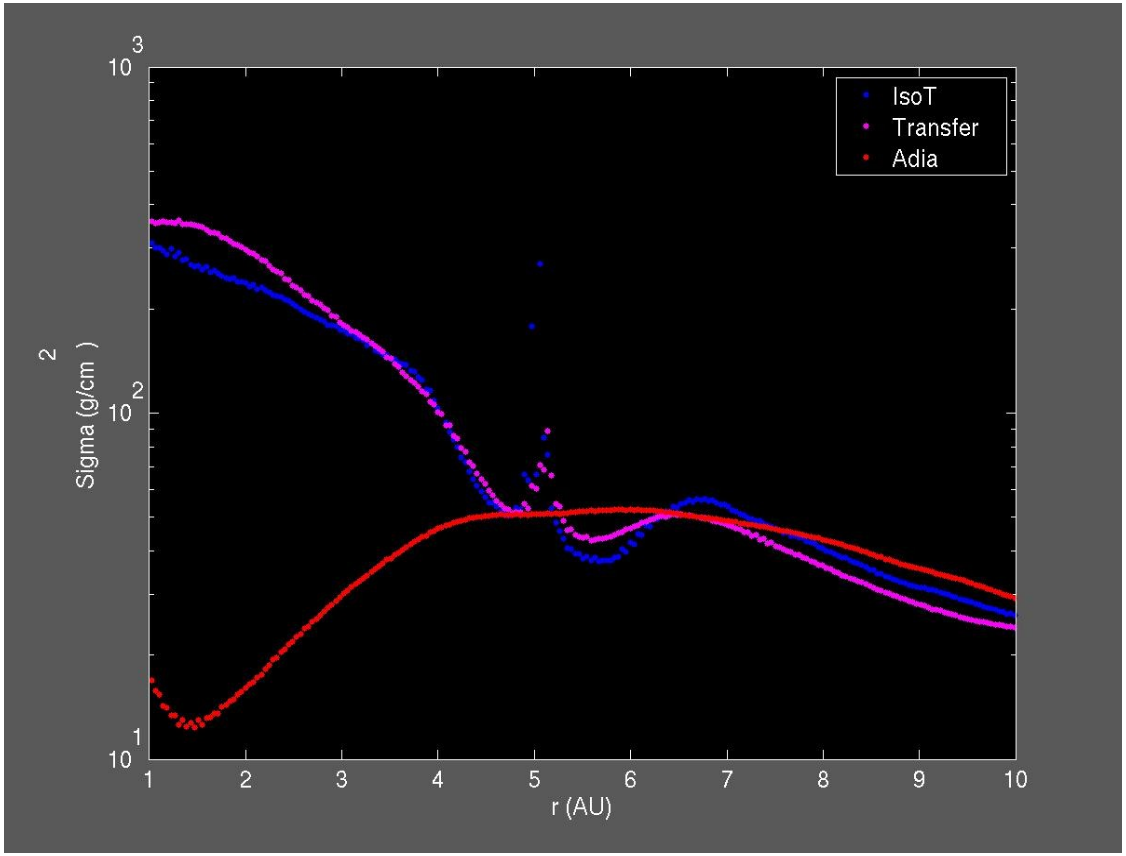
- Average scaleheight larger in the case with transfer. (Interplay between cooling and heating timescales)

Surface density

- Viscous disk => Gap shallower than in the inviscid case.
- => Coupling between planet and disk stronger than in inviscid calculation for Jupiter mass planets.



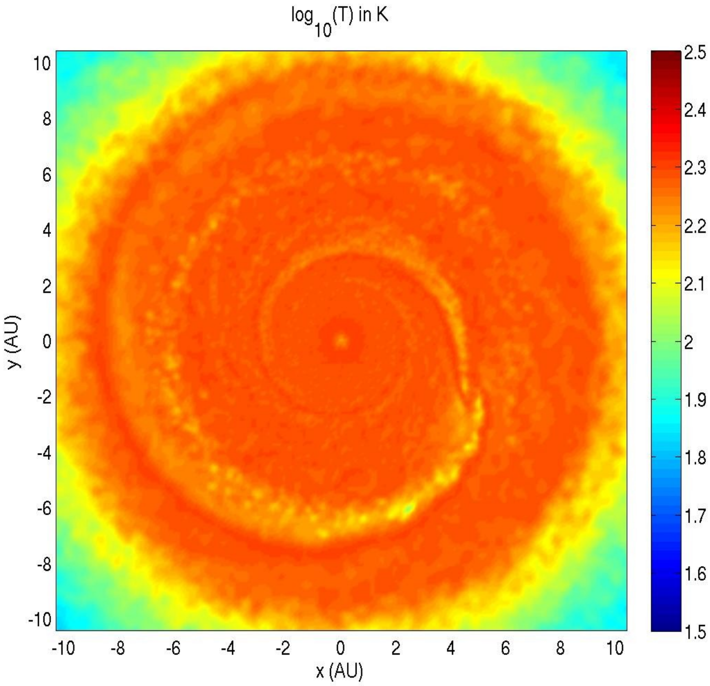
Results
Surface density (after ~ 20 orbits)



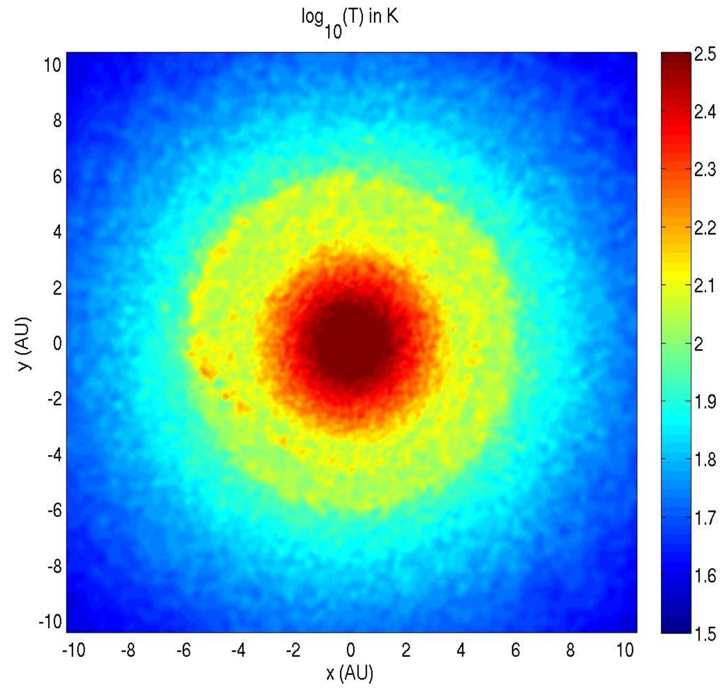
- Gap deeper in the isothermal case than in the transfer one. Inexisting in the adiabatic case.

Results
Comparison transfer/isothermal (temperature)

Transfer, 17.5 orbits



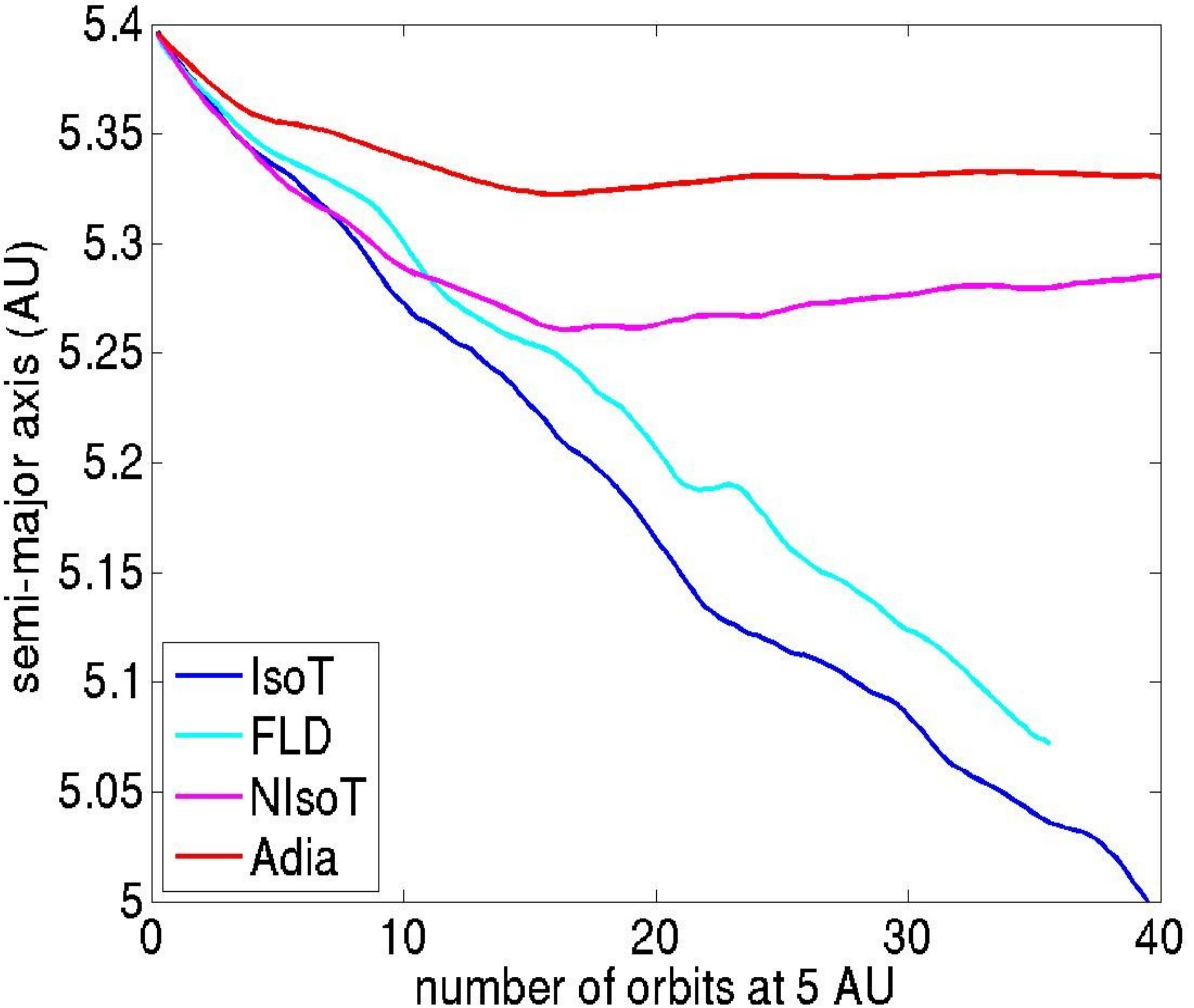
Isothermal, 20 orbits



- Cs and spiral arm opening

Results
Migration rates

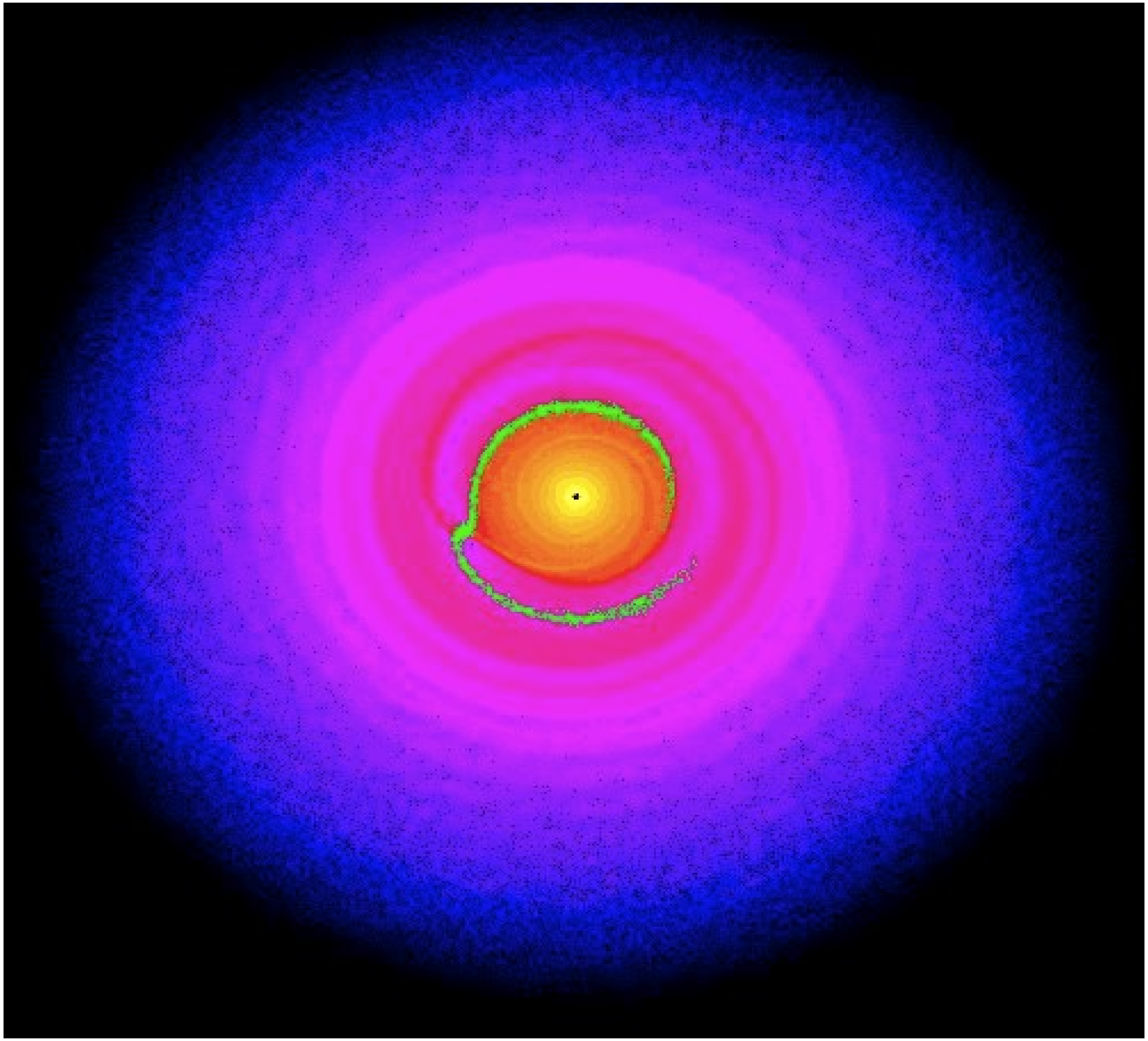
- Isothermal migration : timescale: 3 10^4 yrs compared to 8 10^4 yrs for non SG inviscid with fixed planet (Papaloizou et al. 2007, PPV)
- *Adiabatic* : migration strongly slown down
- Radiative Transfer : sligthly slower 30% effect



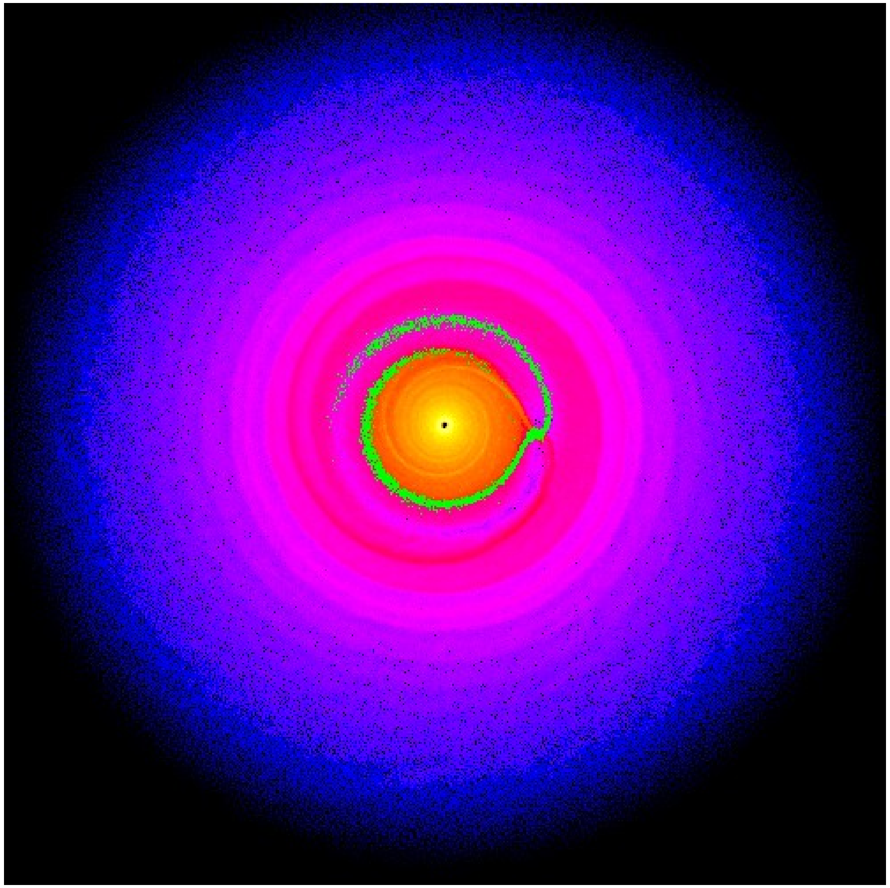
Results
Migration rates

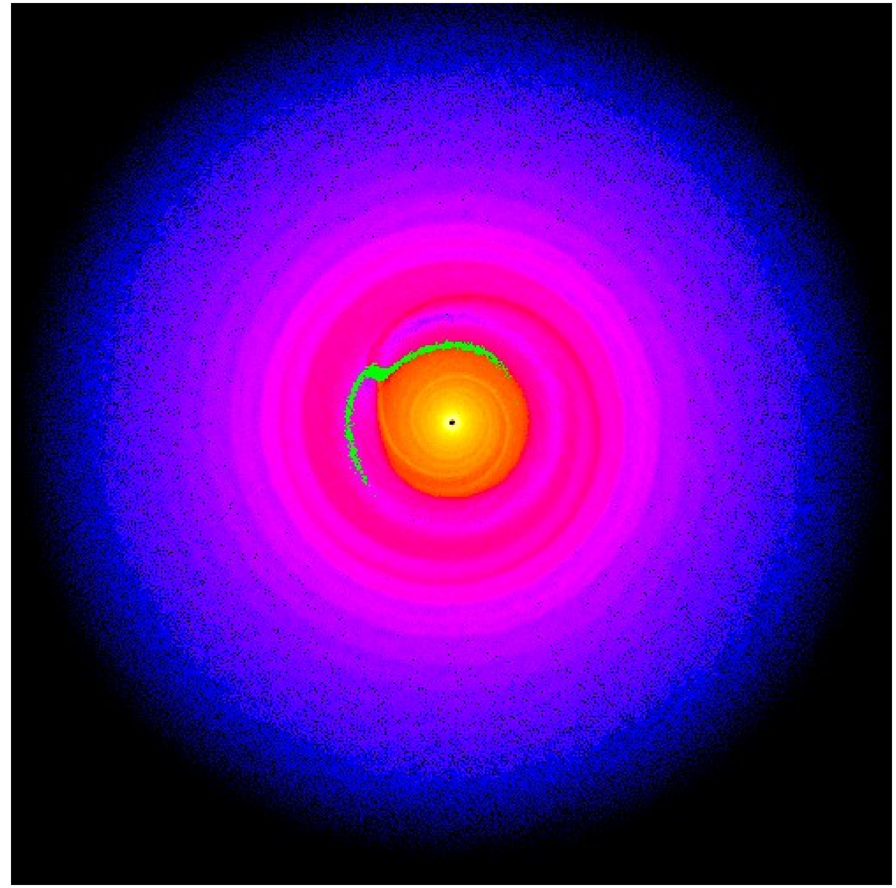
- In the transfer and adiabatic cases
  - gas heated by shocks
  - gas scaleheight increases at the location of the planet → more difficult to open a gap
  - adiabatic case, surface density drop → slow down of migration
  - Entropy related torque (Paardekooper & Mellema 2008)
  - Resolution effects : at low resolution, the shock heating is amplified because it is “spread” over larger distances. Important in adiabatic case (extreme), less important for transfer or isothermal.

Results
Mass feeding Maps



Results
Mass feeding Maps



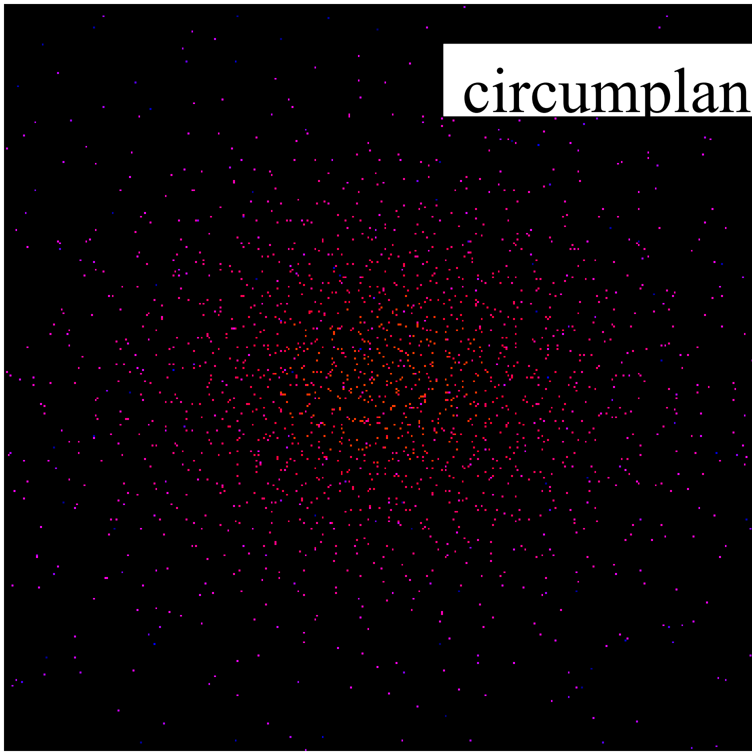


Mass stops at the scale comparable to the gravitational softening of the planet

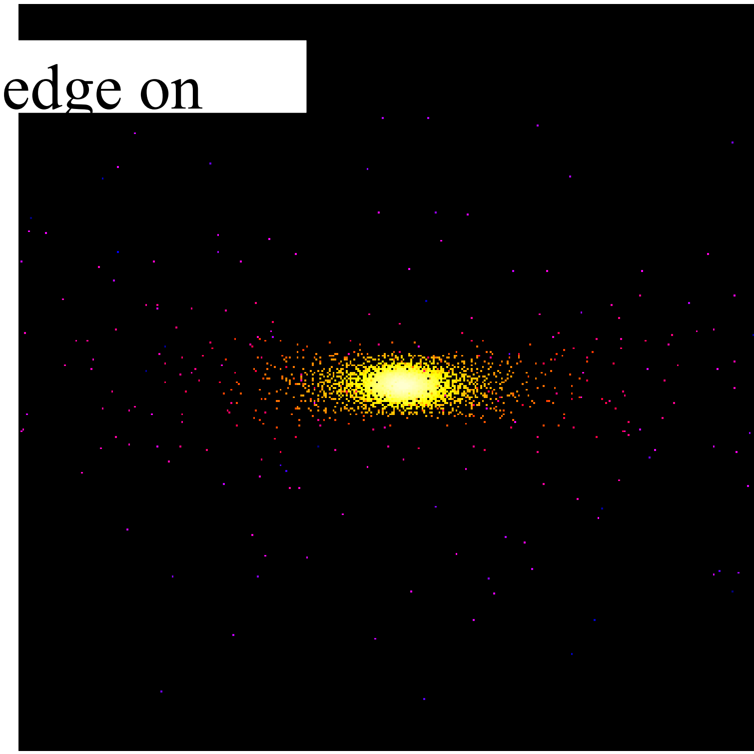
Results

Accretion on the planet : softening

circumplanetary disk seen edge on



Isothermal



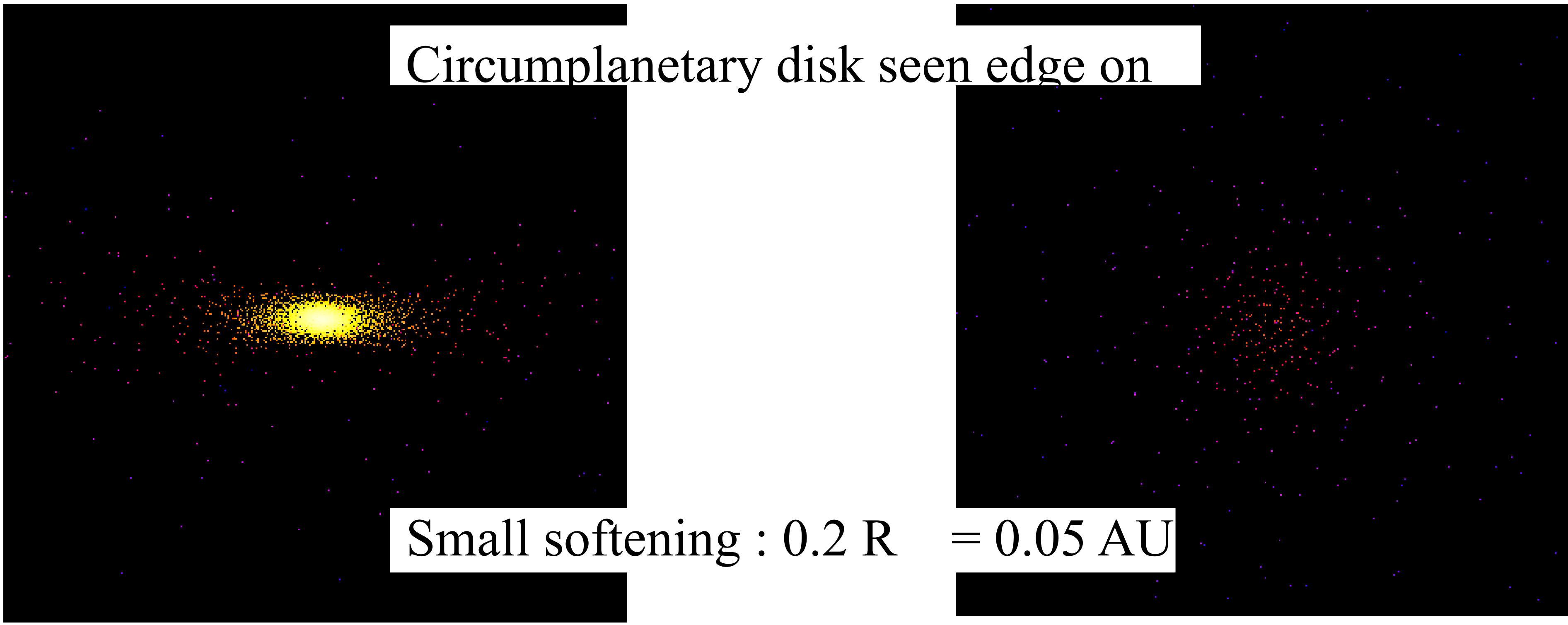
Large softening : 1 R_{Hill}

Small softening : 0.2 R_{Hill}

- Importance of resolution. Formation of a circumplanetary disk.

Results

Accretion on the planet : equation of state



Isothermal

$_{hill}$

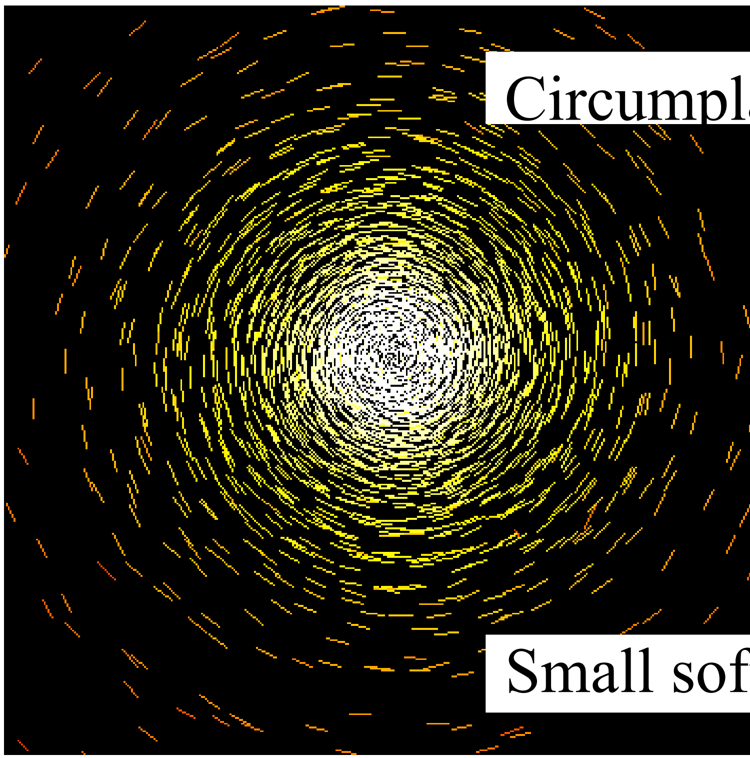
Adiabatic

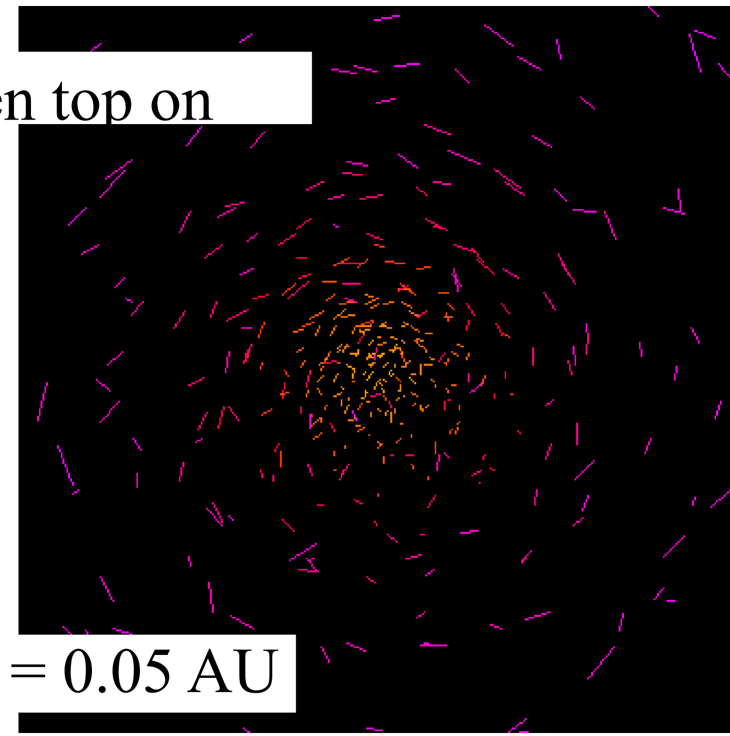
- No disk but a buble in the adiabatic case even with the small softening

Results

Accretion on the planet : equation of state

Circumplanetary disk seen top on





Small softening : $0.2\ R_{hill} = 0.05$ AU

Isothermal

Adiabatic

- Isothermal : keplerian velocity field
- Adiabatic : subkeplerian velocity field

Perspectives
Formation of planetary satellites

- Next step : particle splitting at the location of the planet, resolution eq 10^7 particles to study accretion
- According to Klahr, Kley (2006)
  - 3D, AMR, radiative transfer, low resolution simulations.
  - No circumplanetary disk but rather spherical envelope.
  - Strongly sub-keplerian velocity field ➔ rain down of solid particles at the surface of the planet.
  - ➔ Impossible to form satellites (at this moment).

Conclusions

- Planetary migration very well studied in a defined frame: 2D, locally isothermal, inviscid, fixed mass of the planet, fixed orbit.
- Lots of variations when one plays with these parameters.
- BUT, the overall migration rate is within a factor 2 to 4 of "standard" studies.
- The "problem" of the too fast migration of protoplanetary cores is certainly only theoretical.