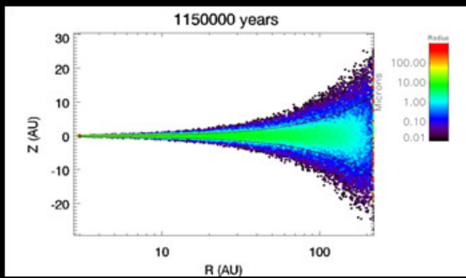
Coupling dynamical and collisional evolution of dust in protoplanetary & debris disks



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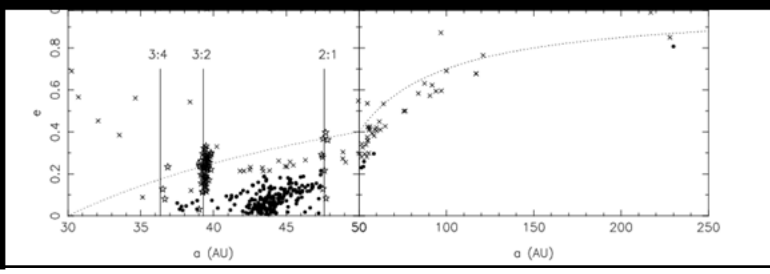
ANR DUSTYDISK

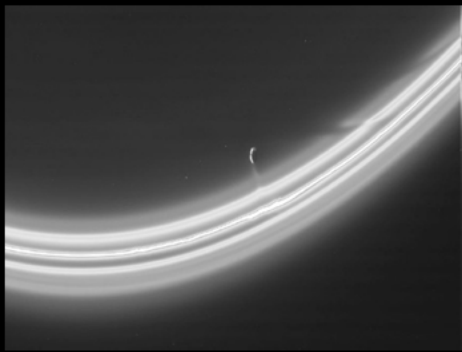
Coupling dynamics and collisional evolution is a general problem that touches many different problems

Evolution of asteroid belt

Evolution of Kuiper Belt

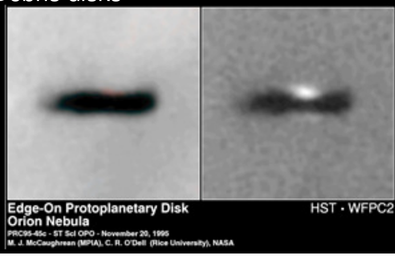


Evolution of faint planetary rings (⇔ debris disks)

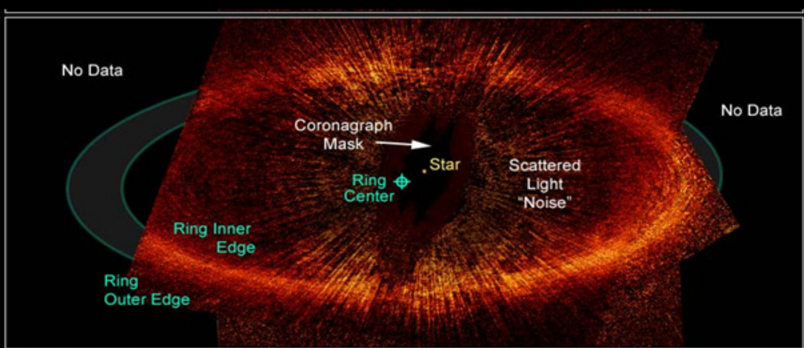


Saturn's F ring

Evolution of PP disk and Debris disks

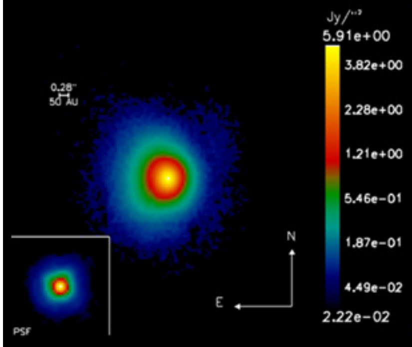


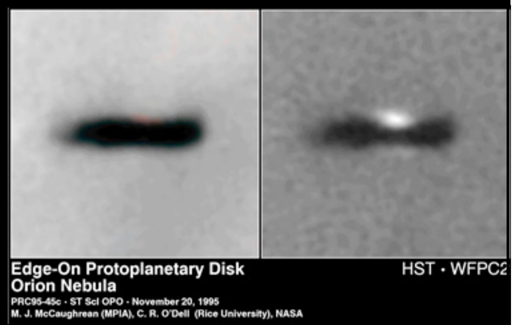
Evolution of debris disks



Protoplanetary disks :
Gas rich disk with micron-sized dust

Canonical : dust/gas ratio ~ 1%



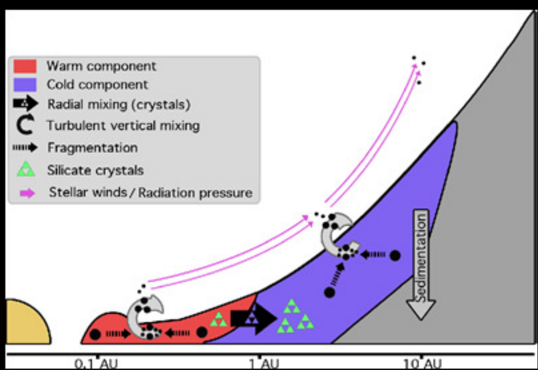


HD97048
Lagage et al., 2007

Dust : a complex dynamics in gaseous disk

dust-gas interactions =>
•sedimentation toward the midplane
• migration toward the protostar
• stirred vertically and radially due to MHD turbulence

dust-gas interactions =>
•Collisions+fragmentation +coagulation



Olofsson et al., 2009

Radial and vertical structuration of the disk

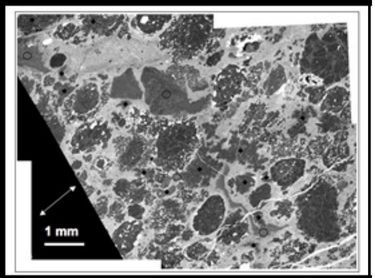
Need for a 3D transport model of dust in P.P. disks

Our Solar System

Isotopic abundancs constrains local
Chemical and thermodynamical conditions
And conditions of meteorites formations

Transport of different isotopic species from
Their respective reservoirs

STARDUST results on transport of cristalline
Silicates (Cf. O.Mousis' talk)



Efremovka Meteoorite
Chondrites : agregates of dust

What is the typical path of a grain in th gaseous nebula ?

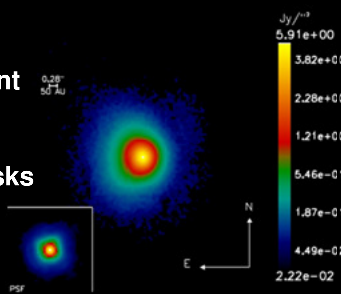
What are the presure/temperature conditions experience by a grain along
Its life in a disk ?

Circumstellar disks

Multiwavelength constrains on the dusty content
(Imagery and spectoretry)

=> Sensitive to radial & Vertical structure of disks

BUT



Lagage et al., 2010

⇒Reconstructing the structure is a degenerated inverse problem
Needing strong hypothesis on the size distribution of dust

What is the radial and vertical distribution of dust (R,Z)
?
What is the size-distribution ?

Representation and physics to include

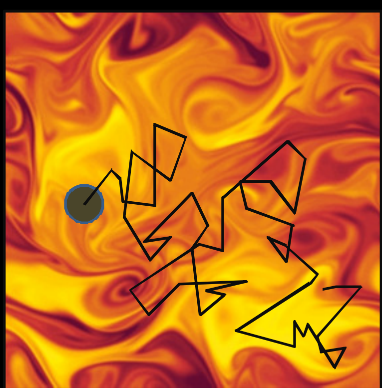
A) Capacity to « follow » individually the dust's path:
=> Lagrangian approach with an implicit solver for stability

B) Physics

- sedimentation (Gas. Drag) ✓ (cf. Brauer et al., 2008)
- radial migration (Gas.drag) ✓ (Dullemond, Dominik etc..)
- Turbulent stirring of dust
- Collision, fragmentation, coagulation

Model of turbulent transport

Taking into account of turbulent diffusion



Ideally :
Coupling a real 3D HD code (ZEUS 3D)
With a dust transport model

BUT : too numerically intensive
Only a few 100-1000 orbits may be simula

(cf. Fromang & Nelson 2009)

Stochastic model of turbulent transport

Turbulence = random forcing of dust

PROBLEM :how to compute a « good » random variable ?
⇒Satisfiesthe « good mixing » conditions
⇒Calibrate on 3D MHD numerical simulation

$$\vec{F} = -\frac{GM_* m}{r^3}\vec{r} + \frac{m}{\tau_s}\left(\vec{v} - <\vec{v}_g>\right) - \frac{m}{\tau_s}\left(\delta\vec{v}_g\right)$$

Average mean transport

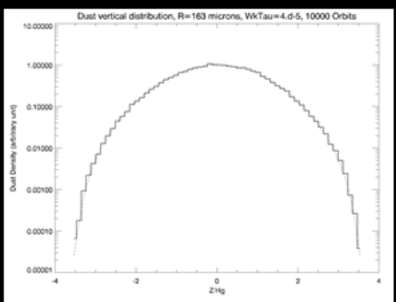
Turbulent diffusion

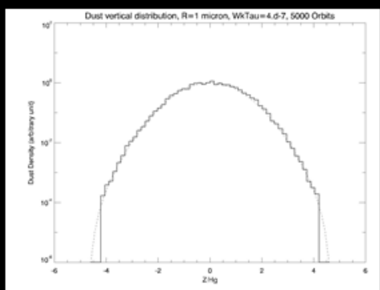
Construction d'un bonne variable Aléatoire (Charnoz , 2010) pour Simuler la turbulence

Test of the lagrangian turbulent algorithm agains Known solutions

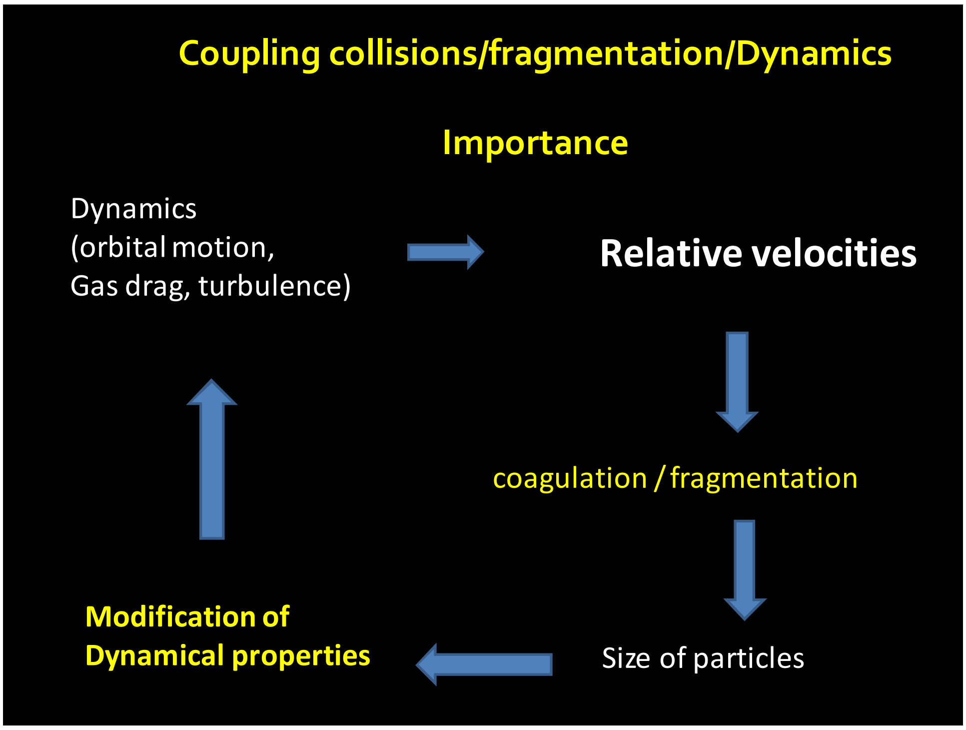
Equilibrium vertical distribution of particles : Constant Diffusion Coefficient

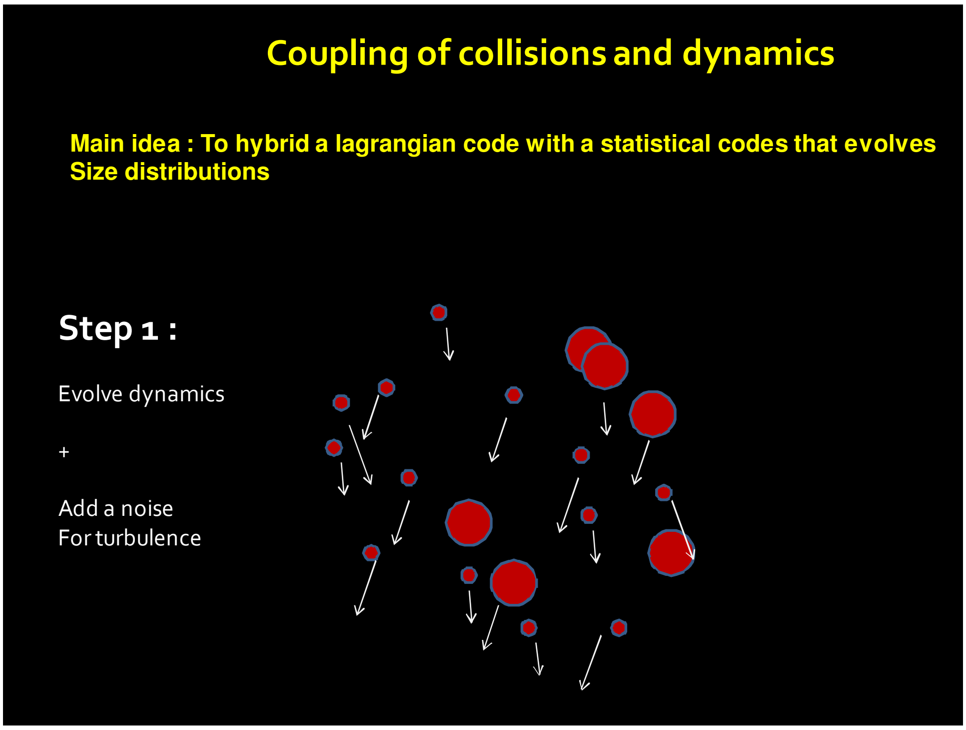
$$\rho_d = \rho_{d,mid} \exp\left[-\frac{(\Omega\tau_s)_{mid}}{\tilde{D}}\left(exp\left(\frac{Z^2}{2H^2}\right) - 1\right) - \frac{Z^2}{2H^2}\right]$$





Excellent match with theoretical models


Coupling collisions/fragmentation/Dynamics
Importance
Dynamics
(orbital motion,
Gas drag, turbulence)
Relative velocities
coagulation / fragmentation
Size of particles
Modification of
Dynamical properties


Coupling of collisions and dynamics
Main idea : To hybrid a lagrangian code with a statistical codes that evolves
Size distributions
Step 1 :
Evolve dynamics
+
Add a noise
For turbulence

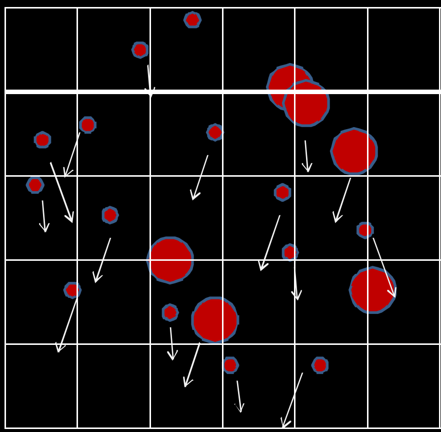
Step 2 :

Project on a grid

+

Compute local
Random velocities

<V> and <ΔV²>

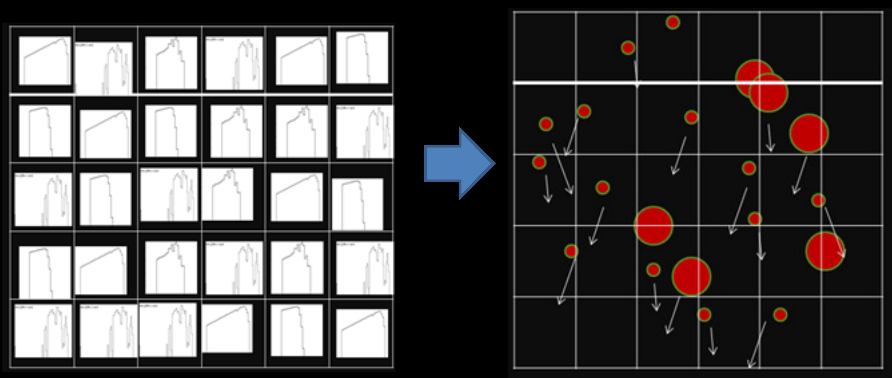


Step 3

Evolve size distributions in each cell

STEP 4:

Reproject the grid on a system of particles



COAGULATION MODEL :

VERY SIMPLE

FRAGMENTATION MODEL :

VERY SIMPLE

THE SAME AS THOSE USED FOR ASTEROIDS / KBO EVOLUTIONS

First examples of use

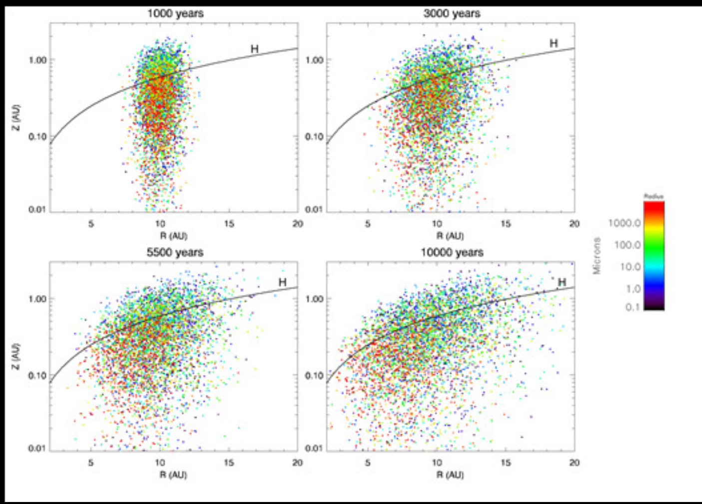
1) Turbulence only: Circumstellar disks

2) Local simulation Coagulation/Fragmentation/Dynamique :
Vertical structure of disk TW Hydra
Comparison with turbulence only

3) Global simulation Coagulation/Fragmentation/Dynamique
TW Hydra

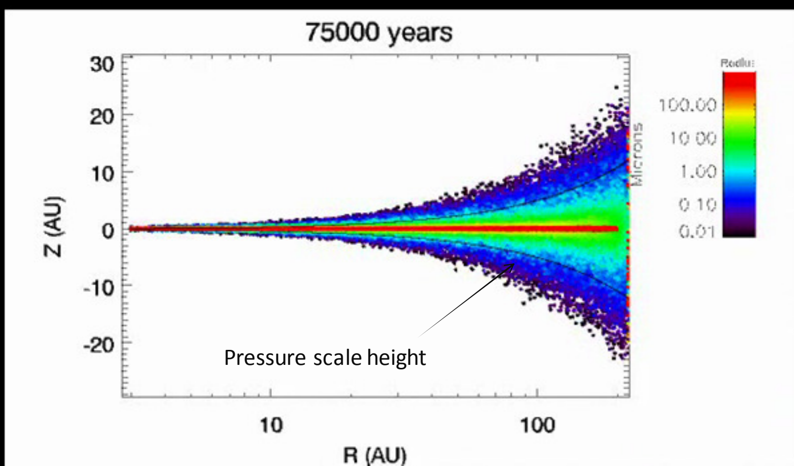
First examples of use

Dust diffusion with turbulence only



Exemple 1 :
TURBULENCE Only

DUST : Sedimentation + MHD turbulence



Particles ' sizes extend
From 0.01 miconrs
To 100 microns

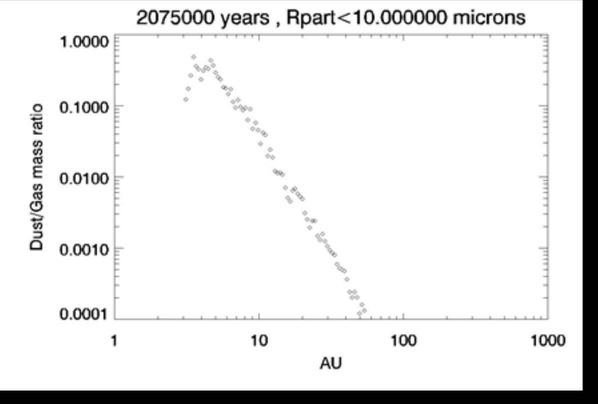
200 K particles

Particles > 80 microns
Are cleaned rapidly
From the disk

Evolution of dust/gas mass ratio,

starting with a distribution dn/dr= K $R^{-3.5}$

Initial : D/G =0.01 , Particle < 10 microns

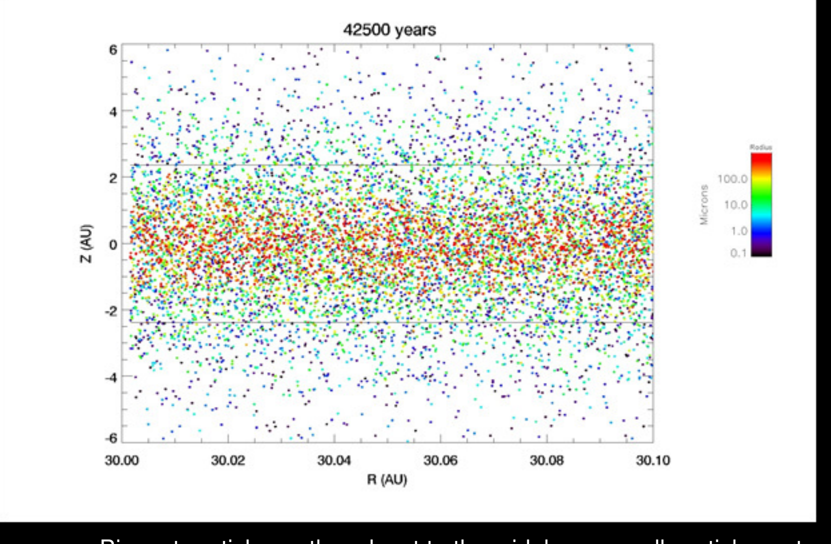


Enhencement of
D/G ratio at small radii

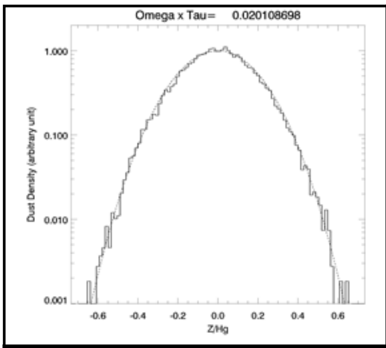
Depletiion of the outer regions

⇒Very good to trigger
⇒Planetesimal formation
⇒At small radii

2nd EXAMPLES : Vertical structuration
A) turbulence, no fragmentation



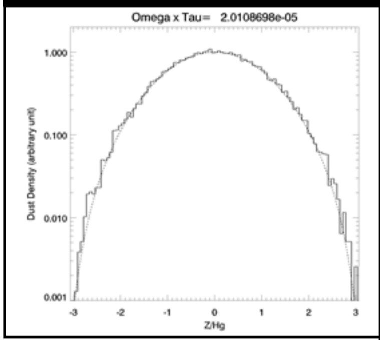
Biggest particles gather closet to the midplane , small particles get
High above in the disk



Vertical distribution

Turbulence (but no fragmentation)

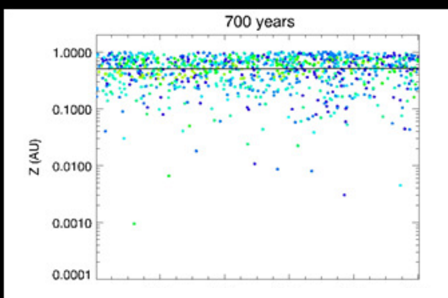
R=100 microns



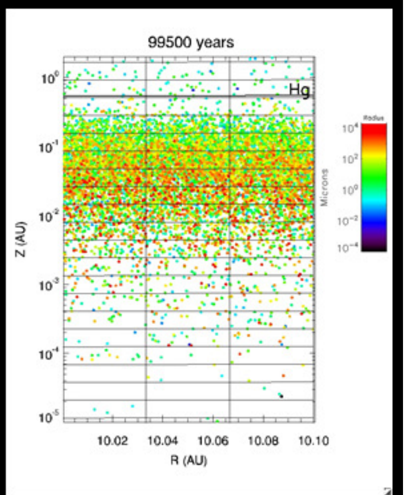
R=0.1 microns

B)TURBULENCE + FRAGMENTATION + COAGULATION

=> Vertical distribution of dust

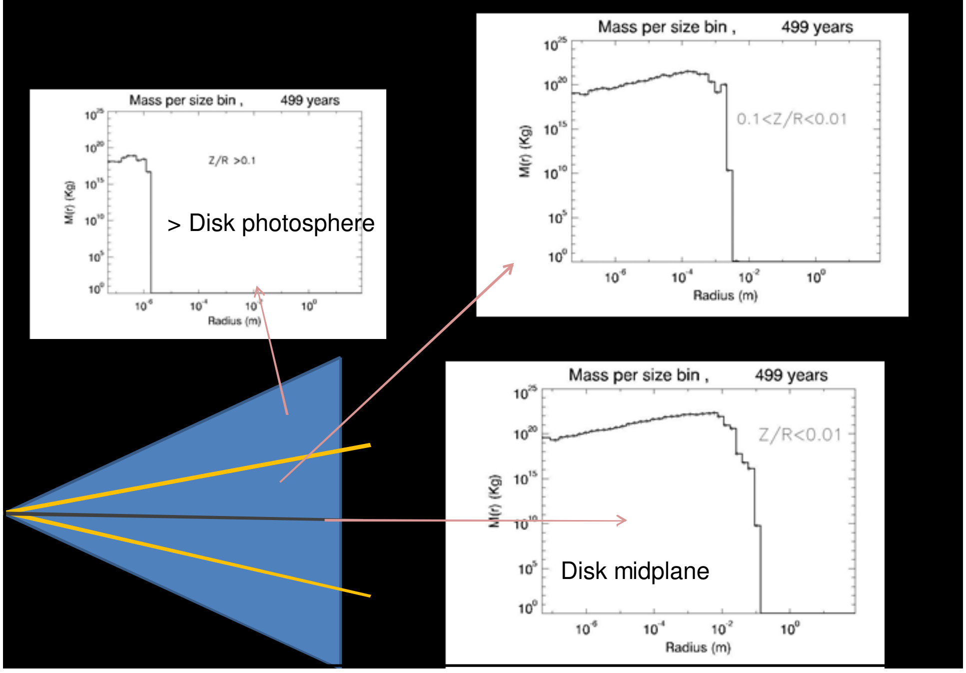


Distribution verticale des particules



ACCRETION + FRAGMENTATION

Vertical Sorting of particles



Compares very well with Brauer et al., 2008, Birnstien et al. 2010

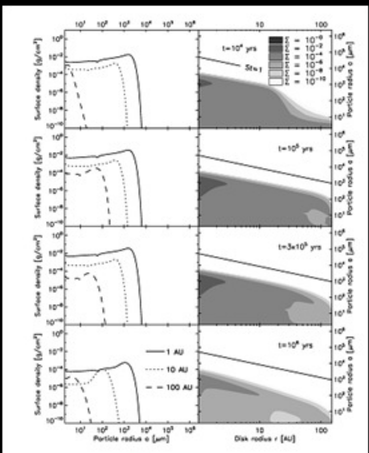
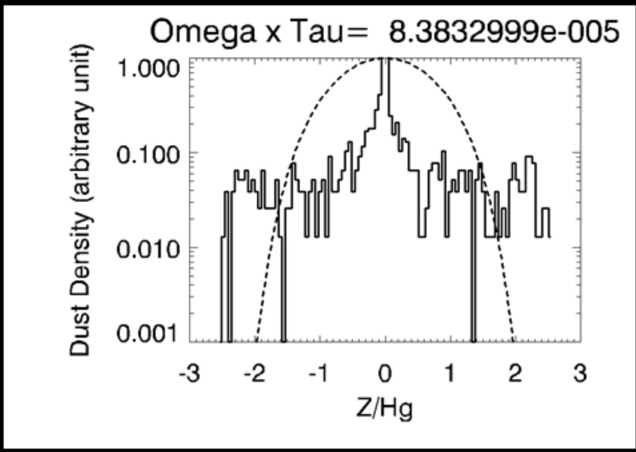
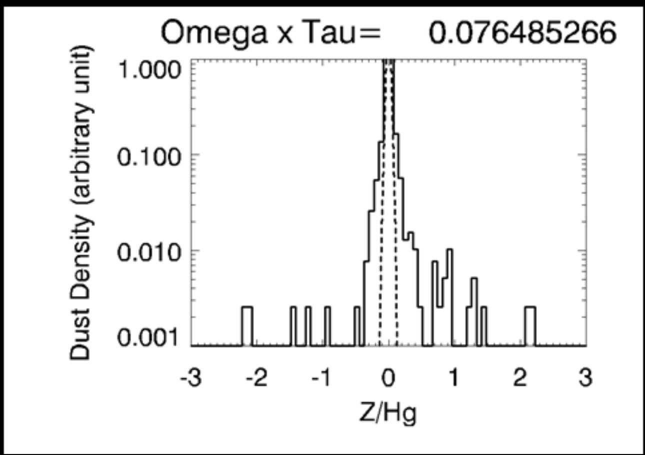


Fig. 13. As Fig. 7 but now also the fragmentation of particles is included in the simulations as discussed in Sec. 3.3.1. The left column shows the surface density as a function of particle radius at 1, 10 and 100 AU. The right column shows the corresponding contour plots of the surface density as a function of disk radius and particle size.

Dust is mainly produced in the midplane
And vertically transported by turbulence

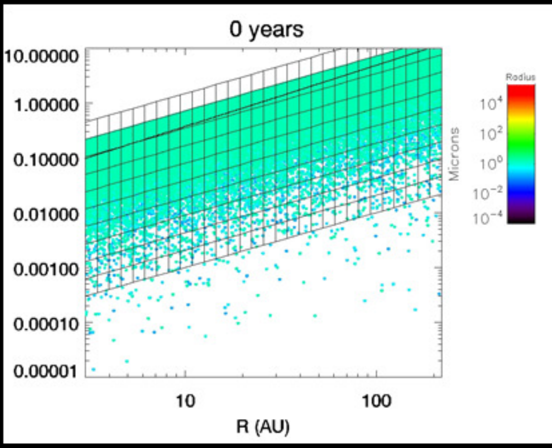


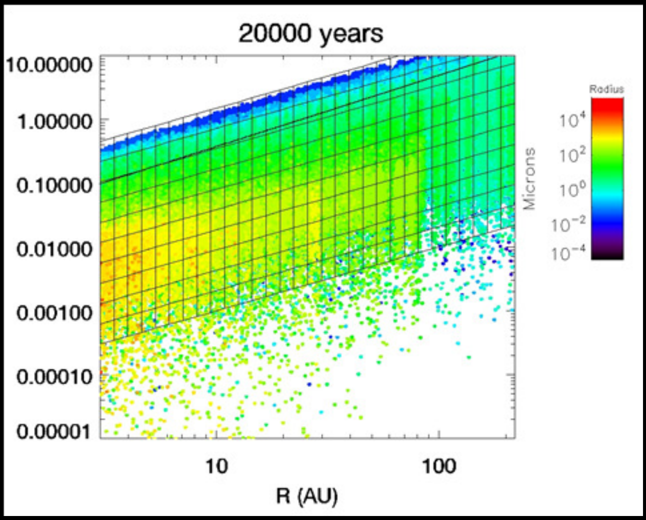
Big particles are produced in the midplane also

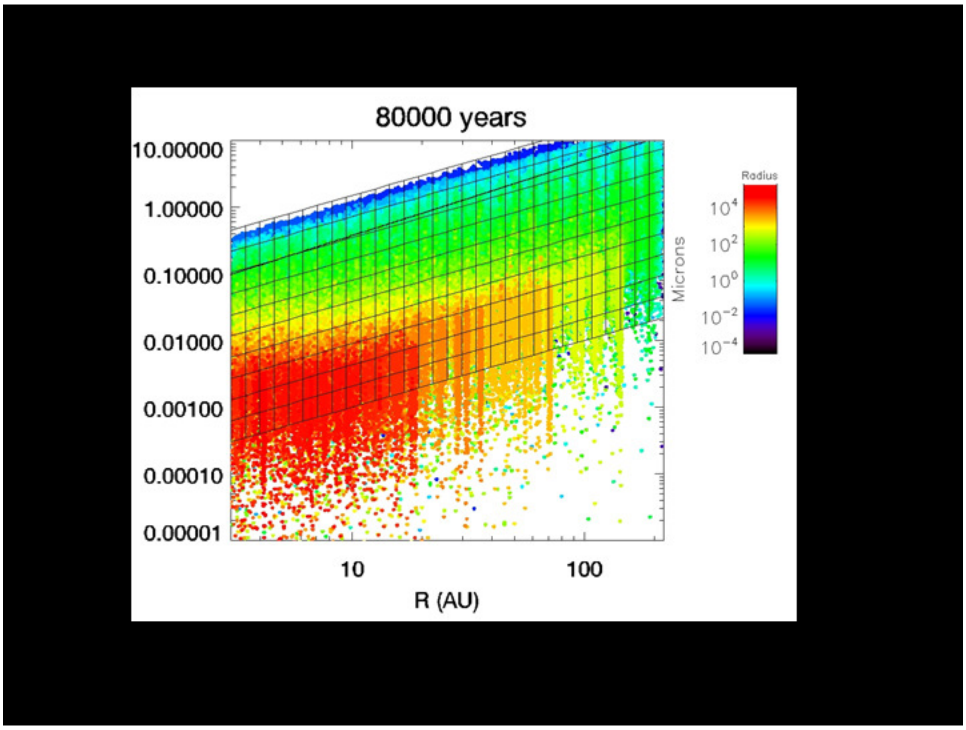


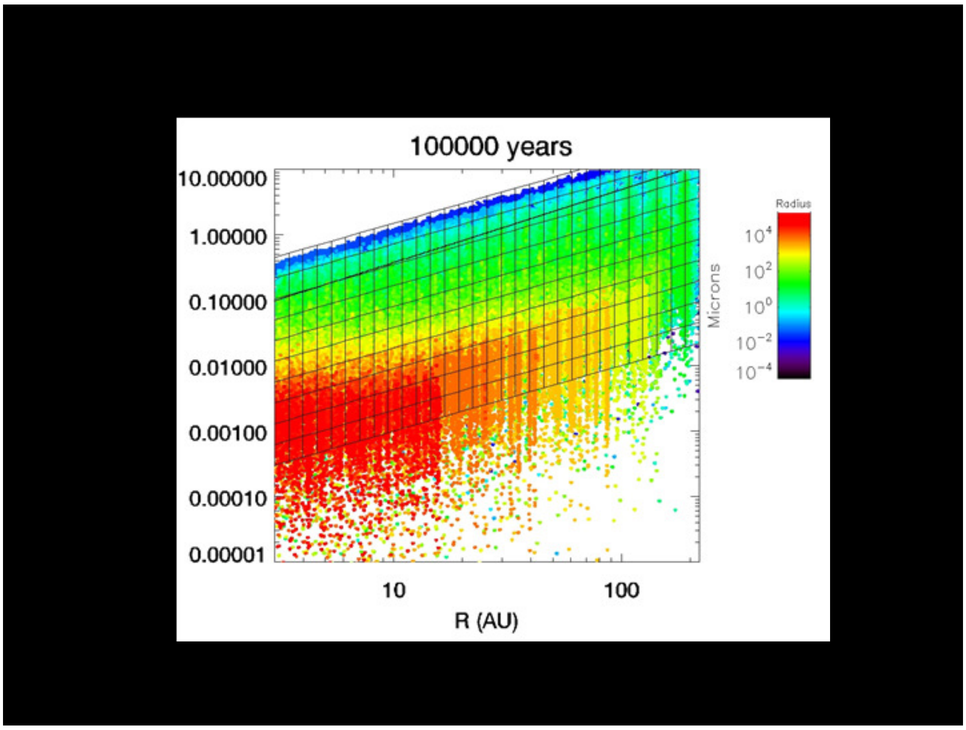
Exemple 4 : FULL DISK(TW HYDRA)

COAGULATION + TURBULENCE + FRAGMENTATION





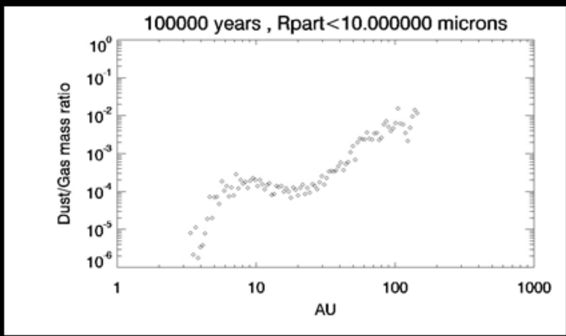

80000 years
10.00000
1.00000
0.10000
0.01000
0.00100
0.00010
0.00001
10
100
R (AU)
Radius
10^4
10^2
10^0
10^{-2}
10^{-4}
Microns

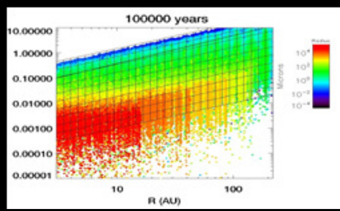

100000 years
10.00000
1.00000
0.10000
0.01000
0.00100
0.00010
0.00001
10
100
R (AU)
Radius
10^4
10^2
10^0
10^{-2}
10^{-4}
Microns

Mass of fine particules in the upper layers / mass of gas dis

⇒Signs of accretion ?

Evolution Dust/gaz ratio due to accretion





May does it serve as a test of coagulation ?

EXTENSION DO DEBRIS DISKS

No Gas

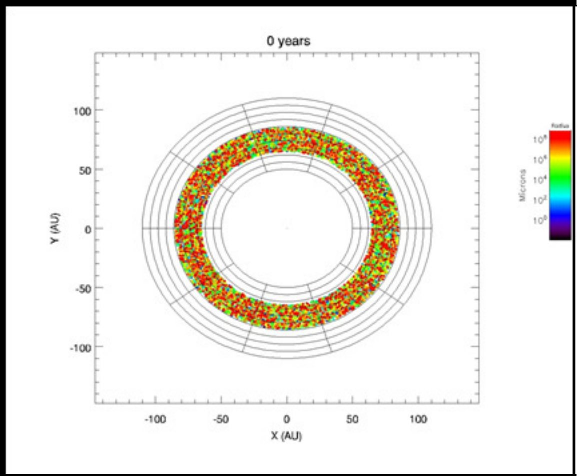
Radiation pressure

Poyting robertson drag

Main information is in the radial/orthoradial direction rather than in the Z direction

Modifications :

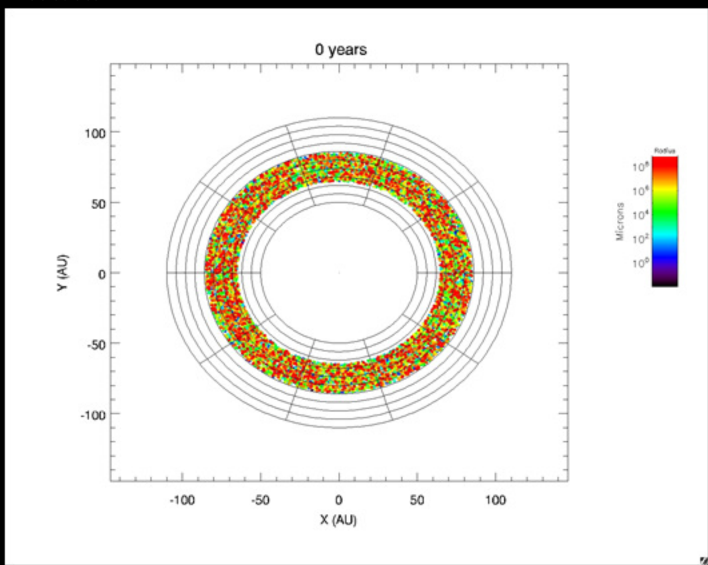
Use of a R/theta grid
rather than a R/Z grid

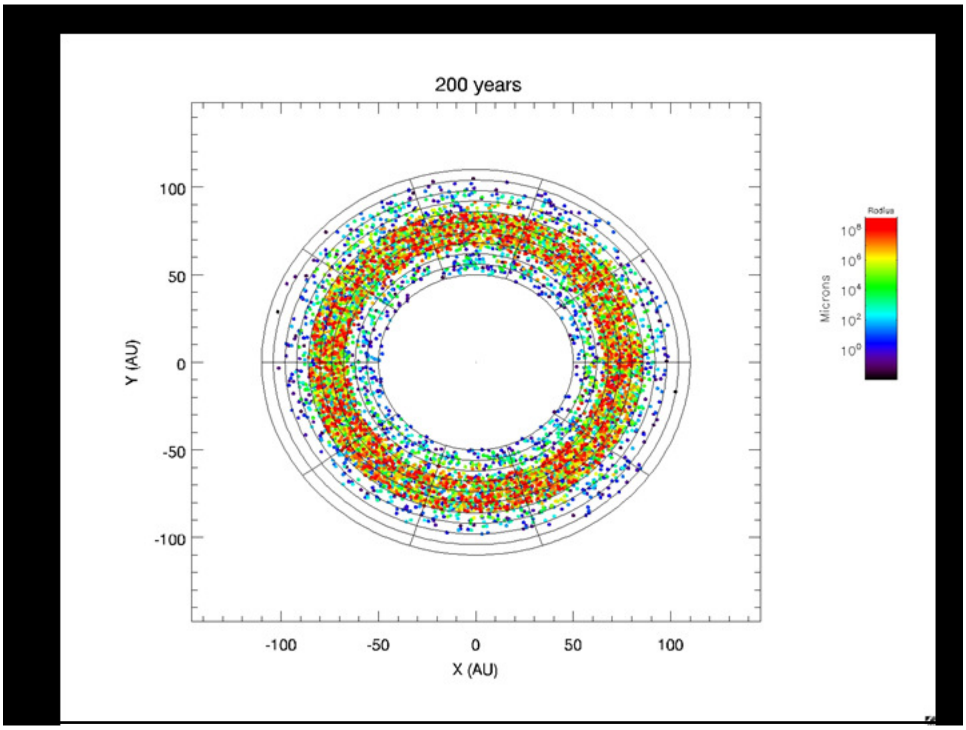


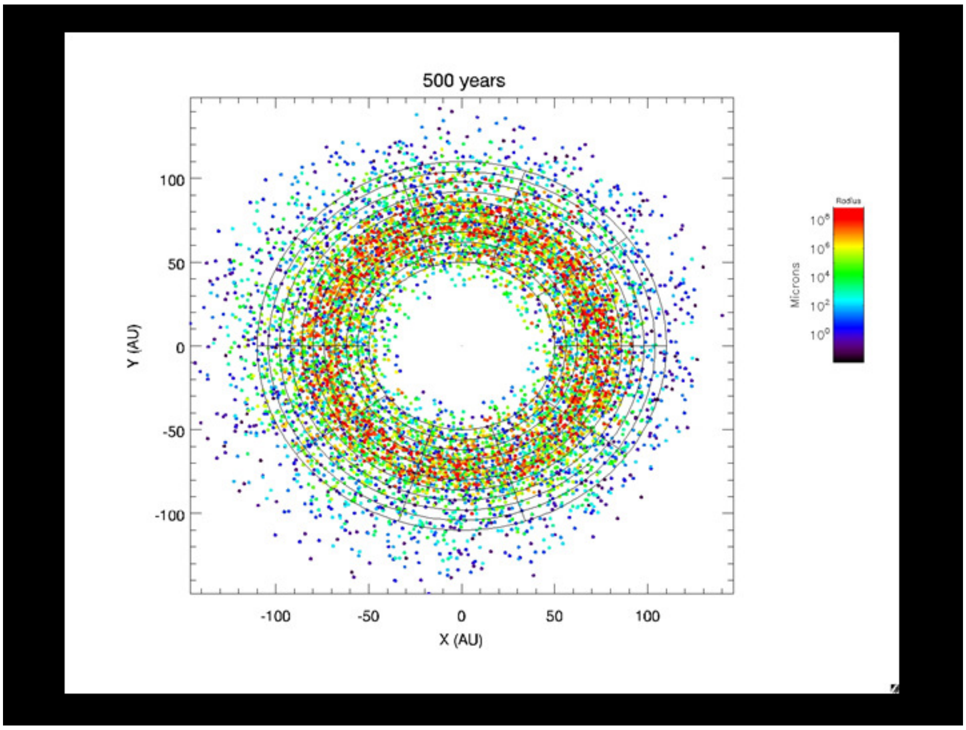
Advantage :
No necessity for
Azimuthal asymetry

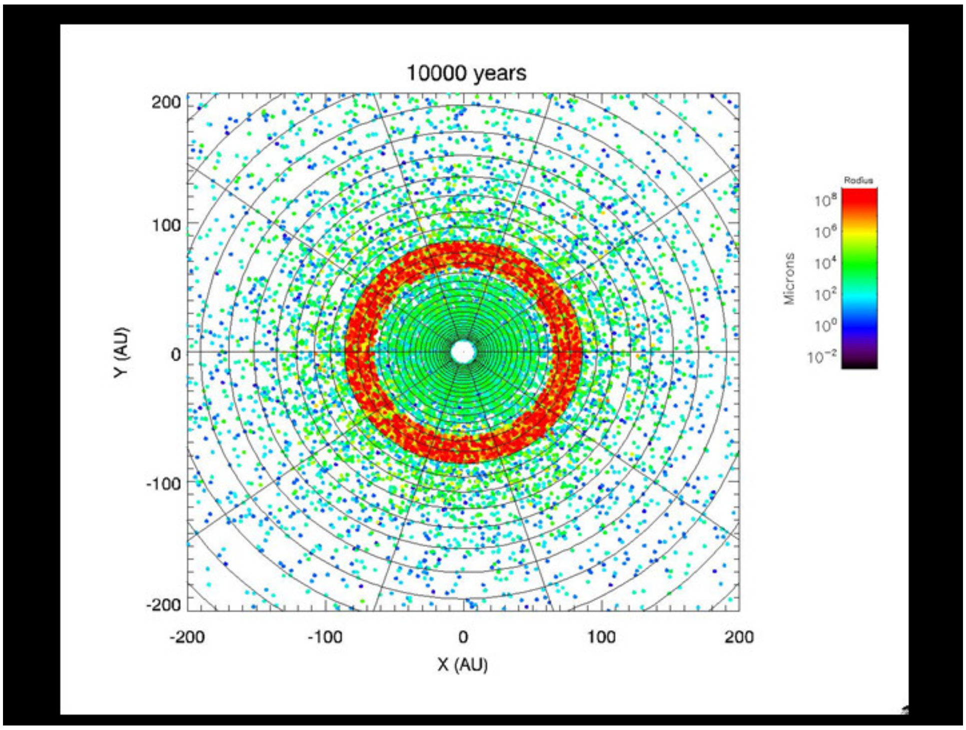
Grid rotating at the local
keplerian velocity
For a good statistics
Of local random
Velocities

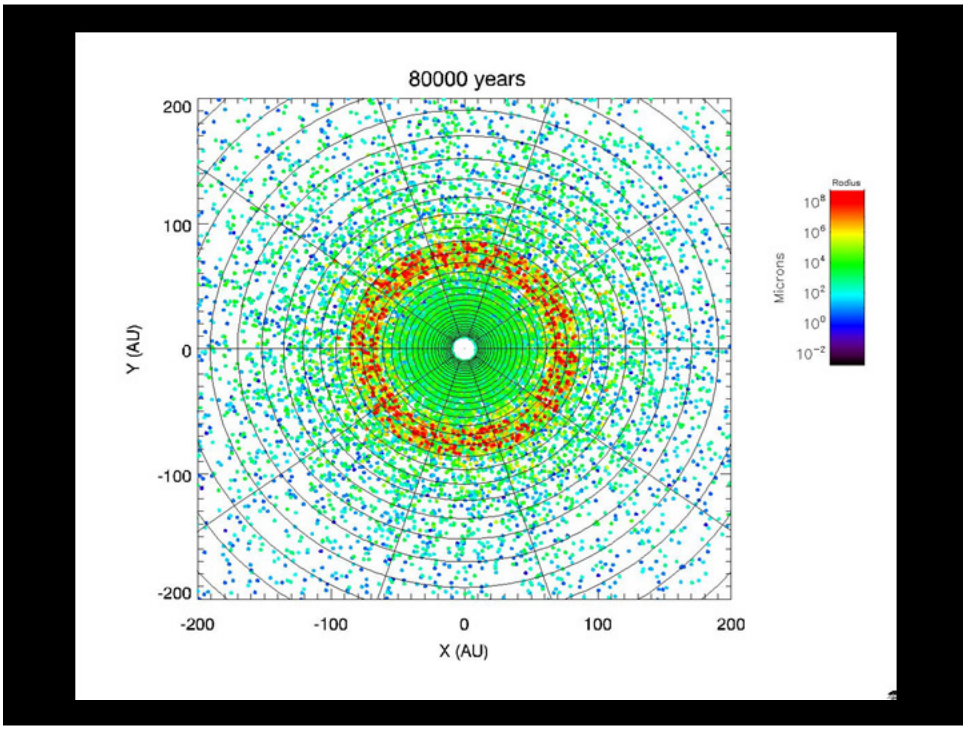
First tests :

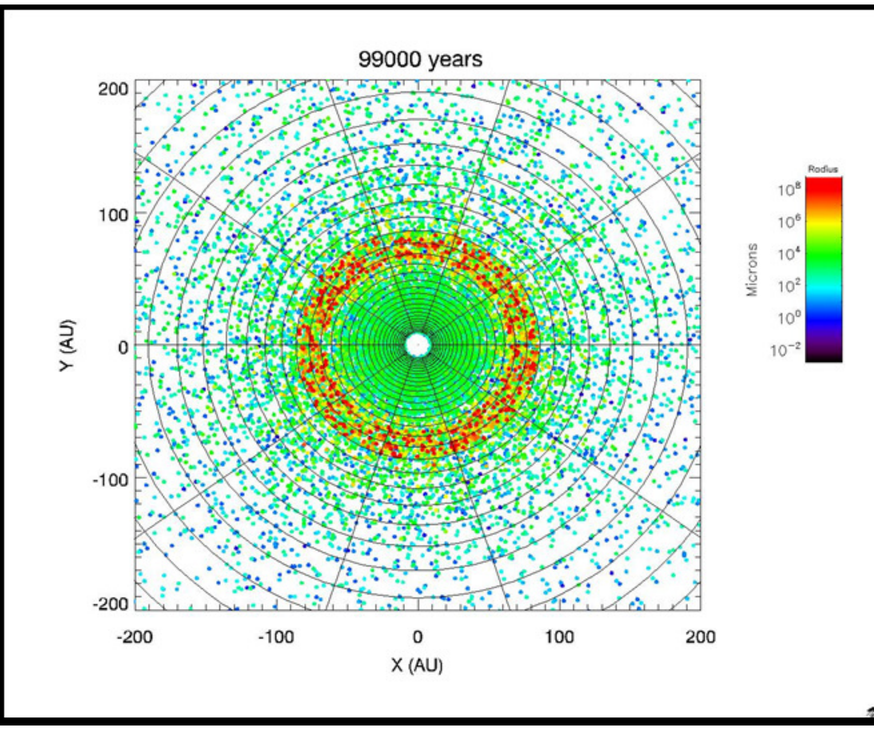



200 years
Y (AU)
X (AU)
Radius
Microns
10^8
10^6
10^4
10^2
10^0
100
50
0
-50
-100
-100
-50
0
50
100

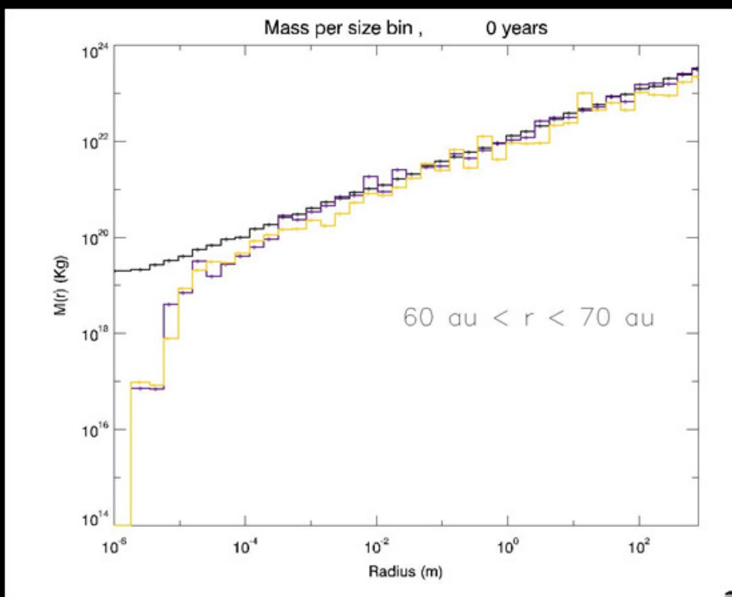

500 years
Y (AU)
X (AU)
Radius
Microns
10^8
10^6
10^4
10^2
10^0
100
50
0
-50
-100
-100
-50
0
50
100


10000 years
200
100
0
-100
-200
Y (AU)
-200
-100
0
100
200
X (AU)
Radius
Microns
10⁸
10⁶
10⁴
10²
10⁰
10⁻²


80000 years
200
100
0
-100
-200
Y (AU)
-200
-100
0
100
200
X (AU)
Radius
Microns
10⁸
10⁶
10⁴
10²
10⁰
10⁻²



First tests are encouraging … but still problem to be fixed



Still little problems in the collisional operator

⇒ Orbits of daughter particles from parent particles

INTEREST

POSSIBILITY TO INCLUDE PLANETS AND ARBITRARY PERTURBATIONS

NOT LIMITED TO BOUND ORBITS

CONCLUSION

Versatil tool

Dust vertical distribution may be very different
from collisional-less case

Dust abundance may be comparatively
very high in the midplane

Radial Dust/gas ratio might be used to infer
If either radial diffusion or fragmentation is active