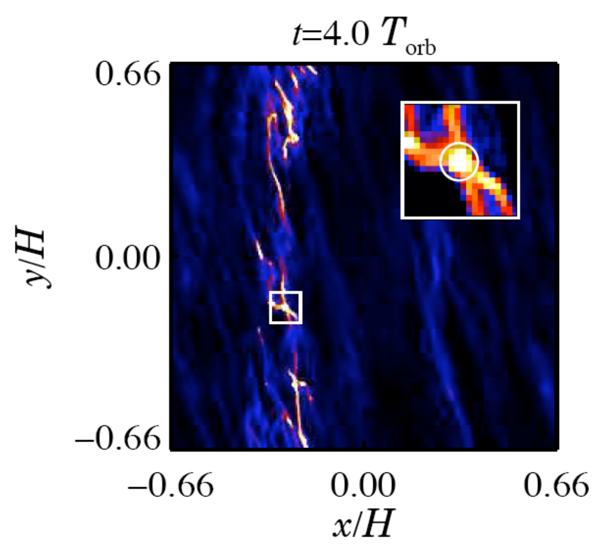
Santa Barbara,
Nov. 30th 2007



-Turbulence, Dust and Gravity-

“Gravoturbulent Formation of ~~Stars~~ oops: Planetesimals”

Hubert Klahr,
Max-Planck-Institut für Astronomie, Heidelberg

Anders Johansen (MPIA), Thomas Henning (MPIA)
Jeffrey S. Oishi (AMNH / U. Virginia), Mordecai-Mark Mac Low (AMNH / MPIA), Andrew Youdin (CITA)

Gravoturbulent star formation

- Dynamic approach to star formation:

Star formation is controlled
by interplay between
gravity and
supersonic turbulence!

- Dual role of turbulence:
  - *stability on large scales*
  - *initiating collapse on small scales*

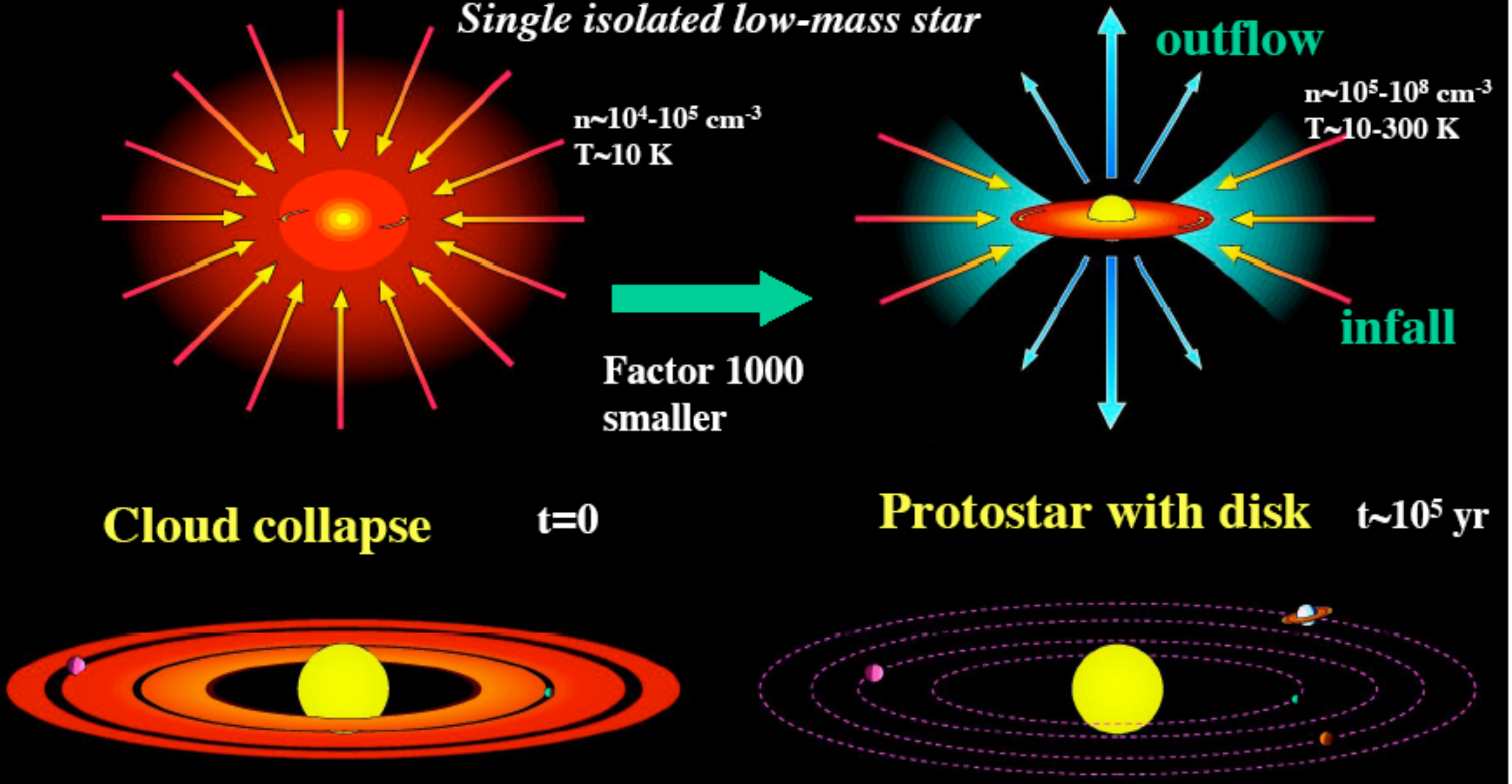
(full detail in Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194)

“from boulders to planetesimals: jumping the meter barrier by a giant leap.”

1. Dust, Gas and Turbulence.
2. Problems in Planetesimal Formation Theory.
3. The “ALL IN ONE SIMULATION” of Planetesimal Formation: “GRAVOTURBULENCE”
    - turbulence, size distribution,
    - self gravity of the boulders
    - including particle feedback on the gas
3. Simulation result: the direct formation of “Ceres” by collapse.
4. Discussion

Scenario for star- and planet formation

Single isolated low-mass star



n~10^4-10^5 cm^{-3}
T~10 K

Factor 1000 smaller

outflow

n~10^5-10^8 cm^{-3}
T~10-300 K

infall

Cloud collapse t=0

Protostar with disk t~10^5 yr

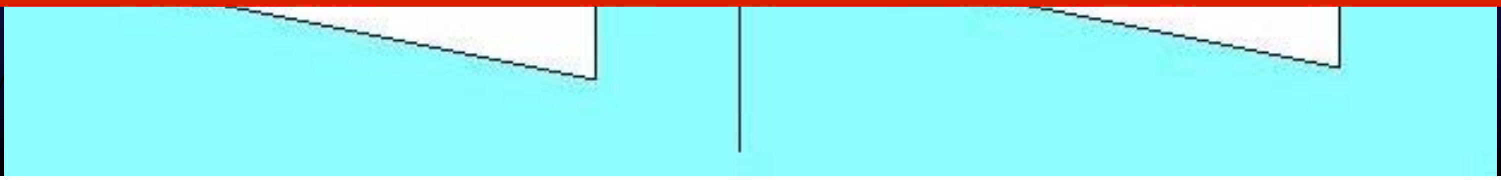
Formation planets t~10^6-10^7 yr

Solar system t>10^8 yr

Planetesimal Formation-
Coagulation and Sedimentation
Collissions & sticking OR self gravity

What is the influence of turbulence?

1. Preventing sedimentation by stirring things up. -> Observation
2. Radial diffusive transport of grains. -> Observation (crystalline)
3. Local concentration of boulders.
4. Generating collisions.
   -> Observation of debris



particles drift inward
= up the pressure gradient

$$\partial_t v_g = -\frac{1}{\rho}\nabla p + \mathrm{forces}$$

$$\partial_t v_d = -\frac{v_d - v_g}{\tau_f} + \mathrm{forces}$$

$$v_d = v_g + \tau_f \frac{1}{\rho}\nabla p$$

Klahr & Lin 2000

Klahr and Bodenheimer 2006

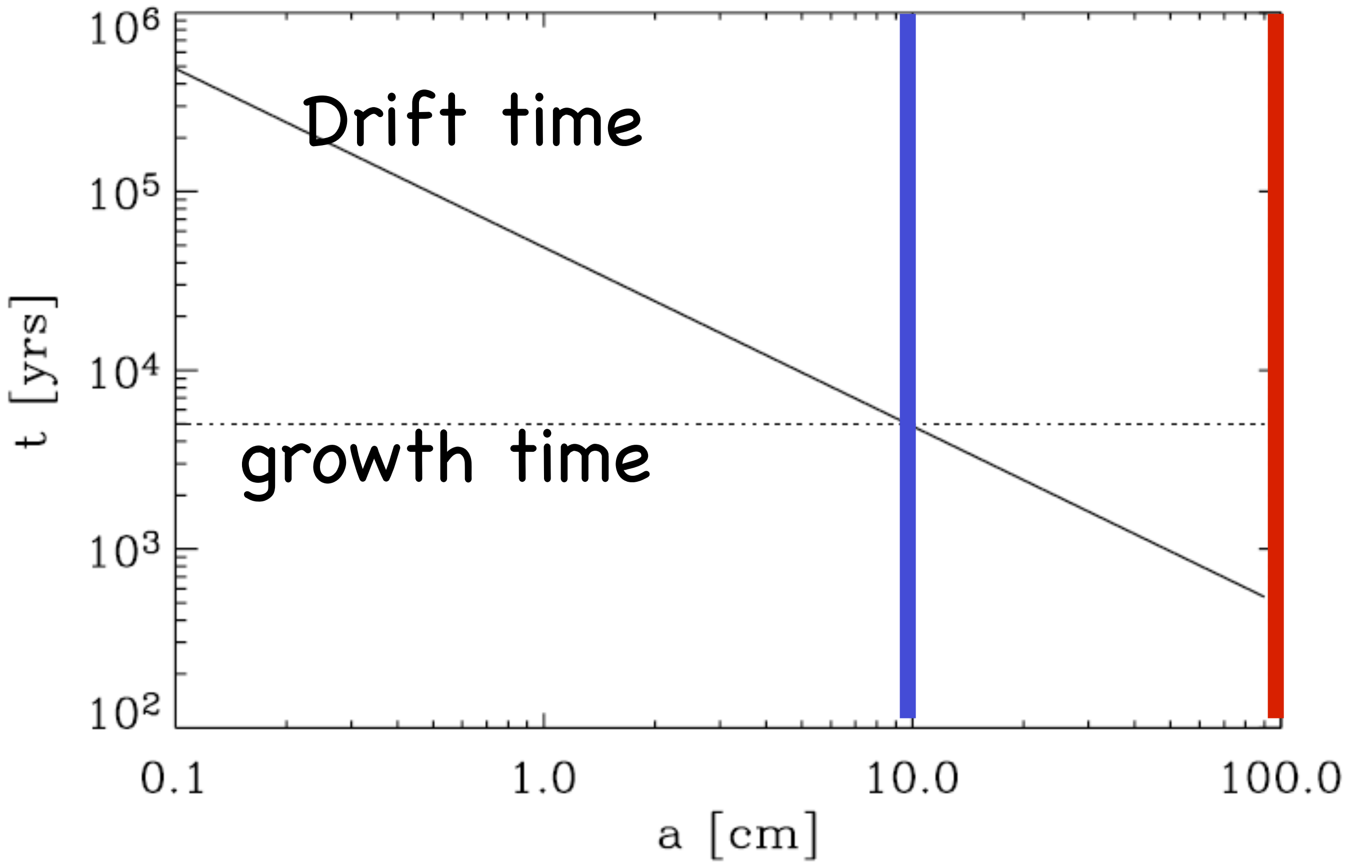


FIG. 1.—Comparison between drift time (*solid line*) and growth time (*dotted line*) for solids as a function of size. The values are calculated using the equations from this paper for a location of 7.5 AU in a minimum mass solar nebula.

Particle response to the gas flow 1:

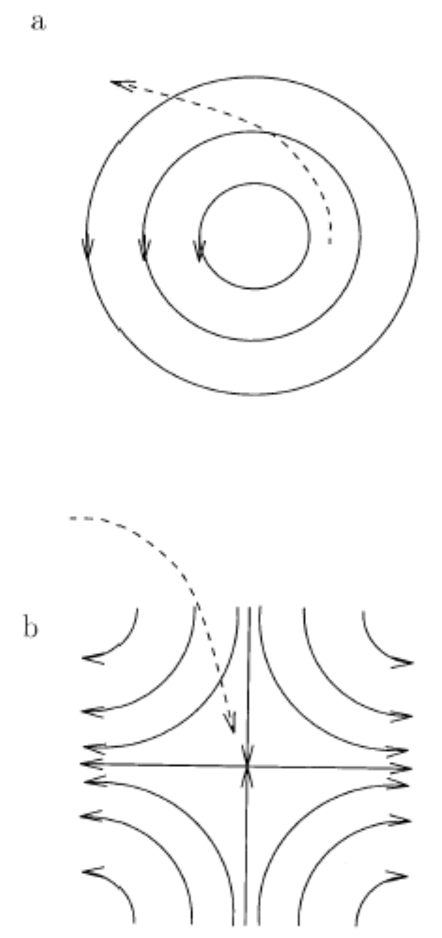
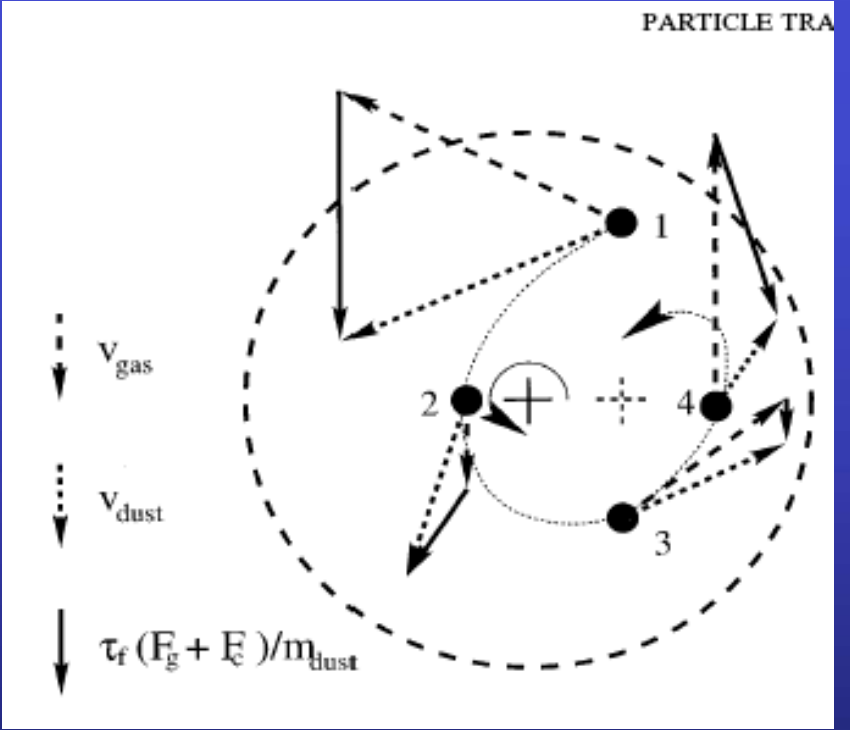


FIG. 1. Under laboratory-observed conditions particles (a) spiral out of the vortices (eddy), but (b) collect in convergence zones (strain fields).

Lab condition,

Cuzzi et al.



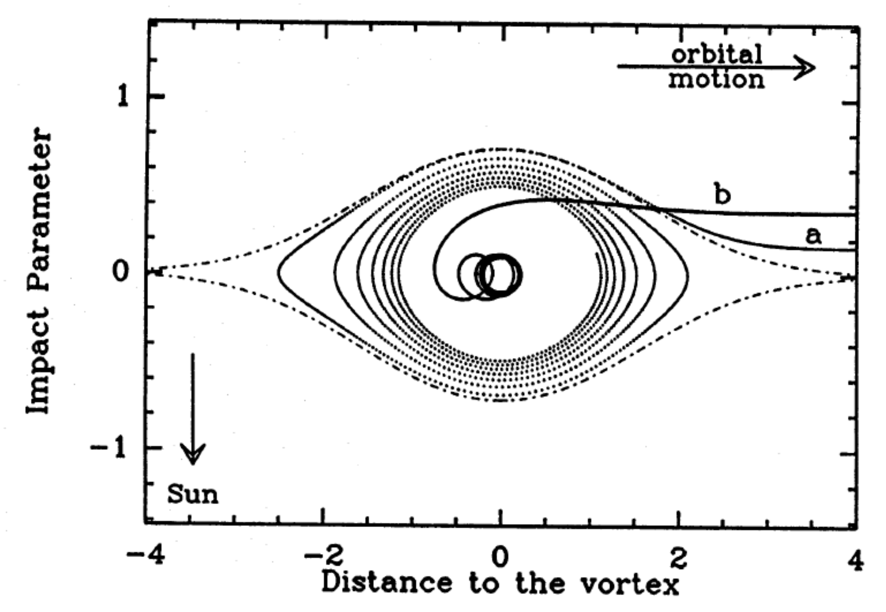
Vortex in the r-z plane:

Aka convection cell

particle concentration.

Klahr & Henning 1997

Particle response to the gas flow 2:



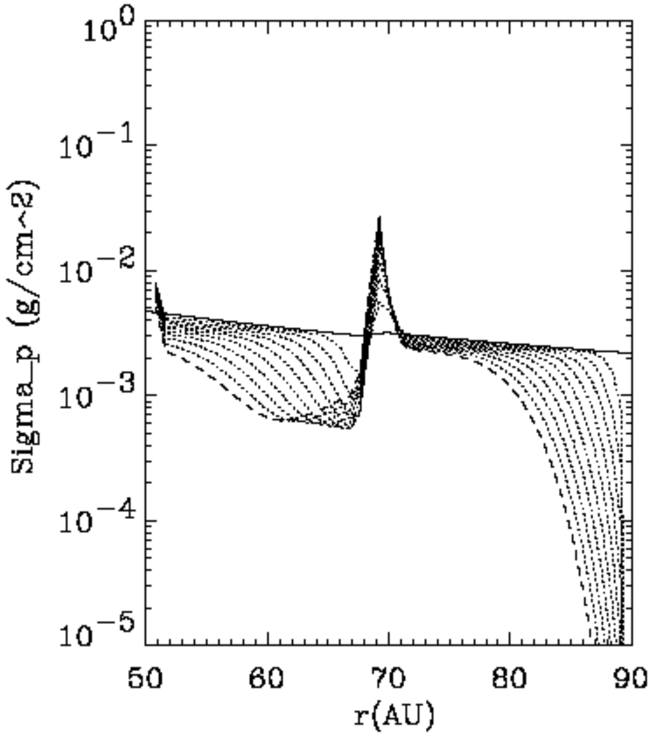


FIG. 7.—Model A: evolution of the 1 m size particle surface density distribution for the model in Fig. 2. The solid line gives the initial distribution. The following lines are snapshots every 10^5 yr.

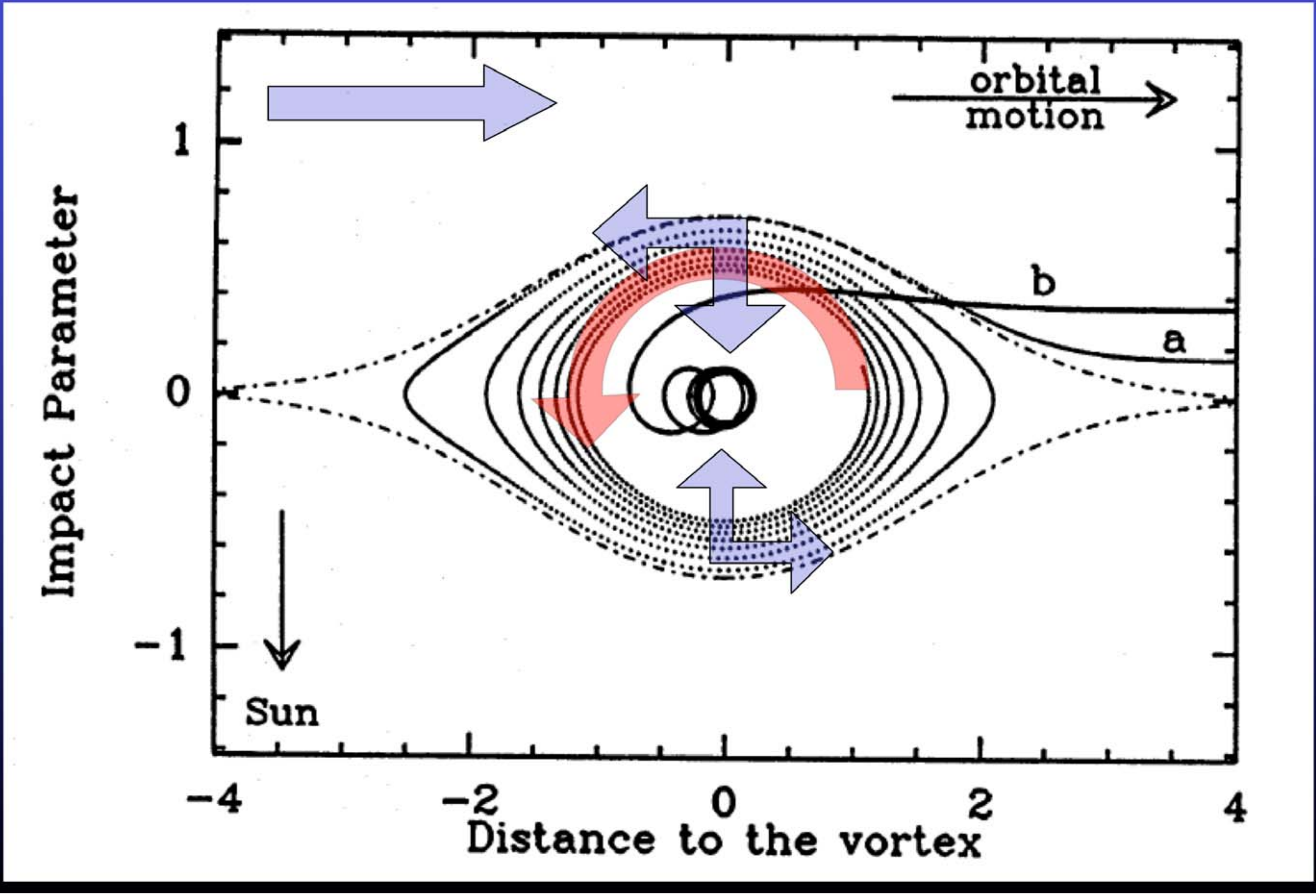
Vortices:

Barge & Sommeria 1995

Pressure maxima:

Klahr & Lin 2000

Large particles in vortex:



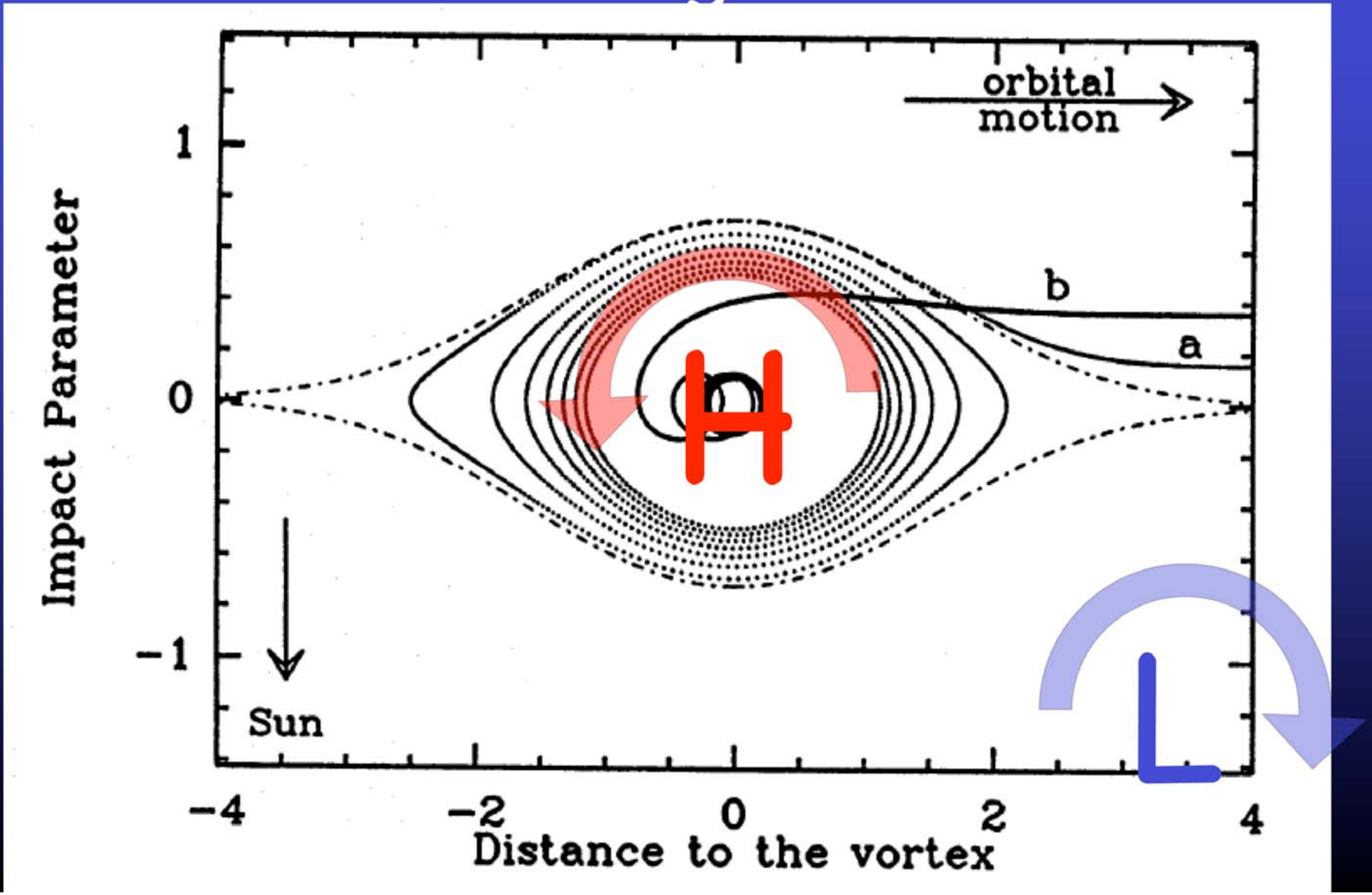
Small particles in pressure maxima

$$\begin{aligned}
\partial_t v_g &= -\frac{1}{\rho}\nabla p + \text{forces} \\
\partial_t v_d &= -\frac{v_d - v_g}{\tau_f} + \text{forces}
\end{aligned}$$

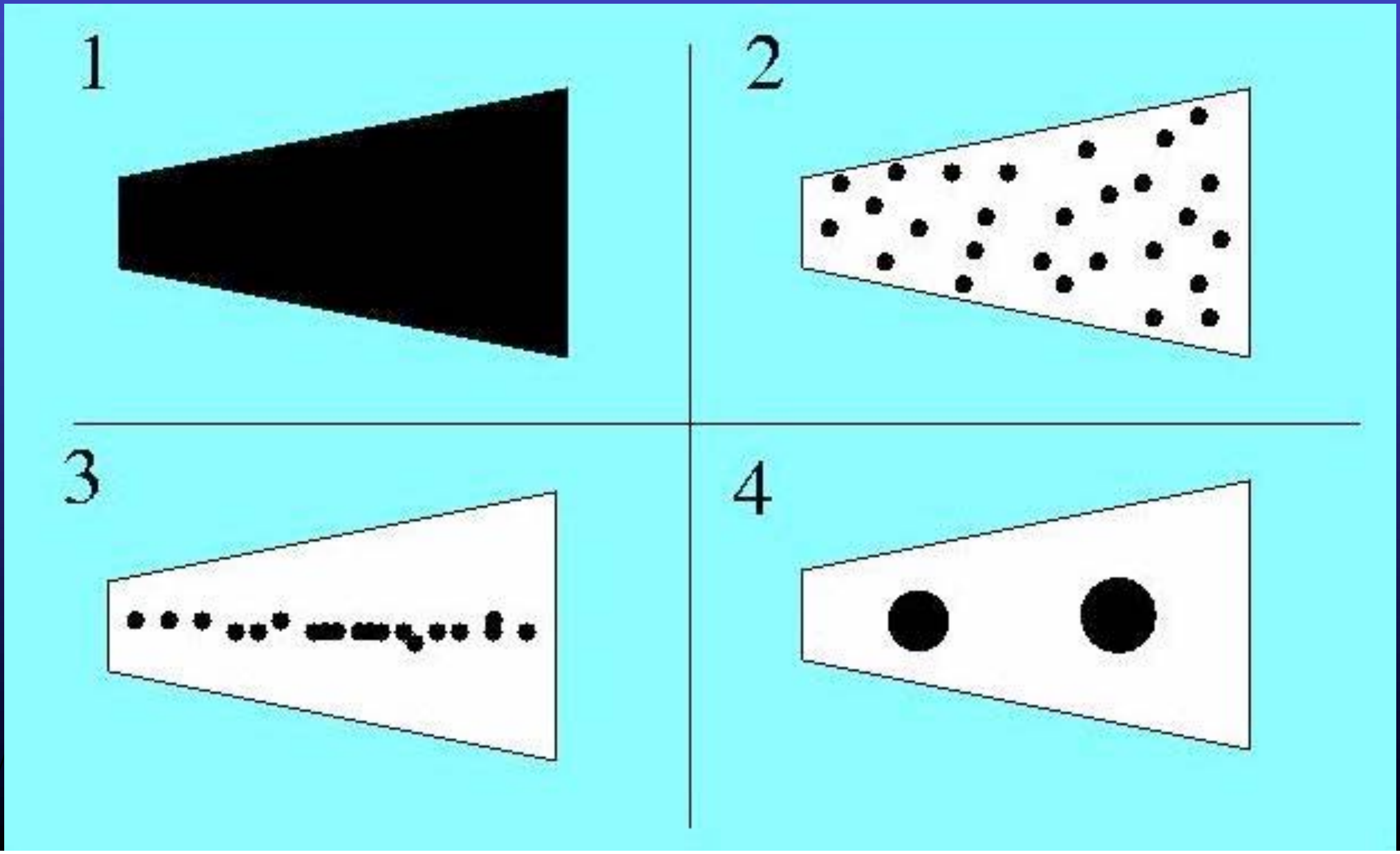
$$v_d = v_g + \tau_f \frac{1}{\rho}\nabla p$$

Klahr & Lin 2000

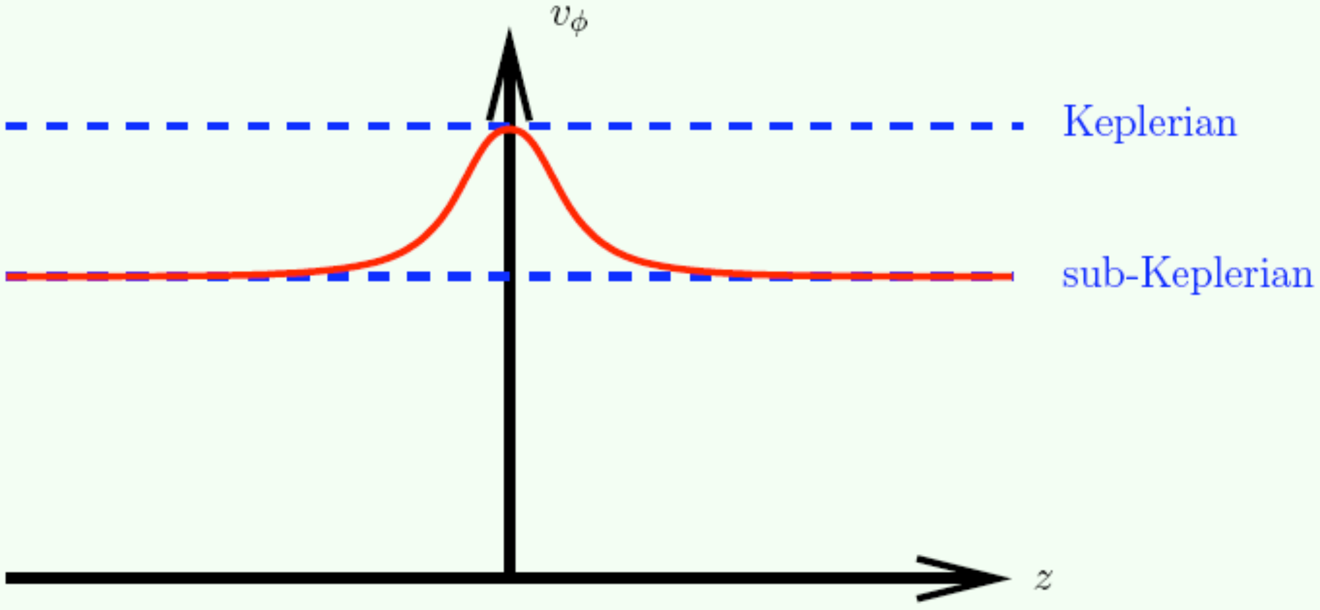
Small particles in pressure maxima e.g. a vortex



What if there is no global turbulence?
=>Sedimentation to the midplane.
Gravitational instability in the dust
midplane layer?
(Safronov 1969, Goldreich & Ward 1973)



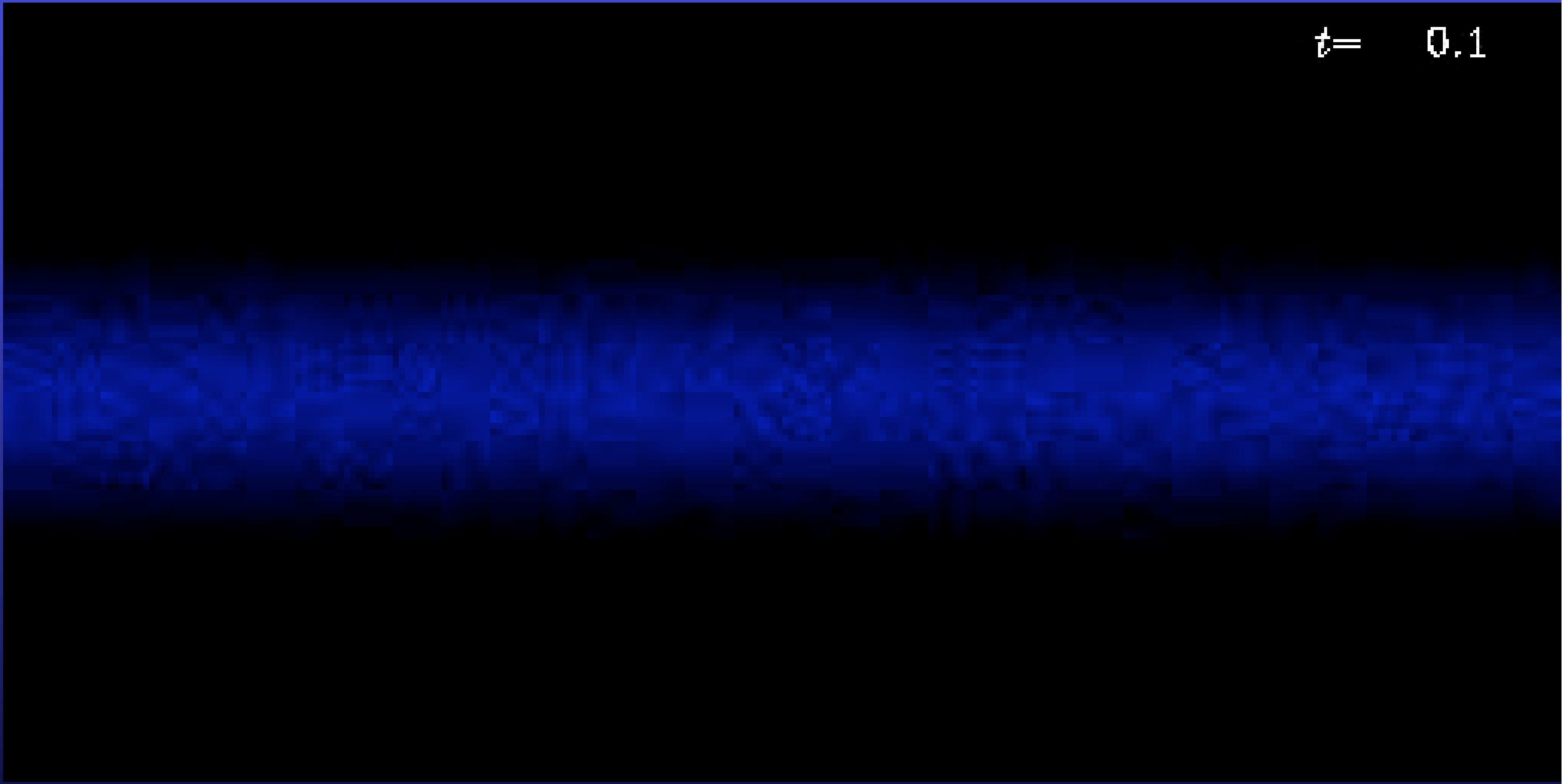
Kelvin-Helmholtz instability



- Gas forced to move sub-Keplerian away from the mid-plane (by the global pressure gradient) and Keplerian in the mid-plane (by the dust)
- Vertical shear is unstable to Kelvin-Helmholtz instability
- Subsequent turbulence lifts up the dust layer and reduces the dust density in the mid-plane

10 cm sized boulders:

vertical



horizontal

Johansen, Henning & Klahr 2006

Conditions for planetesimal formation:

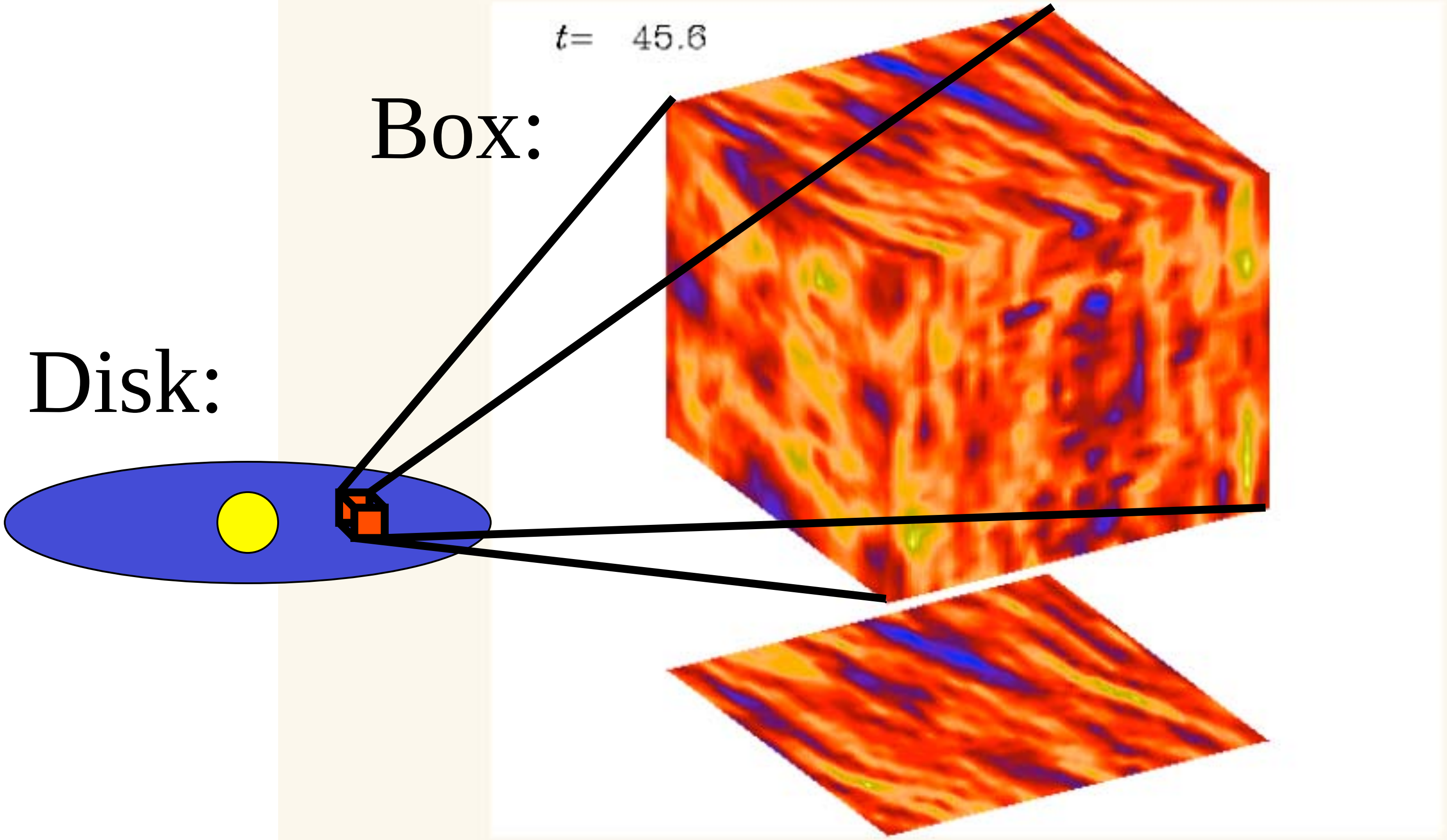
	non-turbulent	turbulent
Coagulation	Stu Weidenschilling	Weidenschilling, Dullemond & Dominik 2005, See also Brauer
Gravitational Collapse	Safronov 1969, Goldreich & Ward 1973	Johansen, Klahr & Henning 2006, Johansen etal. 2007

Apparent Problems in planetesimal formation:

	non-turbulent	turbulent
Coagulation	Radial drift, too fast	Bouncing and Collisional destruction
Gravitational Collapse	No thin midplane layer, because of Kelvin-Helmholtz turbulence ->	No thin midplane (vertical diffusion) BUT: Locally very high densities!

MRI turbulence

…because it is a reliable source for turbulence.



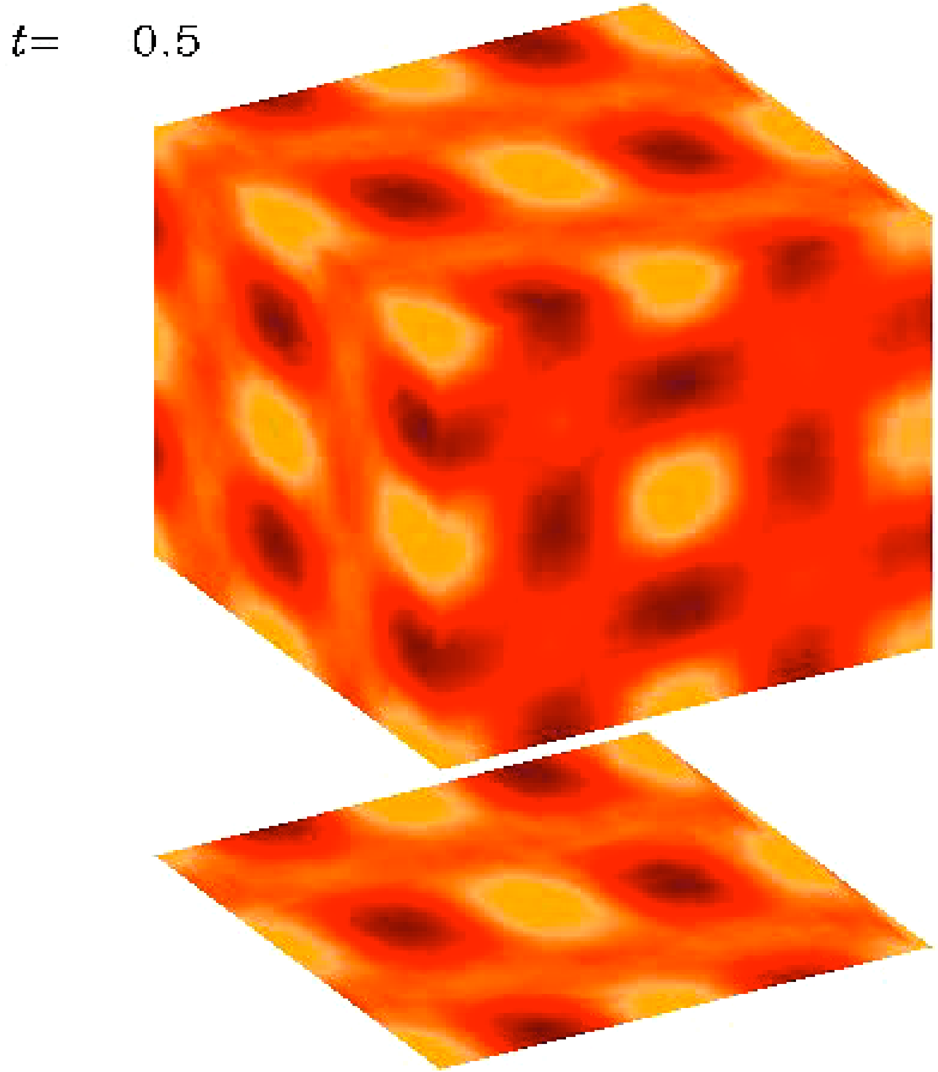
Code: The Pencil-Code [MHD code, finite differences, 6th order in space, 3rd order in time, Brandenburg (2003)]

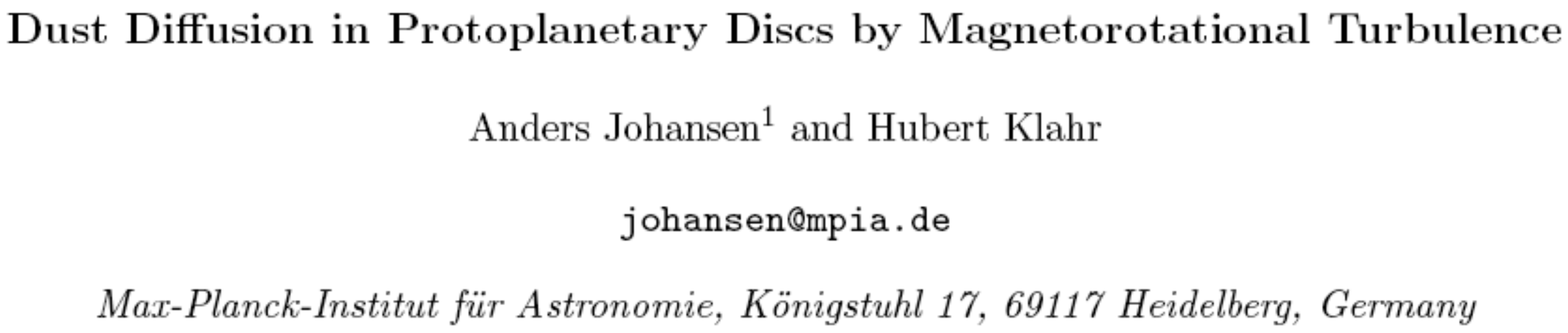
Development of MHD Turbulence

From initial perturbation to saturation of the turbulence

Colors: gas density
yellow = high
blue = low

Standard magneto rotational instability simulation ala Balbus and Hawley





Dust Diffusion in Protoplanetary Discs by Magnetorotational Turbulence

Anders Johansen[1] and Hubert Klahr

johansen@mpia.de

Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany

Johansen & Klahr 2005

SMALL GRAINS e.g.
$0.1\,\mu \leq a \leq 1\mathrm{cm}$ @ 5AU.
Small means a friction time
smaller than the orbital period.

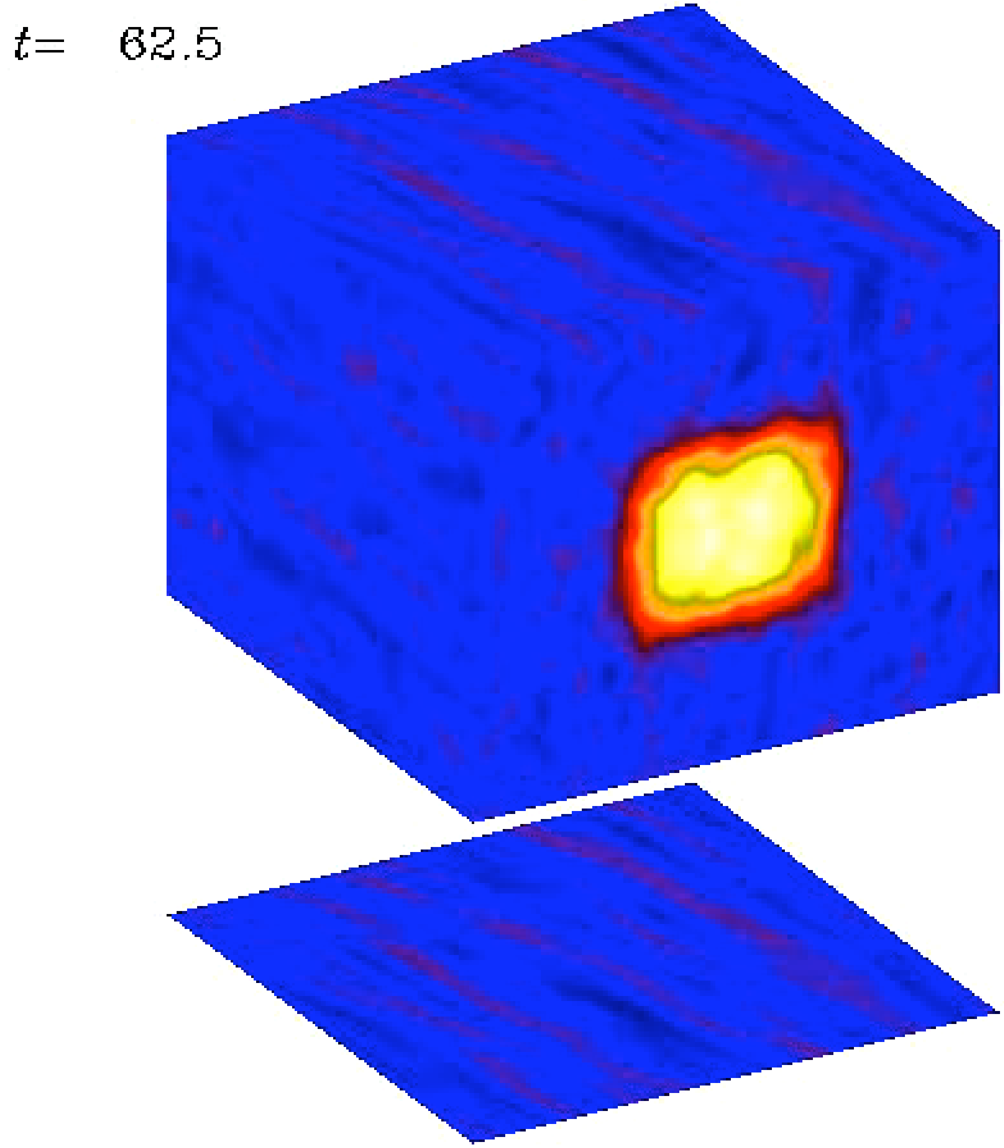
Diffusion of Dust in MHD Turbulence.

Dust is treated as a fluid without pressure, which couples to the gas motion via friction.

No additional forces e.g. gravity.

Colors: dust density
yellow = high
blue = low

Drawback: difficult to measure diffusivity

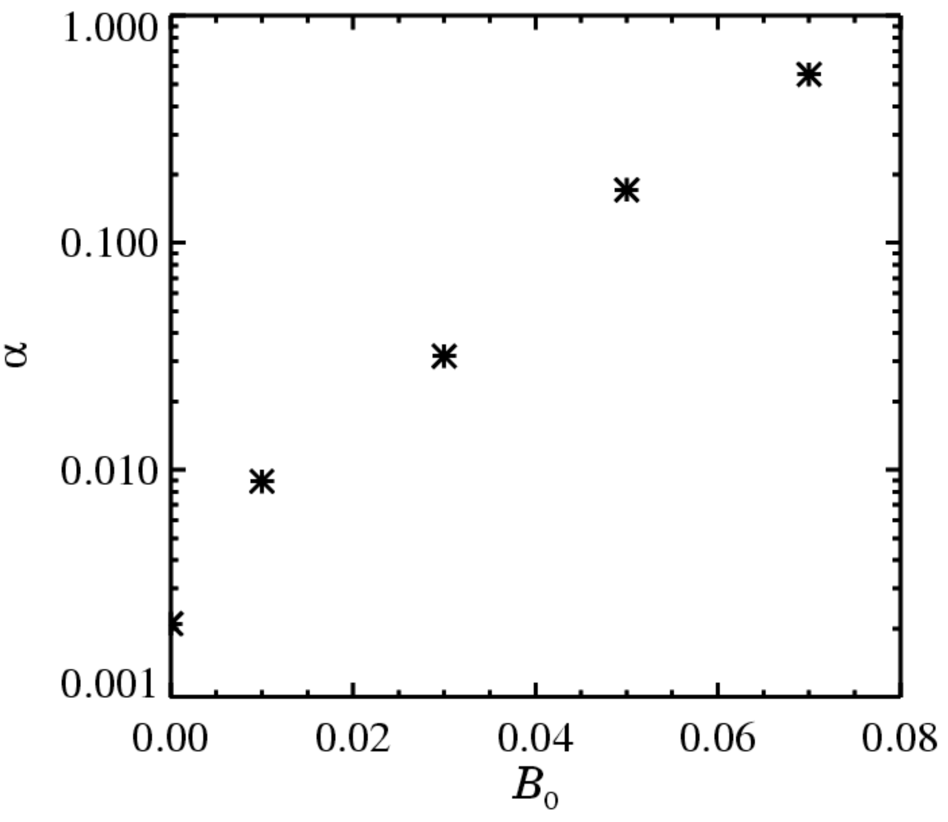


Turbulent diffusion in protoplanetary discs: The effect of an imposed magnetic field

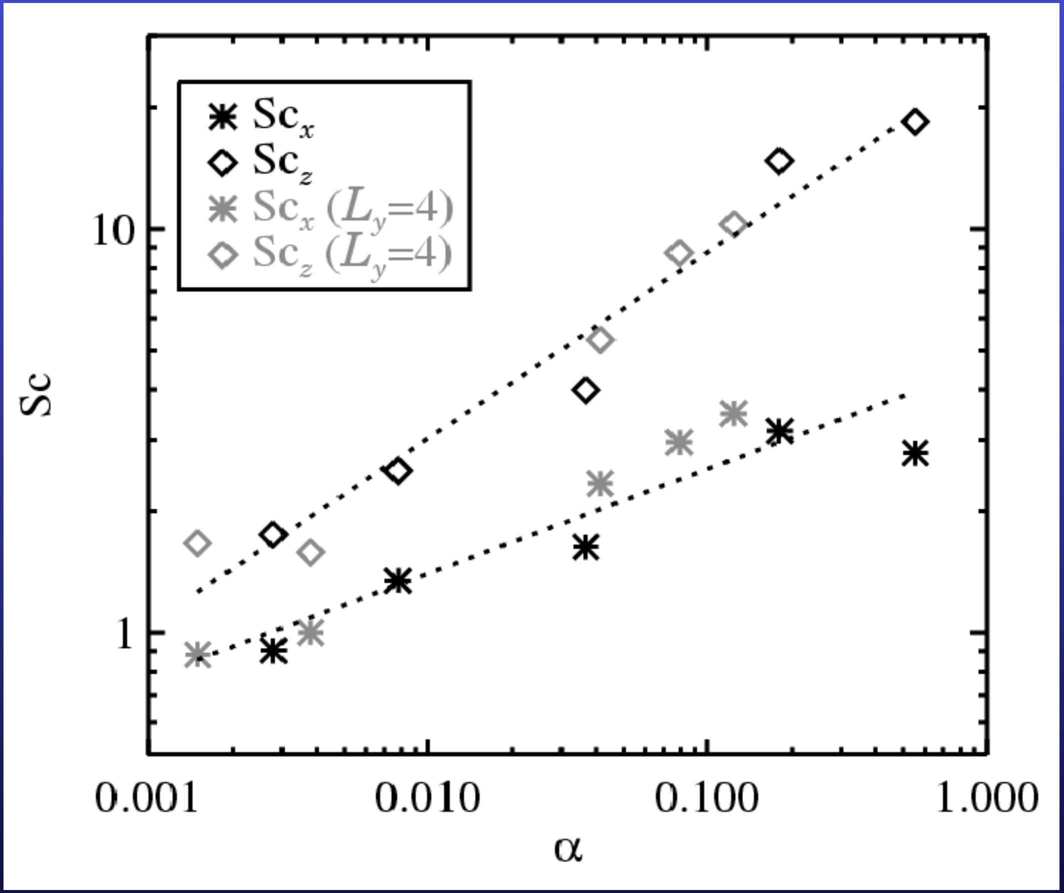
A. Johansen[1], H. Klahr[1] and A.J. Mee[2]
[1] *Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany*
[2] *School of Mathematics and Statistics, University of Newcastle upon Tyne, NE1 7RU, UK*

2006, MNRAS-L

- Strength of MRI depends on boundary conditions, e.g. B_z
- But diffusion is less increased than is alpha!
- Collisions increase
- Influence on concentrations?



Diffusion is not proportional to turbulent strength! What about concentration?



Johansen, Klahr & Mee 2006

Limits of the Diffusion Picture: Turbulence does also:

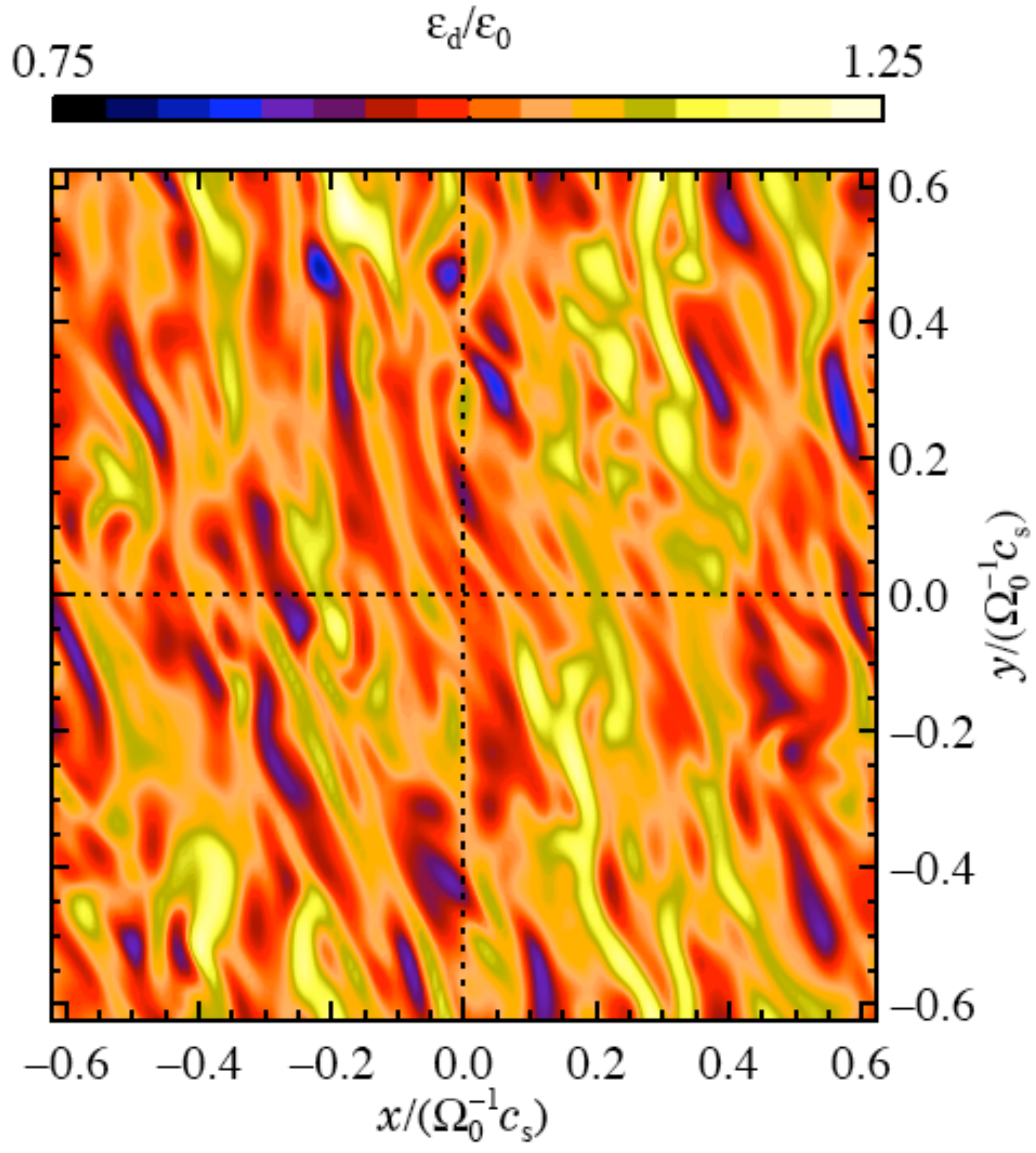
- Size Segregation
- Local concentration of intermediate sized solids
- Subsonic turbulence in the gas yet supersonic turbulence among the particles

Johanson and Klahr 2005

Concentration of cm sized grains in anti-cyclonic eddies in the flow:

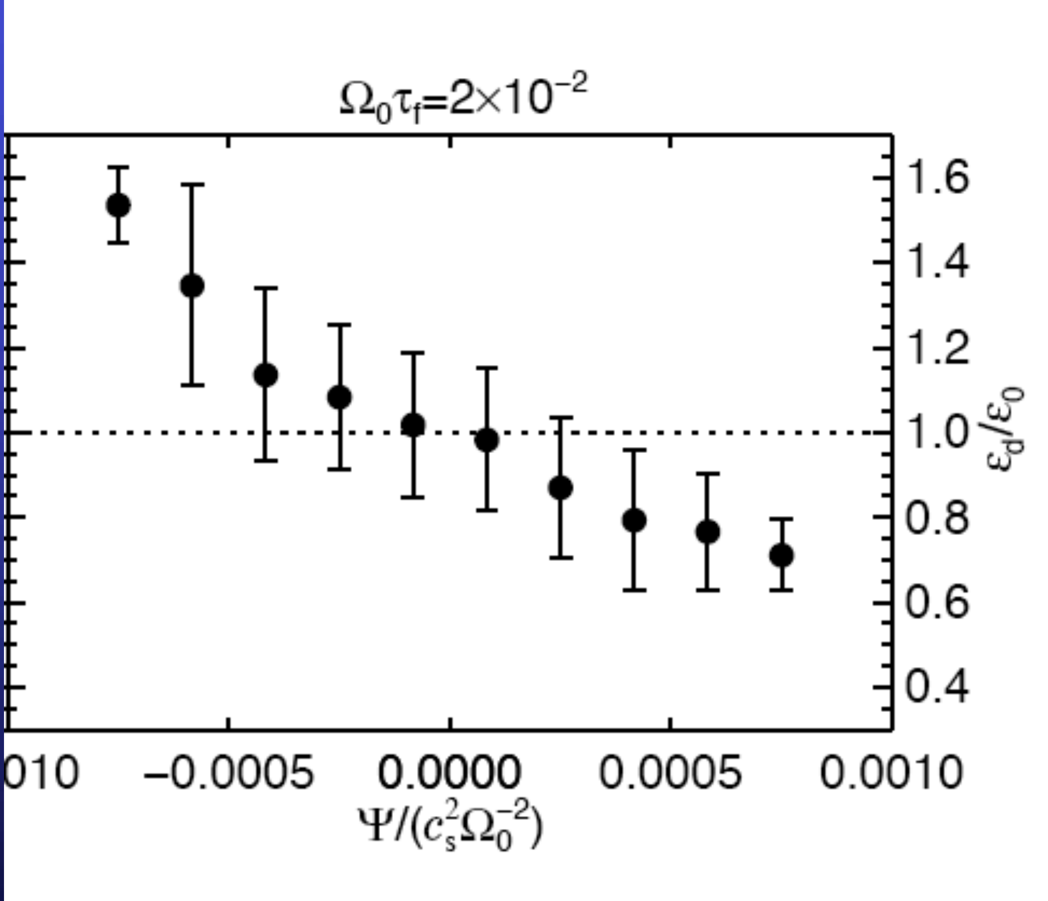
Blue = low number density (-25%)

Red = higher number density (+25%)

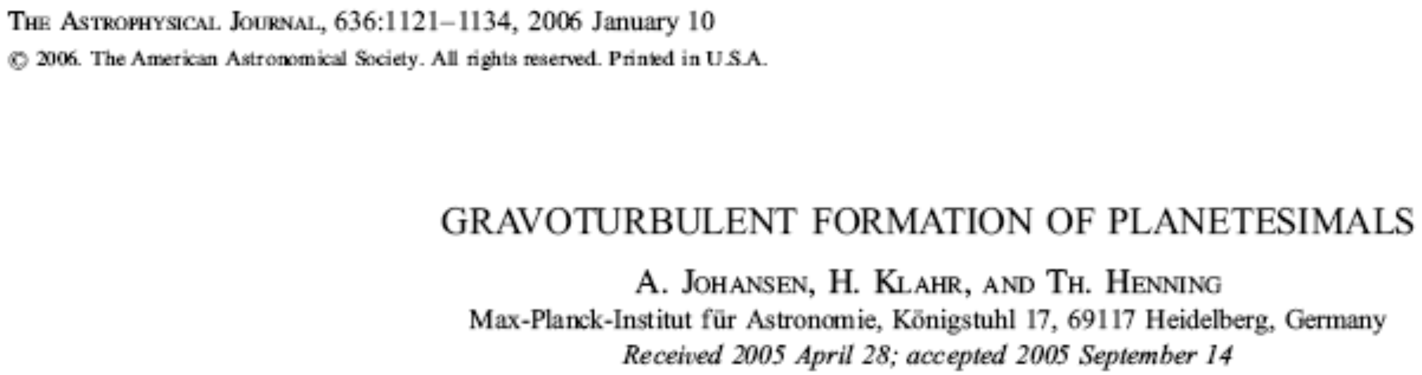


Concentration of cm sized grains in anti-cyclonic eddies in the flow:

Correlation between density and vortex test function Ψ. Negative values of Ψ indicate anti-cyclonic motion and positive values cyclonic motion.



Compare this to Barge and Sommeria 1995



THE ASTROPHYSICAL JOURNAL, 636:1121–1134, 2006 January 10

GRAVOTURBULENT FORMATION OF PLANETESIMALS

A. JOHANSEN, H. KLAHR, AND TH. HENNING
Max-Planck-Institut für Astronomie, Königstuhl 17, 69117 Heidelberg, Germany

Received 2005 April 28; accepted 2005 September 14

Johansen, Klahr and Henning 2006

This work considers boulders e.g. a ≈ 1m @ 5AU.
This means a friction time
of about one sixth of an orbital period: ≈2 yrs!

In this size regime objects climb up any pressure gradient: the global disk gradient, as well as any local pressure perturbation. Remember: cyclonic vortices are low pressure regions and high pressure regions are anti-cyclonic vortices.

gas

$$\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u}\cdot\nabla)\boldsymbol{u} + u_y^{(0)}\frac{\partial \boldsymbol{u}}{\partial y} = \boldsymbol{f}(\boldsymbol{u}) - c_s^2 \nabla \ln \rho + \frac{1}{\rho}\boldsymbol{J}\times\boldsymbol{B} + \boldsymbol{f}_\nu(\boldsymbol{u},\rho),$$

$$\frac{\partial \boldsymbol{A}}{\partial t} + u_y^{(0)}\frac{\partial \boldsymbol{A}}{\partial y} = \boldsymbol{u}\times\boldsymbol{B} + \frac{3}{2}\Omega_0 A_y \hat{\boldsymbol{x}} + \boldsymbol{f}_\eta(\boldsymbol{A}),$$

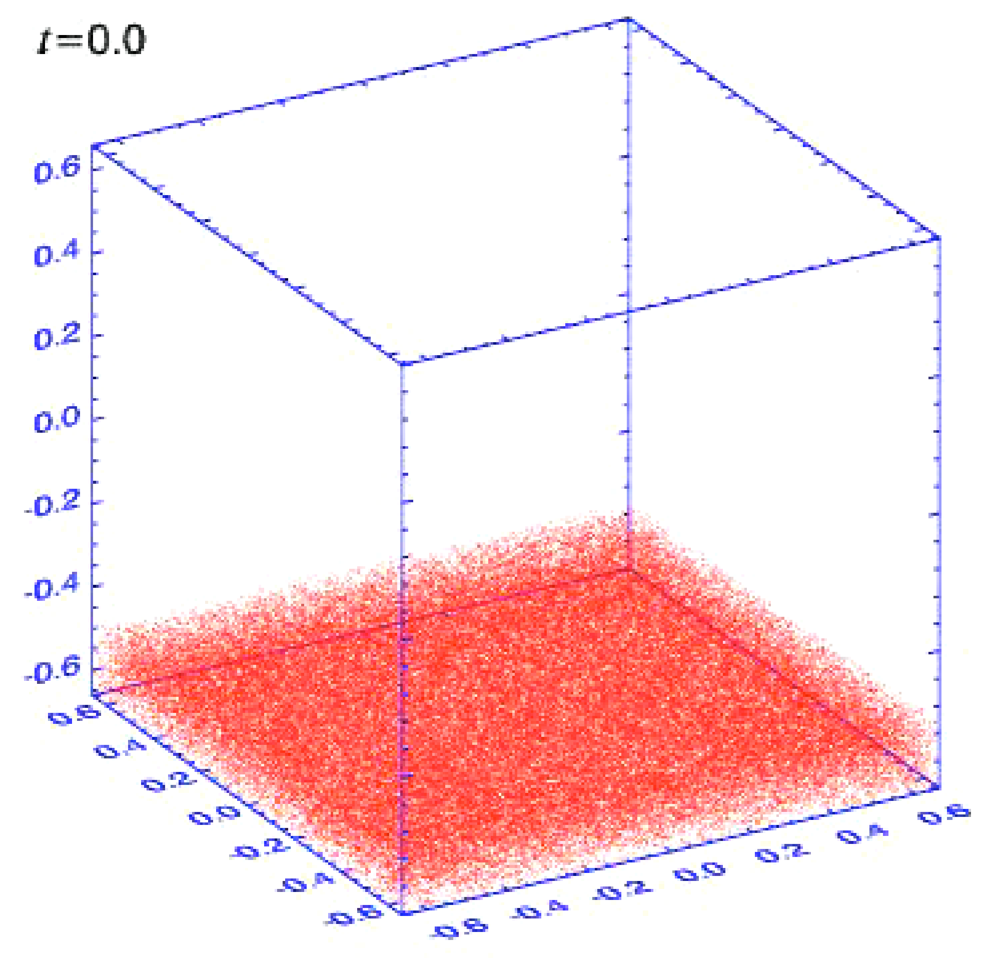
$$\frac{\partial \rho}{\partial t} + \boldsymbol{u}\cdot\nabla\rho + u_y^{(0)}\frac{\partial \rho}{\partial y} = -\rho\nabla\cdot\boldsymbol{u} + f_{\mathrm{D}}(\rho),$$

dust

$$\frac{\partial \boldsymbol{v}_i}{\partial t} = \boldsymbol{f}(\boldsymbol{v}_i) - \frac{1}{\tau_f}(\boldsymbol{v}_i - \boldsymbol{u}) + c_s\Omega_0\beta\hat{\boldsymbol{x}},$$

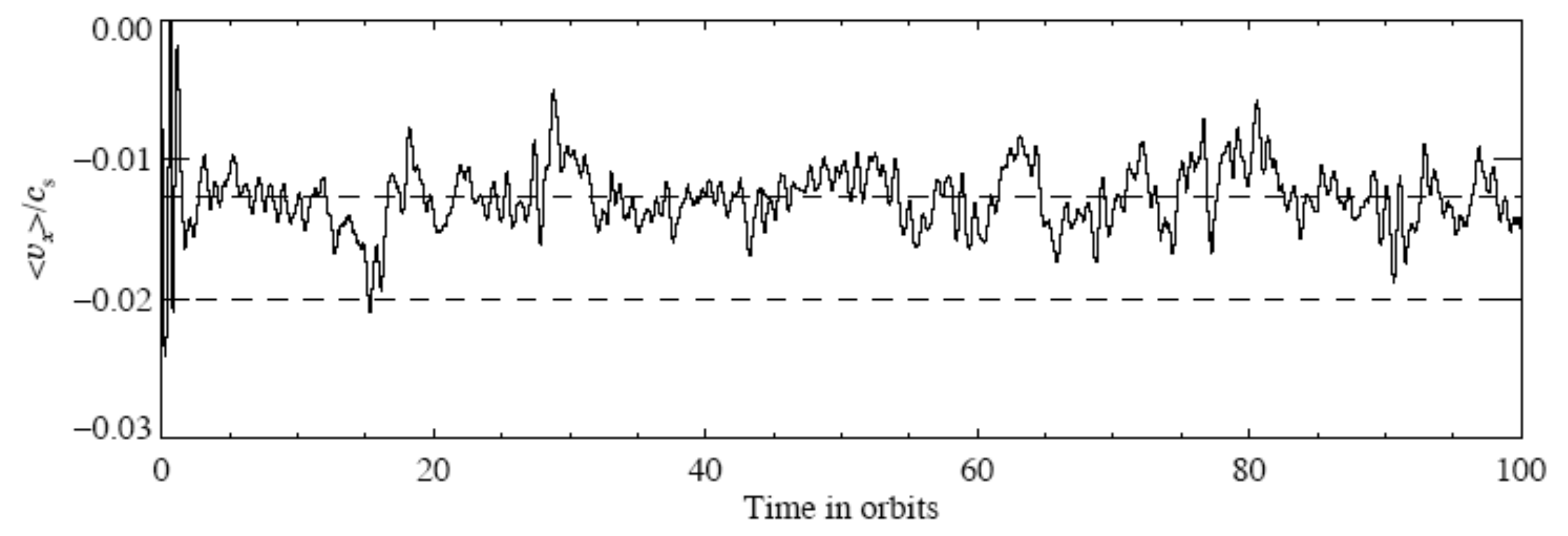
$$\frac{\partial \boldsymbol{x}_i}{\partial t} = \boldsymbol{v}_i + u_y^{(0)}\hat{\boldsymbol{y}}.$$

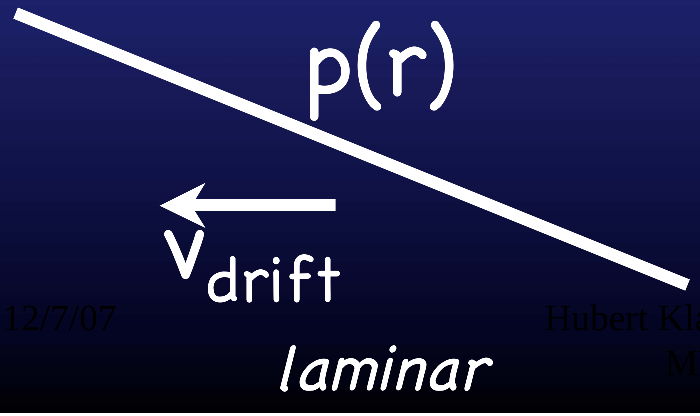
2,000,000 boulders of 1m size

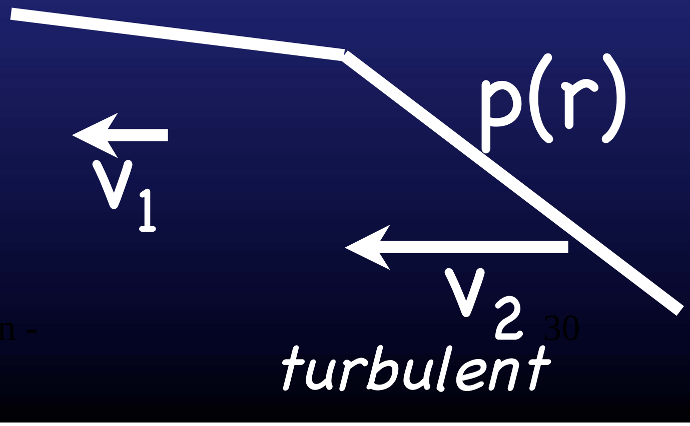


Johansen, Klahr and Henning, 2006

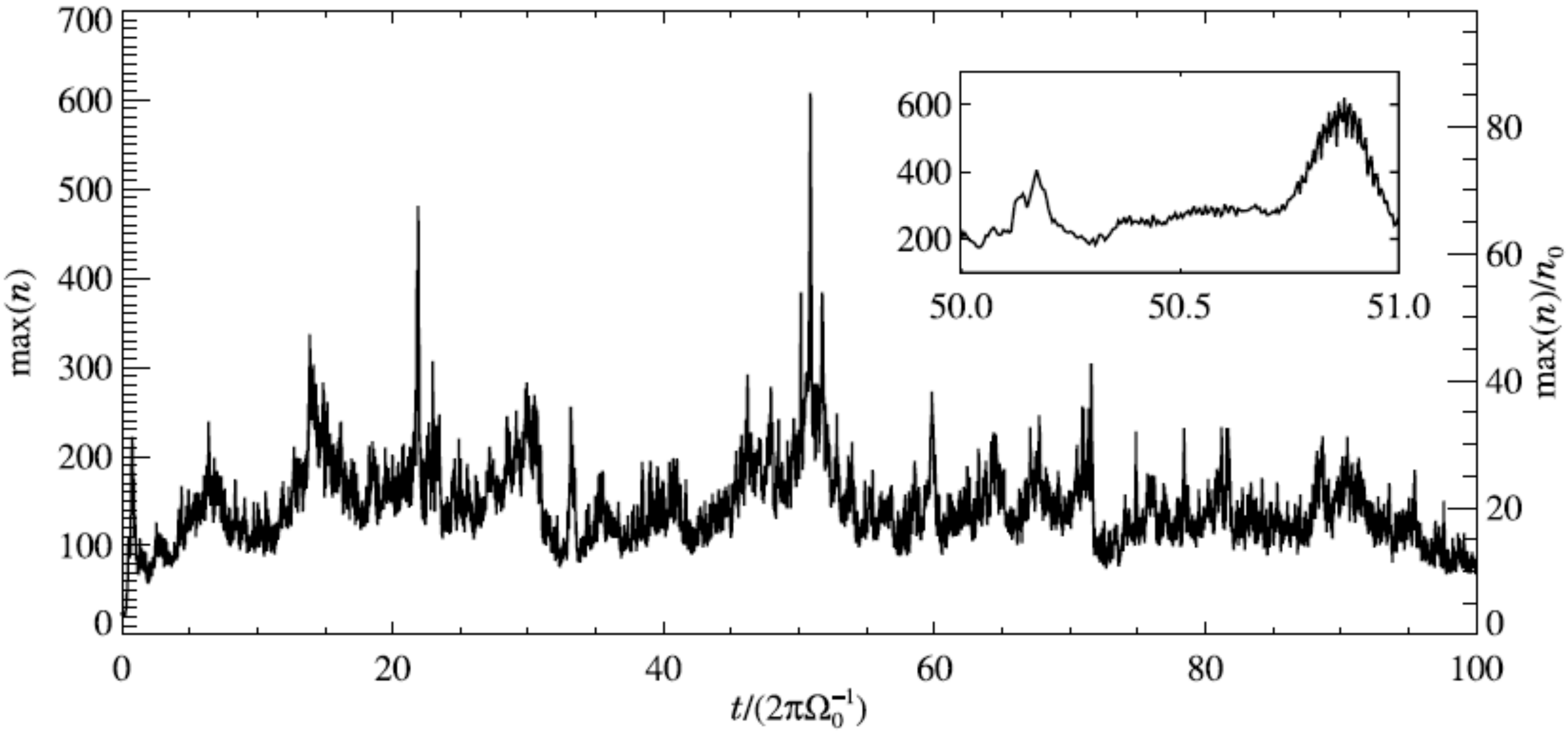
Turbulence slows down radial drift!







1m boulders



700
600
500
400
300
200
100
0
max(n)
0
20
40
60
80
100
$t/(2\pi\Omega_0^{-1})$
80
60
40
20
0
max(n)/n_0
600
400
200
50.0
50.5
51.0

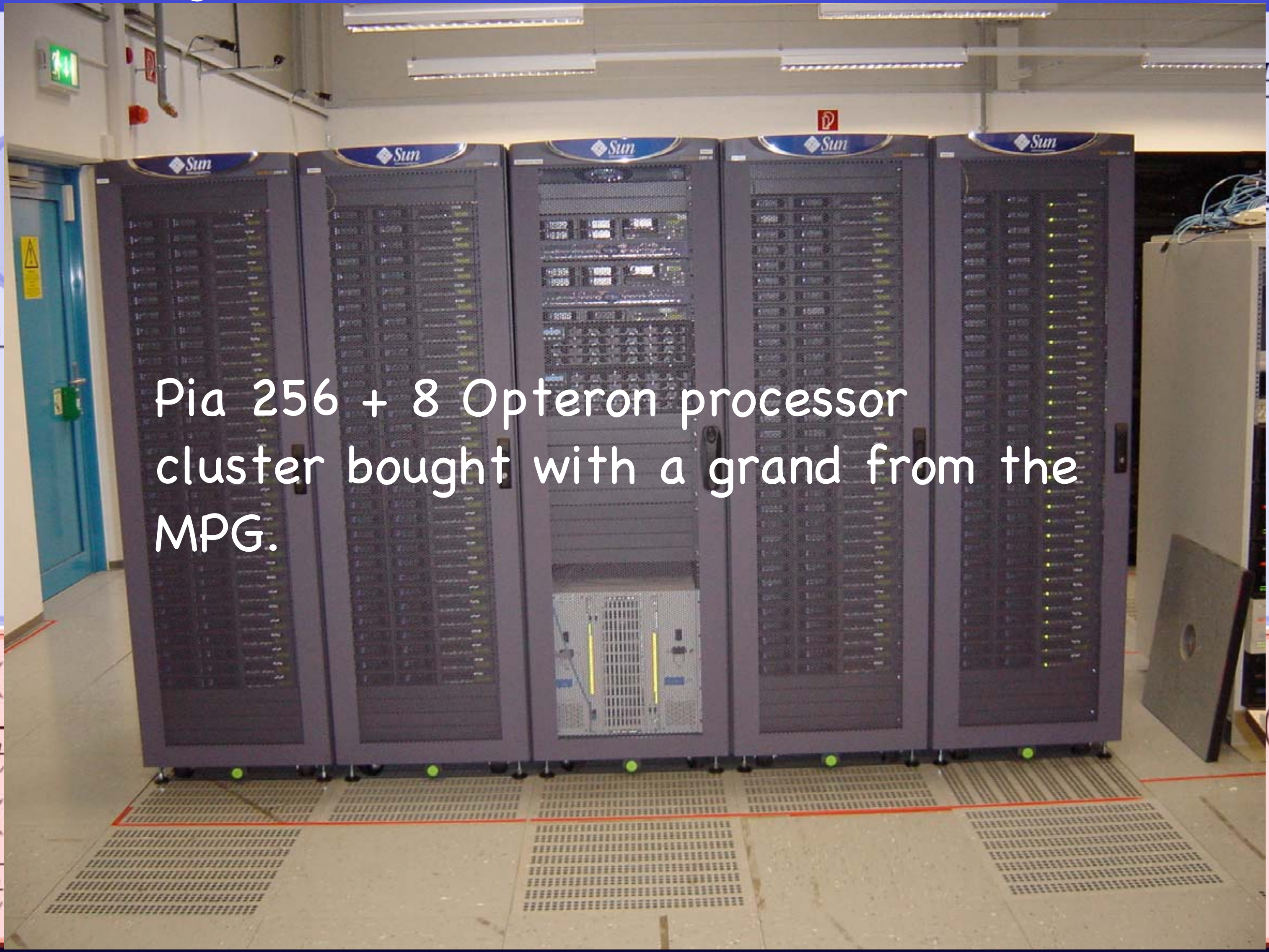
MRI plus self-gravity for the dust, including particle feed back on the gas: collaboration with Mac Low & Oichi AMNH

$$\frac{\partial \boldsymbol{u}}{\partial t} + \quad B$$

$$\frac{\partial \rho}{\partial t} + \quad {}_{\nu}(\boldsymbol{u}, \rho)\,,$$

$$\frac{\partial \boldsymbol{v}^{(}}{\partial t} \quad (\boldsymbol{x}^{(i)})]\,,$$

$$\frac{\partial \boldsymbol{x}^{(}}{\partial t}$$

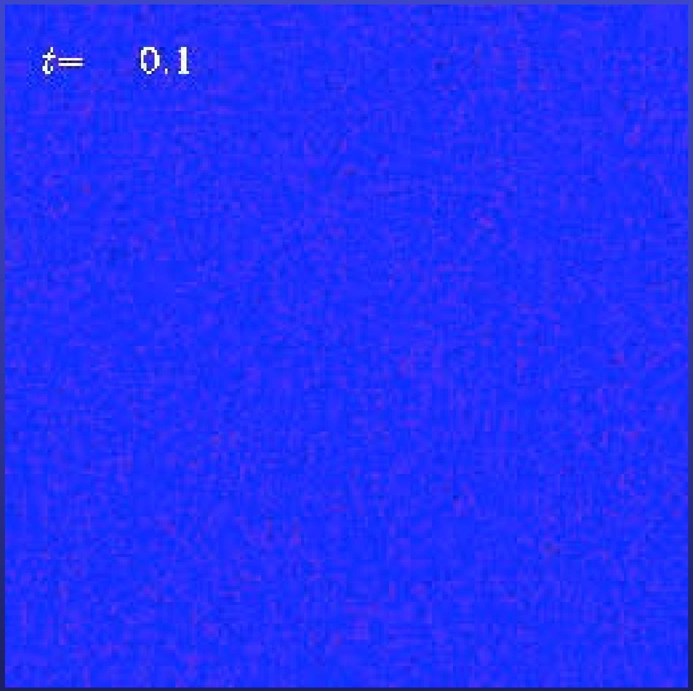


Pia 256 + 8 Opteron processor cluster bought with a grand from the MPG.

Poisson equation solved via FFT in parallel mode: up to 256^3 cells

Streaming instability for radial drift: Johansen and Youdin 2007

vertical



radial

This is what *laminar* radial drift actually looks like!

MRI plus self-gravity for the dust, including particle feed back on the gas: collaboration with Mac Low & Oichi AMNH

gas

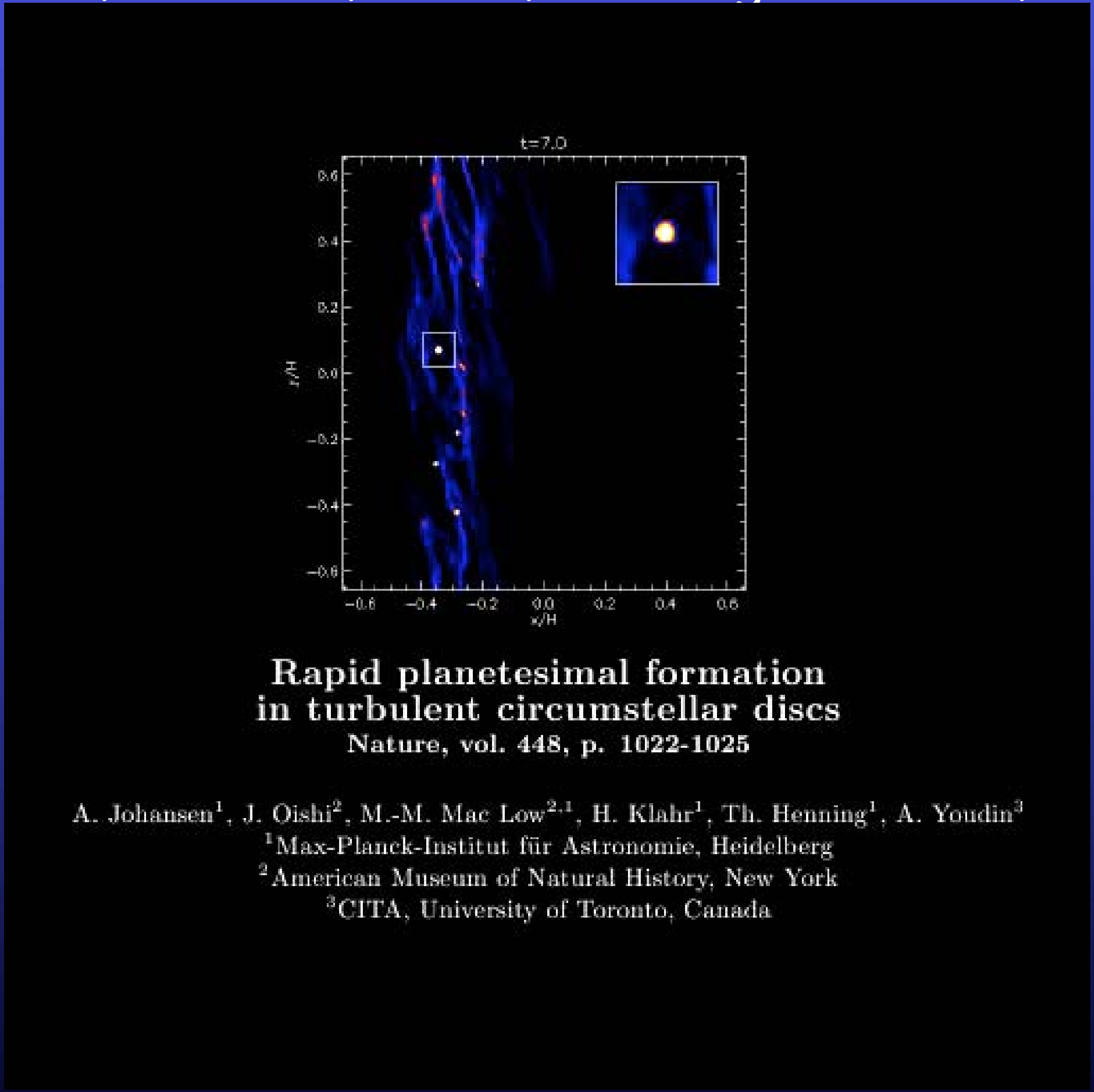
$$\begin{aligned}
\frac{\partial \boldsymbol{u}}{\partial t} + (\boldsymbol{u}\cdot\boldsymbol{\nabla})\boldsymbol{u} + u_y^{(0)}\frac{\partial \boldsymbol{u}}{\partial y} &= 2\Omega u_y \hat{\boldsymbol{x}} - \frac{1}{2}\Omega u_x \hat{\boldsymbol{y}} - \boldsymbol{\nabla}\Phi + \frac{1}{\rho}\boldsymbol{J}\times\boldsymbol{B} \\
&\quad - \frac{1}{\rho}c_{\mathrm{s}}^2\boldsymbol{\nabla}\rho - \frac{\rho_{\mathrm{d}}/\rho}{\tau_{\mathrm{f}}}(\boldsymbol{u}-\boldsymbol{w}) + \boldsymbol{f}_\nu(\boldsymbol{u},\rho)\,, \\
\frac{\partial \rho}{\partial t} + (\boldsymbol{u}\cdot\boldsymbol{\nabla})\rho + u_y^{(0)}\frac{\partial \rho}{\partial y} &= -\rho\boldsymbol{\nabla}\cdot\boldsymbol{u} + f_{\mathrm{D}}(\rho)\,, \\
\frac{\partial \boldsymbol{A}}{\partial t} + u_y^{(0)}\frac{\partial \boldsymbol{A}}{\partial y} &= \frac{3}{2}\Omega A_y\hat{\boldsymbol{x}} + \boldsymbol{u}\times\boldsymbol{B} + \boldsymbol{f}_\eta(\boldsymbol{A})\,, \\
\nabla^2\Phi &= 4\pi G(\rho + \rho_{\mathrm{d}})\,.
\end{aligned}$$

$$\begin{aligned}
\frac{\partial \boldsymbol{v}^{(i)}}{\partial t} &= 2\Omega v_y^{(i)}\hat{\boldsymbol{x}} - \frac{1}{2}\Omega v_x^{(i)}\hat{\boldsymbol{y}} - \Omega^2 z - \boldsymbol{\nabla}\Phi(\boldsymbol{x}^{(i)}) - \frac{1}{\tau_{\mathrm{f}}}[\boldsymbol{v}^{(i)} - \boldsymbol{u}(\boldsymbol{x}^{(i)})]\,, \\
\frac{\partial \boldsymbol{x}^{(i)}}{\partial t} &= \boldsymbol{v}^{(i)} + u_y^{(0)}\hat{\boldsymbol{y}}\,.
\end{aligned}$$

dust

Poisson equation solved via FFT in parallel mode: up to 256^3 cells

Johansen, Oichi, MacLow, Klahr, Henning & Youdin, 2007, nature



Rapid planetesimal formation in turbulent circumstellar discs

Nature, vol. 448, p. 1022-1025

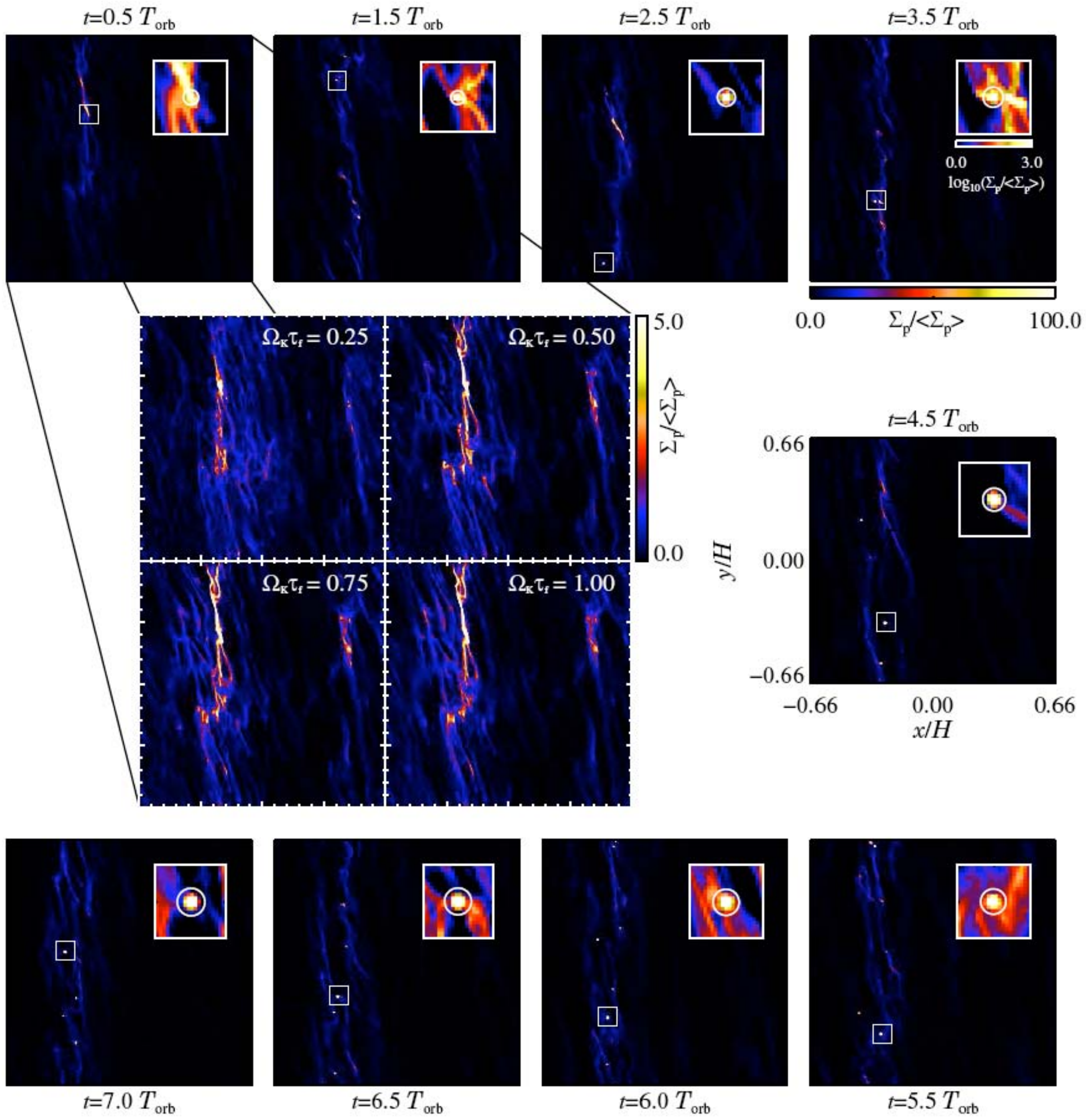
A. Johansen[1], J. Oishi[2], M.-M. Mac Low[2,1], H. Klahr[1], Th. Henning[1], A. Youdin[3]

[1]Max-Planck-Institut für Astronomie, Heidelberg

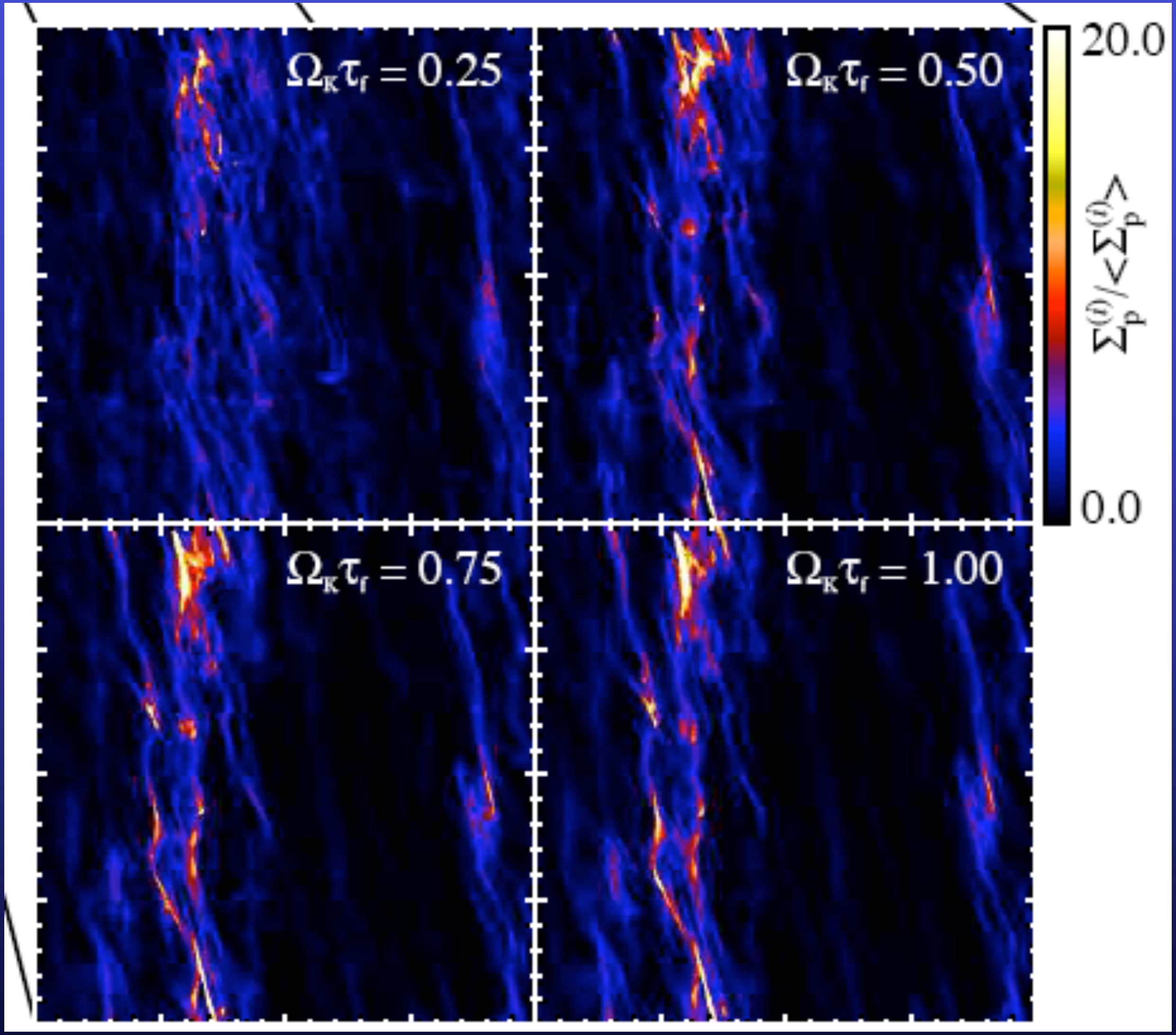
[2]American Museum of Natural History, New York

[3]CITA, University of Toronto, Canada

http://www.mpia.de/homes/johansen/research_en.php

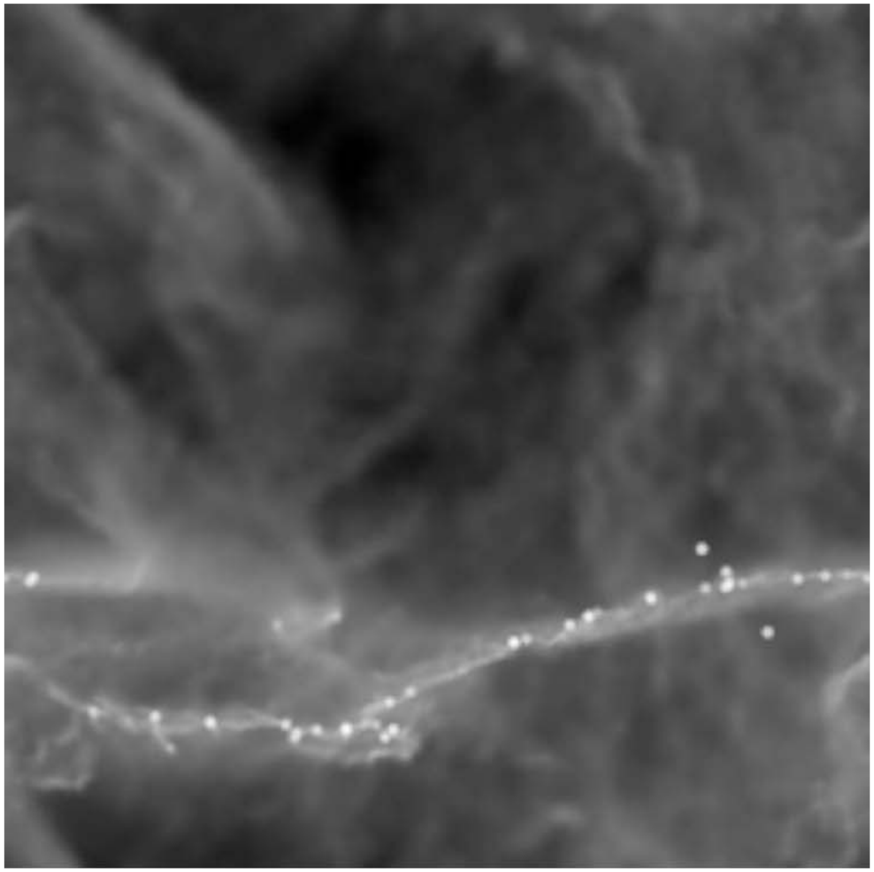

t=0.5 T_orb
t=1.5 T_orb
t=2.5 T_orb
t=3.5 T_orb
0.0
3.0
log10(Σp/<Σp>)
0.0
Σp/<Σp>
100.0
ΩKτf = 0.25
ΩKτf = 0.50
ΩKτf = 0.75
ΩKτf = 1.00
5.0
Σp/<Σp>
0.0
t=4.5 T_orb
0.66
y/H
0.00
−0.66
−0.66
0.00
0.66
x/H
t=7.0 T_orb
t=6.5 T_orb
t=6.0 T_orb
t=5.5 T_orb

Size distribution: 15 - 60 cm



Size distribution: 15 - 60 cm

Gravoturbulent fragmentation



Gravoturbulent fragmentation in molecular clouds:

- SPH model with 1.6×10^6 particles
- large-scale driven turbulence
- Mach number $\mathcal{M} = 6$
- periodic boundaries
- physical scaling:

"Taurus":

→ density $n(H_2) \approx 10^2\,\mathrm{cm}^{-3}$

→ $L = 6\,\mathrm{pc}$, $M = 5000\,M_\odot$

(from Ballesteros-Paredes & Klessen, in preparation)

Ralf Klessen: Acireale, May 19, 2005

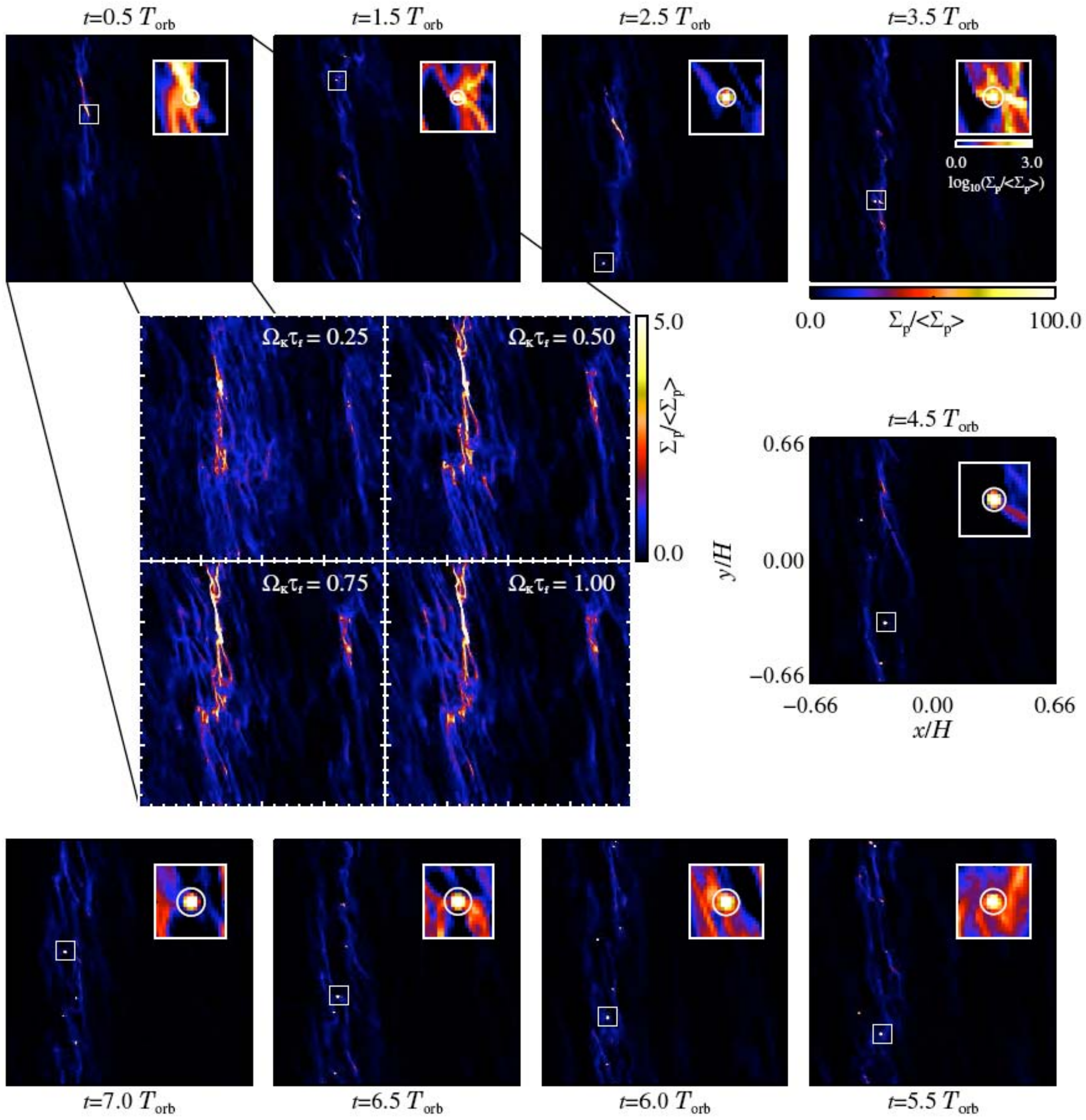
Gravoturbulent star formation

- Dynamic approach to star formation:

Star formation is controlled by interplay between gravity and supersonic turbulence!

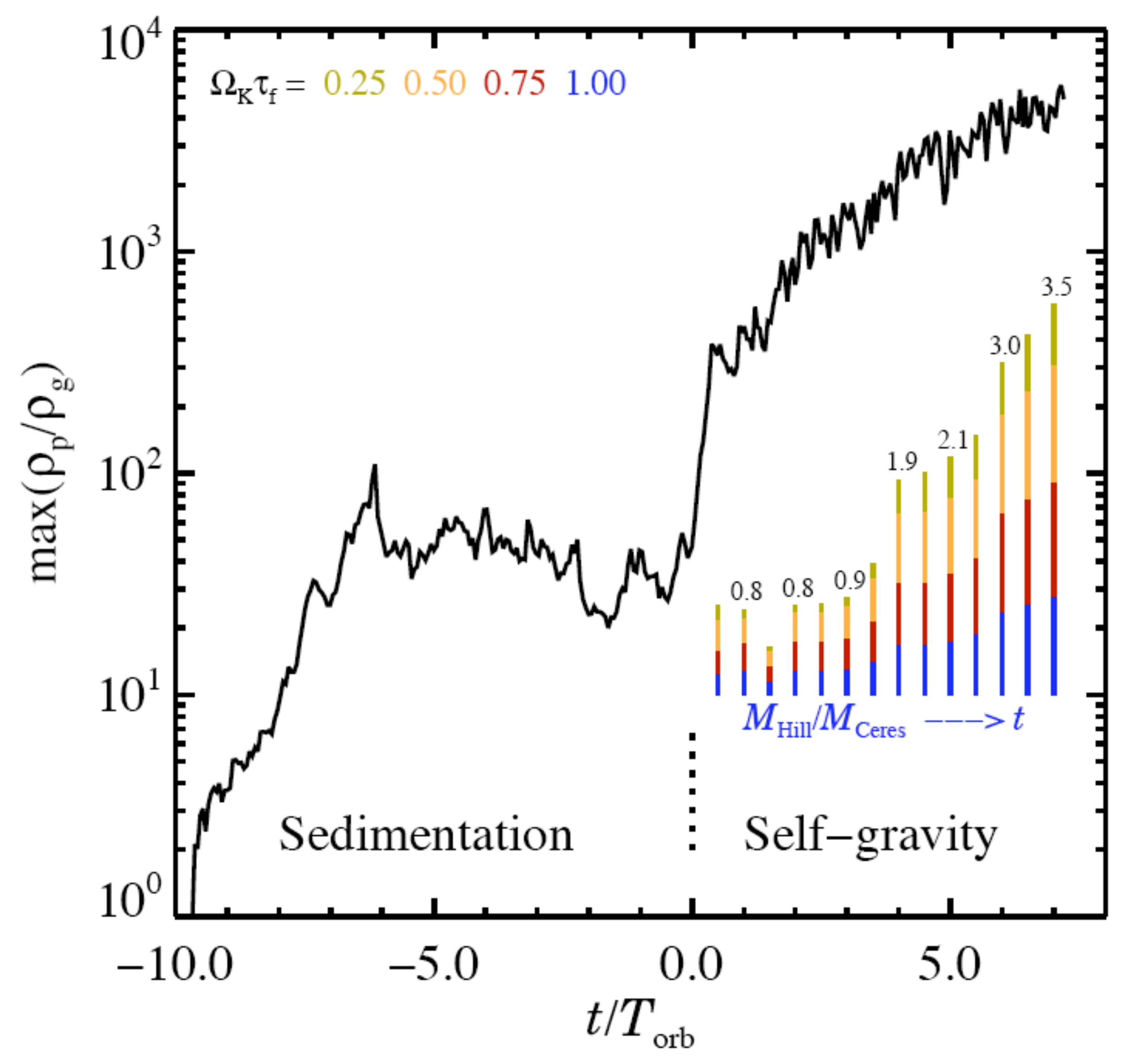
- Dual role of turbulence:
  - *stability on large scales*
  - *initiating collapse on small scales*

(full detail in Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194)

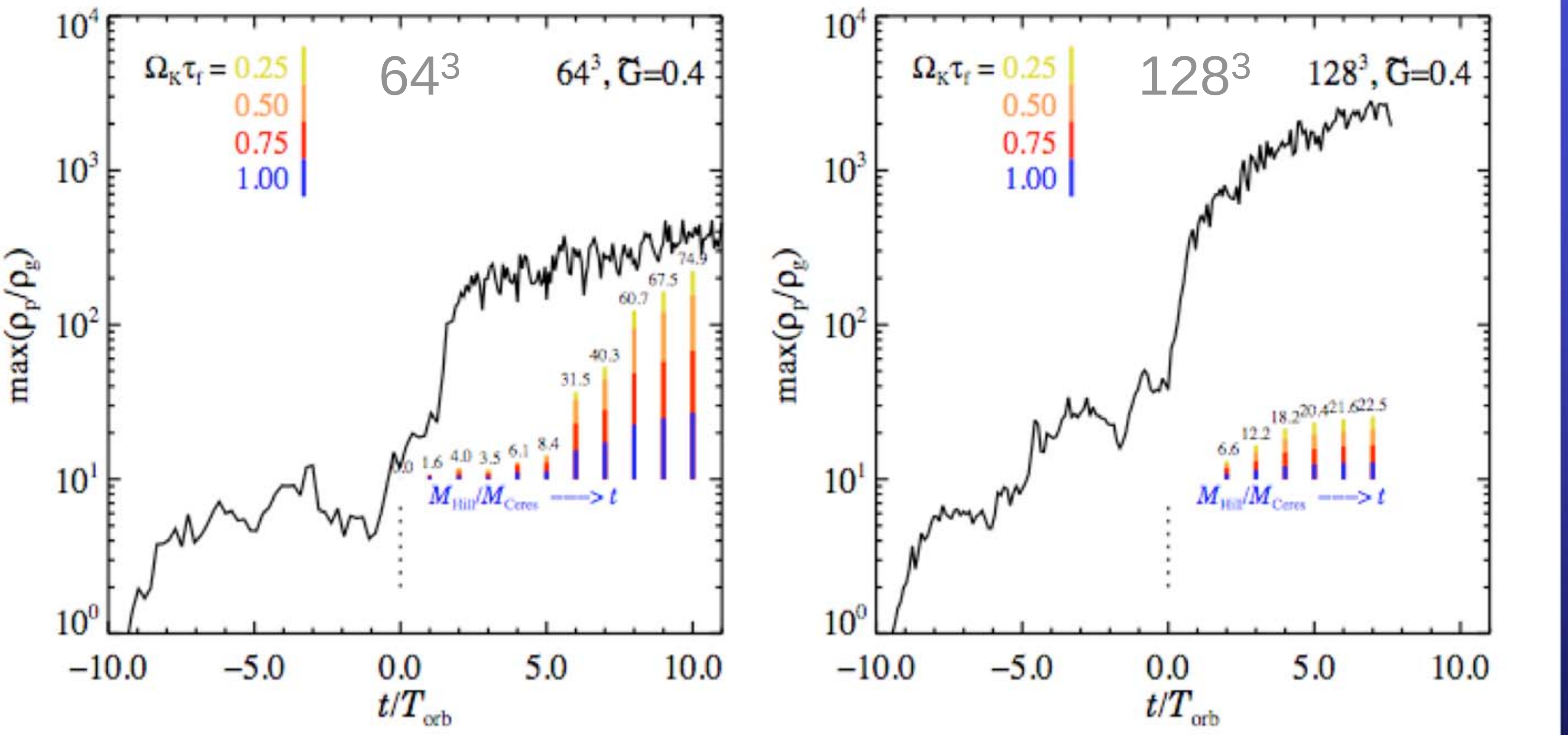


t=0.5 T_orb
t=1.5 T_orb
t=2.5 T_orb
t=3.5 T_orb
0.0
3.0
log10(Σp/<Σp>)
0.0
Σp/<Σp>
100.0
ΩKτf = 0.25
ΩKτf = 0.50
ΩKτf = 0.75
ΩKτf = 1.00
5.0
Σp/<Σp>
0.0
t=4.5 T_orb
0.66
0.00
−0.66
y/H
−0.66
0.00
0.66
x/H
t=7.0 T_orb
t=6.5 T_orb
t=6.0 T_orb
t=5.5 T_orb

Growth of Planetary Core?



Resolution studies:



Higher resolution: smaller cells, higher densities: more planetesimals at lower mass.

For quantitative understanding we need:

1. When do we have where in the disk what number and size distribution of solids?
2. What is when and where the strength of the turbulence? (see Eric's talk)
3. What is the detailed effect of collisional destruction and coagulation during collapse?
4. What is the consequence of leaving out the 10m -> 10km size regime for boulders? Meteoritic evidence?
5. What will the typical masses be in a global disk simulation?

Conclusions:

"We understand qualitatively that Planetesimals can form via gravitational collapse in turbulent disks."

Objects are only slightly larger than in the original *Goldreich-Ward* work. 100-1000 km.

...and now we are working on the quantitative understanding.