Planet formation

Dust in turbulence

Particle concentrations

Kelvin-Helmholtz

Streaming instability

Self-gravity

Conclusions

Planetesimal formation in turbulent protoplanetary discs

Anders Johansen

Max-Planck-Institut für Astronomie, Heidelberg

Stockholm Observatory
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PhD supervisors: Hubert Klahr & Thomas Henning

Planet formation

Planets form in protoplanetary disks from dust grains that collide and stick together (planetesimal hypothesis of Safronov, 1969).

- From dust to planetesimals
  μm $\rightarrow$ m: Contact forces in collisions cause sticking
  m $\rightarrow$ km: ???
- From planetesimals to protoplanets
  km $\rightarrow$ 1,000 km: Gravity
- From protoplanets to planets
  Gas planets: Attract gaseous envelope
  Terrestrial planets: Protoplanets collide

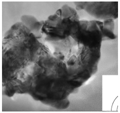 $\rightarrow$  $\rightarrow$  $\rightarrow$ 

Image references:

(1) Andersen et al. (1998); (2) William K. Hartmann

Planetesimals

- *Hypothesised* kilometer-sized objects massive enough to attract each other by gravity (two-body encounters)
- Building blocks of planets
- Formation:
  - μm → cm: Dust grains collide and stick (Blum & Wurm 2000)
  - cm → km: Sticking or gravitational instability (Safronov 1969, Goldreich & Ward 1973)

William K. Hartmann

Planetesimal formation

Problems with forming planetesimals through collisions:

- Macroscopic bodies do not stick (Chokshi, Tielens, & Hollenbach 1993, Benz 2000)
- Radial drift of rocks and boulders in a few 10 orbits of the disc imposes severe time-step constraint (Weidenschilling 1977)

Problems with forming planetesimals by gravitational instability:

- Need to increase solids-to-gas ratio by about factor 10^4
- Global turbulence prevents sedimentation of solids (Weidenschilling & Cuzzi 1993)
- Kelvin-Helmholtz instability caused by sedimentation stirs up mid-plane layer (Goldreich & Ward 1973, Weidenschilling 1980)

Planetesimal formation is an unsolved mystery of modern astrophysics.

Radial drift

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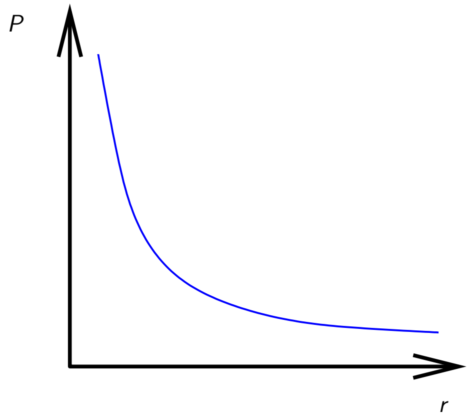

Global pressure gradient:

$P \propto r^{\alpha}$

- Gas feels effectively weaker gravity

  . $\Rightarrow$ sub-Keplerian gas flow
- Solid particles feel sub-Keplerian head wind and lose angular momentum (Weidenschilling 1977)
- Meter-sized objects lost into star in a few hundred orbits

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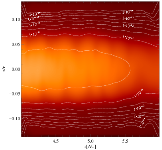
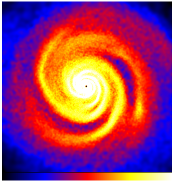
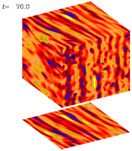
Dust grains are moved around by the turbulent gas in the protoplanetary disk.

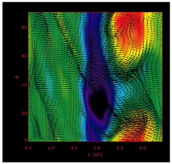
Sources of turbulence:

- Convection (Lin & Papaloizou 1980)
- Self-gravity (Toomre 1964)
- Magnetic fields (Balbus & Hawley 1991)
- Baroclinic conditions (Klahr & Bodenheimer 2003)
- . . .



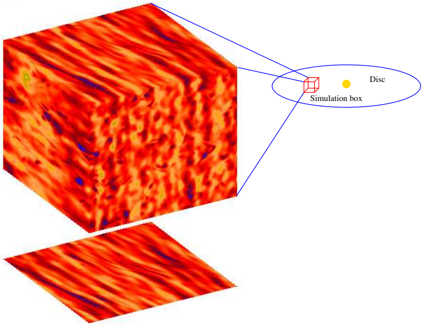






Magnetorotational turbulence

Robust and *reliable* source of turbulence in protoplanetary discs with a sufficient degree of ionization.



Shearing box, no vertical gravity on the gas.

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

Dust dynamics

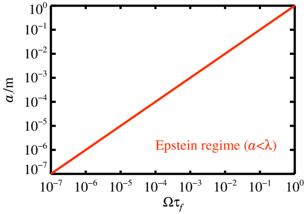
Gas accelerates dust through drag force:

$$\frac{\partial \mathbf{w}}{\partial t} = \ldots - \frac{1}{\tau_{\rm f}}(\mathbf{w} - \mathbf{u})$$

Dust velocity

Gas velocity

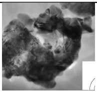
Particle radius a versus friction time $\tau_{\rm f}$ (at $r = 5$ AU):



Important nondimensional parameter: $\Omega_{\rm K}\tau_{\rm f}$ (*Stokes number*).

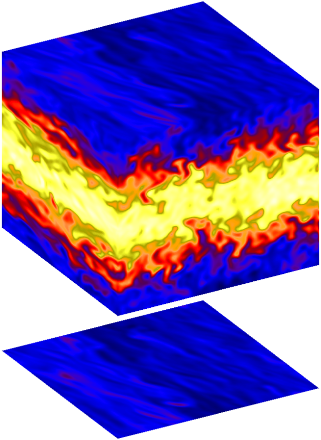
Dust nomenclature

- My suggestion for naming solid particles (not official):

Diameter	Name	
<1 mm	Dust (chondrules, matrix)	
1 mm	Sand	
1 cm	Pebble, gravel	
10 cm	Cobble, rock	
1 m	Boulder	

Sedimentation of solids

Dust grains fall to the mid-plane of a magnetorotationally turbulent disc:



A balance between settling and turbulent diffusion sets in.

Diffusion-sedimentation equilibrium

Diffusion-sedimentation equilibrium:

$$\frac{H_{\rm solids}}{H_{\rm gas}} = \sqrt{\frac{\delta_{\rm t}}{\Omega_{\rm K}\tau_{\rm f}}}$$

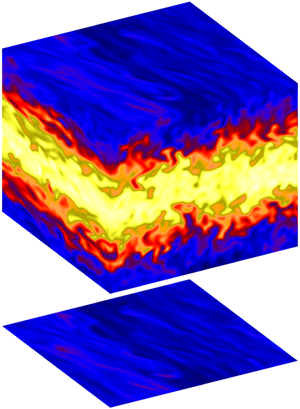
$H_{\rm solids}$ = scale height of solids-to-gas ratio

$H_{\rm gas}$ = scale height of gas

$\delta_{\rm t}$ = turbulent diffusion coefficient, like α-value

$\Omega_{\rm K}\tau_{\rm f}$ = Stokes number, proportional to radius of solid particles

(Johansen & Klahr 2005; Johansen, Klahr, & Mee 2006)



Solids as particles

One can treat solids as a fluid:

Solids are represented by a scalar density field $\rho_{\rm d}(x,y,z)$ and a vector field velocity $\mathbf{w}(x,y,z)$

$$\begin{aligned}\frac{\partial \mathbf{w}}{\partial t} + (\mathbf{w}\cdot\boldsymbol{\nabla})\mathbf{w} &= \mathbf{F}\\ \frac{\partial \rho_{\rm d}}{\partial t} + (\mathbf{w}\cdot\boldsymbol{\nabla})\rho_{\rm d} &= -\rho_{\rm d}\boldsymbol{\nabla}\cdot\mathbf{w}\end{aligned}$$

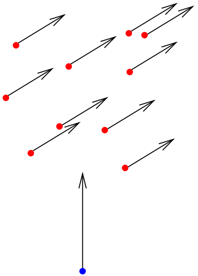
... or as numerical particles: (actually *superparticles*)

Solids are treated as individual bodies each with a velocity vector $\mathbf{v}_i$ and a freely developing space coordinate $\mathbf{x}_i$.

$$\begin{aligned}\frac{\partial \mathbf{v}_i}{\partial t} &= \mathbf{F}_i\\ \frac{\partial \mathbf{x}_i}{\partial t} &= \mathbf{v}_i\end{aligned}$$

Fluid or particle?

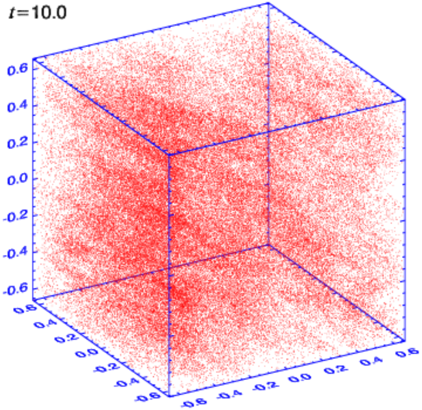
Only bodies with some mechanism for localising the flow can be treated as a fluid:



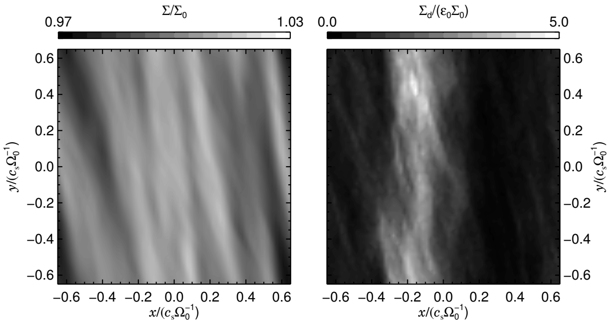
- Solids can be treated as a fluid when the friction force is strong. Valid for small dust grains ($\tau_{\rm f} \ll \Omega_{\rm K}^{-1}$).
- Macroscopic solids are important for planet formation. Then fluid description is no longer valid.

Particle concentrations

Johansen, Klahr, & Henning (2006): 2,000,000 solid particles in magnetorotational turbulence.

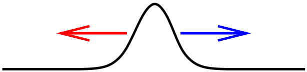


Gas density bumps

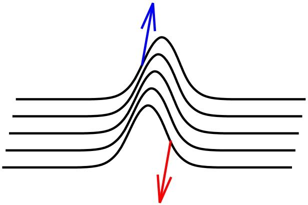


- Strong correlation between high gas density and high particle density.
- Solid particles are caught in gas overdensities (Klahr & Lin 2001, Haghighipour & Boss 2003)
- Gravoturbulent formation of planetesimals

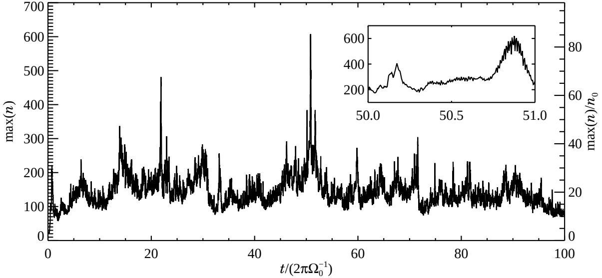
Pressure gradient trapping

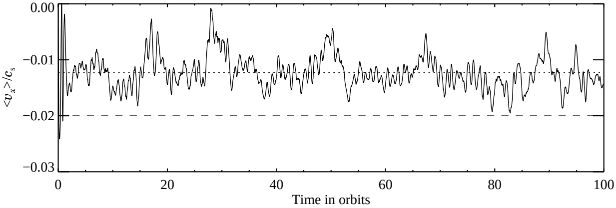


- Outer edge:
  Gas sub-Keplerian. Particles forced by gas drag to move inwards.
- Inner edge:
  Gas super-Keplerian. Particles forced by gas drag to move outwards.



Max density/radial drift





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Question:

What if there is no global source of turbulence in protoplanetary discs?

Can solid particles then fall freely to the mid-plane and form an infinitesimally thin layer?

Answer:

Question:

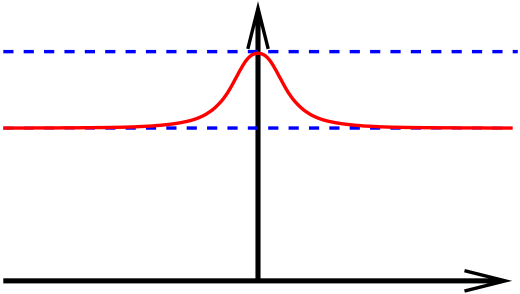
What if there is no global source of turbulence in protoplanetary discs?

Can solid particles then fall freely to the mid-plane and form an infinitesimally thin layer?

Answer:

No way!

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 particles)
- Vertical shear is unstable to Kelvin-Helmholtz instability
- Subsequent turbulence lifts up the particle layer and reduces the particle density in the mid-plane

Richardson number

$$\mathrm{Ri} = \frac{g_z \partial \ln(\rho_\mathrm{g} + \rho_\mathrm{p})/\partial z}{(\partial u_y/\partial z)^2} \, .$$

Stabilising effects:	g_z	(=vertical gravity)
	$\partial \ln(\rho_\mathrm{g} + \rho_\mathrm{p})/\partial z$	(= stratification)
Destabilising effects:	$\partial u_y/\partial z$	(=vertical shear)

Litterature:

Chandrasekhar (1964):

Flows with $\mathrm{Ri} < 1/4$ are unstable, otherwise stable to KHI.

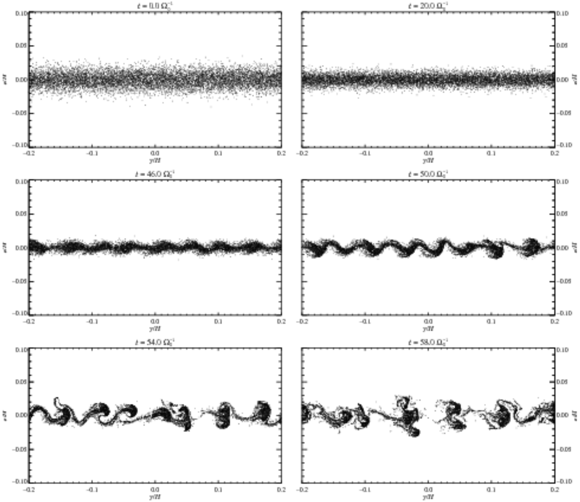
Sekiya (1998):

The particle sedimentation will create a $\mathrm{Ri} = 1/4$ flow.

Other works: Weidenschilling (1980); Nakagawa, Sekiya & Hayashi (1986); Weidenschilling & Cuzzi (1993); Cuzzi, Dobrovolskis & Champney (1993); Youdin & Shu (2002); Gómez & Ostriker (2005)

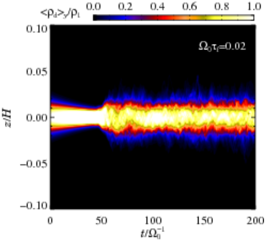
Kelvin-Helmholtz simulations

Johansen, Henning, & Klahr (2006)

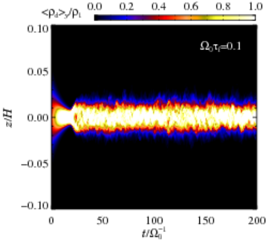


Particle density

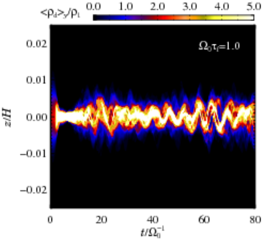
Pebbles (cm)



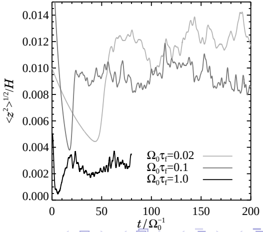
Rocks (dm)



Boulders (m)



Scale height vs. t



Average density

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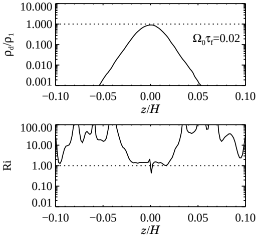
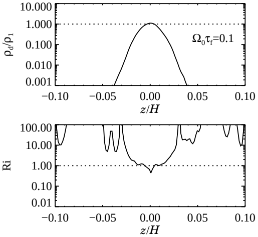
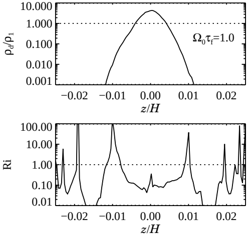
Pebbles

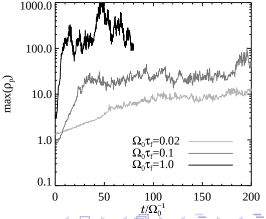


Rocks



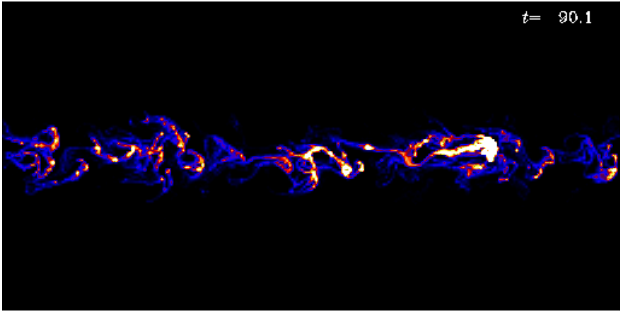
Boulders





Clumping movie

Particle density contours of cm-sized pebbles:
(black=no particles, blue=few particles, bright=lots of particles):

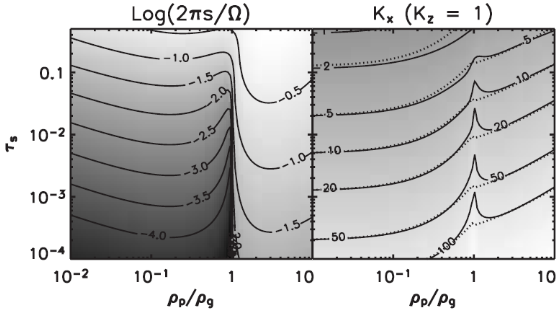


← Sub-Keplerian flow

- The particles density is very non-axisymmetric.

Streaming instability

Youdin & Goodman (2005) :
"Streaming Instabilities in Protoplanetary Disks"



The secret behind the linear instability:

$$w_r = w_r(\epsilon)$$

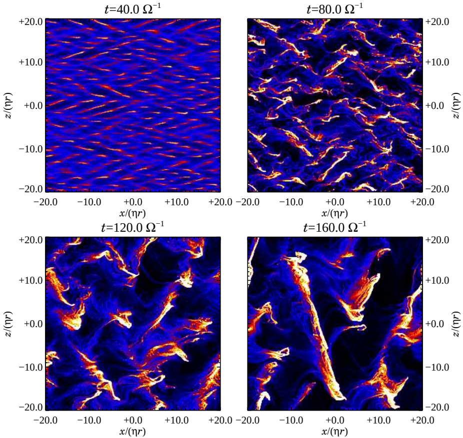
$$w_\phi = w_\phi(\epsilon)$$

Particle velocity depends on solids-to-gas ratio ϵ

(Nakagawa, Sekiya, & Hayashi 1986).

Streaming instability movie

Linear and non-linear evolution of meter-sized boulders ($\Omega_{\mathrm{K}}\tau_{\mathrm{f}} = 1$) with a background dust-to-gas ratio of 0.2:



The radial drift flow of solids is linearly unstable!

(Youdin & Johansen, Johansen & Youdin, submitted)

Streaming instability 3-D

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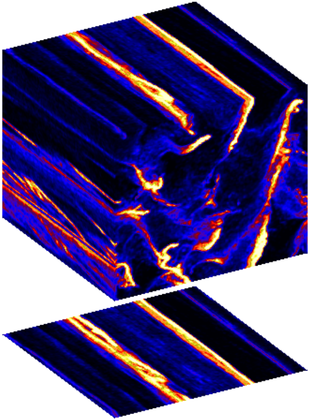
Grid resolution of 128^3, 20,000,000 superparticles, running on 64 processors.



The turbulent diffusion coefficient of the flow is $\delta_{\rm t} = 0.02$ and the Mach number Ma$= 0.05$! Comparable to the strength of MRI turbulence.

Self-gravity

New term in equation of motion of the particles:

$$\frac{\mathrm{d}\boldsymbol{v}_i}{\mathrm{d}t} = \ldots - \boldsymbol{\nabla}\Phi_{\mathrm{self}}$$

The gravitational potential of the particles Φ_{self} is found by solving the Poisson equation

$$\nabla^2\Phi_{\mathrm{self}} = 4\pi G\rho_{\mathrm{par}}$$

We have developed a fully parallel shearing sheet Poisson equation solver. Technical details:

- Solids are treated as particles
- Gravity potential is solved on the mesh using FFT method
- Triangular Shaped Cloud assignment/interpolation scheme (Hockney & Eastwood 1981)
- Much faster than N-body, but resolution limited by mesh

Collaboration with Jeff Oishi and Mordecai Mac Low at the American Museum of Natural History in New York.

The ultimate simulation

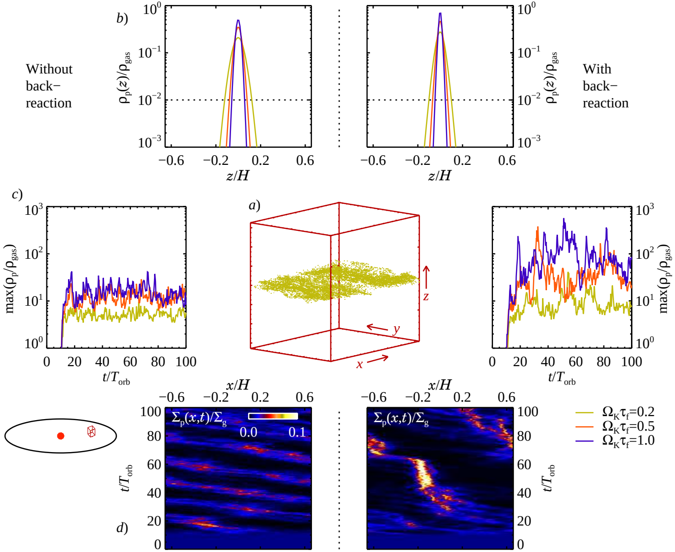
Combine known effects (but never studied together):

- Magnetorotational turbulence
- Sedimentation
- Concentrations in turbulent overdensities
- Streaming instability

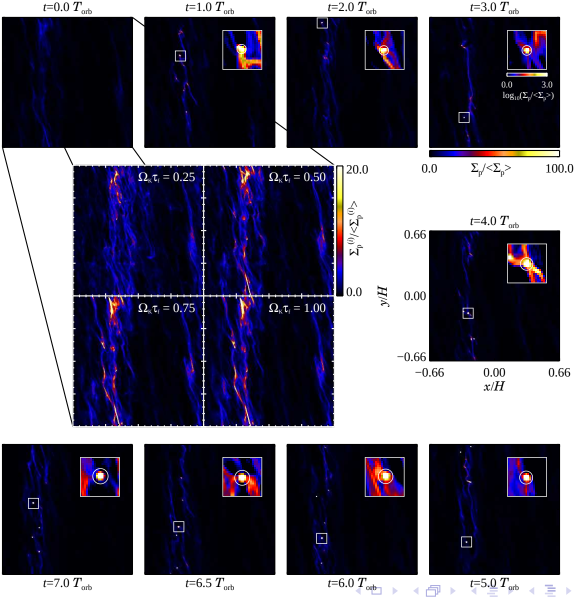
with some new physics:

- Self-gravity of boulders
- Several particle sizes
  Radii from 10 cm to 40 cm
  Differential radial drift of different particle sizes potentially disrupts gravitational collapse (Weidenschilling 1995)
- Collisional cooling
  Collisions between boulders dynamically important for solids-to-gas ratio $\gtrsim 10 \ldots 100$.
  Collisions are highly inelastic $\Rightarrow$ local rms speed of particles damped on collisional time-scale

Topography of the mid-plane layer

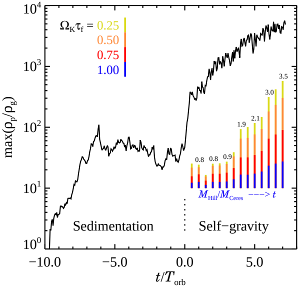


Clump condensation



Accretion

- Turbulent concentrations and streaming instability interact constructively and produce overdensities of several 100 in the mid-plane layer
- Dense clumps condense out even in solar nebula
- Collisional cooling plays an important role in keeping the "temperature" of the particles down
- Differential radial drift of different particle sizes does not disrupt the collapse (Weidenschilling 1995).



Johansen, Oishi, Mac Low, Klahr, Henning, & Youdin (submitted)

“Gravoturbulent” picture of planetesimal formation

- Initially μm dust grains grow into 10 cm - 1 m boulders
- The boulders have formed a dense mid-plane layer with an average solids-to-gas ratio of around unity (up from interstellar 0.01)
- Transient overdensities in the turbulent flow concentrate particles by peak factor 10-100
- Radial drift flow of particles becomes unstable to streaming instability, clumping by additional factor 10
- Collisional cooling keeps the “temperature” of the boulders down, transient overdensities reduce differential radial drift
- Direct formation of 1000 km bodies by self-gravity