PARTICLE-LADEN FLOWS IN ASTROPHYSICS: FROM DUST TO PLANETS

(A REVIEW FOR NON-ASTROPHYSICISTS)

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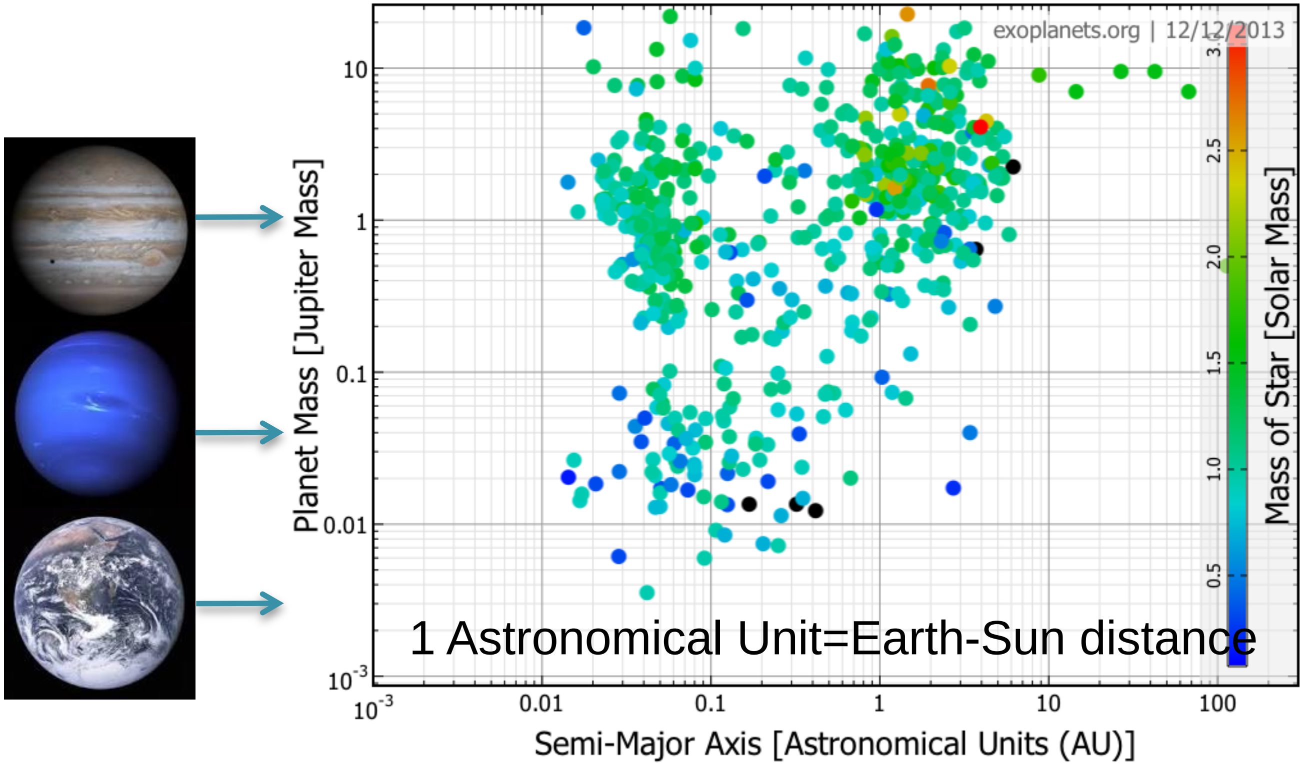
Artist’s impression, D. Darling

Outline

- Evidence and constraints on planet formation
- From dust to pebbles
- From pebbles to planetesimals.

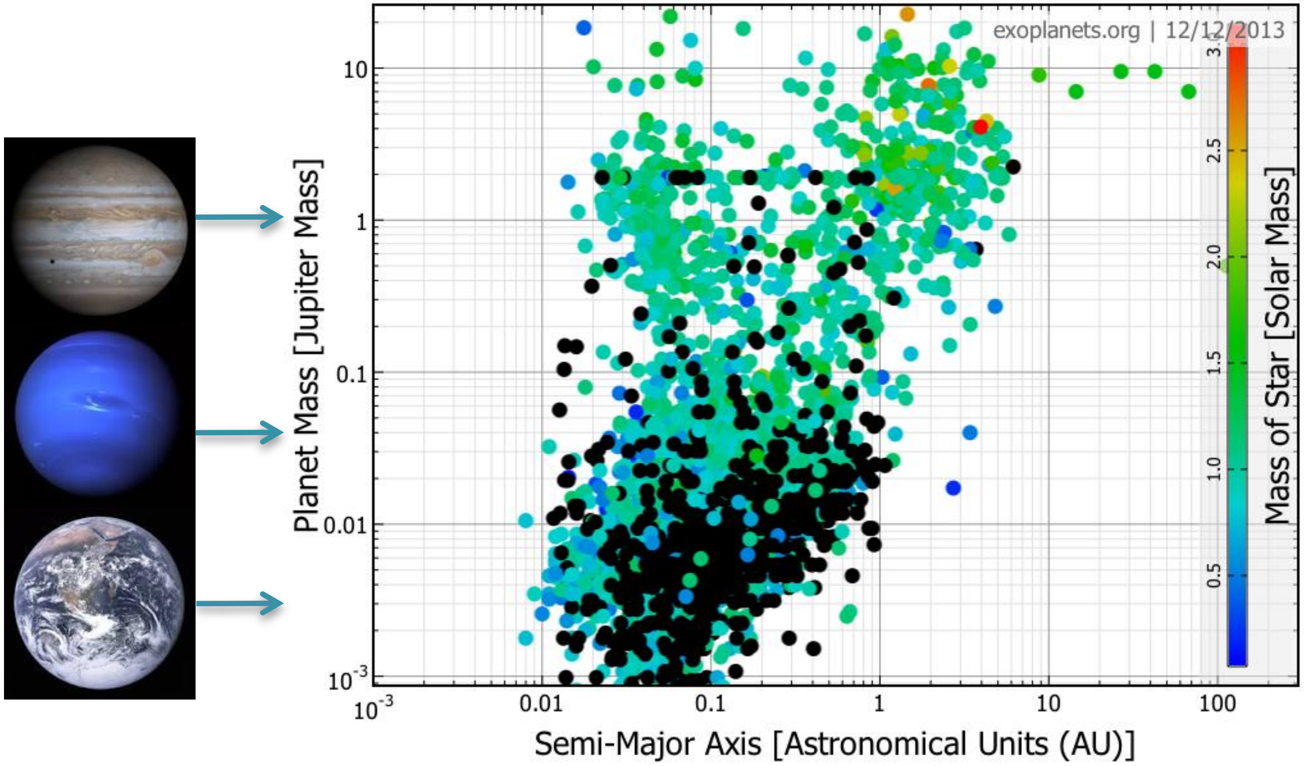
So many planets !



1 Astronomical Unit=Earth-Sun distance

Many planets have been discovered, at all distances from the star, with wide range of masses, types, etc..

So many planets !



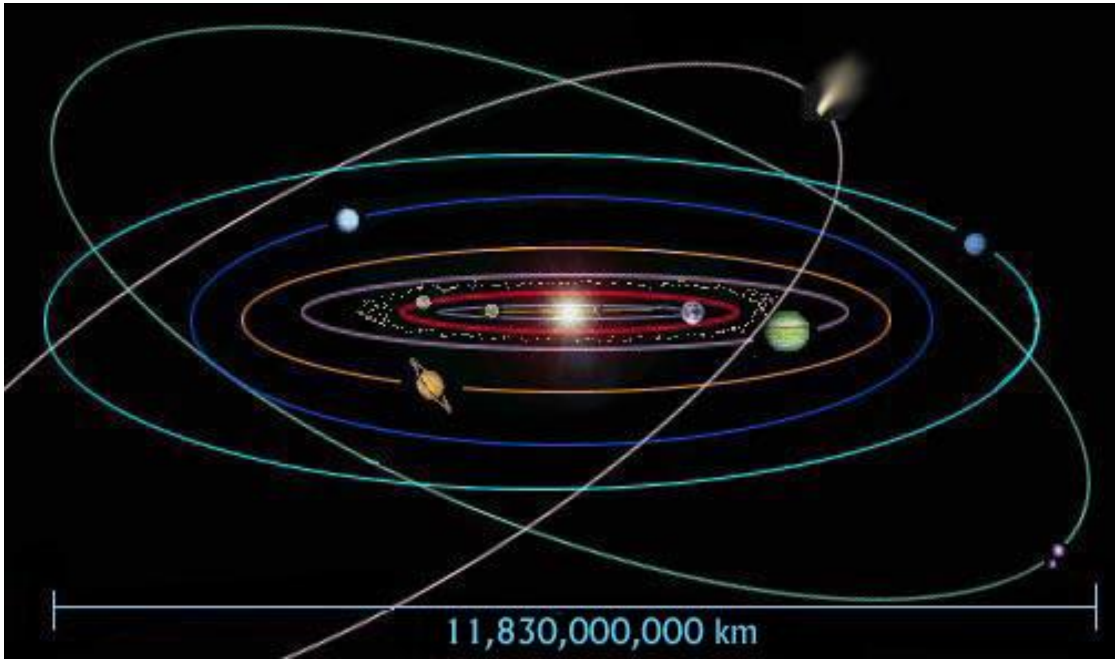
Many planets have been discovered, at all distances from the star, with wide range of masses, types, etc..

Many more planetary candidates from KEPLER**.**

Most stars seem to have planets, with huge diversity in planetary systems discovered.

Protoplanetary disks

- Many planetary systems are coplanar.

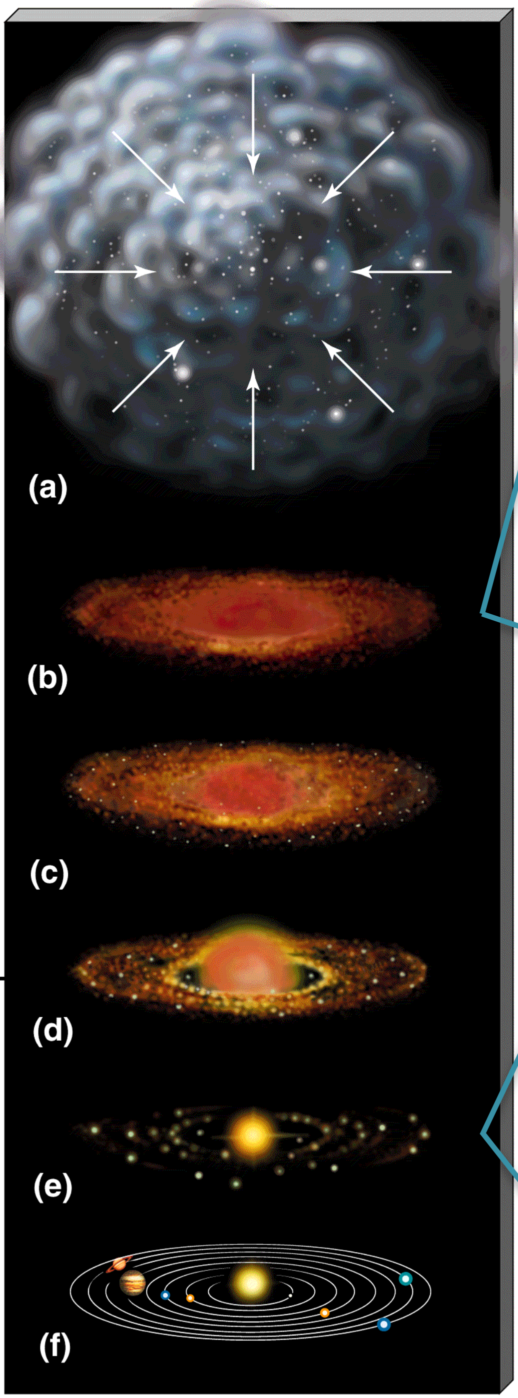


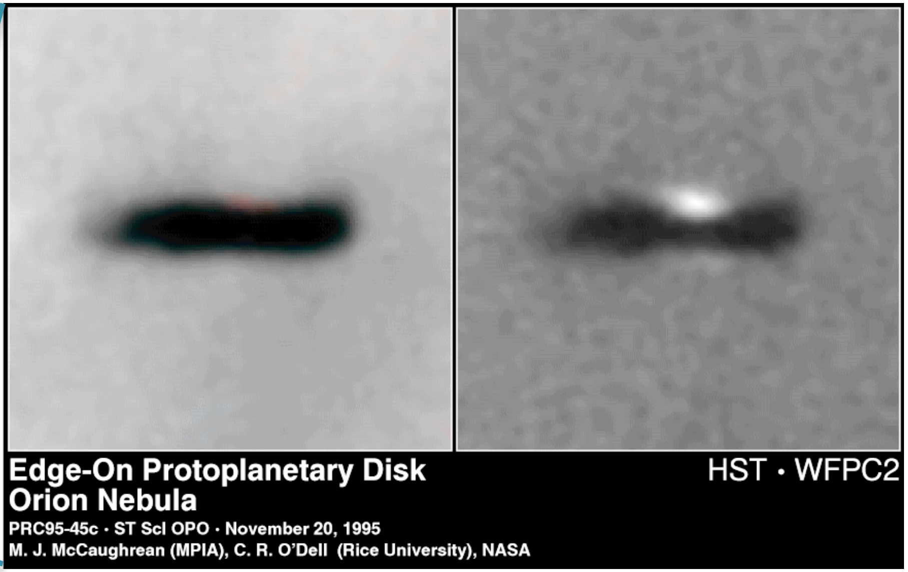
- This observation led to the theory that all planets are formed in dusty disks around young stars.

DUST

PLANETESIMAL

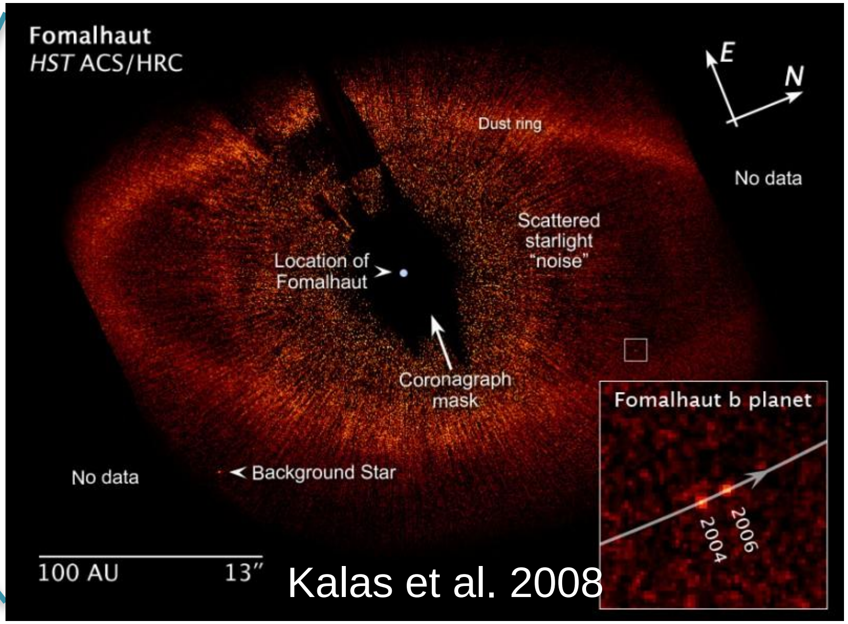
PLANETS




Edge-On Protoplanetary Disk
Orion Nebula

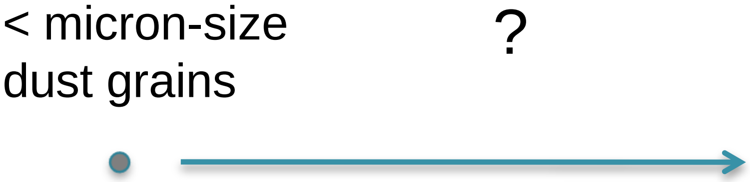
HST • WFPC2

PRC95-45c • ST ScI OPO • November 20, 1995
M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA



Kalas et al. 2008

From dust to planetesimals



< micron-size
dust grains

?

10km-size planetesimals

- One of the most significant unsolved problems in astrophysics
- Involves the study of “particle-laden” flows (dust-laden gas)

From dust to planetesimals

- Involves the study of “particle-laden” flows (dust-laden gas)
- Bears many similarities with Earth-based particle-laden fluids: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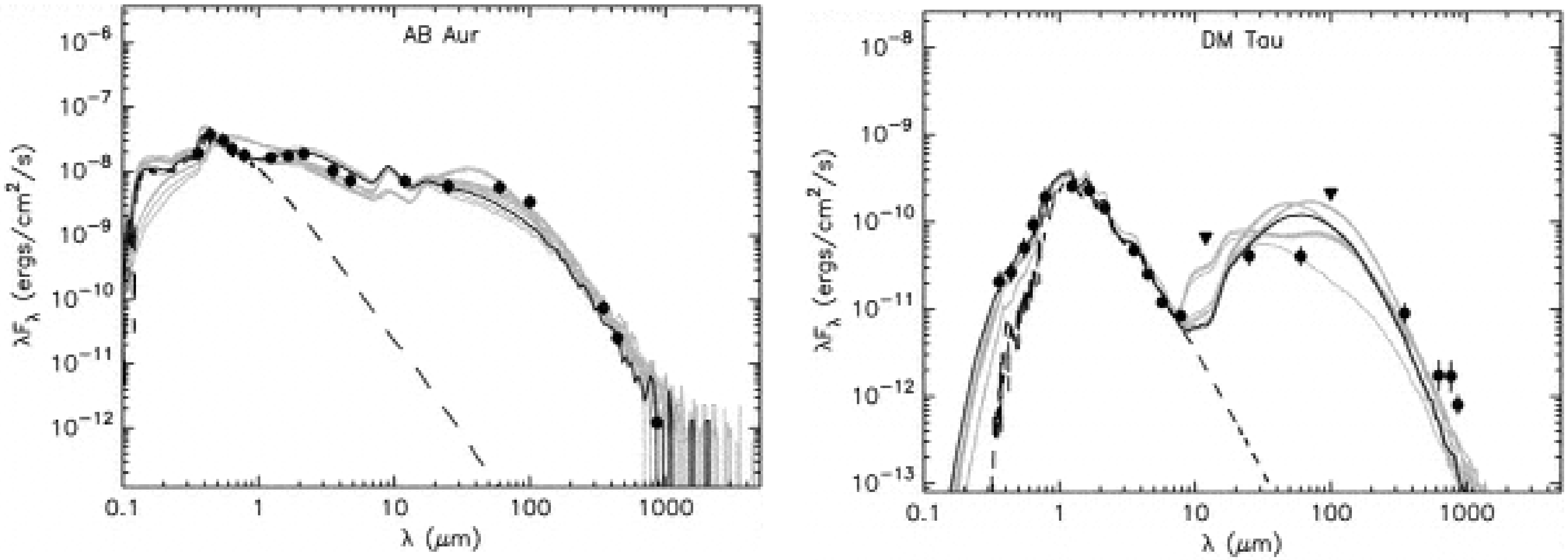
Observational constraints

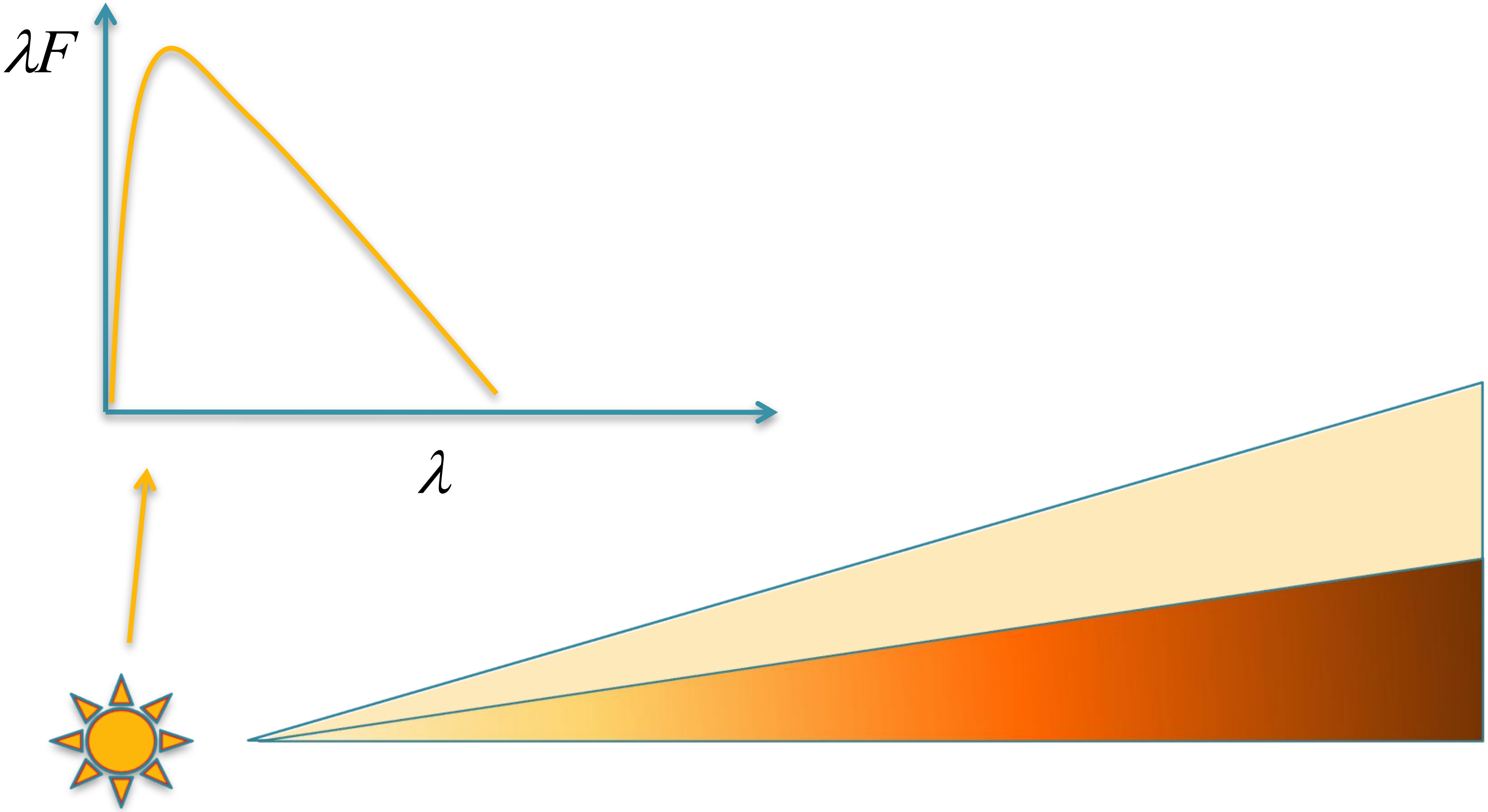
- Very few stars are close-enough for us to get spatially-resolved images. In general, the star & disk appear as point-sources of light.
- However, information about the disk and its dust content can still be obtained from Spectral Energy Distributions.



Robitaille et al. 2006

Observational constraints

- The SED is a composite of the light-spectrum emitted from all the different regions of the disk. It provides information about the amount, location and size of the dust grains in the disk



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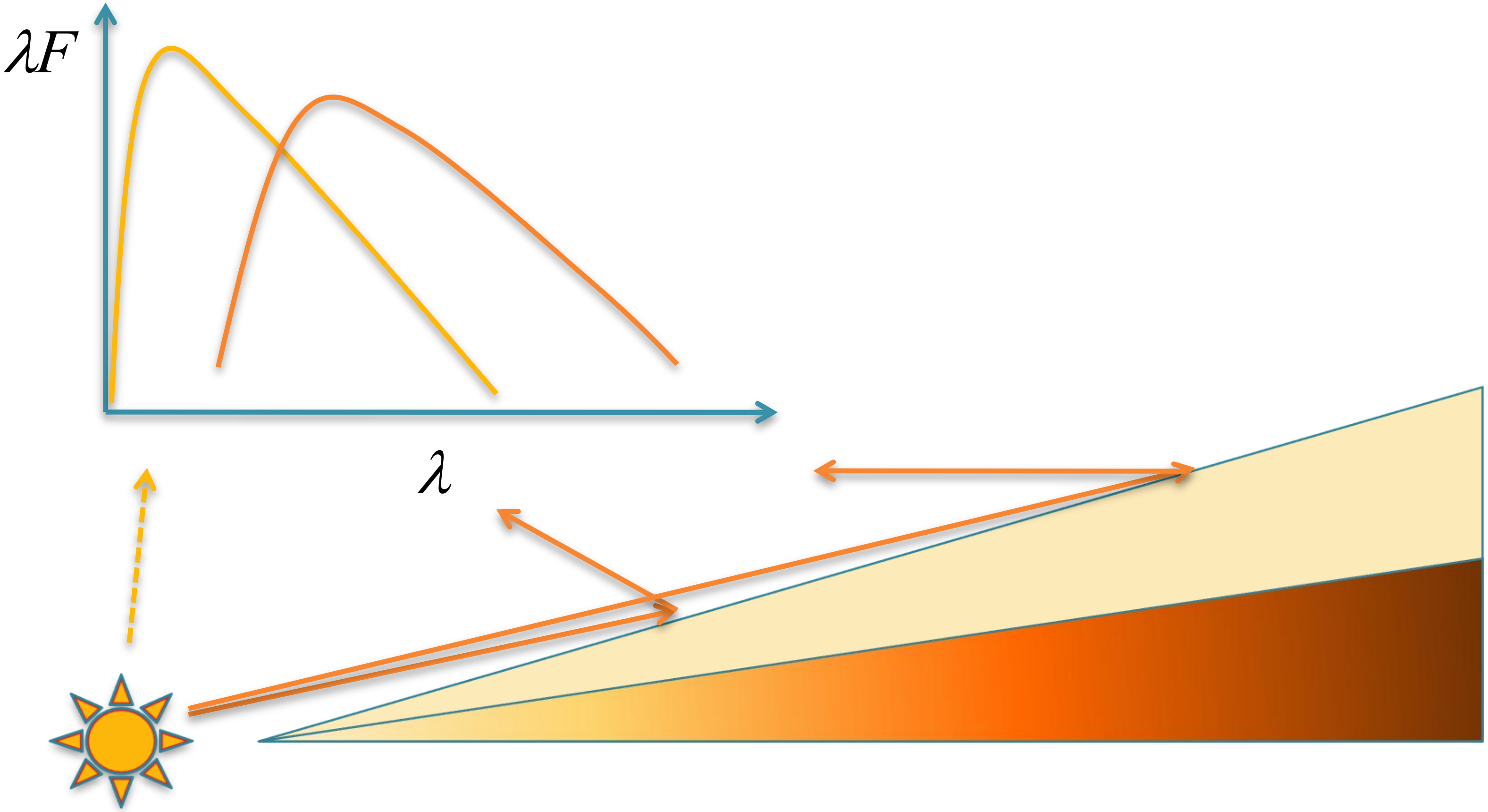

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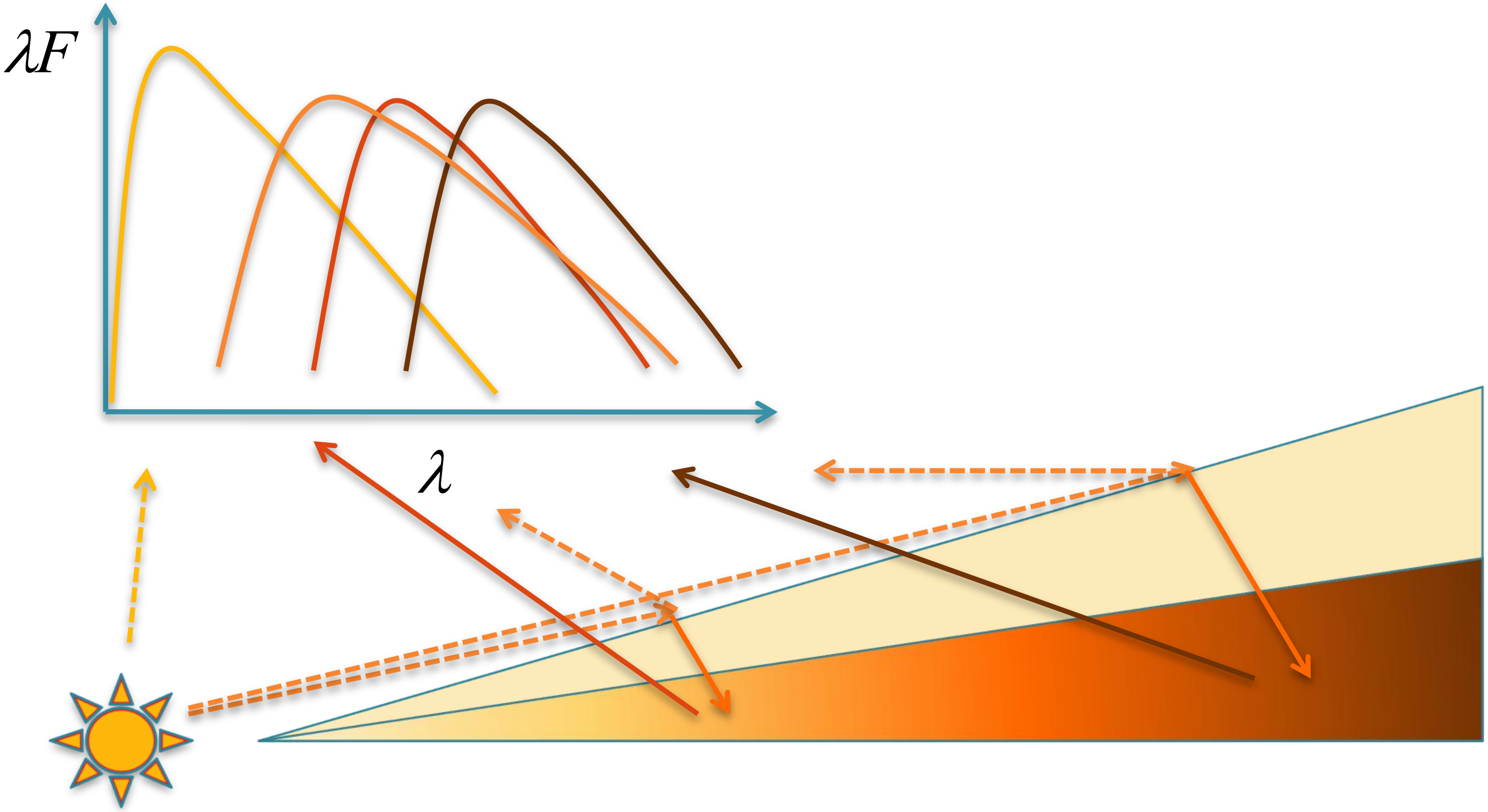

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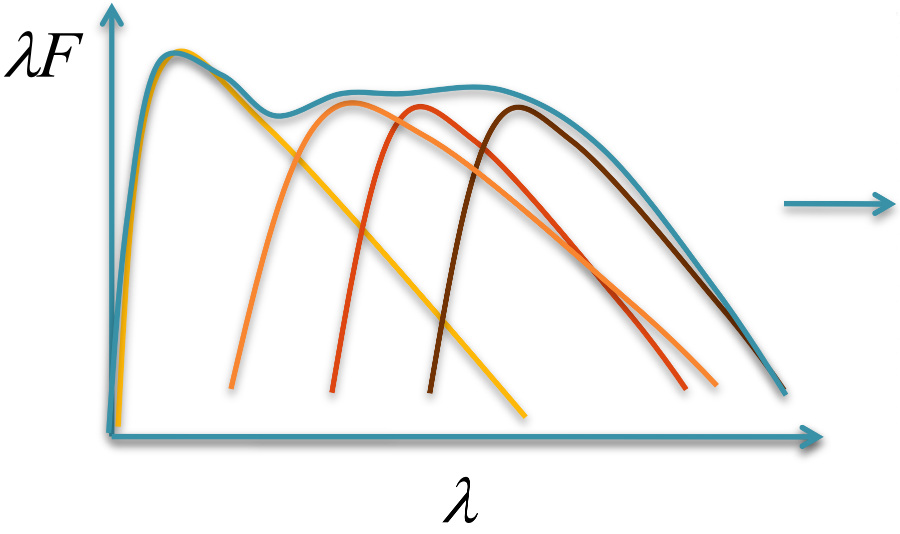

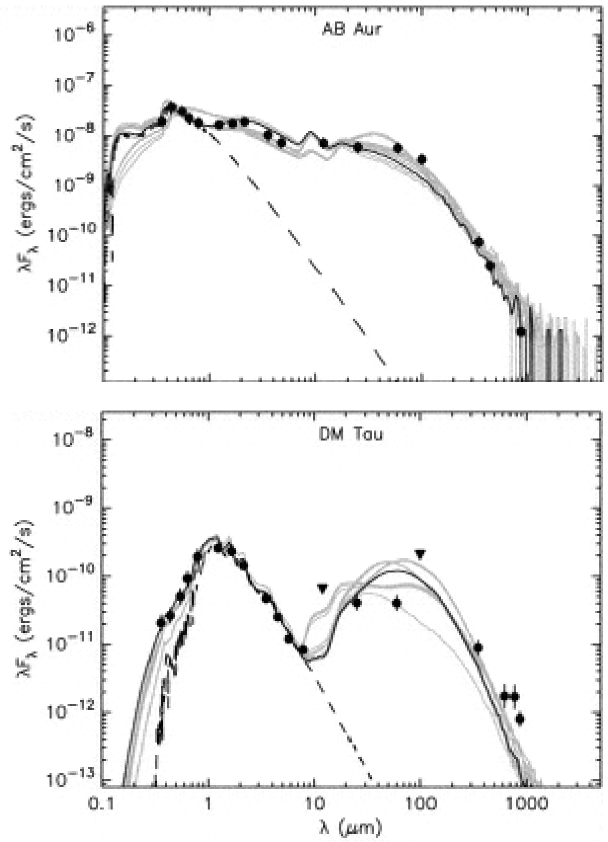

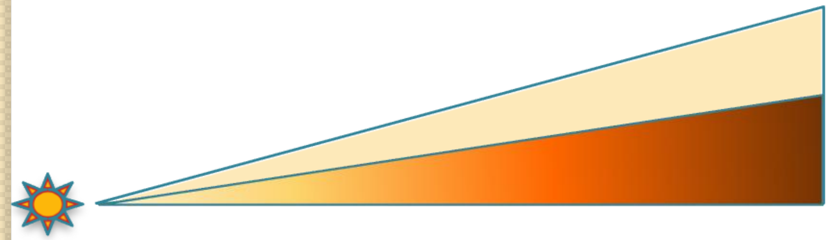

Robitaille et al. 2006

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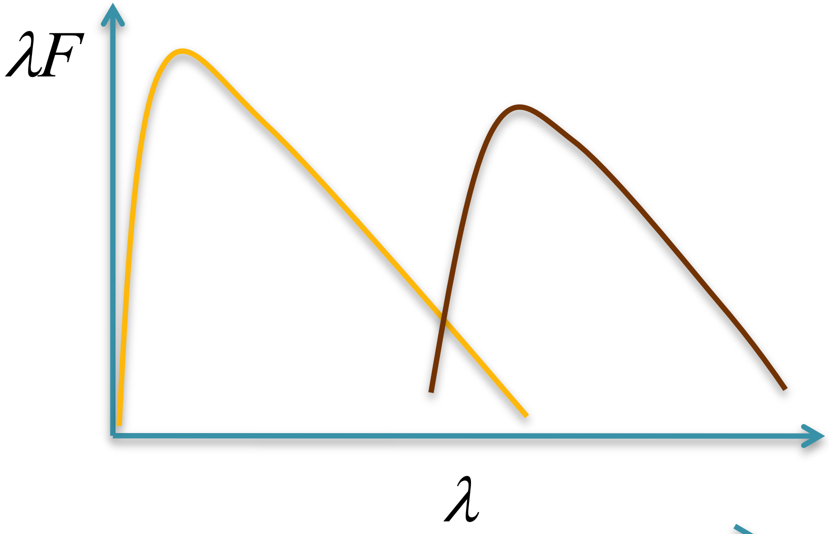
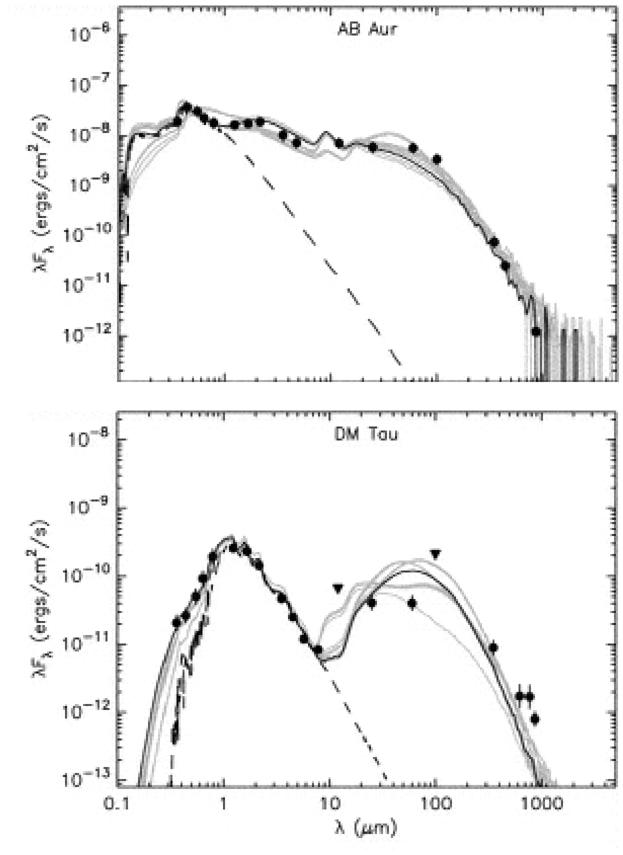
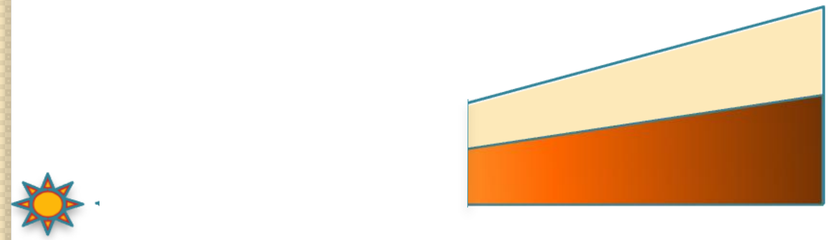


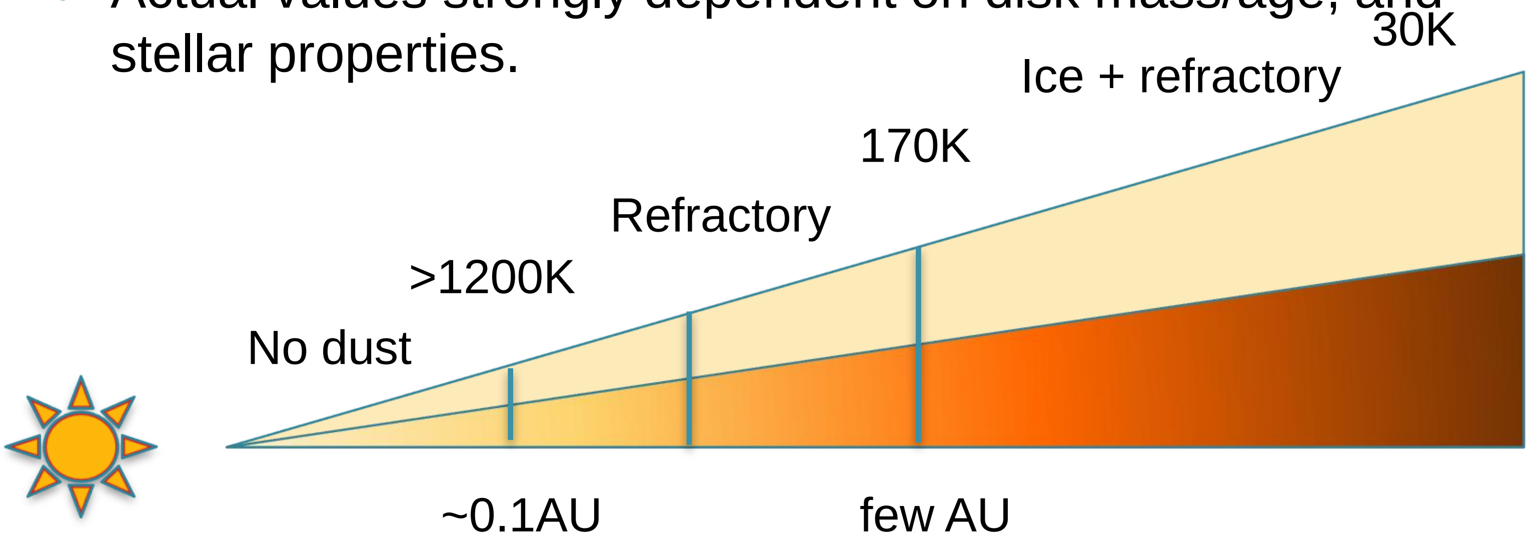


Robitaille et al. 2006



Observational constraints

- Temperature in the disk spans wide range, that includes “snow-line”
- Dust composition varies accordingly.
- Beyond snow line, mean dust-to-gas mass ratio roughly equal to stellar heavy element content (0.5-5%)
- Actual values strongly dependent on disk mass/age, and stellar properties.



30K

Ice + refractory

170K

Refractory

>1200K

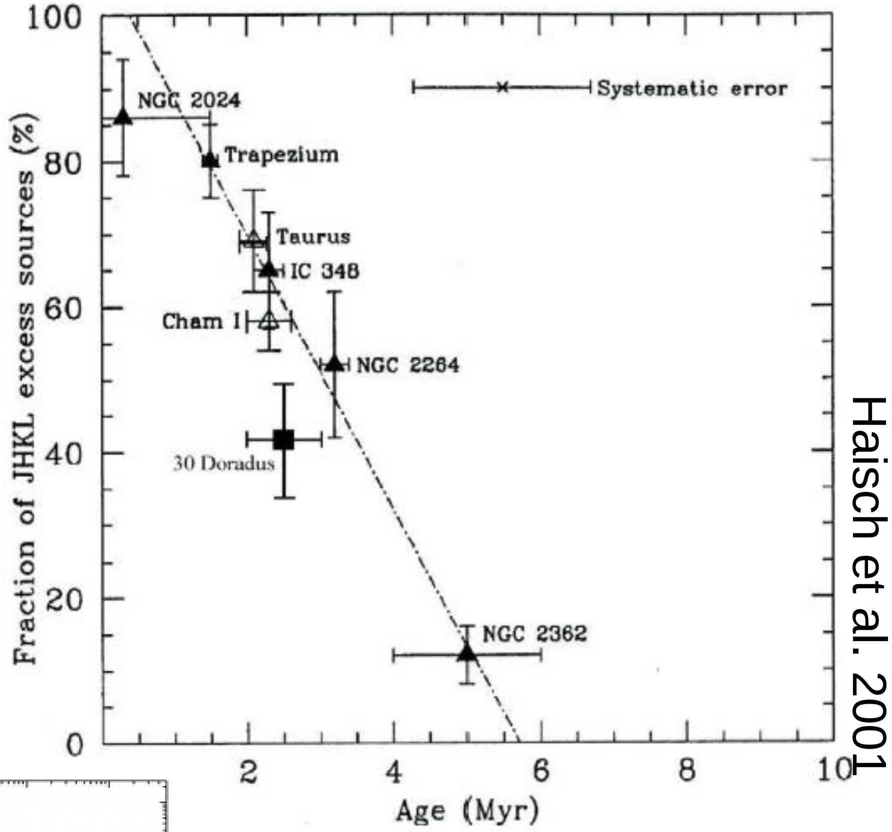
No dust

~0.1AU

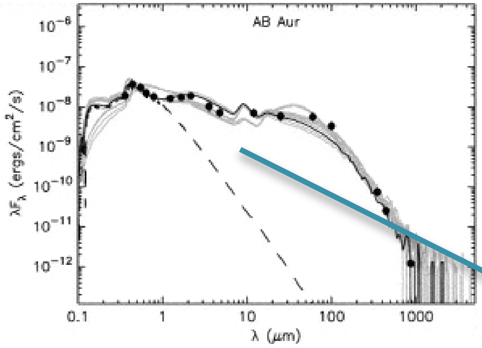
few AU

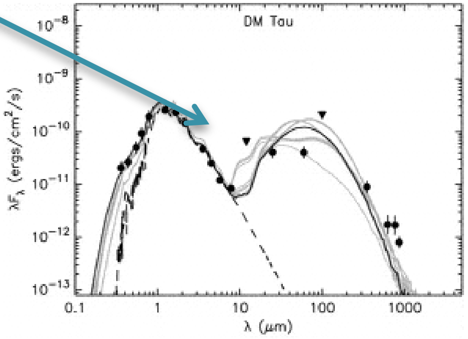
Observational constraints

- The disappearance of inner disks on <10Myr timescale places constraints on timescale for planet formation : dust must grow relatively rapidly into planetesimals.



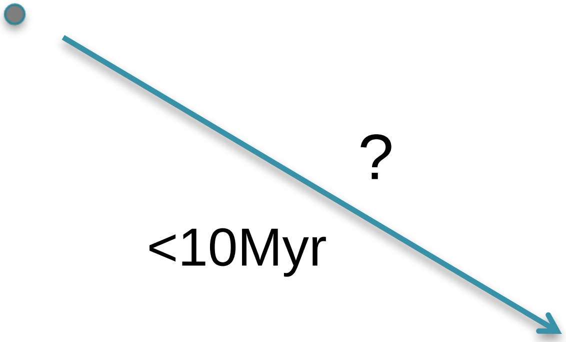
Haisch et al. 2001





The problem

micron-size



?

<10Myr

10km-size

The problem

Particles grow by sticky collisions.

Given a mass distribution function of particles N(m), local growth modeled as:

$$\frac{dN(m)}{dt} = \int K(m;m',m'')N(m')N(m'')dm'\,dm'' - \int F(m,m')N(m')dm'$$

where K, F are coagulation and fragmentation Kernels, related to
- cross section of collision
- probability of coagulation/fragmentation
- probability distribution of the relative velocity of particles during collision

The key to answering the growth problem is to understand each of the following processes:
  - the motion of dust particles, and in particular the relative velocities of colliding particles

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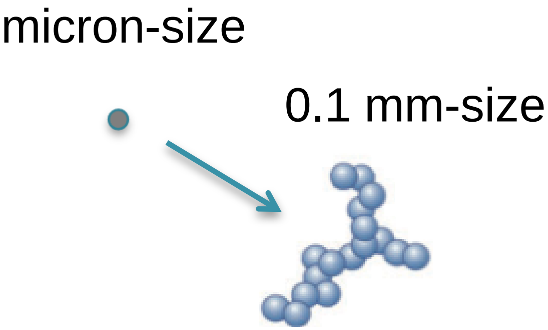
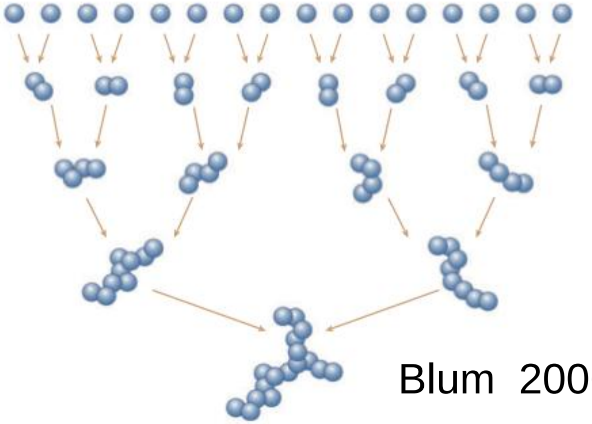
The problem



The first steps of dust growth into planetesimals occurs via Brownian motion.

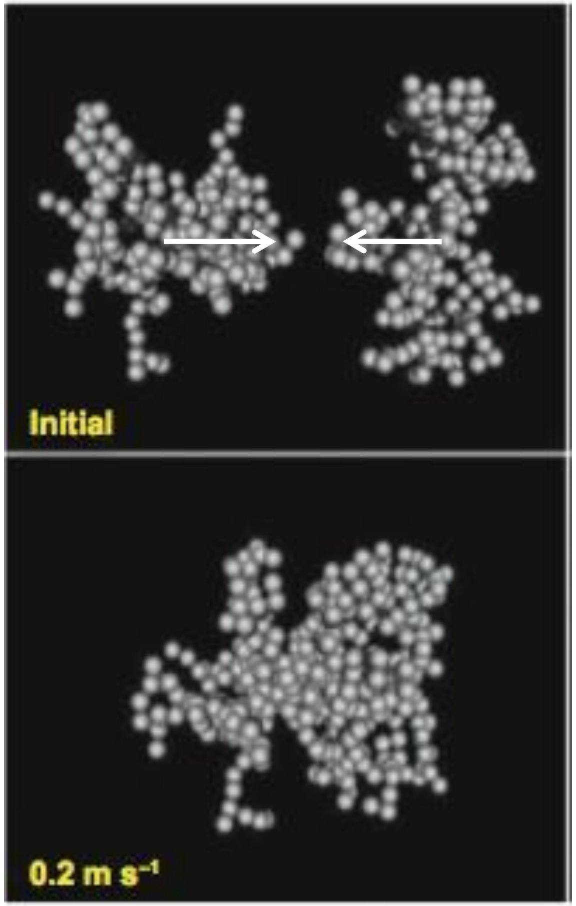
Brownian motion

- Dust particles in gas disk, undergo Brownian motion, collisions are typically low velocity, sticky.
- Drives growth of small fractal grains



Blum 2006

- Further collisions can lead to compactification.



Paszun & Dominik 2006

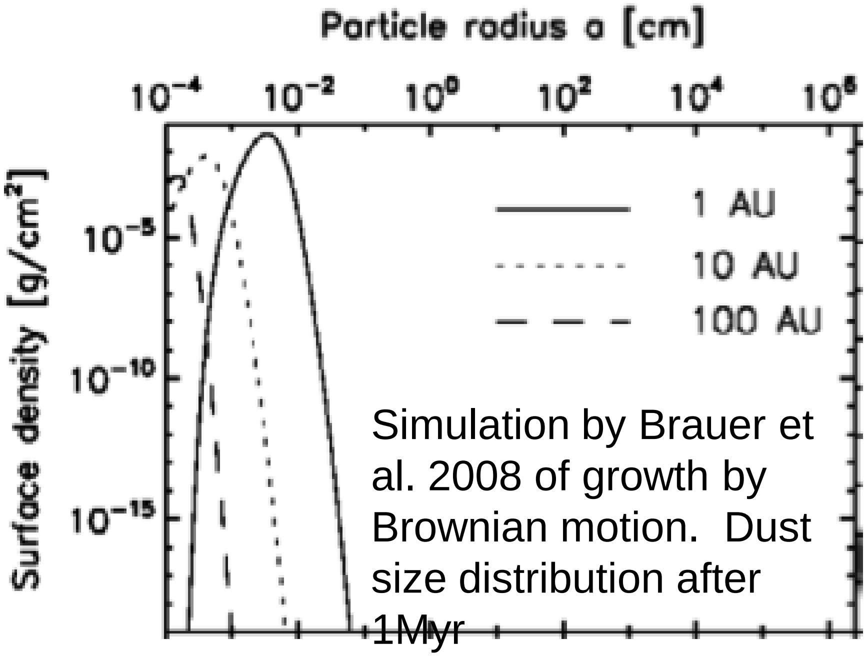
Brownian motion

Growth timescale for Brownian motion:

$$\frac{dm}{dt} = \rho_p v s^2 \approx \rho_p \sqrt{\frac{16kT}{\pi m}} \left(\frac{3m}{4\pi\rho_s} \right)^{2/3} \quad \rightarrow \quad \tau_B = \frac{m}{dm/dt} = \frac{m^{5/6}}{4\rho_p \sqrt{\frac{kT}{\pi}} \left(\frac{3}{4\pi\rho_s} \right)^{2/3}}$$

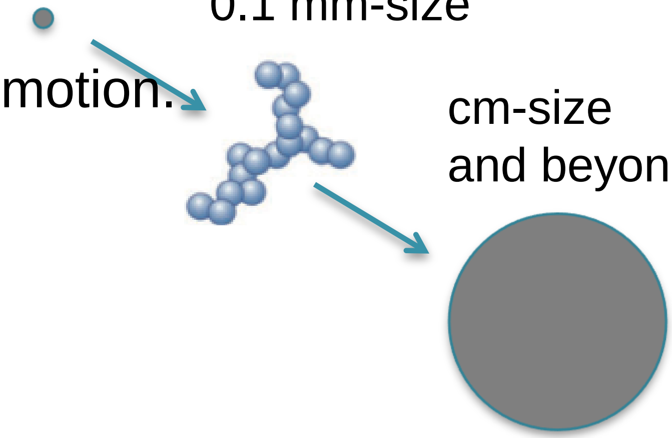
Growth timescale rapidly becomes much longer than disk lifetime

➔ Growth limited to characteristic max size that depends on location in disk and age.



Simulation by Brauer et al. 2008 of growth by Brownian motion. Dust size distribution after 1Myr

The problem



micron-size

0.1 mm-size

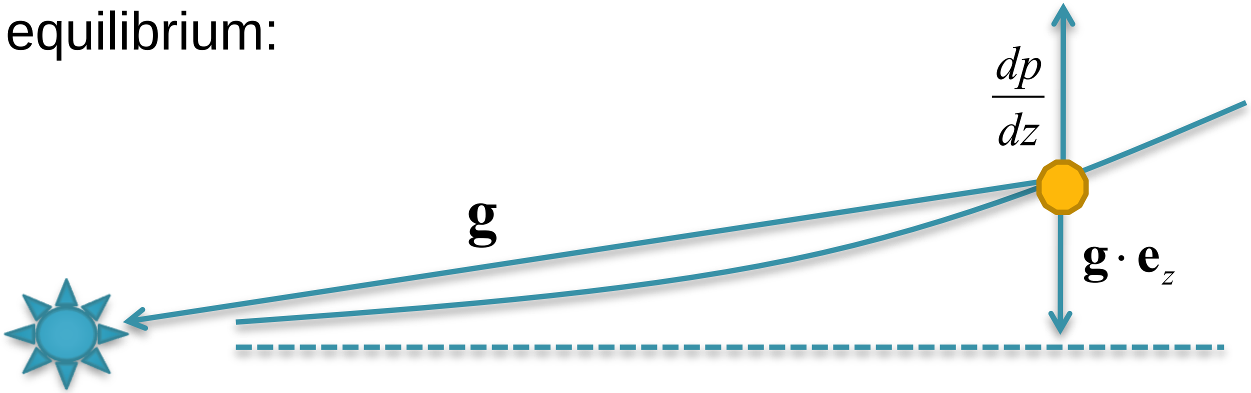
Brownian motion.

cm-size
and beyond ?

The second step probably occurs by sweeping vertical settling

Vertical settling

The vertical structure of the gas disk is in hydrostatic equilibrium:



Dust particles, however, are not pressure-supported and settle towards the mid-plane:

$$\frac{d^2 z_p}{dt^2} = -\frac{1}{\tau_s}\frac{dz_p}{dt} - g(z_p) \rightarrow \frac{dz_p}{dt} \approx -g(z_p)\tau_s$$

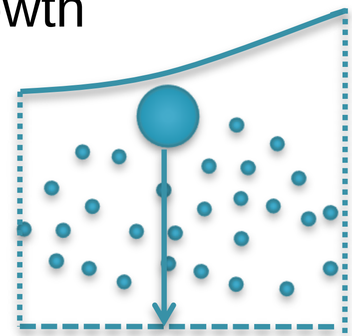
with $\tau_s = \frac{s\rho_s}{c\rho_g}$ is the particle stopping time.

➔ at given height, large particles settle more rapidly.

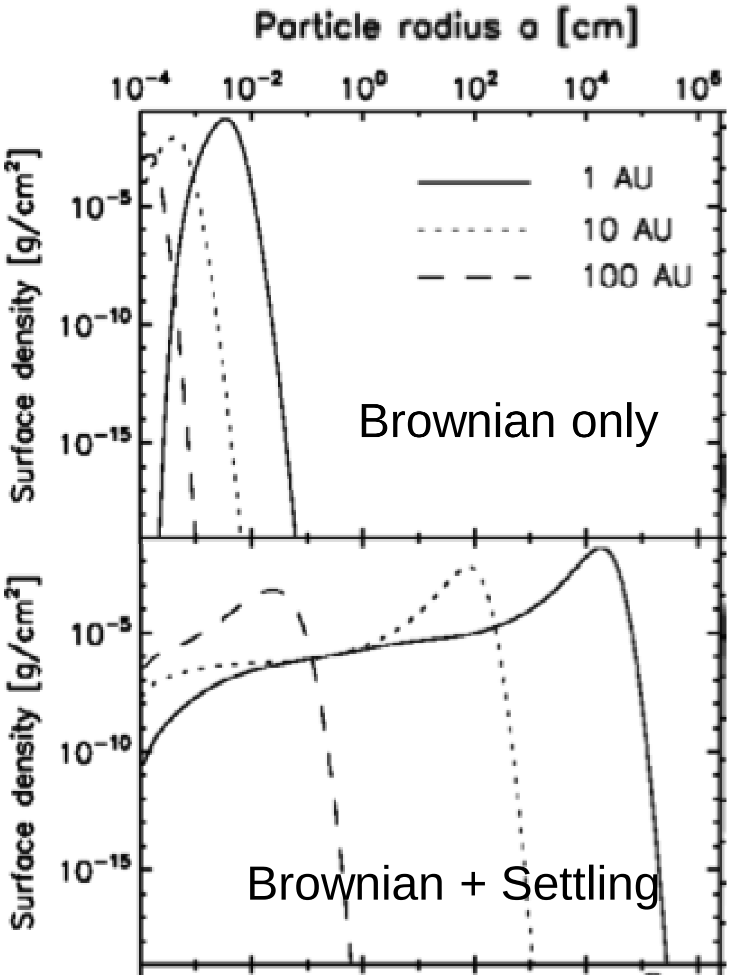
Vertical settling

This has two effects:

- Differential vertical settling causes large particles to “sweep up” smaller ones on the way down, and drives further growth



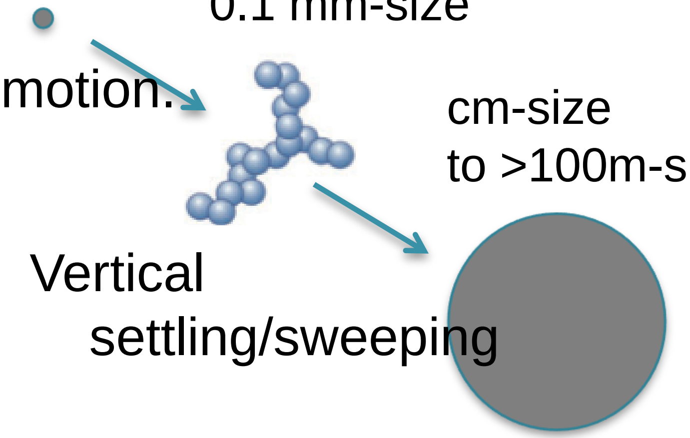
- Large particles accumulate near the midplane : collisions occur more frequently.



Brauer et al. 2008

After 1My, can form 100m size bodies at

The problem



micron-size

0.1 mm-size

Brownian motion:

cm-size
to >100m-size?

Vertical
settling/sweeping

Problem solved?

… unfortunately not.

Radial drift

The interaction between the dust particles and ambient gas also causes them to drift radially. The drift velocity is size-dependent, leading to differential motion.

In the absence of gas, particles would orbit the star at Keplerian angular velocity:

$$m_p r\Omega_K^2(r) = m_p \frac{GM_*}{r^2} \rightarrow \Omega_K^2(r) = \frac{GM_*}{r^3}$$

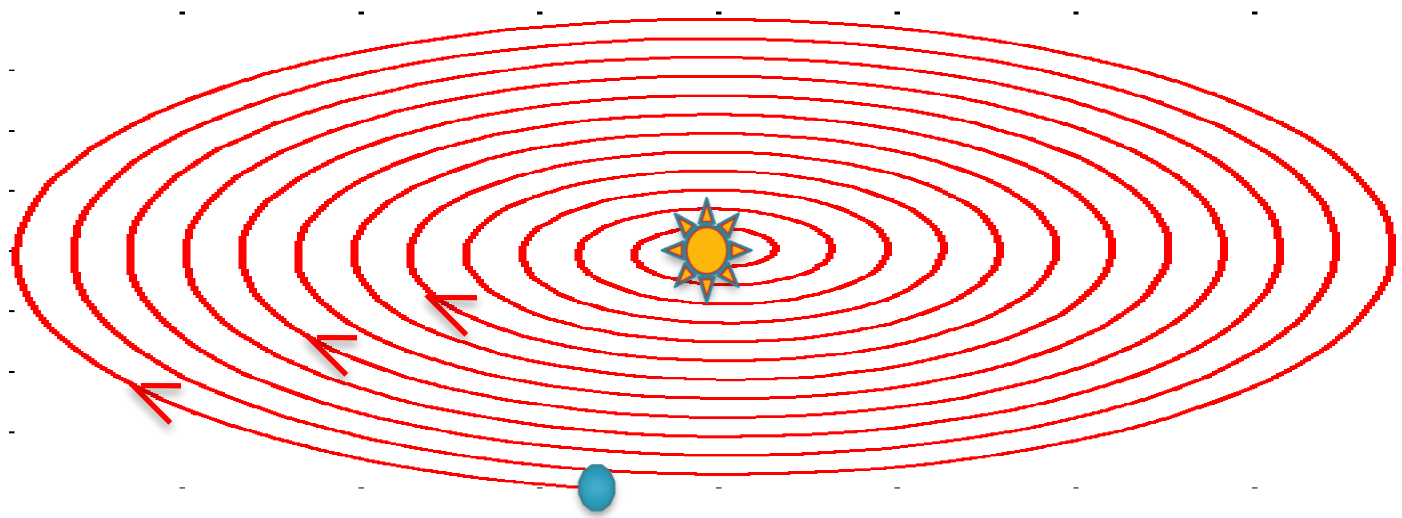
The gas, however, is pressure supported, so orbits the star at slightly sub-Keplerian velocity.

$$\rho r^2\Omega_g^2 = -\frac{dp}{dr} + \rho\frac{GM_*}{r^2} \rightarrow \Omega_g^2(r) = (1-\eta(r))\Omega_K^2(r)$$

where η(r) depends on the thermodynamic structure of the disk (typically of order 0.01 to 0.05)

Radial drift

Particles feel headwind, gradually loose angular momentum, and drift inward.



Radial drift

At a given point in the disk (given gas density and dynamical timescale), the radial drift velocity is strongly dependent on particle size.

Fastest-drifting particles: Stokes number

$$St = \tau_s / \tau_{orb}$$

order unity:

- m-size at 1AU
- mm-size at 30 AU

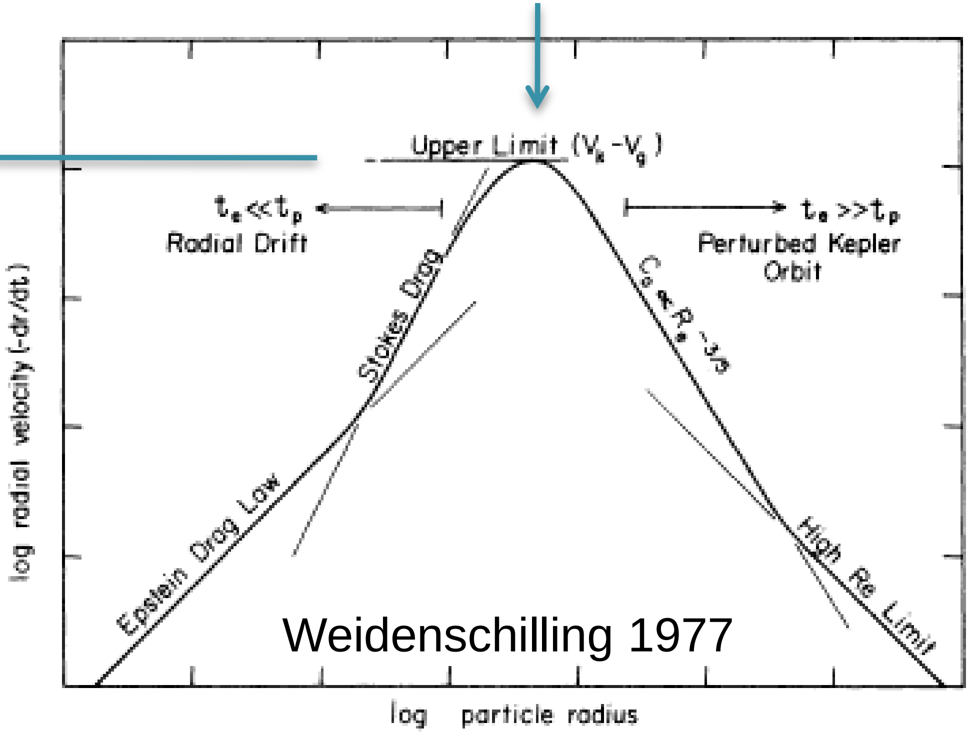
Max-drift velocity is

$$\eta r \Omega_K$$

so drift timescale into central star is about

$$\eta \tau_{orb}$$

- 100 years at 1AU
- 5000 years at 30AU

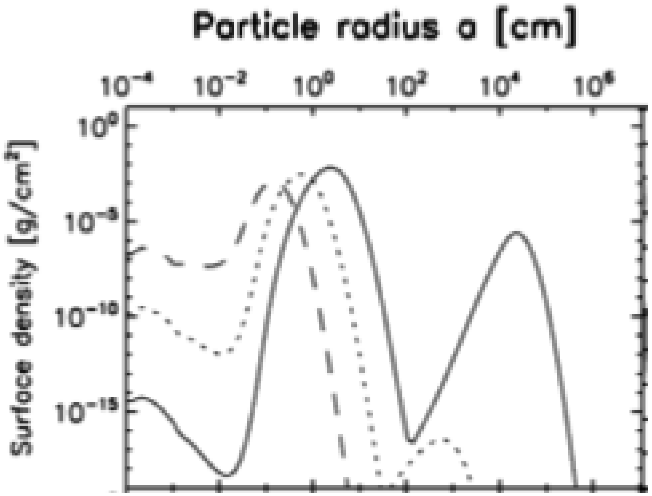


Weidenschilling 1977

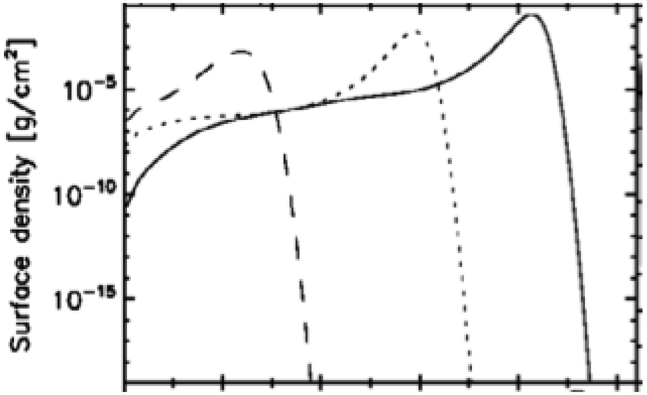
Growth problem

- The 1AU problem:
  - Planets are known to form at 1AU
  - But drift timescale is << growth timescale for 1m size object.
  - How to grow beyond 1m size?

- Similar problems exist at other radii (e.g. mm problem at 30 AU)



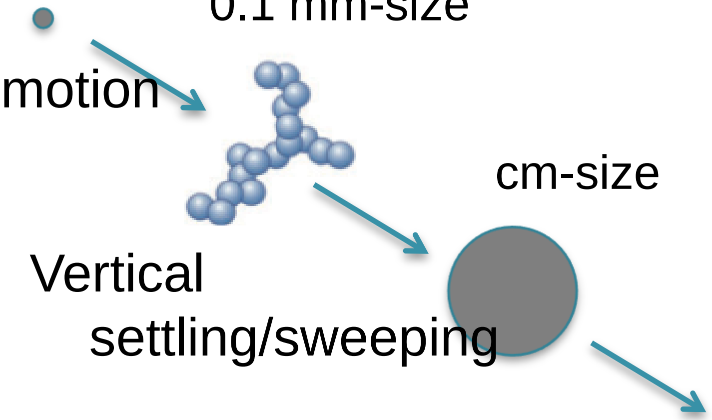
Brownian + Settling + Radial drift



Brownian + Settling only

Brauer et al. 2008

The problem



micron-size

0.1 mm-size

Brownian motion

cm-size

Vertical
settling/sweeping

How to grow beyond critical size despite radial drift?

Ideas :

1. Faster growth
2. Slow down/stall radial drift

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- From pebbles to planetesimals.

OUTLINE

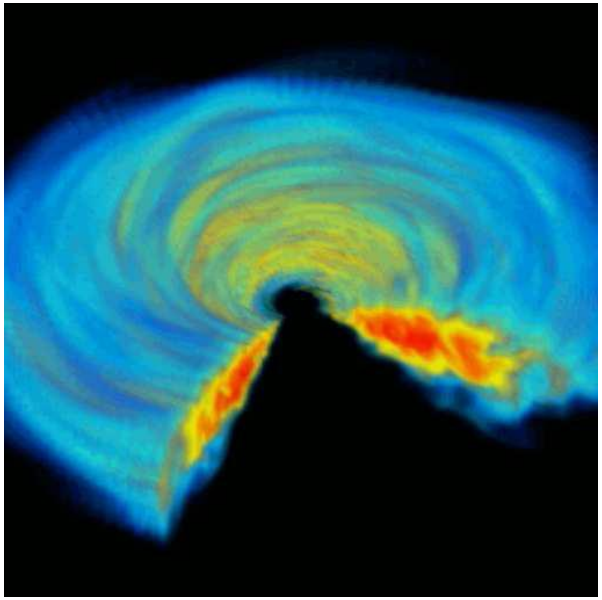
- Evidence and constraints on planet formation
- From dust to pebbles
- From pebbles to planetesimals
  - Interlude.

Turbulence in disks

So far, we have only considered particle motion in a laminar disk. However disks are turbulent.

Many possible origin of turbulence :

- Shear instabilities
  - **Magneto-rotational instability of radial shear**
  - Rossby wave instability of radial PV profile.
  - Kelvin-Helmholtz instability of vertical shear of dust layer
- Convection (vertical, radial)
- Baroclinic instability



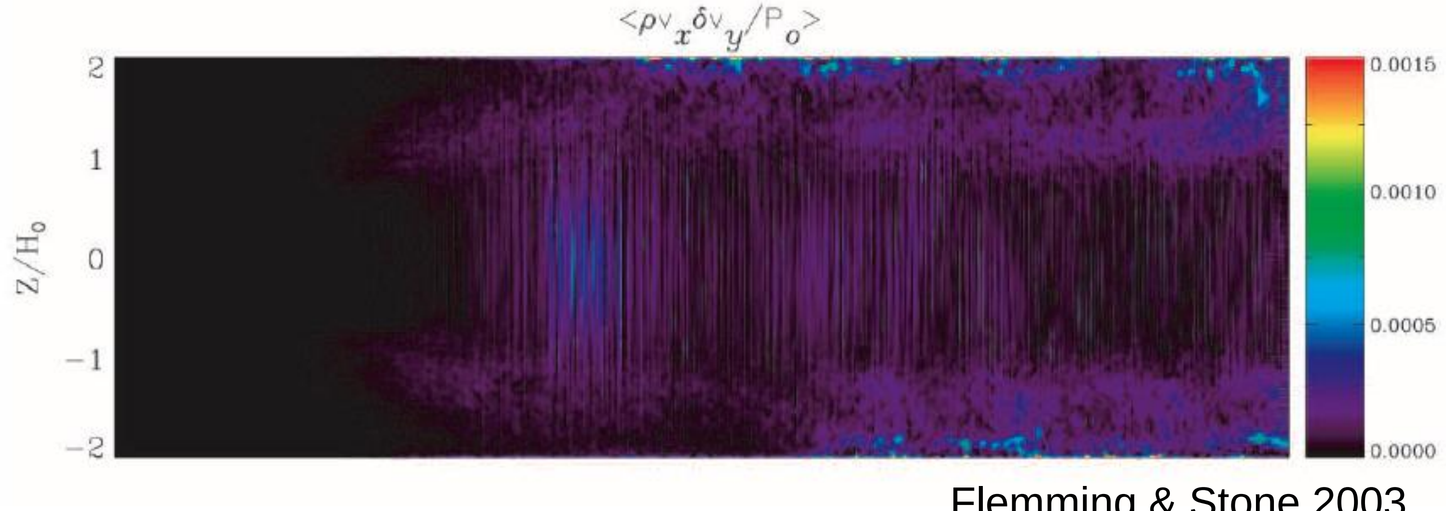
MRI, from Hawley (Scholarpedia)

Dead zones

However, disks are not homogeneously turbulent. In particular, MRI requires gas to be significantly ionized.

Calculation of ionization levels in disks show that some regions are stable to MRI, in particular near disk midplane between few to about 10 AU (i.e. where most planets appear to be).

MRI-dead zones are much more quiescent than MRI-active zones, turbulence limited to surface layers of disk (Gammie 1996).



Flemming & Stone 2003

Dust-laden gas dynamics

In what follows, most of the work is done by solving equations for dust-laden fluid. Two types of formalism commonly used:

- Two-fluid equations (usually for study of small particles)

$$\rho_g\left(\frac{D\mathbf{u}_g}{Dt}+2\Omega_K\times\mathbf{u}_g+\Omega_K\times\Omega_K\times\mathbf{r}\right)=-\nabla p+\rho\mathbf{g}+\mathbf{F}_{drag}+\ldots$$

$$\rho_p\left(\frac{D\mathbf{u}_p}{Dt}+2\Omega_K\times\mathbf{u}_p+\Omega_K\times\Omega_K\times\mathbf{r}\right)=\rho_p\mathbf{g}-\mathbf{F}_{drag}+\ldots$$

$$\frac{\partial\rho_g}{\partial t}+\nabla\cdot\left(\rho_g\mathbf{u}_g\right)=0\ ,\qquad \frac{\partial\rho_p}{\partial t}+\nabla\cdot\left(\rho_p\mathbf{u}_p\right)=0$$

- Individual particle tracking (usually for study of large particles)

$$\rho_g\left(\frac{D\mathbf{u}_g}{Dt}+2\Omega_K\times\mathbf{u}_g+\Omega_K\times\Omega_K\times\mathbf{r}\right)=-\nabla p+\rho\mathbf{g}+\ldots$$

$$\frac{\partial\rho_g}{\partial t}+\nabla\cdot\left(\rho_g\mathbf{u}_g\right)=0\ ,\qquad \mathbf{a}_\mathbf{p}=\frac{\mathbf{u}_g-\mathbf{u}_p}{\tau_s}\ \text{for each particle}$$

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  - Interlude.
  - How to increase growth

How to speed-up growth

Recall that $\frac{dN(m)}{dt} = \int K(m;m',m'')N(m')N(m'')dm'dm''$

$$- \int F(m,m')N(m')dm'$$

where $K \propto \sigma\varepsilon(\Delta v)$.

To enhance particle growth, many possibilities:

1. Faster collision velocities
2. Larger particle density
3. Increased coagulation efficiency/decreased fragmentation effficiency.
4. Increased cross-section…

How to speed-up growth

Faster collision velocities

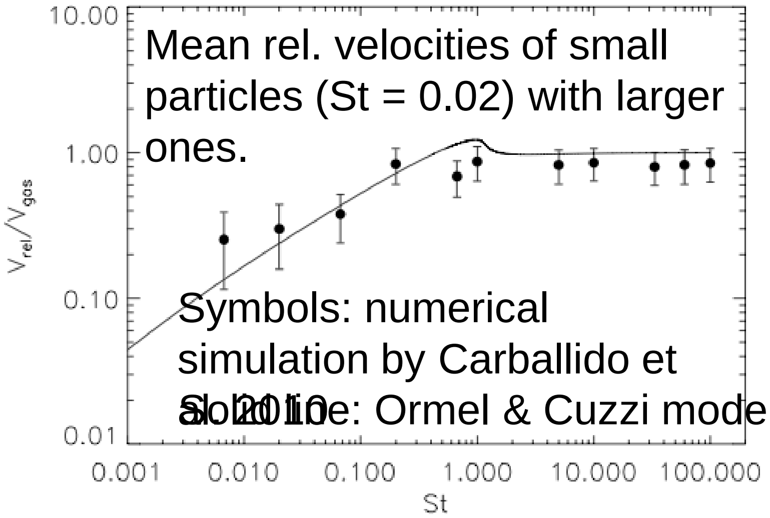
- Turbulence in the disk can increase the mean particle velocity as well as velocity dispersion: smaller collision timescale
- However, collisions that are too fast lead to fragmentation instead of growth.

Which effect wins?

How to speed-up growth

Faster collision velocities

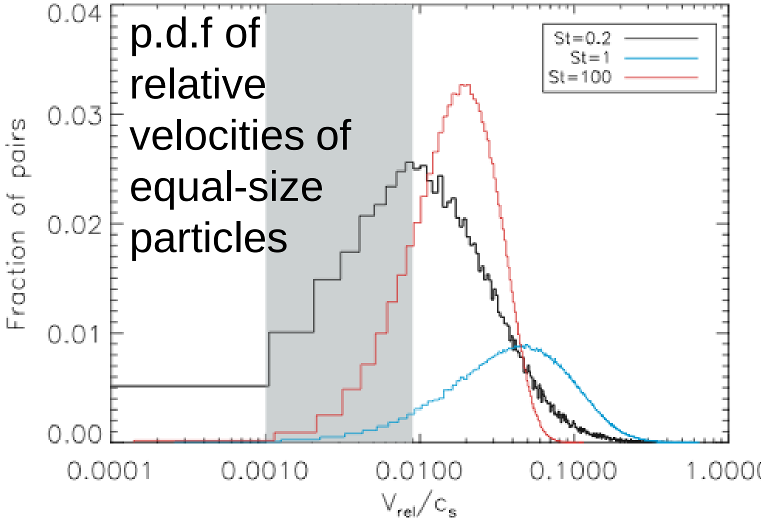
- The p.d.f. of relative velocities of colliding particles in a turbulent accretion disk remains under investigation.
    - p.d.f.s of actual and relative particle velocities have been proposed based on analytical work (e.g. Volk et al. 1980 , Ormel & Cuzzi 2007)
    - Recent numerical simulations have looked at p.d.fs of relative velocities (Carballido et al. 2010)
    - p.d.fs of relative velocities of colliding particles remains tbd.



Mean rel. velocities of small particles (St = 0.02) with larger ones.

Symbols: numerical simulation by Carballido et al. 2010

Solid line: Ormel & Cuzzi model

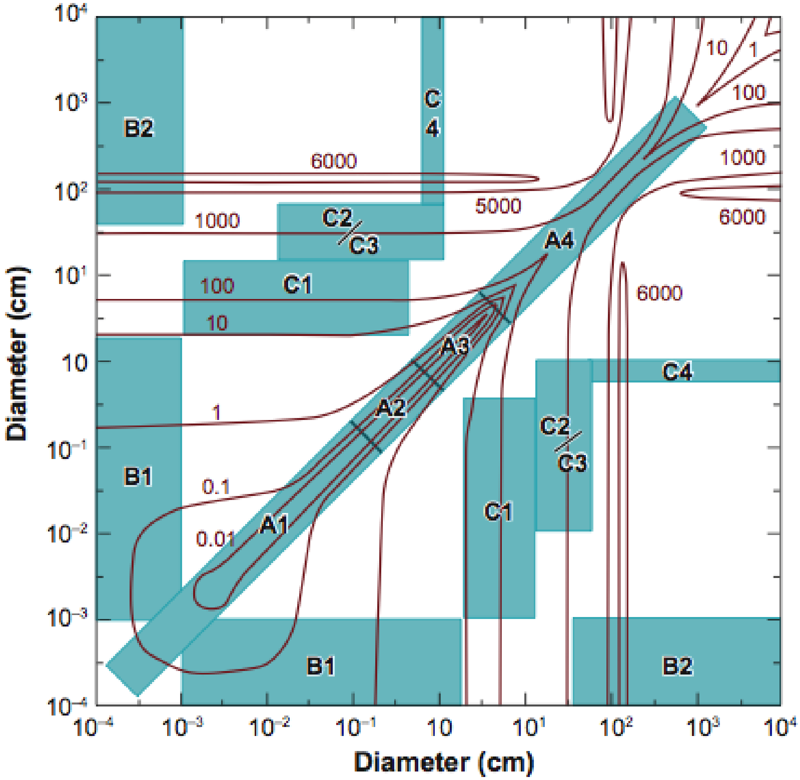


p.d.f of relative velocities of equal-size particles

How to speed-up growth

Faster collision velocities

- Models can be used to estimate relative velocities of particles in disks, as well as origin of relative motion.

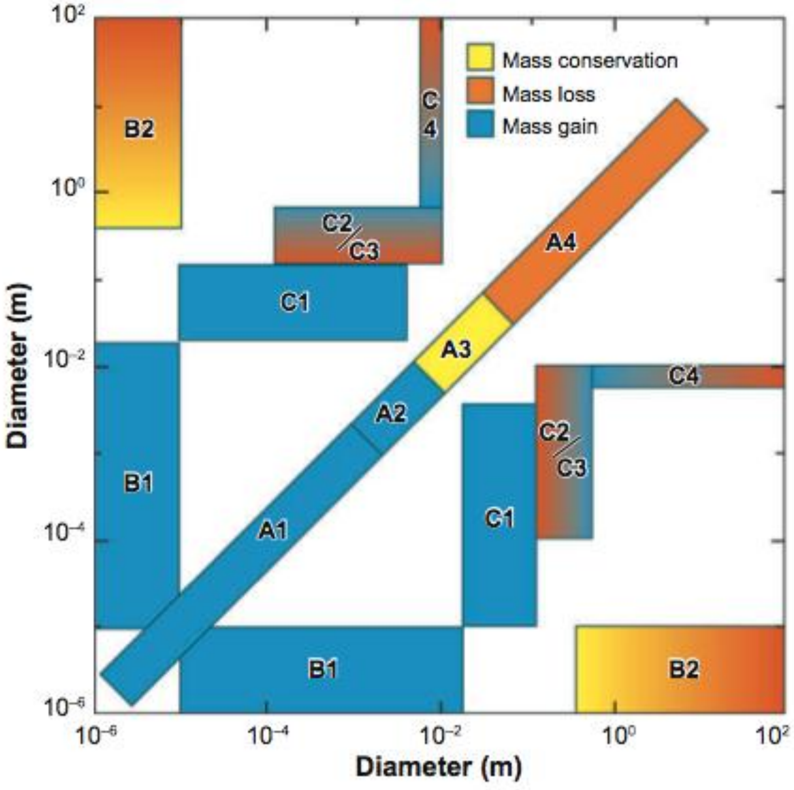


Blum & Wurm 2008
Weidenschilling & Cuzzi 1993

How to speed-up growth

Faster collision velocities

- Models can be used to estimate relative velocities of particles i disks, as well as origir of relative motion.
- At 1AU, collisions between larger particles are mostly destructive!



Blum & Wurm 2008

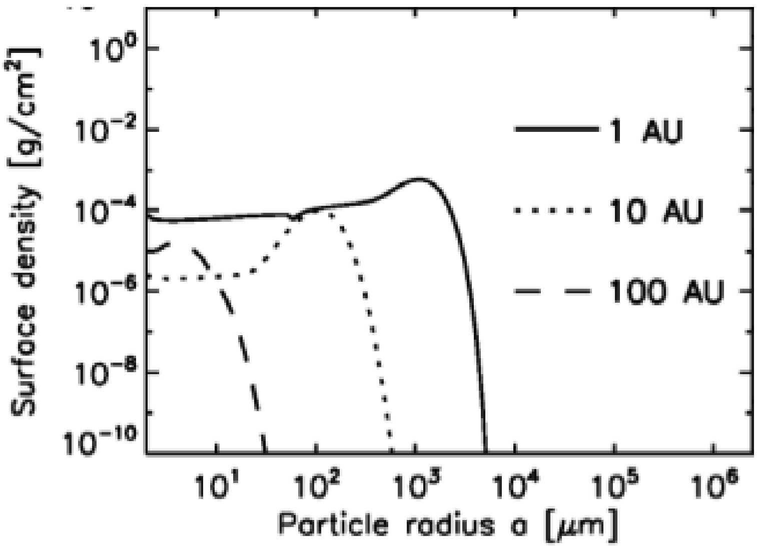
How to speed-up growth

Faster collision velocities

This is a major problem for growth into planetesimals: turbulence tends to accelerate particles too much, so that most collisions are likely to be destructive (fragmentation barrier)

Although there are ways past the fragmentation barrier, they remain to be studied in more detail (Windmark et al. 2012, Garaud et al. 2013)

Brauer et al. 2008

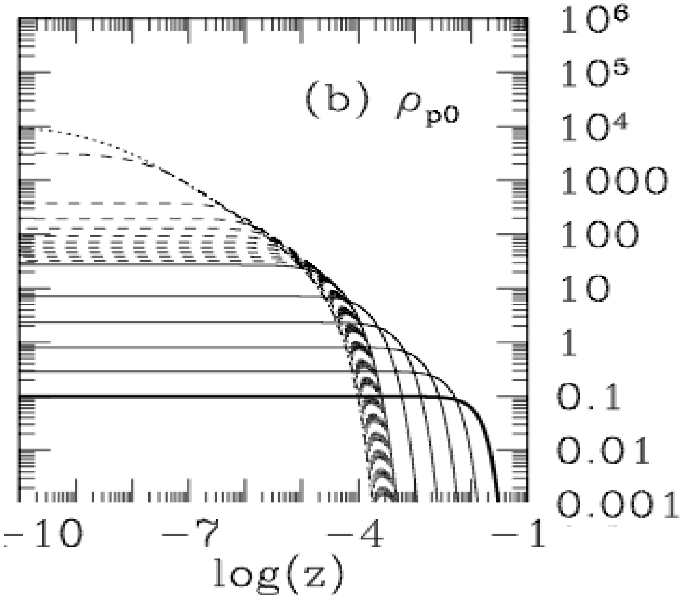


This suggests that dead zones are more likely locations for planetary growth.

How to speed-up growth

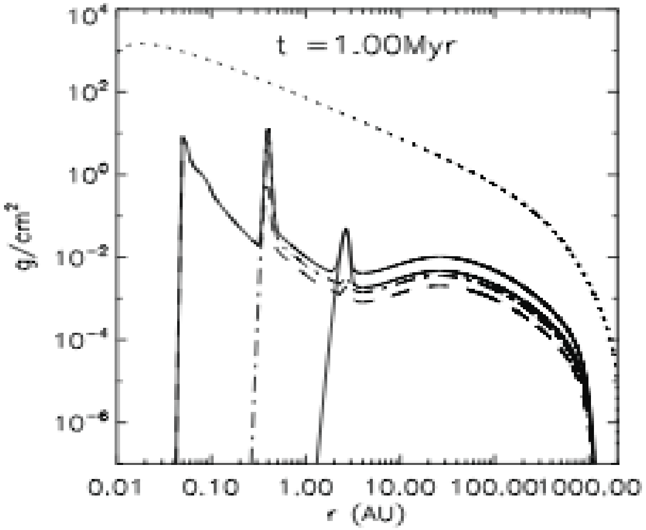
Larger particle density.

Sedimentation towards the midplane, and differential radial drift (near dead-zones and snow-line), can cause particles to accumulate in certain regions of the disk.



Garaud & Lin 2007

This increases the growth rate significantly, but can also trigger gravitational instabilities (in which case the process can even lead to runaway growth). Cf. Goldreich & Ward 1973.



Garaud & Lin 2007

How to speed-up growth

Larger particle density.

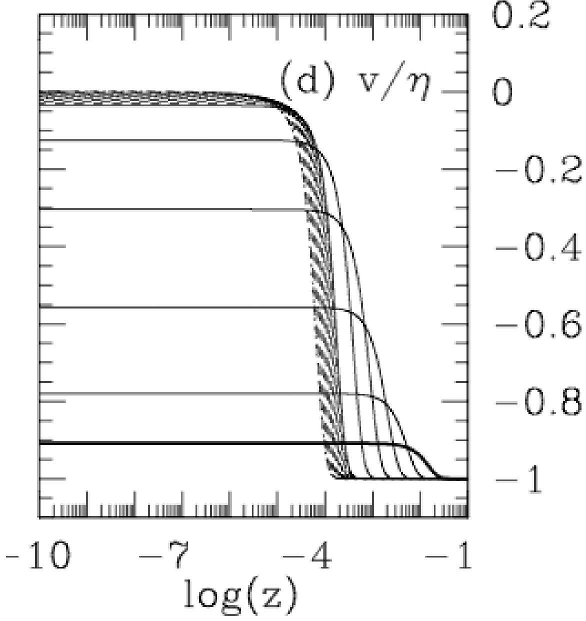
However, increased particle density means that particle+ gas fluid now moving near Keplerian velocity while dust-free gas sub-Keplerian.

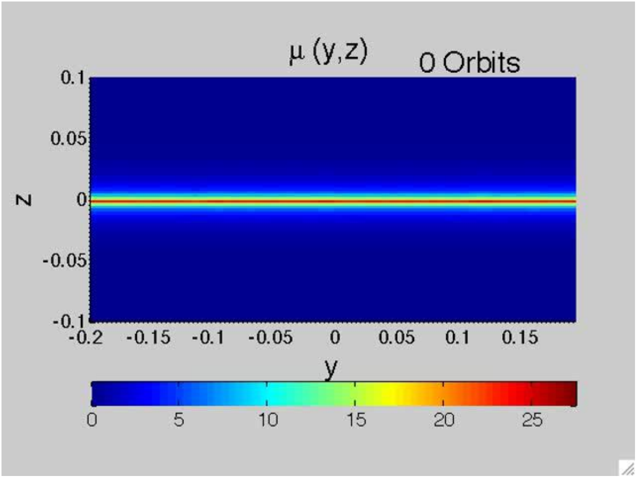
Dusty layer rotates more rapidly than rest of disk, can trigger Kelvin-Helmholtz instabilities before gravitational instabilities kick in

cf. Weidenschilling 1980.

Question remaining: how dense and how turbulent is the resulting dust layer?

Garaud & Lin 2007





Lee et al. 2010

How to speed-up growth

Increased coagulation efficiency

- Near radius where water has phase transition from solid to gas (snow line), can have increased coagulation efficiency/growth.
- Turbulent recirculation of pebbles in and out of condensation line can trigger rapid growth (similar to formation of hailstones).

Increased cross-section

- If particle densities become large-enough, self-gravity of particle clump becomes important and can trigger gravitational instability.

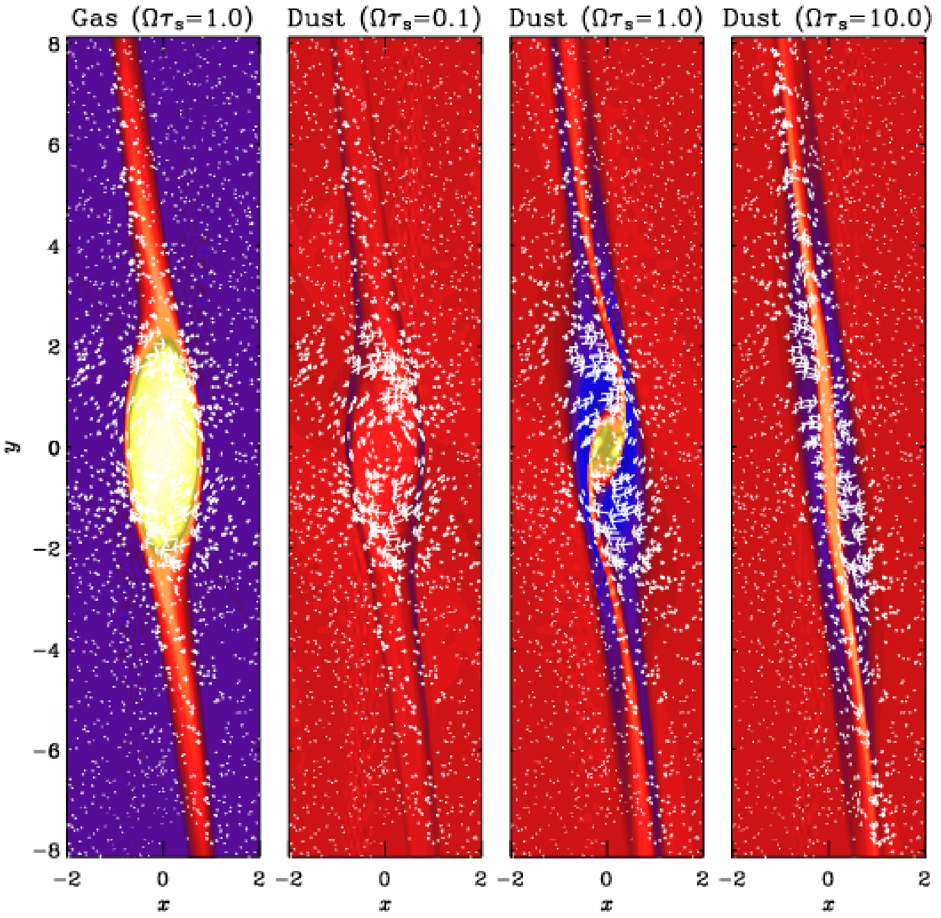
All of these possibilities still the subject of current investigation; most of them promising but all still have problems

OUTLINE

- Evidence and constraints on planet formation
- From dust to pebbles
- From pebbles to planetesimals
  - Interlude.
  - How to increase growth
  - How to stall radial drift

Decreased radial drift.

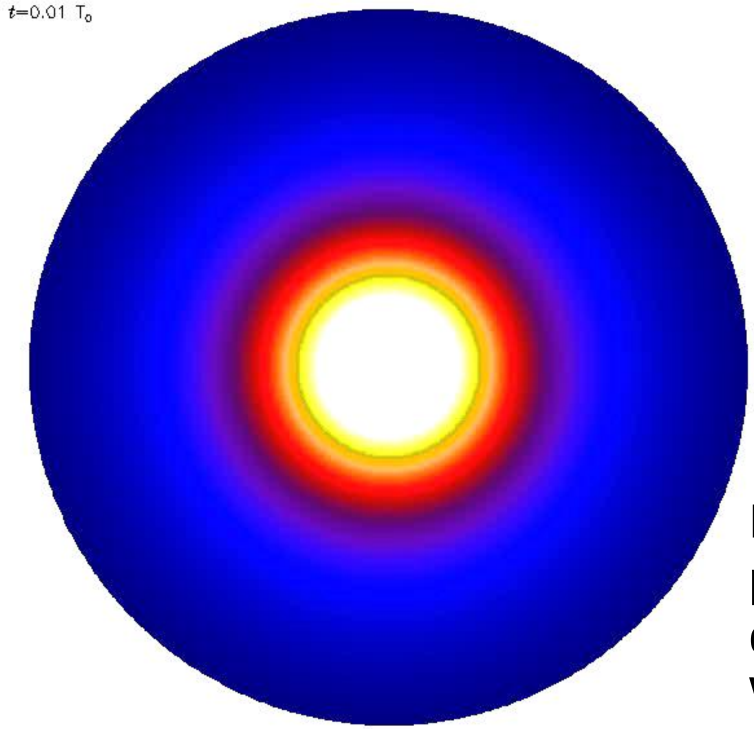
- Turbulence in accretion disks can lead to the formation of vortices.
- For thin, stably stratified disks, large anticyclonic vortices are reasonably long-lived.
- These vortices can trap dust particles of a certain size (Barge & Sommeria 1995)
- Dust concentration in the vortex is large, and radial drift is stalled, at least temporarily.



Johansen et al. 200

Decreased radial drift.

These vortices can form naturally, either by baroclinic instability, or by Rossby-Wave Instability (near edge of dead-zone or edge of gap caused by pre-existing planet)

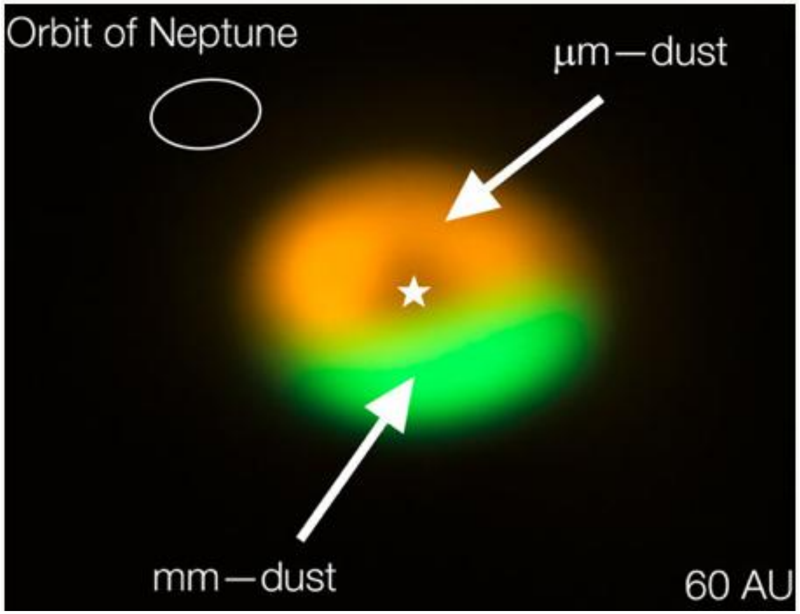


Evolution of density perturbation in protostellar disk subject to Rossby-Wave Instability by Lyra & Mac Low 2012

Decreased radial drift.

Some evidence for particle trapping by very large vortices seems to have been found with ALMA observations.

It is not unlikely that similar vortices closer to the central star could be trapping larger (m-size) planetesimals.



Van der Marel et al. 2013

Conclusion/summary

Observations:

- The formation of planets must be a ubiquitous process and must proceed on timescale < 10Myr

Theory:

- It is easy to grow particles up to cm-size at 1AU (10 micron at 30AU)
- However, larger particles prone to rapid radial drift
- To get past the drift problem, one must *either increase growth rate, or decrease drift rate or both.*
- Many possible solutions have been investigated.

This field bears many similarities with the study of turbidity currents and droplet/hailstone formation in clouds.