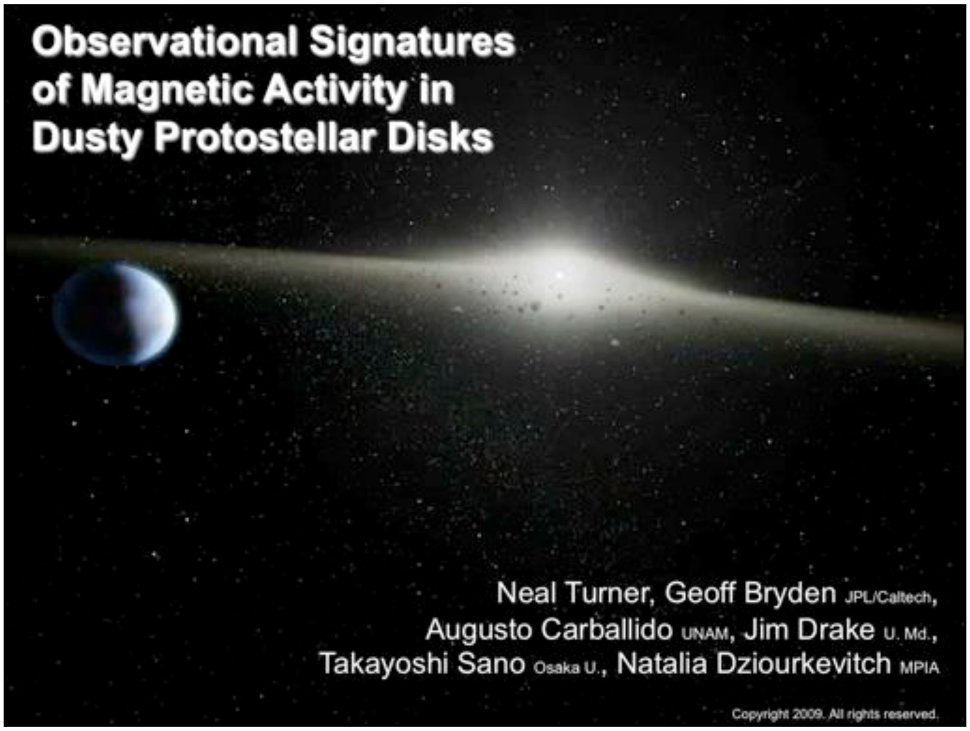
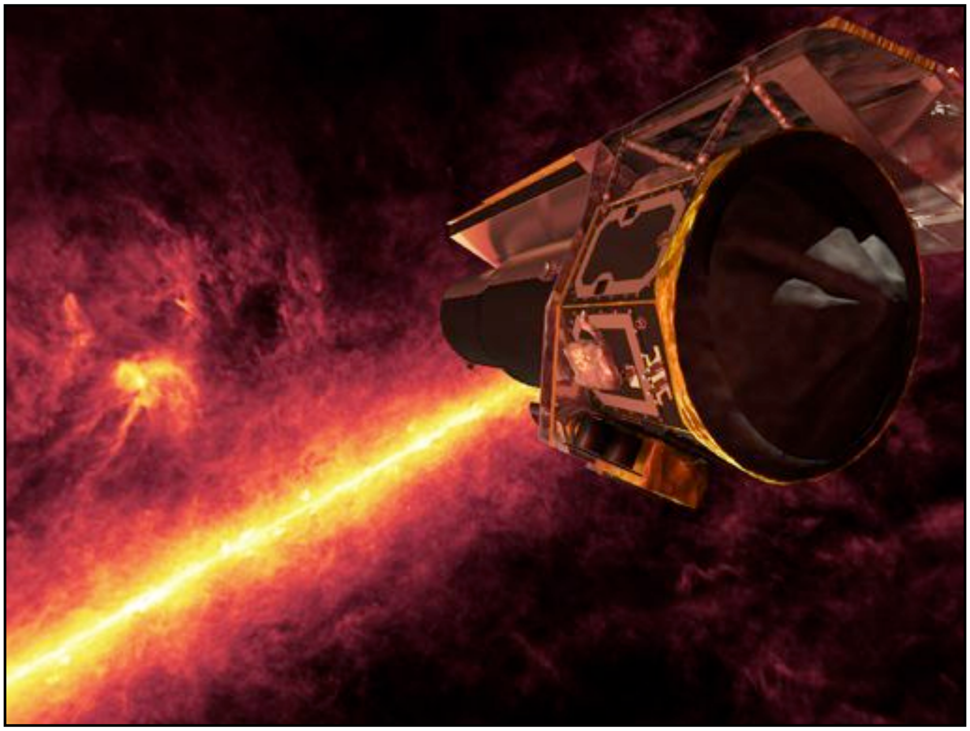


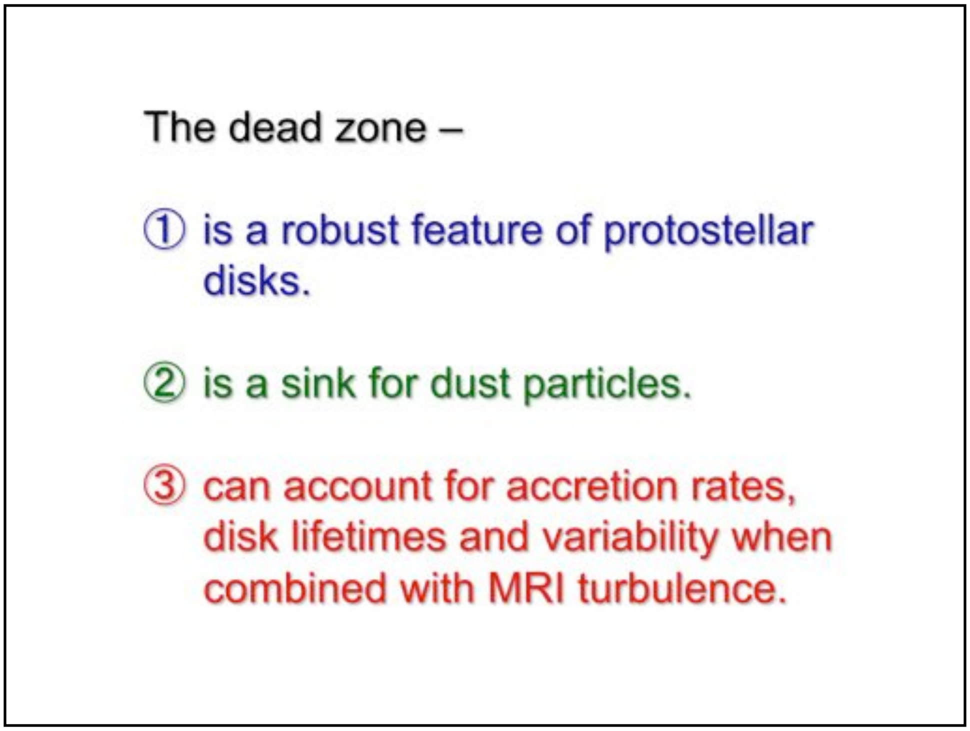
Observational Signatures of Magnetic Activity in Dusty Protostellar Disks

Neal Turner, Geoff Bryden JPL/Caltech,
Augusto Carballido UNAM, Jim Drake U. Md.,
Takayoshi Sano Osaka U., Natalia Dziourkevitch MPIA

Look at settling and transport of grains in magnetically-active YSO disks.
Essential ideas from the following people. Remaining shortcomings are mine.



Spitzer gave treasure trove of mid-infrared spectra. Ran out of cryogen last month and began Warm Mission. Good time to place results in context.



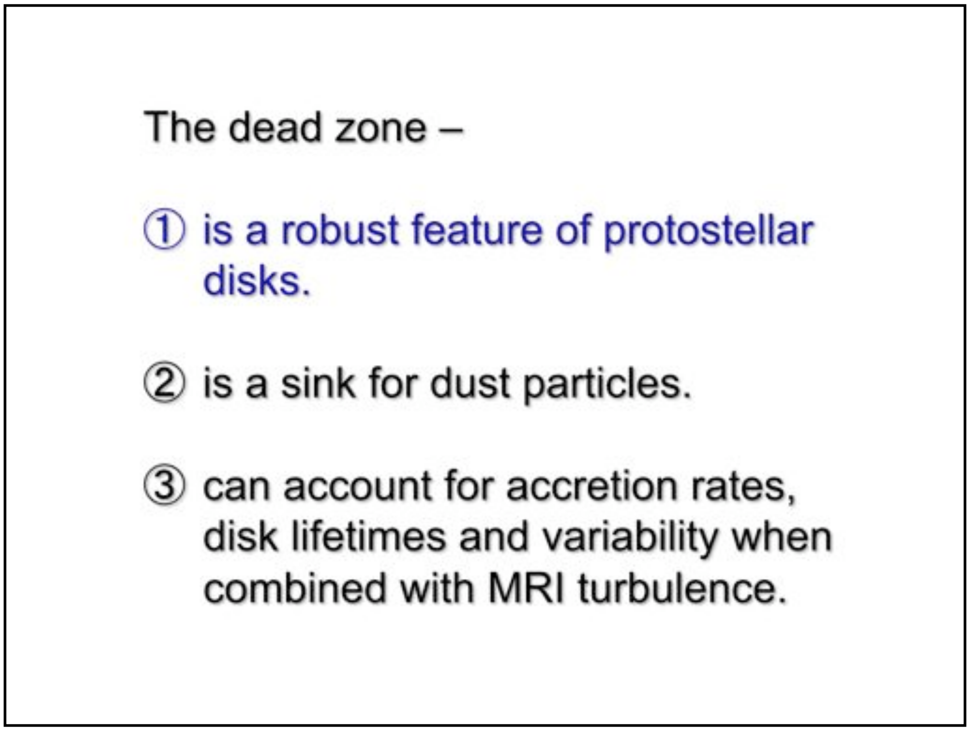
The dead zone –

① is a robust feature of protostellar disks.

② is a sink for dust particles.

③ can account for accretion rates, disk lifetimes and variability when combined with MRI turbulence.

Three sections. Third one makes up about half the talk.



The dead zone –

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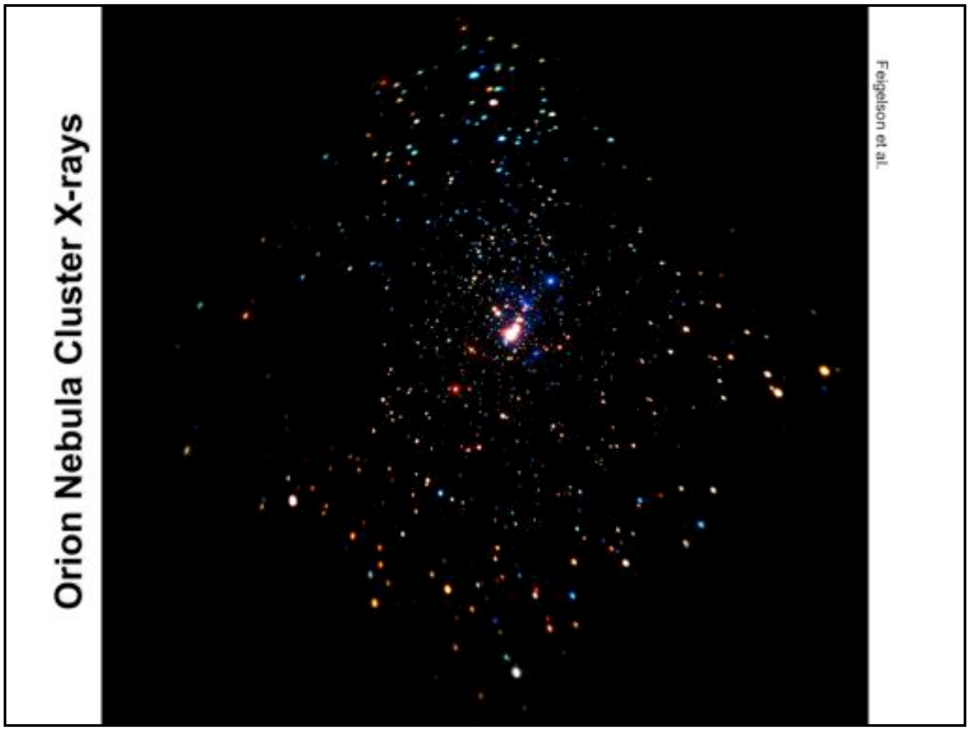
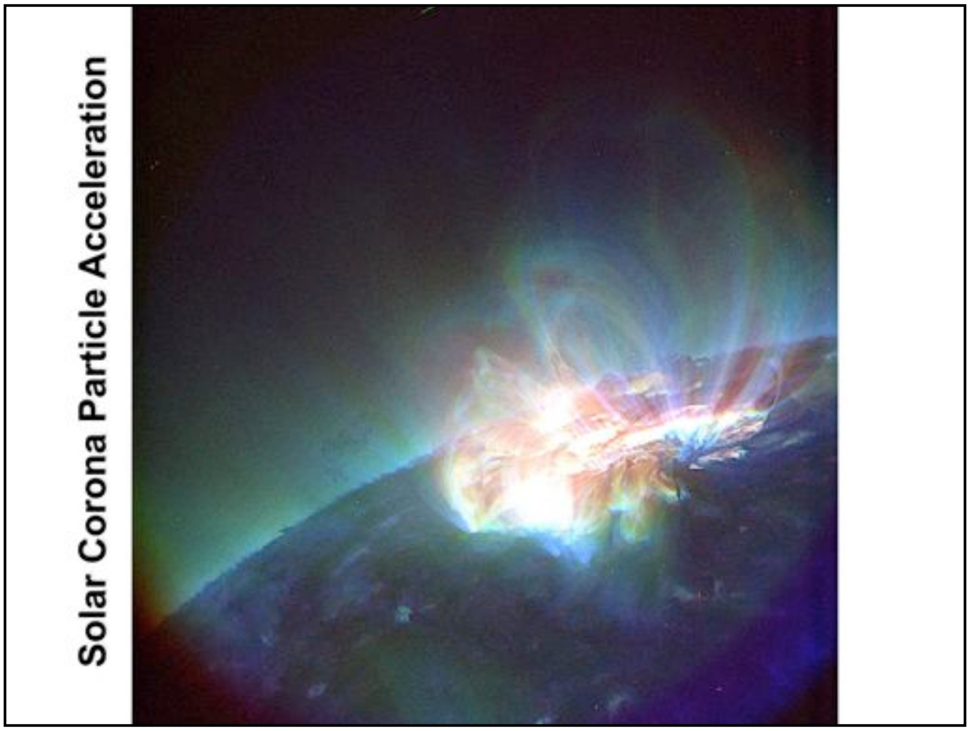
Philosophy: the dead zone is sometimes ignored when modeling YSO disks. We decided to look at whether the DZ can be eliminated from the MMSN under favorable circumstances. Maximize ionization processes and minimize recombination.



Orion Nebula Cluster X-rays

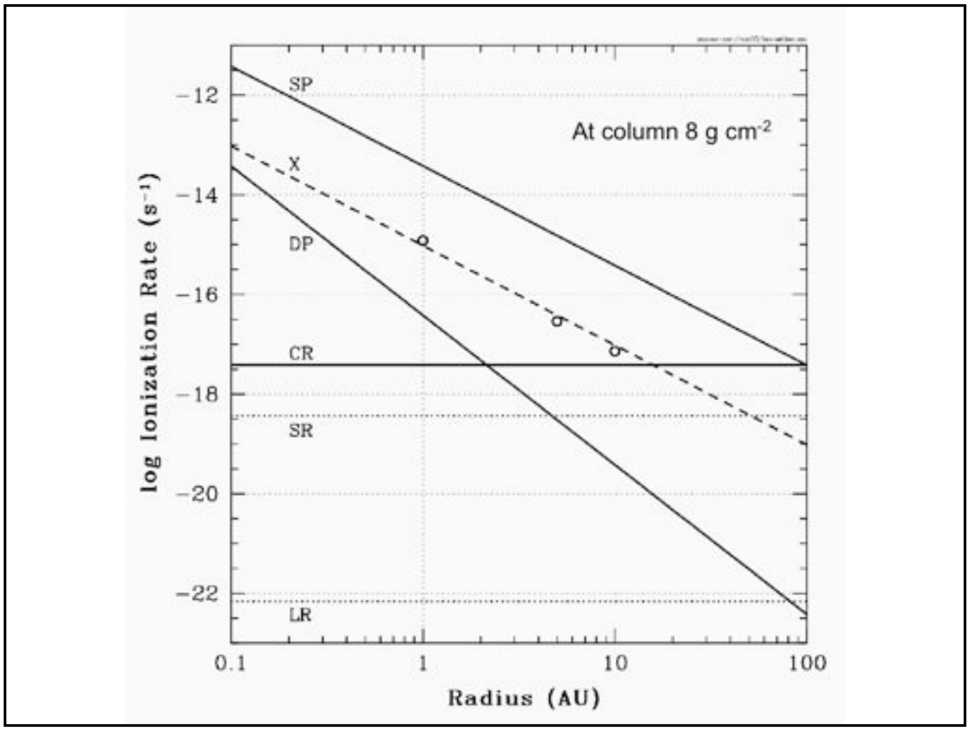
Feigelson et al.

A key source of ionization in protostellar disks is the X-rays from the young star. The column at which X-rays are absorbed is about 10 g/cm^2.

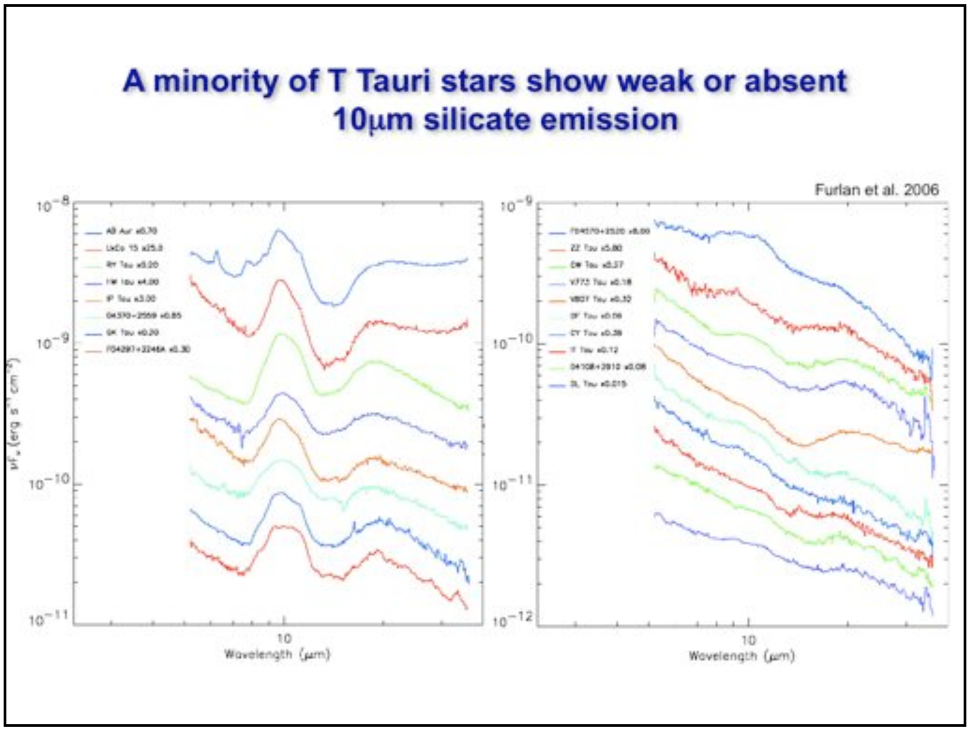


Solar Corona Particle Acceleration

In the Solar corona, magnetic reconnection produces energetic protons as well as X-rays. A small fraction reach the lower end of the cosmic ray energy range and in a YSO disk could penetrate about 100 g/cm^2 before being absorbed.



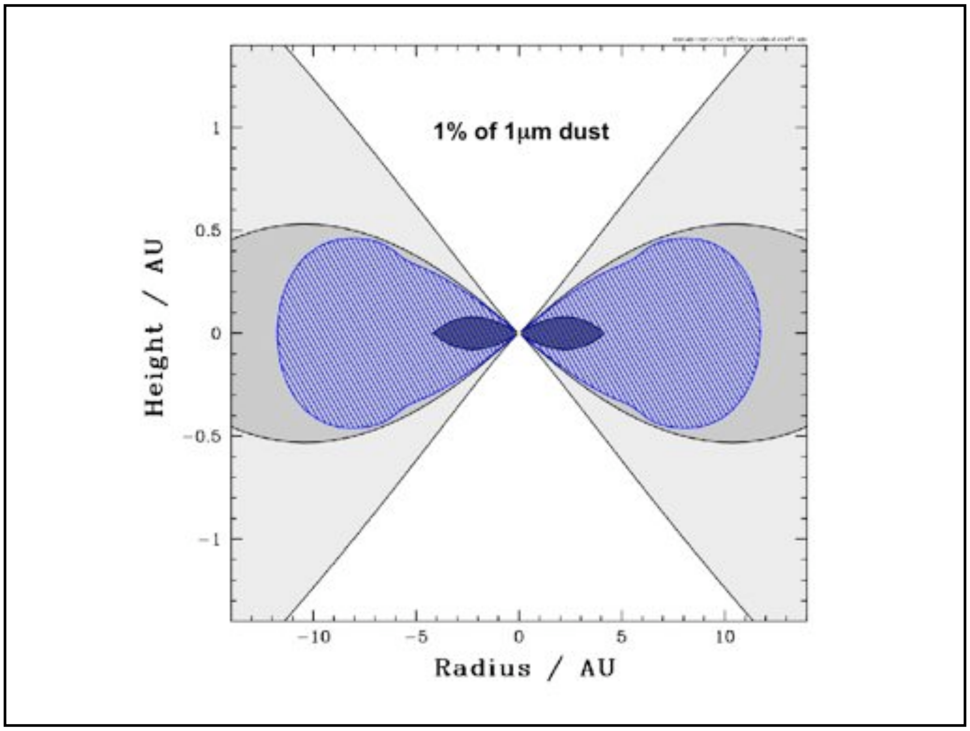
Estimated ionization rates vs. R in MMSN. Processes included: stellar energetic protons, X-rays, disk corona protons, interstellar cosmic rays, short-lived & long-lived radionuclides. X-rays fit to IG99 (circles), scaled to median L_X for Solar-mass YSOs in Orion of 2e30 erg/s. SEPs optimistic because most from flares lasting <1 orbit, and because straight-line propagation assumed. Typical SEP ionization rate more likely at most comparable to X-rays.



A minority of T Tauri stars show weak or absent 10μm silicate emission

Furlan et al. 2006

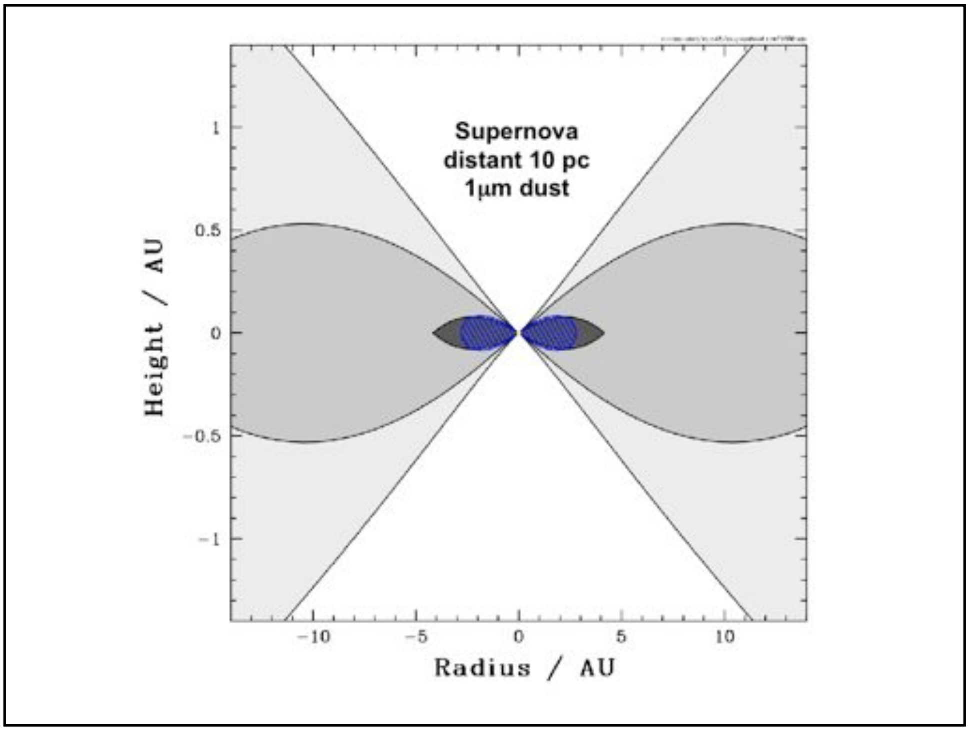
On the other side of the ionization-recombination balance, grains are important. Mid-IR spectra shown are from a sample of 85 TTSs in Taurus by Furlan et al. They conclude that systems like the 10 on the right lack grains smaller than a few microns near the 10-micron disk photosphere in annuli with T~300K.



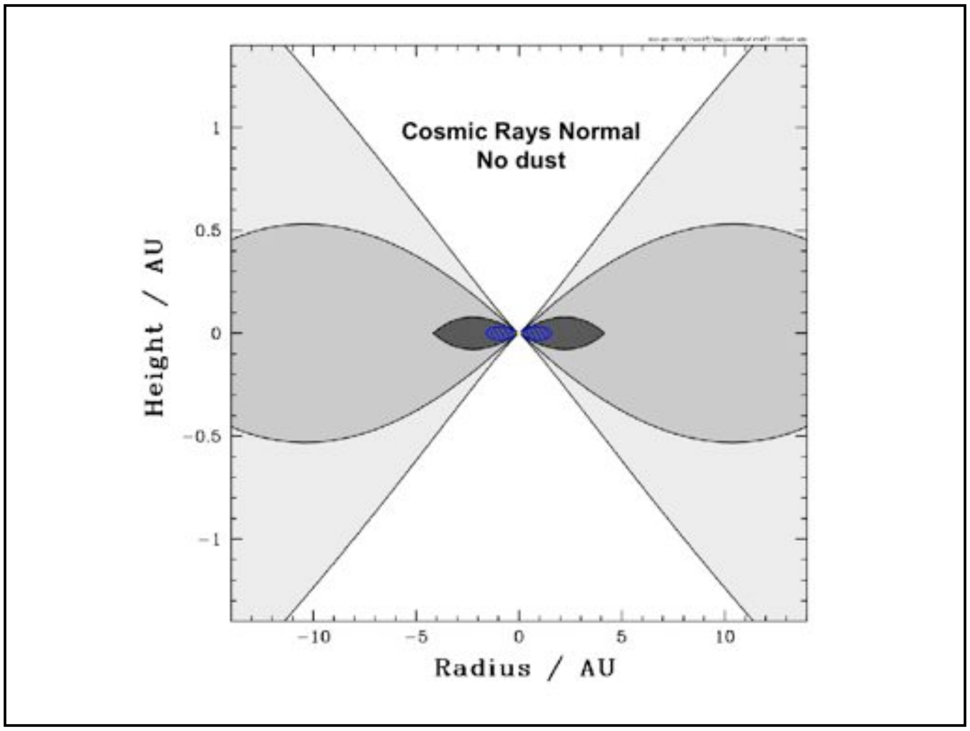
Dead zone calculated using IN06a recombination network with the simple gas-phase chemistry. Includes ionization by CR (following UN09), X-rays, LLRN. DZ extends up to 10g/cm^2 and out to present orbit of Saturn.

Crab Nebula SNR in X-rays

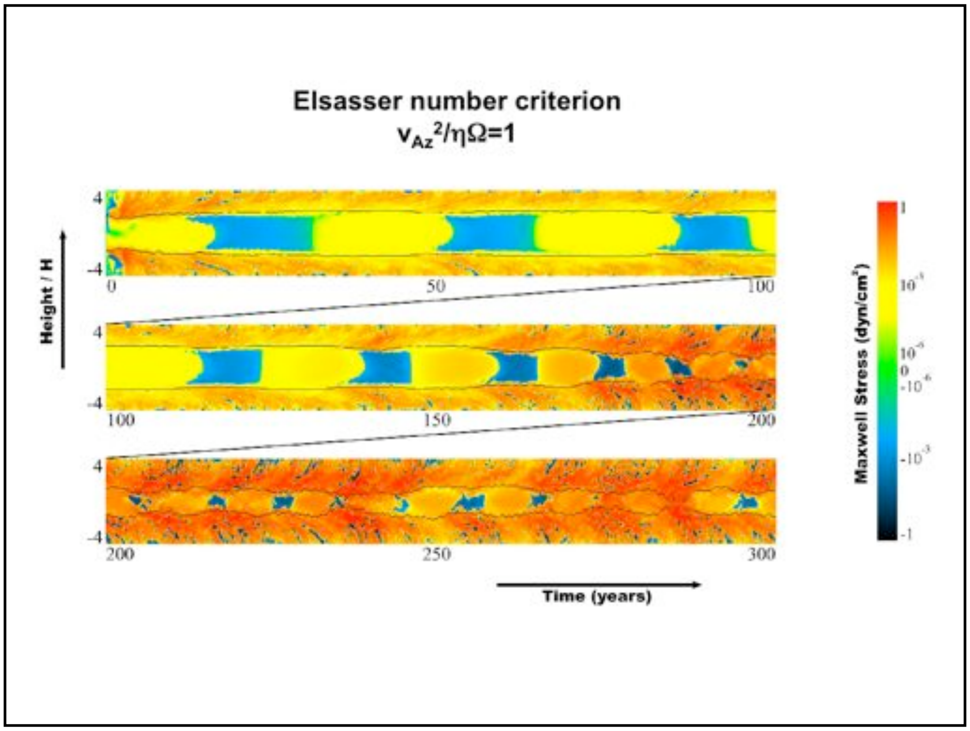
One of the more extreme suggestions for ionization: nearby SN. Fatuzzo et al. 2006.



With supernova, DZ contracts to about 100 g/cm^2 and ends in the asteroid belt.



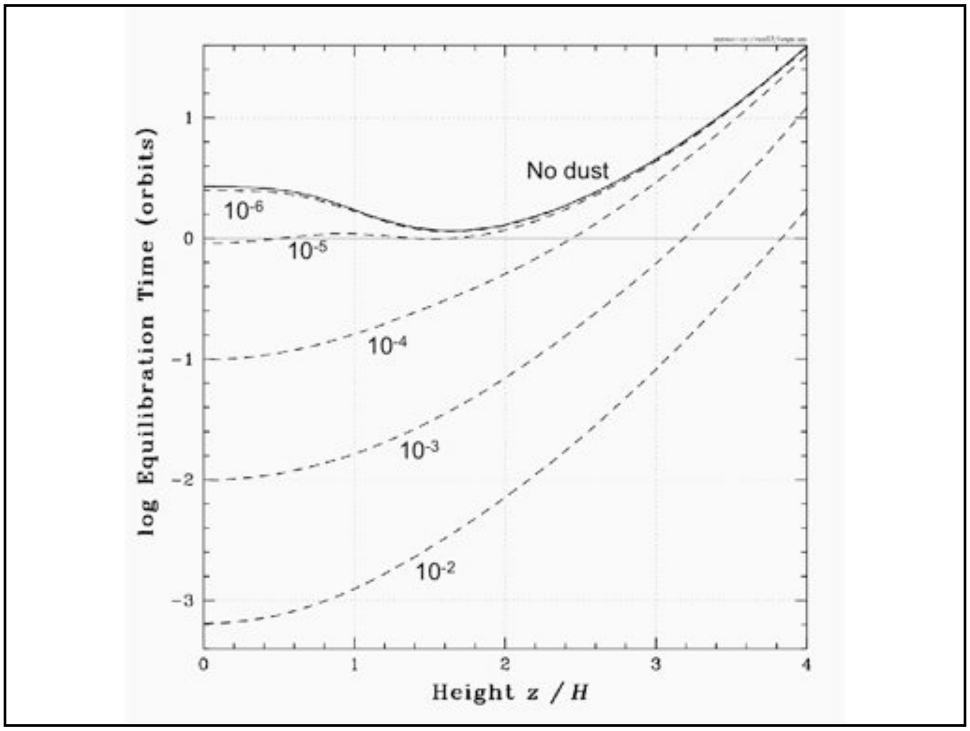
With CRs normal and dust instead removed, DZ ends just outside 1 AU. Evolution of dust is clearly a key to understanding DZ size.


Elsasser number criterion

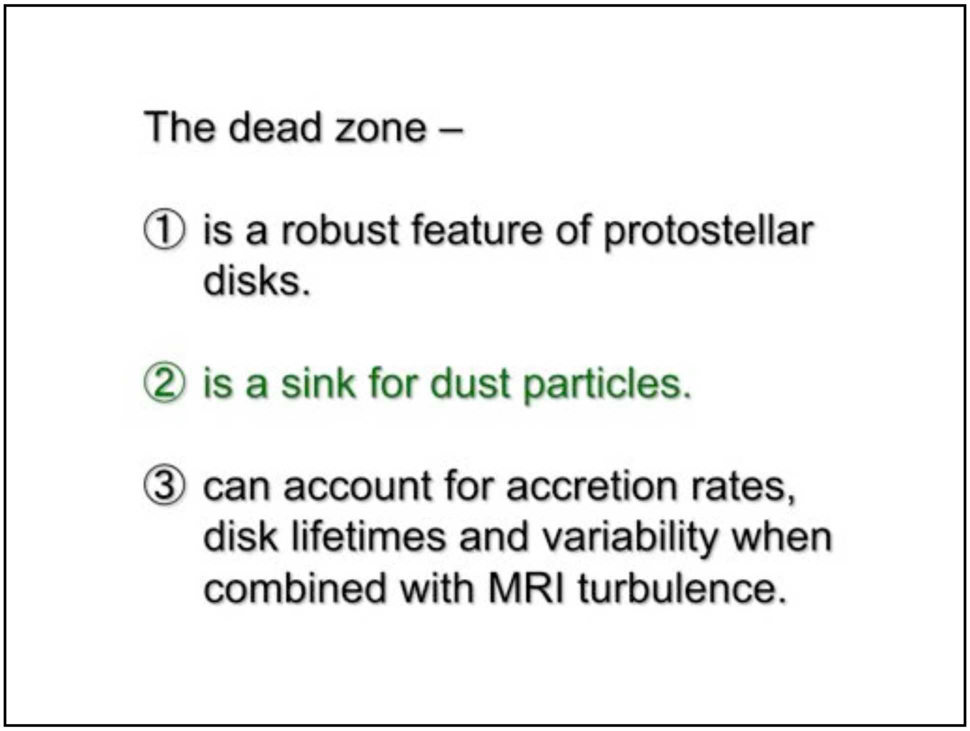
$v_{Az}^2/\eta\Omega=1$

Another possibility for removing DZ: vertical mixing of ionized material into interior. Here horiz.-avg. mag. stress in shearing-box @ 1 AU, including time-dept ionization with no dust.

Mixing almost eliminates DZ by Elsasser criterion. Note use vertical Alfven speed, since Ohmic diffusion kills the turbulence once it crosses shortest dimension of eddy.



Problem: recombination slower than the sound-crossing time requires dust abundance reduced several decades below interstellar. Conclude mixing can change the ionization only after most of the solids are segregated from the gas.



The dead zone –

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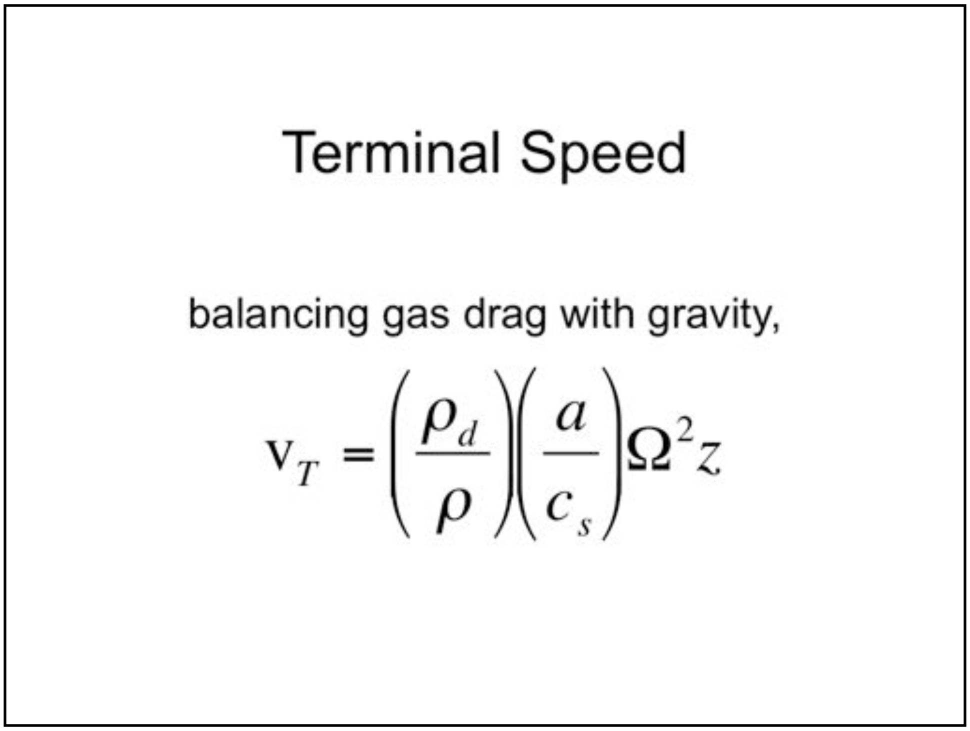
Concentration of the primordial solid material is a basic requirement for planet formation.

Processes involved might include settling, coagulation, radial drift, gravitational instability and preferential loss of gas in a wind. Here we concentrate on settling, which likely operates during the earliest stages of the growth of solid bodies.

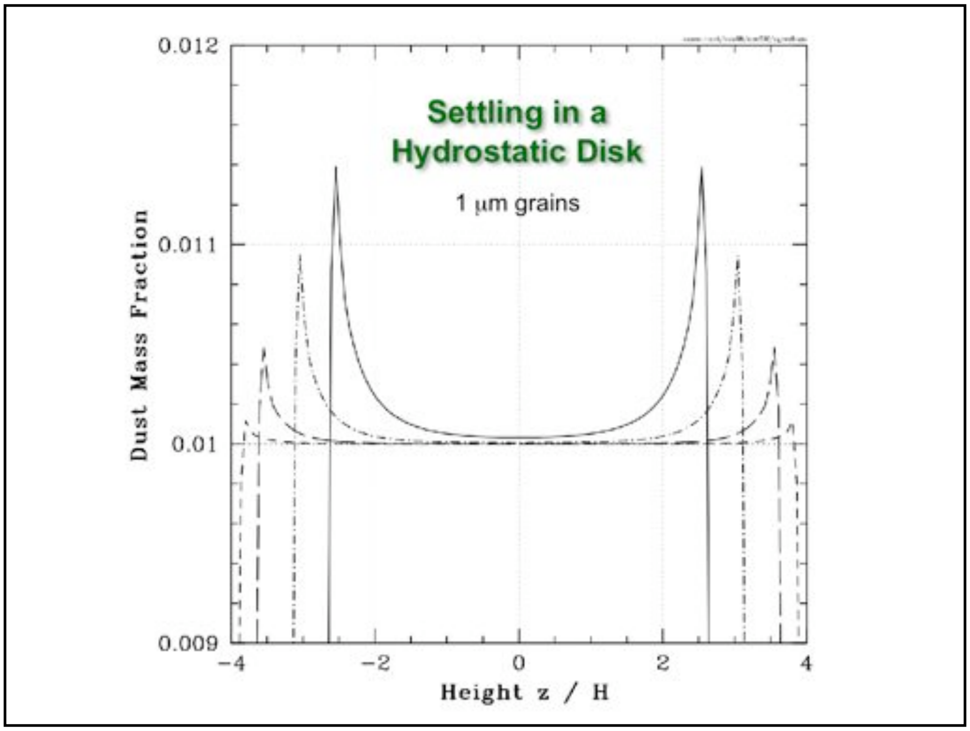


Terminal Speed

balancing gas drag with gravity,

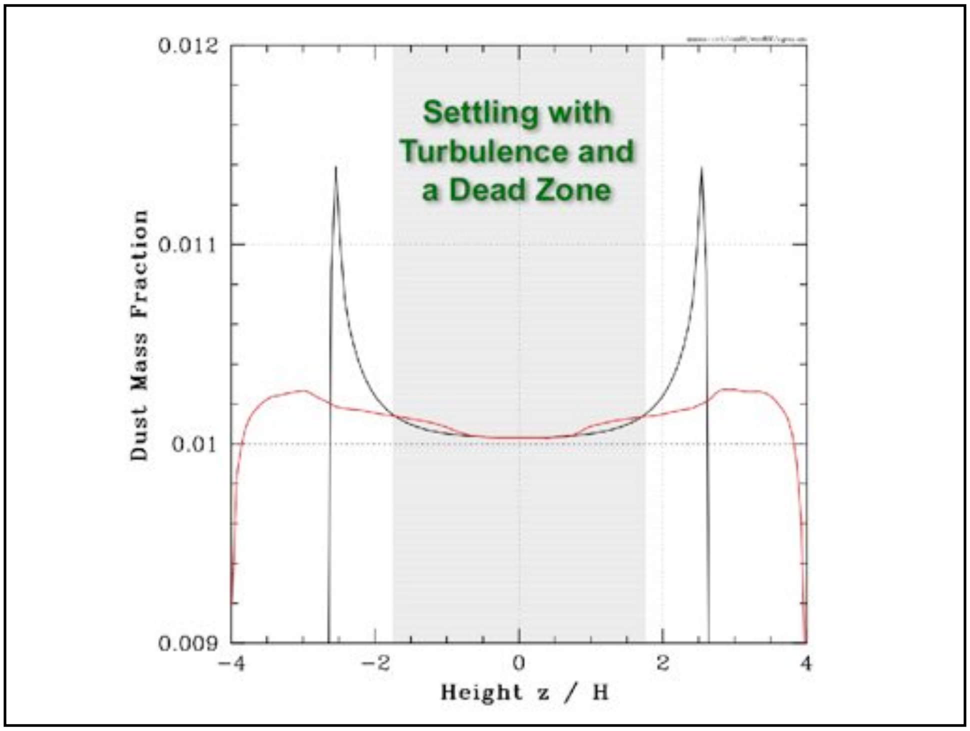
$$v_T = \left(\frac{\rho_d}{\rho}\right)\left(\frac{a}{c_s}\right)\Omega^2 z$$

Show MHD calculations with time-dependent ionization and dust settling at terminal speed. In Epstein regime where gas molecule MFP >> grain size, drag is proportional to grain speed. Use rhod=5 to see settling in half as many orbits.



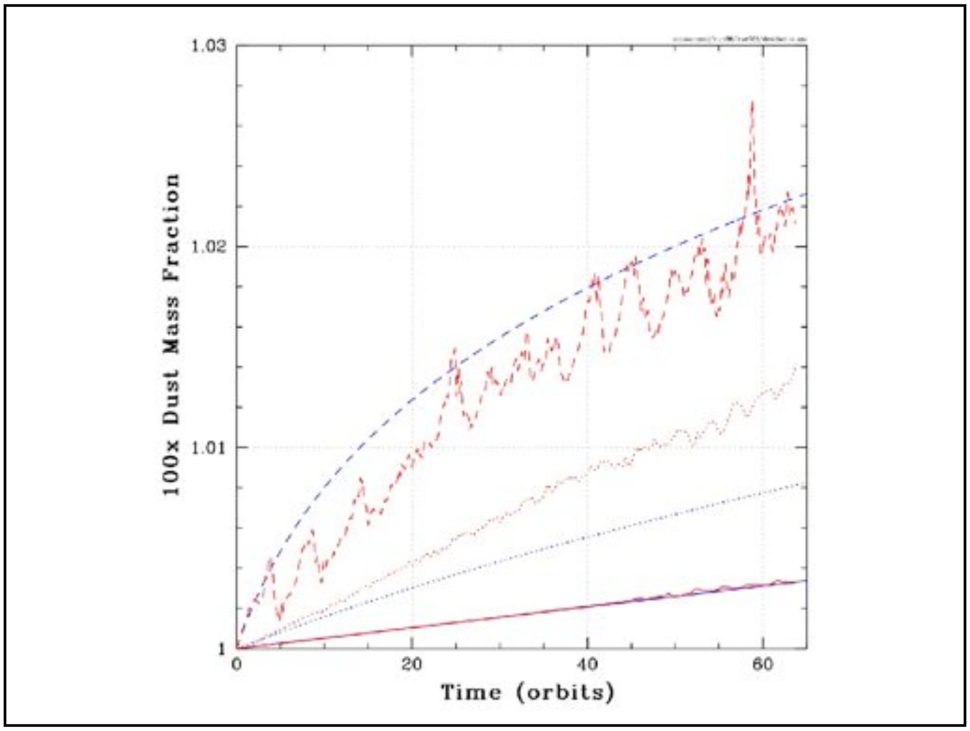
With no turbulence, initially well-mixed dust settles fastest in the outer layers, where the gravity is strong and the low density means weak gas drag.

Settling is quick: the last snapshot is at just 60 orbits. Coagulation can make the settling faster still, but here we assumed the particles do not stick to one another.

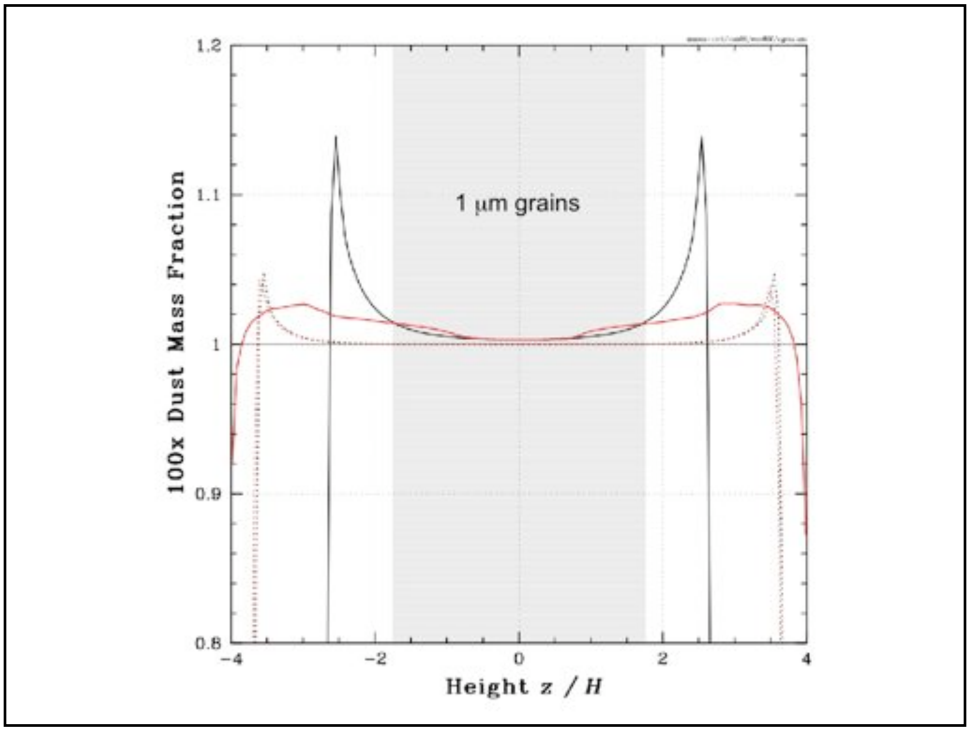


With turbulence, the more-settled material is mixed down to denser layers, leading to faster concentration of the solids there.

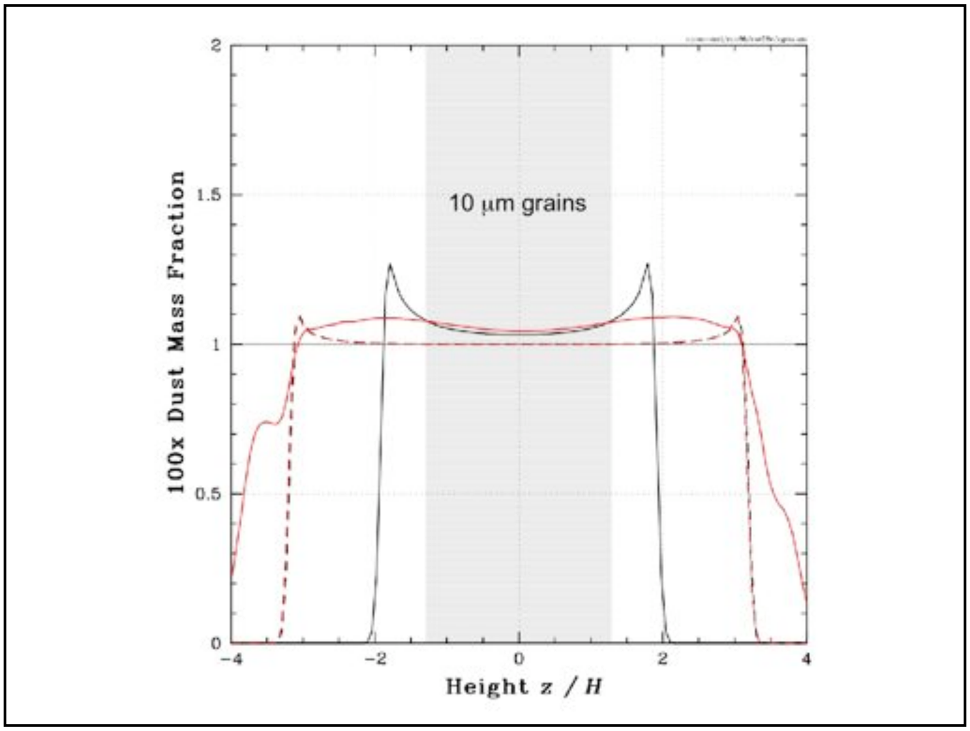
This contradicts the usual wisdom that turbulence counteracts settling.



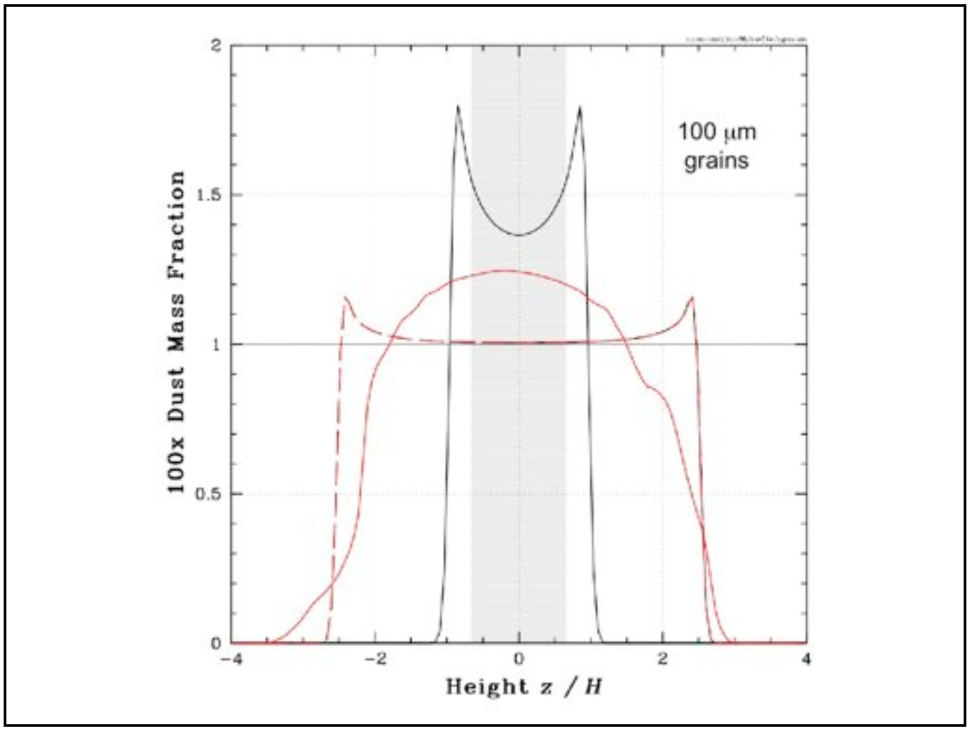
Dust-to-gas mass ratio vs. time at 3 heights: 2.5, 1.5 and 0 H. Blue lines: laminar, with outflow. Red lines: MHD results. Dust abundance at midplane follows laminar curve: settling of dust deep in DZ is unaffected by turbulent layers.



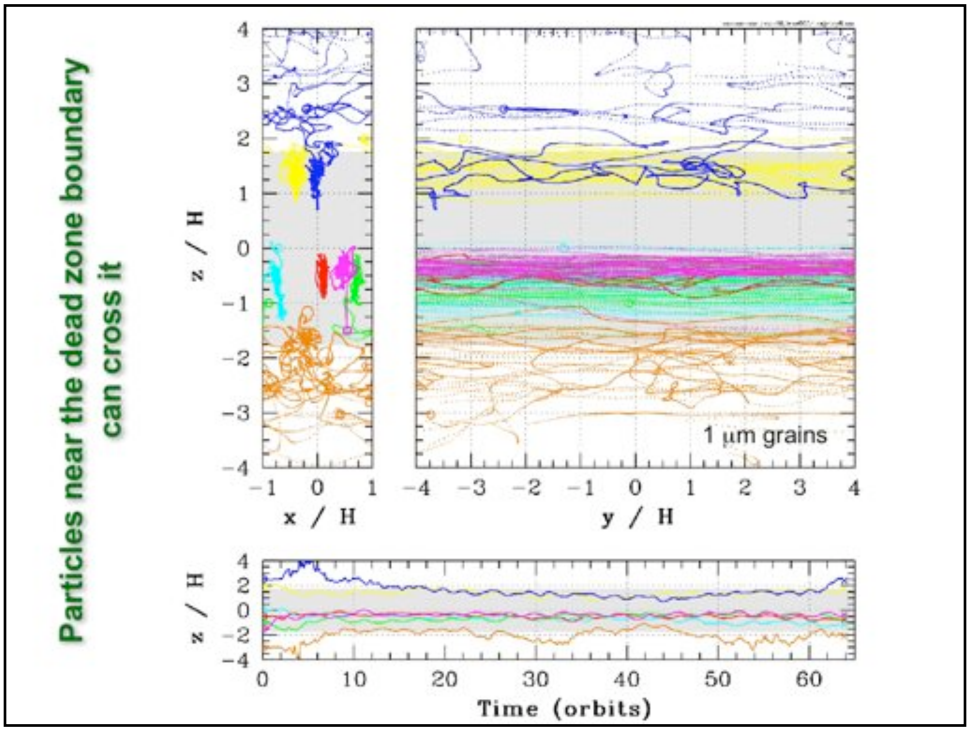
Compare results with different grain sizes, hence different dead zone depths.
(1) 1-micron grains.



(2) 10-micron grains.

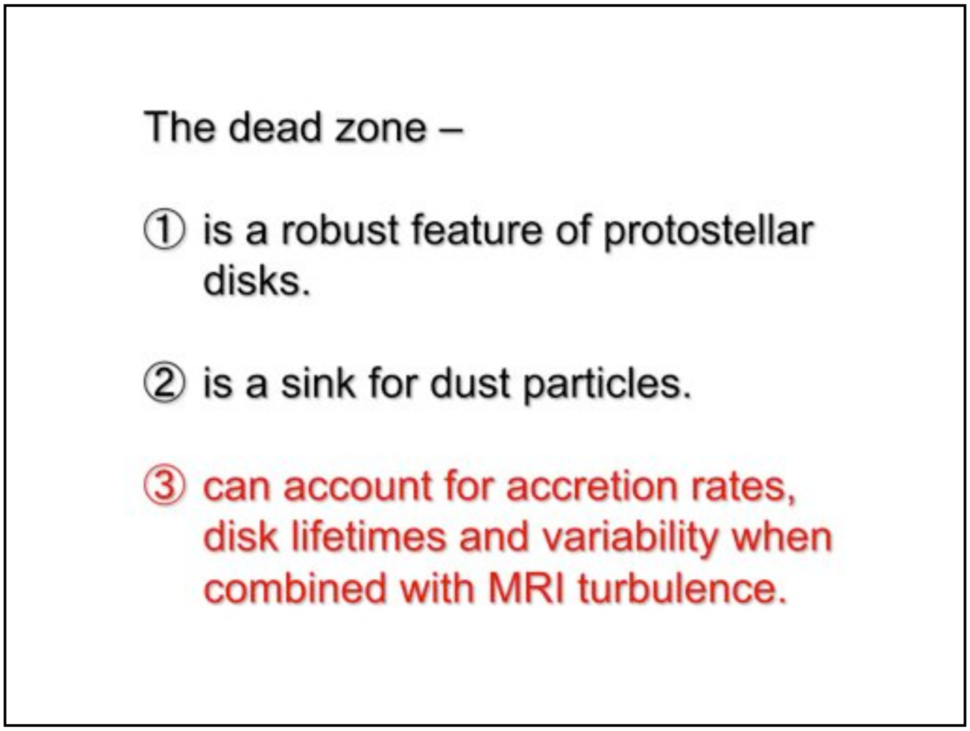


(3) 100-micron grains. Conclude that vertical transport by turbulence extends about 1H into dead zone.



Particles near the dead zone boundary can cross it

We also tracked individual dust grains, finding that they are carried in and out of DZ when turbulent gas motions overshoot DZ boundary.



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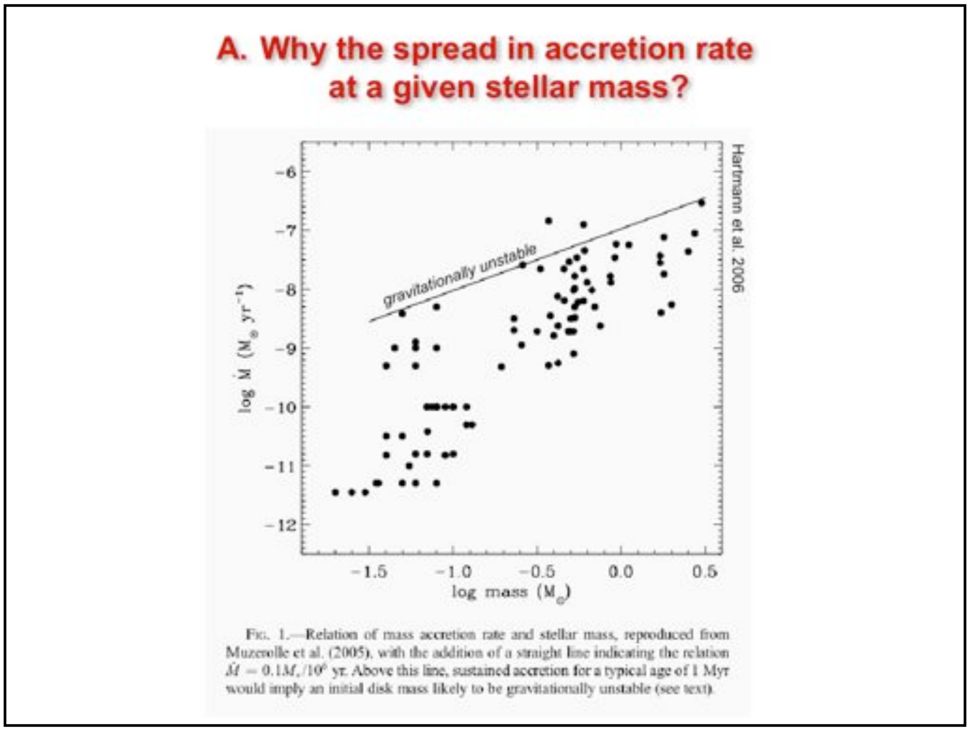
Main section of the talk: DZ and turbulent layer together can account for many observed properties of protostellar disks.

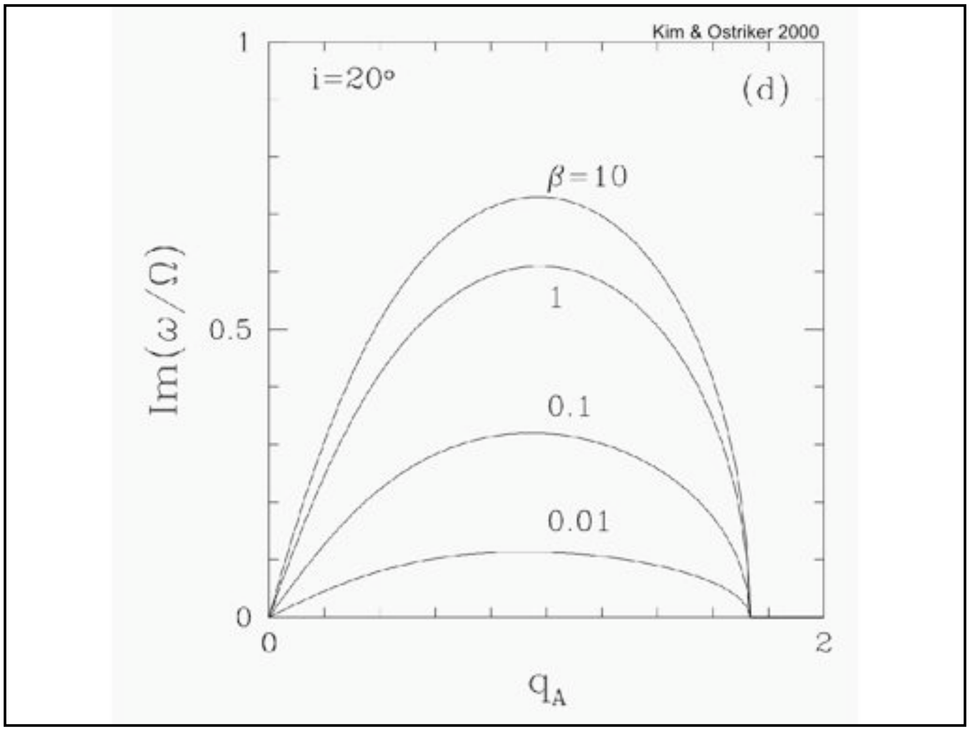


A. Why the spread in accretion rate at a given stellar mass?

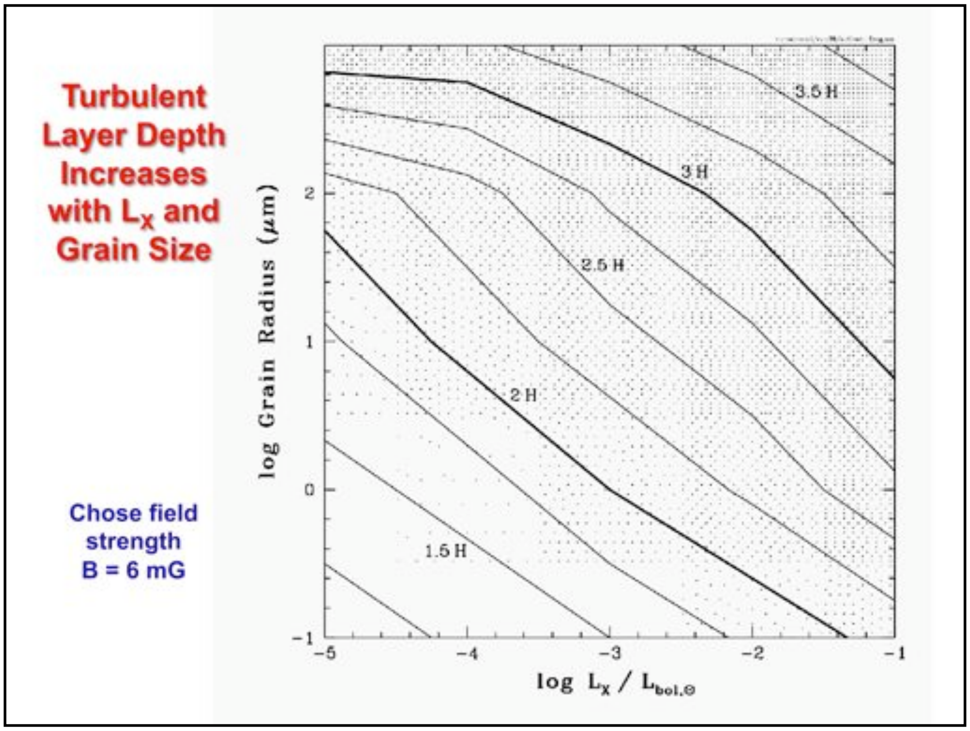
Hartmann et al. 2006

FIG. 1.—Relation of mass accretion rate and stellar mass, reproduced from Muzerolle et al. (2005), with the addition of a straight line indicating the relation $\dot{M} = 0.1 M_*/10^6$ yr. Above this line, sustained accretion for a typical age of 1 Myr would imply an initial disk mass likely to be gravitationally unstable (see text).

We want to understand the range in mass flow rate at a given stellar mass. Existing magnetic accretion models, with a fixed accreting column of 100 g/cm^2 set by the penetration depth of the ionizing cosmic rays, imply a fixed mass flow rate.



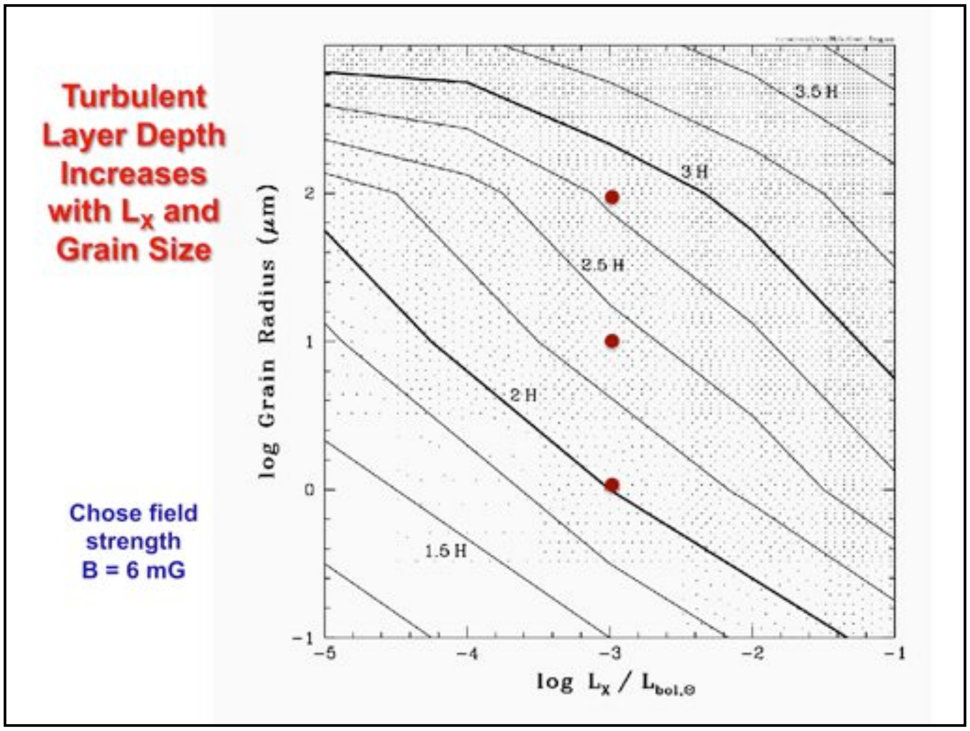
Look at factors affecting accretion rate at 5 AU. Mass flow rate is mean stress times turb. layer thickness. Place turb. layer outer boundary at 4H because linear MRI growth on field with strong toroidal component is slow when plasma beta <0.1. Next: where should inner boundary lie?



Turbulent Layer Depth Increases with L_X and Grain Size

Chose field strength B = 6 mG

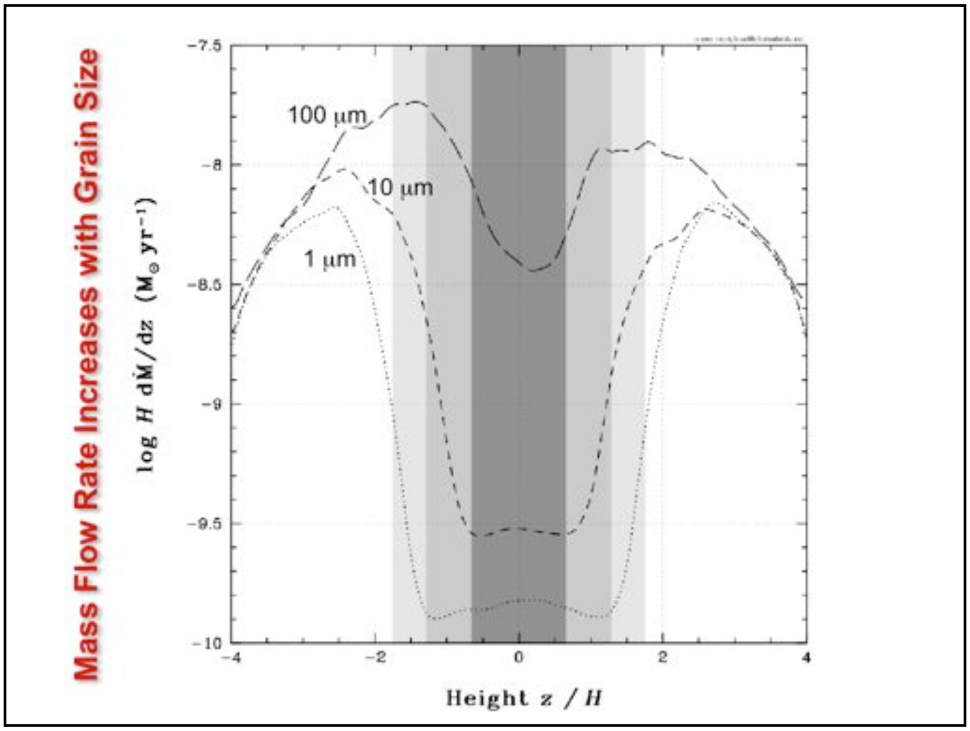
L_X range (horizontal axis) matches observed LX/Lbol range. Still-smaller grains can give even thinner turbulent layer. Conclusion: Can vary active layer thickness by at least a factor 4.



Turbulent Layer Depth Increases with L_X and Grain Size

Chose field strength B = 6 mG

We measured the accretion stresses resulting from MHD turbulence in three MHD calculations with the parameters shown by the red dots.

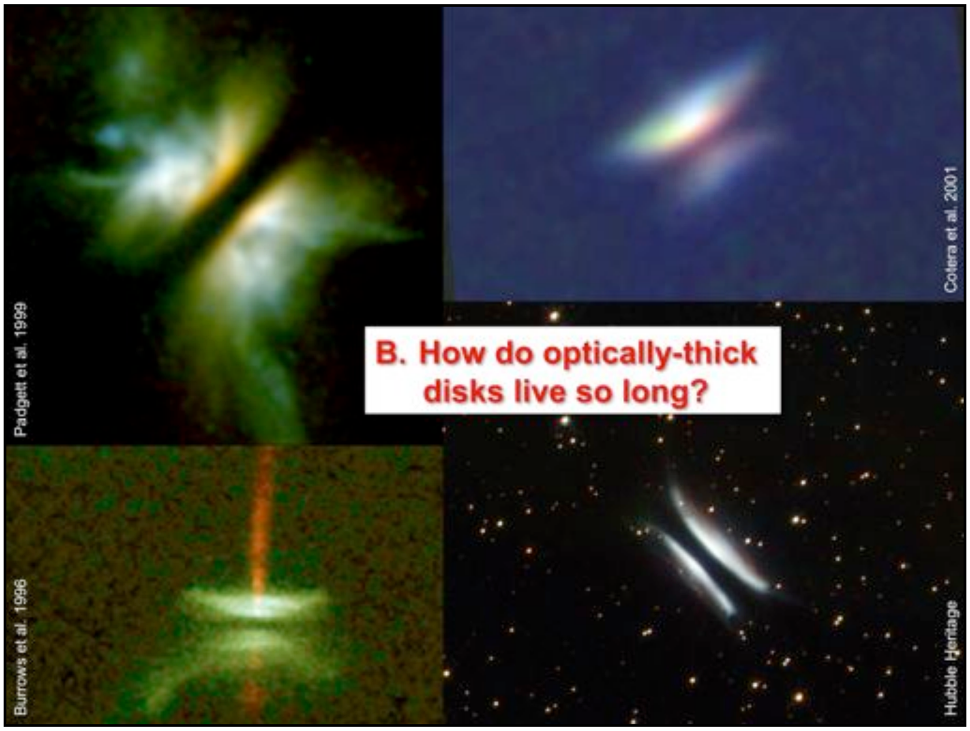


Mass Flow Rate Increases with Grain Size

Mean stress increases w. active layer thickness. Height-integrated accretion rates 2, 3, 7x10^-8 Solar masses/yr.

Variety in grain size or abundance & L_X yields 1-dex spread in accretion rates. Range of magnetic fluxes easily yields another dex.

Accretion rate will depend on radius, so more work is needed before we can say whether turb. layer accounts for stellar accretion rates.



B. How do optically-thick disks live so long?

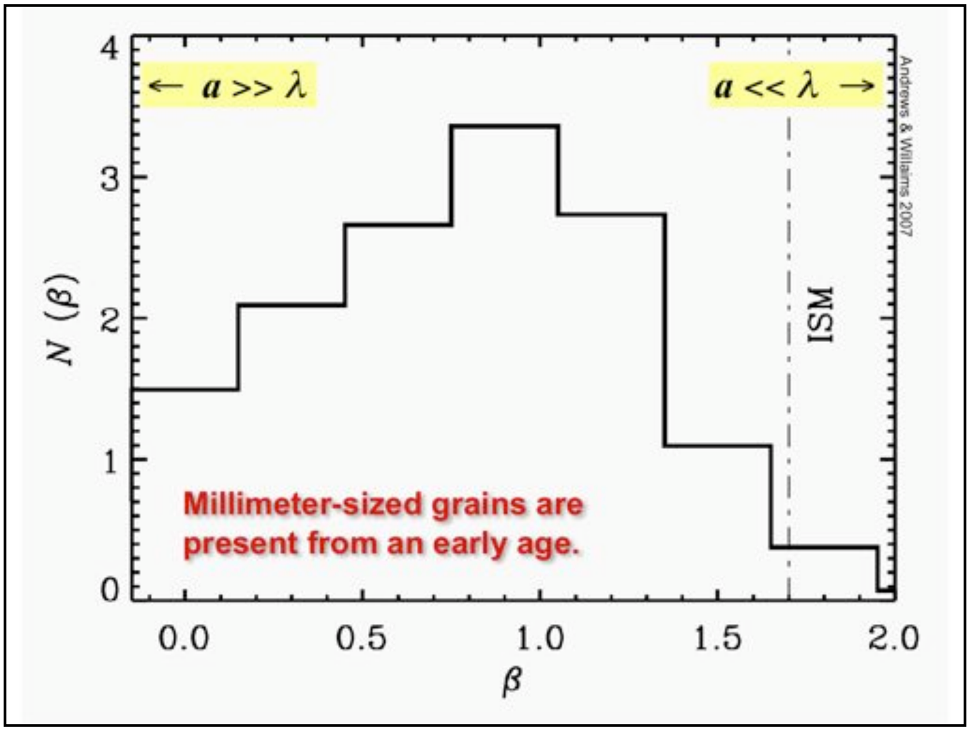
Padgett et al. 1999

Cotera et al. 2001

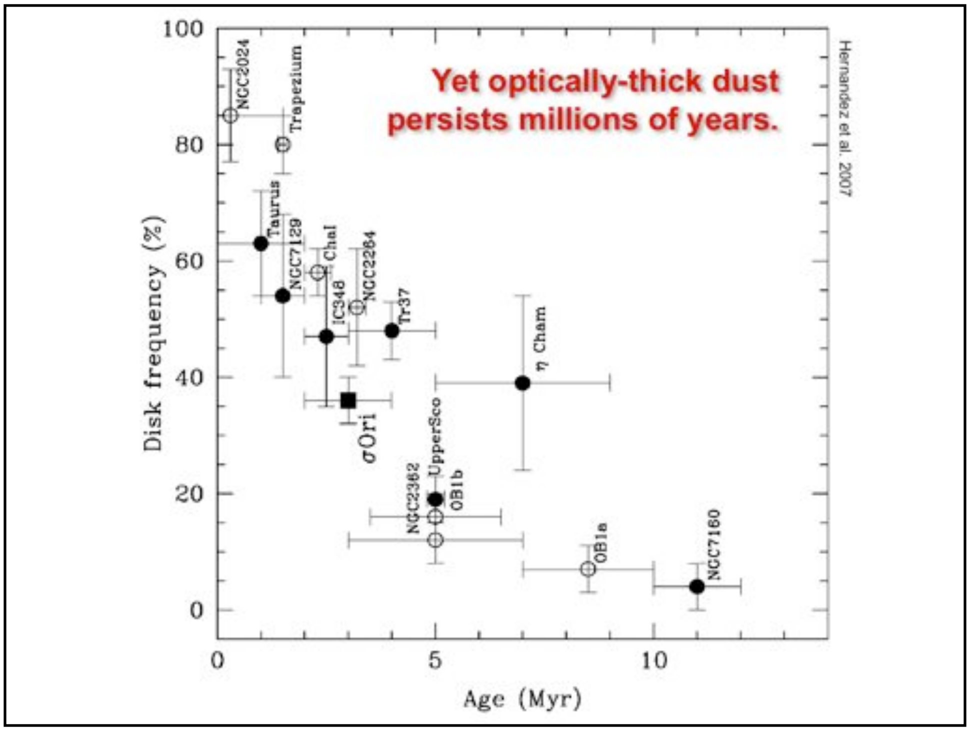
Burrows et al. 1996

Hubble Heritage

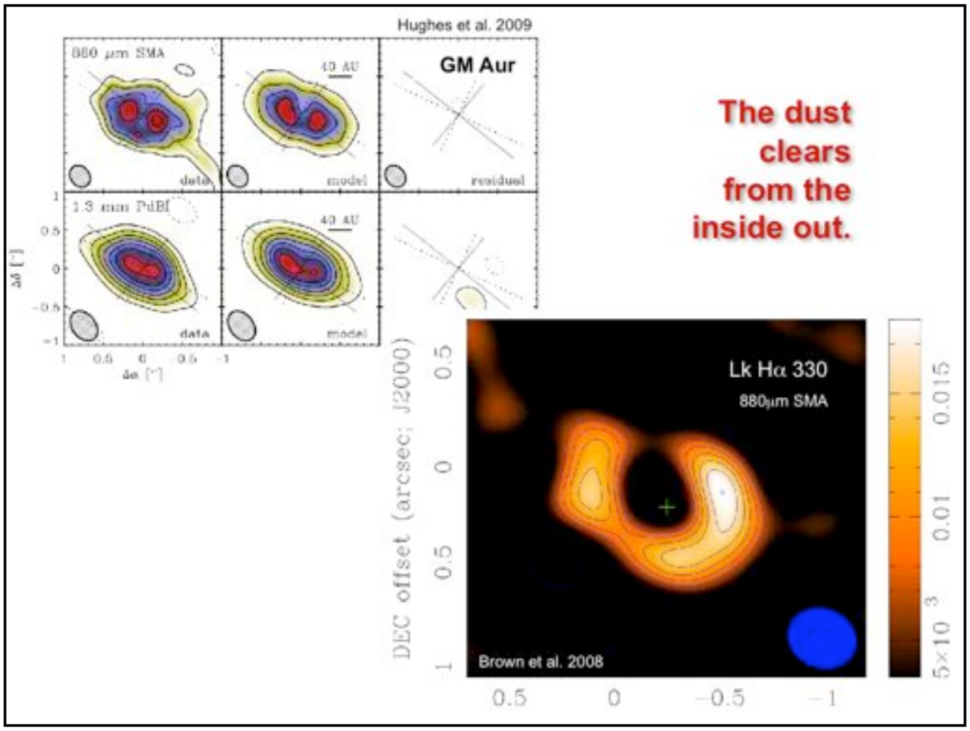
Ample evidence for grains suspended in atmospheres of Myr-old protostellar disks at spatially-resolved scales >20AU.



Ample evidence for growth of grains to millimeter sizes.



Optically-thick dust disks are lost in ~5Myr. Problem: DD05 found if grains readily stick, most dust coagulates and settles out in <10^5 yr.


Hughes et al. 2009

GM Aur

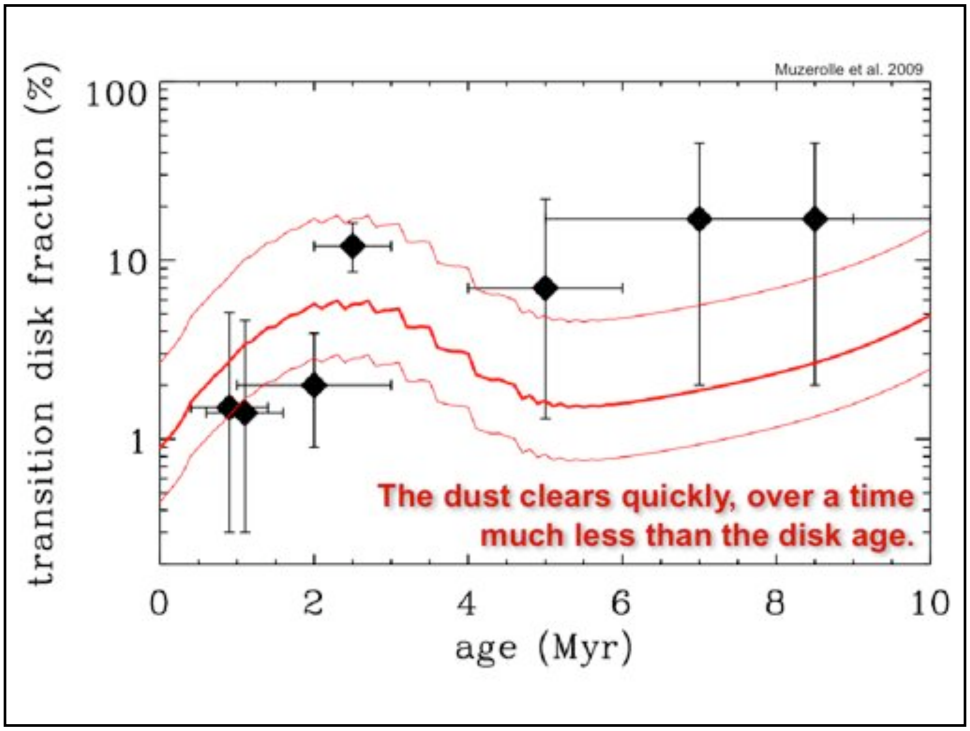
The dust clears from the inside out.

Lk Hα 330

880μm SMA

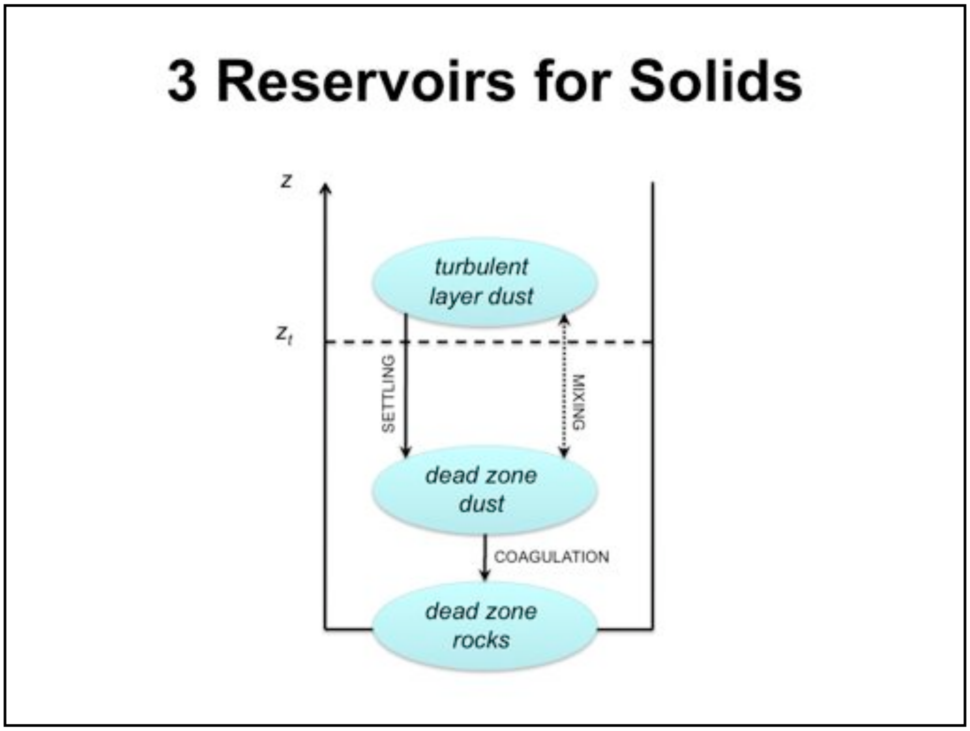
Brown et al. 2008

The dust clears from the inside out, as indicated by “transitional” systems having an optically-thin central hole with radius 1-100 AU, >> dust destruction or stellar magnetospheric radius.



The dust clears quickly, over a time much less than the disk age.

Small fraction of disks have SEDs indicating the larger central holes. Simplest explanation: dust lost in each system within ~10^5 yr.

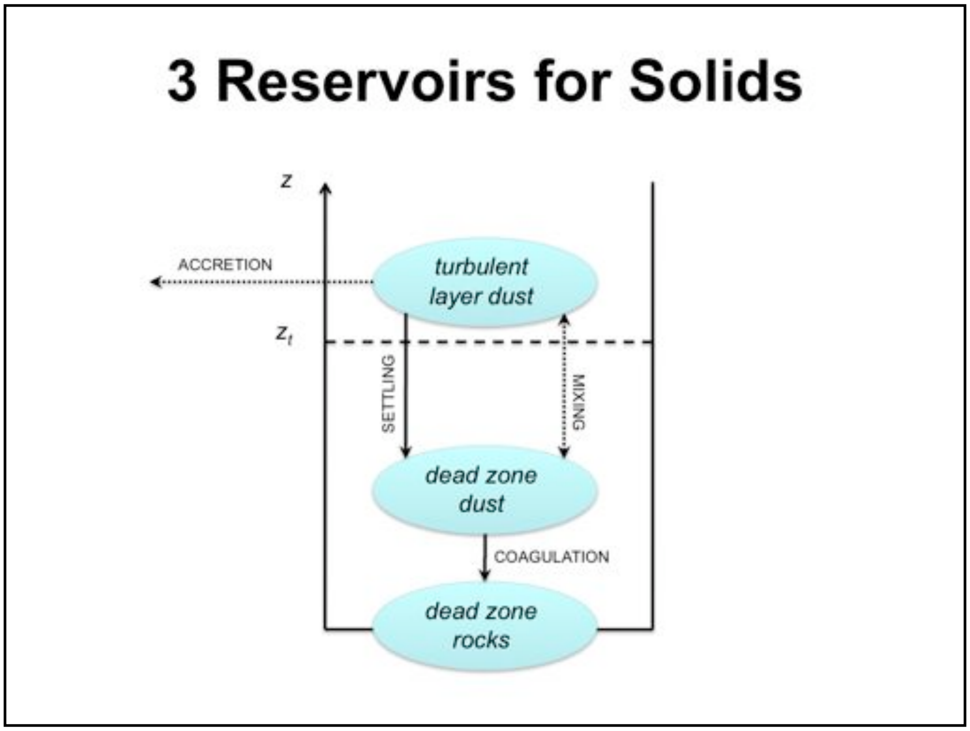


3 Reservoirs for Solids

See whether MRI can reproduce these features. Construct toy model for solids evolution in a disk annulus. Fix the gas distribution.

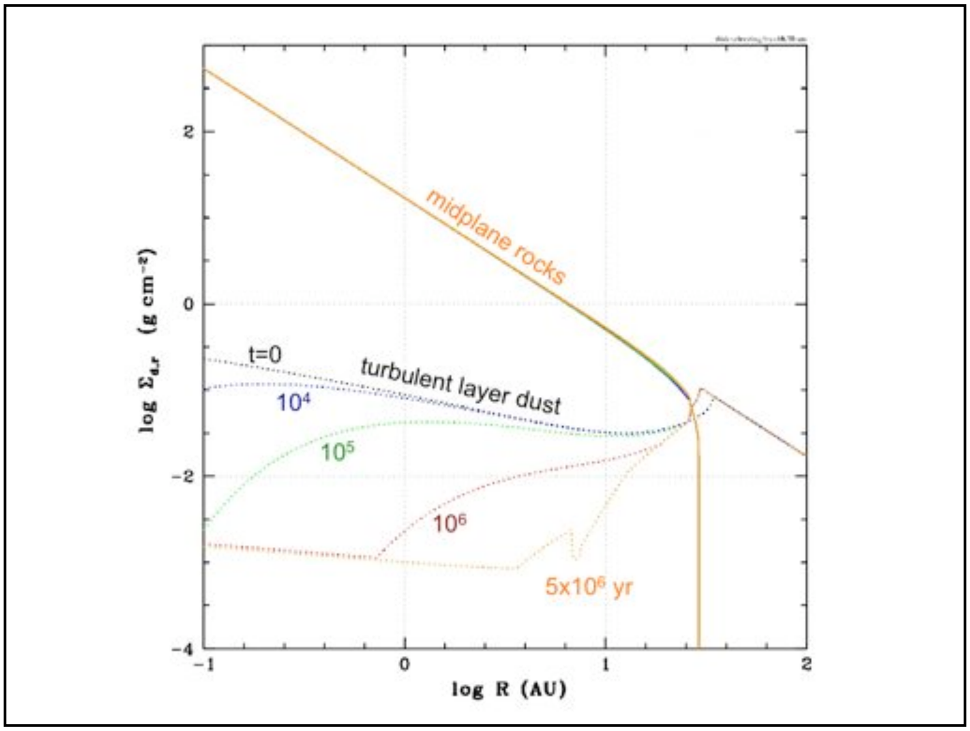
Three reservoirs? Settling, coagulation, mixing timescales? Fragmentation? Turbulent layer height?

Solve 3 coupled ODEs describing time evolution of 3 populations, starting with well-mixed dust at 1% mass fraction.



3 Reservoirs for Solids

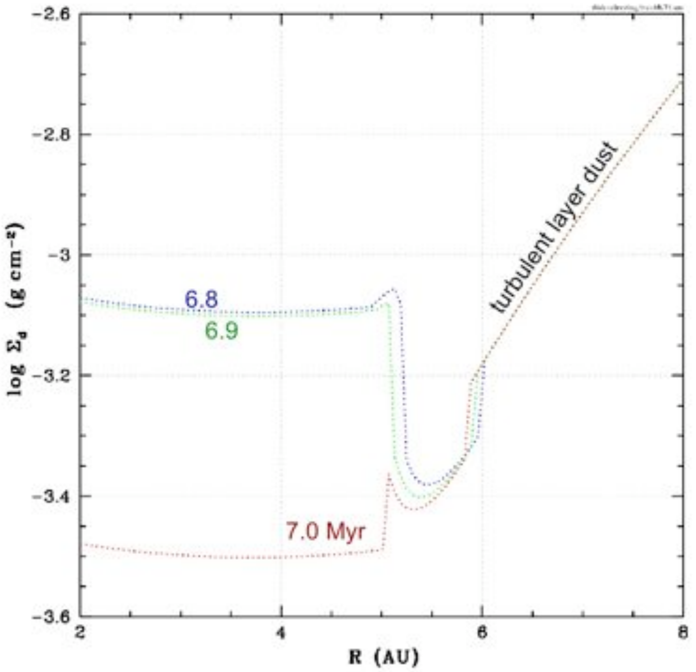
Also include radial advection of the dust when the system age exceeds the local Shakura-Sunyaev accretion timescale.



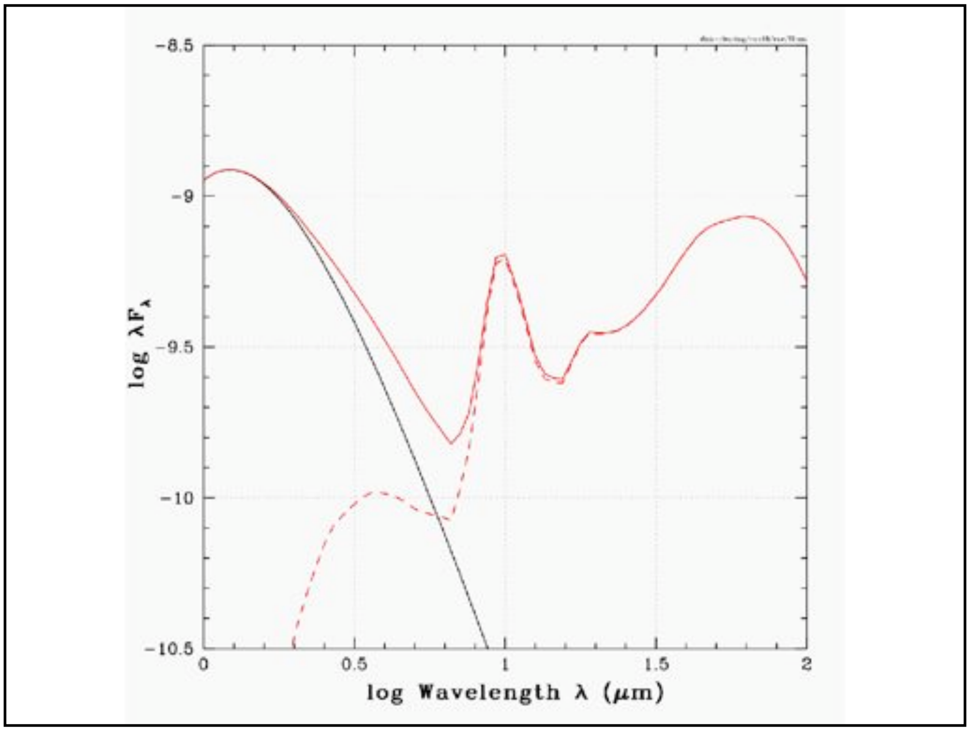
Dead zone dust quickly coagulates into rocks. Disk has optically-thick turbulent layers surrounding optically-thin dead zone.

Timescale for depleting turbulent layer dust is the settling time. Resupply from other annuli is important at disk inner edge by 10^5 yr.

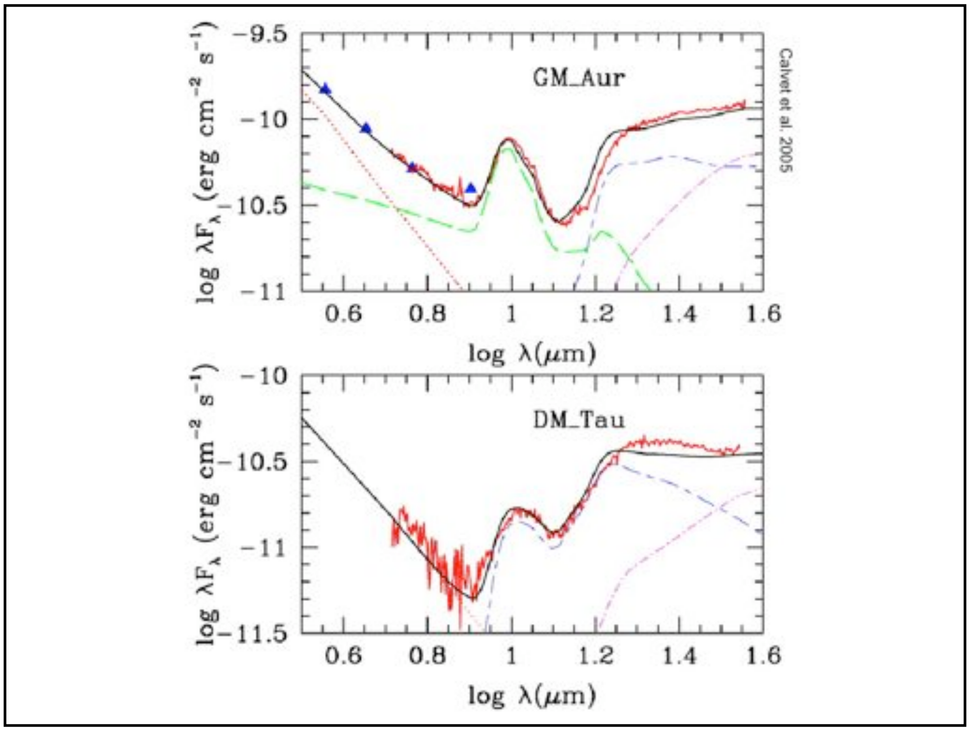
Gap developing at 5 Myr results from mixing of turbulent layer dust into DZ followed by rapid coagulation, in annuli with H>z_t>0.



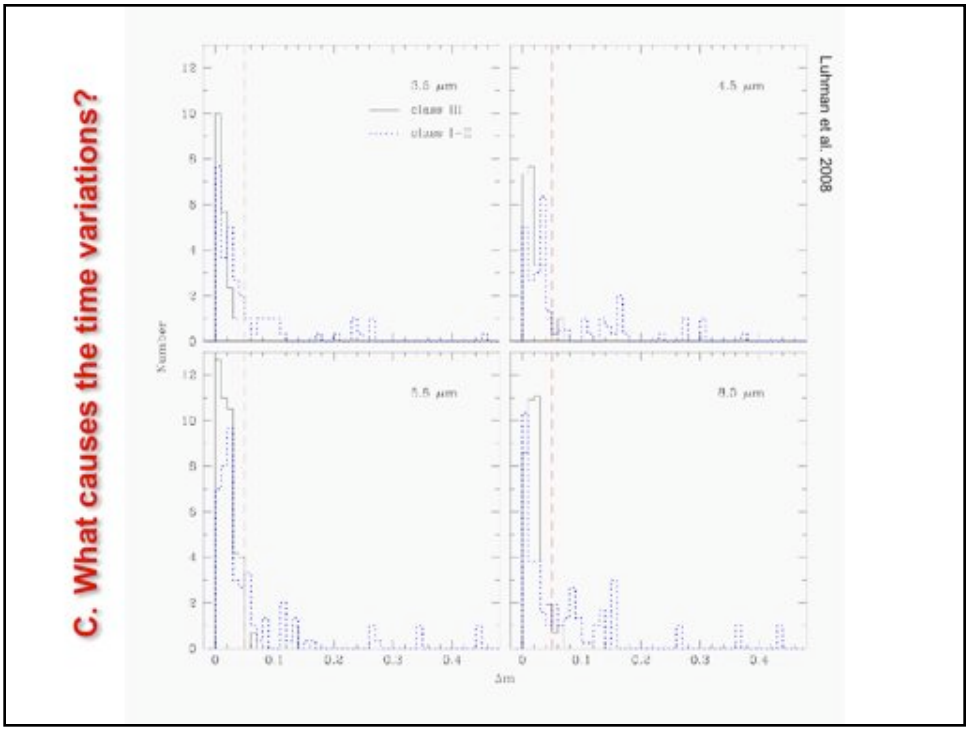
Close-up around 7 Myr. When inward radial transport becomes important as far out as the gap, the dust surface density inside drops several-fold in <10^5 yr.



SED of the model disk plus star at 7 Myr…



…resembles observed SEDs of the transitional objects having central holes.

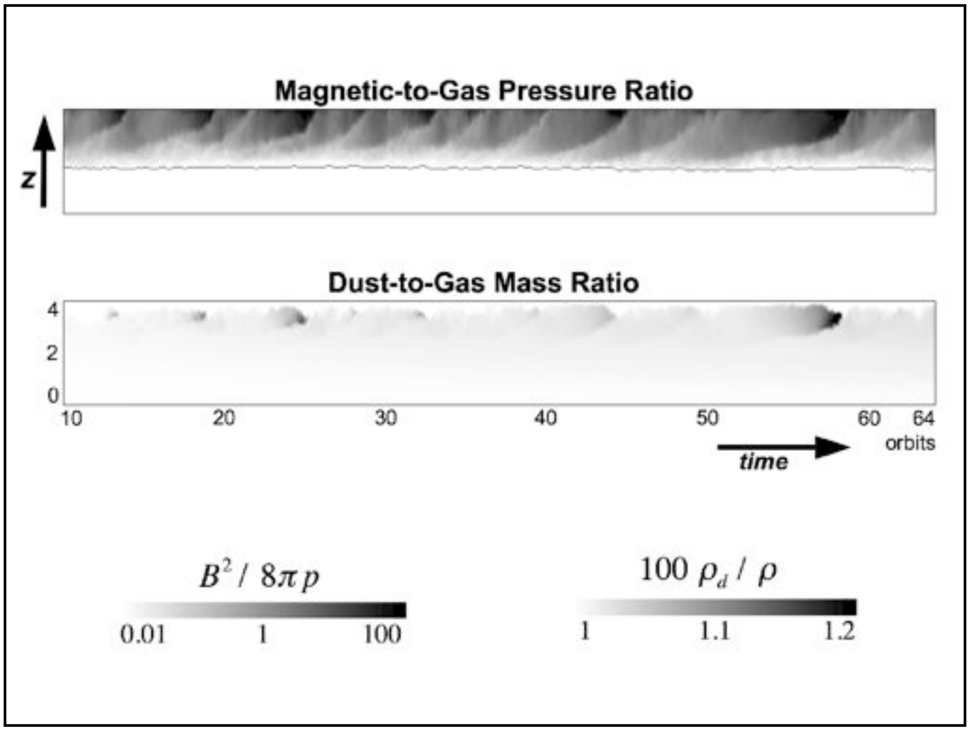


C. What causes the time variations?

Luhman et al. 2008

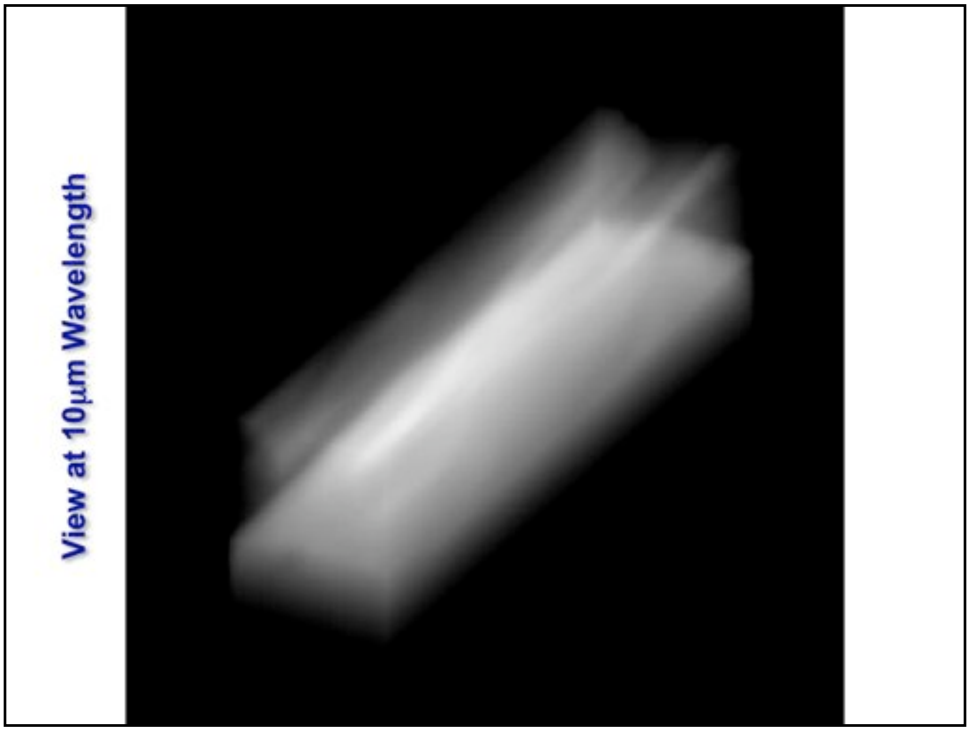
About half of young stars with disks in Taurus that were observed more than once with Spitzer IRAC show variability.

Given limited sampling, probably a majority of young stars vary in the near- to mid-IR.

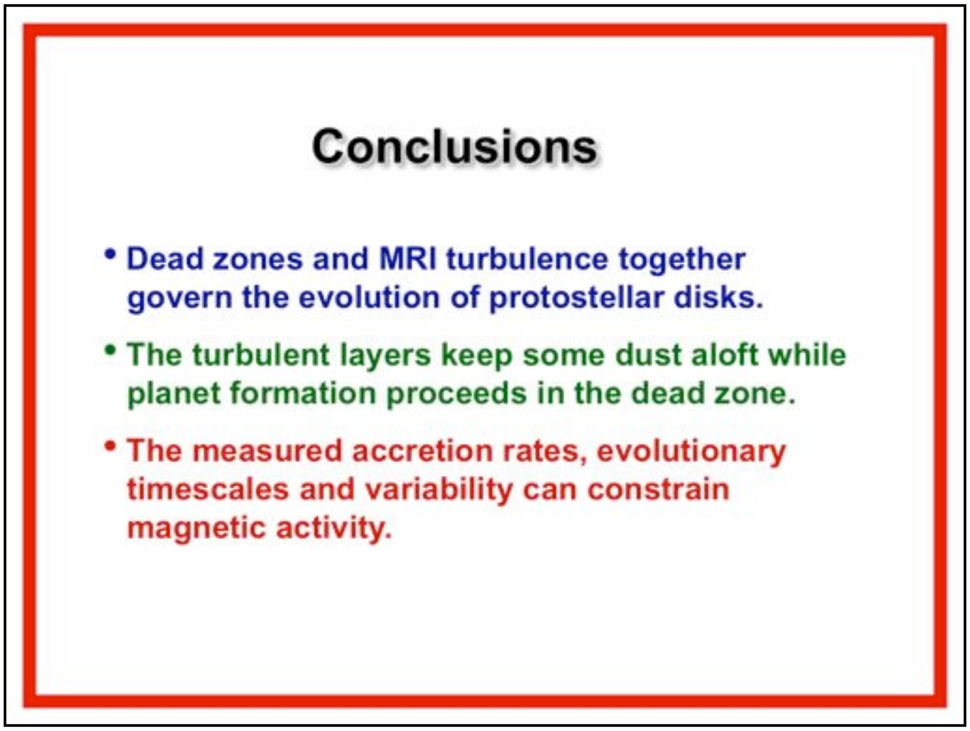


Variability occurs also in the distribution of the dust in the turbulent layers in the shearing-box calculations with settling. Here: 1um run.

Gas becomes more dusty at base of layer with magnetic pressure high relative to gas pressure. Reason: MRI turbulence shuts down, density is low, grains settle.



Every few orbits, toroidal magnetic fields grow strong through shear, become buoyant and rise. Gas coming up below sweeps up dust, lifting the particles above the previous photosphere so they are heated by stellar irradiation and become bright in the 10-micron silicate band. Brightness of disk patch changes by factor two and 10-um photosphere height changes by H over few orbits.



Conclusions

- Dead zones and MRI turbulence together govern the evolution of protostellar disks.
- The turbulent layers keep some dust aloft while planet formation proceeds in the dead zone.
- The measured accretion rates, evolutionary timescales and variability can constrain magnetic activity.

It's been suggested transitional disks result from gap-opening planets. I'd like to propose that in the cases with higher stellar gas accretion rates, the clearing in fact results from magneto-rotational turbulence. There is an exciting potential for using the many new observations of protostellar disks to empirically constrain the properties of the turbulence.