Self-regulated Gravitational Accretion in Protostellar Disks

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Star Formation through Cosmic Time
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Disk Modeling: Various Approaches

- One dimensional, axisymmetric, semi-analytic, α-viscosity models: completely ad-hoc treatment of angular momentum, mass transport
- Three dimensional local simulation (periodic shearing box): high resolution possible but still only a local model
- Three dimensional global simulation: limited dynamic range of spatial and temporal scales currently possible

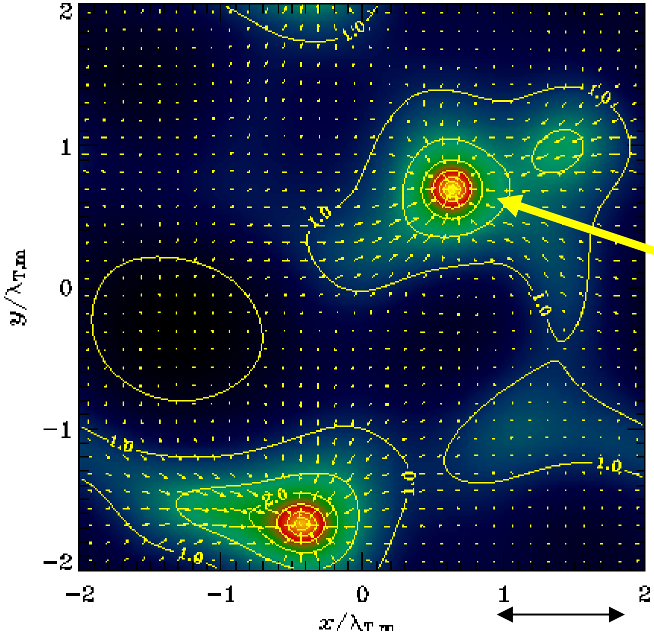
In ALL of these approaches, the disk is usually ISOLATED, and cut off from initial conditions of its parent core and formation process, as well as ongoing interaction with the core envelope!

A New Approach: Global Core → Disk Formation/Accretion Simulation using the Thin-Disk Approximation

Advantages of Thin-Disk Simulation:

- Allows efficient calculation of long-term evolution even with small time stepping, e.g., due to nonuniform mesh. Can study disk accretion for ~ 10^6 yr rather than ~10^3 yr.
- Can study large dynamic range of spatial scales, ~ 10^4 AU down to several AU. Use an (r,ϕ) grid with logarithmic spacing in radial coordinate.
- Can run a very large number of simulations – for statistics and parameter study

A self-consistent model of core collapse leading to protostar and disk formation



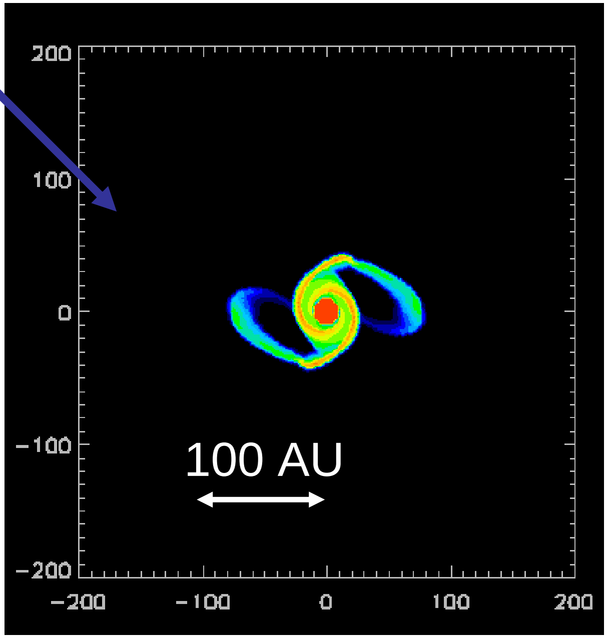
0.5 pc

Molecular cloud cores are at least mildly nonaxisymmetric.

e.g., Basu & Ciolek (2004) - above

Zoom in to simulate the collapse of a rotating nonaxisymmetric supercritical core

A disk that forms naturally from the collapse of the core. Previous models have usually studied ***isolated*** disks.



100 AU

Vorobyov & Basu (2005, 2006)

What’s not included in this model (as of now)

- Magnetic braking
- Ambipolar diffusion or other non-ideal MHD effects
- Physics of inner disk (~ 5 AU) inside central sink cell
- Magnetorotational instability (can’t occur in thin-disk model)
- Stellar irradiation effects on disk
- Radiative transfer in disk (we use barotropic P-ρ relation)

Core initial conditions

$$\Sigma = \frac{r_0 \Sigma_0}{\sqrt{r^2 + r_0^2}},$$

$$\Omega = 2\Omega_0 \left(\frac{r_0}{r}\right)^2 \left[\sqrt{1+\left(\frac{r}{r_0}\right)^2} - 1\right],$$

$$B_z = \alpha 2\pi G^{1/2} \Sigma.$$

These profiles represent best analytic fits to axisymmetric models of magnetically supercritical core collapse (Basu 1997).

All scale as r^{-1} at large radii.

Pick r_0, Ω_0, α, so that core is mildly gravitationally unstable initially.

$$r_0 = 6.4\times 10^{-3}\ \mathrm{pc} = 1.3\times 10^{3}\ \mathrm{AU}$$

$$r_{out} = 0.05\ \mathrm{pc} = 10^{4}\ \mathrm{AU}$$

$$\Omega_0 = 1.5\ \mathrm{km\ s^{-1} pc^{-1}} = 4.9\times 10^{-14}\ \mathrm{rad\ s^{-1}}$$

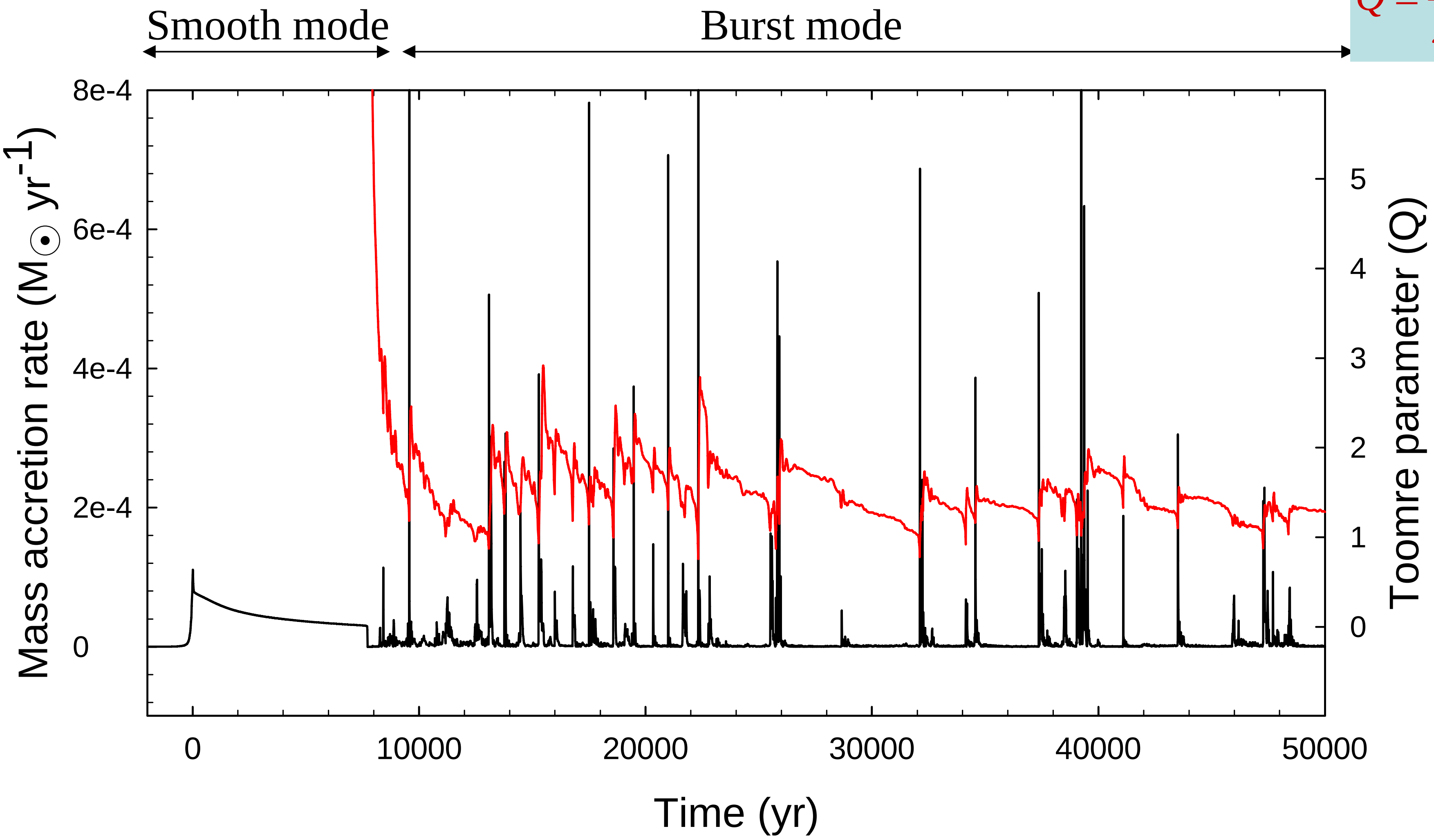
$$\alpha = 0 \text{ or } 0.3$$

Basic qualitative results are independent of details of initial profiles.

Mass accretion bursts and the *Q*-parameter

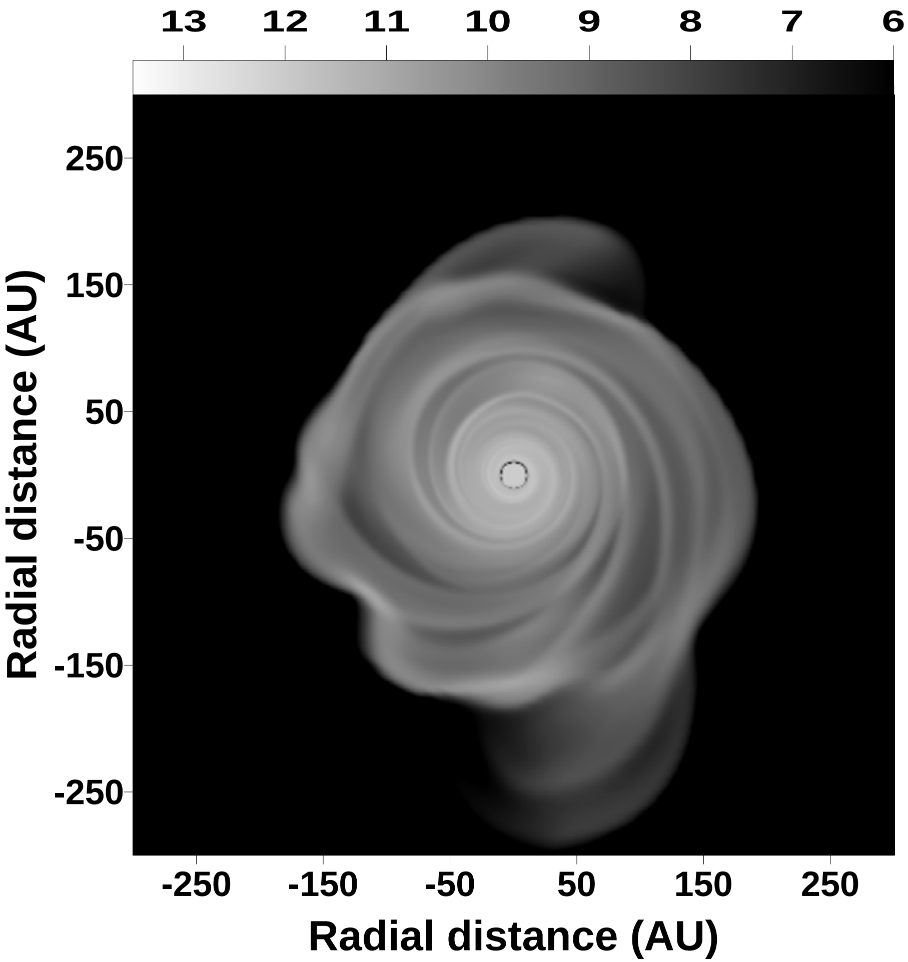
Black line - mass accretion rate onto the protostar; **Red line** – the *Q*-parameter

$$Q = \frac{c_s \kappa}{\pi G \Sigma}$$

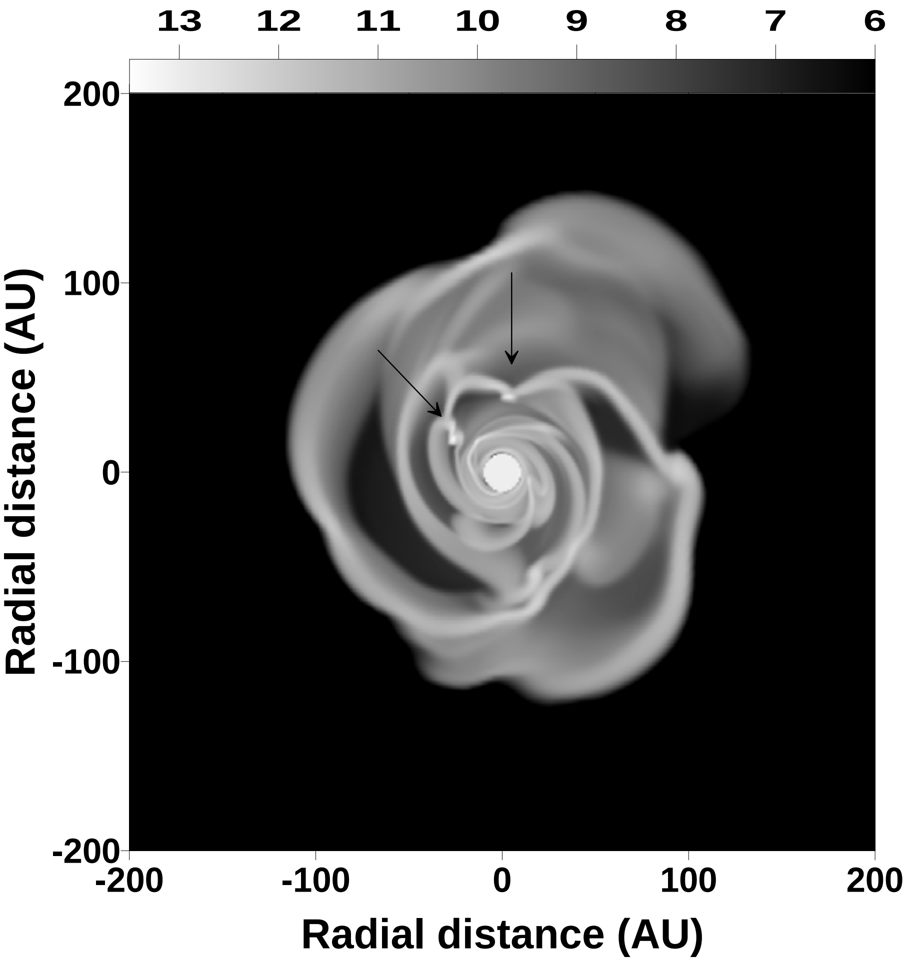


The disk is strongly gravitationally unstable when the bursts occur

Spiral structure and protoplanetary embryo formation

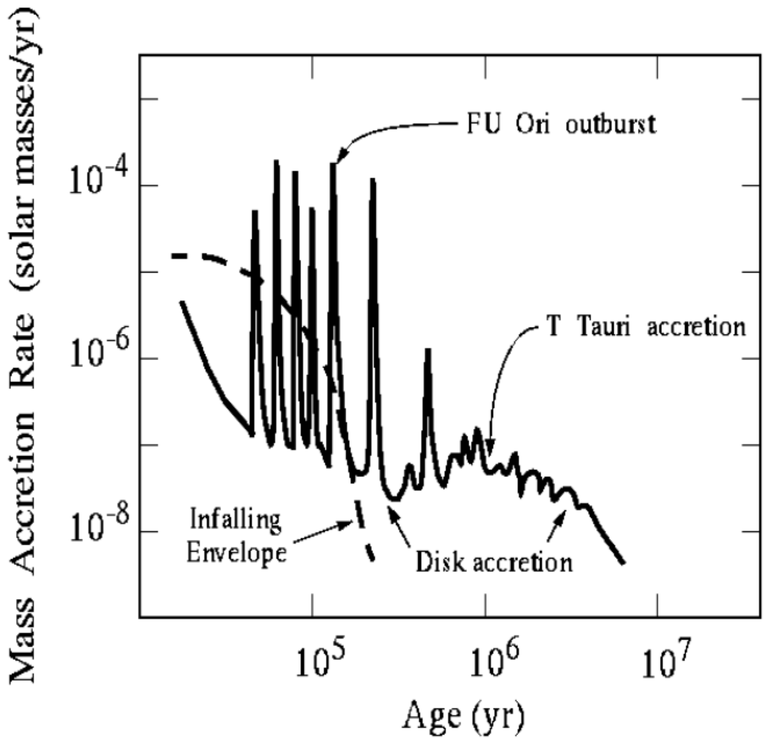


Quiescent phase

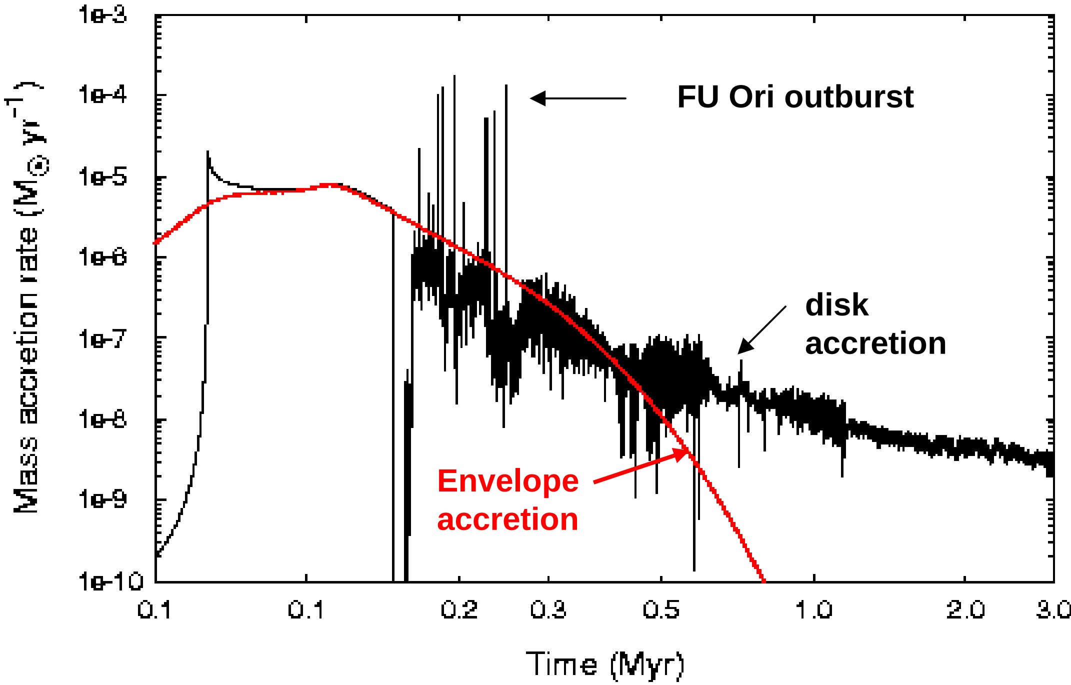


Just before a burst

Accretion history of young protostars

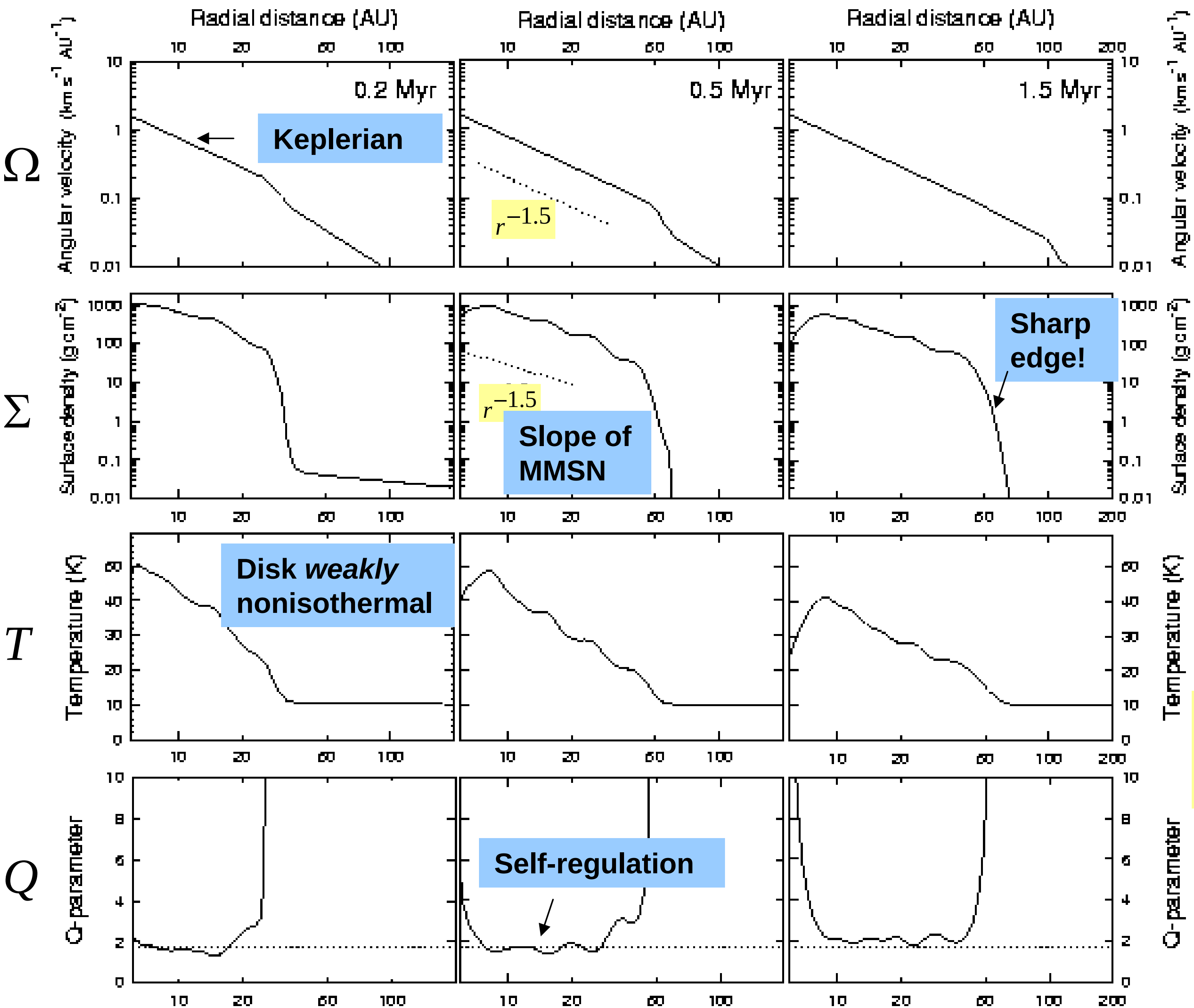


Hartmann (1998) – empirical inference, based on ideas advocated by Kenyon et al. (1990).



Vorobyov & Basu (2006, 2007) – theoretical calculation of disk formation and evolution

A Closer Look at Spatial Profiles – Azimuthally Averaged



Keplerian

$r^{-1.5}$

$r^{-1.5}$

Slope of MMSN

Sharp edge!

Disk *weakly* nonisothermal

Self-regulation

$$Q = \frac{c_s \kappa}{\pi G \Sigma}$$

Accretion and instability help to self-regulate disks to a near-uniform Q distribution

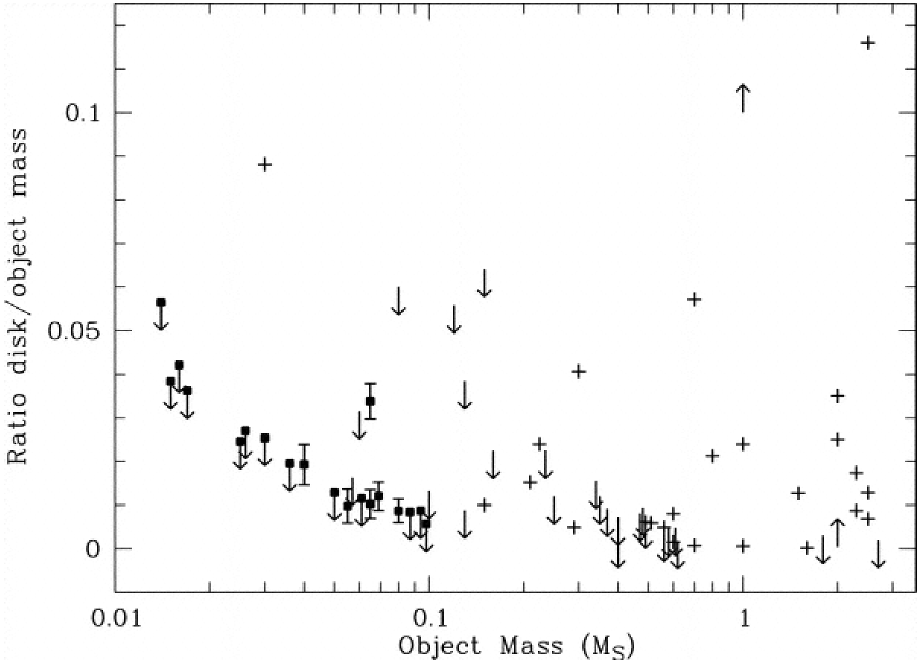
$$\Sigma \propto r^{-3/2}.$$

Nonaxisymmetry is essential for this result.

Vorobyov & Basu (2007)

Conventional Wisdom about Gravitational Accretion

- Vorobyov & Basu model $M_d / M_s \approx 0.05 - 0.1$ after ~ Myr evolution
- Previous simulations (e. g.. Tomley et al. 1991; Laughlin & Bodenheimer 1994) estimate gravitational instabilities if $M_d / M_s \geq 0.1$
- But, observed M_d / M_s □ 0.01 albeit with large scatter

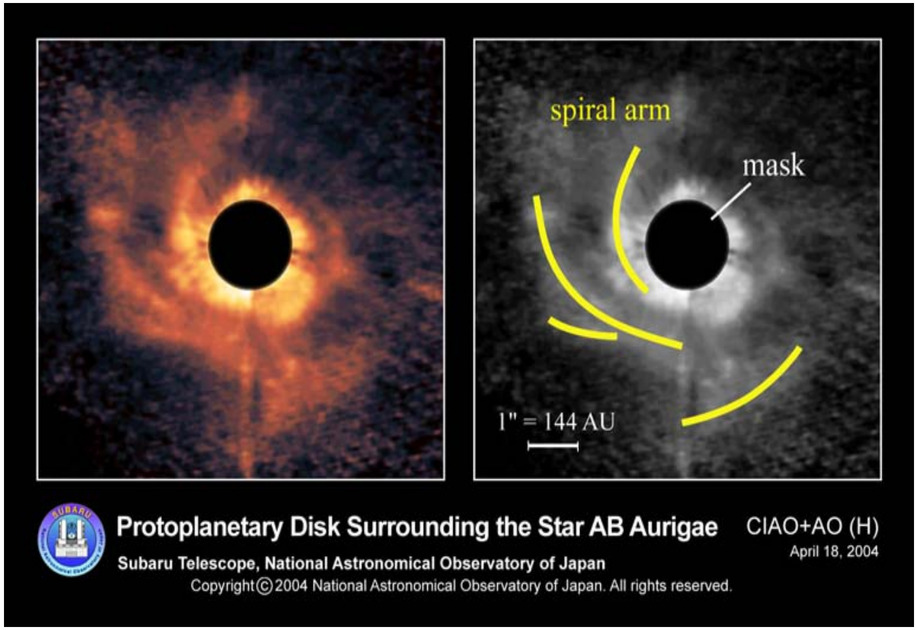


Scholz, Jayawardhana, & Wood (2006)

Gravitationally driven accretion after all?

- Theoretical estimates (Larson 1984): nonaxisymmetric surface density fluctutations ~ few % can yield gravitational torques to drive accretion at T Tauri rates

- Observations of non-axisymmetric structures in protostellar disks of Herbig Ae/Be stars AB Aurigae (Fukagawa et al. 2004) and HD 100546 (Grady et al. 2001)



Protoplanetary Disk Surrounding the Star AB Aurigae CIAO+AO (H)

April 18, 2004

Subaru Telescope, National Astronomical Observatory of Japan

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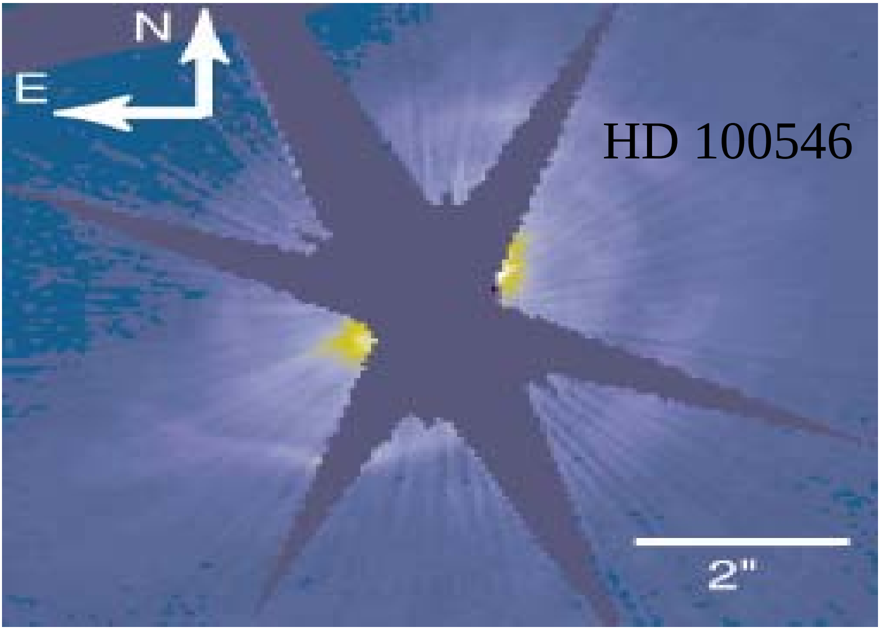
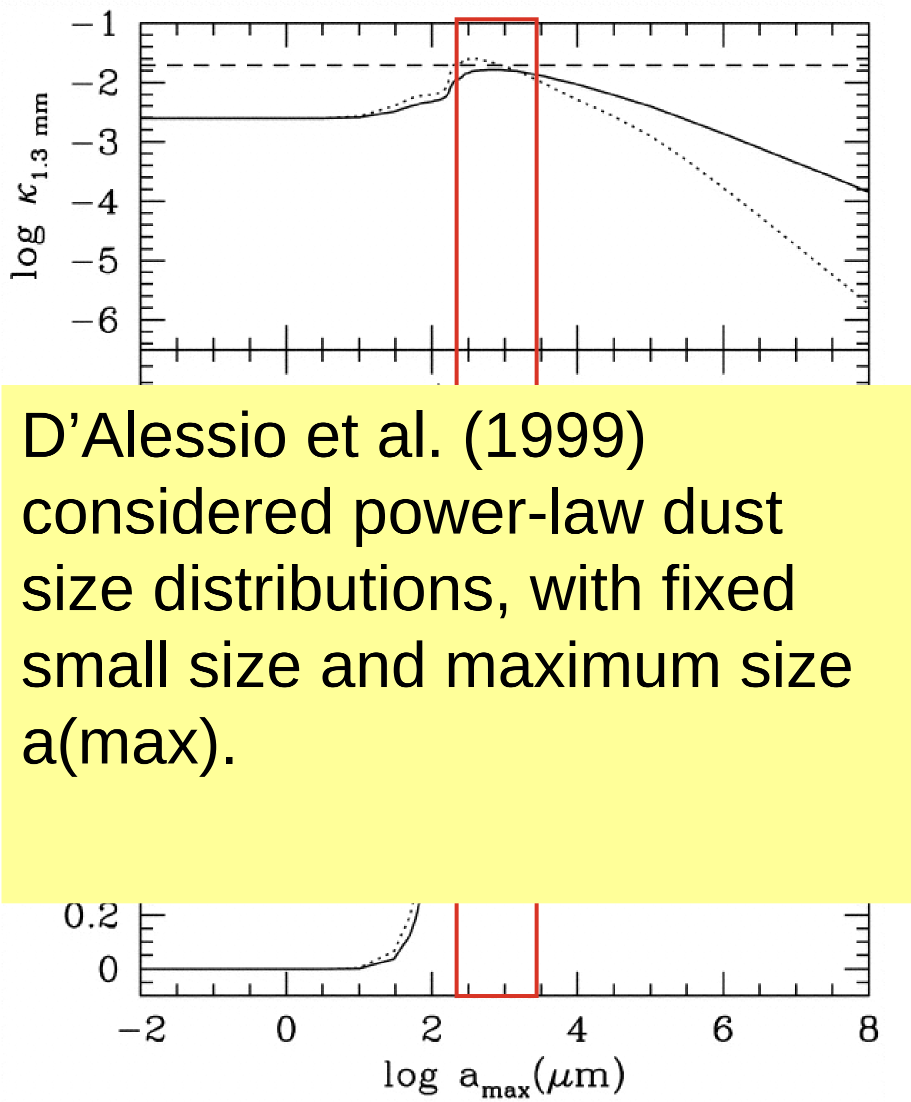


HD 100546

Disk masses and dust opacities

Standard opacity requires grain growth to 1 mm at ~100 AU, but what if they grow further?

The STANDARD dust opacity used for computing disk masses corresponds to a relatively **narrow** range of a(max). Smaller and larger values yield **smaller** opacities and thus **larger masses**.



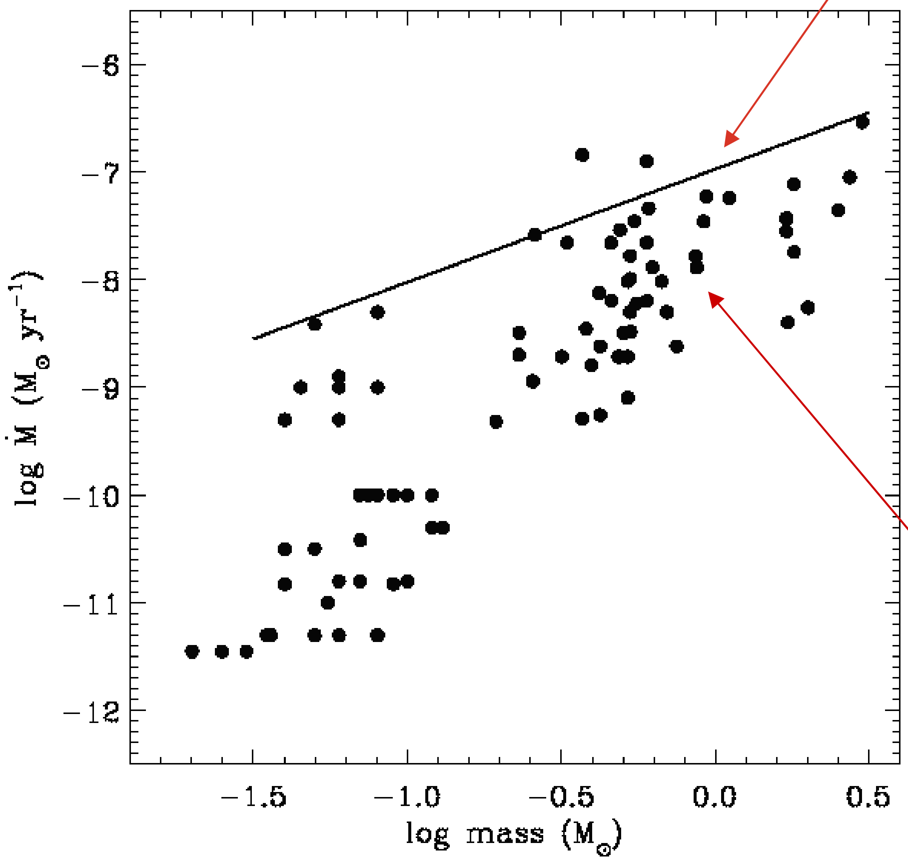
D’Alessio et al. (1999) considered power-law dust size distributions, with fixed small size and maximum size a(max).

Slide courtesy L. Hartmann

Disks can be massive based on accretion rates

lower limit to mass $\frac{dM}{dt} \times 10^6 \text{ yr} = 0.1 M_{sun}$

$t_{age} \approx 1-2 \text{ Myr}$



Hartmann et al. (2006)

$\frac{dM}{dt} \times 10^6 \text{ yr} = 0.01 M_{sun}$

but White & Hilenbrand (2005) argue that dM/dt has been underestimated by neglecting red excess emission, by factor ~ 2.

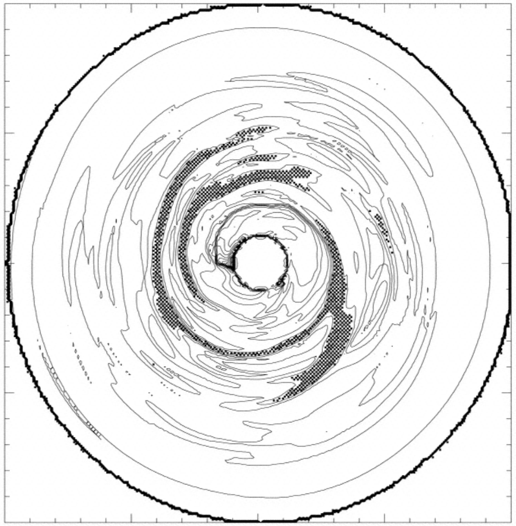
Extrasolar planets – massive disks

- MMSN contains ~ 0.01 M_{sun} material, barely enough to make Jupiter
- Extrasolar systems with M sin i up to several Jupiter masses imply $M_{disk} >> 0.01\ M_{sun}$

Protosolar nebula constraints

- MMSN profile $\Sigma = 1000\left(\frac{r}{AU}\right)^{-3/2}$ g cm^{-2} (Weidenschilling 1977) slope well reproduced by self-regulated disk model of Vorobyov & Basu (2007) – implies that gravitational torques dominate other transport mechanisms

- Mass of MMSN depends on actual density at a given radius. Chondrule formation models (Desch & Connolly 2002; Boss & Durisen 2005) require a high density and $M_d \sim 0.1\ M_{sun}$



Boss & Durisen (2005): shock front at 2-3 AU, propagating at about 5-10 km/s relative to surrounding gas

Conclusions

- Protostellar disks that form self-consistently have a sharp edge and maintain persistent nonaxisymmetric density fluctuations that lead to non-radial gravitational forces → torques that drive accretion at rates comparable to those of CTTS
- Disk mass stays well below stellar mass, typically in 5 - 10% range.
- Self-regulation of disk leads to Q ~ const. and to surface density profile $\Sigma \sim r^{-3/2}$;same slope as MMSN.
- This model applies to disks around relatively massive YSO's (~ 1 M_{sun} and above) but maybe to lower mass objects as well
- Observed disk masses may be systematically underestimated