Brown Dwarfs from Disk Fragmentation and Ejection

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Very Low Mass Stars and Brown Dwarfs
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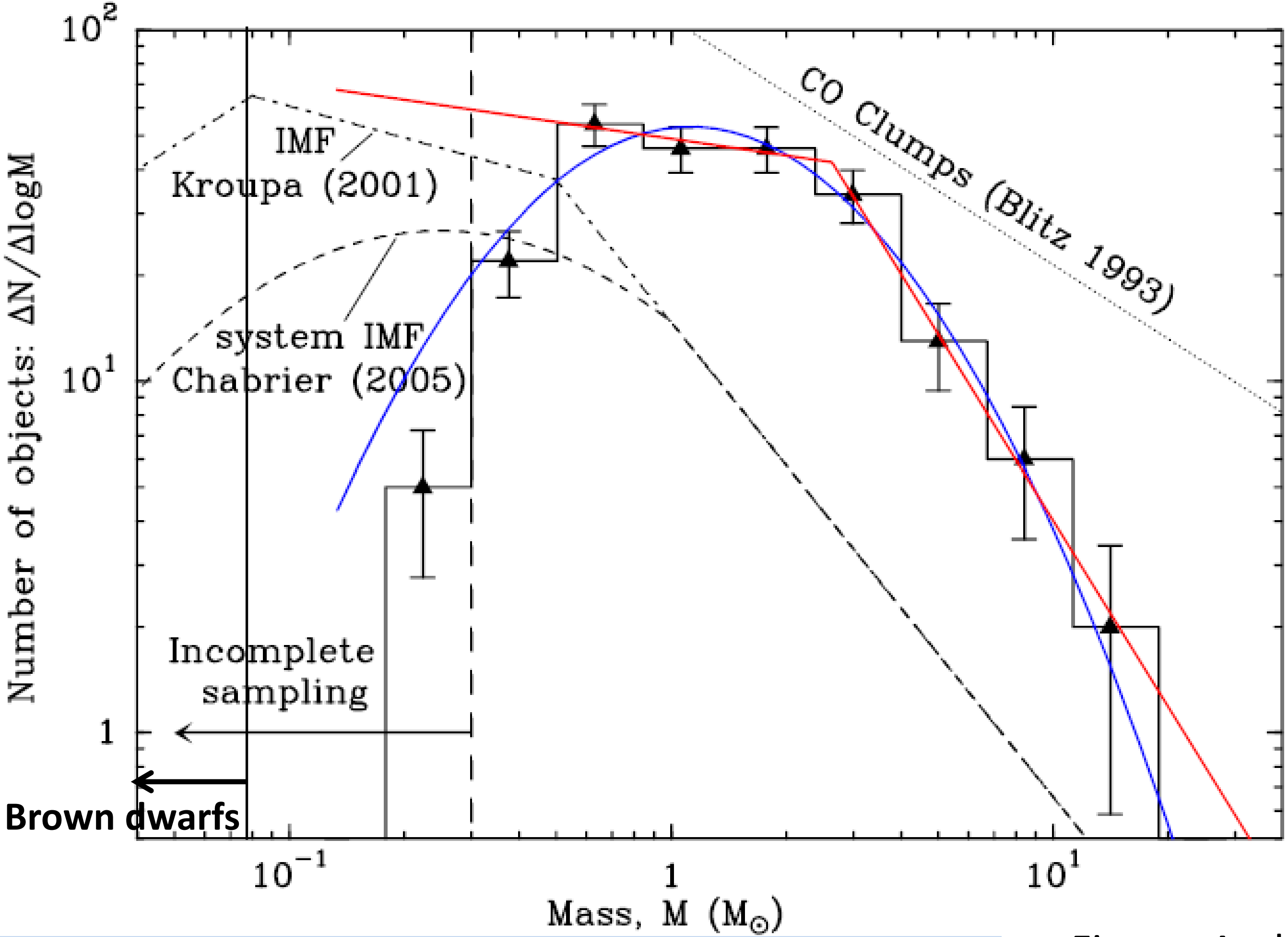
Origin of Low End of Stellar Mass Function?



IMF = initial mass function of stars, i.e., stellar mass distribution, average mass ~ 0.25 M_{sun}

Lowest mass clumps not well sampled, but also may not be gravitationally bound. Where do lowest mass stars come from?

Figure: André, Basu, & Inutsuka (2009)

Gravitational Collapse

Minimum mass for gravity to overcome internal thermal pressure, i.e., Jeans mass:

$$M_J = \left(\frac{\pi^3 c_s^6}{G^3 \rho} \right)^{1/2} \approx 5.5 \left(\frac{T}{10\ \mathrm{K}} \right)^{3/2} \left(\frac{10^4\ \mathrm{cm}^{-3}}{n} \right)^{1/2} M_\odot$$

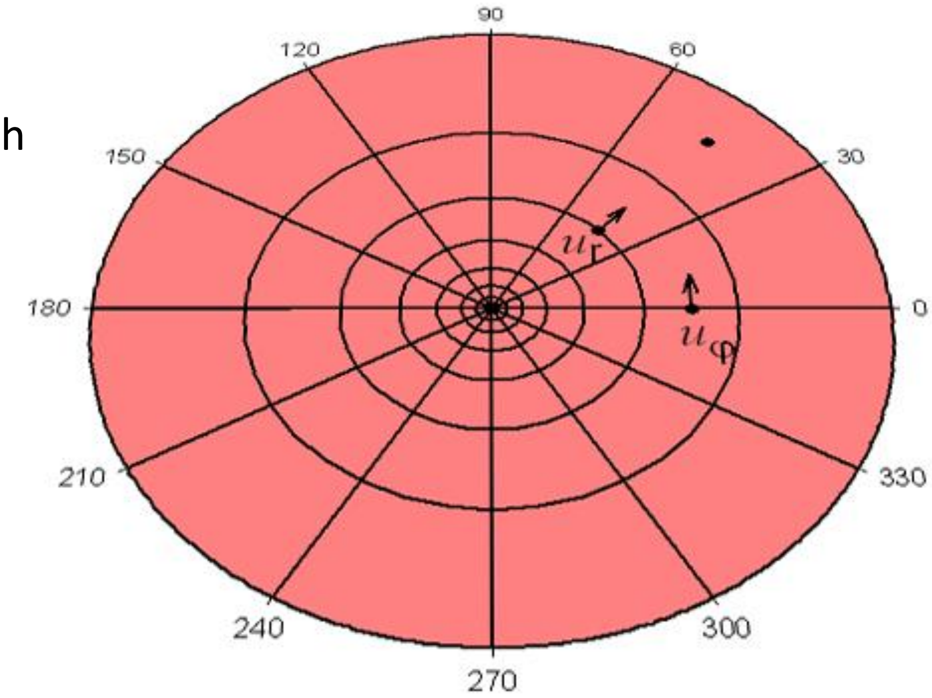
Can direct gravitational collapse from interstellar clouds explain low mass stars, brown dwarfs, planets?

Planets have long been thought to arise from disk processes, so always accompany a star, and not from direct collapse from clouds.

A Global Model, Nonaxisymmetric Model for Disk Formation/Evolution

Logarithmically spaced grid in *r*-direction, uniform in ϕ direction

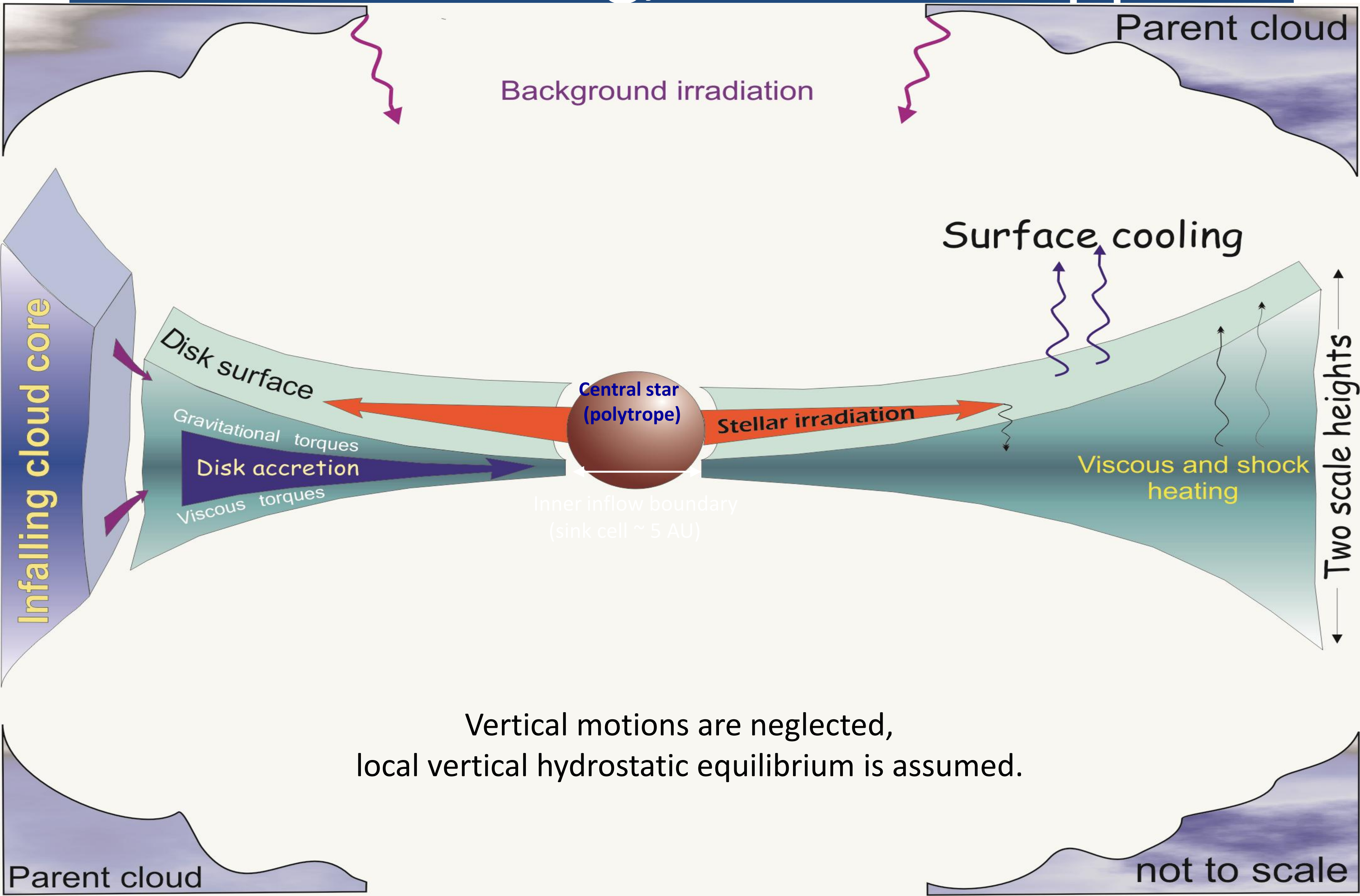
Simulations require high resolution in the inner regions, while a lower resolution may be sufficient in the outer regions



Models run with 128^2, 256^2, 512^2 grids. Span **large dynamic range** in **space** (outer boundary at ~10,000 AU, but innermost grid resolution ~ 0.1 AU) and **time** (can follow evolution for several Myr after disk formation).

Central sink cell with unresolved physics, size 5-10 AU.

Global Modeling, Thin-Disk Approx.



Vertical motions are neglected,
local vertical hydrostatic equilibrium is assumed.

Basic Equations, Thin-Disk Approximation

$$\frac{\partial \Sigma}{\partial t} + \nabla \cdot (\Sigma \mathbf{u}) = 0,$$

$$\frac{\partial (\Sigma \mathbf{u})}{\partial t} + \nabla \cdot (\Sigma \mathbf{u}\mathbf{u}) = -\nabla P - \Sigma \nabla \Phi$$

$$\frac{\partial \varepsilon}{\partial t} + \nabla \cdot (\varepsilon \mathbf{u}) = -P(\nabla \cdot \mathbf{u}) - C\left(T^4 - T_{irr}^4\right)\left(\frac{\tau}{1+\tau^2}\right)$$

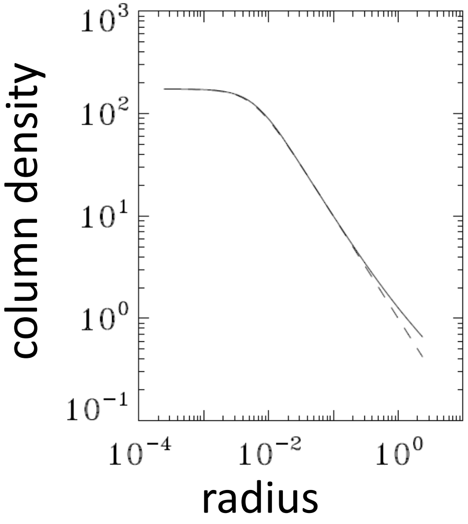
$$\mathbf{u} = \mathrm{u}_r \, \hat{r} + \mathrm{u}_\varphi \, \hat{\varphi}; \quad \nabla = \hat{r} \frac{\partial}{\partial r} + \hat{\varphi}\, r^{-1} \frac{\partial}{\partial \varphi},$$

$\sigma T_{irr}{}^4 = \sigma T_{bg}{}^4 + F_{irr}$, T_{bg} – background temperature, $\mathrm{F}_{irr} = \mathrm{A} \frac{\mathrm{L}_{st}}{4\pi \mathrm{r}^2} \cos \gamma_{irr}$ - stellar irradiation flux

$\tau = \Sigma \kappa / 2$ – midplane optical depth, κ – opacity from Bell & Lin (1990);

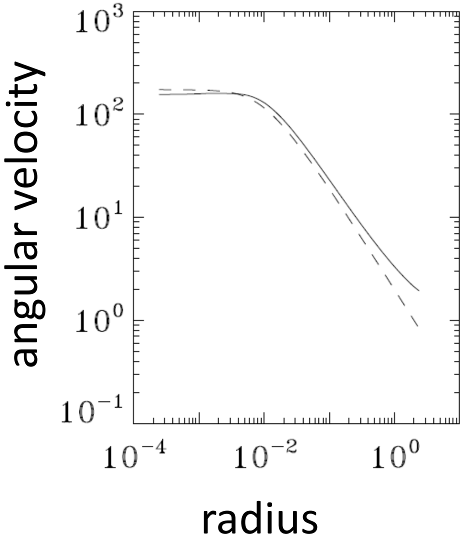
$C = 2 + 20 \tan^{-1} \tau / 3\pi$

Initial Conditions of Prestellar Core



$$\Sigma(r) = \frac{\Sigma_0}{\sqrt{1+(r/a)^2}}, \qquad a \simeq \frac{c_s^2}{G\Sigma_0}, \quad c_s = \text{isothermal sound speed.}$$

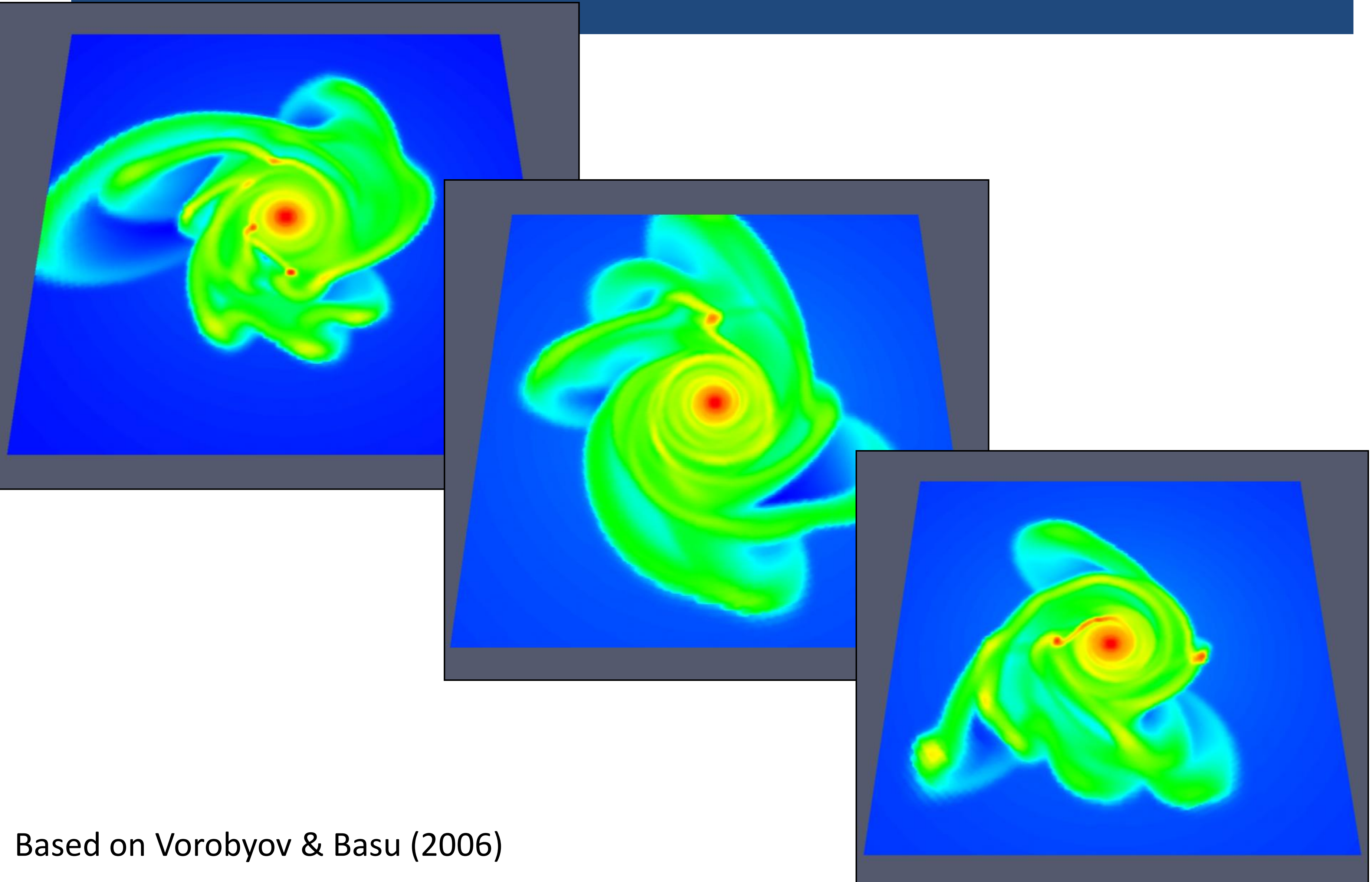
Overall qualitative character of disk evolution is independent of the initial profiles of these quantities.



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

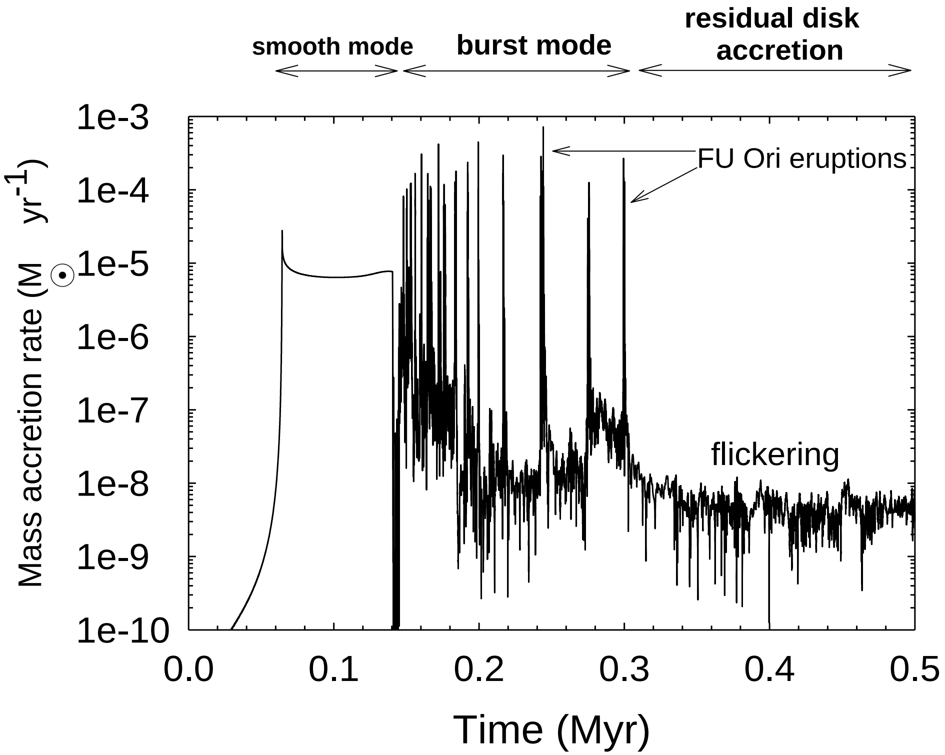
From Basu (1997), analytic fits to power-law profiles that develop in isothermal gravitational collapse.

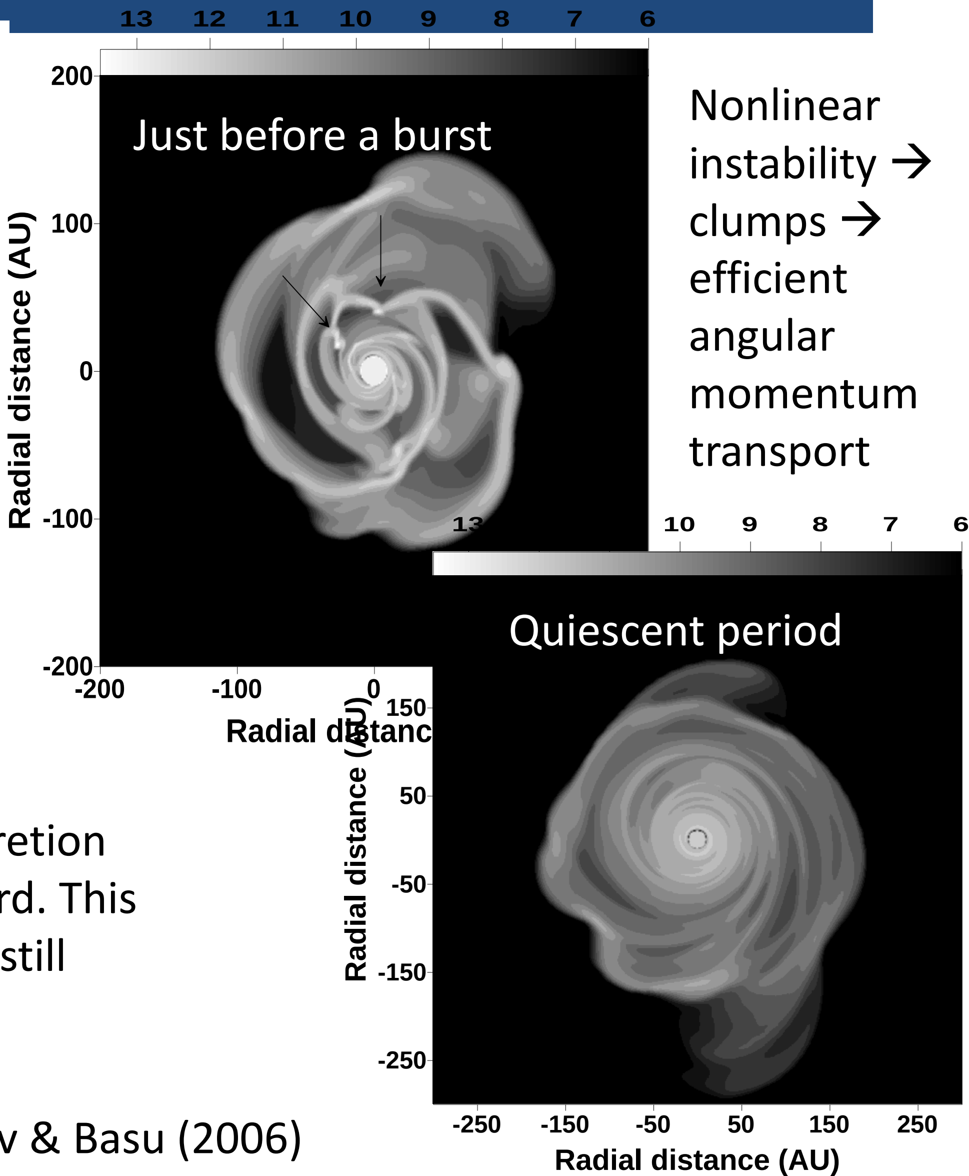
Disk Evolutionary Images



Based on Vorobyov & Basu (2006)

Key Results for Early Accretion Phase





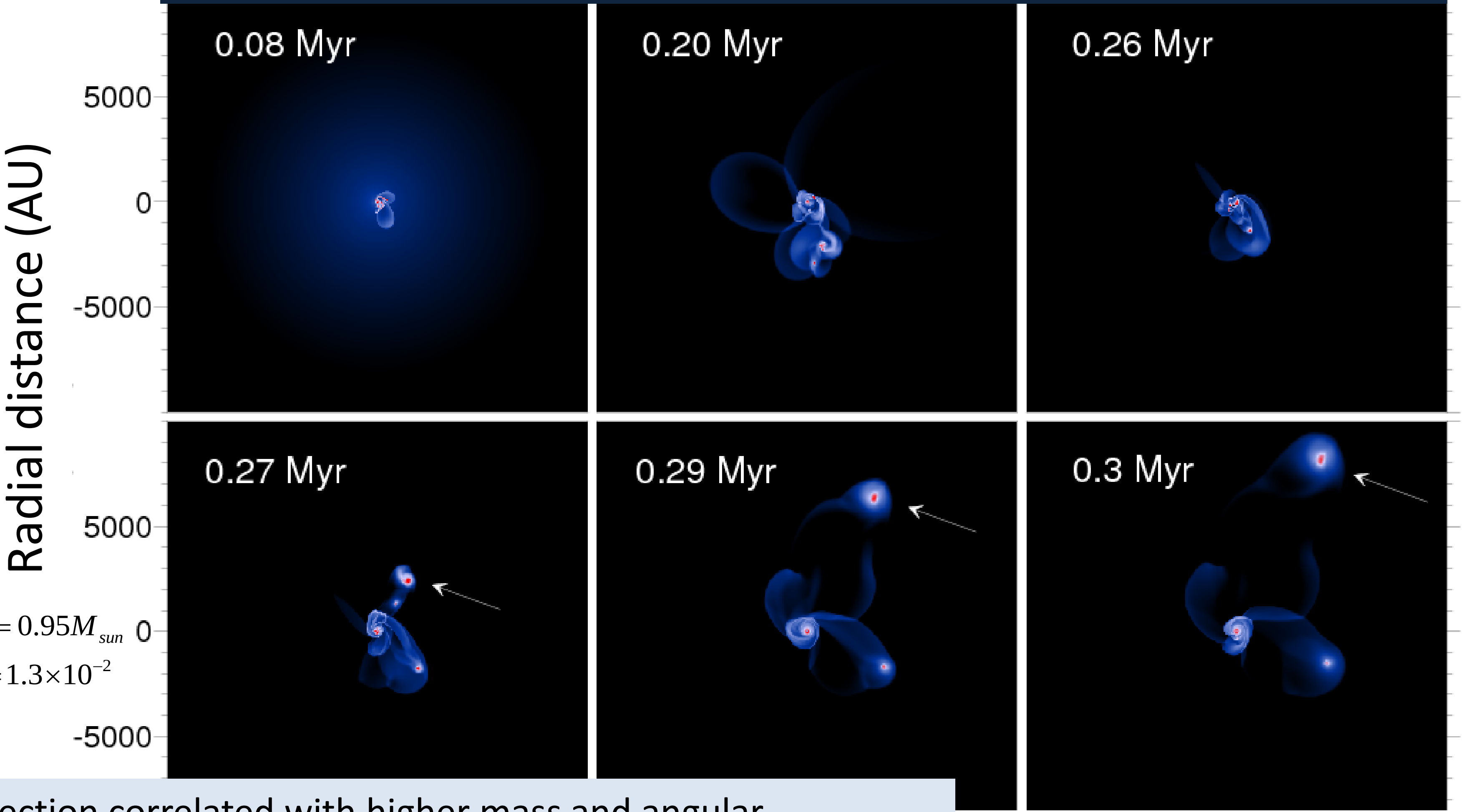
Nonlinear instability → clumps → efficient angular momentum transport

Bursts of accretion occur during the early accretion phase, as clumps are formed and driven inward. This is followed by a more quiescent phase that is still characterized by flickering accretion.

Vorobyov & Basu (2006)

Multiple Fragments in Massive Disk → Ejection of Low Mass Fragment

No sink cells employed to follow clumps, ejected ones or otherwise.



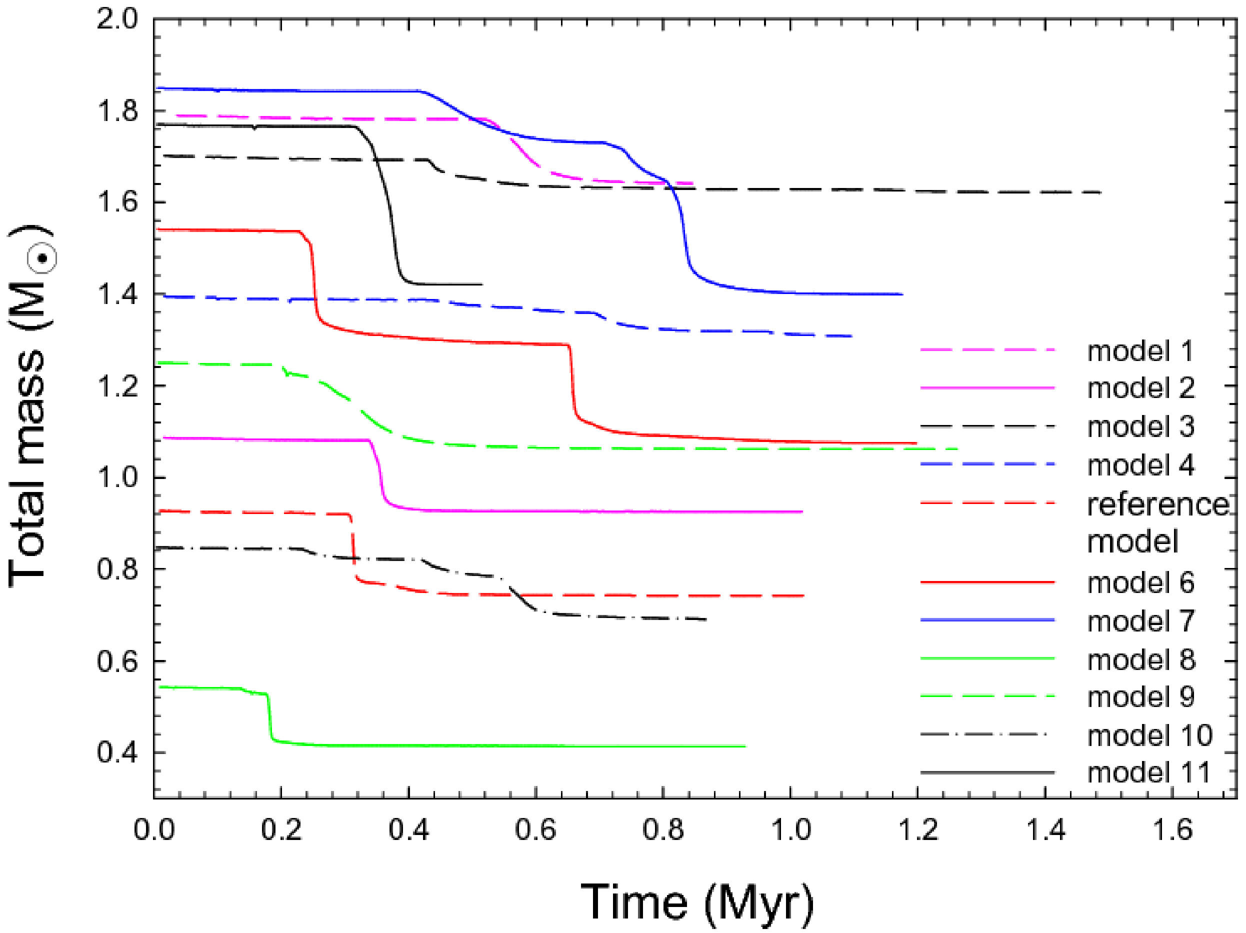
$M = 0.95 M_{sun}$

$\beta = 1.3 \times 10^{-2}$

Ejection correlated with higher mass and angular momentum in initial state.

Basu & Vorobyov (2011)

Ejections occur in many models



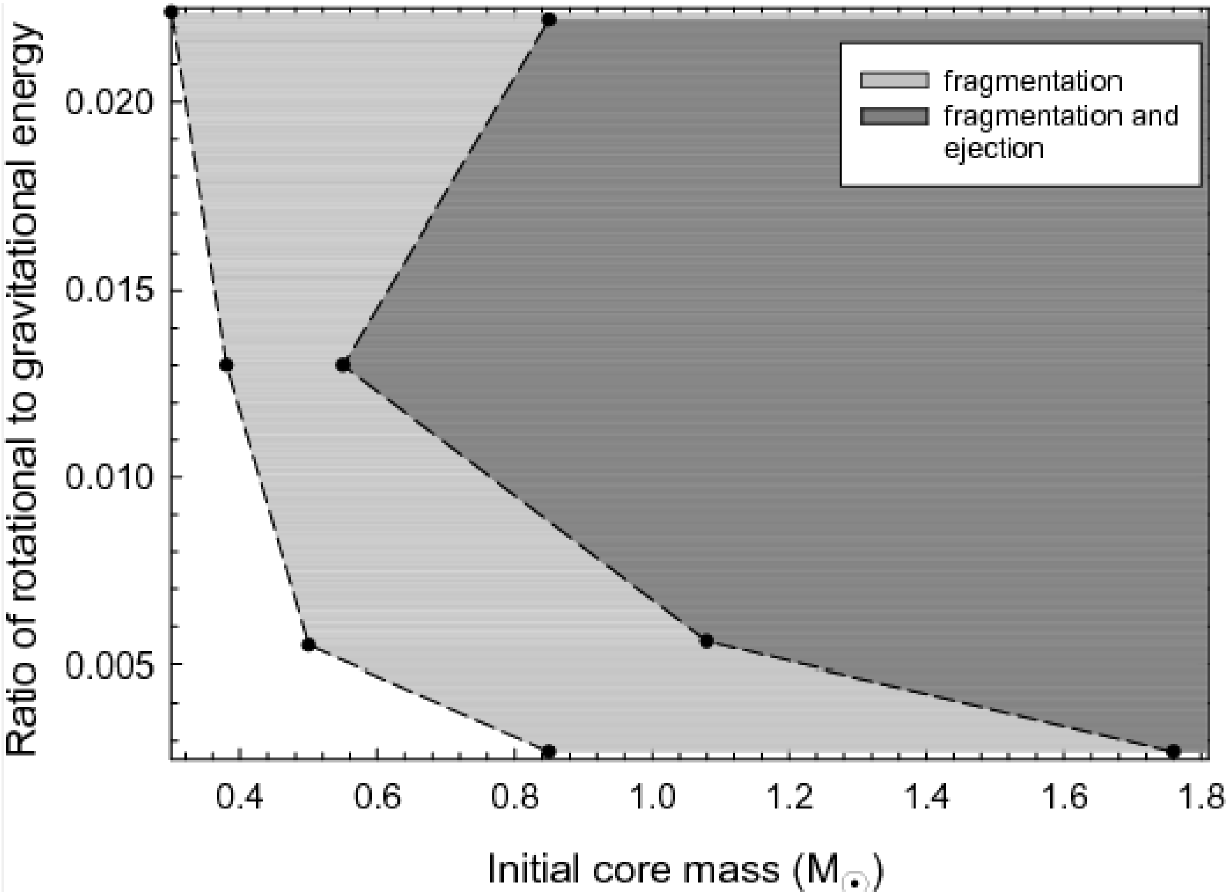
Ejected clumps span the substellar to low mass star regime, and have ejection speeds 0.8 +/- 0.35 km/s.

Some models exhibit multiple ejections

Lowest mass objects more likely to be sheared by tidal effects arising from ejection

Basu & Vorobyov (2011)

Ejections and Initial Conditions



In dark shaded region, about 50% of realizations result in an ejection.

Basu & Vorobyov (2011)

Brown Dwarfs: From Clump Ejections, BD Ejections, or Direct Collapse?

Empirical Property	Clump Ejection	BD ejection	Core Collapse
Can very low mass fragments collapse?	✓	N/A	?
Presence of disks around BDs	✓	?	✓
Isolated very low mass cores	✓	✗	✓
Moderate velocity dispersion of BDs	✓	?	✓
BDs and young stars generally co-located	✓	?	✓
BD-star binaries generally on wide orbits, tens of AU (“brown dwarf desert”)	✓	✓	✗
BD-BD binaries generally very close, few AU	✓	✓	✗
A few wide BD-BD binaries	✗	✗	✓

Summary

- Disk evolution calculated from self-consistent collapse of dense core yields a paradigm of episodic clump formation, migration (leading to episodic accretion), dissolution, or ejection.
- This scenario leads naturally to ejected clumps that straddle the substellar mass limit. Can expect the formation of isolated BDs and VLMSs that have their own disks.
- Ejection speeds are moderate, ~ 1 km/s, arising self-consistently, and not dependent on sink cell approximations. Expect BDs to be co-located with and having same velocity dispersion as stars
- A wide range of BD observations can be understood at least qualitatively using this hybrid scenario of clump ejections arising from interaction of multiple fragments within the disk