Gravitational Instability and the Formation of Clumps, Companions, and Free Floating Objects

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3rd DTA Symposium
NAOJ, Mitaka, Japan
Wednesday, June 3, 2015

Western
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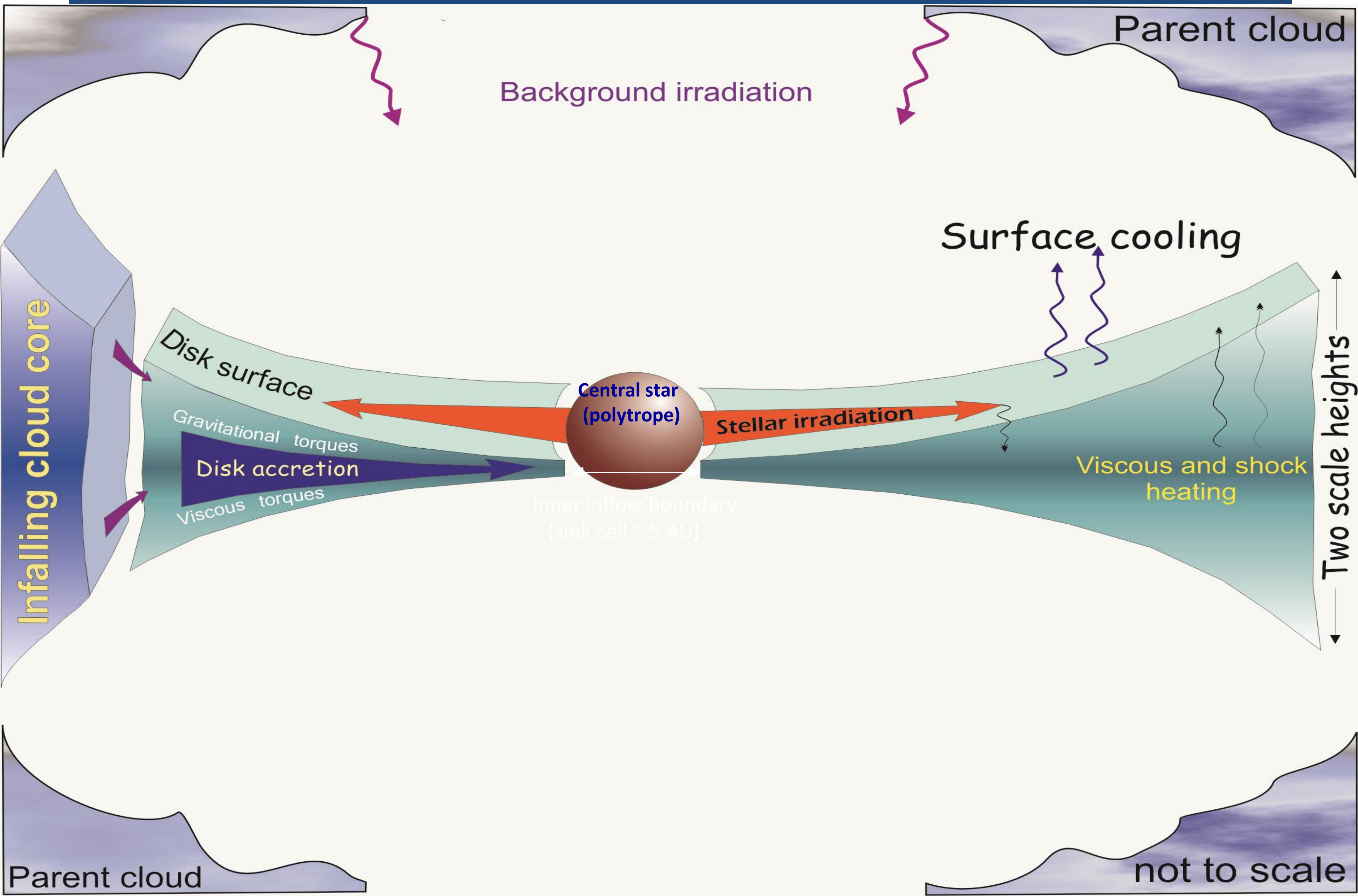
Early Embedded Disk Phase

Takeaway points

- Gravitational instabilities are unavoidable
- Migration (of clumps) starts at this time
- Scattering and ejections can happen
- Rapid chaotic early evolution leaves its imprint at later times

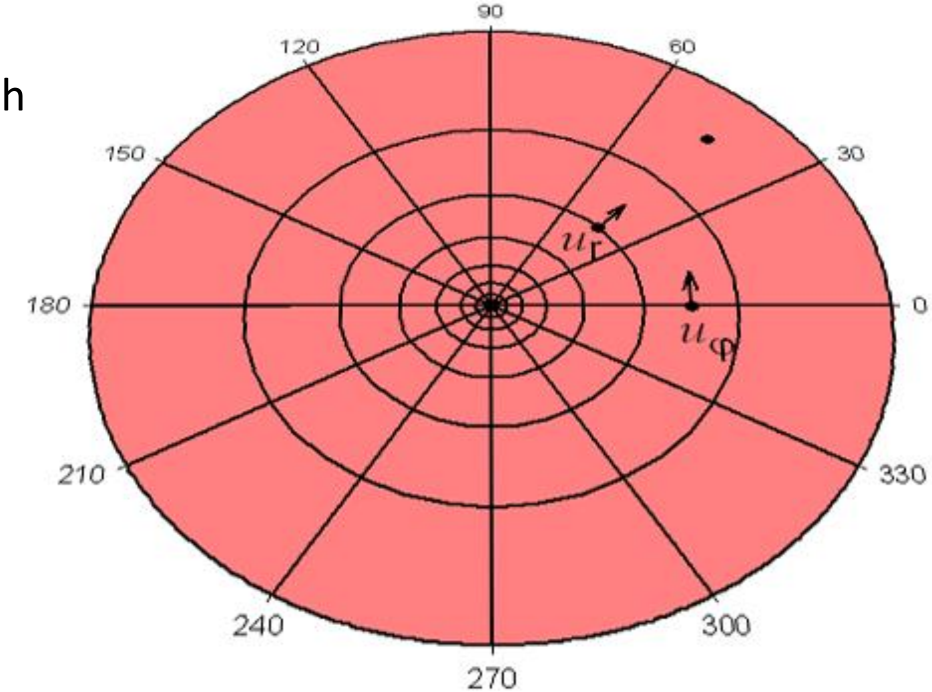
Disk Schematic



Global Model, Nonaxisymmetric

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. Outer boundary at ~10,000 AU. Innermost grid resolution ~ 0.1 AU.

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

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

Series of papers by Vorobyov & Basu

Basic Equations, Thin-Disk Approximation

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

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

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

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

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

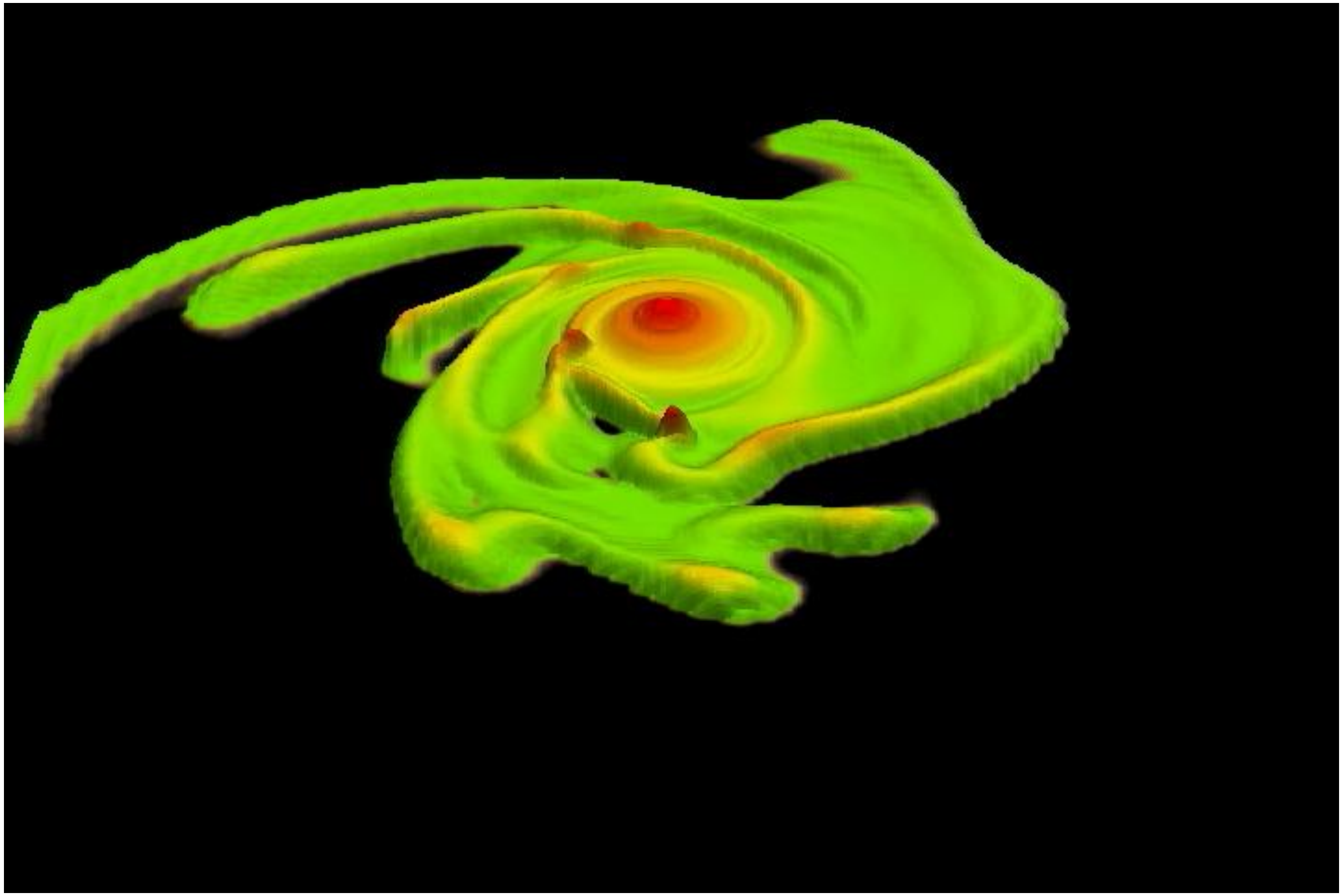
$\tau = \Sigma\kappa / 2$ – midplane optical depth, κ – opacity from Bell & Lin (1990);

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

Vorobyov & Basu (2010)

Migrating Embryo Model

Review in Basu & Vorobyov, Meteoritics & Planetary Science (2012, 47, 1907)
doi: 10.1111/maps.12040



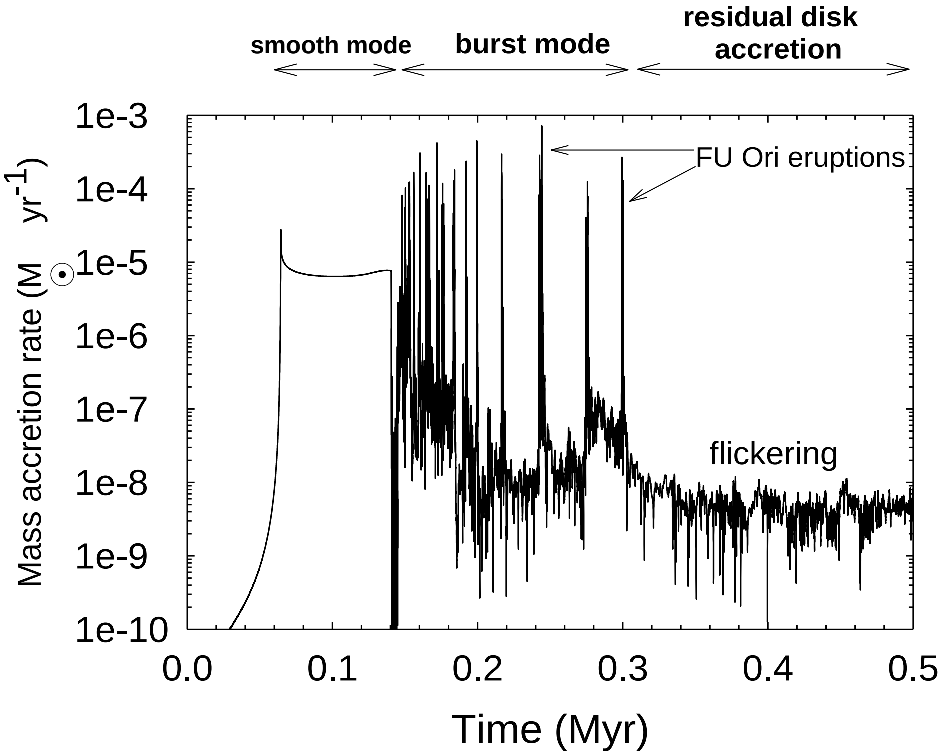
A scenario for early phase disk and stellar evolution.

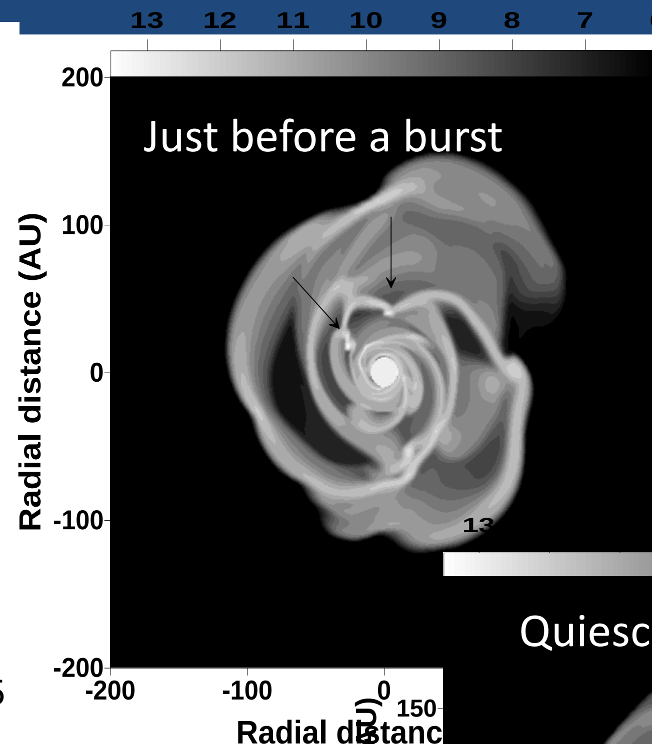
Self-consistent modeling from prestellar phase to protostellar disk formation and few Myr of subsequent evolution.

Model Caveats

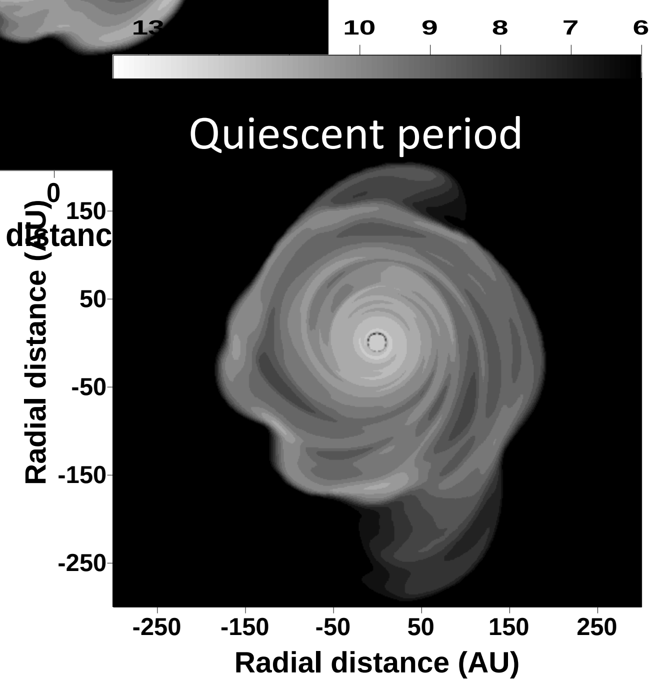
- Central sink cell ~ 6 AU. Matter presumed to find its way to center.
- No outflows. Would occur within sink region
- Burst event and migrating embryo numbers vary according to initial conditions (core mass and rotation rate) and detailed internal physics
- No magnetic field/magnetic braking. Results valid in cases where magnetic braking cannot significantly disrupt disk formation (Machida's talk)
- Number of fragmentation events not predictable but occurrence is robust due to mass loading from envelope in early disk evolution

Key Results for Early Accretion Phase





Nonlinear instability → clumps → efficient angular momentum transport



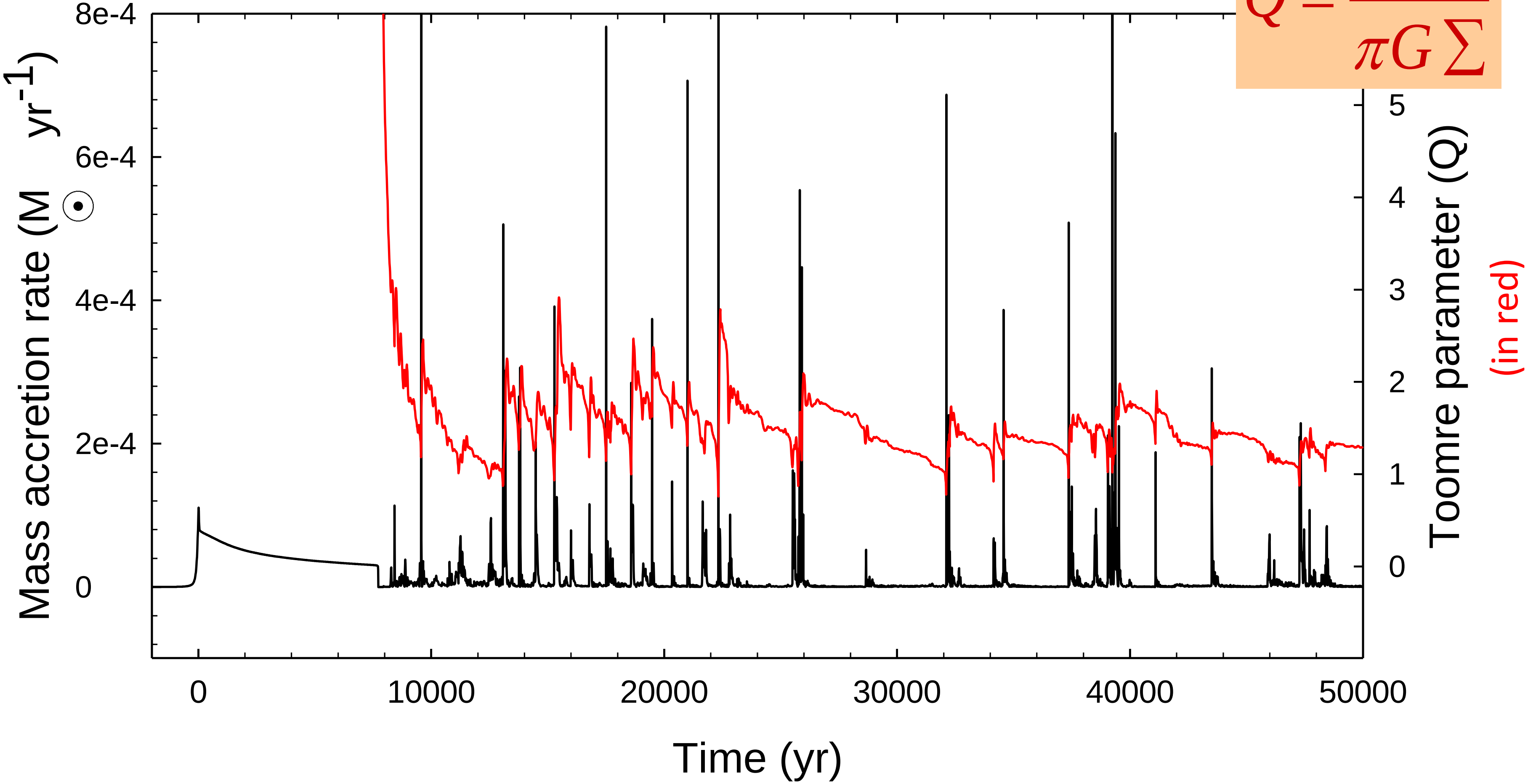
Bursts of accretion occur during the early accretion phase, as clumps are formed and driven inward. This is followed by a more quiescent phase that is still characterized by flickering accretion.

Vorobyov & Basu (2006, ApJ, 650, 956)

Bursts and Toomre Q parameter

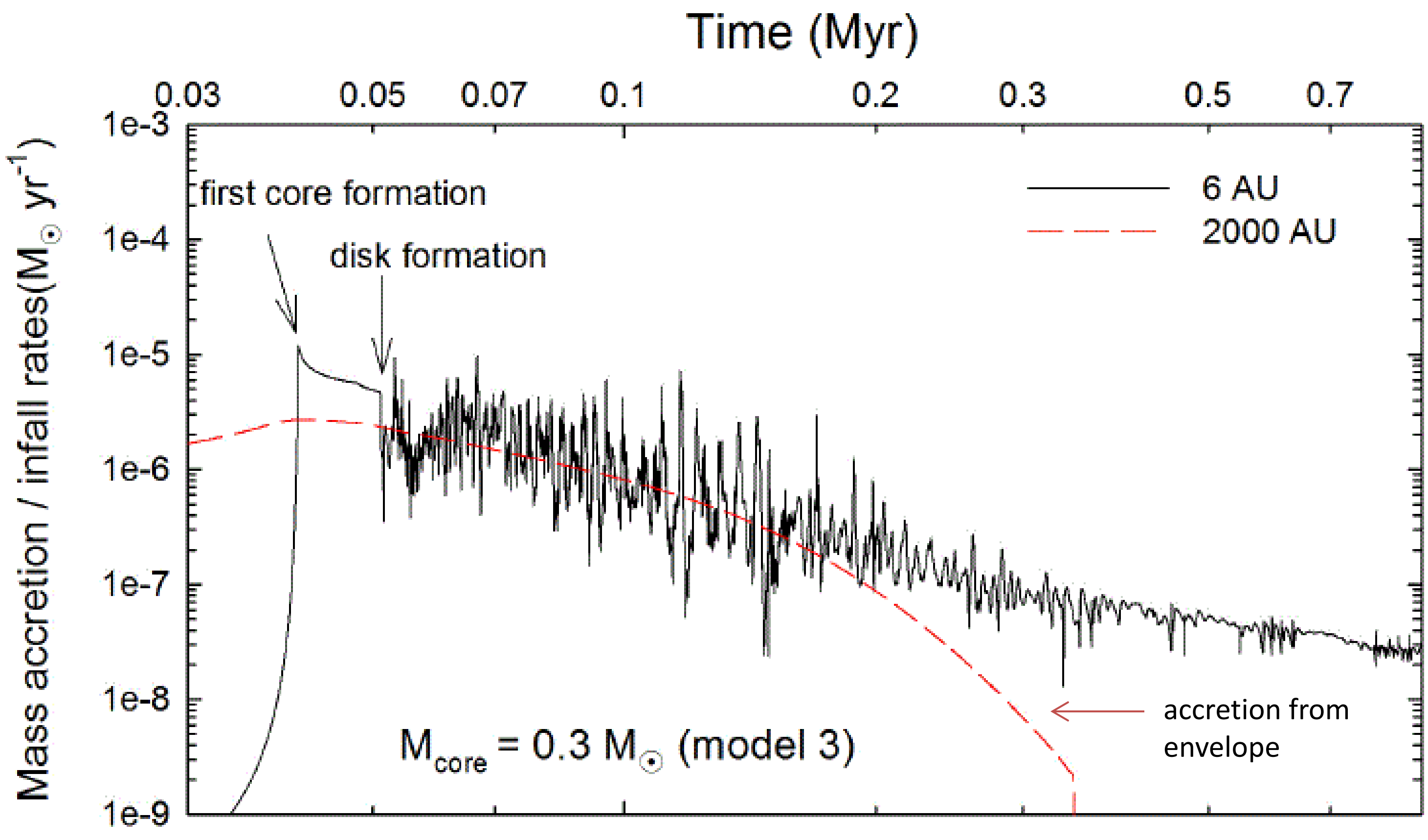
$Q < 1 \Leftrightarrow$ instability, $Q > 1 \Leftrightarrow$ stability

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



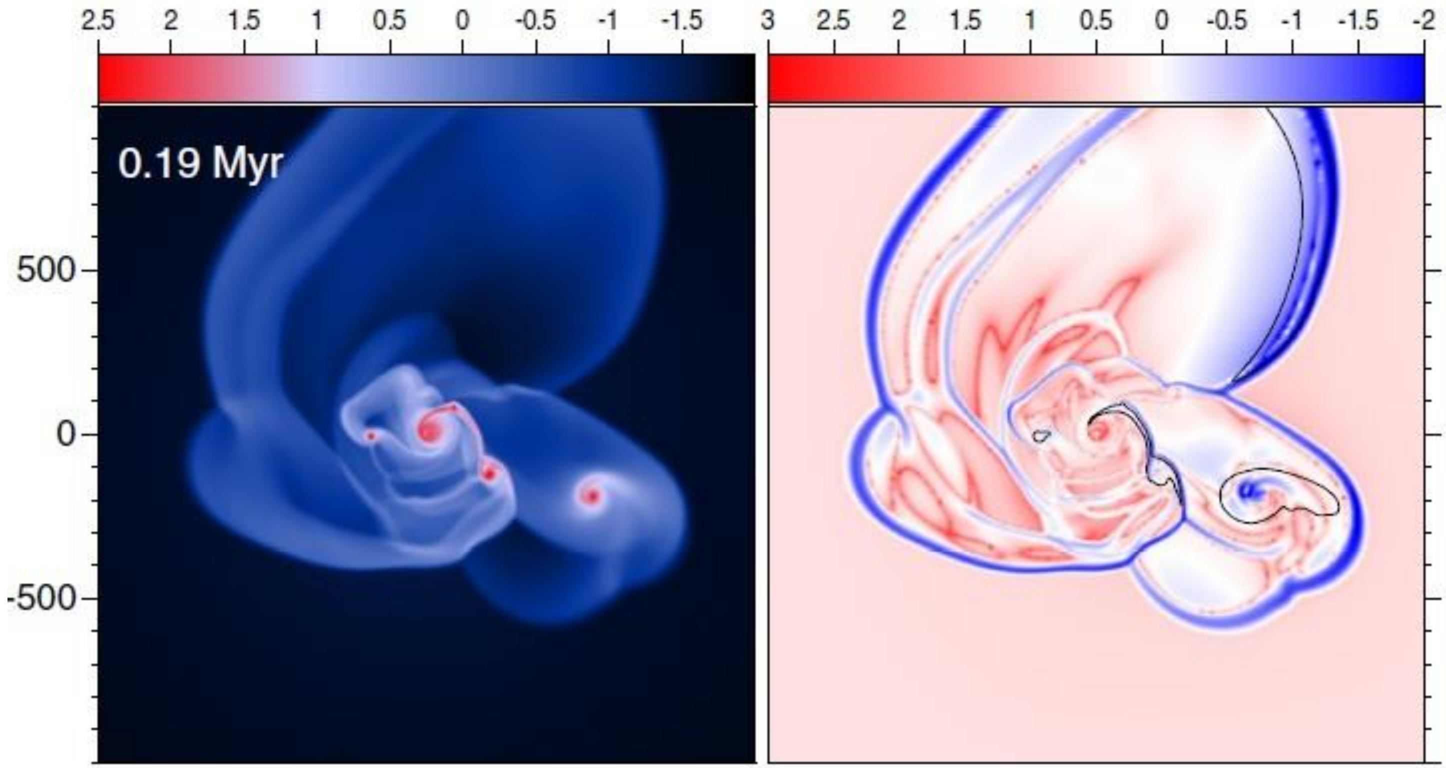
Vorobyov & Basu (2005)

Envelope Accretion



Vorobyov and Basu (2015, ApJ, 805, 115)

Conditions for Gravitational Instability



$M = 0.7 M_\odot$

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

Also important for fragmentation

surface density log g cm^{-2}

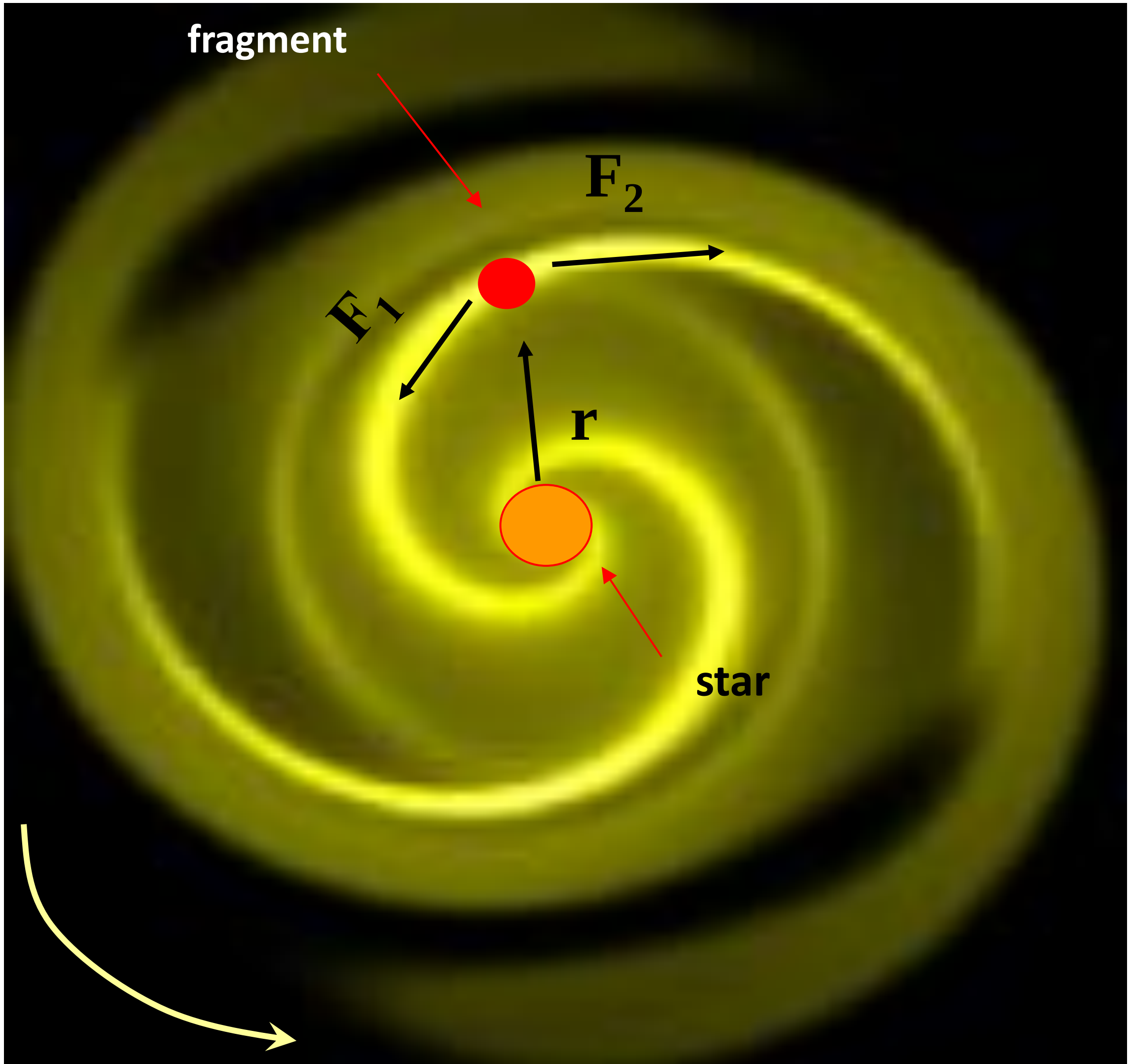
log cooling parameter $G = t_{cool} \Omega$

Black contour where $Q < 1$

Vorobyov and Basu (2010)

Gravitational Torques

Nonaxisymmetry is key!

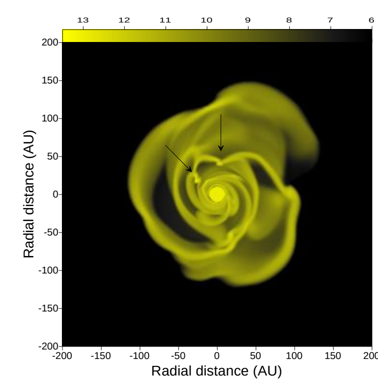


$$\mathbf{\Gamma}_1 = \mathbf{r} \times \mathbf{F}_1 > 0$$

$$\mathbf{\Gamma}_2 = \mathbf{r} \times \mathbf{F}_2 < 0$$

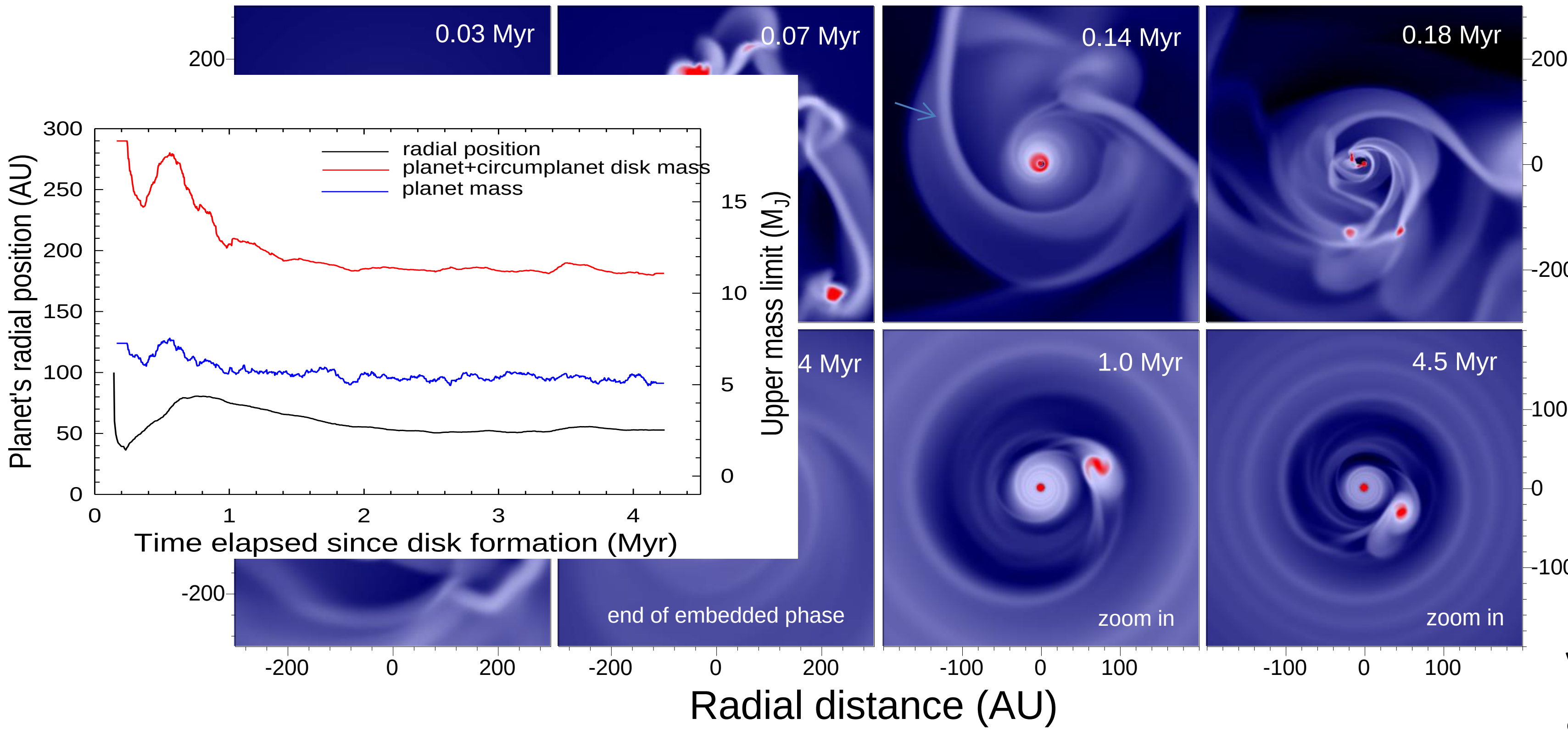
$$\frac{d\mathbf{L}}{dt} = \mathbf{\Gamma}_1 + \mathbf{\Gamma}_2$$

Gravitational torques from spiral arms drive fragments onto the protostar if $\mathbf{\Gamma}_1 + \mathbf{\Gamma}_2 < 0$



Companion Formation by Gravitational Instability

About 50% of observed Sun-like "stars" resolve into multiple systems. Wide orbit giant planets also increasingly detected.



$M = 0.9 M_{sun}$

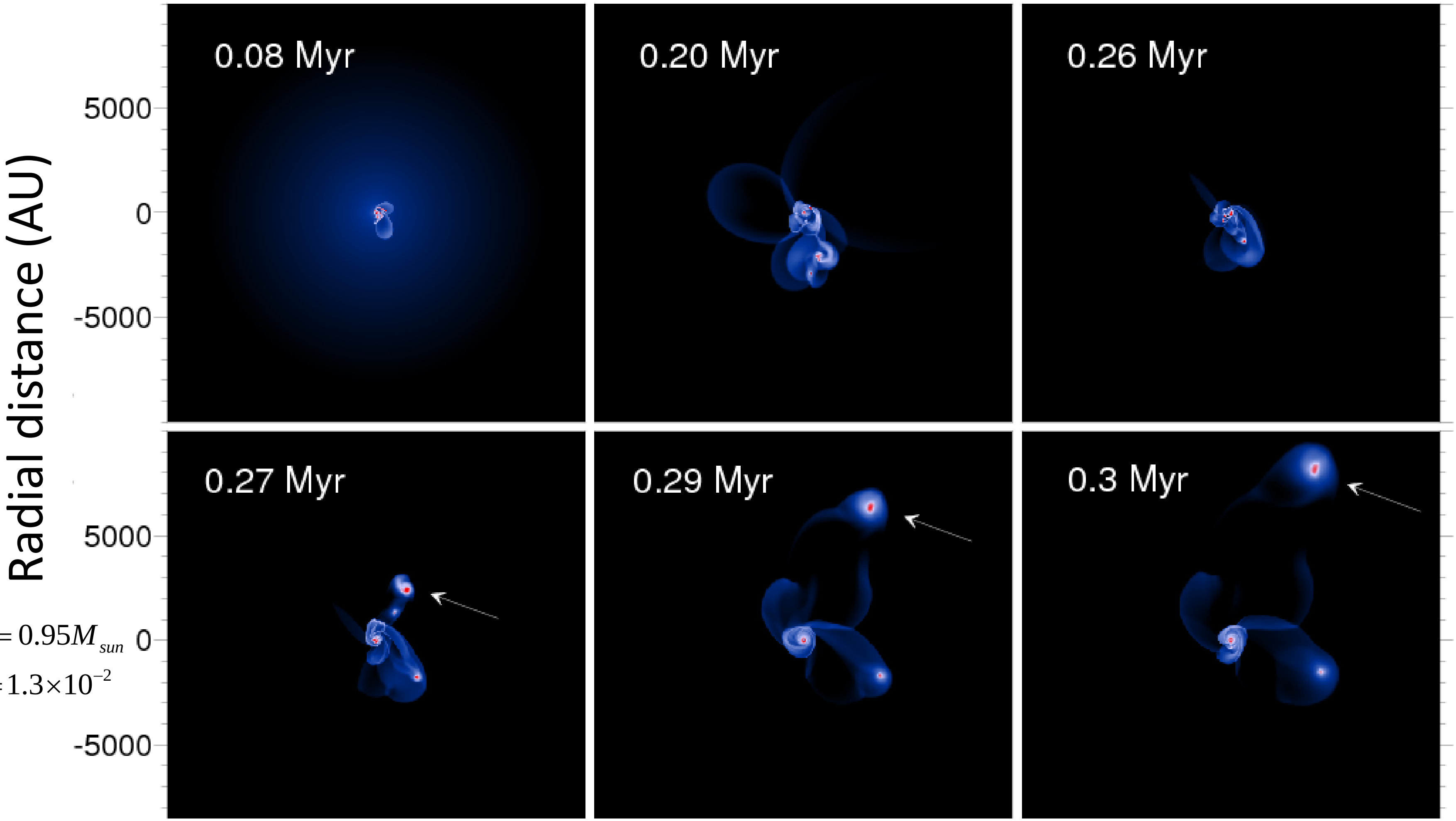
$\beta = 1.3 \times 10^{-2}$

ratio of initial rotational to gravitational energy

Vorobyov & Basu (2010)

For models with sufficient mass and angular momentum, a companion can sometimes open up a gap in the disk and settle into a stable orbit.

Multiple Fragments in Massive Disk → Ejection of Low Mass Fragment



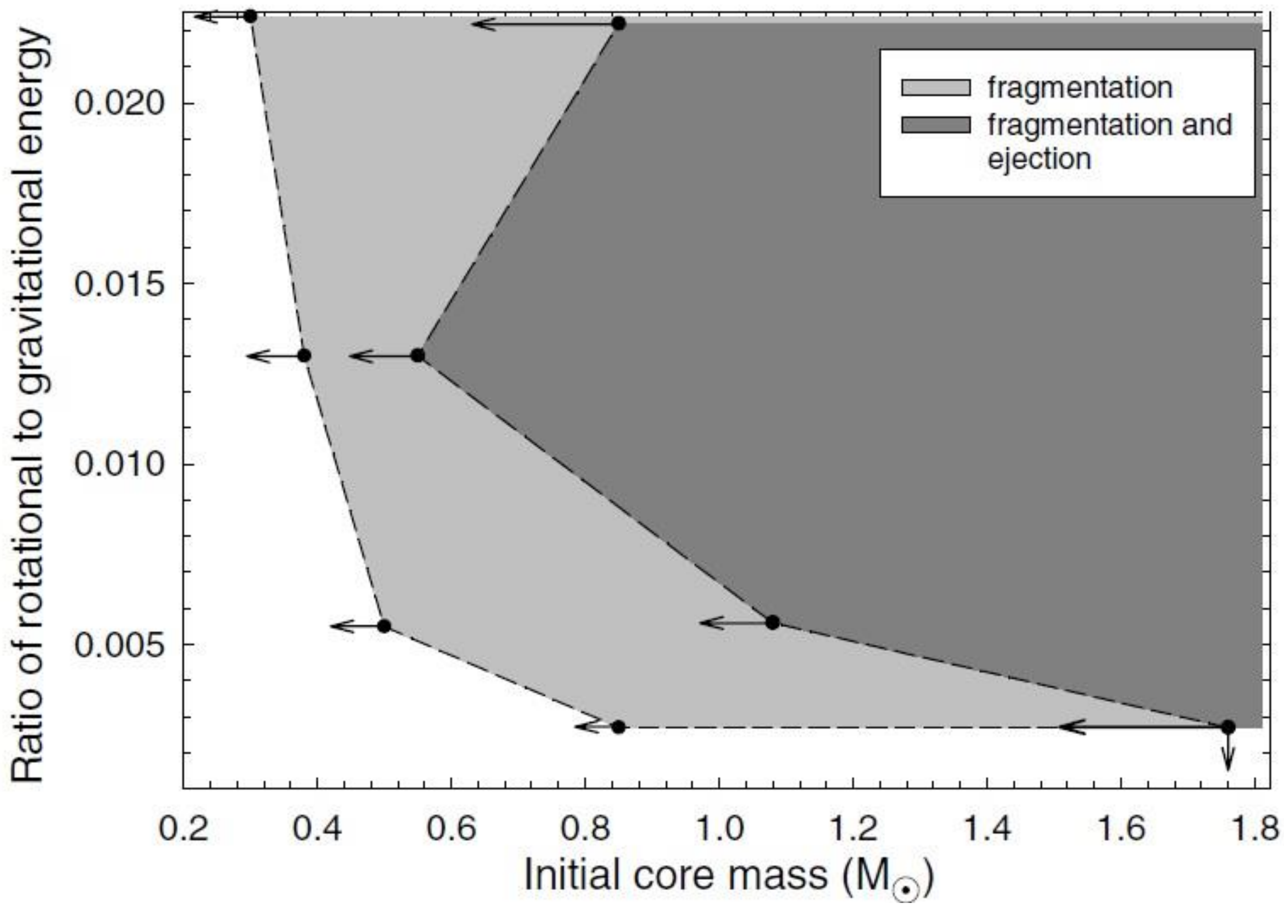
$M = 0.95 M_{sun}$

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

Low mass objects ejected from higher mass clumps.

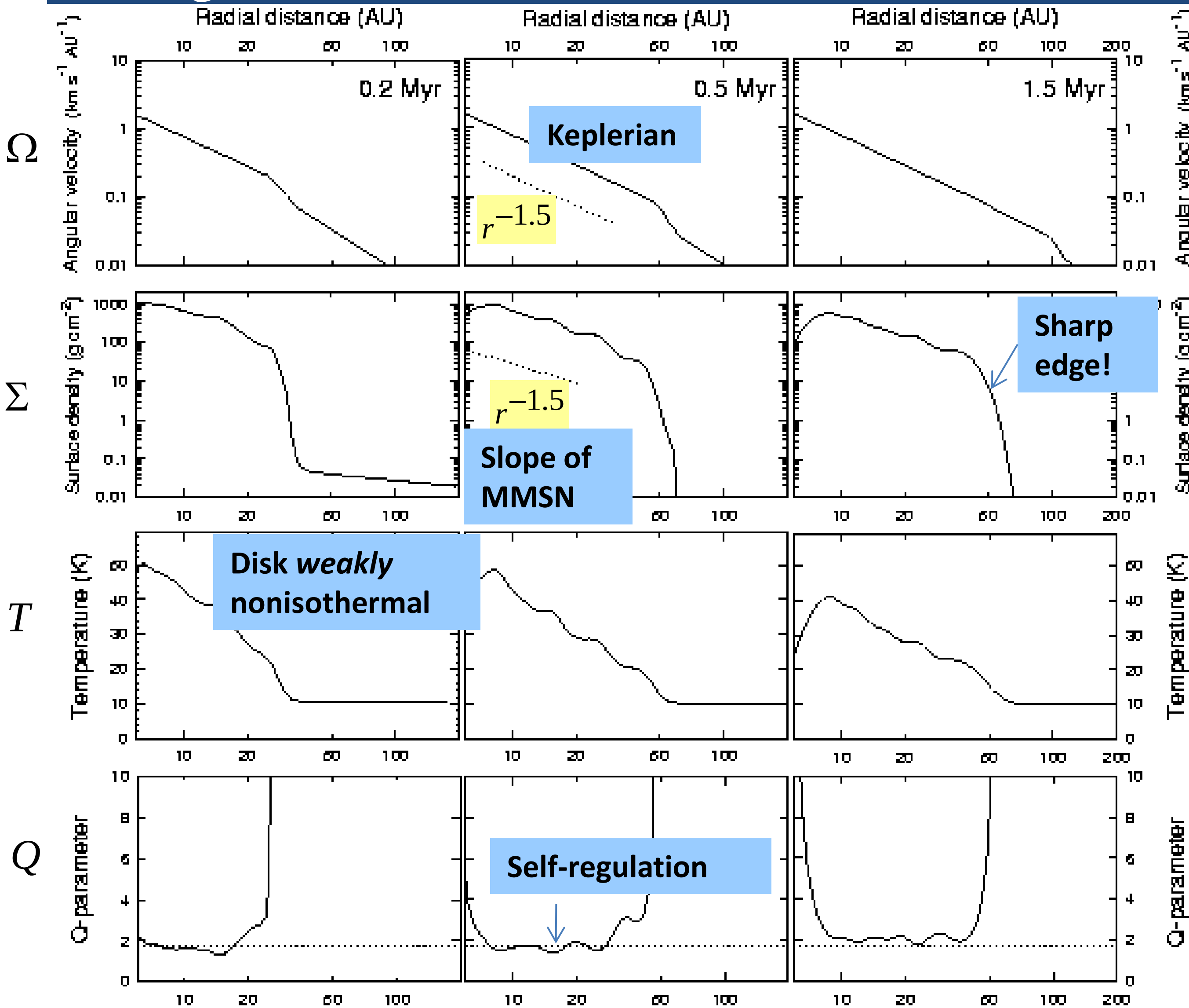
Basu & Vorobyov (2012)

Conditions for vigorous fragmentation



Basu & Vorobyov (2012)

Late Time Accretion: No more bursts, $Q \approx$ uniform and value rises slowly



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

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

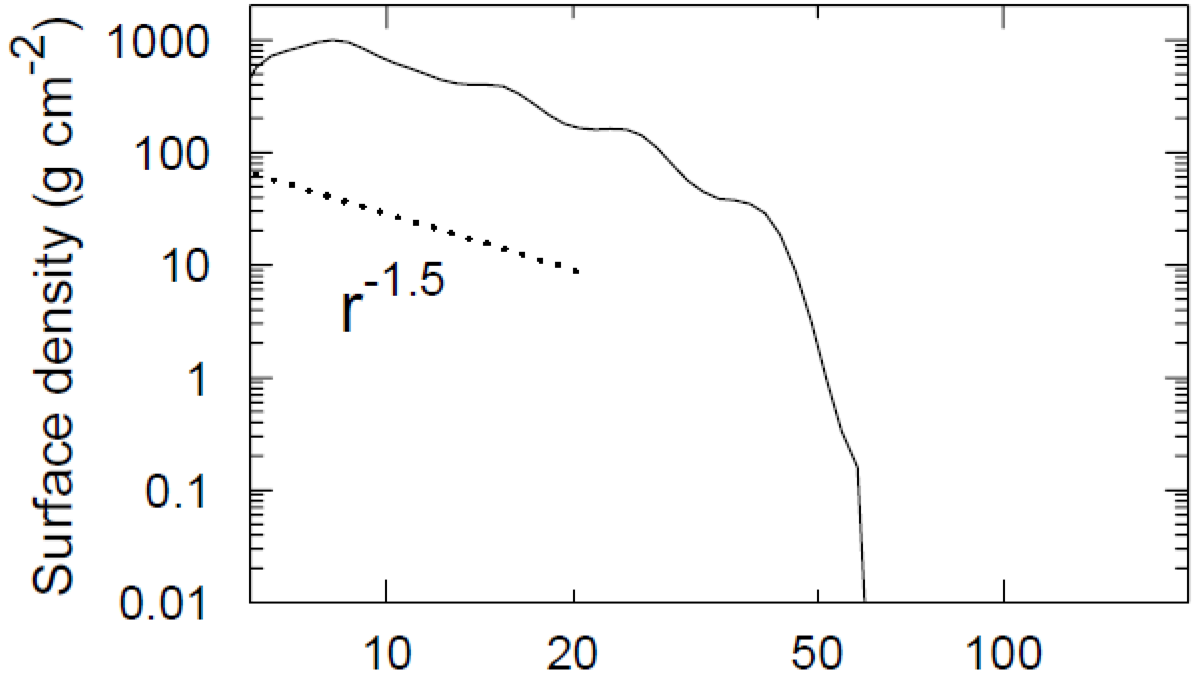
➔

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

Same slope as minimum mass solar nebula (MMSN), but density is 10 times MMSN.

Vorobyov & Basu (2007)

Mean Disk Surface Density Profile



radial distance [AU]

Azimuthal average

Same slope as MMSN but about 10 times greater value.

Vorobyov & Basu (2007, MNRAS, 381, 1009)

Disk Masses

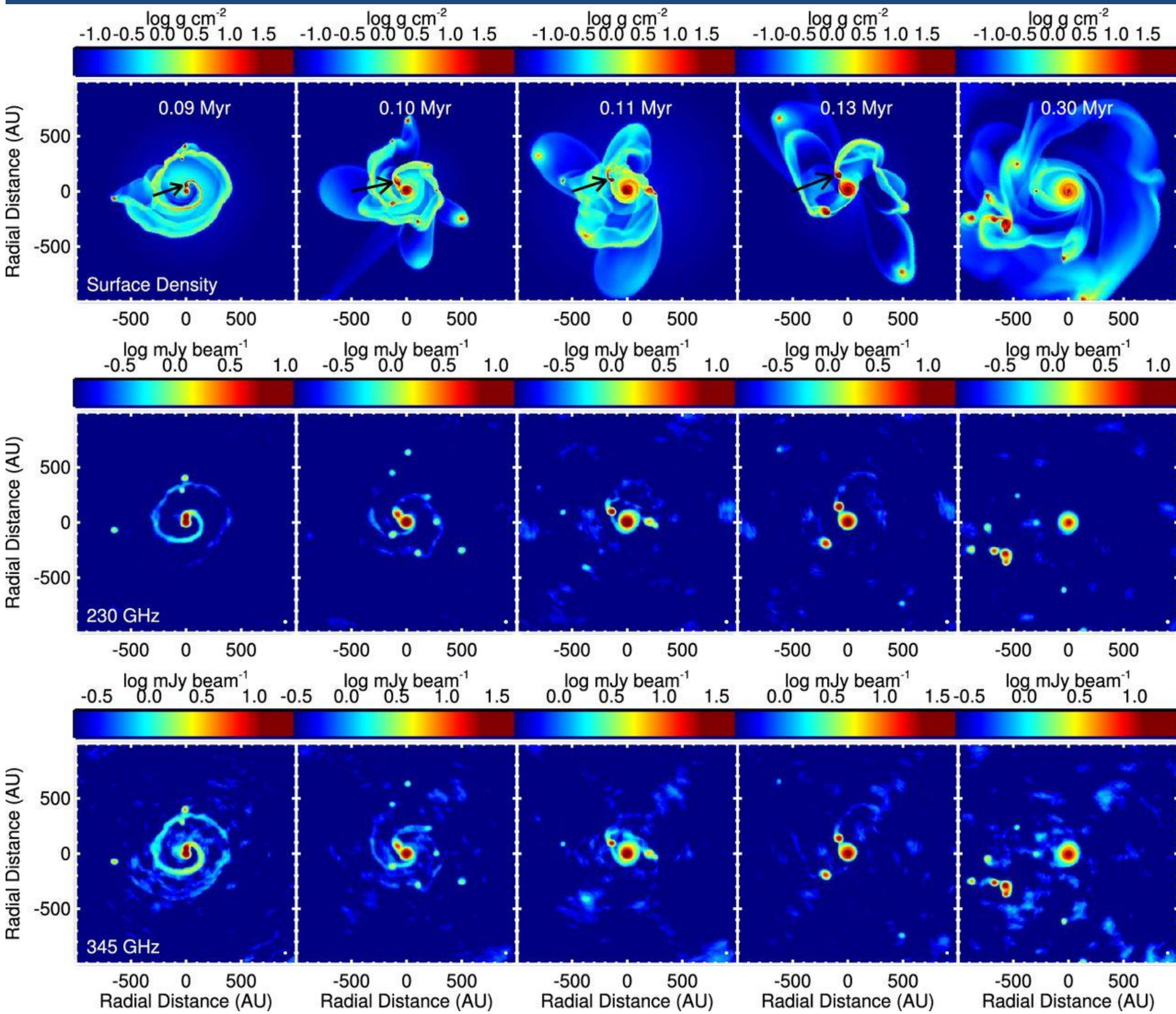
Is M_{disk}/M_{star} more like 0.01 or 0.1?

Class	Median "observed" disk masses (Andrews & Williams 2005)	Median model disk mass (Vorobyov 2010)	Mean model disk mass (Vorobyov 2010)
0	$0.01\ M_\odot$	$0.07\ M_\odot$	$0.1\ M_\odot$
I	$0.03\ M_\odot$	$0.13\ M_\odot$	$0.15\ M_\odot$
II	$0.003\ M_\odot$	$0.04\ M_\odot$	$0.06\ M_\odot$

Significant uncertainties in dust properties, affecting conversion of measured submillimetre flux to a disk mass. Is gas (and dust) hiding in optically thick clumps?

Does gravity drive the late time disk accretion?
Or transport due to turbulence and magnetic fields also important?

Simulated ALMA images



Surface gas density

Simulated face-on detection through an outflow cavity at distance 250 pc. One hour ALMA integration time at 0.1 arcsec resolution detects 1.5 M_J fragments up to 800 AU from protostar.

Vorobyov, Zakhozhay, & Dunham (2013)

Core Accretion Model (CA)

1. Grains in disk grow into planetesimals
2. These grow into solid cores
3. Massive solid cores accrete gaseous envelopes to form giant planets

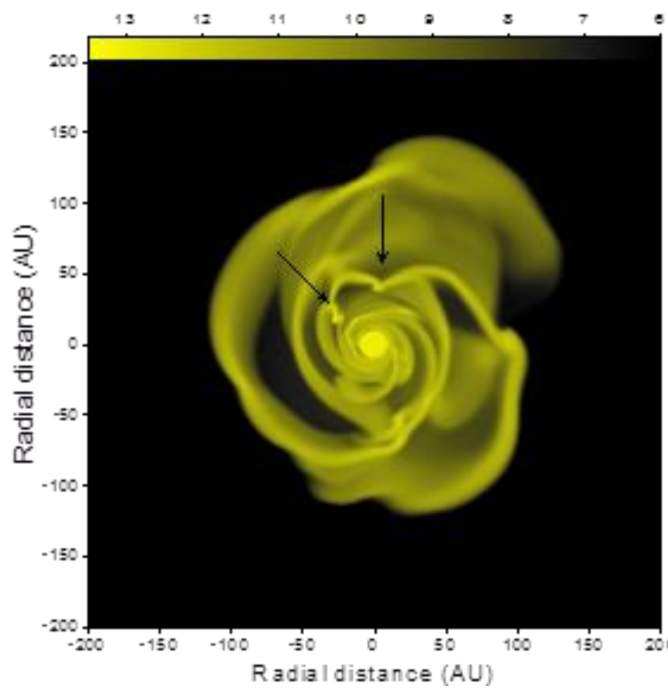
Known problems

1. 1 m sized boulders rapidly migrate into the star – need to stop that to allow further growth
2. When colliding at > 10 m/s, they shatter rather than stick
3. How do you make extrasolar planets observed at very large radii, ~ 100 AU?

Core Sedimentation

Boley et al. (2010), Nayakshin et al. (2011), Vorobyov (2011) suggest that the inward migrating gas clumps may deliver sedimented (during 10^4 yr lifetime of clumps) solids to the INNER solar system. Also Nayakshin & Fletcher (2015). Picks up on old (migrationless) suggestion of Kuiper (1951).

Migrating Embryos may form basis of terrestrial planet formation as well!



Competing Paradigms

Core Accretion Model versus Gravitational Instability Model (plus Migrating Embryo Scenario on top). Neither theory currently has all the answers.

Gravitational Instability Model (GI)

1. Planets form from a disk by gravitational collapse. Direct collapse to planet, like for stars (reintroduced by Boss 1997 and others)
2. Disks cannot fragment to make planets unless the distance to center is approximately 50 AU or greater. Therefore, planets need to migrate inward, then stop!

Known problems

1. Cannot make the Solar System: no way to make a solid/rocky planet; giant planets in SS are more metal rich than the Sun
2. Gas spheres that are a few Jupiter masses or less cannot even directly collapse due to gravity

Migrating Embryo (ME) Scenario

Hybrid approach that incorporates parts of both CA and GI models.

1. Massive young disk undergoes gravitational instability with clumps of ~ 10 M_J formed at radii > 50 AU
2. Clumps migrate inward due to gravitational torques
3. Dust sediments inside the clumps and makes solid cores. The inward migration period allows enough time for dust settling
4. Gas envelopes are removed at AU radii by tidal disruption
5. Terrestrial protoplanets continue their growth in the inner disk as in CA model

Summarized by Basu & Vorobyov (2012, Meteoritics and Planetary Science). Sedimentation effects – Boley et al. (2010) , Nayakshin et al. (2011), Cha & Nayakshin (2011), Nayakshin (2015)

Conclusions

- Migrating Embryo Model for early disk evolution: episodic gravitational instability driven by envelope, clumps, accretion bursts, companions, and ejections
- In later phase, class I-II, gravitational torques alone explain many properties of disk accretion, but may require additional accretion drivers to reduce disk masses
- Migrating Embryos may even give a boost to Core Accretion process by supplying processed solid material to inner planetary system
- Emerging observations of structured disks from ALMA and Subaru provides synergy for comparison with theoretical models