The Earliest Stages of Disk Evolution

What the solids tell us about the wild years of disk evolution: Part I

Les Houches, February 2013

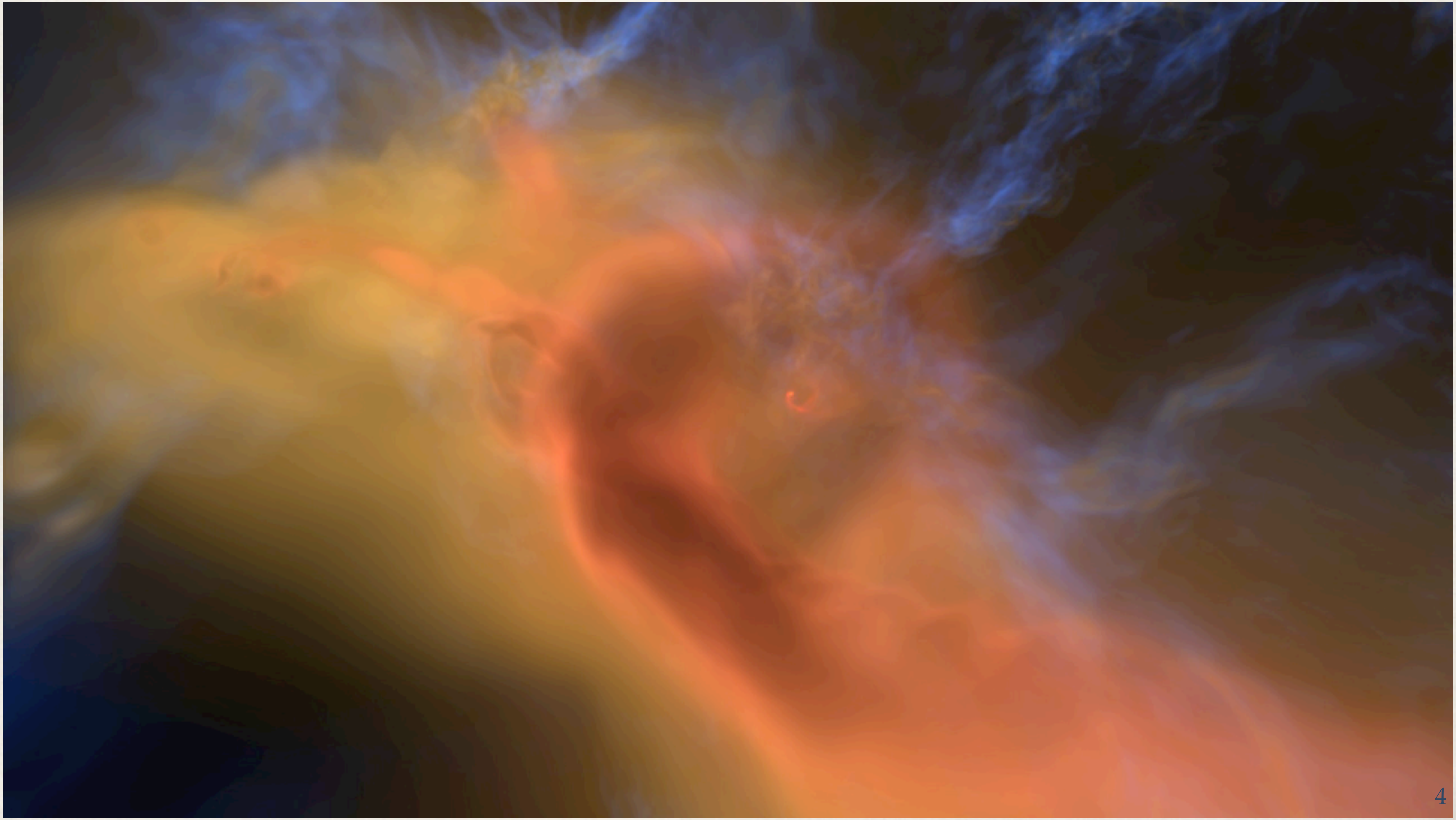
Topics

- Timescales
  - *When things happen and understanding context*
- Gravitational Instability
  - *What conditions can cause very violently unstable disks*
- Consequences of Massive Disks
  - *Why instabilities matter for solids*
- Timing in the Meteoritic Record
  - *The constraints for the Solar System*
- Summary

Disk Evolution

- We can think of disk evolution in three rough evolutionary phases
  - **Newly-forming disks**
    - Class 0 to Class 1 protostars. Roughly few X 10^5 yr.
  - **Established disks**
    - Your "typical" disk ~ few X 10^6 yr.
  - **Debris disks**
    - Leftovers banging together. Ongoing, but bright for 10^8 yr.
- Note that these are not necessarily consistent with observational phases

A Cinematic Approach



Major Questions for Planet Formation

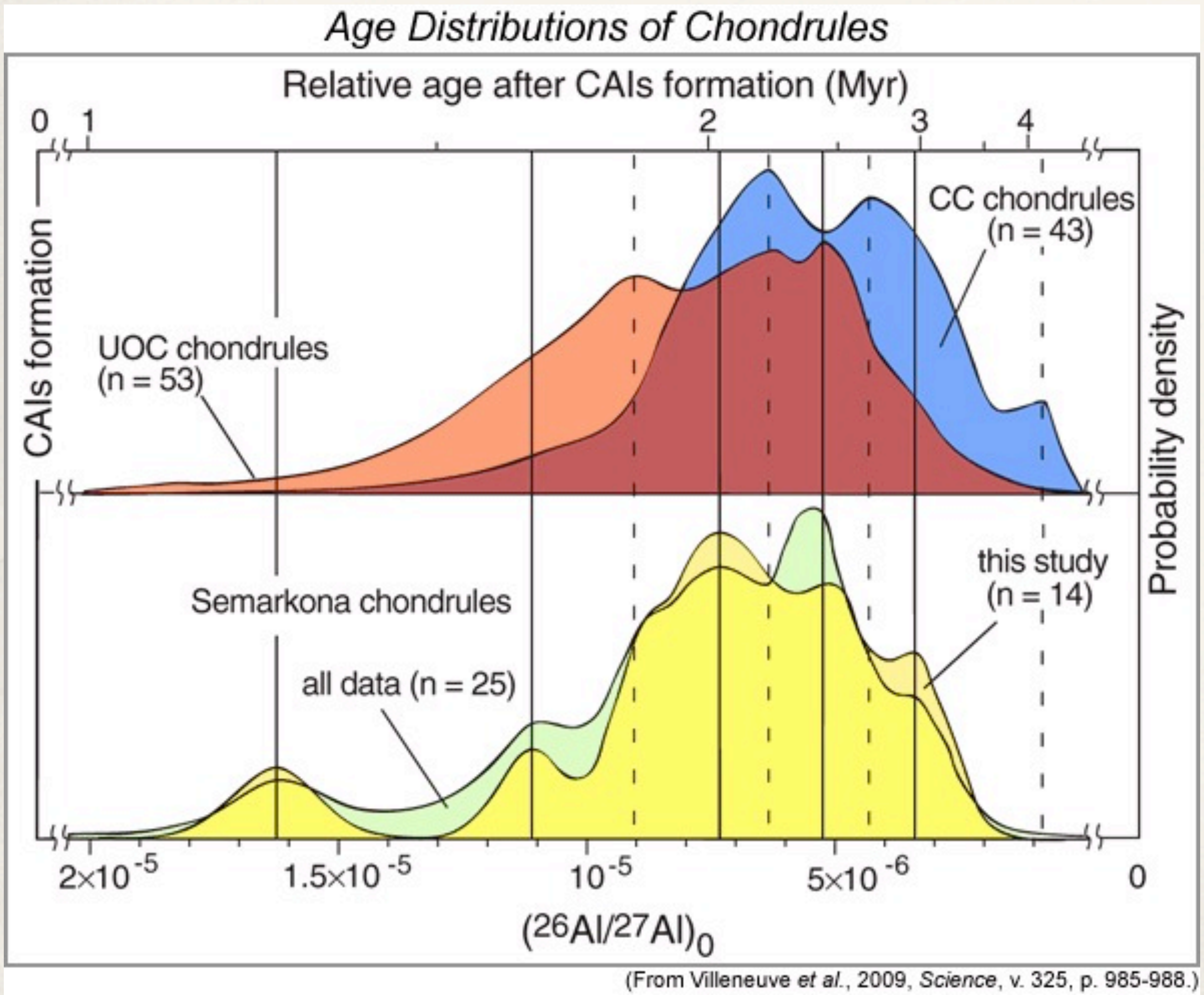
- When does planet formation begin?
- When does t_{disk}=0 correspond to t_{solid}=0?
- What are the environments of planet formation?
- What are the phases of planet formation?
- What modes of planet formation are possible?
- For the Solar System, meteorites give us clues

What Is This Talk About

- Focusing on the early disk early epoch, i.e., the "Newly-Forming Disks."
  - Mass infall period ⇒ Embedded
  - Denser, hotter than other stages of disk evolution

What are consequences of this phase of disk evolution for planet formation throughout the disk's lifetime?

Why Worry About Newly-Forming Disks?

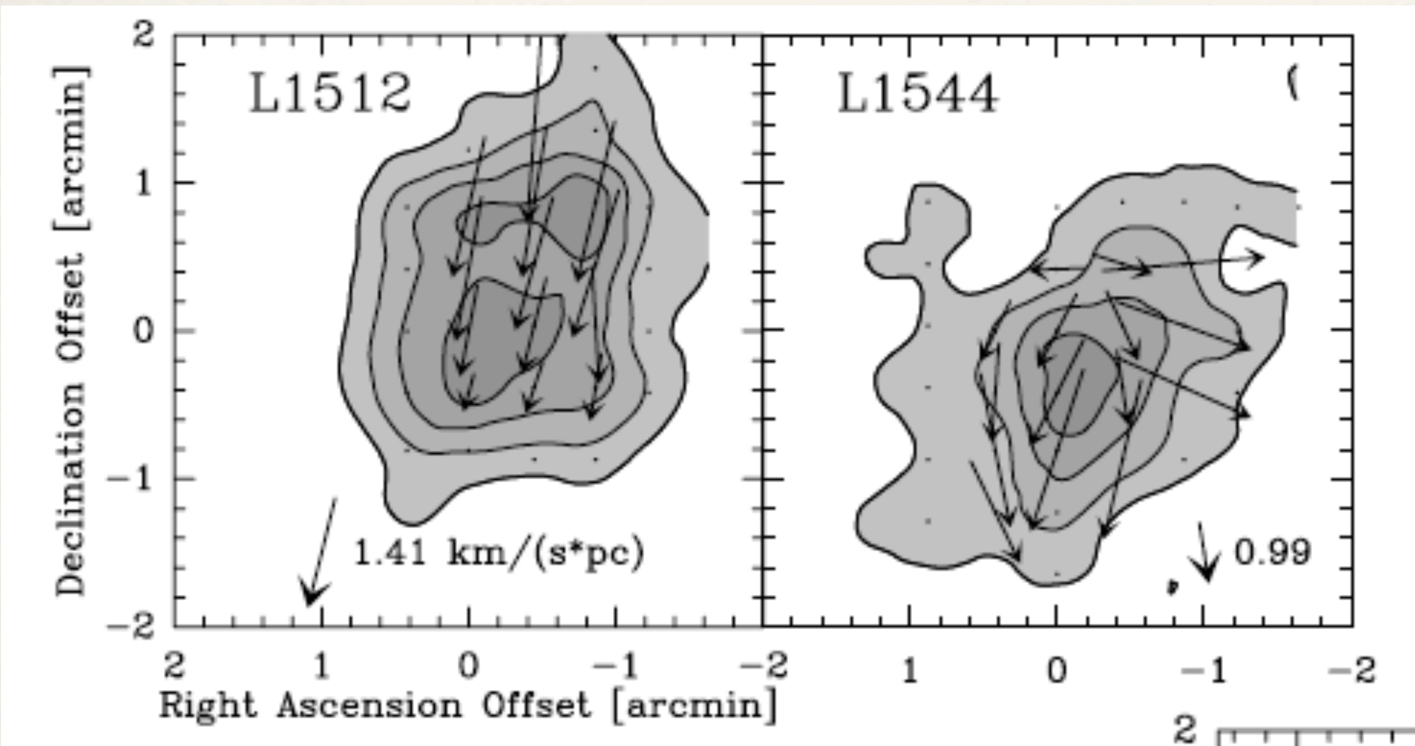


Calcium-Aluminum-rich Inclusions (CAIs) are old, and clustered around 100 000 yr of each other

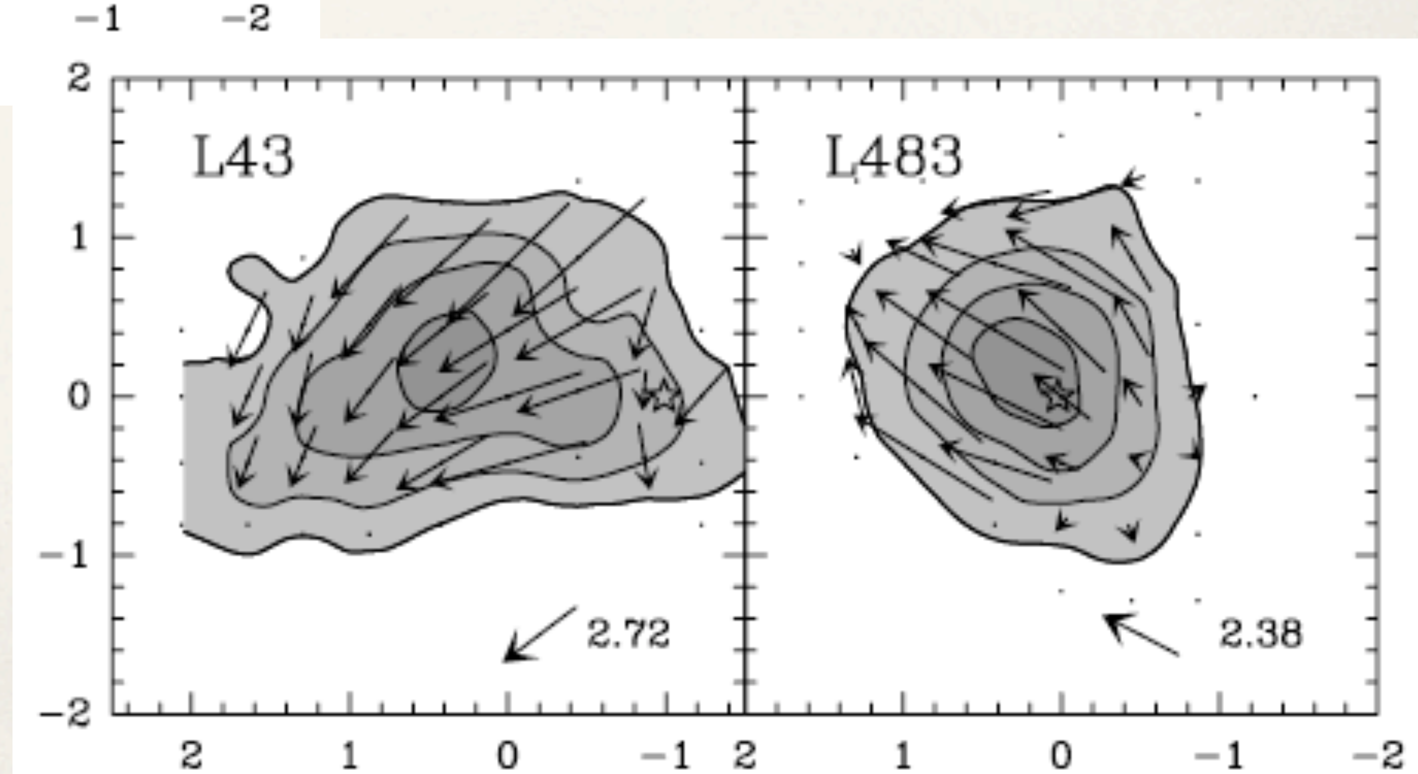
Forming A Star: A Conceptual Take

- A cloud core collapses:
  - Maybe due to diffusion of charged particles, compression from turbulence, multiple factors at once, etc.
- Low angular momentum gas forms a stellar core
- High angular momentum gas falls onto a disk
- There will be a distribution of disk masses and initial sizes
- Temperatures and densities become very different than in cloud core

Cloud Core Velocity Gradients



Caselli et al. 2002



~35% have $r_{init} \gtrsim 100$ AU

(My estimate -- see Boley et al. 2012)

Mass Accretion

- Consider the mass infall rate during star formation
- Use the basics of a Jeans instability in a uniform cloud as a starting point
  - $\lambda_{Jeans} = [\pi P/(G\varrho^2)]^{1/2}$
  - $M_{Jeans} = \varrho\ (4\pi/3)\ (\lambda_{Jeans}/2)^3$
  - $t_{ff} = [3\pi/(32\ G\ \varrho)]^{1/2}$
  - $\varrho = \mu\ m_p\ n$
  - $M_{Jeans}/t_{ff} = 5.4\ c_i^3/G$
    - Shu 1977 self-similar collapse $\Rightarrow M_{Jeans}/t_{ff} \sim c_i^3/G$

Mass Accretion

- Let's put some values into those equations
  - Herschel results find ~1 M_{Sun} cores with densities $n \sim 10^5$ g/cc and temperatures as low as 15 K.
  - $t_{ff} \sim 100\,000$ yr
  - $\dot{M} \sim 1.5 \times 10^{-5}\ M_{Sun}/yr$ ($\sim 3 \times 10^{-6}\ M_{Sun}/yr$) for T = 15 K

The Land of Gravitational Instability

- Toomre Q (1964) stability parameter
  - Consider first a patch of a thin, uniformly rotating disk in the frame of that patch
    - $\partial\Sigma/\partial t + \nabla\cdot(\Sigma v) = 0$
    - $\partial v/\partial t + (v\cdot\nabla)v = -\nabla P/\Sigma - \nabla\Phi - 2\Omega\times v + \Omega^2(x\hat{e}_x + y\hat{e}_y)$
    - $\nabla^2\Phi = 4\pi G\Sigma\delta(z)$
  - Now consider a small perturbation
    - $\Sigma = \Sigma_0 + \varepsilon\Sigma_1(x,y,t)$; $v = v_0 + \varepsilon v_1(x,y,t)$; $\Phi = \Phi_0 + \varepsilon\Phi_1(x,y,t)$
    - Keep only linear terms in ε
    - Take the perturbation to have a form $\exp(-i(\mathbf{k}\cdot\mathbf{x} - \omega t))$
  - Analysis gives dispersion relation (see Binney & Tremaine)

Instability

- For uniform rotation, the disk becomes unstable when
  - $2\, c_s\, \Omega / (\pi\, G\, \Sigma_0) < 1$
  - $c_s^2 = \partial P / \partial \Sigma$ at $\Sigma_0 \Rightarrow$ sound speed
- For a differentially rotating disk (see Binney & Tremaine), unstable when
  - $\mathbf{c_s\, \kappa / (\pi\, G\, \Sigma_0) < 1}$ $\Rightarrow$ ring instability
  - $\kappa^2 = R\, d\Omega^2 / dR + 4\Omega^2$ at guiding center $\Rightarrow$ epicyclic frequency
- Stability of disk against gravitational perturbations
- Long wavelengths are stabilized by shear (κ)
- Short wavelengths are stabilized by the sound speed

H.E. in z direction

$$\frac{1}{\rho}\frac{dP}{dz} = -\frac{d\Phi}{dz}$$

$$F_z = -\frac{GM}{R^2+z^2}\sin\left(\frac{z}{R}\right) \simeq -\frac{GM}{R^3}z$$

$$= -\Omega^2 z$$

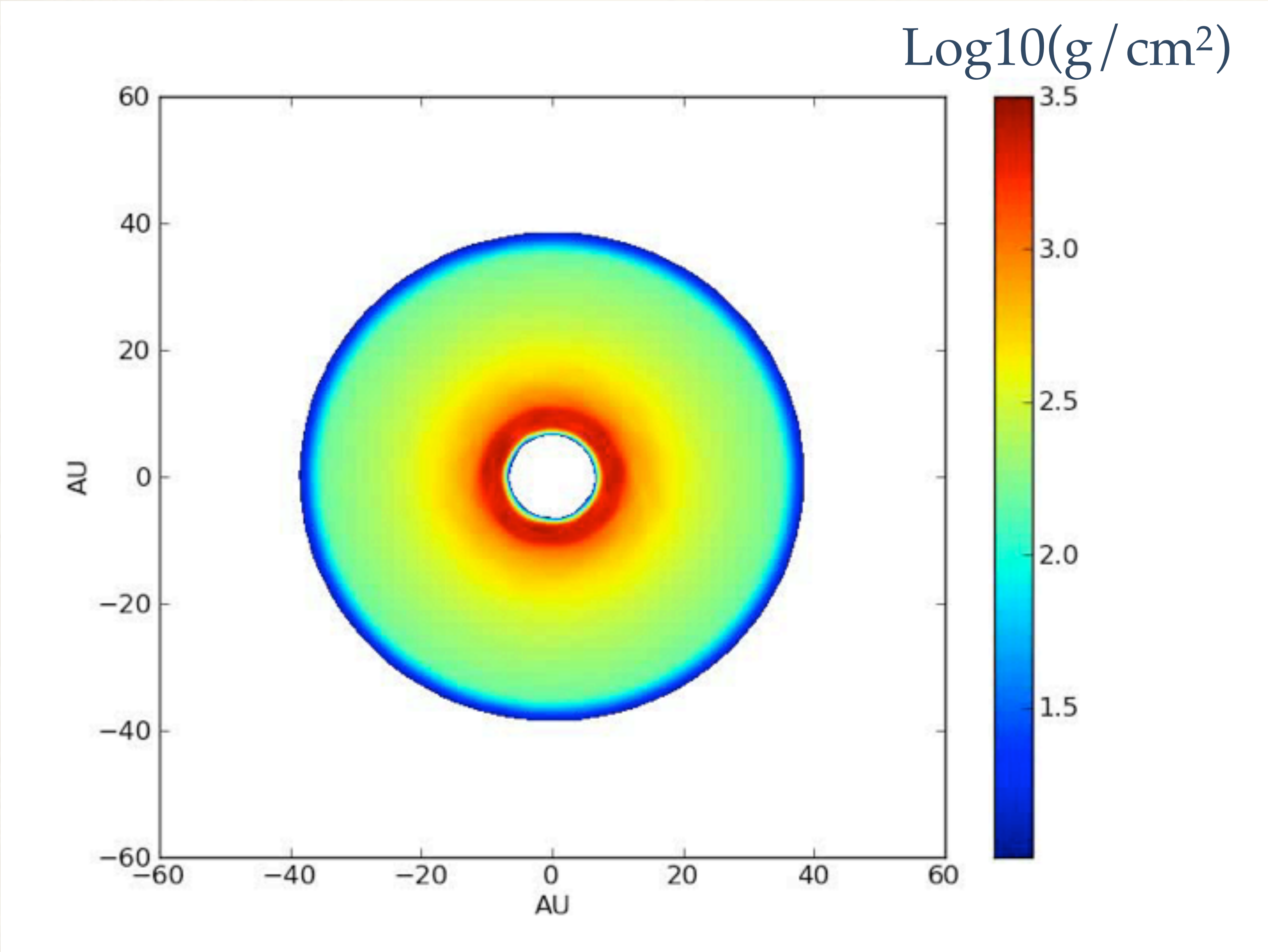
If isothermal with $P = \rho c^2$

$$\frac{d\rho}{\rho} = -\frac{\Omega^2 z}{c^2}\,dz \Rightarrow \rho = \rho_0\left(-\frac{\Omega^2 z^2}{2c^2}\right)$$

Energy Budget

- Take scaleheight $H = c_s/\Omega$
- Thermal energy ~ c_s^2
- Gravitational energy ~ $\Omega^2 H^2$
- Rotational energy ~ $\Omega^2 R^2$
- Thermal to rotational energy and Gravitational to Rotational energy ~ $(H/R)^2$
- $H/R \sim 0.1$, so instabilities only need to tap a small amount of rotational energy

How Do Instabilities Manifest Themselves?



When Q ≲1.7
The spiral instability can set in
(Durisen et al. 2007)

$$Q \approx \frac{c_s \Omega}{\pi G \Sigma} = \frac{c_s \Omega^2}{\pi G \Sigma \Omega}$$

$$\approx \frac{H}{R} \frac{M_*}{\pi R^2 \Sigma} \sim \frac{H}{R} \frac{M_*}{M_d}$$

$$\bar{\Sigma} \sim \frac{0.1 M_\odot}{\pi (10\,AU)^2} \sim 3000\, g/cm^2$$

$$\pi G \Sigma \approx c_s \Omega = \left(\frac{R T_0}{\mu}\right)^{1/2} \left(\frac{R}{R_0}\right)^{-p/2} \Omega_0 \left(\frac{R}{R_0}\right)^{-3/2}$$

For $T \sim R^{-1/2}$, $\Sigma \sim R^{-1.75}$

For $T \sim R^{-3/4}$, $\Sigma \sim R^{-1.875}$

Use α model for conceptual tool

$$\dot{M} = 3\pi \nu \Sigma \quad , \quad \text{where } \nu = \alpha c_s H \approx \alpha c_s^2/\Omega$$

$$\dot{M}_{disk} \approx 3\pi\alpha c_s^2 \frac{\Sigma}{\Omega} = 3\pi\alpha \frac{c_s^3 G \Sigma}{c_s G \Omega} = \frac{3\alpha c_s^3}{G Q}$$

Recall:

$$\dot{M}_{envelope} \approx 5 \frac{c_s^3}{G}$$

If $c_s(\text{disk}) \approx c_s(\text{envelope})$

$$\frac{\dot{M}_{disk}}{\dot{M}_{envelope}} \approx \frac{3\alpha}{5Q} \; !$$

α typically does not exceed 0.1 in local limit!

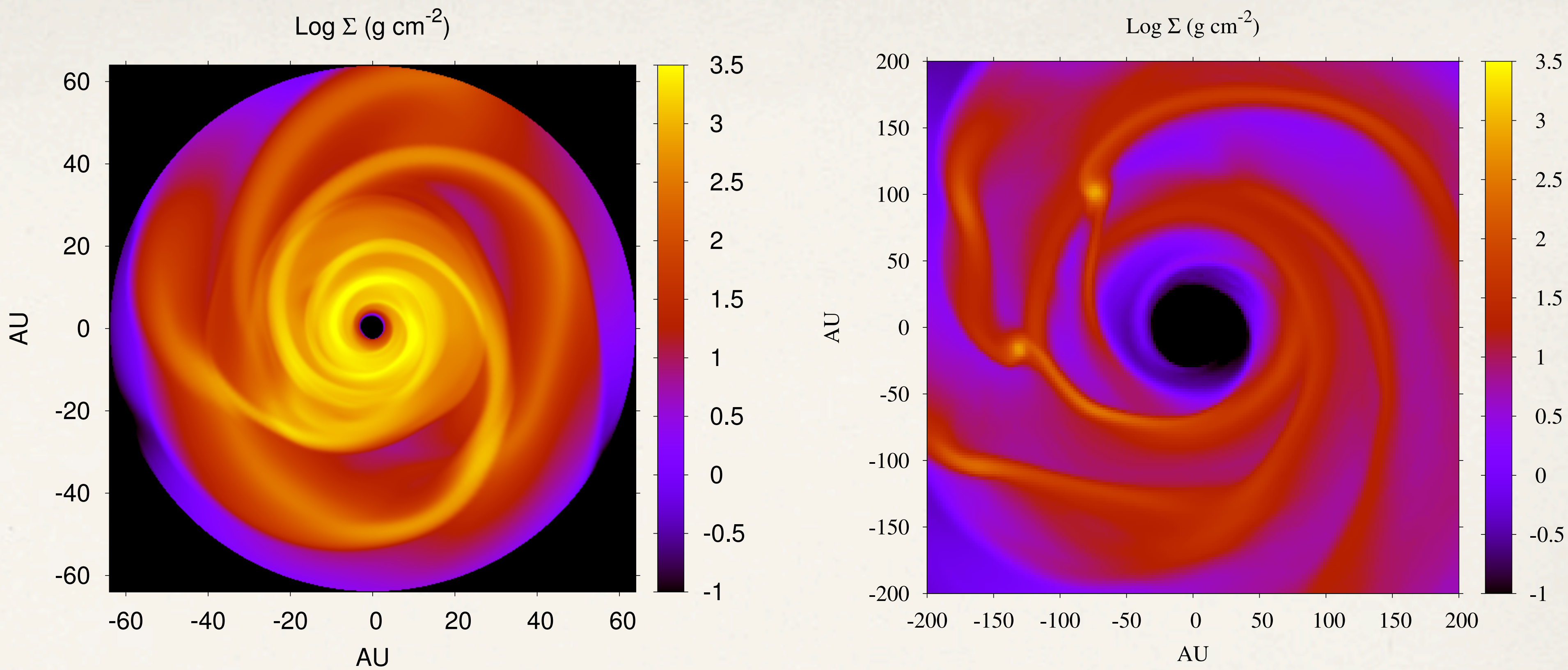
Driving The Instability

- Ways out? Disk becomes much hotter than sound speed of envelope (definitely possible)
- But! Depending how infall is distributed, instabilities could still in principle occur even with a very hot disk
- What about magnetic fields? Definitely something to consider. Simulations show that strong disk instability can still happen.

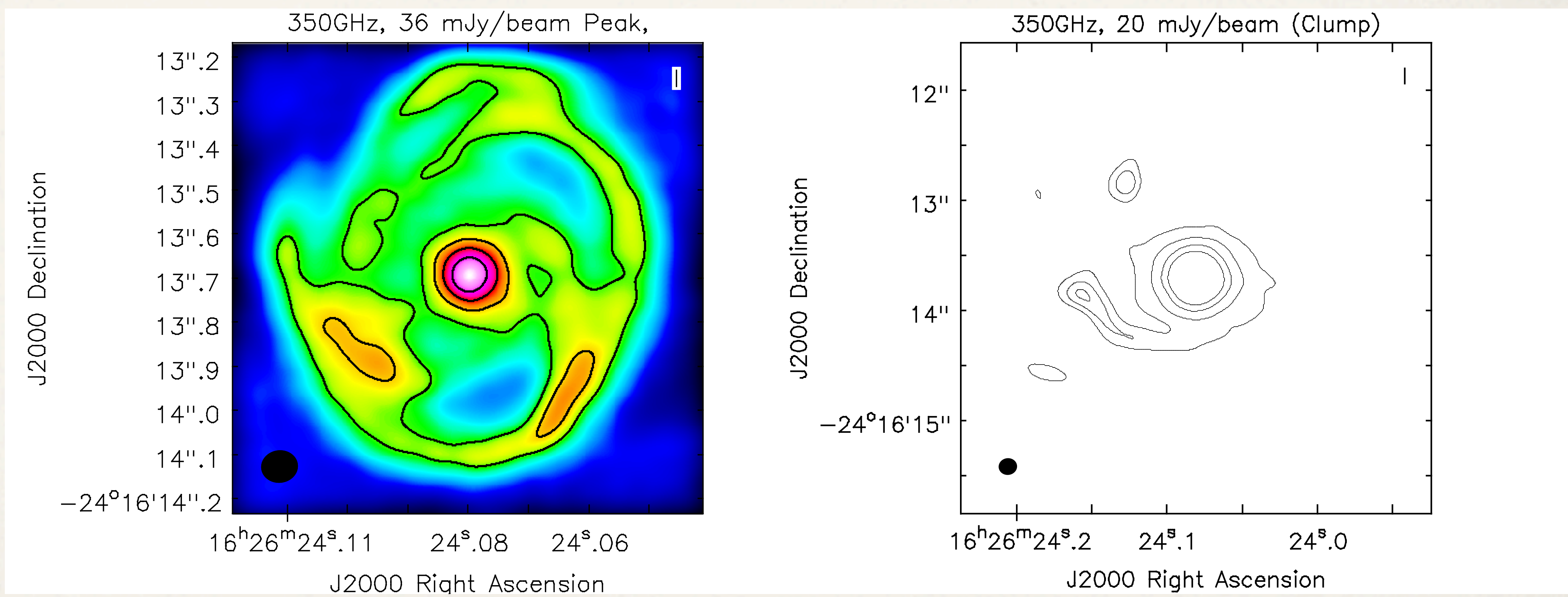
Evolution of the Instability

- Whenever $Q \lesssim 1.7 \Rightarrow$ Spiral instability
  - Spirals create shocks and drive mass transport
  - Under likely conditions, can balance cooling
  - Disk just evolves with lots of non-axisymmetric structure
    - Called self-regulation
- Under some conditions, which are STILL being explored, self-regulation can fail and produce clumps
  - Will discuss later

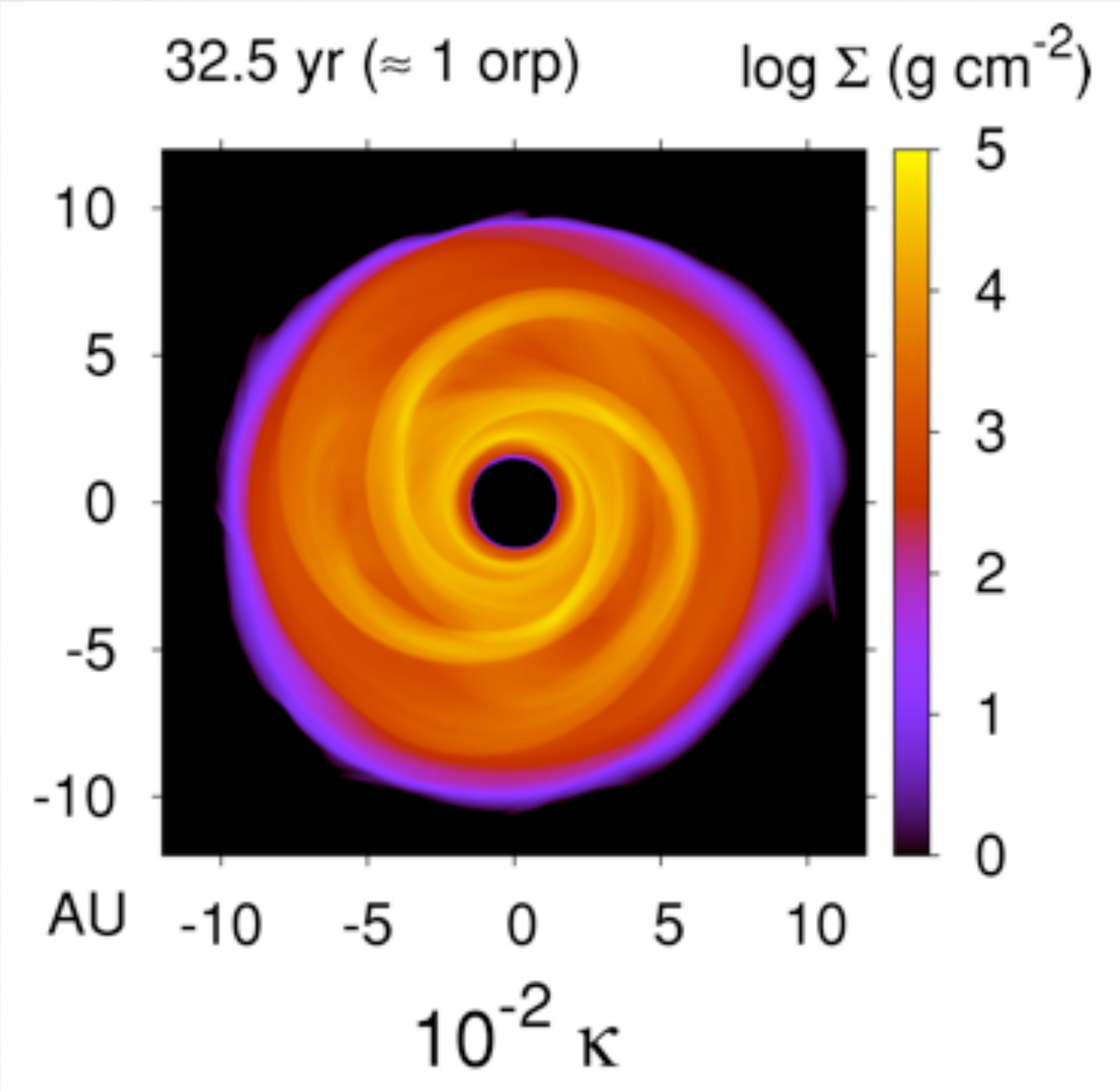
Surface Density

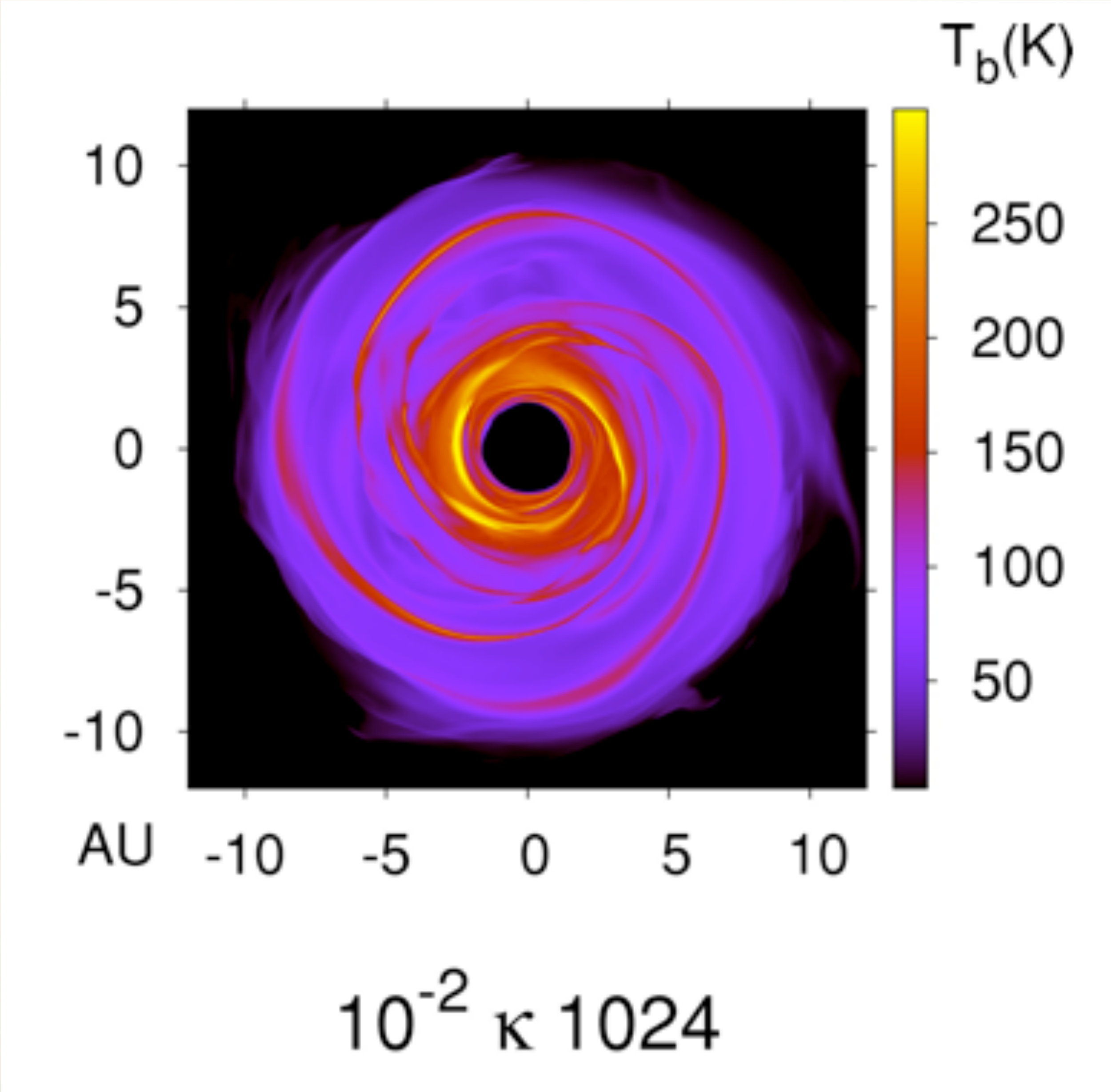


Synthetic ALMA IMAGES

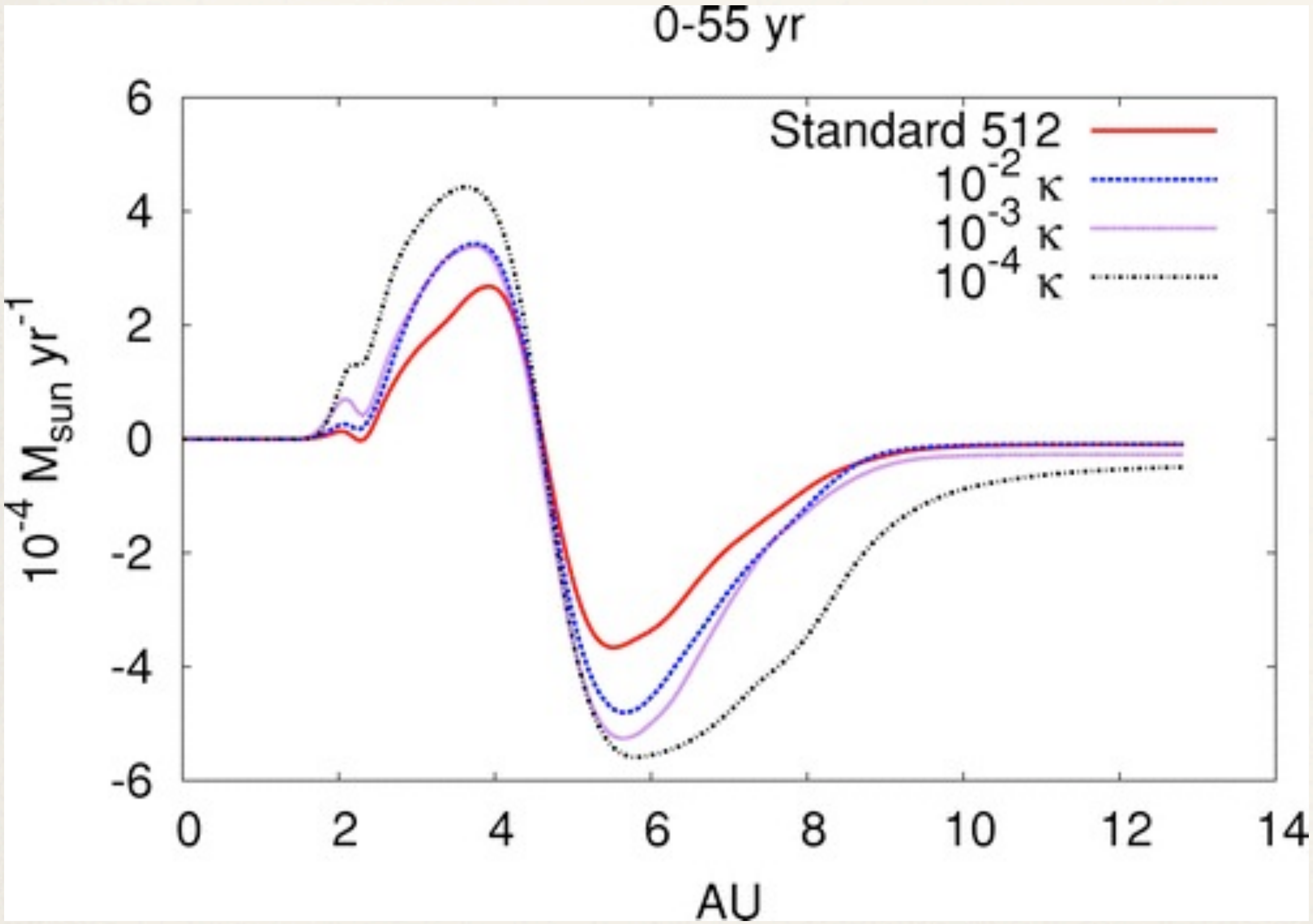


Shocks Give Localized Heating

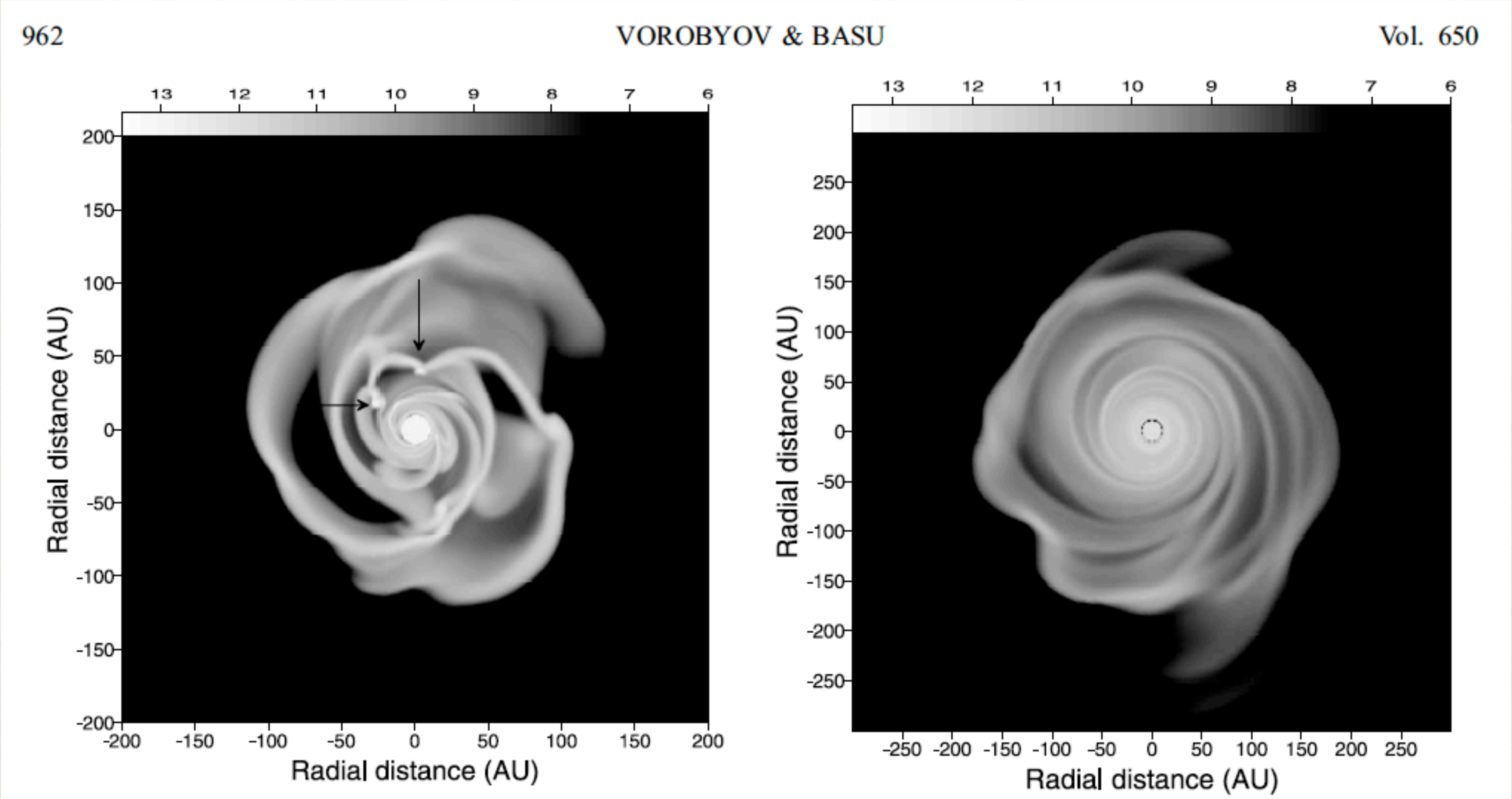




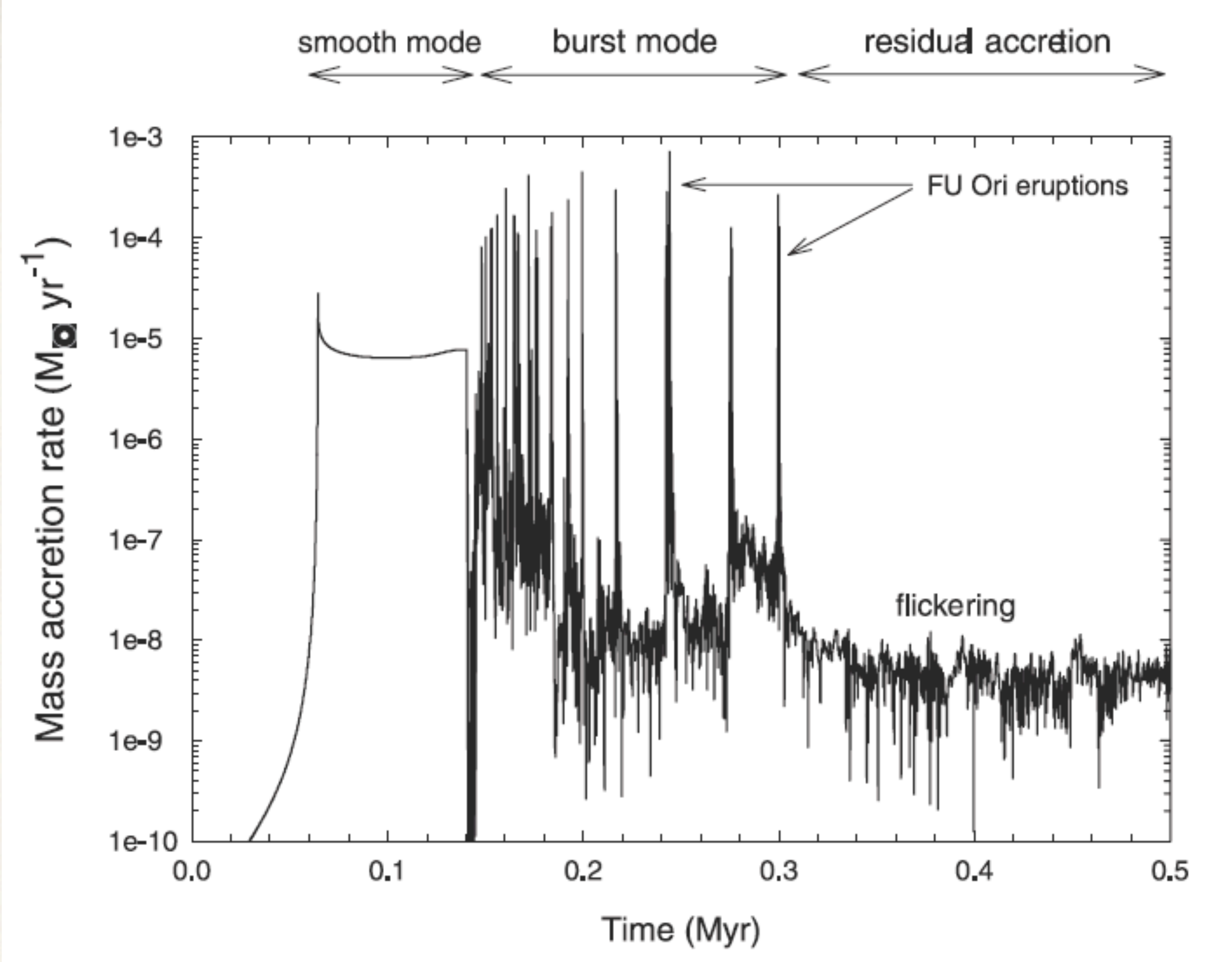
Non-Axisymmetry and Torques



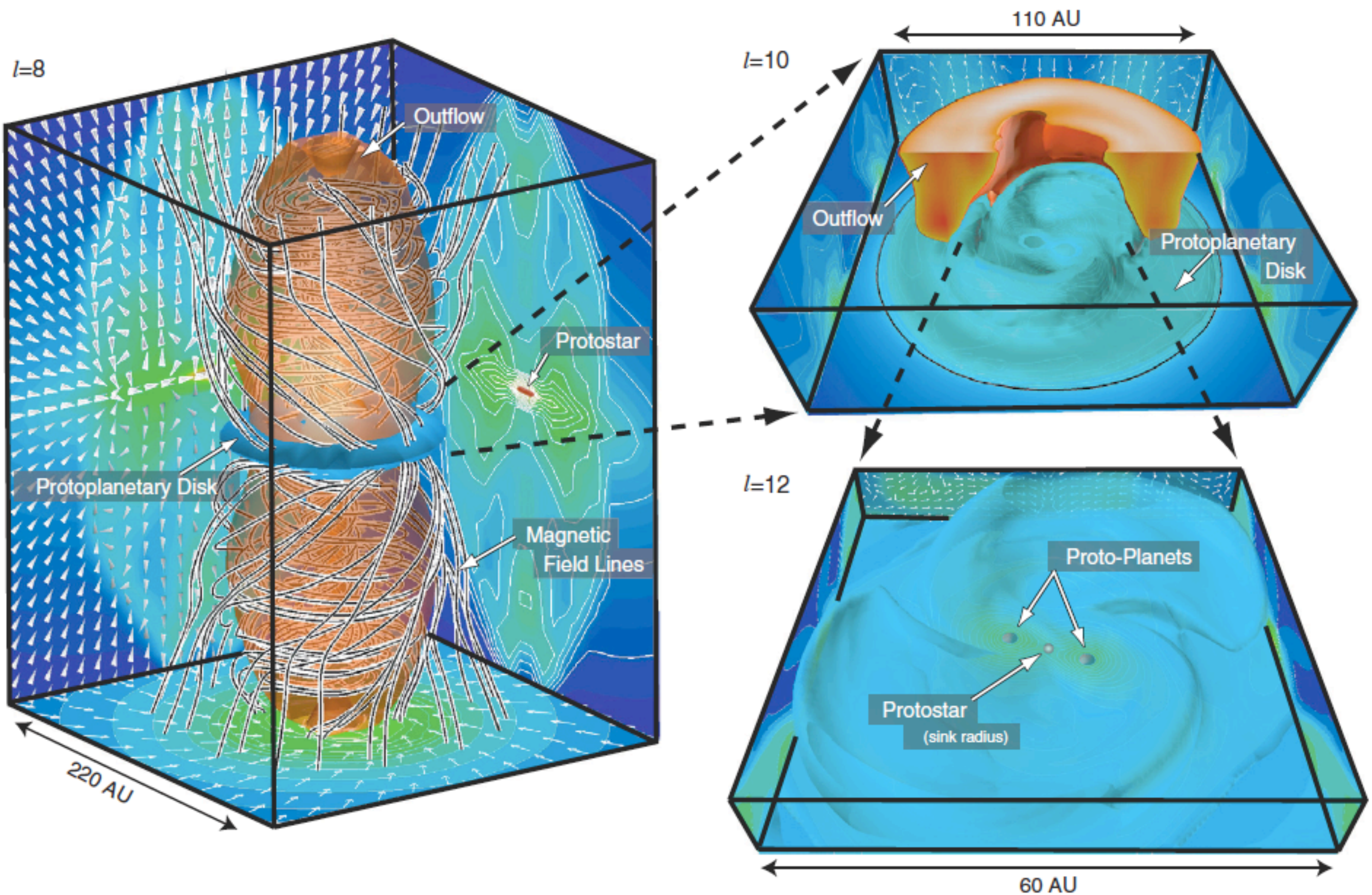
Bursts of instability can give rise to extremely high mass accretion rates



Simple EOS. Includes B fields. 2D. Vorobyov & Basu 2006

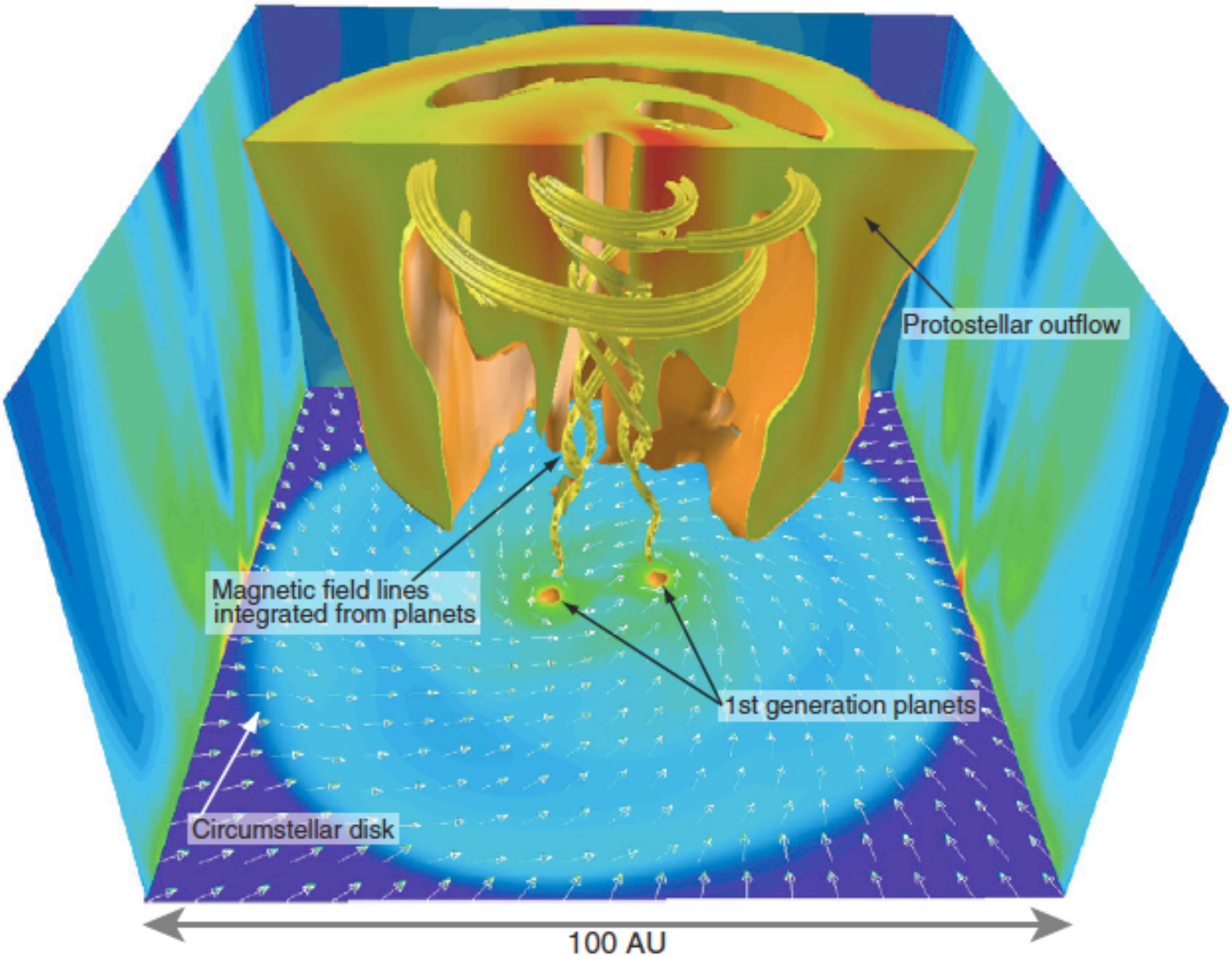


Vorobyov & Basu 2006



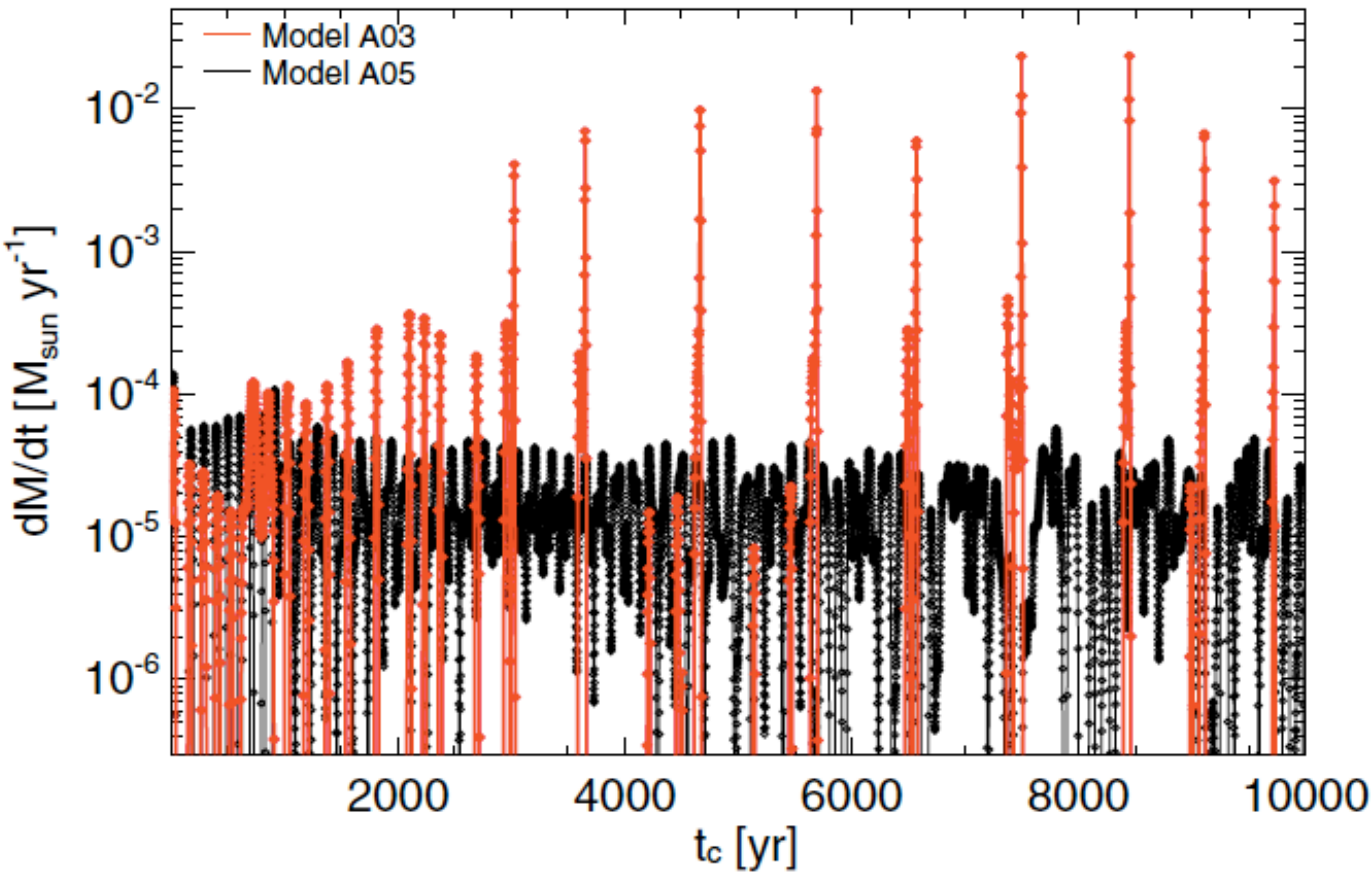
Inutsuka et al. 2010. Magnetic decoupling at n = 10^{10} / cc. Simple EOS

Machida et al. 2011



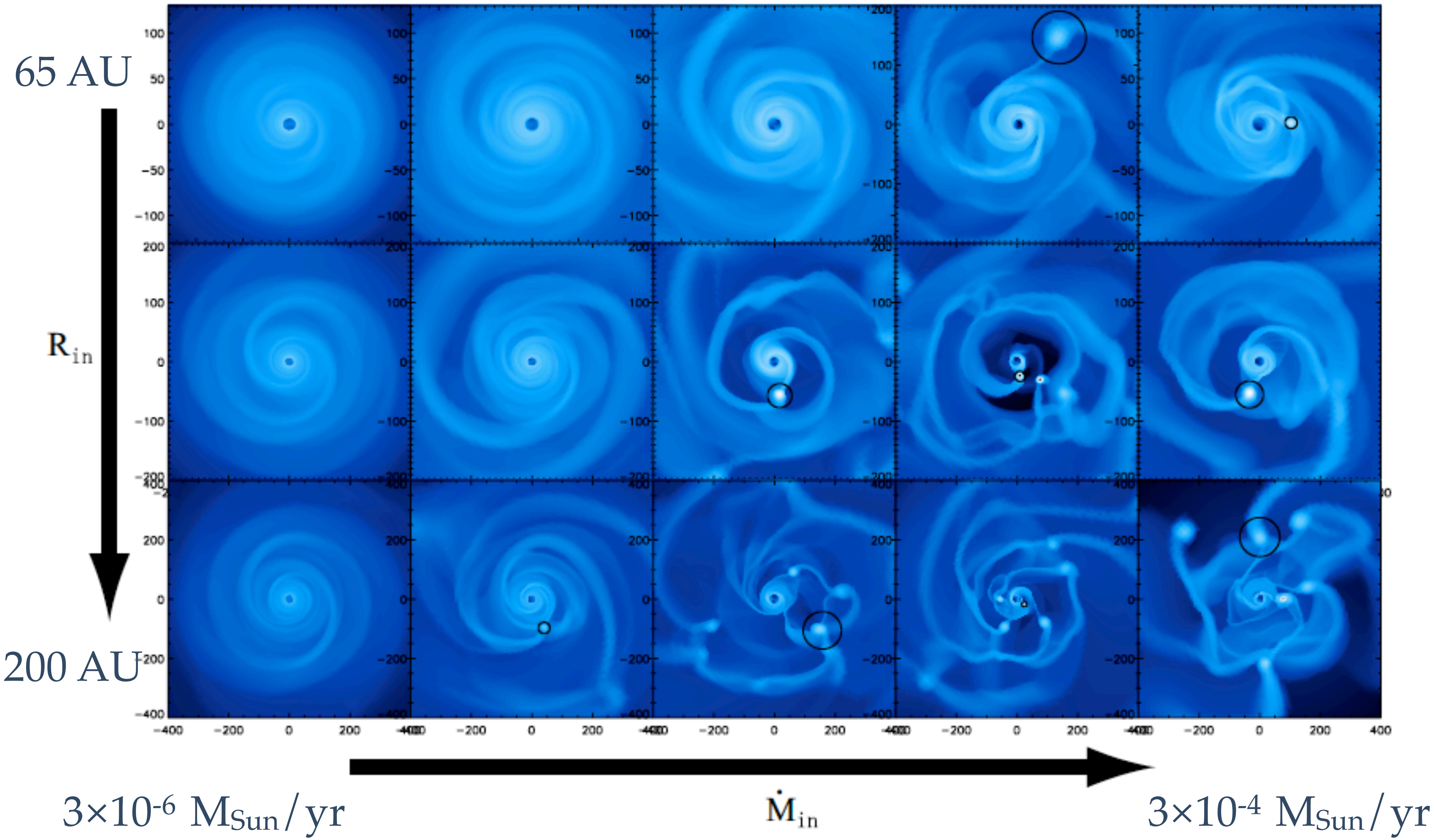
of protostellar outflow at $t_c = 843$ yr is shown by yellow volume, in which color indicates outflow speed. The den

THE ASTROPHYSICAL JOURNAL, 729:42 (17pp), 2011 March 1



Machida et al. 2011

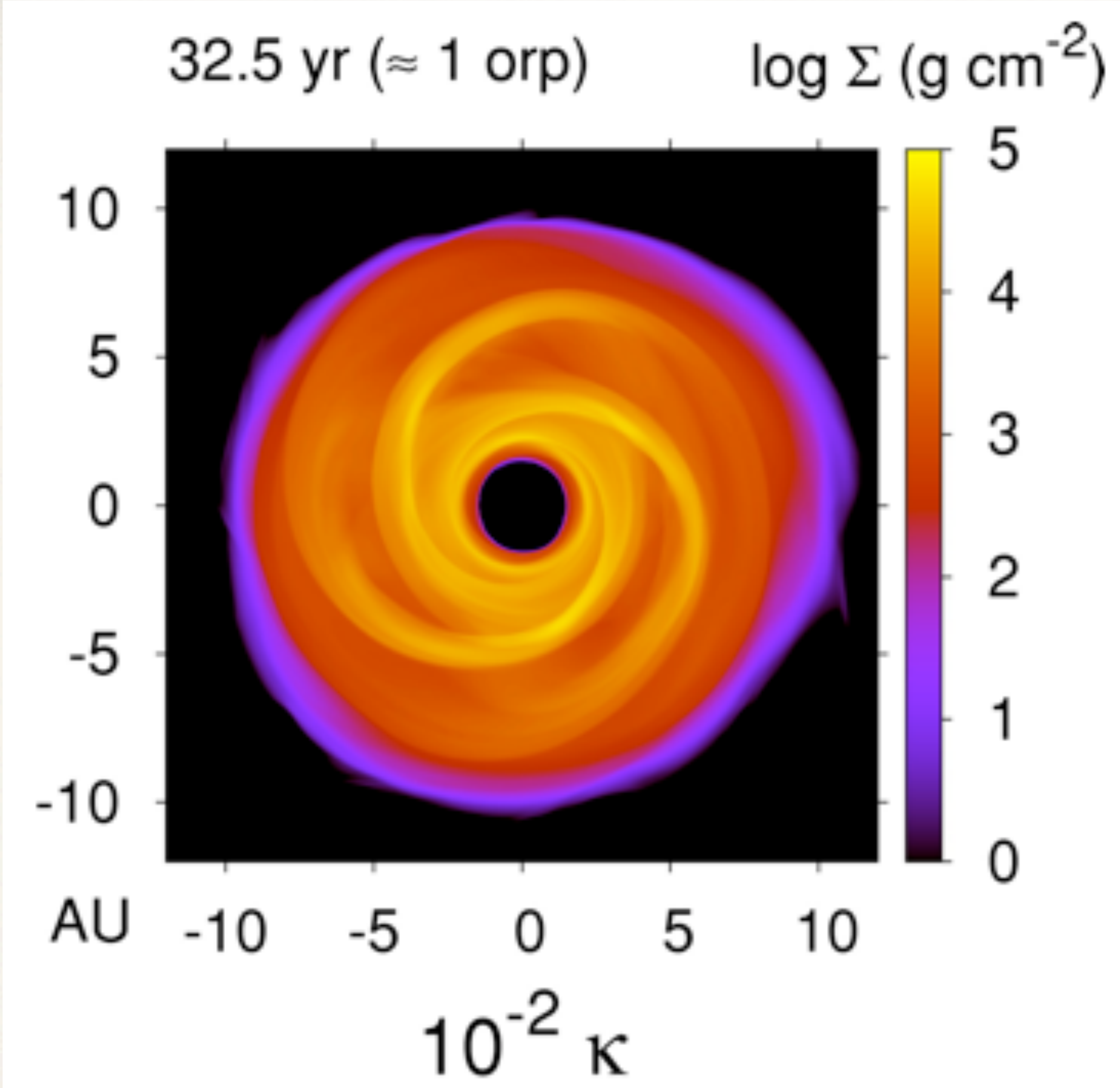
The Astrophysical Journal, 746:110 (26pp), 2012 February 10 Zhu et al.



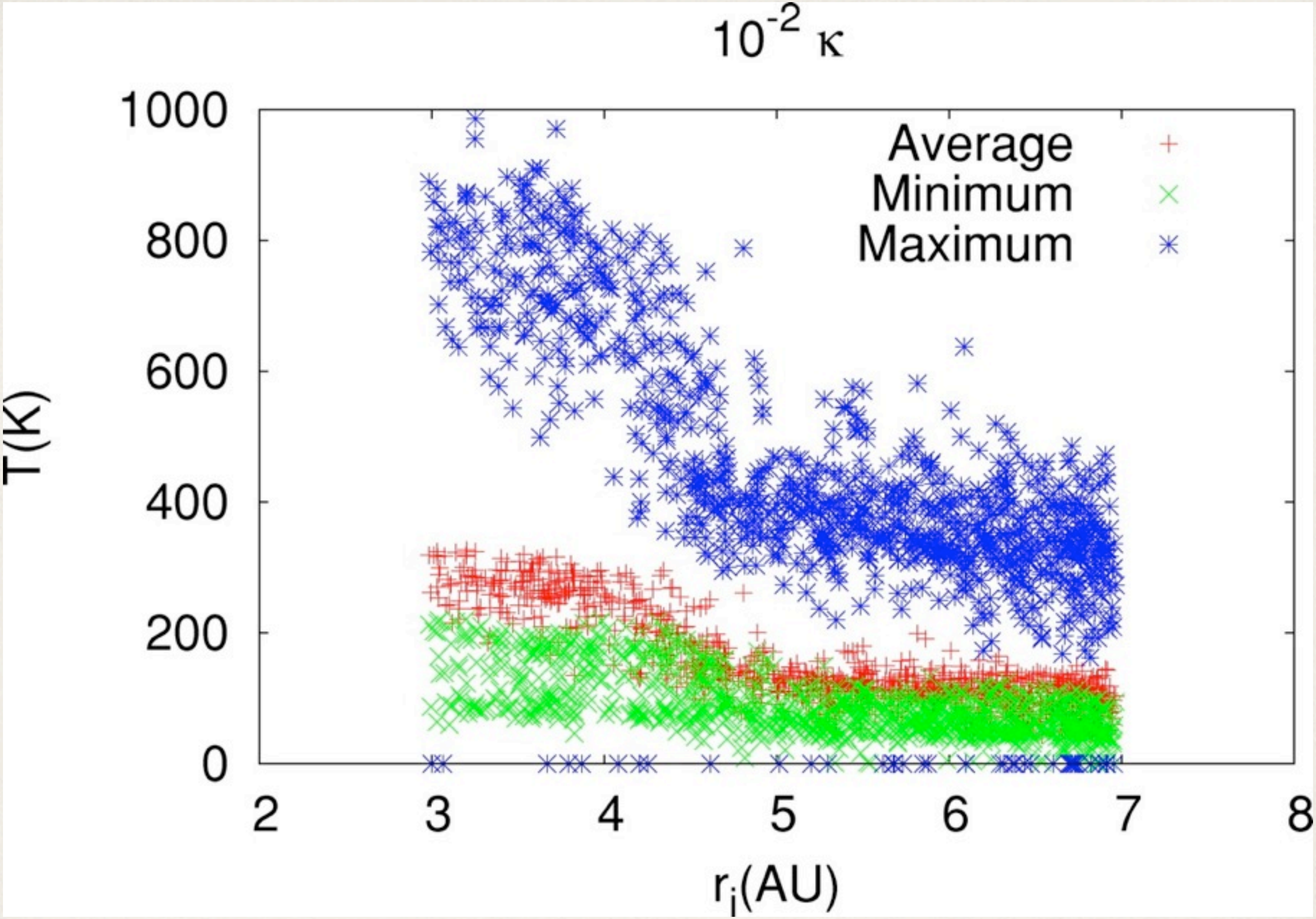
2D simulations. Variation in accretion rate and infall radius. Form of radiative cooling

Summary for Disk Instability

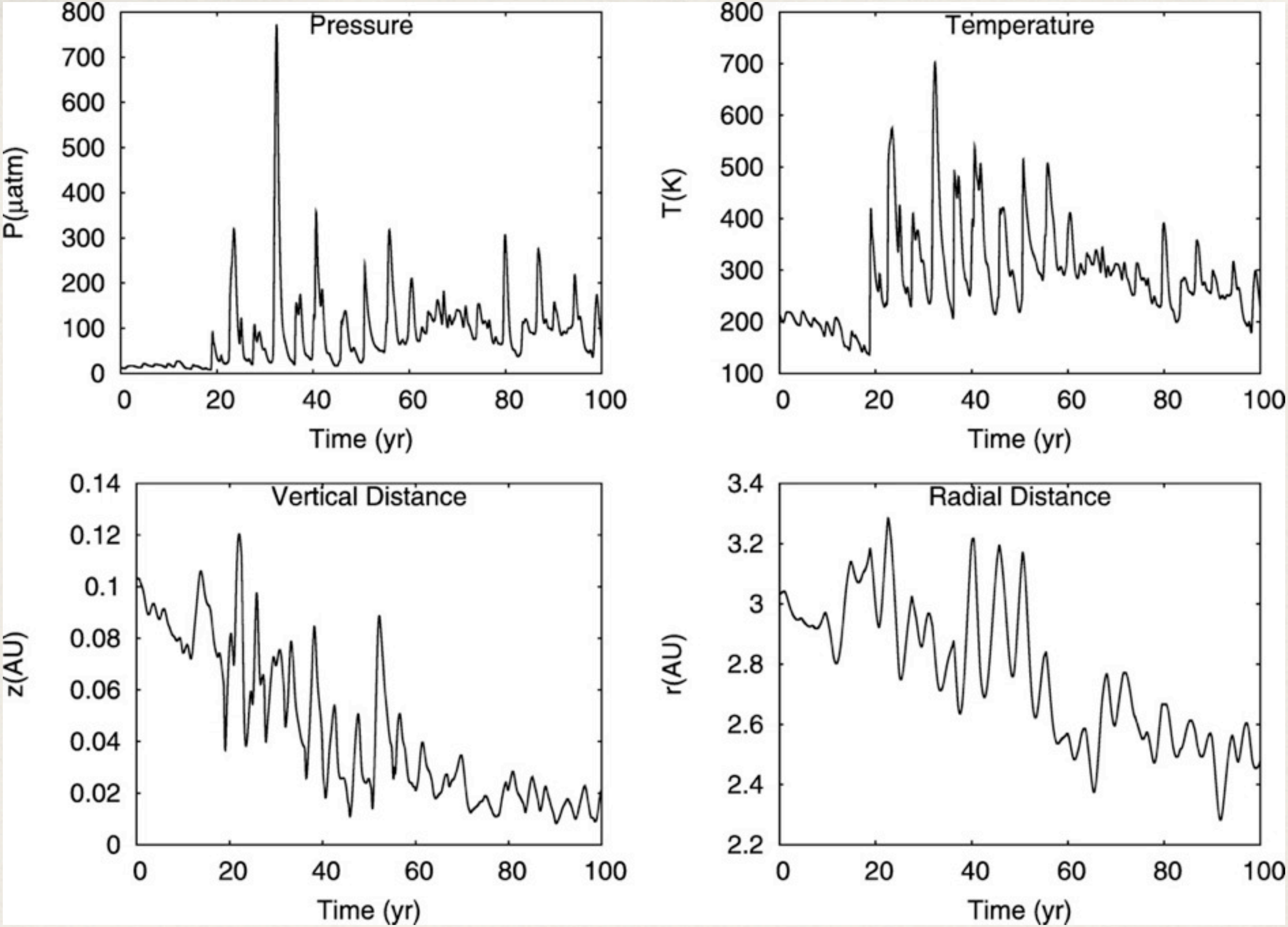
- Star formation process can lead naturally to a period of intense disk heating on timescales of 100 000 yr
- Mass accretion ultimately drives the instability, and can feed episodic bursts of activity
- Spiral structure is a natural outcome of disk instability, creating shocks and can lead to prodigious mass transport
- Fragmentation can happen. Many of resulting fragments are destroyed
- Period of intense disk instability expected to last for a period of time that is similar to the age spread in CAIs



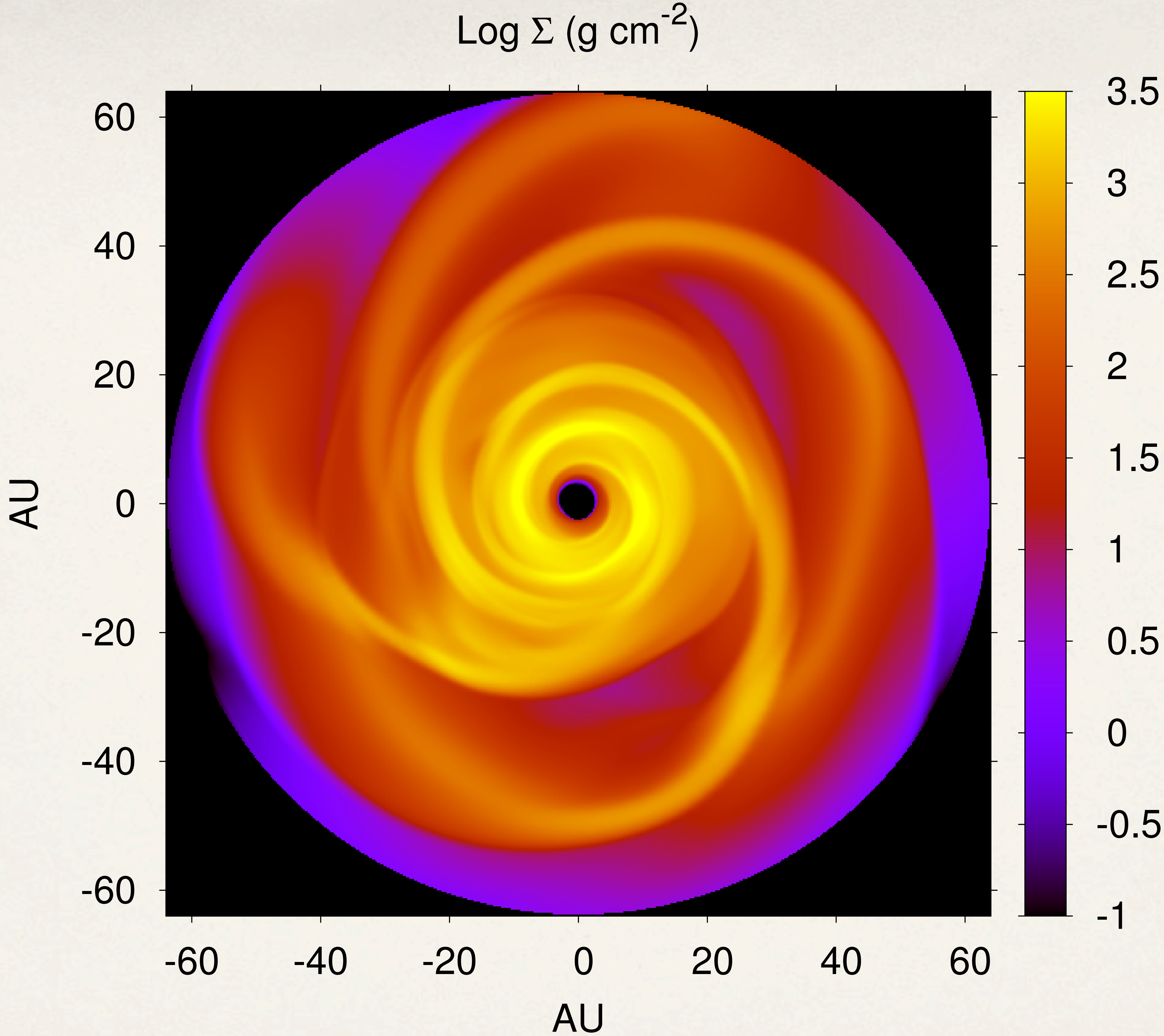
Spiral Structure



Boley & Durisen 2008. Fluid element temperature excursions.



Fluid element histories from Boley & Durisen 2008



Ilee et al. 2011. Base simulation.

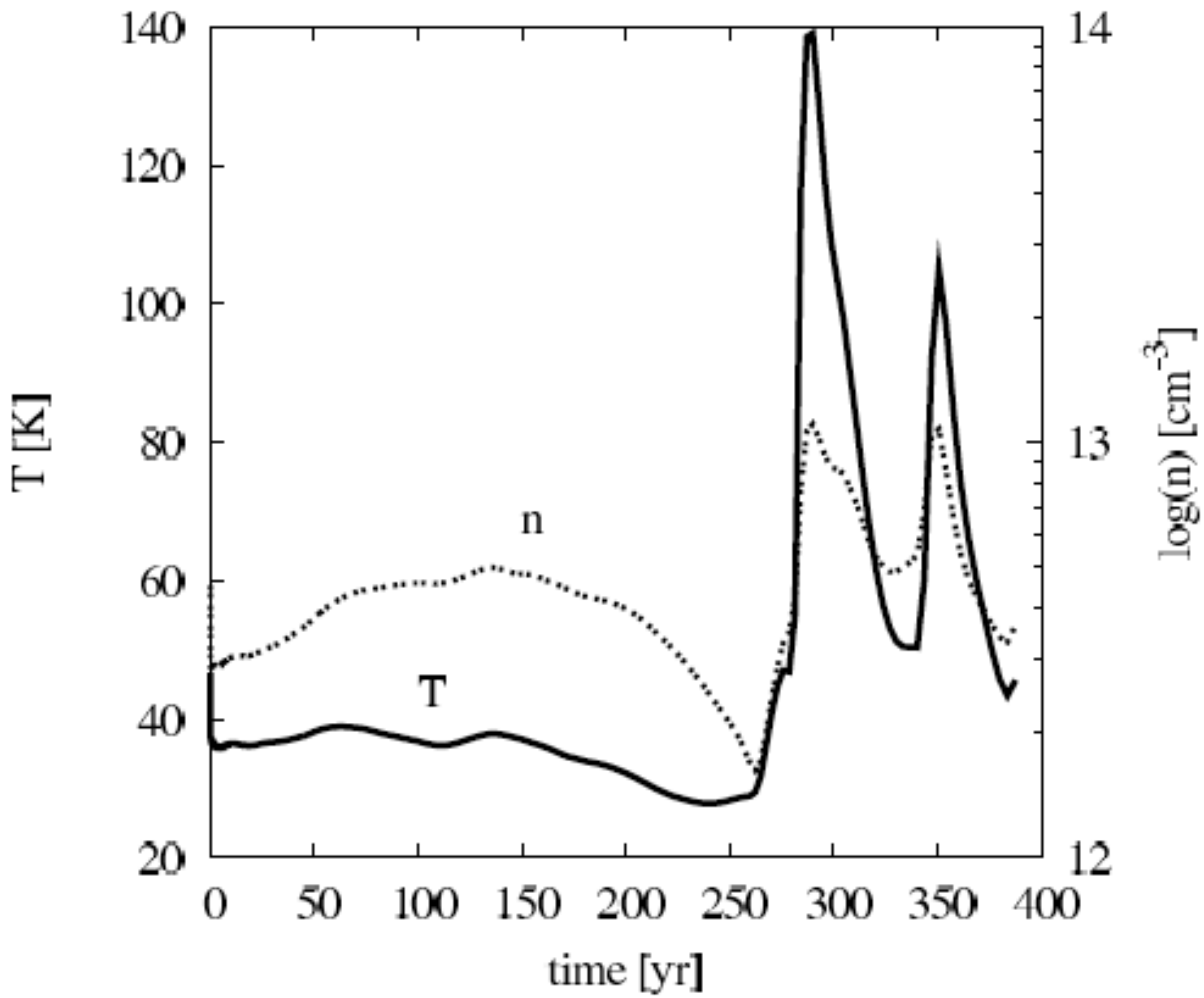
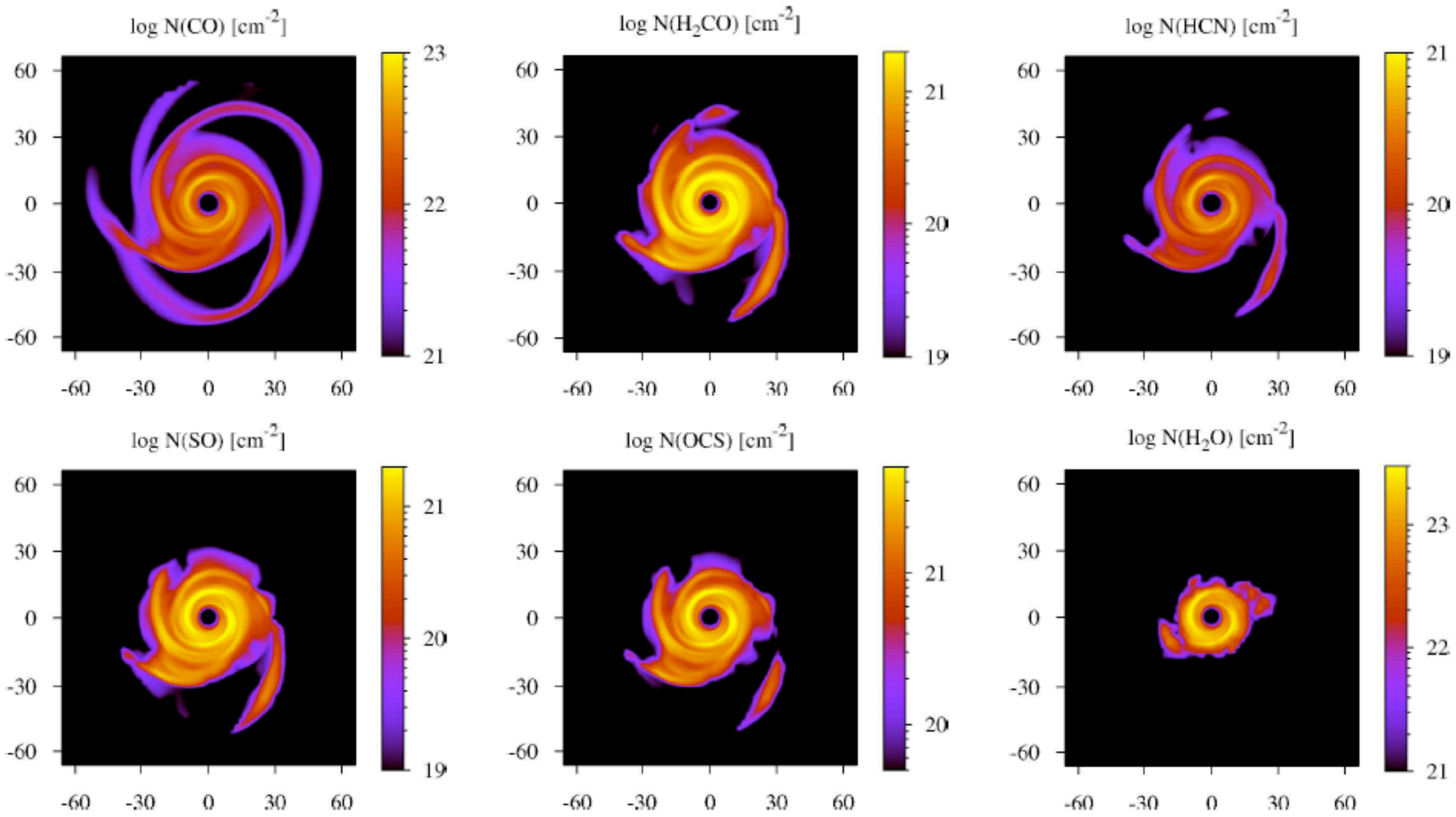
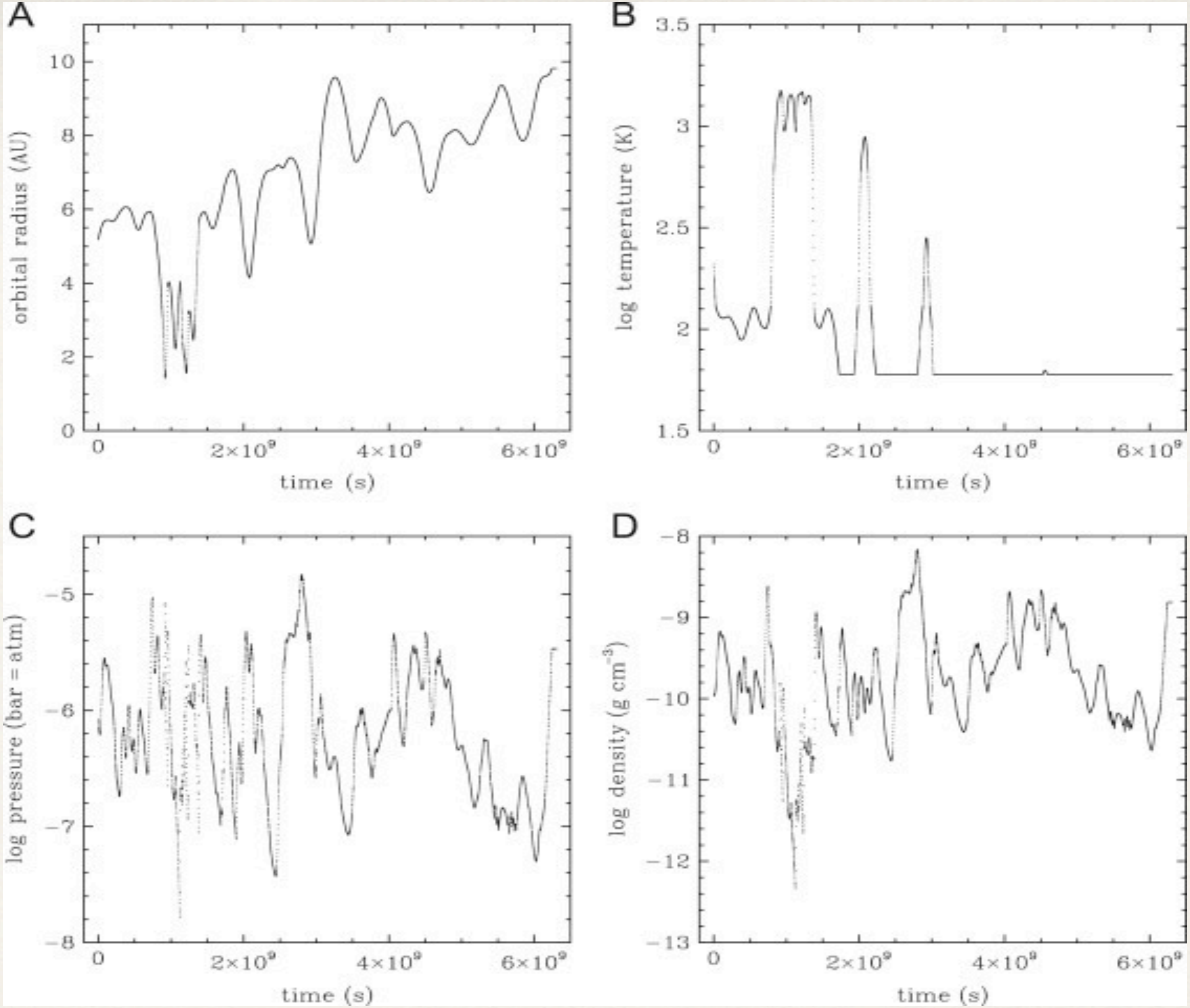


Figure 5. Temperature and number density history of a fluid parcel from the disc. This particular parcel encounters a shock at about 270 years and again at 350 years.

Ilee et al. 2011



Ilee et al. 2011. Chemical models based on simulations.

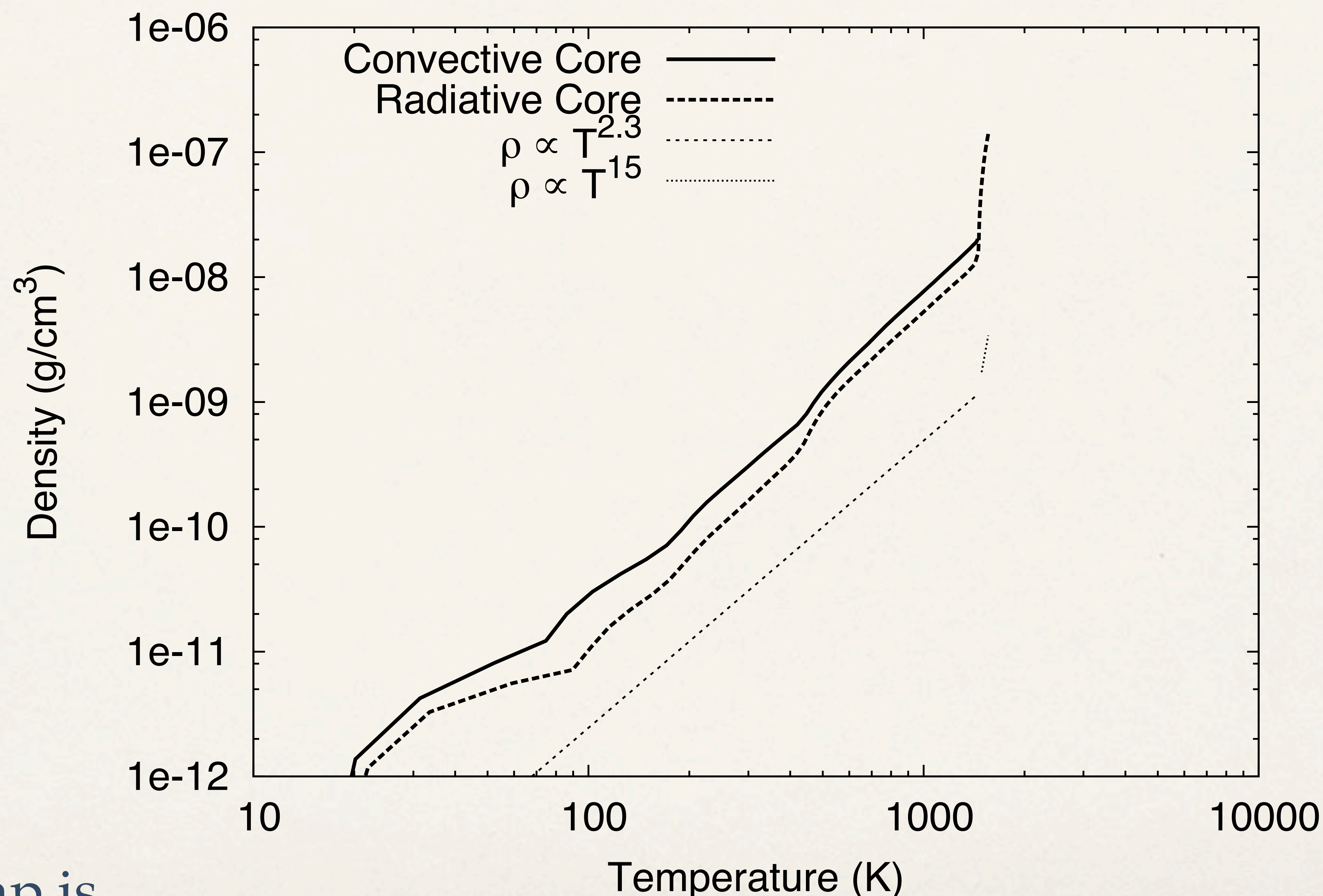


Alan P. Boss , Conel M.O'D. Alexander , Morris Podolak 2012

Consequences of Spiral Shocks

- Spiral shocks repeatedly create changes in environment
- Heating profiles can have rapid rise, followed by protracted cooling, or "rapid" rise and "rapid" cooling
- Many near-sonic heating events (Boley & Durisen 2008; Cossins et al. 2009)
  - Everything is processed to some degree
  - Very strong shocks are rare
  - Spiral pitch angles are ~10° (in WKB $\tan i \sim \beta\, h/r \sim \beta\, c_s/v_\phi$)
- But, spirals are not the only thing that can heat

Why Fragments Matter

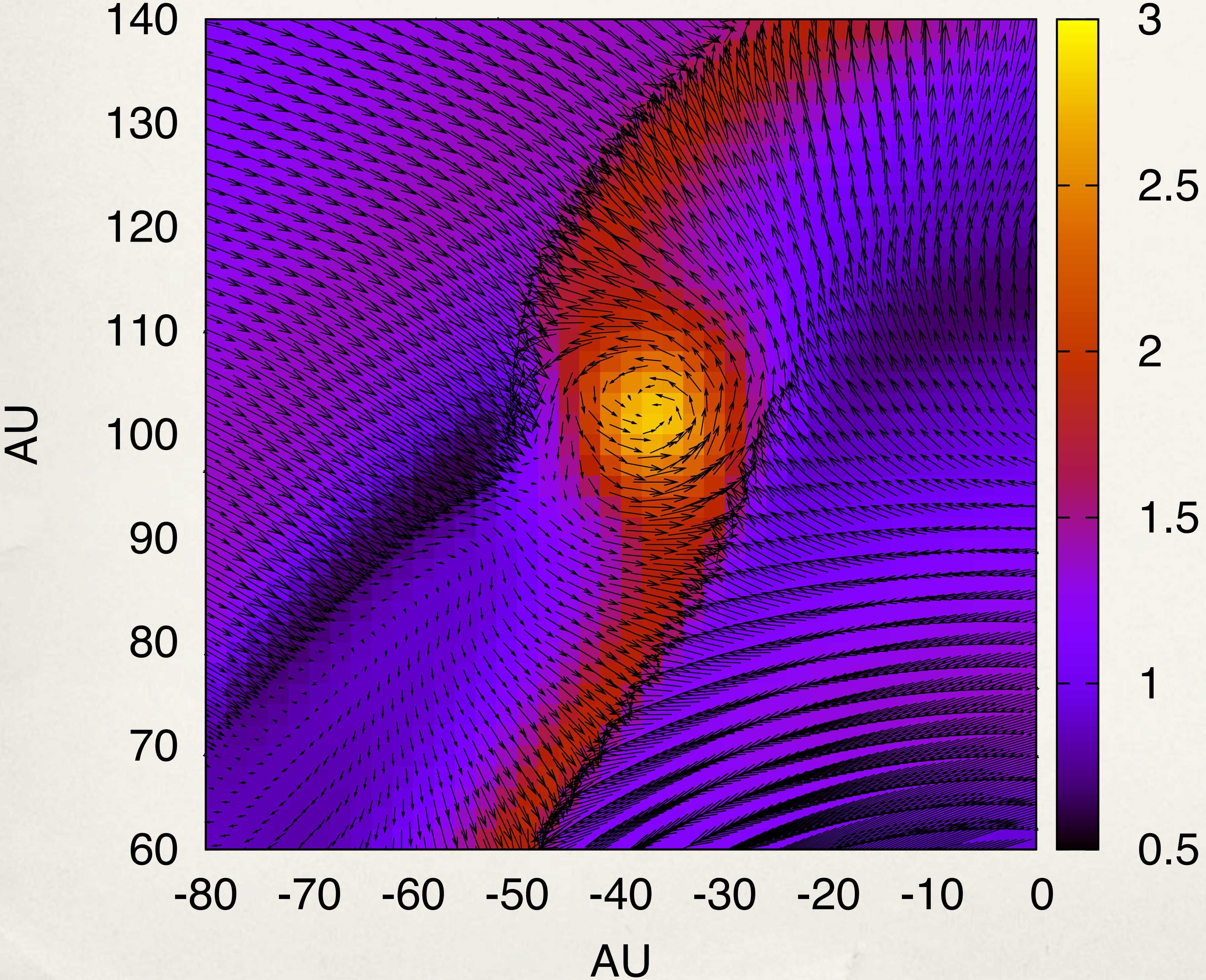


Each clump is
a mini nebula

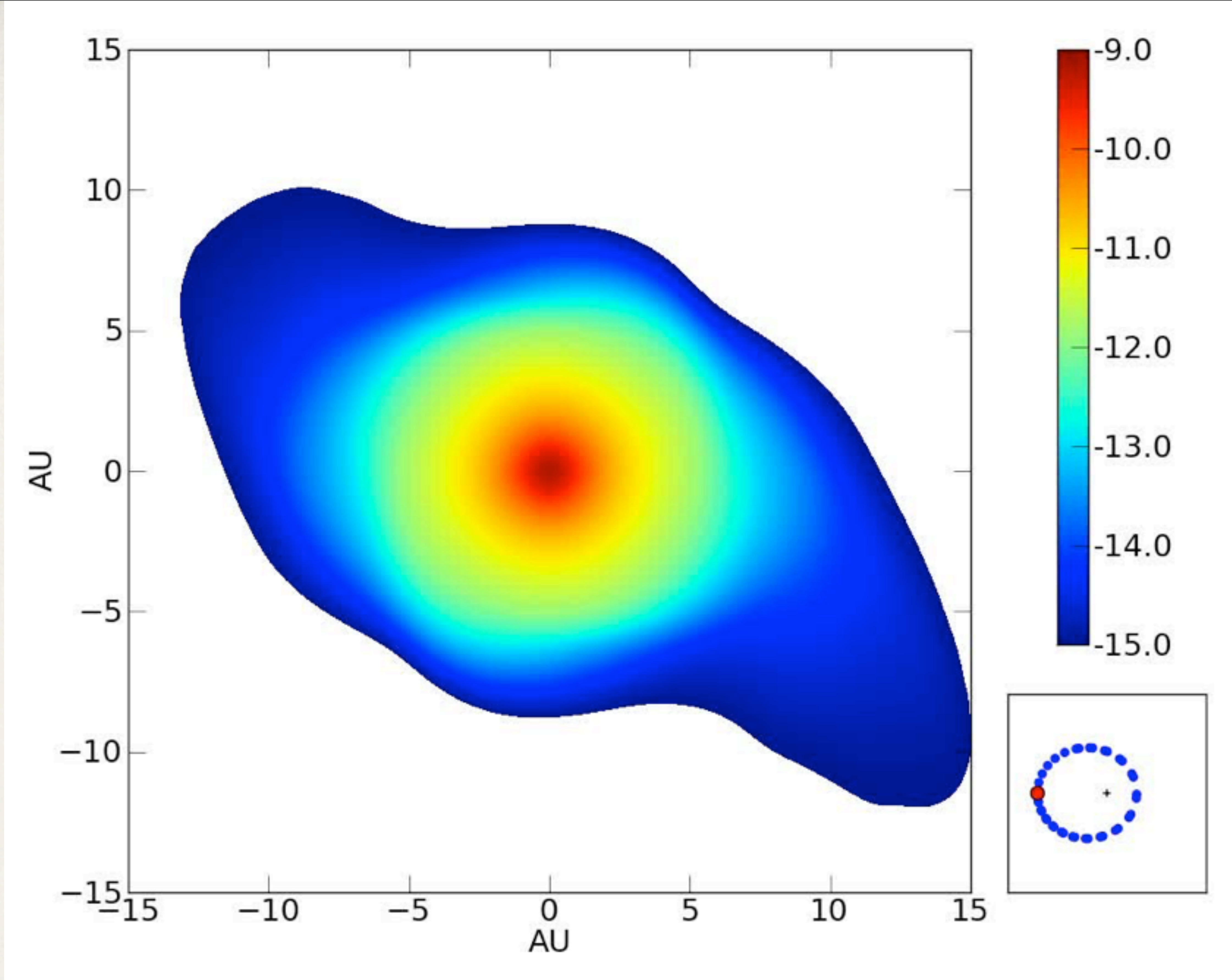
Why Should They Be Destroyed?

- Initial clump size will be multiple AU in size
  - $R_{Hill} = a\ (M_c/(3M_{Star}))^{1/3}$
  - For $q=M_c/M_{Star}=10^{-3}$, $R_{Hill} \sim 0.07a$
  - For $q = 10^{-2}$, $R_{Hill}{\sim}0.15a$
- Eccentric orbits, clump-clump interactions, clump-disk interactions ⇒ clump overflow its Hill sphere

A Clump From A Global Sim



Surface Density
$\log 10(g/cm^2)$



Clumps are fragile. Tides can destroy them with ease.

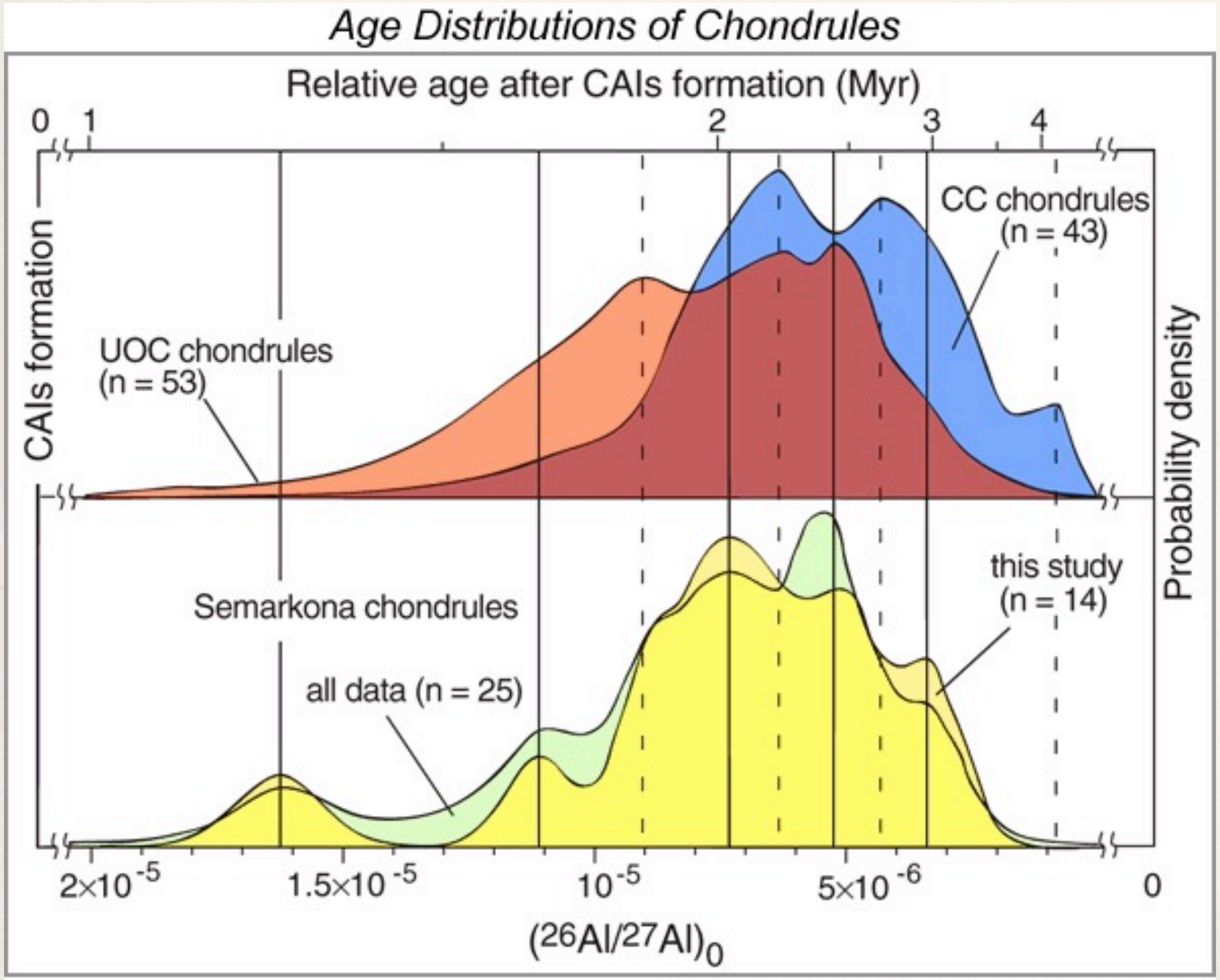
Consequences of Clump Destruction

- Each clump is a mini nebula
- Release processed solids into the nebula
  - Solid and chemical alteration
- Could in principle form cores before destruction
  - Tidal stripping/tidal downsizing (Boley et al. 2010; Nayakshin 2010)

Overall and Future Direction

- Multiple mechanisms for heating the disk during very early times
- Does anything make it through unscathed?
  - Very large radii?
- Significant work to be done before the regime of CAI formation is modeled
  - We have only scratched the surface, and the studies are largely insufficient
- Other ideas?
  - Processing by the protostar itself? (e.g., Gail et al. 2009)

Food For Thought



(From Villeneuve *et al.*, 2009, *Science*, v. 325, p. 985-988.)

- CAIs 4567 Myr [1]
- Iron meteorite parent body formation for ~1.5 Myr [2]
- Mars half assembled by 1.8 Myr [3]
- Most chondrules are younger than CAIs, iron meteorite parent bodies, and maybe planetoids

[1] Amelin et al. 2002; [2] Schersten et al. 2006; [3] Dauphas & Pourmand 2011