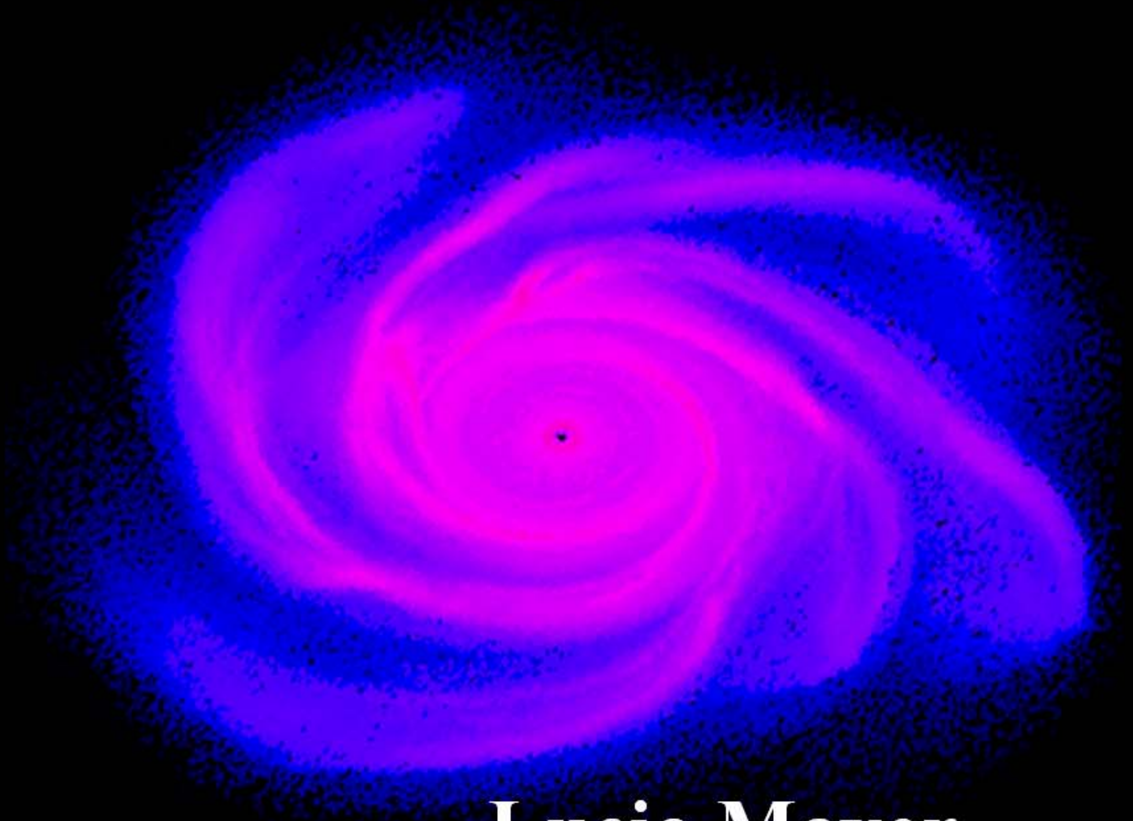
The direct collapse model for giant planet formation



Lucio Mayer

University of Zurich / ETH Zurich

Thomas Quinn (UW), James Wadsley (McMaster)
Tristen Hayfield (Zurich), Aaron Boley (Zurich/Florida)

OUTLINE

- DISK INSTABILITY : OVERVIEW
  - Conditions for disk fragmentation and outcome
  - Numerics
  - Role of thermodynamics: cooling vs. heating

- FRAGMENTATION OF THE OUTER DISK (R > 50 AU)
  - The role of envelope accretion
  - Insights from protostellar collapse; single vs. binary systems

- PROPERTIES AND EVOLUTION OF PROTOPLANETS:
  - The initial mass function, why typical mass close to 1 Mj
  - Angular momentum and internal structural evolution; collapse to planetary density and final mass

- CORE FORMATION AND ENVELOPE ENRICHMENT

Disk instability

Massive (~ 0.1-0.2 Mo) gaseous protoplanetary disk fragments directly into Jupiter-sized gas giants (Kuiper 1951; Cameron 1978. Boss 1997)

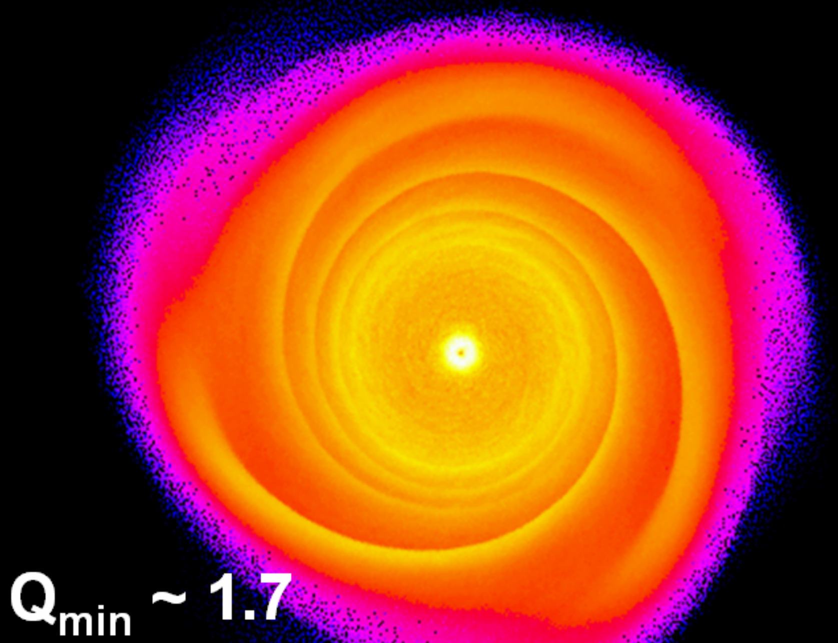
- Criterion for fragmentation *(NON-ACCRETING DISKS)*

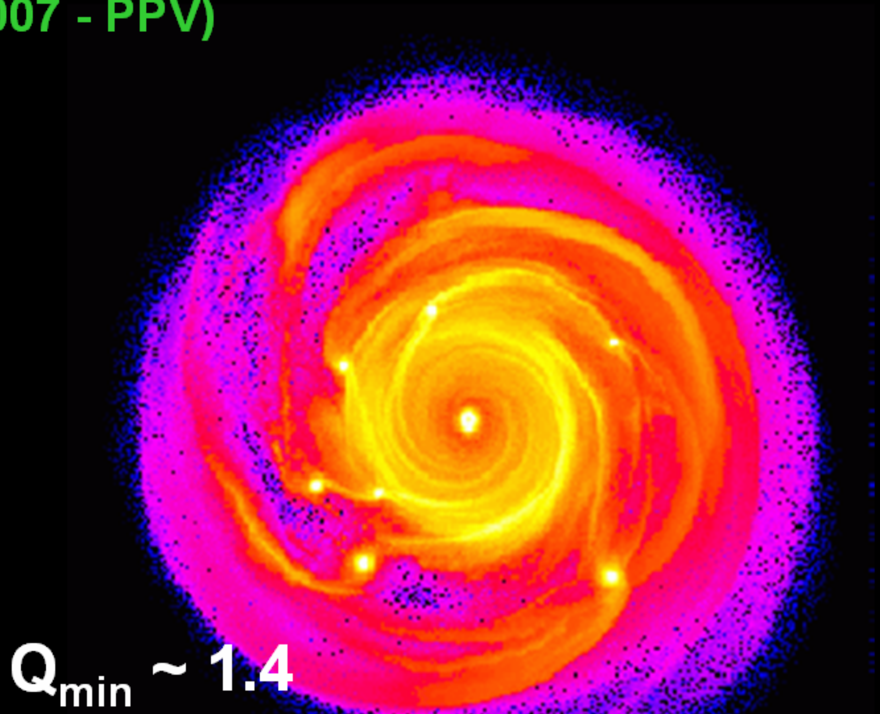
Toomre $Q=v_s\Omega/\pi G\Sigma < 1.5$ somewhere + efficient cooling (tcool <~ torb) (Boss 2001,; Gammie 2001; Mayer et al. 2002,2003, 2004; Rice et al. 2002, 2003; Clarke et al. 2007;Boley et al. 2006; 2007; Boley & Durisen 2008; Durisen et al. 2007 (PPV))

Competition between heating from GIs (self-gravitational energy dissipated in spiral shocks – GIs as effective viscosity see e.g. Lin & Pringle 1987) and radiative cooling.

Q < 1.5 only at R > 5-10 AU for realistic disk temperatures (T ~ 50-100 K)

- If conditions met, fragmentation very fast -- a few disk orbits(~100-1000 years) (Boss 1998; Mayer et al. 2004; Durisen et al. 2007 - PPV)





Disk instability

**Massive (~ 0.1-0.2 Mo) ga ments directly
into Jupiter-sized gas gia oss 1997)**

- **Criterion for fragmentation *(N***

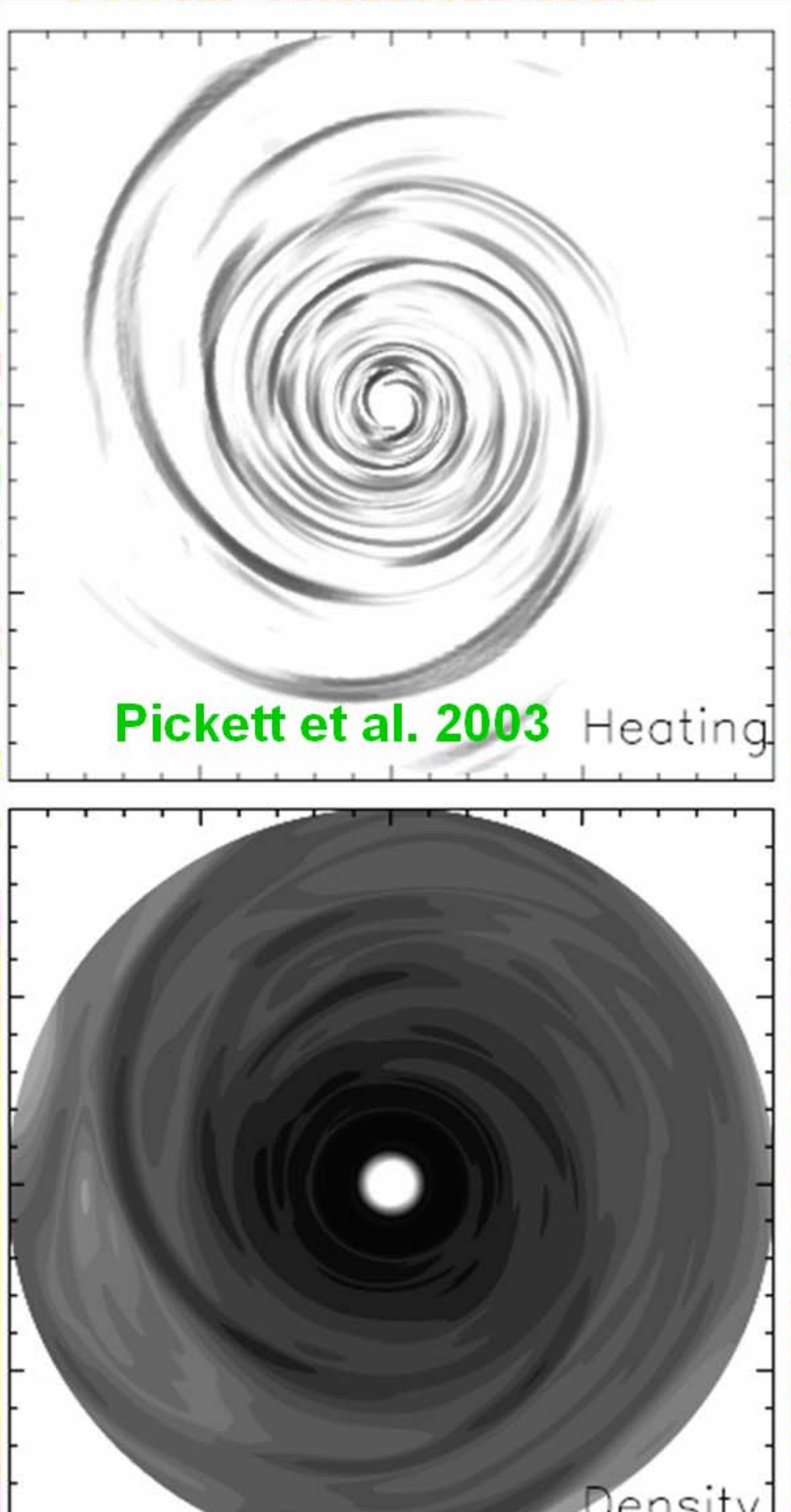
**Toomre $Q=v_s\Omega/\pi G\Sigma < 1.5$ son <~ torb) (Boss 2001,;
Gammie 2001; Mayer et al. 20 3; Clarke et al. 2007;Boley
et al. 2006; 2007; Boley & Du))**

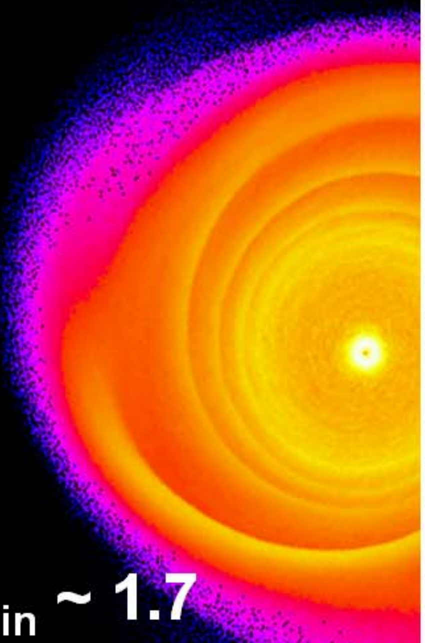
***Competition between heating dissipated in spiral
shocks – GIs as effective vis and radiative cooling.***

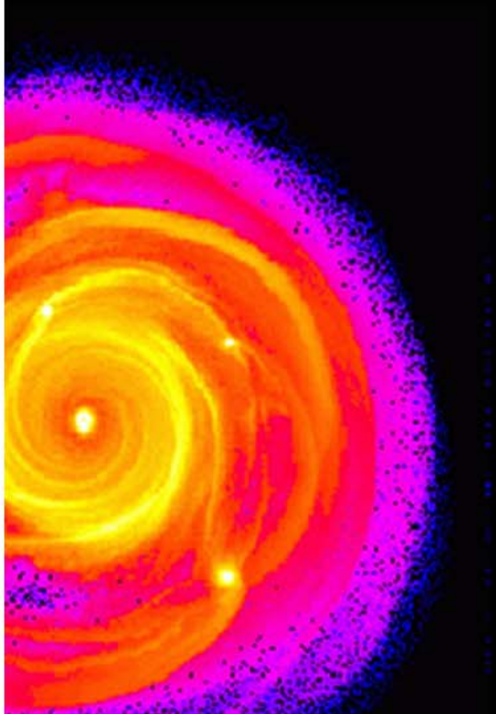
Q < 1.5 only at R > 5-10 AU f 0-100 K)

- **If conditions met, fragmenta 100-1000 years)**

(Boss 1998; Mayer et al. 200


Pickett et al. 2003

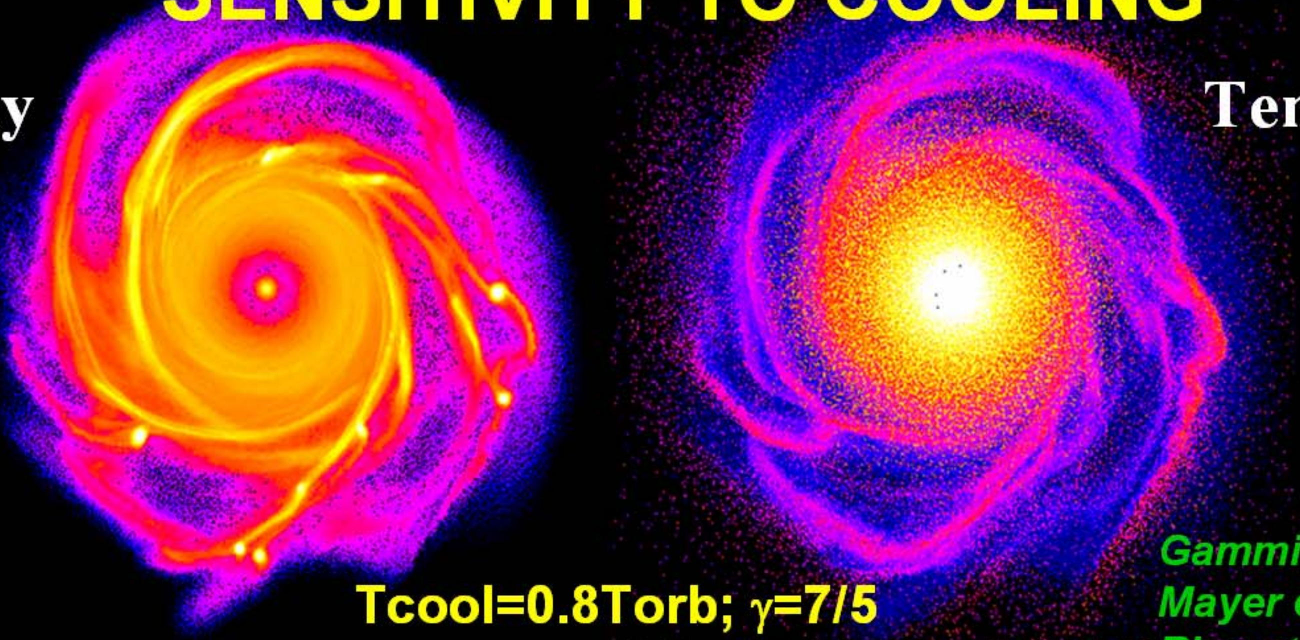




SENSITIVITY TO COOLING

Density

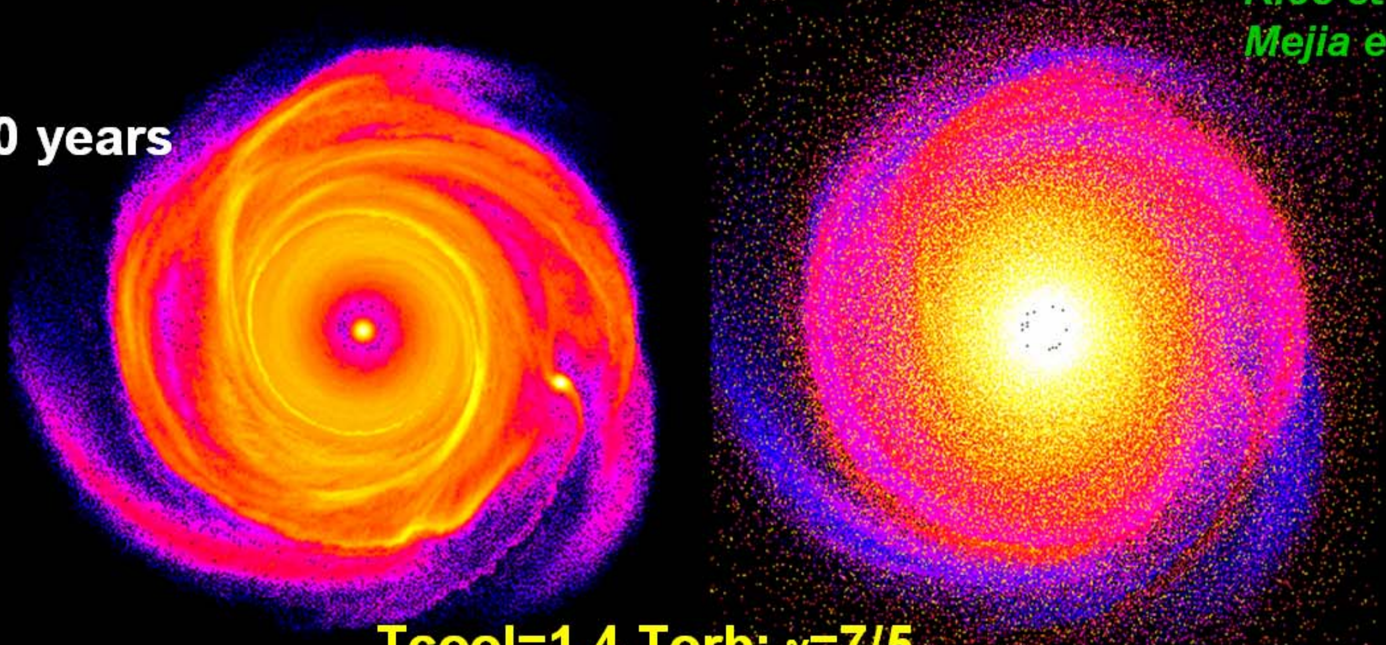
Temperature



Tcool=0.8Torb; $\gamma=7/5$

Gammie 2001;
Mayer et al . (2003, 2005),
Rice et al. (2002, 2003, 2005),
Mejia et al. 2005

T=300 years



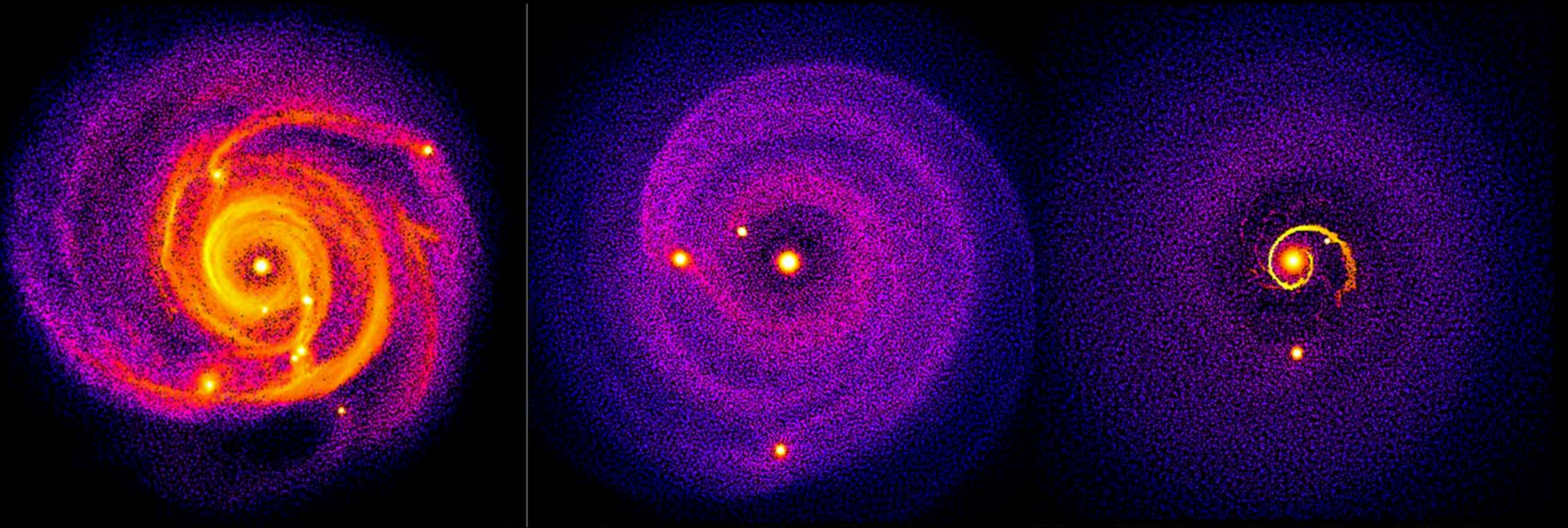
Tcool=1.4 Torb; $\gamma=7/5$

Snapshots of sims with different Tcool, all after ~ 10 Torb at (10 AU) ~ 300 years

High resolution SPH simulations showed clumps not transient structures → Gravitationally bound + tidally stable

Mayer et al. 2002; 2004; Durisen et al. 2007

Simulations shown: locally isothermal EOS, then switches to adiabatic EOS when clumps become optically thick



T = 320 yr

T = 1900 yr (~ 70 orbital times at 10 AU)

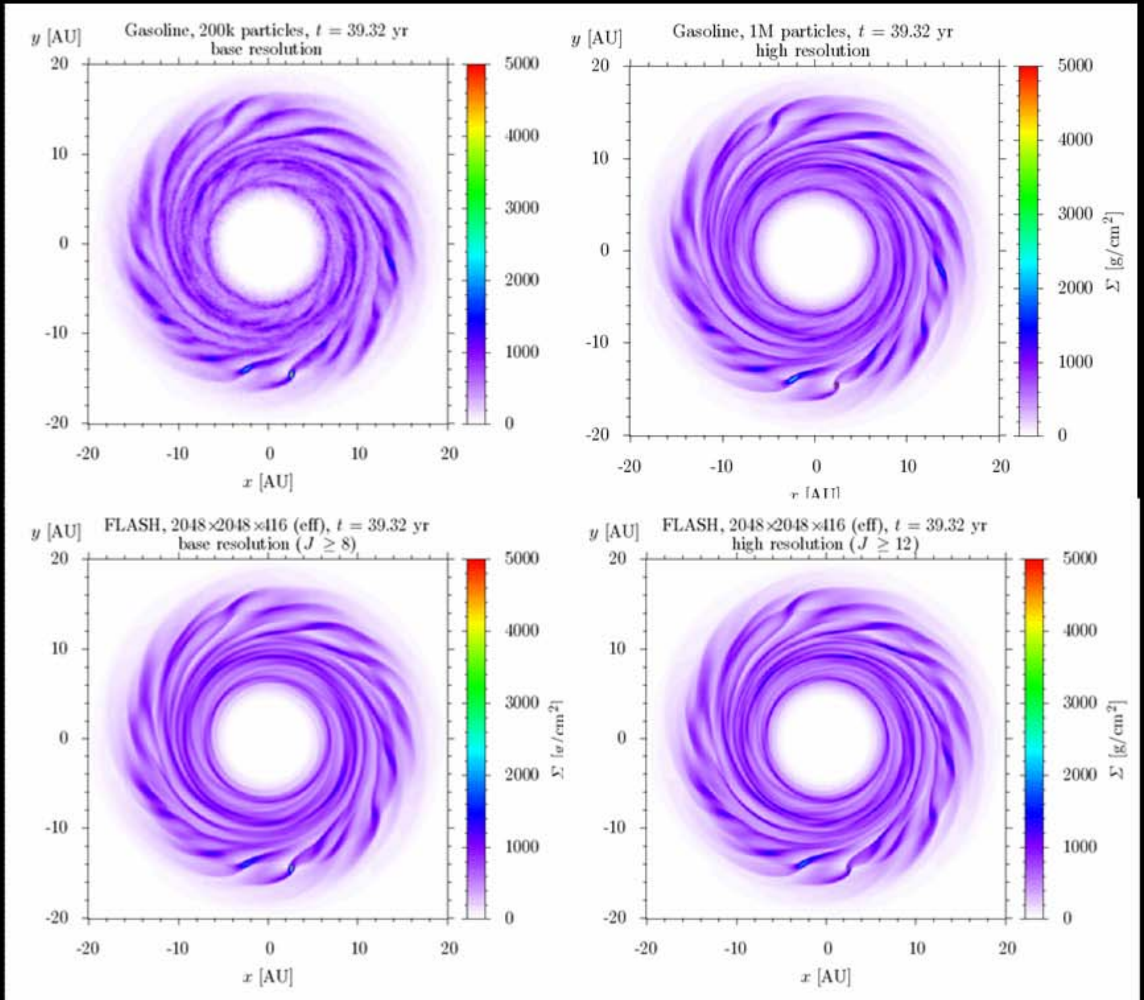
T = 4000 yr (~ 150 orbital times at 10 AU)

-- Merging drastically reduces the number of clumps. Only a few remain after > 1000 yr, with masses $1\ M_j < 7\ M_j$ (but mass > 10 Mj if EOS remains isothermal – see Mayer et al. 2004).

-- Orbits are eccentric (e ~ 0.1-0.3) (Durisen et al. 2007)

Numerical digression

(1) Nelson (2006); > 6 SPH smoothing volumes or > 8 cells per Toomre mass to resolve fragmentation correctly (insuff. resolution can produce artificial fragmentation)
(2) For fast-cooling disks fragmentation into gravitationally bound clumps well established result confirmed by different numerical techniques (Durisen et al. 2007; Mayer & Gawryszczak 2008; Gawryszcak et al. 2010)
(3) For each numerical technique fragmentation more robust with increasing resolution (clumps denser and more gravitationally bound)



RADIATIVE TRANSFER SIMULATIONS:

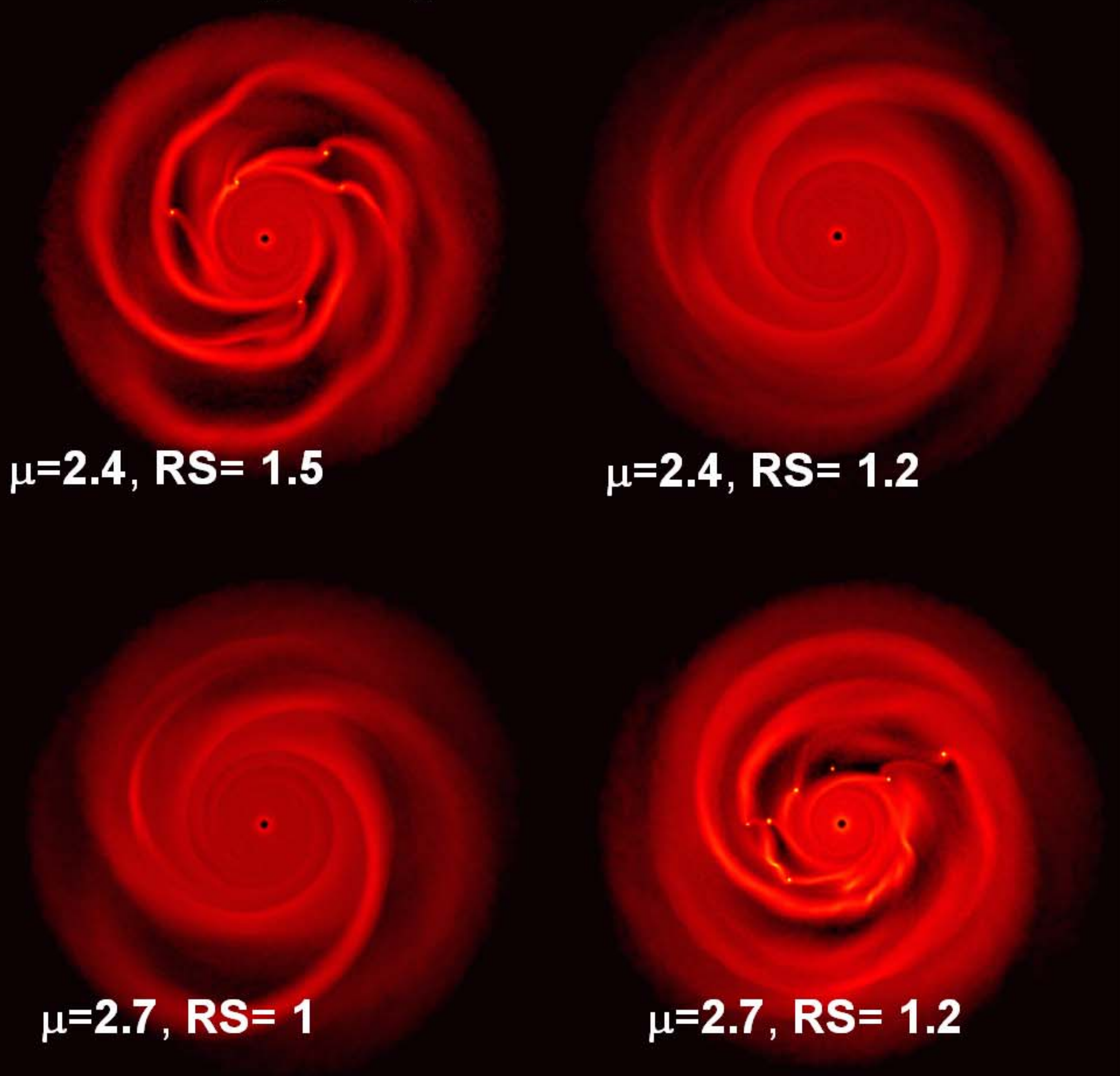
Fragmentation of inner disk (R ~5-30 AU) (Mayer et al. 2007)

M > 0.15 Mo for fragmentation
Cooling time = *photon diffusion time from midplane* (*τ >>1*) *to surface* + *surface cooling* > 10 orbital times for standard opacity (D'Alessio et al. 2001)
Subsonic convective-like motions can shorten cooling to Tcool ~1-3 Torb in some models (Mayer et all. 2007) or in most (Boss 2002;2003;2007;2009).

Fragmentation sensitive to

- mean molecular weight and adiabatic index $\gamma \rightarrow$ affect PdV heating (also Rice & Lodato 2005)
- efficiency of radiative cooling at optically thin boundary (need t_{cool} within $1\text{-}2t_{orb}$)

RS=emitting area/geometric surface area



μ=2.4, RS= 1.5

μ=2.4, RS= 1.2

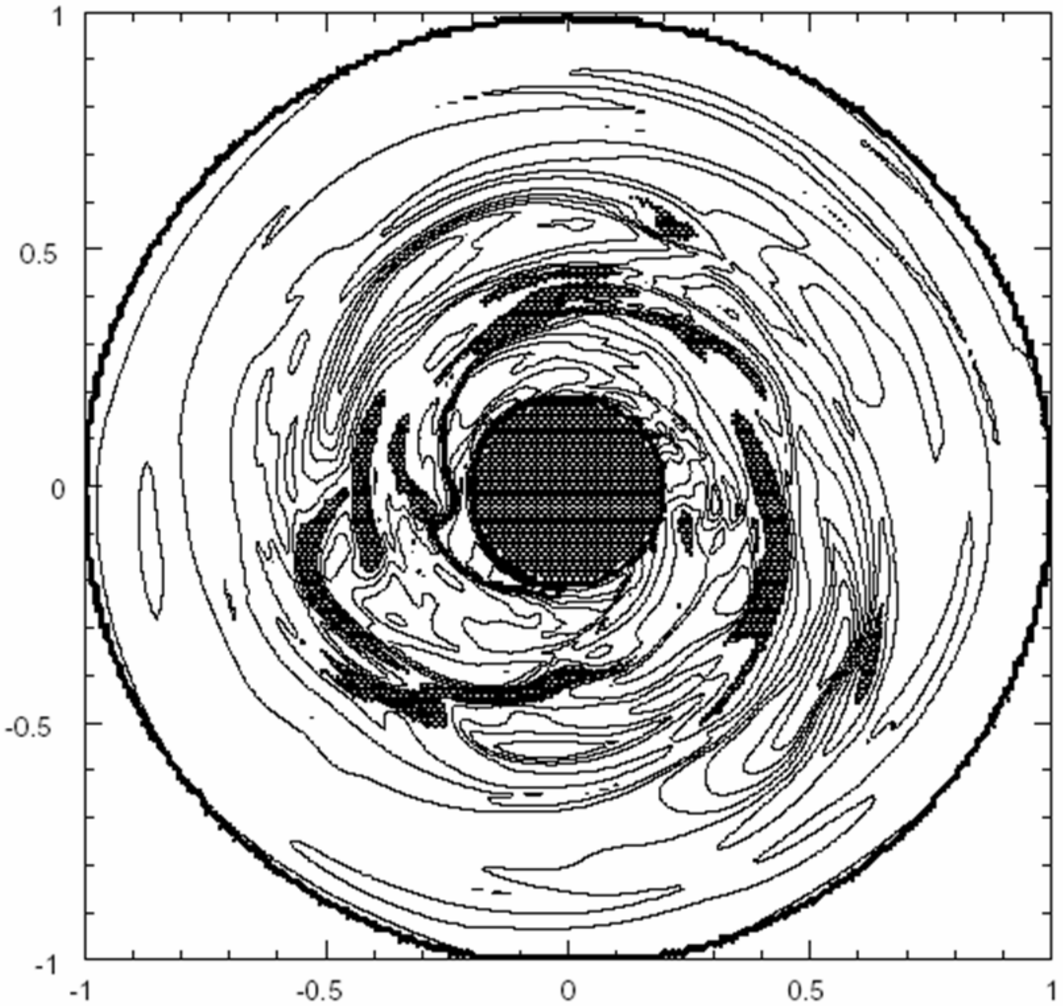
μ=2.7, RS= 1

μ=2.7, RS= 1.2

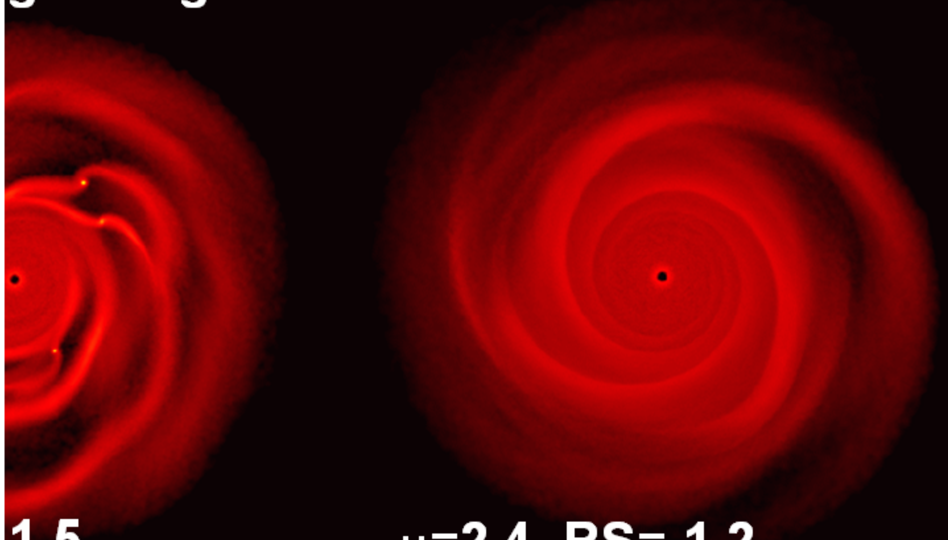
SIMULATIONS:

~5-30 AU) (Mayer et al. 2007)

g area/geometric surface area

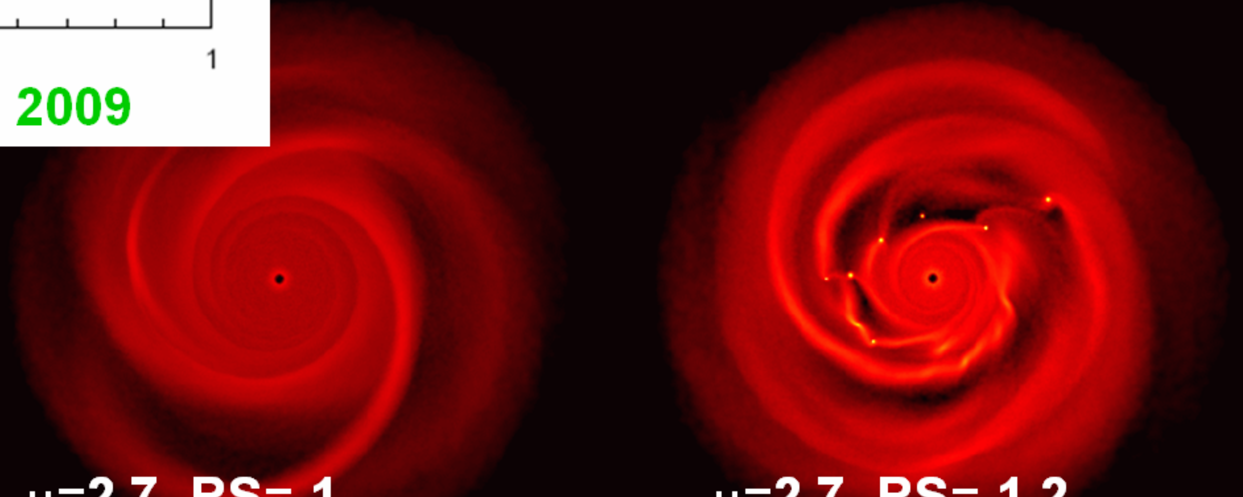


Boss 2009



1.5

μ=2.4, RS= 1.2



μ=2.7, RS= 1

μ=2.7, RS= 1.2

- mean molecular weight and adiabatic index γ → affect PdV heating (also Rice & Lodato 2005)

- efficiency of radiative cooling at optically thin boundary (need t_{cool} within $1\text{-}2t_{orb}$)

Effect of varying molecular weight

(Mayer et al. 2007)

Mean molecular weight higher than solar favors fragmentation because it lowers compressional heating rate in spiral arms

($PdV = \rho k_b T/\mu\, dV$)

How can one get changes of μ in spiral arms?

Example: **ice grains (~30 % of dust grains) vaporized in spiral shocks because T > 200 K ---> $\mu \sim 2.5$ instead of 2.38 for H_20 returned to gas phase for solar met. gas + dust/gas ratio pumped up by a factor of 10 in spiral arms (Haghighipour & Boss 2003, Rice et al. 2005, 2006; Mejia, Quinn & Mayer 2006)**

Effect of varying molecular weight

(Mayer et al. 2007)

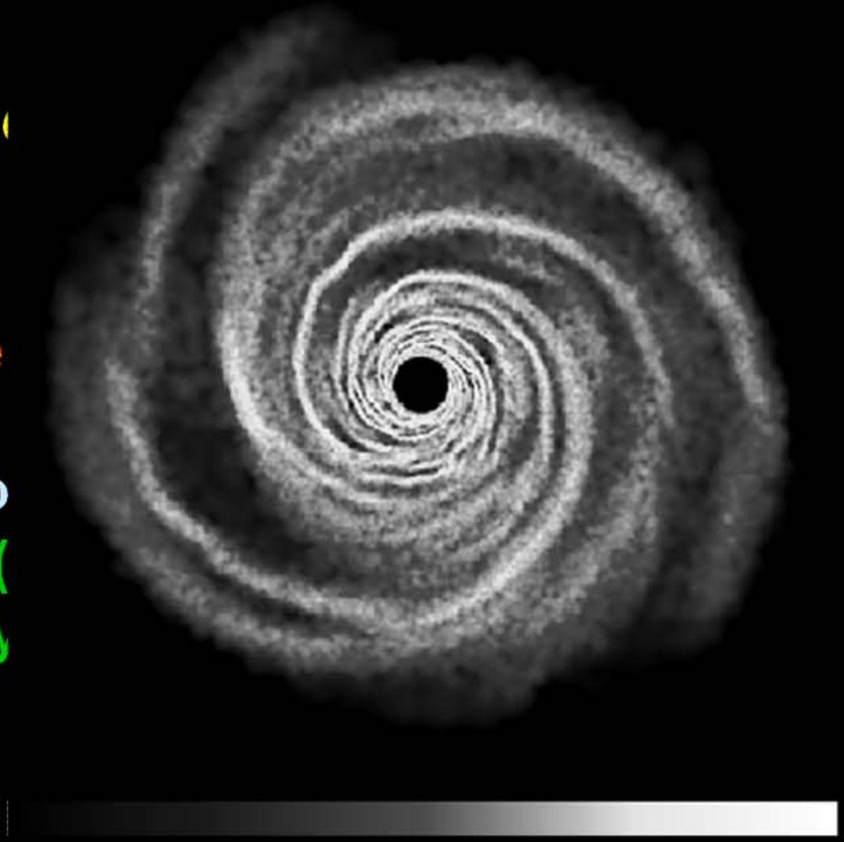
Mean molecular weight higher than solar favors fragmentation because it lowers compressional heating rate in spiral arms

$(PdV = \rho k_b T/\mu\, dV)$

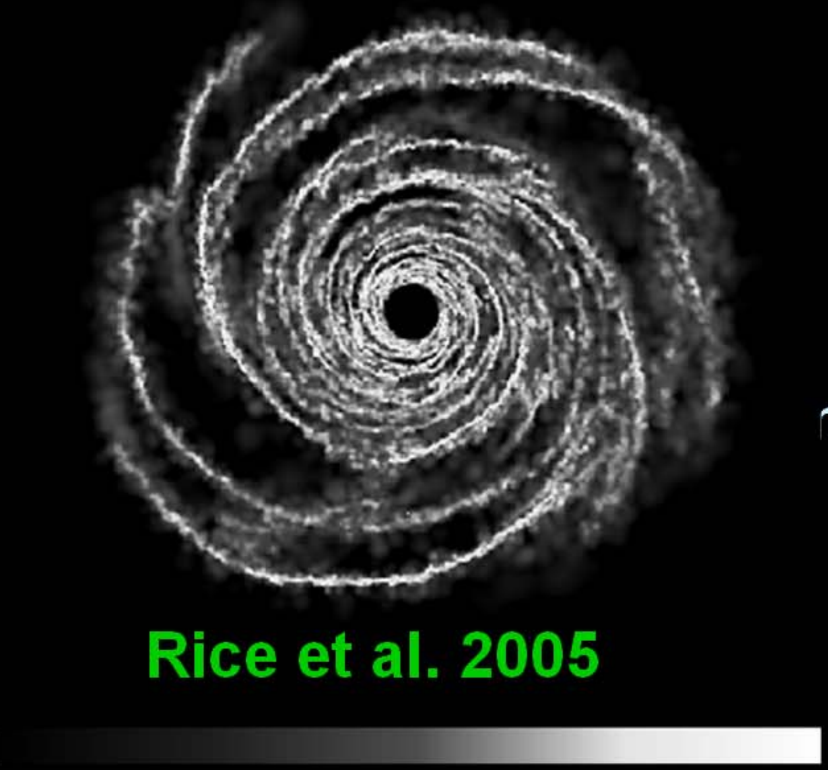
How can on

Example: **ice**
because T >
phase for so
spiral arms (
Quinn & May

n



50 cm particles



Rice et al. 2005

Effect of varying molecular weight

(Mayer et al. 2007)

Mean molecular weight higher than solar favors fragmentation because it lowers compressional heating rate in spiral arms

($PdV = \rho k_b T/\mu\, dV$)

How can one get changes of μ in spiral arms?

Example: **ice grains (~30 % of dust grains) vaporized in spiral shocks because T > 200 K ---> $\mu \sim 2.5$ instead of 2.38 for H_20 returned to gas phase for solar met. gas + dust/gas ratio pumped up by a factor of 10 in spiral arms (Haghighipour & Boss 2003, Rice et al. 2005, 2006; Mejia, Quinn & Mayer 2006)**

If gas 3 times solar (assuming metallicity ~ dust content) same mechanism gives $\mu \sim 2.85$ in spiral arms

---→higher metallicity might favour giant planet formation by GI via molecular weight effect

Boley et al. (2006) and Boley & Durisen 2008: no convective motions and

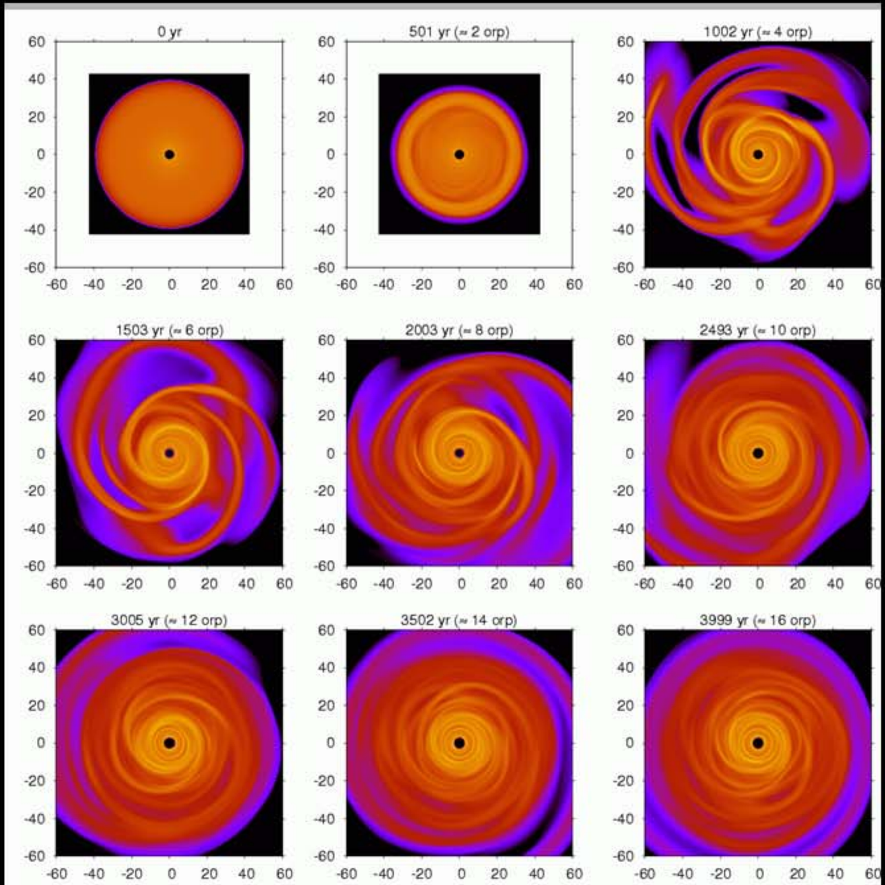
no fragmentation in general ***Note however disk models lighter and more extended than***

in Mayer et al. 2007 → similar Q but surface density at Q_{min} lower by factor ~ 3

Fragmentation in extreme cases with sudden large opacity drops *(dust settling?)*

Cossins et al. (2009) also show fragmentation more likely if cooling rate

has sudden dips, e.g. near opacity gap (see also Johnson & Gammie 2003)



From Boley et al. 2007

Boley et al. (2006) and **Boley & Durisen 2008**: no convective motions and

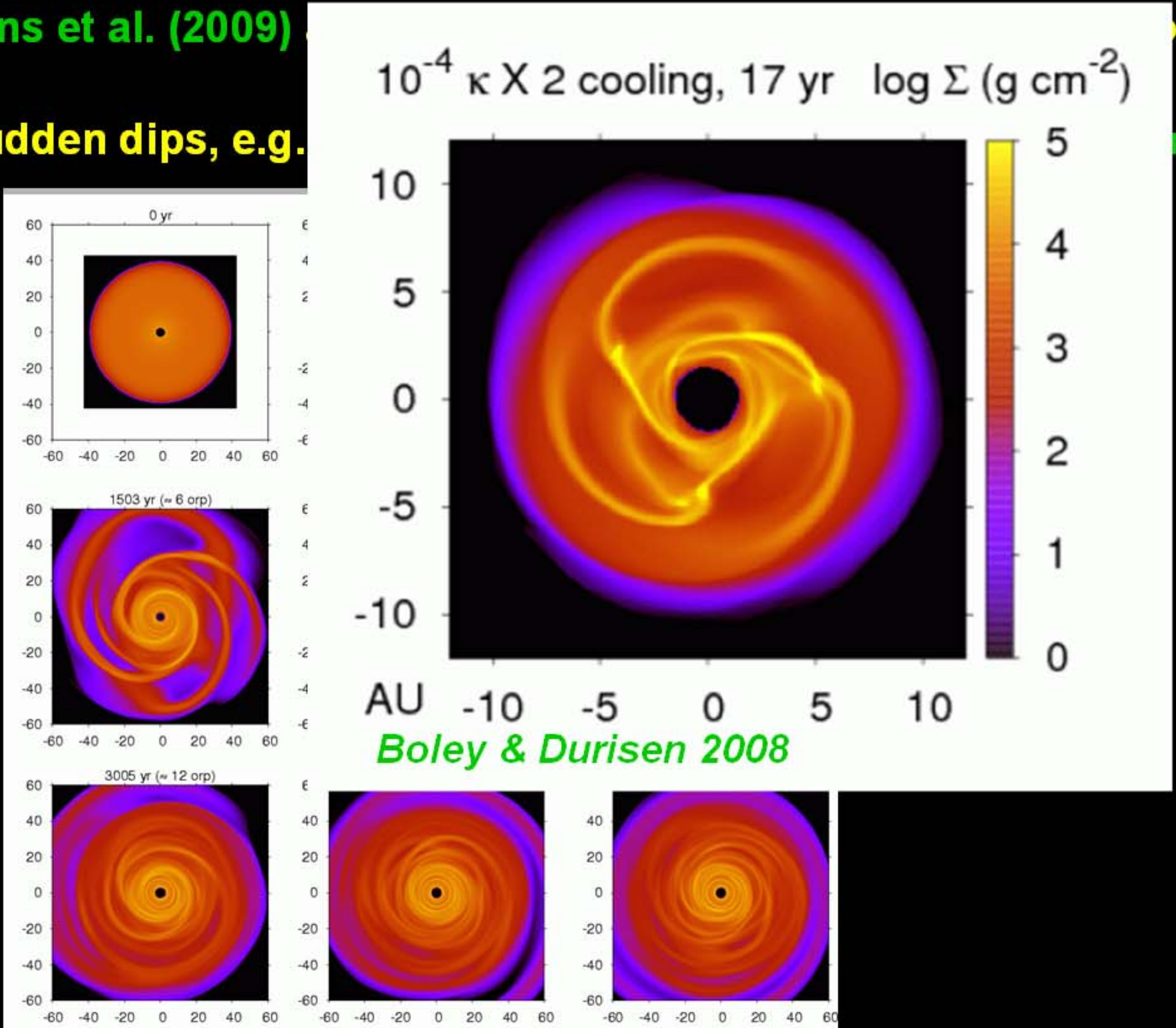
no fragmentation in general *Note however disk models lighter and more extended than in* ***Mayer et al. 2007*** → *similar Q but surface density at Q_{min} lower by factor ~ 3*

Fragmentation in extreme cases with sudden large opacity drops *(dust settling?)*

Cossins et al. (2009) ling rate

has sudden dips, e.g. mie 2003)

From Boley et al. 2007



Boley & Durisen 2008

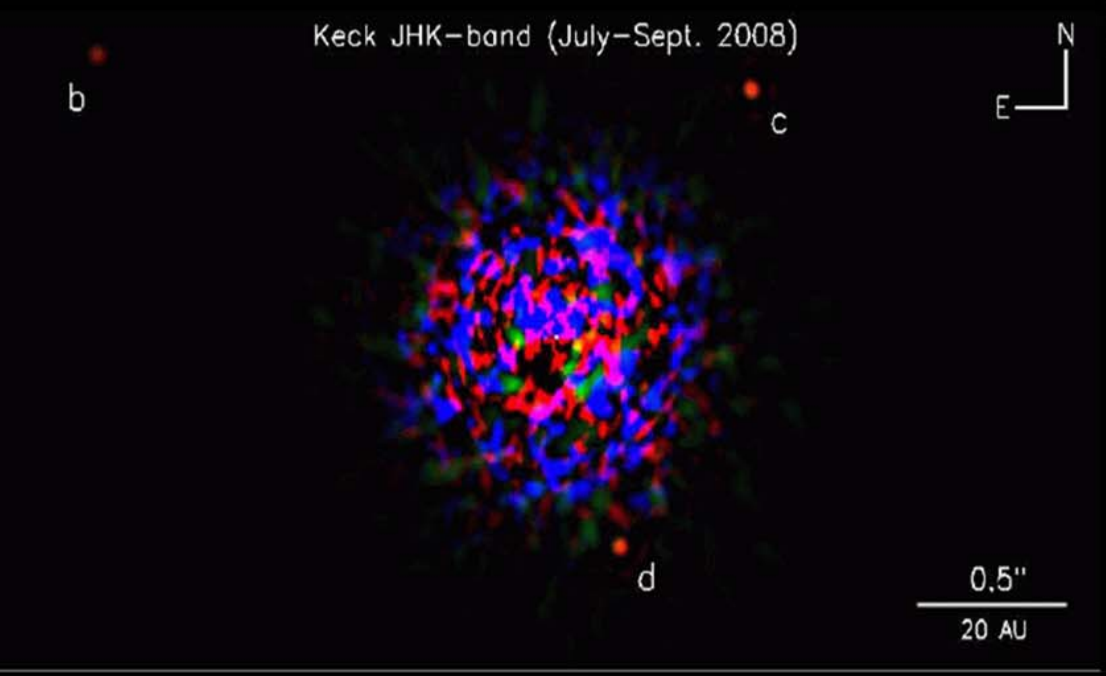
Disk fragmentation at large radii (r > 50 AU)

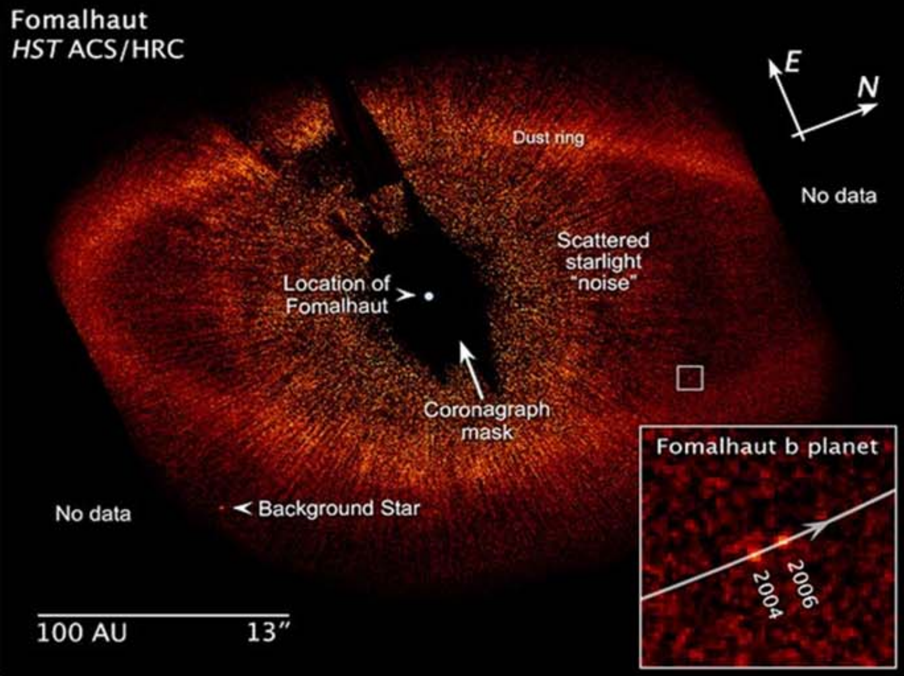
(Stamatellos et al. 2009; Boley 2009; Boley et al. 2010; Vorobyov & Basu 2010)

Large radiative losses easier to achieve – both surface AND midplane optically thin, $\tau < 1$ hence Tcool < Torb -→ *necessary condition for fragmentation satisfied, no need for non-radiative mechanism for vertical energy transport*

(see also Rafikov 2007; Clarke et al. 2007 for analytics)

Disk fragmentation at large radii (r > 50 AU)



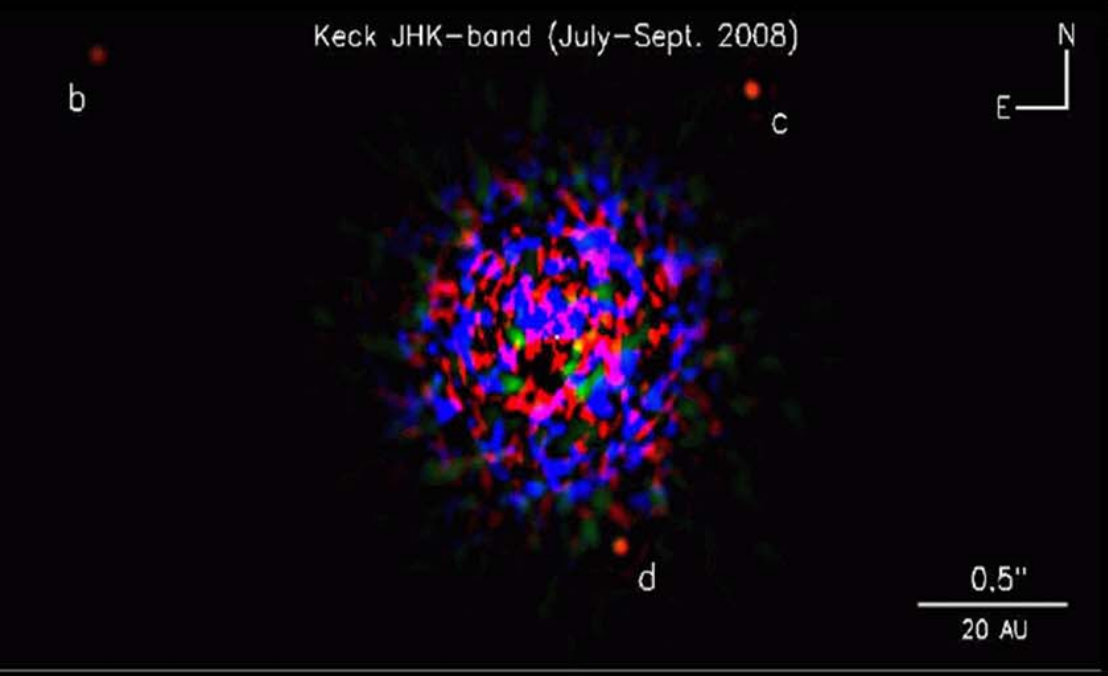


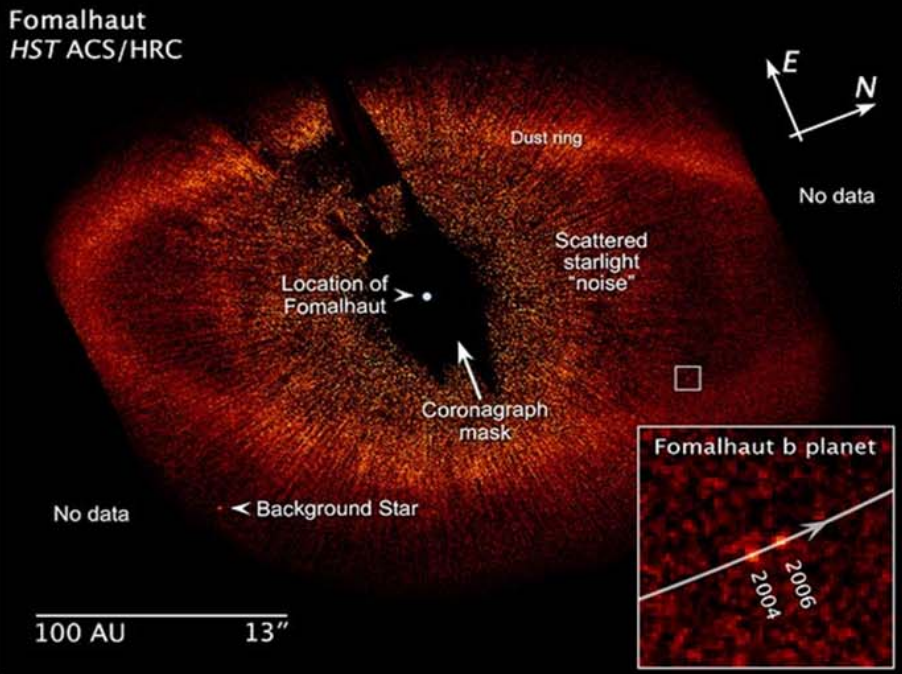
ation

Highly relevant to planets discovered in imaging surveys

(Kalas et al. 2008; Lefreniere et al. 2009; Marois et al. 2008; Dodson-Robinson et al. 2009)

Disk fragmentation at large radii (r > 50 AU)





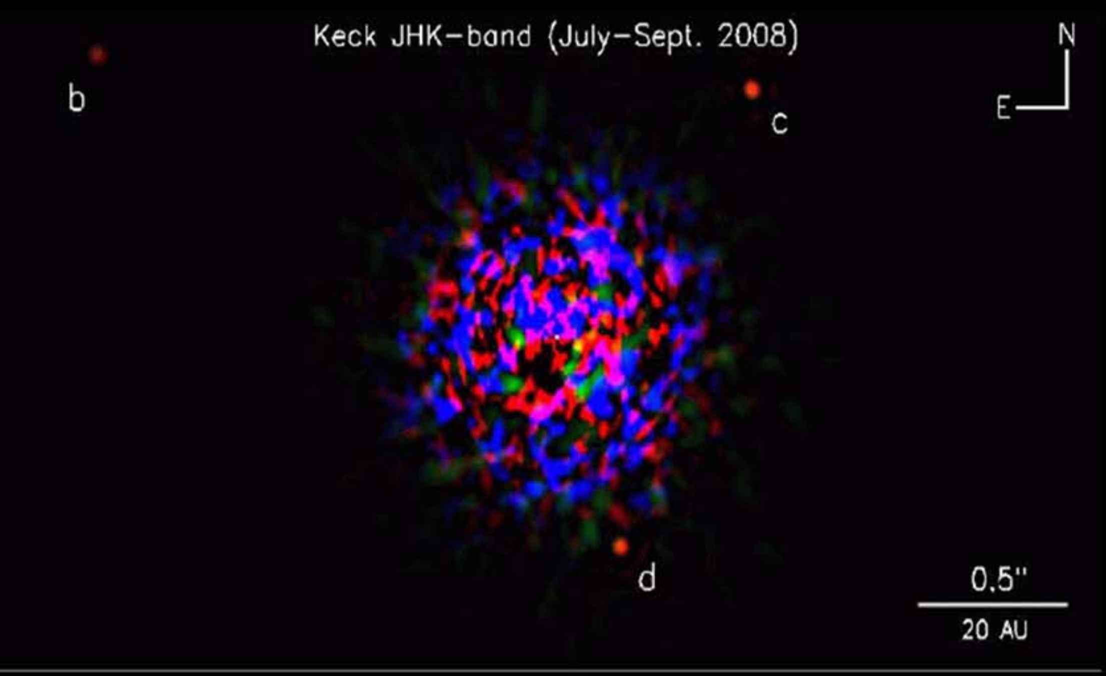
ation

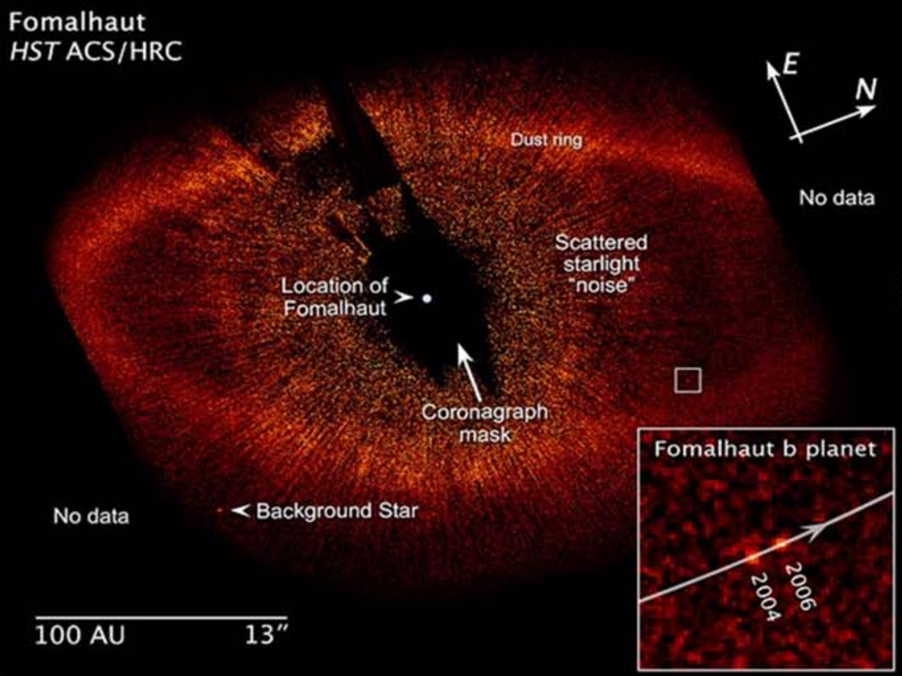
Highly relevant to planets discovered in imaging surveys

(Kalas et al. 2008; Lefreniere et al. 2009; Marois et al. 2008; Dodson-Robinson et al. 2009)

BUT: outer disk lighter, harder to maintain Q low enough (< 1.4)

Disk fragmentation at large radii (r > 50 AU)





ation

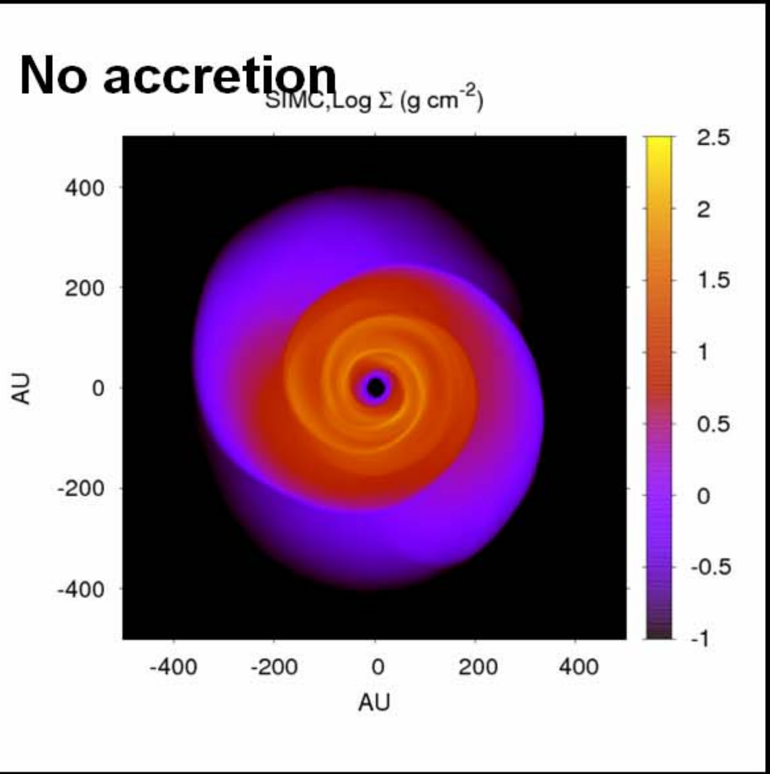
Highly relevant to planets discovered in imaging surveys

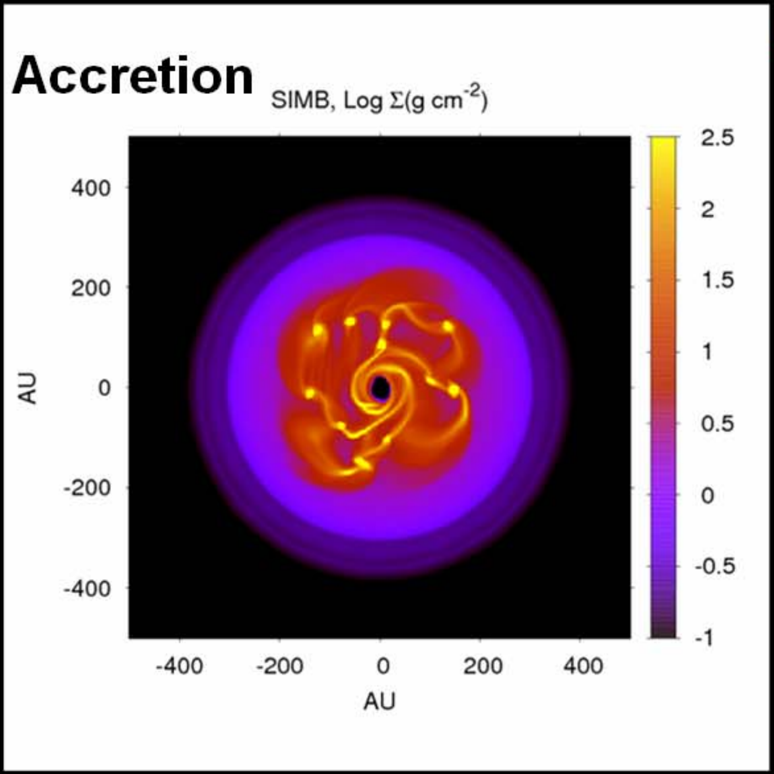
(Kalas et al. 2008; Lefreniere et al. 2009; Marois et al. 2008; Dodson-Robinson et al. 2009)

BUT: outer disk lighter, harder to maintain Q low enough (< 1.4)

At large R (R > 50 AU) low surface density along inward mass transport by spiral waves tends to raise Q above stability threshold at large radii (Boss 2006).

EFFECT OF ENVELOPE ACCRETION





Boley 2009

Envelope Accretion at

~ 5 x 10^{-5} - 10^{-4} Mo/yr

for T_{env} ~ 50 K

Mdisk = 0.15-0.3 Mo

Mstar = 0.3 - 1 Mo

High envelope accretion can drive jumps in surface density that are not readily redistributed by GI torques (Rafikov 2009 - has to be > 10^{-5} Mo/yr)

$$\frac{d\ln Q}{dt} = \frac{1}{2}\frac{d\ln c_s^2}{dt} + \frac{d\ln \kappa}{dt} - \frac{d\ln \Sigma}{dt}.$$

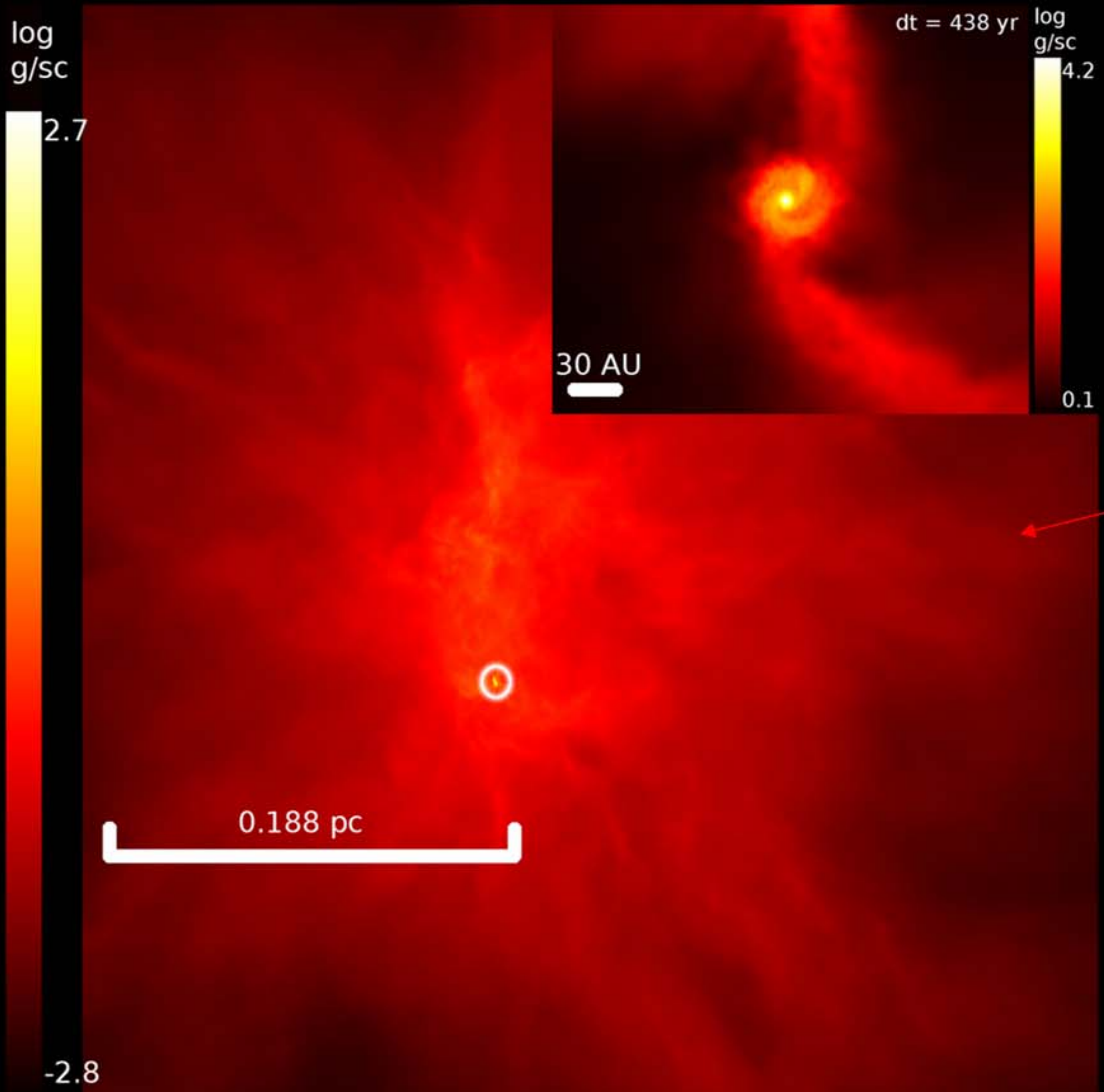
Set by cooling time

Set by ratio between envelope accretion rate $\dot{M}_e \sim c_s^3/G$ *and mass transport rate through disk by GIs* $\dot{M}_c \approx 3\alpha_c c_s^3/(GQ$

For α_{max} ~ 0.06, Q ~ 1 (Lodato & Rice 2005) envelope accretion dominates!

Protostellar collapse simulations: accreting disks

– high envelope accretion rates in Class 0 to Class 1 phase, ~ 10^4-10^5 years after molecular cloud collapse (e.g Yorke & Bodenheimer 1999; Vorobyov & Basu 2007;2008; Vorobyov 2009) i.e. before T Tauri phase (disk properties poorly known in embedded phase - ALMA, JWST will shed light)



From turbulent cloud collapse to disk formation (~ 10^5 years) max. resolution ~ 0.5 AU (in 0.2 pc box)

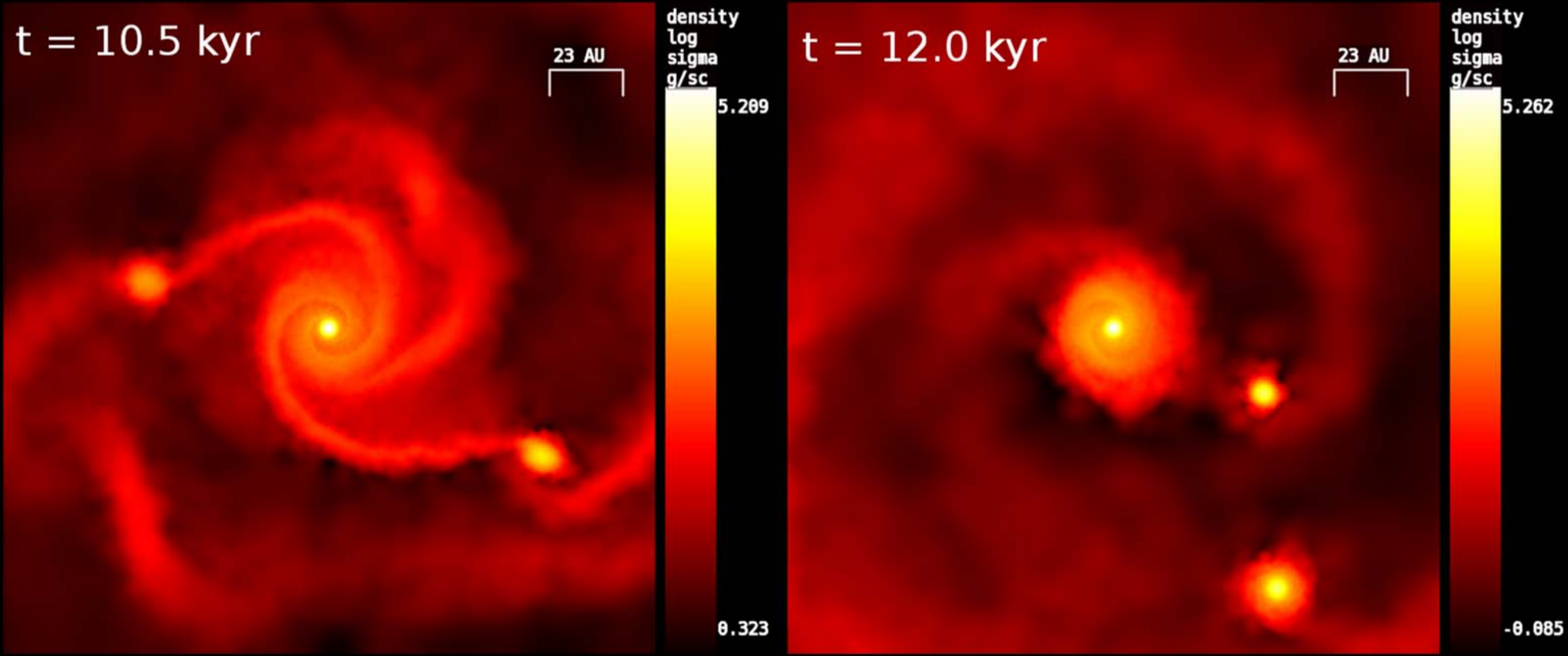
Disk evolution followed for ~ 10^4 yr

Hayfield, Mayer et al. 2010

Fragmentation at large radii (~ 60-70 AU)

Gas is evolved with adiabatic EOS (so $t_{cool} >> T_{orb}$) and yet it fragments because of mass loading (envelope accretion rate ~ 5×10^{-4} Mo/yr, similar to peak accretion rate assumed in Boley 2009)

Initial clump masses 5.5 Mj and 7.4 Mj

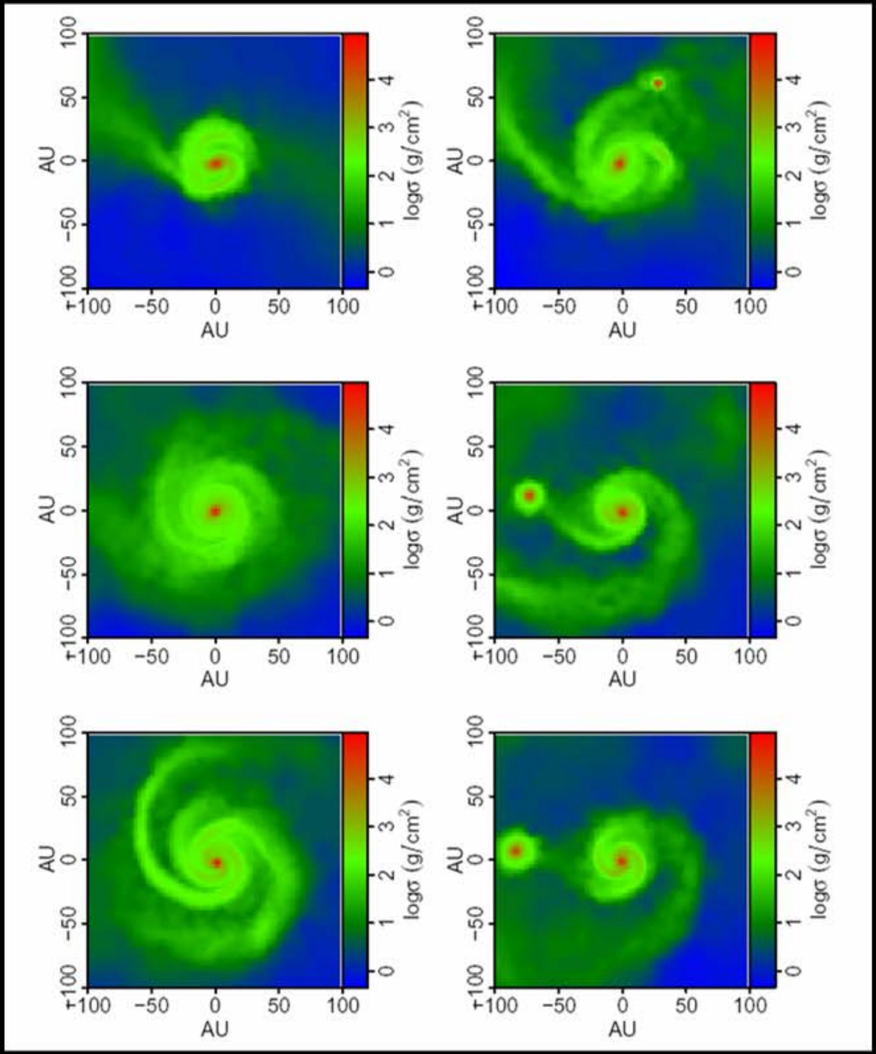


Hayfield, Mayer et al, 2010.

The environment matters for disk formation and evolution; *singles vs. binary protostellar systems* with similar total mass, angular momentum and temperature have different behaviour for disk

--→ binary system does not fragment

below different rows are 2 Kyr apart

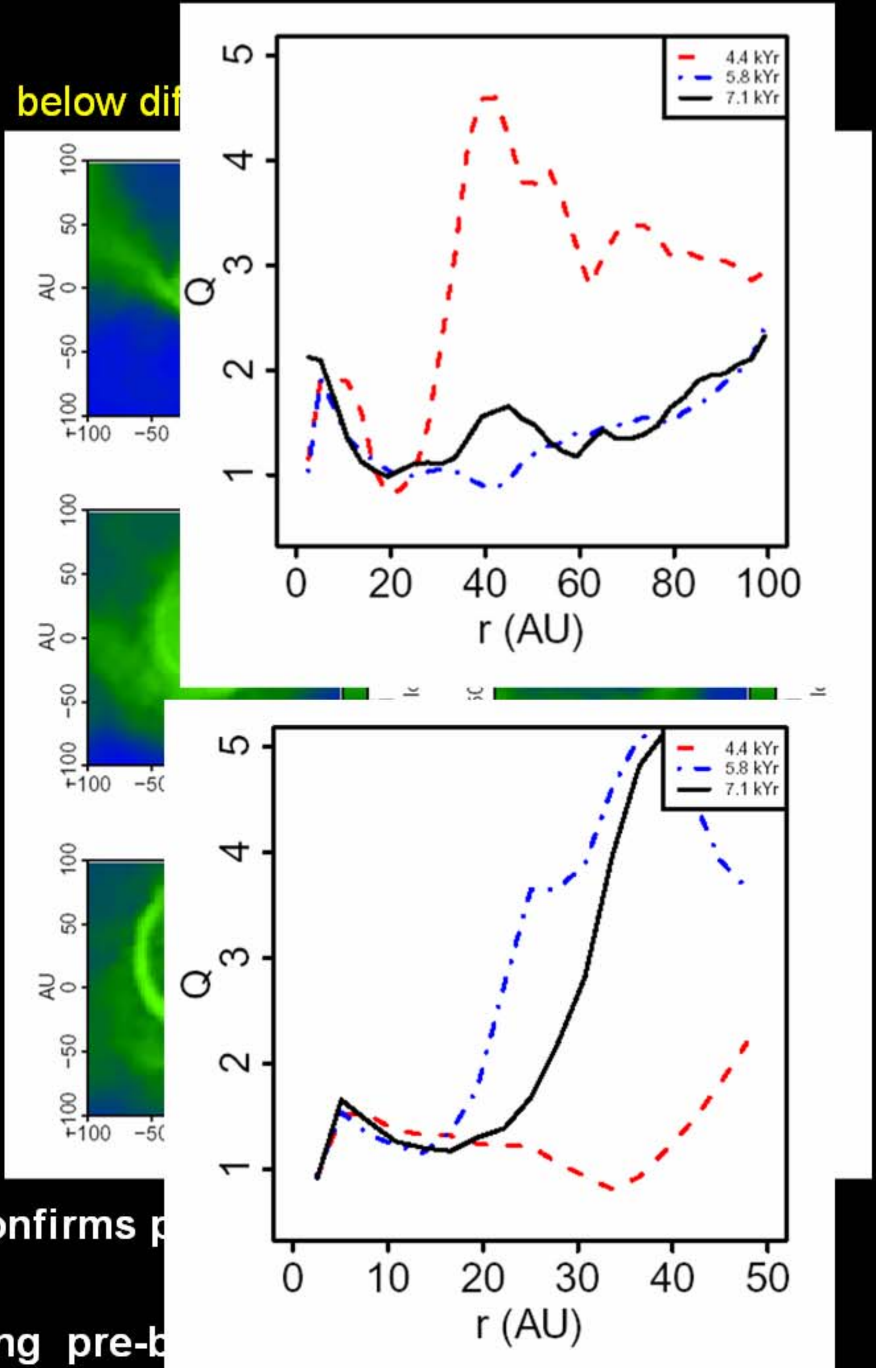


Suppression of fragmentation in binary system confirms previous results (Nelson 2000; Mayer et al. 2005 – but see Boss 2005) using pre-built non-accreting disks

The environment matters for disk formation and evolution; ***singles vs. binary protostellar systems*** **with similar total mass, angular momentum and temperature have different behaviour for disk**

--→ *binary system does not fragment*

below dif



Suppression of fragmentation in binary system confirms p

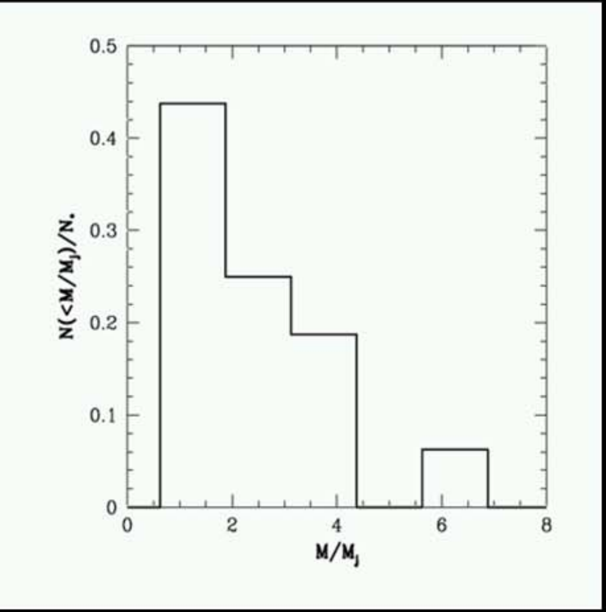
2000; Mayer et al. 2005 – but see Boss 2005) using pre-b

Initial mass function of protoplanets

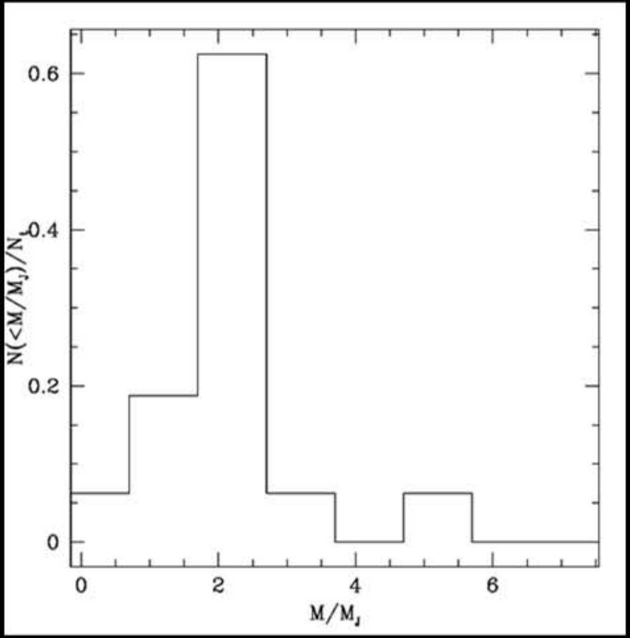
Mass function a few orbital times after gravitationally bound fragments form in disks with masses ~ 0.1-0.3 Mo and sizes 40-200 AU

Initial masses in the range 1-6 M_{jup} -- *NOT* > 10 M_{jup}

(Boss 2001;2006;Mayer et al. 2004; Mayer 2010; Durisen et al. 2007; Boley 2009;Boley, Hayfield, Mayer & Wadsley 2010)



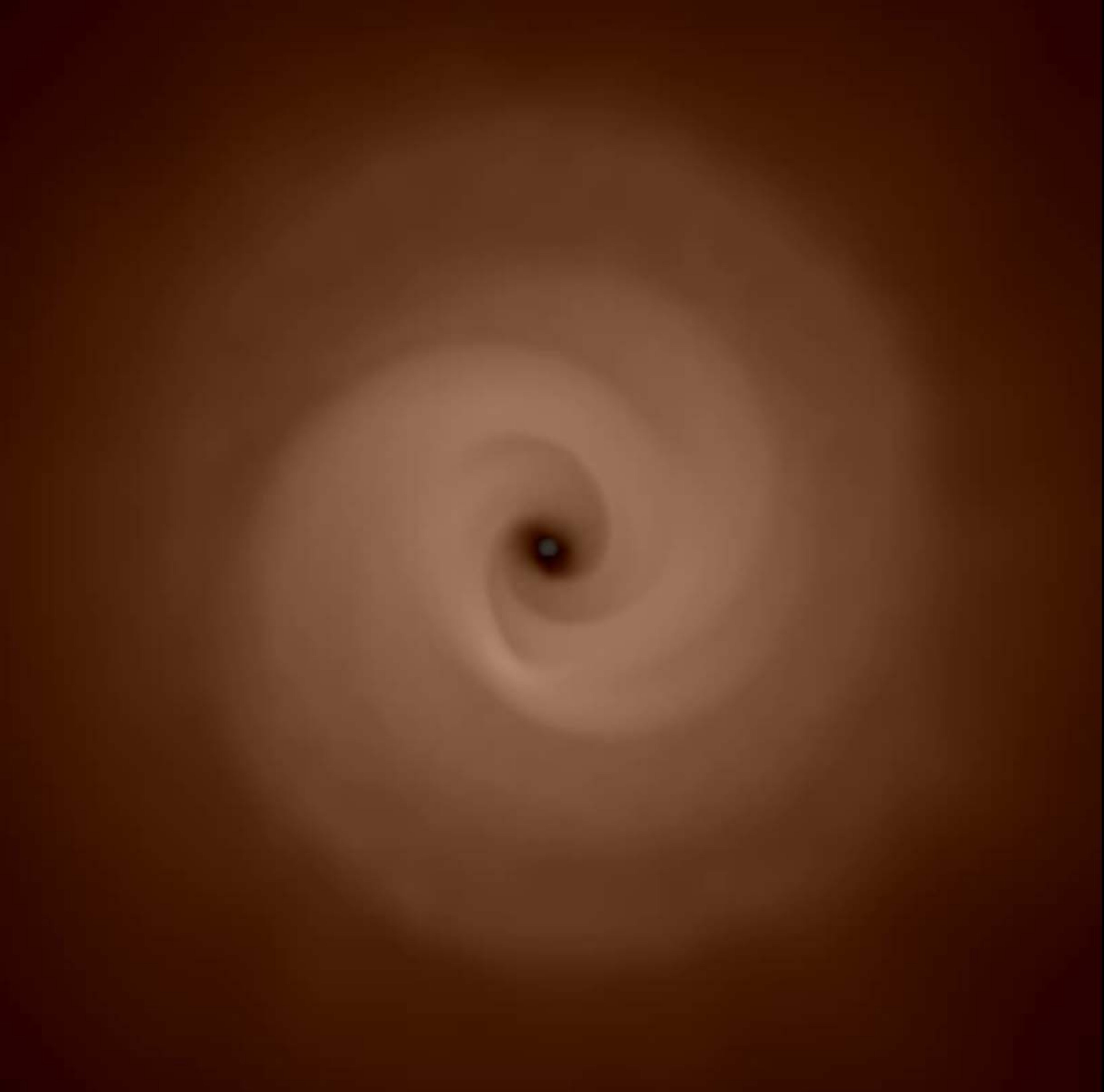
Simulations with no rad. transfer (Mayer et al. 2002; 2004)



Rad. Trans. simulations (Mayer et al. 2007; Mayer 2010)

NOTE: fragmenting disks have 50% higher masses relative to non-RT sims

Note: Stamatellos et al. 2009 find typical masses in the range 10-100 Mj in very massive, extended disks (M~ 0.3-0.5 Mo, R = 500 AU) which go unstable on very few orbital times



Boley, Hayfield

, Mayer & Durisen 2010

+ Hayfield et al., in prep

Hi-res 3D SPH sim

Mdisk = 0.19 Mo

Mstar = 0.3 Mo

Envelope Accretion

rate = 10^{-4} Mo/yr

Lagrangian tracking of clump formation within spiral arm: actual size of collapsing regions

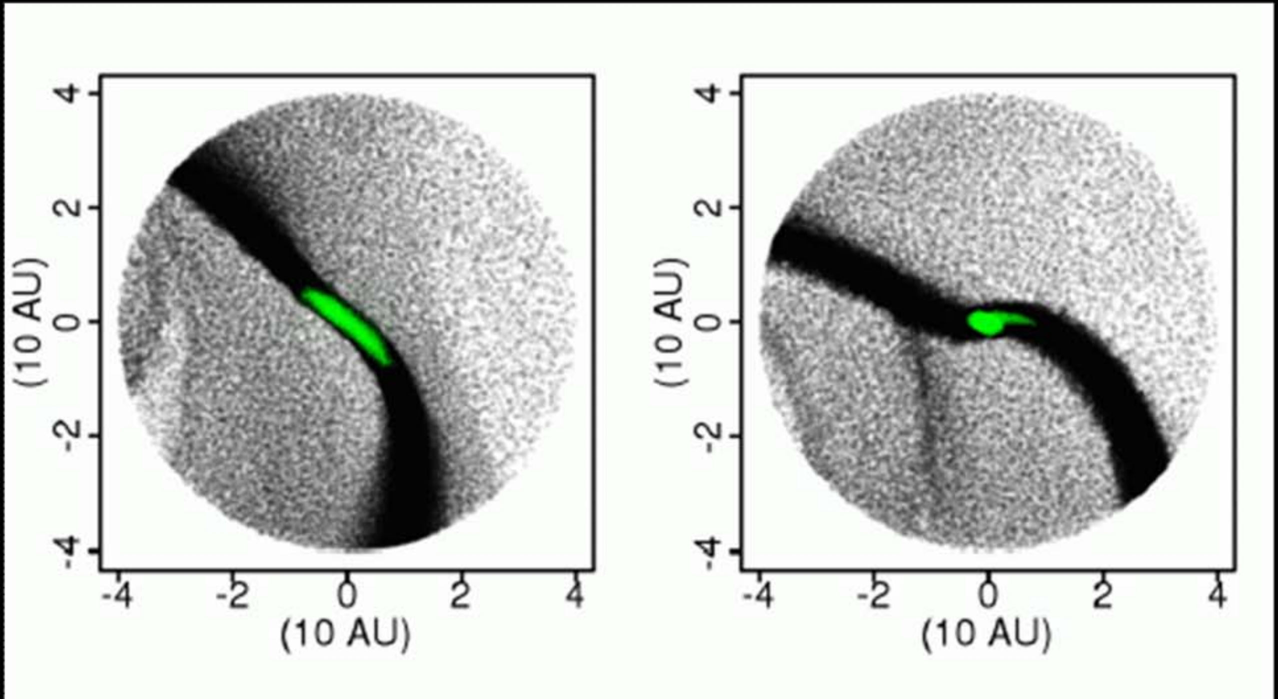
Toomre wavelength $\lambda_T = 2c_s^2/(G\Sigma)$ gives unstable region has size ~ 40 AU

but simulation shows only a region ~ 18 AU in size (green) collapses to form a bound clump

This is characteristic dr size associated with modified

Toomre wavelength that can be calculated from spiral wave dynamics in self-gravitating disk

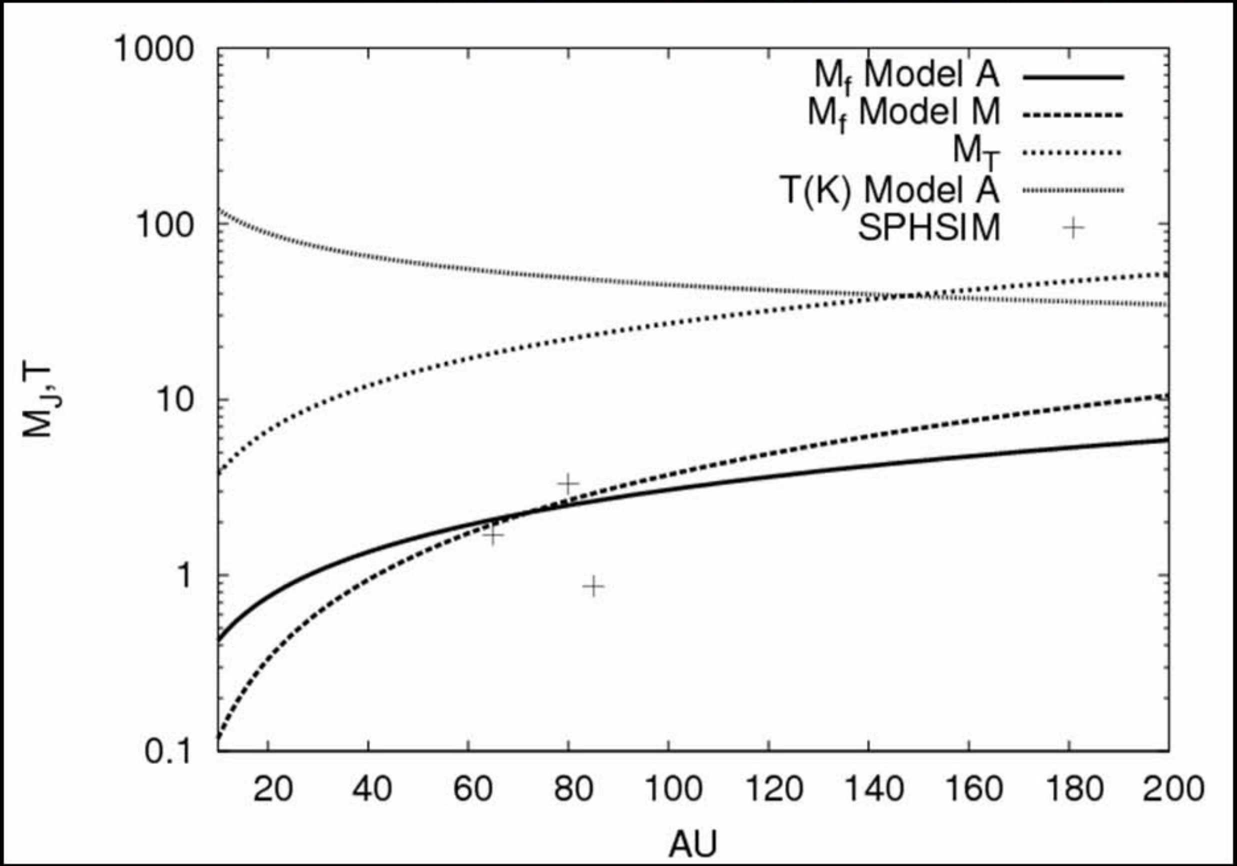
(Durisen et al. 2008)



Why is the initial mass in the few Mj range?

Toomre analysis comes from linear perturbation theory -→

not valid in highly nonlinear regime of clump formation (Mayer et al. 2004)



$$M_f = 2\lambda_T \frac{\Sigma c_s}{\Omega f_g}.$$

$f_g \sim 2.5$

c_s/Ω = H (height)

Modified "nonlinear " Toomre mass

(Boley et al. 2010; Durisen et al. 2008)

>> Local conditions in self-gravitating region of spiral arm matter for fragmentation not those in axisymmeric disk!

>> Fragmentation in spiral arm happens near corotation

Toomre mass and wavelength

$$M_T = \pi(\lambda_T/2)^2\Sigma$$

$$\lambda_T = 2c_s^2/(G\Sigma)$$

would give masses > 8 Mj

An inner disk clump (Mayer et al. 2004)

Properties of clumps

(Mayer et al. 2004; Boley, Hayfield, Mayer & Wadsley 2010)

Color-coded velocity field shown

Clumps are:

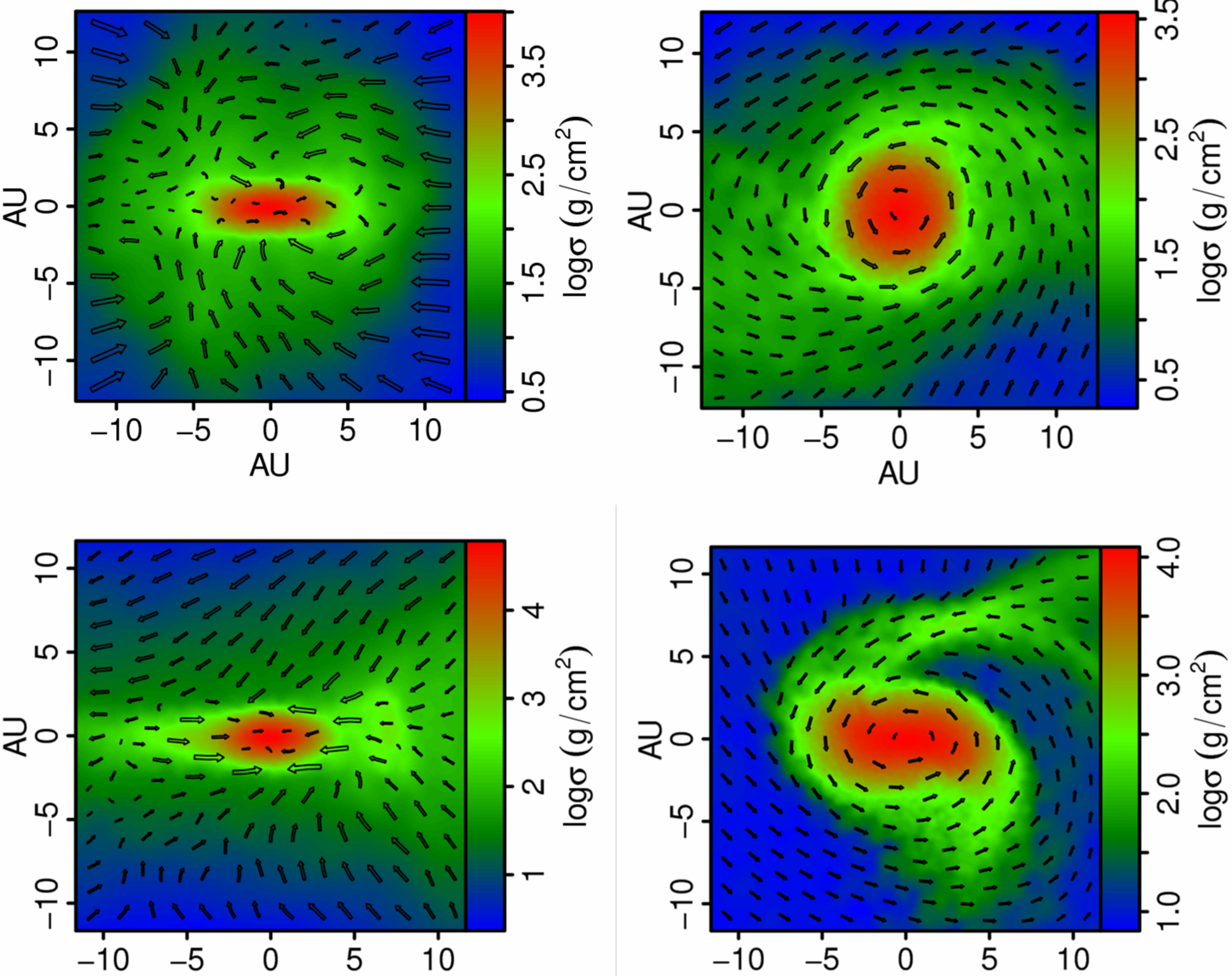
-in differential rotation, on coplanar orbits along disk midplane

- flattened oblate spheroids with c/a ~ 0.7-0.9 (esp. in inner disk, R < 50 AU) as well as prolate bar-unstable objects (c/a ~ 0.2-0.3, in outer disk R > 50 AU)

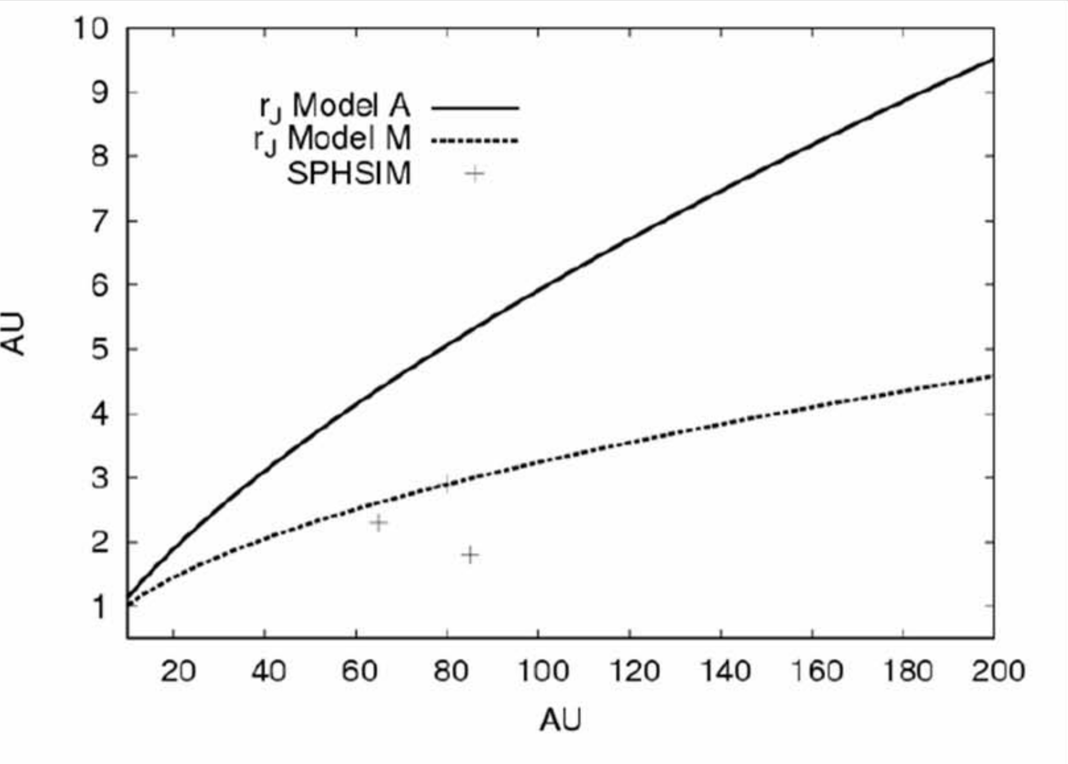
-have a wide range of obliquities, from 2 to 180 degrees. Clump-clump and disk-clump J exchange.

-initial temperatures 200-300 K in inner disk (R < 50 AU), 20-50 K in outer disk (R > 50 AU)

Outer disk clumps (Boley et al. 2010); Hayfield et al., in prep.



Initial angular momentum of clumps



Boley et al. 2010

J of clumps in outer disk (R > 50 AU) is

2 orders of mangitude higher than Jupiter's, but:

-- Could be redistributed significantly (> 80%

transported outward) by e.g. bar instabilities (see e.g.

Umemura et al. 2000 on bar-unstable protostars)

-- High J gas possibly stored in circumplanetary

disk(need higher resolution to "separate" protopl, core

from disk)

$$r_J \approx \frac{\pi^2 \langle Q\rangle^2 v_K f_g r}{144 c_s \mathcal{M}^4},$$

Centrifugal eq. radius

From assumption that angular momentum of clumps (defined from modified Toomre mass/size)

is the difference between the initial angular momentum at its centroid and at its boundary plus

treating clump as a rigid rod

NOTE: r_j a few AU ~ clump size -→ rotation important

Structural evolution of clumps: towards a gas giant

What are "final" masses, temperatures, spins of clumps?

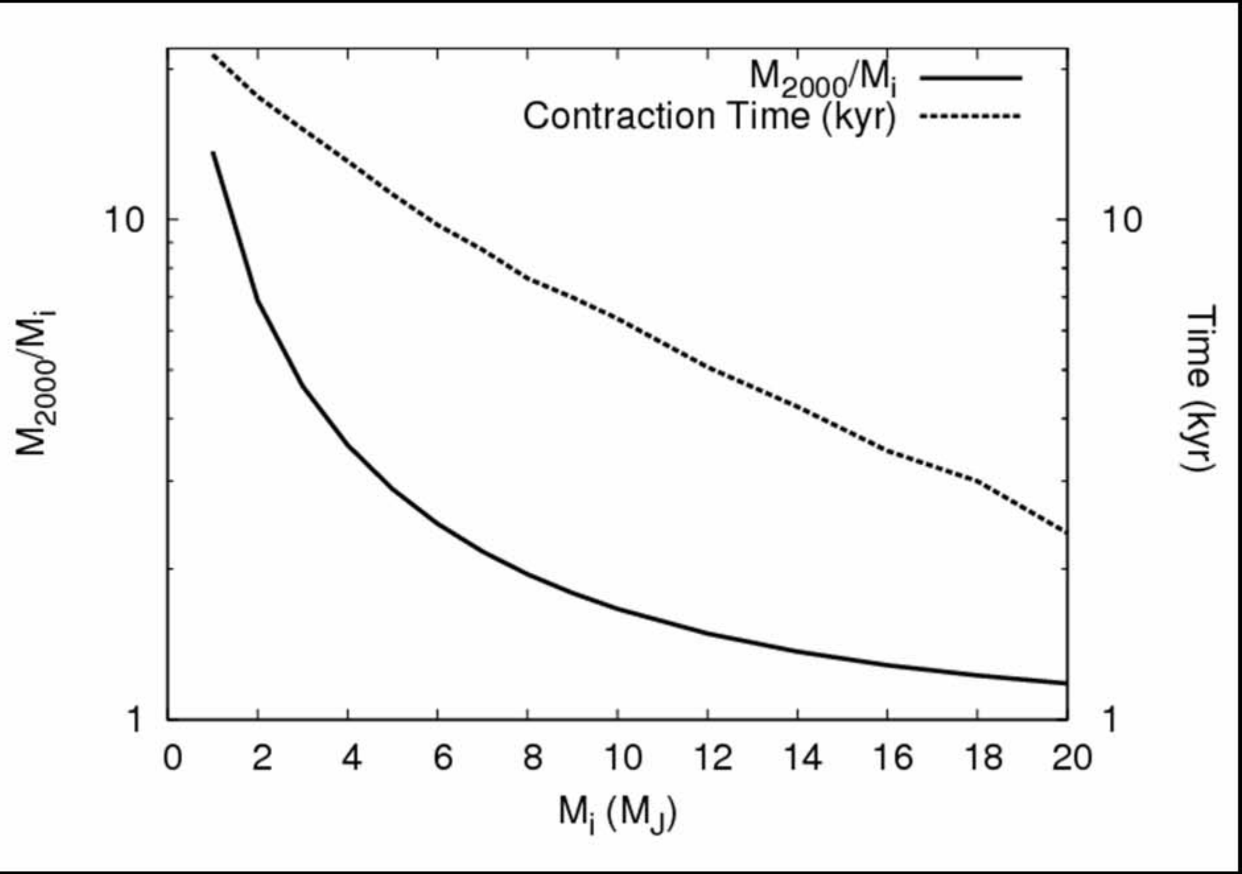
Where we set the "final" time?

Definition : final mass of planet is the mass of the protoplanet after "second" core formation (i.e. after H_2 dissociation ad dynamical collapse) – see e.g. Helled et al.2008

Accretion complex process due to combination of thermodynamical (e.g. KH timescale relevant, as in protostars) and dynamics (role of angular momentum and dynamical instabilities)

The final masses of protoplanets: an upper limit

Simulations cannot restimate final masses of protoplanets formed by GI yet – impossible to follow internal clump evolution at hi-res on long enough timescales (> >10 orbits) including dissociation and formation of second core



Hybrid approach (Boley et al. 2010)

Clump structure from 3D sim

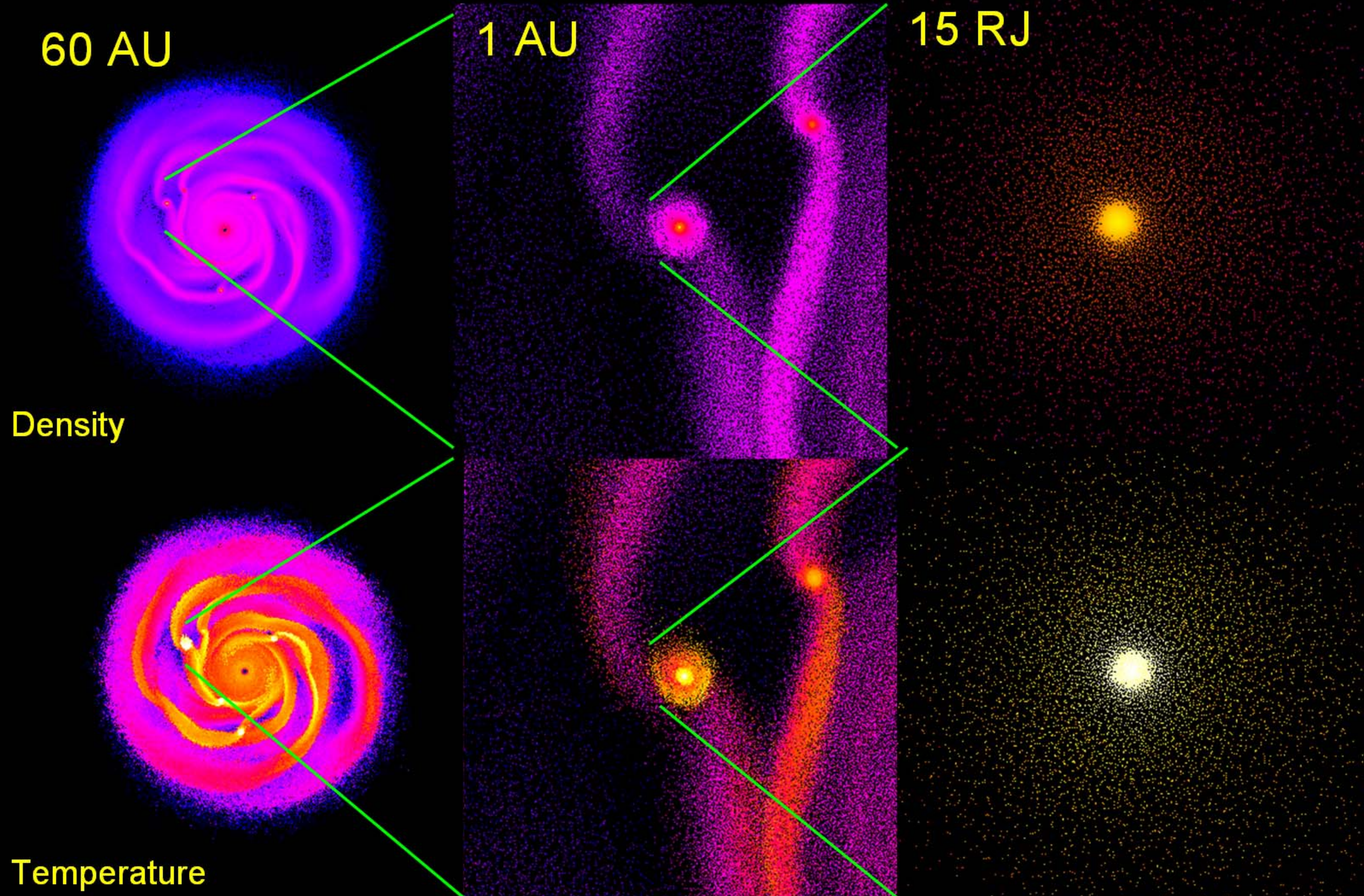
(1) Fit with polytrope +

(2) Evolve further in time using spherical quasi-static collapse model

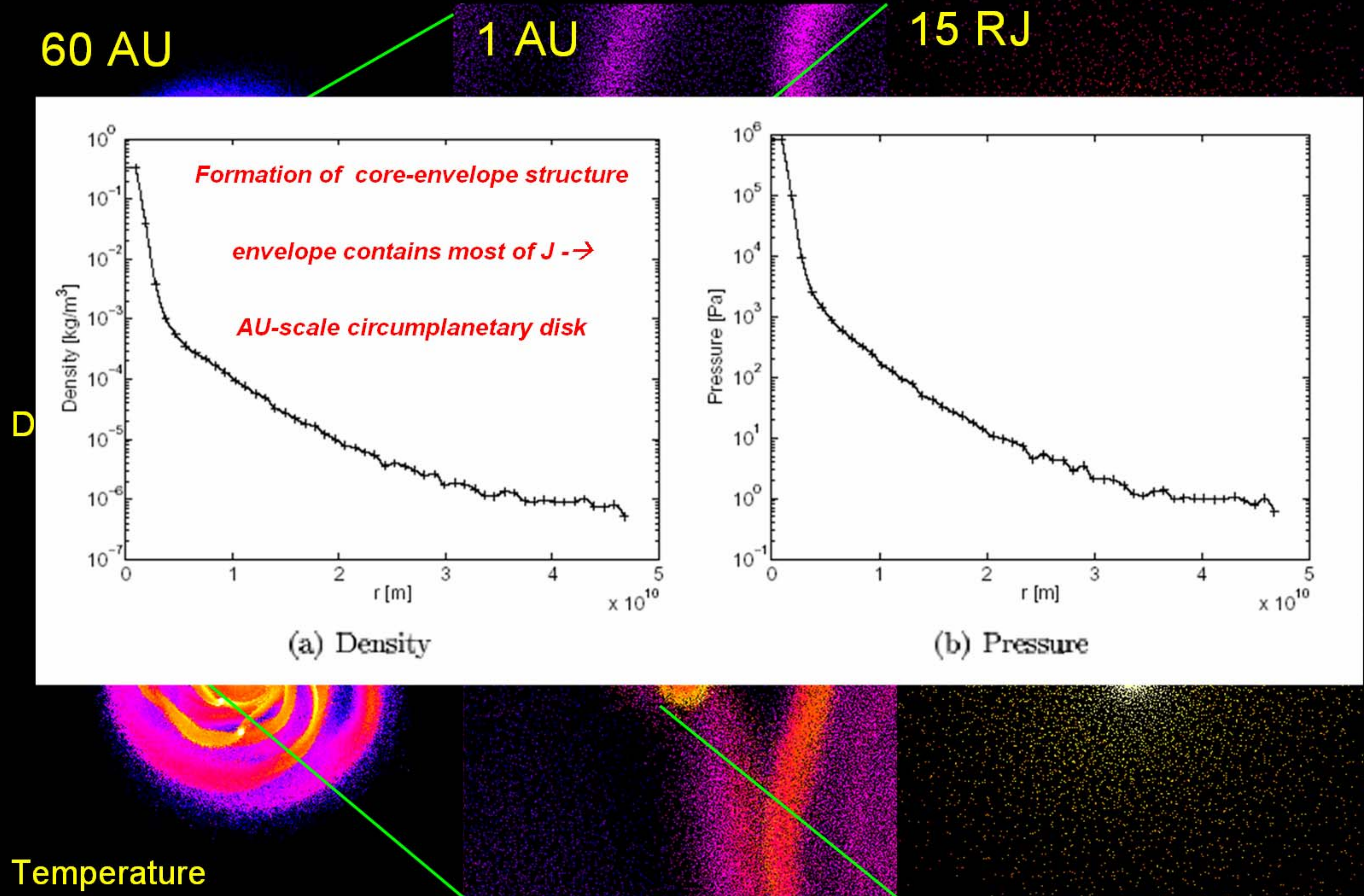
$$\dot{M} \approx 2 \times 10^{-7}\ \mathrm{M_\odot\ yr^{-1}} \left(\frac{\mathrm{r_0}}{100\ \mathrm{AU}}\right)^{1/2} \left(\frac{\mathrm{M}}{\mathrm{M_J}}\right)^{2/3} \left(\frac{\mathrm{M_{star}}}{\mathrm{M_\odot}}\right)^{-1/6} \frac{\Sigma}{10\ \mathrm{g\ cm^{-2}}}$$

Upper limit on clump mass, = mass flux within Hill radius of clump plus assumption that final mass reached after second core formation (contraction timescale)

High resolution collapse of individual clumps (Mayer 2010)
1.5 Mj clump contracts to ~ 3 Rj (resolution limit) and reaches
Tc ~ 1000 K in a few disk orbits



High resolution collapse of individual clumps (Mayer 2010)
1.5 Mj clump contracts to ~ 3 Rj (resolution limit) and reaches
Tc ~ 1000 K in a few disk orbits



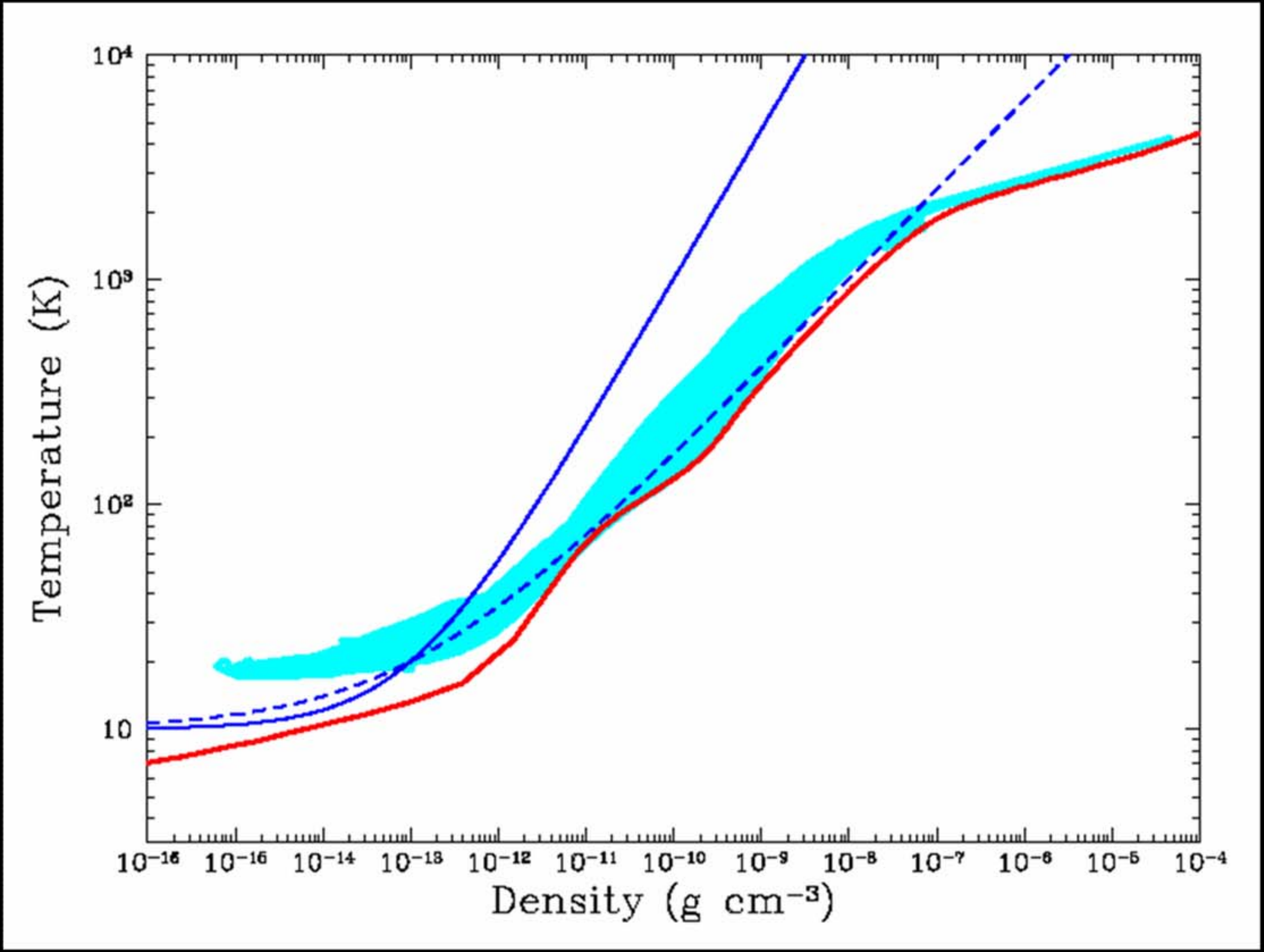
Formation of core-envelope structure

envelope contains most of J -→

AU-scale circumplanetary disk

(a) Density (b) Pressure

The effect of H_2 dissociation: formation of second core resolved in largest clumps (M > 5 Mj) which contract most rapidly *(Stamatellos et al. 2009)*



Processes that can limit the final mass:

-- Thermodynamics

Clump heats up and radiates as it contracts – pressure gradient and radiation oppose further mass accretion (KH timescale limits mass accretion to 10^{-3} Mj/yr for 1Mj clump – see Nelson & Benz 2003)

-- Gap opening → gap "starvation" mass (e.g. Kratter et al. 2009).

Needs low viscosity (lower than GI and MRI viscosity, but GI could saturate after fragmentation burst + unclear whether disk MRI active in clump forming region)

-- Outer protopl. disk dissipation by GIs (timescale >~ 10^4 yr based on extrapolation in time of sim results in Mayer et al 2004; Durisen et l. 2007)

-- Separate high J circumplanetary disk+ small J core

Only core becomes gas giant, higher J material forms disk (viscous accretion?)

-- Inward Migration via clump-clump scattering and clump-spiral wave interaction (Boley et al. 2010; Hayfield et al. in prep.)

as clump moves inward outer envelope easily stripped of by tides and further accretion stifled (in extreme cases complete disruption)

Processes that can limit the final mass:

-- **Thermodynamics**

Clump heats up and radiates as it contracts – pressure gradient and radiation oppose further mass accretion (KH timescale limits mass accretion to 10^{-3} Mj/yr for 1Mj clump – see Nelson & Benz 2003)

-- **Gap opening → gap "starvation" mass (e.g.**

Needs low viscosity (lower than GI and MRI

saturate after fragmentation burst + unclear

lump

forming region)

$$M_{\rm starve} \approx 8 M_{\rm Jup} \left(\frac{\alpha}{4\times10^{-4}}\right)\left(\frac{\Delta}{5R_H}\right)^3 \left(\frac{T}{40\ {\rm K}}\right)\left(\frac{r}{70\ {\rm AU}}\right)$$

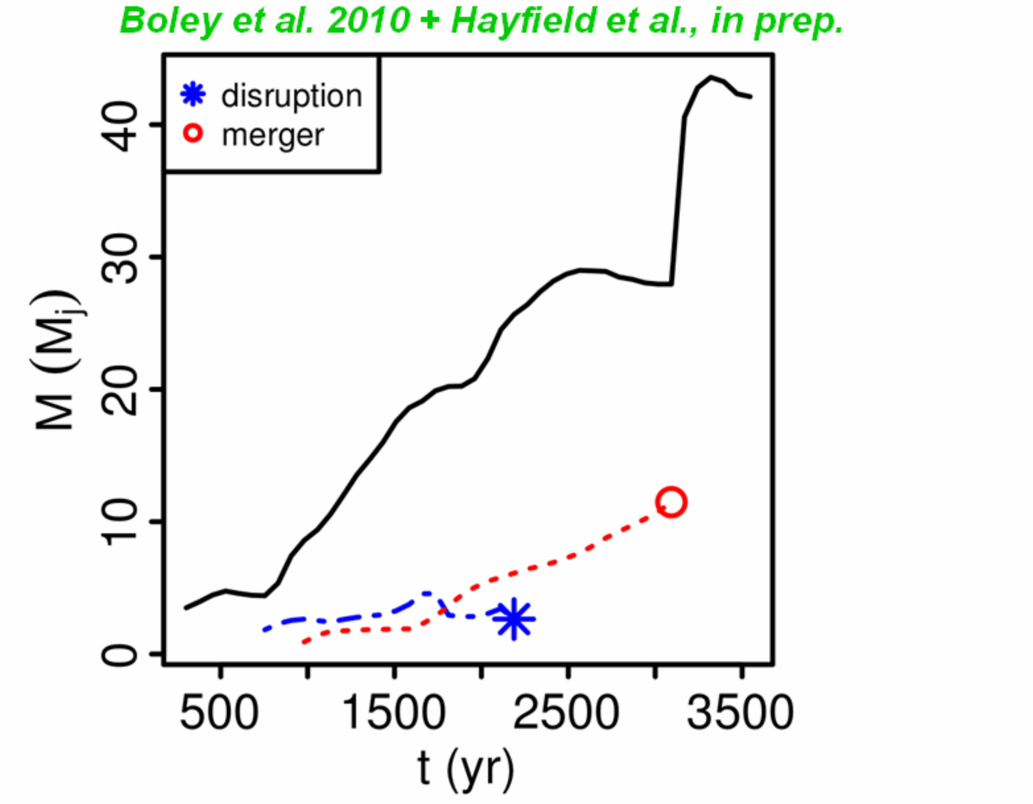
-- **Outer protopl. disk dissipation by GIs** (timescale >~ 10^4 yr based on extrapolation in time of sim results in Mayer et al 2004; Durisen et l. 2007)

-- **Separate high J circumplanetary disk+ small J core**

Only core becomes gas giant, higher J material forms disk (viscous accretion?)

-- **Inward Migration via clump-clump scattering and clump-spiral wave interaction** (Boley et al. 2010; Hayfield et al. in prep.)

as clump moves inward outer envelope easily stripped of by tides and further accretion stifled (in extreme cases complete disruption)



t the final mass:

ntracts – pressure gradient and radiation
mescale limits mass accretion to
& Benz 2003)

(e.g.
d MRI
nclear

$$M_{\rm starve} \approx 8 M_{\rm Jup} \left(\frac{\alpha}{4\times10^{-4}}\right)\left(\frac{\Delta}{5R_H}\right)^3 \left(\frac{T}{40\ {\rm K}}\right)\left(\frac{r}{70\ {\rm AU}}\right)$$

lump

-- **Outer protopl. disk dissipation by GIs** (timescale >~ 10^4 yr based on extrapolation in time of sim results in Mayer et al 2004; Durisen et l. 2007)

-- **Separate high J circumplanetary disk+ small J core**
Only core becomes gas giant, higher J material forms disk (viscous accretion?)

-- **Inward Migration via clump-clump scattering and clump-spiral wave interaction** (Boley et al. 2010; Hayfield et al. in prep.)
as clump moves inward outer envelope easily stripped of by tides
and further accretion stifled (in extreme cases complete disruption)

…But clump-clump mergers can increase final mass

Core formation + envelope enrichment in disk instability

Disk instability *per se* produces gaseous protoplanets with nebular abundance (e.g. solar) and no solid core

Core-accretion naturally predicts solid core (needs $M_{core} > 10\ M_{earth}$) in order for runaway gas accretion to start and predicts super-solar abundances in envelope (Ida & Lin 2004; Alibert et al. 2005)

→abundance of solids/presence of core best way to distinguish between giant planet formation scenarios?

Solar System giants (Jupiter and Saturn) have super-solar abundances and perhaps a core:
Mz (envelope) ~ 0-30 Mearth, Mcore = 0-20 Mearth, Mz(tot)= 6-20 Mearth (Guillot 2005)
Extrasolar planets? Transiting planets around stars with solar metallicities likely have small cores (Mcore < 10 Mearth), those around metal rich stars can have large cores (e.g for HD149026b Mcore > 50 Mearth) – Guillot et al. (2006); Burrows et al. 2007

Existing 3D simulations of fragmenting disks do not model dust/planetesimals dynamics in clumps -→ no predictions on core formation/envelope enrichment
What if gaseous clump accretes dust grains and planetesimals during and after its formation (e.g.Boss 1998)?

Accretion of planetesimals by clumps

Helled et al. (2006;2008;2009) - 1D spherical "stellar" collapse model for gaseous clump + interaction with dust and planetesimals within R_H
A protoplanet of a few Jupiter masses evolves through 3 phases:

1) Quasi-static contraction with **cool internal temperatures** (**T ~ 50-500 K**), molecular hydrogen, and radius a few thousand times R_J: **pre-collapse ~ 10^3 - 10^5 yr**
2) Once the central temperature reaches ~ 2000 K, H_2 dissociates and initiates a dynamical collapse (radius is a few times R_J) - **on a dynamical timescale ~ few years**
3) Slow contraction on a long time-scale (~ 10^9 yr).

Phase 1 is the crucial one for capture of solids and core formation

Giant gaseous protoplanets can be enriched with high-Z material by accretion of planetesimals (ablation and fragmentation of planetesimals included)

The final composition of a protoplanet changes considerably with the planetary mass (massive planets: stronger gravitational pull but shorter contraction times) and its *'birth environment'*:

- **Radial distance from the star (accretion rate decreases with increasing radial distance)**
- **Metallicity (solid surface density)**
- **Disk properties (disk mass, density distribution, planetesimal properties etc.)**

Many free parameters -→ mass range of accreted high-Z material in the range 1-100 Earth masses for planet masses 1-10 Mj

Solid Core formation via grain sedimentation

- Cores can form in gaseous protoplanets by coagulation and sedimentation of grains. Grains can settle to the center before the protoplanet contracts to planetary densities and temperatures -→ *time available for core formation proportional to duration of phase(1).*
- Clumps are fully convective (thin radiative outer layer) and grains must grow large enough to decouple from the gas and form a core.
- Ice and CHON grains evaporate almost immediately in the planetary envelope, enriching it with volatiles. Silicate grains can reach the center and form a rocky core -> *ice giants unlikely to form from disk instability*
- The pre-collapse time-scale of low mass bodies is longer, and the internal temperatures and convective velocities are lower → *low mass planets have more favorable conditions for core formation. -> Jupiter could have formed in outer GI unstable region of disk and accrete a core of a few solar masses consistent with observational constraints (Helled & Schubert 2009)*

Protoplanets of ~ 5 M_J or larger are too hot even in their initial states for silicate grains to survive and therefore cannot form a core (→ planets in e.g HR8799 would have no core). Instead, grains evaporate in the planetary envelopes enriching them with refractory material. NOTE: conclusion based on assuming T ~ 1300 K sublimation temperature for all refractory materials (would depend on size and compossition)

The final core mass depends on the mass of the protoplanetary clumps but also on the mass and size distribution of accreted solid material + metallicity, mass of disk and formation location in disk all matter).

F. Carron (2008)– Master thesis at UniBern with **W. Benz, Y. Alibert, C. Mordasini** and **L.Mayer**

CONFIRM CORE FORMATION + ENVELOPE ENRICHMENT IN CLUMPS

(1) Feed (T,ρ, P) structure of clumps from 3D disk instability simulation (Mayer et al. 2007; Mayer 2010) to same impact code used in core-accretion models by Mordasini et al. (2009). Clump treated as static, i.e. no collapse

(2) Get distribution of colliding planetesimals

Given by previous N-body simulation of planetesimals with sizes 10-1000 km moving in a <u>minimum mass solar *nebula*</u> *(conservative assumption on disk mass/mass of solids*) disk with a Jupiter-sized planet (with Mercury code)

(3) Follow interaction of impactors with clump for 10^5 yr (no dust considered)

Include aerodynamical drag, thermal and mechanical ablation of two types of planetesimals ("ices" and "stones") as they fall into the clump envelope+ uniform re-distribution of dust grains created by planetesimal ablation in the envelope due to convection (no sedimentation)

- *Accreted planetesimals = colliding planetesimals – ejected planetesimals (i.e. end up at $R > 2\ R_{Hill}$)*

- *Accreted planetesimals – planetesimals ablated in envelope= planetesimals contributing to **solid core***

F. Carron (2008)– Master thesis at UniBern with **W. Benz, Y. Alibert, C. Mordasini** and **L.Mayer**

CONFIRM CORE FORMATION + ENVELOPE ENRICHMENT IN CLUMPS

(1) Feed (T,ρ, P) structure of clumps from 3D disk instability simulation

(Ma

mod

(2) C

Give

mov

mas

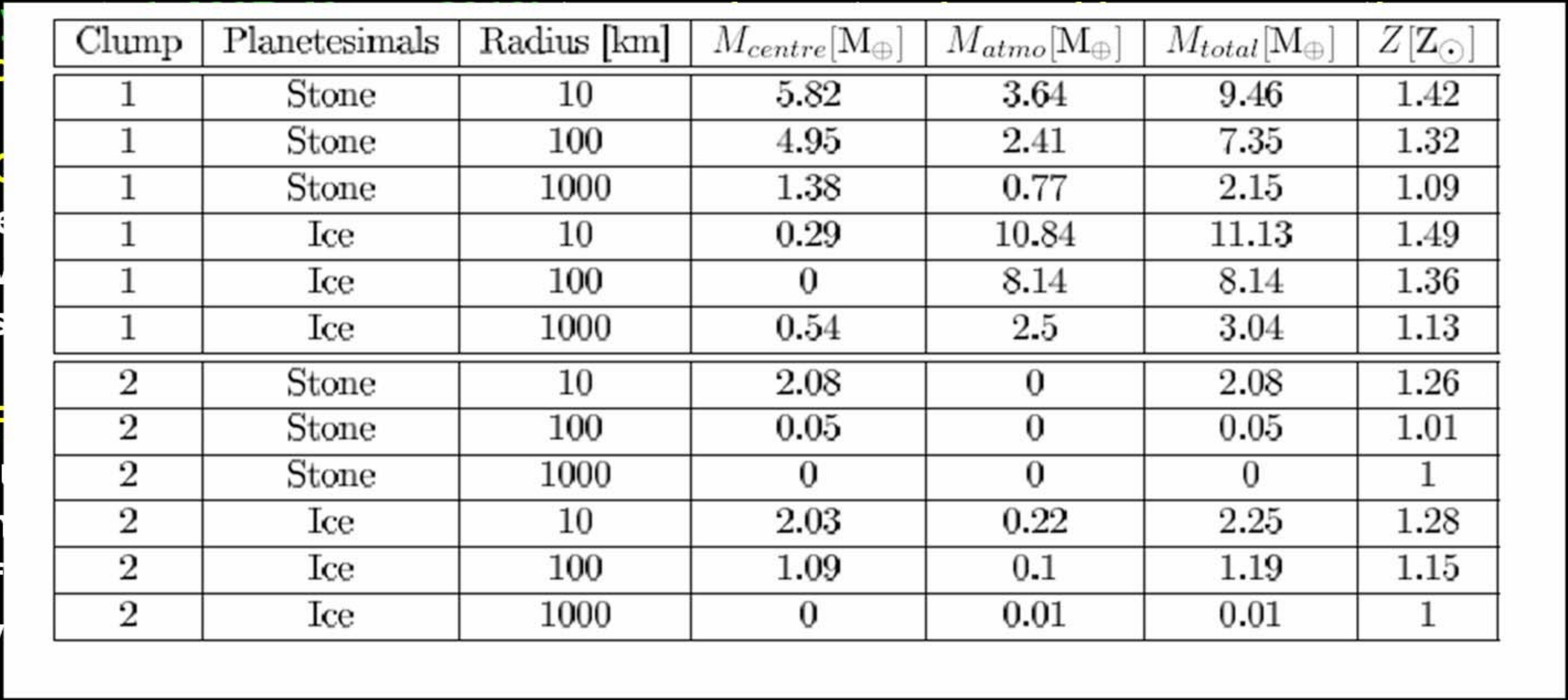
(3) F

Incl

plan

unif

env



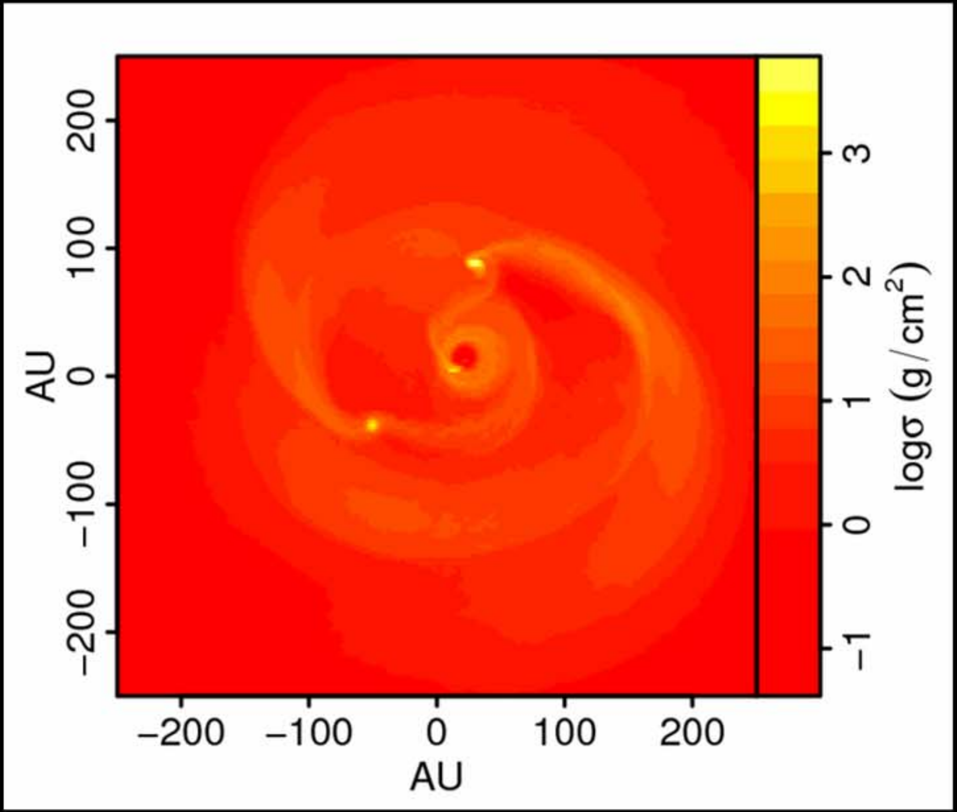
Clump	Planetesimals	Radius [km]	M_{centre}[$M_\oplus$]	M_{atmo}[$M_\oplus$]	M_{total}[$M_\oplus$]	Z[$Z_\odot$]
1	Stone	10	5.82	3.64	9.46	1.42
1	Stone	100	4.95	2.41	7.35	1.32
1	Stone	1000	1.38	0.77	2.15	1.09
1	Ice	10	0.29	10.84	11.13	1.49
1	Ice	100	0	8.14	8.14	1.36
1	Ice	1000	0.54	2.5	3.04	1.13
2	Stone	10	2.08	0	2.08	1.26
2	Stone	100	0.05	0	0.05	1.01
2	Stone	1000	0	0	0	1
2	Ice	10	2.03	0.22	2.25	1.28
2	Ice	100	1.09	0.1	1.19	1.15
2	Ice	1000	0	0.01	0.01	1

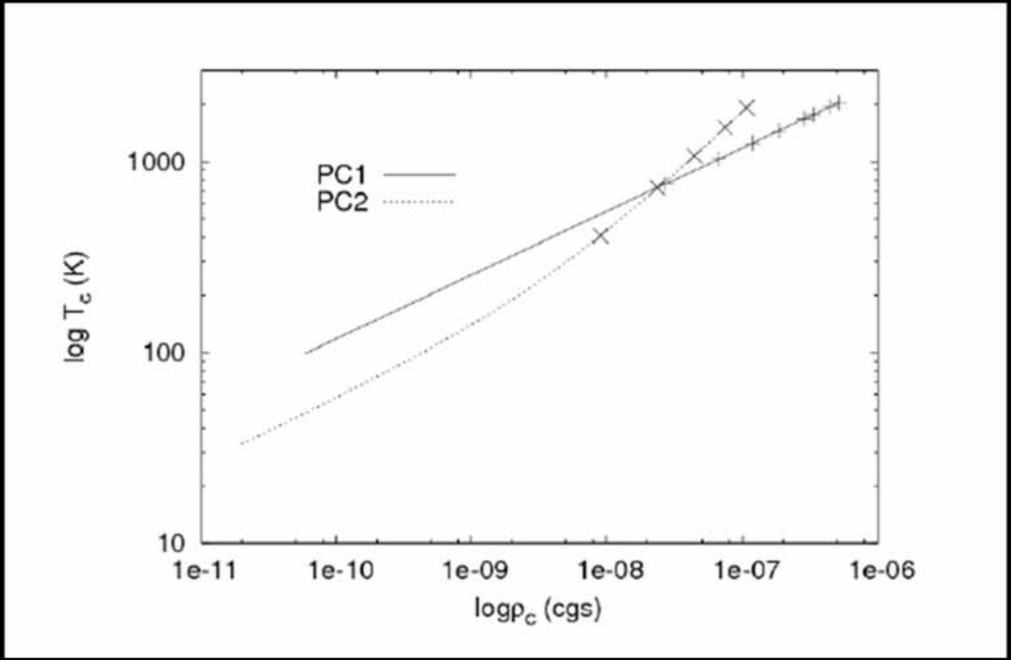
- *Accreted planetesimals = colliding planetesimals – ejected planetesimals (i.e. end up at R > 2 R_{Hill})*
- *Accreted planetesimals – planetesimals ablated in envelope= planetesimals contributing to **solid core***

Another GP formation pathway; from disk instability to accreting cores

"failed" clumps as incubators for GP cores/Super Earth formation

(Boley, Hayfield, Mayer & Durisen 2010 + Hayfield et al., in prep.)





-- Disk instability ar R > 50 AU produces clumps that migrate inwards to < 10 AU, in < 10^5 yr after formation, and are tidally disupted by central star

-- Using dust sedimentation/coagulation model *Helled et al. (2008,2009)* find a few Earth mass core can form within gas clumps formed by disk instability in ~ 10^4 years, i.e. before clump disrupts -→ *possible rapid core formation, < 10^5 yr, faster than in standard core-accretion → can then accrete gas to become eg. Jupiter or Saturn*

Perhaps GG planets in Solar System case of "failed" clump formation?

Giant planets from disk instability: a summary

(i)Fragmentation at large radii, R ~ 5-20 AU debated, very model dependent.
At radii R > 50 AU very robust because of efficient cooling

(ii)Protoplanets with initial masses around 1 M_j , on eccentric orbits,
initial e ~ 0.2-0.3, and with significant rotation
Fragmentation scal e from modified Toomre wavelength (Boley et al. 2010)
Boss 2003,2007 : Lower mass planets, ice giants and super-Earth-scale from
photoevaporation in UV-irradiated disk.

(iii) Final masses still uncertain - high complexity, several effects determine growth
Clumps that do not undergo mergers expected to have Mmax =10-20 Mj , with
mergers grow to brown dwarf masses

(iv) Envelope accretion rate important to drive fragmentation in outer disk
-- criterion additional to usual coolling time criterion
Shown by simulations (including protostellr collapse models) and analytics
(Boley 2009. Boley et al. 2010, Rafikov 2009)

(v) Solid core formation and heavy envelope enrichment possible , possibly
matching heavy element content in SS giants *(Helled et al. 2007;2008).2009*
(always recall Mcore = 0-10 Mearth for Jupiter (Saumon & Guillot 2004))

(vi) Correlation with disk/star metallicity? Unclear…
Boss (2002, 2003) – instability insensitive to metallicity (via opacity)
Cai et al. (2006)- instability stronger at lower metallicty (via opacity)
Mayer et al. (2007) – instability stronger at higher metallicity (via mol. weight)