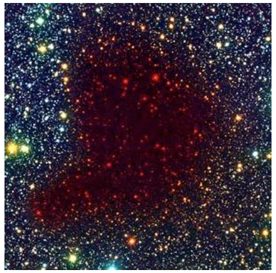
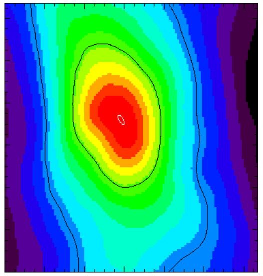
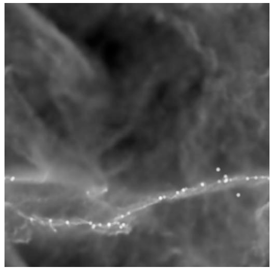
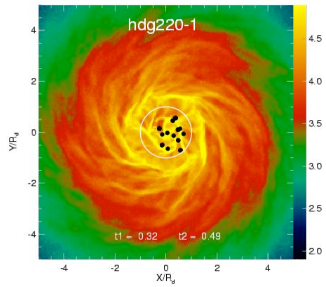
Modelling Star Cluster Formation: Building the IMF





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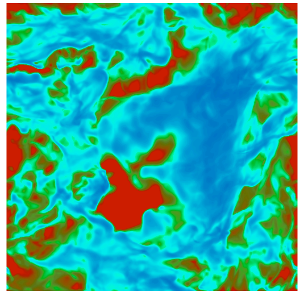
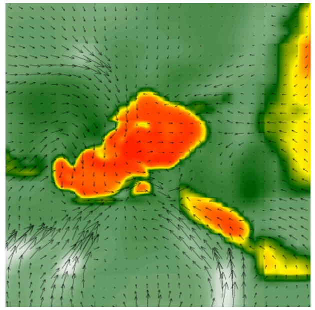
agenda

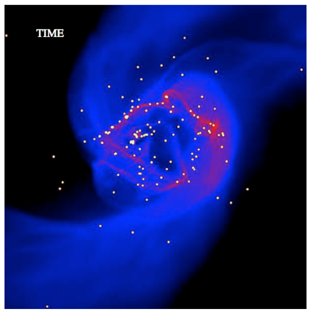
- a simple cartoon picture
  - *dynamic star formation theory*



- controversial issues & open issues
  - *what drives turbulence?*
  - *how do high-mass stars & their clusters form?*
  - *initial conditions for cluster formation?*
  - *importance of thermodynamics, or are there (still) low-mass Pop III stars?*
  - *magnetic fields at z~20?*



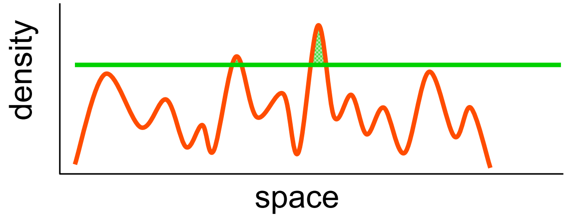
- TreeCol
  - *tree-based radiative transfer*



basic ideas

dynamical SF in a nutshell

- interstellar gas is highly *inhomogeneous*
  - *gravitational instability*
  - *thermal instability*
  - *turbulent compression* (in shocks $\delta\rho/\rho \propto \mathcal{M}^2$; in atomic gas: $\mathcal{M} \approx 1...3$)



- cold *molecular clouds* can form rapidly in high-density regions at *stagnation points* of *convergent large-scale flows*
  - chemical *phase transition*: atomic → molecular
  - process is *modulated* by large-scale *dynamics* in the galaxy
- inside *cold clouds:* turbulence is highly supersonic ($\mathcal{M} \approx 1...20$)
  → *turbulence* creates large density contrast,
  gravity selects for collapse

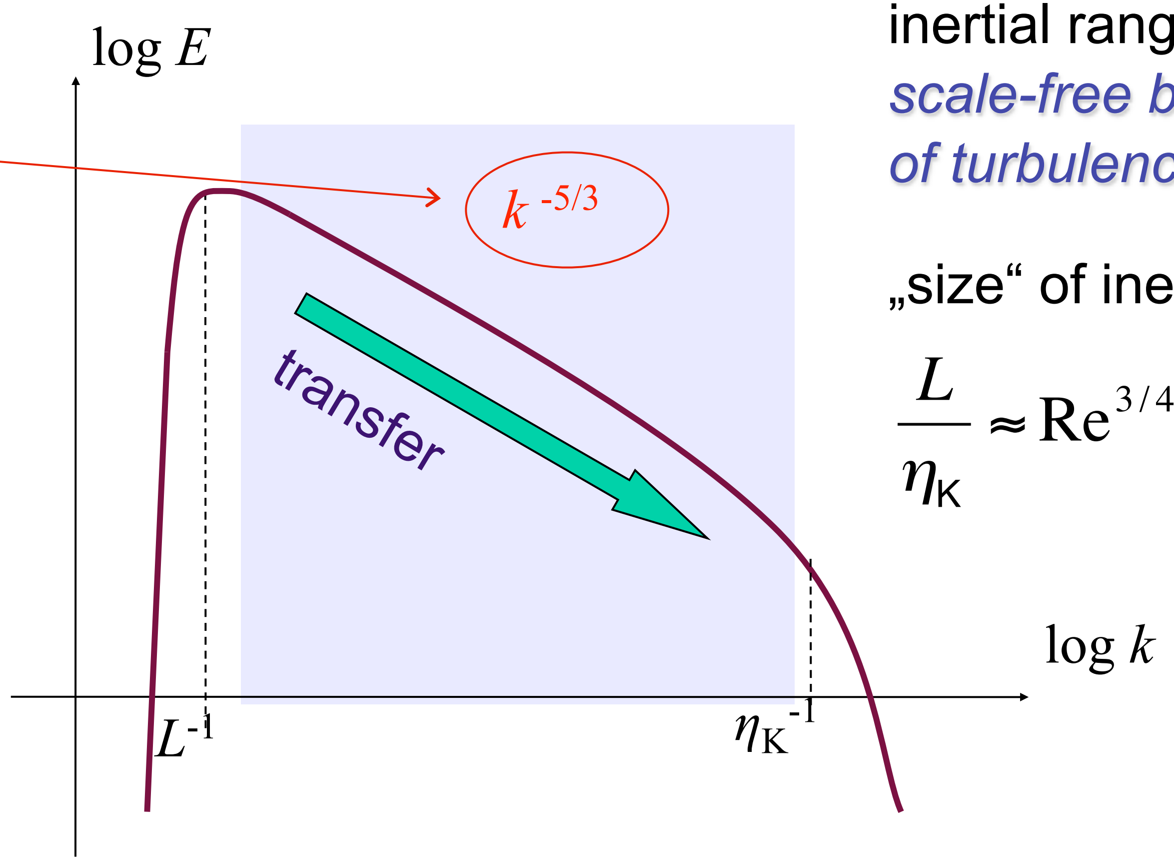
→ ***GRAVOTUBULENT FRAGMENTATION***

- *turbulent cascade:* local compression *within* a cloud provokes collapse → formation of individual *stars* and *star clusters*

(e.g. Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125, McKee & Ostriker, 2007, ARAA, 45, 565)

Turbulent cascade

Kolmogorov (1941) theory
incompressible turbulence



energy
input
scale

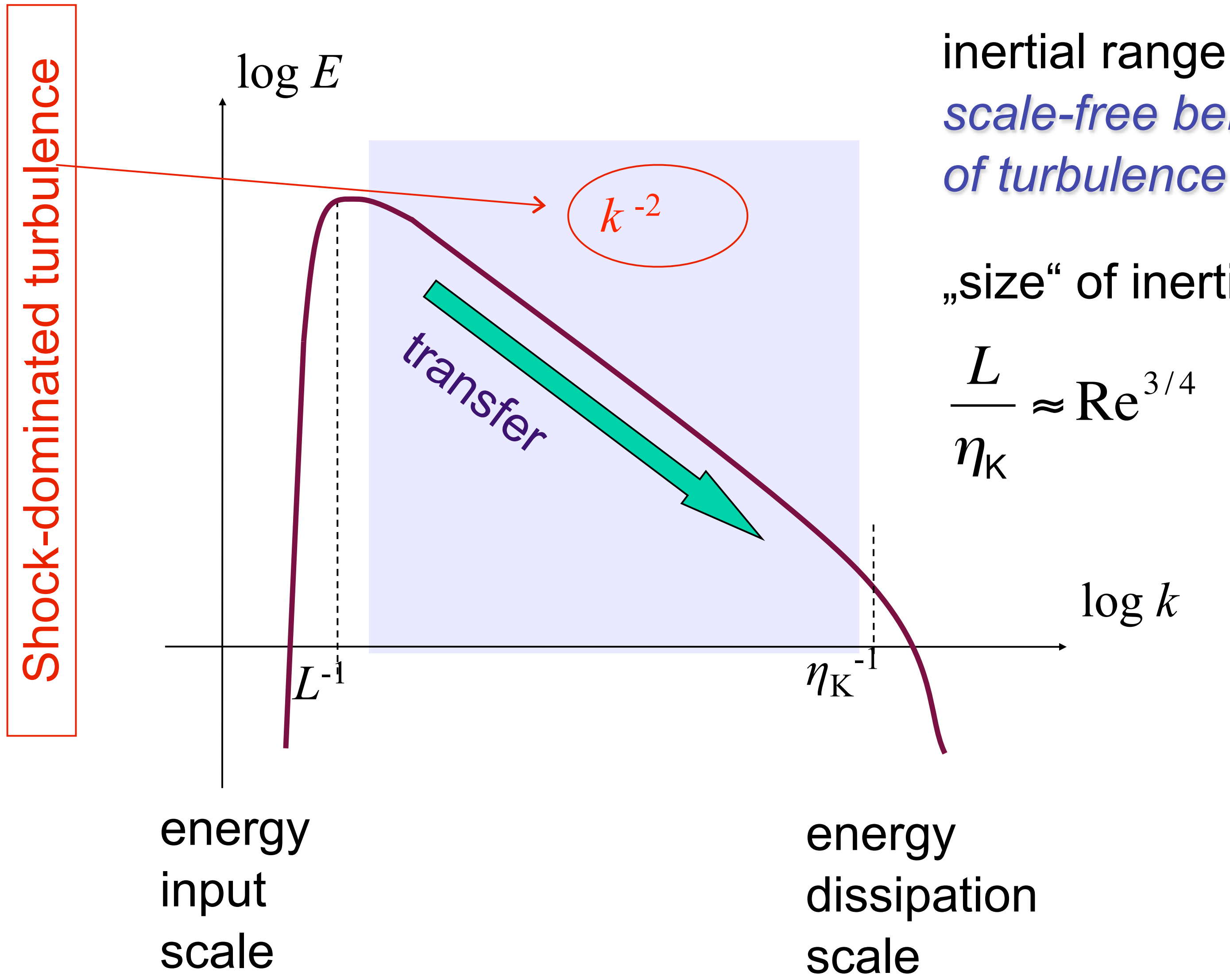
energy
dissipation
scale

inertial range:
scale-free behavior of turbulence

„size“ of inertial range:

$$\frac{L}{\eta_K} \approx \mathrm{Re}^{3/4}$$

Turbulent cascade



inertial range:

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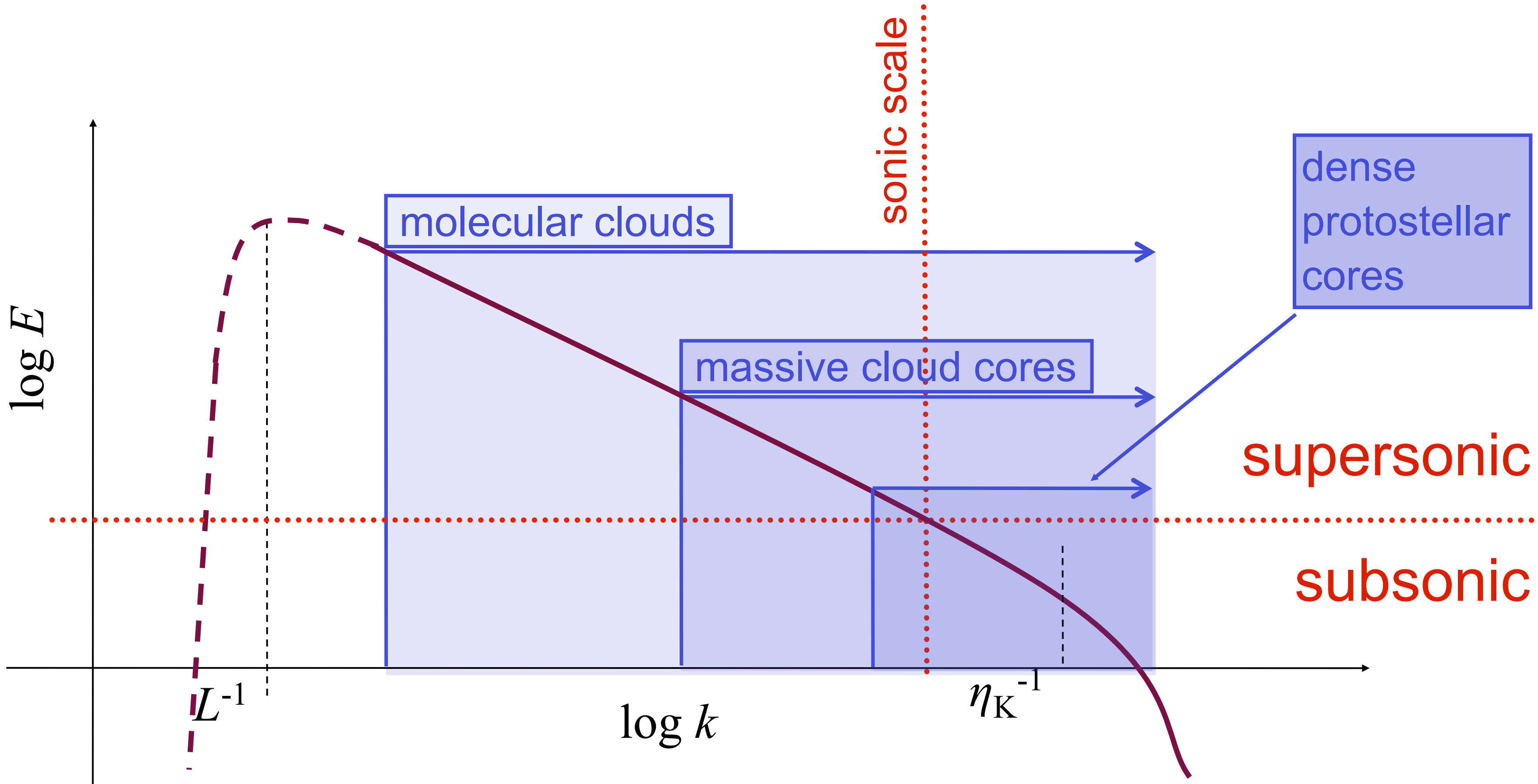
Turbulent cascade in ISM

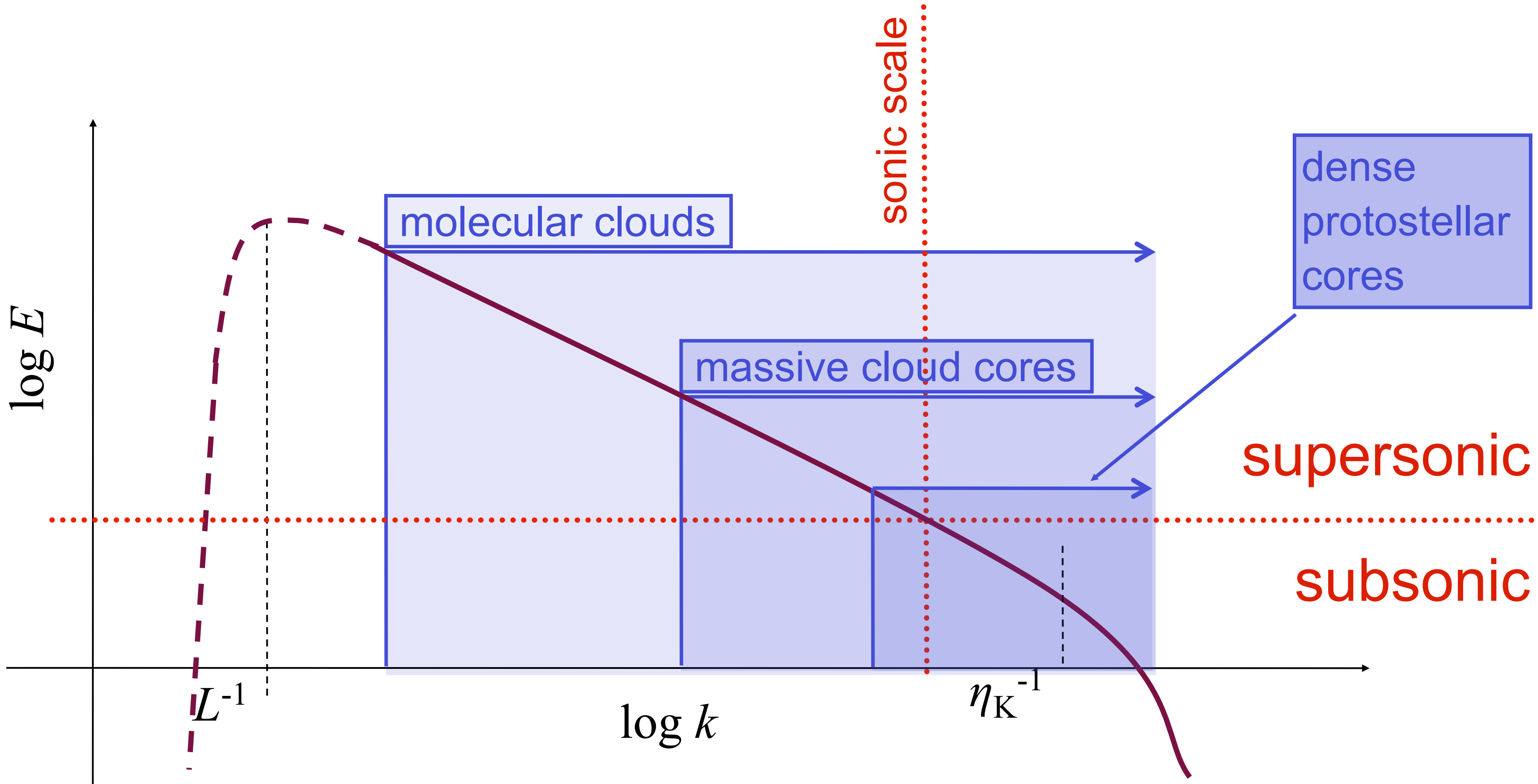


energy source & scale
NOT known

σ_{rms} << 1 km/s
$M_{rms} \le 1$
L ≈ 0.1 pc

dissipation scale not known
(ambipolar diffusion,
molecular diffusion?)

Turbulent cascade in ISM

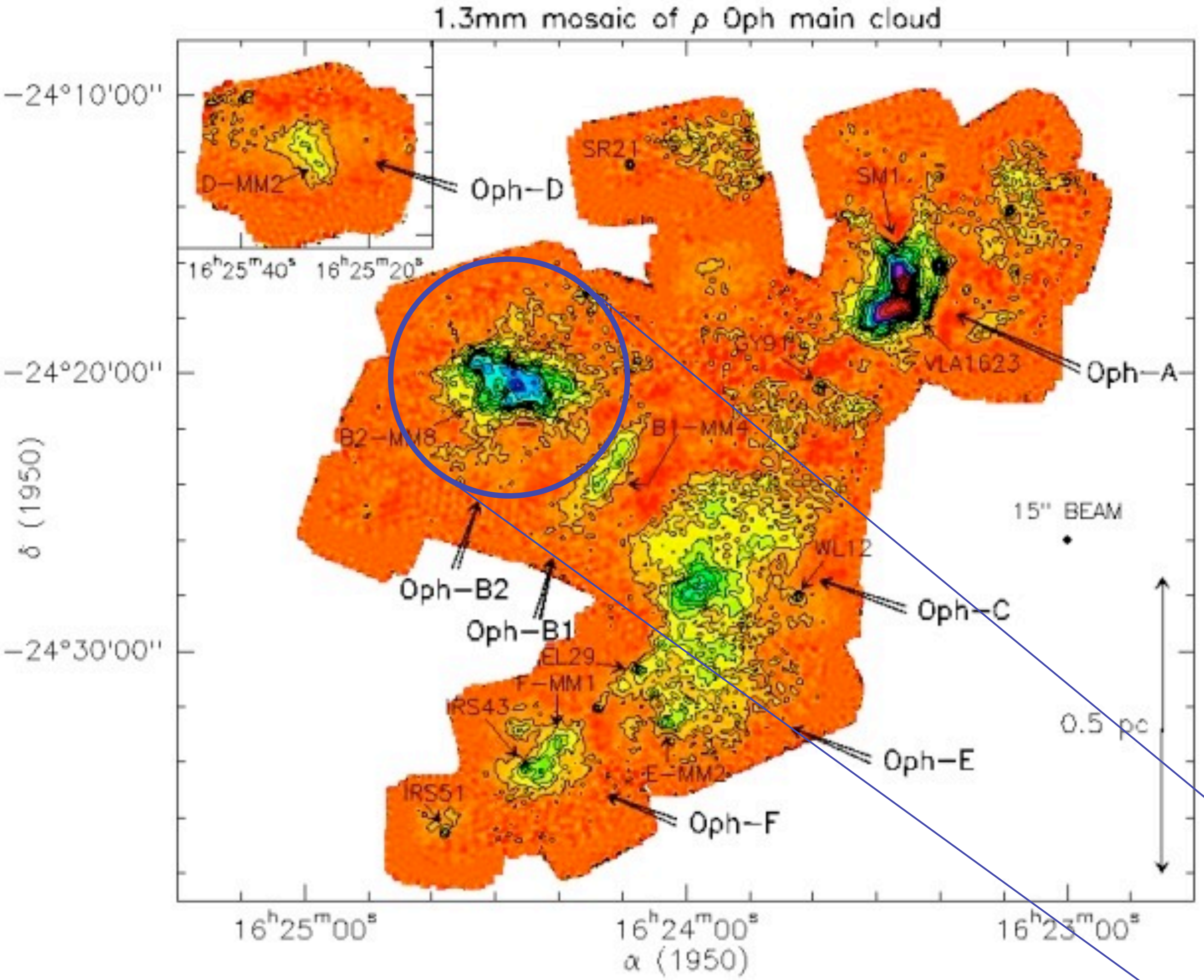


energy source & scale *NOT known* (supernovae, winds, global instabilities, ***accretion***)

σ_{rms} << 1 km/s
$M_{rms} \leq 1$
L ≈ 0.1 pc

dissipation scale not known (ambipolar diffusion, molecular diffusion?)

Density structure of MC's



(Motte, André, & Neri 1998)

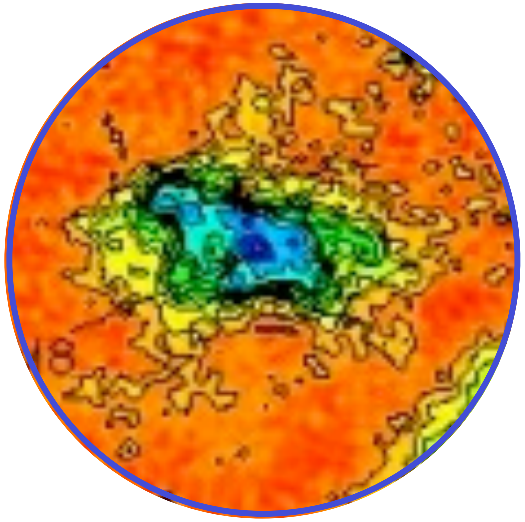
molecular clouds are highly inhomogeneous

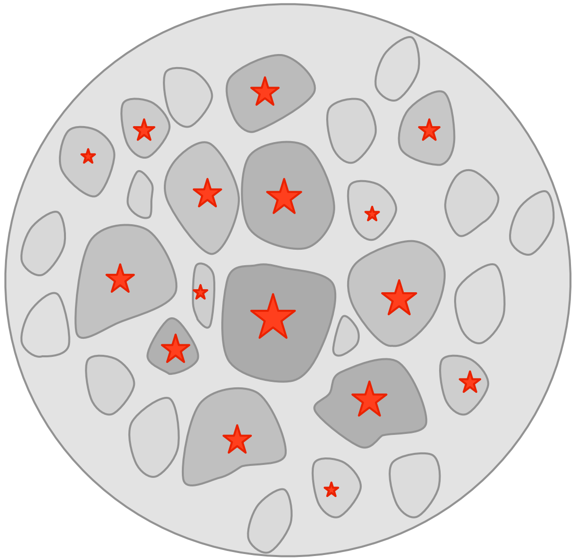
stars form in the densest and coldest parts of the cloud

ρ-Ophiuchus cloud seen in dust emission

let's focus on a cloud core like this one

Evolution of cloud cores

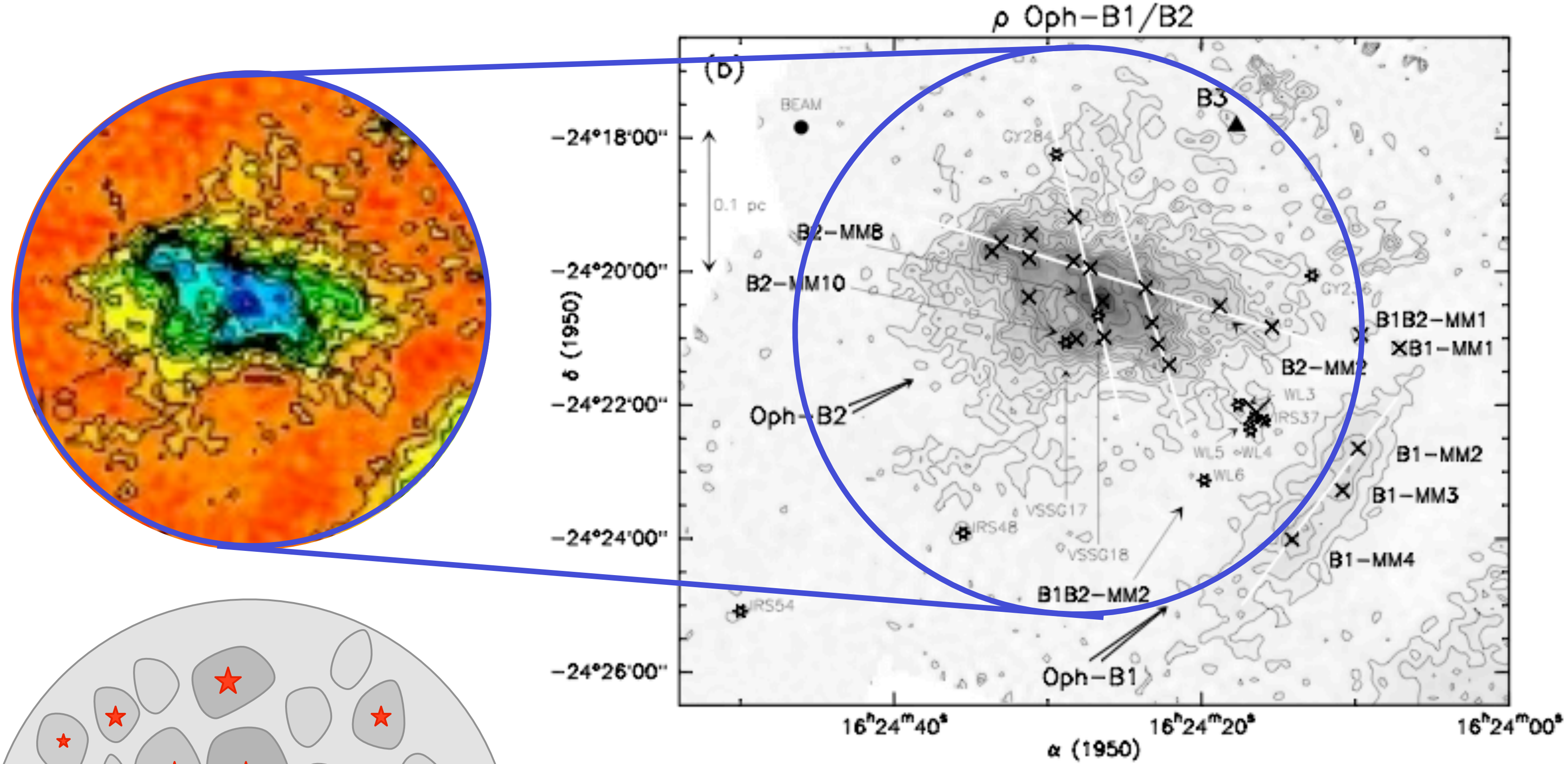


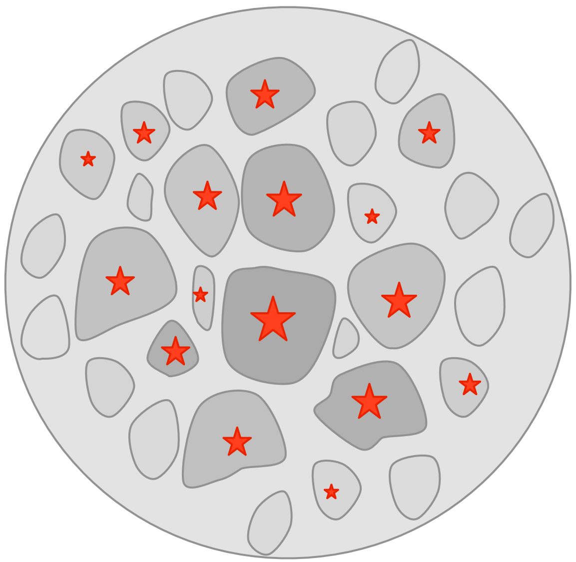


- How does this core evolve?
  Does it form one single massive star or cluster with mass distribution?

- Turbulent cascade „goes through“ cloud core
  --> NO *scale separation* possible
  --> NO *effective sound speed*
- Turbulence is supersonic!
  --> produces strong density contrasts:
  $\delta\rho/\rho \approx M^2$
  --> with typical $M \approx 10$ --> $\delta\rho/\rho \approx 100$!
- many of the shock-generated fluctuations are Jeans unstable and go into collapse
- --> expectation: *core breaks up and forms a cluster of stars*

Evolution of cloud cores



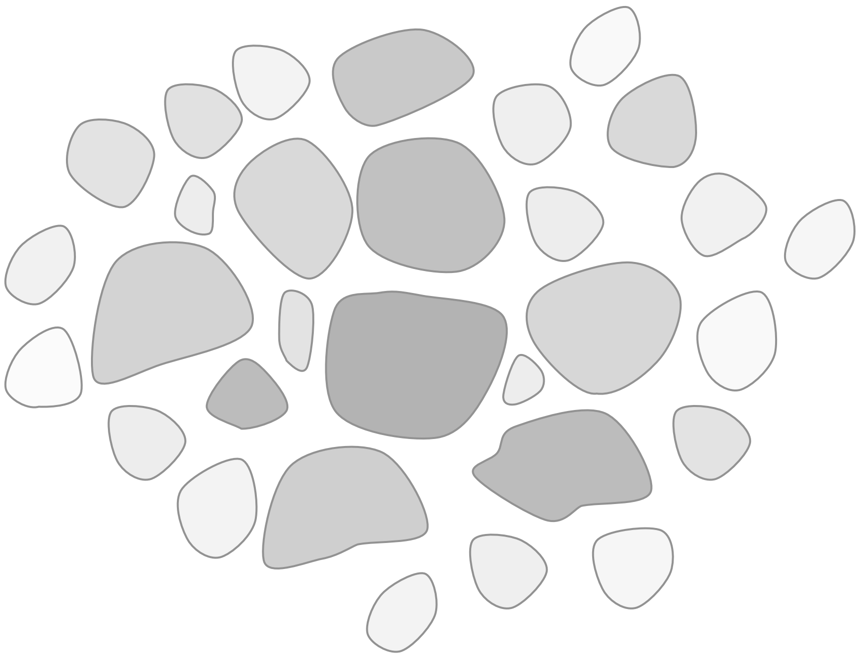


indeed ρ-Oph B1/2 contains several cores ("starless" cores are denoted by ×, cores with embedded protostars by ☆)

(Motte, André, & Neri 1998)

Formation and evolution of cores

What happens to distribution of cloud cores?



Two exteme cases:

(1) turbulence dominates energy budget:

$\alpha = E_{kin}/|E_{pot}| > 1$

--> individual cores do *not* interact

--> *collapse* of *individual* cores dominates *stellar mass growth*

--> *loose cluster of low-mass stars*

(2) turbulence decays, i.e. gravity dominates:

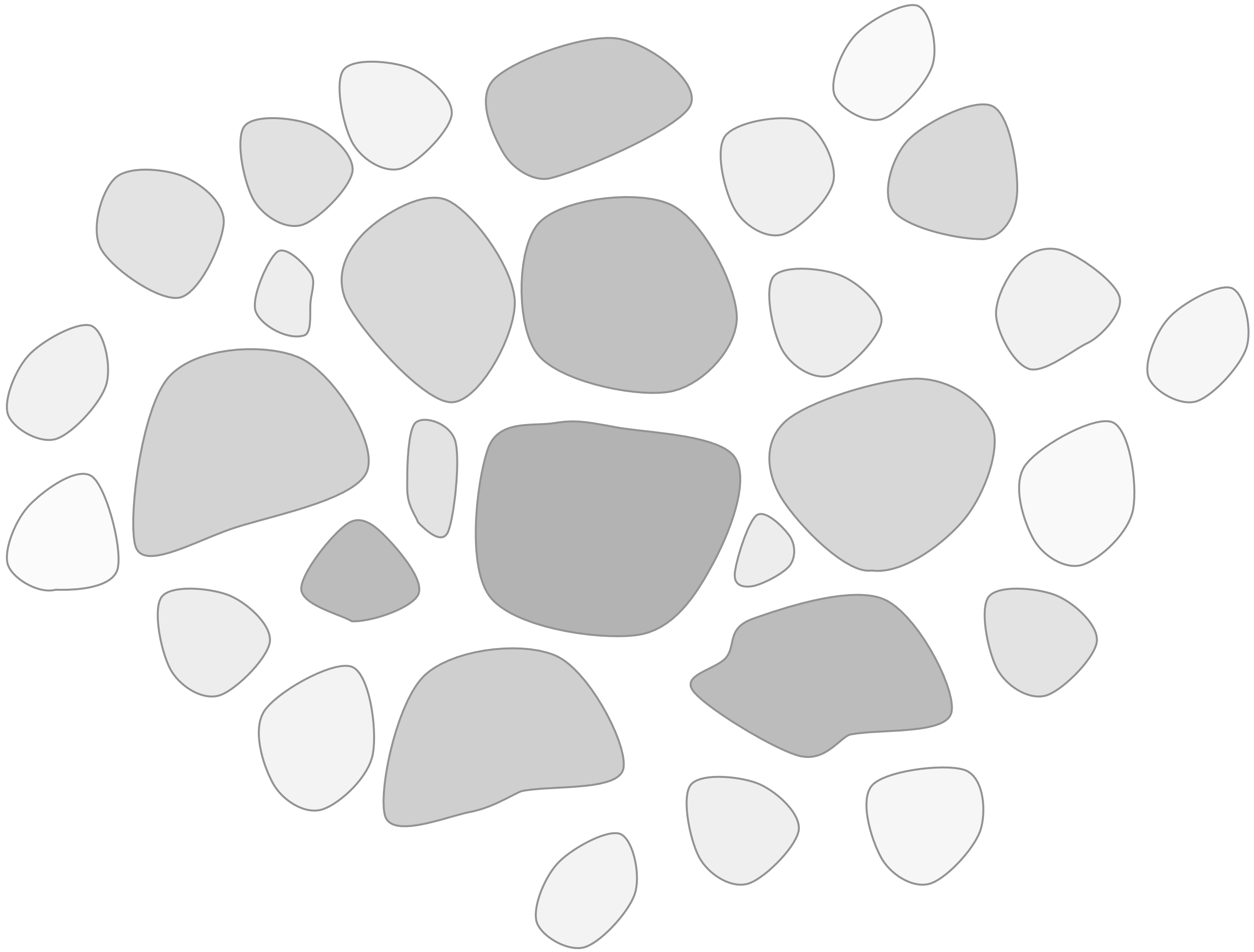
$\alpha = E_{kin}/|E_{pot}| < 1$

--> *global contraction*

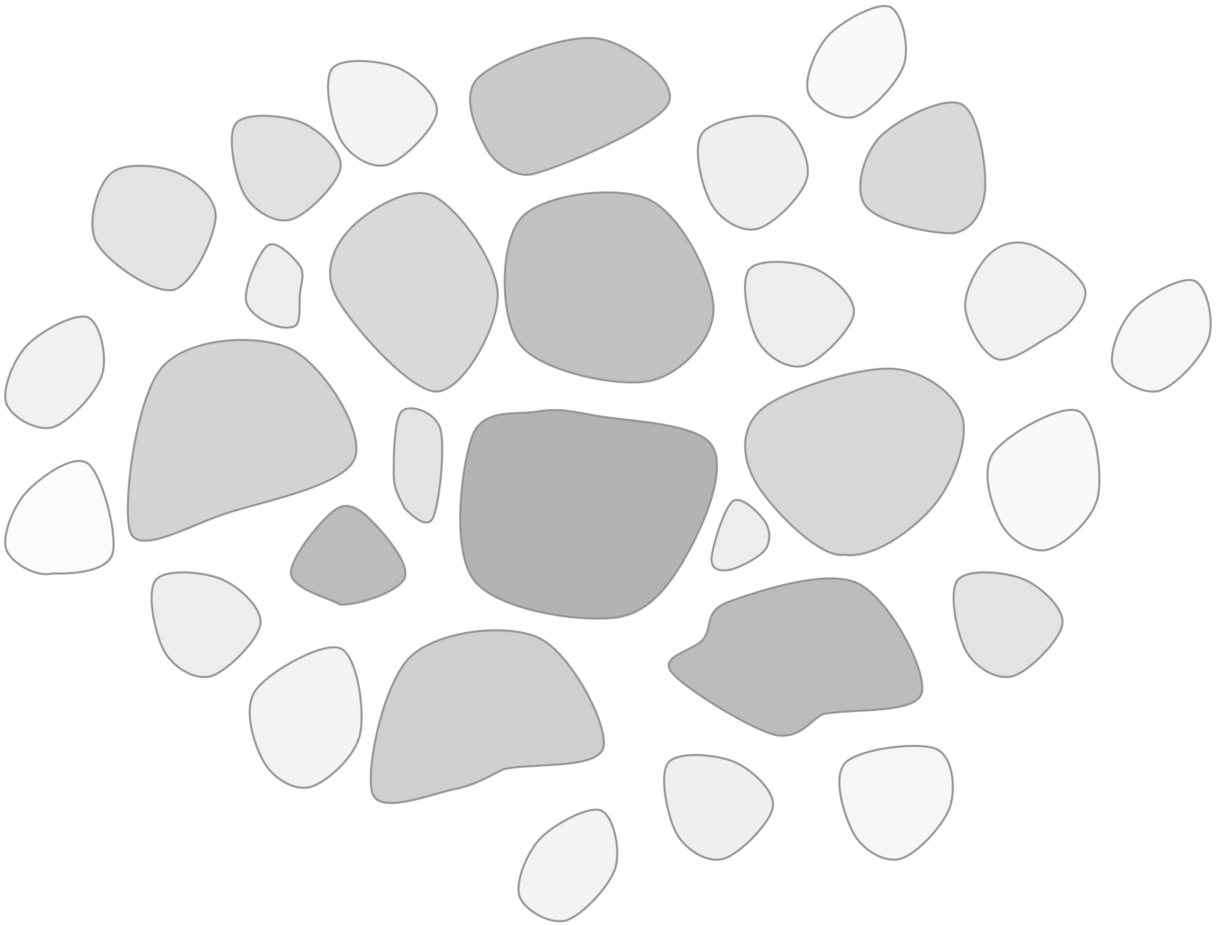
--> core do *interact* while collapsing

--> *competition* influences *mass growth*

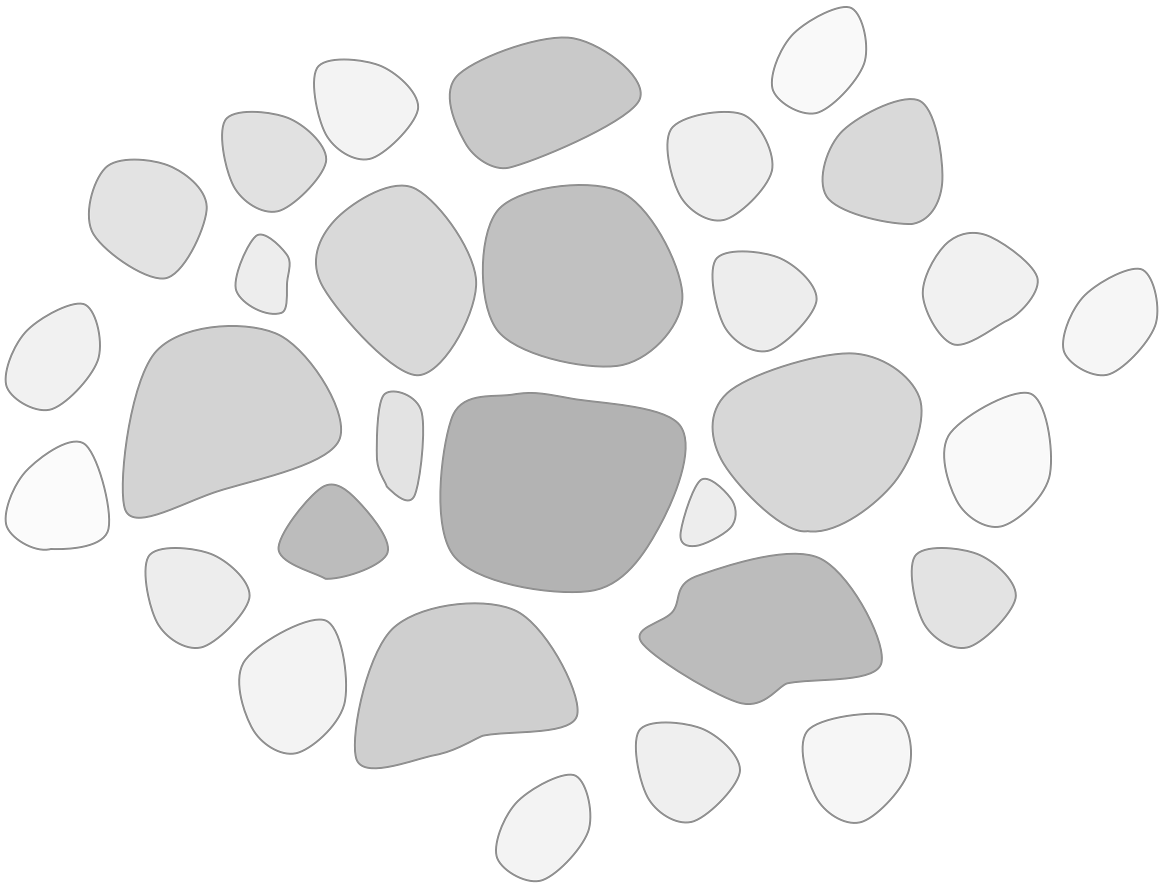
--> *dense cluster with high-mass stars*



turbulence creates a hierarchy of clumps



as turbulence decays locally, contraction sets in



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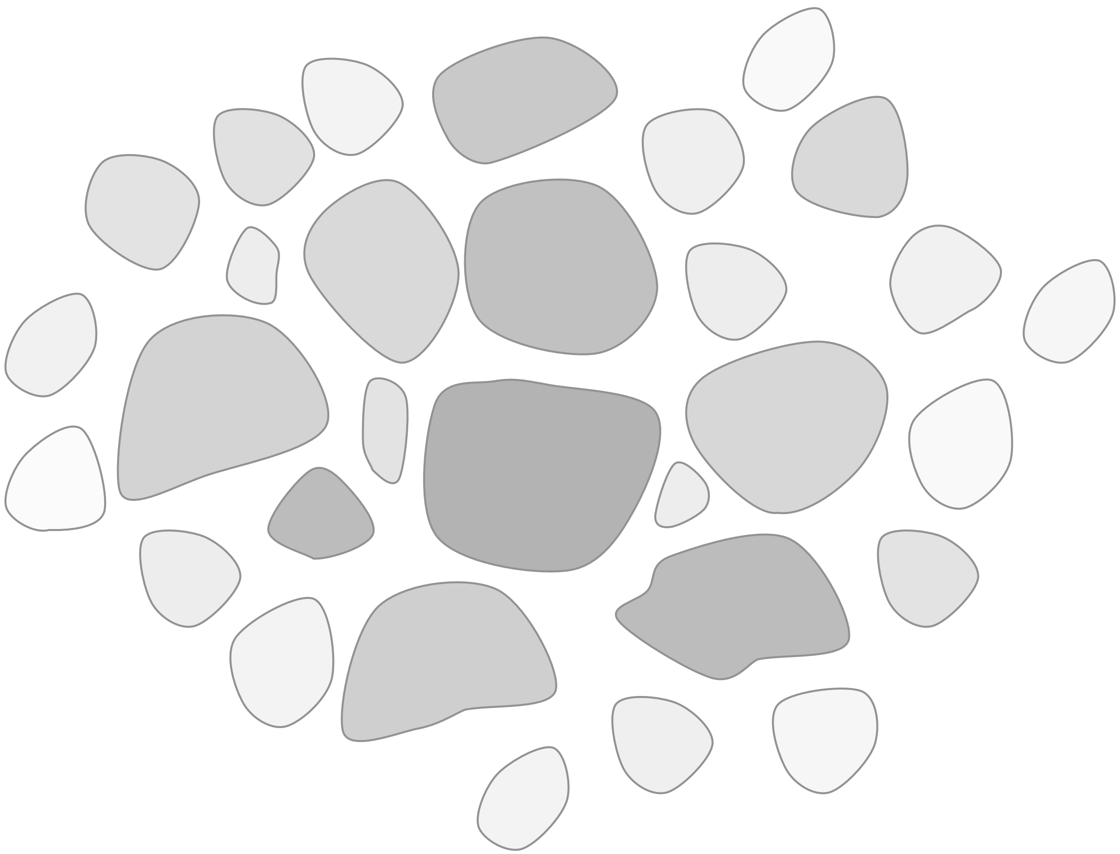
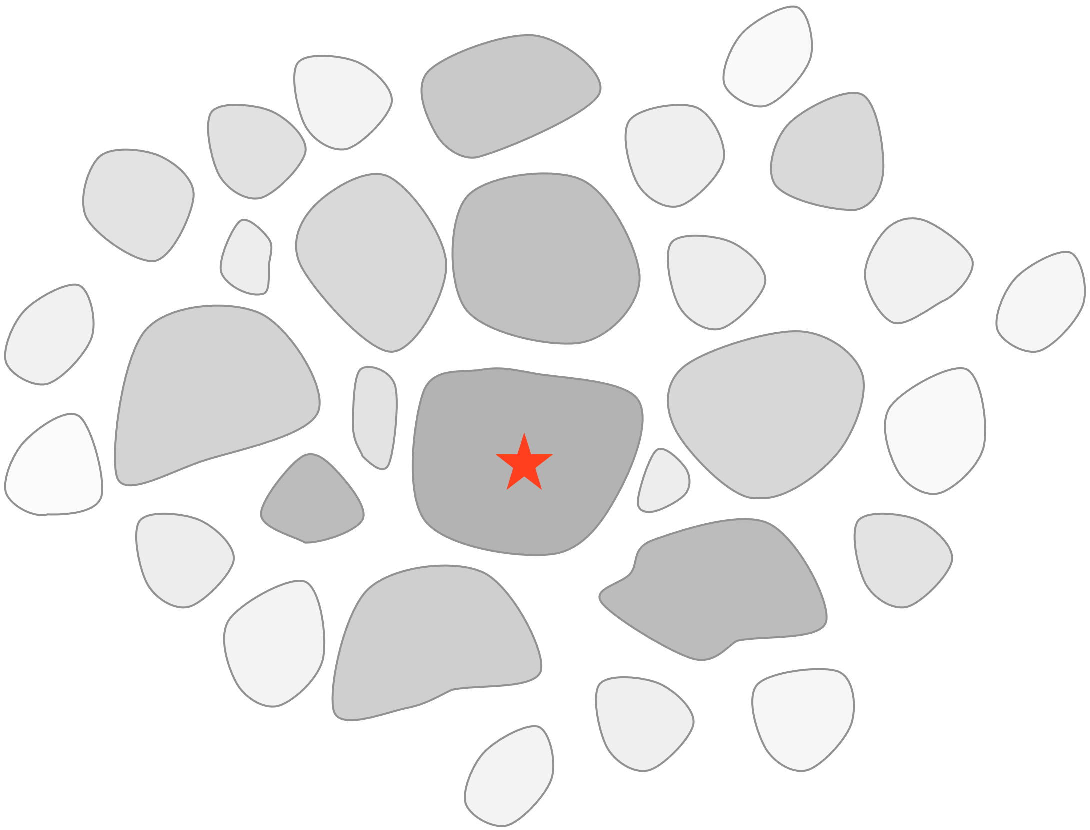


while region contracts, individual clumps collapse to form stars



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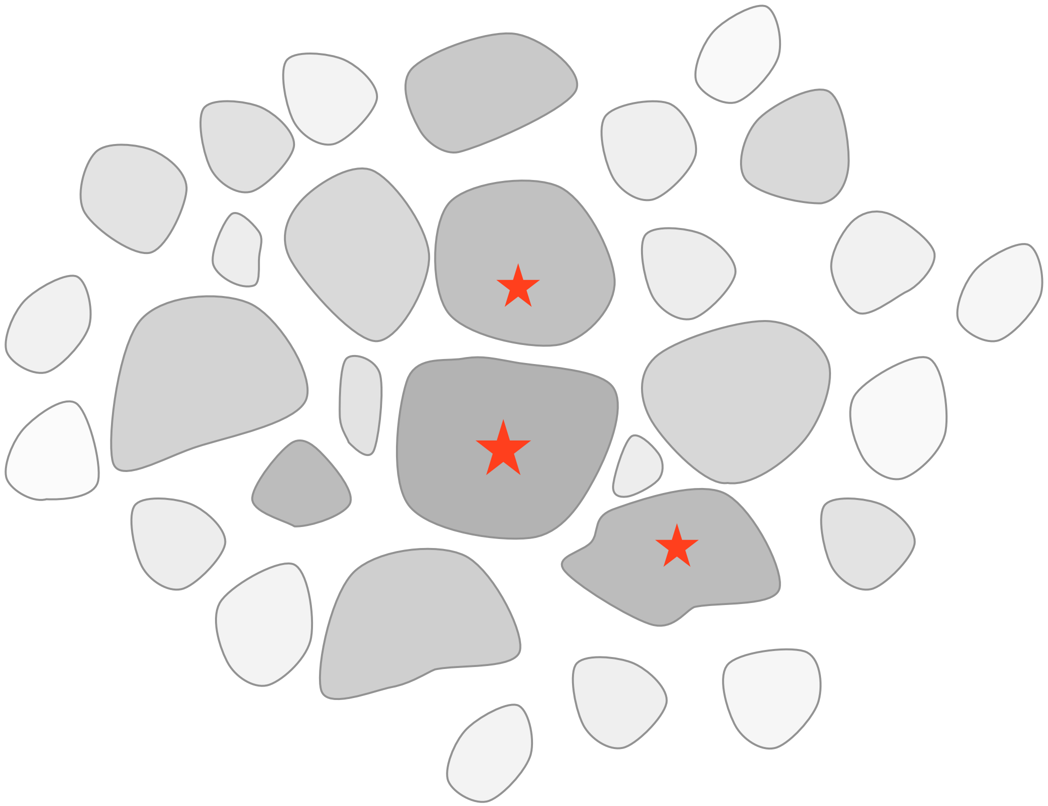

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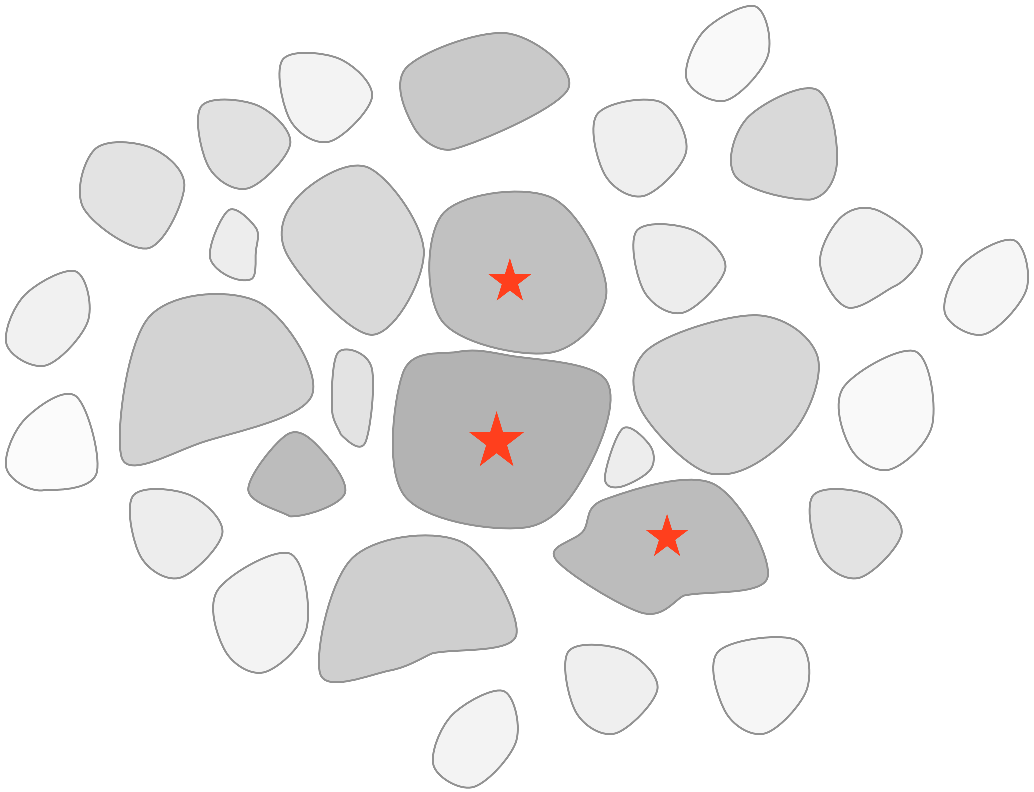

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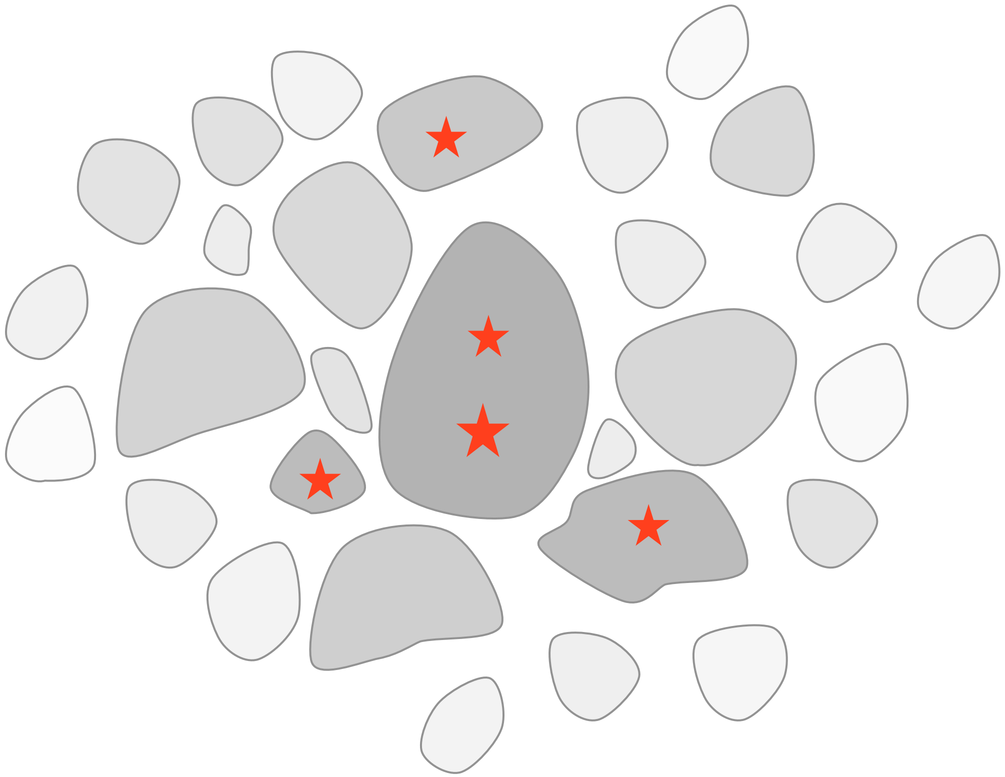
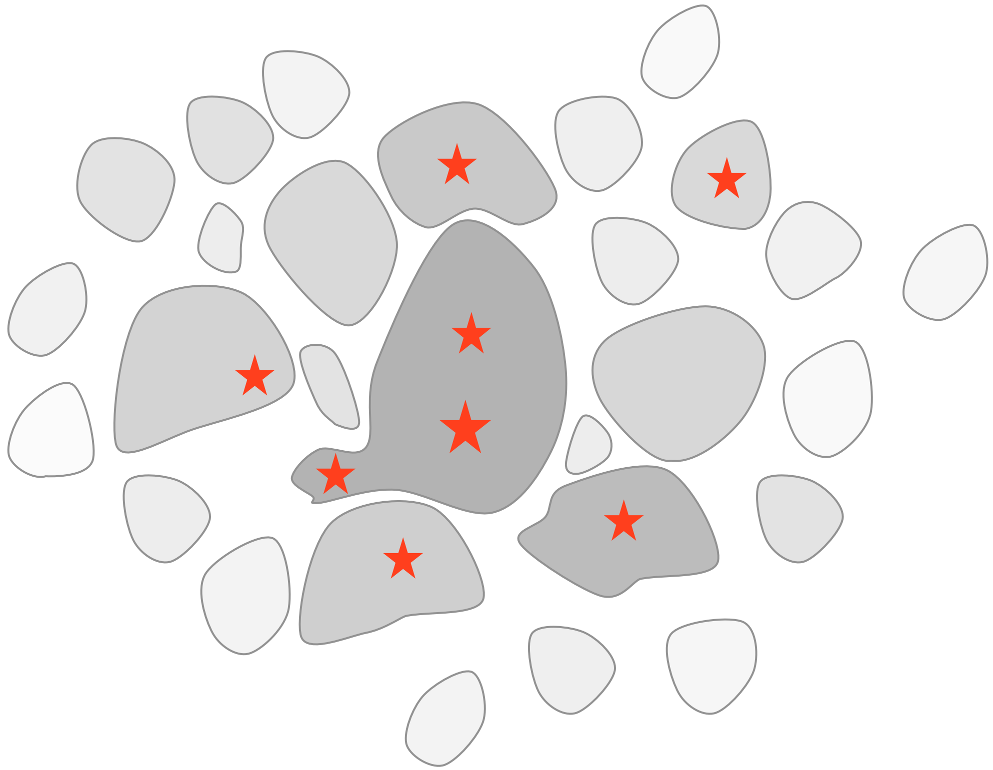


$\alpha = E_{kin}/|E_{pot}| < 1$

in *dense clusters*, clumps may merge while collapsing
--> then contain multiple protostars



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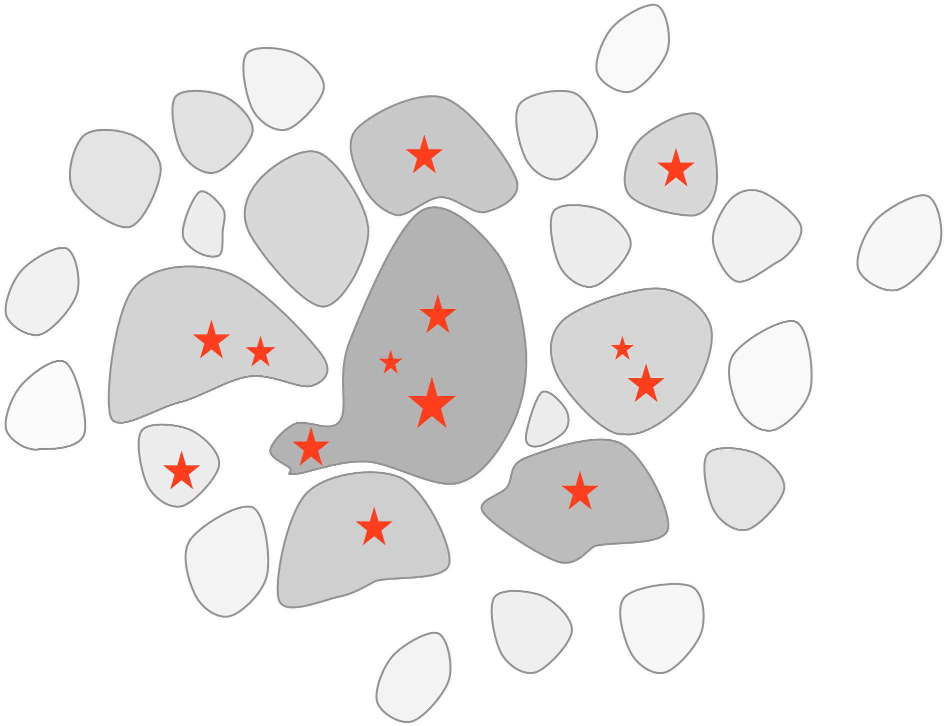

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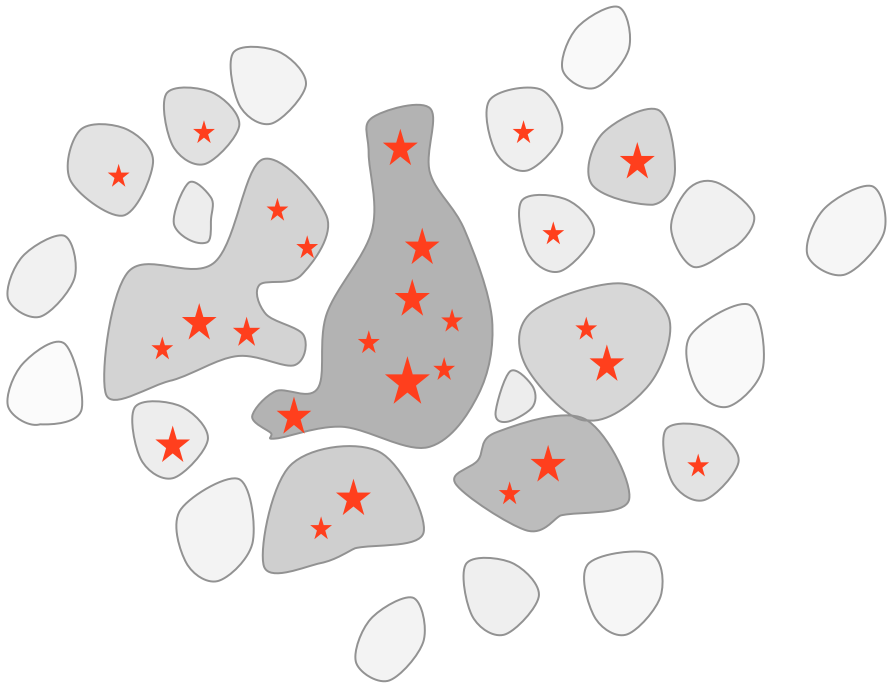
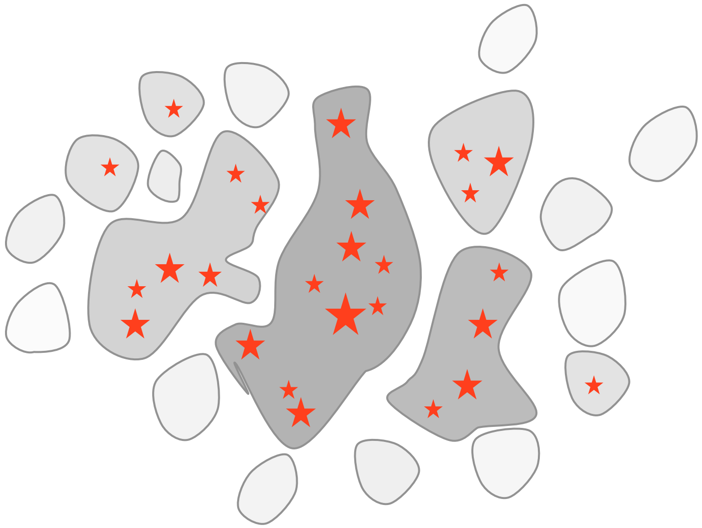


in *dense clusters*, competitive mass growth becomes important



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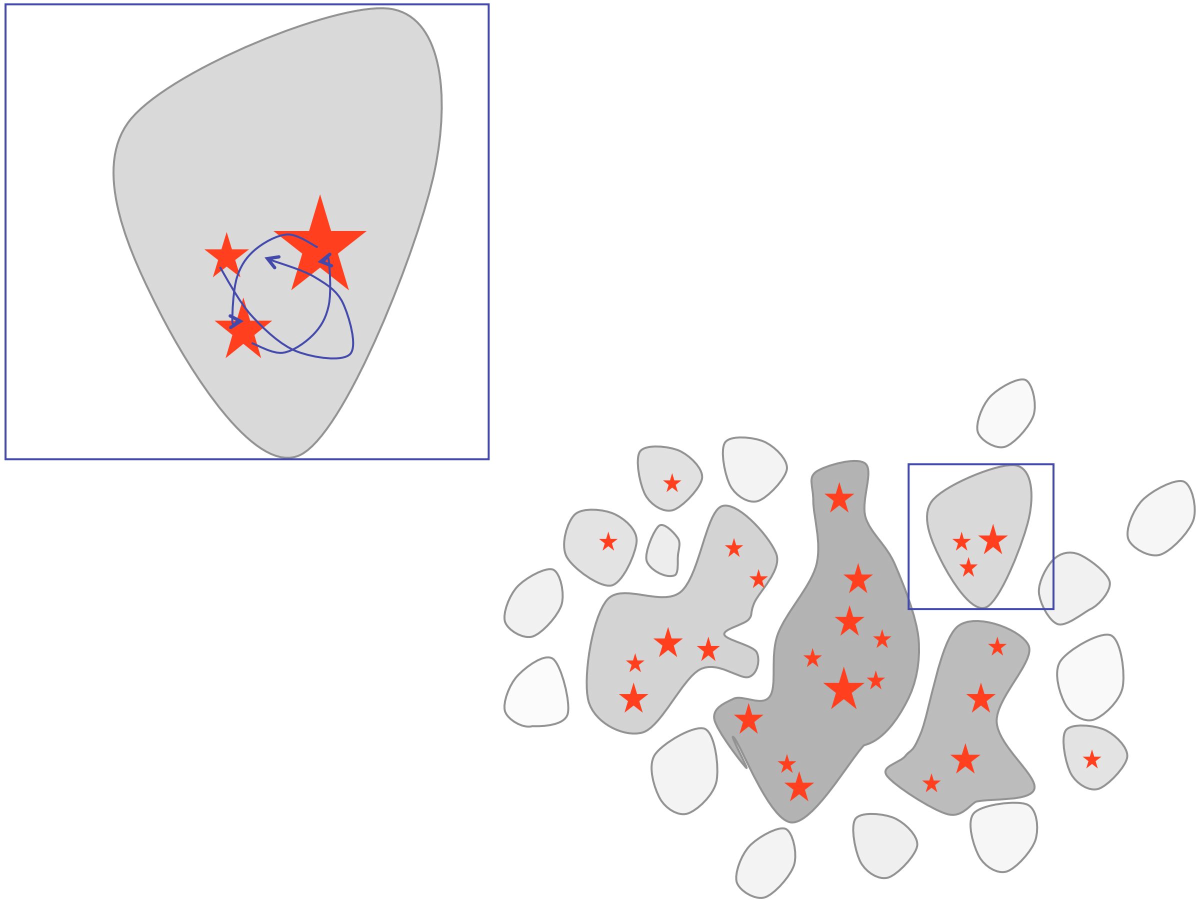
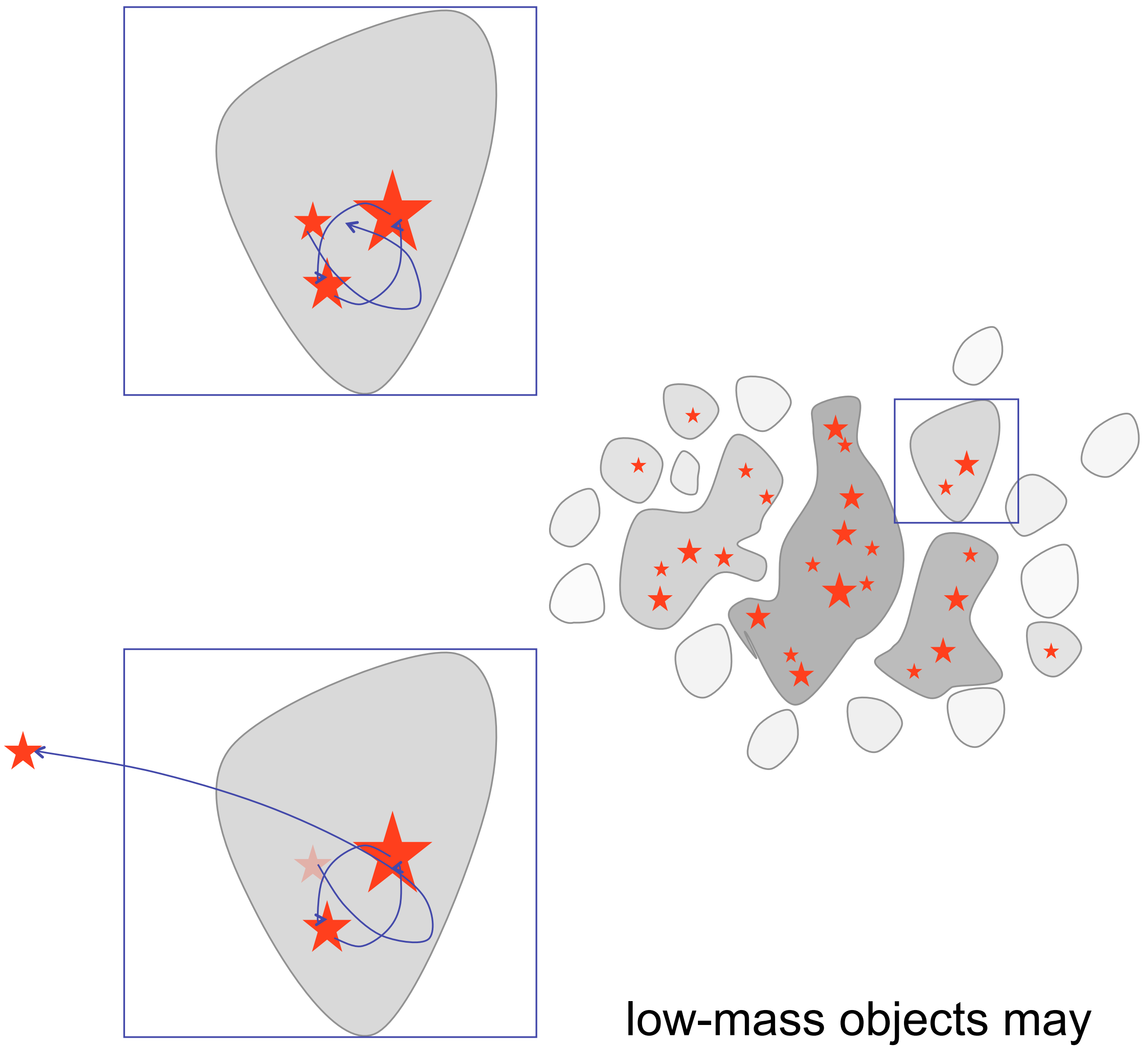
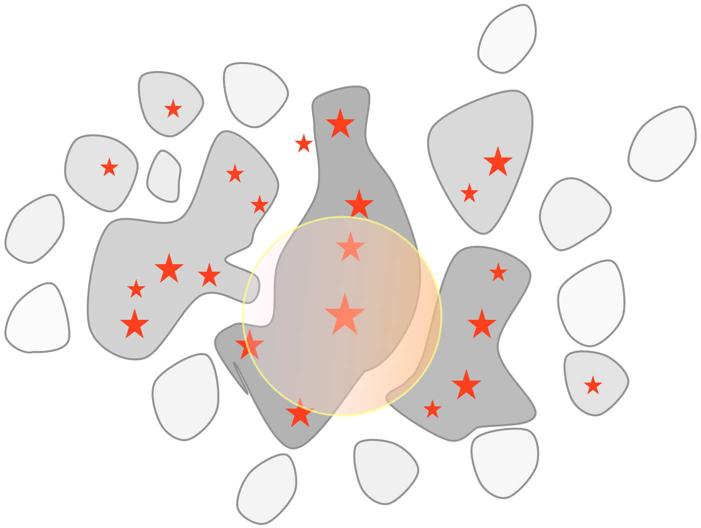


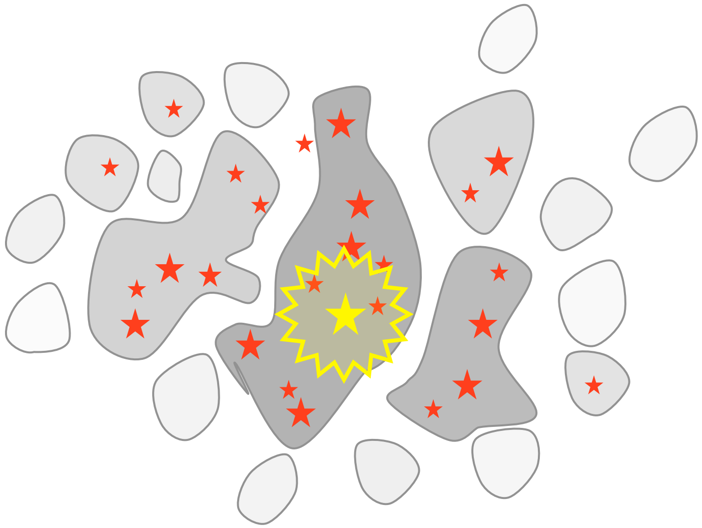
in *dense clusters*, *N*-body effects influence mass growth



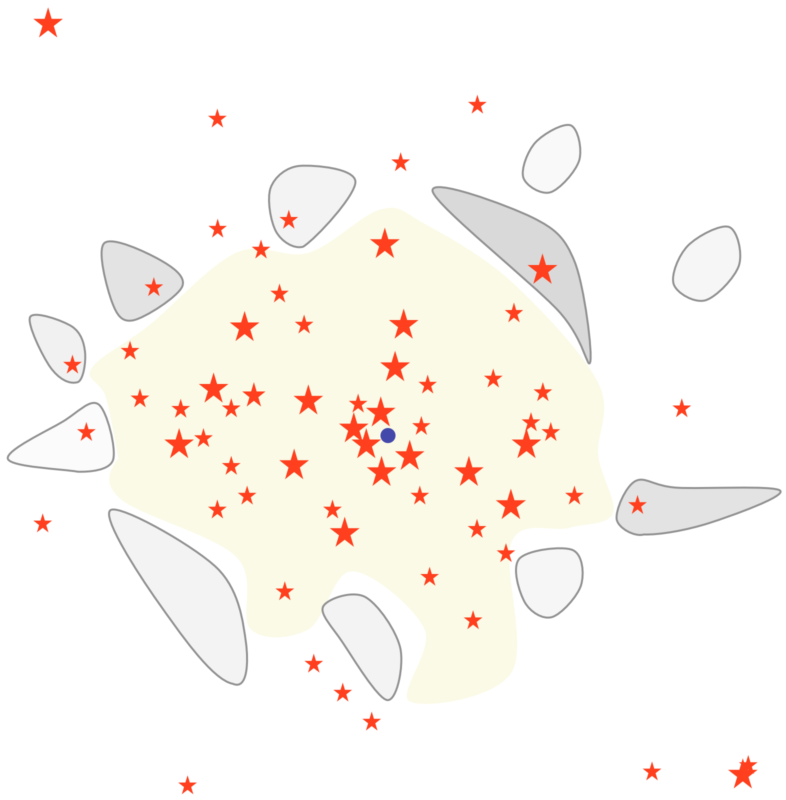
low-mass objects may
become ejected --> accretion stops



feedback could influence fragmentation behavior



feedback terminates star formation



result: *star cluster*, possibly with HII region

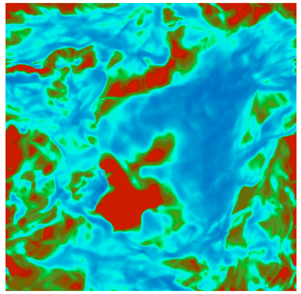
NGC 602 in the LMC: Hubble Heritage Image

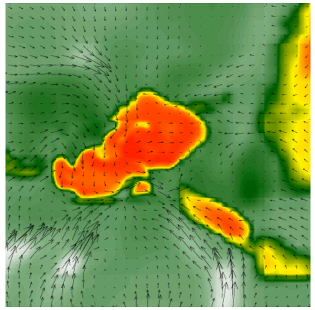
result: *star cluster* with HII region

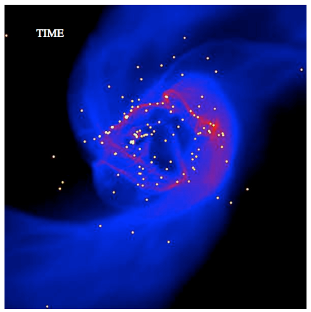
controversies & open questions

agenda

- a simple cartoon picture
  - *dynamic star formation theory*
- controversial issues & open issues
  - *what drives turbulence?*
  - *how do high-mass stars & their clusters form?*
  - *initial conditions for cluster formation?*
  - *importance of thermodynamics, or are there (still) low-mass Pop III stars?*
  - *magnetic fields at z~20?*
- TreeCol
  - *tree-based radiative transfer*







key questions

- *what drives turbulence?*
  --> accretion driven turbulence on ALL scales
  galaxies, molecular clouds, protostellar disks
- *how do high-mass stars & their clusters form?*
  --> fragmentation-induced starvation
- *what are the initial conditions for cluster formation?*
  --> initial density profile matters
- *are there (still) low-mass metal-free stars?*
  --> importance of thermodynamics
- *magnetic fields in the early universe?*
  --> generation of the first strong fields by turbulent dynamos

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what drives ISM turbulence?

- seems to be driven on large scales, and there is little difference between star-forming and non-SF clouds
  - *rules out internal sources*
- proposals in the literature
  - *supernovae*
  - *expanding HII regions / stellar winds / outflows*
  - *spiral density waves*
  - *magneto-rotational instability*
  - *new idea: accretion onto disk*

accretion driven turbulence

- thesis:
  - astrophysical objects *form* by *accretion* of ambient material
  - the *kinetic energy* associated with this process is a key agent *driving internal turbulence*.
  - this works on *ALL* scales:
    - galaxies
    - molecular clouds
    - protostellar accretion disks

Klessen & Hennebelle (2010, A&A, 520, A17)

concept

- turbulence decays on a crossing time

$$\tau_{\rm d} \approx \frac{L_{\rm d}}{\sigma}$$

- energy decay rate

$$\dot{E}_{\rm decay} \approx \frac{E}{\tau_{\rm d}} = -\frac{1}{2}\frac{M\sigma^3}{L_{\rm d}}$$

- kinetic energy of infalling material

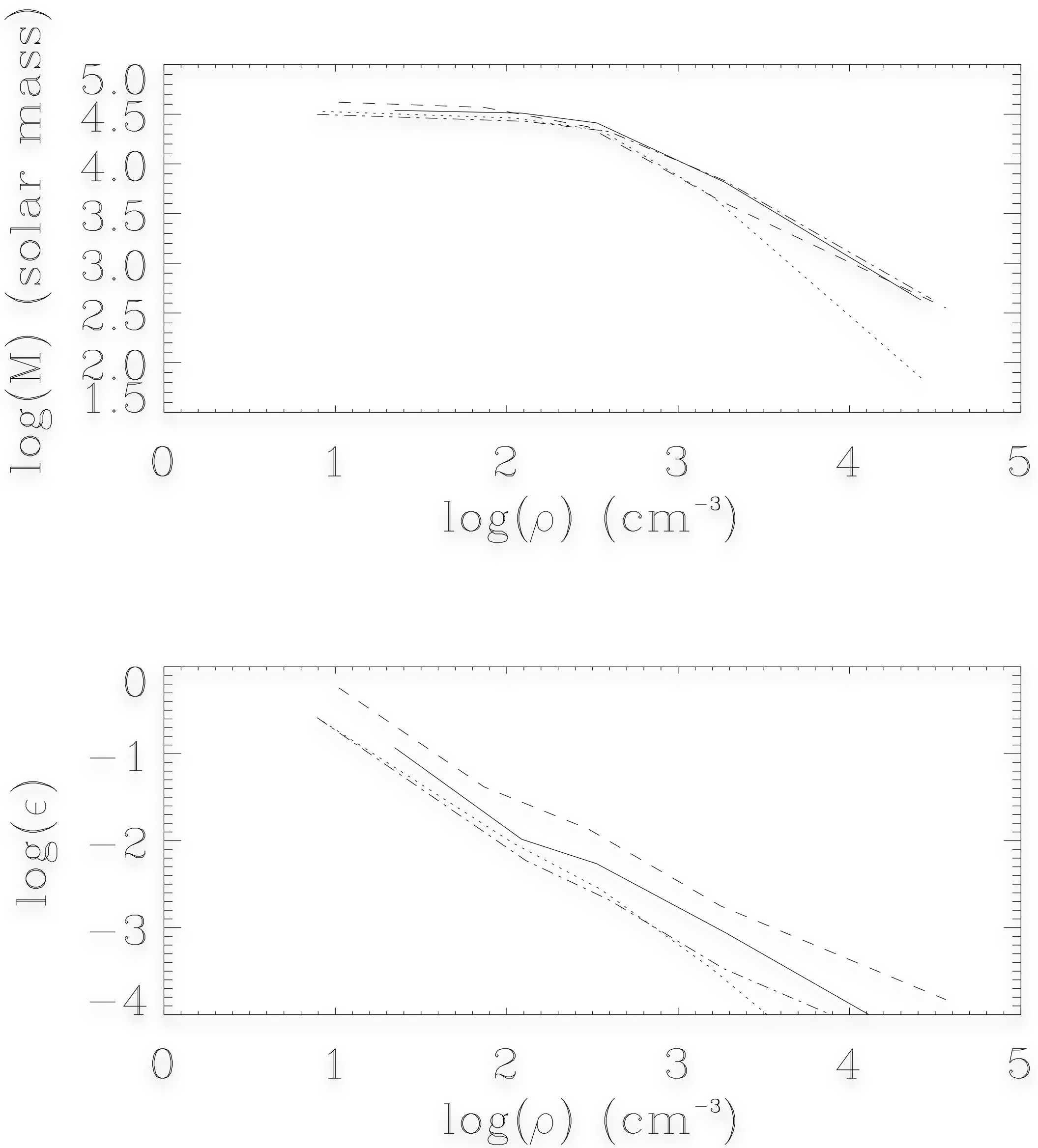
$$\dot{E}_{\rm in} = \frac{1}{2}\dot{M}_{\rm in}v_{\rm in}^2$$

- can both values match, modulo some efficiency?

$$\epsilon = \left|\frac{\dot{E}_{\rm decay}}{\dot{E}_{\rm in}}\right|$$

Klessen & Hennebelle (2010, A&A, 520, A17)

some estimates from convergent flow studies



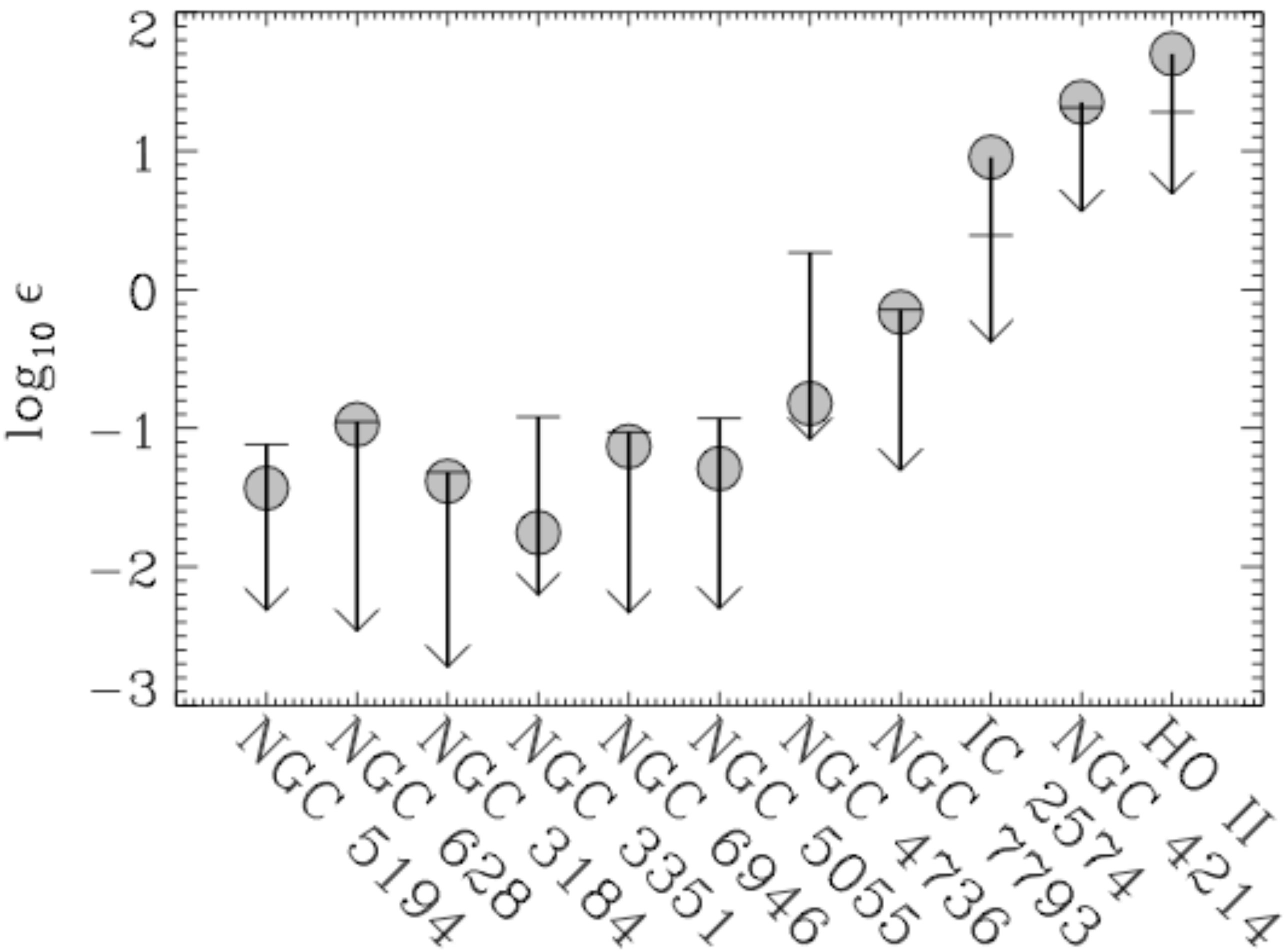
Klessen & Hennebelle (2010, A&A, 520, A17)

application to galaxies

- underlying assumption
  - galaxy is in steady state
    ---> accretion rate equals star formation rate
  - what is the required efficiency for the method to work?
- study Milky Way and 11 THINGS
  - excellent observational data in HI:
    velocity dispersion, column density, rotation curve

Klessen & Hennebelle (2010, A&A, 520, A17)

11 THINGS galaxies



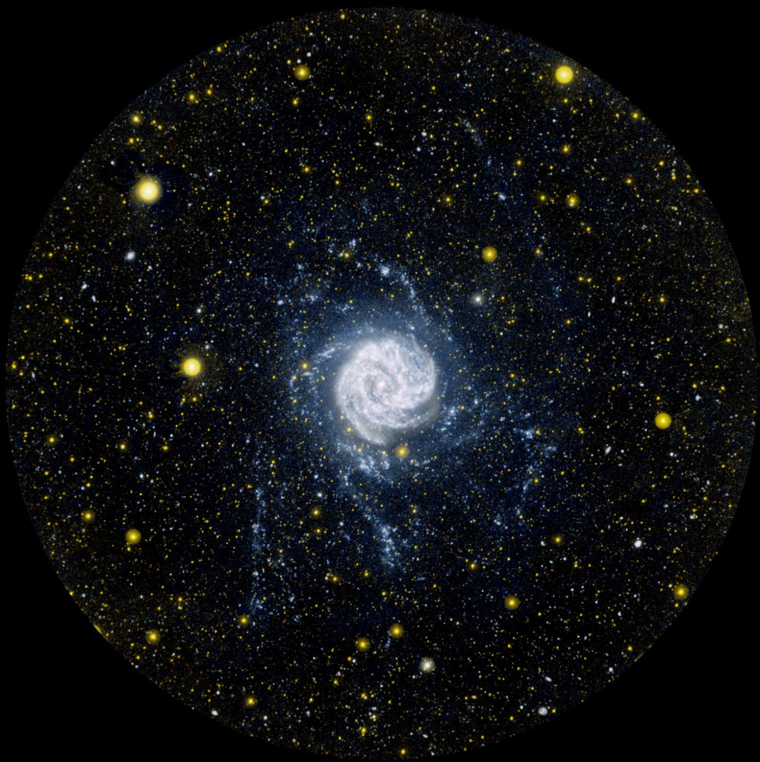
Klessen & Hennebelle (2010, A&A, 520, A17)

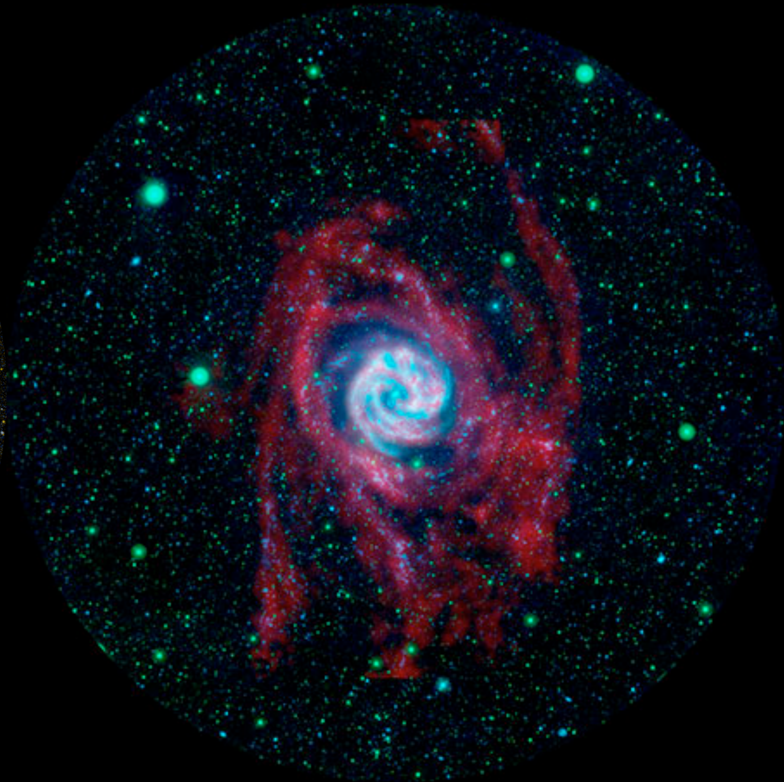
some further thoughts

- method works for Milky Way type galaxies:
  - required efficiencies are ~1% only!
- relevant for outer disks (extended HI disks)
  - there are not other sources of turbulence (certainly not stellar sources, maybe MRI)
- works well for molecular clouds
  - example clouds in the LMC (Fukui et al. 2009)
- potentially interesting for TTS
  - model reproduces dM/dt - M relation (e.g Natta et al. 2006, Muzerolle et al. 2005, Muhanty et al. 2005, Calvet et al. 2004, etc.)

Klessen & Hennebelle (2010, A&A, 520, A17)

M83

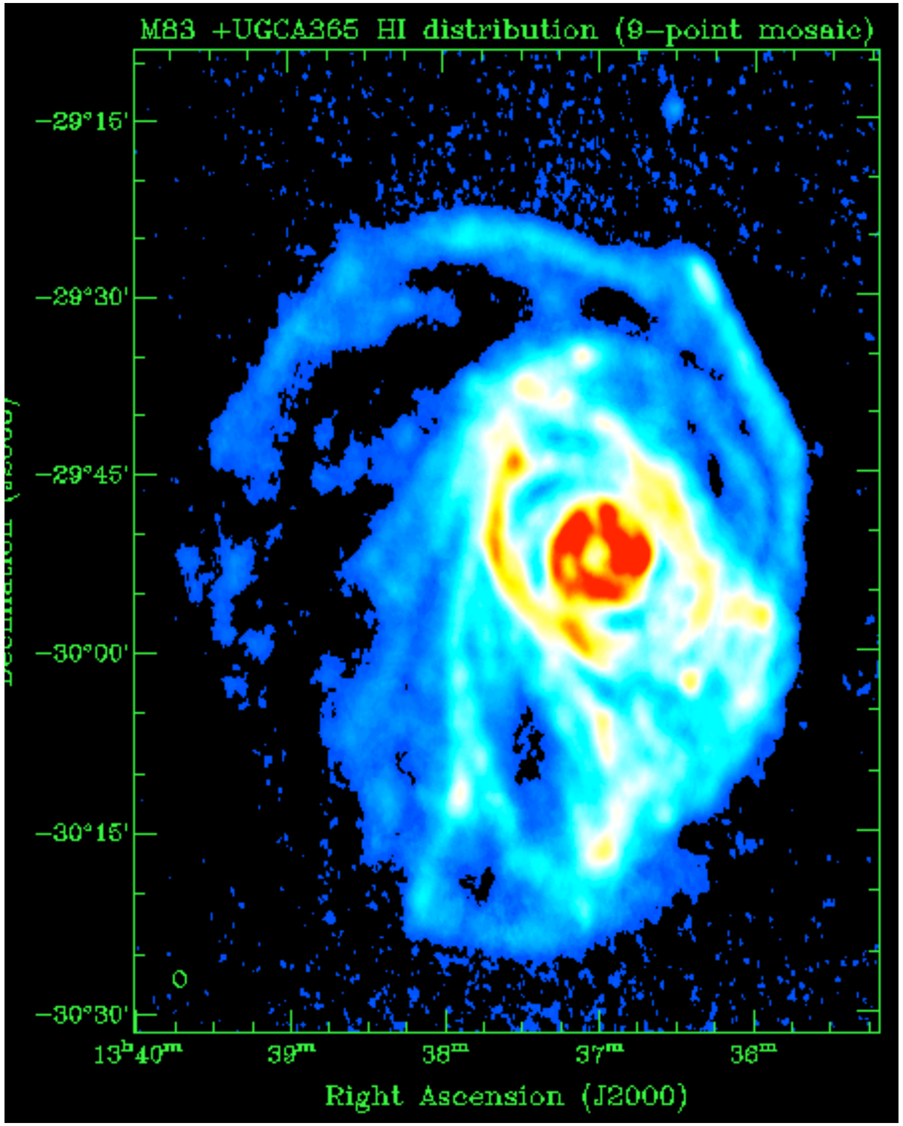




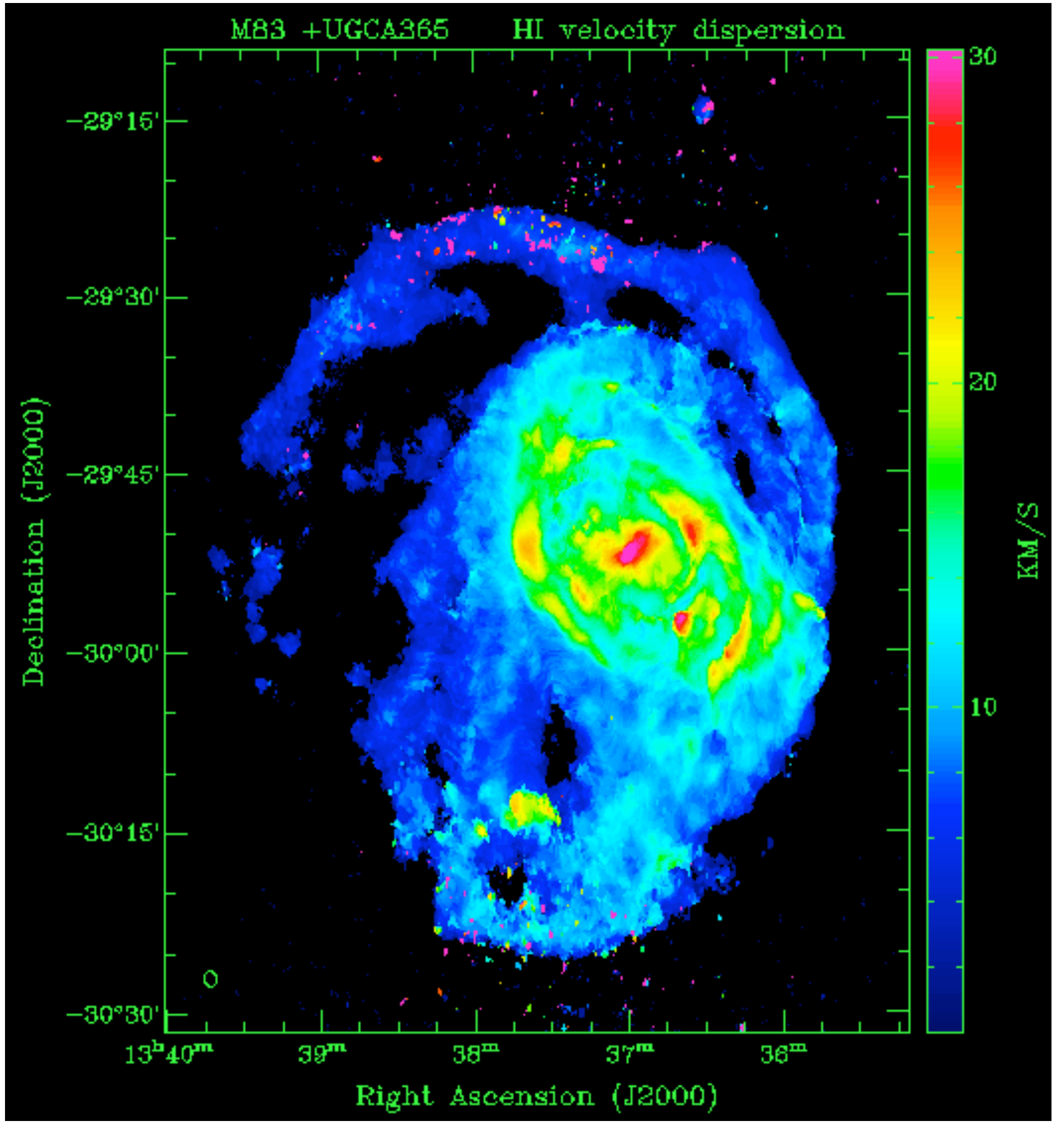
Do we actually see the flow through the disk?
ANSWER: Yes in M83!

M83

M83 HI column



M83 HI velocity dispersion



M83

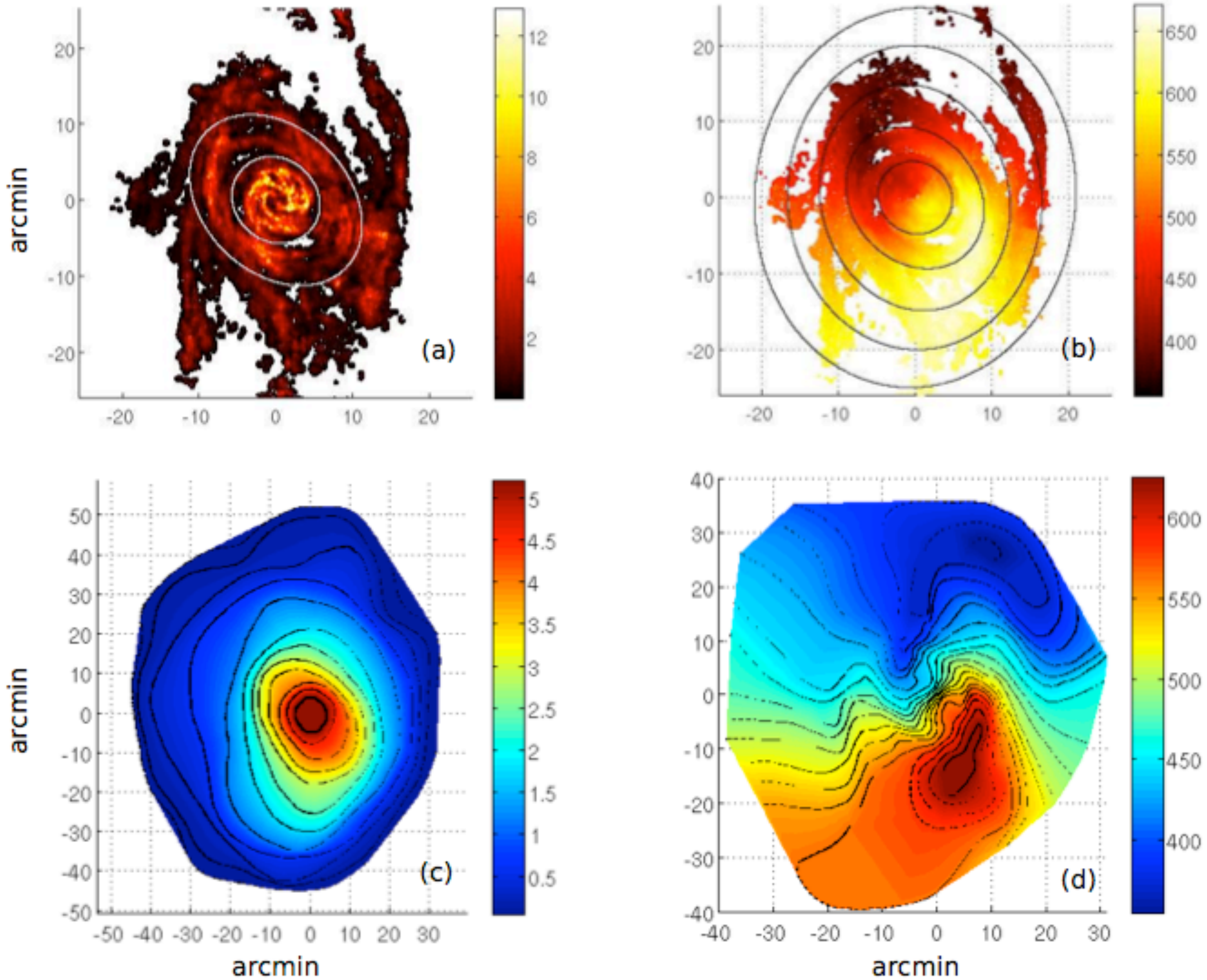


Figure 1. (a) The zeroth moment in units of $M_\odot$ pc^{-2} of the THINGS map. The white ellipses correpond to the black vertical lines ($R = 6', 12.75'$) shown in Fig. 3b, which define the region of the bright HI ring. (b) The first moment in units of km s^{-1} of the THINGS map. Each black ellipse is a result of a tilted circular ring at radii 5′, 10′, 15′, 20′, 25′, with a PA and an inclination extracted from the tilted-ring analysis. To associate structures with the corresponding radii, these ellipses serve as a coordinate system for the fiducial model with $V_{\rm max} = 180$ km s^{-1}. (c) Reconstructed HI intentisty map in units of column density $M_\odot$ pc^{-2} of the Effelsberg map. (d) Reconstructed line-of-sight velocity, $V_{\rm los}$ [km s^{-1}], of the Effelsberg map. The contours shown in (c) and (d) are extracted from HB81 and are used to reconstruct the Effelsberg map.

M83

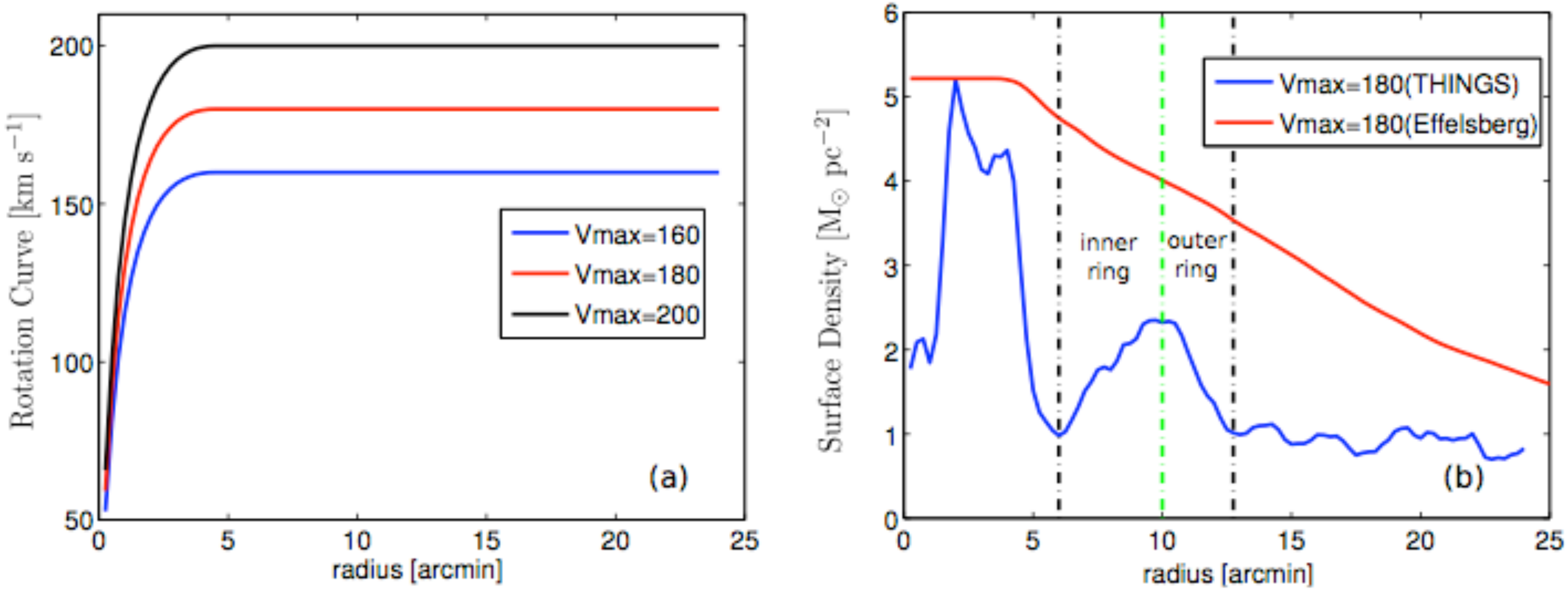


Figure 3. (a) The Brandt-type flat rotation curves as described in Eq. (13). Due to the low inclination of M83, we bracket the real situation with a range of different rotation curves and corresponding fit parameters from the tilted ring model. We assume $n = 0.8$, $R_{\rm max} = 4.5'$, $V_{\rm max} = 160, 180, 200$ km s^{-1}. As suggested in HB81, we take the model with $V_{\rm max} = 180$ as our fiducial case, which will then be justified in § 5. (b) The averaged surface density of the THINGS map (blue curve) and of the Effelsberg map (red curve). They are extracted from the fiducial model. The black vertical lines situated at $6'$ and $12.75'$ define the region of ring structure, which is also shown as the area enclosed by the white ellipses in Fig. 1a and the black ellipses in Fig. 7. The green vertical line marks the location of the density peak and further divides the ring into an inner ring and an outer ring.

M83

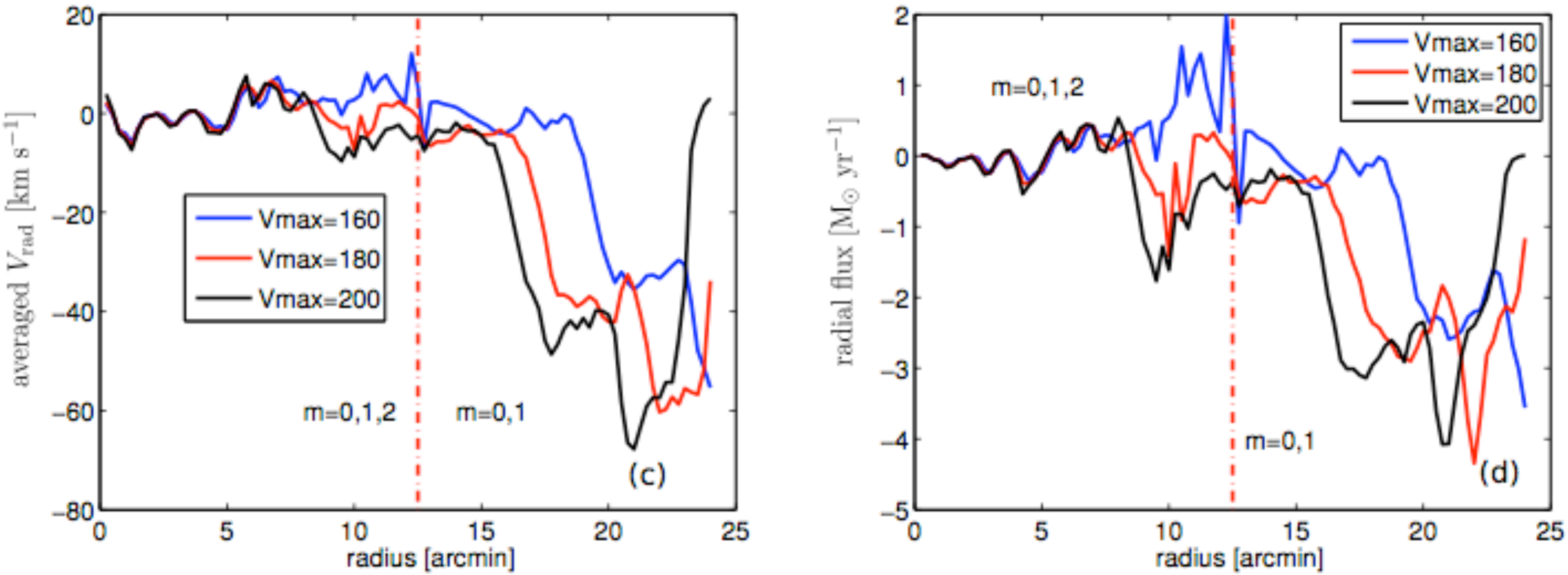


Figure 5. (a) PA and (b) inclination models used to infer radial motion of the gas in the THINGS map. (c) The inferred radial velocity. (d) The inferred radial mass flow. PA and inclination inside the vertical line ($R = 12.5'$) are extracted from the THINGS map, while in the other part we extrapolate these quantities from the Effelsberg map. The Fourier coefficients are fitted for the harmonics $m = 0, 1, 2$ for the radial regime to the left of the vertical line, while only $m = 0, 1$ for the outer parts of the map. In the outer disk, the radial shift is due the different inclinations corresponding to the different models. In all models, the common features are the prominent radial inflow in the outer disk, epicyclic motion in the transition zone (where the HI is organized into a ring like structure, see also Fig. 7 and an indication of moderate radial inflow in the inner disk.

key questions

- *what drives turbulence?*

  --> accretion driven turbulence on ALL scales
  galaxies, molecular clouds, protostellar disks

- *how do high-mass stars & their clusters form?*

  --> radiative feedback & fragmentation-induced starvation

- *what are the initial conditions for cluster formation?*

  --> initial density profile matters

- *are there (still) low-mass metal-free stars?*

  --> importance of thermodynamics

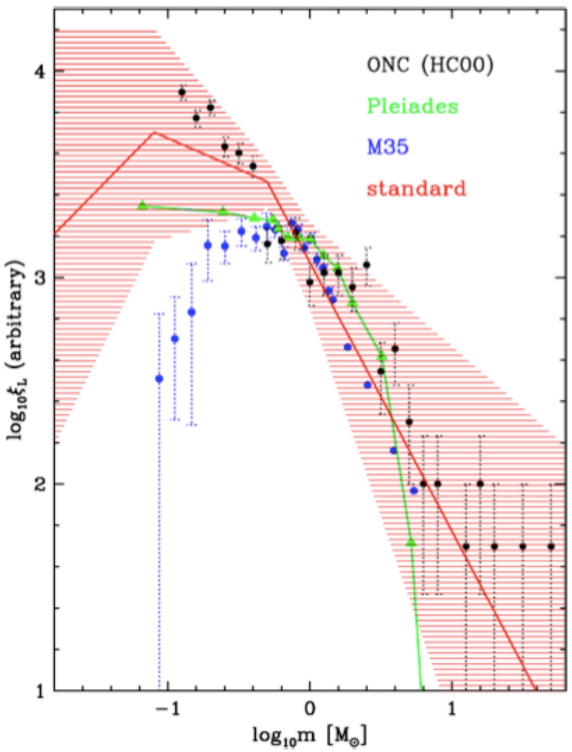
- *magnetic fields in the early universe?*

  --> generation of the first strong fields by turbulent dynamos

Introduction

We want to address the following questions:

- What determines the upper stellar mass limit?
- What is the physics behind the observed HII regions?



IMF (Kroupa 2002)

Rosetta nebula (NGC 2237)

Feedback Processes

- radiation pressure on dust particles
- ionizing radiation
- stellar wind
- jets and outflows

Feedback Processes

- radiation pressure on dust particles
- ionizing radiation
- stellar wind
- jets and outflows

Radiation Pressure

has gained the most attention in the literature, most recent simulations by Krumholz et al. 2009

Ionization

only a few numerical studies so far (eg. Dale et al. 2007, Gritschneder et al. 2009), but H II regions around massive protostars can be observed!
$\longrightarrow$ direct comparison with observations possible

high-mass star formation

- focus on collapse of individual high-mass cores...
  - massive core with 1,000 $M_\odot$
  - Bonnor-Ebert type density profile
    (flat inner core with 0.5 pc and rho ~ $r^{-3/2}$ further out)
  - initial m=2 perturbation, rotation with β = 0.05
  - sink particle with radius 600 AU and threshold density of 7 x 10^{-16} g cm^{-3}
  - cell size 100 AU

Peters et al. (2010a, ApJ, 711, 1017), Peters et al. (2010b, arXiv:1003.4998), Peters et al. (2010c,1005.3271)

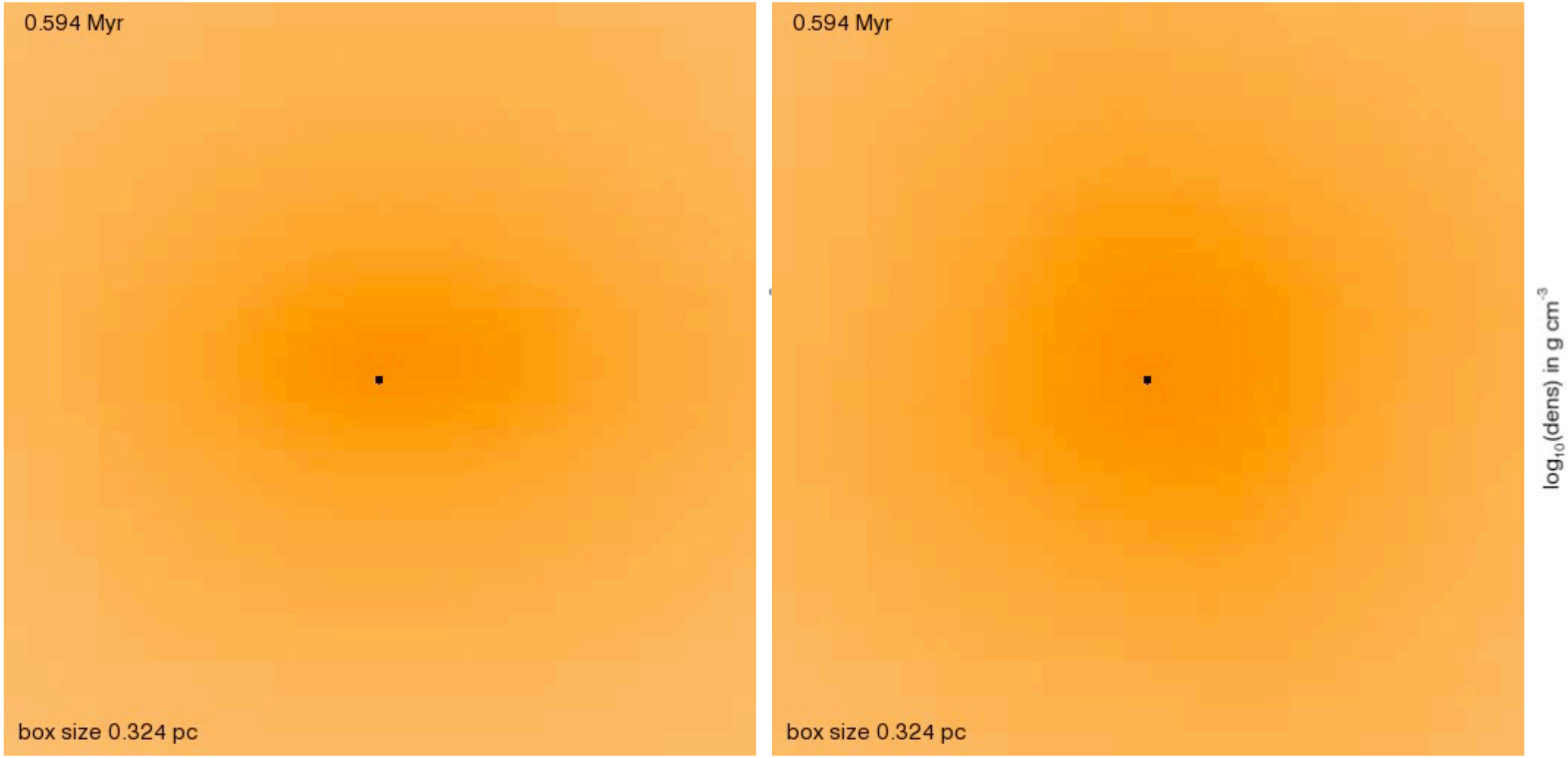
high-mass star formation

- method:
  - FLASH with ionizing and non-ionizing radiation using raytracing based on hybrid-characteristics
  - protostellar model from Hosokawa & Omukai
  - rate equation for ionization fraction
  - relevant heating and cooling processes

  - *first 3D calculations that consistently treat both ionizing and non-ionizing radiation in the context of high-mass star formation*

Peters et al. (2010a,b,c)

model with suppressed disk frag.

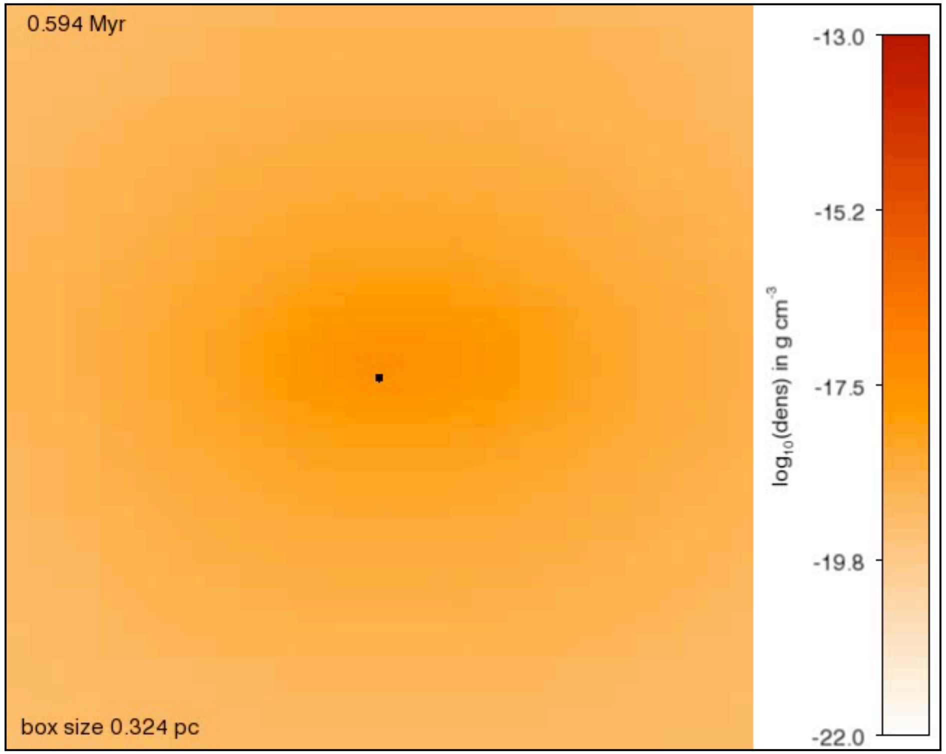


Disk edge on

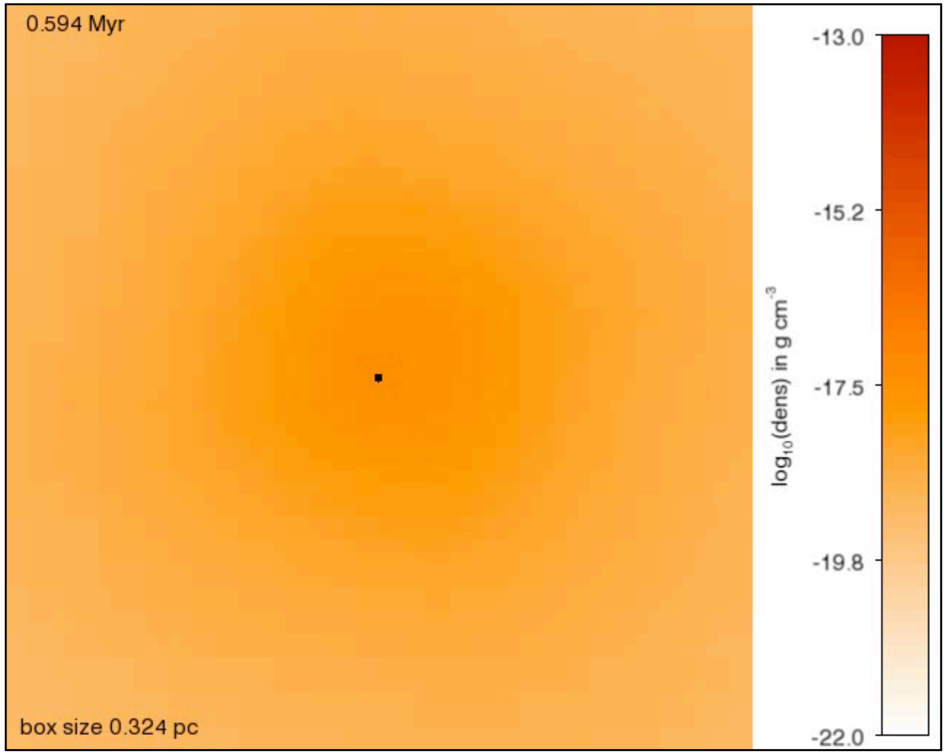
Disk plane

Peters et al. (2010a,b,c)

model with multiple protostars

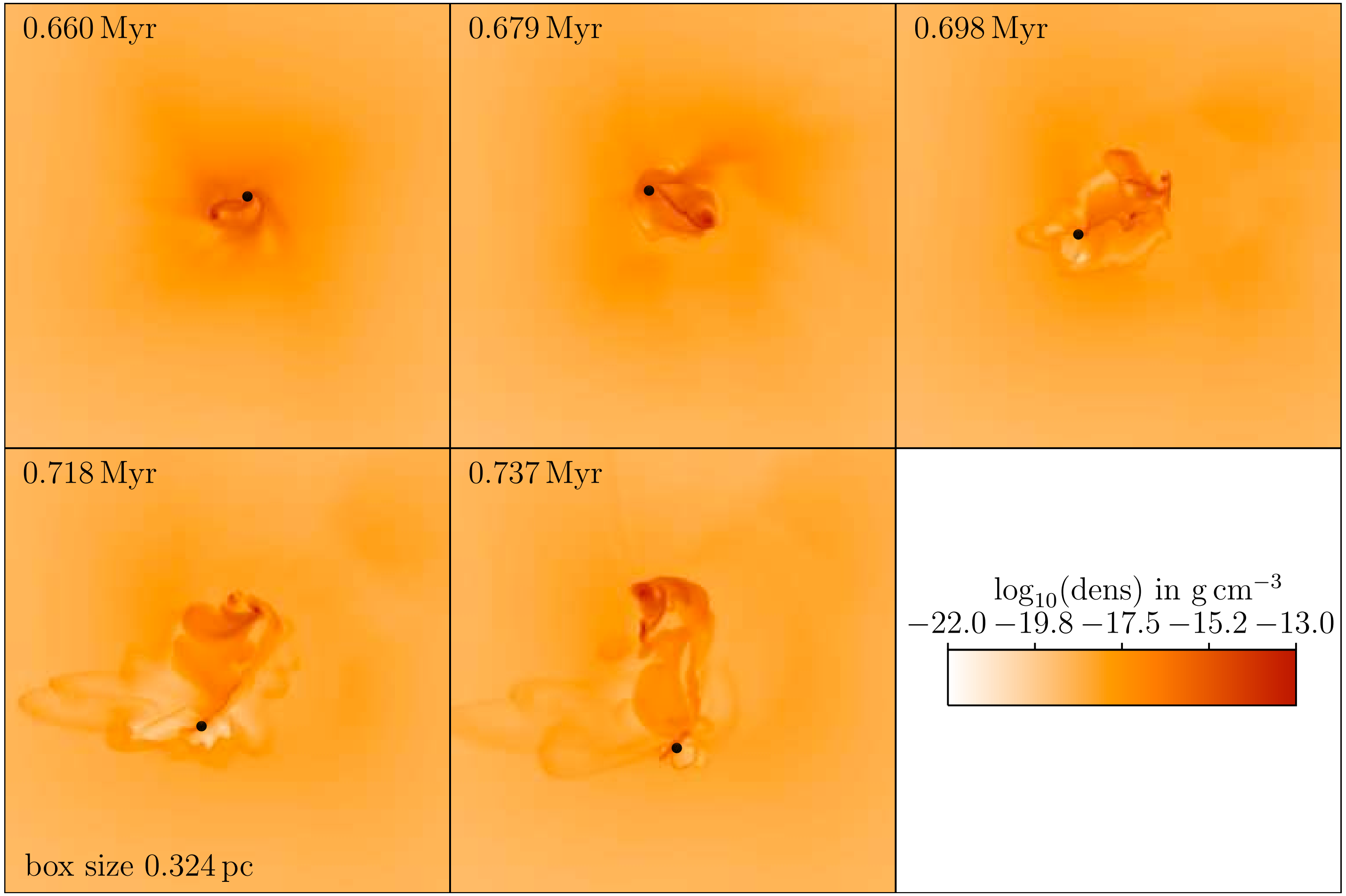


Disk edge on



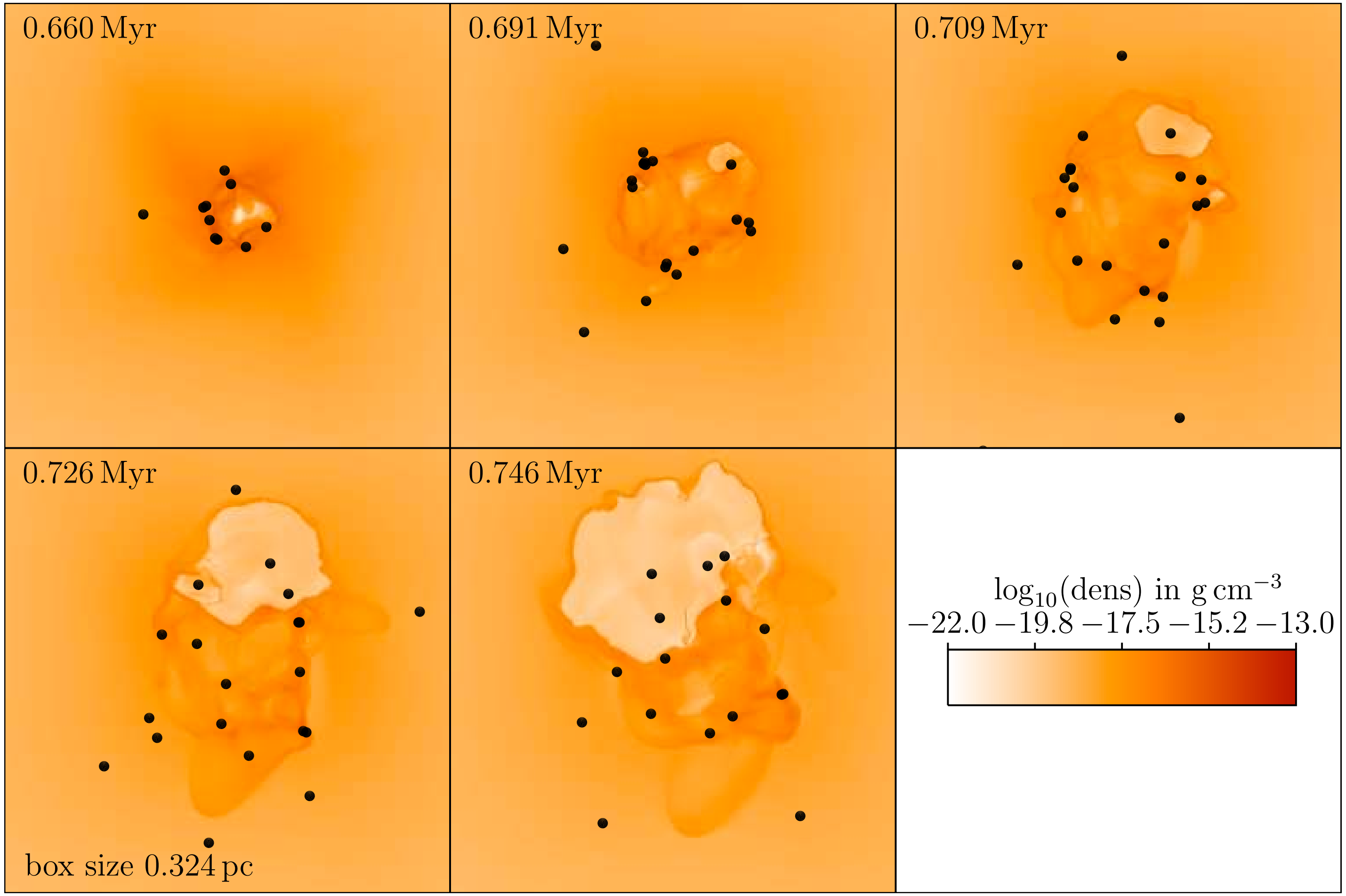
Disk plane

Peters et al. (2010a,b,c)



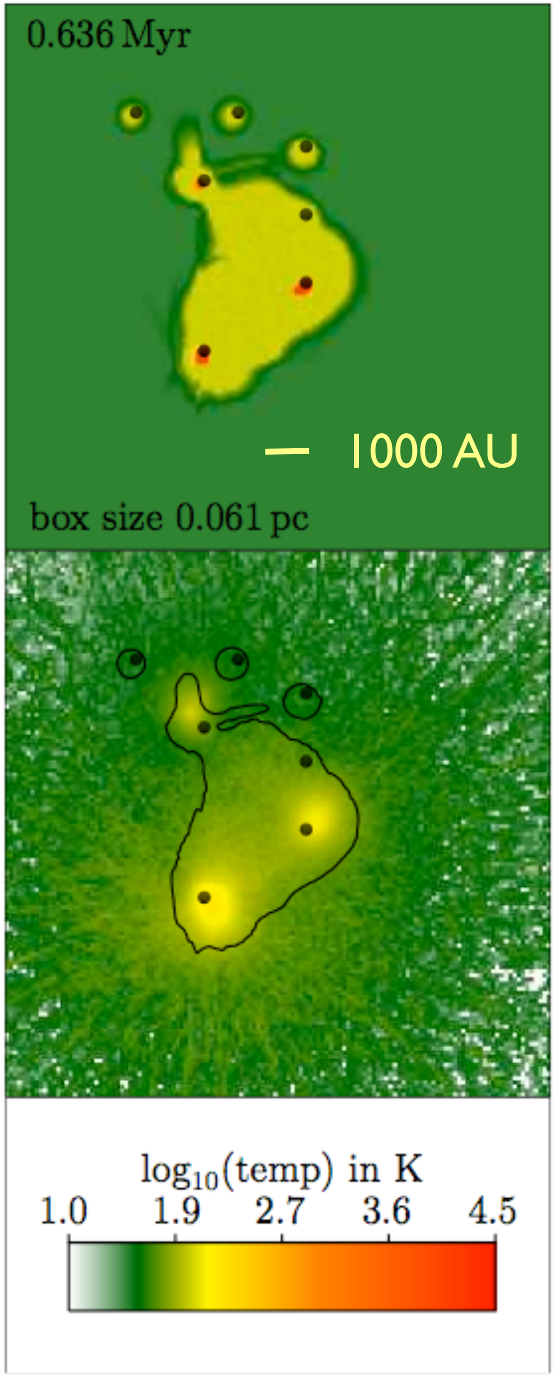
- disk is gravitationally unstable and fragments
- we suppress secondary sink formation by “Jeans heating”
- H II region is shielded effectively by dense filaments
- ionization feedback does not cut off accretion!

Peters et al. (2010a,b,c)



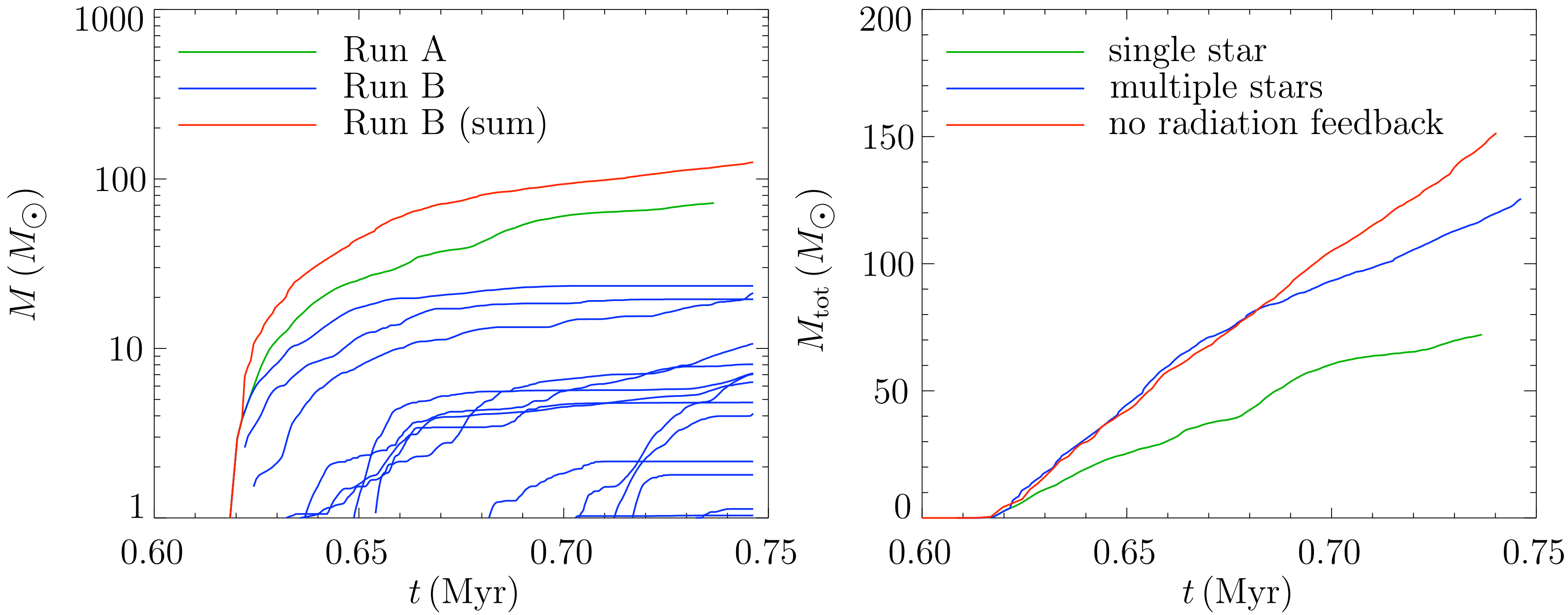
- all protostars accrete from common gas reservoir
- accretion flow suppresses expansion of ionized bubble
- cluster shows “fragmentation-induced starvation”
- halting of accretion flow allows bubble to expand

Peters et al. (2010a,b,c)



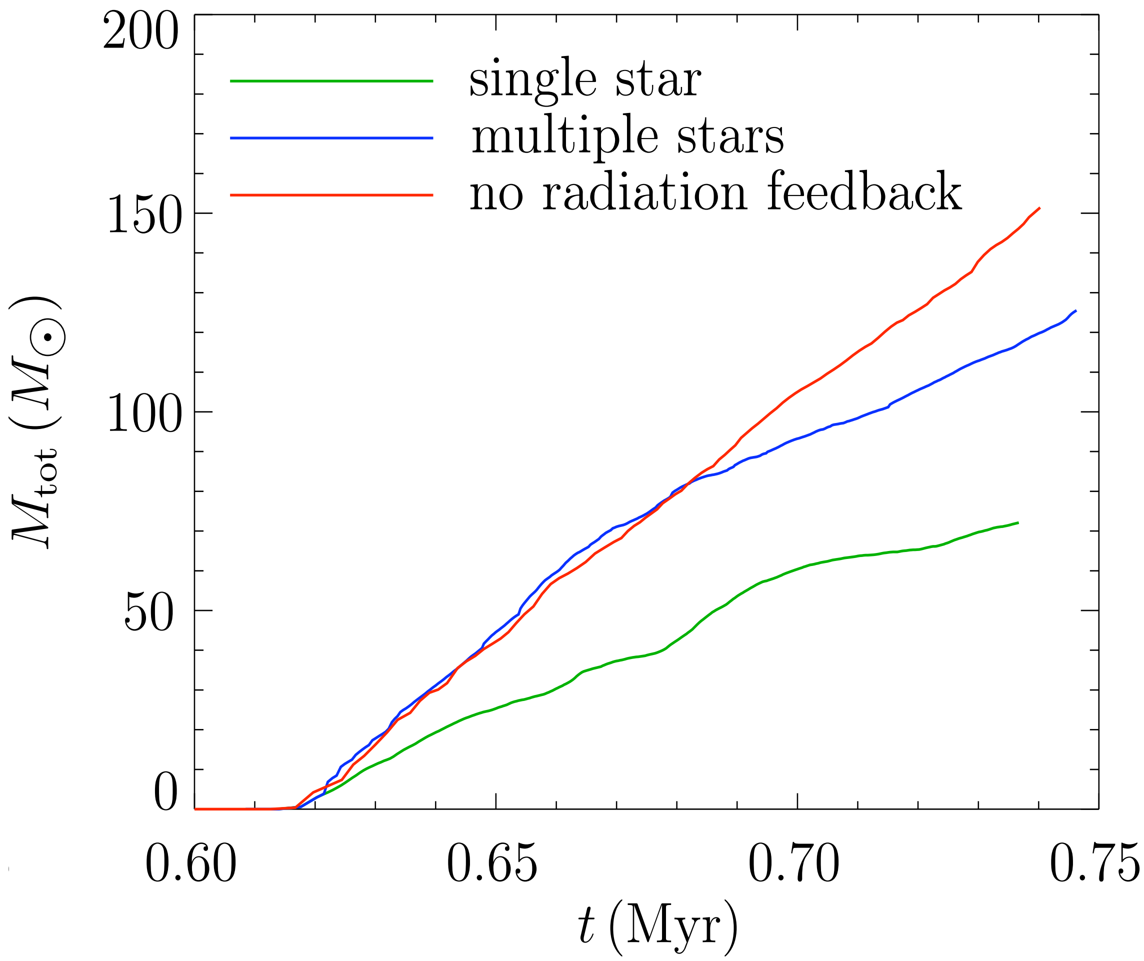
ray tracing method (hydrid characteristics)

Monte Carlo: full RT (with scattered radiation)



- compare with control run without radiation feedback
- total accretion rate does not change with accretion heating
- expansion of ionized bubble causes turn-off
- no triggered star formation by expanding bubble

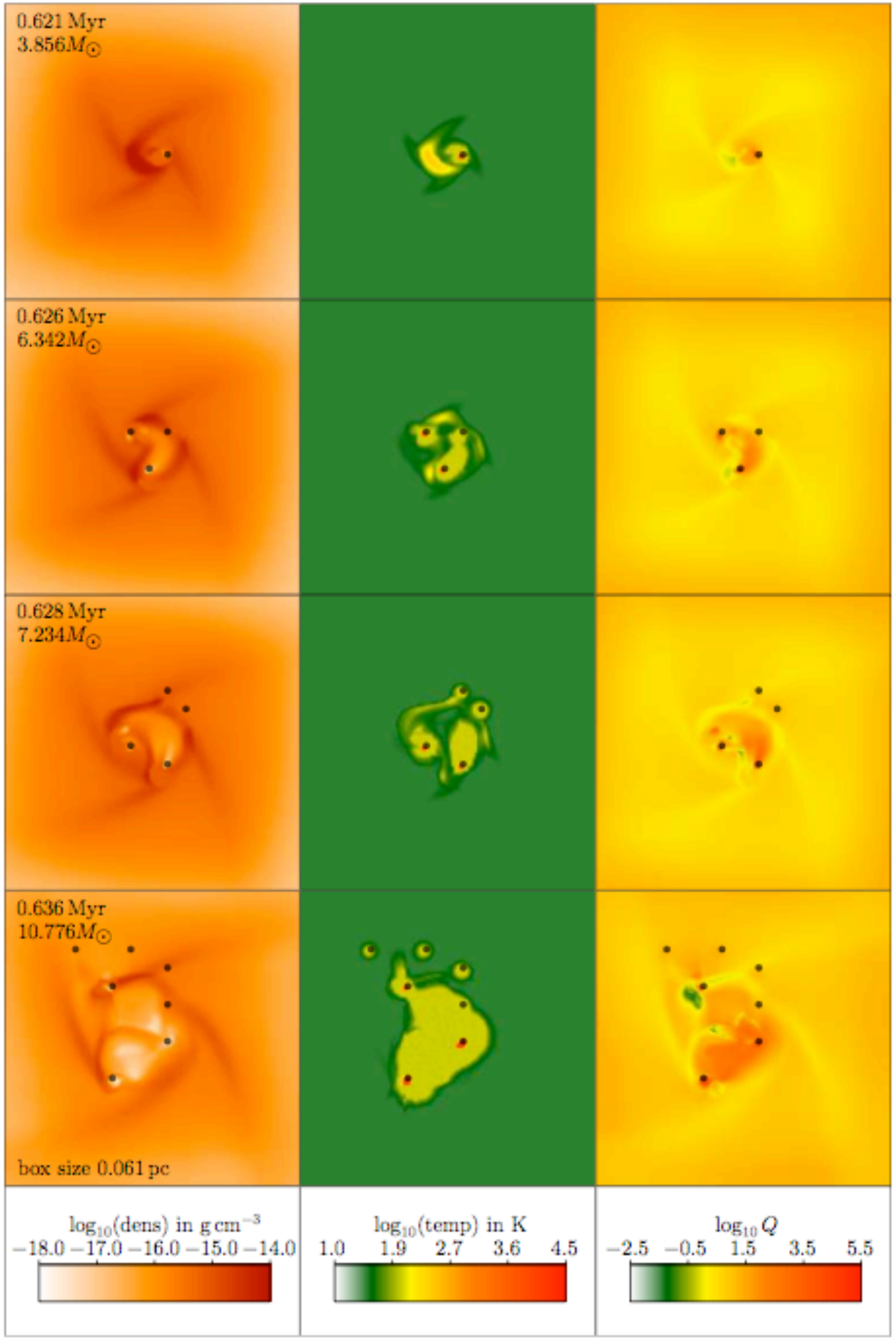
Peters et al. (2010a,b,c)

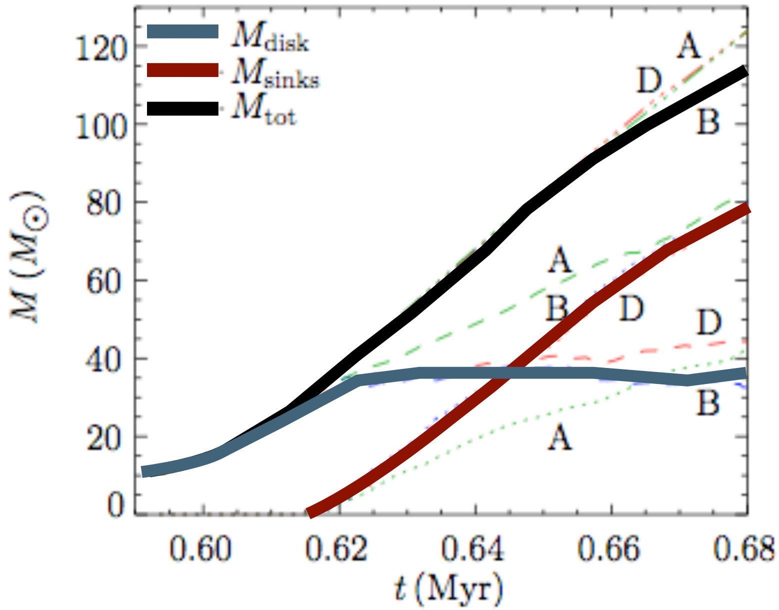


OVERVIEW OF COLLAPSE SIMULATIONS.

Name	Resolution	Radiative Feedback	Multiple Sinks	$M_{\rm sinks}$ ($M_\odot$)	$N_{\rm sinks}$	$M_{\rm max}$ ($M_\odot$)
Run A	98 AU	yes	no	72.13	1	72.13
Run B	98 AU	yes	yes	125.56	25	23.39
Run D	98 AU	no	yes	151.43	37	14.64

Peters et al. (2010a,b,c)

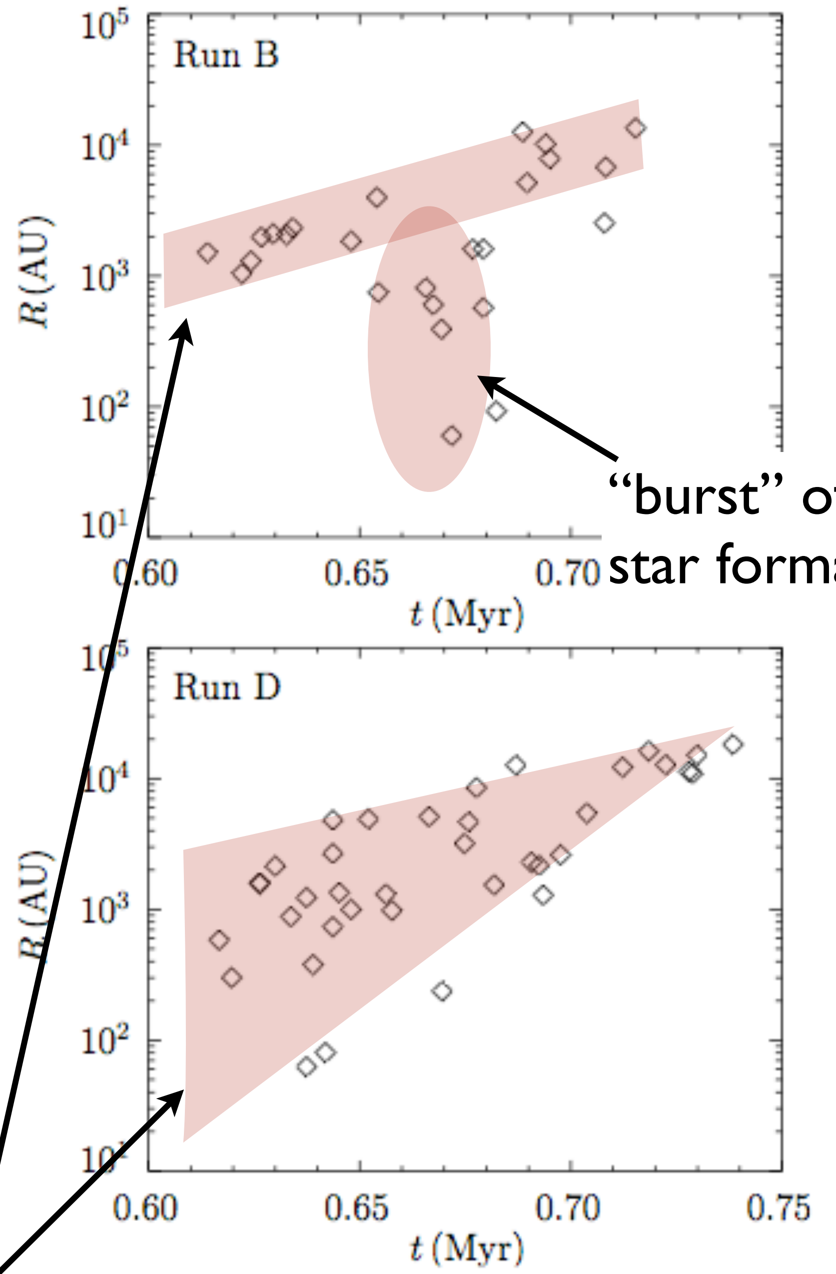




mass load onto the disk exceeds inward transport --> becomes gravitationally unstable (see also Kratter & Matzner 2006, Kratter et al. 2010)

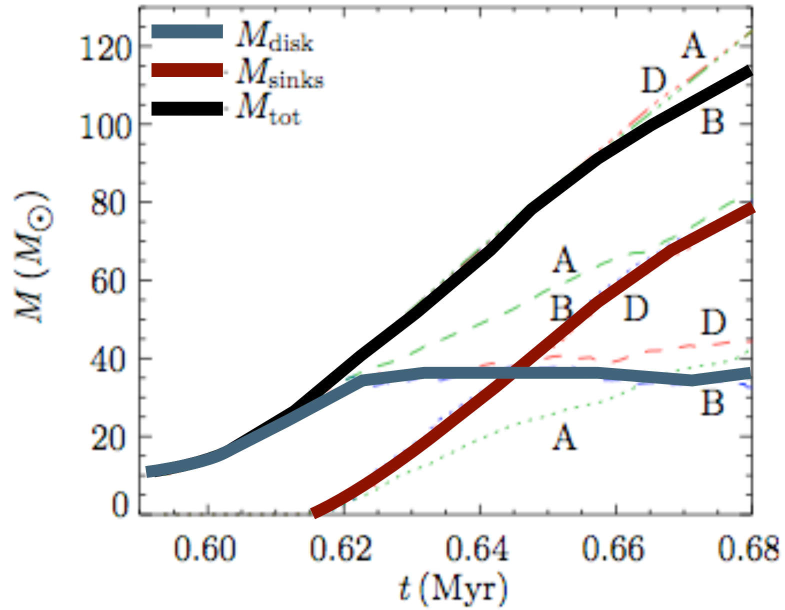
fragments to form multiple stars --> explains why high-mass stars are seen in clusters

Peters et al. (2010a,b,c)



“burst” of star formation

younger protostars form at larger radii



mass load onto the disk exceeds inward transport --> becomes gravitationally unstable (see also Kratter & Matzner 2006, Kratter et al. 2010)

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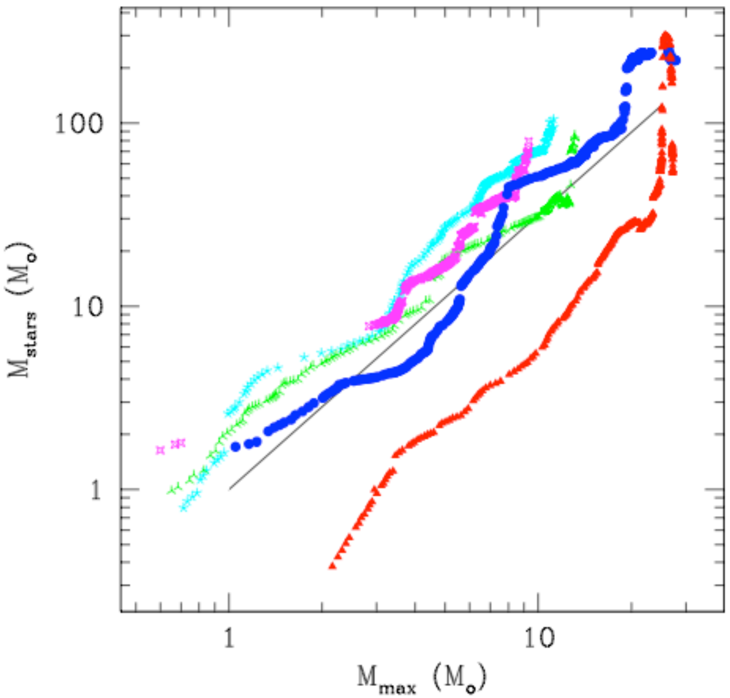
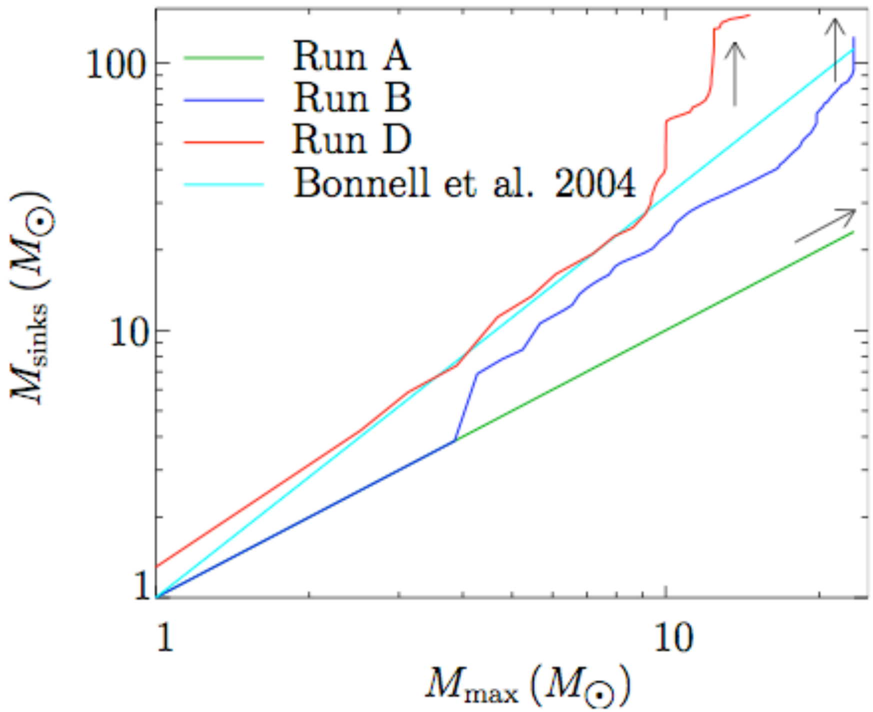
Peters et al. (2010a,b,c)

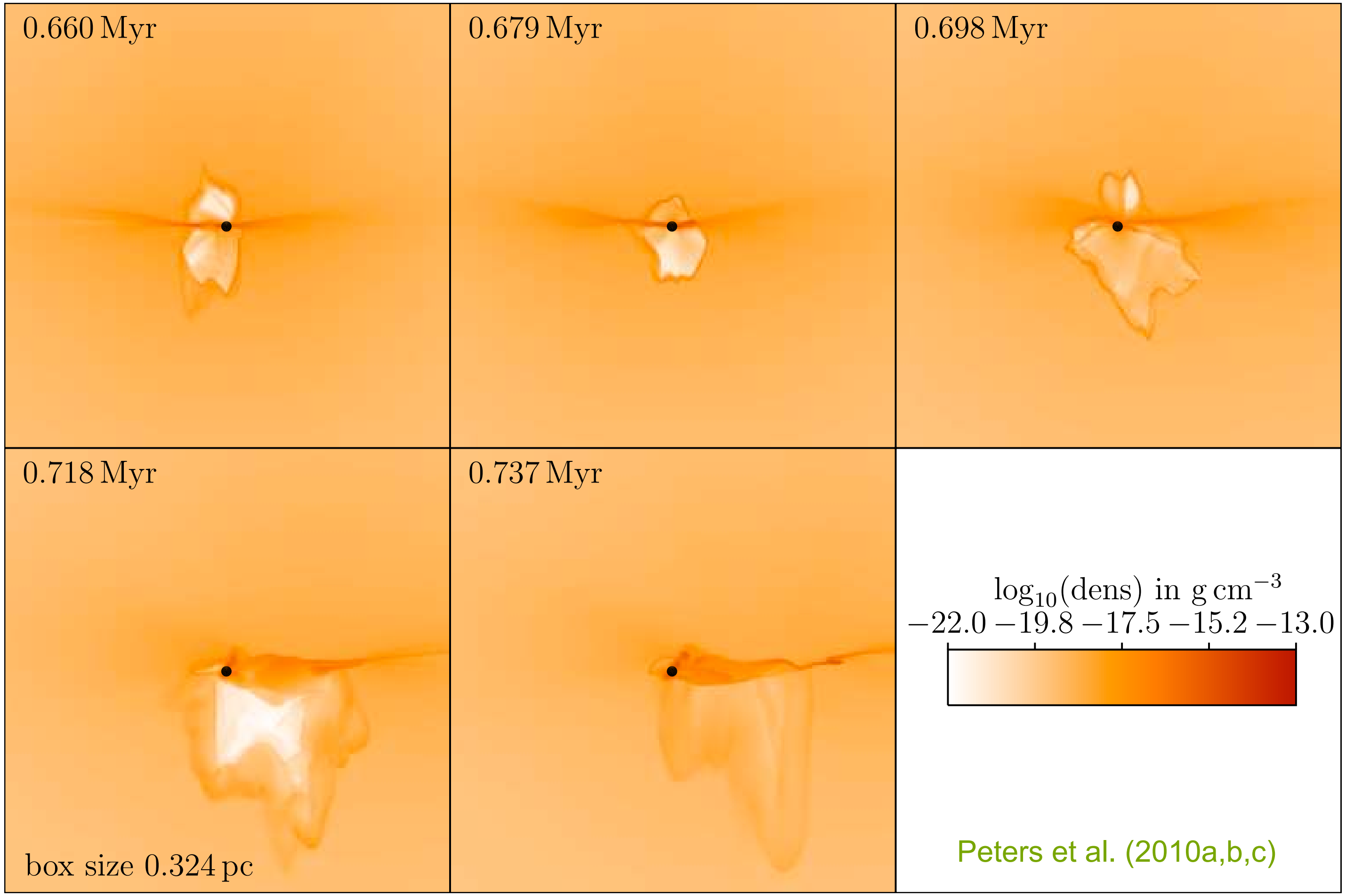
relation between maximum stellar mass and total stellar mass



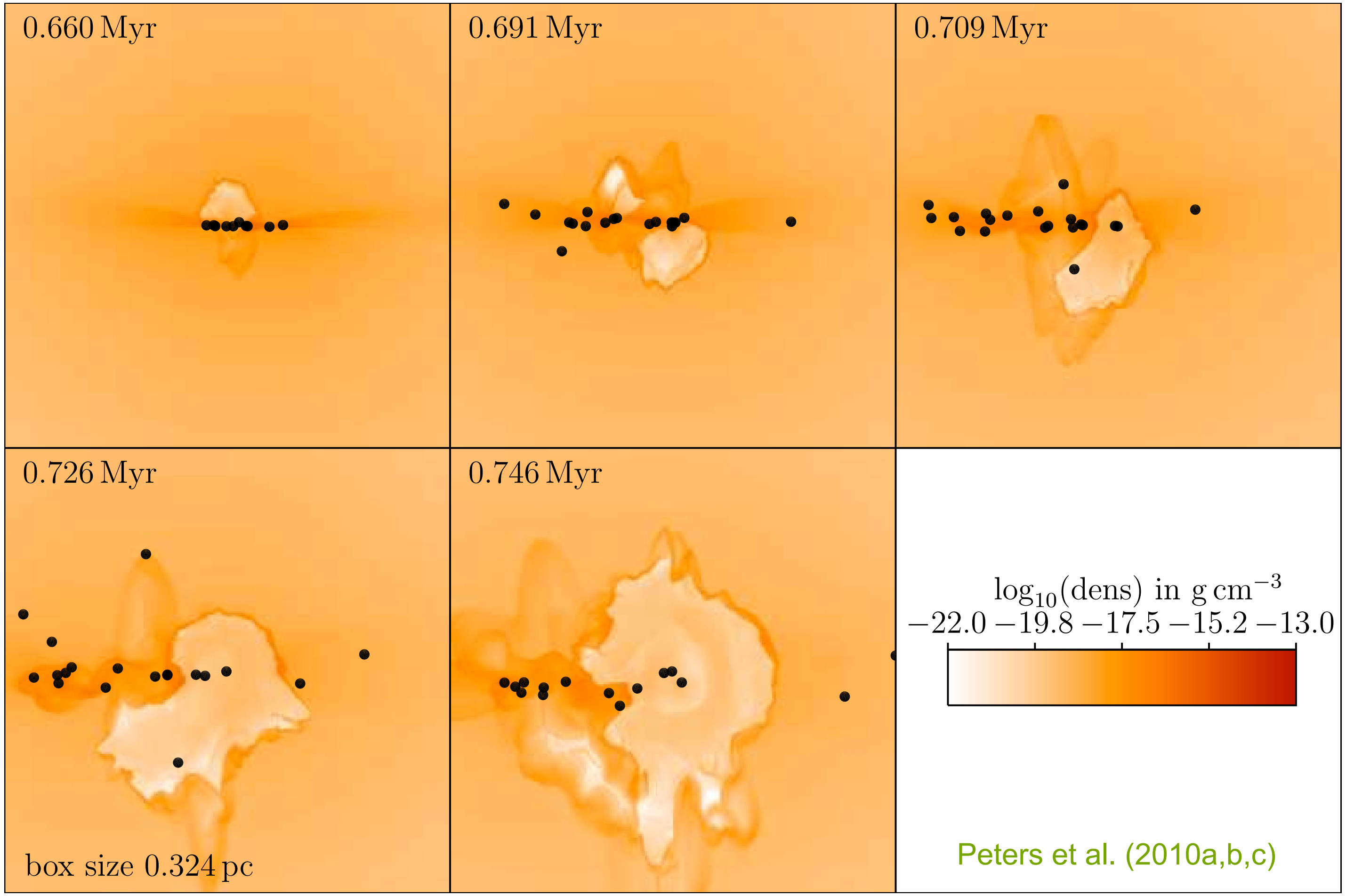


Bonnell et al. (2004):
competitive accretion

Peters et al. (2010):
fragmentation-induced starvation



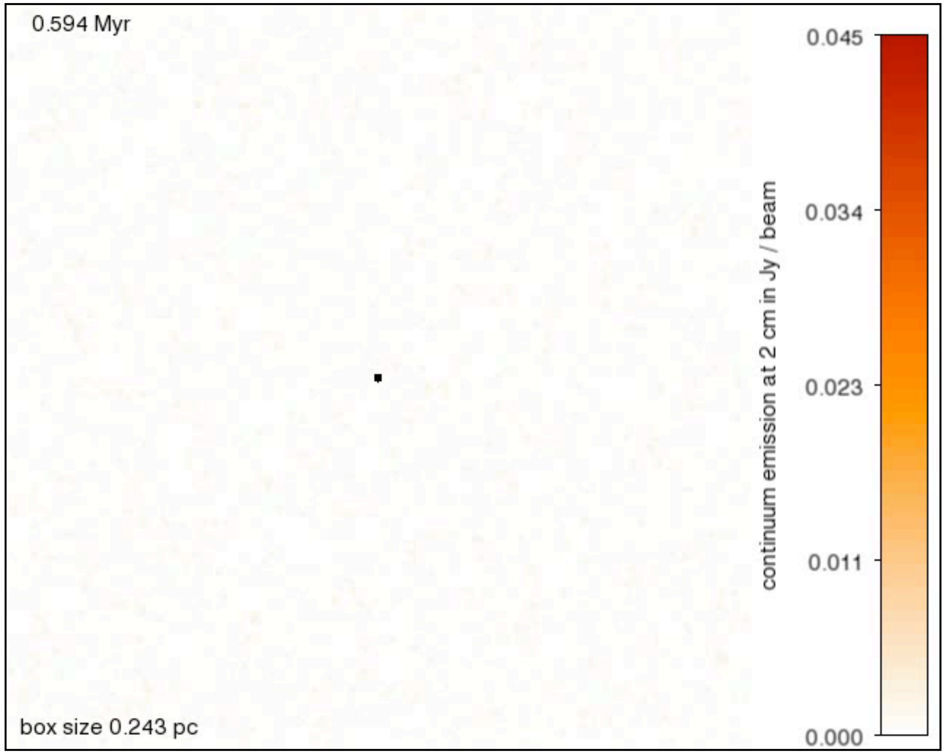
- thermal pressure drives bipolar outflow
- filaments can effectively shield ionizing radiation
- when thermal support gets lost, outflow gets quenched again
- no direct relation between mass of star and size of outflow



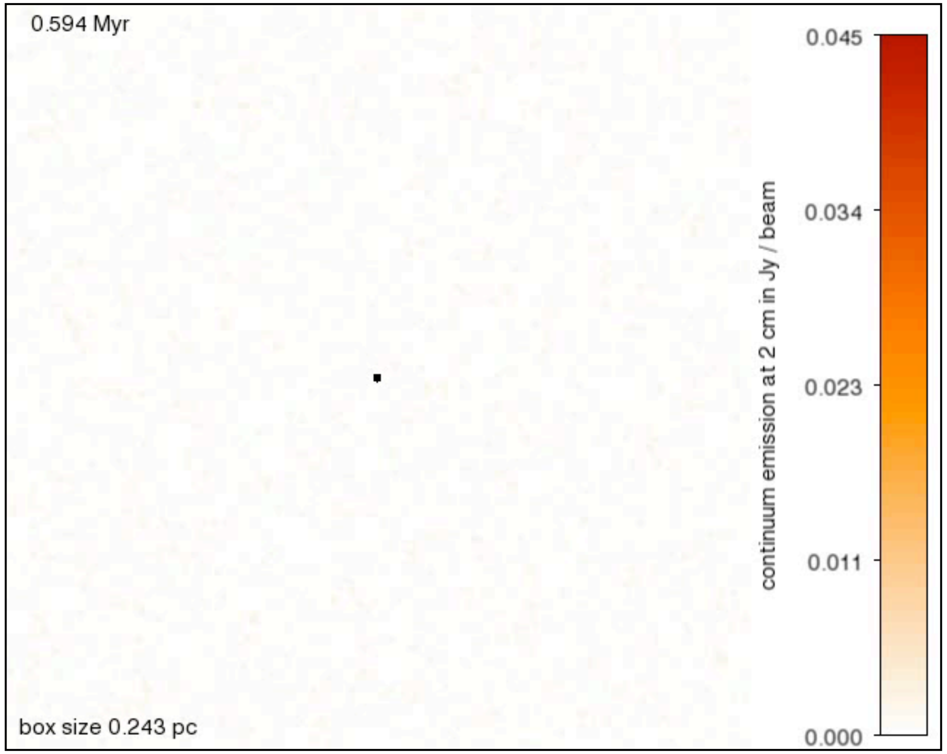
- bipolar outflow during accretion phase
- when accretion flow stops, ionized bubble can expand
- expansion is highly anisotropic
- bubbles around most massive stars merge

- numerical data can be used to generate continuum maps
- calculate free-free absorption coefficient for every cell
- integrate radiative transfer equation (neglecting scattering)
- convolve resulting image with beam width
- VLA parameters:
  - distance $2.65\,\mathrm{kpc}$
  - wavelength $2\,\mathrm{cm}$
  - FWHM $0\farcs14$
  - noise $10^{-3}\,\mathrm{Jy}$

Peters et al. (2010a,b,c)



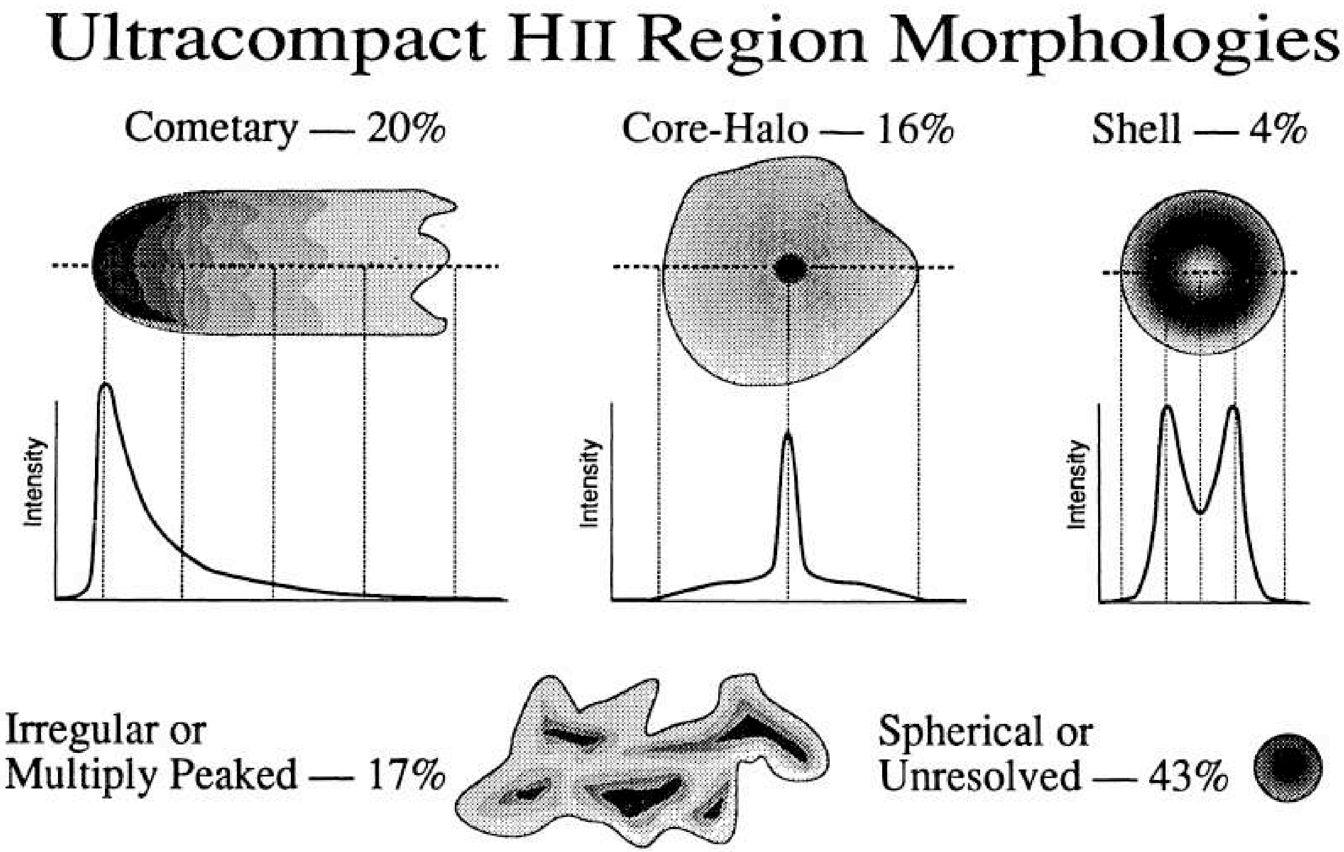
Disk face on



Disk edge on

Peters et al. (2010a,b,c)

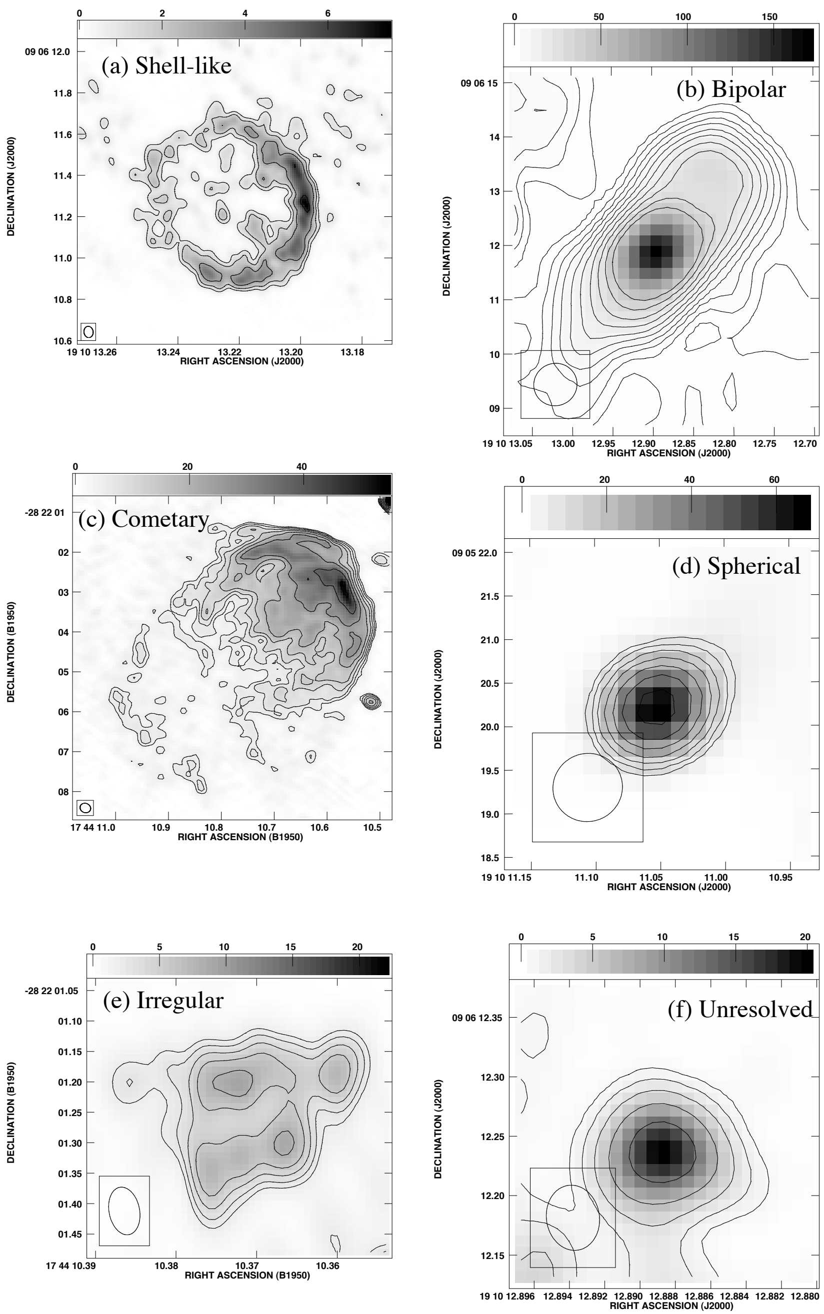
Classification of UC H II Regions

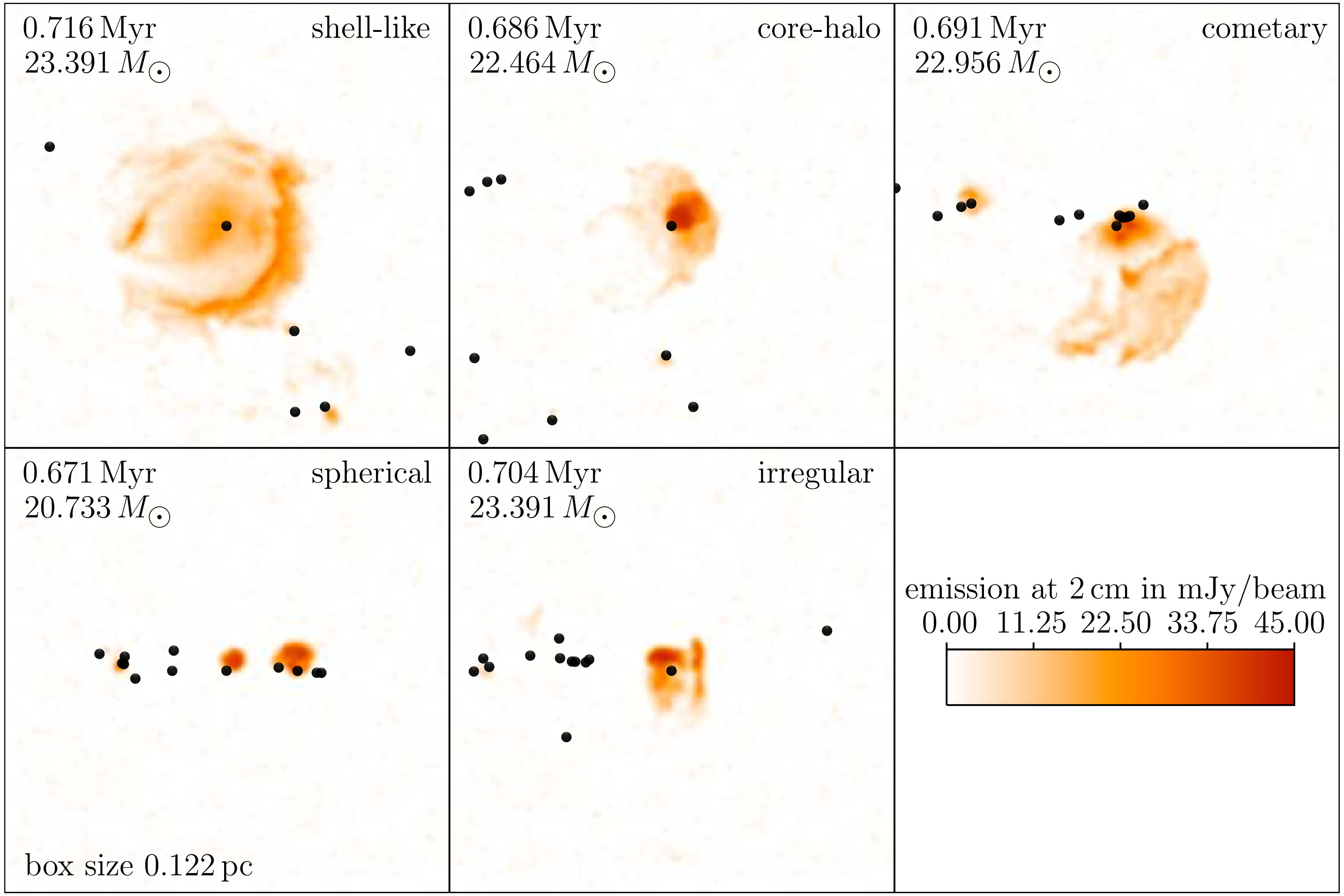


- Wood & Churchwell 1989 classification of UC H II regions
- Question: What is the origin of these morphologies?
- UC H II lifetime problem: Too many UC H II regions observed!

Classification of UC H II Regions

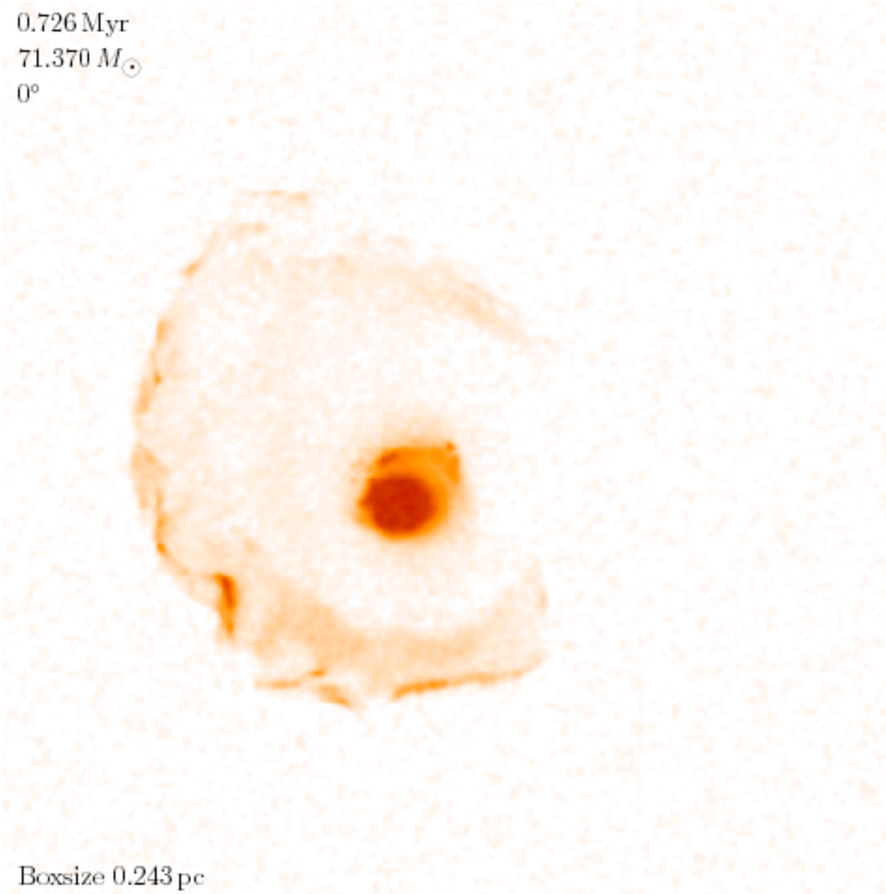
- comparison with De Pree et al. 2005 classification of UC H II regions in W49A and Sagittarius B2
- "irregular" is any resolved region which does fall into one of the other categories





- synthetic VLA observations at $2\,\mathrm{cm}$ of simulation data
- interaction of ionizing radiation with accretion flow creates high variability in time and shape
- flickering resolves the lifetime paradox!

Peters et al. (2010a,b,c)



Morphology of HII region depends on viewing angle

Peters et al. (2010a,b,c)

H II Region Morphologies

Type	WC89	K94	single	multiple
Spherical/Unresolved	43	55	19	60 ± 5
Cometary	20	16	7	10 ± 5
Core-halo	16	9	15	4 ± 2
Shell-like	4	1	3	5 ± 1
Irregular	17	19	57	21 ± 5

WC89: Wood & Churchwell 1989, K94: Kurtz et al. 1994

- statistics over 25 simulation snapshots and 20 viewing angles
- statistics can be used to distinguish between different models
- single sink simulation does not reproduce lifetime problem

Peters et al. (2010a,b,c)

Conclusions and Outlook

Conclusions

- Ionization feedback cannot stop accretion
- Ionization drives bipolar outflow
- H II region shows high variability in time and shape
- All classified morphologies can be observed in one run
- Lifetime of H II region determined by accretion time scale
- Rapid accretion through dense, unstable flows
- Fragmentation-induced mass limits of massive stars

key questions

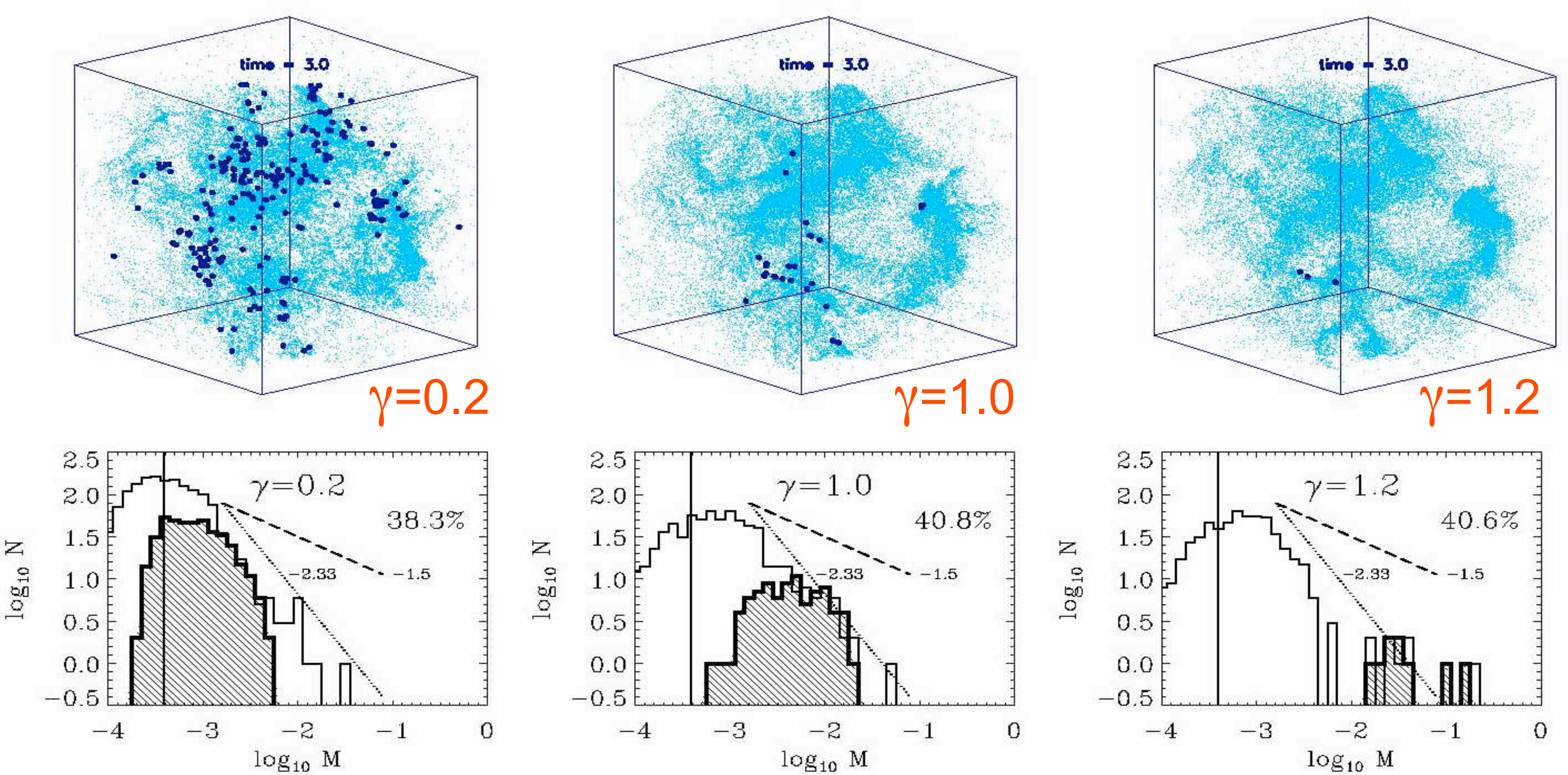
- *what drives turbulence?*
  --> accretion driven turbulence on ALL scales
  galaxies, molecular clouds, protostellar disks
- *how do high-mass stars & their clusters form?*
  --> radiative feedback & fragmentation-induced starvation
- *what are the initial conditions for cluster formation?*
  --> initial density profile matters
- *are there (still) low-mass metal-free stars?*
  --> importance of thermodynamics, use of sink particles
- *magnetic fields in the early universe?*
  --> generation of the first strong fields by turbulent dynamos

dependency on EOS

- degree of fragmentation depends on *EOS!*

- polytropic EOS: $\mathbf{p} \propto \rho^{\gamma}$
- $\gamma<1$: dense cluster of low-mass stars
- $\gamma>1$: isolated high-mass stars
- (see Li, Klessen, & Mac Low 2003, ApJ, 592, 975; also Kawachi & Hanawa 1998, Larson 2003)

dependency on EOS



for $\gamma<1$ fragmentation is enhanced → *cluster of low-mass stars*

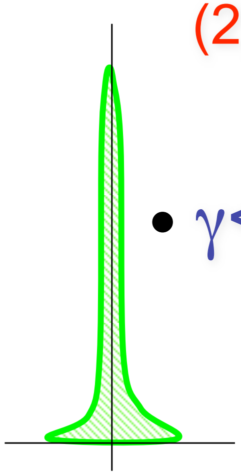
for $\gamma>1$ it is suppressed → formation of *isolated massive stars*

(from Li, Klessen, & Mac Low 2003, ApJ, 592, 975)

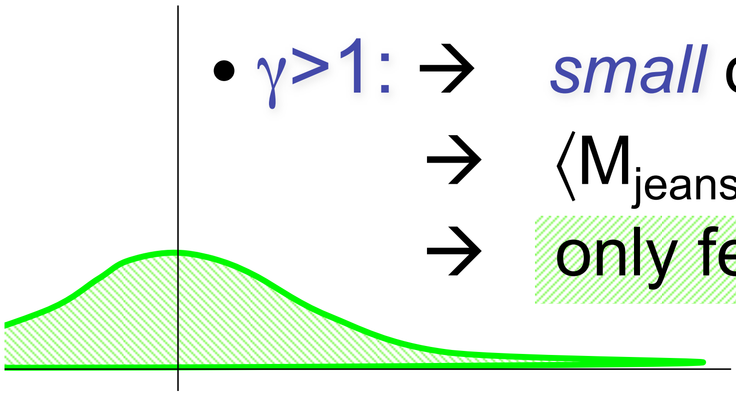
how does that work?

(1) $\mathbf{p} \propto \rho^{\gamma} \rightarrow \rho \propto \mathbf{p}^{1/\gamma}$

(2) $\mathbf{M_{jeans}} \propto \gamma^{3/2} \rho^{(3\gamma-4)/2}$



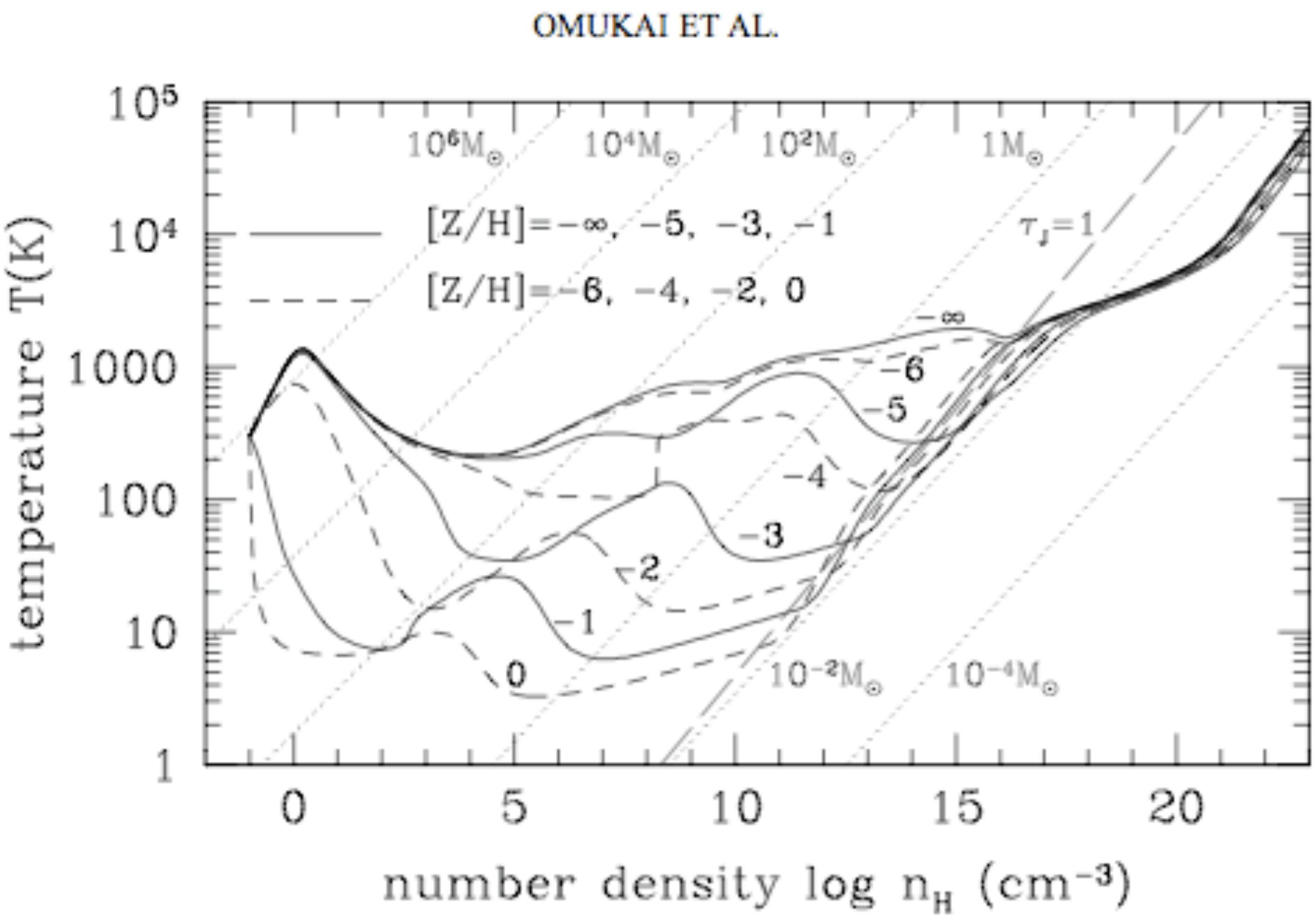
- $\gamma<1$: → *large* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ becomes small
  → number of fluctuations with $M > M_{jeans}$ is large



- $\gamma>1$: → *small* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ is large
  → only few and massive clumps exceed M_{jeans}

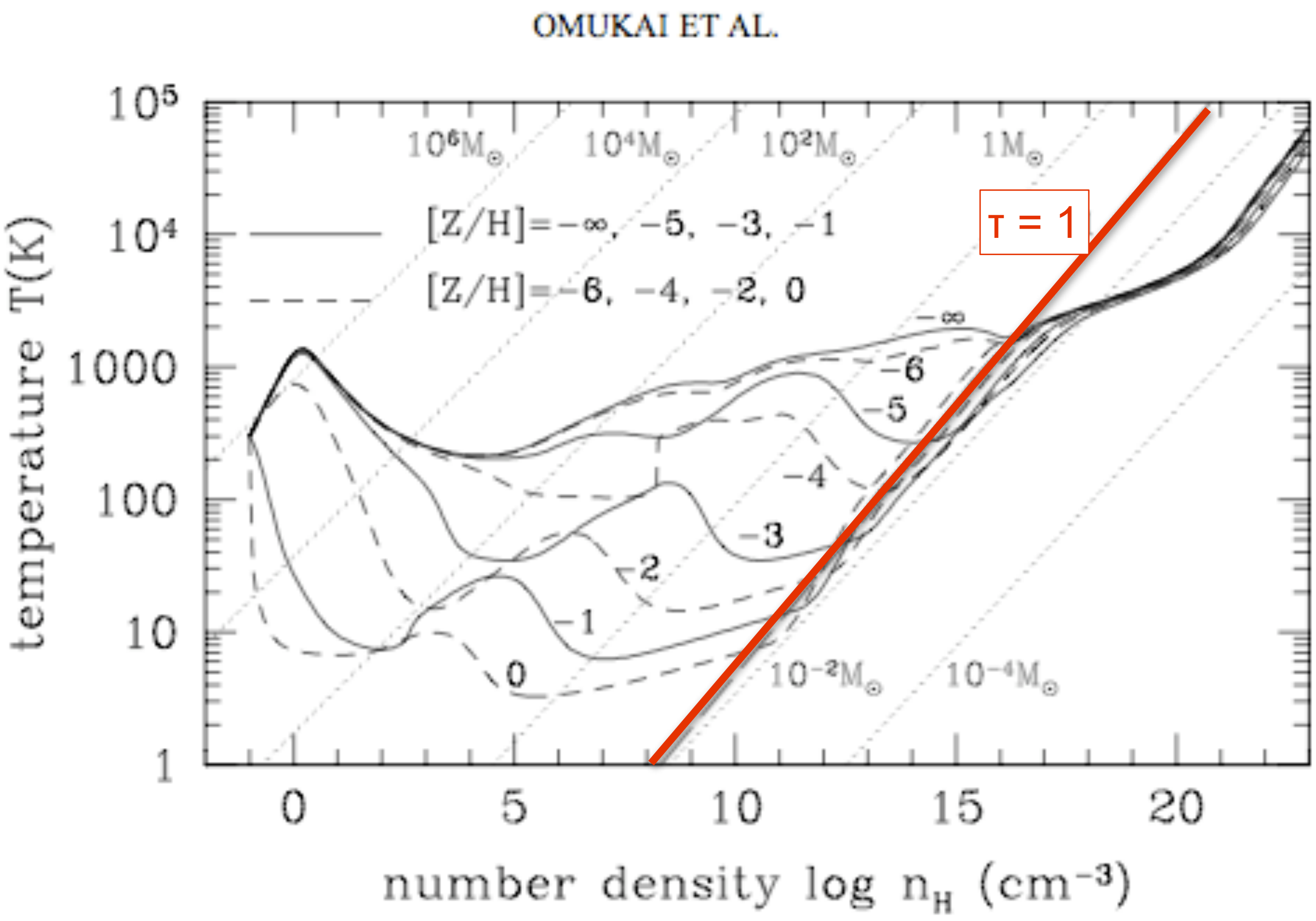
EOS in different environments

EOS as function of metallicity



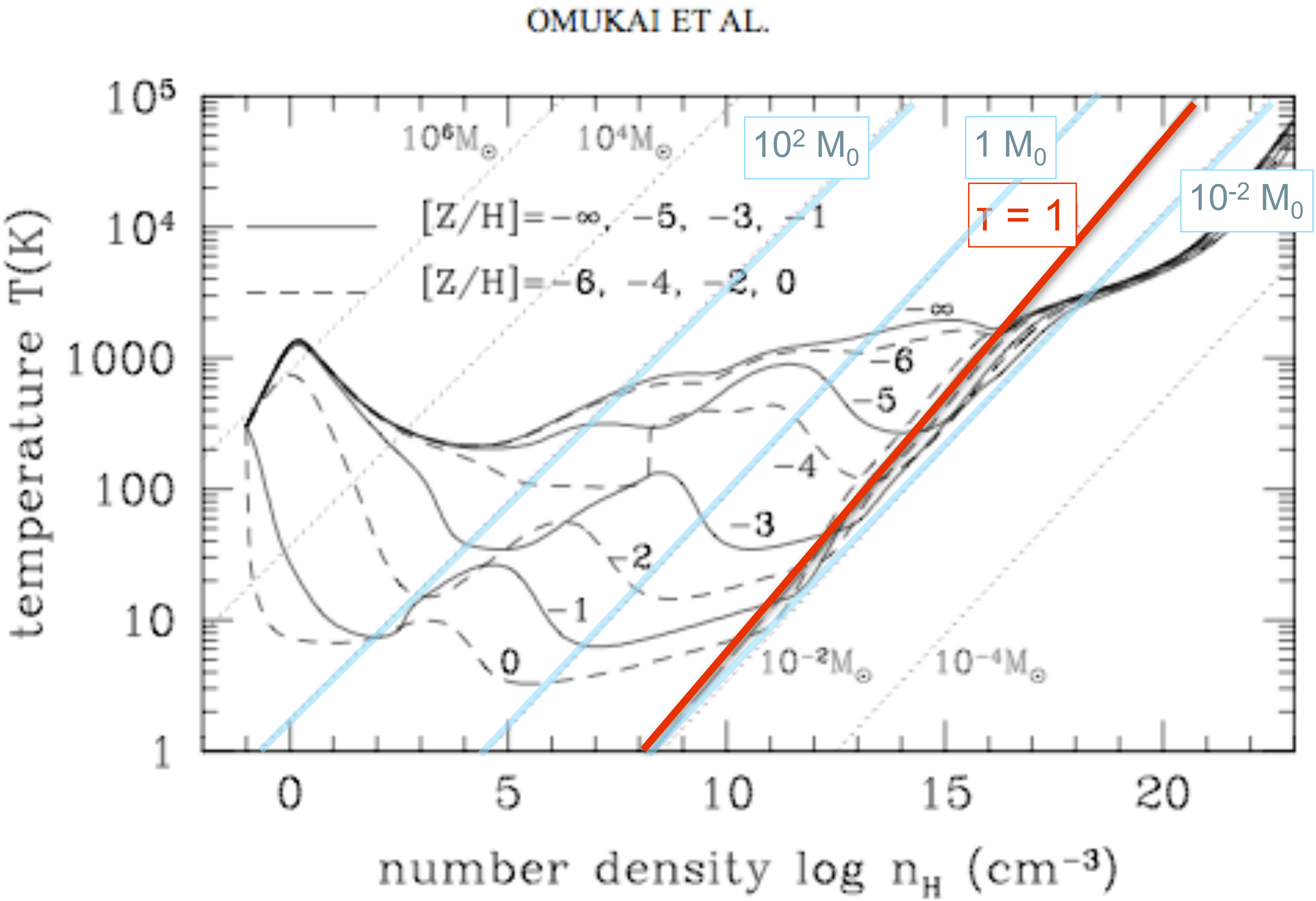
(Omukai et al. 2005)

EOS as function of metallicity



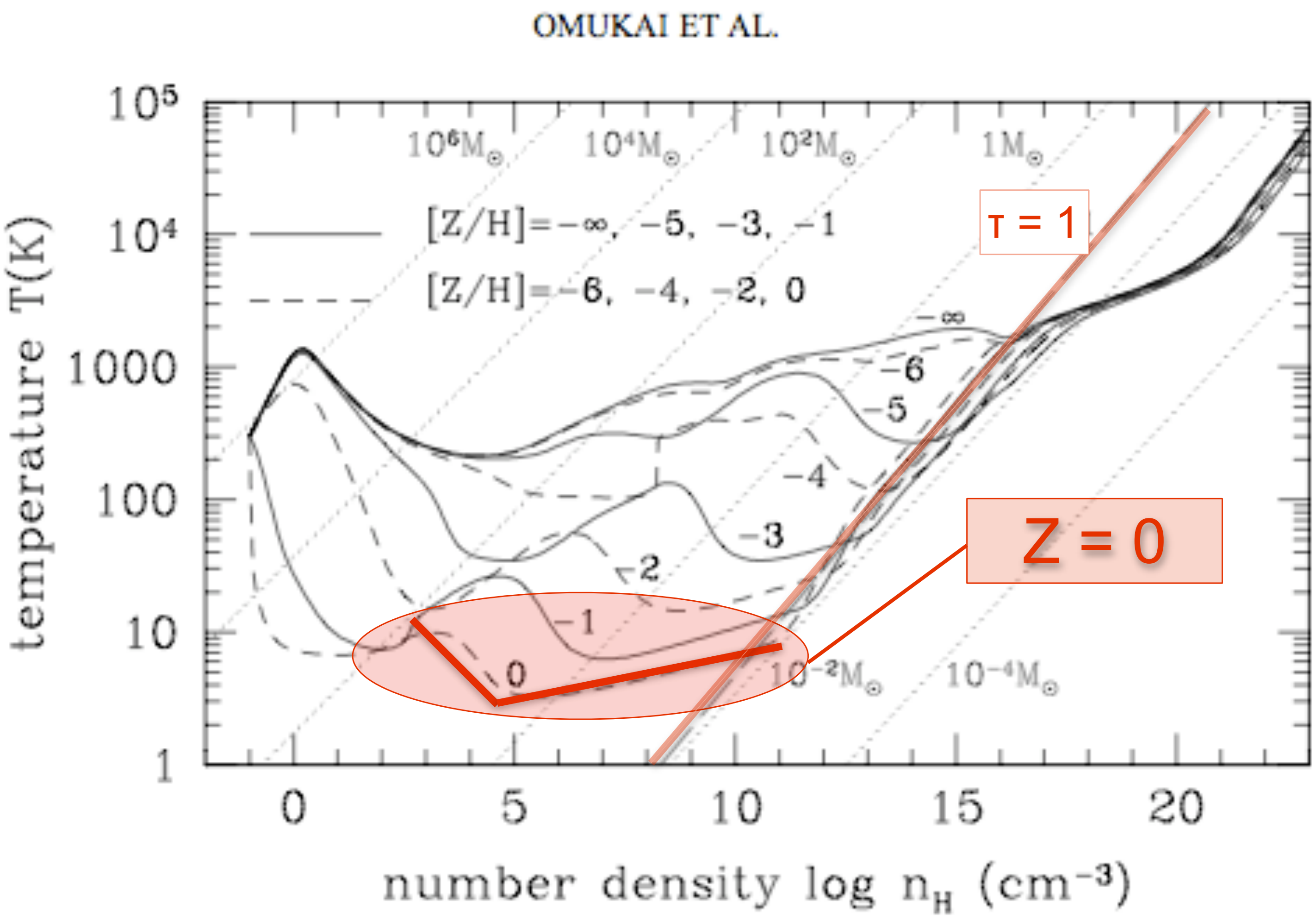
(Omukai et al. 2005)

EOS as function of metallicity



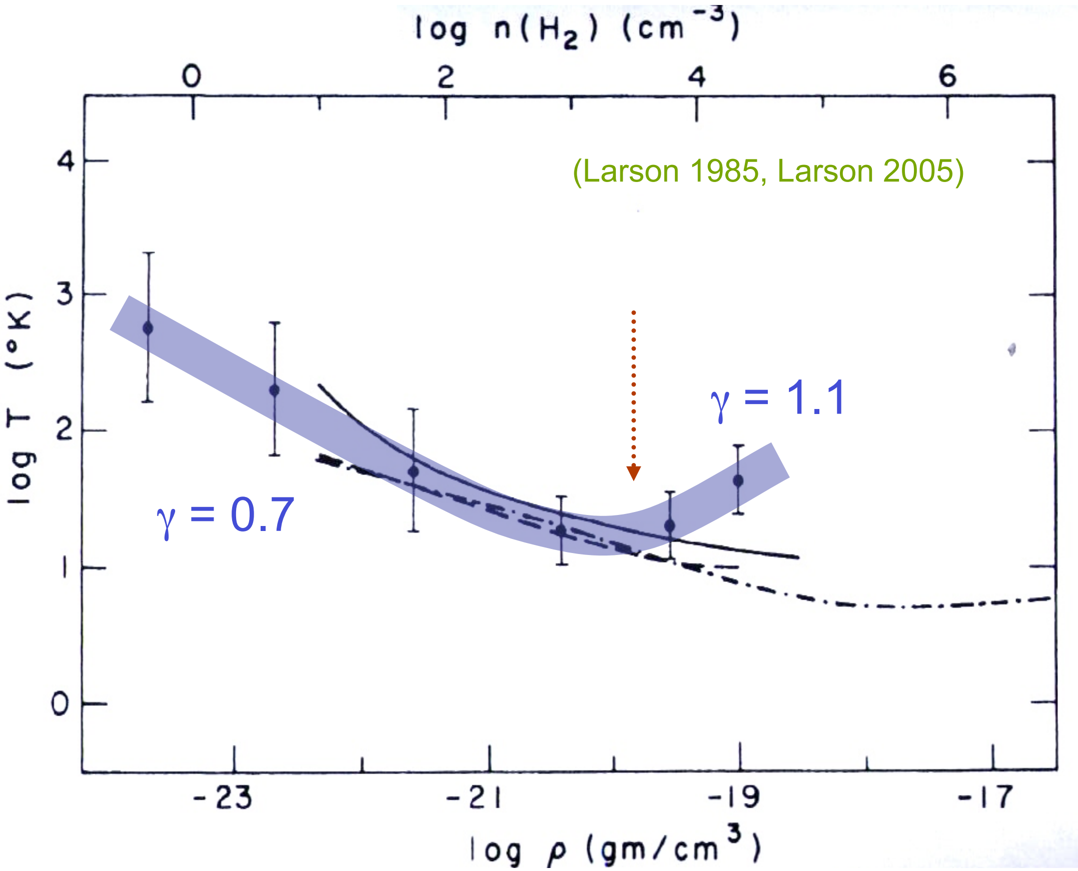
(Omukai et al. 2005)

present-day star formation



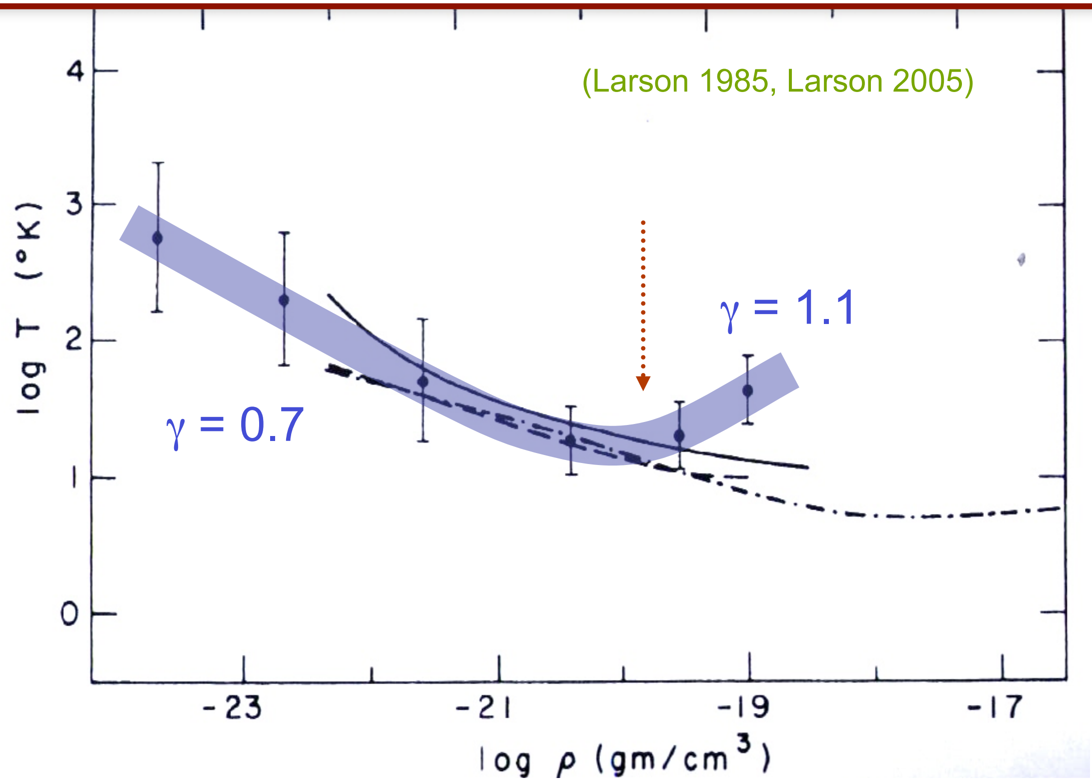
(Omukai et al. 2005, Jappsen et al. 2005, Larson 2005)

present-day star formation



present-day star formation

This kink in EOS is very insensitive to environmental conditions such as ambient radiation field
--> reason for universal for of the IMF? (Elmegreen et al. 2008)



IMF from simple piece-wise polytropic EOS

$\gamma_1 = 0.7$

$\gamma_2 = 1.1$

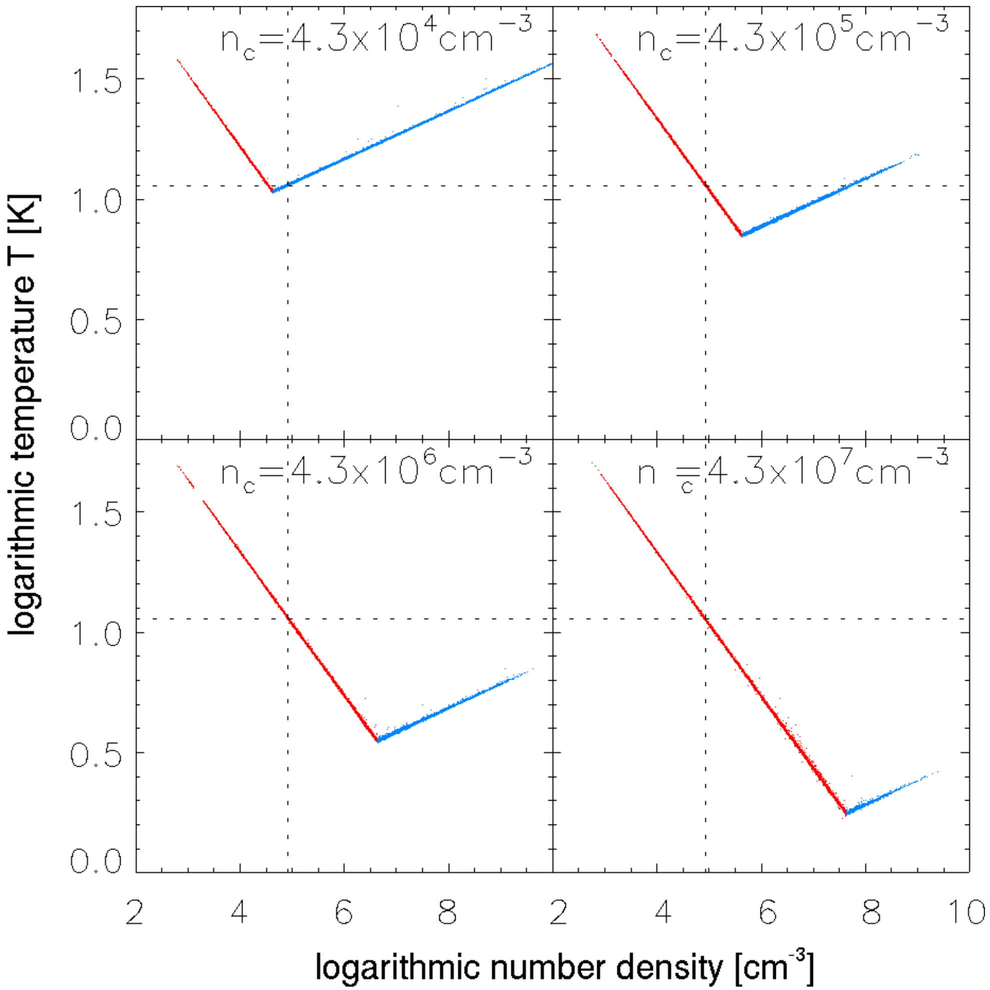
$T \sim \rho^{\gamma-1}$

EOS and Jeans Mass:

$\mathbf{p} \propto \rho^{\gamma} \rightarrow \rho \propto \mathbf{p}^{1/\gamma}$

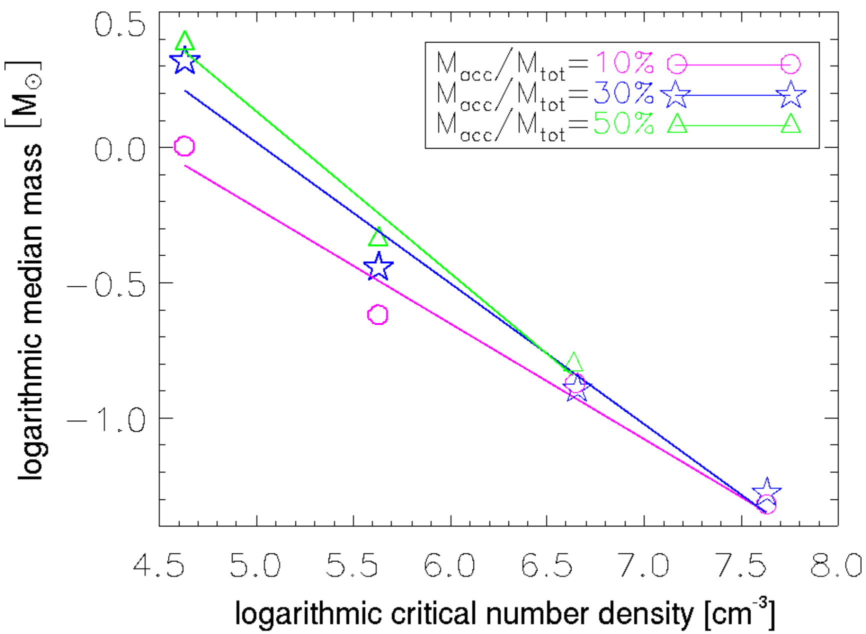
$M_{jeans} \propto \gamma^{3/2} \rho^{(3\gamma-4)/2}$

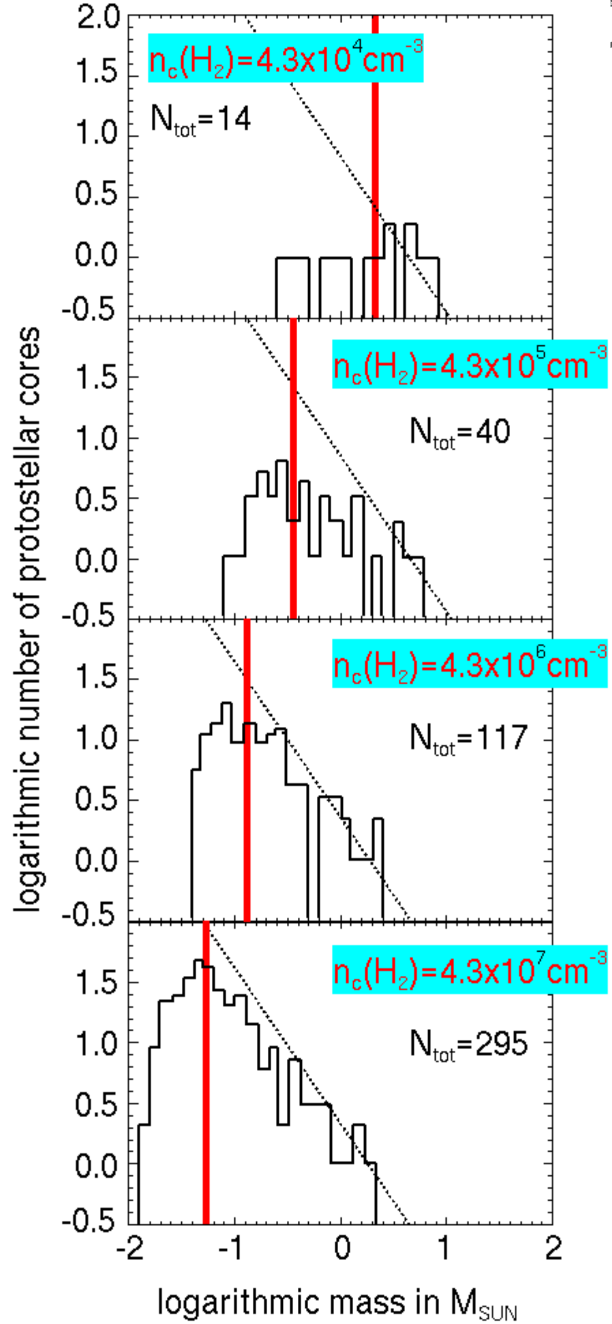
(Jappsen et al. 2005)



IMF from simple piece-wise EOS

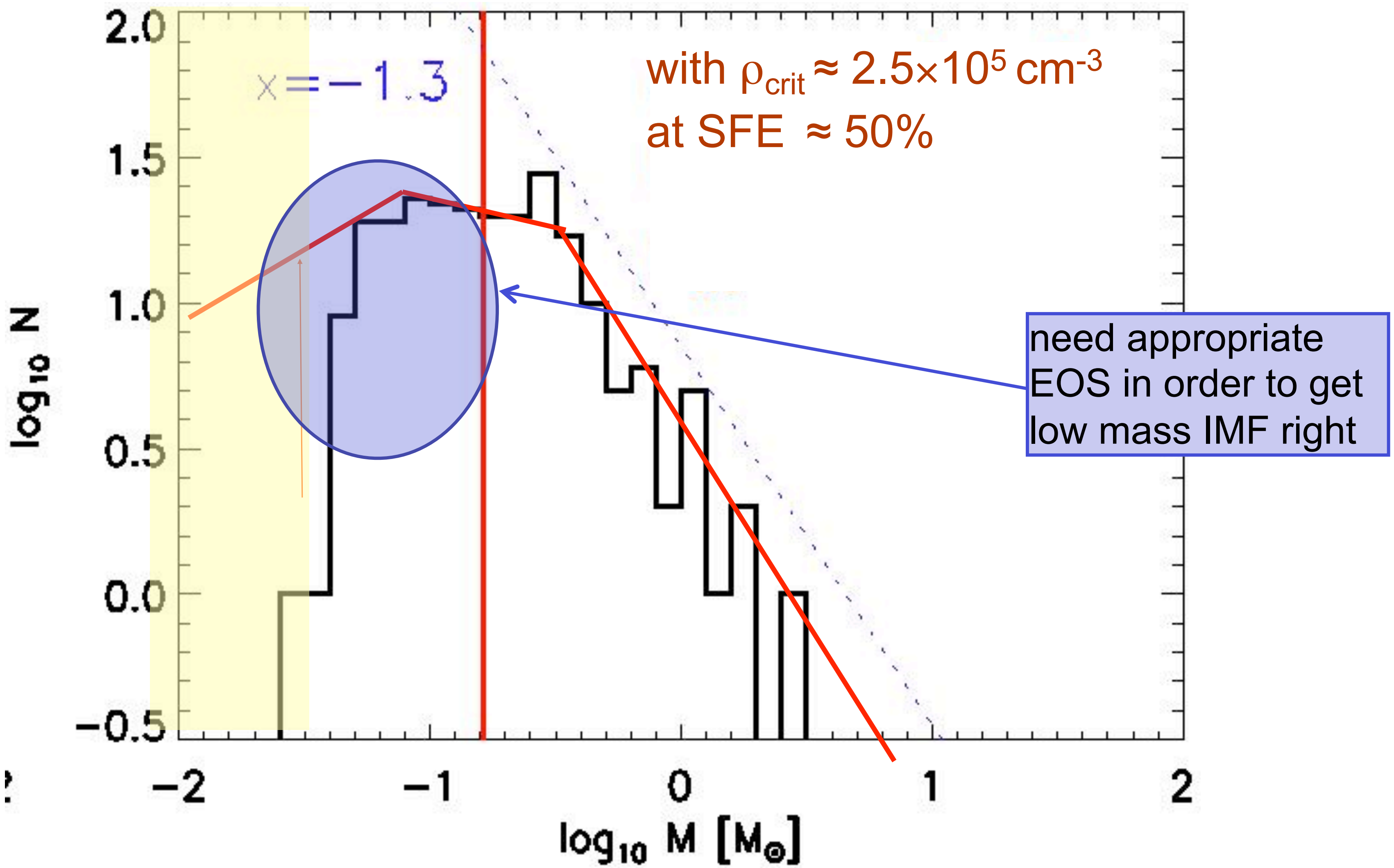
critical density ⬆ ⟹ median mass ⬇





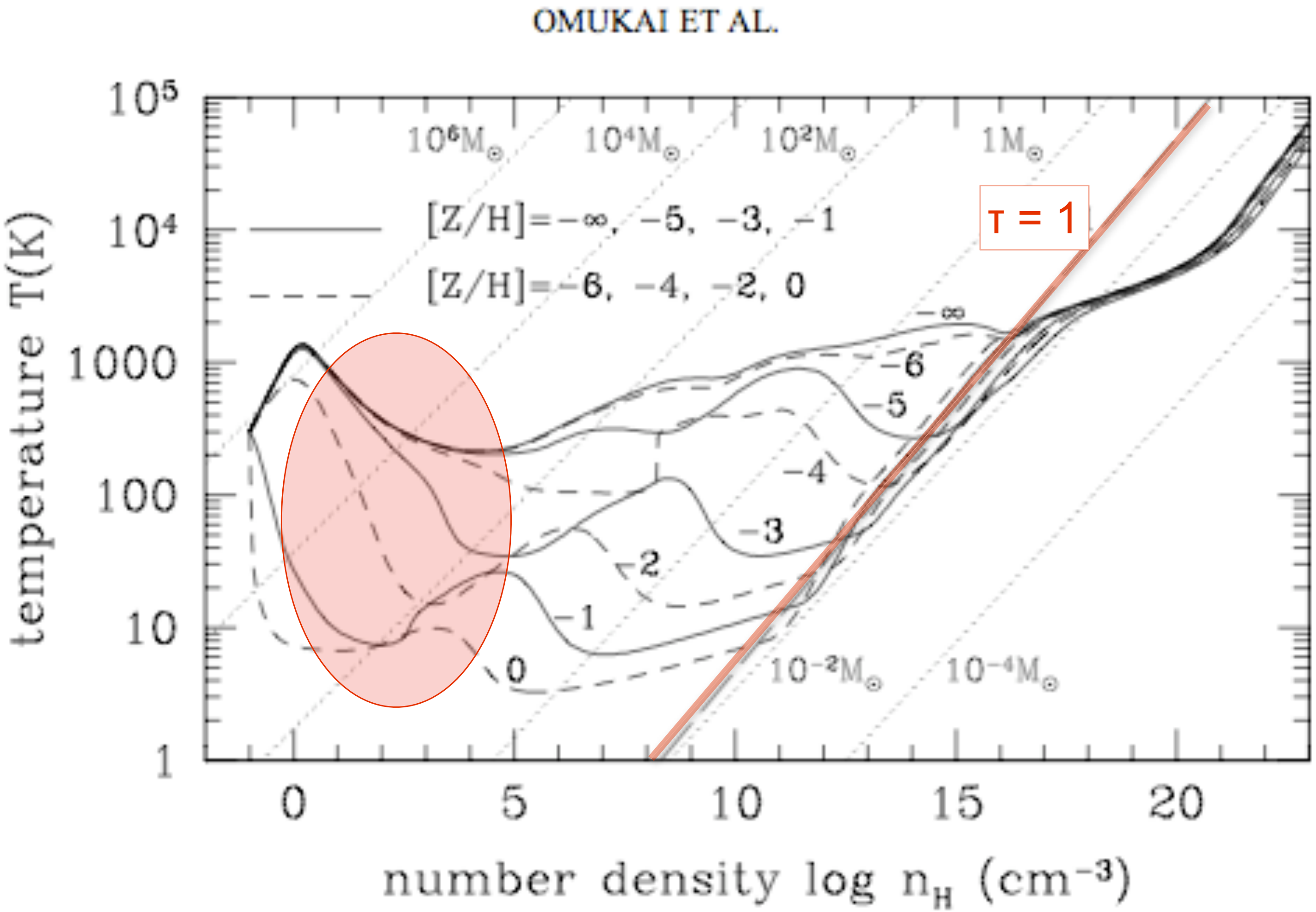
(Jappsen et al. 2005)

IMF in nearby molecular clouds



(Jappsen et al. 2005, A&A, 435, 611)

dependence on Z at low density



(Omukai et al. 2005)

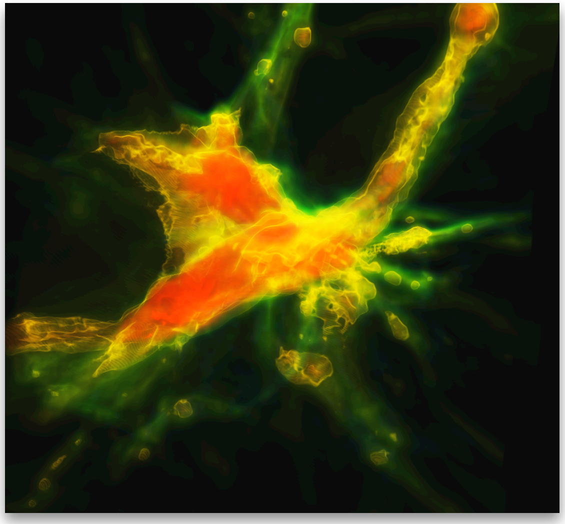
dependence on Z at low density

- at densities $n < 10^2$ cm^{-3} and metallicities $Z < 10^{-2}$ *H_2 cooling* dominates behavior.
  (Jappsen et al. 2007)

- fragmentation depends on *initial conditions*
  - example 1: *solid-body rotating top-hat* initial conditions with dark matter fluctuations (a la Bromm et al. 1999) fragment no matter what metallicity you take (in regime $n \leq 10^6$ cm^{-3})
    because *unstable disk* builds up
    (Jappsen et al. 2009a)
  - example 2: *centrally concentrated halo* does *not* fragment up to densities of $n \approx 10^6$ cm^{-3} up to metallicities $Z \approx -1$ (Jappsen et al. 2009b)

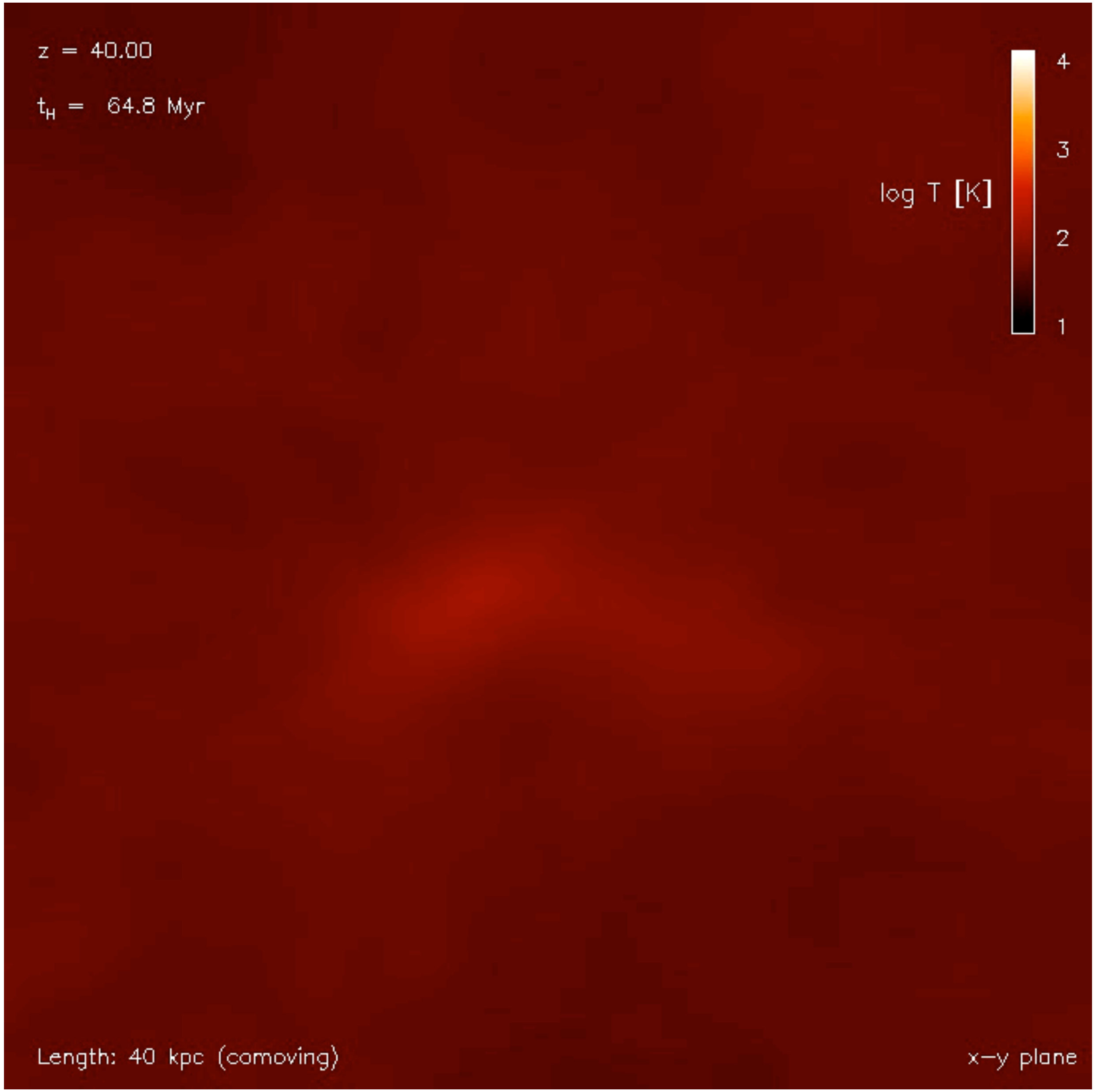
implications for Pop III

- star formation will depend on *degree of turbulence* in protogalactic halo
- speculation: *differences in stellar mass function*?
- speculation:
  - low-mass halos → low level of turbulence → relatively massive stars
  - high-mass halos (atomic cooling halos) → high degree of turbulence → wider mass spectrum with peak at lower-masses?

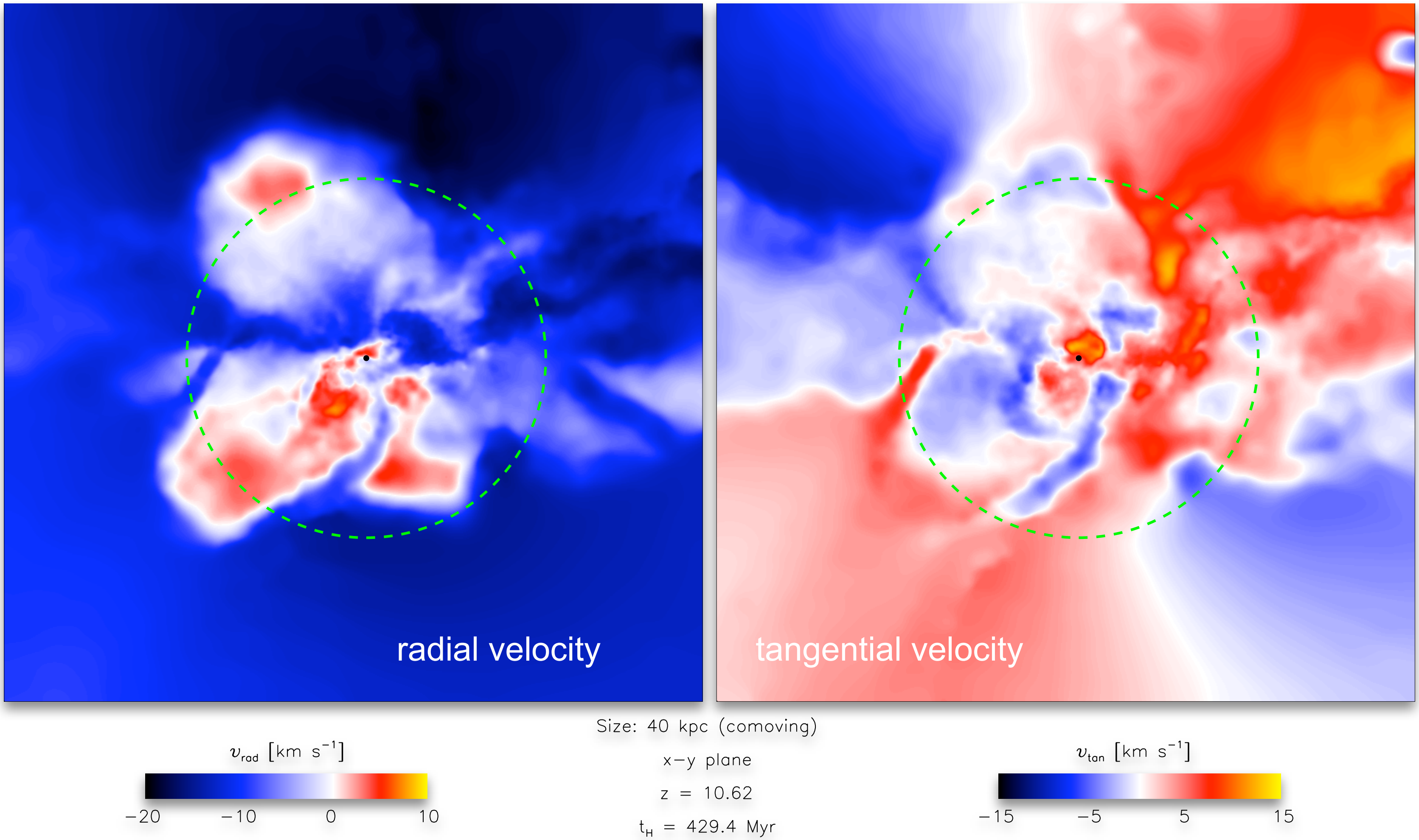


(Greif et al. 2008)

turbulence developing in an atomic cooling halo



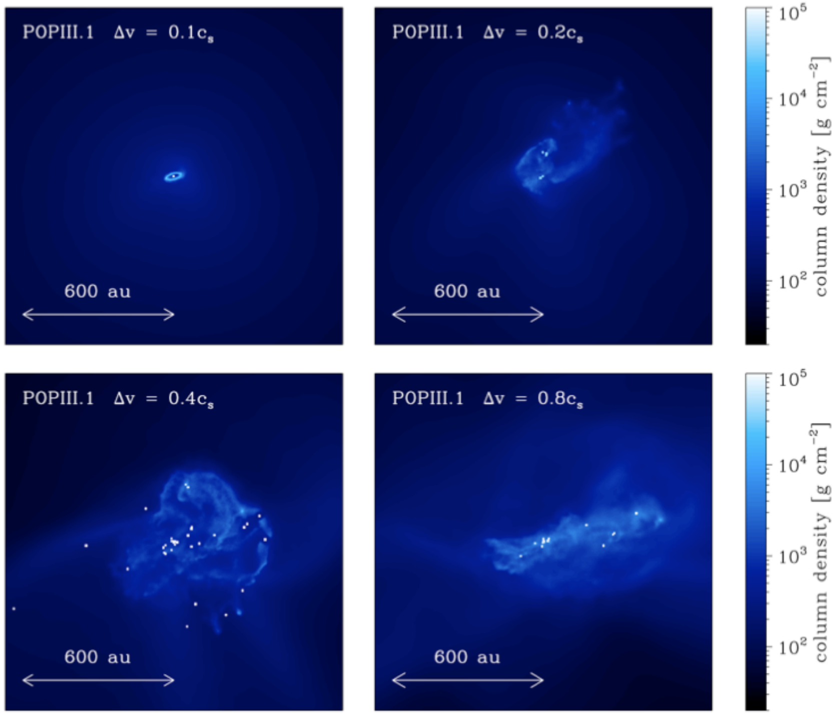
(Greif et al. 2008, see also Wise & Abel 2007)

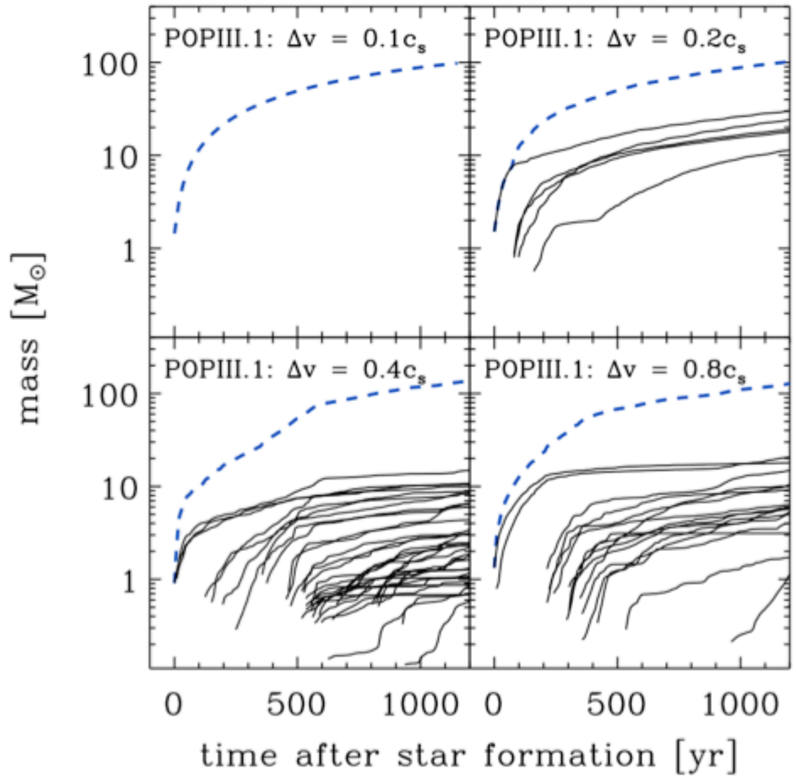


turbulence developing in an atomic cooling halo

(Greif et al. 2008)

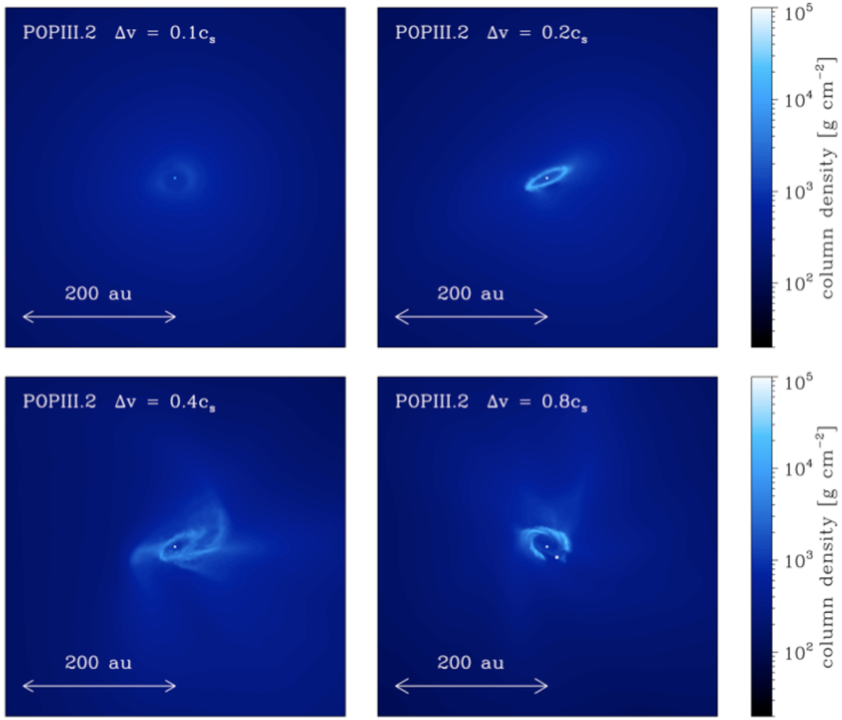
Pop III.1

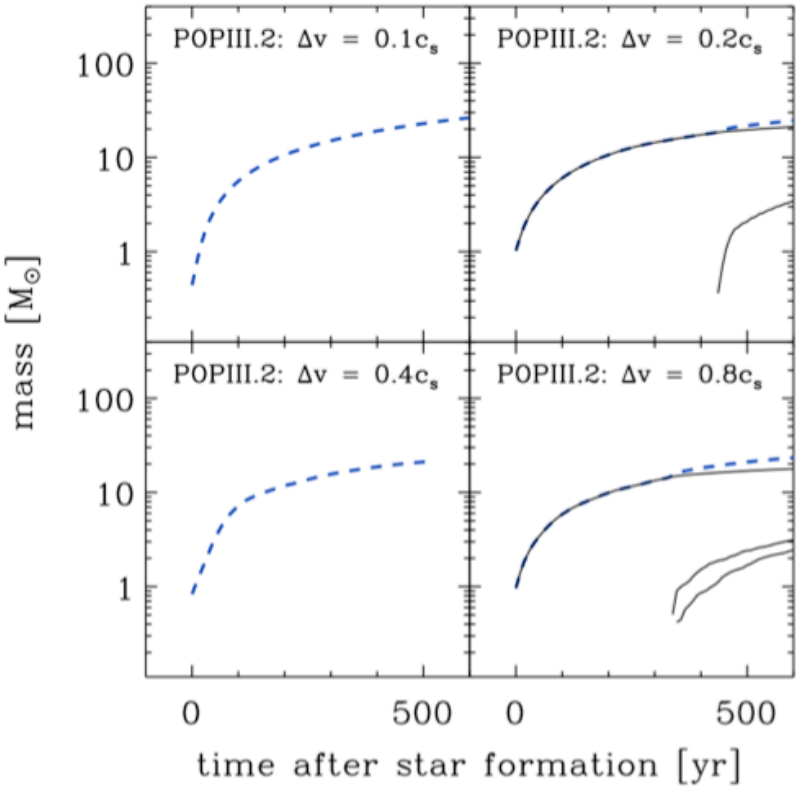




(Clark et al, submitted)

Pop III.2





(Clark et al, submitted)

once again: thermodynamics

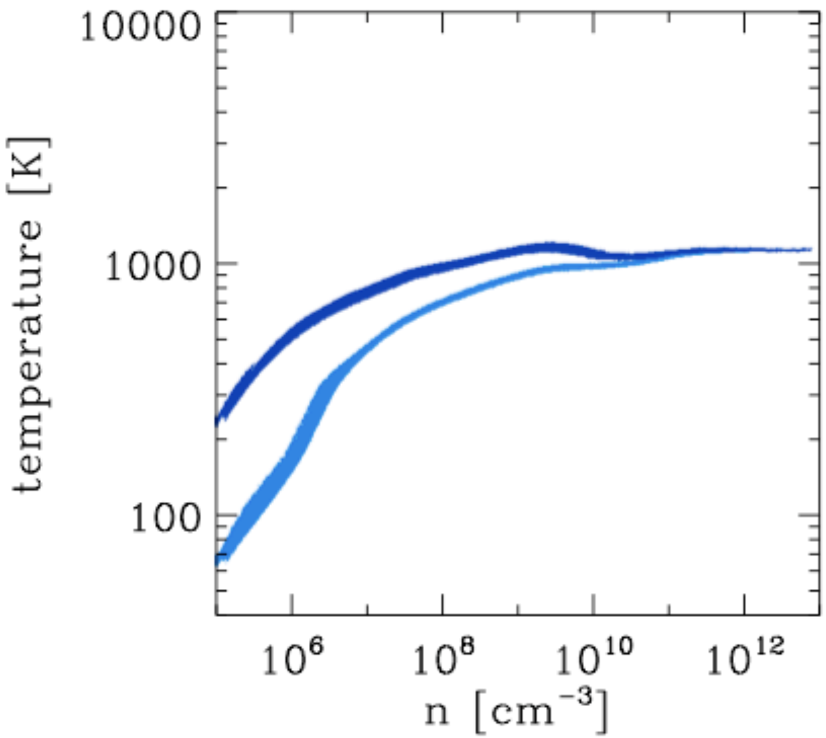


FIG. 6.— Temperature as a function of number density for the Pop. III.1 (dark blue) and Pop. III.2 (light blue) $\Delta v_{\rm turb} = 0.1\, c_{\rm s}$ simulations. In both cases, the curves denote the state of the cloud at the point just before the formation of the sink particle.

also Pop III.2 gas heats up above the CMB

--> weaker fragmentation!

once again: thermodynamics

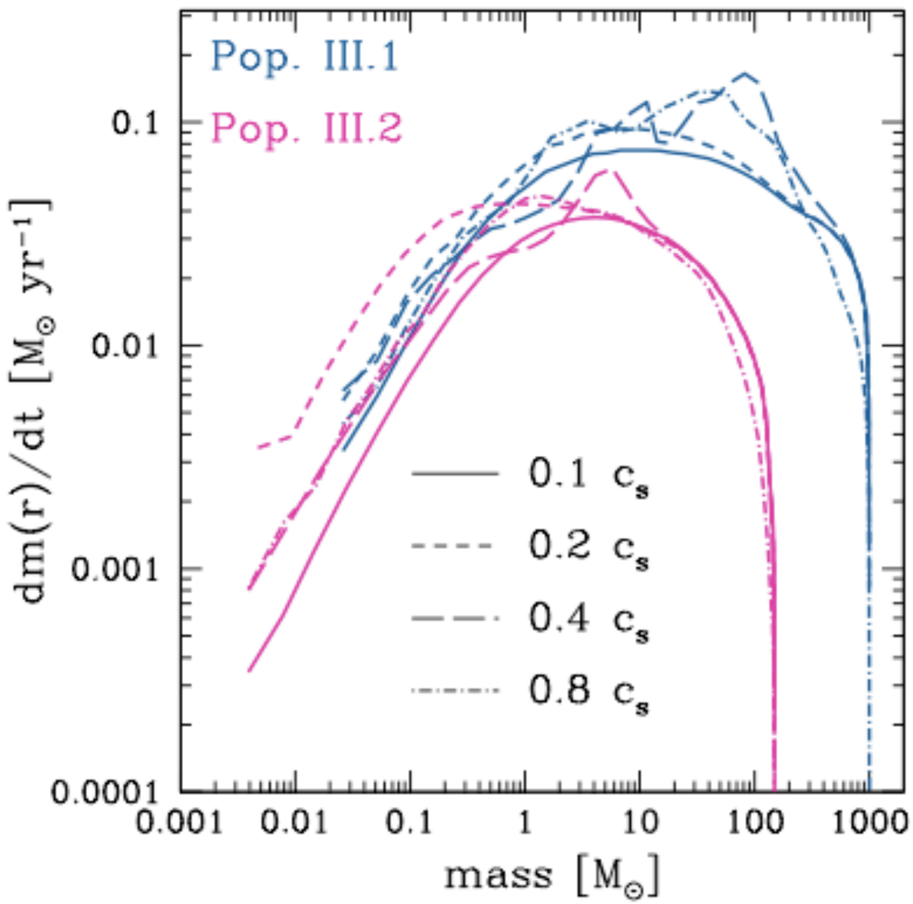
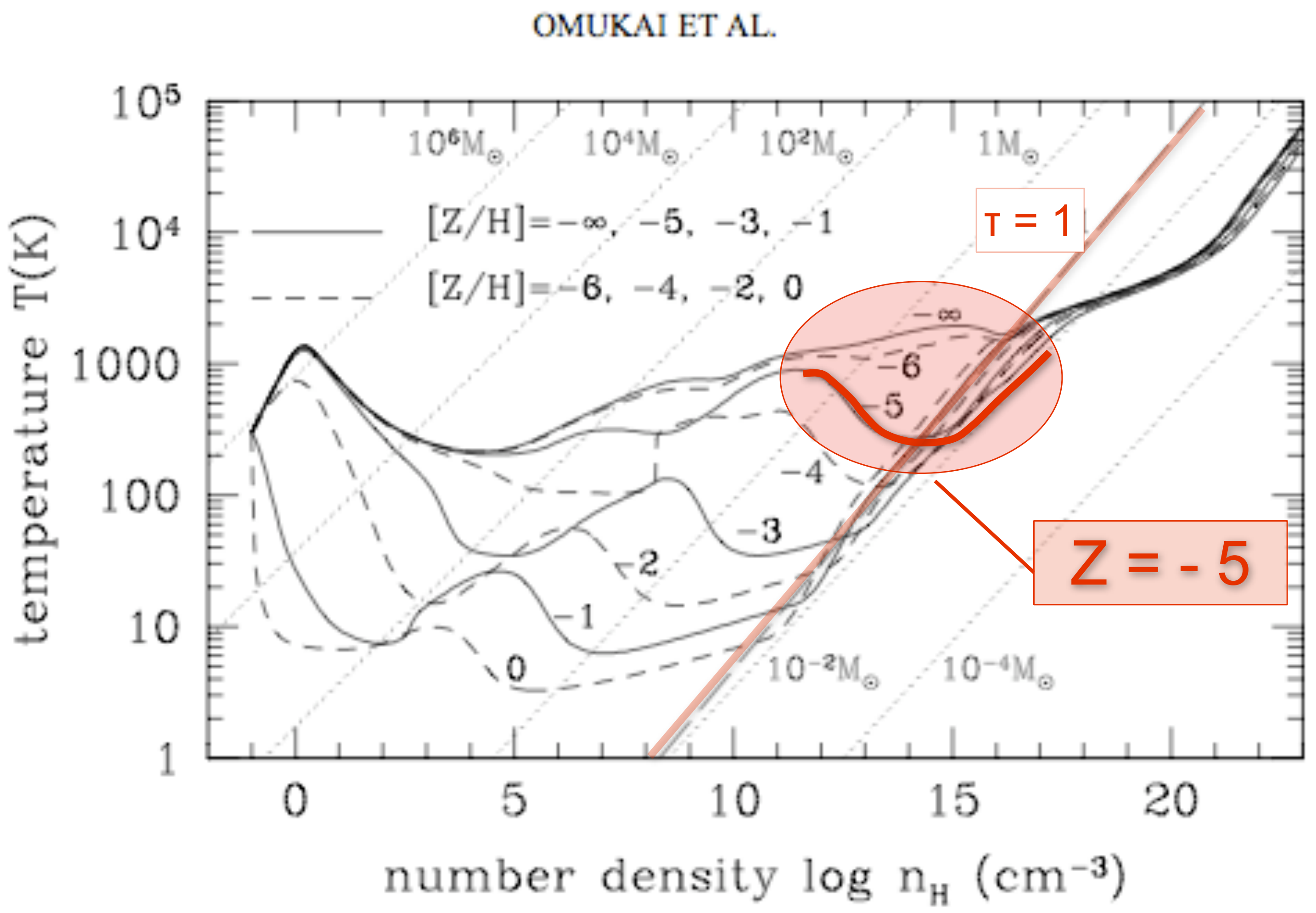


FIG. 8.— Accretion rates as a function of enclosed gas mass in the Pop. III.1 (upper lines; blue) and Pop. III.2 (lower lines; magenta) simulations, estimated as described in Section 4.1. Note that the sharp decline in the accretion rates for enclosed masses close to the initial cloud mass is an artifact of our problem setup; we would not expect to see this in a realistic Pop. III halo.

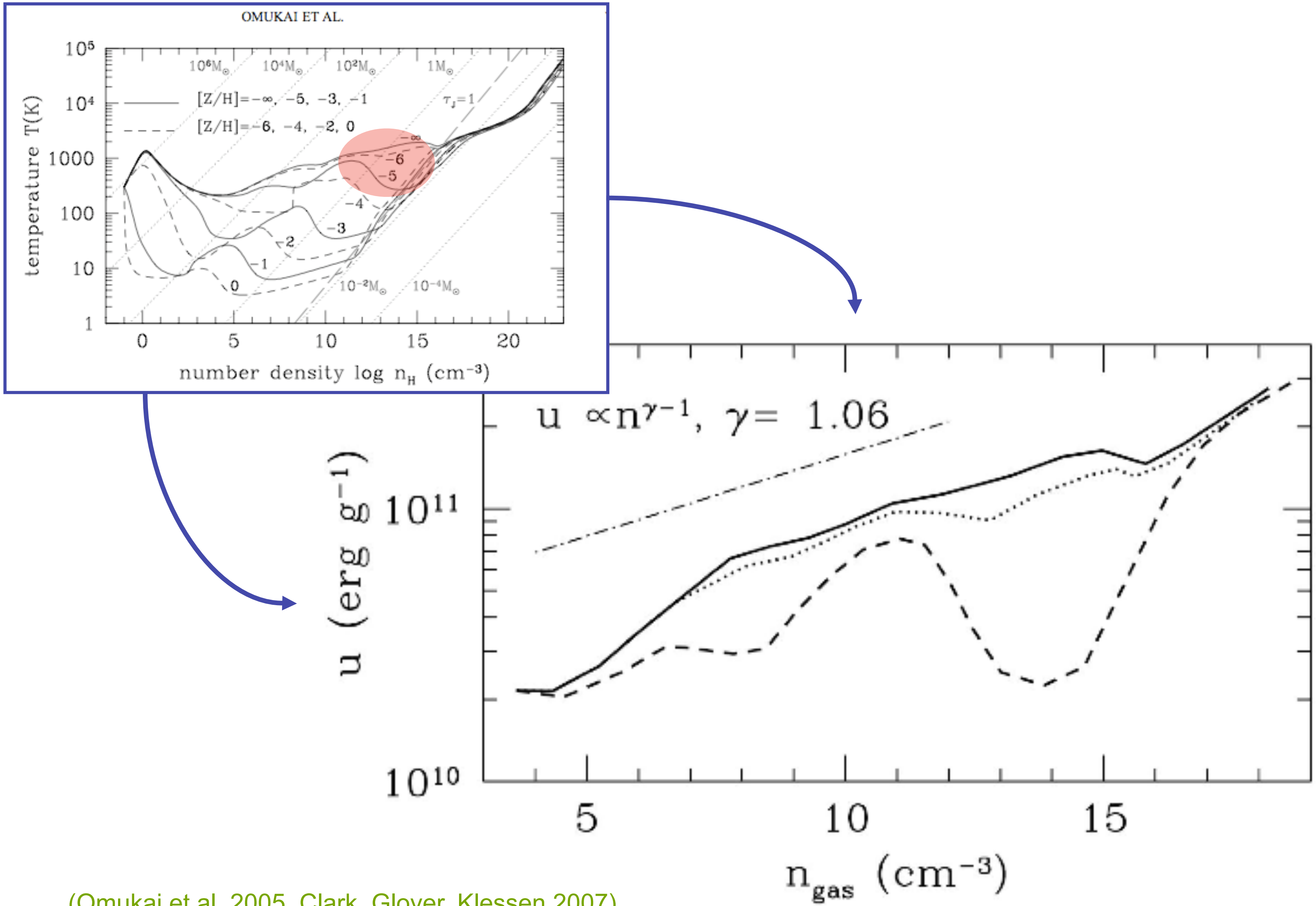
comparison of accretion rates...

transition: Pop III to Pop II.5



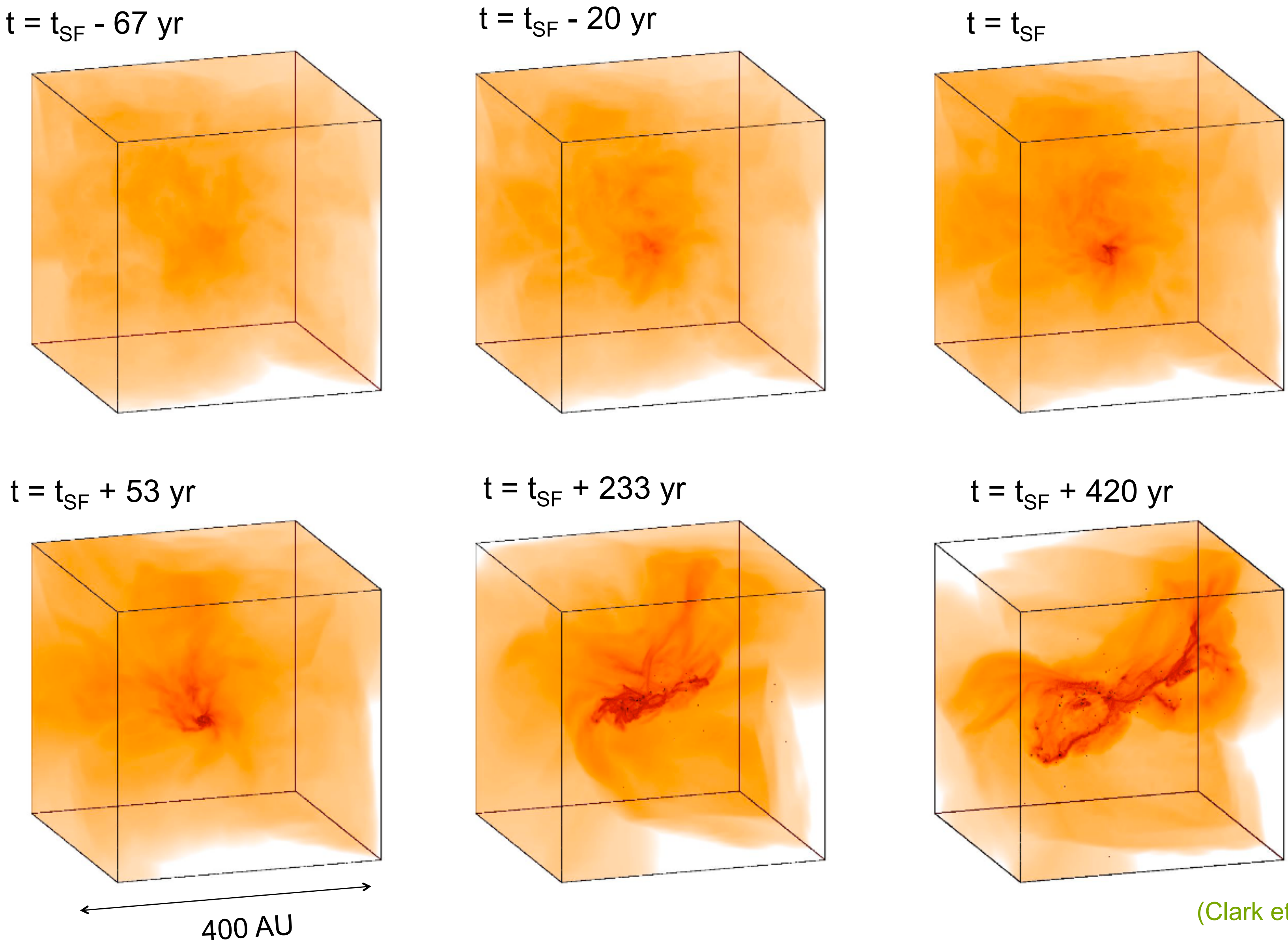
(Omukai et al. 2005)

transition: Pop III to Pop II.5



(Omukai et al. 2005, Clark, Glover, Klessen 2007)

dust induced fragmentation at $Z=10^{-5}$



(Clark et al. 2007)

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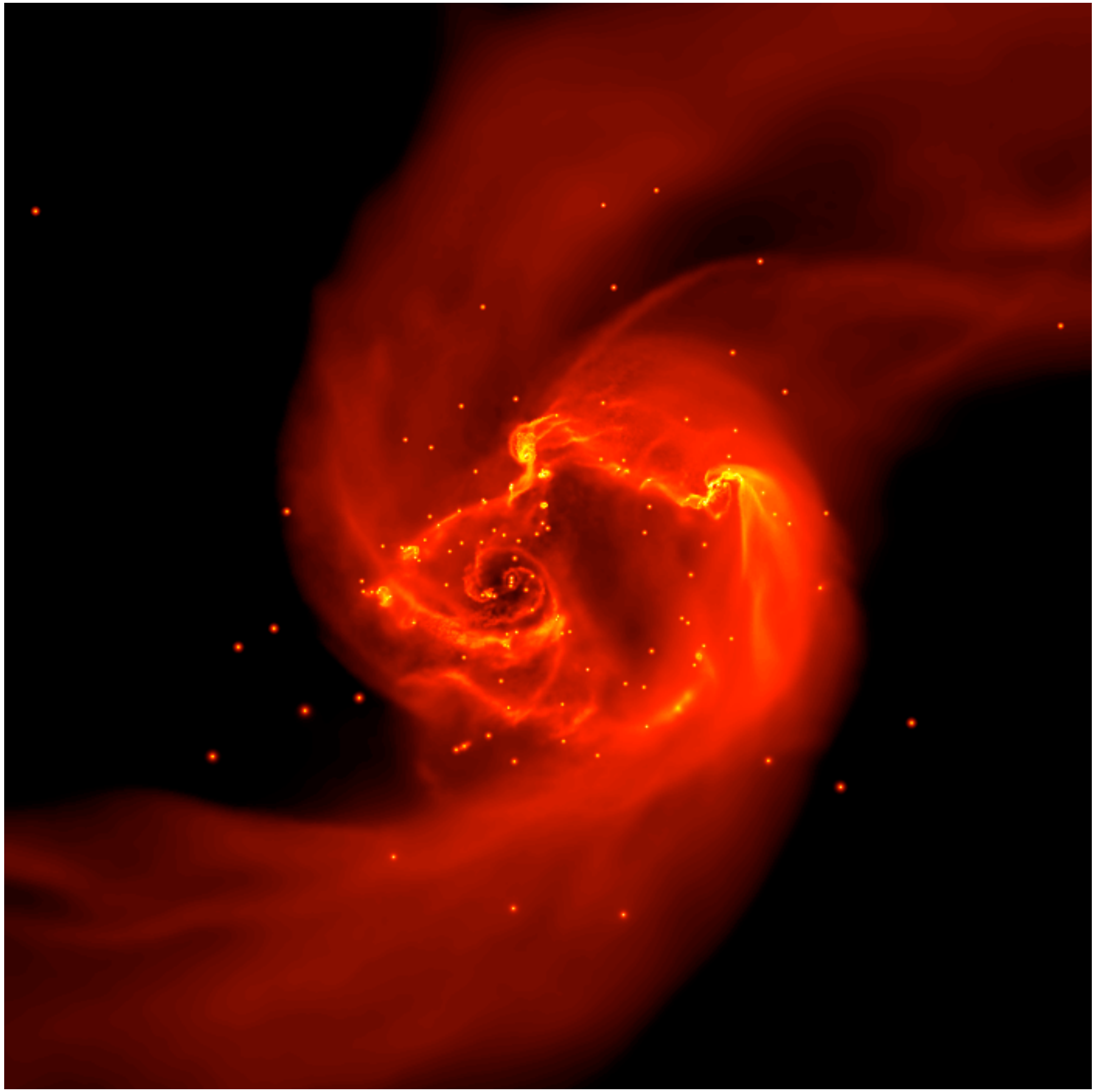
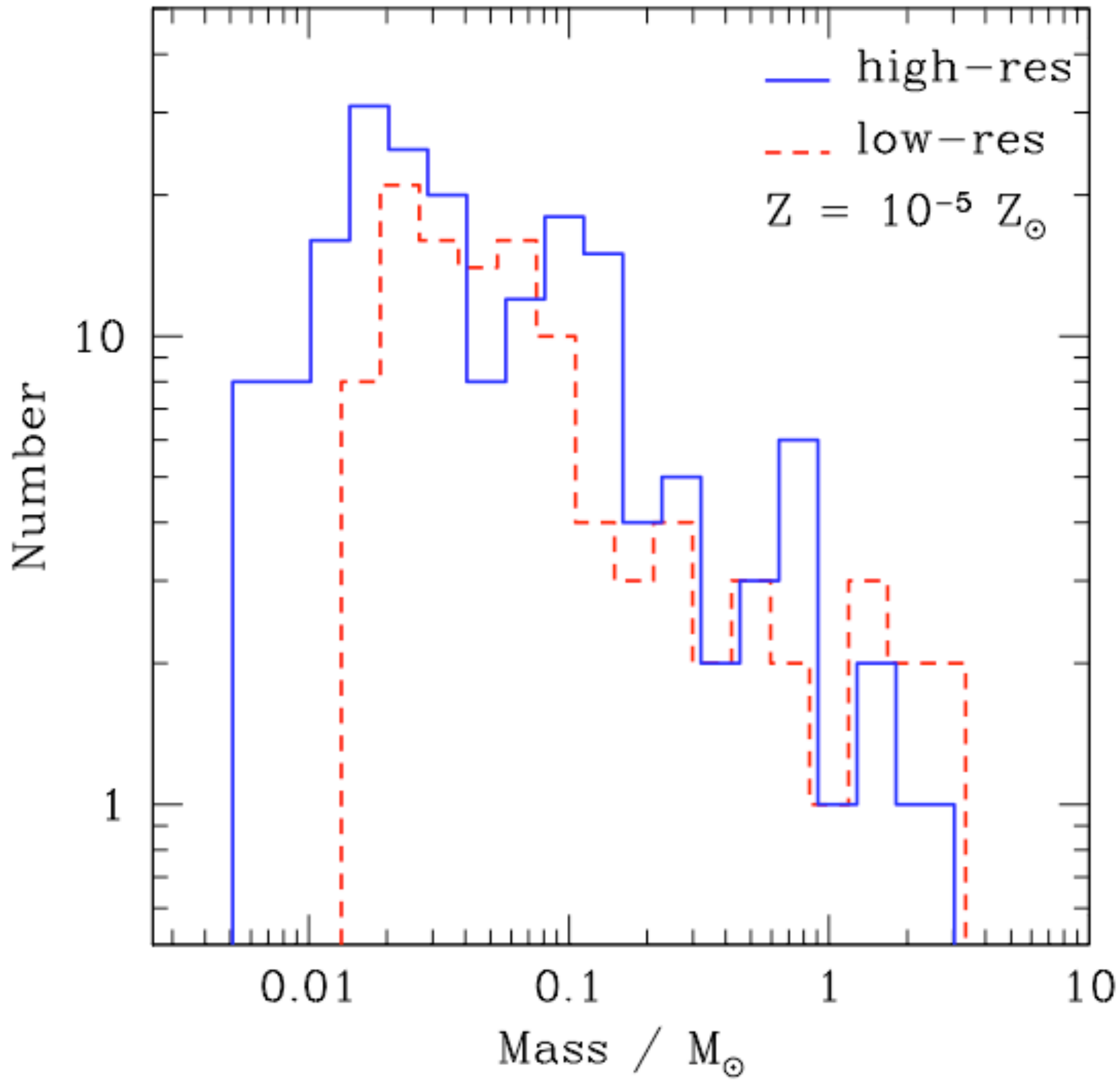


dense cluster of low-mass protostars builds up:

- mass spectrum peaks *below* $1\ M_{sun}$
- cluster VERY dense $n_{stars} = 2.5 \times 10^9\ pc^{-3}$
- fragmentation at density $n_{gas} = 10^{12} - 10^{13}\ cm^{-3}$

(Clark et al. 2008, ApJ 672, 757)

dust induced fragmentation at $Z=10^{-5}$



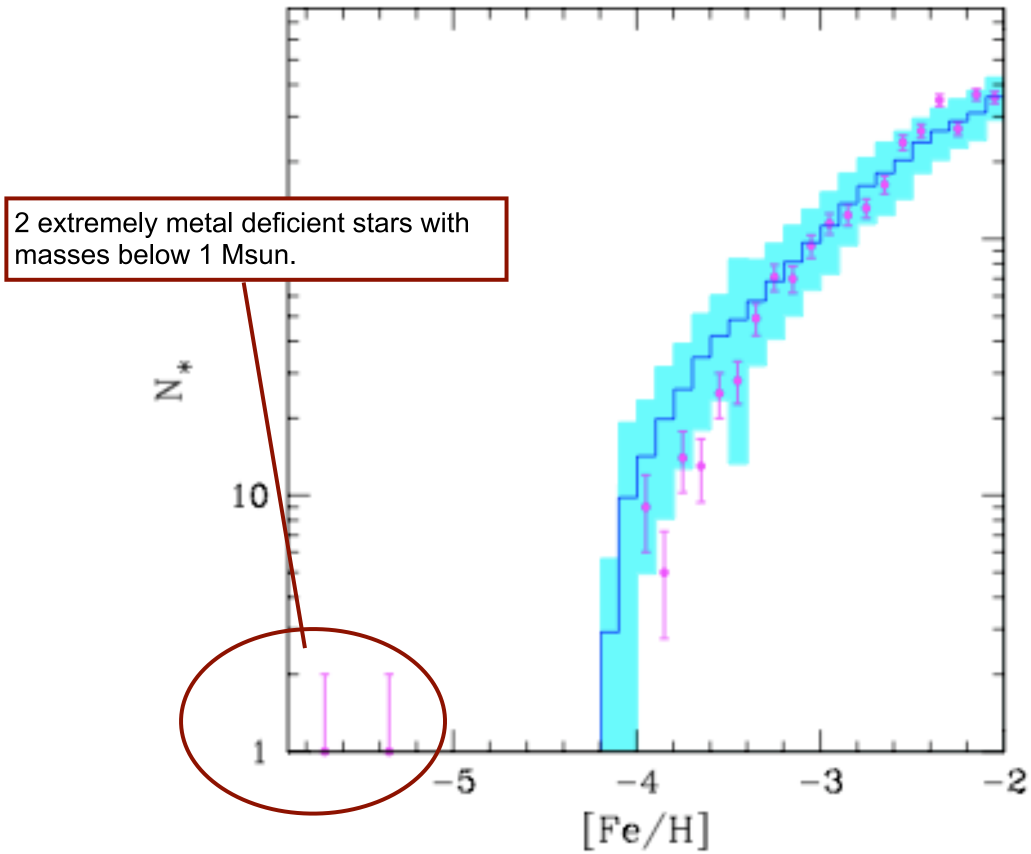
dense cluster of low-mass protostars builds up:

- mass spectrum peaks below 1 M_{sun}
- cluster VERY dense $n_{stars} = 2.5 \times 10^9 \, pc^{-3}$

- *predictions:*
  * low-mass stars with [Fe/H] ~ 10^{-5}
  * high binary fraction

(Clark et al. 2008)

dust induced fragmentation at $Z=10^{-5}$



(plot from Salvadori et al. 2006, data from Frebel et al. 2005)

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- mass spectrum peaks below 1 M_{sun}
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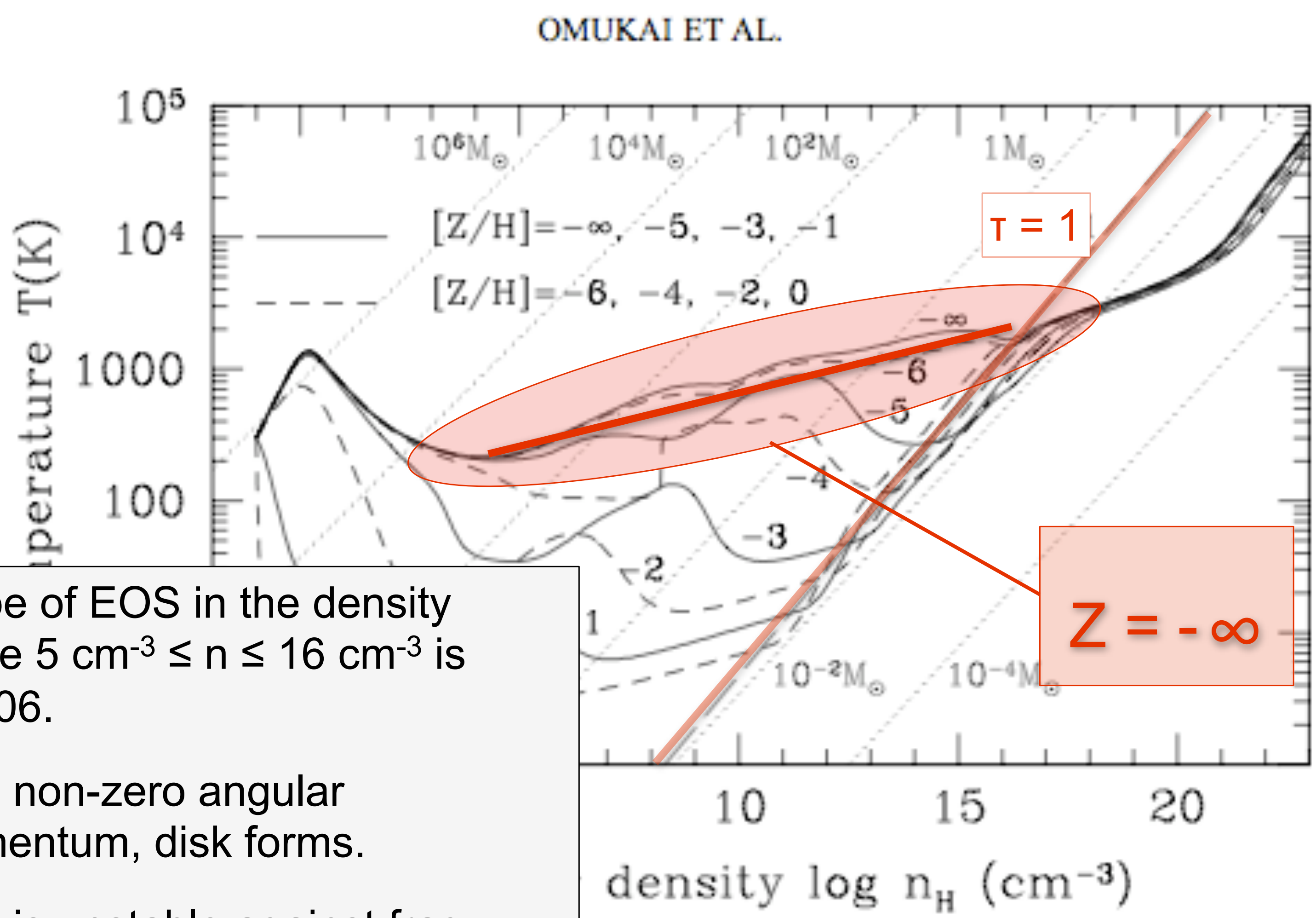
metal-free star formation



- slope of EOS in the density range 5 cm^{-3} ≤ n ≤ 16 cm^{-3} is $\gamma \approx 1.06$.
- with non-zero angular momentum, disk forms.
- disk is unstable against fragmentation at high density

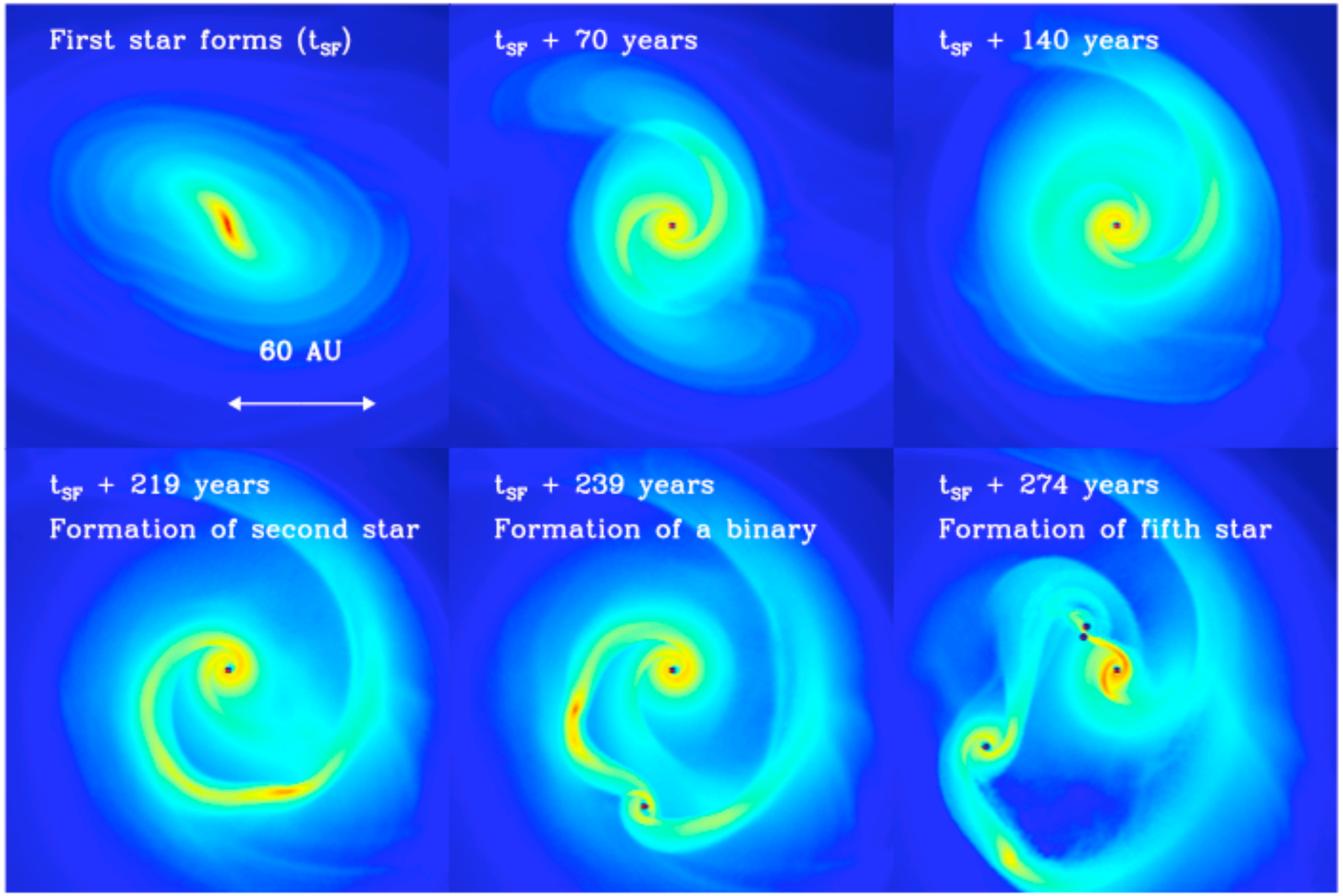


Figure 1: Density evolution in a 180 AU region around the first protostar, showing the build-up of the protostellar disk and its eventual fragmentation. The prominent two-arm spiral structure is caused by the gravitational instability in the disk, and the resulting gravitational torques provide the main source of angular momentum transport that allows disk material to accrete onto the protostar. Eventually, as mass continues to pour onto the disk from the in-falling envelope, the disk becomes so unstable that regions in the spiral arms become self-gravitating in their own right: the disk fragments and a multiple system is formed. The color table is stretched over number densities ranging from 10^{11} (dark blue) to 10^{16} cm^{-3} (red).

(Clark et al. 2010)

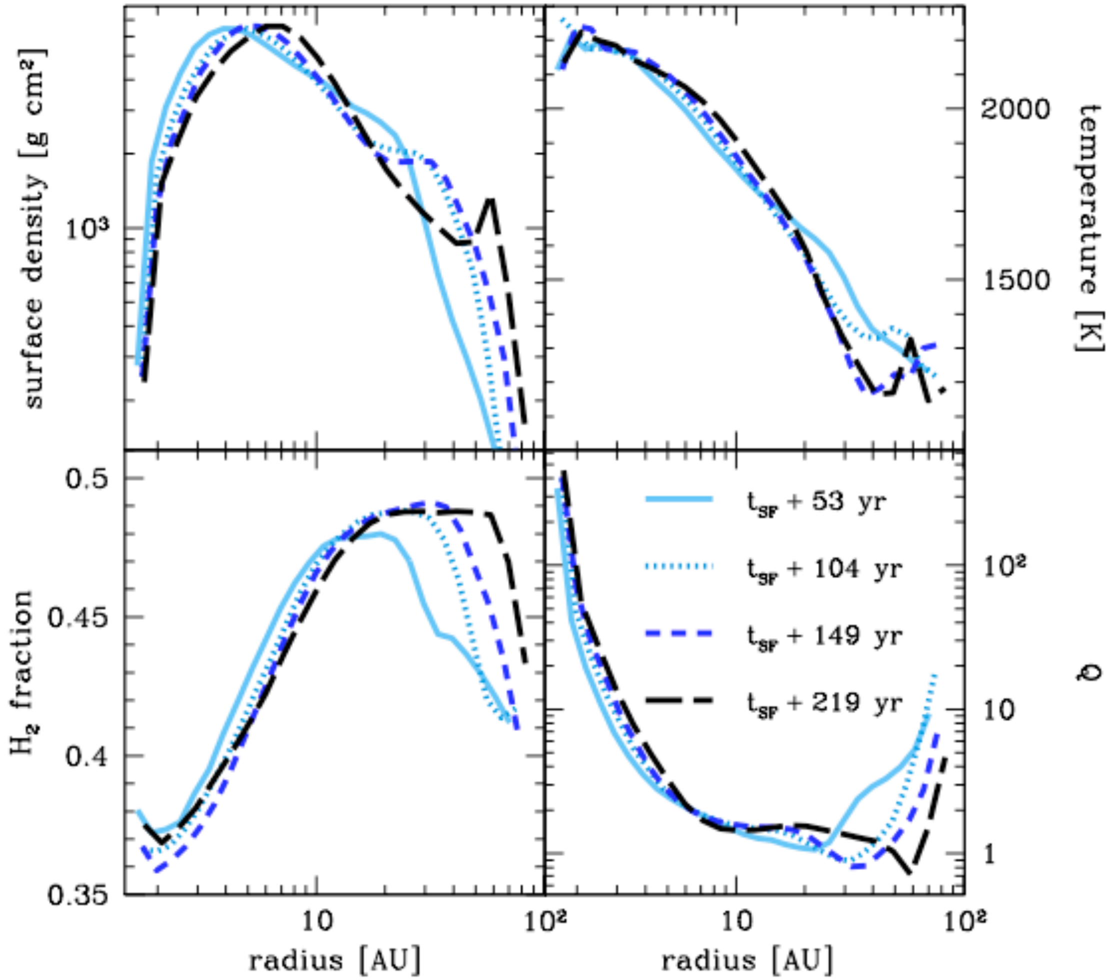


Figure 2: Radial profiles of the disk's physical properties, centered on the first protostellar core to form. The quantities are mass-weighted and taken from a slice through the midplane of the disk. In the lower right-hand plot we show the radial distribution of the disk's Toomre parameter, $Q = c_s\kappa/\pi G\Sigma$, where c_s is the sound speed and κ is the epicyclic frequency. Since our disk is Keplerian, we adopt the standard simplification, and replace κ with the orbital frequency.

(Clark et al. 2010)

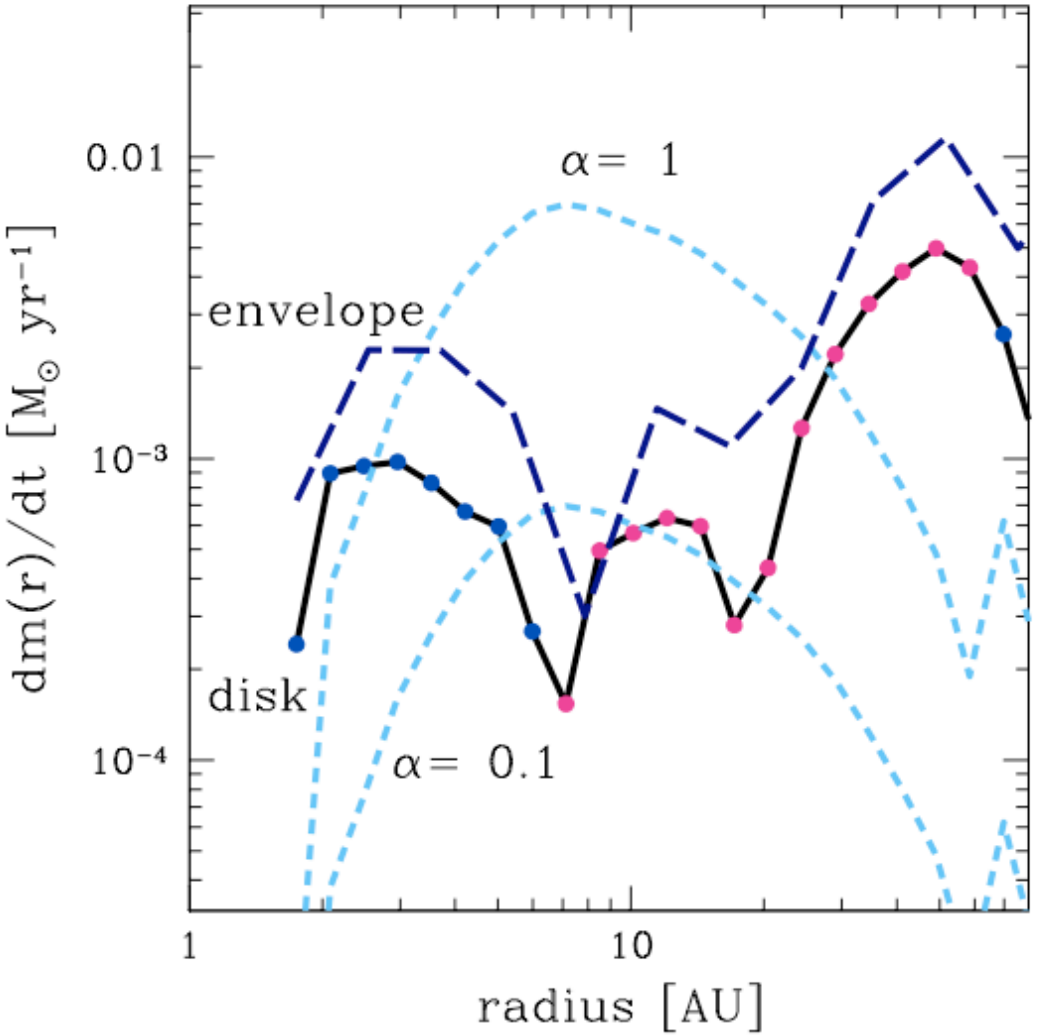
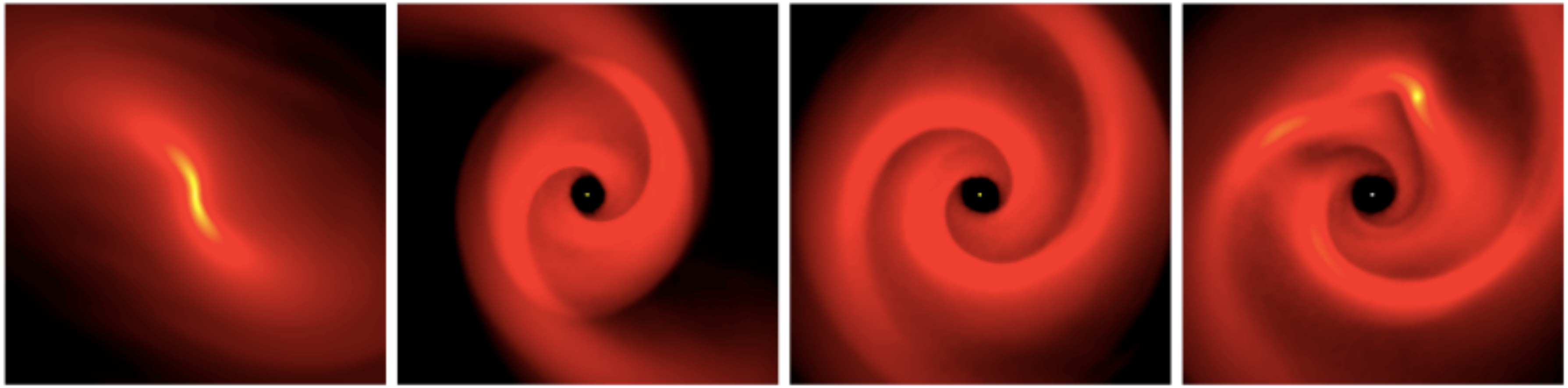


Figure 3: Mass transfer through the disk and in-falling envelope as a function of radius from the central protostar at the onset of disk fragmentation. In the case of the disk we have denoted annuli that are moving towards the protostar with blue dots, and those moving away in pink. The light blue dashed lines show the accretion rates expected from an 'alpha' (thin) disk model, where $\dot{M}(r) = 3\pi\,\alpha\,c_s(r)\,\Sigma(r)\,H(r)$, with two global values of alpha and where $c_s(r)$, $\Sigma(r)$, and $H(r)$ are (respectively) the sound speed, surface density and disk thickness at radius r.

(Clark et al. 2010)

primordial star formation



- first star formation is not less complex than present-day star formation
- brave claim: *all* Pop III stars form in multiple systems
- even braver claim: some Pop III stars fall in the mass range < 0.5 $M_\odot$ ---> they should still *be around*!!!!

key questions

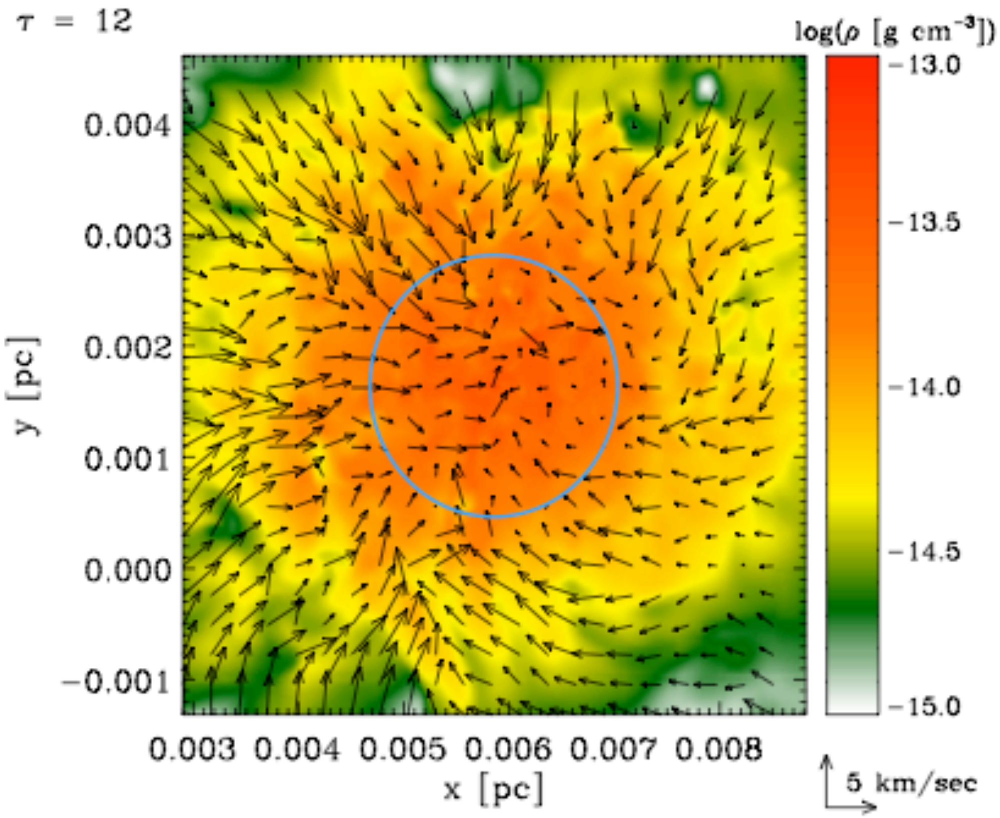
- *what drives turbulence?*
  --> accretion driven turbulence on ALL scales
  galaxies, molecular clouds, protostellar disks
- *how do high-mass stars & their clusters form?*
  --> radiative feedback & fragmentation-induced starvation
- *what are the initial conditions for cluster formation?*
  --> initial density profile matters
- *are there (still) low-mass metal-free stars?*
  --> importance of thermodynamics, use of sink particles
- *magnetic fields in the early universe?*
  --> generation of the first strong fields by turbulent dynamos

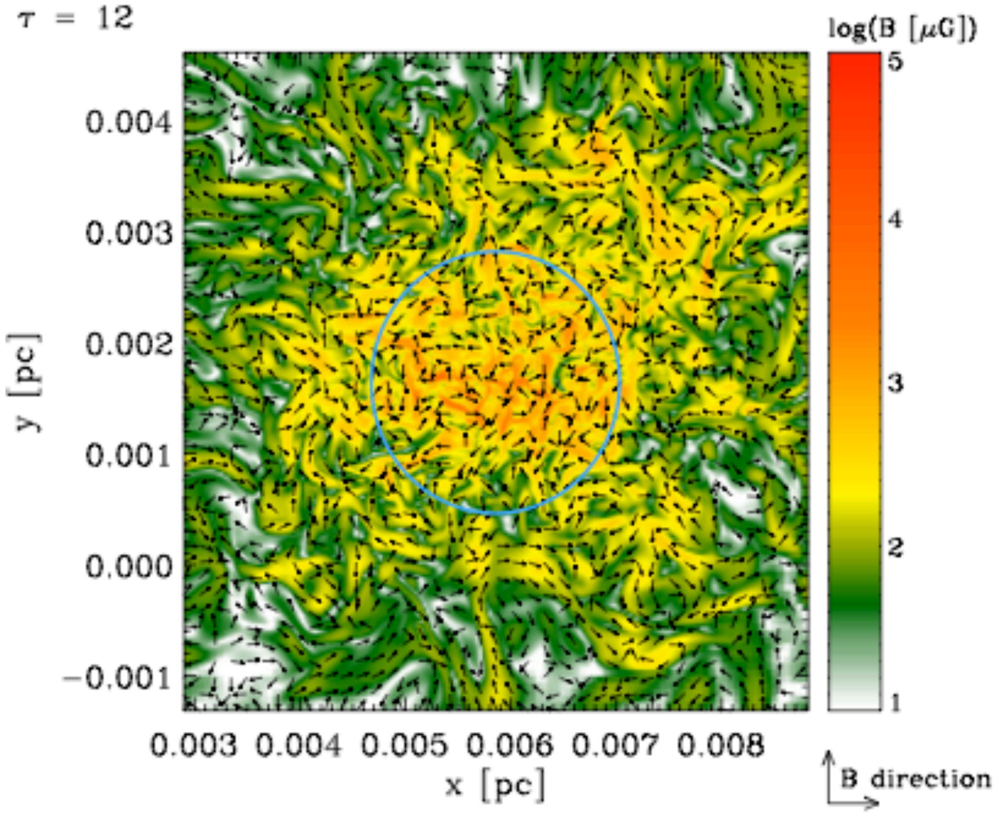
how to make strong B-fields

- we know the universe is magnetized (now)
- knowledge about B-fields in the high-redshift universe is extremely uncertain
  - inflation / QCD phase transition / Biermann battery / Weibel instability
- they are thought to be extremely small
- however, THIS MAY BE WRONG!

small-scale turbulent dynamo

- *idea:* the small-scale turbulent dynamo can generate strong magnetic fields from very small seed fields
- *approach:* model collapse of primordial gas ---> formation of the first stars in low-mass halo at redshift $z \sim 20$
- *method:* solve ideal MHD equations with very high resolution
  - grid-based AMR code FLASH
  - resolution up to 128^3 cells per Jeans volume (effective resolution 65536^3 cells)

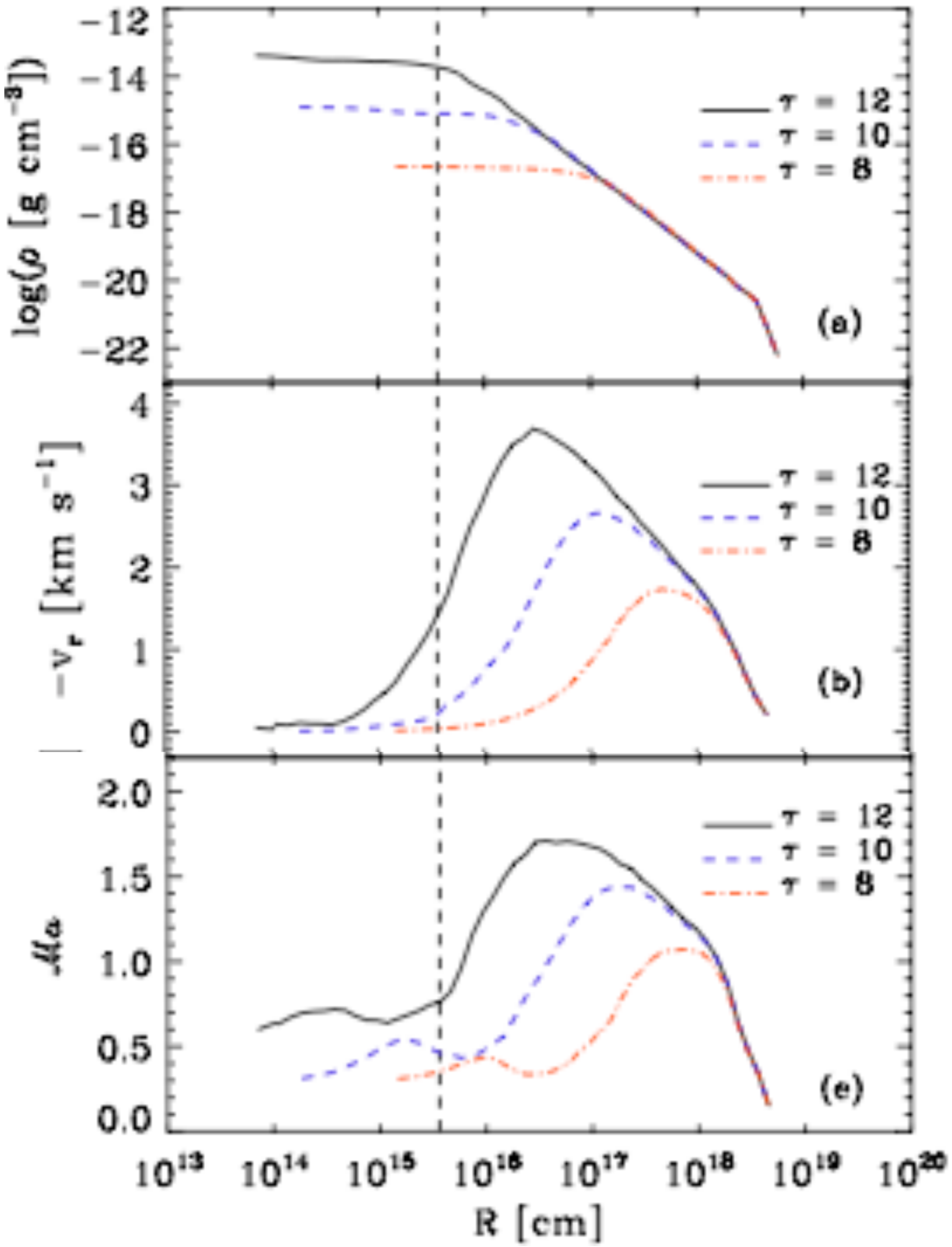




magnetic field structure

density structure

(Sur et al. 2010, ApJ, 721, L734)

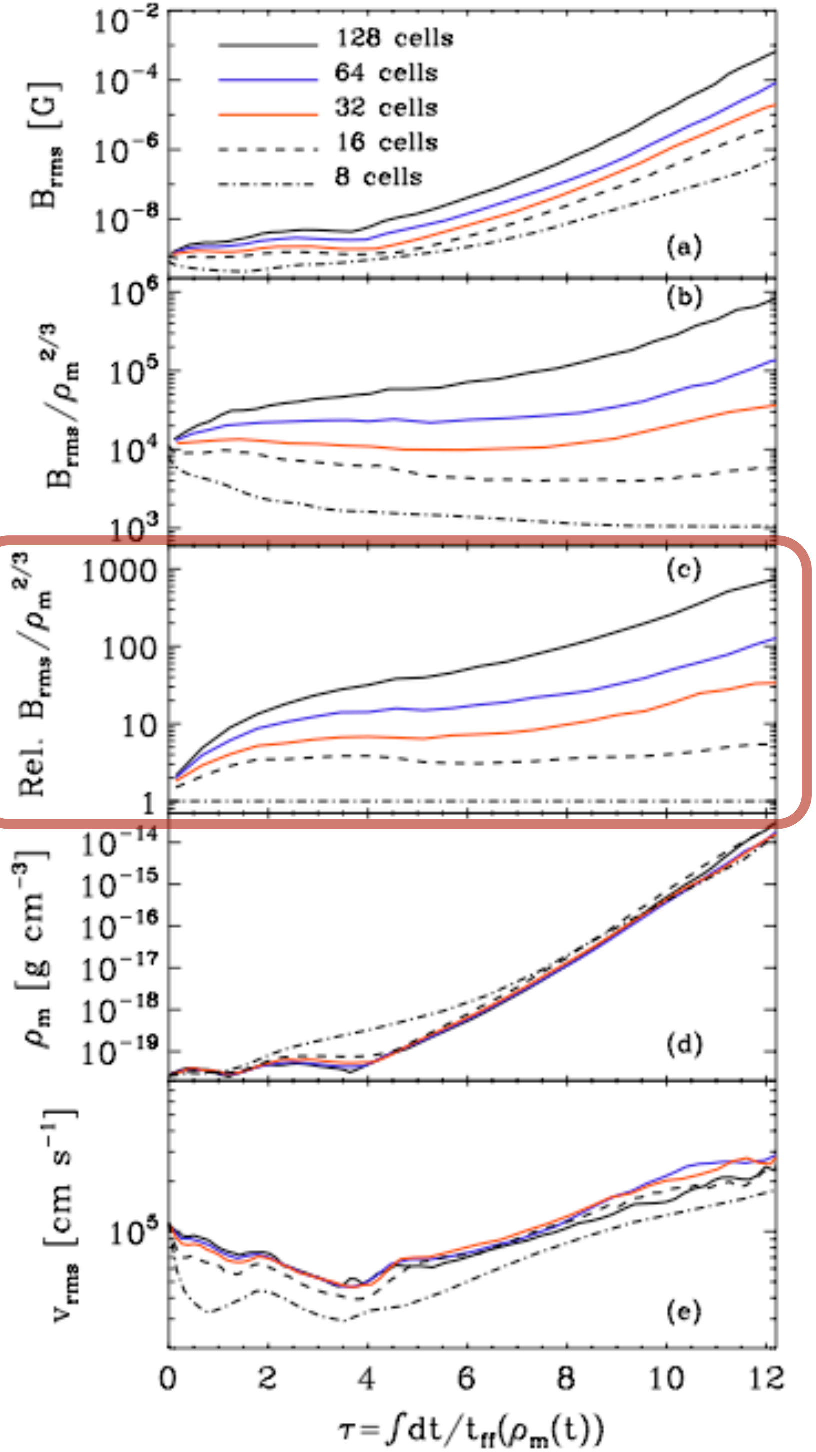


radial density profile

radial velocity profile

Mach number profile

(Sur et al. 2010, ApJ, 721, L734)



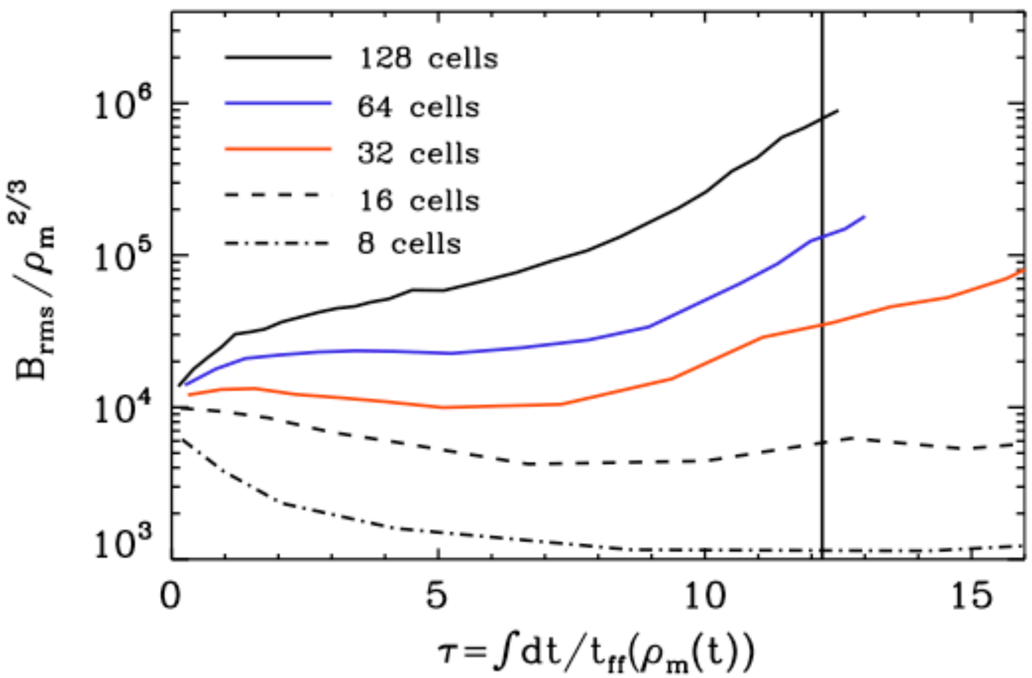


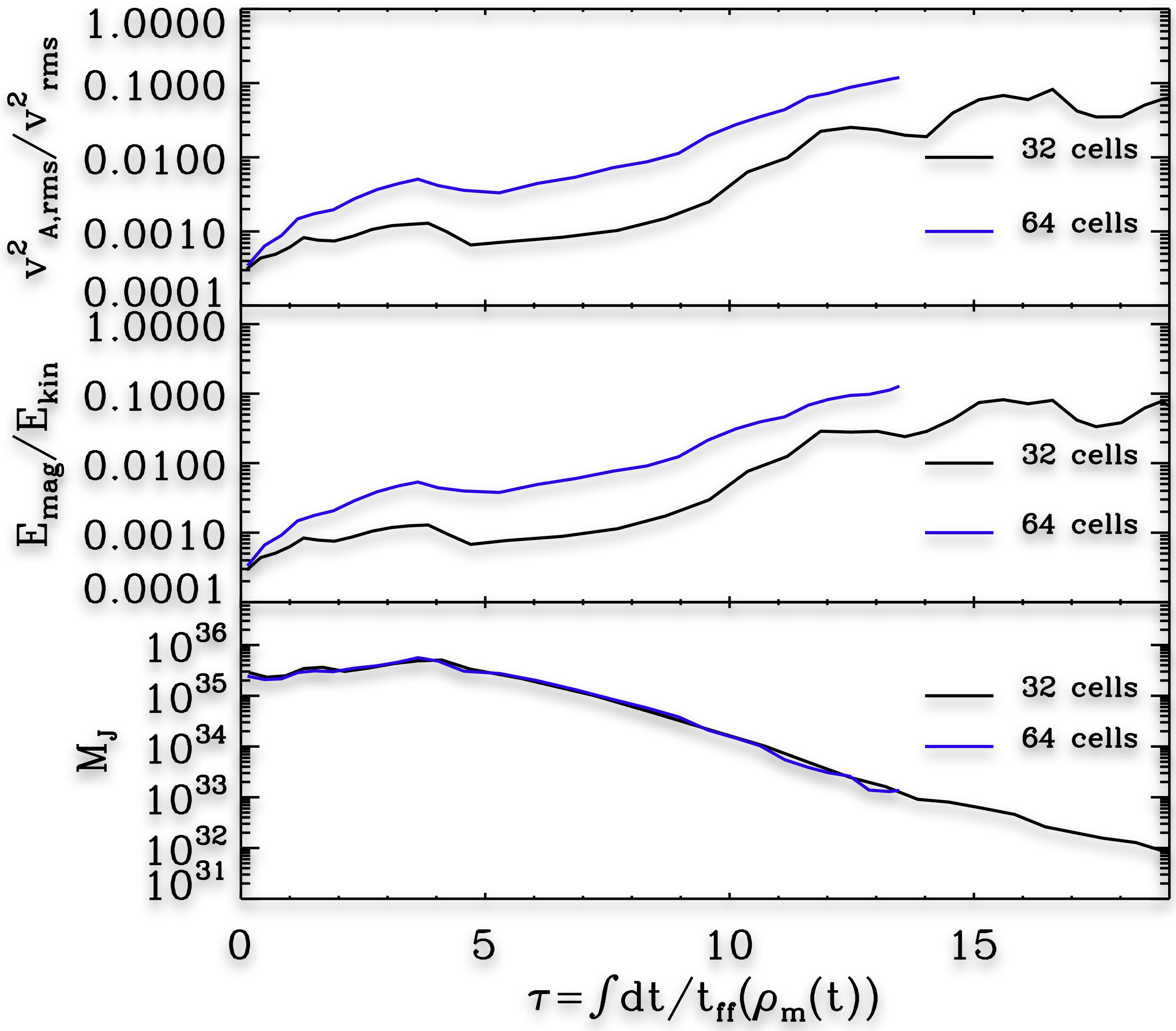
Figure 4. Illustration of the minimum resolution criterion required to capture the growth of the magnetic field due to small-scale dynamo action. The dynamo begins to be observed for simulations where λ_J is resolved by a minimum of 32 cells. Simulations performed with the Jeans length resolved by either 8 cells or 16 cells are decaying in nature with weak fluctuations. The vertical line indicates the values of $B_{rms}/\rho_m^{2/3}$ obtained in the different resolution runs at $\tau = 12.2$.

Field amplification during first collapse seems unavoidable.

QUESTION: What is the saturation value? Can the field reach dynamically important strength?

(Sur et al. 2010, ApJ, 721, L734)

first attempts to calculate the saturation level.



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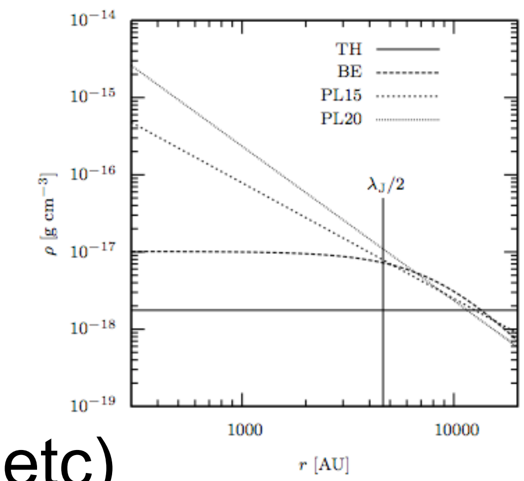
- *magnetic fields in the early universe?*

  --> generation of the first strong fields by turbulent dynamos

ICs of star cluster formation

- key question:
  - what is the initial density profile of cluster forming cores? how does it compare low-mass cores?
- theorists answer:
  - top hat (Larson Penston)
  - Bonnor Ebert (like low-mass cores)
  - power law $\rho \propto r^{-1}$ (logotrop)
  - power law $\rho \propto r^{-3/2}$ (Krumholz, McKee, etc)
  - power law $\rho \propto r^{-2}$ (Shu)
  - and many more



different density profiles

- does the density profile matter?

  .

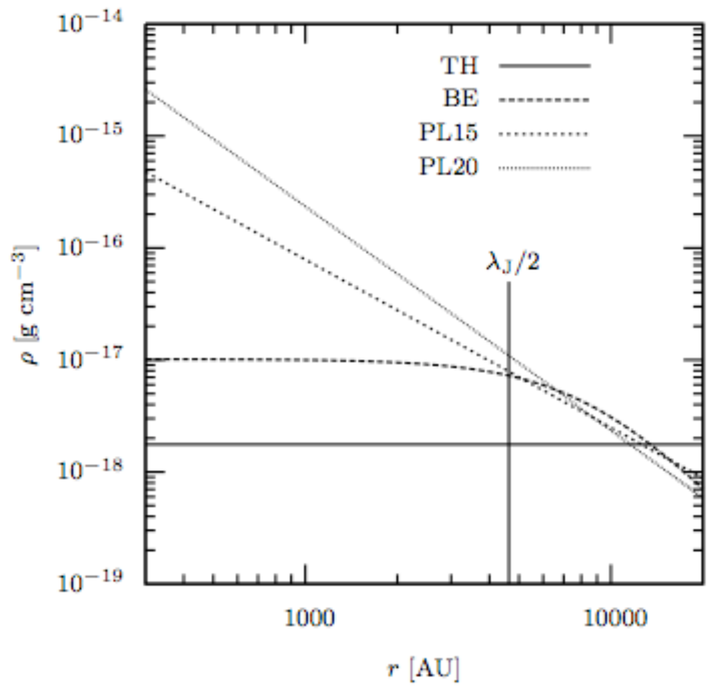
  .

  .

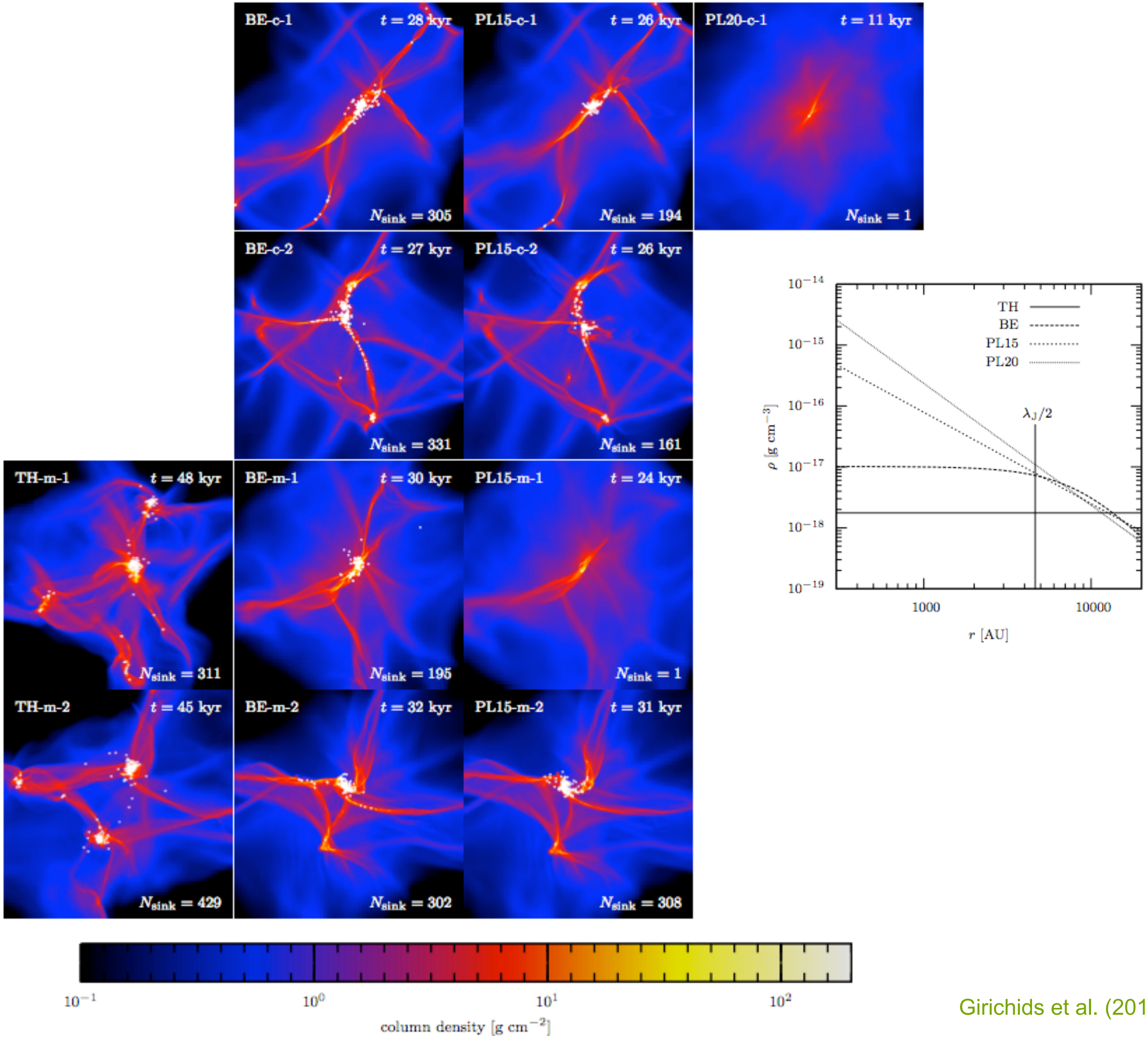
- in comparison to
  - turbulence ...
  - radiative feedback ...
  - magnetic fields ...
  - thermodynamics ...

different density profiles

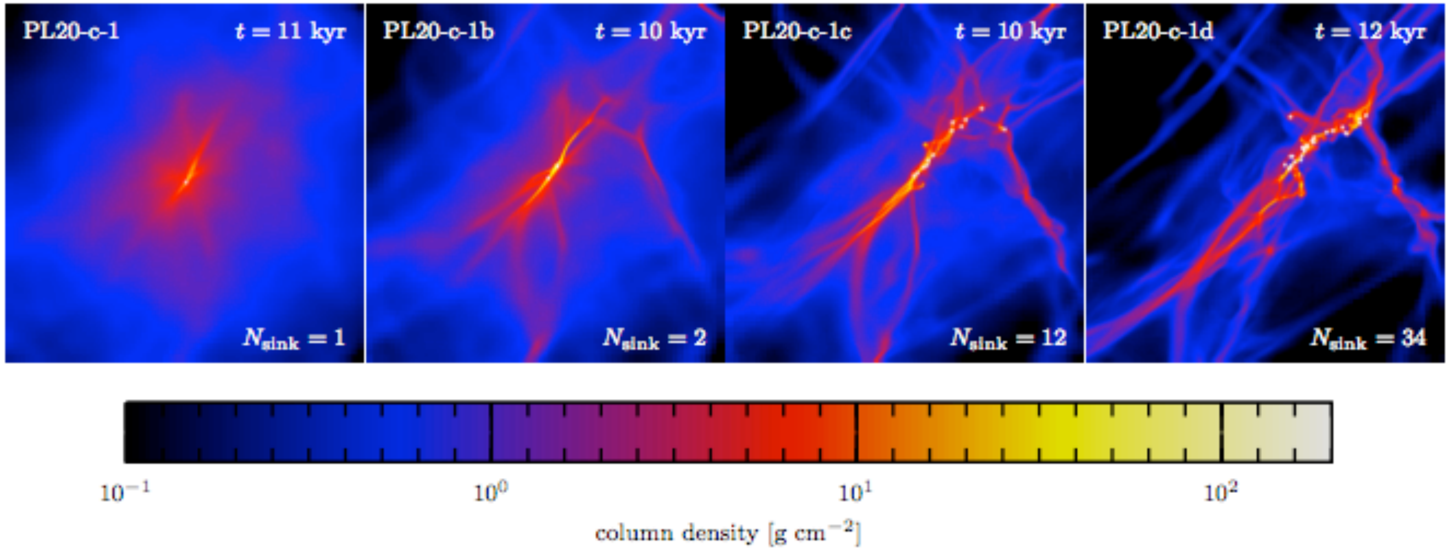
- answer: ***YES! it matters big time!***
- approach: extensive parameter study
  - different profiles (top hat, BE, $r^{-3/2}$, r^{-3})
  - different turbulence fields
    - different realizations
    - different Mach numbers
    - solenoidal turbulence
      dilatational turbulence
      both modes
  - no net rotation, no B-fields
    (at the moment)



Girichids et al. (2010)



Girichids et al. (2010)



M=3 M=6 M=12 M=18

for the r^{-2} profile you need to crank up turbulence a lot to get some fragmentation!

Girichids et al. (2010)

Run	t_{sim} [kyr]	t_{sim}/t_{ff}^{core}	t_{sim}/t_{ff}	N_{sinks}	$\langle M \rangle$ [$M_{\odot}$]	M_{max}
TH-m-1	48.01	0.96	0.96	311	0.0634	0.86
TH-m-2	45.46	0.91	0.91	429	0.0461	0.74
BE-c-1	27.52	1.19	0.55	305	0.0595	0.94
BE-c-2	27.49	1.19	0.55	331	0.0571	0.97
BE-m-1	30.05	1.30	0.60	195	0.0873	1.42
BE-m-2	31.94	1.39	0.64	302	0.0616	0.54
BE-s-1	30.93	1.34	0.62	234	0.0775	1.14
BE-s-2	35.86	1.55	0.72	325	0.0587	0.51
PL15-c-1	25.67	1.54	0.51	194	0.0992	8.89
PL15-c-2	25.82	1.55	0.52	161	0.1244	12.3
PL15-m-1	23.77	1.42	0.48	1	20	20.0
PL15-m-2	31.10	1.86	0.62	308	0.0653	6.88
PL15-s-1	24.85	1.49	0.50	1	20	20.0
PL15-s-2	35.96	2.10	0.72	422	0.0478	4.50
PL20-c-1	10.67	0.92	0.21	1	20	20.0
PL20-c-1b	10.34	0.89	0.21	2	10.139	20.0
PL20-c-1c	9.63	0.83	0.19	12	1.67	17.9
PL20-c-1d	11.77	1.01	0.24	34	0.593	13.3

solenoidal turbulence tends to form fewer sinks (see also Ant Whitworth's talk yesterday)

Girichids et al. (2010)

Run	t_{sim} [kyr]	t_{sim}/t_{ff}^{core}	t_{sim}/t_{ff}	N_{sinks}	$\langle M \rangle$ [$M_\odot$]	M_{max}
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however, the real situation is more complex: need to analyze time scales for local collapse with the one of global collapse, which depends on details of realization.....

Girichids et al. (2010)

different density profiles

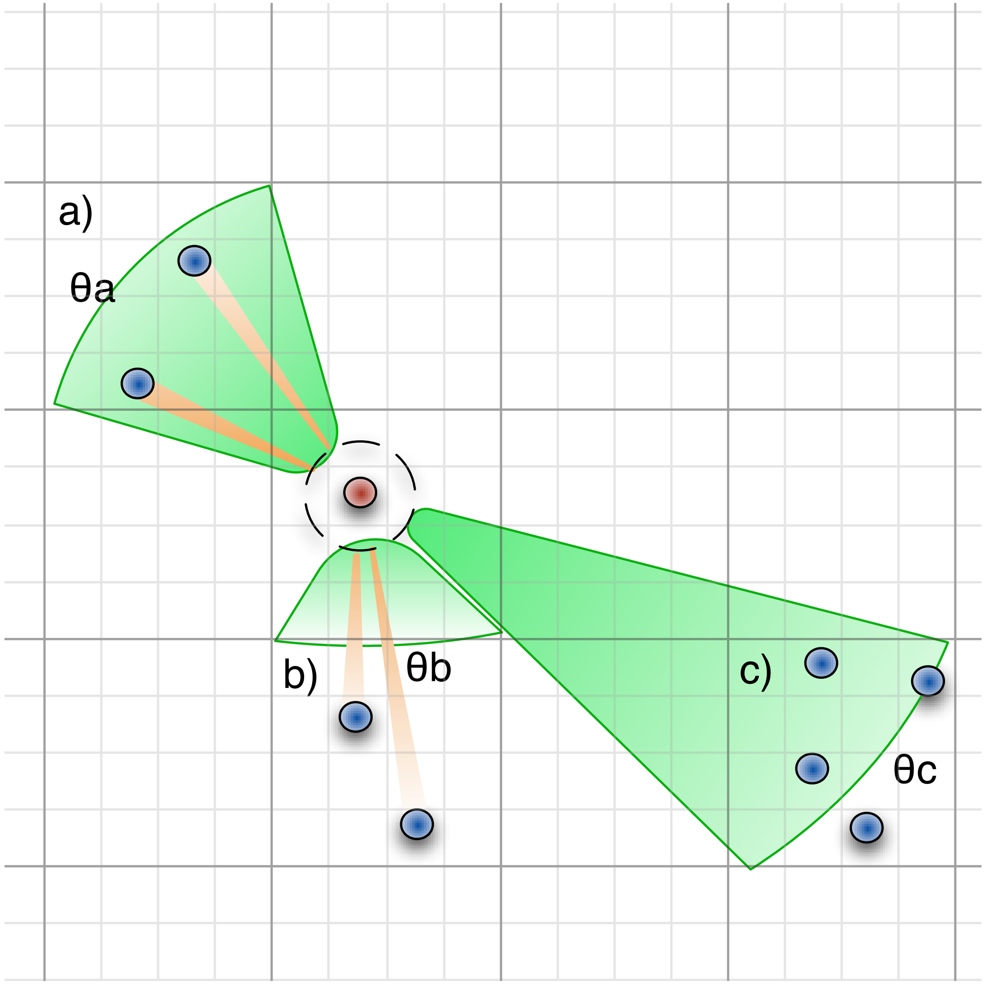
- answer: ***YES! it matters big time!***

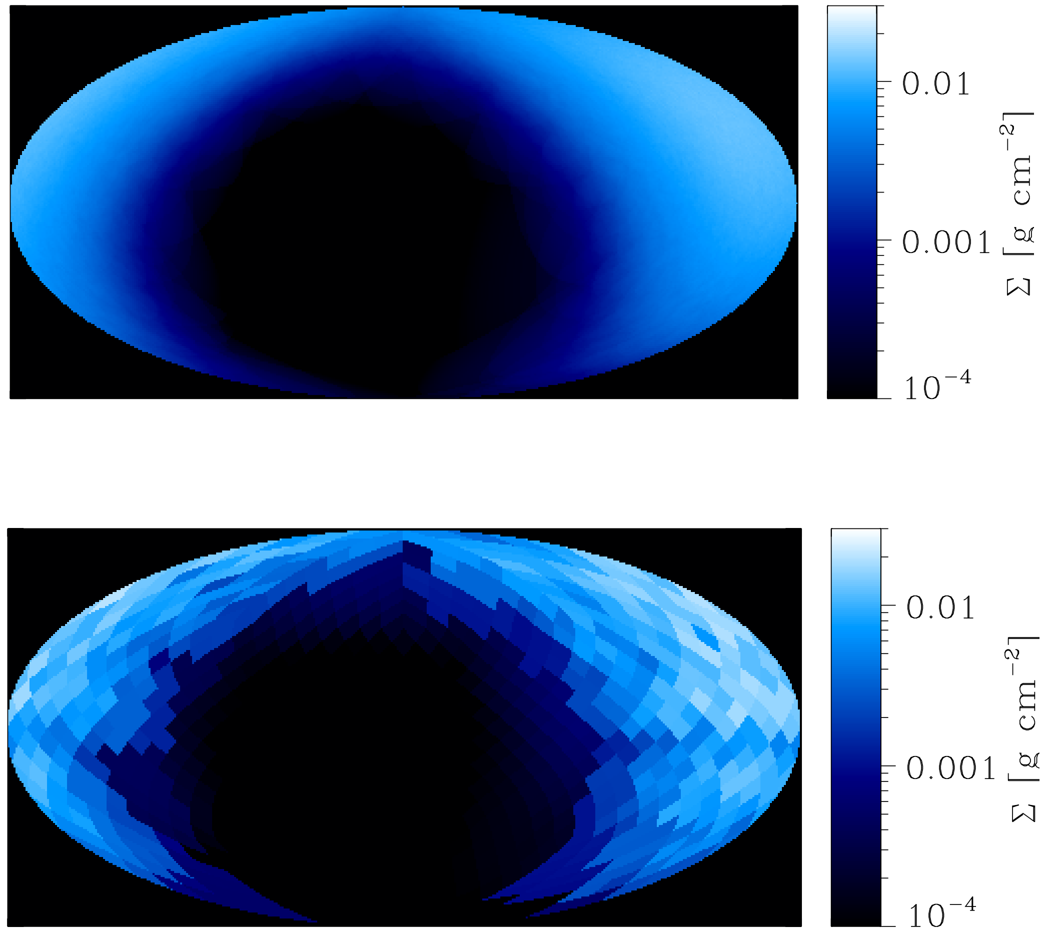
- however: this is good, because it may explain some of the theoretical controversy, we (currently) have in the field
(hopefully).

Girichids et al. (2010)

TreeCol (extend to TreeRad?)

Get column densities while walking the tree!





summary