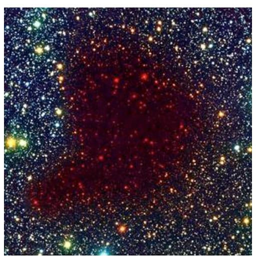
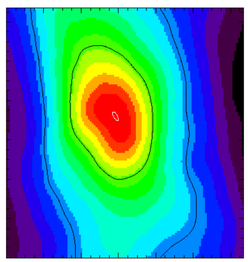
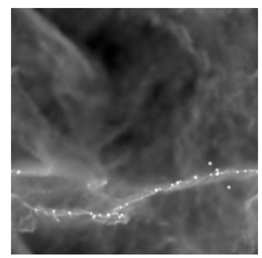
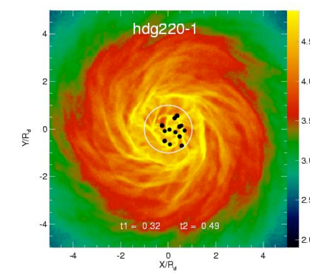
Star Cluster Formation: Turbulence & Thermodynamics









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ASTRONET

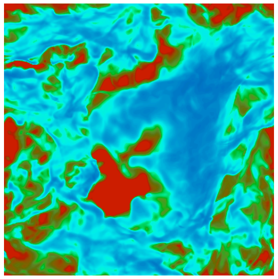
LANDESSTIFTUNG Baden-Württemberg

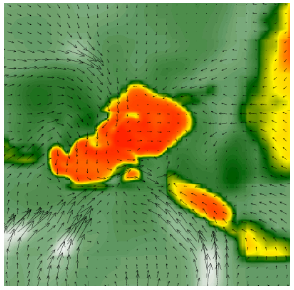
HGSFP

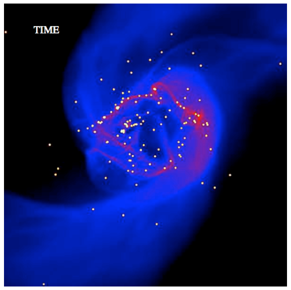
IMPRS

agenda

- phenomenology
- dynamic star formation theory
  - gravity vs. turbulence (and all the rest)
  - importance of thermodynamics
- examples and predictions
  - example A
  - example B
  - example C







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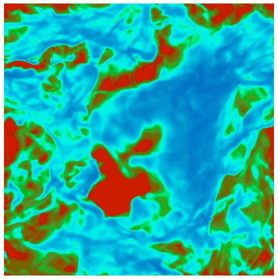
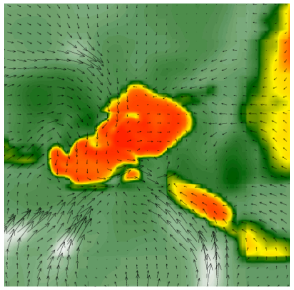
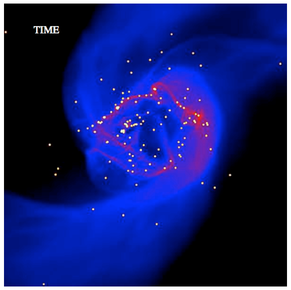
SKIP these parts!!







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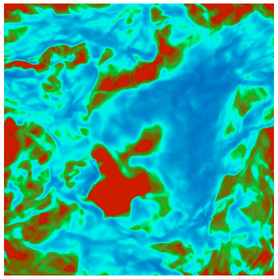
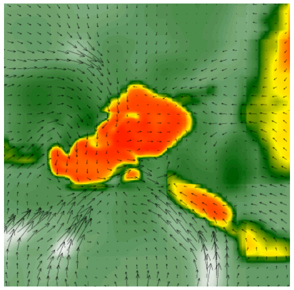
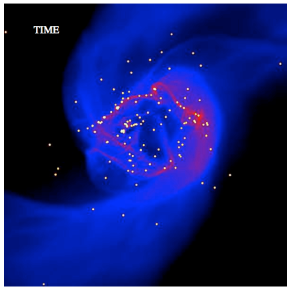
- ***controversial issues***
  - accretion driven turbulence
  - fragmentation-induced starvation
  - fragmentation depends on density profile
  - first stars form in clusters with (almost) normal IMF







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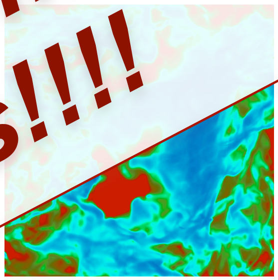
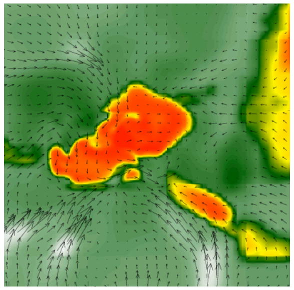
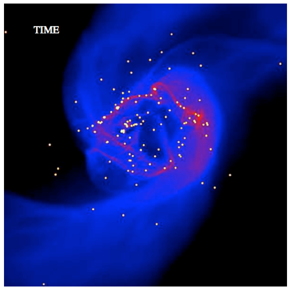
WARNING: presentation may contain personal biases!!!!







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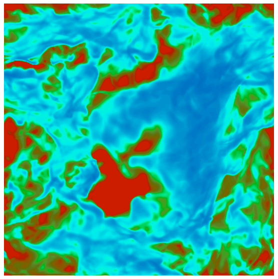
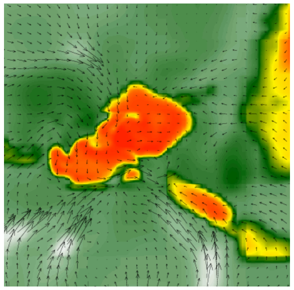
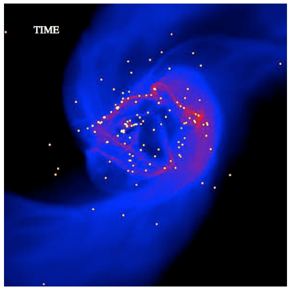
  - INITIAL CONDITONS MATTER BIG TIME



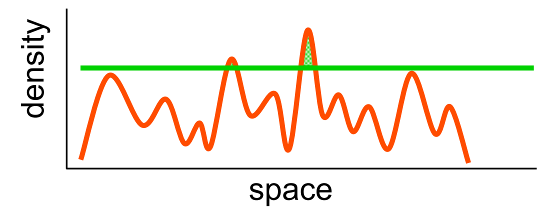




basic idea

dynamical SF in a nutshell

- interstellar gas is highly *inhomogeneous*

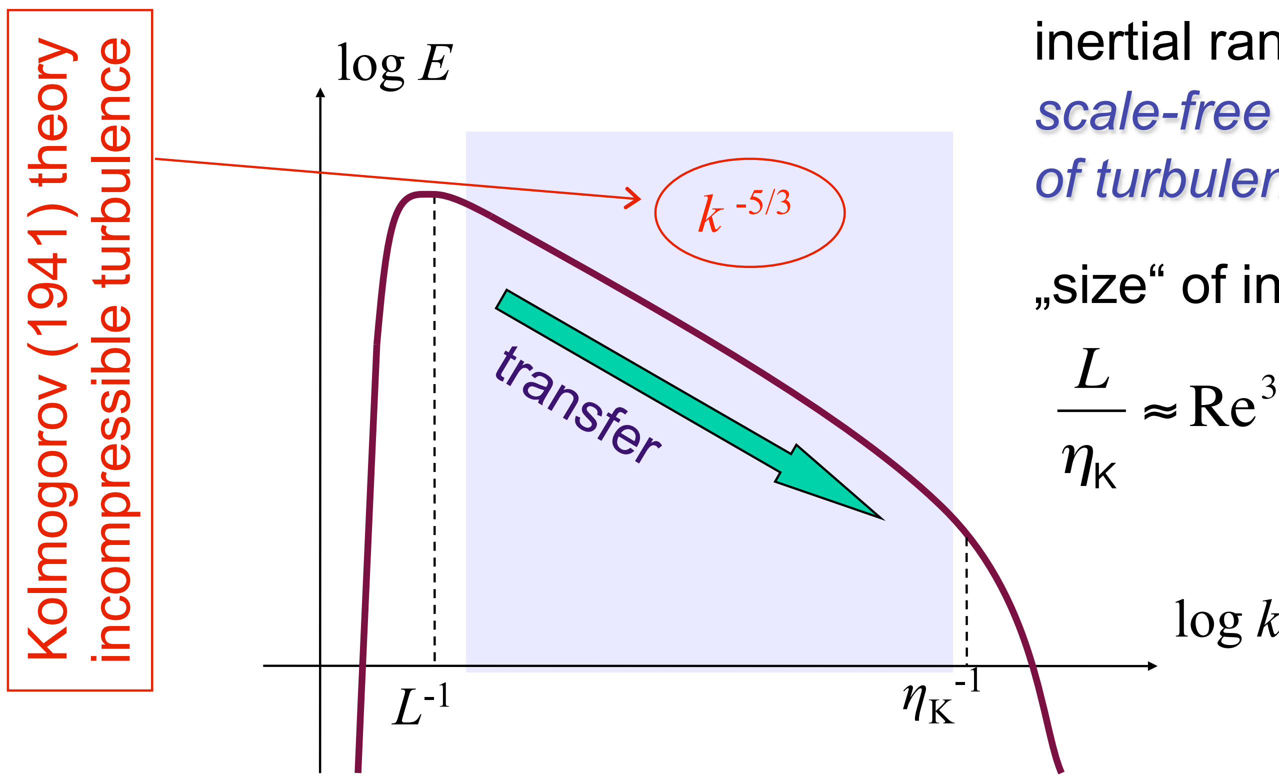


  - *gravitational instability*
  - *thermal instability*
  - *turbulent compression* (in shocks $\delta\rho/\rho \propto \mathcal{M}^2$; in atomic gas: $\mathcal{M} \approx 1...3$)
- cold *molecular clouds* can form rapidly in high-density regions at *stagnation points* of *convergent large-scale flows*
  - 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, 125-194)

Turbulent cascade



inertial range:
scale-free behavior of turbulence

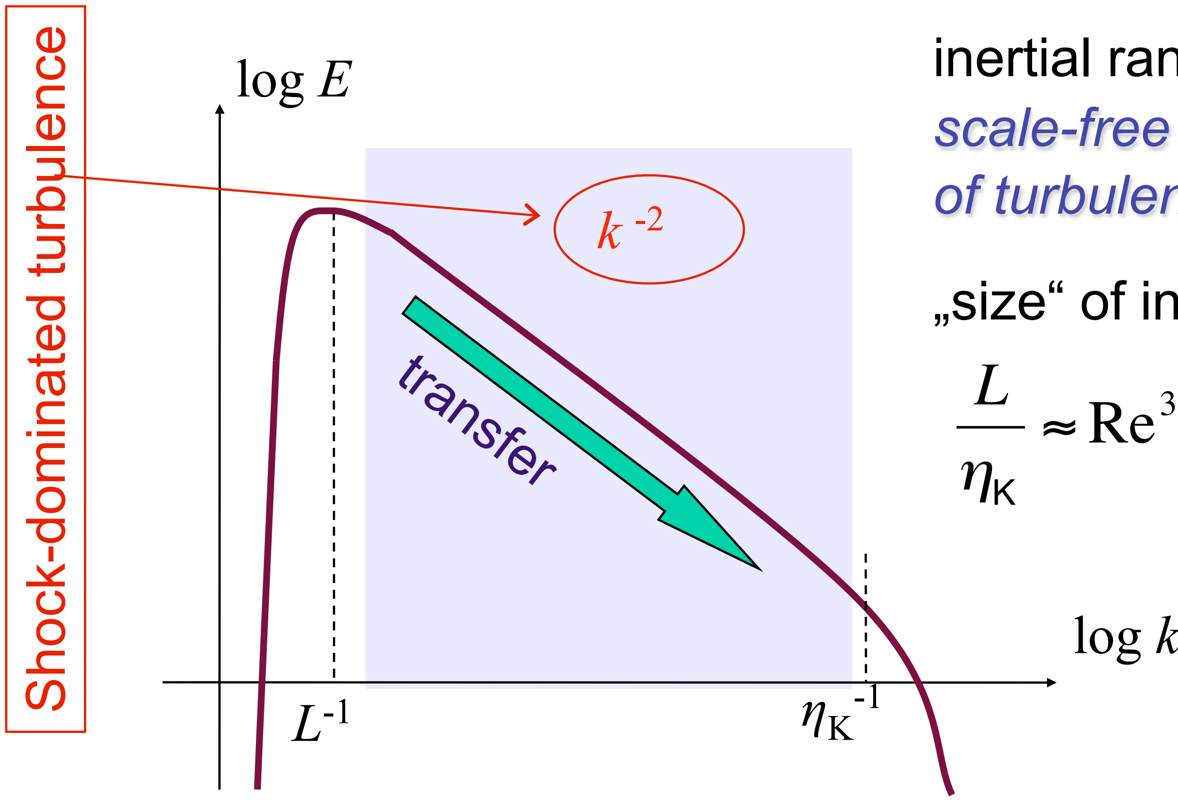
„size“ of inertial range:

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

energy input scale

energy dissipation scale

Turbulent cascade



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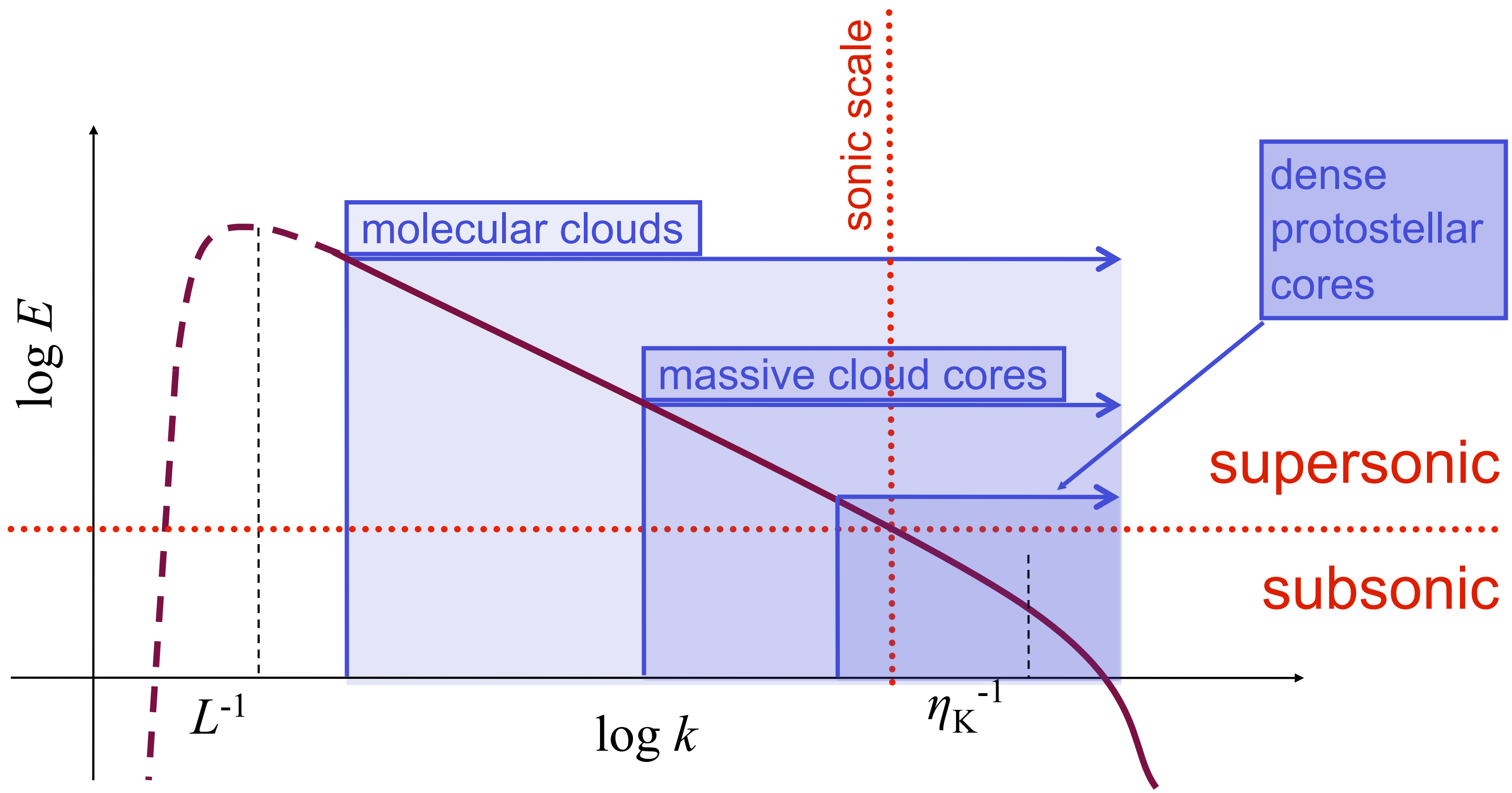
Turbulent cascade in ISM

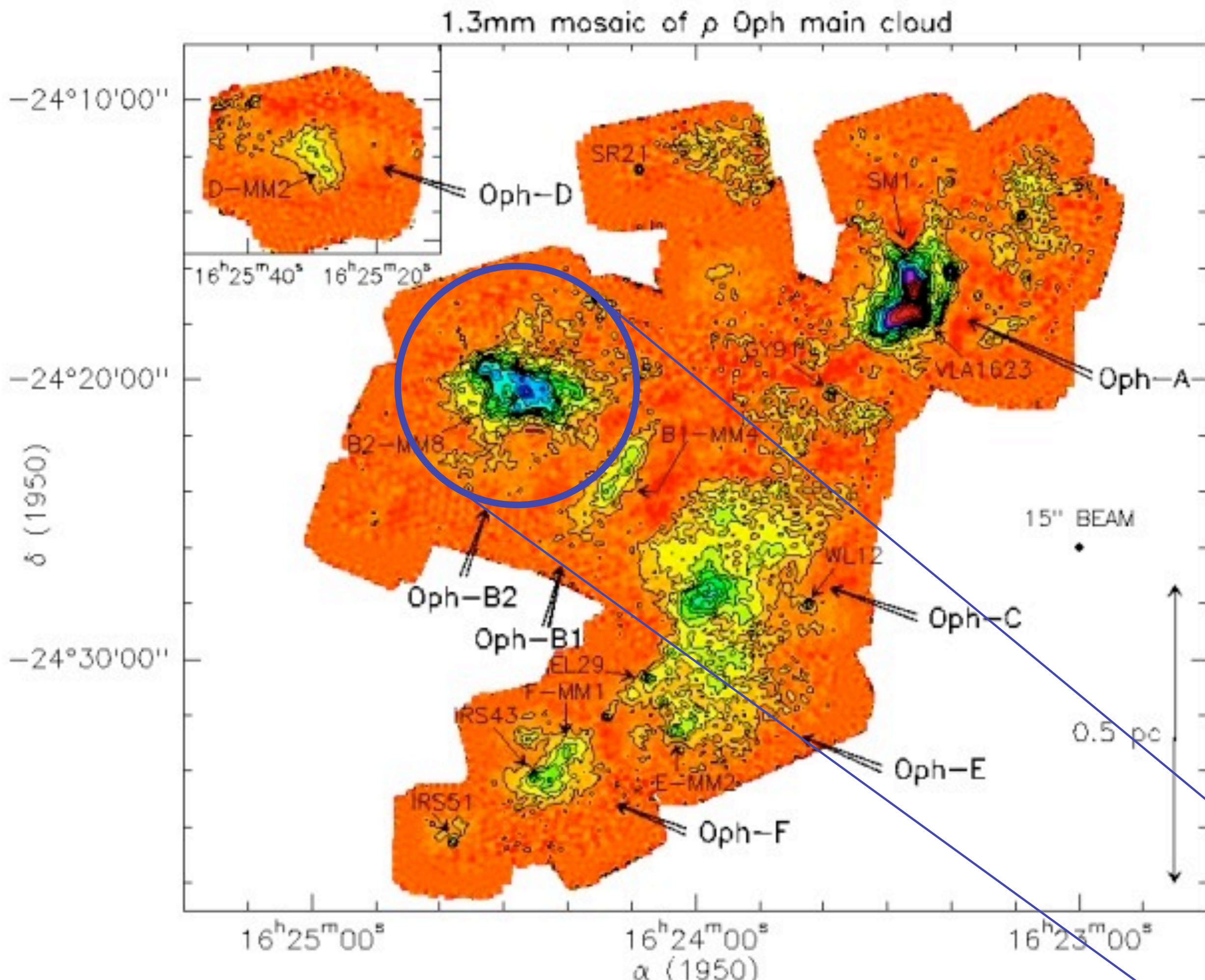


energy source & scale
NOT known
(supernovae, winds,
spiral density waves?)

$\sigma_{rms} << 1$ km/s
$M_{rms} \leq 1$
$L \approx 0.1$ pc

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

Density structure of MC's



(Motte, André, & Neri 1998)

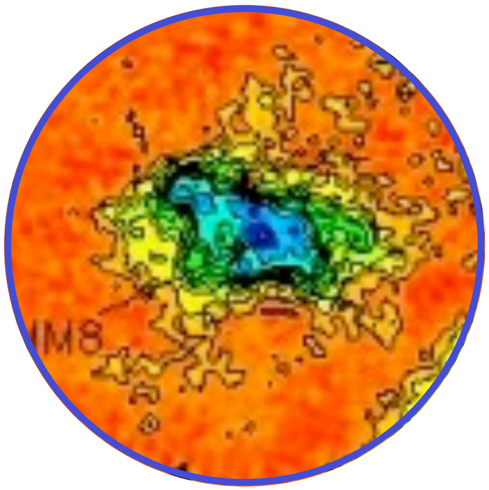
molecular clouds are highly inhomogeneous

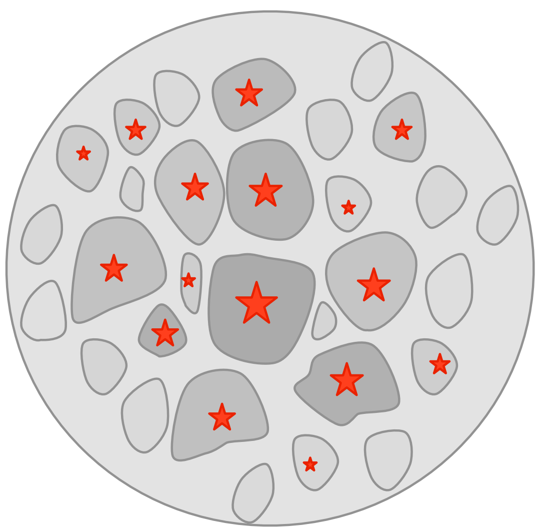
stars form in the densest and coldest parts of the cloud

ρ-Ophiuchus cloud seen in dust emission

let's focus on a cloud core like this one

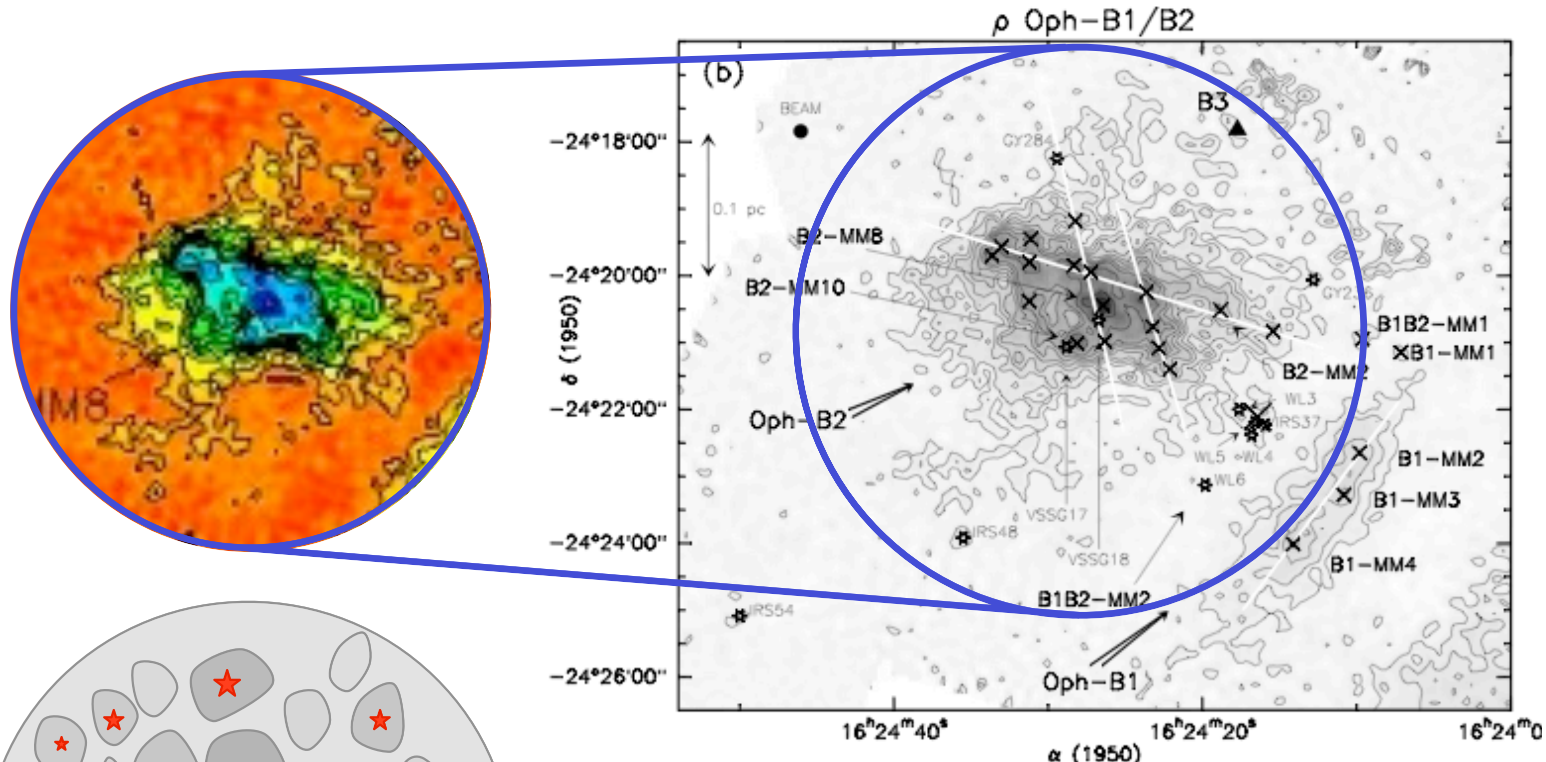
Evolution of cloud cores

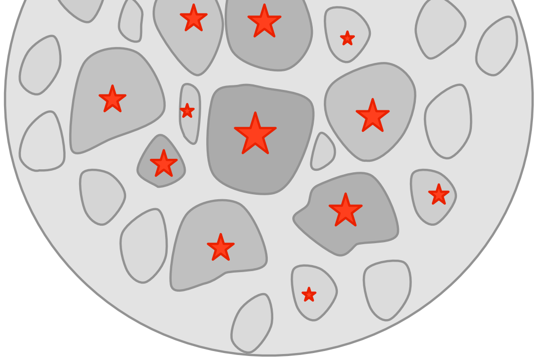




- How does this core evolve?
  Does it form one single massive star or cluster with mass distribution?
- Turbulent cascade „goes through“ cloud core
  --> NO *scale separation* possible
  --> NO *effective sound speed*
- Turbulence is supersonic!
  --> produces strong density contrasts:
  $\delta\rho/\rho \approx M^2$
  --> 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



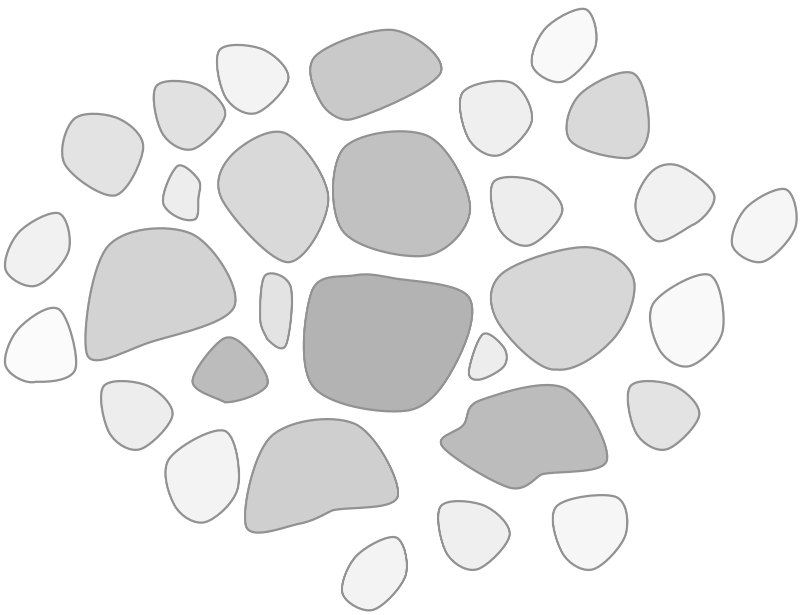


indeed ρ-Oph B1/2 contains several cores ("starless" cores are denoted by ×, cores with embedded protostars by ☆)

(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*

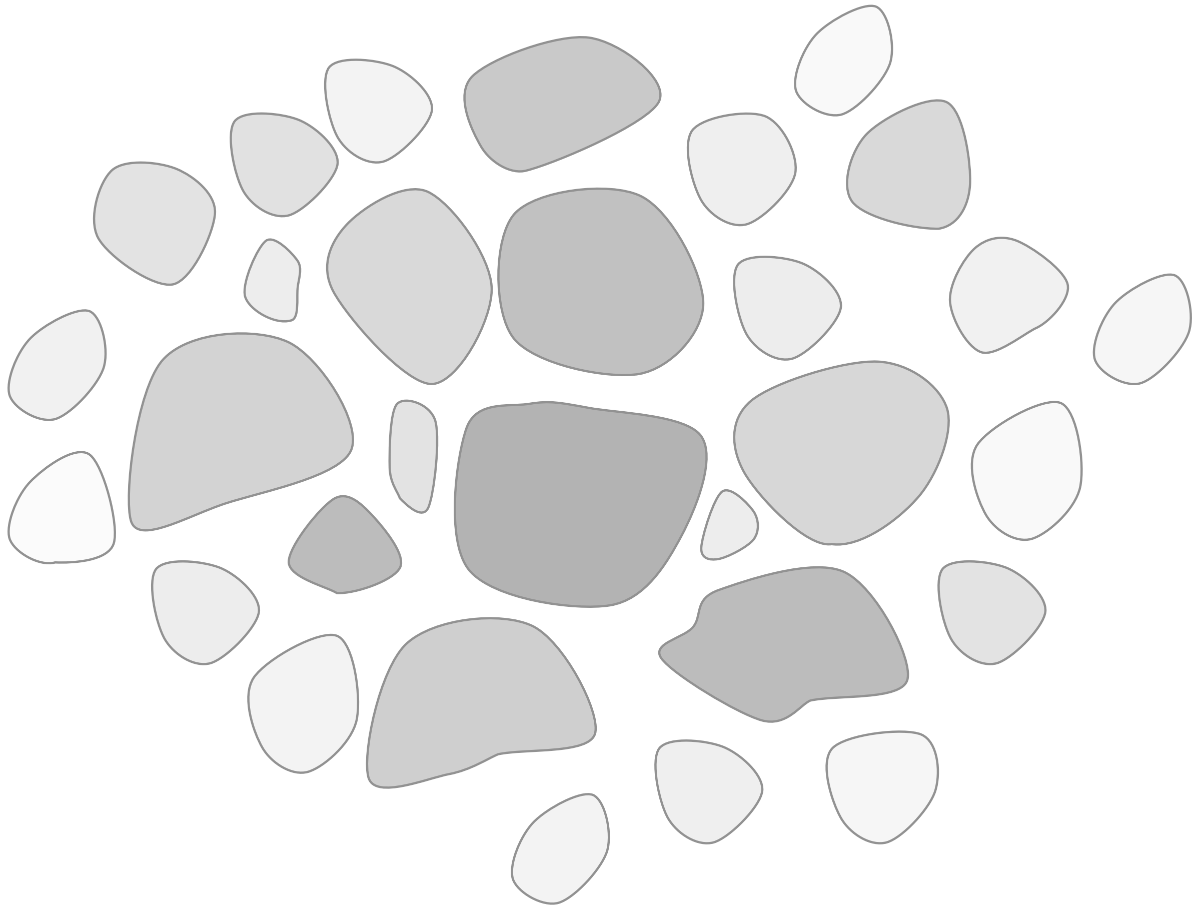
(2) turbulence decays, i.e. gravity dominates: $\alpha = E_{kin}/|E_{pot}| < 1$

--> *global contraction*

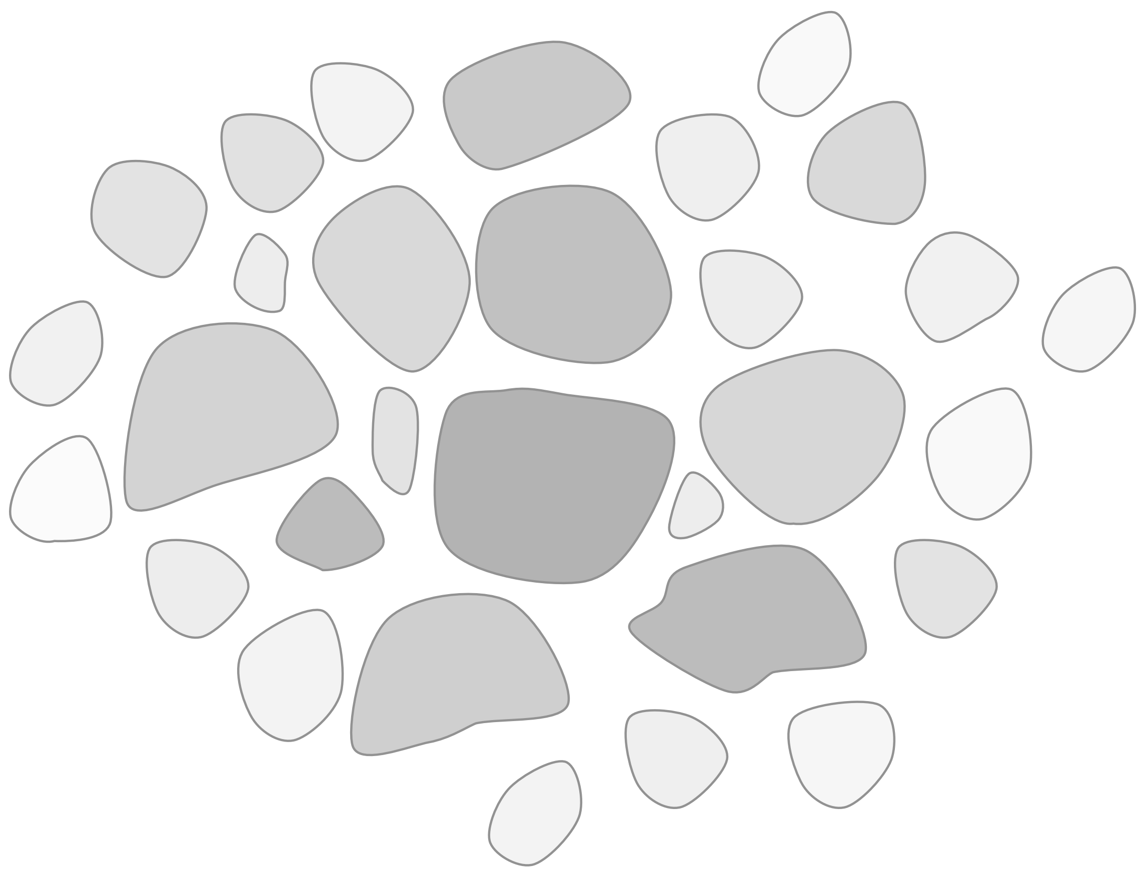
--> core do *interact* while collapsing

--> *competition* influences *mass growth*

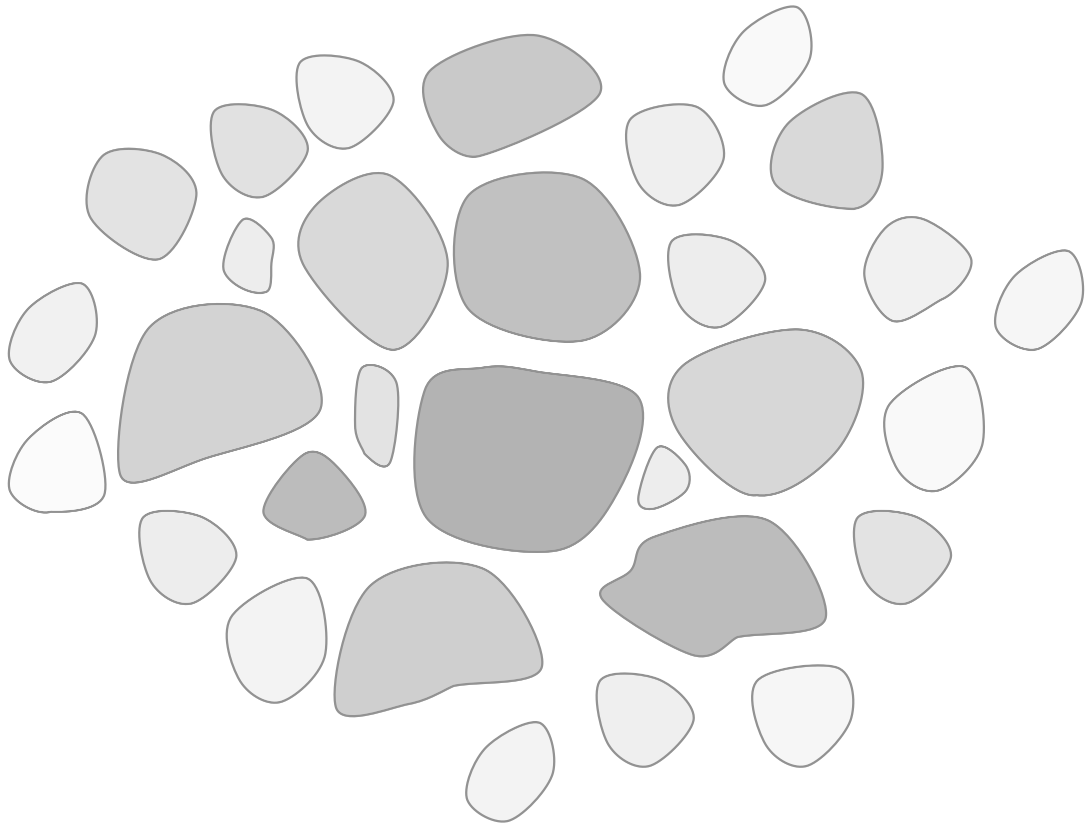
--> *dense cluster with high-mass stars*



turbulence creates a hierarchy of clumps



as turbulence decays locally, contraction sets in



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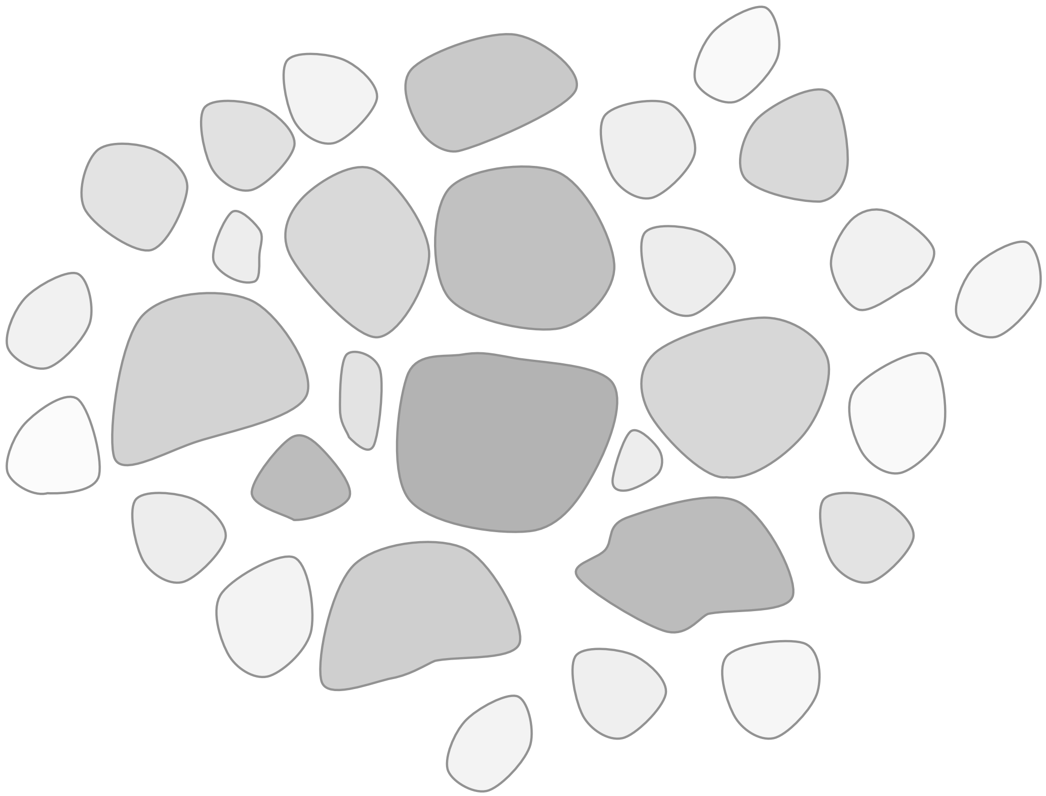
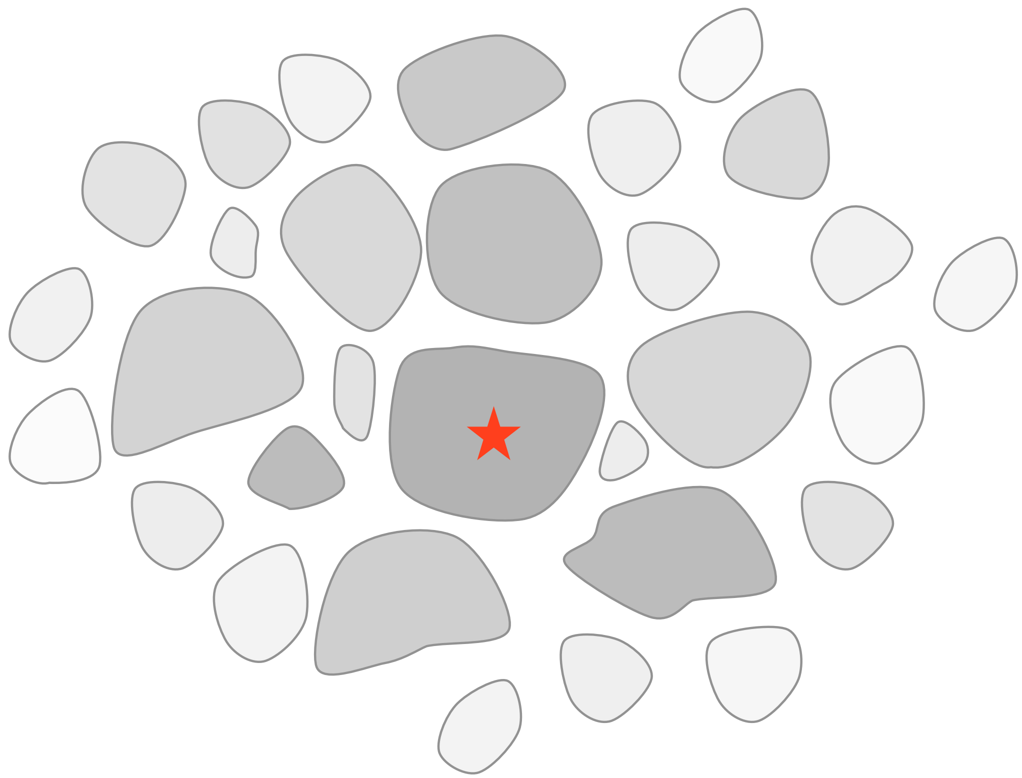


while region contracts, individual clumps collapse to form stars



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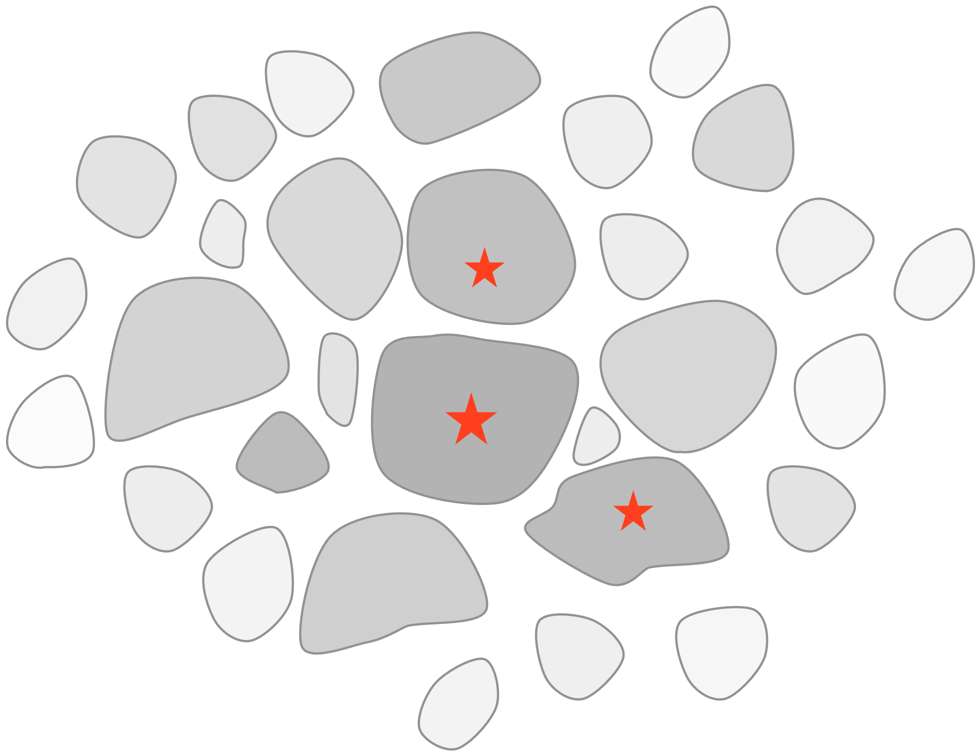

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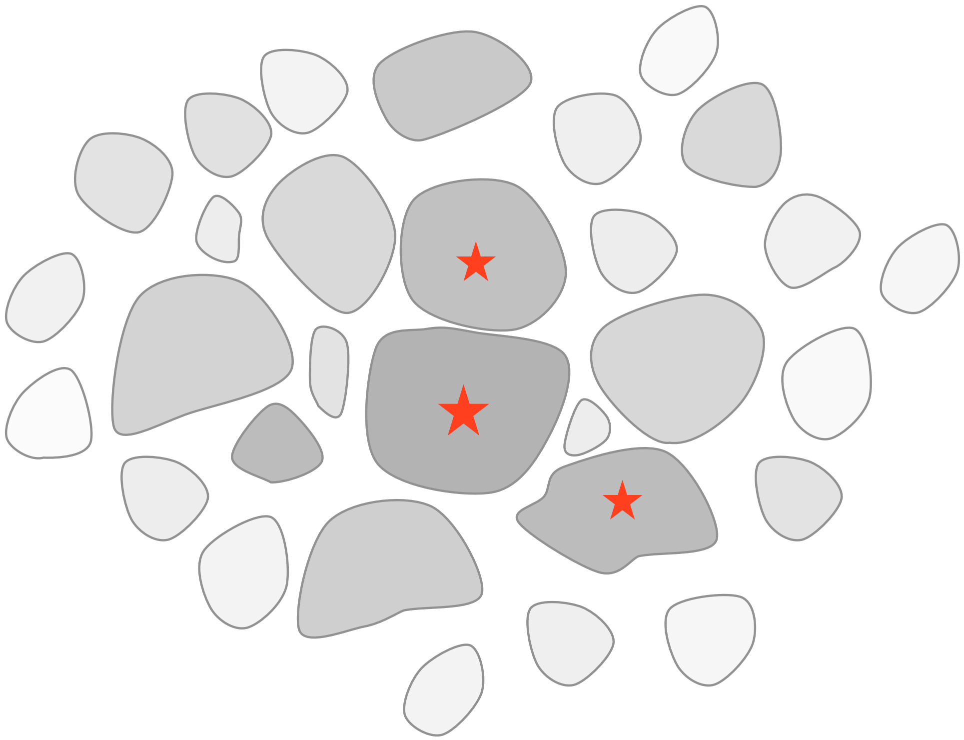

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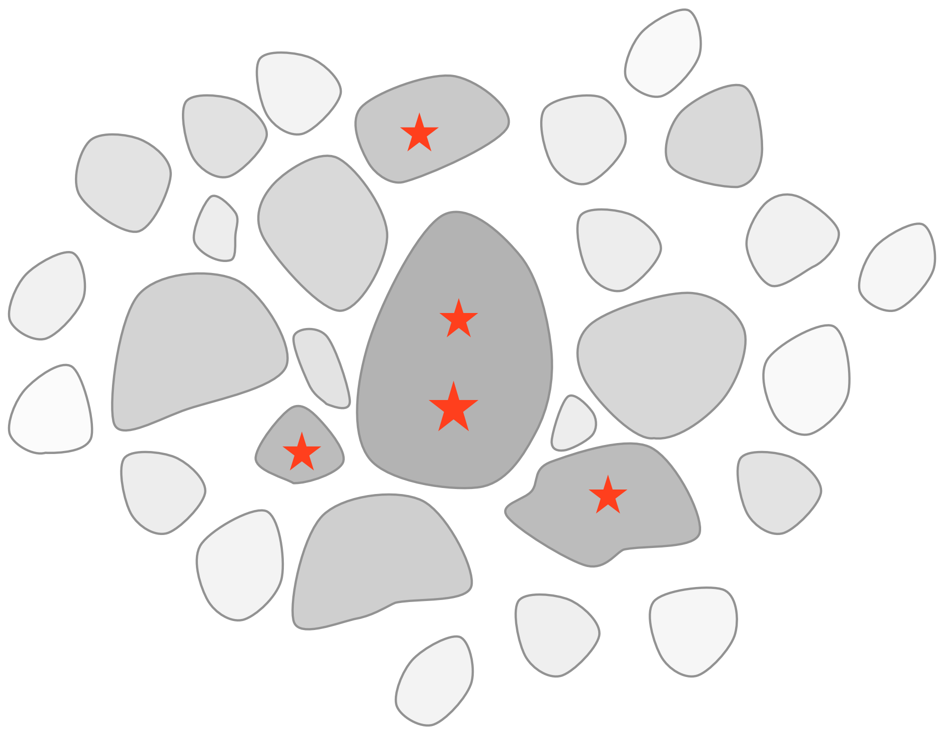
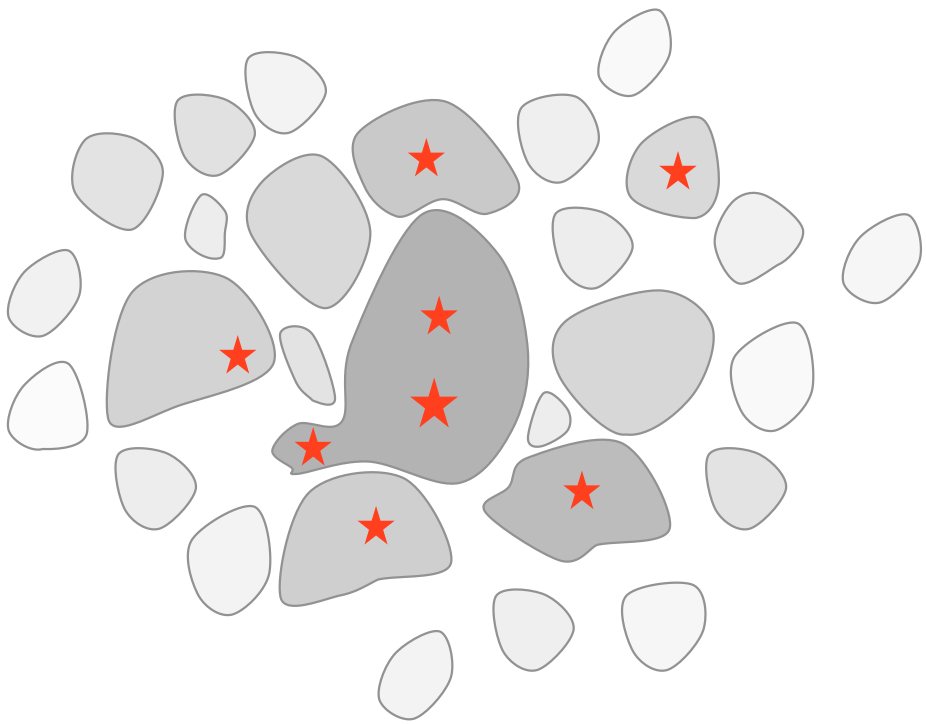


$\alpha = E_{kin}/|E_{pot}| < 1$

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



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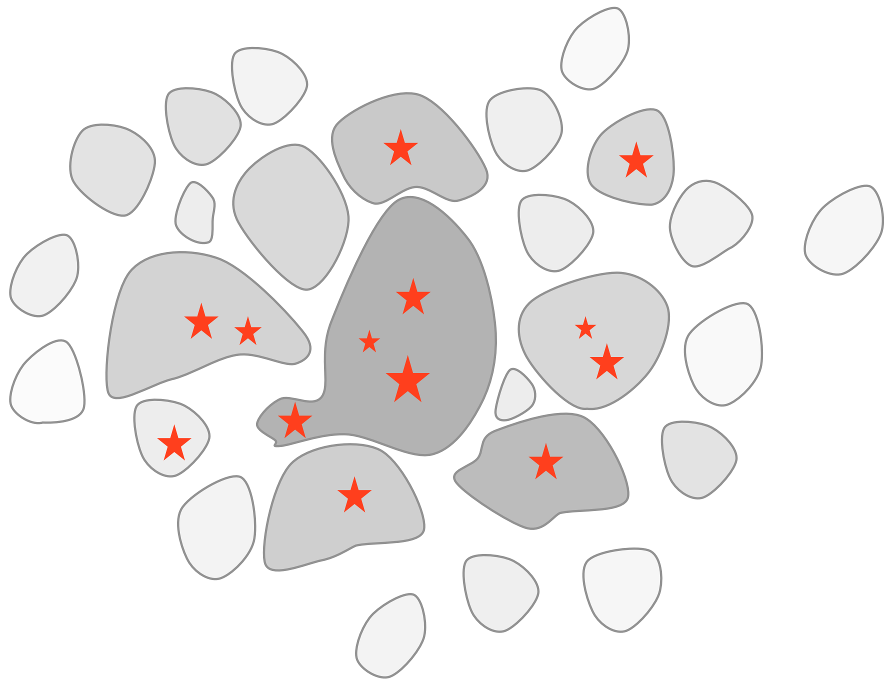

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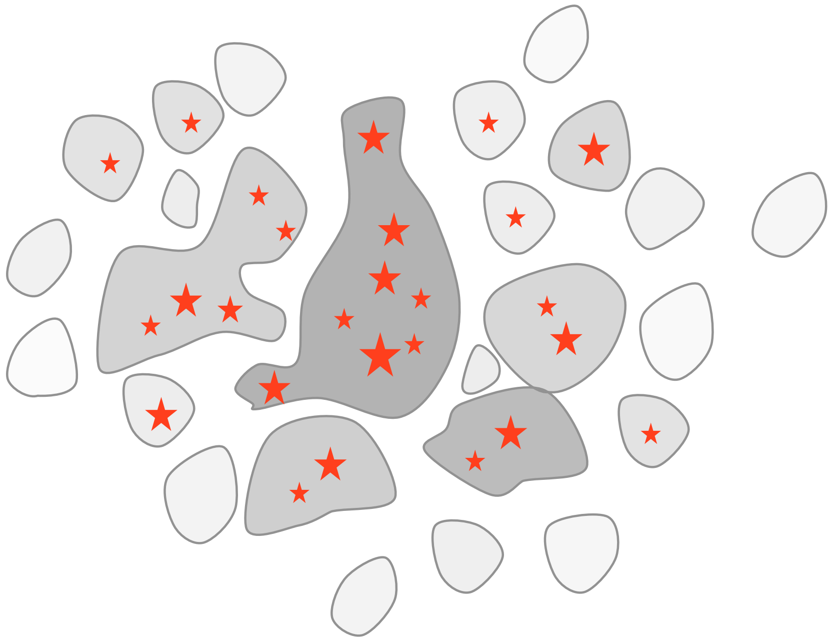
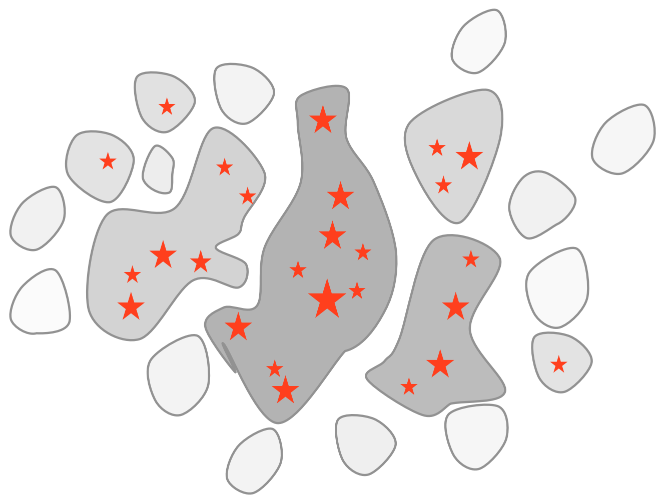


in *dense clusters*, competitive mass growth becomes important



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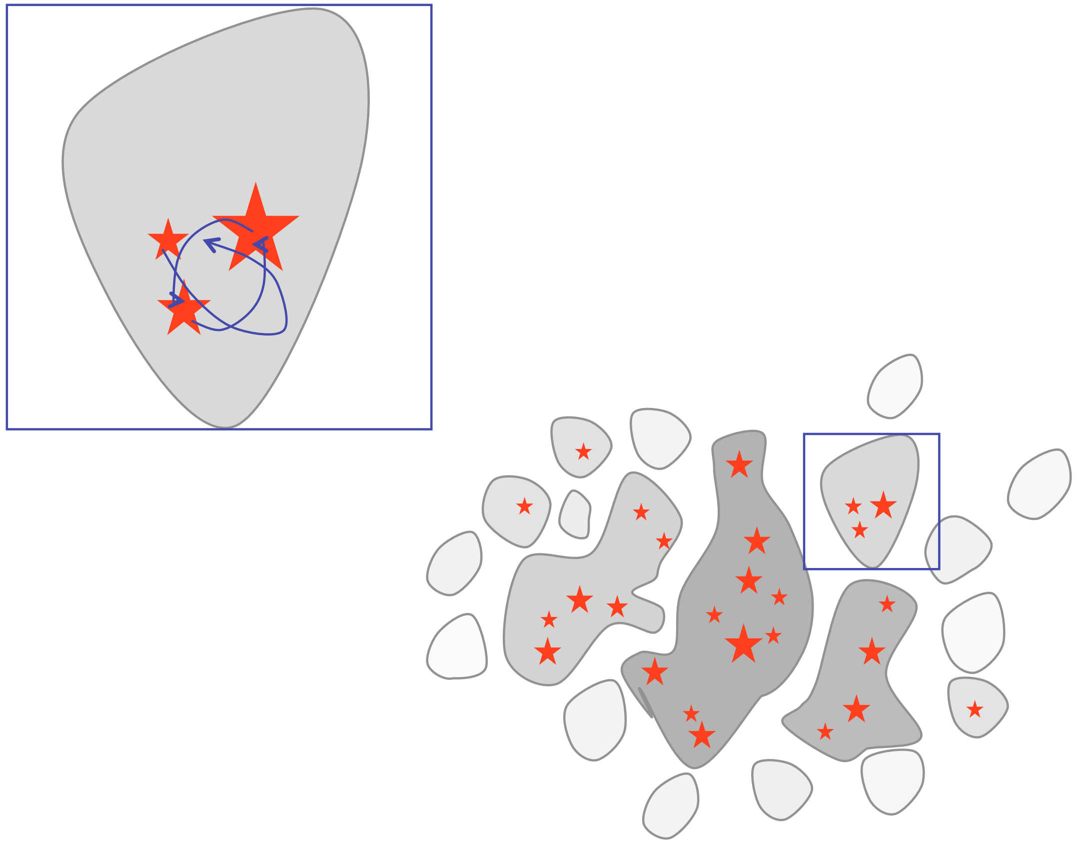
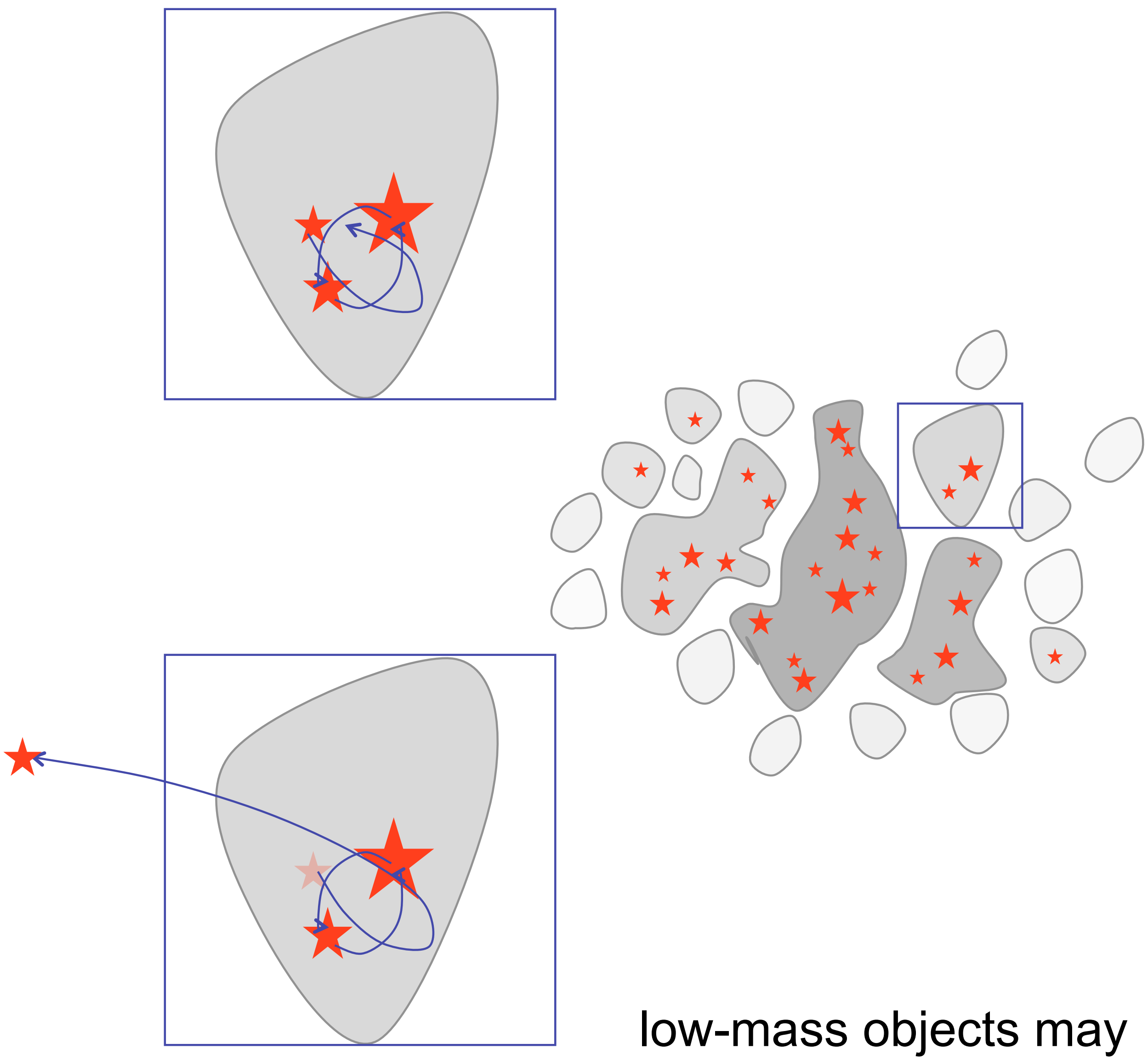
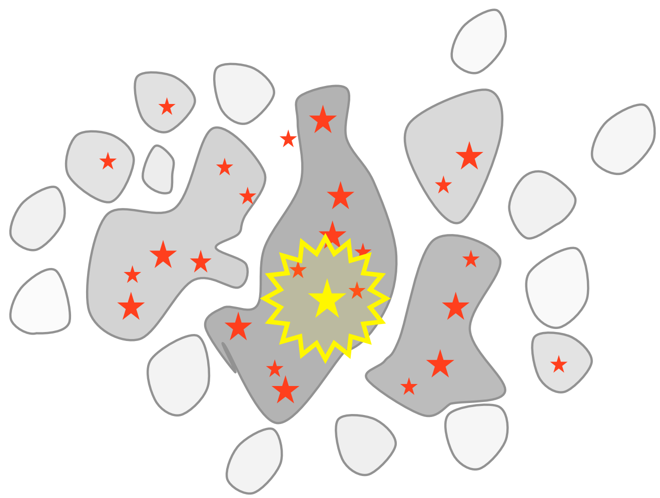


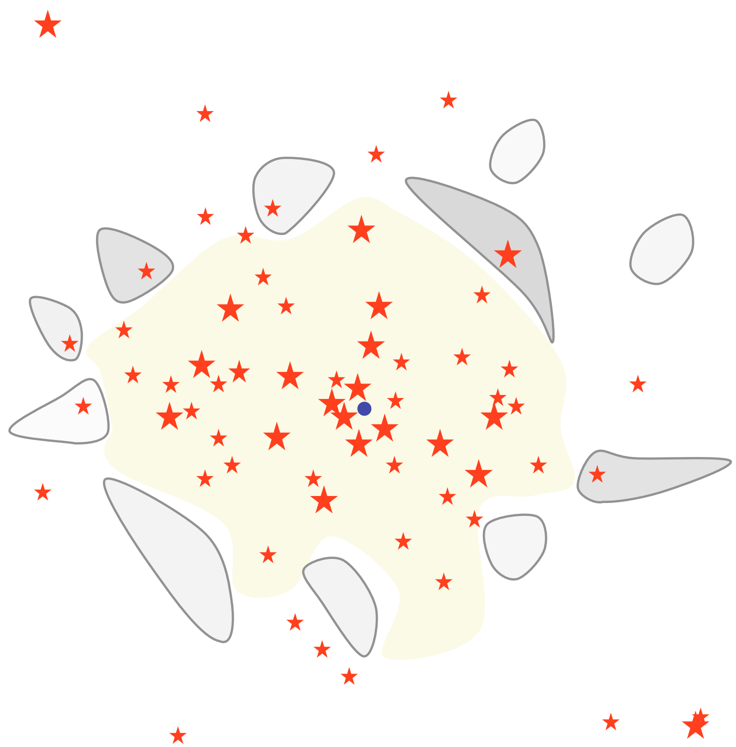
in *dense clusters*, *N*-body effects influence mass growth



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



feedback terminates star formation



result: *star cluster*, possibly with HII region

NGC 602 in the LMC: Hubble Heritage Image

result: *star cluster* with HII region

controversial issues

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
- *when do the first star clusters form?*
  --> the very first stars form in clusters

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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, in press)

concept

- turbulence decays on a crossing time

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

- energy decay rate

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

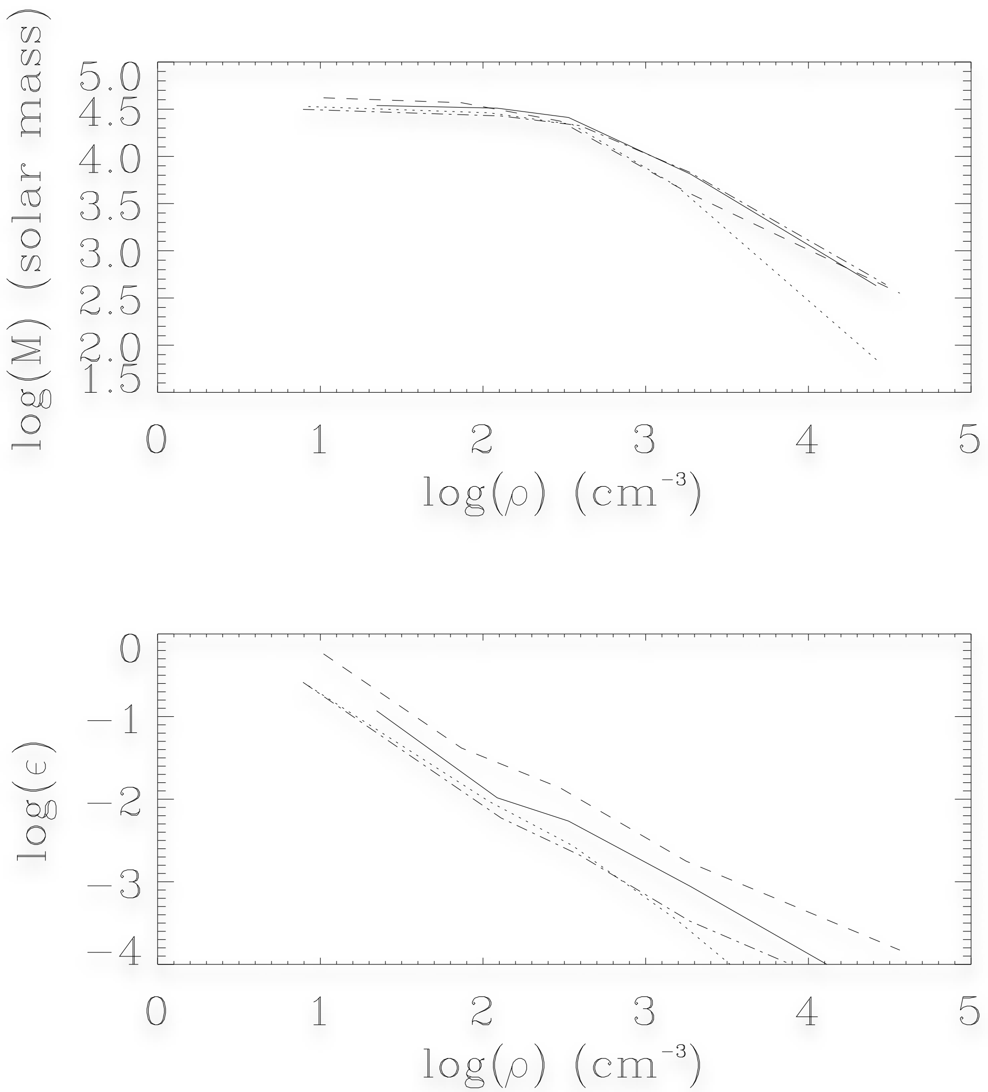
- kinetic energy of infalling material

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

- can both values match, modulo some efficiency?

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

(Field et al.. 2008, MNRAS, 385, 181, Mac Low & Klessen 2004, RMP, 76, 125) some estimates from convergent flow studies



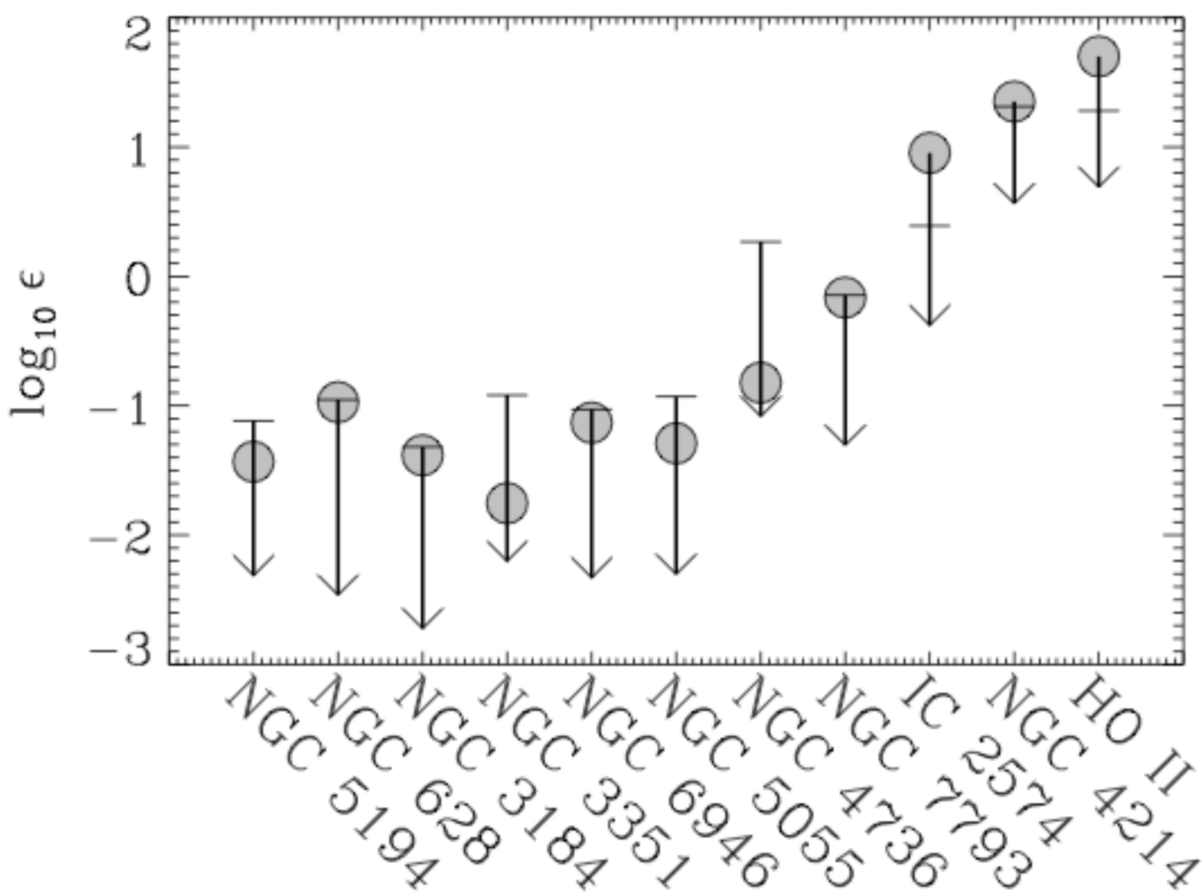
Klessen & Hennebelle (2010, A&A, in press)

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, in press)

11 THINGS galaxies



Klessen & Hennebelle (2010, A&A, in press)

galactic disks

- 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.)
- 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, in press)

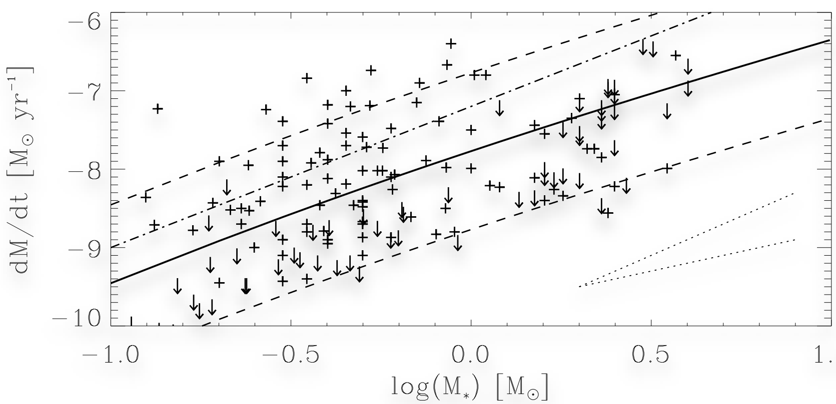


Fig. 7. Prediction of the accretion rate onto the disk as a function of the mass of the star. The solid line corresponds to a mean density of $\bar{n} = 100\,\mathrm{cm}^{-3}$ while the two dashed lines are for $\bar{n} = 1000\ \mathrm{cm}^{-3}$ (upper curve) and $\bar{n} = 10\ \mathrm{cm}^{-3}$ (lower curve). To guide your eye the dotted lines indicate the slope of the relations $\dot{M} \propto M_*^2$ and $\dot{M} \propto M_*$. We compare with data from Calvet et al. (2004), Mohanty et al. (2005), Muzerolle et al. (2005), and Natta et al. (2006) as displayed in Figure 3 of Garcia Lopez et al. (2006), where crosses indicate detections and arrows upper limits. The dot-dashed line is the fit proposed by Natta et al. (2006).

Klessen & Hennebelle (2010, A&A, in press)

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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 7×10^{-16} g cm^{-3}
  - cell size 100 AU

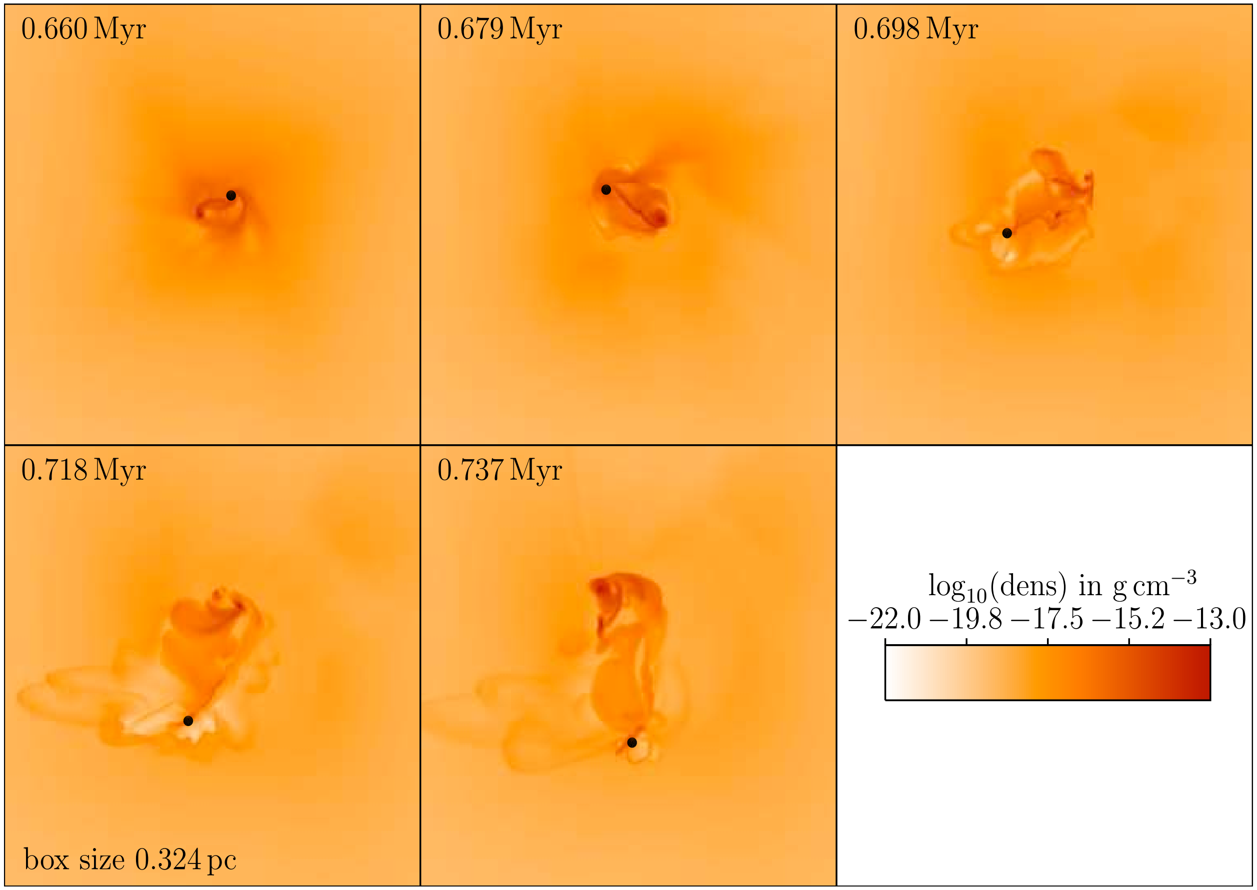
Peters et al. (2010a, ApJ, 711, 1017), Peters et al. (2010b, arXiv:1003.4998), Peters et al. (2010c,1005.3271)

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

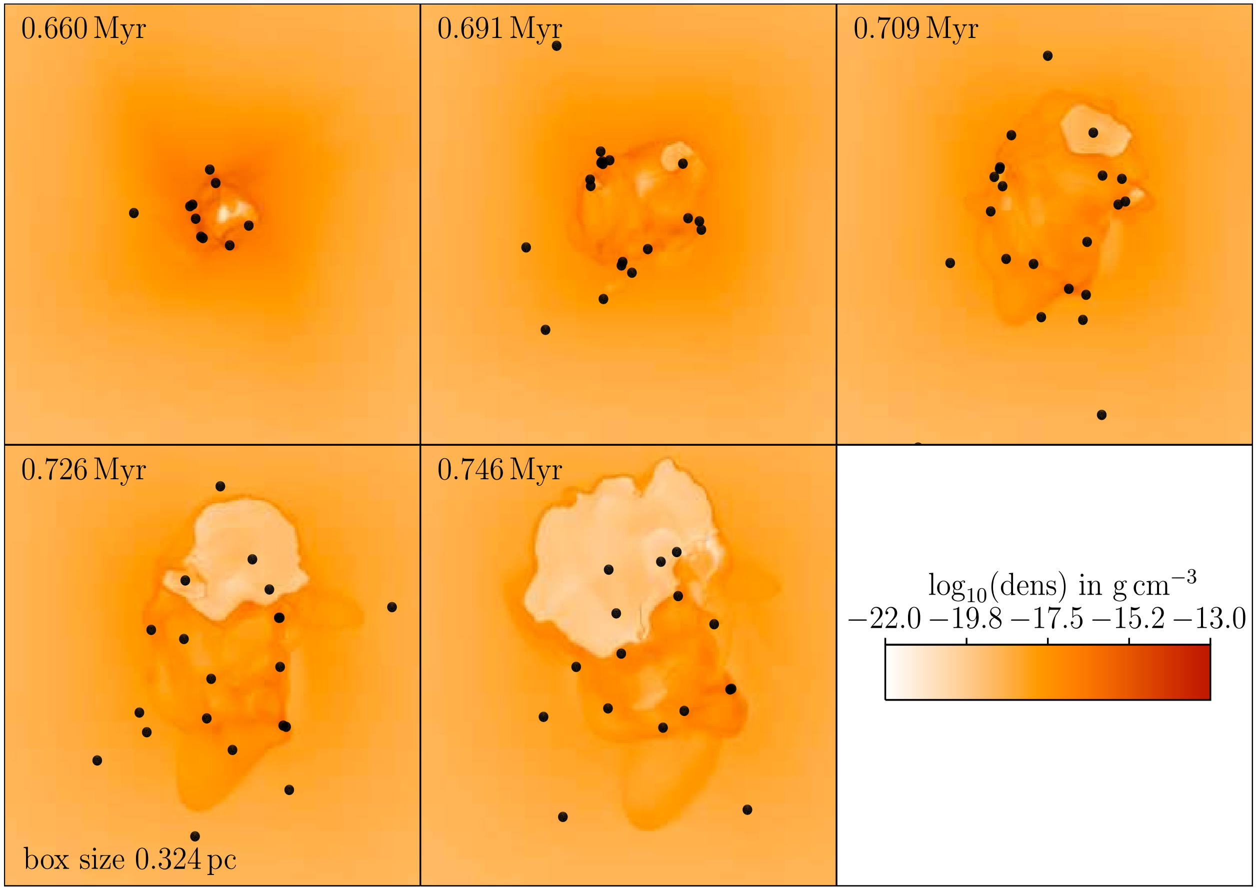
  - *first 3D calculations that consistently treat both ionizing and non-ionizing radiation in the context of high-mass star formation*

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



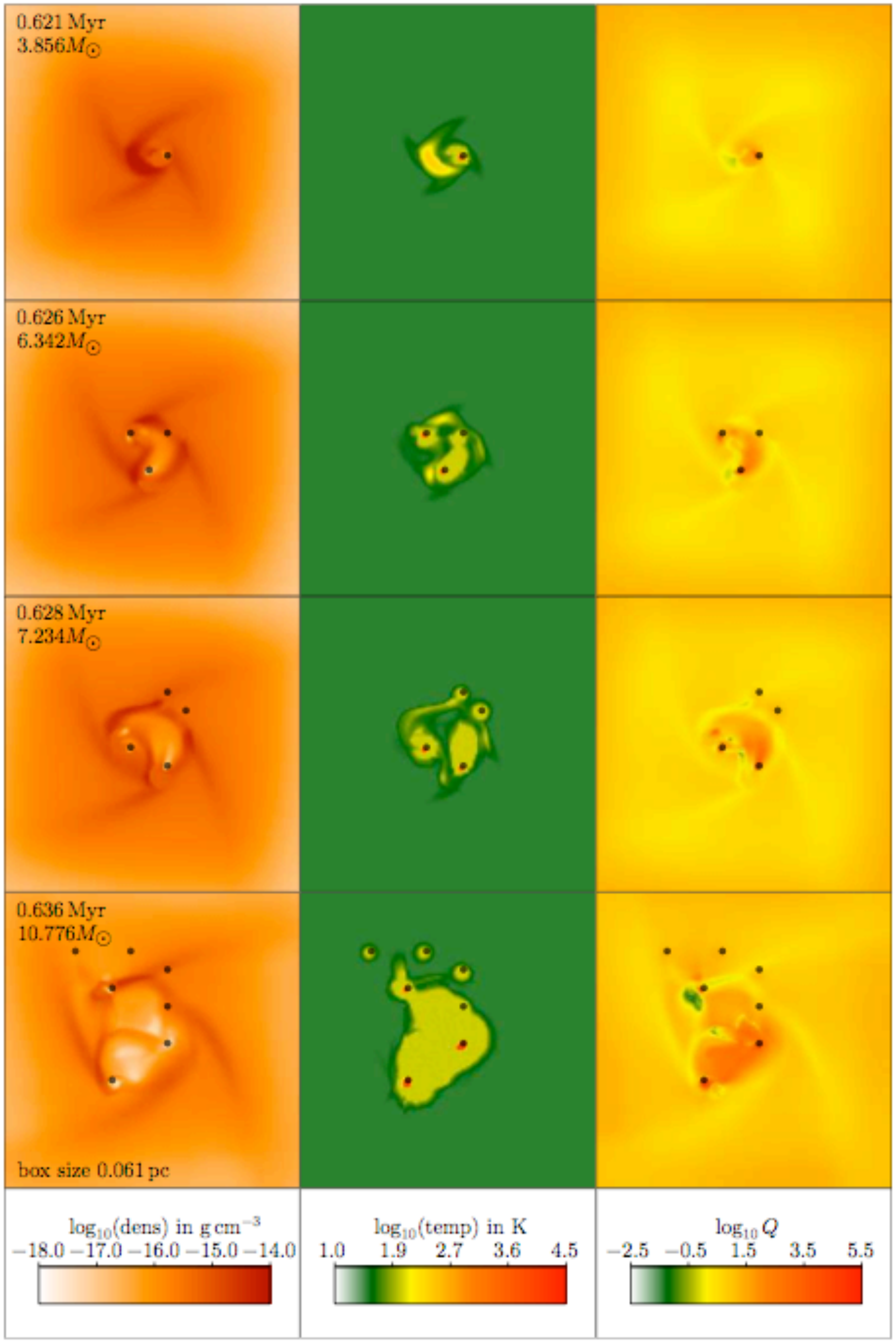
- disk is gravitationally unstable and fragments
- we suppress secondary sink formation by “Jeans heating”
- H II region is shielded effectively by dense filaments
- ionization feedback does not cut off accretion!

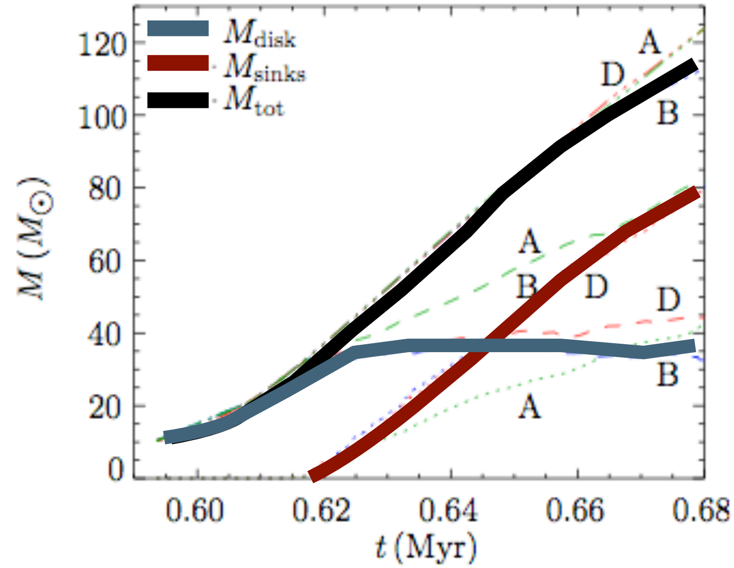
Peters et al. (2010a,b,c)



- 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)

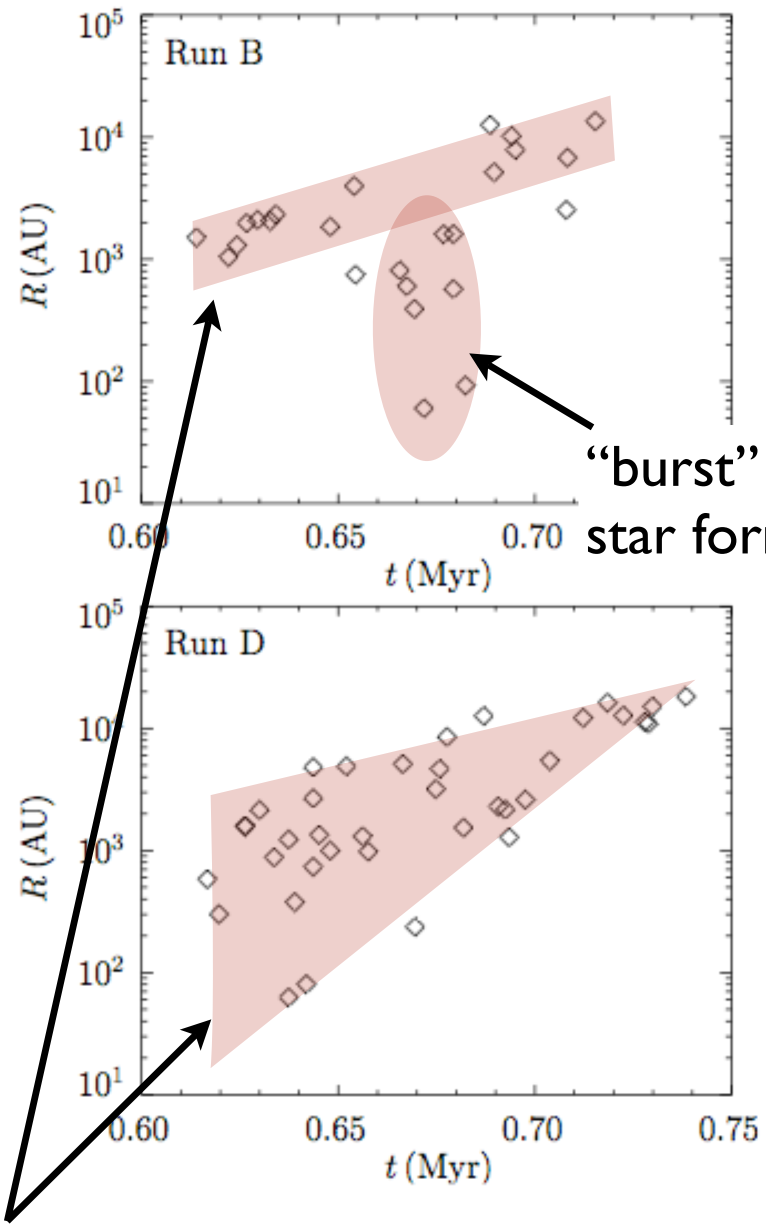




mass load onto the disk exceeds inward transport --> becomes gravitationally unstable (see also Kratter & Matzner 2006, Kratter et al. 2010)

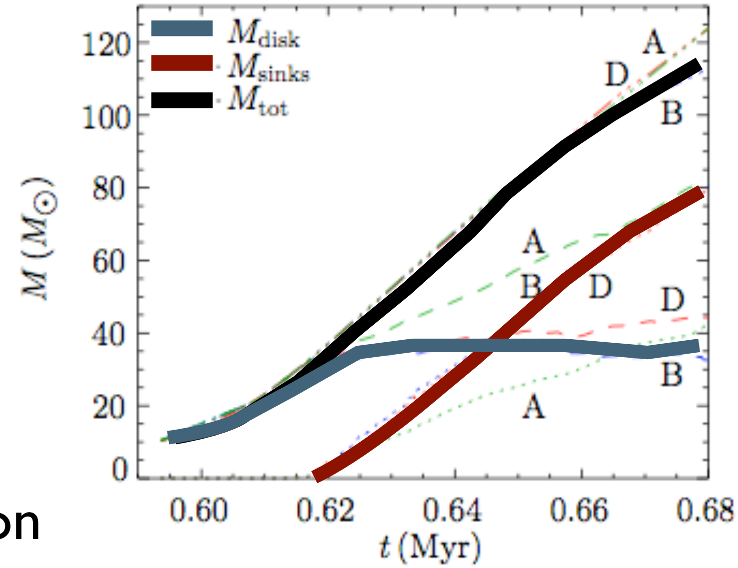
fragments to form multiple stars --> explains why high-mass stars are seen in clusters

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



"burst" of star formation

younger protostars form at larger radii



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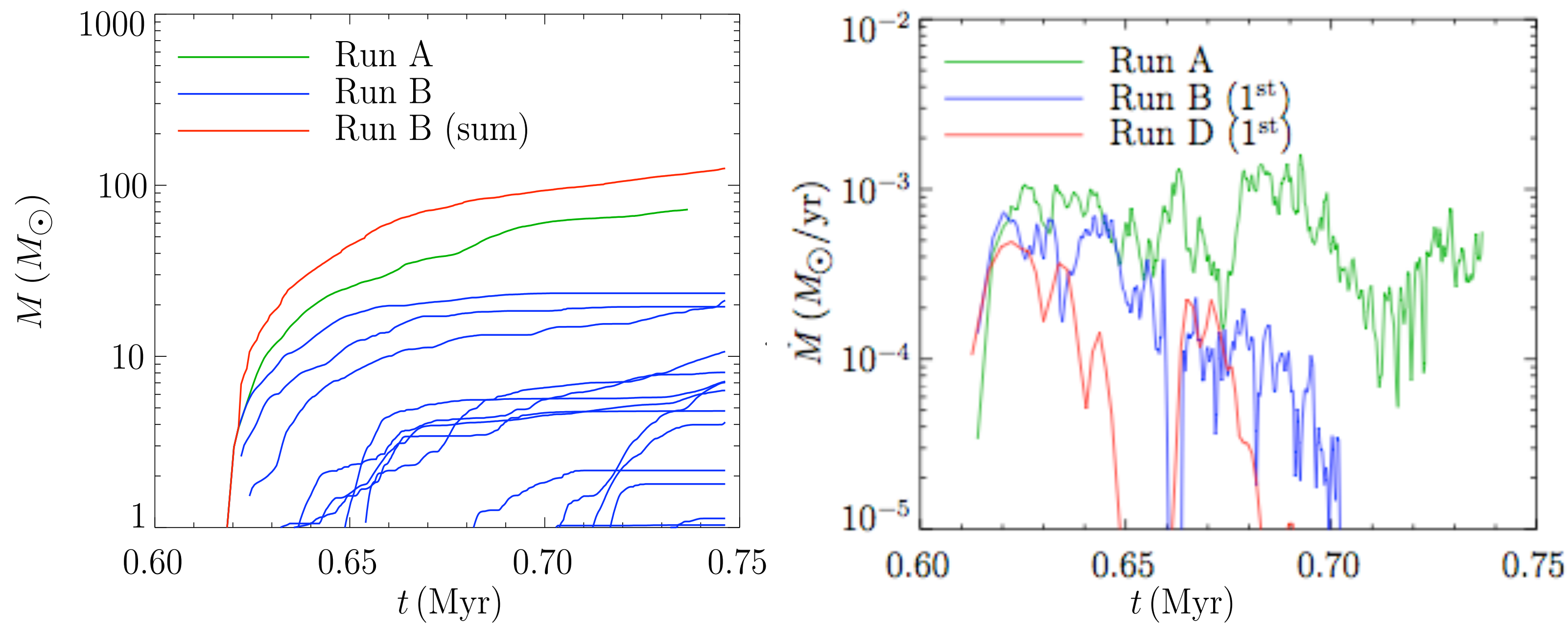
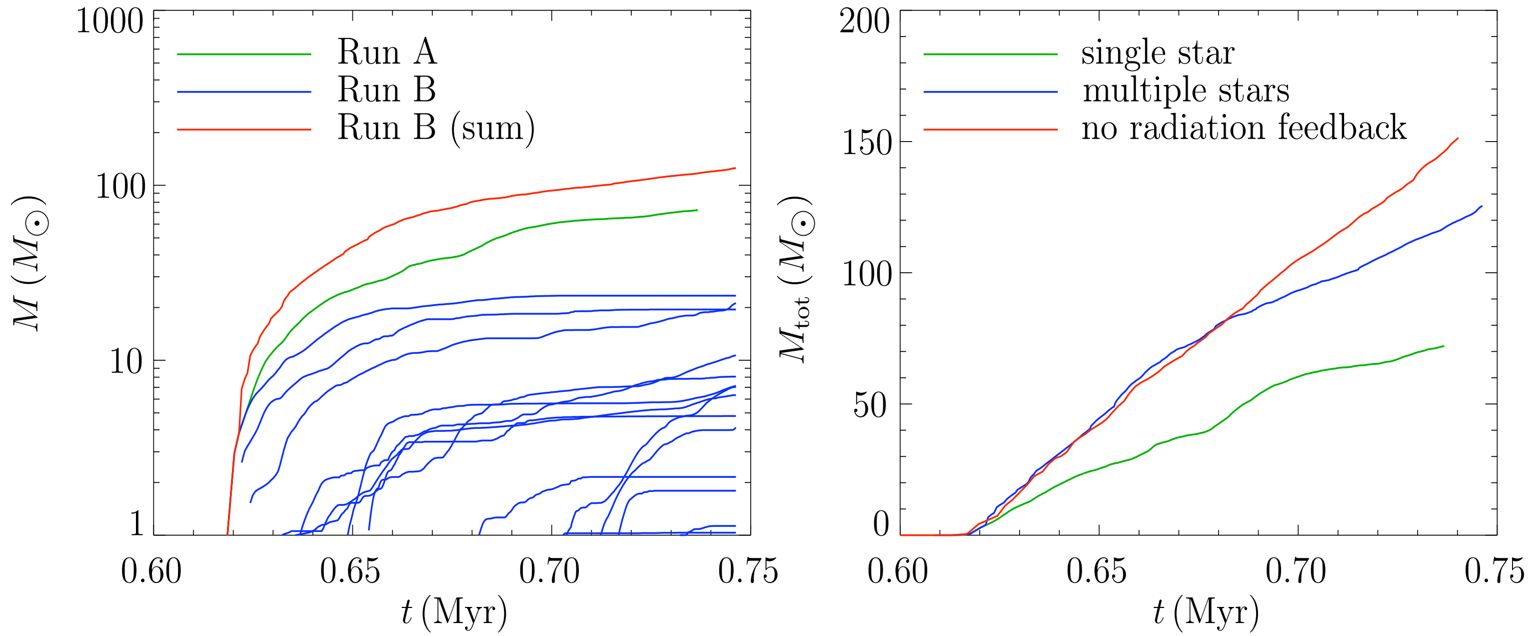
Peters et al. (2010a,b,c)



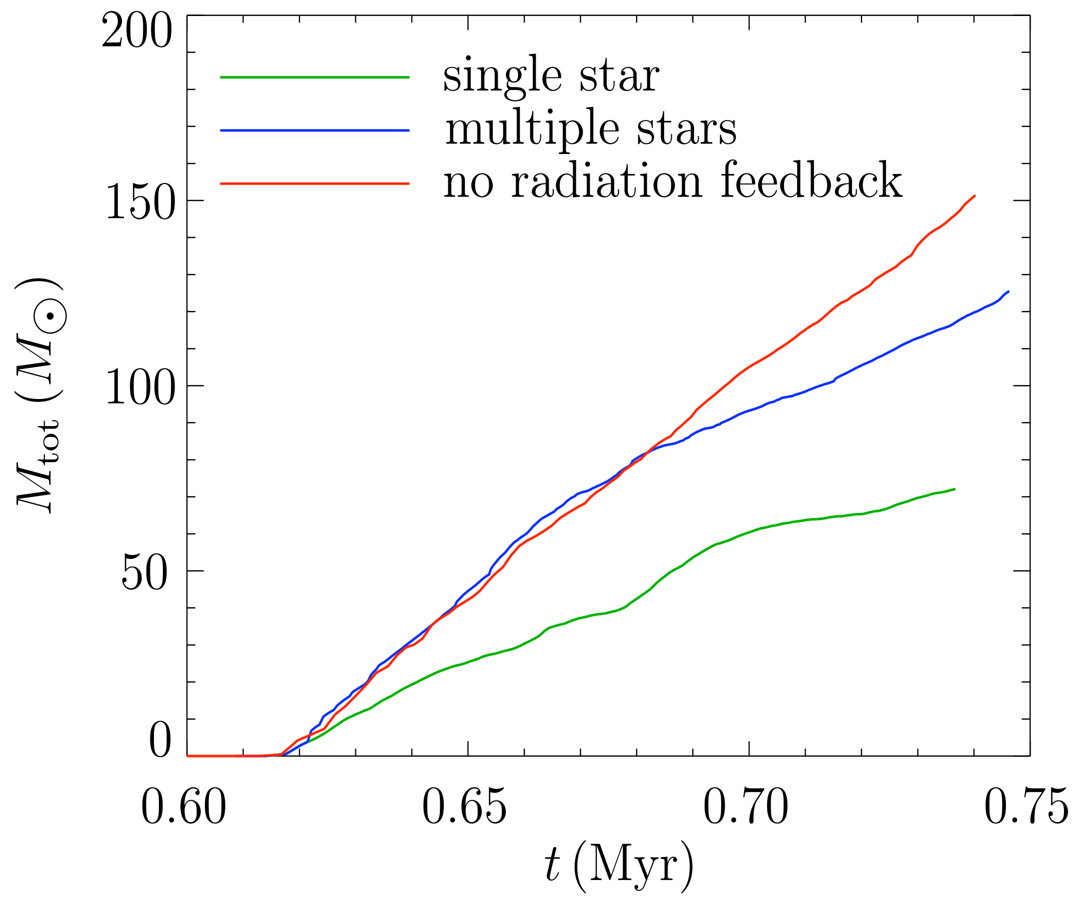
- single protostar accretes $72 M_\odot$ in $120\,\mathrm{kyr}$ (Run A)
- ionization feedback alone is unable to stop accretion
- accretion is limited when multiple protostars can form (Run B)
- no star in multi sink simulation reaches more than $30 M_\odot$

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



- 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

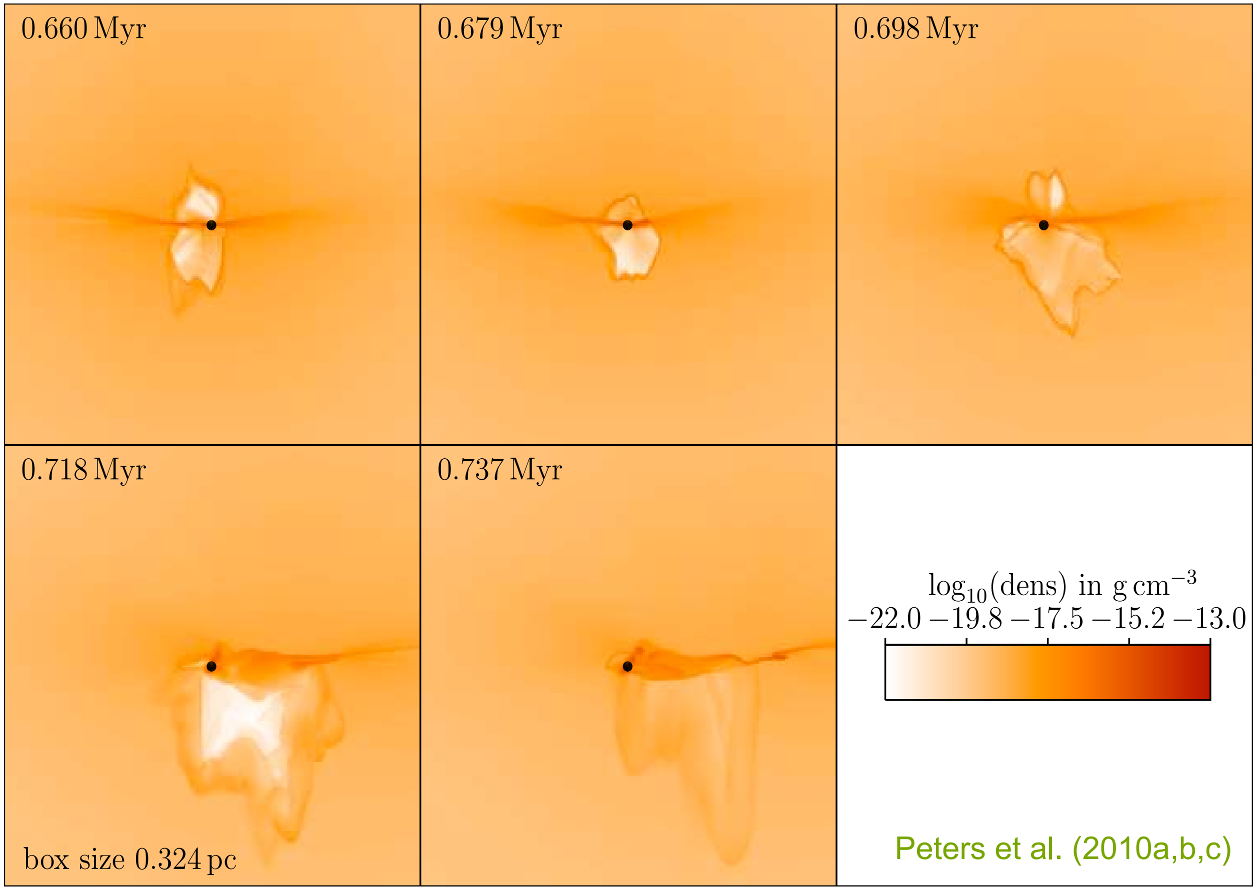
Peters et al. (2010a,b,c)



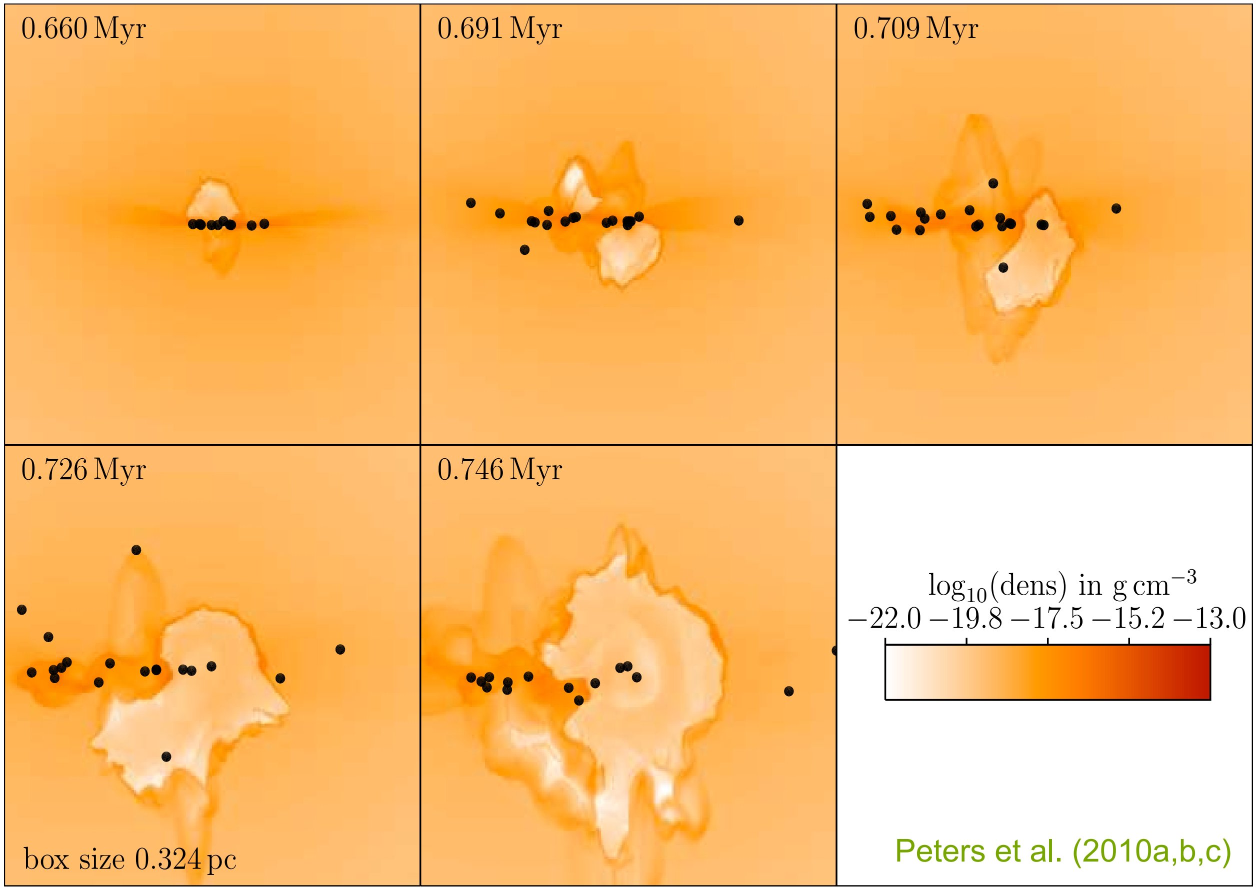
OVERVIEW OF COLLAPSE SIMULATIONS.

Name	Resolution	Radiative Feedback	Multiple Sinks	M_{sinks} ($M_\odot$)	N_{sinks}	M_{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)



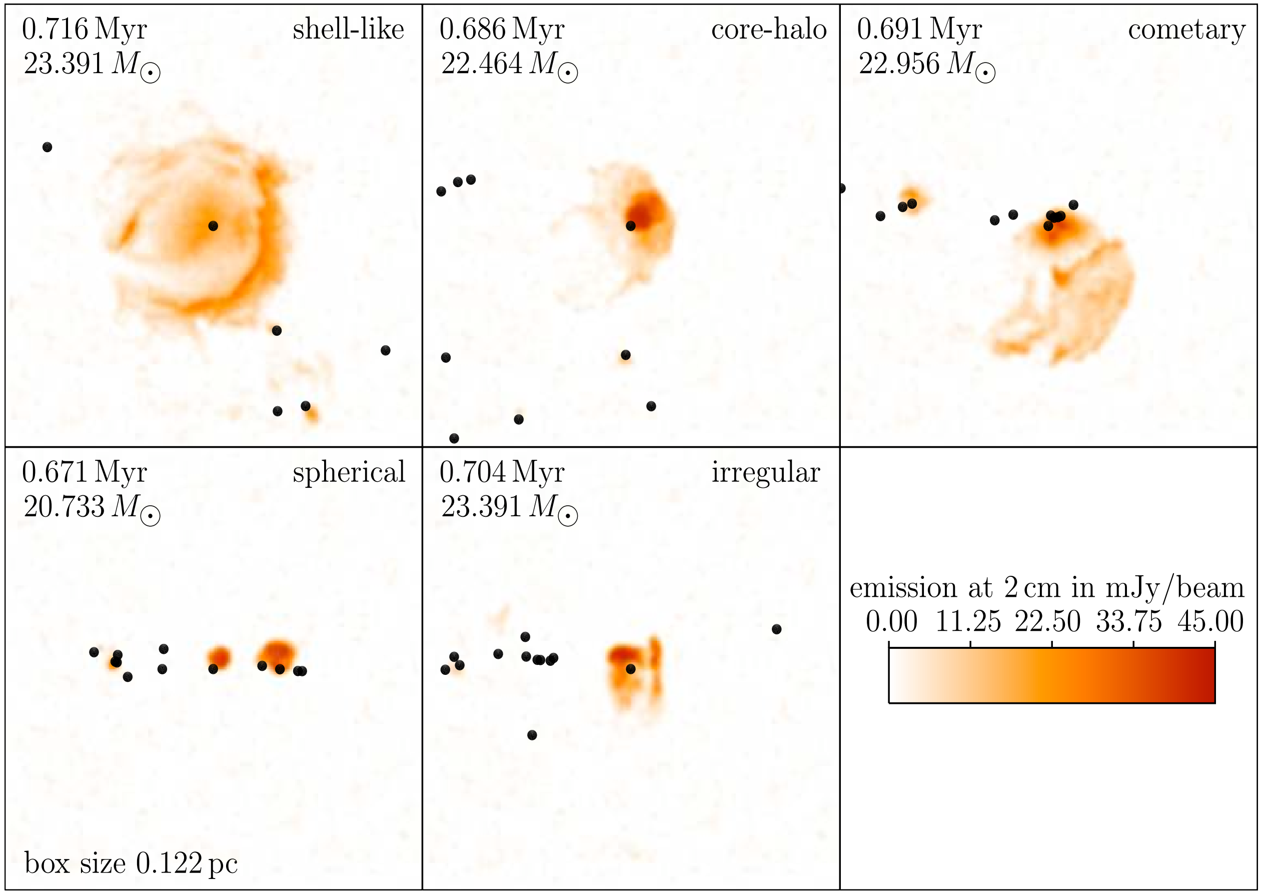
- thermal pressure drives bipolar outflow
- filaments can effectively shield ionizing radiation
- when thermal support gets lost, outflow gets quenched again
- no direct relation between mass of star and size of outflow



- 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)



- 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)

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)

key questions

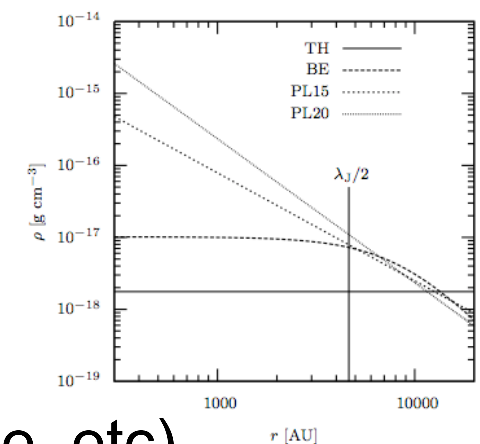
- *what drives turbulence?*
  --> accretion driven turbulence on ALL scales
  galaxies, molecular clouds, protostellar disks
- *how do high-mass stars & their clusters form?*
  --> fragmentation-induced starvation
- *what are the initial conditions for cluster formation?*
  --> initial density profile matters
- *when do the first star clusters form?*
  --> the very first stars form in clusters

ICs of star cluster formation

- the “Hans Zinnecker” question:
  - what is the initial density profile of cluster forming cores? how does it compare low-mass cores?
- observational answer:

ICs of star cluster formation

- the “Hans Zinnecker” 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?

  .

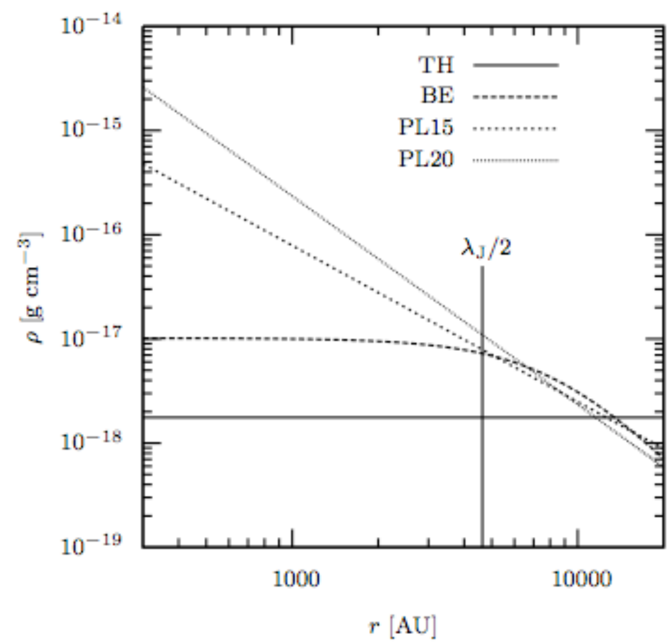
  .

  .

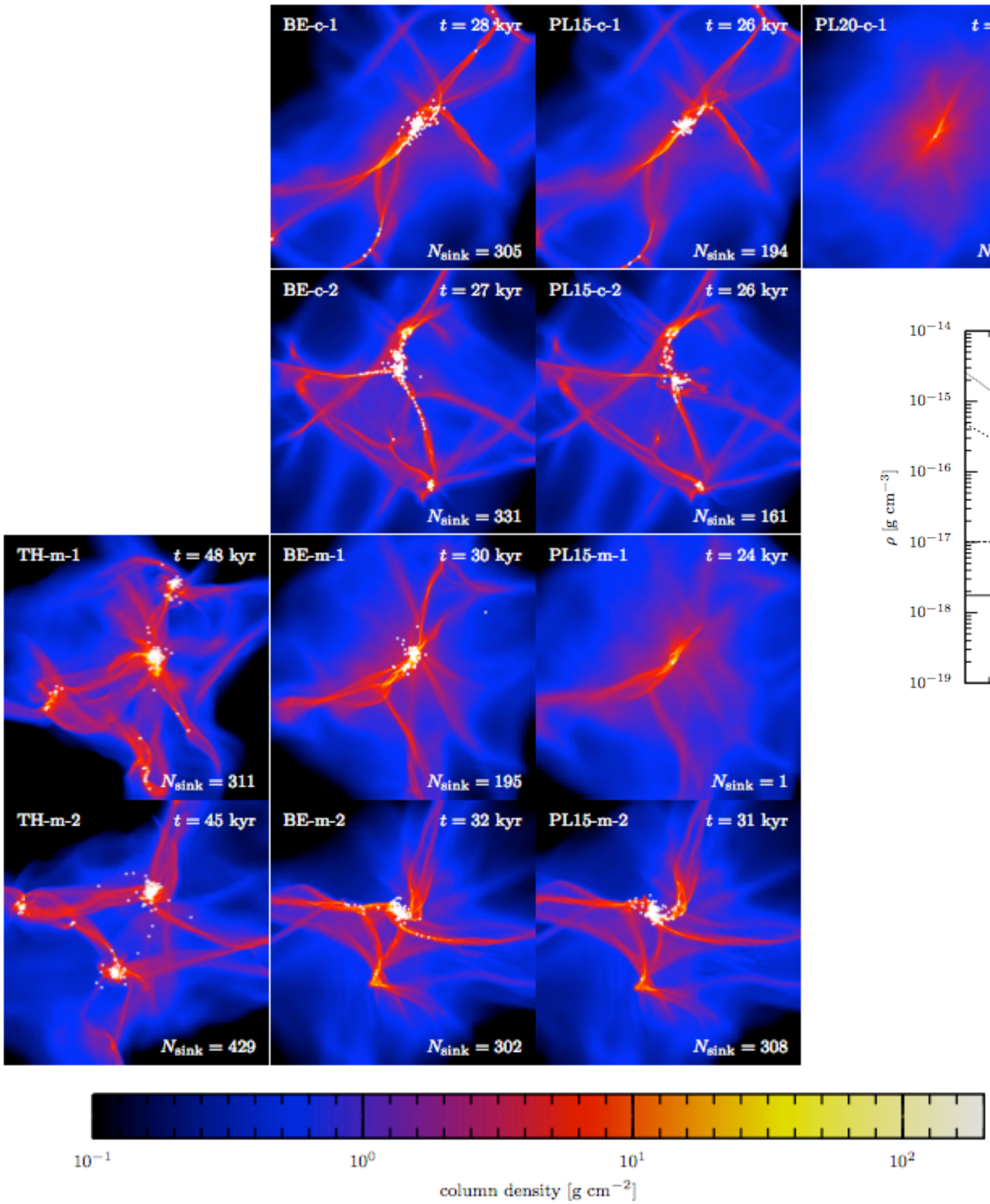
- in comparison to
  - turbulence ...
  - radiative feedback ...
  - magnetic fields ...
  - thermodynamics ...

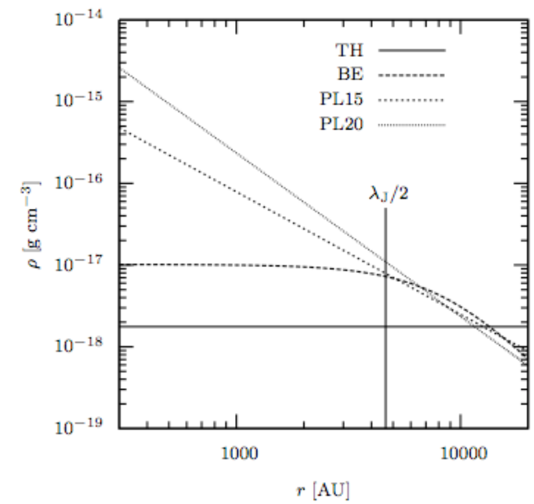
different density profiles

- 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)

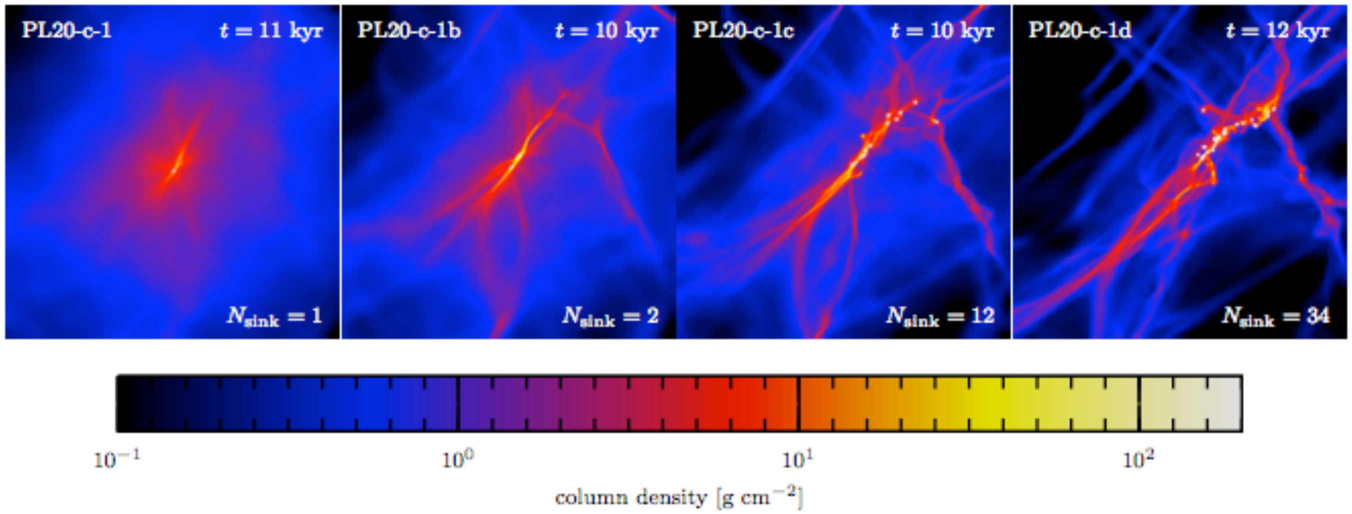


Girichids: Poster





Girichids: Poster



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: Poster

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: Poster

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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PL20-c-1d	11.77	1.01	0.24	34	0.593	13.3

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: Poster

different density profiles

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

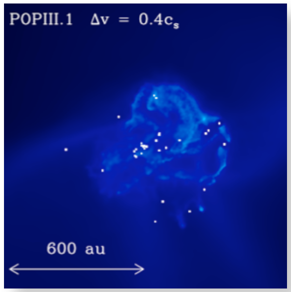
- however: this is good, because it may explain some of the theoretical controversy, we (currently) have in the field (hopefully).

Girichids: Poster

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
- *when do the first star clusters form?*
  --> the very first stars form in clusters

first stars

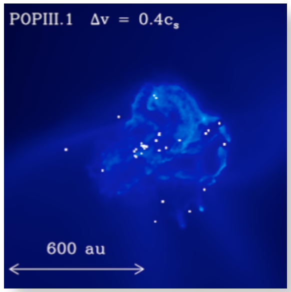


- let's look for an applications in an "unusual" place:

Is this relevant for first star formation?

- answer: ***probably YES!***
- first hints:
  - Machida (2008), Machida et al. (2009), Turk et al. (2009), Stacy et al. (2010) find signs of binary fragmentation
  - Clark et al. (2008) find hints for cluster-type fragmentation

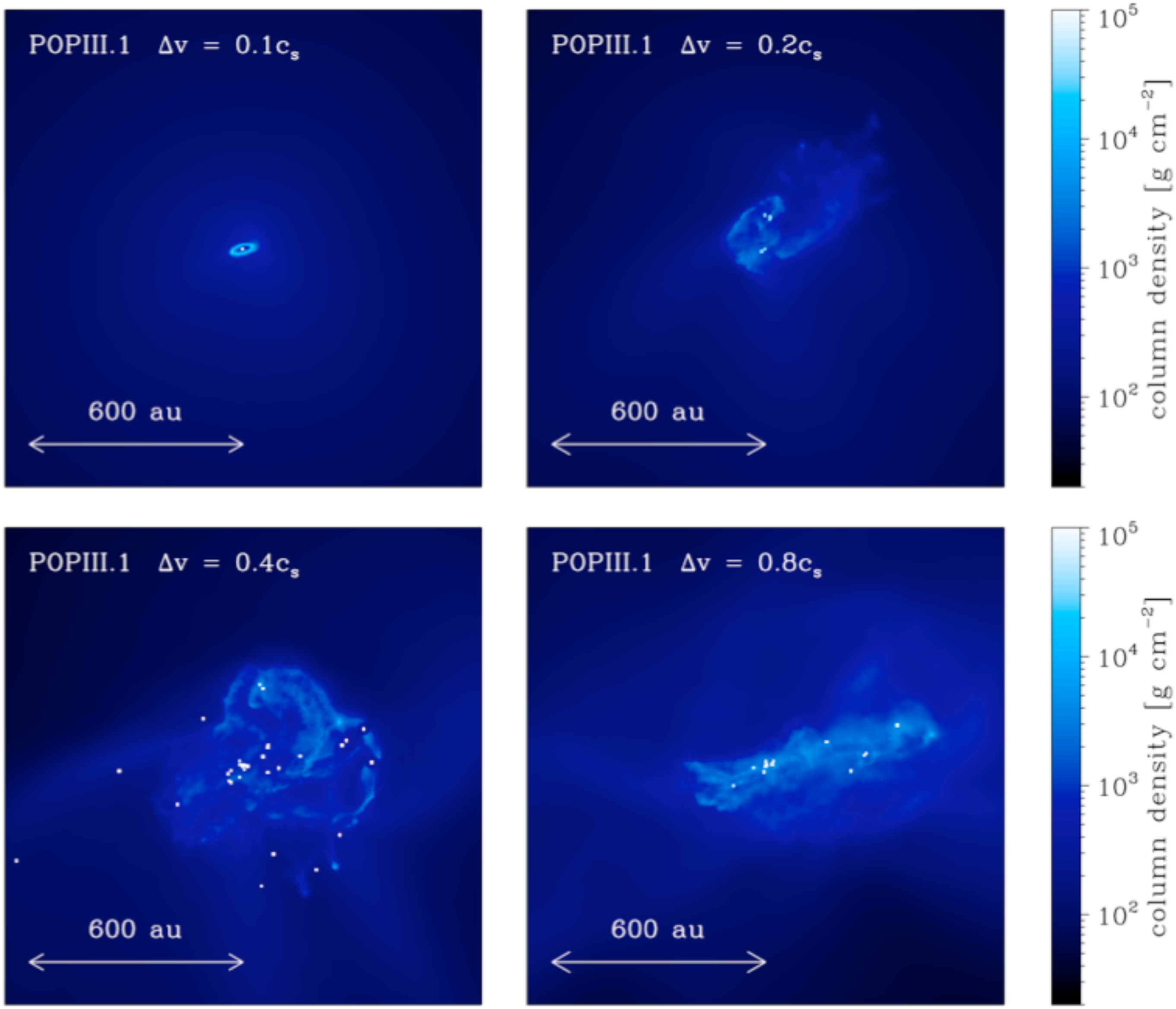
first stars



- numerical experiments of cooling and collapse in primordial halos
  - consider Pop III.1 and Pop III.2 case
  - consider realistic halo parameters
    (such as resulting from cosmological calculations, Abel, Bromm, Greif, etc.)
  - use full fledged time-dependent chemistry
    (Glover, Savin, Jappsen 2006, Glover 2008, Glover & Abel 2008)
  - use SPH with 2 million particles (Springel 2005)
  - focus on central 1,000 Msun (150 Msun)
  - do *extended parameter study* by ***varying*** degree of ***turbulence*** *(Mach numbers 0, 0.2, 0.4, 0.8)*

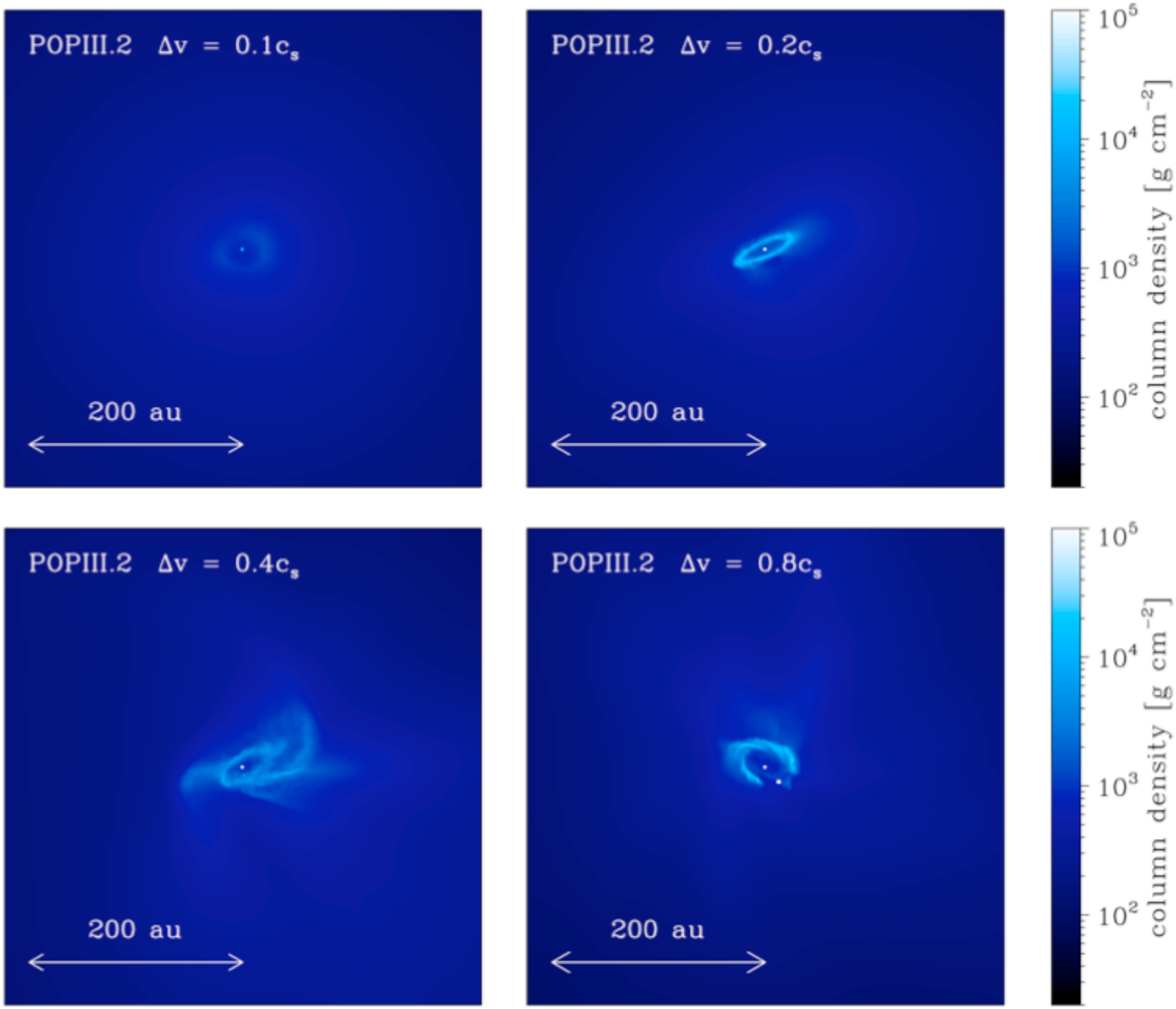
Clark et al. (submitted)

Pop III.1 case: truly pristine primordial gas



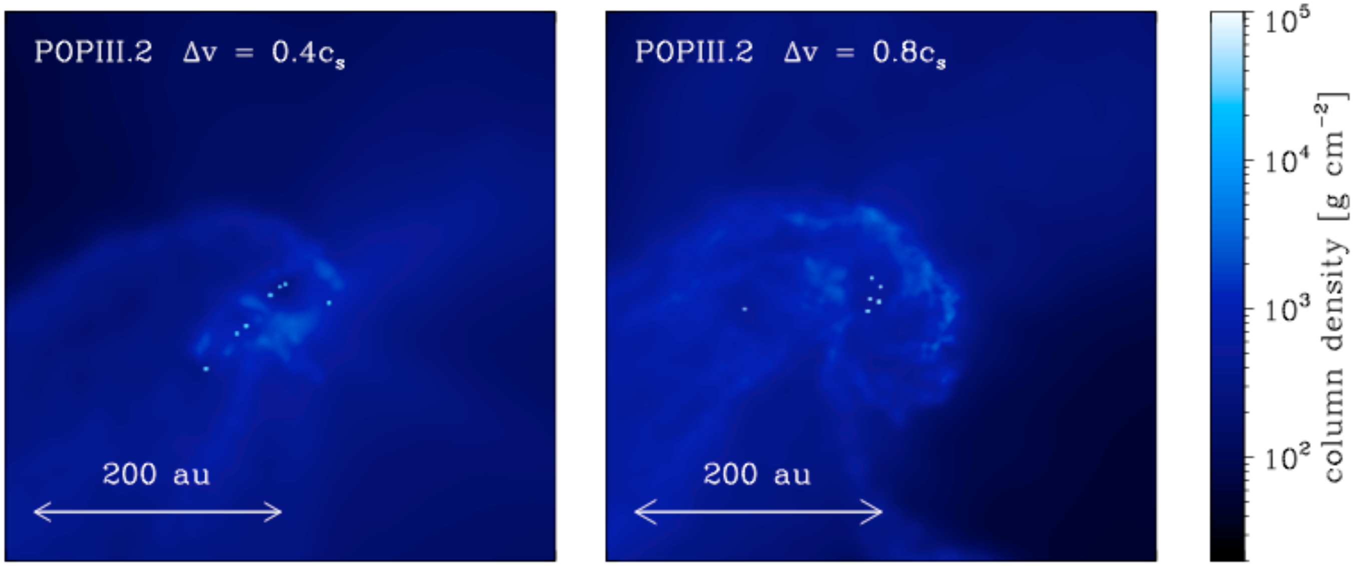
Clark et al. (submitted)

Pop III.2 case: preionized gas (150 Msun core)



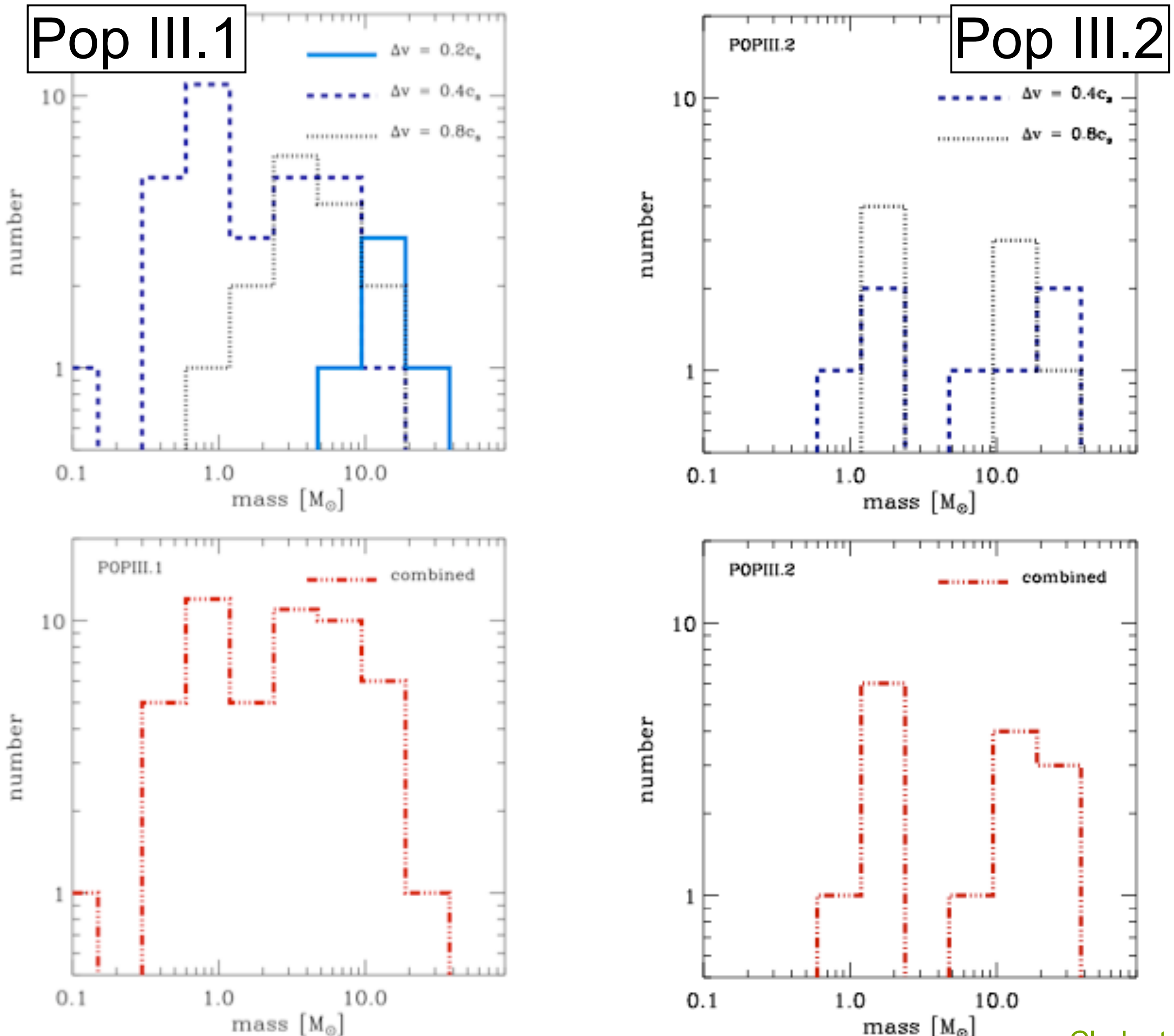
Clark et al. (submitted)

Pop III.2 case: preionized gas (1,000 Msun core)



Clark et al. (submitted)

mass spectra



Clark et al. (submitted)

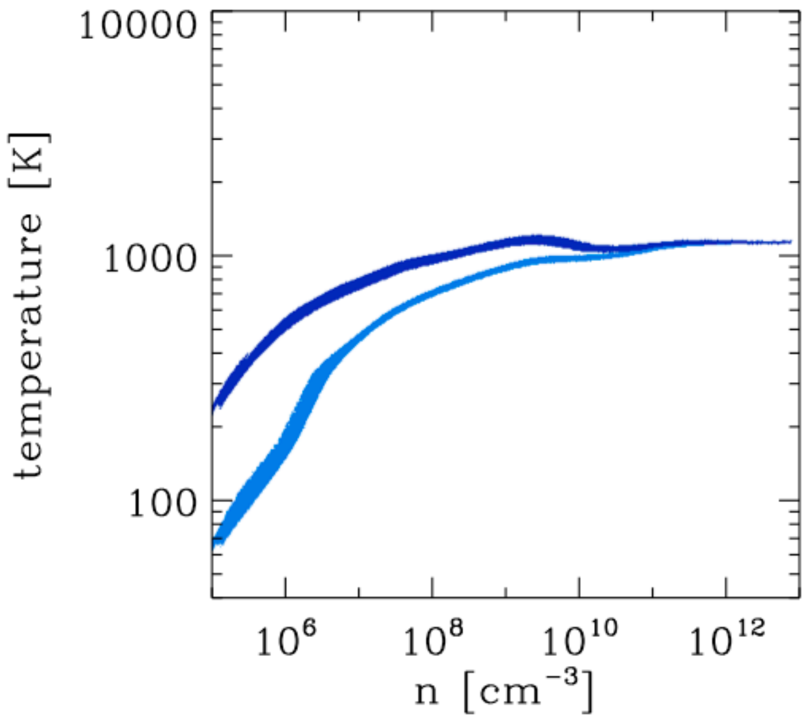


FIG. 5.— Temperature as a function of number density for the Pop. III.1 (dark blue) and Pop. III.2 (light blue) $\Delta v_{\rm turb} = 0.1\, c_{\rm s}$ simulations. In both cases, the curves denote the state of the cloud at the point just before the formation of the sink particle.

Combination of turbulence and thermodynamics determines fragmentation behavior.

Clark et al. (submitted)

relevance?

- key question: is there turbulence in the primordial accretion flow?
- answer: very likely!
  - seen in numerical simulations
    (e.g. Wise & Abel 2007, 2008, Greif et al. 2008, Dekel et al. 2009, Dubois & Teyssier 2009)
  - expected theoretically

summary

- *agreement:*
  - star clusters form through the complex interplay between *self-gravity* and *turbulence*, *thermo-dynamics* (chemistry, heating, cooling), *magnetic fields*, and radiative and mechanical *feedback*!
- *controversial:*
  - what drives turbulence? is it *accretion*?
  - how do massive stars form (and their clusters)? *fragmentation induced starvation*?
  - what are the initial conditions of Galactic star clusters? *importance of density profile...*
  - where do the first star clusters form? *already Pop III?*

summary

- main message:

INITIAL CONDITIONS MATTER!