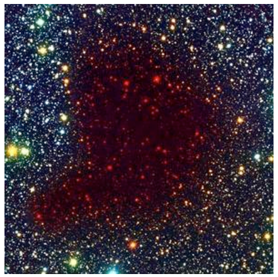
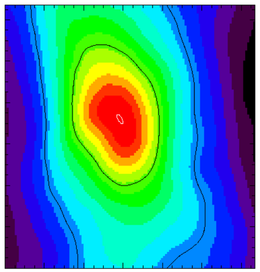
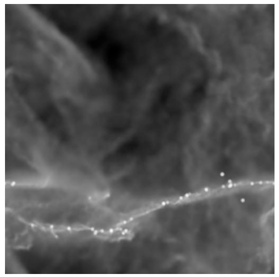
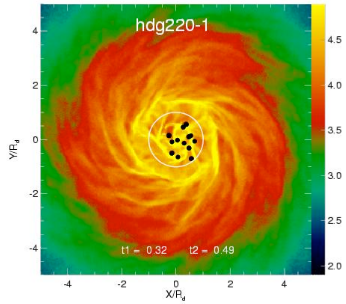
Star Formation: Now and Then





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Institut für Theoretische Astrophysik

thanks to ...

... people in the group in Heidelberg:

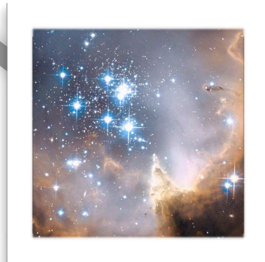
Robi Banerjee, Simon Glover, Rahul Shetty, Sharanya Sur, Daniel Seifried, Milica Milosavljevic, Florian Mandl, Christian Baczynski, Rowan Smith, Gustavo Dopcke, Jonathan Downing, Jayanta Dutta, Faviola Molina, Christoph Federrath, Erik Bertram, Lukas Konstandin, Paul Clark, Stefan Schmeja, Ingo Berentzen, Thomas Peters, Hsiang-Hsu Wang

... many collaborators abroad!

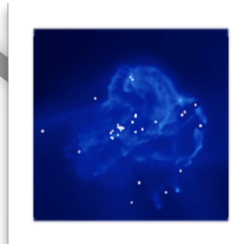
agenda

- a simple cartoon picture of dynamic star formation theory
- some applications, open issues, and questions

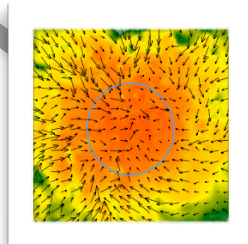
agenda



High-mass star formation

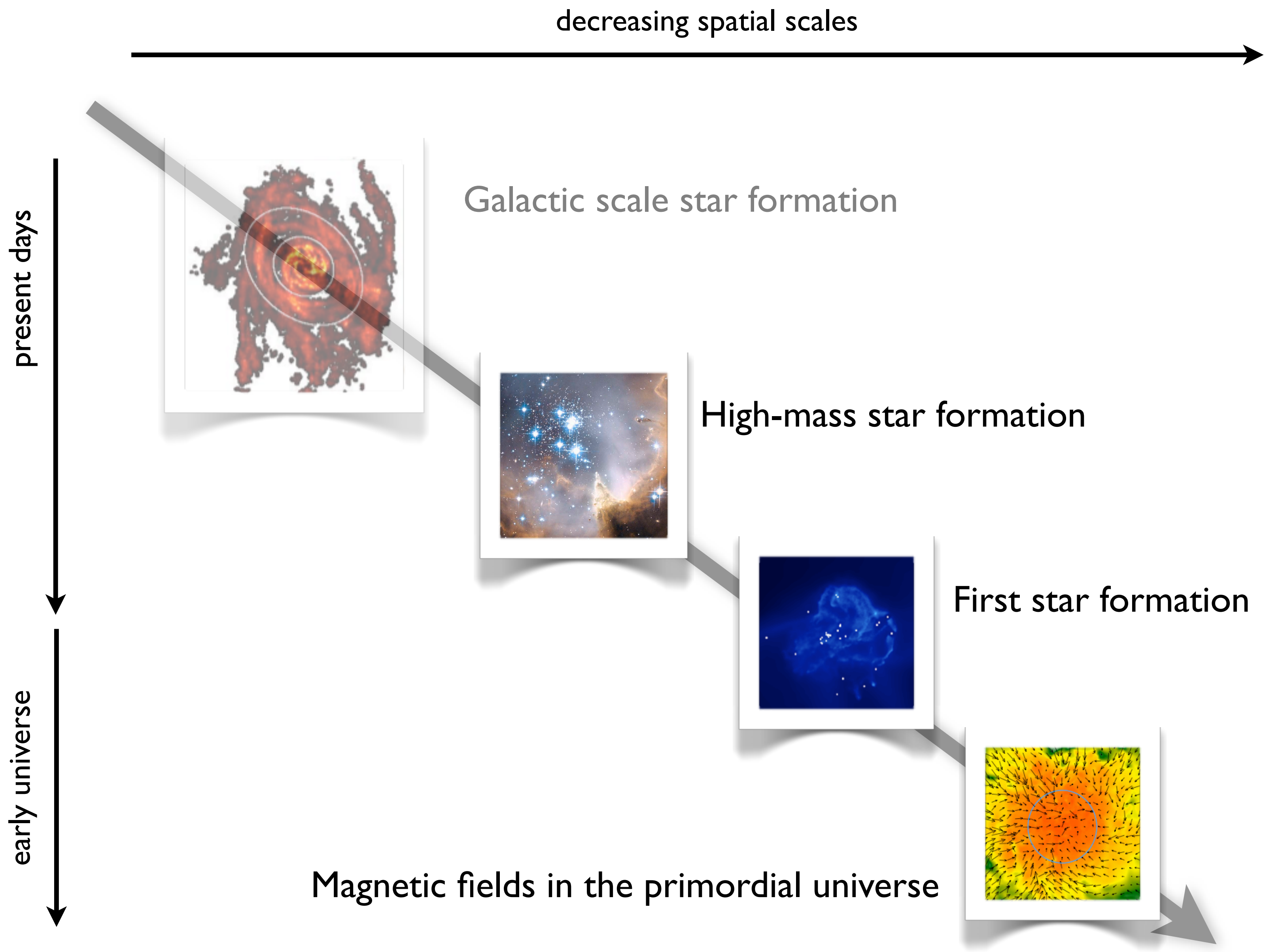


First star formation



Magnetic fields in the primordial universe

agenda


decreasing spatial scales
present days
early universe
Galactic scale star formation
High-mass star formation
First star formation
Magnetic fields in the primordial universe

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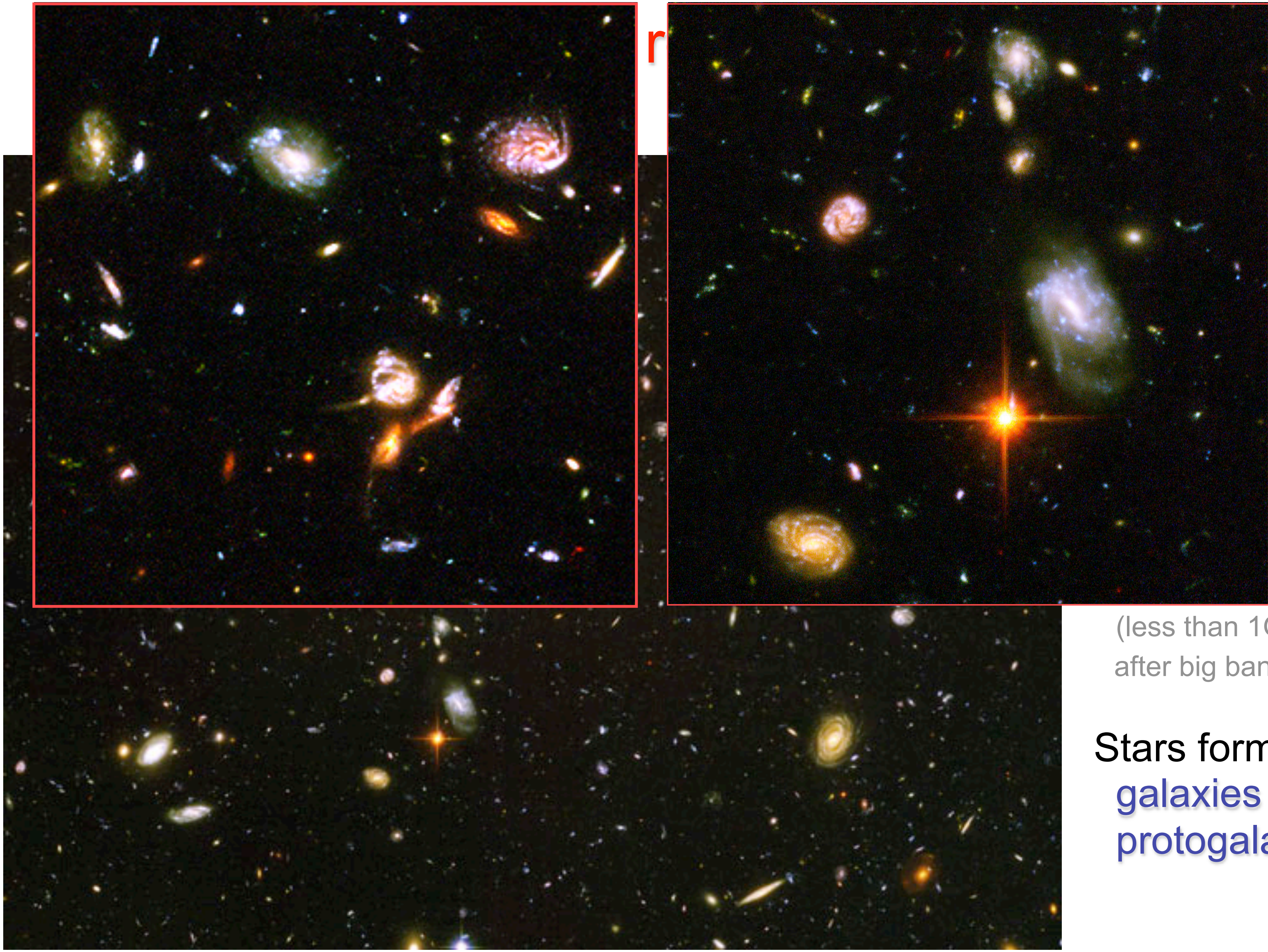


ation

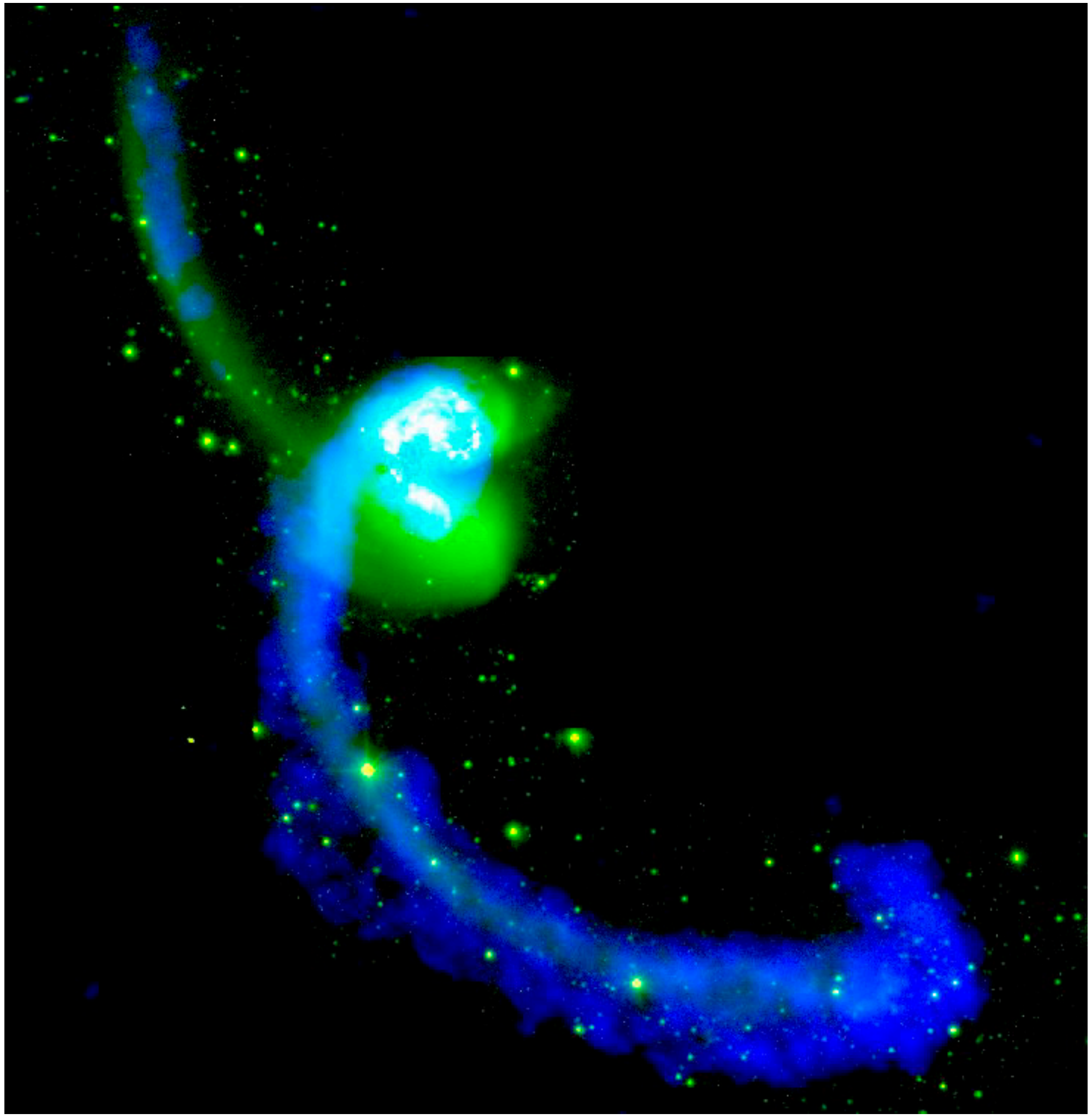
arly

(less than 1Gyr after big bangl)

Stars form in galaxies and protogalaxies

(Hubble Ultra-Deep Field, from HST Web site)

Star formation in interacting galaxies:

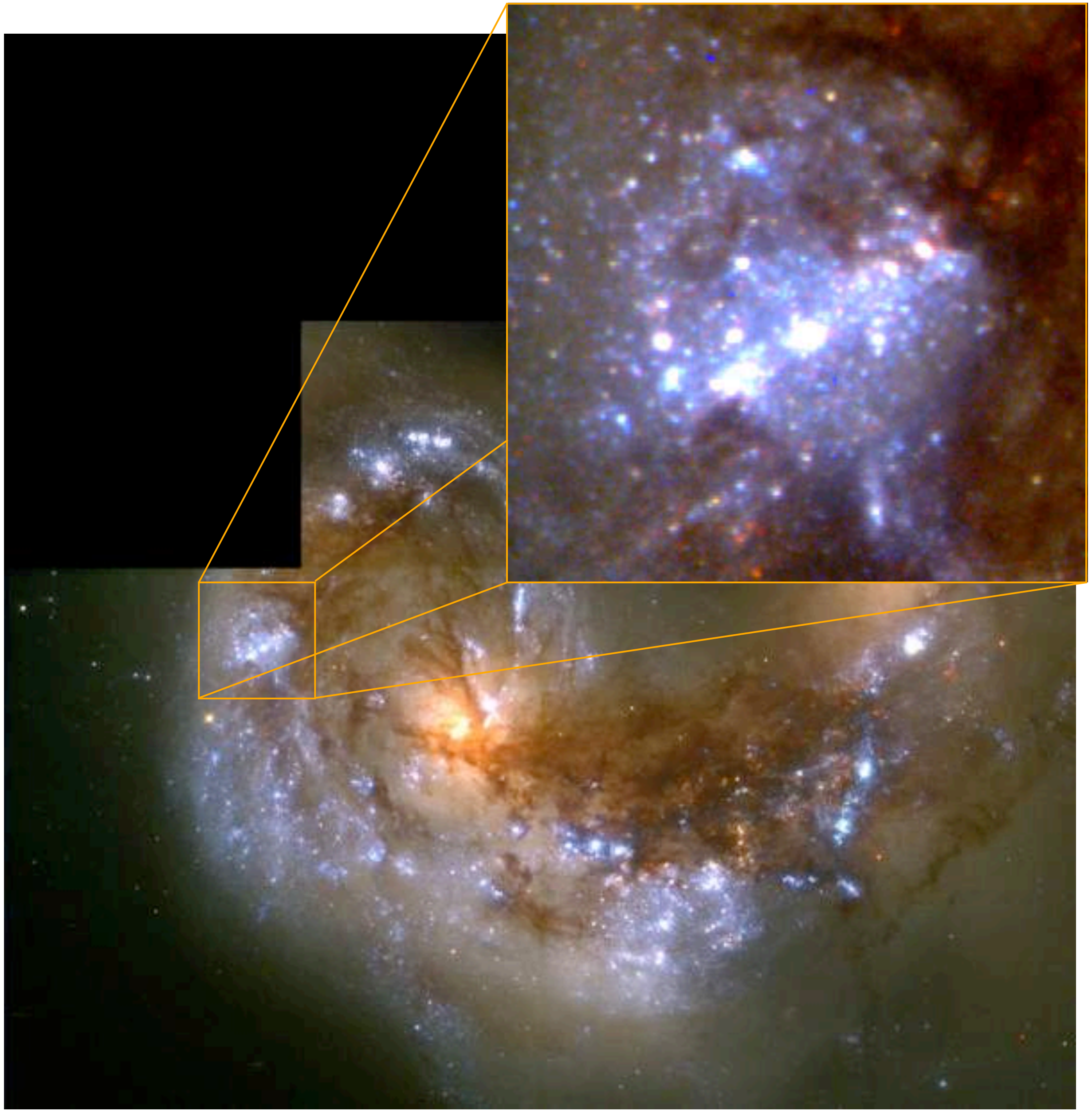


(from the Chandra Webpage)

Antennae galaxy

- *NGC4038/39*
- *distance: 19.2Mpc*
- *vis. Magn: 11.2*
- *optical: white, green*
- *radio: blue*

Star formation in interacting galaxies:



(HST: Whitmore & Schweizer 1997)

Antennae galaxy

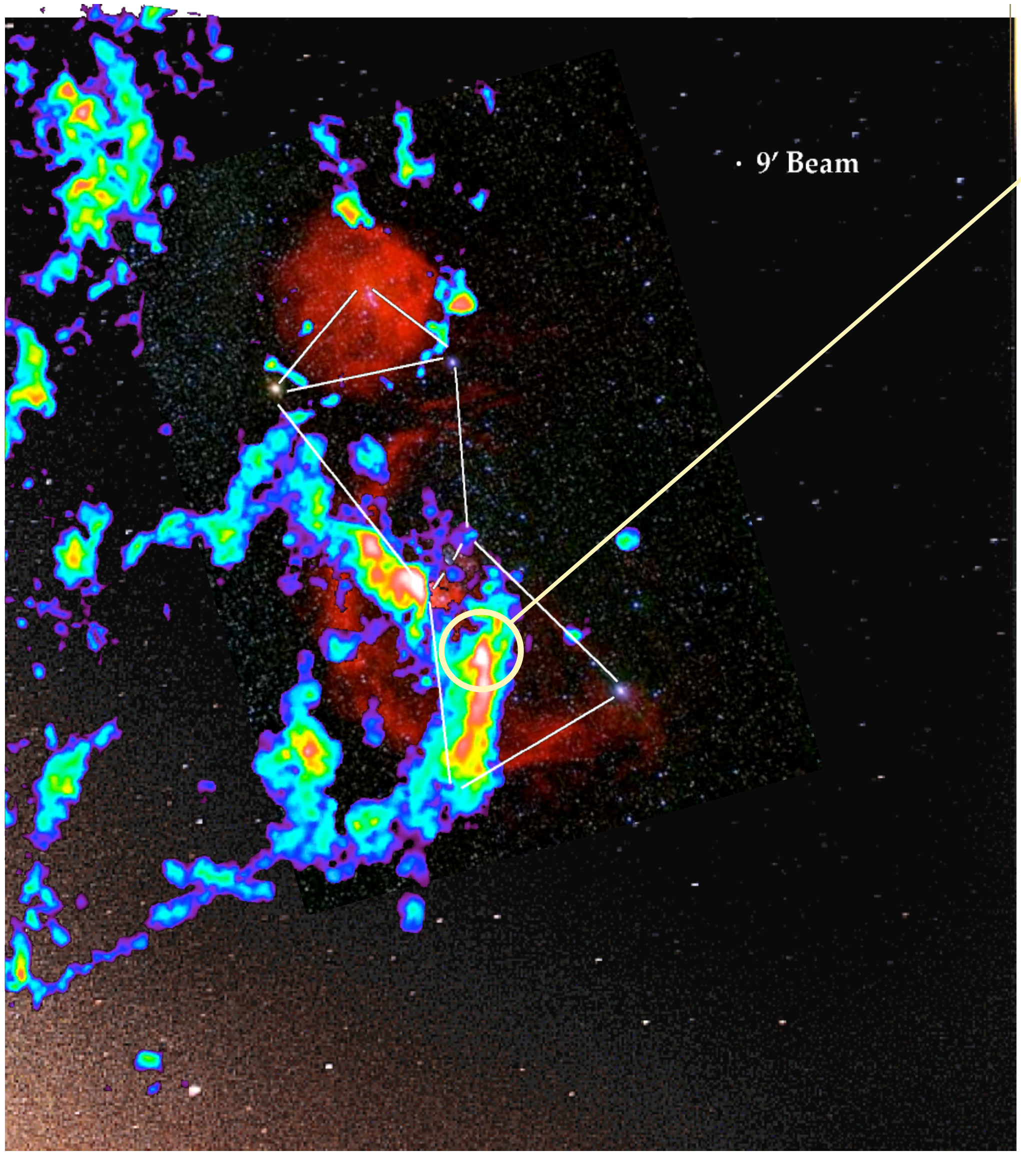
- Star formation burst in interacting (merging) galaxies
- Strong perturbation SF in tidal “tales”
- Large-scale gravitational motion determines SF
- Stars form in “knobs” (i.e. superclusters)

young stars in spiral galaxies

(NGC 4622 from the Hubble Heritage Team)

- Star formation *always* is associated with *clouds of gas and dust*.
- Star formation is essentially a *local phenomenon* (on ~pc scale)
- HOW is star formation is *influenced* by *global* properties of the galaxy?

example: Orion



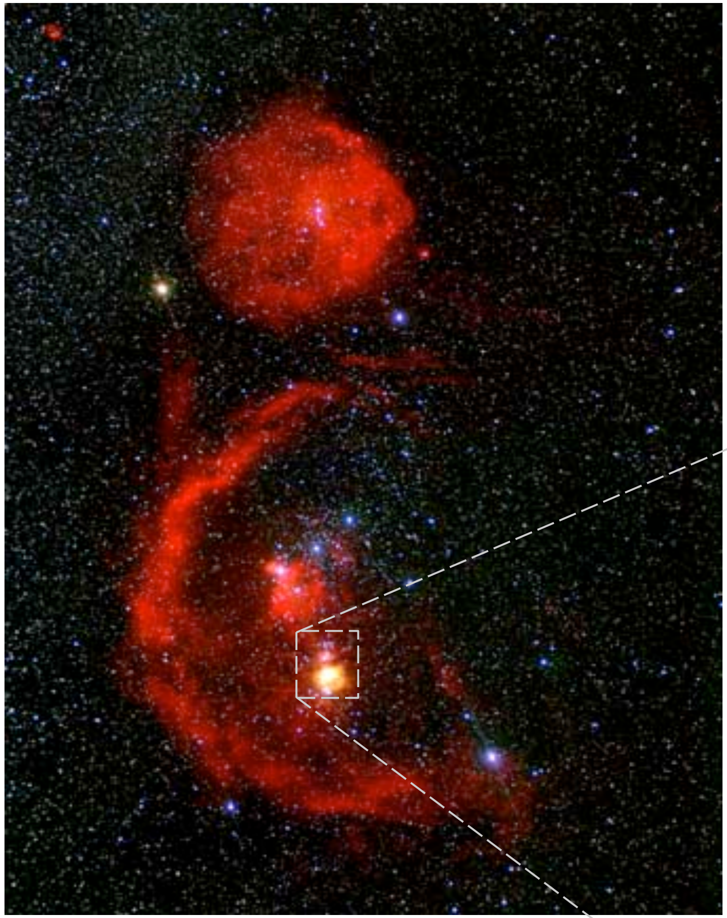
let's look at the Orion Nebula Cluster (ONC)

We see

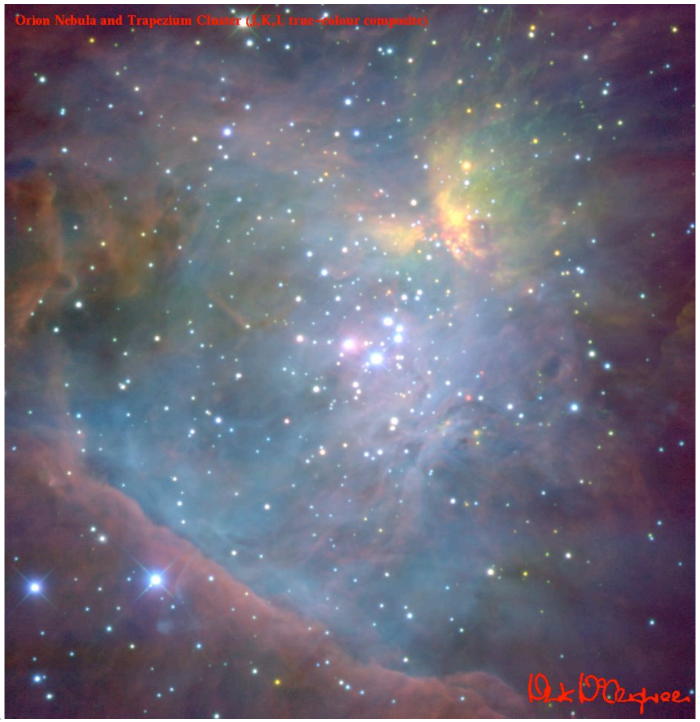
- *Stars* (in visible light)
- Atomic hydrogen (in Hα -- red)
- Molecular hydrogen H_2 (radio emission

The Orion molecular cloud is the birth- place of several young embedded star clusters.

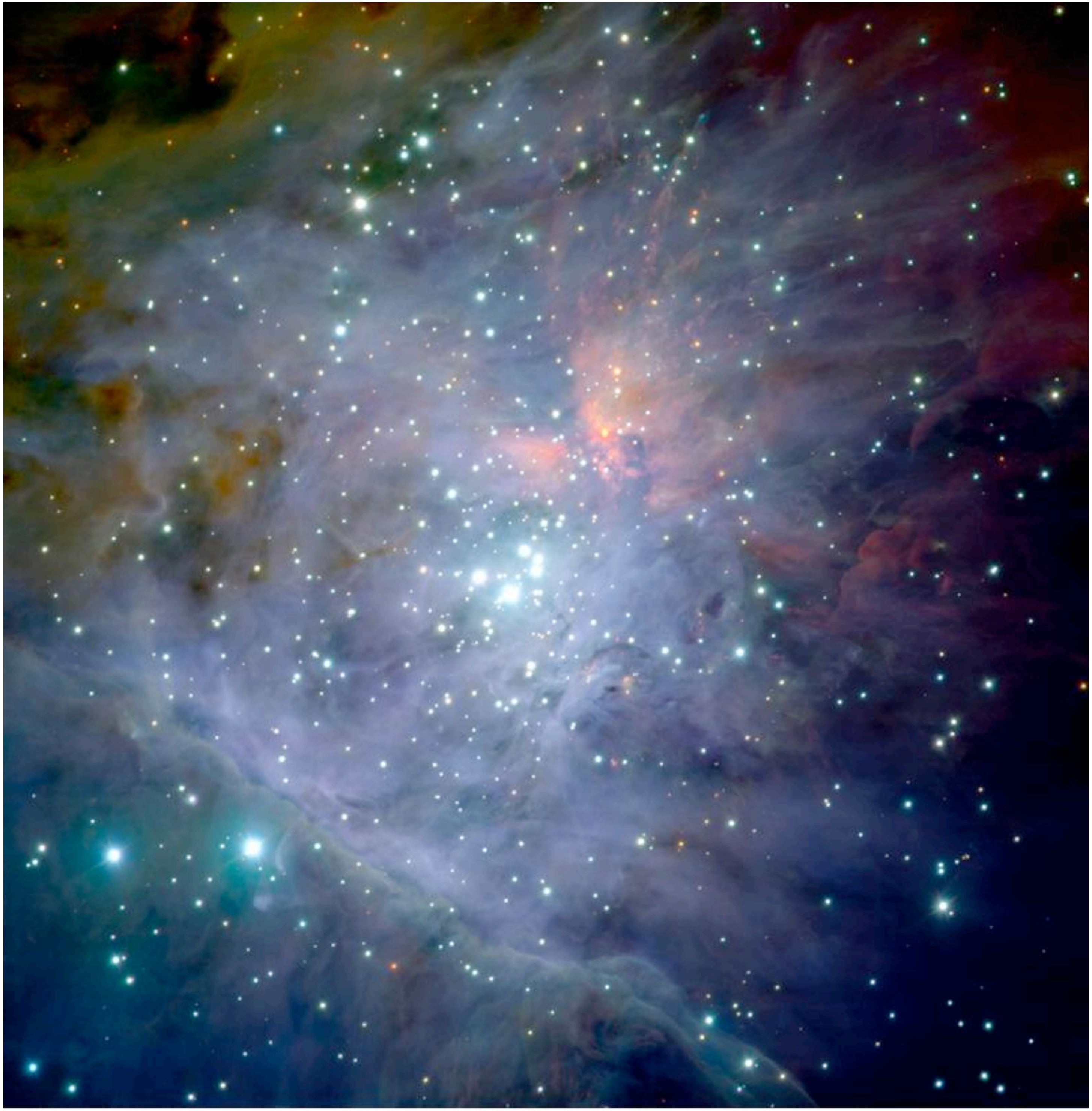
The Trapezium cluster is only visible in the IR and contains about 2000 newly born stars.



Orion molecular cloud



Trapezium cluster



Trapezium Cluster

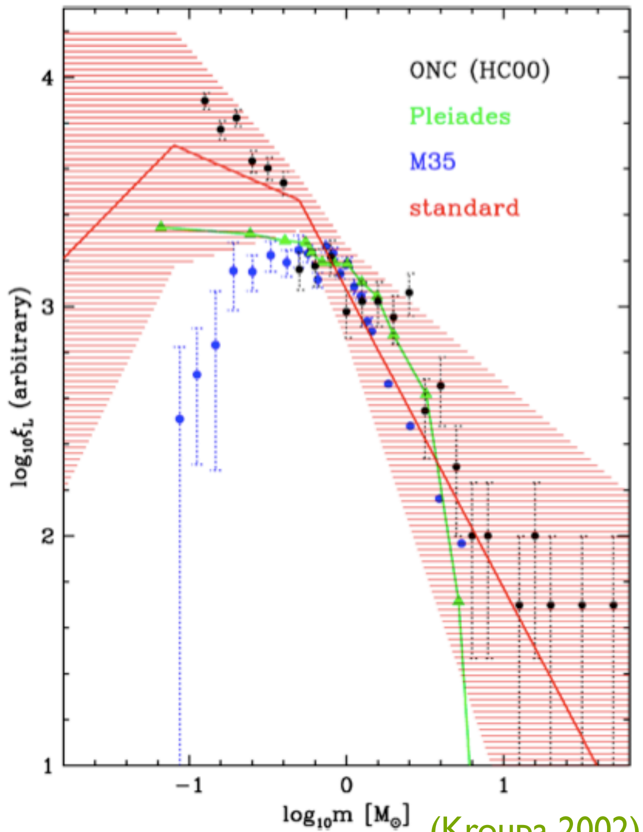
(detail)

- stars form in clusters
- stars form in molecular clouds
- (proto)stellar feedback is important

(color composite J,H,K by M. McCaughrean, VLT, Paranal, Chile)

stellar mass fuction

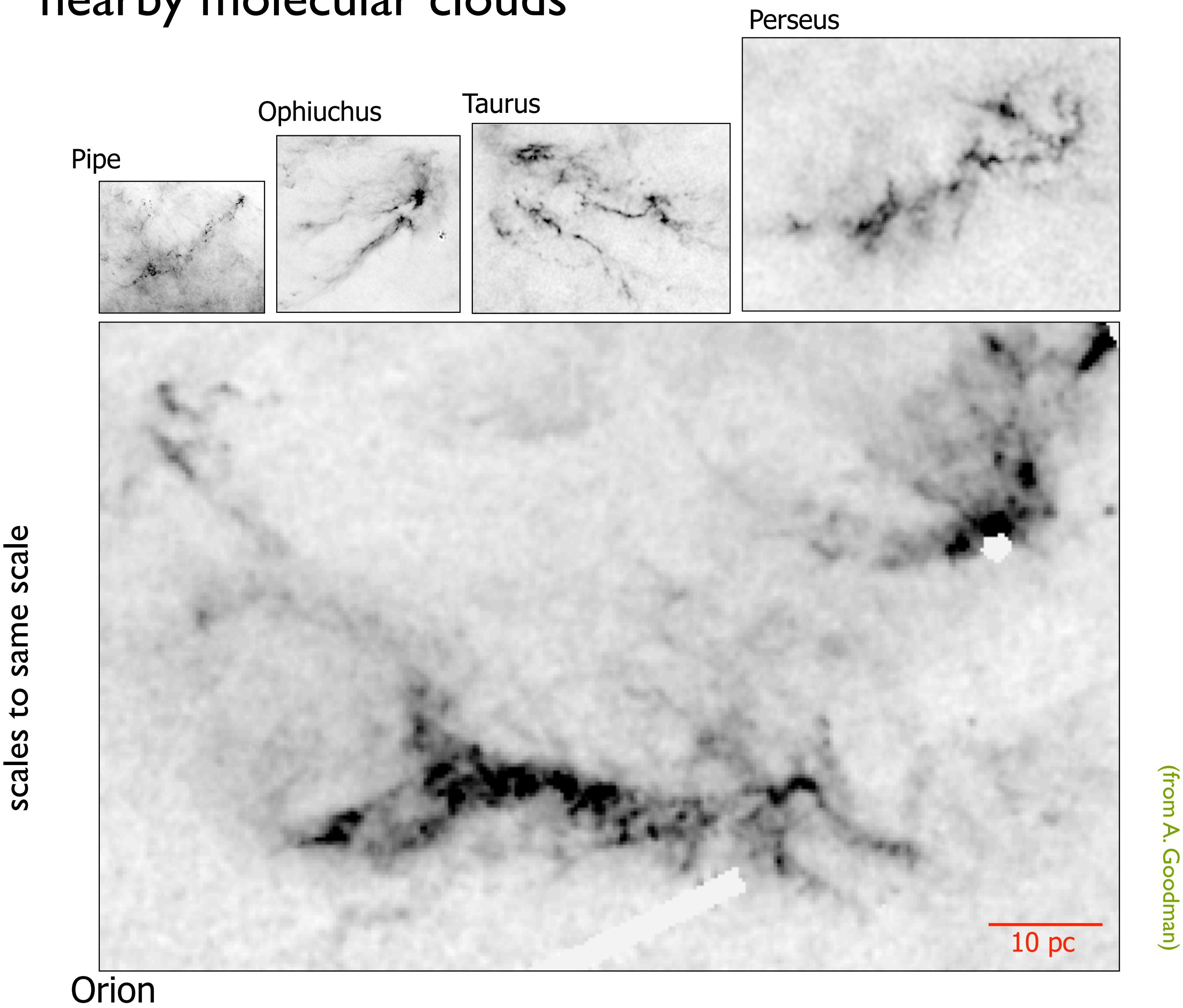
stars seem to follow a universal mass function at birth --> IMF



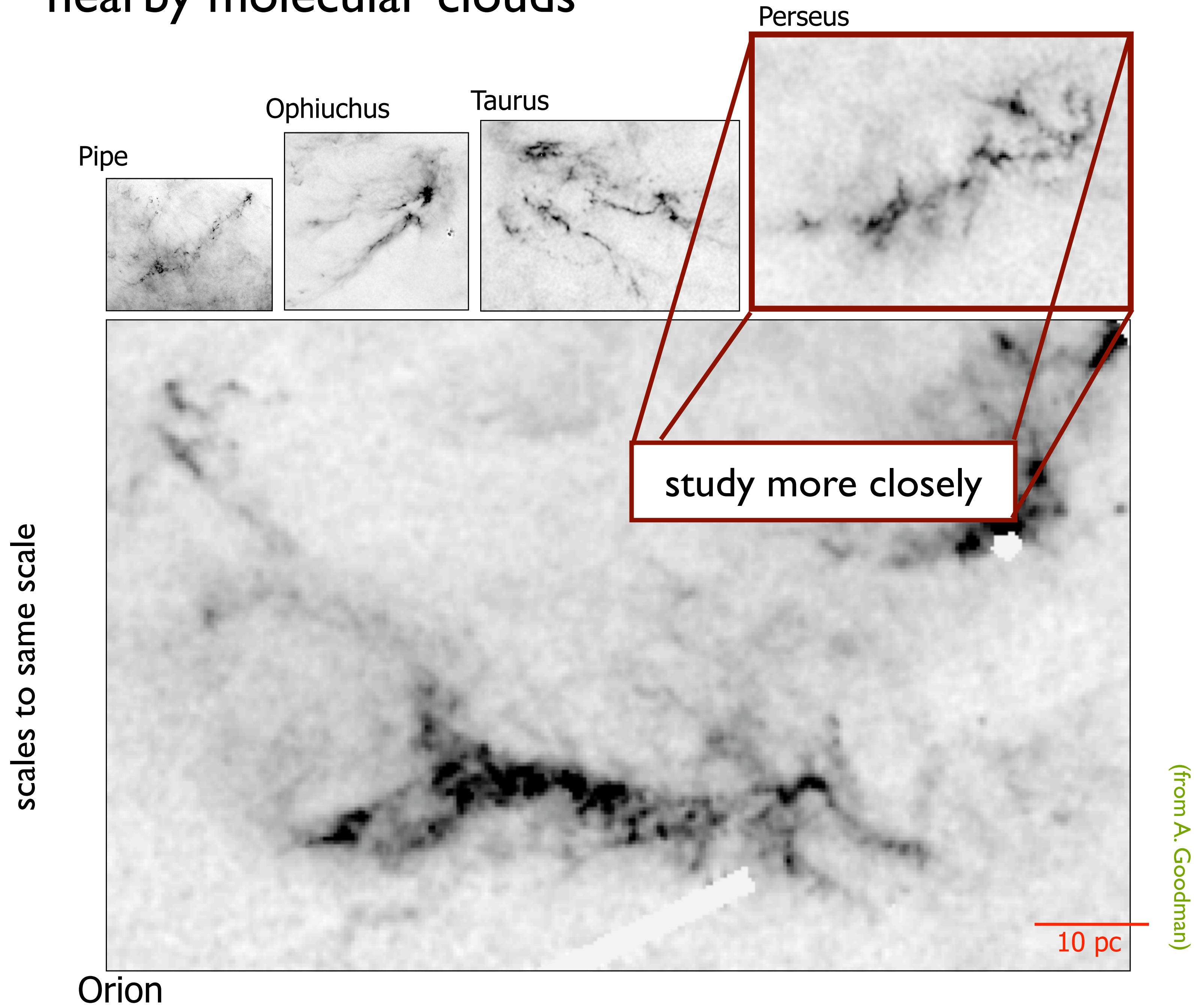
(Kroupa 2002)

Orion, NGC 3603, 30 Doradus
(Zinnecker & Yorke 2007)

nearby molecular clouds



nearby molecular clouds



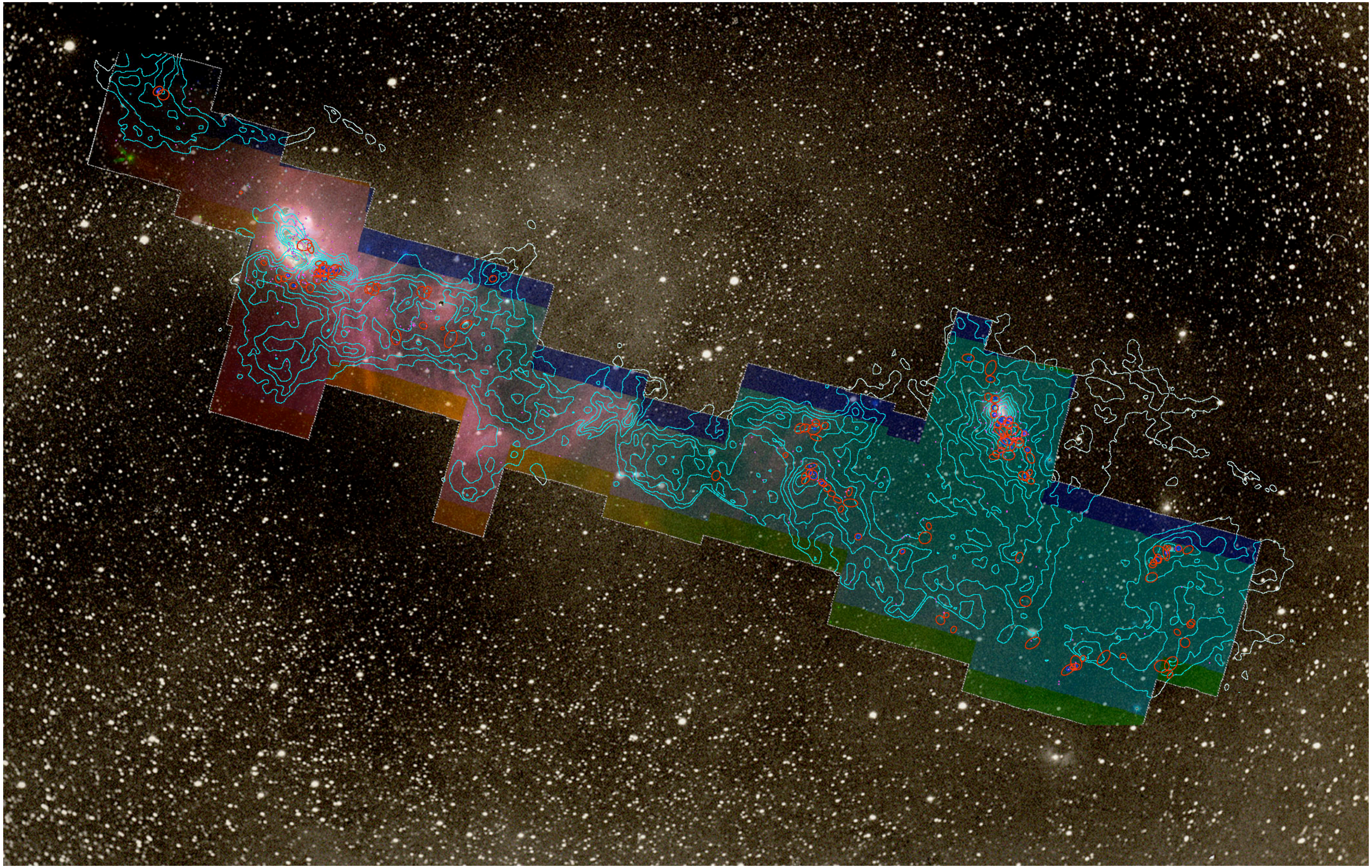
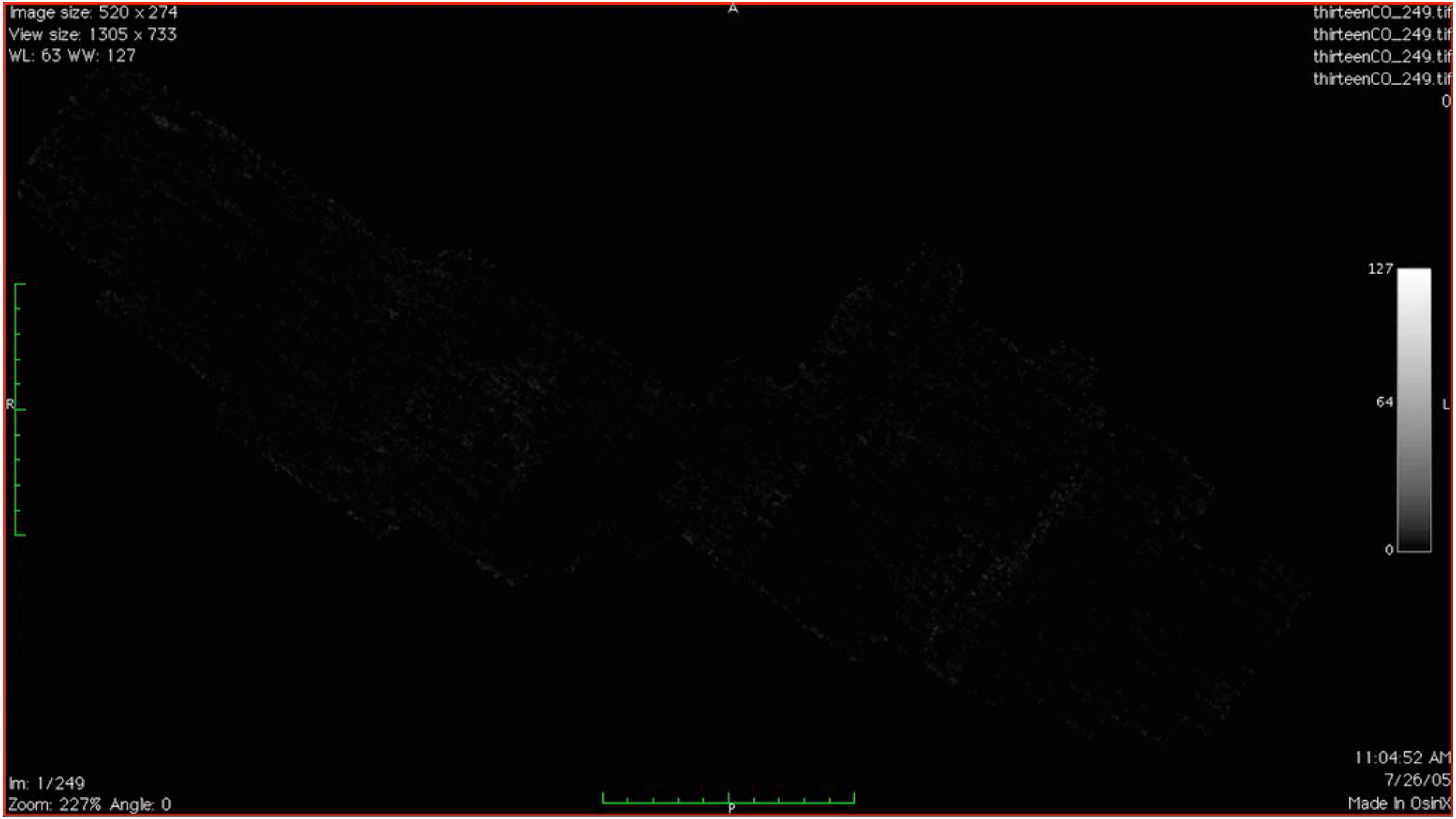
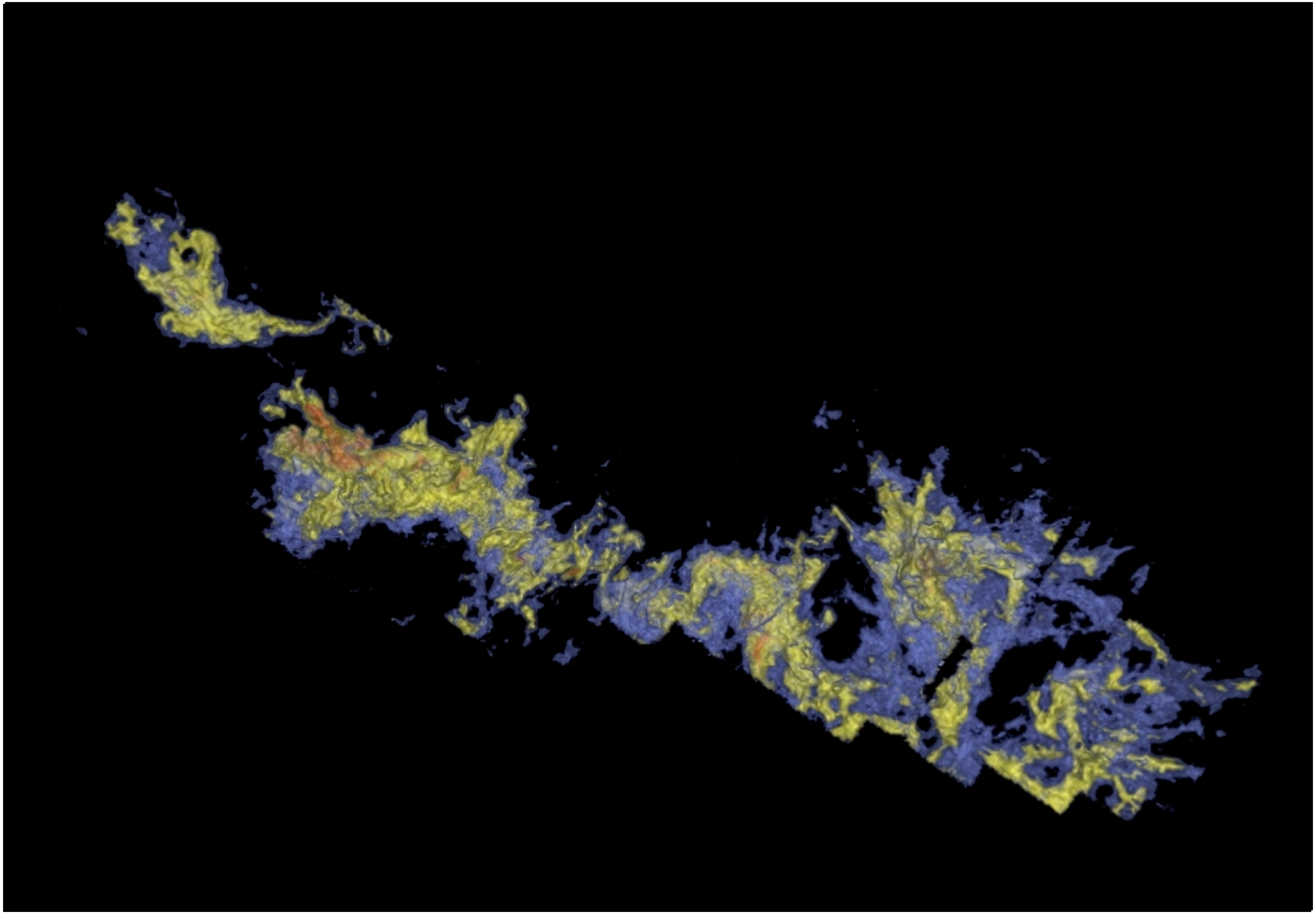


image from Alyssa Goodman: COMPLETE survey



velocity distribution in Perseus

velocity cube from Alyssa Goodman: COMPLETE survey



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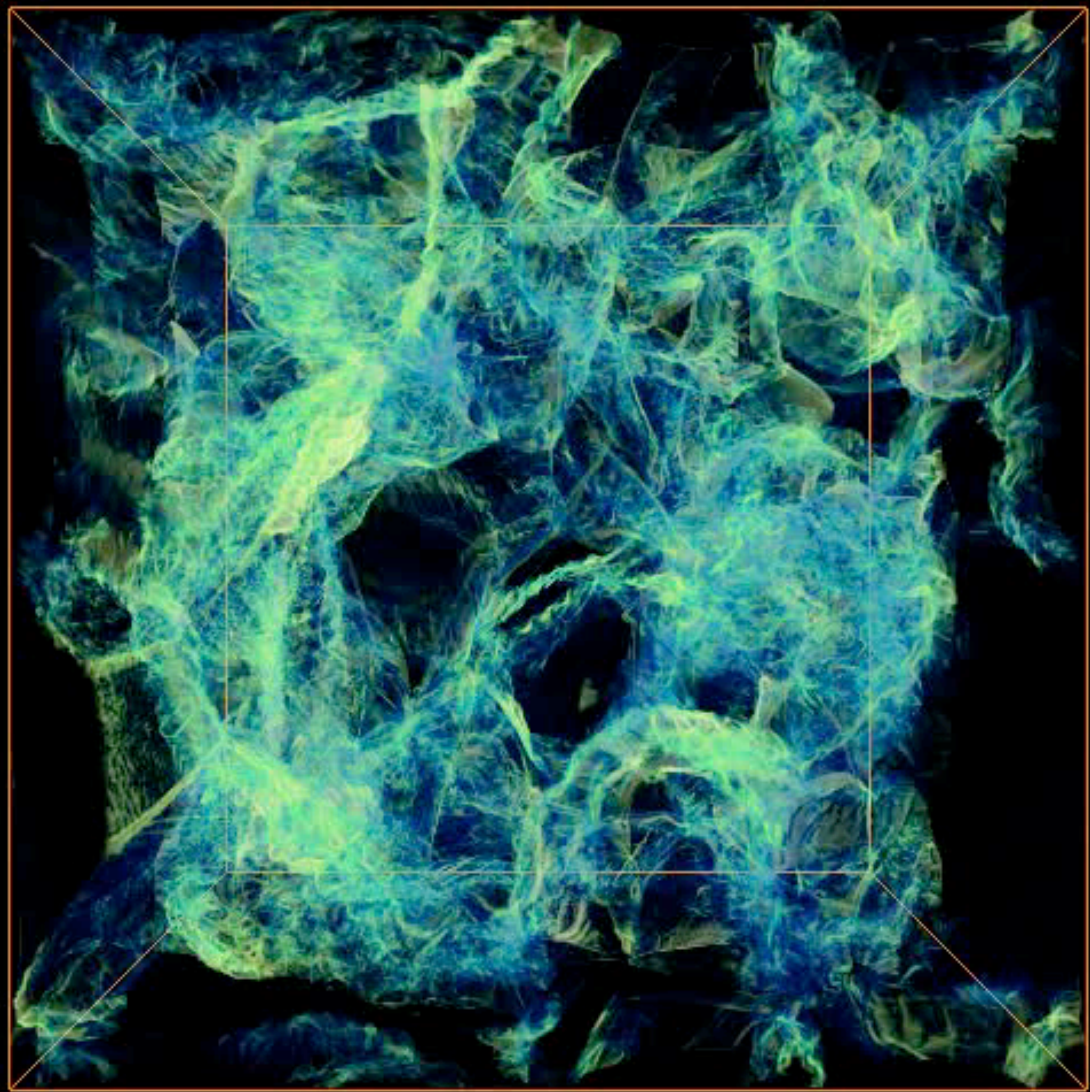
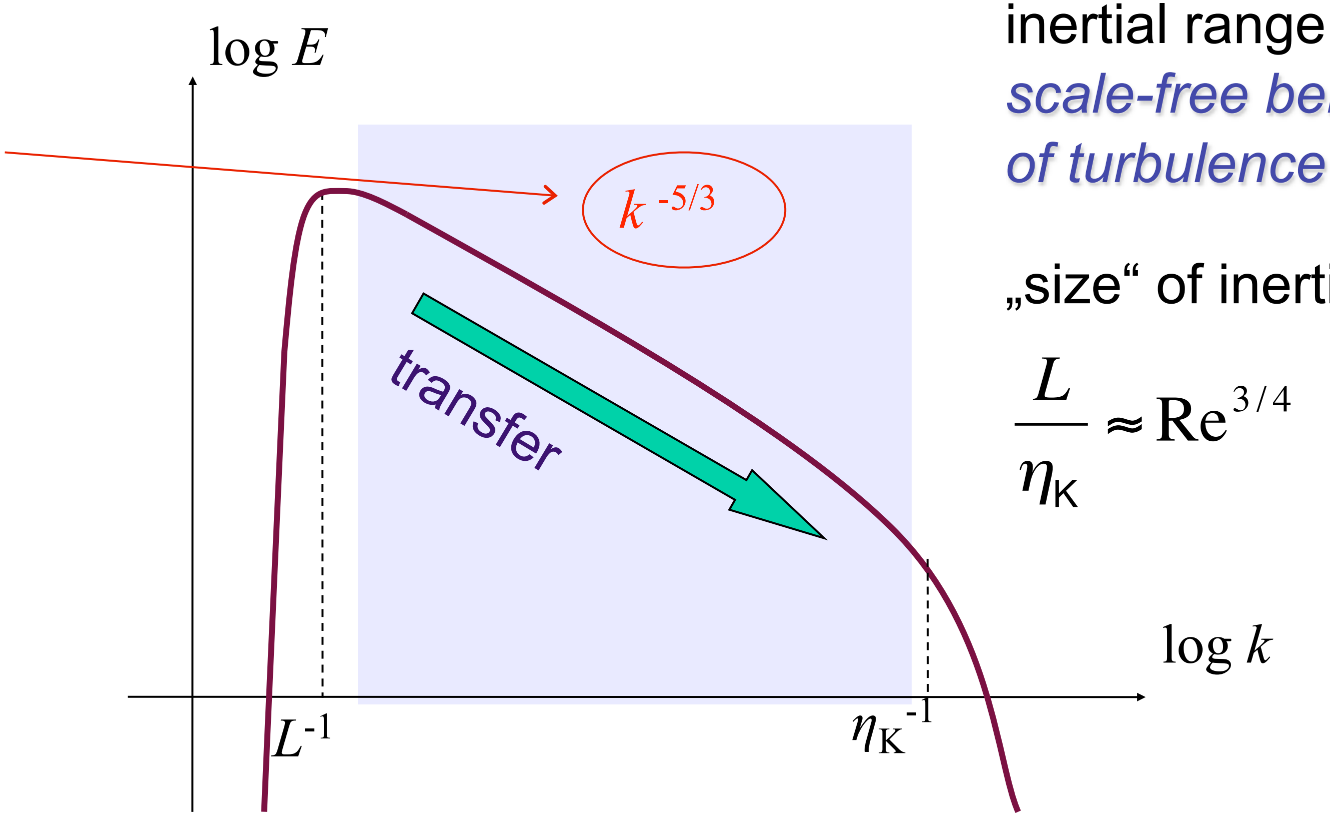


(movie from Christoph Federrath)

Turbulent cascade

Kolmogorov (1941) theory
incompressible turbulence



energy
input
scale

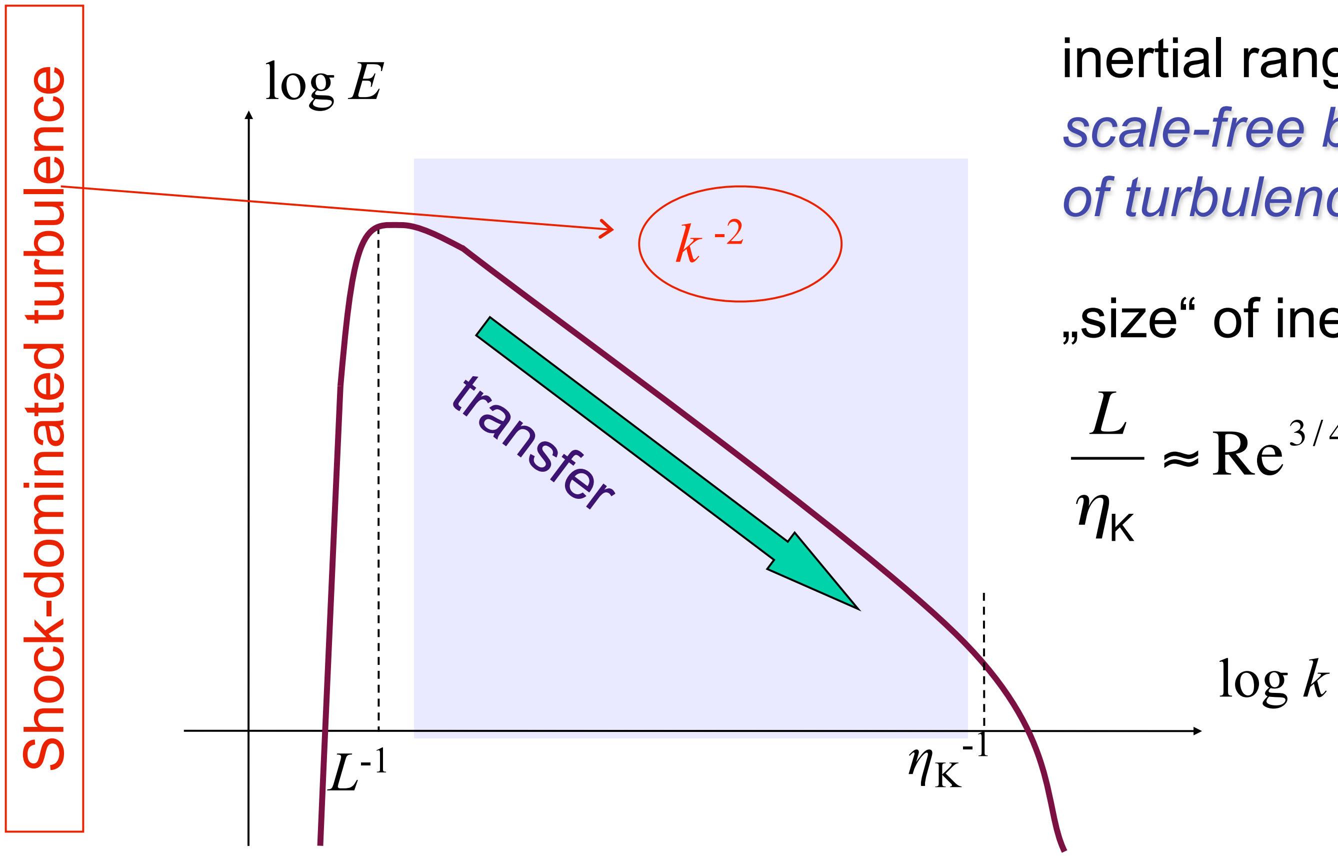
energy
dissipation
scale

inertial range:
scale-free behavior of turbulence

„size“ of inertial range:

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

Turbulent cascade



energy
input
scale

energy
dissipation
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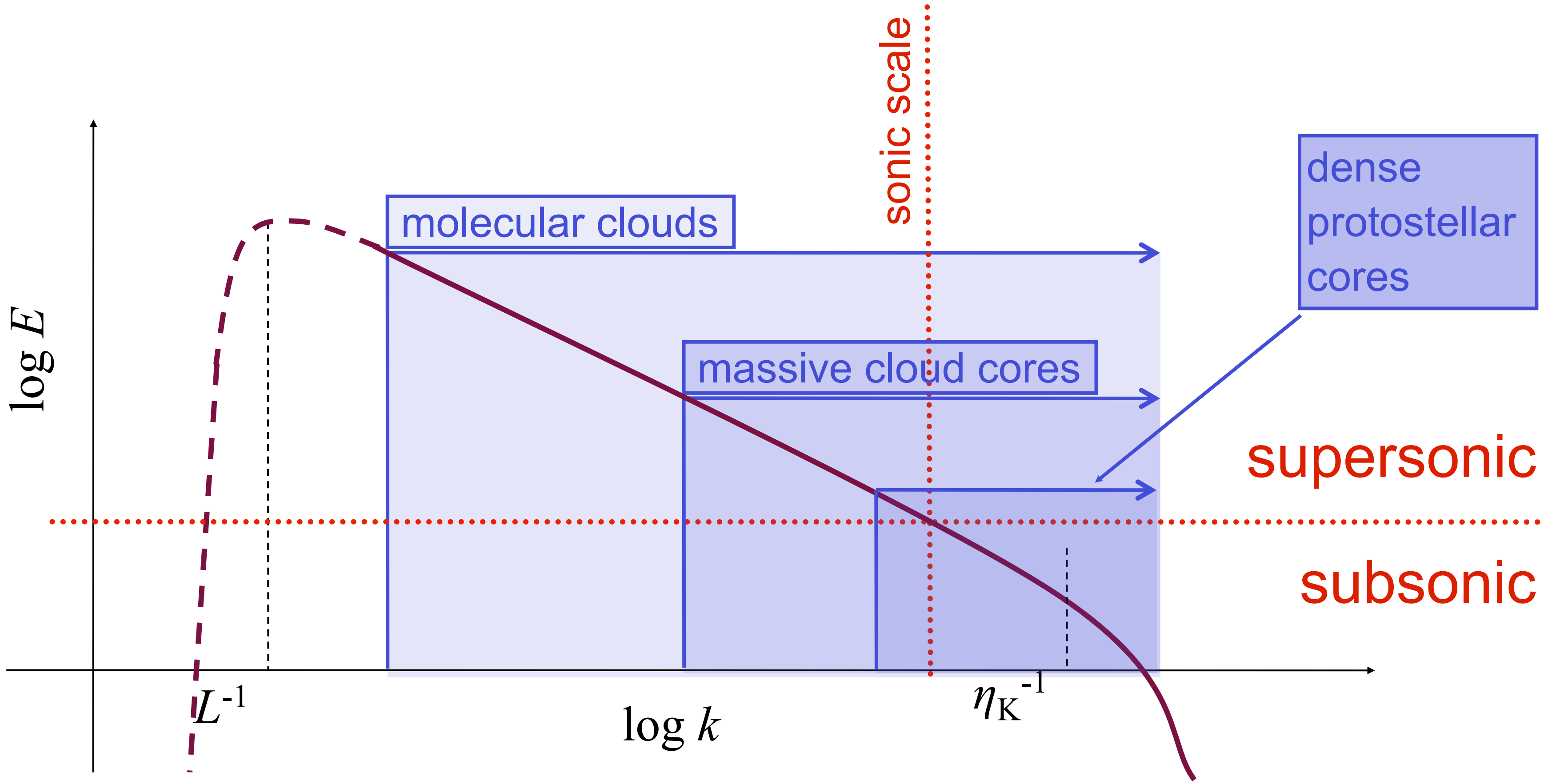
inertial range:
scale-free behavior of turbulence

„size“ of inertial range:

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

Turbulent cascade in ISM



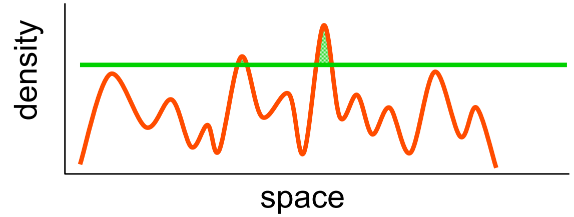
energy source & scale *NOT known* (supernovae, winds, spiral density waves?)

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

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

dynamical SF in a nutshell

- interstellar gas is highly *inhomogeneous*



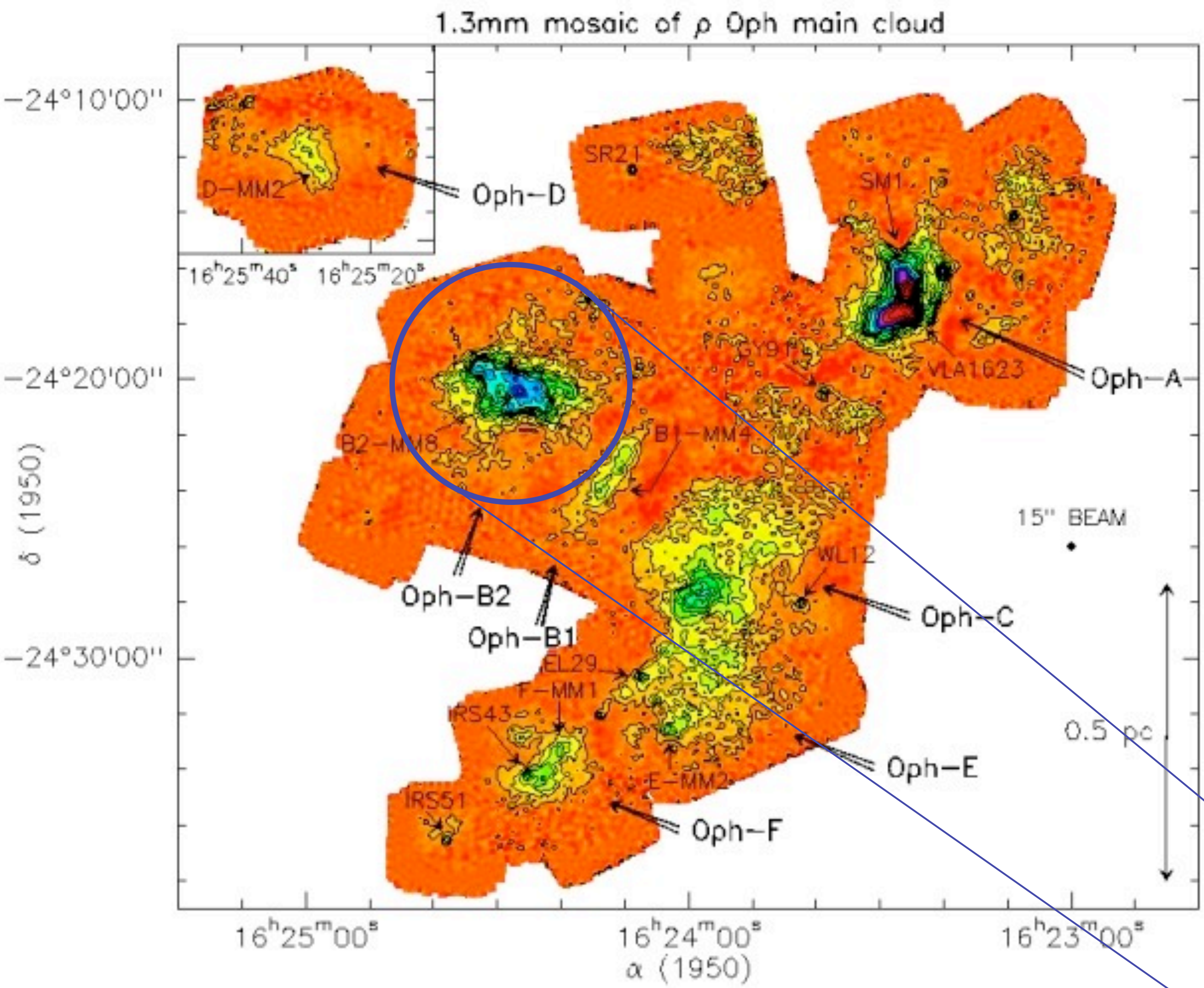
  - *gravitational instability*
  - *thermal instability*
  - *turbulent compression* (in shocks $\delta\rho/\rho \propto \mathcal{M}^2$; in atomic gas: $\mathcal{M} \approx 1...3$)
- cold *molecular clouds* can form rapidly in high-density regions at *stagnation points* of *convergent large-scale flows*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

Density structure of MC's



(Motte, André, & Neri 1998)

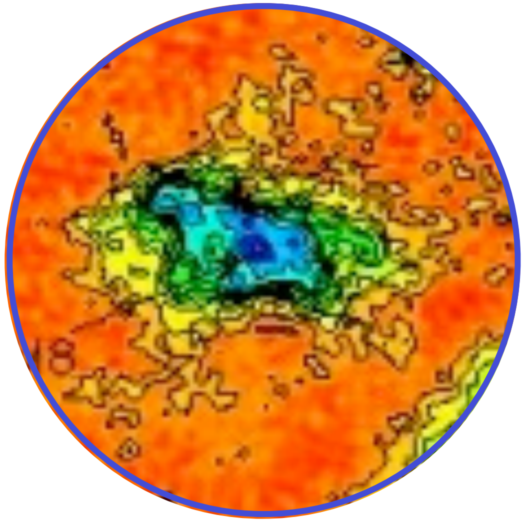
molecular clouds are highly inhomogeneous

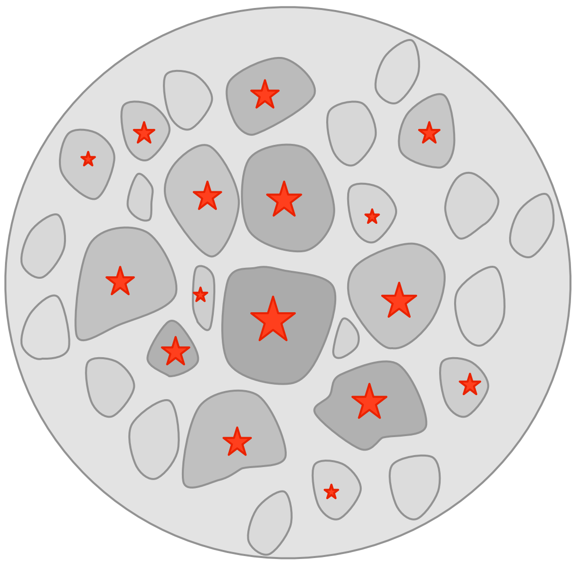
stars form in the densest and coldest parts of the cloud

ρ-Ophiuchus cloud seen in dust emission

let's focus on a cloud core like this one

Evolution of cloud cores

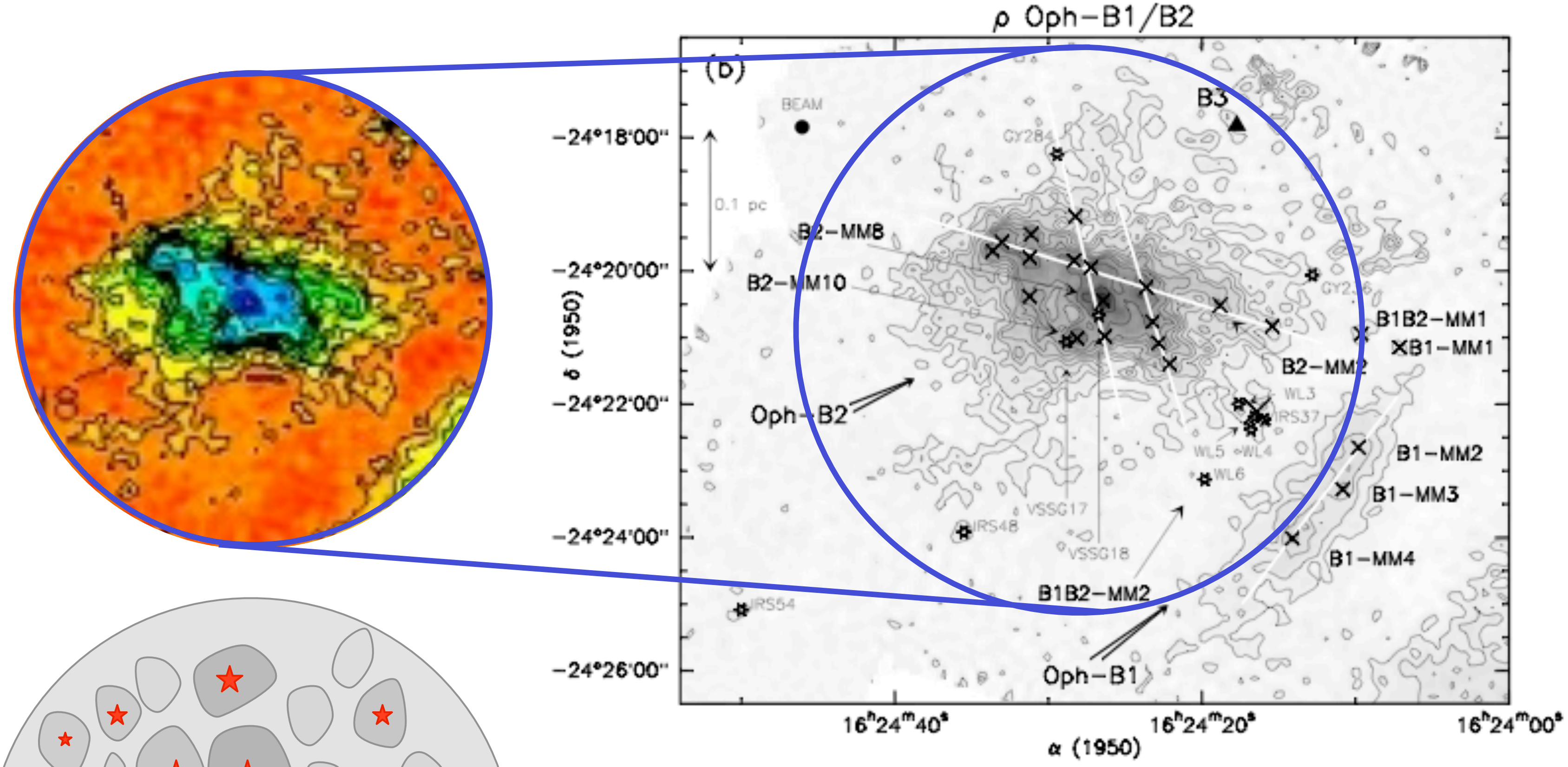


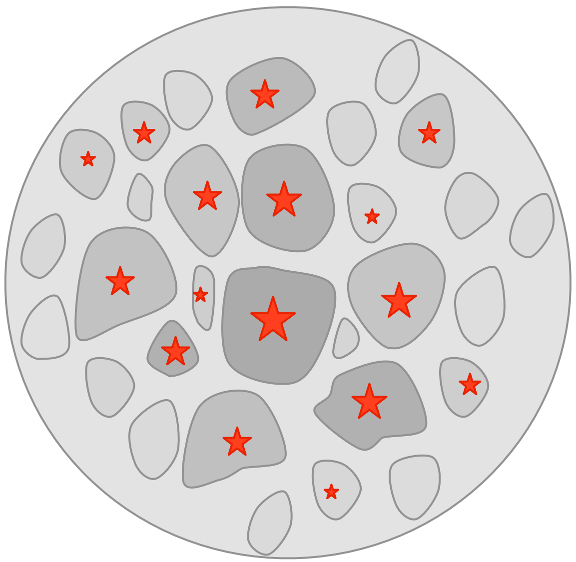


- How does this core evolve?
  Does it form one single massive star or cluster with mass distribution?

- 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

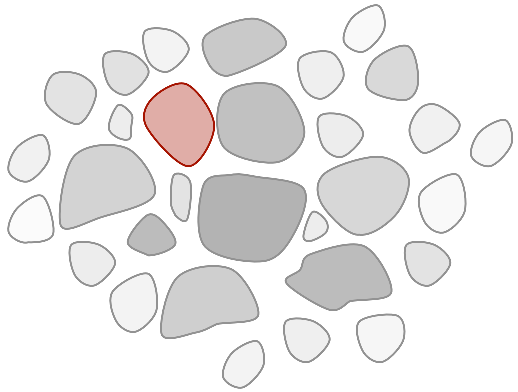




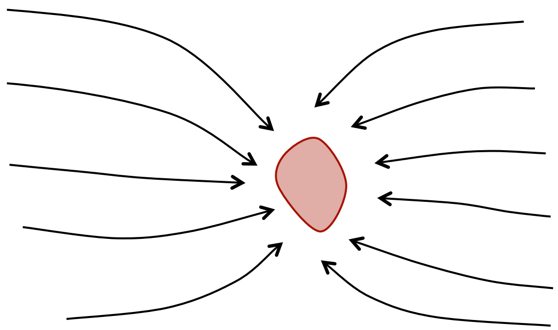
indeed ρ-Oph B1/2 contains several cores ("starless" cores are denoted by ×, cores with embedded protostars by ☆)

(Motte, André, & Neri 1998)

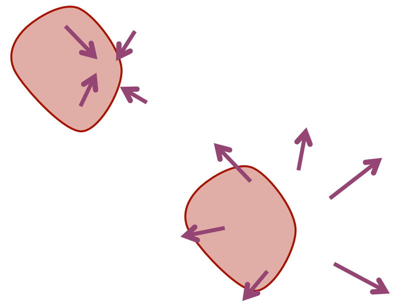
Formation and evolution of cores



- protostellar cloud cores form at *stagnation point* in *convergent turbulent flows*



- if $M > M_{crit} \propto \rho^{-1/2}\,T^{3/2}$: collapse & star formation
- pf $M < M_{crit} \propto \rho^{-1/2}\,T^{3/2}$: reexpansion after end of external compression

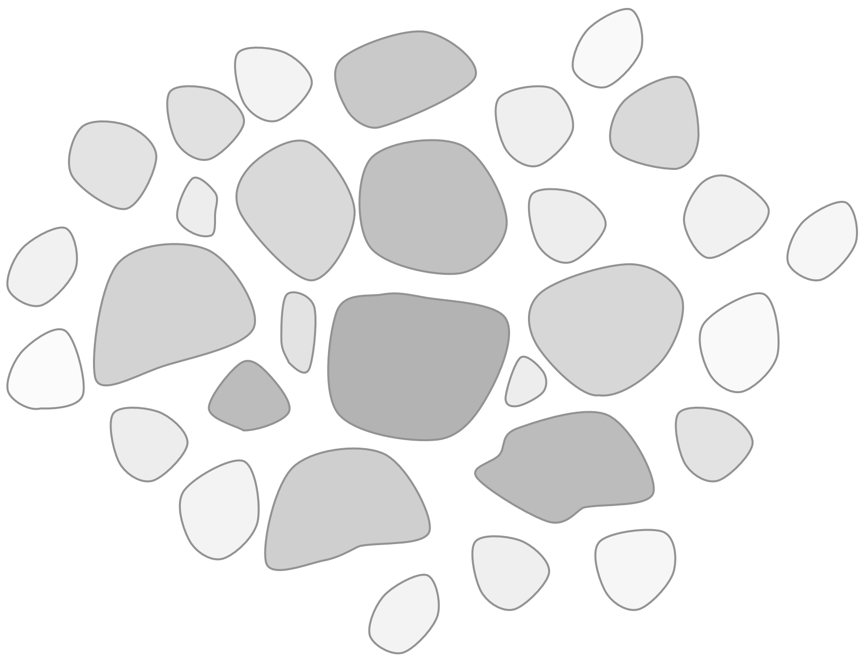


(e.g. Vazquez-Semadeni et al 2005)

- typical timescale: $t \approx 10^4 \ldots 10^5$ yr

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:

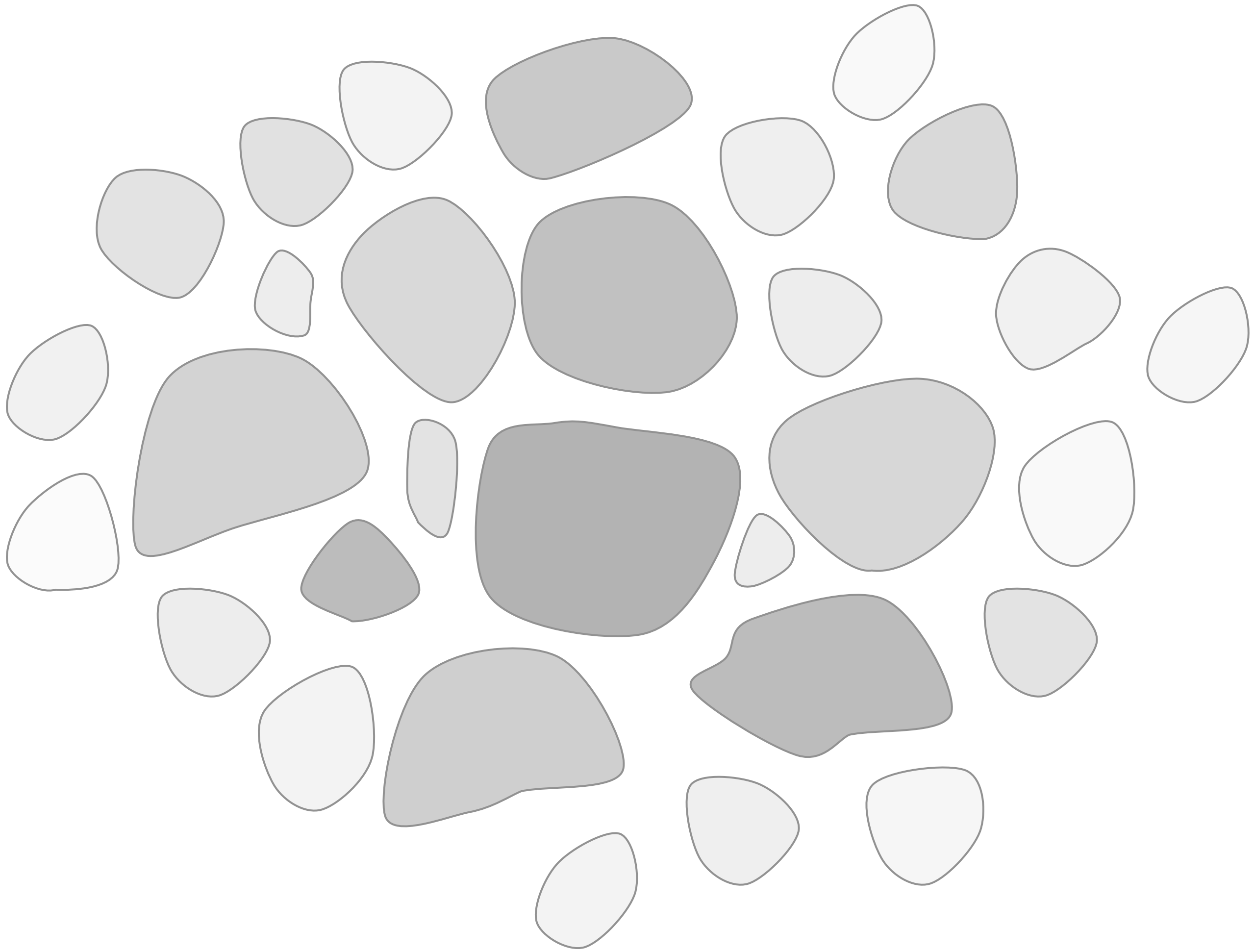
$\alpha = E_{kin}/|E_{pot}| < 1$

--> *global contraction*

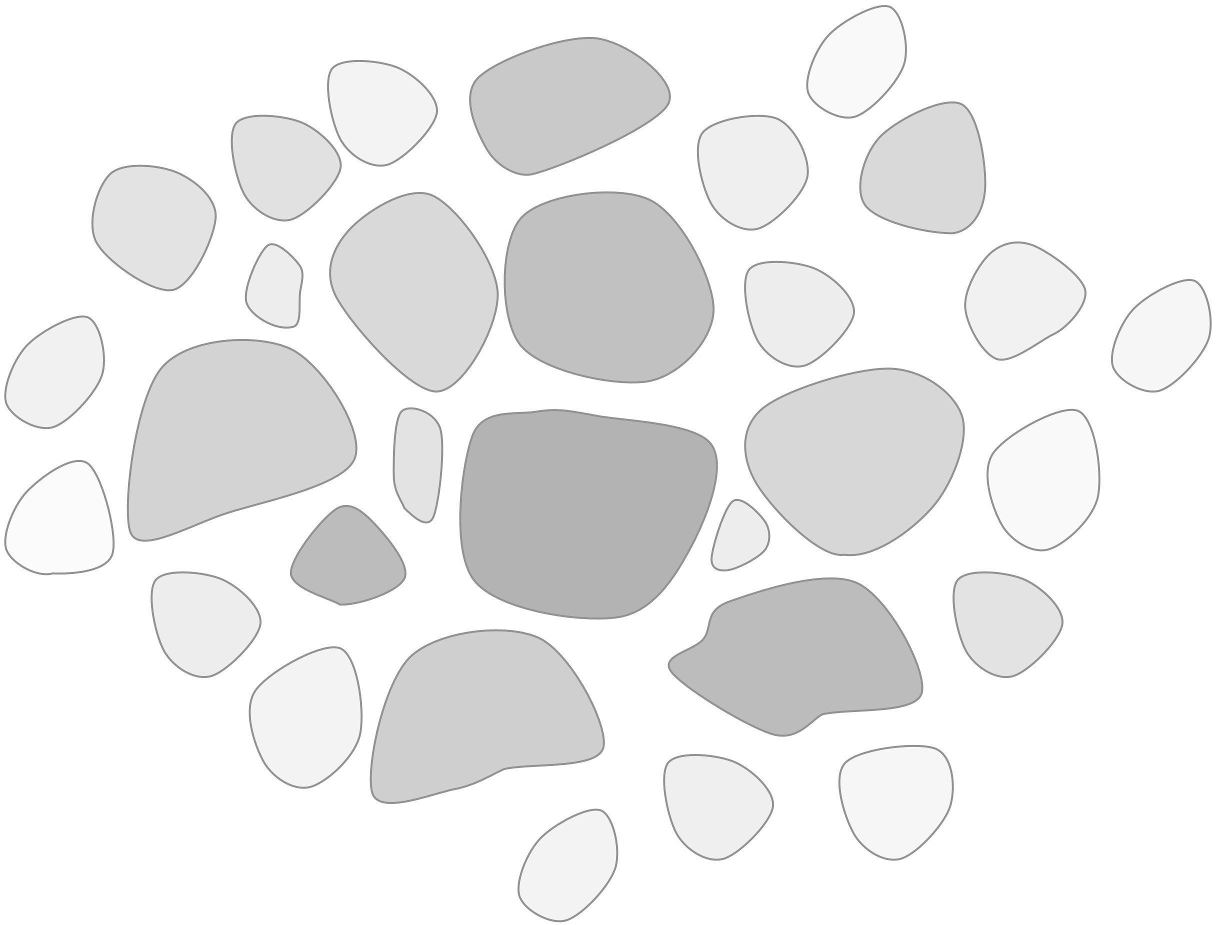
--> core do *interact* while collapsing

--> *competition* influences *mass growth*

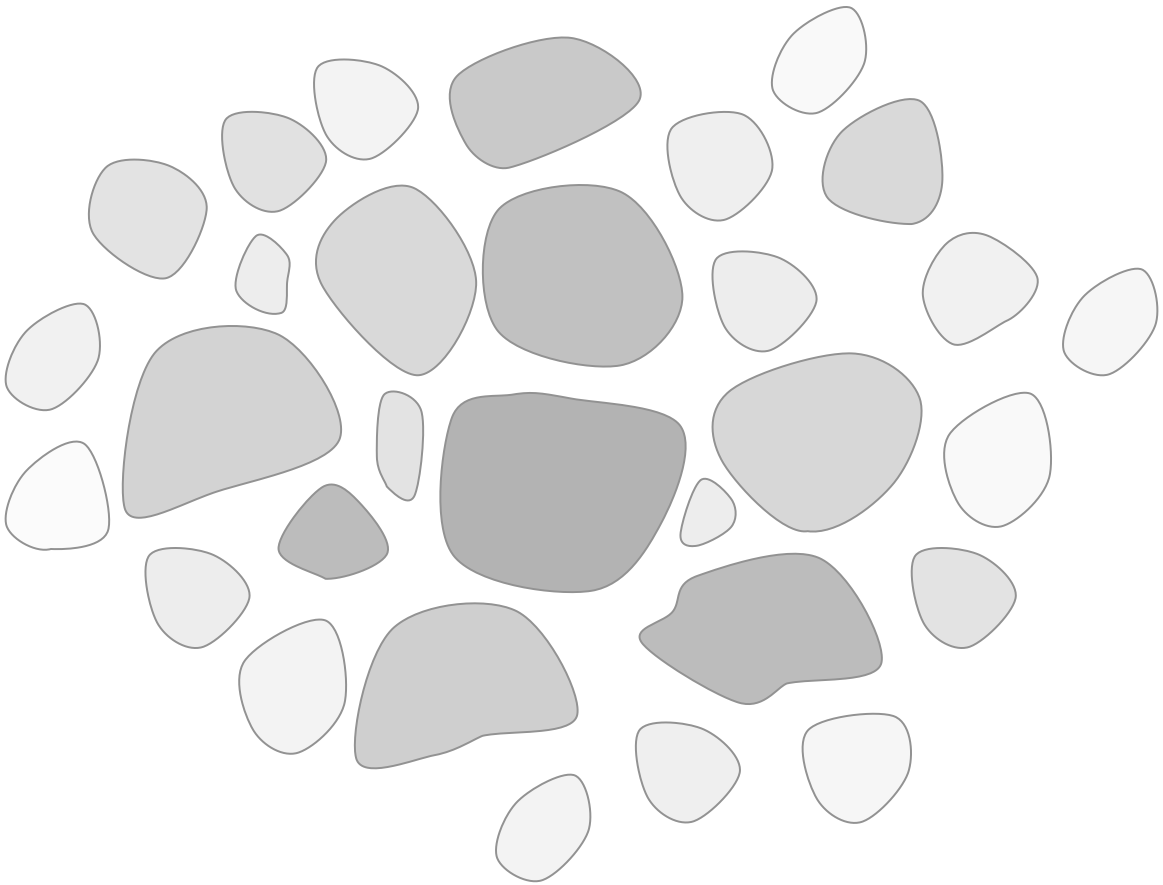
--> *dense cluster with high-mass stars*



turbulence creates a hierarchy of clumps



as turbulence decays locally, contraction sets in



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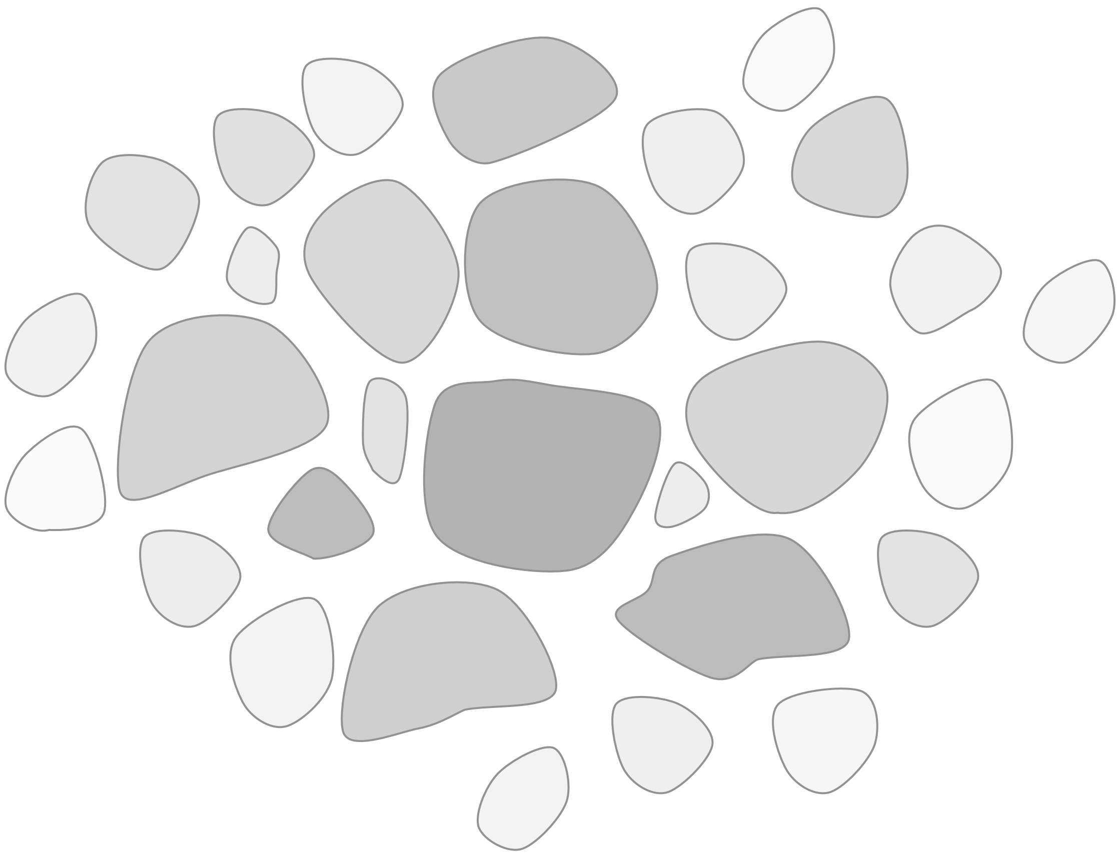
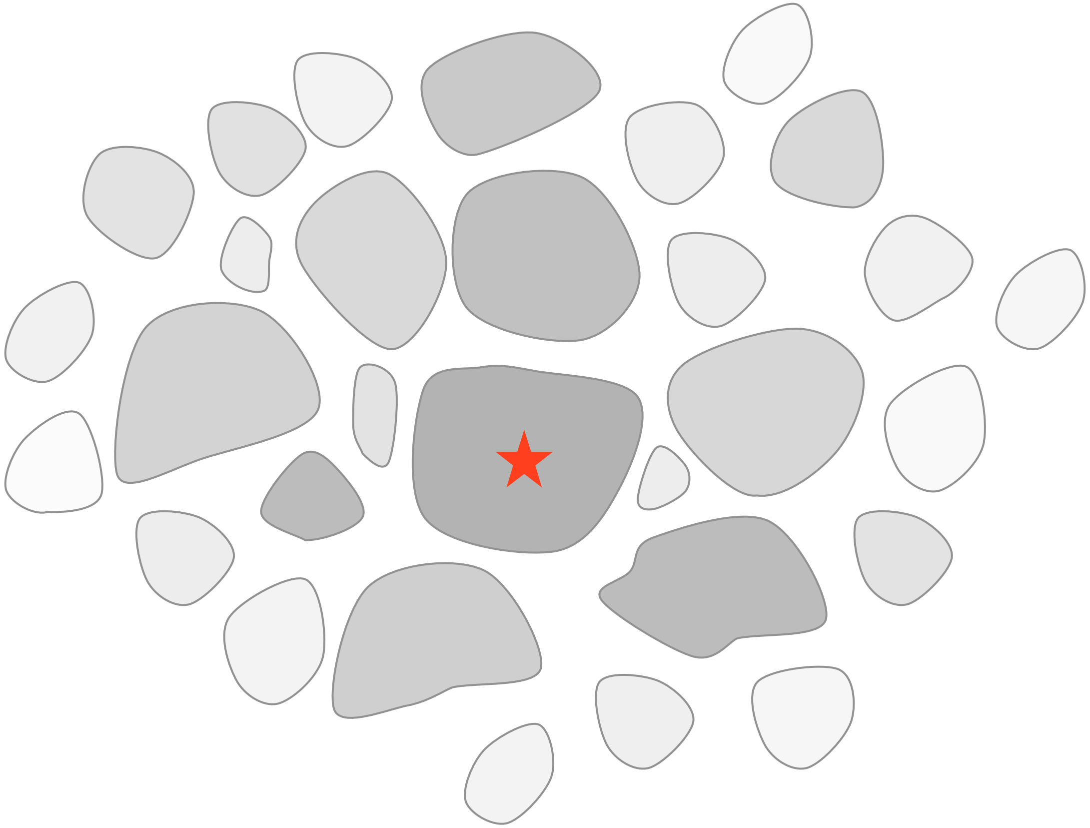


while region contracts, individual clumps collapse to form stars



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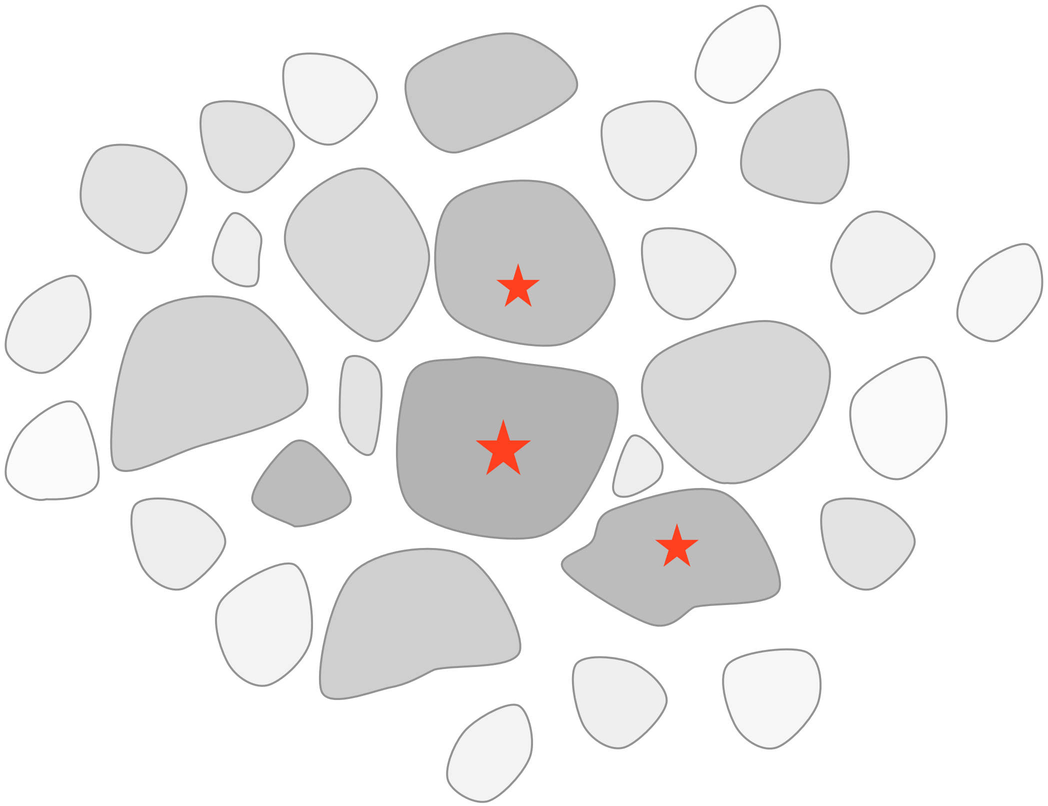
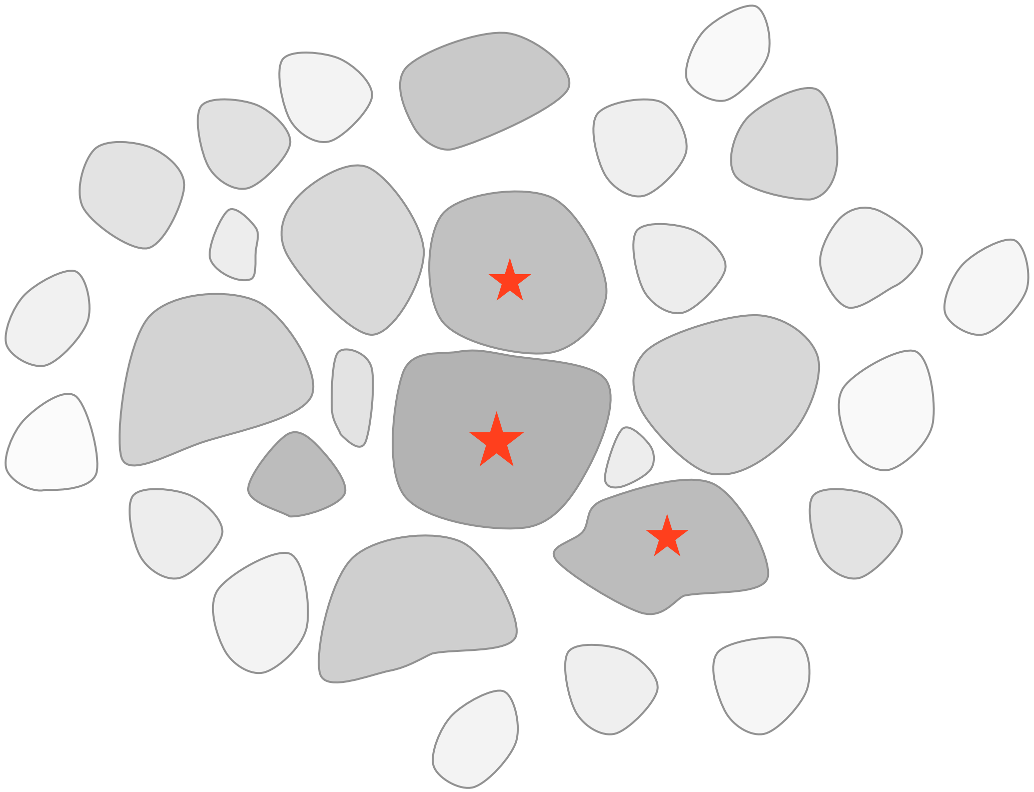


individual clumps collapse to form stars



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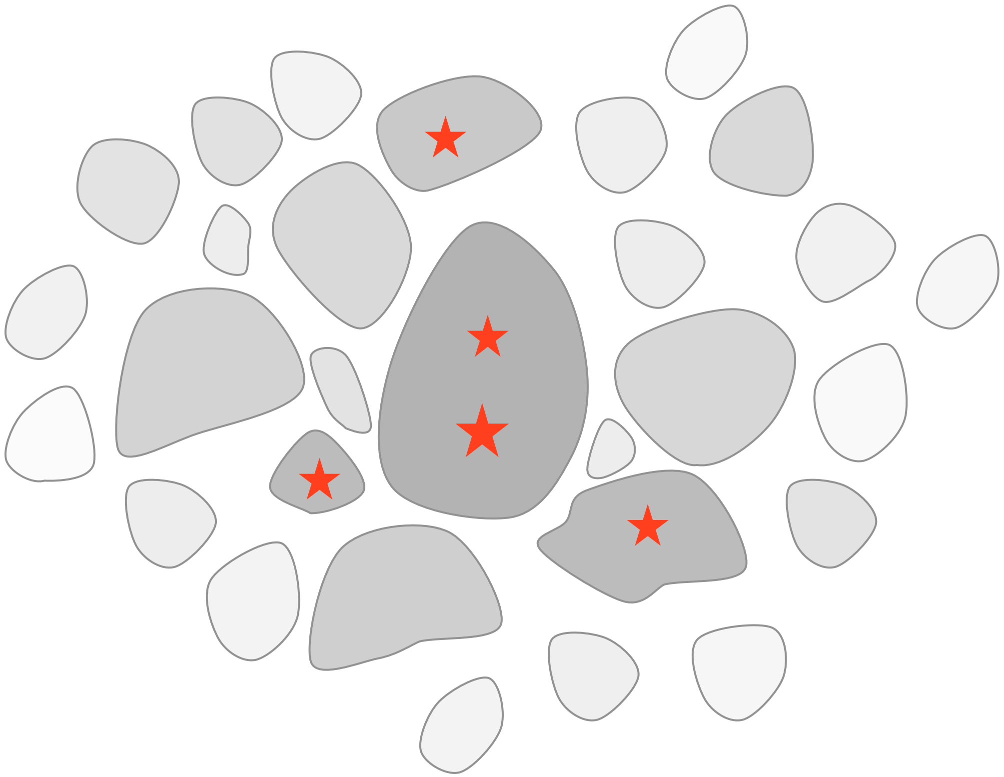
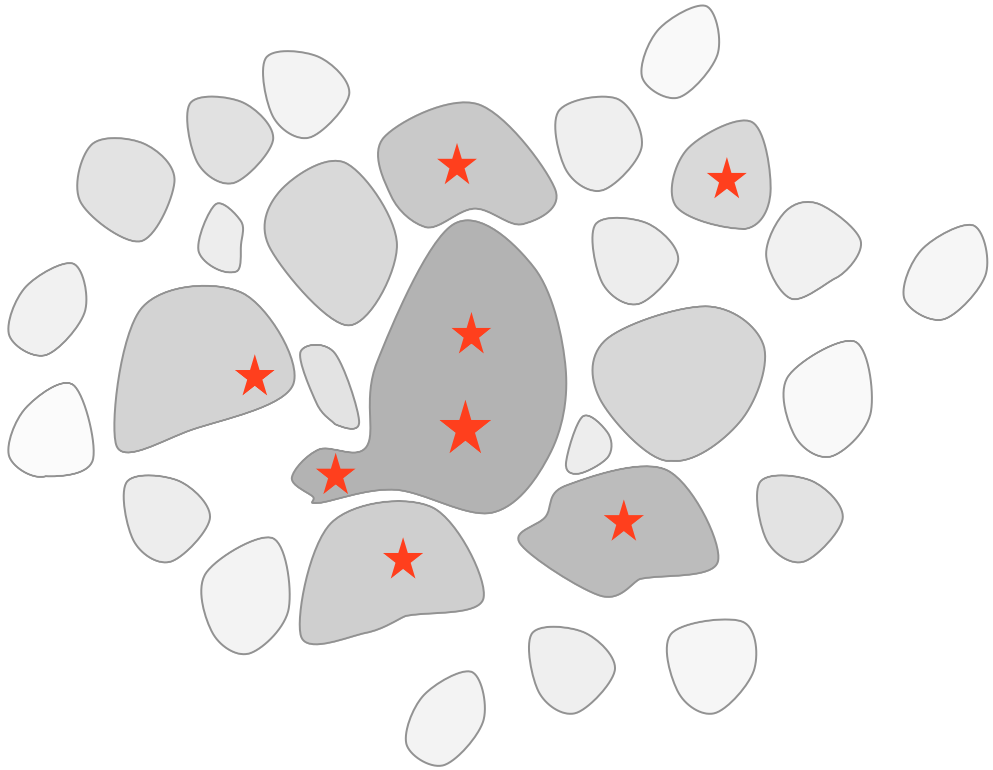


$\alpha = E_{kin}/|E_{pot}| < 1$

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



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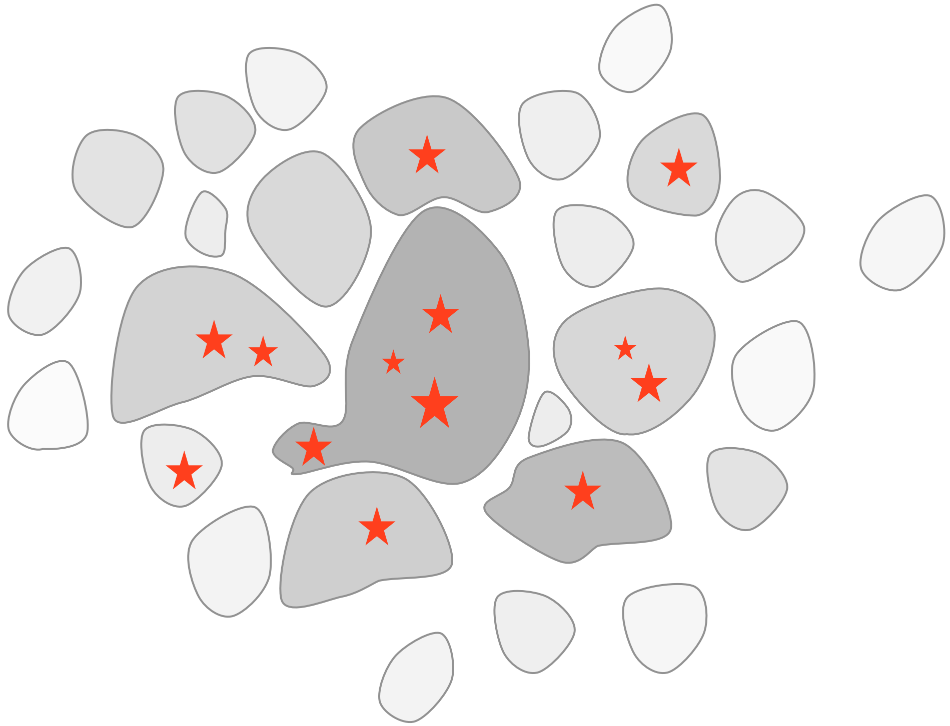

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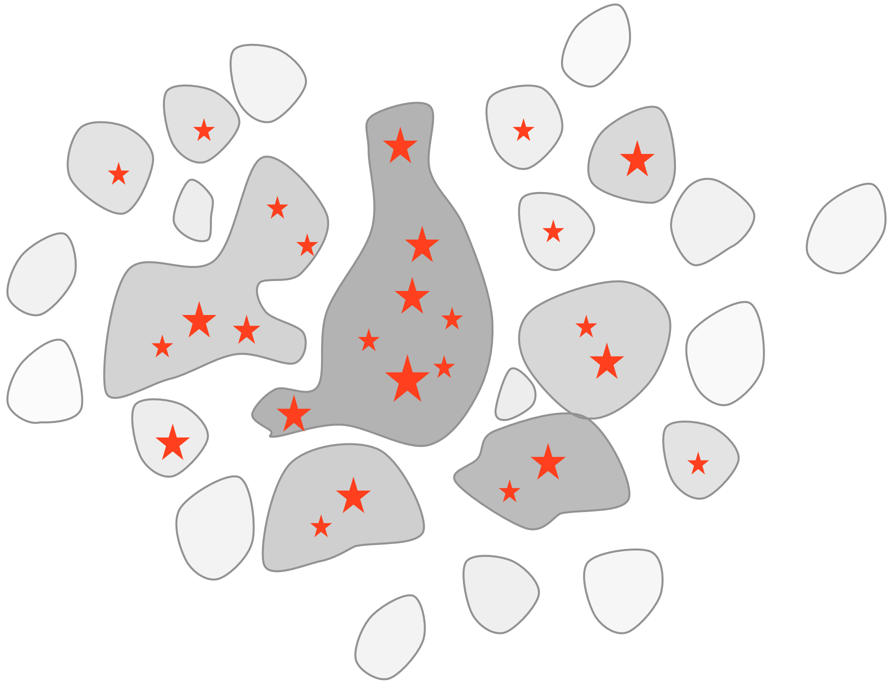
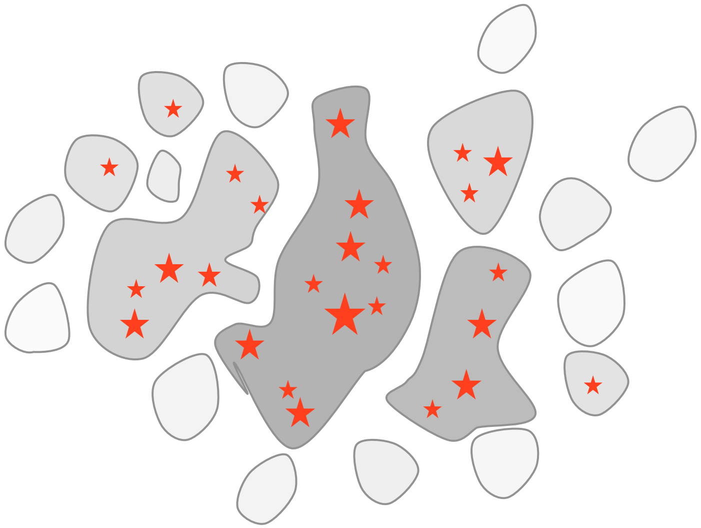


in *dense clusters*, competitive mass growth becomes important



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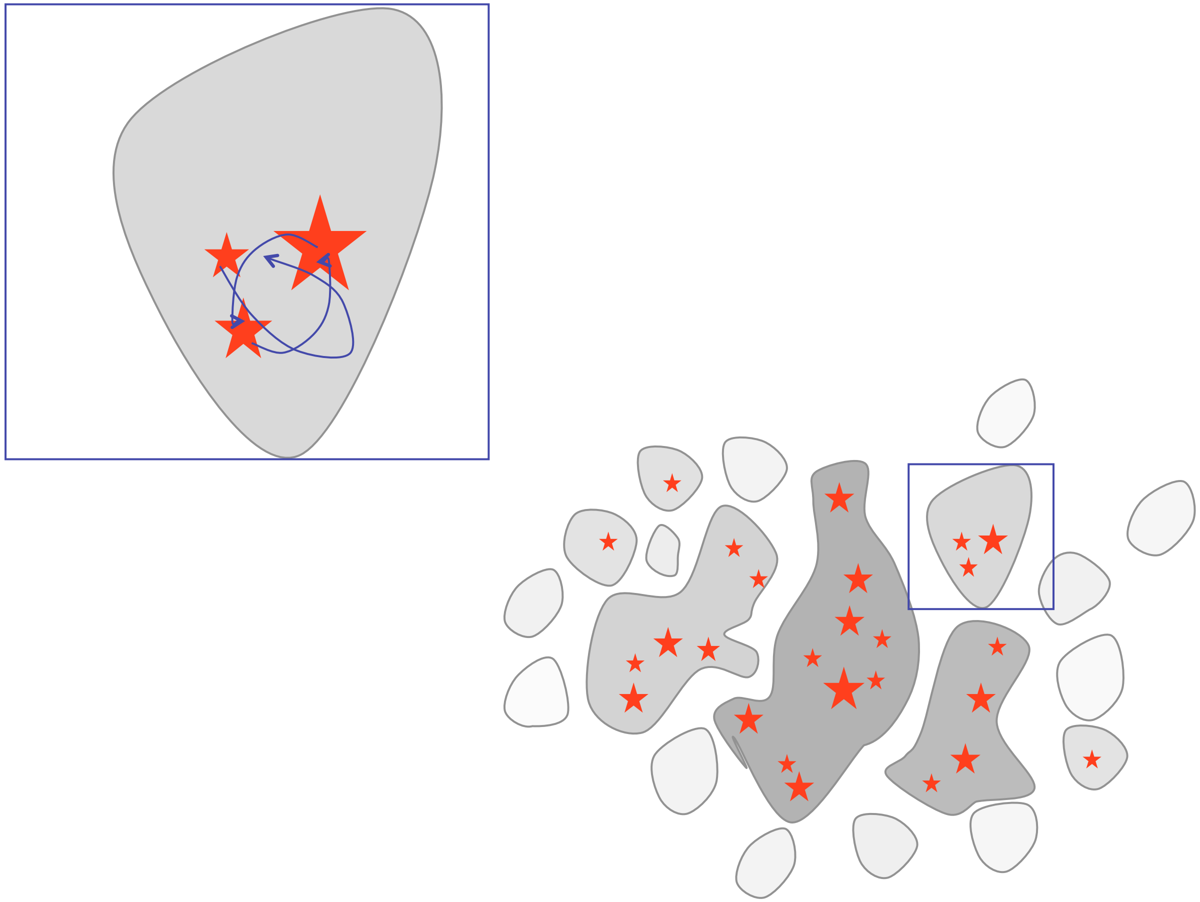
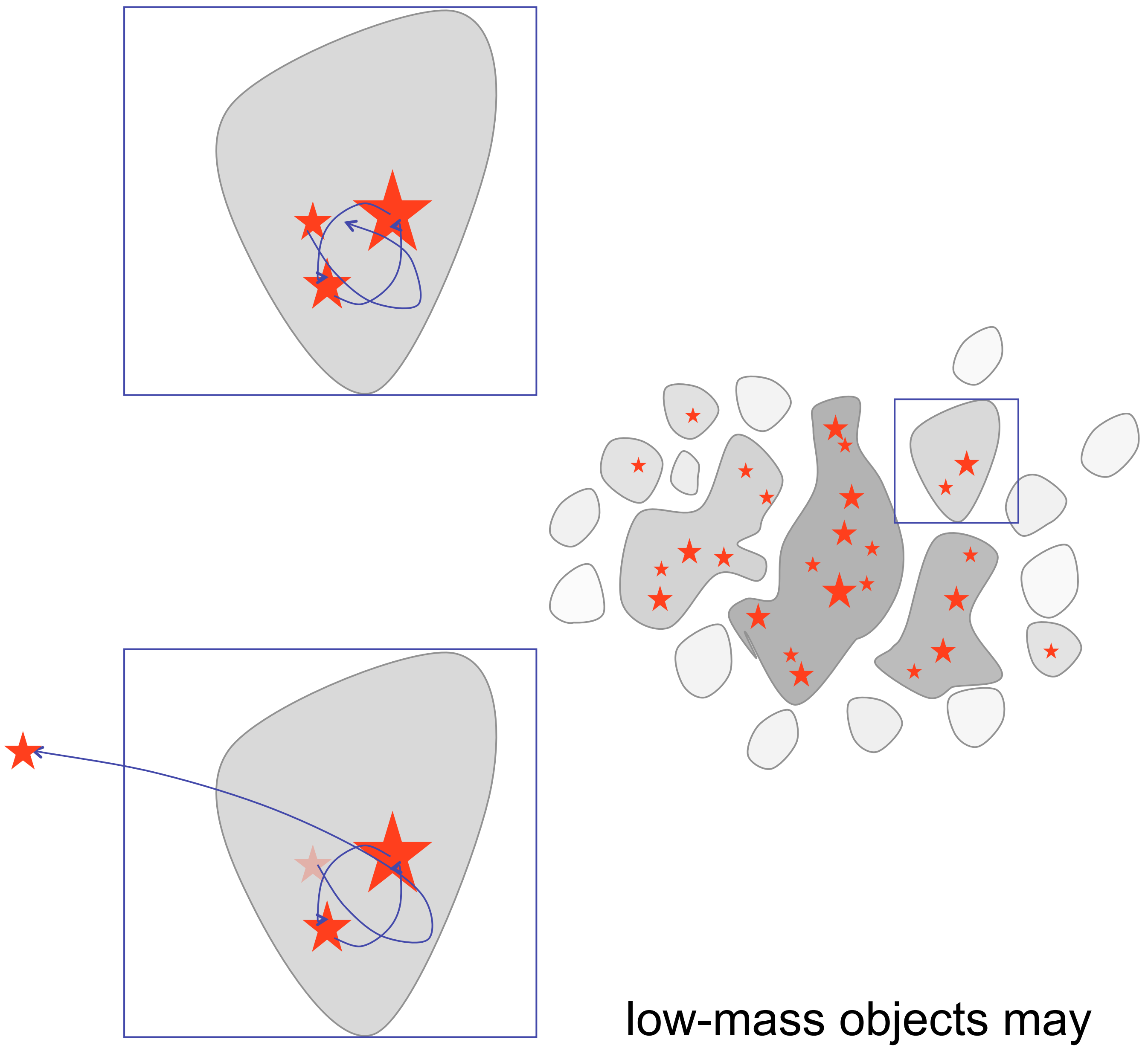
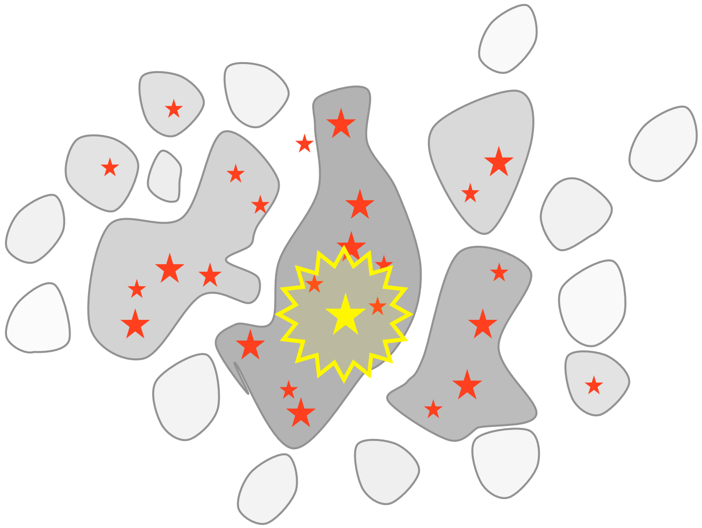


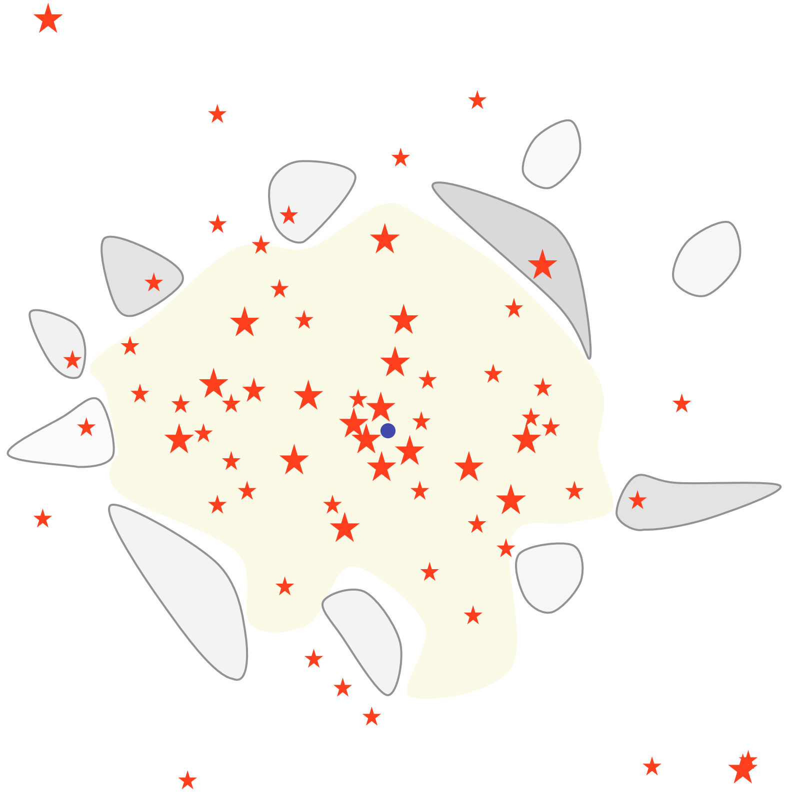
in *dense clusters*, *N*-body effects influence mass growth



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



feedback terminates star formation

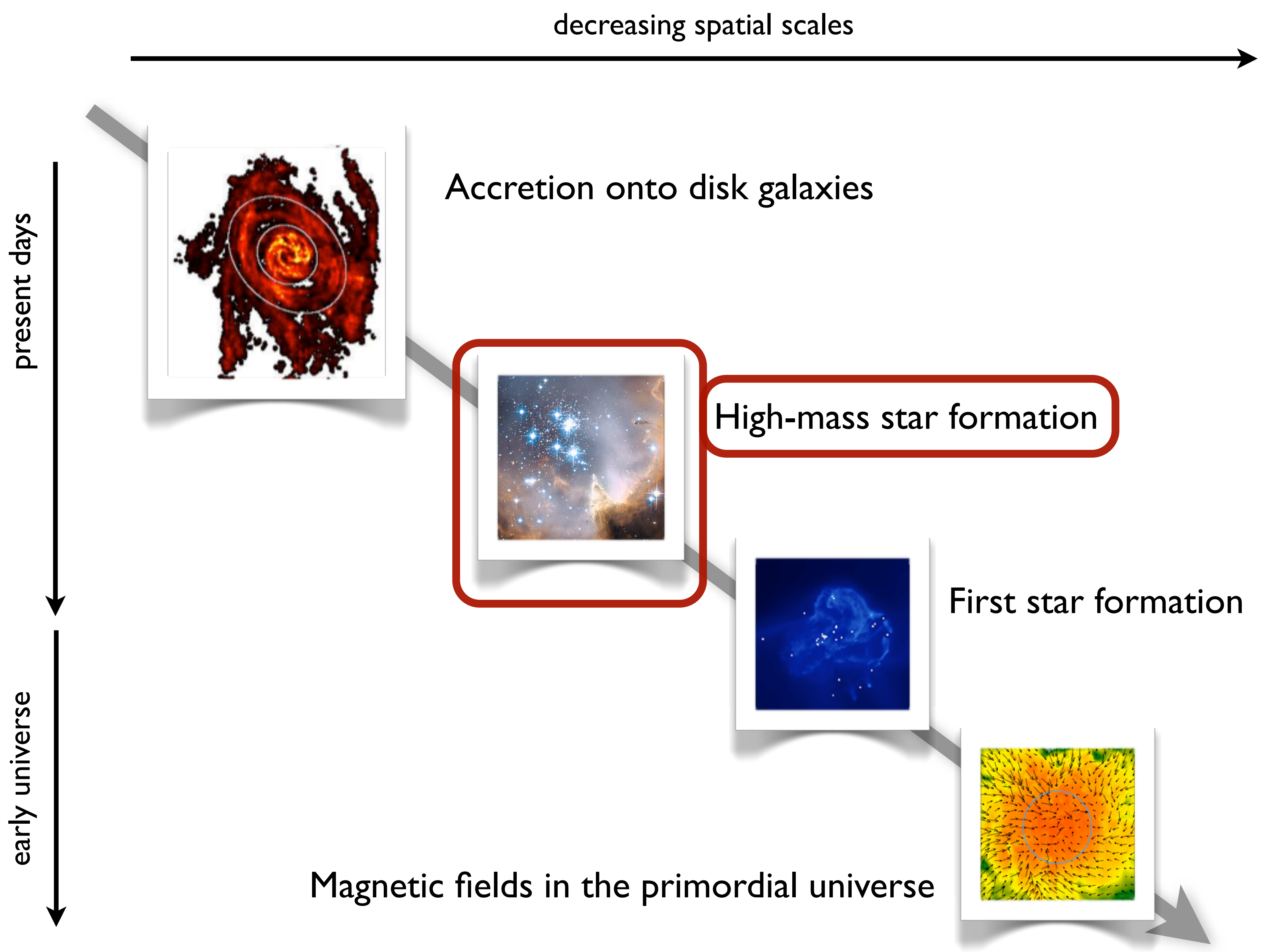


result: *star cluster*, possibly with H II region

NGC 602 in the LMC: Hubble Heritage Image

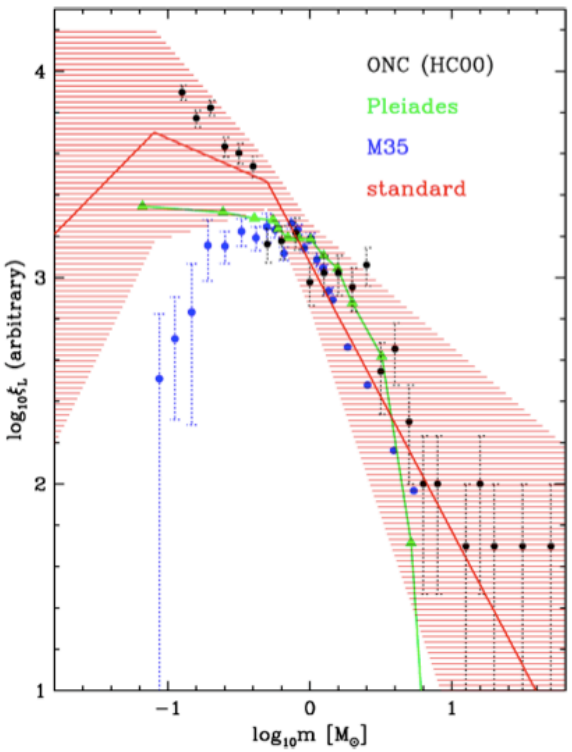
result: *star cluster* with HII region

agenda


decreasing spatial scales
present days
early universe
Accretion onto disk galaxies
High-mass star formation
First star formation
Magnetic fields in the primordial universe

We want to address the following questions:

- how do massive stars (and their associated clusters) form?
- what determines the upper stellar mass limit?
- what is the physics behind observed HII regions?



IMF (Kroupa 2002)

Rosetta nebula (NGC 2237)

(proto)stellar feedback processes

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

- radiation pressure on dust particles
  - has gained most attention in the literature (see e.g. Krumholz et al. 2007, 2008, 2009)
- ionization
  - few numerical studies so far (e.g. Dale 2007, Gritschneder et al. 2009), detailed collapse calculations with ionizing and non-ionizing feedback still missing
  - HII regions around massive stars are directly observable --> direct comparison between theory and observations

our (numerical) approach

- 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

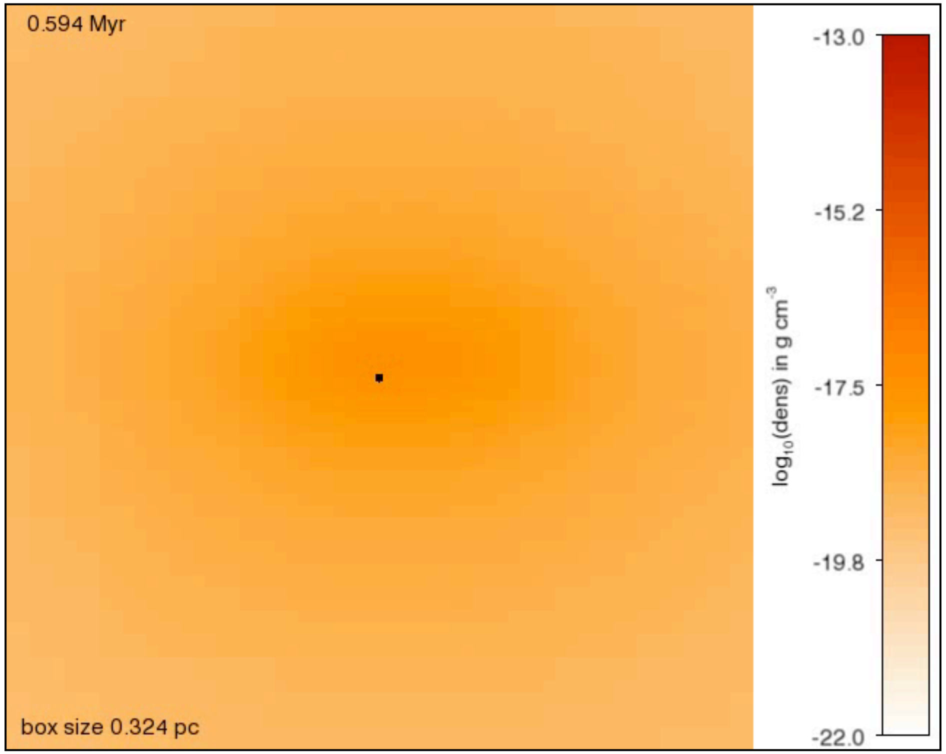
Peters et al. (2010a, ApJ, 711, 1017), Peters et al. (2010b, arXiv:1003.4998), Peters et al. (2010c, 1005.3271)

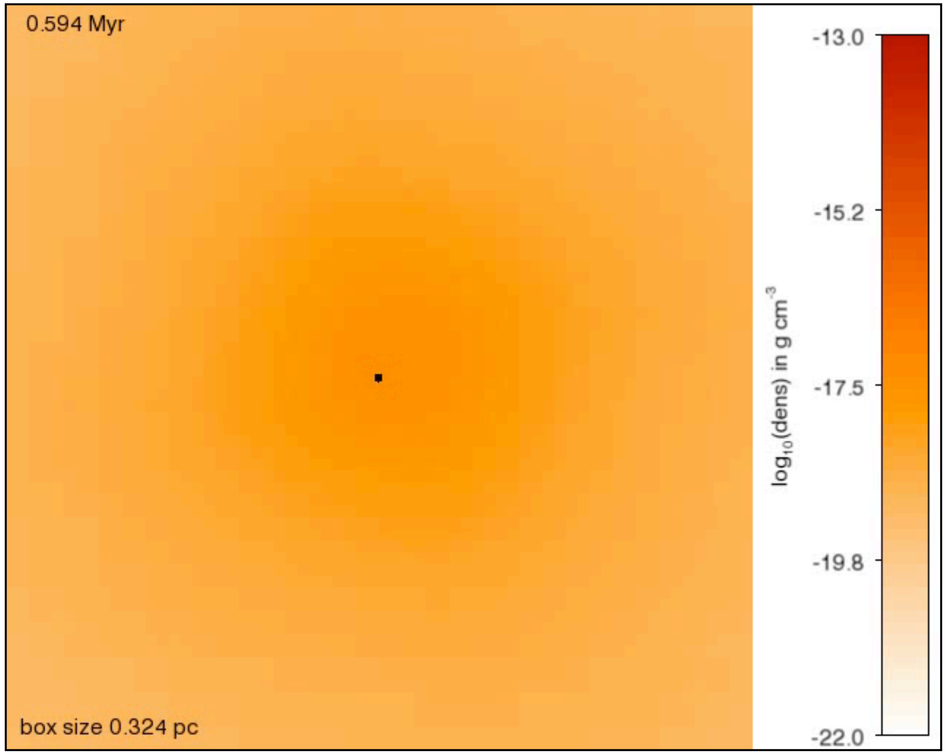
our (numerical) approach

- 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
  - some models include magnetic fields
  - *first 3D MHD 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 of high mass star formation

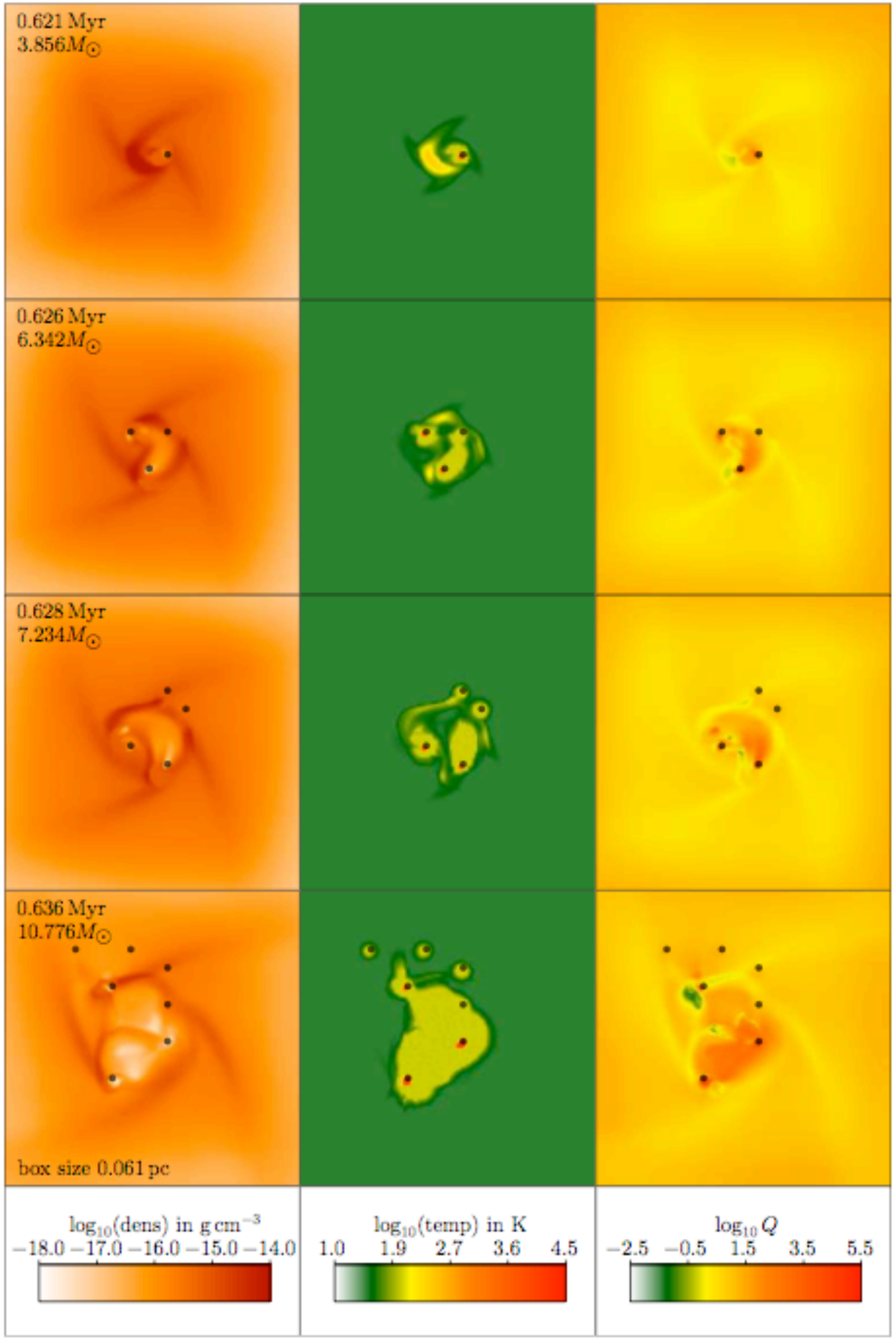


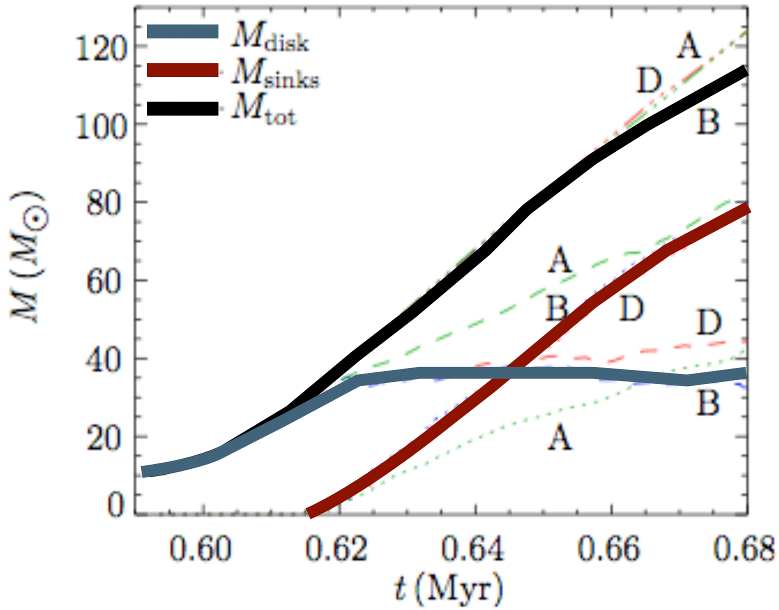


Disk edge on

Disk plane

(Peters et al. 2010, ApJ, 711, 1017)

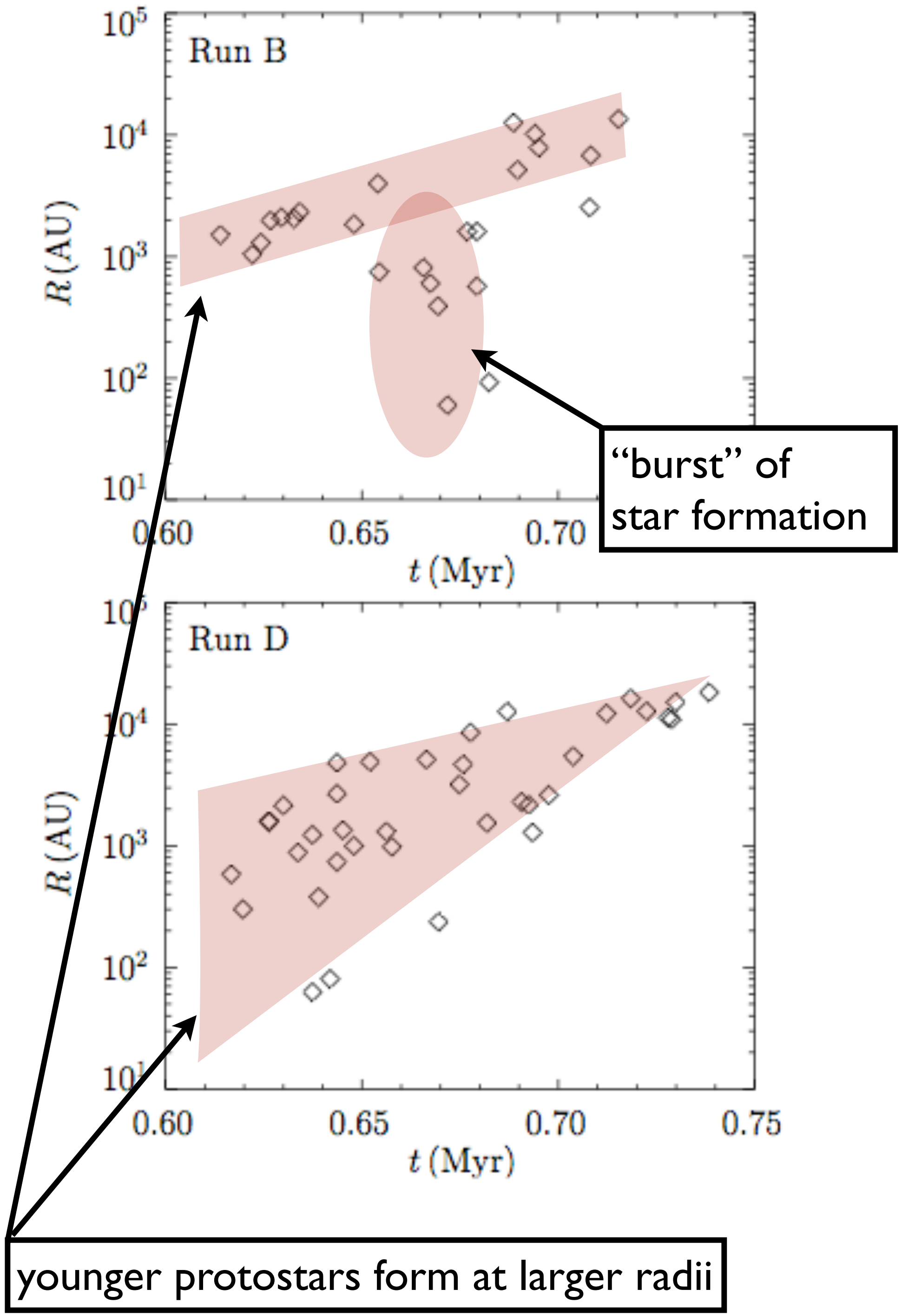


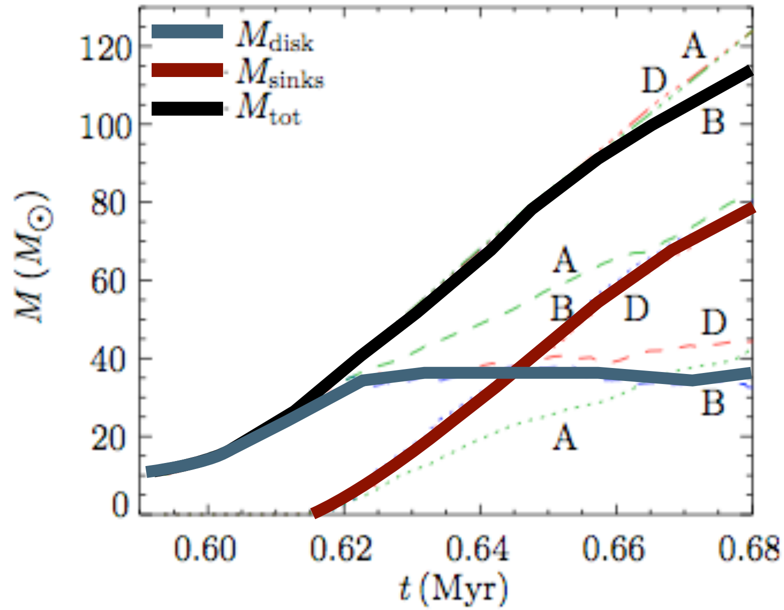


mass load onto the disk exceeds inward transport
--> becomes gravitationally unstable (see also Kratter & Matzner 2006, Kratter et al. 2010)

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

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





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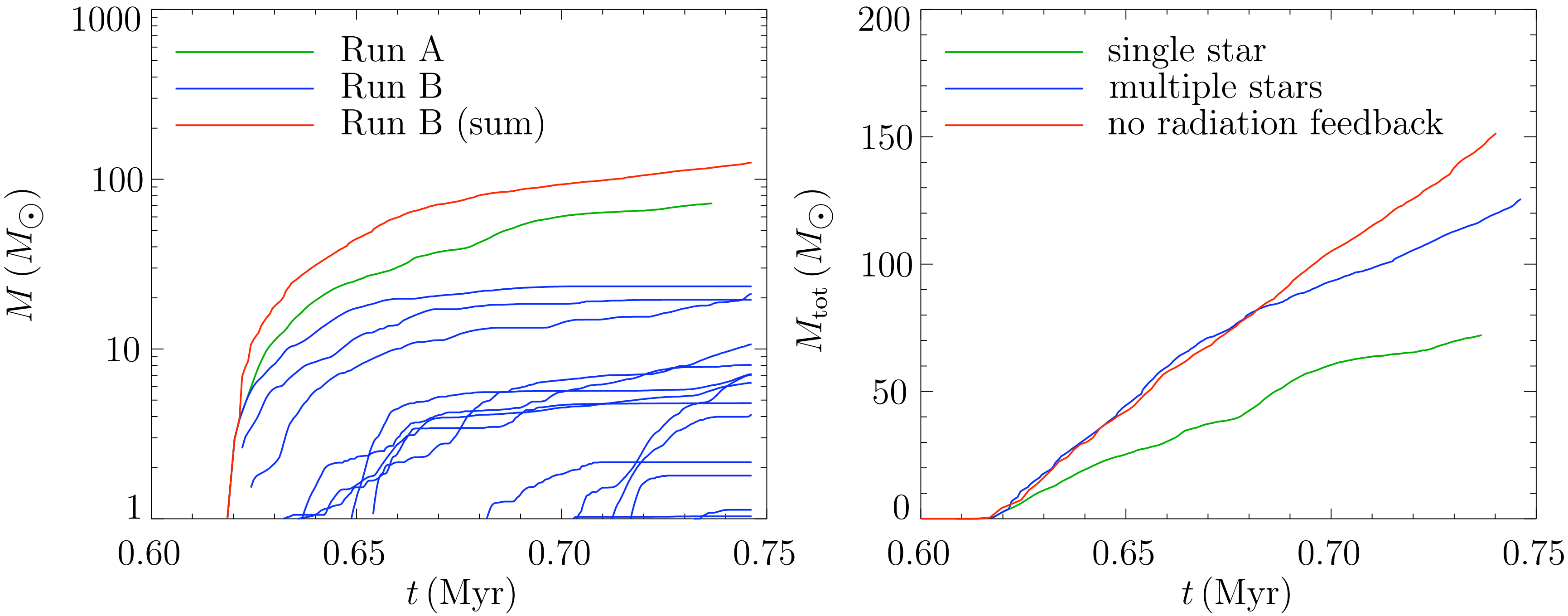
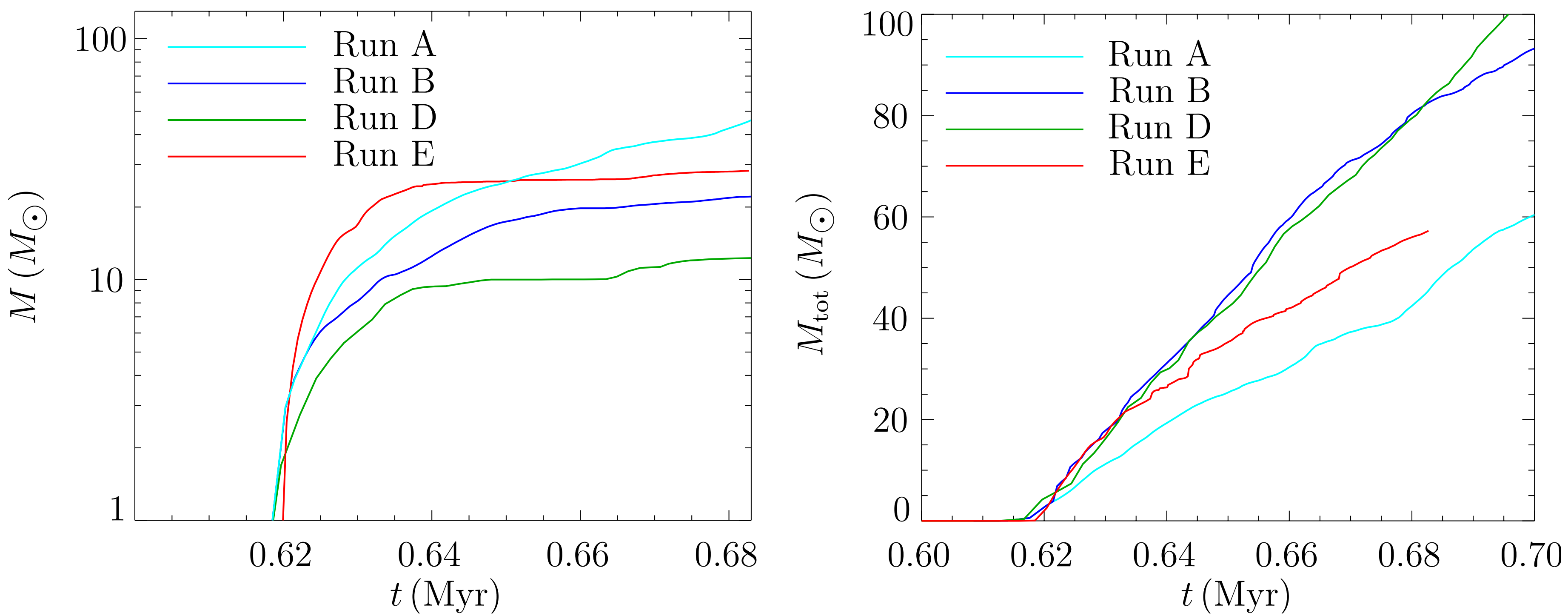


- compare with control run without radiation feedback
- total accretion rate does not change with accretion heating
- expansion of ionized bubble causes turn-off
- no triggered star formation by expanding bubble

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

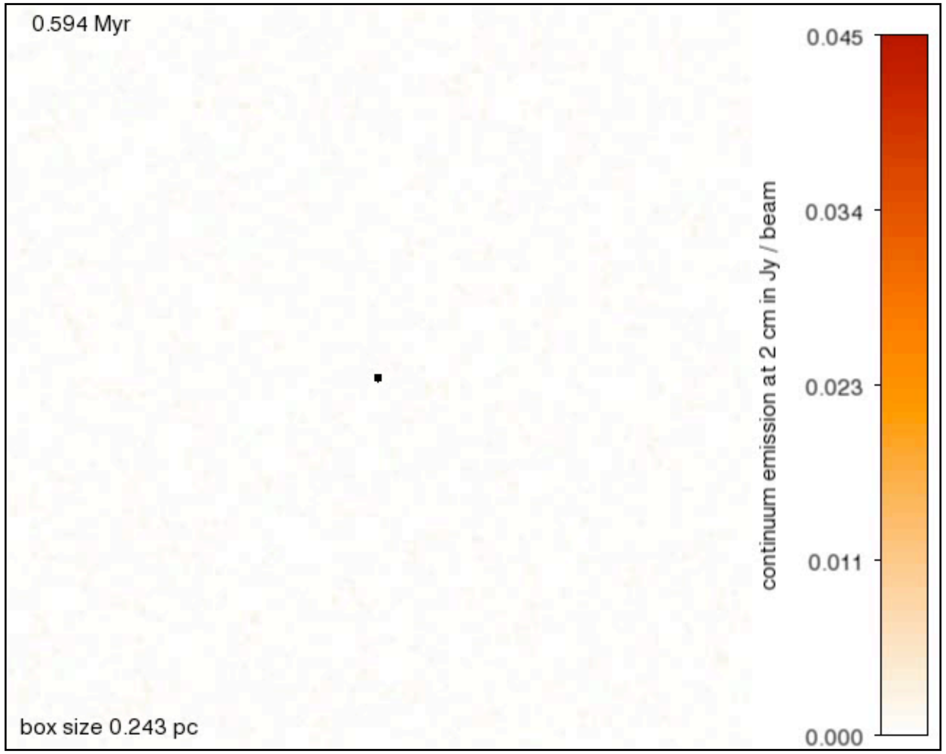


- magnetic fields lead to weaker fragmentation
- central star becomes more massive (magnetic breaking

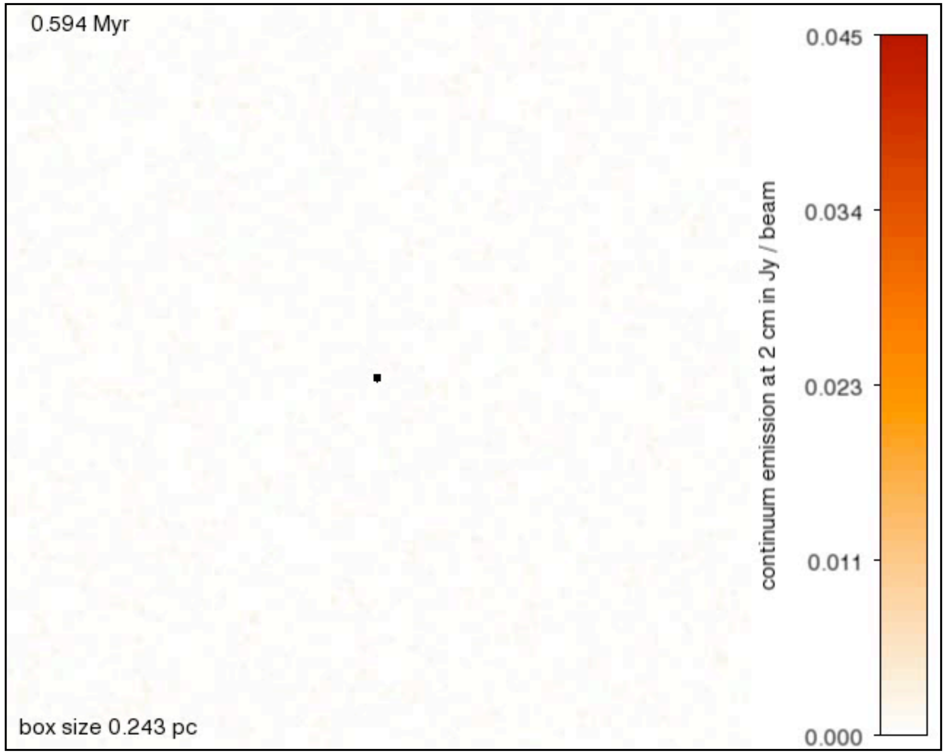
Peters et al. (2010a,b,c,d)

- 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)

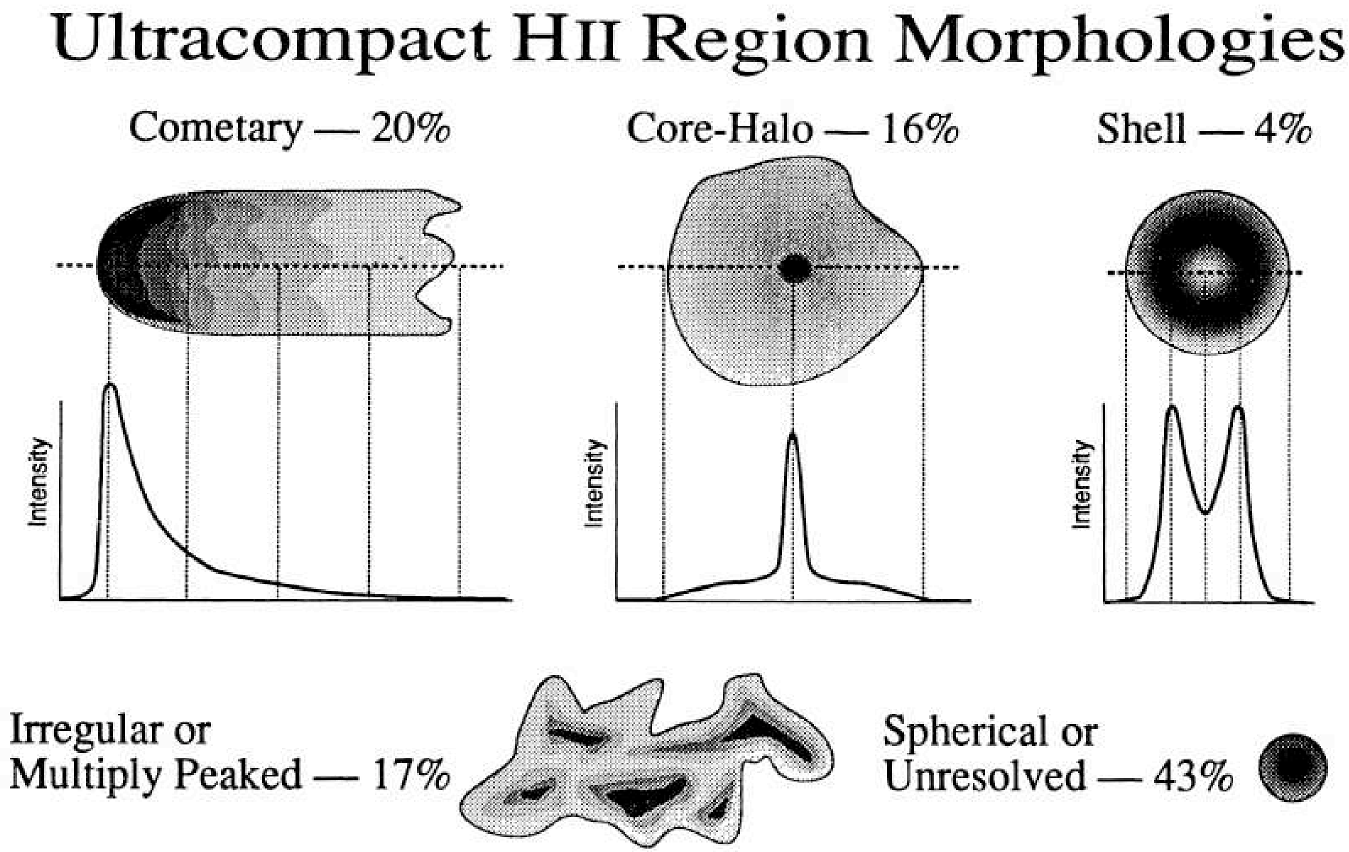


Disk face on

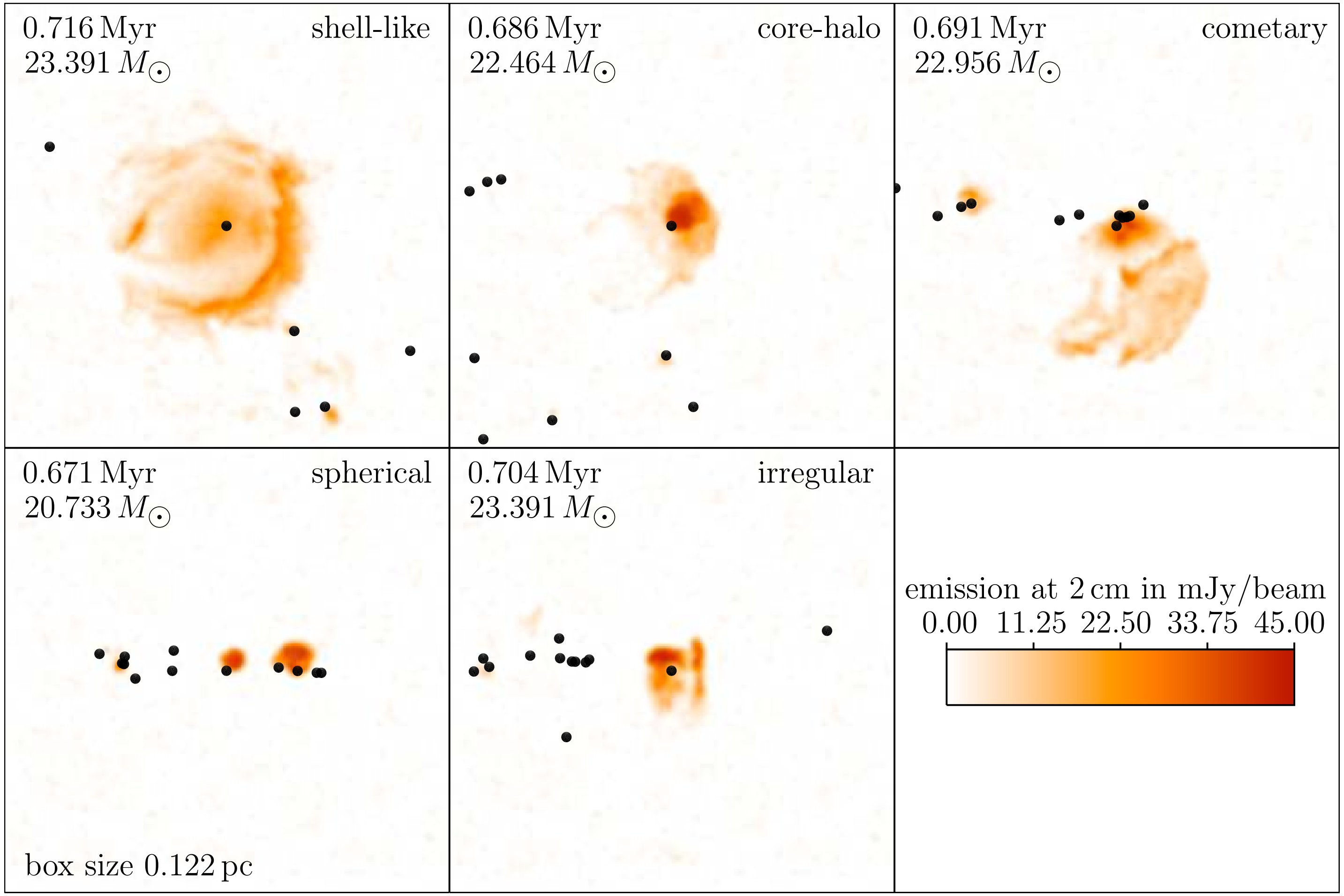


Disk edge on

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

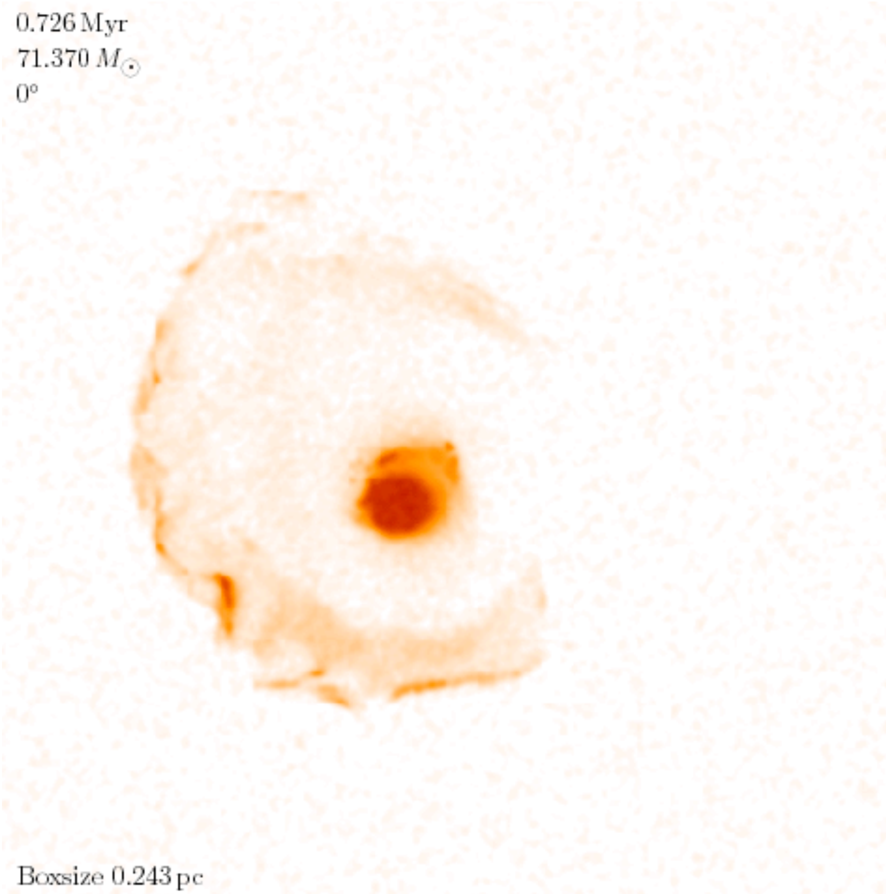


- Wood & Churchwell 1989 classification of UC H II regions
- Question: What is the origin of these morphologies?
- UC H II lifetime problem: Too many UC H II regions observed!



- 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)

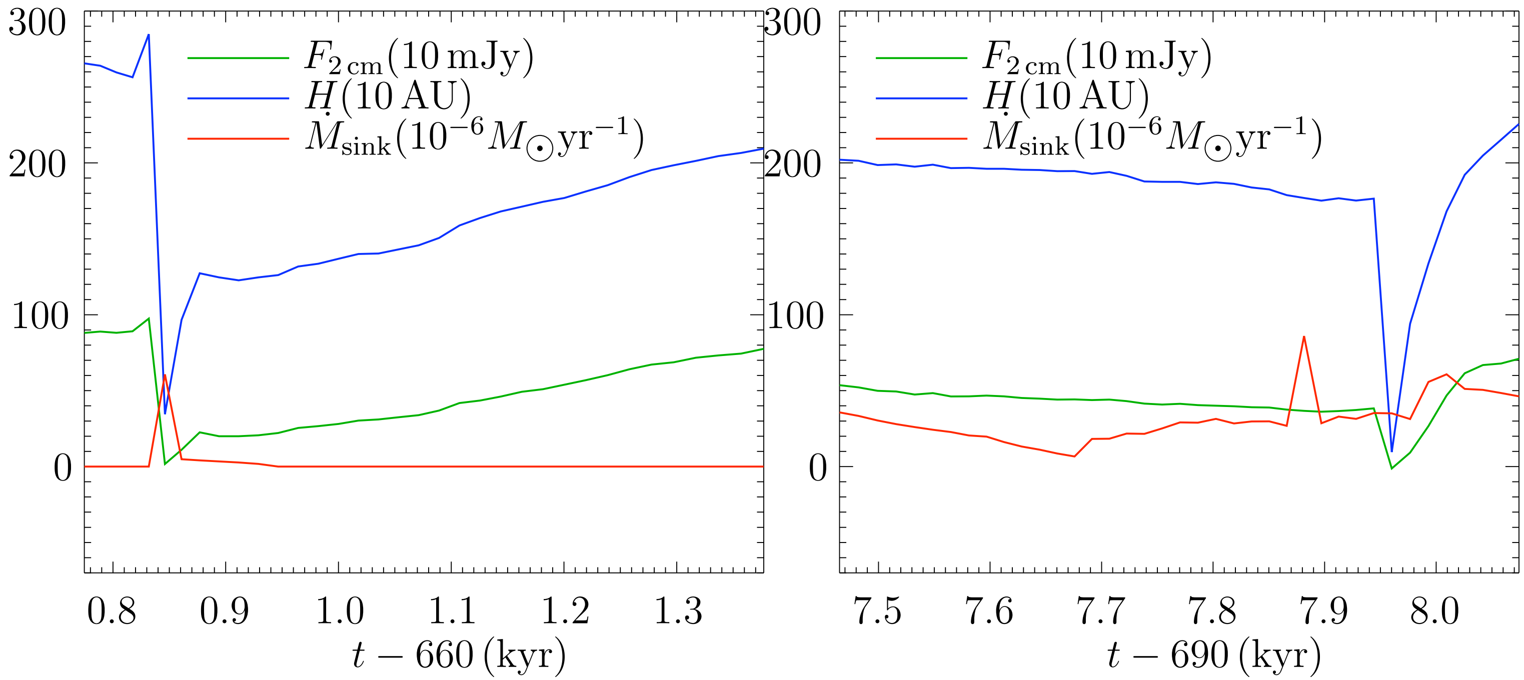
Type	WC89	K94	single	multiple
Spherical/Unresolved	43	55	19	60 ± 5
Cometary	20	16	7	10 ± 5
Core-halo	16	9	15	4 ± 2
Shell-like	4	1	3	5 ± 1
Irregular	17	19	57	21 ± 5

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)

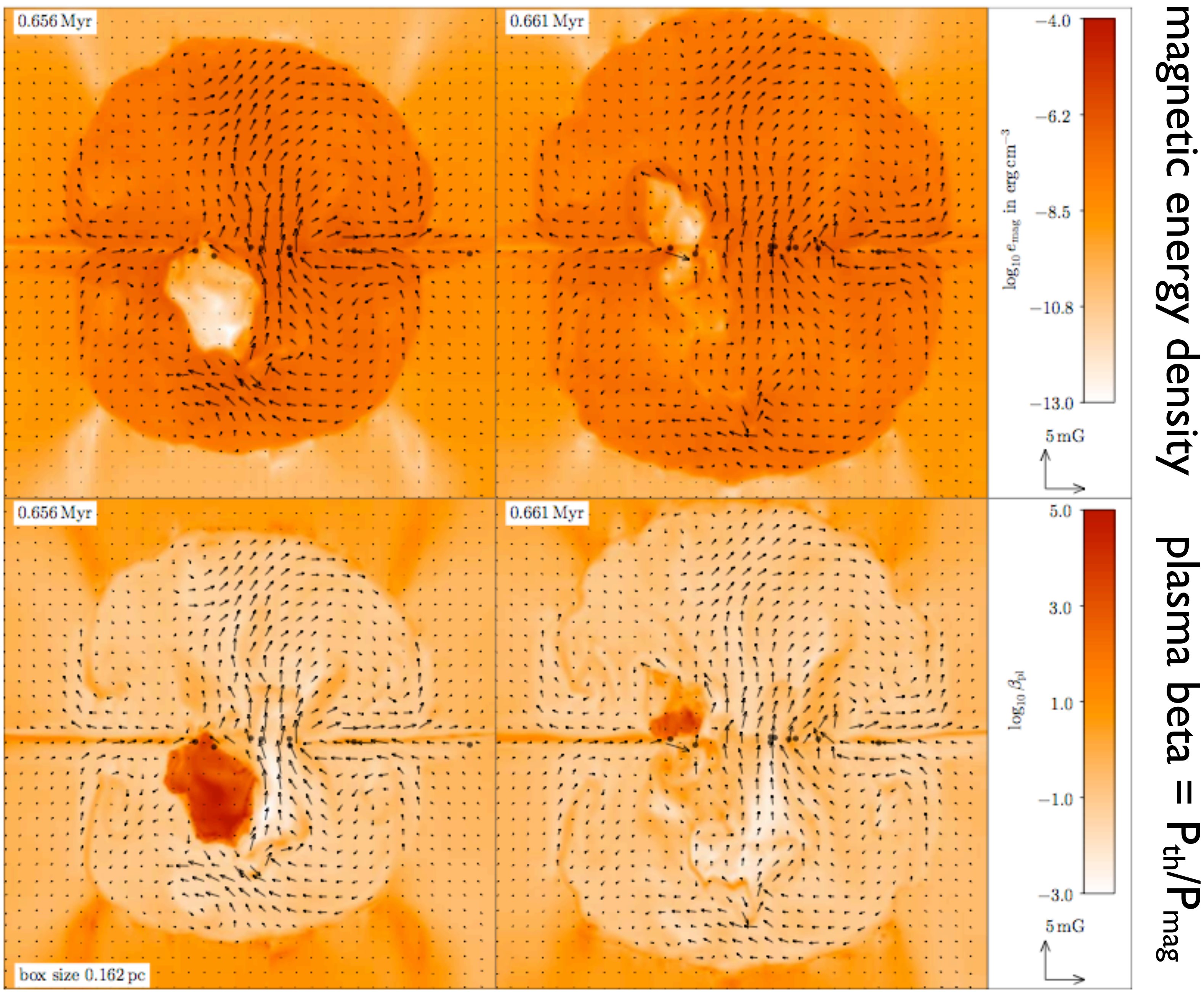
time variability



- correlation between accretion events and H II region changes
- time variations in size and flux have been observed
- changes of size and flux of 5–$7\%\mathrm{yr}^{-1}$ match observations

  Franco-Hernández et al. 2004, Rodríguez et al. 2007, Galván-Madrid et al. 2008

(Galvan-Madrid et al. 2011, submitted)

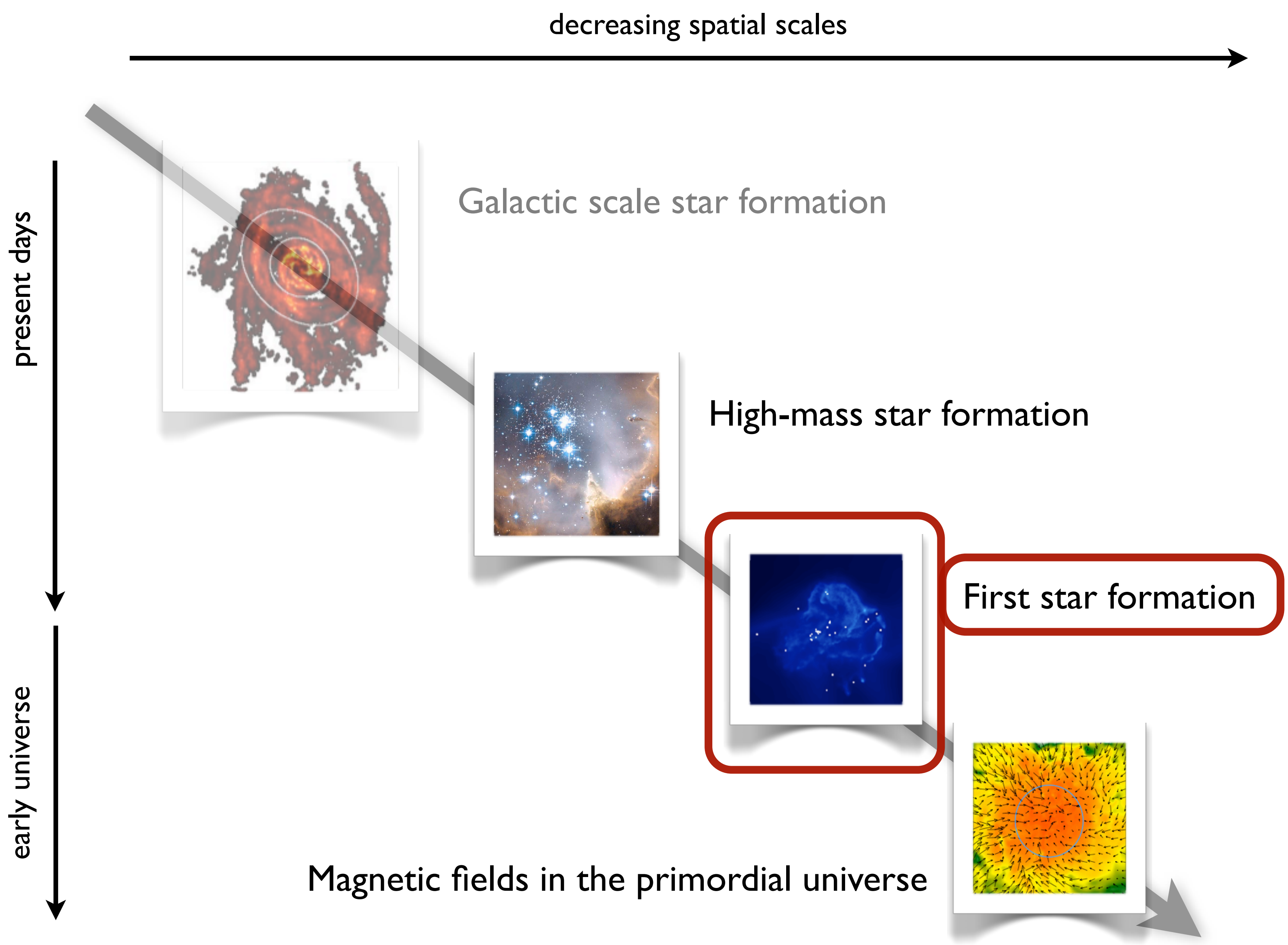


- magnetic tower flow creates roundish bubble
- magnetic field does not change HII morphology

Some results

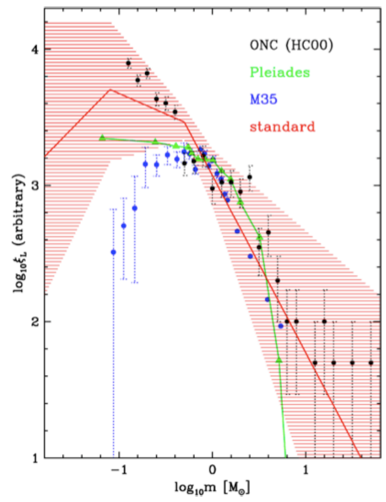
- Ionization feedback cannot stop accretion
- Ionization drives bipolar outflow
- H II region shows high variability in time and shape
- All classified morphologies can be observed in one run
- Lifetime of H II region determined by accretion time scale
- Rapid accretion through dense, unstable flows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

agenda


decreasing spatial scales
present days
early universe
Galactic scale star formation
High-mass star formation
First star formation
Magnetic fields in the primordial universe

stellar masses

- distribution of stellar masses depends on
  - turbulent initial conditions
    --> mass spectrum of prestellar cloud cores
  - collapse and interaction of prestellar cores
    --> competitive accretion and *N*-body effects
  - thermodynamic properties of gas
    --> balance between heating and cooling
    --> EOS (determines which cores go into collapse)
  - (proto) stellar feedback terminates star formation
    ionizing radiation, bipolar outflows, winds, SN



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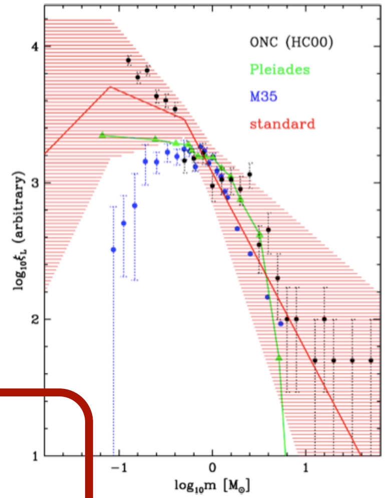


application to first star formation

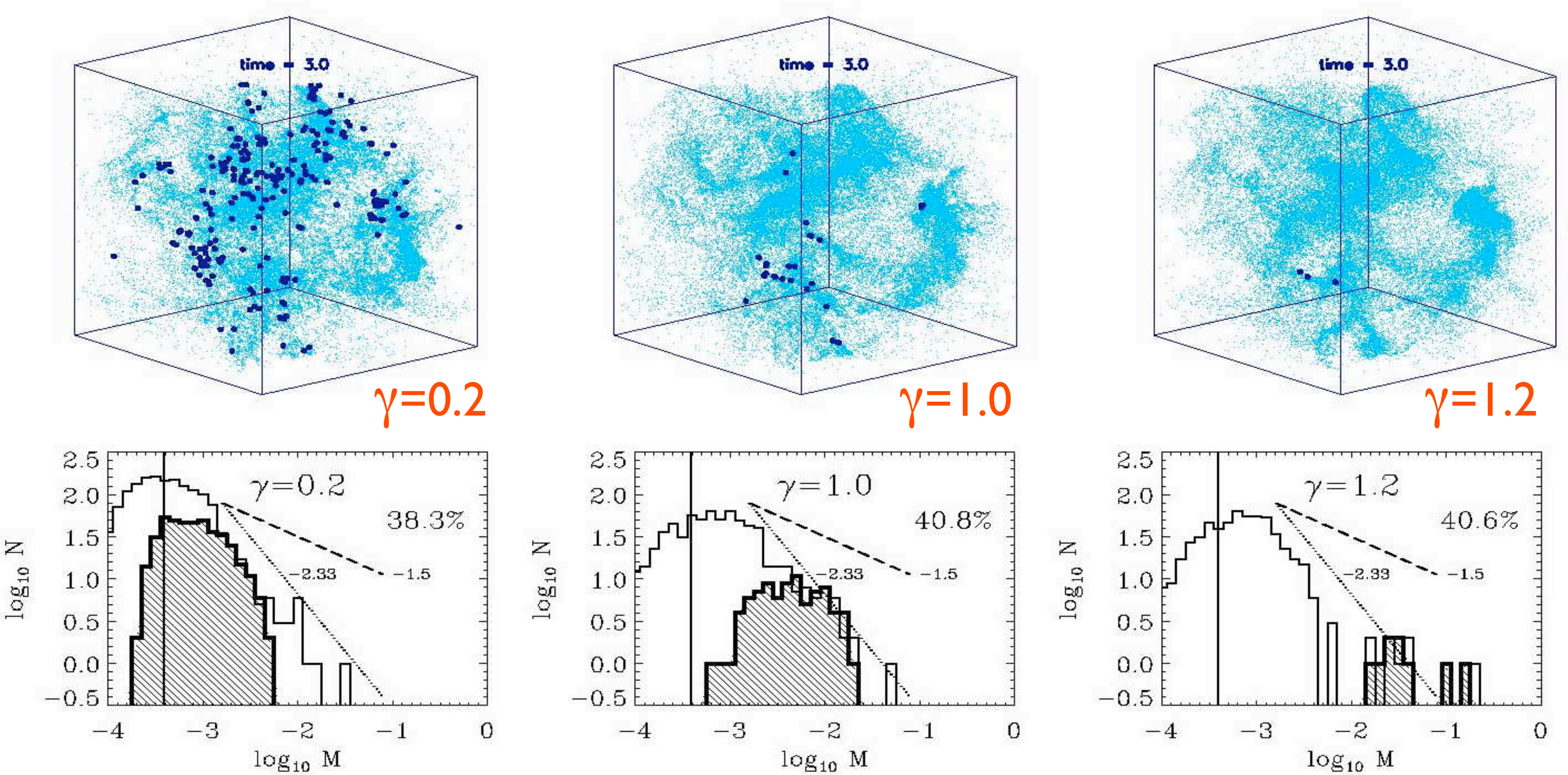
thermodynamics & fragmentation

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 et al. 2003; also Kawachi & Hanawa 1998, Larson 2003)

dependency on EOS



for γ<1 fragmentation is enhanced → *cluster of low-mass stars*

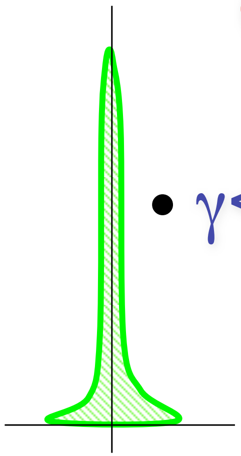
for γ>1 it is suppressed → formation of *isolated massive stars*

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

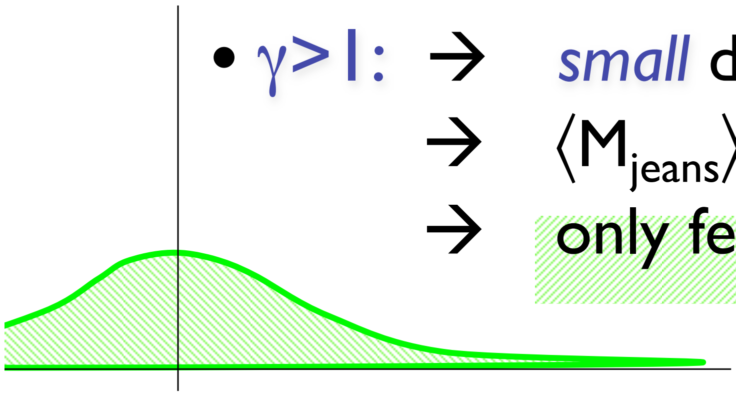
how does that work?

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

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

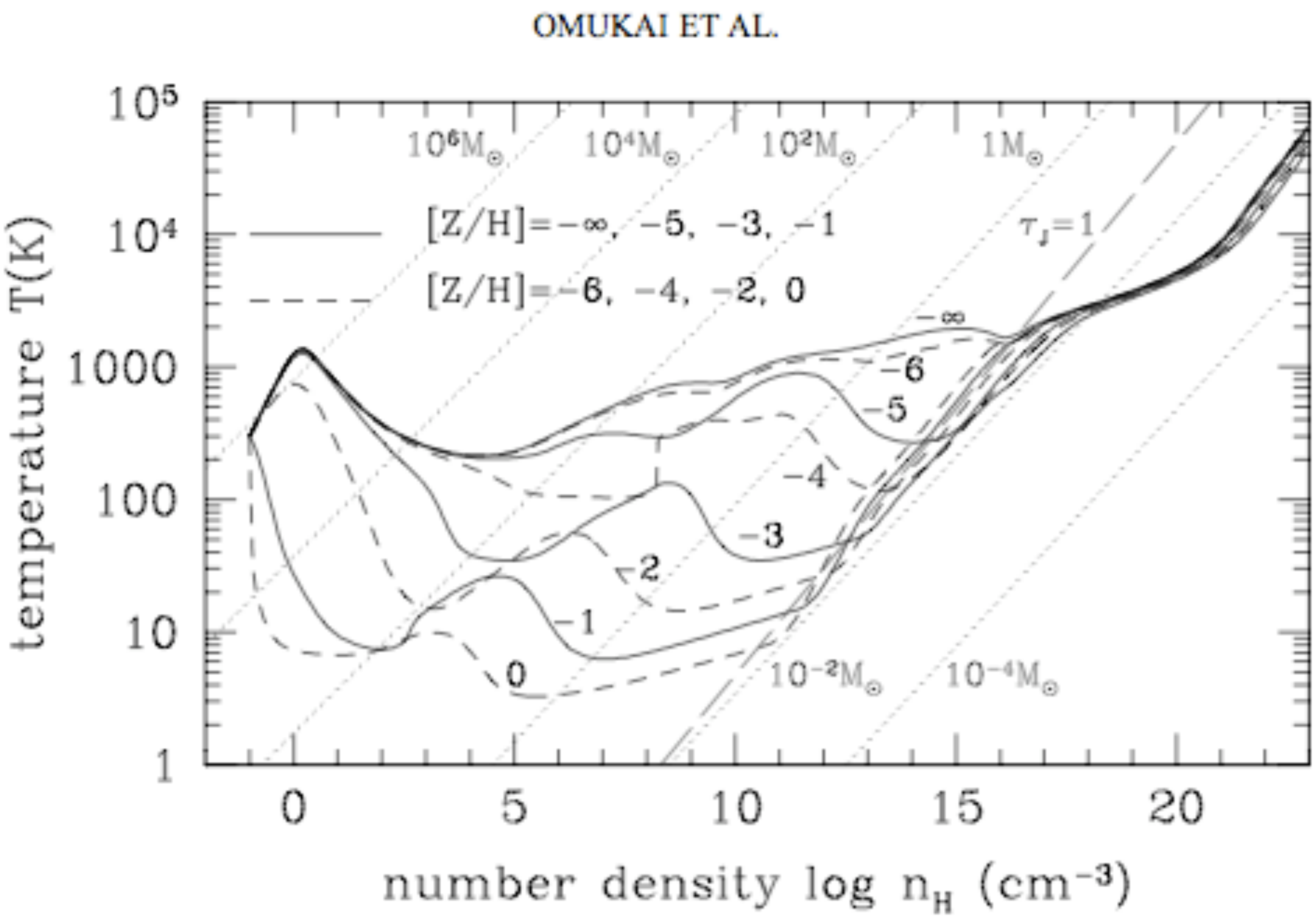


- $\gamma<1$: → *large* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ becomes small
  → number of fluctuations with $M > M_{jeans}$ is large



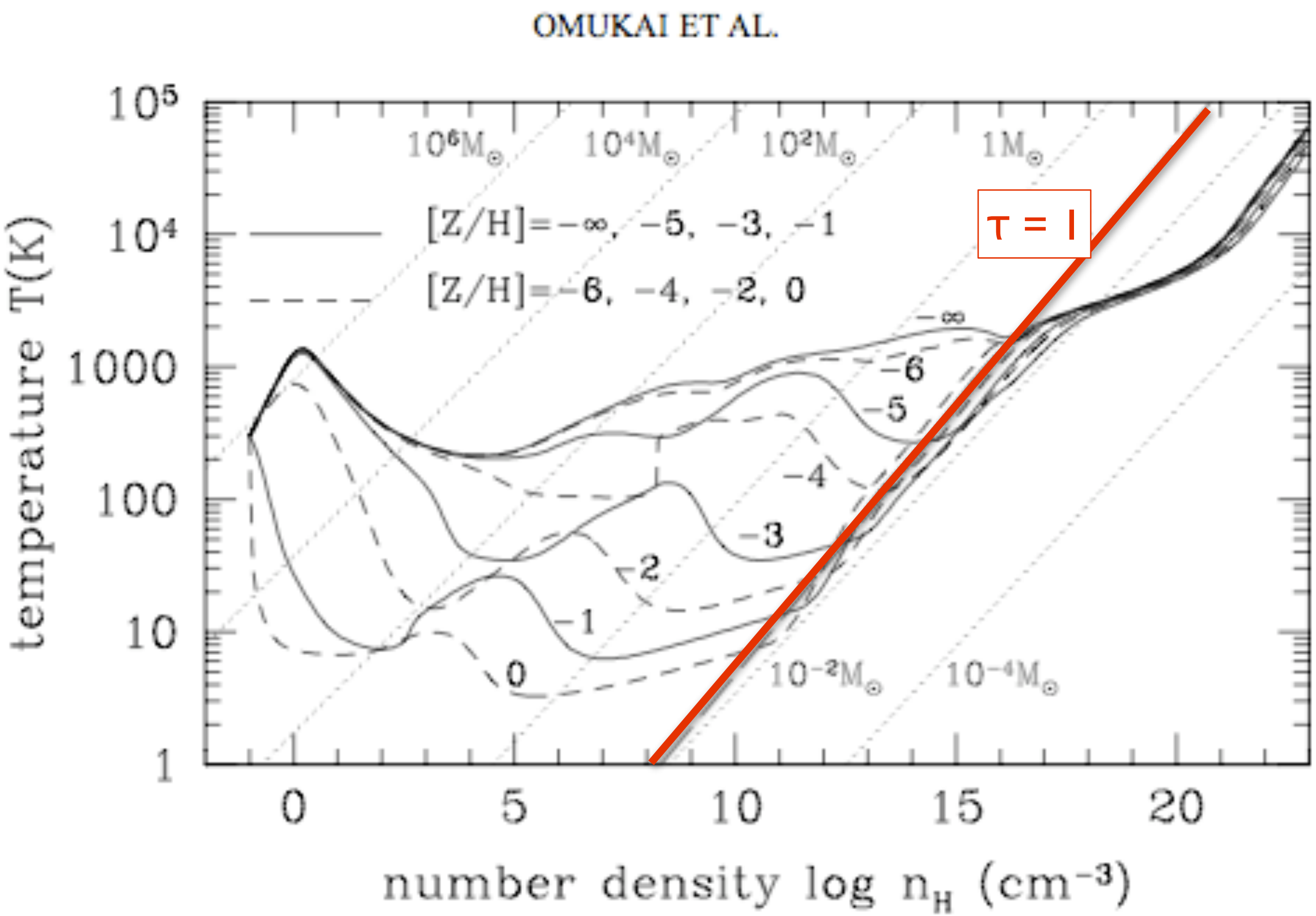
- $\gamma>1$: → *small* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ is large
  → only few and massive clumps exceed M_{jeans}

EOS as function of metallicity



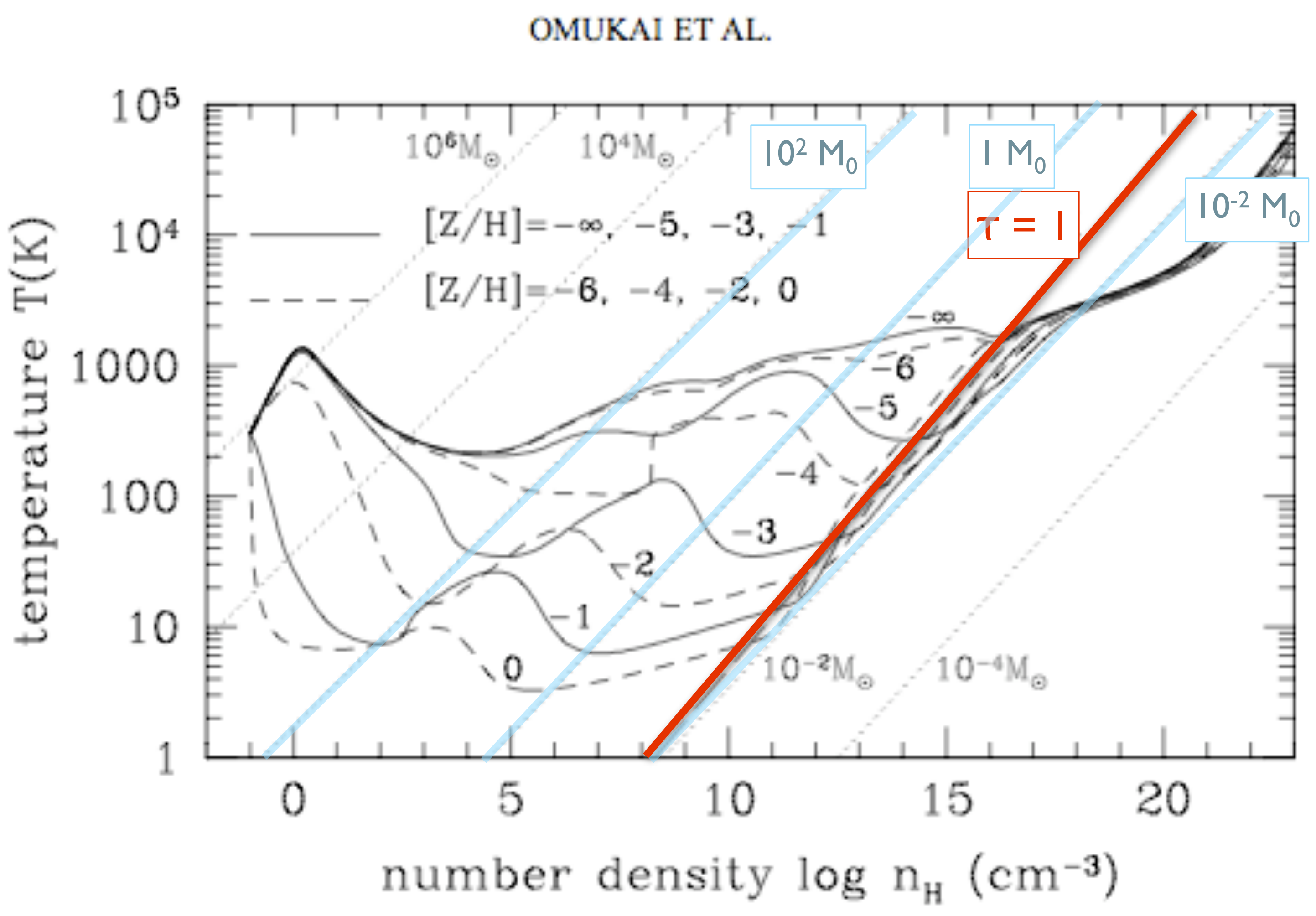
(Omukai et al. 2005)

EOS as function of metallicity



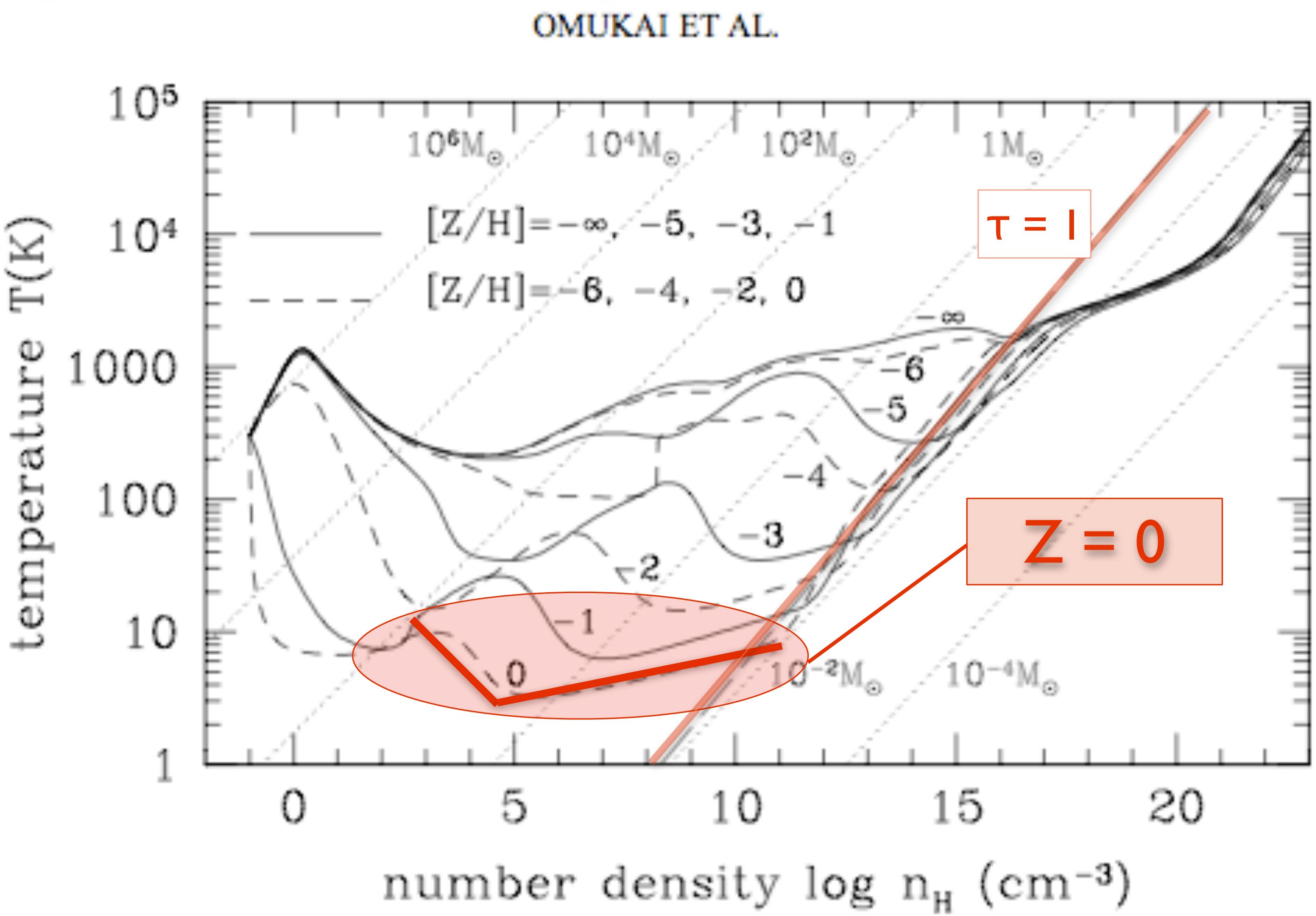
(Omukai et al. 2005)

EOS as function of metallicity



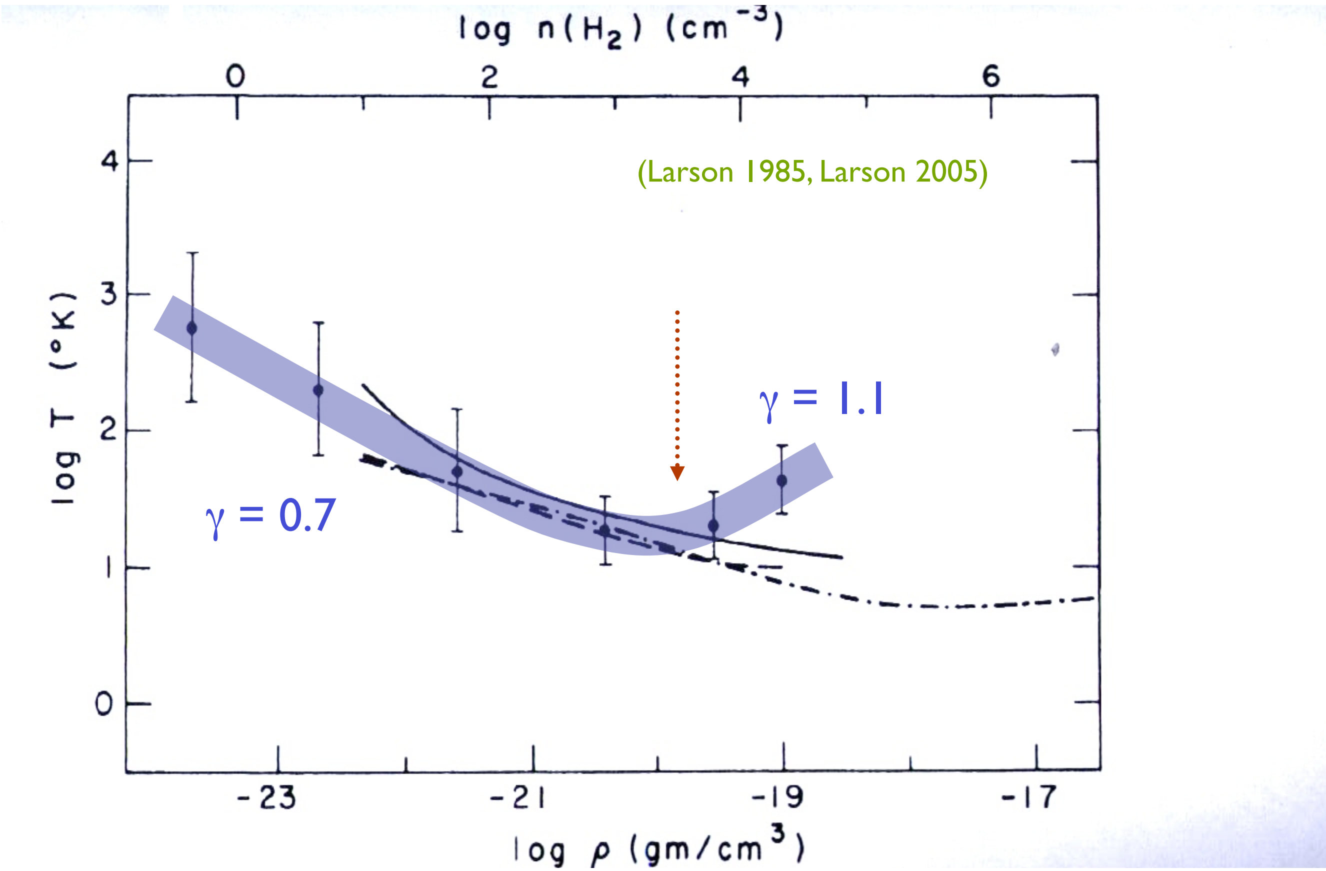
(Omukai et al. 2005)

present-day star formation



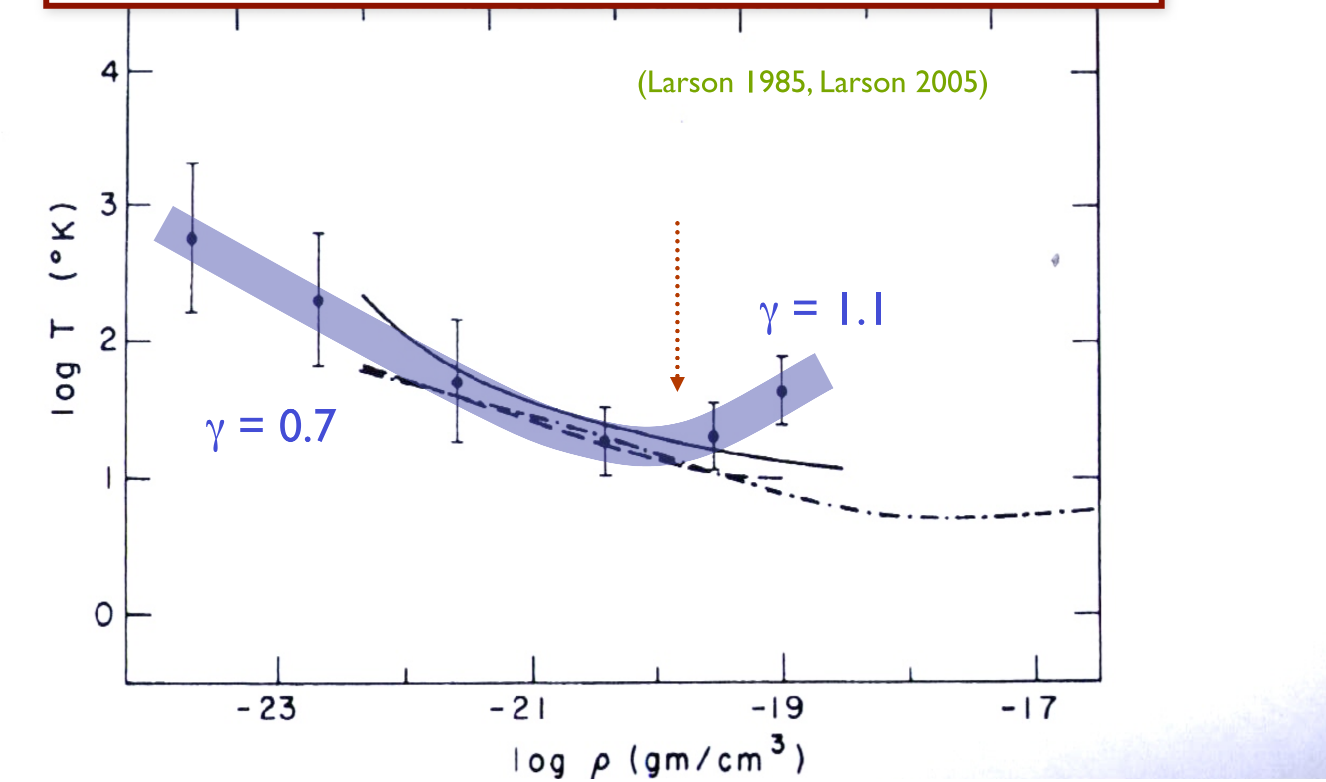
(Omukai et al. 2005, Jappsen et al. 2005, Larson 2005)

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

$\gamma_1 = 0.7$

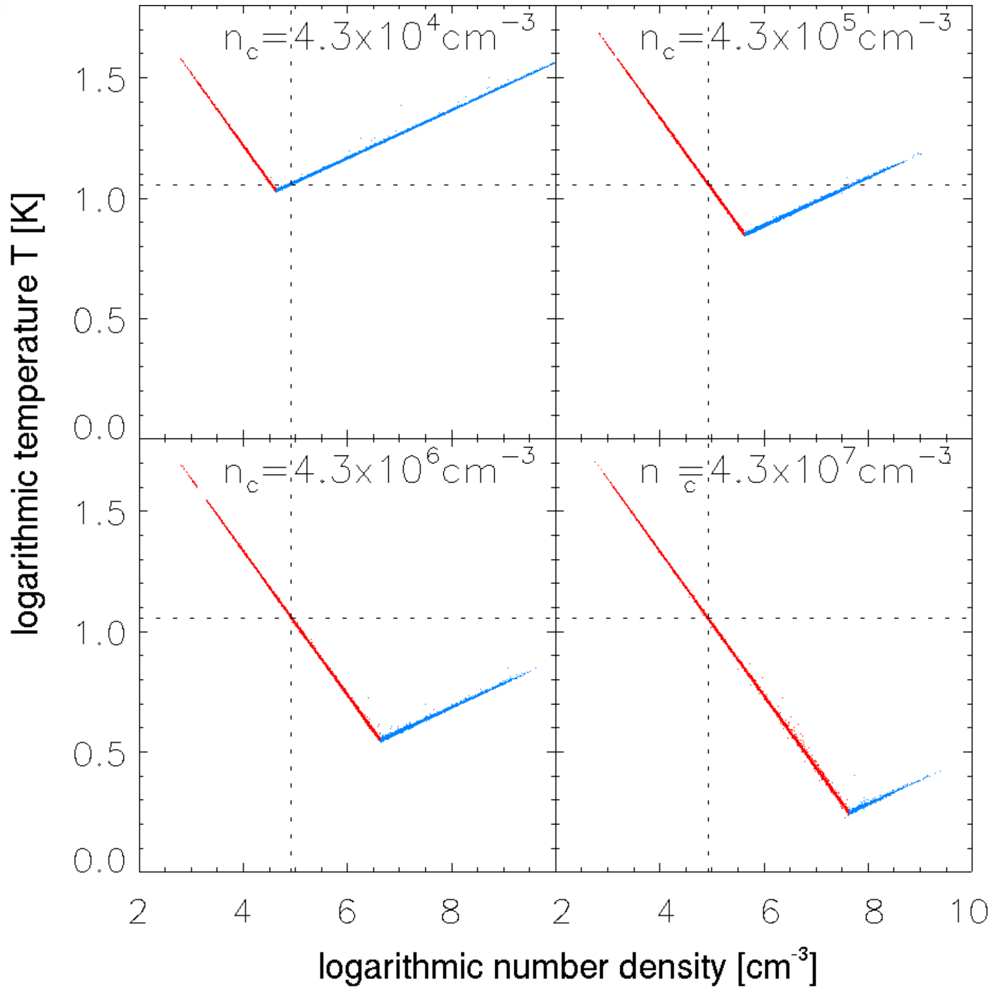
$\gamma_2 = 1.1$

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

EOS and Jeans Mass:

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

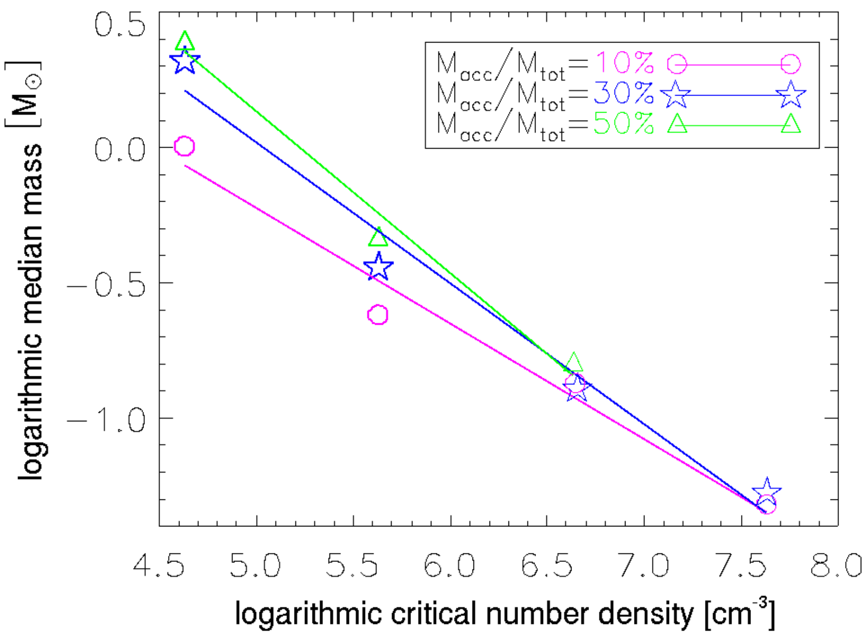
$\mathbf{M}_{\mathbf{jeans}} \propto \gamma^{3/2} \rho^{(3\gamma-4)/2}$

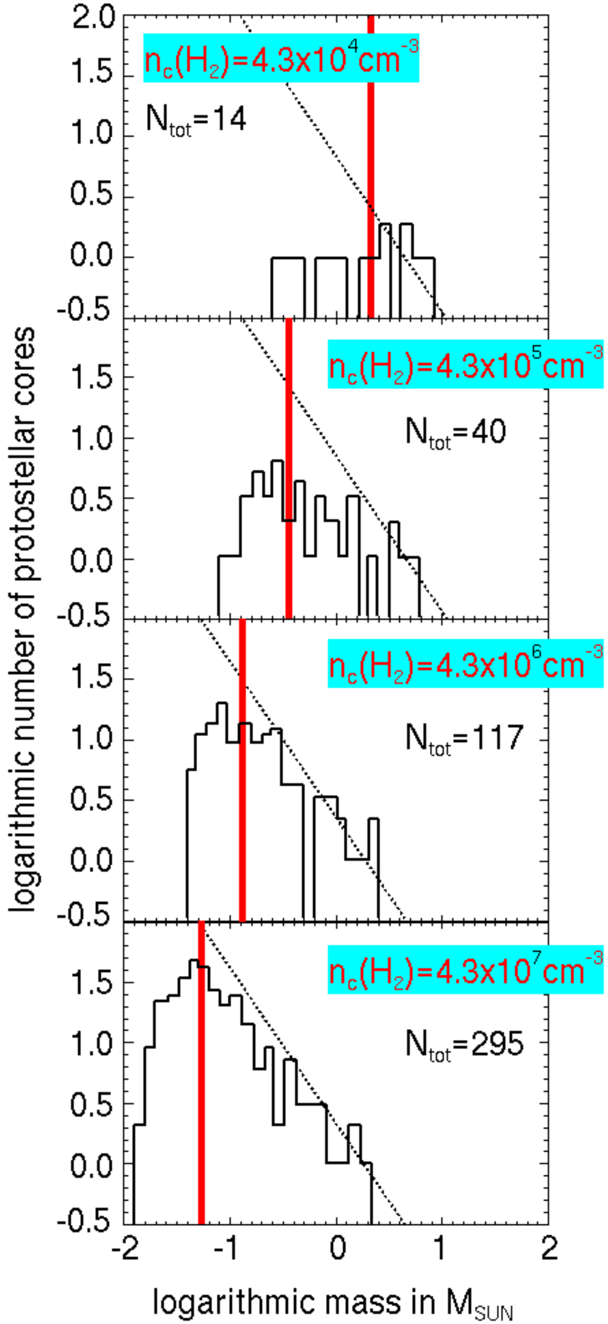


(Jappsen et al. 2005)

IMF from simple polytropic EOS

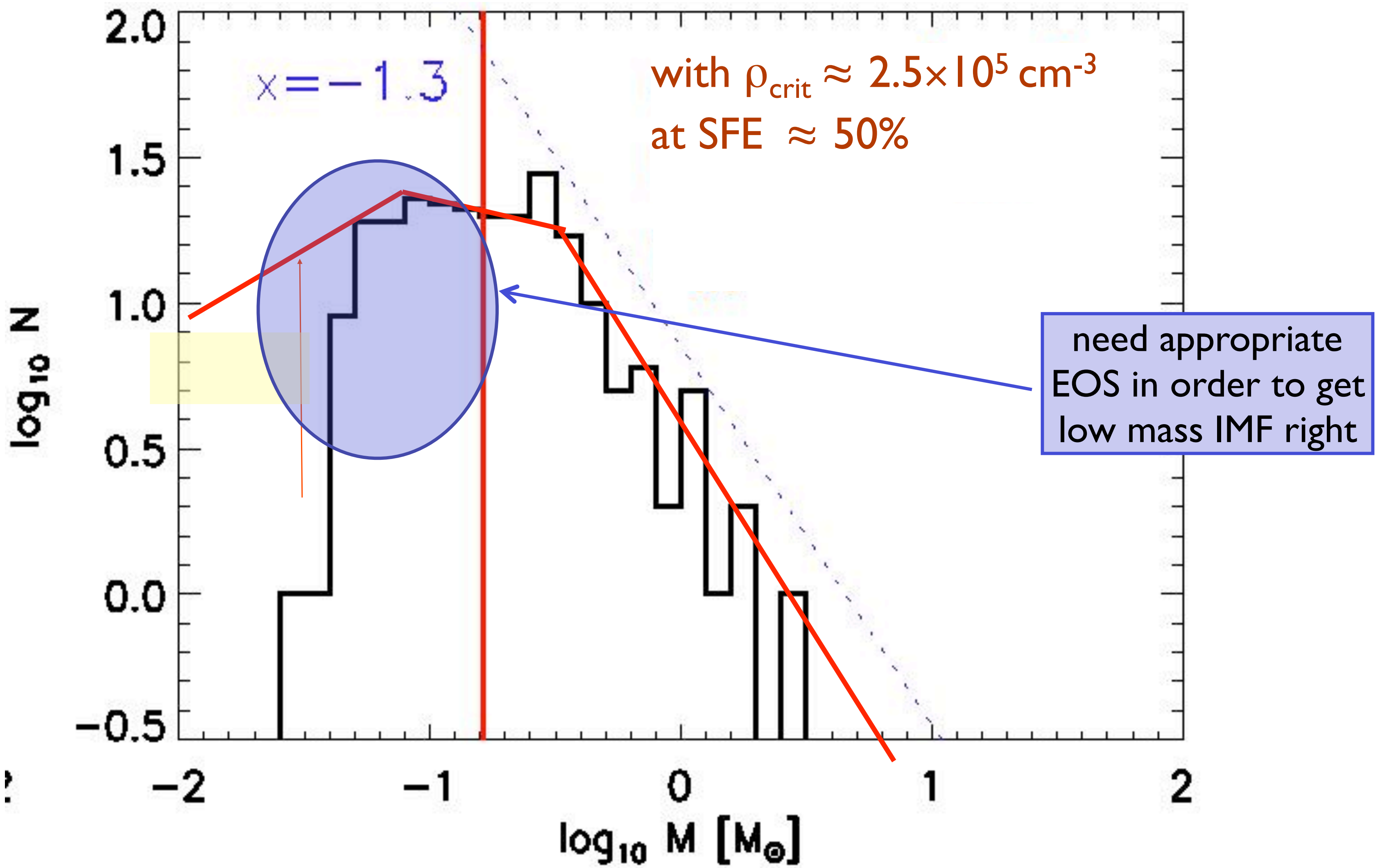
critical density ⬆ ⟹ median mass ⬇





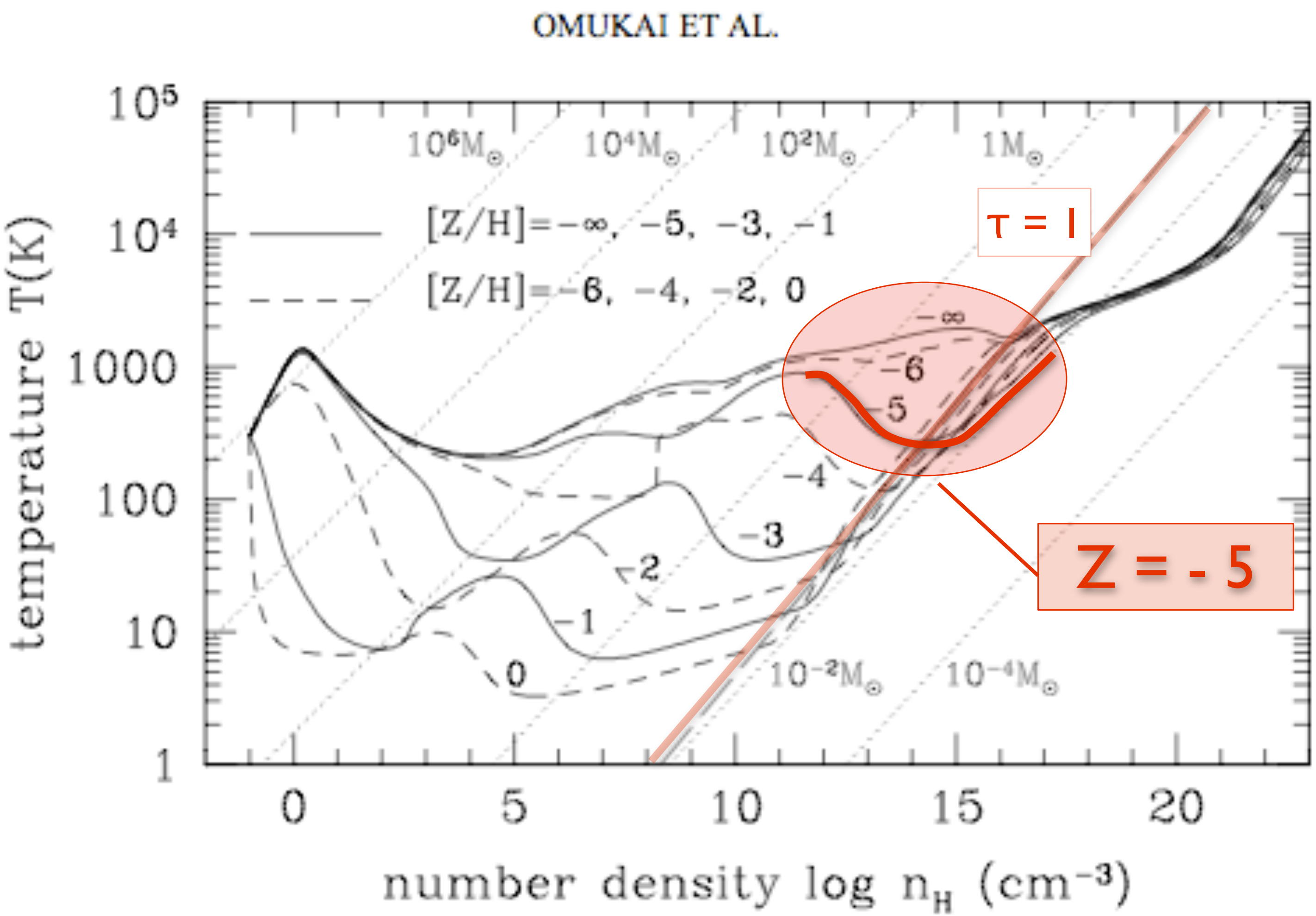
(Jappsen et al. 2005)

IMF in nearby molecular clouds



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

transition: Pop III to Pop II.5



(Omukai et al. 2005)

transition: Pop III to Pop II.5

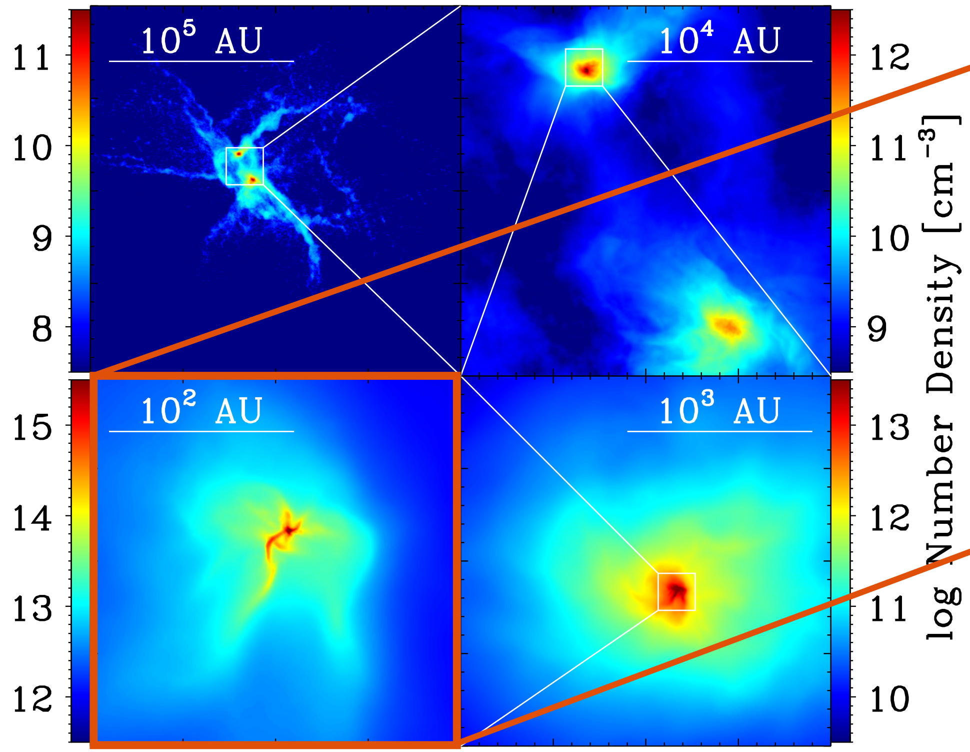


FIG. 2.— Number density maps for a slice through the high density region. The image shows a sequence of zooms in the density structure in the gas immediately before the formation of the first protostar.

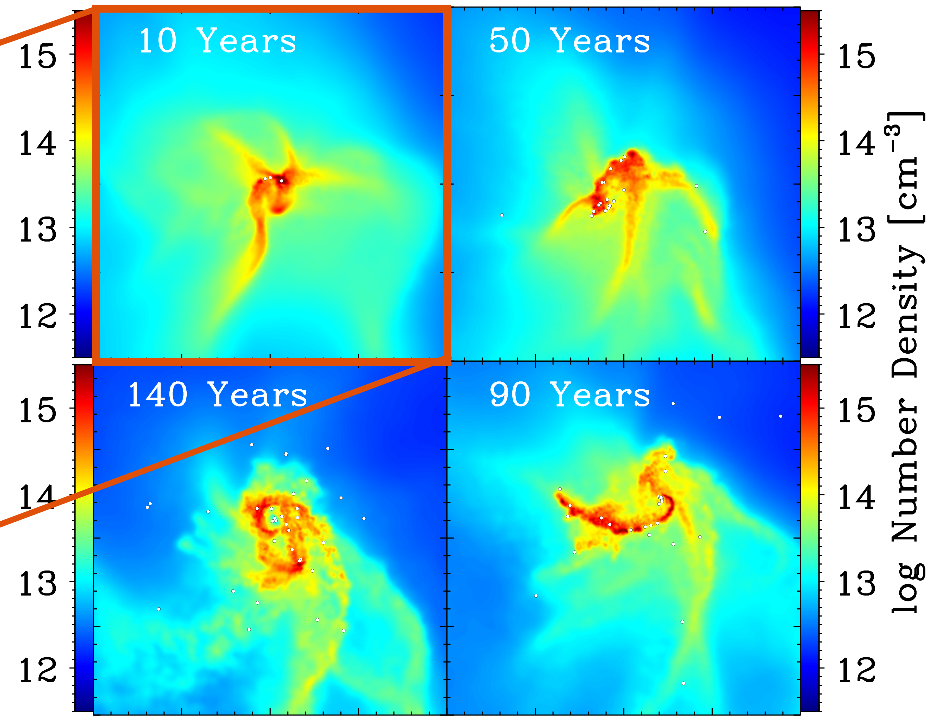
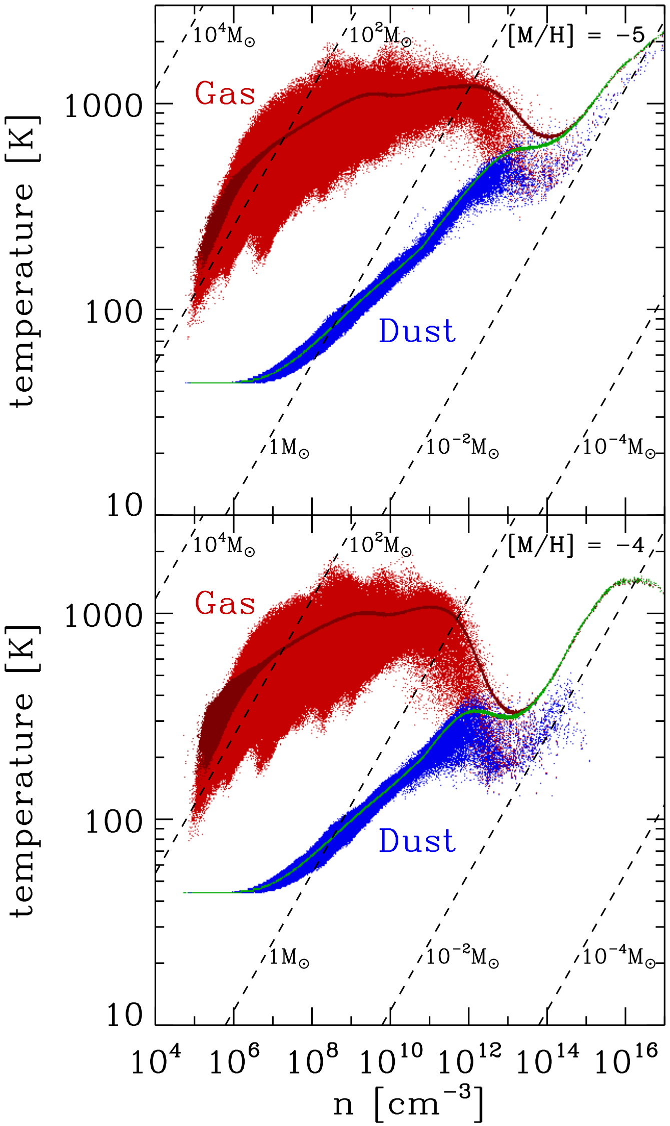


FIG. 3.— Number density map showing a slice in the densest clump, and the sink formation time evolution, for the 40 million particles simulation, and Z = $10^{-4} Z_\odot$. The box is 100AU x 100AU and the time is measured from the formation of the first sink particle.

Dopcke et al. (2011, ApJ 729, L3)

transition: Pop III to Pop II.5



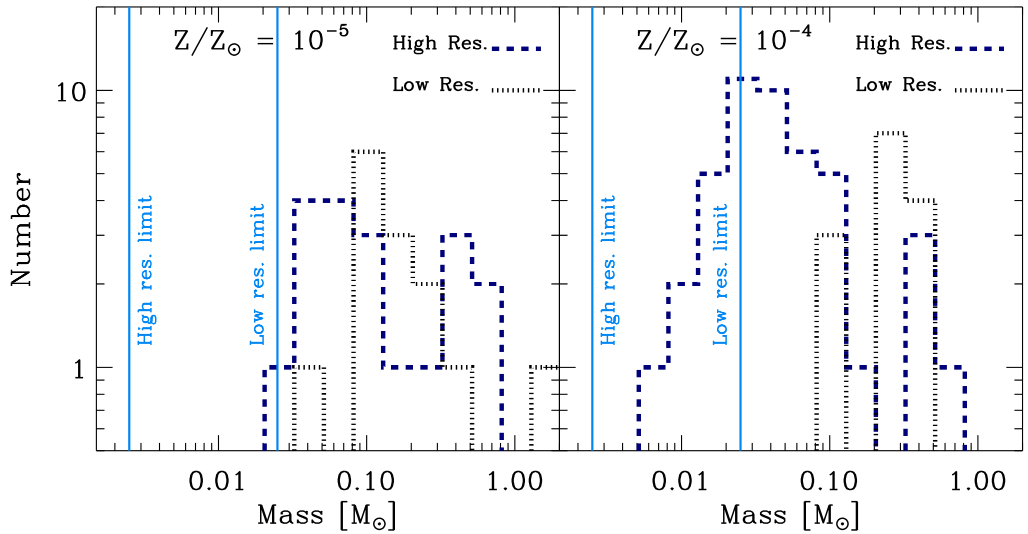
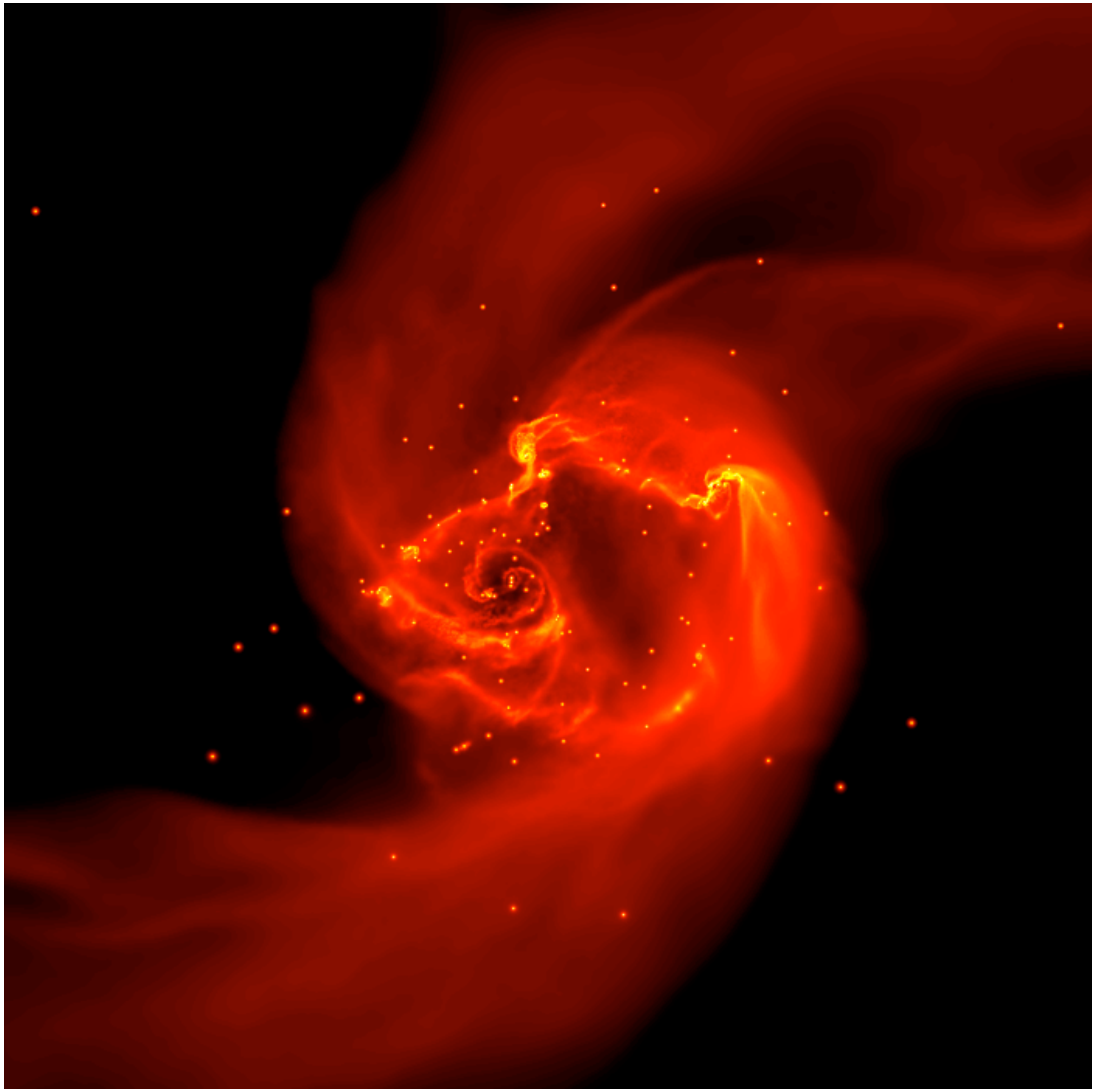


FIG. 4.— Sink particle mass function at the end of the simulations. High and low resolution results and corresponding resolution limits are shown. To resolve the fragmentation, the mass resolution should be smaller than the Jeans mass at the point in the temperature-density diagram where dust and gas couple and the compressional heating starts to dominate over the dust cooling. At the time shown, around 5 $M_\odot$ of gas had been accreted by the sink particles in each simulation.

red / blue: turbulence and rotation
dark red / green: simple collapse

Dopcke et al. (2011, ApJ 729, L3)

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

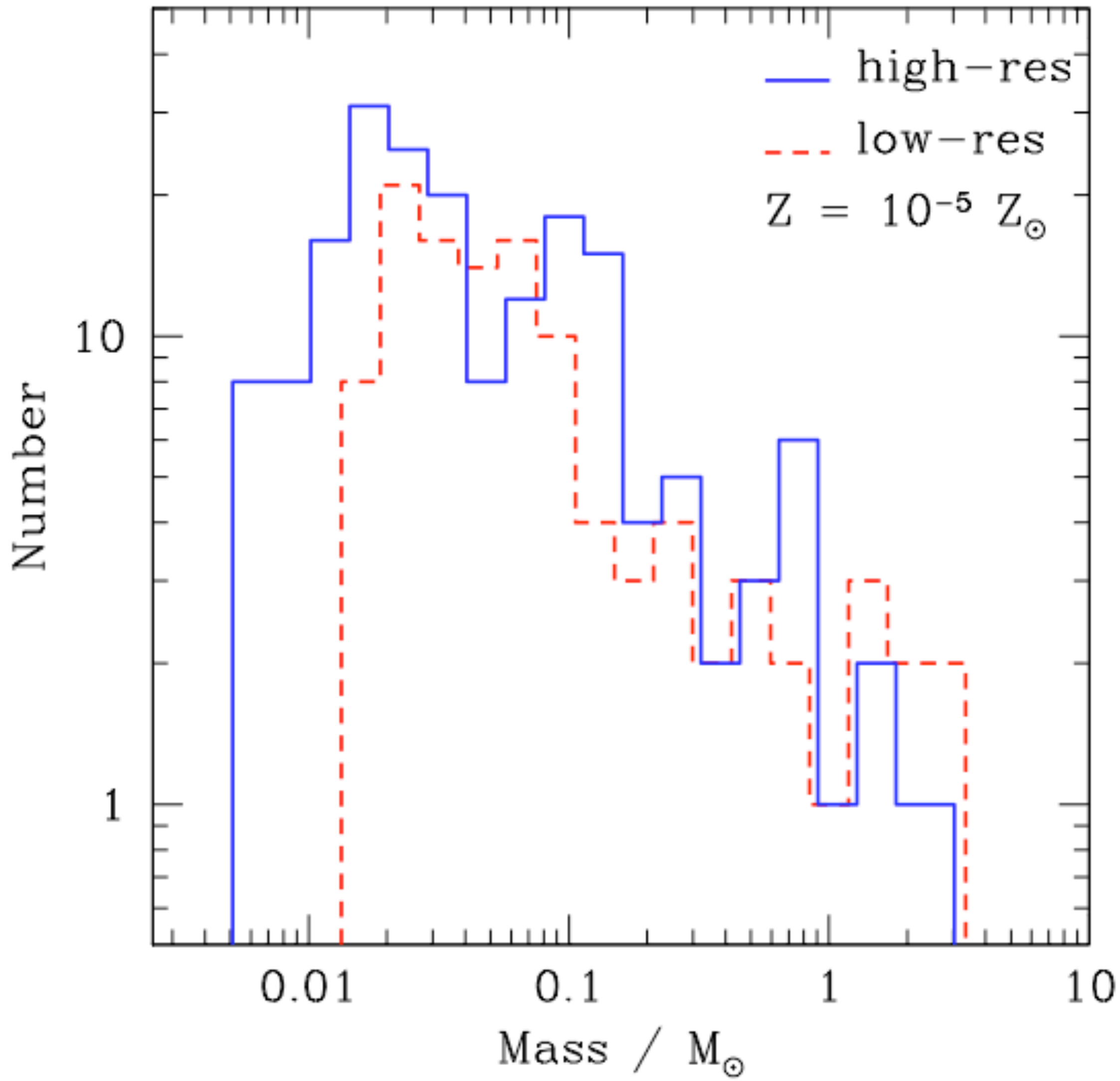


dense cluster of low-mass protostars builds up:

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

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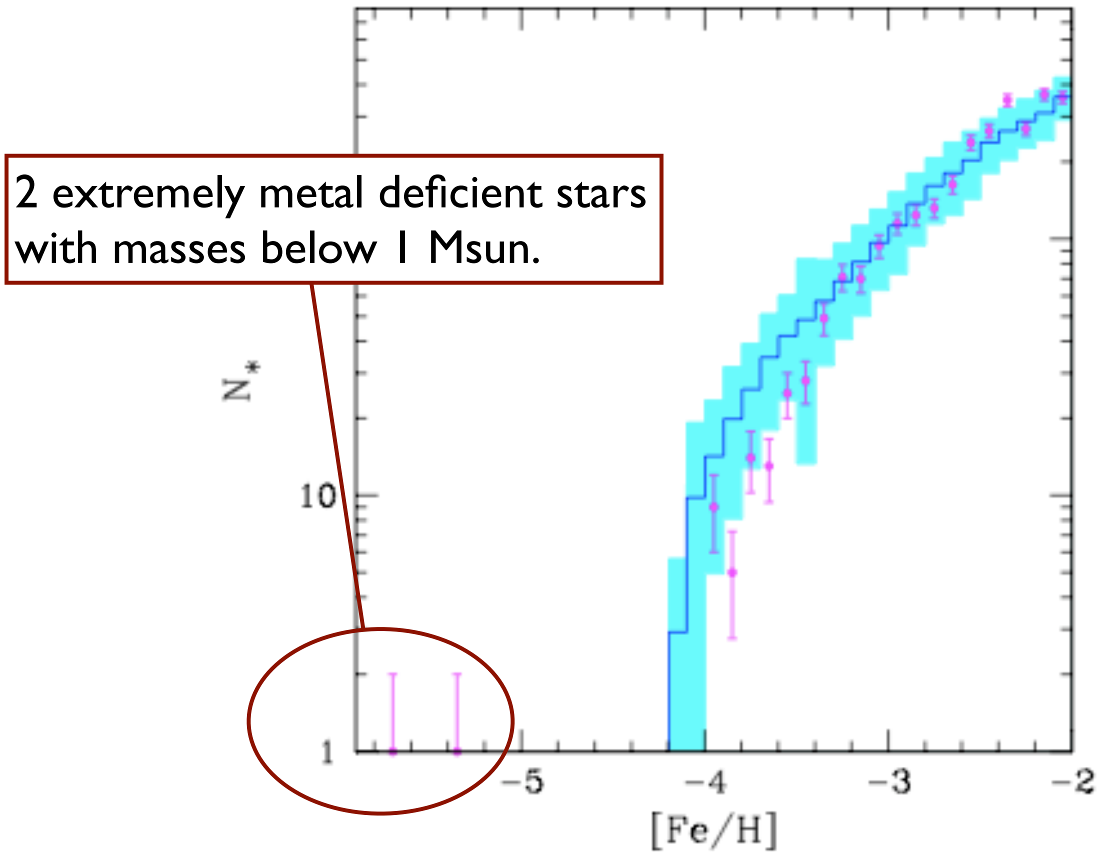
- *predictions:*
  * low-mass stars with [Fe/H] ~ 10^{-5}
  * high binary fraction

(Clark et al. 2008)

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



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

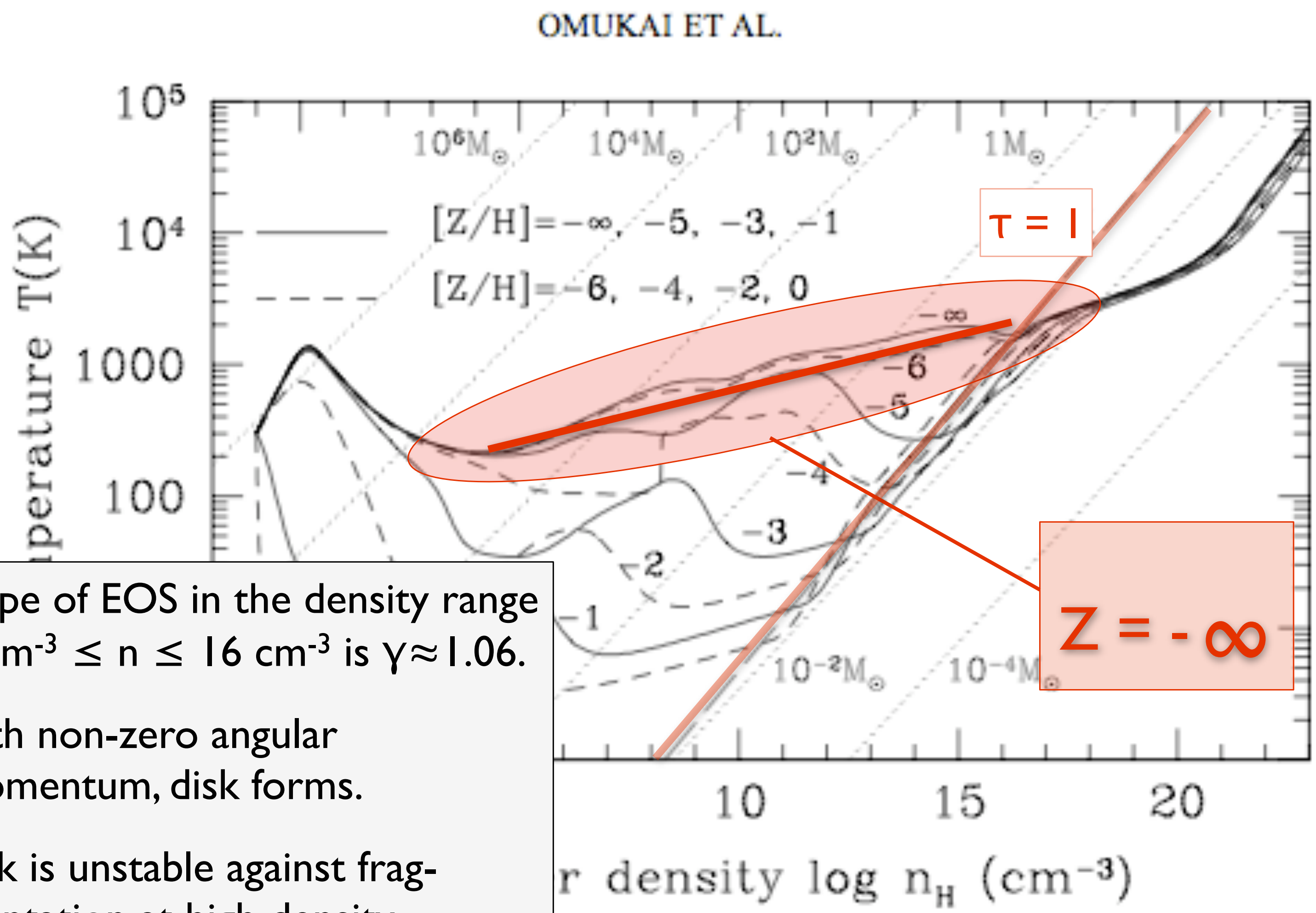
dense cluster of low-mass protostars builds up:

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

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

(Clark et al. 2008)

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

(Omukai et al. 2005)

metal-free star formation

- most current numerical simulations of Pop III star formation predict very massive objects

  (e.g. Abel et al. 2002, Yoshida et al. 2008, Bromm et al. 2009)

- similar for theoretical models (e.g. Tan & McKee 2004)

- there are some first hints of fragmentation, however

  (Turk et al. 2009, Stacy et al. 2010)

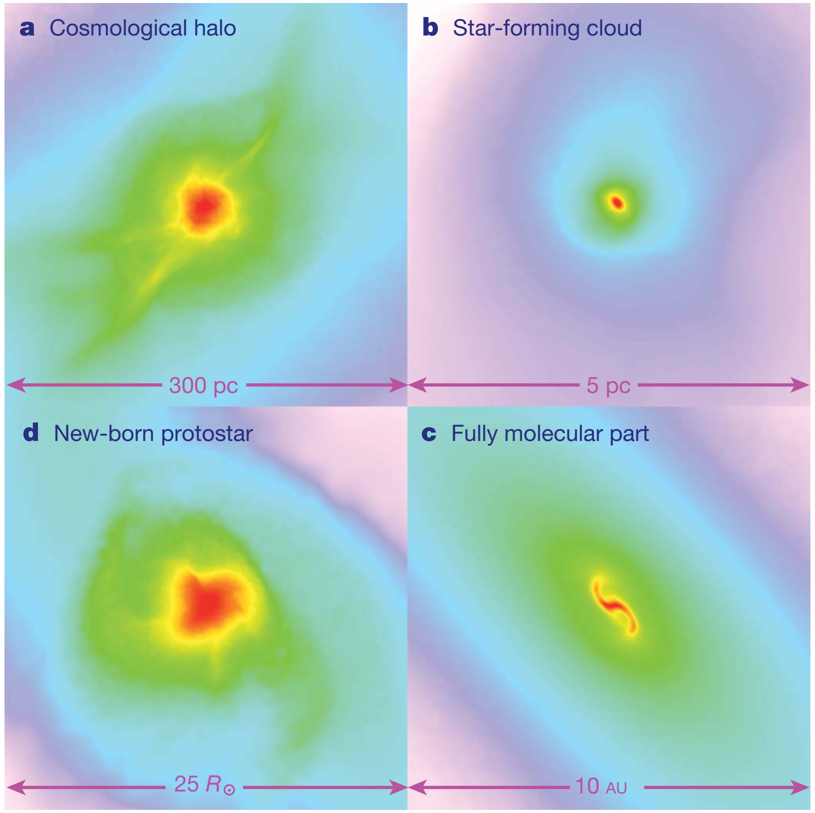
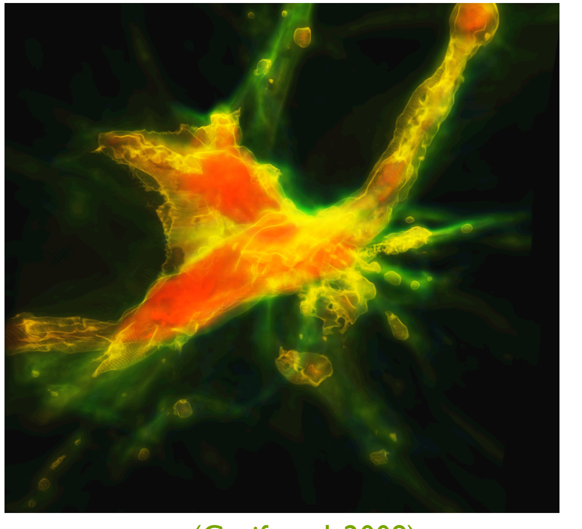


Figure 1 | Projected gas distribution around a primordial protostar. Shown is the gas density (colour-coded so that red denotes highest density) of a single object on different spatial scales. **a**, The large-scale gas distribution around the cosmological minihalo; **b**, a self-gravitating, star-forming cloud; **c**, the central part of the fully molecular core; and **d**, the final protostar. Reproduced by permission of the AAAS (from ref. 20).

(Yoshida et al. 2008, Science, 321, 669)

turbulence in Pop III halos

- star formation will depend on *degree of turbulence* in protogalactic halo
- speculation: *differences in stellar mass function*, just like in present-day star formation



(Greif et al. 2008)

turbulence in Pop III halos

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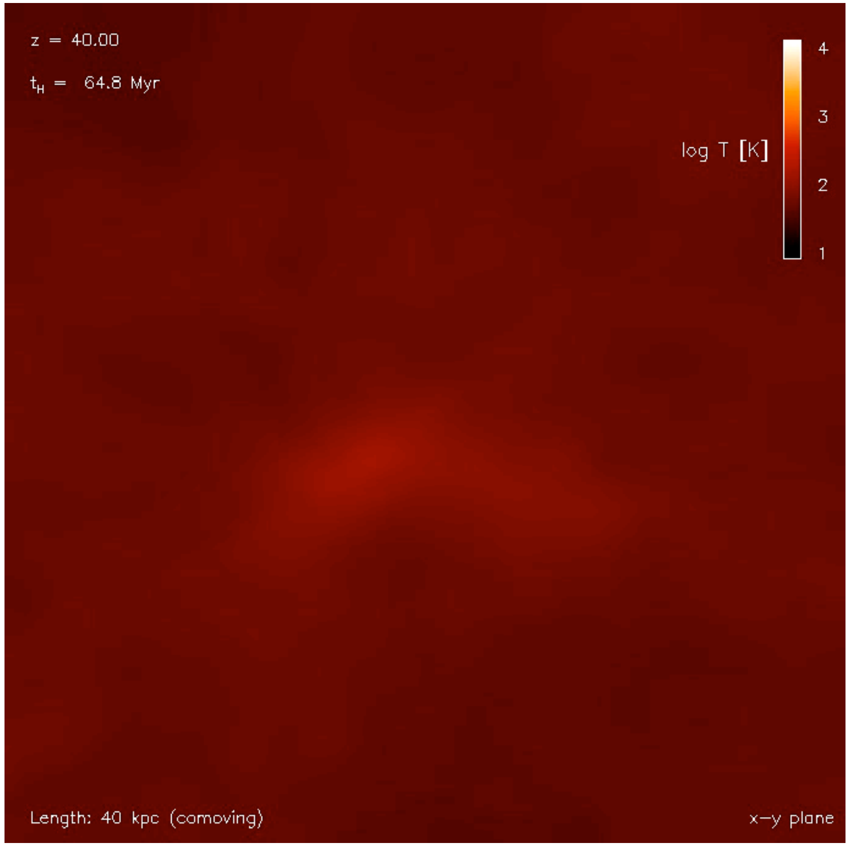
- speculation: *differences in stellar mass function*, just like in present-day star formation

turbulence developing in an atomic cooling halo

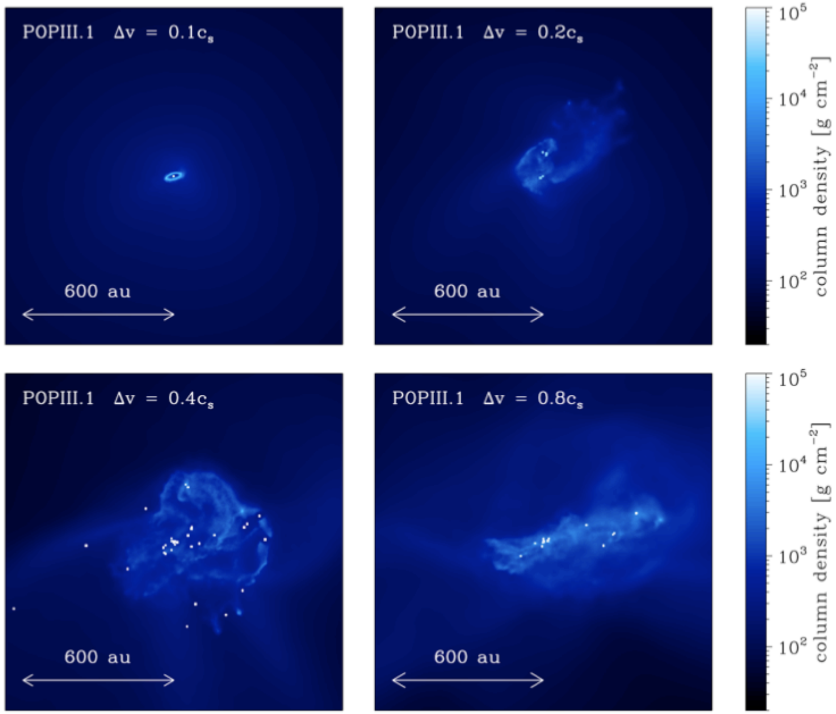


(Greif et al. 2008)

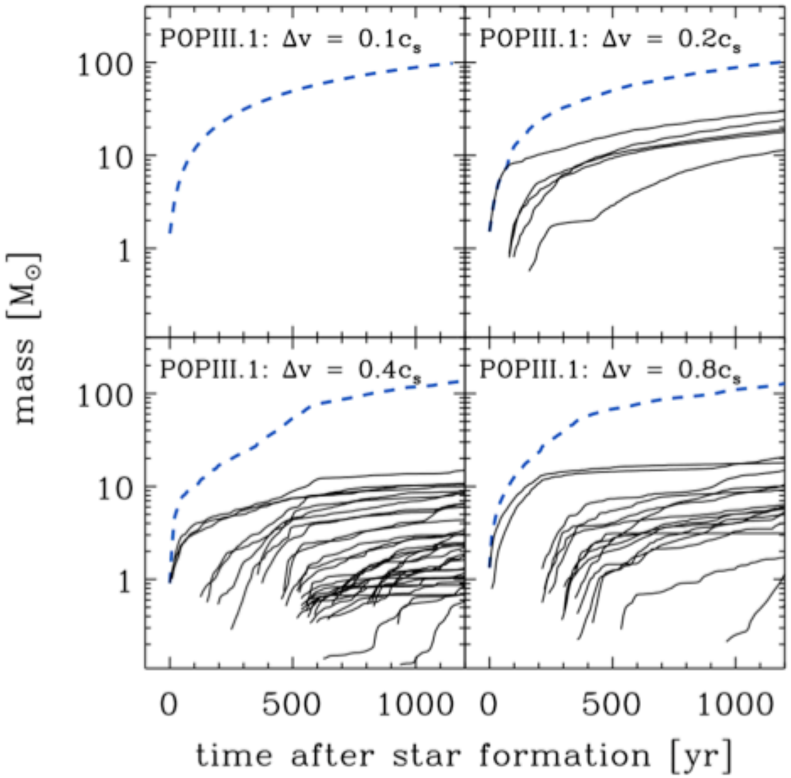
multiple Pop III stars in halo

- parameter study with different strength of turbulence using SPH: study Pop III.1 and Pop III.2 case (Clark et al., 2011a, ApJ, 727, 110)
- 2 very high resolution studies of Pop III star formation in cosmological context
  - SPH: Clark et al. 2011b, Science (arXiv:1101.5284)
  - Arepo: Greif et al. 2011a, ApJ, submitted (arXiv:1101.5491)
  - complementary approaches with interesting similarities and differences....

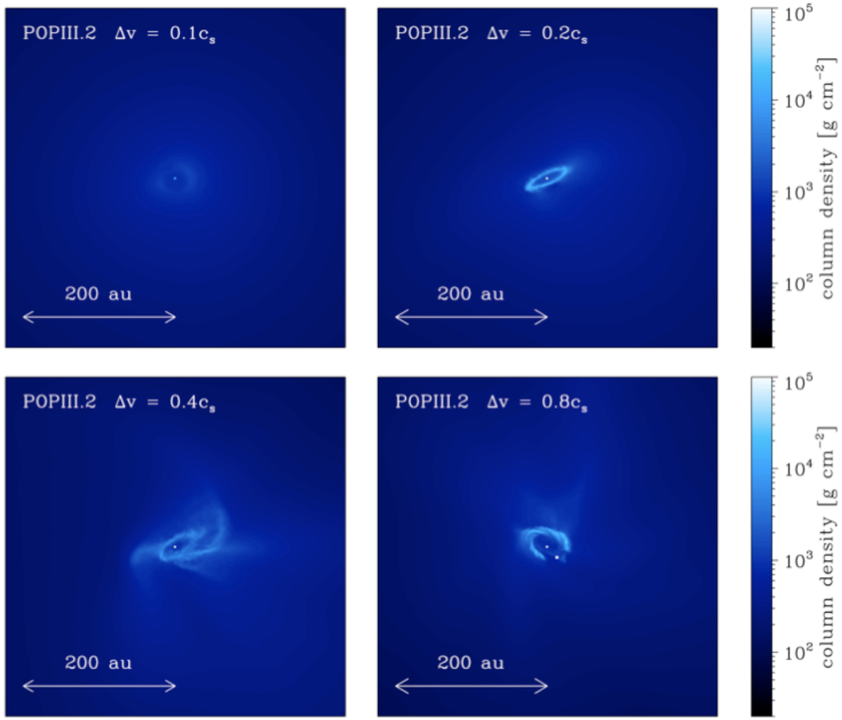
Pop III.1



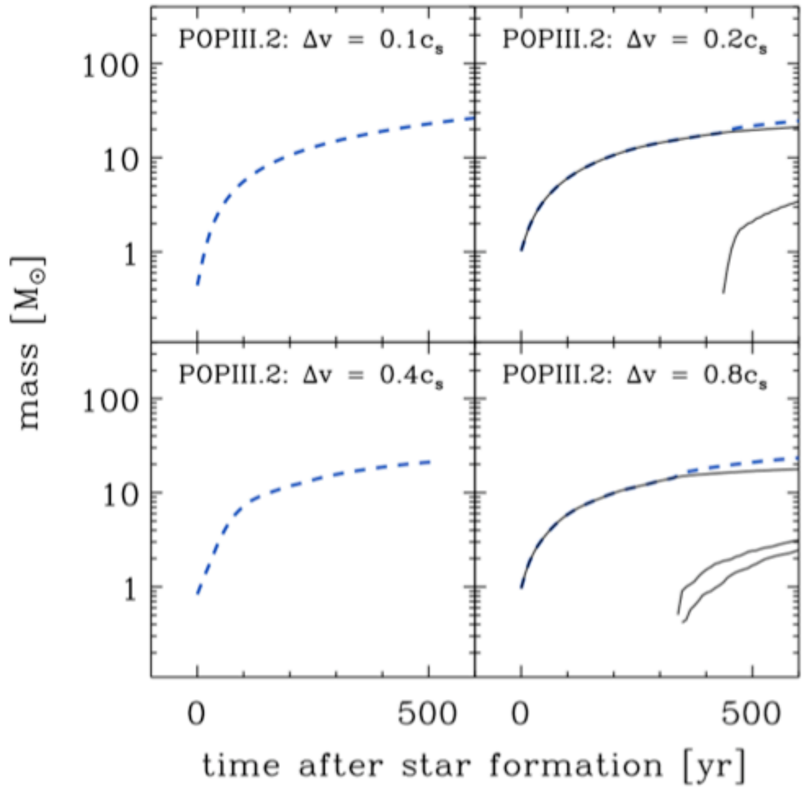
(Clark et al, 2011a)



Pop III.2



(Clark et al, 2011a)



SPH study: face on look at accretion disk

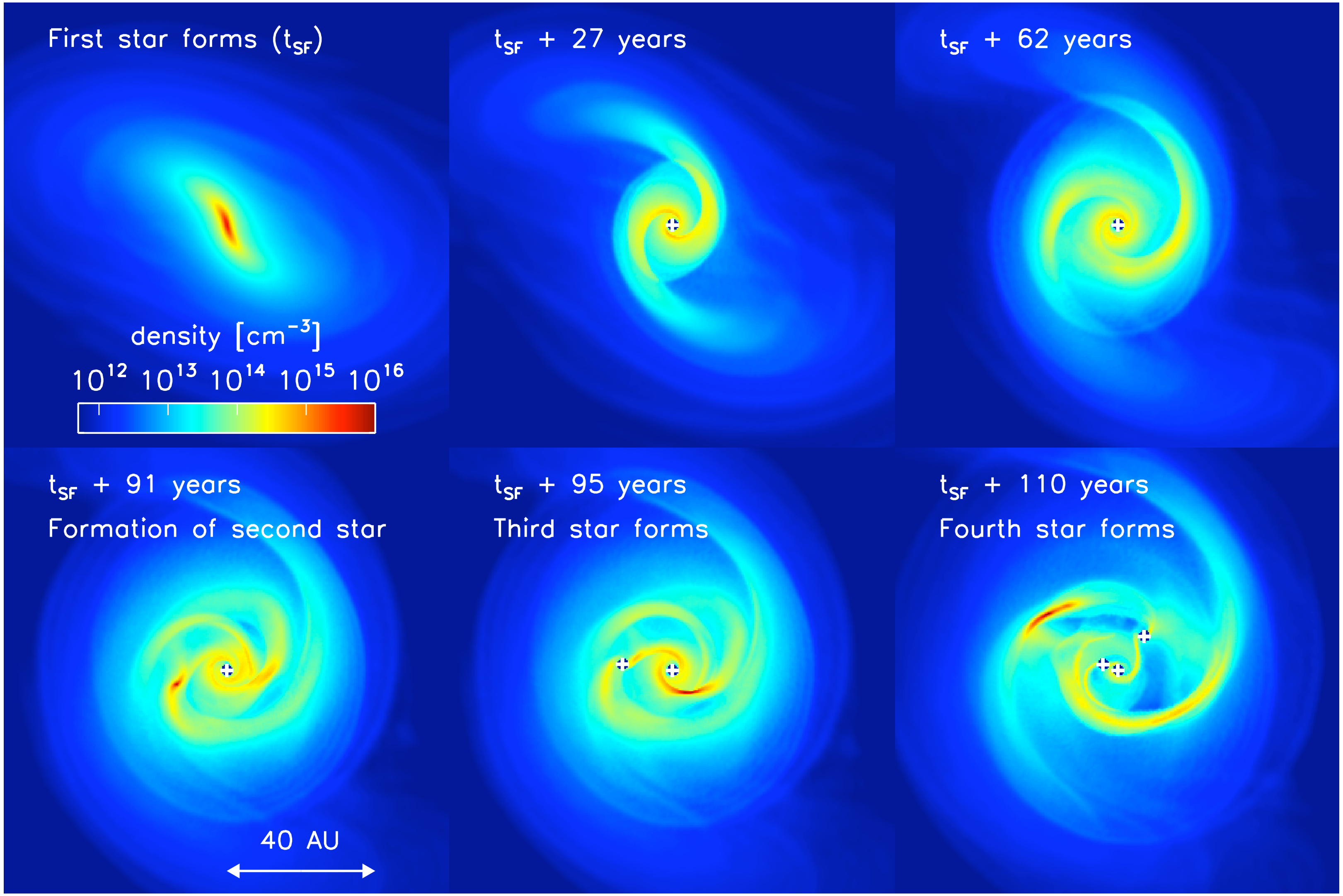


Figure 1: Density evolution in a 120 AU region around the first protostar, showing the build-up of the protostellar disk and its eventual fragmentation. We also see 'wakes' in the low-density regions, produced by the previous passage of the spiral arms.

(Clark et al. 2011b, Science, 331, 1040)

SPH study: some disk parameters

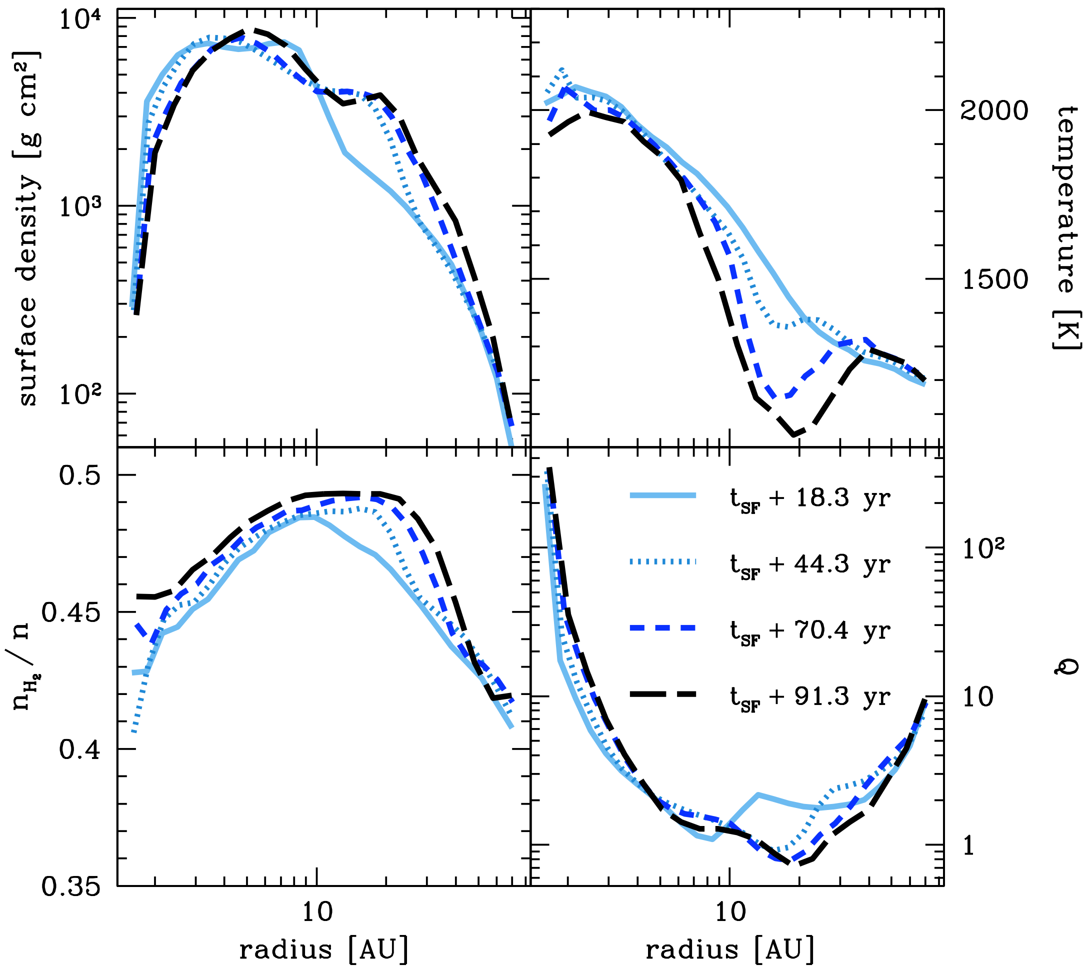


Figure 2: Radial profiles of the disk's physical properties, centered on the first protostellar core to form. The quantities are mass-weighted and taken from a slice through the midplane of the disk. In the lower right-hand plot we show the radial distribution of the disk's Toomre parameter, $Q = c_s\kappa/\pi G\Sigma$, where c_s is the sound speed and κ is the epicyclic frequency. Beause our disk is Keplerian, we adopted the standard simplification, and replaced κ with the orbital frequency. The molecular fraction is defined as the number density of hydrogen molecules (n_{H_2}), divided by the number density of hydrogen nuclei (n), such that fully molecular gas has a value of 0.5

(Clark et al. 2011b, Science, 331, 1040)

SPH study: mass accretion onto disk and onto protostars

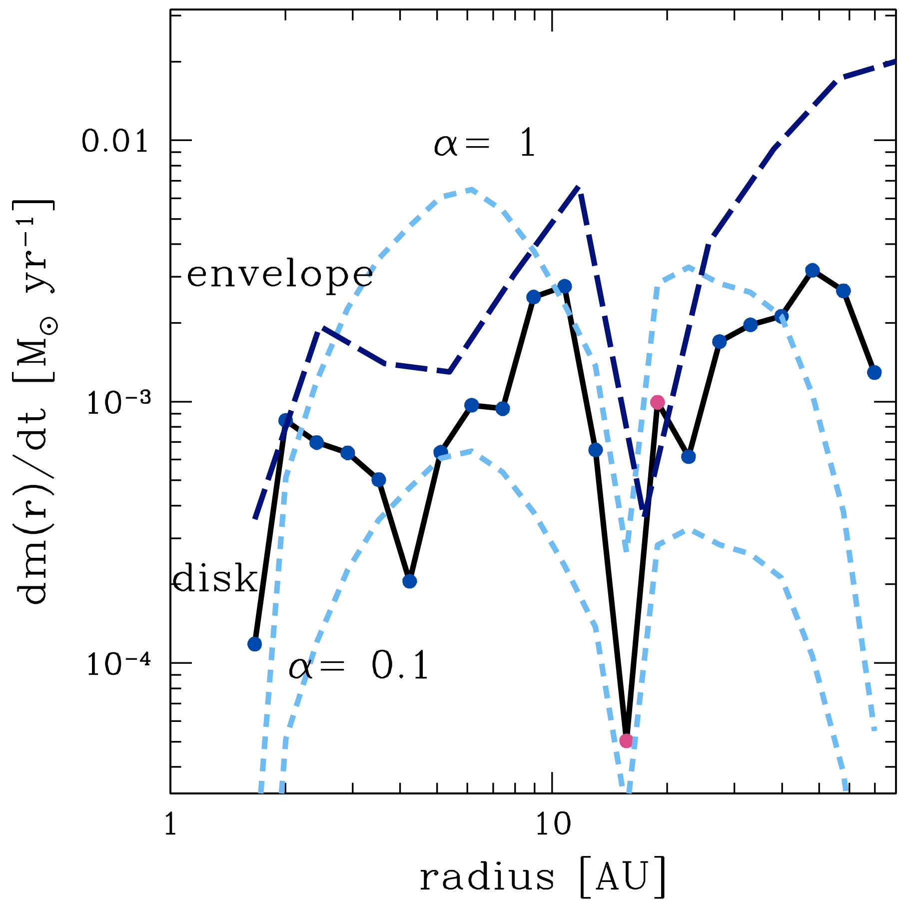


Figure 3: The mass transfer rate through the disk is denoted by the solid black line, while the mass infall rate through spherical shells with the specified radius is shown by the dark blue dashed line. The latter represents the total amount of material flowing through a given radius, and is thus a measure of the material flowing through *and onto* the disk at each radius. Both are shown at the onset of disk fragmentation. In the case of the disk accretion we have denoted annuli that are moving towards the protostar with blue dots, and those moving away in pink (further details can be found in Section 6 of the online material). 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. 2011b, Science, 331, 1040)

SPH study: comparison of all relevant heating and cooling processes

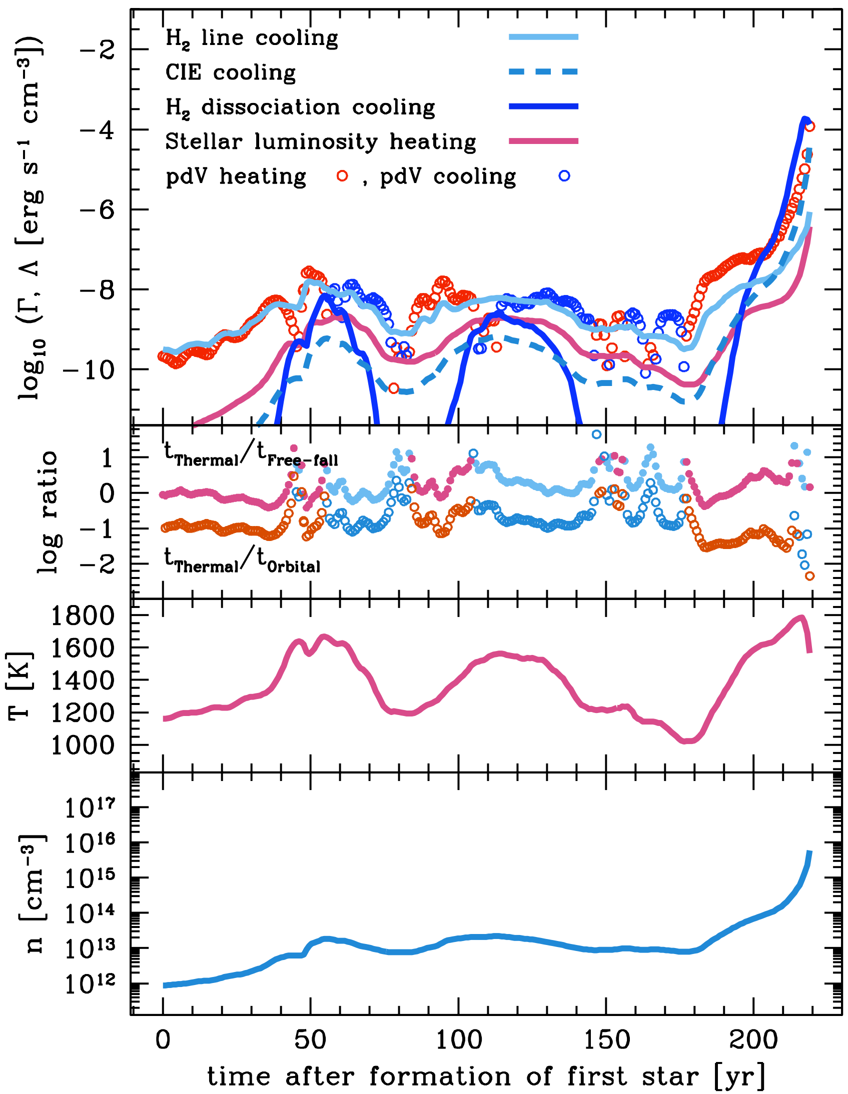
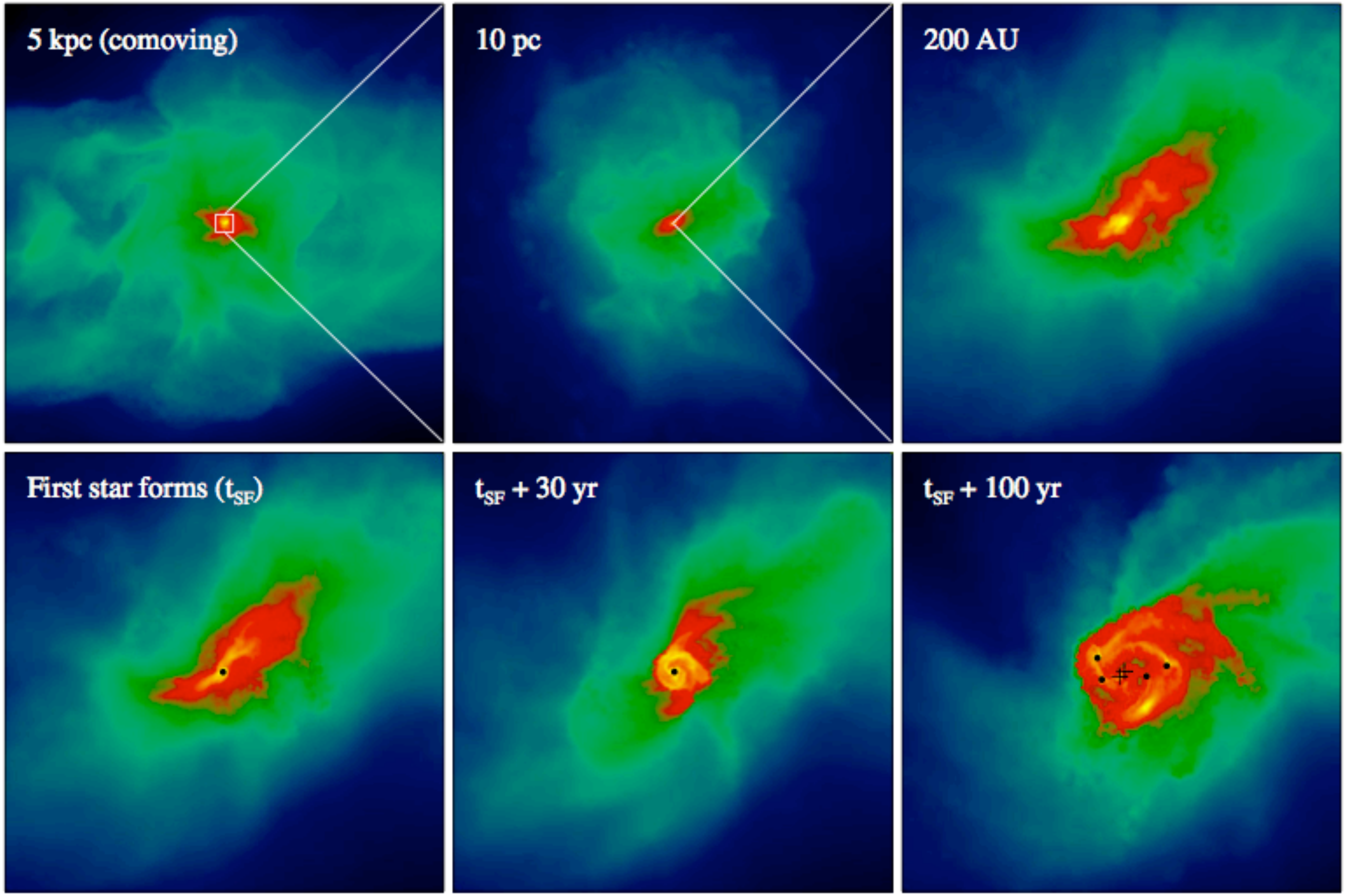


Figure 7: (a) Dominant heating and cooling processes in the gas that forms the second sink particle. (b) Upper line: ratio of the thermal timescale, $t_{\rm thermal}$, to the free-fall timescale, $t_{\rm ff}$, for the gas that forms the second sink particle. Periods when the gas is cooling are indicated in blue, while periods when the gas is heating are indicated in red. Lower line: ratio of $t_{\rm thermal}$ to the orbital timescale, $t_{\rm orbital}$, for the same set of SPH particles (c) Temperature evolution of the gas that forms the second sink (d) Density evolution of the gas that forms the second sink

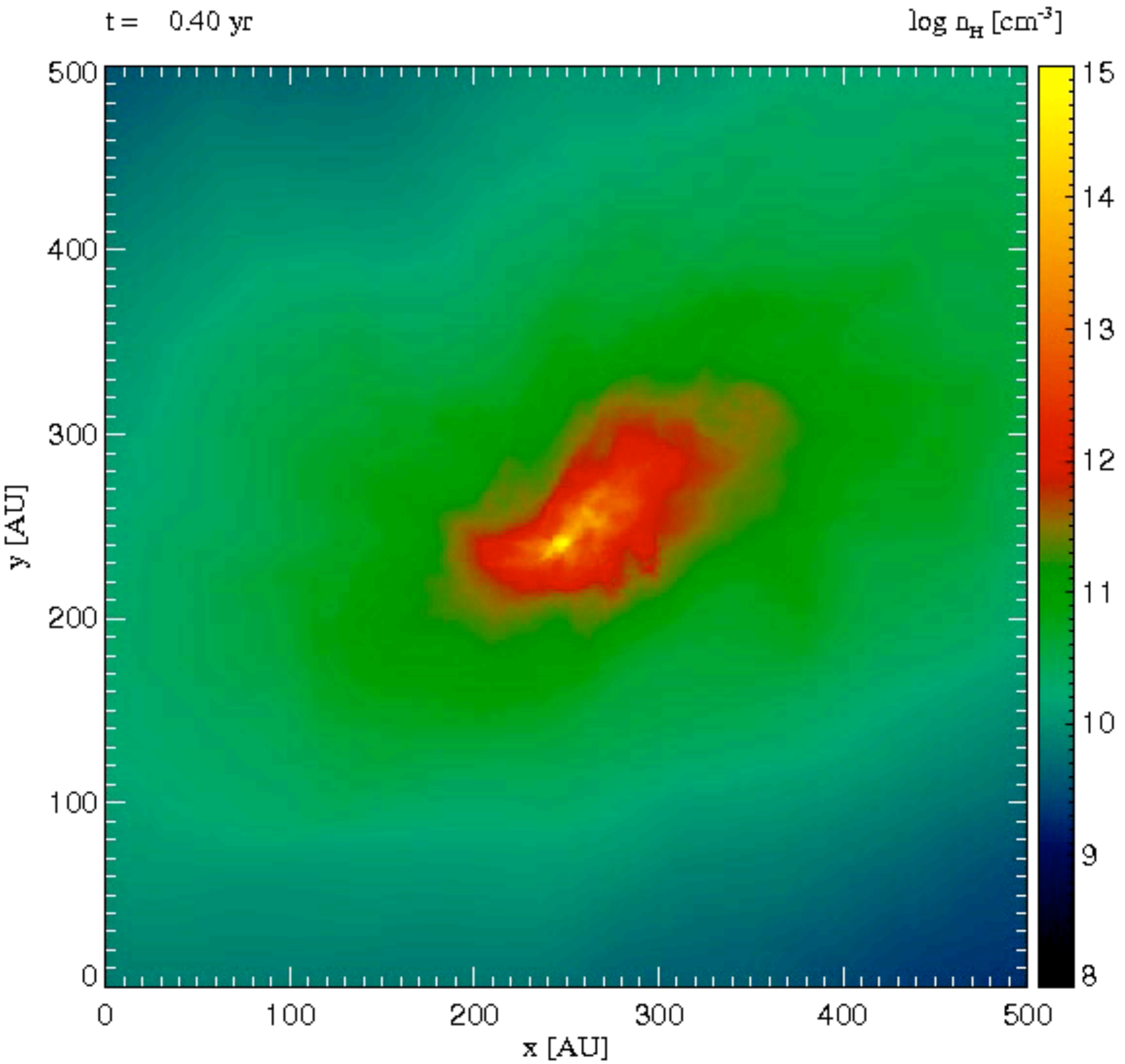
(Clark et al. 2011b, Science, 331, 1040)

Arepo study: surface density at different times



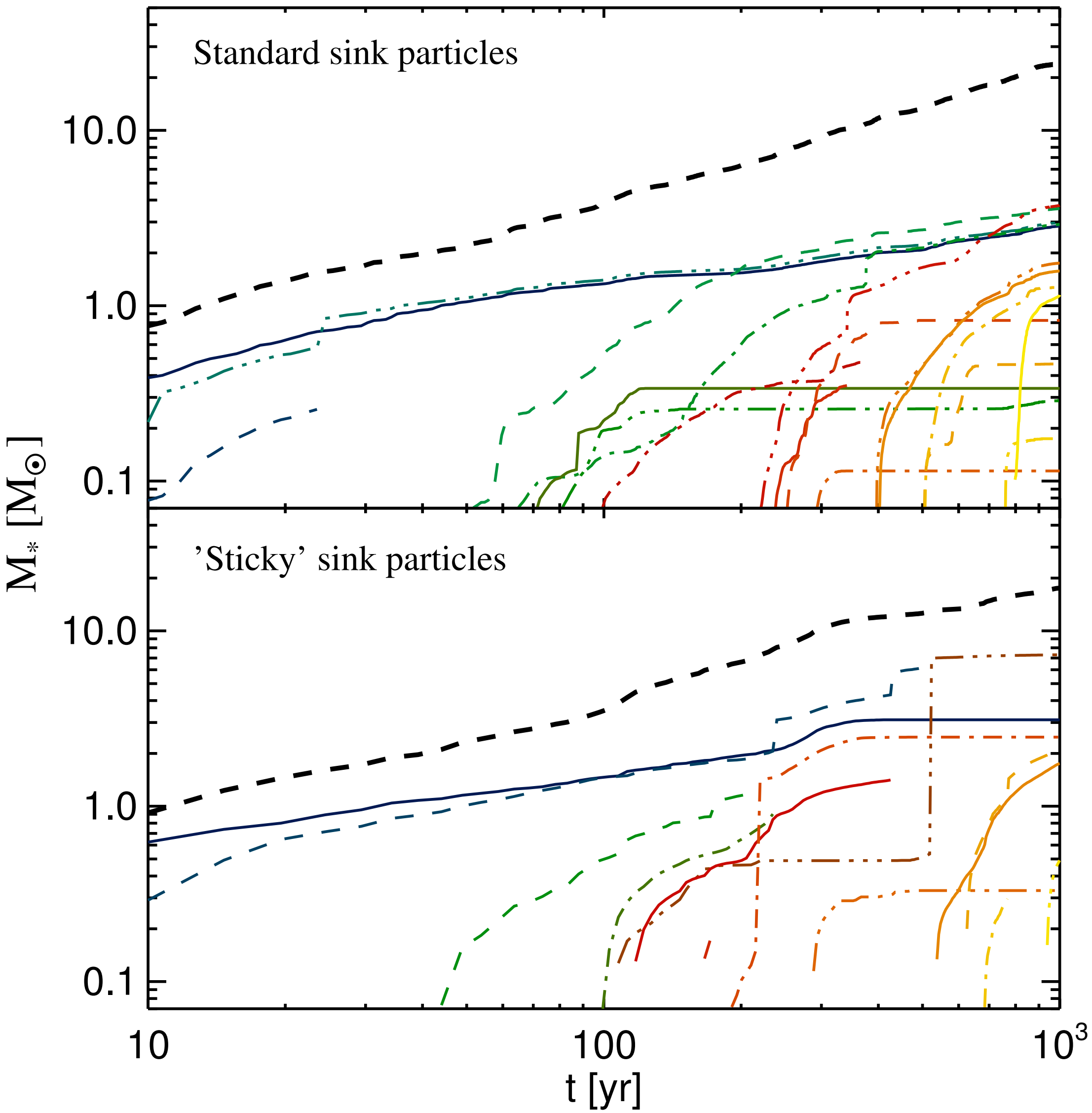
one out of five halos

(Greif et al. 2011a, submitted)



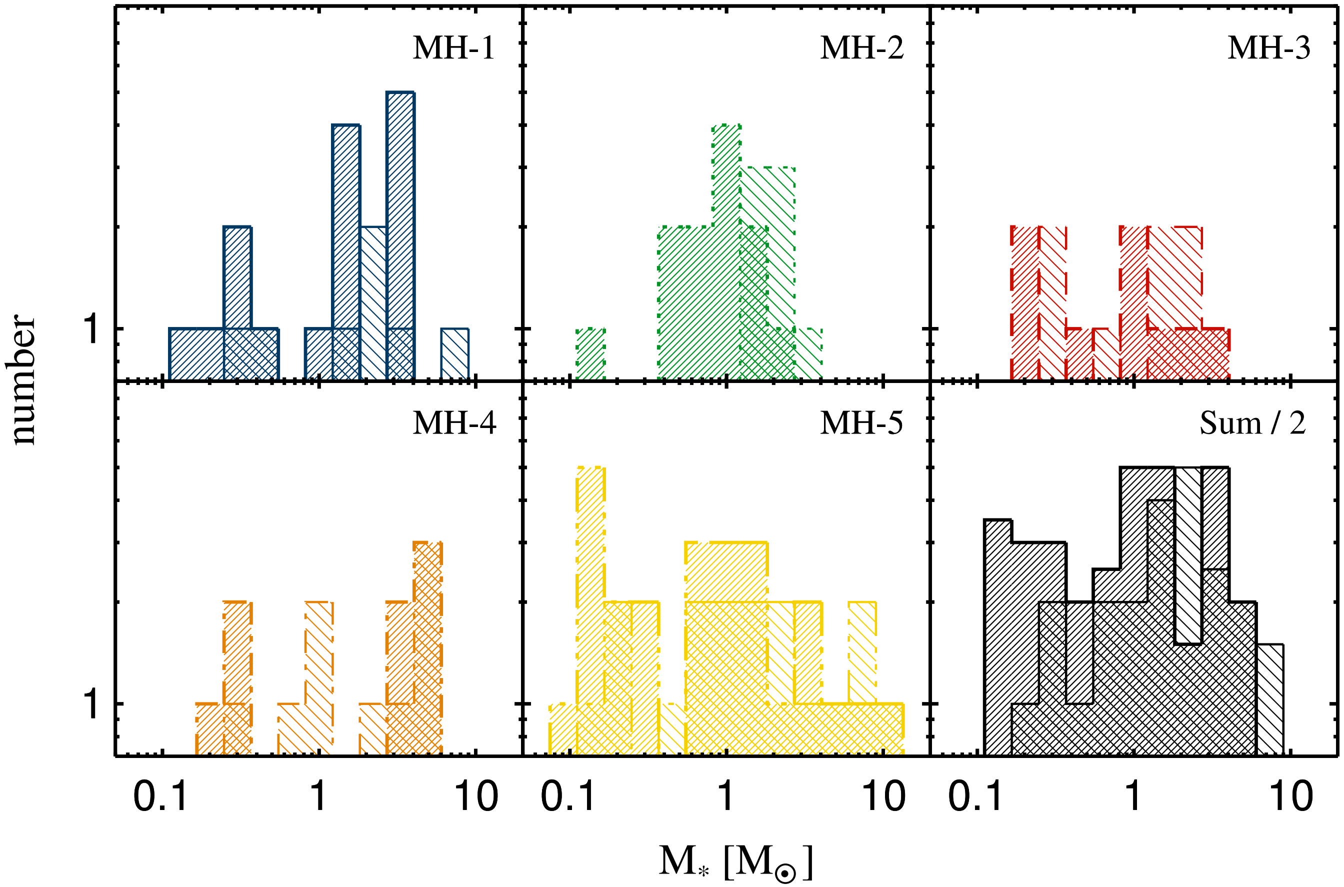
(Greif et al. 2011a, submitted)

Arepo study: protostellar mass accretion rates



(Greif et al. 2011a, submitted)

Arepo study: mass spectrum of fragments

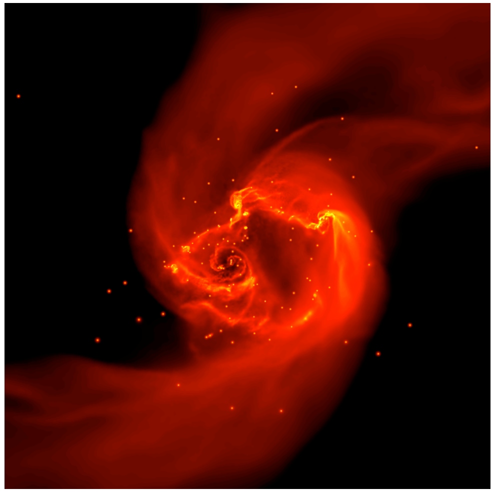


(Greif et al. 2011a, submitted)

primordial star formation

- just like in present-day SF, we expect
  - *turbulence*
  - *thermodynamics*
  - *magnetic fields*
  - *feedback*

  to influence Pop III/II star formation.

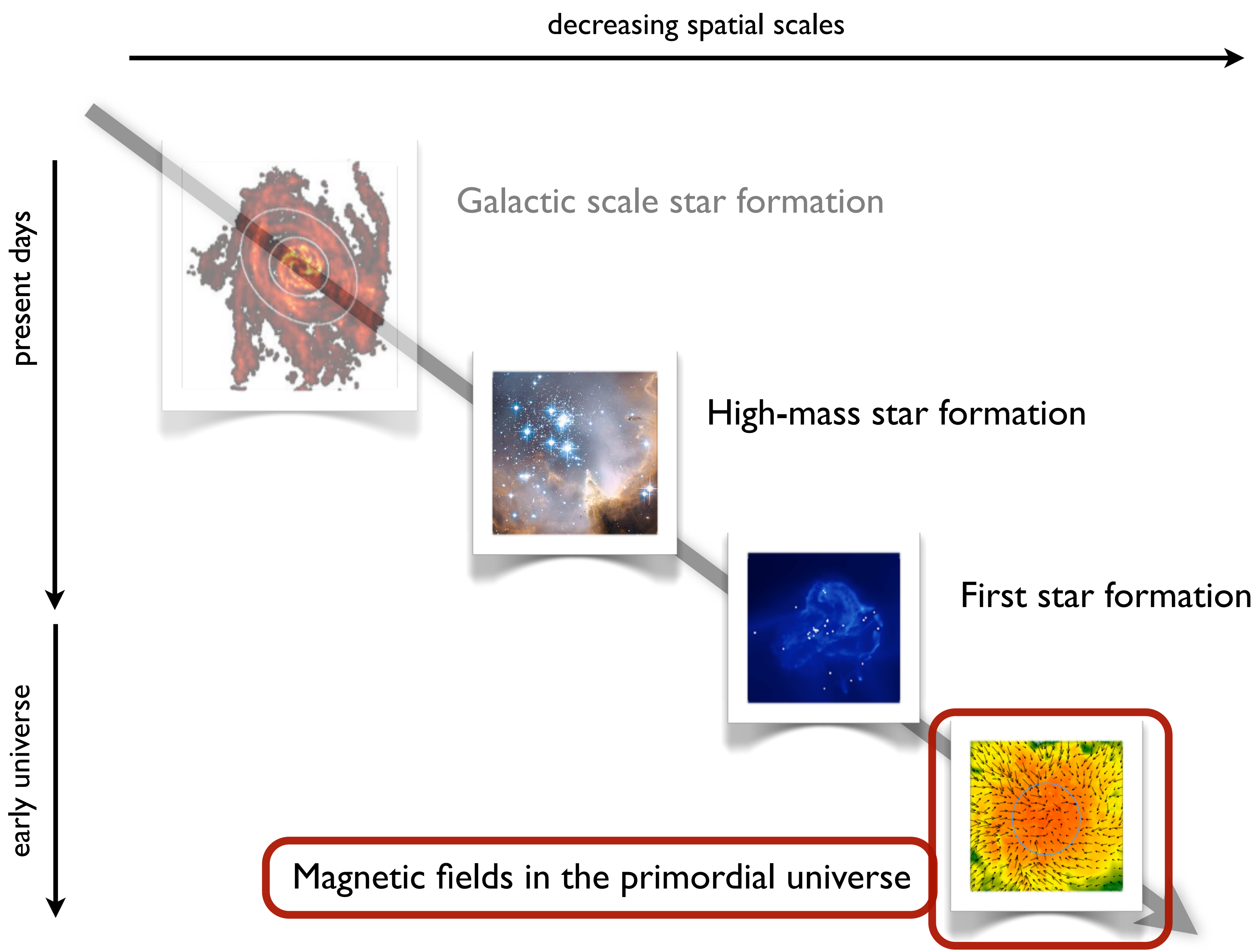


- masses of Pop III stars still *uncertain* (expect surprises from new generation of high-resolution calculations that go beyond first collapse)
- disks unstable: Pop III stars should be *binaries* or *part of small clusters*
- effects of feedback less important than in present-day SF

questions

- is claim of Pop III stars with $M \sim 0.5\ M_\odot$ really justified?
  - stellar collisions
  - magnetic fields
  - radiative feedback
- how would we find them?
  - spectral features
- where should we look?
- what about magnetic fields?

agenda

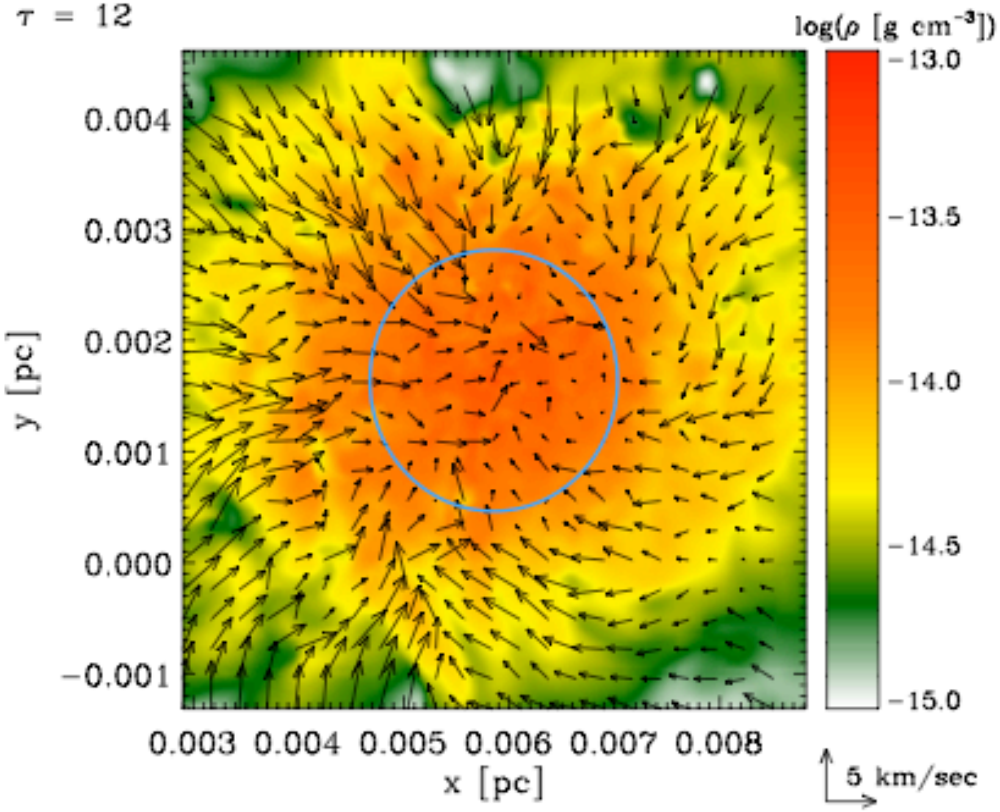

decreasing spatial scales
present days
early universe
Galactic scale star formation
High-mass star formation
First star formation
Magnetic fields in the primordial universe

B fields in the early universe?

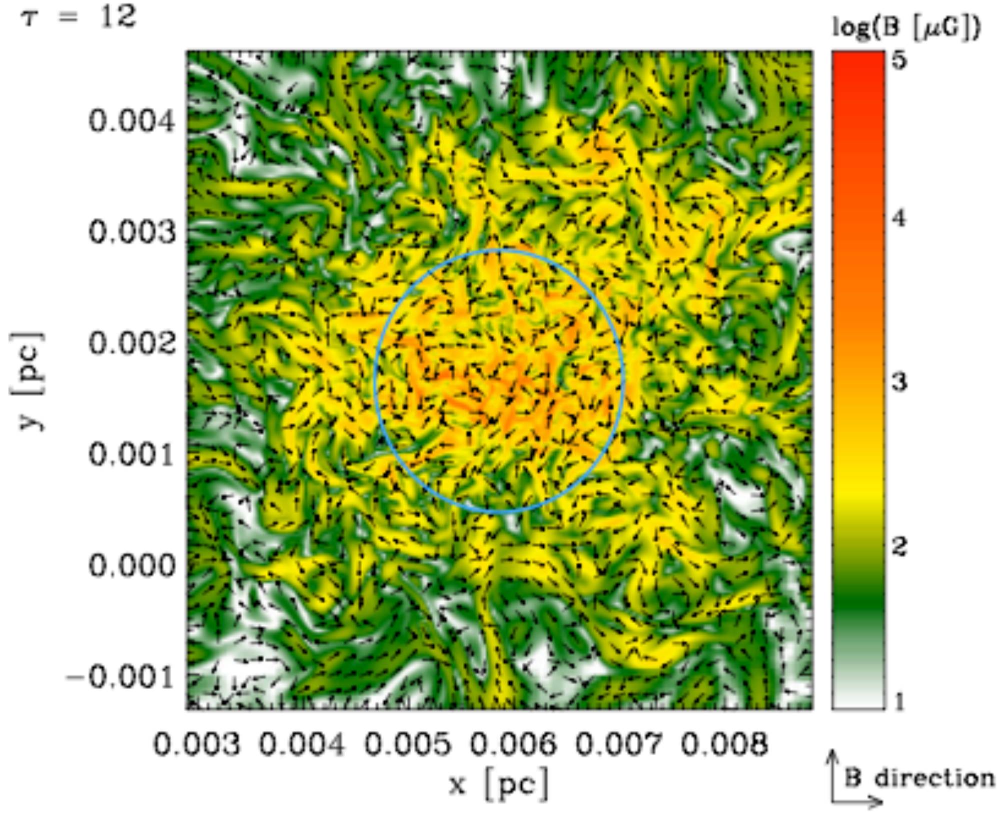
- we know the universe is magnetized (now)
- knowledge about B-fields in the high-redshift universe is extremely uncertain
  - inflation / QCD phase transition / Biermann battery / Weibel instability
- they are thought to be extremely small
- however, THIS MAY BE WRONG!

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 ~ 20
- *method:* solve ideal MHD equations with very high resolution
  - grid-based AMR code FLASH
    (effective resolution 65536^3)

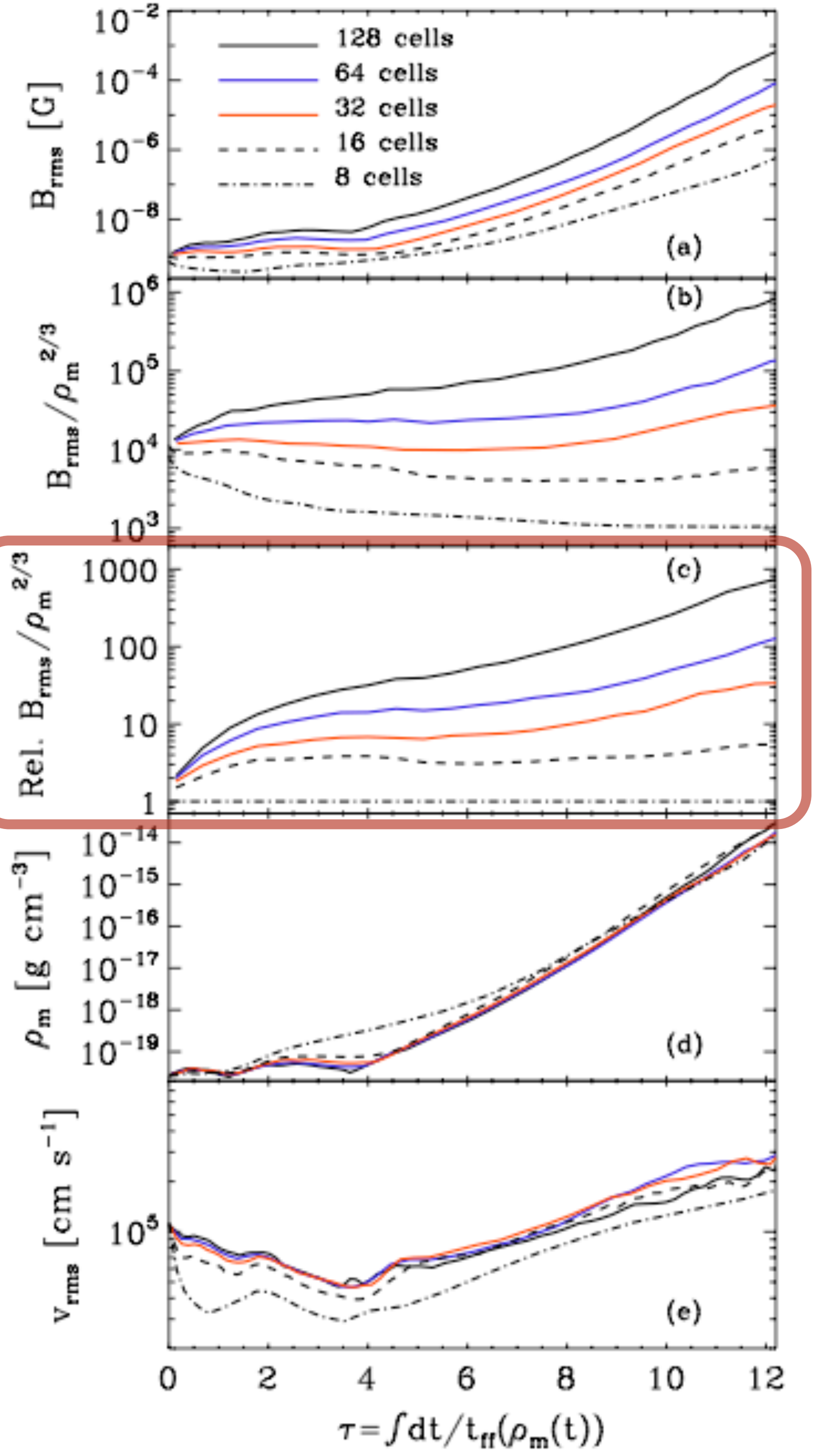


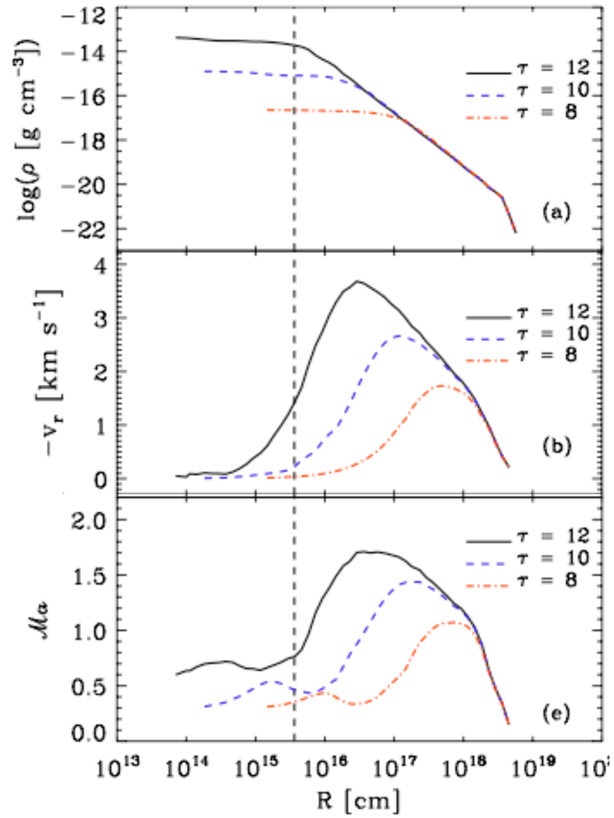
magnetic field structure



density structure

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





radial density profile

radial velocity profile

Mach number profile

Field amplification during first collapse seems unavoidable.

QUESTIONS:

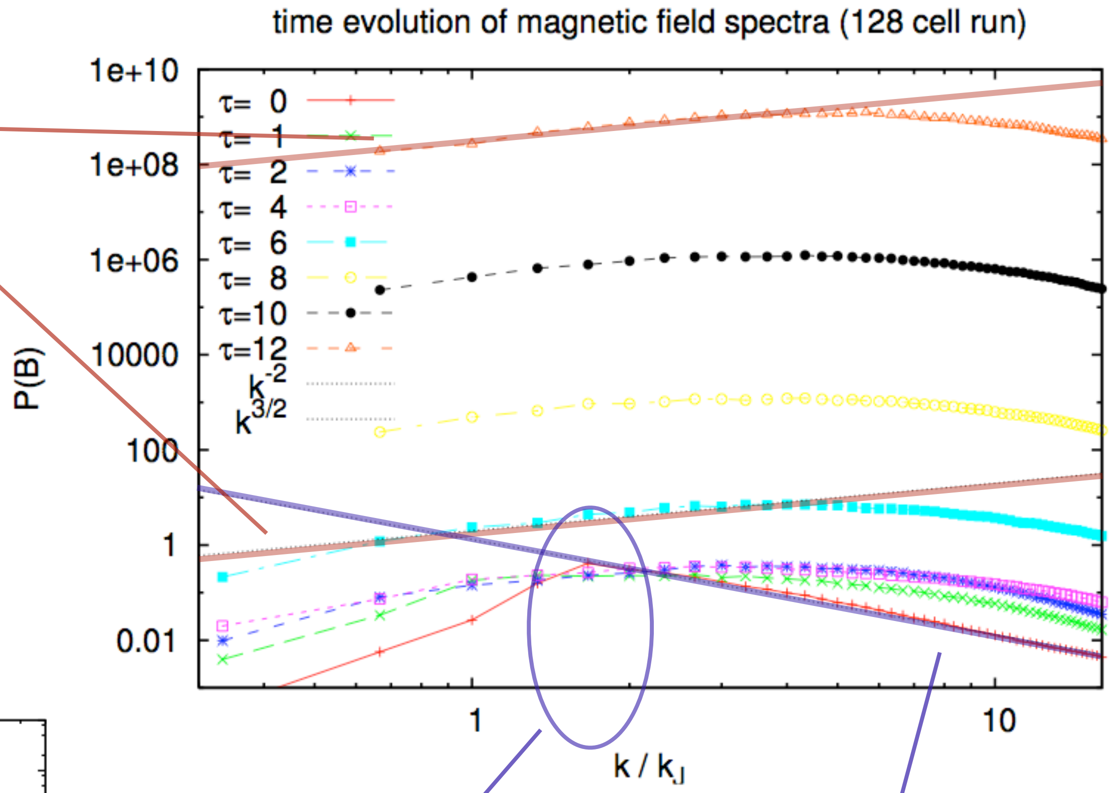
- Is it really the small scale dynamo?
- What is the saturation value?
  Can the field reach dynamically important strength?

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

analysis of magnetic field spectra

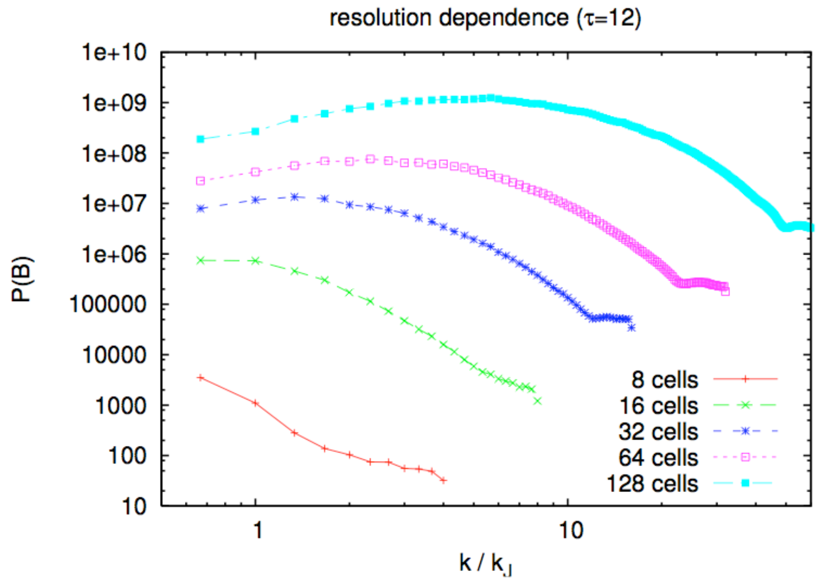
Slope +3/2 of
Kazantsev theory

(e.g. Brandenburg & Subramanian, 2005, Phys. Rep., 417, 1)



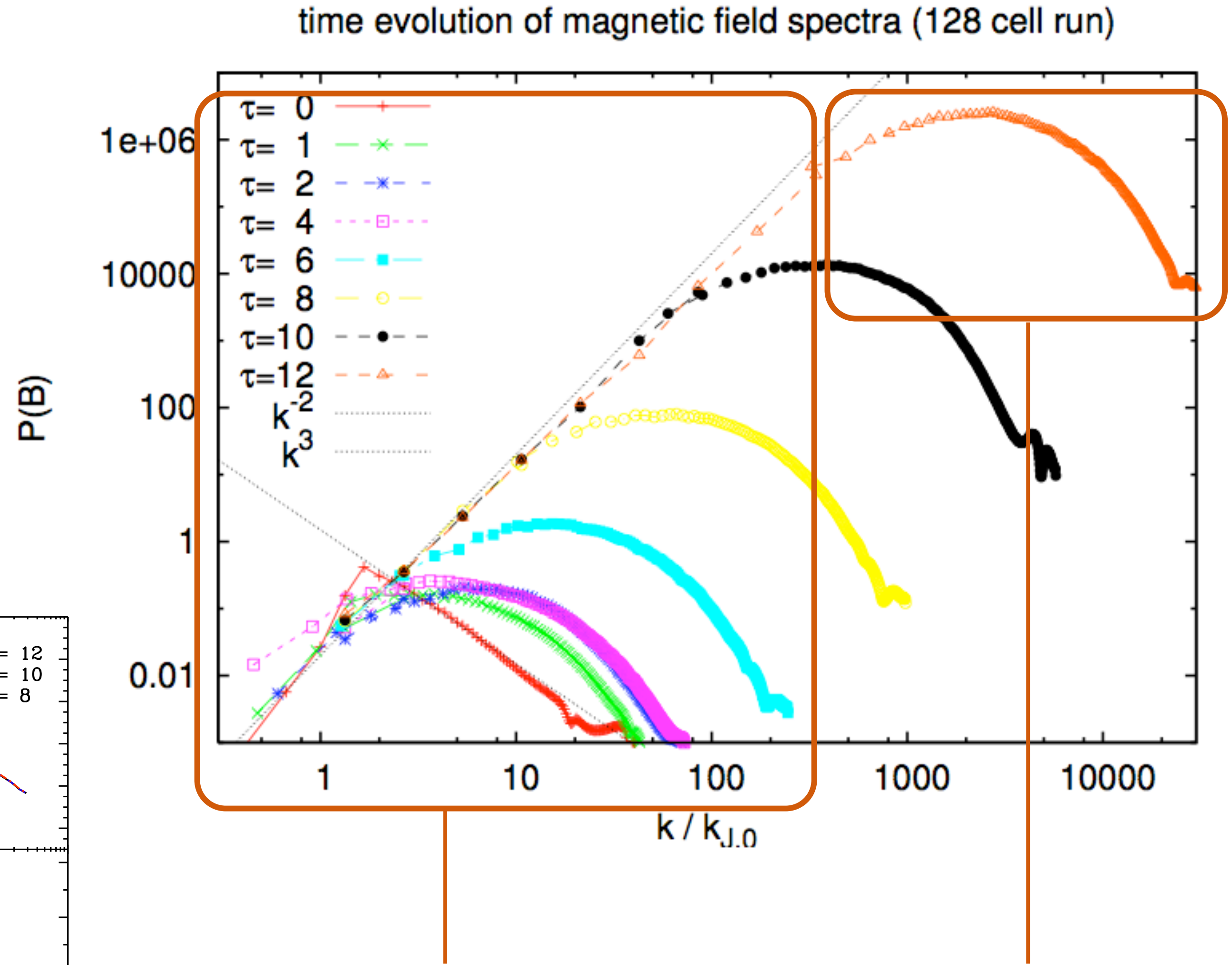
initial peak of
B fluctuation
spectrum

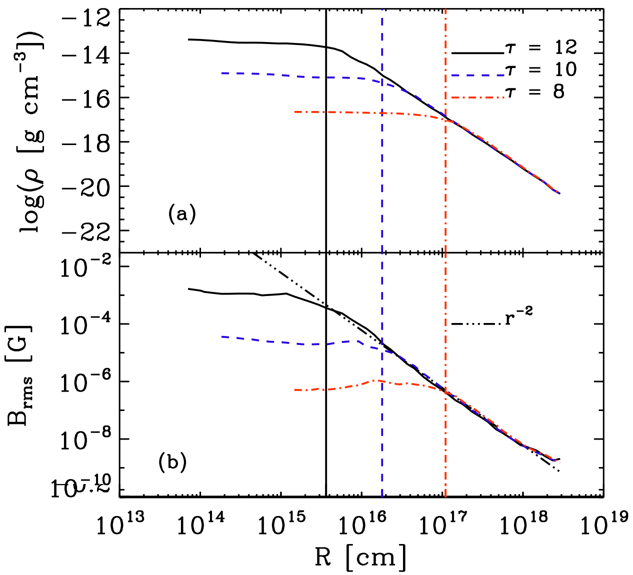
initial slope of
B fluctuations



(Federrath et al., 2010, ApJ)

analysis of magnetic field spectra



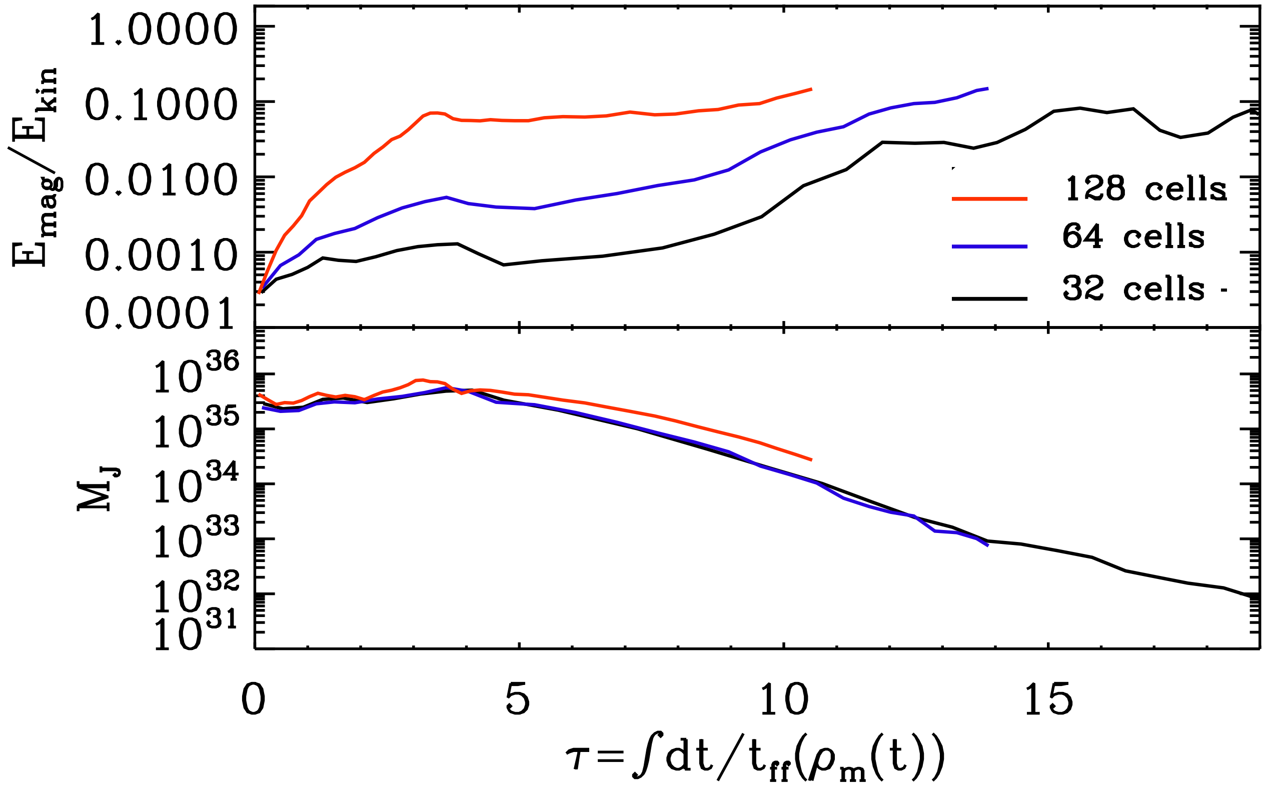


B fluctuation spectrum in $1/r^2$ fall-off

B fluctuation spectrum in flat inner core

(Federrath et al., 2010, ApJ)

first attempts to calculate the saturation level.



ratio of magnetic to kinetic energy

Jeans mass

We seem to get a saturation level of ~10% (see, e.g., Subramanian 1997, or Brandenburg & Subramanian 2005)

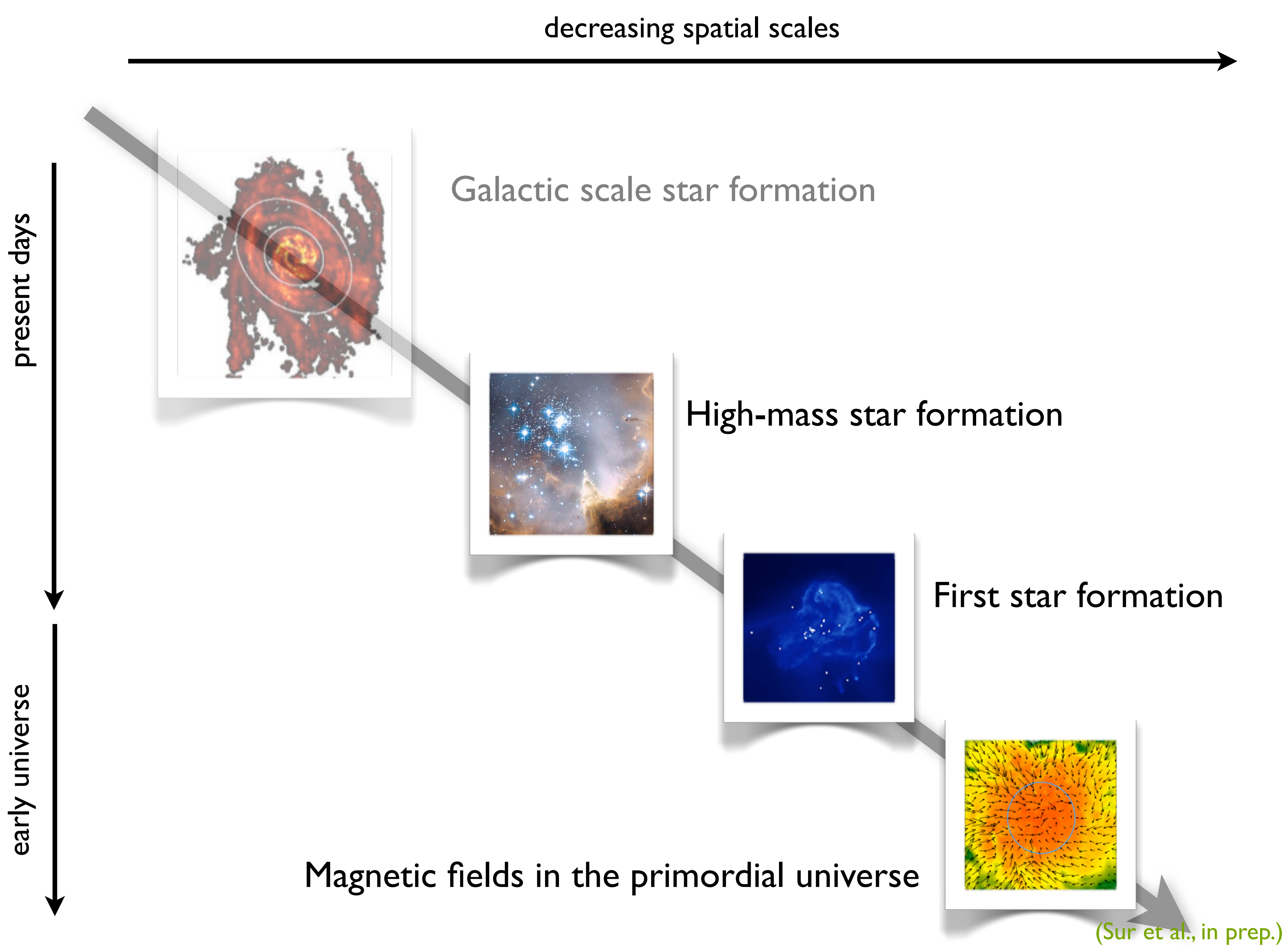
QUESTIONS:
- Is this true in a proper cosmological context?
- What does it mean for the formation of the first stars

(Sur et al., in prep.)

questions

- *small-scale turbulent dynamo* is expected to operate during Pop III star formation
- simple models indicate *saturation levels of ~10%* --> larger values via $\alpha\Omega$ dynamo?
- *QUESTIONS:*
  - does this hold for “proper” halo calculations (with chemistry and cosmological context)?
  - what is the strength of the seed magnetic field?

summary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present days
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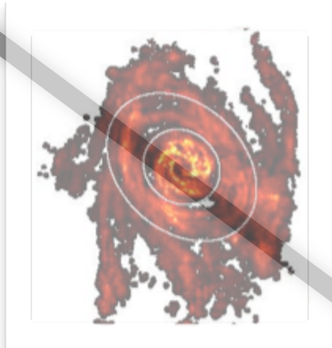
Magnetic fields in the primordial universe
(Sur et al., in prep.)

summary

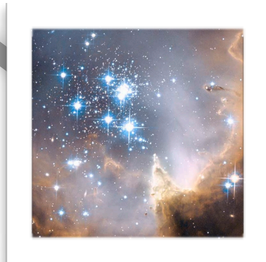
decreasing spatial scales

present days

early universe



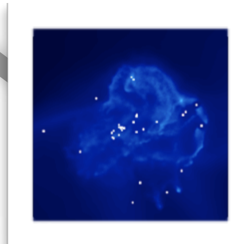
Galactic scale star formation



High-mass star formation:

What set upper stellar mass limit?

Can we see UC HII regions flicker?



First star formation:

Are there still Pop III stars around?

How can we see them? And where?

Magnetic fields in the primordial universe:

Is there a minimum primordial field?

What is the influence of B on Pop III star?