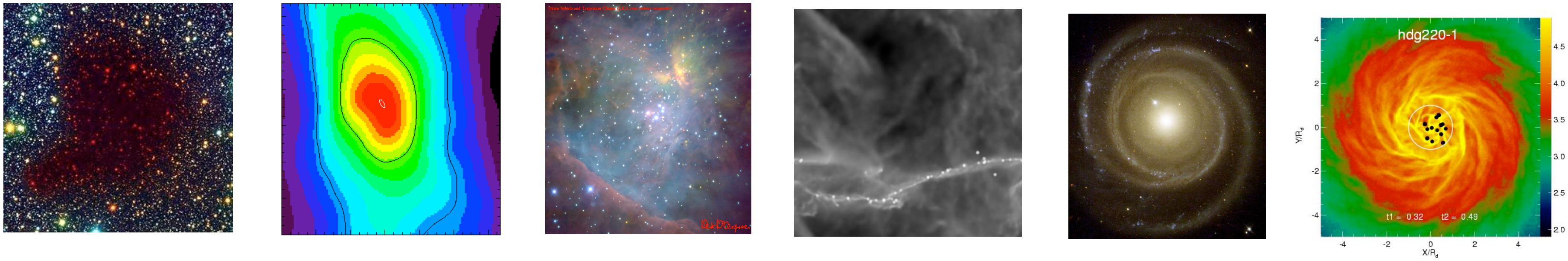
Possible Lessons from Present-Day Star Formation



Ralf Klessen

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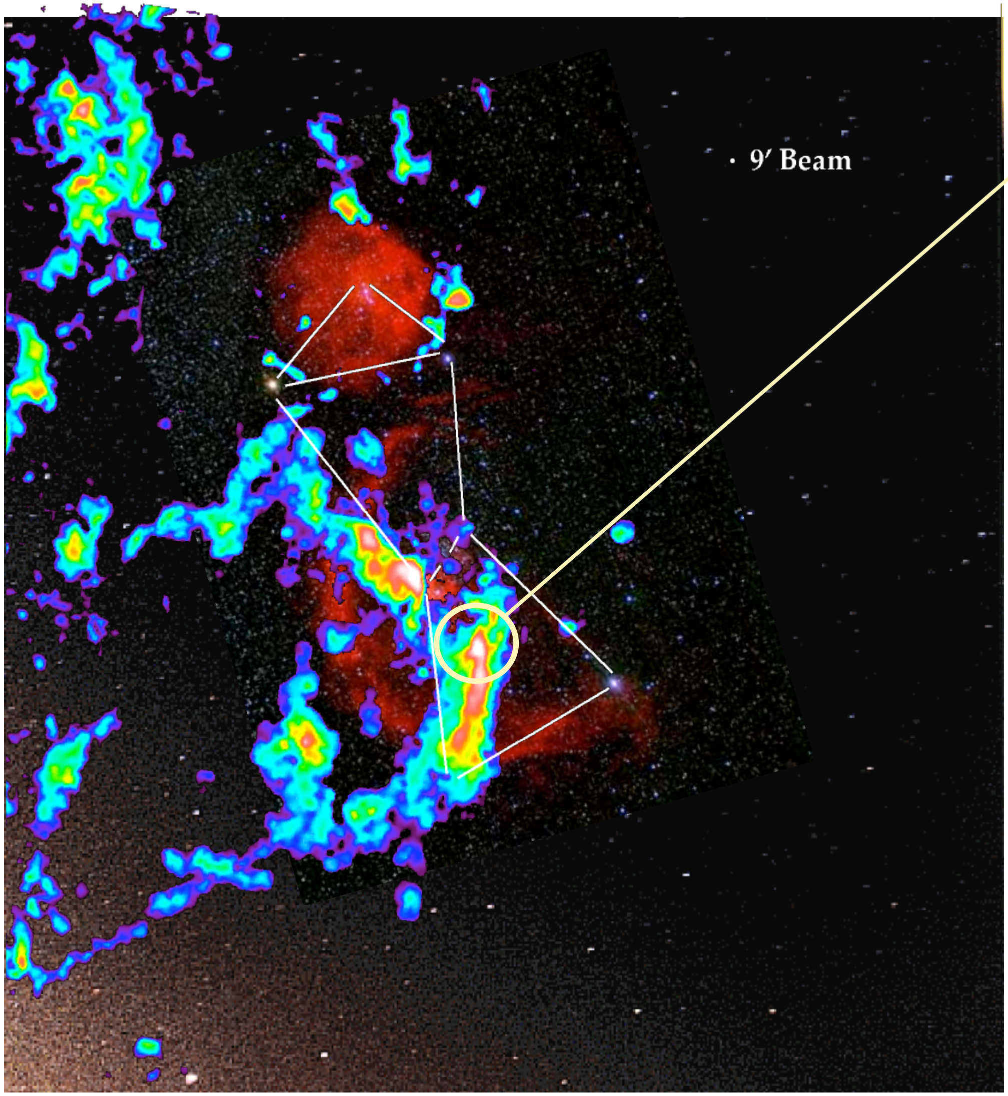
Institut für Theoretische Astrophysik

agenda

- some phenomenology
- processes that influence present-day SF and their possible relevance for high-z SF:
  - turbulence
  - thermodynamics
  - magnetic fields
  - feedback

example: Orion

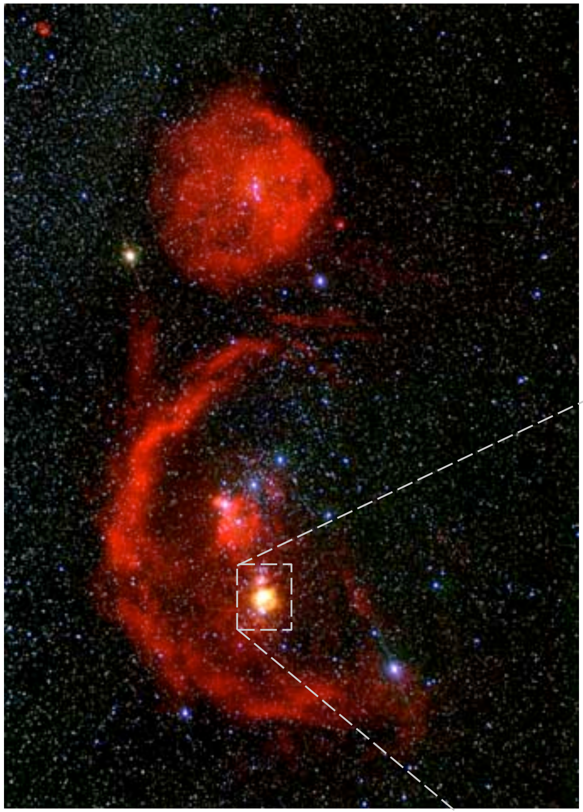


lets look at the Orion Nebula Cluster (ONC)

We see

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

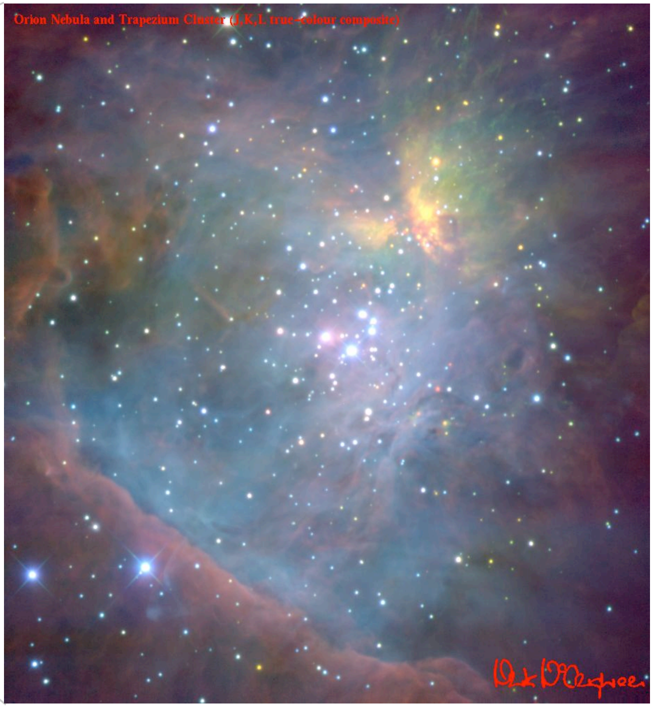
example: Orion



Orion molecular cloud

The Orion molecular cloud is the birthplace of several young embedded star clusters.

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



Trapezium cluster

example: Orion

Trapezium
Cluster

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

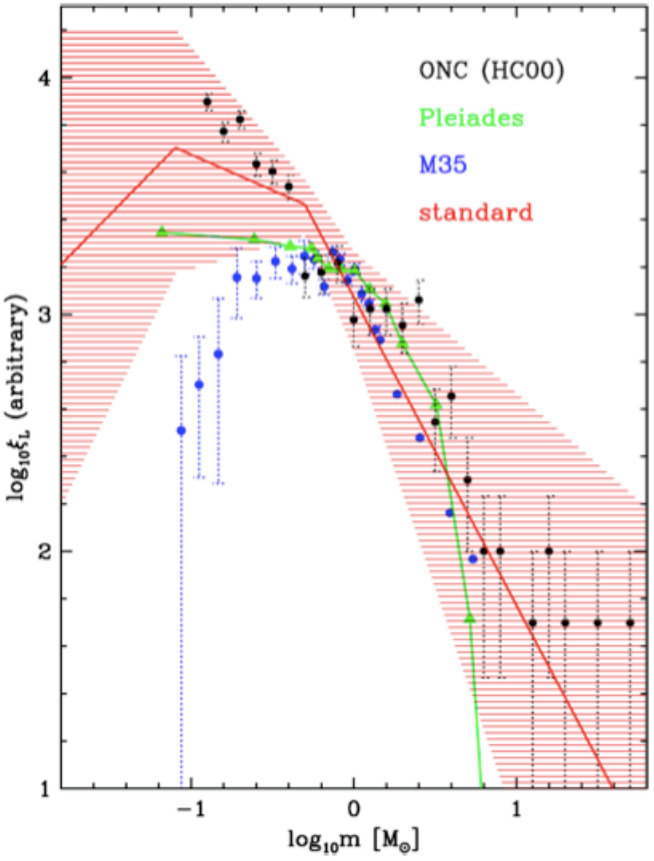
(color composite J,H,K
by M. McCaughrean,

NGC 602 in LMC

NGC 602 in the LMC: Hubble Heritage Image

end of formation phase: star cluster with HII region

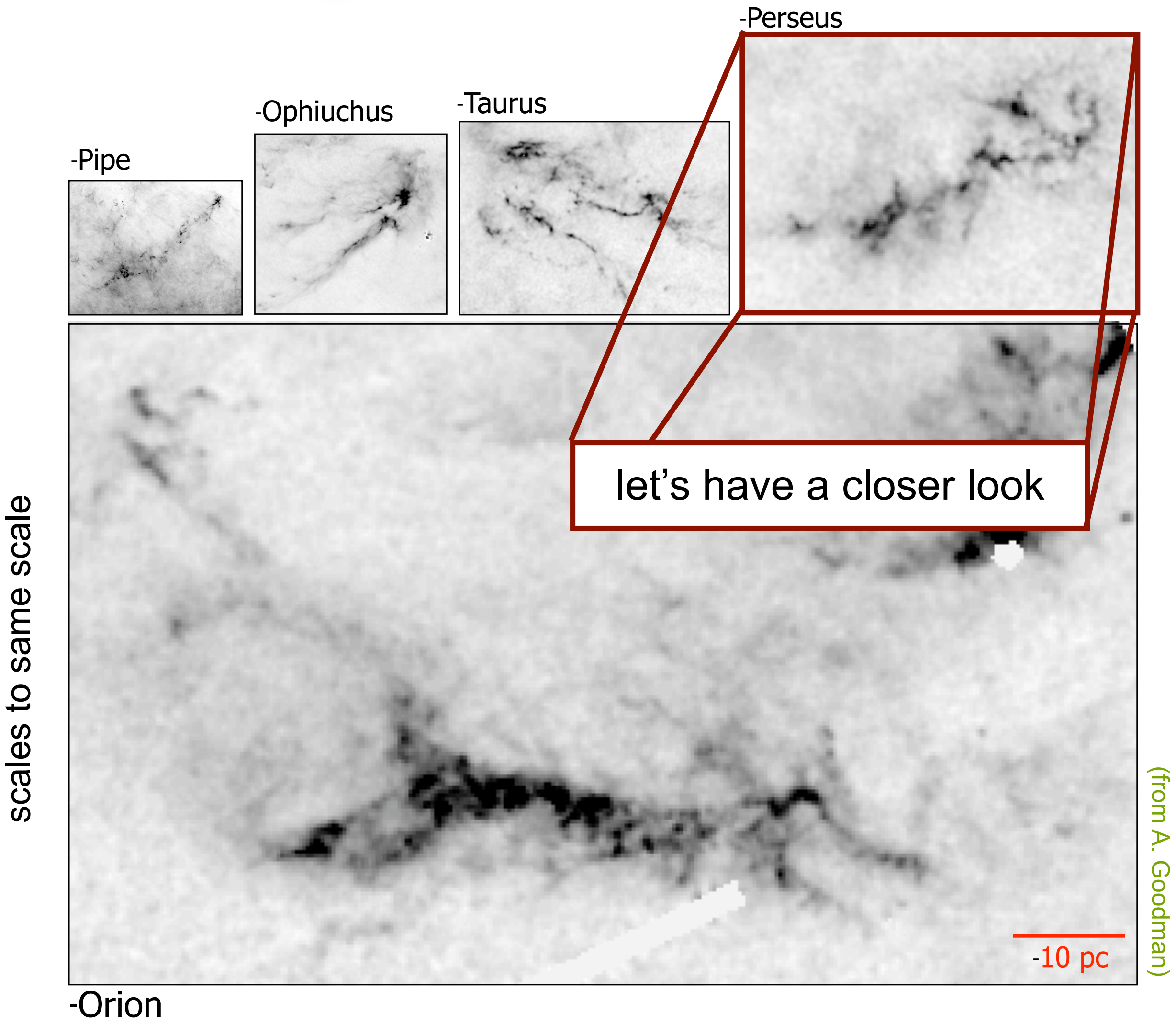
stellar mass function



(Kroupa 2002, Science, 295, 82)

Orion, NGC 3603, 30 Doradus (Zinnecker & Yorke 2007, ARAA, 45, 481)

nearby molecular clouds



let’s have a closer look

scales to same scale

(from A. Goodman)

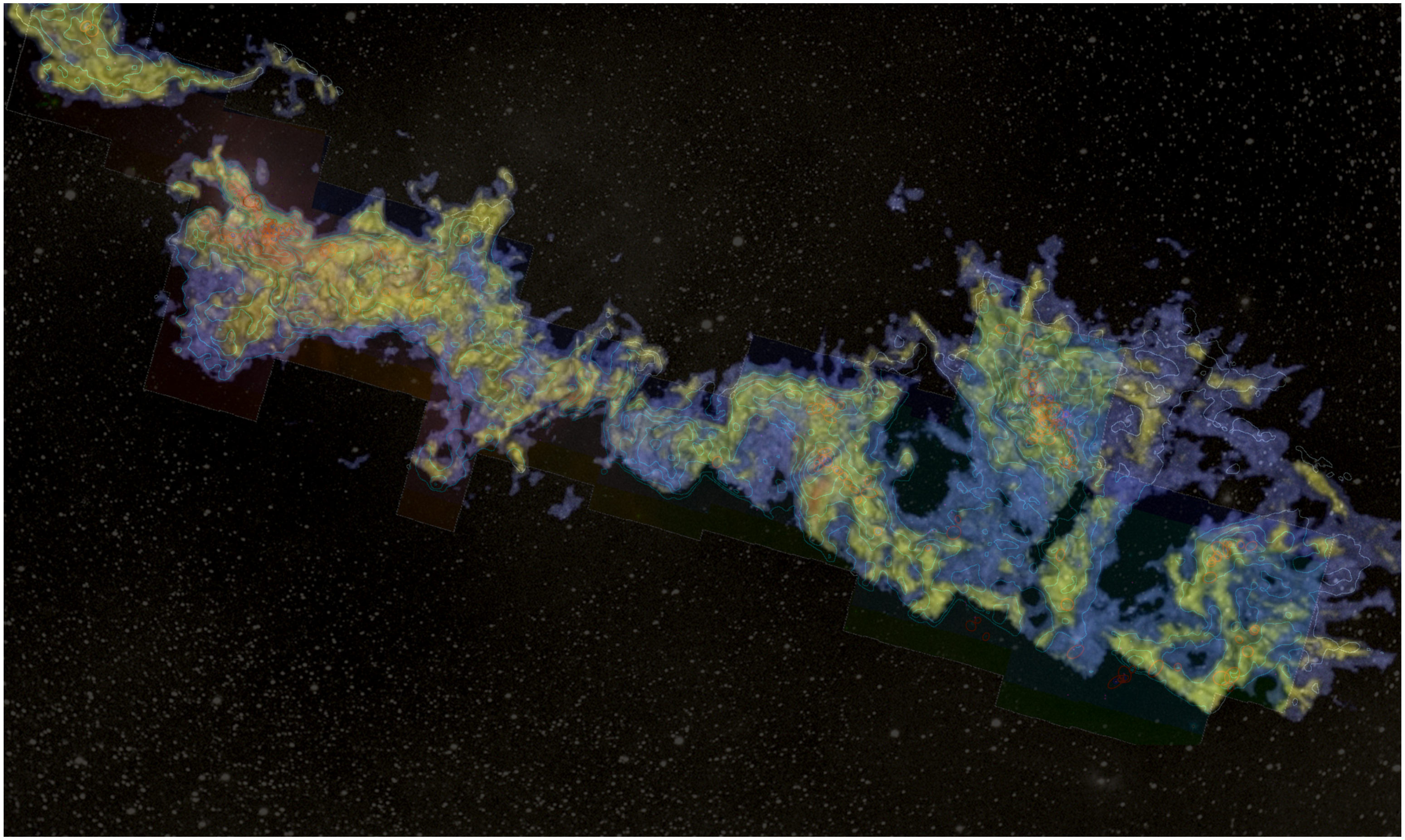


image from Alyssa Goodman: COMPLETE survey

agenda

- some phenomenology
- processes that influence present-day SF and their possible relevance for high-z SF:
  - turbulence
  - thermodynamics
  - magnetic fields
  - feedback

agenda

- some phenomenology
- processes that influence present-day SF and their possible relevance for high-z SF:
  - *turbulence plus cluster environment*
  - thermodynamics
  - magnetic fields
  - feedback

example: model of Orion

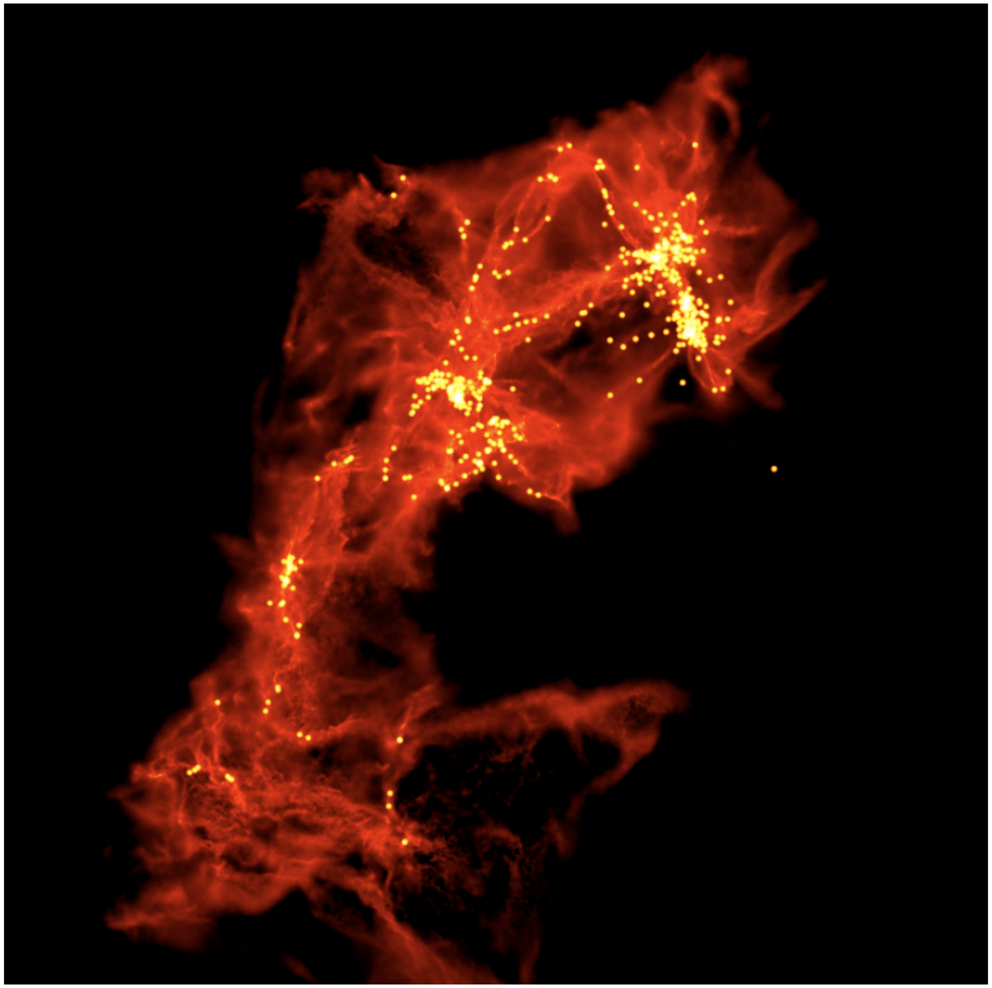
„model“ of Orion cloud: 15.000.000 SPH particles, 10^4 M_{sun} in 10 pc, mass resolution 0,02 M_{sun}, forms ~2.500 „stars“ (sink particles)

isothermal EOS, top bound, bottom unbound

has clustered as well as distributed „star“ formation

efficiency varies from 1% to 20%

develops full IMF (distribution of sink particle masses)



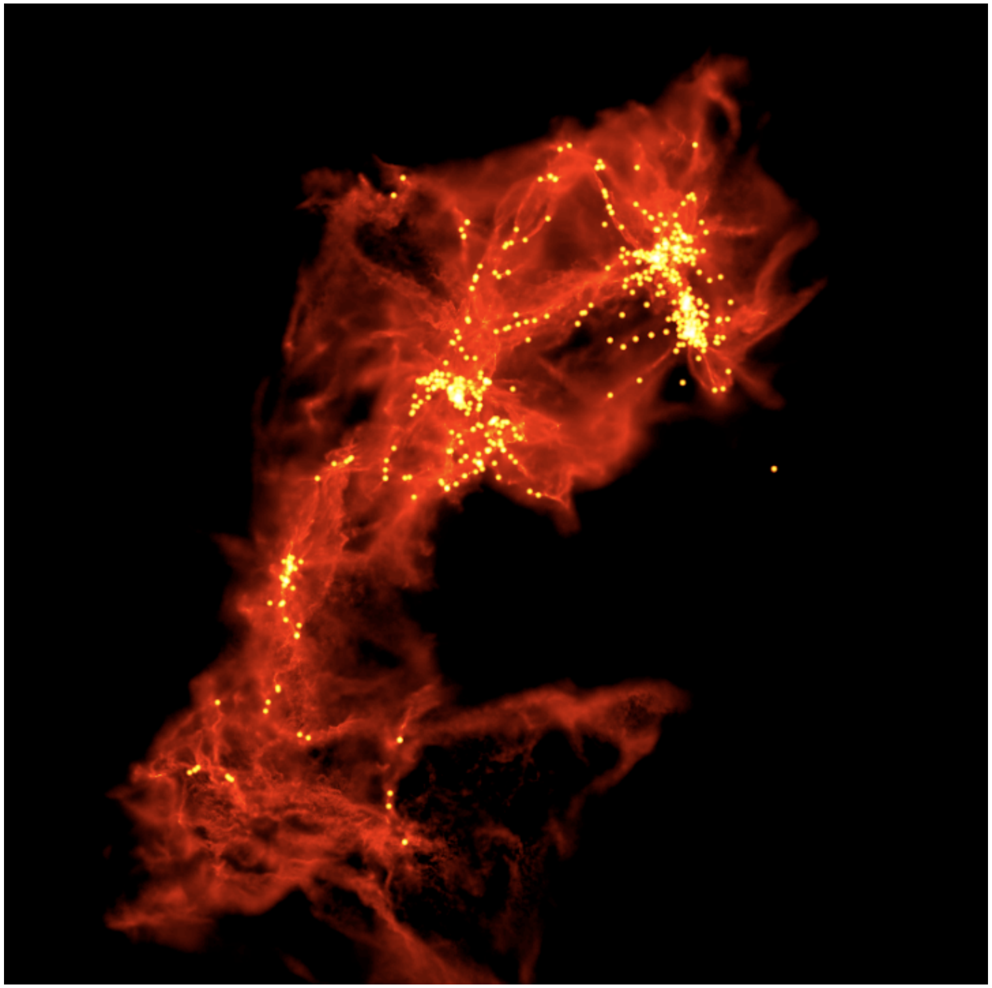
(calculation by Ian Bonnell & Paul Clark)

example: model of Orion

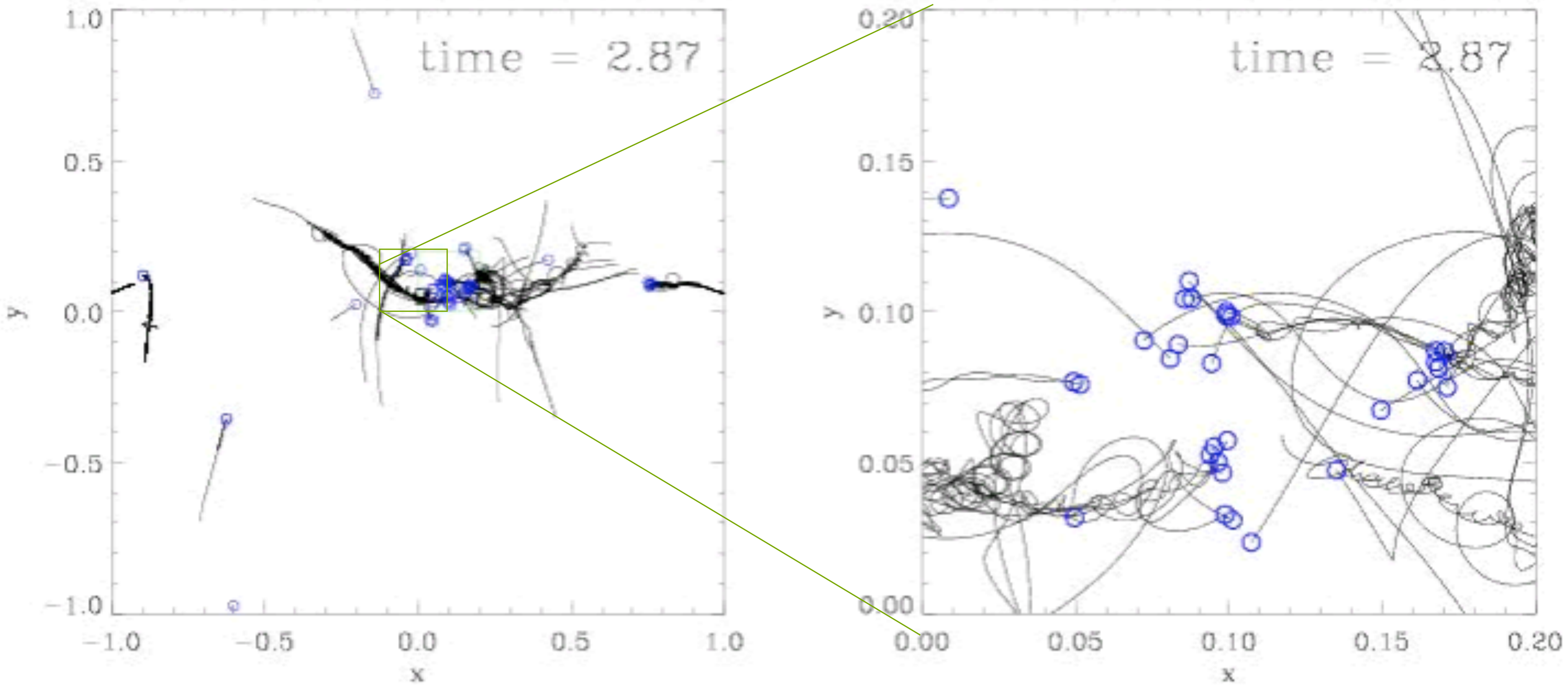
„model“ of Orion cloud:
15.000.000 SPH particles,
10^4 M_{sun} in 10 pc, mass
resolution 0,02 M_{sun}, forms
~2.500 „stars“ (sink particles)

MASSIVE STARS
- form early in high-density gas clumps (cluster center)
- high accretion rates, maintained for a long time

LOW-MASS STARS
- form later as gas falls into potential well
- high relative velocities
- little subsequent accretion



(calculation by Ian Bonnell & Paul Clark) in dense clusters protostellar interaction may be come important!



Trajectories of protostars in a nascent dense cluster created by gravoturbulent fragmentation
(from Klessen & Burkert 2000, ApJS, 128, 287)

turbulence leads to fragmentation

- this is true even for Z=0 (see talk by *Paul Clark*)

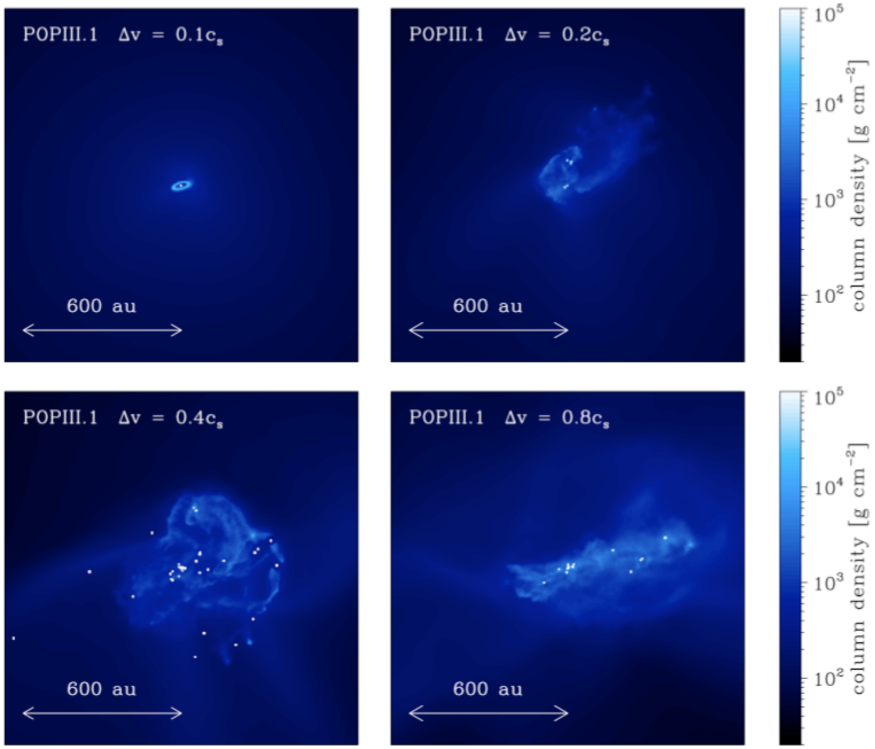


FIG. 1.— The column density images show the state of the POPIII.1 clouds after they have accreted 10 percent of their mass (100 $M_\odot$). The sink particles are denoted in the images by the white dots. In our lowest level of turbulence in which $\Delta v = 0.1c_s$, the velocities contain enough angular momentum to produce a disk around the sink particle. However once the strength of the initial velocities is increased – to as little as 0.2 times the initial sound speed in the gas – the turbulence leads to fragmentation of the gas. At the point at which the simulations are shown here, the 0.1, 0.2, 0.4 and 0.8 c_s have produced 1, 6, 34 and 17 sink particles respectively.

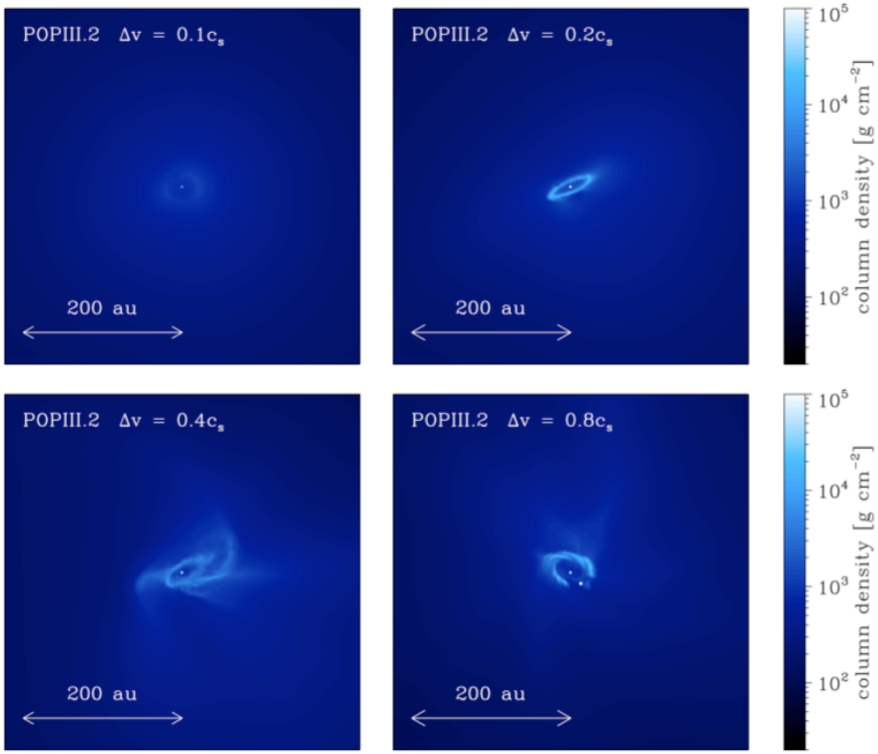


FIG. 2.— Similar to Fig 1, the column density images show the state of the POPIII.2 clouds after they have accreted 10 percent of their mass (15 $M_\odot$). Note that the scale in this figure differs from that in Fig 1. The clouds exhibit a different behaviour from their POPIII.1 counterparts. Although the clouds all form disks around their sink particles, due to the angular momentum contained in the initial turbulent motions, only the $\Delta v = 0.8c_s$ turbulent cloud has undergone fragmentation by this point in the evolution.

turbulence leads to fragmentation

- this is true even for $Z=0$
  (see talk by *Paul Clark*)

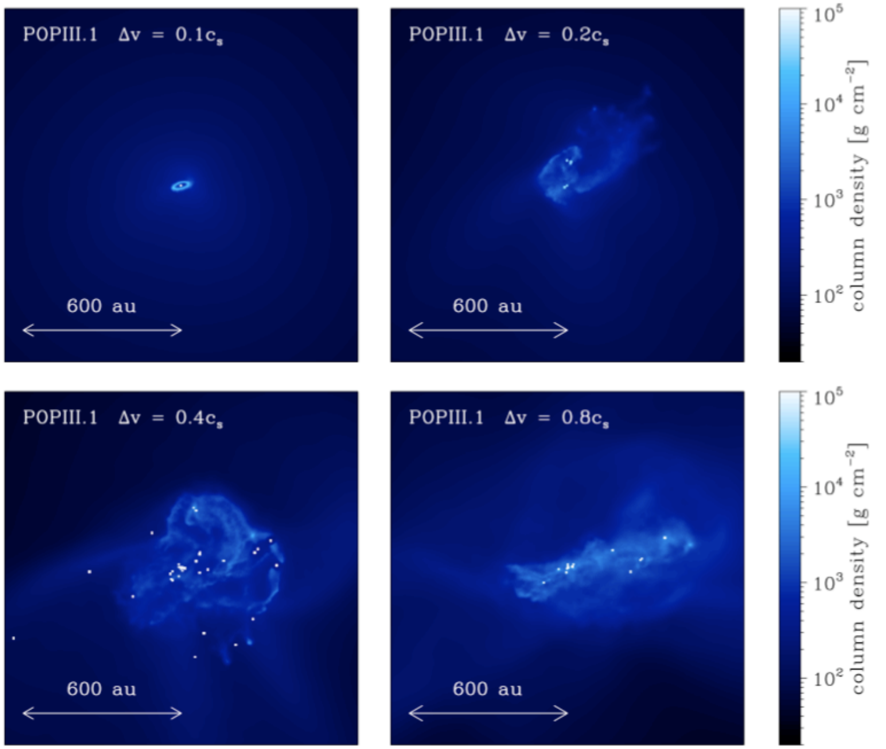
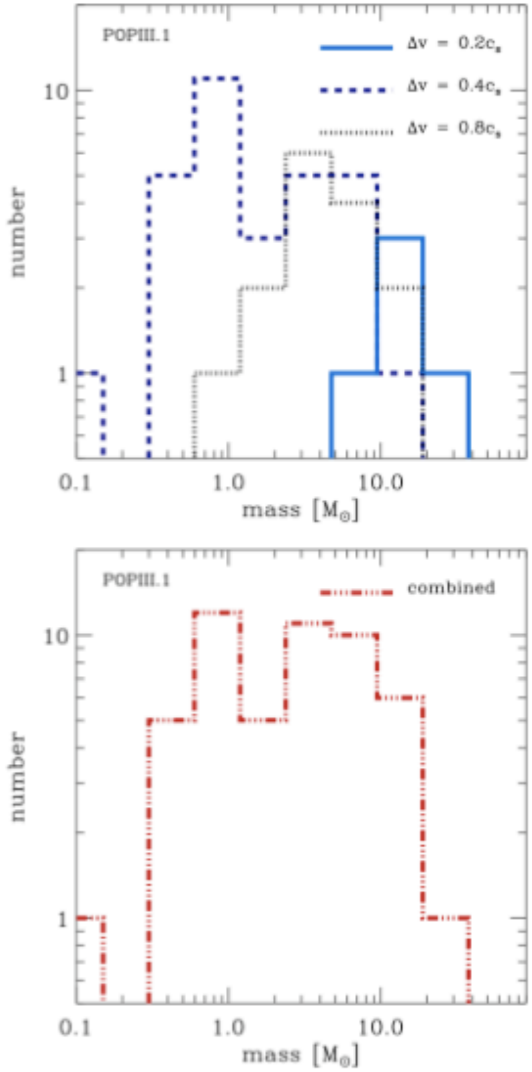


FIG. 1.— The column density images show the state of the POPIII.1 clouds after they have accreted 10 percent of their mass (100 $M_\odot$). The sink particles are denoted in the images by the white dots. In our lowest level of turbulence in which $\Delta v = 0.1 c_s$, the velocities contain enough angular momentum to produce a disk around the sink particle. However once the strength of the initial velocities is increased – to as little as 0.2 times the initial sound speed in the gas – the turbulence leads to fragmentation of the gas. At the point at which the simulations are shown here, the 0.1, 0.2, 0.4 and 0.8 c_s have produced 1, 6, 34 and 17 sink particles respectively.



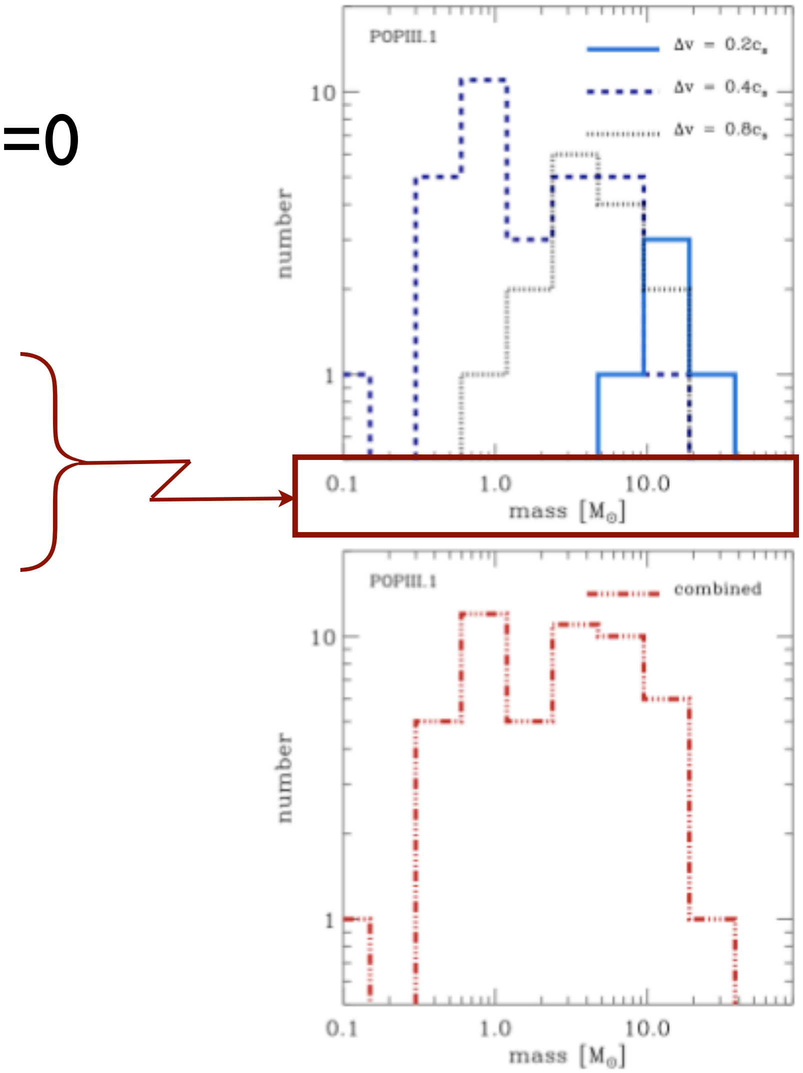
turbulence leads to fragmentation

- this is true even for $Z=0$
  (see talk by *Paul Clark*)

- full stellar mass range from brown dwarf regime onwards?

- it could be that Pop III.2 stars are more massive than Pop III.1

- key questions: which processes could prevent or weaken fragmentation?



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  - *thermodynamics (balance heating / cooling)*
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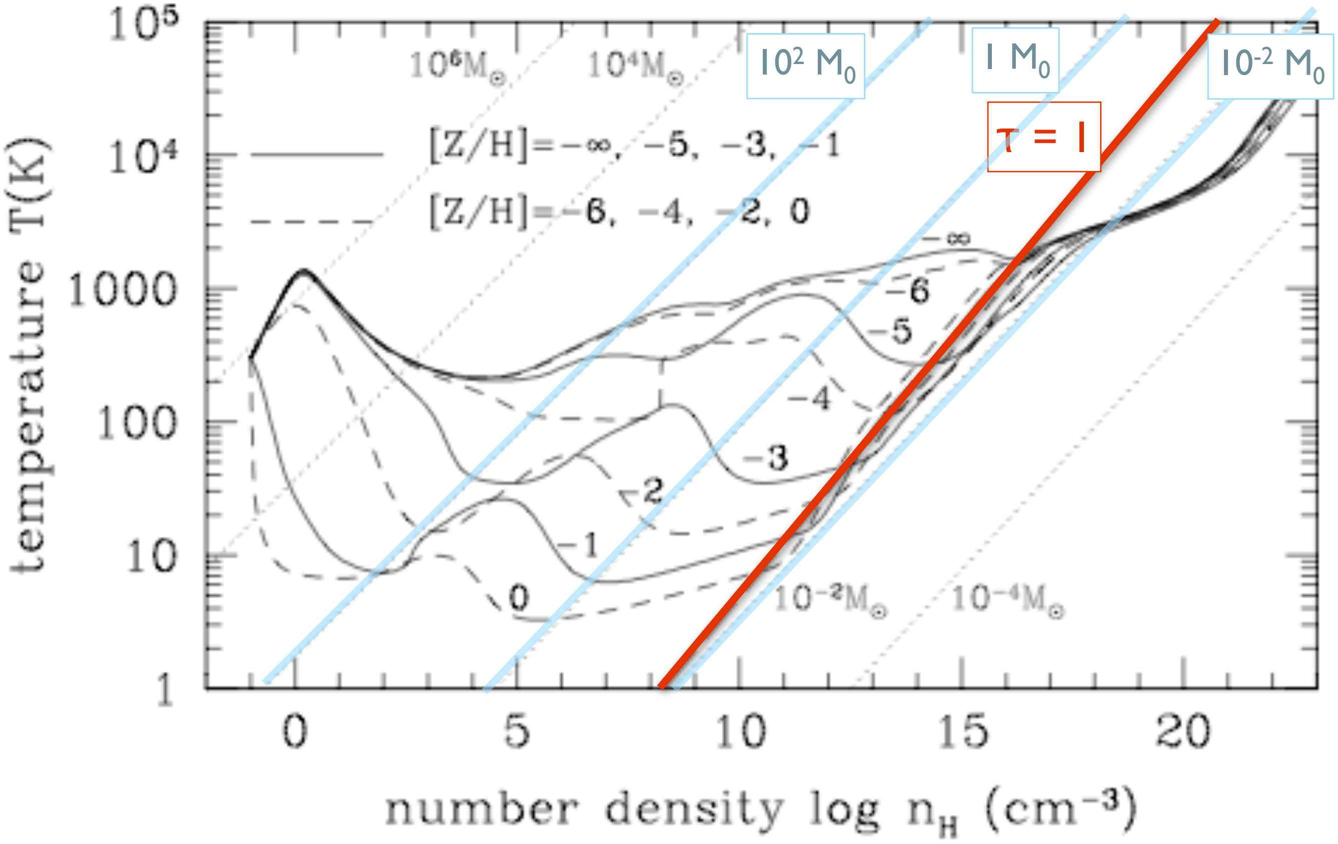
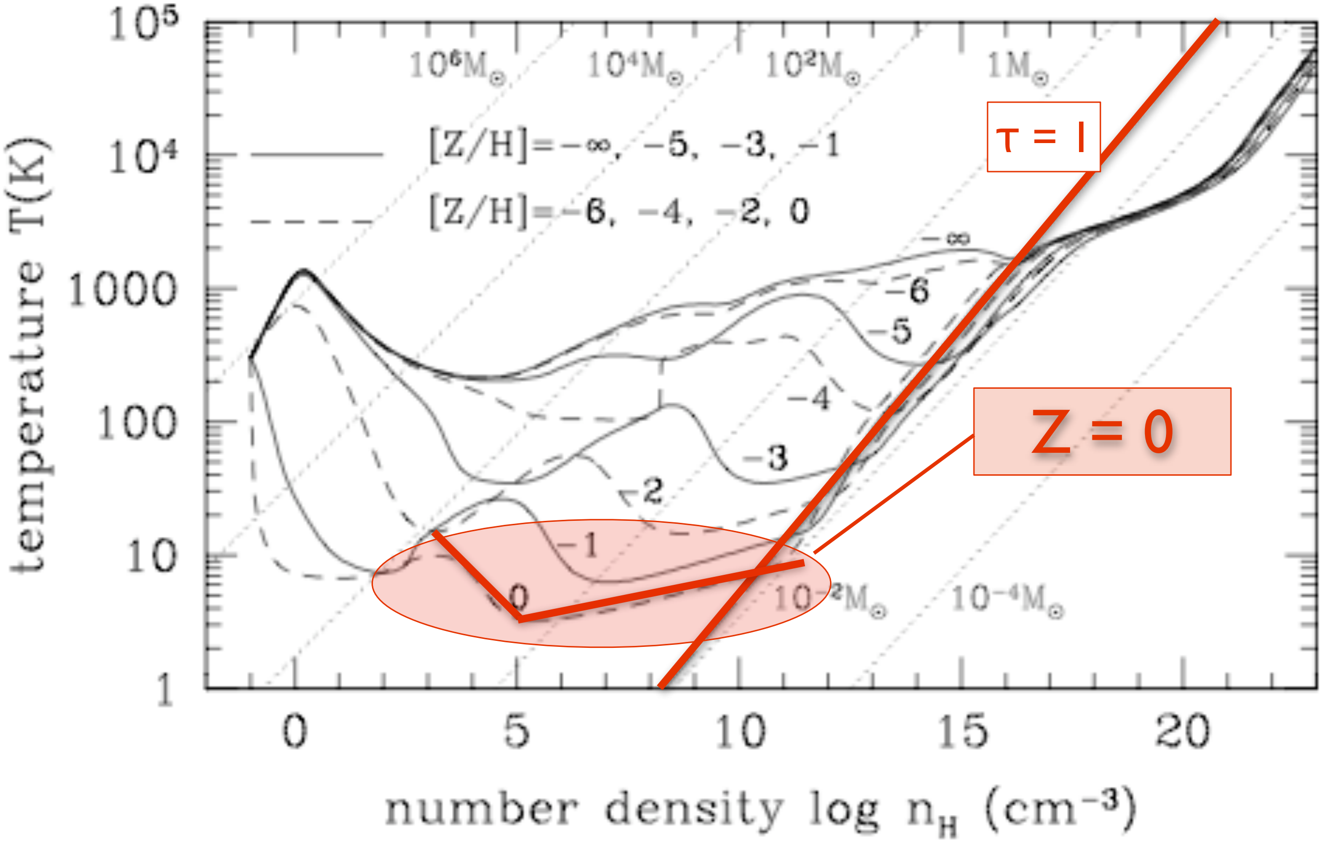
EOS as function of metallicity



(Omukai et al. 2005, ApJ, 626, 627)

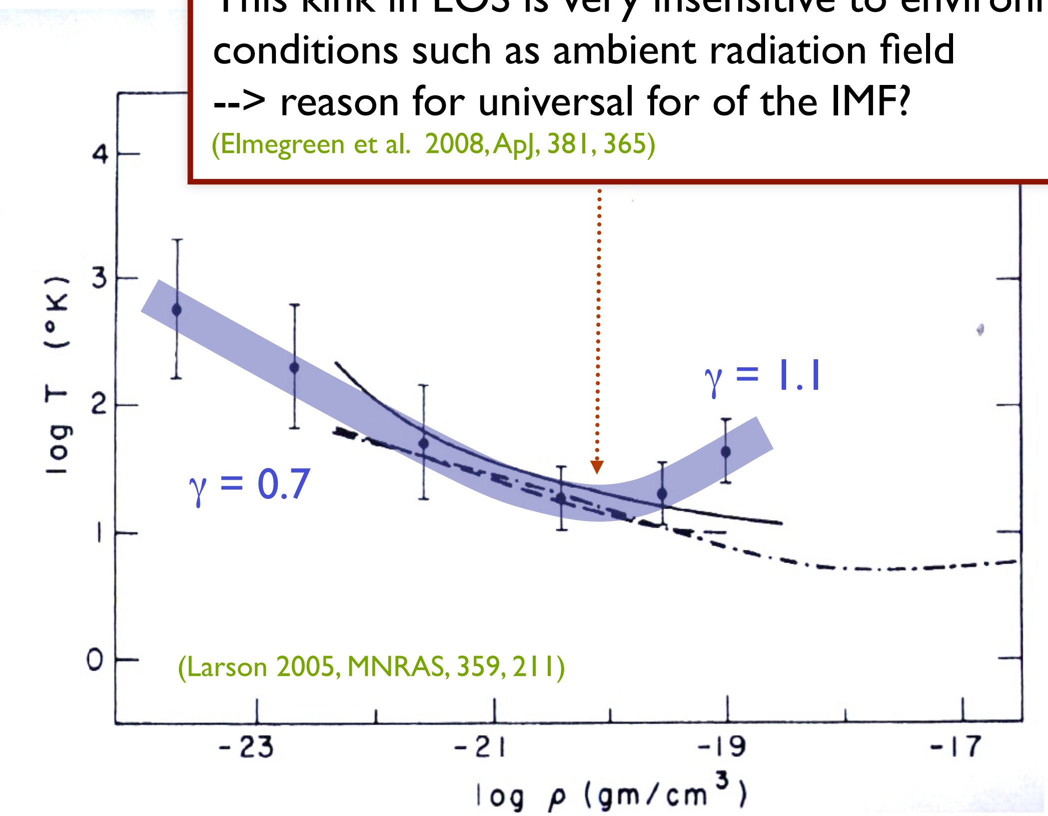
present-day star formation



(Omukai et al. 2005, ApJ, 626, 627, Jappsen et al. 2005, A&A, 435, 611, Larson 2005, MNRAS, 359, 211)

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, ApJ, 381, 365)



(Larson 2005, MNRAS, 359, 211)

IMF from simple piece-wise polytropic EOS

$\gamma_1 = 0.7$

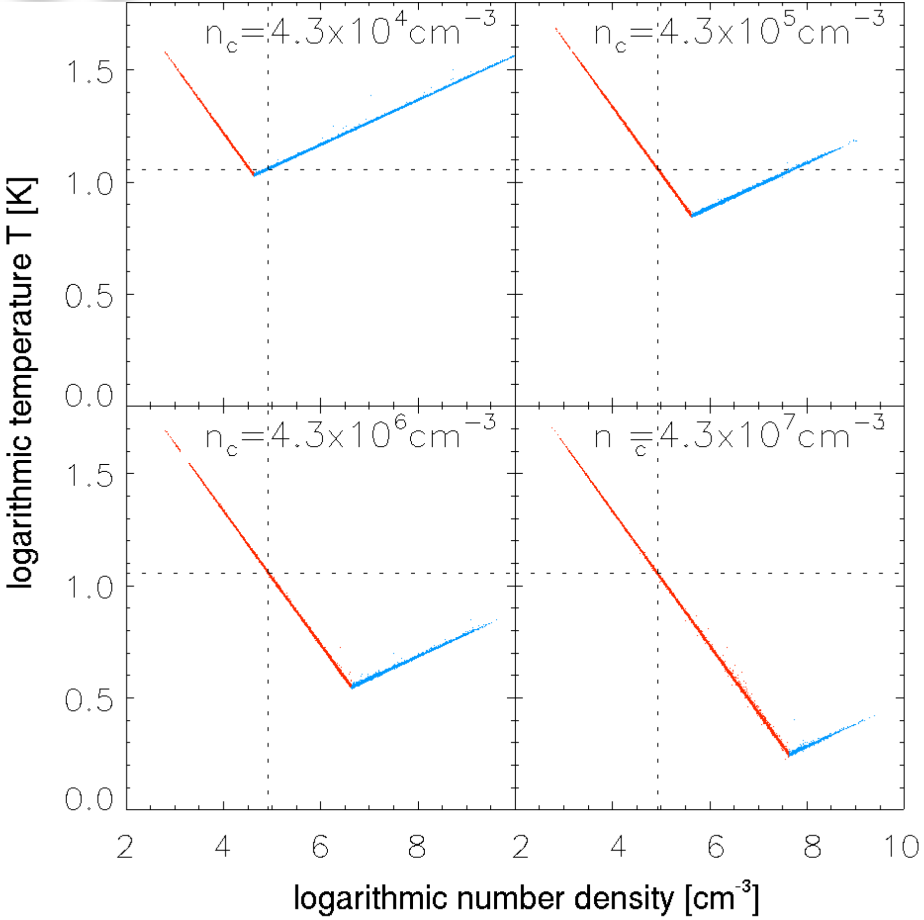
$\gamma_2 = 1.1$

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

EOS and Jeans Mass:

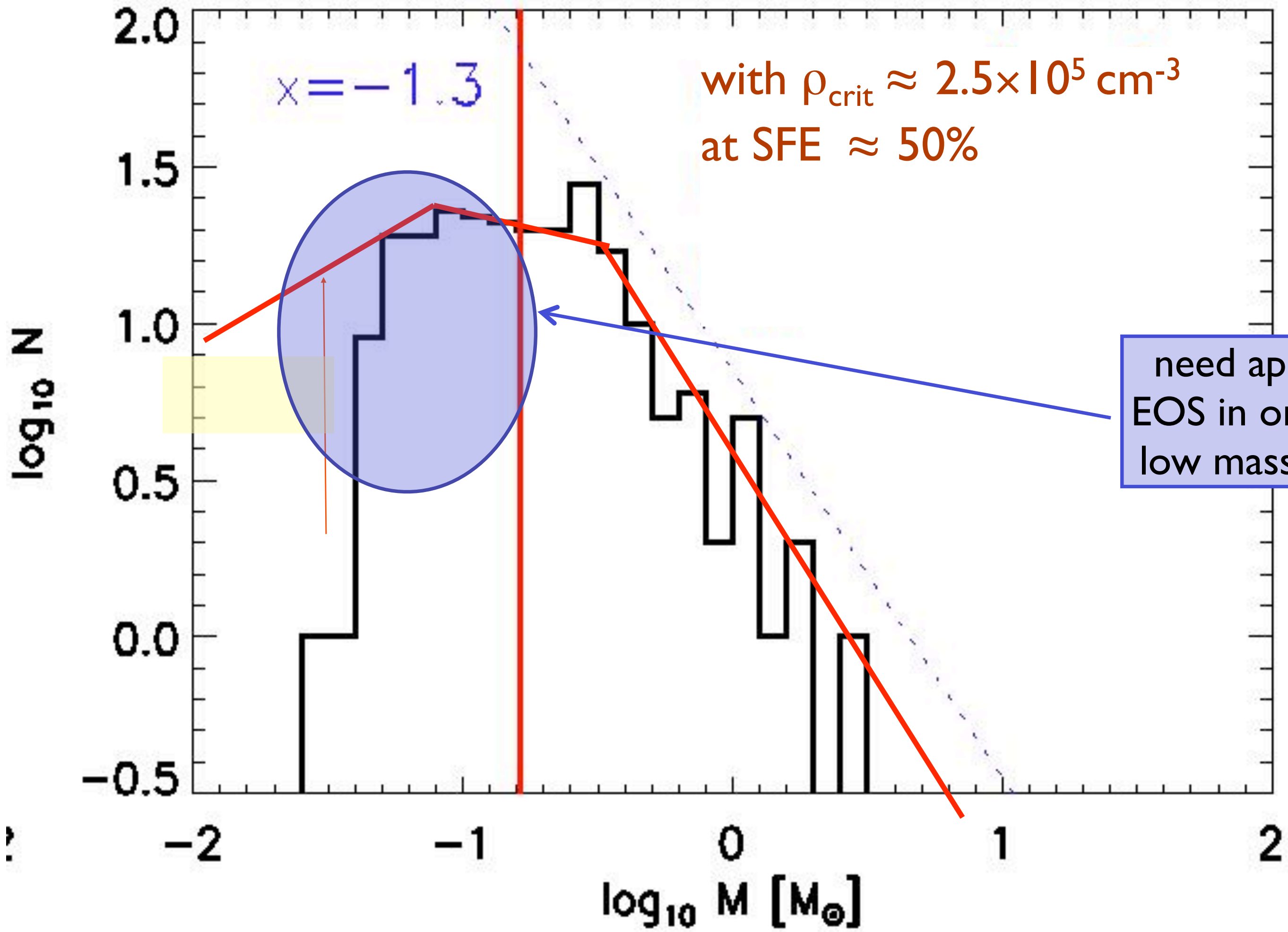
$\mathbf{p} \propto \rho^{\gamma} \rightarrow \rho \propto \mathbf{p}^{1/\gamma}$

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



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

IMF in nearby molecular clouds



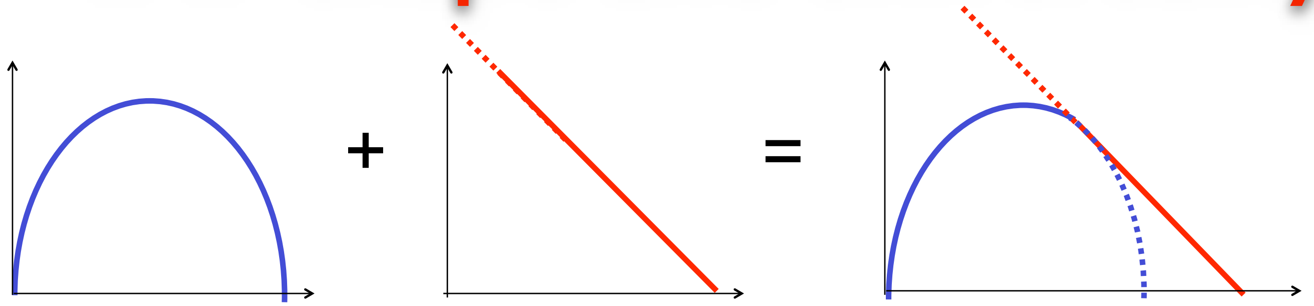
with $\rho_{crit} \approx 2.5\times10^5$ cm^{-3}

at SFE $\approx$ 50%

need appropriate
EOS in order to get
low mass IMF right

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

IMF shape and universality

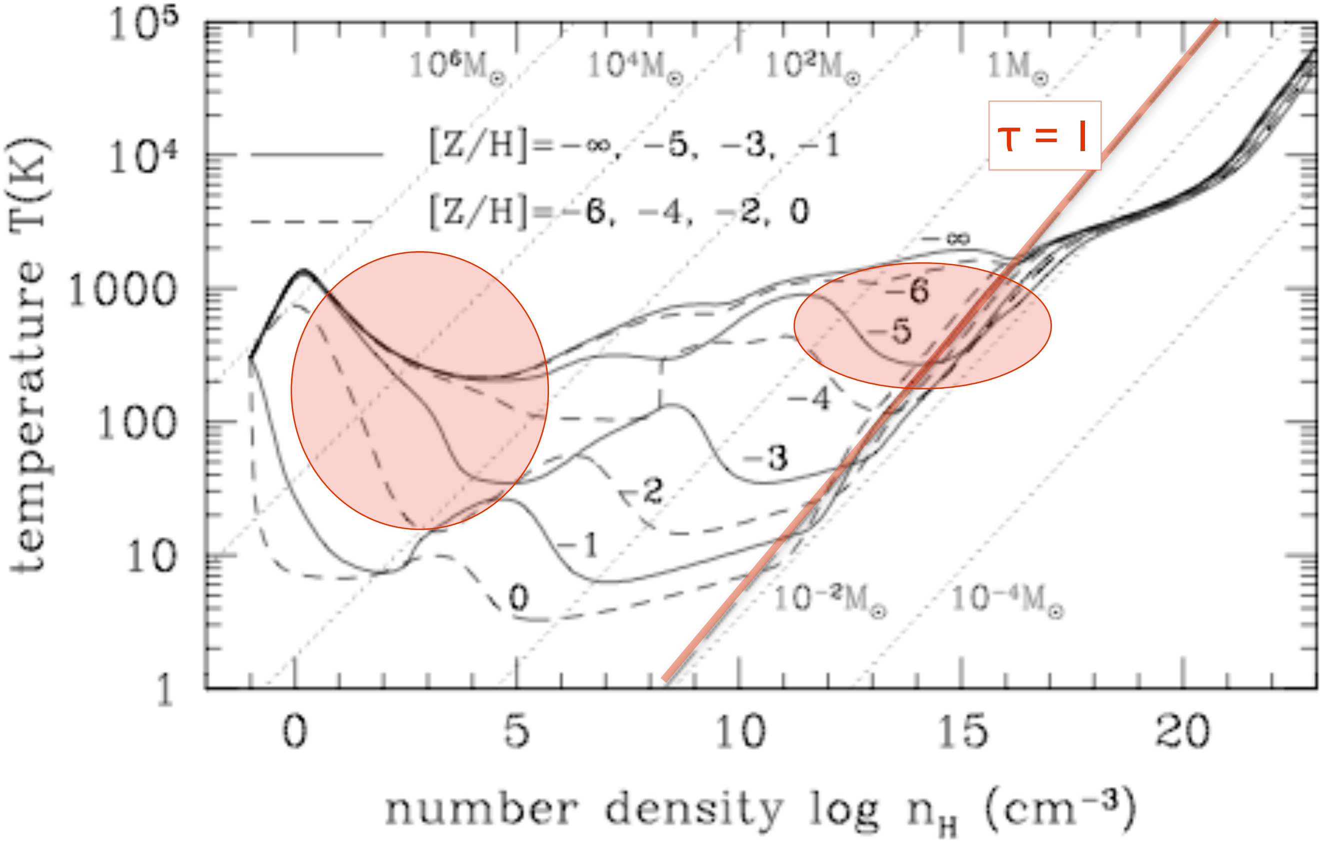


- combine scale free process → *POWER LAW BEHAVIOR*
  - turbulence (Padoan & Nordlund 2002, Hennebelle & Chabrier 2008, 2009)
  - gravity in dense clusters (Bonnell & Bate 2006, Klessen 2001)
  - universality: dust-induced EOS kink insensitive to radiation field (Elmegreen et al. 2008)

- with highly stochastic processes → central limit theorem → *GAUSSIAN DISTRIBUTION*
  - basically mean thermal Jeans length (or feedback)
  - universality: insensitive to metallicity (Clark et al. 2010, submitted)

transition Pop III to Pop II.5

what is more relevant? metal-line cooling or dust cooling?



(Omukai et al. 2005, ApJ, 626, 627)

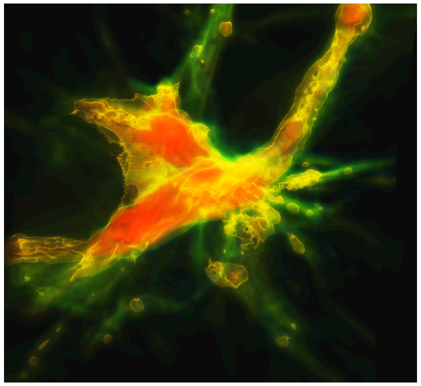
dependence on Z at low density

- 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)

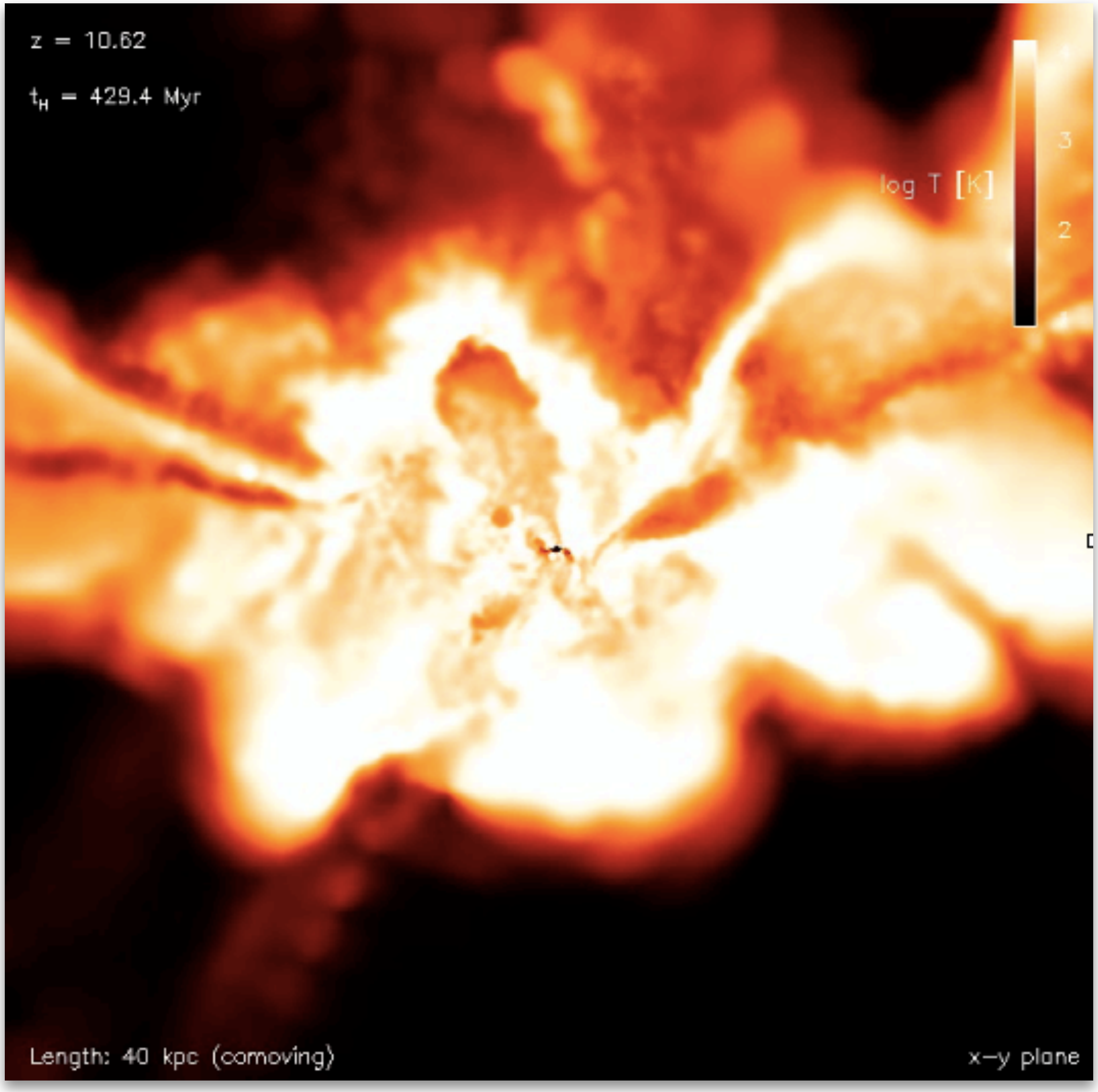
transition Pop III to Pop II.5

- star formation will depend on *degree of turbulence* in protogalactic halo (see talk by *Paul Clark*)
- 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, peak at lower-masses?



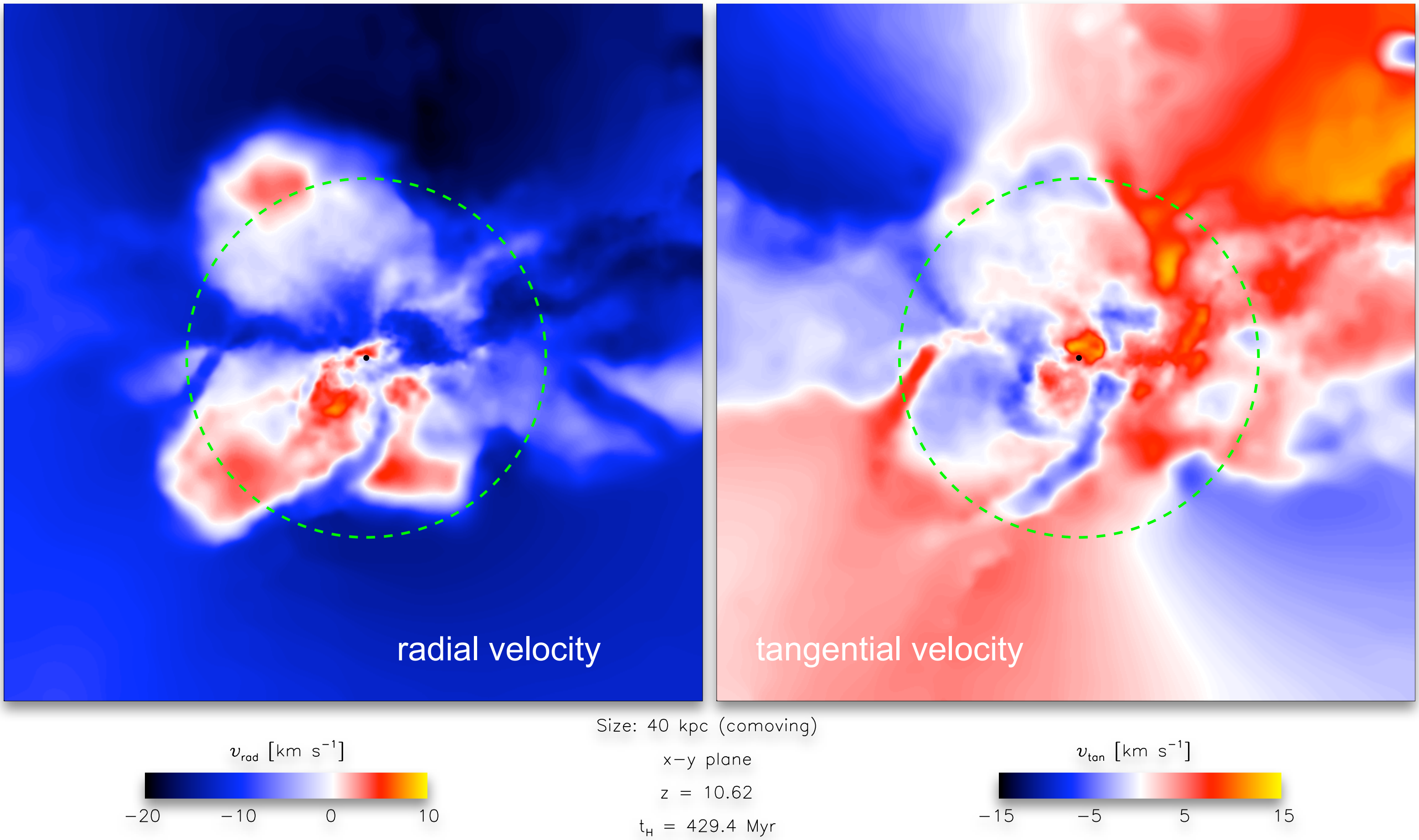
(Greif et al. 2008, MNRAS, 387, 1021)

turbulence developing in an atomic cooling halo



(Greif et al. 2008, MNRAS, 387, 1021, see also Wise & Abel 2007)

see also talk
by *Thomas Greif*

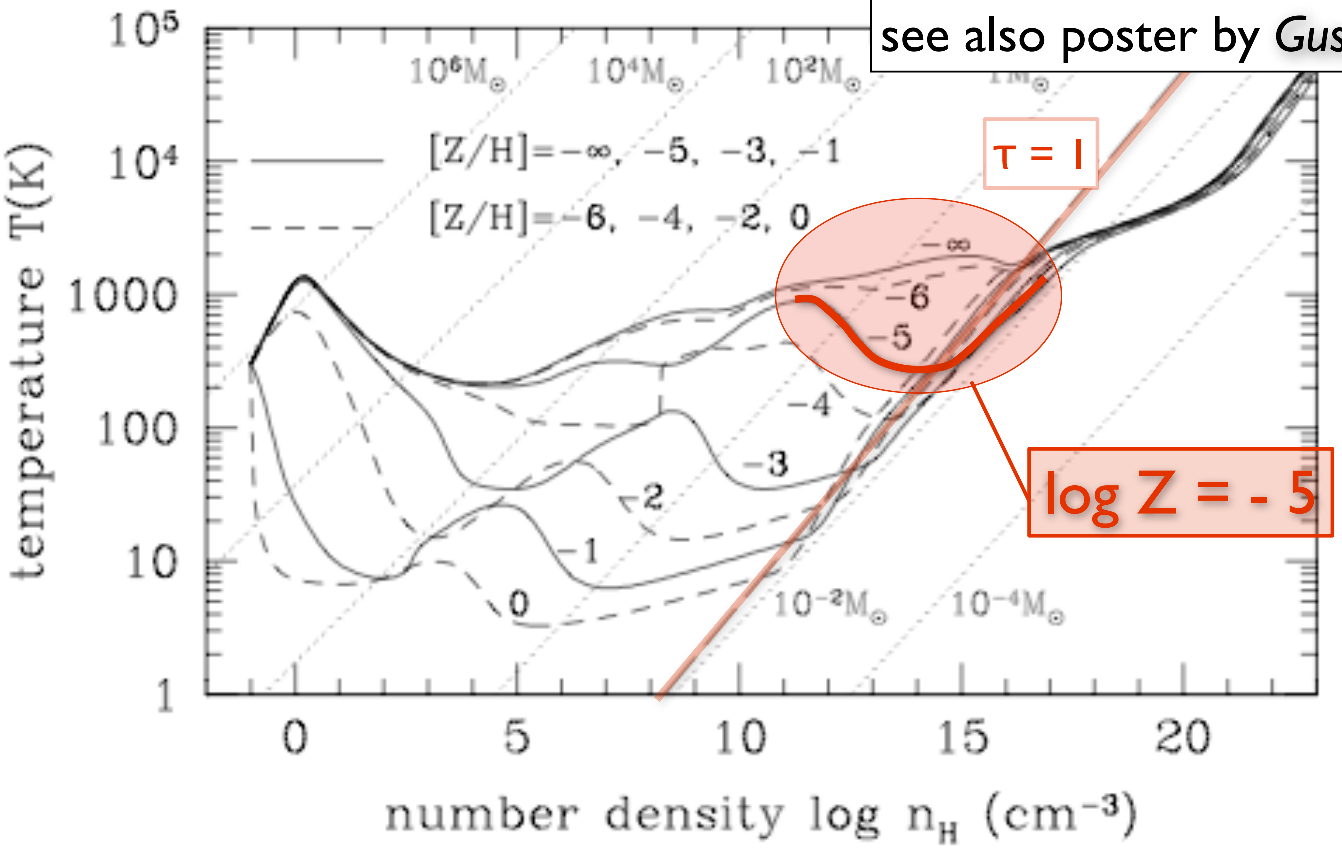


turbulence developing in an atomic cooling halo

(Greif et al. 2008, MNRAS, 387, 1021)

see also talk
by *Thomas Greif*

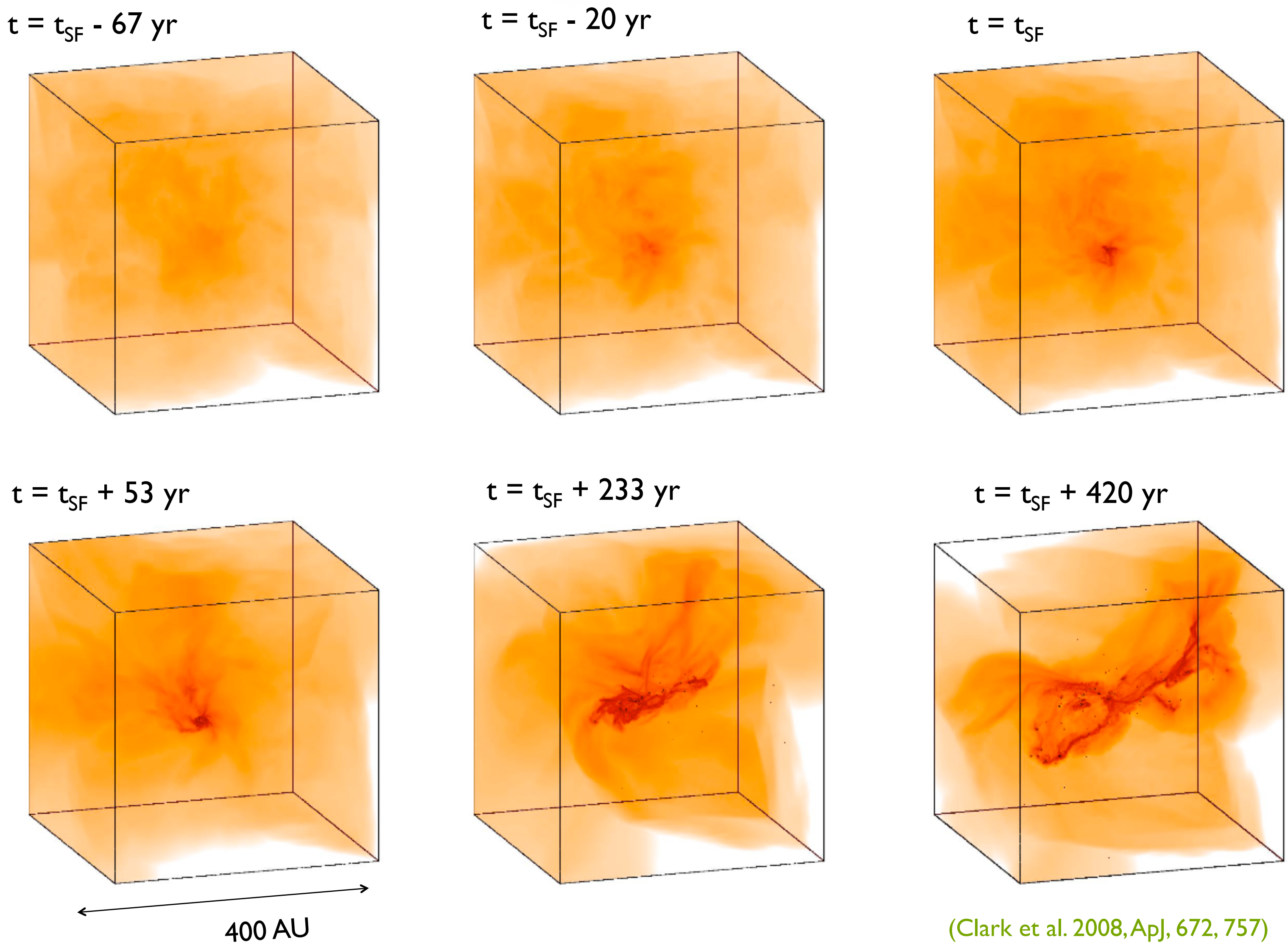
transition: Pop III to Pop II.5



on the dust-induced cooling dip:
see also poster by *Gustavo Dopcke*

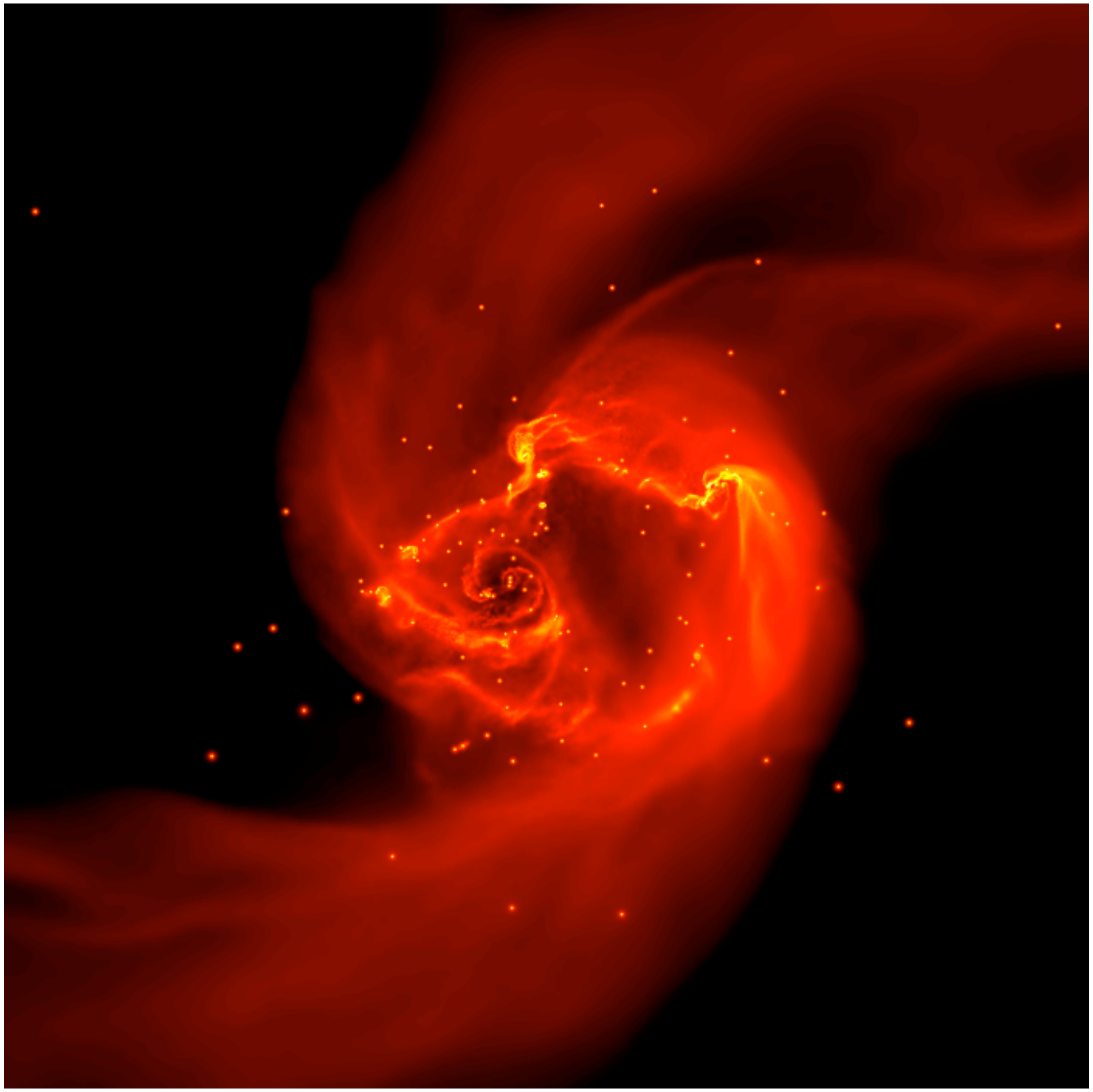
(Omukai et al. 2005, ApJ, 626, 627, also Schneider et al. 2006, MNRAS, 369, 1437)

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



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

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

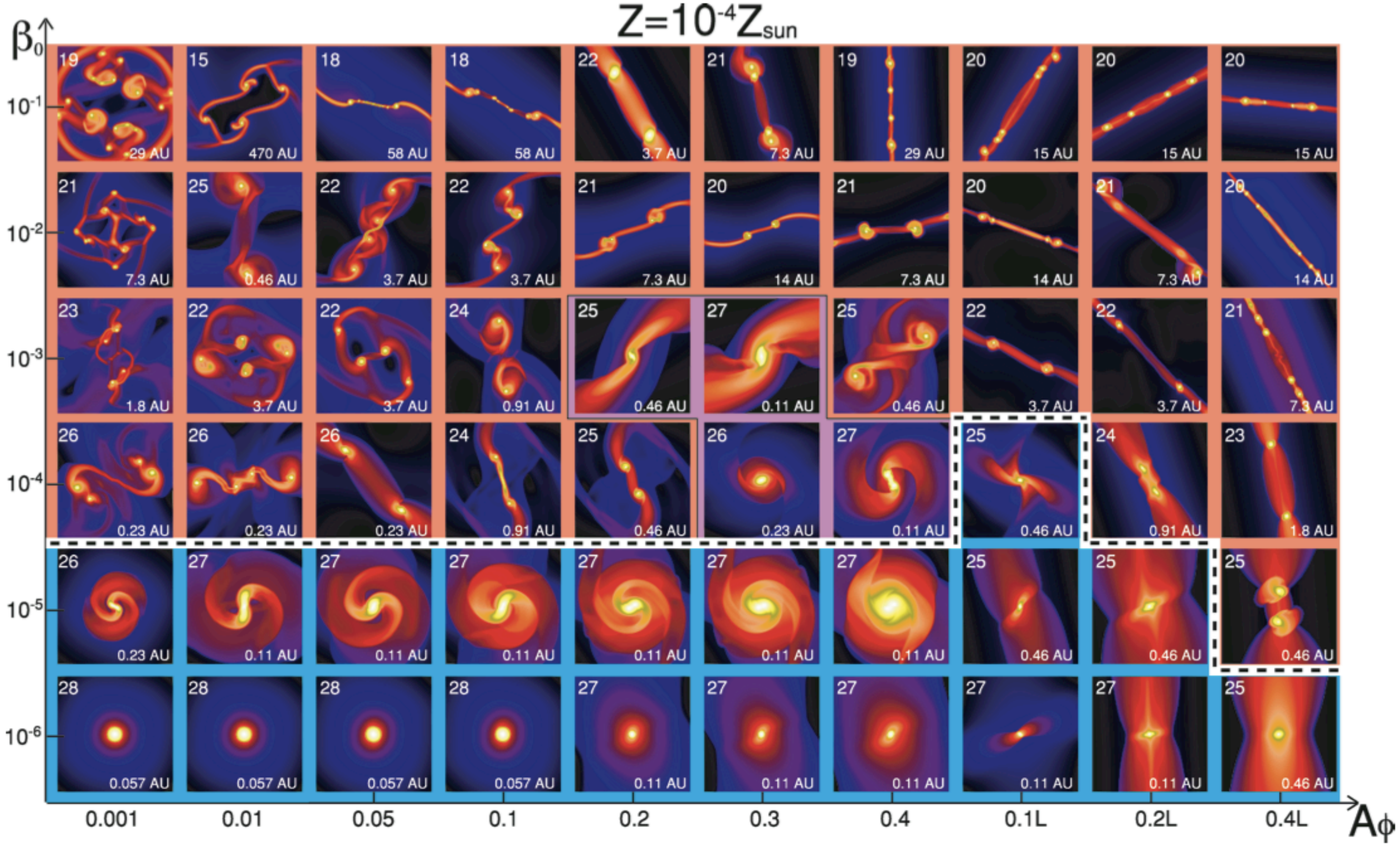


dense cluster of low-mass protostars builds up:

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

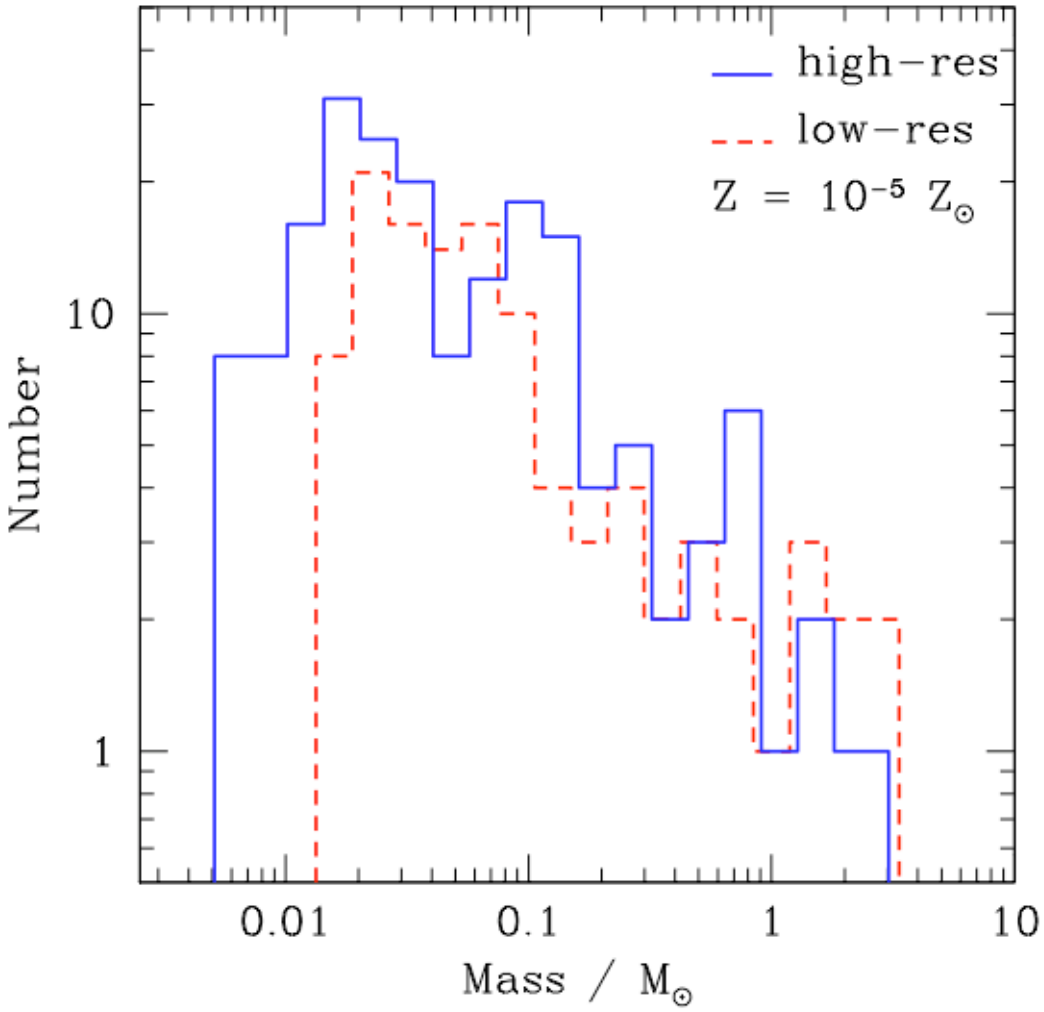
(Clark et al. 2008, ApJ, 672, 757,
see also Machida et al. 2009, 399, 1255)

binary fragmentation ($Z=10^{-4}$)



(Machida et al. 2009, 399,1255)

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



dense cluster of low-mass protostars builds up:

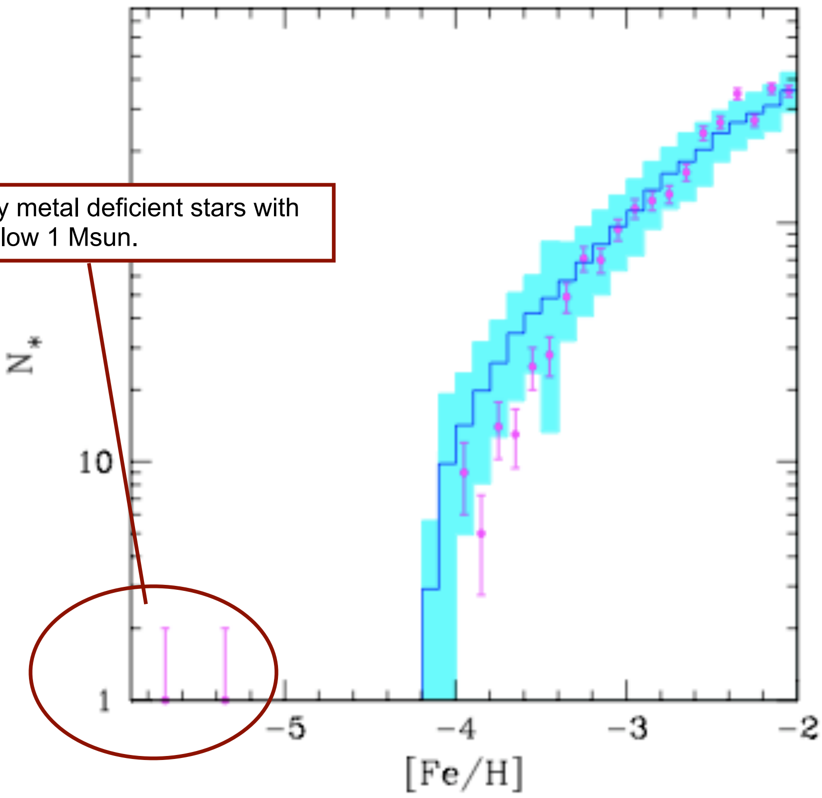
- mass spectrum peaks below 1 M_{sun}
- cluster VERY dense $n_{stars} = 2.5 \times 10^9\ pc^{-3}$

- *predictions:*

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

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

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



2 extremely metal deficient stars with masses below 1 Msun.

(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] ~ 10^{-5}

* high binary fraction

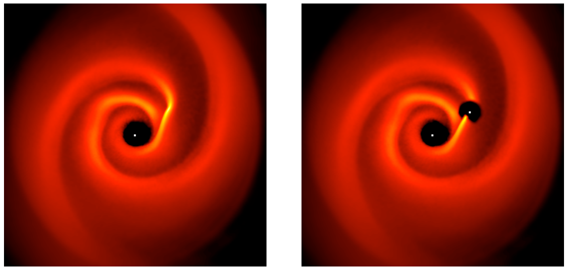
(Clark et al. 2008, ApJ, 672, 757)

caveats / questions

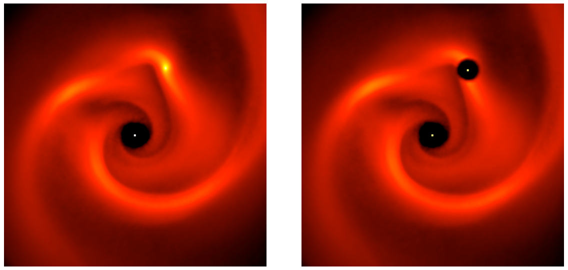
- how good is EOS approach?
  - time to reach chemical + thermal equilibrium shorter than dynamical time?
  - how does EOS depend on dynamics? (e.g. 1D collapse with large-gradient approx. versus complex 3D turbulent flows)
- how important is heating from stars?
  - accretion luminosity may heat gas and reduce degree of cloud fragmentation (cluster formation vs. high-mass SF)
- how can we model that best?
  - full radiation transfer vs. approximate schemes

effects of accretion heating

- how important is heating from stars?
  - accretion luminosity may heat gas and reduce degree of cloud fragmentation (cluster formation vs. high-mass SF)
  - HOWEVER: the effect is *NOT large* (see poster by *Rowan Smith*)



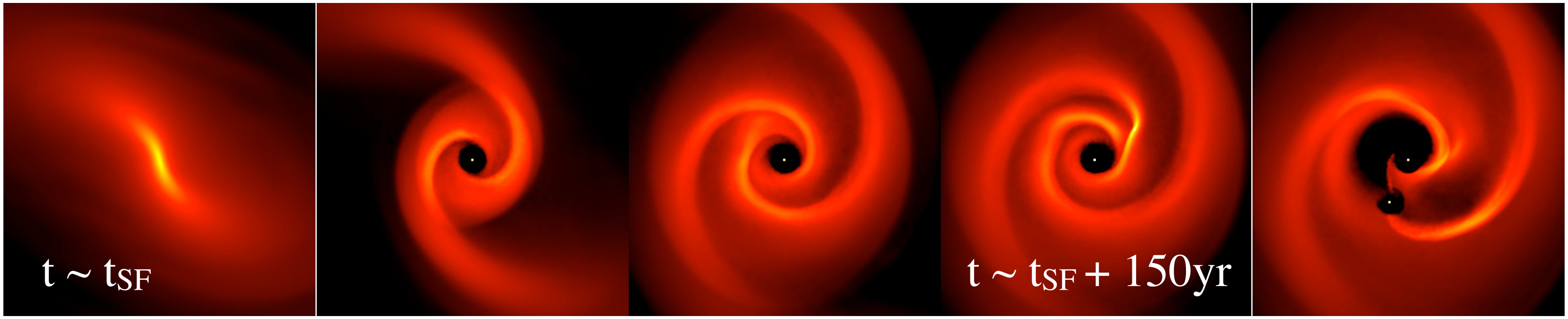
fragmentation of Pop III disk (Z=0) *without* accretion heating
--> fragmentation radius 10.4 AU



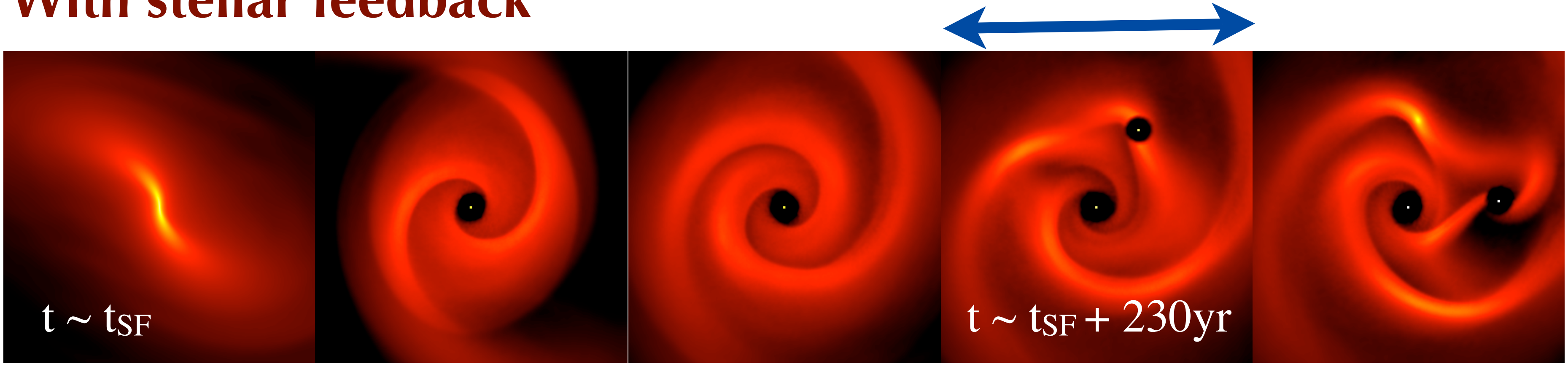
fragmentation of Pop III disk (Z=0) *with* accretion heating
--> fragmentation radius 18.9 AU

Evolution of the protostellar disc

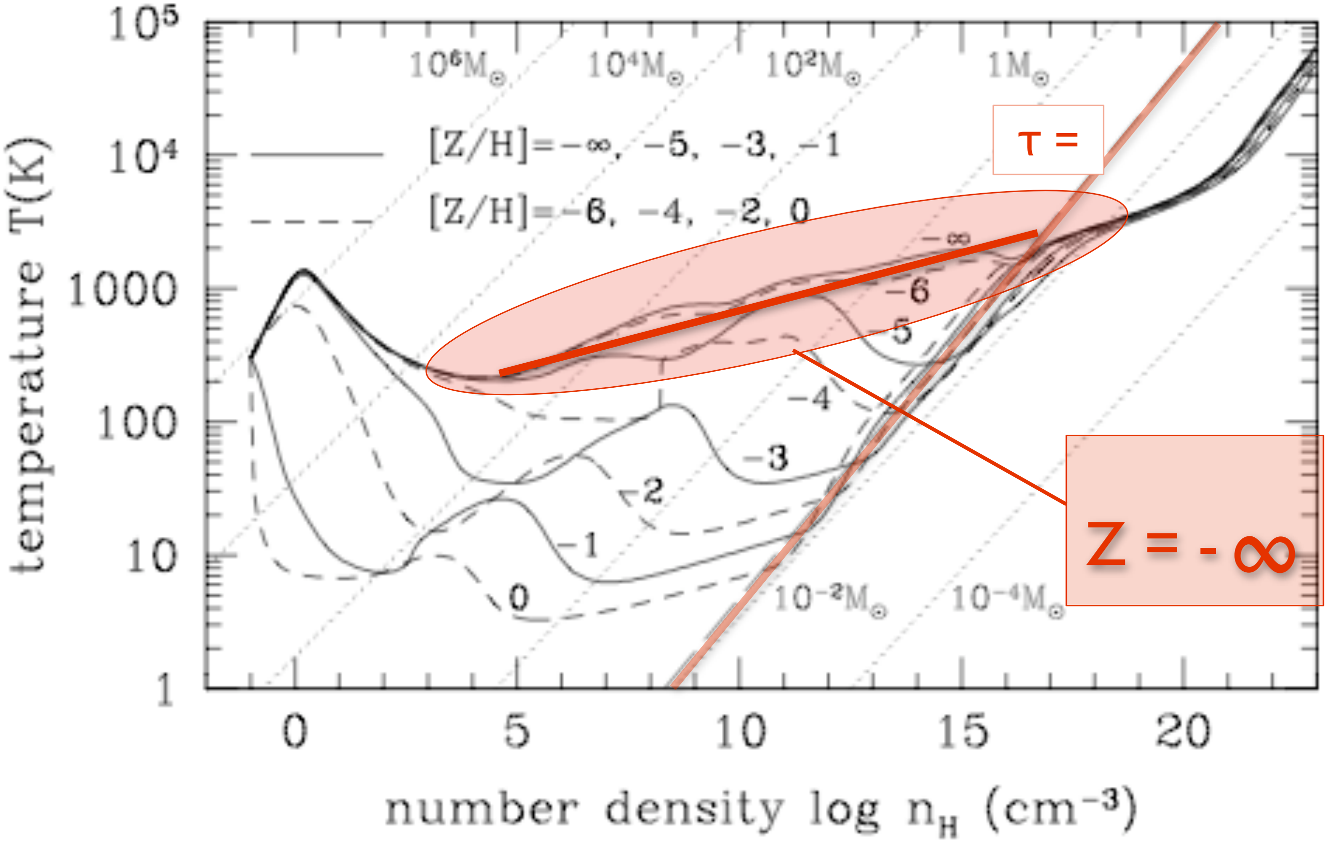
No stellar feedback



With stellar feedback



metall-free star formation



(Omukai et al. 2005, ApJ, 626, 627)

metall free star formation

- first disks are expected to fragment!
  - halos have large angular momentum --> disk forms around first protostar --> roughly isothermal disk are known to be unstable (see talk by *Paul Clark*)
    (see also Turk, Abel. & O'Shea 2009, Science, 325,601, Stacy, Greif, & Bromm, 2010, MNRAS, in press, Clark et al. in preparation)
  - also *turbulence* may lead to fragmentation!
    (see talk by *Paul Clark*)
- do first all first stars form in *small clusters*?
  what is the *IMF*?

agenda

- some phenomenology
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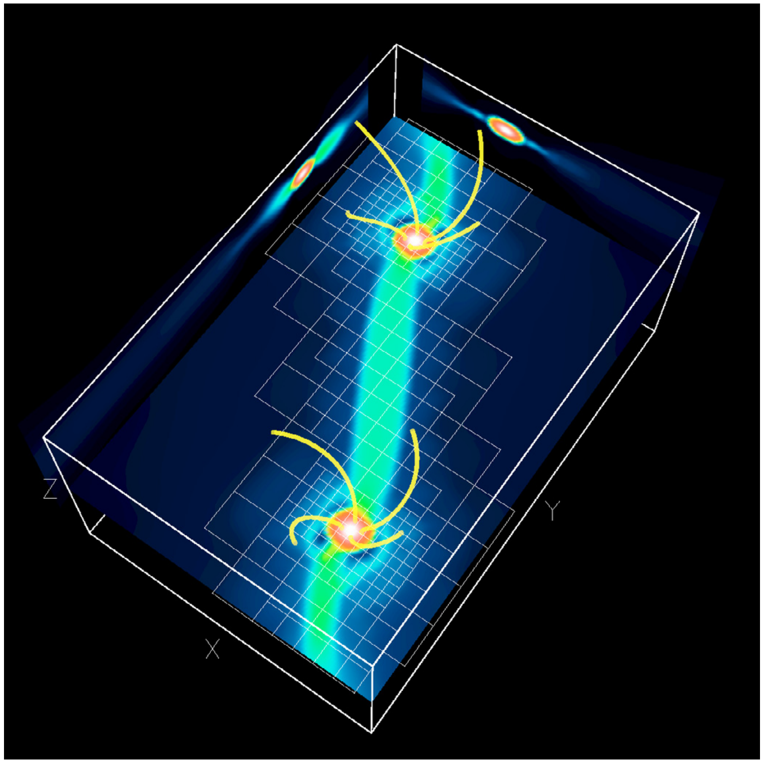
  - turbulence
  - thermodynamics
  - *magnetic fields*
  - feedback

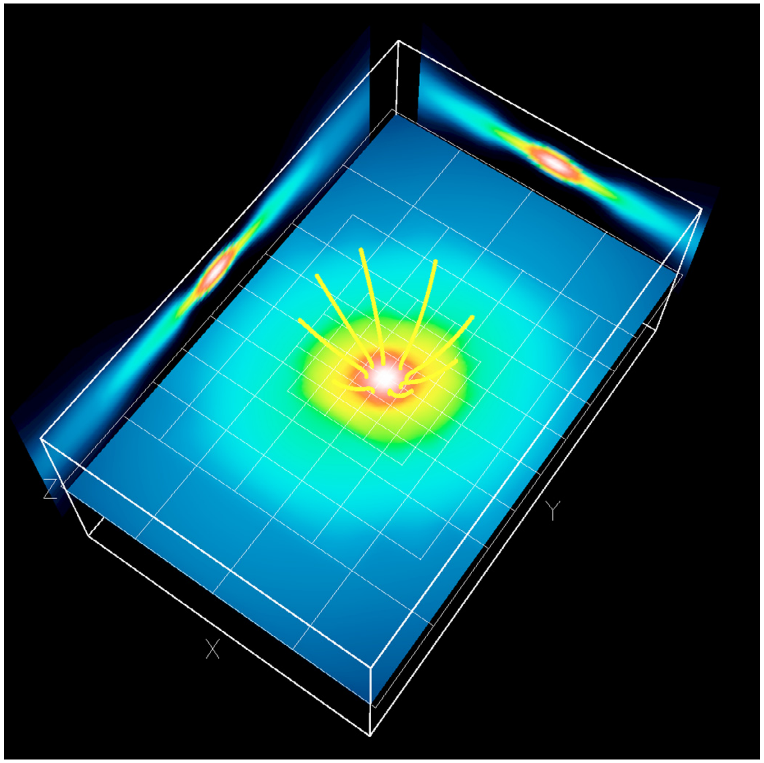
effects of magnetic fields

- magnetic fields can
  - suppress disk fragmentation
    (Ziegler 2005, A&A, 435, 385, Hennebelle & Fromang 2008, A&A, 477, 9 , Hennebelle & Teyssier 2008, A&A, 477, 25)
  - drive jets and outflows (Machida et al. 2006, ApJ, 647, L1)
  - induce additional turbulence (MRI / dynamo)
    (Balbus & Hawley 1998, RMP, 70, 1, Brandenburg & Subramanian 2005, Phy. Rep. 417, 1)
  - maybe present even in Z=0 gas
    (either as primordial fields or generated by dynamo action)
    see talk by *Dominik Schleicher* on Thursday
- need to be taken into account *!!*

effects of magnetic fields



weak field: binary formation



sufficient field strength: single star

(protostellar collapse with m=2 perturbation and B-field: Ziegler 2005, A&A, 435, 385,
for further discussion, see Hennebelle & Teyssier 2008, A&A, 477, 25

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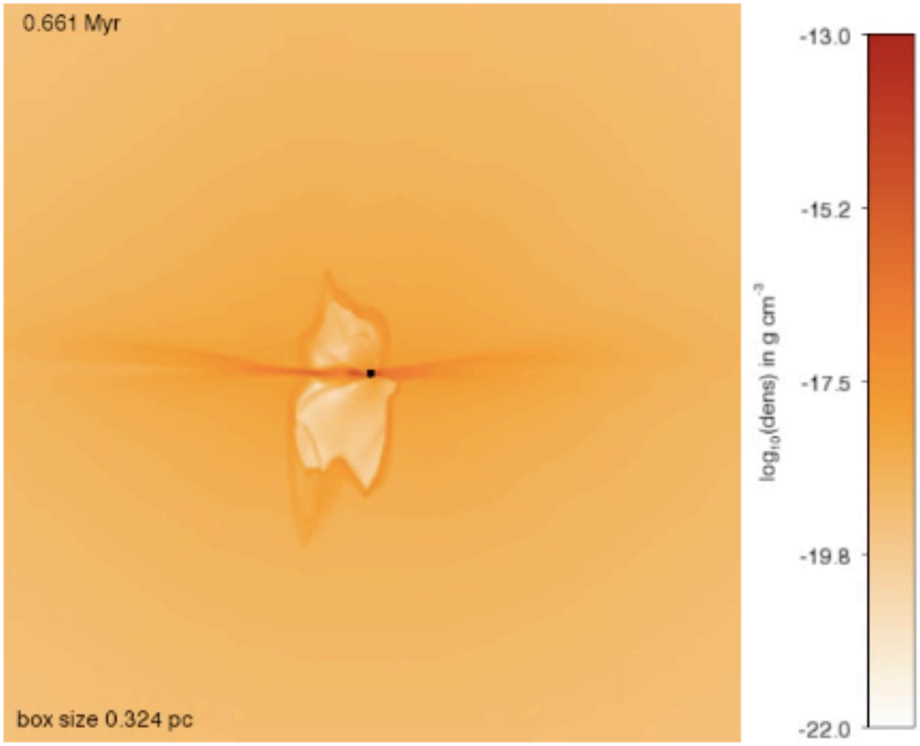
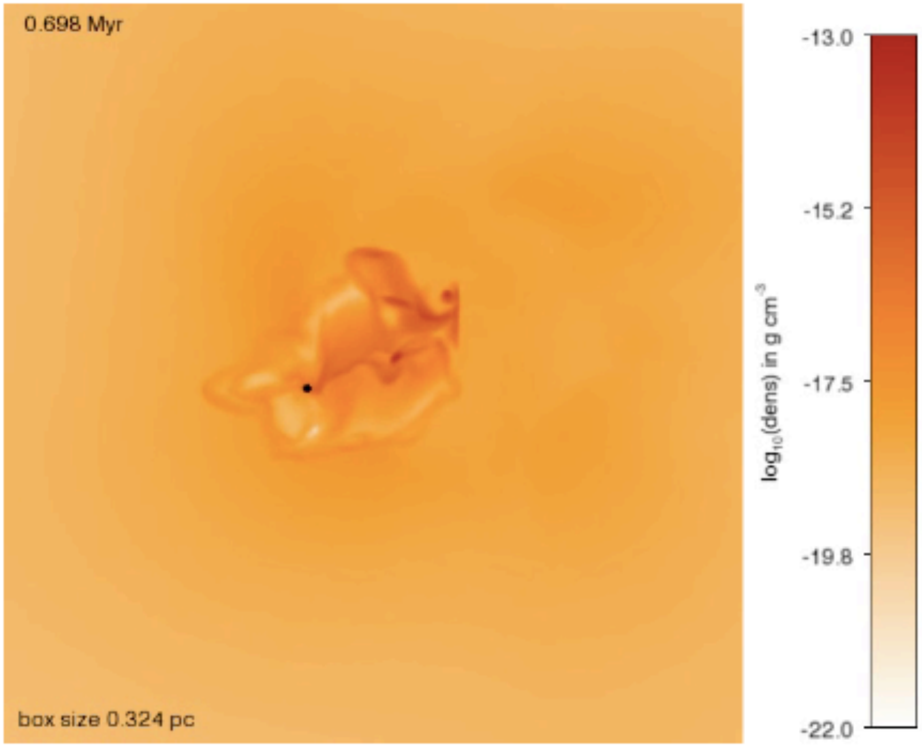
  - *magnetic fields*
  - *feedback (focus on ionizing feedback)*

single star: HII region and outflow



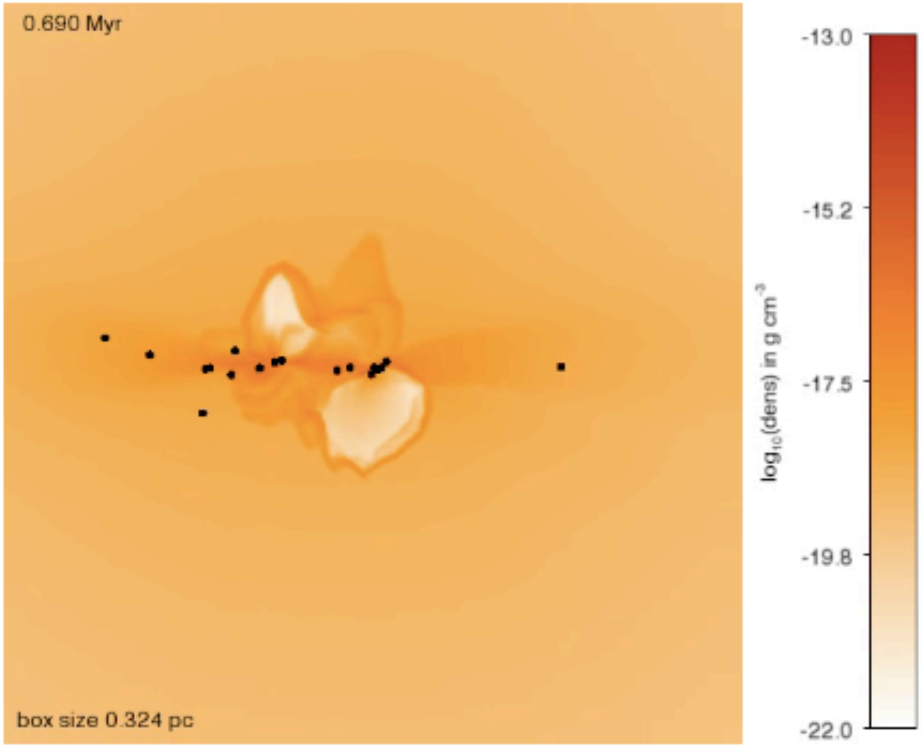
disk edge on



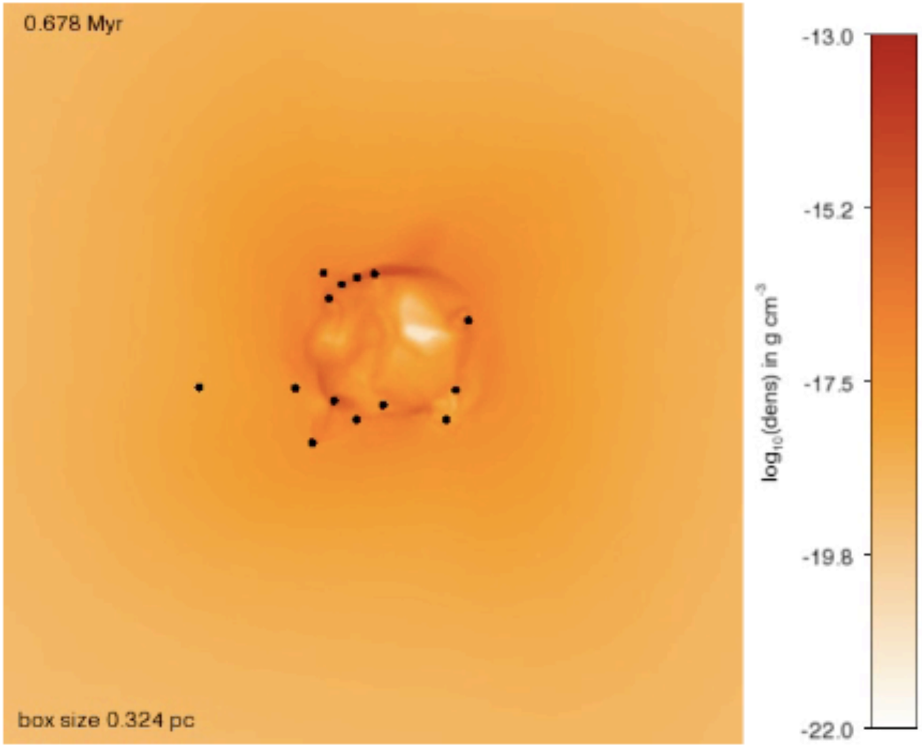
disk plane

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

multiple protostars: dynamics of HII regions



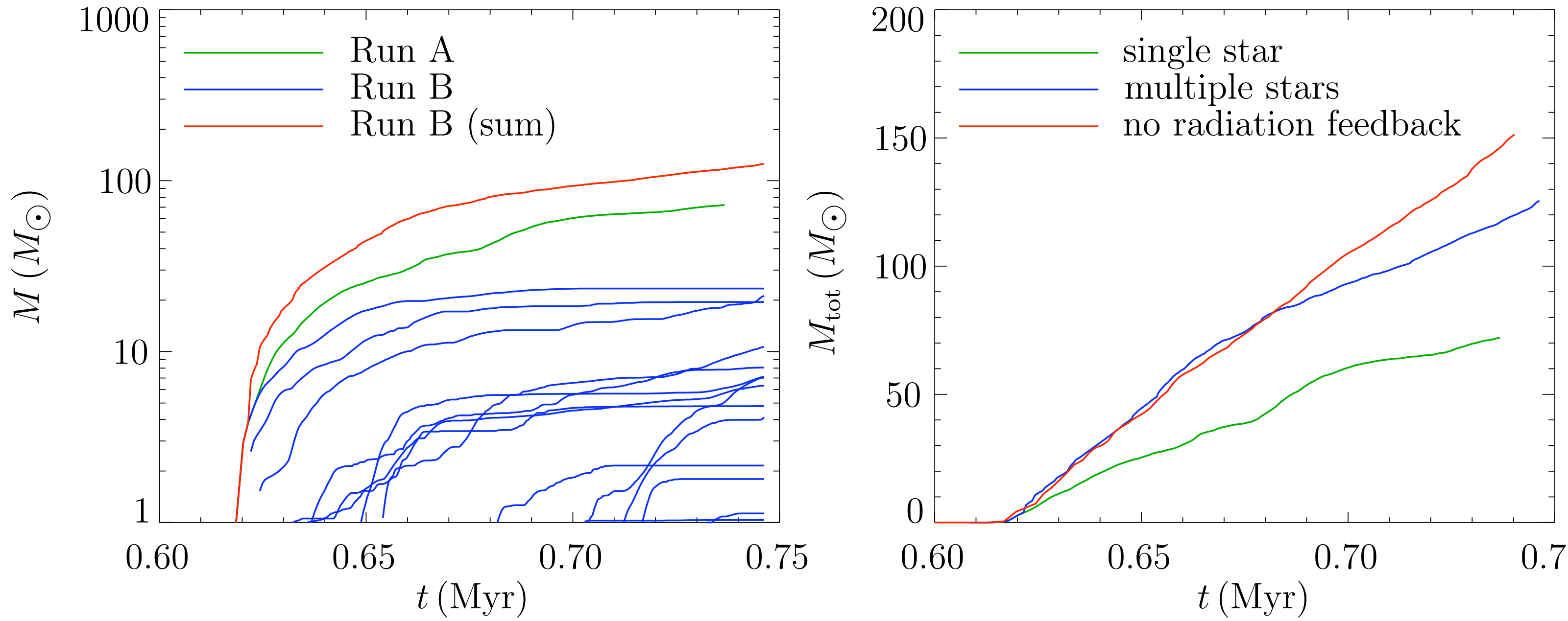
disk edge on



disk plane

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

accretion history



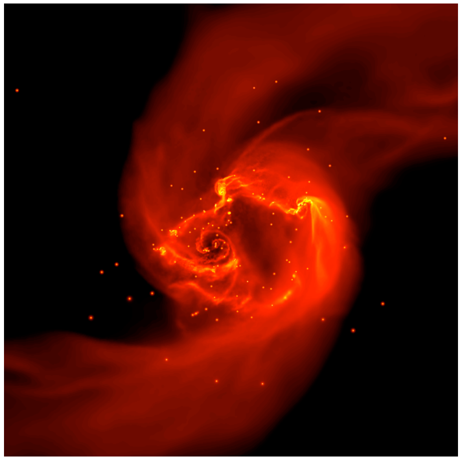
- ionizing radiation cannot stop accretion
- however, fragmentation of disk can stop mass growth of the central star

  --> *fragmentation induced starvation* (Peters et al. 2010, ApJ, 711, 1017)

feedback in Pop III star formation

- we expect *feedback* during PopIII protostellar collapse
  - *NOT* to stop fragmentation (but possibly *reduce* number of fragments)
  - *NOT* to prevent mass growth (if at all *fragmentation induced starvation* stops further mass growth)
- we expect the effects of *magnetic fields* to be potentially more important.

summary



- 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 cluster
- effects of feedback less important than in present-day SF

thanks!