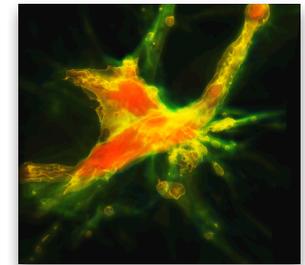
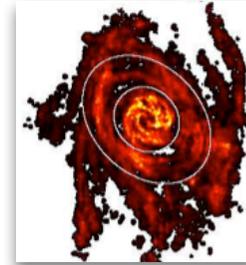
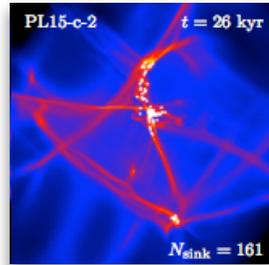
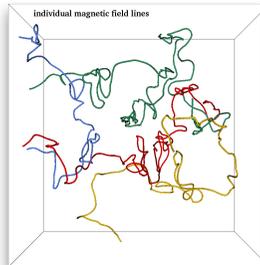


# Die Geburt der Sterne



**Ralf Klessen**



Zentrum für Astronomie der Universität Heidelberg  
Institut für Theoretische Astrophysik



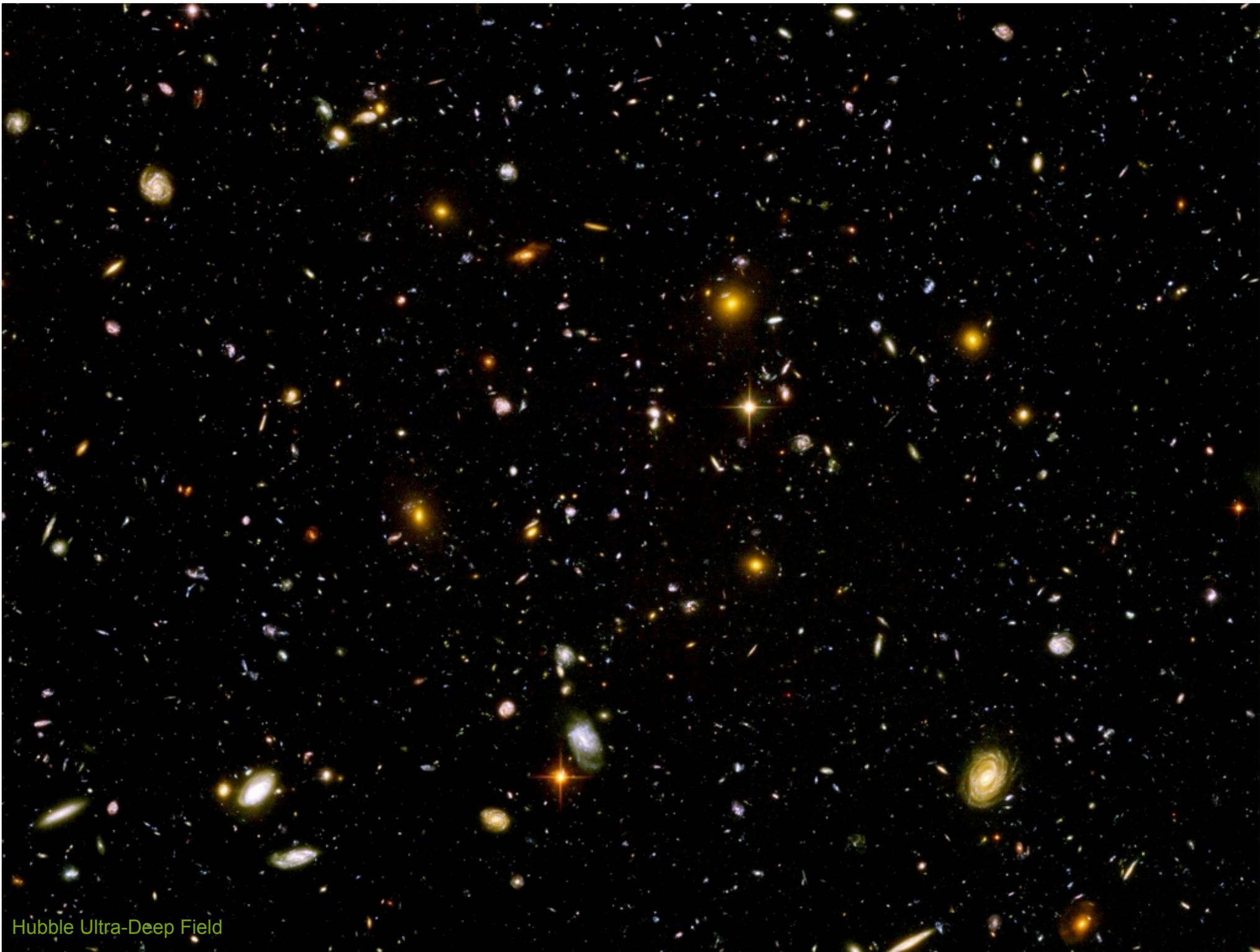
# agenda

- star formation theory
  - phenomenology
  - historic remarks
  - our current understanding and its limitations
- application
  - the stellar mass function at birth (IMF)

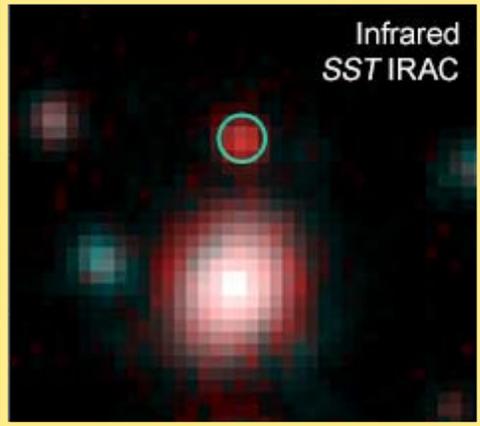
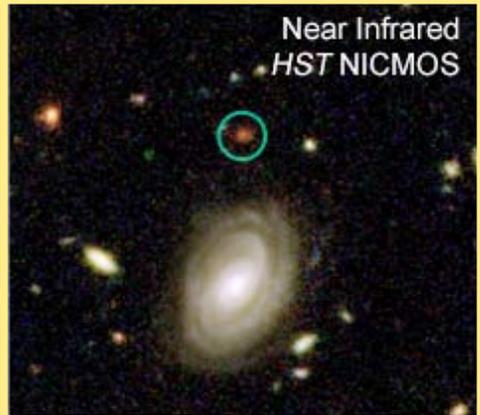
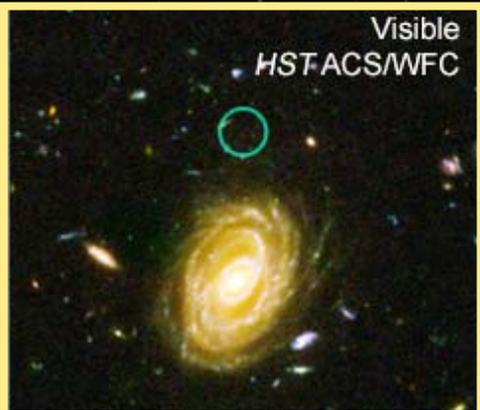


NGC 3324 (Hubble, NASA/ESA)

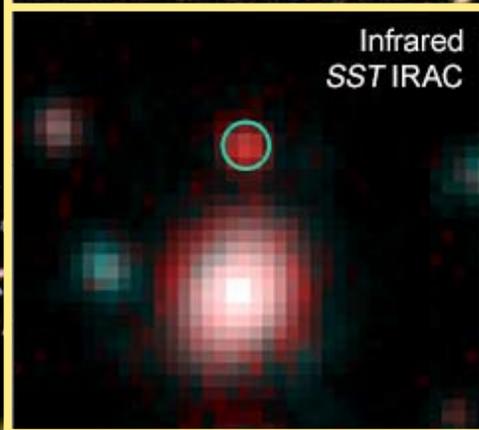
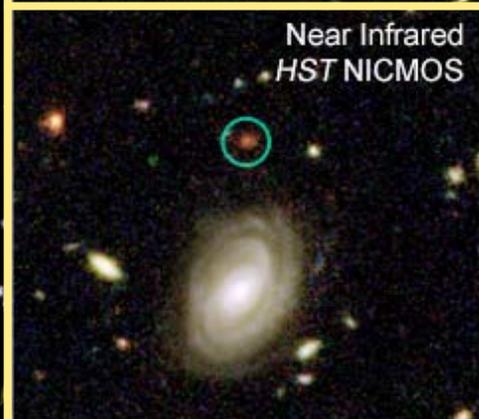
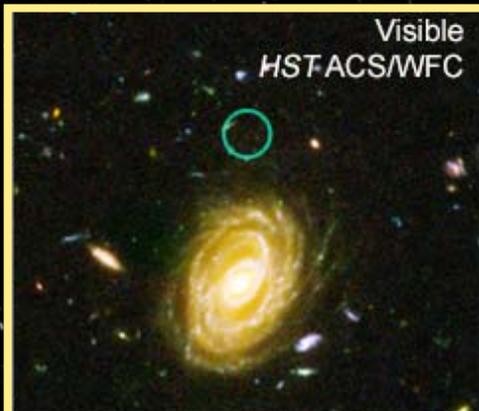
Phenomenology



Hubble Ultra-Deep Field

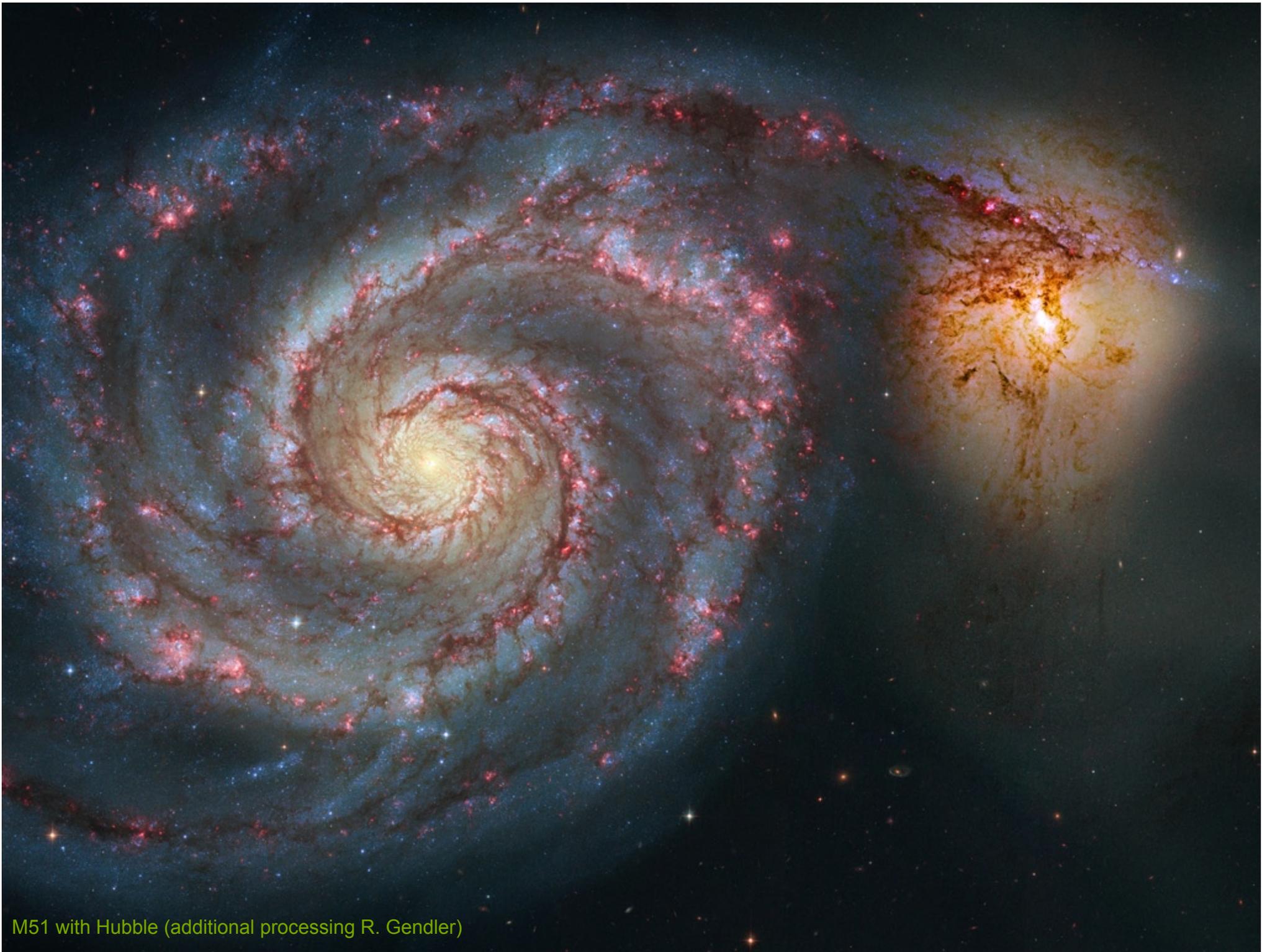


Hubble Ultra-Deep Field

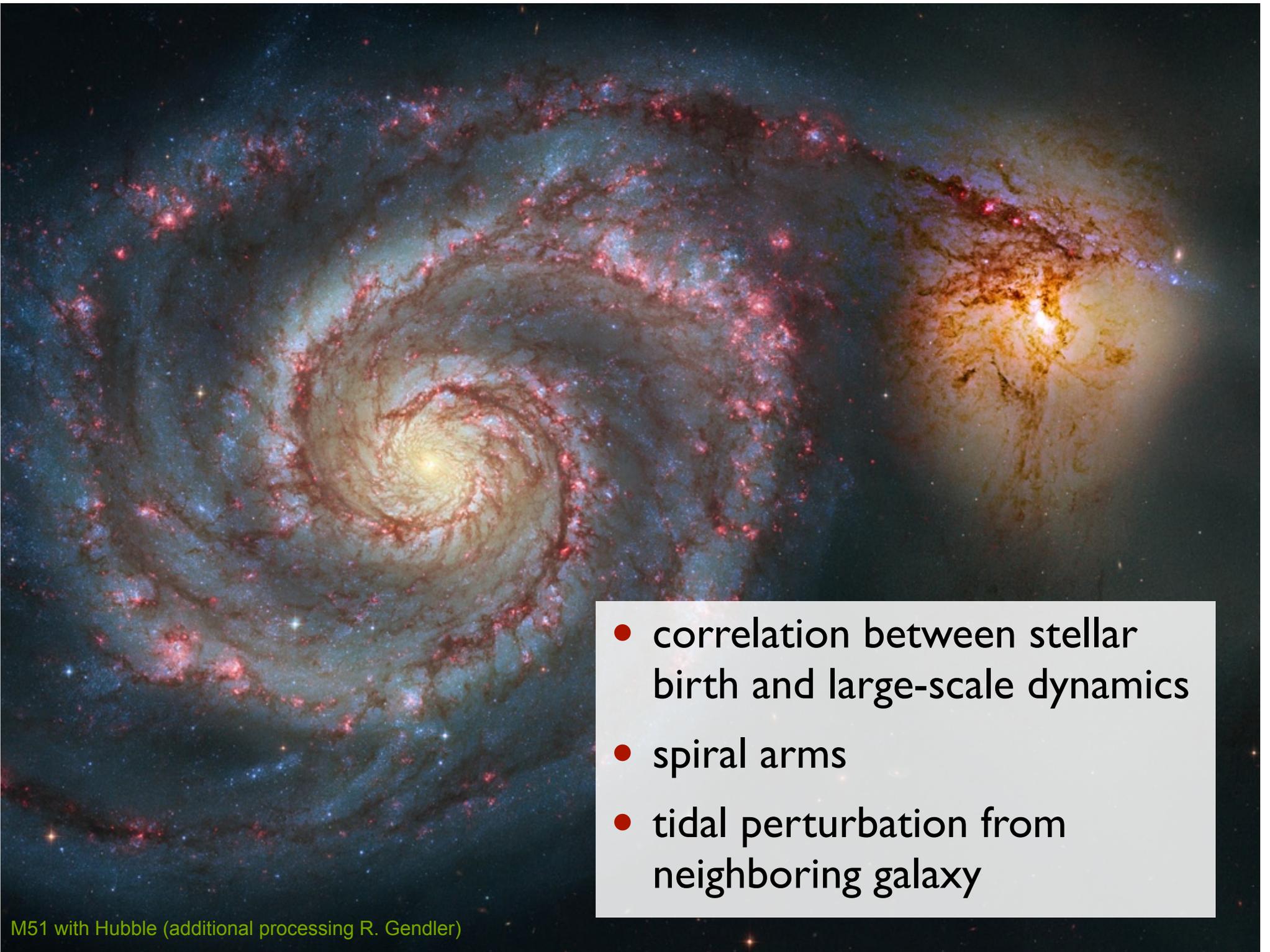


- star formation sets in very early after the big bang
- stars always form in galaxies and protogalaxies
- we cannot see the first generation of stars, but maybe the second one





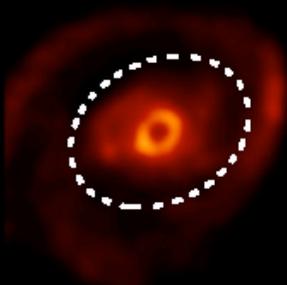
M51 with Hubble (additional processing R. Gendler)



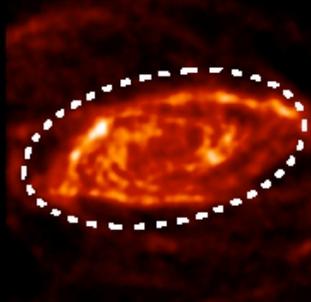
- correlation between stellar birth and large-scale dynamics
- spiral arms
- tidal perturbation from neighboring galaxy

M51 with Hubble (additional processing R. Gendler)

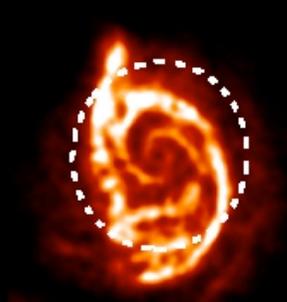
NGC 4736



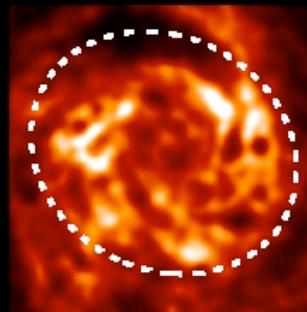
NGC 5055



NGC 5194

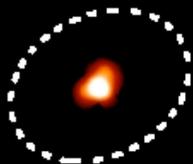


NGC 6946

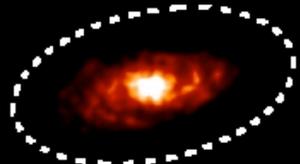


atomic hydrogen

NGC 4736



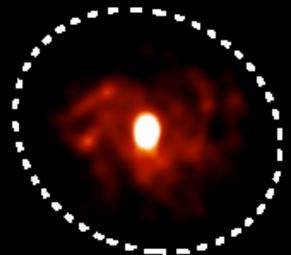
NGC 5055



NGC 5194



NGC 6946

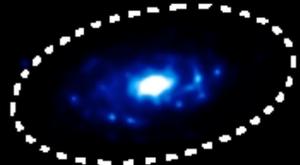


molecular hydrogen

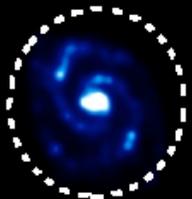
NGC 4736



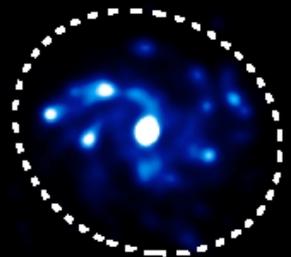
NGC 5055



NGC 5194

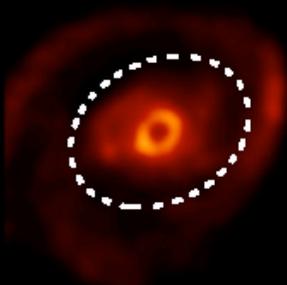


NGC 6946

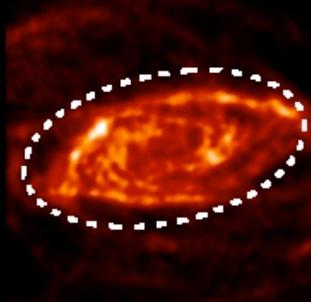


star formation

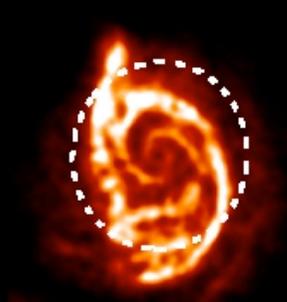
NGC 4736



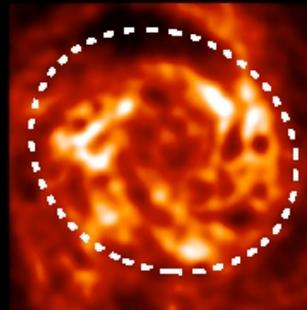
NGC 5055



NGC 5194

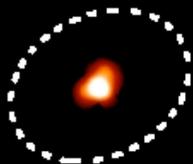


NGC 6946

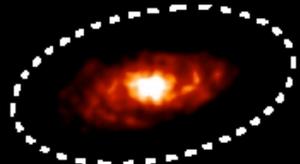


atomic hydrogen

NGC 4736



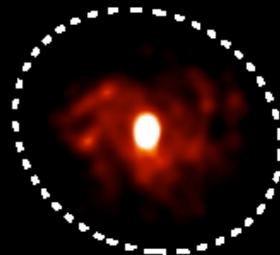
NGC 5055



NGC 5194



NGC 6946

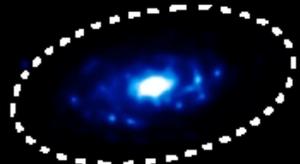


molecular hydrogen

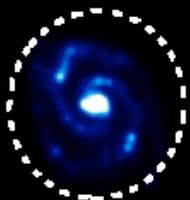
NGC 4736



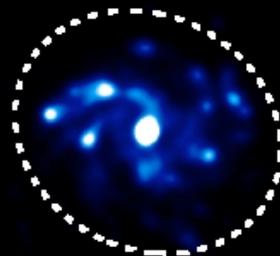
NGC 5055



NGC 5194

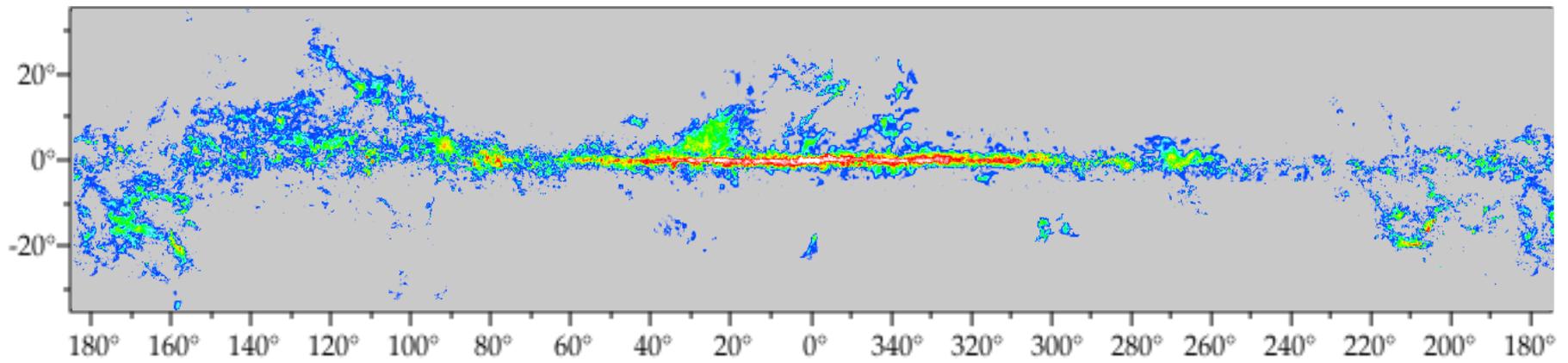


NGC 6946



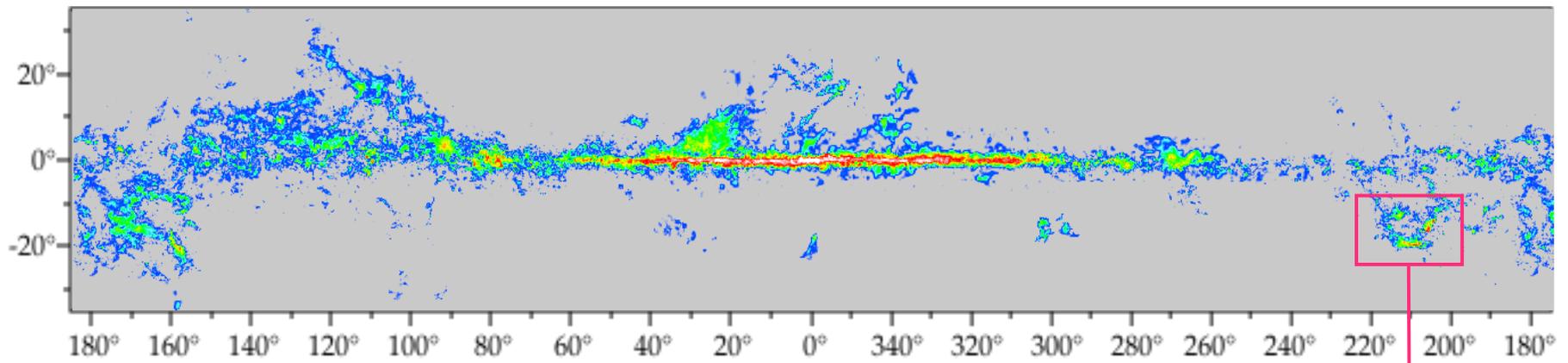
star formation

- HI gas more extended
- H2 and SF well correlated

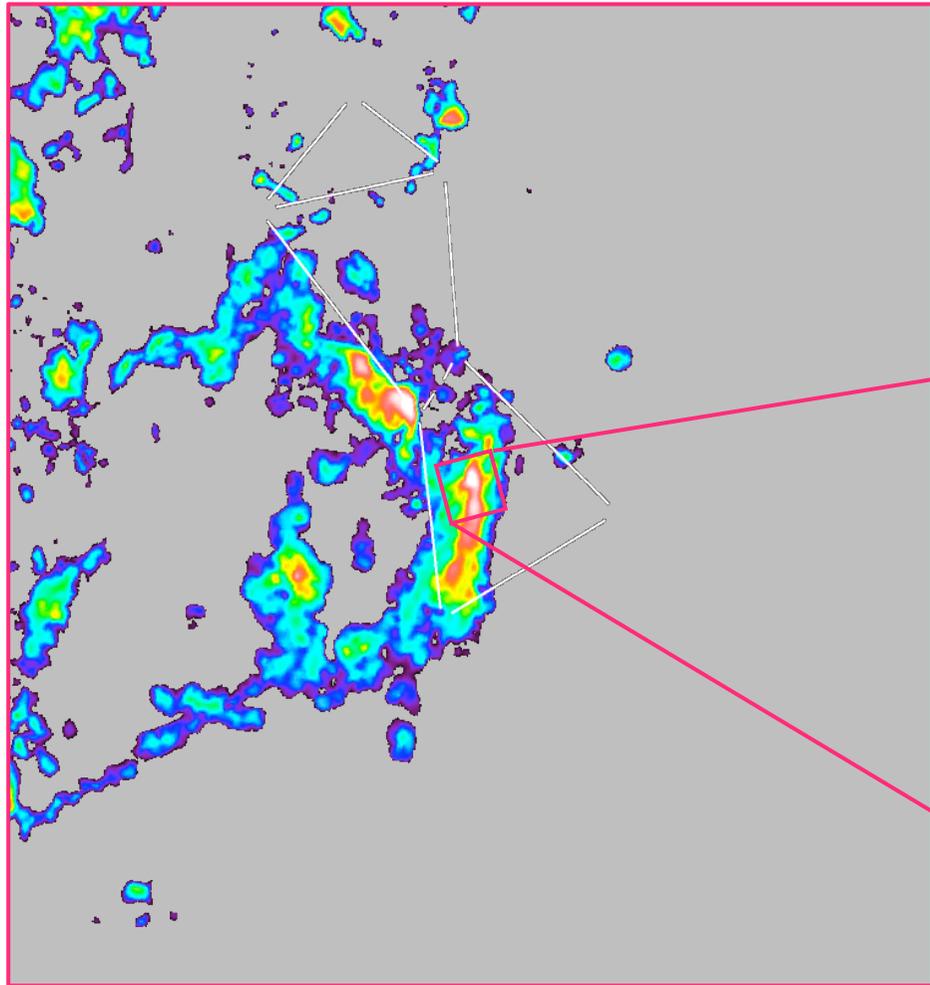


distribution of molecular  
gas in the Milky Way as  
traced by CO emission

data from T. Dame (CfA Harvard)



Orion



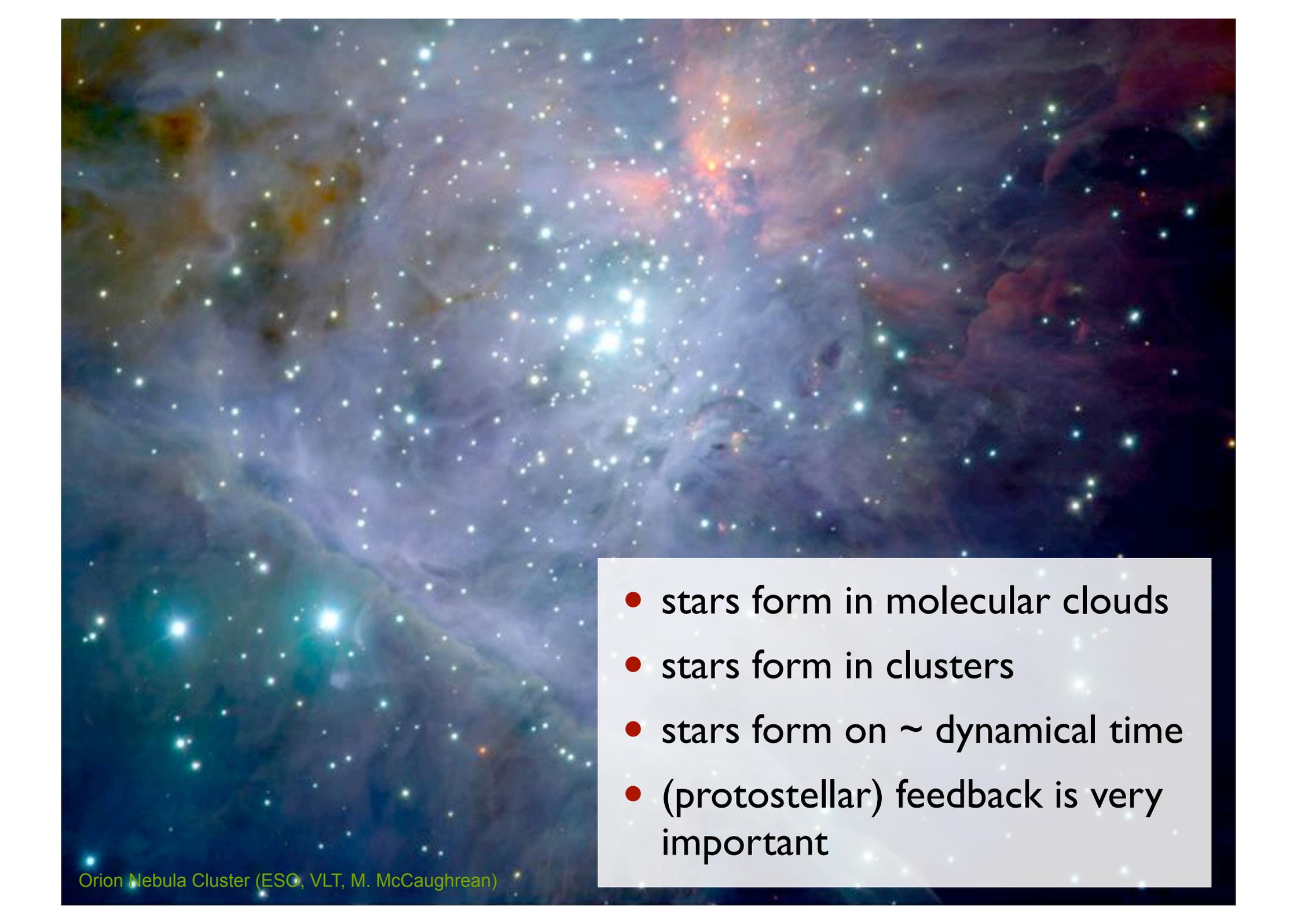
data from T. Dame (CfA Harvard)



Orion Nebula Cluster (ESO, VLT, M. McCaughrean)

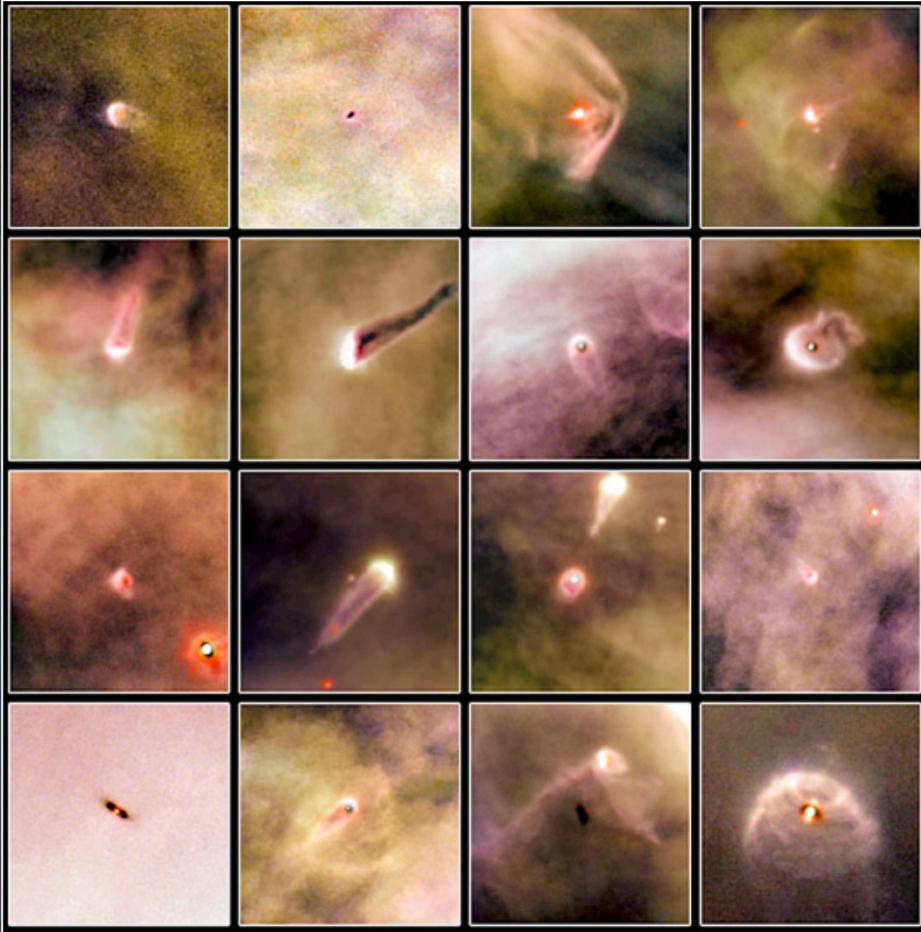


Orion Nebula Cluster (ESO, VLT, M. McCaughrean)

- 
- A wide-field astronomical image of the Orion Nebula Cluster. The image shows a vast field of stars, many of which are bright and blue, set against a backdrop of colorful interstellar dust and gas. The dust is primarily blue and purple, with some reddish and orange hues. The stars are scattered throughout the field, with some appearing in small, dense clusters. The overall scene is a complex and dynamic environment of star formation.
- stars form in molecular clouds
  - stars form in clusters
  - stars form on  $\sim$  dynamical time
  - (protostellar) feedback is very important



Trapezium stars in the center of the ONC (HST, Johnstone et al. 1998)



- strong feedback: UV radiation from  $\Theta$ 1C Orionis affects star formation on all cluster scales



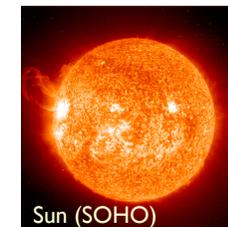
Trapezium stars in the center of the ONC (HST, Johnstone et al. 1998)



eventually, clusters like the ONC  
(1 Myr) will evolve into clusters  
like the Pleiades (100 Myr)

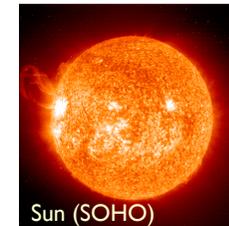
theoretical  
approach

decrease in spatial scale / increase in density



- density
  - density of ISM: few particles per  $\text{cm}^3$
  - density of molecular cloud: few 100 particles per  $\text{cm}^3$
  - density of Sun:  $1.4 \text{ g/cm}^3$
- spatial scale
  - size of molecular cloud: few 10s of pc
  - size of young cluster:  $\sim 1 \text{ pc}$
  - size of Sun:  $1.4 \times 10^{10} \text{ cm}$

decrease in spatial scale / increase in density



- contracting force
  - only force that can do this compression is **GRAVITY**
- opposing forces
  - there are several processes that can oppose gravity
  - **GAS PRESSURE**
  - **TURBULENCE**
  - **MAGNETIC FIELDS**
  - **RADIATION PRESSURE**

Modern star formation theory is based on the complex interplay between *all* these processes.

# early theoretical models

- *Jeans (1902)*: Interplay between self-gravity and thermal pressure
  - stability of homogeneous spherical density enhancements against gravitational collapse
  - dispersion relation:

$$\omega^2 = c_s^2 k^2 - 4\pi G \rho_0$$

- instability when  $\omega^2 < 0$

- minimal mass:  $M_J = \frac{1}{6} \pi^{-5/2} G^{-3/2} \rho_0^{-1/2} c_s^3 \propto \rho_0^{-1/2} T^{+3/2}$



Sir James Jeans, 1877 - 1946

# first approach to turbulence

- *von Weizsäcker (1943, 1951) and Chandrasekhar (1951): concept of **MICROTURBULENCE***

- BASIC ASSUMPTION: separation of scales between dynamics and turbulence

$$l_{\text{turb}} \ll l_{\text{dyn}}$$

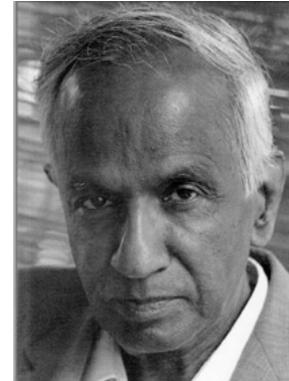
- then turbulent velocity dispersion contributes to effective soundspeed:

$$c_c^2 \mapsto c_c^2 + \sigma_{rms}^2$$

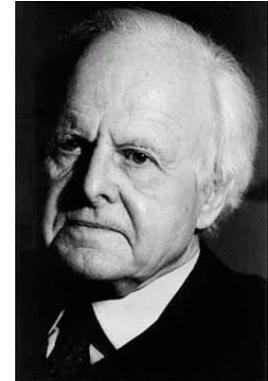
- → Larger effective Jeans masses → more stability

- BUT: (1) *turbulence depends on  $k$* :  $\sigma_{rms}^2(k)$

$$(2) \text{ supersonic turbulence } \rightarrow \sigma_{rms}^2(k) \gg c_s^2 \text{ usually}$$



S. Chandrasekhar,  
1910 - 1995



C.F. von Weizsäcker,  
1912 - 2007

# problems of early dynamical theory

- molecular clouds are *highly Jeans-unstable*, yet, they do *NOT* form stars at high rate and with high efficiency (Zuckerman & Evans 1974 conundrum) (the observed global SFE in molecular clouds is  $\sim 5\%$ )  
→ *something prevents large-scale collapse.*
- all throughout the early 1990's, molecular clouds had been thought to be long-lived quasi-equilibrium entities.
- molecular clouds are *magnetized*

# magnetic star formation

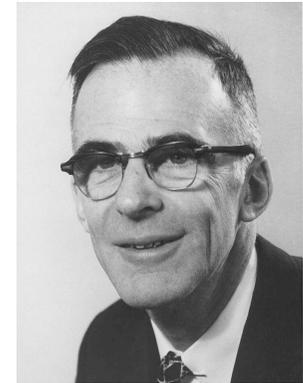
- *Mestel & Spitzer (1956)*: Magnetic fields can prevent collapse!!!
  - Critical mass for gravitational collapse in presence of B-field

$$M_{cr} = \frac{5^{3/2}}{48\pi^2} \frac{B^3}{G^{3/2} \rho^2}$$

- Critical mass-to-flux ratio (Mouschovias & Spitzer 1976)

$$\left[ \frac{M}{\Phi} \right]_{cr} = \frac{\xi}{3\pi} \left[ \frac{5}{G} \right]^{1/2}$$

- Ambipolar diffusion can initiate collapse



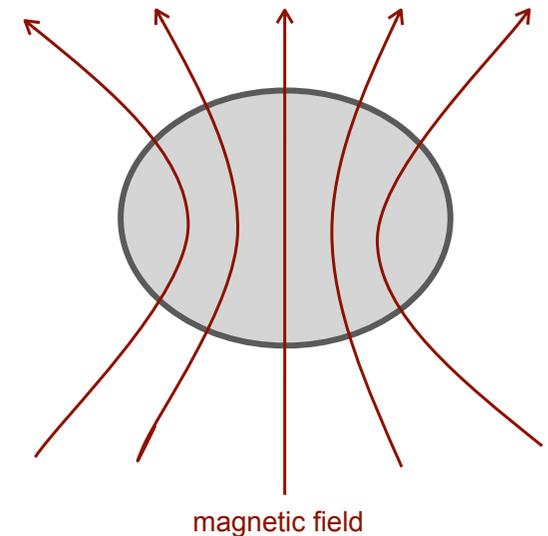
Lyman Spitzer, Jr., 1914 - 1997

# “standard theory” of star formation

- BASIC ASSUMPTION: Stars form from magnetically highly subcritical cores
- Ambipolar diffusion slowly increases  $(M/\Phi)$ :  $\tau_{AD} \approx 10\tau_{ff}$
- Once  $(M/\Phi) > (M/\Phi)_{crit}$  : dynamical collapse of SIS
  - Shu (1977) collapse solution
  - $dM/dt = 0.975 c_s^3/G = \text{const.}$
- Was (in principle) only intended for isolated, low-mass stars



Frank Shu, 1943 -



# problems of “standard theory”

- Observed B-fields are weak, at most marginally critical (Crutcher 1999, Bourke et al. 2001)
- Magnetic fields cannot prevent decay of turbulence (Mac Low et al. 1998, Stone et al. 1998, Padoan & Nordlund 1999)
- Structure of prestellar cores (e.g. Bacman et al. 2000, Alves et al. 2001)
- Strongly time varying  $dM/dt$  (e.g. Hendriksen et al. 1997, André et al. 2000)
- More extended infall motions than predicted by the standard model (Williams & Myers 2000, Myers et al. 2000)
- Most stars form as binaries (e.g. Lada 2006)
- As many prestellar cores as protostellar cores in SF regions (e.g. André et al 2002)
- Molecular cloud clumps are chemically young (Bergin & Langer 1997, Pratap et al 1997, Aikawa et al 2001)
- Stellar age distribution small ( $\tau_{\text{ff}} \ll \tau_{\text{AD}}$ ) (Ballesteros-Paredes et al. 1999, Elmegreen 2000, Hartmann 2001)
- Strong theoretical criticism of the SIS as starting condition for gravitational collapse (e.g. Whitworth et al 1996, Nakano 1998, as summarized in Klessen & Mac Low 2004)
- Standard AD-dominated theory is incompatible with observations (Crutcher et al. 2009, 2010ab, Bertram et al. 2011)

# gravoturbulent star formation

- BASIC ASSUMPTION:

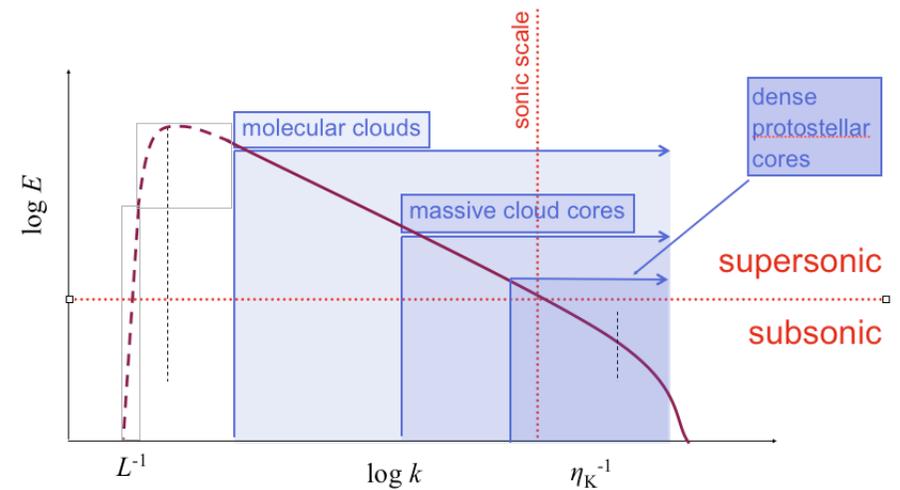
star formation is controlled by interplay between supersonic turbulence and self-gravity

- turbulence plays a *dual role*:

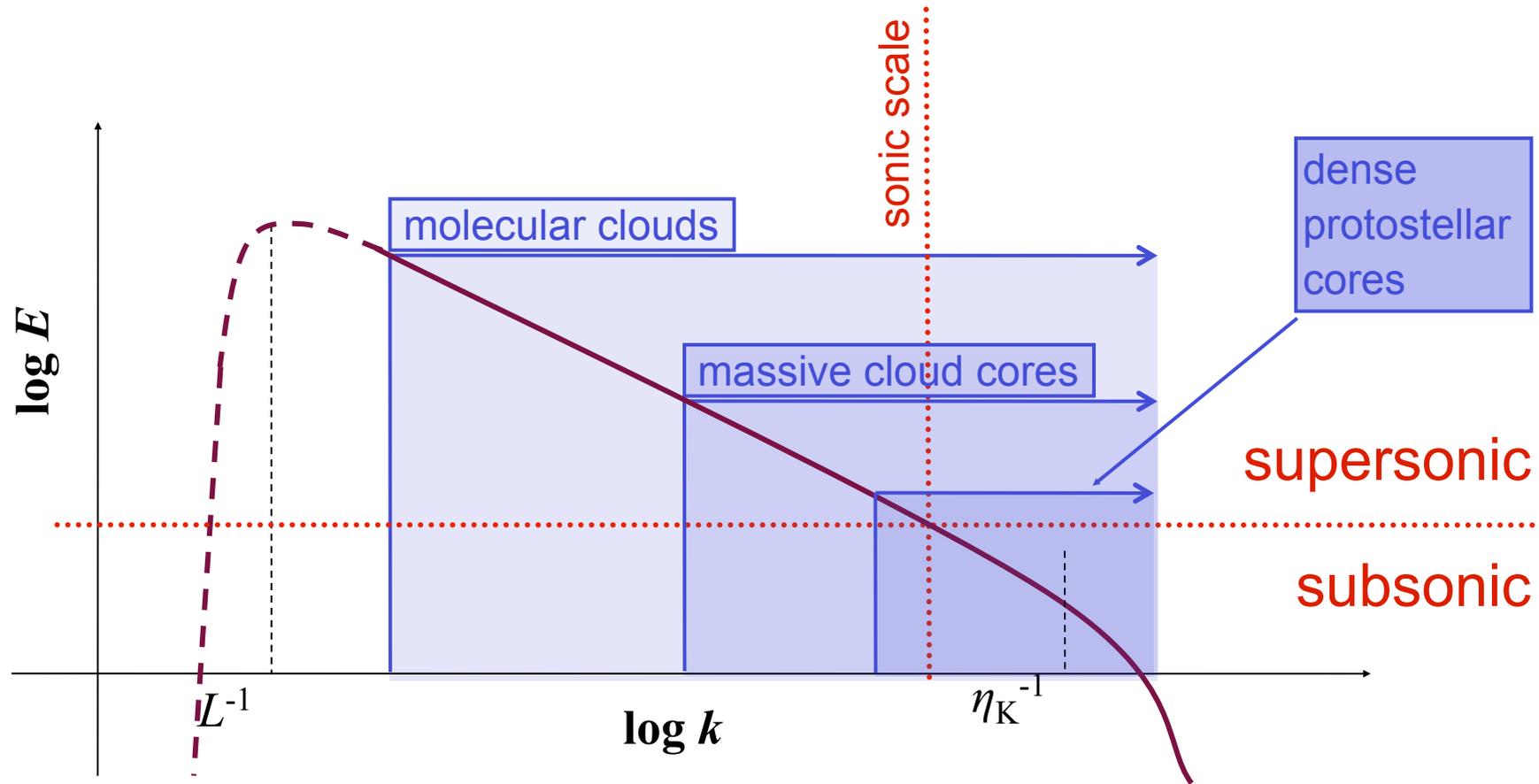
- on *large scales* it *provides support*
- on *small scales* it can *trigger collapse*

- some predictions:

- dynamical star formation timescale  $\tau_{\text{ff}}$
- high binary fraction
- complex spatial structure of embedded star clusters
- and many more . . .



# turbulent cascade in the ISM



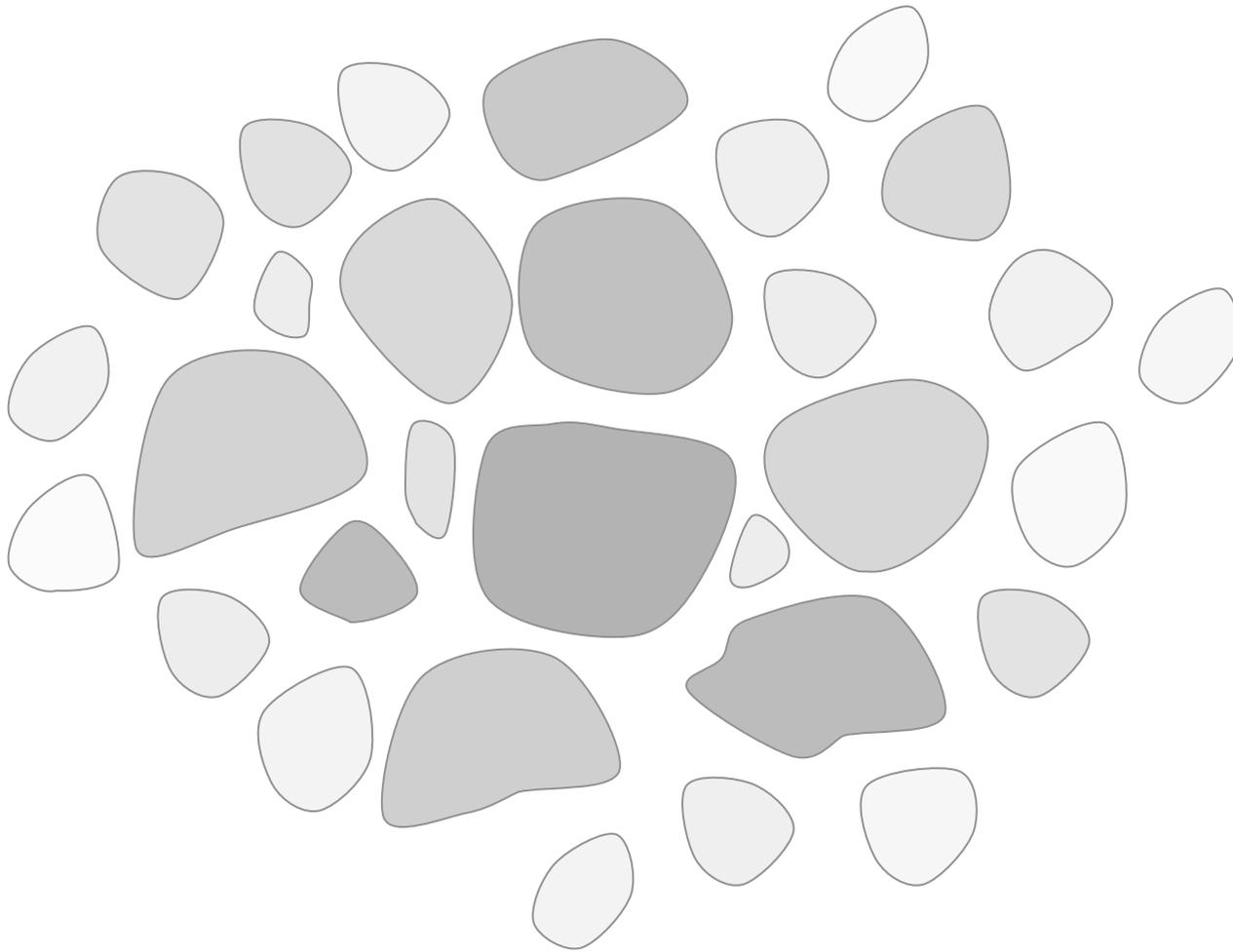
energy source & scale  
*NOT known*  
 (supernovae, winds,  
 spiral density waves?)

$$\sigma_{\text{rms}} \ll 1 \text{ km/s}$$

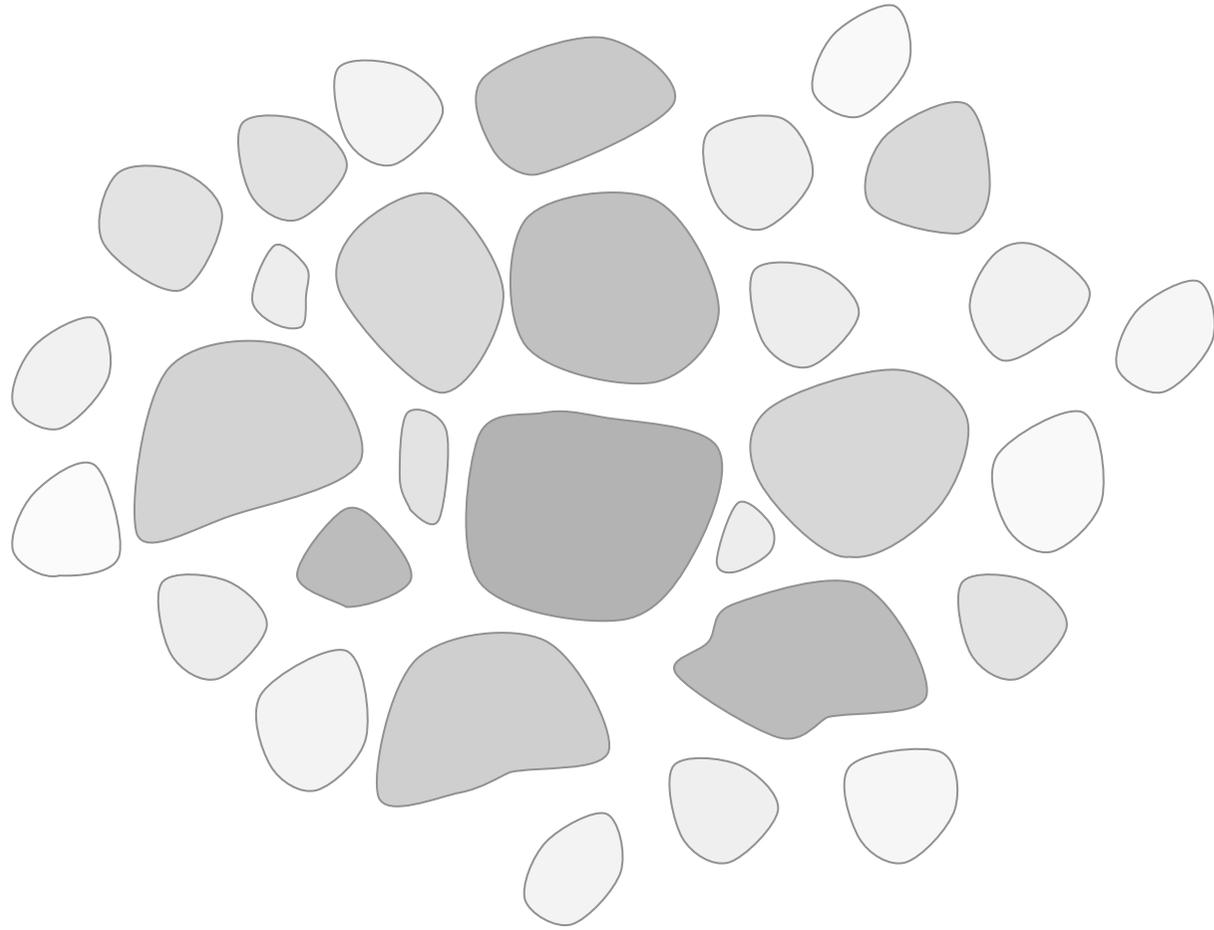
$$M_{\text{rms}} \leq 1$$

$$L \approx 0.1 \text{ pc}$$

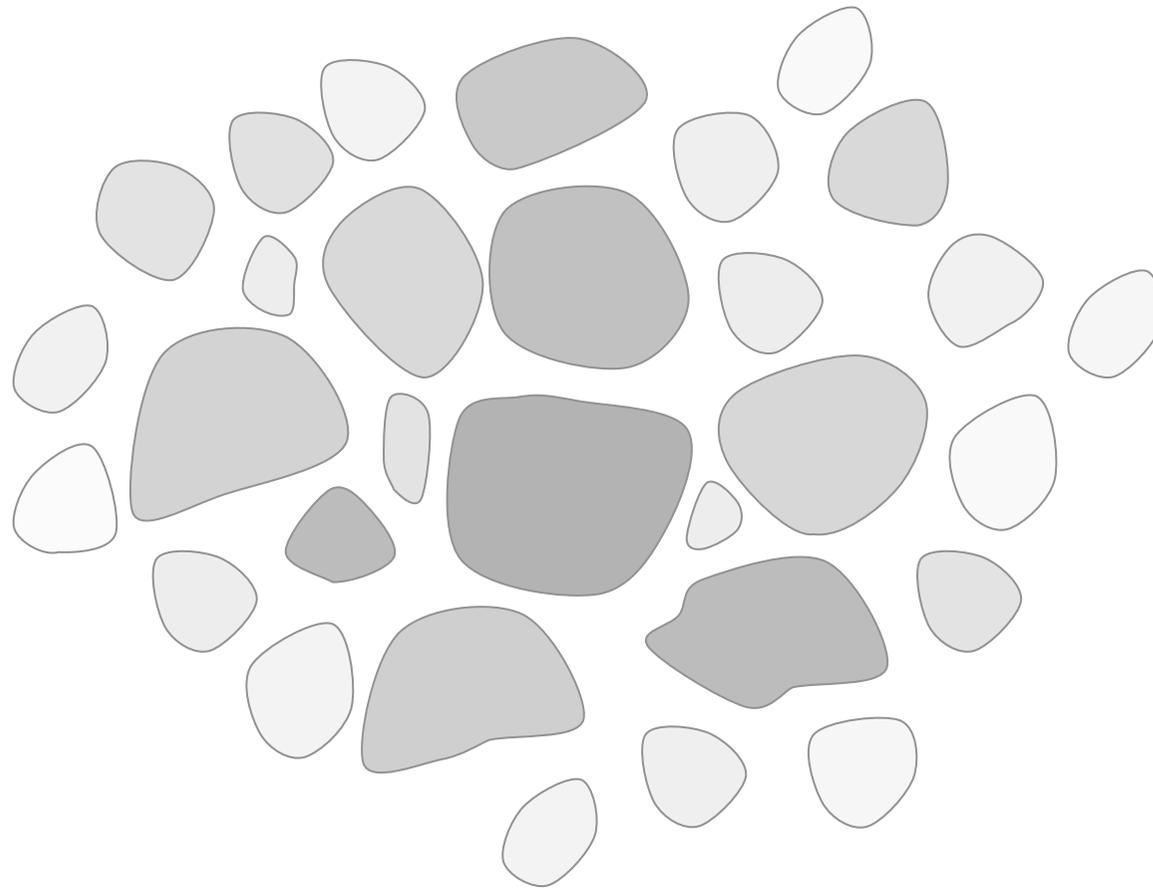
dissipation scale not known  
 (ambipolar diffusion,  
 molecular diffusion?)



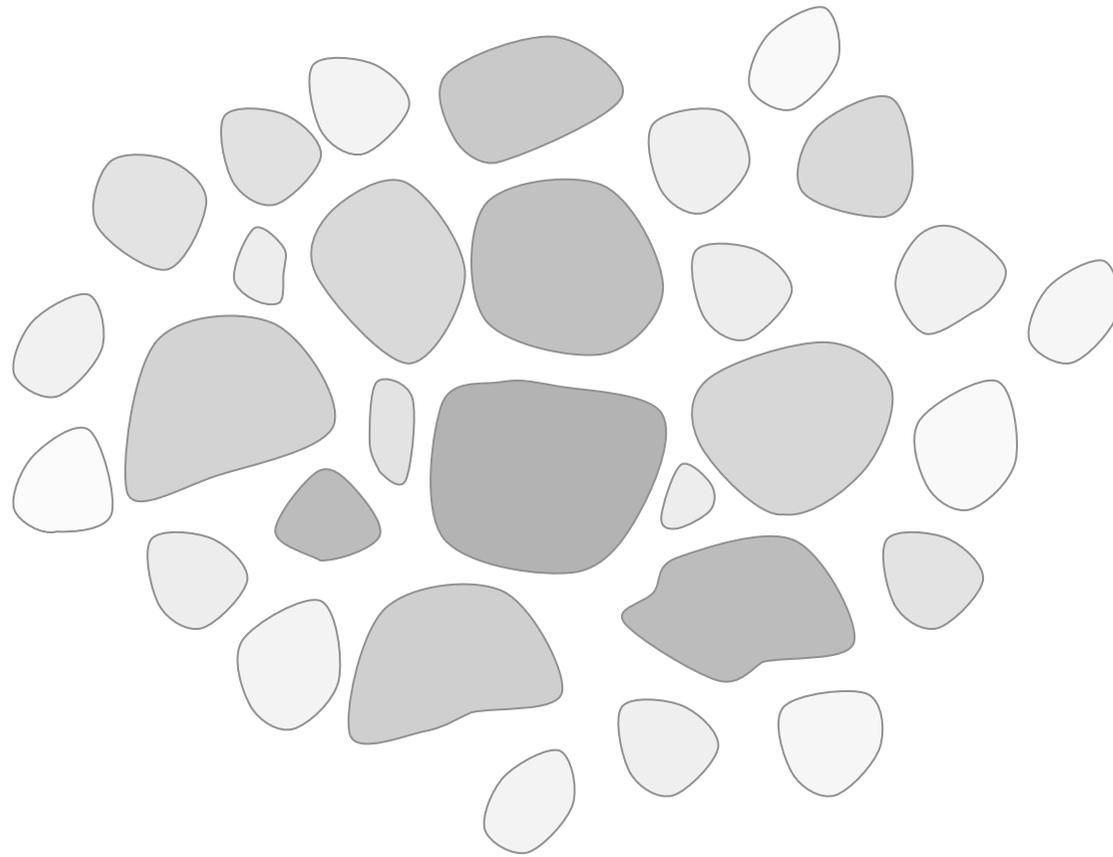
turbulence creates a hierarchy of clumps



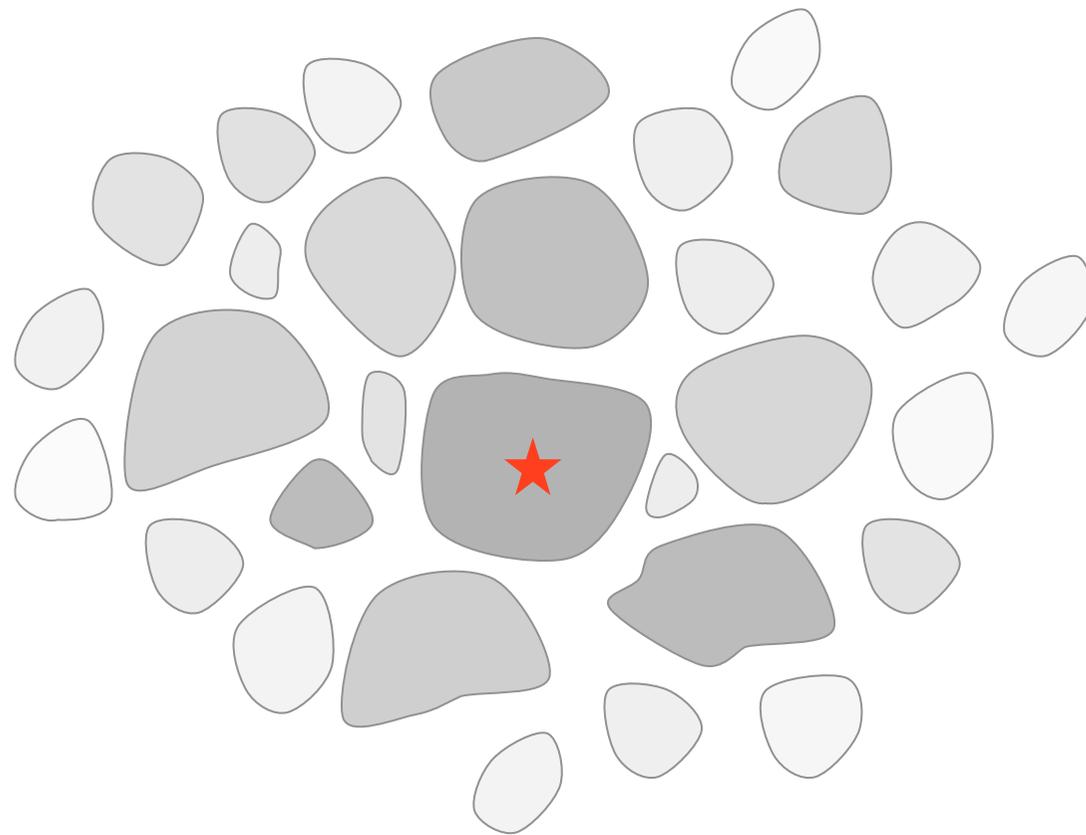
as turbulence decays locally, contraction sets in



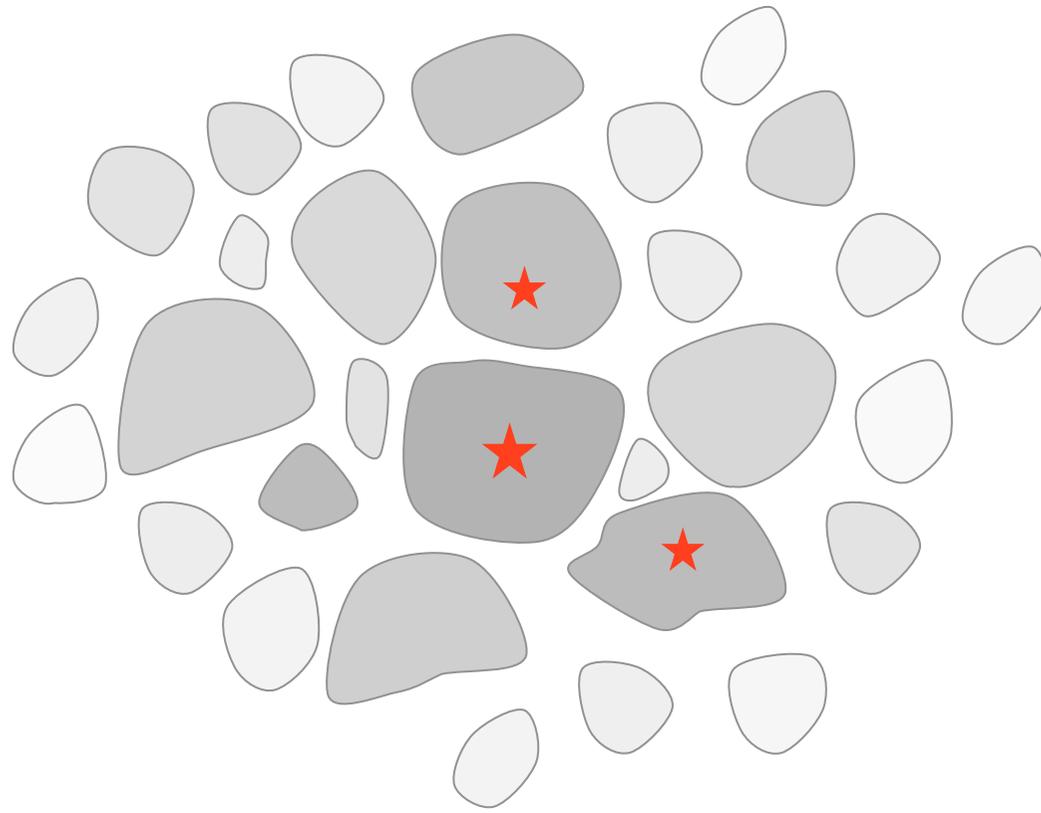
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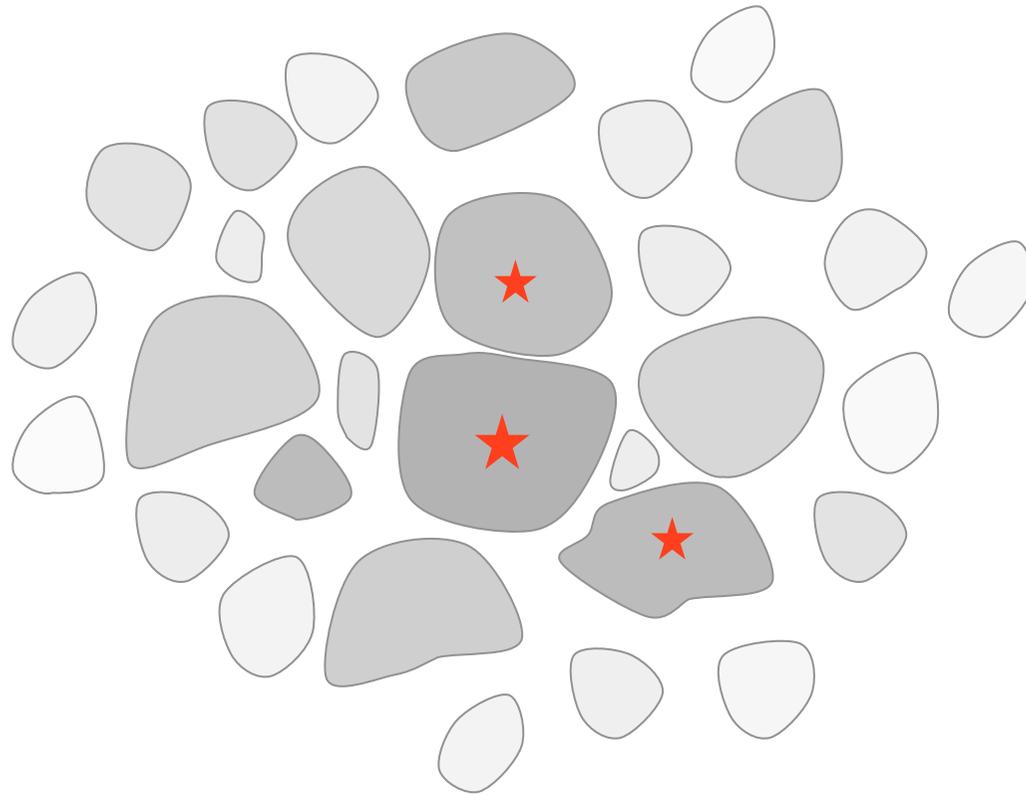
while region contracts, individual clumps collapse to form stars



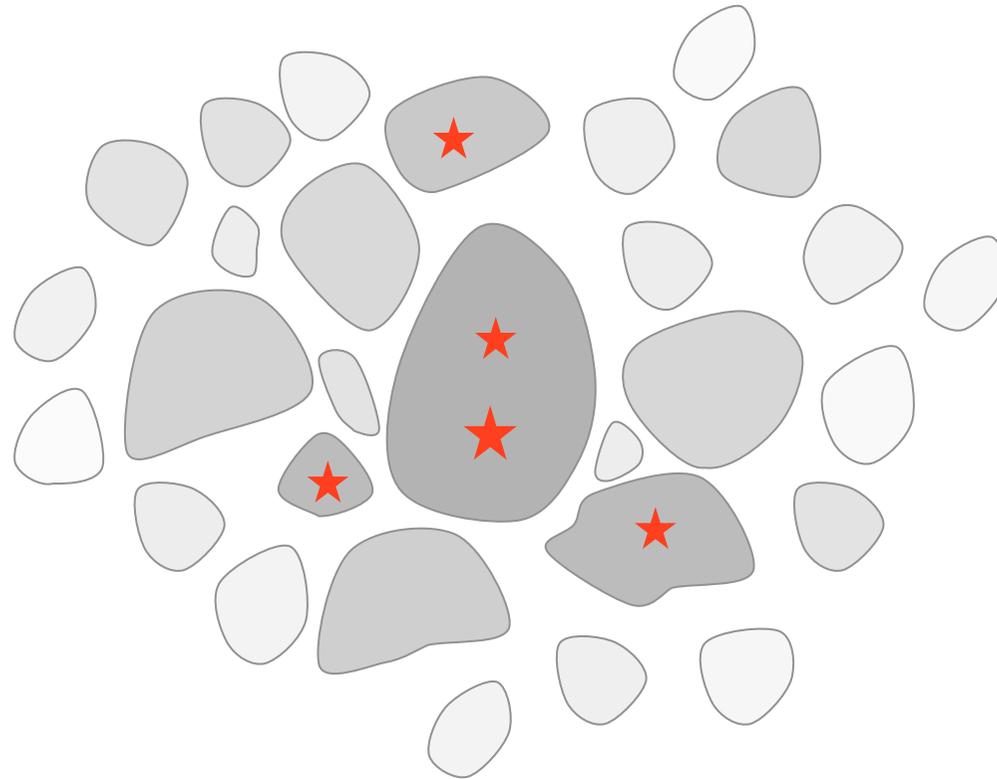
while region contracts, individual clumps collapse to form stars



individual clumps collapse to form stars

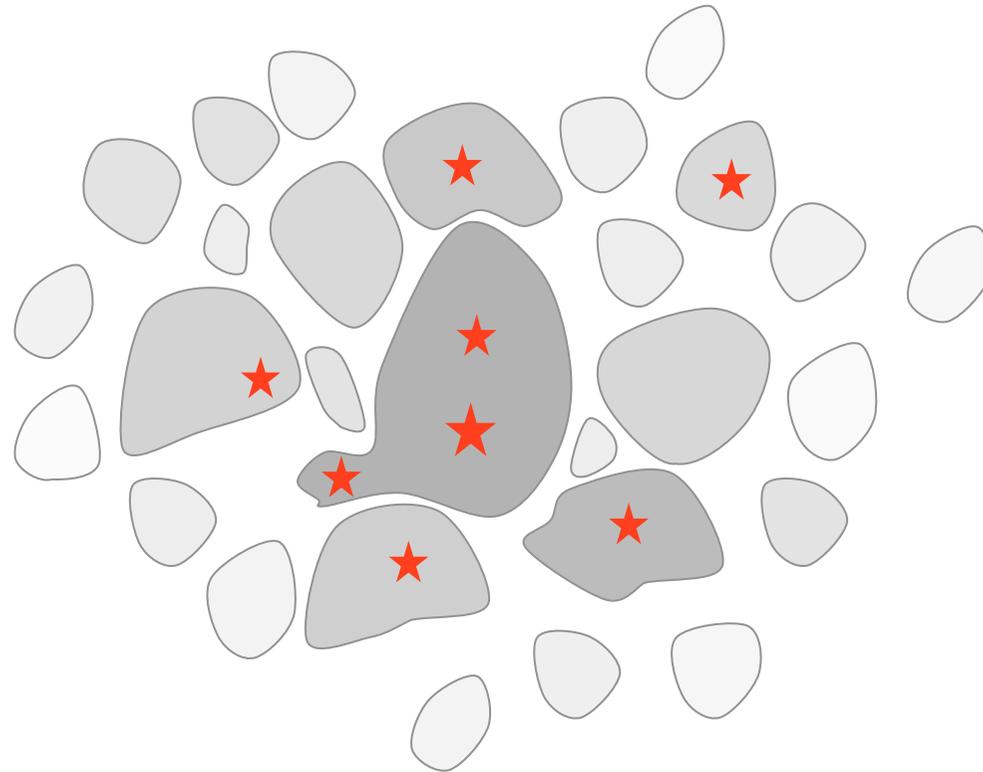


individual clumps collapse to form stars

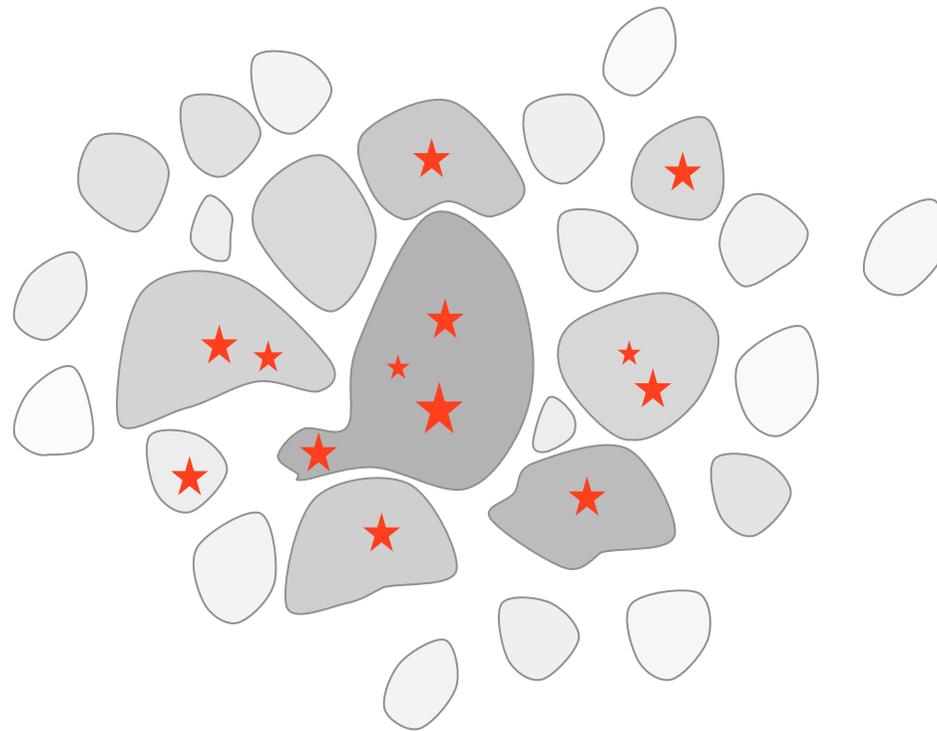


$$\alpha = E_{\text{kin}} / |E_{\text{pot}}| < 1$$

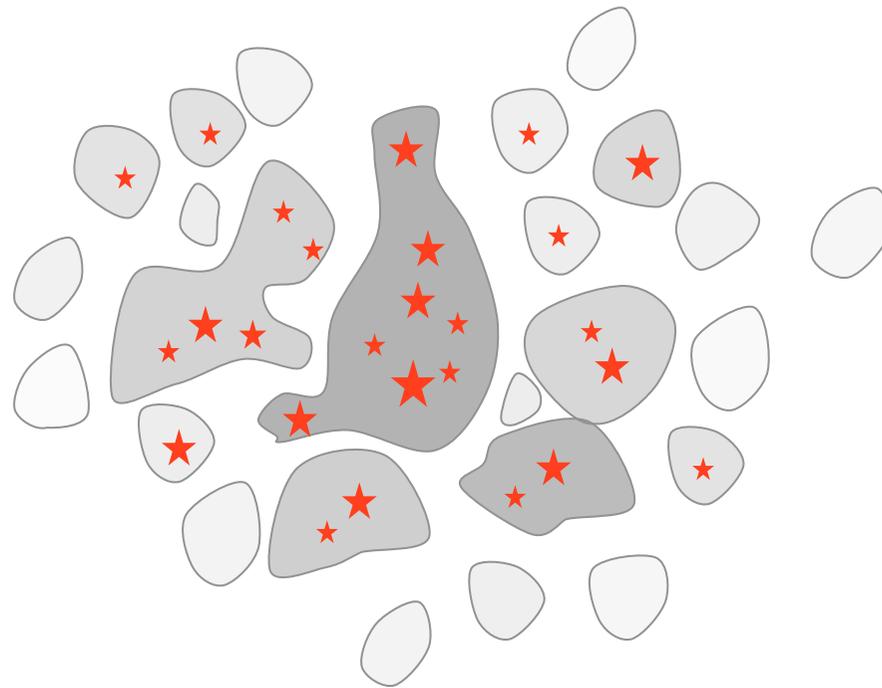
in *dense clusters*, clumps may merge while collapsing  
--> then contain multiple protostars



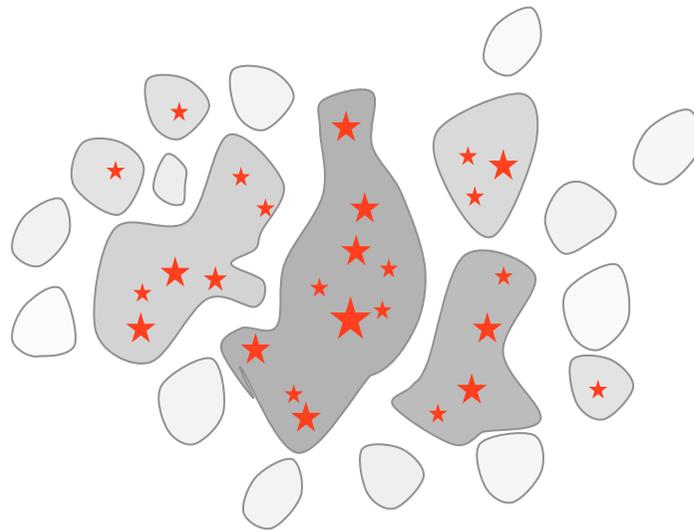
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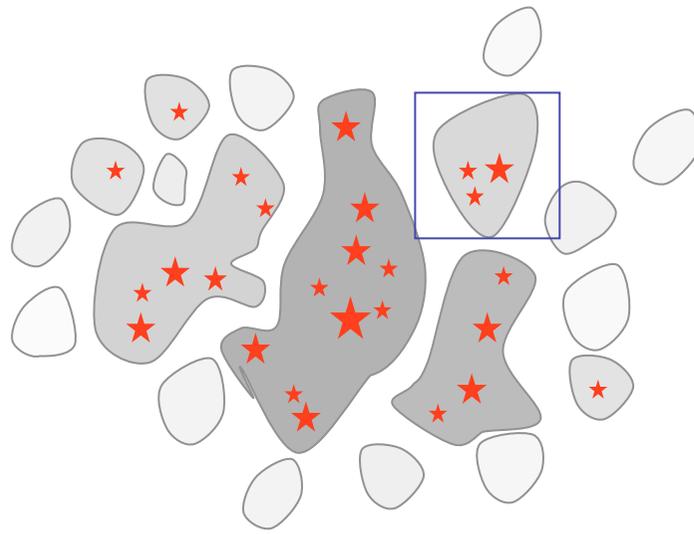
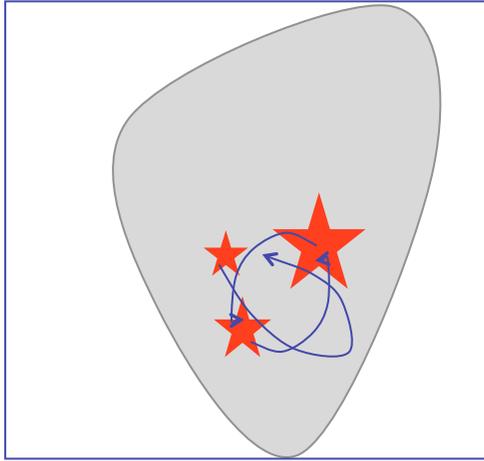
in *dense clusters*, clumps may merge while collapsing  
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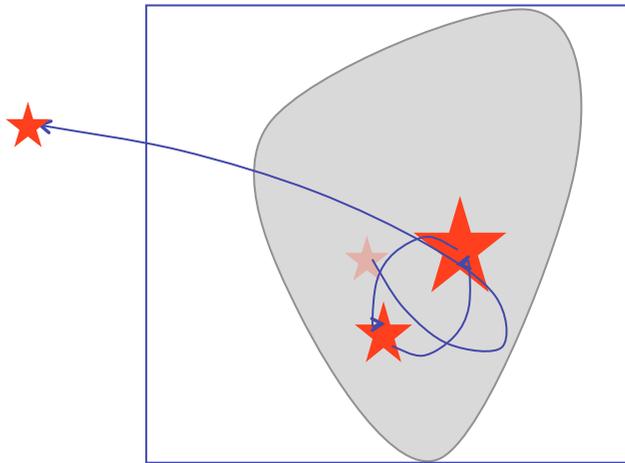
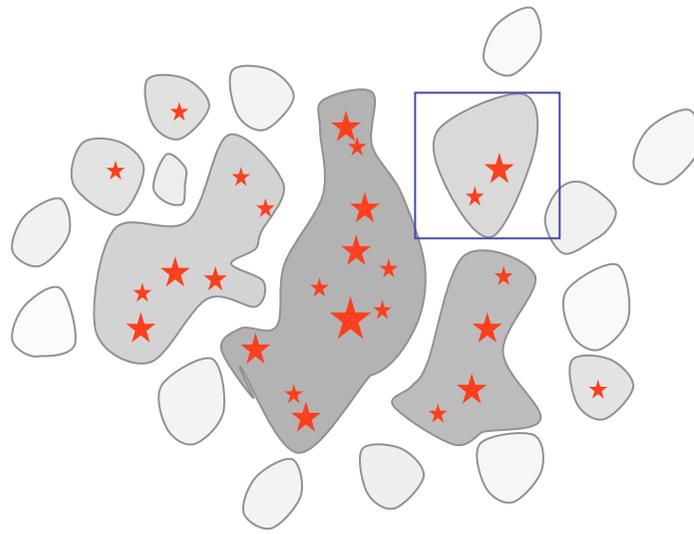
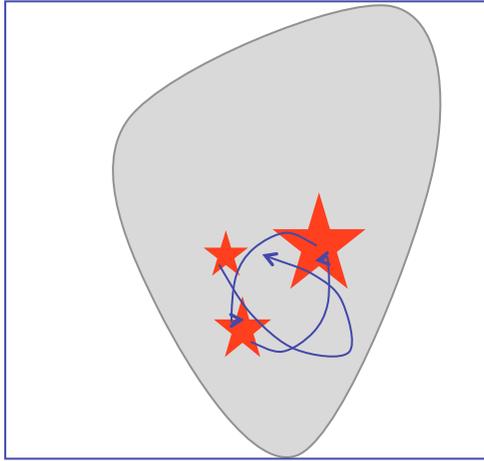
in *dense clusters*, competitive mass growth becomes important



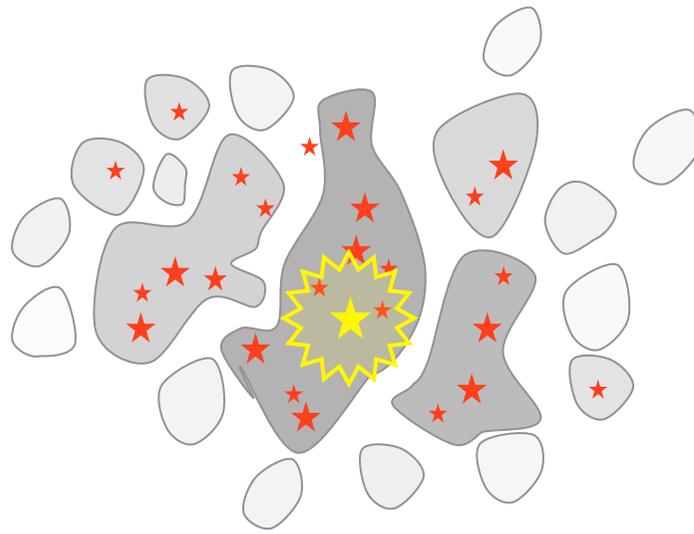
in *dense clusters*, competitive mass growth becomes important



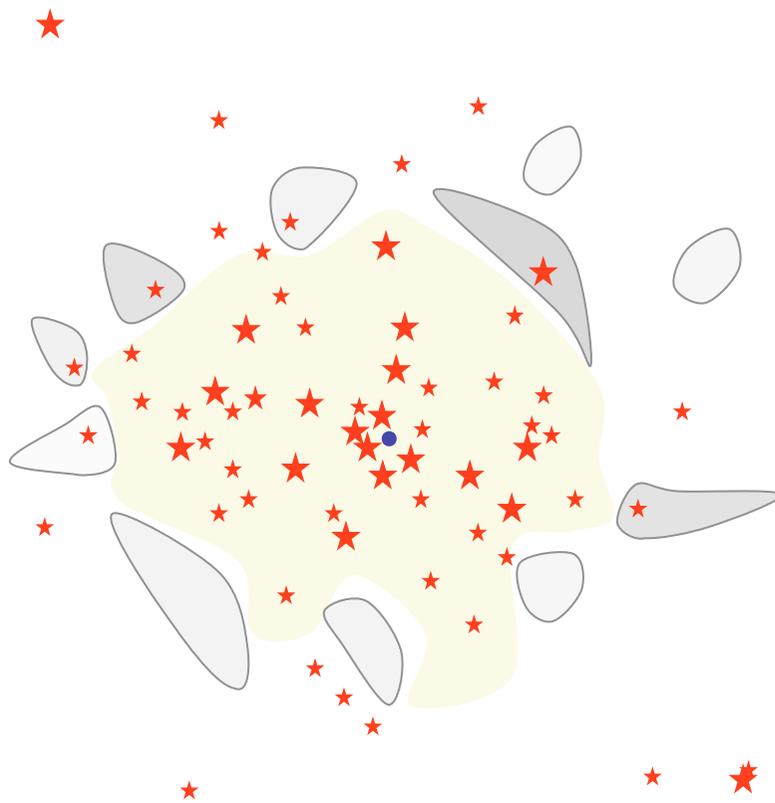
in *dense clusters*,  $N$ -body effects influence mass growth



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



feedback terminates star formation



result: *star cluster*, possibly with H<sub>II</sub> region

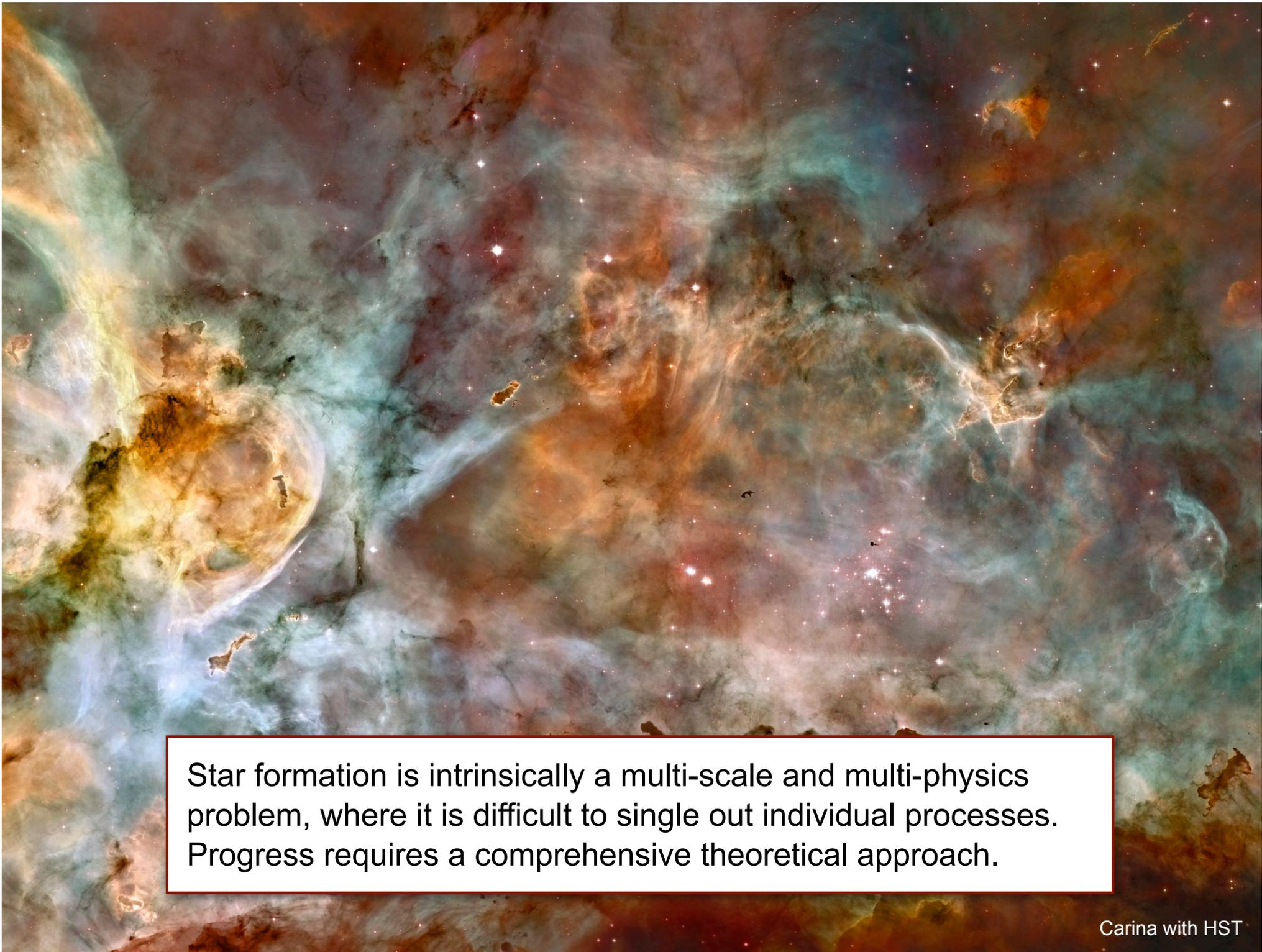


NGC 602 in the LMC: Hubble Heritage Image

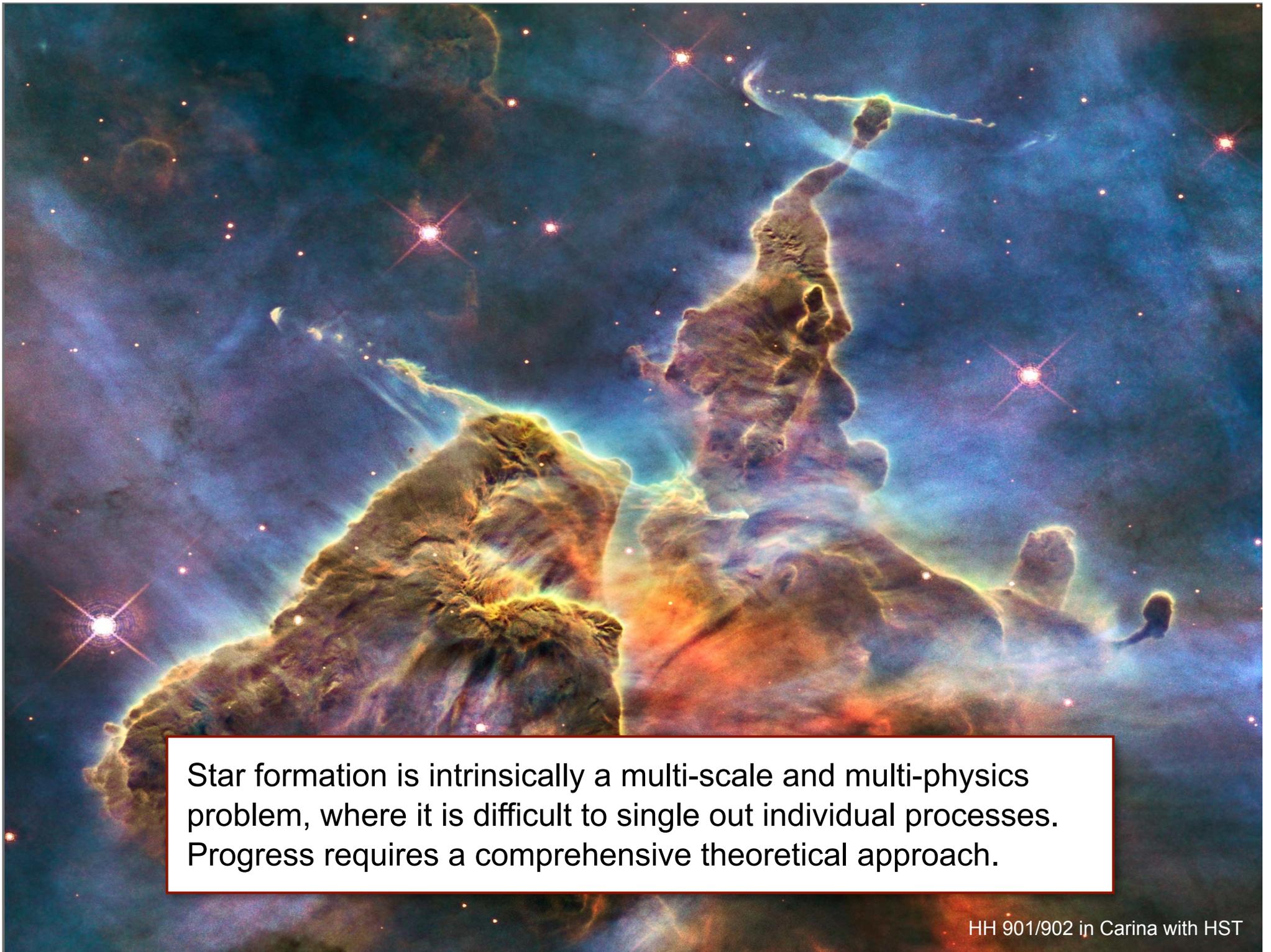
# current status

- *stars form from the complex interplay of self-gravity and a large number of competing processes (such as turbulence, B-field, feedback, thermal pressure)*
  - *the relative importance of these processes depends on the environment*
    - prestellar cores --> thermal pressure is important
    - molecular clouds --> turbulence dominates } (Larson's relation:  $\sigma \propto L^{1/2}$ )
  - massive star forming regions (NGC602): radiative feedback is important
  - small clusters (Taurus): evolution maybe dominated by external turbulence
- *star formation is regulated by various feedback processes*
  - *star formation is closely linked to global galactic dynamics (KS relation)*

Star formation is intrinsically a multi-scale and multi-physics problem, where it is difficult to single out individual processes. Simple theoretical approaches usually fail.



Star formation is intrinsically a multi-scale and multi-physics problem, where it is difficult to single out individual processes. Progress requires a comprehensive theoretical approach.



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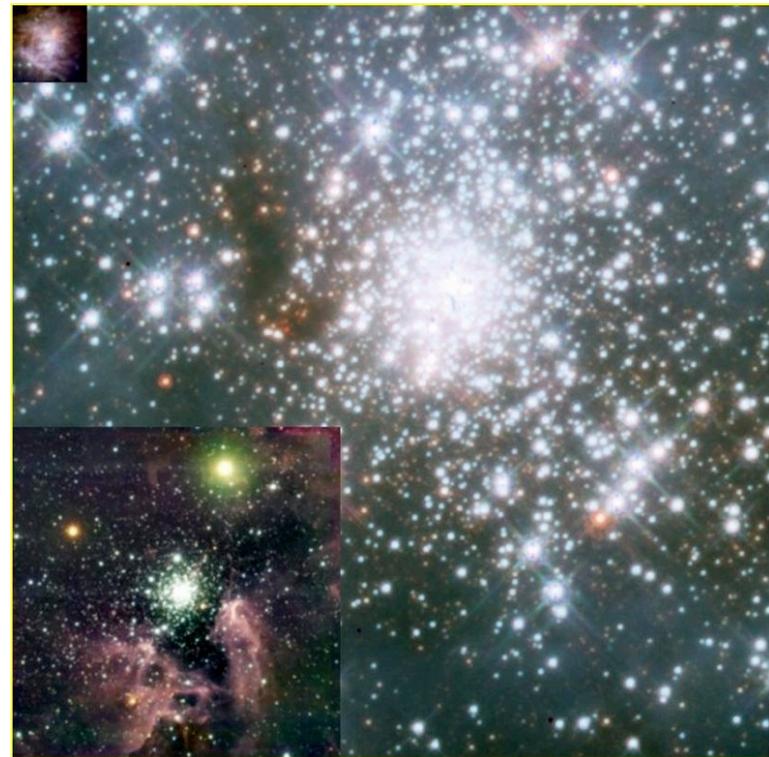
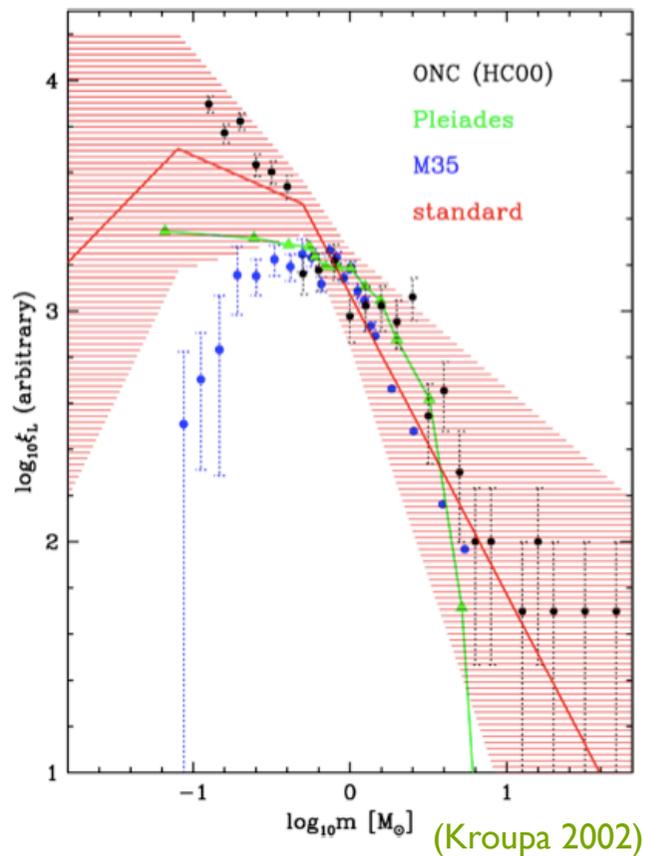
# selected open questions

- what processes determine the initial mass function (IMF) of stars?
- what are the initial conditions for star cluster formation?  
how does cloud structure translate into cluster structure?
- how do molecular clouds form and evolve?
- what drives turbulence?
- what triggers / regulates star formation on galactic scales?
- how does star formation depend on metallicity?  
how do the first stars form?
- star formation in extreme environments (galactic center, starburst, etc.),  
how does it differ from a more “normal” mode?

stellar mass  
function

# stellar mass function

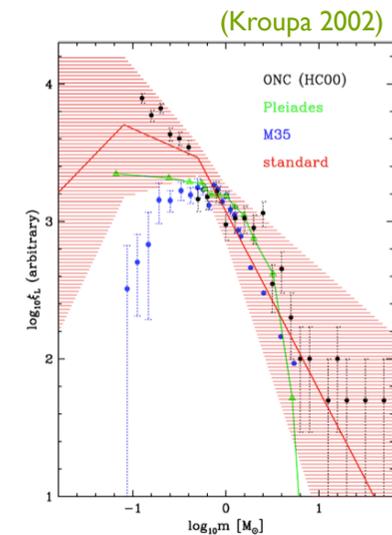
stars seem to follow a universal mass function at birth --> IMF



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

# stellar masses

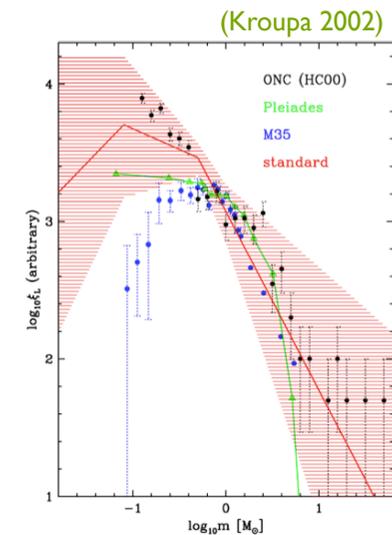
- distribution of stellar masses depends on
  - turbulent initial conditions
    - > mass spectrum of prestellar cloud cores
  - collapse and interaction of prestellar cores
    - > accretion and  $N$ -body effects
  - thermodynamic properties of gas
    - > balance between heating and cooling
    -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



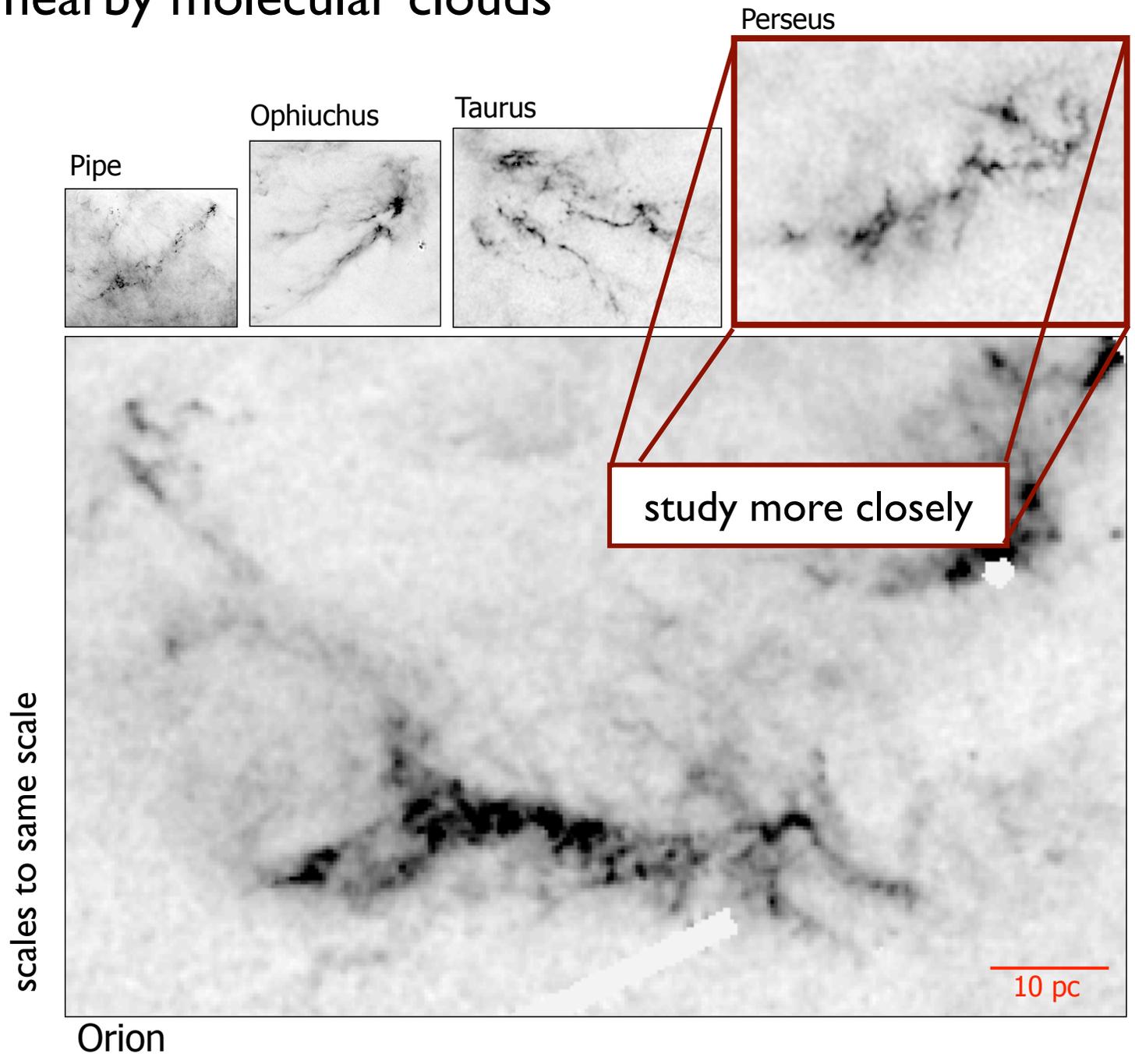
# stellar masses

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# nearby molecular clouds



(from A. Goodman)

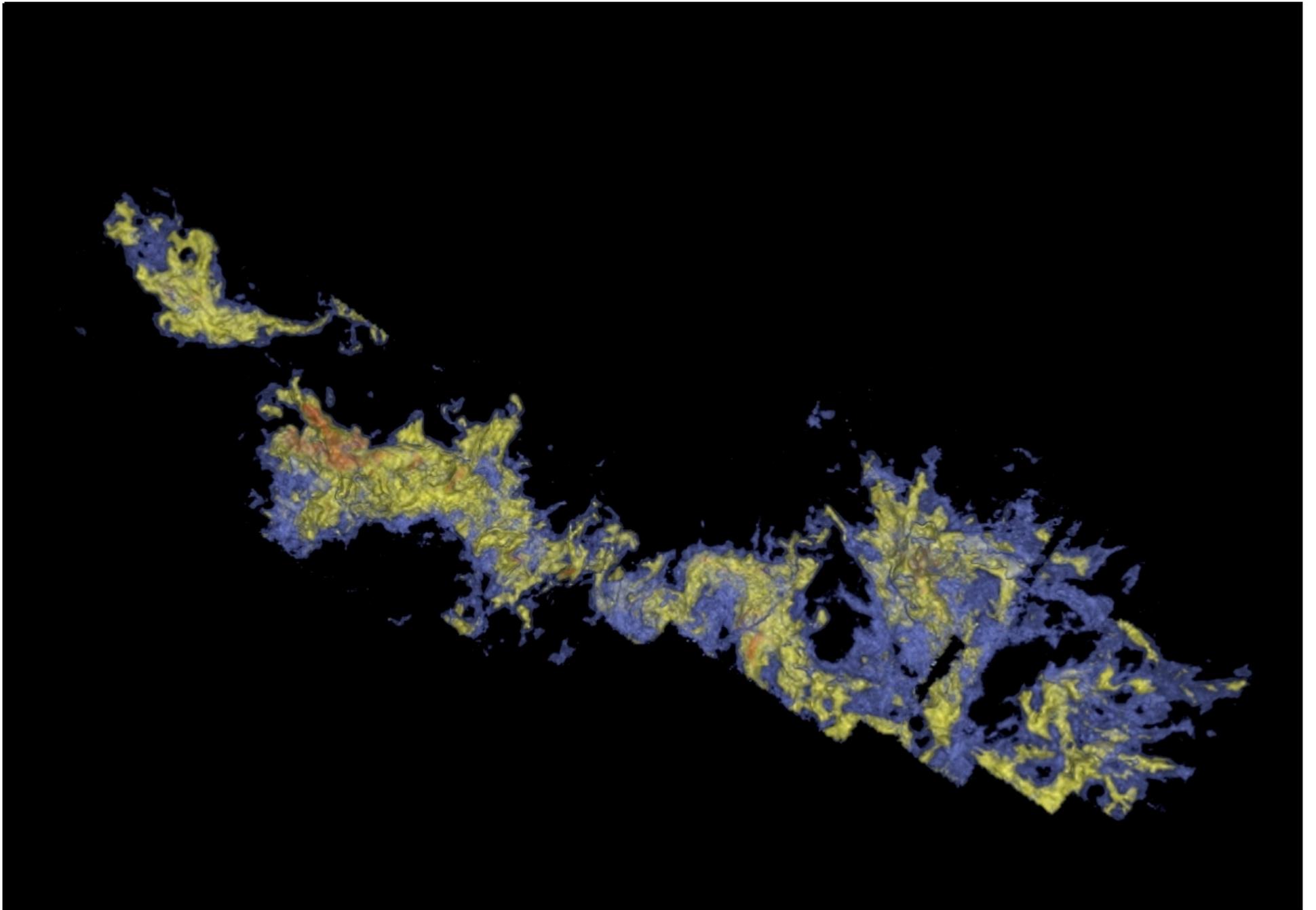
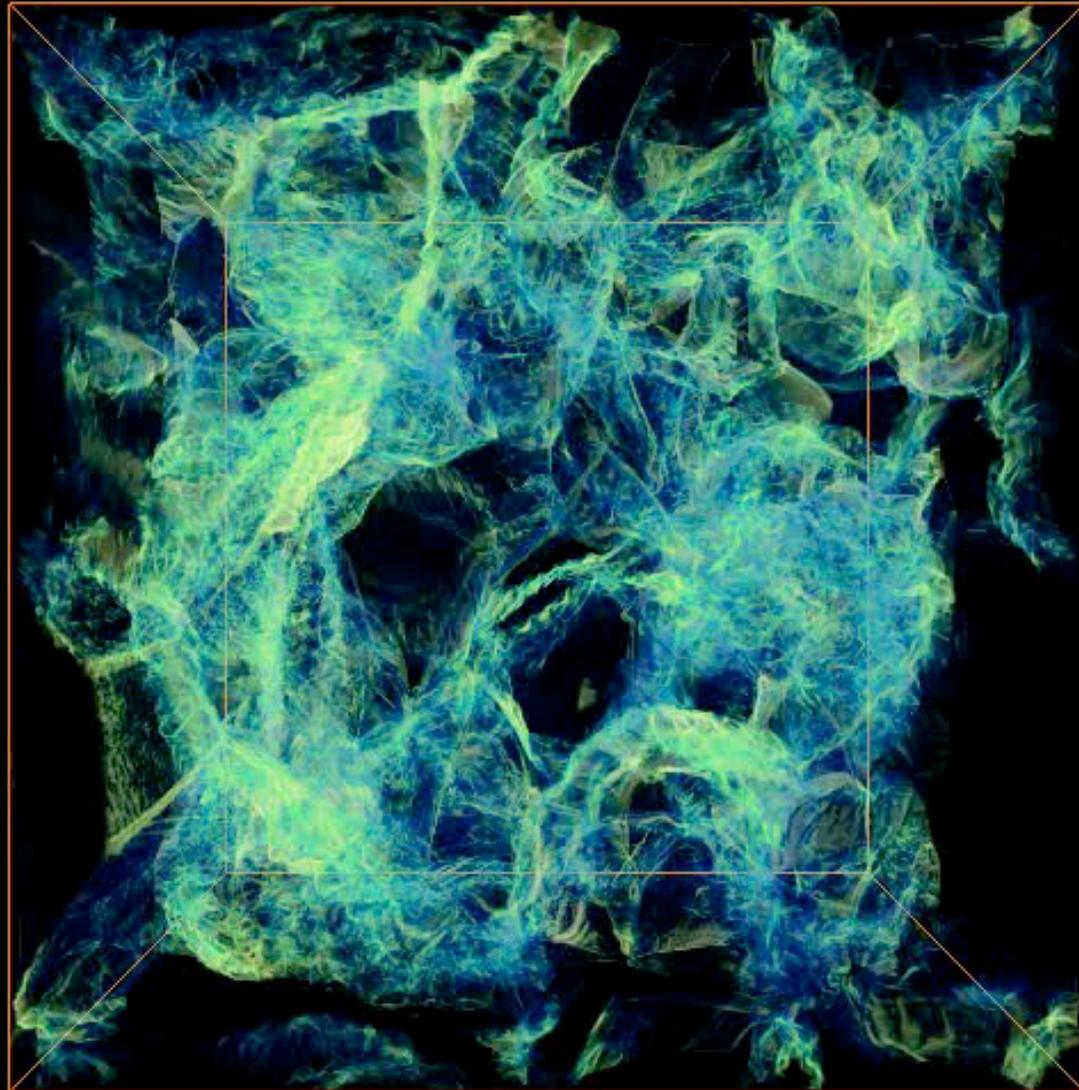


image from Alyssa Goodman: COMPLETE survey



Schmidt et al. (2009, A&A, 494, 127)



# example: model of Orion cloud

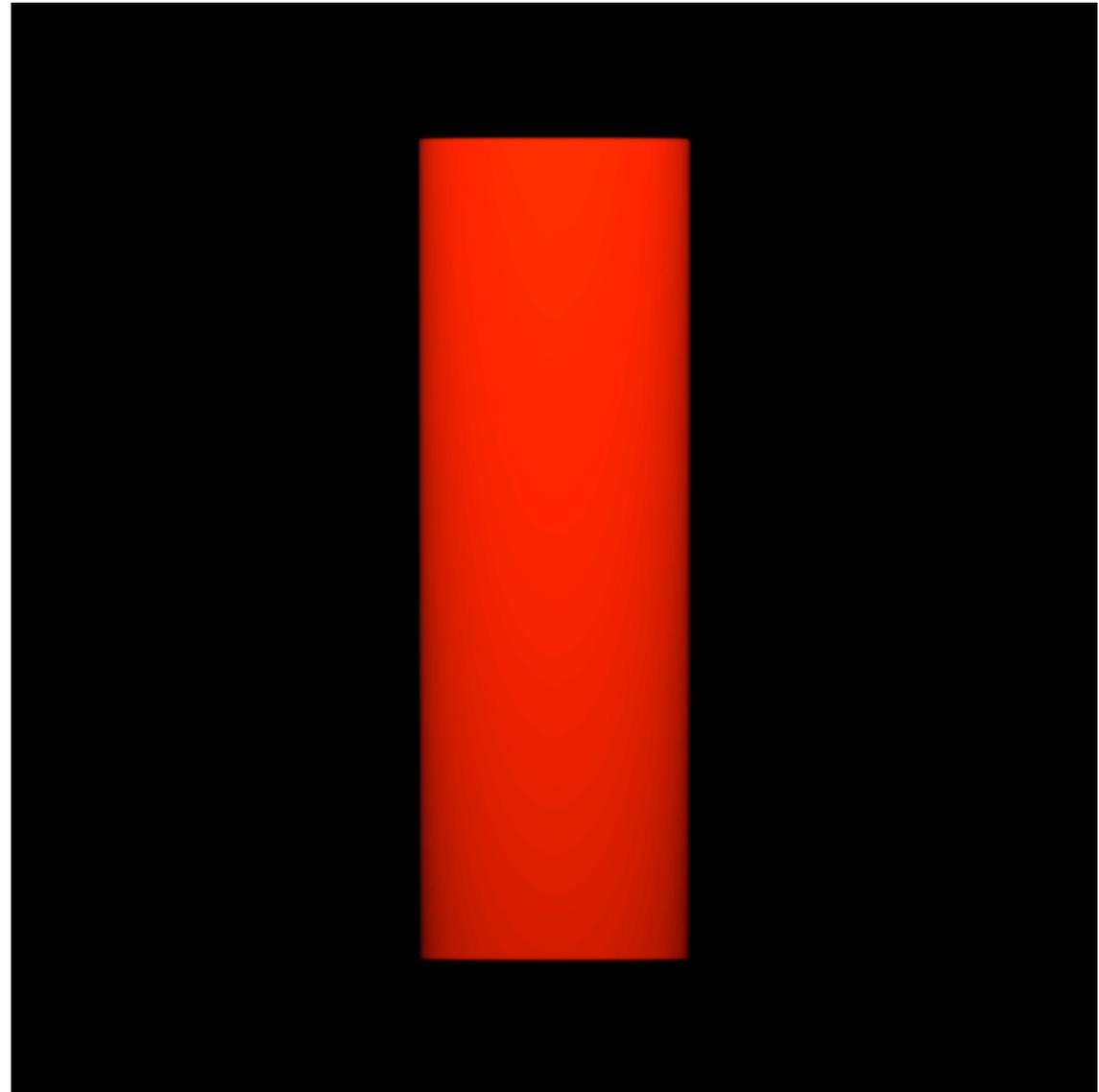
„model“ of Orion cloud:  
15.000.000 SPH particles,  
 $10^4 M_{\text{sun}}$  in 10 pc, mass resolution  
 $0,02 M_{\text{sun}}$ , forms  $\sim 2.500$   
„stars“ (sink particles)

isothermal EOS, top bound, bottom unbound

has clustered as well as distributed  
„star“ formation

efficiency varies from 1% to 20%

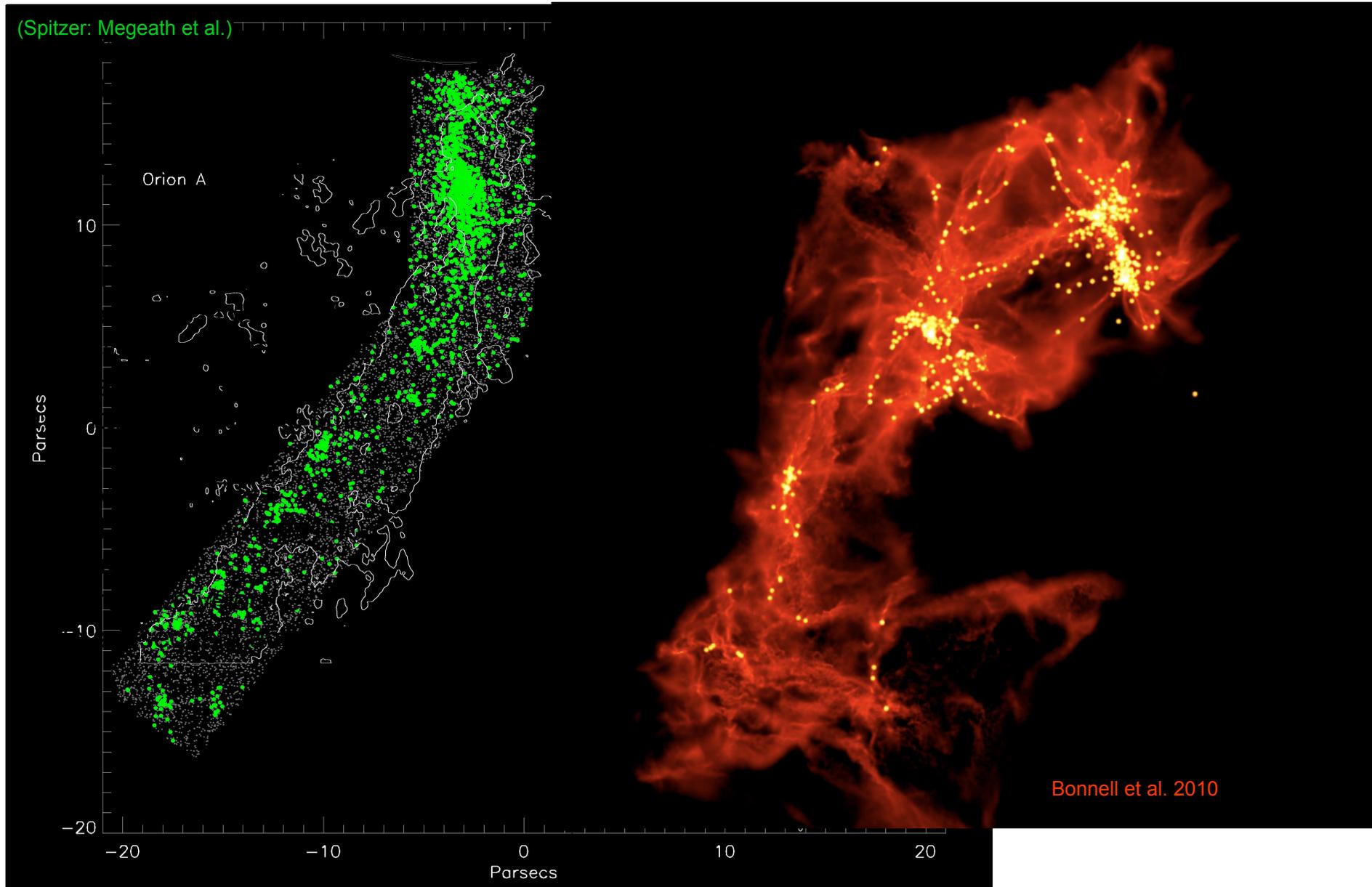
develops full IMF  
(distribution of sink particle masses)



(Bonnell, Smith, Clark, & Bate 2010, MNRAS, 410, 2339)



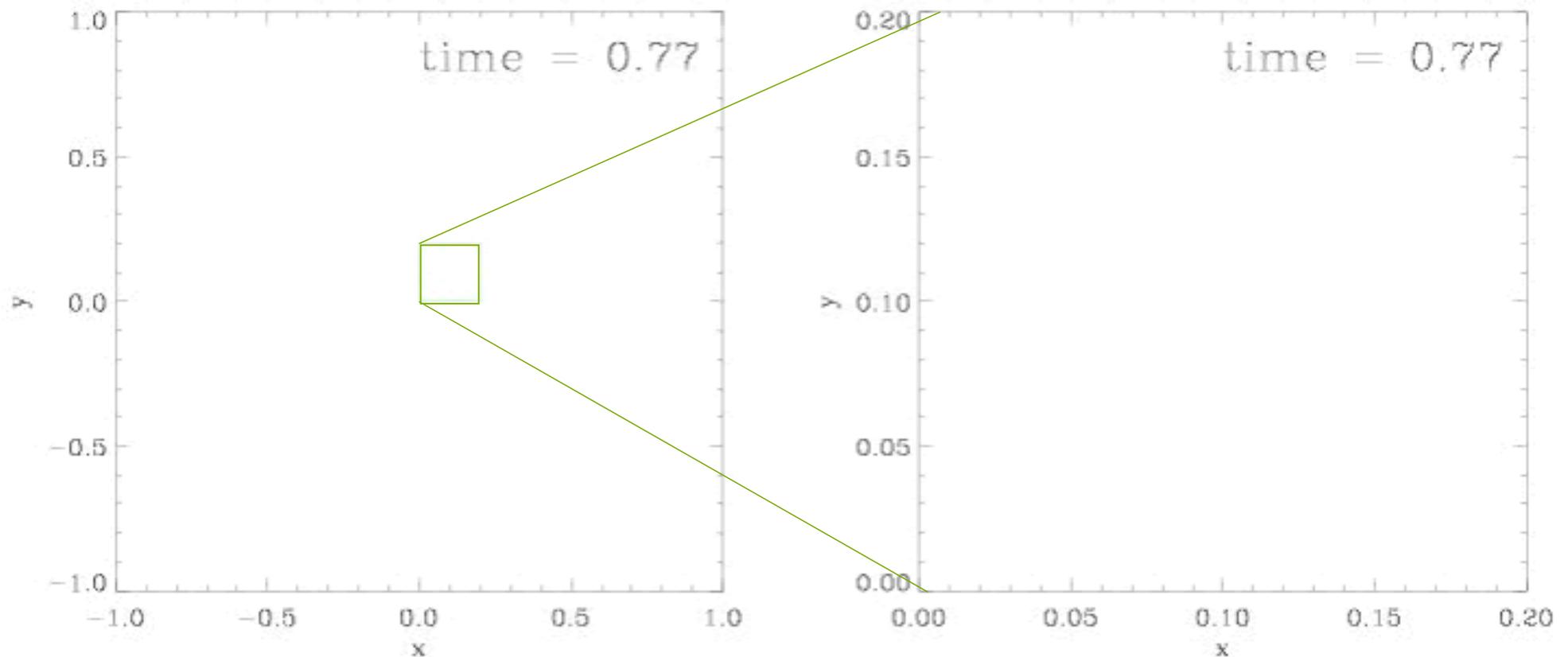
# example: model of Orion cloud





# dynamics of nascent star cluster

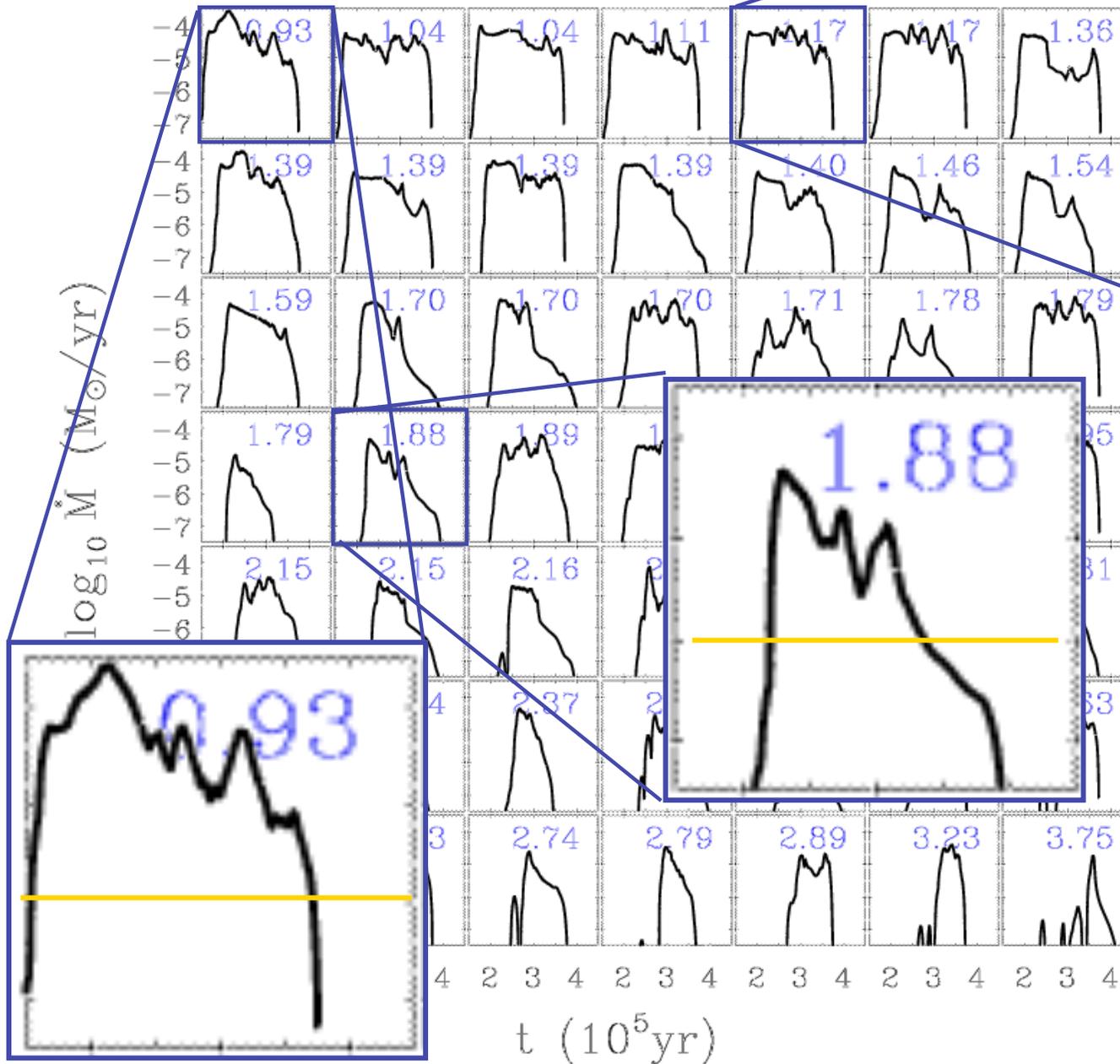
in dense clusters protostellar interaction may become important!



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



# accretion rates in clust

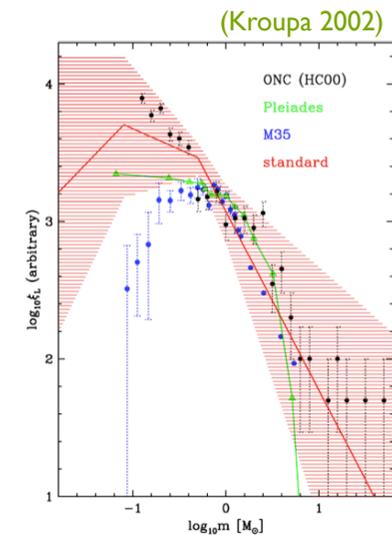


Mass accretion rates *vary with time* and are strongly *influenced* by the *cluster environment*.

(Klessen 2001, ApJ, 550, L77; also Schmeja & Klessen, 2004, A&A, 419, 405)

# stellar mass function

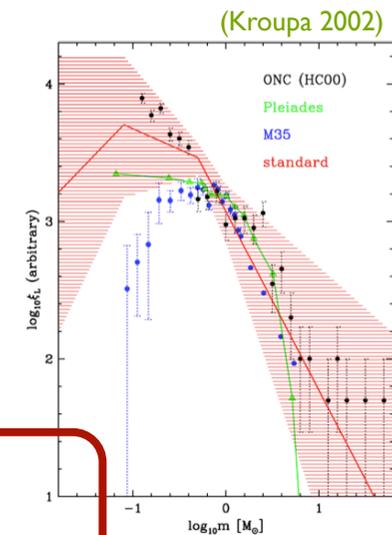
- distribution of stellar masses depends on
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# stellar mass function

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application to early star formation



# thermodynamics & fragmentation

degree of fragmentation depends on *EOS!*

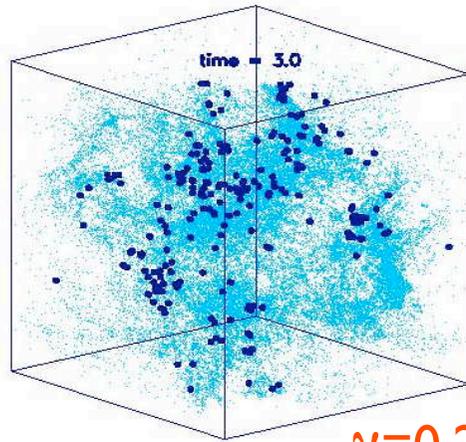
polytropic EOS:  $p \propto \rho^\gamma$

$\gamma < 1$ : dense cluster of low-mass stars

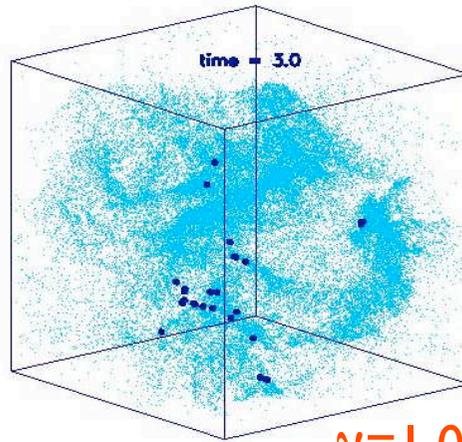
$\gamma > 1$ : isolated high-mass stars

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

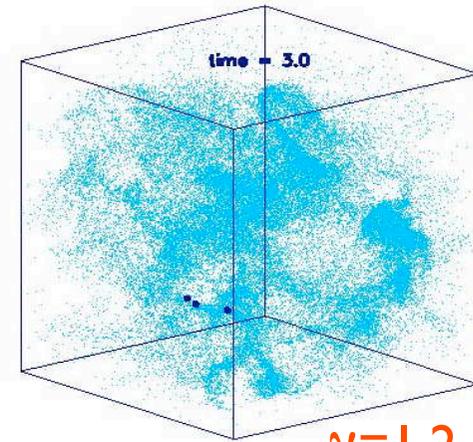
# dependency on EOS



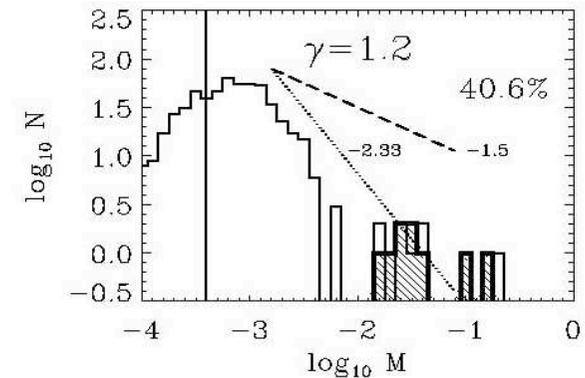
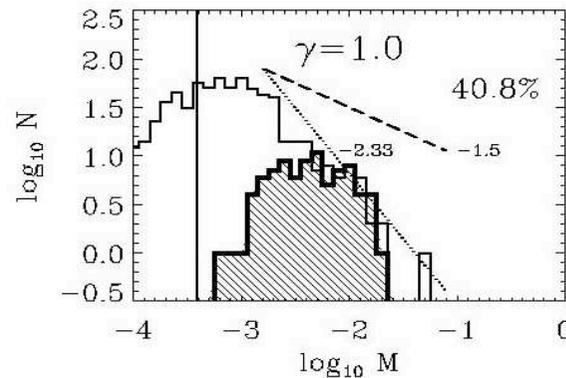
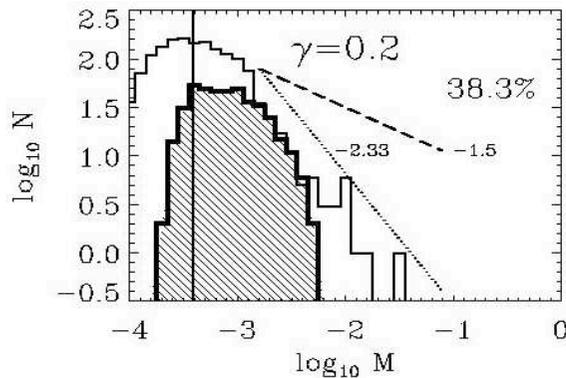
$\gamma = 0.2$



$\gamma = 1.0$



$\gamma = 1.2$

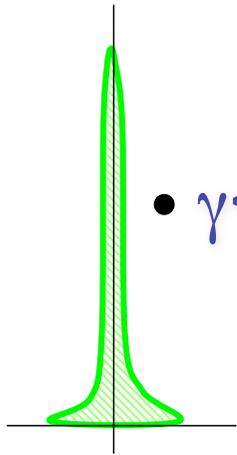


for  $\gamma < 1$  fragmentation is enhanced  $\rightarrow$  *cluster of low-mass stars*  
for  $\gamma > 1$  it is suppressed  $\rightarrow$  *isolated massive stars*

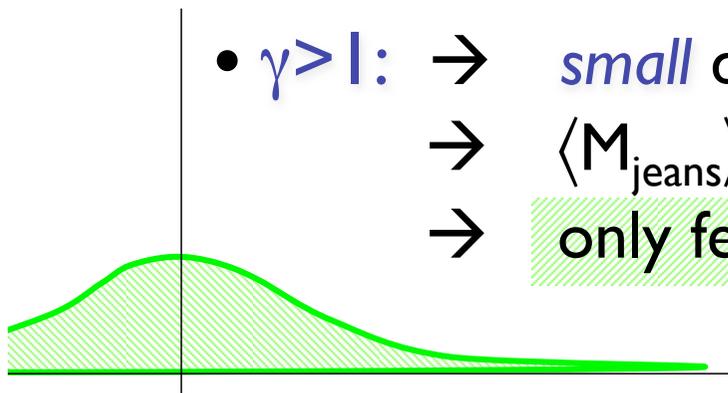
# how does that work?

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

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

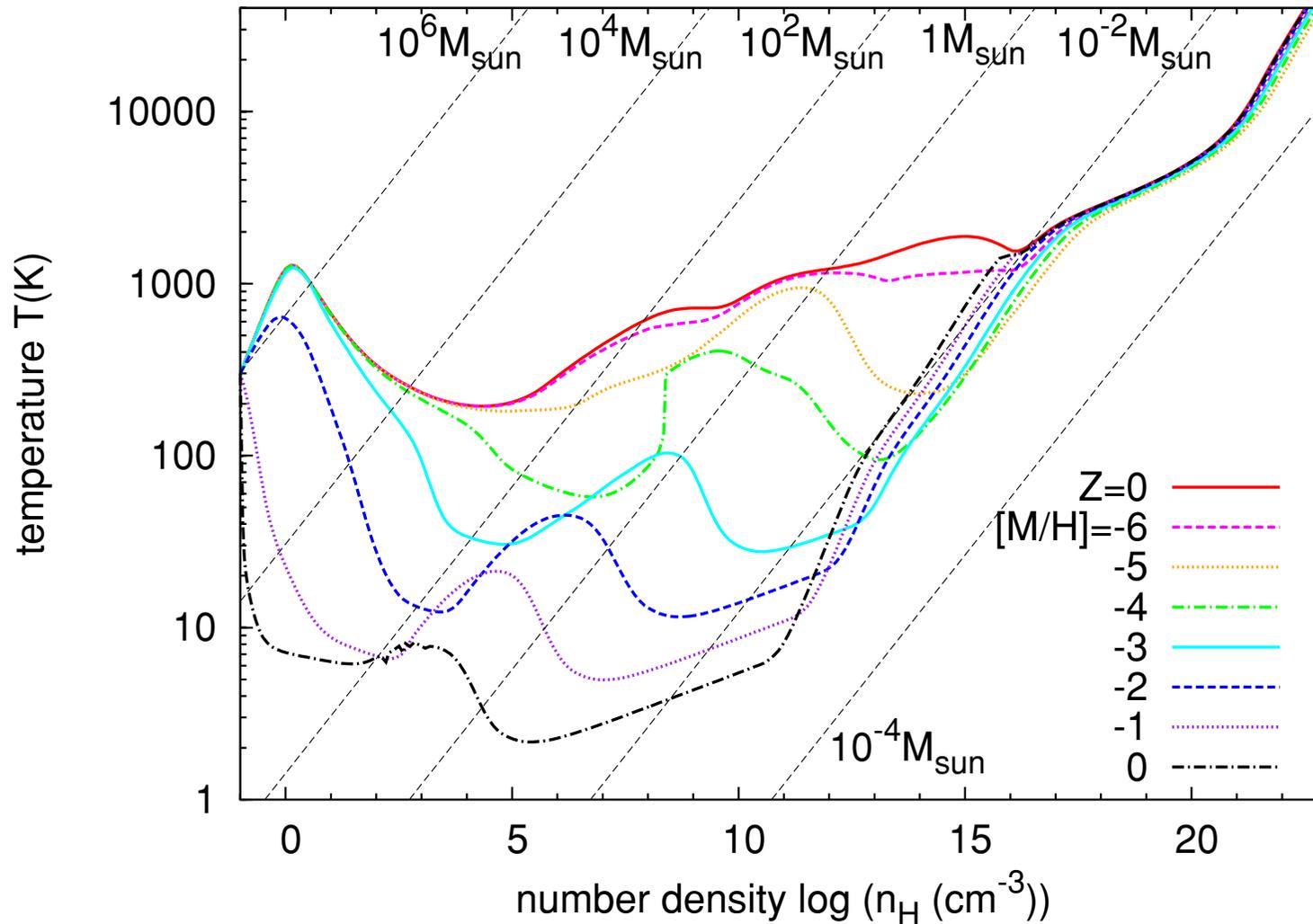


- $\gamma < 1$ :  $\rightarrow$  *large* density excursion for given pressure
  - $\rightarrow$   $\langle M_{\text{jeans}} \rangle$  becomes small
  - $\rightarrow$  number of fluctuations with  $M > M_{\text{jeans}}$  is large



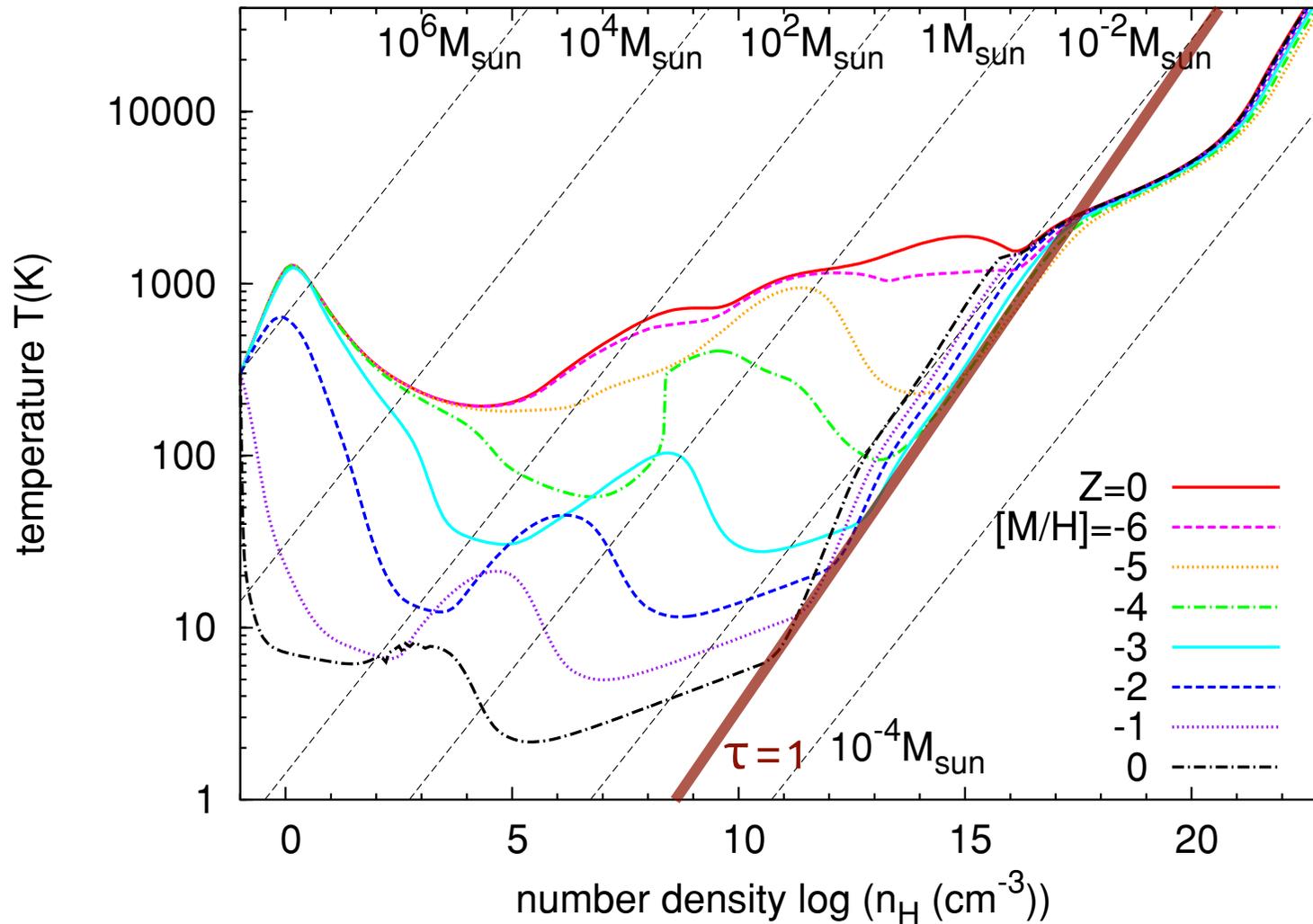
- $\gamma > 1$ :  $\rightarrow$  *small* density excursion for given pressure
  - $\rightarrow$   $\langle M_{\text{jeans}} \rangle$  is large
  - $\rightarrow$  only few and massive clumps exceed  $M_{\text{jeans}}$

# EOS as function of metallicity



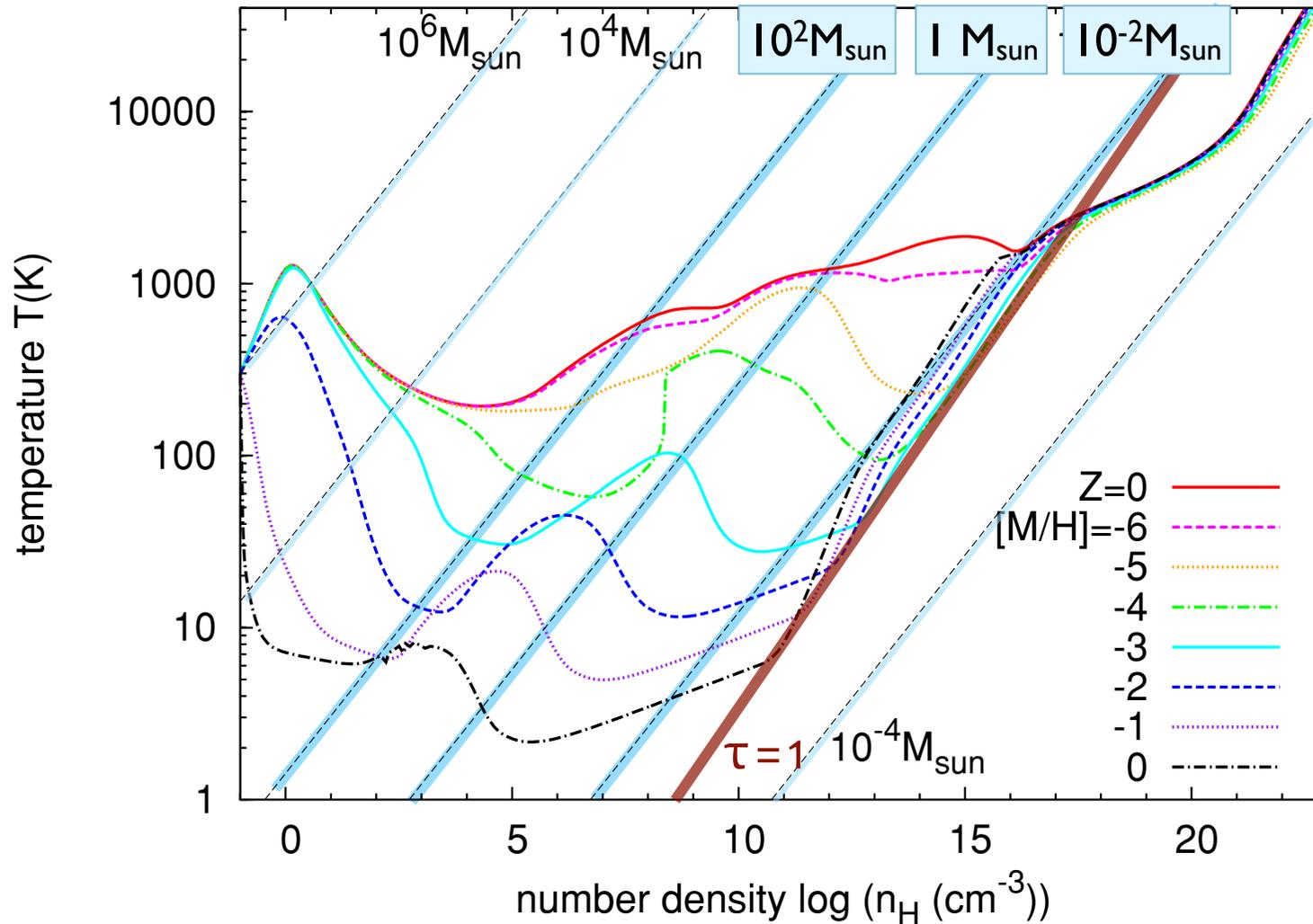
(Omukai et al. 2005, 2010)

# EOS as function of metallicity



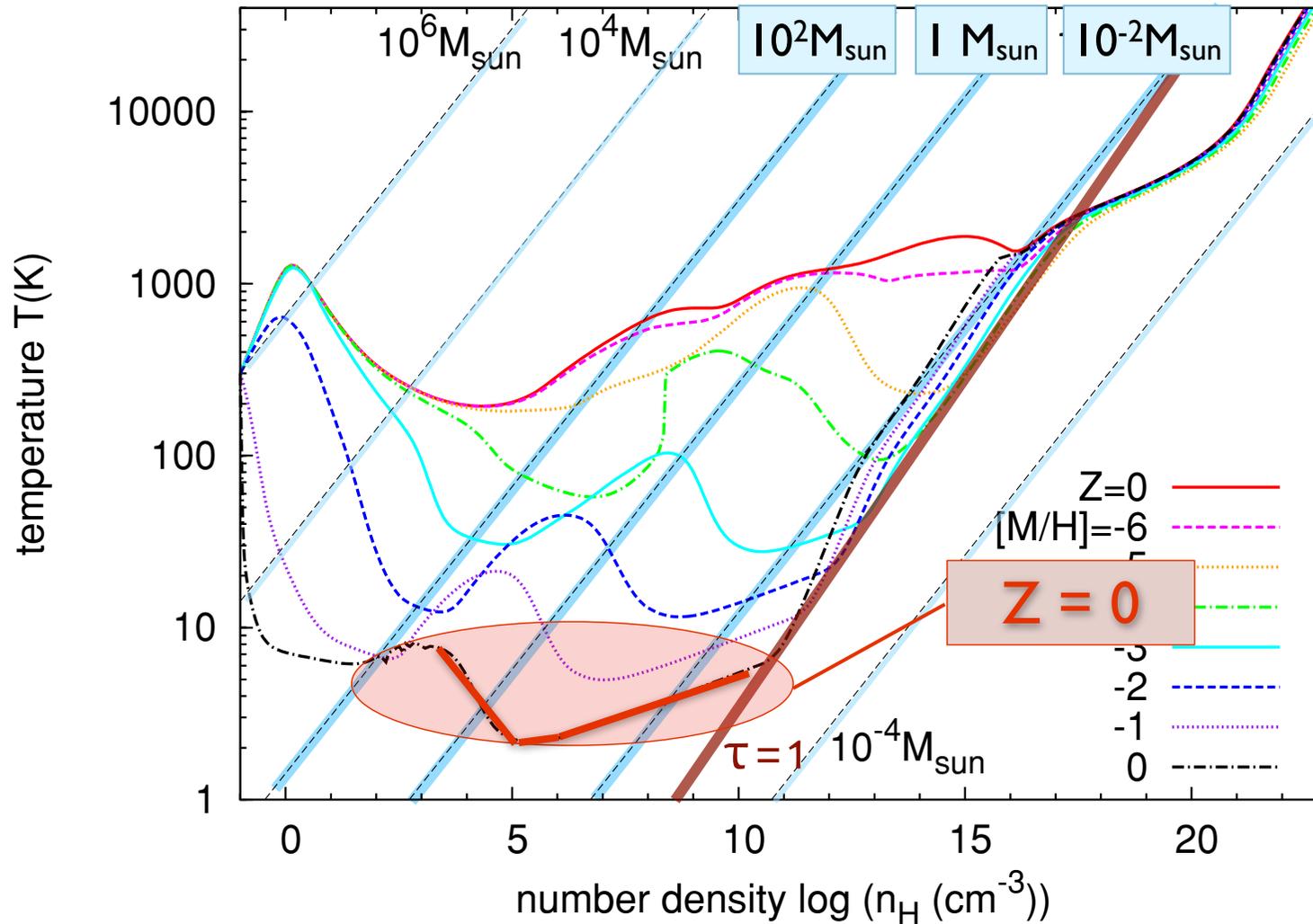
(Omukai et al. 2005, 2010)

# EOS as function of metallicity



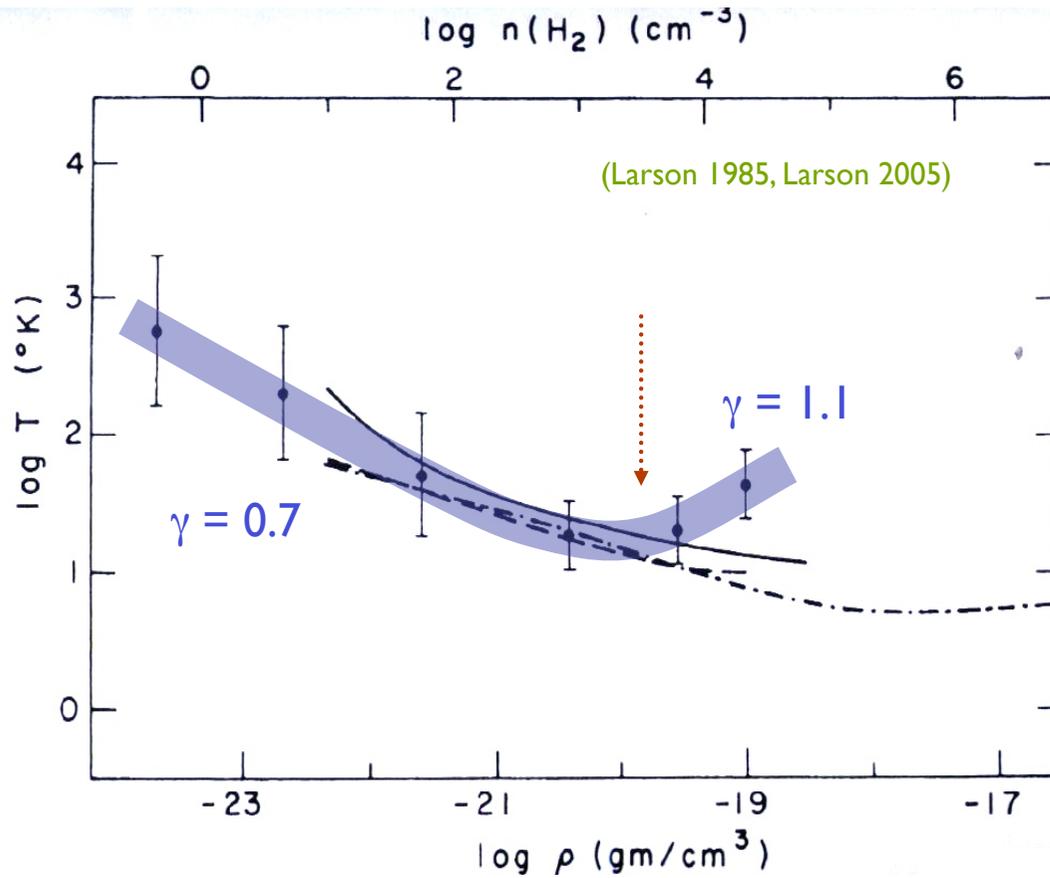
(Omukai et al. 2005, 2010)

# EOS as function of metallicity

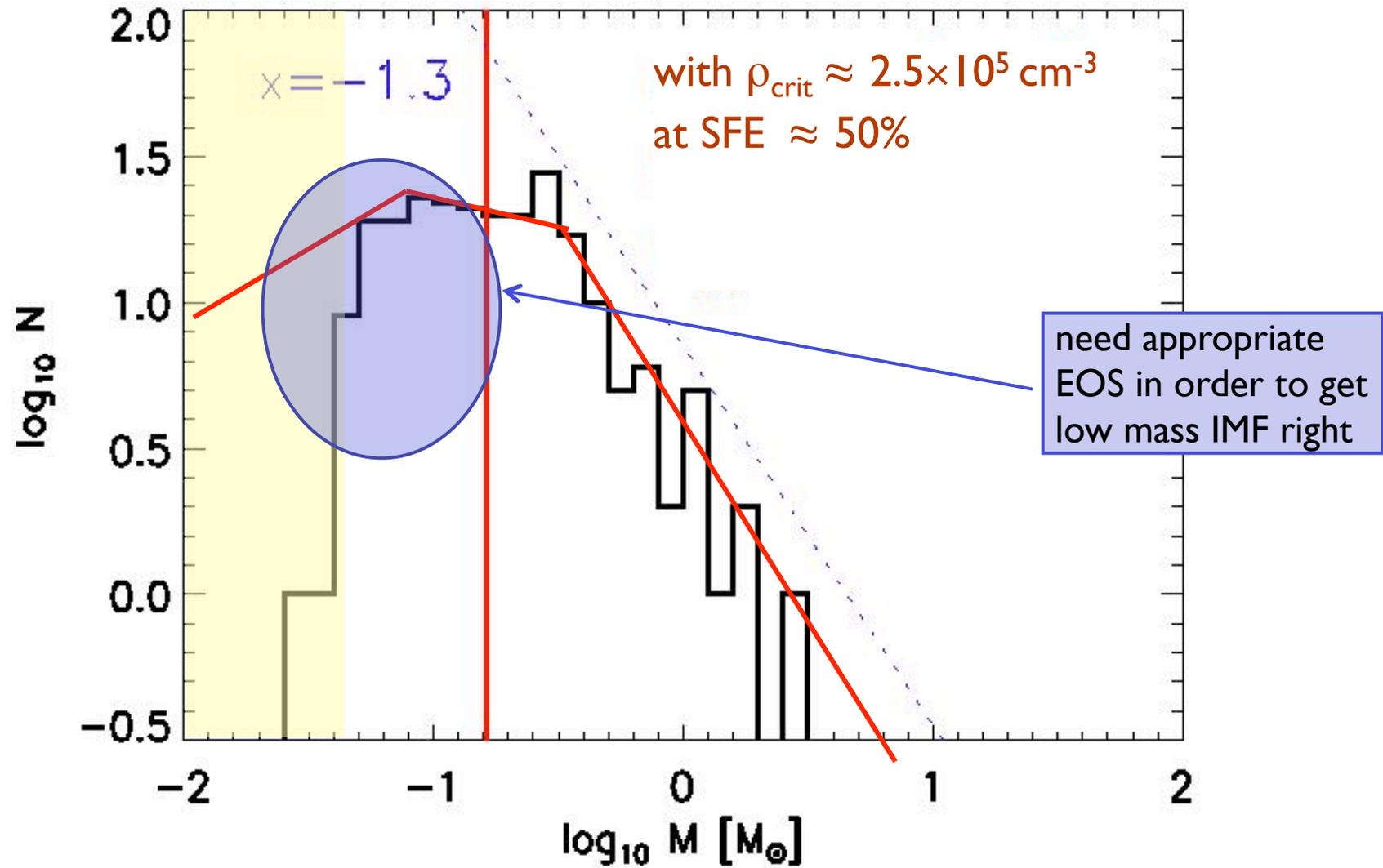


(Omukai et al. 2005, 2010)

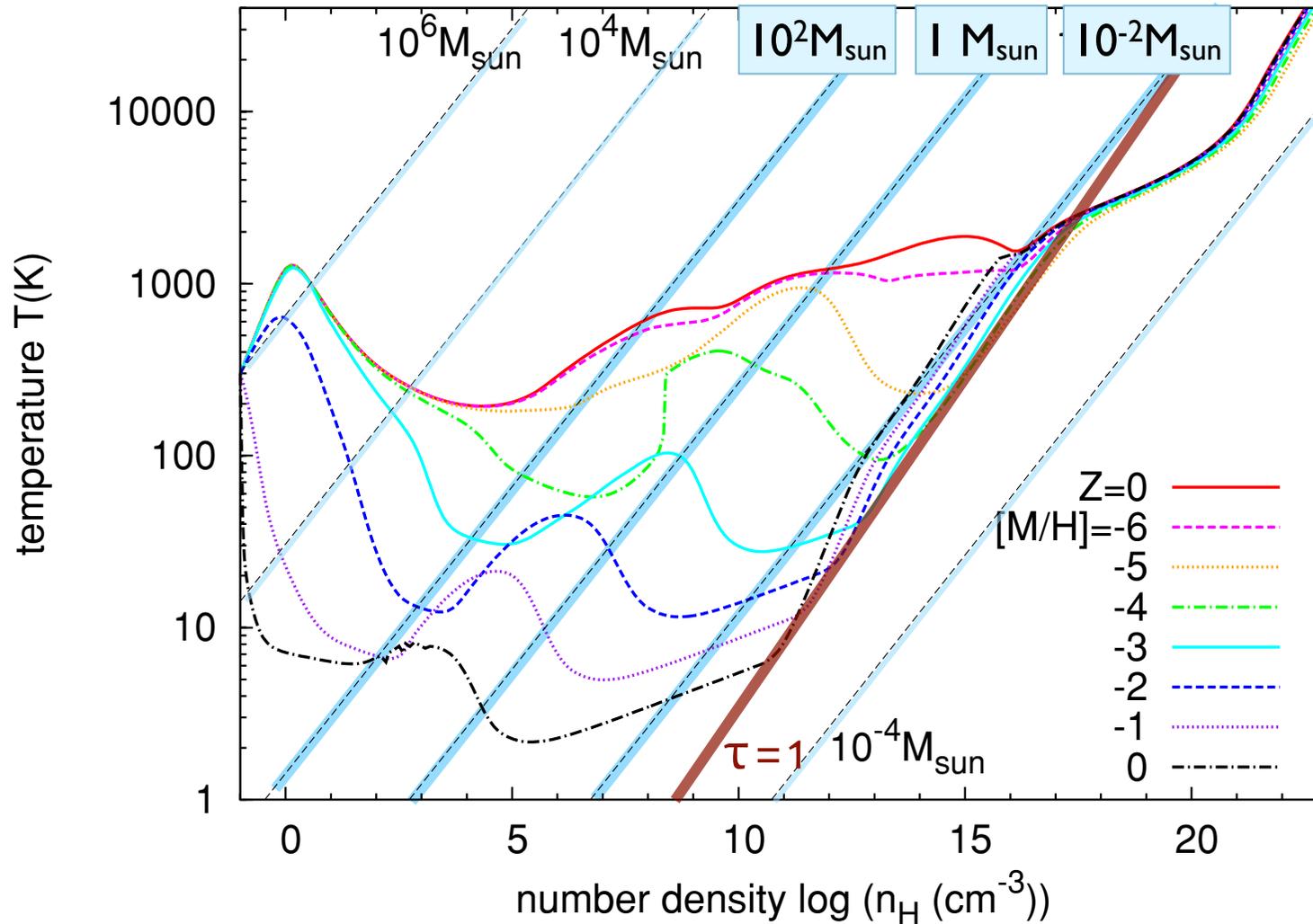
# present-day star formation



# IMF in nearby molecular clouds

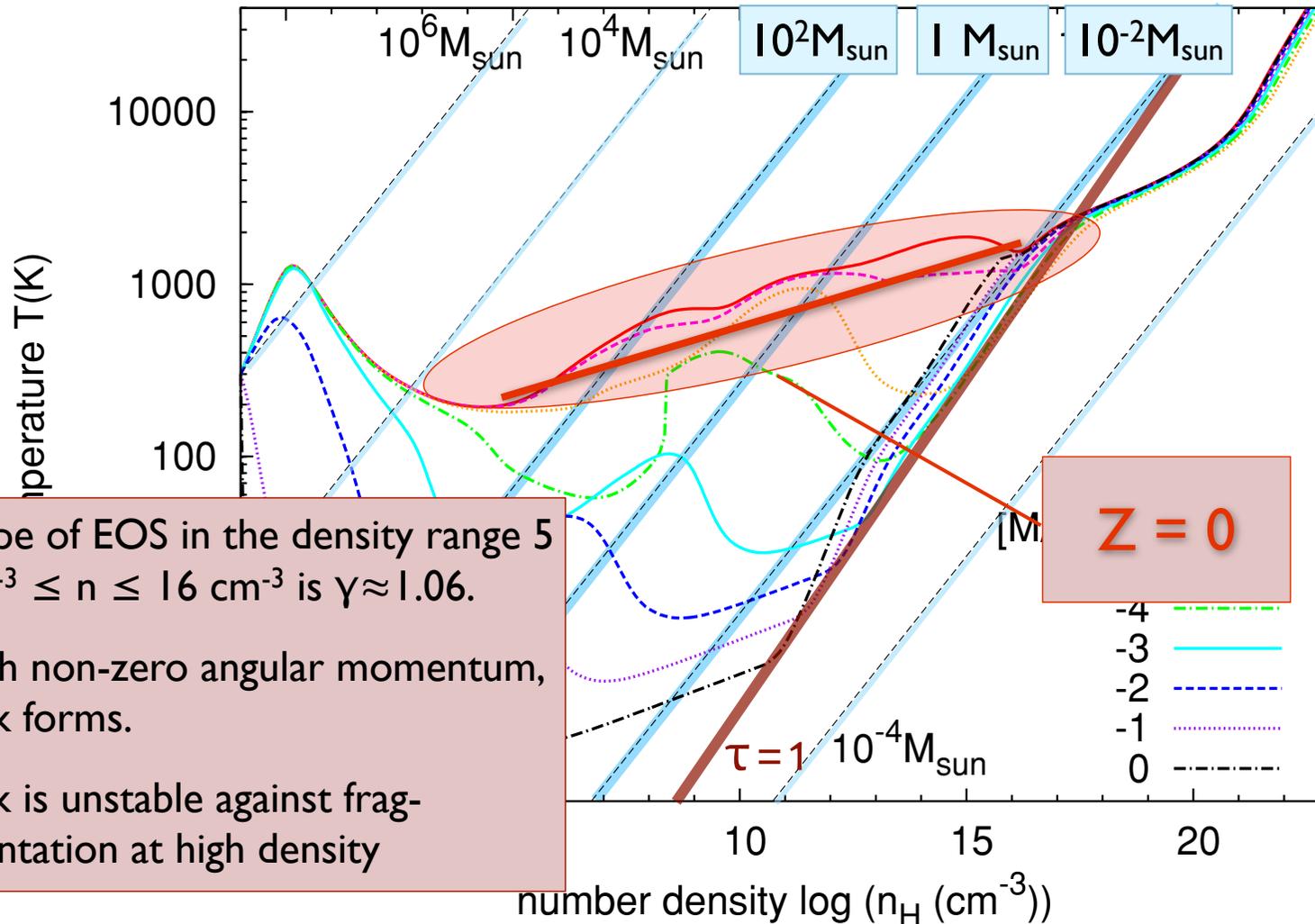


# EOS as function of metallicity



(Omukai et al. 2005, 2010)

# EOS as function of metallicity

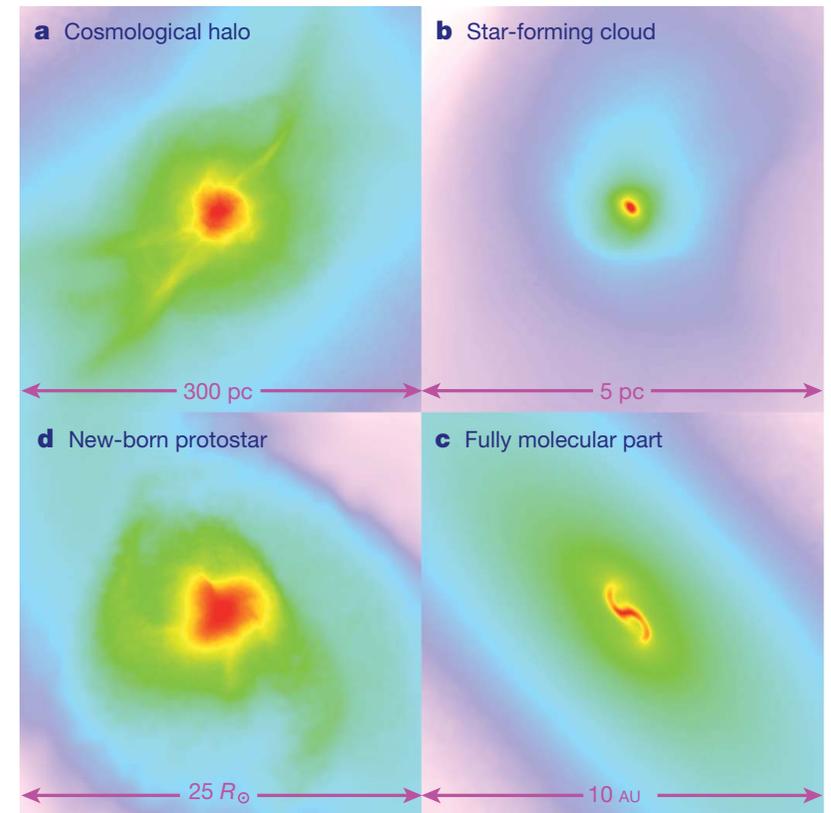


- slope of EOS in the density range  $5 \text{ cm}^{-3} \leq n \leq 16 \text{ cm}^{-3}$  is  $\gamma \approx 1.06$ .
- with non-zero angular momentum, disk forms.
- disk is unstable against fragmentation at high density

(Omukai et al. 2005, 2010)

# 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)

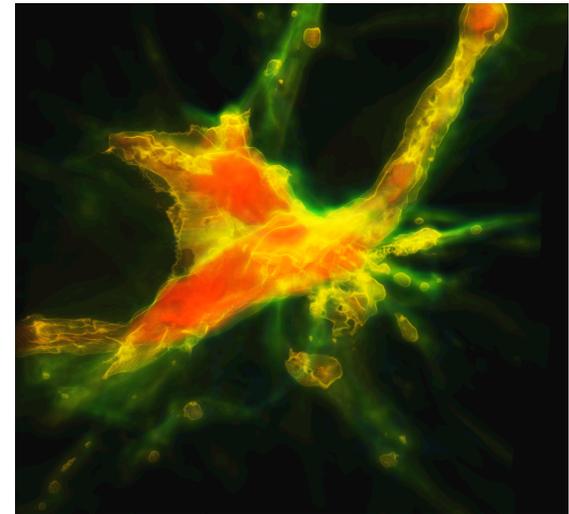


**Figure 1 | Projected gas distribution around a primordial protostar.** Shown is the gas density (colour-coded so that red denotes highest density) of a single object on different spatial scales. **a**, The large-scale gas distribution around the cosmological minihalo; **b**, a self-gravitating, star-forming 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

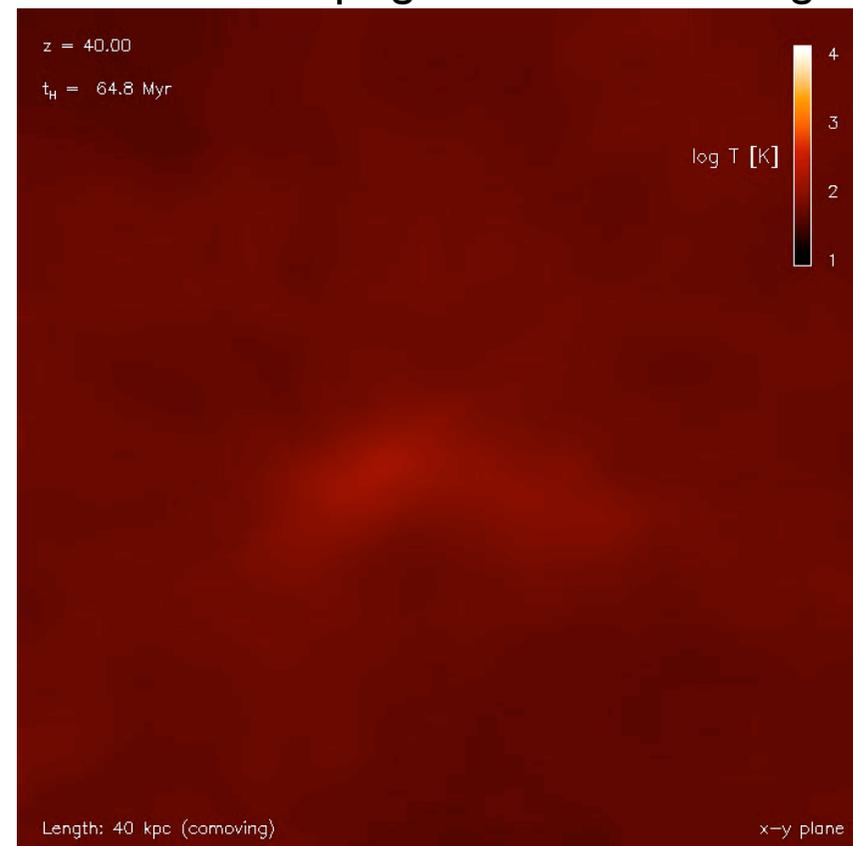


(Greif et al. 2008)

# turbulence in Pop III halos

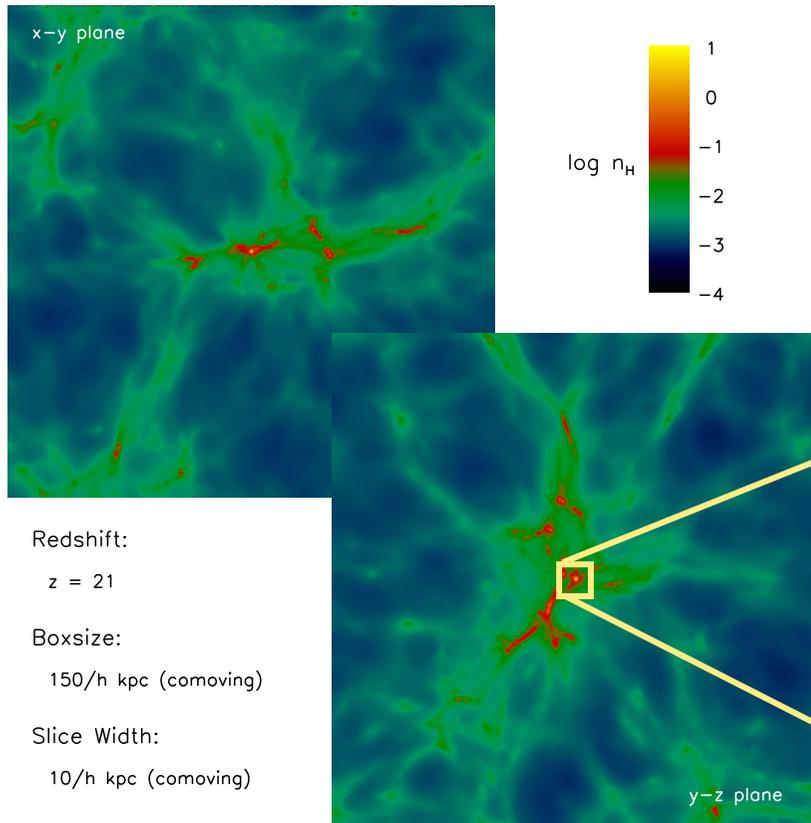
- star formation will depend on *degree of turbulence* in protogalactic halo
- speculation: *differences in stellar mass function*, just like in present-day star formation

turbulence developing in an atomic cooling halo

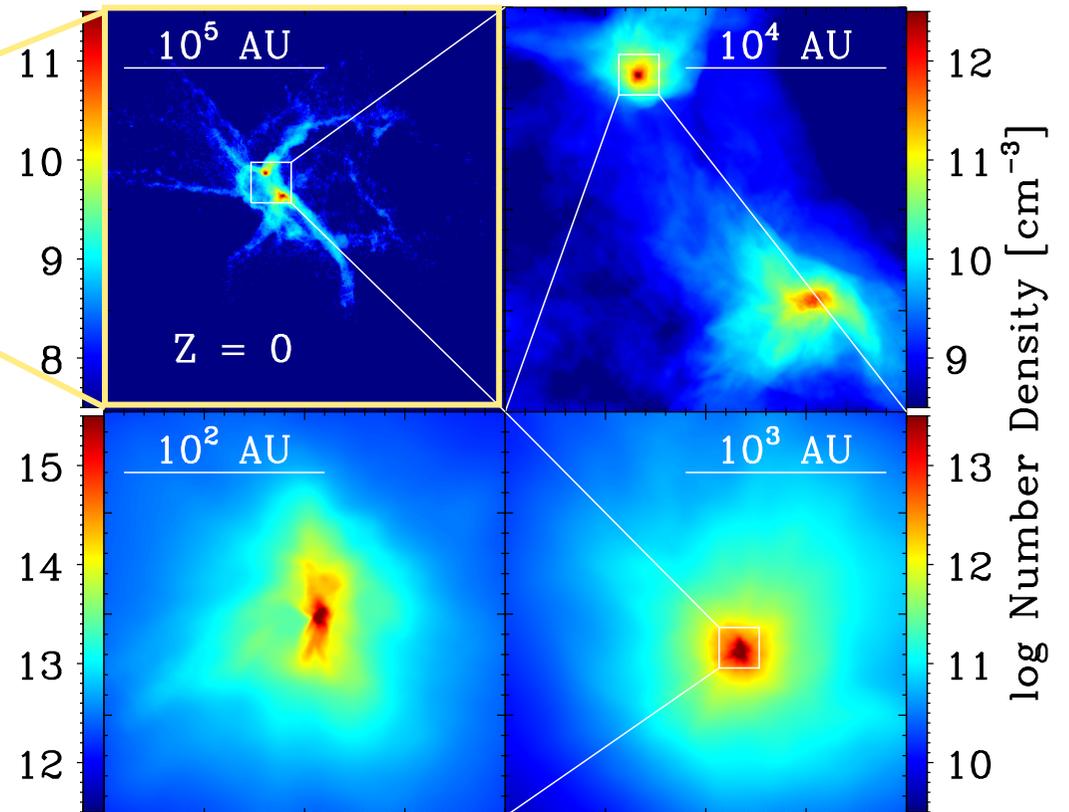


(Greif et al. 2008)

# detailed look at accretion disk around first star



successive zoom-in calculation from cosmological initial conditions (using SPH and new grid-code AREPO)

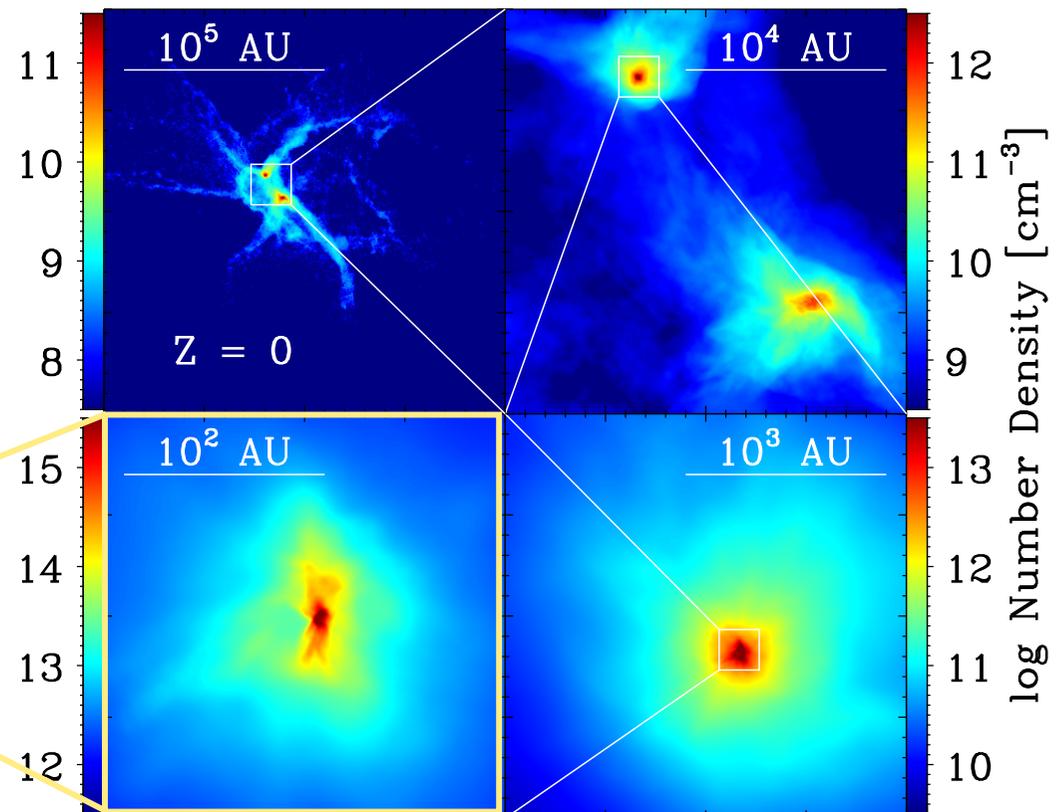


(Greif et al., 2007, ApJ, 670, 1)

(Greif et al. 2011, ApJ, 737, 75, Greif et al. 2012, MNRAS, 424, 399, Dopcke et al. 2012, ApJ submitted, arXiv/1203.6842)

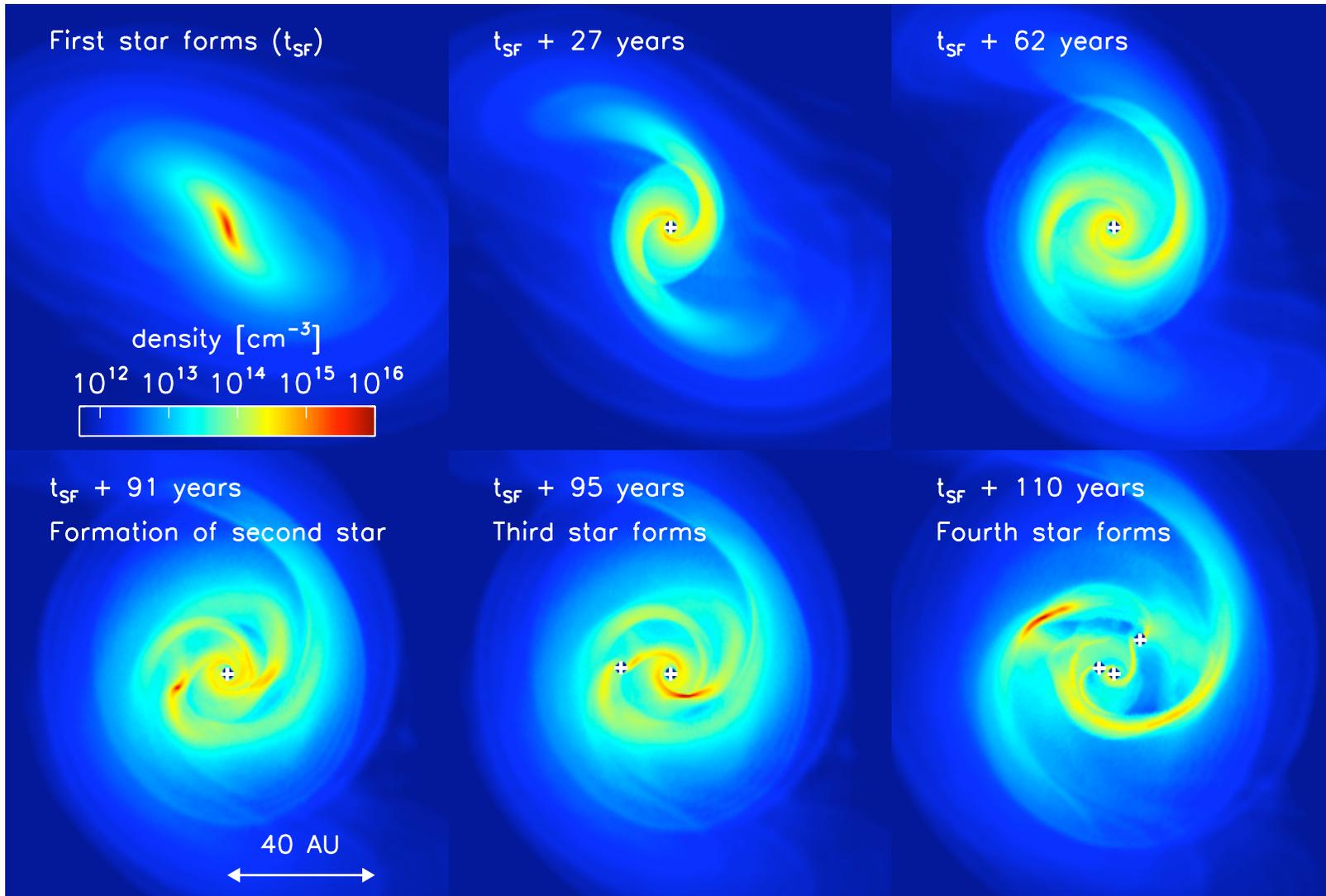
# detailed look at accretion disk around first star

successive zoom-in calculation from cosmological initial conditions (using SPH and new grid-code AREPO)



what is the time evolution of accretion disk around first star to form?

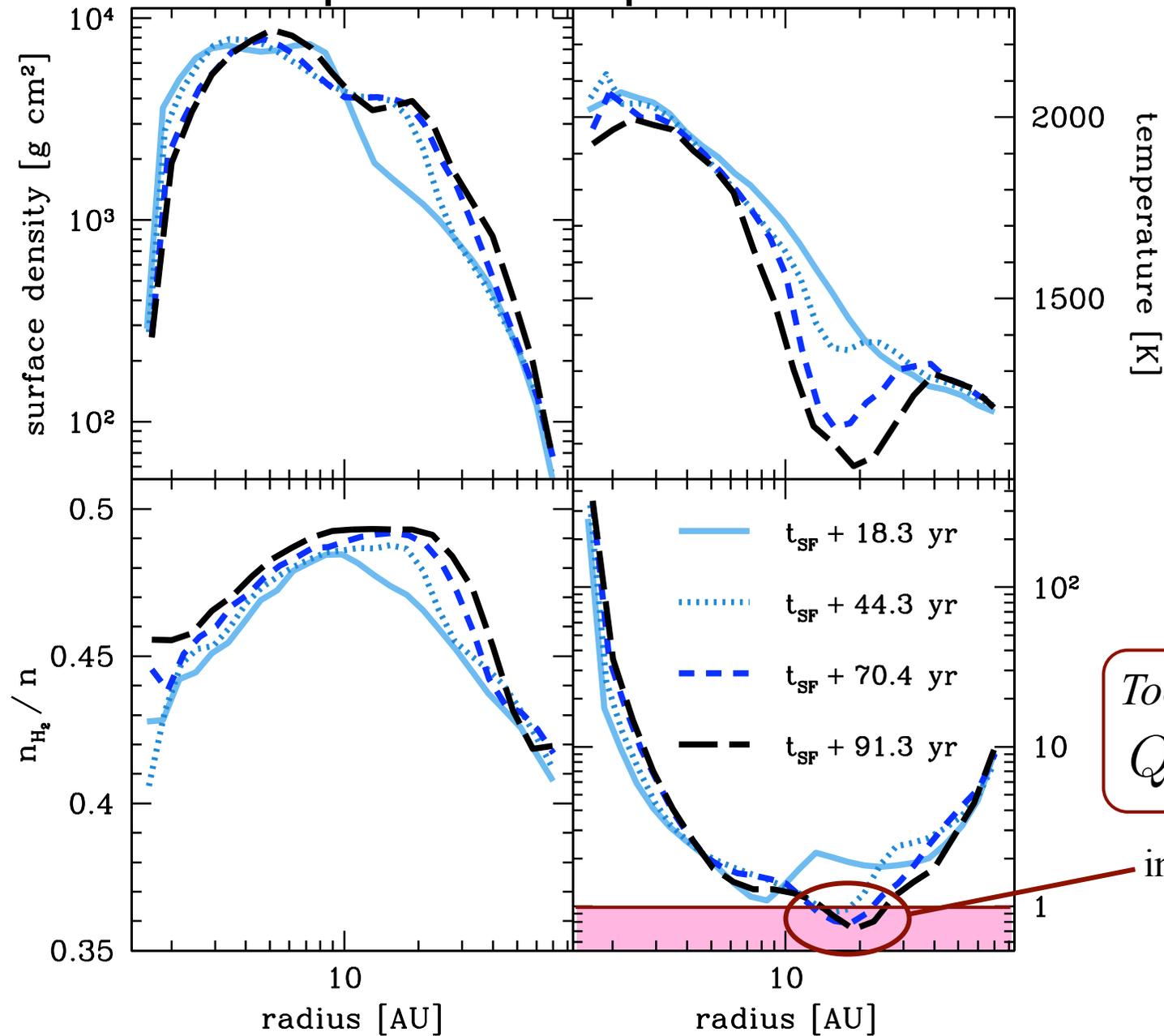
(Greif et al. 2011, ApJ, 737, 75, Greif et al. 2012, MNRAS, 424, 399, Dopcke et al. 2012, ApJ submitted, arXiv/1203.6842)



detailed 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.

# important disk parameters

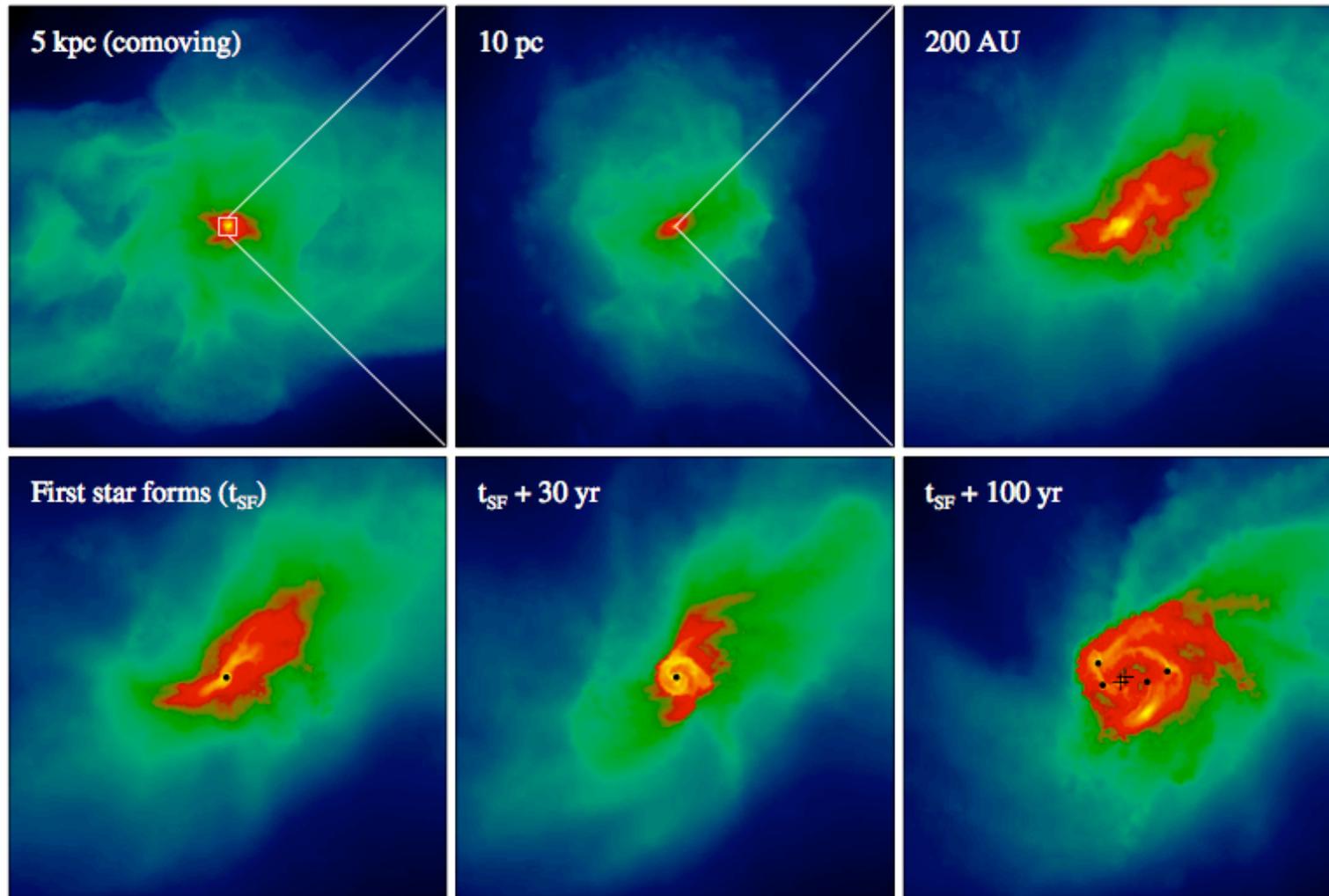


Toomre  $Q$ :

$$Q = c_s \kappa / \pi G \Sigma$$

instability for  $Q < 1$

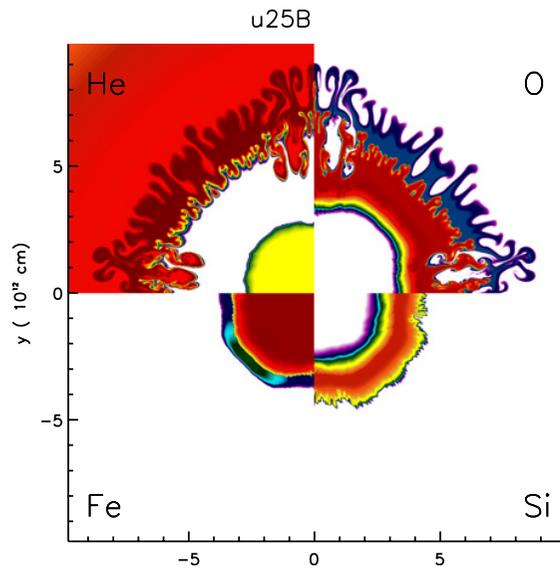
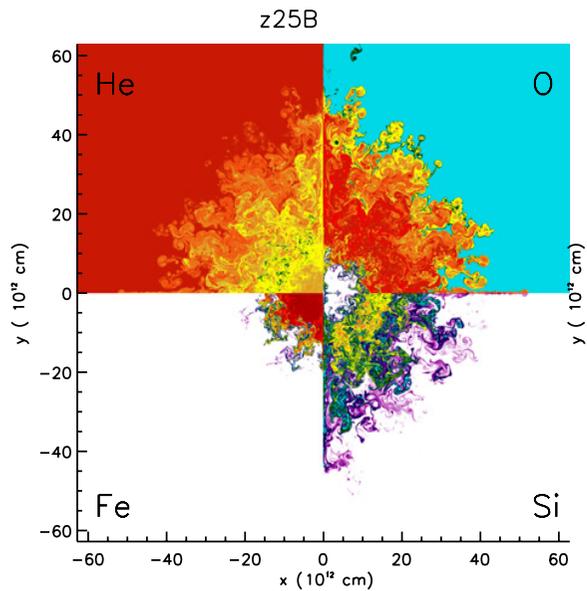
similar study with very different numerical method (AREPO)



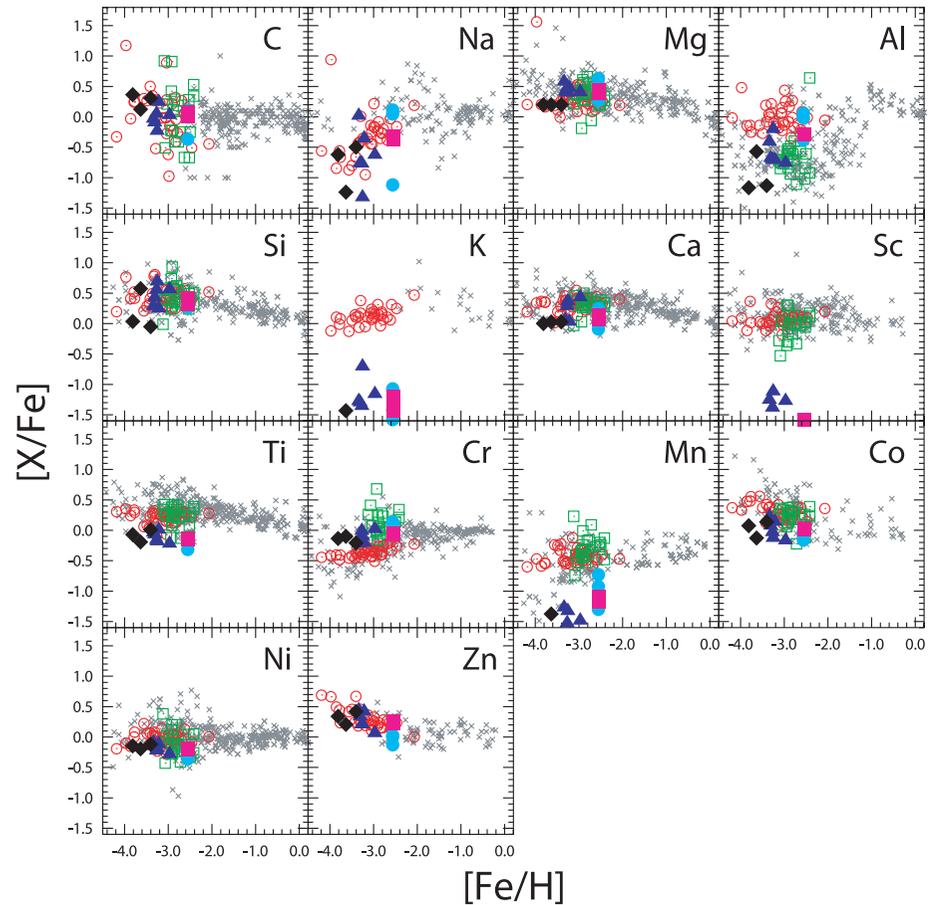
one out of five halos

# expected mass spectrum

- *expected IMF is flat* and covers a wide range of masses
- implications
  - because slope  $> -2$ , most *mass is in massive objects* as predicted by most previous calculations
  - most high-mass Pop III stars should be in *binary systems* --> source of *high-redshift gamma-ray bursts*
  - because of ejection, some *low-mass objects* ( $< 0.8 M_{\odot}$ ) might have *survived* until today and could potentially be found in the Milky Way
- consistent with abundance patterns found in second generation stars



(Joggerst et al. 2009, 2010)



(Tominaga et al. 2007)

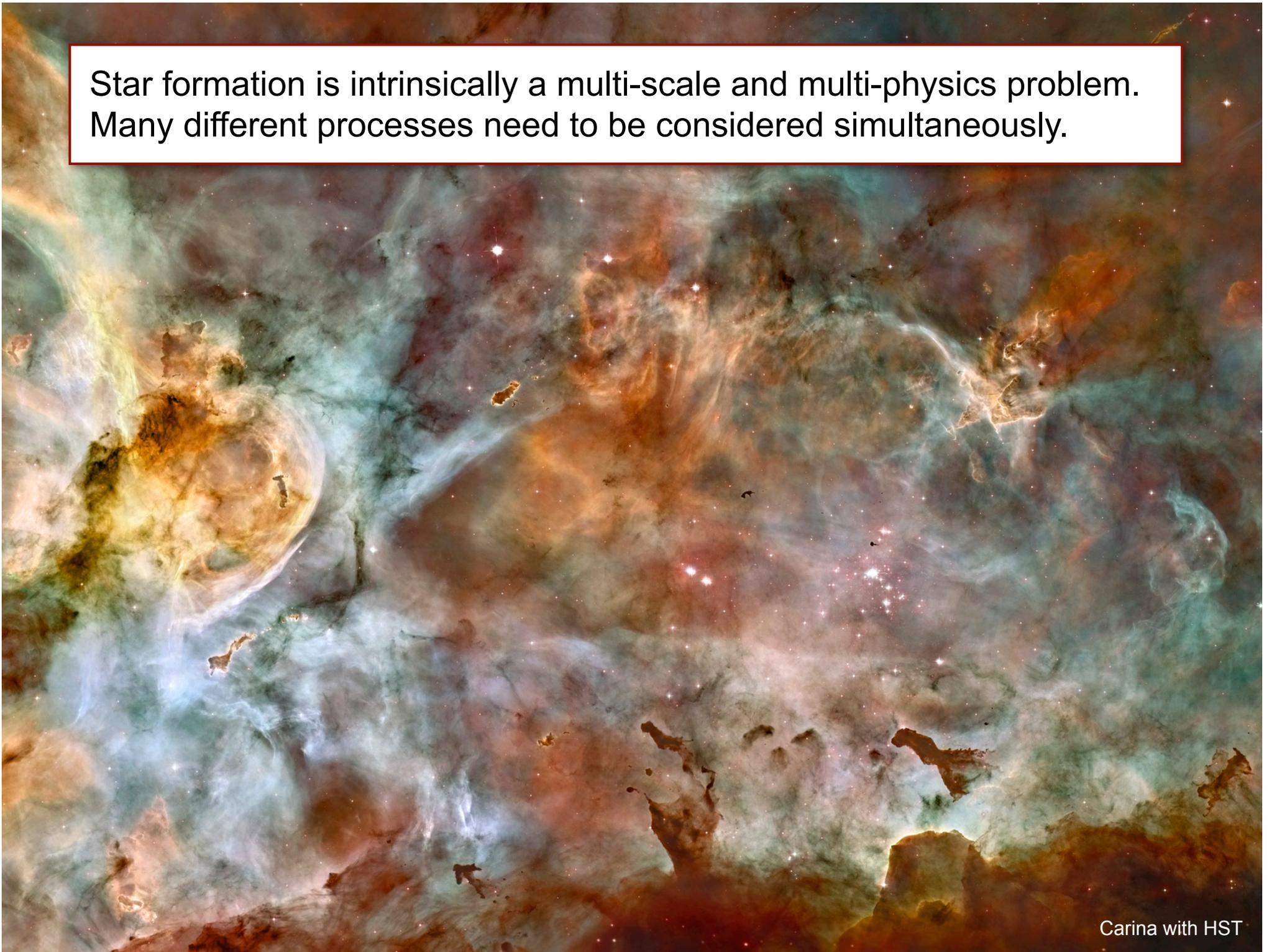
The metallicities of extremely metal-poor stars in the halo are consistent with the yields of core-collapse supernovae, i.e. progenitor stars with 20 - 40  $M_{\odot}$

(e.g. Tominaga et al. 2007, Izutani et al. 2009, Joggerst et al. 2009, 2010)

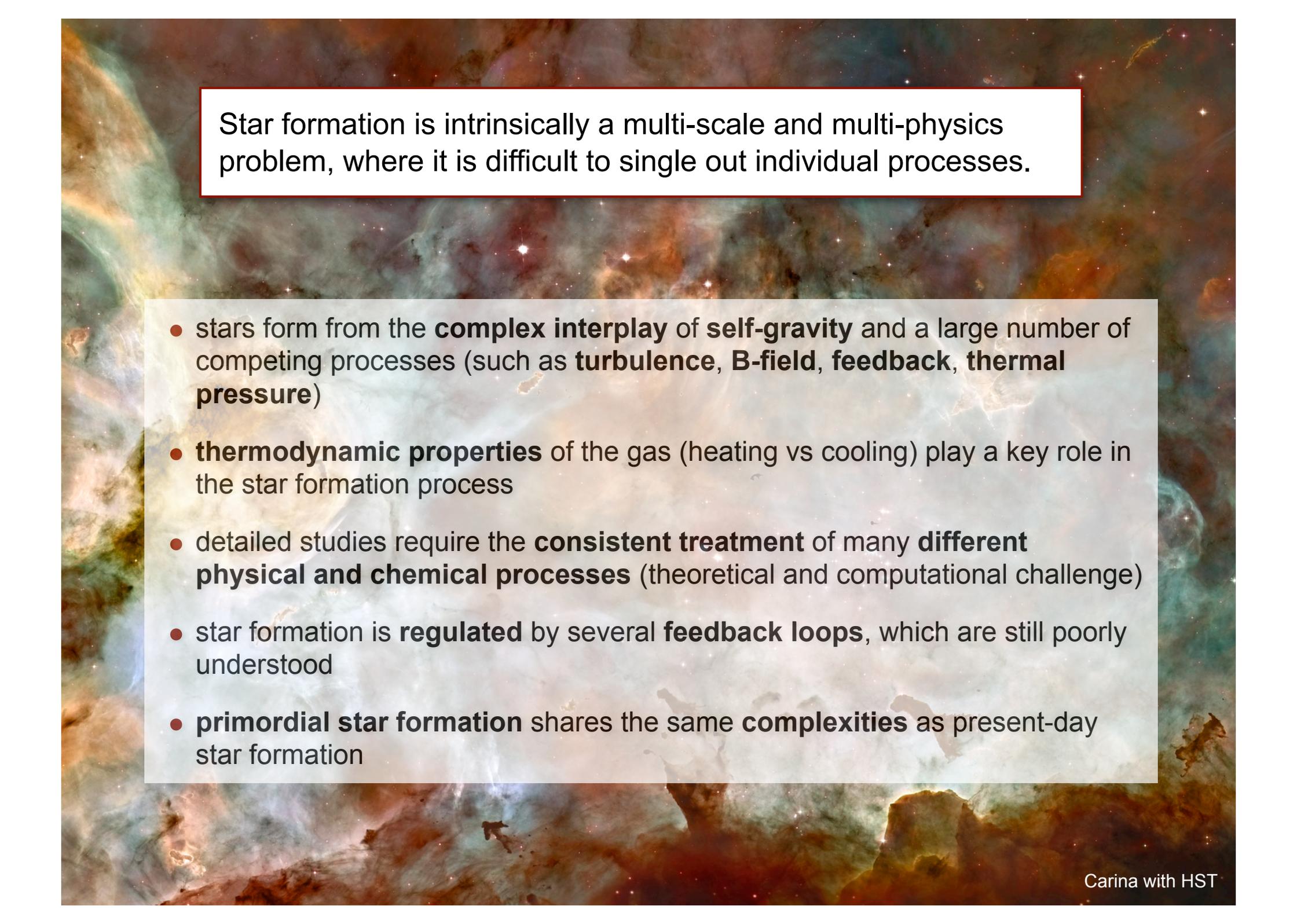


Carina with HST

Star formation is intrinsically a multi-scale and multi-physics problem. Many different processes need to be considered simultaneously.



Carina with HST



Star formation is intrinsically a multi-scale and multi-physics problem, where it is difficult to single out individual processes.

- stars form from the **complex interplay** of **self-gravity** and a large number of competing processes (such as **turbulence**, **B-field**, **feedback**, **thermal pressure**)
- **thermodynamic properties** of the gas (heating vs cooling) play a key role in the star formation process
- detailed studies require the **consistent treatment** of many **different physical and chemical processes** (theoretical and computational challenge)
- star formation is **regulated** by several **feedback loops**, which are still poorly understood
- **primordial star formation** shares the same **complexities** as present-day star formation

# thanks to ...



... people in the group in Heidelberg:

Christian Baczynski, Erik Bertram, Frank Bigiel, Rachel Chicharro, Roxana Chira, Paul Clark, Gustavo Dopcke, Jayanta Dutta, Volker Gaibler, Simon Glover, Lukas Konstandin, Faviola Molina, Mei Sasaki, Jennifer Schober, Rahul Shetty, Rowan Smith, László Szűcs, Svitlana Zhukovska

... former group members:

Robi Banerjee, Ingo Berentzen, Christoph Federrath, Philipp Girichidis, Thomas Greif, Milica Micic, Thomas Peters, Dominik Schleicher, Stefan Schmeja, Sharanya Sur

... many collaborators abroad!



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Forschungsgemeinschaft  
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**BADEN-  
WÜRTTEMBERG**  
STIFTUNG  
Wir stiften Zukunft

  
HGSP

  
IMPRS

thanks

