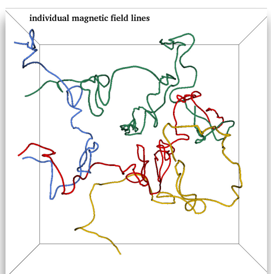
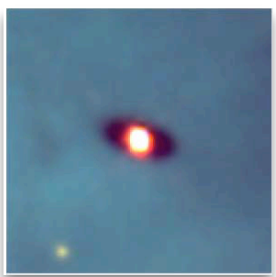
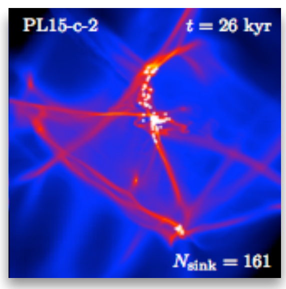
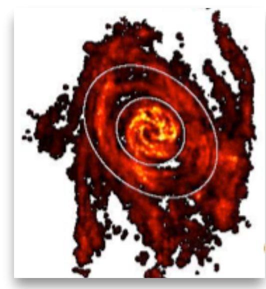
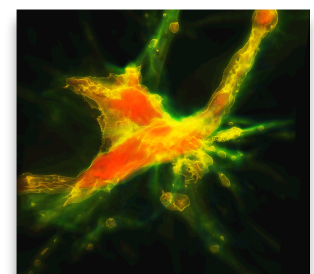
Die Geburt der Sterne



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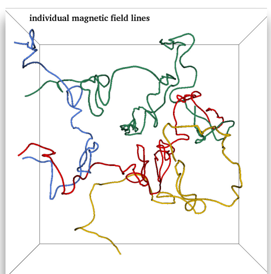
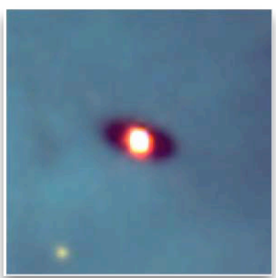
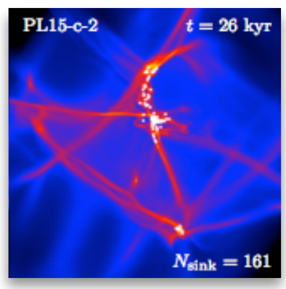
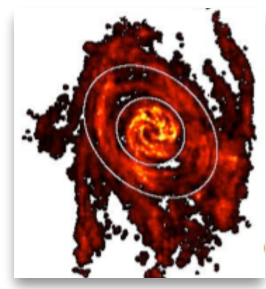
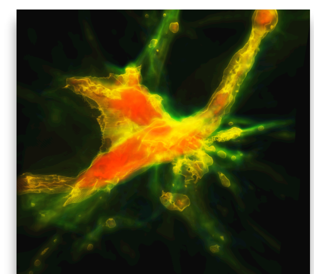
Institut für Theoretische Astrophysik

Star Formation



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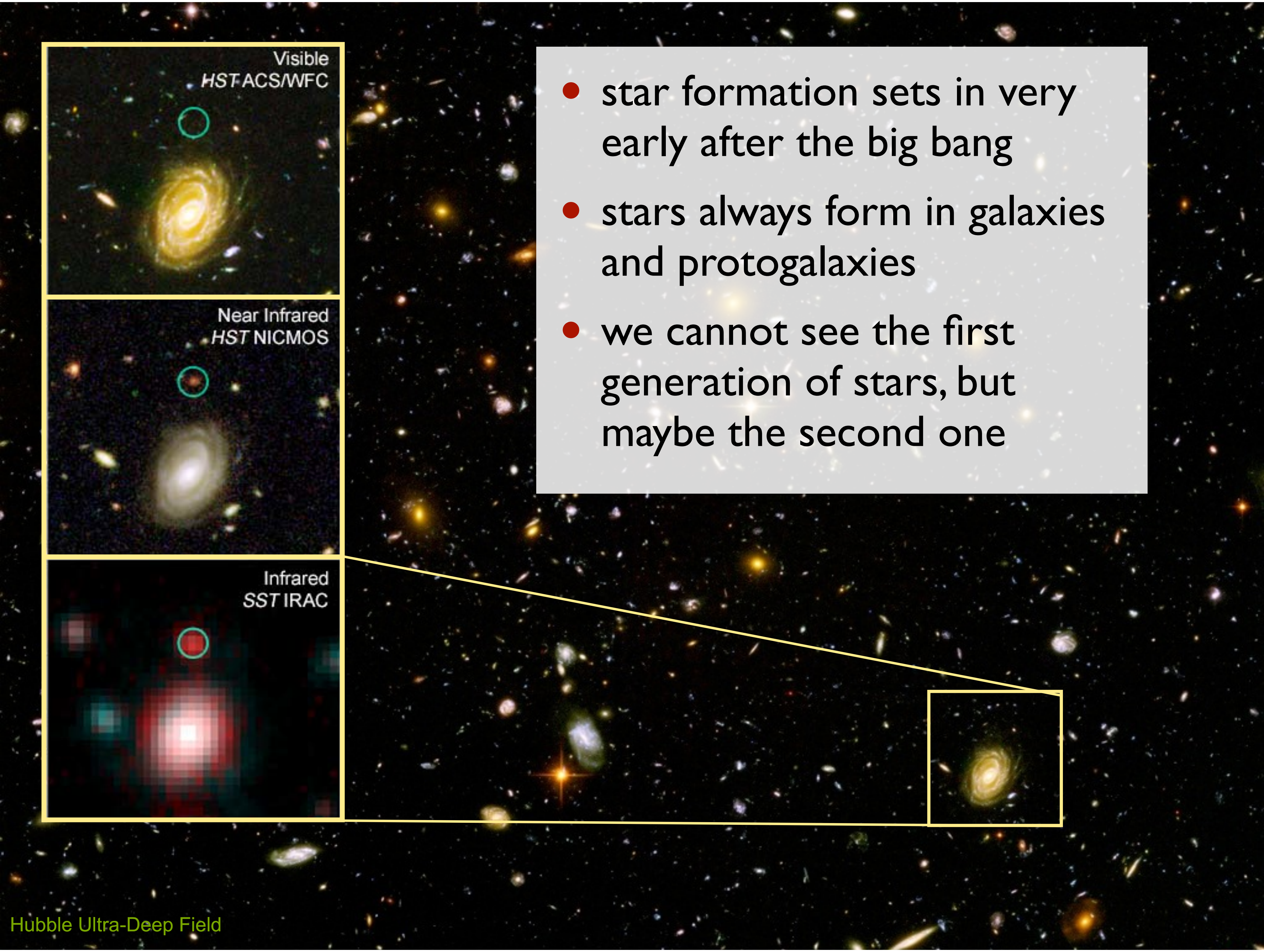
agenda

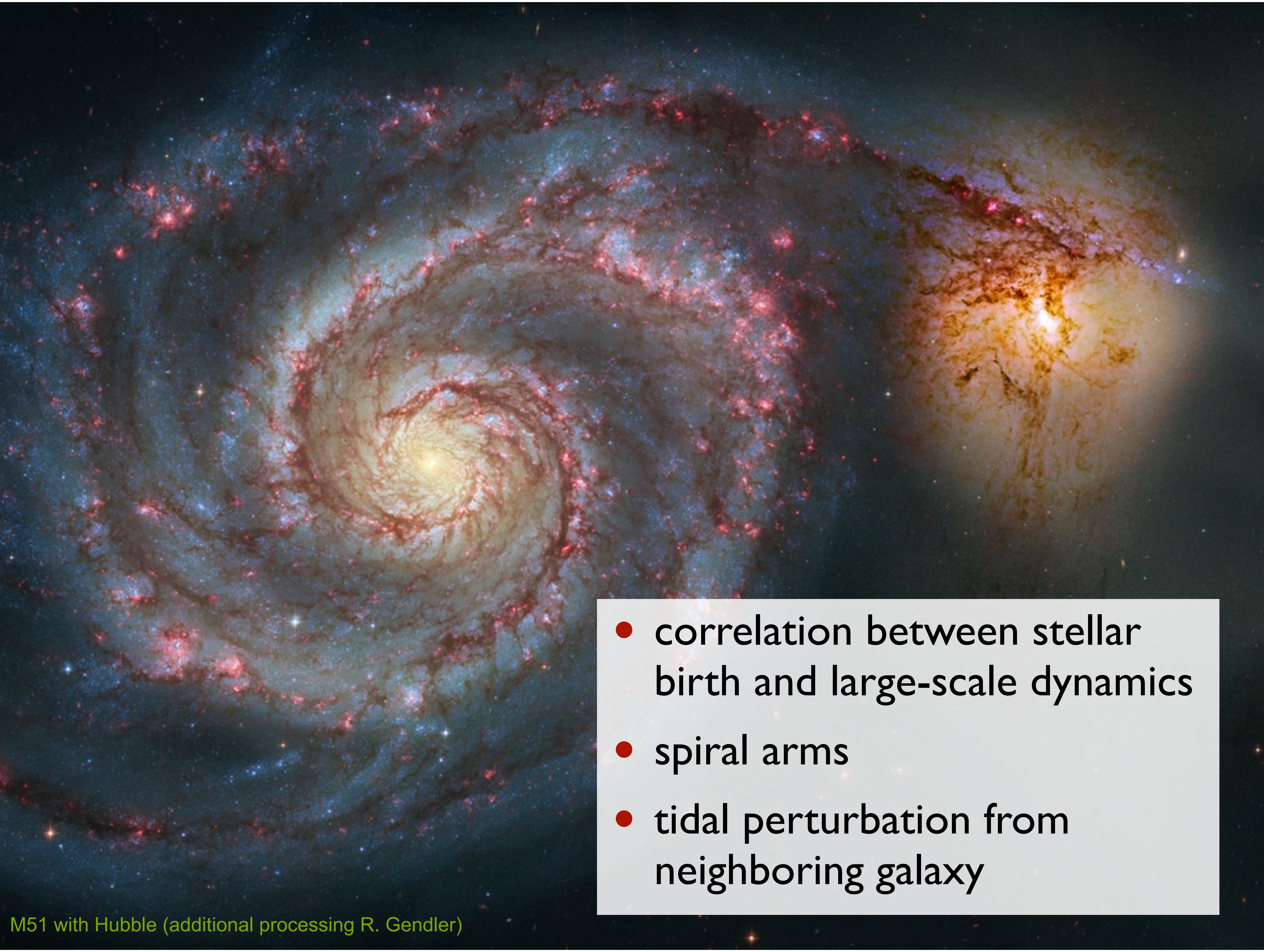
- star formation theory
  - phenomenology
  - historic remarks
  - our current understanding and its limitations
- application
  - the stellar mass function at birth (IMF)

NGC 3324 (Hubble, NASA/ESA)

Phenomenology

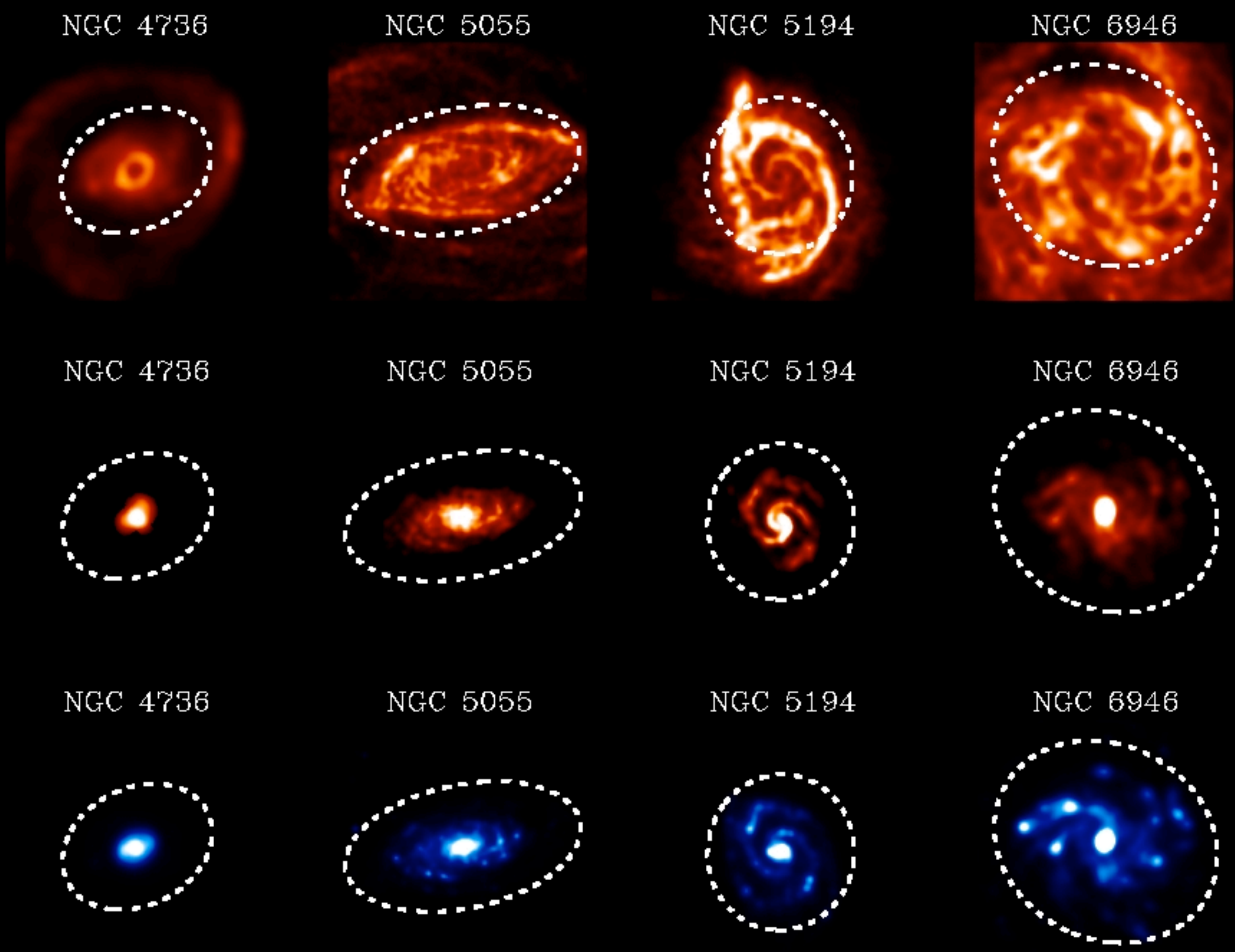
- star formation sets in very early after the big bang
- stars always form in galaxies and protogalaxies
- we cannot see the first generation of stars, but maybe the second one





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

M51 with Hubble (additional processing R. Gendler)



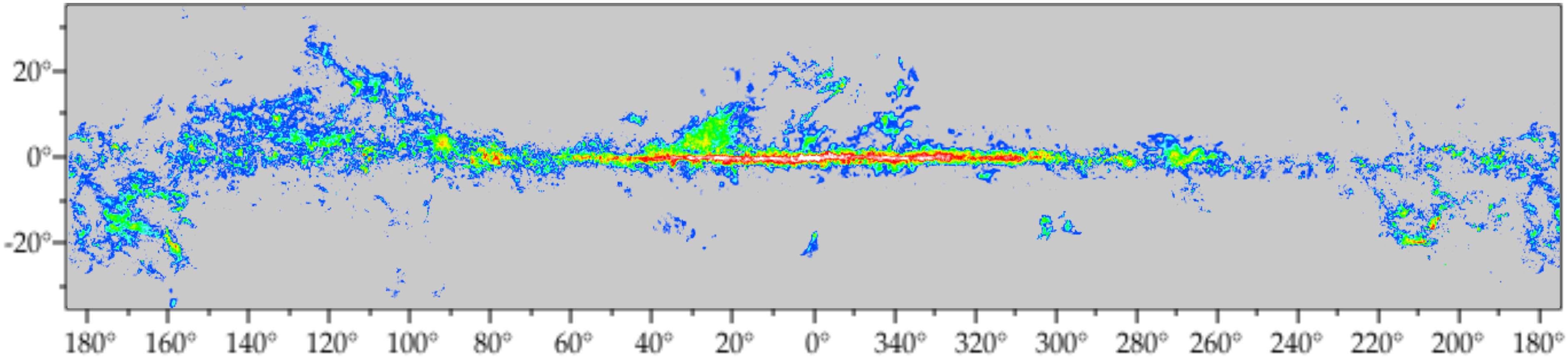
atomic hydrogen

molecular hydrogen

star formation

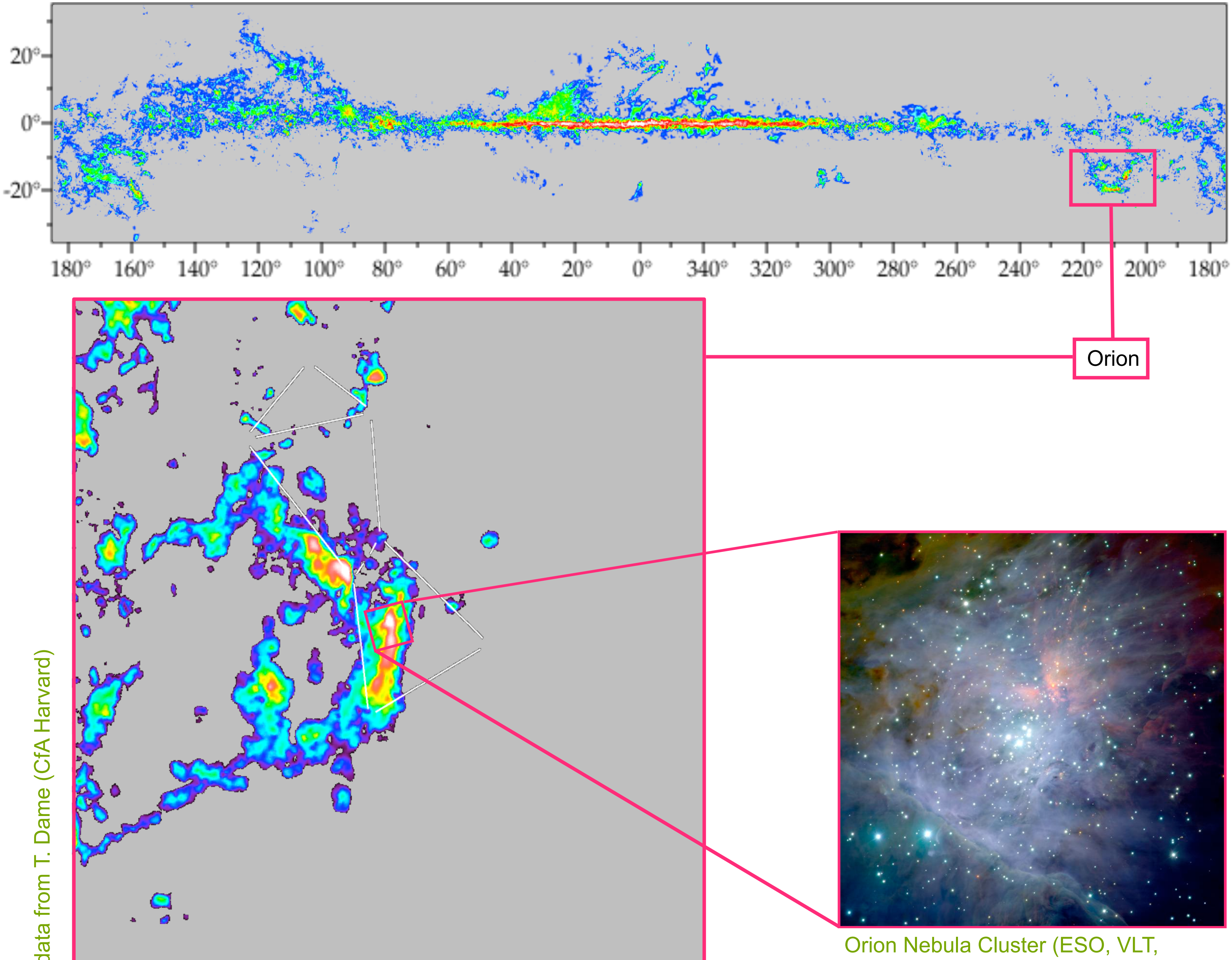
- HI gas more extended
- H2 and SF well correlated

galaxies from THINGS and HERACLES survey
(images from Frank Bigiel, ZAH/ITA)



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

data from T. Dame (CfA Harvard)



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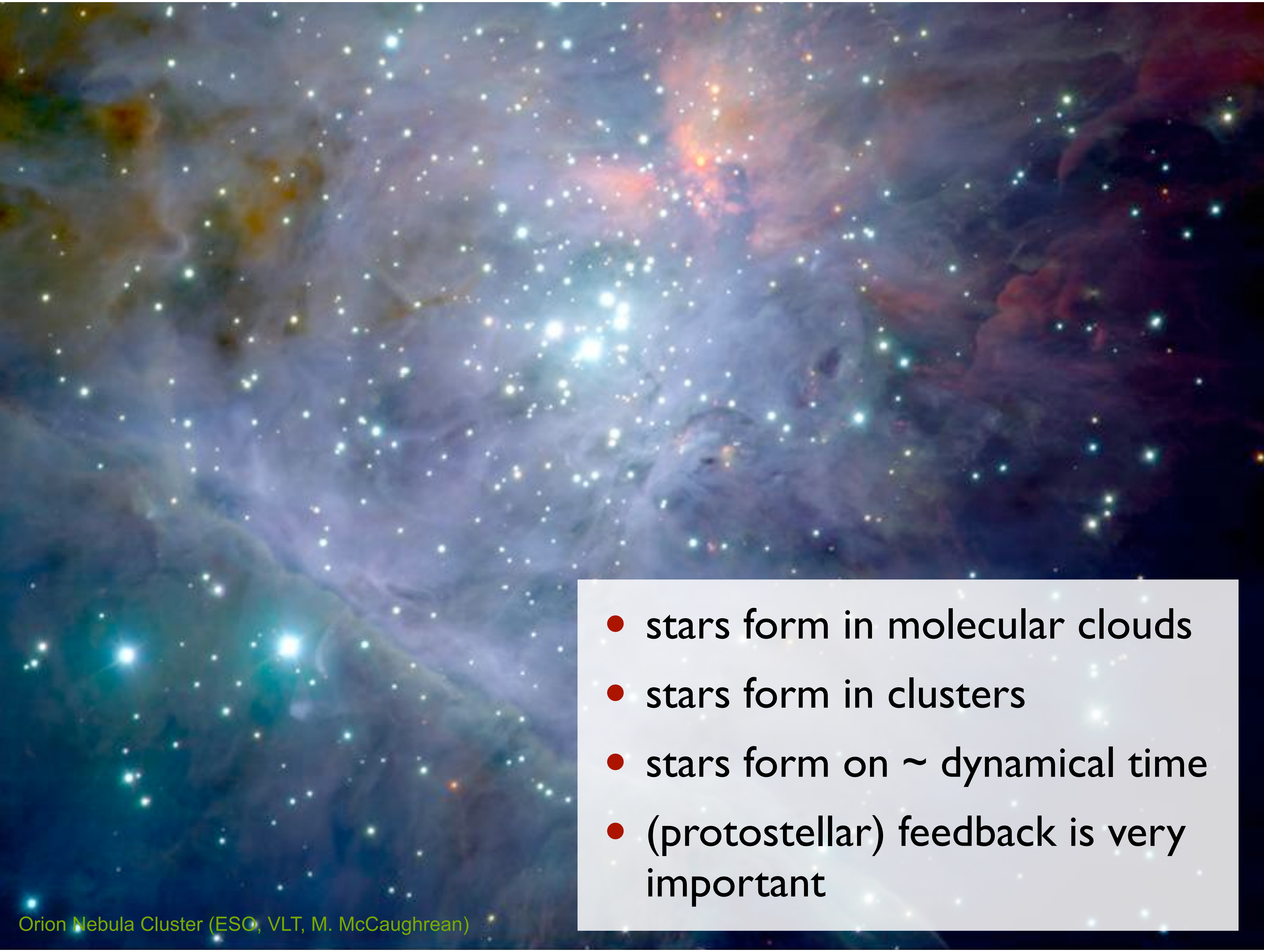
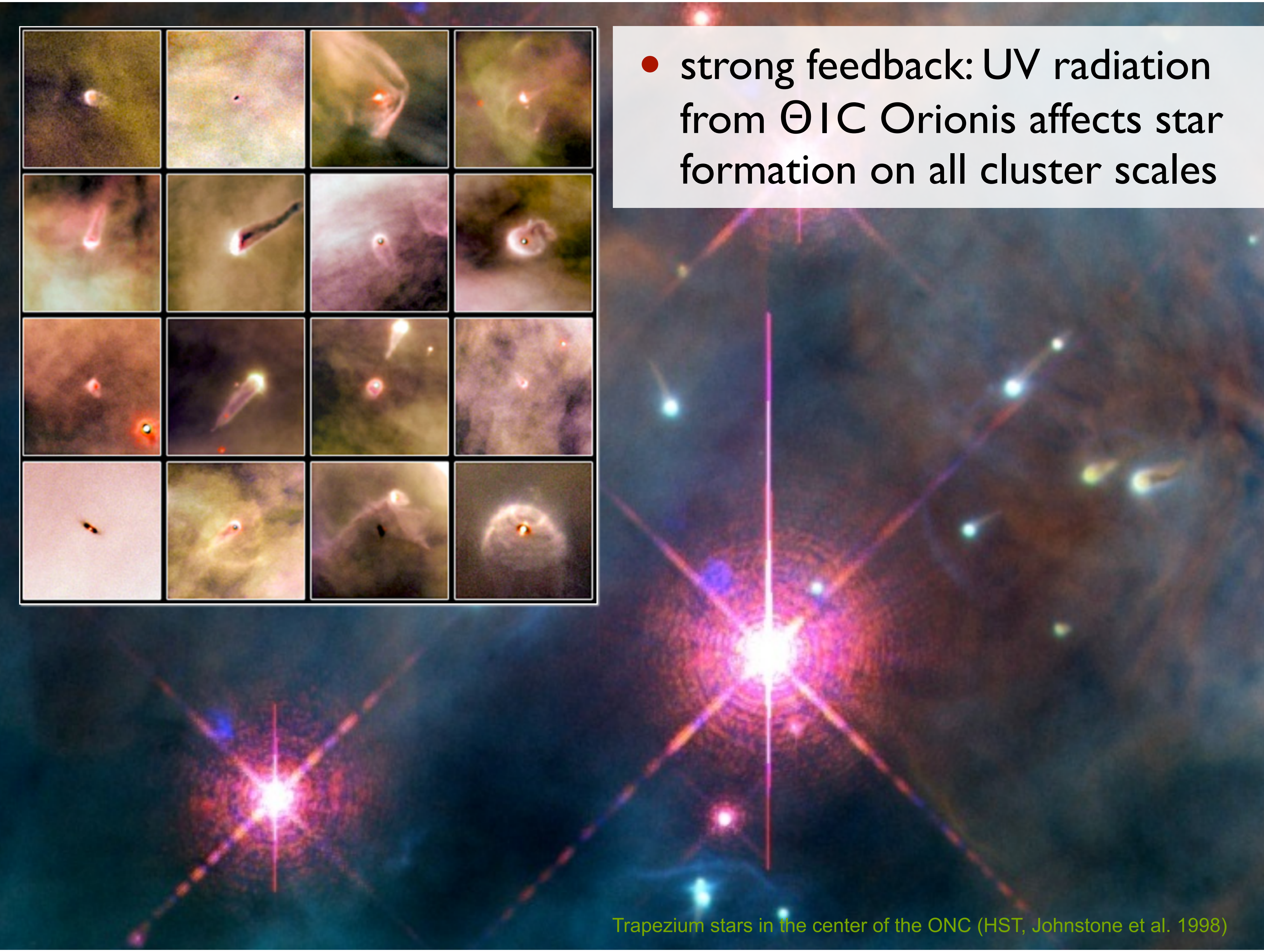
Orion Nebula Cluster (ESO, VLT, M. McCaughrean)



- stars form in molecular clouds
- stars form in clusters
- stars form on ~ dynamical time
- (protostellar) feedback is very important

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



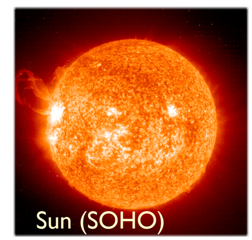
- strong feedback: UV radiation from Θ1C Orionis affects star formation on all cluster scales

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

Pleiades (DSS, Palomar Observatory Sky Survey)

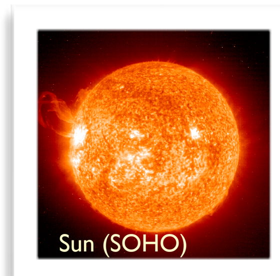
theoretical
approach

decrease in spatial scale / increase in density



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

decrease in spatial scale / increase in density



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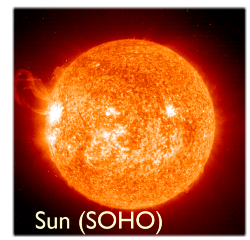
decrease in spatial scale / increase in density

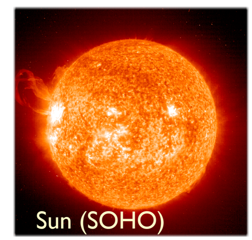
- density
  - density of ISM:
  - density of molec
  - density of Sun: 1.4
- spatial scale
  - size of molecular cloud: few 10s
  - size of young cluster: ~ 1
  - size of Sun: 1.4 x 10

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*

decrease in spatial scale / increase in density



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  - *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

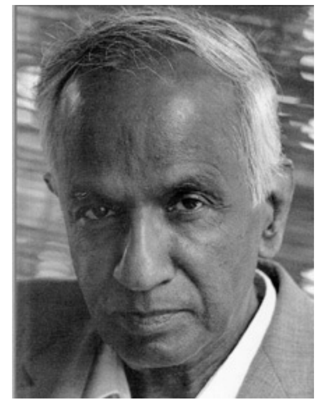
- *von Weizsäcker (1943, 1951)* and *Chandrasekhar (1951):* concept of ***MICROTURBULENCE***
  - BASIC ASSUMPTION: separation of scales between dynamics and turbulence

    $\ell_{turb} \ll \ell_{dyn}$
  - then turbulent velocity dispersion contributes to effective soundspeed:

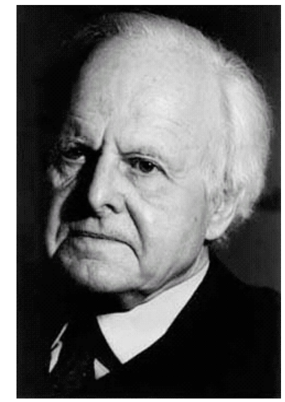
$$c_c^2 \mapsto c_c^2 + \sigma_{rms}^2$$

  - → Larger effective Jeans masses → more stability
  - BUT: *(1) turbulence depends on k:* $\sigma_{rms}^2(k)$

    (2) supersonic turbulence → $\sigma_{rms}^2(k) >> c_s^2$ *usually*



S. Chandrasekhar, 1910 - 1995



C.F. von Weiszäcker, 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 *~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

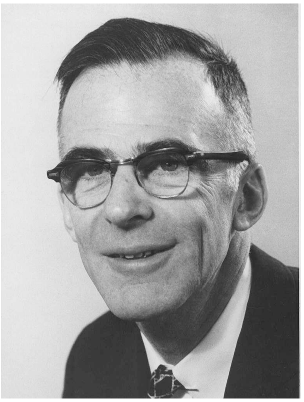
- *Mestel & Spitzer (1956):* Magnetic fields can prevent collapse*!!!*
  - Critical mass for gravitational collapse in presence of B-field

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

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

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

  - Ambipolar diffusion can initiate collapse

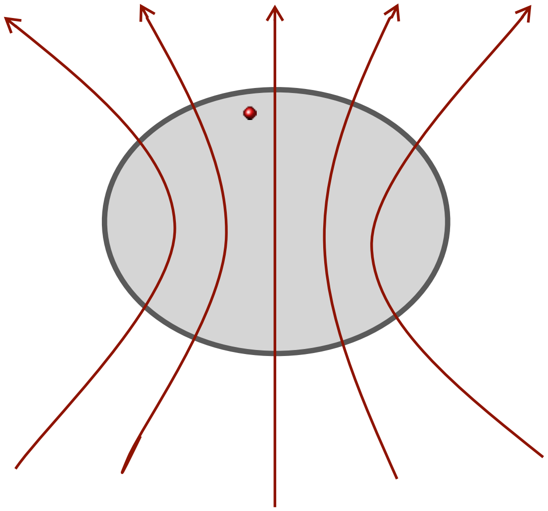


Lyman Spitzer, Jr., 1914 - 1997

“standard theory” of star formation

- BASIC ASSUMPTION: Stars form from magnetically highly subcritical cores
- Ambipolar diffusion slowly increases (M/Φ): $\tau_{AD} \approx 10\tau_{ff}$
- 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 ($\tau_{ff} << \tau_{AD}$)
  (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)

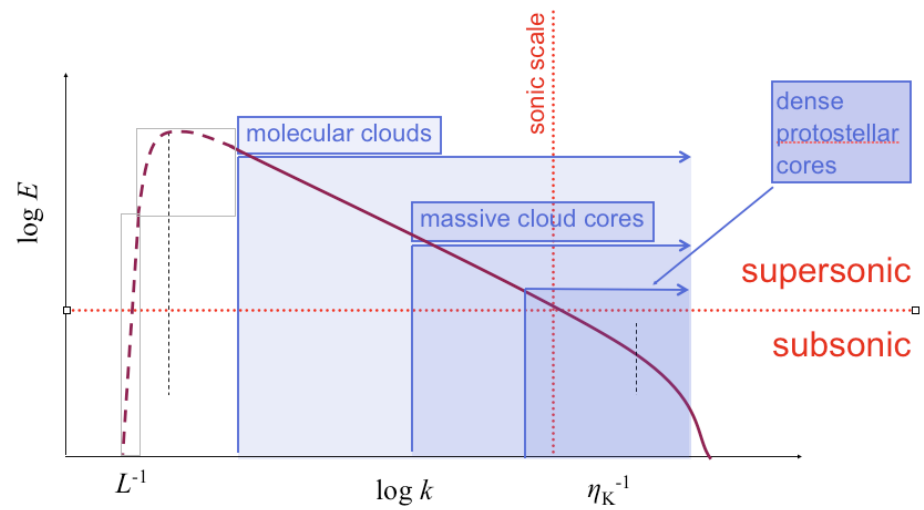
(see e.g. Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194)

gravoturbulent star formation

- BASIC ASSUMPTION:

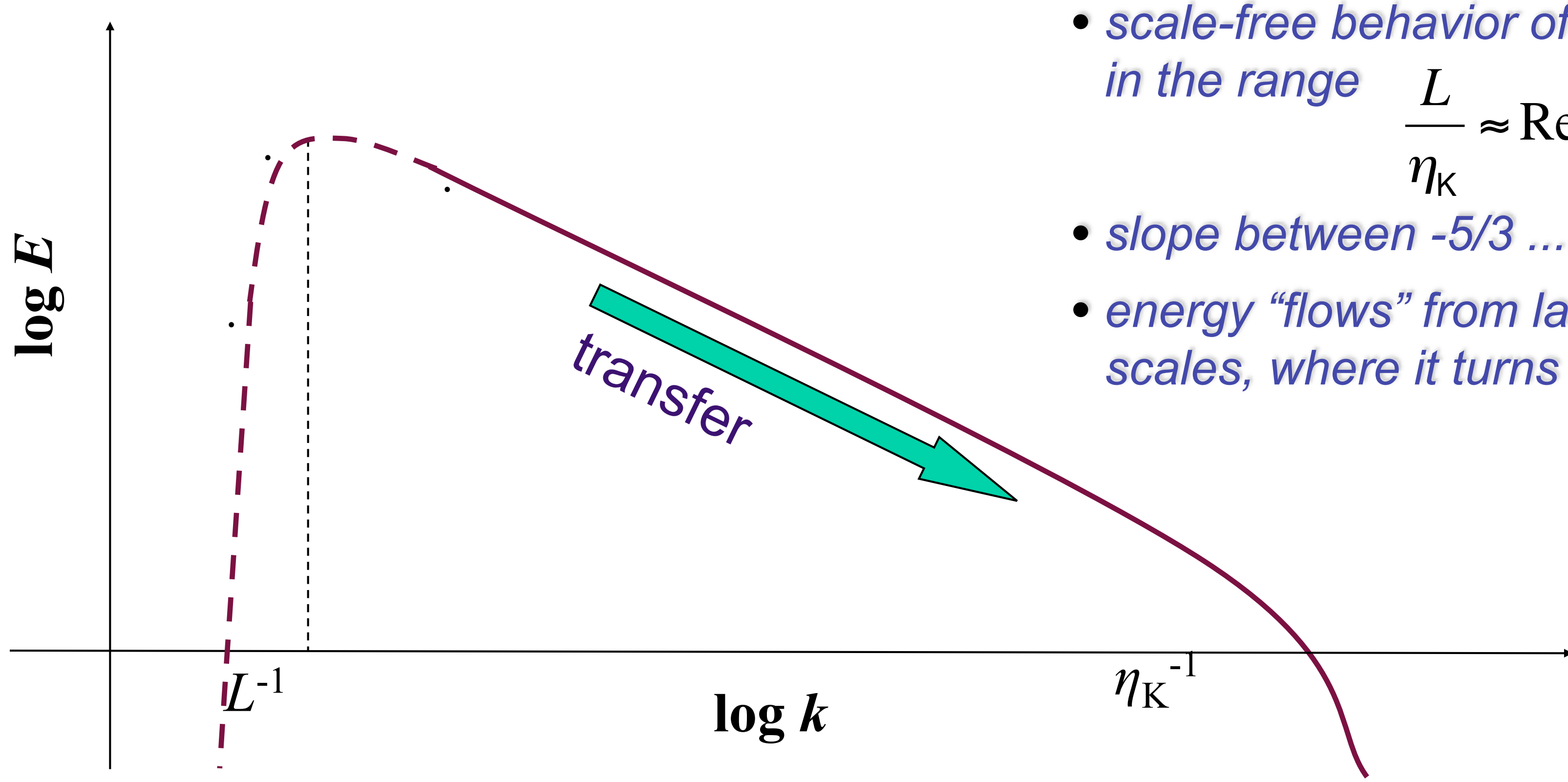
> star formation is controlled by interplay between supersonic turbulence and self-gravity

- turbulence plays a *dual role*:
  - on *large scales* it *provides support*
  - on *small scales* it can *trigger collapse*
- some predictions:
  - dynamical star formation timescale τ_{ff}
  - high binary fraction
  - complex spatial structure of embedded star clusters
  - and many more . . .



Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194
McKee & Ostriker, 2007, ARAA, 45, 565

turbulent cascade in the ISM



- *scale-free behavior of turbulence in the range* $\frac{L}{\eta_K} \approx \mathrm{Re}^{3/4}$
- *slope between -5/3 ... -2*
- *energy "flows" from large to small scales, where it turns into heat*

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

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

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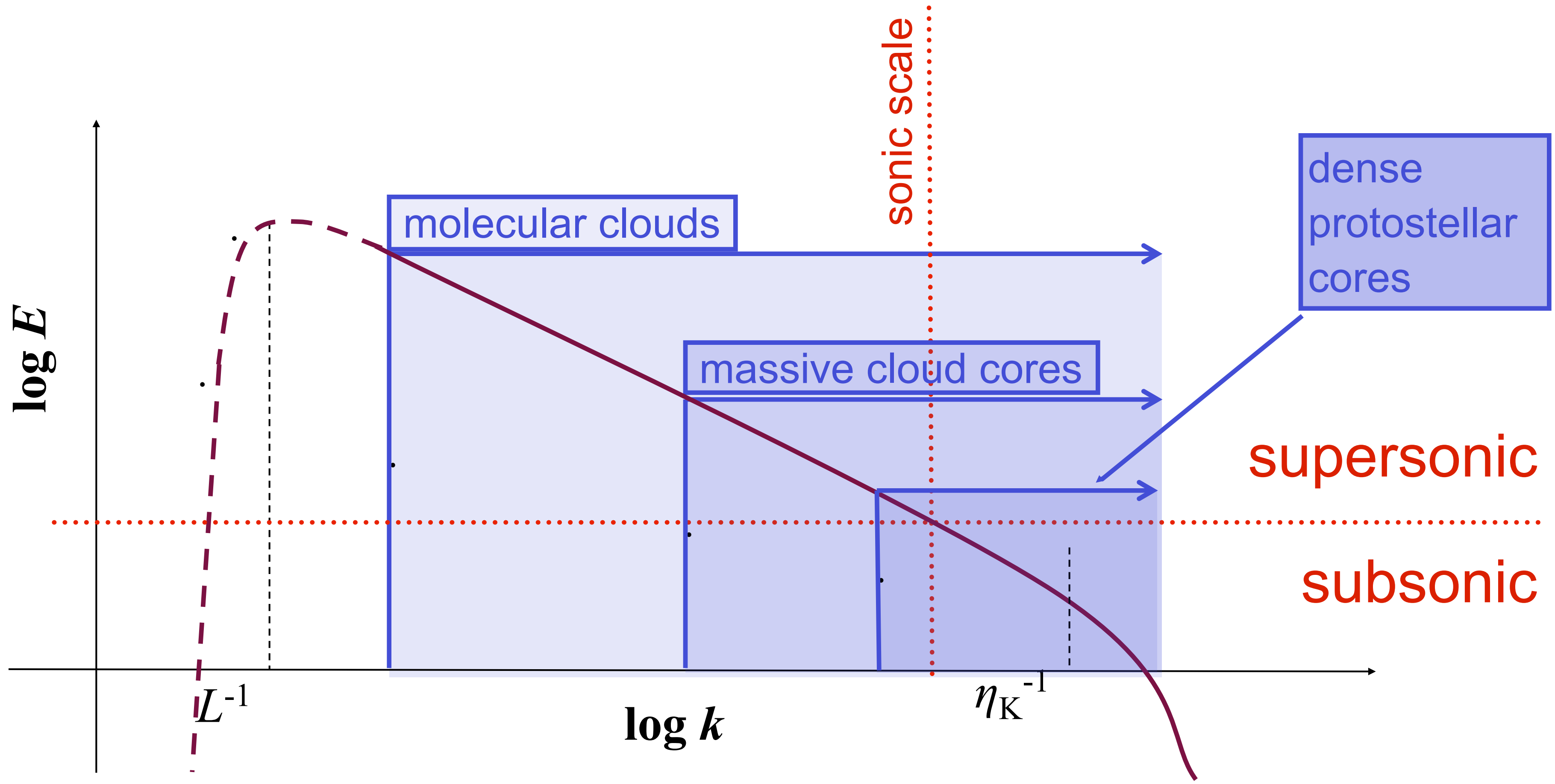
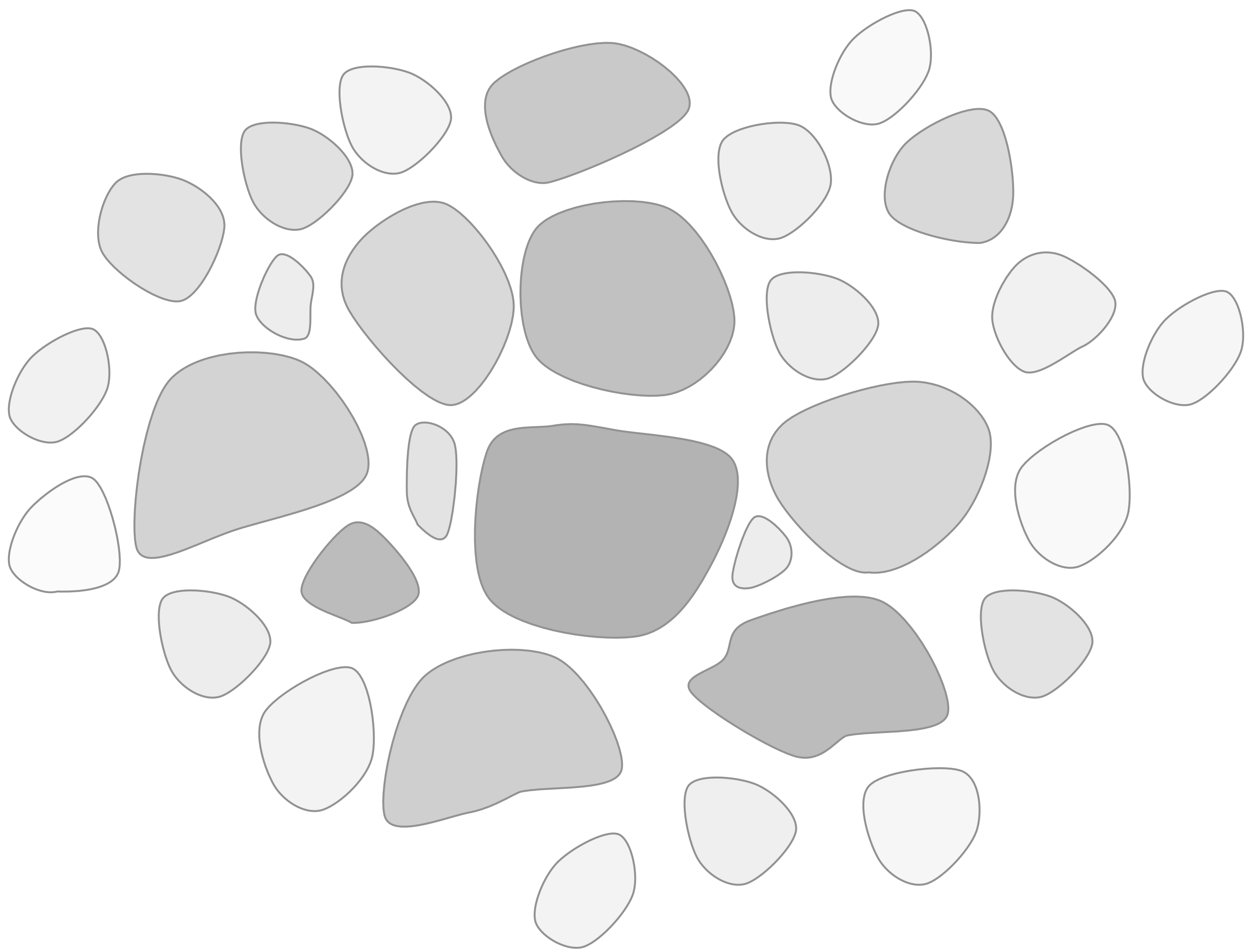


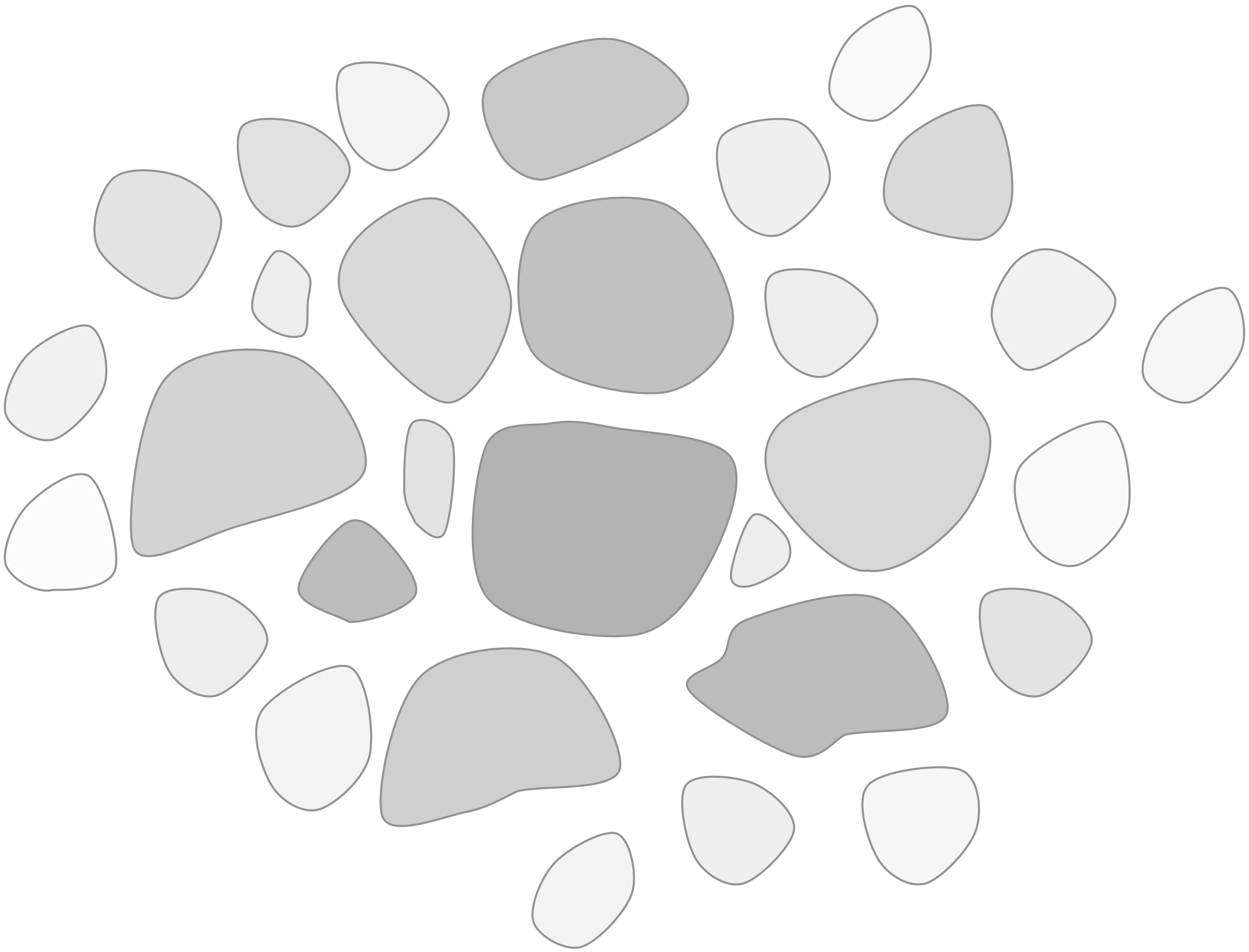
energy source & scale *NOT known* (supernovae, winds, spiral density waves?)

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

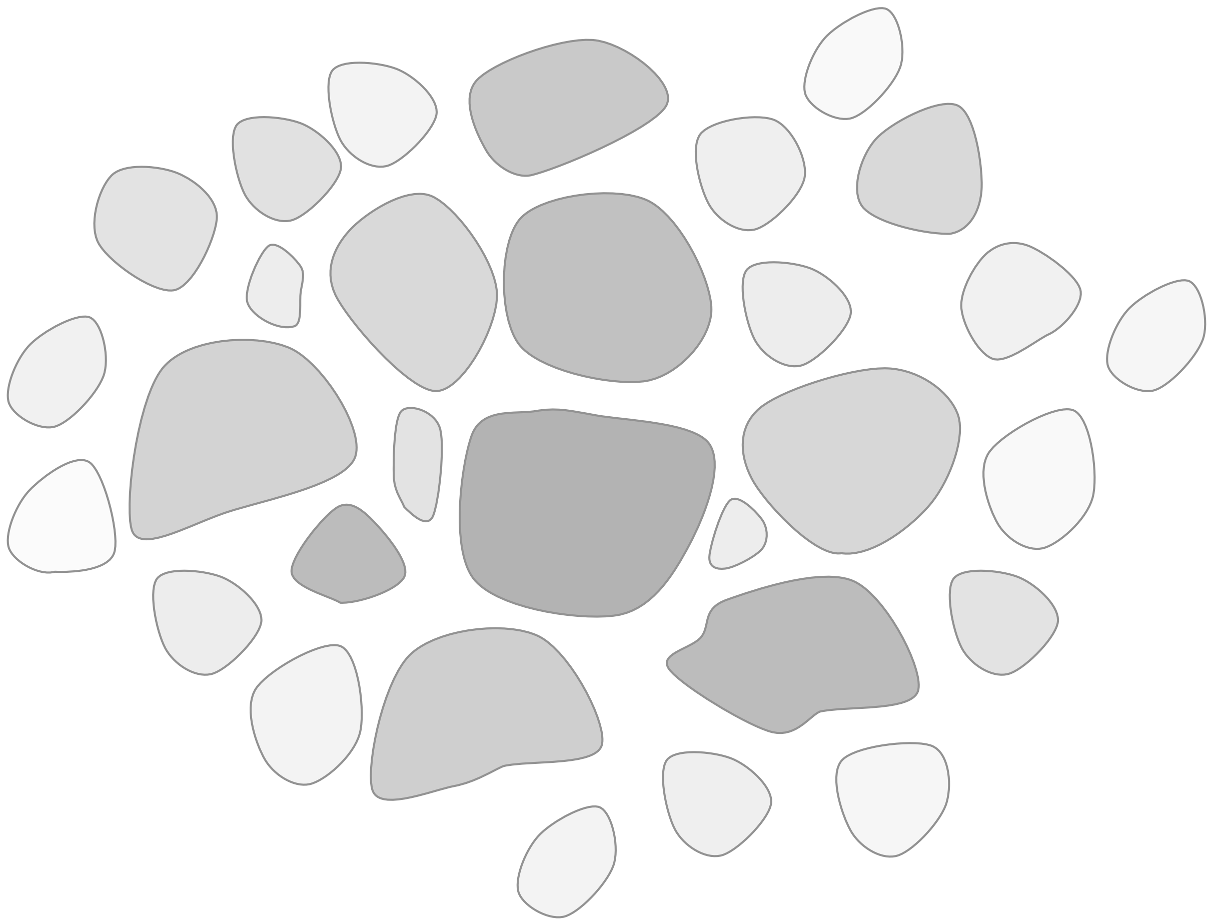
dissipation scale not known (ambipolar diffusion, molecular diffusion?)



turbulence creates a hierarchy of clumps



as turbulence decays locally, contraction sets in



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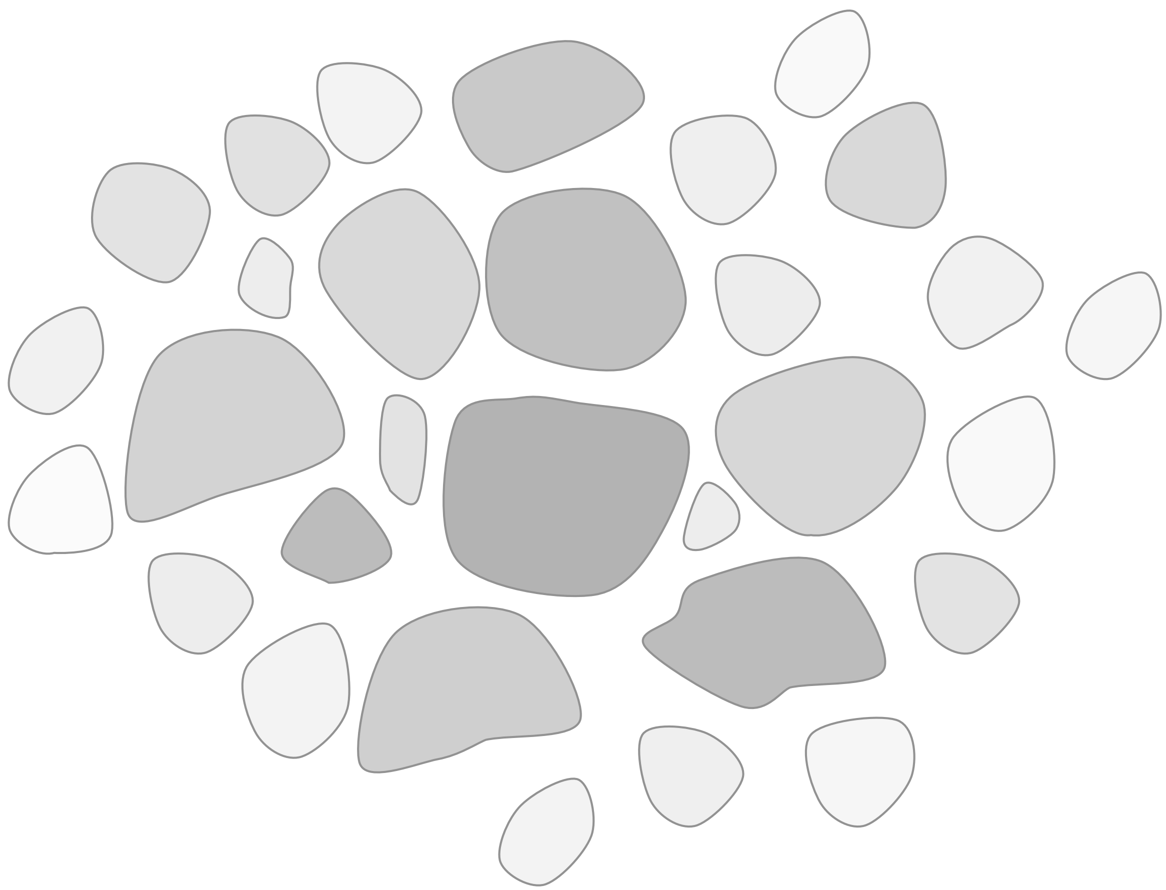
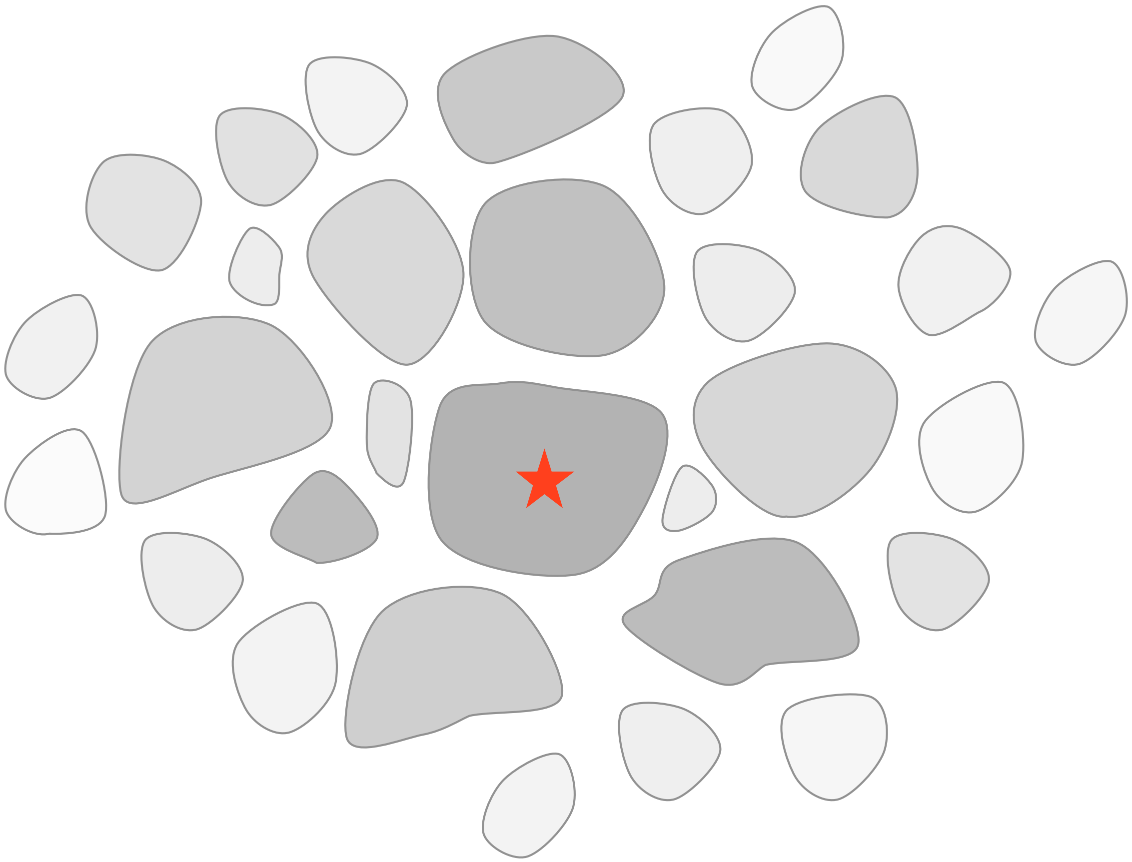


while region contracts, individual clumps collapse to form stars



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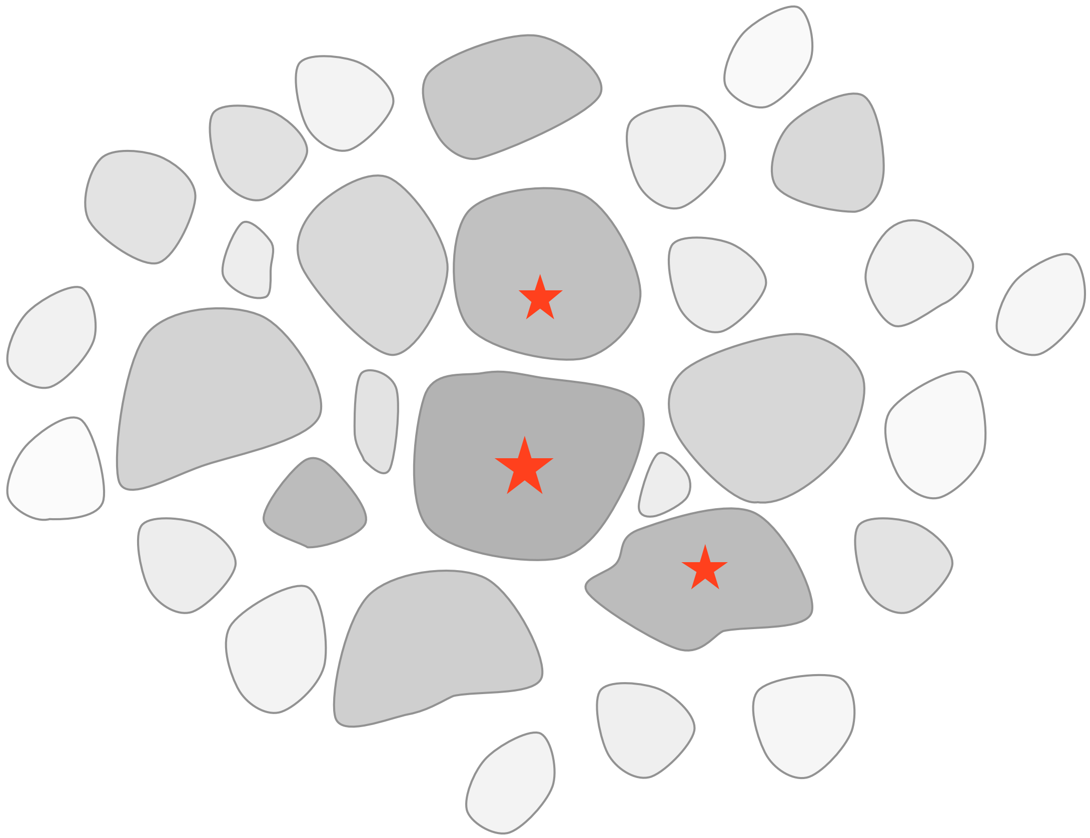

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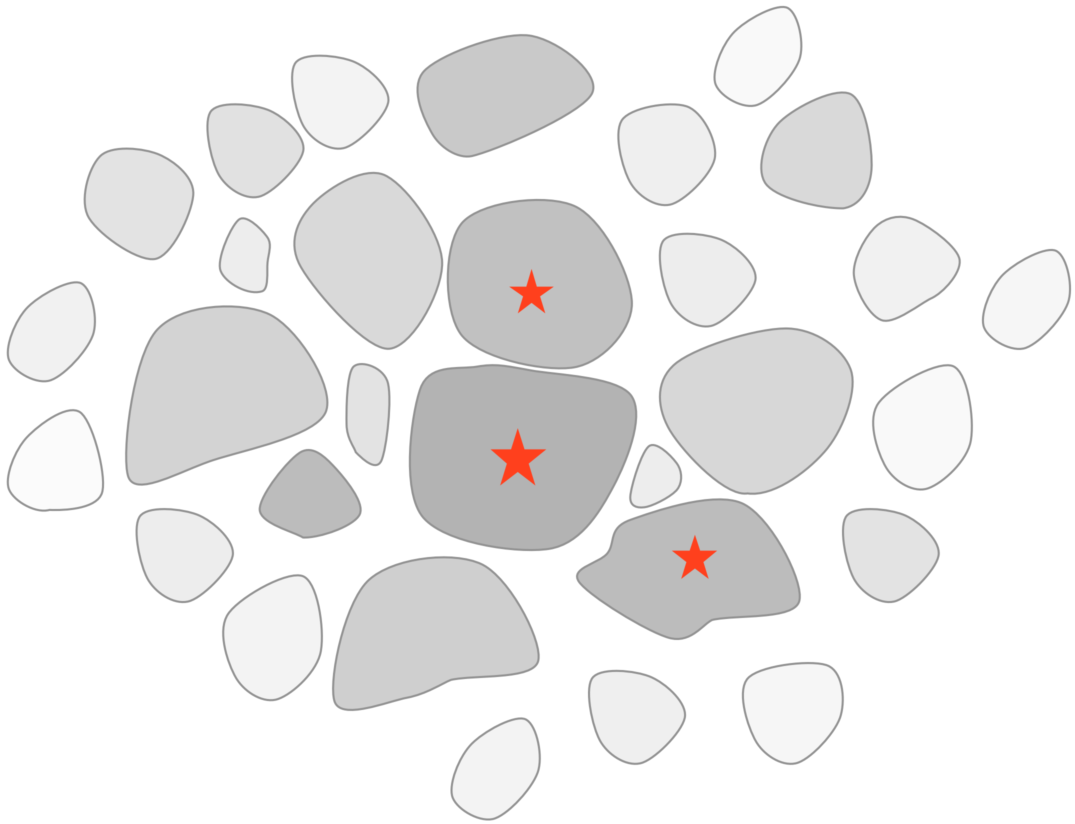

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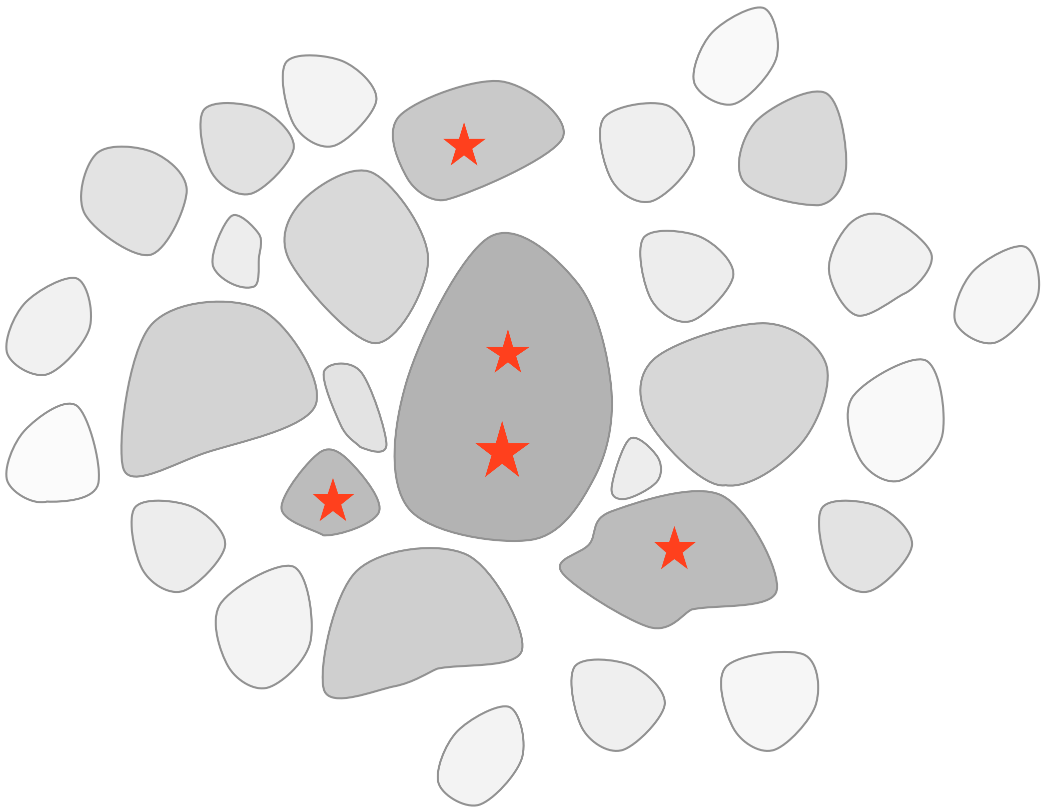
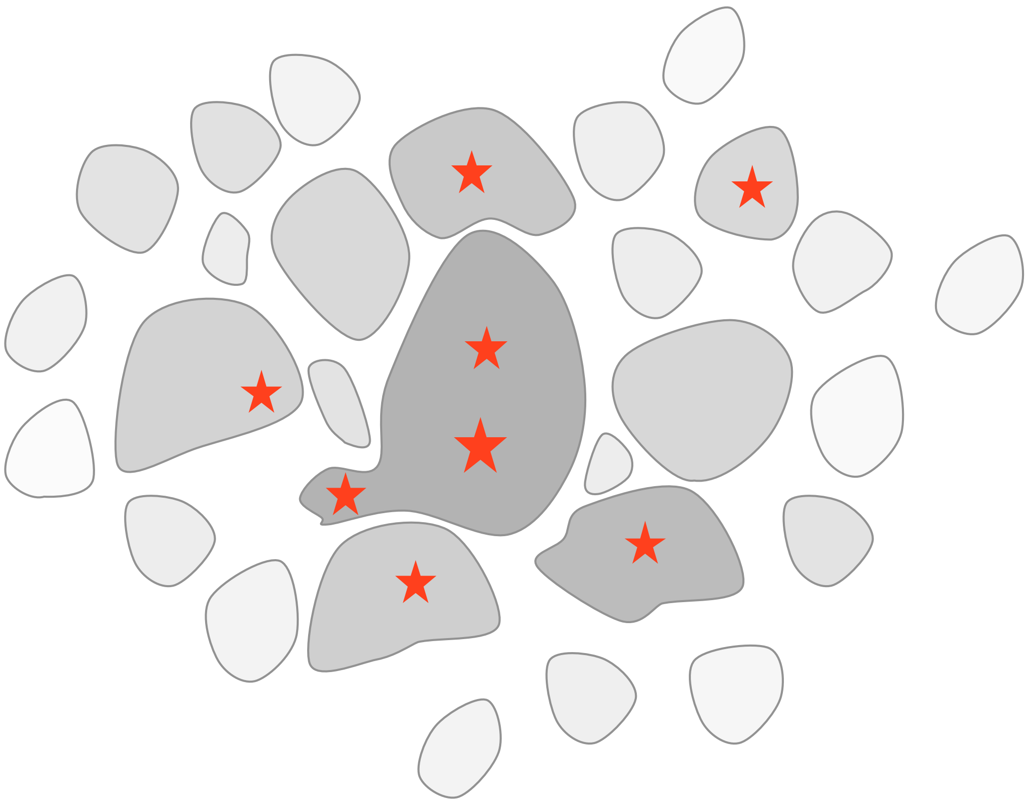


$\alpha = E_{kin}/|E_{pot}| < 1$

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



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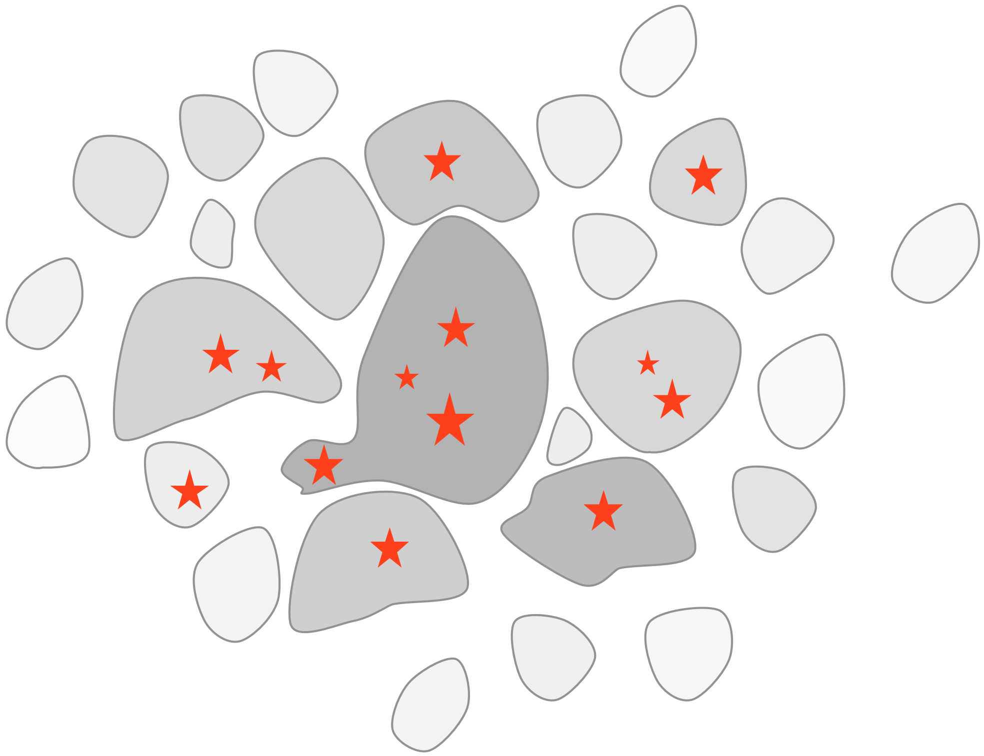

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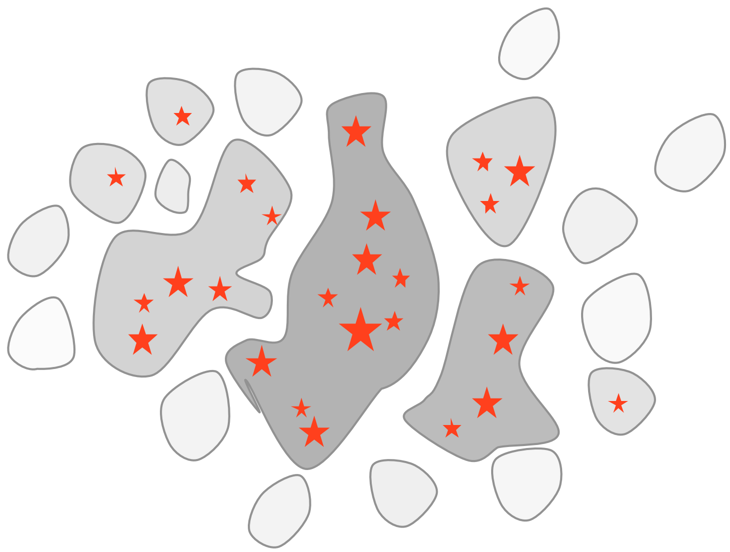
in *dense clusters*, competitive mass growth becomes important



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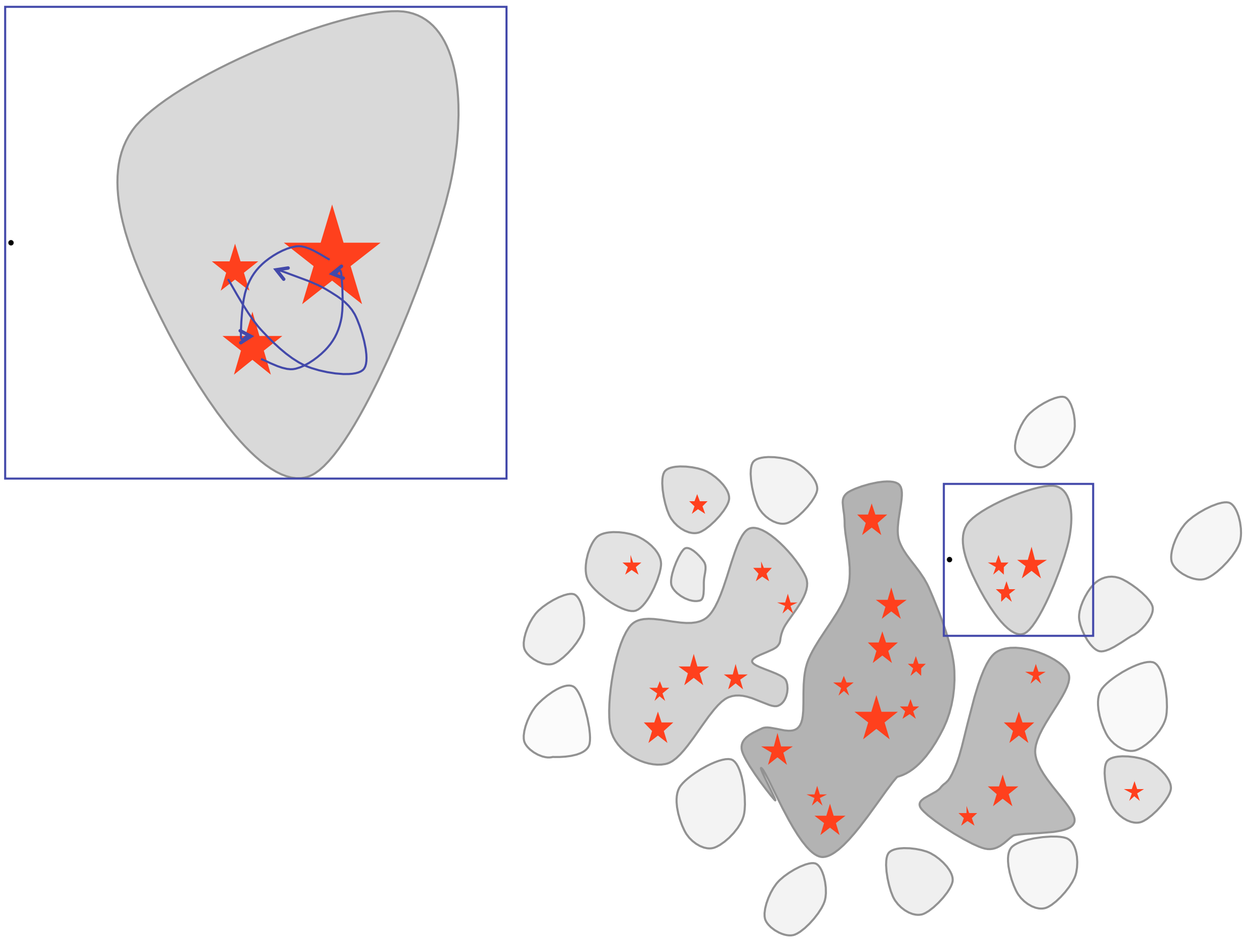
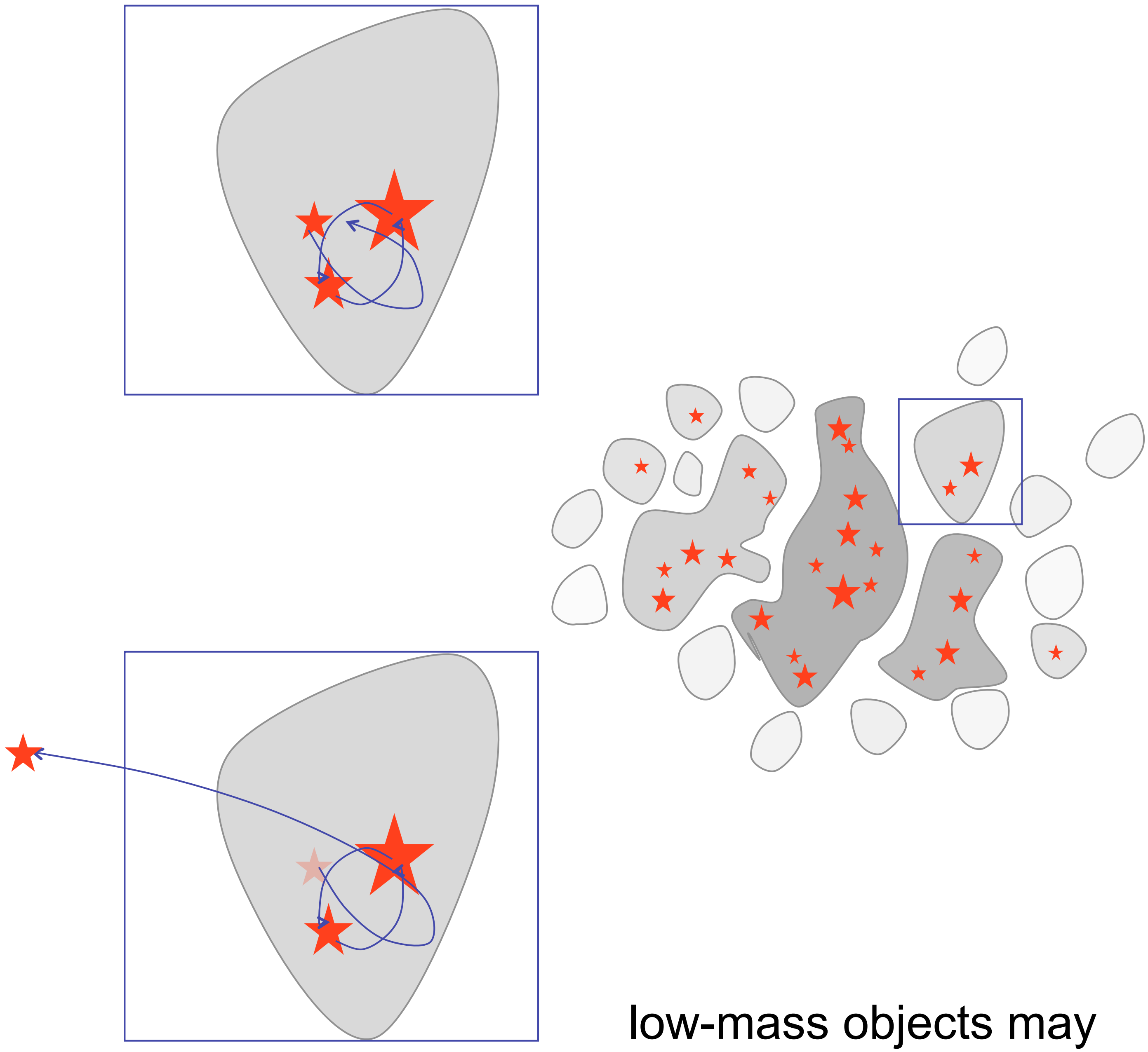
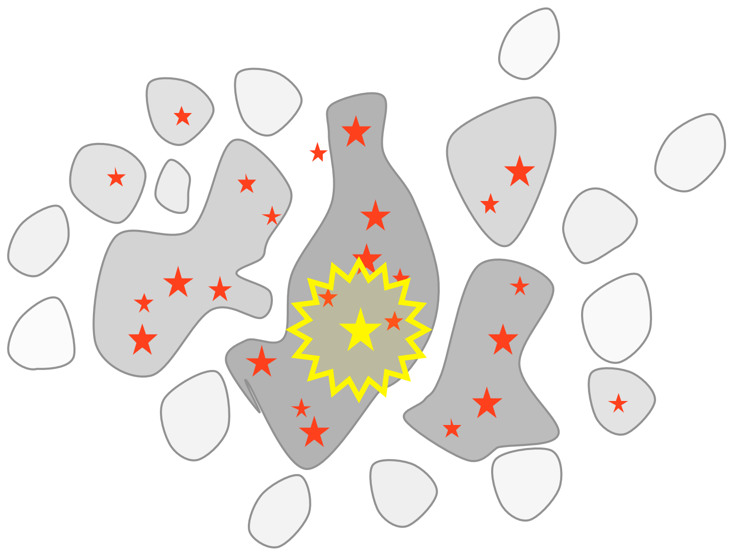


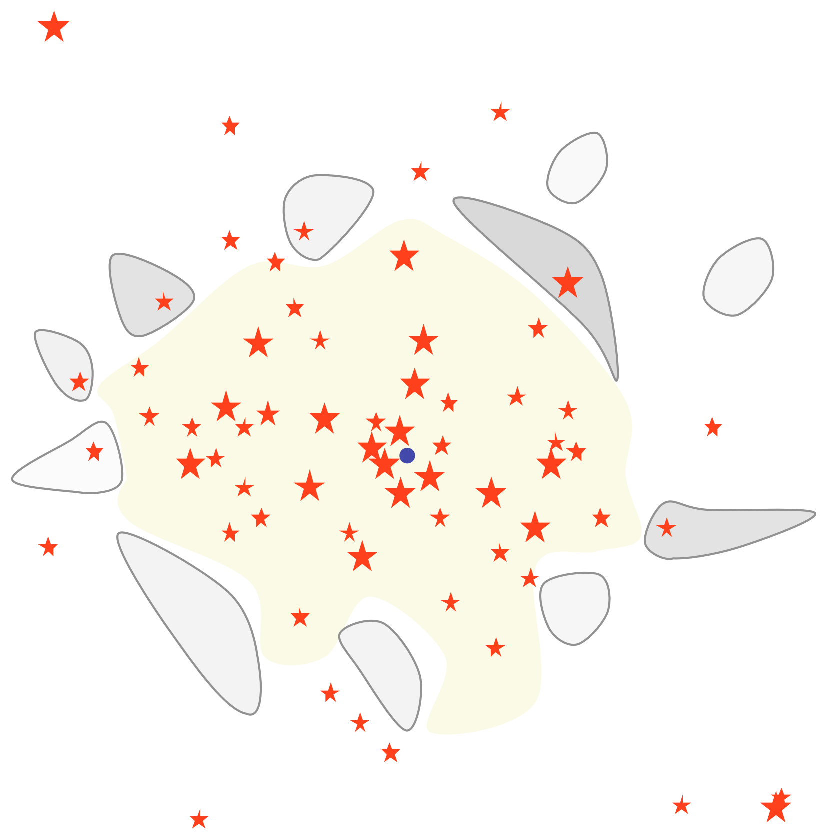
in *dense clusters*, *N*-body effects influence mass growth



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



feedback terminates star formation



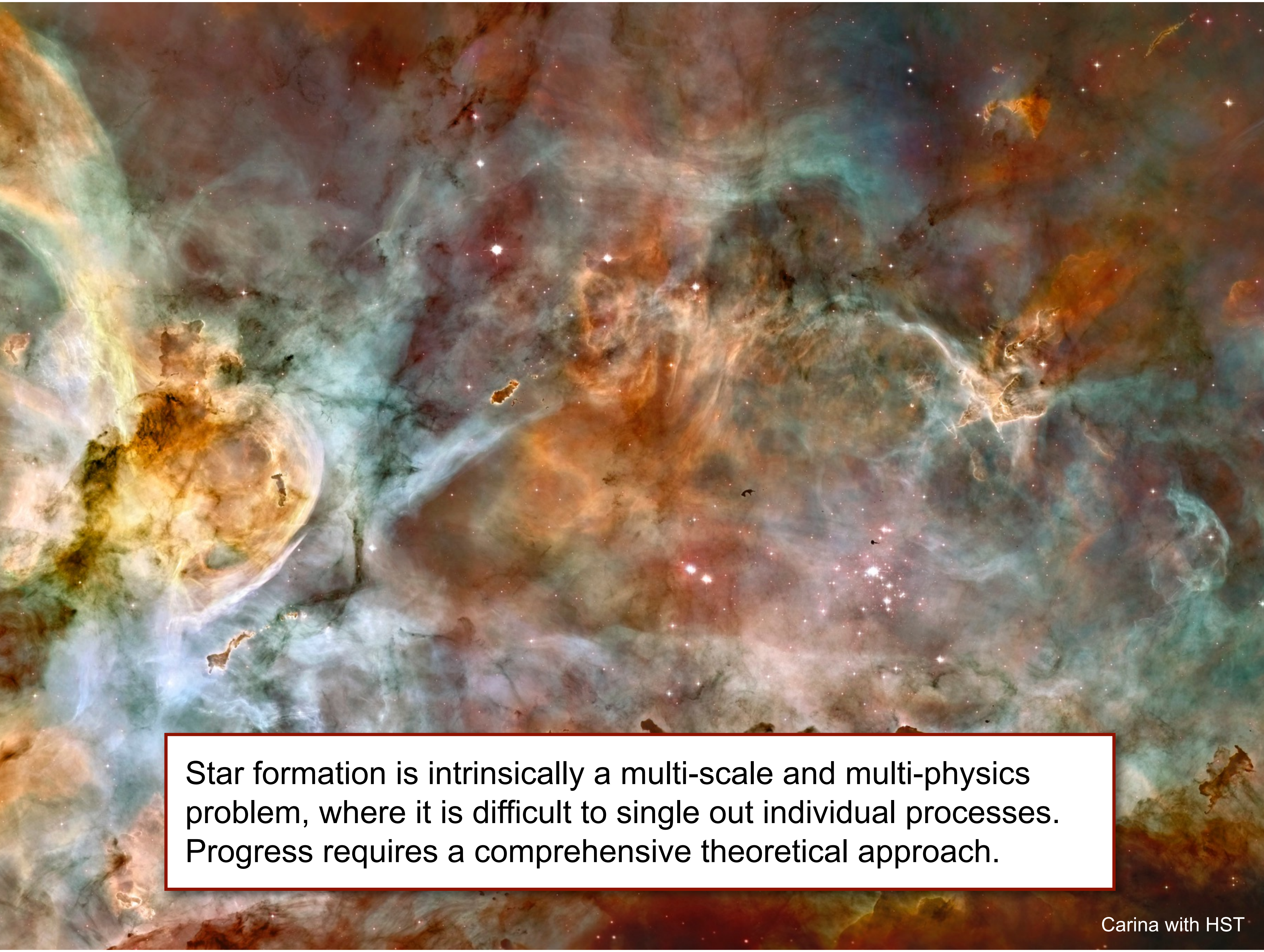
result: *star cluster*, possibly with HII region

NGC 602 in the LMC: Hubble Heritage Image

current status

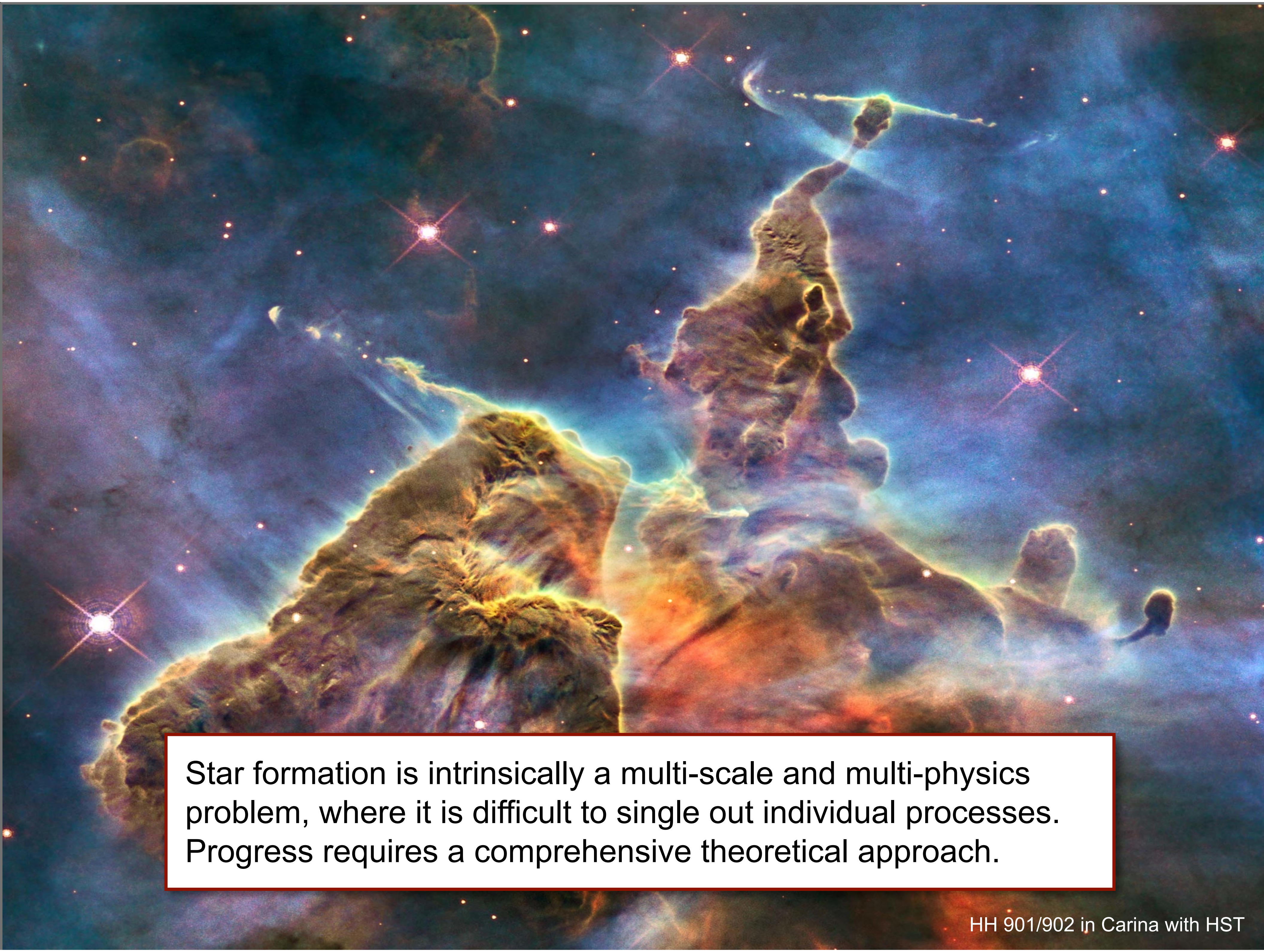
- *stars form from the complex interplay of self-gravity and a large number of competing processes (such as turbulence, B-field, feedback, thermal pressure)*
- *the relative importance of these processes depends on the environment*
  - prestellar cores --> thermal pressure is important
    molecular 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.

Carina with HST



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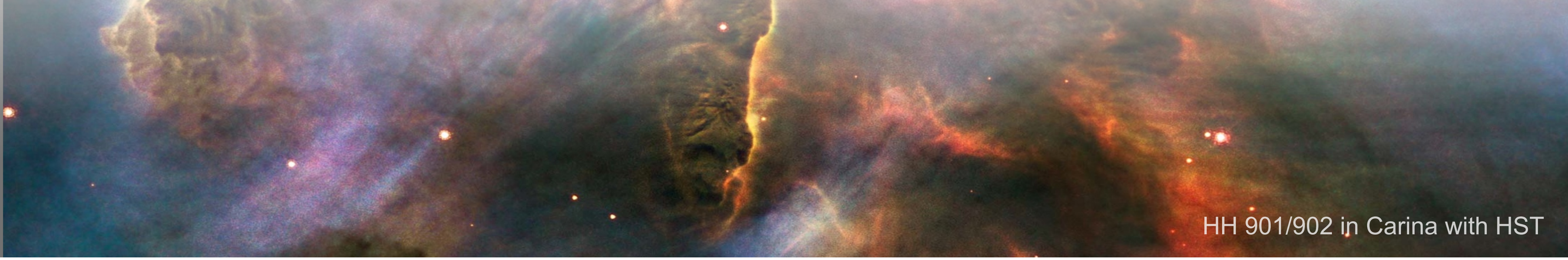
HH 901/902 in Carina with HST

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?



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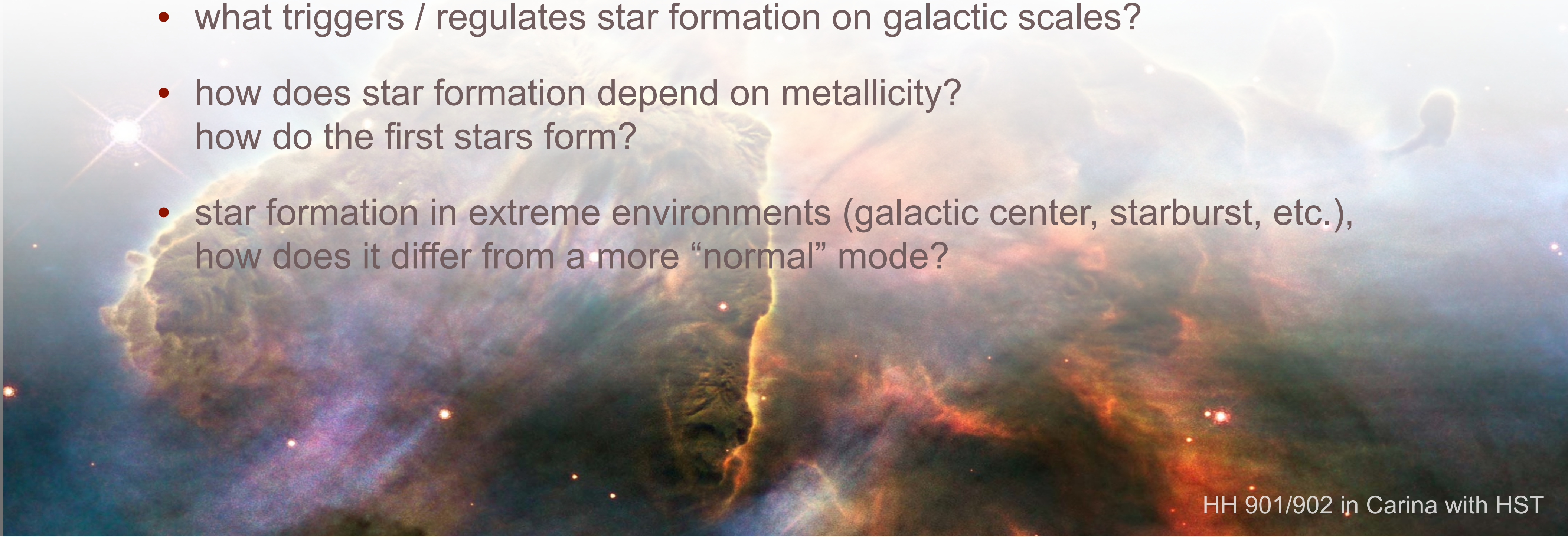
- star formation in extreme environments (galactic center, starburst, etc.),
  how does it differ from a more “normal” mode?

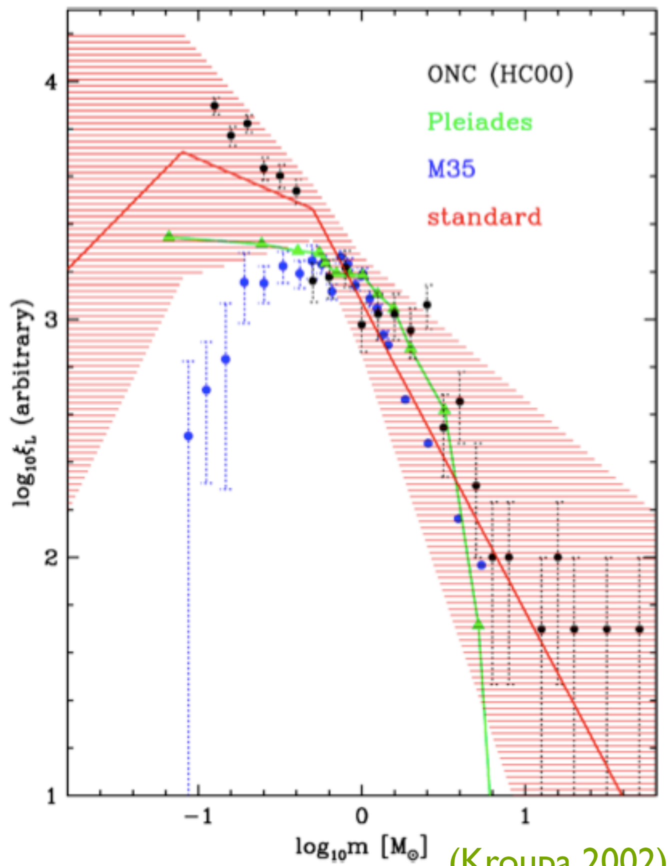


HH 901/902 in Carina with HST

stellar mass function

stellar mass fuction

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



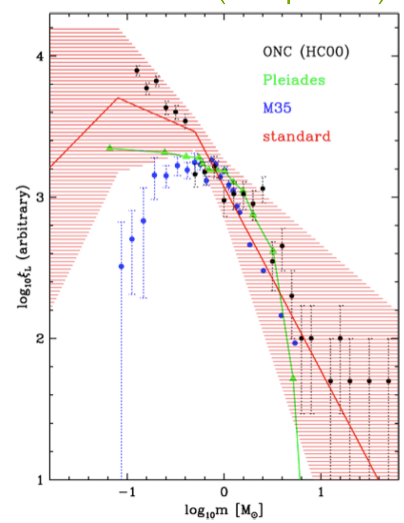
(Kroupa 2002)

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

(Kroupa 2002)



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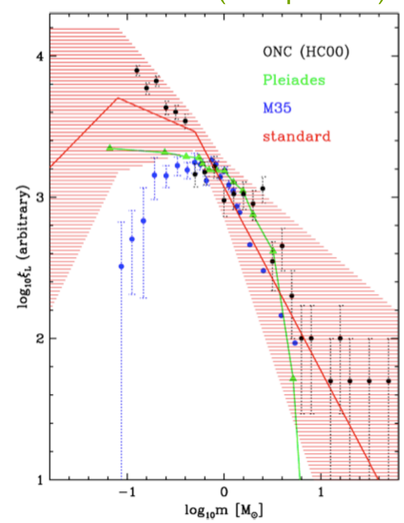
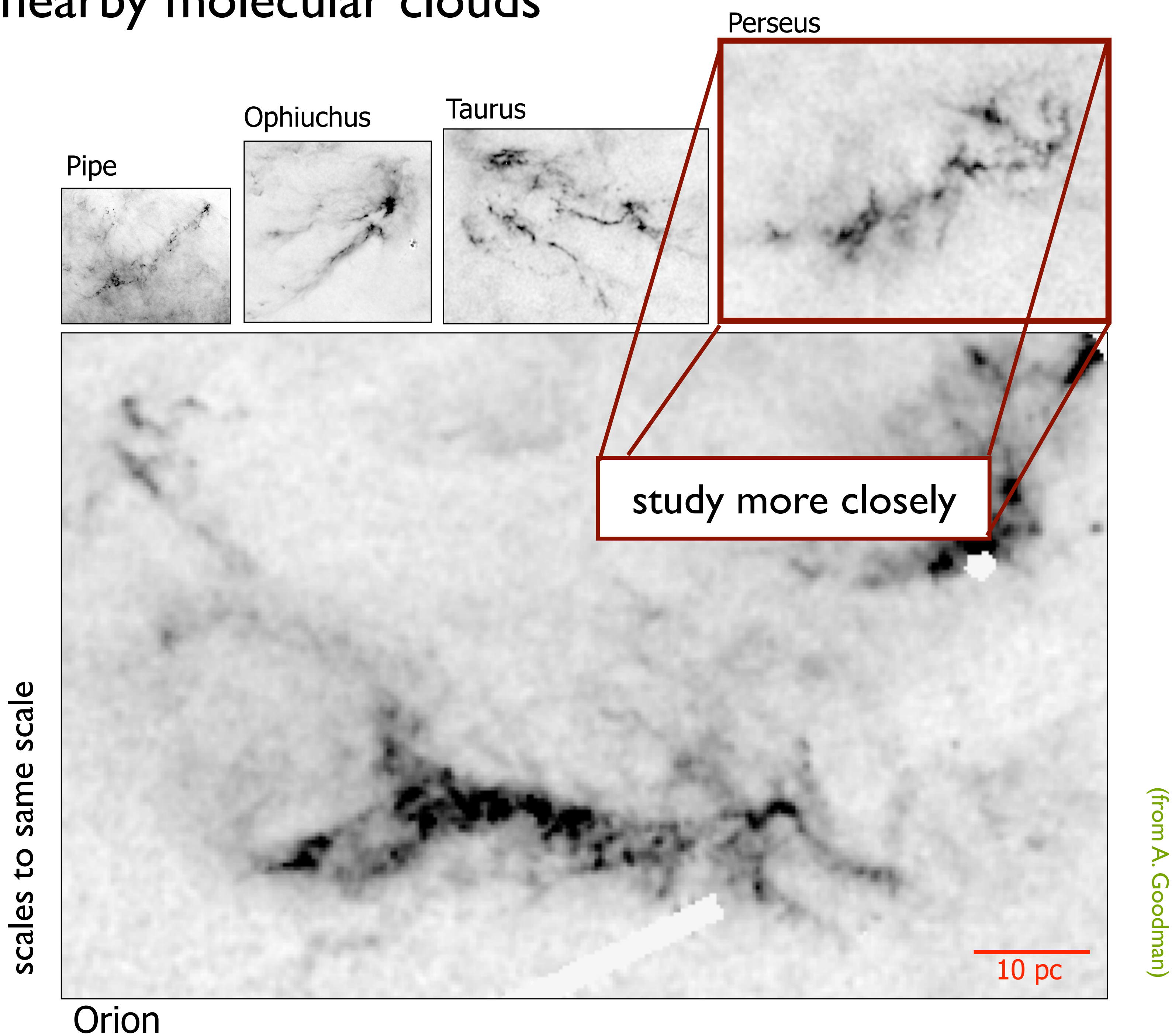


nearby molecular clouds



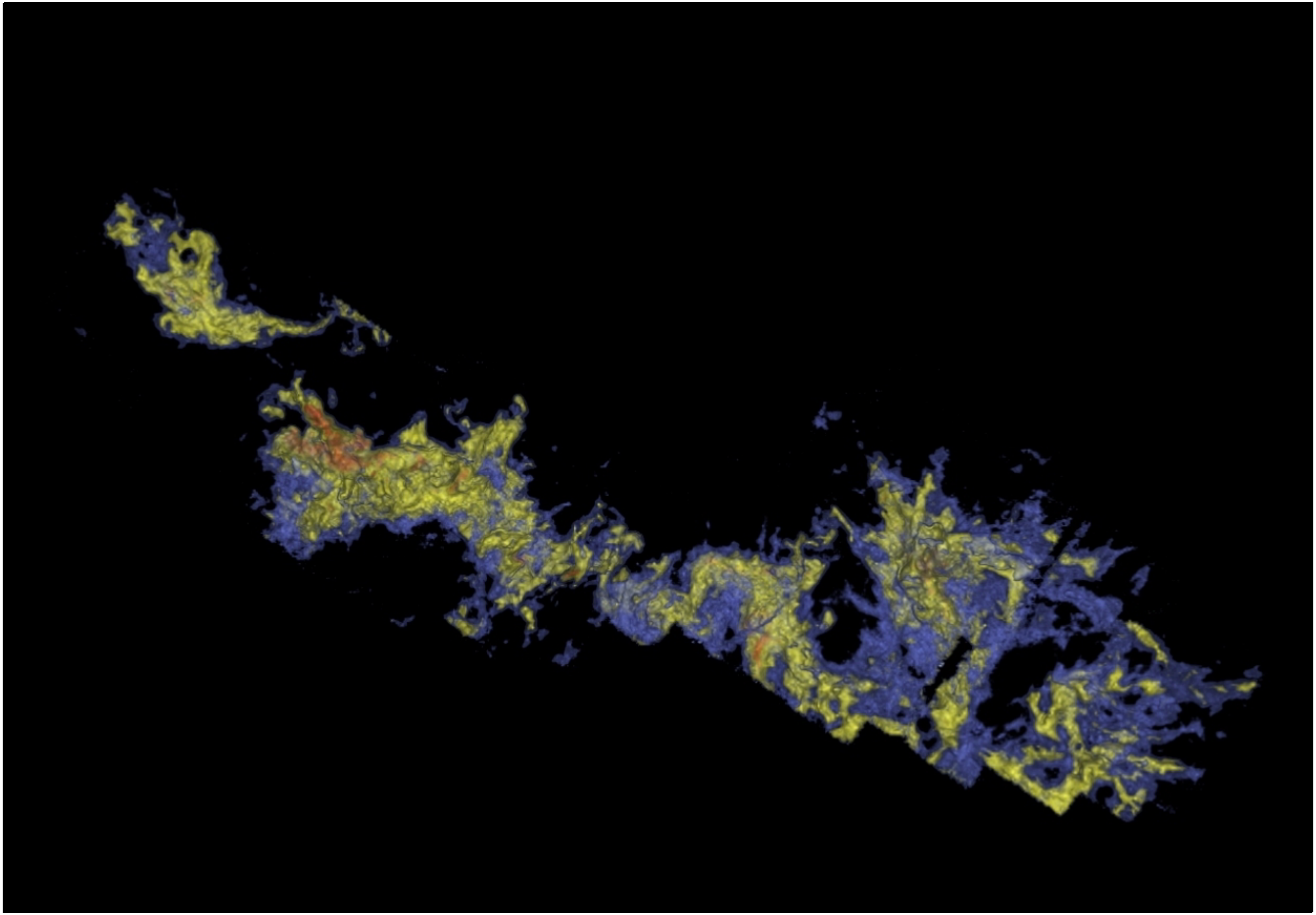
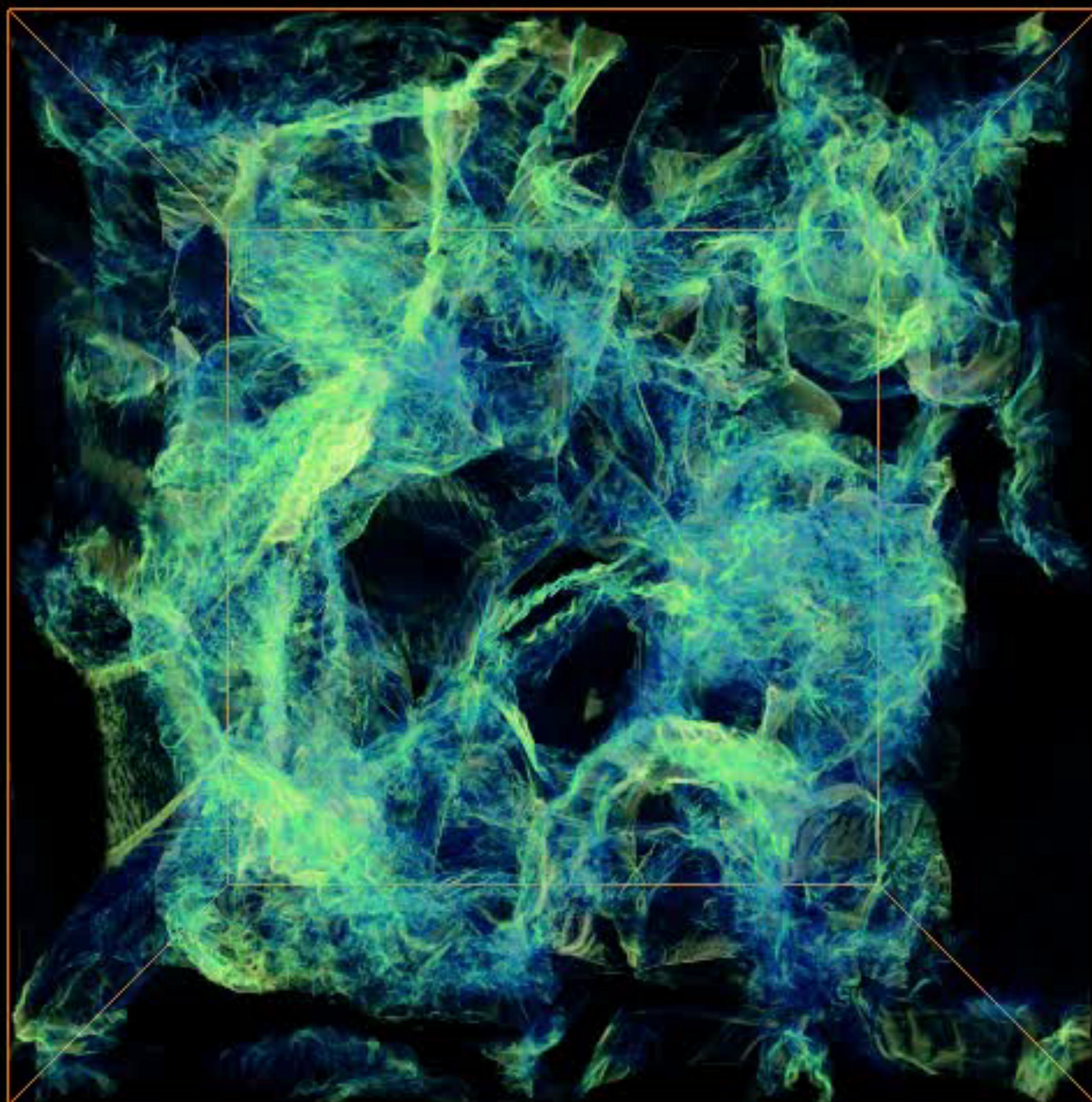


image from Alyssa Goodman: COMPLETE survey



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

example: model of Orion cloud

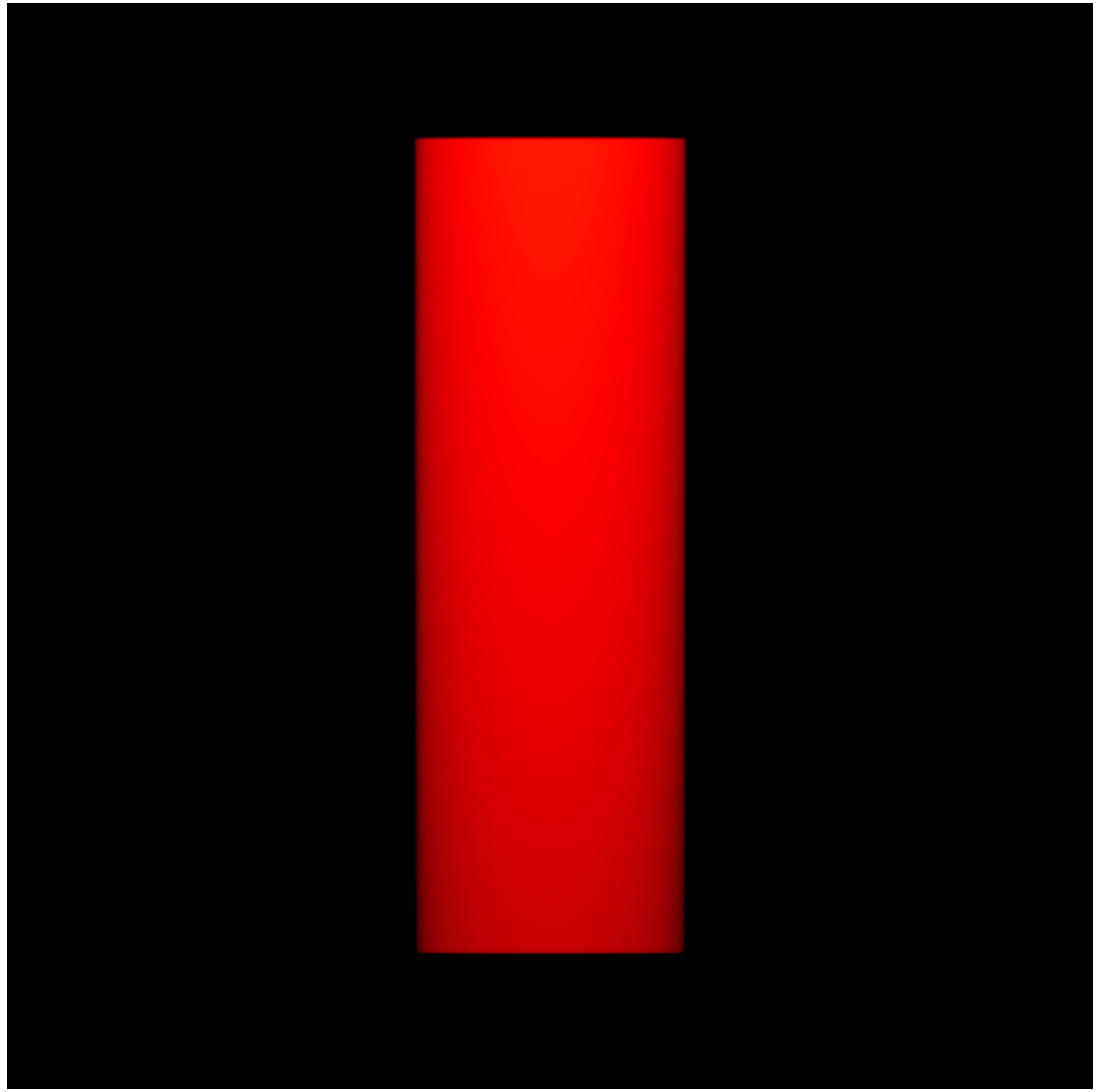
„model“ of Orion cloud: 15.000.000 SPH particles, 10^4 M_{sun} in 10 pc, mass resolution 0,02 M_{sun}, forms ~2.500 „stars“ (sink particles)

isothermal EOS, top bound, bottom unbound

has clustered as well as distributed „star“ formation

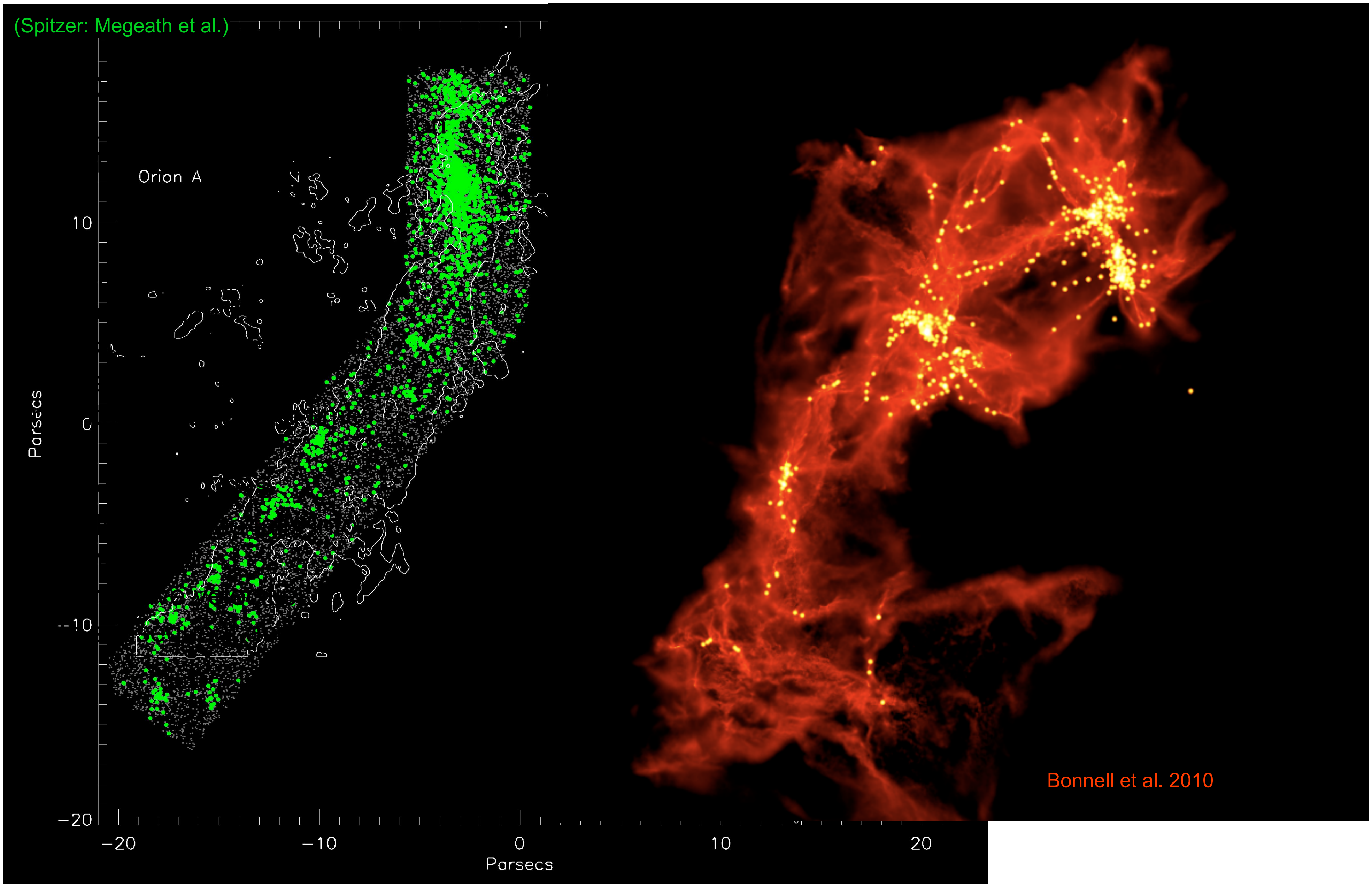
efficiency varies from 1% to 20%

develops full IMF
(distribution of sink particle masses)



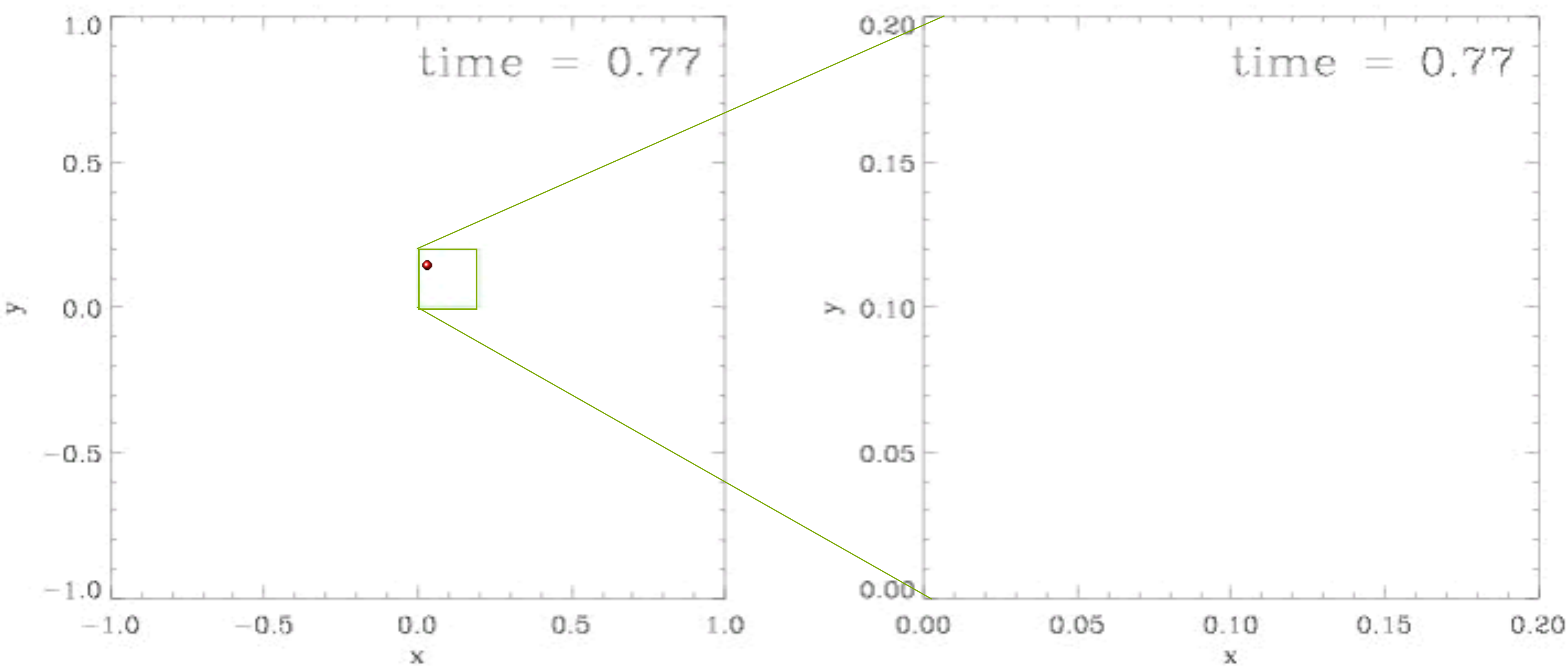
(Bonnell, Smith, Clark, & Bate 2010, MNRAS, 410, 2339)

example: model of Orion cloud



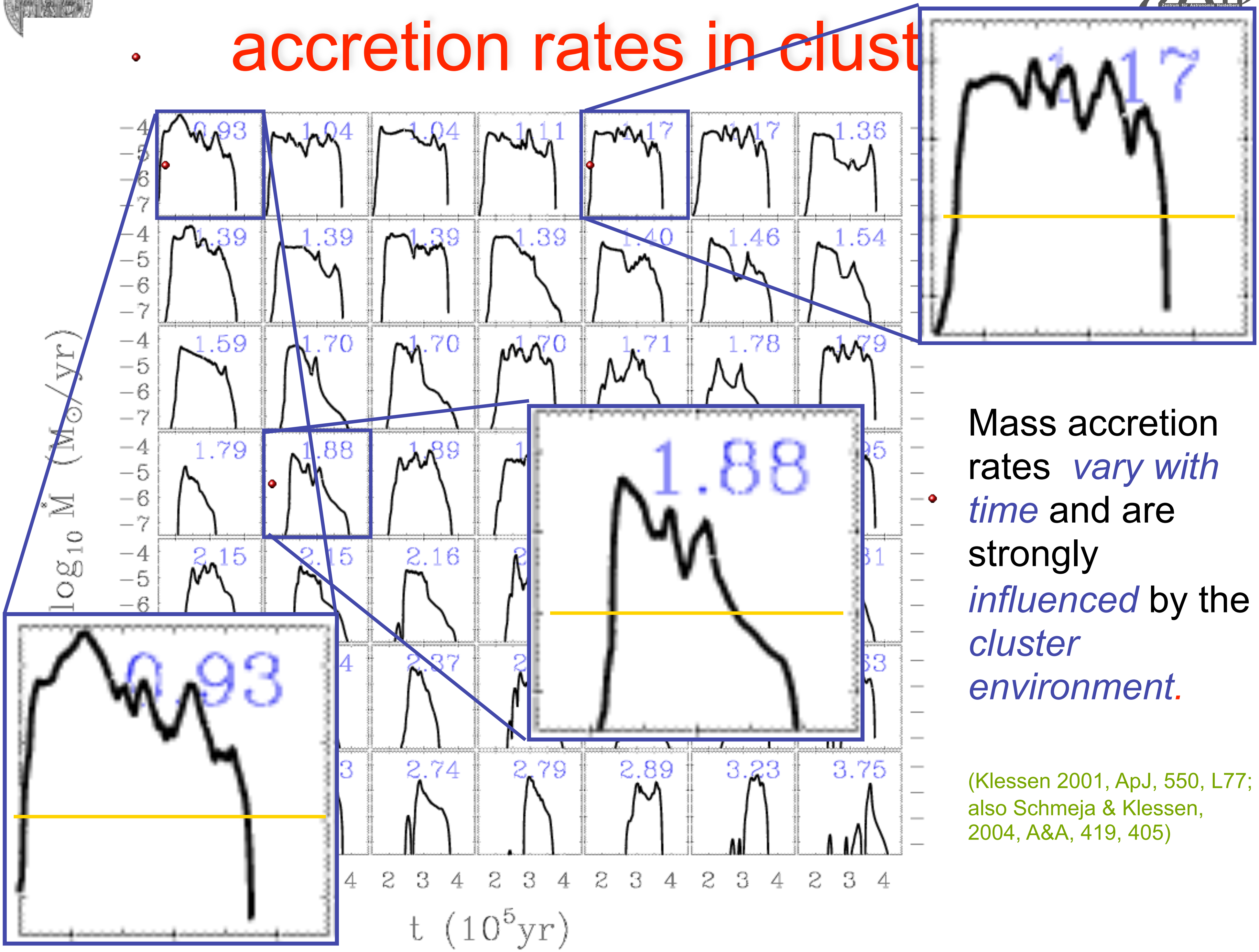
dynamics of nascent star cluster

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)

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 fuction

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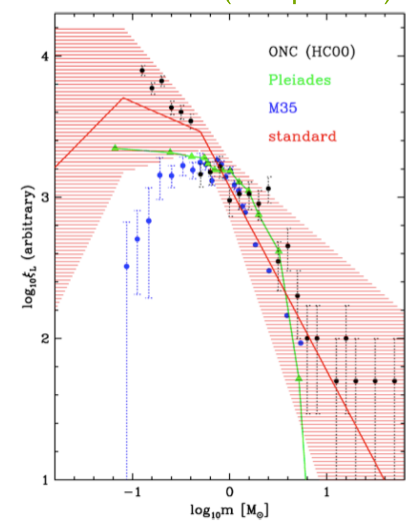

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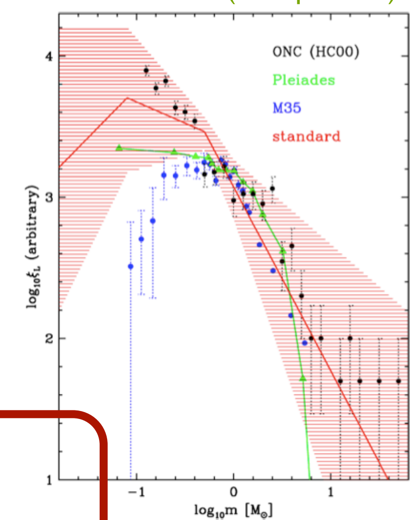


application to early star formation

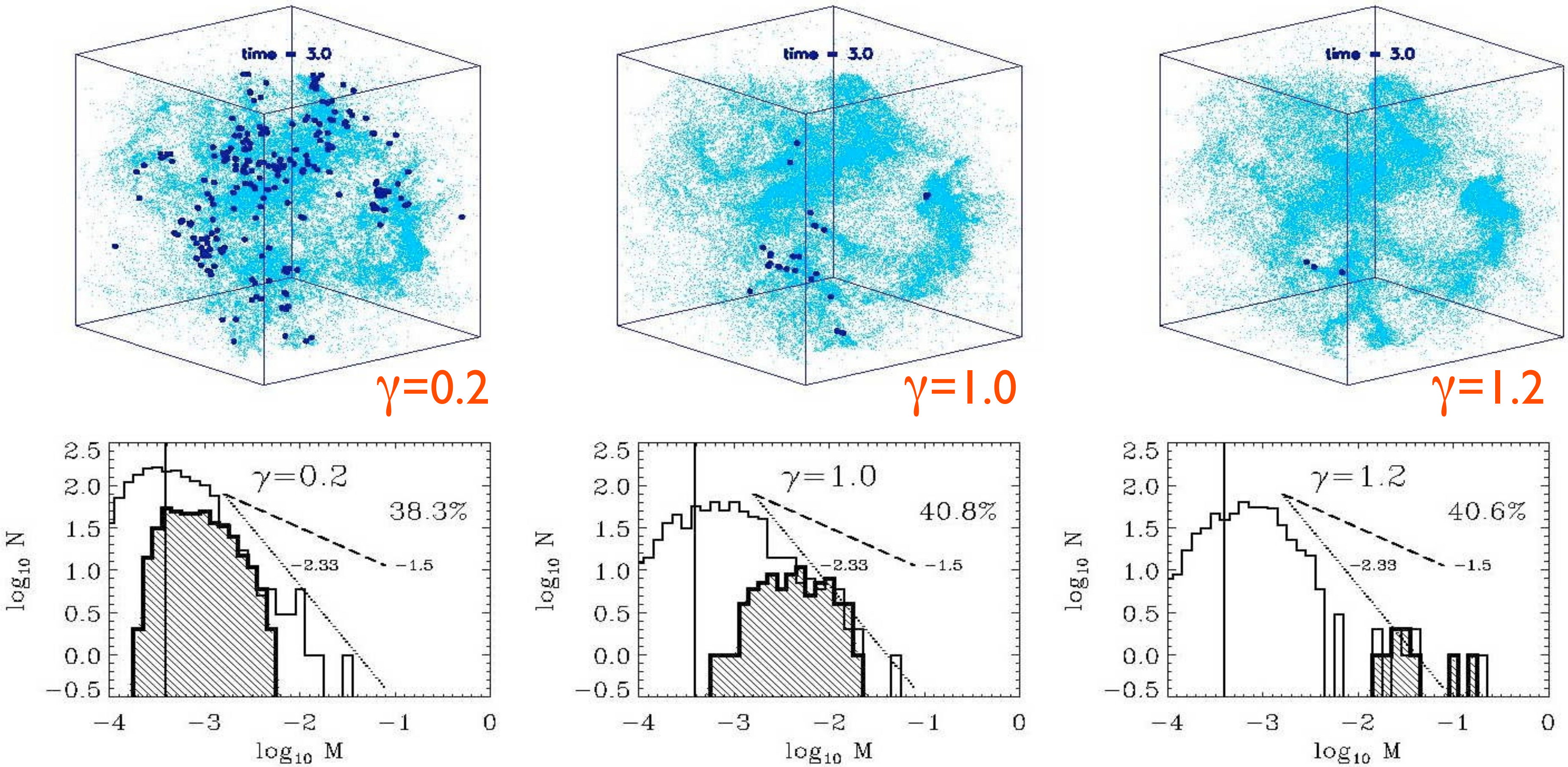
thermodynamics & fragmentation

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



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

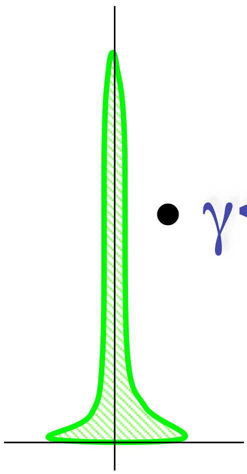
for $\gamma>1$ it is suppressed → *isolated massive stars*

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

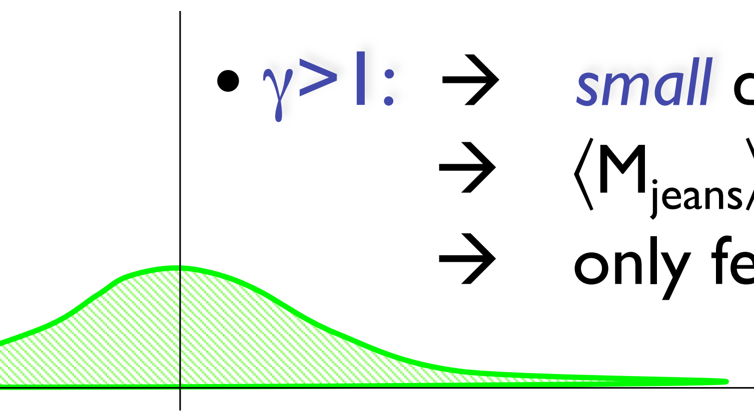
how does that work?

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

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

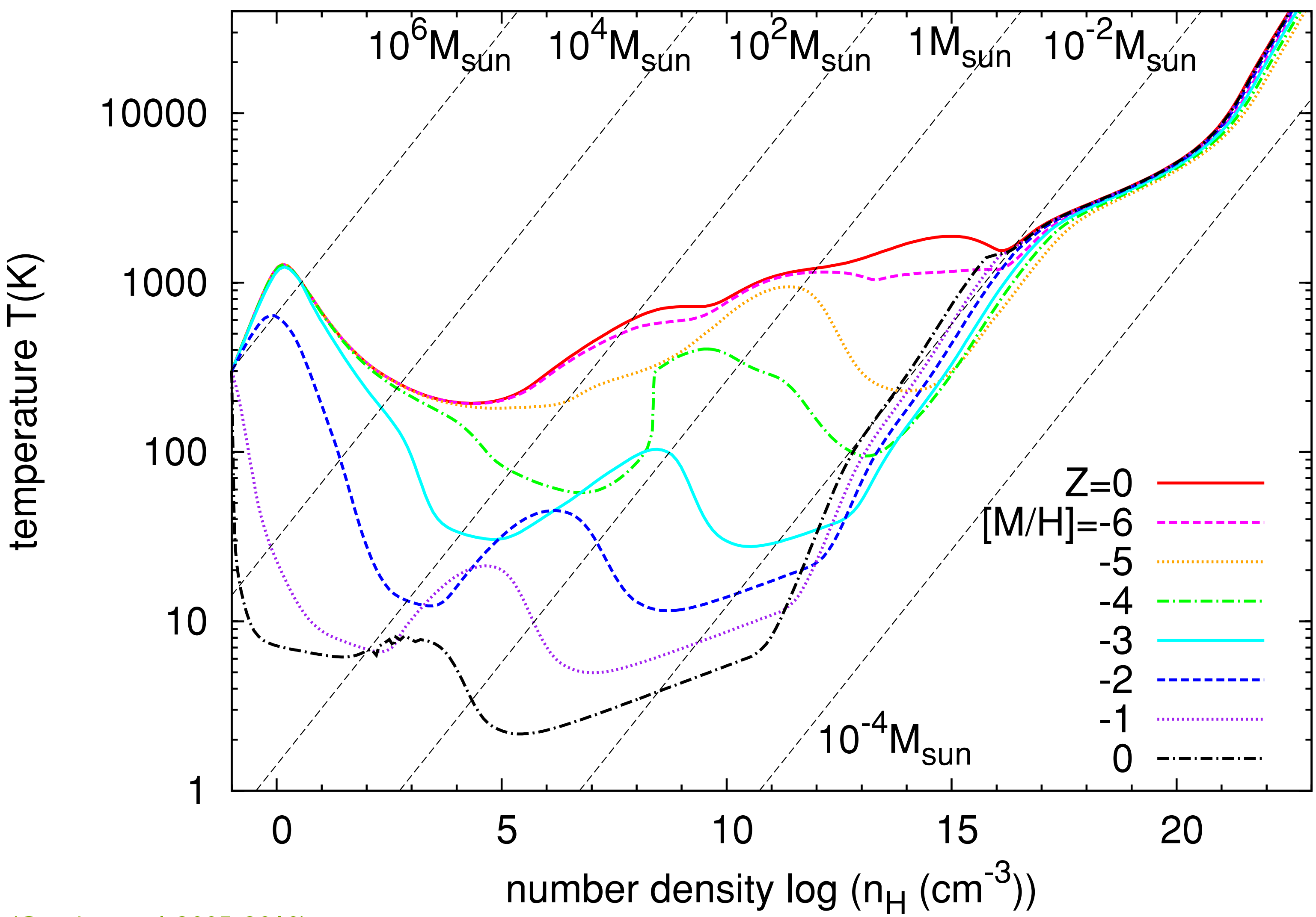


- $\gamma<1$: $\rightarrow$ *large* density excursion for given pressure
  $\rightarrow$ $\langle M_{jeans} \rangle$ becomes small
  $\rightarrow$ number of fluctuations with $M > M_{jeans}$ is large



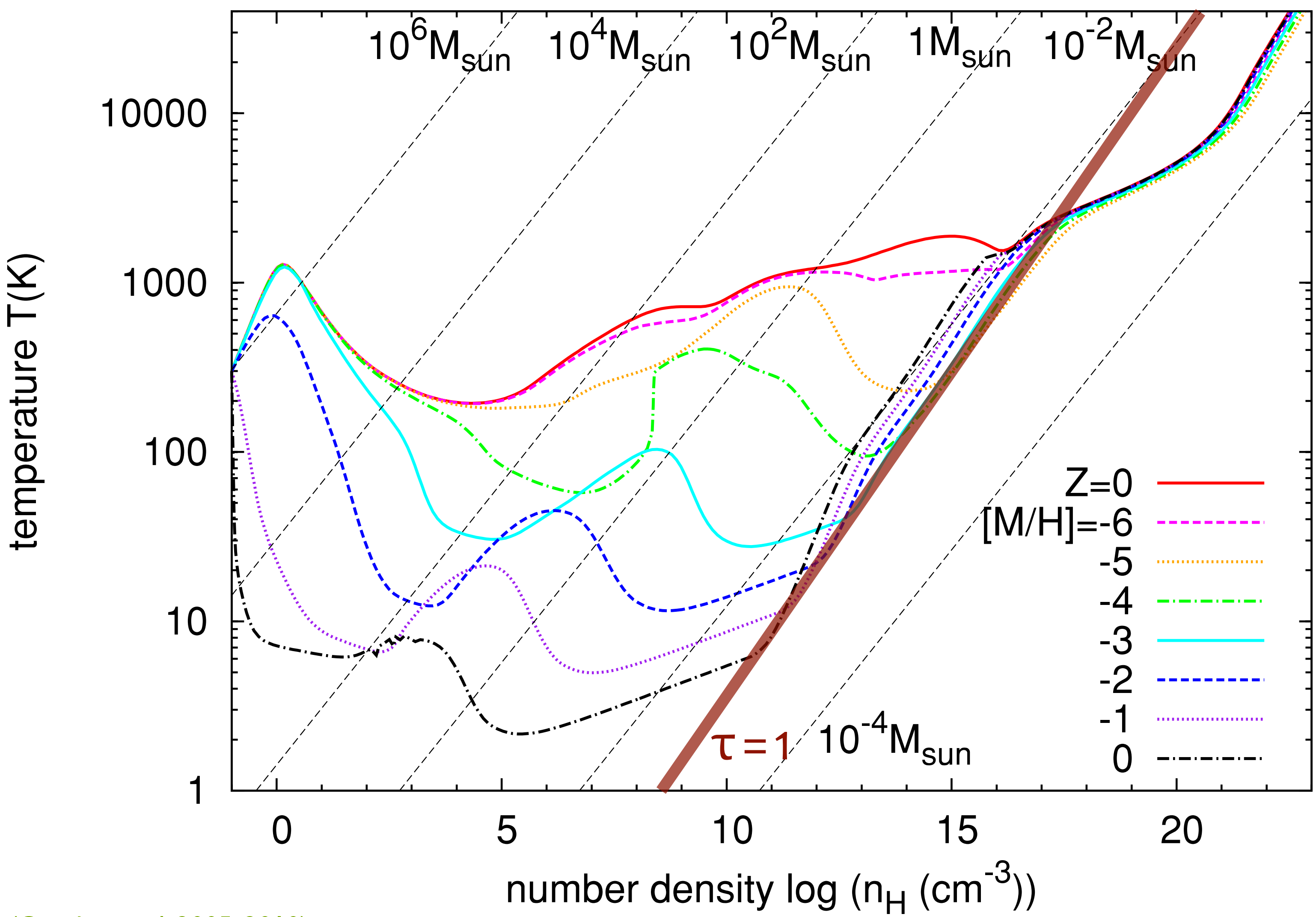
- $\gamma>1$: $\rightarrow$ *small* density excursion for given pressure
  $\rightarrow$ $\langle M_{jeans} \rangle$ is large
  $\rightarrow$ only few and massive clumps exceed M_{jeans}

EOS as function of metallicity



(Omukai et al. 2005, 2010)

EOS as function of metallicity



(Omukai et al. 2005, 2010)

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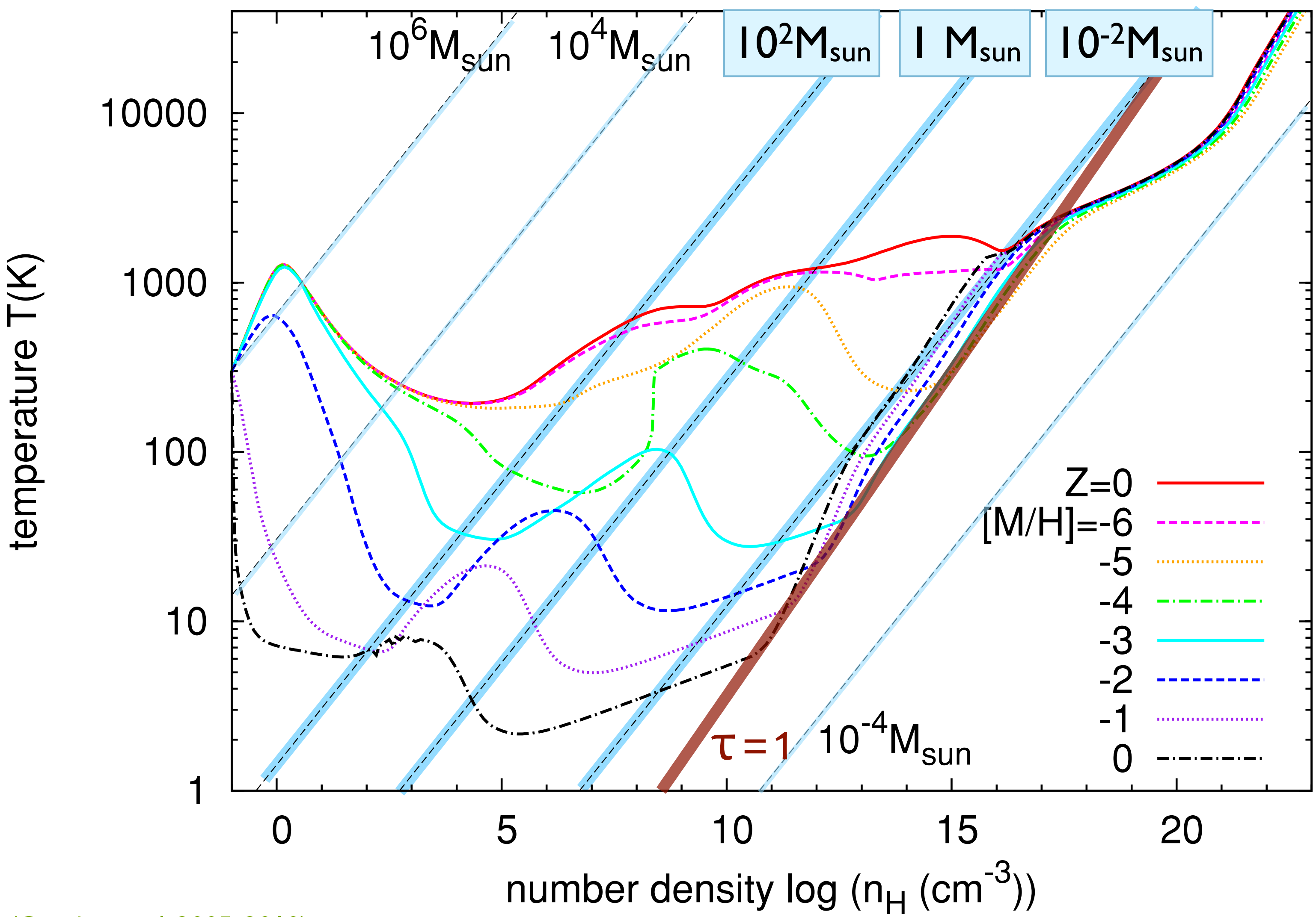
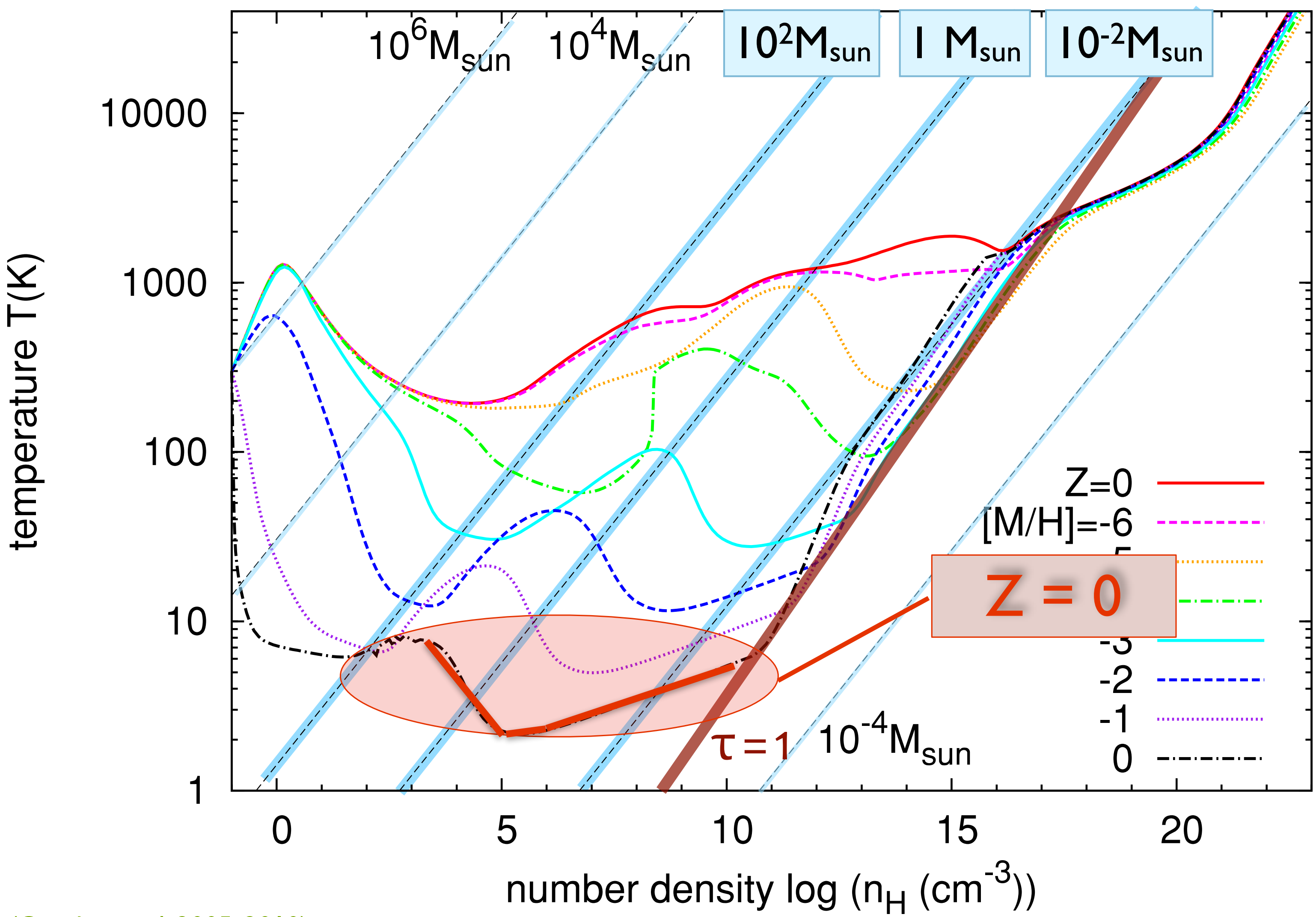


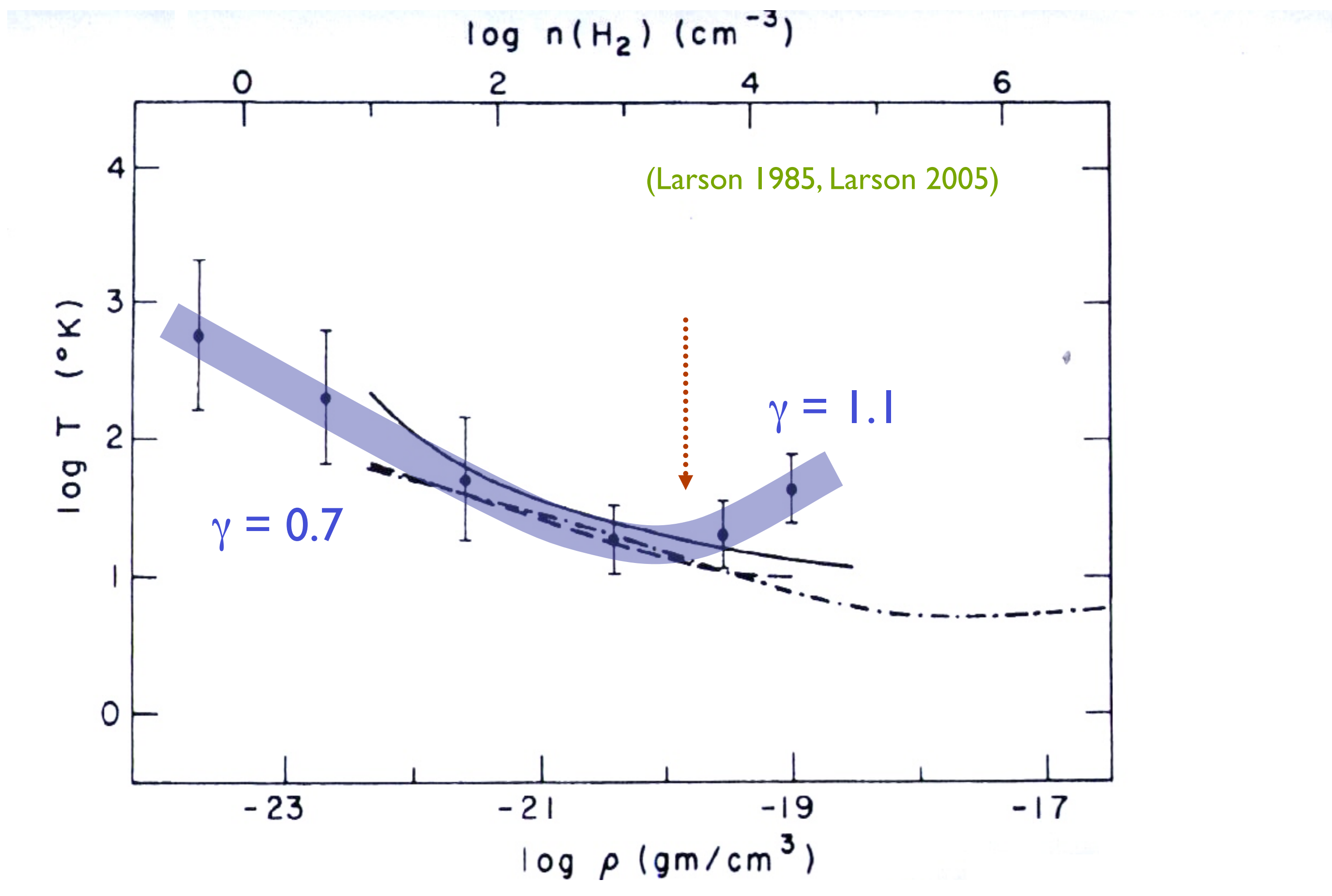
(Omukai et al. 2005, 2010)

EOS as function of metallicity

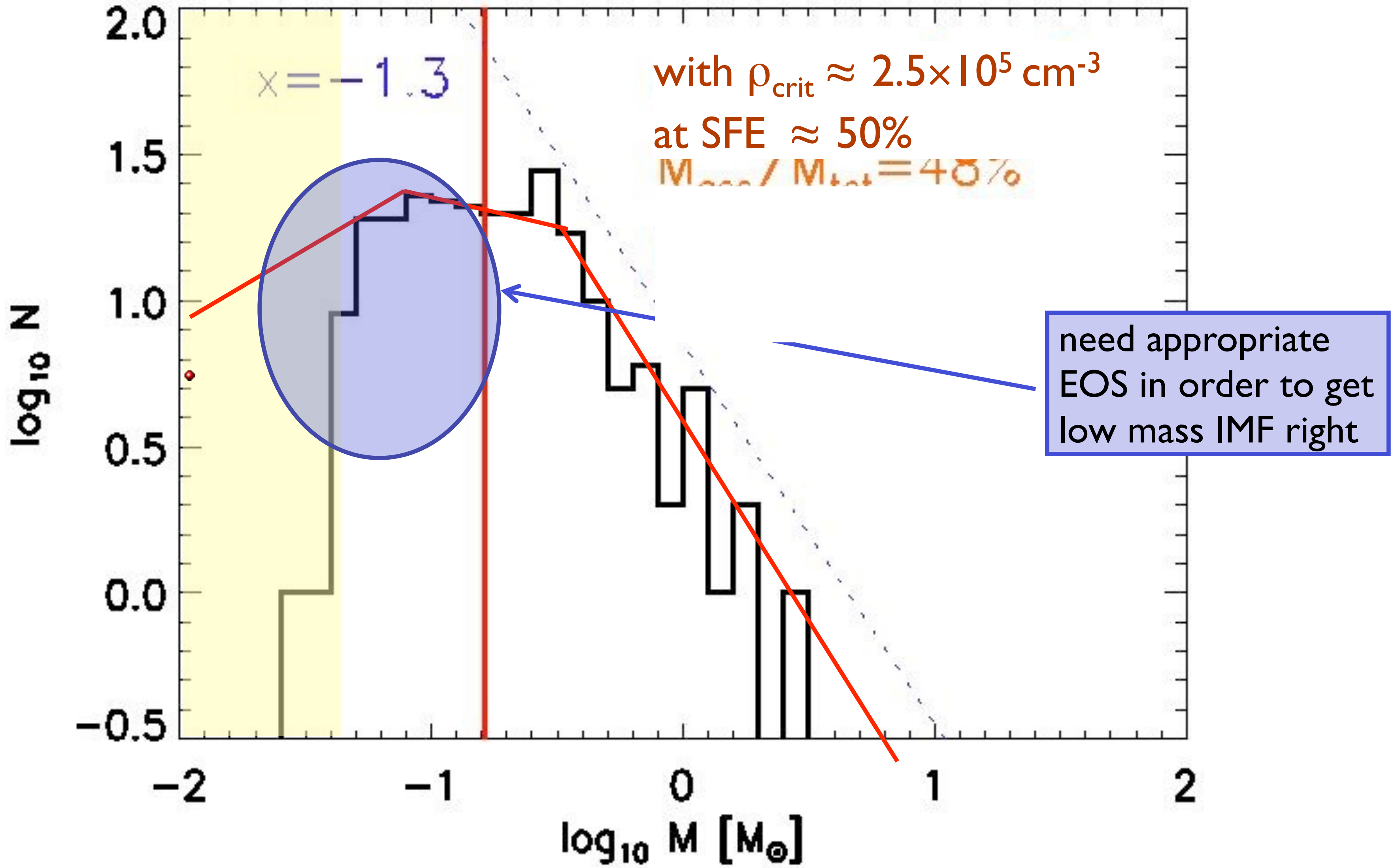


(Omukai et al. 2005, 2010)

present-day star formation

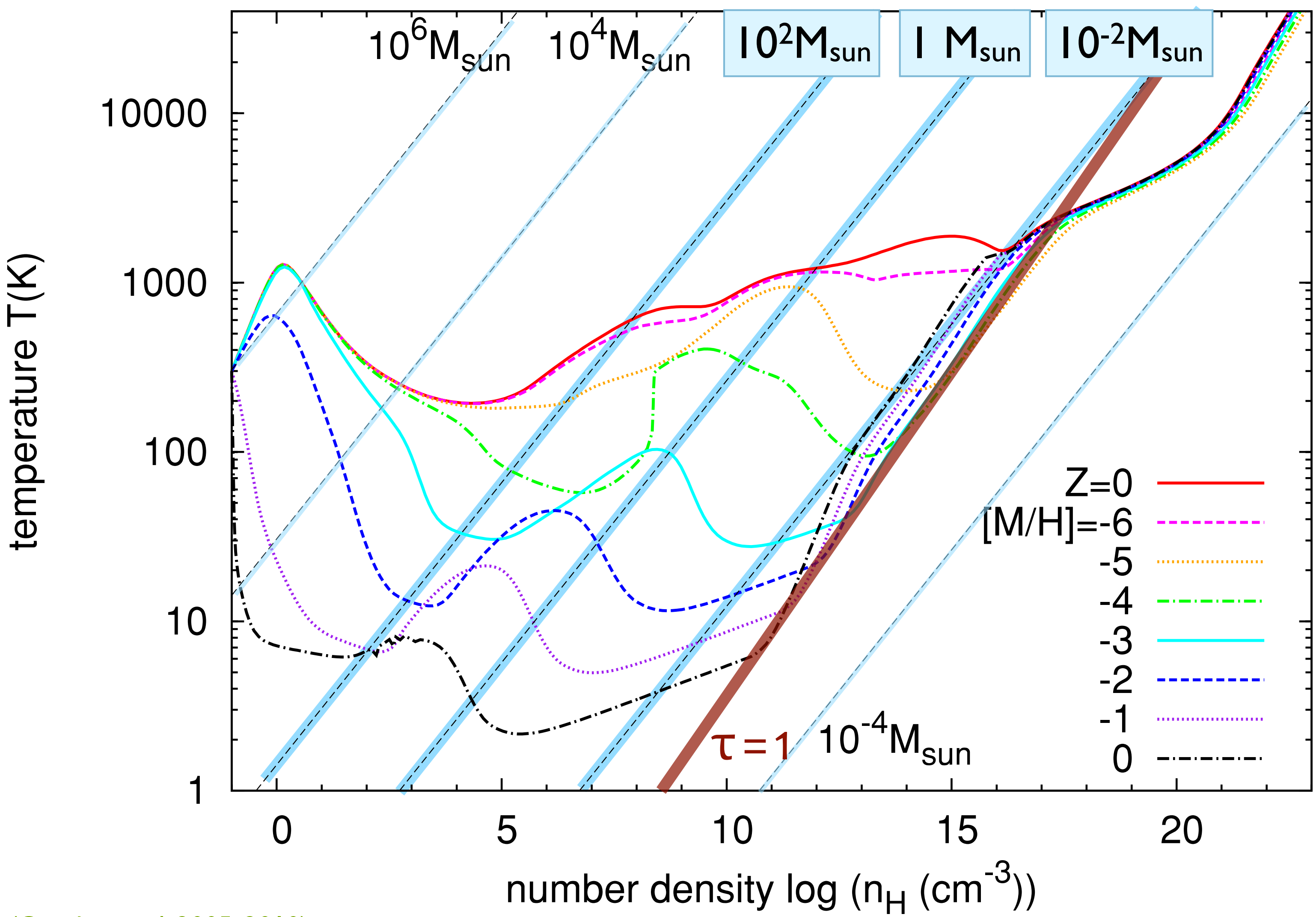


IMF in nearby molecular clouds



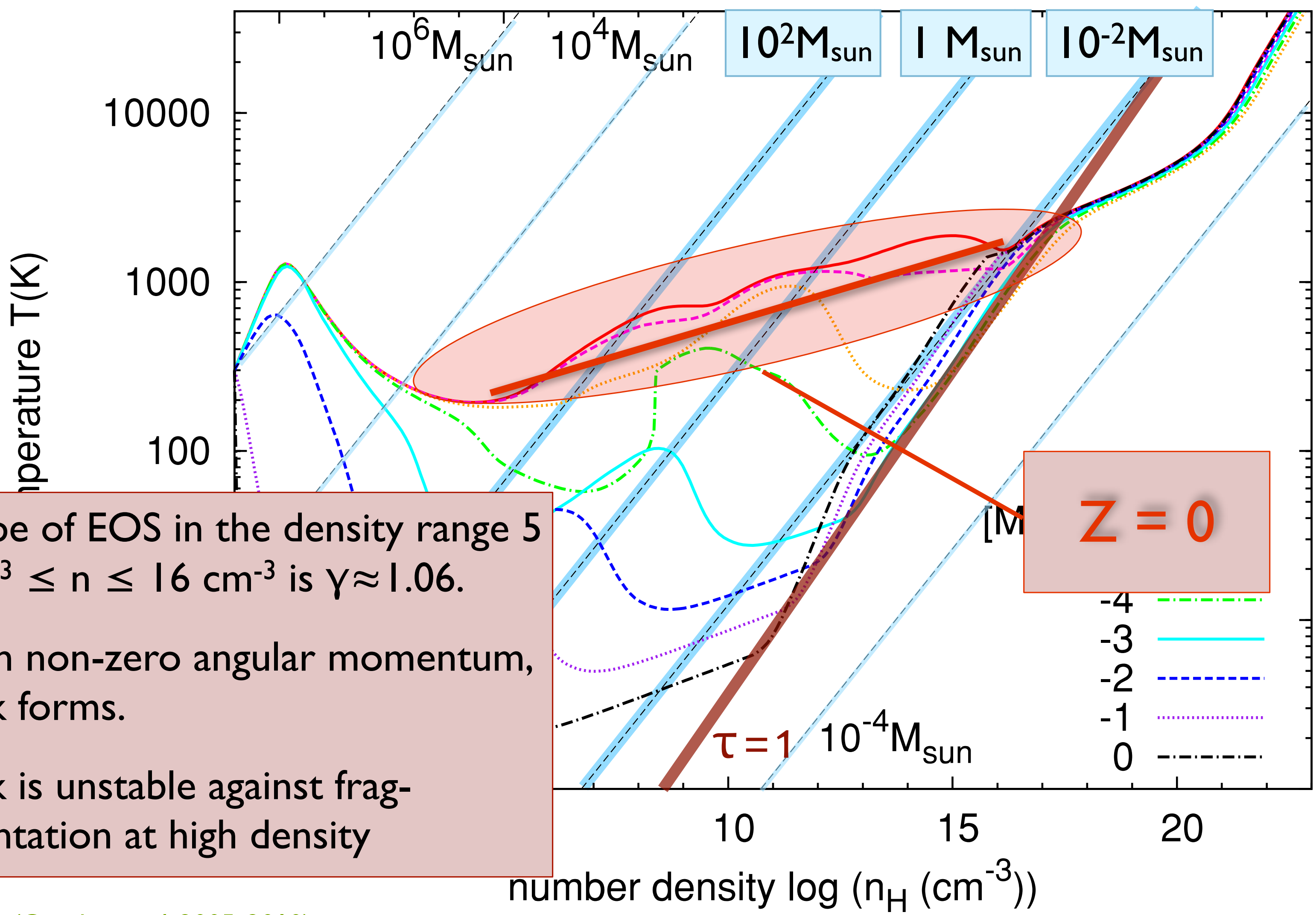
(Jappsen et al. 2005, A&A, 435, 611)

EOS as function of metallicity



(Omukai et al. 2005, 2010)

EOS as function of metallicity

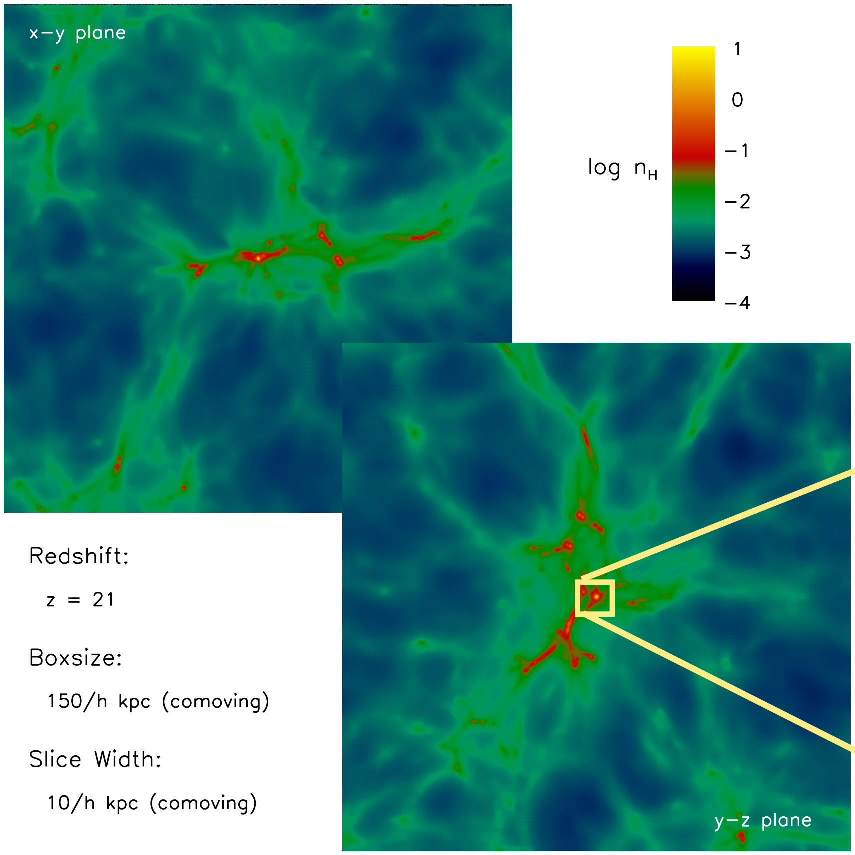


- slope of EOS in the density range 5 $cm^{-3} \leq n \leq 16\ cm^{-3}$ is $\gamma \approx 1.06$.
- with non-zero angular momentum, disk forms.
- disk is unstable against frag-mentation at high density

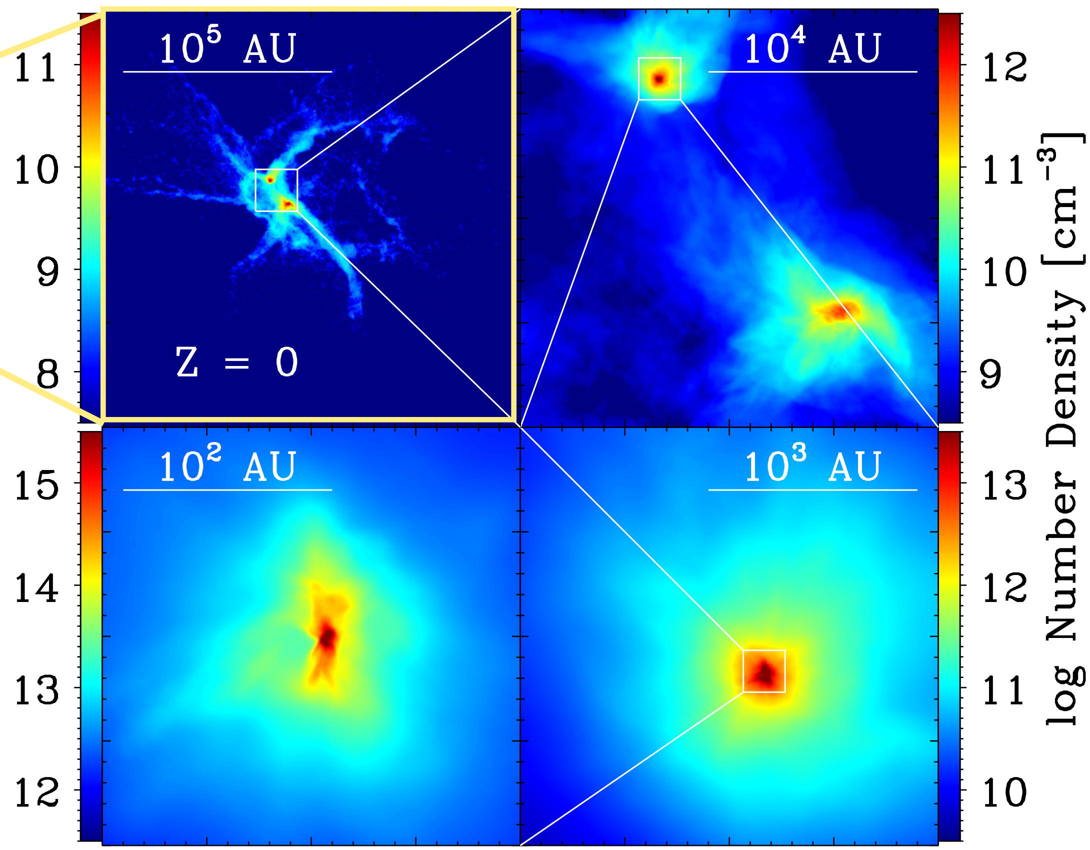
(Omukai et al. 2005, 2010)

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, arXiv1203.6842)

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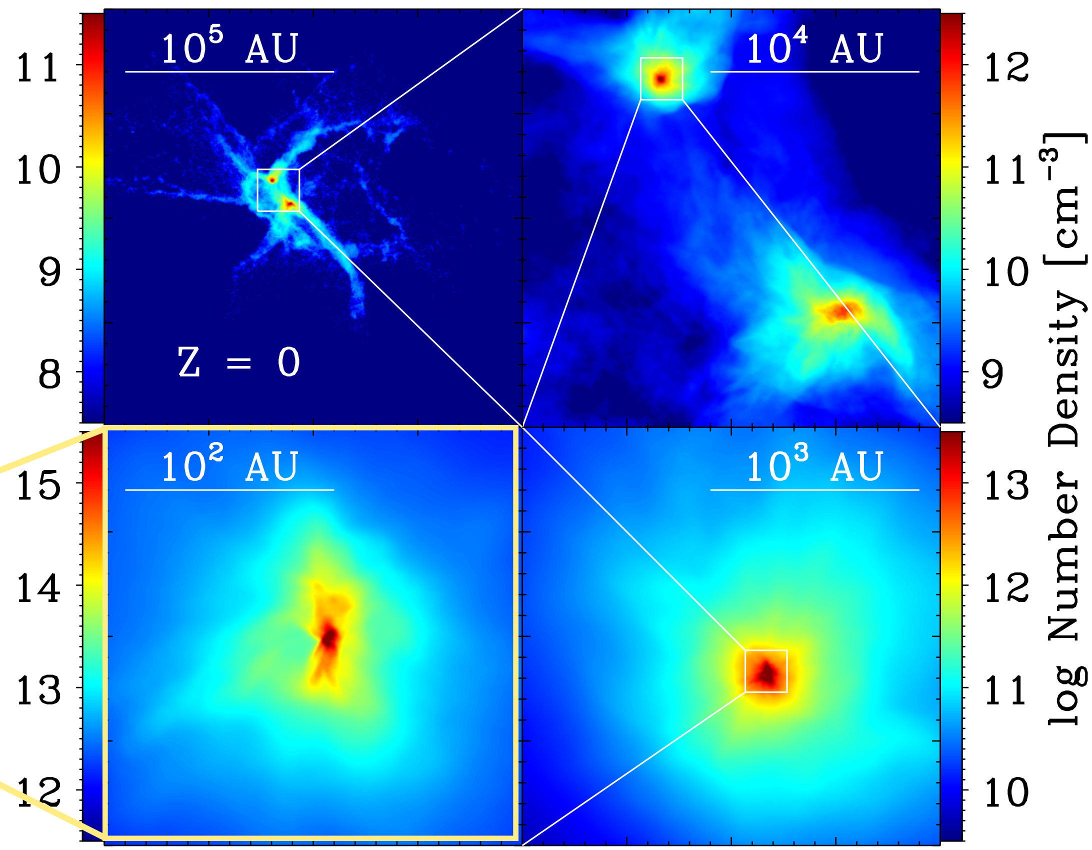
successive zoom-in calculation from cosmological initial conditions (using SPH and new grid-code AREPO)

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



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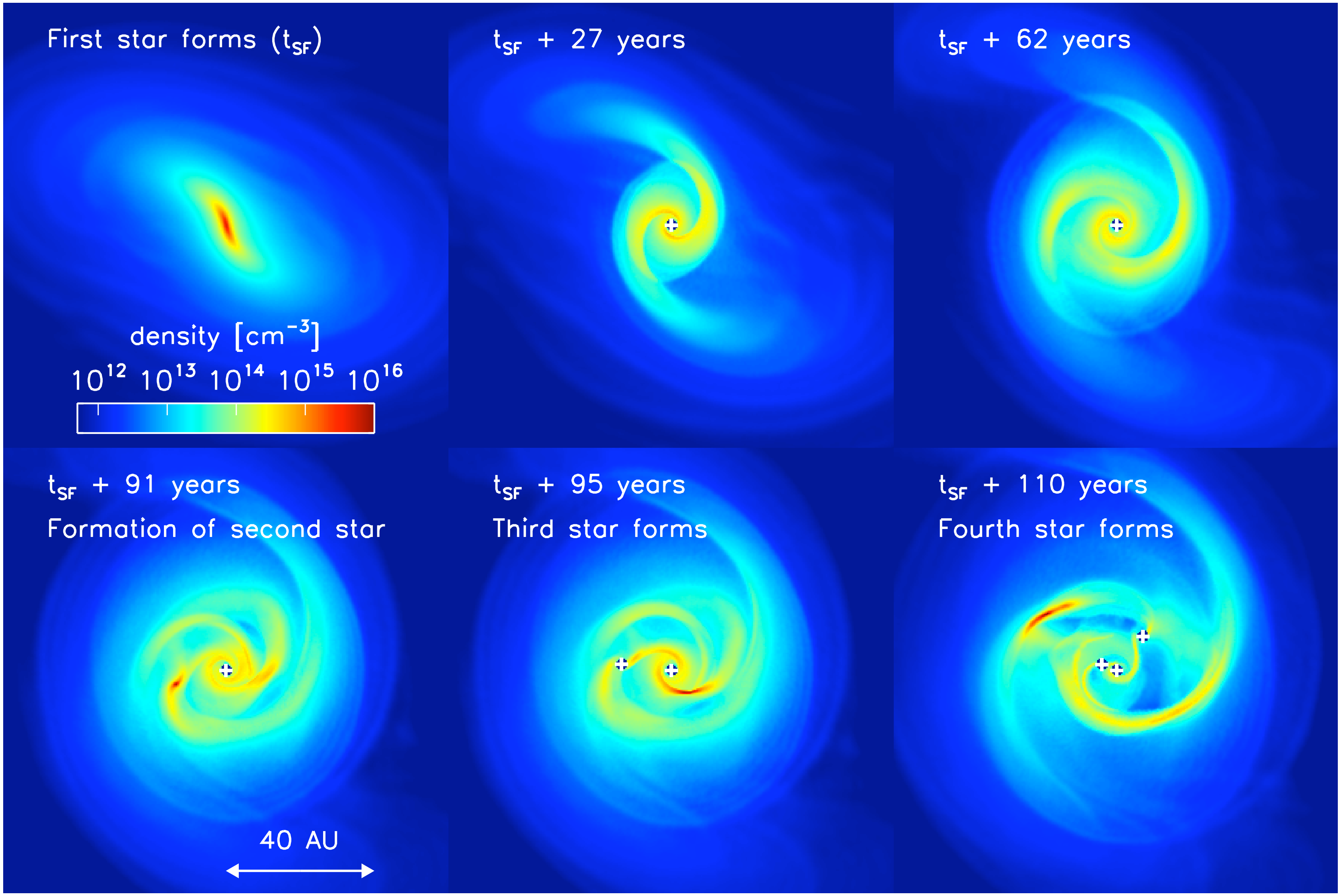
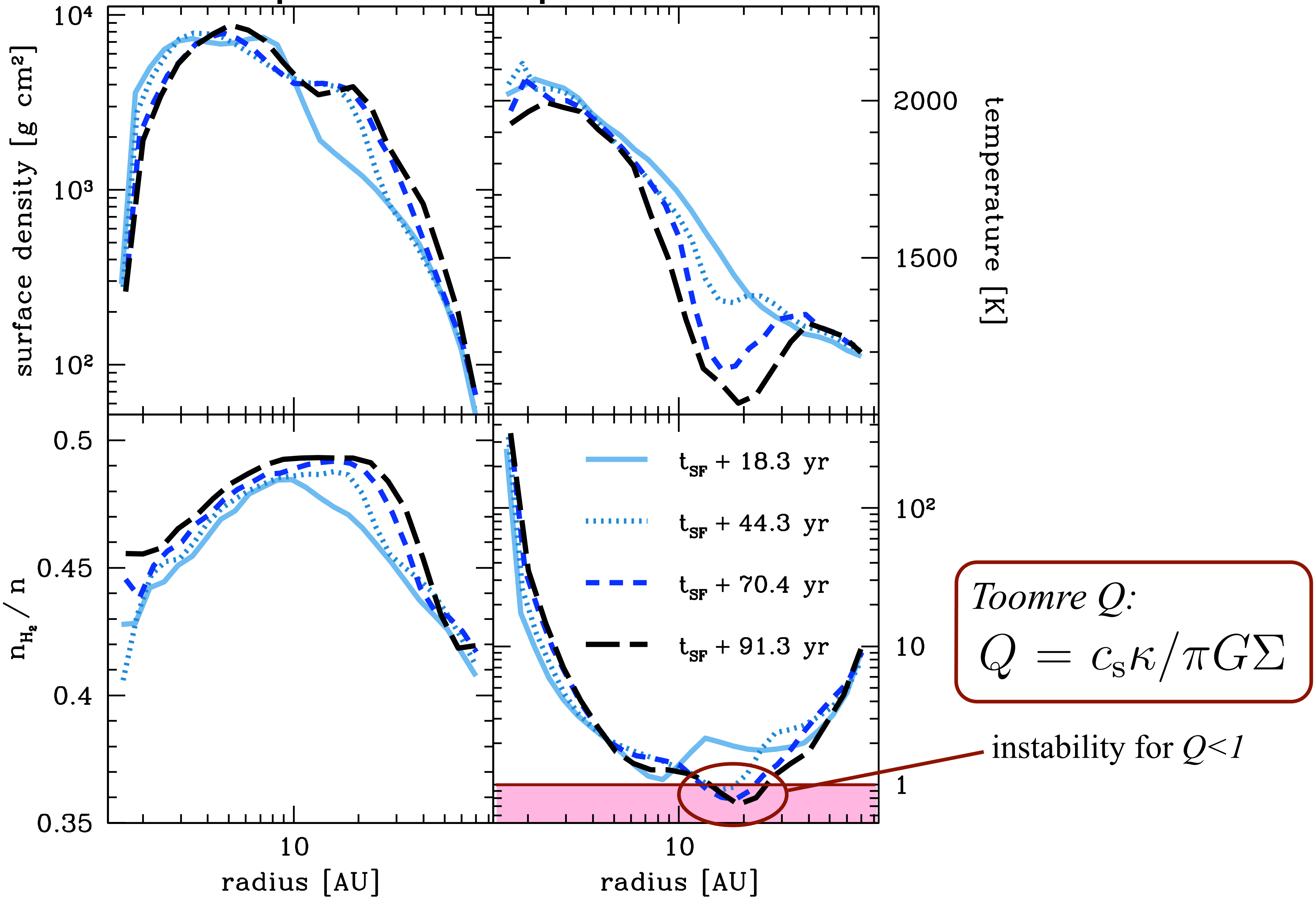


detailed look at accretion disk

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.

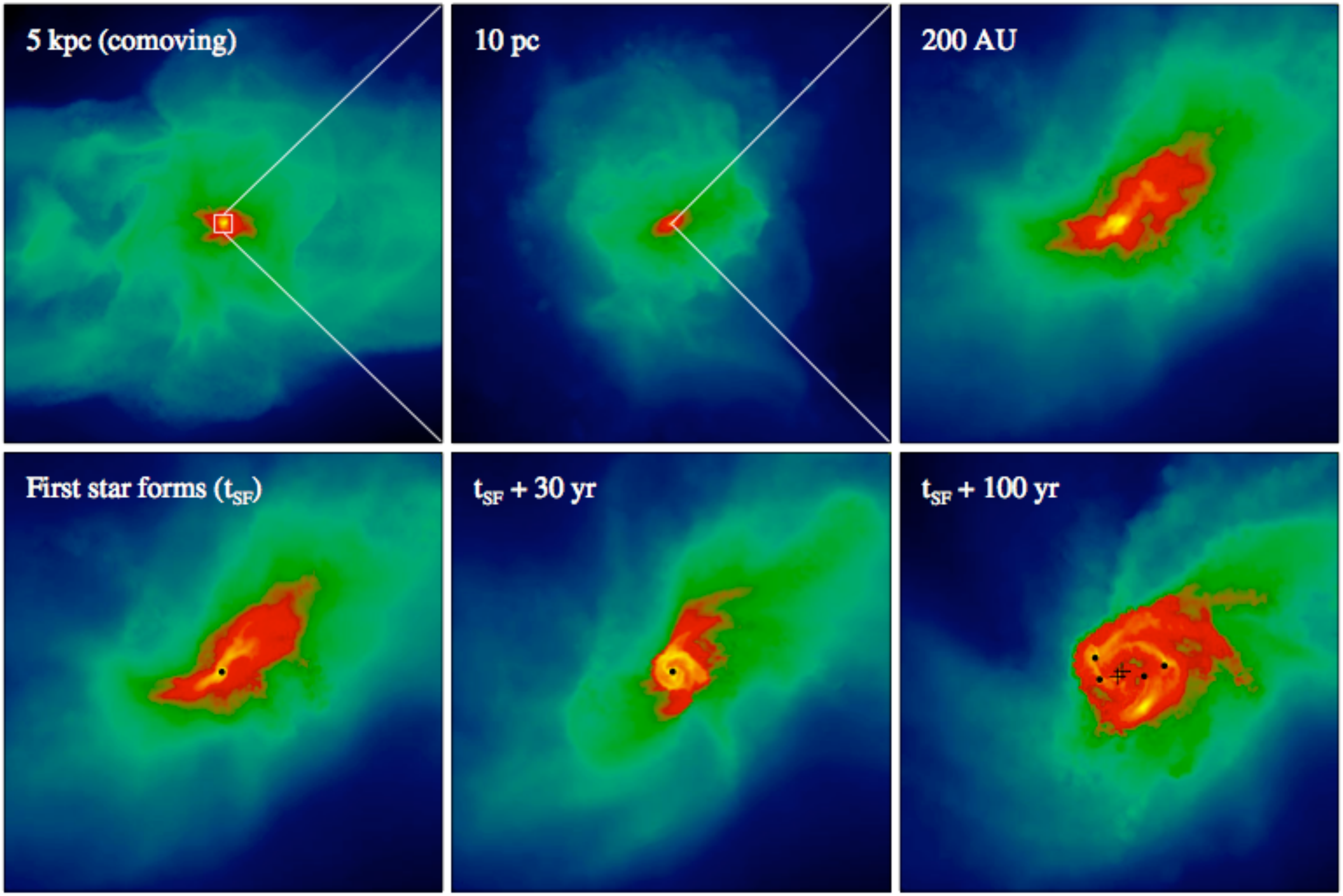
(Clark et al. 2011b, Science, 331, 1040)

important disk parameters



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

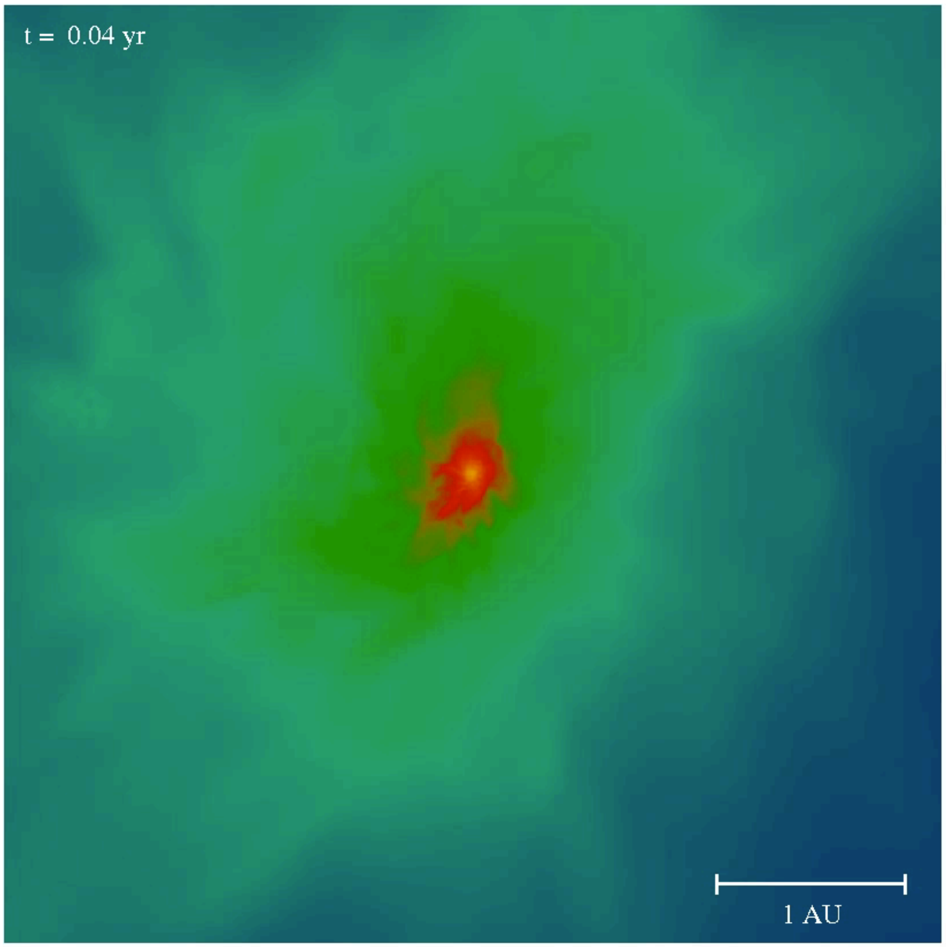
similar study with very different numerical method (AREPO)



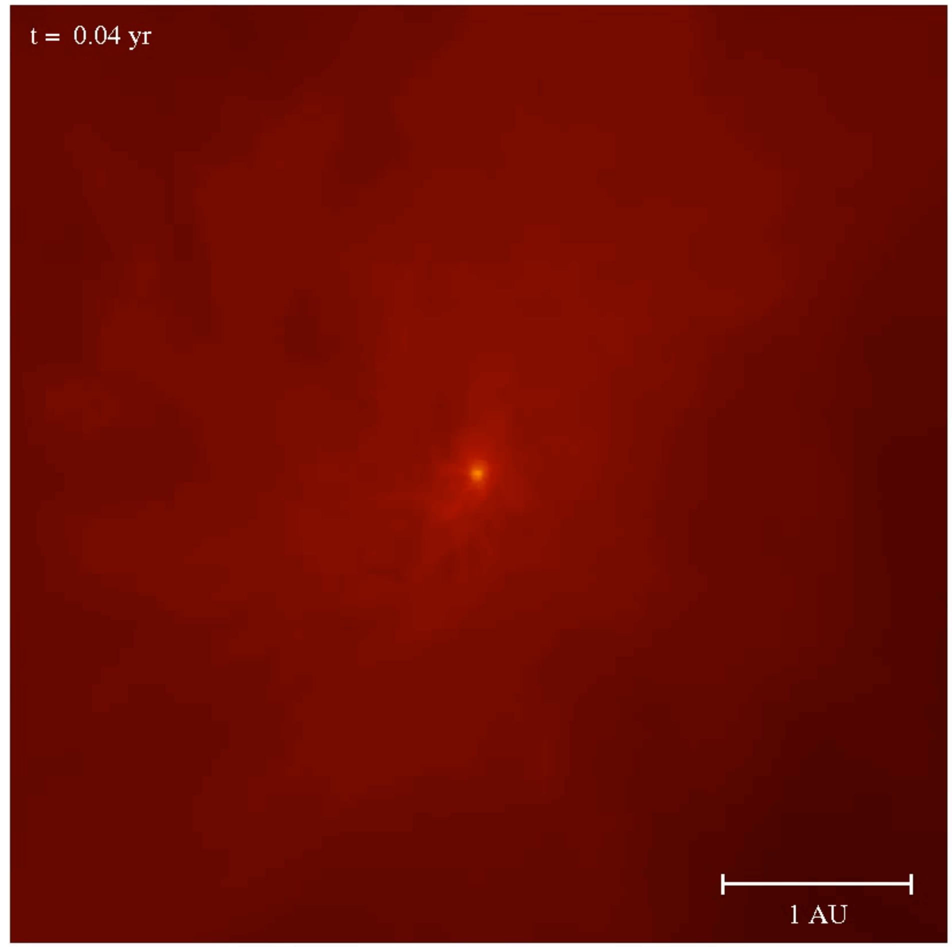
one out of five halos

(Greif et al. 2011a, ApJ)

Most recent calculations:
fully sink-less simulations, following the disk build-up over ~10 years (resolving the protostars - first cores - down to 10^5 km ~ 0.01 $R_\odot$)



density

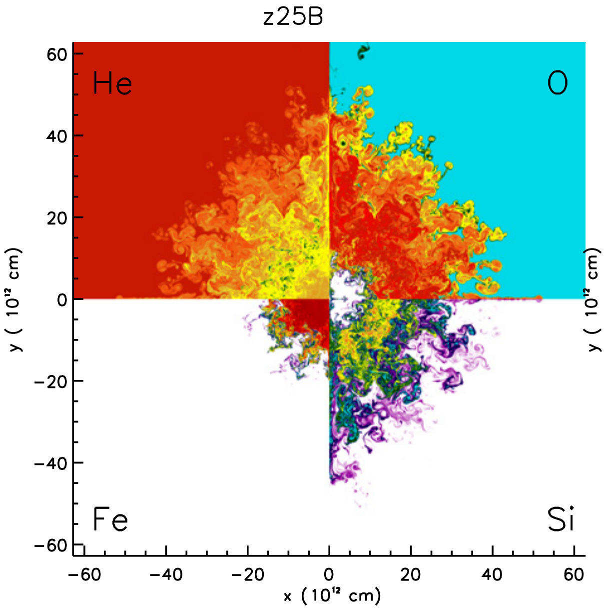


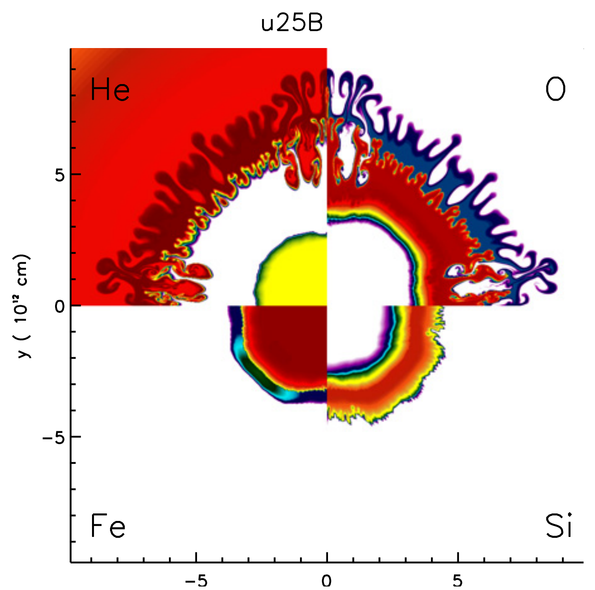
temperature

(Greif et al., 2012, MNRAS, 424, 399)

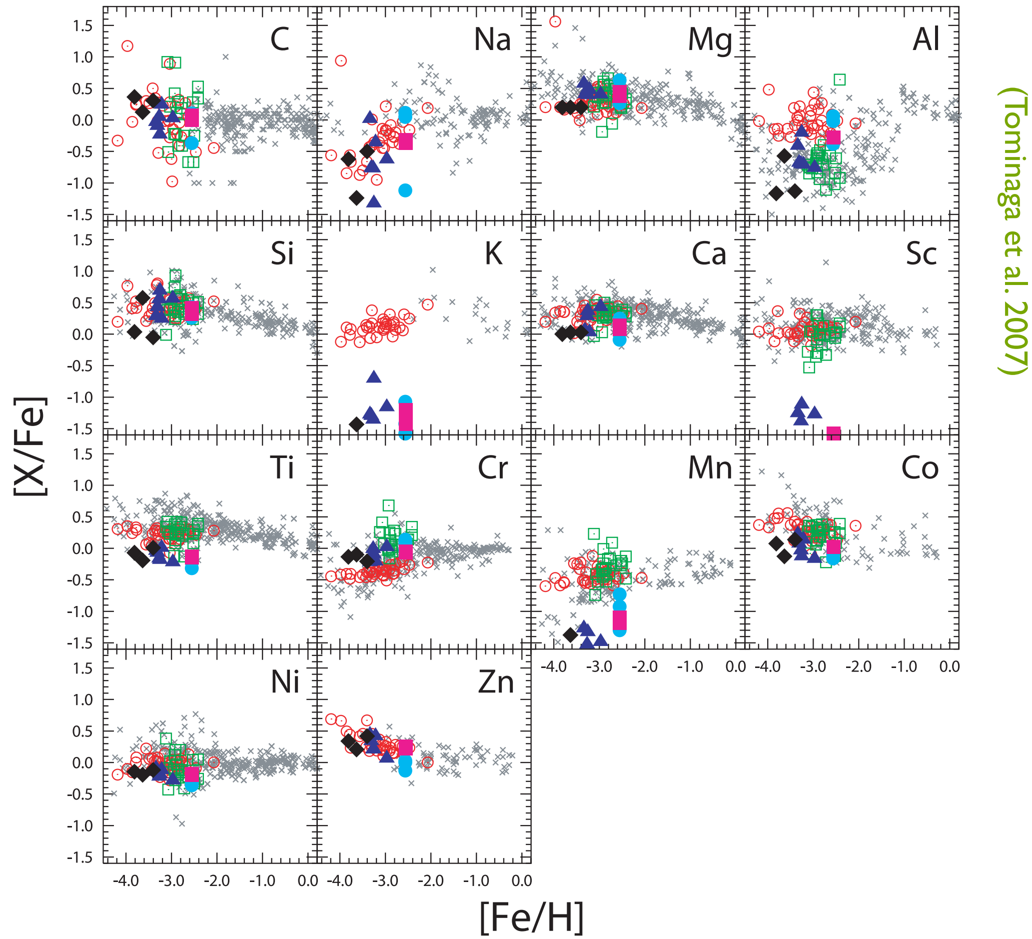
expected mass spectrum

- *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)

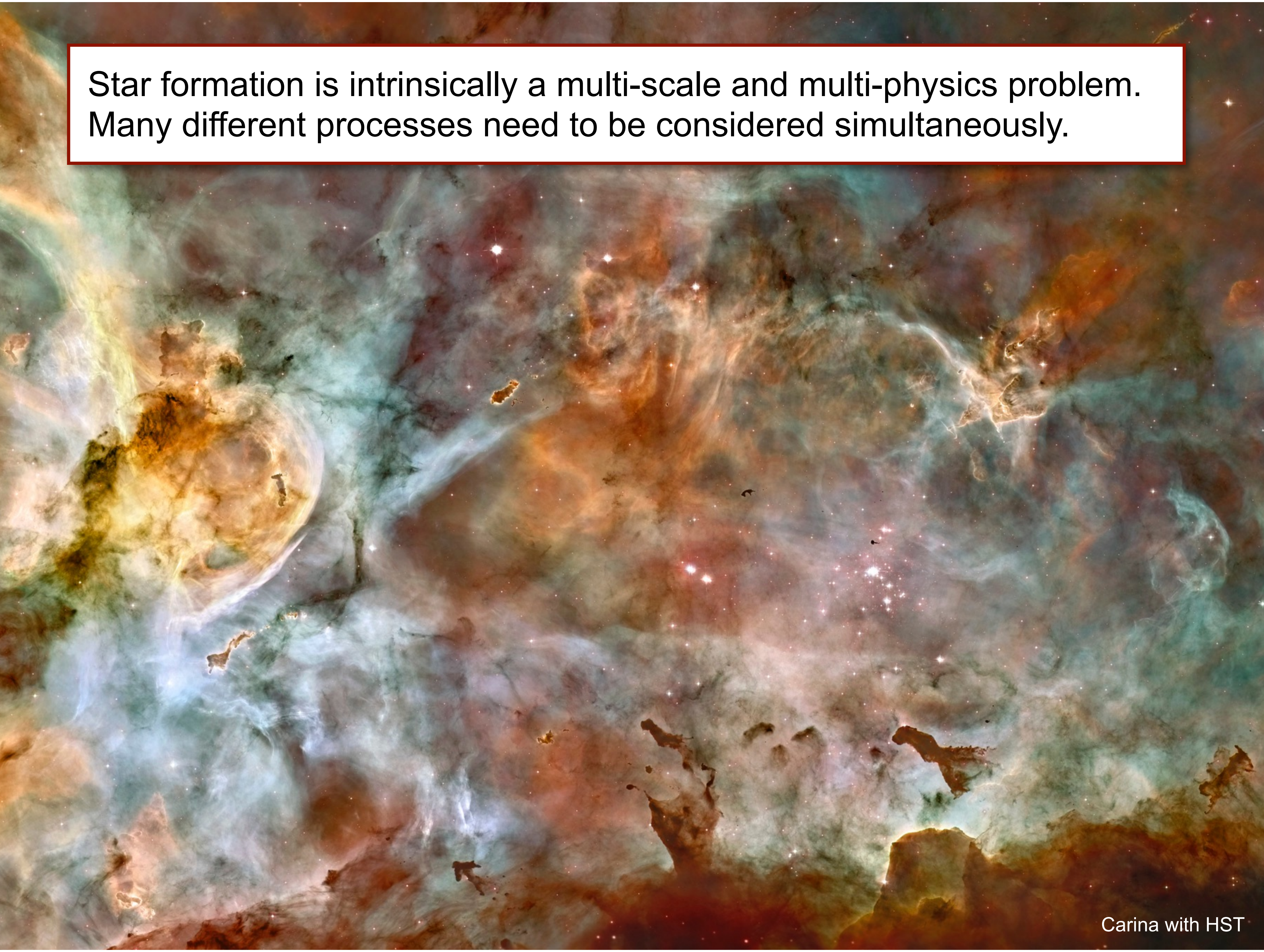


The metallicities of extremely metal-poor stars in the halo are consistent with the yields of core-collapse supernovae, i.e. progenitor stars with 20 - 40 $M_\odot$

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


Carina with HST

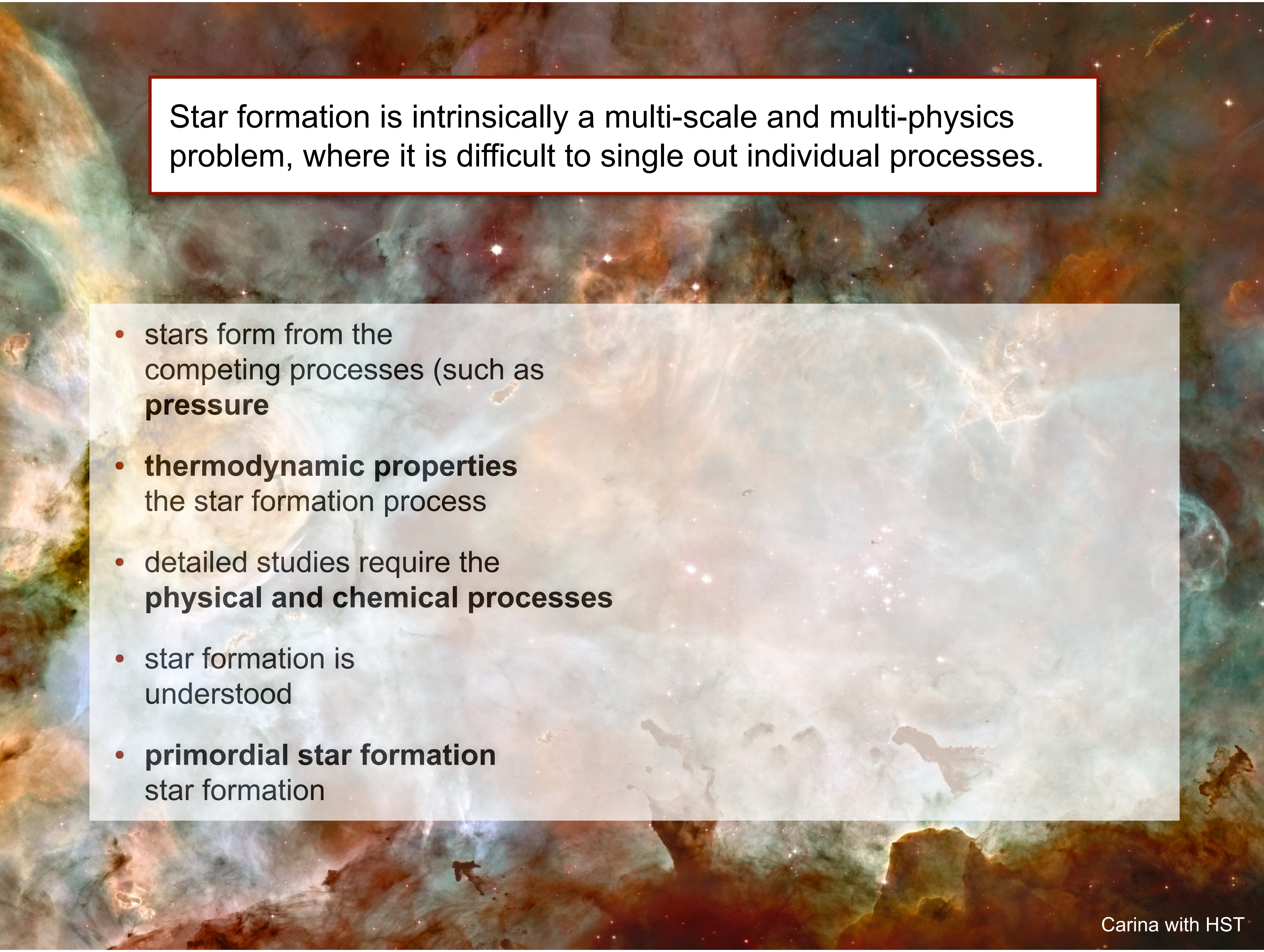
Star formation is intrinsically a multi-scale and multi-physics problem. Many different processes need to be considered simultaneously.



Carina with HST

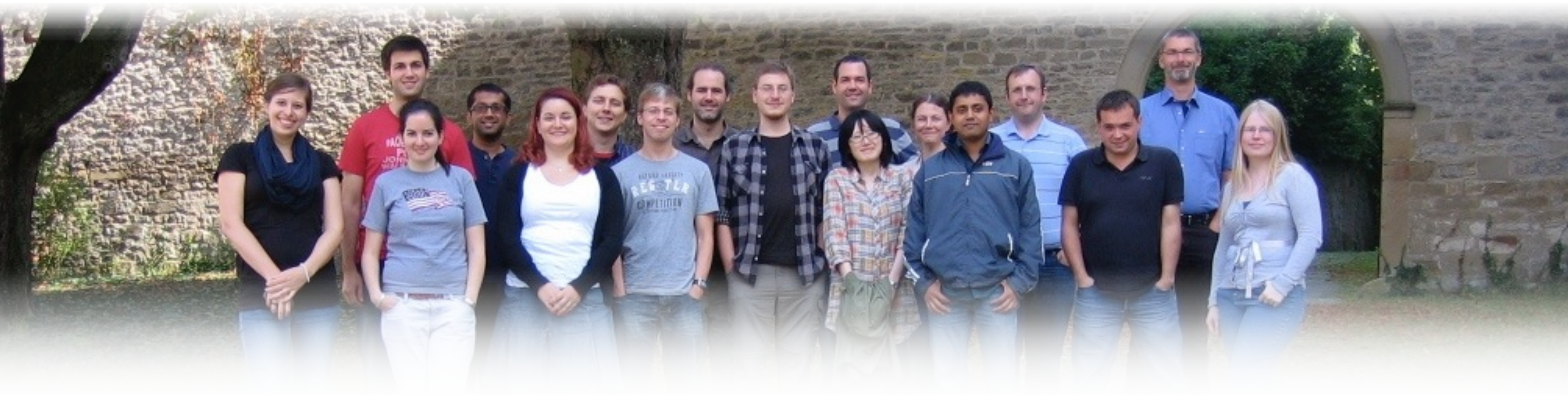
Star formation is intrinsically a multi-scale and multi-physics problem, where it is difficult to single out individual processes.

- stars form from the competing processes (such as **pressure**
- **thermodynamic properties** the star formation process
- detailed studies require the **physical and chemical processes**
- star formation is understood
- **primordial star formation** star formation



Carina with HST

thanks to ...



... people in the star formation group at Heidelberg University:

Christian Baczynski, Erik Bertram, Frank Bigiel, Andre Bubel, Diane Cormier, Volker Gaibler, Simon Glover, Dimitrious Gouliermis, Tilman Hartwig, Juan Ibanez, Christoph Klein, Lukas Konstandin, Mei Sasaki, Jennifer Schober, Rahul Shetty, Rowan Smith, László Szűcs

... former group members:

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

... many collaborators abroad!

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BADEN-WÜRTTEMBERG STIFTUNG Wir stiften Zukunft
HGSFP
IMPRS
erc European Research Council

thanks