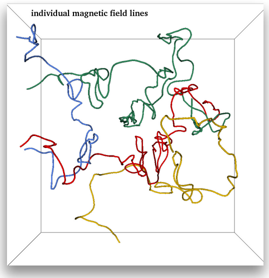
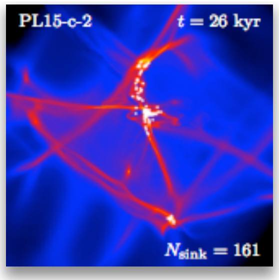
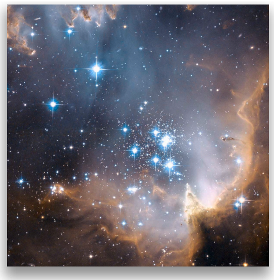
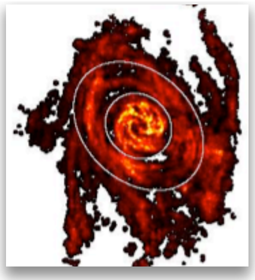
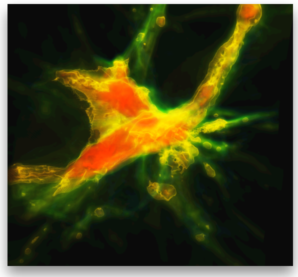
Star Formation



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thanks to ...

... people in the group in Heidelberg:

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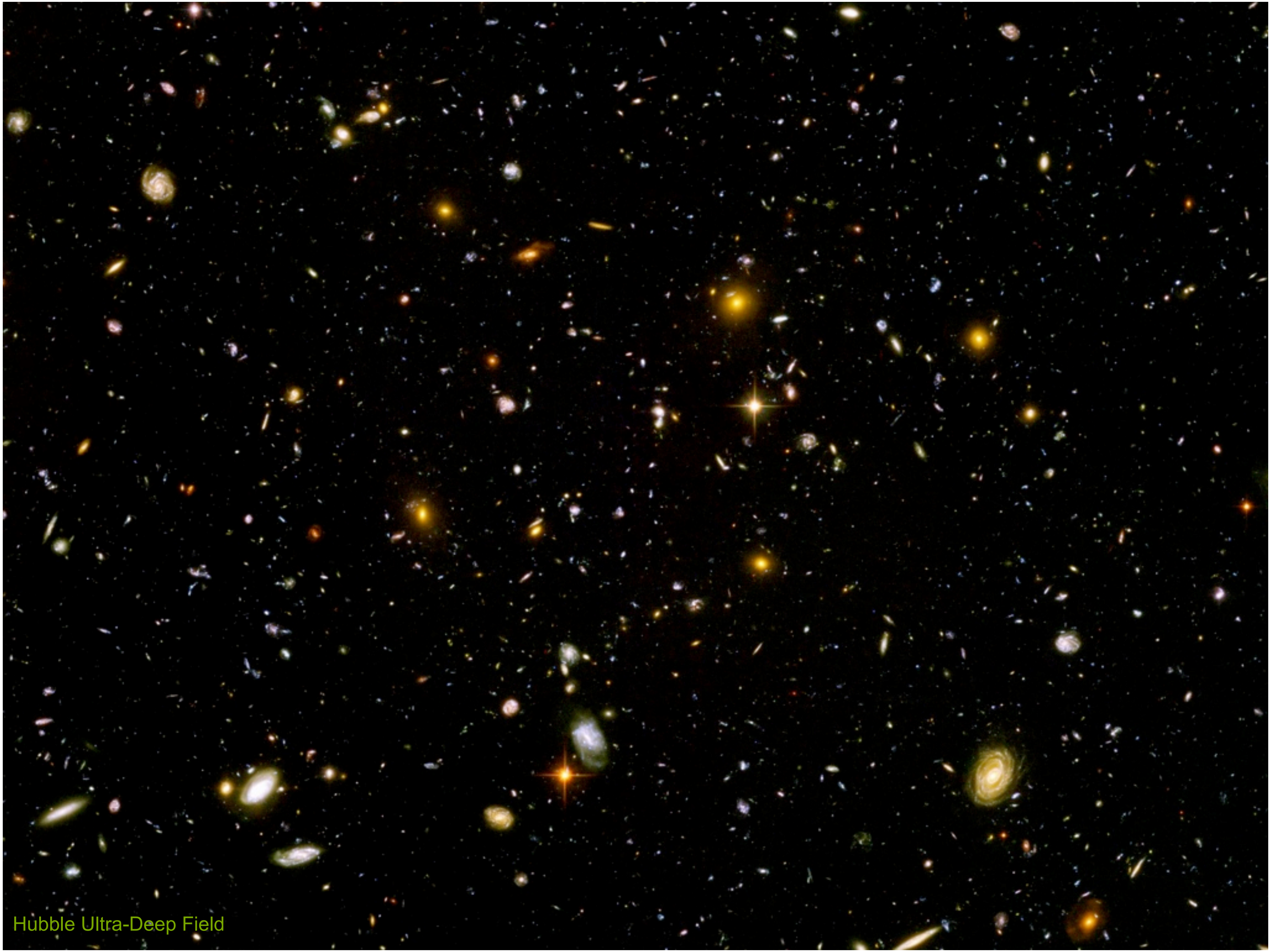
IMPRS

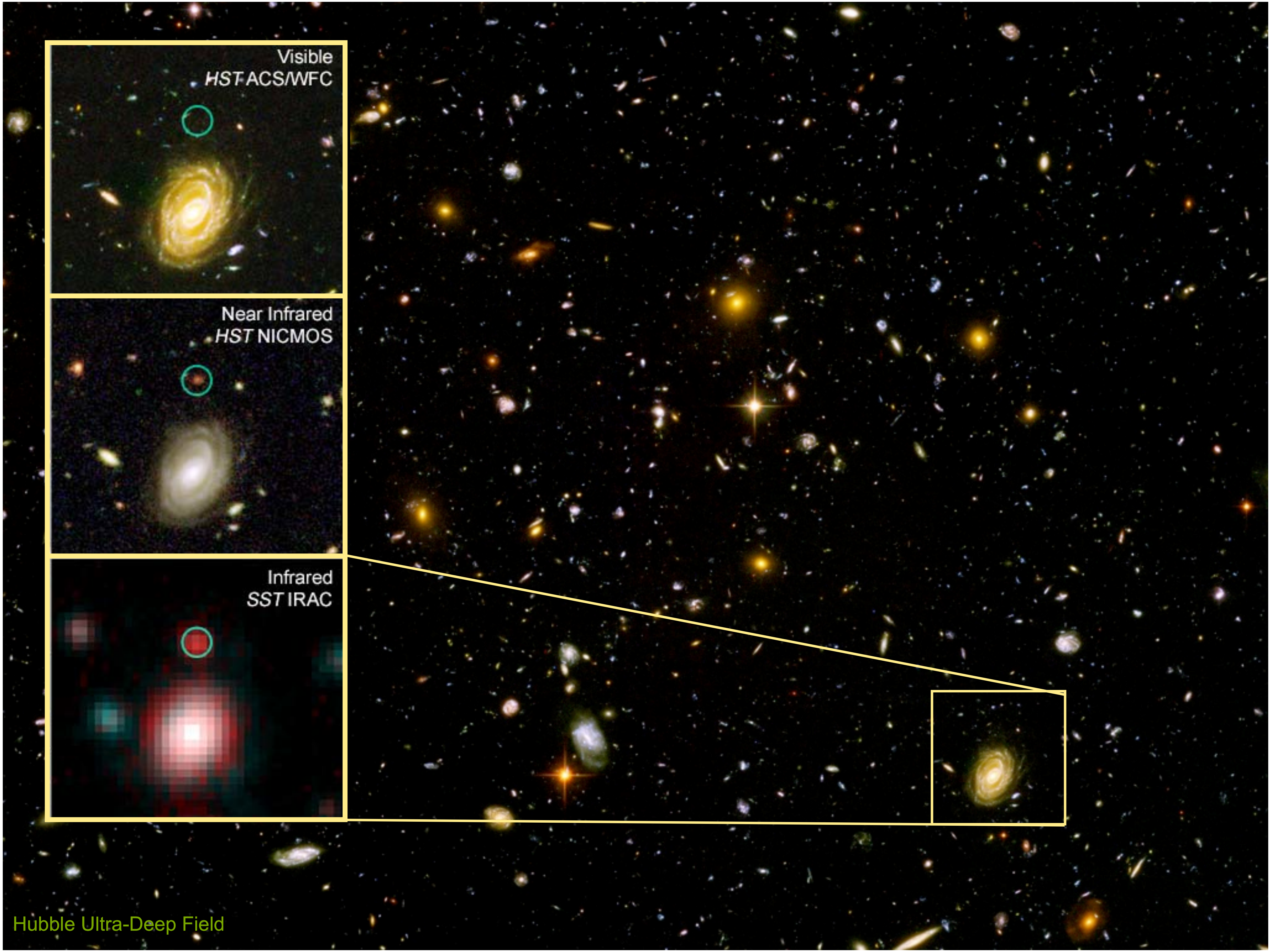
agenda

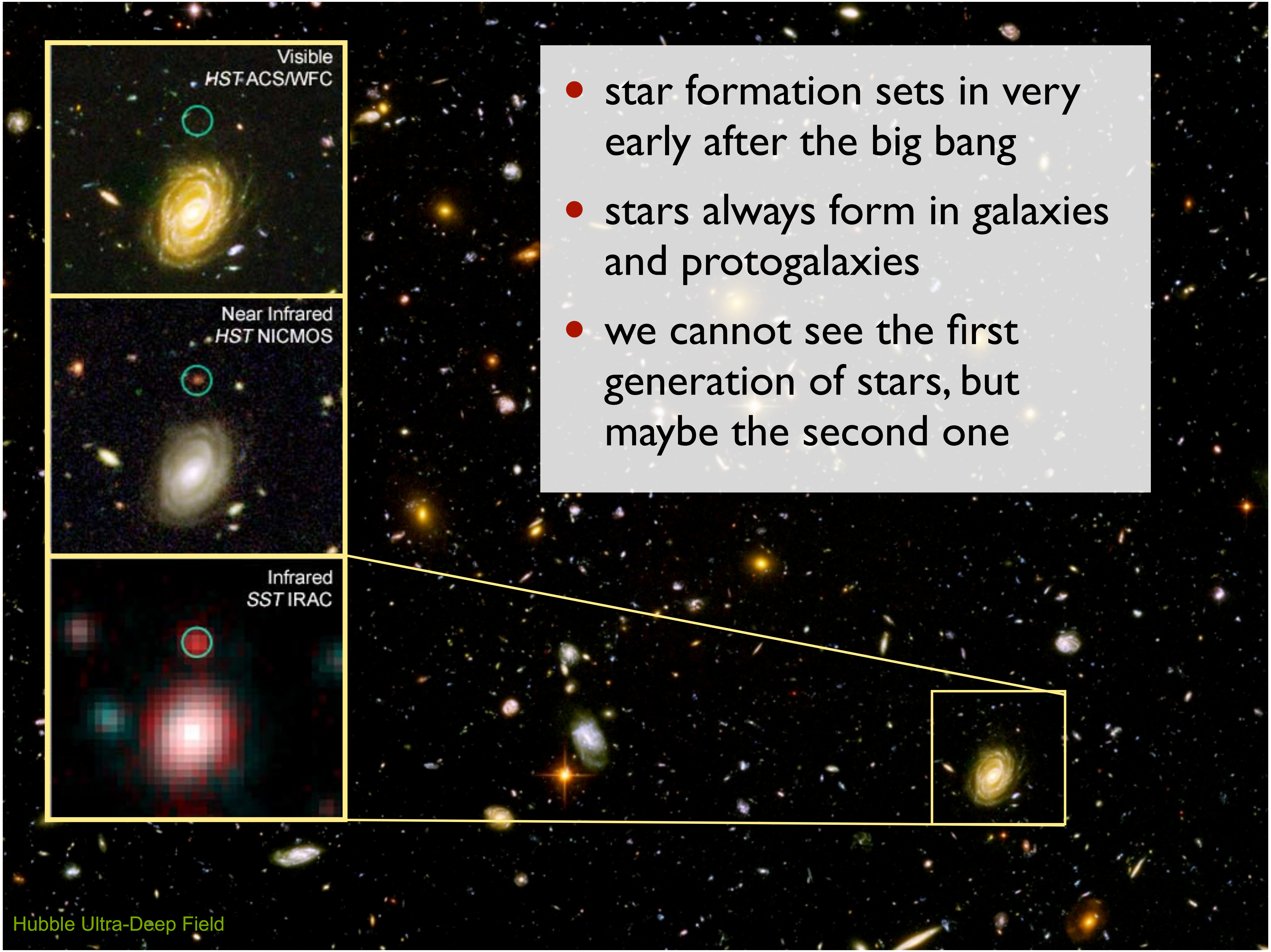
- star formation theory
  - phenomenology
  - historic remarks
  - our current understanding and its limitations
- some speculation about origin of stellar masses
  - is the stellar mass function universal?
  - what are the differences between star formation today and in the early universe?

NGC 3324 (Hubble, NASA/ESA)

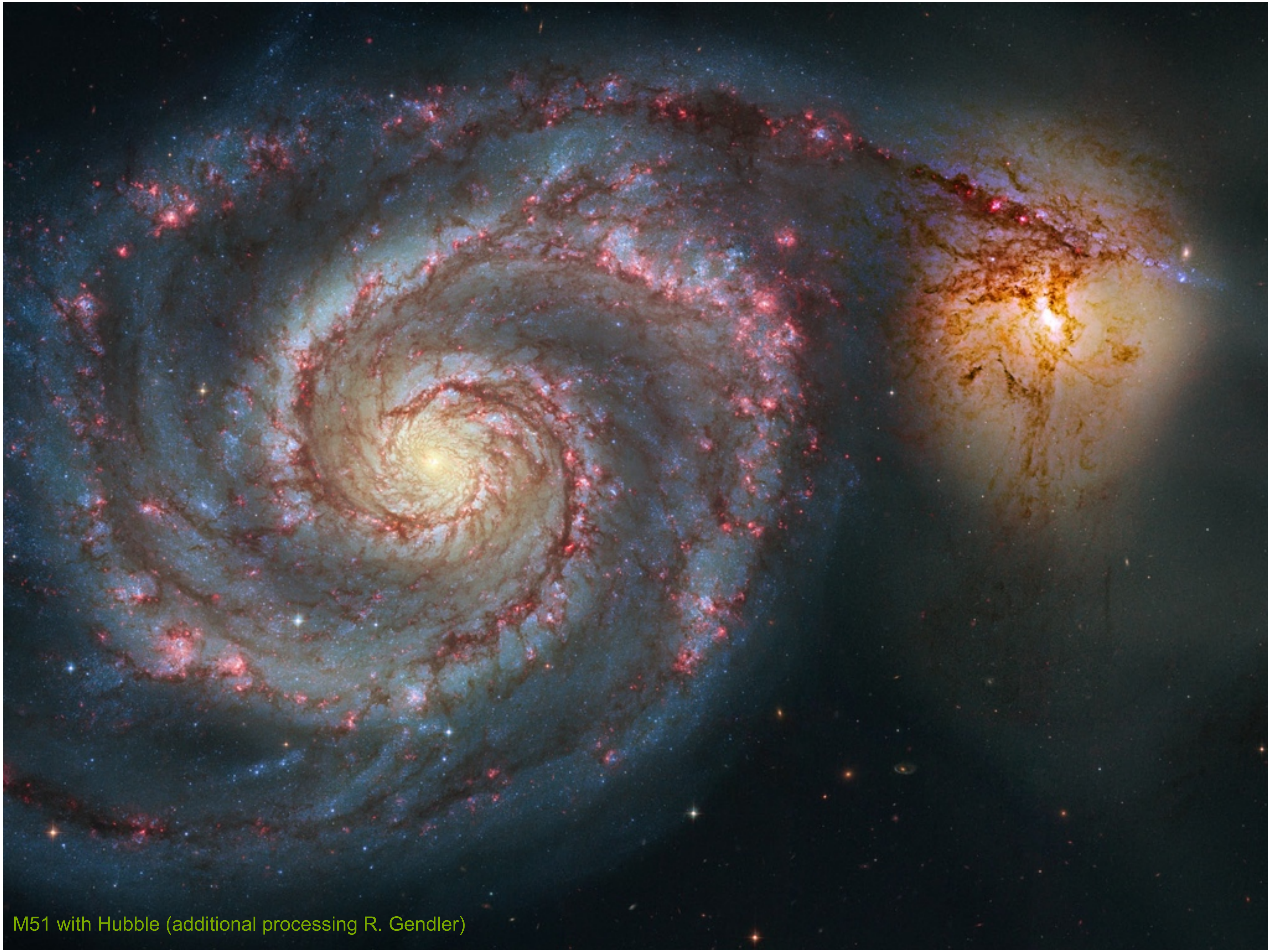
phenomenology


Hubble Ultra-Deep Field

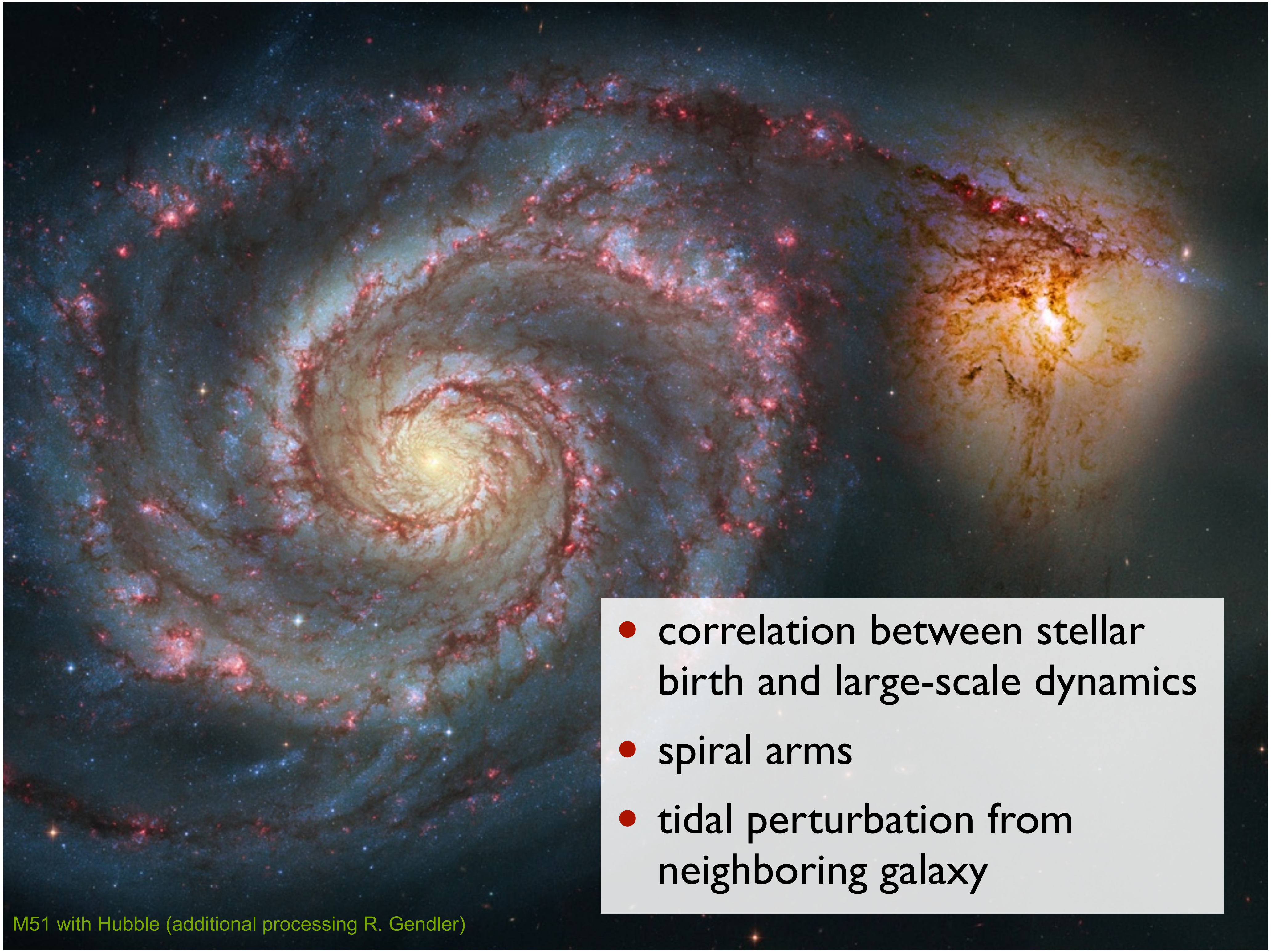

Visible
HST ACS/WFC
Near Infrared
HST NICMOS
Infrared
SST IRAC
Hubble Ultra-Deep Field



- 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

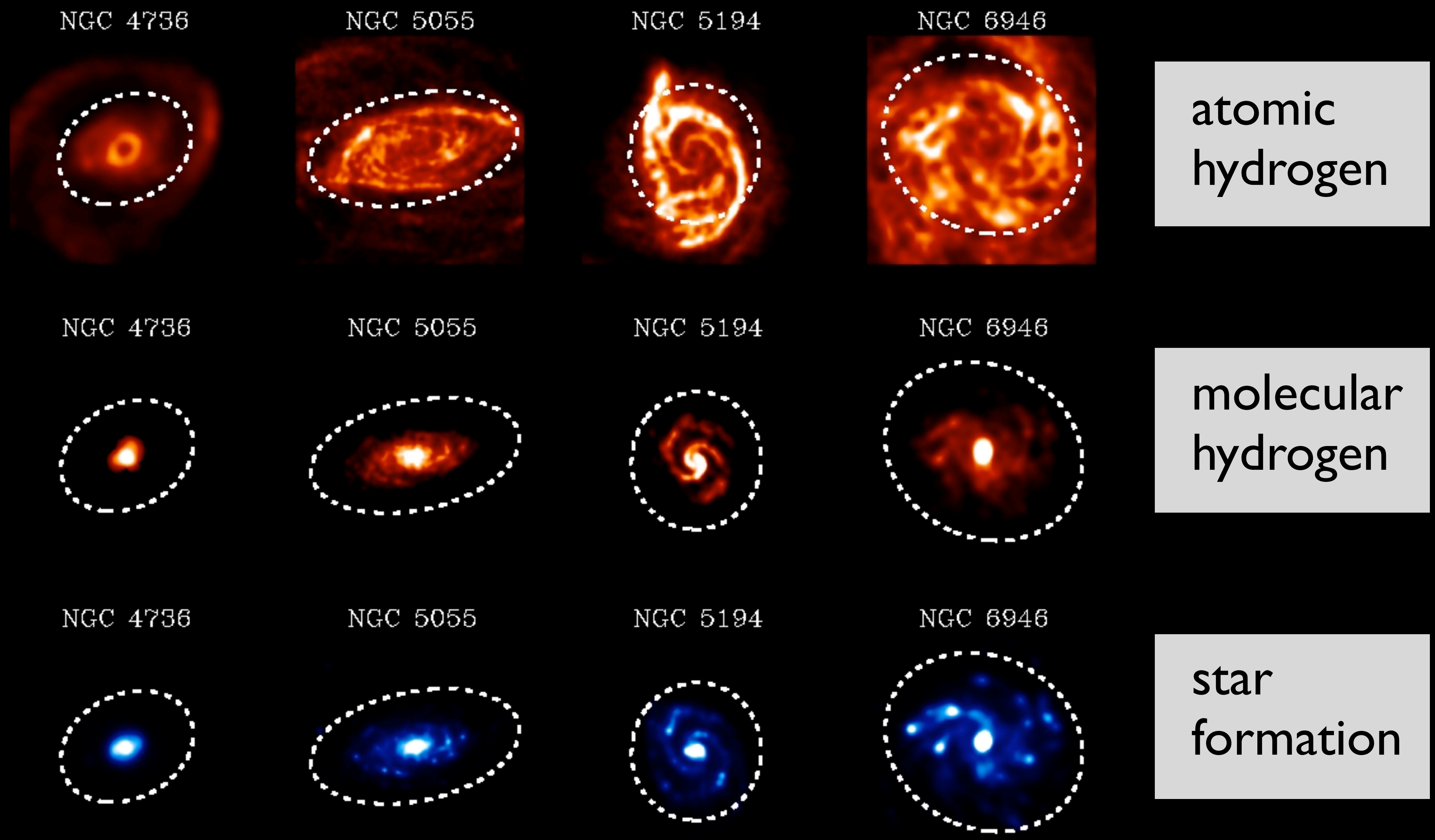


M51 with Hubble (additional processing R. Gendler)

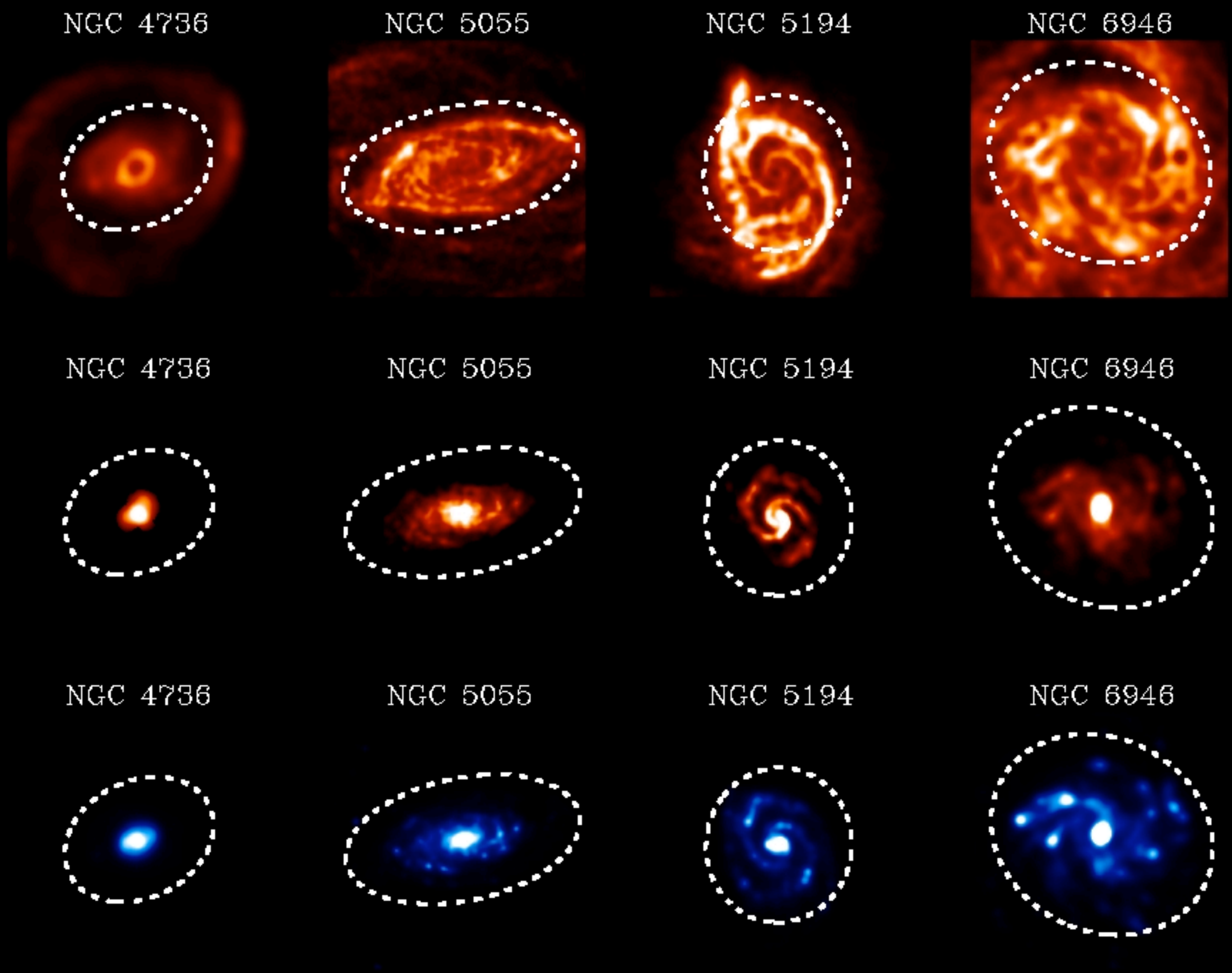


- correlation between stellar birth and large-scale dynamics
- spiral arms
- tidal perturbation from neighboring galaxy

M51 with Hubble (additional processing R. Gendler)



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



atomic hydrogen

molecular hydrogen

star formation

- HI gas more extended
- H2 and SF well correlated

galaxies from THINGS and HERACLES survey
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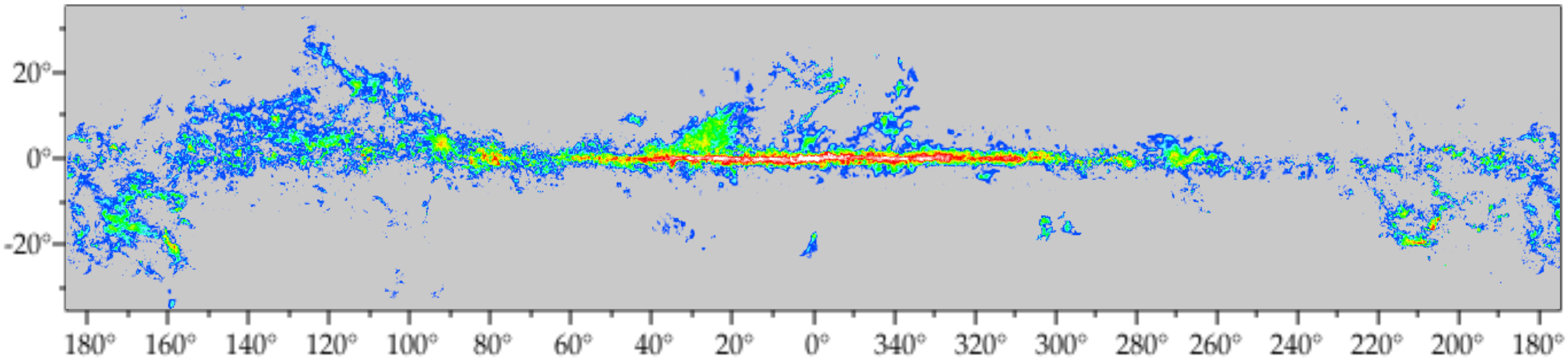
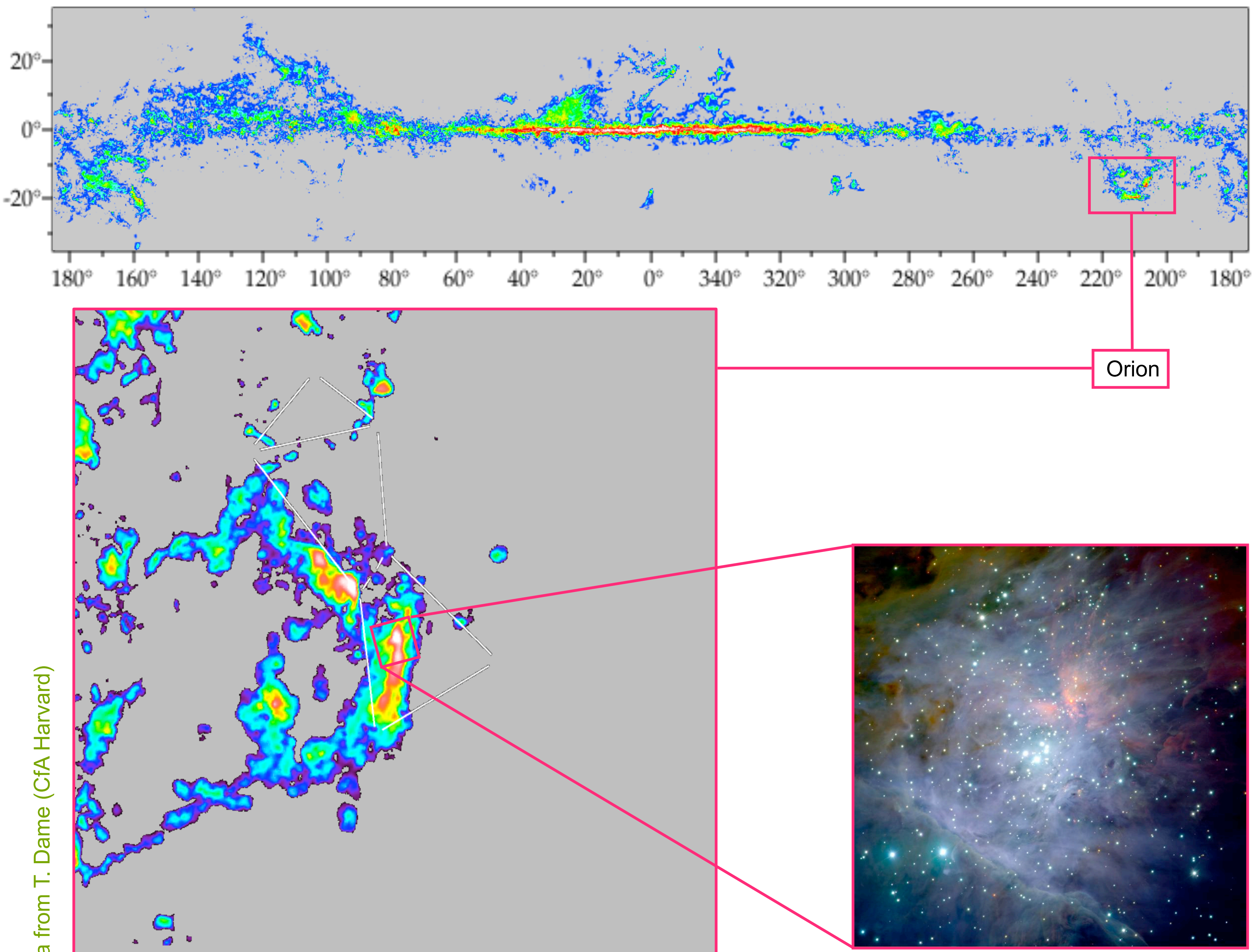


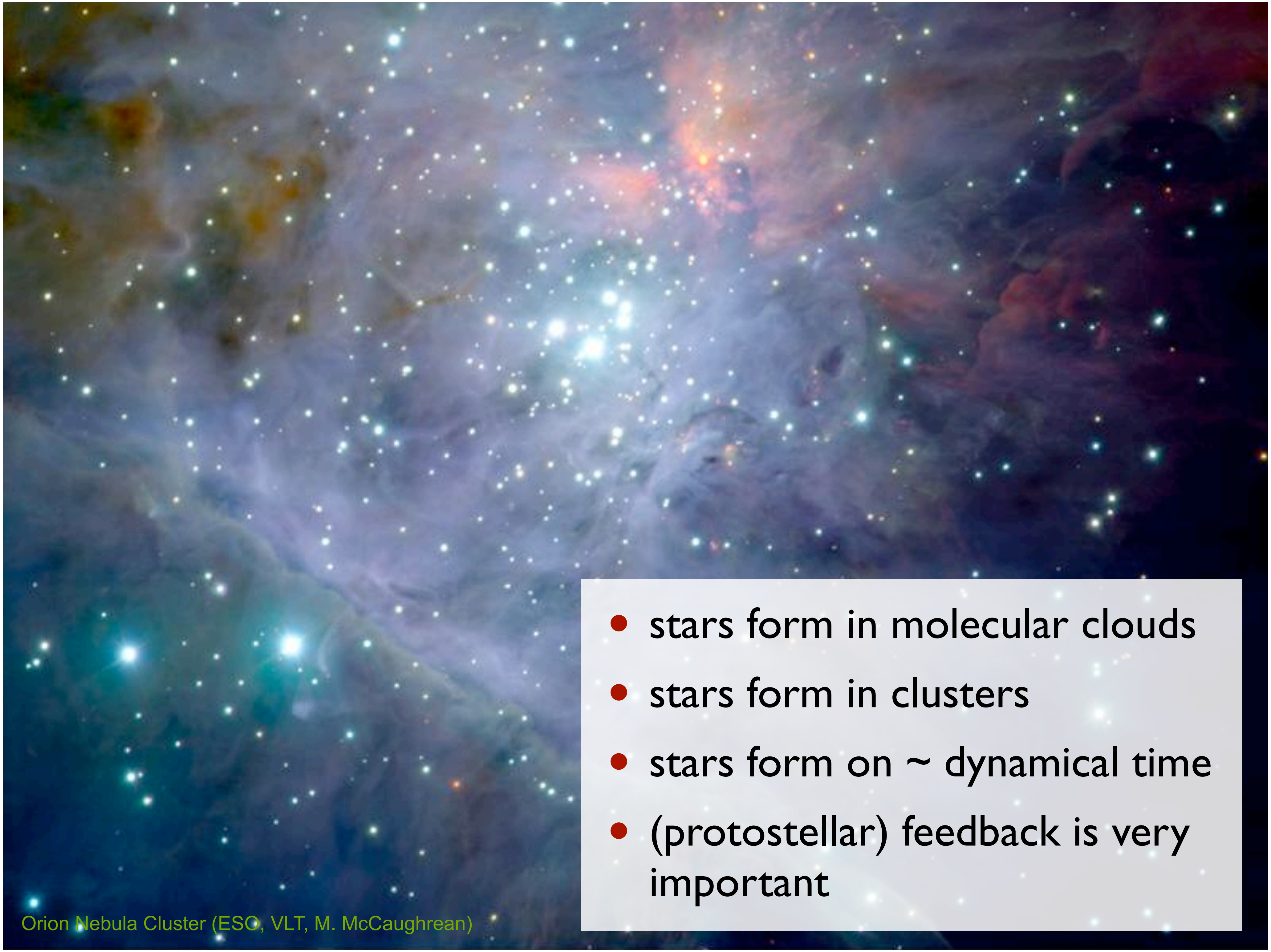
distribution of molecular gas in the Milky Way as traced by CO emission

data from T. Dame (CfA Harvard)



data from T. Dame (CfA Harvard)

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

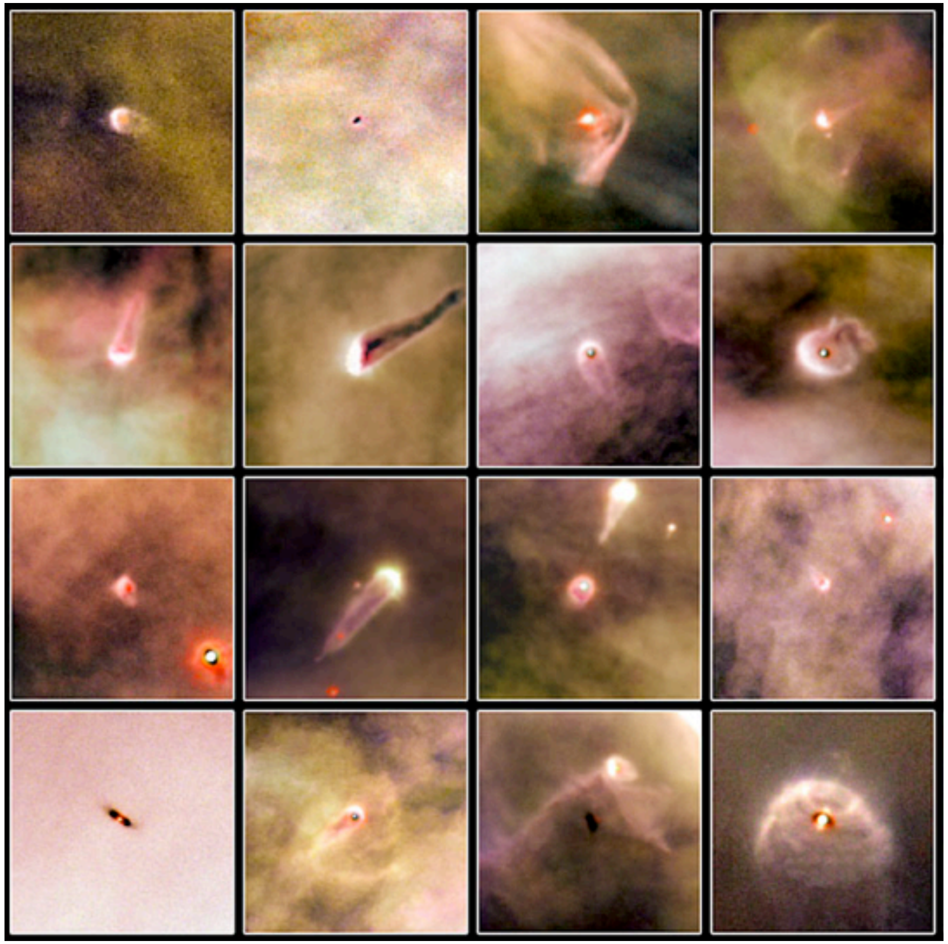


- stars form in molecular clouds
- stars form in clusters
- stars form on ~ dynamical time
- (protostellar) feedback is very important

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

Trapezium Cluster: Central Region

Ionizing radiation from central star **Θ1C Orionis**



Proplyds: Evaporating ``protoplanetary´´ disks around young low-mass protostars

(Johnstone et al. 1998, Hubble)

(Ricci et al. 2008, Hubble)

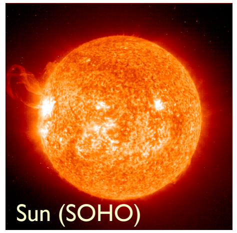
theoretical
approach

decrease in spatial scale / increase in density


Andromeda (R. Gendler)


NGC 602 in LMC (Hubble)


Proplyd in Orion (Hubble)


Sun (SOHO)


Earth

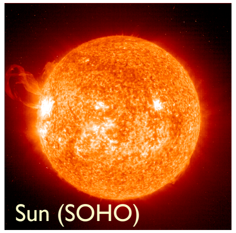
- density
  - density of ISM: few particles per cm^3
  - density of molecular cloud: few 100 particles per cm^3
  - density of Sun: 1.4 g/cm^3
- spatial scale
  - size of molecular cloud: few 10s of pc
  - size of young cluster: ~ 1 pc
  - size of Sun: 1.4 x 10^{10} cm

decrease in spatial scale / increase in density


Andromeda (R. Gendler)


NGC 602 in LMC (Hubble)


Proplyd in Orion (Hubble)


Sun (SOHO)


Earth

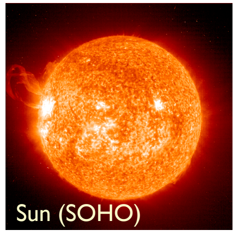
- contracting force
  - only force that can do this compression is ***GRAVITY***
- opposing forces
  - there are several processes that can oppose gravity
  - ***GAS PRESSURE***
  - ***TURBULENCE***
  - ***MAGNETIC FIELDS***
  - ***RADIATION PRESSURE***

decrease in spatial scale / increase in density


Andromeda (R. Gendler)


NGC 602 in LMC (Hubble)


Proplyd in Orion (Hubble)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  - ***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:

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

  - instability when $\omega^2 < 0$
  - minimal mass: $\boxed{M_J = \frac{1}{6}\pi^{-5/2} G^{-3/2} \rho_0^{-1/2} c_s^3 \propto \rho_0^{-1/2} T^{+3/2}}$

Sir James Jeans, 1877 - 1946

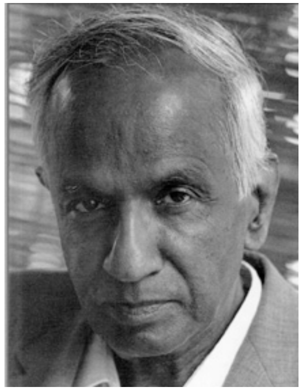
first approach to turbulence

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

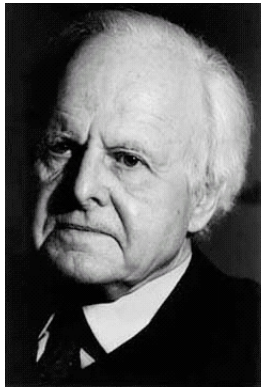
    $\ell_{turb} \ll \ell_{dyn}$
  - then turbulent velocity dispersion contributes to effective soundspeed:

    $$\boxed{c_c^2 \mapsto c_c^2 + \sigma_{rms}^2}$$
  - → 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
  (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

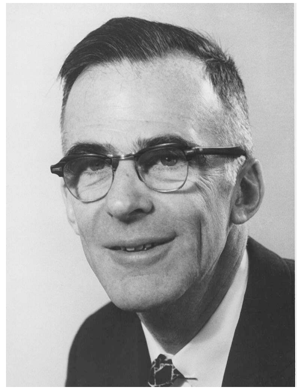
- *Mestel & Spitzer (1956):* Magnetic fields can prevent collapse*!!!*
  - Critical mass for gravitational collapse in presence of B-field

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

  - 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

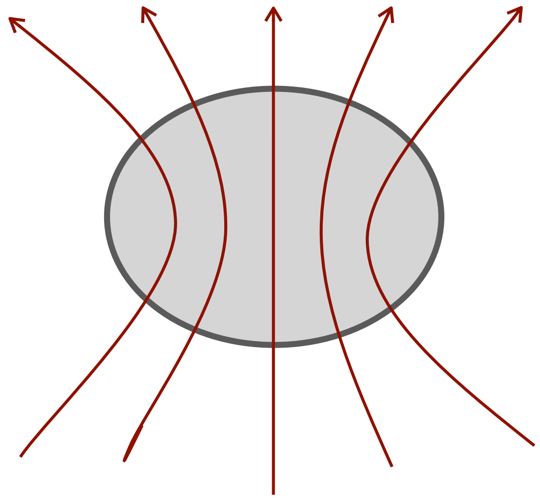


Lyman Spitzer, Jr., 1914 - 1997

“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)

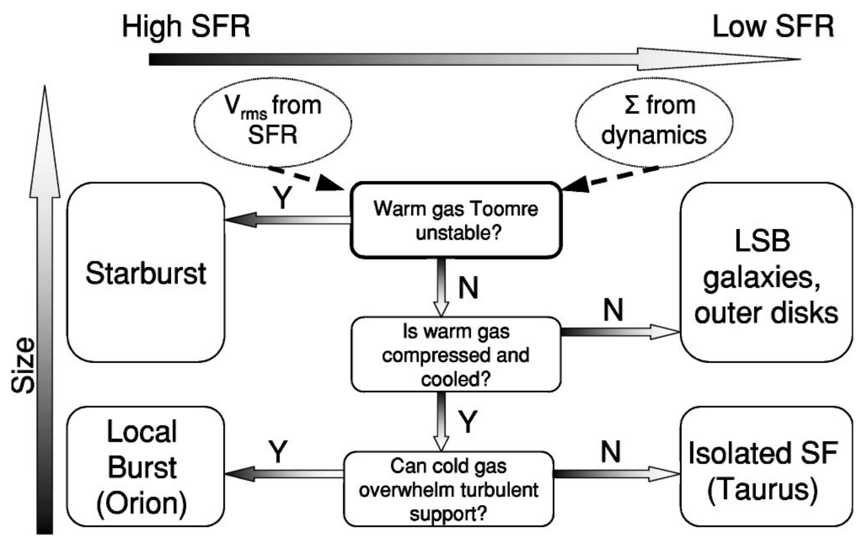
(see, e.g. the overview by Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194)

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

some concerns

- *energy balance*
  - in molecular clouds:

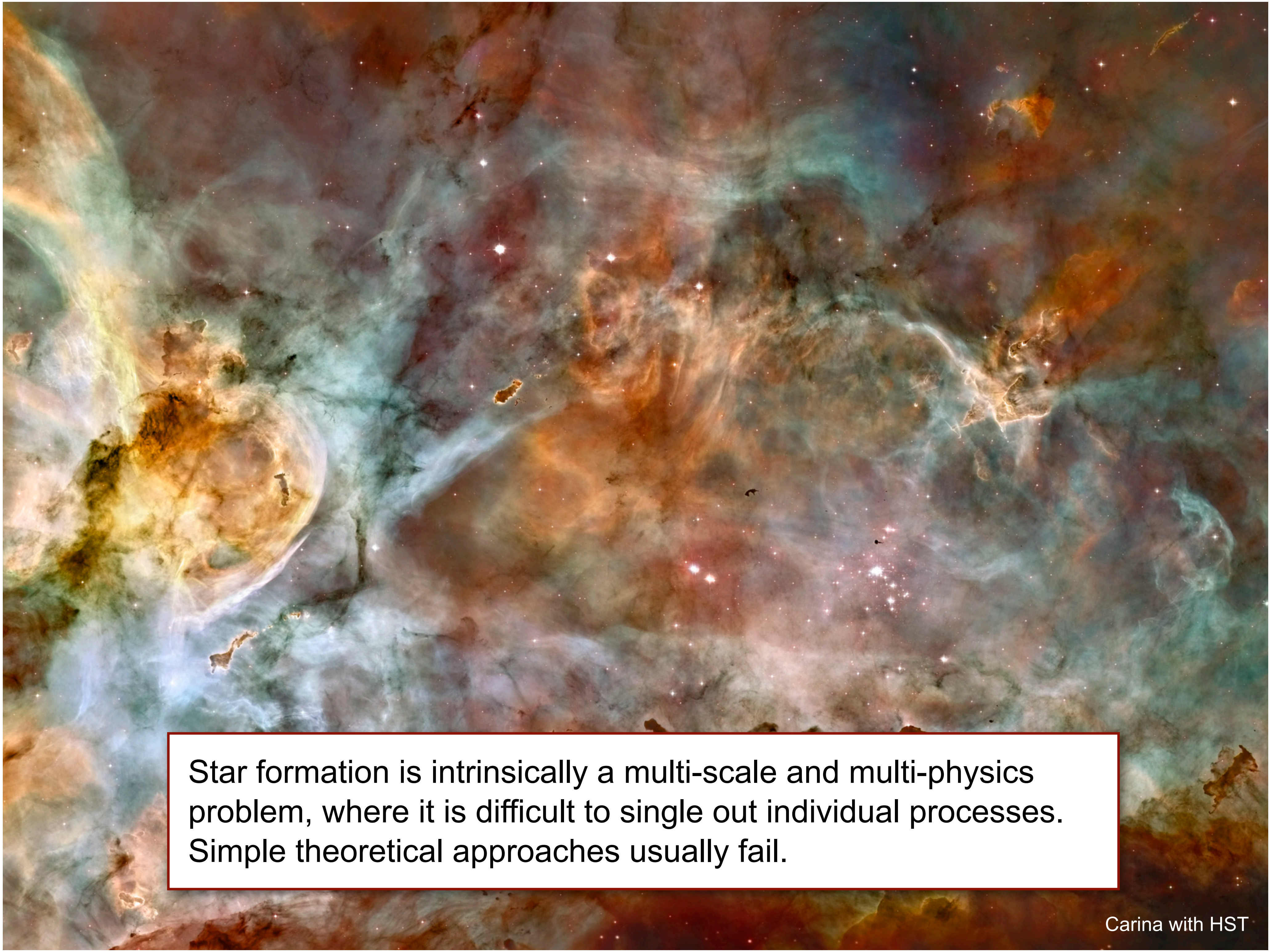
    kinetic energy ~ potential energy ~ magnetic energy > thermal energy

  - models based on HD turbulence misses important physics
  - in certain environments (Galactic Center, star bursts), energy density in cosmic rays and radiation is important as well
- *time scales*
  - star clusters form fast, but more slowly than predicted by HD only (feedback and magnetic fields do help)
  - initial conditions do matter (turbulence does not erase memory of past dynamics)
- *star formation efficiency (SFE)*
  - SFE in gravoturbulent models is too high (again more physics needed)

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*

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.



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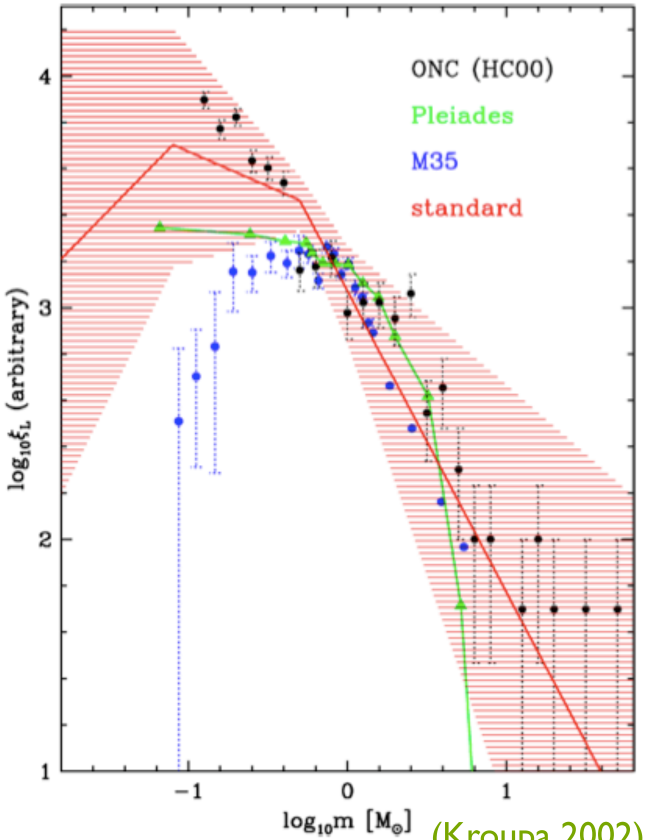
Carina with HST


HH 901/902 in Carina with HST

Stellar mass function

stellar mass fuction

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



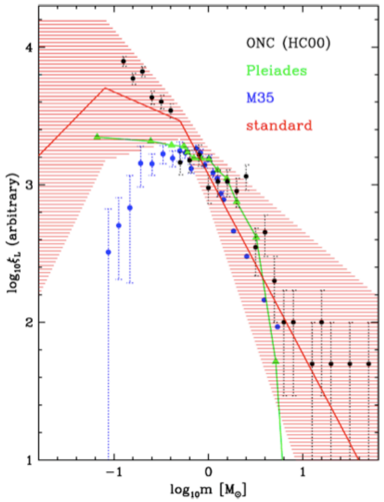
(Kroupa 2002)

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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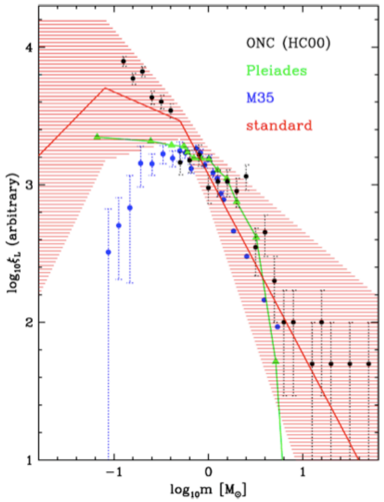
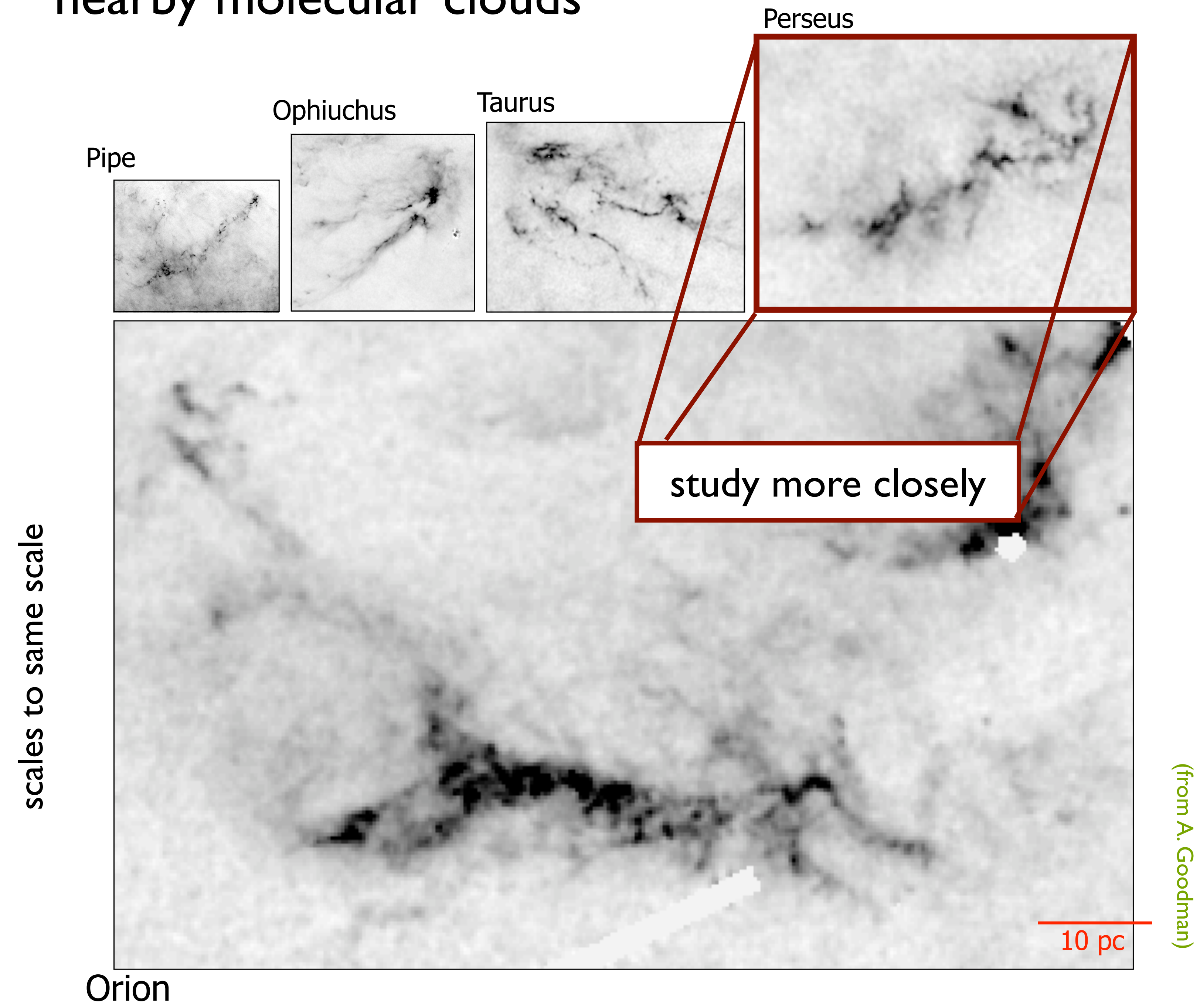


nearby molecular clouds



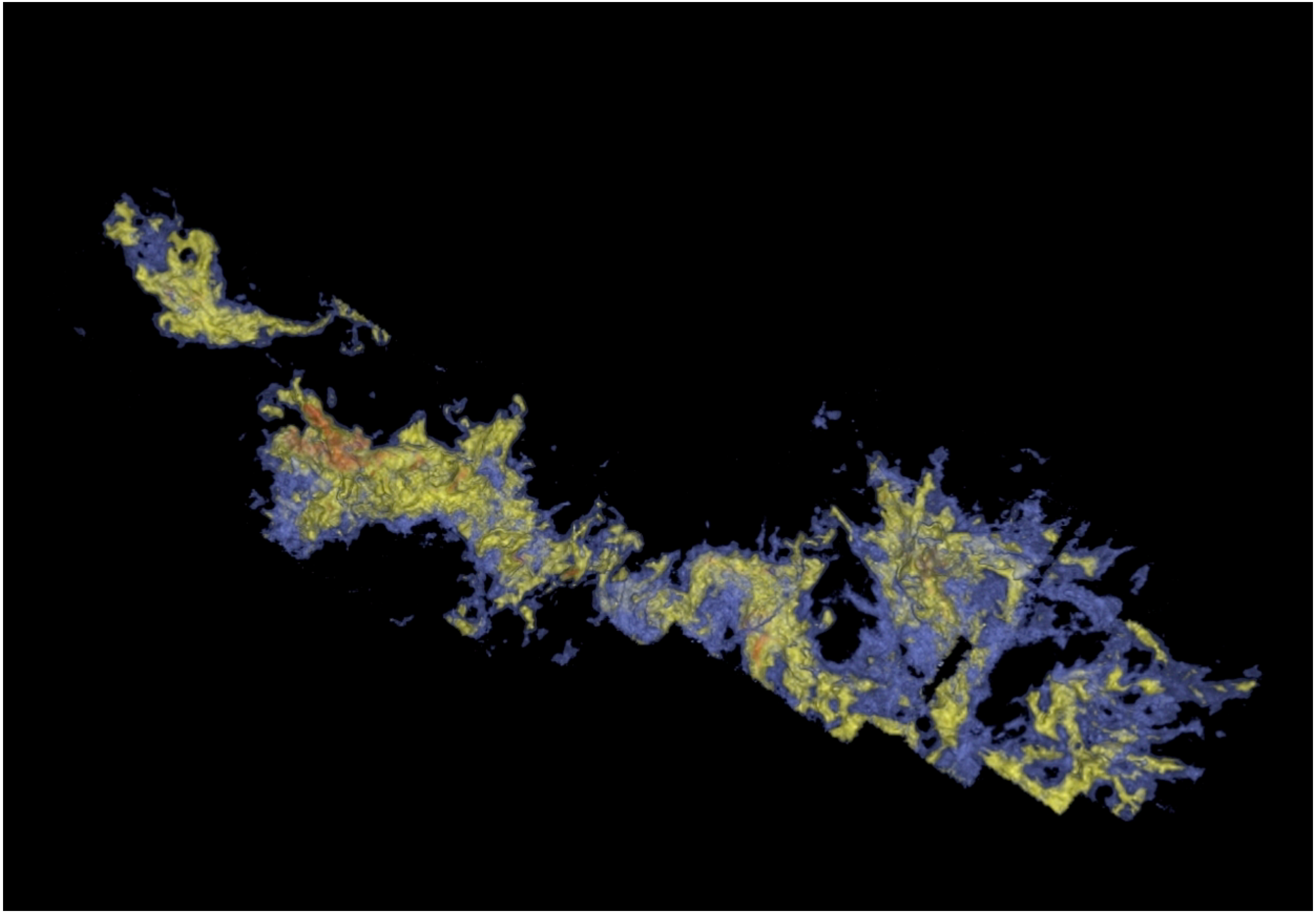
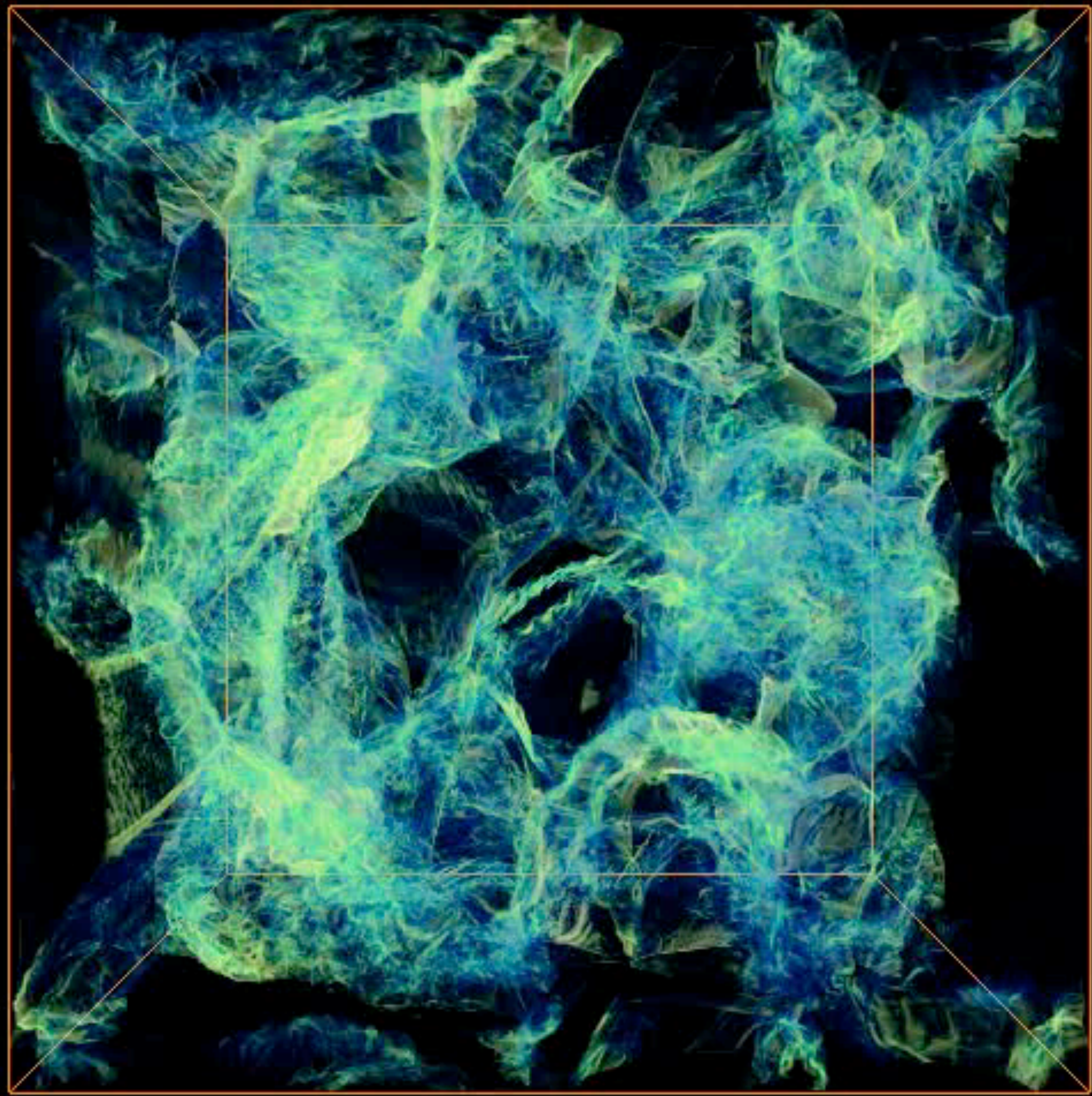


image from Alyssa Goodman: COMPLETE survey



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

example: model of Orion cloud

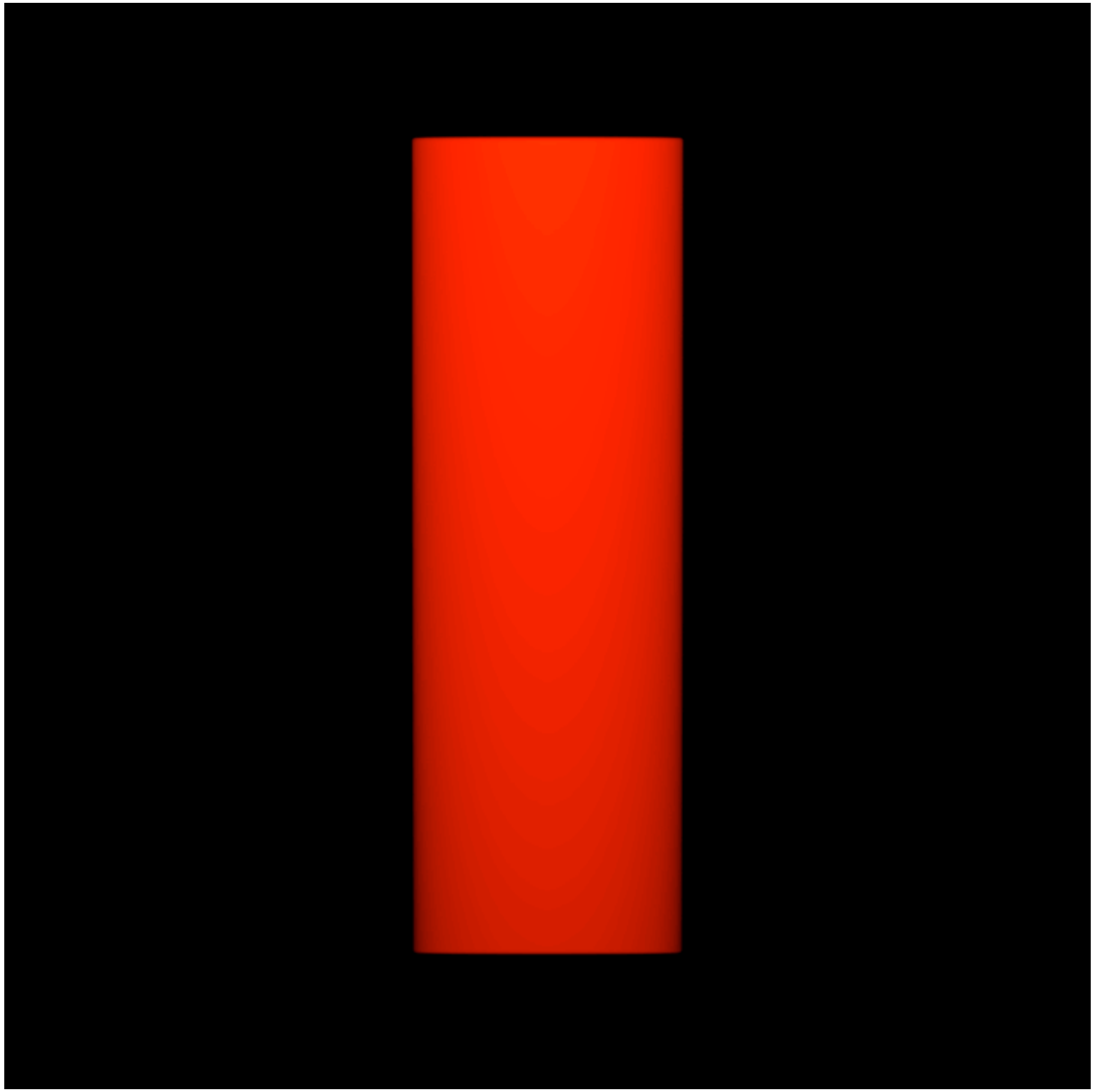
„model“ of Orion cloud:
15.000.000 SPH particles,
10^4 M_{sun} in 10 pc, mass resolution
0,02 M_{sun}, forms ~2.500
„stars“ (sink particles)

isothermal EOS, top bound, bottom
unbound

has clustered as well as distributed
„star“ formation

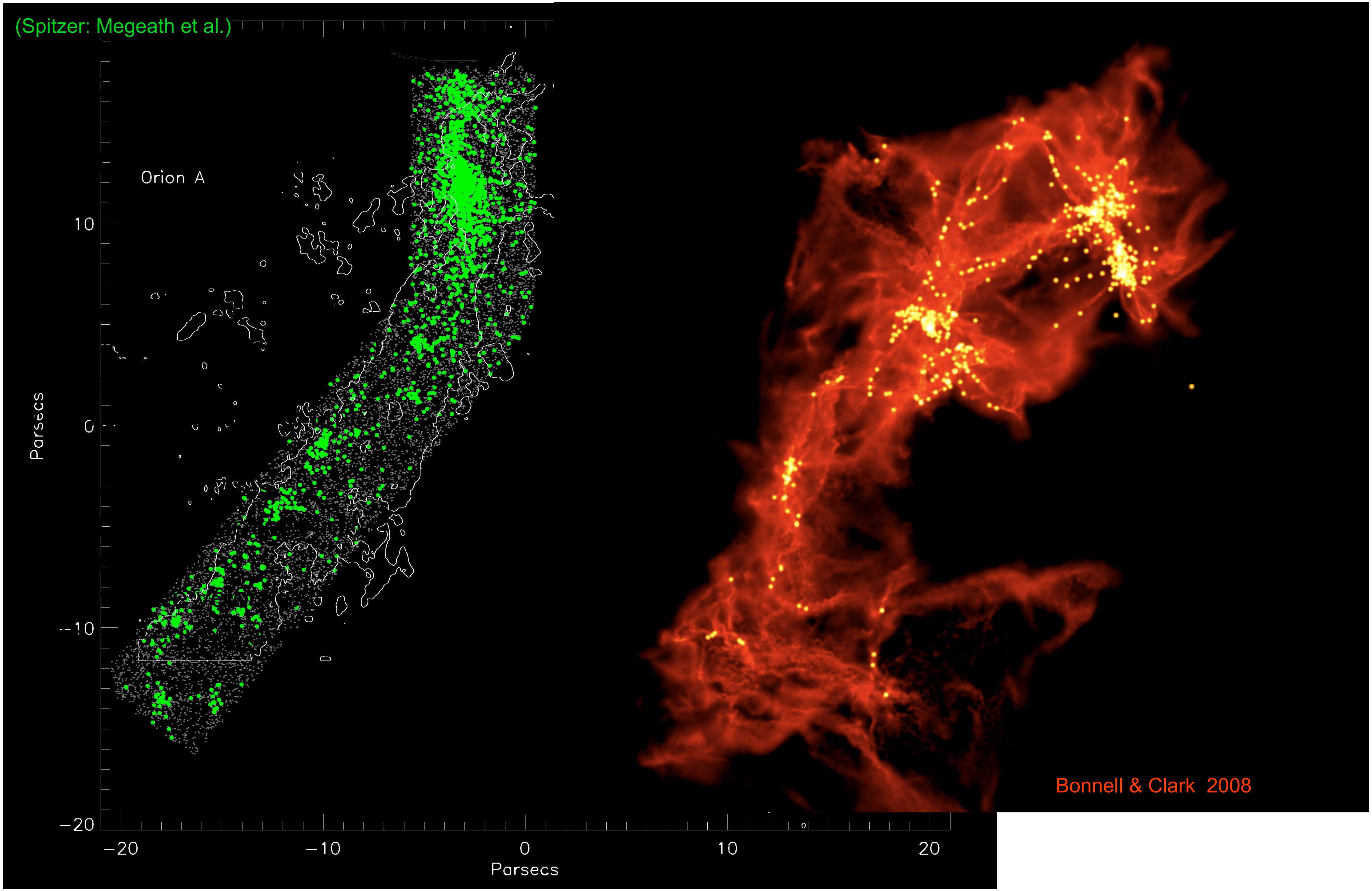
efficiency varies from 1% to 20%

develops full IMF
(distribution of sink particle masses)



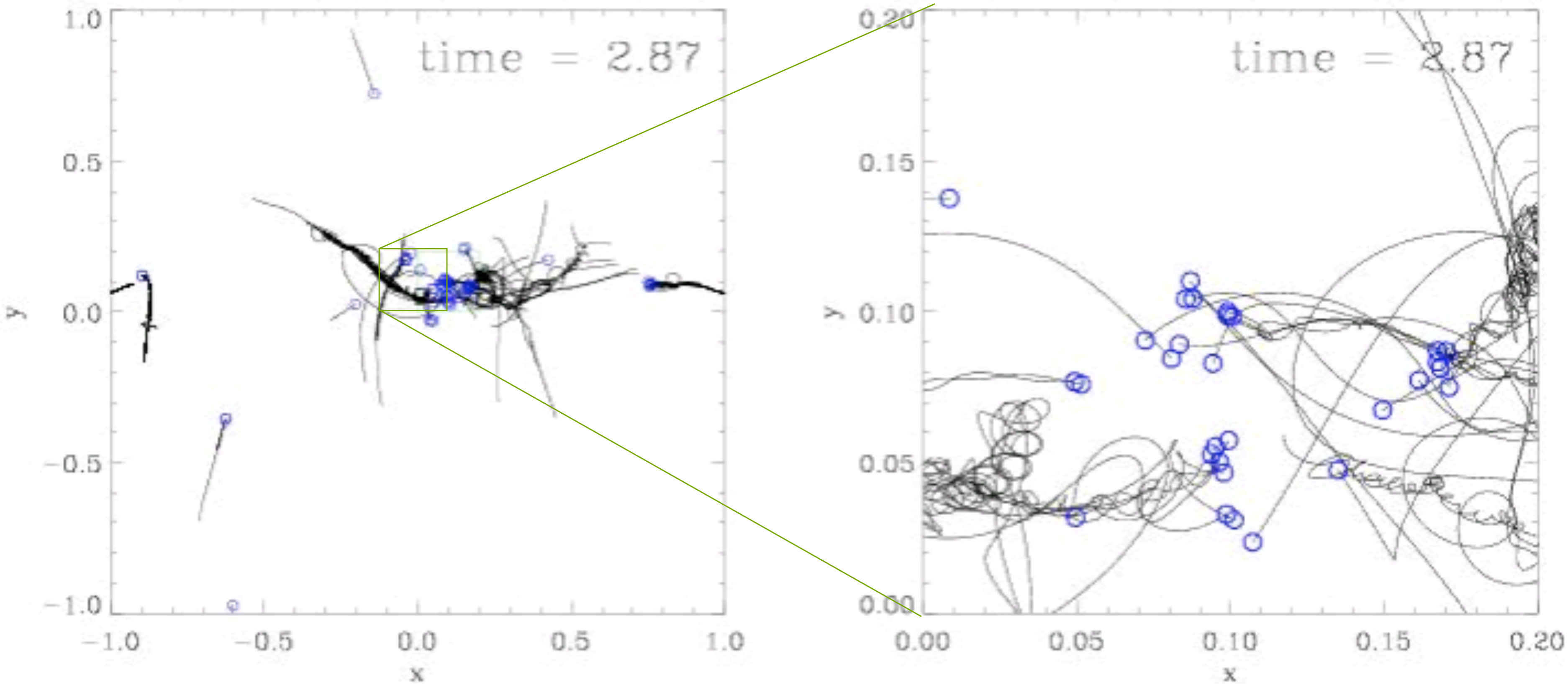
(Bonnell & Clark 2008)

example: model of Orion cloud



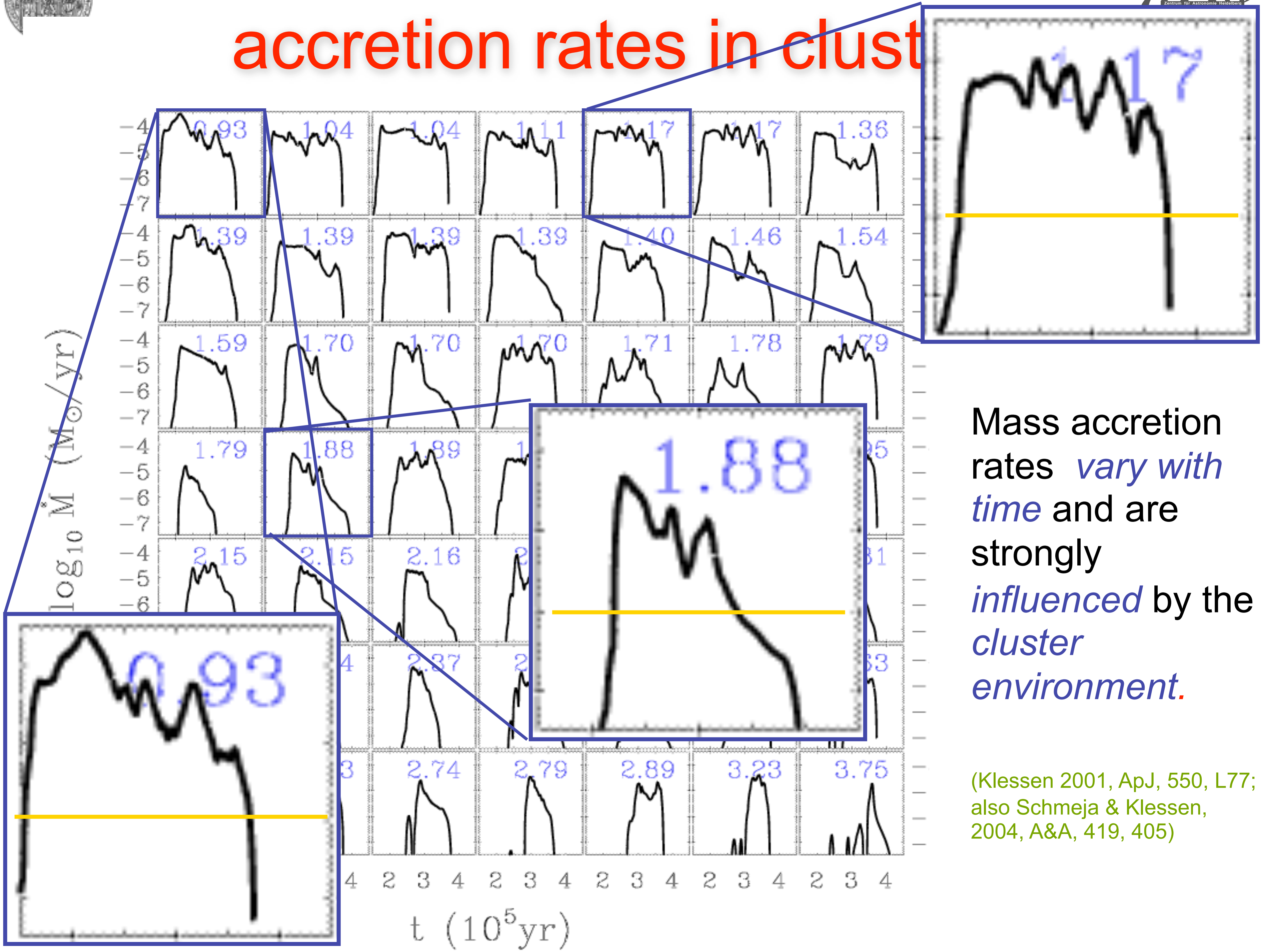
Dynamics of nascent star cluster

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 masses

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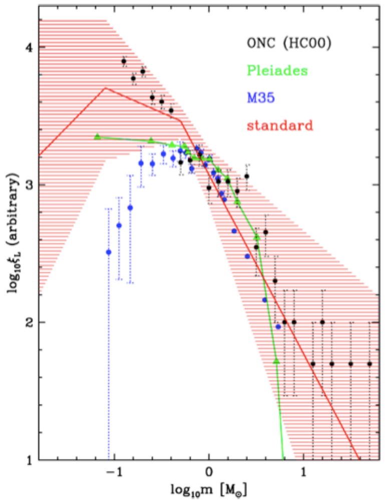

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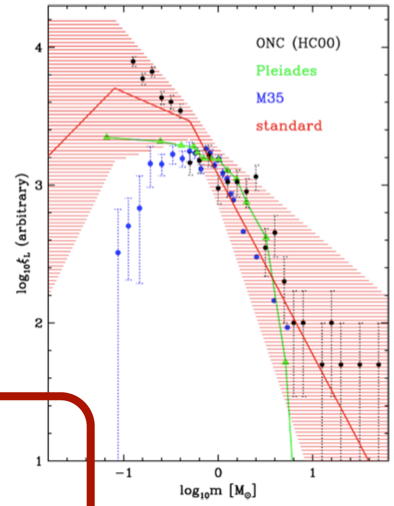


application to first star formation

thermodynamics & fragmentation

degree of fragmentation depends on *EOS!*

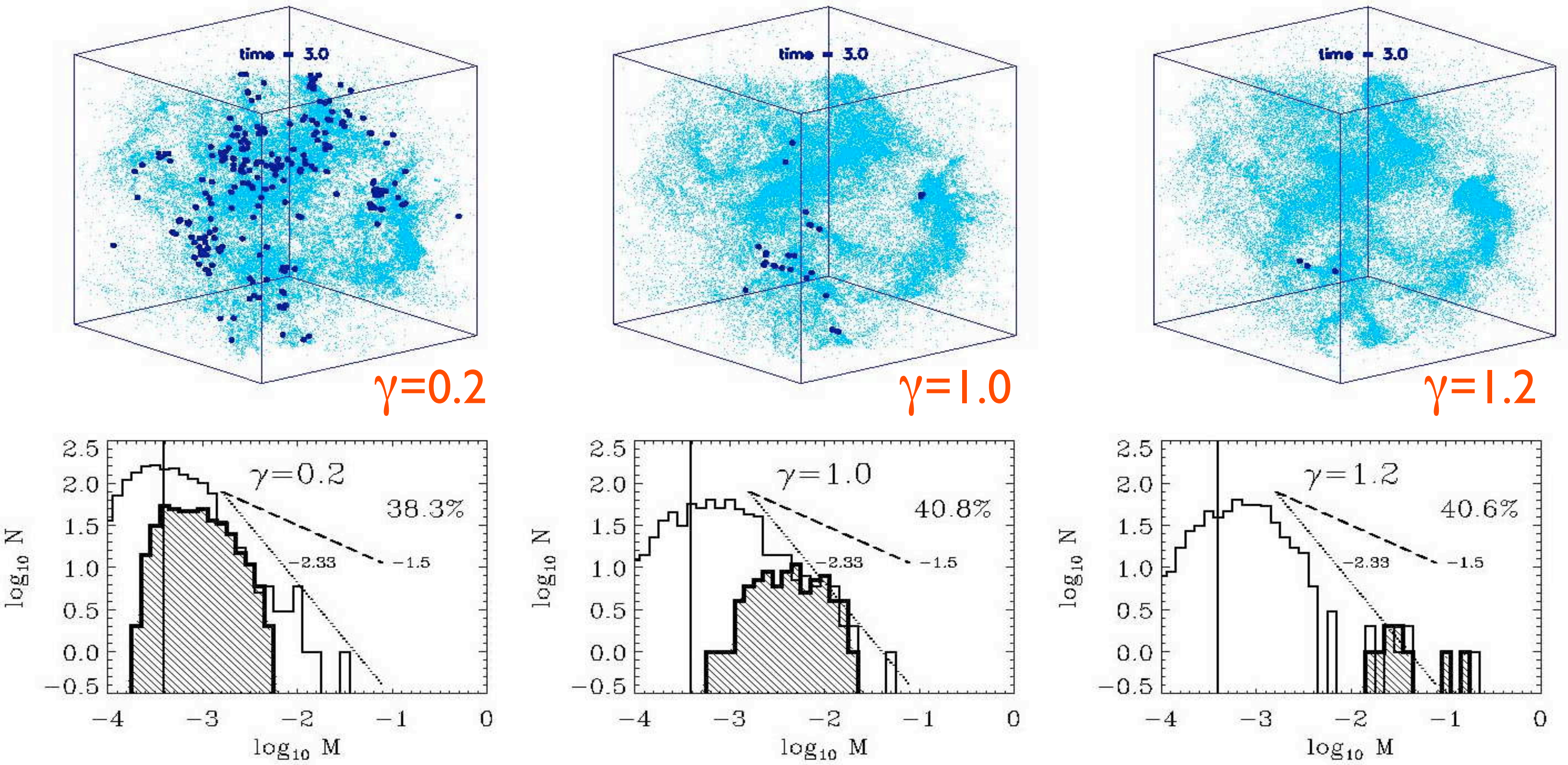
polytropic EOS: $\mathbf{p} \propto \rho^{\gamma}$

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

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

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

dependency on EOS



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

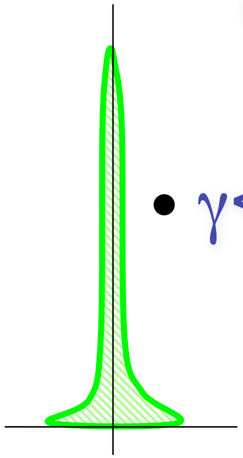
for $\gamma>1$ it is suppressed → formation of *isolated massive stars*

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

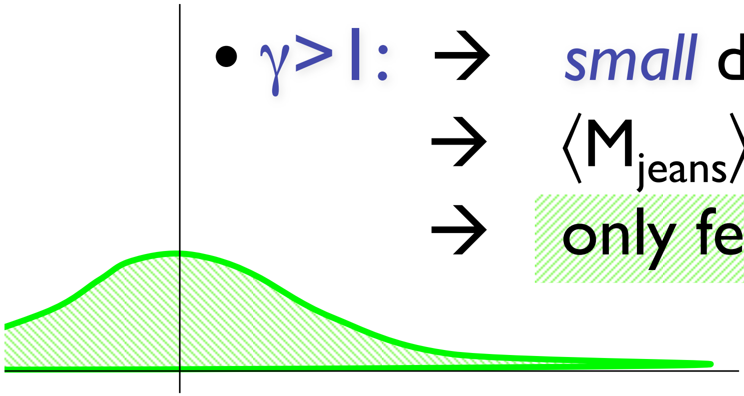
how does that work?

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

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

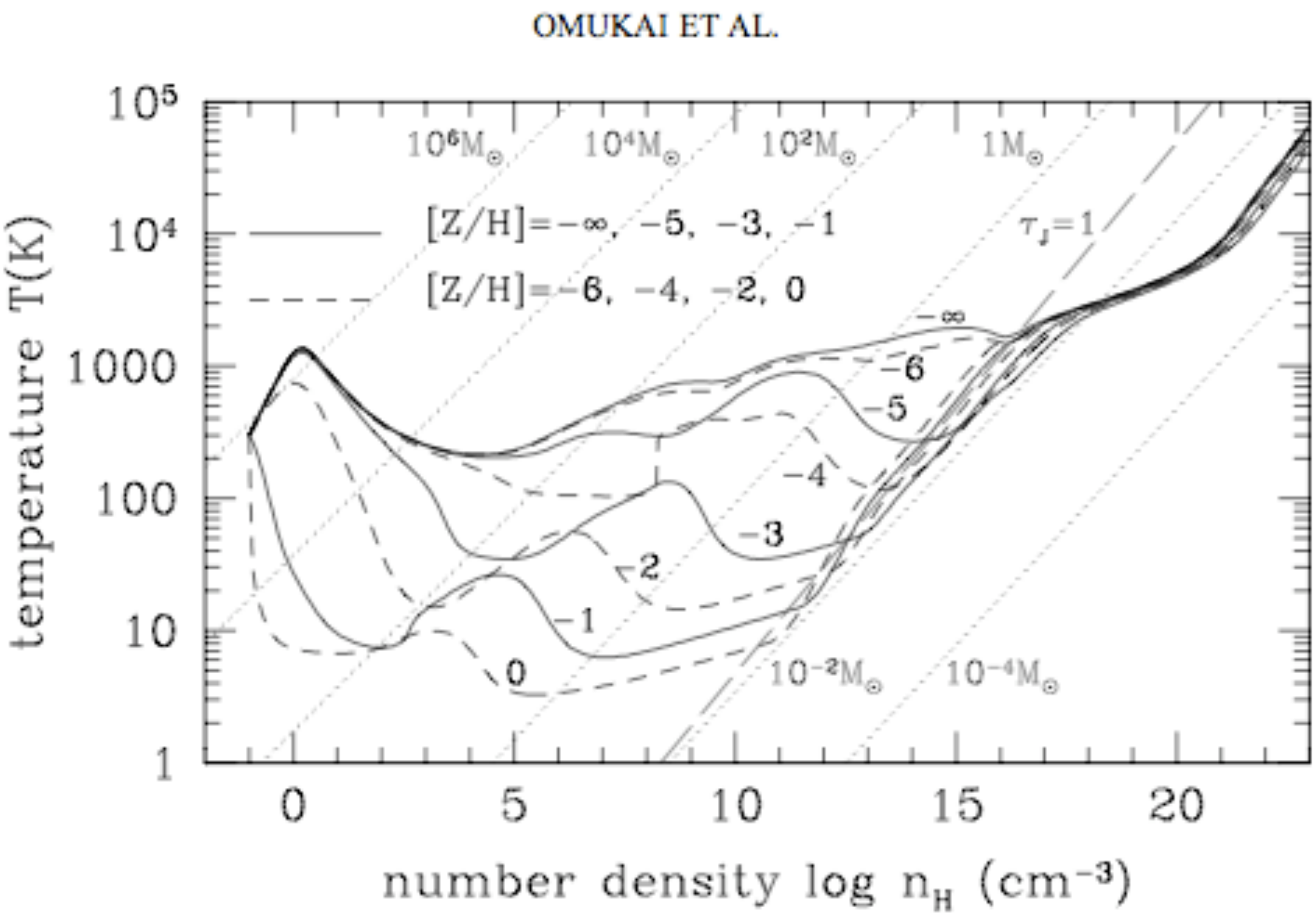


- $\gamma<1$: → *large* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ becomes small
  → number of fluctuations with $M > M_{jeans}$ is large



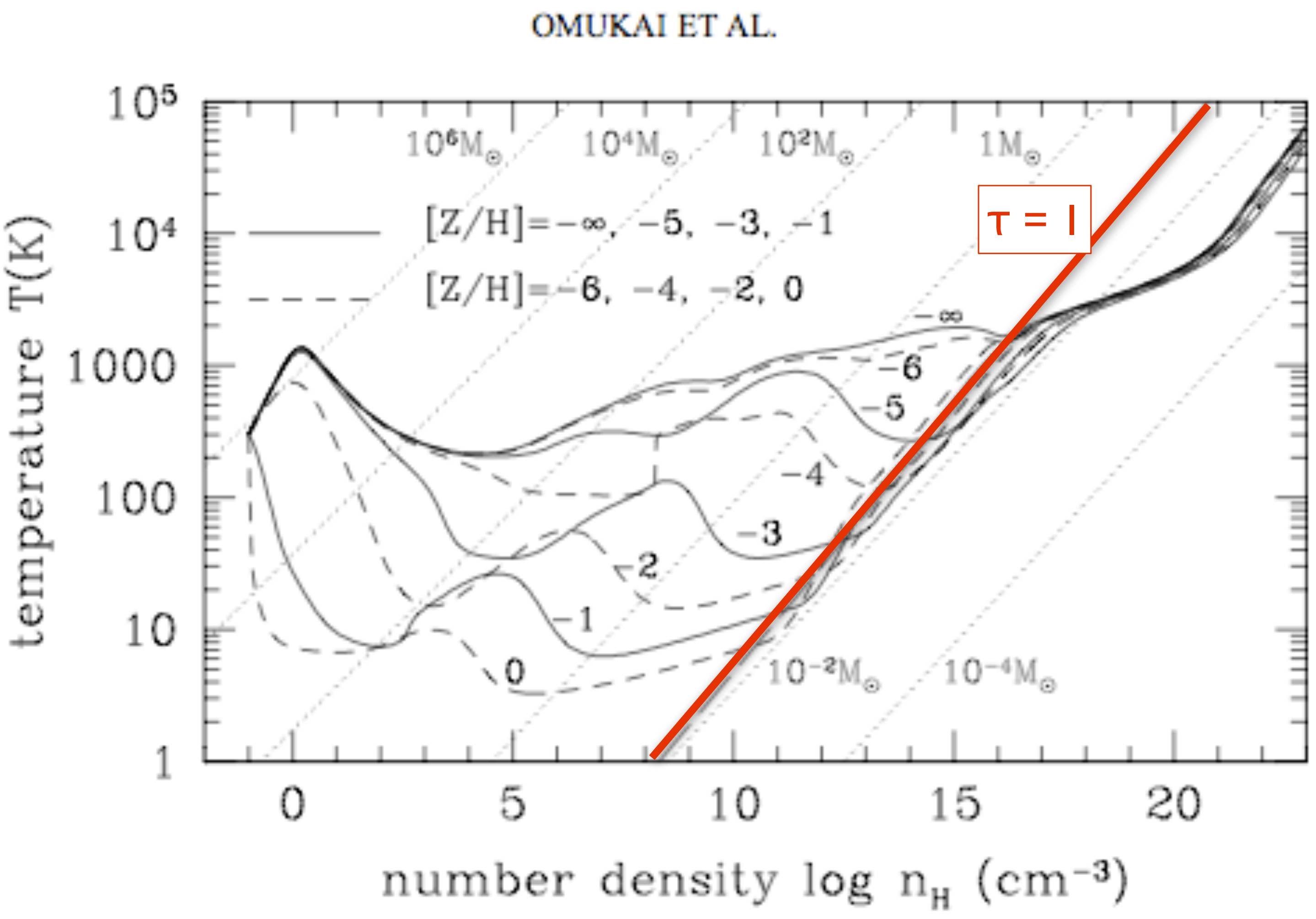
- $\gamma>1$: → *small* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ is large
  → only few and massive clumps exceed M_{jeans}

EOS as function of metallicity



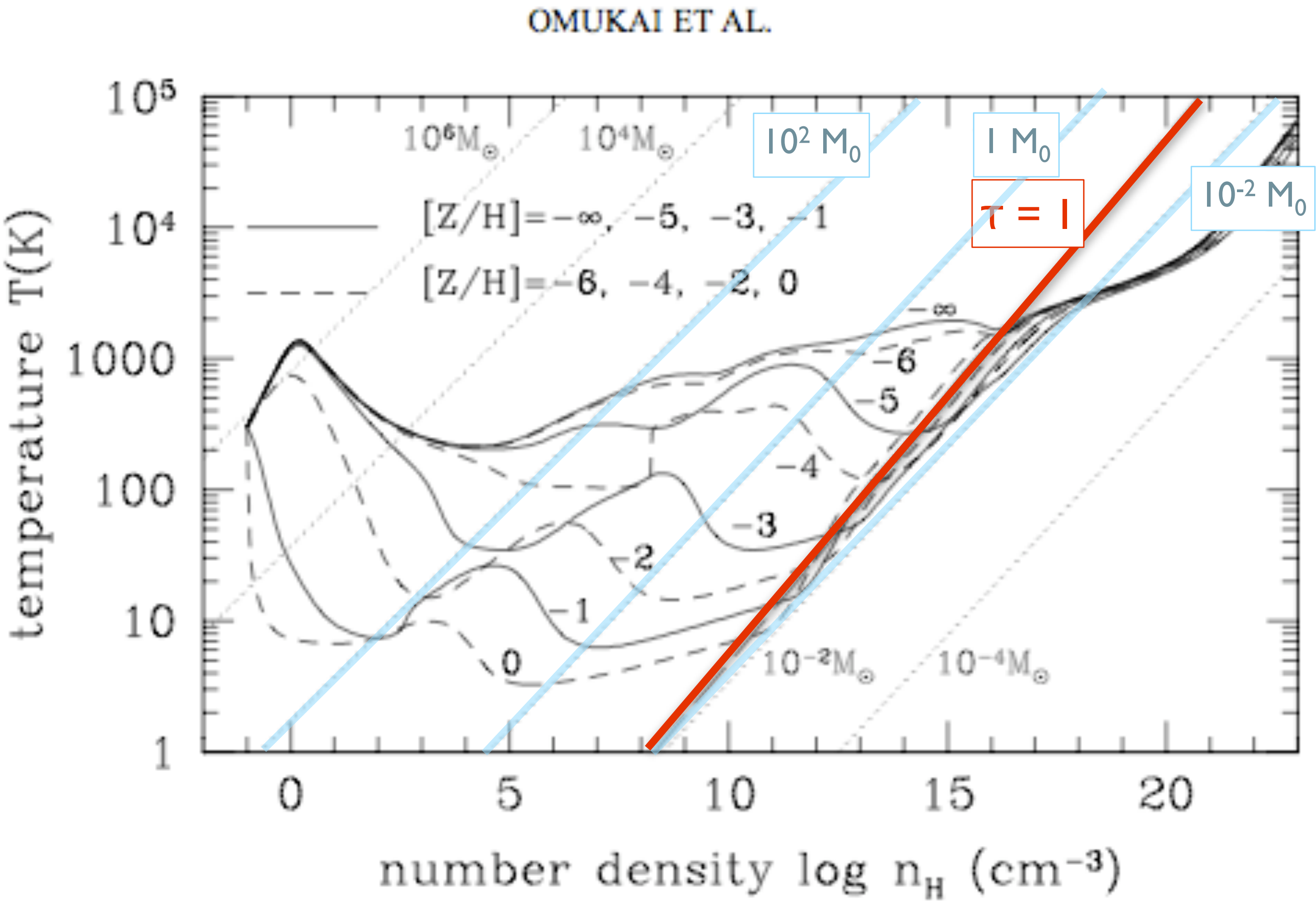
(Omukai et al. 2005)

EOS as function of metallicity



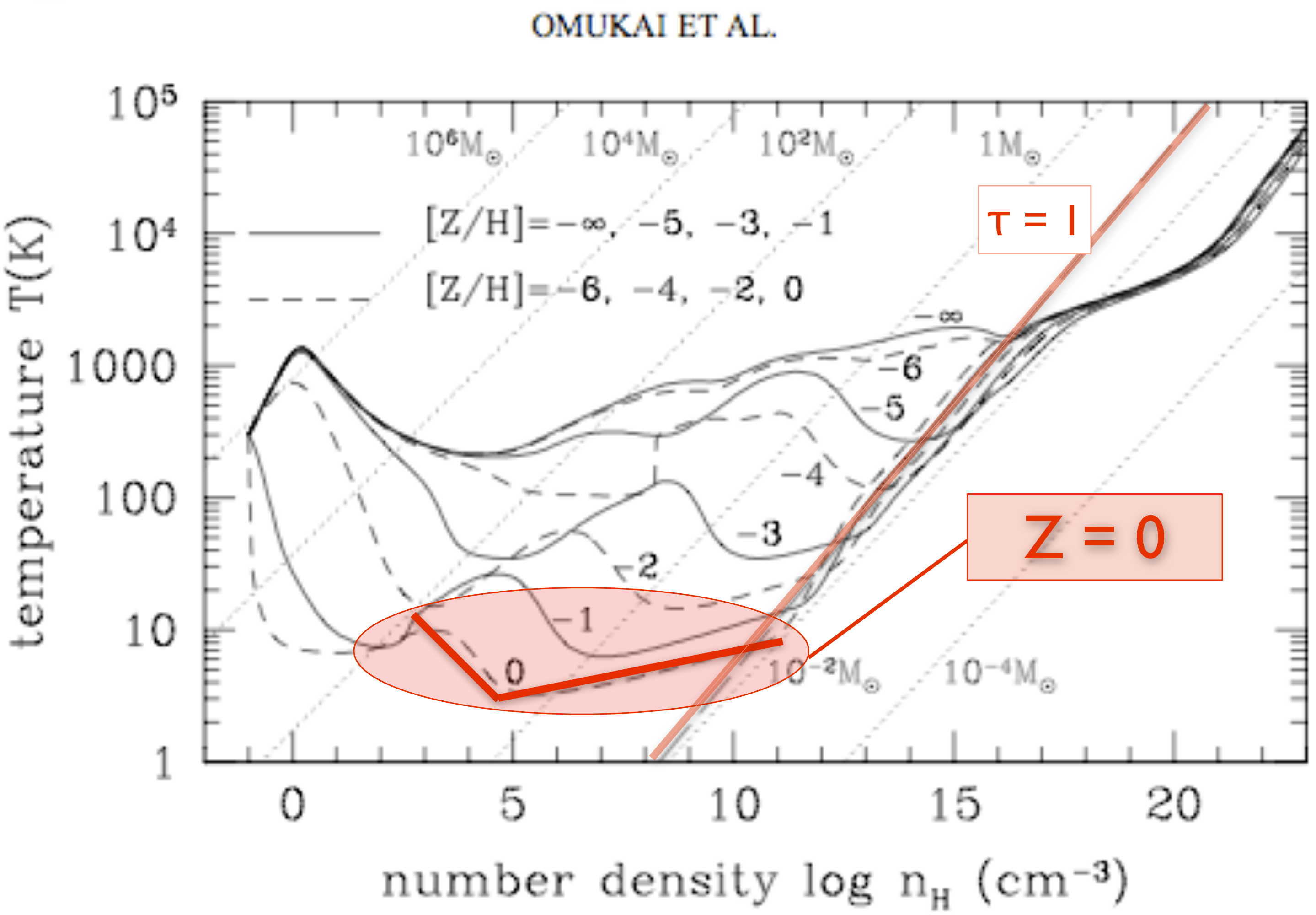
(Omukai et al. 2005)

EOS as function of metallicity



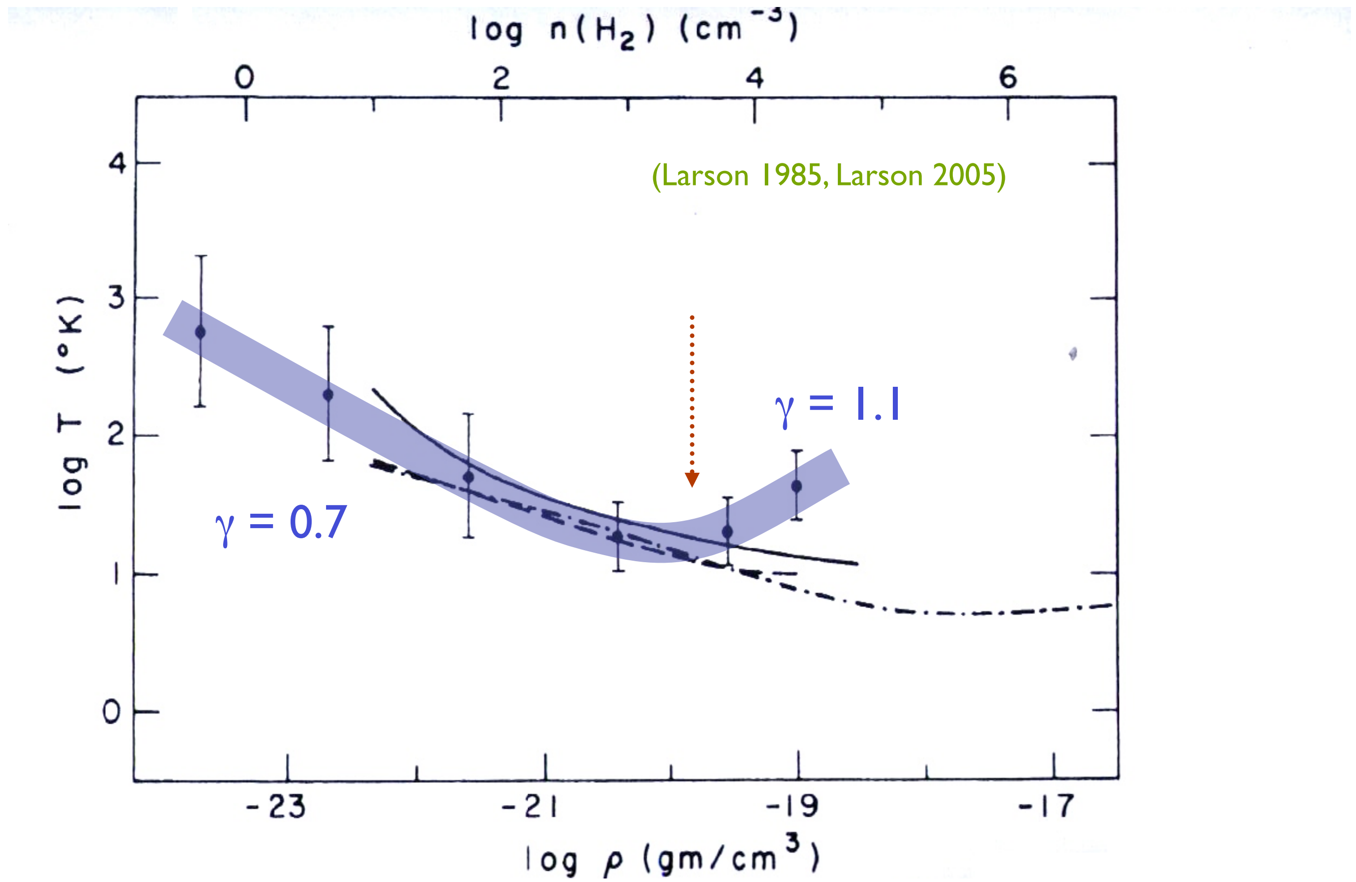
(Omukai et al. 2005)

present-day star formation

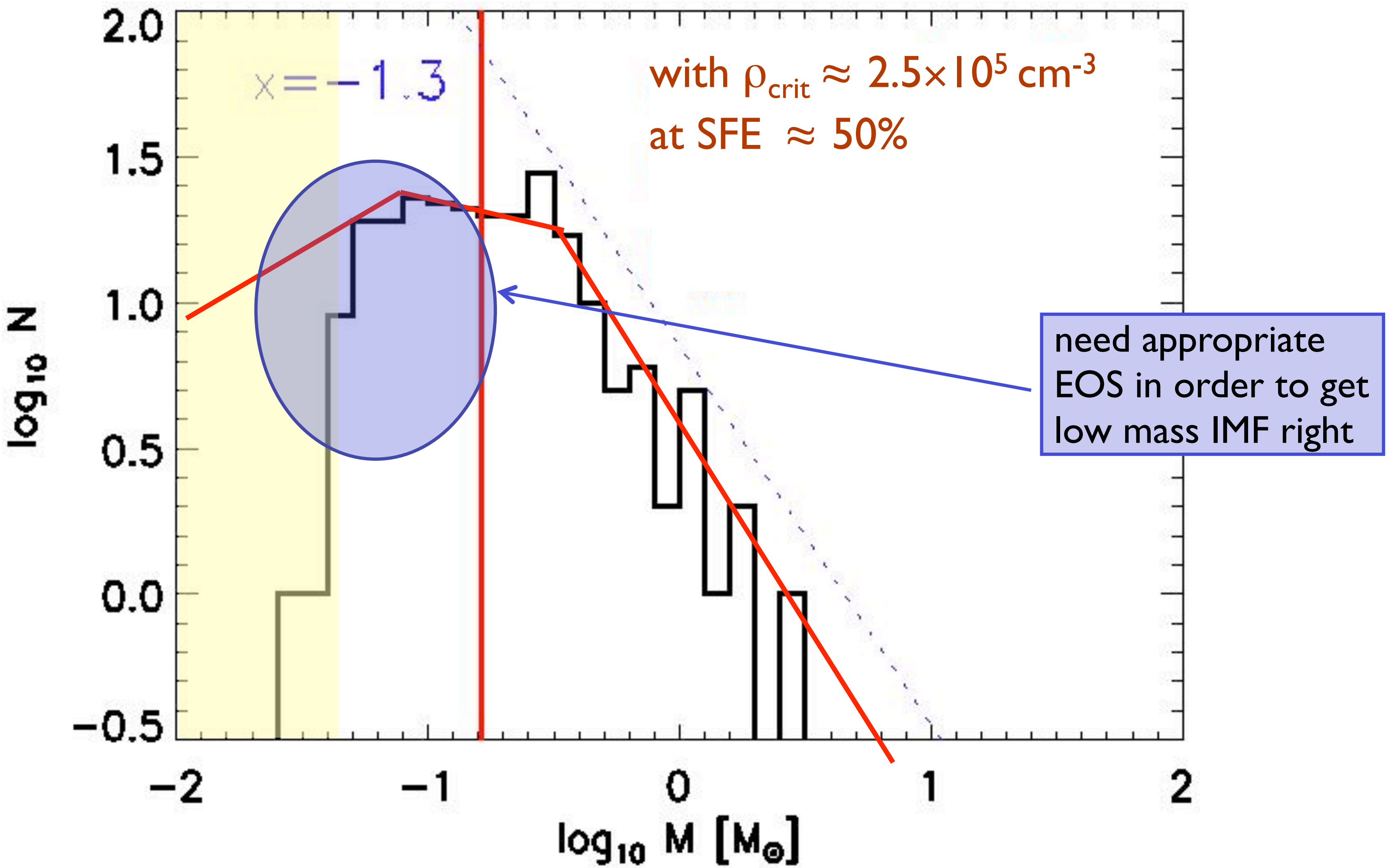


(Omukai et al. 2005, Jappsen et al. 2005, Larson 2005)

present-day star formation

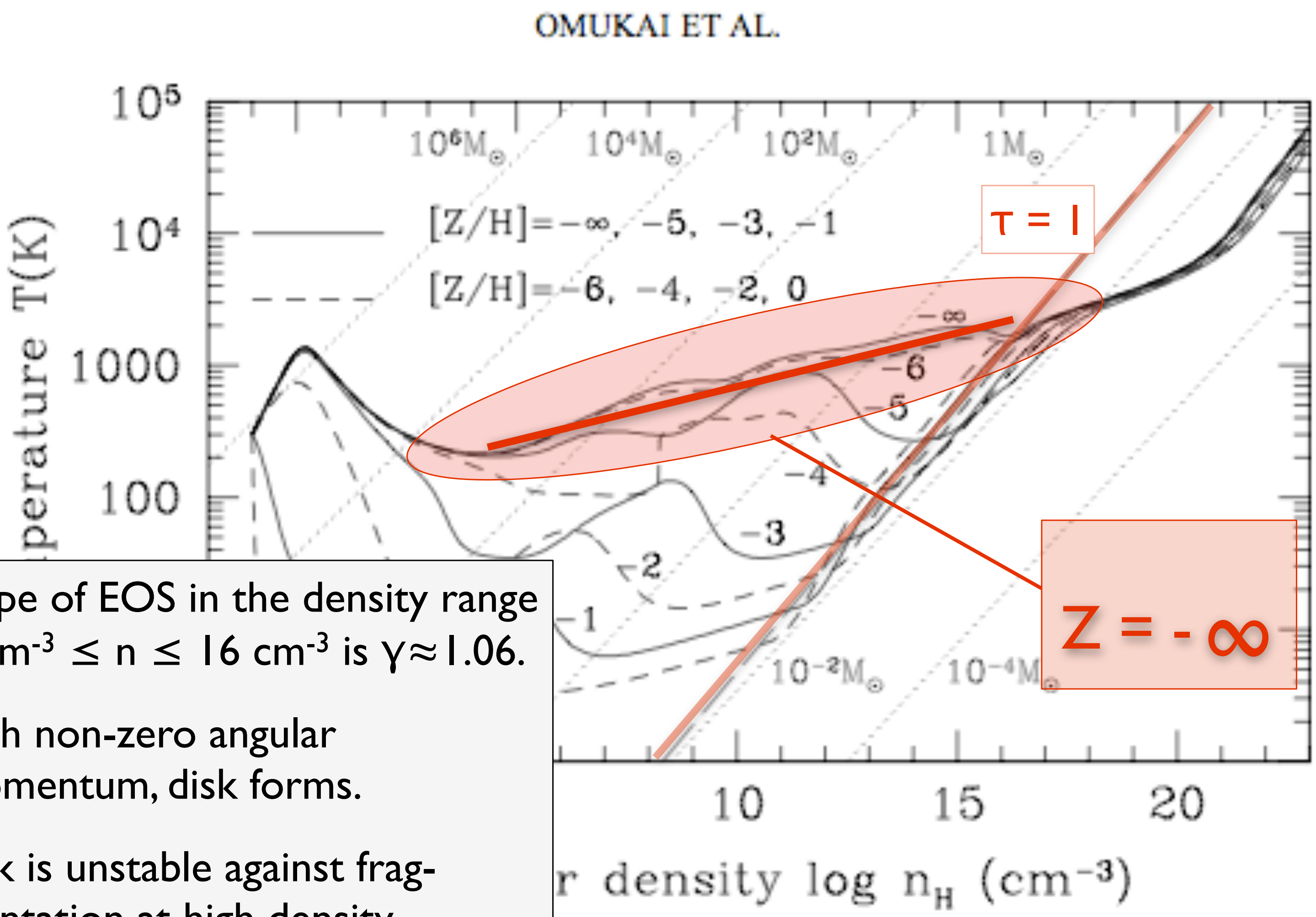


IMF in nearby molecular clouds



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

metal-free star formation



- 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 fragmentation at high density

(Omukai et al. 2005)

metal-free star formation

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

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

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

- there are some first hints of fragmentation, however

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

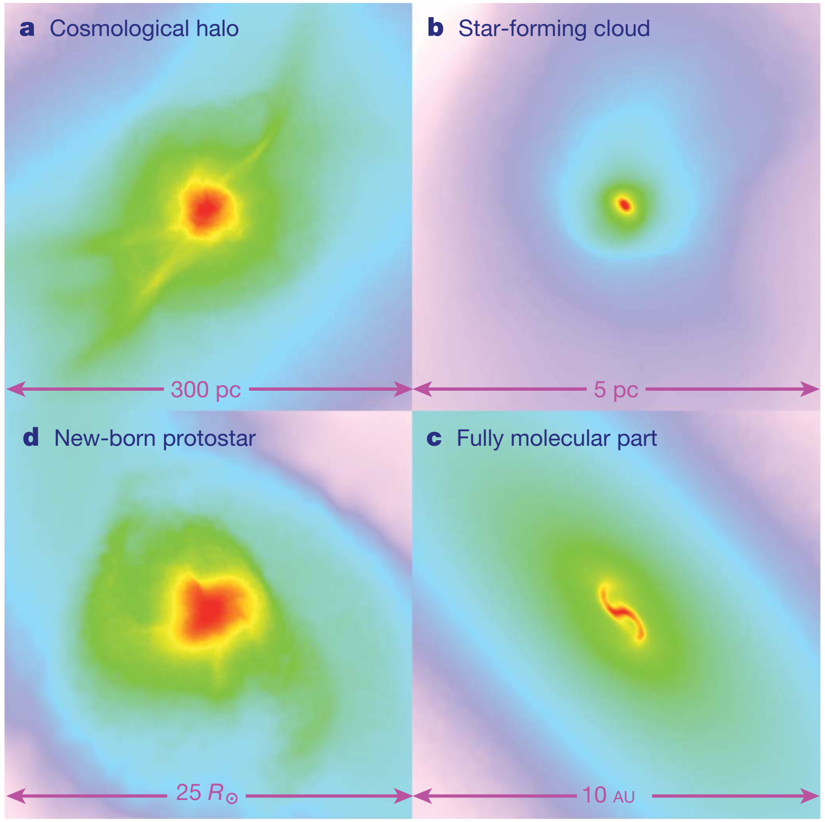
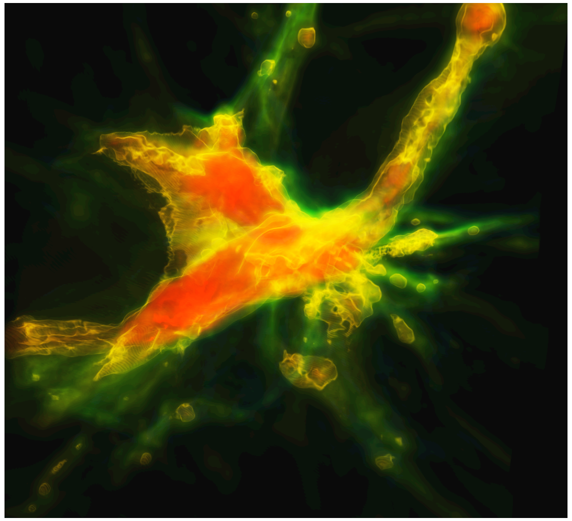


Figure 1 | Projected gas distribution around a primordial protostar. Shown is the gas density (colour-coded so that red denotes highest density) of a single object on different spatial scales. **a**, The large-scale gas distribution around the cosmological minihalo; **b**, a self-gravitating, star-forming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

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

turbulence in Pop III halos

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

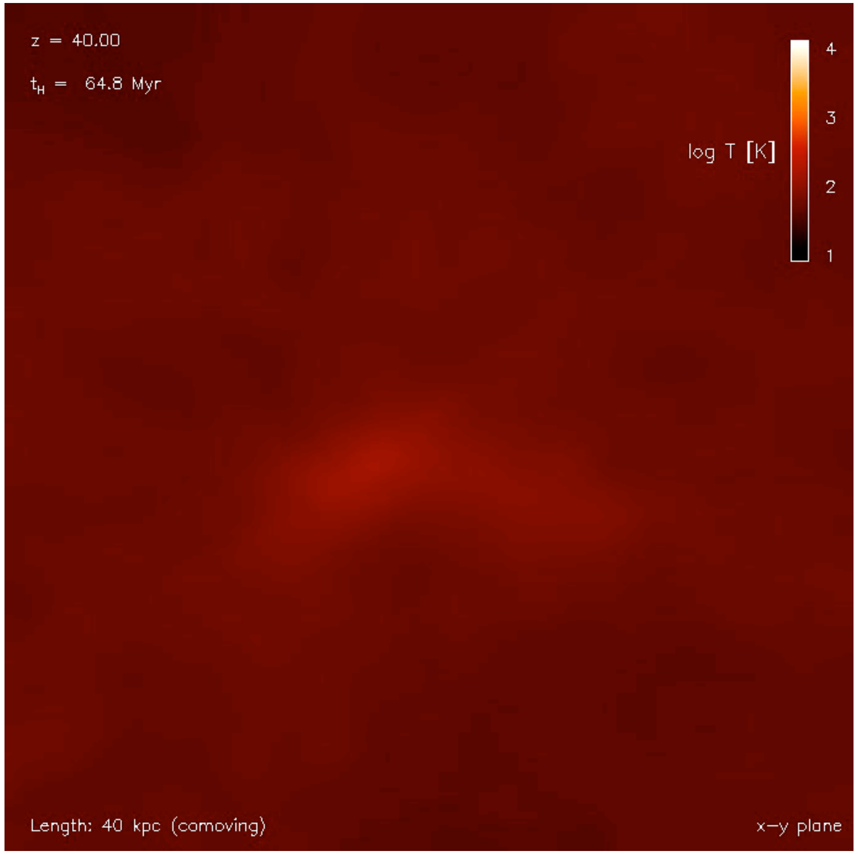


(Greif et al. 2008)

turbulence in Pop III halos

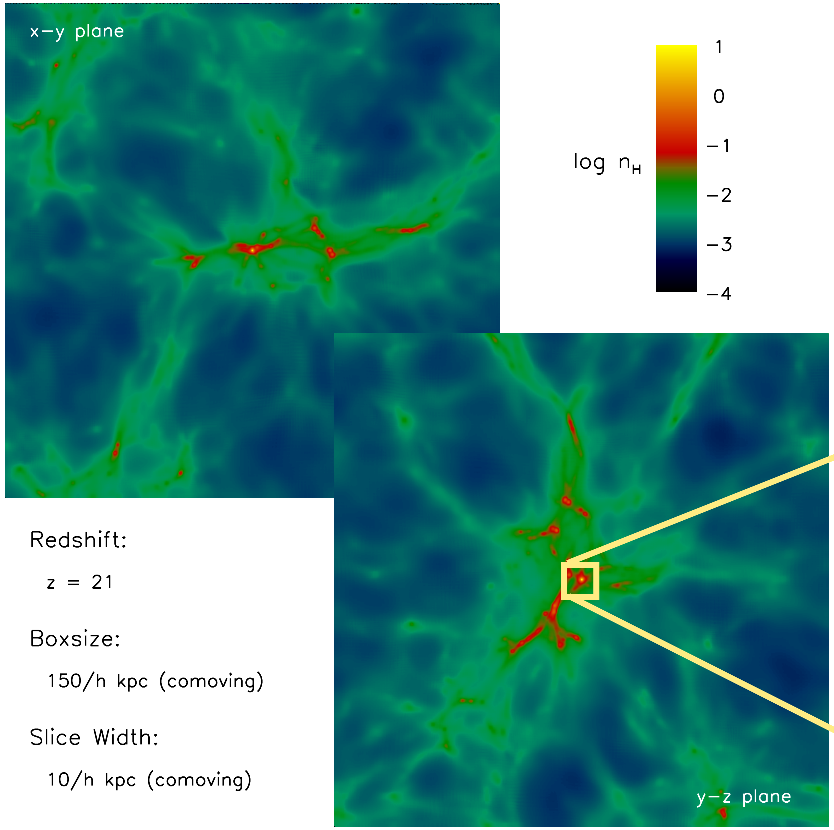
- star formation will depend on *degree of turbulence* in protogalactic halo
- speculation: *differences in stellar mass function*, just like in present-day star formation

turbulence developing in an atomic cooling halo

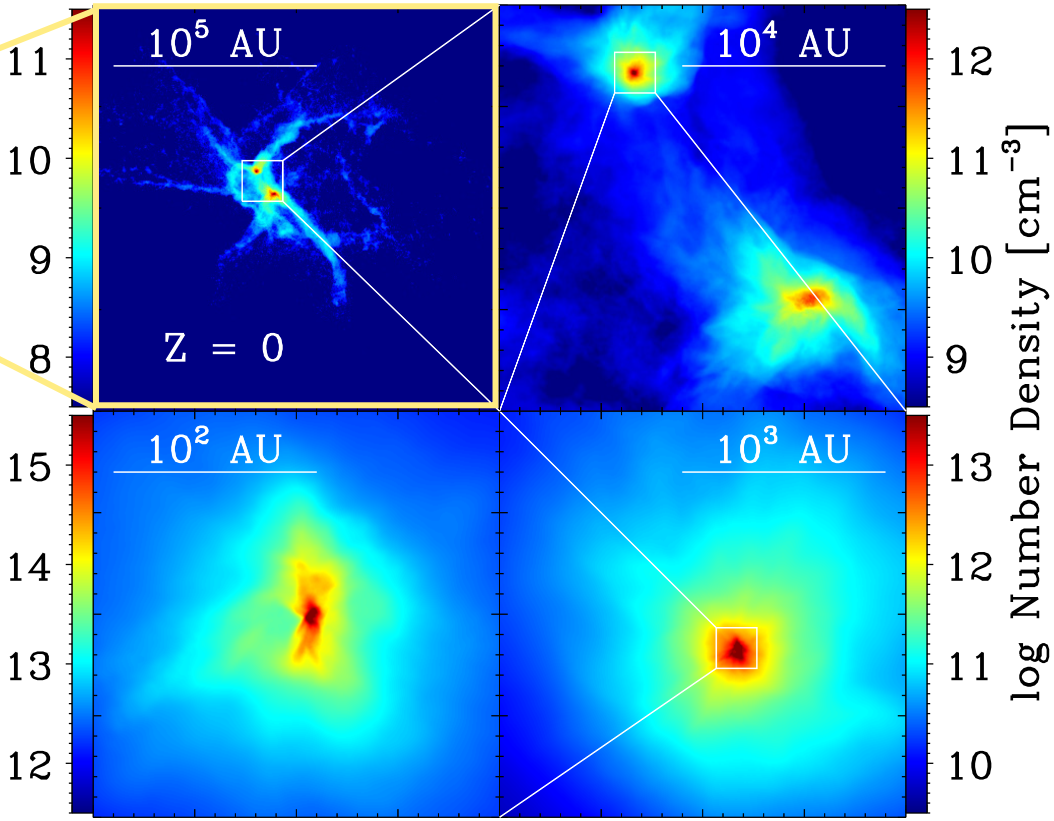


(Greif et al. 2008)

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)

(Dopcke et al., in preparation)

detailed look at accretion disk around first star

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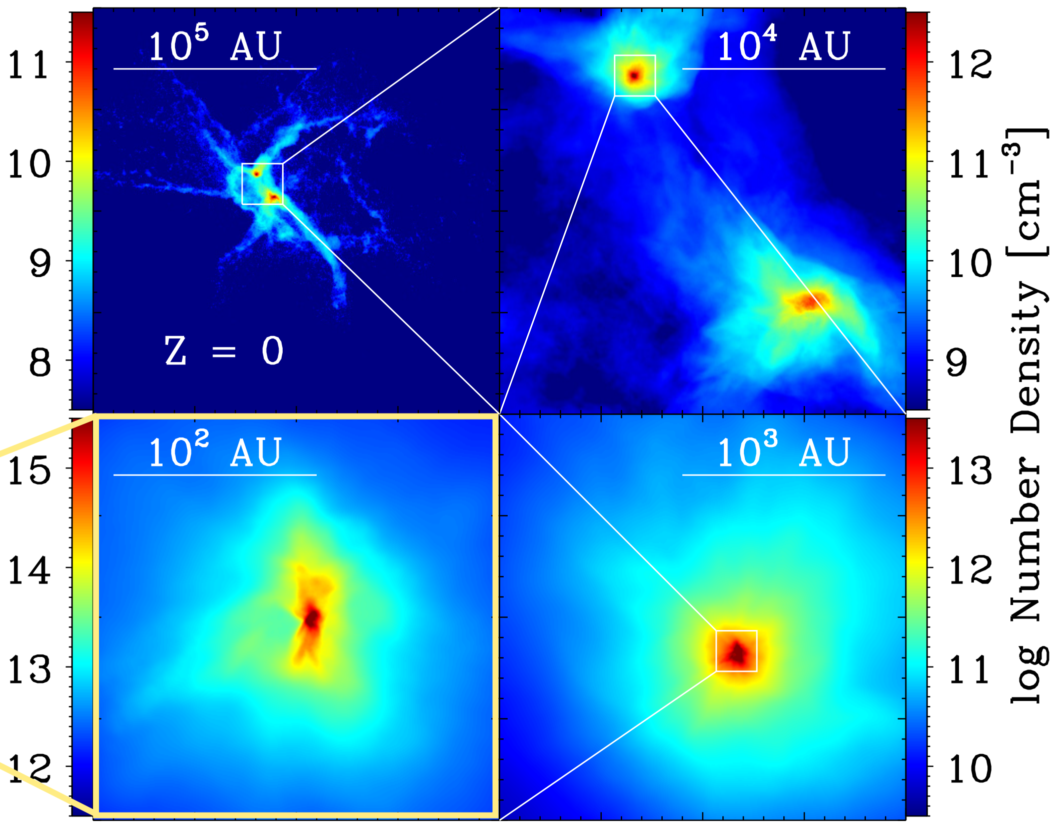
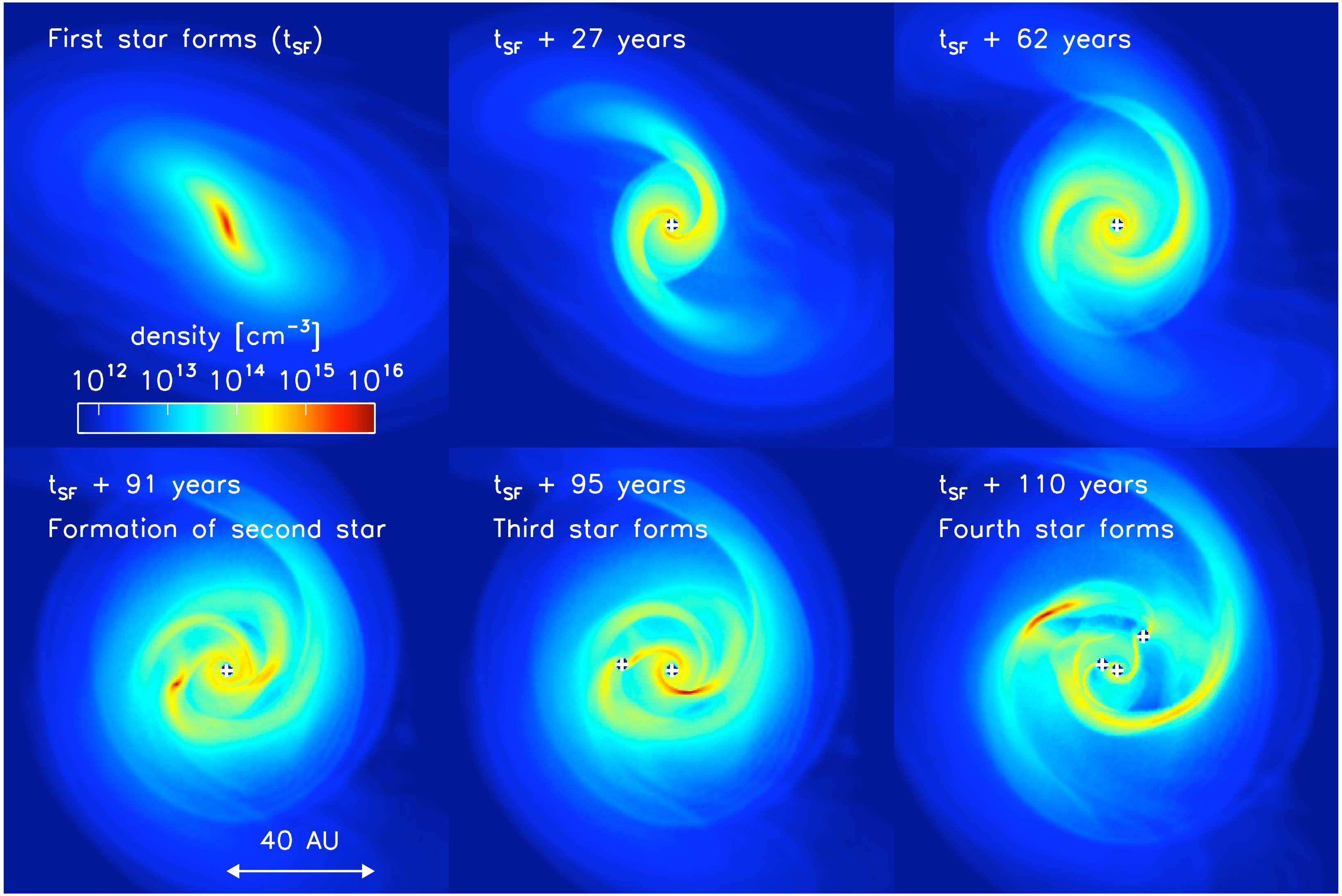


(Dopcke et al., in preparation)

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

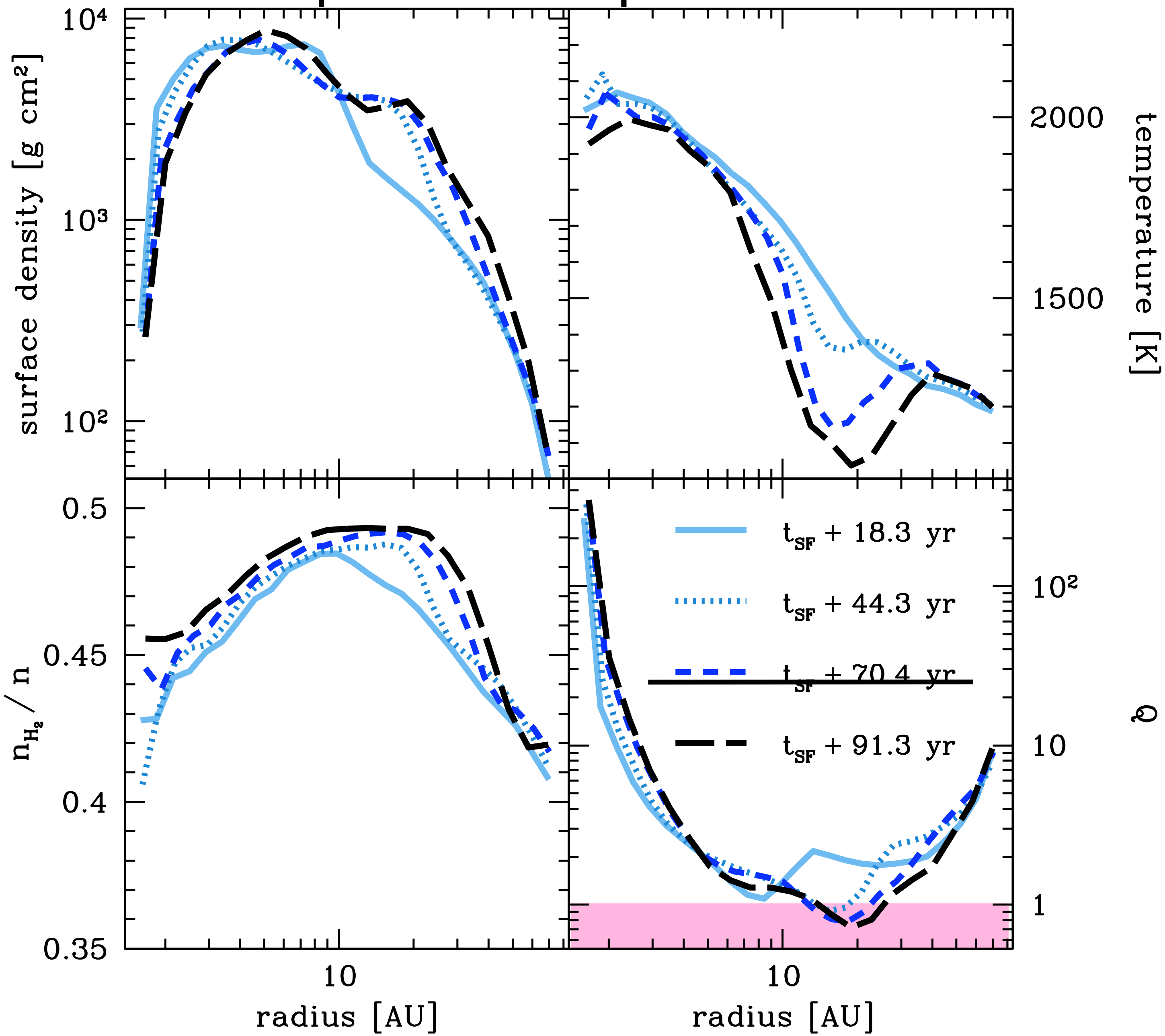


detailed look at accretion disk

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



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

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

comparison of all relevant heating and cooling processes

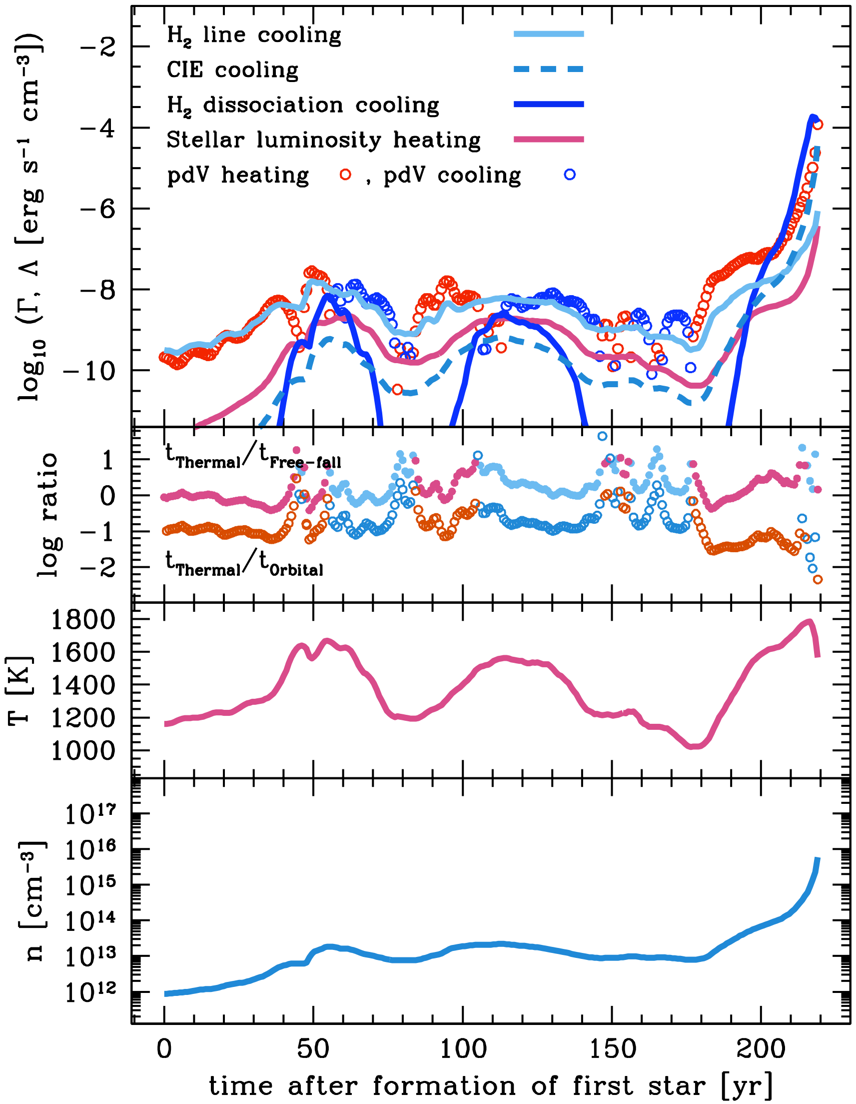
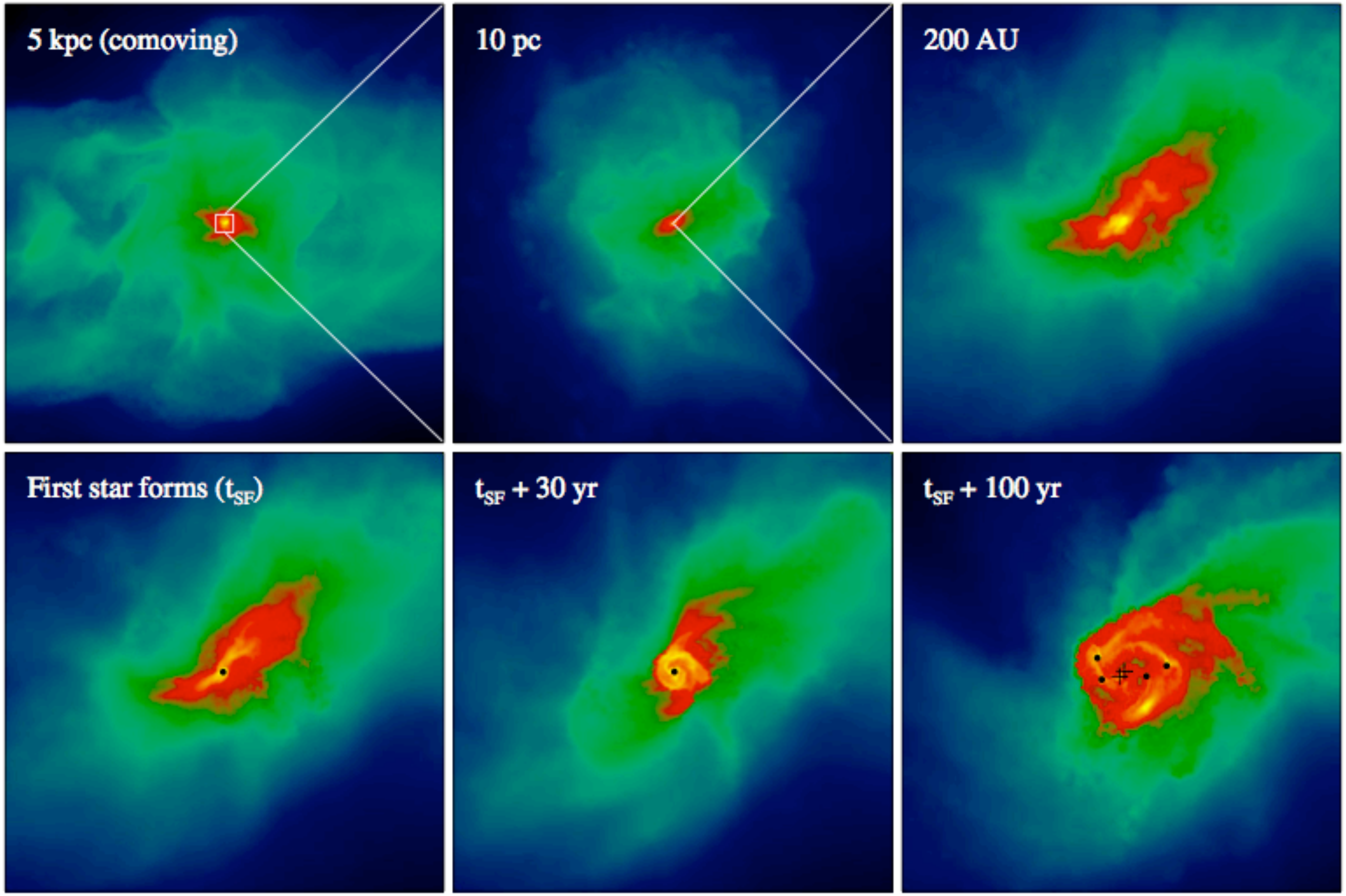


Figure 7: (a) Dominant heating and cooling processes in the gas that forms the second sink particle. (b) Upper line: ratio of the thermal timescale, $t_{\rm thermal}$, to the free-fall timescale, $t_{\rm ff}$, for the gas that forms the second sink particle. Periods when the gas is cooling are indicated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

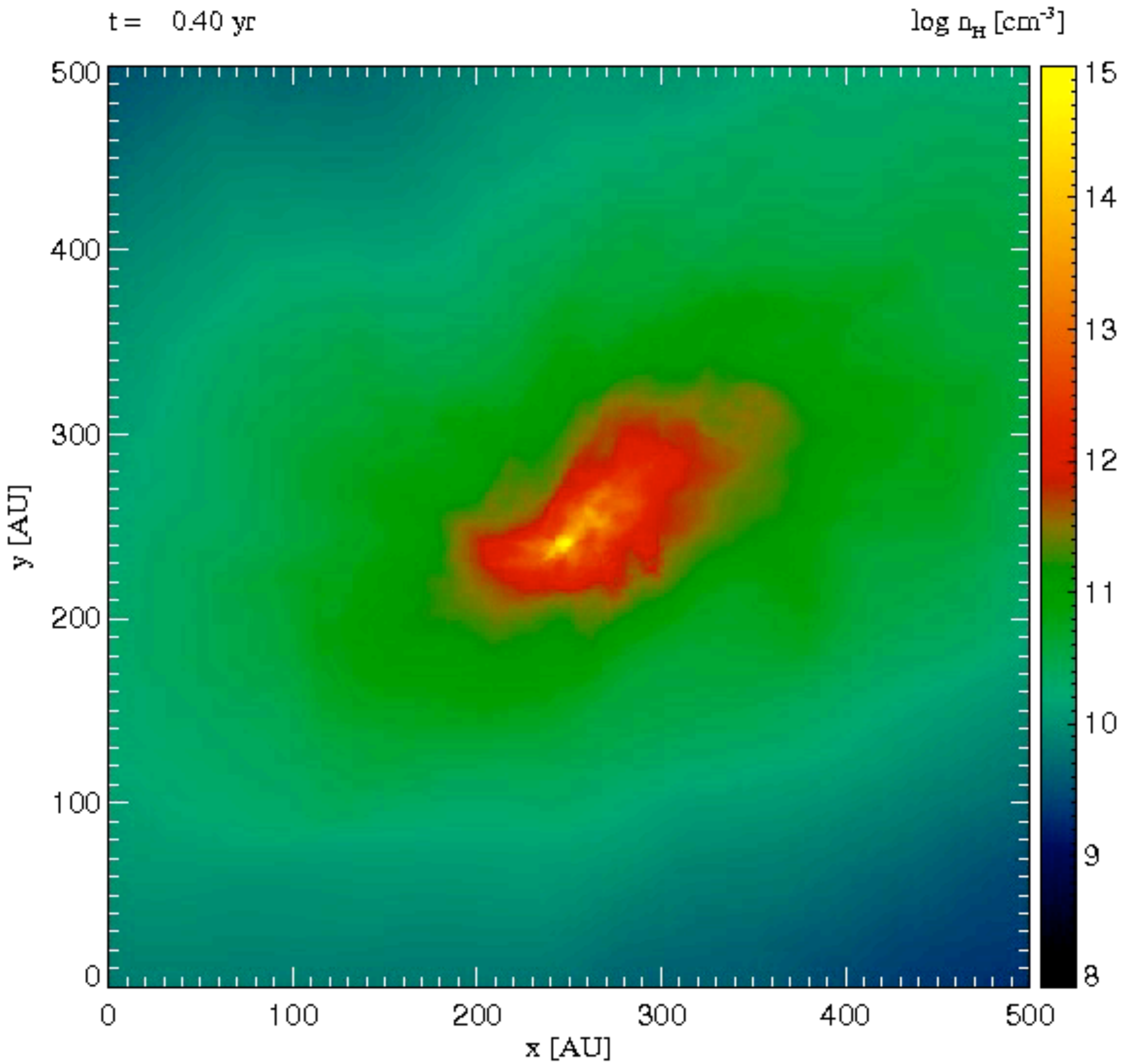
(Clark et al. 2011b, Science, 331, 1040)

similar study with very different numerical method (AREPO)



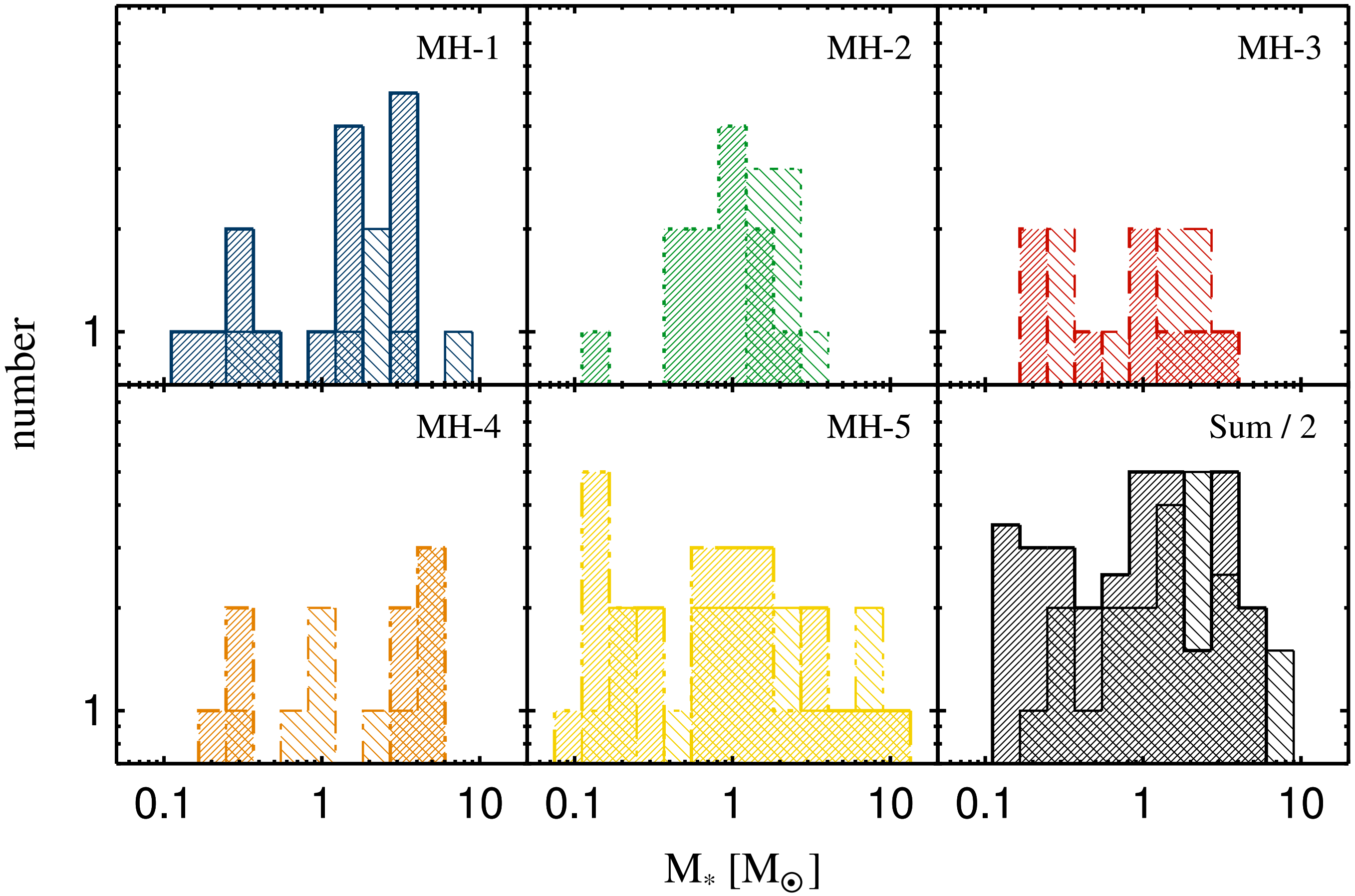
one out of five halos

(Greif et al. 2011a, ApJ)



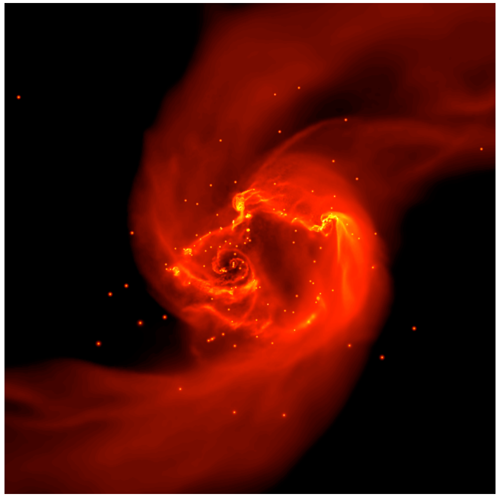
(Greif et al. 2011a, ApJ)

Arepo study: mass spectrum of fragments



(Greif et al. 2011a, ApJ)

primordial star formation



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

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


Carina with HST

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

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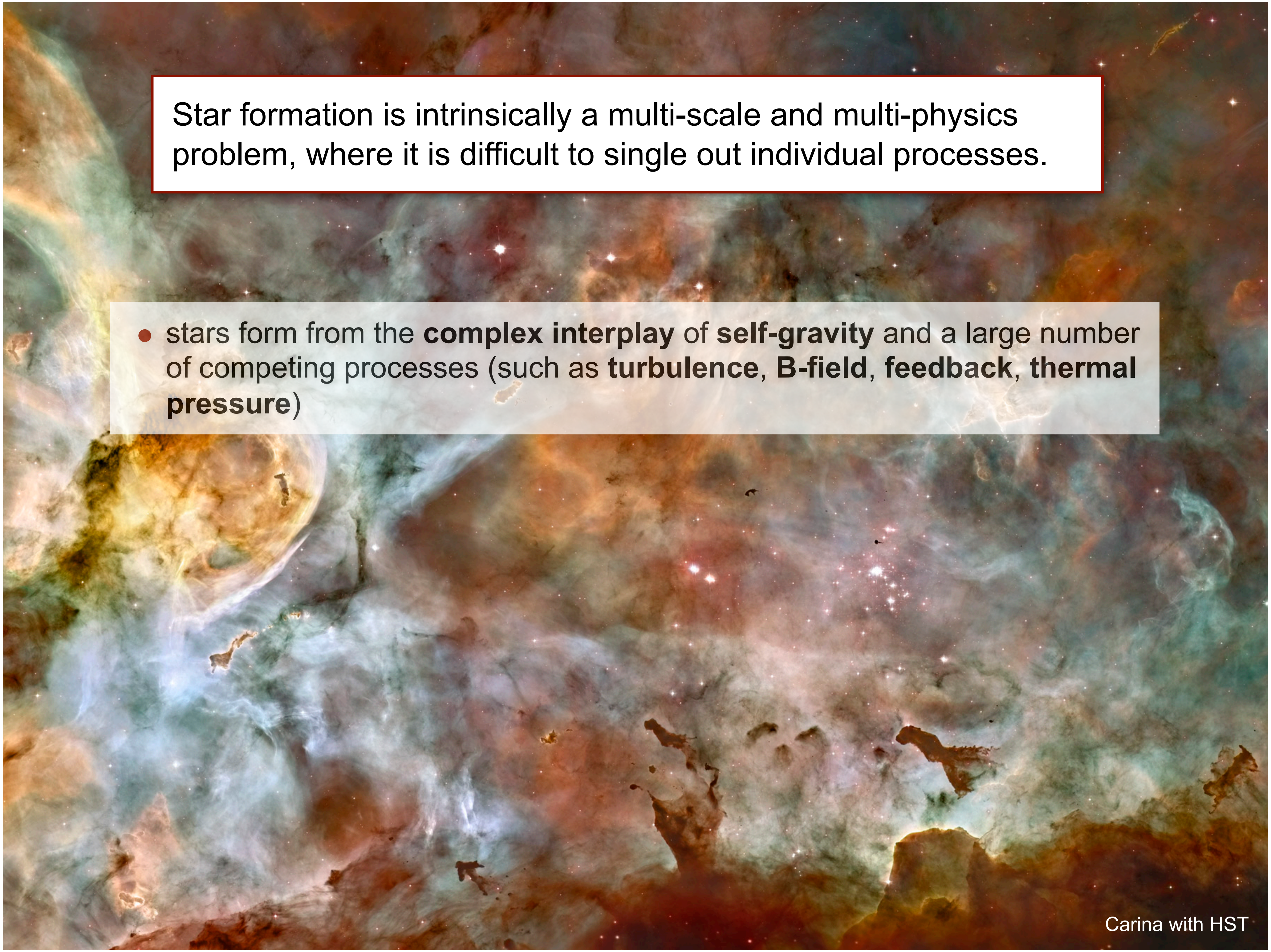
- stars form from the **complex interplay** of **self-gravity** and a large number of competing processes (such as **turbulence**, **B-field**, **feedback**, **thermal pressure**)



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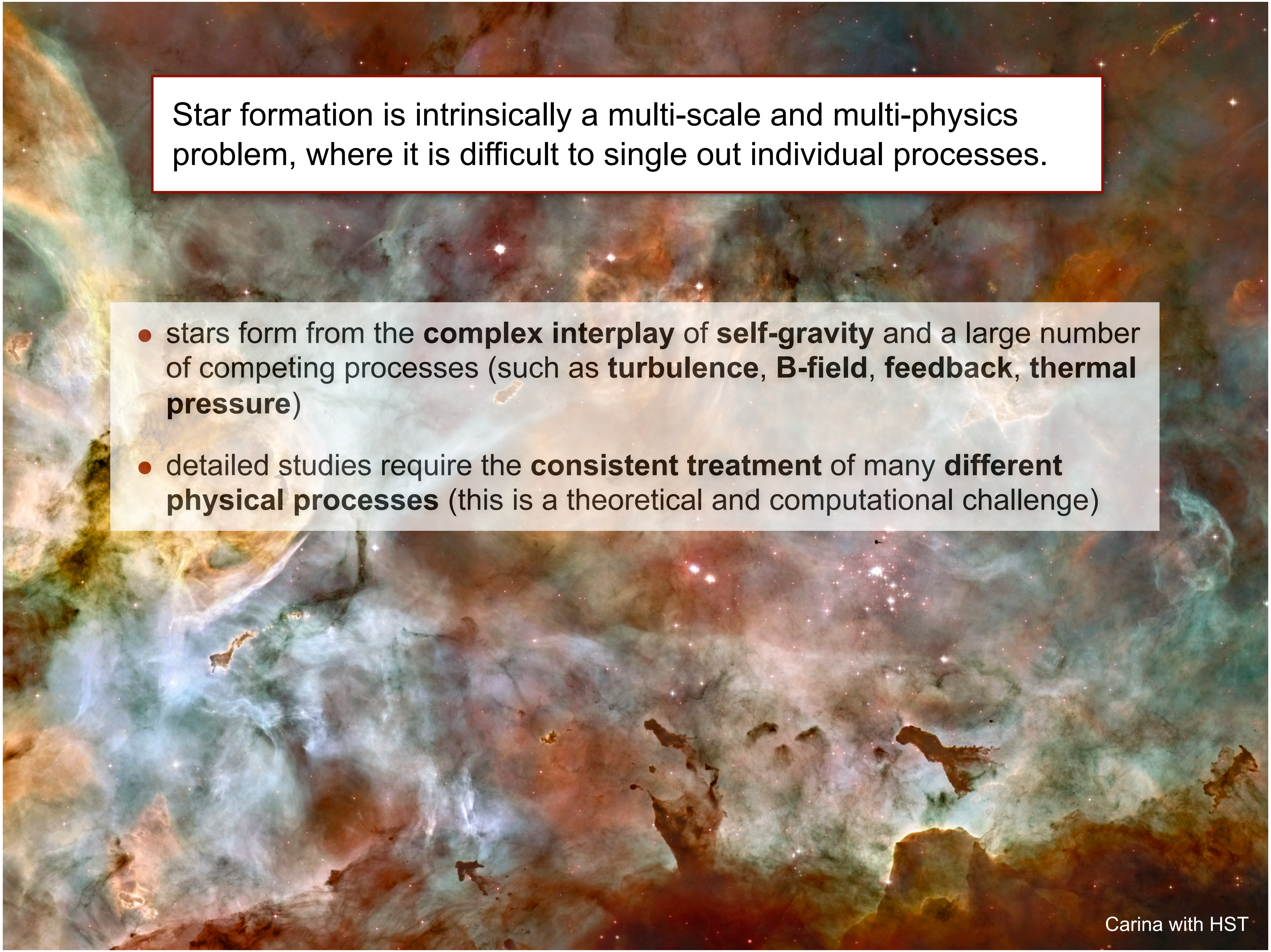

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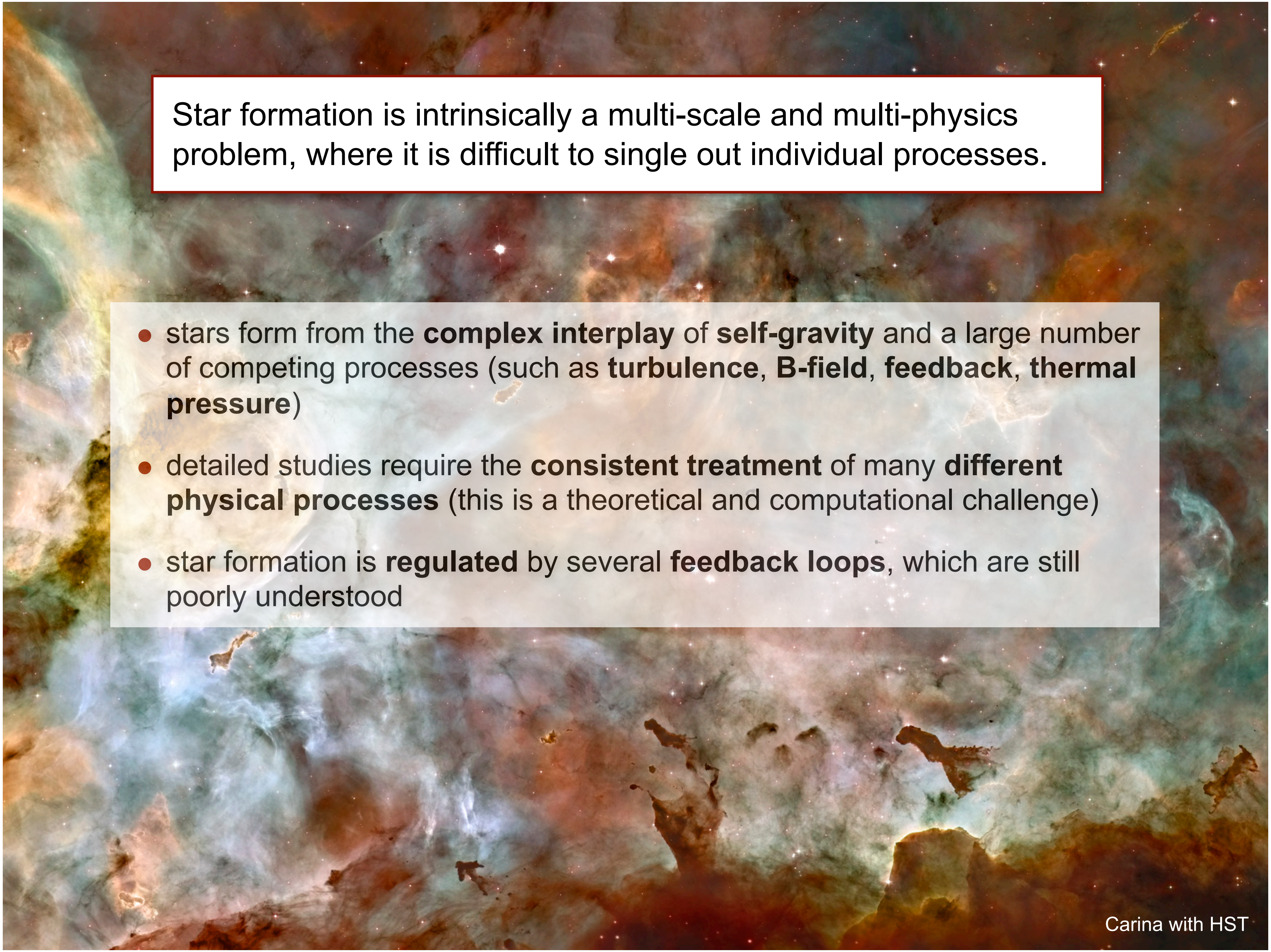

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studying the processes that initiate and regulate the birth of stars is a highly challenging and exciting field of astrophysics

Carina with HST


PPVI comes to Heidelberg
in summer 2013


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in summer 2013
... hope to see you there!!!