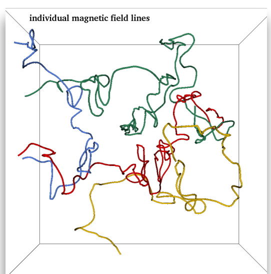
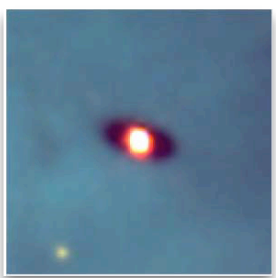
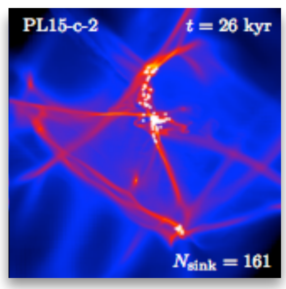
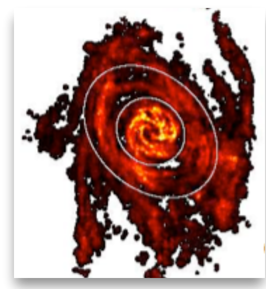
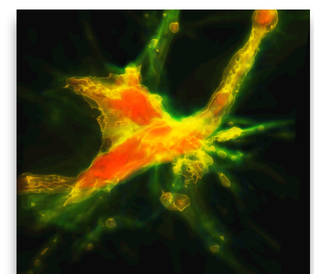
From Molecular Clouds to Star Formation







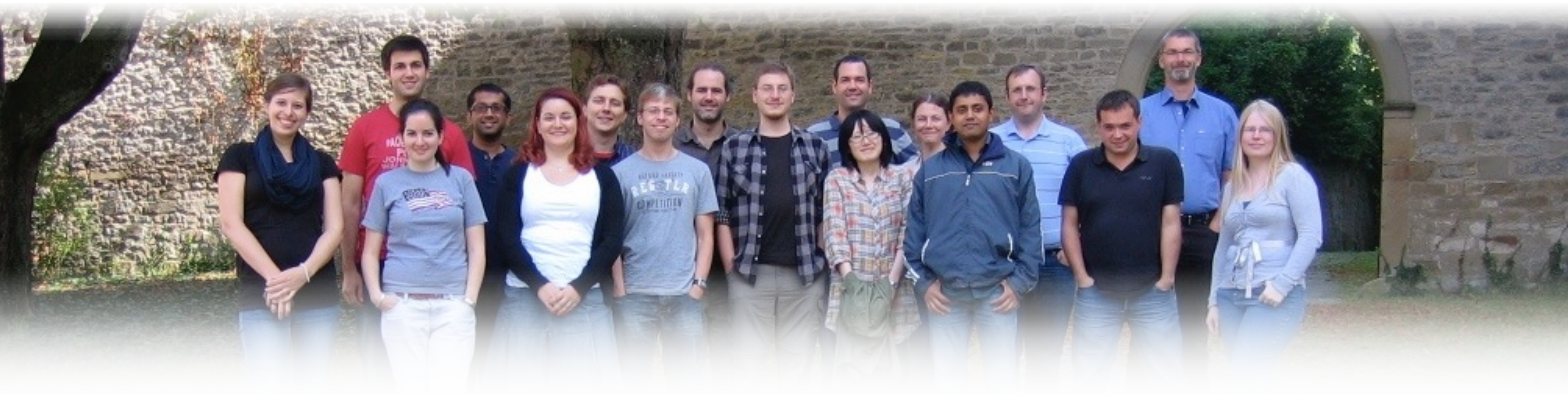




Ralf Klessen

Universität Heidelberg, Zentrum für Astronomie
Institut für Theoretische Astrophysik

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:

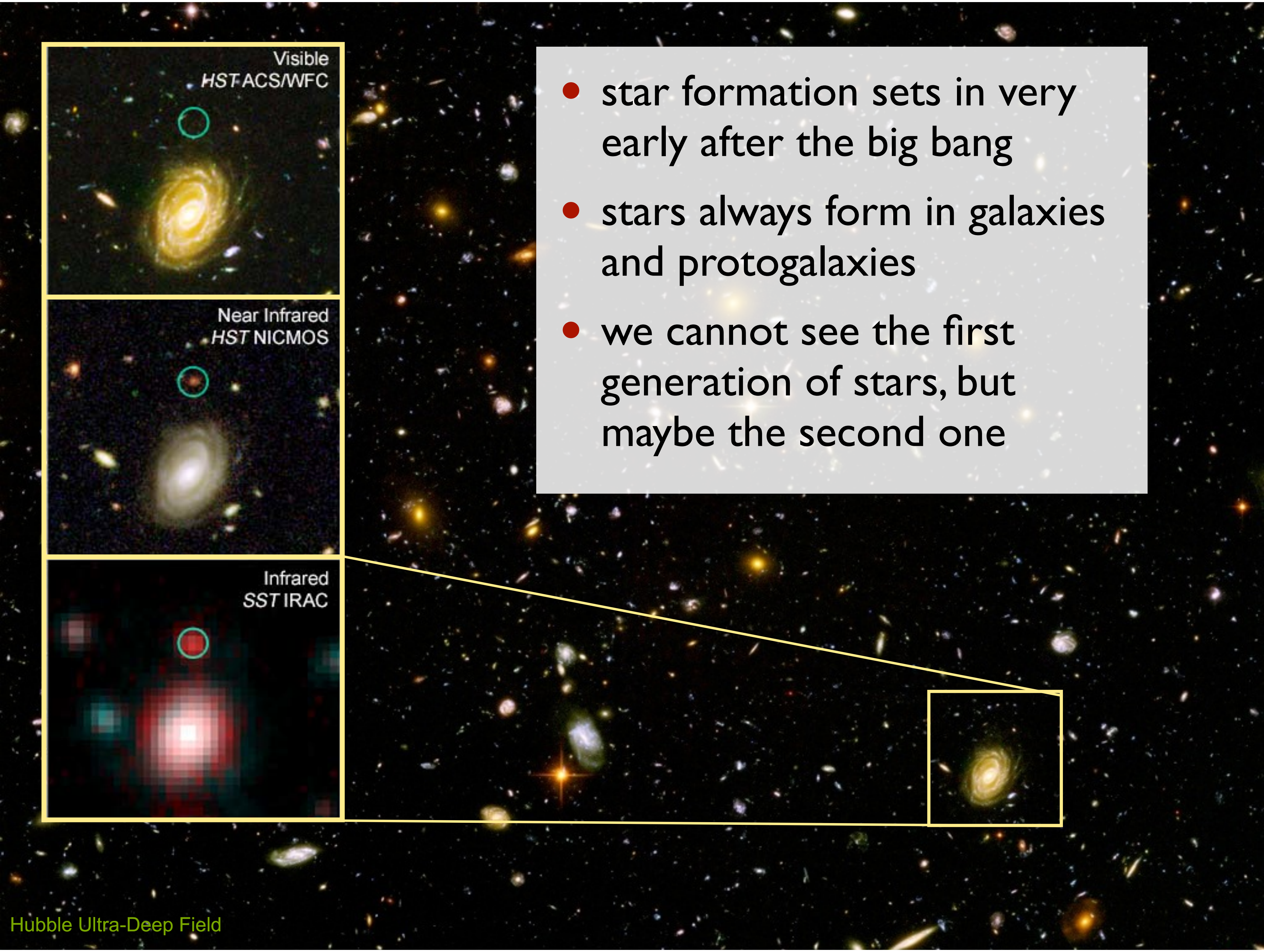
Robi Banerjee, Ingo Berentzen, Paul Clark, Christoph Federrath, Philipp Girichidis, Thomas Greif, Milica Micic, Thomas Peters, Dominik Schleicher, Stefan Schmeja, Sharanya Sur, . . .

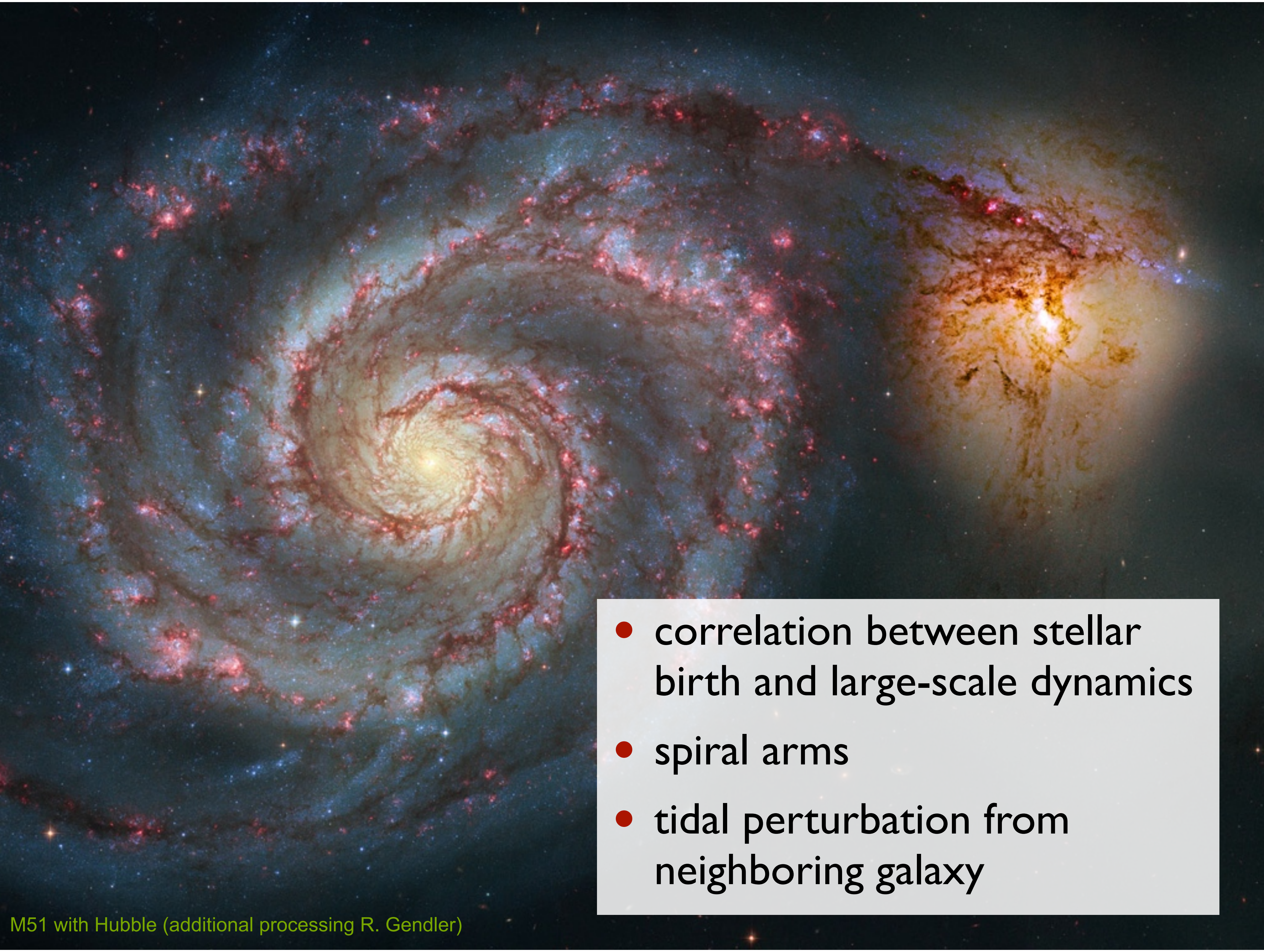
... many collaborators abroad!

Deutsche Forschungsgemeinschaft DFG
DFG Priority Program 1573 ISM-SPP Interstellar Medium
BADEN-WÜRTTEMBERG STIFTUNG Wir stiften Zukunft
HGSFP
IMPRS
erc European Research Council

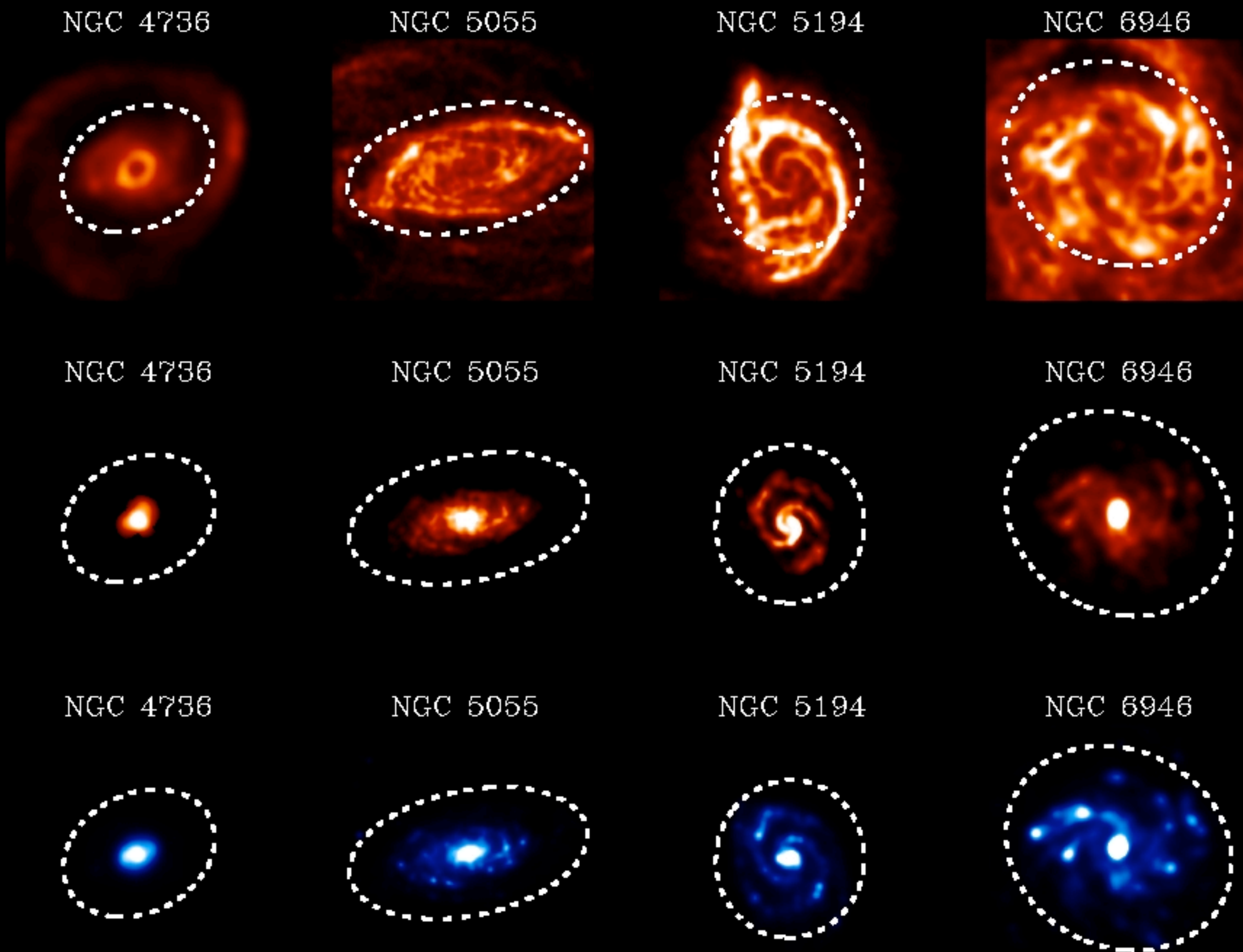
Phenomenology

- 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





M51 with Hubble (additional processing R. Gendler)



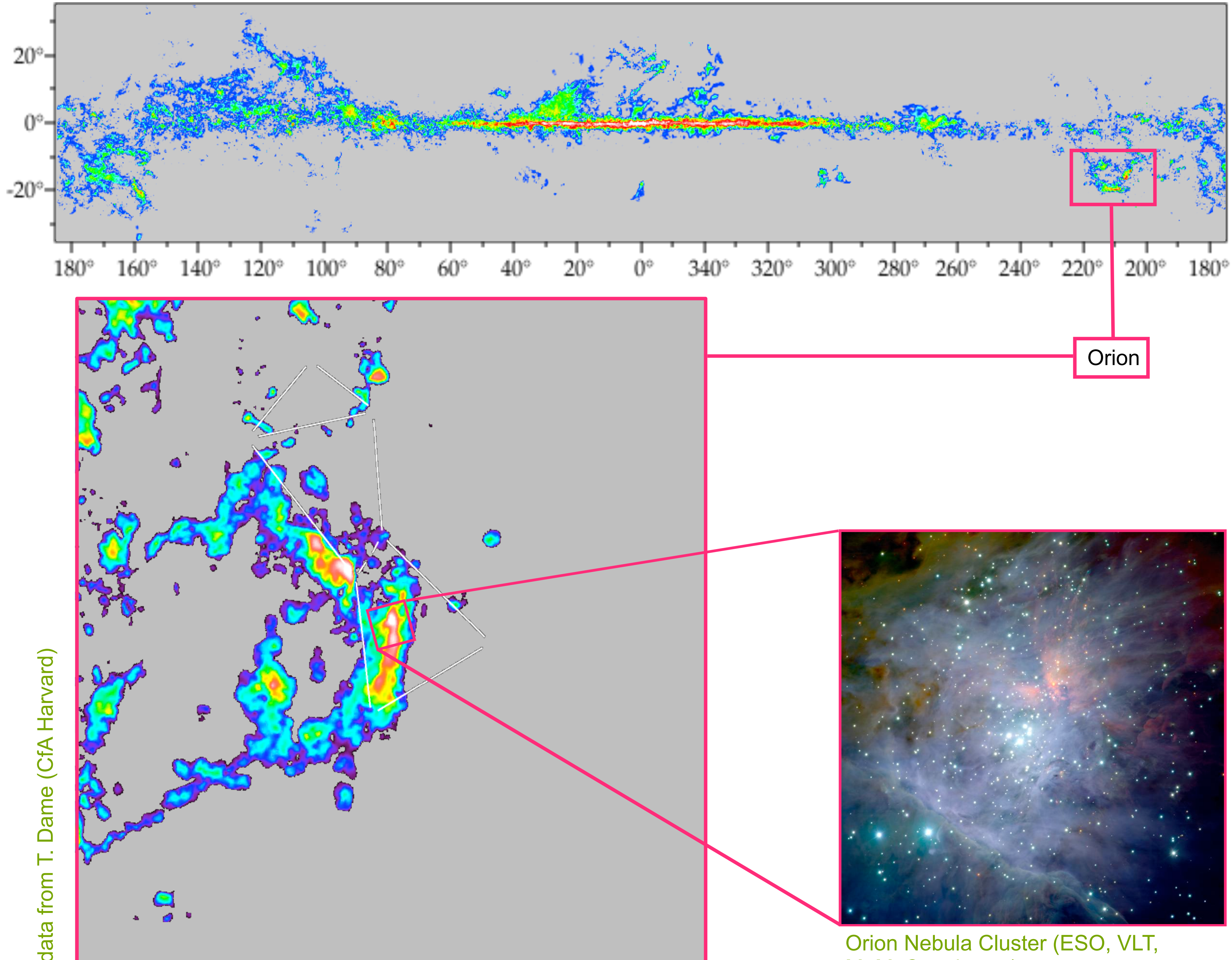
atomic hydrogen

molecular hydrogen

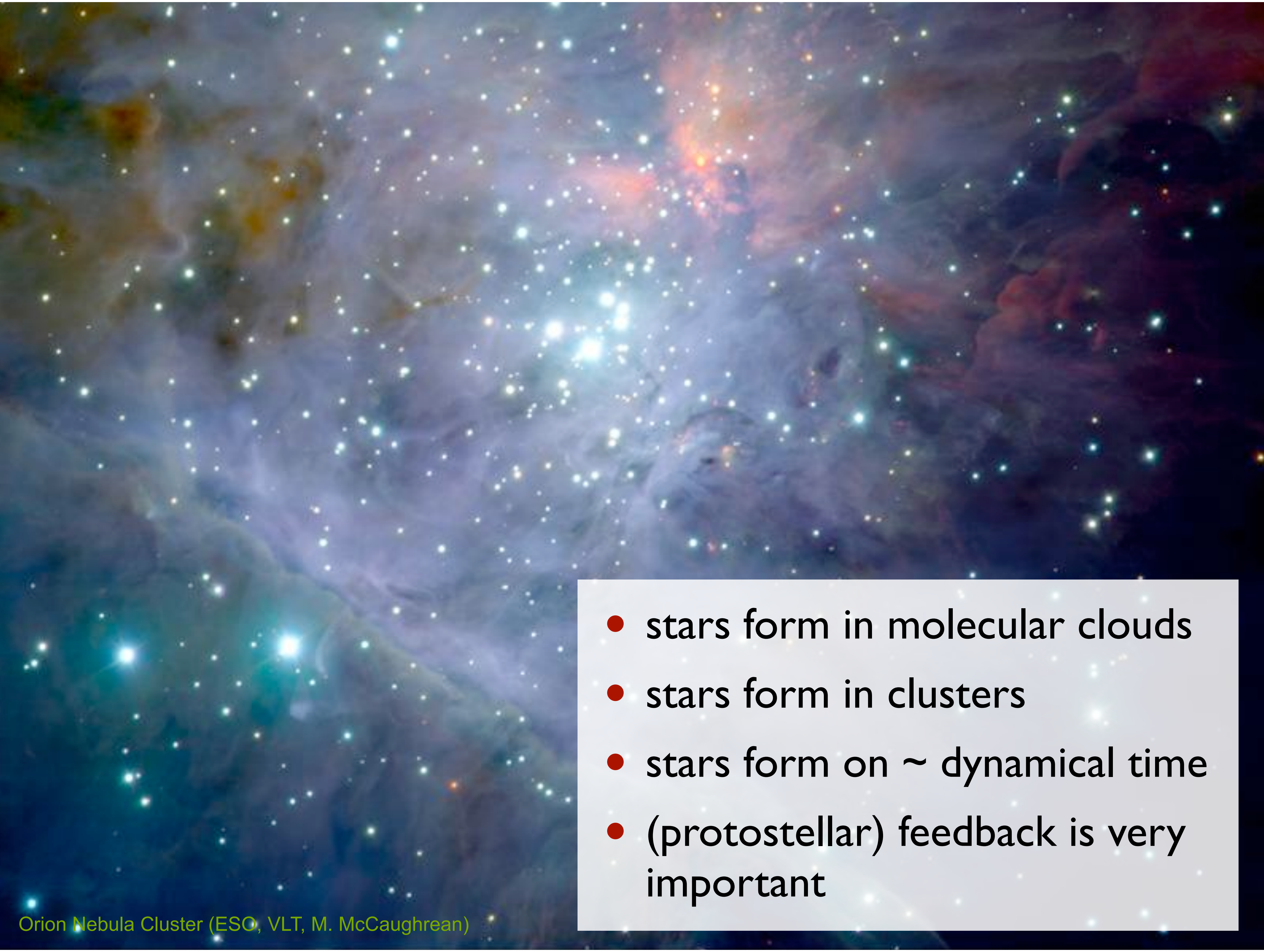
star formation

- HI gas more extended
- H2 and SF well correlated

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



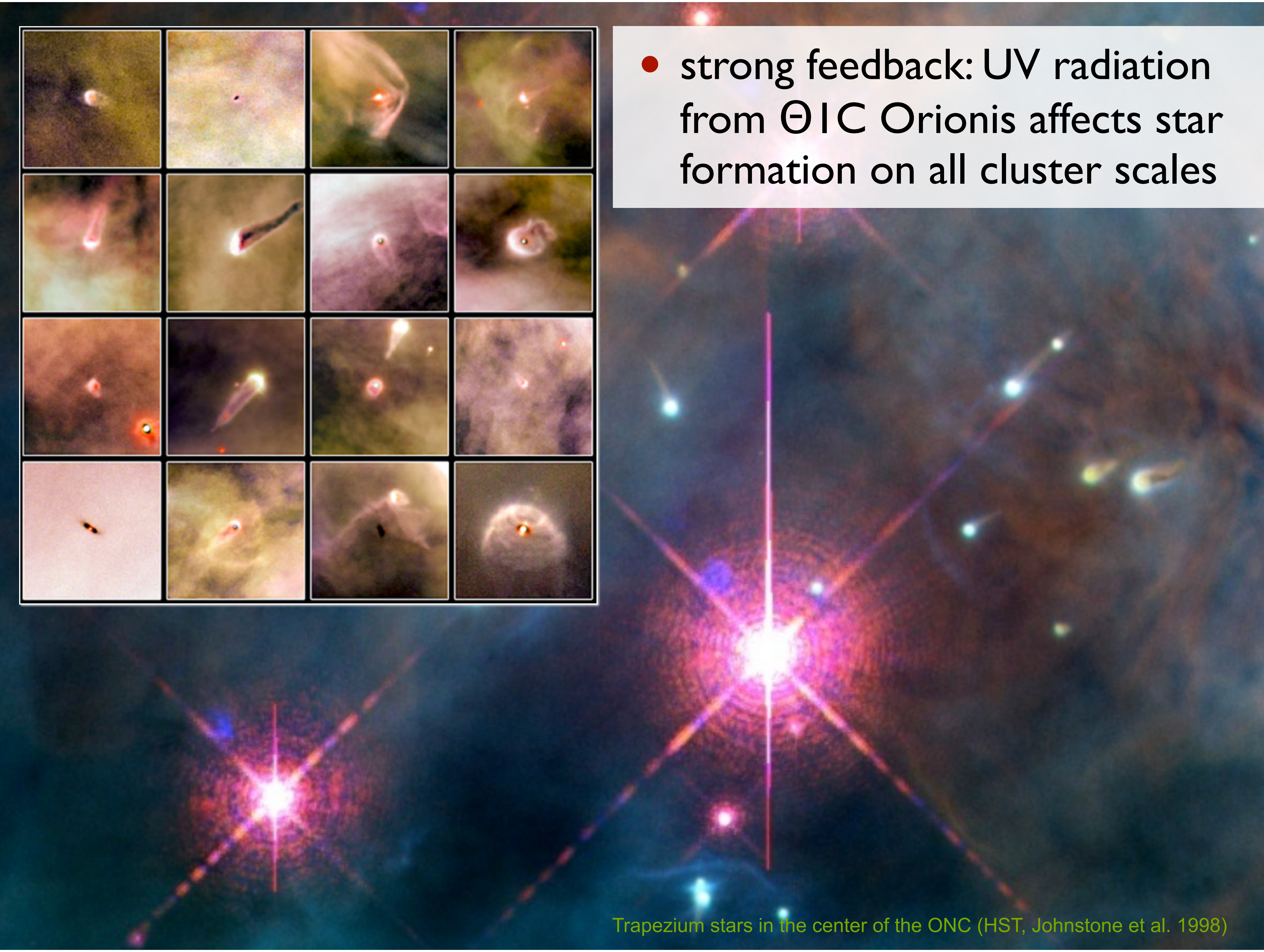
Orion Nebula Cluster (ESO, VLT,
M. McCaughrean)



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

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



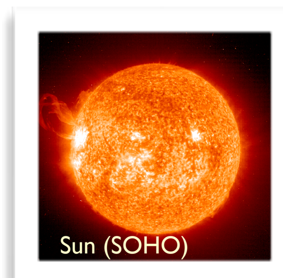
Trapezium stars in the center of the ONC (HST, Johnstone et al. 1998)

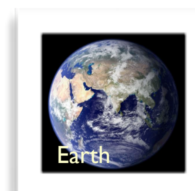
eventually, clusters like the ONC (1 Myr) will evolve into clusters like the Pleiades (100 Myr)

Pleiades (DSS, Palomar Observatory Sky Survey)

theoretical
approach

decrease in spatial scale / increase in density





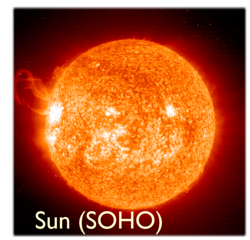
- density
  - density of ISM: few particles per cm^3
  - density of molecular cloud: few 100 particles per cm^3
  - density of Sun: 1.4 g/cm^3
- spatial scale
  - size of molecular cloud: few 10s of pc
  - size of young cluster: ~ 1 pc
  - size of Sun: 1.4×10^{10} cm

decrease in spatial scale / increase in density


Andromeda (R. Gendler)


NGC 602 in LMC (Hubble)


Proplyd in Orion (Hubble)


Sun (SOHO)


Earth

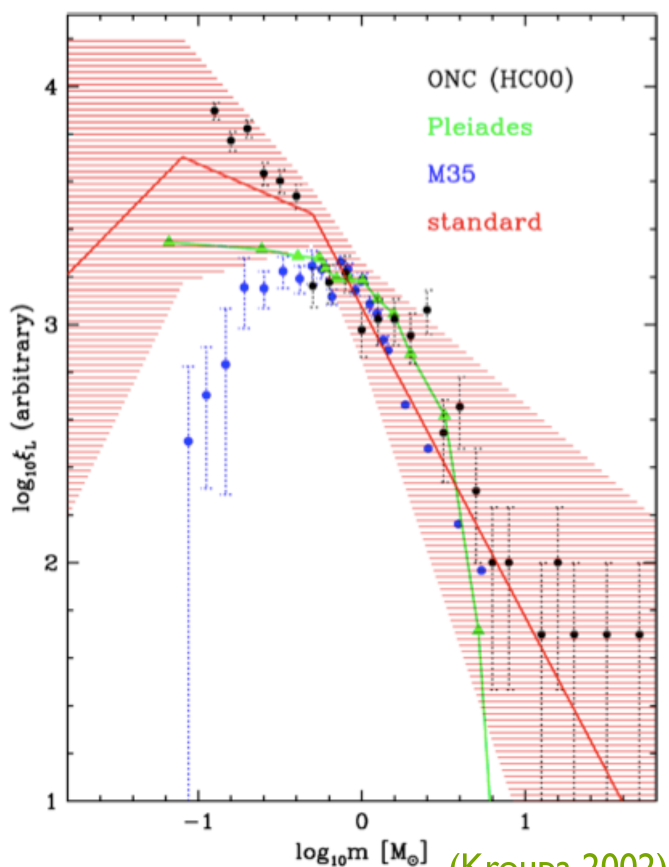
- contracting force
  - only force that can do this compression is *GRAVITY*
- opposing forces
  - there are several processes that can oppose gravity
  - *GAS PRESSURE*
  - *TURBULENCE*
  - *MAGNETIC FIELDS*
  - *RADIATION PRESSURE*

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

from clouds
to stars

stellar mass fuction

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



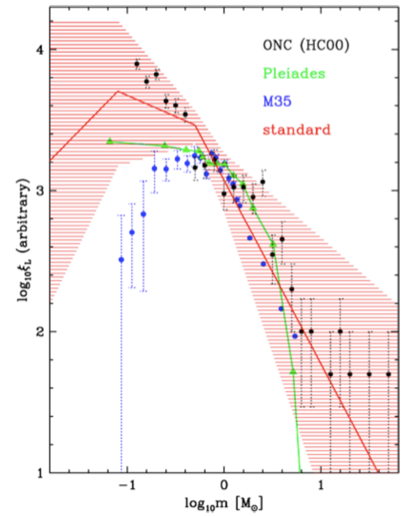
(Kroupa 2002)

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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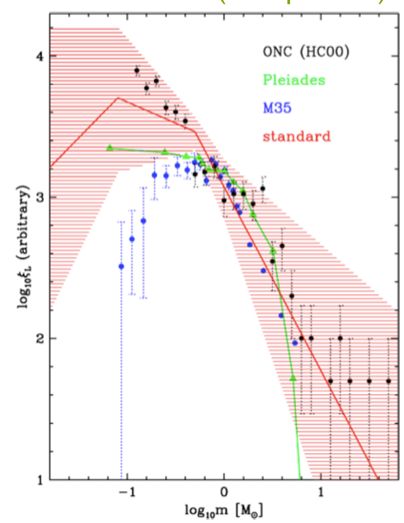
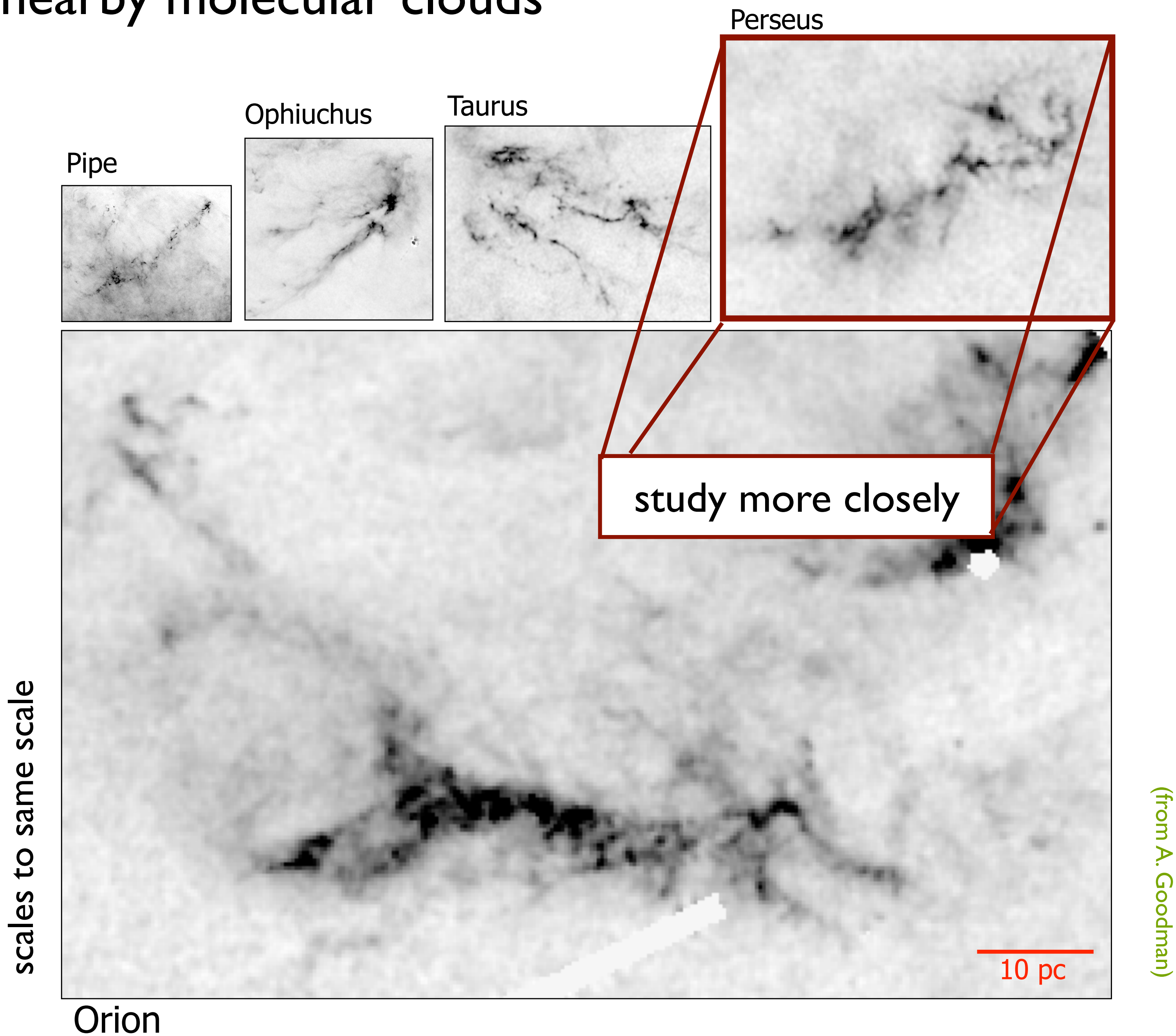


nearby molecular clouds



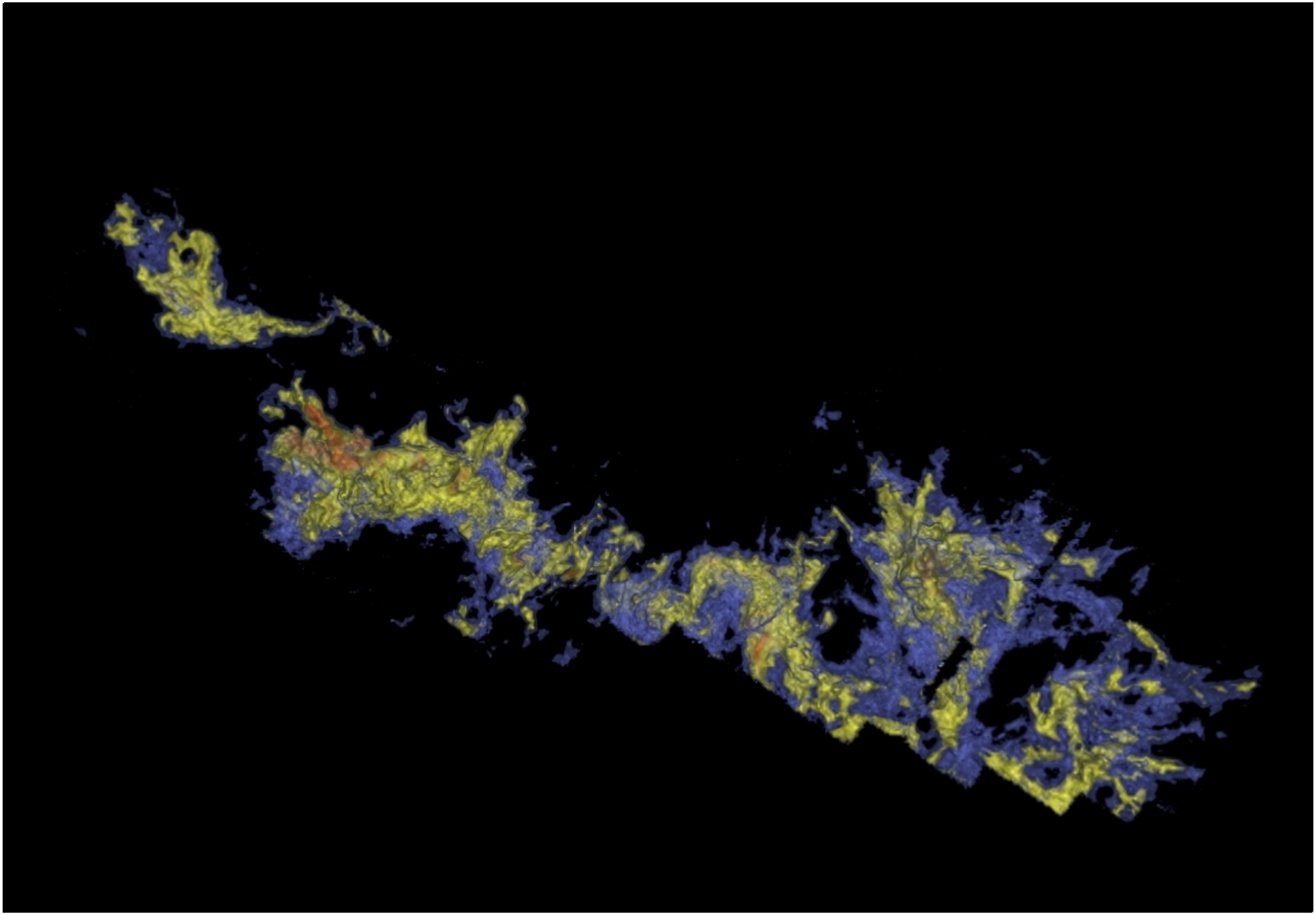
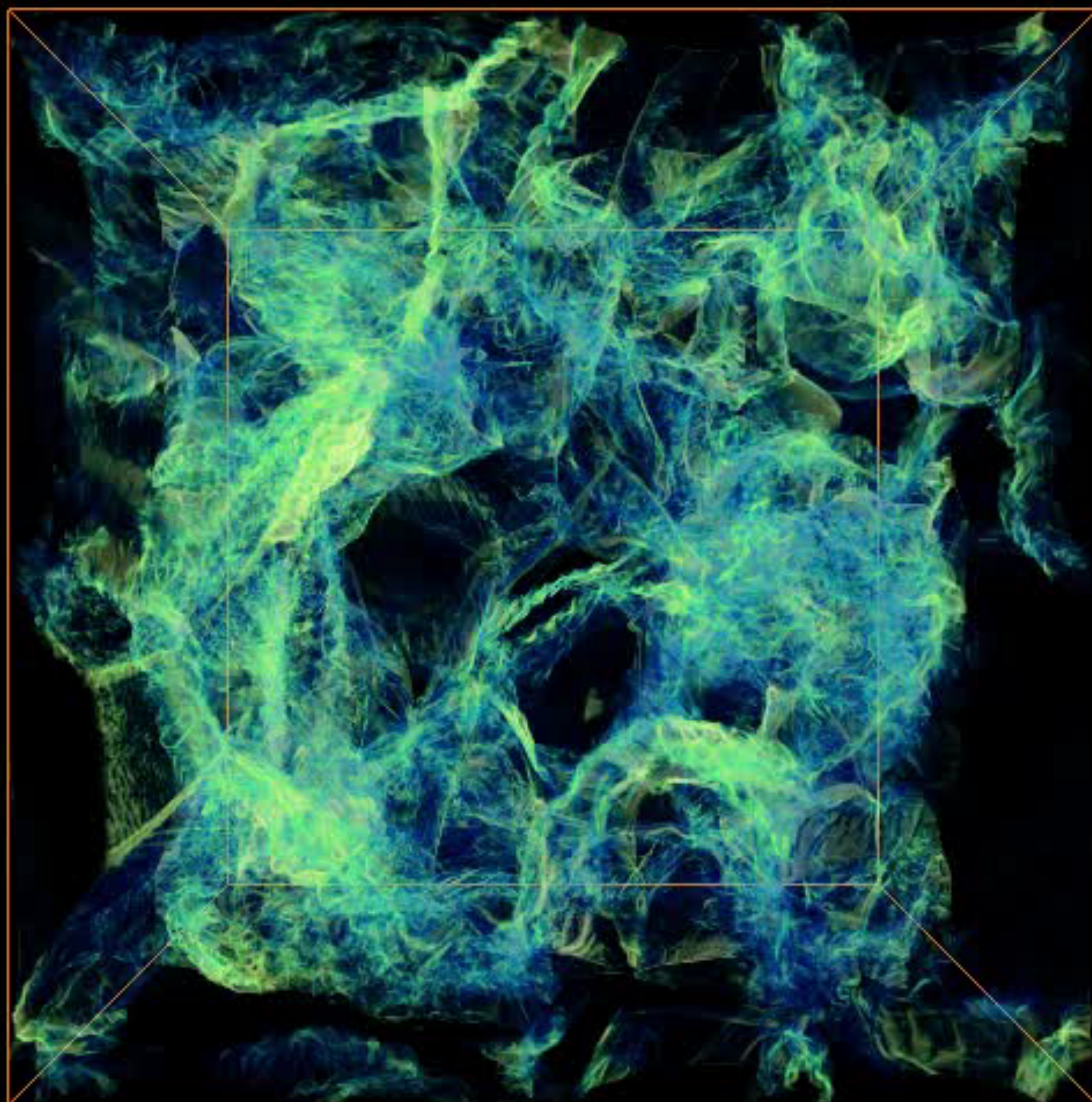


image from Alyssa Goodman: COMPLETE survey



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

example: model of Orion cloud

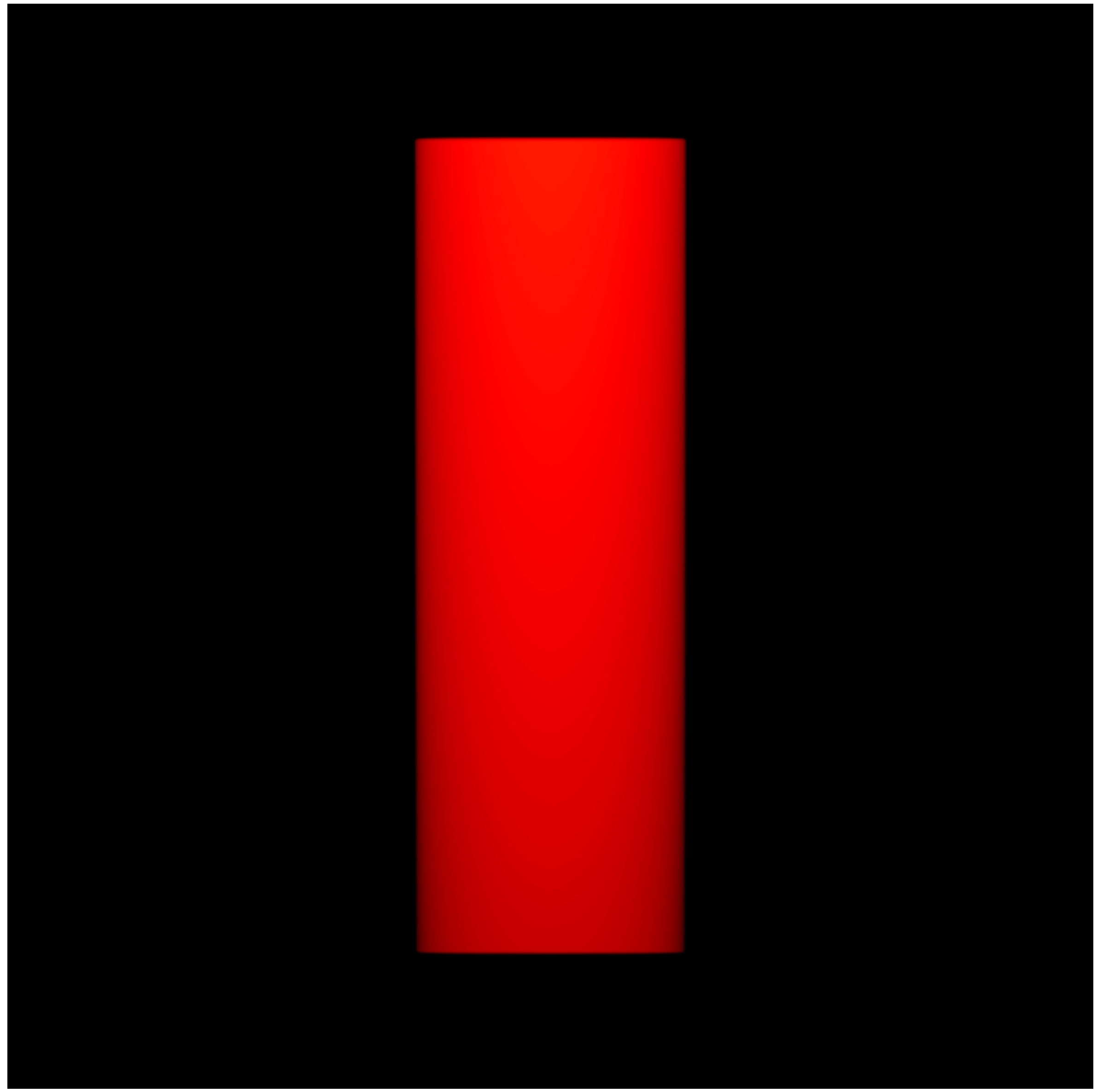
„model“ of Orion cloud:
15.000.000 SPH particles,
10^4 M_{sun} in 10 pc, mass resolution
0,02 M_{sun}, forms ~2.500
„stars“ (sink particles)

isothermal EOS, top bound, bottom unbound

has clustered as well as distributed „star“ formation

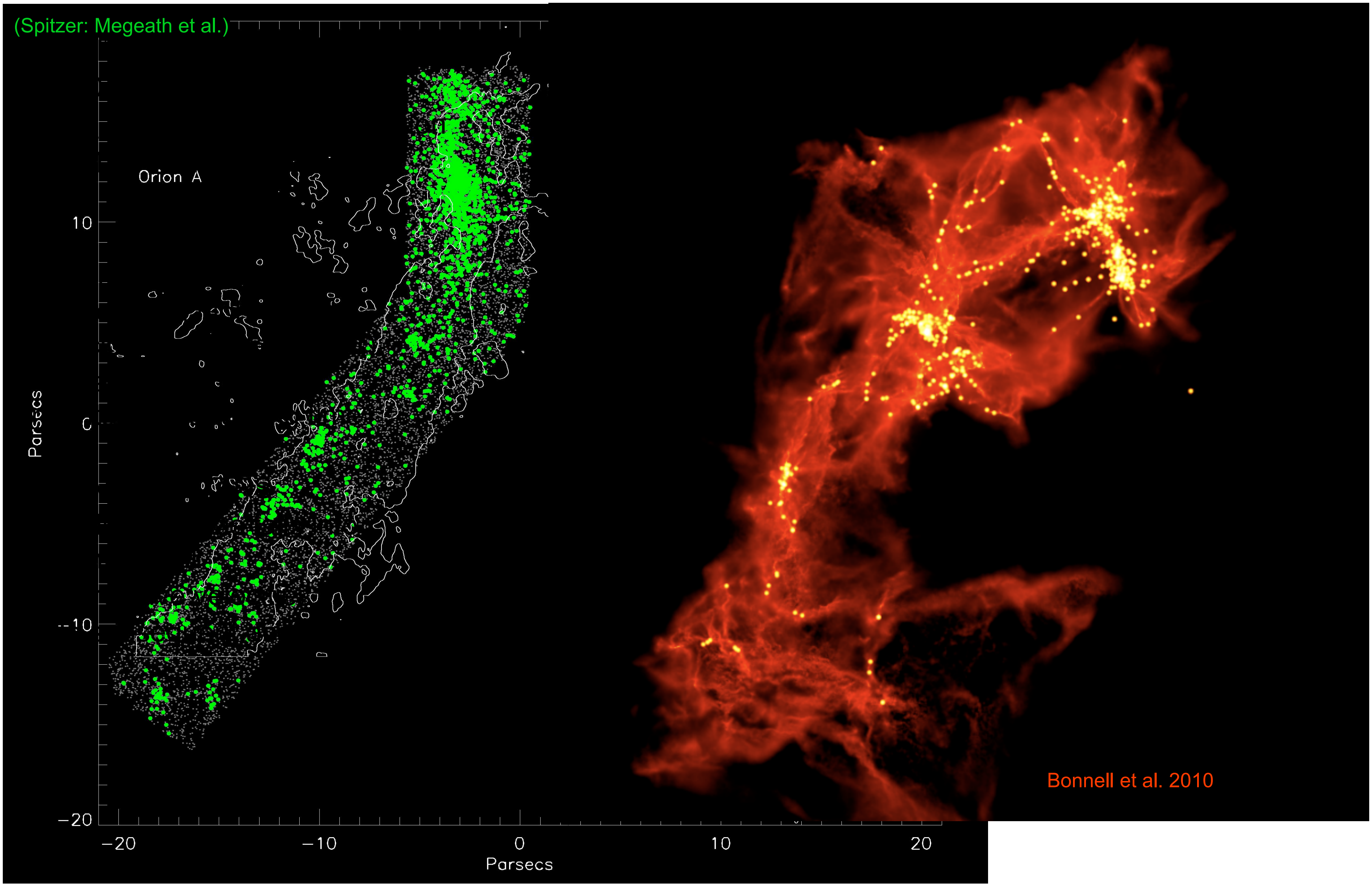
efficiency varies from 1% to 20%

develops full IMF
(distribution of sink particle masses)



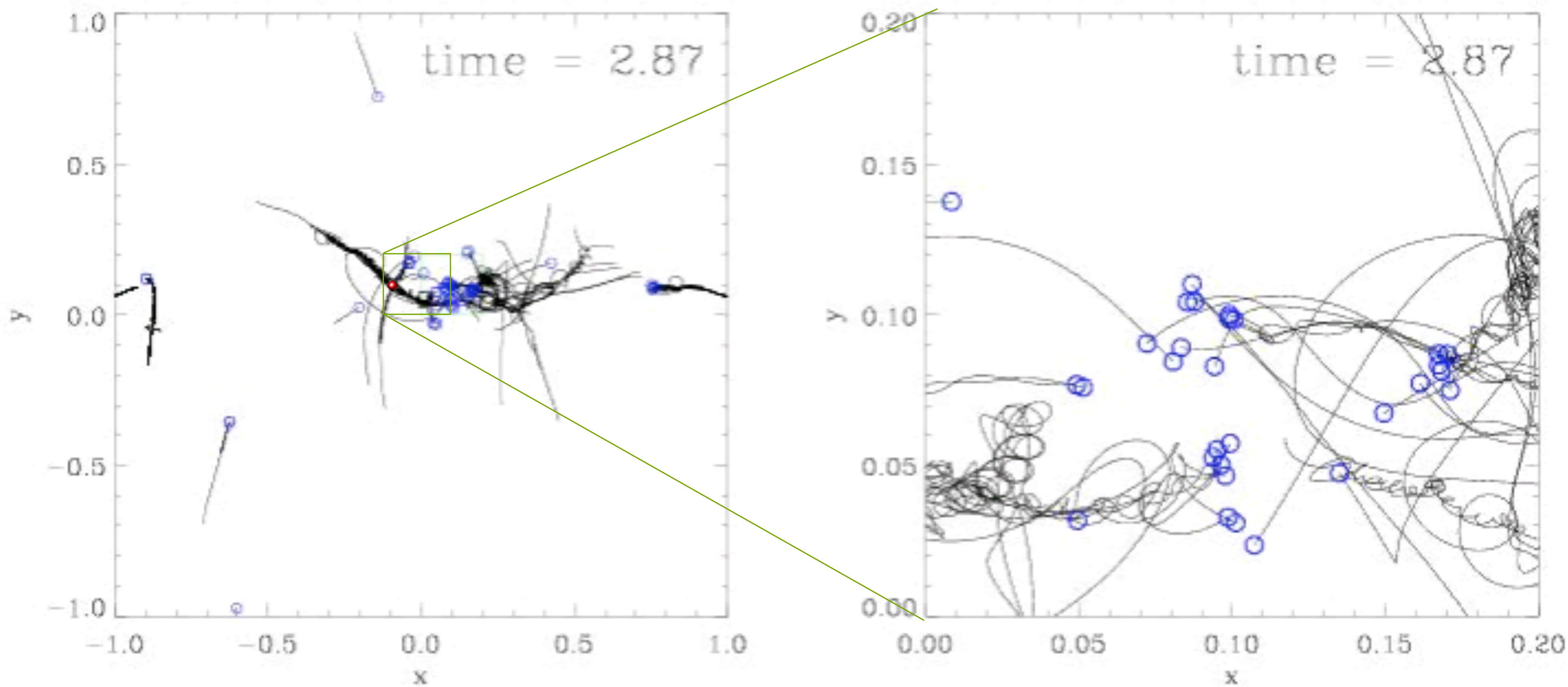
(Bonnell, Smith, Clark, & Bate 2010, MNRAS, 410, 2339)

example: model of Orion cloud



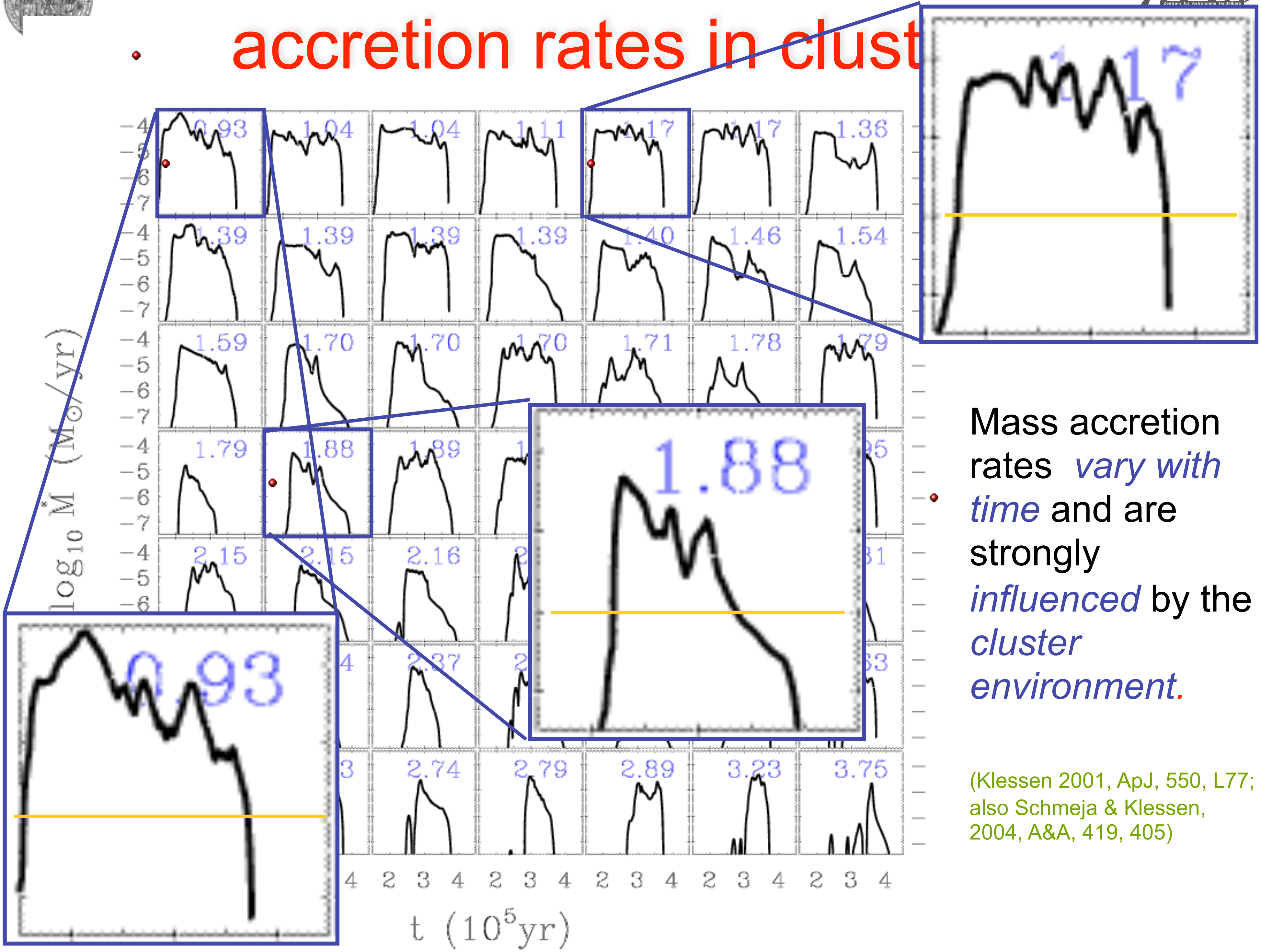
Dynamics of nascent star cluster

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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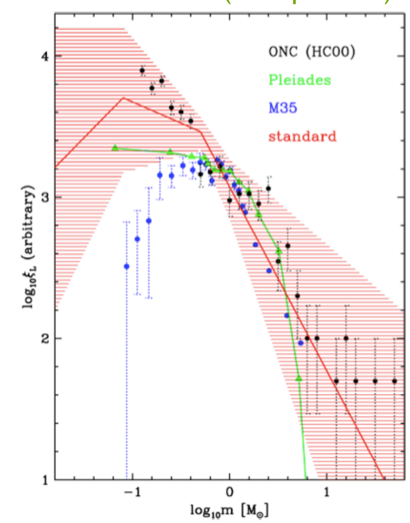

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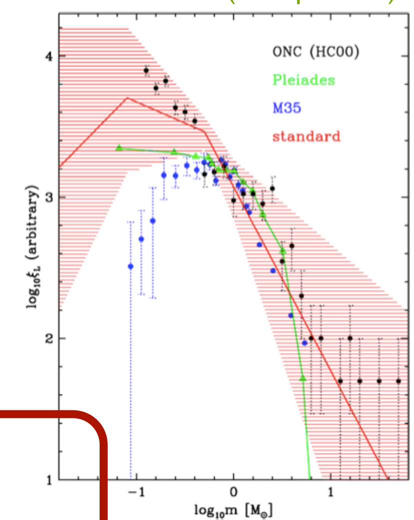


application to early star formation

thermodynamics & fragmentation

degree of fragmentation depends on *EOS!*

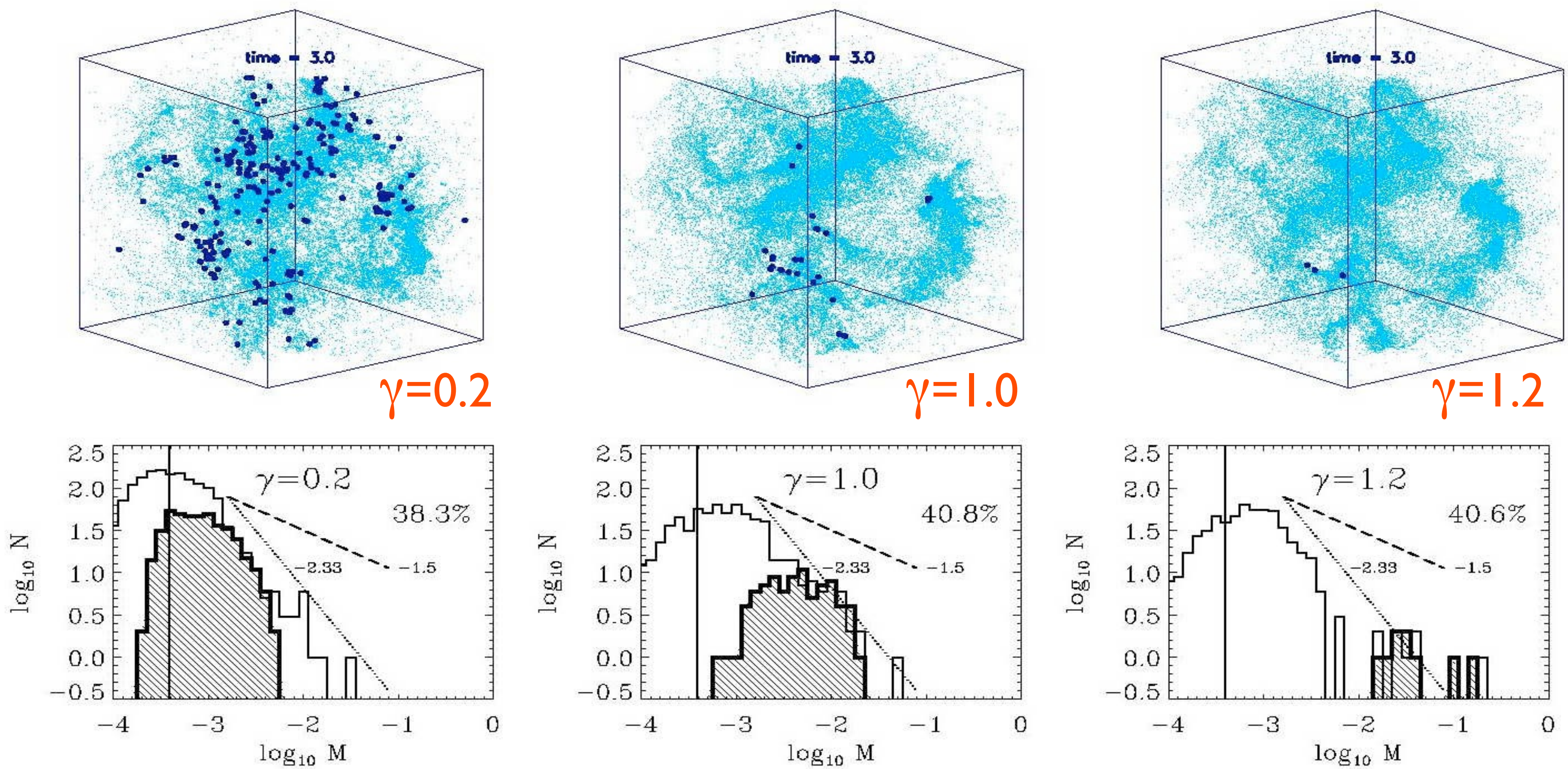
polytropic EOS: $p \propto \rho^{\gamma}$

$\gamma<1$: 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*

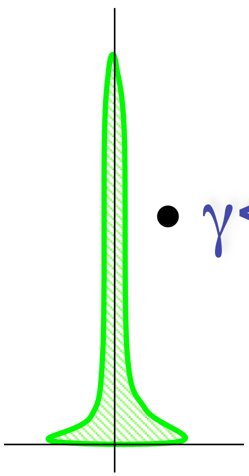
for $\gamma>1$ it is suppressed → *isolated massive stars*

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

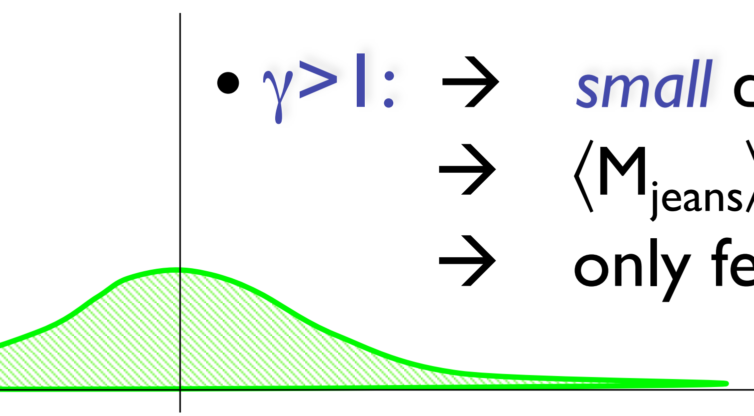
how does that work?

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

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

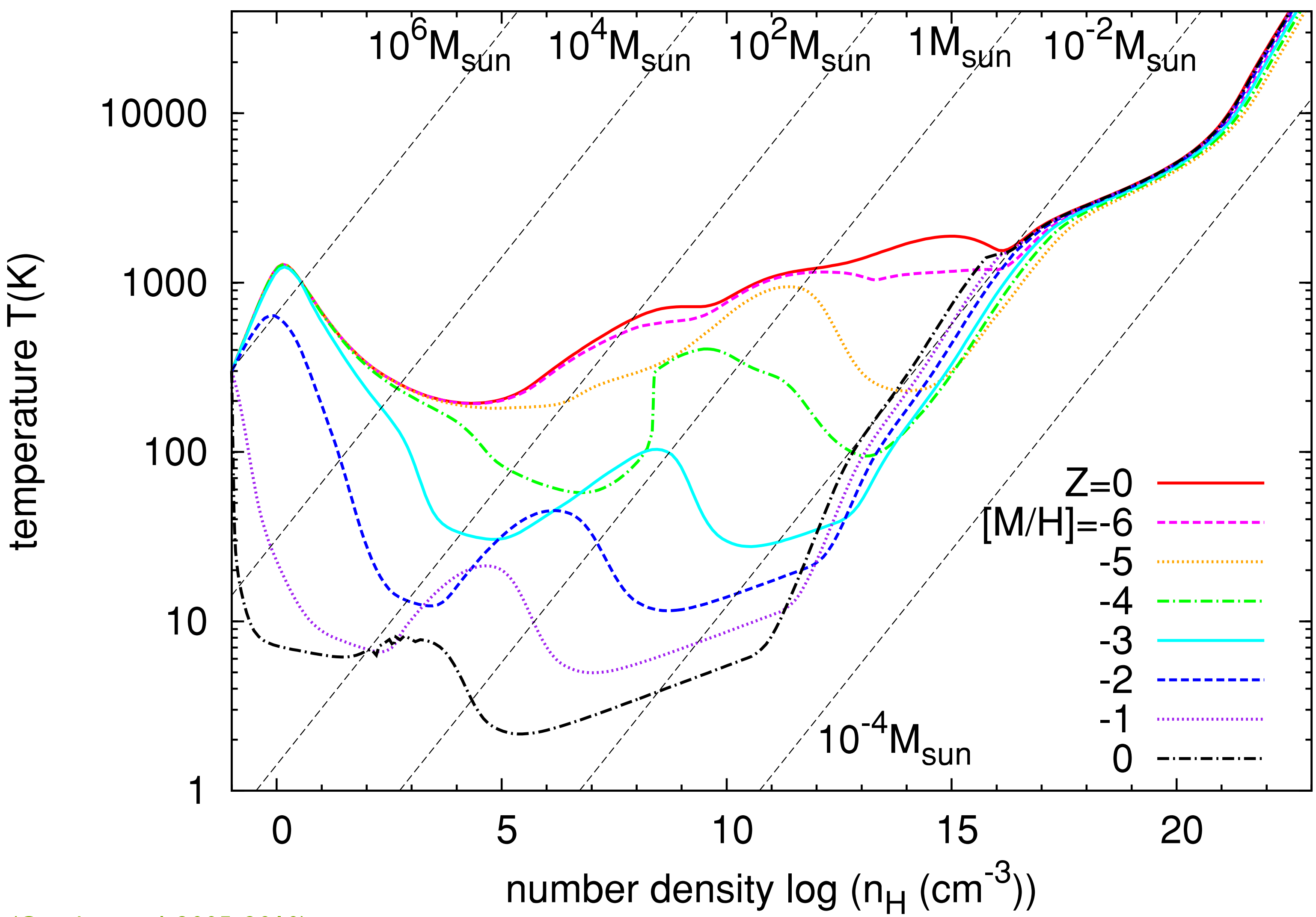


- $\gamma<1$: → *large* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ becomes small
  → number of fluctuations with $M > M_{jeans}$ is large



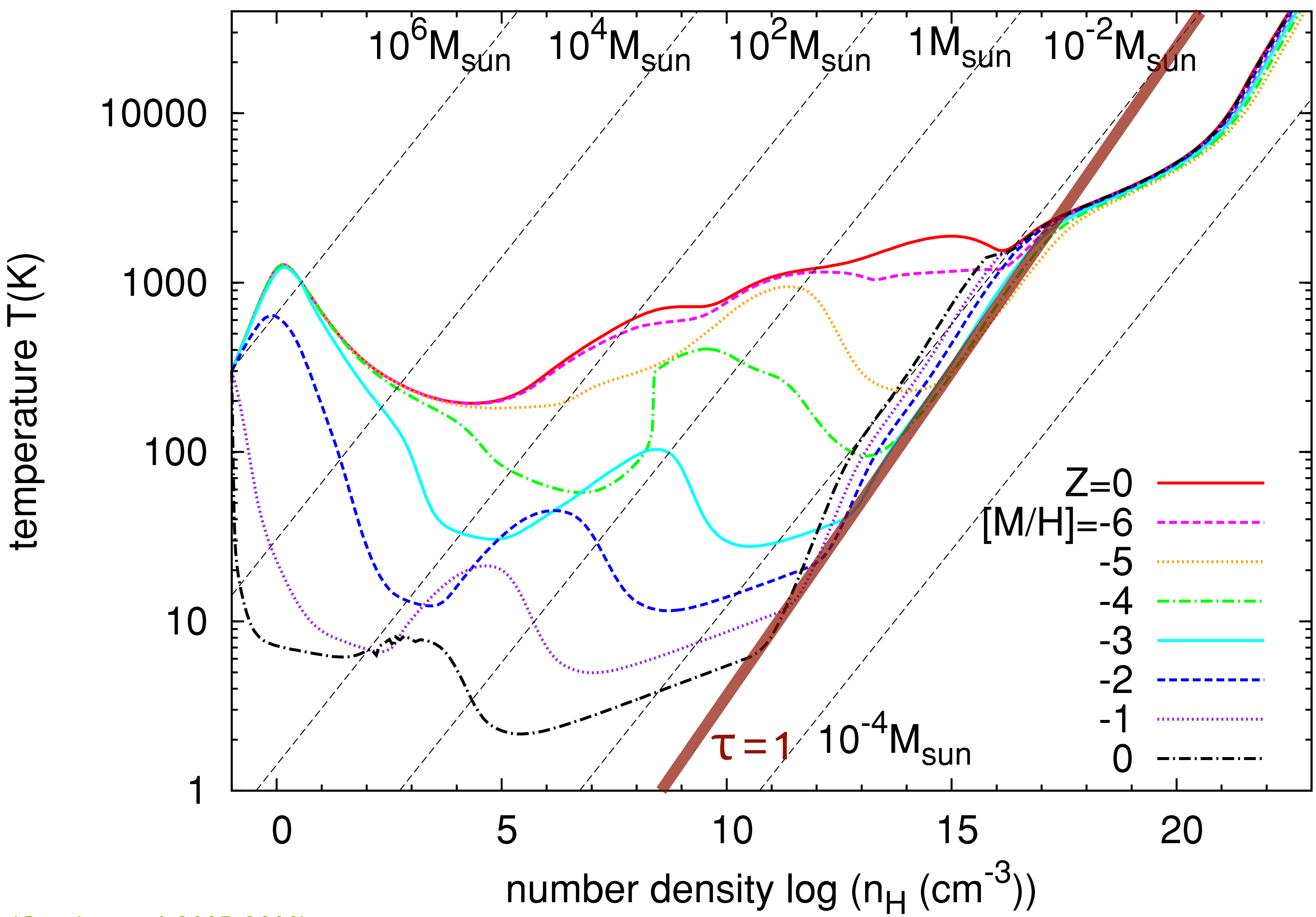
- $\gamma>1$: → *small* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ is large
  → only few and massive clumps exceed M_{jeans}

EOS as function of metallicity



(Omukai et al. 2005, 2010)

EOS as function of metallicity



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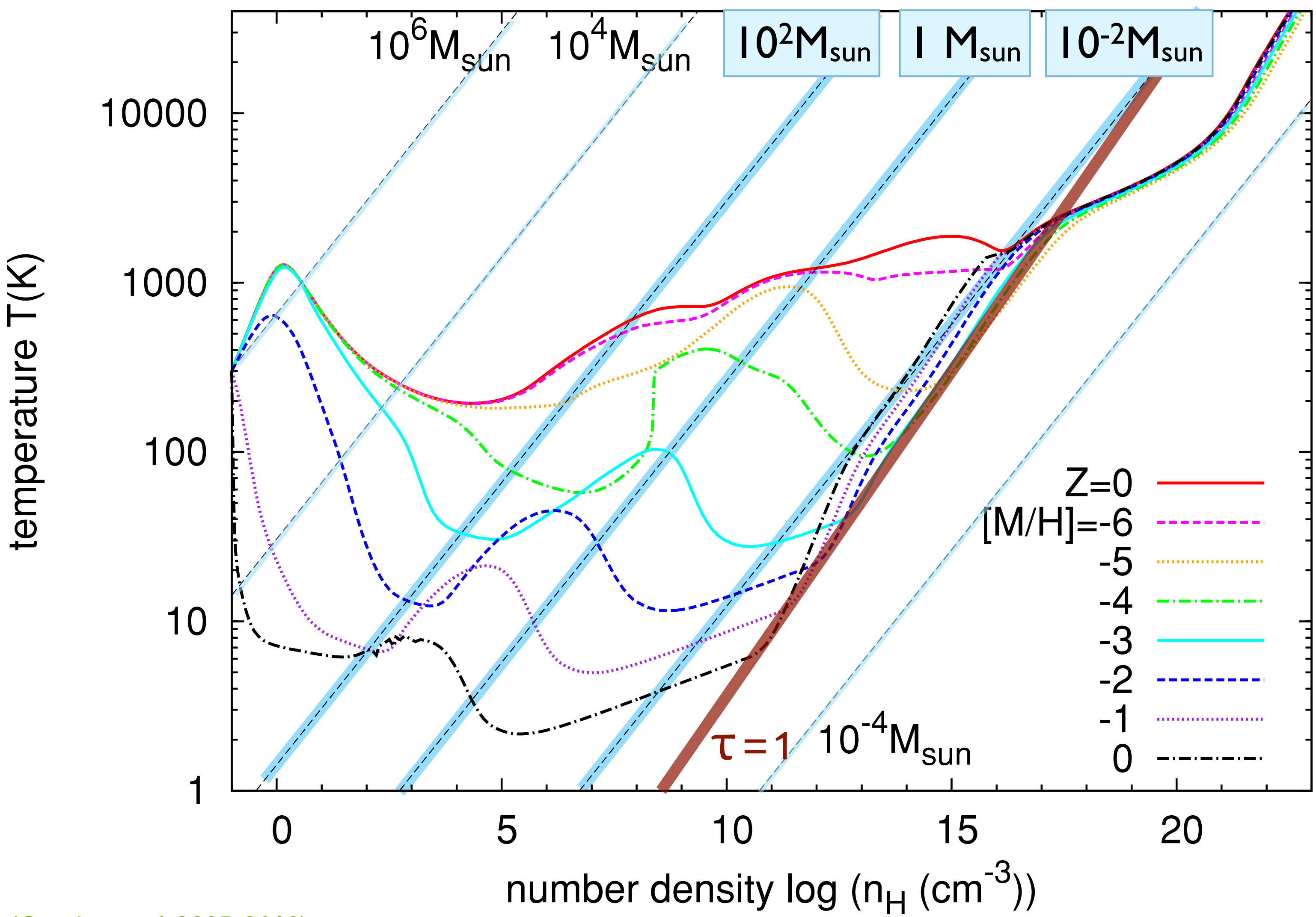

(Omukai et al. 2005, 2010)

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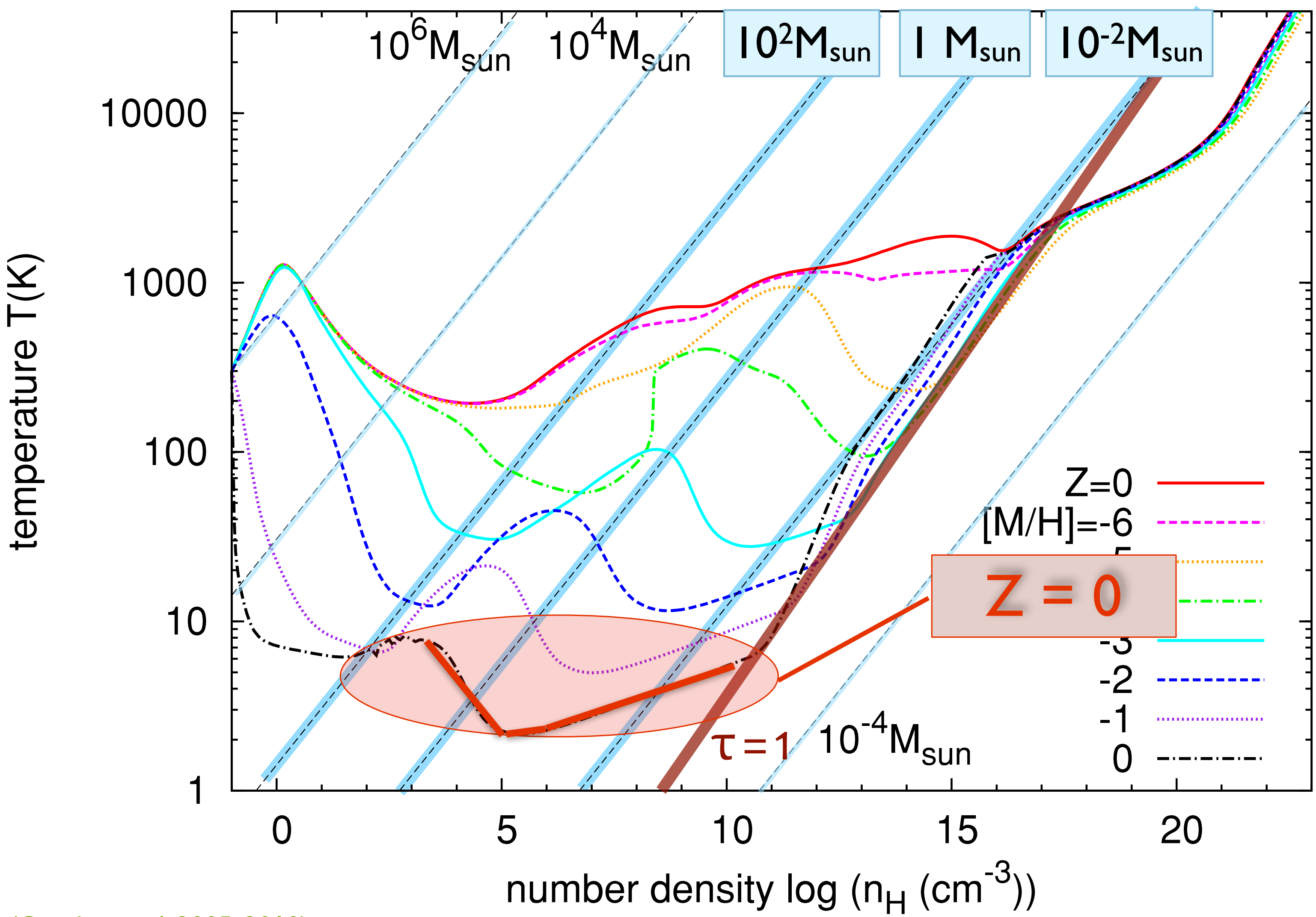
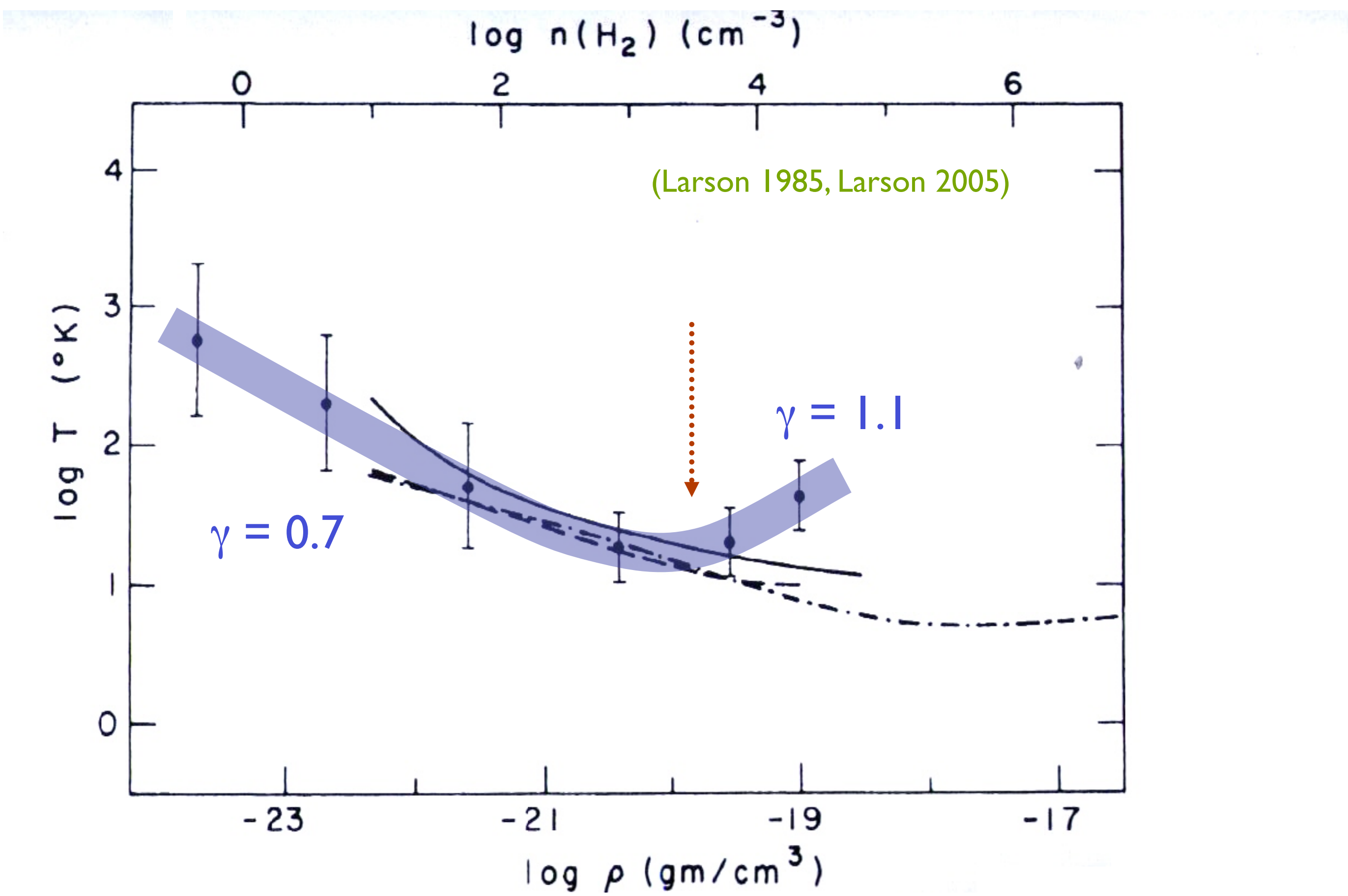
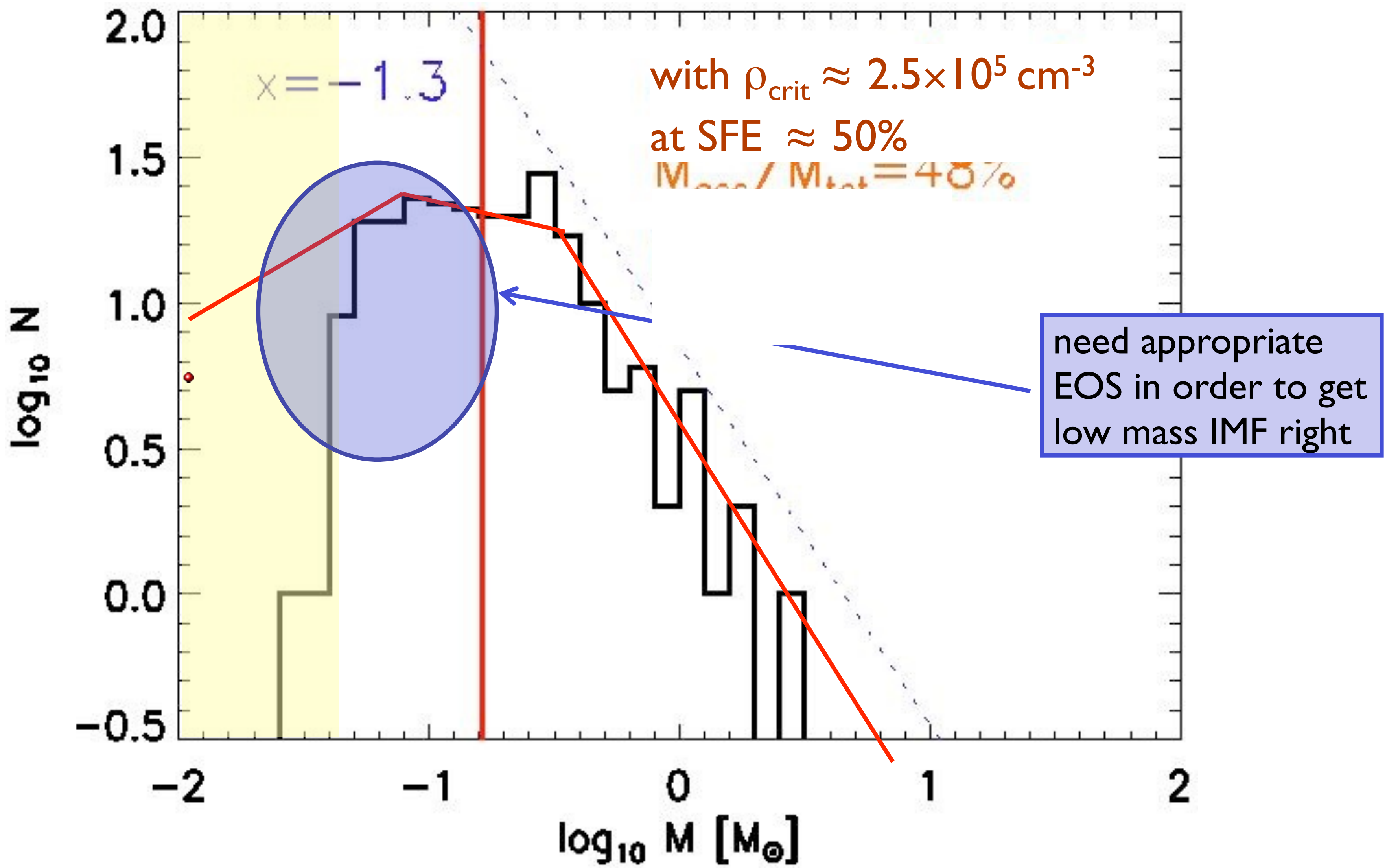


(Omukai et al. 2005, 2010)

present-day star formation

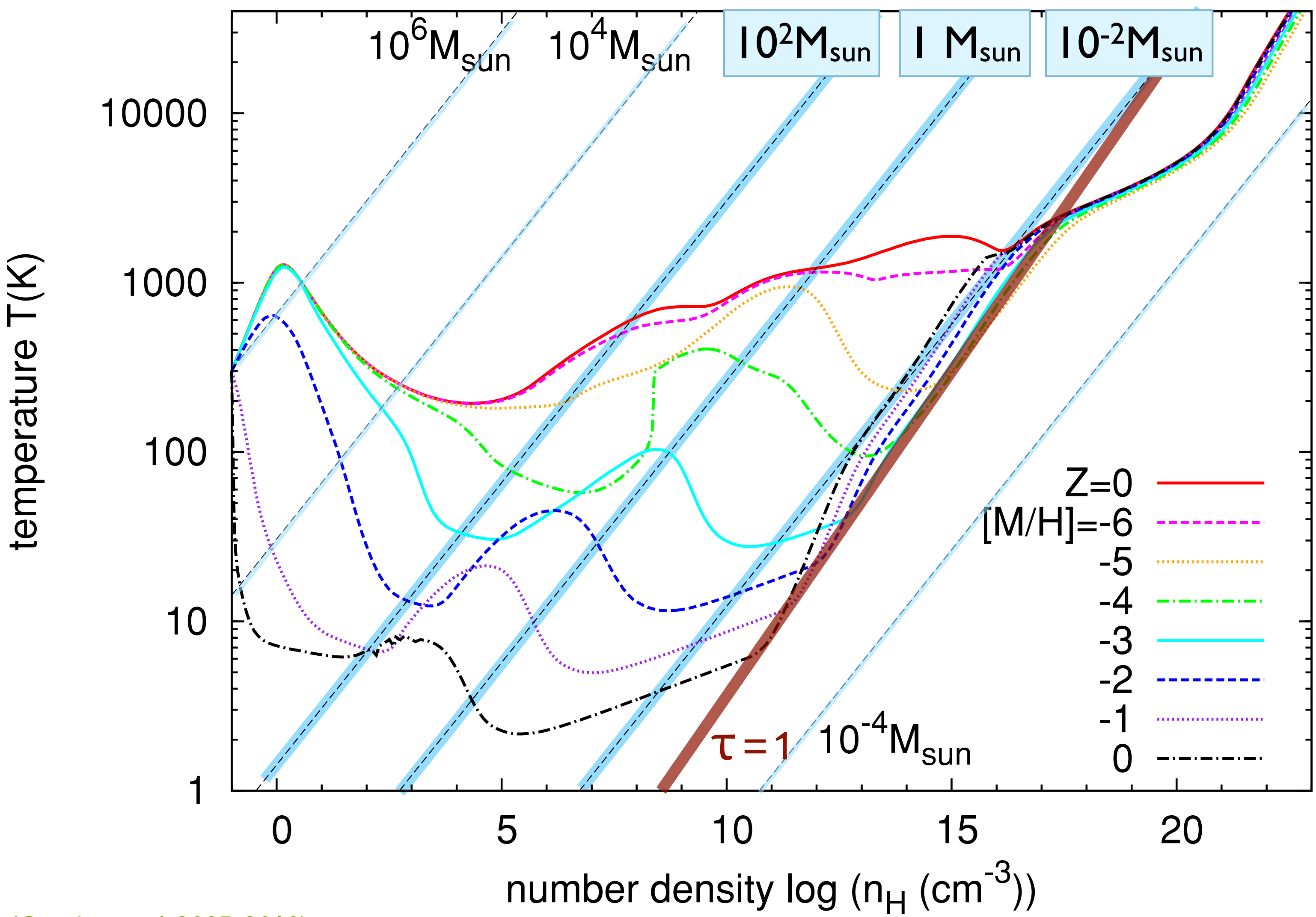


IMF in nearby molecular clouds



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

EOS as function of metallicity



(Omukai et al. 2005, 2010)

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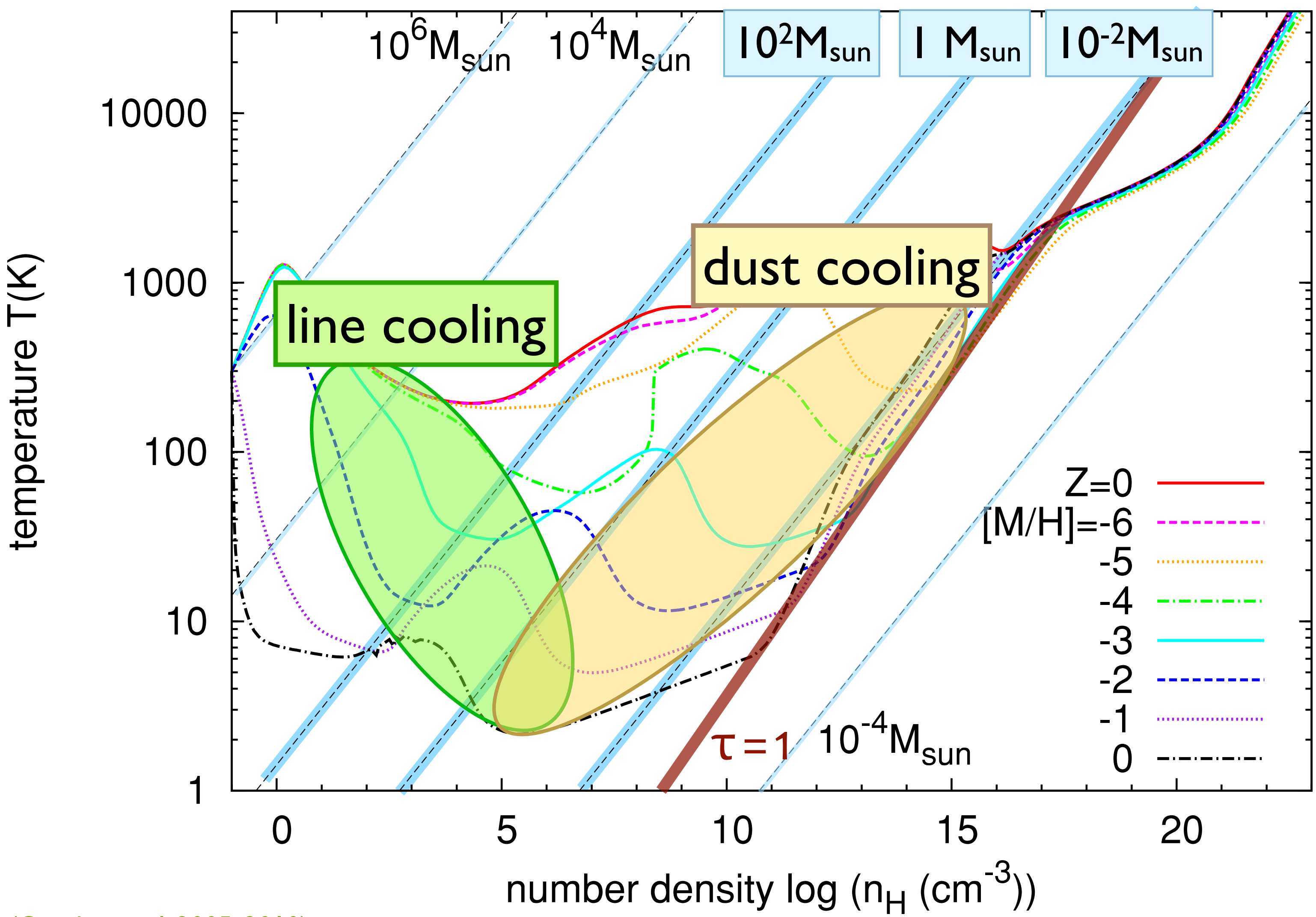
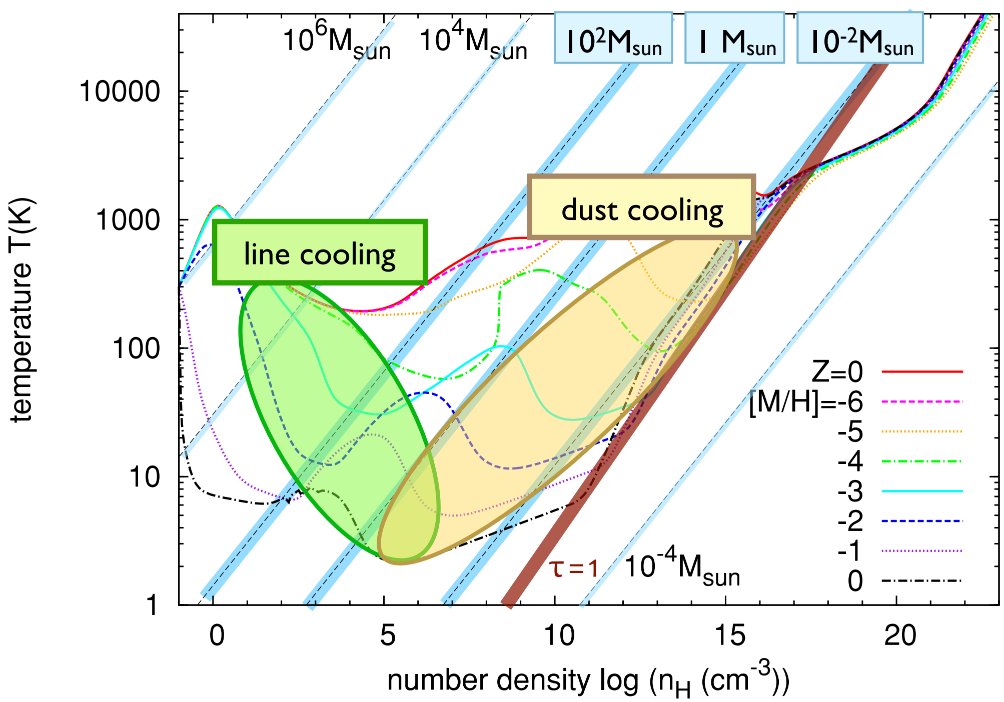


(Omukai et al. 2005, 2010)

transition: Pop III to Pop II.5



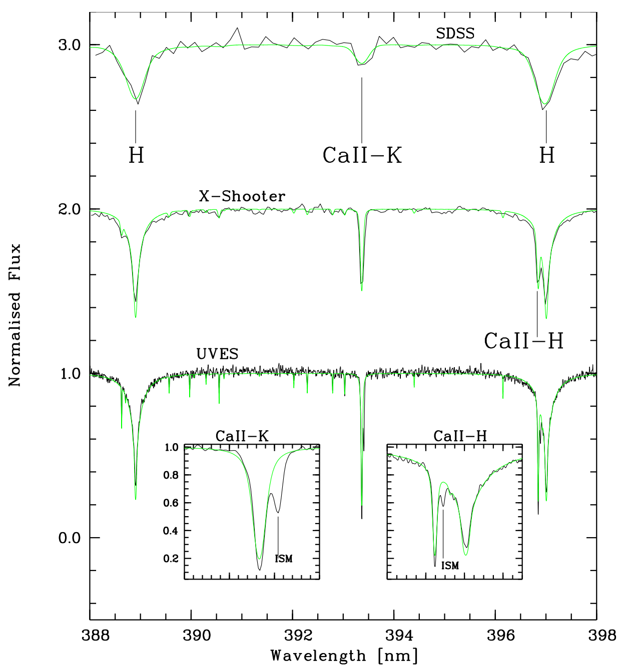
(Omukai et al. 2005, 2010)

two competing models:

- cooling due to atomic fine-structure lines ($Z > 10^{-3.5} Z_{sun}$)
- cooling due to coupling between gas and dust ($Z > 10^{-5...-6} Z_{sun}$)

- which one explains origin of extremely metal-poor stars? *NB:* lines would only make very massive stars, with $M >$ few x10 M_{sun}.

transition: Pop III to Pop II.5



SDSS J1029151+172927

- is first ultra metal-poor star with Z ~ $10^{-4.5}$ Z_{sun} for all metals seen (Fe, C, N, etc.)
  [see Caffau et al. 2011]
- this is in regime, where metal-lines cannot provide cooling
  [e.g. Schneider et al. 2011, 2012, Klessen et al. 2012]

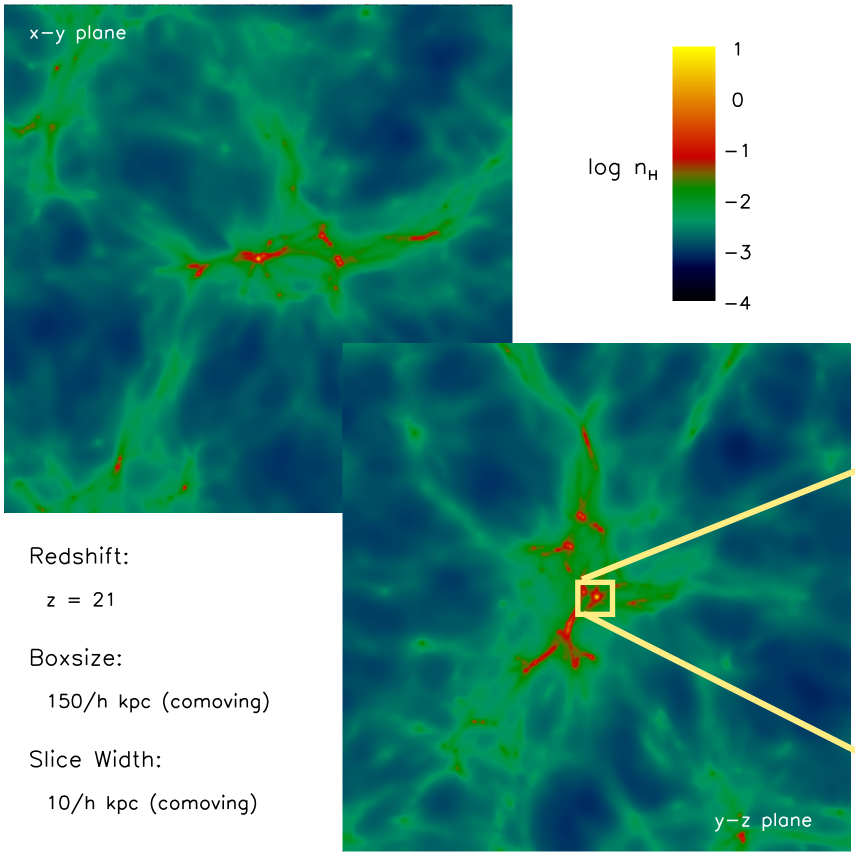
Element		+3Dcor.	[X/H]$_{1D}$ +NLTE cor.	+ 3D cor + NLTE cor	N lines	S_H	A(X)$_\odot$
C	≤ −3.8	≤ −4.5			G-band		8.50
N	≤ −4.1	≤ −5.0			NH-band		7.86
Mg I	−4.71 ± 0.11	−4.68 ± 0.11	−4.52 ± 0.11	−4.49 ± 0.12	5	0.1	7.54
Si I	−4.27	−4.30	−3.93	−3.96	1	0.1	7.52
Ca I	−4.72	−4.82	−4.44	−4.54	1	0.1	6.33
Ca II	−4.81 ± 0.11	−4.93 ± 0.03	−5.02 ± 0.02	−5.15 ± 0.09	3	0.1	6.33
Ti II	−4.75 ± 0.18	−4.83 ± 0.16	−4.76 ± 0.18	−4.84 ± 0.16	6	1.0	4.90
Fe I	−4.73 ± 0.13	−5.02 ± 0.10	−4.60 ± 0.13	−4.89 ± 0.10	43	1.0	7.52
Ni I	−4.55 ± 0.14	−4.90 ± 0.11			10		6.23
Sr II	≤ −5.10	≤ −5.25	≤ −4.94	≤ −5.09	1	0.01	2.92

- new ESO large program to find more of these stars (120h x-shooter, 30h UVES)
  [PI E. Caffau]

(Caffau et al. 2011, 2012)

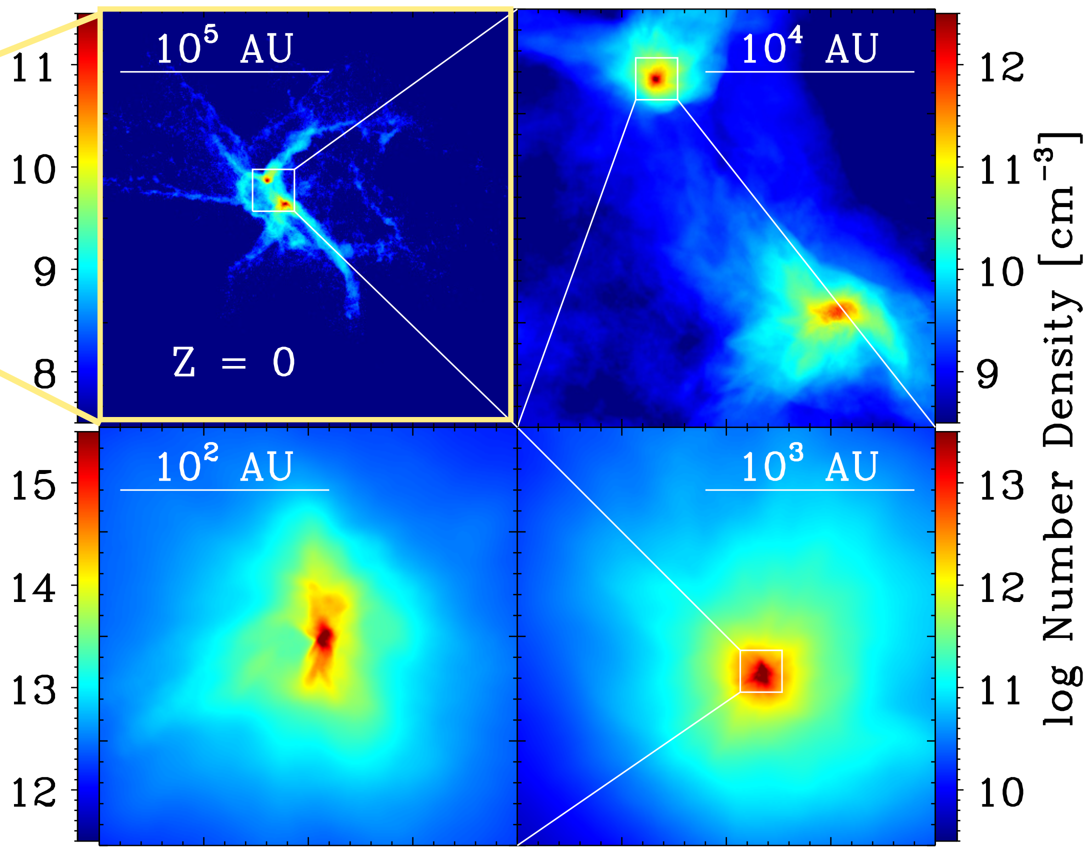
(Schneider et al. 2011,2012, Klessen et al. 2012)

modeling the formation of the first/second stares

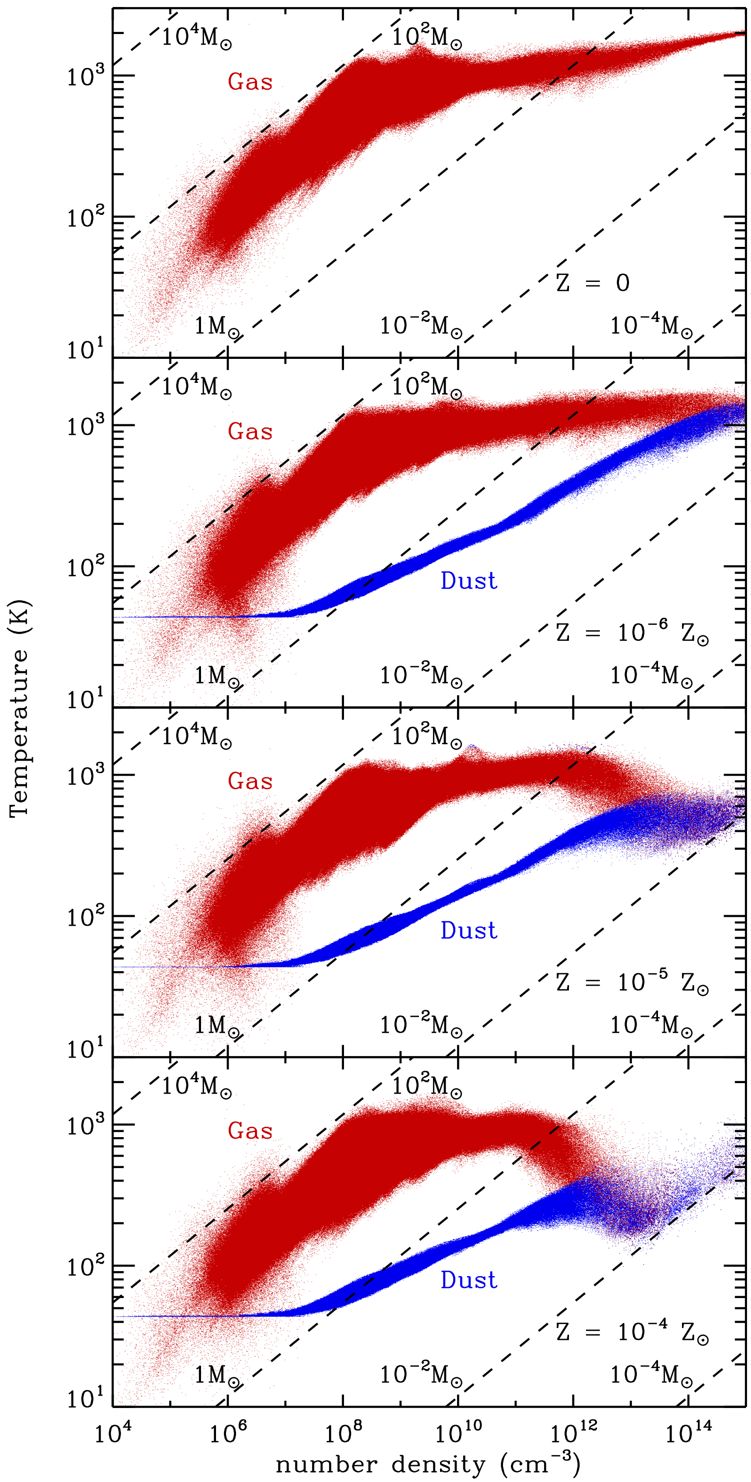


successive zoom-in calculation from cosmological initial conditions (using SPH and new grid-code AREPO)

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



(Greif et al. 2011, ApJ, 737, 75, Greif et al. 2012, MNRAS, 424, 399, Dopcke et al. 2013, ApJ, 776, 103)



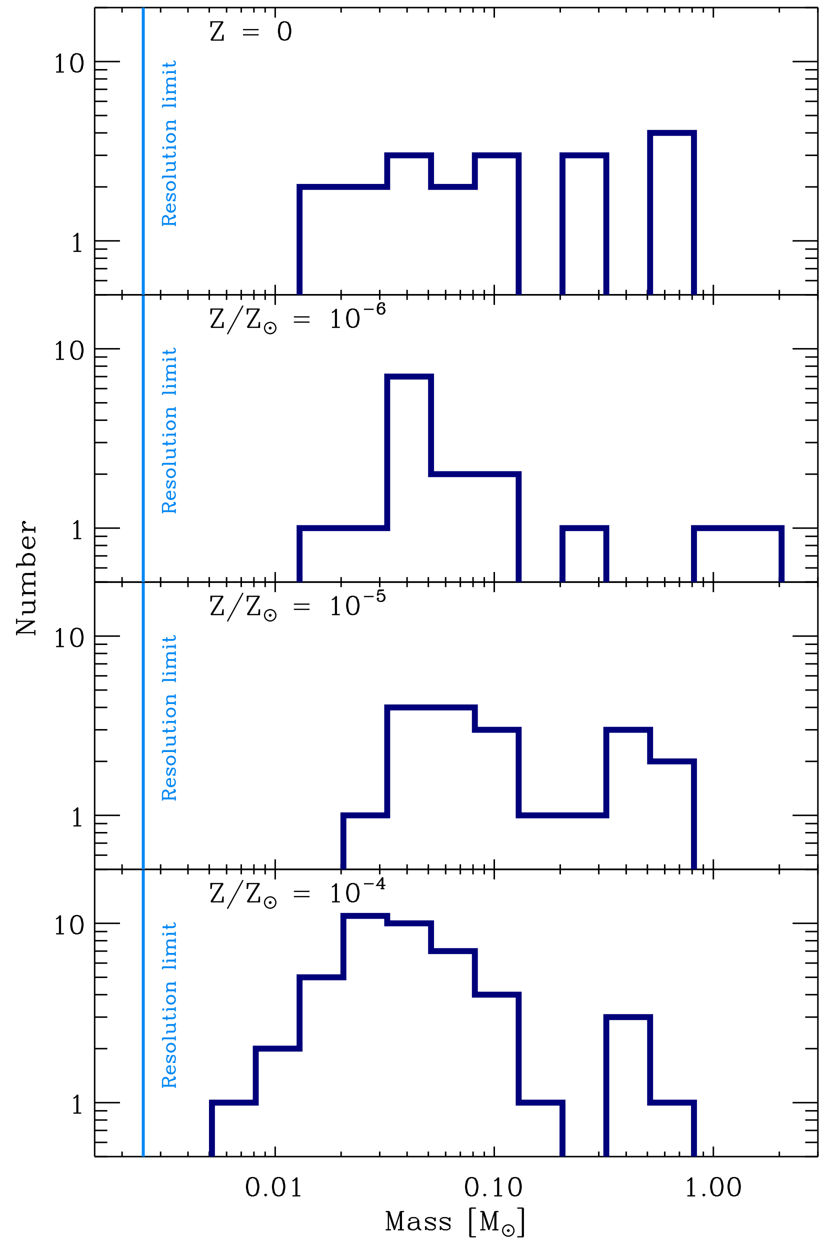
[M/H] = -ininity

[M/H] = -6

[M/H] = -5

[M/H] = -4

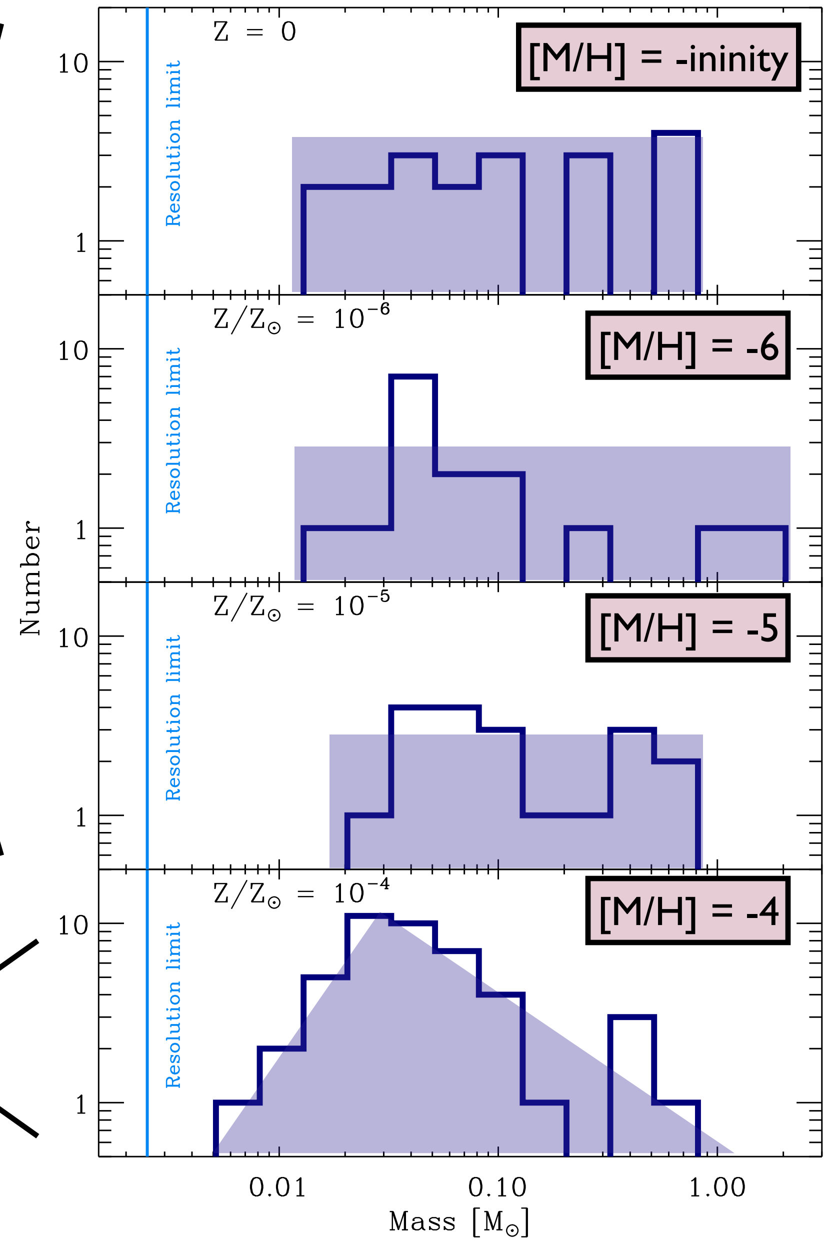
red : gas
blue: dust



Dopcke et al., 2012, submitted to ApJ, arXiv:1203.6842) hints for differences in mass spectrum

disk fragmentation mode

gravoturbulent fragmentation mode



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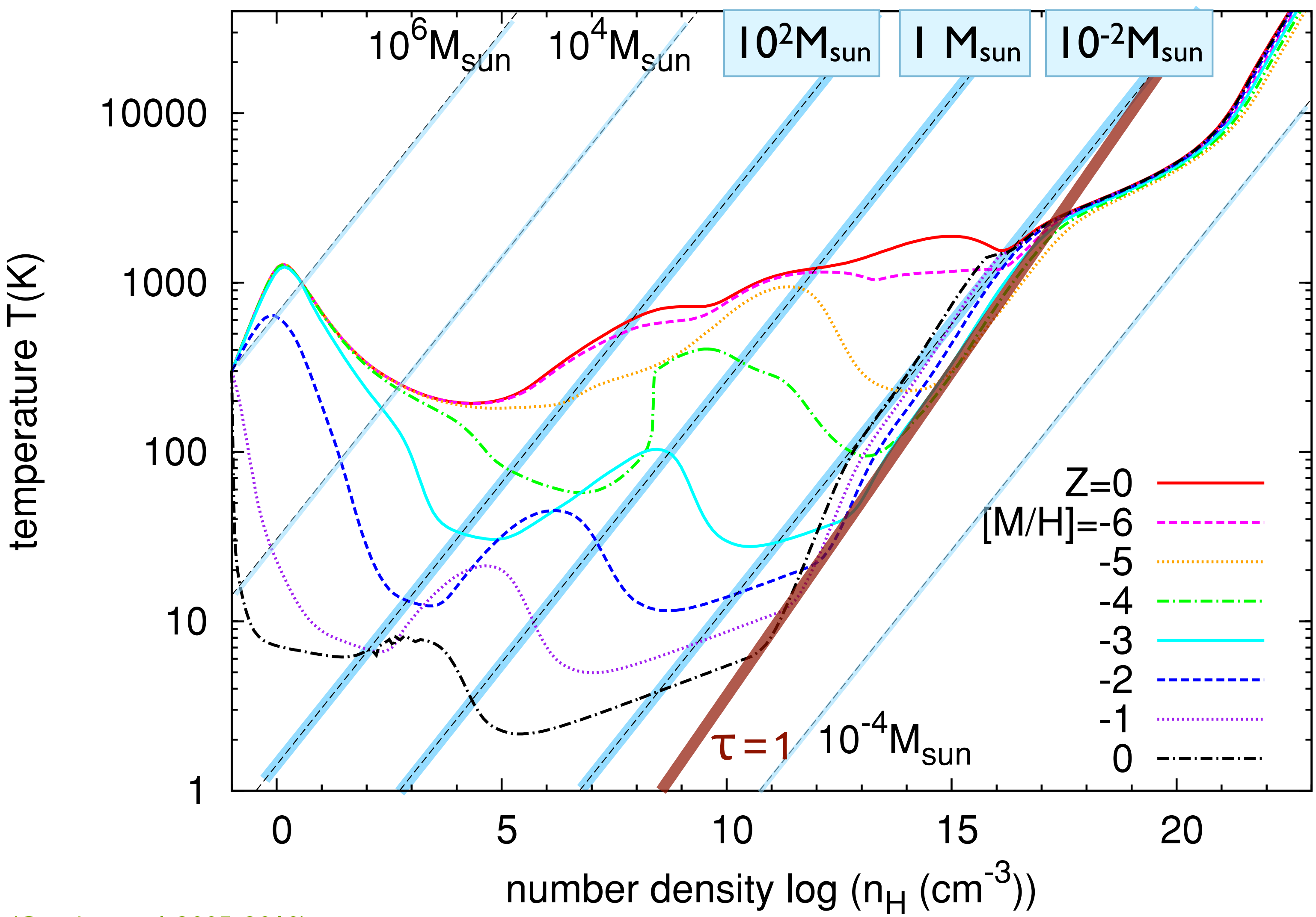
EOS as function of metallicity



(Omukai et al. 2005, 2010)

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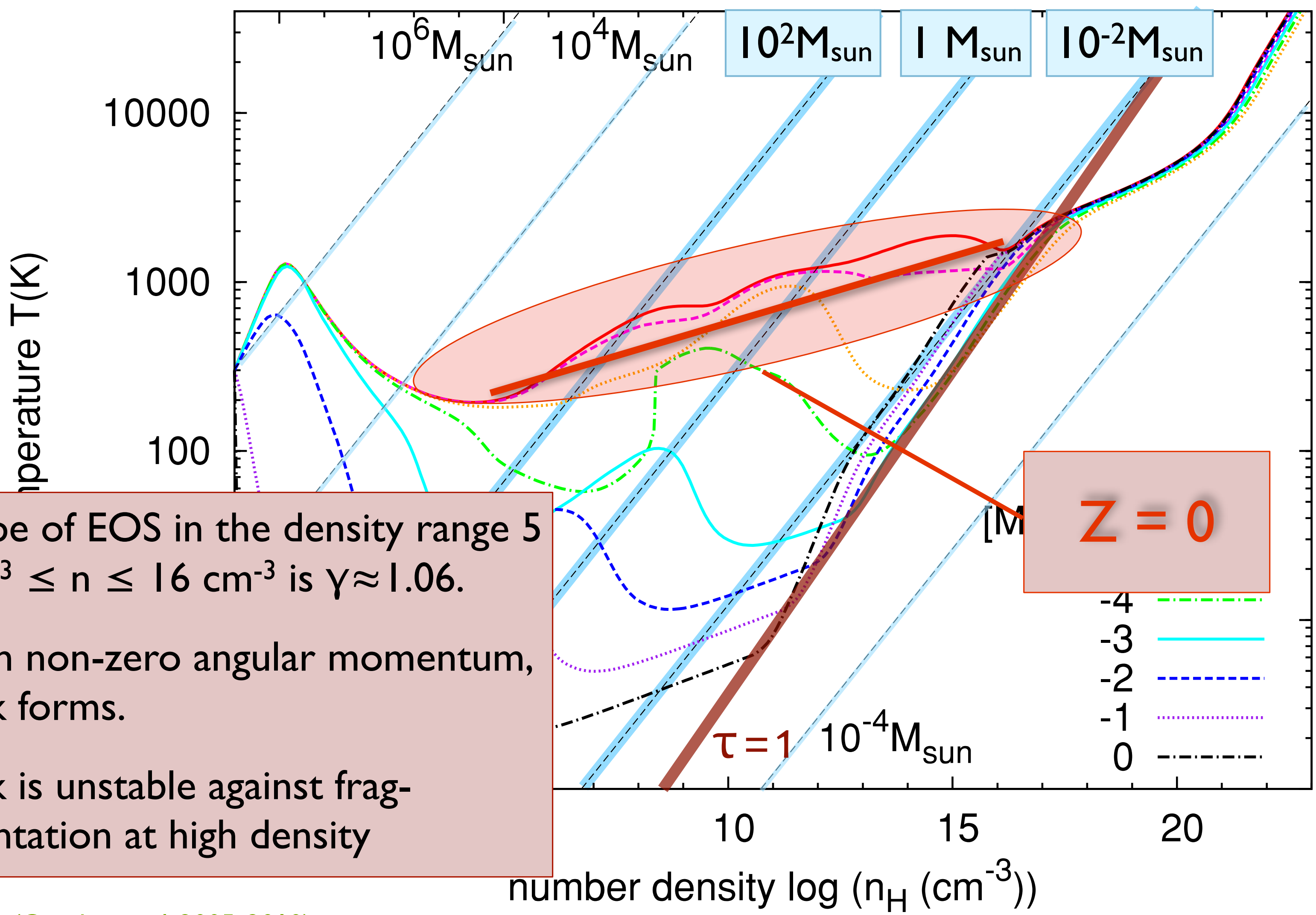
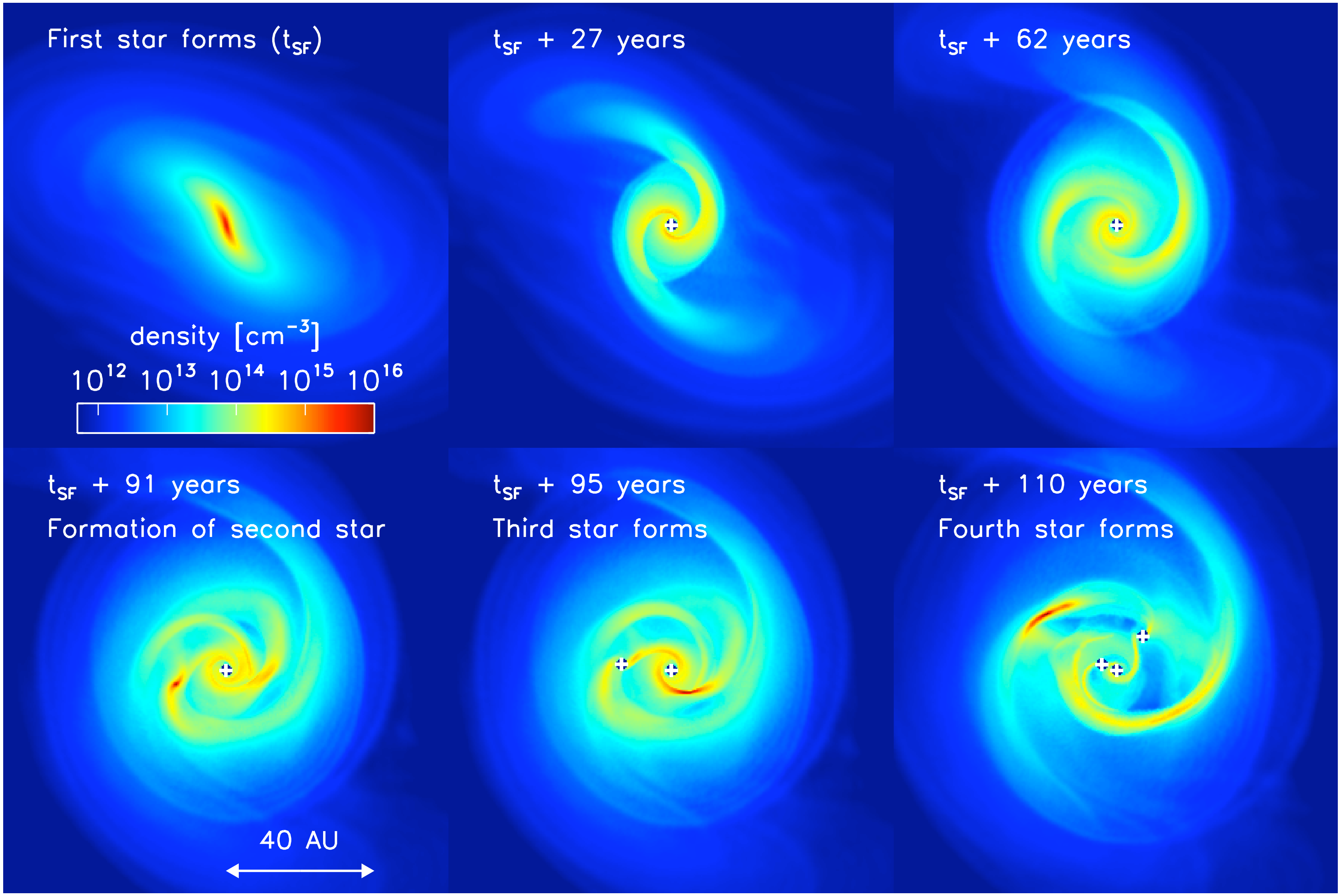


- slope of EOS in the density range 5 $cm^{-3} \leq n \leq 16\ cm^{-3}$ is $\gamma \approx 1.06$.
- with non-zero angular momentum, disk forms.
- disk is unstable against fragmentation at high density

(Omukai et al. 2005, 2010)

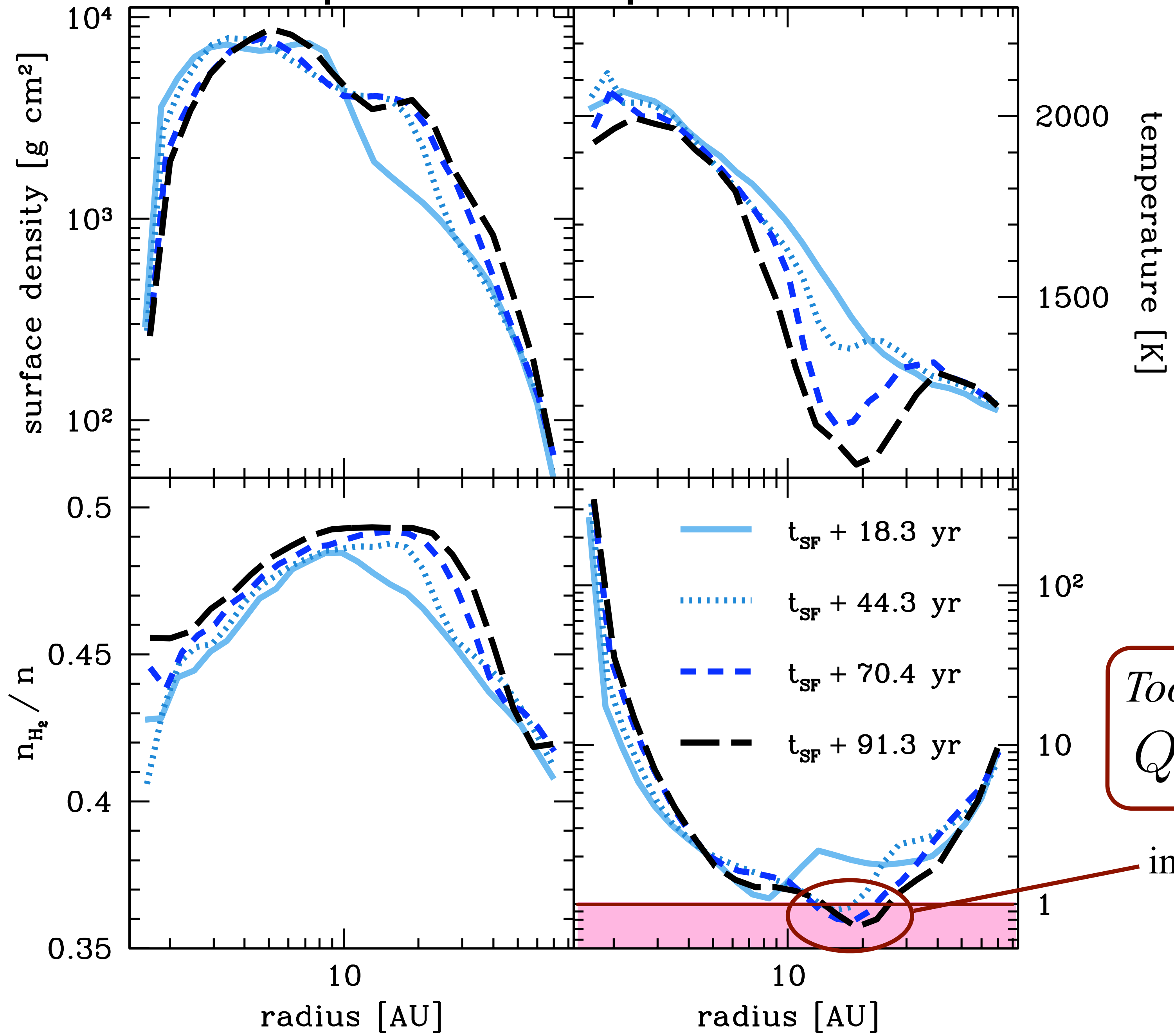


detailed look at accretion disk

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



Toomre Q:

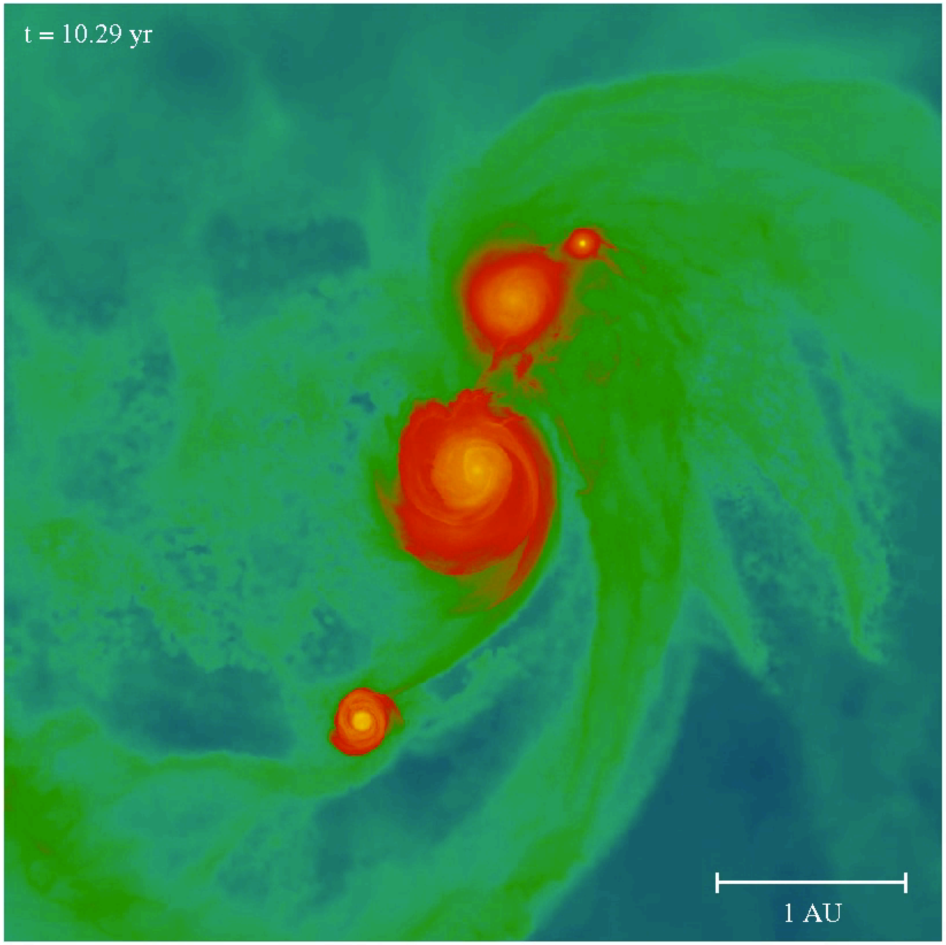
$$Q = c_s \kappa / \pi G \Sigma$$

instability for *Q<1*

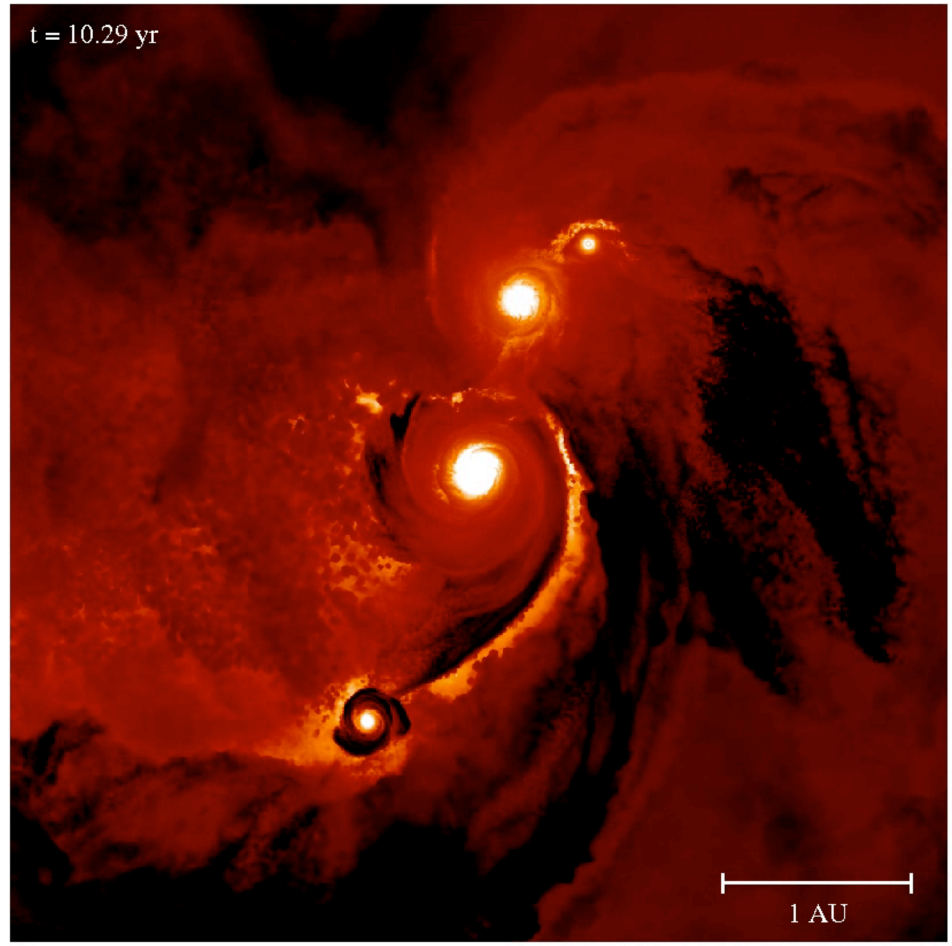
(Clark et al. 2011b, Science, 331, 1040)

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 $R_\odot$)



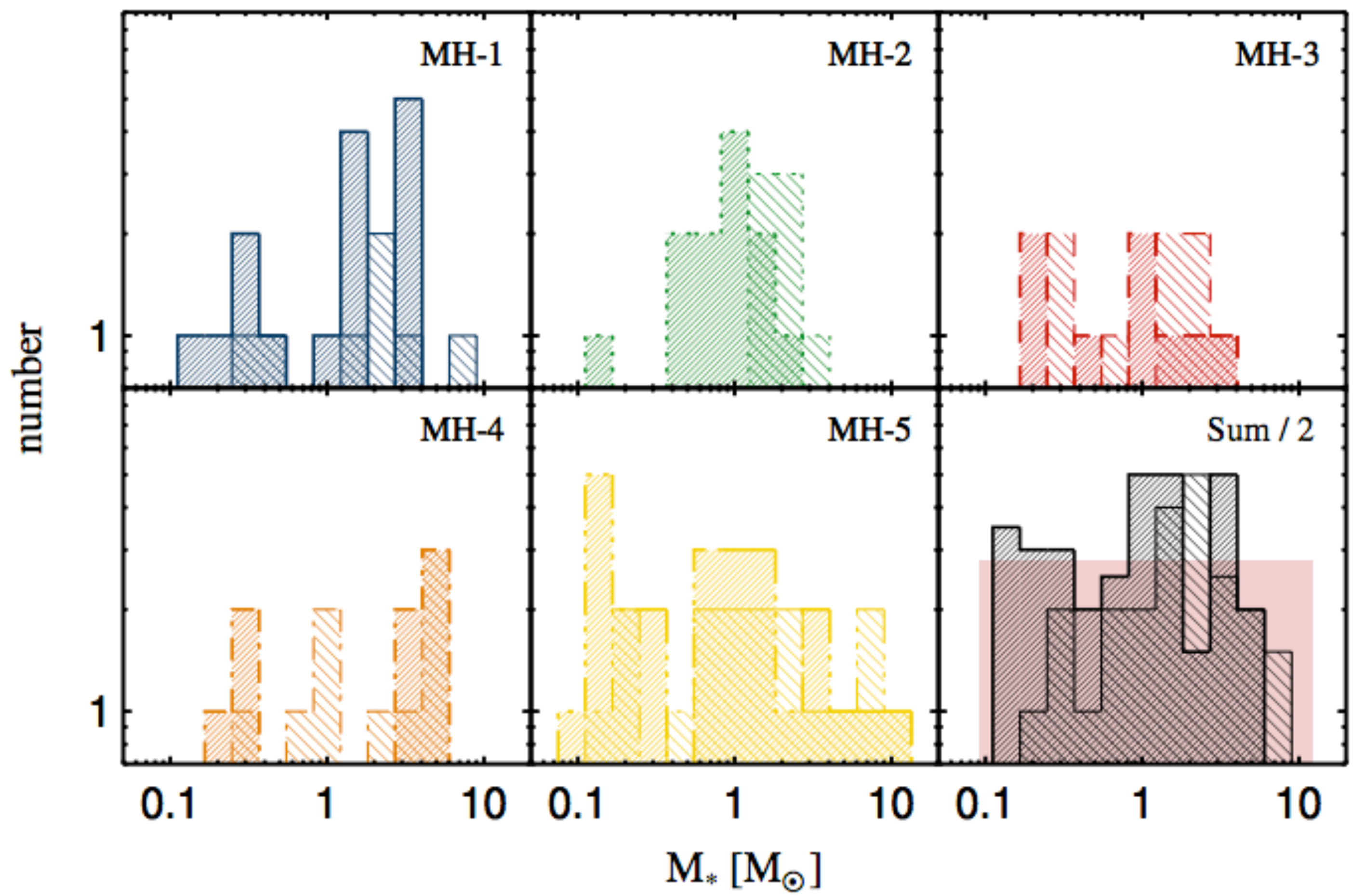
density



temperature

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

expected mass spectrum

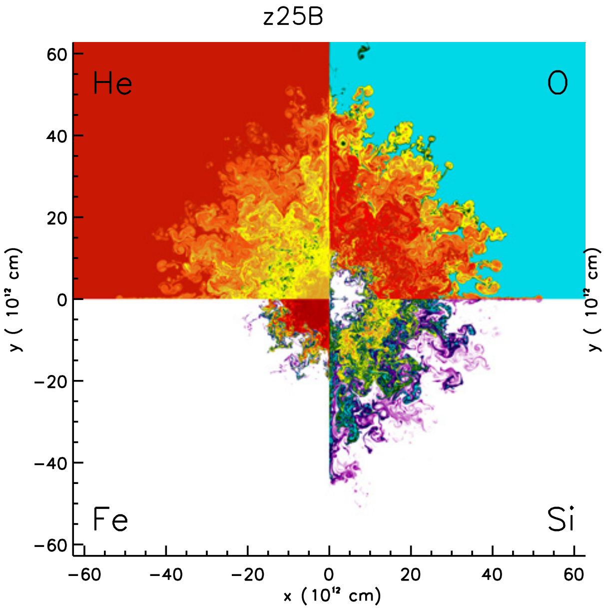


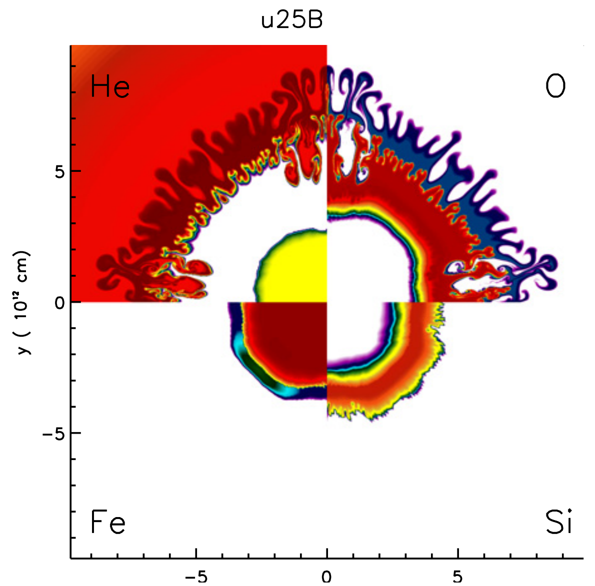
we see "flat" mass spectrum

Greif et al. 2011, ApJ, 737, 75, Clark et al. 2011b, Science, 331, 1040, Smith et al. 2011, MNRAS, 414, 3633, Dopcke et al., 2013, ApJ, 766, 103
also talk by Athena Stacy

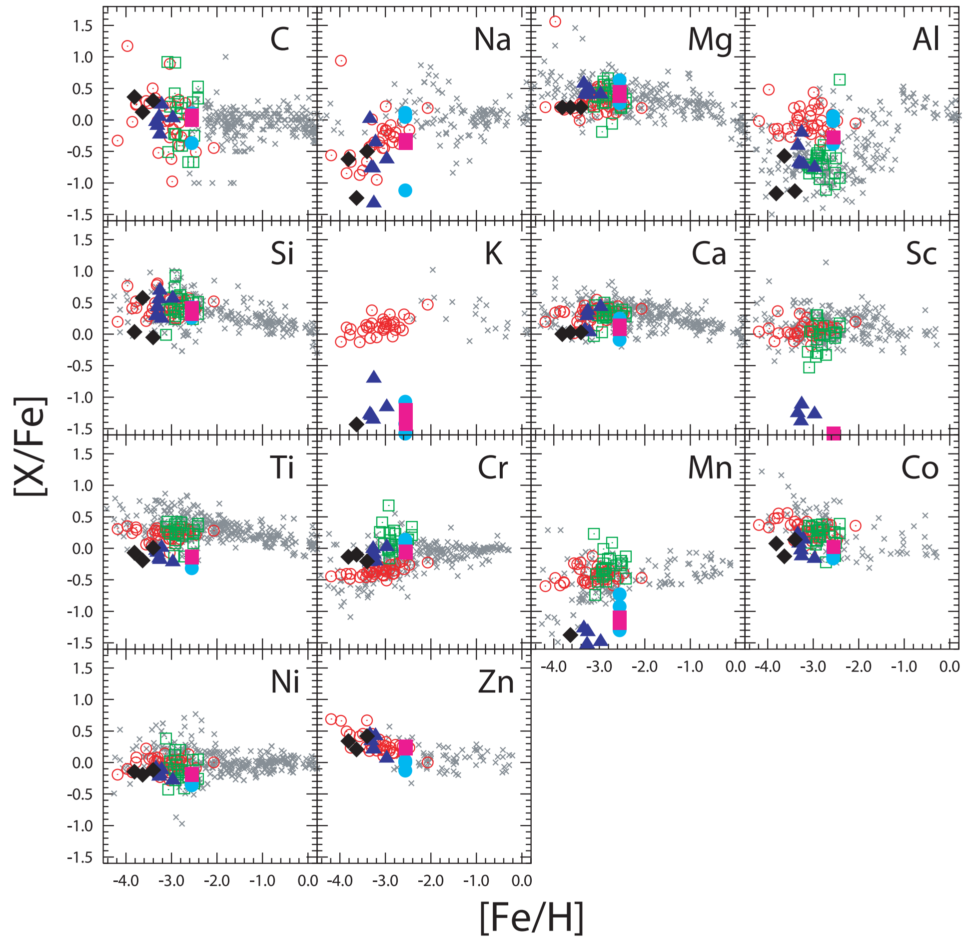
expected mass spectrum

- *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)

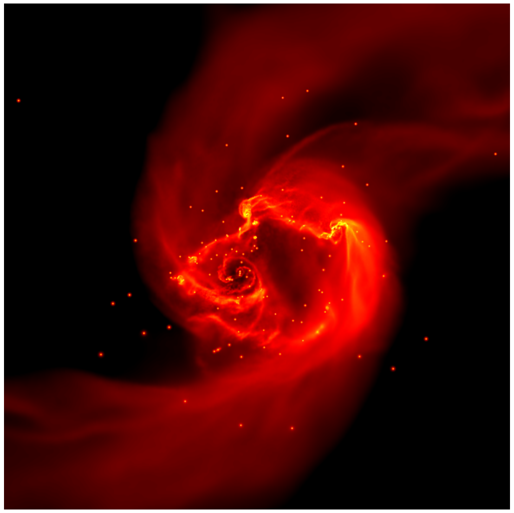


(Tominaga et al. 2007)

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)

primordial star formation



- just like in present-day SF, we expect
  - *turbulence*
  - *thermodynamics (i.e. heating vs. cooling)*
  - *feedback*
  - *magnetic fields*

  to influence first star formation.
- masses of first stars still *uncertain*, but we expect a *wide mass range* with *typical masses* of *several 10s of* $M_{\odot}$
- disks unstable: first stars in *binaries* or *part of small clusters*
- current frontier: include *feedback* and *magnetic fields* and possibly *dark matter annihilation*...

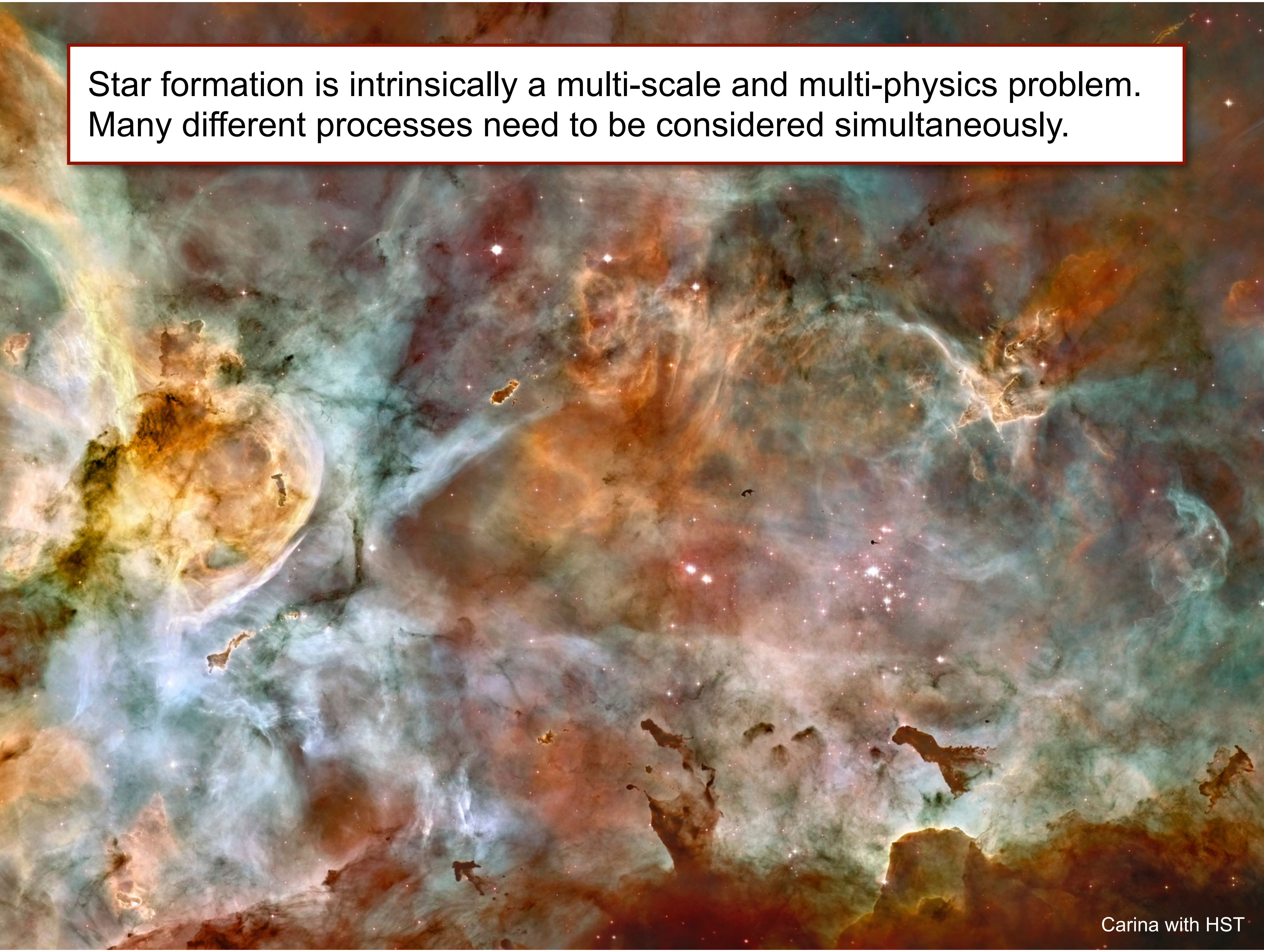
reducing fragmentation

- from present-day star formation theory we know, that
  - magnetic fields: Peters et al. 2011, Seifried et al. 2012, Hennebelle et al. 2011
  - accretion heating: Peters et al. 2010, Krumholz et al. 2009, Kuipers et al. 2011

  can influence the fragmentation behavior.
- in the context of Pop III
  - radiation: Hosokawa et al. 2012, Stacy et al. 2012a
  - magnetic fields: Turk et al. 2012, but see also Bovino et al. 2013
    Schleicher et al. 2010, Sur et al. 2010, Federrath et al. 2011, Schober et al. 2012ab, 2013
- all these will reduce degree of fragmentation
  (but not by much, see Rowan Smith et al. 2011, 2012, at least for accretion heating)
- DM annihililation might become important for disk dynamics and fragmentation (Ripamonti et al. 2011, Stacy et al. 2012b, Rowan Smith et al. 2012)


Carina with HST

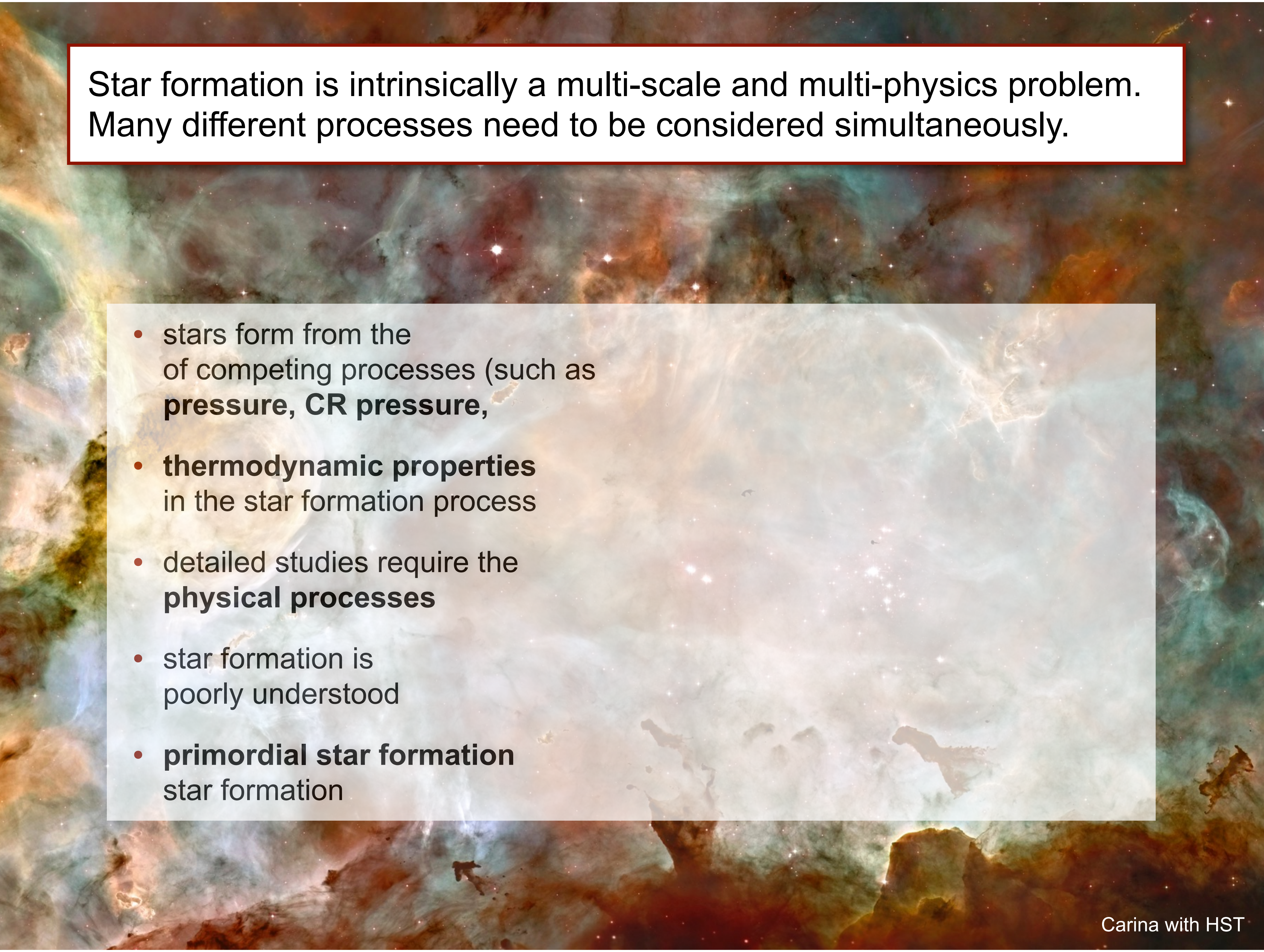
Star formation is intrinsically a multi-scale and multi-physics problem. Many different processes need to be considered simultaneously.



Carina with HST

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

- stars form from the
  of competing processes (such as
  pressure, CR pressure,
- **thermodynamic properties**
  in the star formation process
- detailed studies require the
  physical processes
- star formation is
  poorly understood
- **primordial star formation**
  star formation



Carina with HST