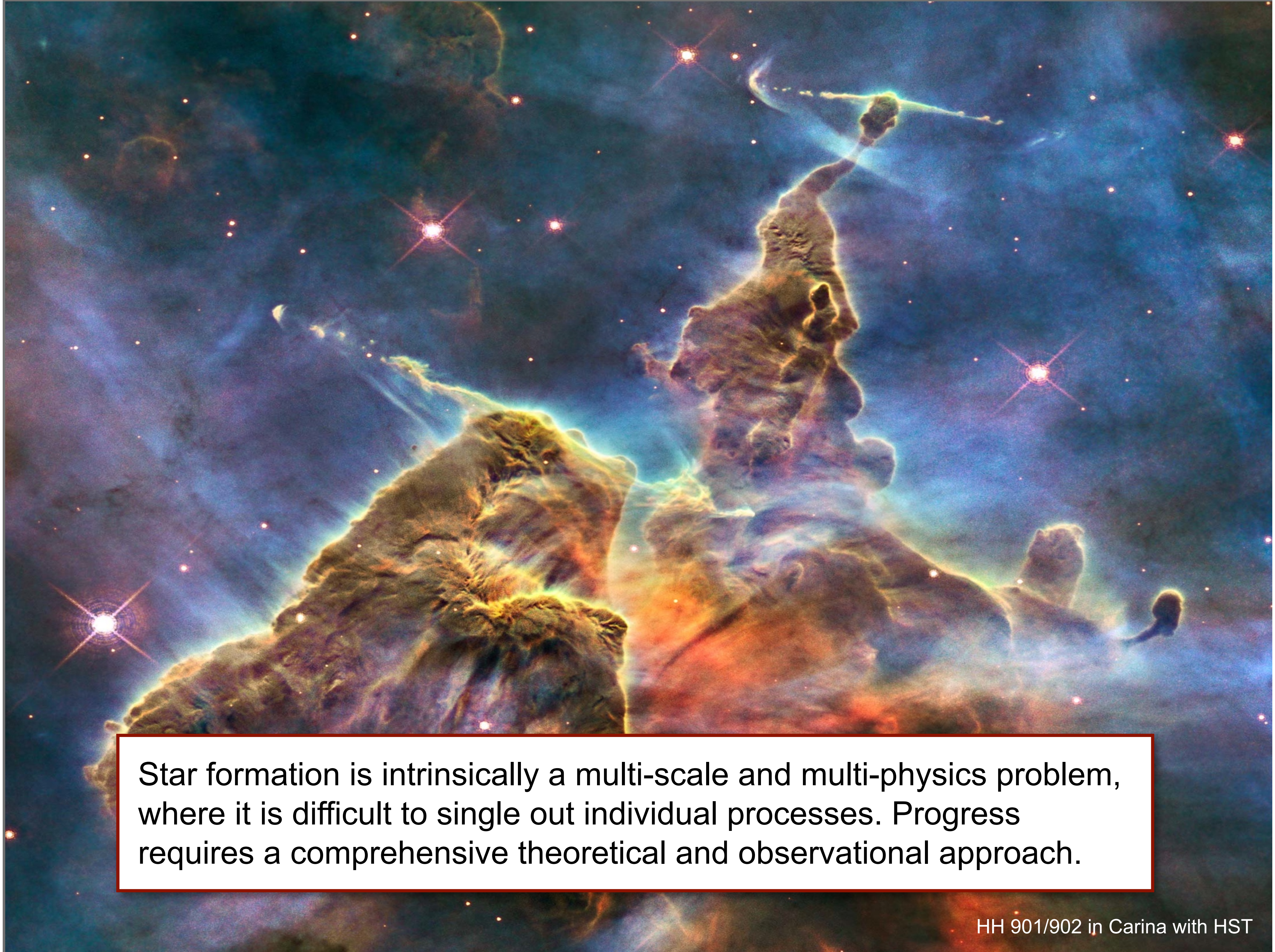

Carina with HST

HH 901/902 in Carina with HST



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 and observational approach.

HH 901/902 in Carina with HST

Stellar Initial Mass Function

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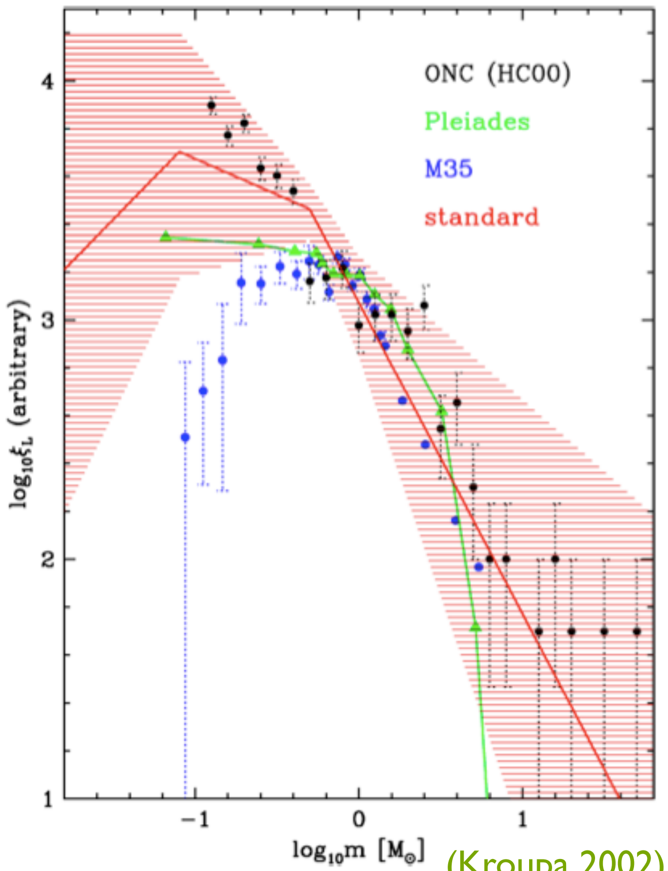
HH 901/902 in Carina with HST

stellar mass fuction

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



(Kroupa 2002)

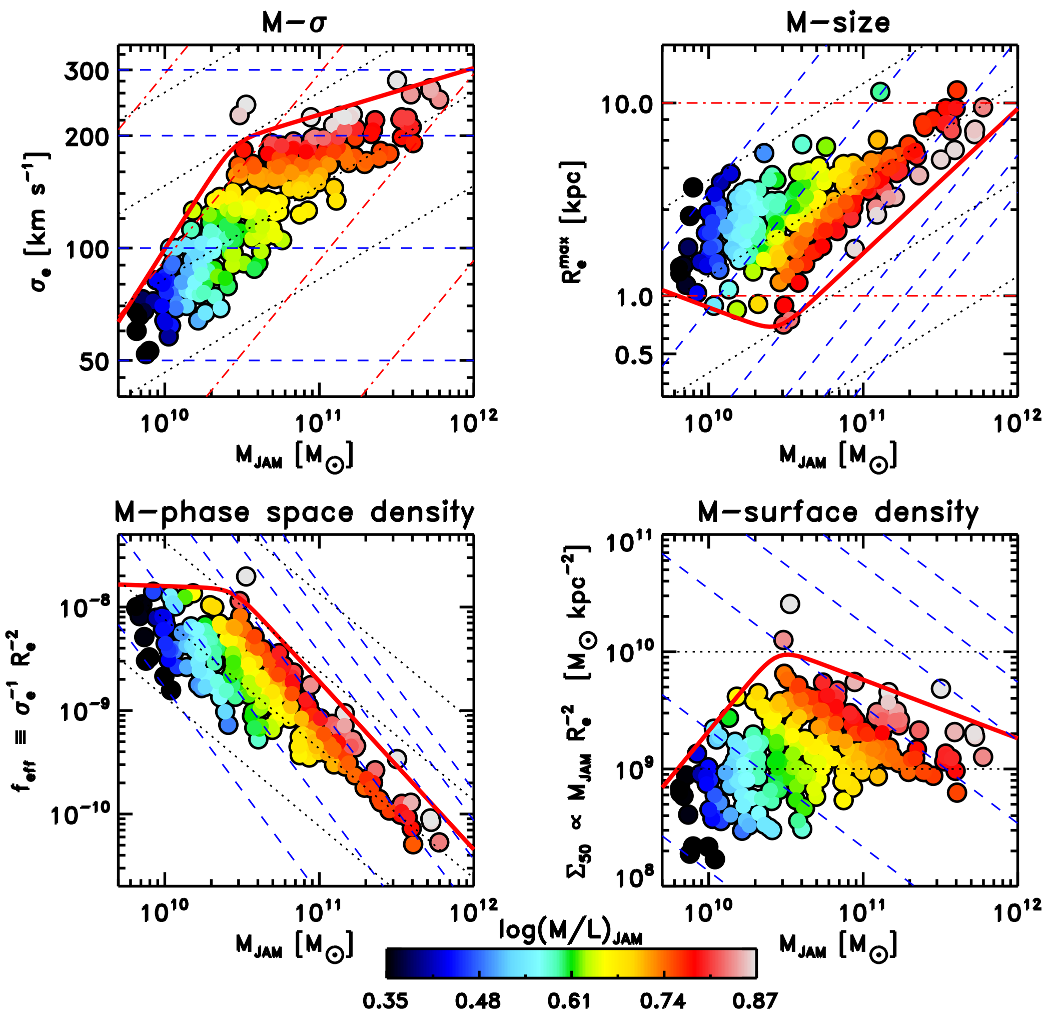
Orion, NGC 3603, 30 Doradus
(Zinnecker & Yorke 2007)

stellar mass fuction

BUT: maybe variations with galaxy type (bottom heavy in the centers of large ellipticals)

from JAM (Jeans anisotropic multi Gaussian expansion) modeling

inferred excess of low-mass stars compared to Kroupa IMF

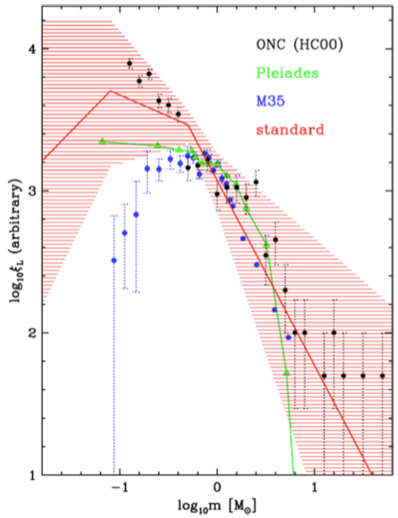


(Cappellari et al. 2012, Nature, 484, 485, Cappellari et al. 2012ab, MNRAS, submitted, also van Dokkum & Conroy 2010, Nature, 468, 940, Wegner et al. 2012, AJ, 144, 78, and others)

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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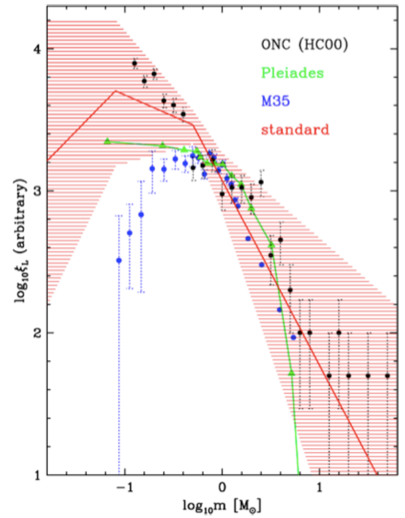


example: model of Orion cloud

„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

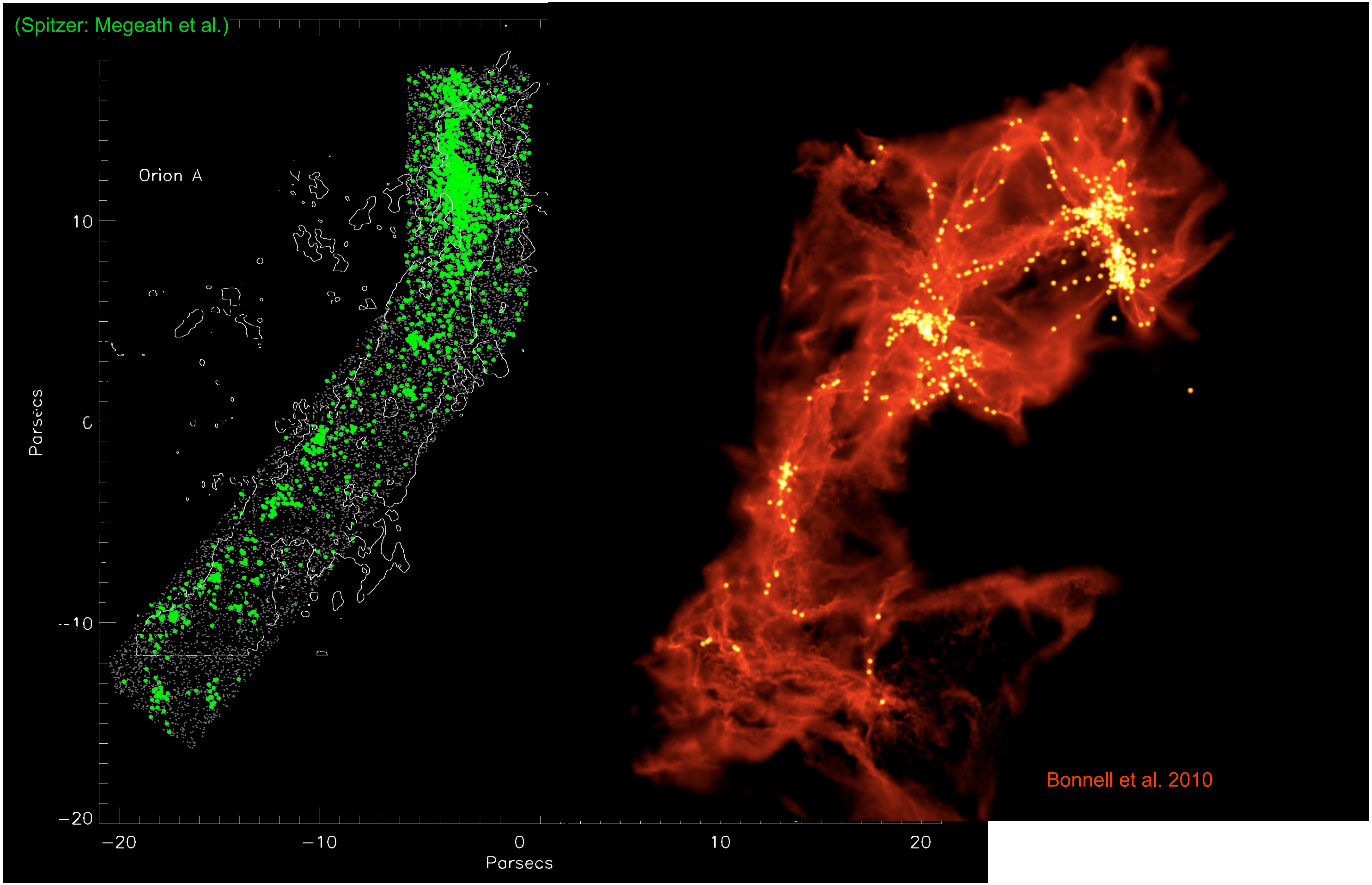
has clustered as well as distributed „star“ formation

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



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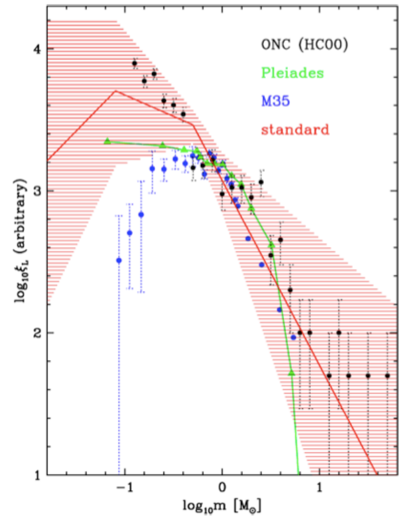

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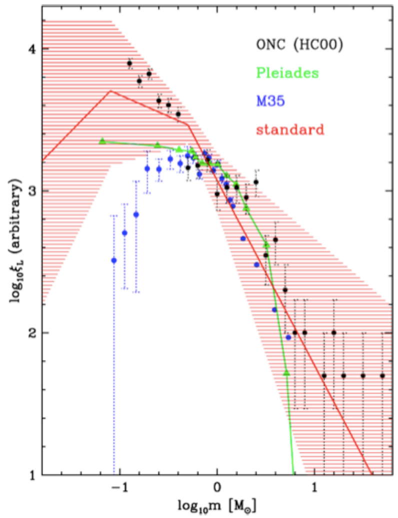
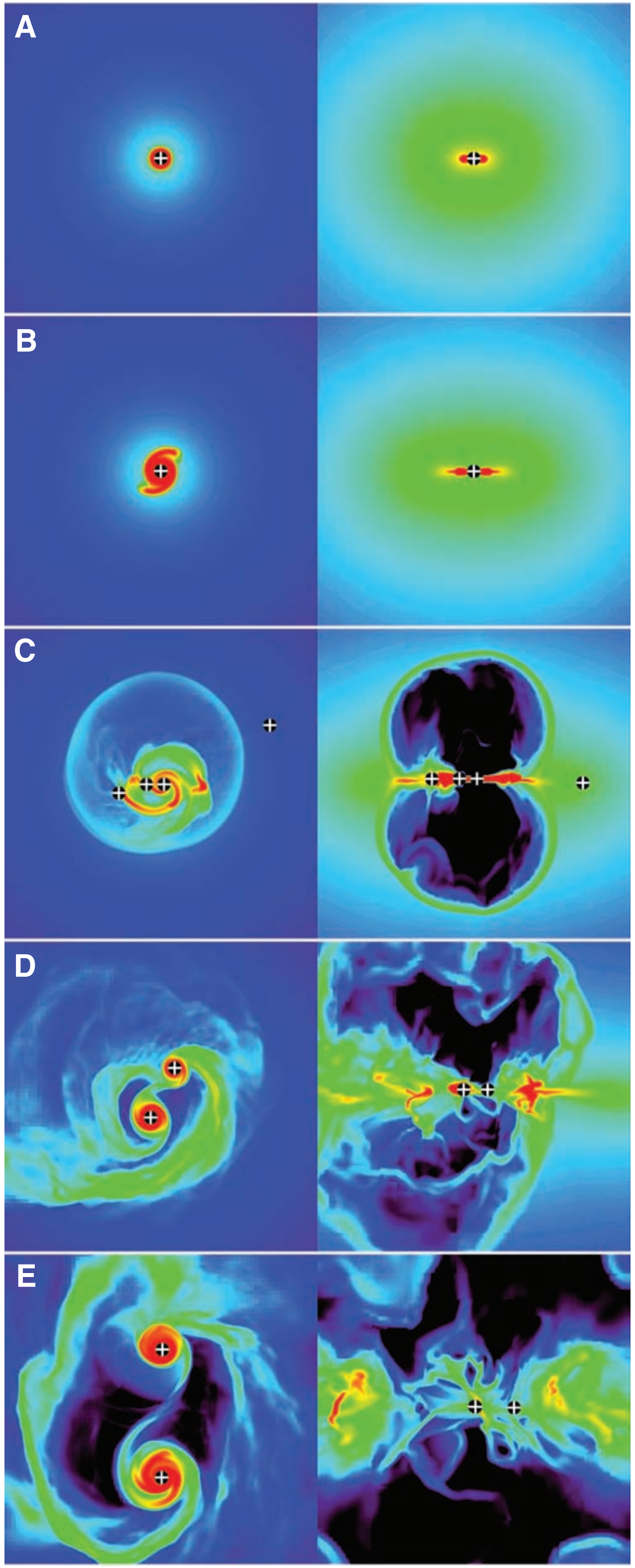


feedback

- star formation has many many feedback loops
  - mechanical 1: protostellar outflows, stellar winds
    —> *lots of momentum and kinetic energy input*
  - mechanical 2: supernovae
    —> *key driver of ISM turbulence? triggered SF?*
  - radiative 1: thermal energy from stars
    —> *local heating, changes in IMF?*
  - radiative 2: ionizing radiation
    —> *expanding HII regions driving turbulence? local termination of SF?*
  - chemical: enrichment by massive stars
    —> *changes heating and cooling, influence on collapse & fragmentation*
  - more indirect processes
    —> *cosmic rays, global interstellar radiation field, chemical*
  - AGN feedback

Rosetta nebula (NGC 2237)

Fig. 1. Snapshots of the simulation at (**A**) 17,500 years, (**B**) 25,000 years, (**C**) 34,000 years, (**D**) 41,700 years, and (**E**) 55,900 years. In each panel, the left image shows column density perpendicular to the rotation axis in a $(3000\ \mathrm{AU})^2$ region; the right image shows volume density in a $(3000\ \mathrm{AU})^2$ slice along the rotation axis. The color scales are logarithmic (black at the minimum, red at the maximum), from 10^0 to $10^{2.5}$ g cm^{-2} on the left and 10^{-18} to 10^{-14} g cm^{-3} on the right. Plus signs indicate the projected positions of stars. See figs. S1 to S3 and movie S1 for additional images.



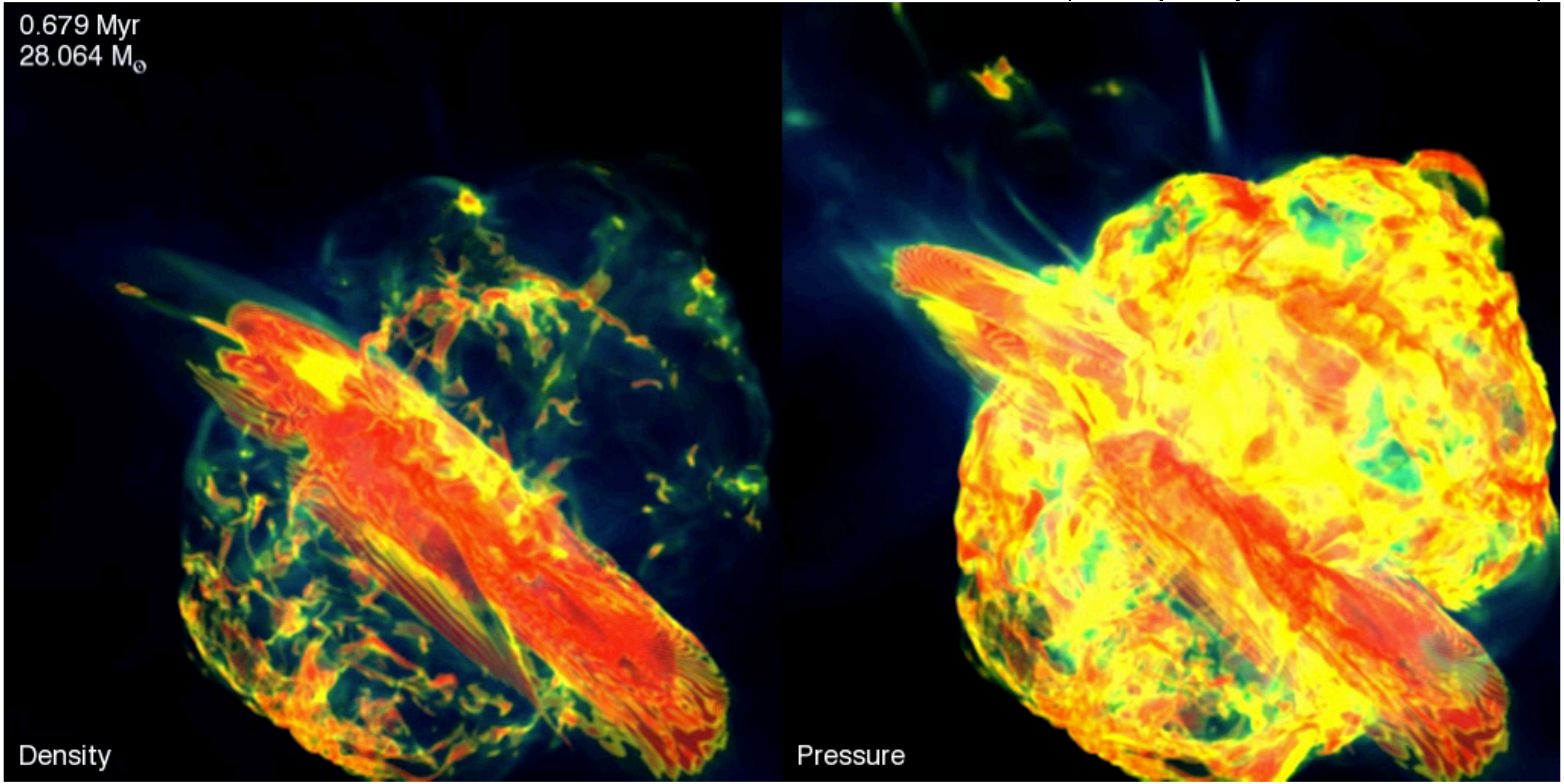
radiative feedback does ***not limit disk accretion*** (radiation modeled as radiation pressure)

(example by Krumholz et al. 2009)

Krumholz et al. (2009)

ionizing feedback with B-fields:

(example by Peters et al. 2011)

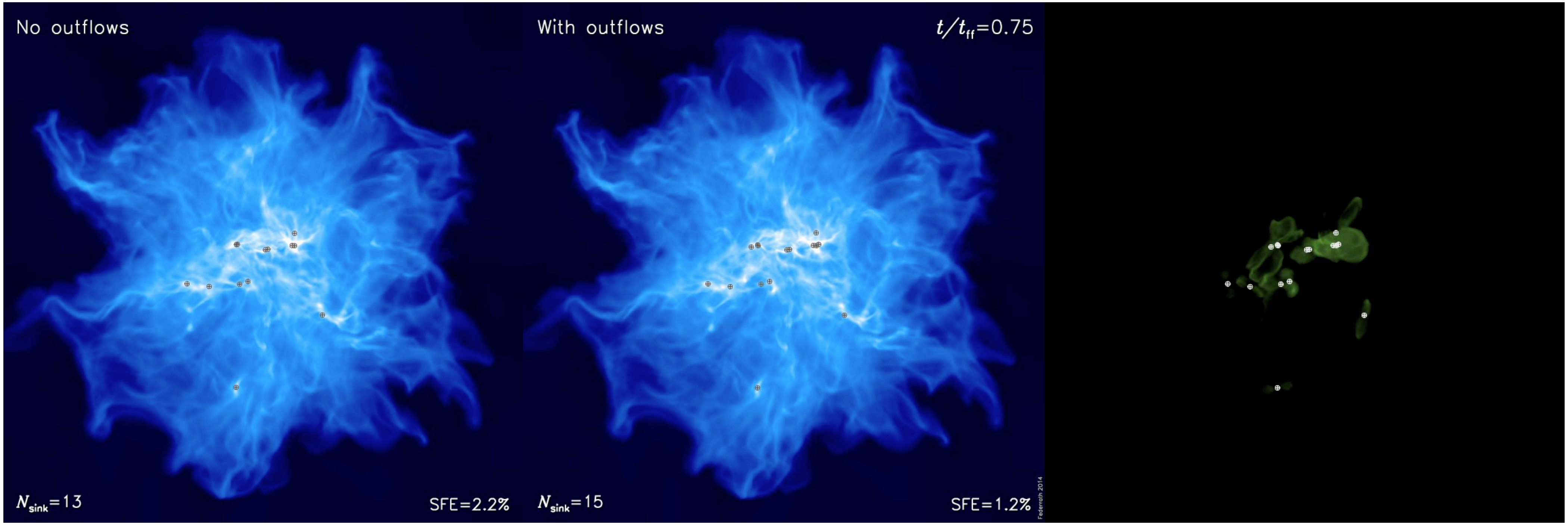


Peters et al. (2011)

in disk around high-mass stars, ***fragmentation is reduced (by factor of 2) but rarely fully suppressed***, see Peters et al. (2011), Hennebelle et al. (2011), Seifried et al. (2011)

protostellar outflows in cluster

(example by Federrath et al. 2014)



Federrath et al. (2014, ApJ, to be sumitted soon)

outflows disrupt filaments and increase the level of fragmentation

—> ***stellar masses get smaller by factor of 1/3***

(also Li & Nakamura 2006, Li et al. 2010, Nakamura & Li 2007, 2011, 2014, Wang et al. 2010, Carroll et al. 2010, Cunningham et al. 2011, Hansen et al. 2012)

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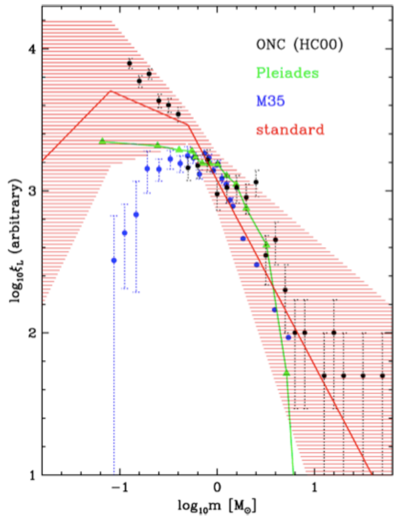

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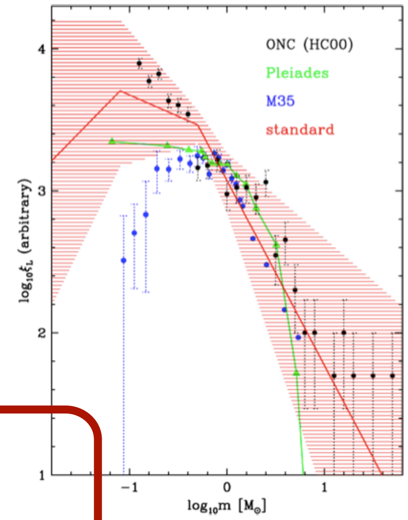


application to early star formation

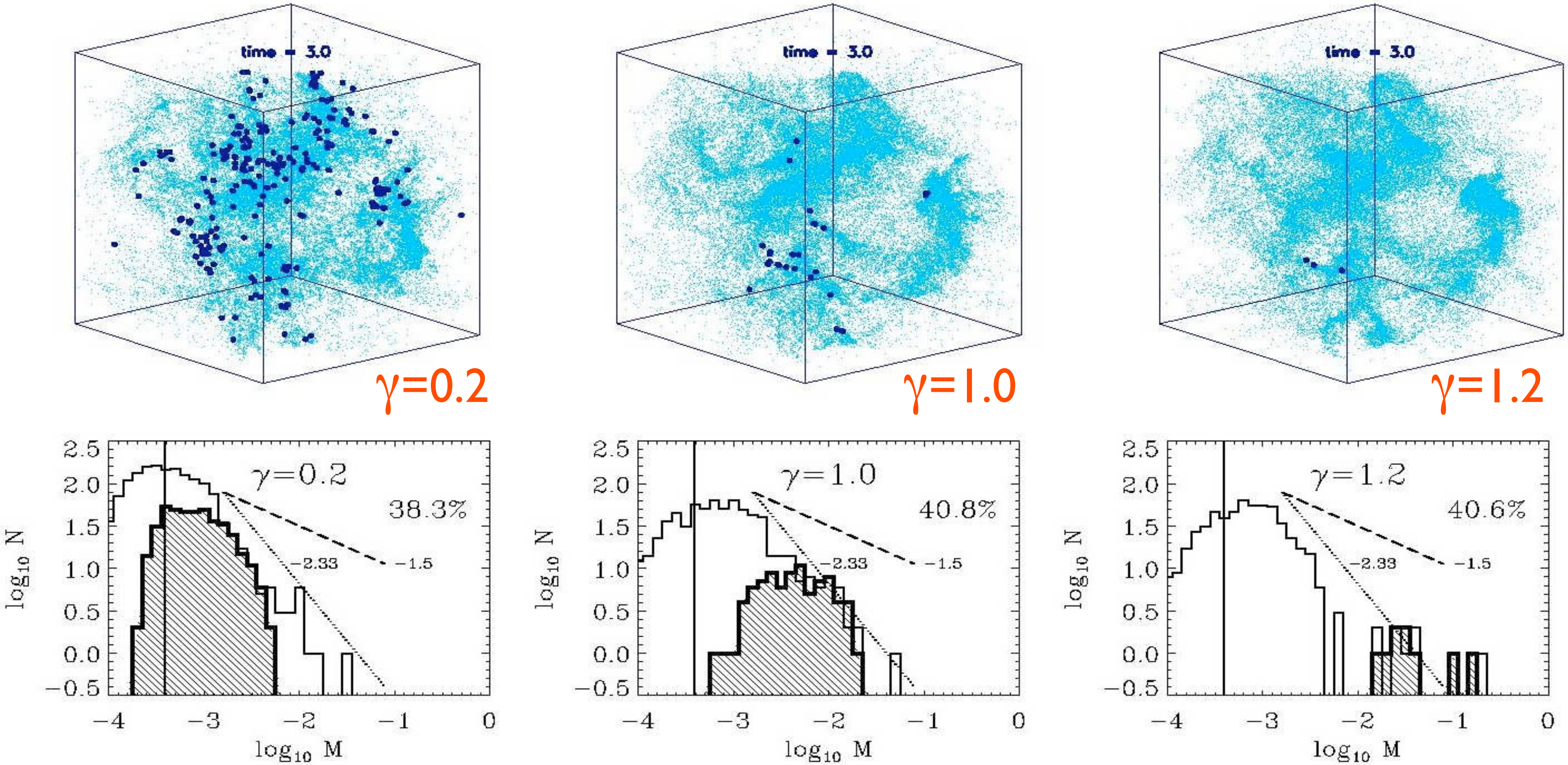
thermodynamics & fragmentation

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 γ<1 fragmentation is enhanced → *cluster of low-mass stars*

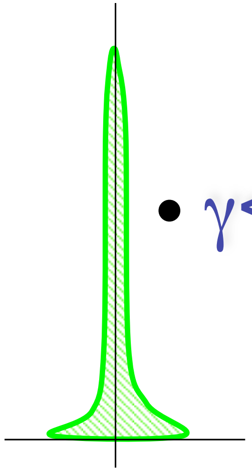
for γ>1 it is suppressed → *isolated massive stars*

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

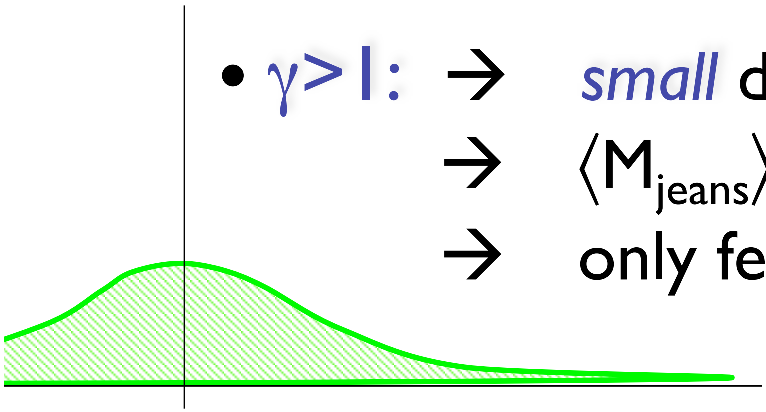
how does that work?

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

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

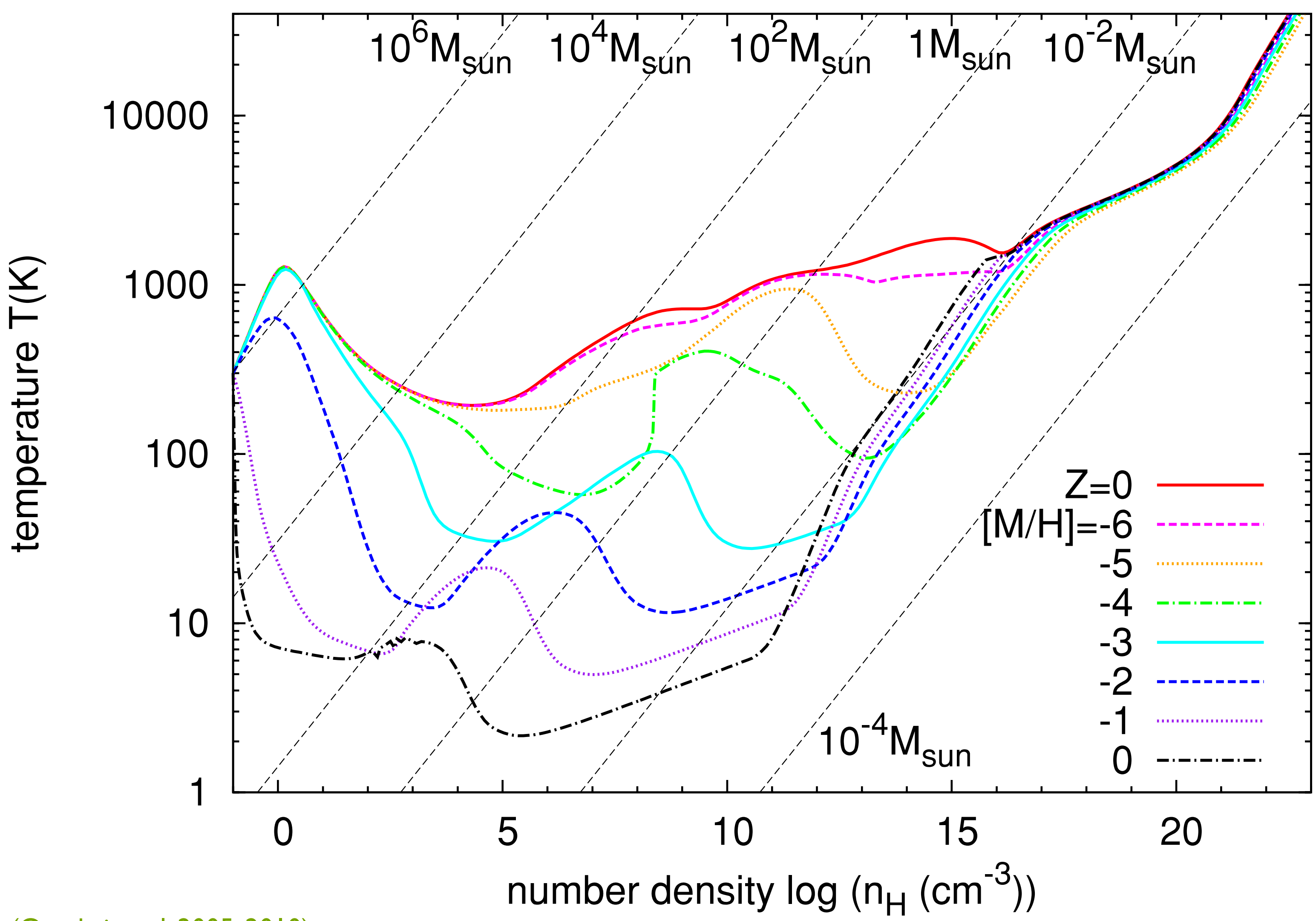


- $\gamma < 1$: → *large* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ becomes small
  → number of fluctuations with $M > M_{jeans}$ is large



- $\gamma > 1$: → *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)

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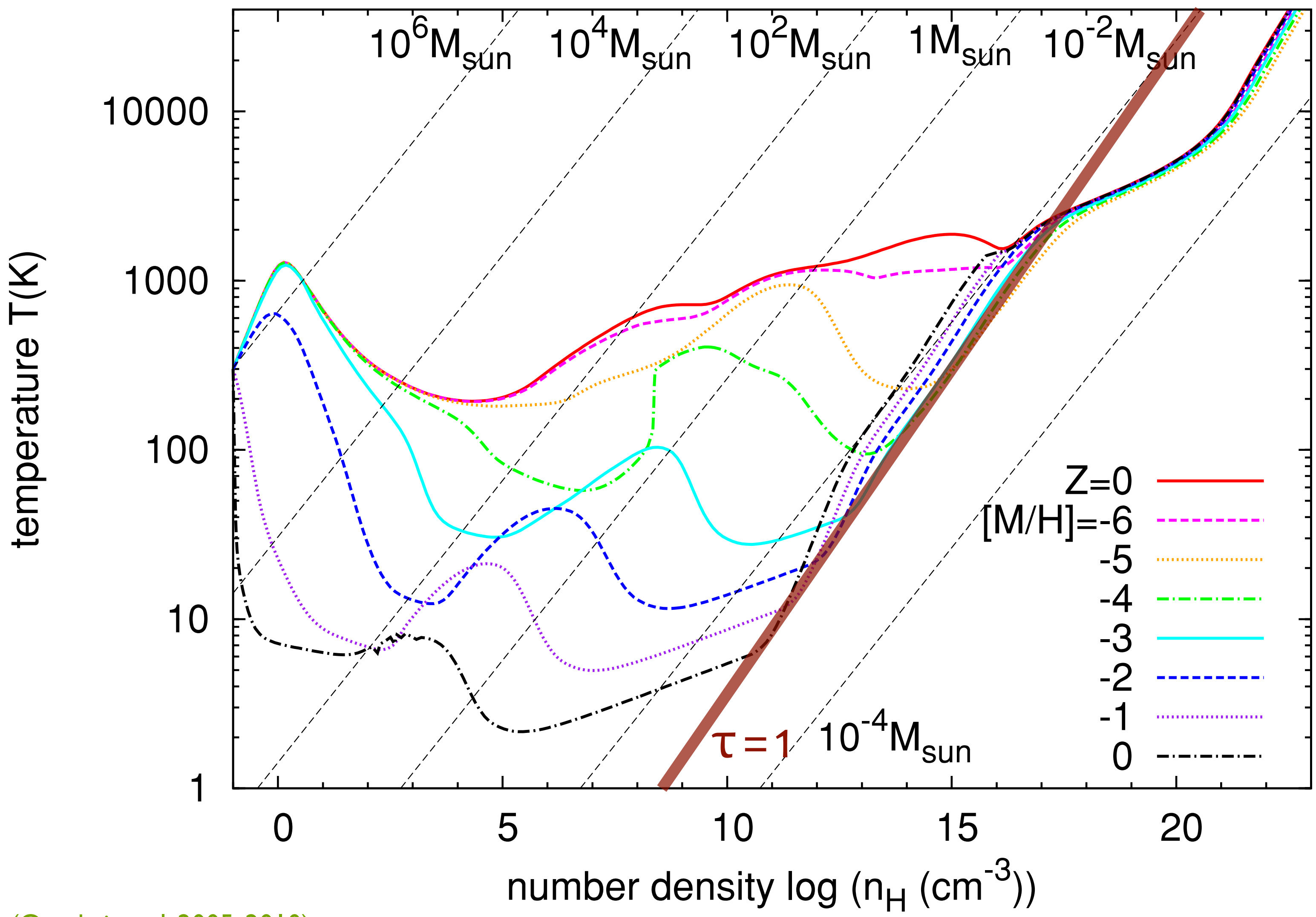

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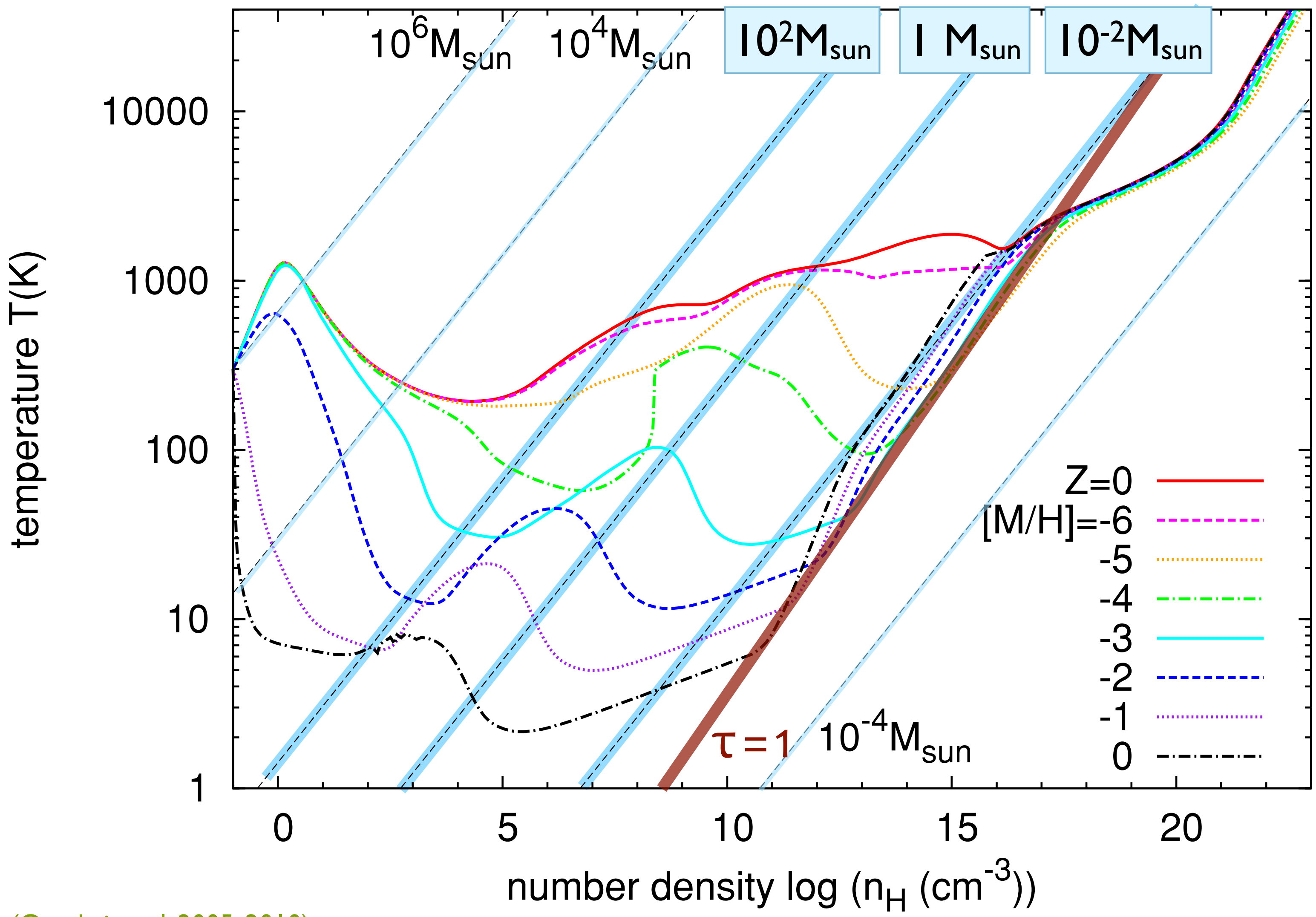

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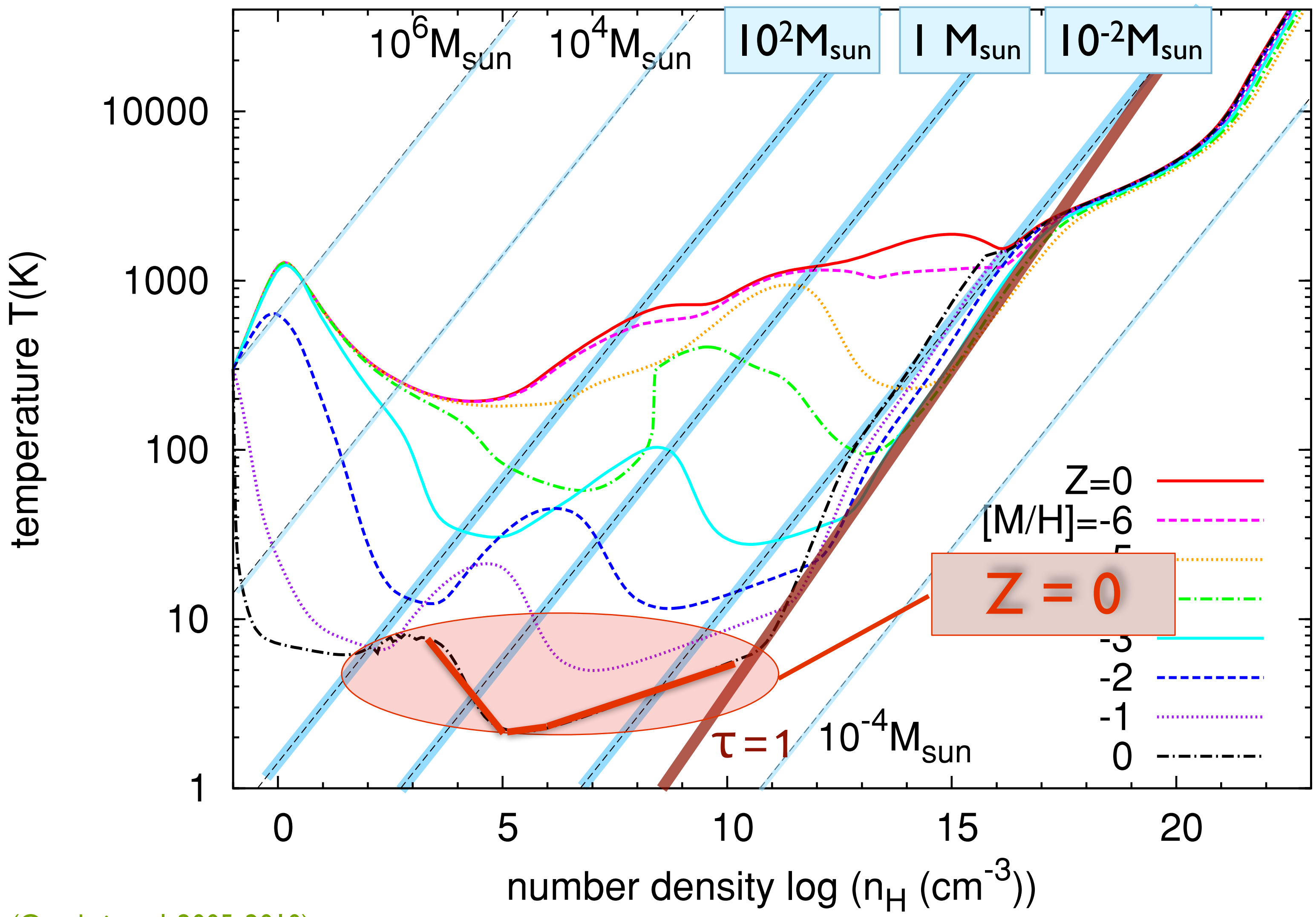
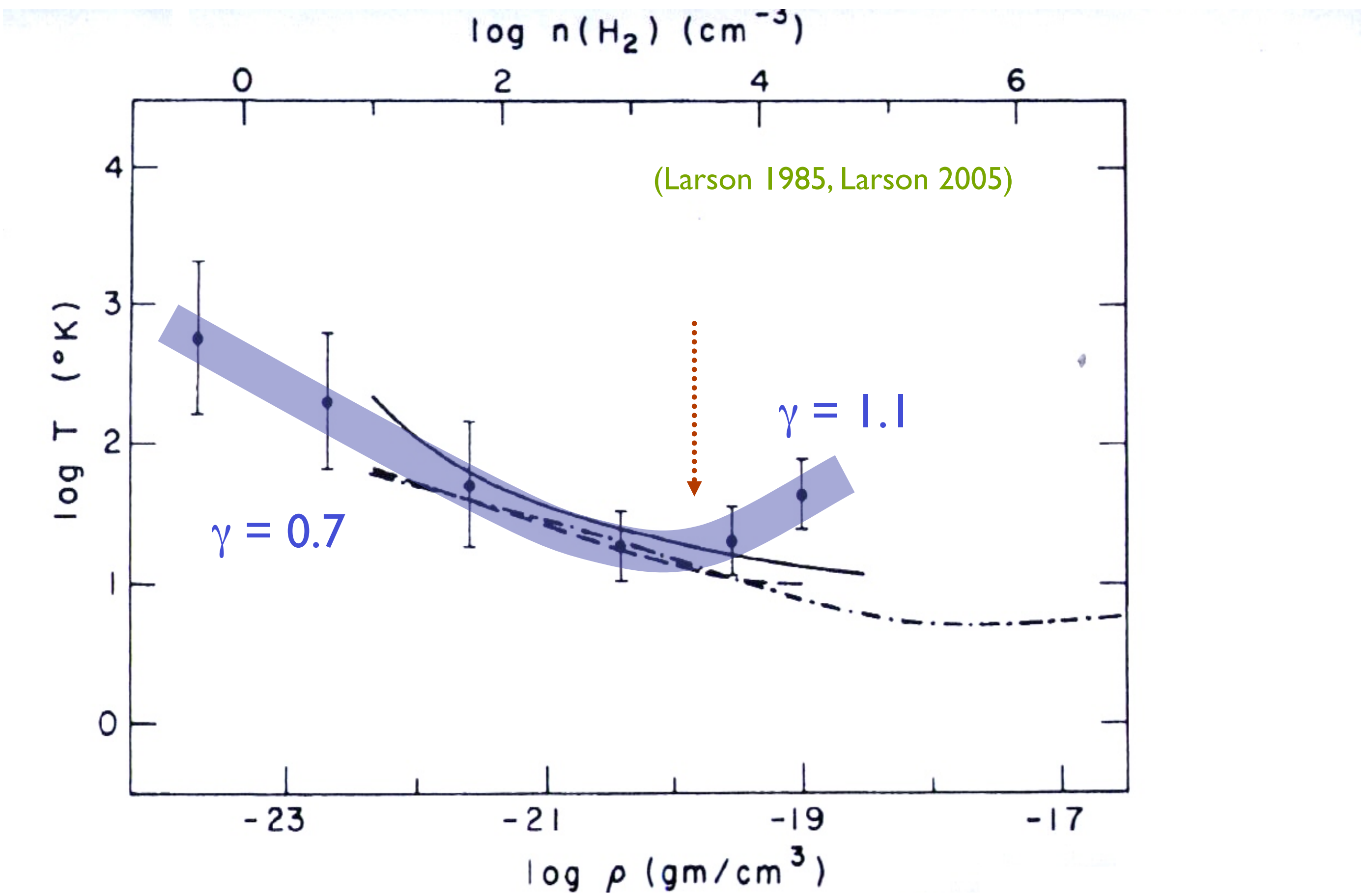
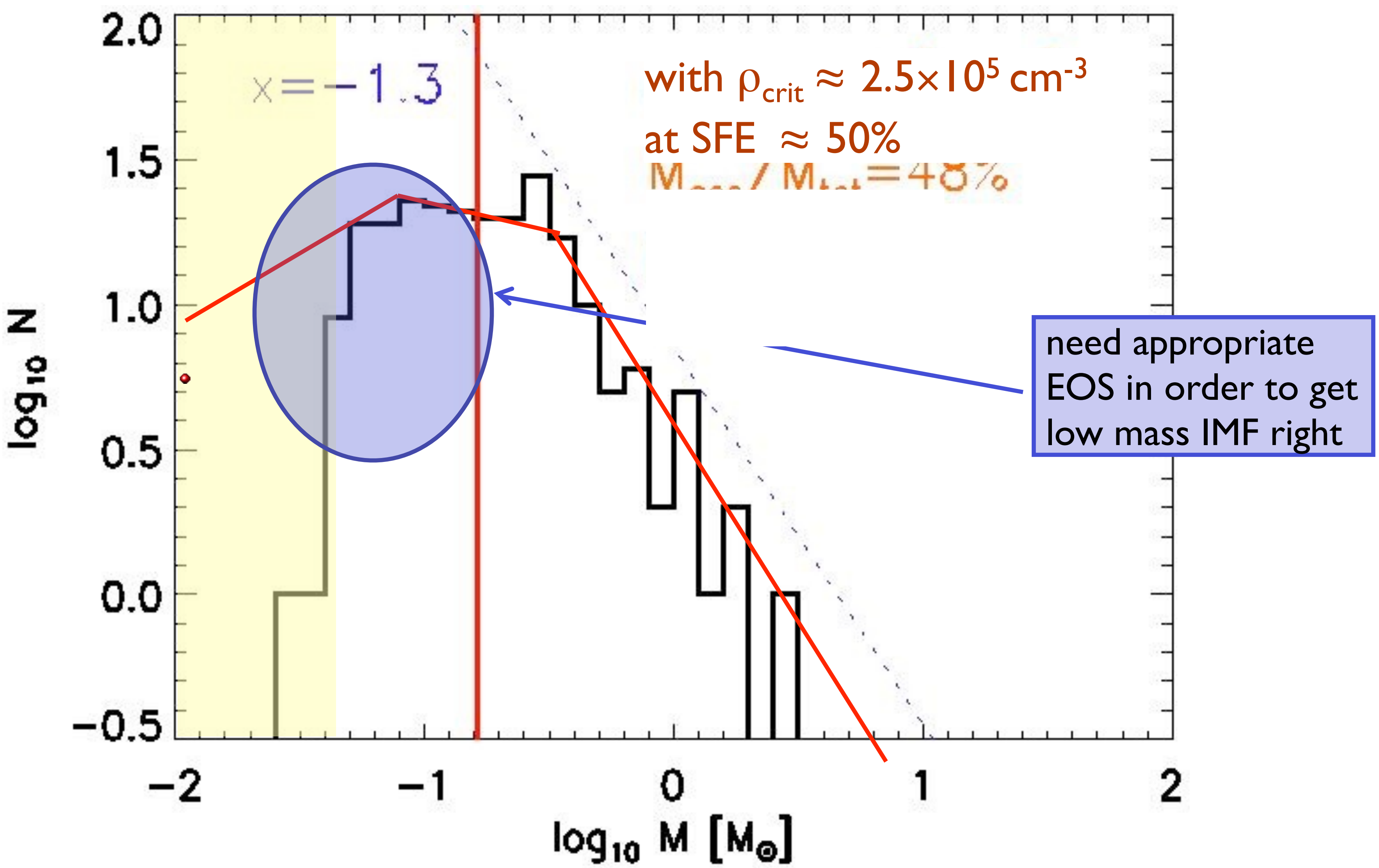


(Omukai et al. 2005, 2010)

present-day star formation

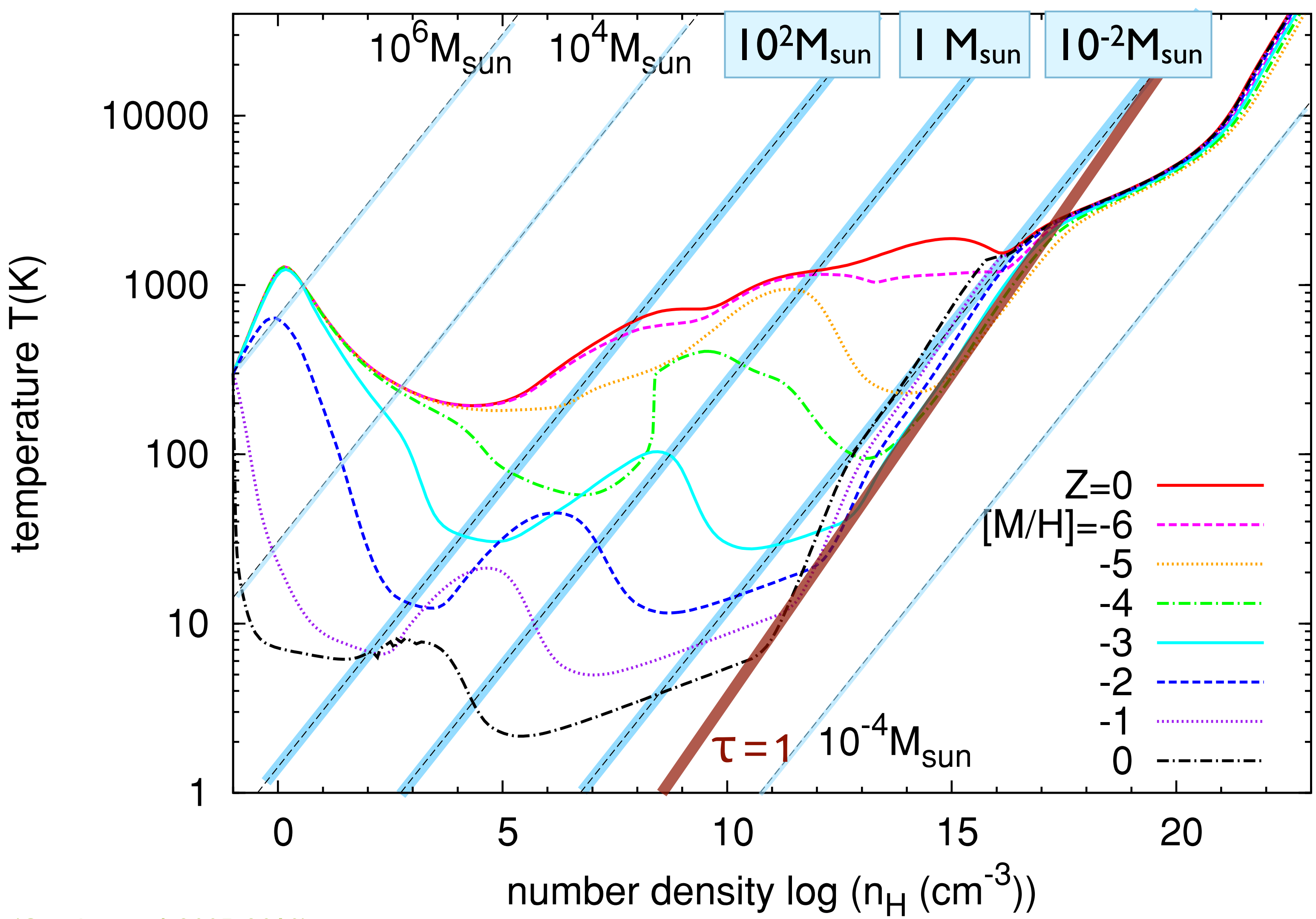


IMF in nearby molecular clouds



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

EOS as function of metallicity



(Omukai et al. 2005, 2010)

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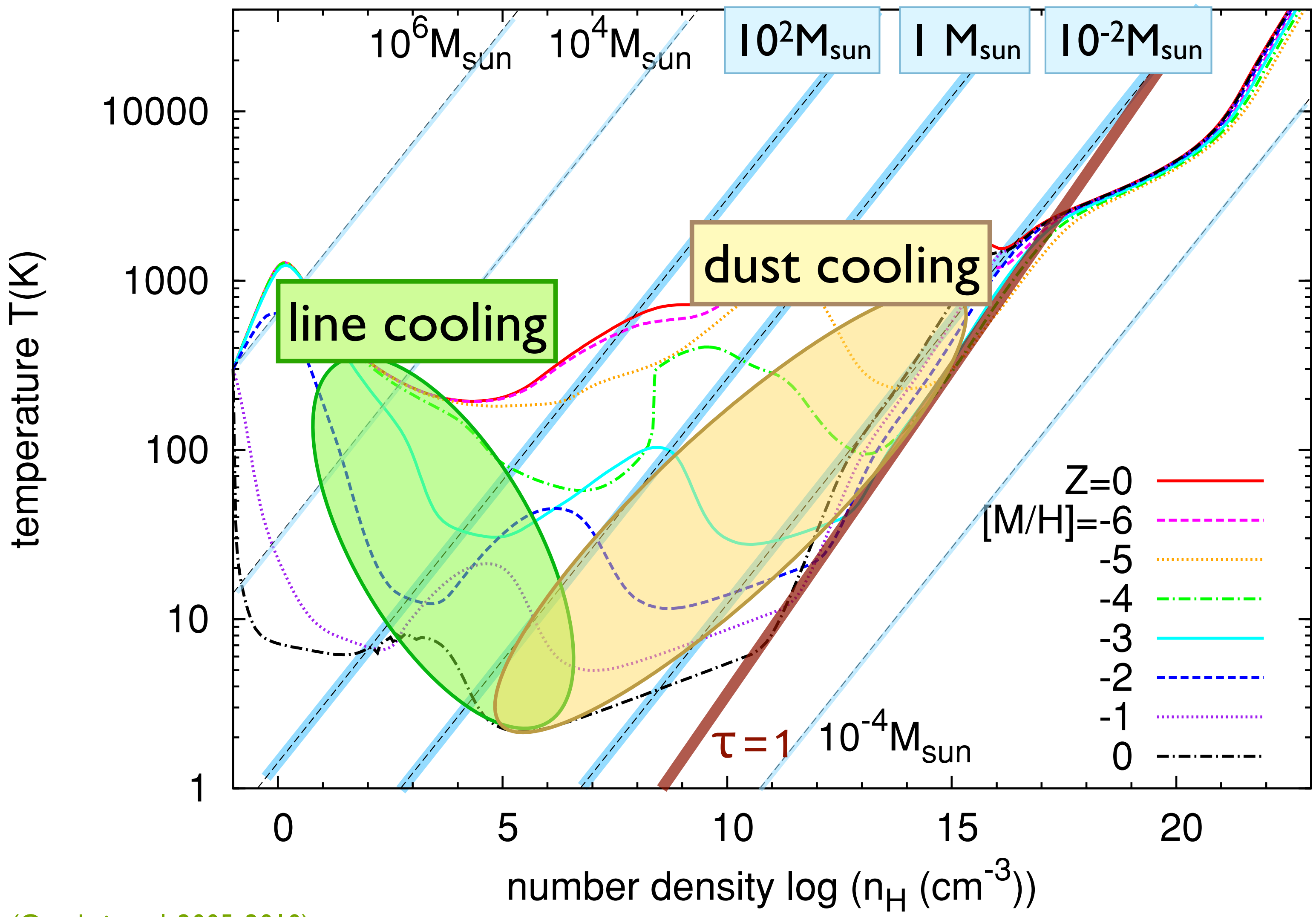
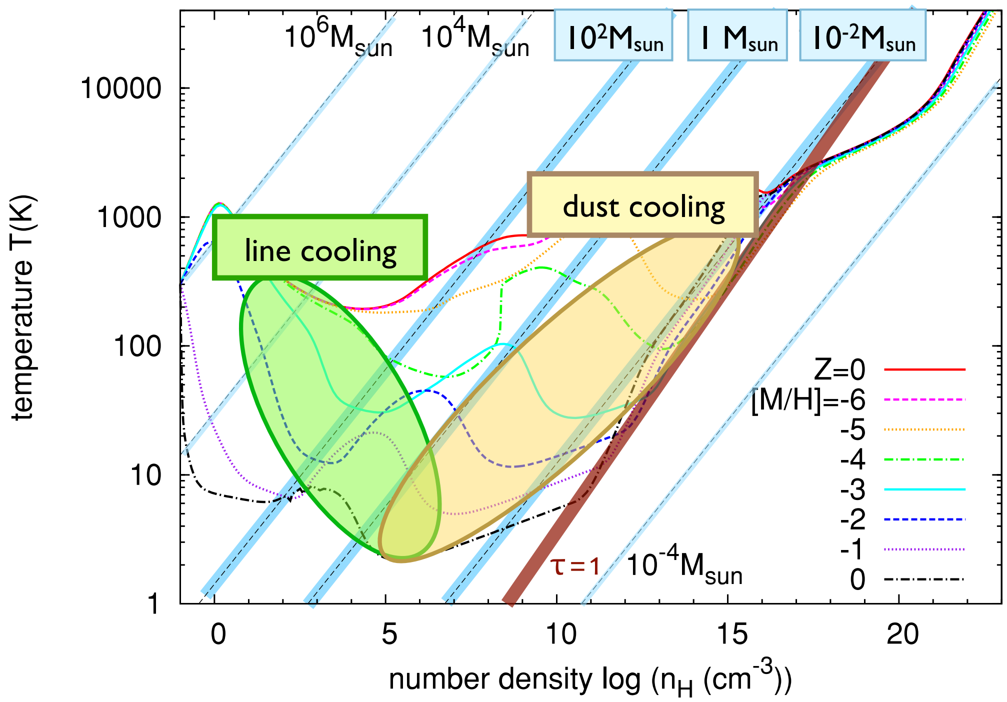


(Omukai et al. 2005, 2010)

transition: Pop III to Pop II.5



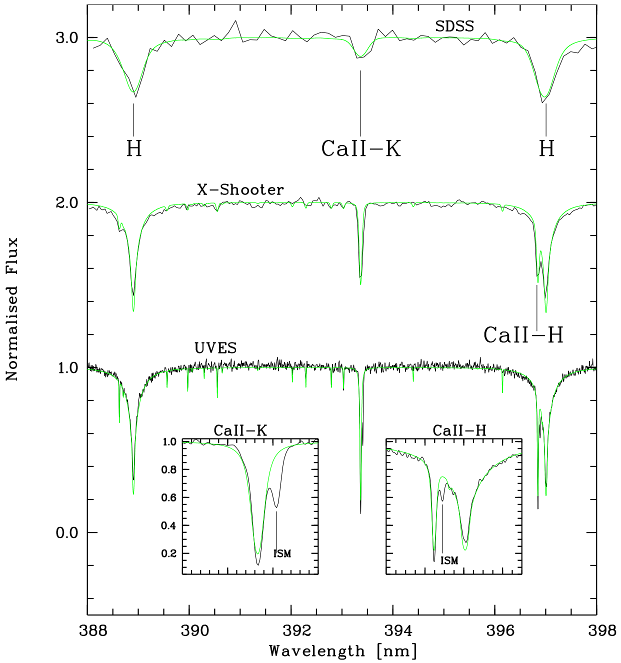
two competing models:

- 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}.

(Omukai et al. 2005, 2010)

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]

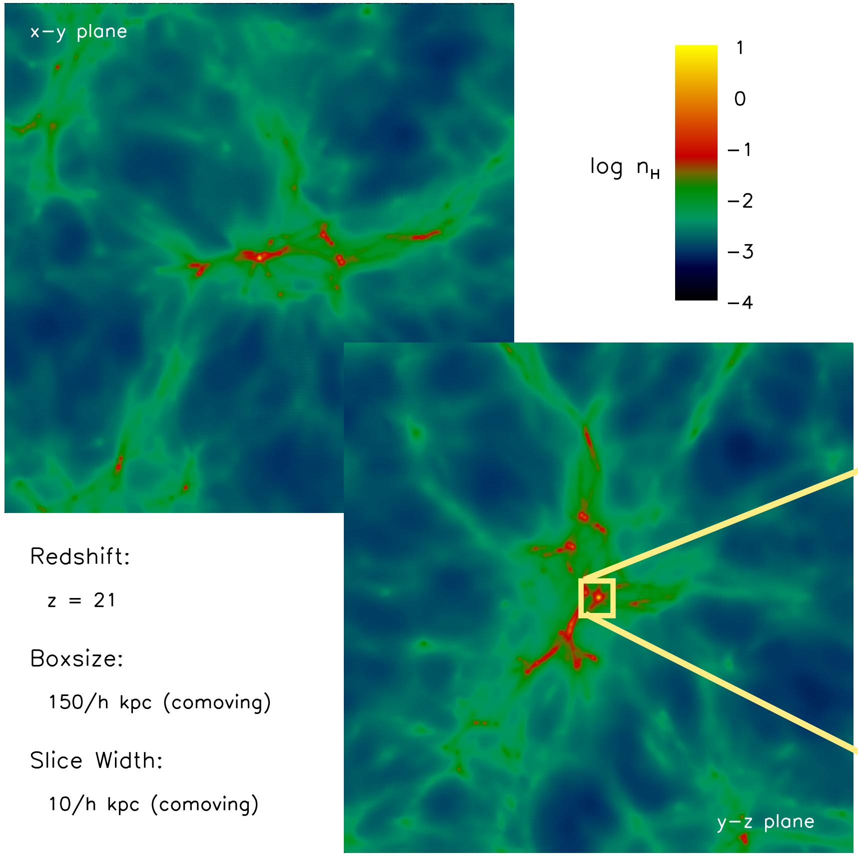
Element		[X/H]$_{1D}$ +3Dcor.	+NLTE cor.	+ 3D cor + NLTE cor	N lines	S_H	A(X)$_\odot$
C	≤ −3.8	≤ −4.5			G-band		8.50
N	≤ −4.1	≤ −5.0			NH-band		7.86
Mg I	−4.71 ± 0.11	−4.68 ± 0.11	−4.52 ± 0.11	−4.49 ± 0.12	5	0.1	7.54
Si I	−4.27	−4.30	−3.93	−3.96	1	0.1	7.52
Ca I	−4.72	−4.82	−4.44	−4.54	1	0.1	6.33
Ca II	−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]

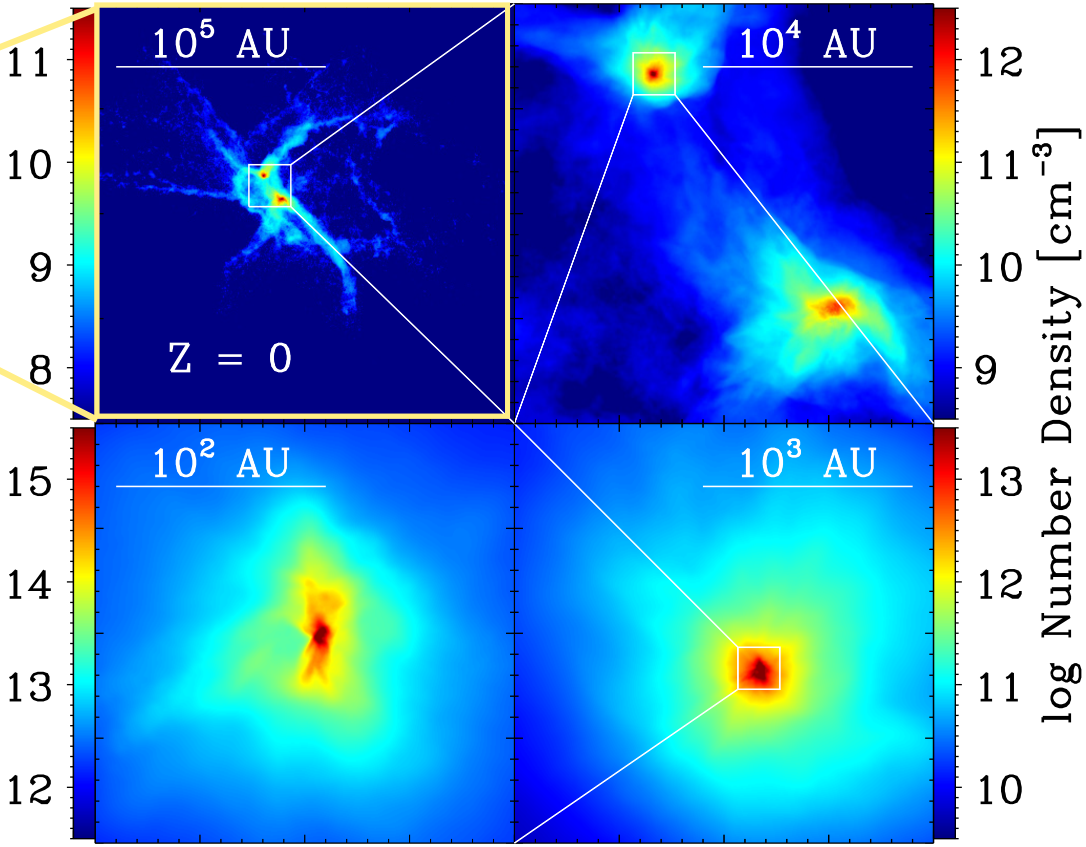
(Caffau et al. 2011, 2012)

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

modeling the formation of the first/second stares

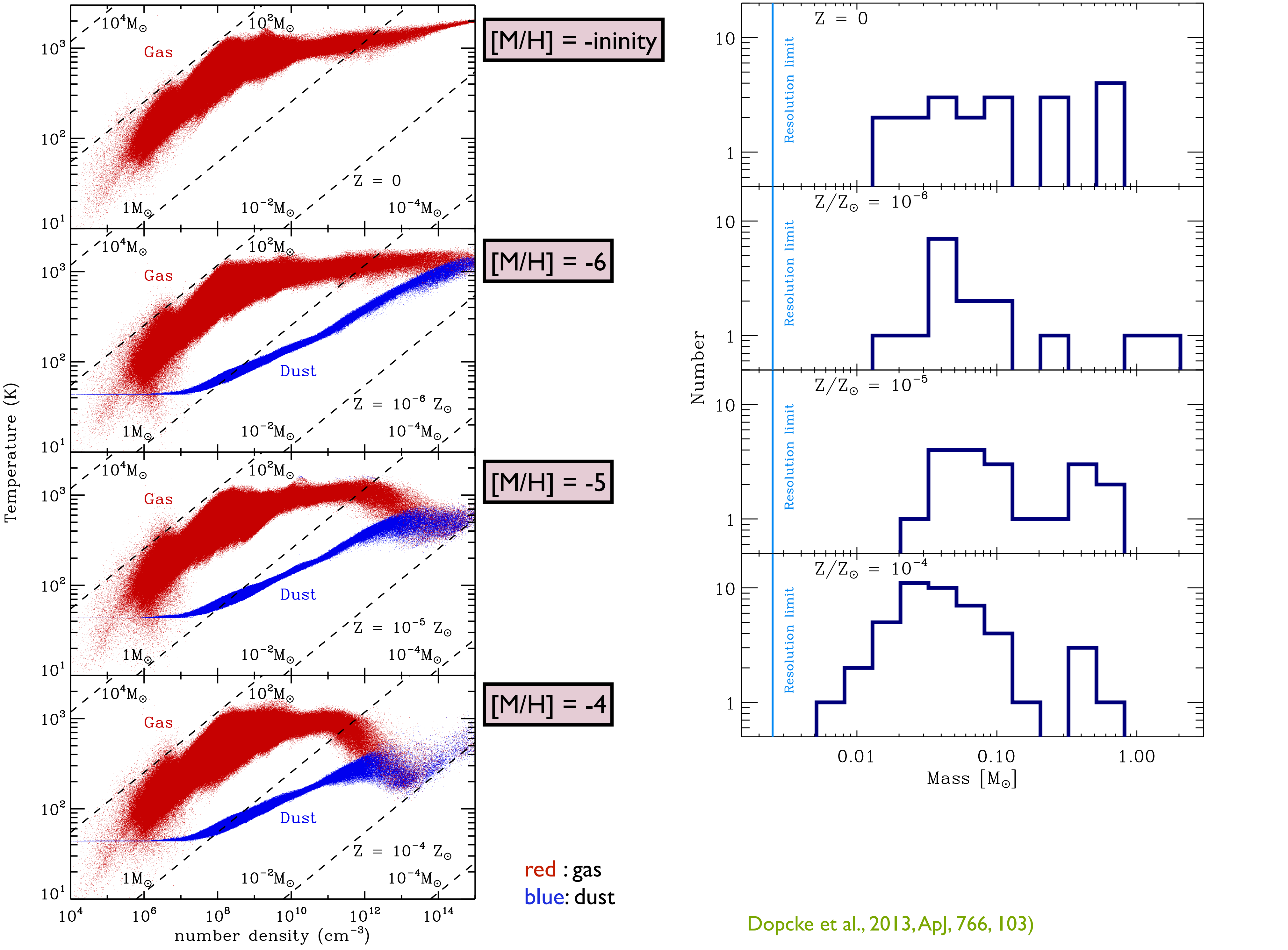


successive zoom-in calculation from cosmological initial conditions (using SPH and new grid-code AREPO)



(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)

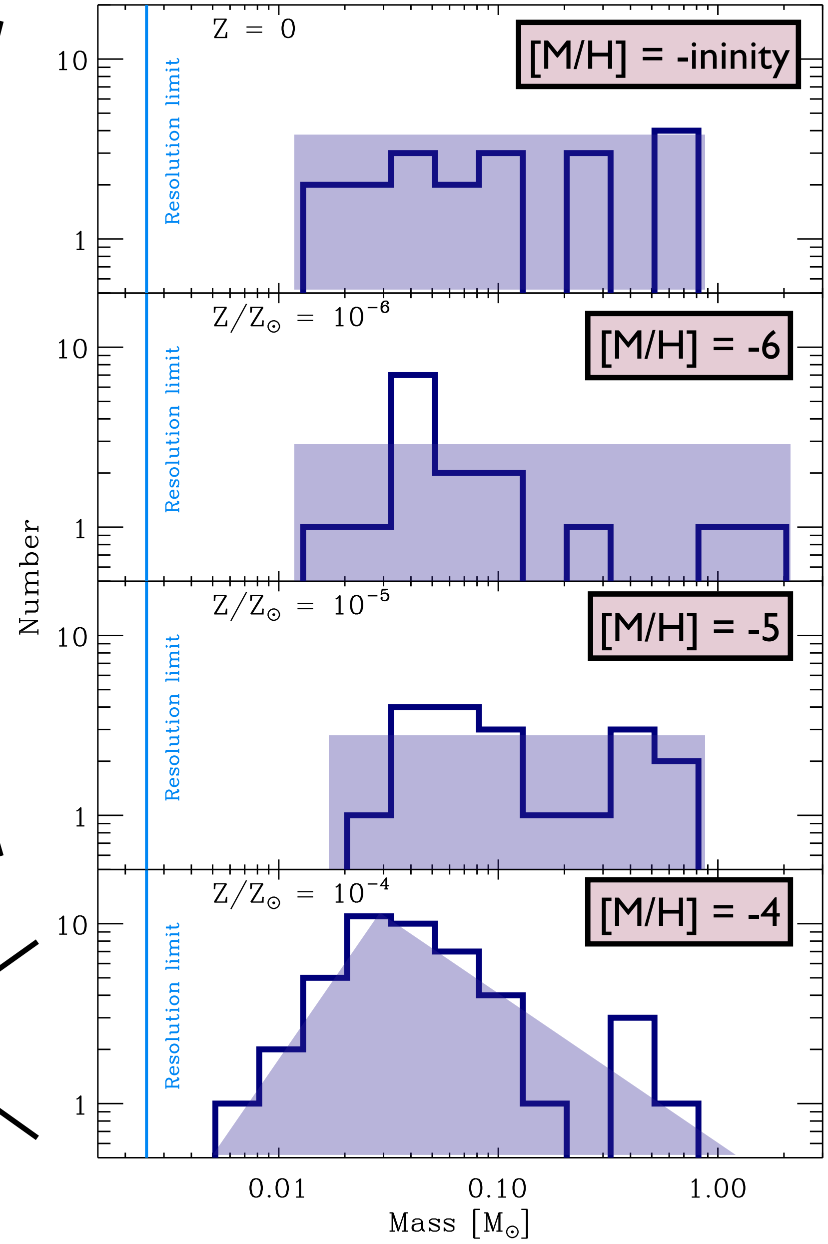


Dopcke et al., 2013, ApJ, 766, 103)

hints for differences in mass spectrum

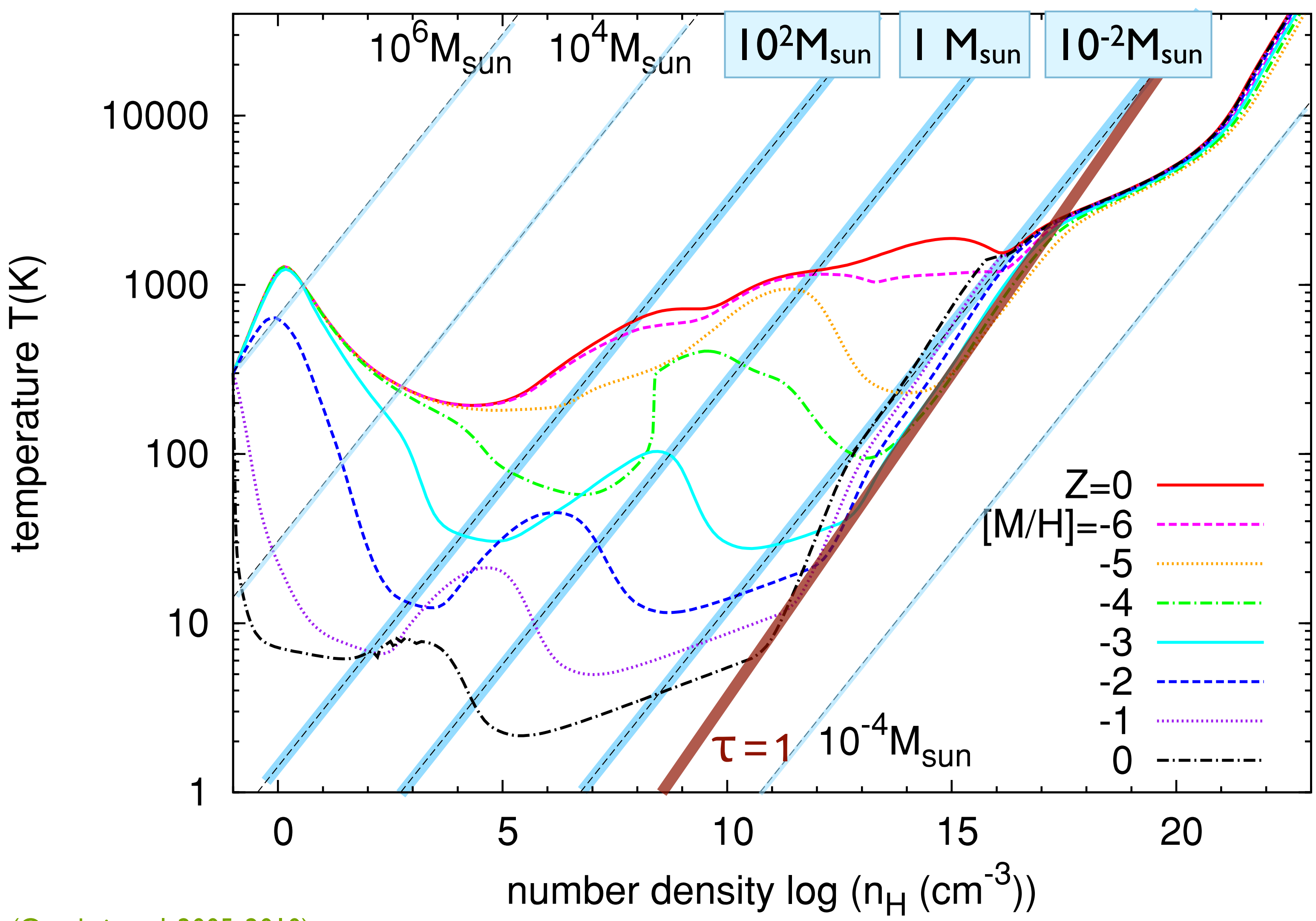
disk fragmentation mode

gravoturbulent fragmentation mode



Dopcke et al., 2013, ApJ, 766, 103)

EOS as function of metallicity



(Omukai et al. 2005, 2010)

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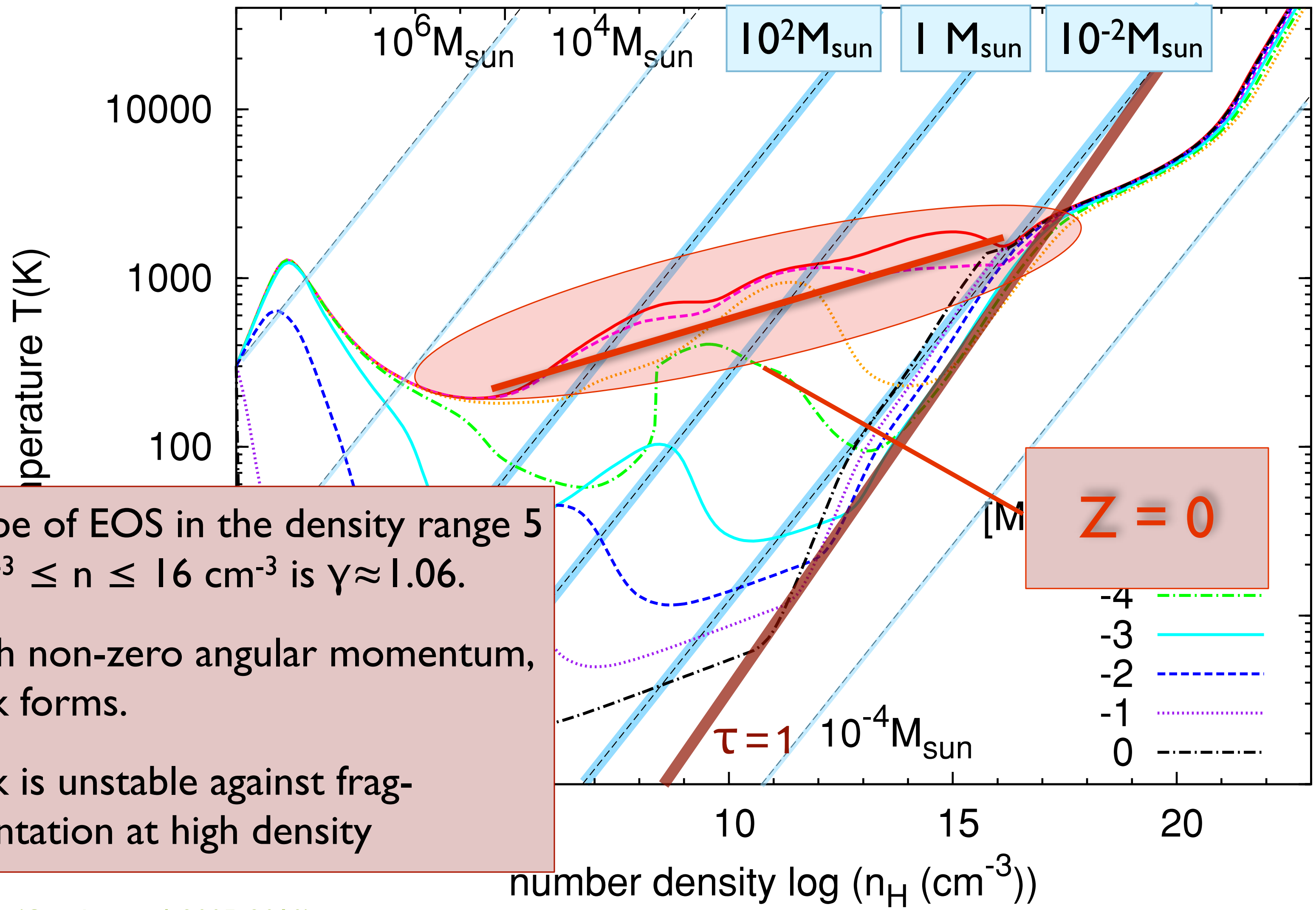
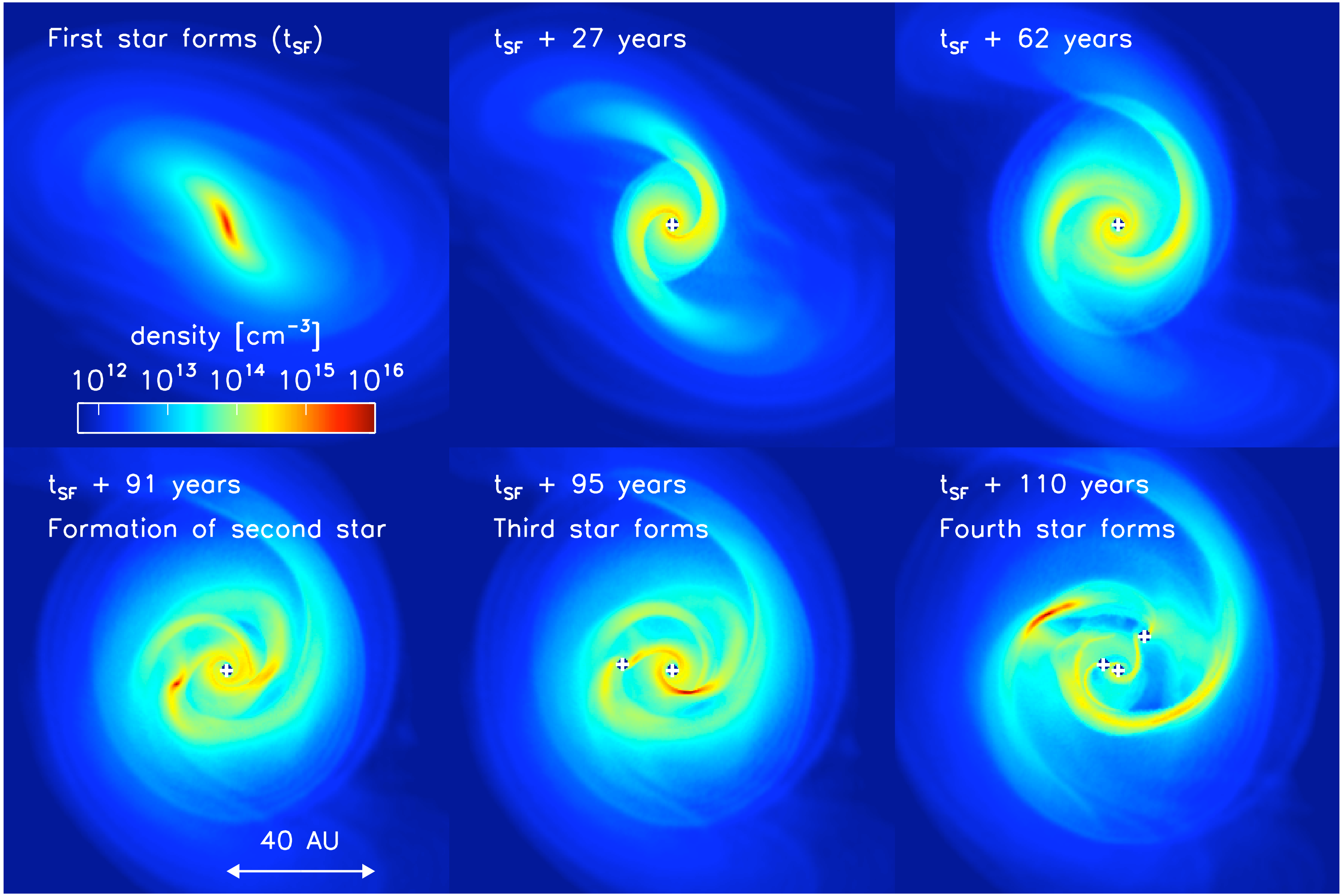


- slope of EOS in the density range 5 $cm^{-3} \le n \le 16\ cm^{-3}$ is $\gamma \approx 1.06$.
- with non-zero angular momentum, disk forms.
- disk is unstable against frag-mentation at high density

(Omukai et al. 2005, 2010)

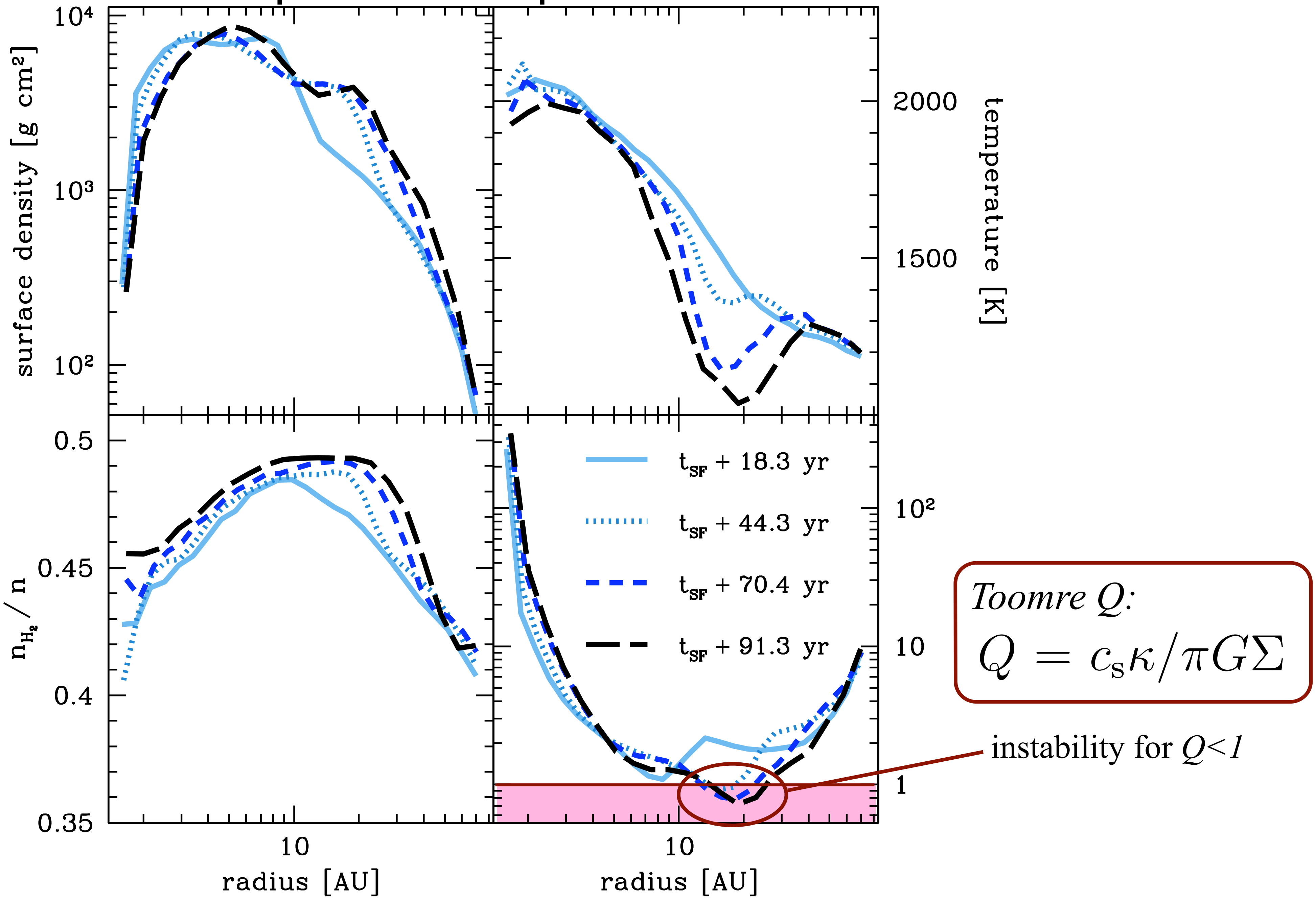


detailed look at accretion disk

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.

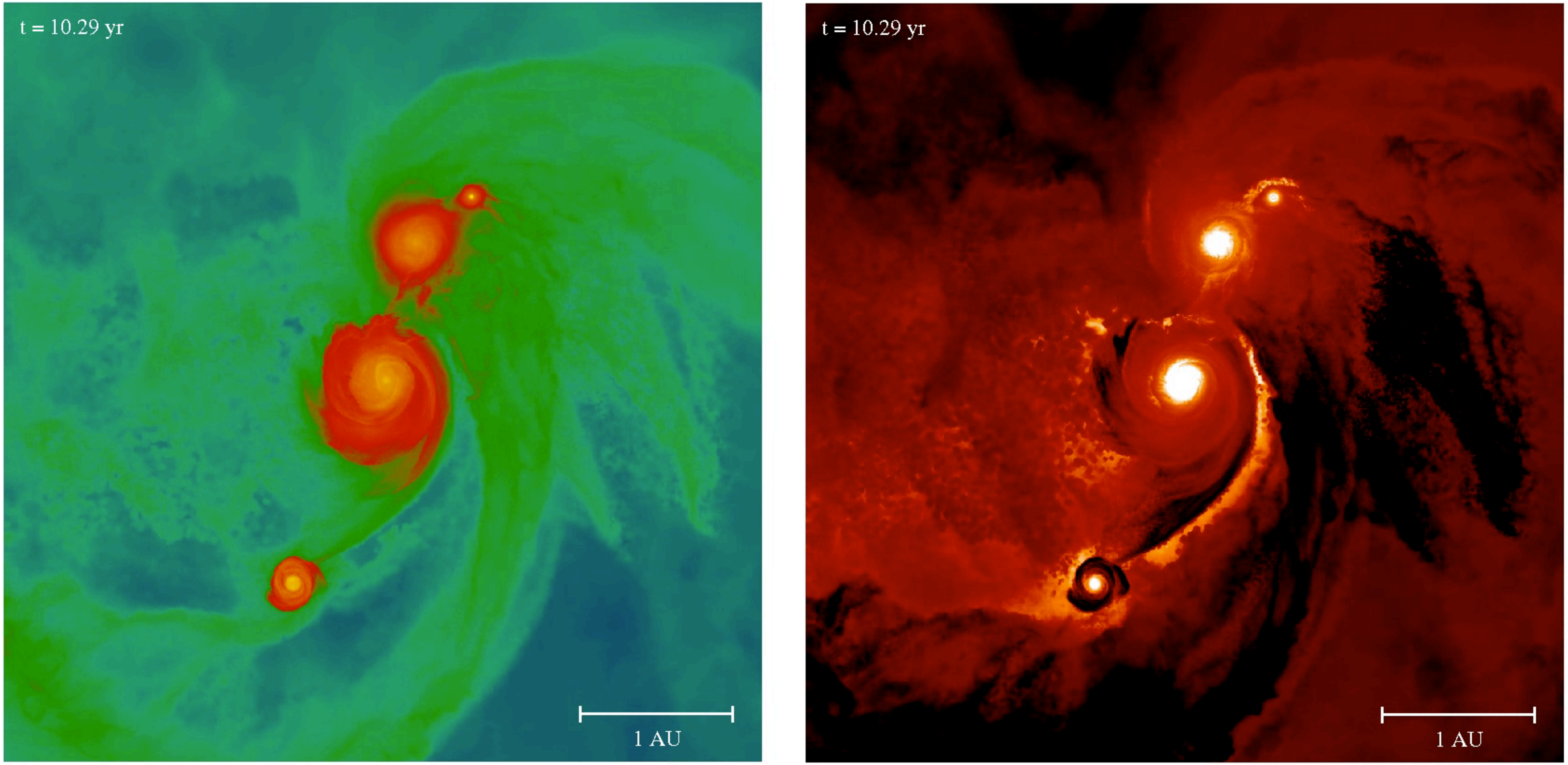
(Clark et al. 2011b, Science, 331, 1040, see talk by Athena Stacy)

important disk parameters



(Clark et al. 2011b, Science, 331, 1040, Smith et al. 2011, MNRAS, 414, 3633, also talk by Athena Stacy)

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 $R_\odot$)

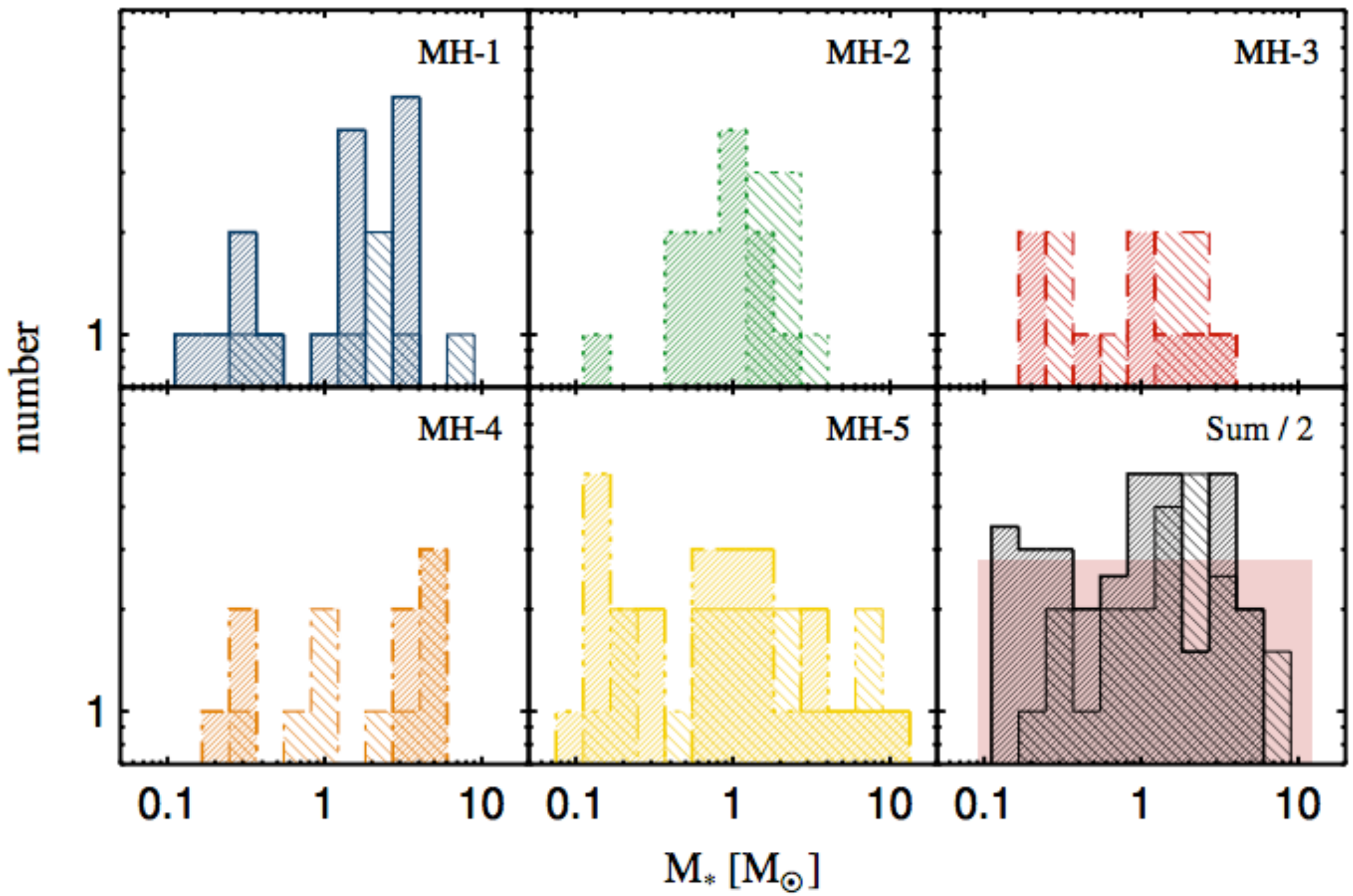


density

temperature

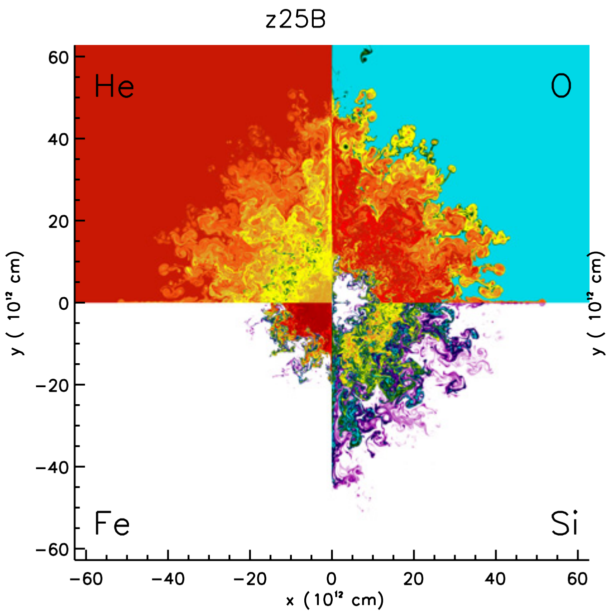
(Greif et al., 2012, MNRAS, 424, 399)

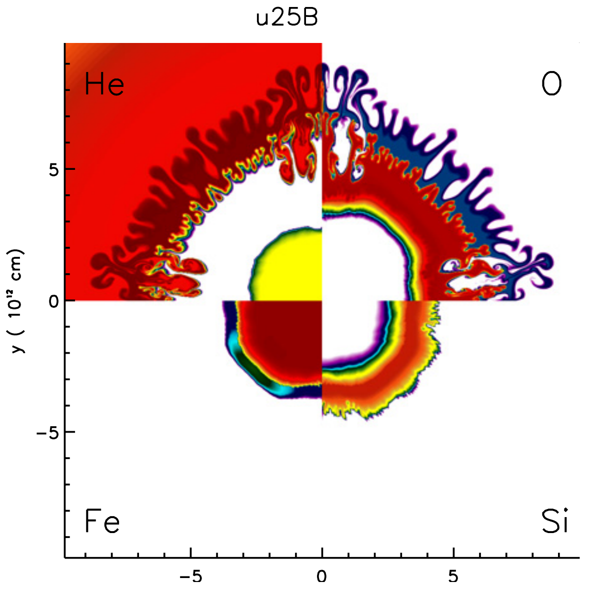
expected mass spectrum



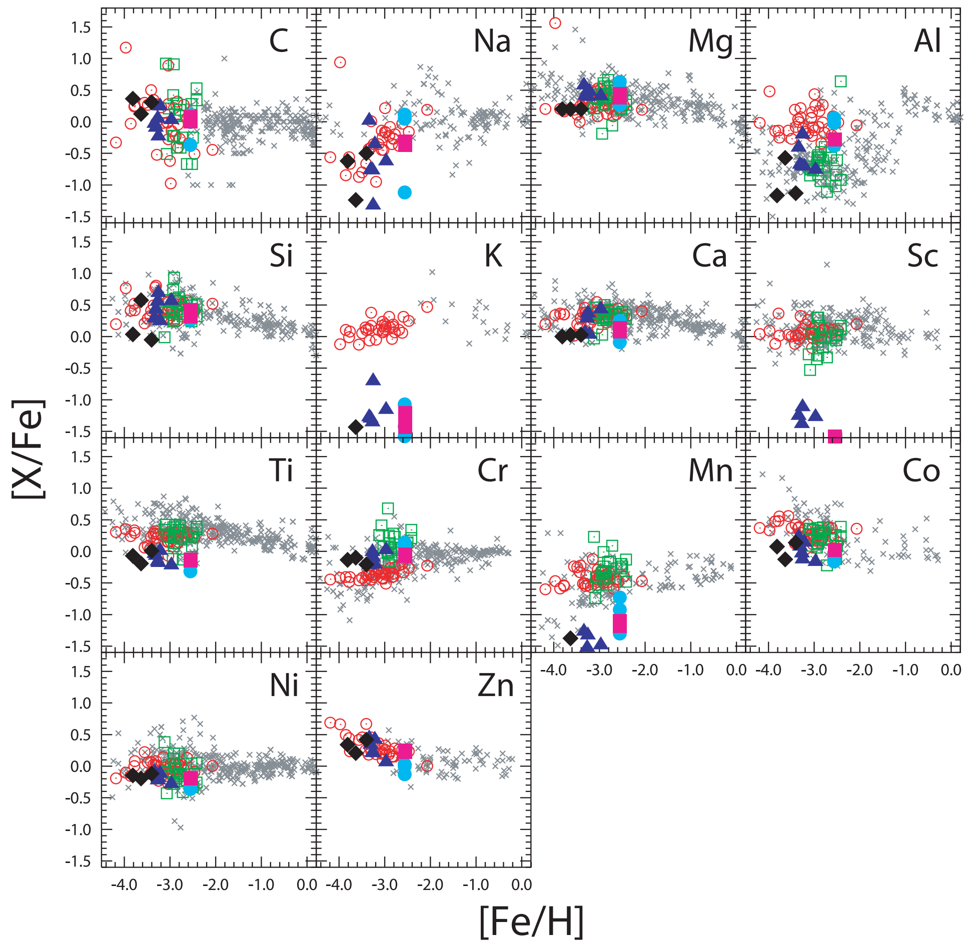
we see "flat" mass spectrum

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





(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, see also talk by John Norris and Heather Jacobsen)

predicting number of Pop III stars

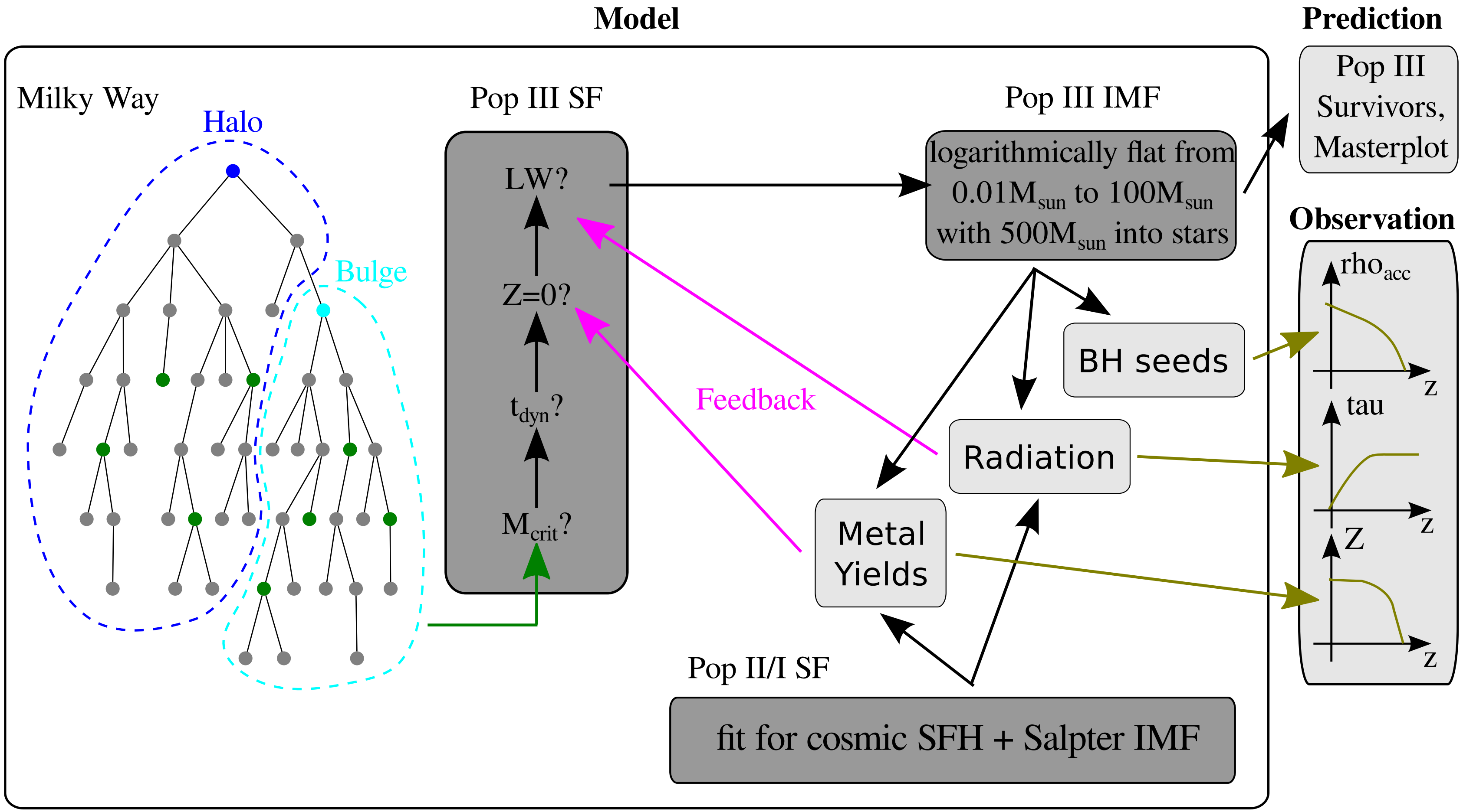
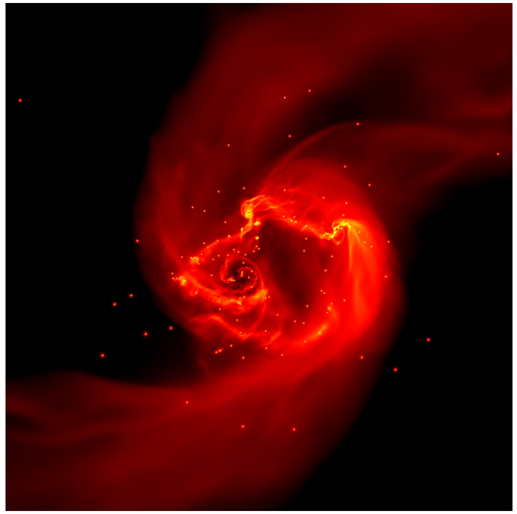


Figure 1. Illustration of the model we use. Based on the merger tree, we check which halos are able to form Pop III stars based on their critical mass, the absence of dynamical heating due to mergers, no pollution by metals and the strength of the LW background. We assign an individual number of Pop III stars to each successful halo and determine the influence on their environment. The influence of Pop I/II star formation is modelled based on the cosmic star formation history. By comparing these influences to existing observations, we can gauge our model assumptions. Finally, we derive a prediction for the number of Pop III survivors in the Milky Way and determine constraints to the primordial IMF. Tilman: too many arrows - probably combine BH seeds, Radiation and Metal Yields?

Poster by Tilman Hartwig in coffee room

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)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thoughts for IMF discussion

- What
  form
- Does the
- We agree on importance of
  turbulence
  What are the effects of
- Is the
  Probably not, better maybe
  abundance patterns
- ***What do we miss?***
  cosmic rays, anything else?)

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