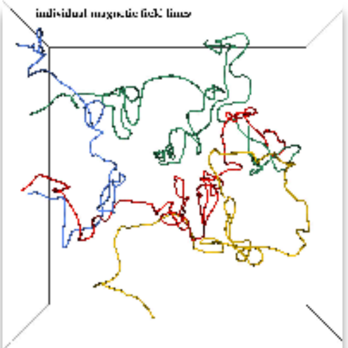
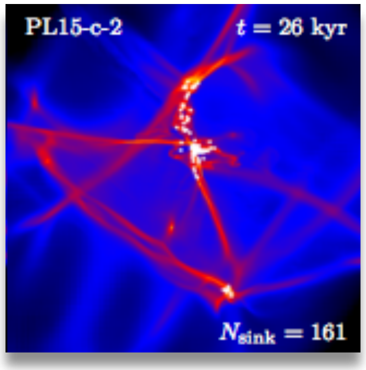
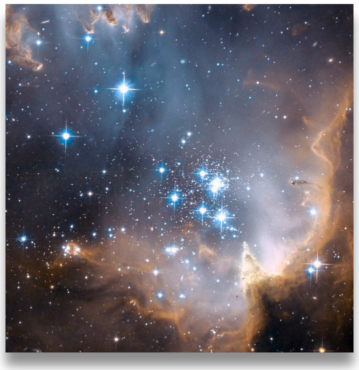
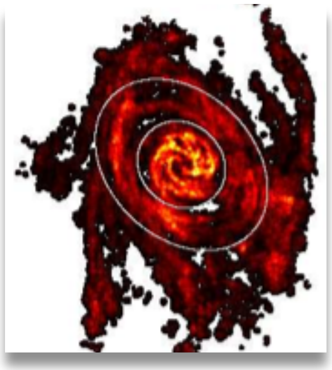
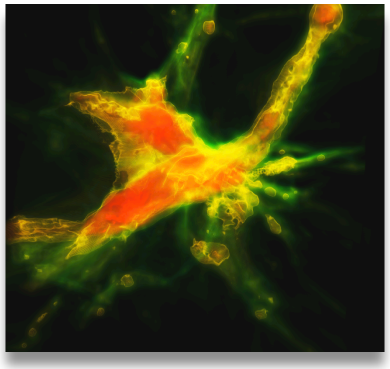
ISM Dynamics and Star Formation







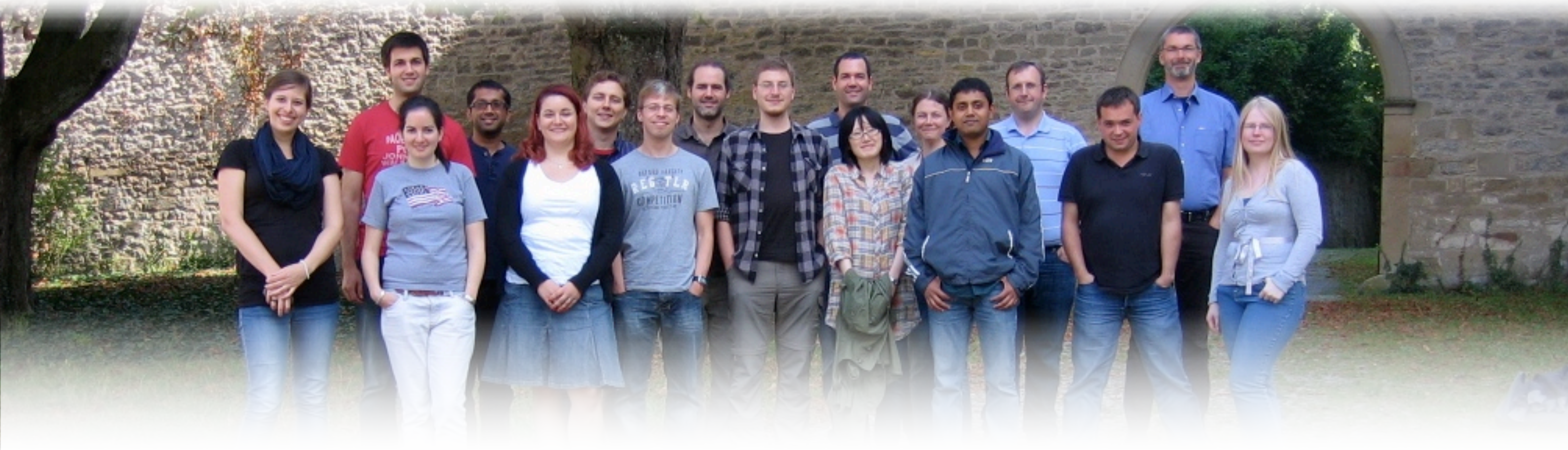




~~Ralf Klessen~~ Simon Glover

Zentrum für Astronomie der Universität Heidelberg
Institut für Theoretische Astrophysik

thanks to ...



... people in the group in Heidelberg:

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

... former group members:

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

... many collaborators abroad!

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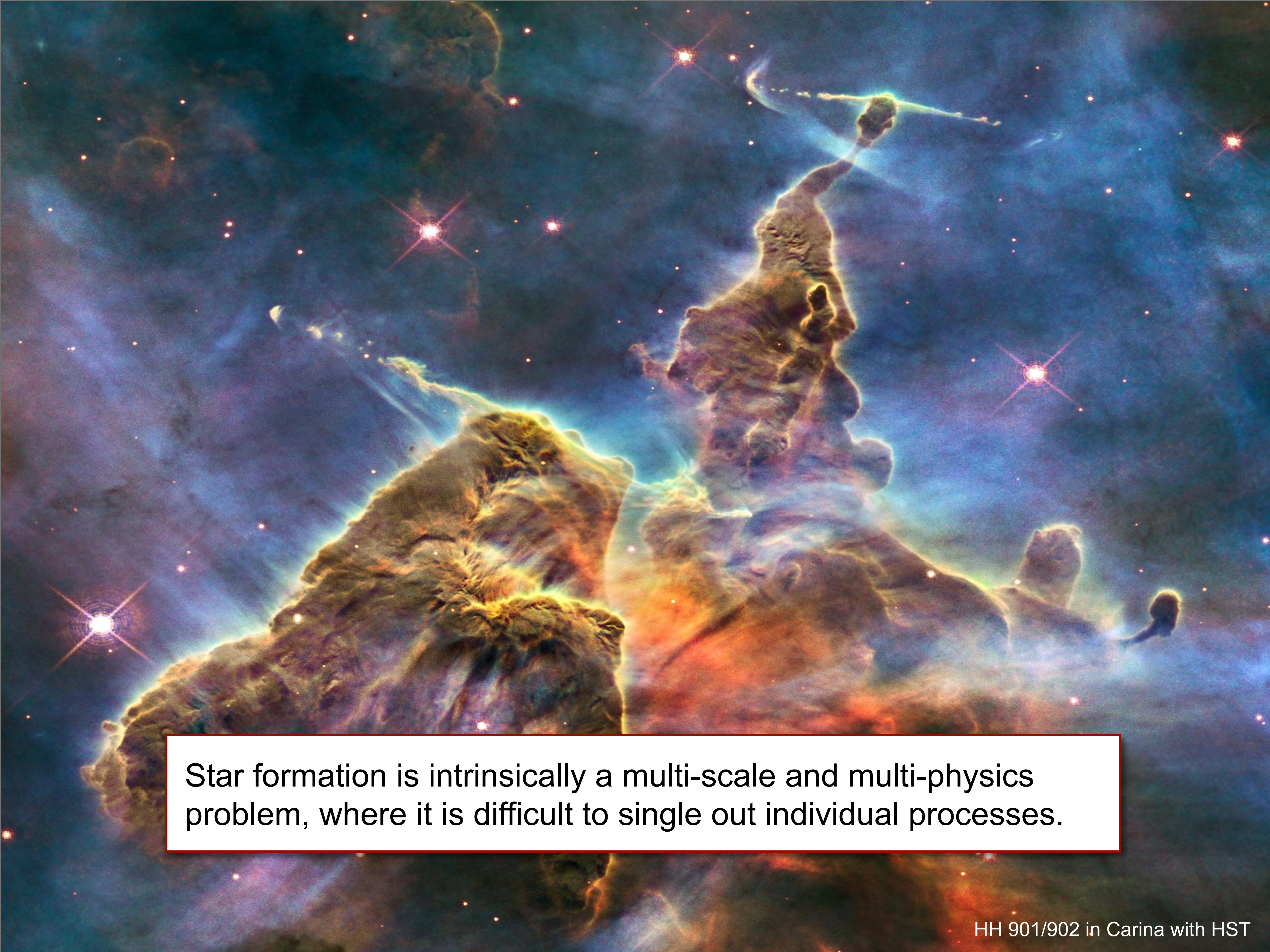
IMPRS

Carina with HST

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

Carina with HST



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

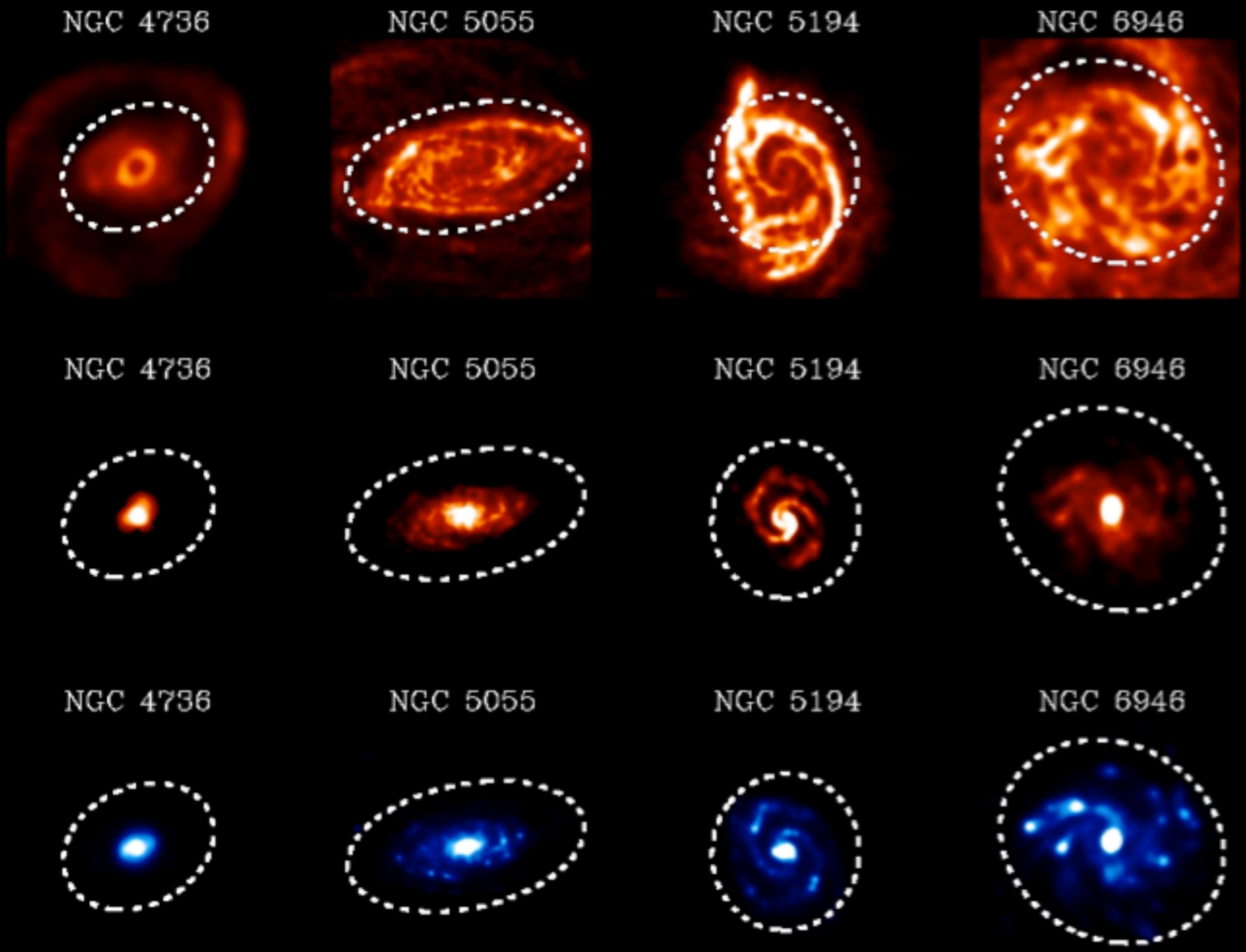
HH 901/902 in Carina with HST

examples

- large scales: Kennicutt-Schmidt type relations
  - how does star formation depend on galactic environment?
- intermediate scales: molecular cloud formation
  - how to connect ISM dynamics to galactic dynamics?
- small scales: star cluster formation
  - what is the physical origin of the ISM?

HH 901/902 in Carina with HST

global SF relations

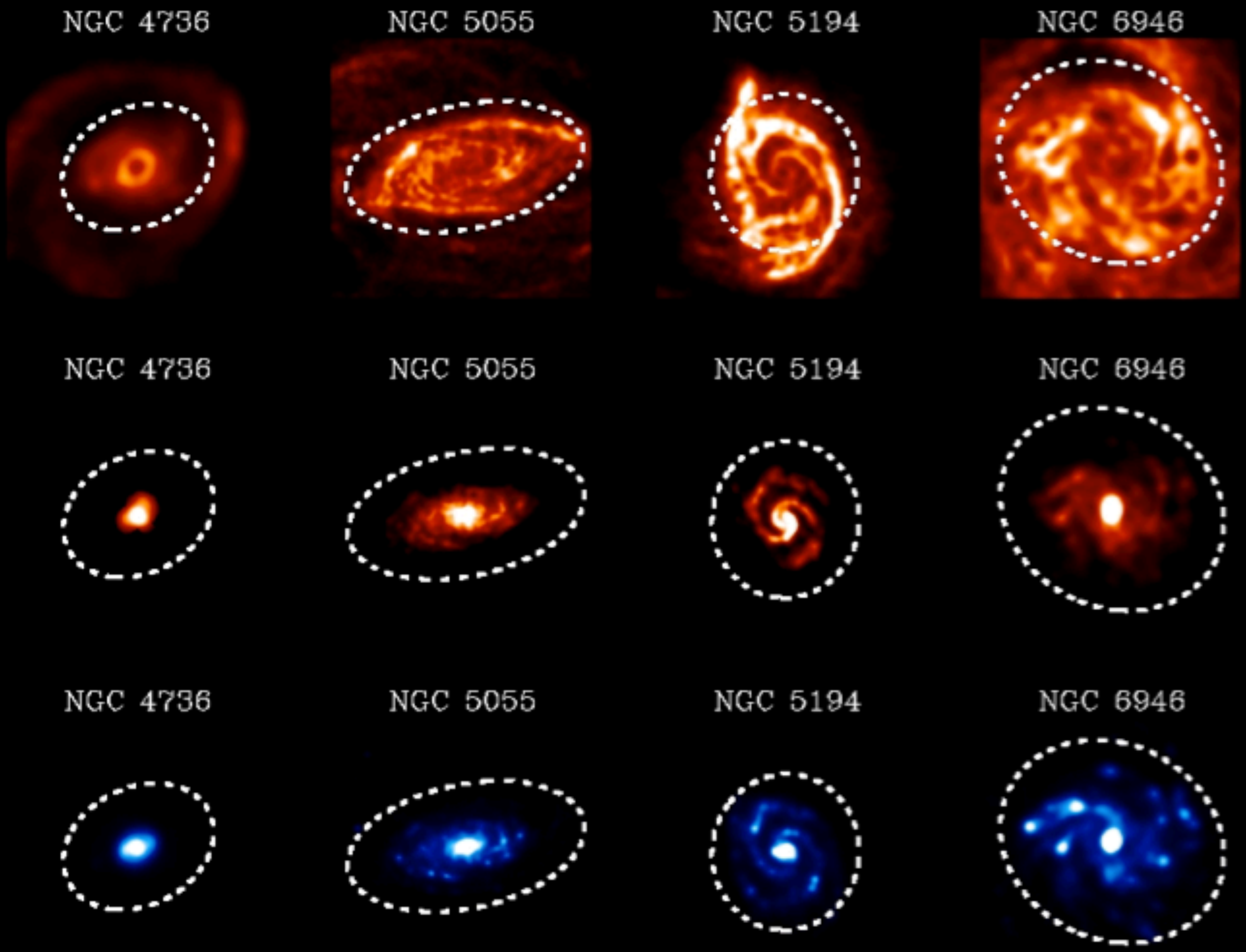


atomic hydrogen

molecular hydrogen

star formation

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



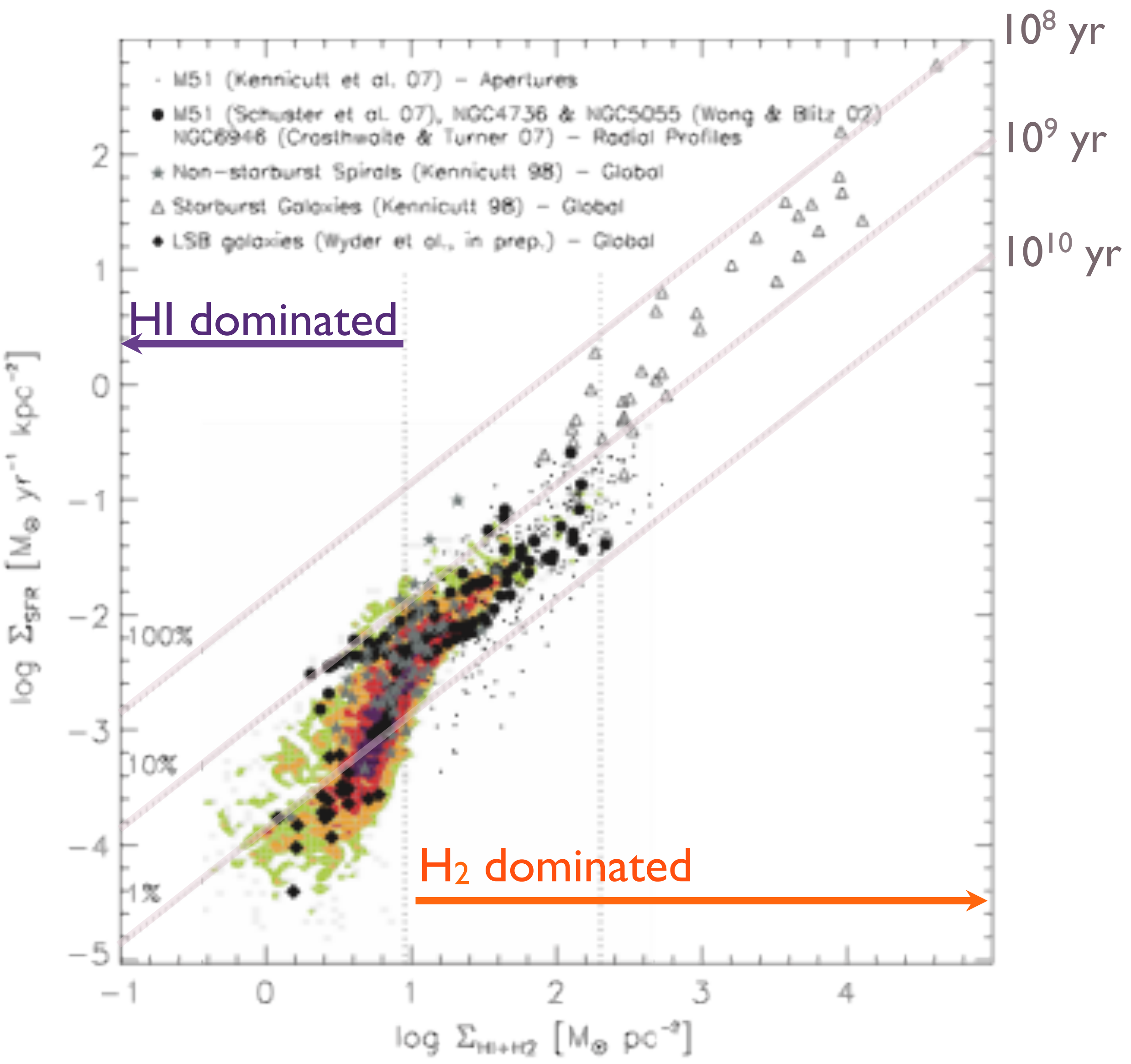
atomic hydrogen

molecular hydrogen

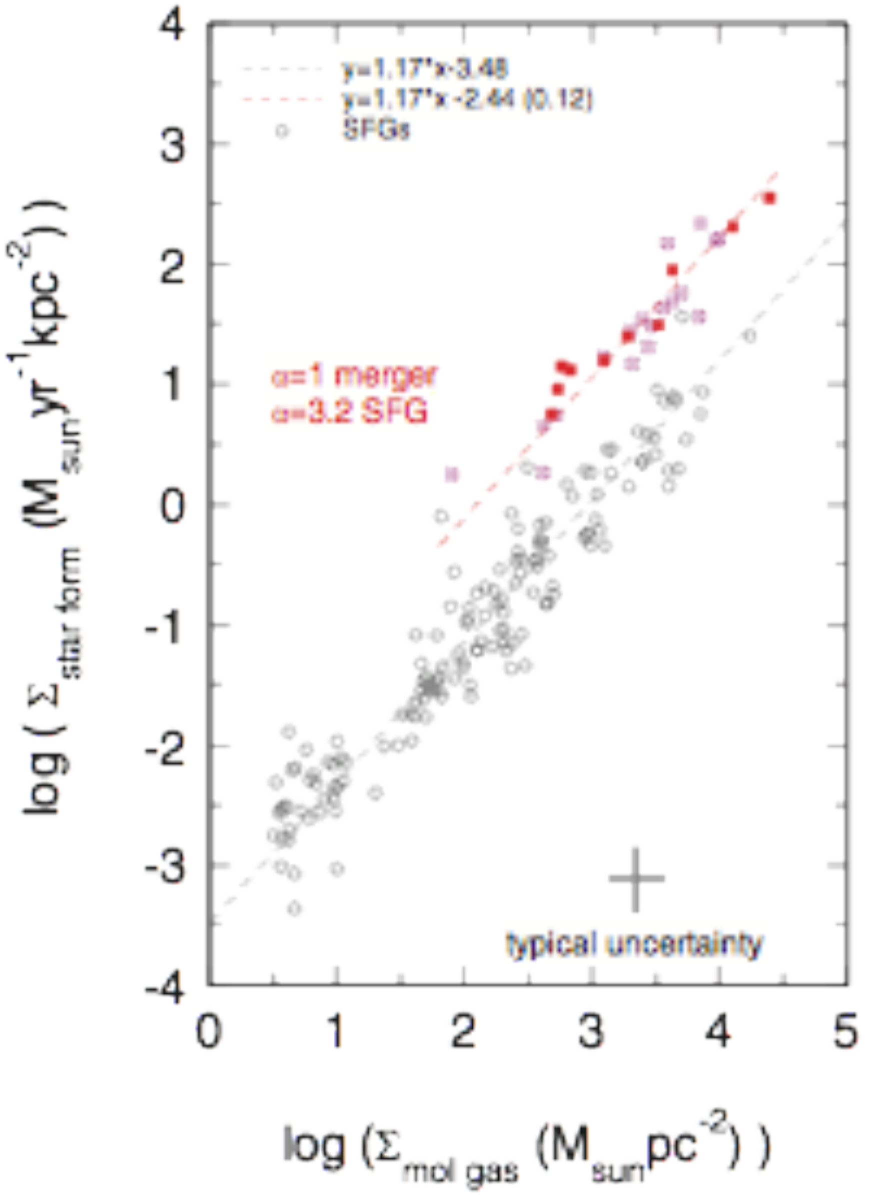
star formation

- HI gas more extended
- H2 and SF well correlated

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



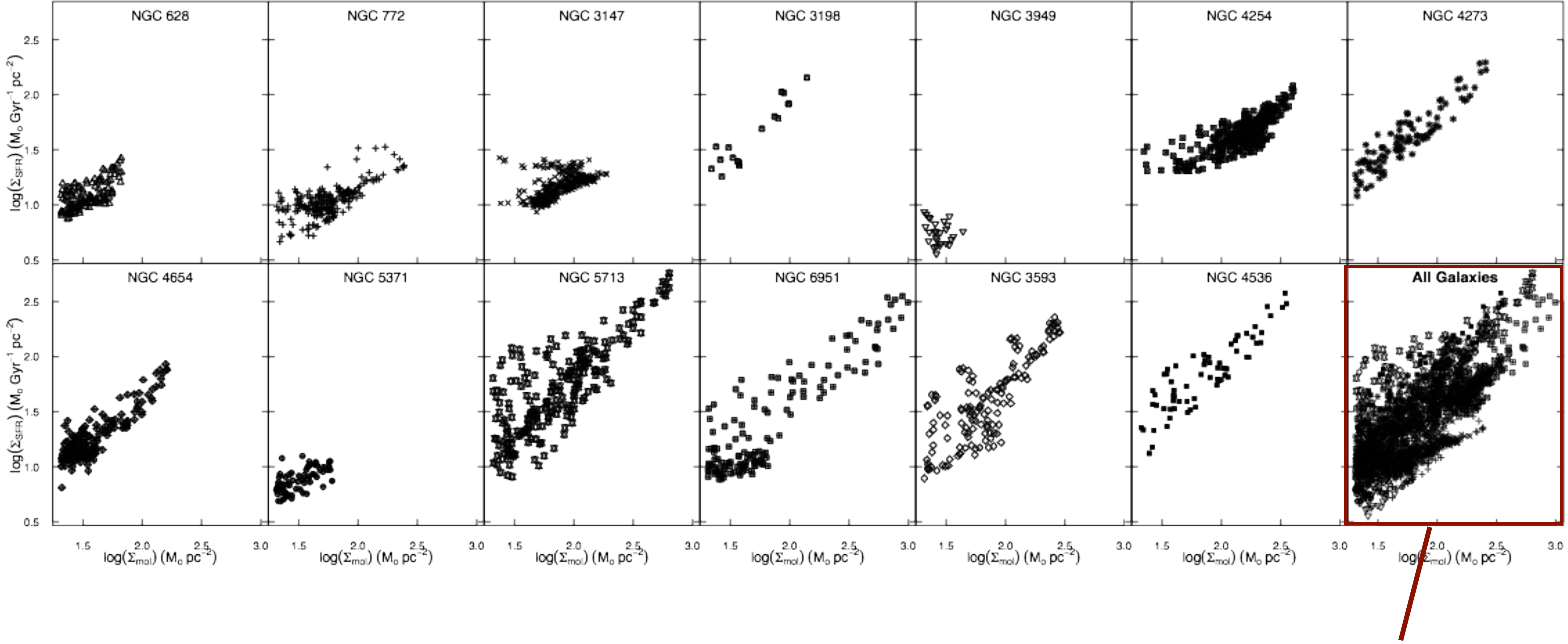
Bigiel et al. (2008, AJ, 136, 2846)



Genzel et al. (2010, MNRAS, AJ, 407, 2091)

- standard model: roughly linear relation between H_2 and SFR
- standard model: roughly constant depletion time: few x 10^9 yr
- super-linear relation between total gas and SFR

data from STING survey (Rahman et al. 2011, 2012)

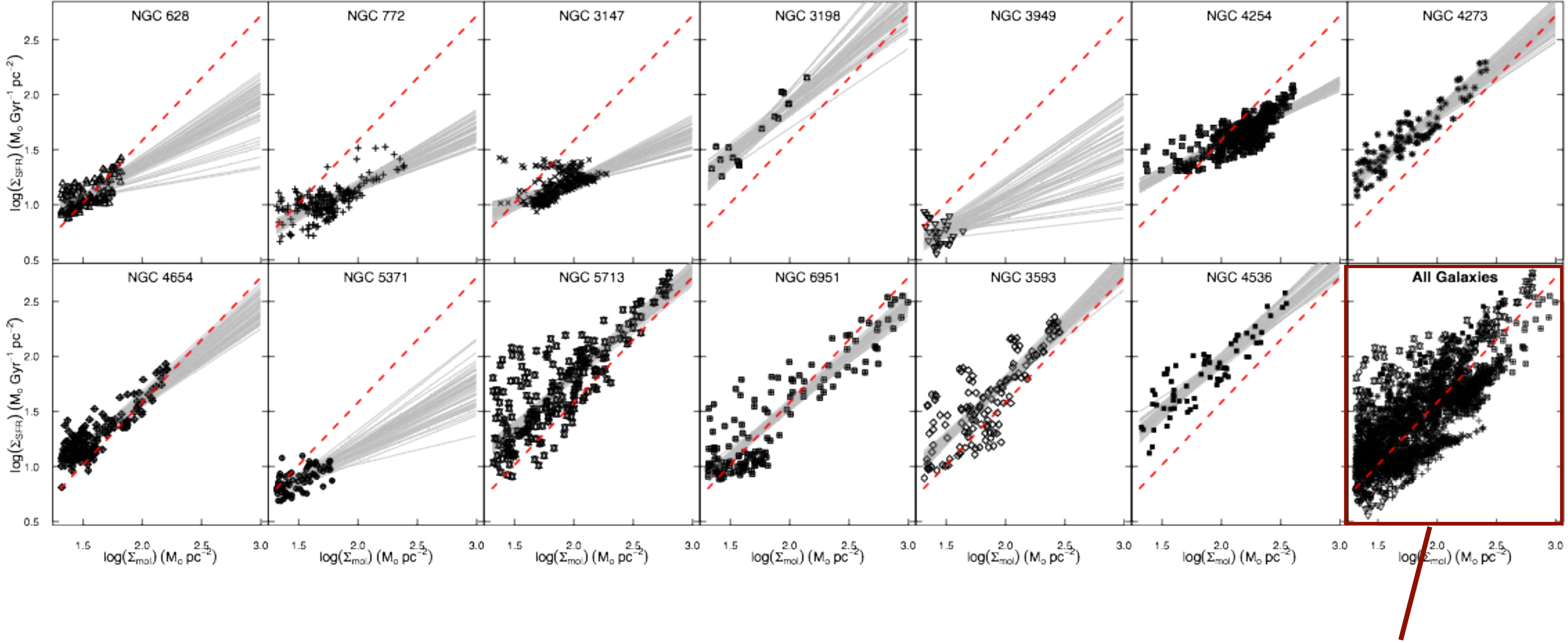


all galaxies

- QUIZ: do you see a universal Σ_{H2} - Σ_{SFR} relation?

Shetty et al. (2013, MNRAS submitted, arXiv:1306.2951, see also Shetty, Kelly, Bigiel, 2013, MNRAS, 430, 288)

data from STING survey (Rahman et al. 2011, 2012)

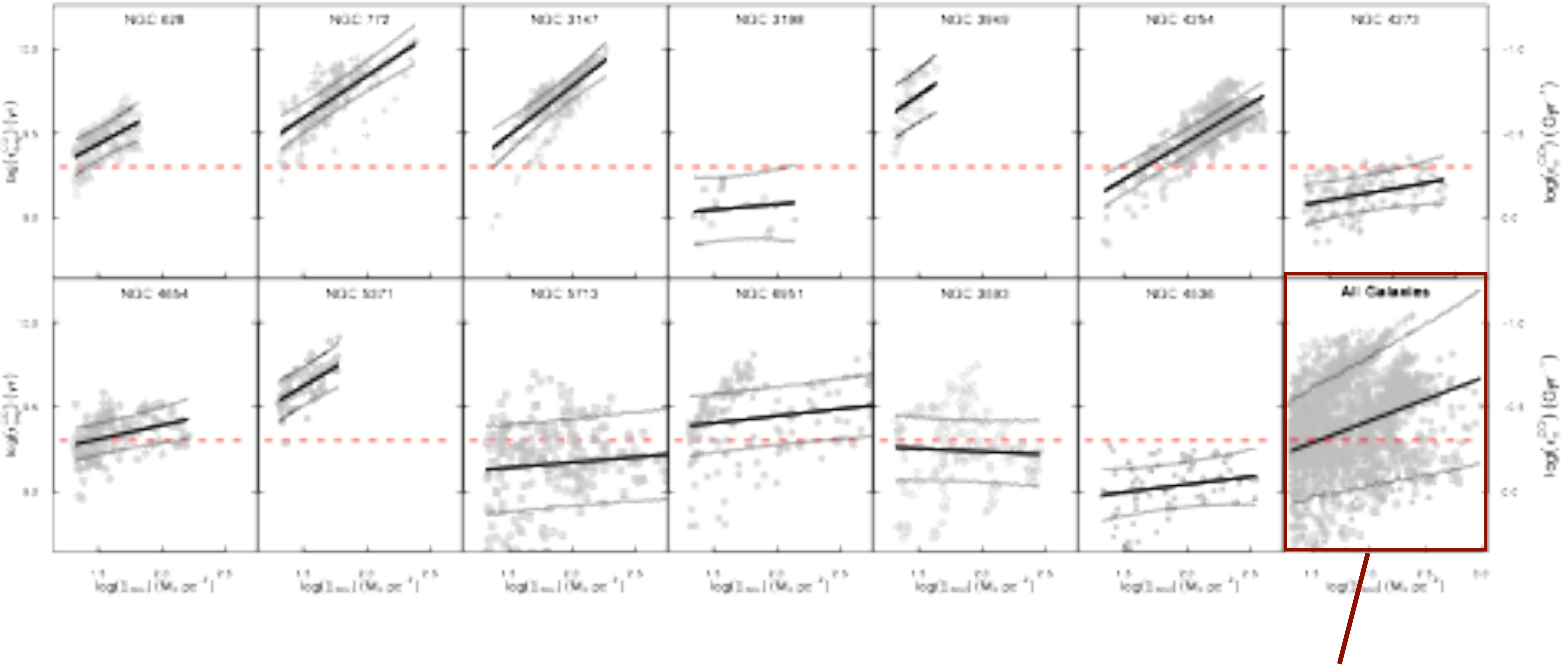


all galaxies

- QUIZ: do you see a universal Σ_{H2} - Σ_{SFR} relation?
- ANSWER: - probably not
  - in addition, the relation often is sublinear

Shetty et al. (2013, MNRAS submitted, arXiv:1306.2951, see also Shetty, Kelly, Bigiel, 2013, MNRAS, 430, 288)

data from STING survey (Rahman et al. 2011, 2012)

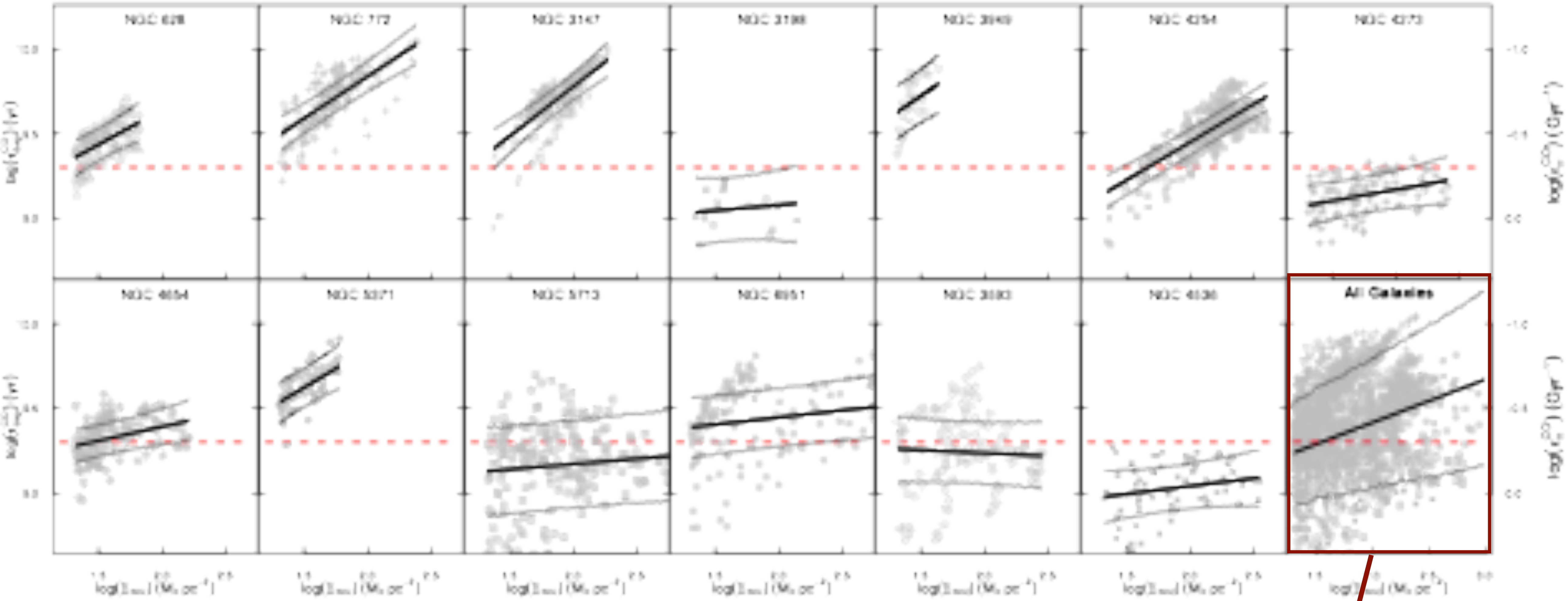


all galaxies

Hierarchical Bayesian model for STING galaxies indicate *varying depleting times.*

Shetty et al. (2013, arXiv:1306.2951)

data from STING survey (Rahman et al. 2011, 2012)



all galaxies

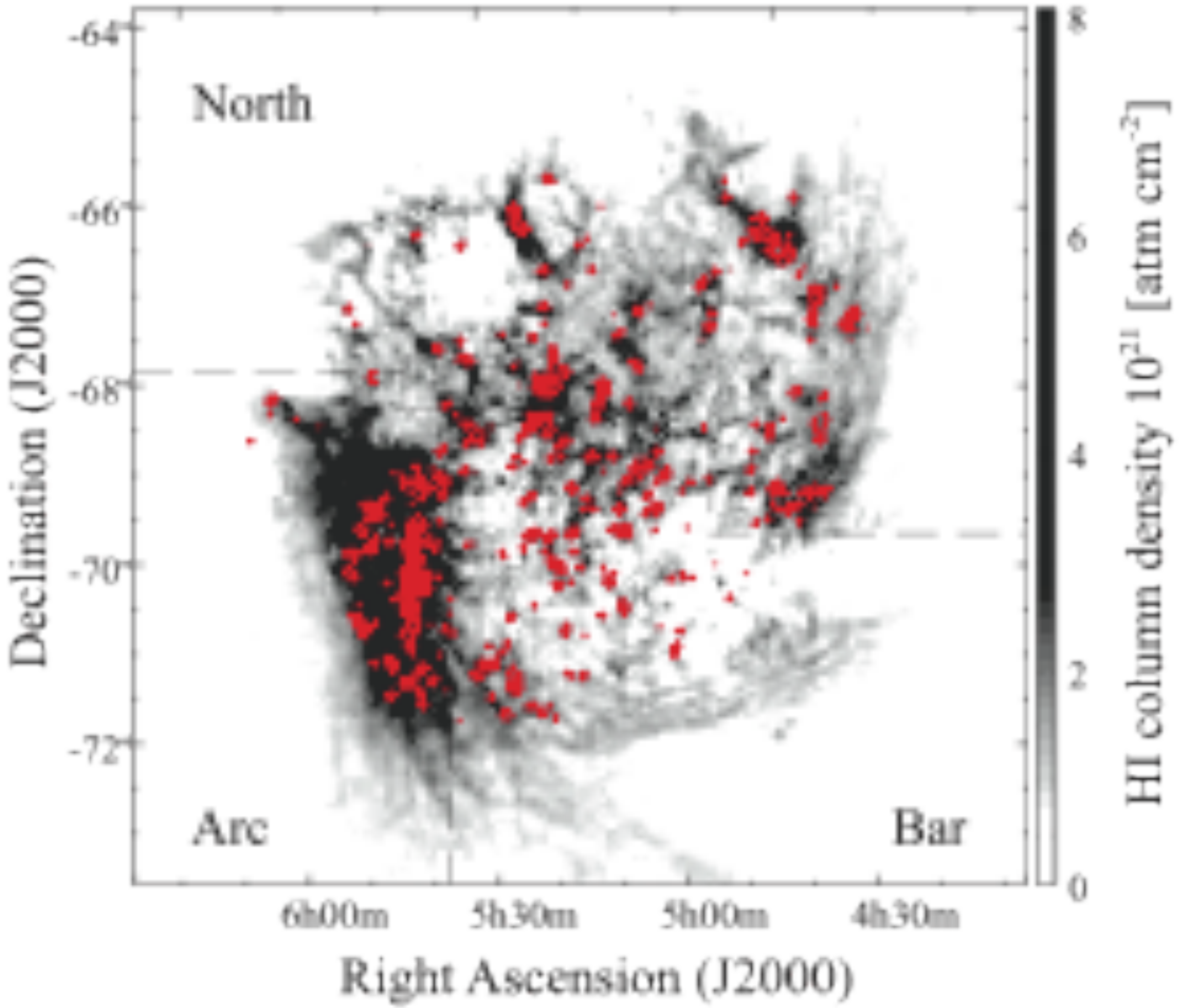
physical origin of this behavior?

- maybe strong shear in dense arms (example M51, Meidt et al. 2013)...
- maybe non-star forming H_2 gas becomes traced by CO at high column densities (i.e. high extinctions)...

Shetty et al. (2013, MNRAS submitted, arXiv:1306.2951, see also Shetty, Kelly, Bigiel, 2013, MNRAS, 430, 288)

molecular cloud formation

molecular cloud formation



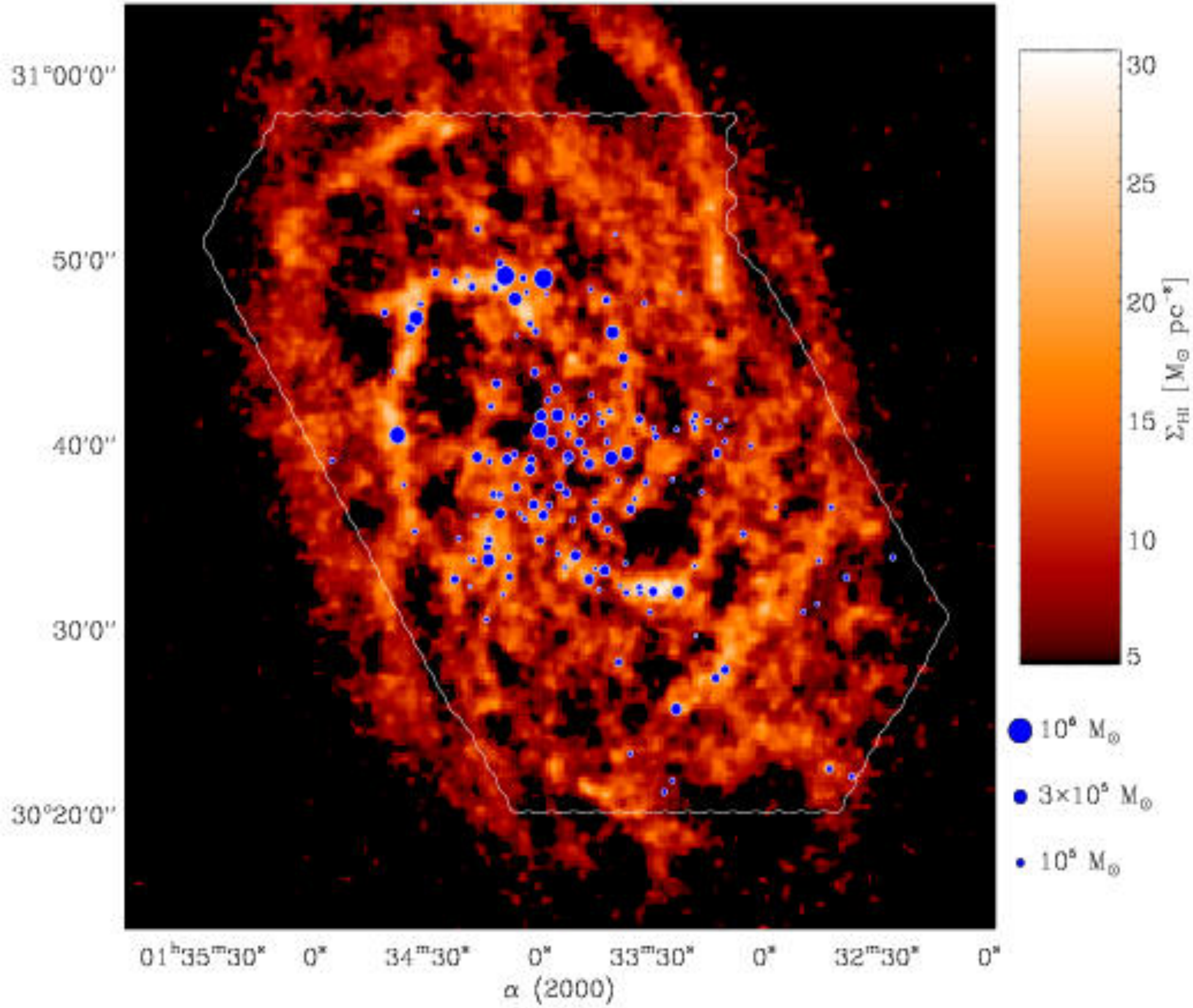
Fukui et al. (2009)

Idea:

Molecular clouds form at *stagnation points* of large-scale convergent flows, mostly triggered by global (or external) perturbations. Their internal turbulence is driven by accretion, i.e. by the process of cloud formation

- molecular clouds grow in mass
- this is inferred by looking at molecular clouds in different evolutionary phases in the LMC (Fukui et al. 2008, 2009)

molecular cloud formation

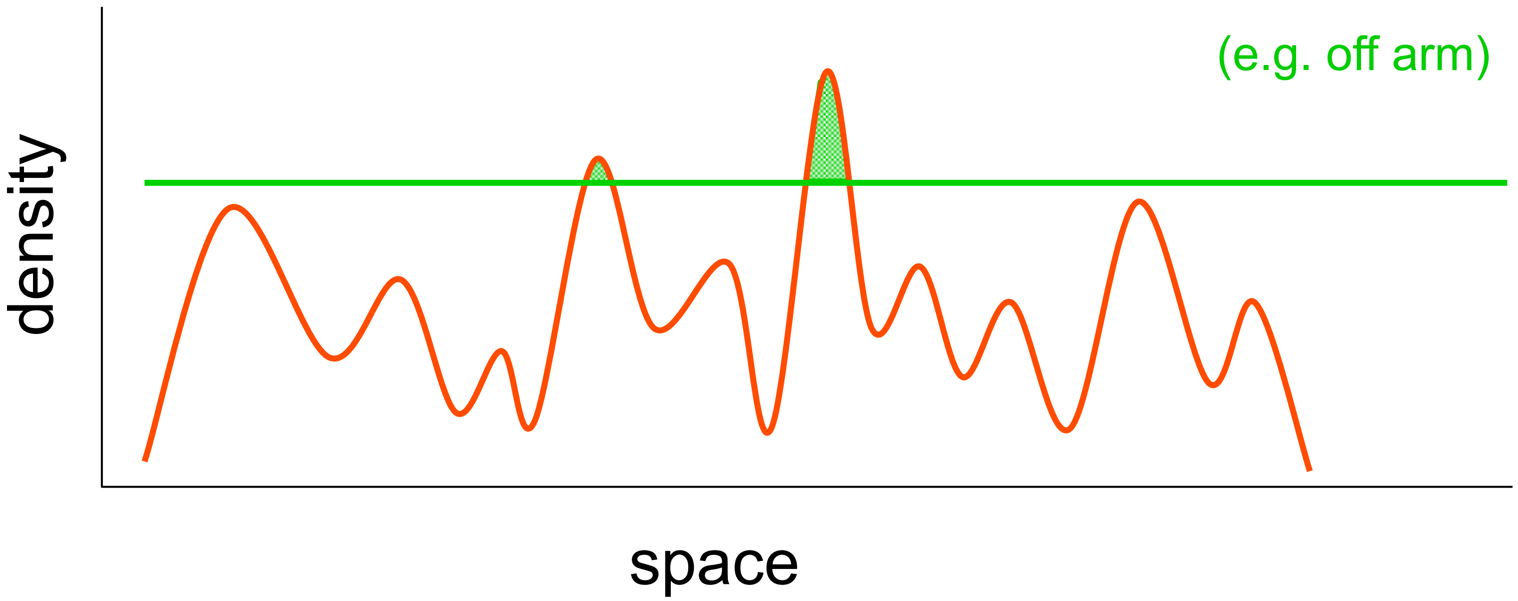


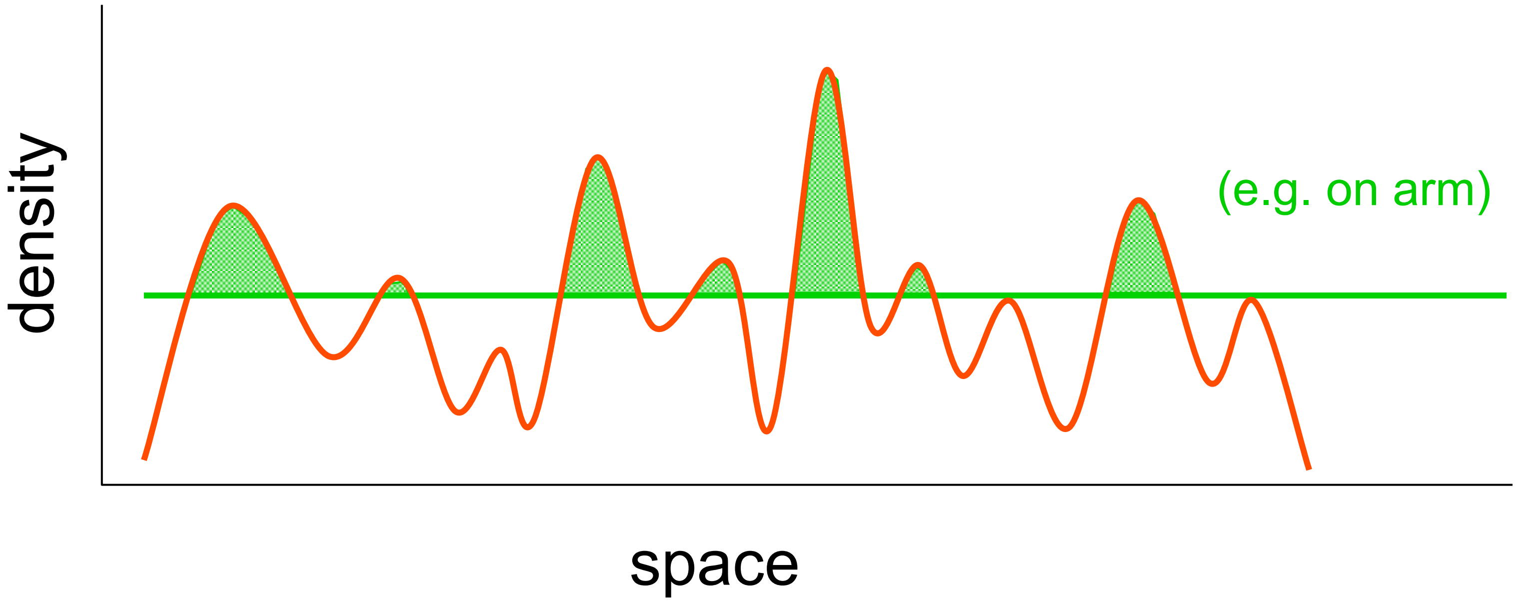
Thesis:

Molecular clouds form at *stagnation points* of large-scale convergent flows, mostly triggered by global (or external) perturbations.

(Deul & van der Hulst 1987, Blitz et al. 2004)

correlation with large-scale perturbations





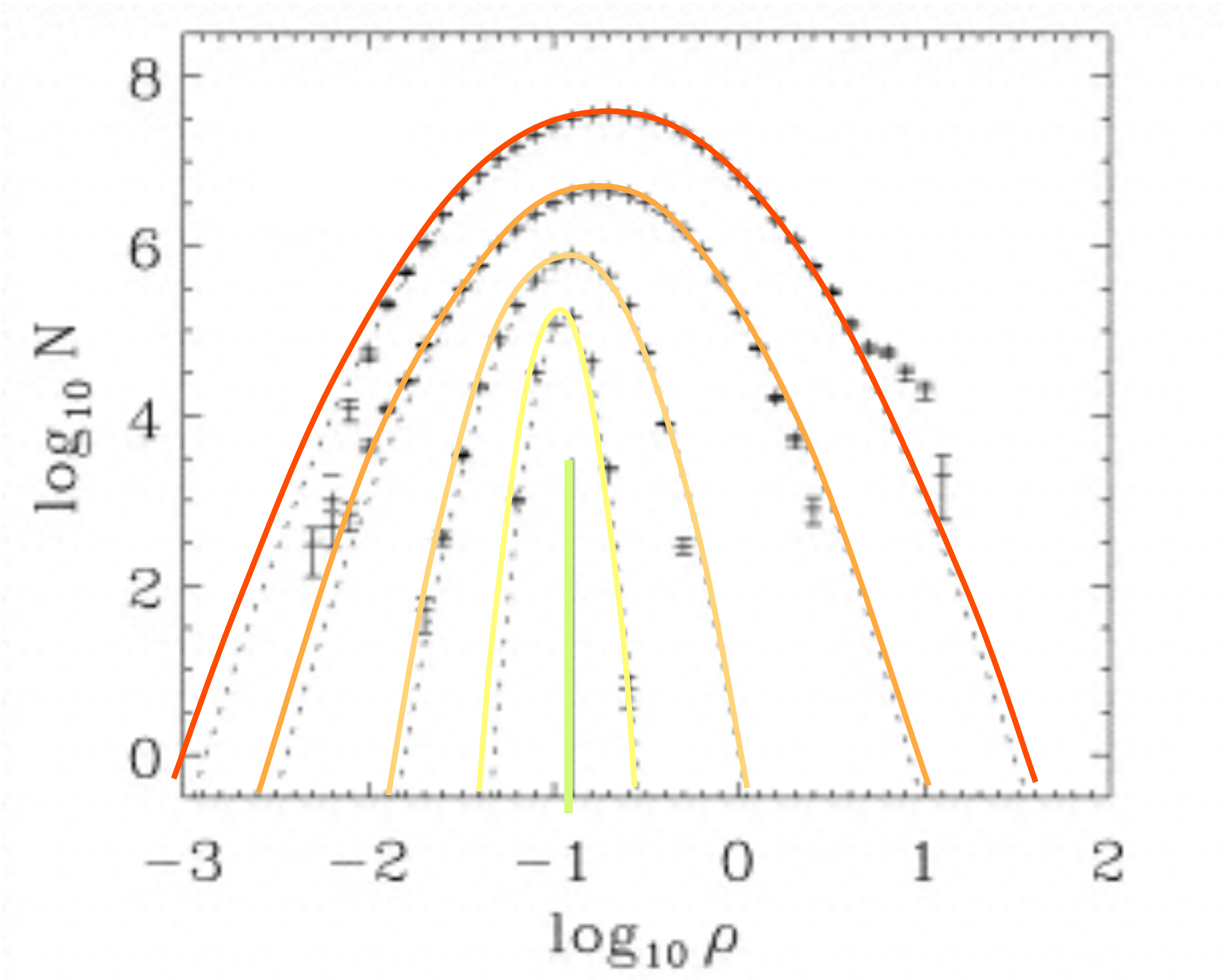
density/temperature fluctuations in warm atomic ISM are caused by *thermal/ gravitational instability* and/ or *supersonic turbulence*

some fluctuations are *dense* enough to *form* H_2 within "*reasonable time*"

→ *molecular cloud*

external perturbations (i.e. potential changes) *increase* likelihood

star formation on *global* scales



probability distribution function of the density *(ρ-pdf)*

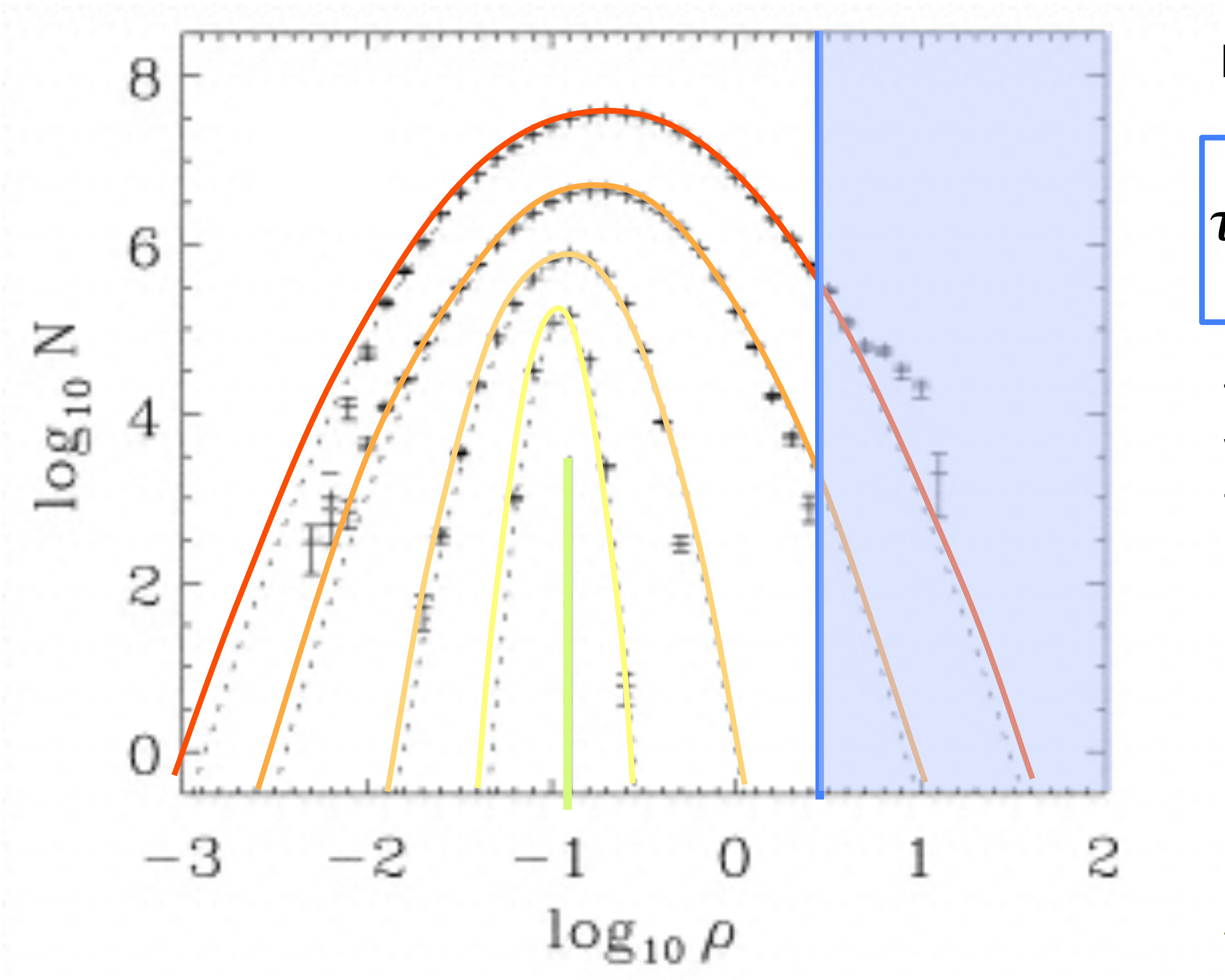
varying rms Mach numbers:

M1 > M2 >
M3 > M4 > 0

mass weighted ρ-pdf, each shifted by ΔlogN=1

(from Klessen, 2001; also Gazol et al. 2005, Krumholz & McKee 2005, Glover & Mac Low 2007ab)

star formation on *global* scales



mass weighted ρ-pdf, each shifted by ΔlogN=1

(rate from Hollenback, Werner, & Salpeter 1971)

H_2 formation rate:

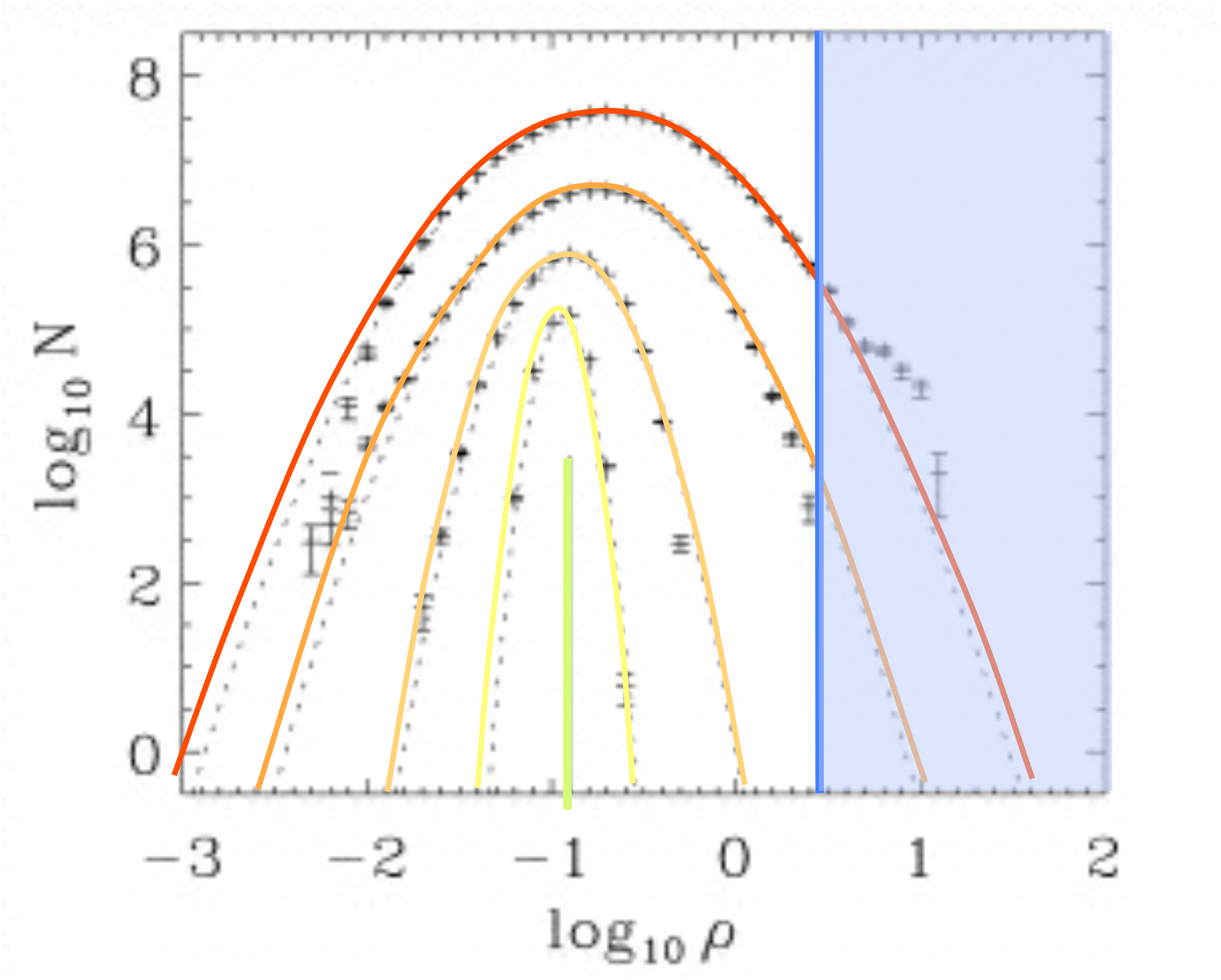
$$\boxed{\tau_{H_2} \approx \frac{1.5\,\mathrm{Gyr}}{n_H / 1\mathrm{cm}^{-3}}}$$

for $n_H \geq 100\ \mathrm{cm}^{-3}$, H_2 forms within 10 Myr, this is about the lifetime of typical MC's.

in turbulent gas, the H_2 fraction can become very high on short timescale

(for models with coupling between cloud dynamics and time-dependent chemistry, see Glover & Mac Low 2007a,b)

star formation on *global* scales



mass weighted ρ-pdf, each shifted by $\Delta\log N=1$

(rate from Hollenback, Werner, & Salpeter 1971)

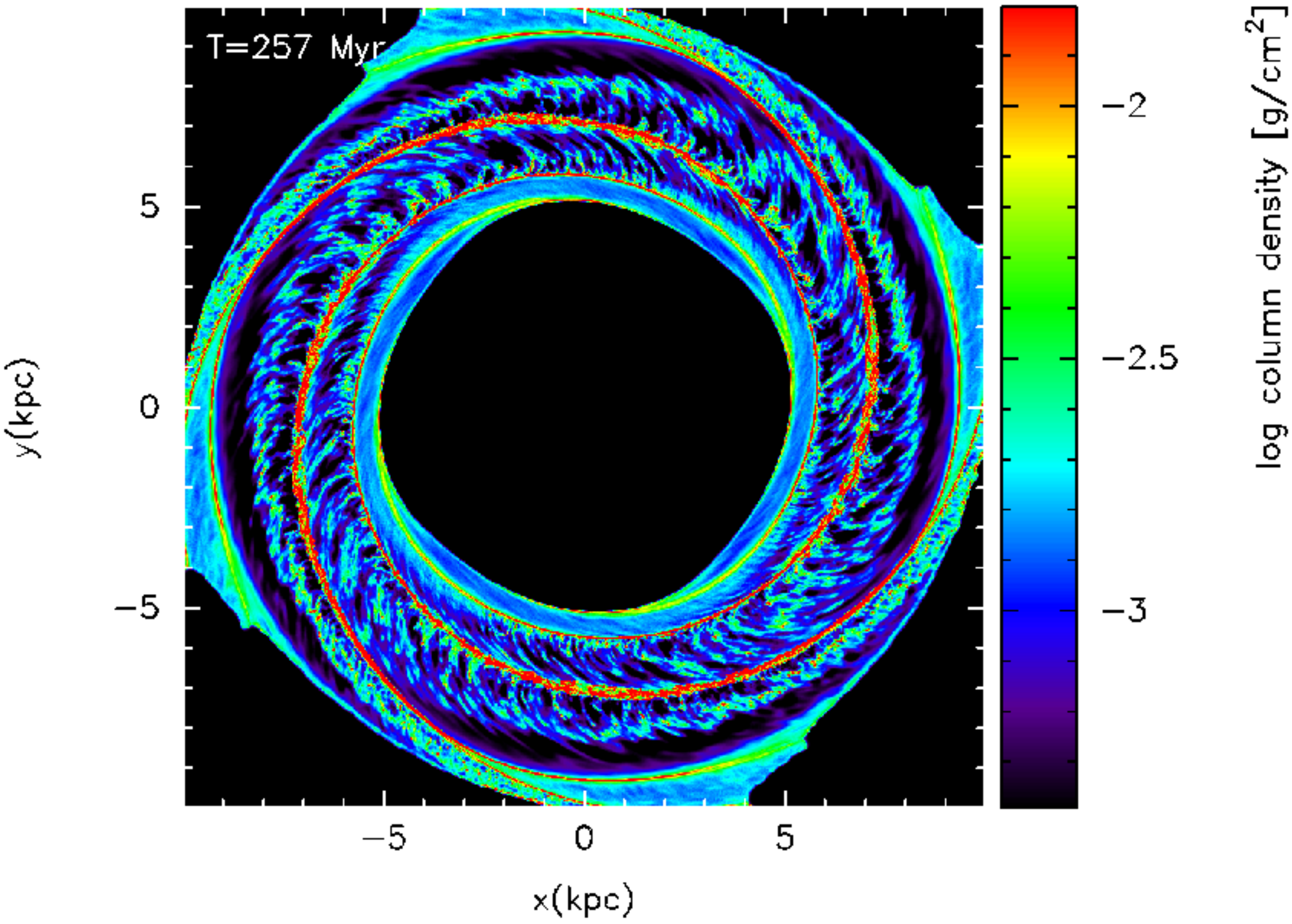
BUT: *it doesn't work* (at least not so easily):

Chemistry has a memory effect!

H_2 forms more quickly in high-density regions as it gets destroyed in low-density parts.

(for models with coupling between cloud dynamics and time-dependent chemistry, see Glover & Mac Low 2007a,b)

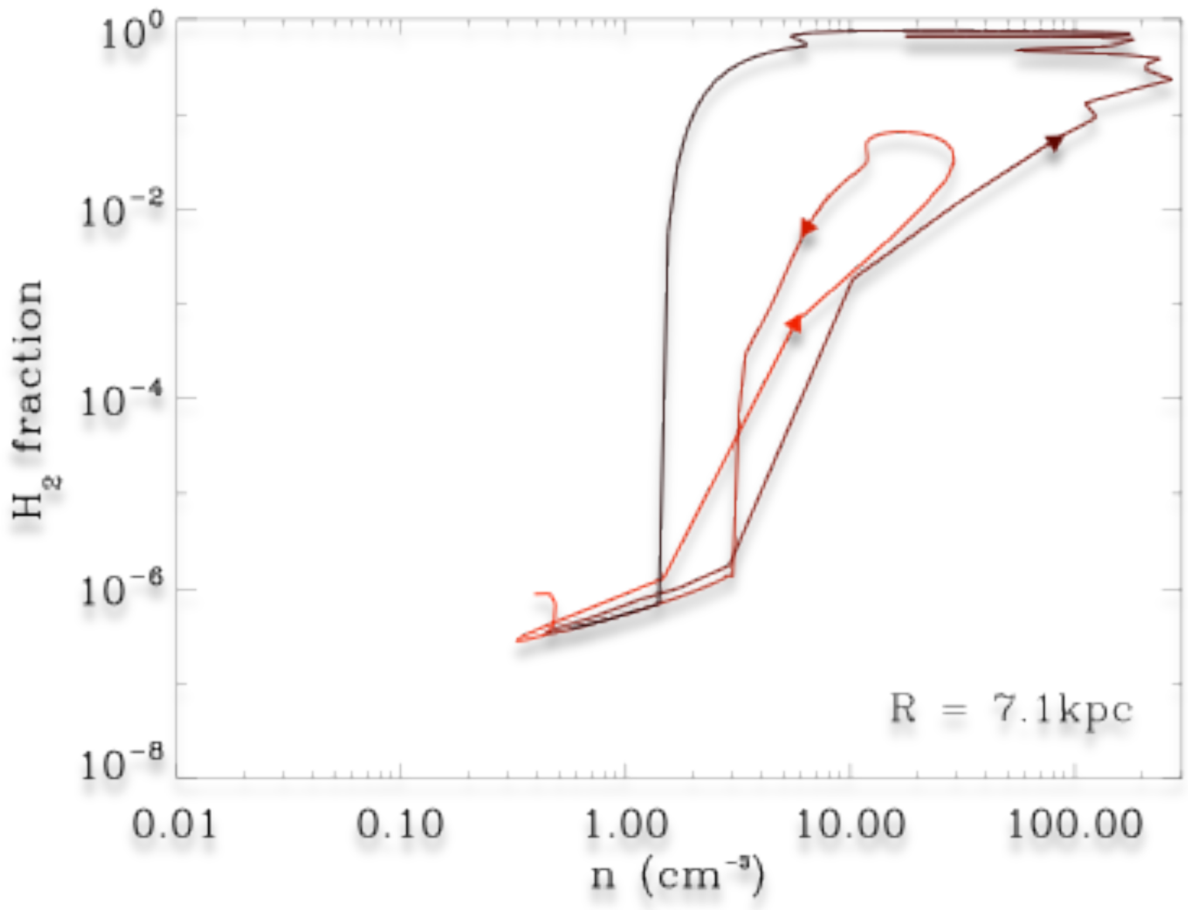
molecular cloud formation



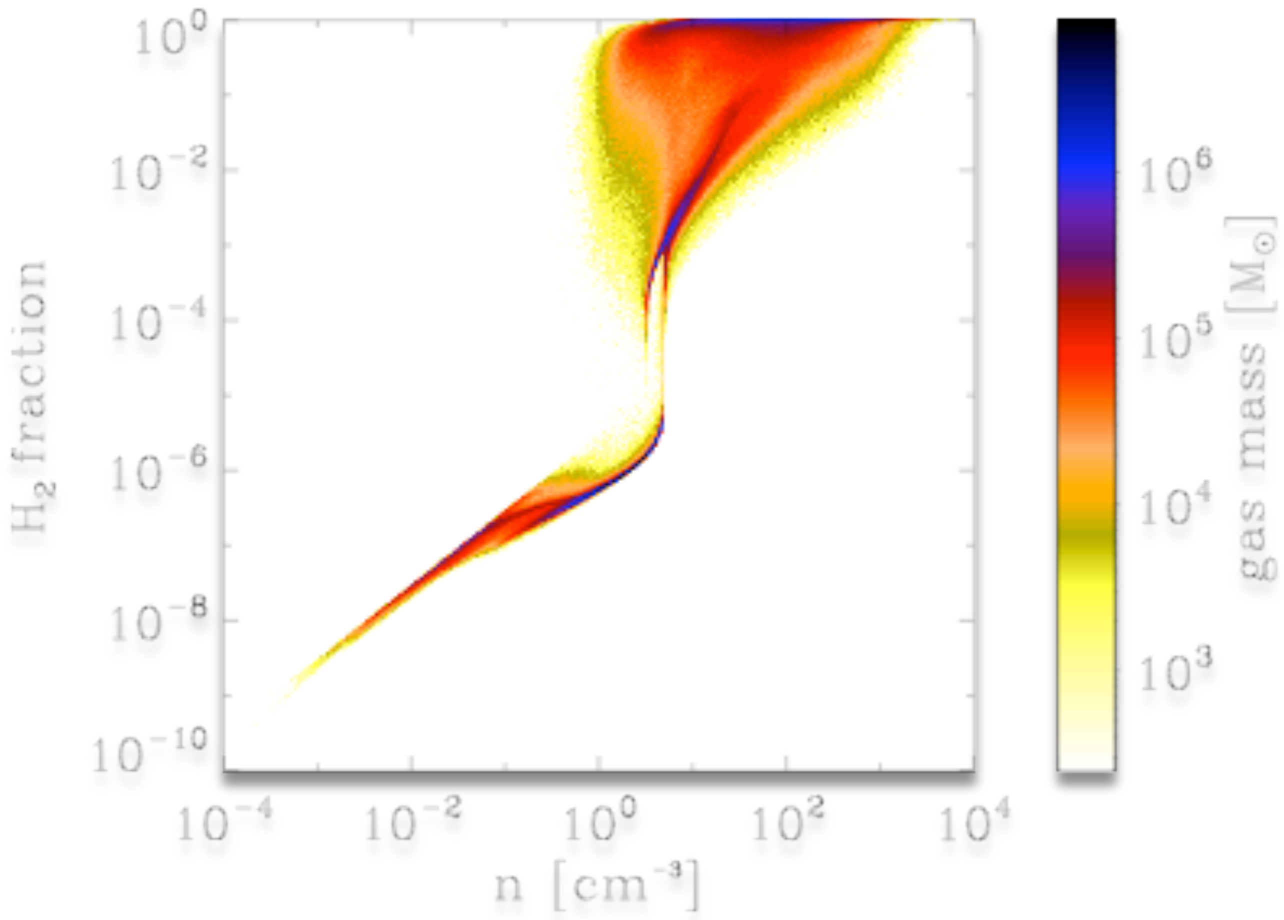
(from Dobbs et al. 2008)

molecular cloud formation

molecular gas fraction of fluid element as function of time

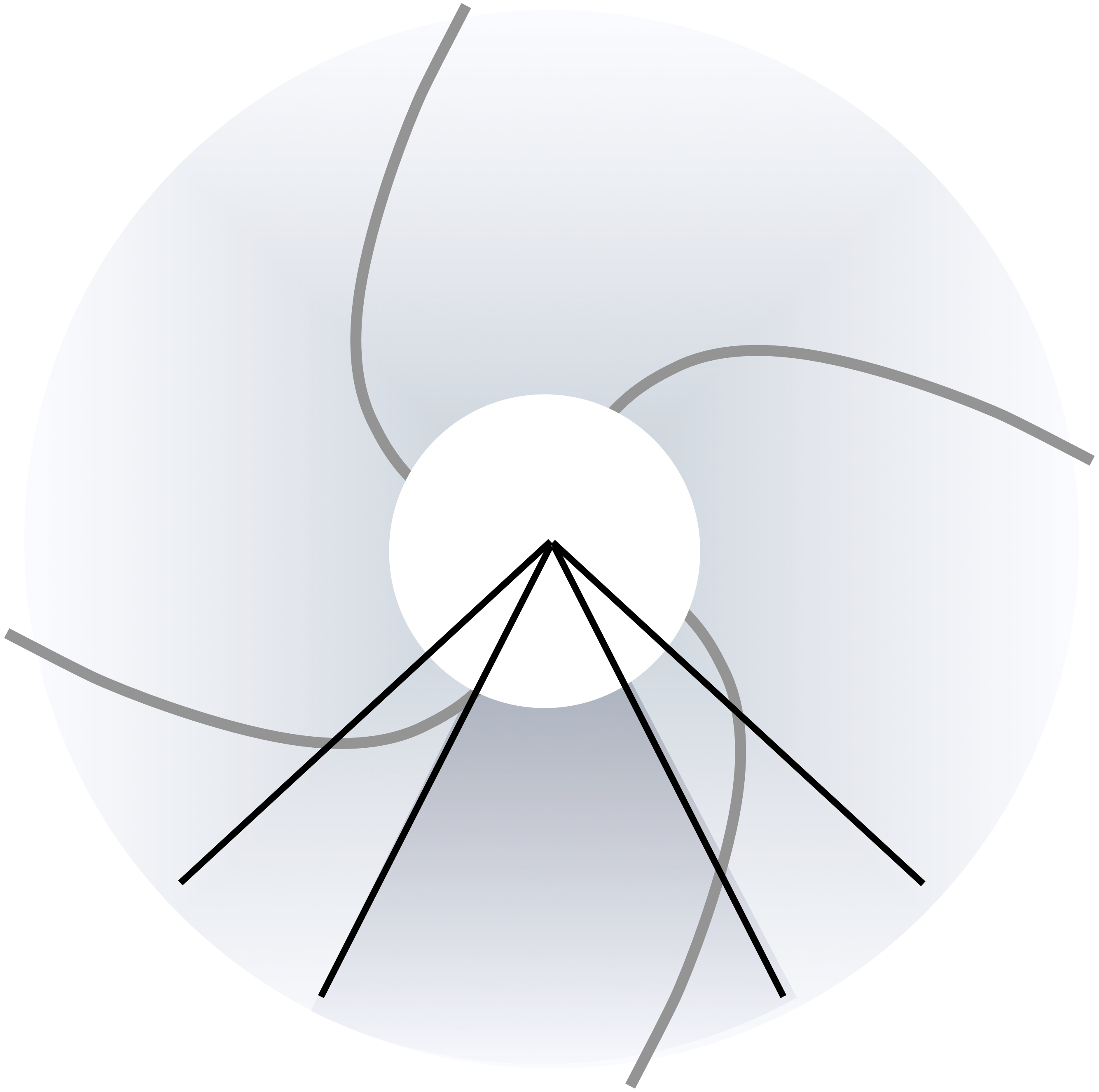


molecular gas fraction as function of density



(Dobbs et al. 2008)

Modelling the galactic ISM dynamics



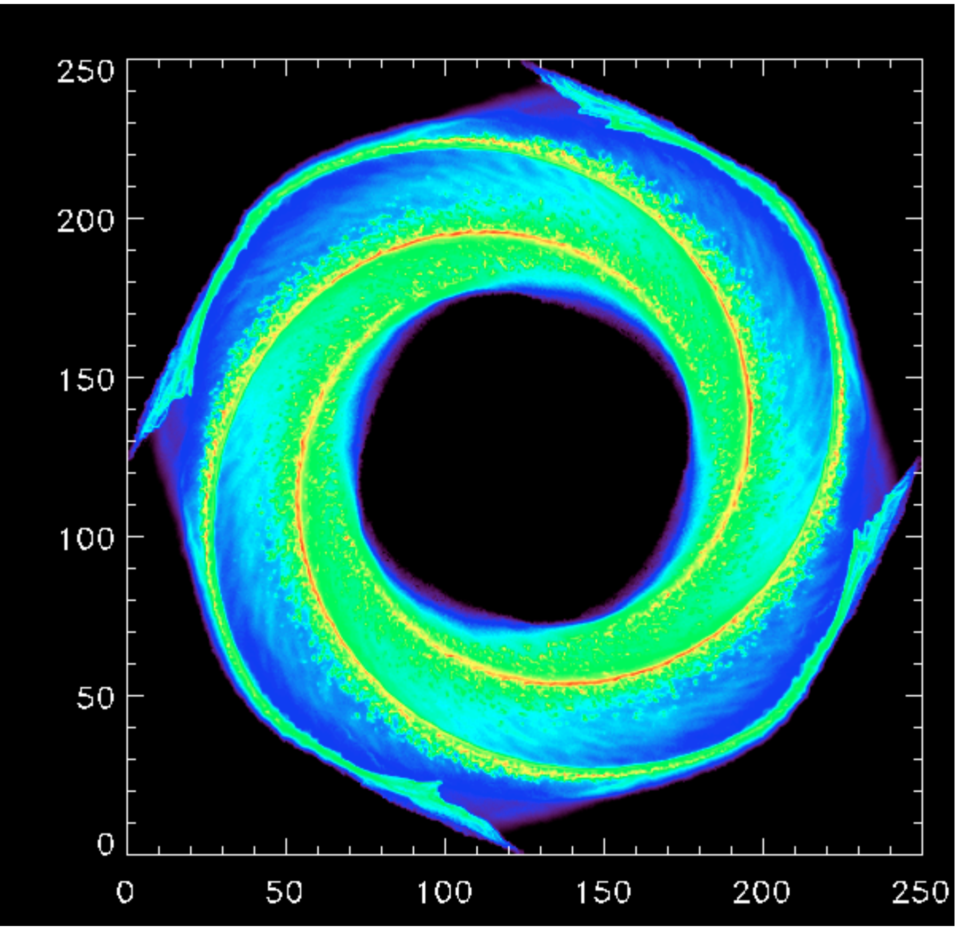
- use Arepo (Springel 2012)
- simplified H_2 and CO chemistry (Glover & Clark 2012)
- external potential with 4-arm spiral (e.g. Dobbs et al. 2008)
- resolve down to 4 M_{sun}!

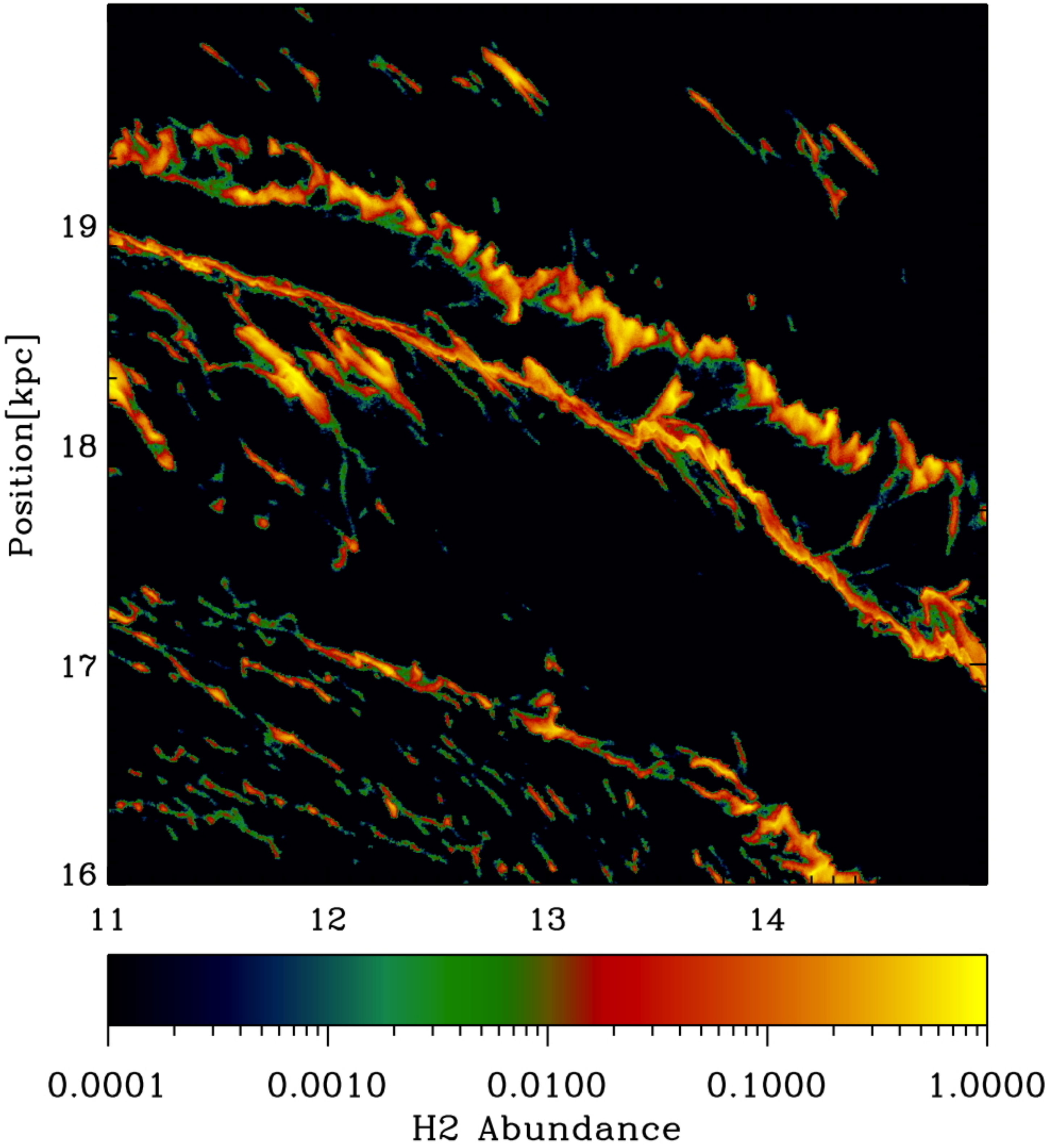
- produce synthetic maps in CO, HI, H_2, etc.
- include feedback (soon!)

(Rowan Smith et al. in preparation)

Modelling the galactic ISM dynamics

H_2 formation in a spiral potential

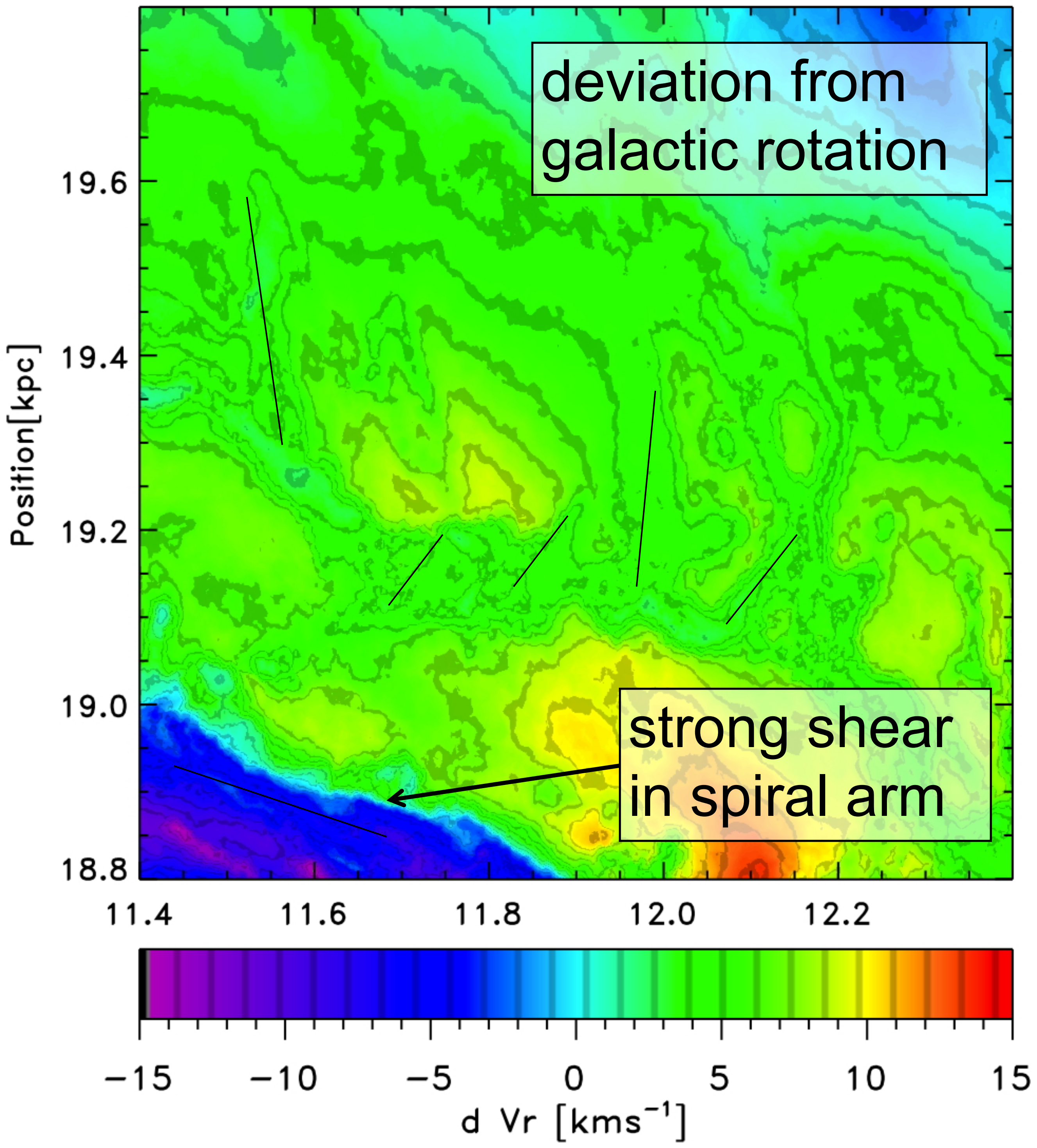




(Rowan Smith et al. in preparation)

Modelling the galactic ISM dynamics

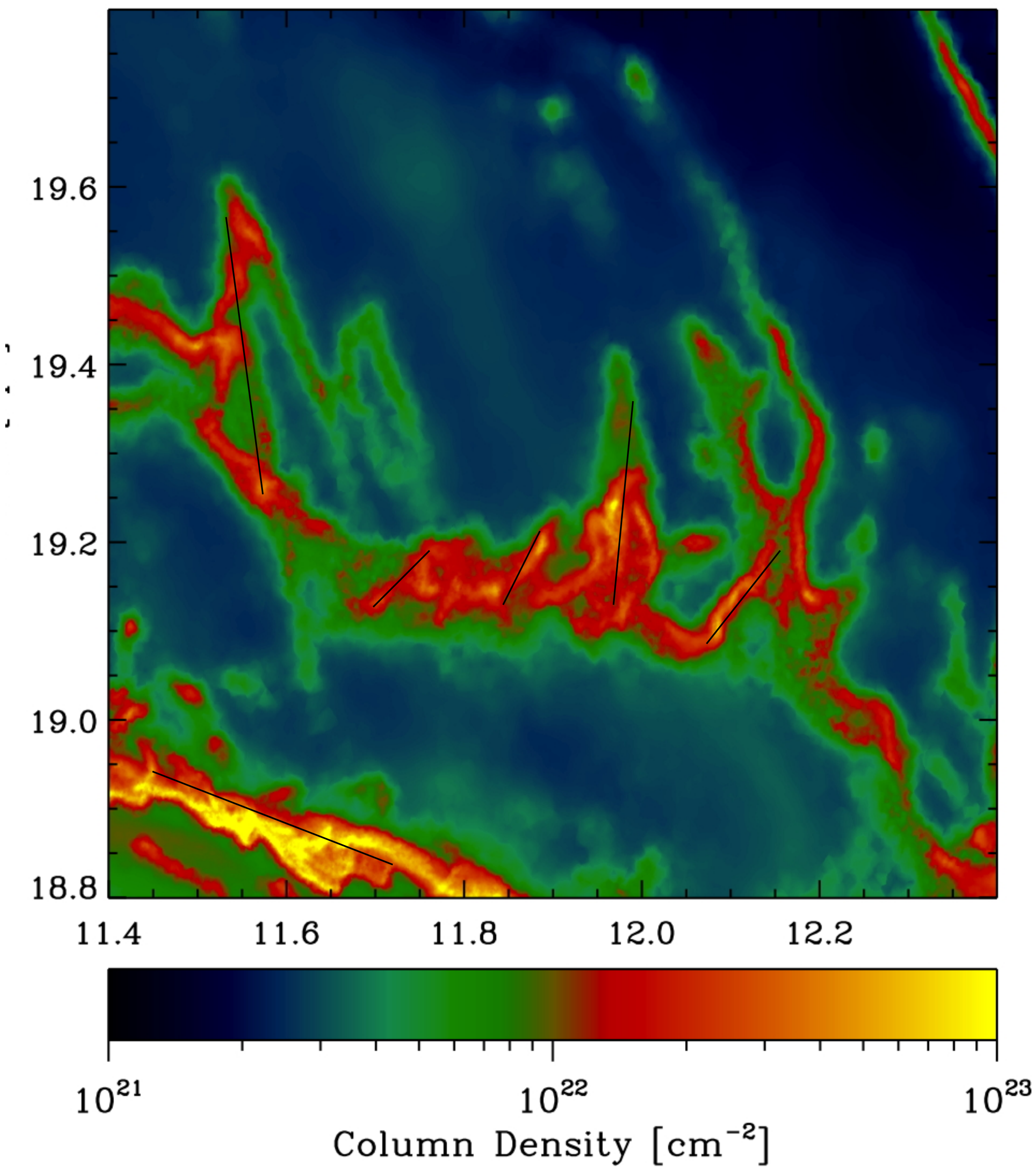
velocity



deviation from galactic rotation

strong shear in spiral arm

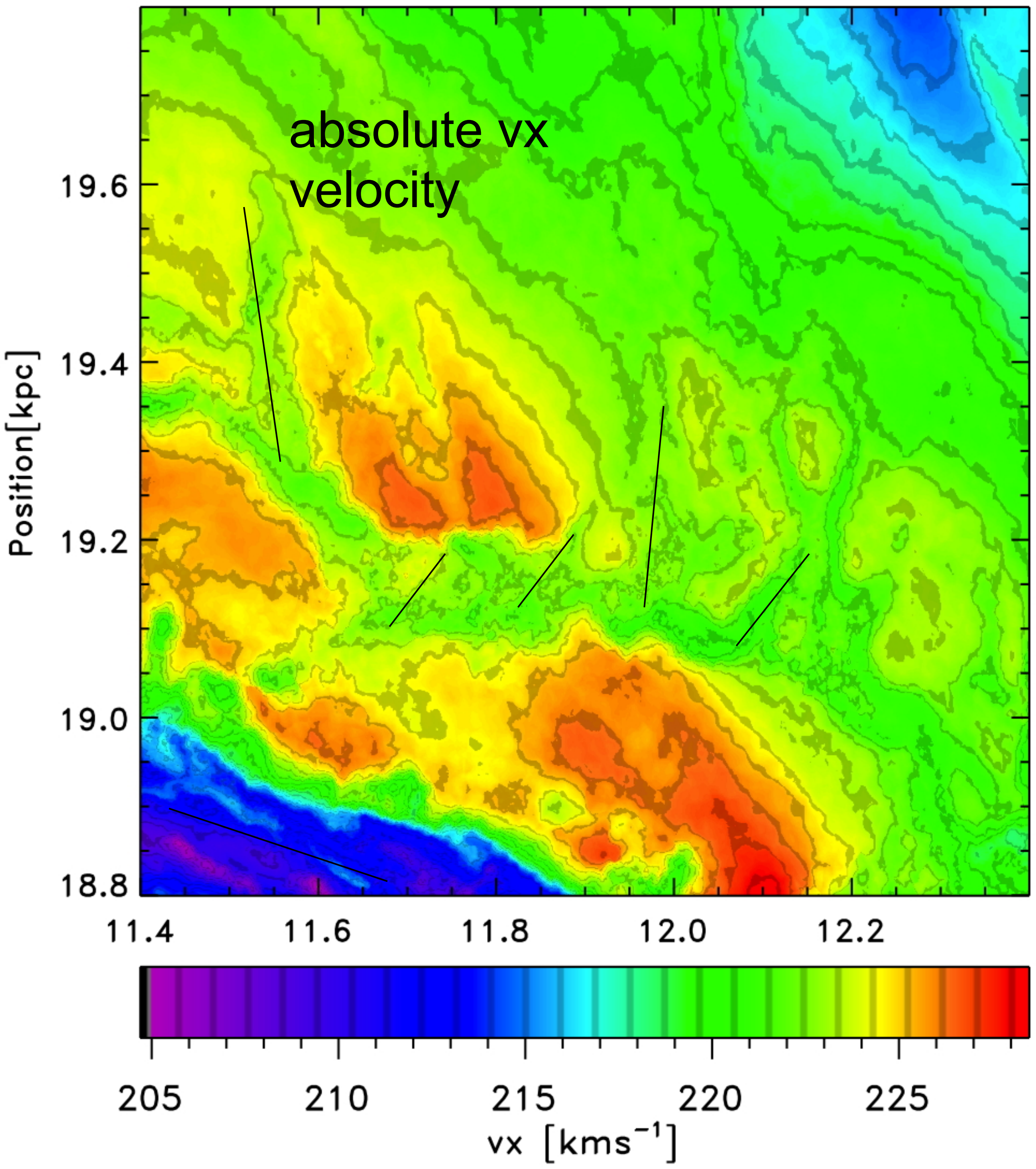
density

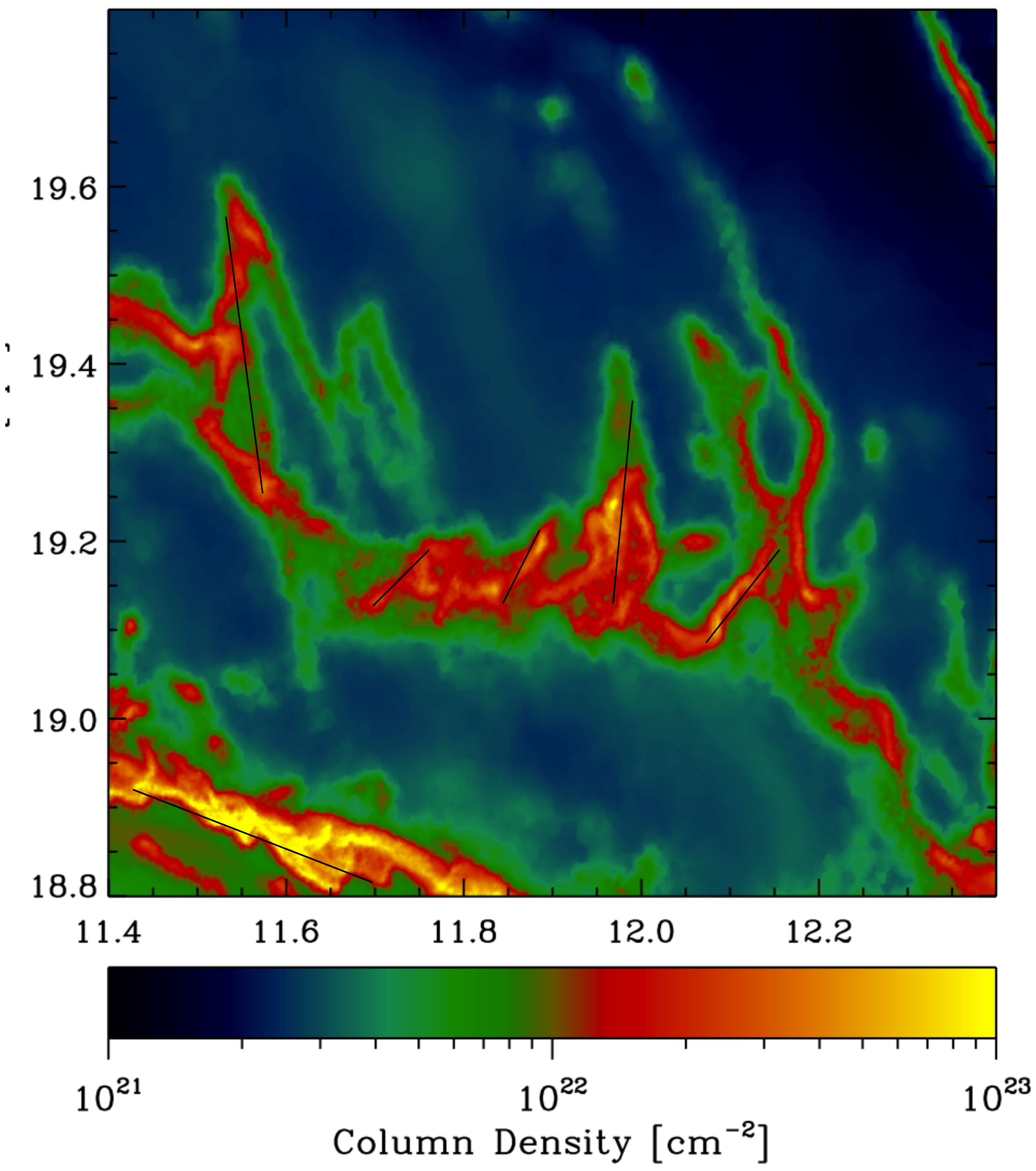


(Rowan Smith et al. in preparation)

Modelling the galactic ISM dynamics

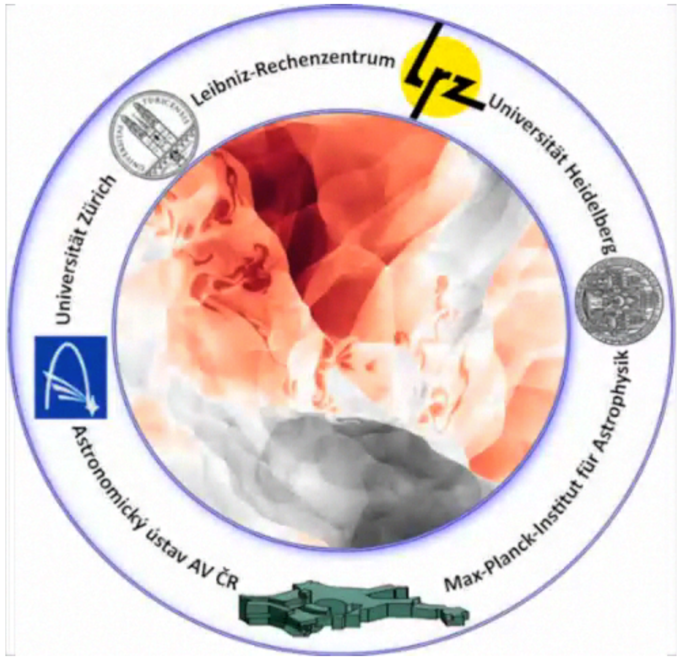
velocities


absolute vx velocity

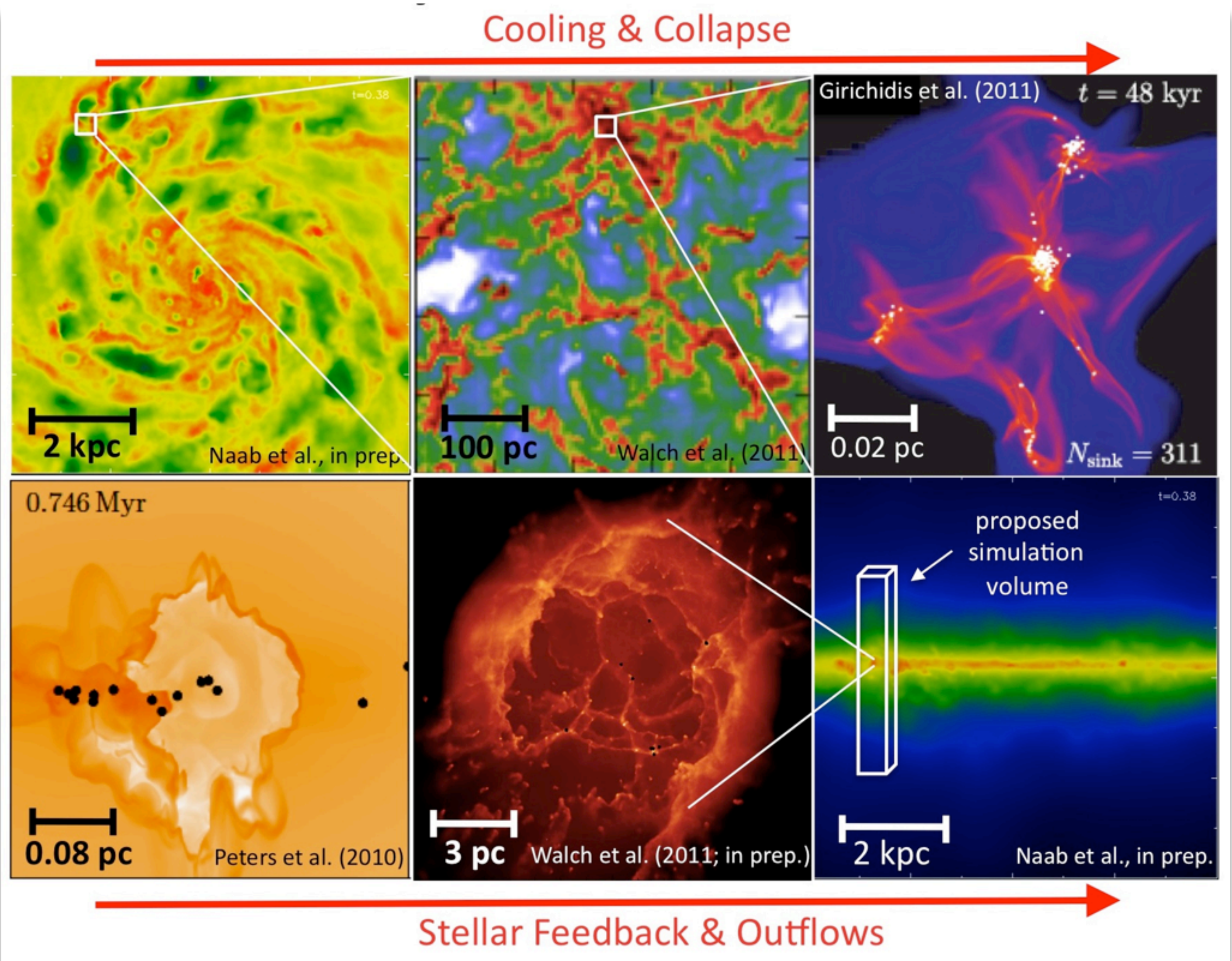


(Rowan Smith et al. in preparation)

Modelling the ISM on 1 kpc scale:



- SILCC project (42 million CPU-h on Super-MUC, PI: Steffi Walch, MPA soon Cologne)
- model 1 x 1 x 4 kpc^3 region of Galactic ISM as consistently as possible
  - extremely high-resolution AMR MHD simulations (FLASH4)
  - SN driven turbulence
  - resolve star formation down to 500 AU
  - radiative + mechanical feedback from stars
  - time-dependent chemistry
  - Galactic potential
- goal is to better understand
  - formation and evolution of molecular clouds
  - larger-scale SF relations
  - Galactic fountains
  - Galactic matter cycle



are there “dark” clouds?

- there is increasing evidence that a significant fraction of the H_2 gas in galaxies is not traced by CO (see e.g. Jorge Pineda’s talk yesterday)

- 3D simulations of colliding HI gas forming molecular clouds at the stagnation region performed by Paul Clark in Heidelberg

  - SPH + CO chemistry + TREECOL for calculating extinction
  - ‘standard’ dust model
  - sink particles to account for local collapse (star formation)
  - two models: slow and fast flow

are there “dark” clouds?

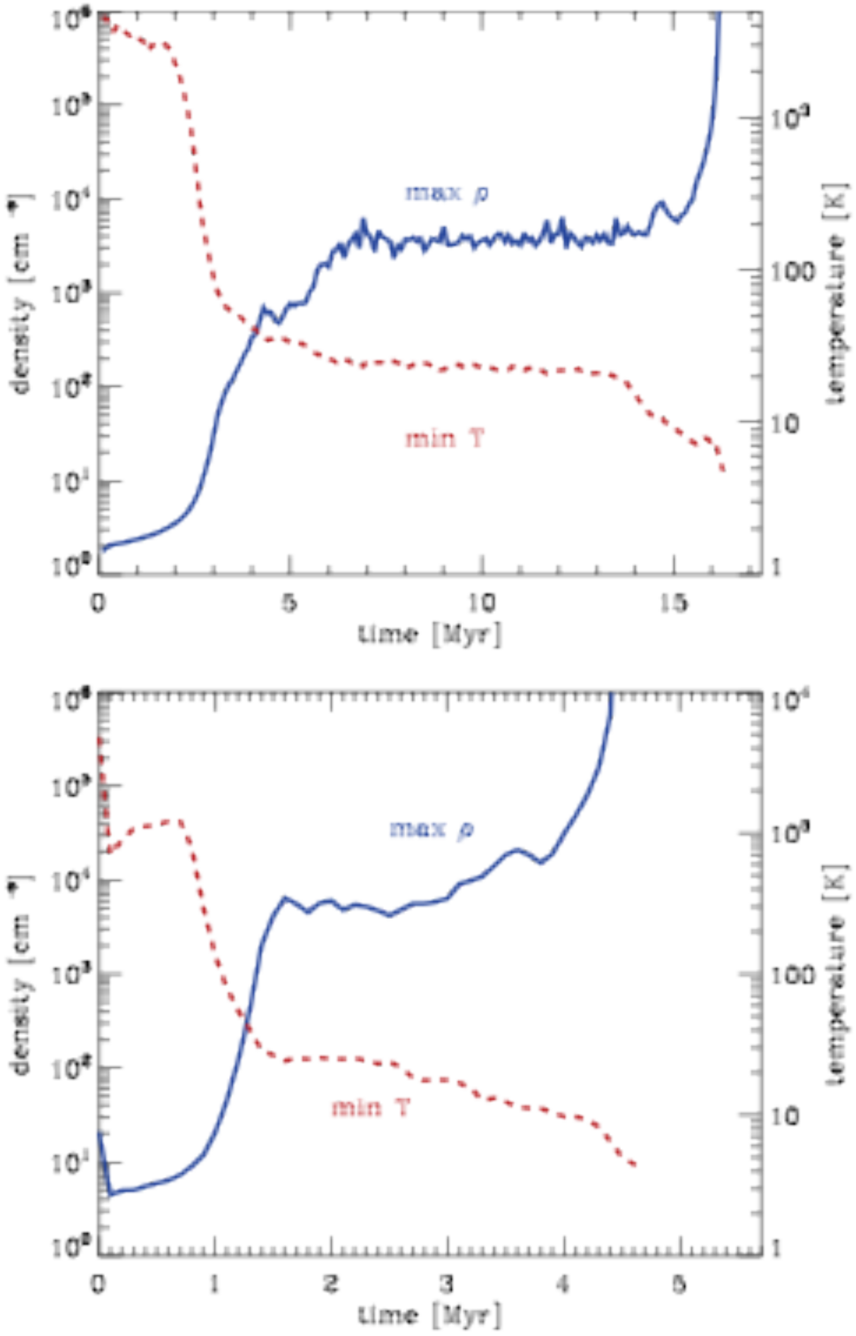
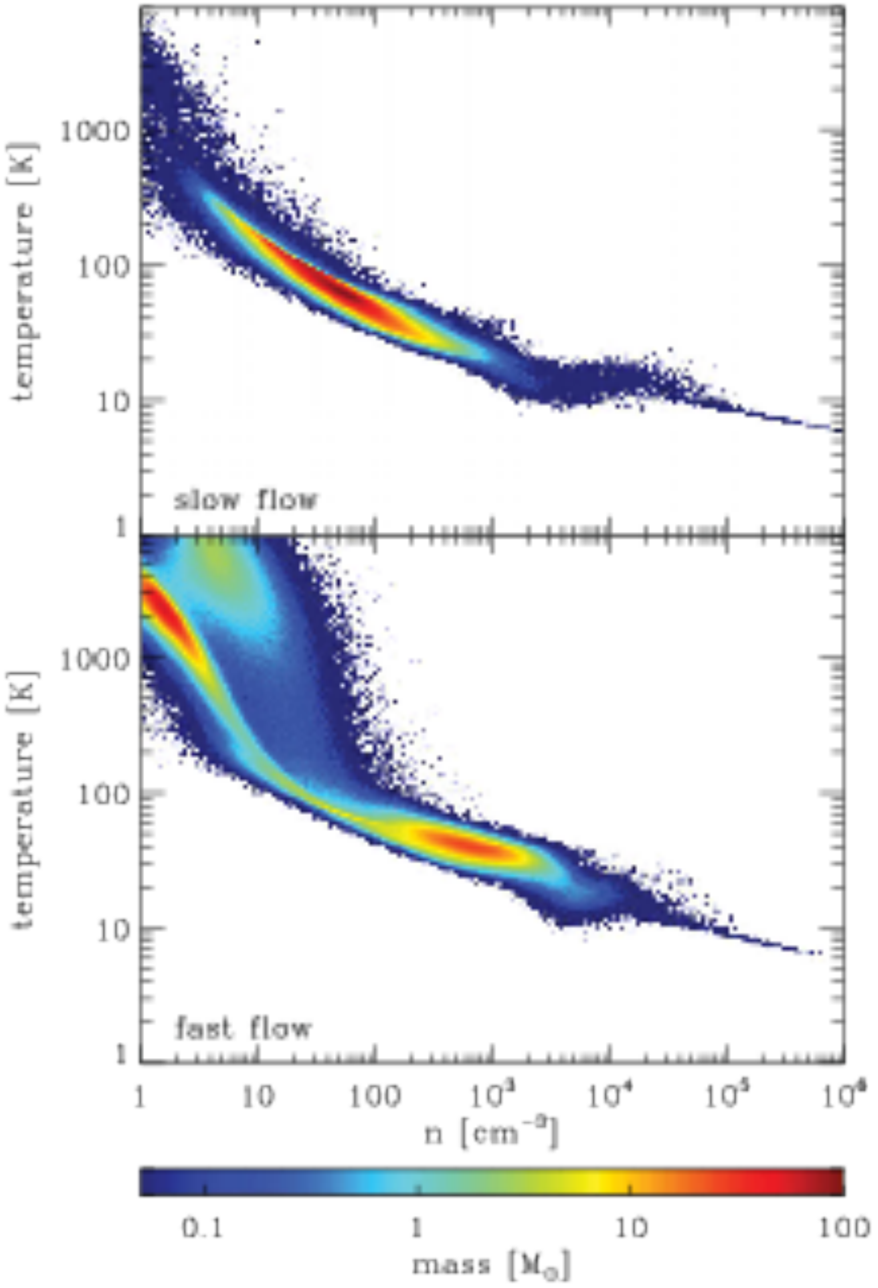


Figure 3. Evolution with time of the maximum density (blue, solid line) and minimum temperature (red, dashed line) in the slow flow (top panel) and the fast flow (bottom panel). Note that at any given instant, the coldest SPH particle is not necessarily the densest, and so the lines plotted are strictly independent of one another.



slow flow

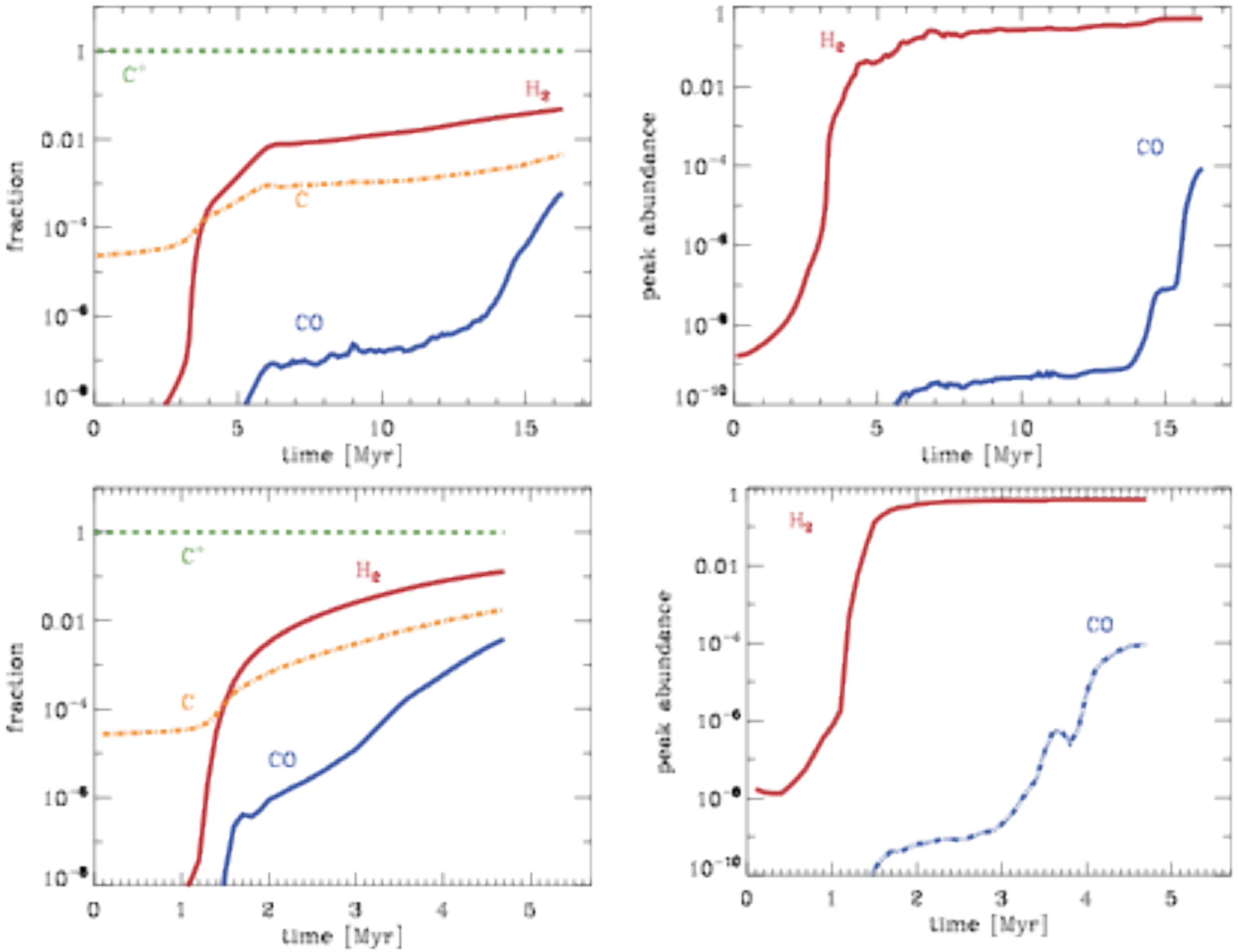
fast flow

Figure 5. The gas temperature–density distribution in the flows at the onset of star formation.

Clark et al. (2012)

see also Pringle, Allen, Lubov (2001), Hosokawa & Inutsuka (2007)

are there “dark” clouds?



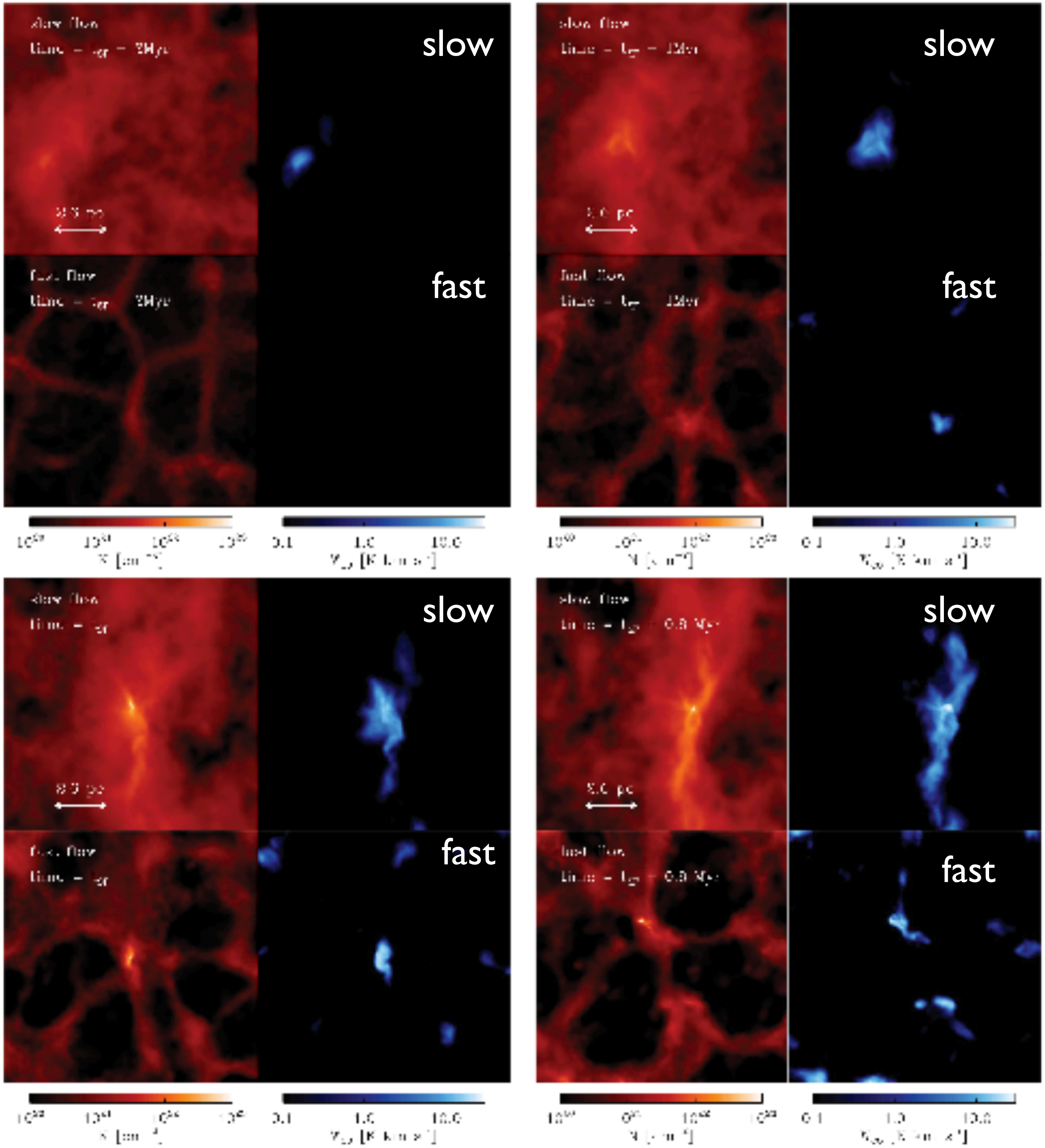
slow flow

fast flow

Figure 6. Chemical evolution of the gas in the flow. In the left-hand column, we show the time evolution of the fraction of the total mass of hydrogen that is in the form of H_2 (red solid line) for the 6.8 km s^{-1} flow (upper panel) and the 13.6 km s^{-1} flow (lower panel). We also show the time evolution of the fraction of the total mass of carbon that is in the form of C^+ (green dashed line), C (orange dot–dashed line) and CO (blue double-dot–dashed line). In the right-hand column, we show the peak values of the fractional abundances of H_2 and CO. These are computed relative to the total number of hydrogen nuclei, and so the maximum fractional abundances of H_2 and CO are 0.5 and 1.4×10^{-4}, respectively. Again, we show results for the 6.8 km s^{-1} flow in the upper panel and the 13.6 km s^{-1} flow in the lower panel. Note that the scale of the horizontal axis differs between the upper and lower panels.

Clark et al. (2012)

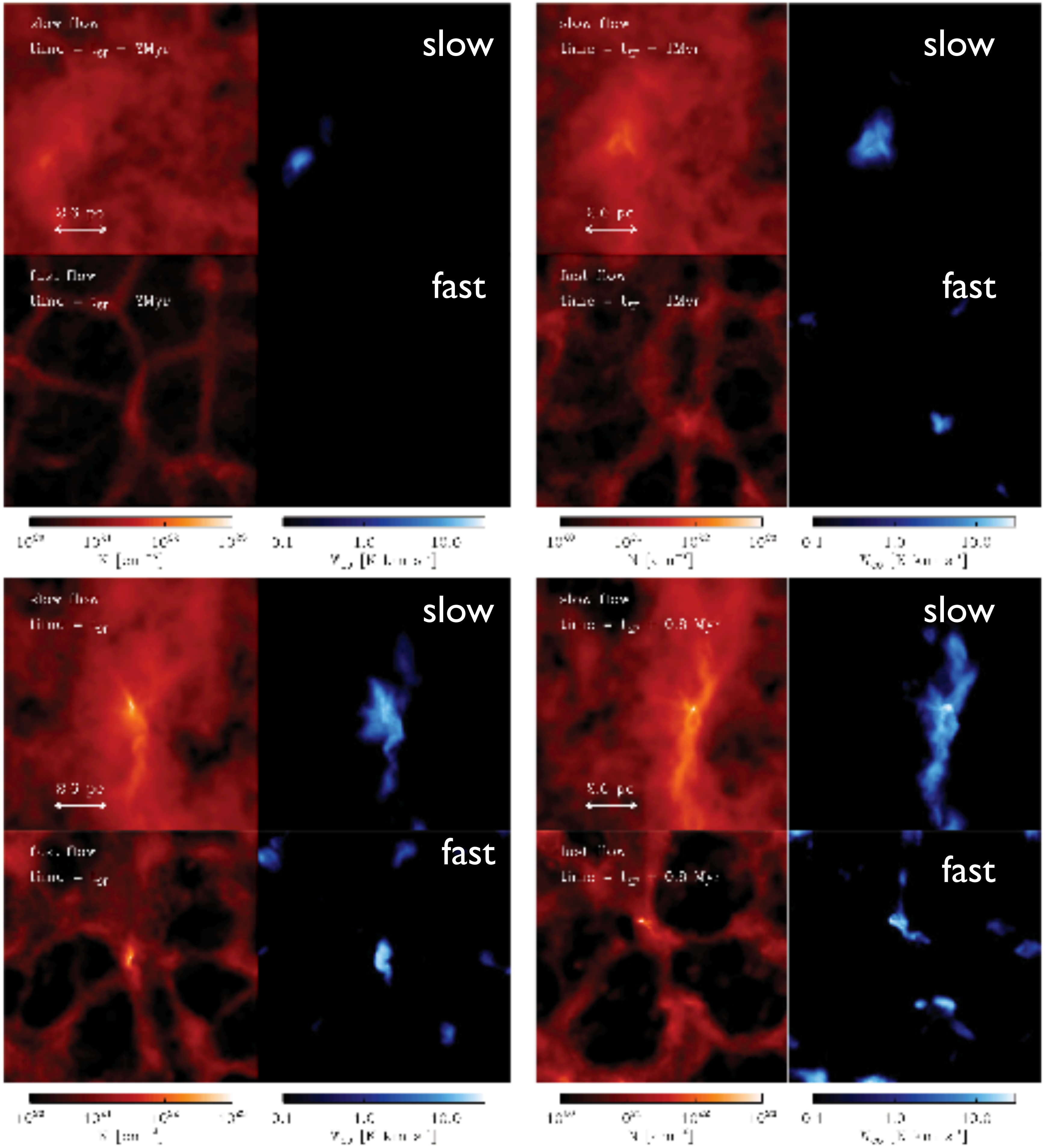
see also Pringle, Allen, Lubov (2001), Hosokawa & Inutsuka (2007)



H_2 column

CO emission

Clark et al. (2012)



H$_2$ column

CO emission

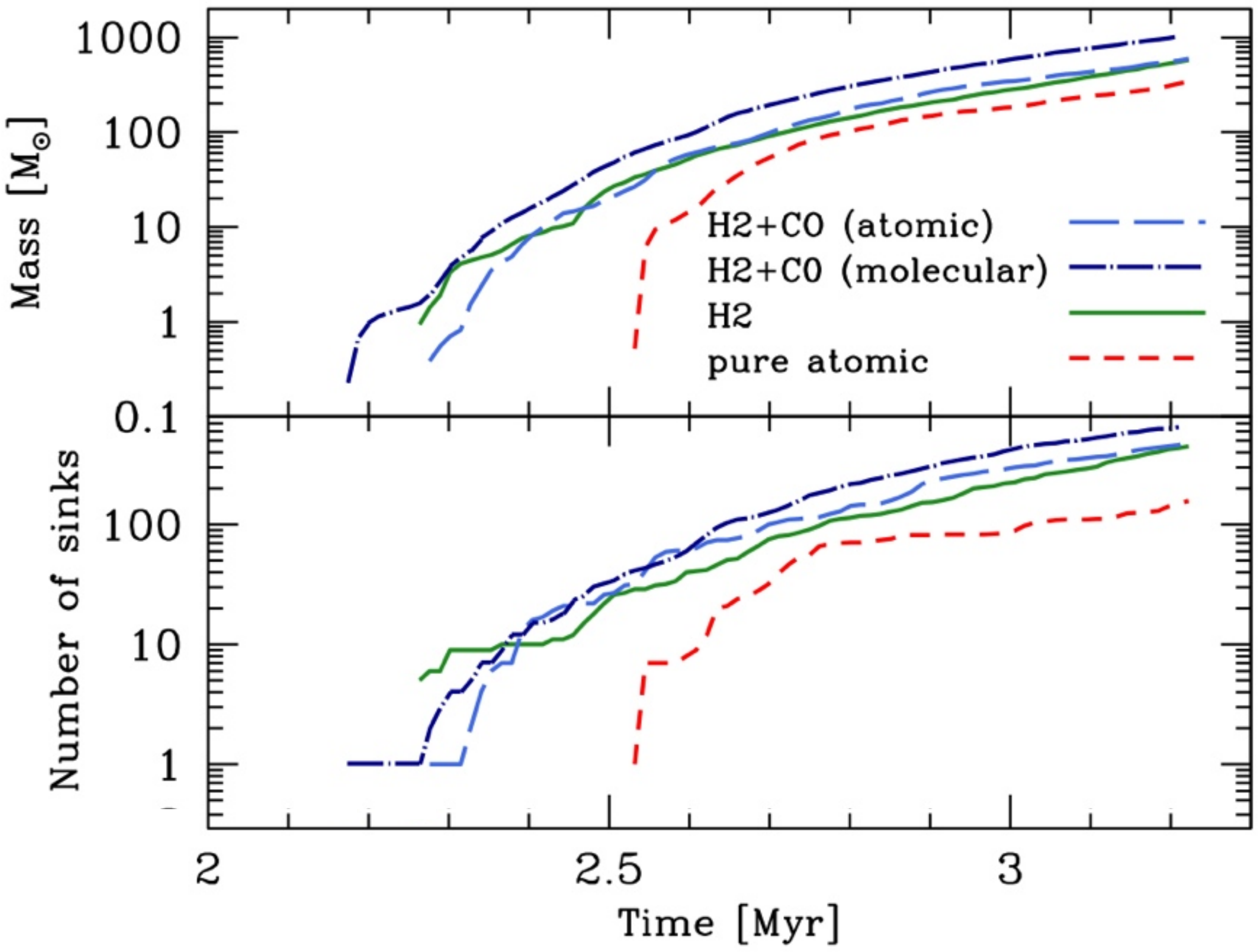
fraction of CO dark gas will also change with metallicity and with ambient radiation field

Clark et al. (2012)

are molecules needed for star formation?

- it has been proposed that molecule formation (H_2, CO, etc.) is a prerequisite for star formation
  (e.g. Schaye 2004; Krumholz & McKee 2005; Elmegreen 2007; Krumholz et al. 2009)
- the idea is that CO is a necessary coolant for collapse
- however, also C^+ and C are very efficient coolants
- see what is needed for star formation, by artificially switching off certain chemical pathways
  (Glover & Clark 2012)

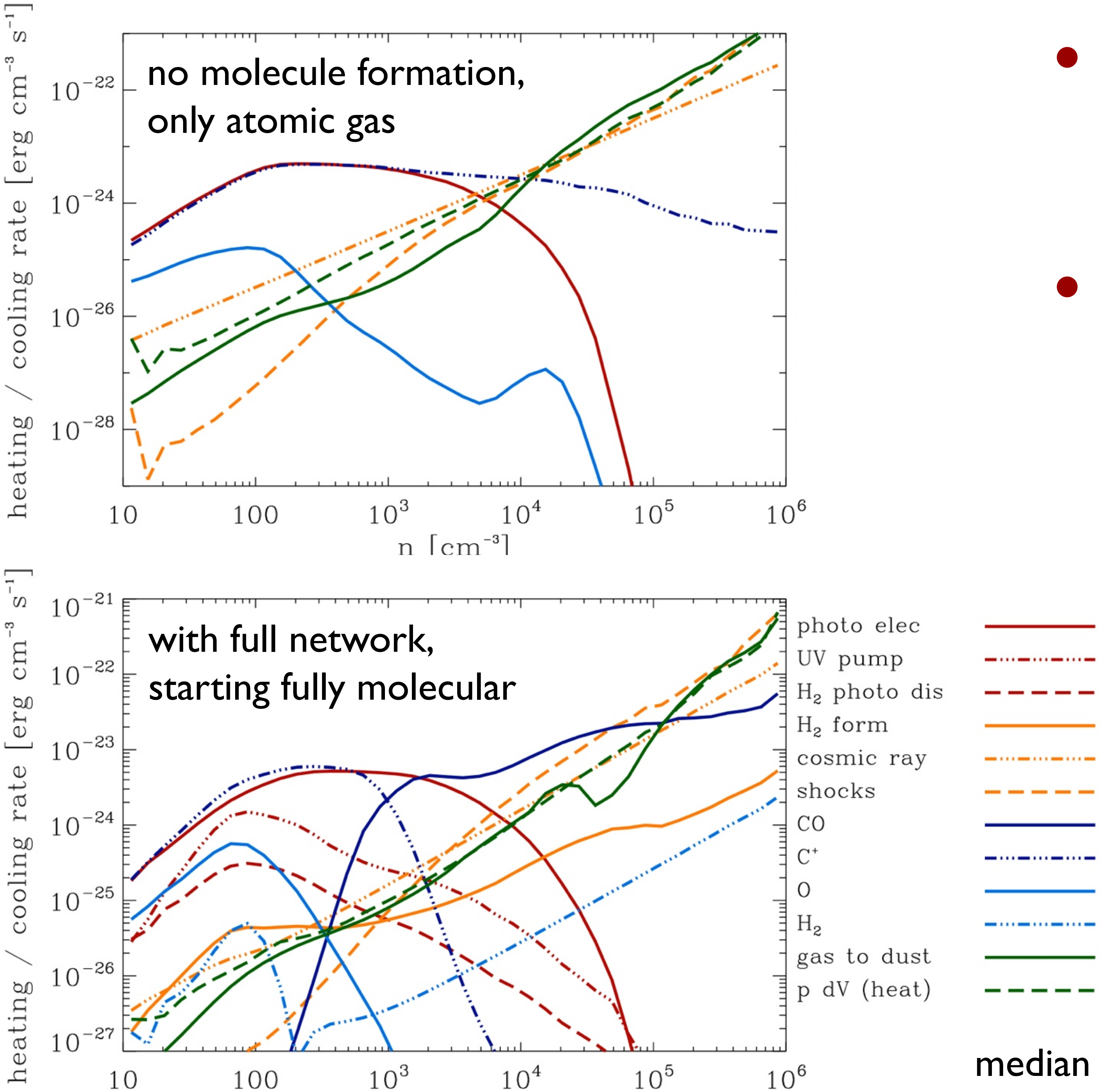
are molecules needed for star formation?



presence of molecular gas has only very minor influence on ability of cloud to form stars

Glover & Clark (2012)

are molecules needed for star formation?

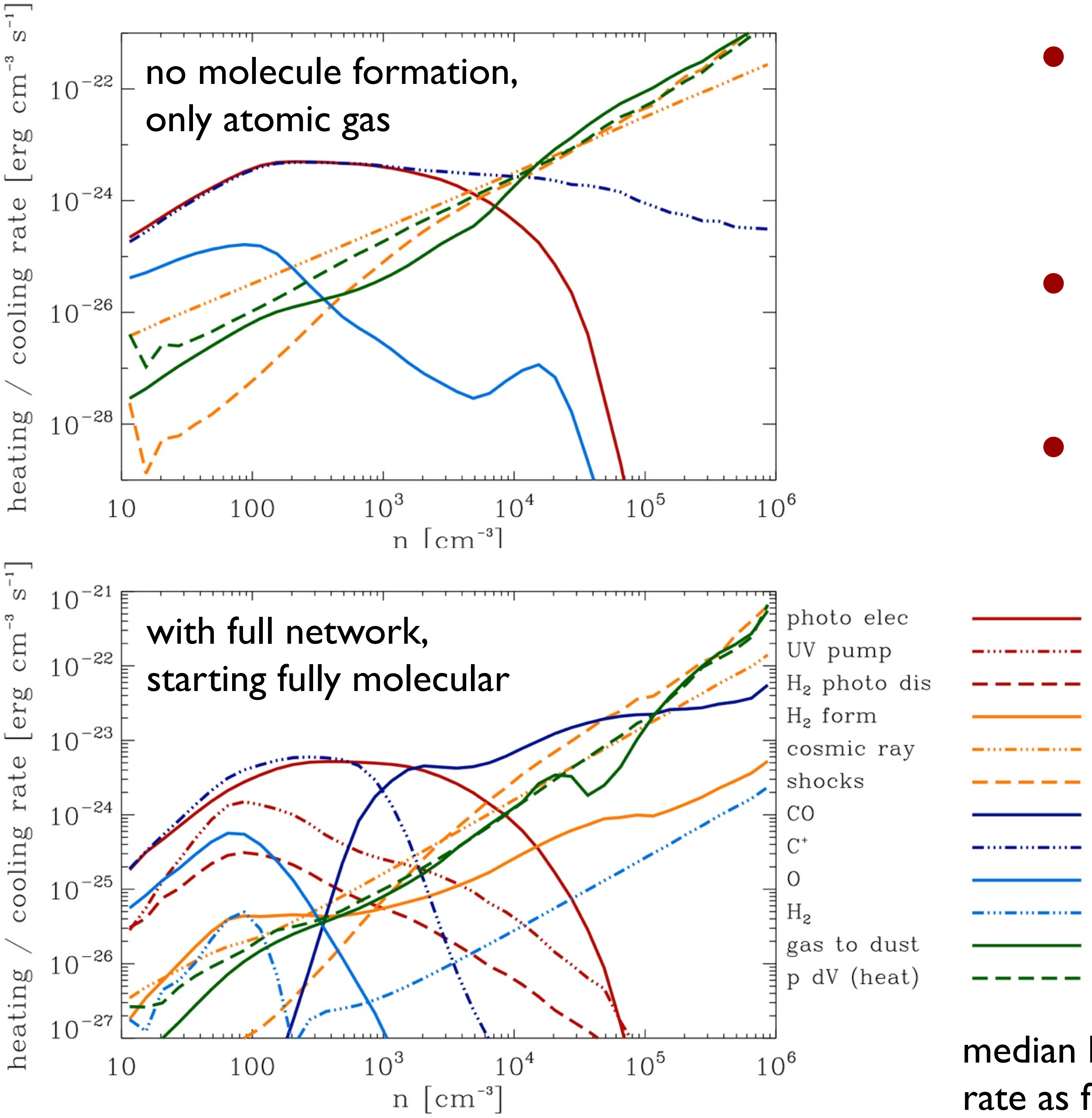


- presence of molecular gas has only very minor influence on ability of cloud to form stars
- C^+ is equally efficient coolant in atomic phase as CO in molecular

median heating and cooling rate as function of density

Glover & Clark (2012)

are molecules needed for star formation?

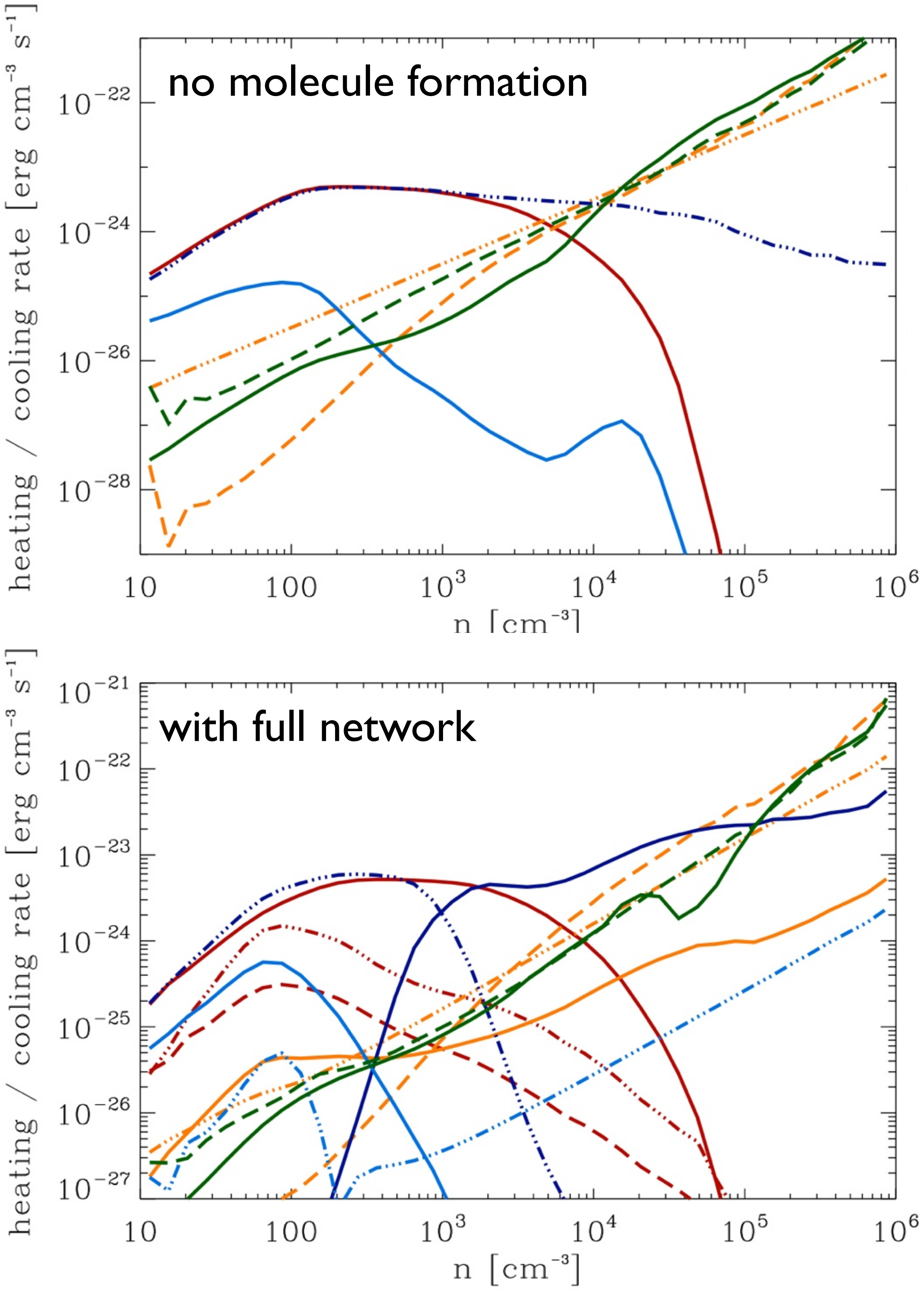


- presence of molecular gas has only very minor influence on ability of cloud to form stars
- C^+ is equally efficient coolant in atomic phase as CO in molecular
- shielding is important at high densities: photoelectric emission from dust grains is no longer dominant heating process

median heating and cooling rate as function of density

Glover & Clark (2012)

are molecules needed for star formation?



Glover & Clark (2012)

- presence of molecular gas has only very minor influence on ability of cloud to form stars
- C^+ is equally efficient coolant in atomic phase as CO in molecular
- what is crucial is the ability of cloud to shield itself from interstellar radiation field
- but clouds that are big/dense enough to shield themselves will be molecular! **this suggests that the correlation between H_2 and star formation is a coincidence**

metallicity dependence

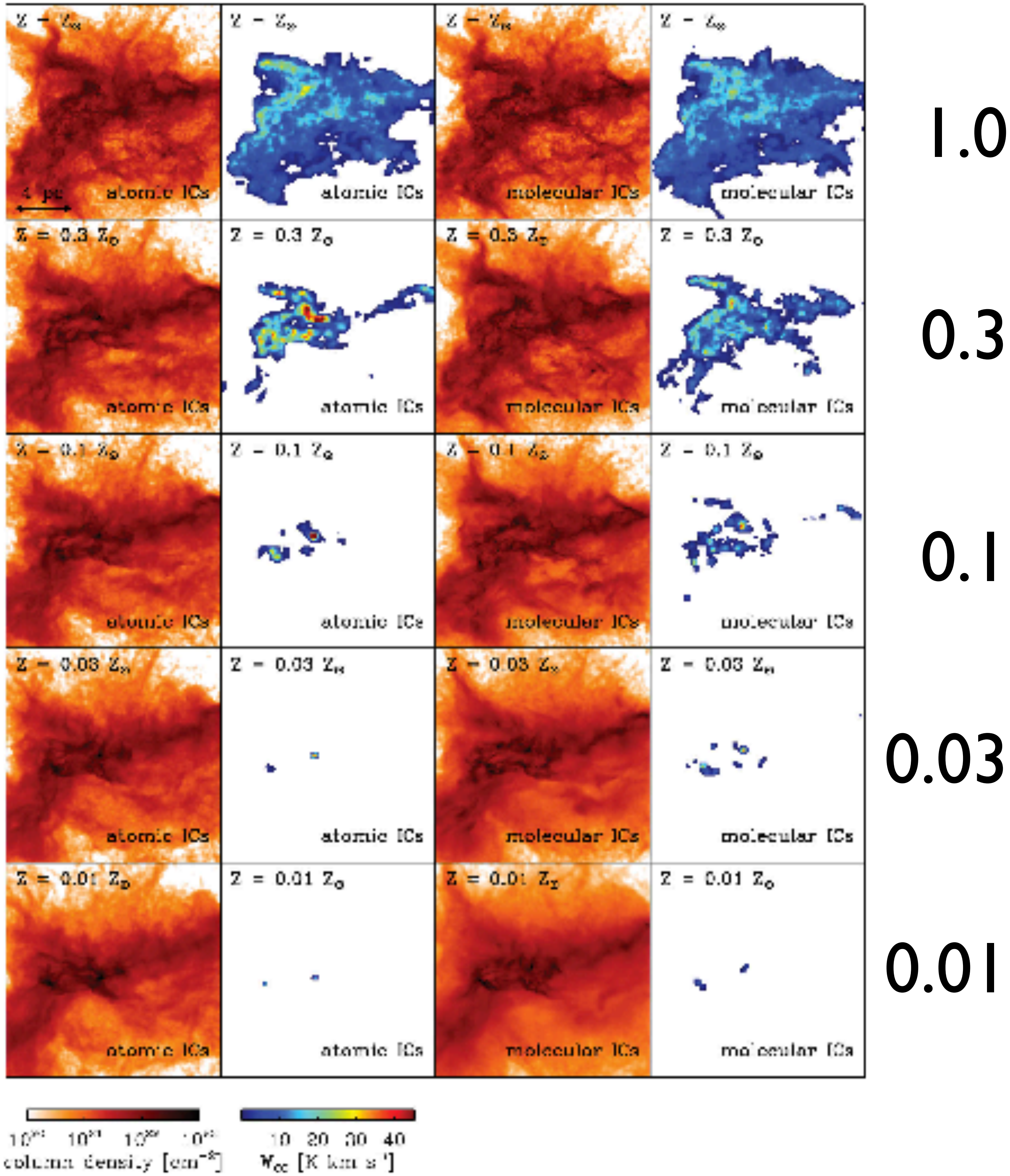


Figure 5. Maps of column density (first and third columns) and integrated intensity in the $J = 1\text{–}0$ rotational transition of ^{12}CO (second and fourth columns) for each of the simulations. The maps show a region of side length 16.2 pc that includes roughly 80 per cent of the total cloud mass, but almost all of the CO emission. The CO integrated intensity maps were produced using the RADMC-3D radiative transfer code, as described in the text.

Glover & Clark (2012)

metallicity dependence

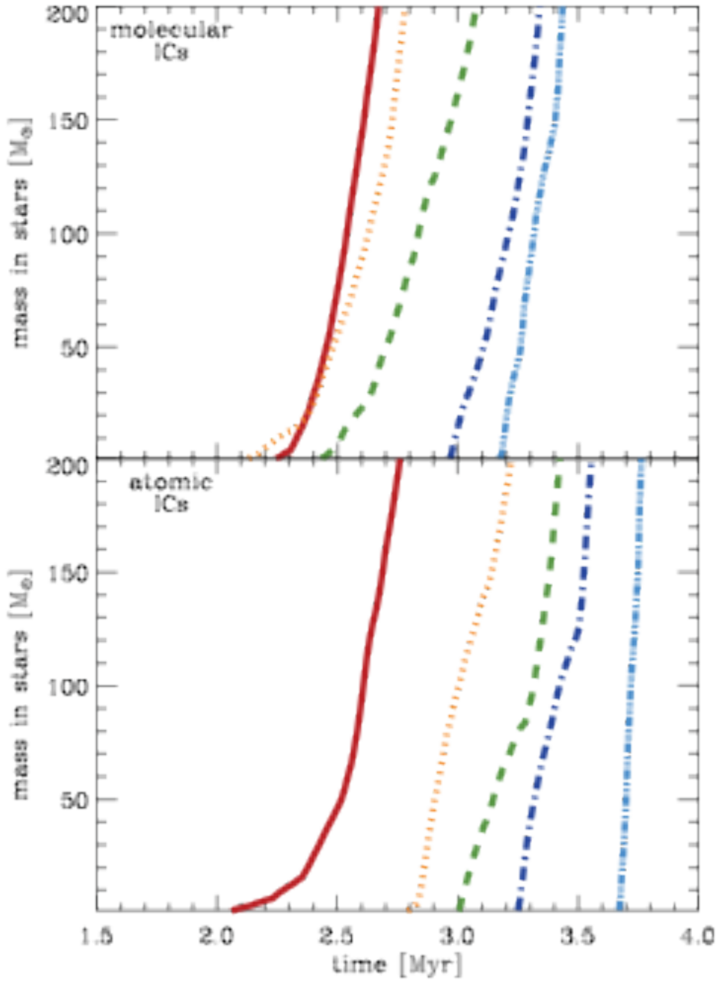


Figure 1. Upper panel: mass in sinks, plotted as a function of time, for runs Z1-M (solid line), Z03-M (dotted line), Z01-M (dashed line), Z003-M (dot-dashed line) and Z001-M (double-dot-dashed line). In these runs, hydrogen was initially in fully molecular form. Lower panel: the same quantity, but for runs Z1-A (solid line), Z03-A (dotted line), Z01-A (dashed line), Z003-A (dot-dashed line) and Z001-A (double-dot-dashed line). In these runs, hydrogen was initially fully atomic.

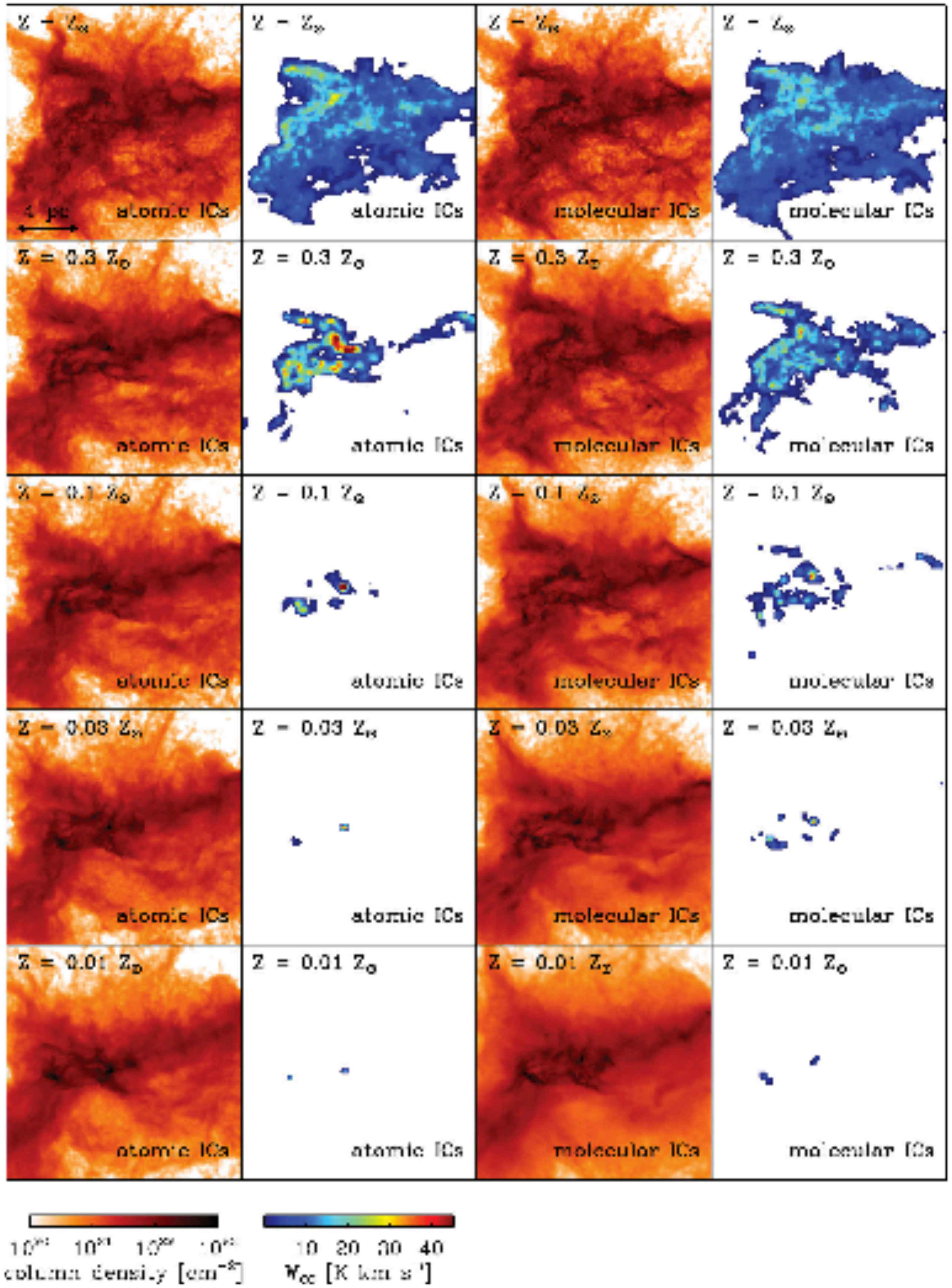


Figure 5. Maps of column density (first and third columns) and integrated intensity in the $J = 1$–0 rotational transition of ^{12}CO (second and fourth columns) for each of the simulations. The maps show a region of side length 16.2 pc that includes roughly 80 per cent of the total cloud mass, but almost all of the CO emission. The CO integrated intensity maps were produced using the RADMC-3D radiative transfer code, as described in the text.

1.0

0.3

0.1

0.03

0.01

Glover & Clark (2012)

BUT: at low metallicities, H2 and HD cooling may indeed matter!

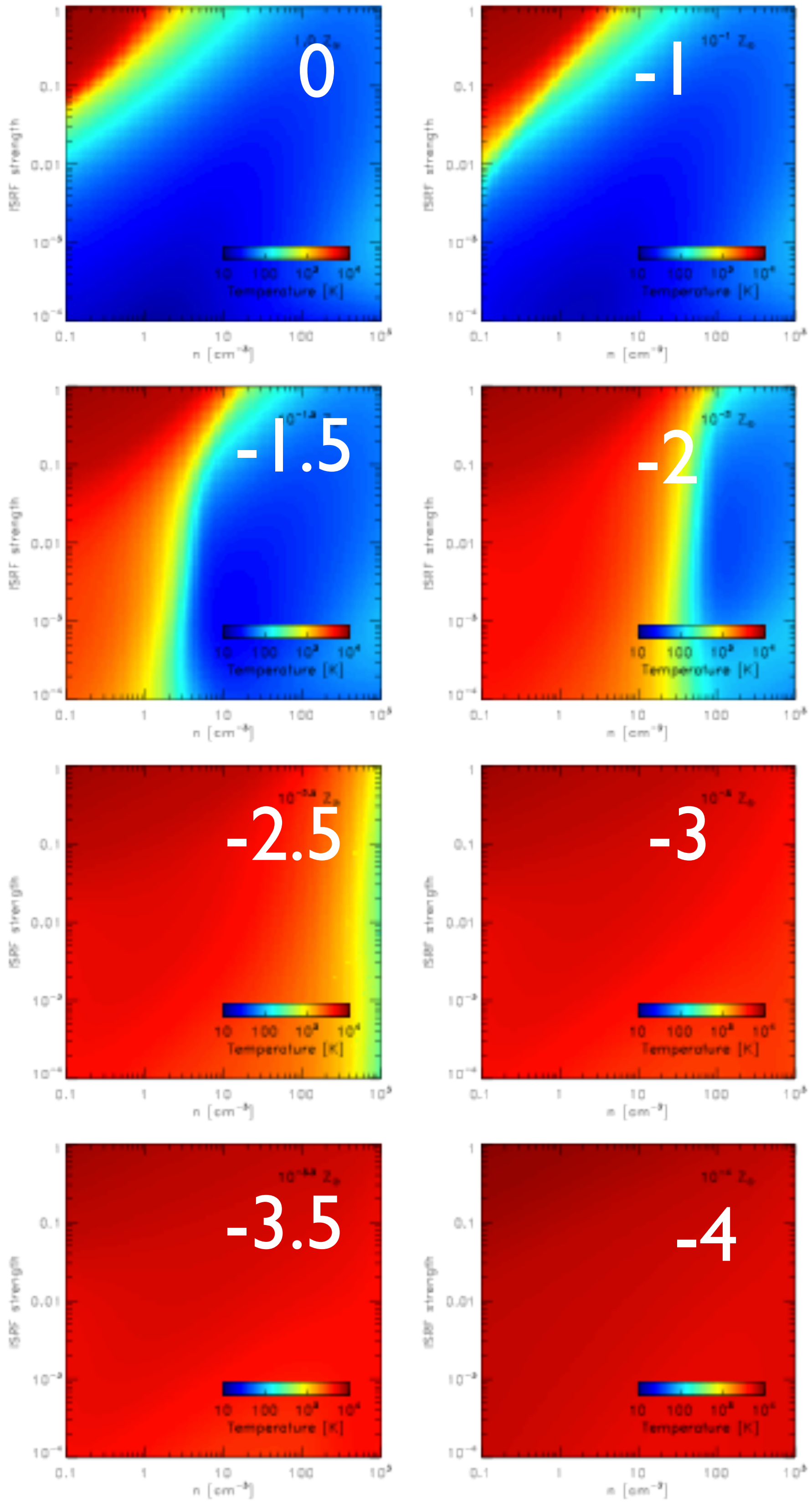


Figure 1. Gas temperature at $t = t_{ff}$, computed as a function of the number density of hydrogen nuclei, n, and the strength of the interstellar radiation field in units of the standard value, G_0, for a set of runs covering a range of metallicities between $Z = Z_\odot$ and $Z = 10^{-4}\,Z_\odot$. In these runs, the effects of H_2 and HD cooling were not included.

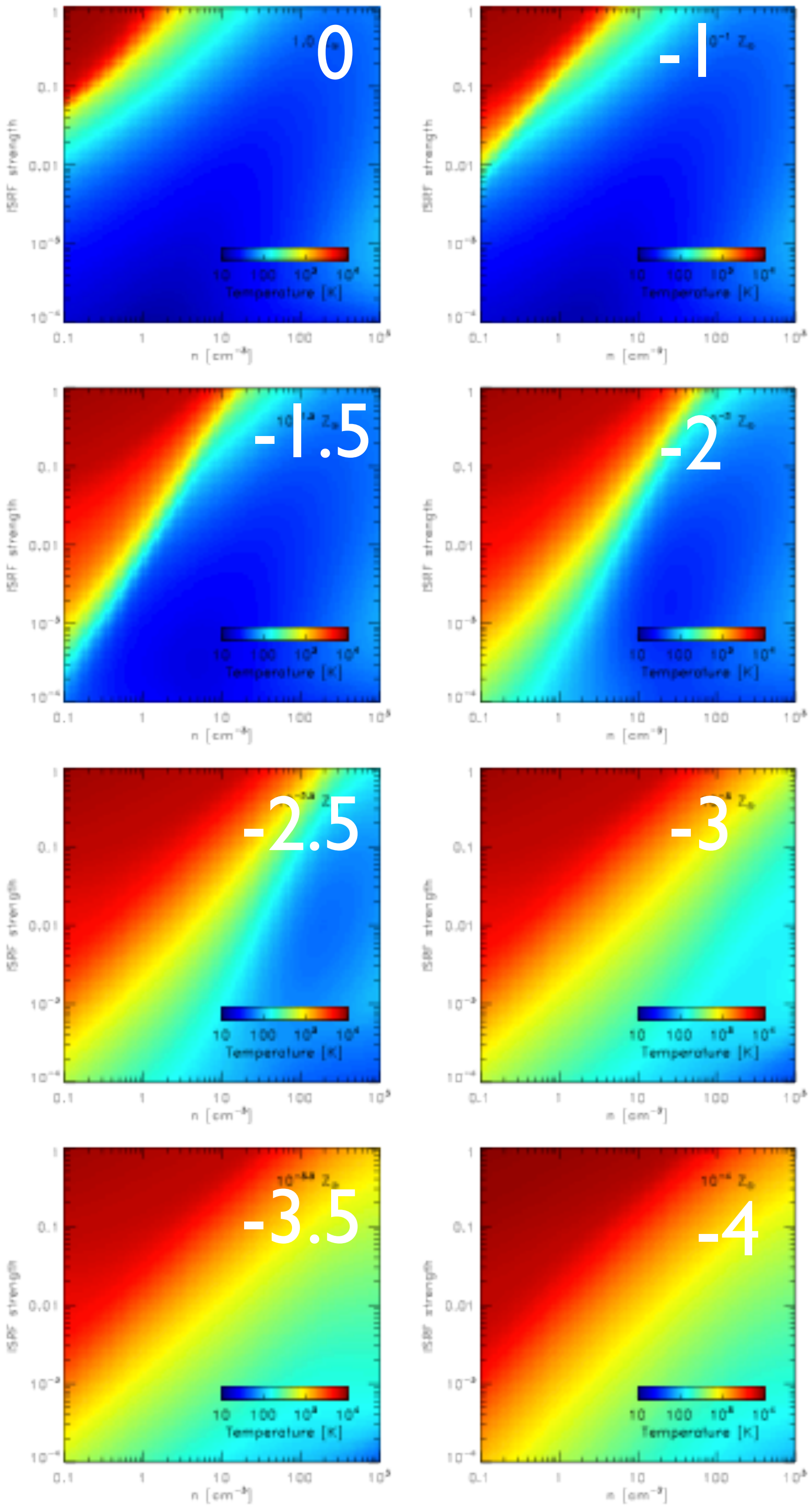


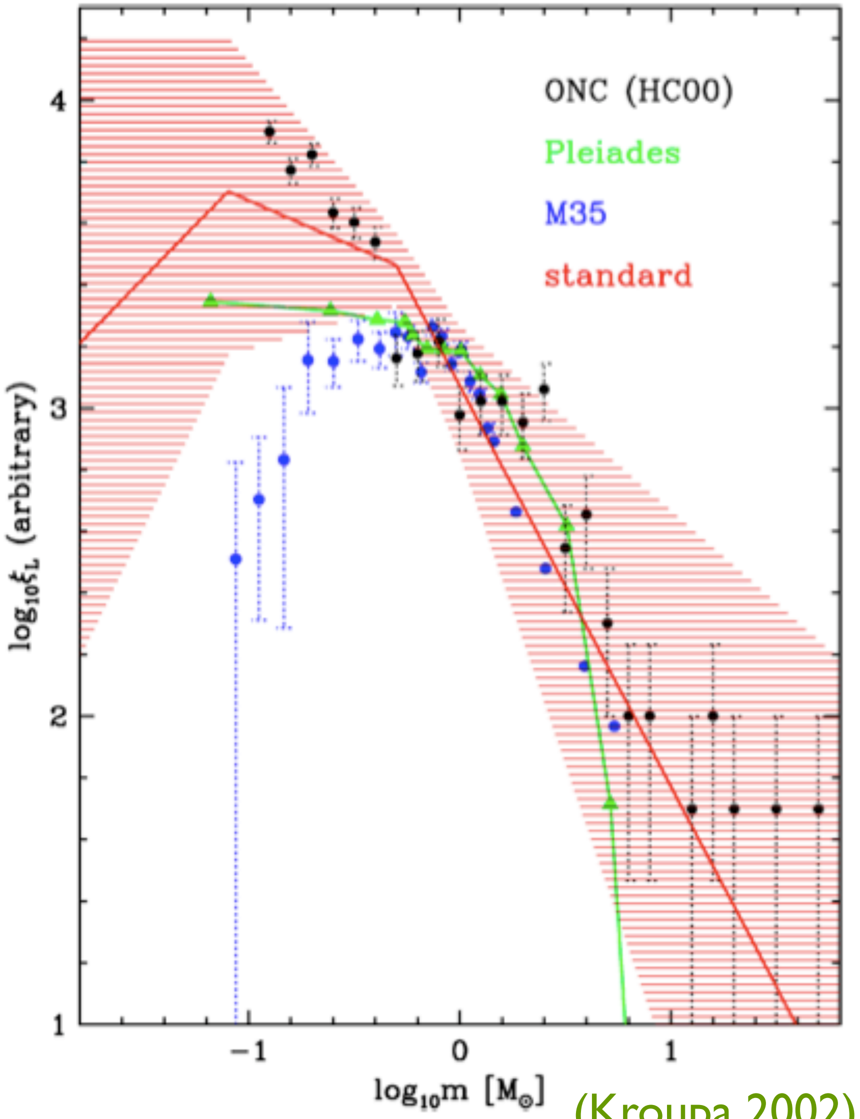
Figure 2. As Figure 1, but for a set of runs that included the effects of H_2 and HD cooling.

Glover & Clark (2013)

star cluster formation: IMF

stellar mass fuction

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



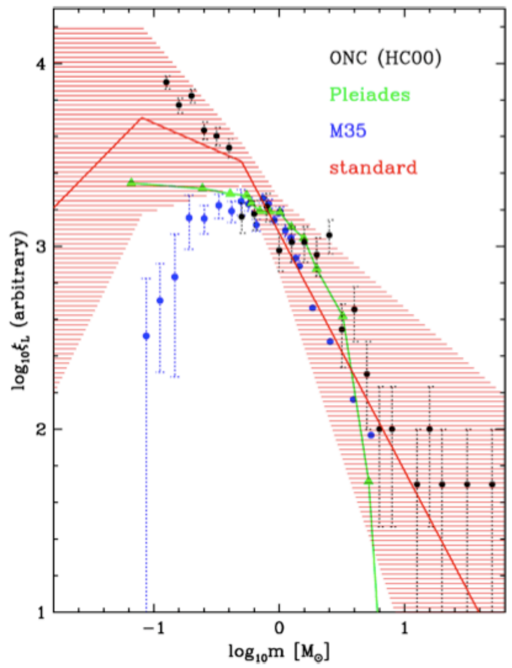
(Kroupa 2002)

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)



stellar mass fuction

- distribution of stellar masses depends on
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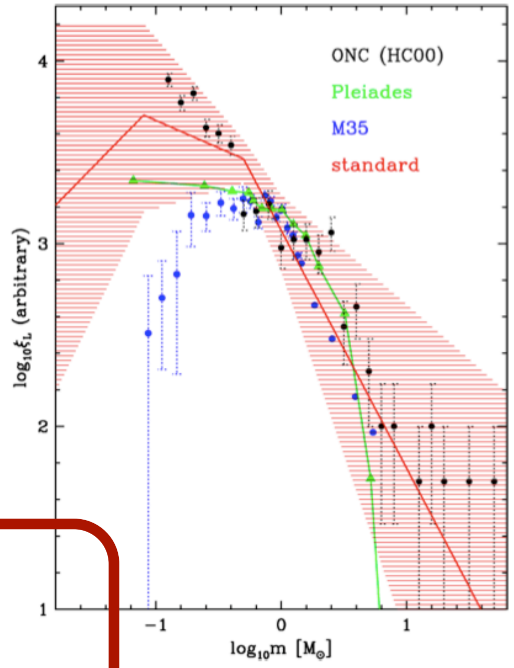
    --> EOS (determines which cores go into collapse)
  - (proto) stellar feedback terminates star formation
    ionizing radiation, bipolar outflows, winds, SN, etc.

application to early star formation

(Kroupa 2002)



thermodynamics & fragmentation

degree of fragmentation depends on *EOS!*

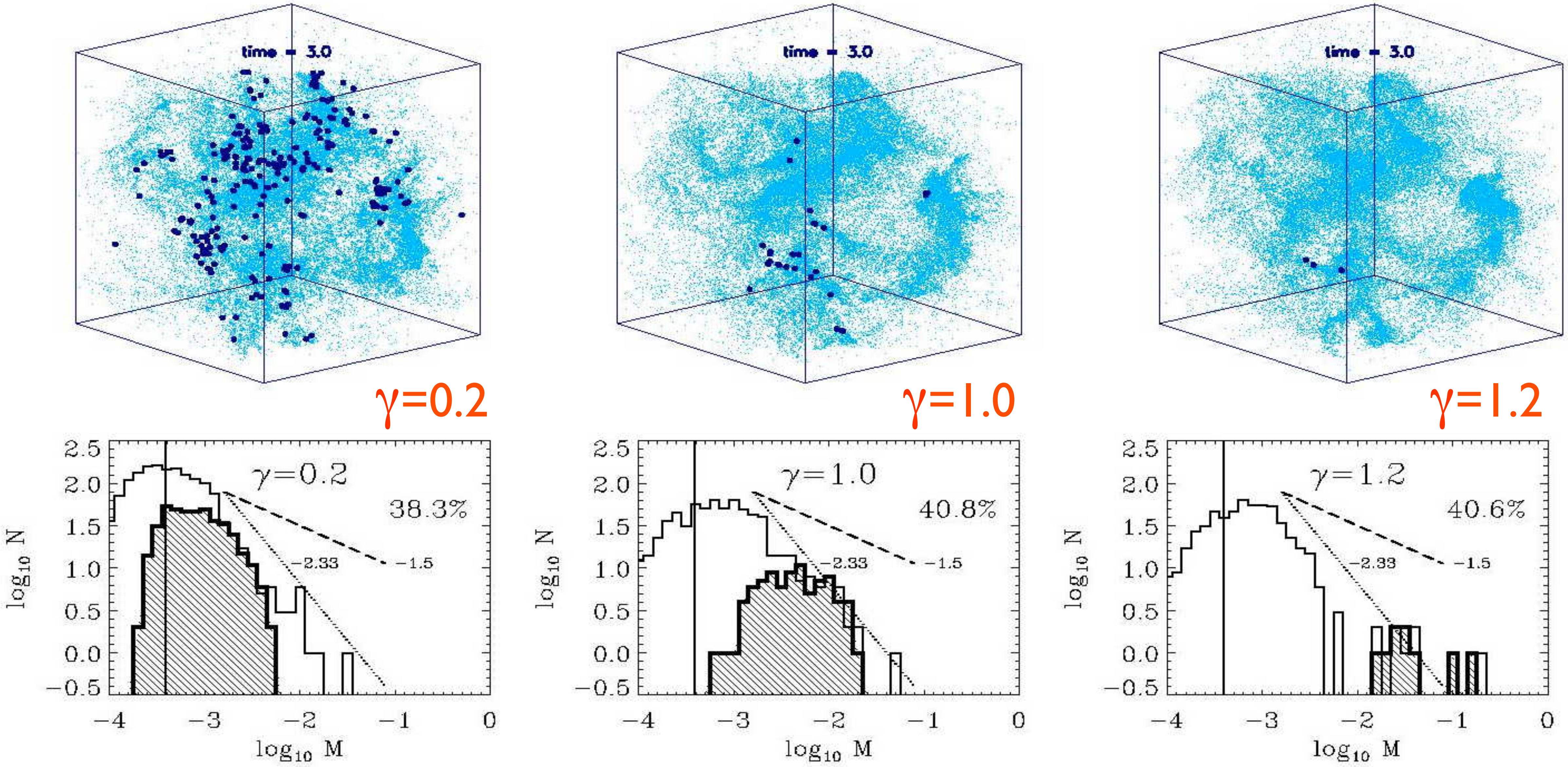
polytropic EOS: $\mathbf{p} \propto \rho^{\gamma}$

$\gamma < 1$: 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*

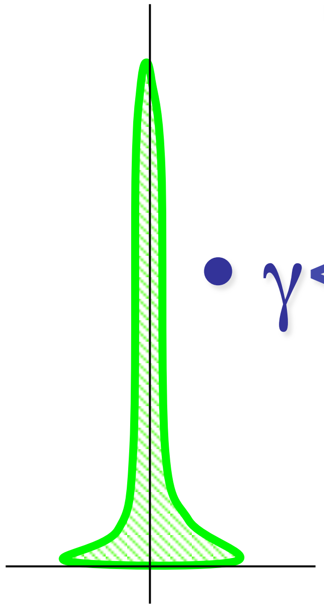
for $\gamma>1$ it is suppressed → *isolated massive stars*

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

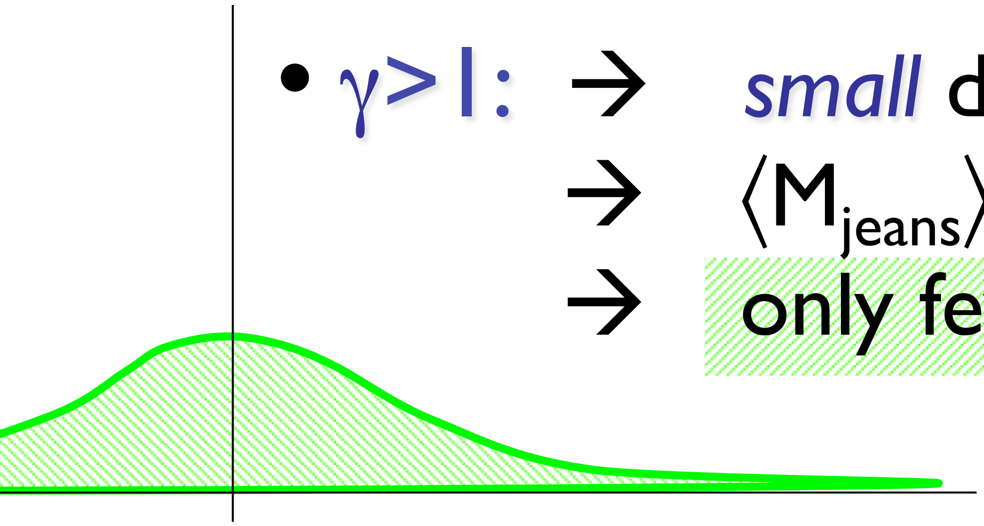
how does that work?

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

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

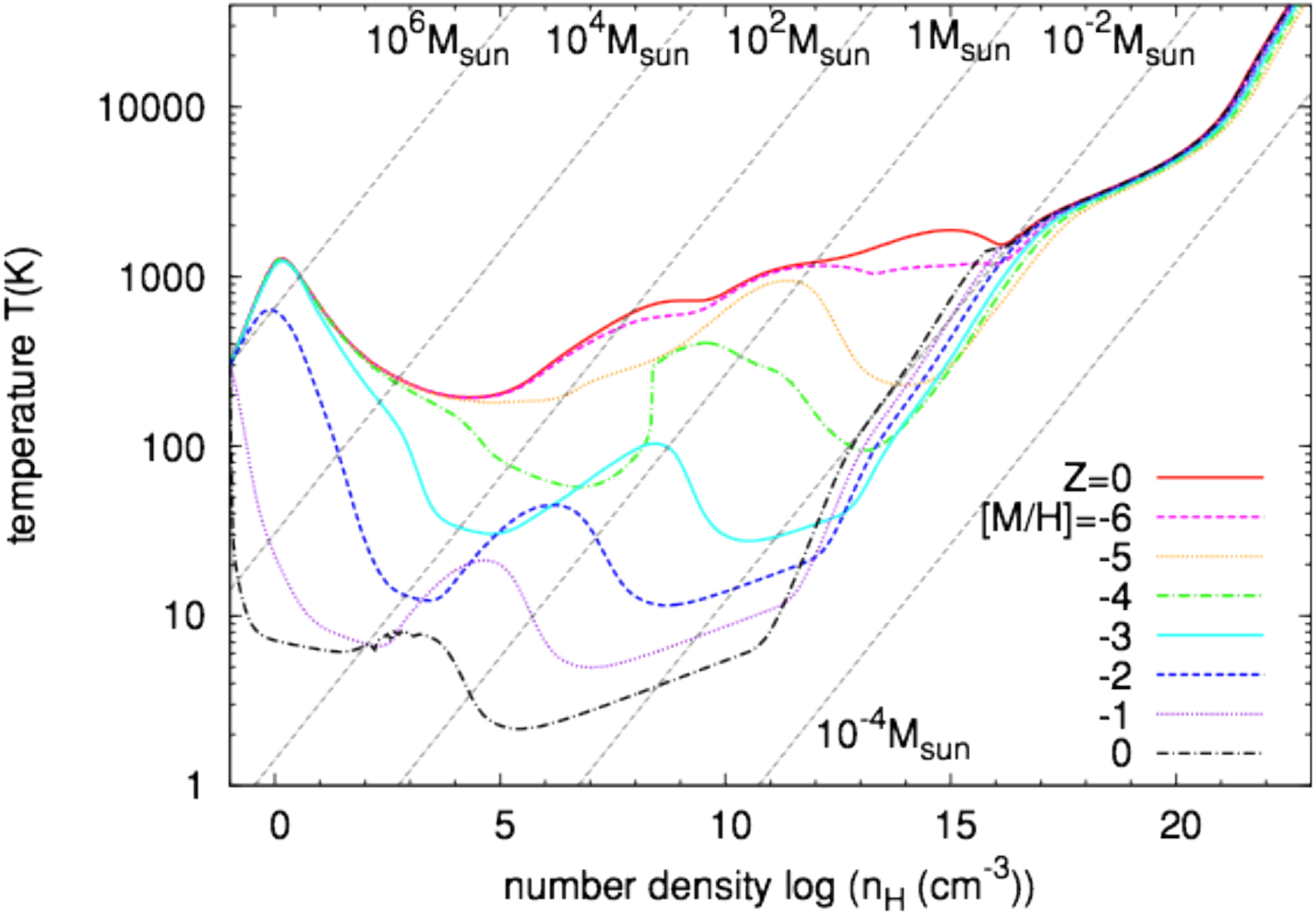


- $\gamma<1$: → *large* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ becomes small
  → number of fluctuations with $M > M_{jeans}$ is large



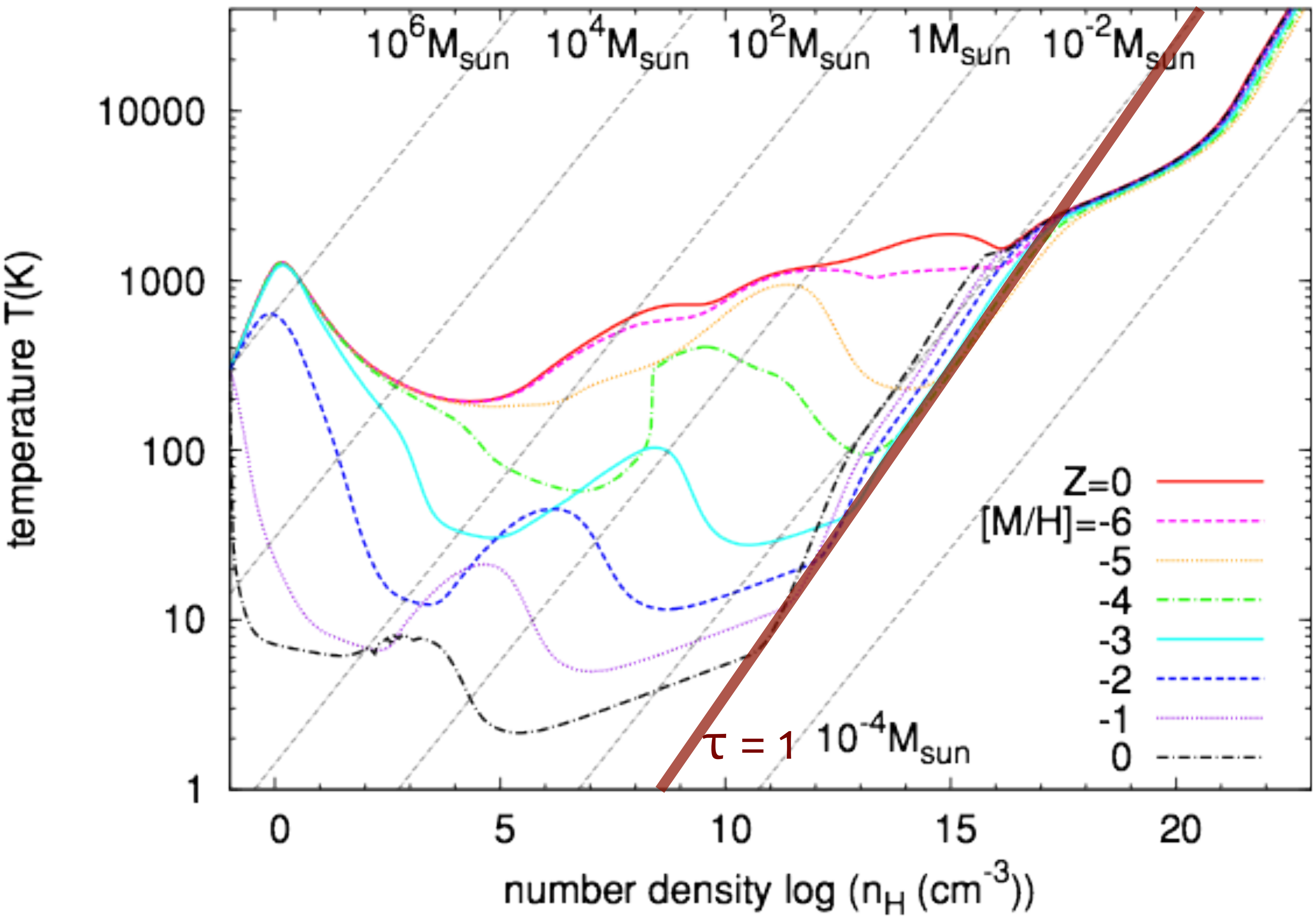
- $\gamma>1$: → *small* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ is large
  → only few and massive clumps exceed M_{jeans}

EOS as function of metallicity



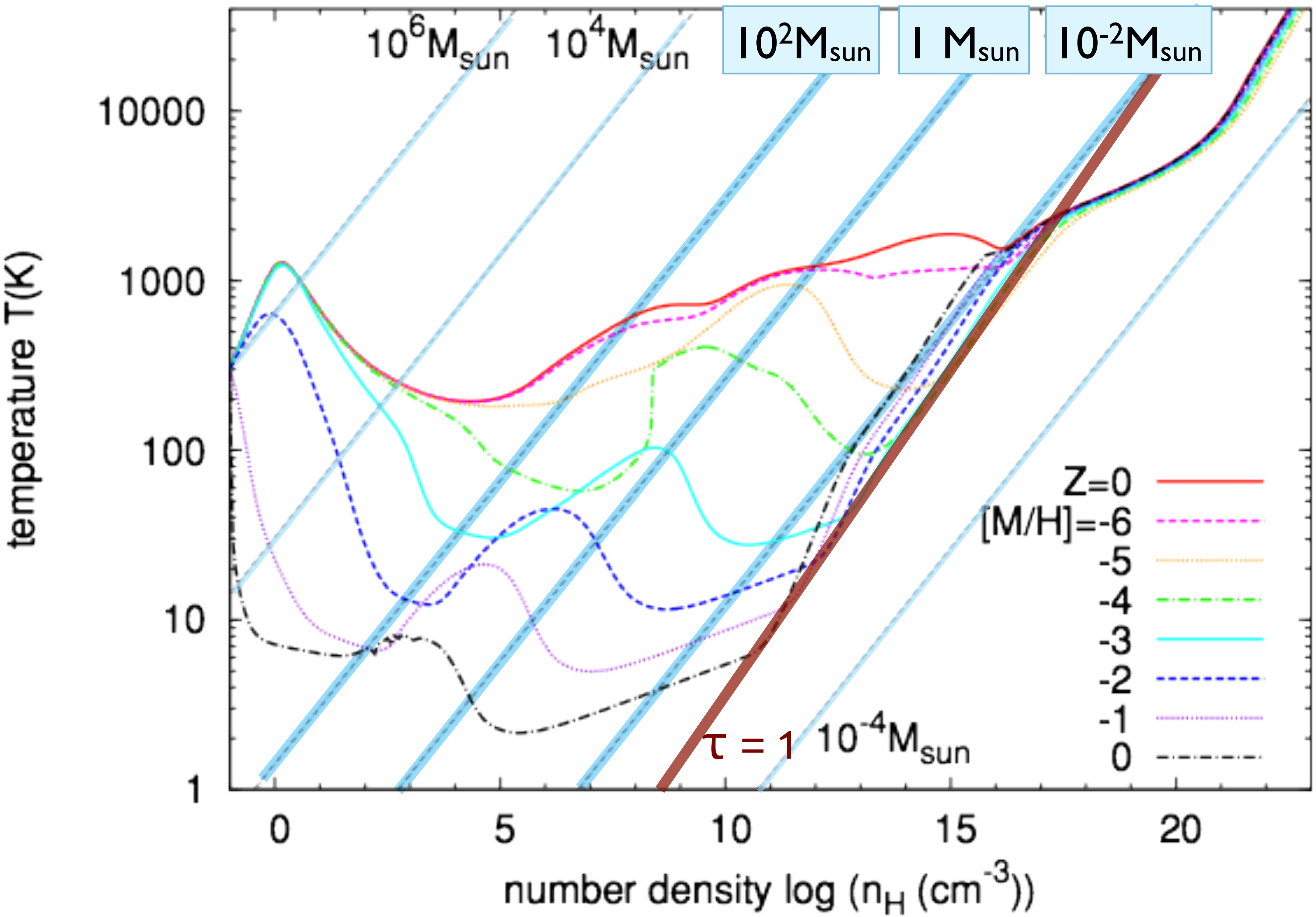
(Omukai et al. 2005, 2010)

EOS as function of metallicity



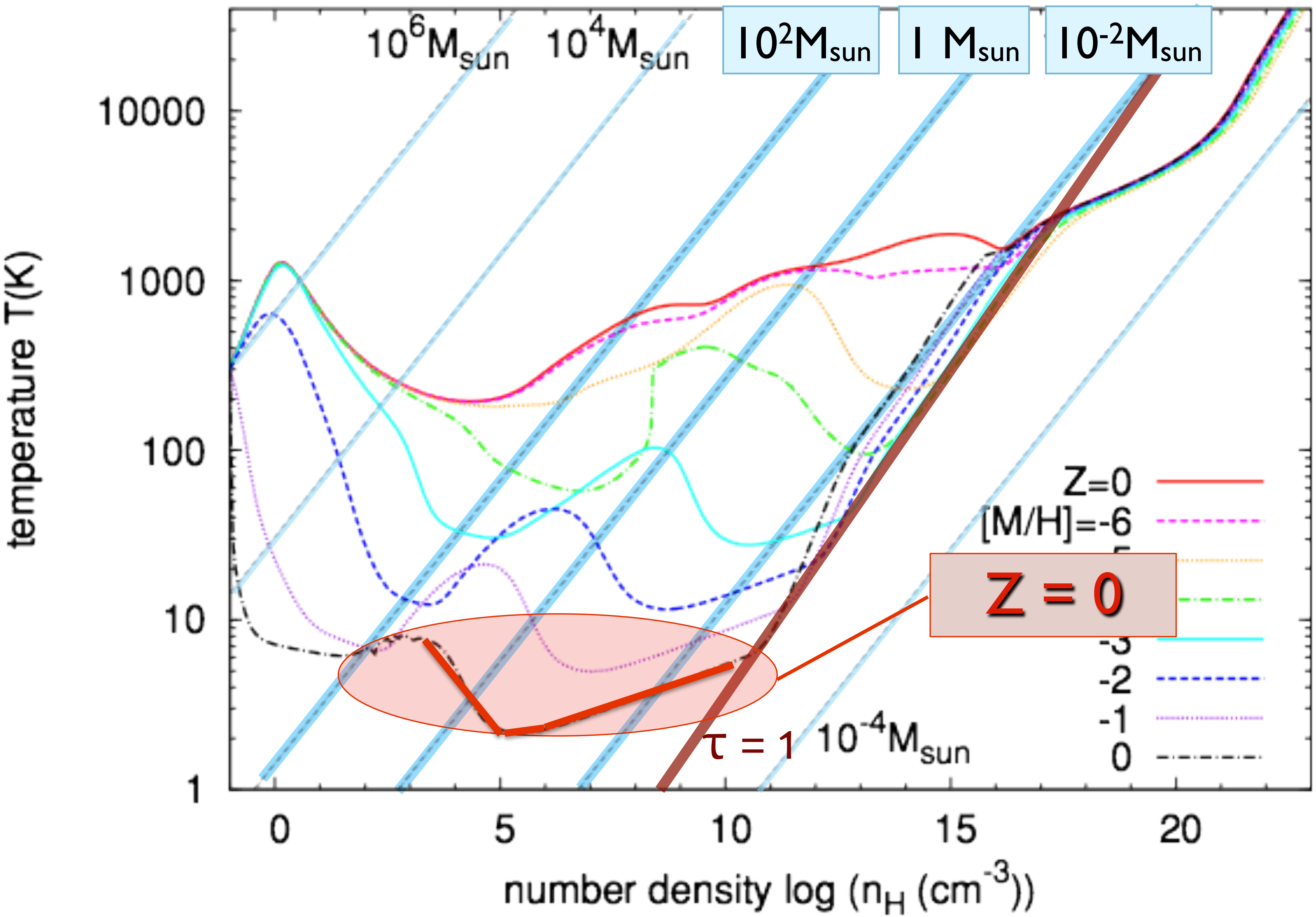
(Omukai et al. 2005, 2010)

EOS as function of metallicity



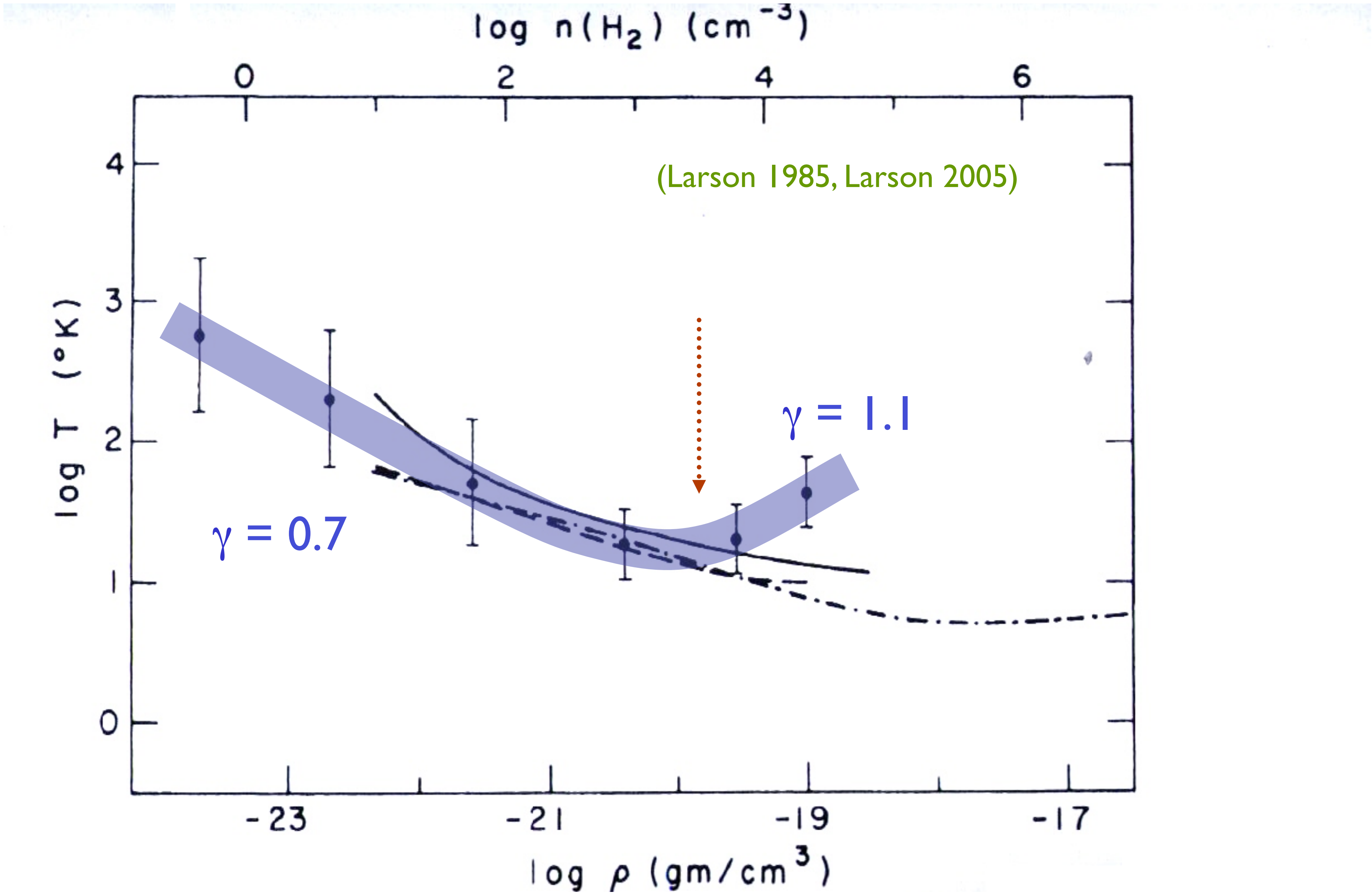
(Omukai et al. 2005, 2010)

EOS as function of metallicity

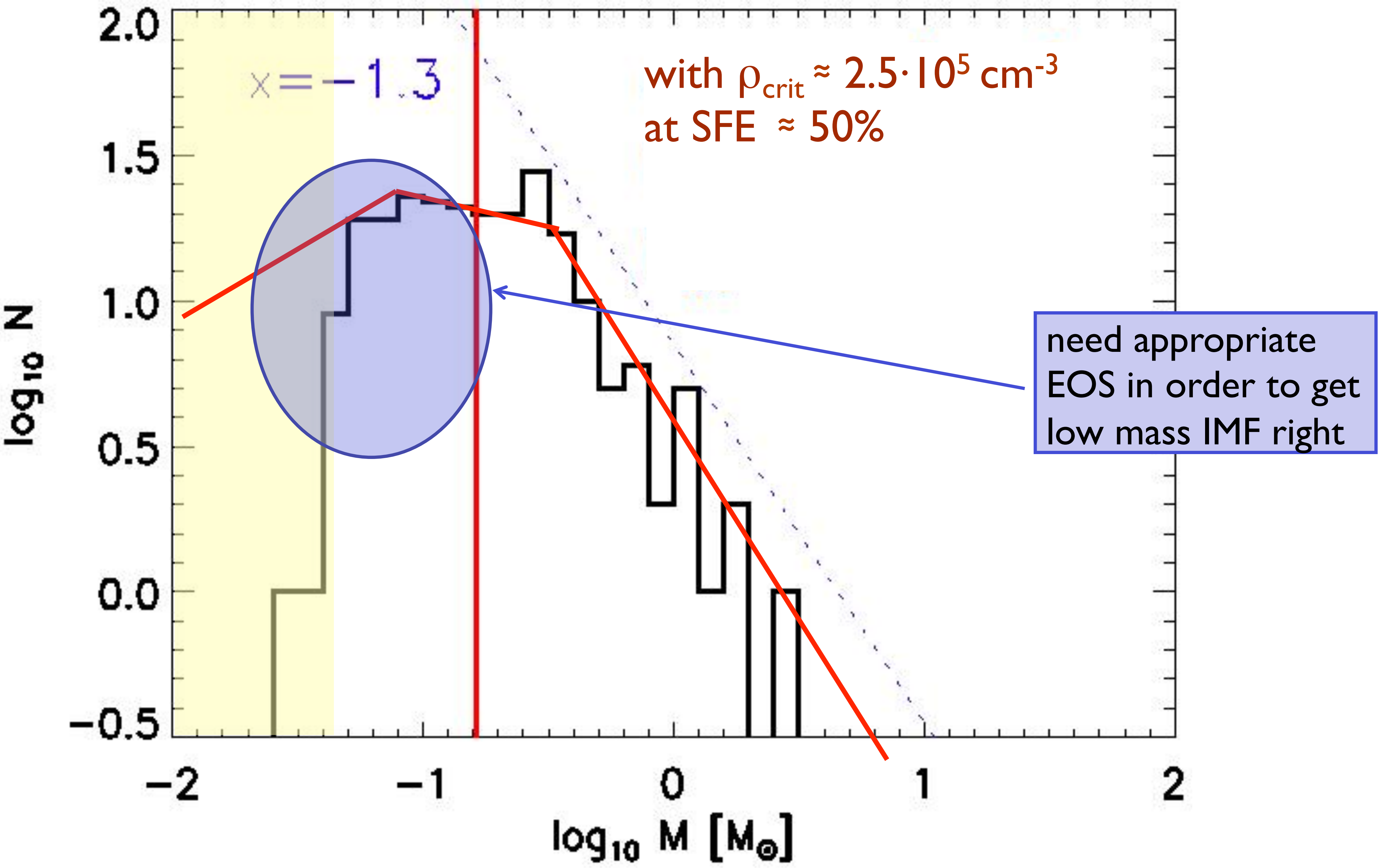


(Omukai et al. 2005, 2010)

present-day star formation



IMF in nearby molecular clouds

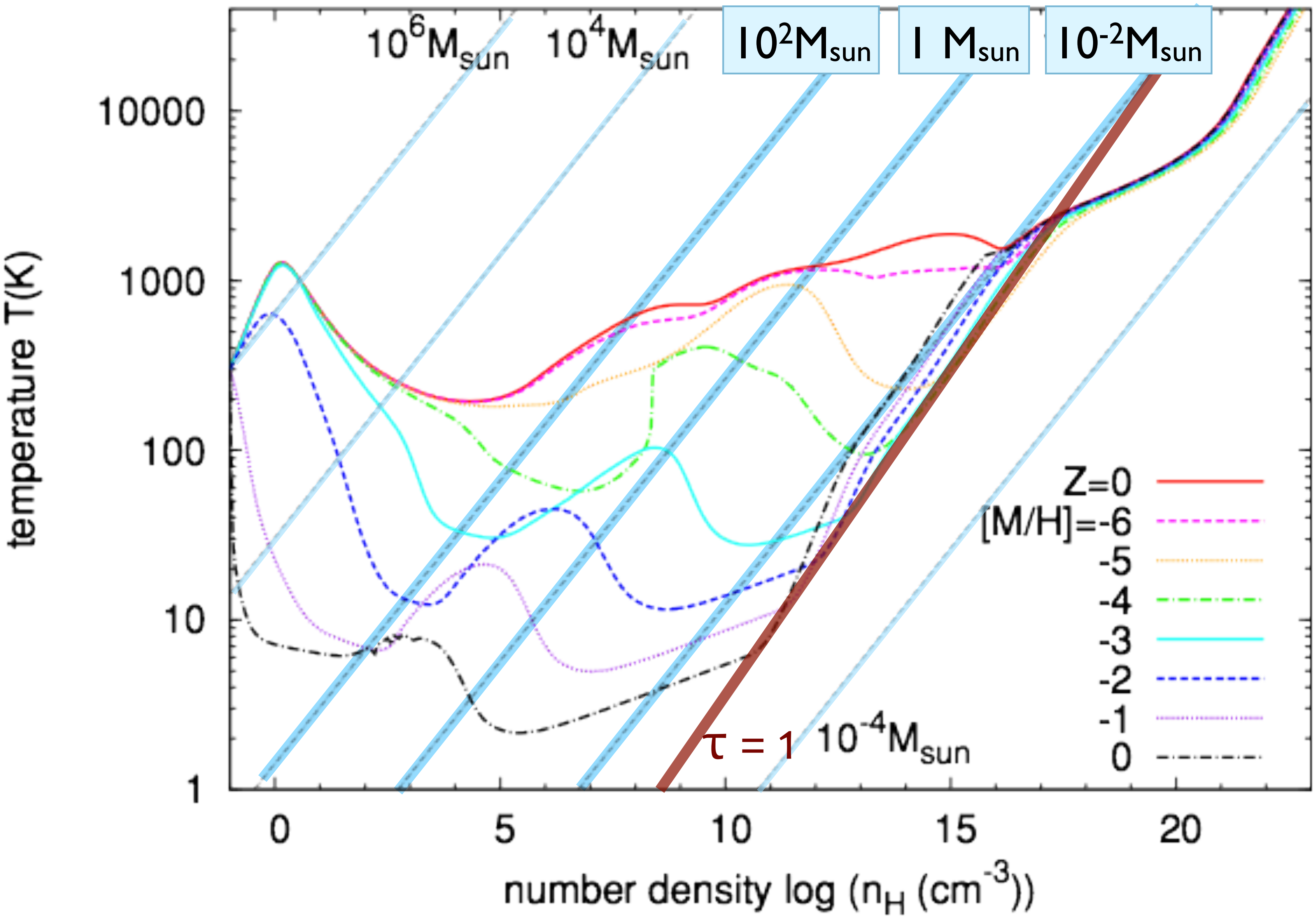


with $\rho_{crit} \approx 2.5 \cdot 10^5$ cm^{-3}
at SFE ≈ 50%

need appropriate EOS in order to get low mass IMF right

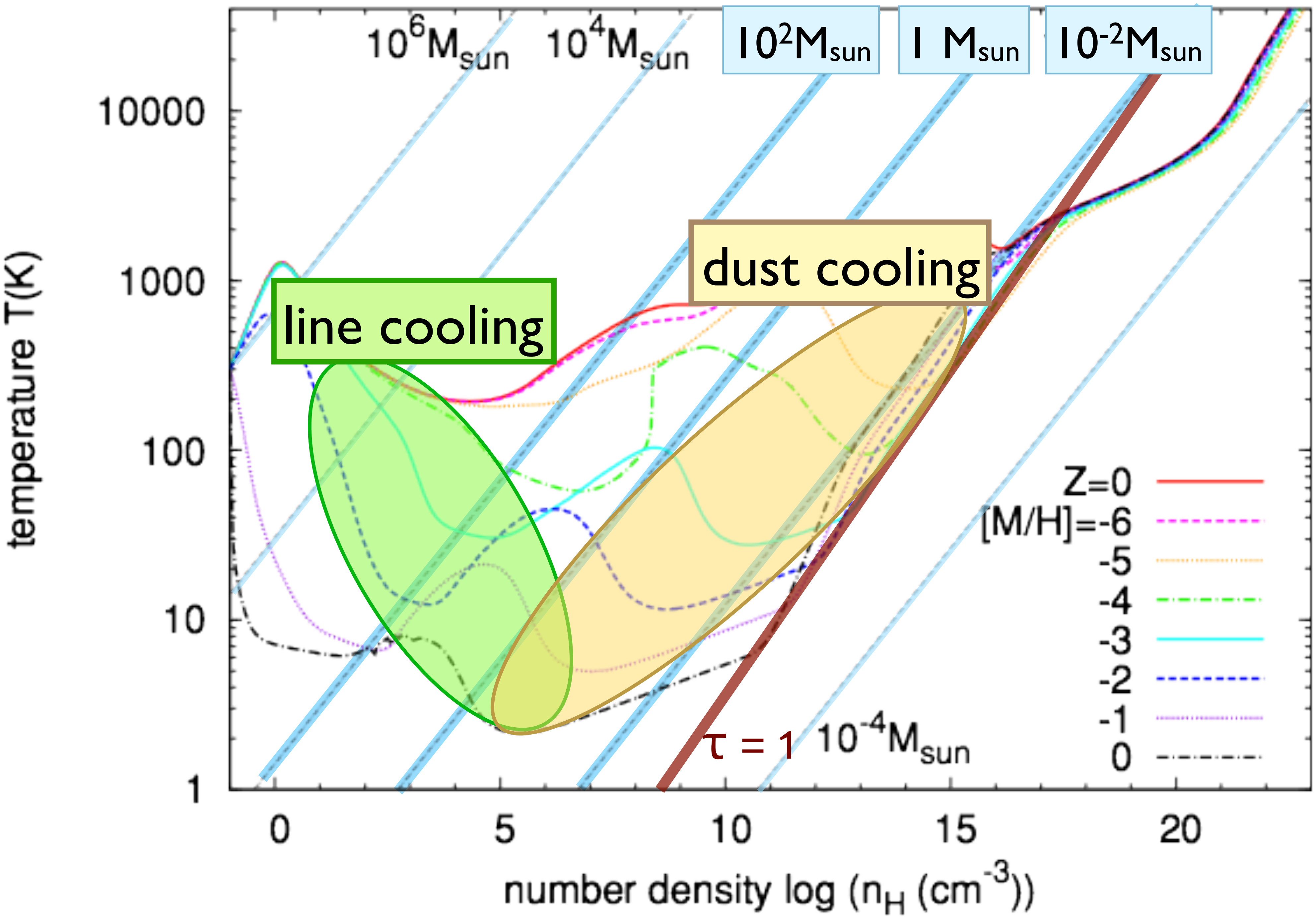
(Jappsen et al. 2005, A&A, 435, 611)

EOS as function of metallicity



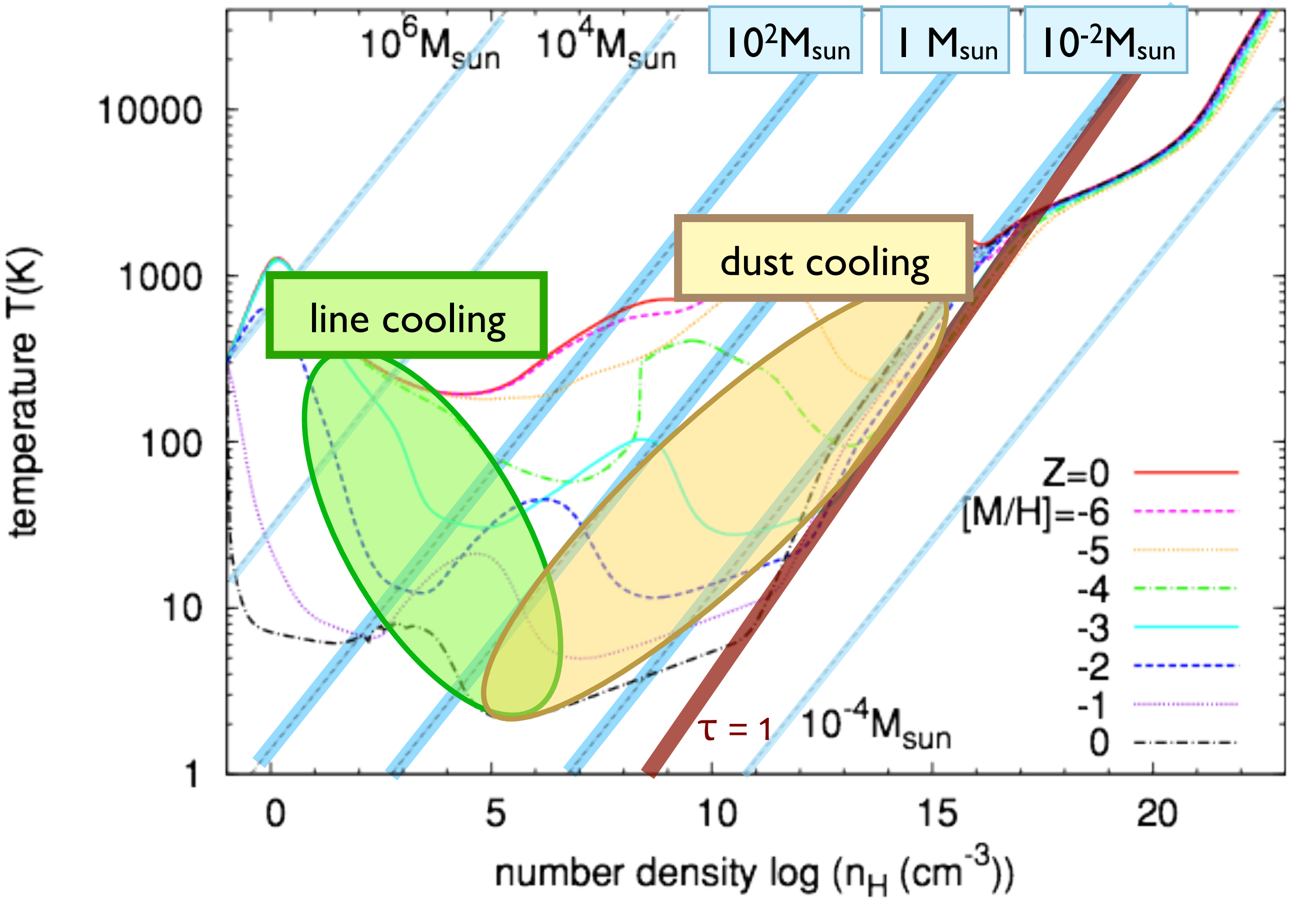
(Omukai et al. 2005, 2010)

EOS as function of metallicity



(Omukai et al. 2005, 2010)

transition: Pop III to Pop II.5



(Omukai et al. 2005, 2010)

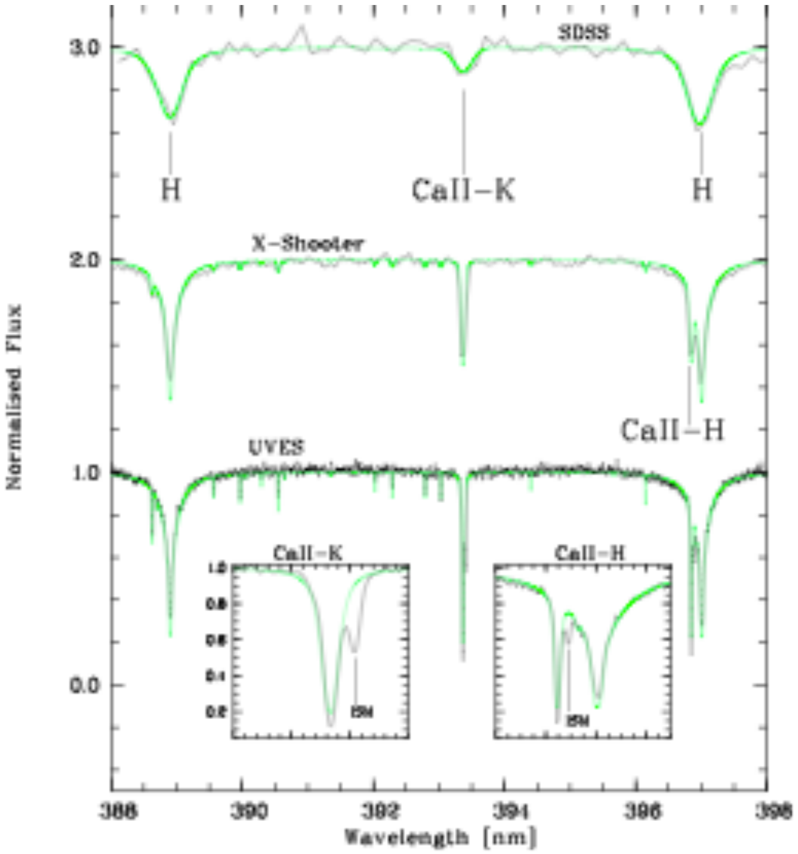
two competing models:

- 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 $Z \sim 10^{-4.5} Z_{sun}$ 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]

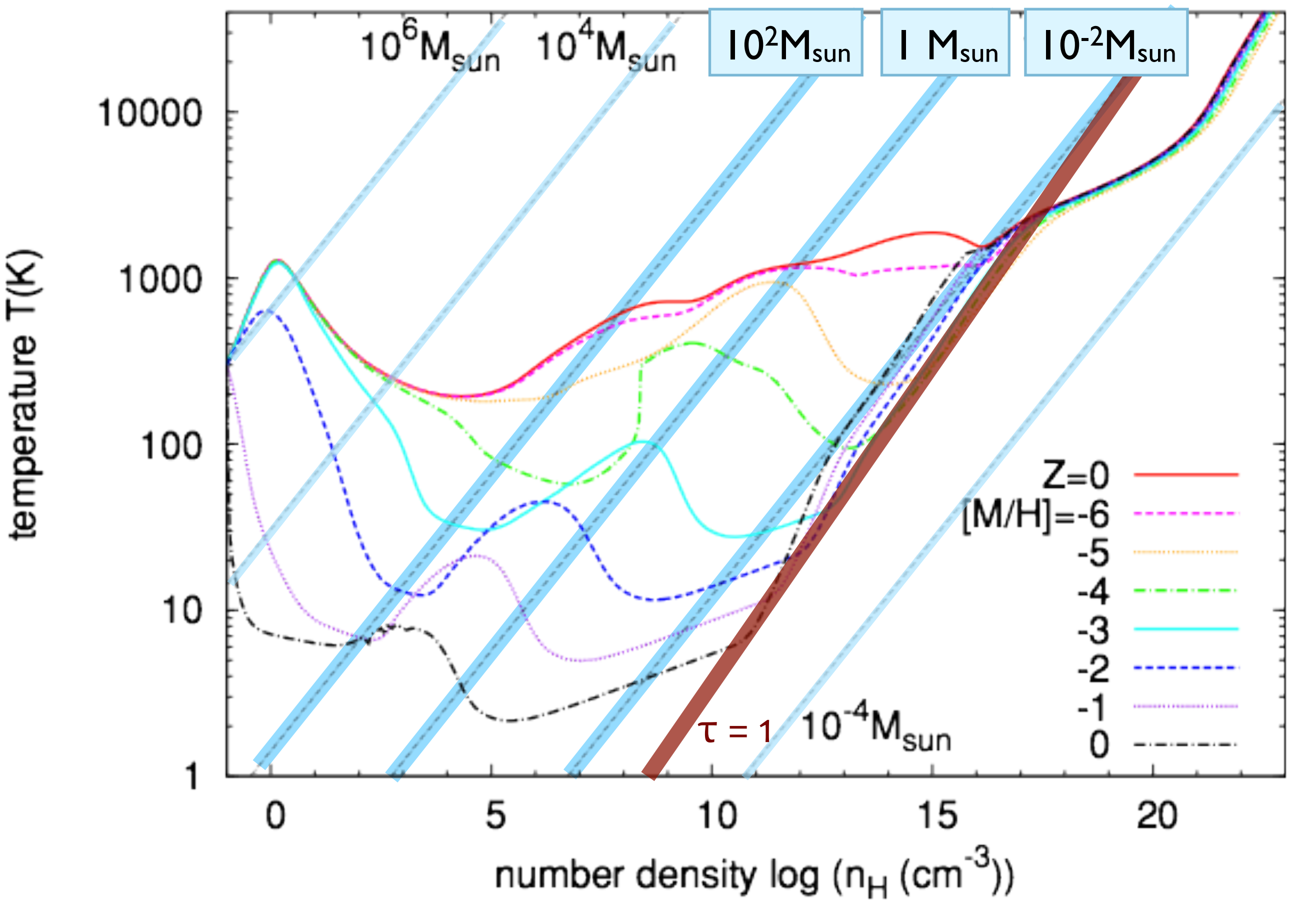
Element	$[X/H]_{1D}$	+3Dcor.	+NLTE cor.	+ 3D cor + NLTE cor	N lines	S_H	$A(X)_\odot$
C	≤ -3.8	≤ -4.5			G-band		8.50
N	≤ -4.1	≤ -5.0			NH-band		7.86
Mg I	-4.71 ± 0.11	-4.68 ± 0.11	-4.52 ± 0.11	-4.49 ± 0.12	5	0.1	7.54
Si I	-4.27	-4.30	-3.93	-3.96	1	0.1	7.52
Ca I	-4.72	-4.82	-4.44	-4.54	1	0.1	6.33
Ca II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

(Caffau et al. 2011, 2012)

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

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

transition: Pop III to Pop II.5

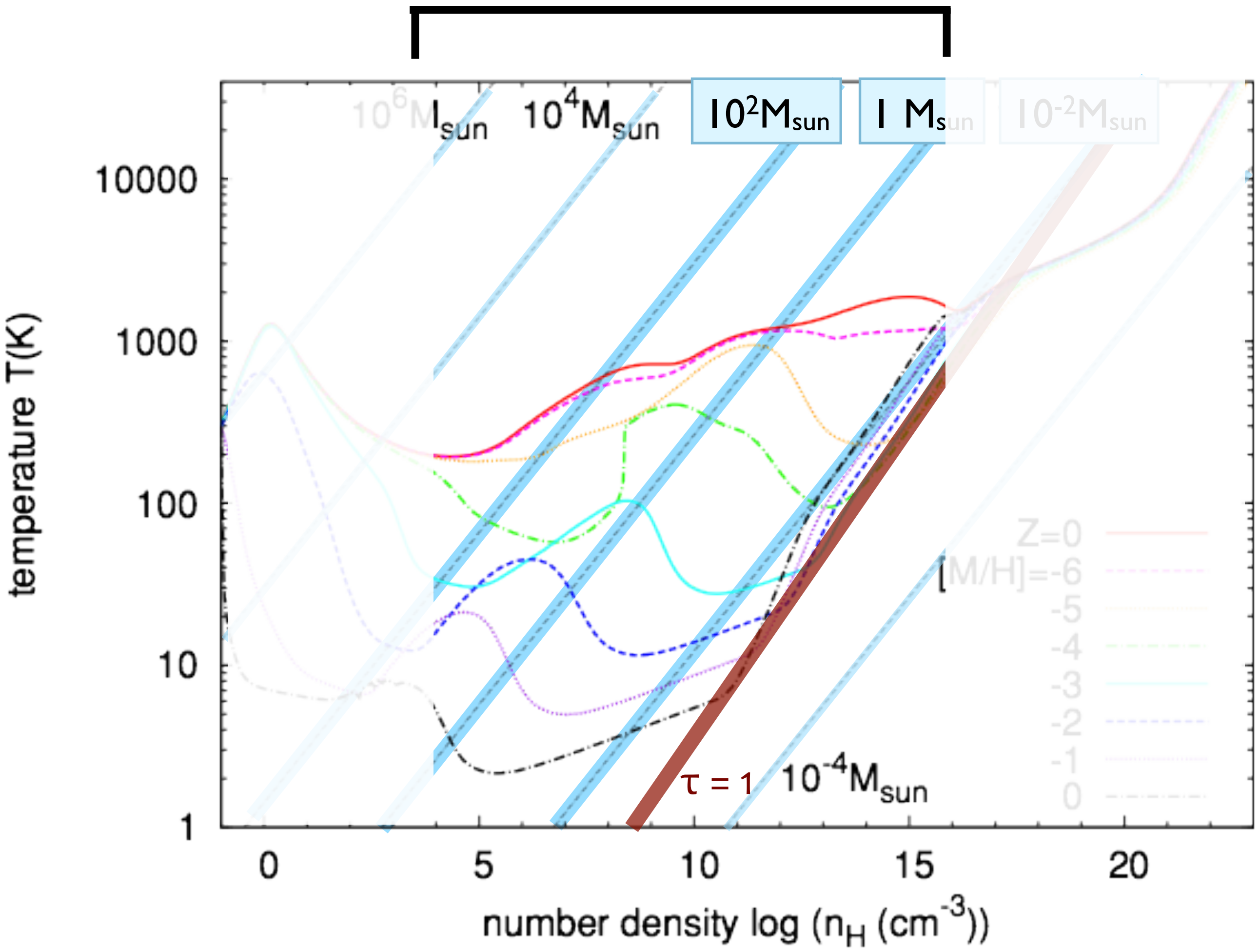


approach problem with high-resolution hydrodynamic calculations of central parts of high-redshift halos

- SPH (40 million particles)
- time-dependent chemistry (with dust)
- sink particles to model star formation
- external dark-matter potential

(Omukai et al. 2005, 2010)

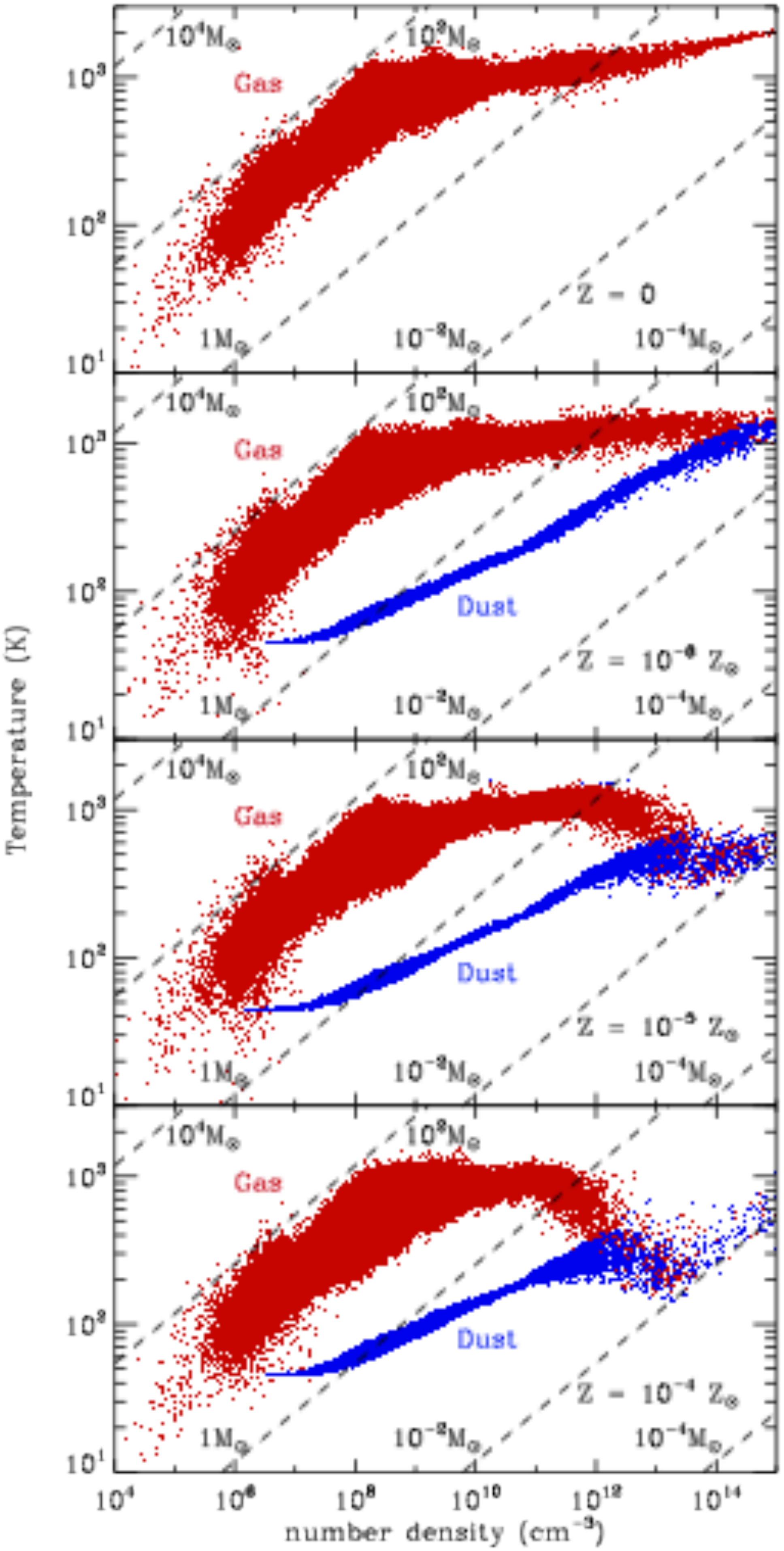
transition: Pop III to Pop II.5



approach problem with high-resolution hydrodynamic calculations of central parts of high-redshift halos

- SPH (40 million particles)
- time-dependent chemistry (with dust)
- sink particles to model star formation
- external dark-matter potential
- focus on relevant density regime
(i.e. include dust dip and optically thick regime)

(Omukai et al. 2005, 2010)



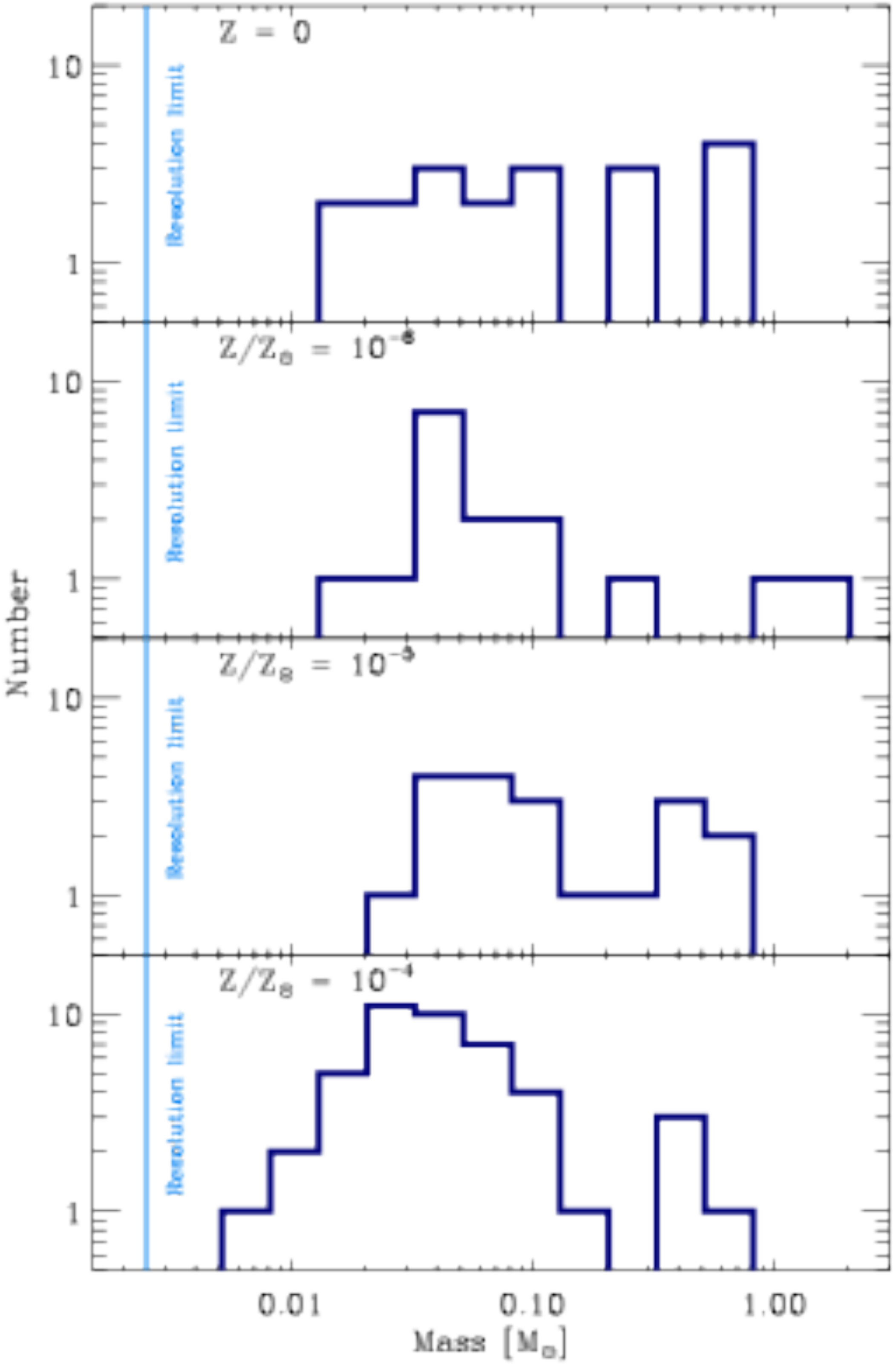
[M/H] = -ininity

[M/H] = -6

[M/H] = -5

[M/H] = -4

red : gas
blue: dust

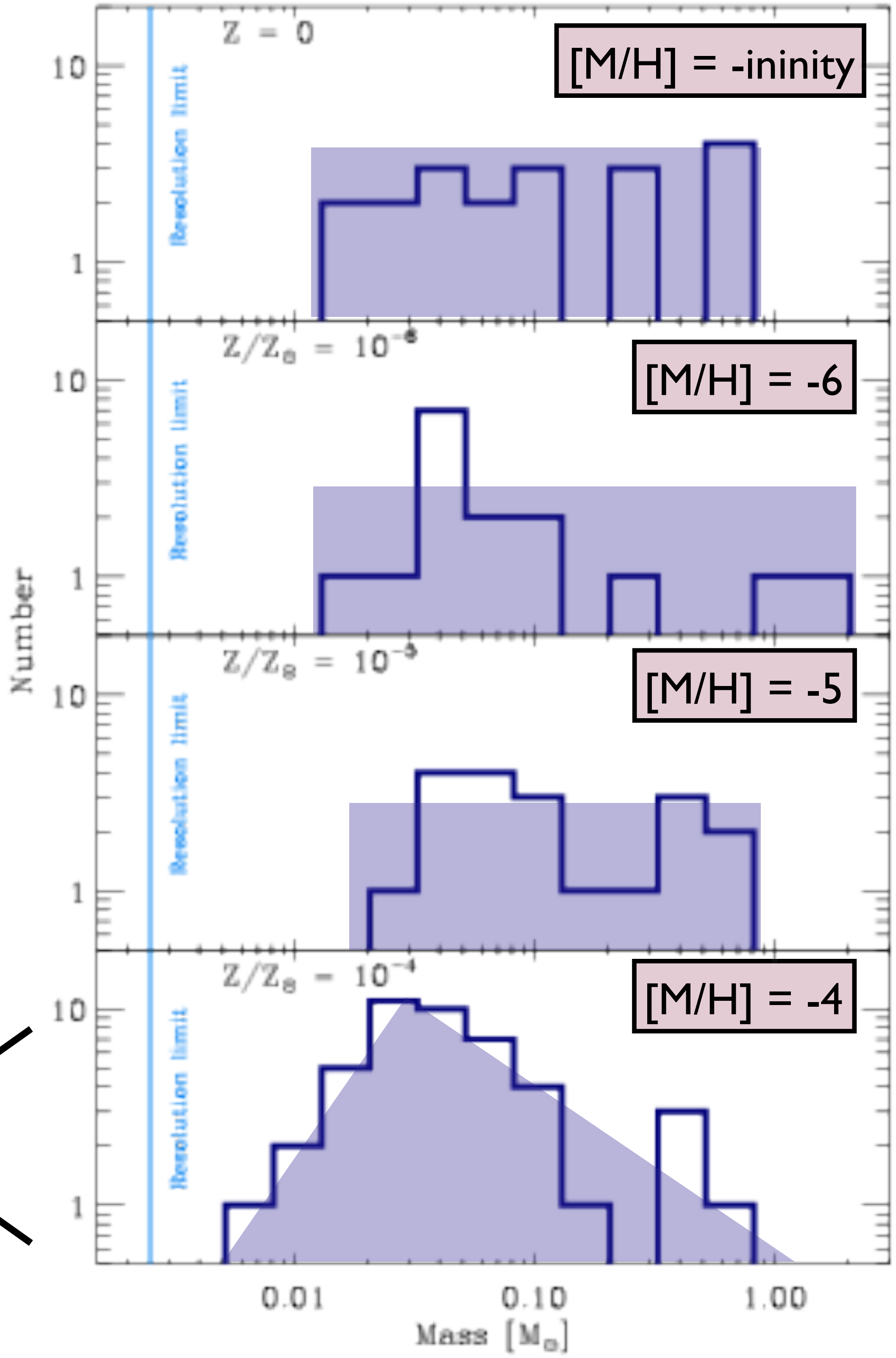


Dopcke et al., 2012, submitted to ApJ, arXiv:1203.6842)

hints for differences
in mass spectrum

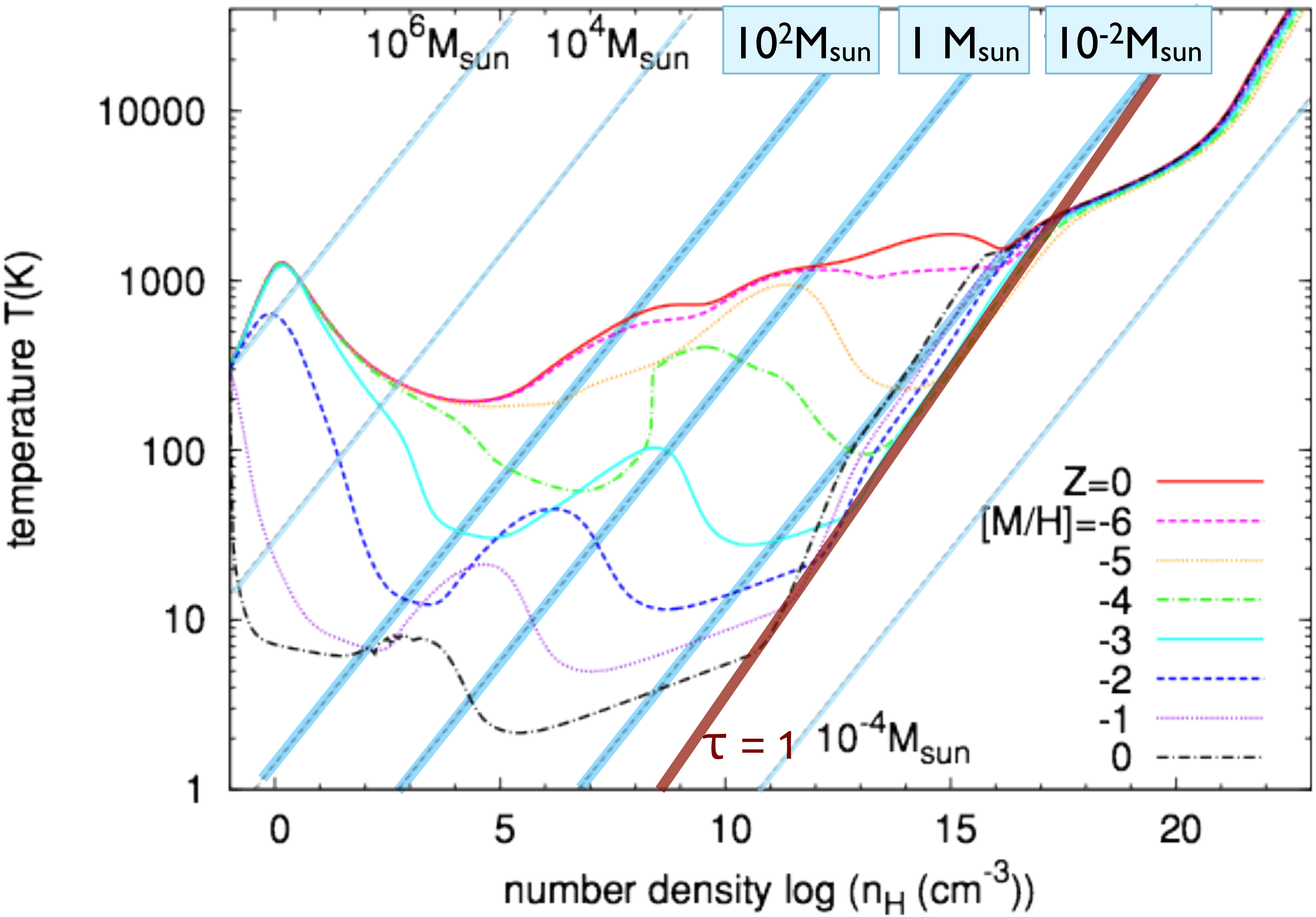
disk fragmentation mode

gravoturbulent fragmentation mode



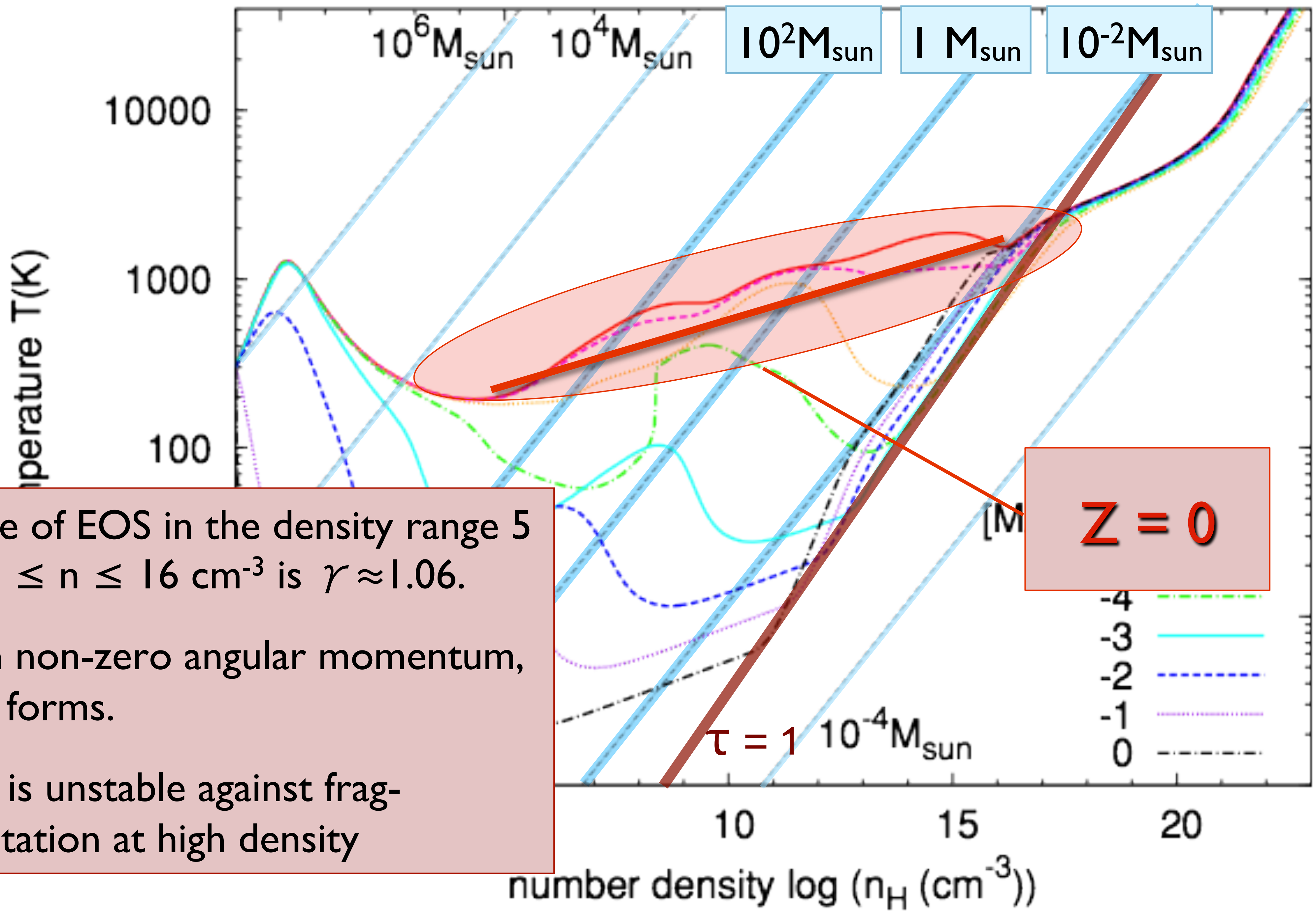
Dopcke et al., 2012, submitted to ApJ, arXiv:1203.6842)

EOS as function of metallicity



(Omukai et al. 2005, 2010)

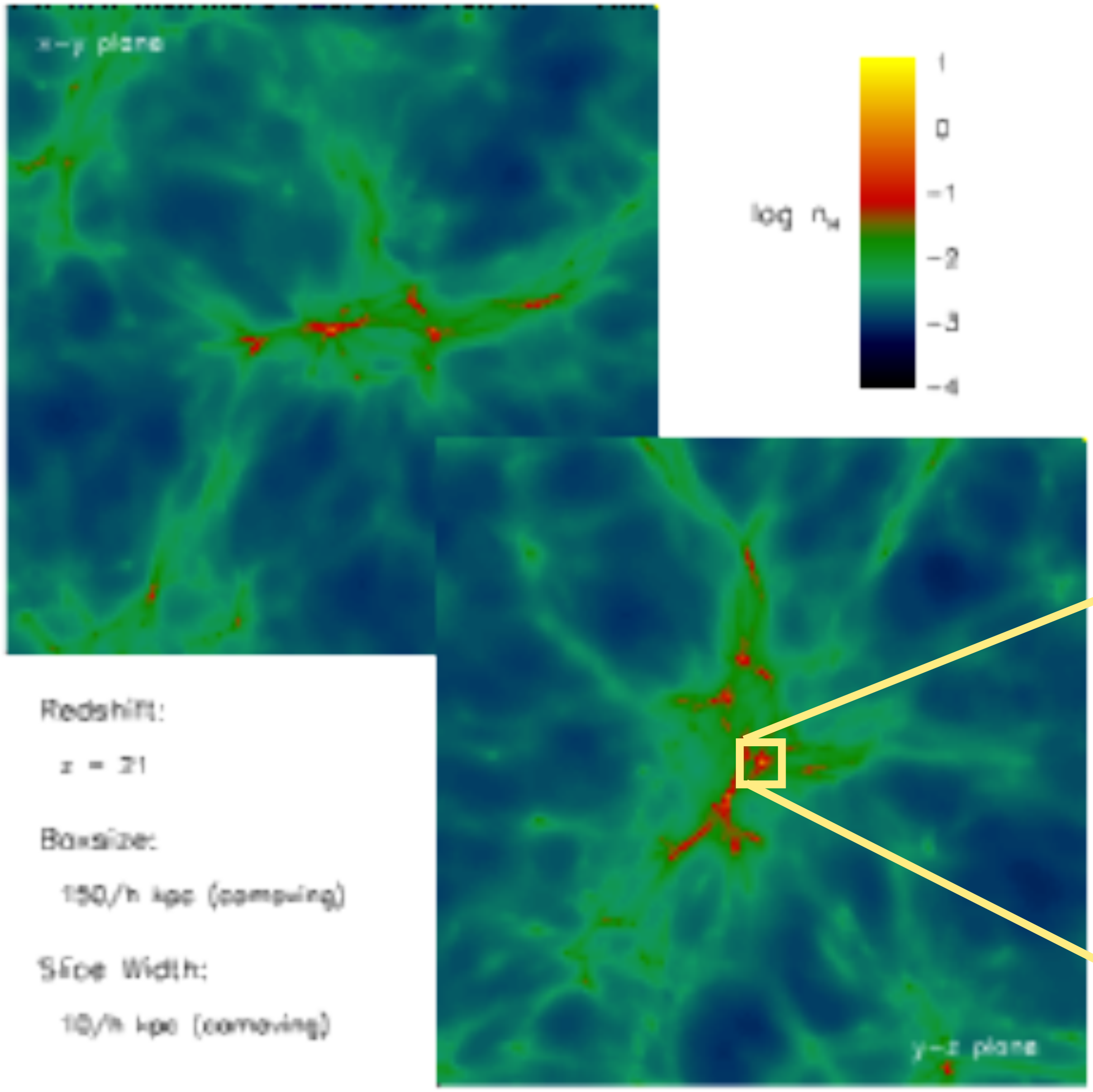
EOS as function of metallicity



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

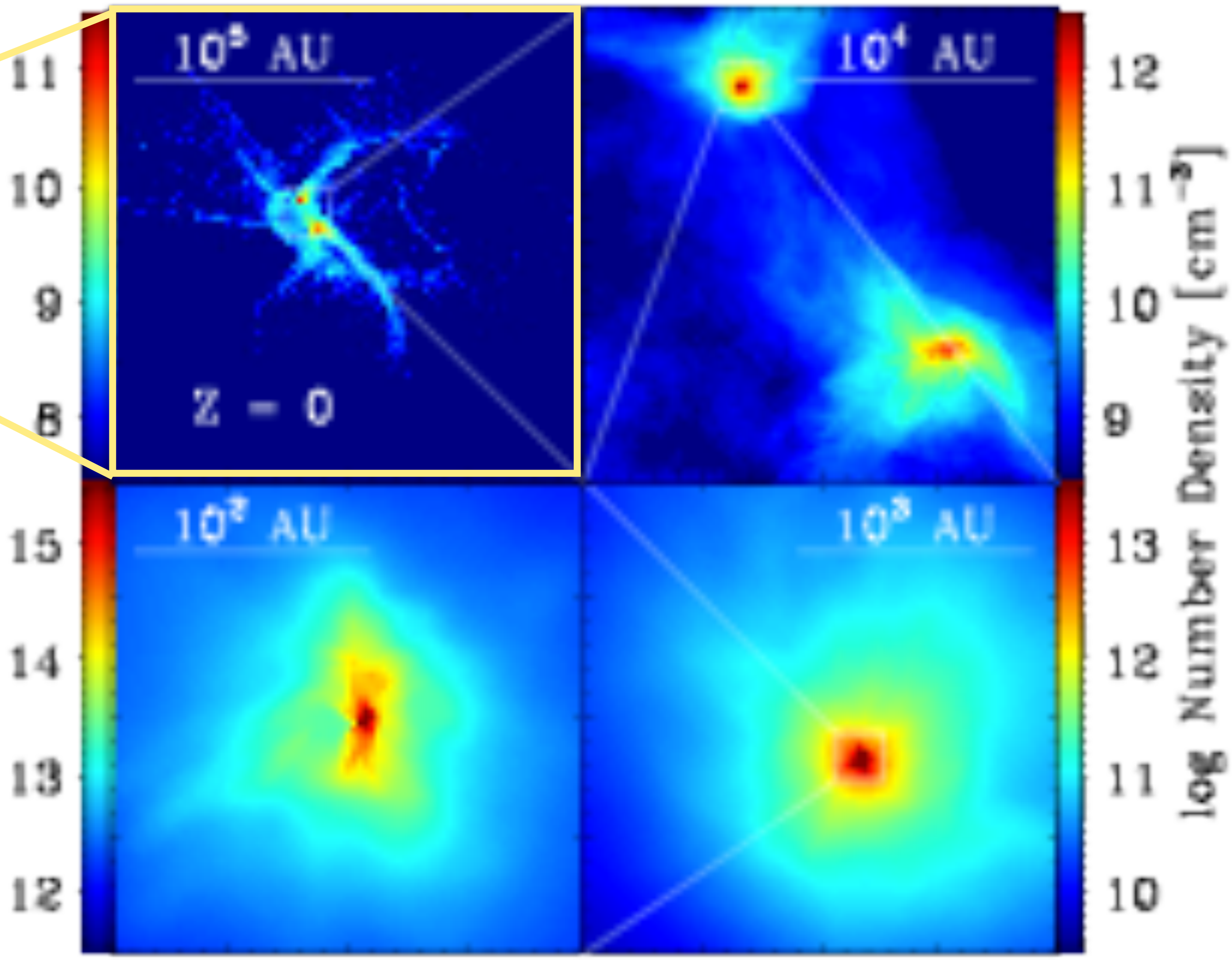
(Omukai et al. 2005, 2010)

model the formation of the first stars



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

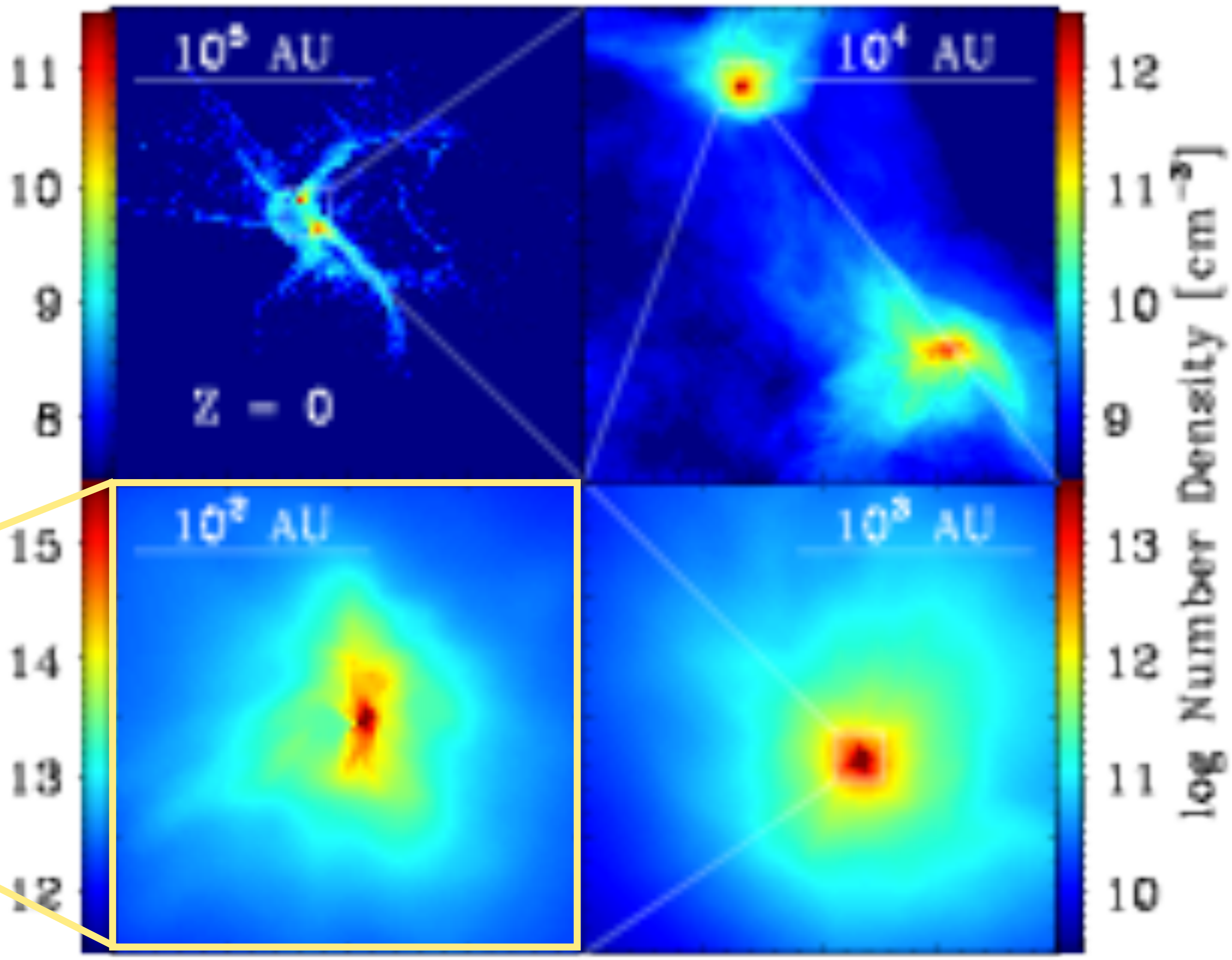
successive zoom-in calculation from cosmological initial conditions (using SPH and new grid-code AREPO)



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

detailed look at accretion disk around first star

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



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

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

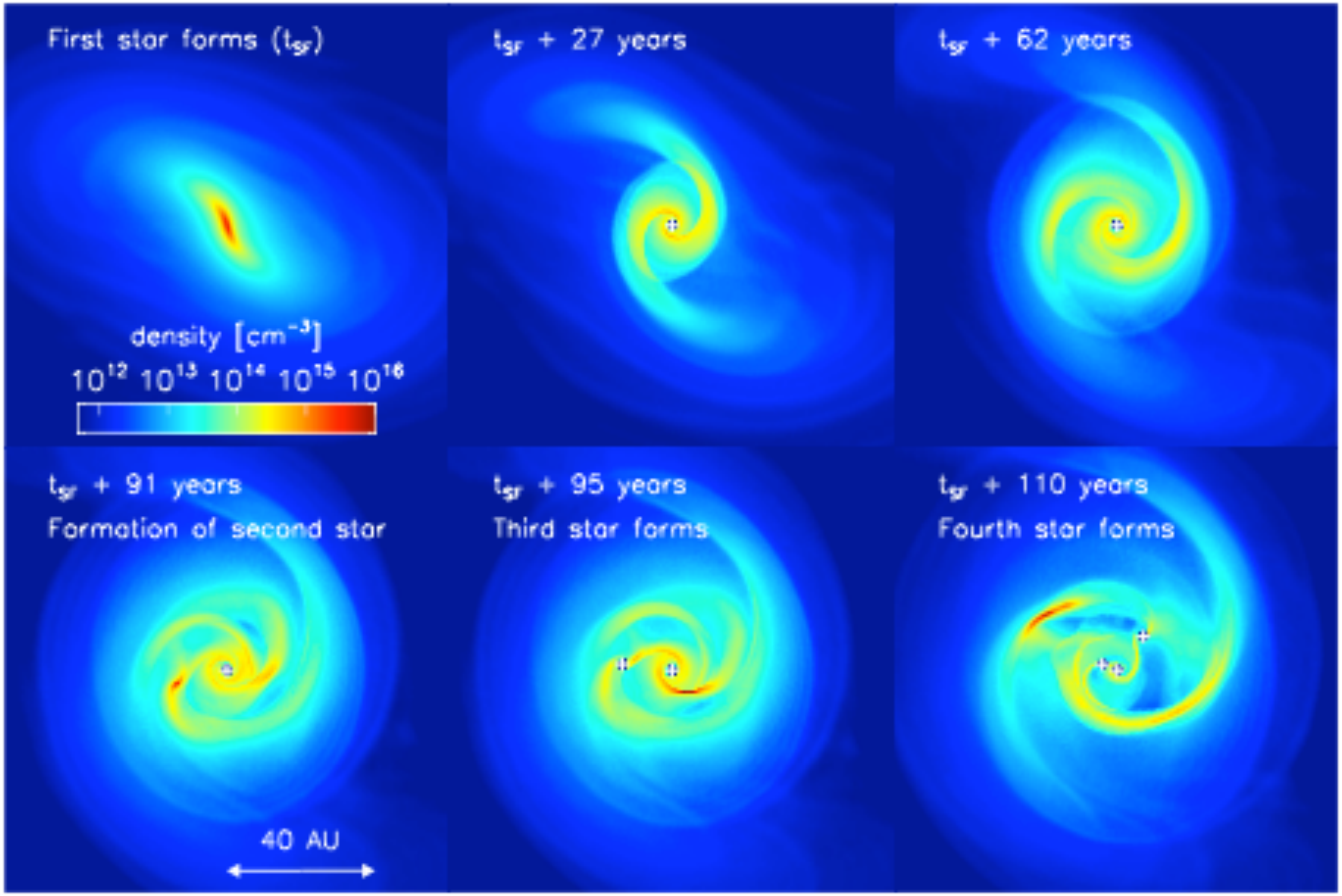
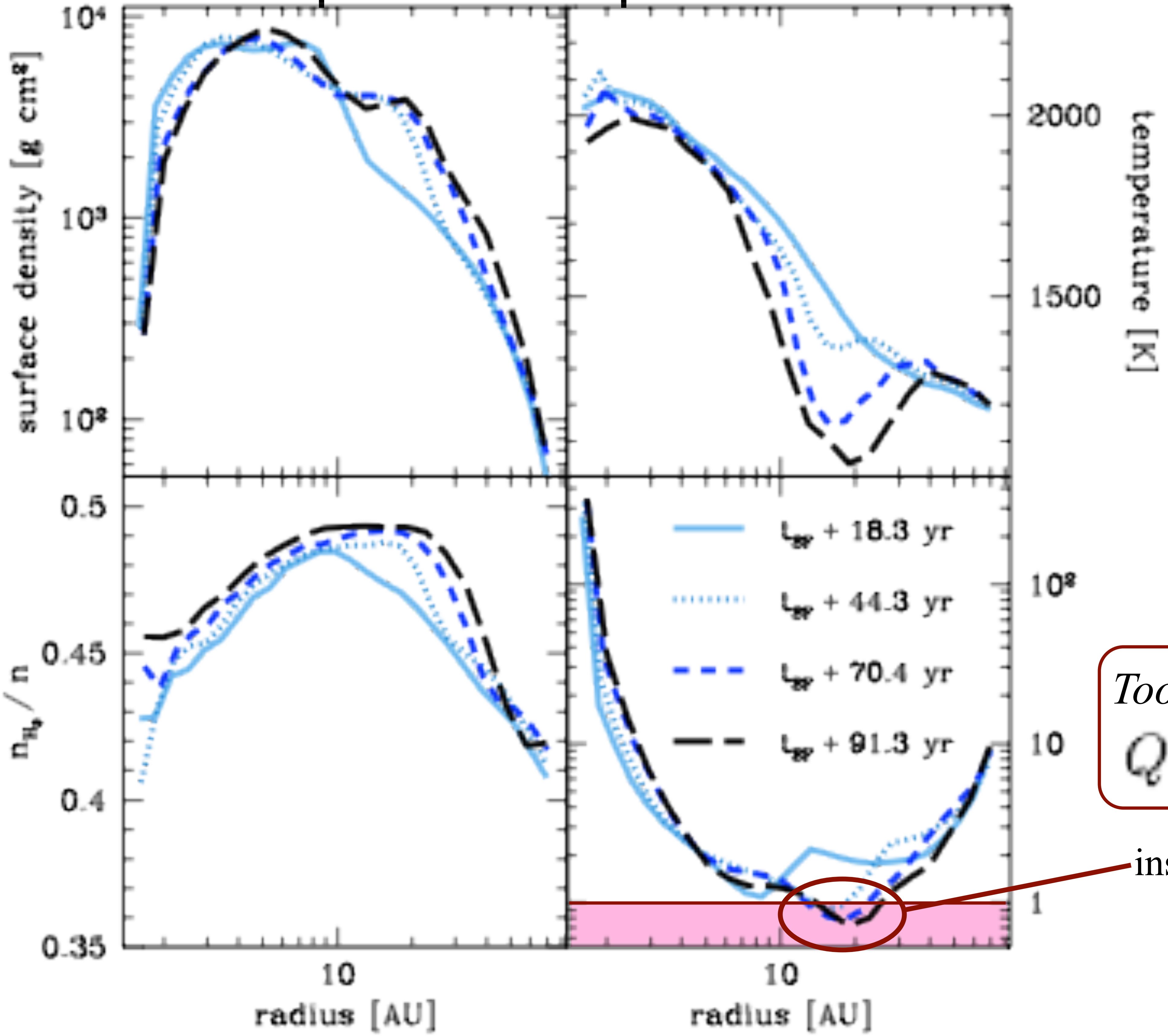


Figure 1: Density evolution in a 120 AU region around the first protostar, showing the build-up of the protostellar disk and its eventual fragmentation. We also see 'wakes' in the low-density regions, produced by the previous passage of the spiral arms.

detailed look at accretion disk

(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)

comparison of all relevant heating and cooling processes

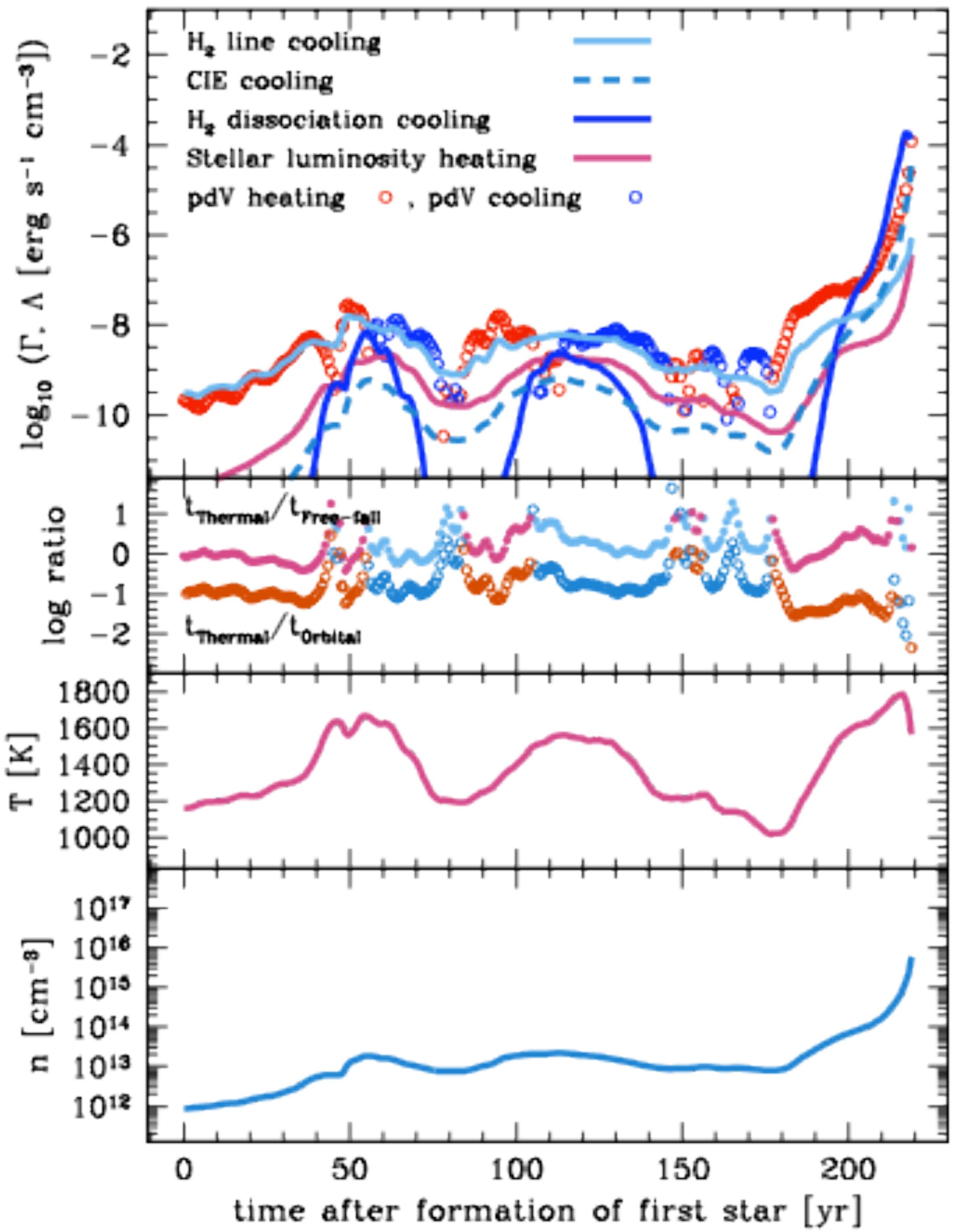
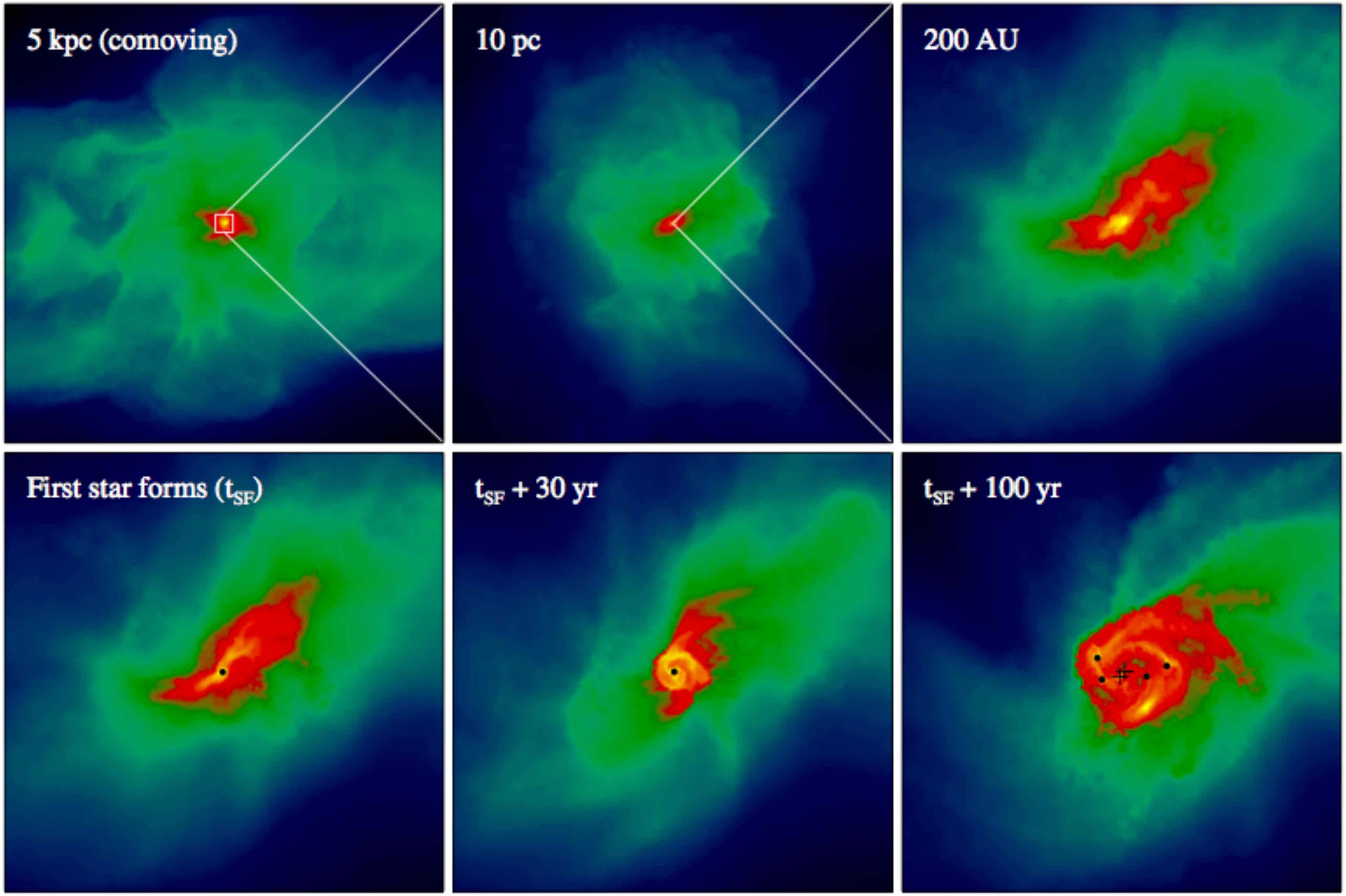


Figure 7: (a) Dominant heating and cooling processes in the gas that forms the second sink particle. (b) Upper line: ratio of the thermal timescale, $t_{\rm thermal}$, to the free-fall timescale, $t_{\rm ff}$, for the gas that forms the second sink particle. Periods when the gas is cooling are indicated 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)

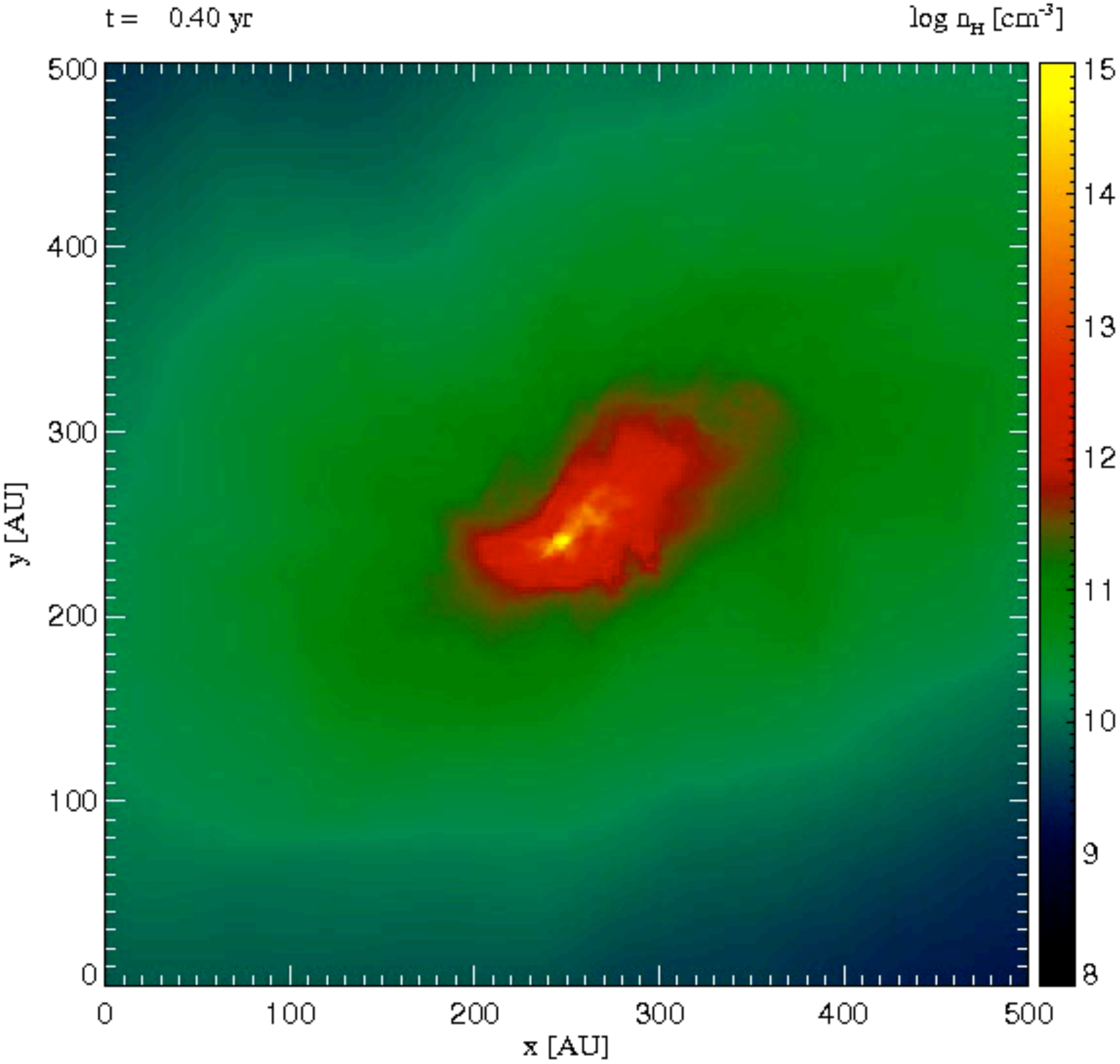
similar study with very different numerical method (AREPO)



one out of five halos

(Greif et al. 2011a, ApJ)

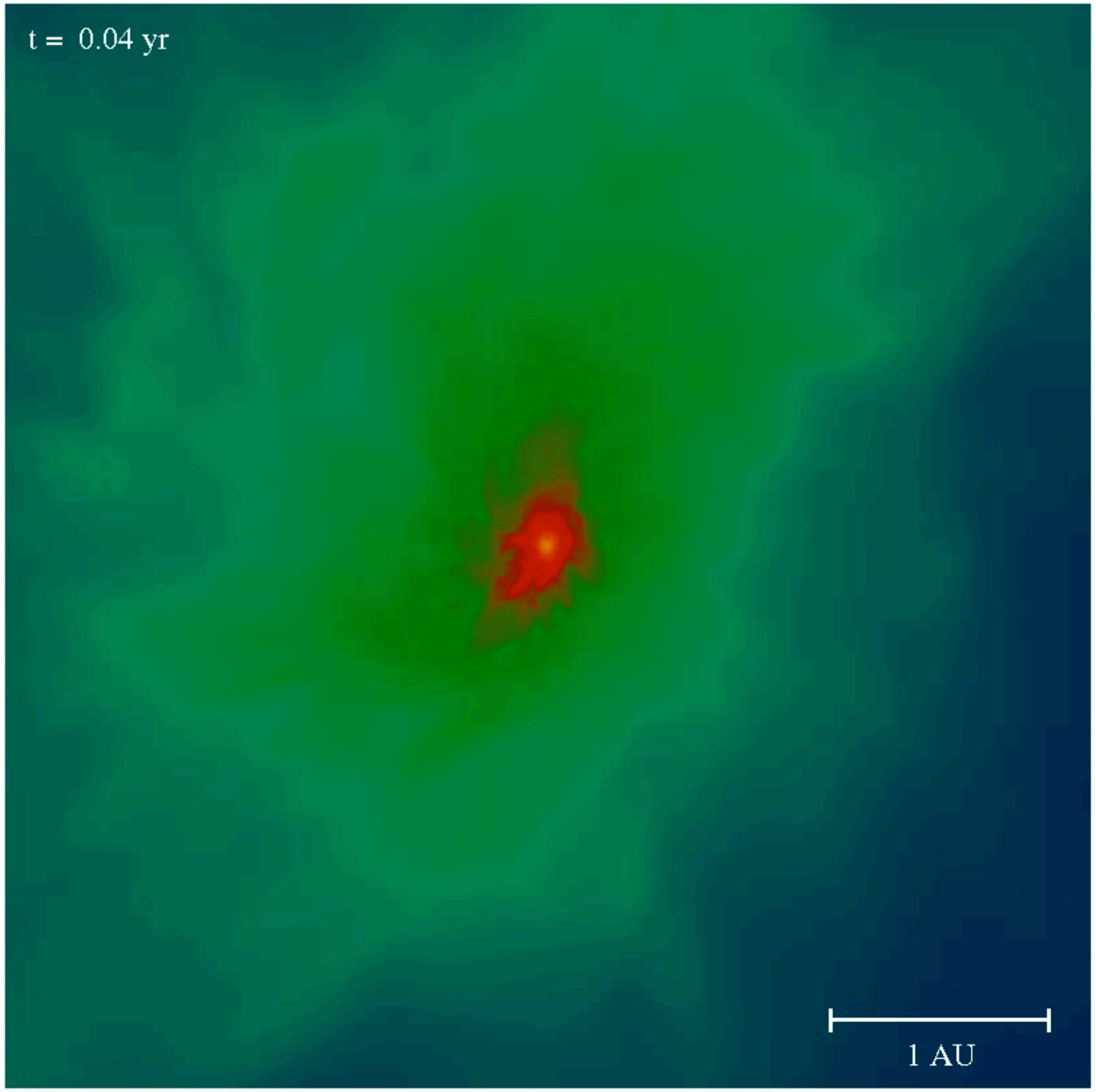
similar study with very different numerical method (AREPO)



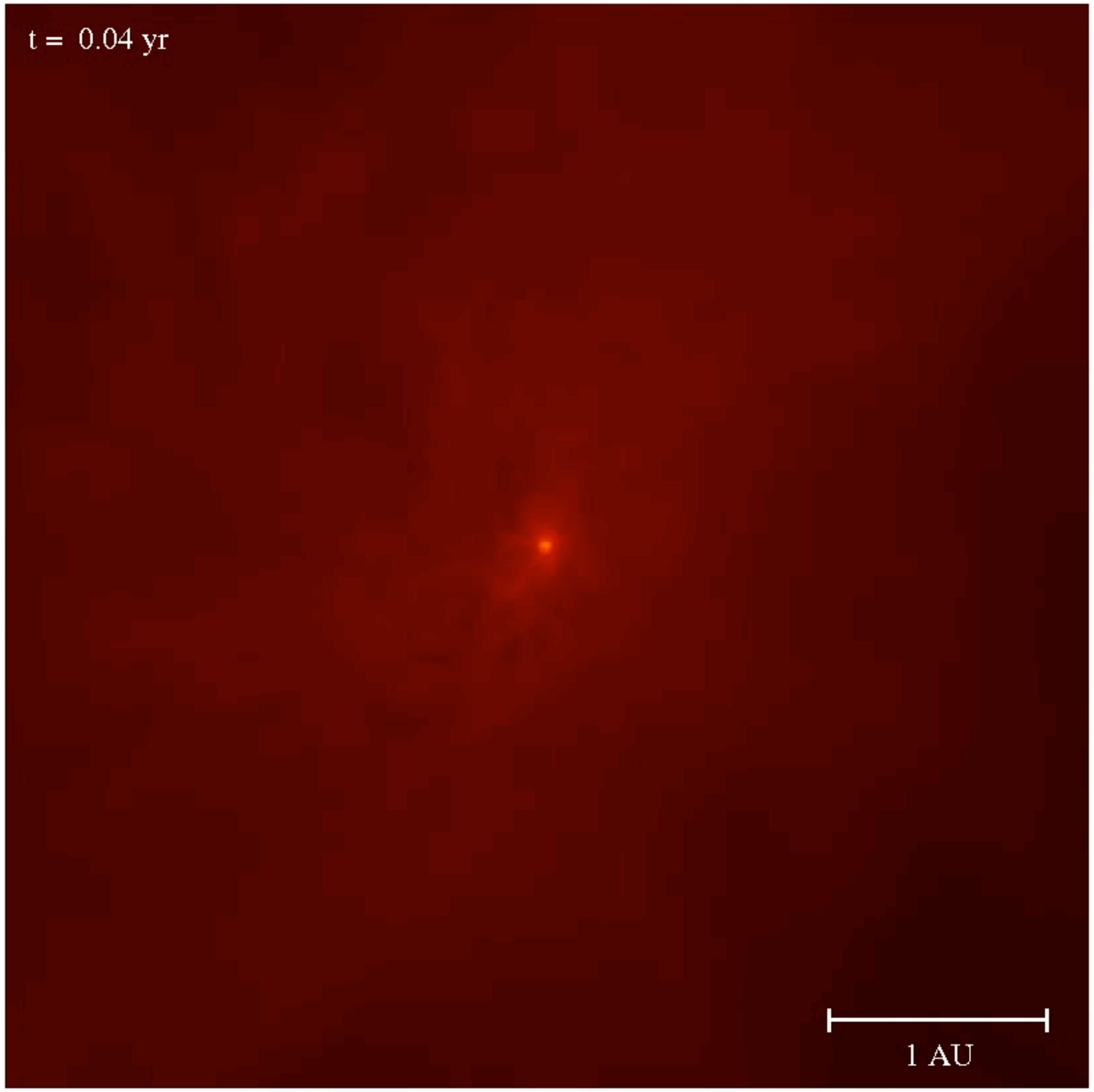
(Greif et al. 2011, ApJ, 737, 75)

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

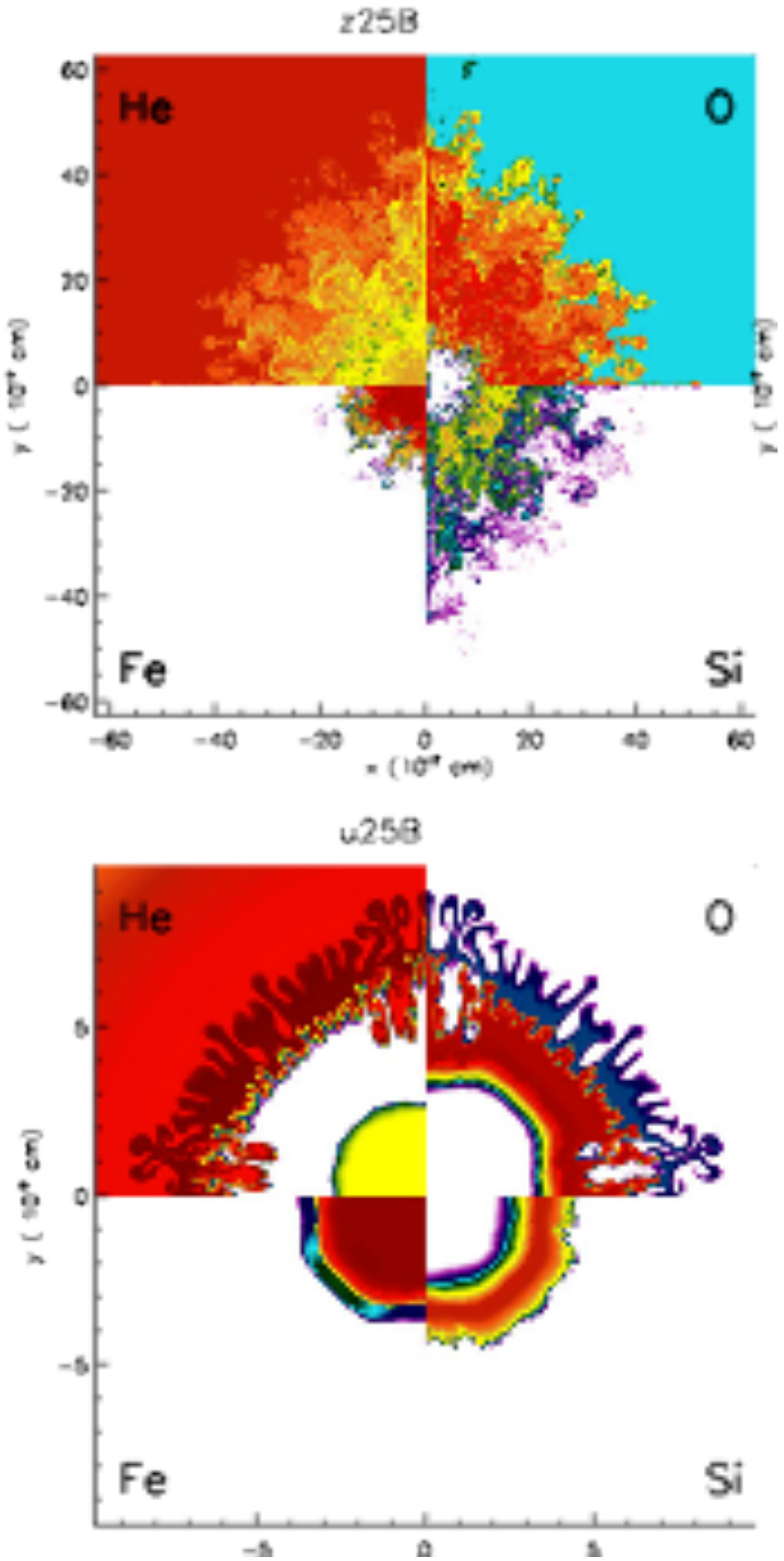


temperature

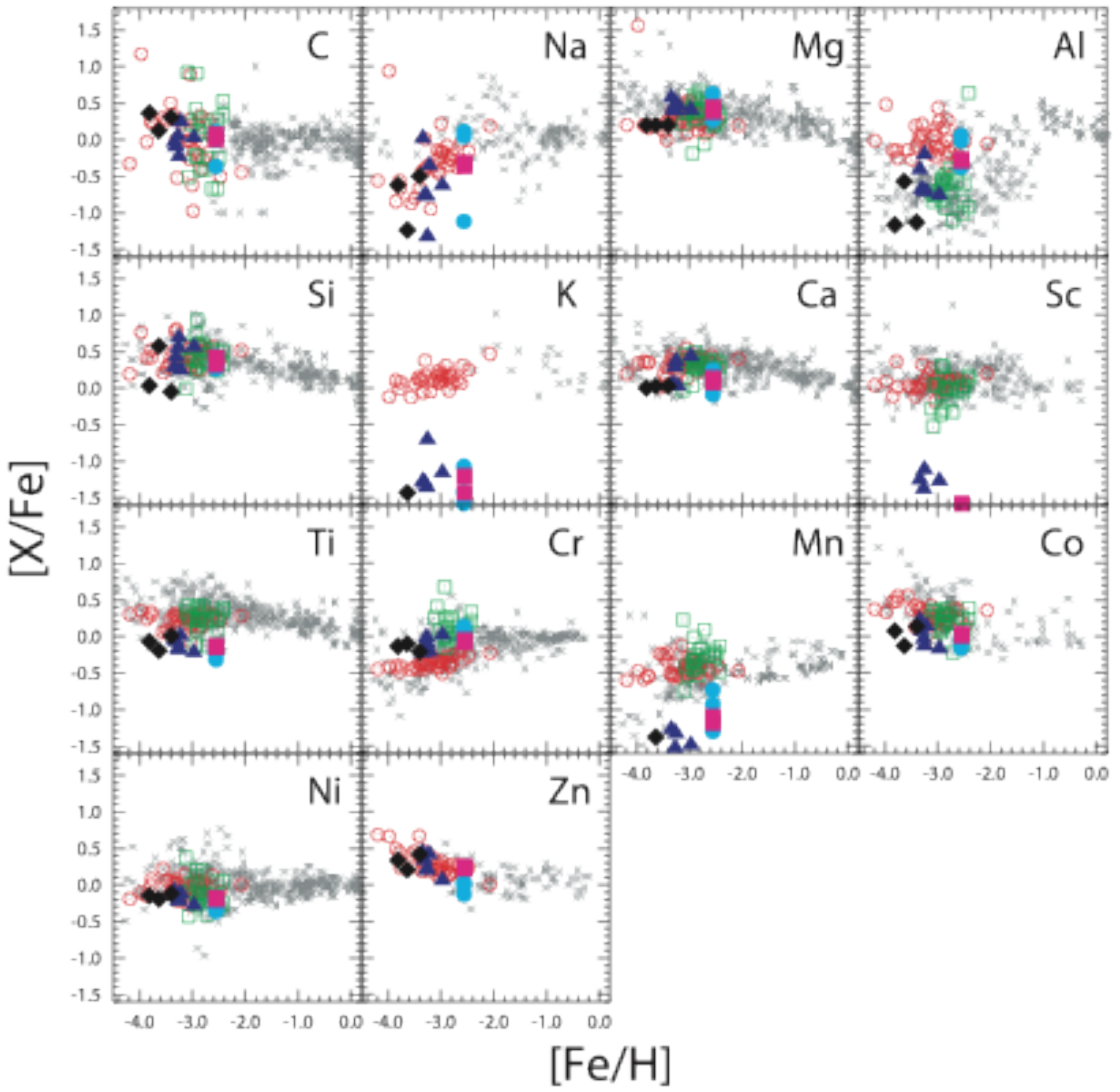
(Greif et al., 2012, MNRAS, 424, 399)

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)

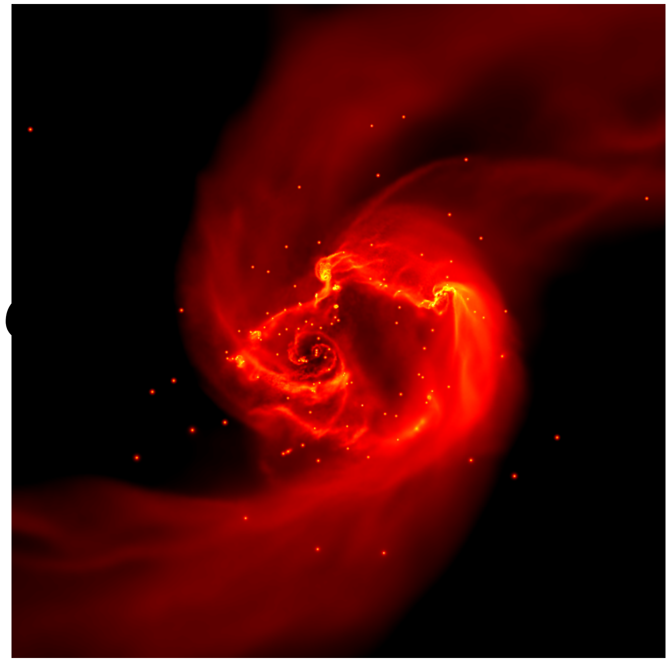


(Tominaga et al. 2007)

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. balance between he*
  - *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*...

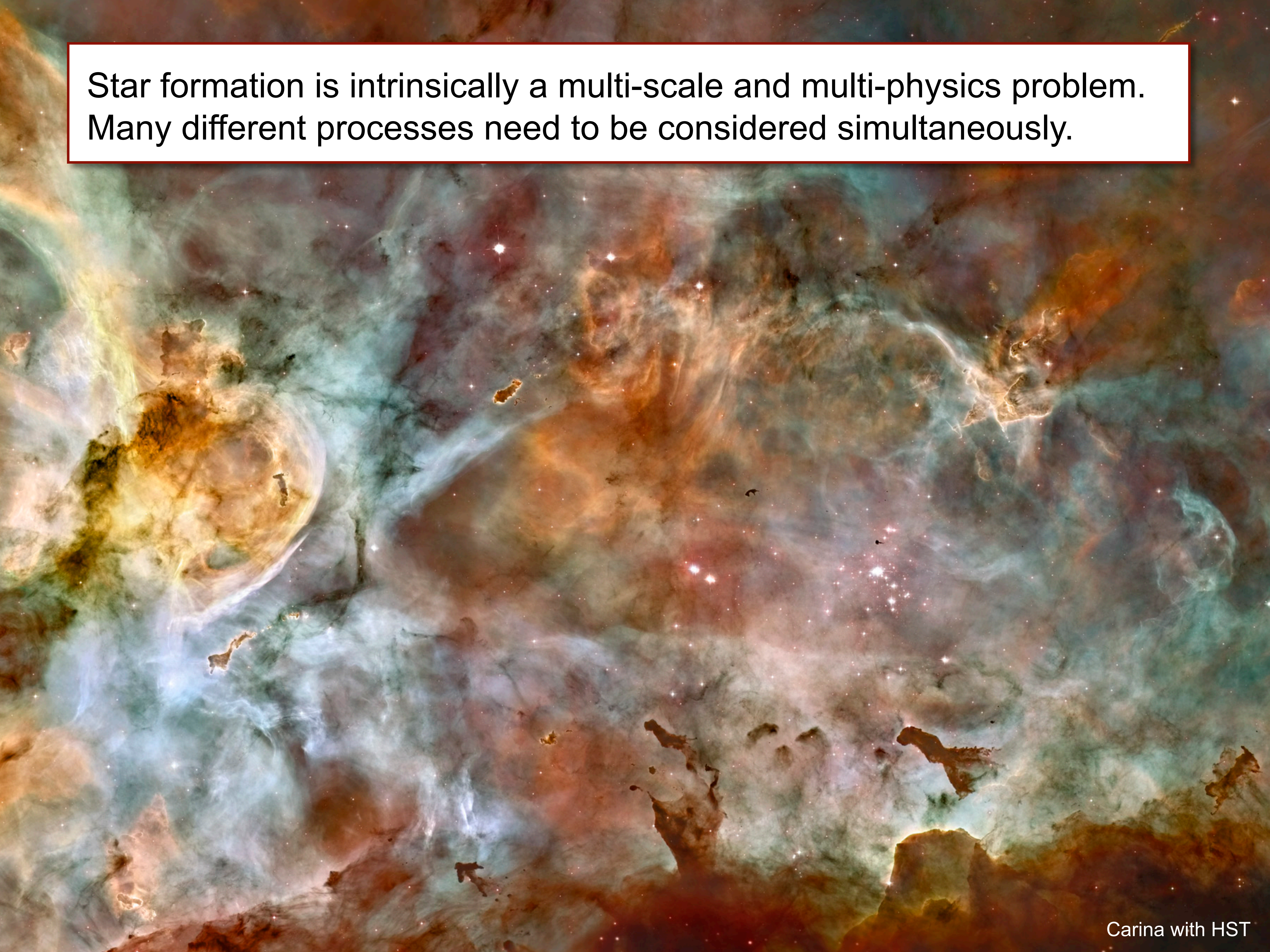
reducing fragmentation

- 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

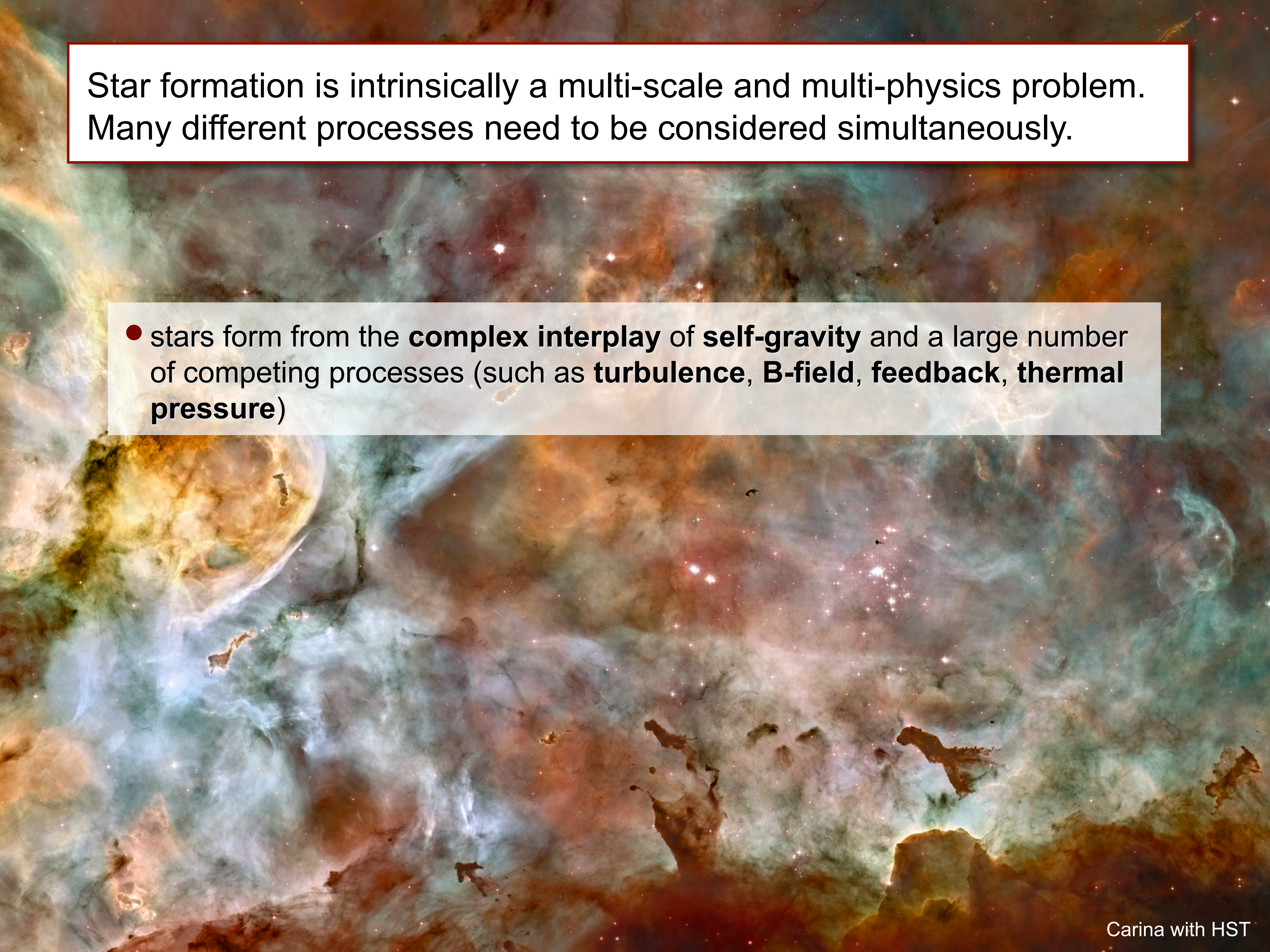


Star formation is intrinsically a multi-scale and multi-physics problem. Many different processes need to be considered simultaneously.

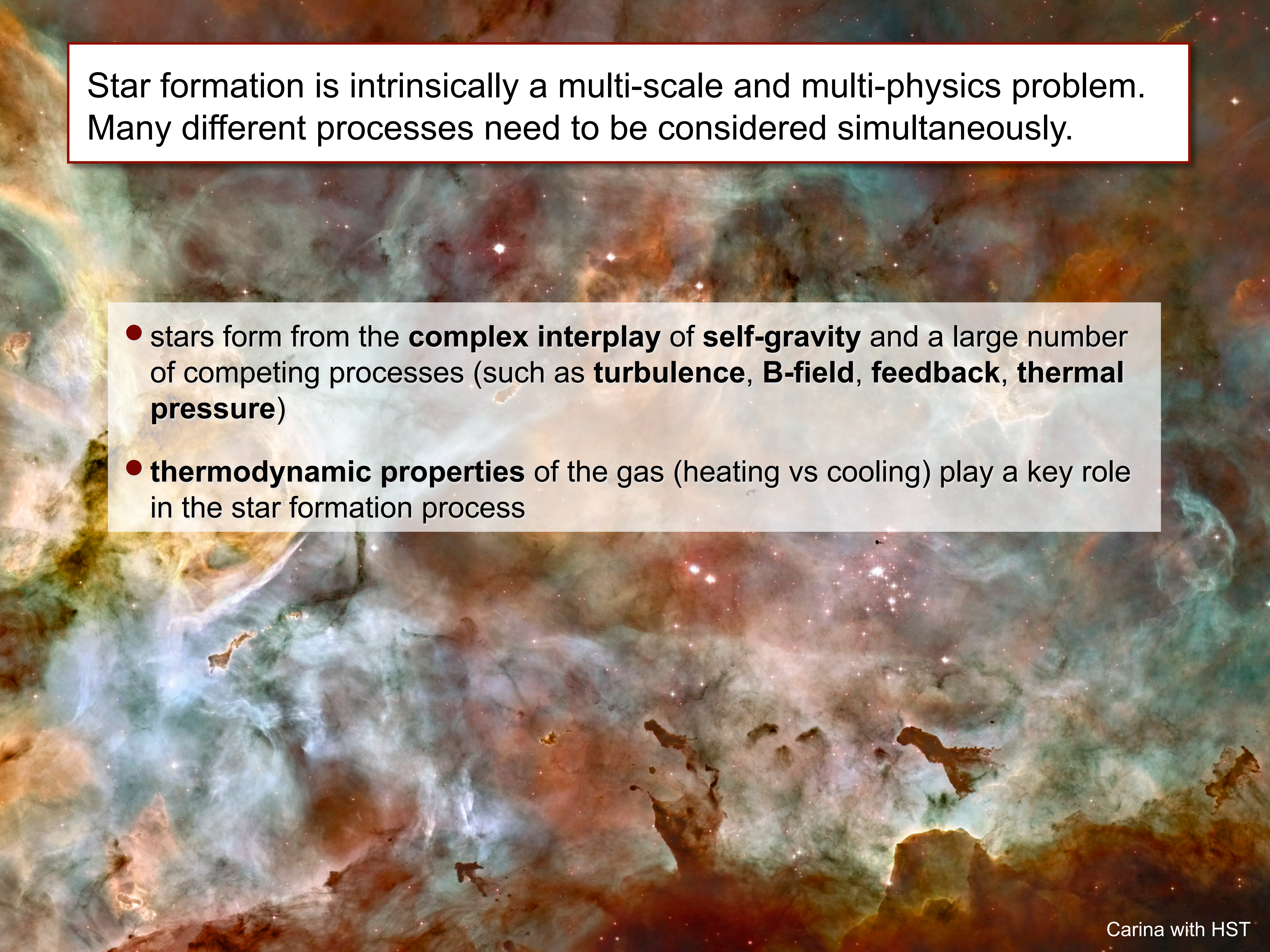
Carina with HST

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

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



Carina with HST



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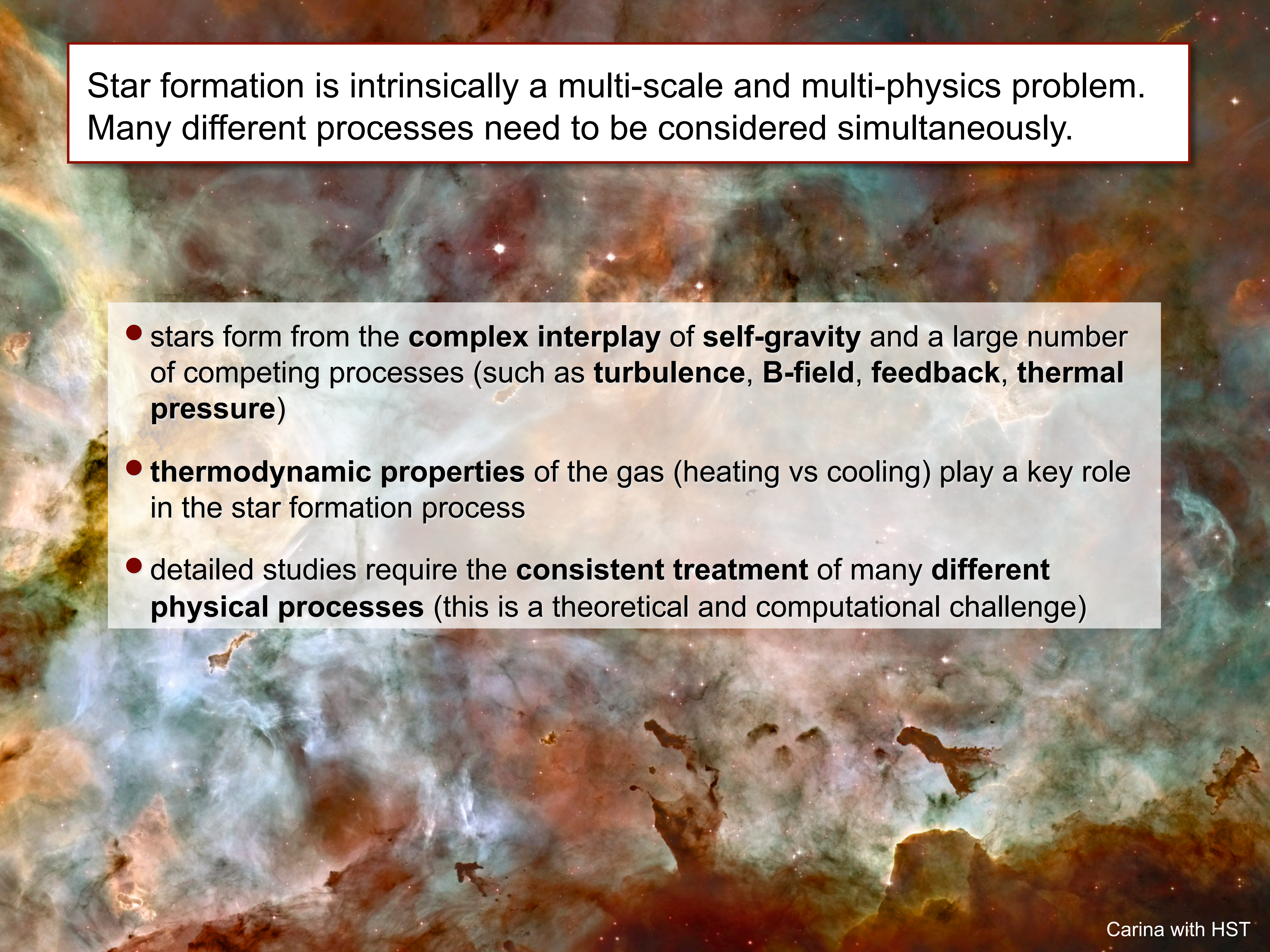

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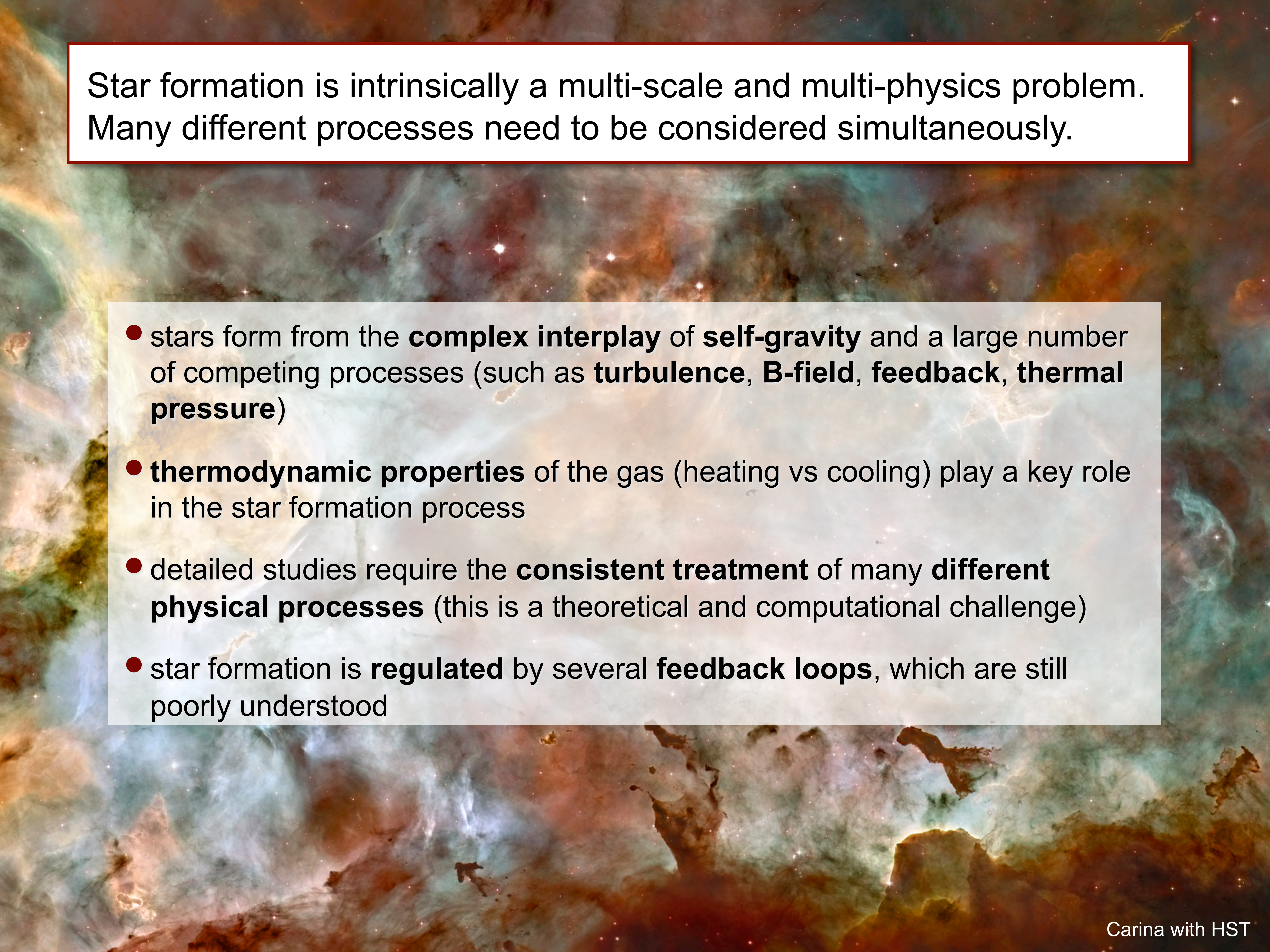

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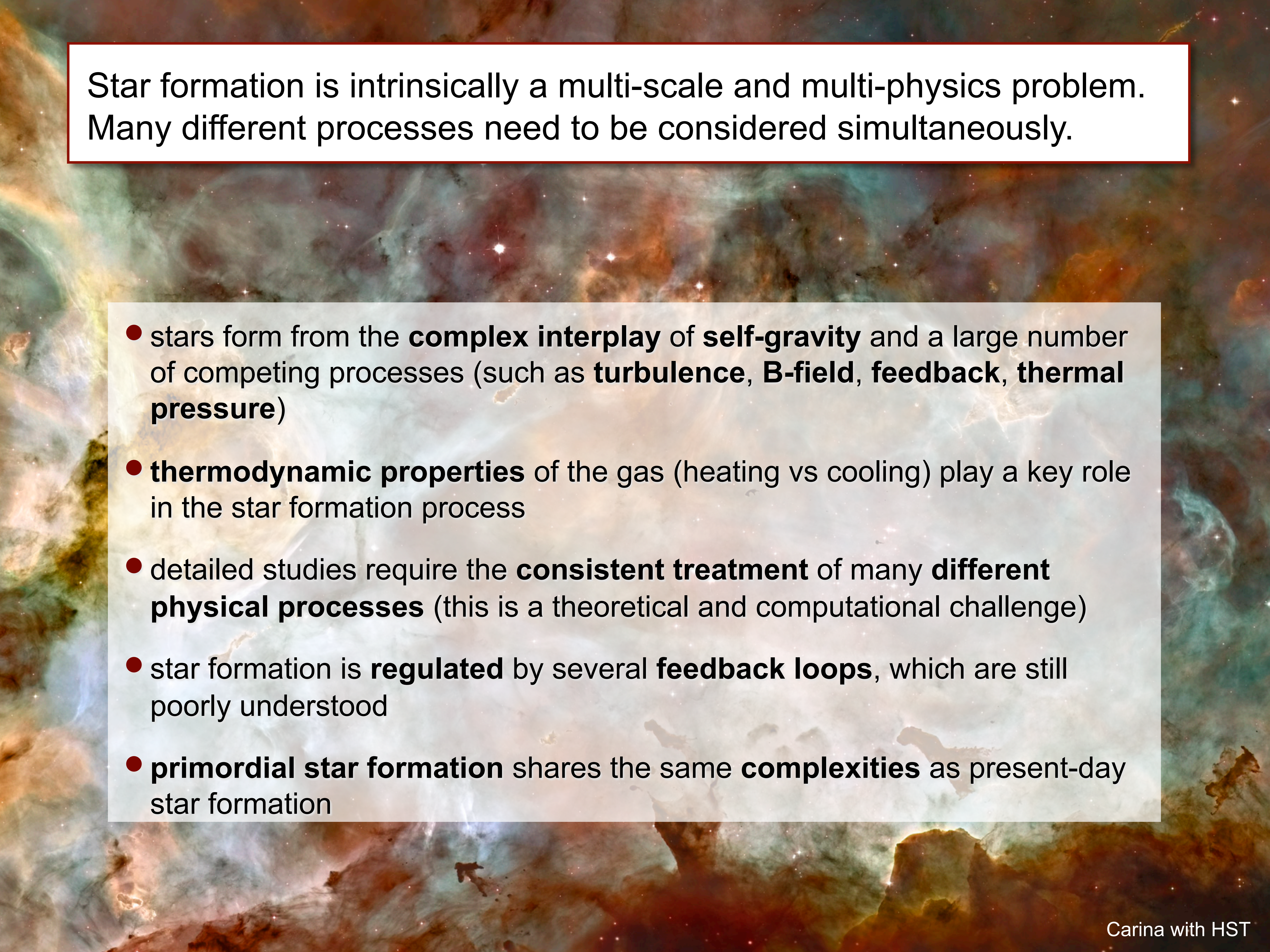
- **primordial star formation** shares the same **complexities** as present-day star formation



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