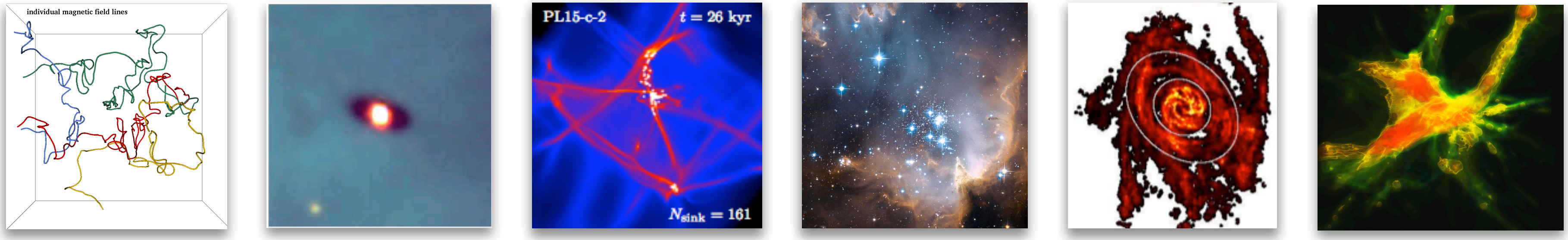
Star Formation at Different Metallicities



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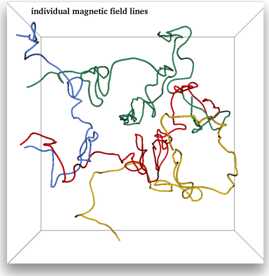
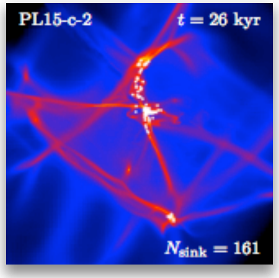
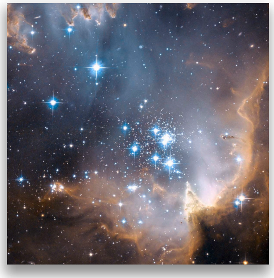
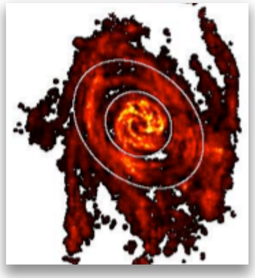
Star Formation

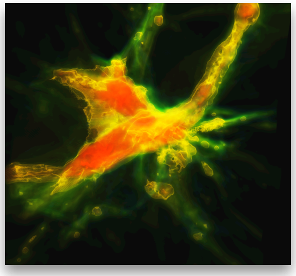
what can we learn from present-days about the primordial universe?











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thanks to ...

... people in the group in Heidelberg:

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

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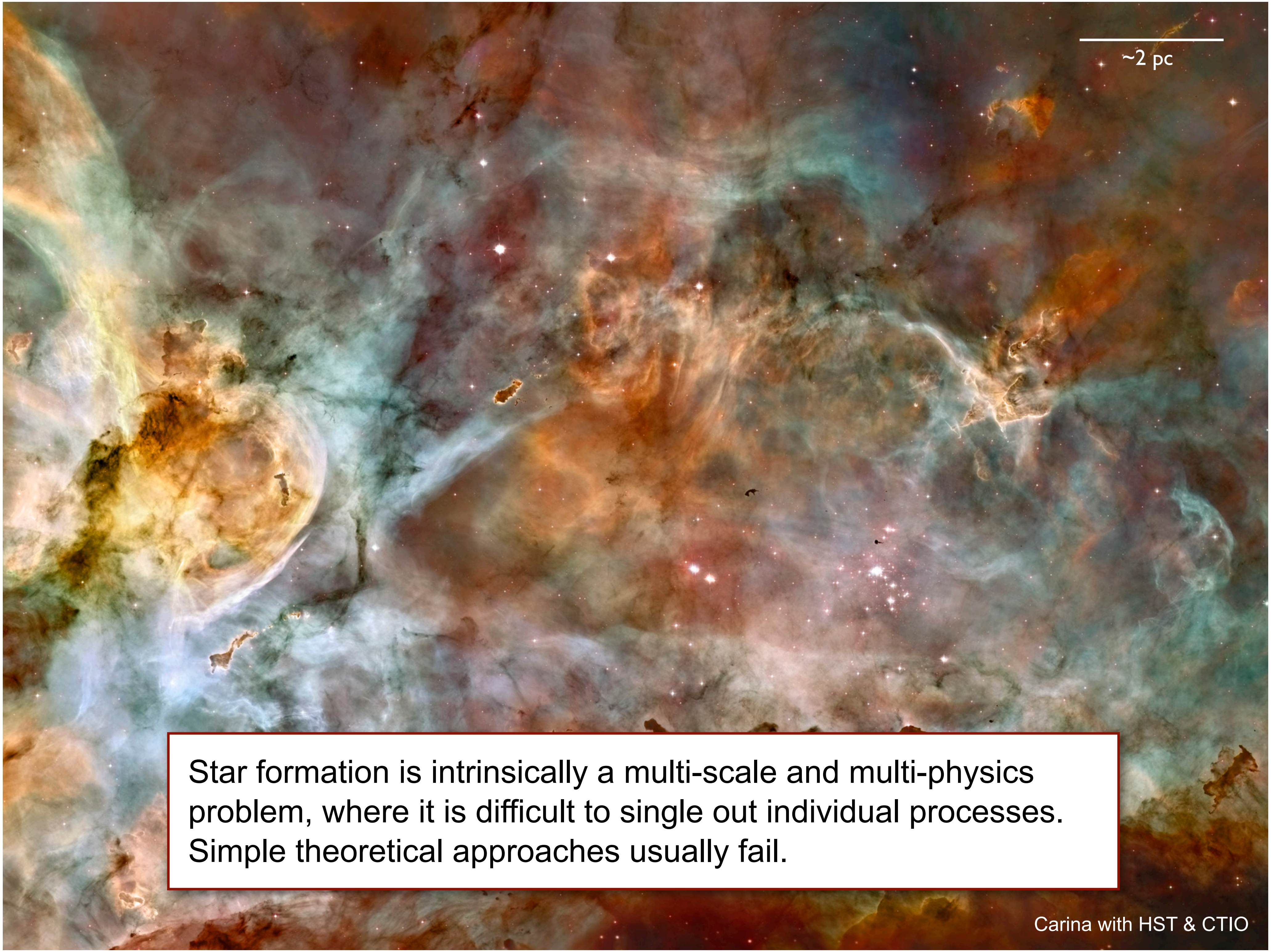
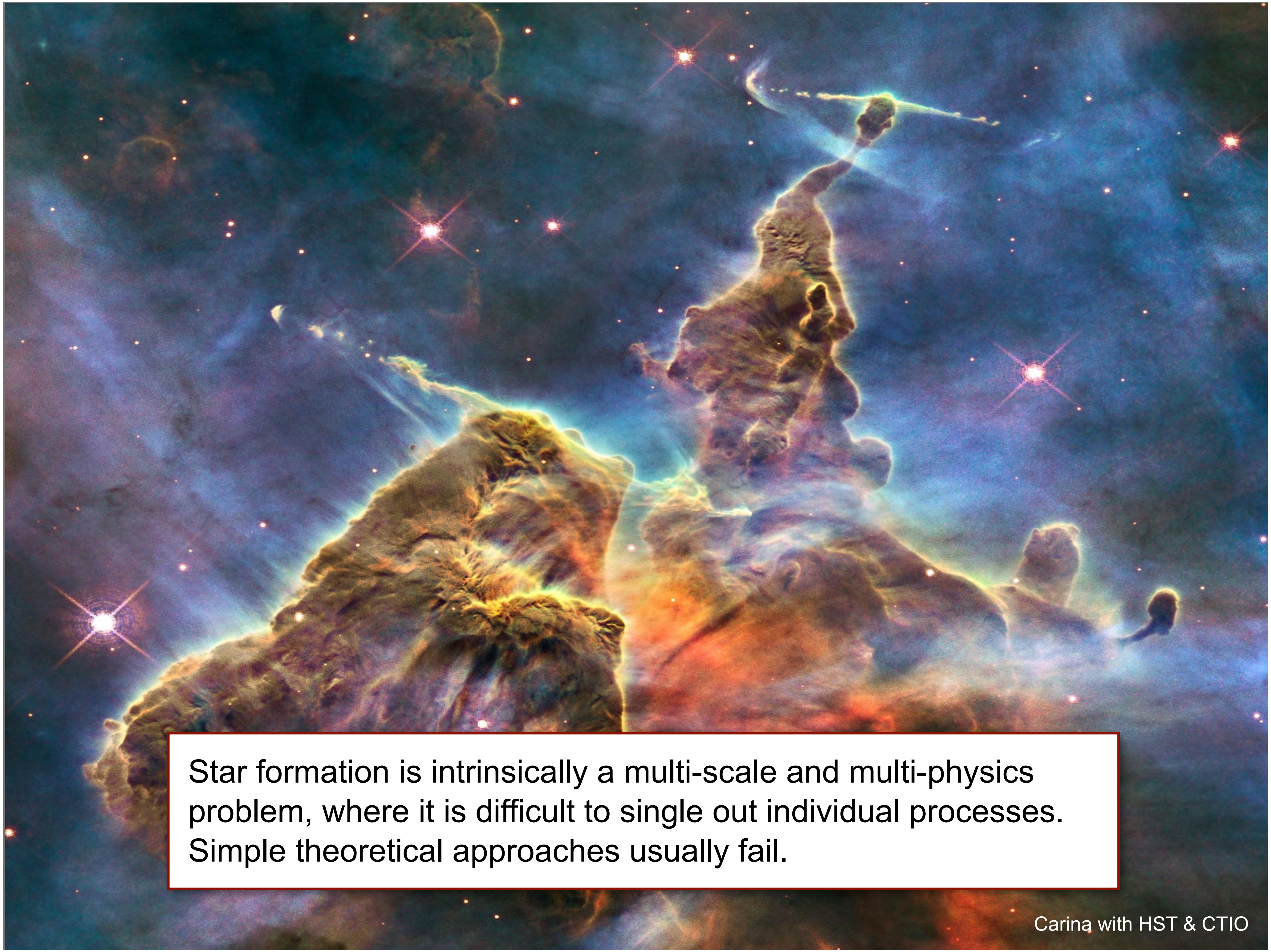


Star formation is intrinsically a multi-scale and multi-physics problem, where it is difficult to single out individual processes. Simple theoretical approaches usually fail.

Carina with HST & CTIO



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.

Carina with HST & CTIO

selected open questions

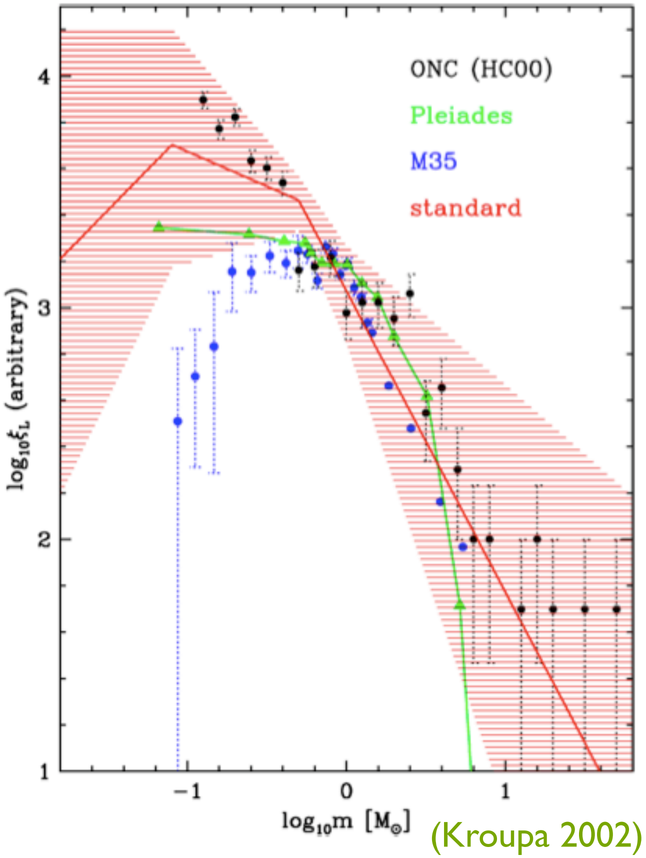
- what processes determine the initial mass function (IMF) of stars?
- what are the initial conditions for star cluster formation?
  how does cloud structure translate into cluster structure?
- how do molecular clouds form?
- what drives turbulence?
- what triggers / regulates star formation on galactic scales?
- how does star formation depend on metallicity?

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
  - initial conditions
    --> statistical properties of star-forming cores
  - collapse and interaction of prestellar cores
    --> accretion and *N*-body effects
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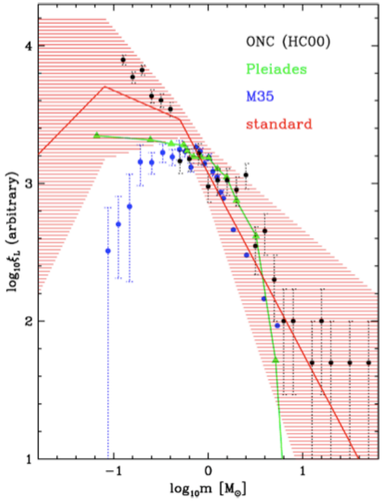
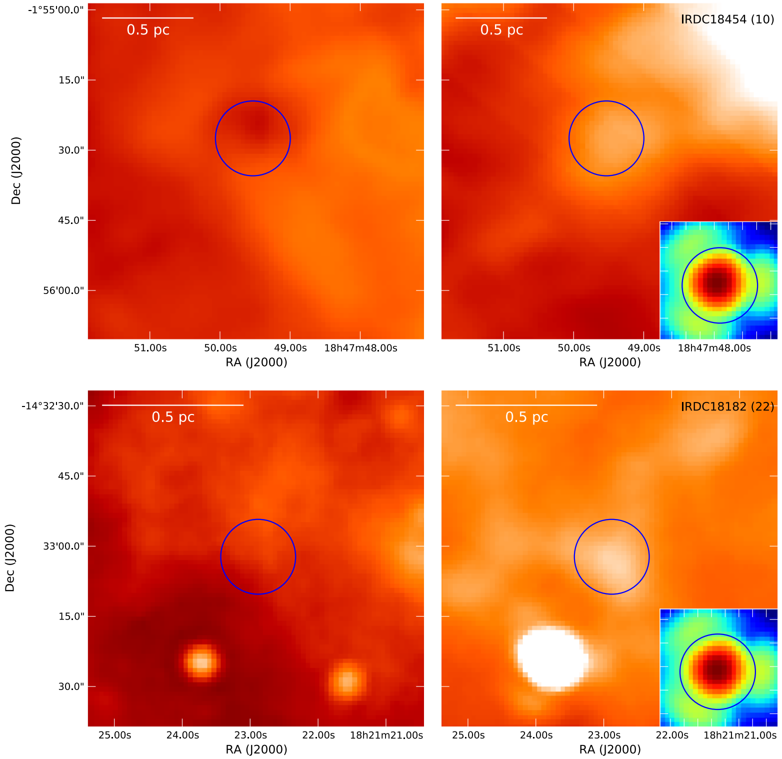


(Kroupa 2002)

ICs of star cluster formation

- key question:
  - what is the initial density profile of cluster forming cores? how does it compare low-mass cores?
- observers answer:

“this is not really well known . . .”



from Sarah Ragan’s epic paper on the EPoS IRDC’s (arXiv:1207.6518)

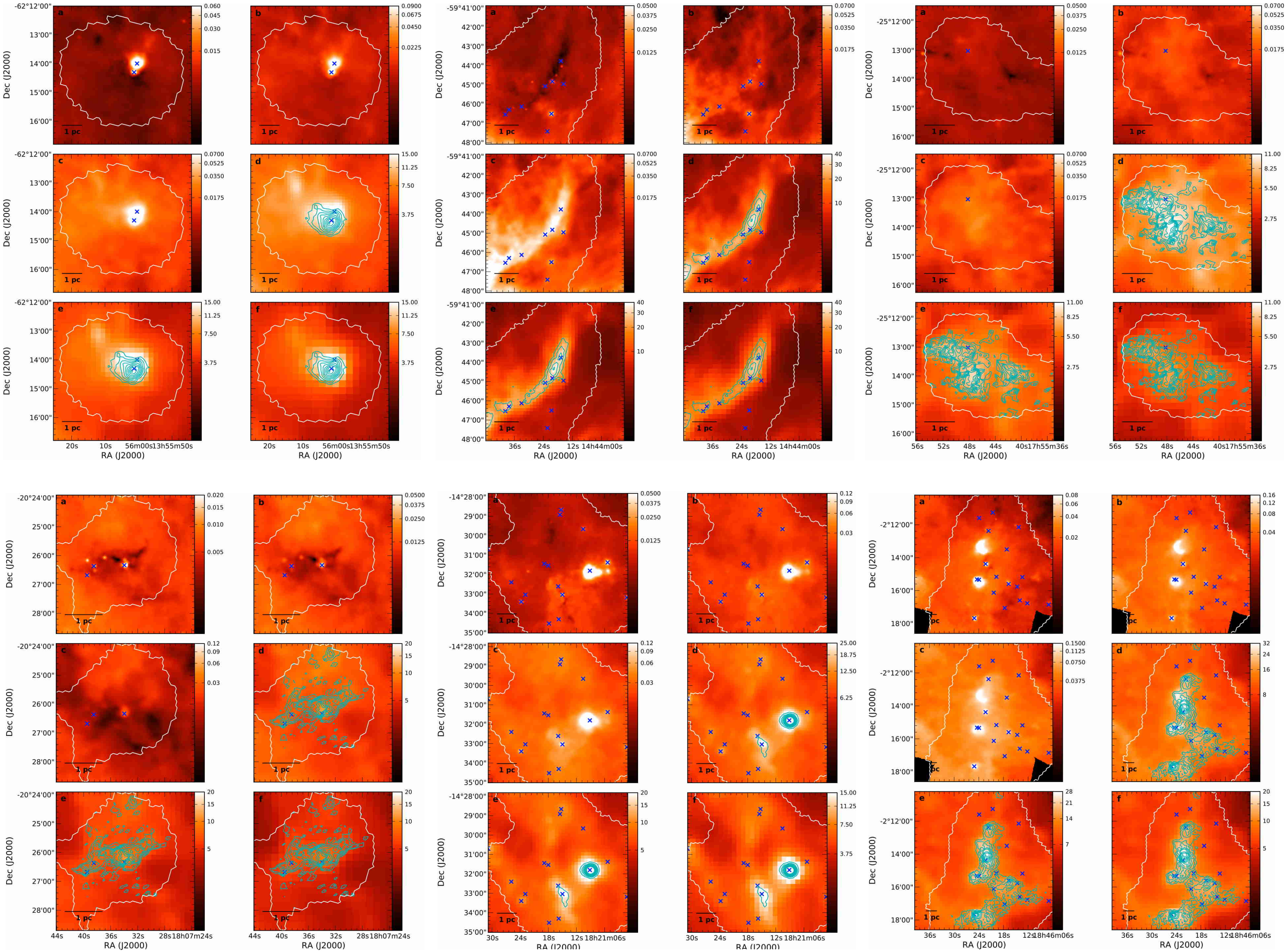


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image: freiburgrockt.net

ICs of star cluster formation

- key question:
  - what is the initial density profile of cluster forming cores? how does it compare low-mass cores?
- theorists answer:

“this is easy, I know exactly the right answer . . .”

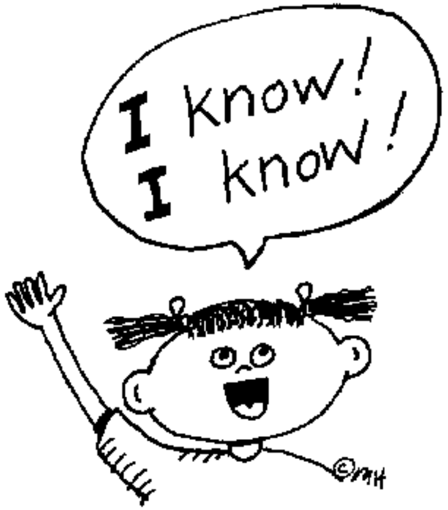
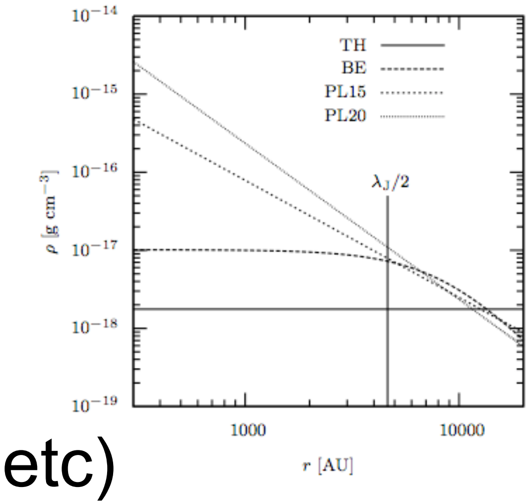


image by Mark A. Hicks

ICs of star cluster formation

- key question:
  - what is the initial density profile of cluster forming cores? how does it compare low-mass cores?
- theorists answer:
  - top hat (Larson Penston)
  - Bonnor Ebert (like low-mass cores)
  - power law $\rho \propto r^{-1}$ (logotrop)
  - power law $\rho \propto r^{-3/2}$ (Krumholz, McKee, etc)
  - power law $\rho \propto r^{-2}$ (Shu)
  - and many more



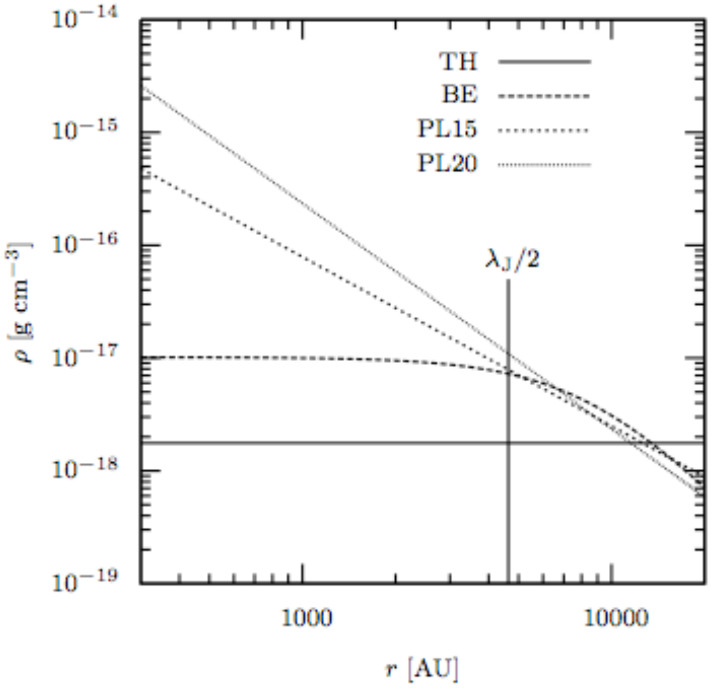
different density profiles

- more precisely: does the density profile matter?

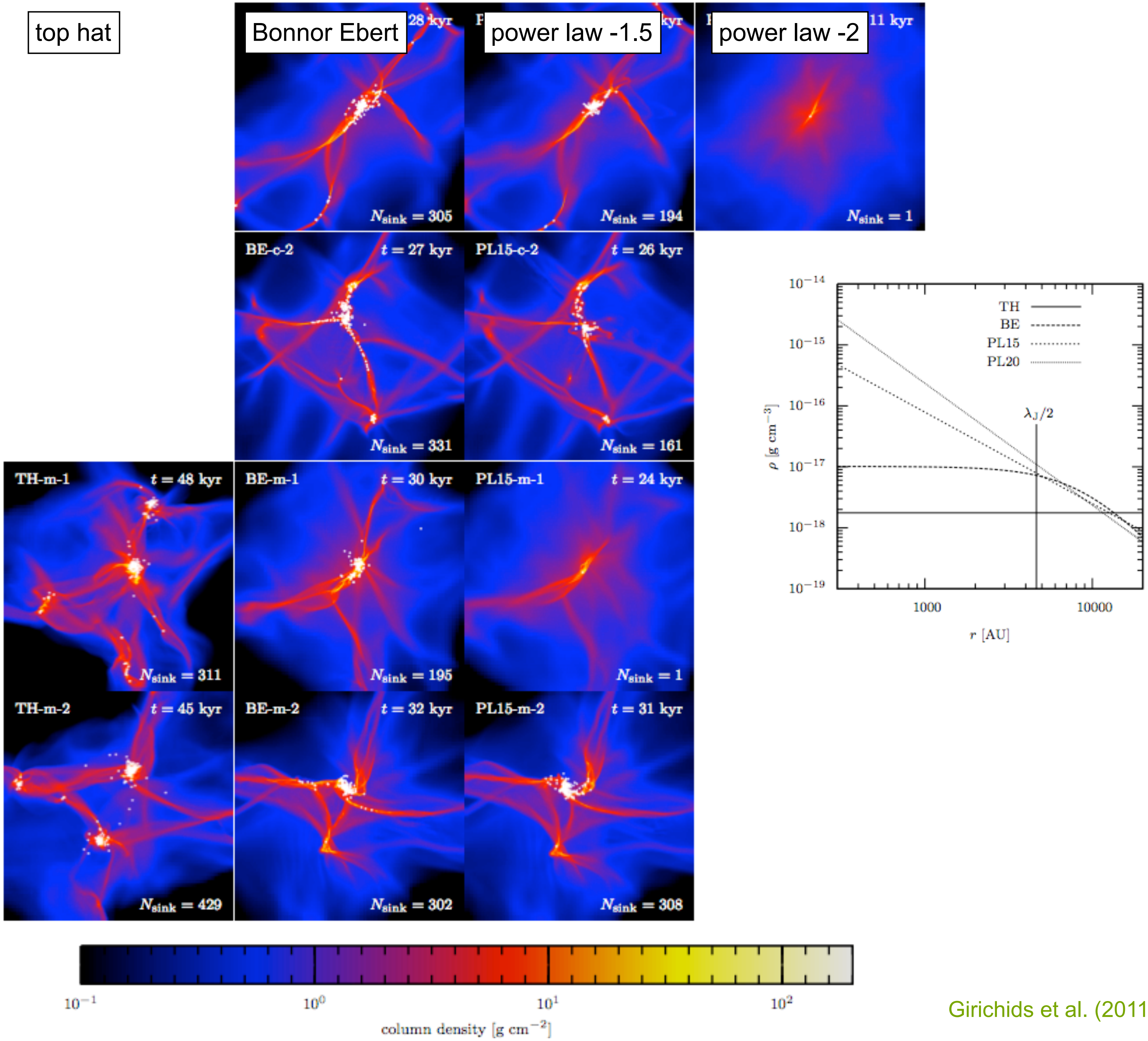
- in comparison to
    - turbulence ...
    - radiative feedback ...
    - magnetic fields ...
    - thermodynamics ...

different density profiles

- answer: ***YES! it matters big time!***
- approach: extensive parameter study
  - different profiles (top hat, BE, $r^{-3/2}$, r^{-3})
  - different turbulence fields
    - different realizations
    - different Mach numbers
    - solenoidal turbulence
      dilatational turbulence
      both modes
  - no net rotation, no B-fields
    (at the moment)



Girichids et al. (2011, 2012a,b)



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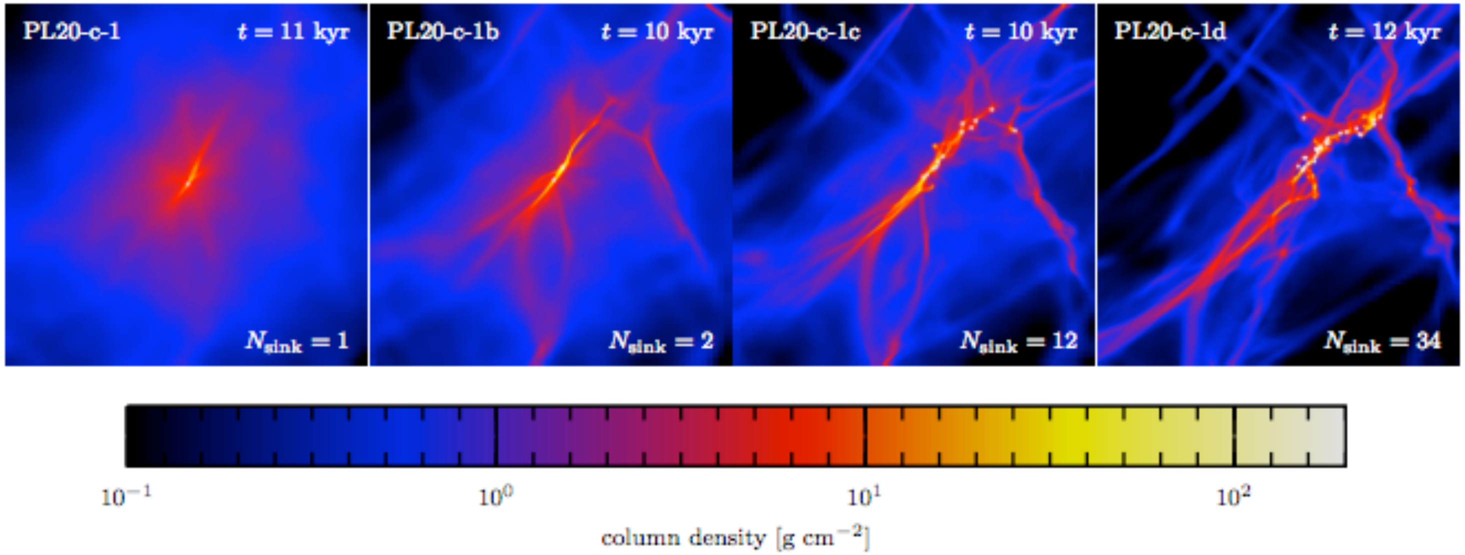
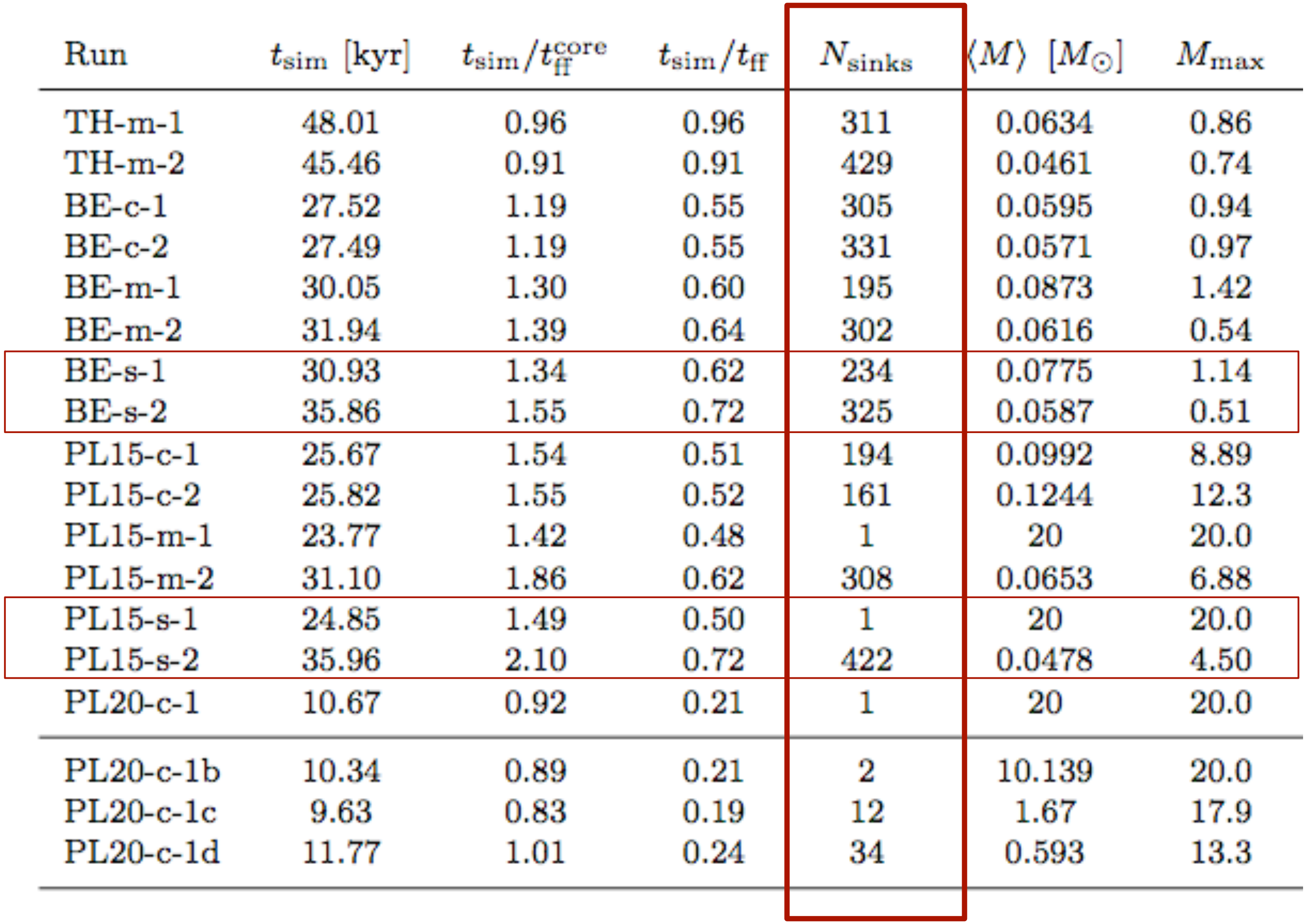


M=3 M=6 M=12 M=18

for the r^{-2} profile you need to crank up turbulence a lot to get some fragmentation!

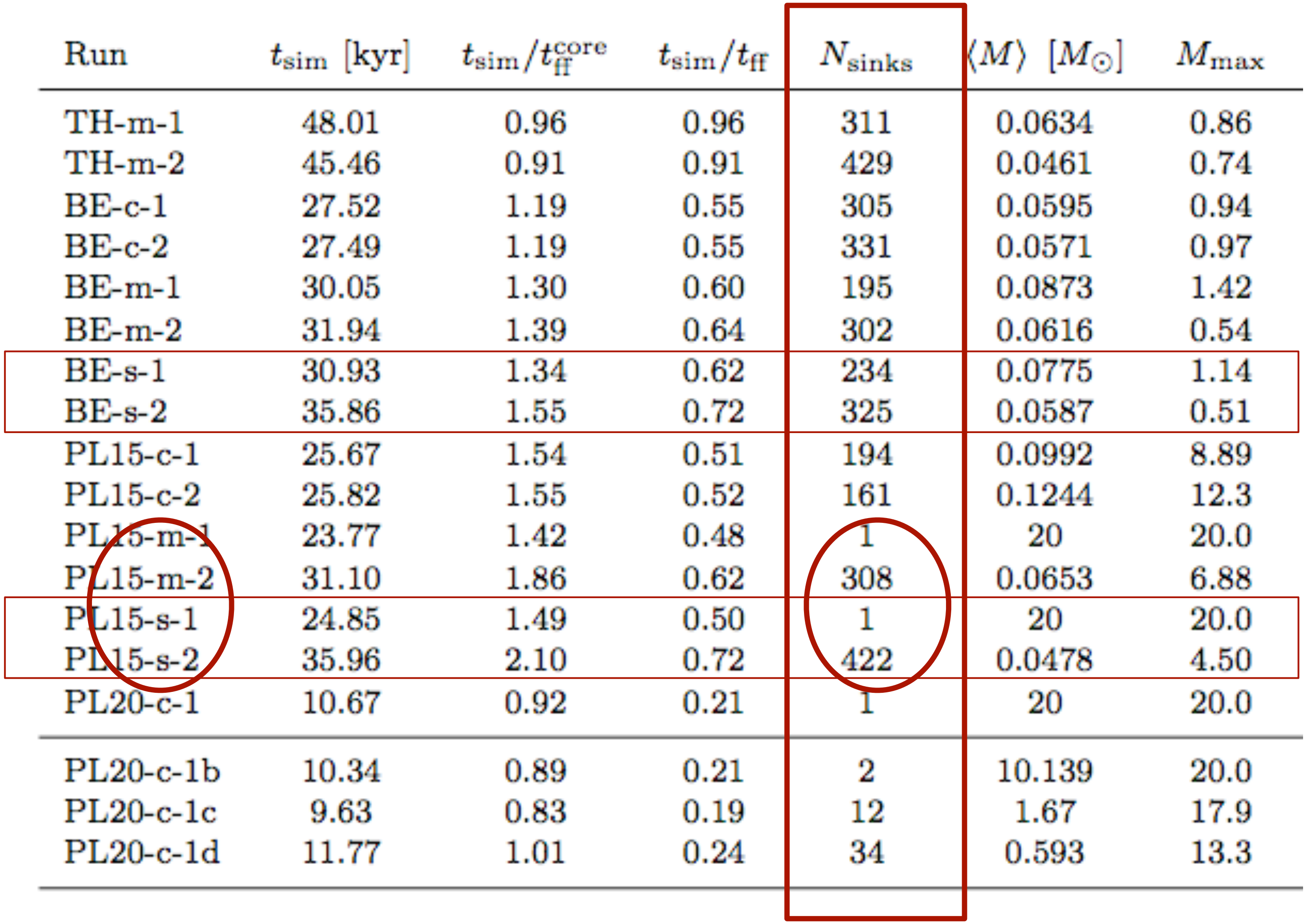
Girichids et al. (2011, 2012a,b)



Run	$t_{\rm sim}$ [kyr]	$t_{\rm sim}/t_{\rm ff}^{\rm core}$	$t_{\rm sim}/t_{\rm ff}$	$N_{\rm sinks}$	$\langle M \rangle$ [$M_\odot$]	$M_{\rm max}$
TH-m-1	48.01	0.96	0.96	311	0.0634	0.86
TH-m-2	45.46	0.91	0.91	429	0.0461	0.74
BE-c-1	27.52	1.19	0.55	305	0.0595	0.94
BE-c-2	27.49	1.19	0.55	331	0.0571	0.97
BE-m-1	30.05	1.30	0.60	195	0.0873	1.42
BE-m-2	31.94	1.39	0.64	302	0.0616	0.54
BE-s-1	30.93	1.34	0.62	234	0.0775	1.14
BE-s-2	35.86	1.55	0.72	325	0.0587	0.51
PL15-c-1	25.67	1.54	0.51	194	0.0992	8.89
PL15-c-2	25.82	1.55	0.52	161	0.1244	12.3
PL15-m-1	23.77	1.42	0.48	1	20	20.0
PL15-m-2	31.10	1.86	0.62	308	0.0653	6.88
PL15-s-1	24.85	1.49	0.50	1	20	20.0
PL15-s-2	35.96	2.10	0.72	422	0.0478	4.50
PL20-c-1	10.67	0.92	0.21	1	20	20.0
PL20-c-1b	10.34	0.89	0.21	2	10.139	20.0
PL20-c-1c	9.63	0.83	0.19	12	1.67	17.9
PL20-c-1d	11.77	1.01	0.24	34	0.593	13.3

number of fragments depends on initial profile:
flat profiles ---> lots of (low-mass) fragments
steep profiles ---> bias to single (high-mass) objects

Girichids et al. (2011, 2012a,b)



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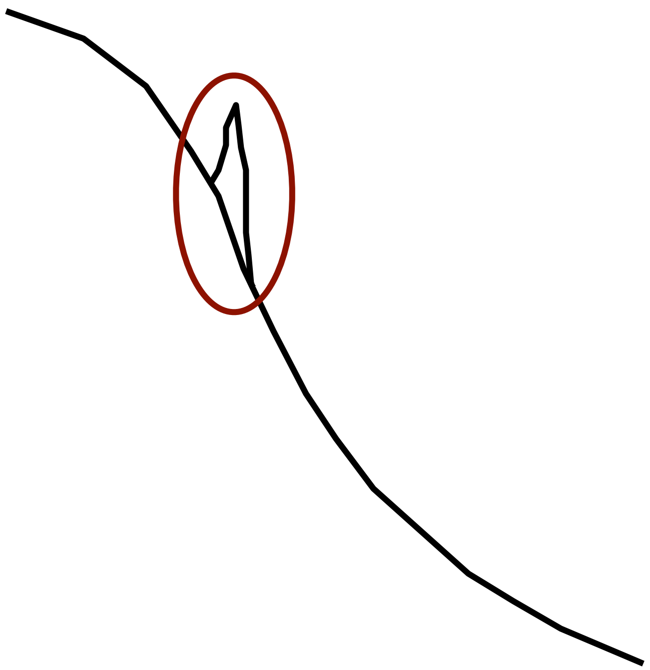
however, the real situation is more complex:
for example, $r^{-1.5}$ is a limiting case where tidal forces roughly balance self-gravity of perturbation

Girichids et al. (in prep)



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stellar masses

- distribution of stellar masses depends on
  - initial conditions
    --> statistical properties of star-forming cores
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    --> accretion and *N*-body effects
  - thermodynamic properties of gas
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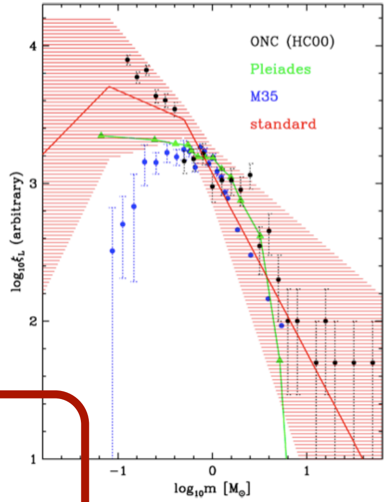
    ionizing radiation, bipolar outflows, winds, SN

(Kroupa 2002)



application to early star formation

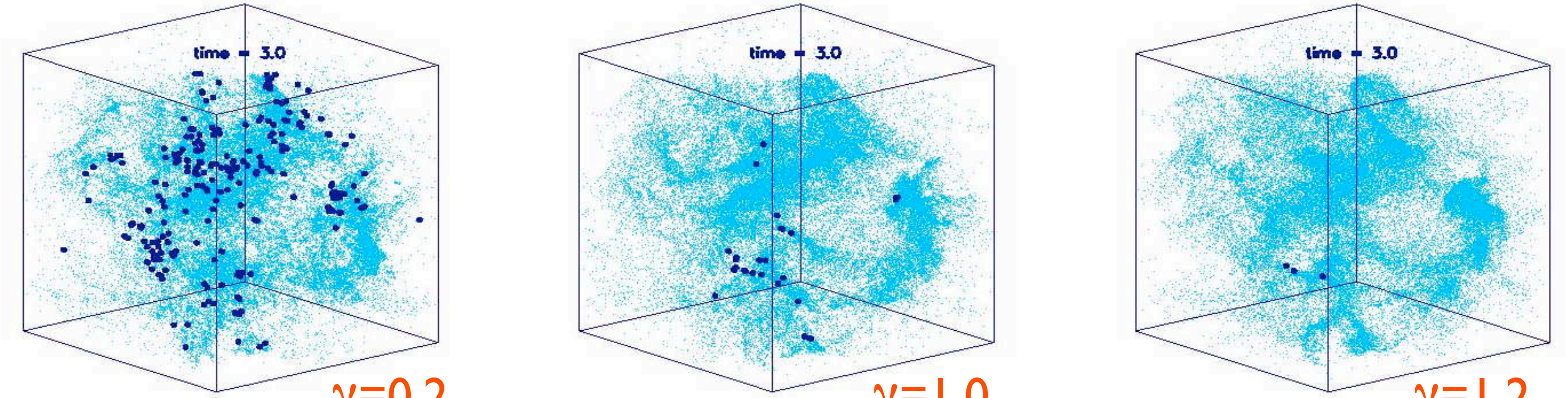
thermodynamics & fragmentation

degree of fragmentation depends on *EOS!*

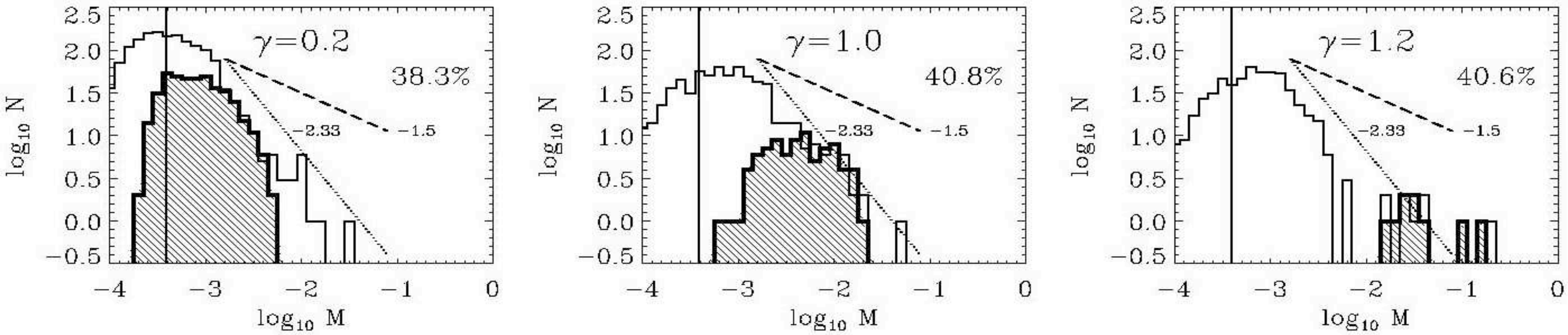
polytropic EOS: $\mathbf{p} \propto \rho^{\gamma}$
$\gamma < 1$: dense cluster of low-mass stars
$\gamma > 1$: isolated high-mass stars

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

dependency on EOS



γ=0.2 γ=1.0 γ=1.2



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

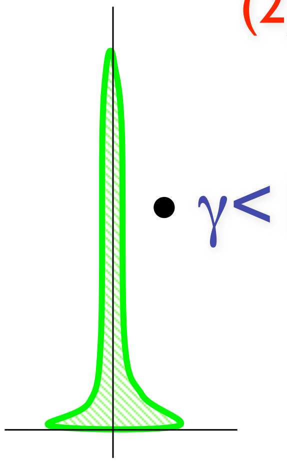
for γ>1 it is suppressed → formation of *isolated massive stars*

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

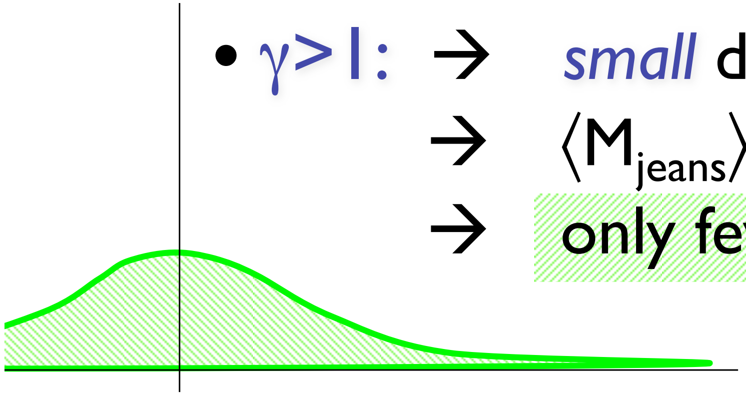
how does that work?

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

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

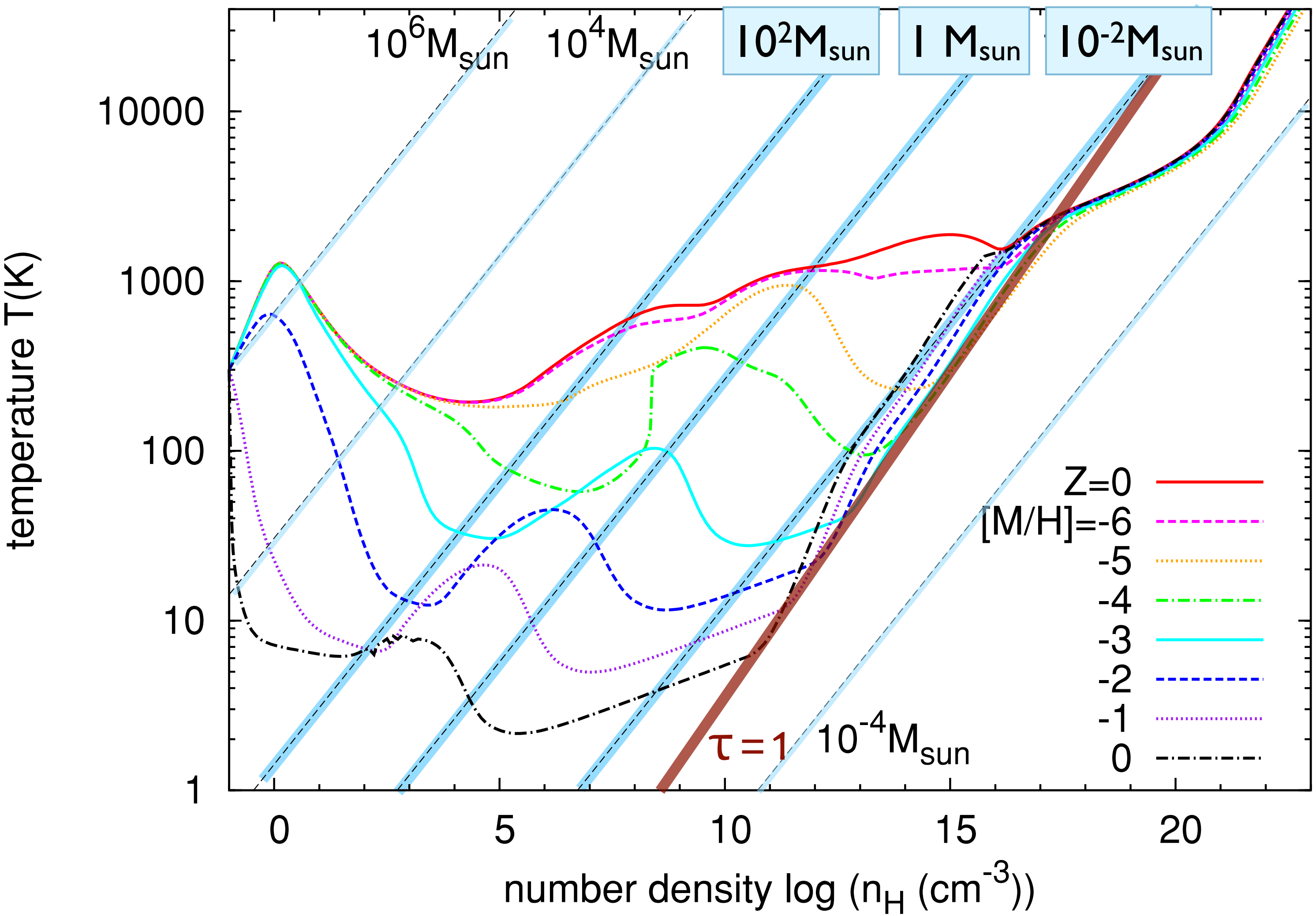


- $\gamma<1$: → *large* density excursion for given pressure
  - → $\langle M_{\mathrm{jeans}} \rangle$ becomes small
  - → number of fluctuations with $M > M_{\mathrm{jeans}}$ is large



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

EOS as function of metallicity



(Omukai et al. 2005, 2010)

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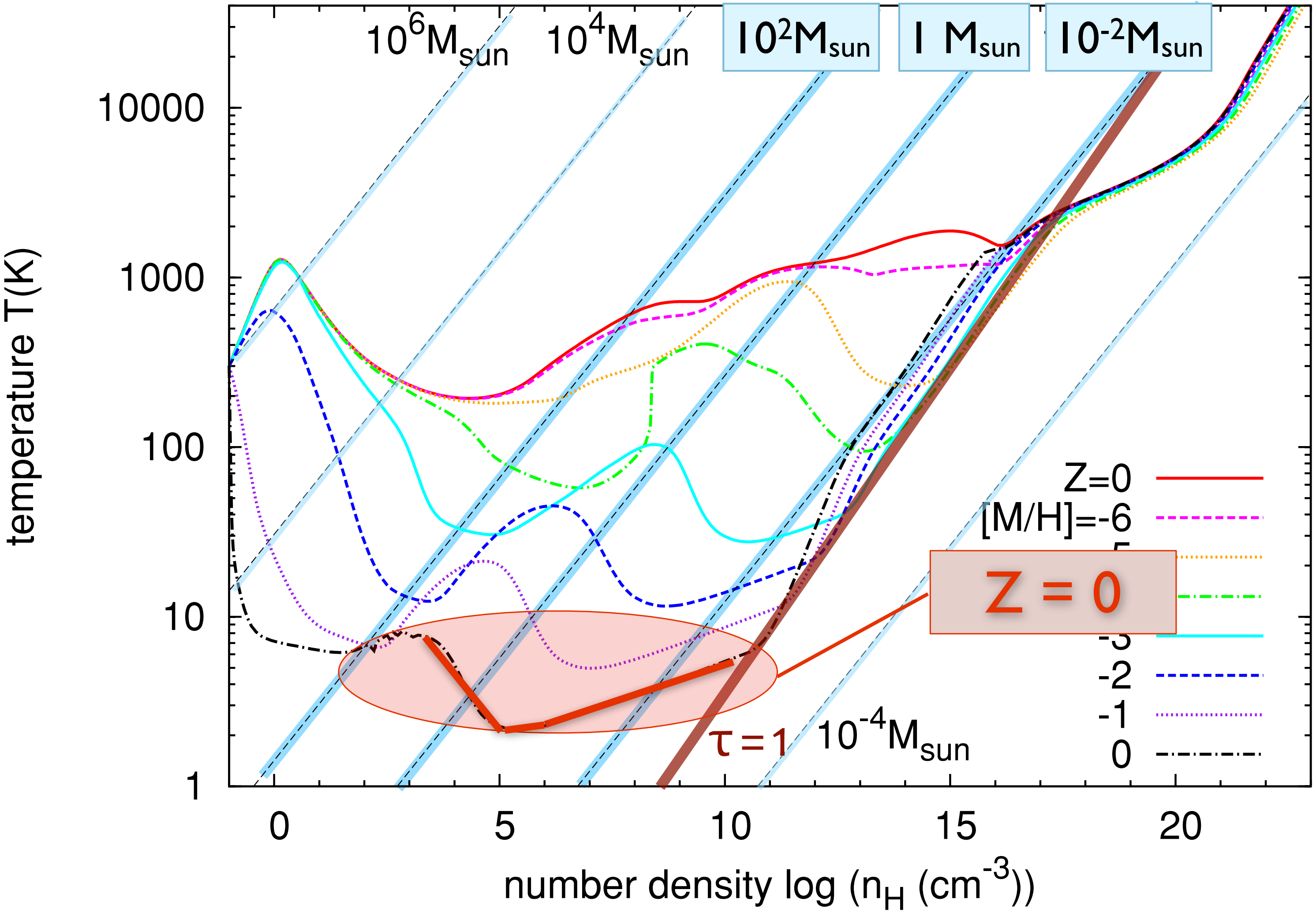

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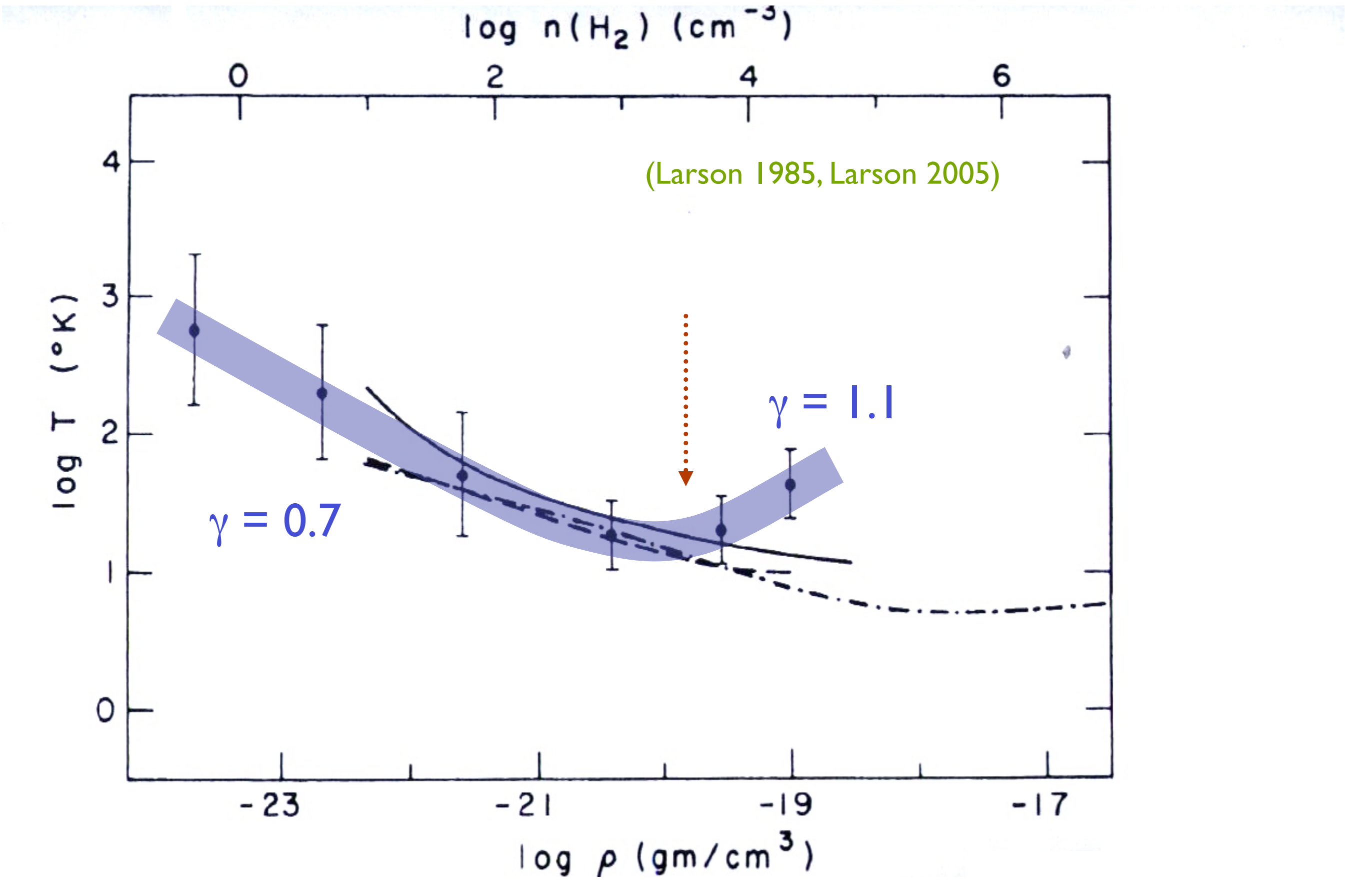
present-day star formation



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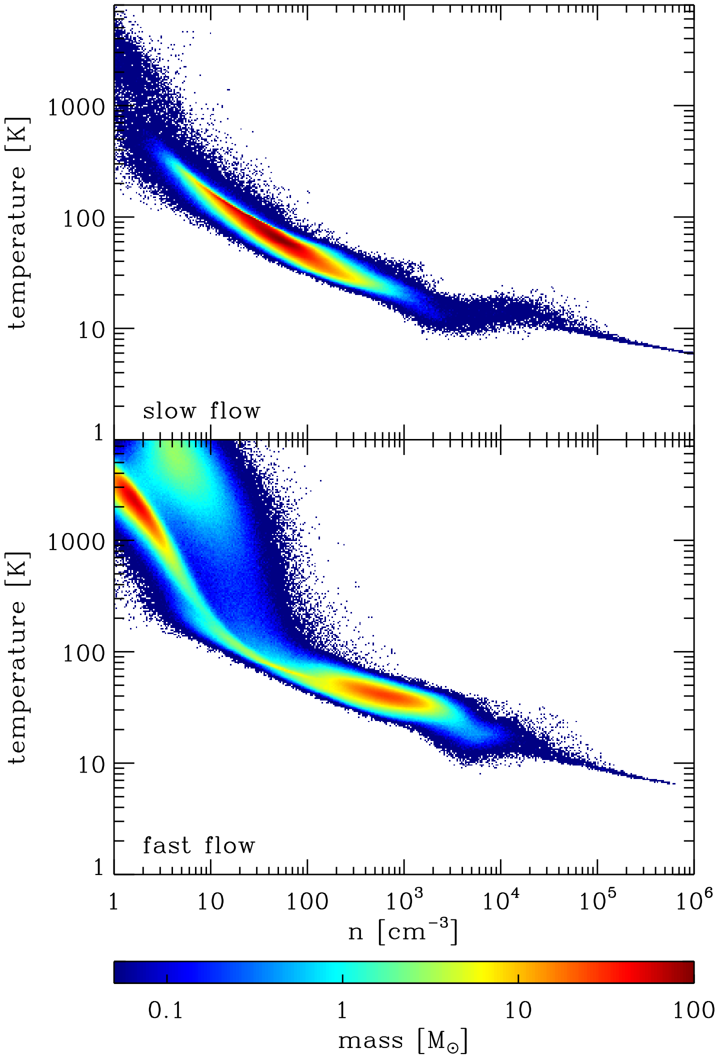
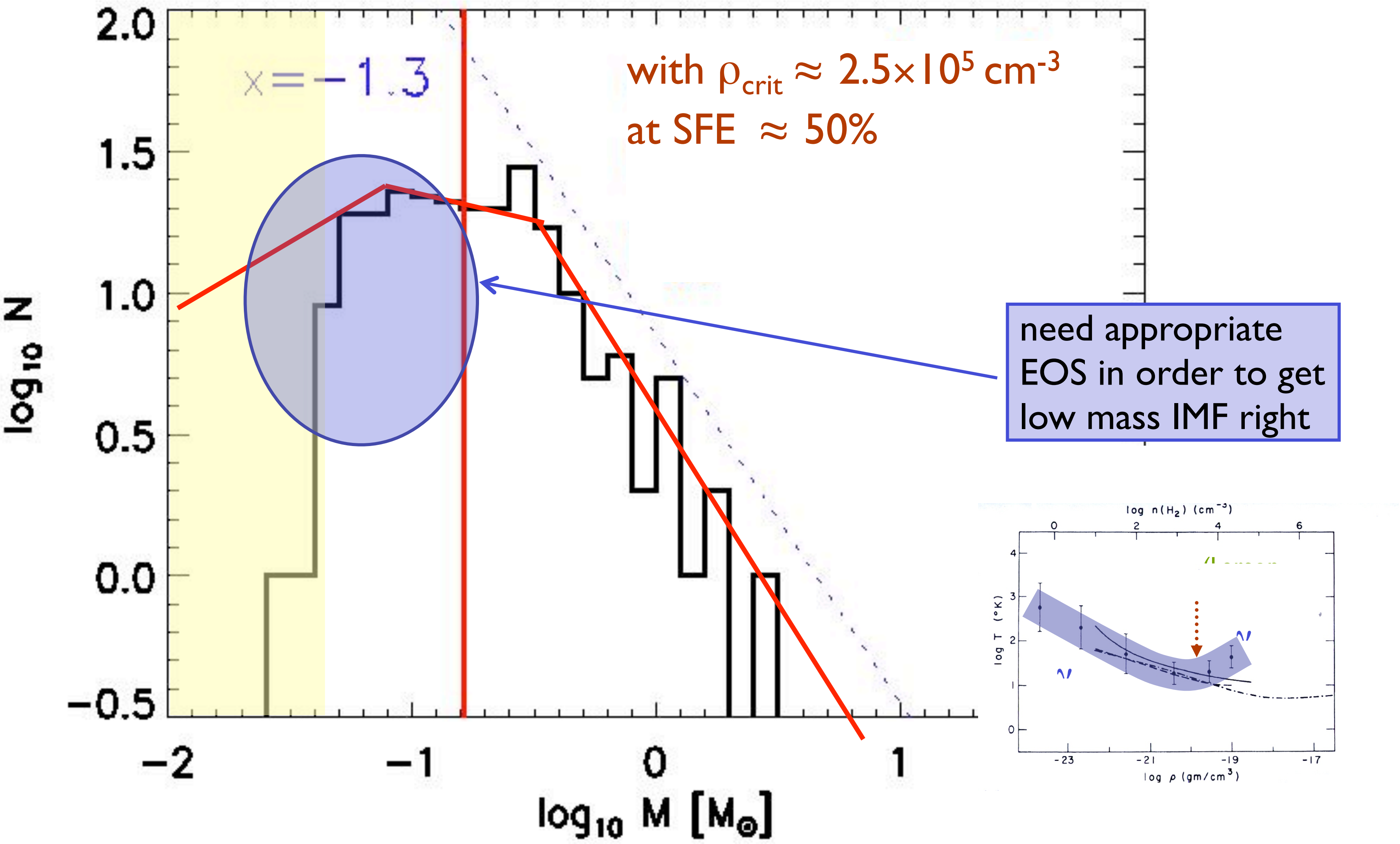


real situation may be more complex and depend on flow properties, radiation field, total mass & size of cloud (extinction), etc.

(Clark et al. 2012)

IMF in nearby molecular clouds

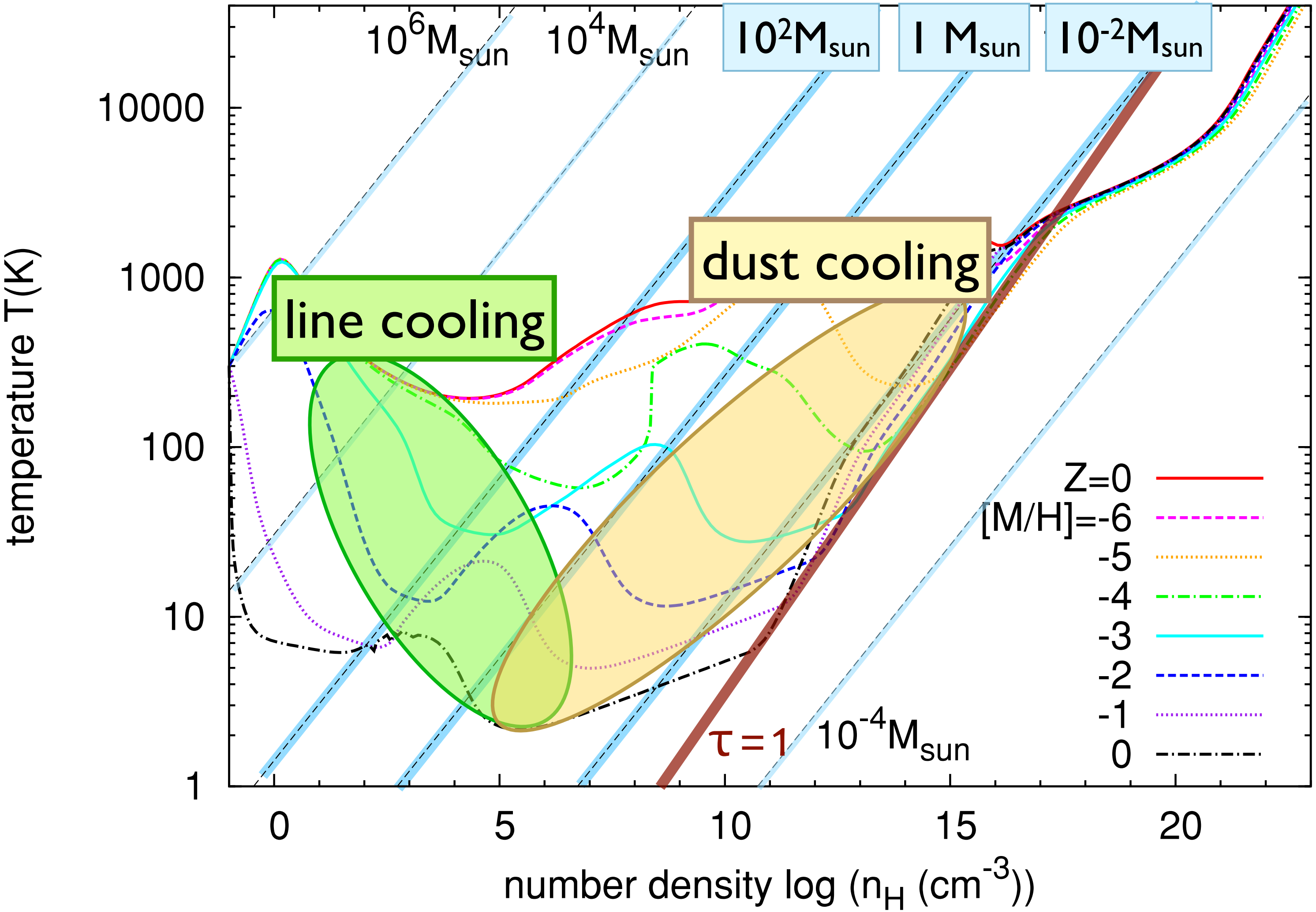


with $\rho_{crit} \approx 2.5 \times 10^5$ cm^{-3}
at SFE $\approx$ 50%

need appropriate EOS in order to get low mass IMF right

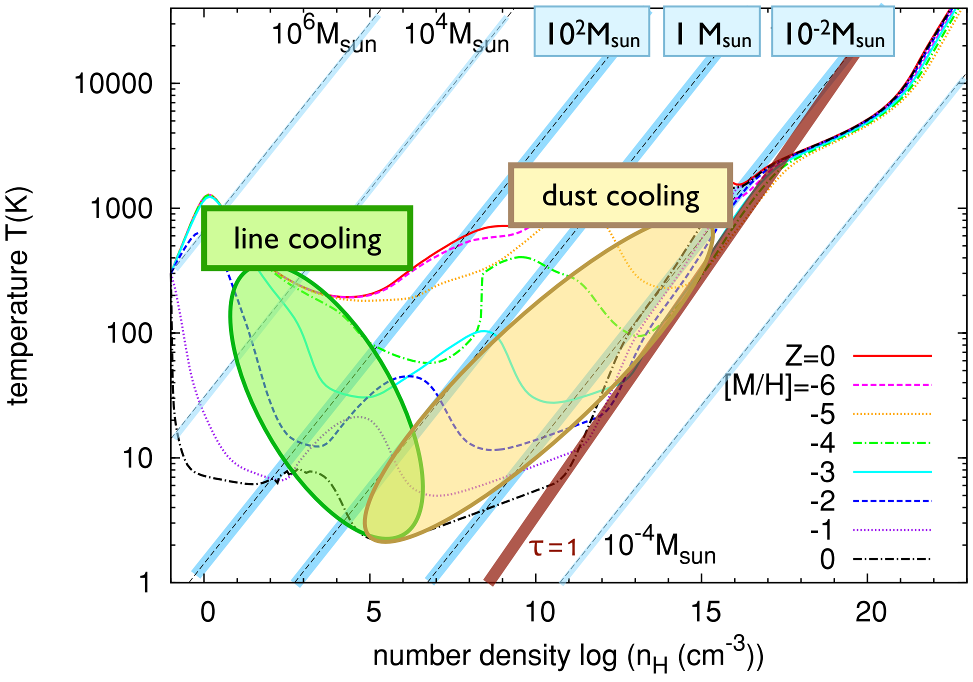
(Jappsen et al. 2005, A&A, 435, 611)

EOS as function of metallicity



(Omukai et al. 2005, 2010)

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 ($Z > 10^{-5...-6} Z_{sun}$)

NB: line cooling would only make very massive stars, with M > few x10 M_{sun}.

(Omukai et al. 2005, 2010)

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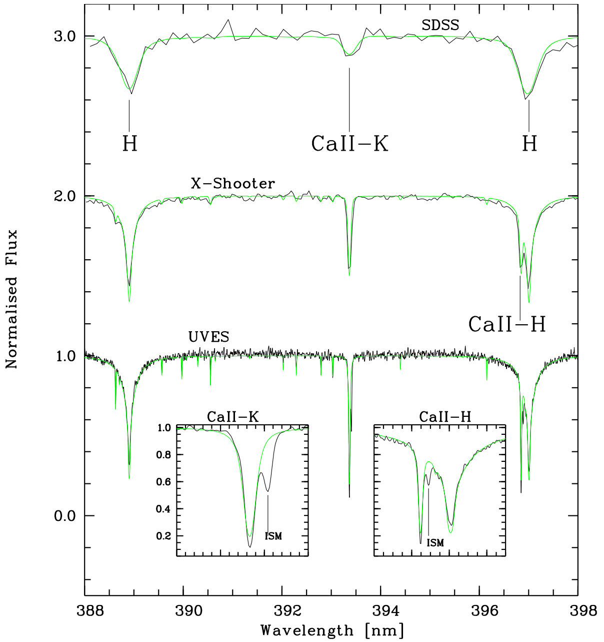

SDSS J1029151+172927

- 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)

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inferring masses of previous generations of stars based on the Leo star abundance patterns (Heger et al., see also Tominaga et al. 2007, Izutani et al. 2009, Joggerst et al. 2009, 2010)

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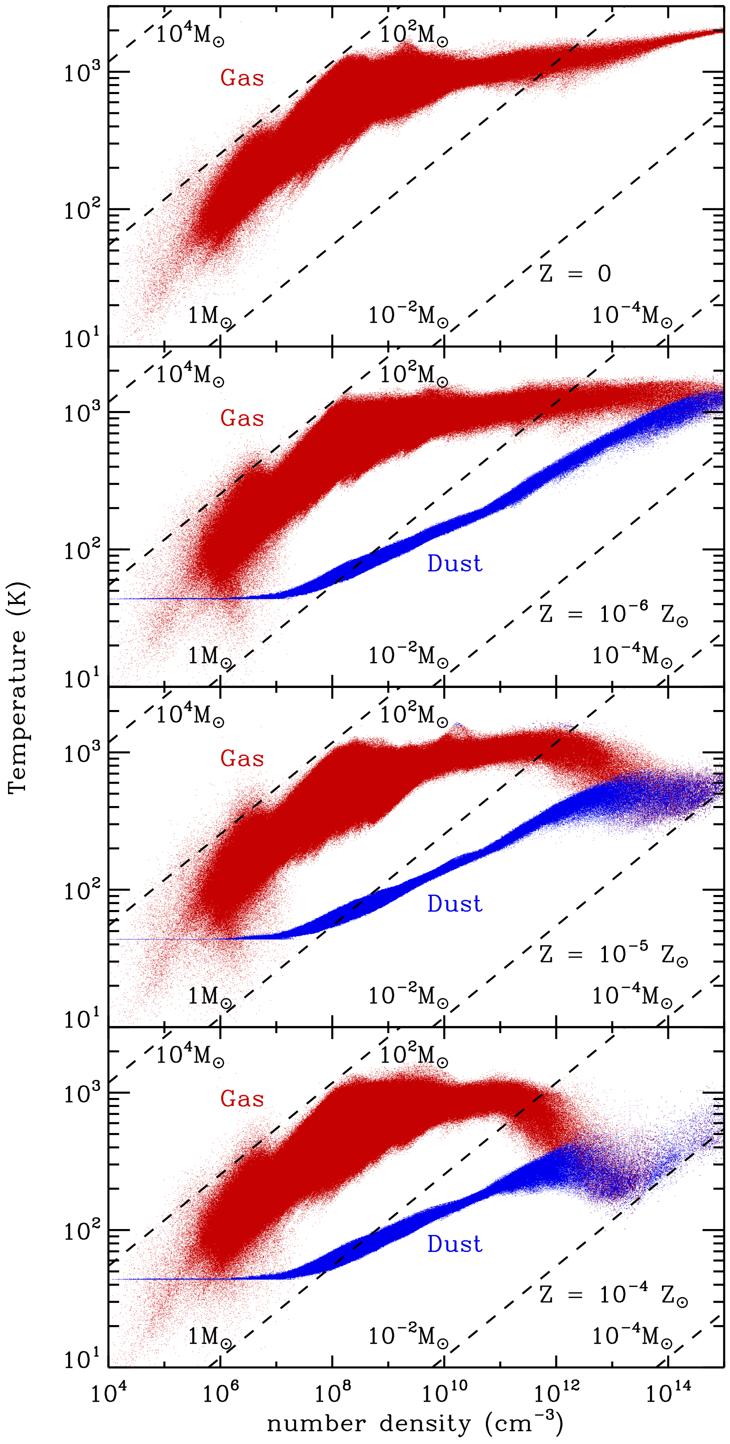
Fe I	−4.73 ± 0.13	−5.02 ± 0.10	−4.60 ± 0.13	−4.89 ± 0.10	43	1.0	7.52
Ni I	−4.55 ± 0.14	−4.90 ± 0.11			10		6.23
Sr II	≤ −5.10	≤ −5.25	≤ −4.94	≤ −5.09	1	0.01	2.92

(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)



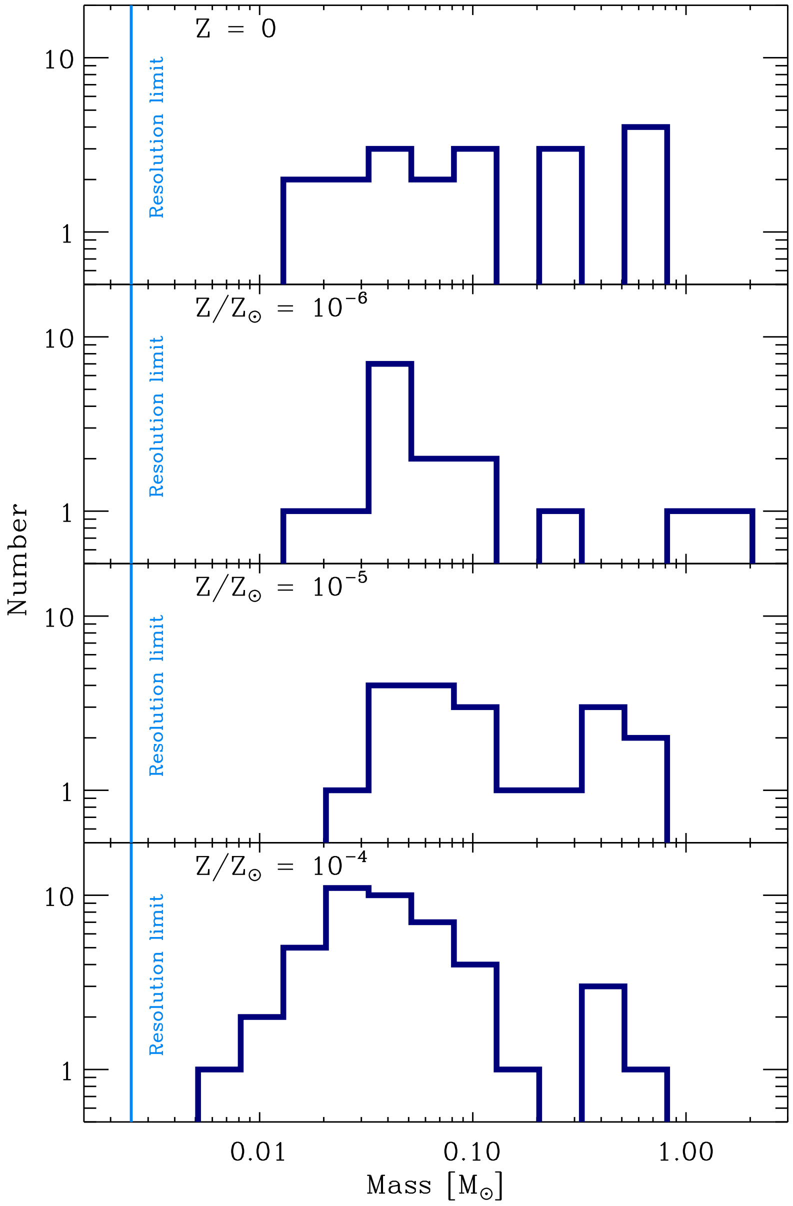
[M/H] = -ininity

[M/H] = -6

[M/H] = -5

[M/H] = -4

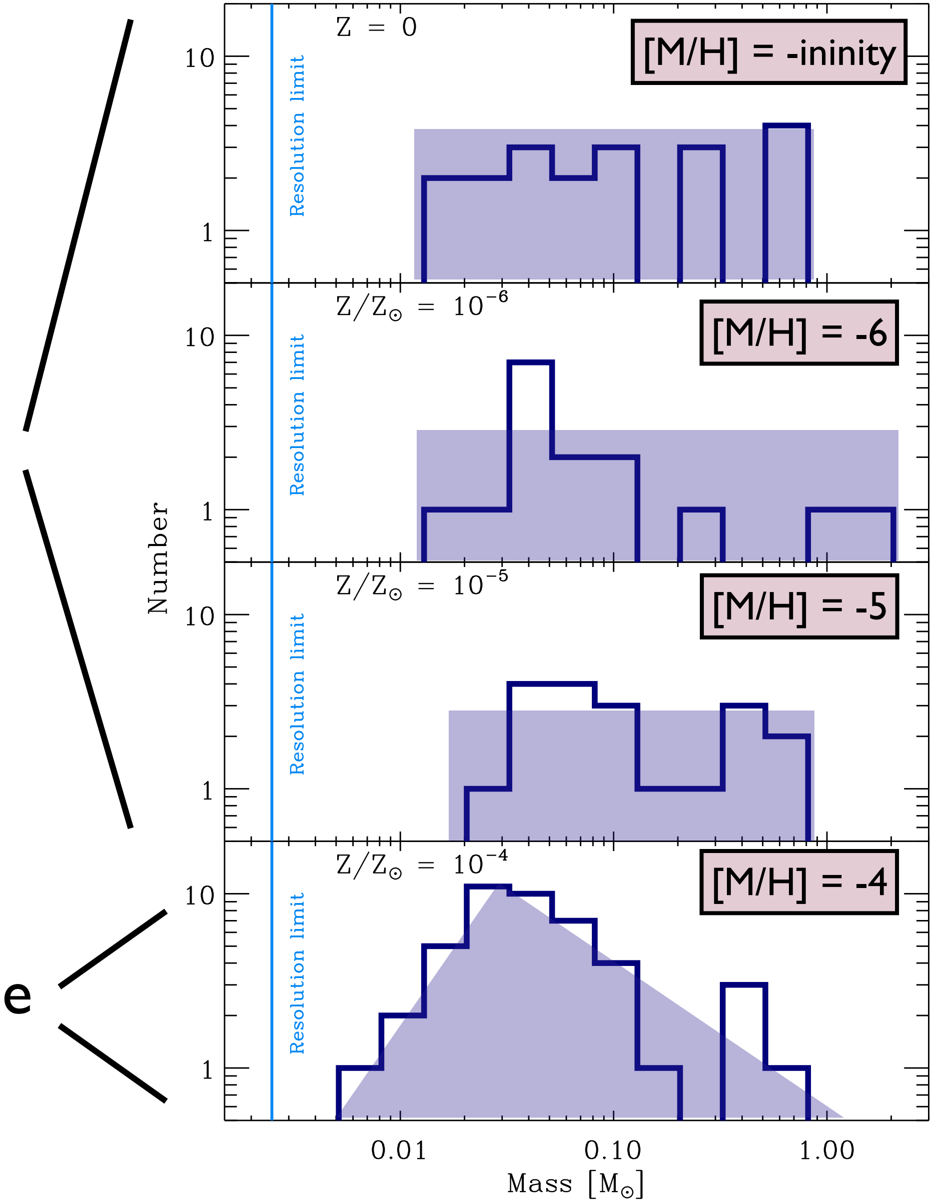
red : gas
blue: dust



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

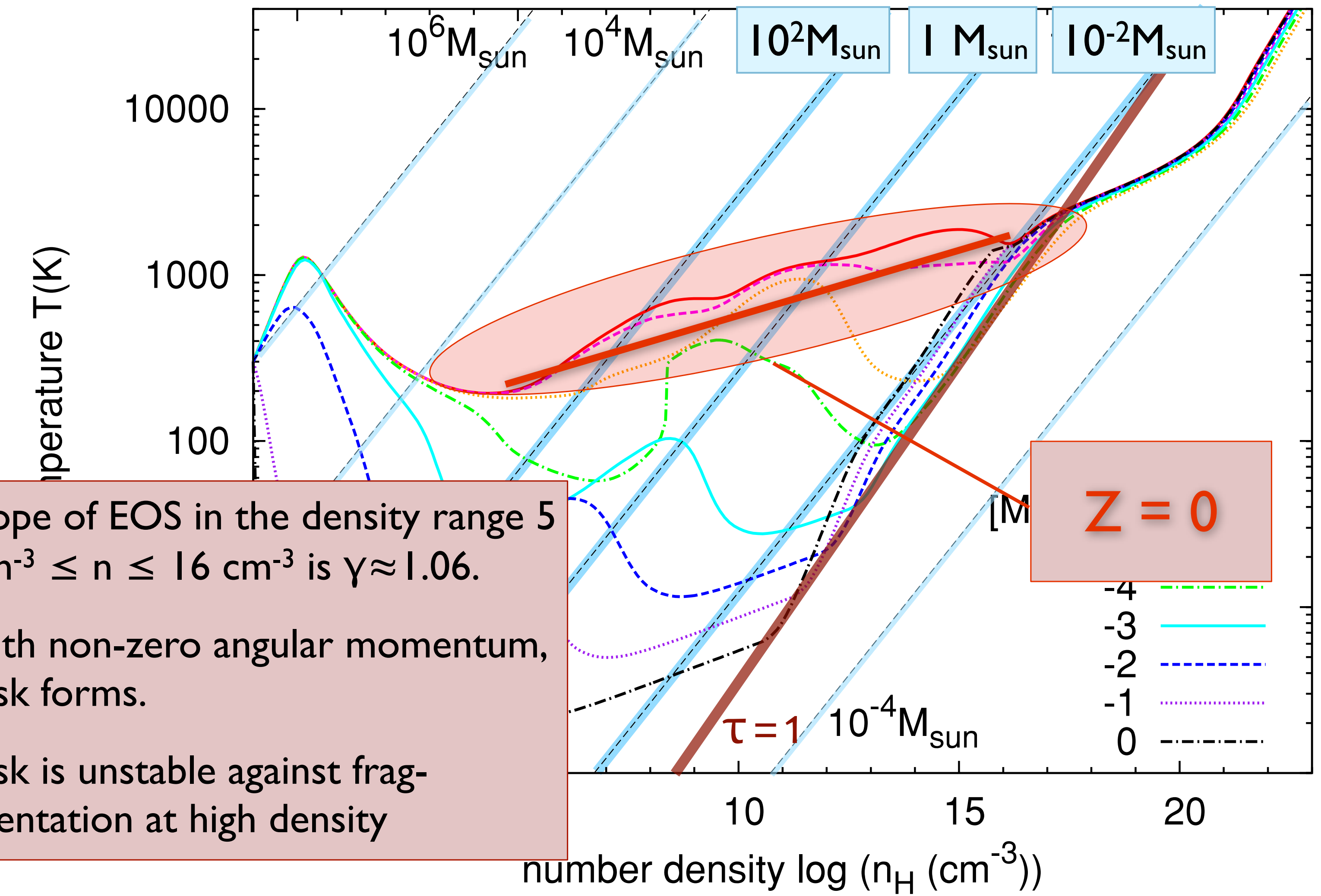
disk fragmentation mode

gravoturbulent fragmentation mode



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

EOS as function of metallicity



Z = 0

- 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 fragmentation at high density

(Omukai et al. 2005, 2010)

“classical” picture

- 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)

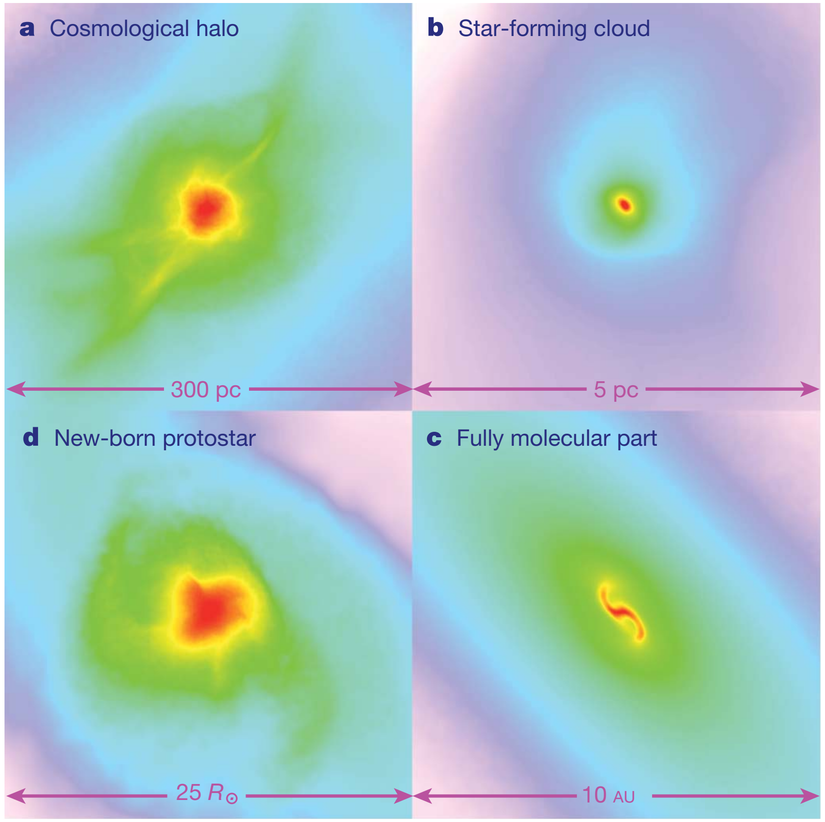
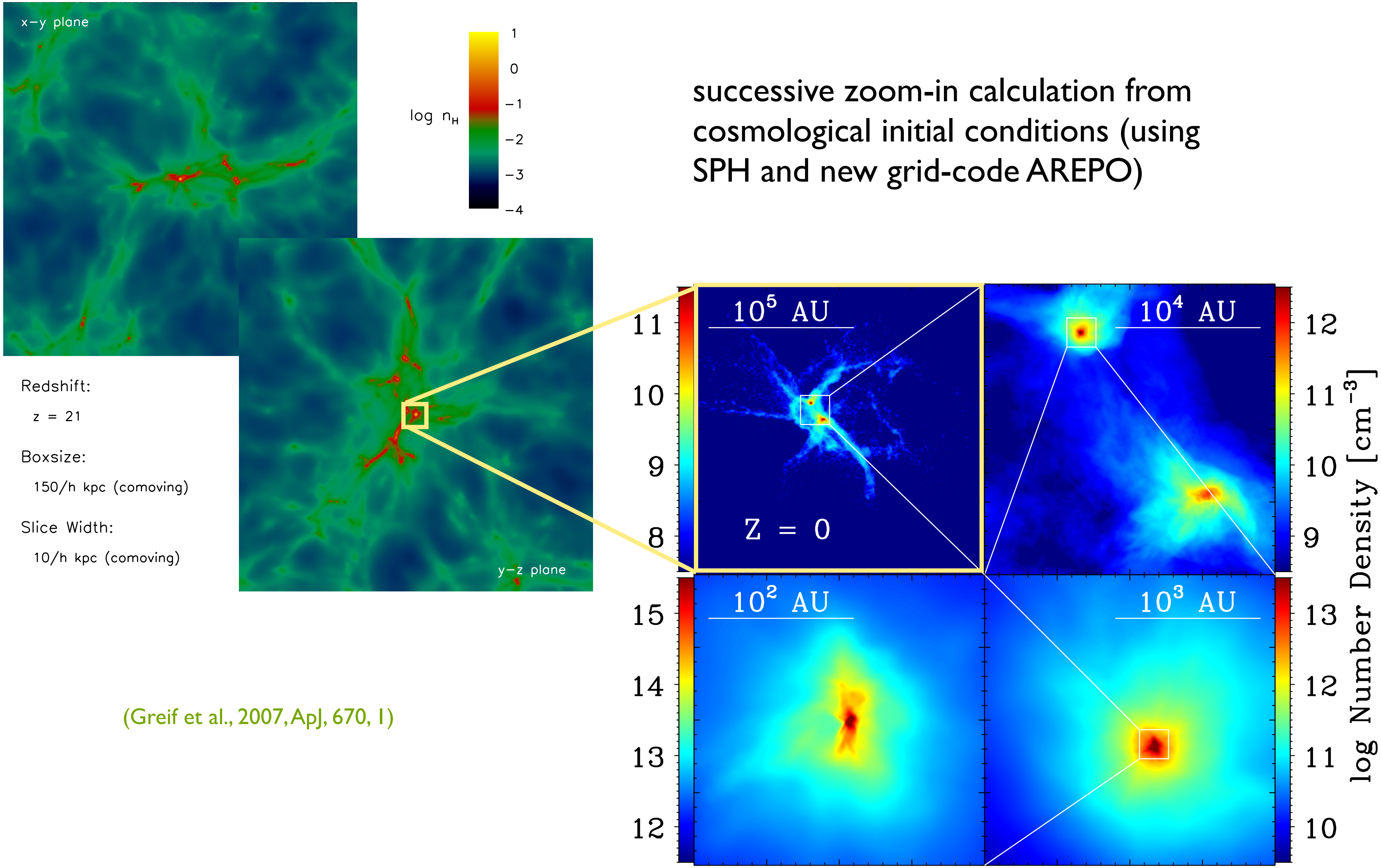


Figure 1 | Projected gas distribution around a primordial protostar. Shown is the gas density (colour-coded so that red denotes highest density) of a single object on different spatial scales. **a**, The large-scale gas distribution around the cosmological minihalo; **b**, a self-gravitating, star-forming 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)

detailed look at accretion disk around first star

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

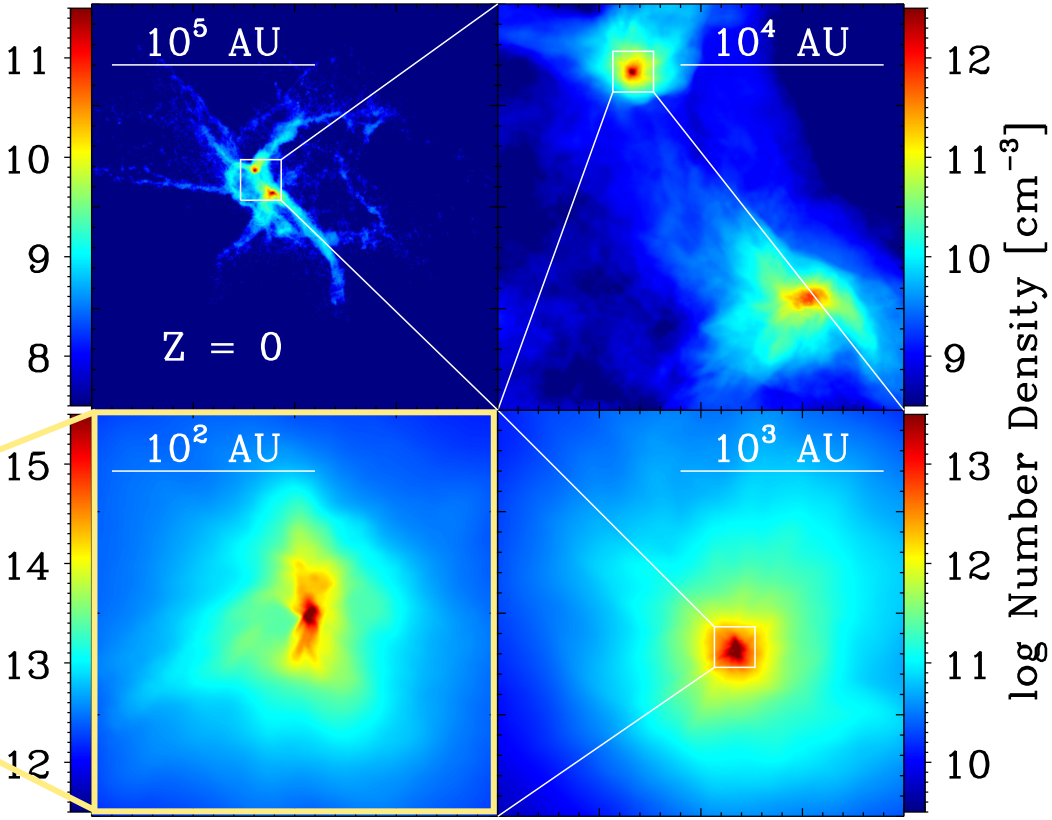


(Greif et al., 2007, ApJ, 670, 1)

(Greif et al. 2011, ApJ, 737, 75, Dopcke et al. 2012, ApJ submitted, arXiv1203.6842)

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, Dopcke et al. 2012, ApJ submitted, arXiv1203.6842)

detailed look at accretion disk

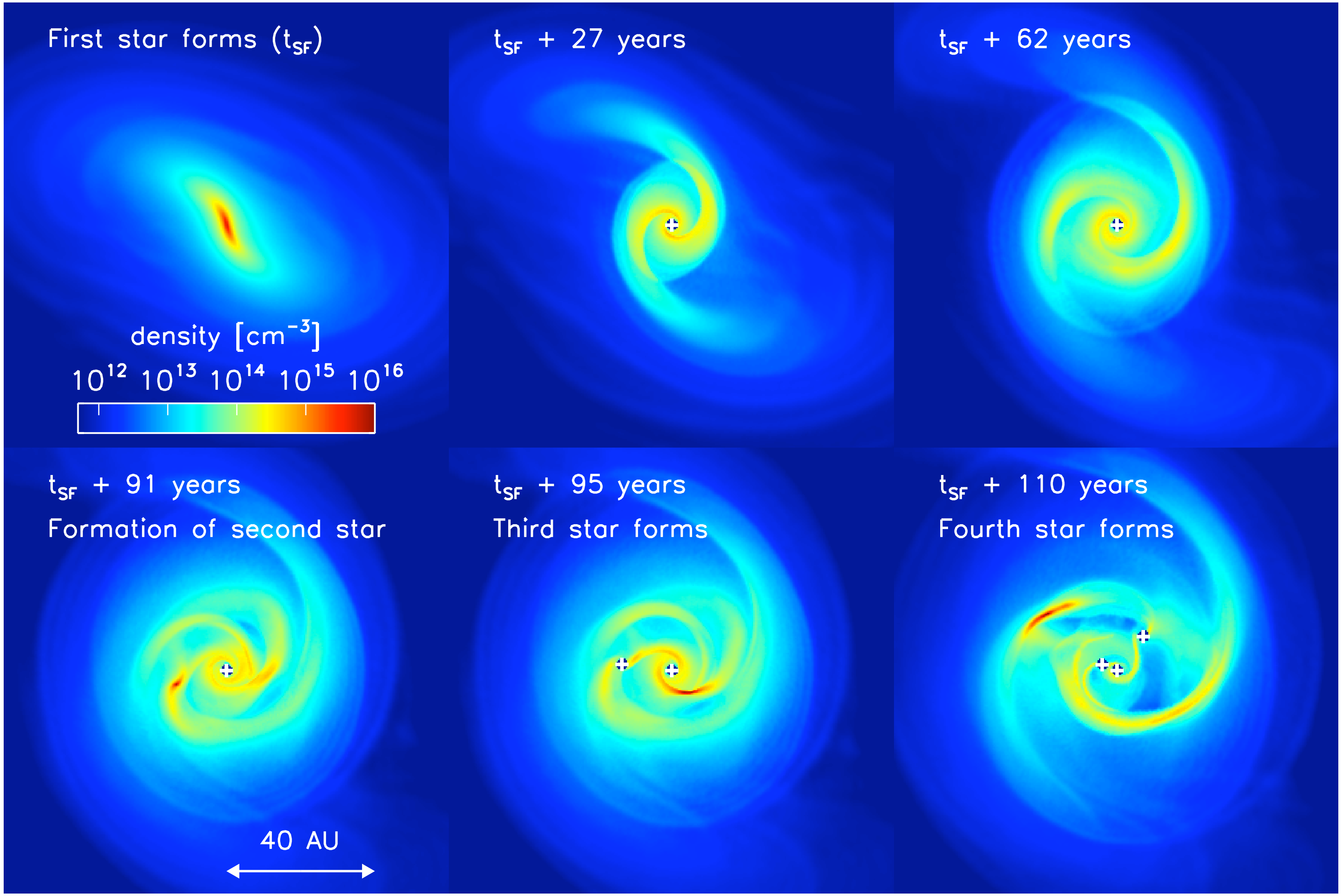
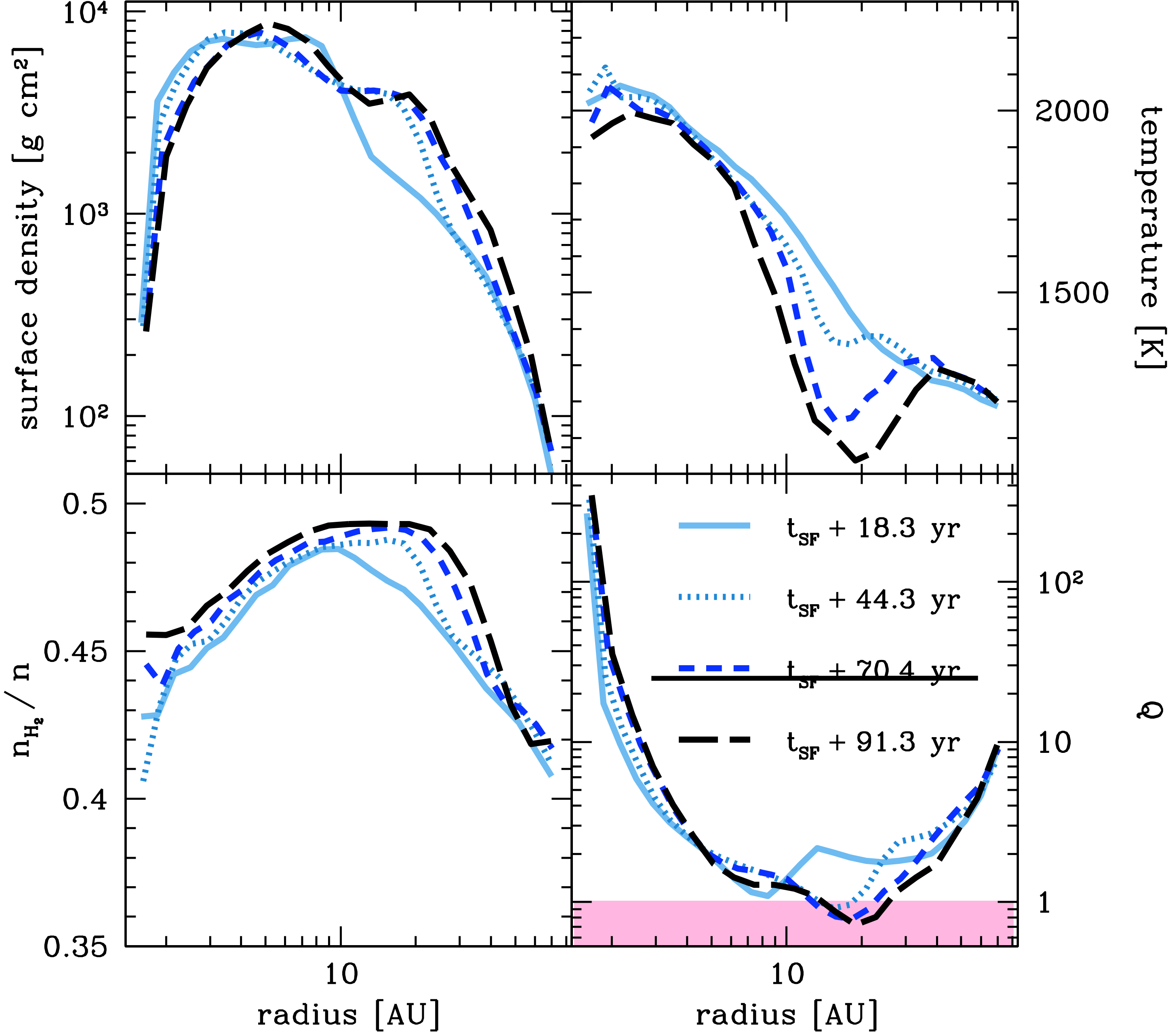


Figure 1: Density evolution in a 120 AU region around the first protostar, showing the build-up of the protostellar disk and its eventual fragmentation. We also see 'wakes' in the low-density regions, produced by the previous passage of the spiral arms.

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

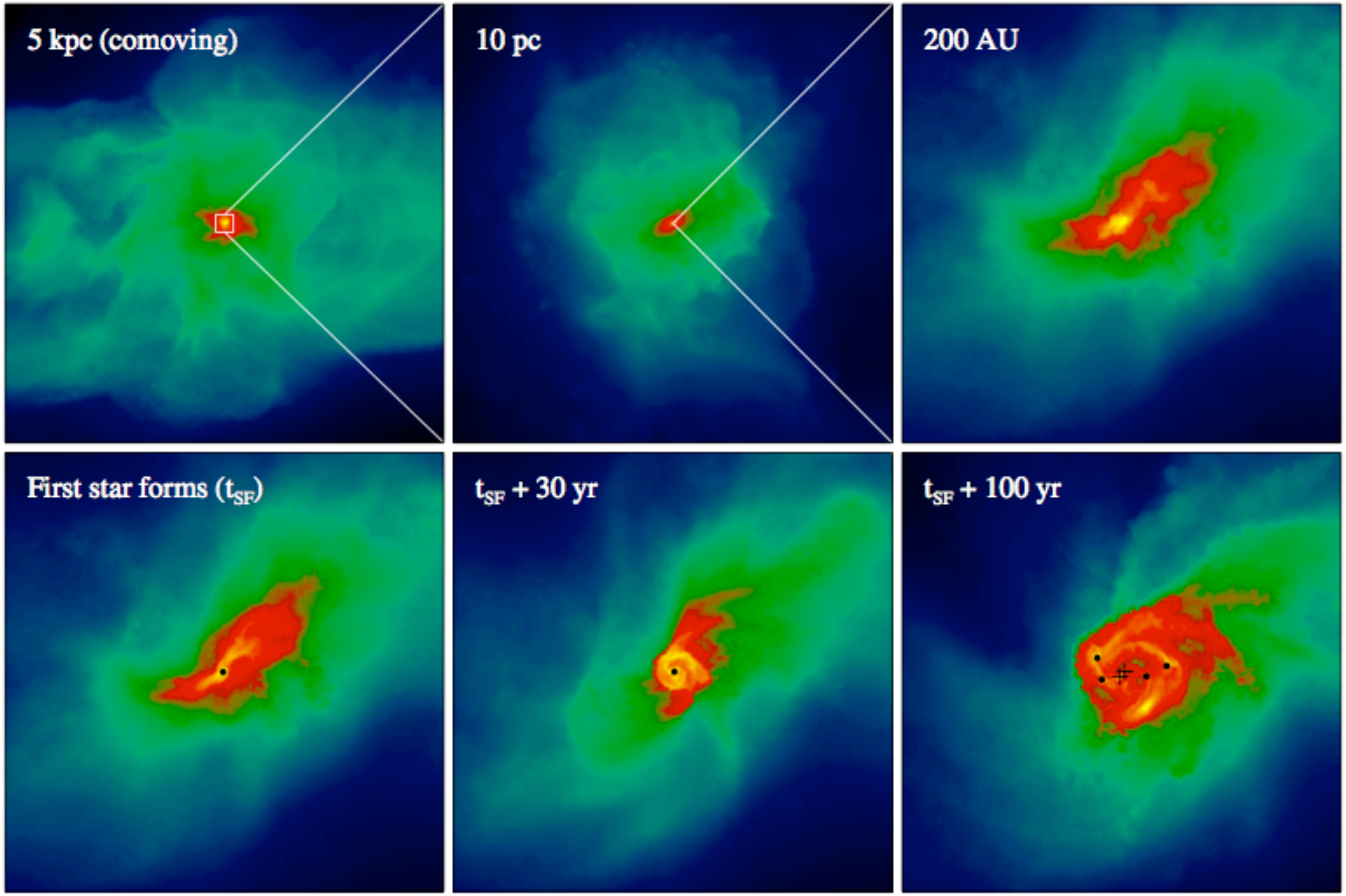
important disk parameters



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

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

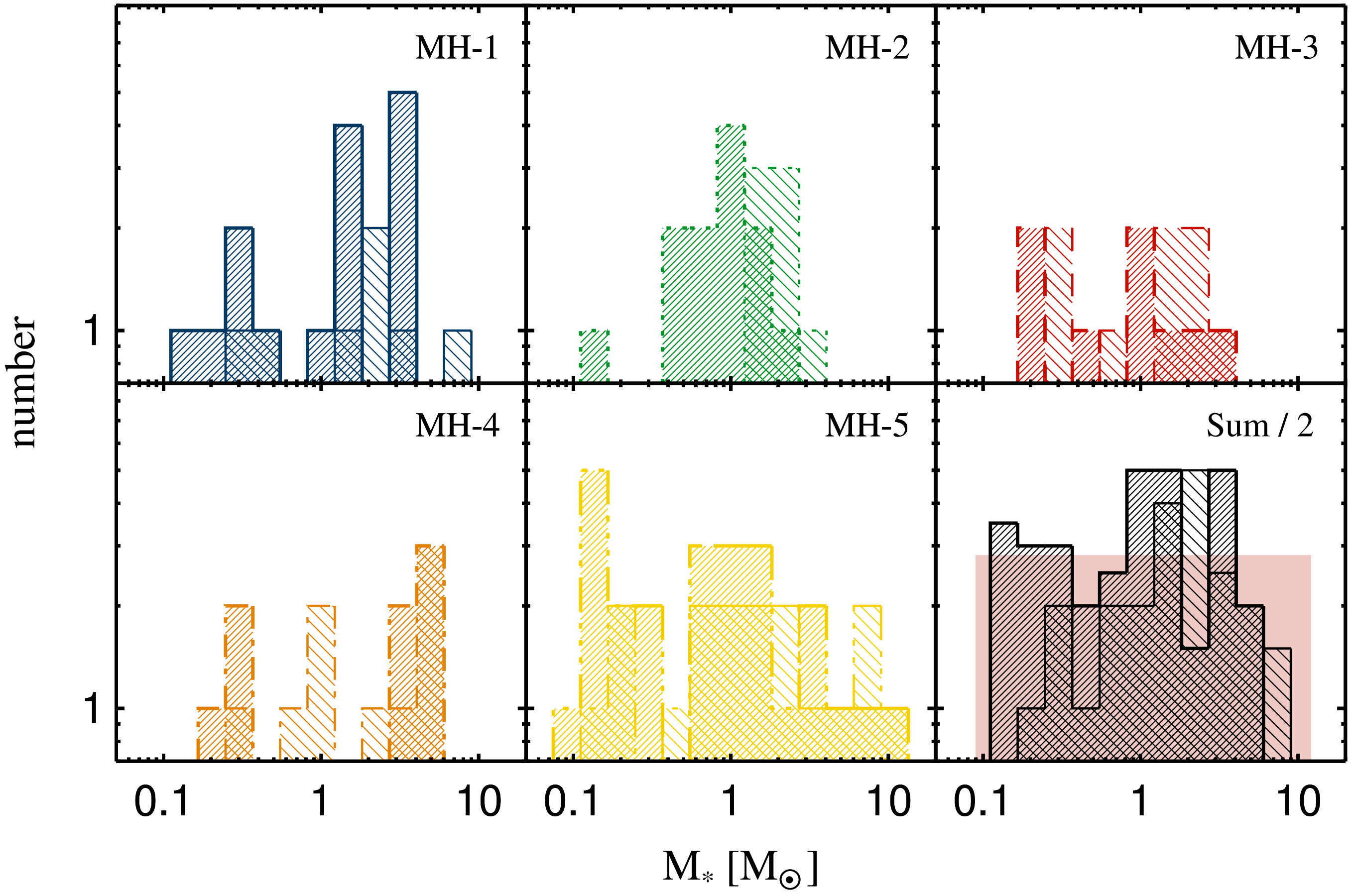
similar study with very different numerical method (AREPO)



one out of five halos

(Greif et al. 2011a, ApJ)

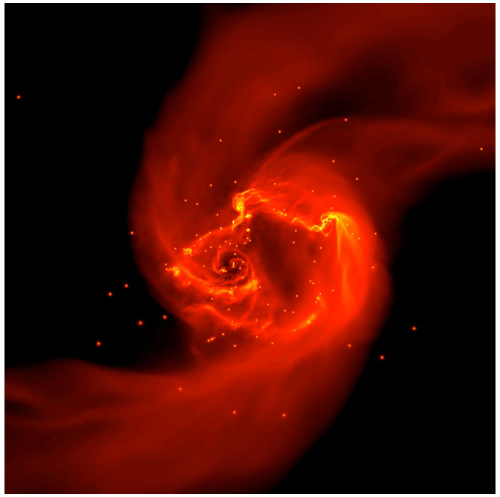
expected mass spectrum



we see “flat” mass spectrum

(Greif et al. 2011, ApJ, 737, 75, also Dopcke et al. 2012 ApJ submitted, arXiv1203.6842)

primordial star formation

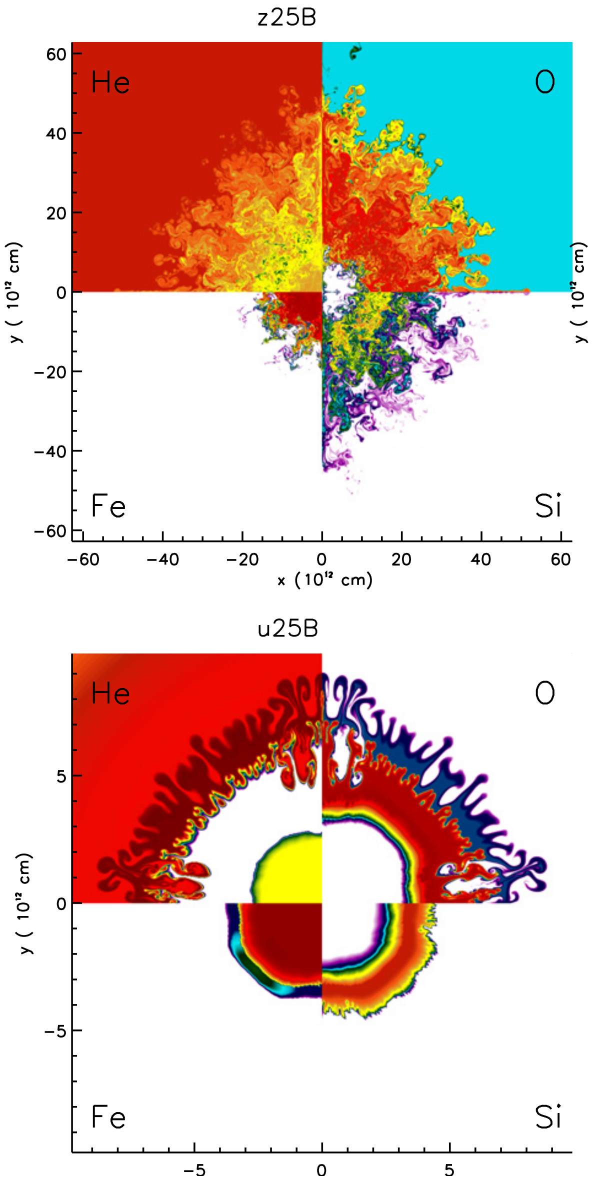


- just like in present-day SF, we expect
  - *turbulence*
  - *thermodynamics*
  - *feedback*
  - *magnetic fields*

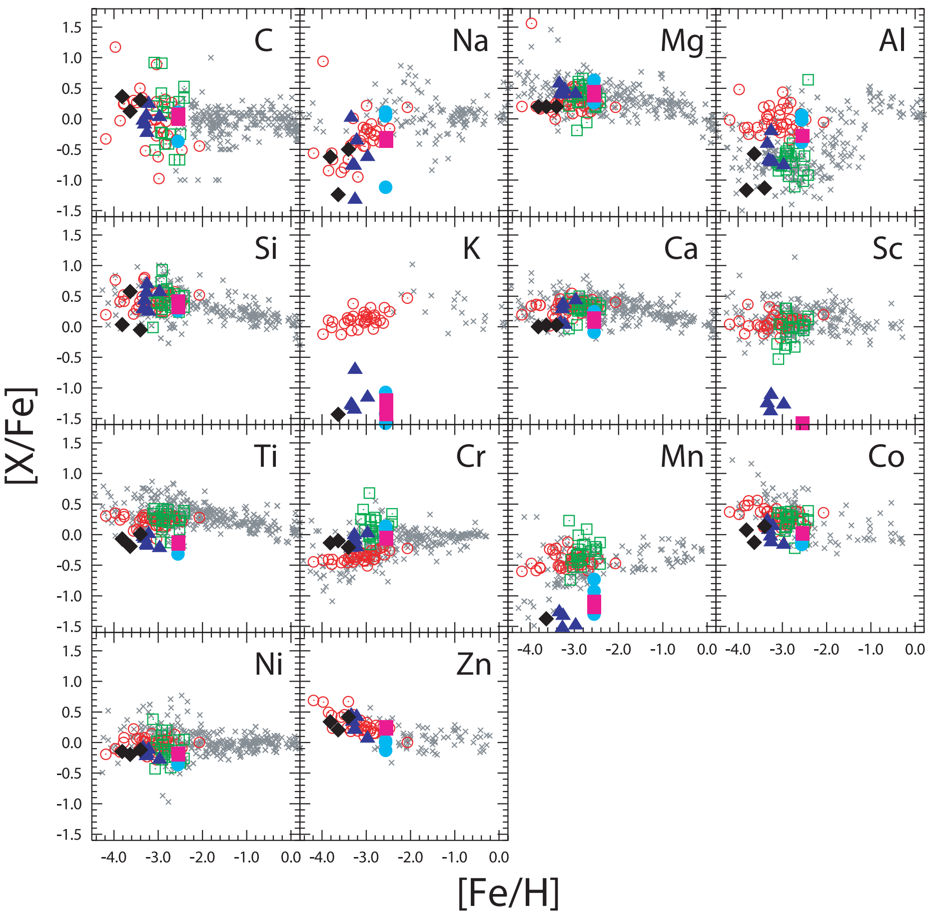
  to influence first star formation.
- masses of first stars still *uncertain* (surprises from new generation of high-resolution calculations that go beyond first collapse)
- disks unstable: first stars should be *binaries* or *part of small clusters*
- effects of feedback less important than in present-day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

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)

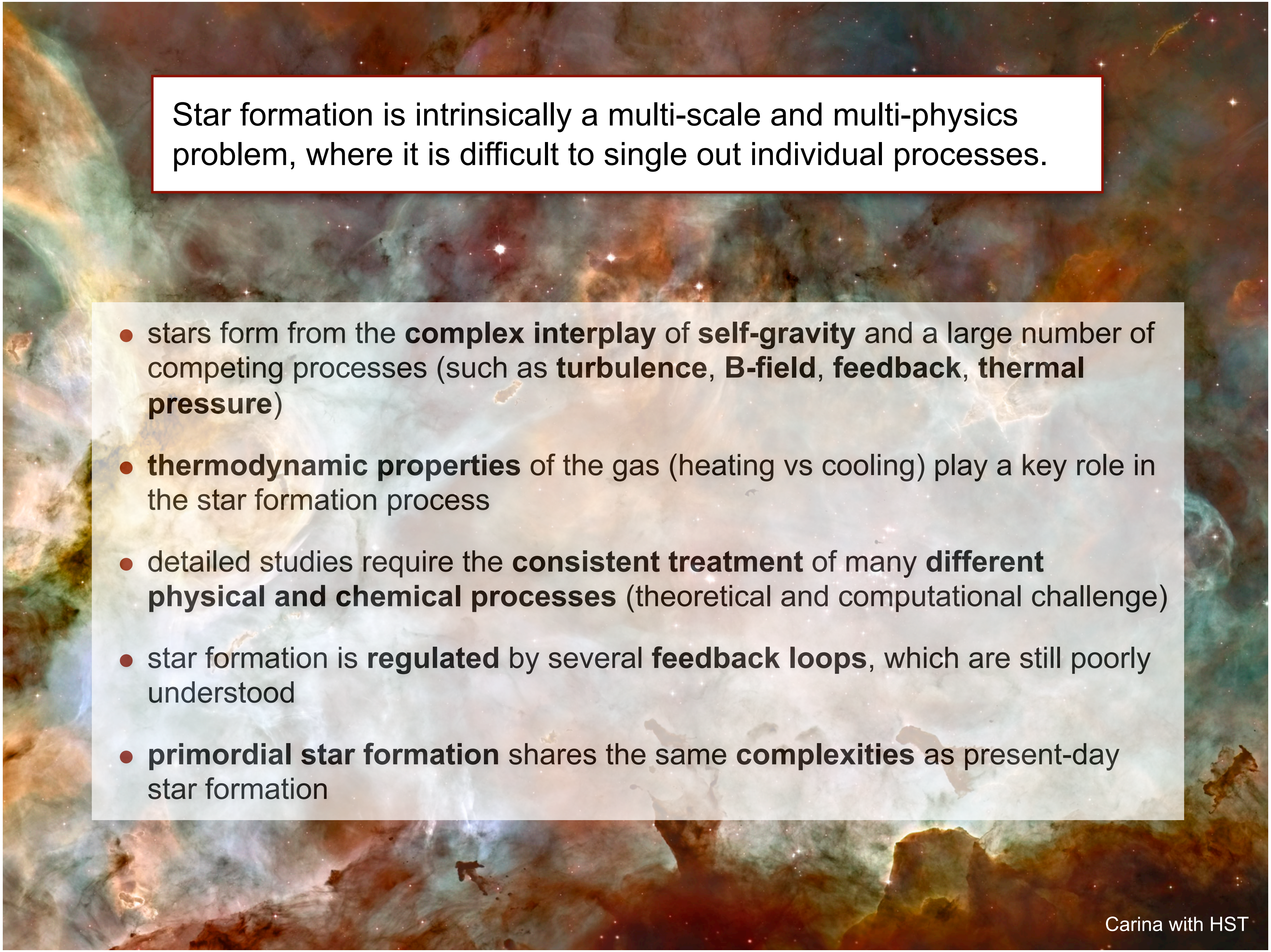
The metallicities of extremely metal-poor stars in the halo are consistent with the yields of core-collapse supernovae, i.e. progenitor stars with 20 - 40 $M_\odot$

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

Carina with HST

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

- stars form from the **complex interplay** of **self-gravity** and a large number of competing processes (such as **turbulence**, **B-field**, **feedback**, **thermal pressure**)
- **thermodynamic properties** of the gas (heating vs cooling) play a key role in the star formation process
- detailed studies require the **consistent treatment** of many **different physical and chemical processes** (theoretical and computational challenge)
- star formation is **regulated** by several **feedback loops**, which are still poorly understood
- **primordial star formation** shares the same **complexities** as present-day star formation



Carina with HST

Protostars and Planets VI in Summer 2013

July 15 - 20

... hope to see you there!!!

(www.ppvi.org)