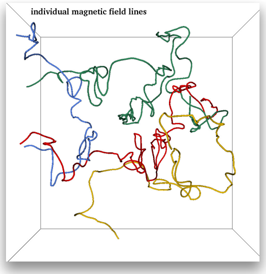
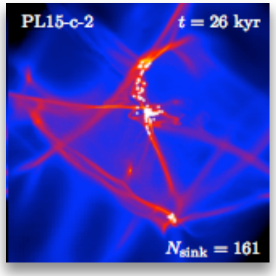
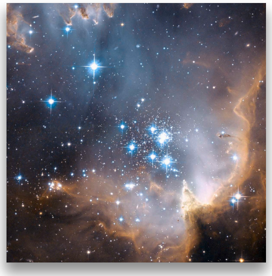
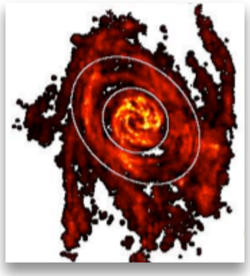
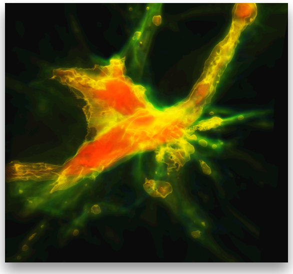
The IMF at different metallicities







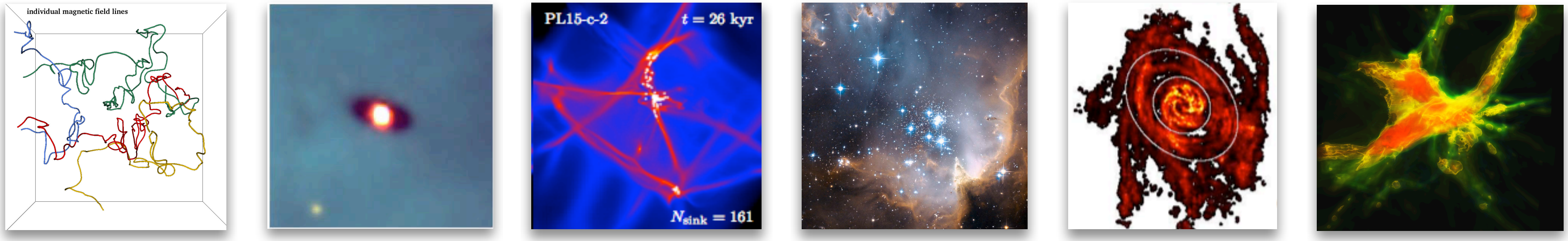




Ralf Klessen

Universität Heidelberg, Zentrum für Astronomie
Institut für Theoretische Astrophysik

Some Open Issues in Star Formation



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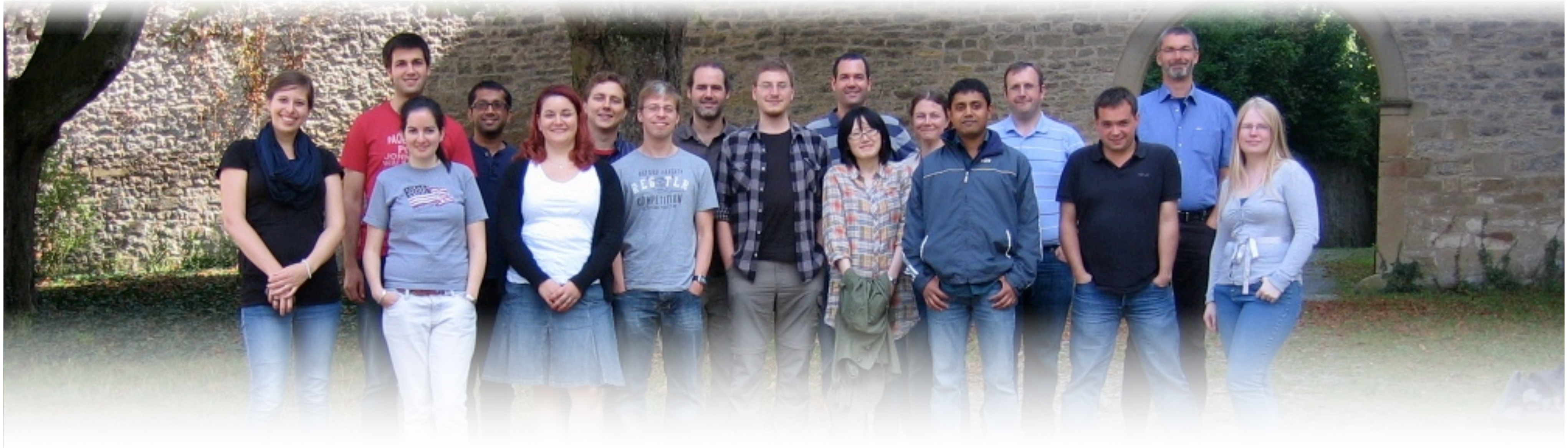
thanks to ...



... 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, Sharanya Sur

... many collaborators abroad!

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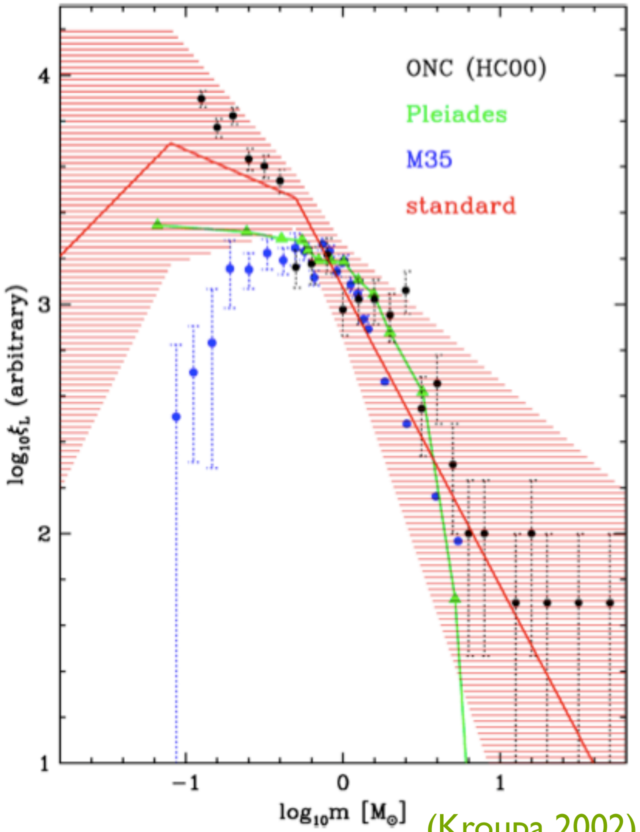
Wir stiften Zukunft

HGSFP

IMPRS

stellar mass fuction

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



(Kroupa 2002)

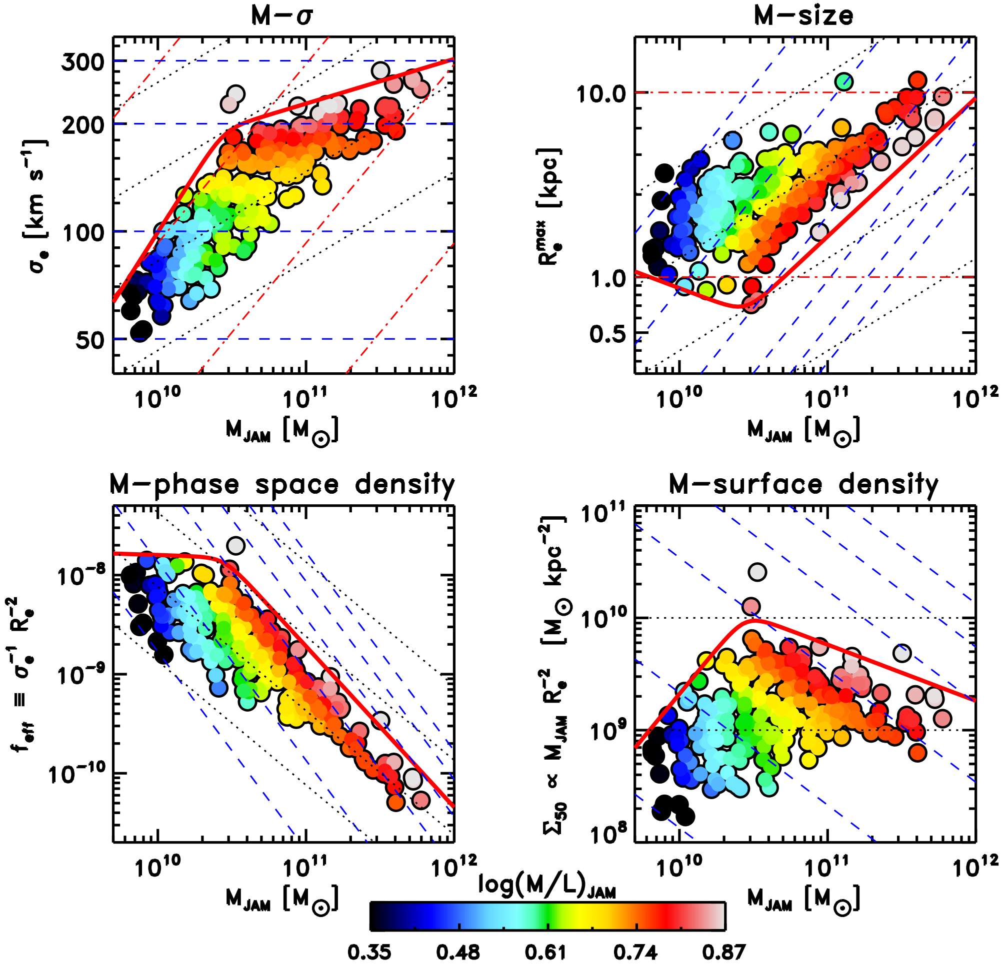
Orion, NGC 3603, 30 Doradus
(Zinnecker & Yorke 2007)

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)

IMF

- distribution of stellar masses depends on
  - turbulent initial conditions
    --> mass spectrum of prestellar cloud cores
  - collapse and interaction of prestellar cores
    --> competitive 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

(e.g. Larson 2003, Prog. Rep. Phys.; Mac Low & Klessen, 2004, Rev. Mod. Phys, 76, 125 - 194)

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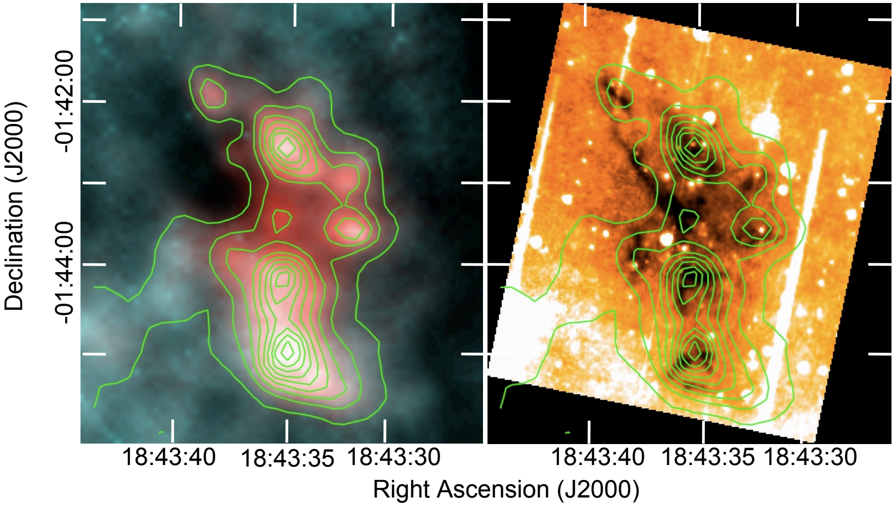
initial conditions for cluster formation

ICs of star cluster formation

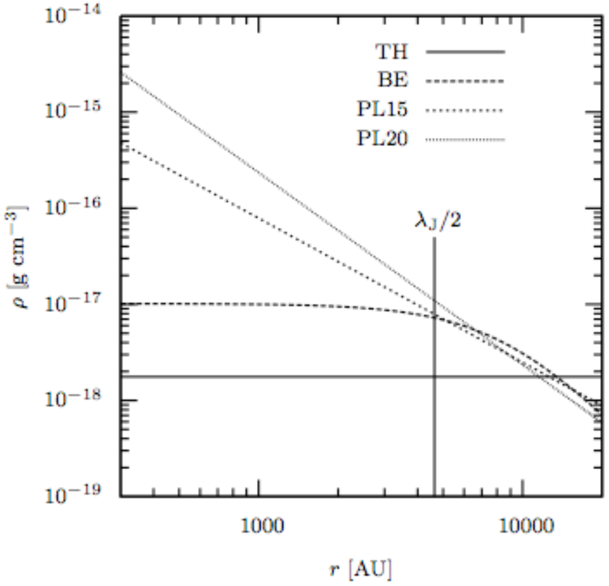
- key question:
  - what is the initial density profile of cluster forming cores? how does it compare low-mass cores?
- observers answer:
  - very difficult to determine!
    - most high-mass cores have some SF inside
    - infra-red dark clouds (IRDCs) are difficult to study
  - but: new results with Herschel



IRDC observed with Herschel, Peretto et al. (2010)

different density profiles

- 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, et
  - power law $\rho \propto r^{-2}$ (Shu)
  - and many more



different density profiles

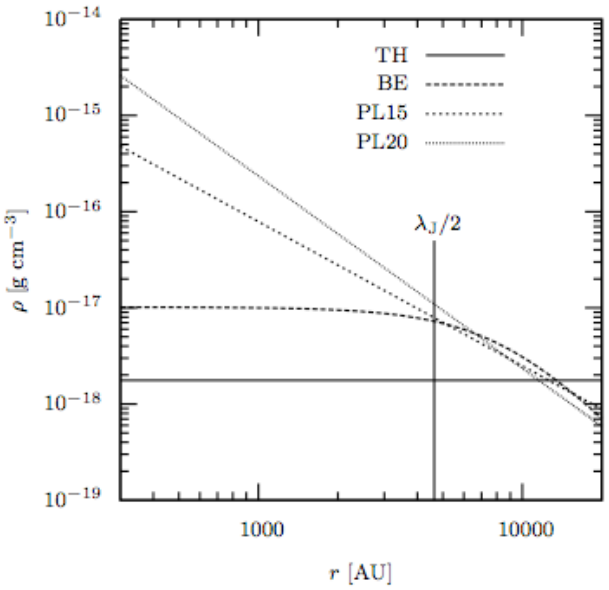
- does the density profile matter?

  .

  .

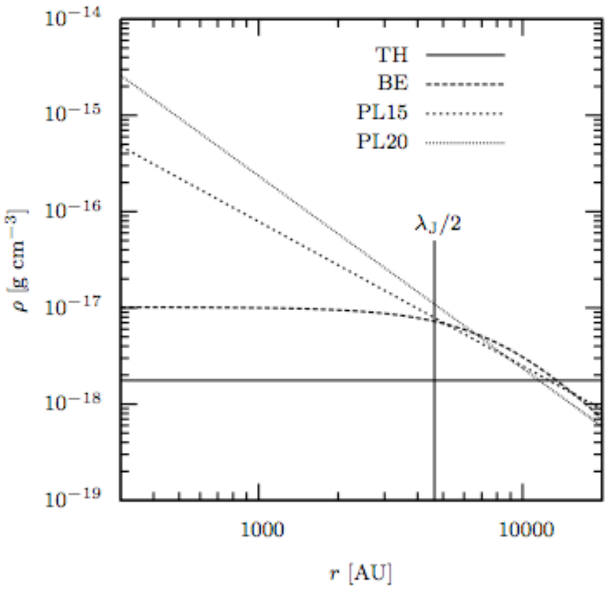
  .

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

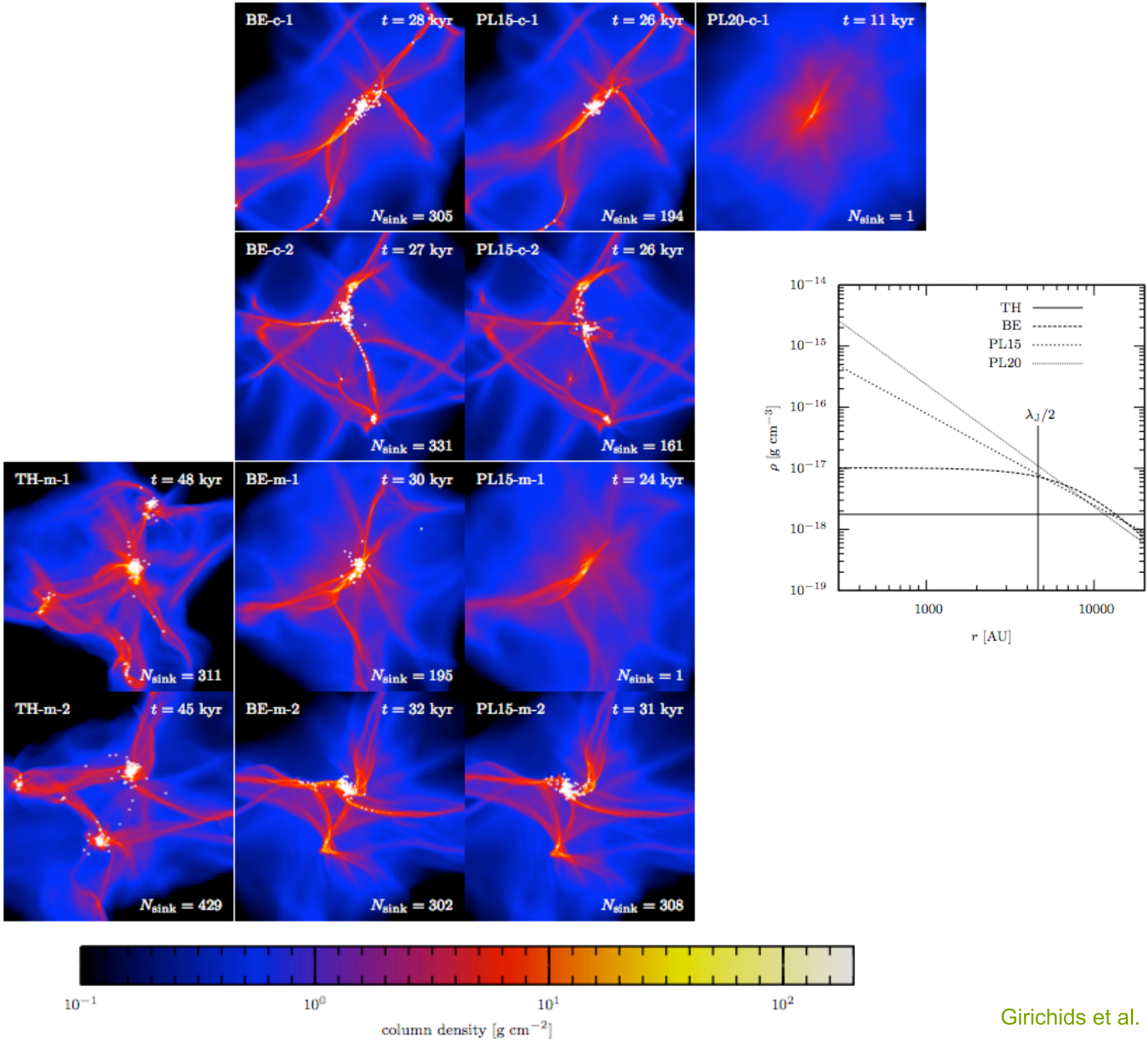


different density profiles

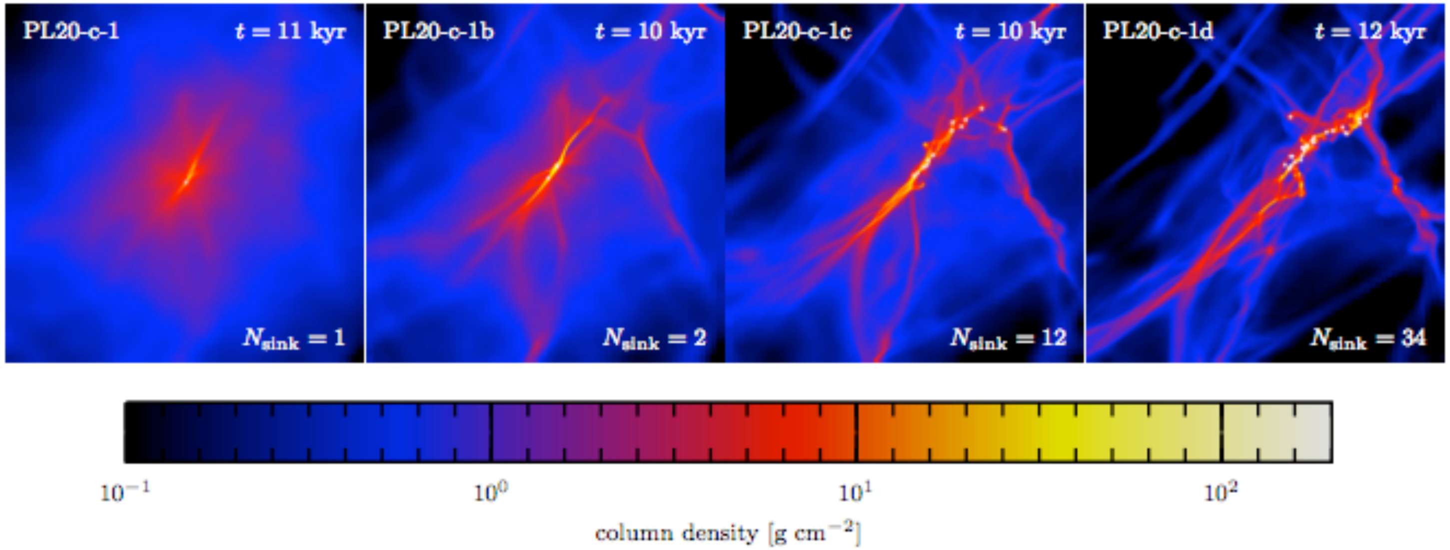
- address question in simple numerical experiment
- perform extensive parameter study
  - different profiles (top hat, BE, $r^{-3/2}$, r^{-3})
  - different turbulence fields
    - different realizations
    - different Mach numbers
    - solenoidal turbulence
      dilatational turbulence
      both modes
  - no net rotation, no B-fields
    (at the moment)



Girichids, Federrath, Banerjee, Klessen (2011abc)



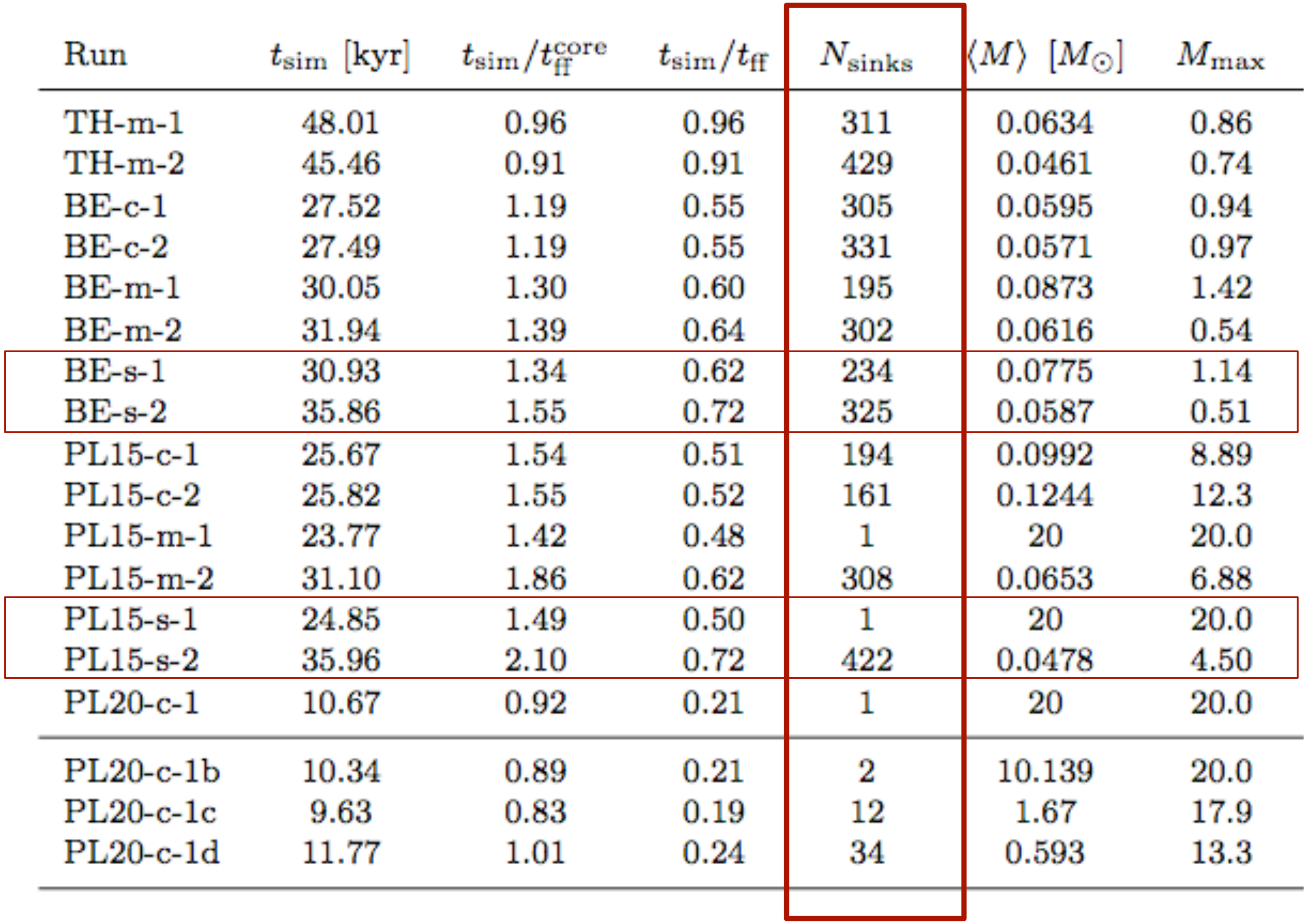
Girichids et al. (2011abc)



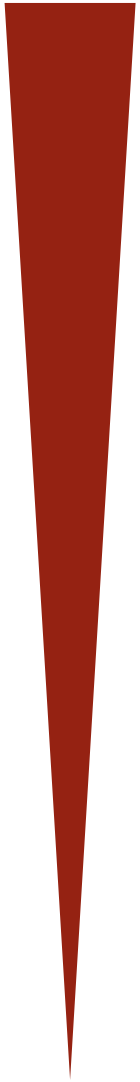
M=3 M=6 M=12 M=18

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

Girichids et al. (2011abc)



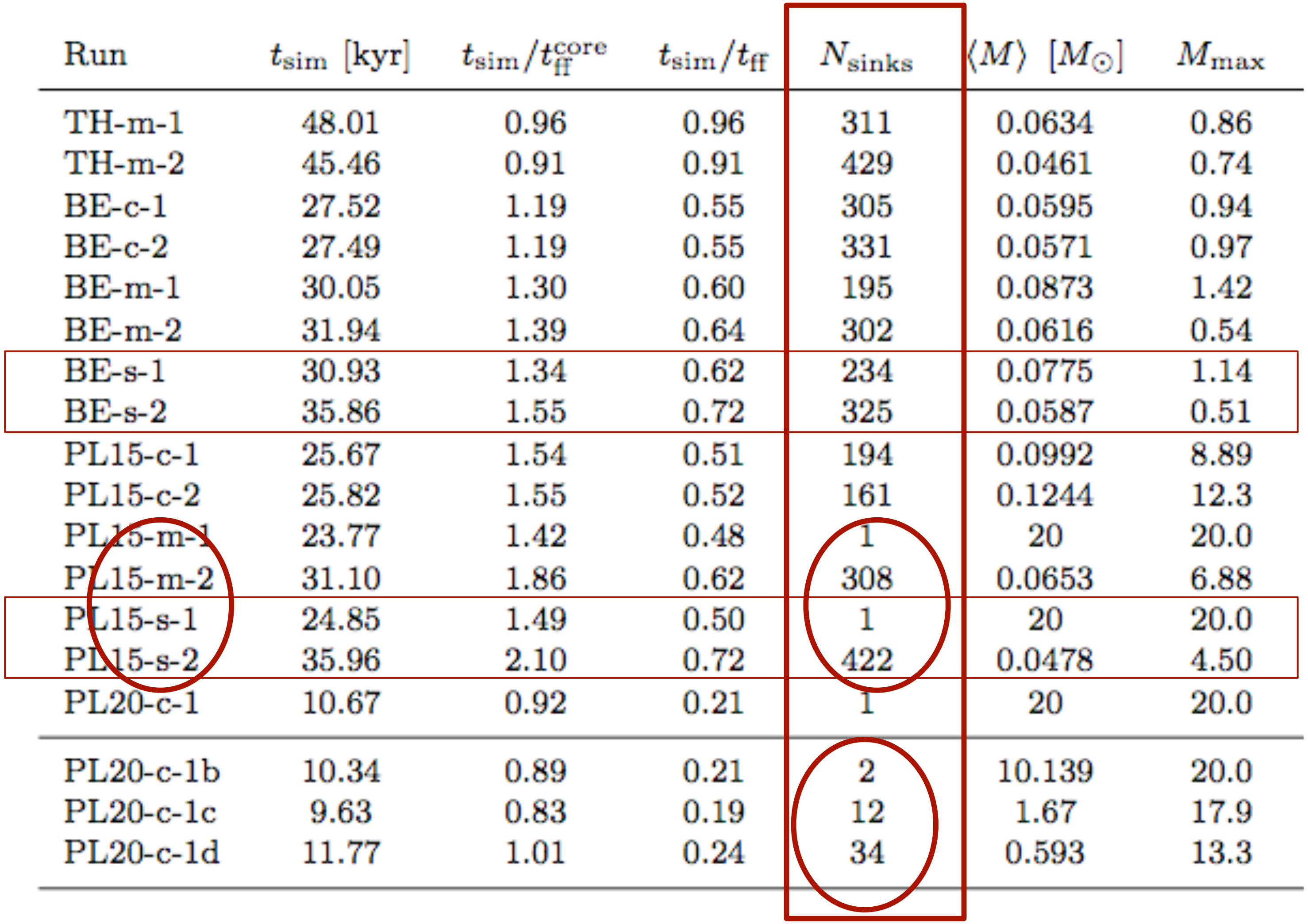
Run	$t_{\rm sim}$ [kyr]	$t_{\rm sim}/t_{\rm ff}^{\rm core}$	$t_{\rm sim}/t_{\rm ff}$	$N_{\rm sinks}$	$\langle M \rangle$ [$M_\odot$]	$M_{\rm max}$
TH-m-1	48.01	0.96	0.96	311	0.0634	0.86
TH-m-2	45.46	0.91	0.91	429	0.0461	0.74
BE-c-1	27.52	1.19	0.55	305	0.0595	0.94
BE-c-2	27.49	1.19	0.55	331	0.0571	0.97
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 protostars

ICs with flat inner density profile form more fragments

Girichids et al. (2011abc)



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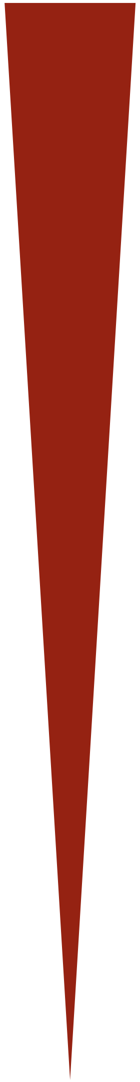

number of protostars

however, the real situation is very complex: details of the initial turbulent field matter

very high Mach numbers are needed to make SIS fragment

Girichids et al. (2011abc)

different density profiles

- different density profiles lead to very different fragmentation behavior
- fragmentation is strongly suppressed for very peaked, power-law profiles

- this is *good* because it may explain some of the theoretical controversy, we have in the field
- this is *bad*, because all current calculations are "wrong" in the sense that the formation process of the star-forming core is neglected.

Girichids et al. (2011abc)

IMF

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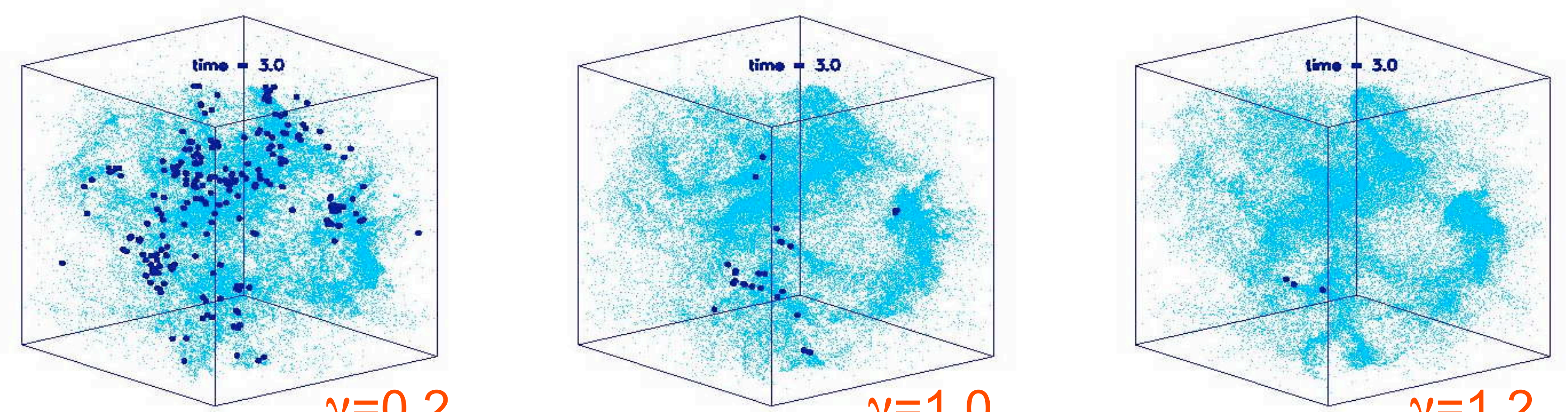
(e.g. Larson 2003, Prog. Rep. Phys.; Mac Low & Klessen, 2004, Rev. Mod. Phys, 76, 125 - 194)

dependency on EOS

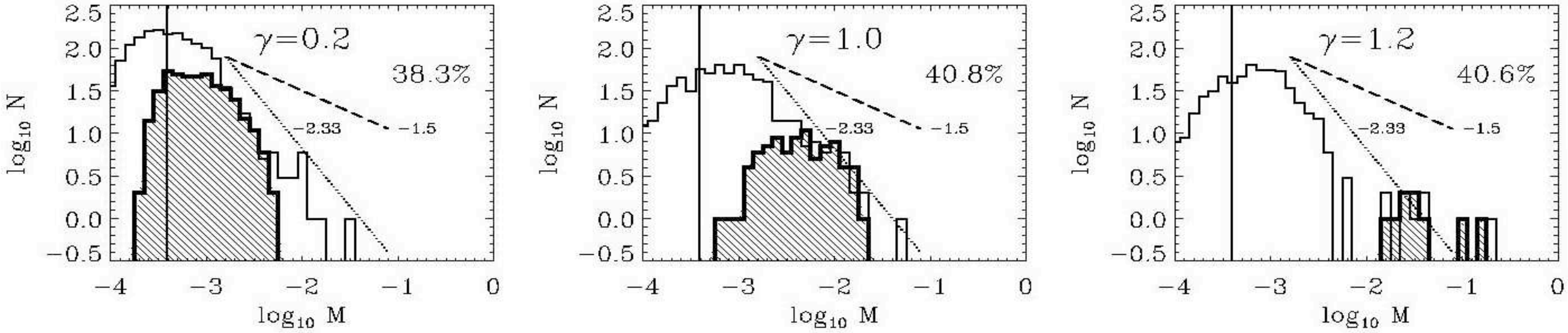
- degree of fragmentation depends on *EOS!*

- polytropic EOS: $p \propto \rho^{\gamma}$
- $\gamma<1$: dense cluster of low-mass stars
- $\gamma>1$: isolated high-mass stars
- (see Li, Klessen, & Mac Low 2003, ApJ, 592, 975; also Kawachi & Hanawa 1998, Larson 2003)

dependency on EOS



γ=0.2 γ=1.0 γ=1.2



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

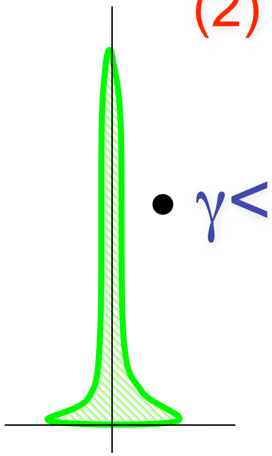
for $\gamma>1$ it is suppressed → formation of *isolated massive stars*

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

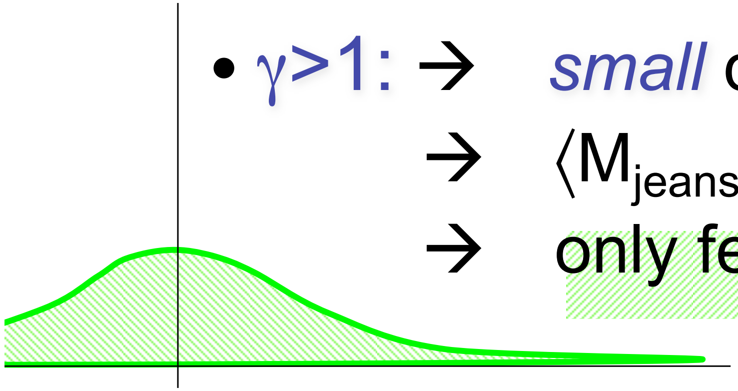
how does that work?

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

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



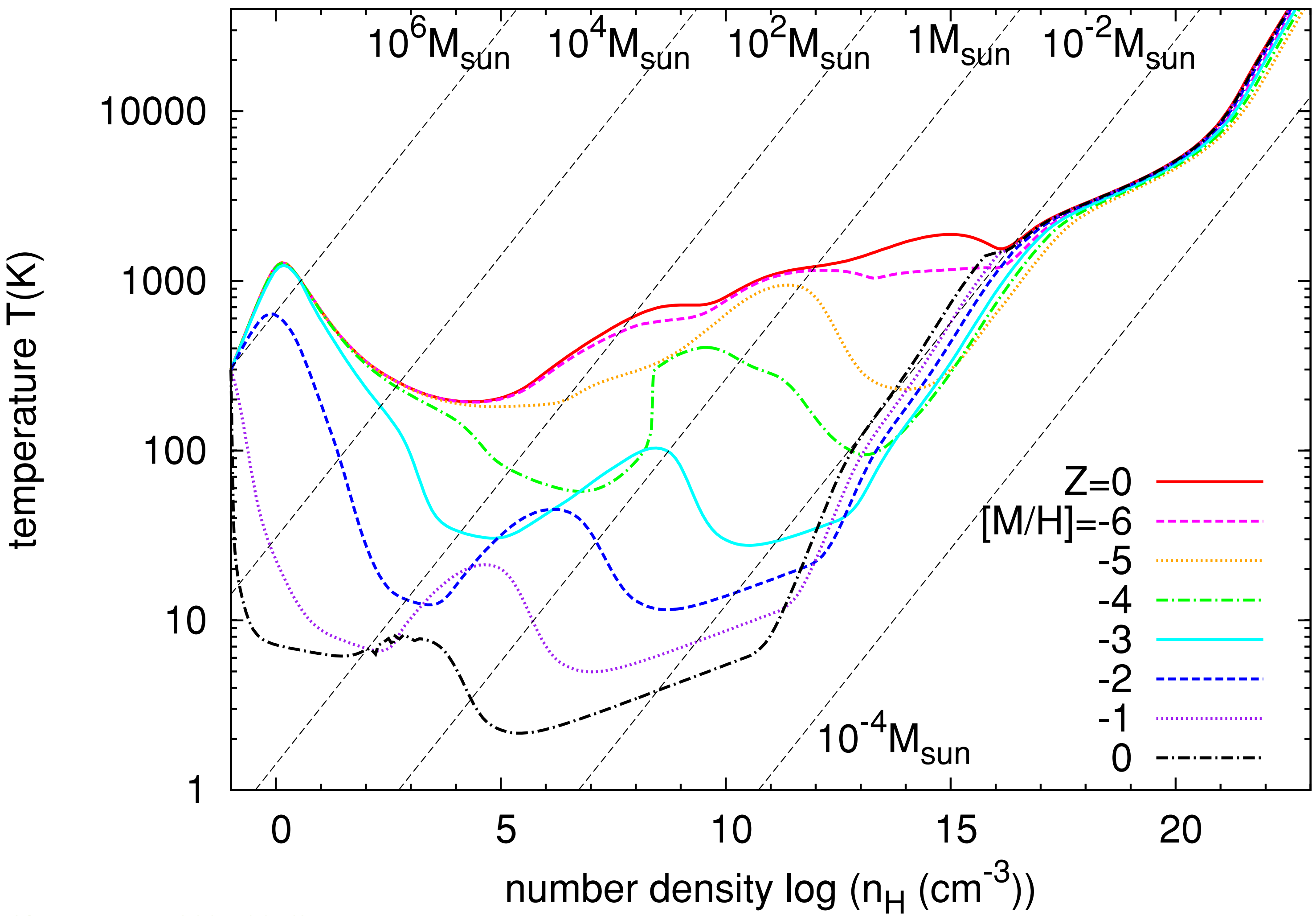
- $\gamma<1$: → *large* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ becomes small
  → number of fluctuations with $M > M_{jeans}$ is large



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

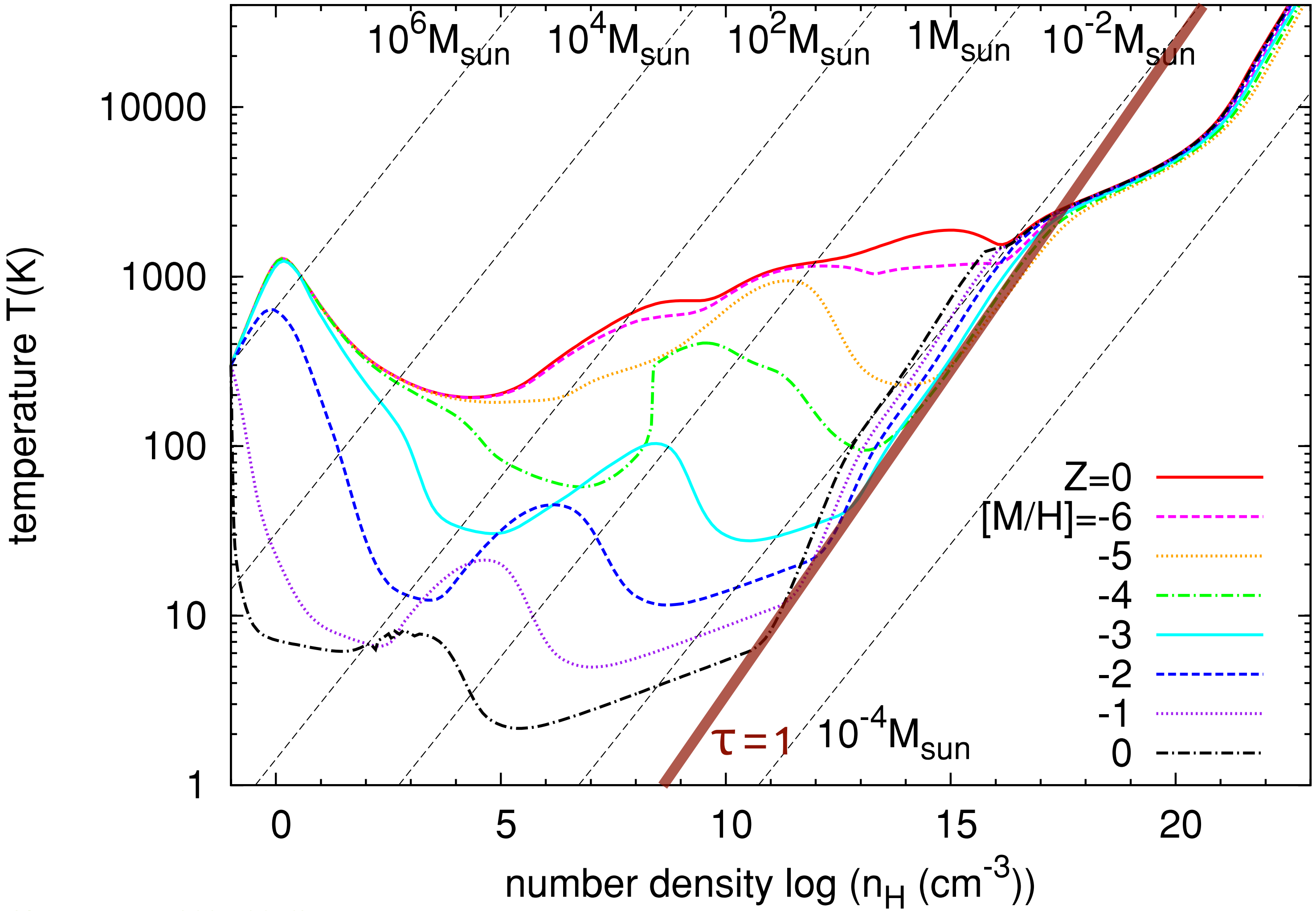
EOS in different environments

EOS as function of metallicity



(Omukai et al. 2005, 2010)

EOS as function of metallicity



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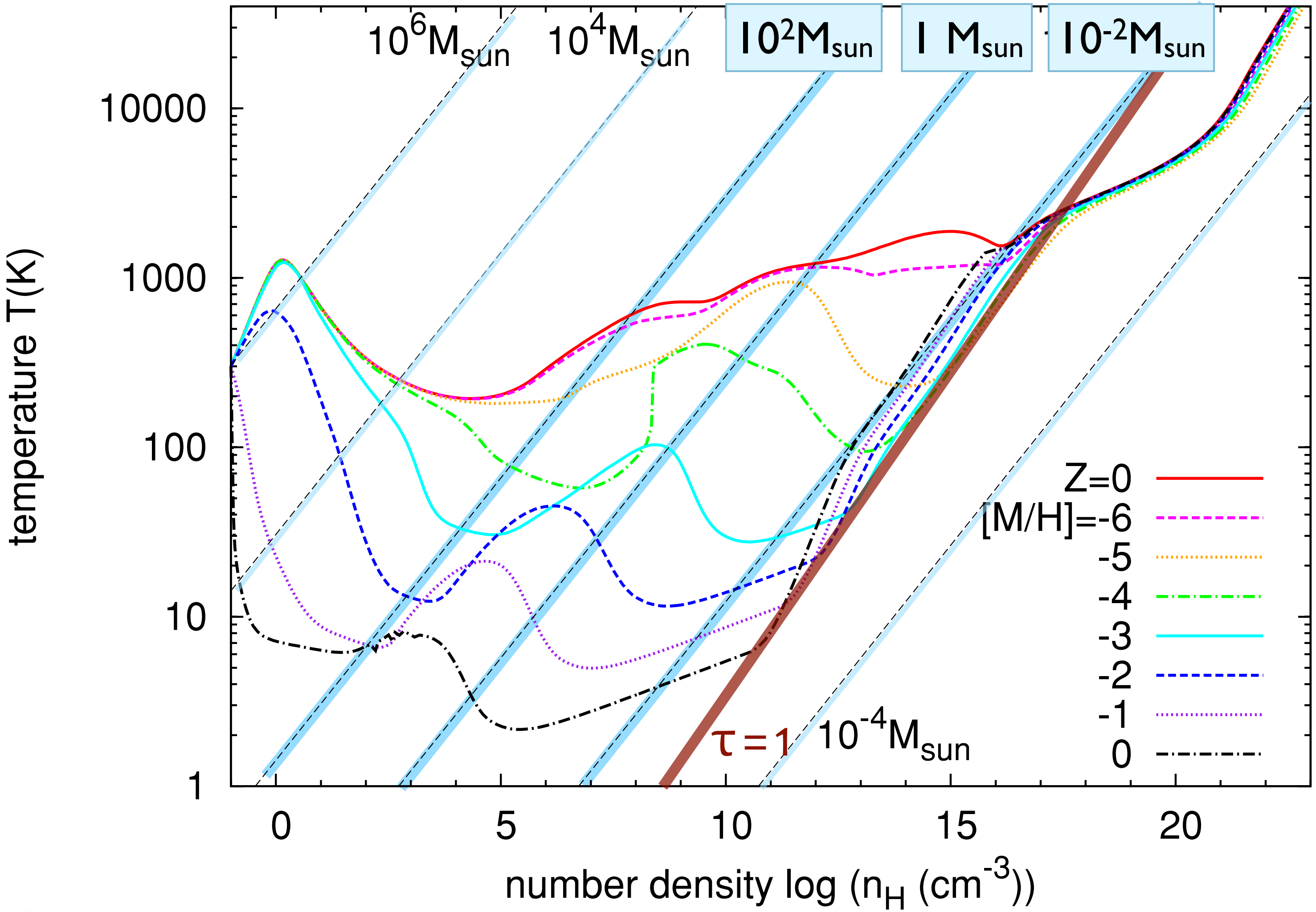
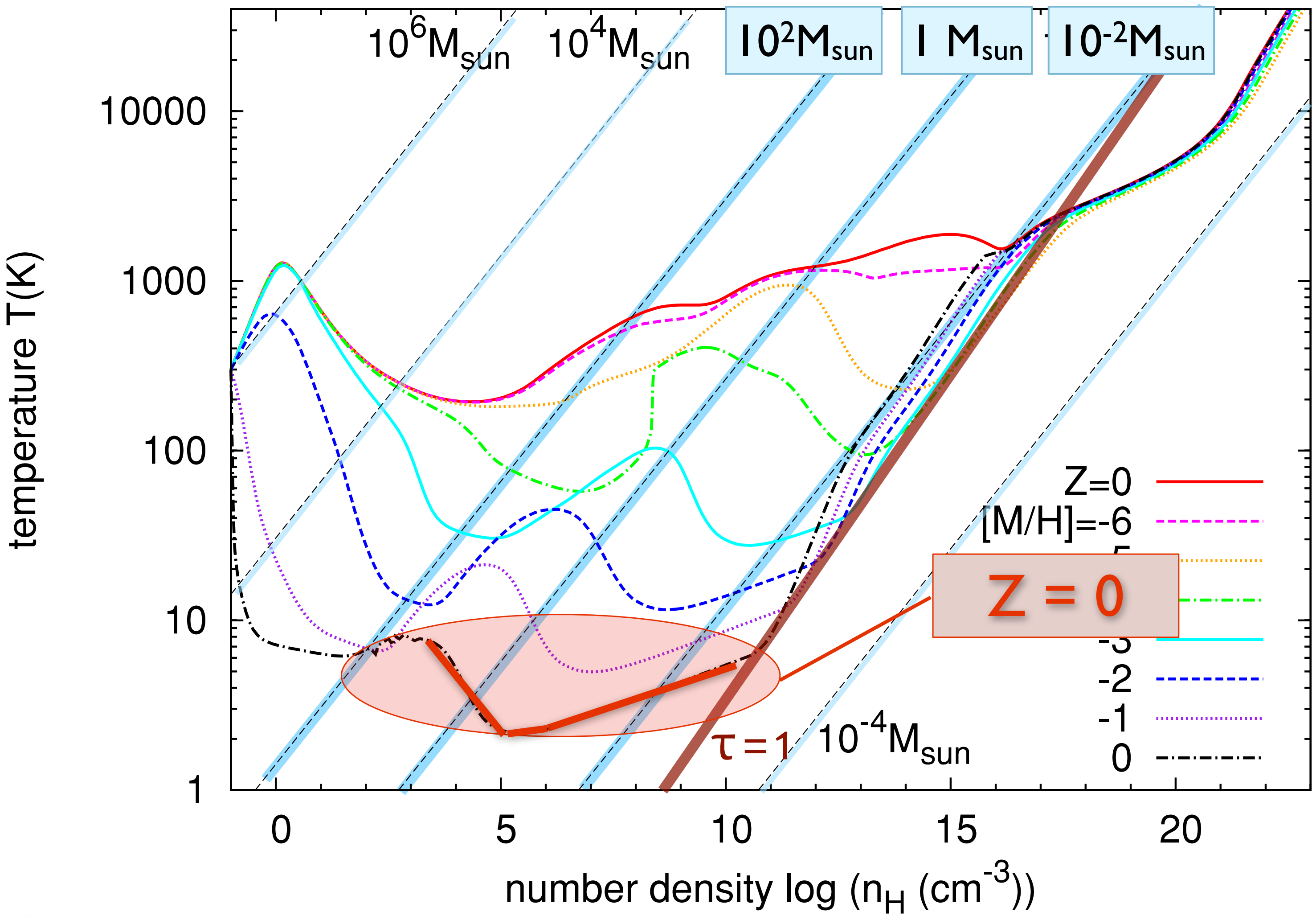
EOS as function of metallicity



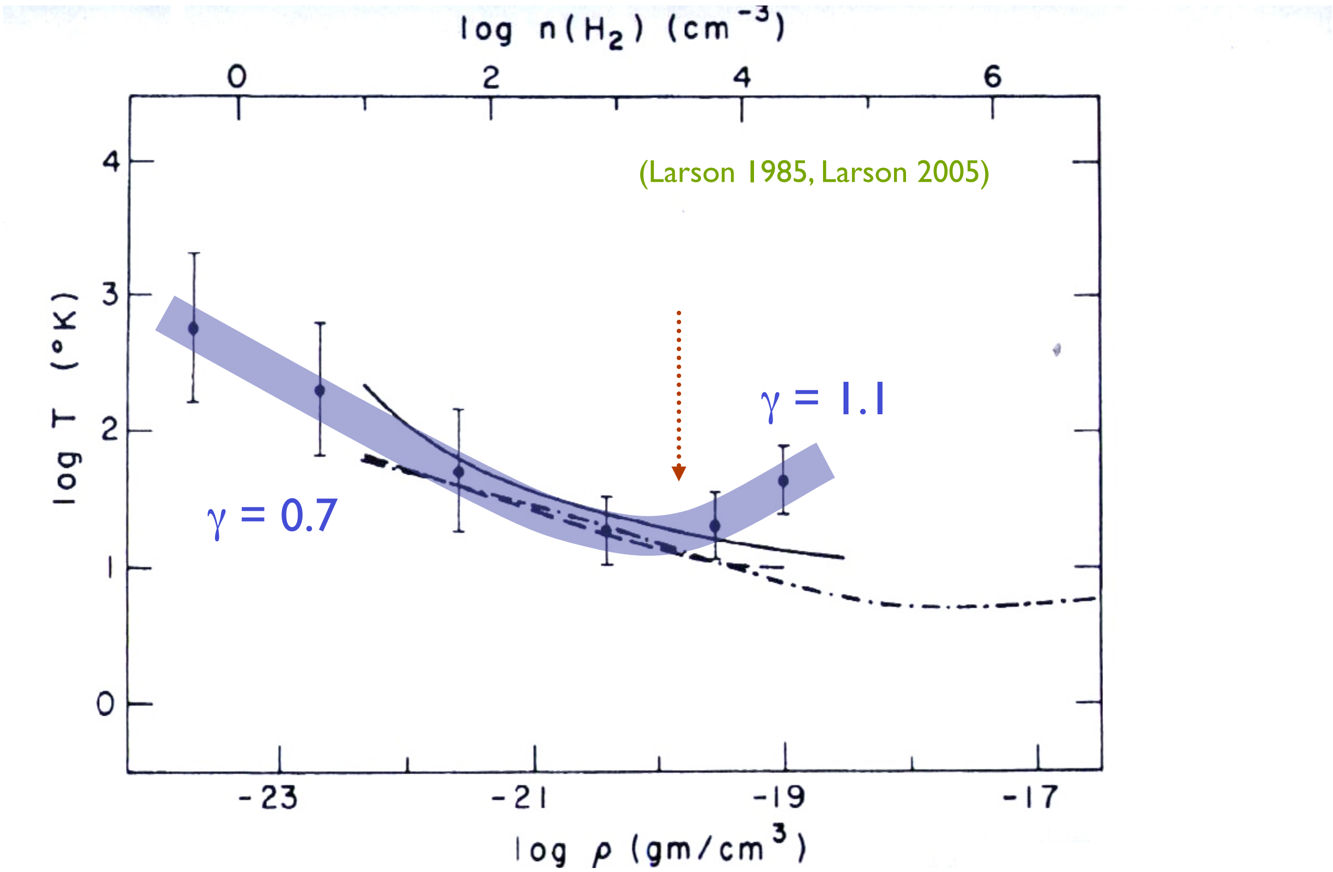
(Omukai et al. 2005, 2010)

EOS as function of metallicity

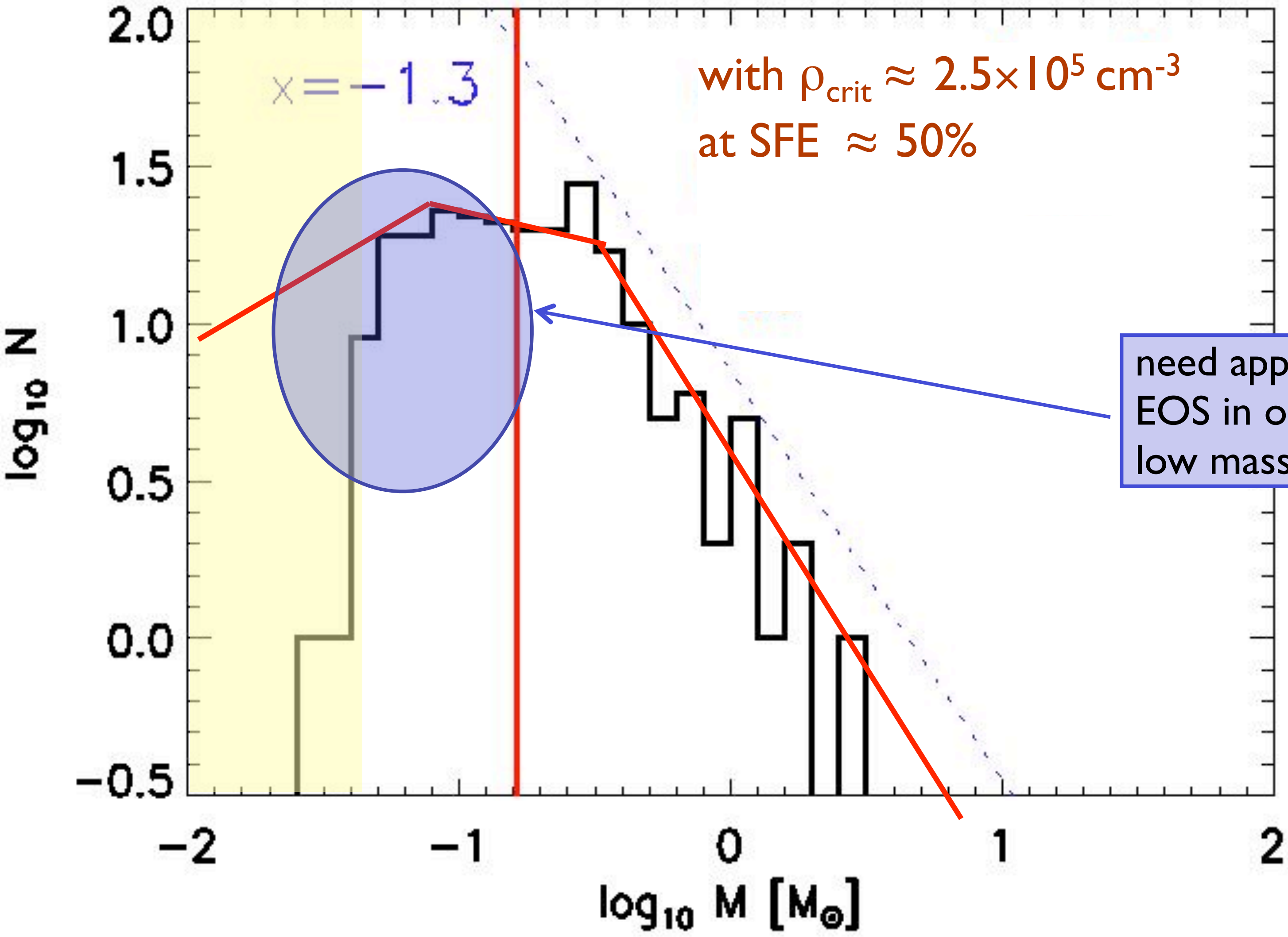


(Omukai et al. 2005, 2010)

present-day star formation



IMF in nearby molecular clouds

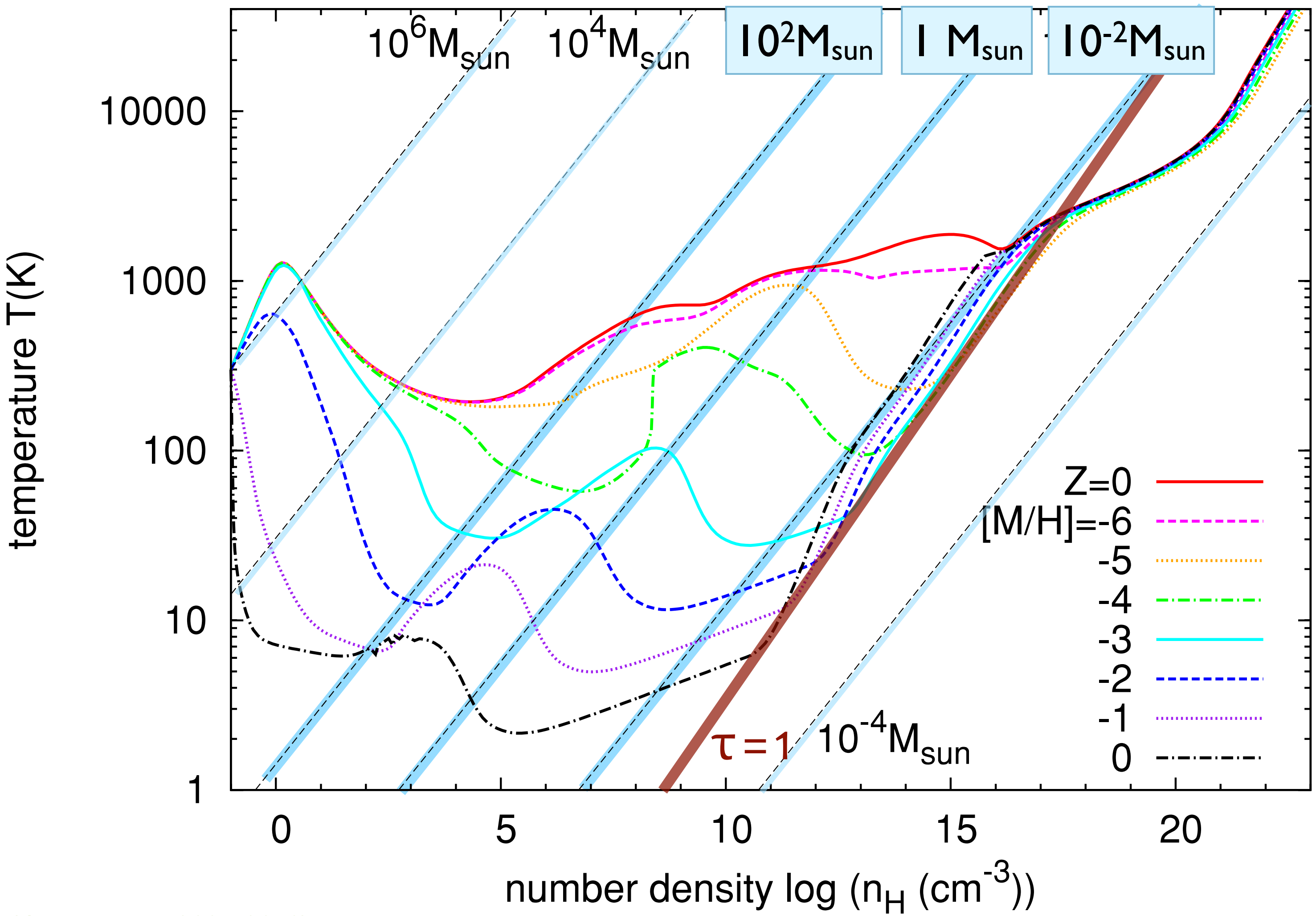


with $\rho_{crit} \approx 2.5\times10^5\ cm^{-3}$
at SFE ≈ 50%

need appropriate EOS in order to get low mass IMF right

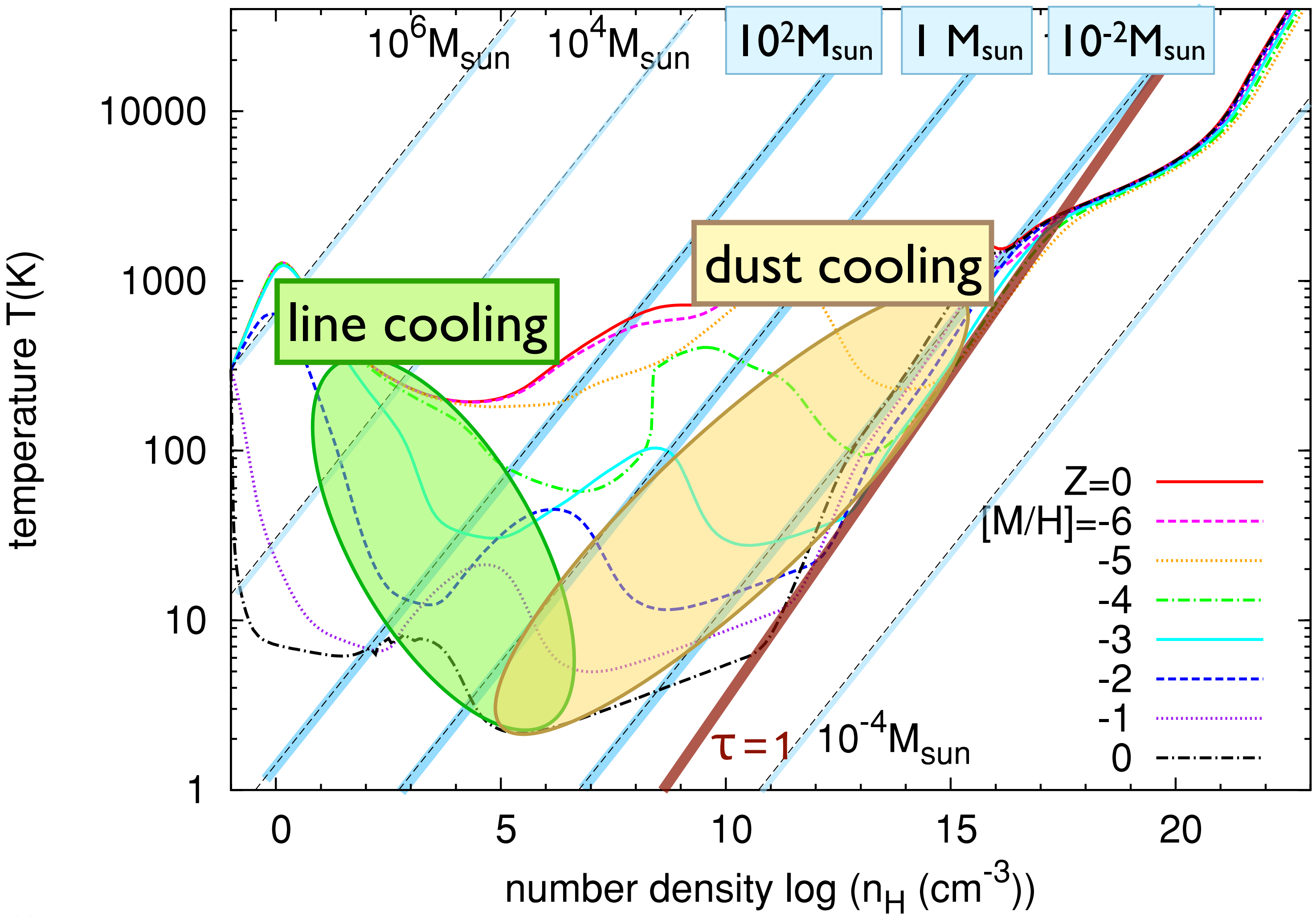
(Jappsen et al. 2005, A&A, 435, 611)

EOS as function of metallicity



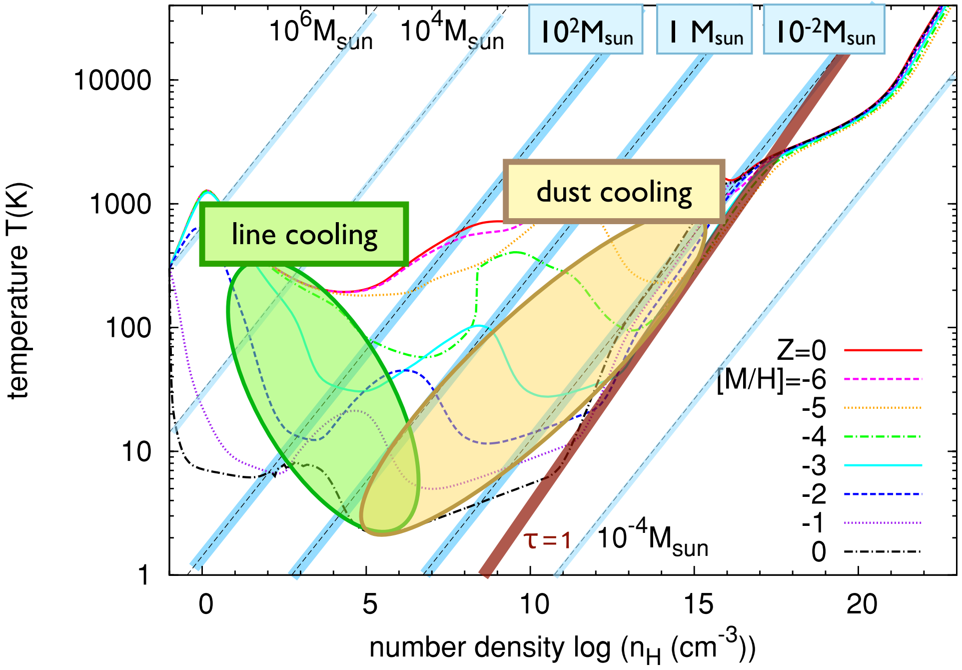
(Omukai et al. 2005, 2010)

EOS as function of metallicity



(Omukai et al. 2005, 2010)

transition: Pop III to Pop II.5



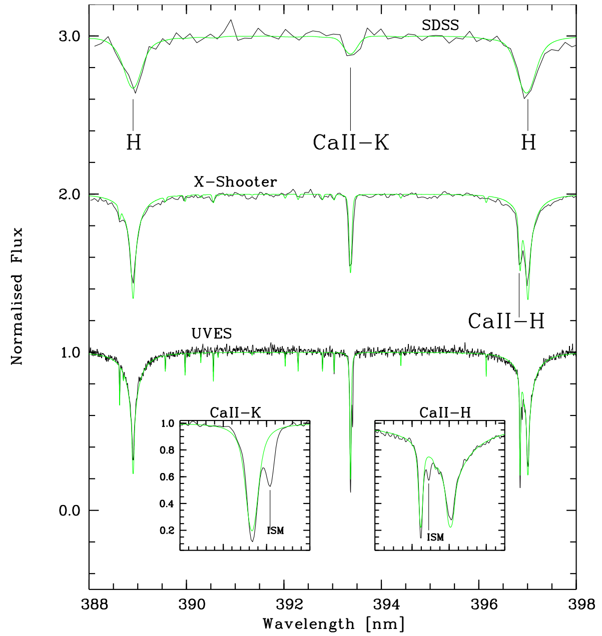
two competing models:

- 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 is 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	$[X/H]_{1D}$				N lines	S_H	$A(X)_\odot$
		+3Dcor.	+NLTE cor.	+ 3D cor + NLTE cor			
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)

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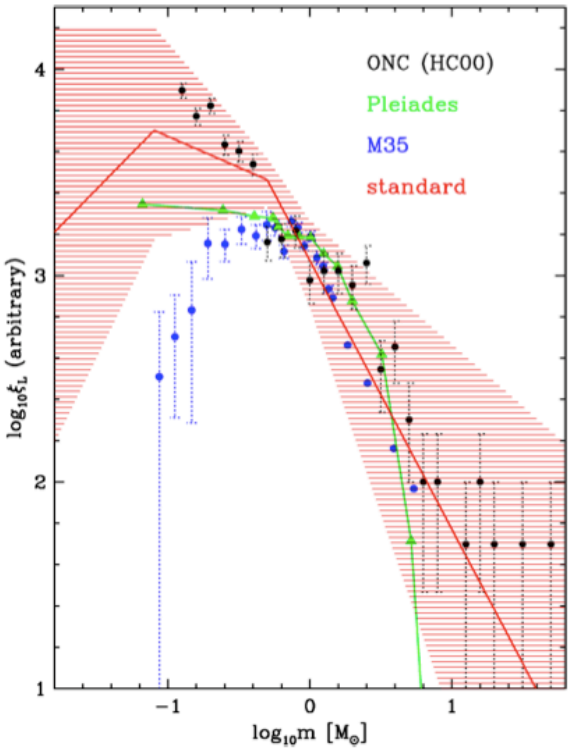
high-mass star formation

We want to address the following questions:

- how do massive stars (and their associated clusters) form?
- what determines the upper stellar mass limit?
- what is the physics behind observed HII regions?



IMF (Kroupa 2002)

Rosetta nebula (NGC 2237)

(proto)stellar feedback processes

- radiation pressure on dust particles
- ionizing radiation
- stellar winds
- jets and outflows

ionization

- few numerical studies so far (e.g. Dale 2007, Gritschneder et al. 2009)
- detailed collapse calculations with ionizing and non-ionizing feedback needed (see also work by Kuiper et al. 2011, 2012)
- HII regions around massive stars are directly observable --> direct comparison between theory and observations

numerical approach

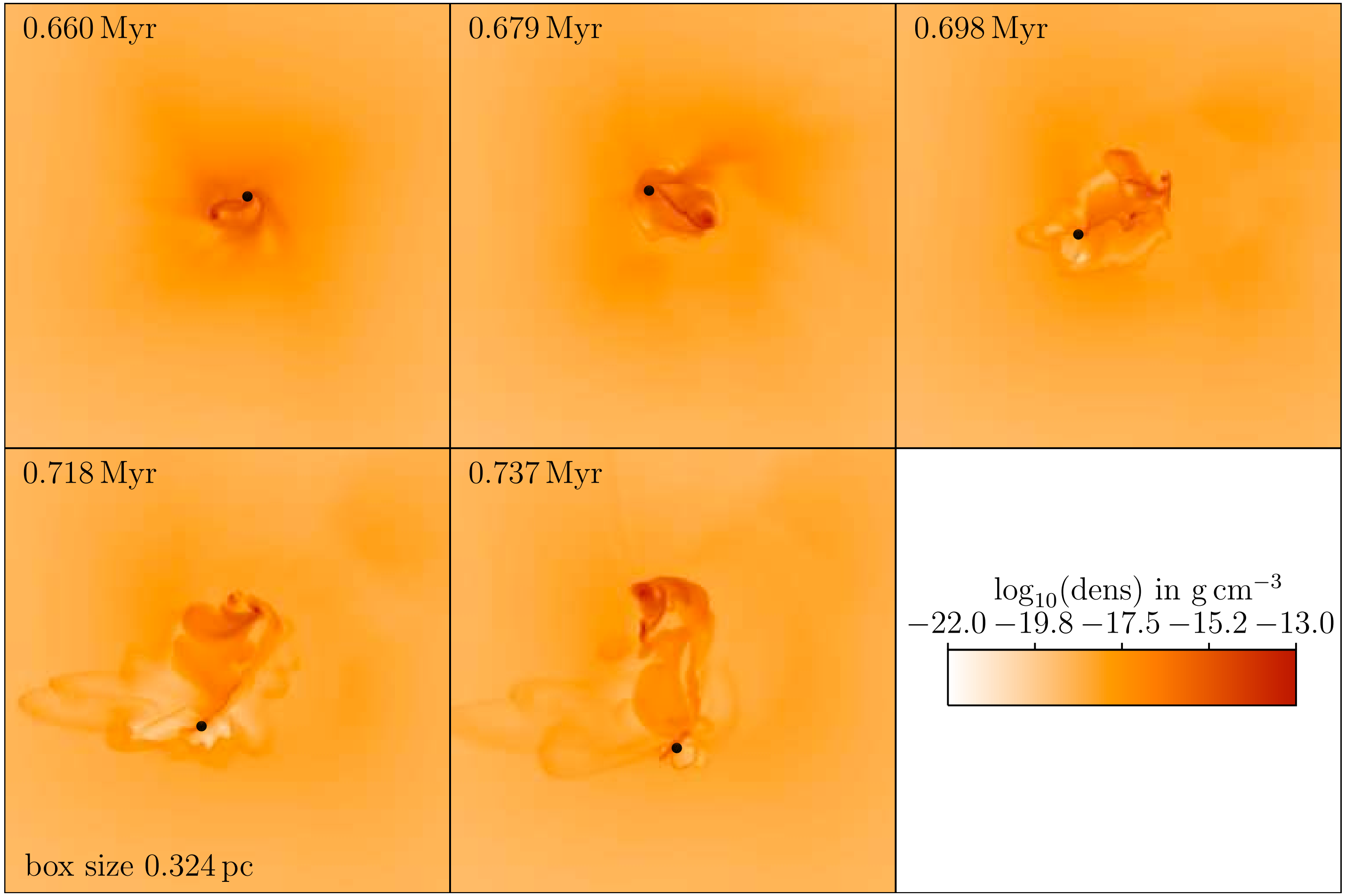
- focus on collapse of individual high-mass cores...
  - massive core with 1,000 $M_\odot$
  - Bonnor-Ebert type density profile (flat inner core with 0.5 pc and rho ~ $r^{-3/2}$ further out)
  - initial m=2 perturbation, rotation with $\beta = 0.05$
  - sink particle with radius 600 AU and threshold density of 7×10^{-16} g cm^{-3}
  - cell size 100 AU

Peters et al. (2010a, ApJ, 711, 1017), Peters et al. (2010b, ApJ, 719, 831), Peters et al. (2010c, ApJ, 725, 134)

numerical approach

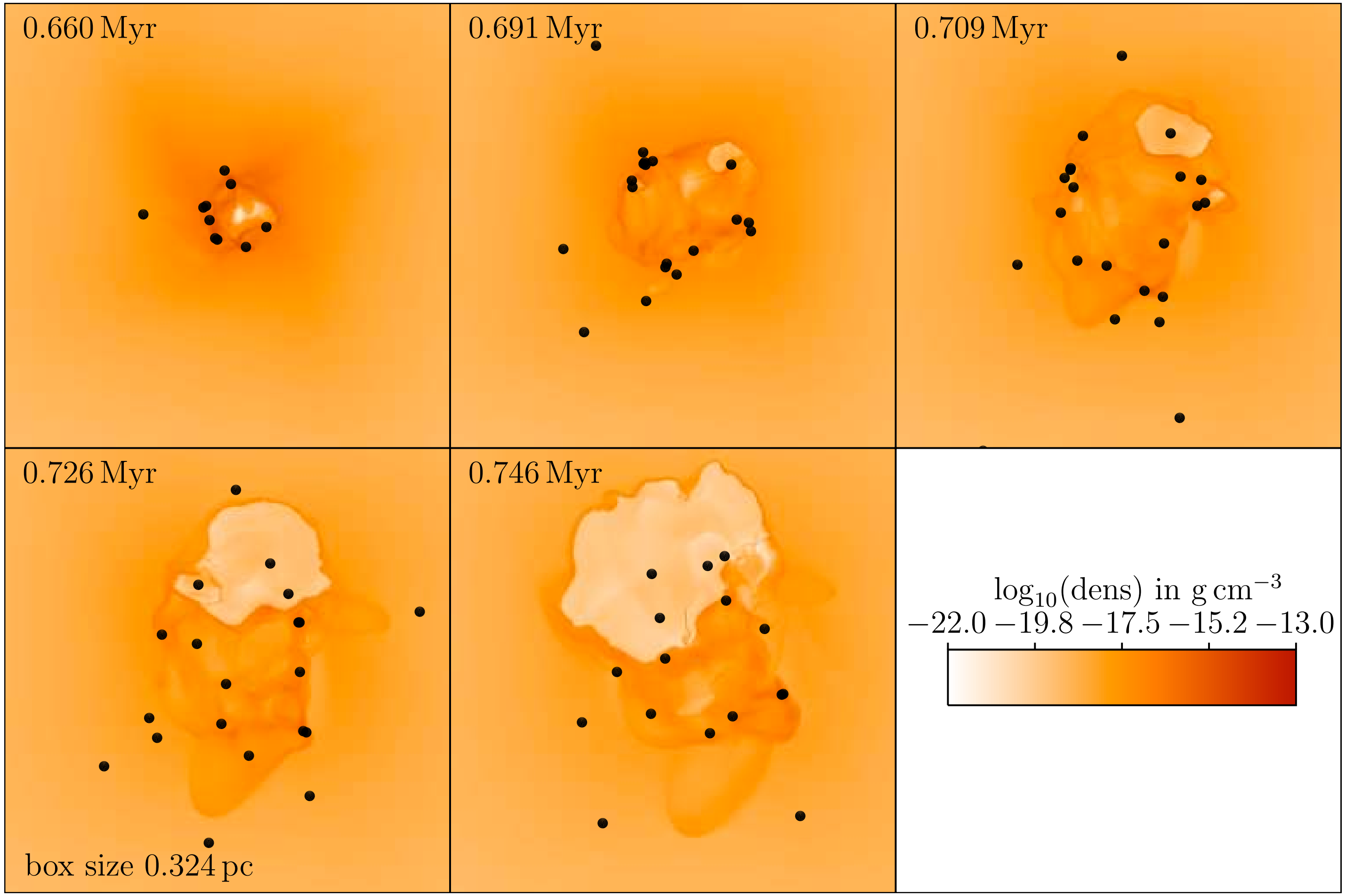
- method:
  - FLASH with ionizing and non-ionizing radiation using raytracing based on hybrid-characteristics
  - protostellar model from Hosokawa & Omukai
  - rate equation for ionization fraction
  - relevant heating and cooling processes
  - some models include magnetic fields
  - *first 3D MHD calculations that consistently treat both ionizing and non-ionizing radiation in the context of high-mass star formation*

Peters et al. (2010a,b,c)



- disk is gravitationally unstable and fragments
- we suppress secondary sink formation by “Jeans heating”
- H II region is shielded effectively by dense filaments
- ionization feedback does not cut off accretion!

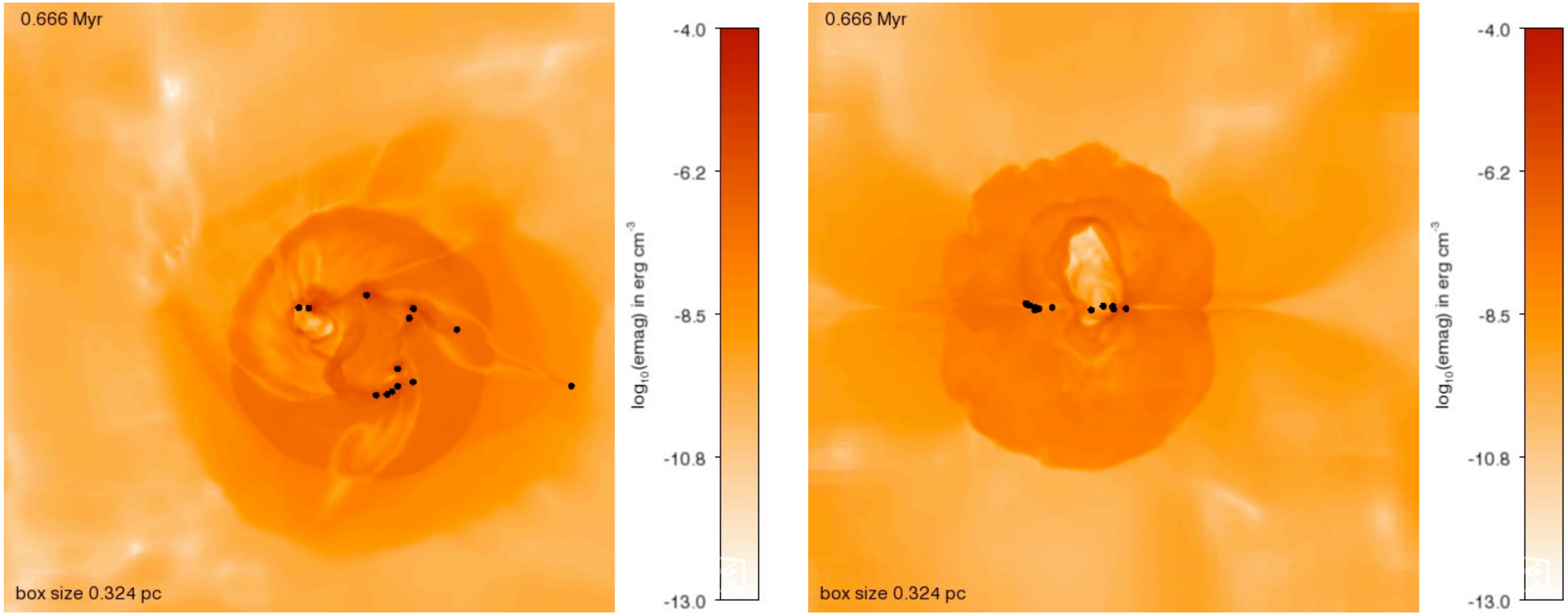
Peters et al. (2010a,b,c)



- all protostars accrete from common gas reservoir
- accretion flow suppresses expansion of ionized bubble
- cluster shows “fragmentation-induced starvation”
- halting of accretion flow allows bubble to expand

Peters et al. (2010a,b,c)

influence of B on disk evolution



Peters et al. (2011)

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

interplay of ionization and B-field

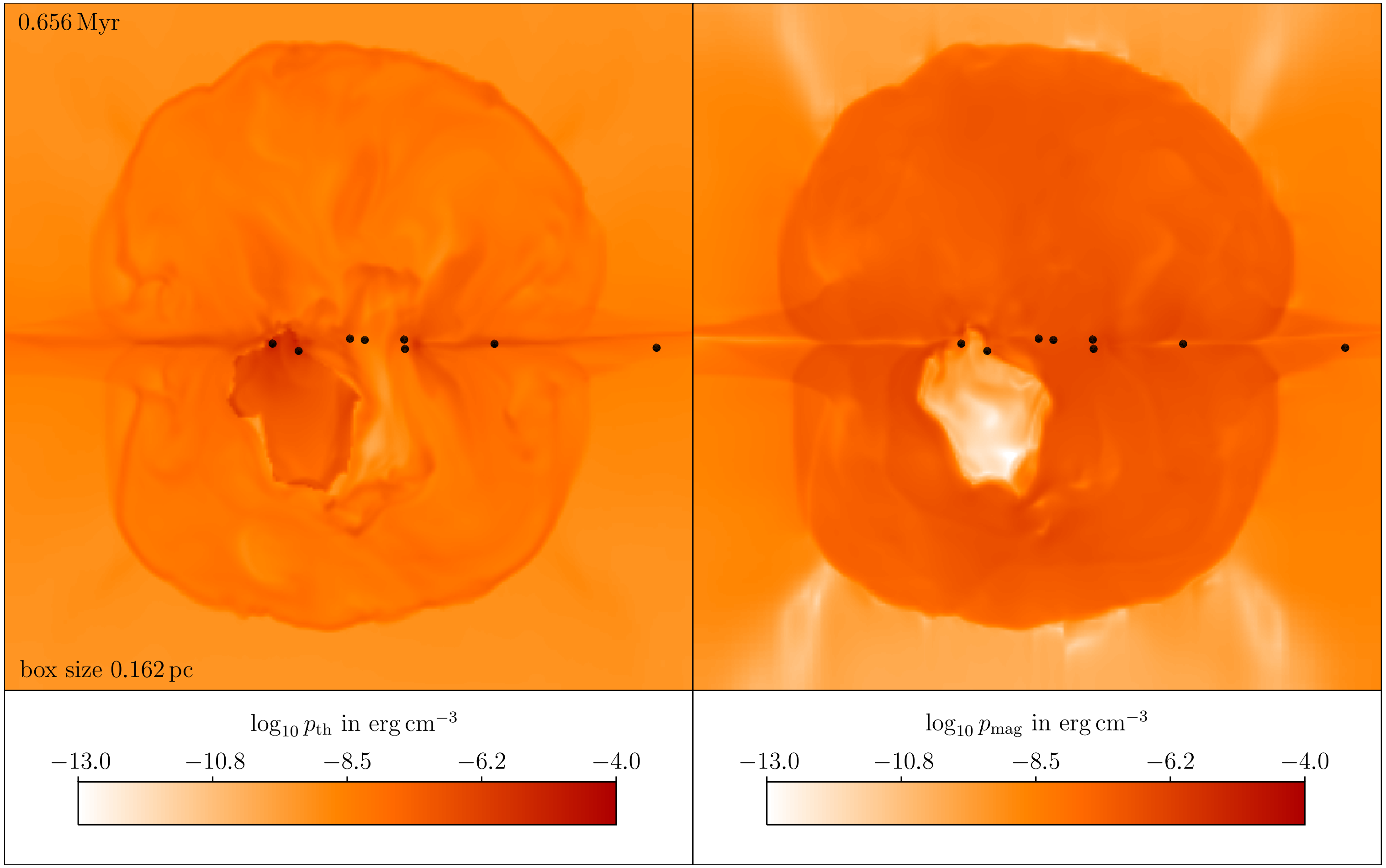
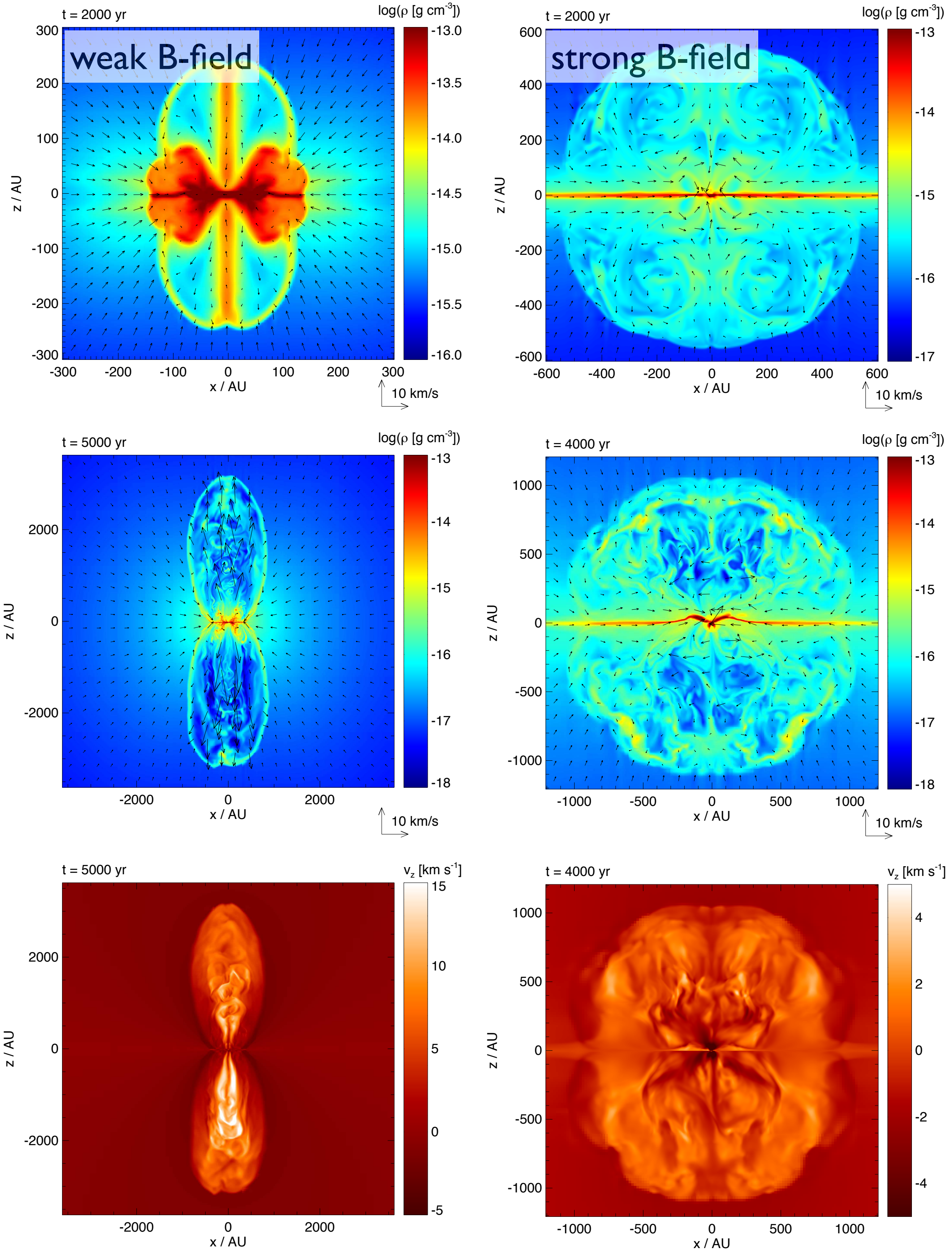


Figure 10. Comparison of thermal and magnetic pressure for the data from the lefthand panels in Figure 5. The thermal pressure p_{th} inside the H II region (left) is of comparable magnitude to the magnetic pressure p_{mag} outside the H II region (right). Thus, magnetic pressure plays a significant role in constraining the size of expanding H II regions. The black dots represent sink particles.

Peters et al. (2011)

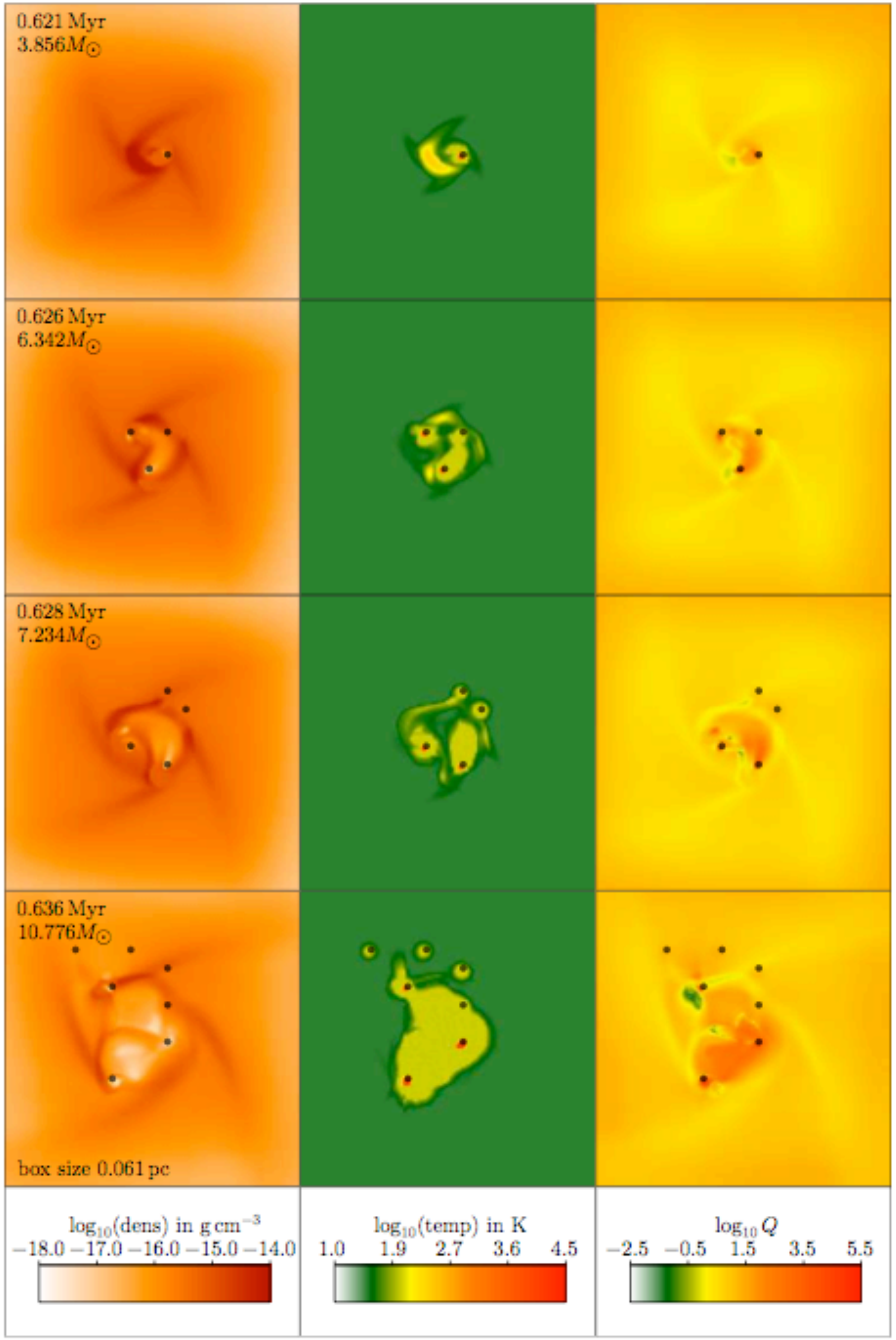


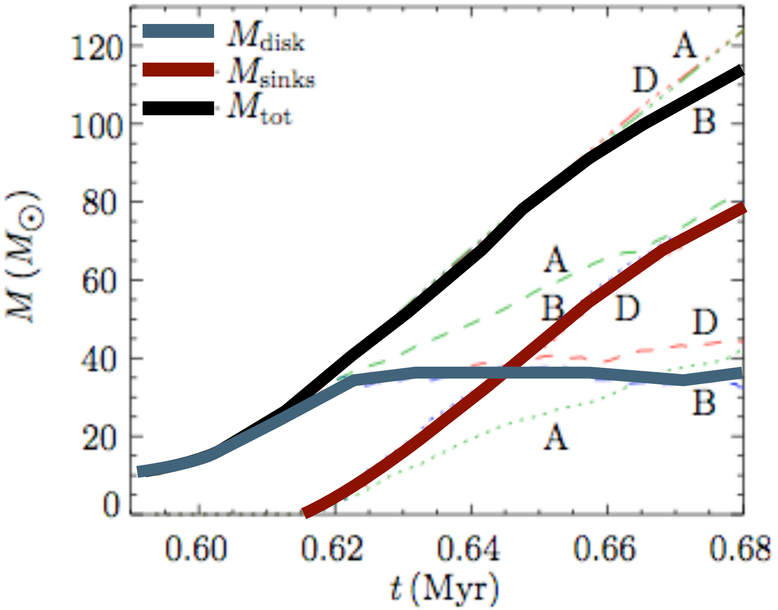
density in inner region
and early times

density on larger scales
and later times

velocity on larger scales
and later times

Seifried, Pudrith, Banerjee, Duffin, Klessen (2011)



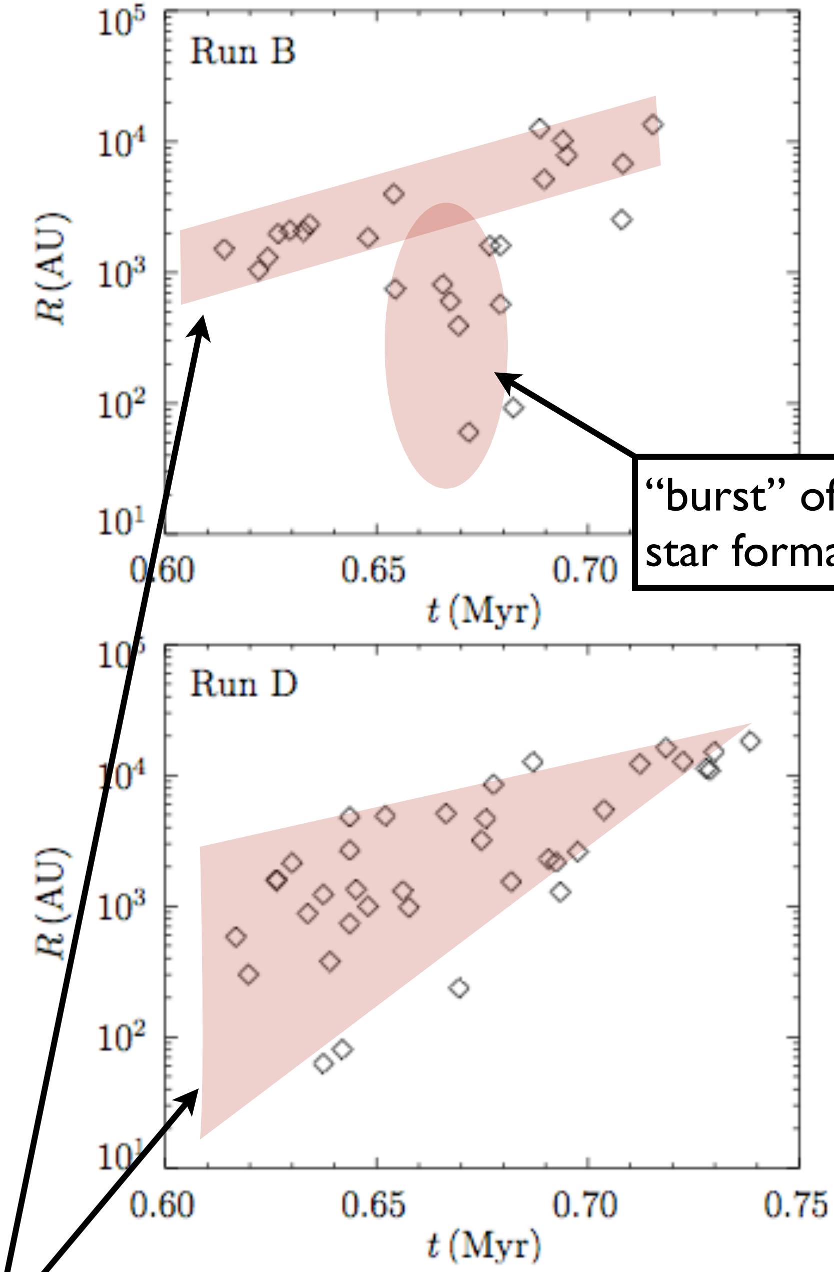


mass load onto the disk exceeds inward transport

--> becomes gravitationally unstable (see also Kratter & Matzner 2006, Kratter et al. 2010)

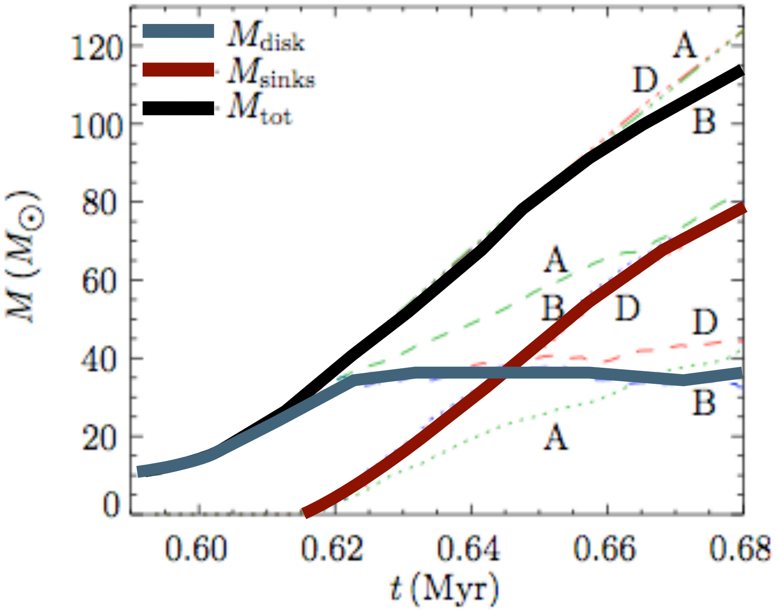
fragments to form multiple stars --> explains why high-mass stars are seen in clusters

Peters et al. (2010a, ApJ, 711, 1017),
Peters et al. (2010b, ApJ, 719, 831),
Peters et al. (2010c, ApJ, 725, 134)



"burst" of star formation

younger protostars form at larger radii



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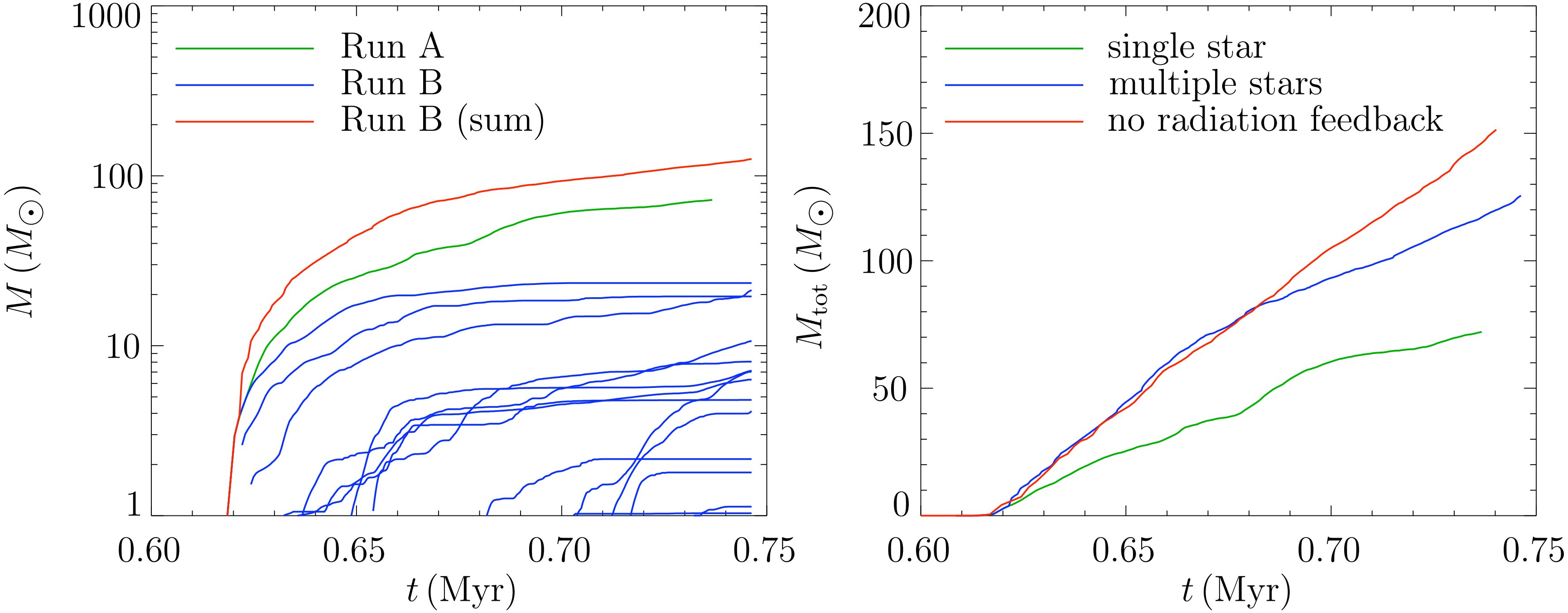
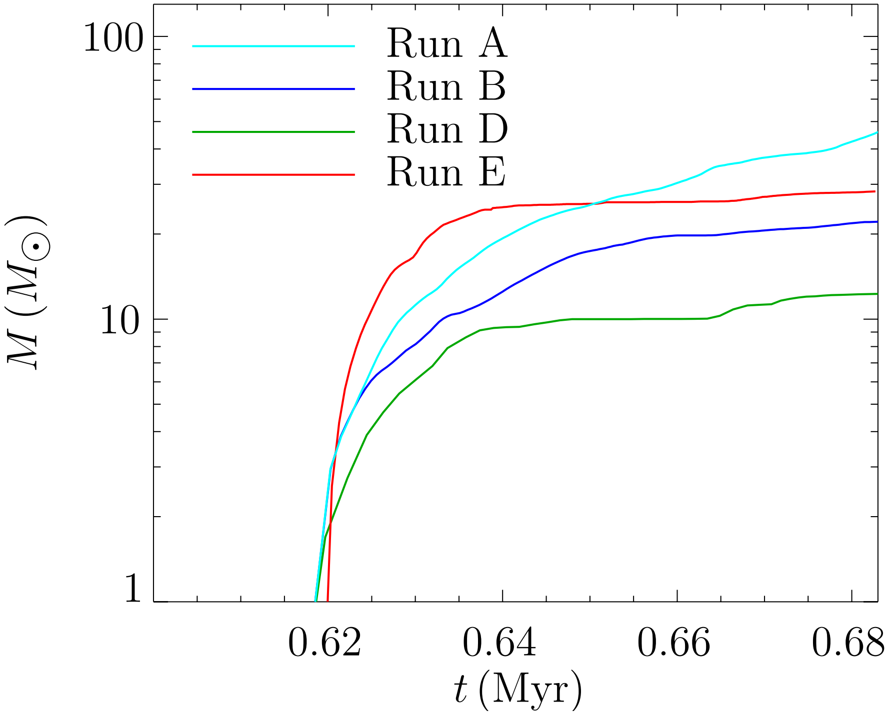
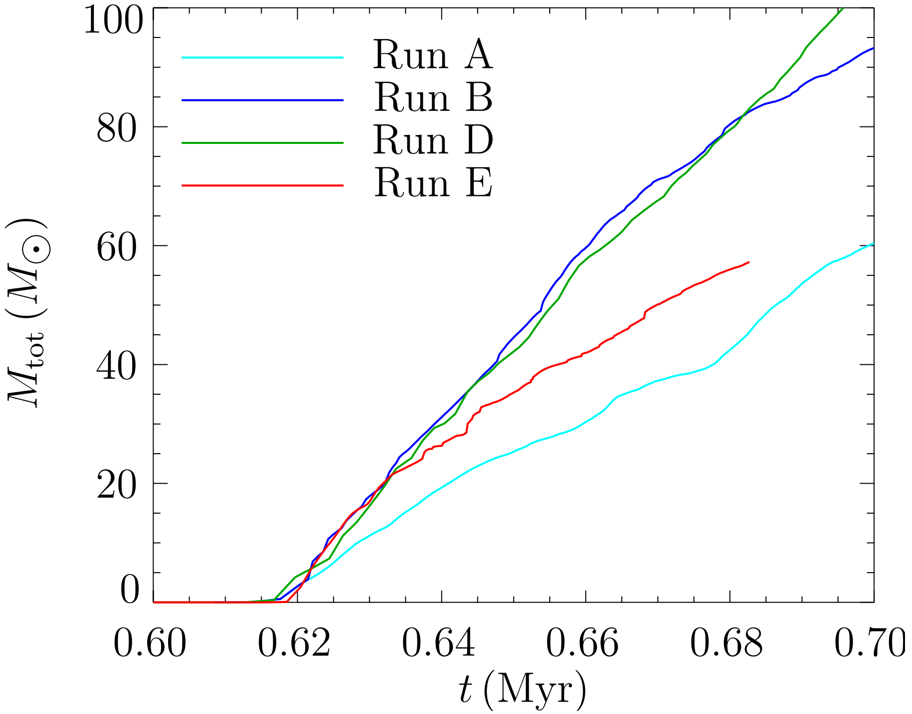


- compare with control run without radiation feedback
- total accretion rate does not change with accretion heating
- expansion of ionized bubble causes turn-off
- no triggered star formation by expanding bubble

Peters et al. (2010a, ApJ, 711, 1017), Peters et al. (2010b, ApJ, 719, 831), Peters et al. (2010c, ApJ, 725, 134)

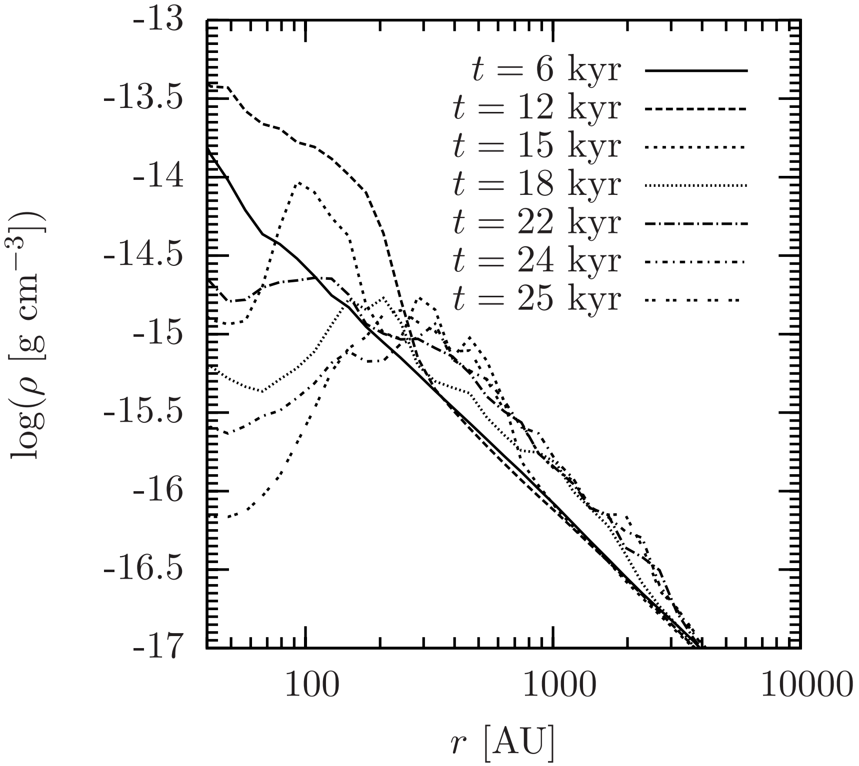




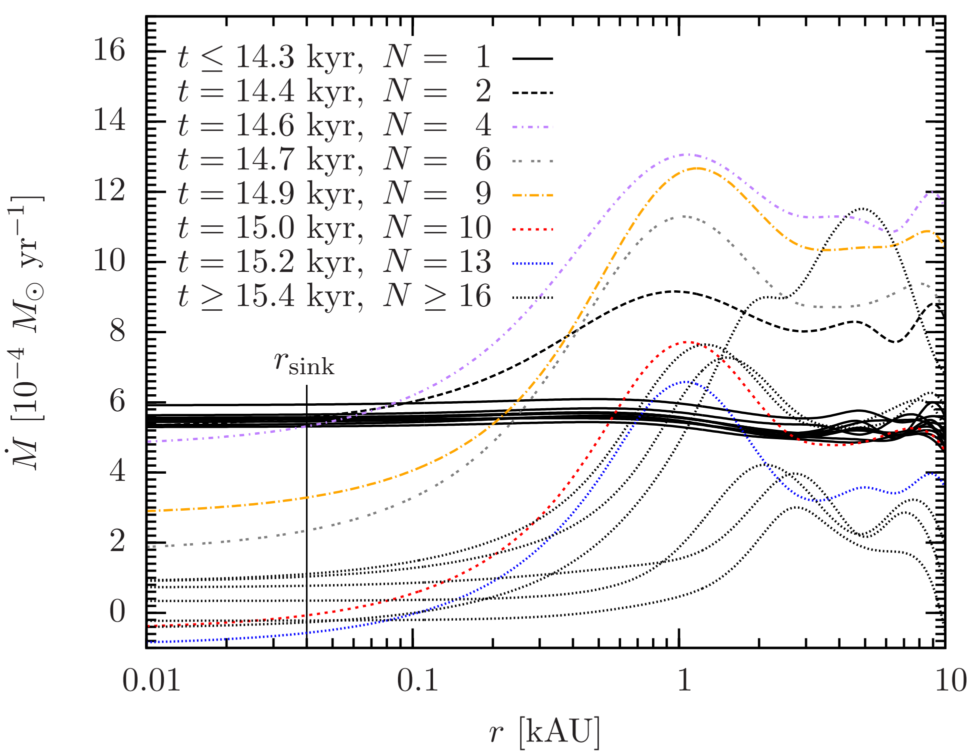
- magnetic fields lead to weaker fragmentation
- central star becomes more massive (magnetic breaking

Peters et al. (2010a, ApJ, 711, 1017), Peters et al. (2010b, ApJ, 719, 831), Peters et al. (2010c, ApJ, 725, 134), Peters et al. (2011, ApJ, 729, 72

Fragmentation-induced starvation in a complex cluster



gas density as function of radius
at different times



mass flow towards the center as
function of radius at different times

Girichidis et al. (2011a,b)

summary

summary

- star formation is a complex multi-scale, multi-physics process, where different processes ALL contribute to the result
  (it is not possible to single out individual processes)
- initial conditions are important and influence properties of forming star clusters
  (IMF, binarity, spatial distribution, kinematics, age spread, etc.)
- thermodynamics is important
  (determines the dynamic response of the gas to “external” perturbations, say self-gravity, turbulence)
- (radiative) feedback influences IMF, but probably to a lesser degree than dynamics

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Thanks!