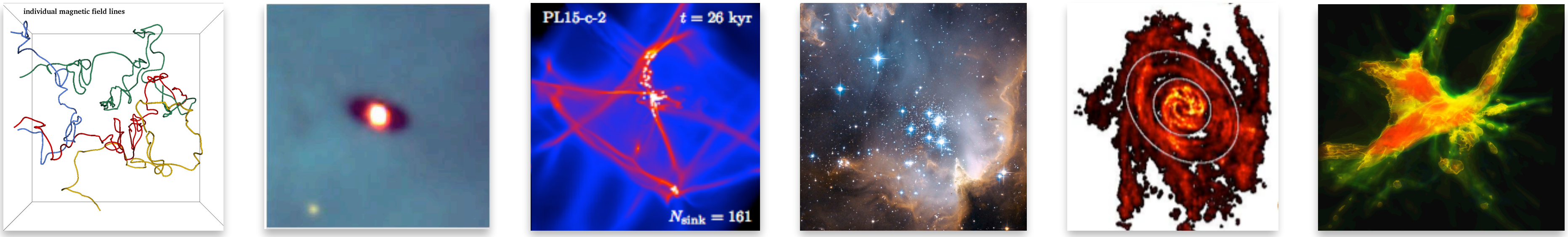
Star Formation

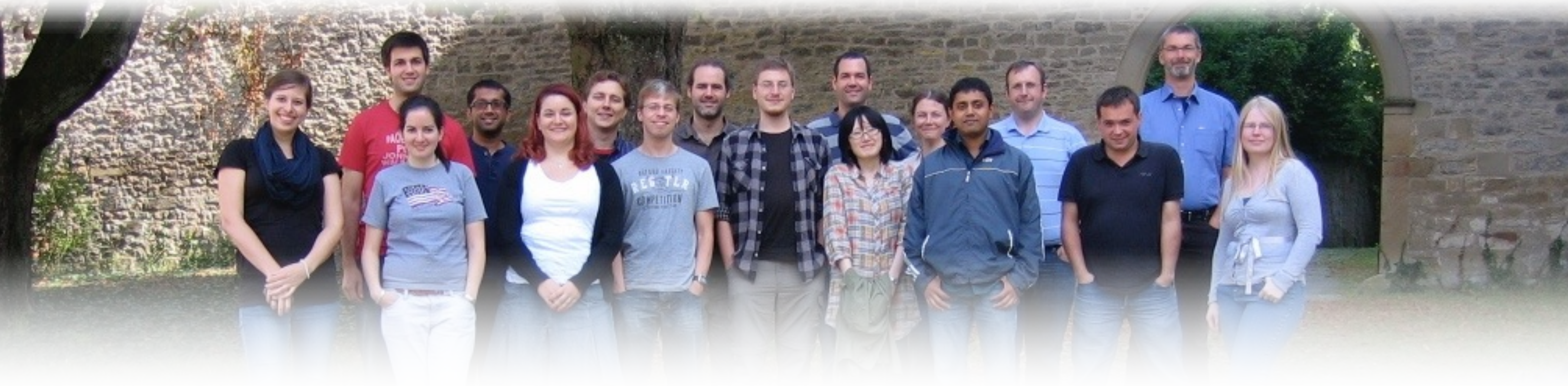
(part 2)



Ralf Klessen

Zentrum für Astronomie der Universität Heidelberg
Institut für Theoretische Astrophysik

thanks to ...



... people in the star formation group at Heidelberg University:

Christian Baczynski, Erik Bertram, Frank Bigiel, Andre Bubel, Diane Cormier, Volker Gaibler, Simon Glover, Dimitrious Gouliermis, Tilman Hartwig, Juan Ibanez, Christoph Klein, Lukas Konstandin, Mei Sasaki, Jennifer Schober, Rahul Shetty, Rowan Smith, László Szűcs

... former group members:

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

... many collaborators abroad!

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

agenda

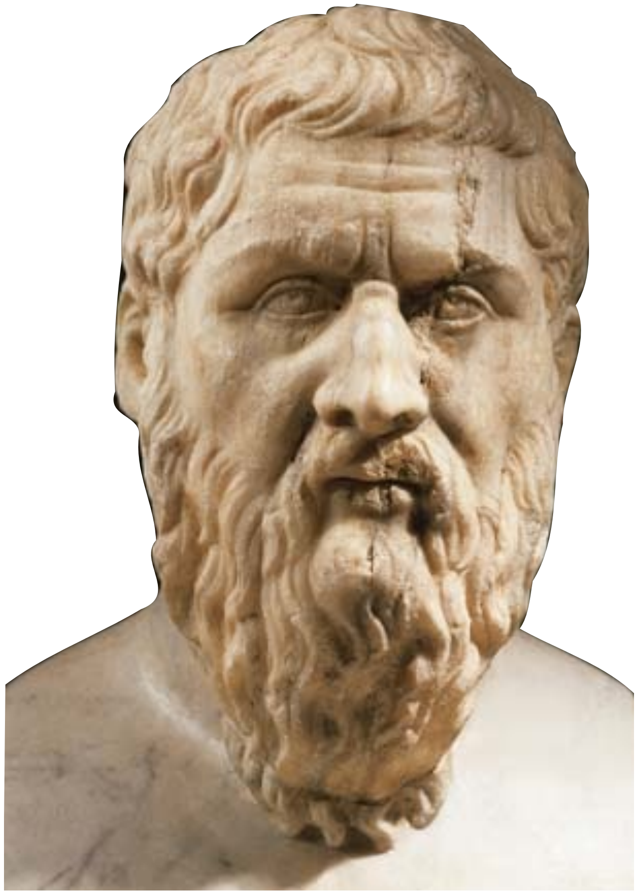
- star formation theory
  - phenomenology
  - historic remarks
  - our current understanding and its limitations
- applications
  - formation of molecular clouds
  - the stellar mass function at birth (IMF)

NGC 3324 (Hubble, NASA/ESA)

agenda

- star formation theory
  - ~~phenomenology~~
  - ~~historic~~ remarks on observations
  - ~~our current understanding and its limitations~~
- applications *& controversies*
  - *global star formation relations*
  - *ICs for cluster formation*
  - the stellar mass function at birth (IMF)

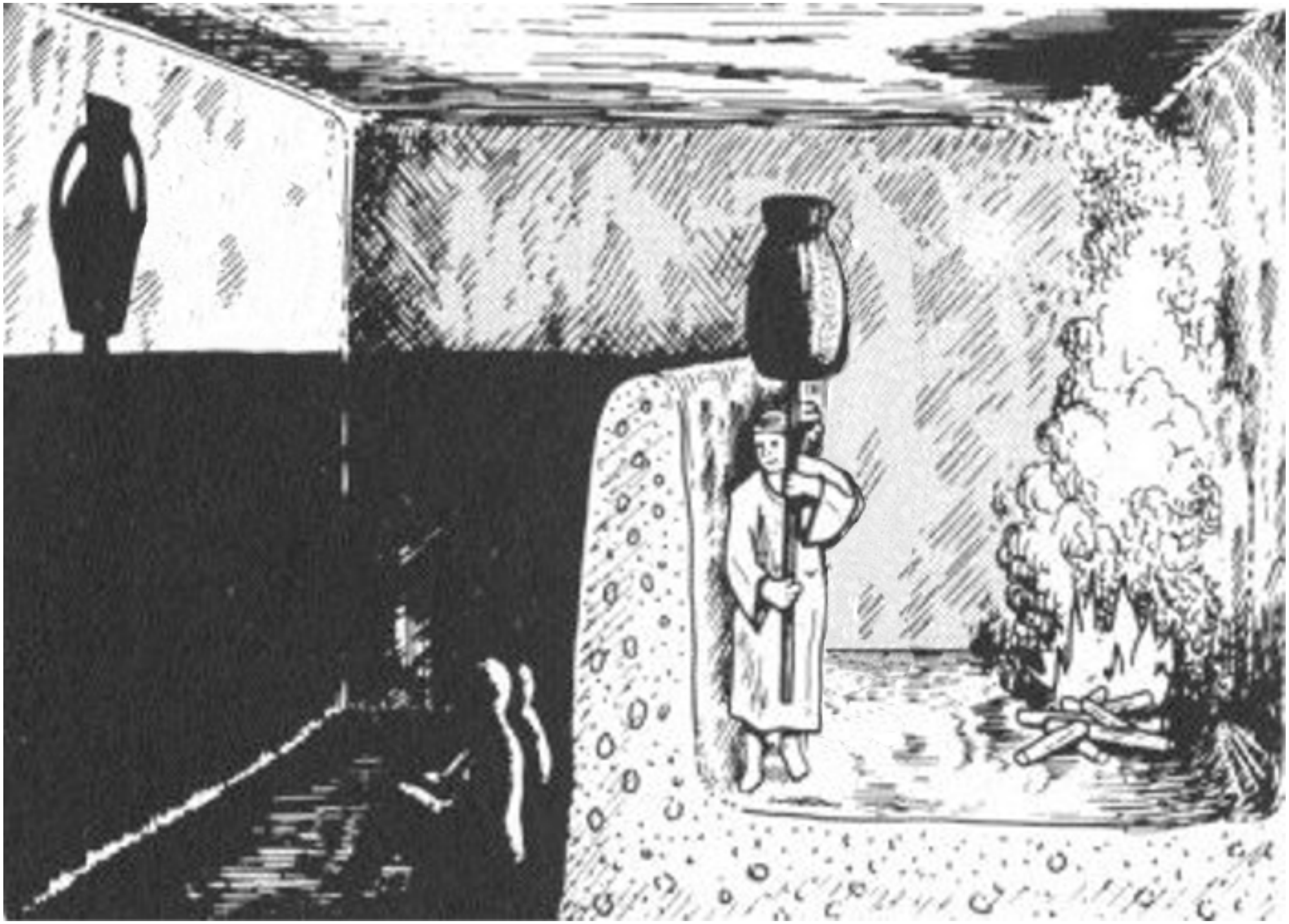

NGC 3324 (Hubble, NASA/ESA)



Platon
428/427–348/347 BC

Capitoline Museum, Rome.

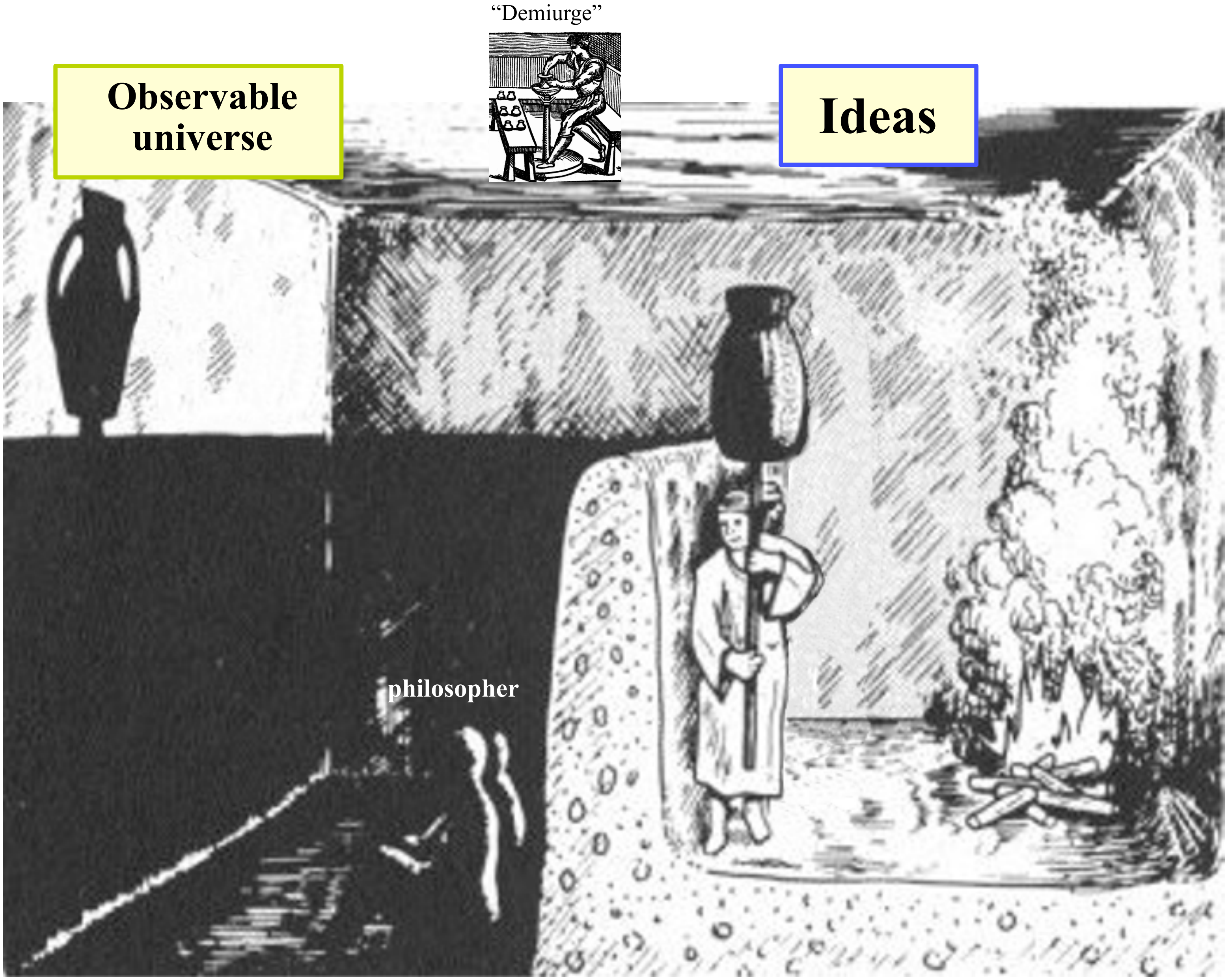
Plato's allegory of the cave*



Laszlo Szücs, image from criticalthinking-mc205.wikispaces.com

* The Republic
(514a-520a)

Plato's allegory of the cave*



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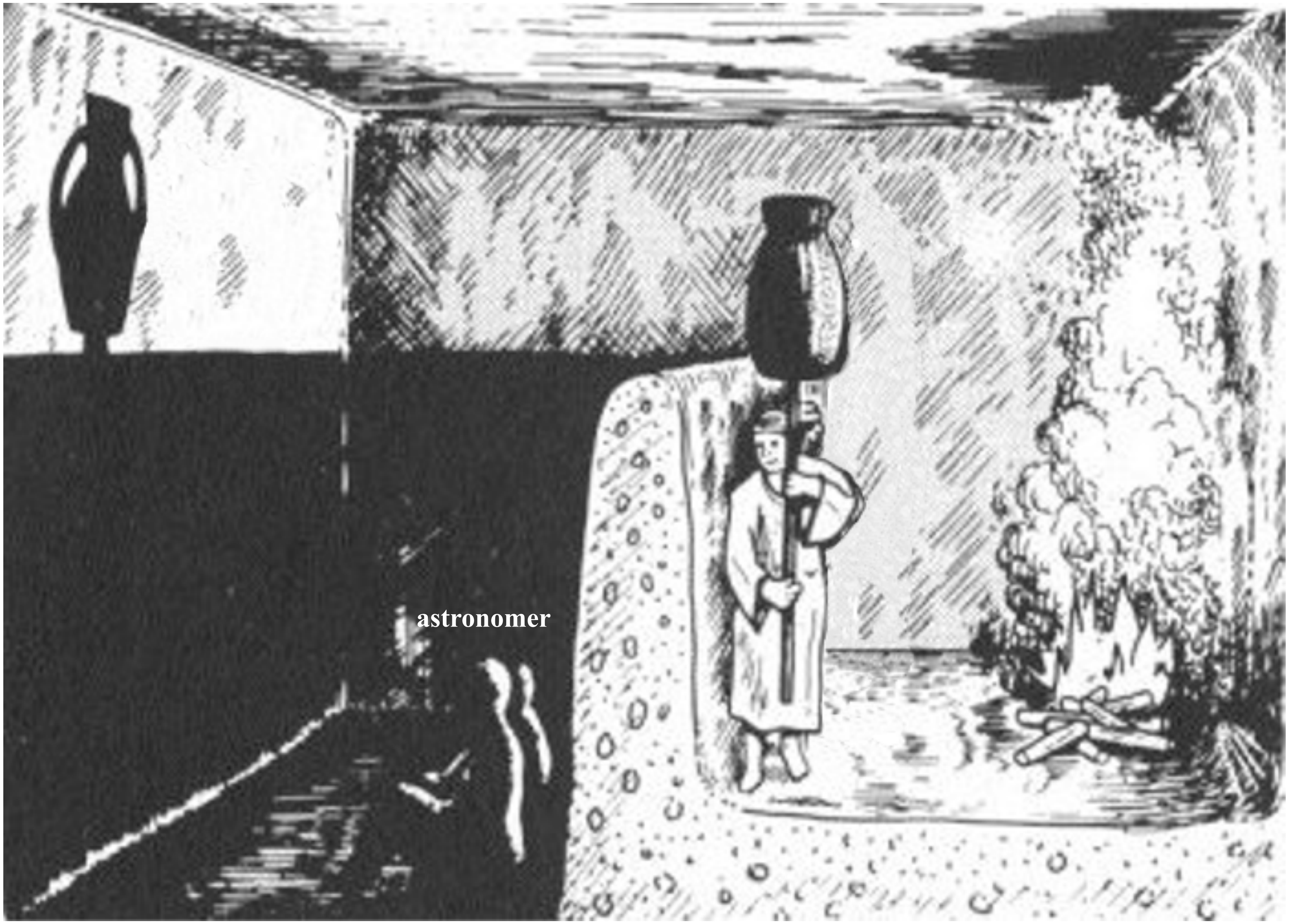
Plato's allegory of the cave* ↔ Astronomical observations



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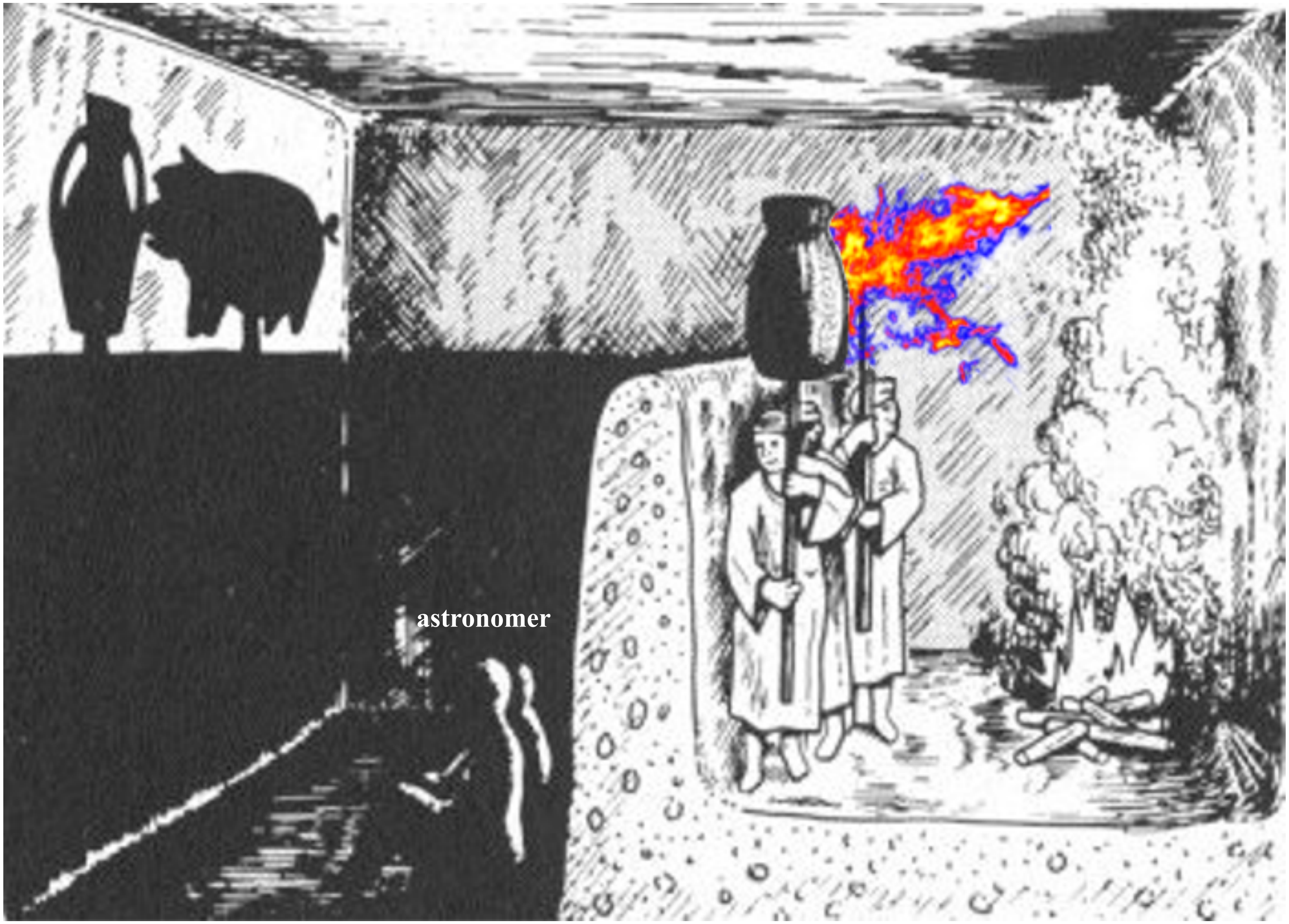

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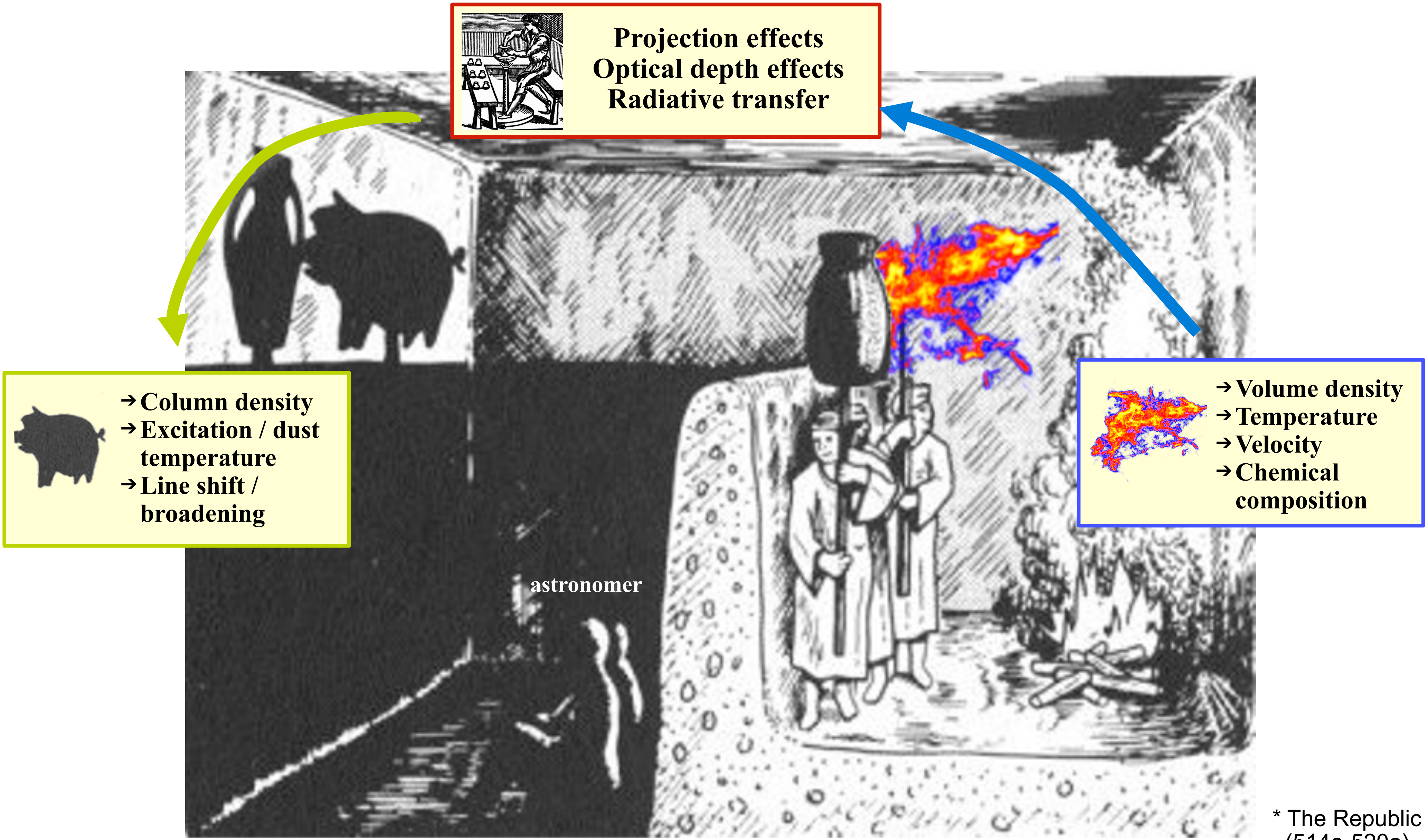

Projection effects
Optical depth effects
Radiative transfer

- → **Column density**
- → **Excitation / dust temperature**
- → **Line shift / broadening**

- → **Volume density**
- → **Temperature**
- → **Velocity**
- → **Chemical composition**

Laszlo Szücs, image from criticalthinking-mc205.wikispaces.com

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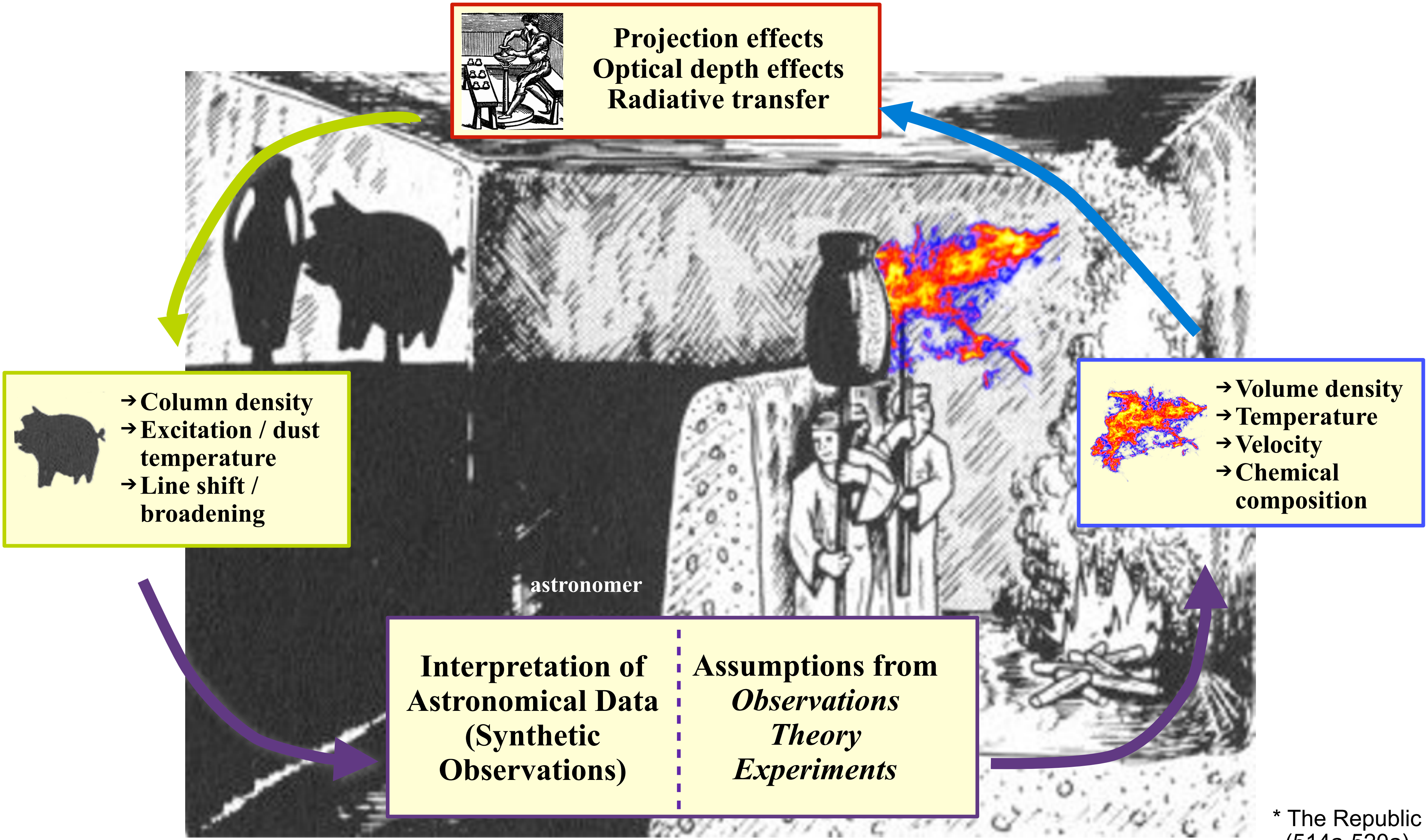
Plato's allegory of the cave* ↔ Astronomical observations



Projection effects
Optical depth effects
Radiative transfer

→ Column density
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→ Temperature
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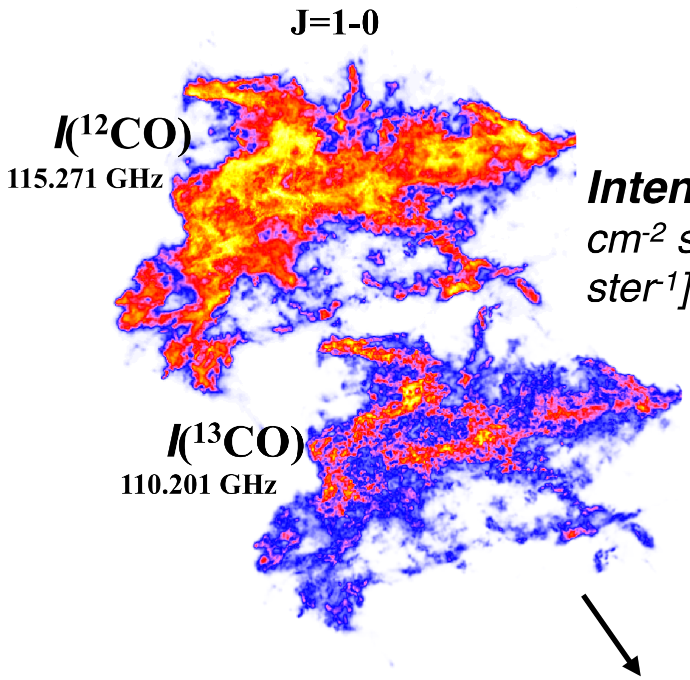
Interpretation of Astronomical Data (Synthetic Observations)

Assumptions from
Observations
Theory
Experiments

Laszlo Szücs, image from criticalthinking-mc205.wikispaces.com

* The Republic (514a-520a)

Example: from CO emission to total column density



Intensity *[erg cm-2 s-1 Hz-1 ster-1]*

Brightness temperature *[K]*

T_B^{12}

T_B^{13}

Following Wilson et al. 2009

Assumptions I.

$I(^{12}CO)$ is optically thick

$I(^{13}CO)$ is optically thin

Along a line of sight uniform T_{ex} and same for ^{12}CO and ^{13}CO

$$T_{\rm ex} = 5.5/\ln\left(1 + \frac{5.5}{T_B^{12} + 0.82}\right)$$

$$\tau_{13}(v) = -\ln\left[1 - \frac{T_{\rm B}^{13}}{5.3}\left\{\exp\left(\frac{5.3}{T_{\rm ex}} - 1\right)^{-1} - 0.16\right\}^{-1}\right]$$

LTE

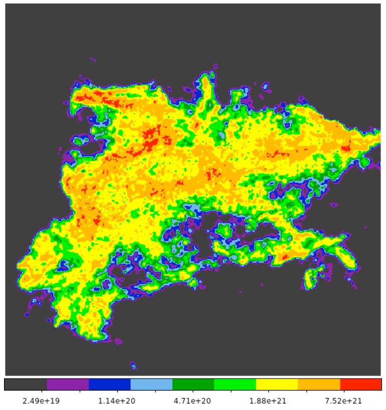
$$N(^{13}{\rm CO}) = 3.0 \times 10^{14} \frac{T_{\rm ex}\int \tau_{13}(v)dv}{1 - \exp(-5.3/T_{\rm ex})}$$

Assumptions II.

Uniform $N(^{12}CO)/N(^{13}CO) \sim 60$ *

$N(H_2)/N(^{12}CO)$ ratio ~ $6.6{\times}10^3$ **

Column density [cm-2]



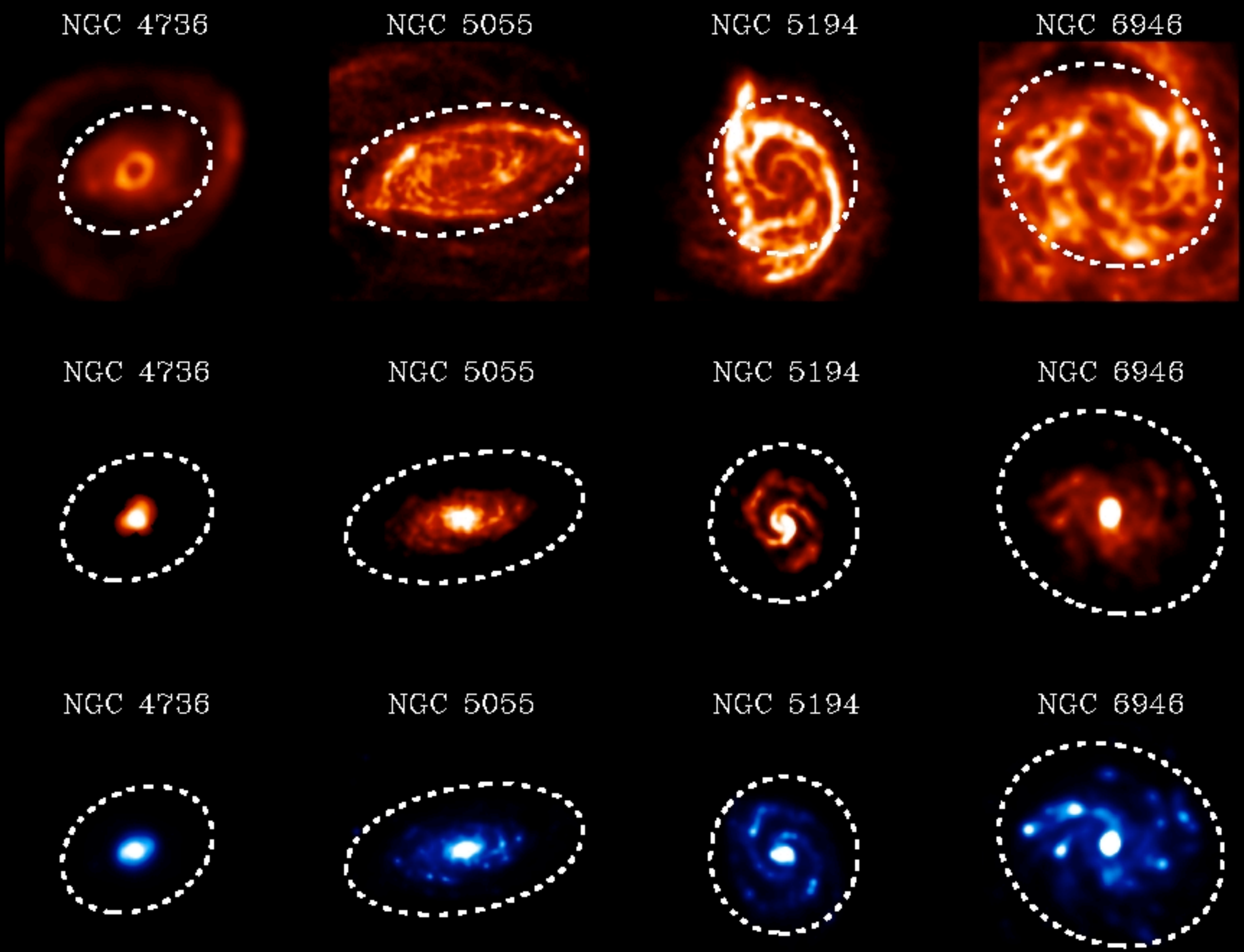
Astrophysical interpretation

Laszlo Szücs et al., MNRAS, 445, 4055)

* Langer & Penzias (1990)

** Pineda et al. (2009)

global SF relations



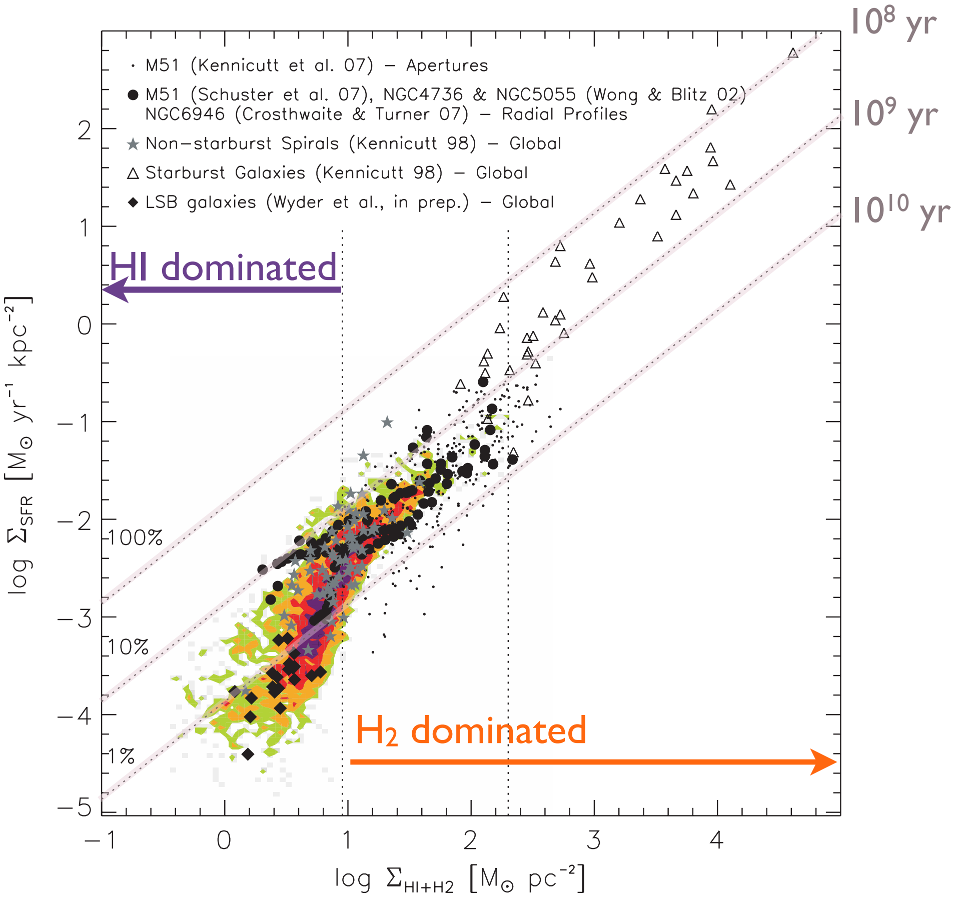
atomic hydrogen

molecular hydrogen

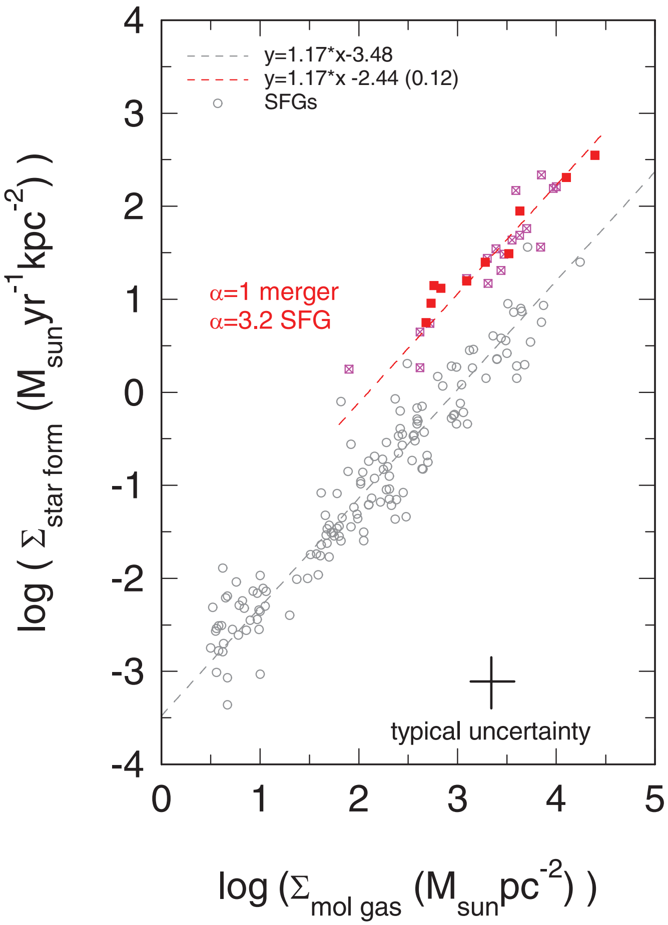
star formation

- HI gas more extended
- H2 and SF well correlated

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



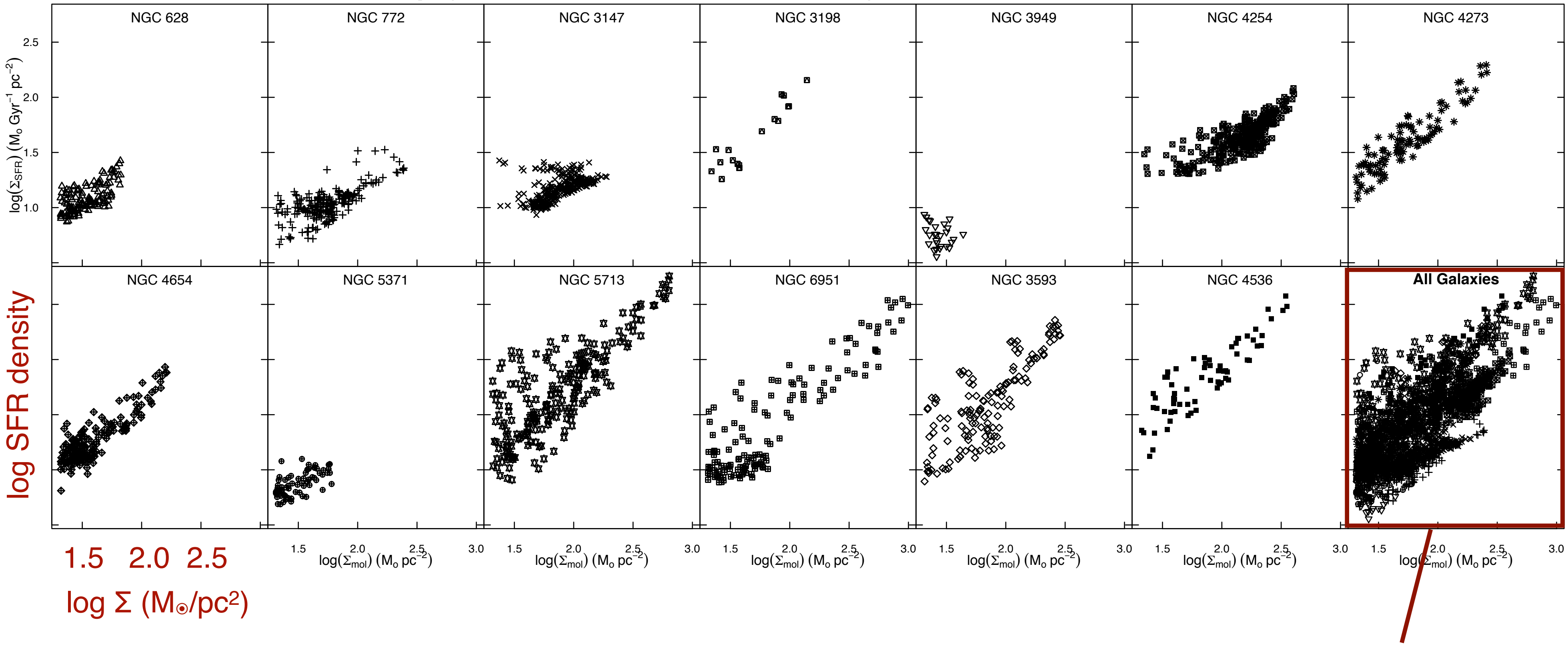
Bigiel et al. (2008, AJ, 136, 2846)



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

- standard model: roughly linear relation between H
- standard model: roughly constant depletion time: few x 10
- super linear relation between total gas and SFR

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

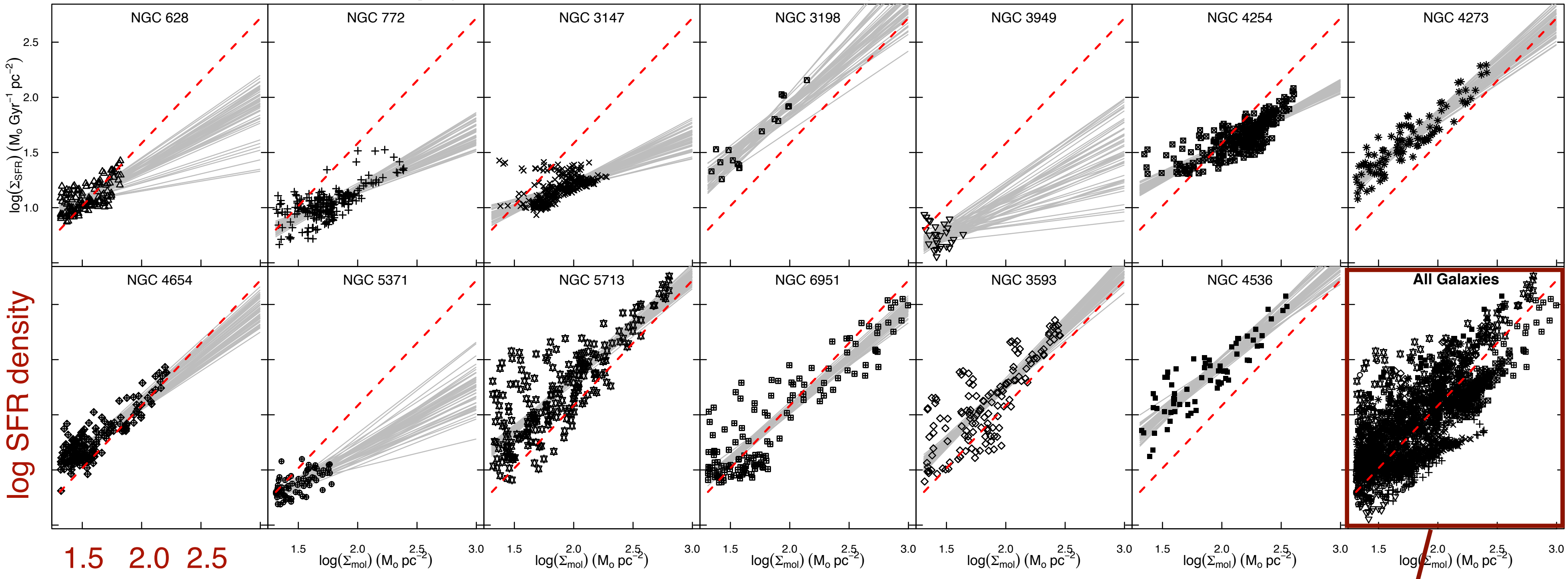


all galaxies

- QUIZ: do you see a universal

Shetty et al. (2014, MNRAS, 437, L61, see also Shetty, Kelly, Bigiel, 2013, MNRAS, 430, 288)

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



log SFR density

1.5 2.0 2.5

log Σ (M⊙/pc²)

all galaxies

- QUIZ: do you see a universal
- ANSWER: - probably not
  - in addition, the relation often is sublinear

Shetty et al. (2014, MNRAS, 437, L61, see also Shetty, Kelly, Bigiel, 2013, MNRAS, 430, 288)

Hierarchical Bayesian models give more reliable estimates of the *slope* and the *intercept* of a power-law fit compared to least-square fits (or bisector fits).

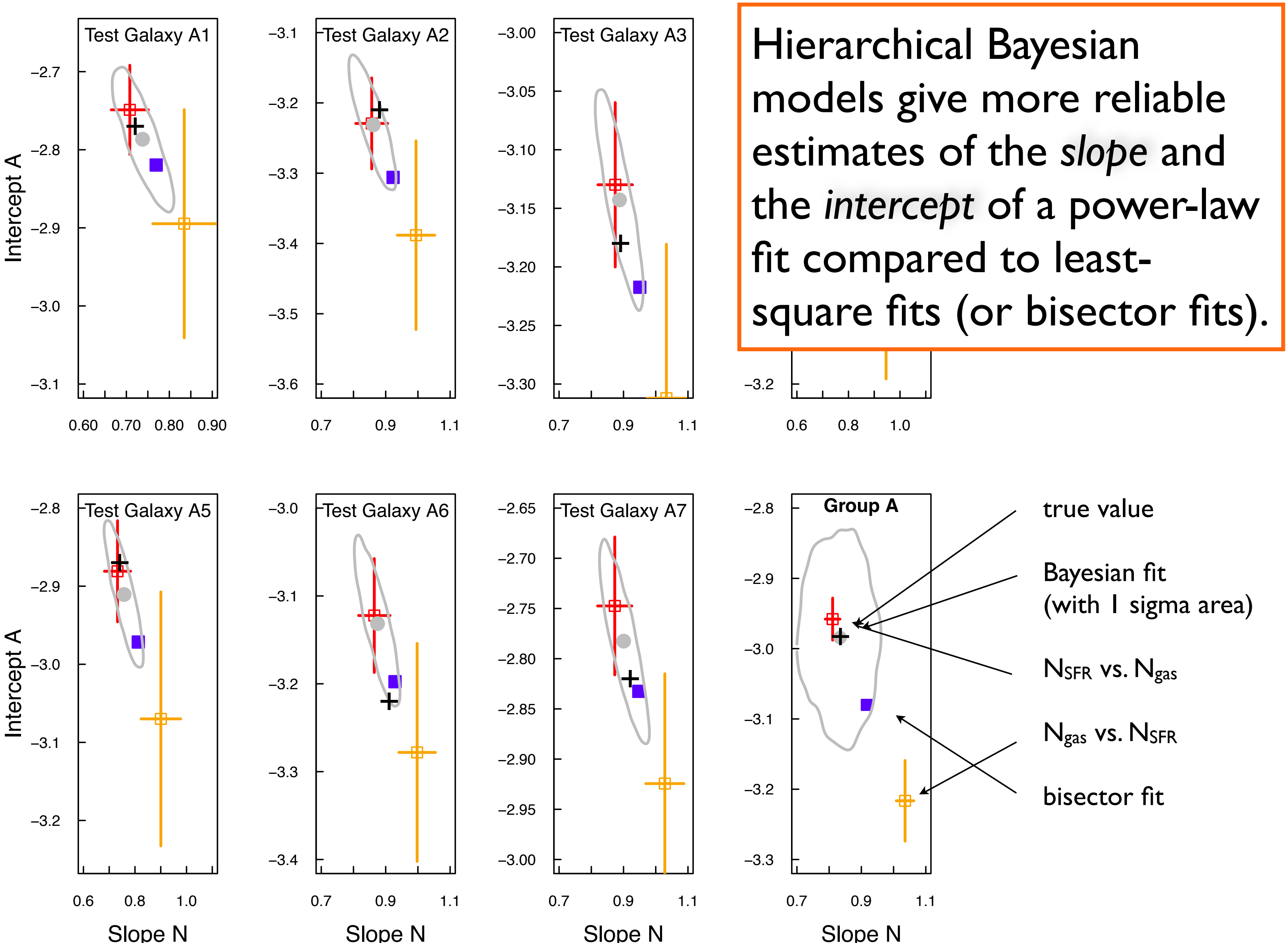
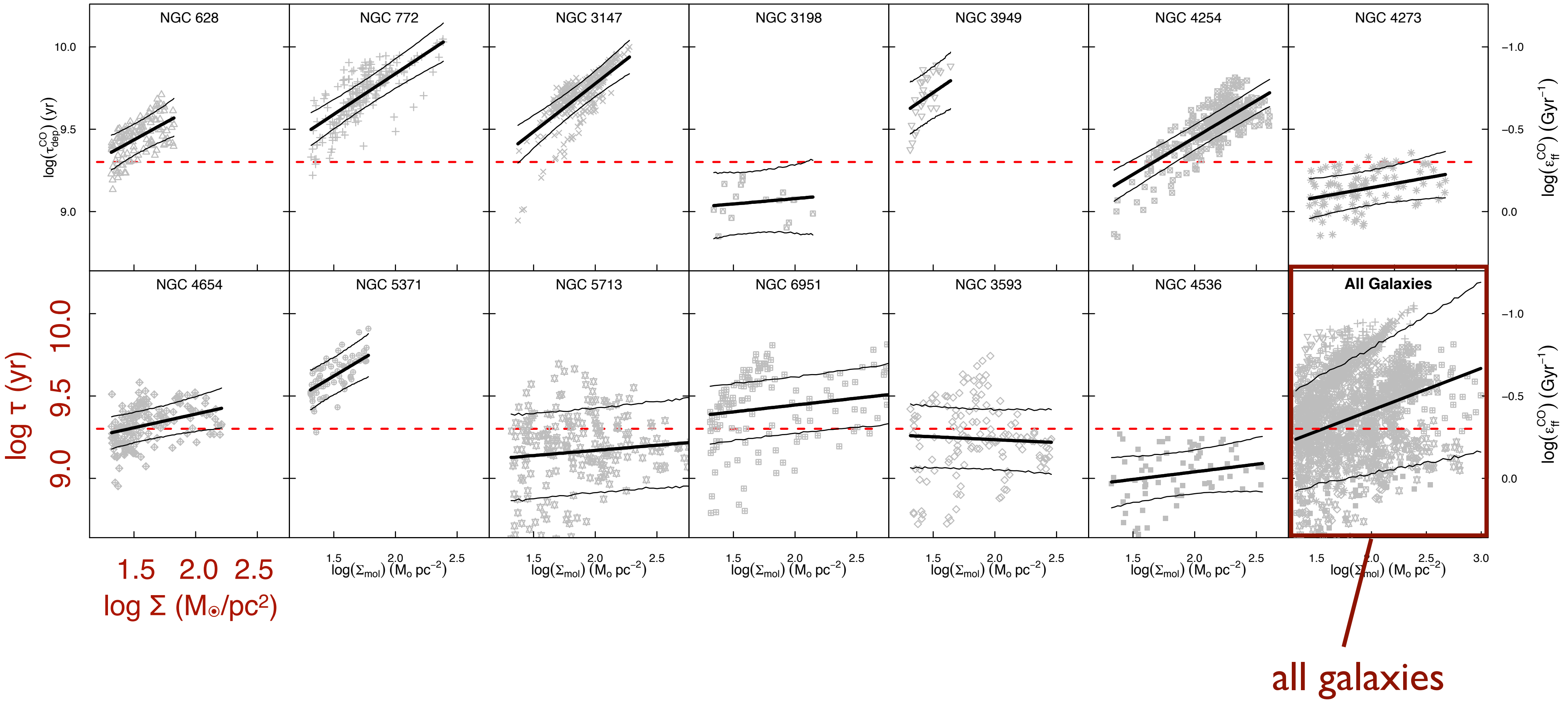


Figure 1. Slope and intercept of test galaxies in Group A. Black cross shows the true values. Red and orange squares show the OLS($\Sigma_{\rm SFR}|\Sigma_{\rm mol}$) and OLS($\Sigma_{\rm mol}|\Sigma_{\rm SFR}$) results, with their 1σ uncertainties, respectively. The gray circles indicate the estimate provided by the median of hierarchical Bayesian posterior result, and the contours mark the 1σ deviation. The filled blue squares mark the bisector estimates. The last panel on the bottom row shows the group parameters and fit estimates.

Shetty et al. (2013, MNRAS, 430, 288)

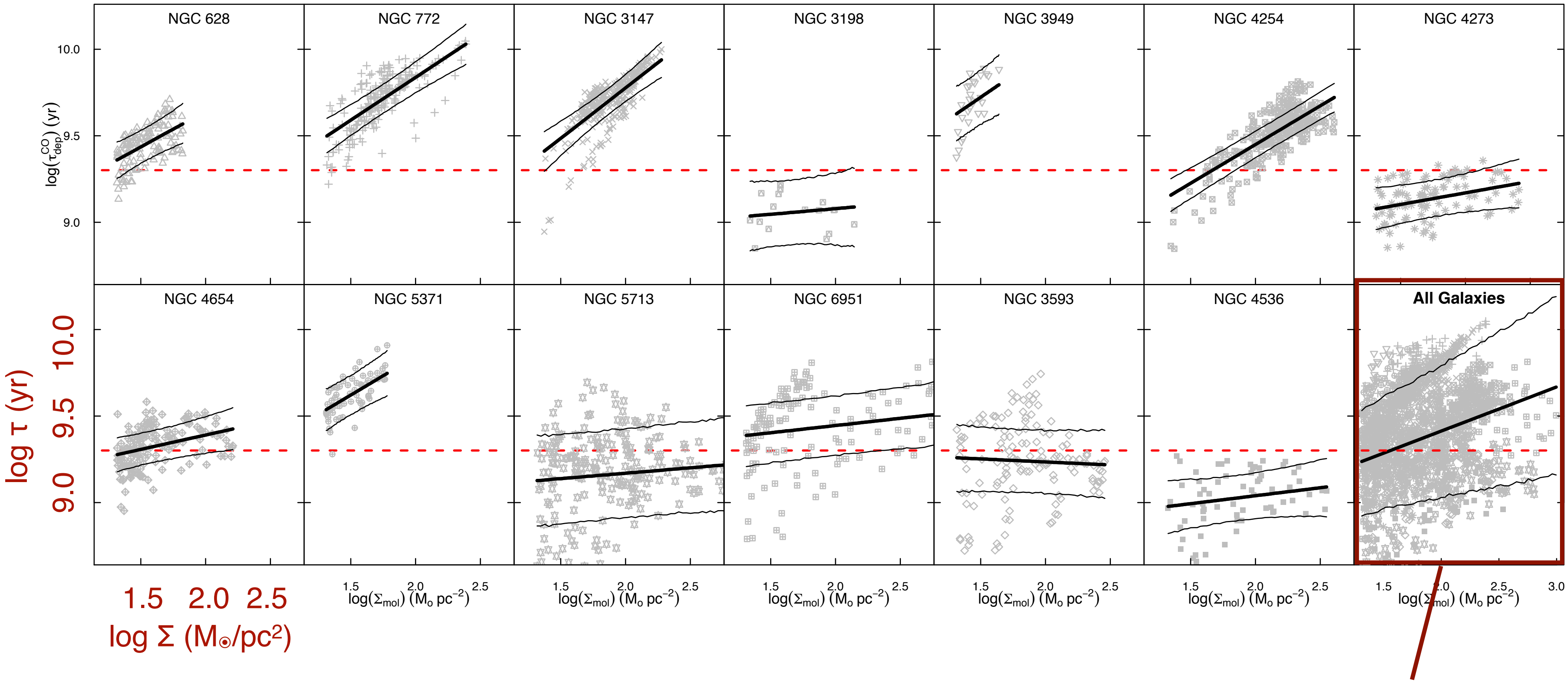
data from STING survey (Rahman et al. 2011, 2012)



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

Shetty et al. (2014, MNRAS, 437, L61)

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

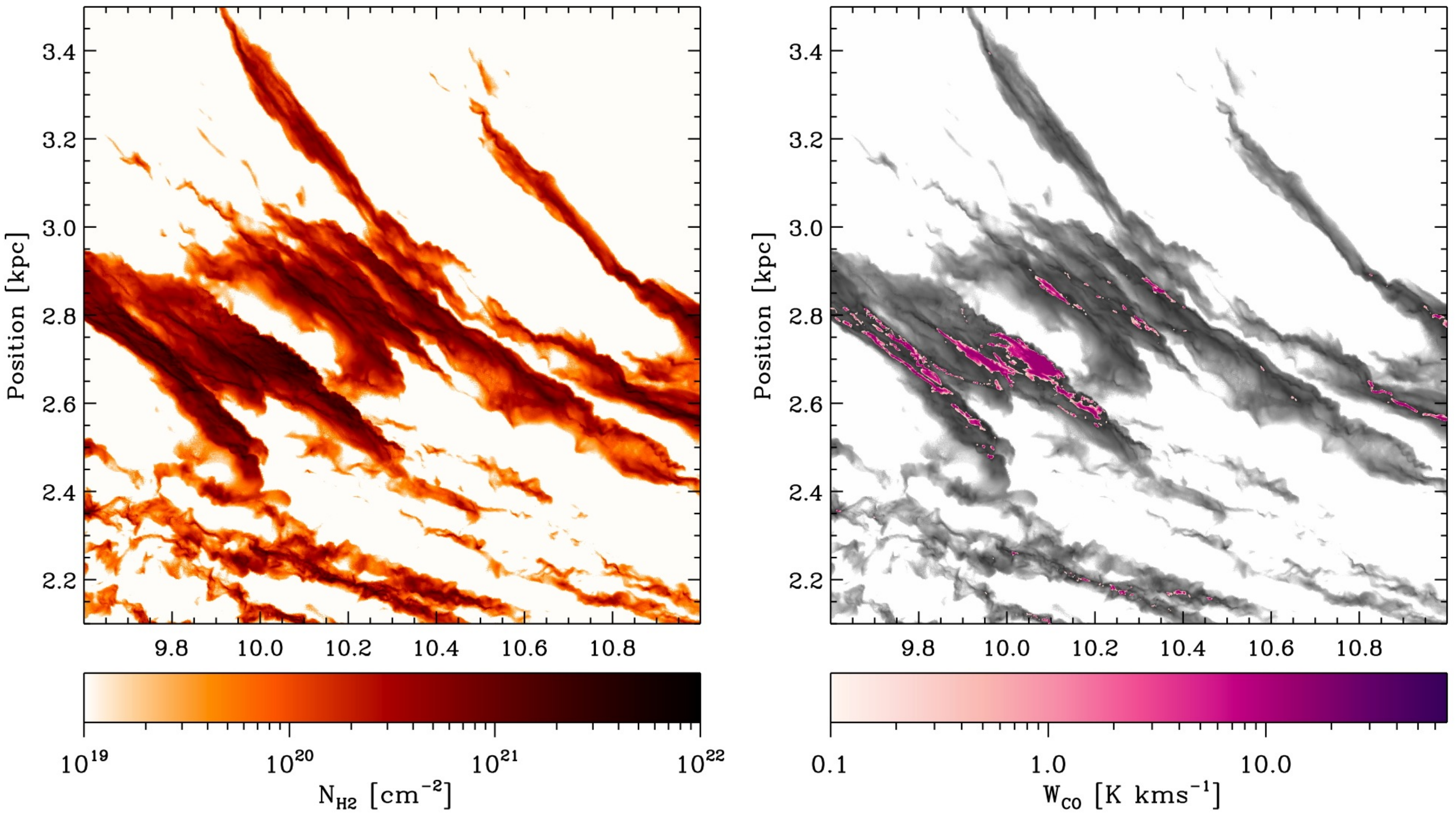


all galaxies

physical origin of this behavior?

- maybe strong shear in dense arms (example M51, Meidt et al. 2013)...
- maybe non-star forming H
  densities (recall H
  [see part 1 on December 19, 2014]

Shetty et al. (2013, MNRAS, 437, L61, see also Shetty, Kelly, Bigiel, 2013, MNRAS, 430, 288)



Smith et al. (2014, MNRAS, 441, 1628)

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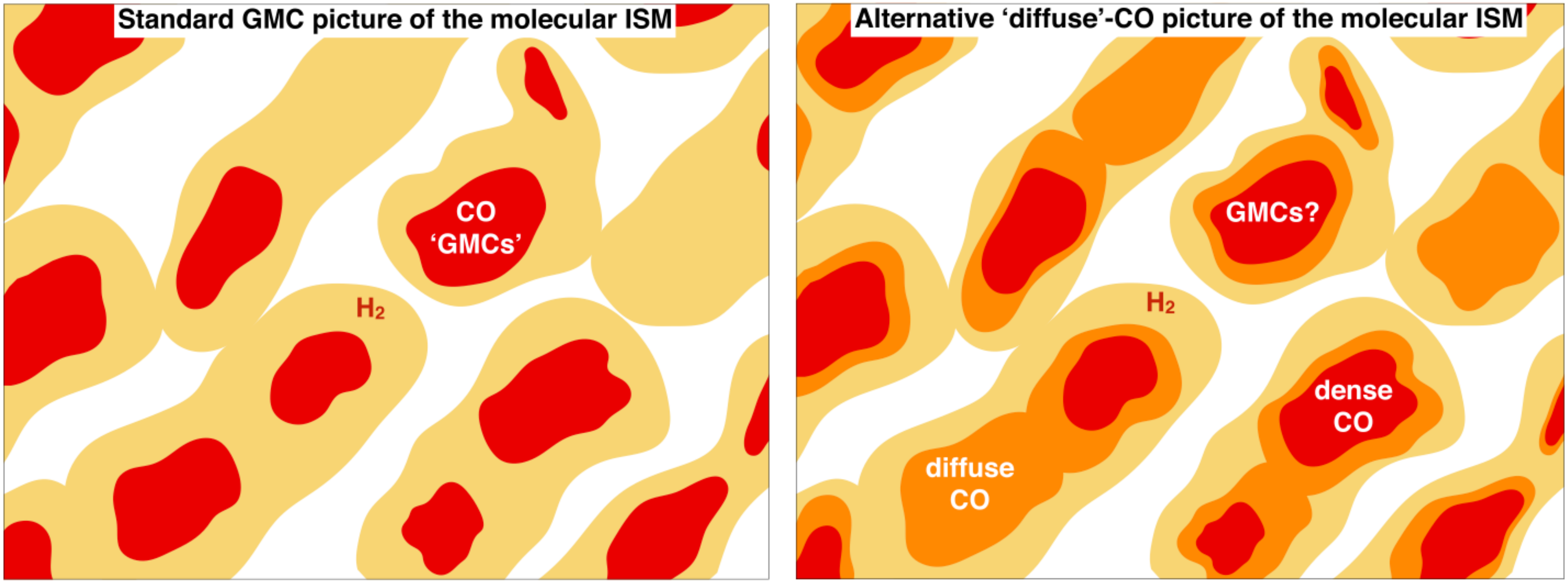
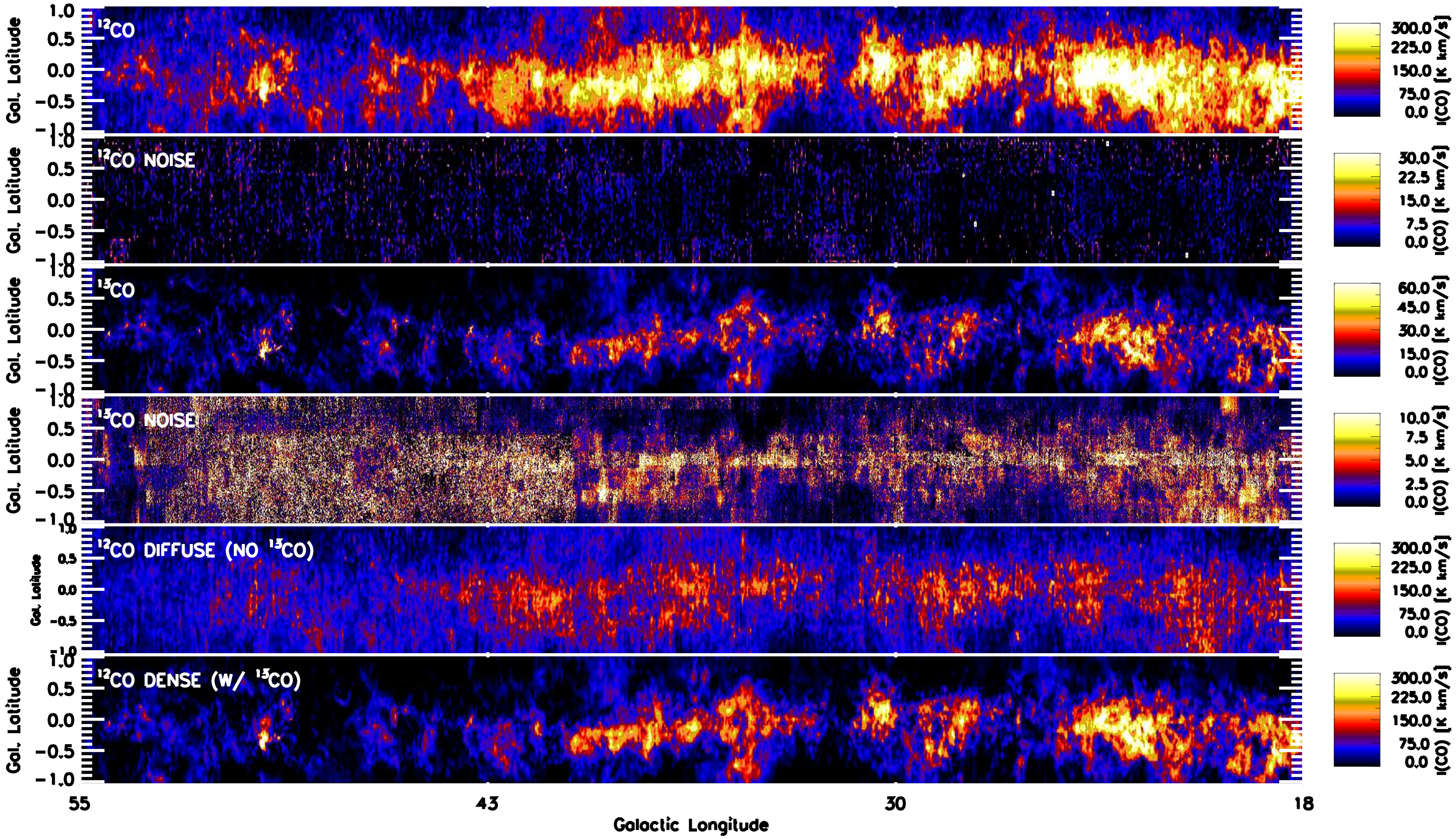


in addition:

- maybe a large fraction of H
  dense clouds, but in a diffuse state!

Shetty et al. (2014, MNRAS, 422, 2208)



^{12}CO

^{13}CO

^{12}CO diffuse

^{12}CO dense

Galactic Ring Survey (GRS)

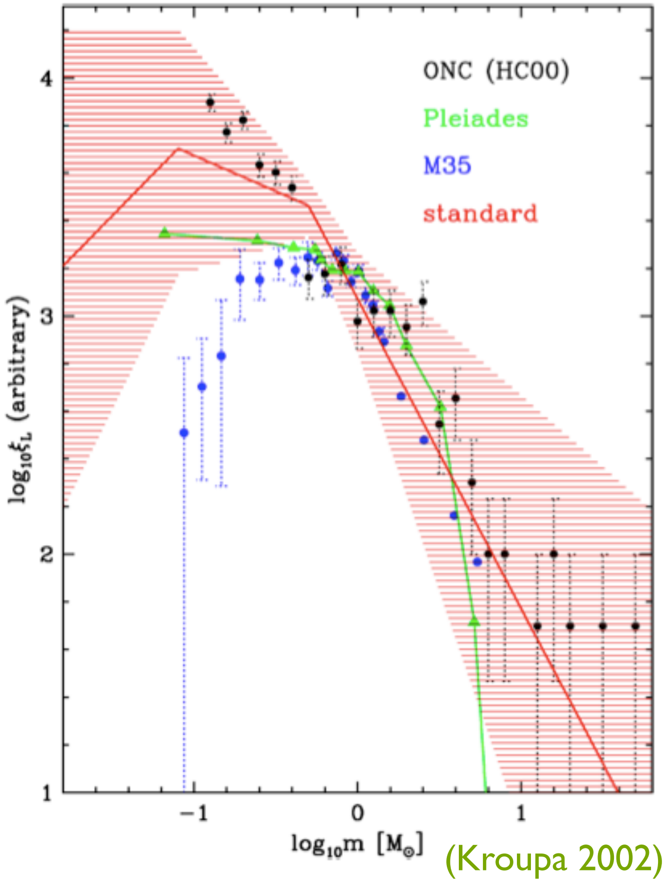
- comparison of
  tracing all the gas (including the more diffuse component)

Roman-Duval et al. (2015, in prep.)

stellar mass function

stellar mass fuction

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



(Kroupa 2002)

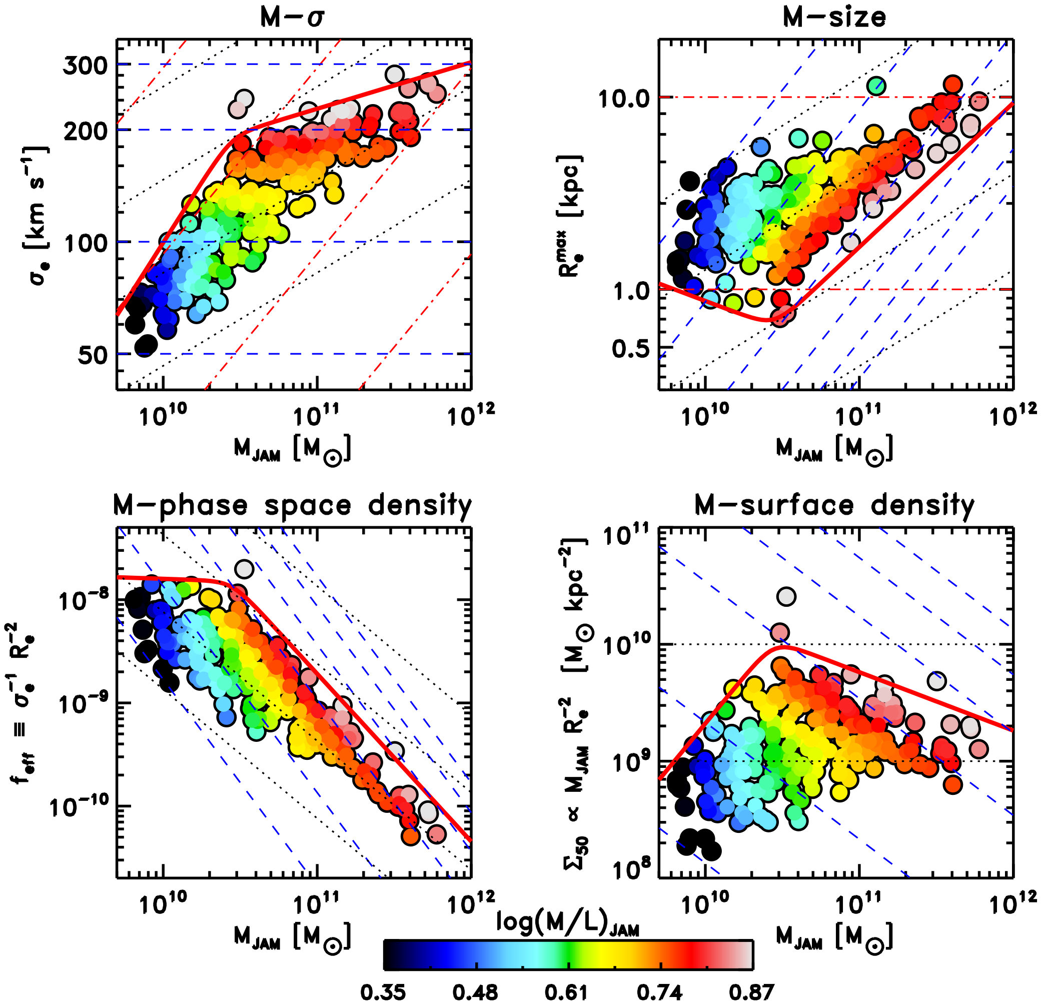
Orion, NGC 3603, 30 Doradus
(Zinnecker & Yorke 2007)

stellar mass fuction

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

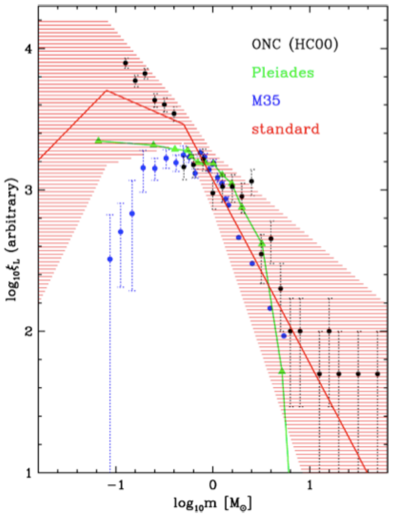
from JAM (Jeans anisotropic multi Gaussian expansion) modeling

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



(Kroupa 2002)

- 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

stellar masses

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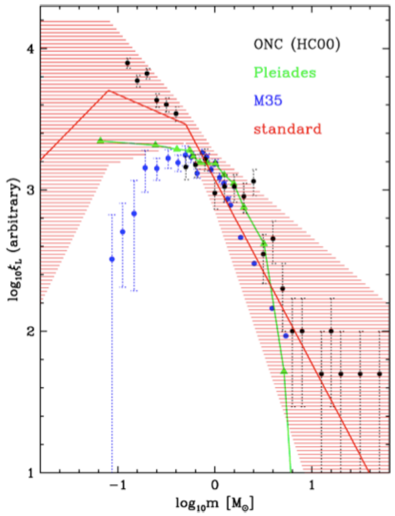
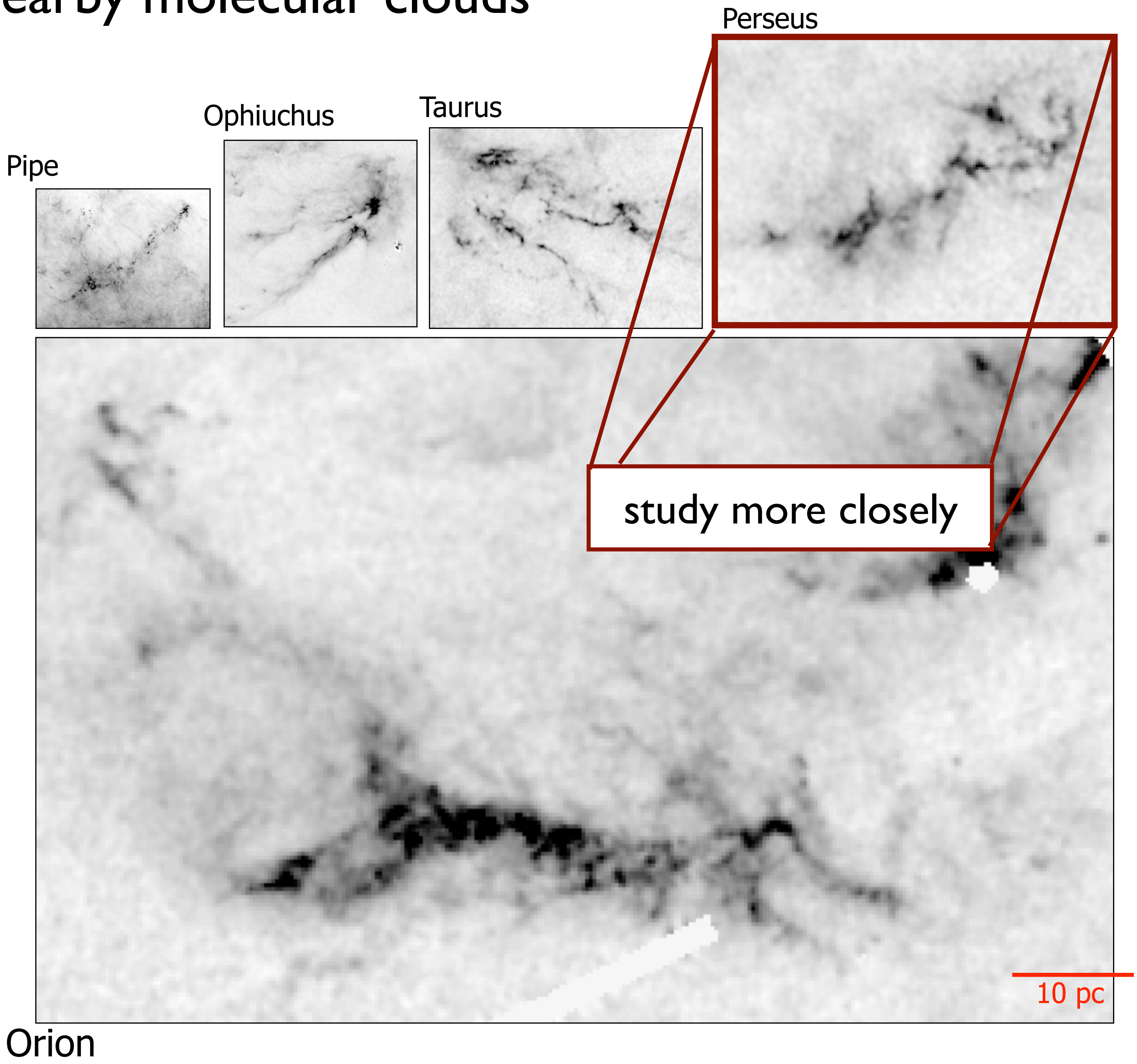


(Kroupa 2002)

nearby molecular clouds



study more closely

scales to same scale

(from A. Goodman)

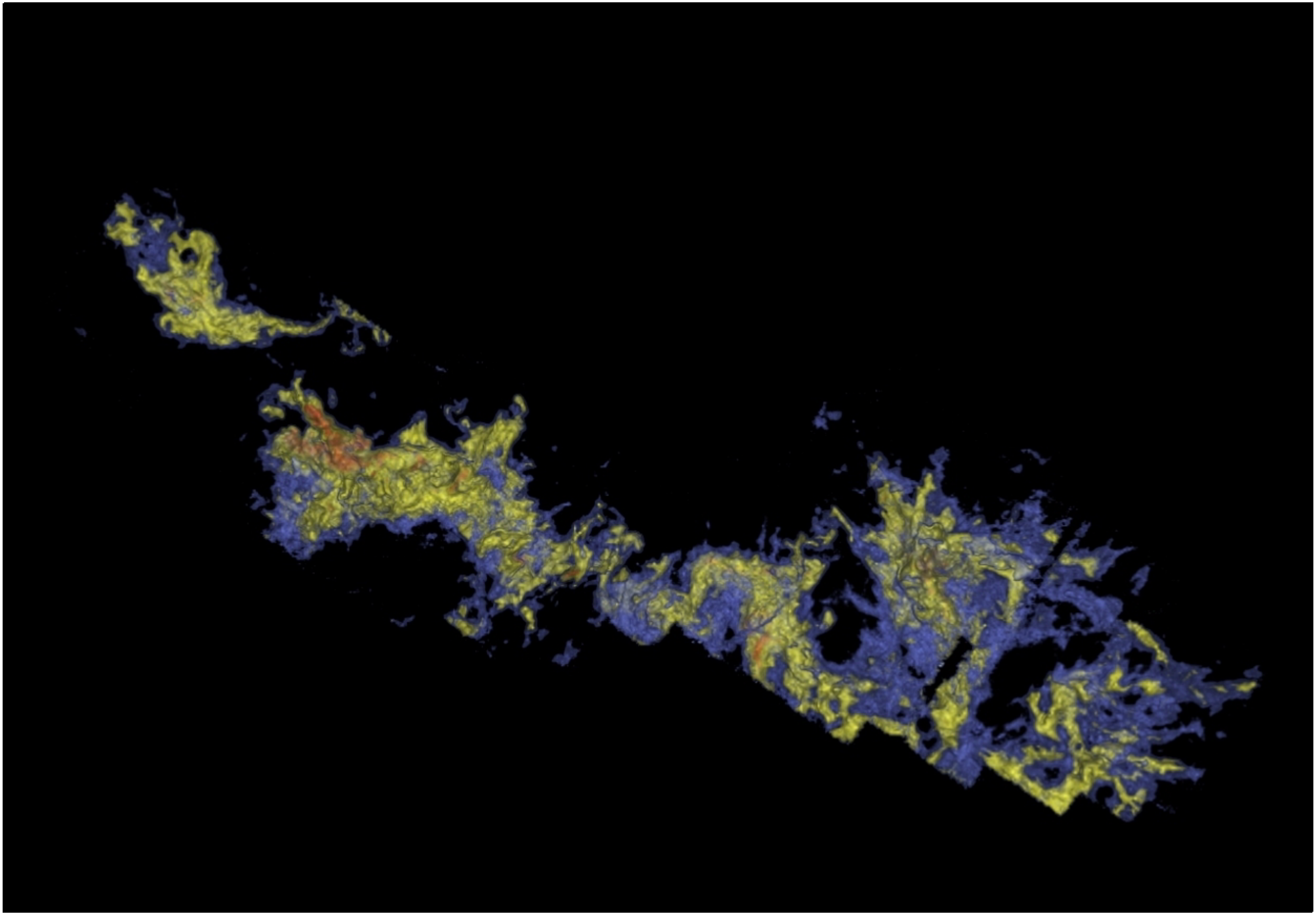
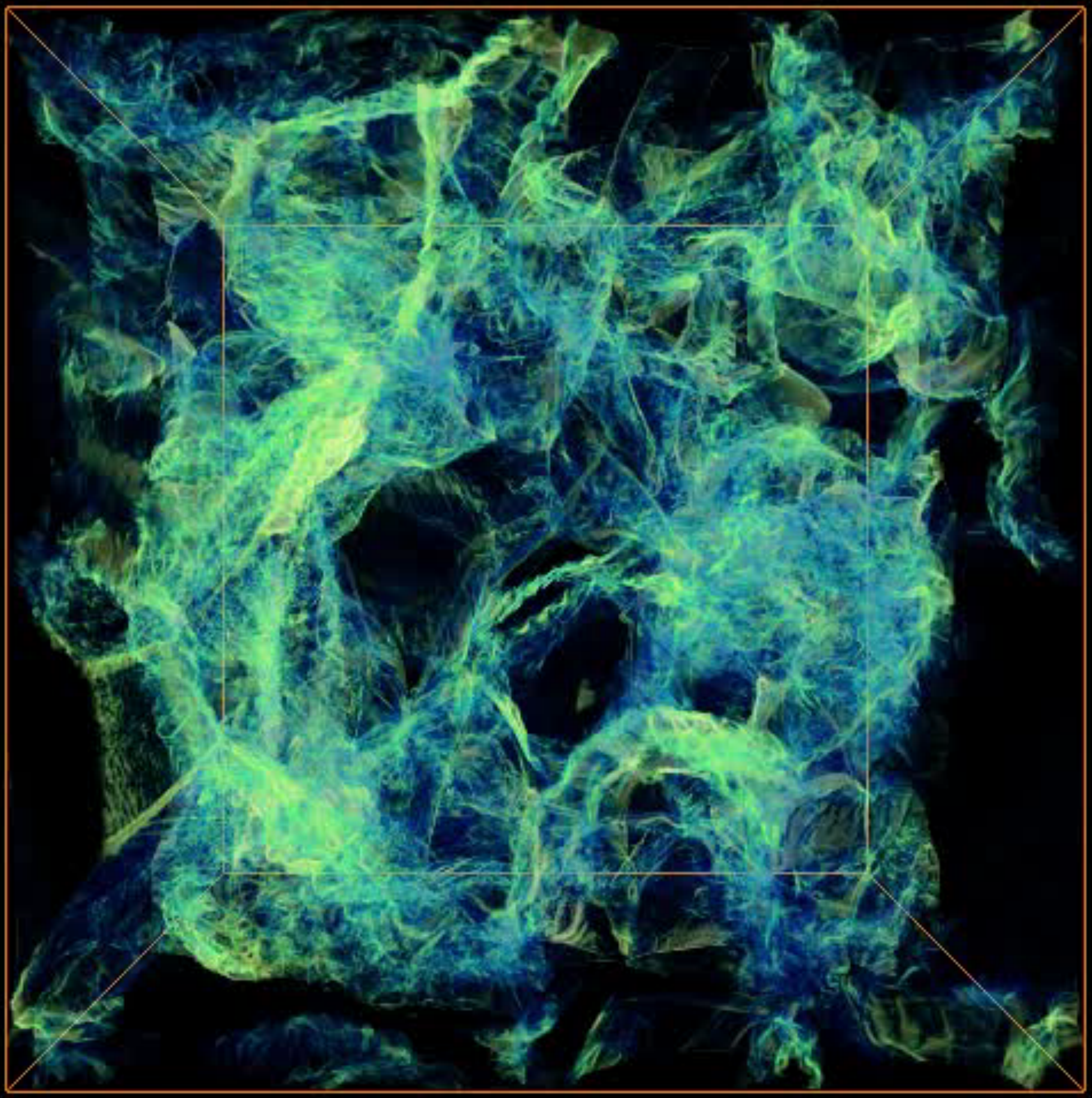


image from Alyssa Goodman: COMPLETE survey



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

example: model of Orion cloud

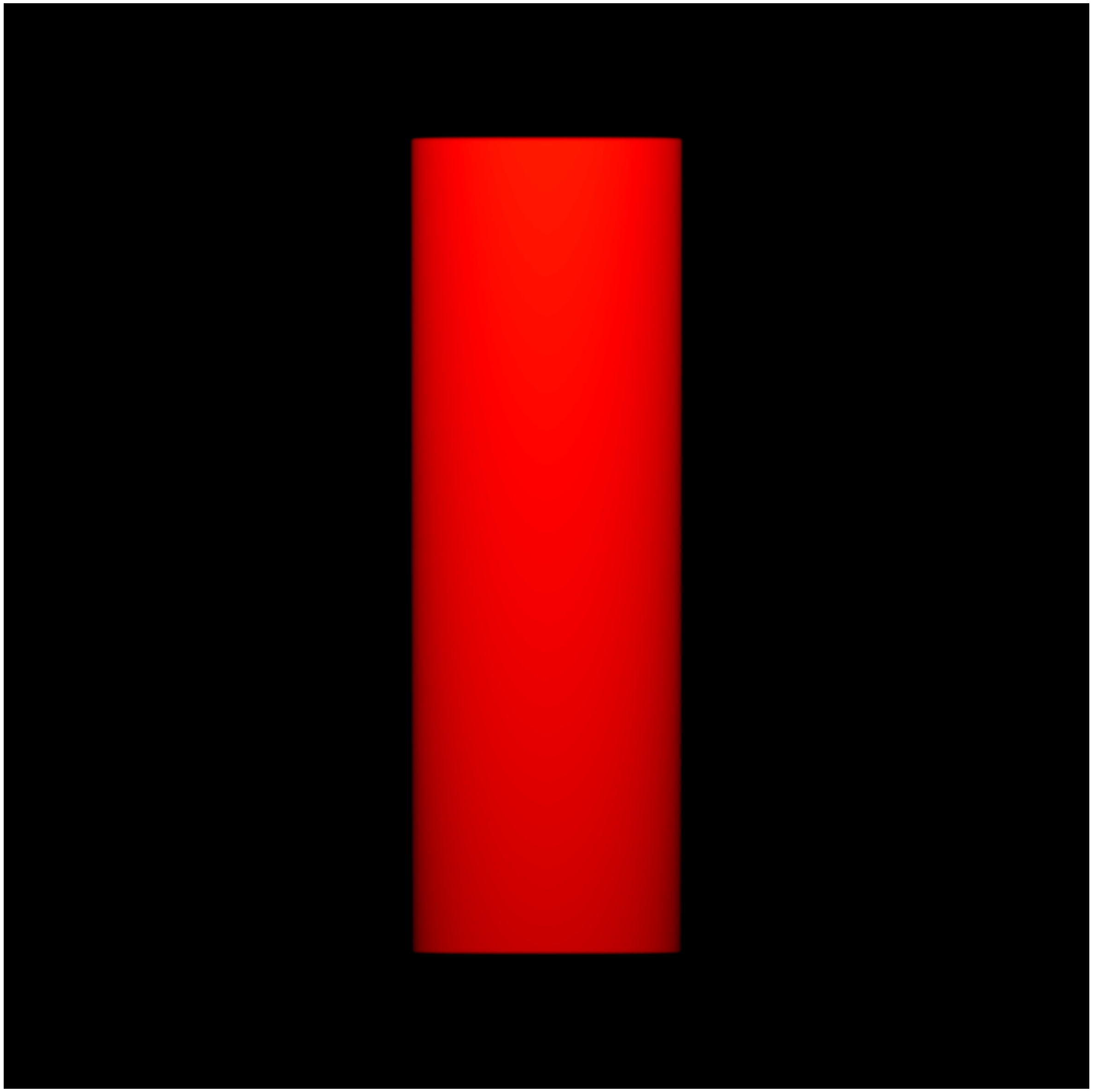
„model“ of Orion cloud:
15.000.000 SPH particles,
10^4 M_{sun} in 10 pc, mass resolution
0,02 M_{sun}, forms ~2.500
„stars“ (sink particles)

isothermal EOS, top bound, bottom unbound

has clustered as well as distributed „star“ formation

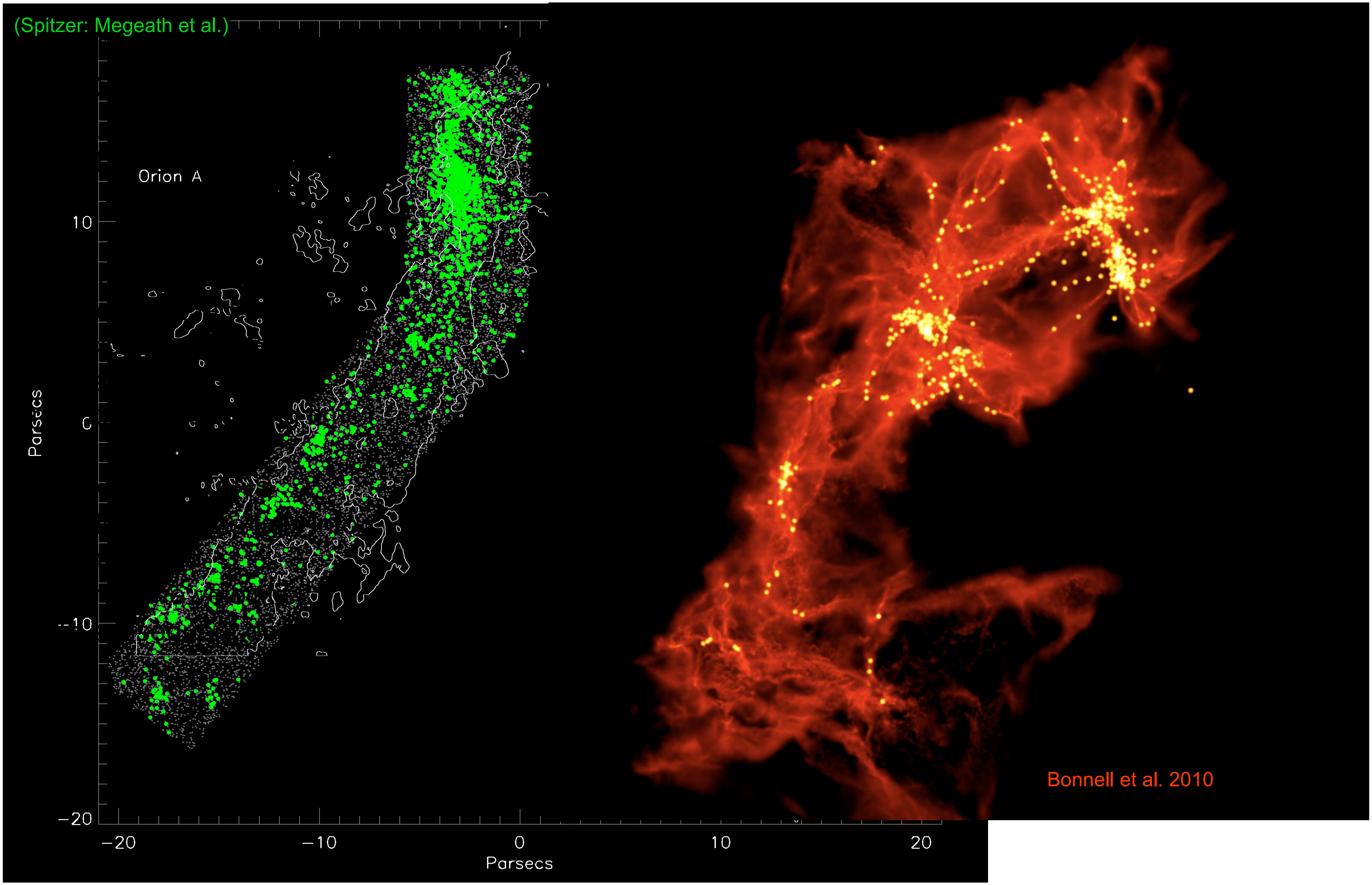
efficiency varies from 1% to 20%

develops full IMF
(distribution of sink particle masses)



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

example: model of Orion cloud

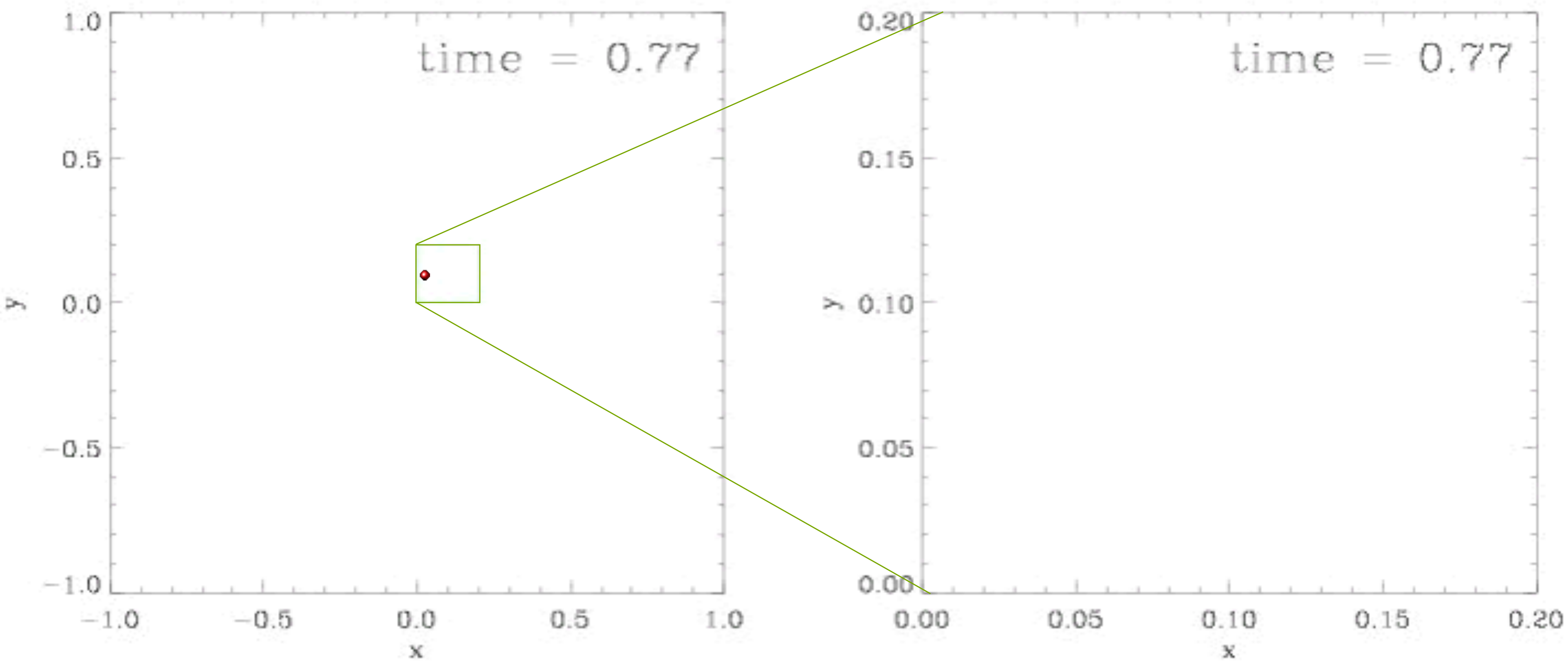


(Spitzer: Megeath et al.)

Bonnell et al. 2010

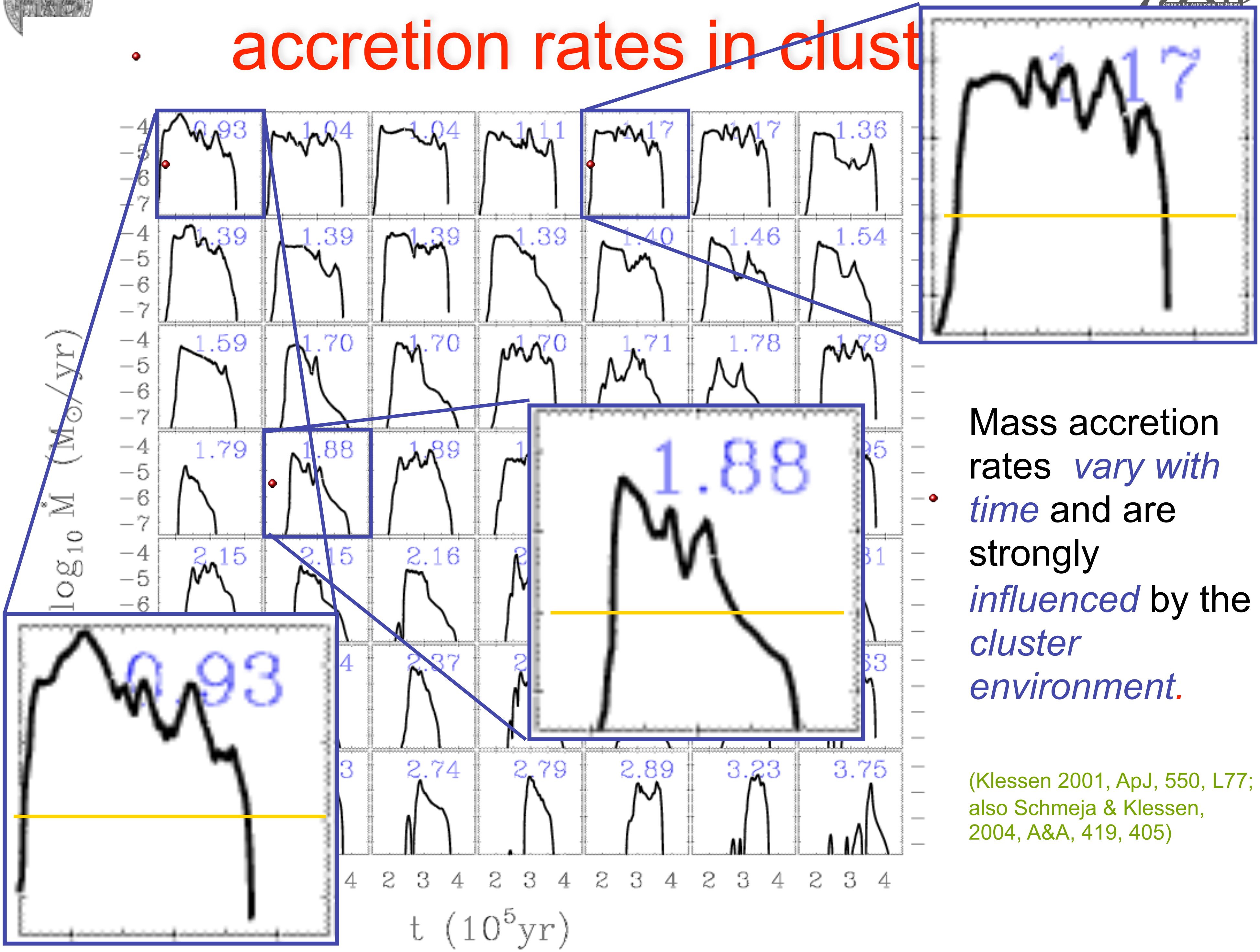
dynamics of nascent star cluster

in dense clusters protostellar interaction may be come important!



Trajectories of protostars in a nascent dense cluster created by gravoturbulent fragmentation
(from Klessen & Burkert 2000, ApJS, 128, 287)

accretion rates in clust



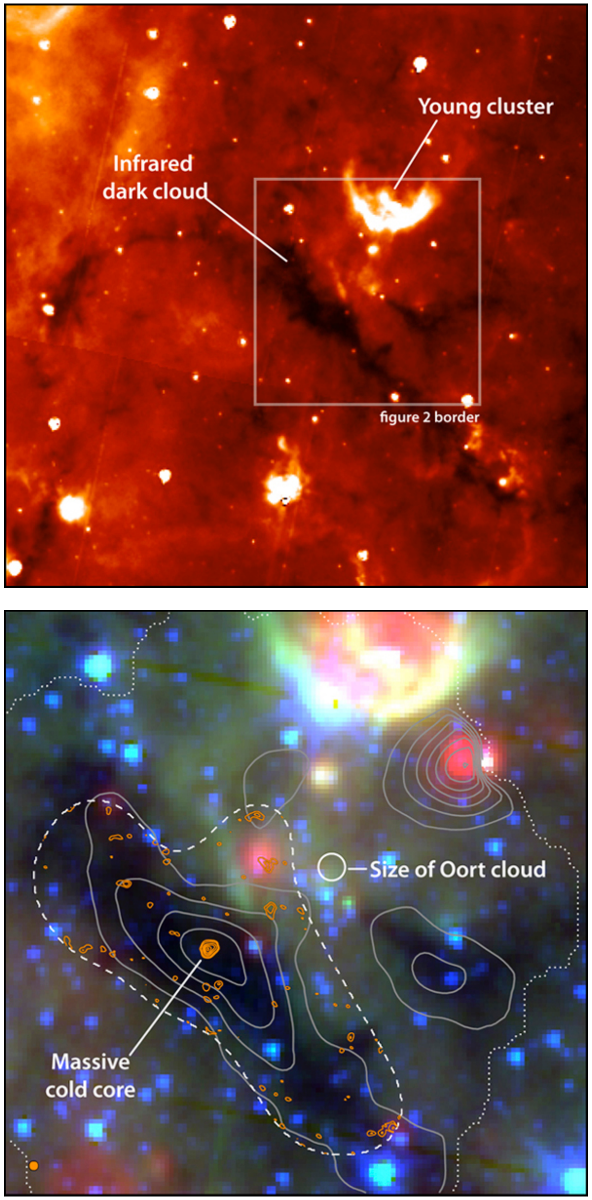
- Mass accretion rates *vary with time* and are strongly *influenced* by the *cluster environment*.

(Klessen 2001, ApJ, 550, L77; also Schmeja & Klessen, 2004, A&A, 419, 405)

important caveat:
initial conditions?

ICs of star cluster formation

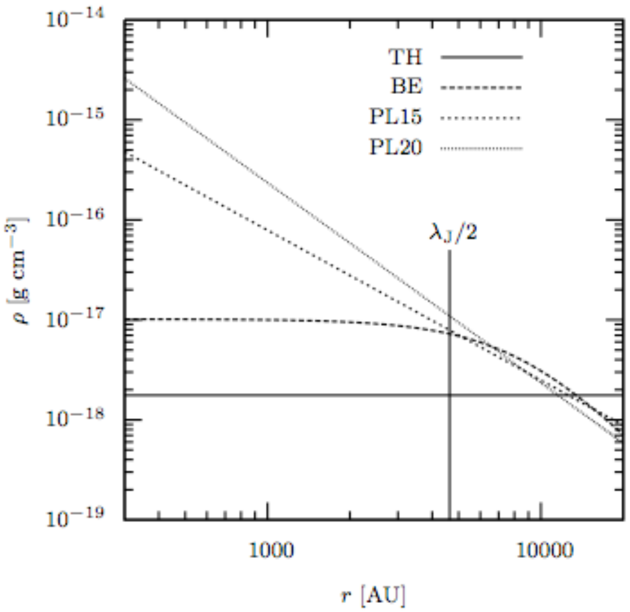
- key question:
  - what is the initial density profile of cluster forming cores? how does it compare low-mass cores?
- observers answer:
  - very difficult to determine!
    - most high-mass cores have some SF inside
    - infra-red dark clouds (IRDCs) are difficult to study
  - but, new results with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



IRDC near Aquila rift, studied with the SMA: J. Swift & E. Churchwell

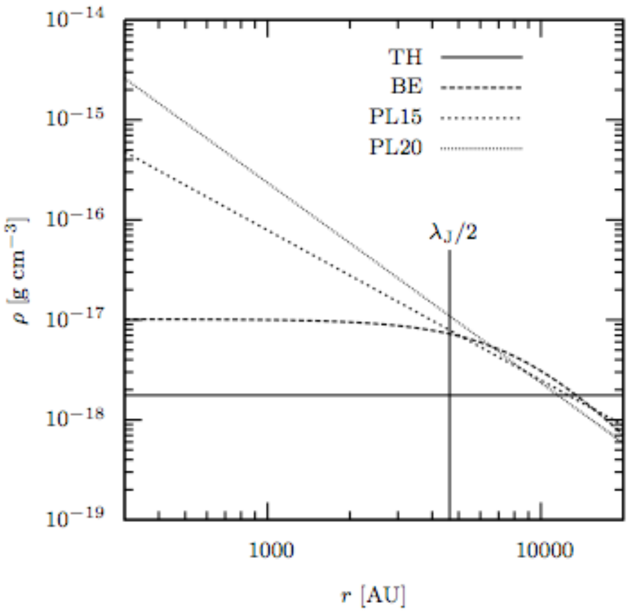
ICs of star cluster formation

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



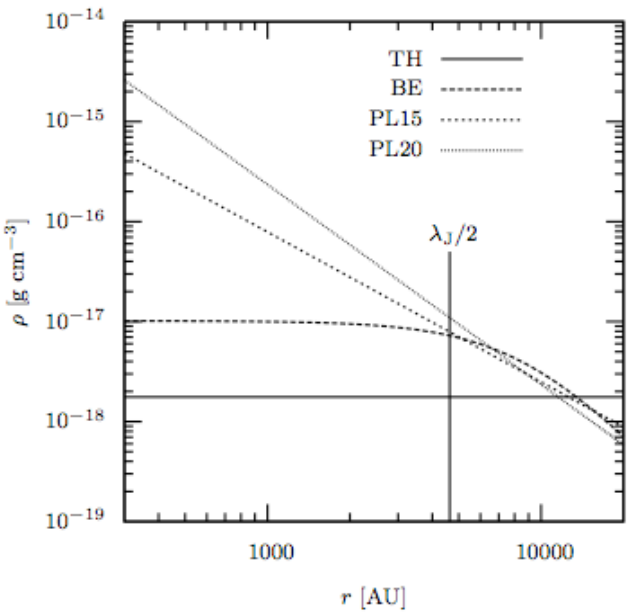
different density profiles

- does the density profile matter?
  .
  .
  .
- in comparison to
  - turbulence ...
  - radiative feedback ...
  - magnetic fields ...
  - thermodynamics ...

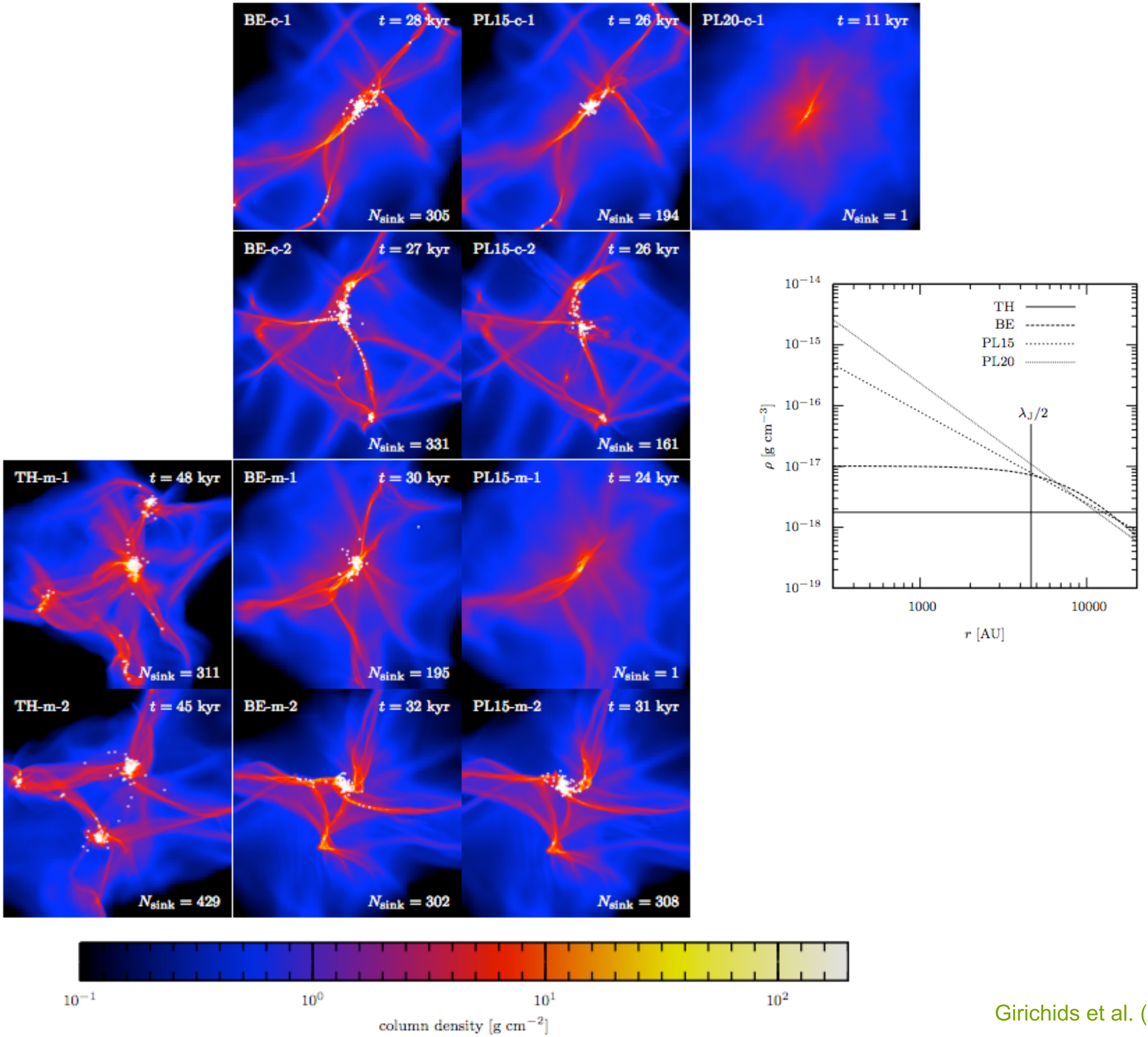


different density profiles

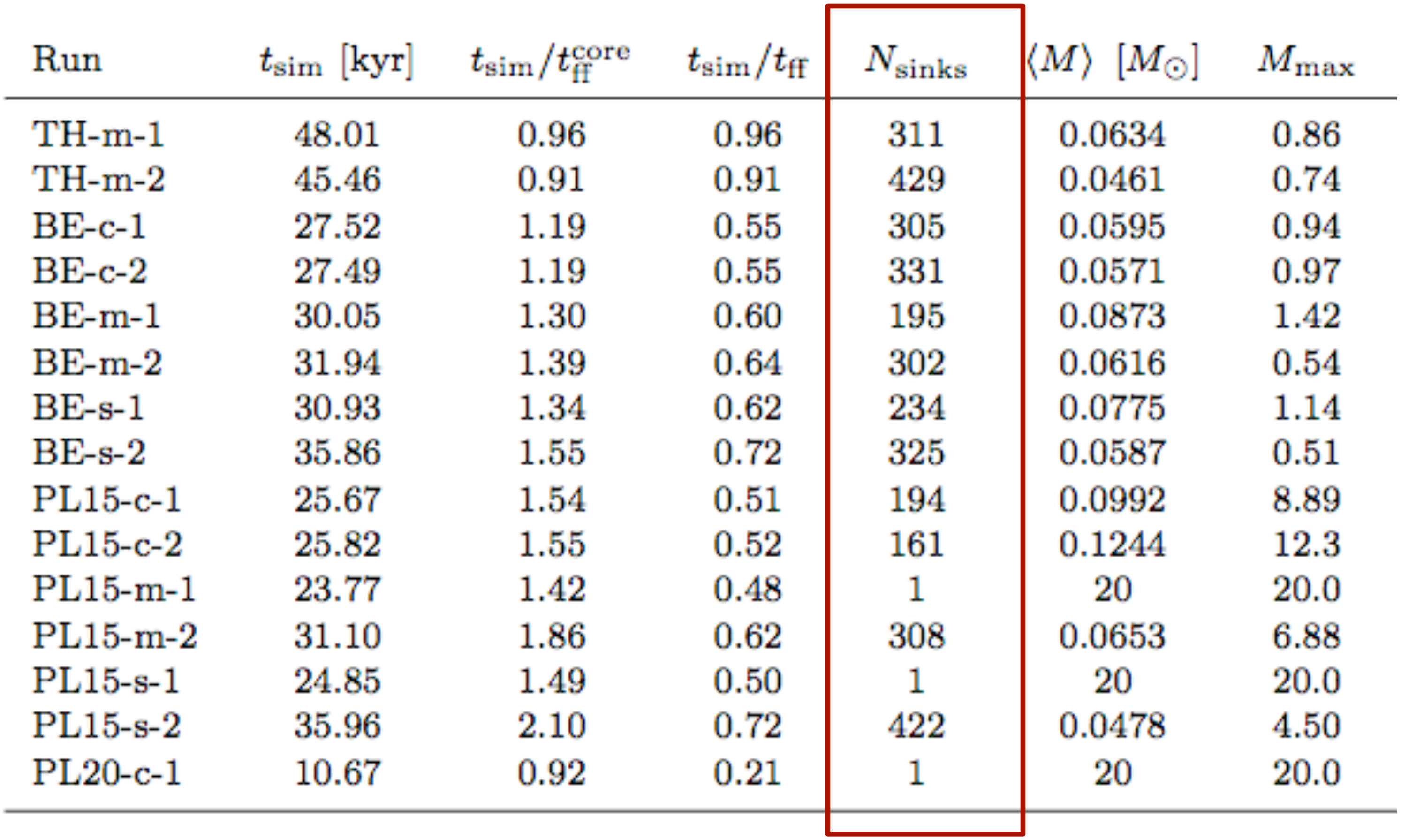
- address question in simple numerical experiment
- perform extensive parameter study
  - different profiles (top hat, BE, $r^{-3/2}$, r^{-3})
  - different turbulence fields
    - different realizations
    - different Mach numbers
    - solenoidal turbulence
      dilatational turbulence
      both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



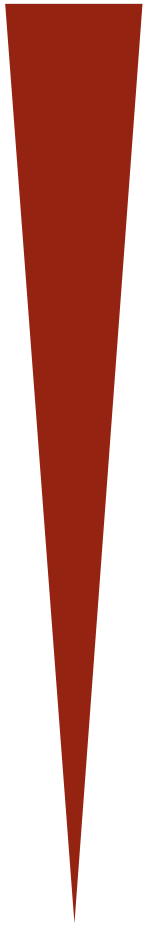
Girichids, Federrath, Banerjee, Klessen (2011abc)



Girichids et al. (2011abc)



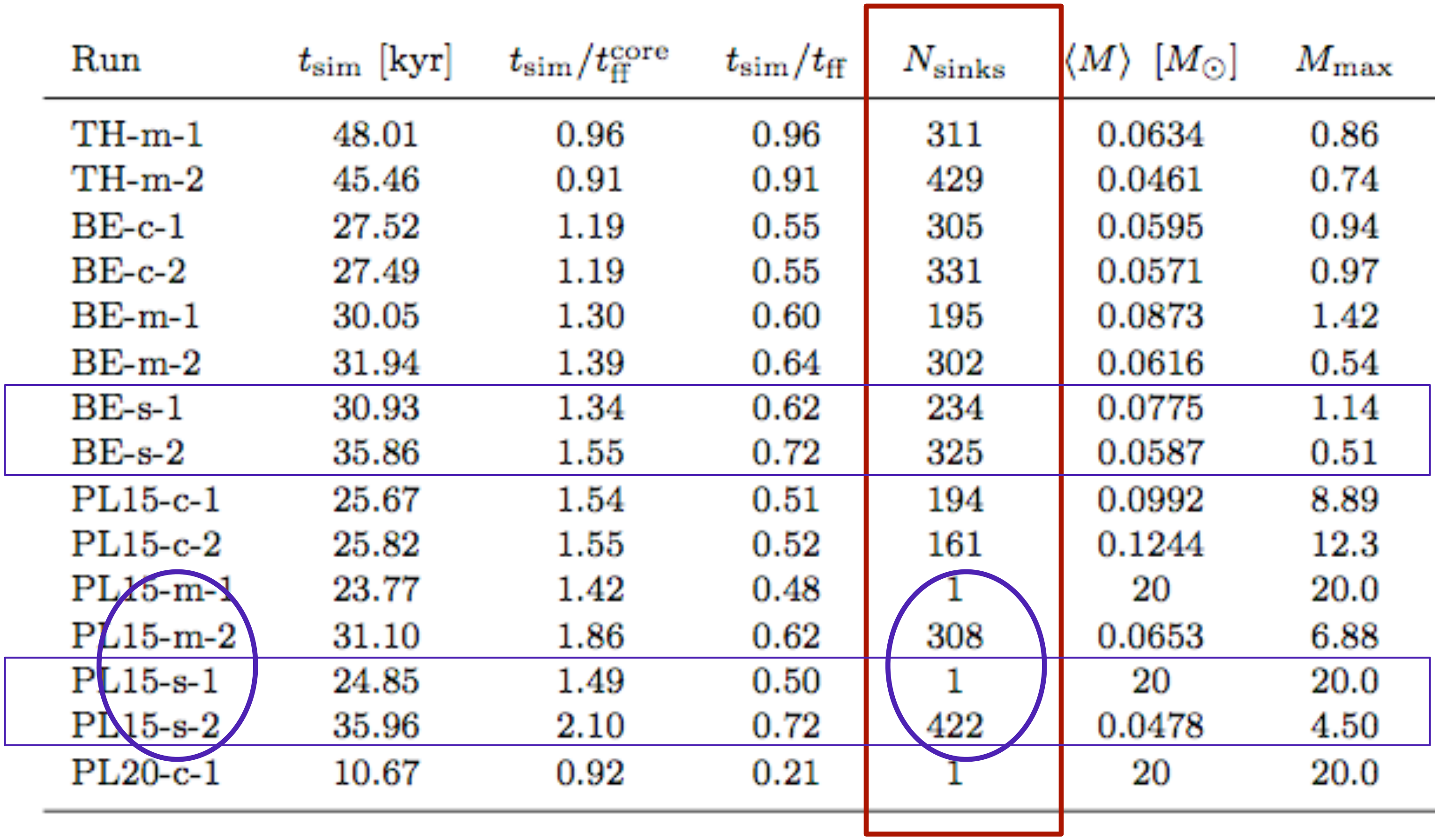
Run	t_{sim} [kyr]	$t_{\mathrm{sim}}/t_{\mathrm{ff}}^{\mathrm{core}}$	$t_{\mathrm{sim}}/t_{\mathrm{ff}}$	N_{sinks}	$\langle M\rangle$ $[M_\odot]$	M_{max}
TH-m-1	48.01	0.96	0.96	311	0.0634	0.86
TH-m-2	45.46	0.91	0.91	429	0.0461	0.74
BE-c-1	27.52	1.19	0.55	305	0.0595	0.94
BE-c-2	27.49	1.19	0.55	331	0.0571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



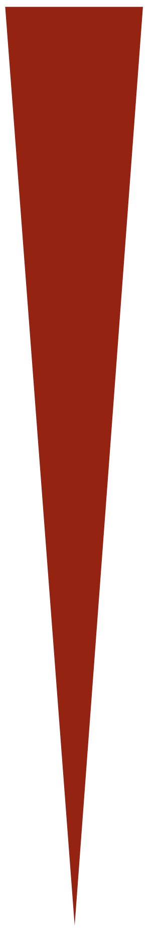
number of protostars

ICs with flat inner density profile on average form more fragments

Girichids et al. (2011abc)



Run	t_{sim} [kyr]	$t_{\mathrm{sim}}/t_{\mathrm{ff}}^{\mathrm{core}}$	$t_{\mathrm{sim}}/t_{\mathrm{ff}}$	N_{sinks}	$\langle M \rangle$ $[M_{\odot}]$	M_{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



number of protostars

ICs with flat inner density profile on average form more fragments

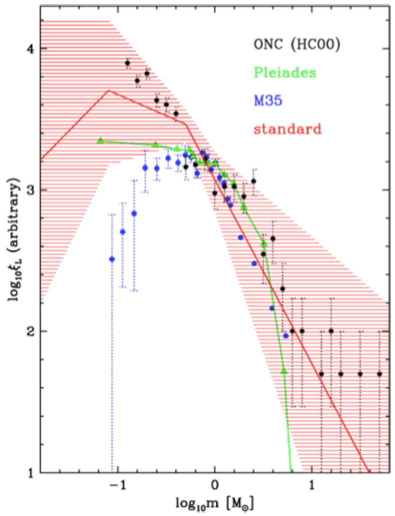
however, the real situation is very complex: details of the initial turbulent field matter

Girichids et al. (2011abc)

stellar mass fuction

- 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, etc.

(Kroupa 2002)



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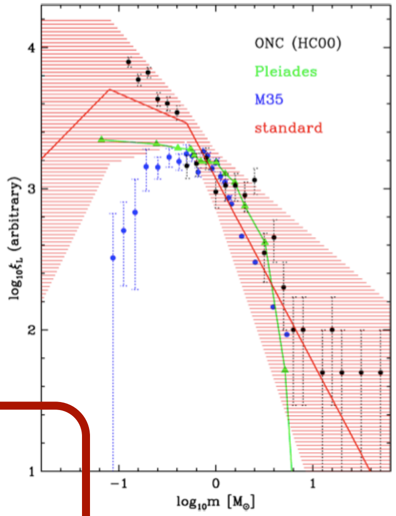


application to early star formation

thermodynamics & fragmentation

degree of fragmentation depends on *EOS!*

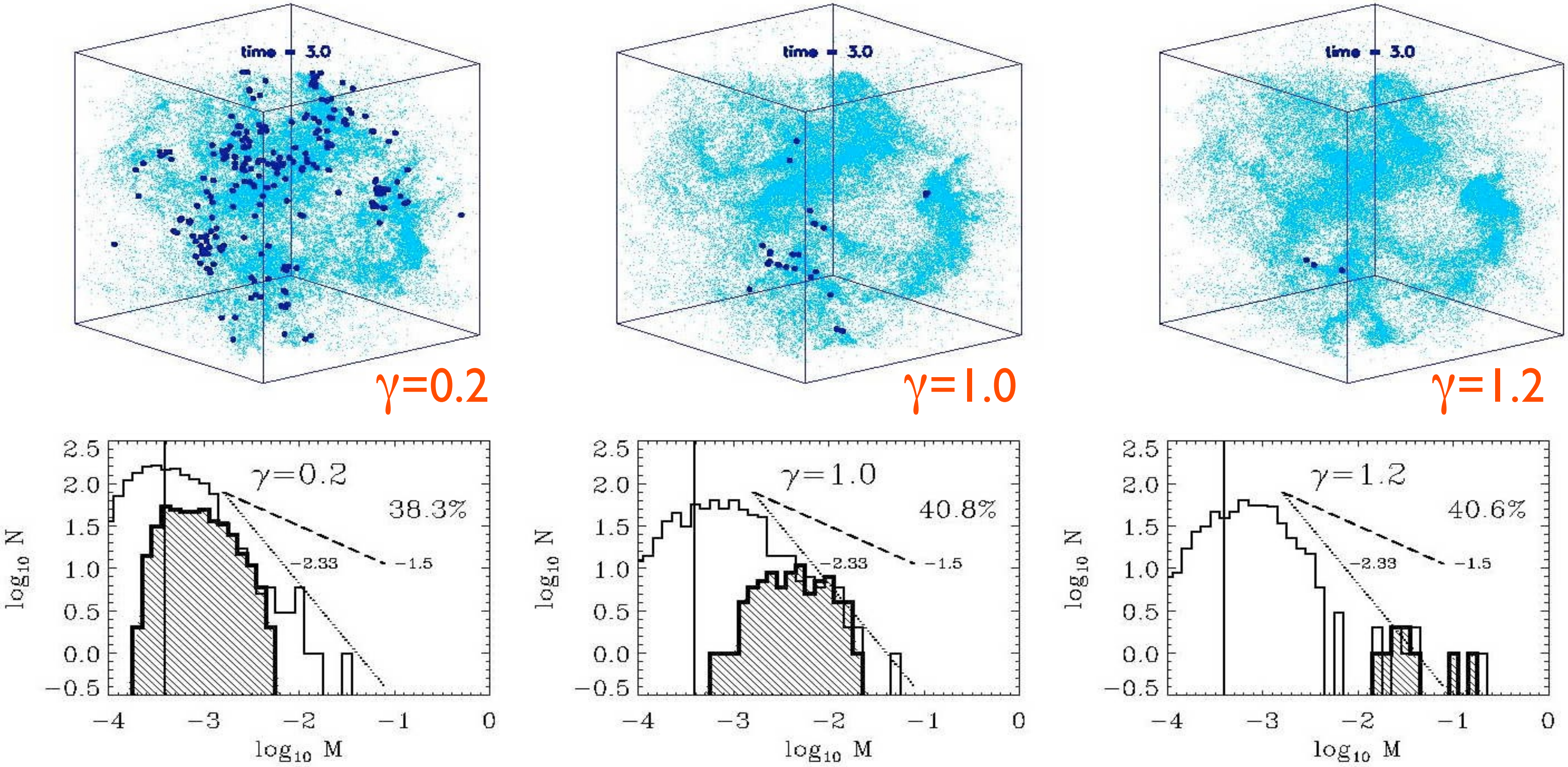
polytropic EOS: $p \propto \rho^{\gamma}$

$\gamma<1$: 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*

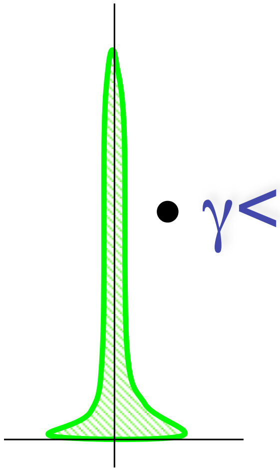
for γ>1 it is suppressed → *isolated massive stars*

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

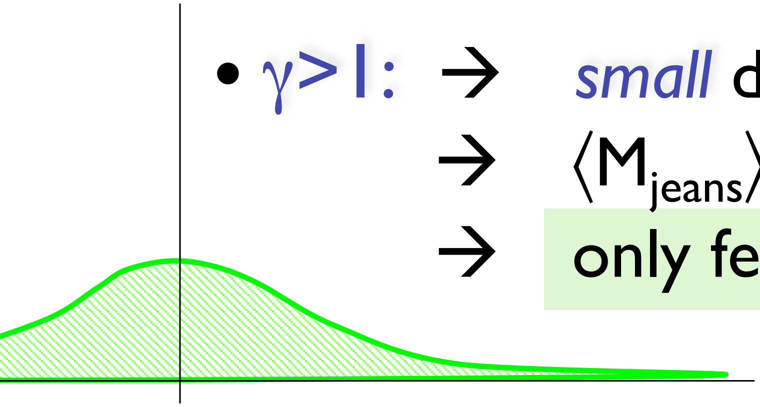
how does that work?

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

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

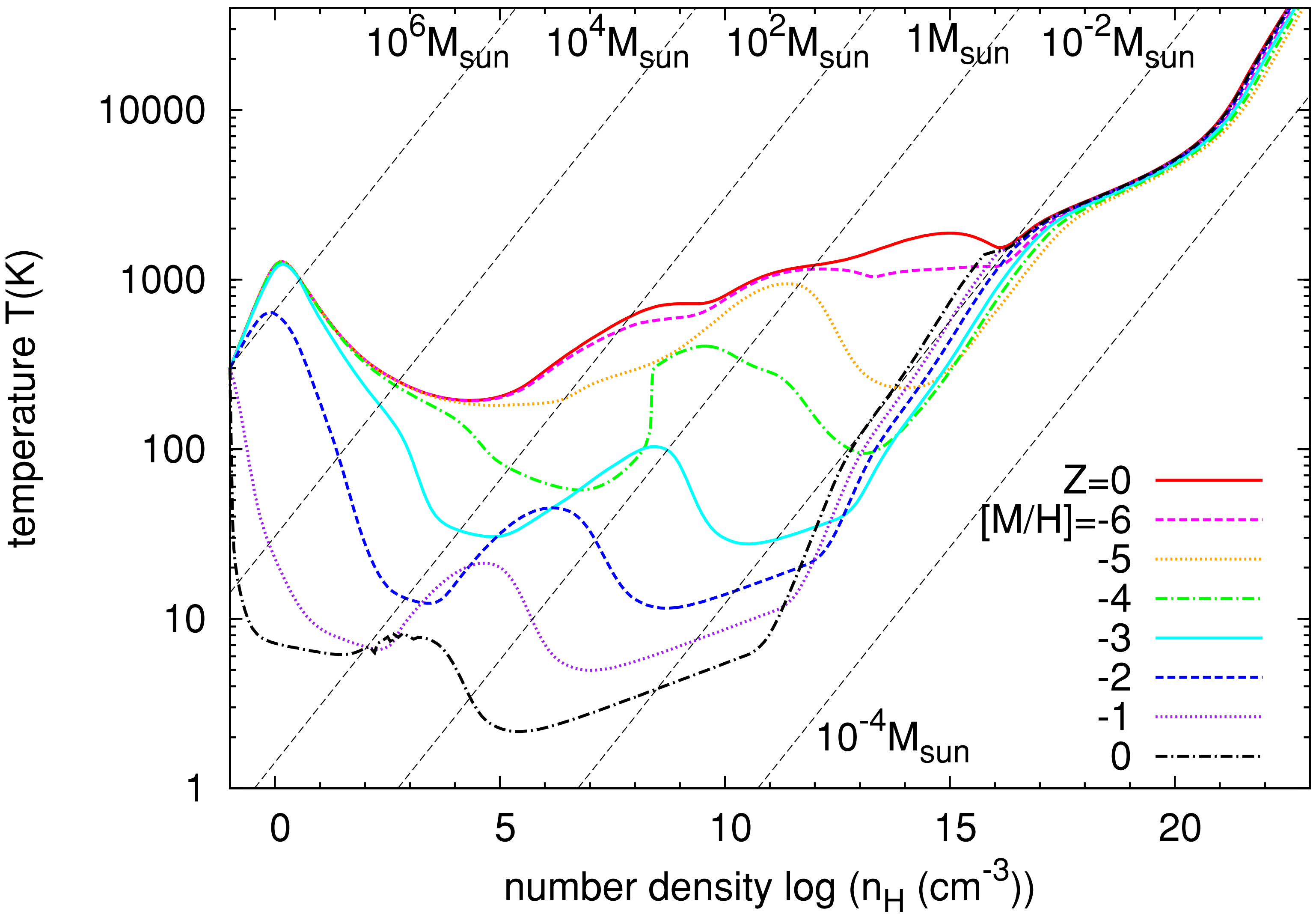


- $\gamma<1$: → *large* density excursion for given pressure
  → $\langle M_{\mathrm{jeans}} \rangle$ becomes small
  → number of fluctuations with $M > M_{\mathrm{jeans}}$ is large



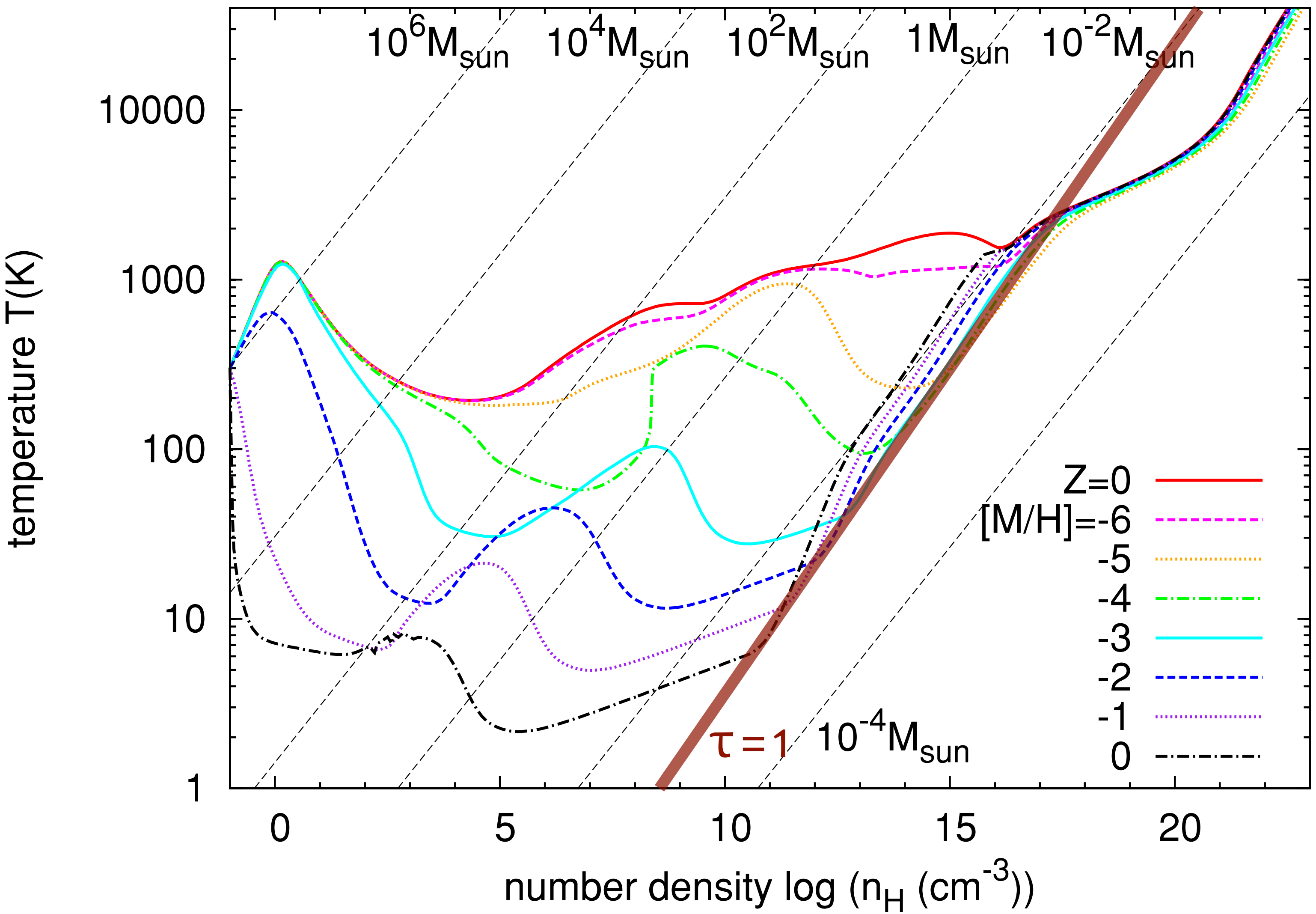
- $\gamma>1$: → *small* density excursion for given pressure
  → $\langle M_{\mathrm{jeans}} \rangle$ is large
  → only few and massive clumps exceed M_{jeans}

EOS as function of metallicity



(Omukai et al. 2005, 2010)

EOS as function of metallicity



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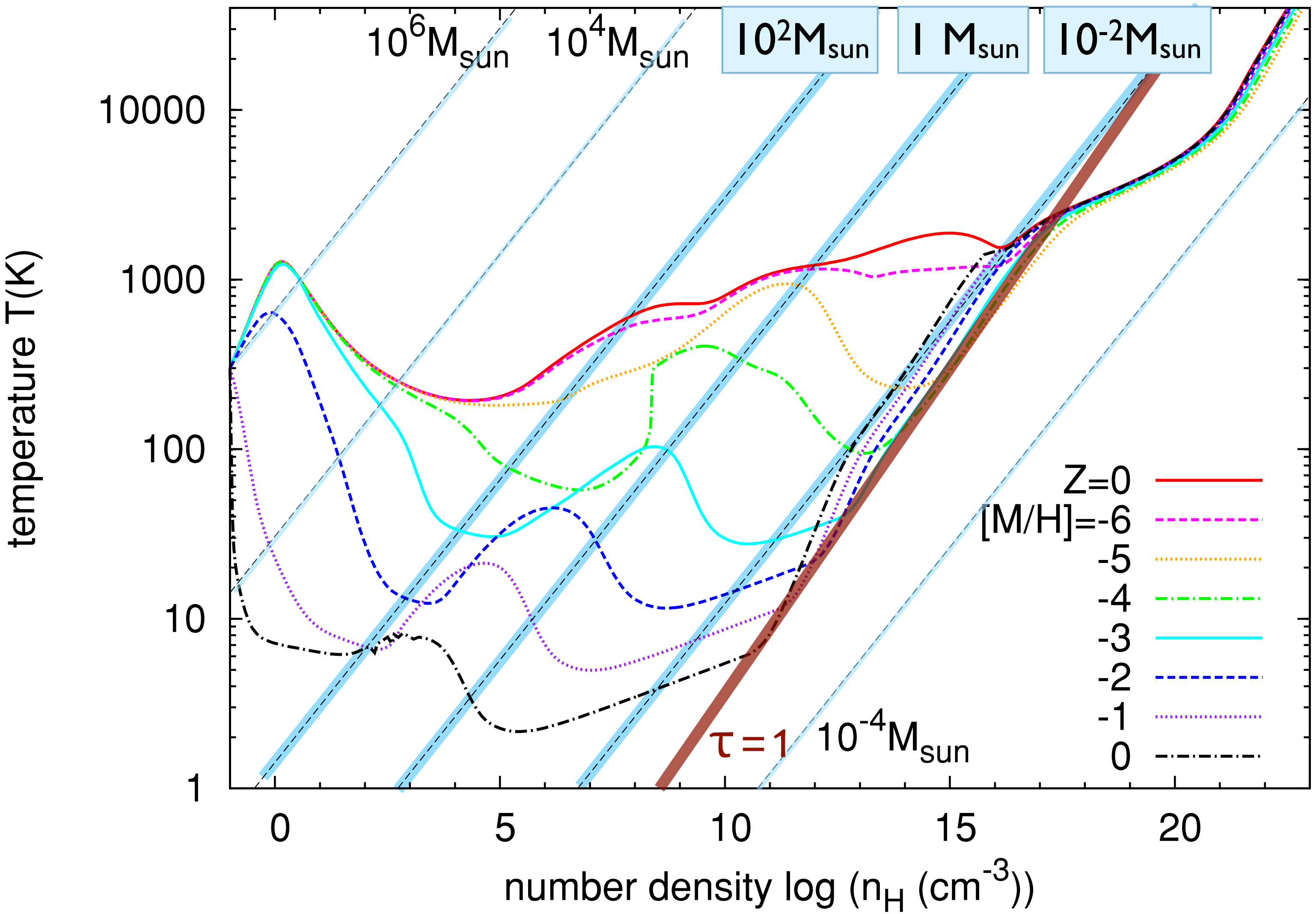
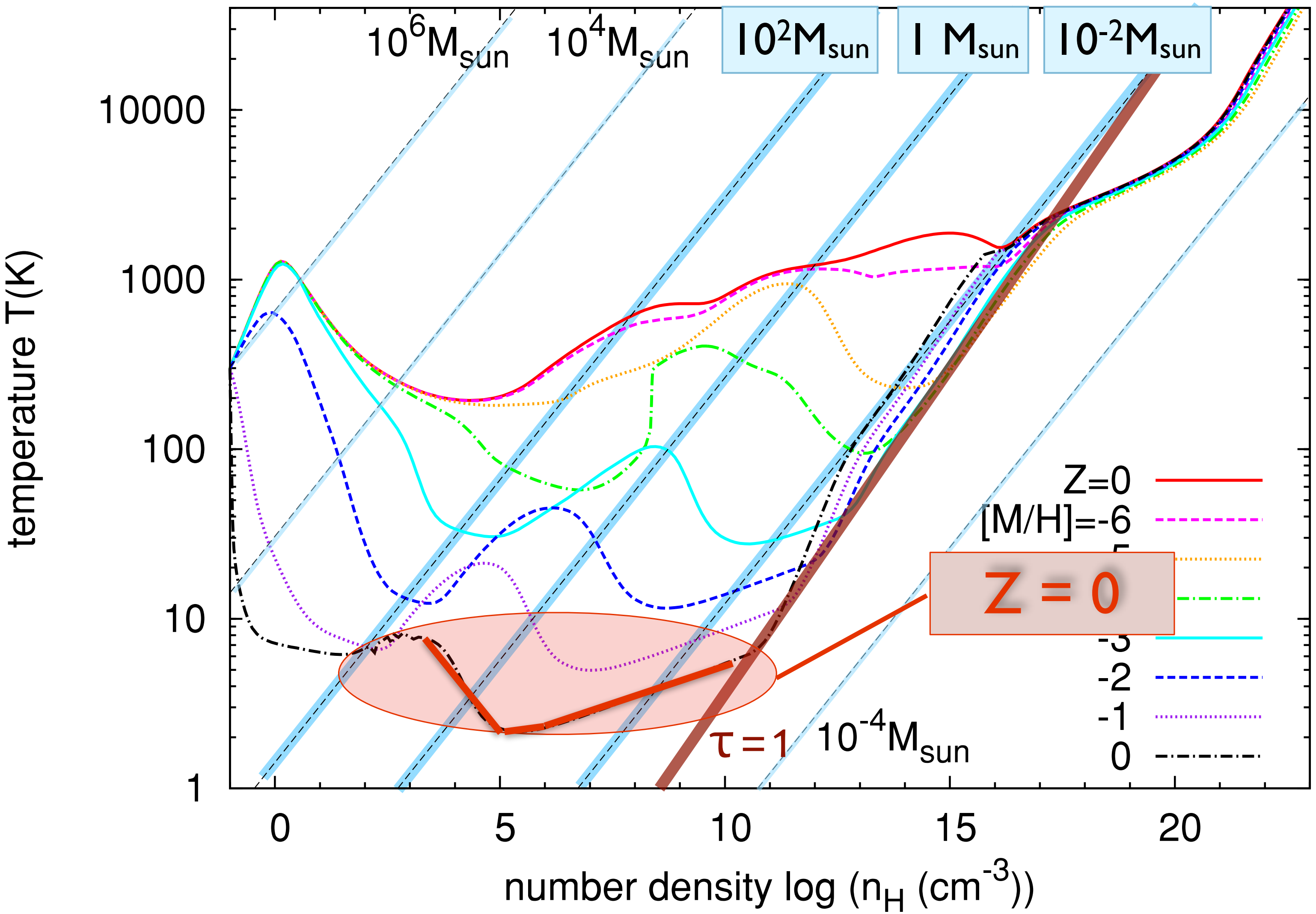
EOS as function of metallicity



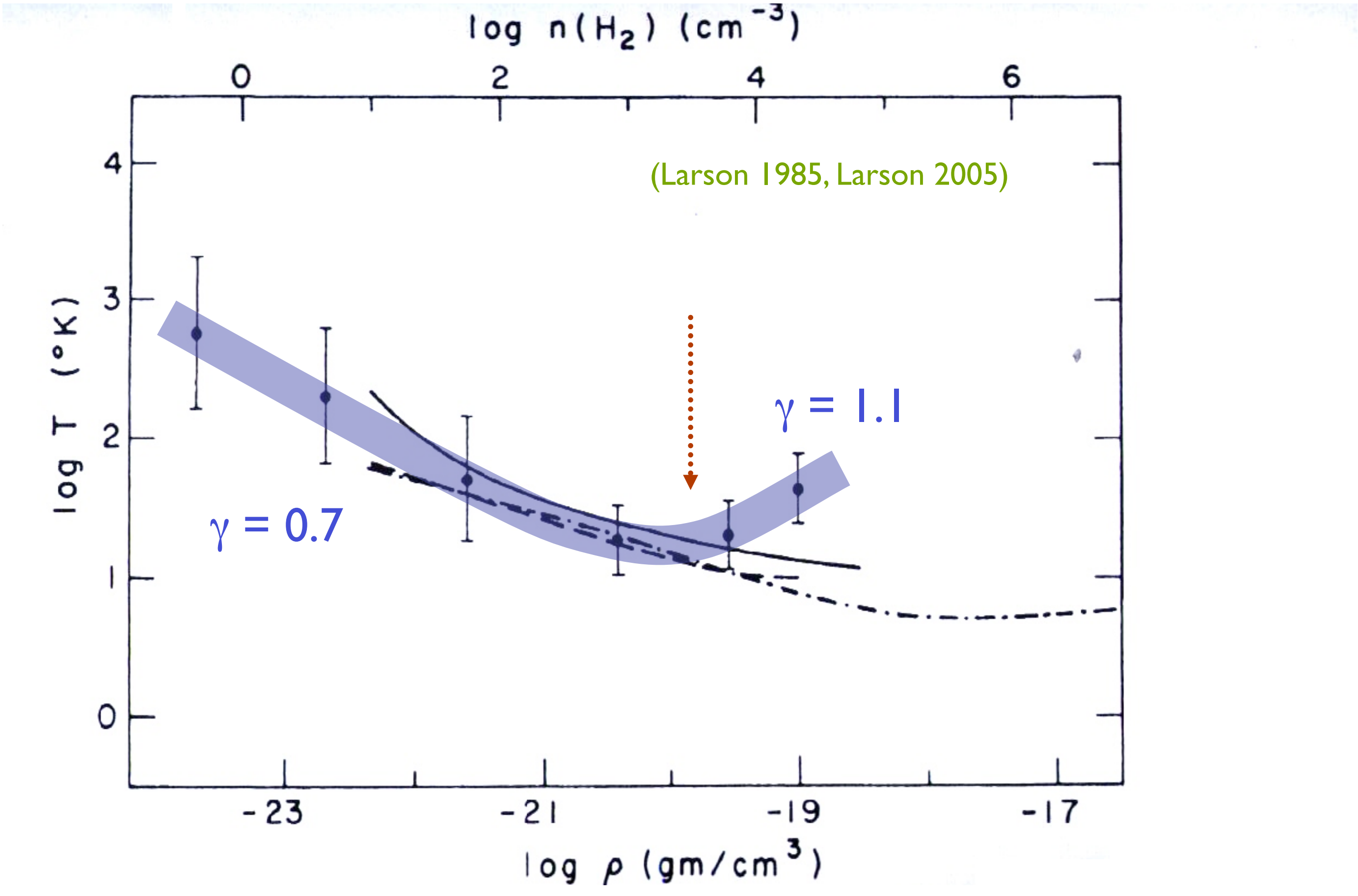
(Omukai et al. 2005, 2010)

EOS as function of metallicity

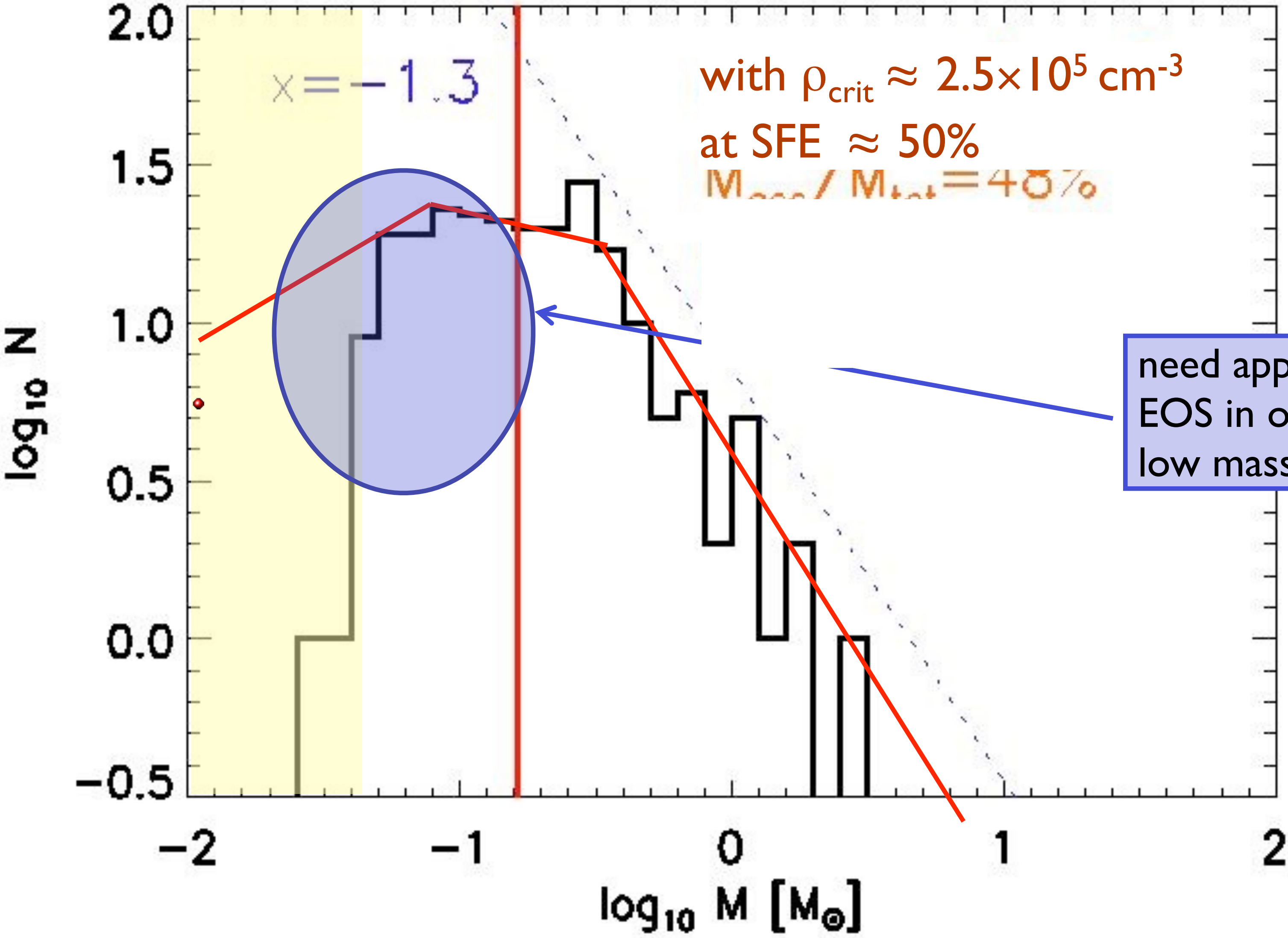


(Omukai et al. 2005, 2010)

present-day star formation



IMF in nearby molecular clouds



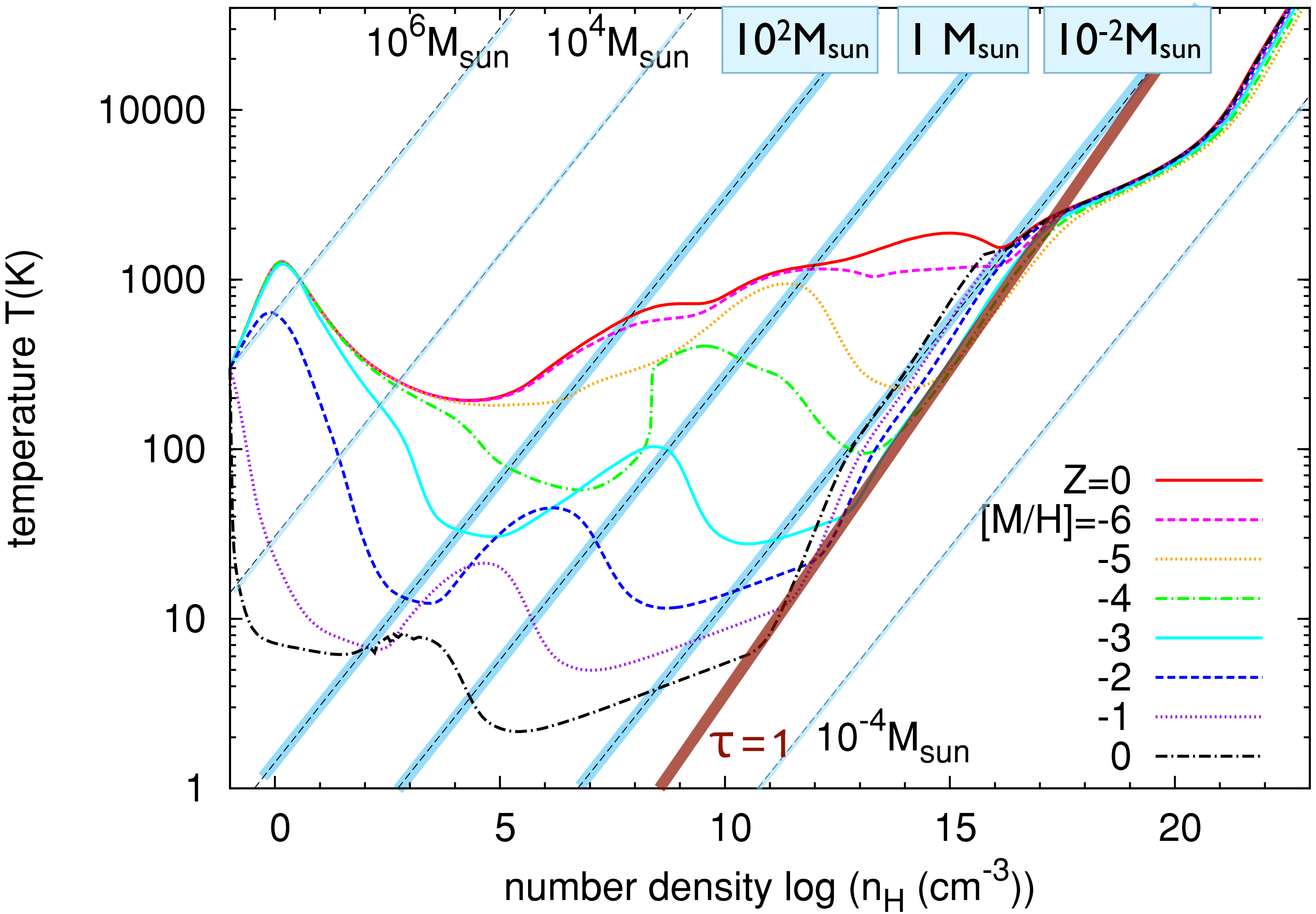
with $\rho_{crit} \approx 2.5\times10^5$ cm^{-3}

at SFE ≈ 50%

need appropriate EOS in order to get low mass IMF right

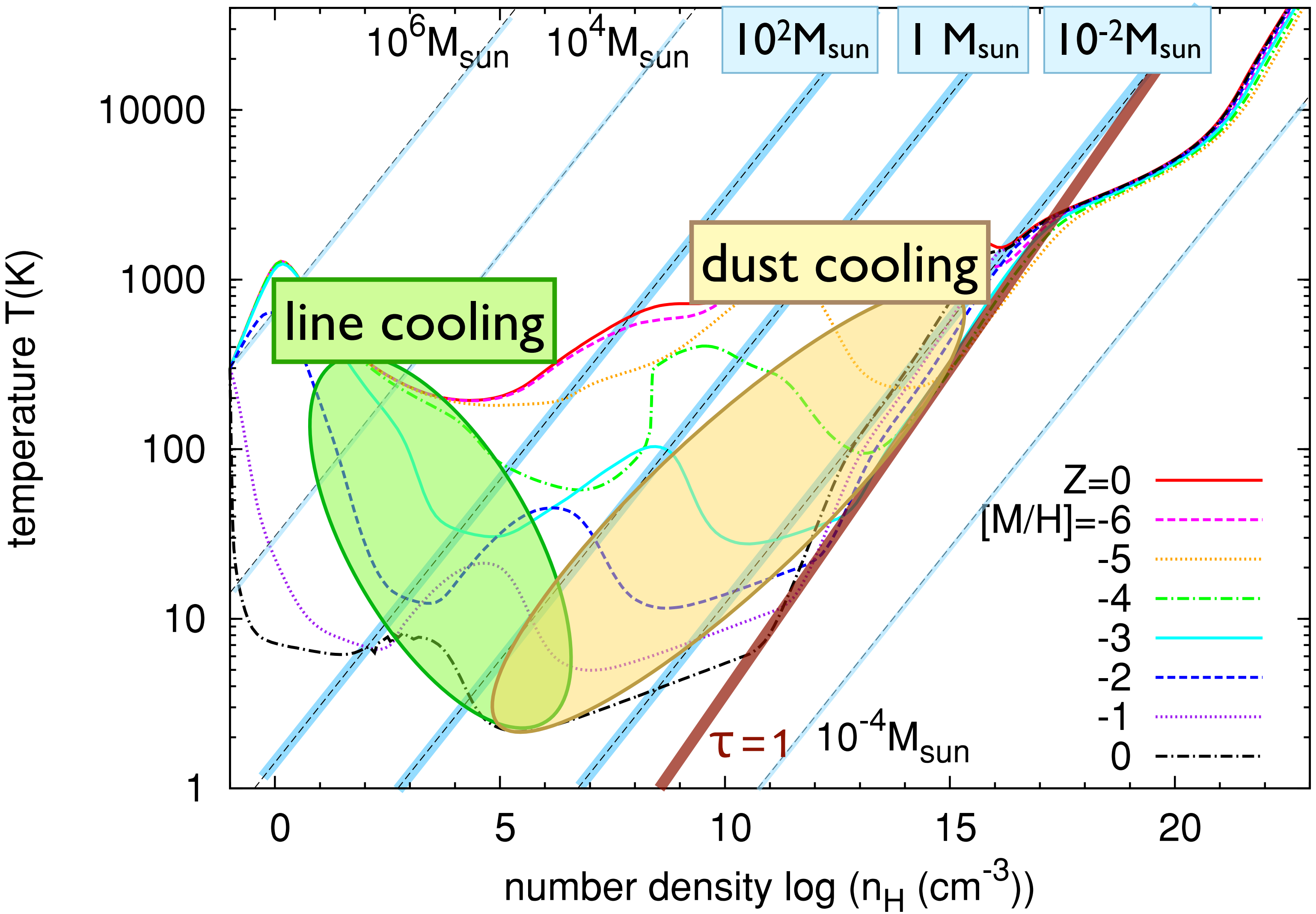
(Jappsen et al. 2005, A&A, 435, 611)

EOS as function of metallicity



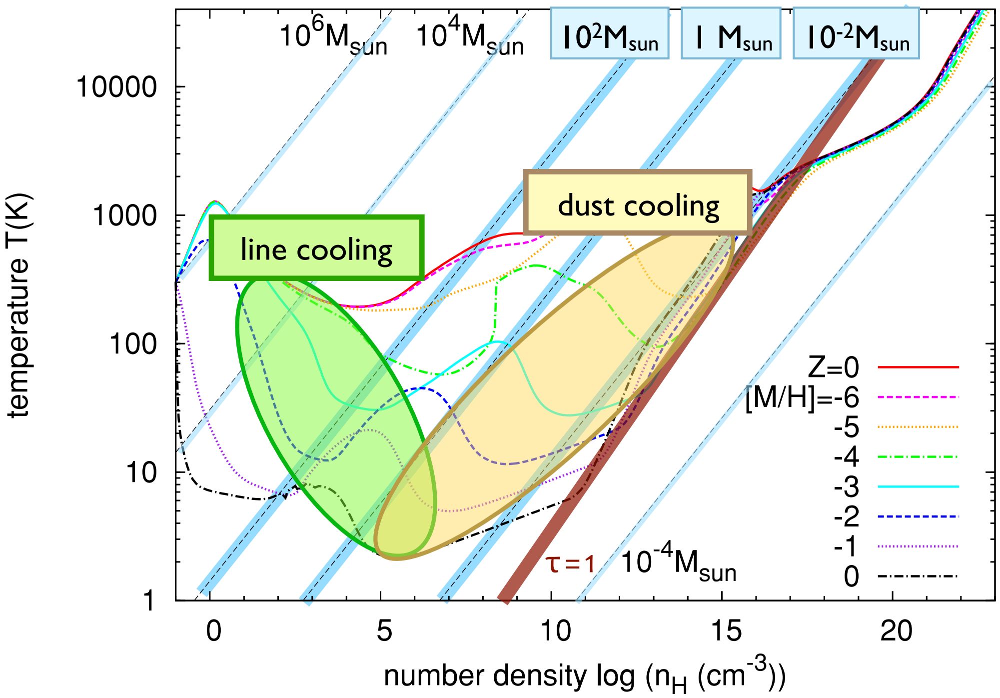
(Omukai et al. 2005, 2010)

EOS as function of metallicity



(Omukai et al. 2005, 2010)

transition: Pop III to Pop II.5



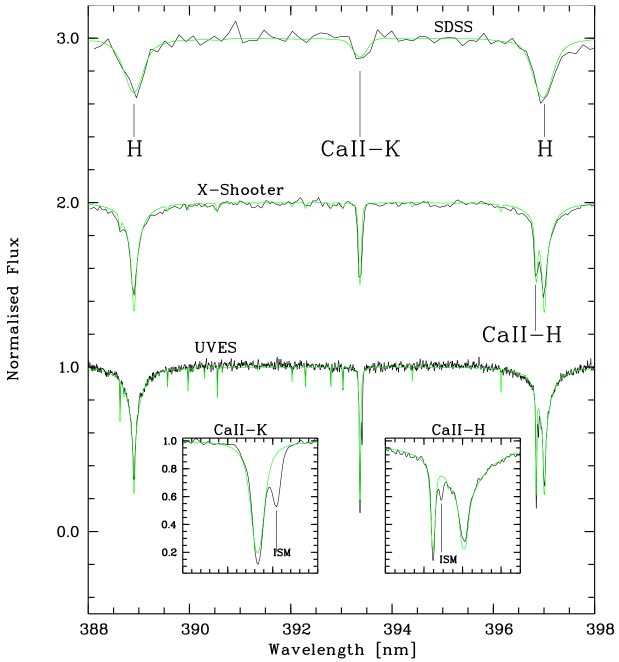
two competing models:

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

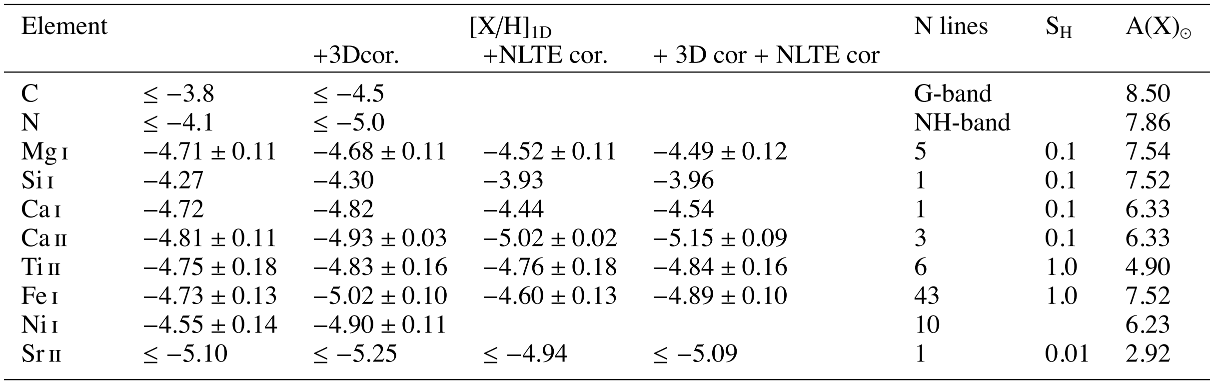
(Omukai et al. 2005, 2010)

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)

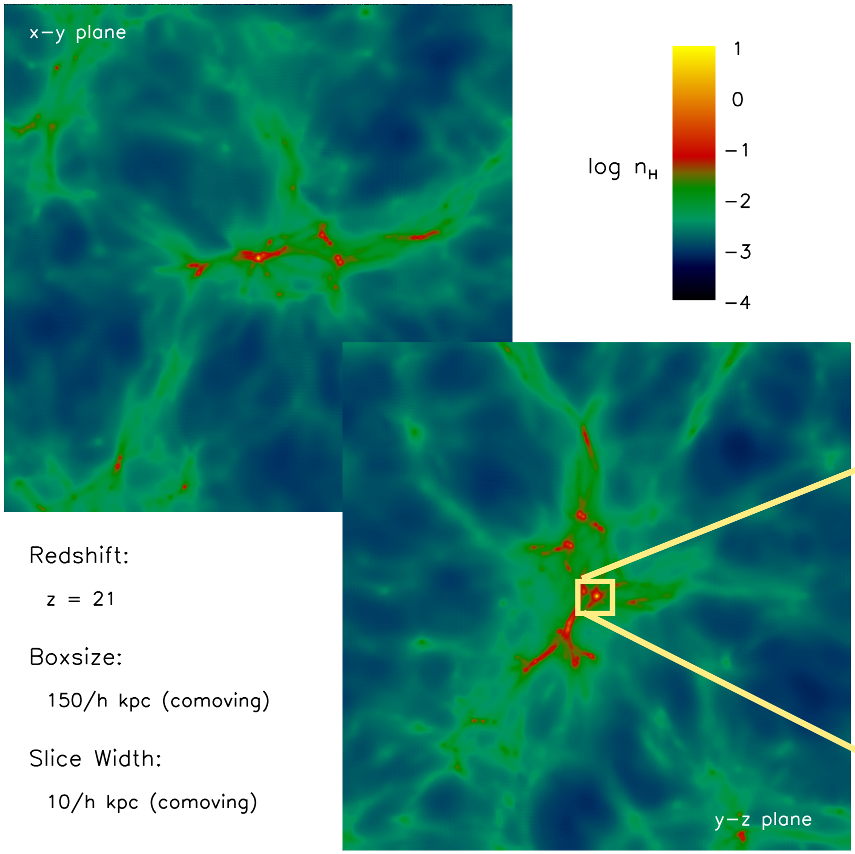
- TOPoS ESO large program to find more of these stars (120h x-shooter, 30h UVES)

(Caffau et al. 2013, A&A, 560, A71, Bonifacio et al. 2014, in prep)

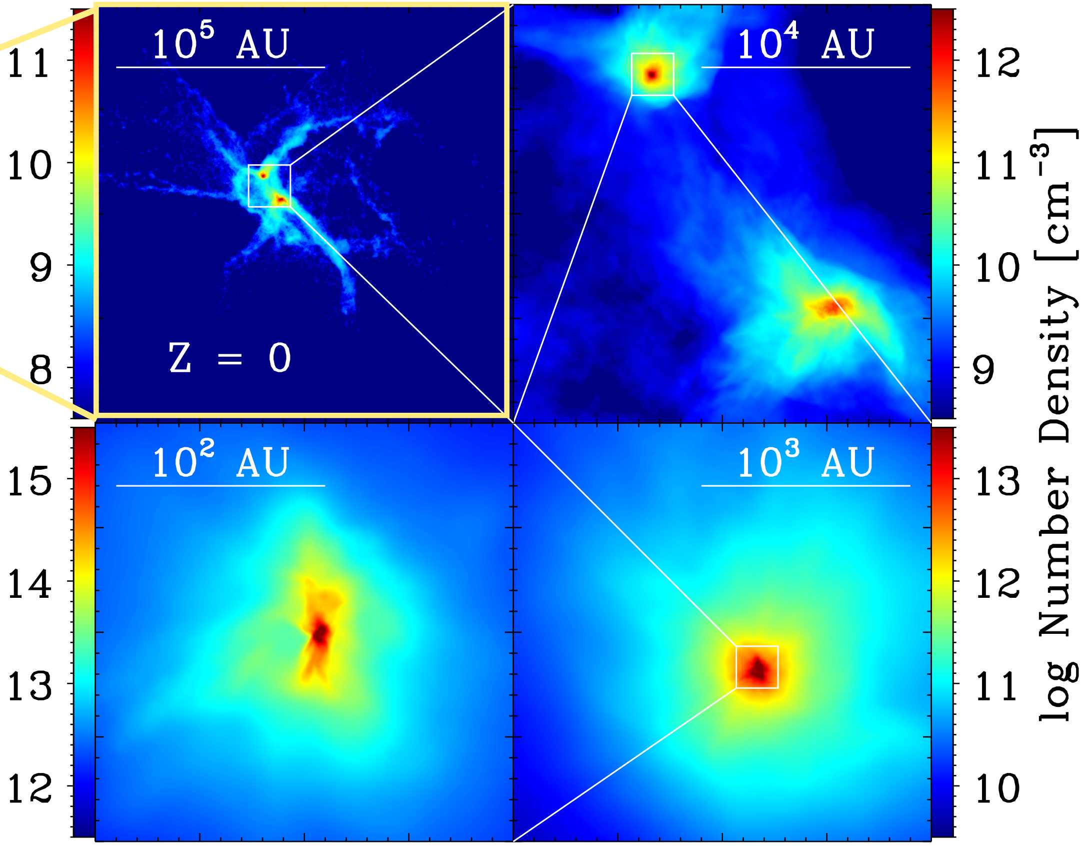
(Schneider et al. 2011,2012, Klessen et al. 2012)

modeling the formation of the first/second stares

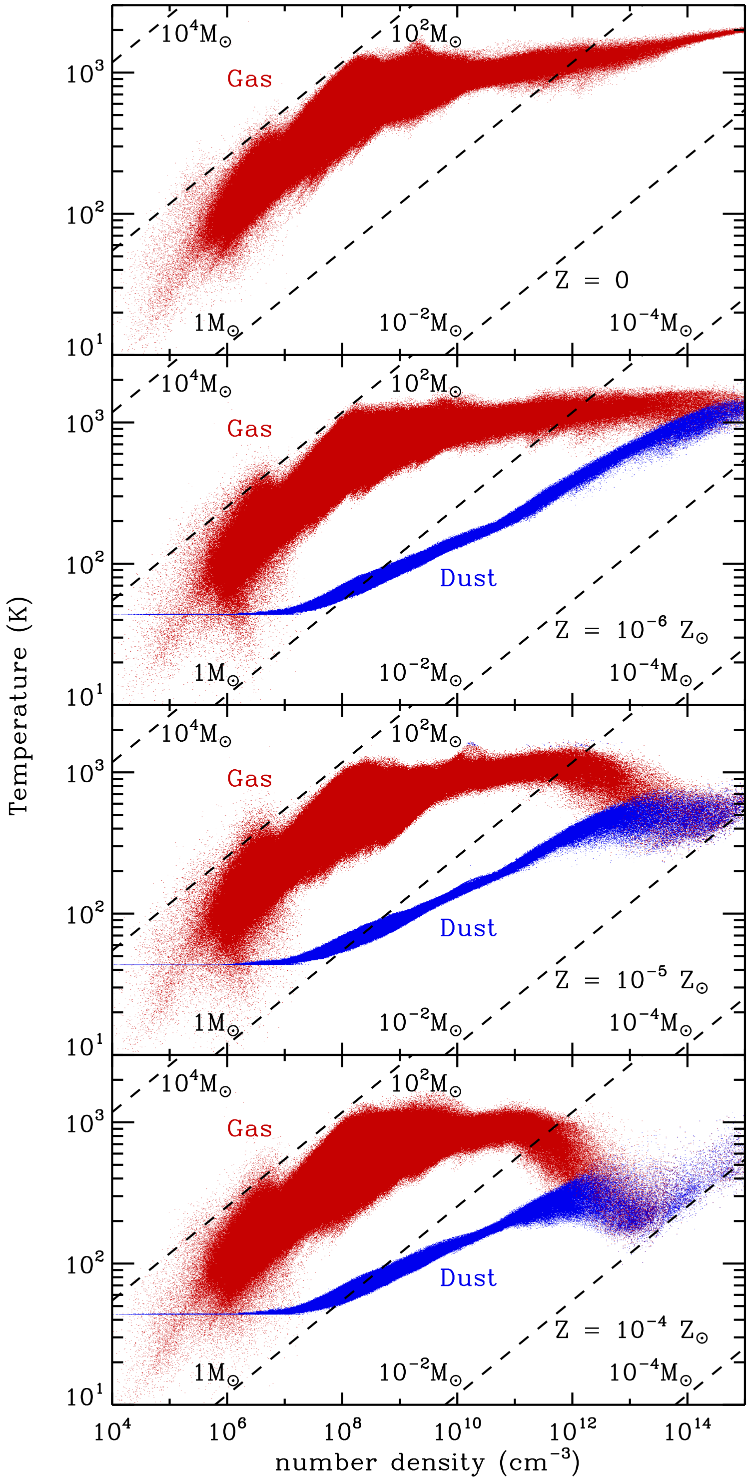
successive zoom-in calculation from cosmological initial conditions (using SPH and new grid-code AREPO)



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



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



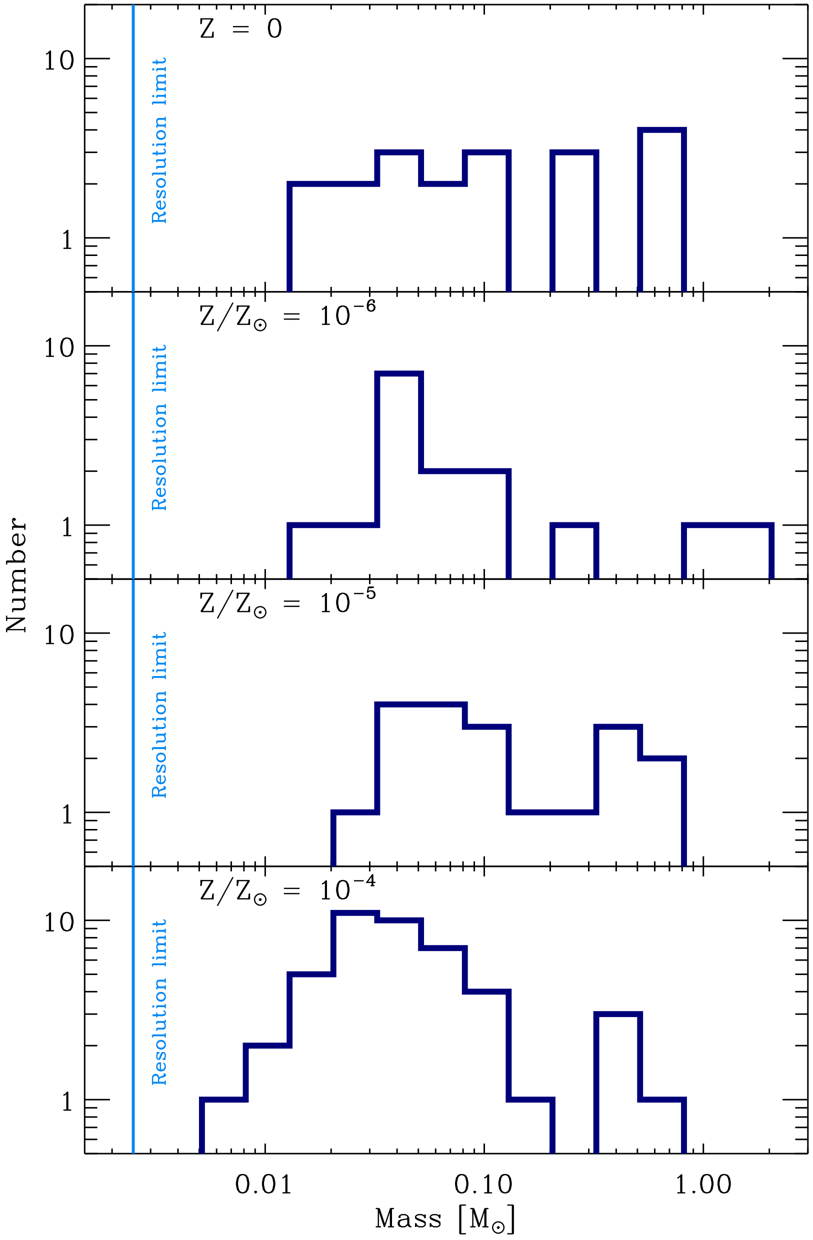
[M/H] = -ininity

[M/H] = -6

[M/H] = -5

[M/H] = -4

red : gas
blue: dust

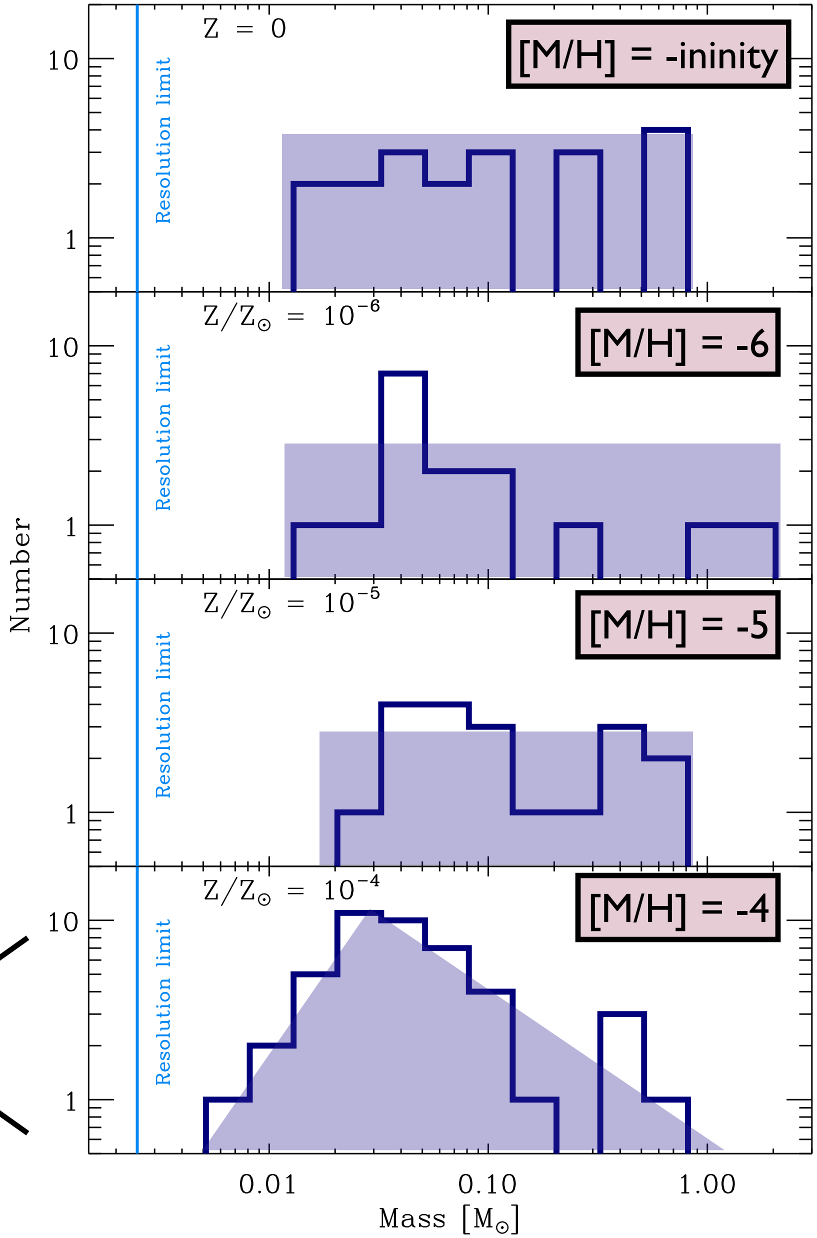


Dopcke et al. 2013, ApJ, 776, 103

hints for differences in mass spectrum

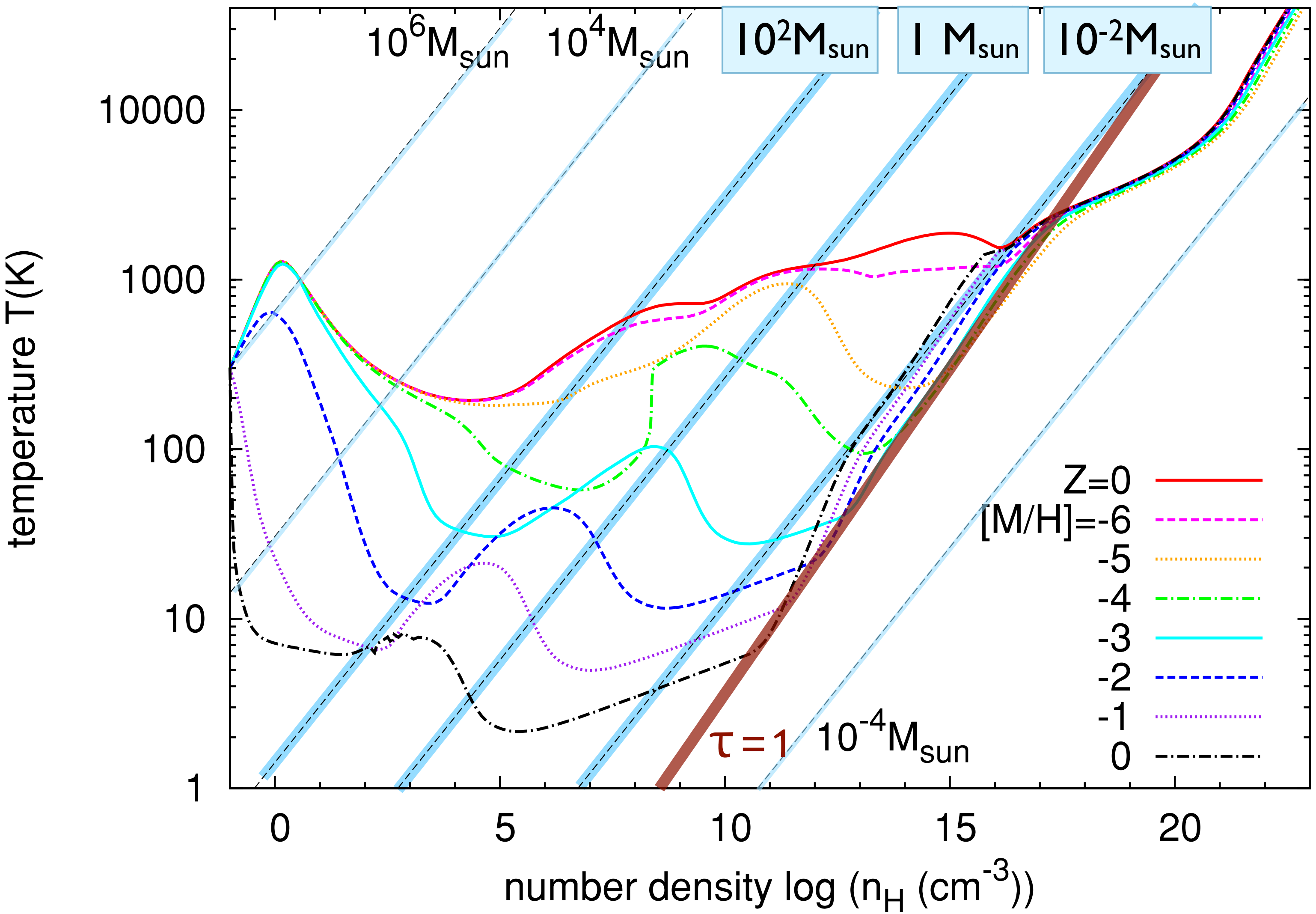
disk fragmentation mode

gravoturbulent fragmentation mode



Dopcke et al. 2013, ApJ, 776, 103

EOS as function of metallicity



(Omukai et al. 2005, 2010)

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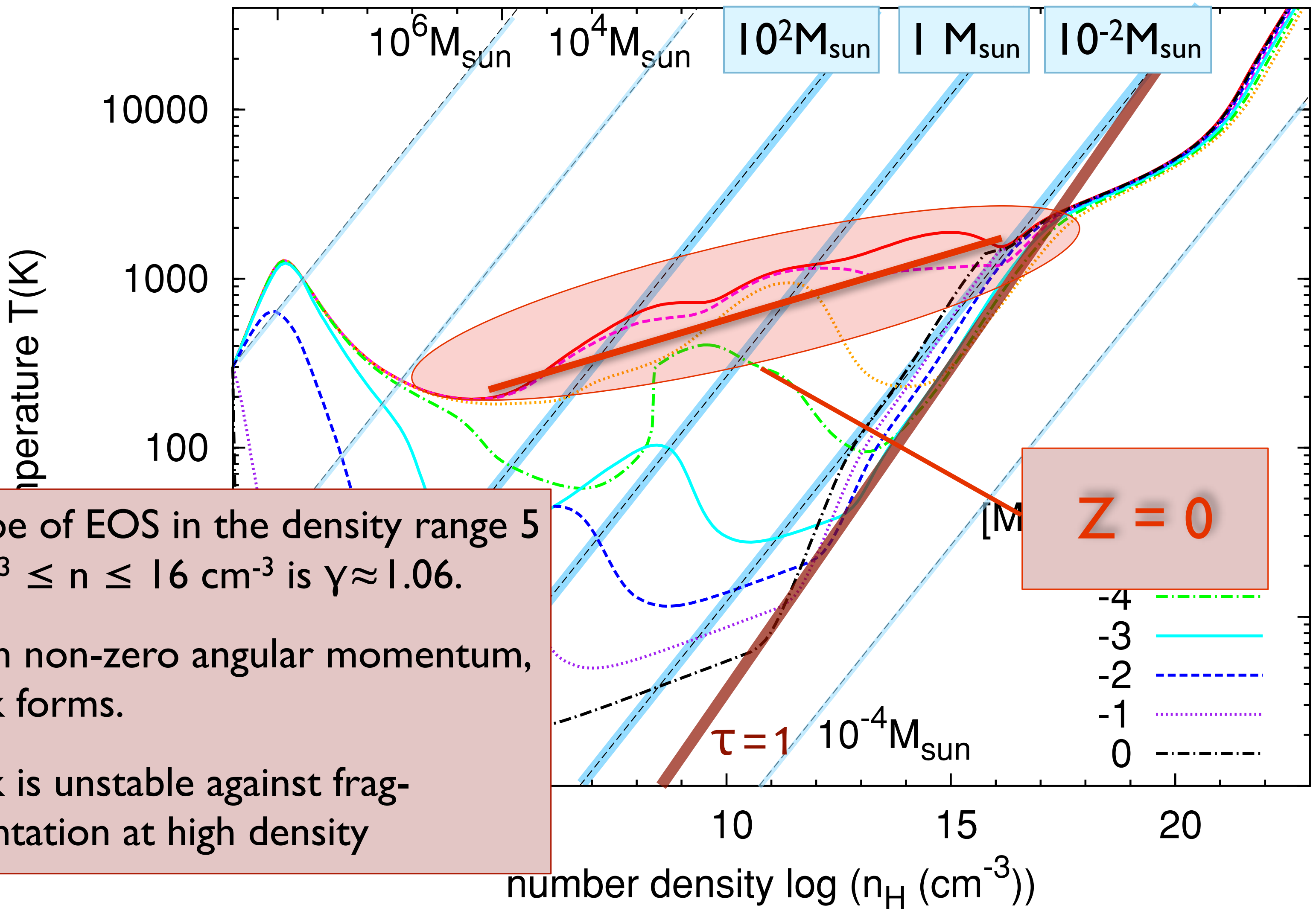
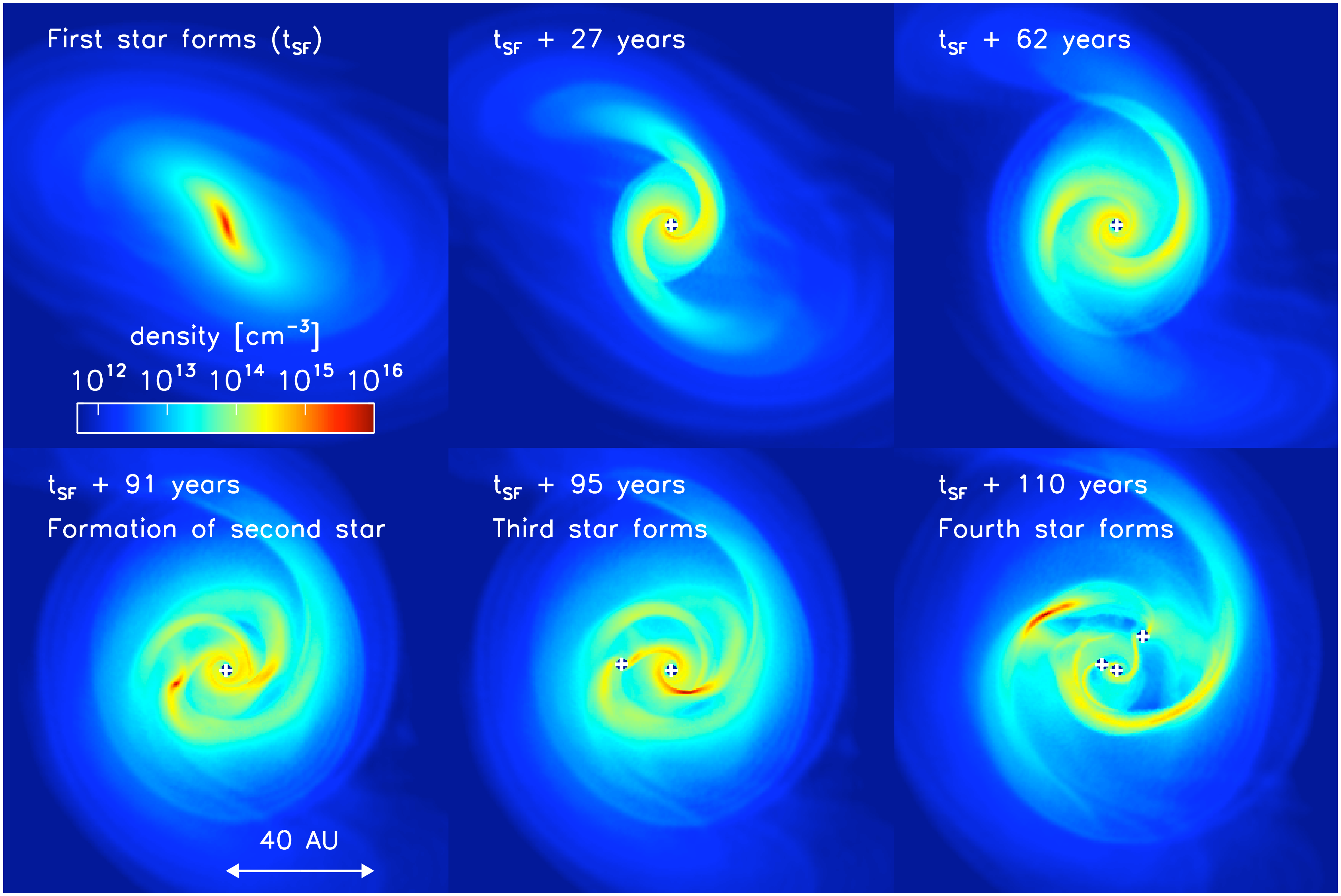


- slope of EOS in the density range 5 cm^{-3} $\leq n \leq$ 16 cm^{-3} is $\gamma \approx 1.06$.
- with non-zero angular momentum, disk forms.
- disk is unstable against fragmentation at high density

(Omukai et al. 2005, 2010)

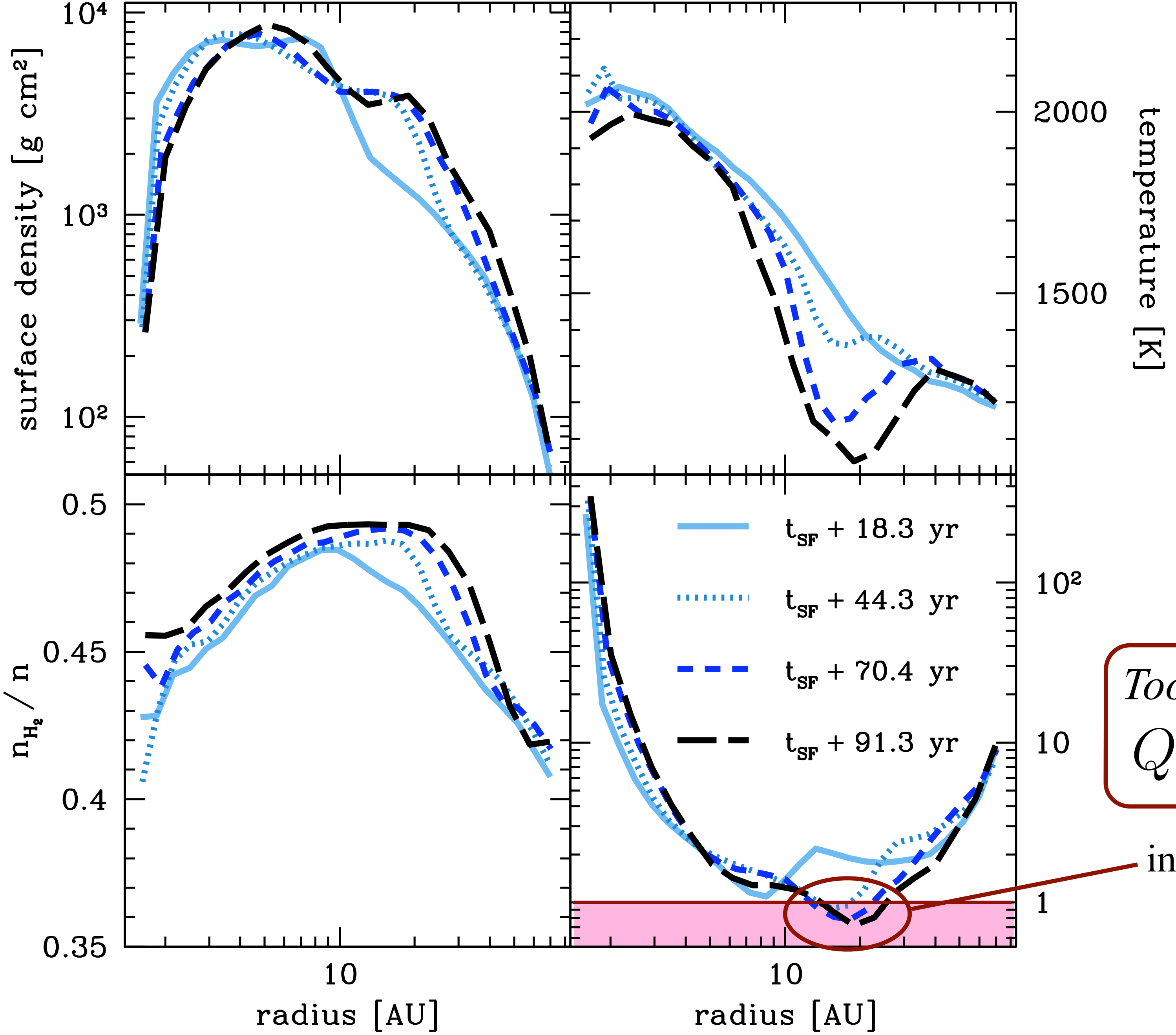


detailed look at accretion disk

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

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

important disk parameters



Toomre Q:

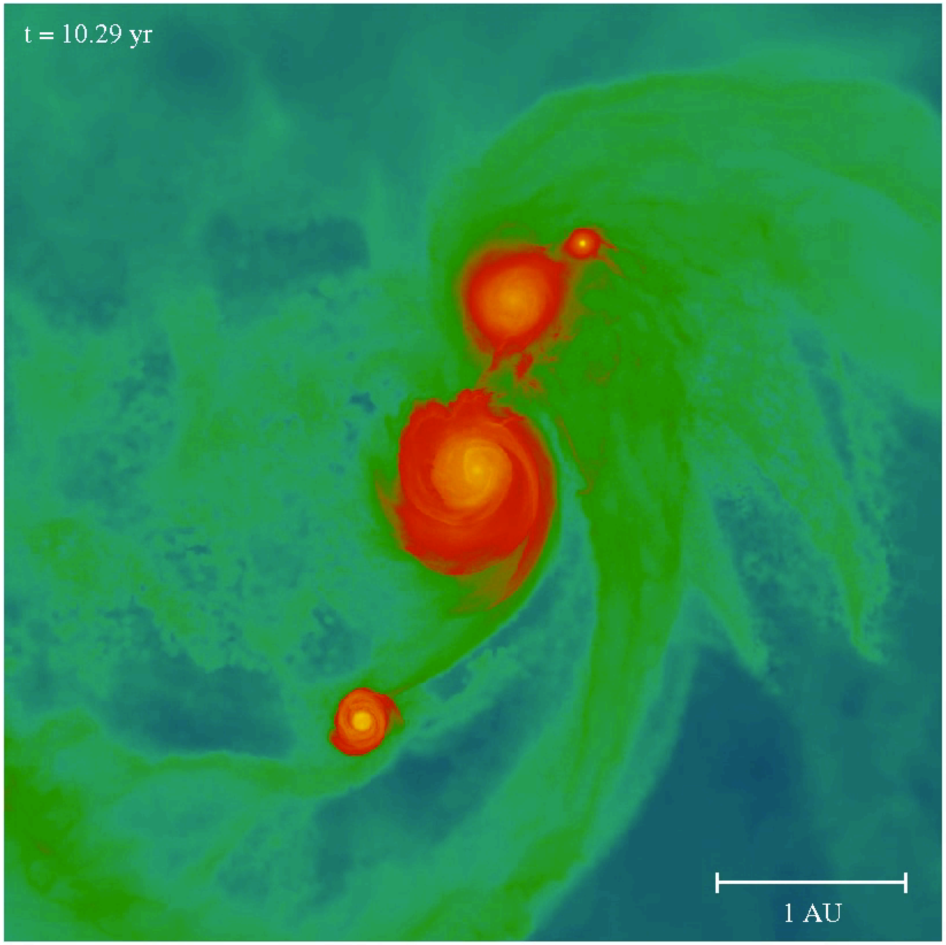
$$Q = c_s \kappa / \pi G \Sigma$$

instability for *Q<1*

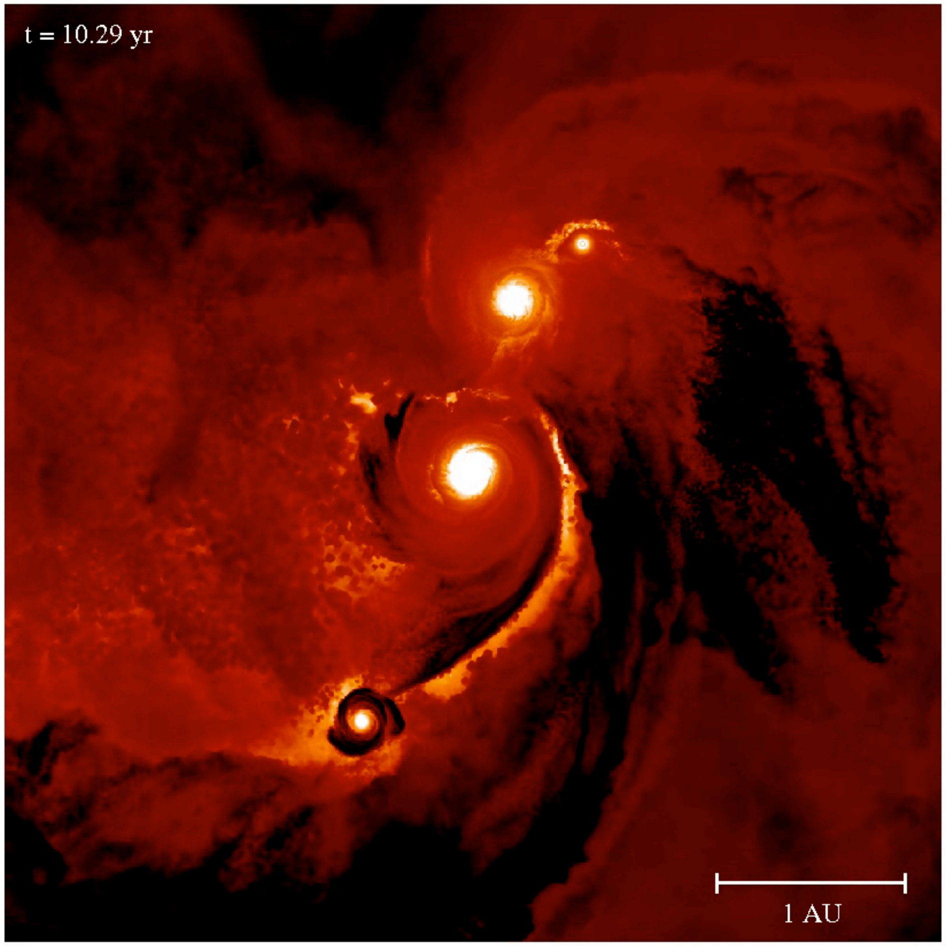
(Clark et al. 2011b, Science, 331, 1040)

Most recent calculations:

fully sink-less simulations, following the disk build-up over ~10 years
(resolving the protostars - first cores - down to 10^5 km ~ $0.01\ R_\odot$)



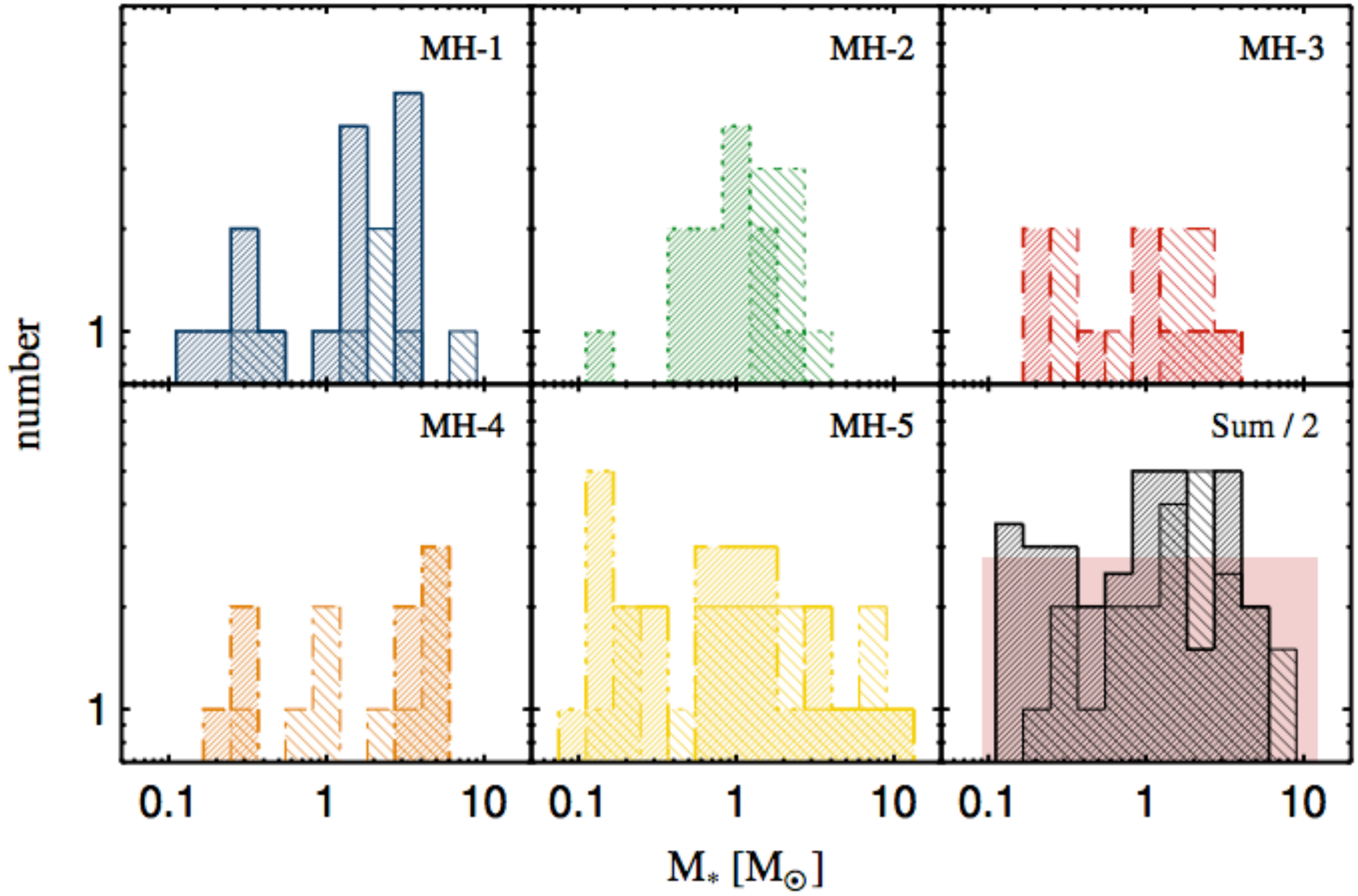
density



temperature

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

expected mass spectrum

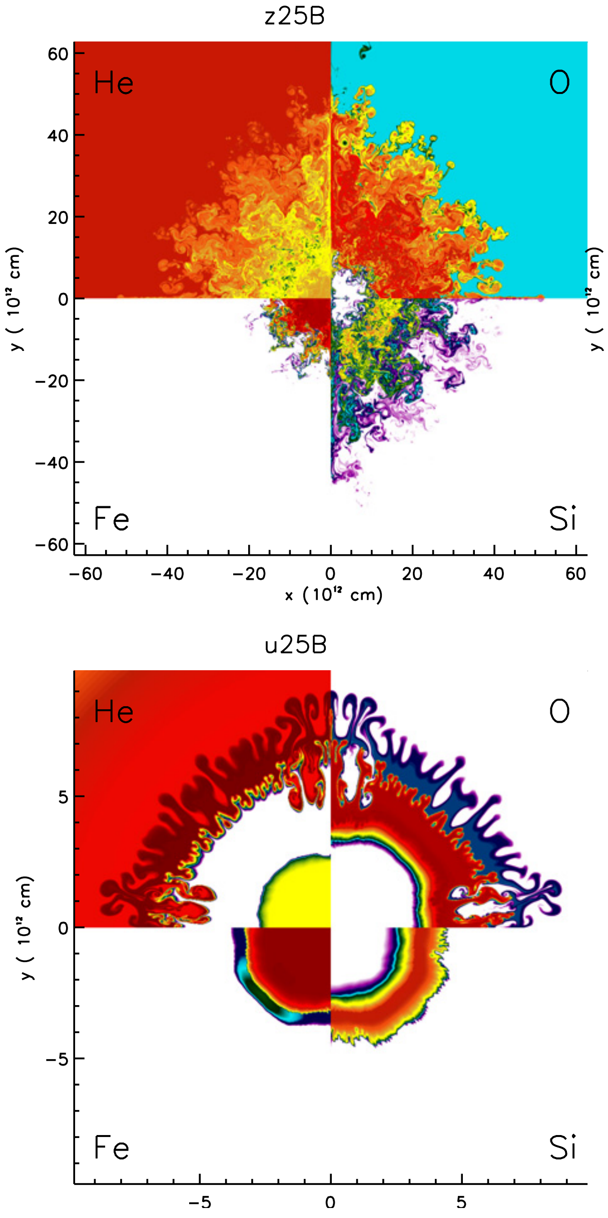


we see "flat" mass spectrum

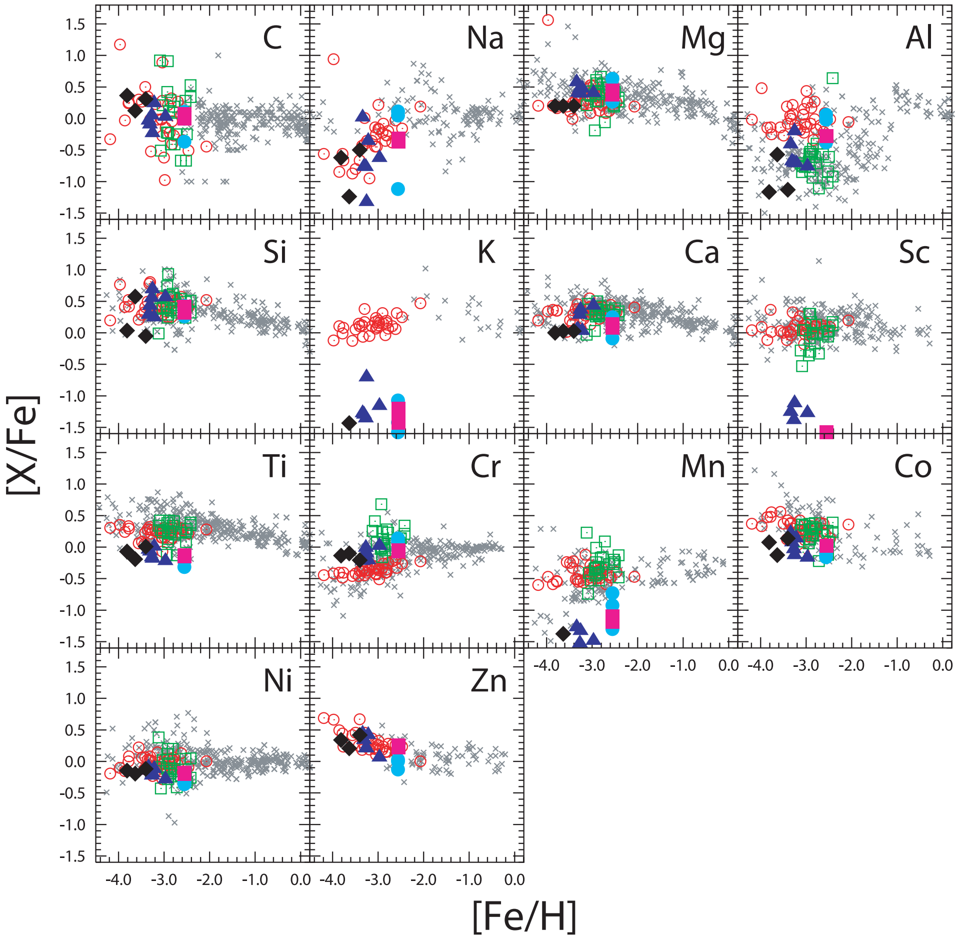
Greif et al. 2011, ApJ, 737, 75, Clark et al. 2011b, Science, 331, 1040, Smith et al. 2011, MNRAS, 414, 3633, Dopcke et al., 2013, ApJ, 766, 103

expected mass spectrum

- *expected IMF is flat* and covers a wide range of masses
- implications
  - because slope > -2, most *mass is in massive objects* as predicted by most previous calculations
  - most high-mass Pop III stars should be in *binary systems* --> source of *high-redshift gamma-ray bursts*
  - because of ejection, some *low-mass objects* ($< 0.8\ M_\odot$) might have *survived* until today and could potentially be found in the Milky Way
- consistent with abundance patterns found in second generation stars



(Joggerst et al. 2009, 2010)

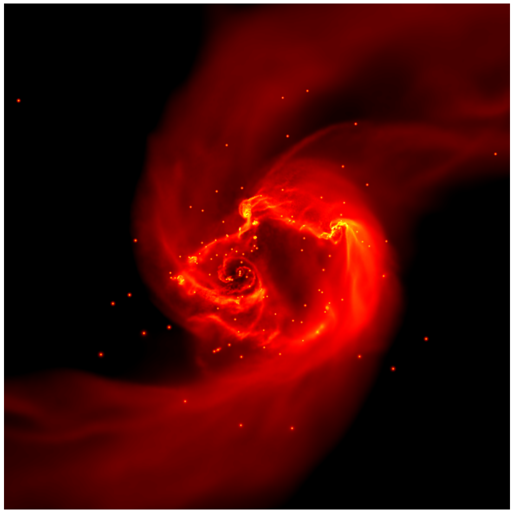


(Tominaga et al. 2007)

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

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

primordial star formation



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

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

primordial star formation

- 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)

stellar archeology

- *if* genuine Pop III stars with $M<0.8\ M_\odot$ have been formed, they should be still be around *!*
- could be seen in current (and future) surveys of searching for extremely metal-poor stars
- QUESTION:
  can we constrain the *low-mass end* of the *primordial IMF?*

stellar archeology

- can we constrain the *low-mass end* of the *primordial IMF?*

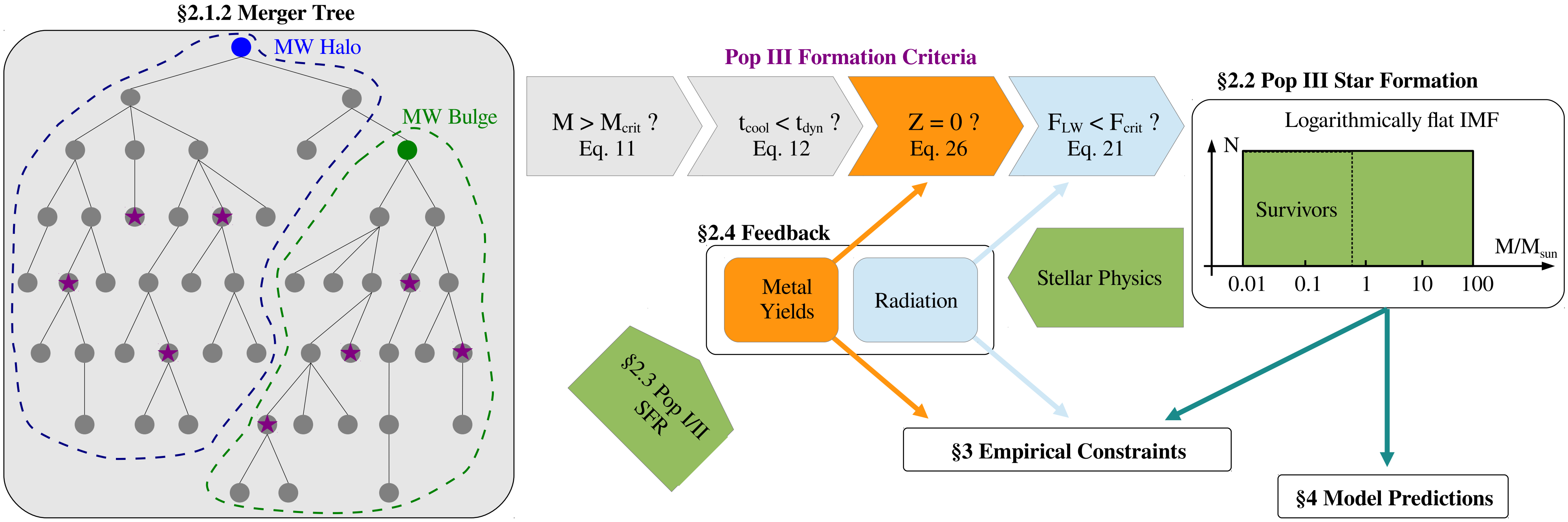
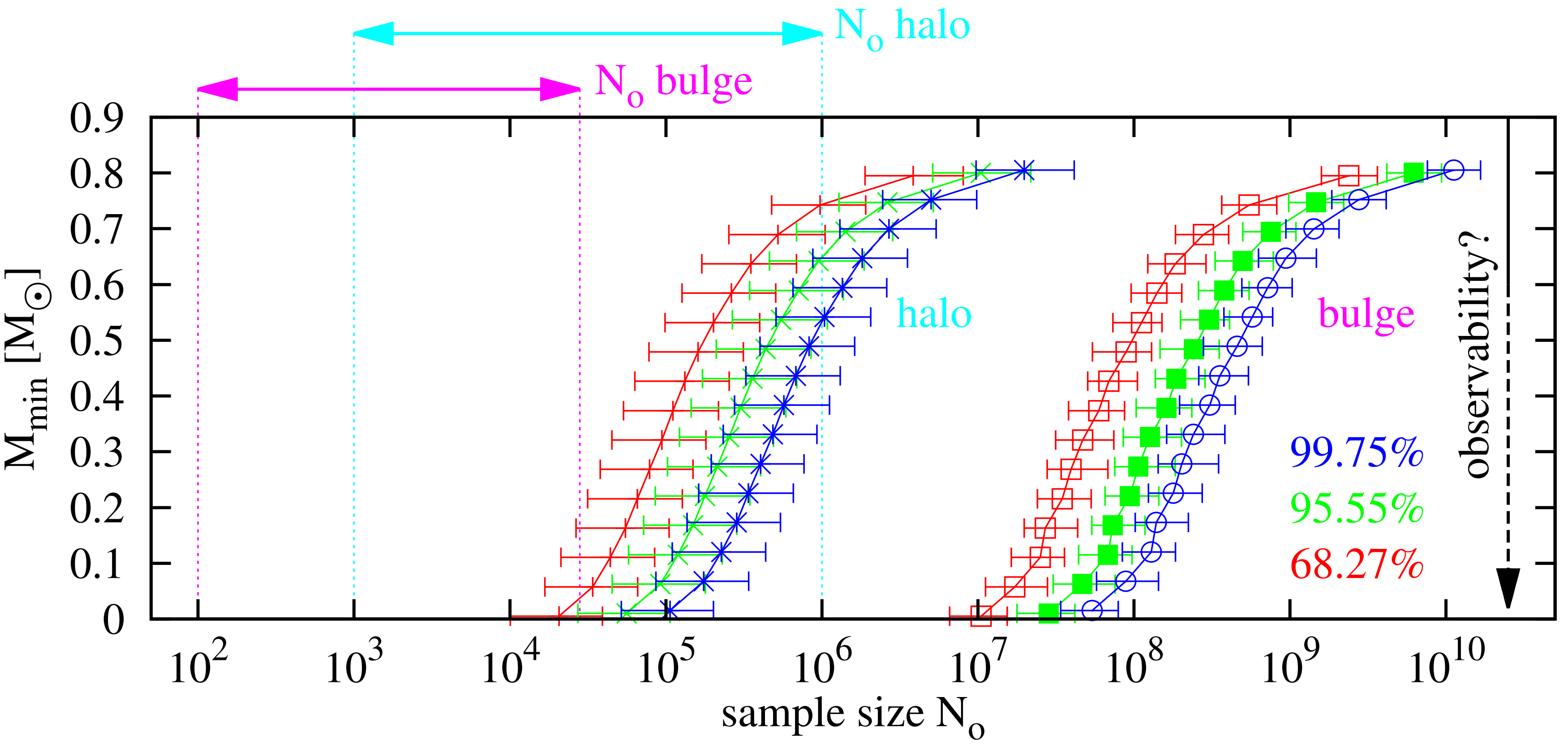


Figure 1. Roadmap, illustrating our model, with references to the relevant sections and equations. Based on the merger tree, we check which haloes are able to form Pop III stars. These checks include the critical mass, the absence of dynamical heating due to mergers, no pollution by metals and the strength 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 contribution of Pop I/II star formation is modelled based on the analytical cosmic star formation history. By comparing to existing observations, we can calibrate our model parameters. Finally, we derive a prediction for the number of Pop III survivors in the Milky Way and determine constraints on the primordial IMF.

Hartwig et al. (2015, MNRAS, arXiv:1411.1238)

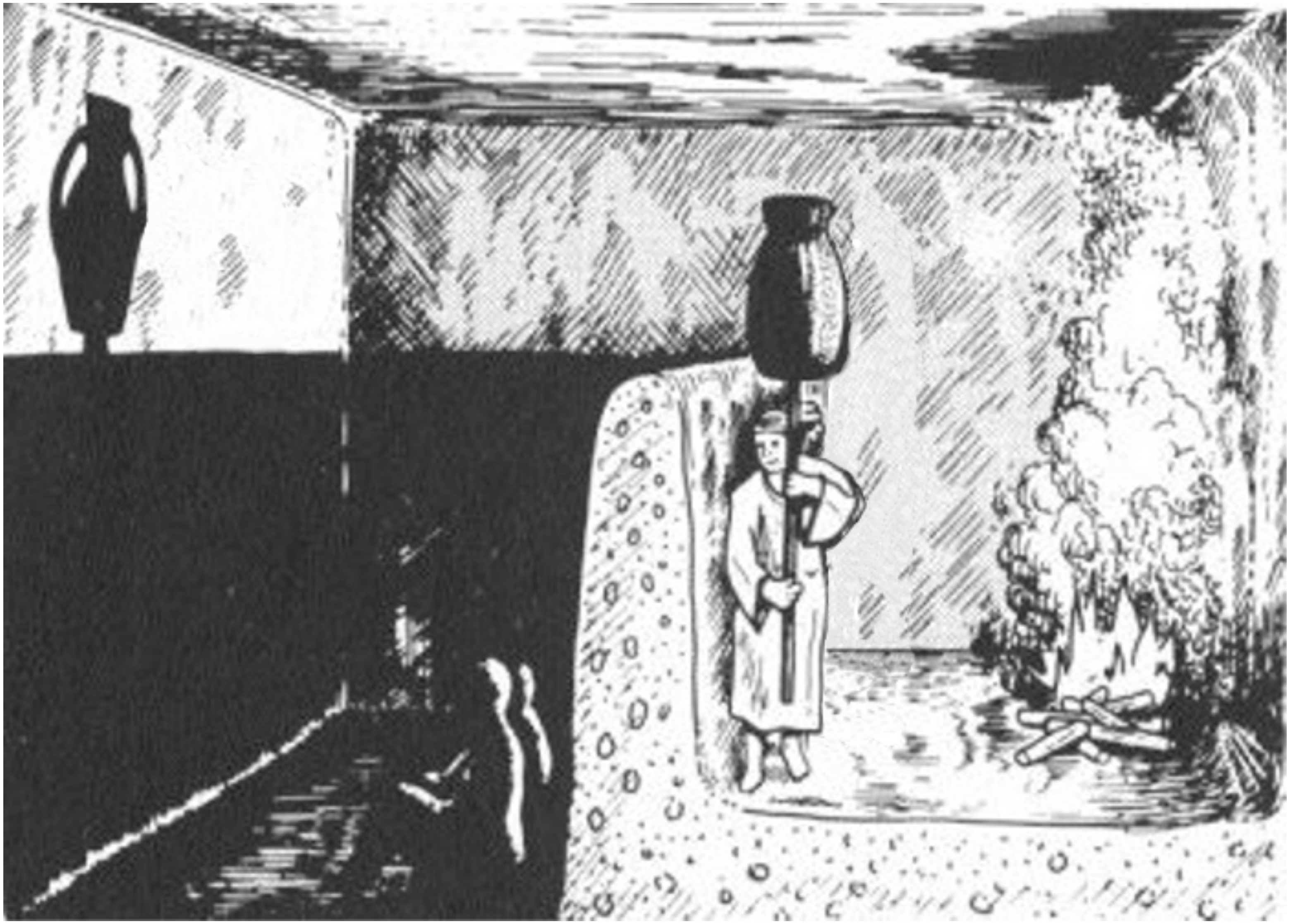
stellar archeology

- can we constrain the *low-mass end* of the *primordial IMF?*



Hartwig et al. (2015, MNRAS, arXiv:1411.1238)

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



* The Republic
(514a-520a)

Laszlo Szücs, image from criticalthinking-mc205.wikispaces.com

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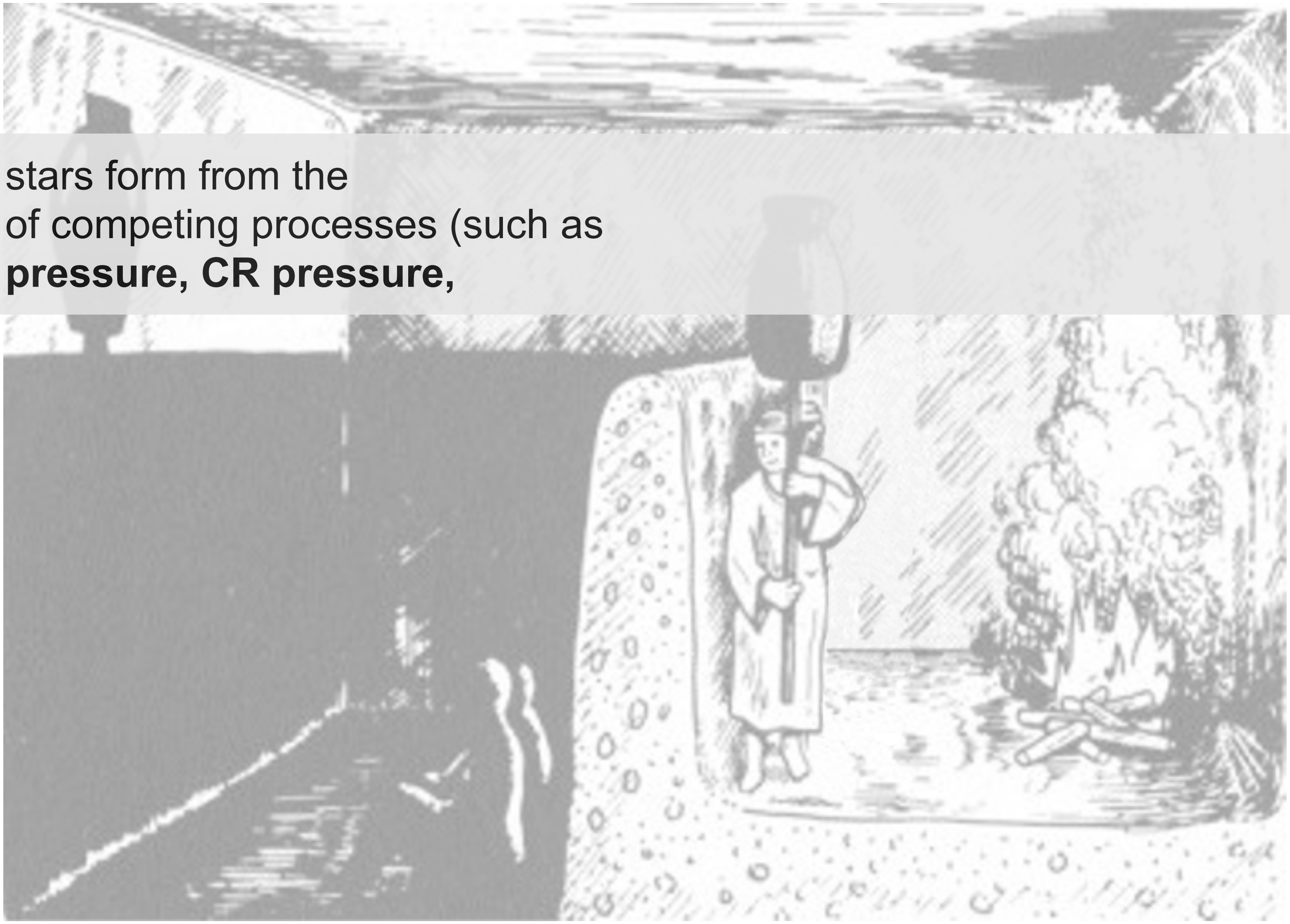

- stars form from the
  of competing processes (such as
  pressure, CR pressure,

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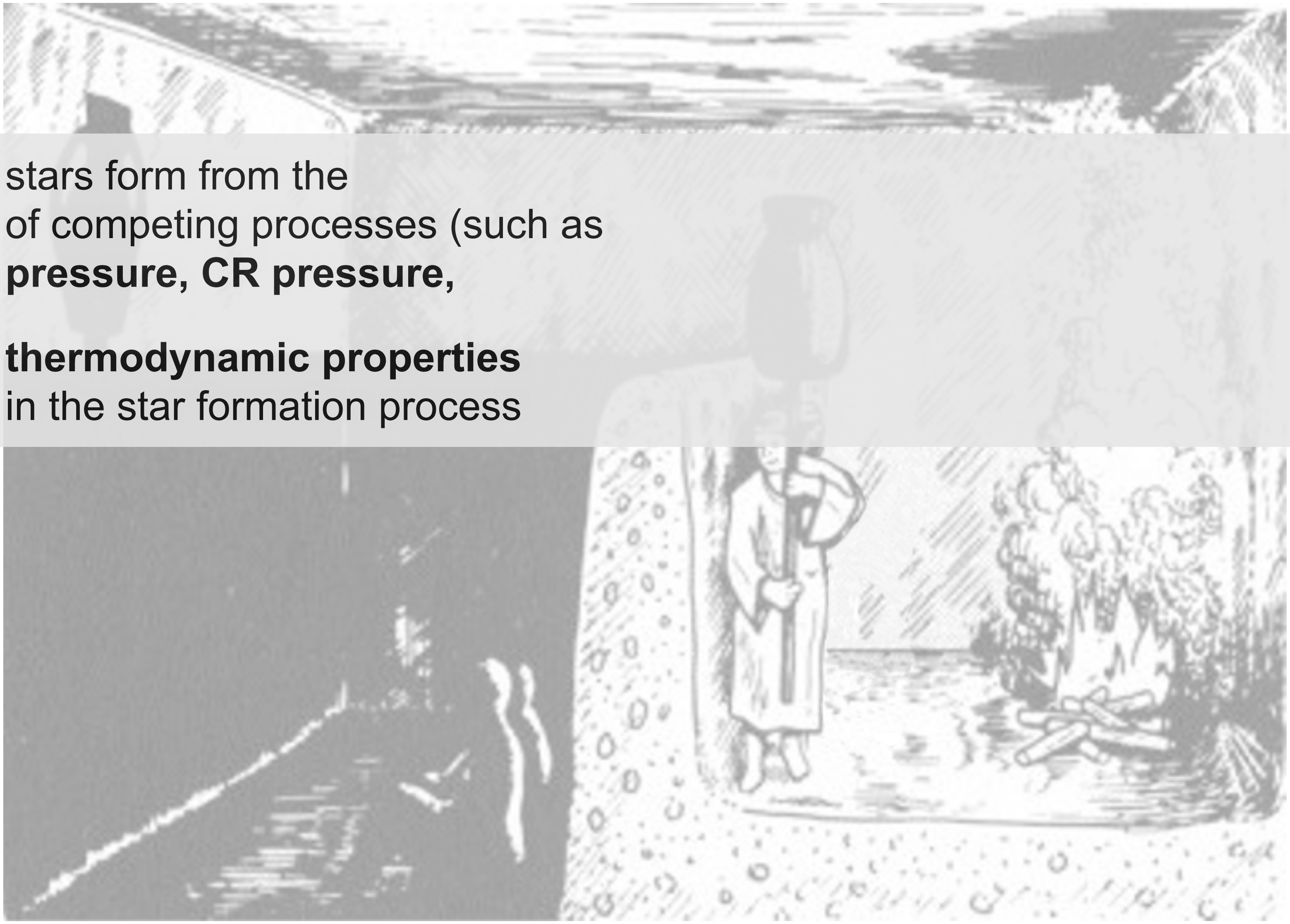

- stars form from the of competing processes (such as **pressure, CR pressure,**
- **thermodynamic properties** in the star formation process

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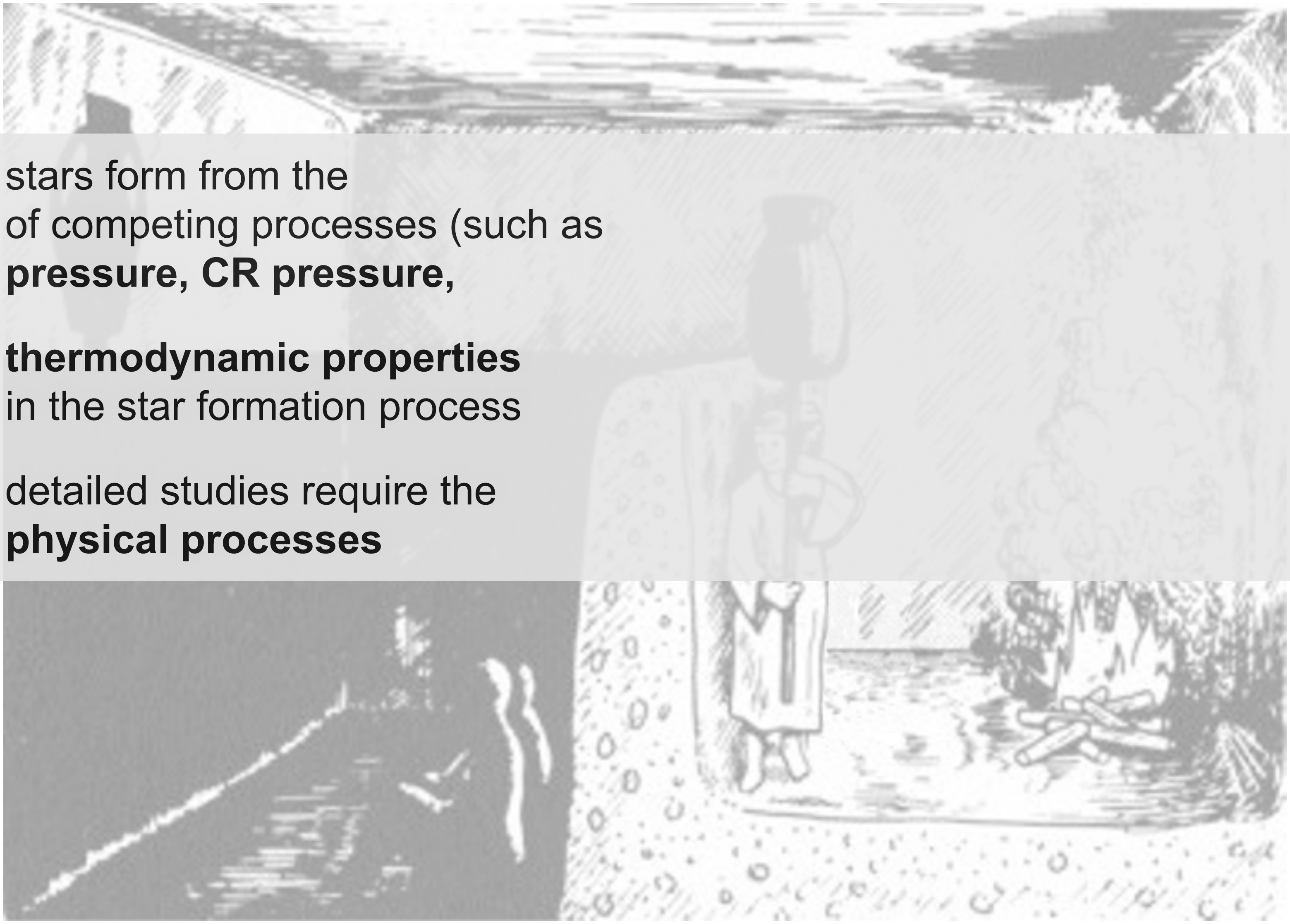
(514a-520a)

Laszlo Szücs, image from criticalthinking-mc205.wikispaces.com

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



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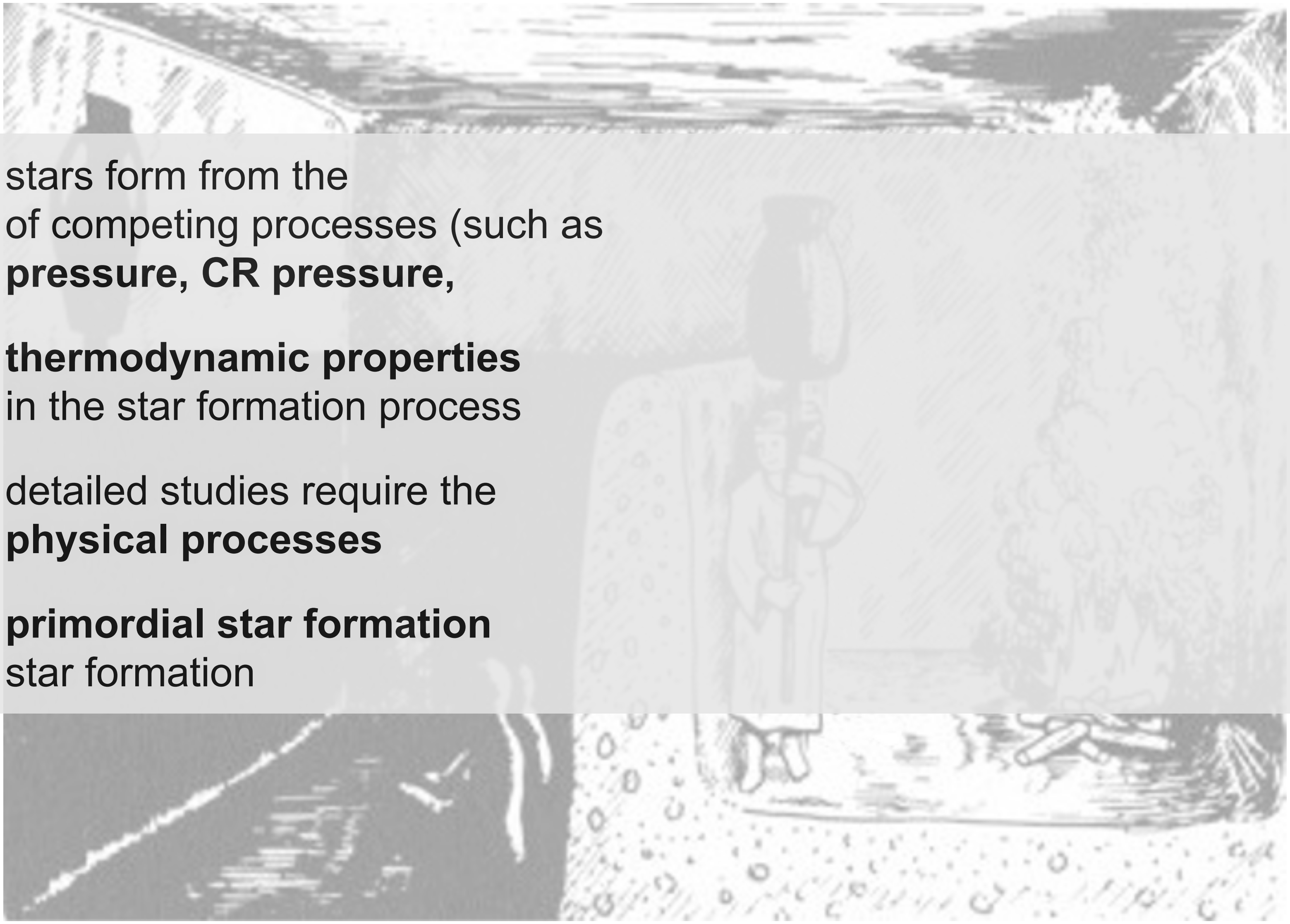

- stars form from the
  of competing processes (such as
  pressure, CR pressure,
- **thermodynamic properties**
  in the star formation process
- detailed studies require the
  physical processes
- **primordial star formation**
  star formation

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