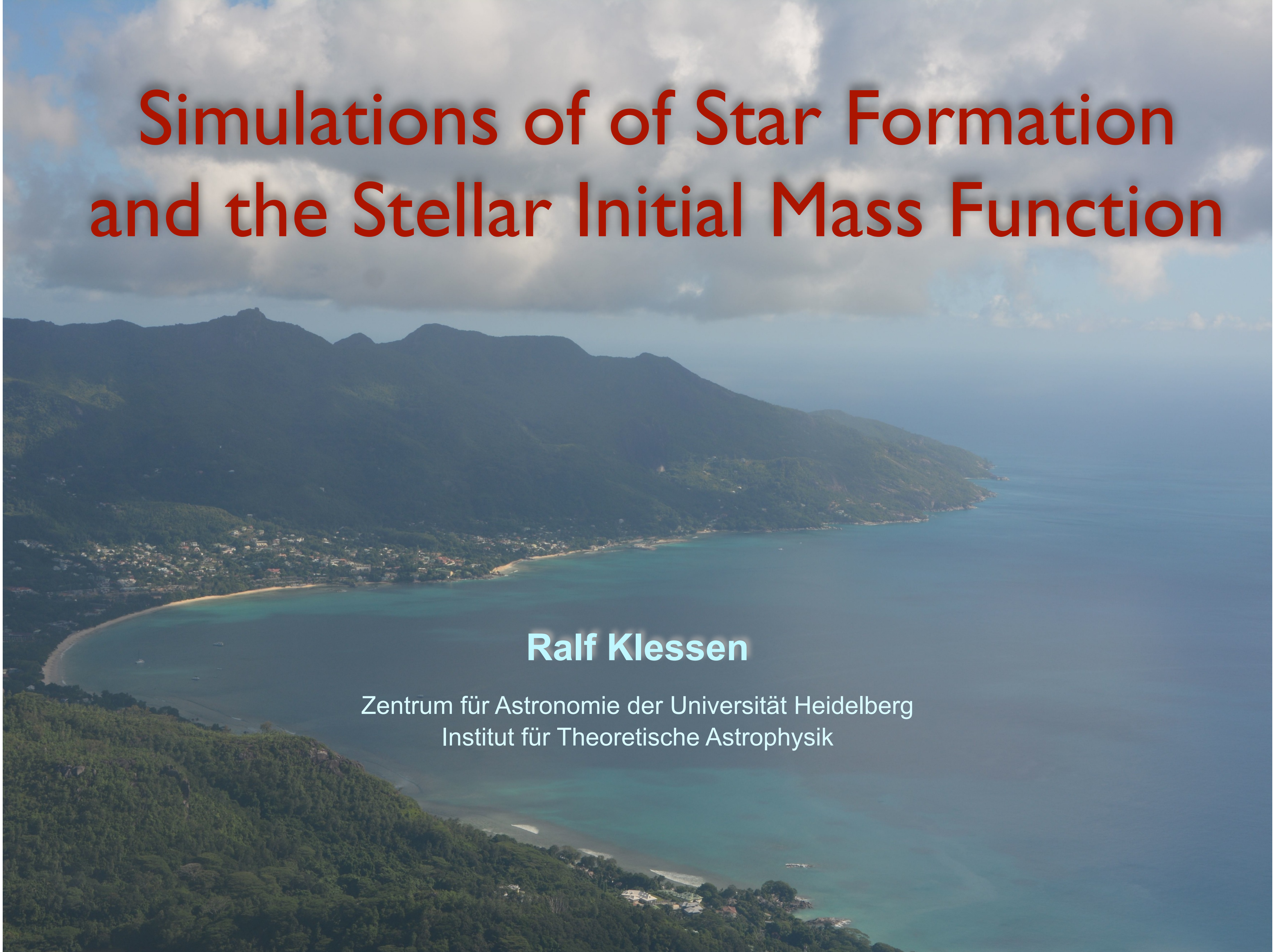
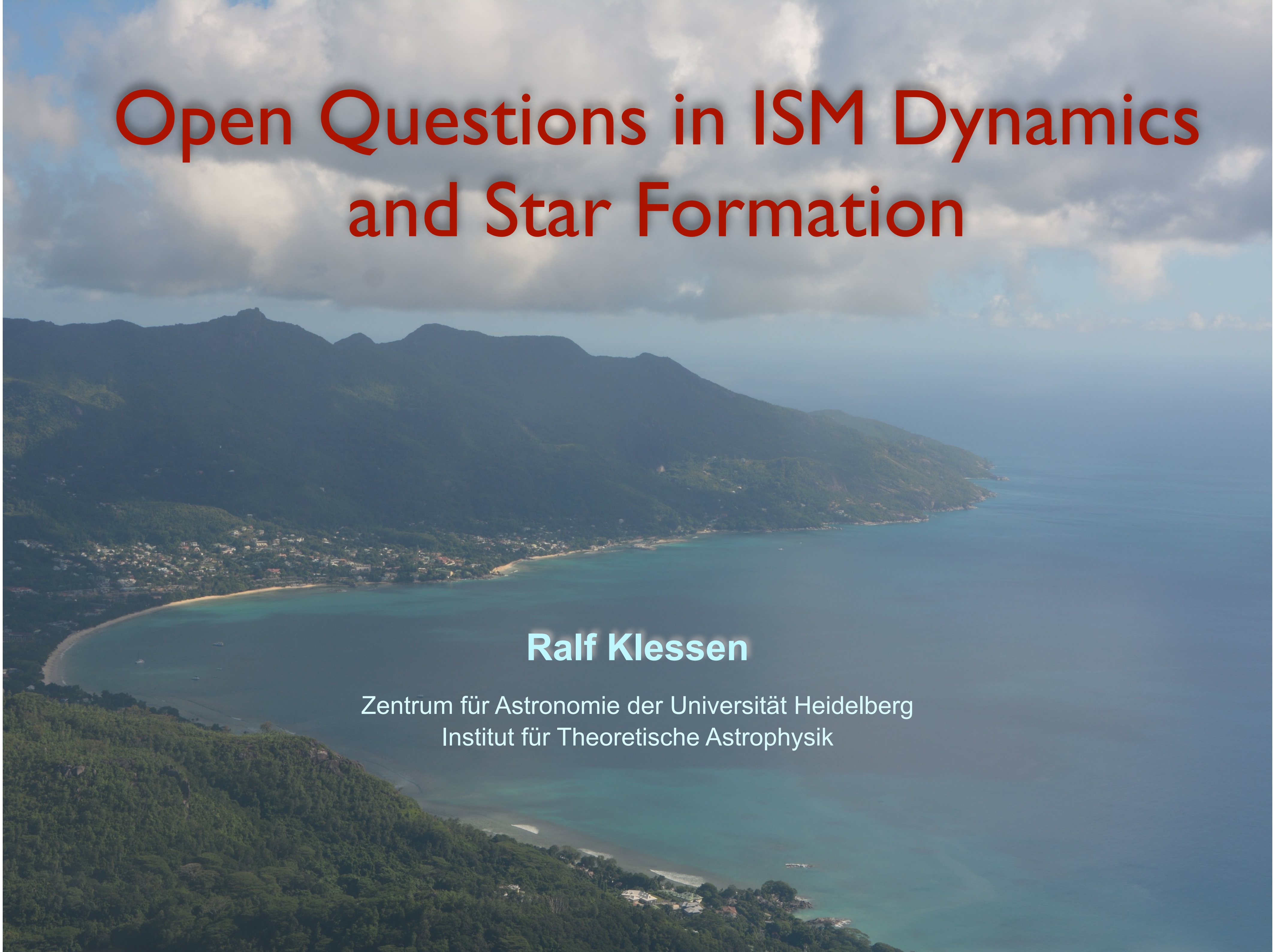


Simulations of of Star Formation and the Stellar Initial Mass Function

Ralf Klessen

Zentrum für Astronomie der Universität Heidelberg
Institut für Theoretische Astrophysik



Open Questions in ISM Dynamics and Star Formation

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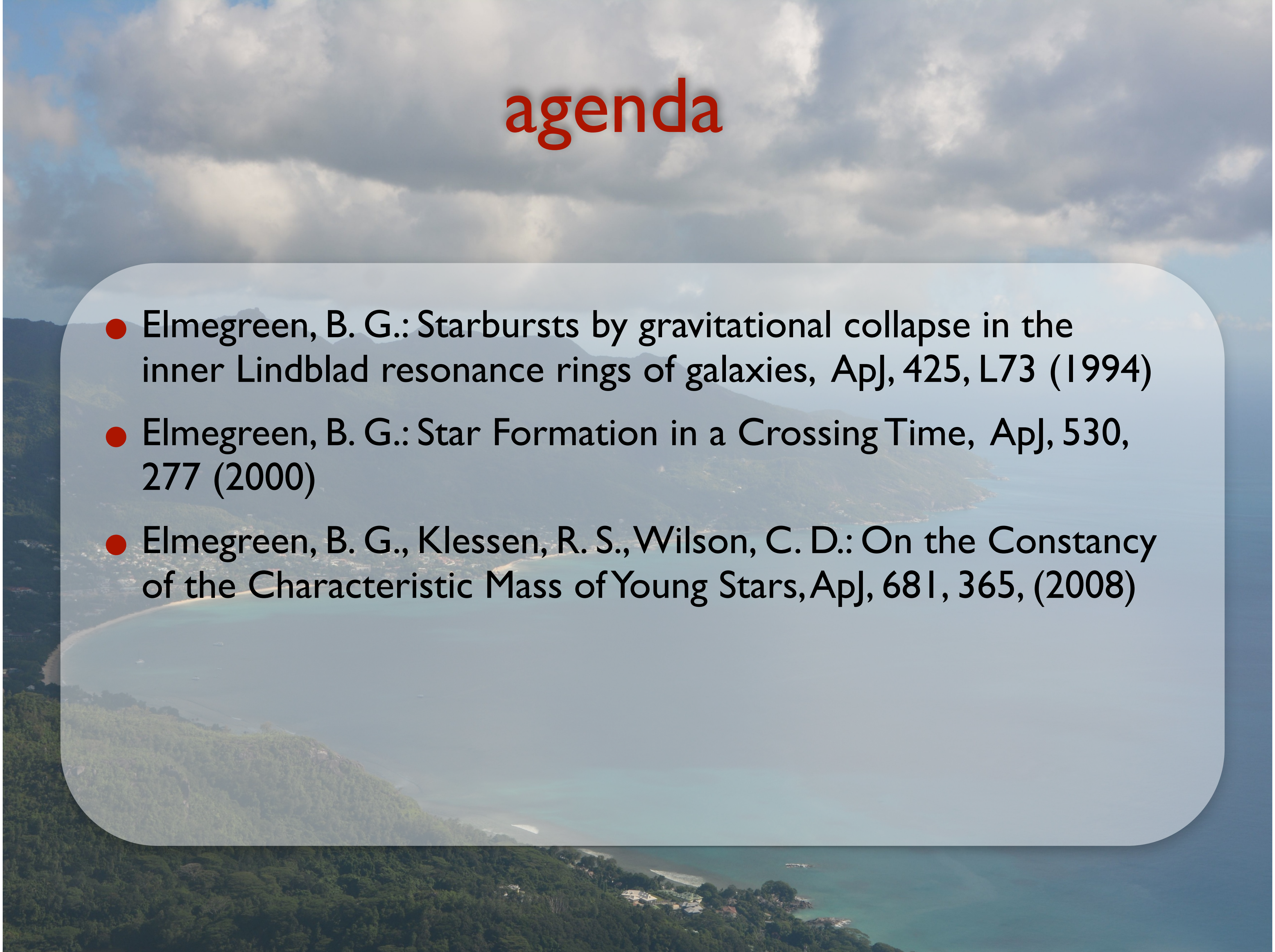
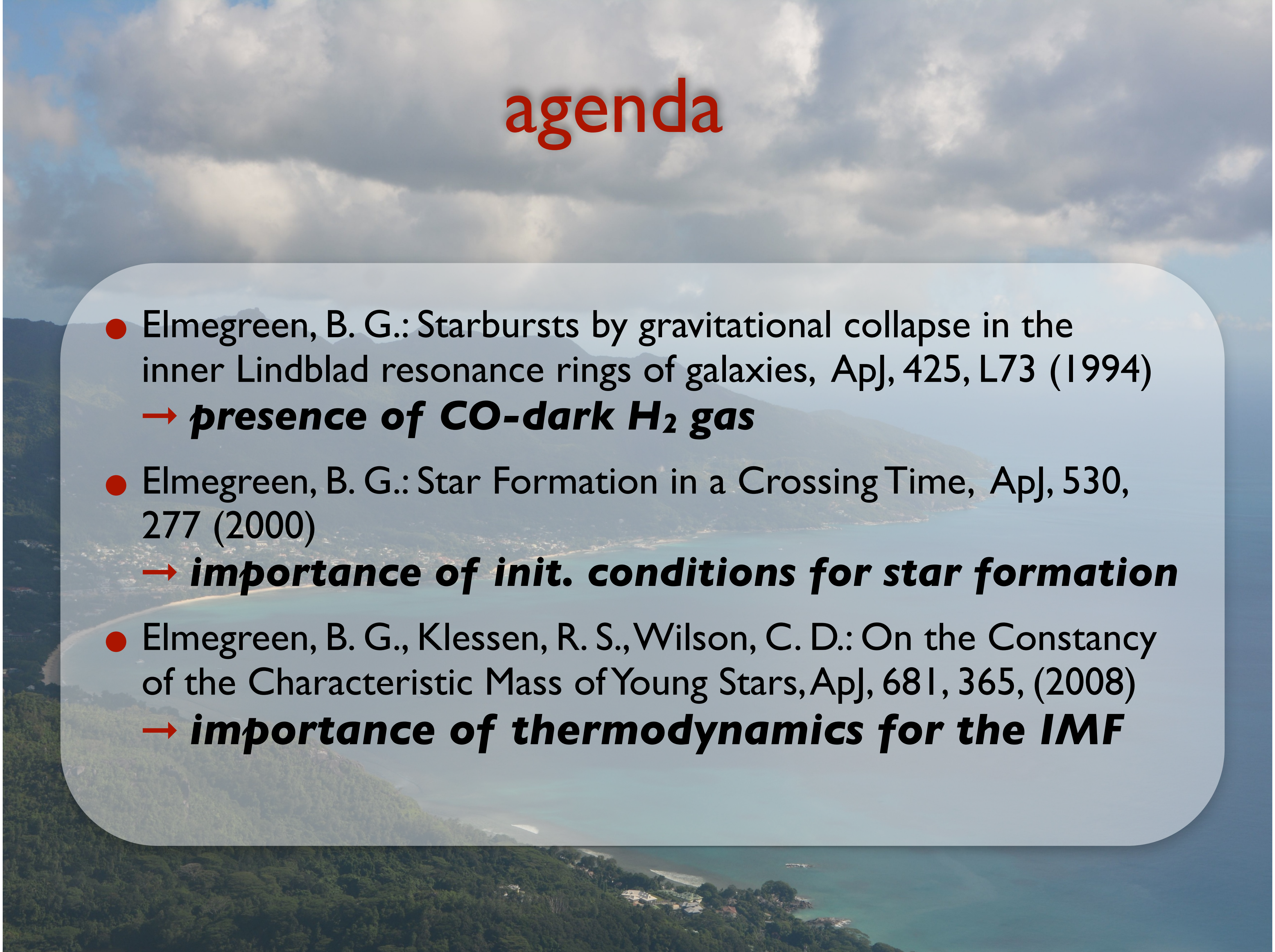


agenda

- Elmegreen, B. G.: Starbursts by gravitational collapse in the inner Lindblad resonance rings of galaxies, ApJ, 425, L73 (1994)
- Elmegreen, B. G.: Star Formation in a Crossing Time, ApJ, 530, 277 (2000)
- Elmegreen, B. G., Klessen, R. S., Wilson, C. D.: On the Constancy of the Characteristic Mass of Young Stars, ApJ, 681, 365, (2008)



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- Elmegreen, B. G.: Starbursts by gravitational collapse in the inner Lindblad resonance rings of galaxies, ApJ, 425, L73 (1994)
  → ***presence of CO-dark H_2 gas***
- Elmegreen, B. G.: Star Formation in a Crossing Time, ApJ, 530, 277 (2000)
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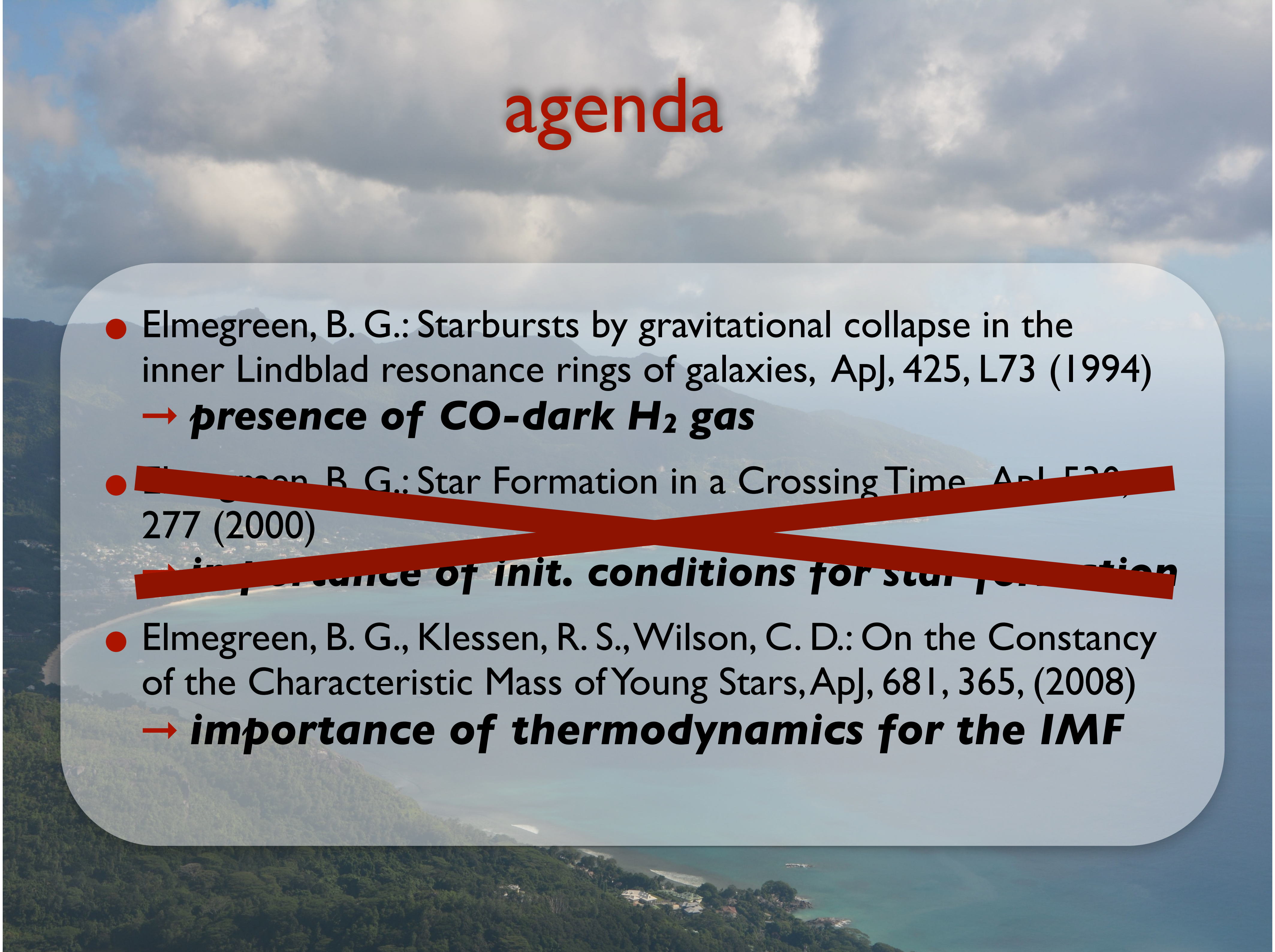
  → ***importance of thermodynamics for the IMF***



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  → ***importance of thermodynamics for the IMF***

THE ASTROPHYSICAL JOURNAL, 425:L73–L76, 1994 April 20

STARBURSTS BY GRAVITATIONAL COLLAPSE IN THE INNER LINDBLAD RESONANCE RINGS OF GALAXIES

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Received 1993 November 29; accepted 1994 February 8

ABSTRACT

Starbursts in inner Lindblad resonance rings are proposed to result from gravitational instabilities that fragment the ring into several bound clouds. Each cloud forms a separate star cluster or hot spot after further energy dissipation and collapse. A linear instability analysis including accretion and an azimuthal magnetic field suggests that the ring instability occurs only after a critical density is reached, which presumably follows a relatively long epoch of gas accretion from bar or spiral torques. The critical density is very high in the inner regions because the Coriolis and tidal forces are high. Typical densities are >100 cm^{-3}, depending on the inner Lindblad resonance radius, rotation curve, accretion rate, and other parameters. The rapid star formation in the starburst follows from the high density at the expected rate $\epsilon\omega\rho$ for local efficiency per cloud ϵ, instability growth rate ω, and density ρ. Most of the high rate comes from the density dependence of $\omega(\rho)\rho$, but the efficiency ϵ could also increase if the ambient velocity dispersion is high in the ring.

Subject headings: galaxies: starburst — stars: formation — instabilities

THE ASTROPHYSICAL JOURNAL, 425:L73–L76, 1994 April 20

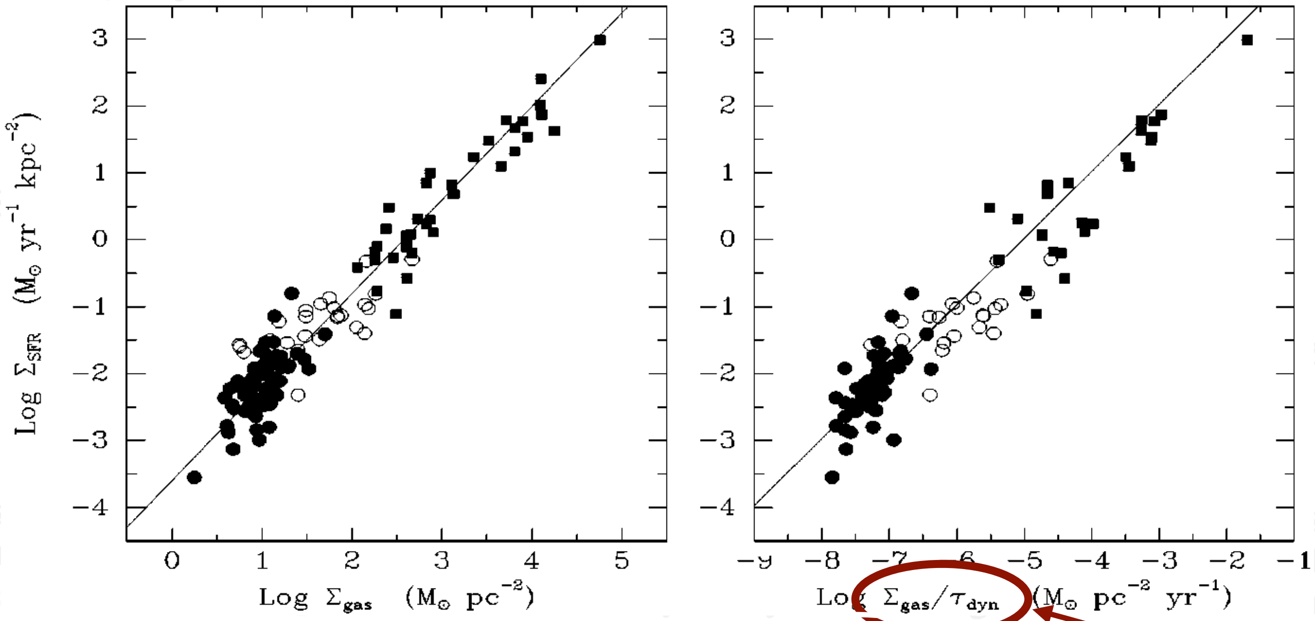


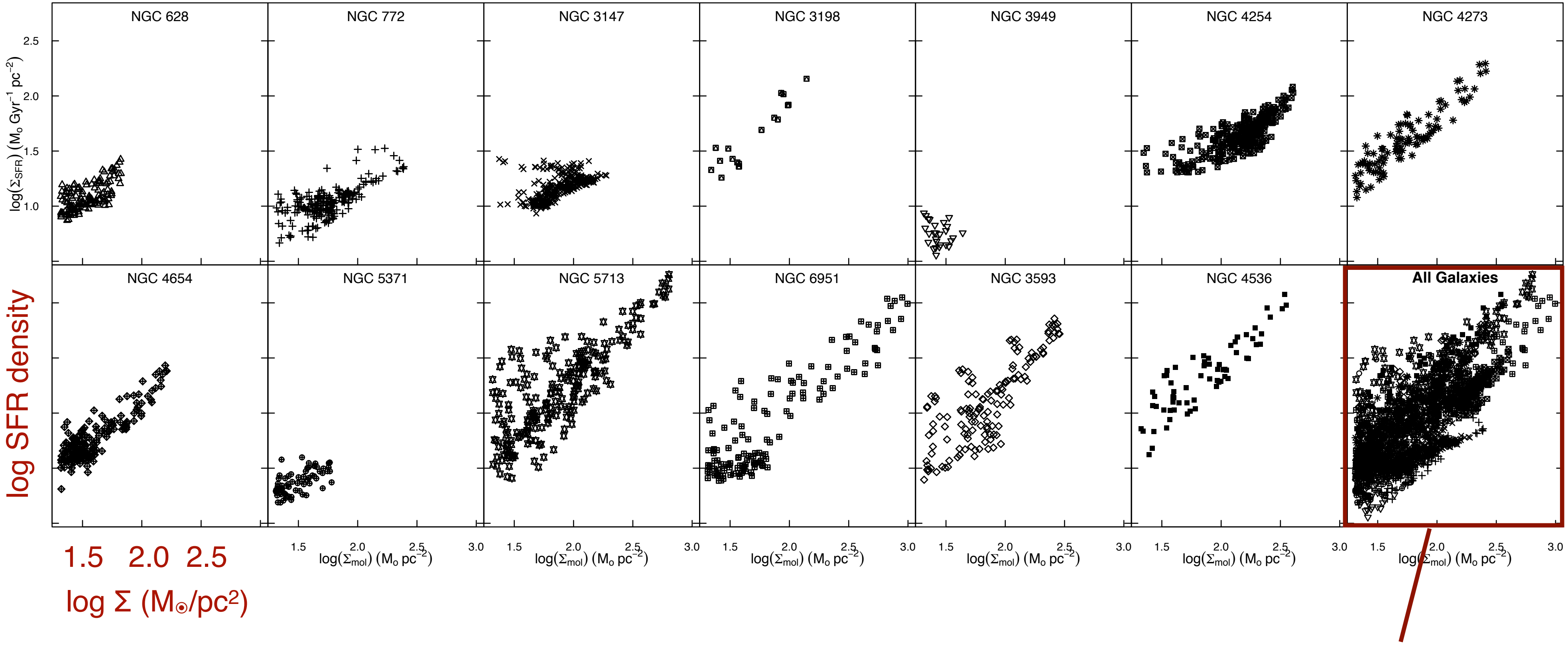
Figure 9 (*Left*) The global Schmidt law in galaxies. *Solid points* denote the normal spirals in Figure 5, *squares* denote the circumnuclear starbursts in Figure 7. The *open circles* show the SFRs and gas densities of the central regions of the normal disks. (*Right*) The same SFR data but plotted against the ratio of the gas density to the average orbital time in the disk. Both plots are adapted from Kennicutt (1998).

$$\boxed{\Sigma_{SFR} = (2.5 \pm 0.7) \times 10^{-4} \left(\frac{\Sigma_{gas}}{1\ M_\odot\ \mathrm{pc}^{-2}} \right)^{1.4\pm0.15} \quad M_\odot\ \mathrm{year}^{-1}\ \mathrm{kpc}^{-2},}$$

"As discussed by Larson (1992) and Elmegreen (1994), a large-scale Schmidt law with index $N \sim 1.5$ would be expected for self-gravitating disks if the SFR scales as the ratio of the gas density (ϱ) to the free-fall time scale ($\propto \varrho^{-0.5}$) and the average gas scale height is roughly constant across the sample ($\Sigma \propto \varrho$)."

Kennicutt (1998, ARAA, 36, 189)

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

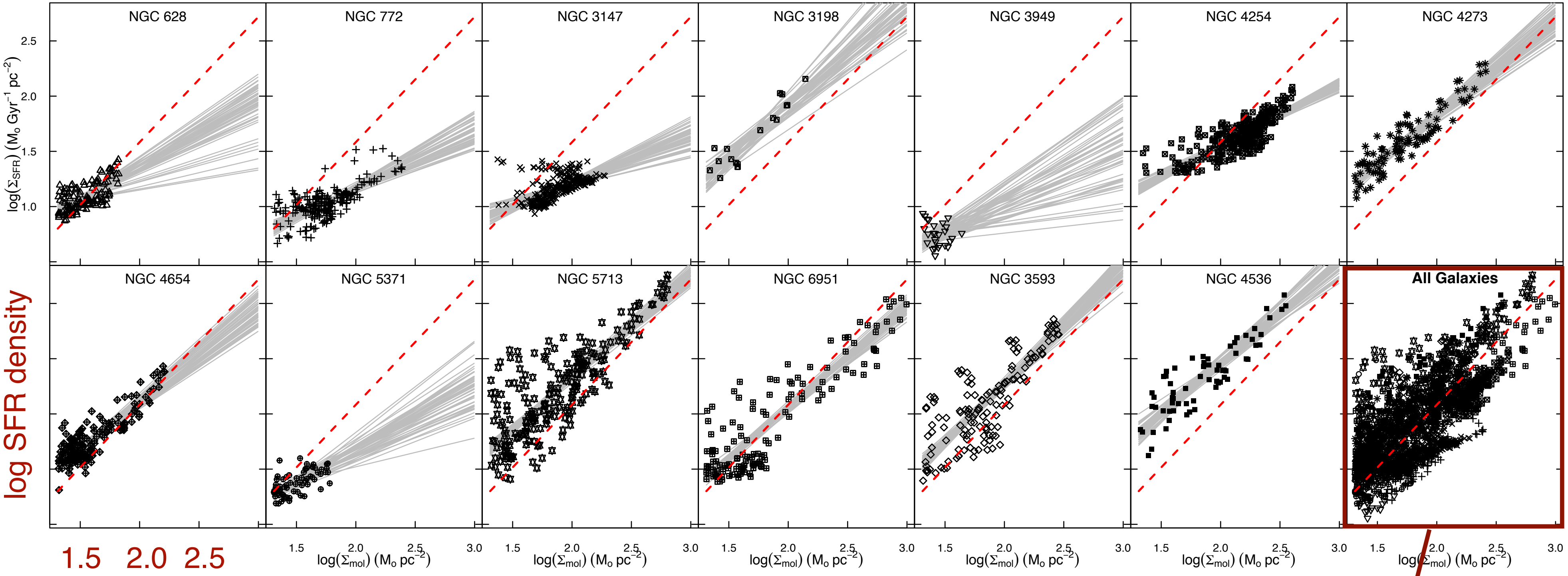


all galaxies

- 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

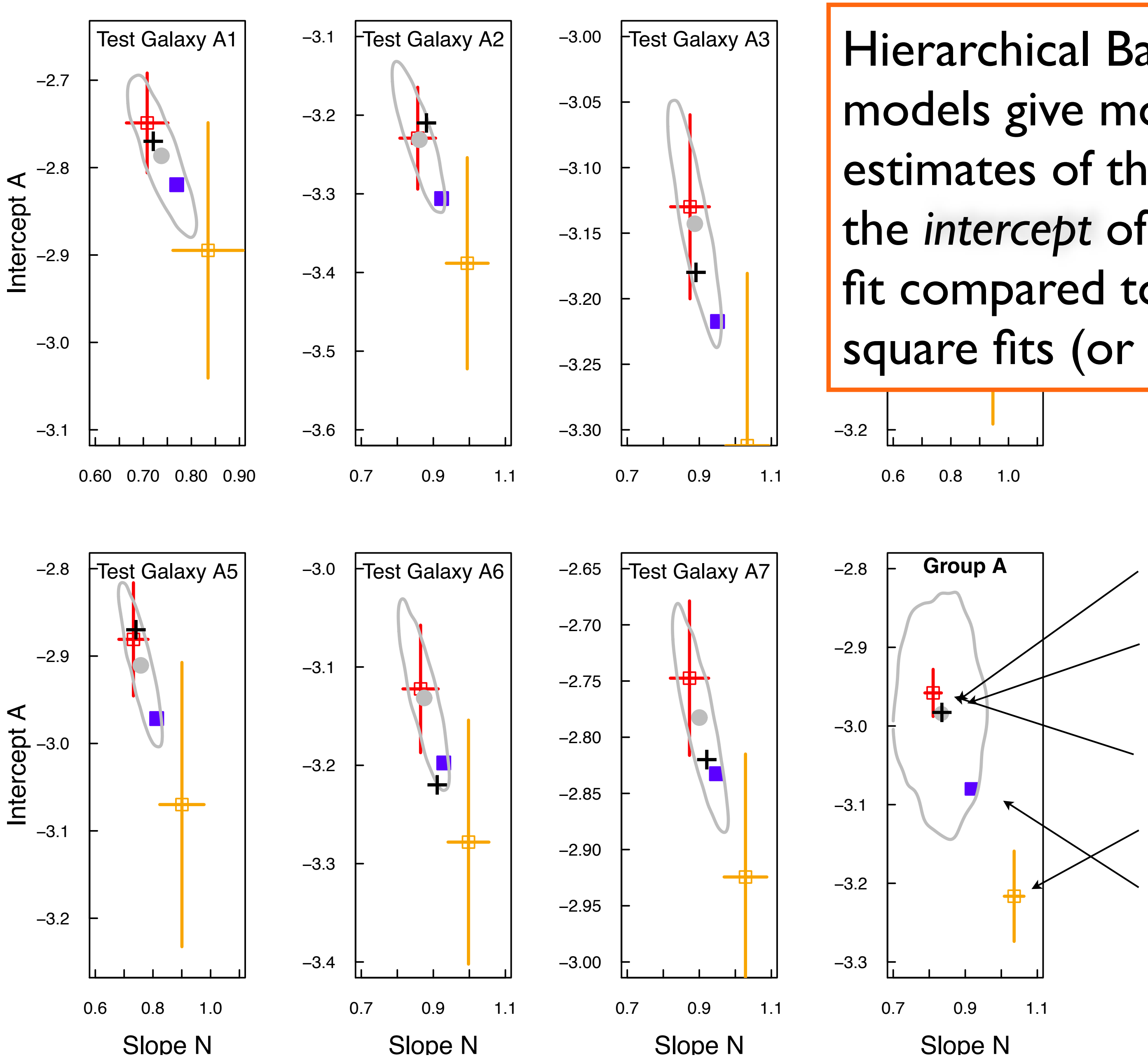
log Σ ($M_\odot/pc^2$)

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).



true value

Bayesian fit
(with 1 sigma area)

N_{SFR} vs. N_{gas}

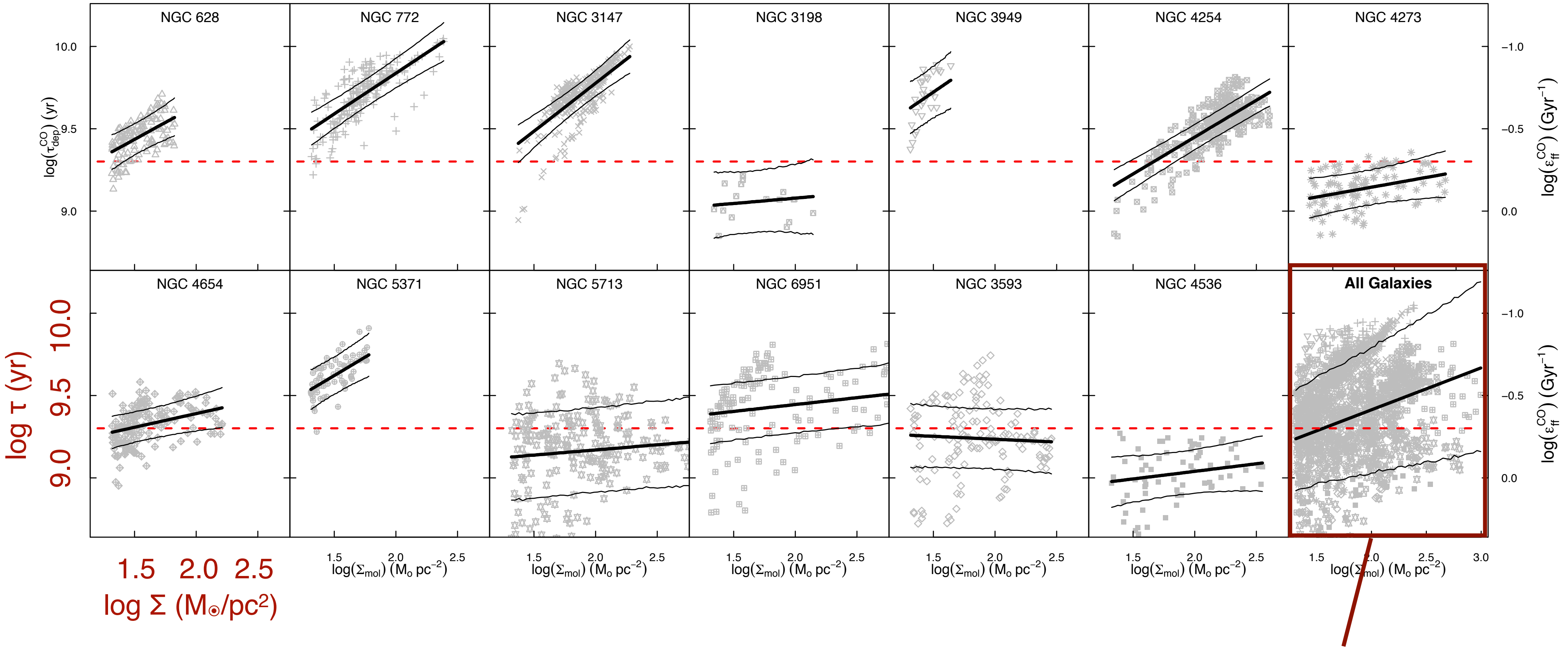
N_{gas} vs. N_{SFR}

bisector fit

Figure 1. Slope and intercept of test galaxies in Group A. Black cross shows the true values. Red and orange squares show the $\mathrm{OLS}(\Sigma_{\mathrm{SFR}}|\Sigma_{\mathrm{mol}})$ and $\mathrm{OLS}(\Sigma_{\mathrm{mol}}|\Sigma_{\mathrm{SFR}})$ 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)

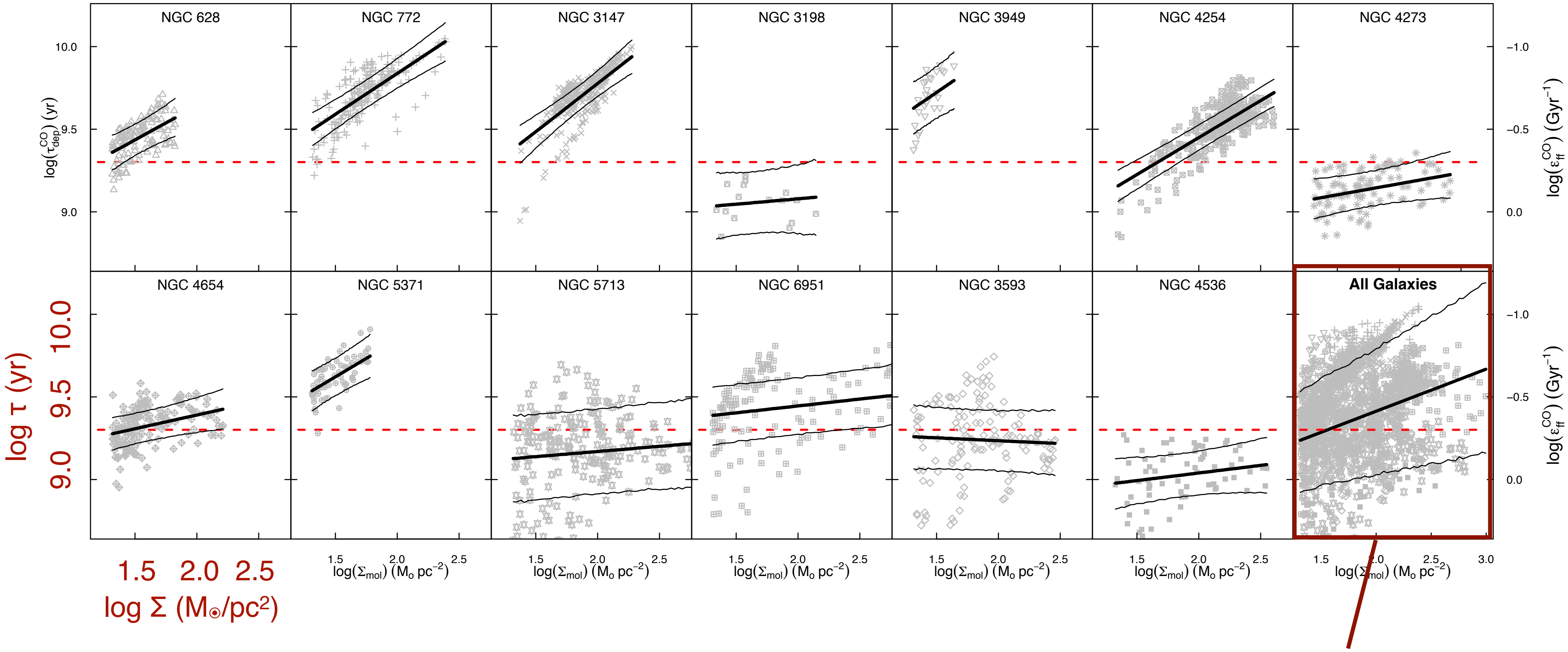


all galaxies

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)



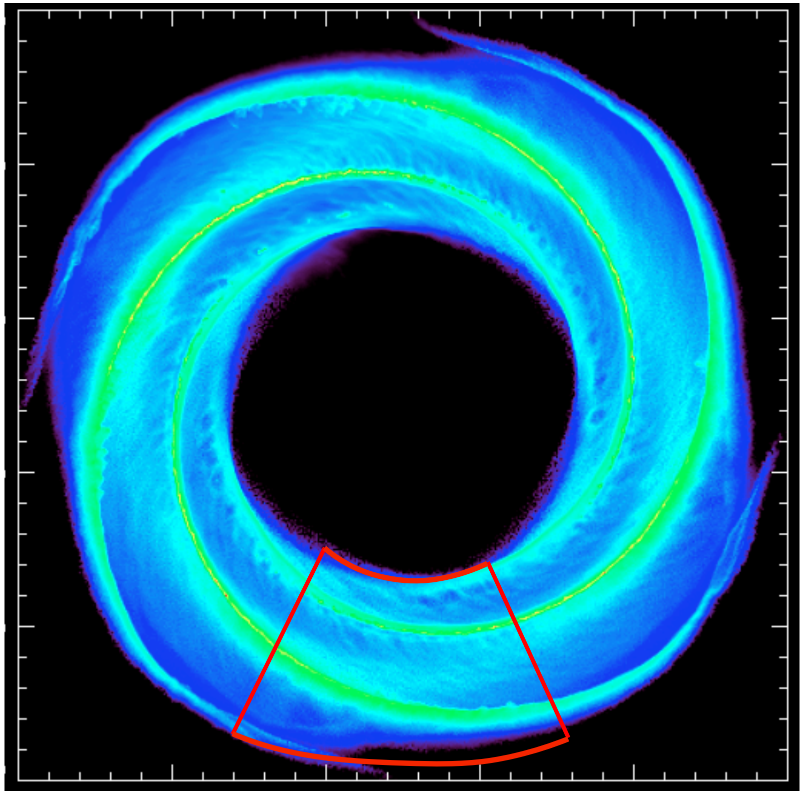
all galaxies

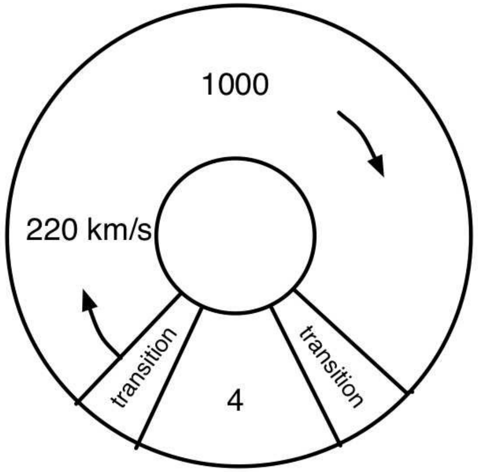
physical origin of this behavior?

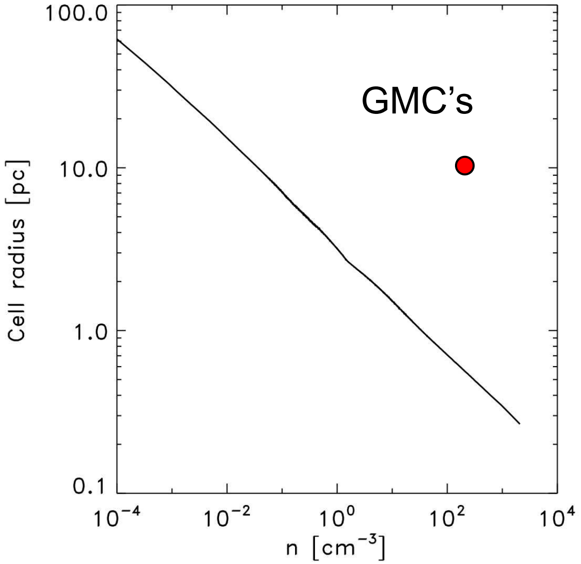
- maybe strong shear in dense arms (example M51, Meidt et al. 2013)...
- maybe non-star forming H
  column densities (recall H

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

molecular cloud formation





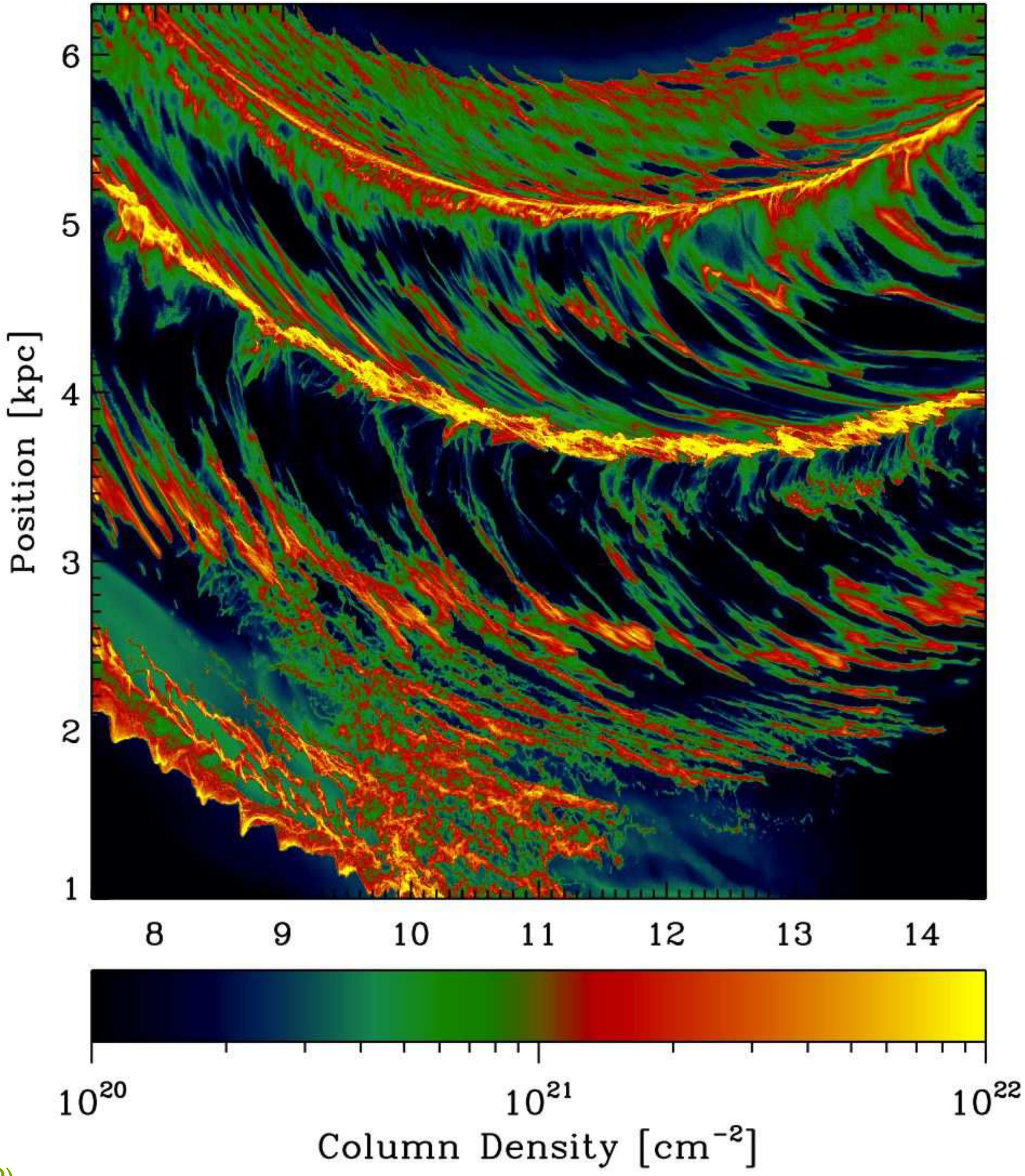


Simulation	Surface Density $M_\odot\ \mathrm{pc}^{-2}$	Radiation Field G_0
Milky Way	10	1
Low Density	4	1
Strong Field	10	10
Low & Weak	4	0.1

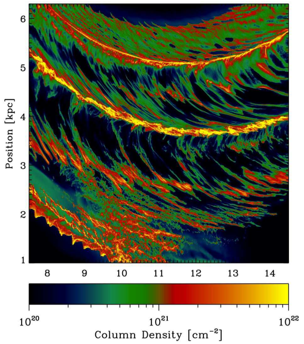
- Arepo moving mesh code *(Springel 2010)*
- time dependent chemistry *(Glover et al. 2007)* gives heating & cooling in a 2 phase medium
- two layers of refinement with mass resolution down to 4 $M_\odot$ in full Galaxy simulation
- UV field and cosmic rays
- TreeCol *(Clark et al. 2012)*
- external spiral potential *(Dobbs & Bonnell 2006)*
- no gas self-gravity, SN, or magnetic fields yet

(Smith et al., 2014, MNRAS in press, arXiv1403.1589)

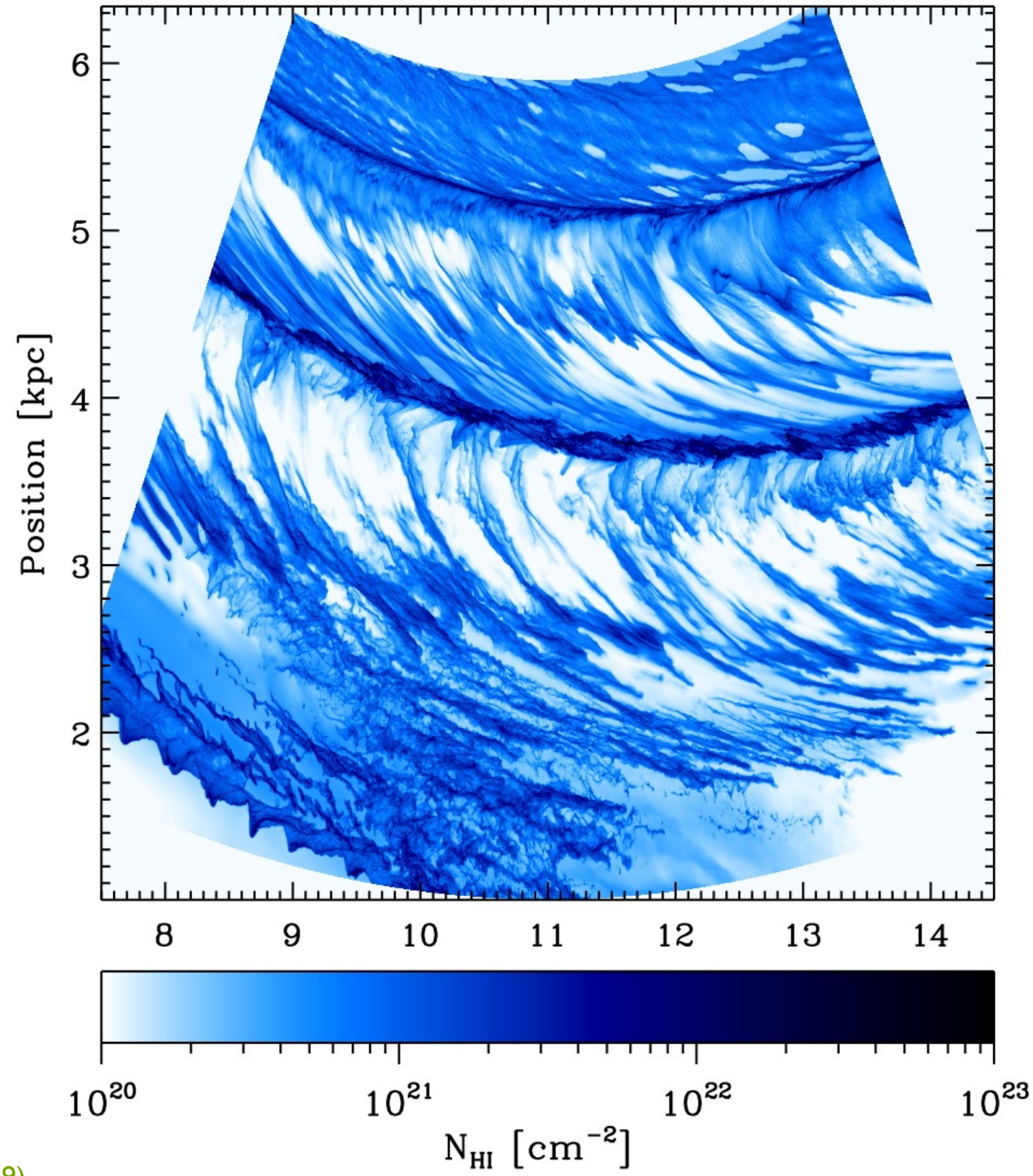
total column density



(Smith et al., 2014, MNRAS in press, arXiv1403.1589)

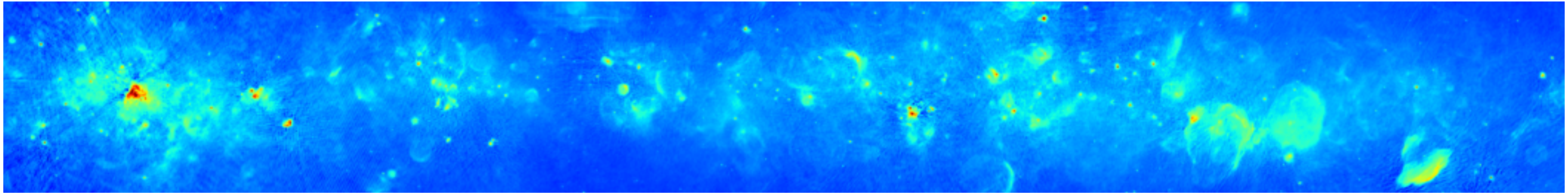


HI column density

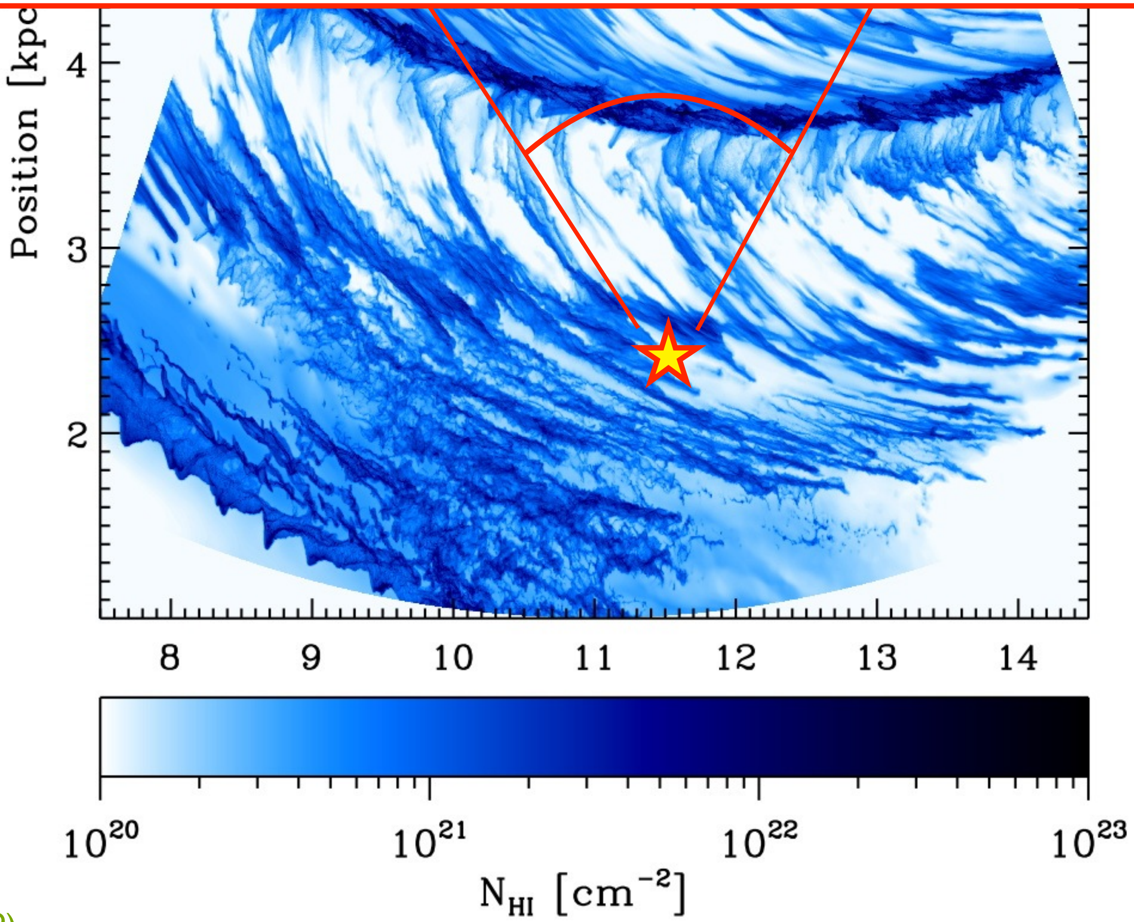


(Smith et al., 2014, MNRAS in press, arXiv1403.1589)

preliminary image from THOR Galactic plane survey (PI H. Beuther)

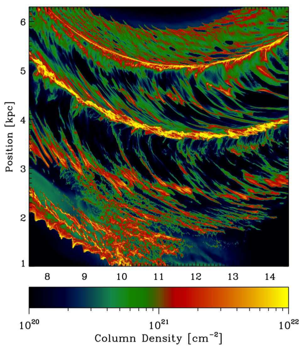


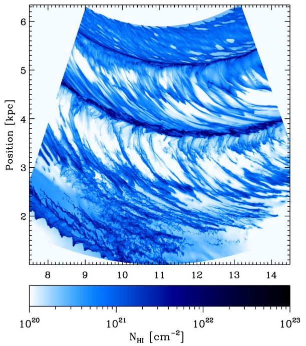
next step: produce all sky maps at various positions in the model galaxy (use RADMC-3D)

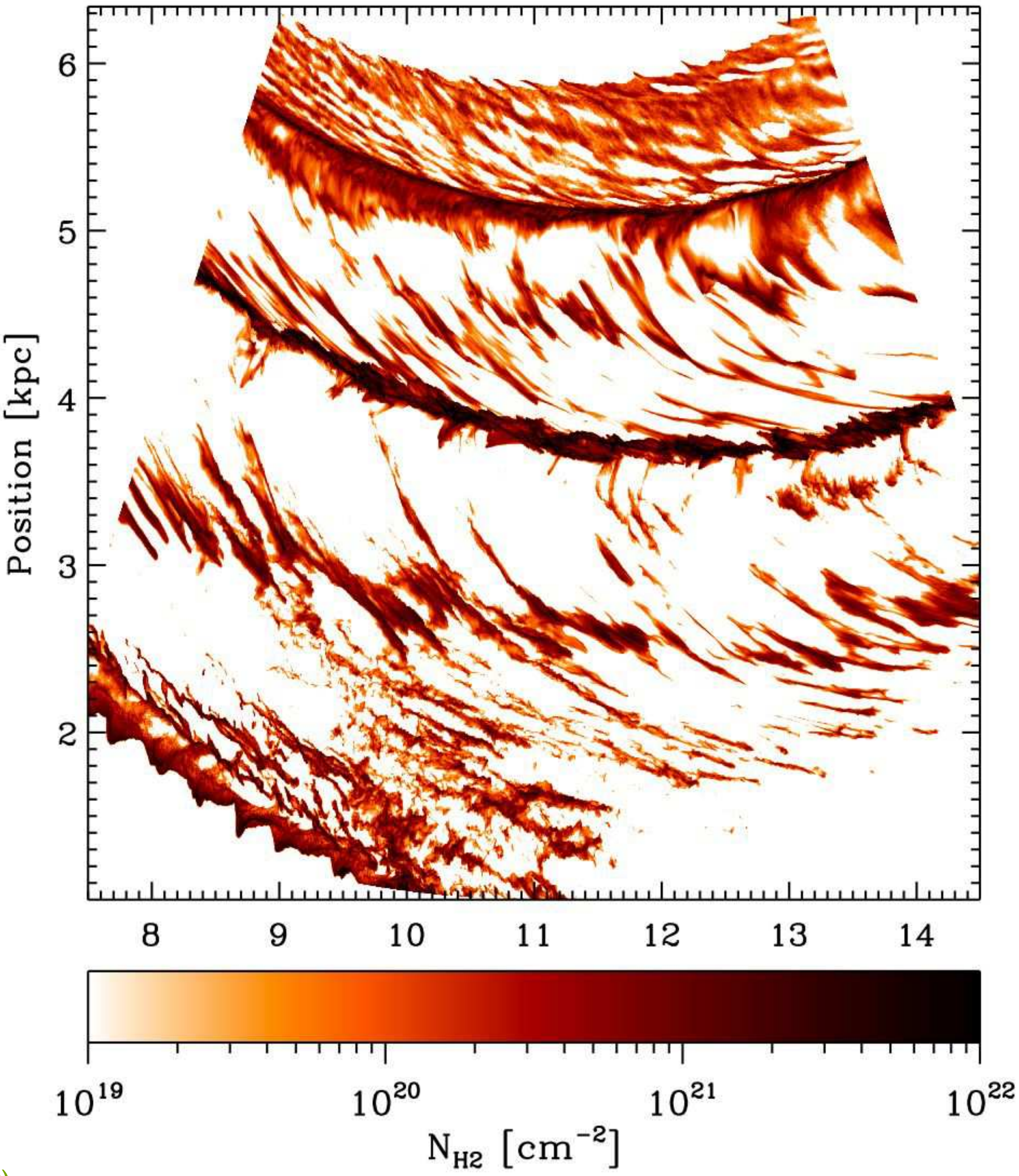


(Smith et al., 2014, MNRAS in press, arXiv1403.1589)

H_2 column density

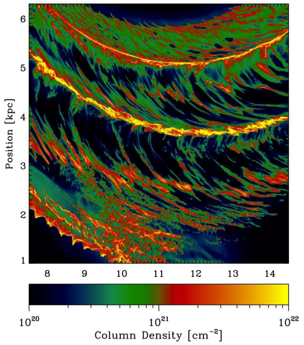


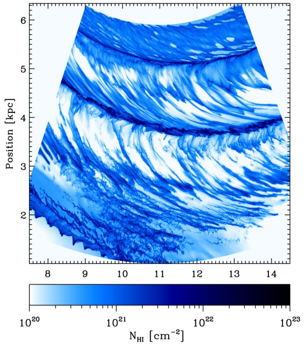


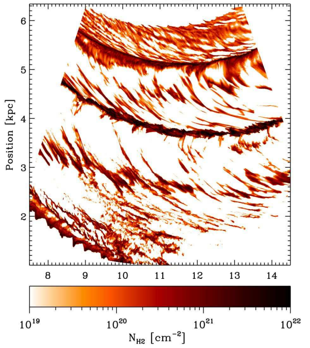


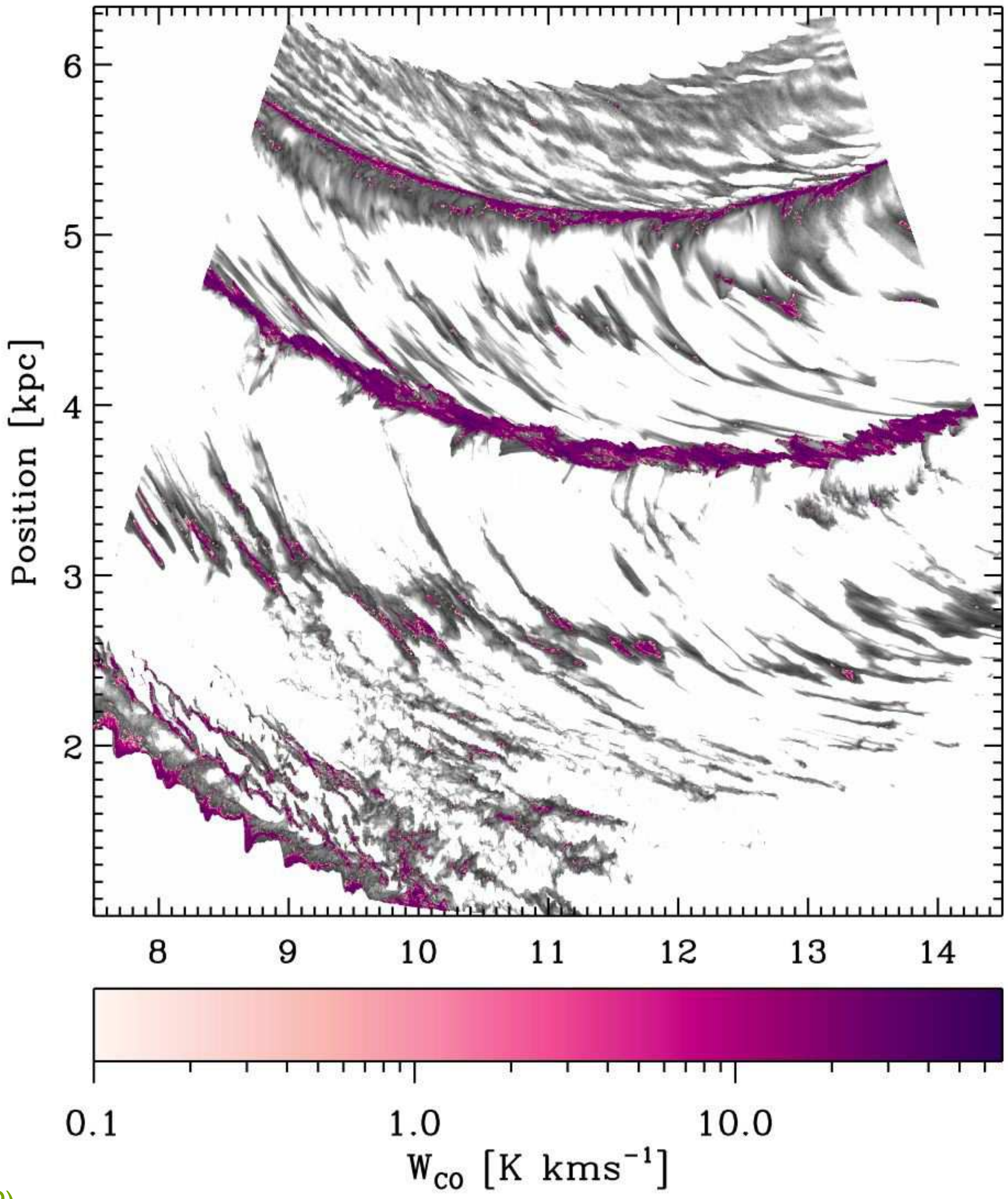
(Smith et al., 2014, MNRAS in press, arXiv1403.1589)

CO column density



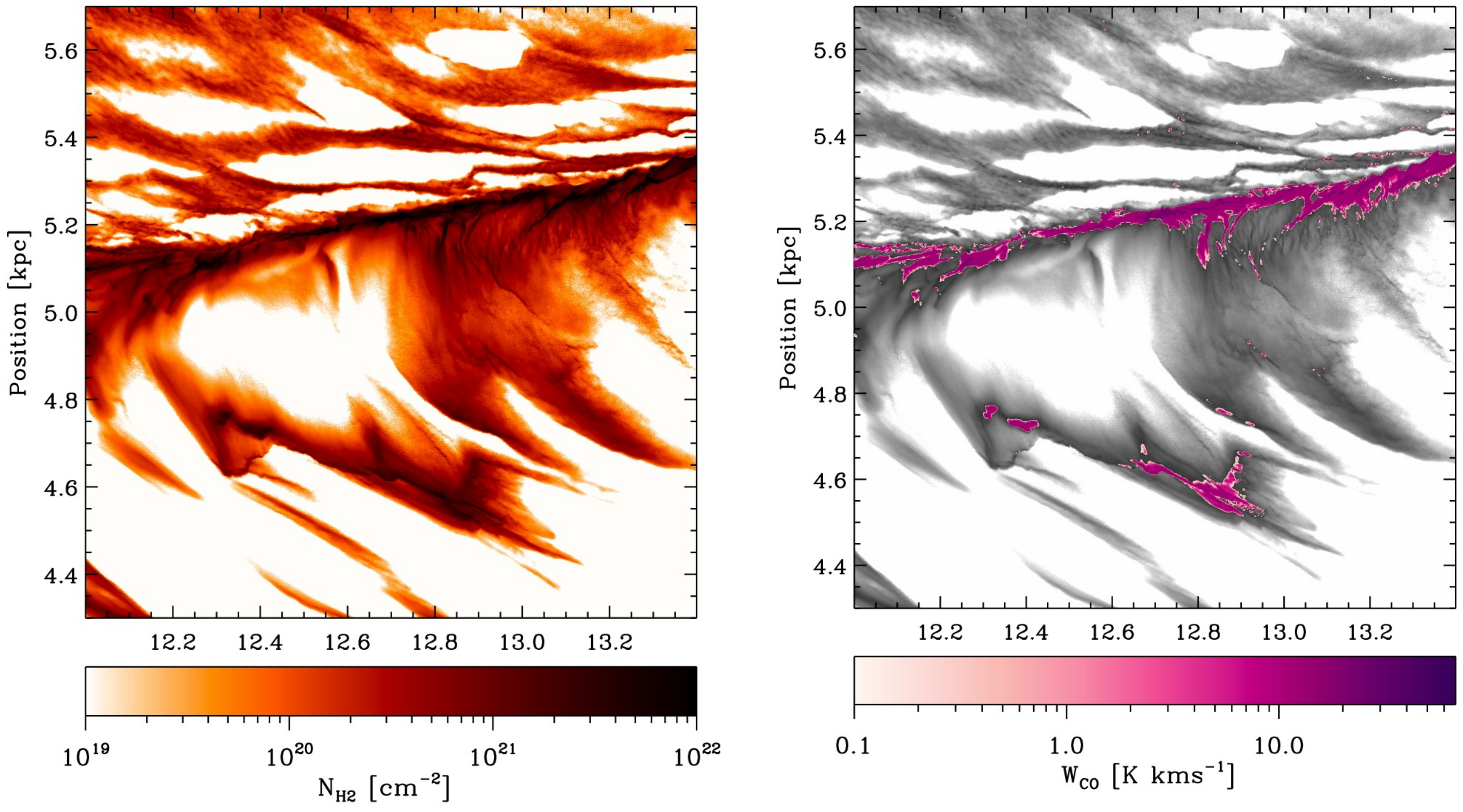






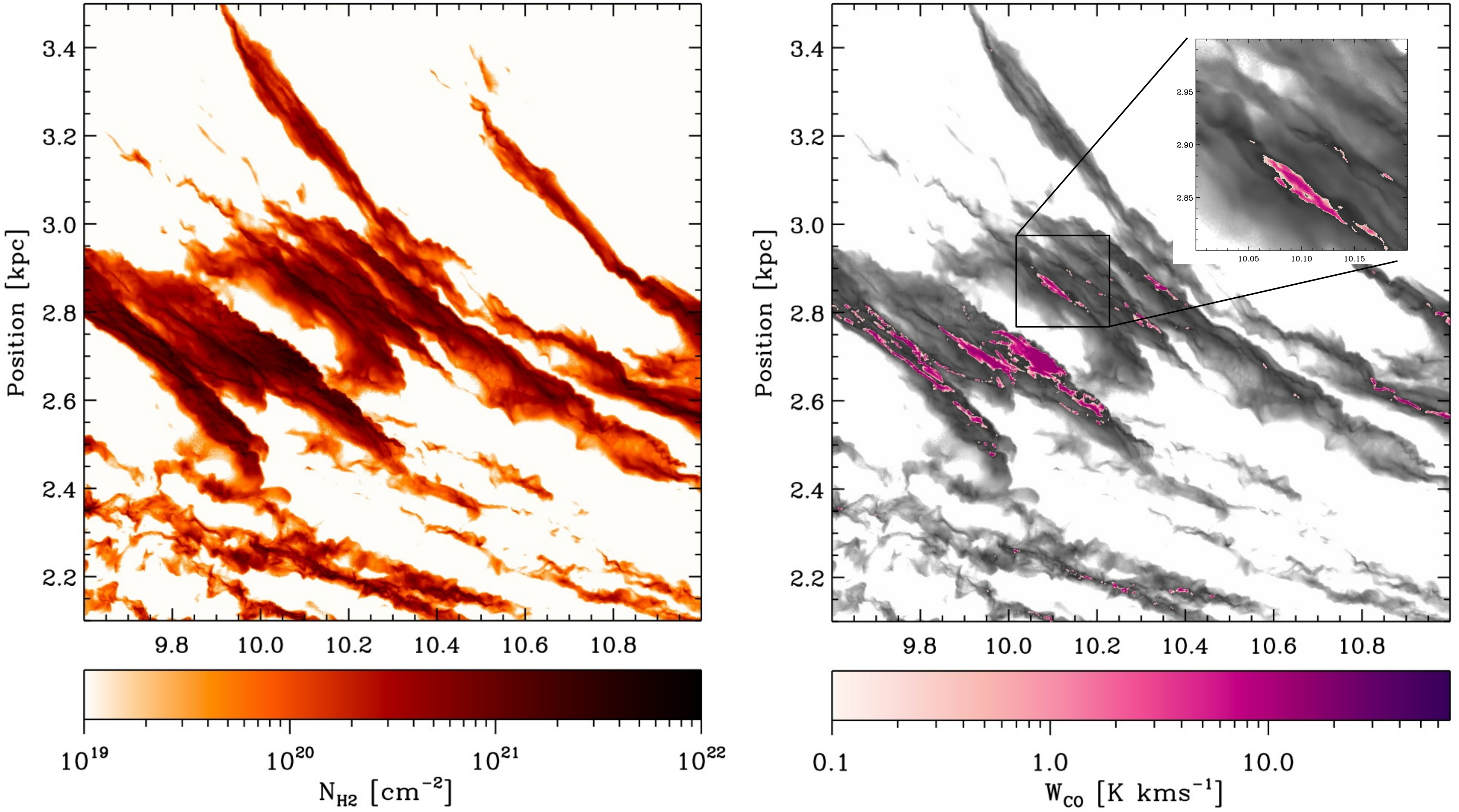
(Smith et al., 2014, MNRAS in press, arXiv1403.1589)

relation between CO and H_2



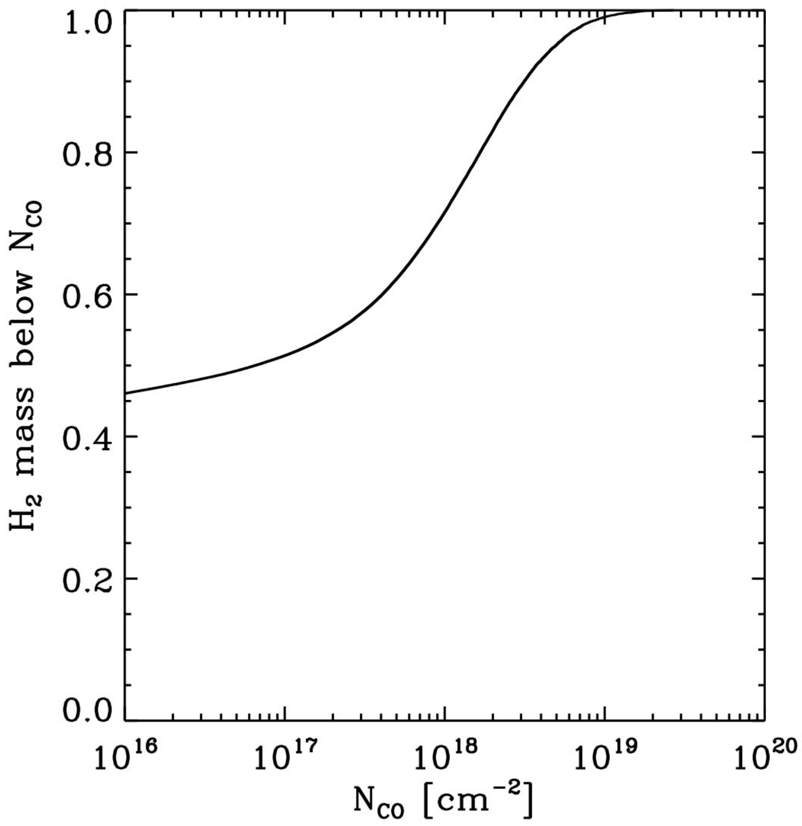
(Smith et al., 2014, MNRAS in press, arXiv1403.1589)

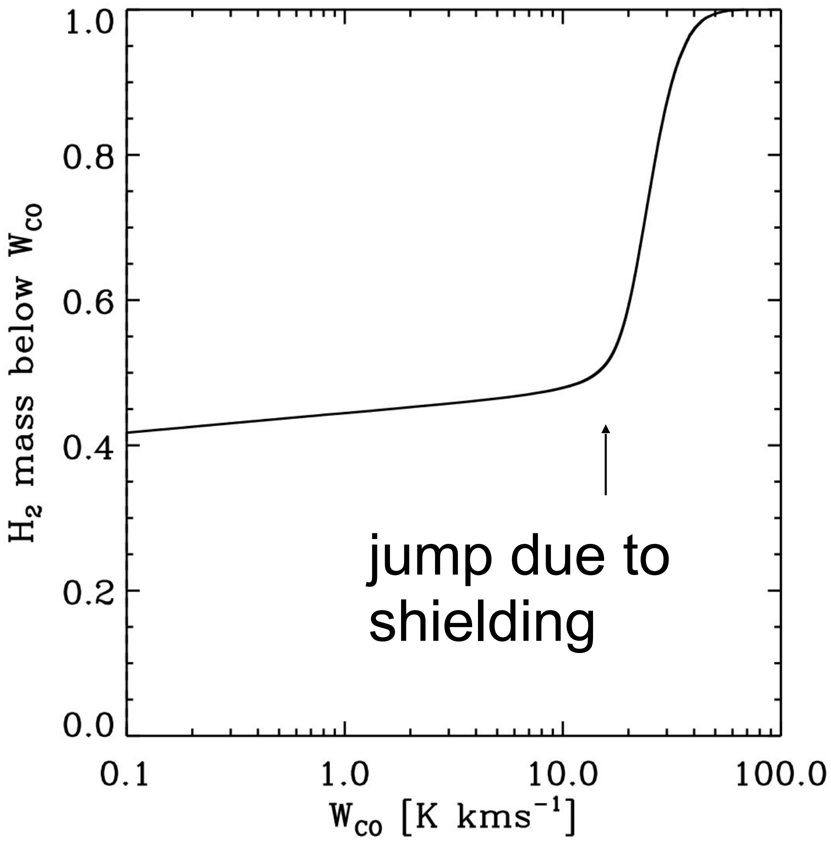
relation between CO and H_2



Filamentary molecular clouds in inter-arm regions are likely only the observable parts of much larger structures.

dark gas fraction





jump due to shielding

46% molecular gas below CO column densities of 10^{16} cm^{-2}

42% has an integrated CO emission of less than 0.1 K kms^{-1}

$f_{DG} = 0.42$ $X_{co}=2.2 \times 10^{20}\ cm^{-2}K^{-1}km^{-1}s$

dark gas fraction

Observational estimates:

Wolfire et al. 2010 $f_{DG} \approx 0.30$

Grenier et al. 2005 $f_{DG} = 0.33\text{-}0.5$

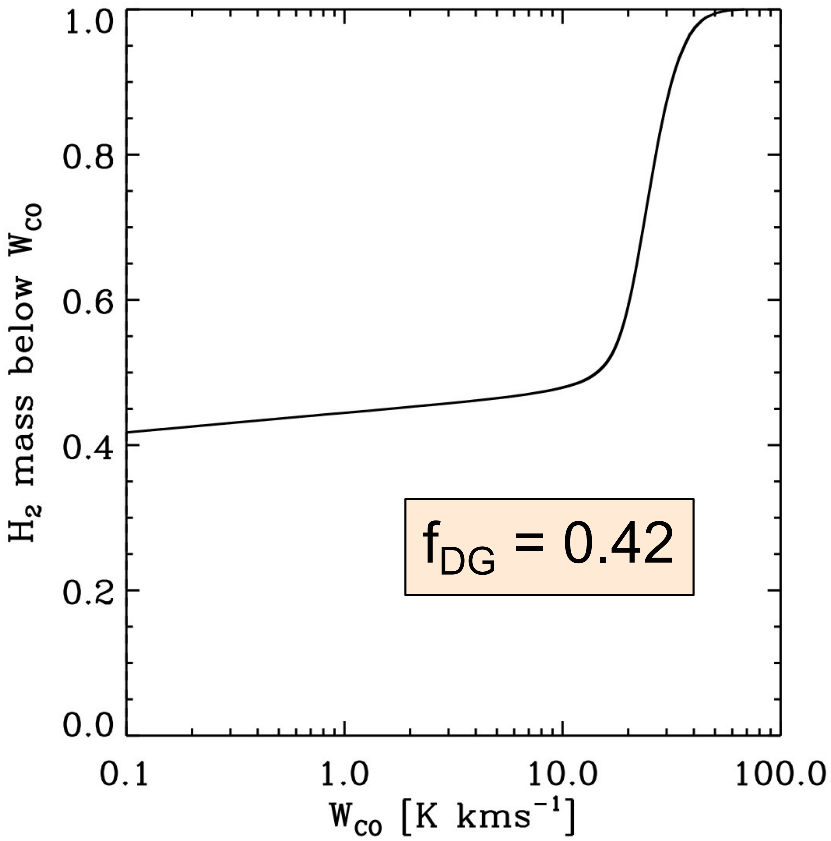
Planck collaboration 2011* $f_{DG} = 0.54$

Paradis et al. 2012* $f_{DG} = 0.62$

inner $f_{DG} = 0.71$, outer $f_{DG} = 0.43$

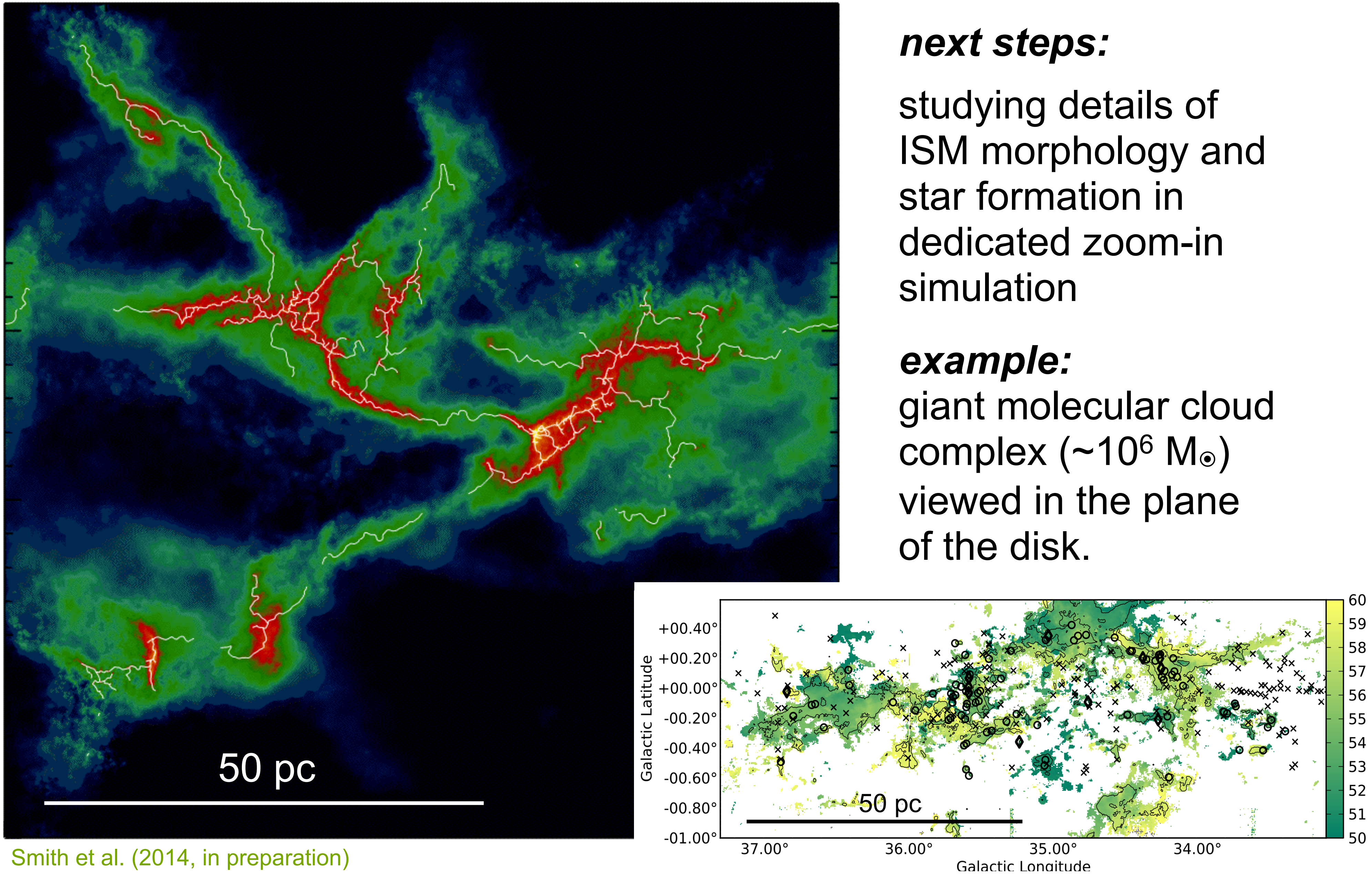
Pineda et al. 2013 $f_D = 0.3$

* dust methods have large uncertainties.



$f_{DG} = 0.42$

large-scale filaments



Smith et al. (2014, in preparation)

Ragan et al., 2014, A&A submitted, arXiv:1403.1450)

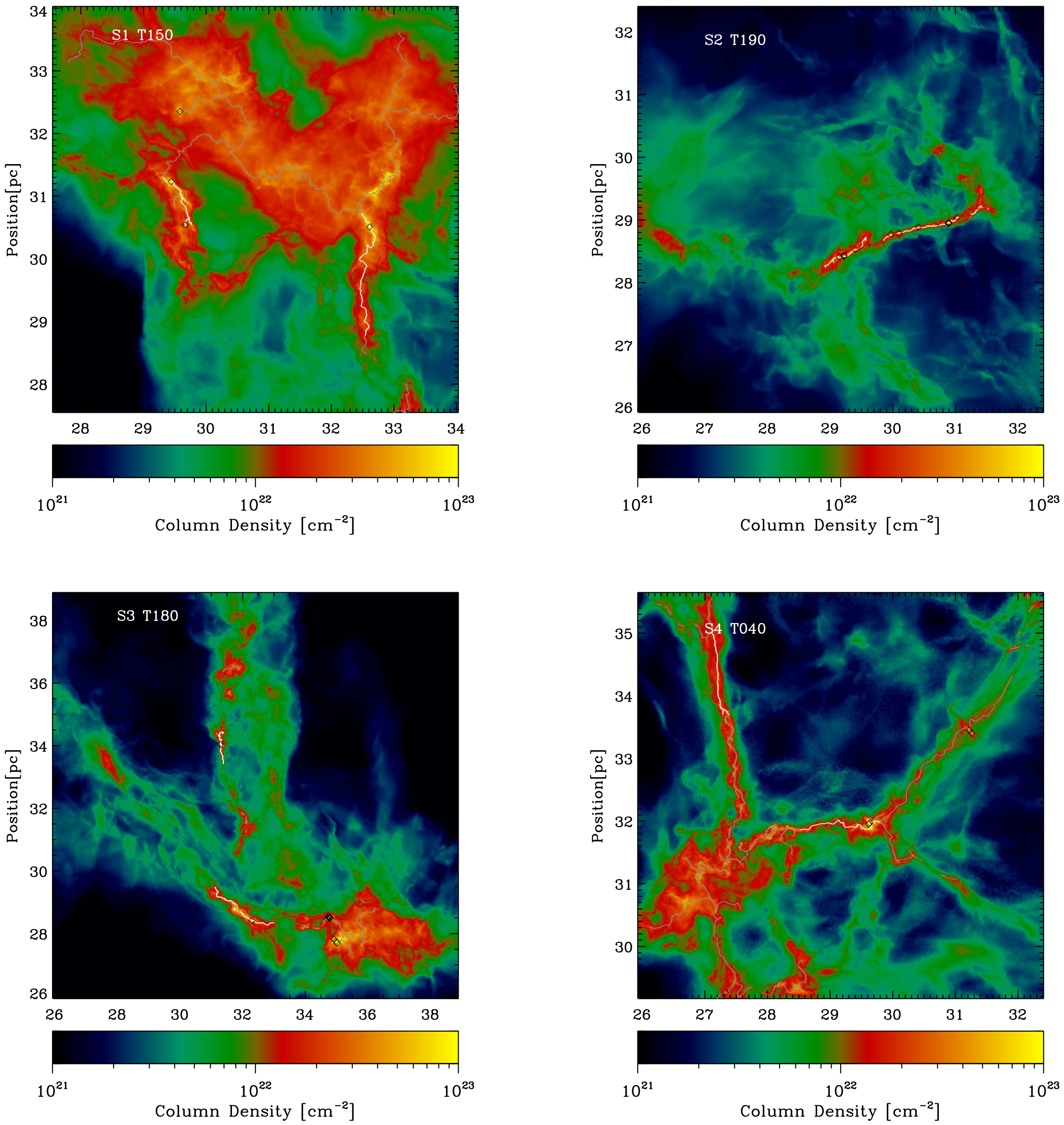
next steps:

studying details of ISM morphology and star formation in dedicated zoom-in simulation

example:

giant molecular cloud complex (~10^6 M$_\odot$) viewed in the plane of the disk.

zoom-in on filaments



next steps:

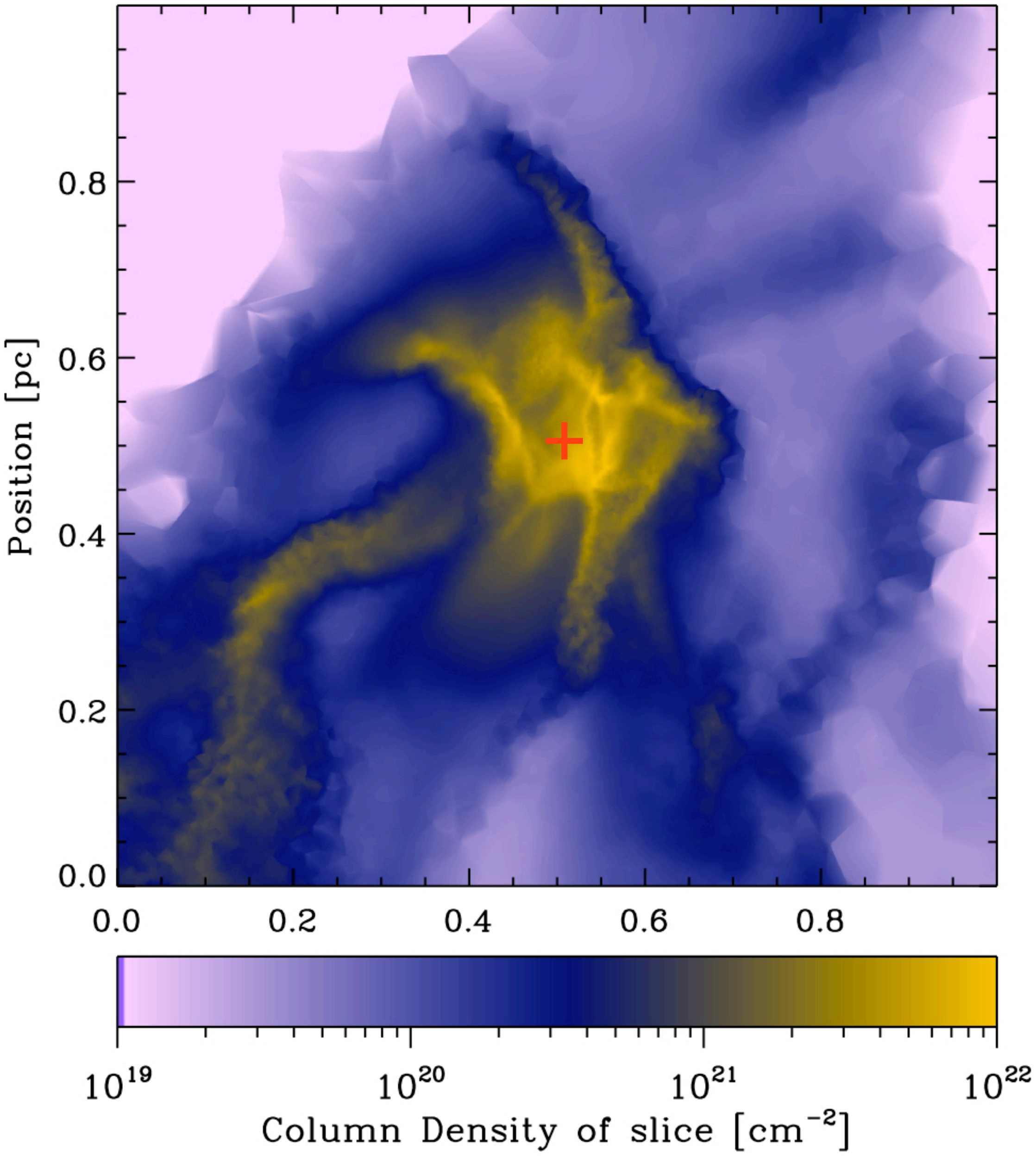
studying details of ISM morphology and star formation in dedicated zoom-in simulation *(resolution ≲2000 AU, with full chemistry)*

analysis:

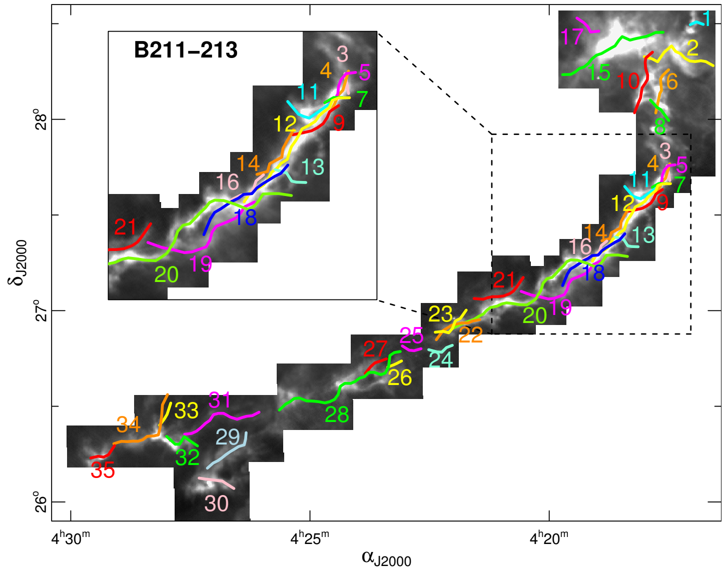
- morphology
- velocity
- chemistry
- observations (dust maps for Herschel, CO, N_2H+, HCN, etc. for line obs.)

Smith et al. (2014, in preparation)

walk along the filament



- walking along the filament exhibits complex 3D structure that is now (fully) seen in projected density
- is this similar to the filament fibers proposed by Hacar et al. (2013, A&A, 554, 55)



THE ASTROPHYSICAL JOURNAL, 681:365–374, 2008 July 1

ON THE CONSTANCY OF THE CHARACTERISTIC MASS OF YOUNG STARS

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Received 2008 February 15; accepted 2008 March 31

ABSTRACT

The characteristic mass M_c in the stellar initial mass function (IMF) is about constant for most star-forming regions. Numerical simulations consistently show a proportionality between M_c and the thermal Jeans mass $M_{\rm J}$ at the time of cloud fragmentation, but no models have explained how it can be the same in diverse conditions. Here we show that $M_{\rm J}$ depends weakly on density, temperature, metallicity, and radiation field in three environments: the dense cores where stars form, larger star-forming regions ranging from GMCs to galactic disks, and the interiors of H II regions and super star clusters. In dense cores, the quantity $T^{3/2}n^{-1/2}$ that appears in $M_{\rm J}$ scales with core density as $n^{0.25}$ or with radiation density as $U^{0.1}$ at the density where dust and gas come into thermal equilibrium. On larger scales, this quantity varies with ambient density as $n^{-0.05}$ and ambient radiation field as $U^{-0.033}$ when the Kennicutt-Schmidt law of star formation determines $U(n)$. In super star clusters with ionization and compression of prestellar globules, $M_{\rm J}$ varies as the 0.13 power of the cluster column density. These weak dependencies on n, U, and column density imply that most environmental variations affect the thermal Jeans mass by at most a factor of $\sim$2. Cosmological increases in $M_{\rm J}$, which have been suggested by observations, may be explained if the star formation efficiency is systematically higher at high redshift for a given density and pressure, if dust grains are smaller at lower metallicity, and so hotter for a given radiation field, or if small prestellar cores are more severely ionized in extreme starburst conditions.

Subject headings: dust, extinction — stars: formation — stars: luminosity function, mass function

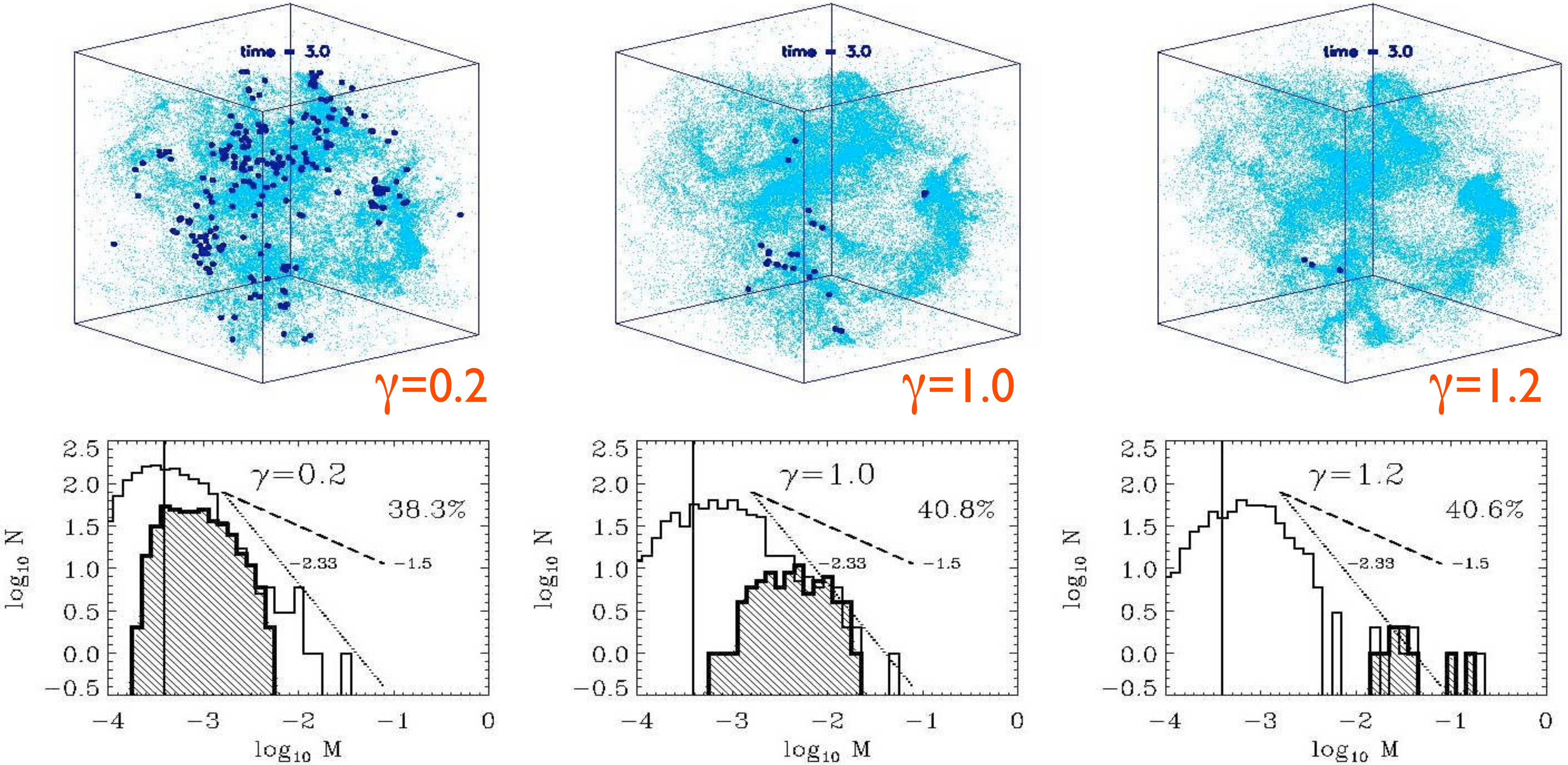
thermodynamics & fragmentation

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



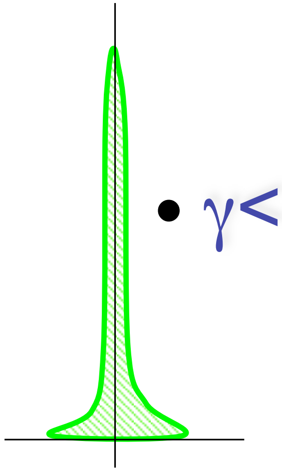
for $\gamma<1$ fragmentation is enhanced → *cluster of low-mass stars*
for $\gamma>1$ it is suppressed → *isolated massive stars*

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

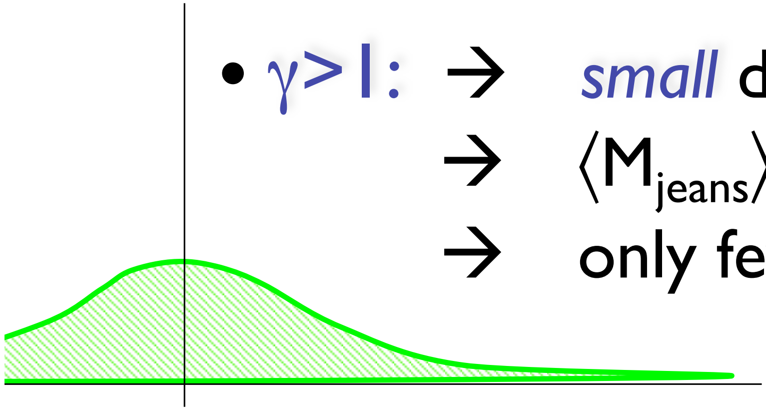
how does that work?

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

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

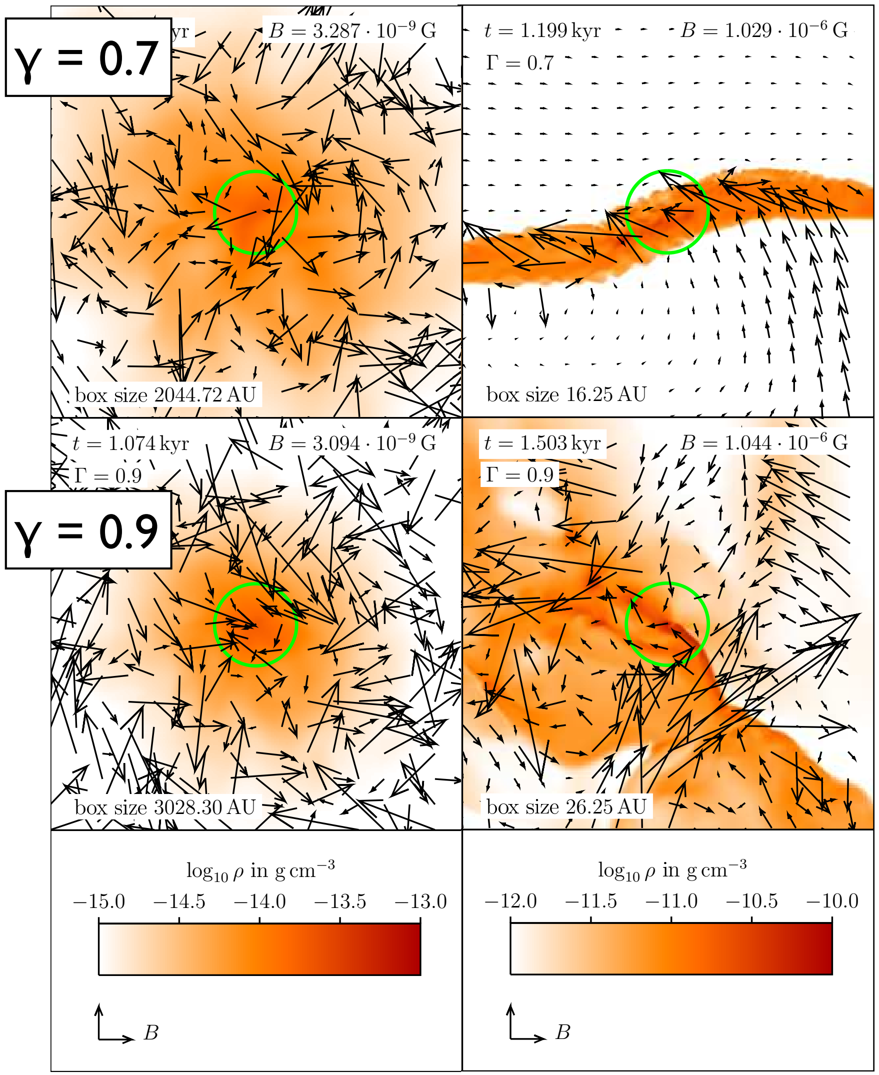


- $\gamma<1$: → *large* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ becomes small
  → number of fluctuations with $M > M_{jeans}$ is large

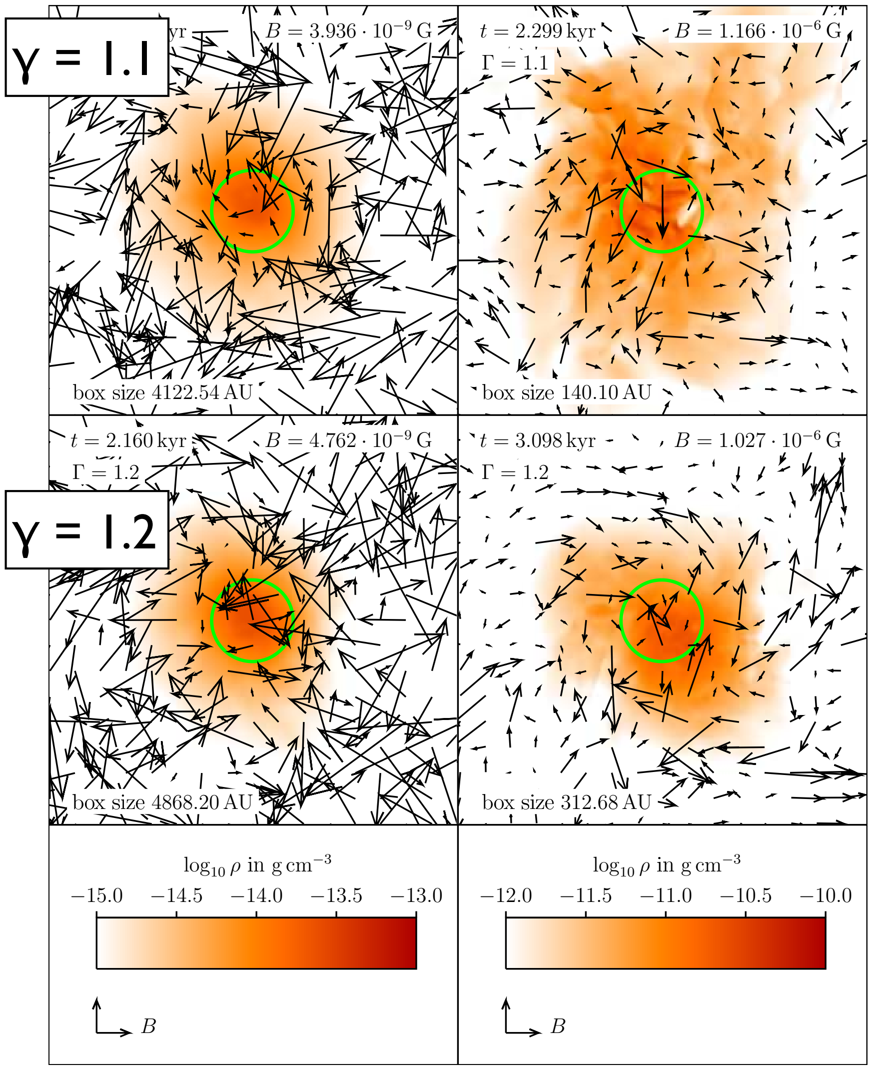


- $\gamma>1$: → *small* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ is large
  → only few and massive clumps exceed M_{jeans}

gas cools when compressed



gas heats up when compressed

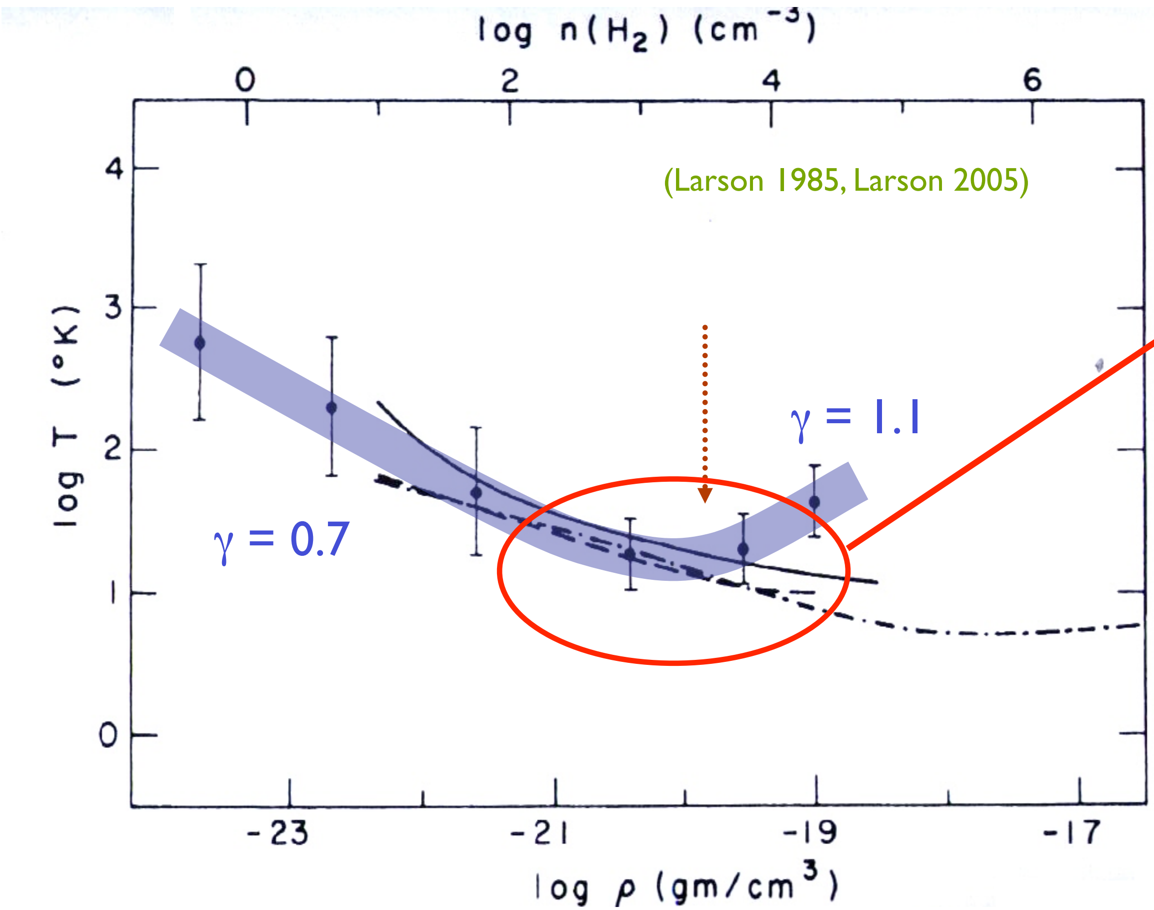


— filaments form easier in a cooling regime (gamma < 1) as the pressure drops when the density increases

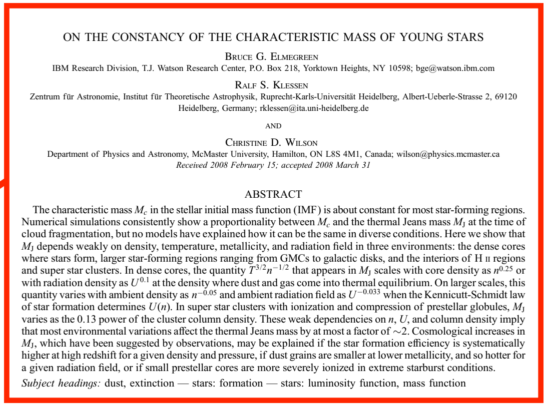
— relevance for Herschel filaments?

Peters et al. (2012, ApJ, 760, L28)

SF in present-day IMF



(Larson 1985, Larson 2005)



ON THE CONSTANCY OF THE CHARACTERISTIC MASS OF YOUNG STARS

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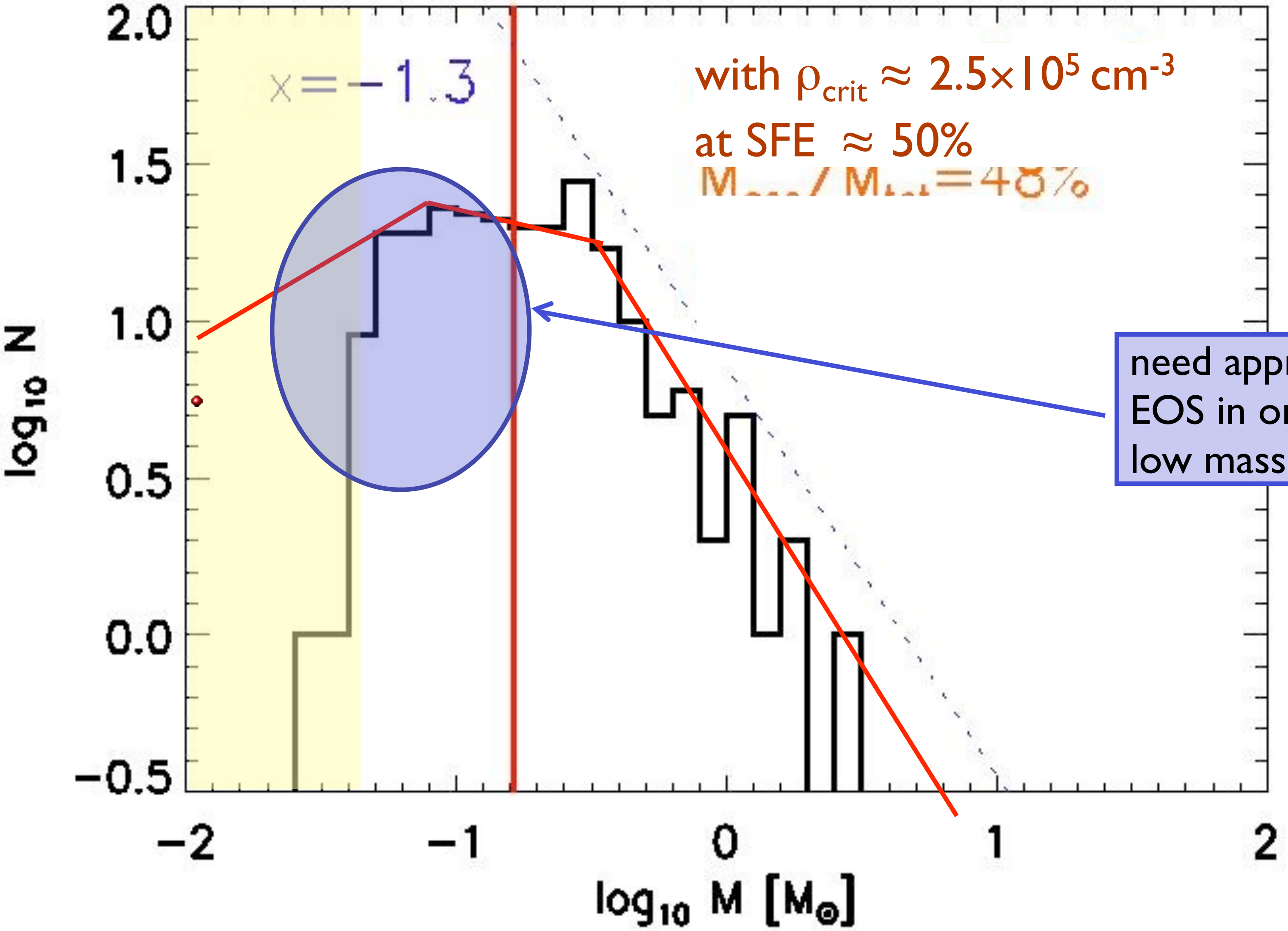
ABSTRACT

The characteristic mass M_c in the stellar initial mass function (IMF) is about constant for most star-forming regions. Numerical simulations consistently show a proportionality between M_c and the thermal Jeans mass $M_{\rm J}$ at the time of cloud fragmentation, but no models have explained how it can be the same in diverse conditions. Here we show that $M_{\rm J}$ depends weakly on density, temperature, metallicity, and radiation field in three environments: the dense cores where stars form, larger star-forming regions ranging from GMCs to galactic disks, and the interiors of H II regions and super star clusters. In dense cores, the quantity $T^{3/2}n^{-1/2}$ that appears in $M_{\rm J}$ scales with core density as $n^{0.25}$ or with radiation density as $U^{0.1}$ at the density where dust and gas come into thermal equilibrium. On larger scales, this quantity varies with ambient density as $n^{-0.05}$ and ambient radiation field as $U^{-0.033}$ when the Kennicutt-Schmidt law of star formation determines $U(n)$. In super star clusters with ionization and compression of prestellar globules, $M_{\rm J}$ varies as the 0.13 power of the cluster column density. These weak dependencies on n, U, and column density imply that most environmental variations affect the thermal Jeans mass by at most a factor of $\sim$2. Cosmological increases in $M_{\rm J}$, which have been suggested by observations, may be explained if the star formation efficiency is systematically higher at high redshift for a given density and pressure, if dust grains are smaller at lower metallicity, and so hotter for a given radiation field, or if small prestellar cores are more severely ionized in extreme starburst conditions.

Subject headings: dust, extinction — stars: formation — stars: luminosity function, mass function

(Elmegreen et al. 2008)

SF in present-day IMF



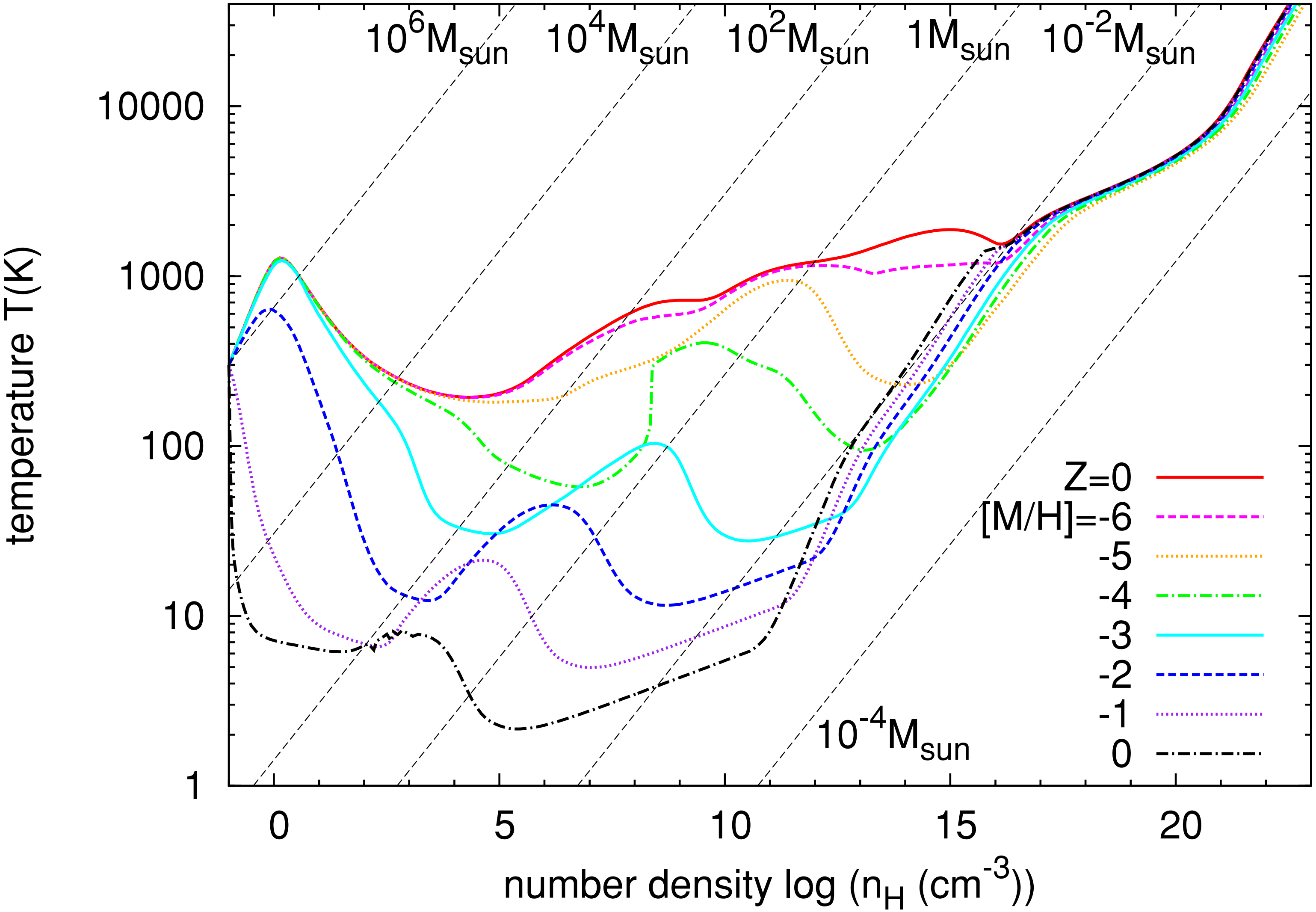
with $\rho_{crit} \approx 2.5\times10^5$ cm^{-3}

at SFE ≈ 50%

need appropriate EOS in order to get low mass IMF right

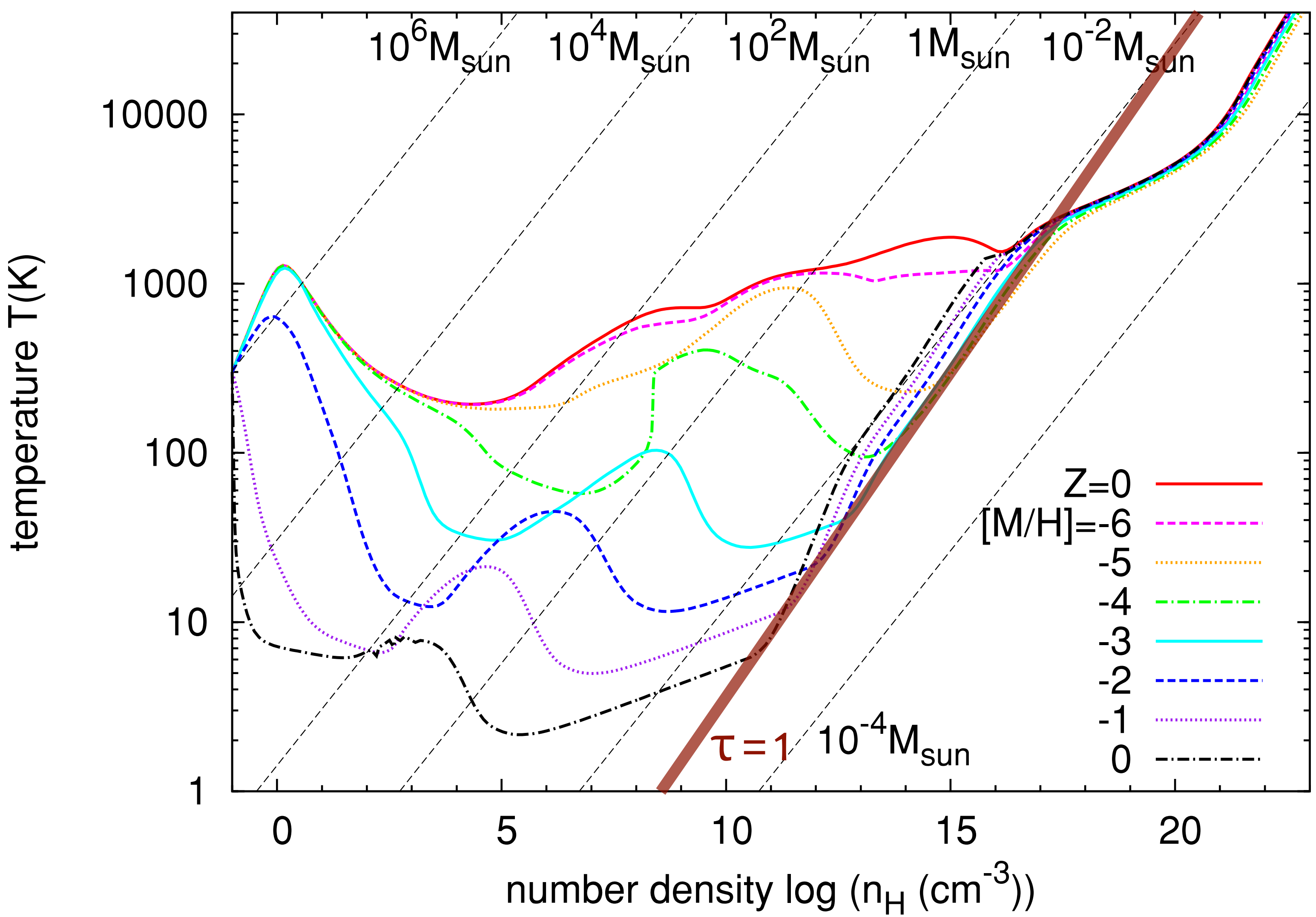
(Jappsen et al. 2005, A&A, 435, 611)

EOS as function of metallicity



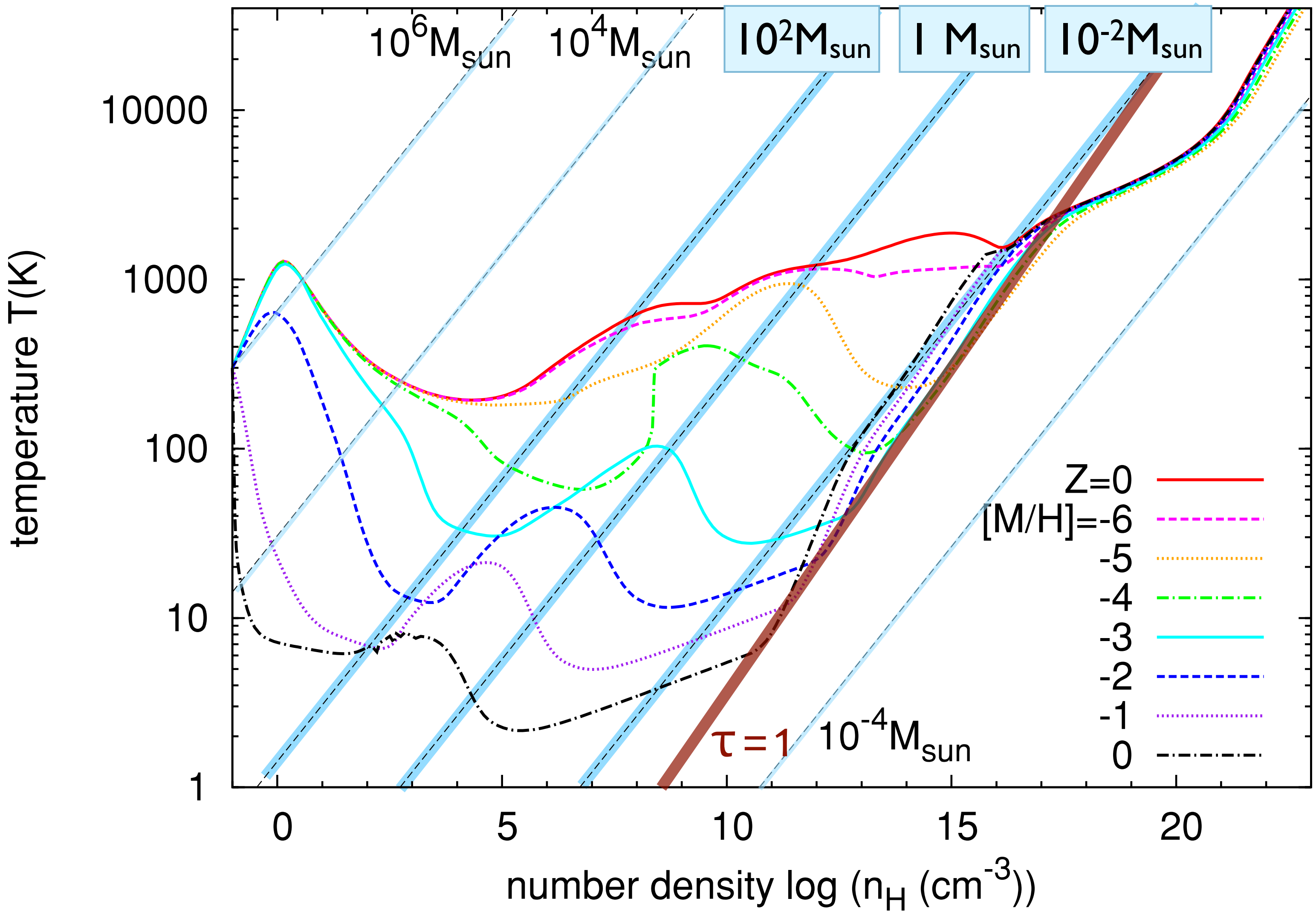
(Omukai et al. 2005, 2010)

EOS as function of metallicity



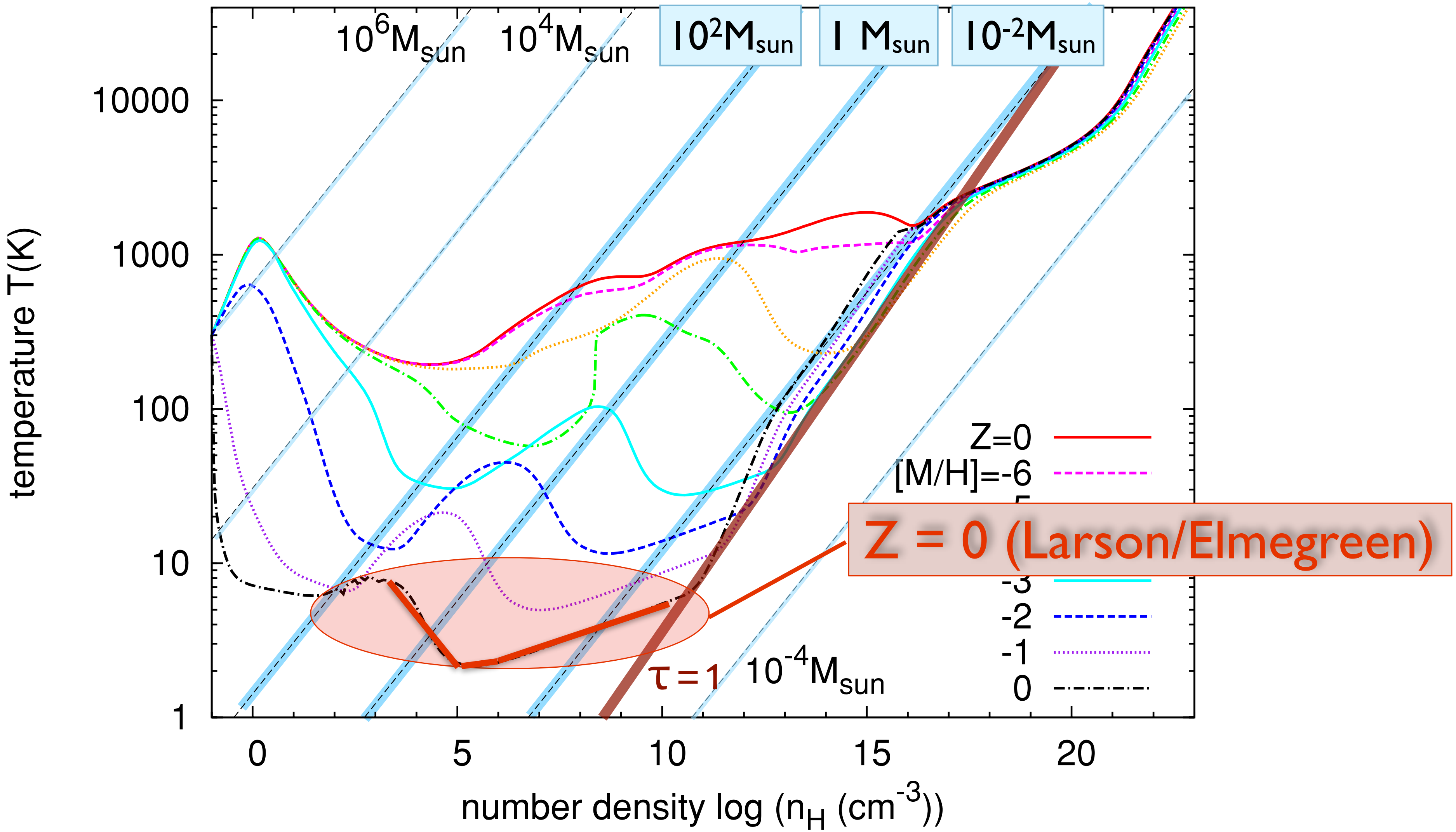
(Omukai et al. 2005, 2010)

EOS as function of metallicity



(Omukai et al. 2005, 2010)

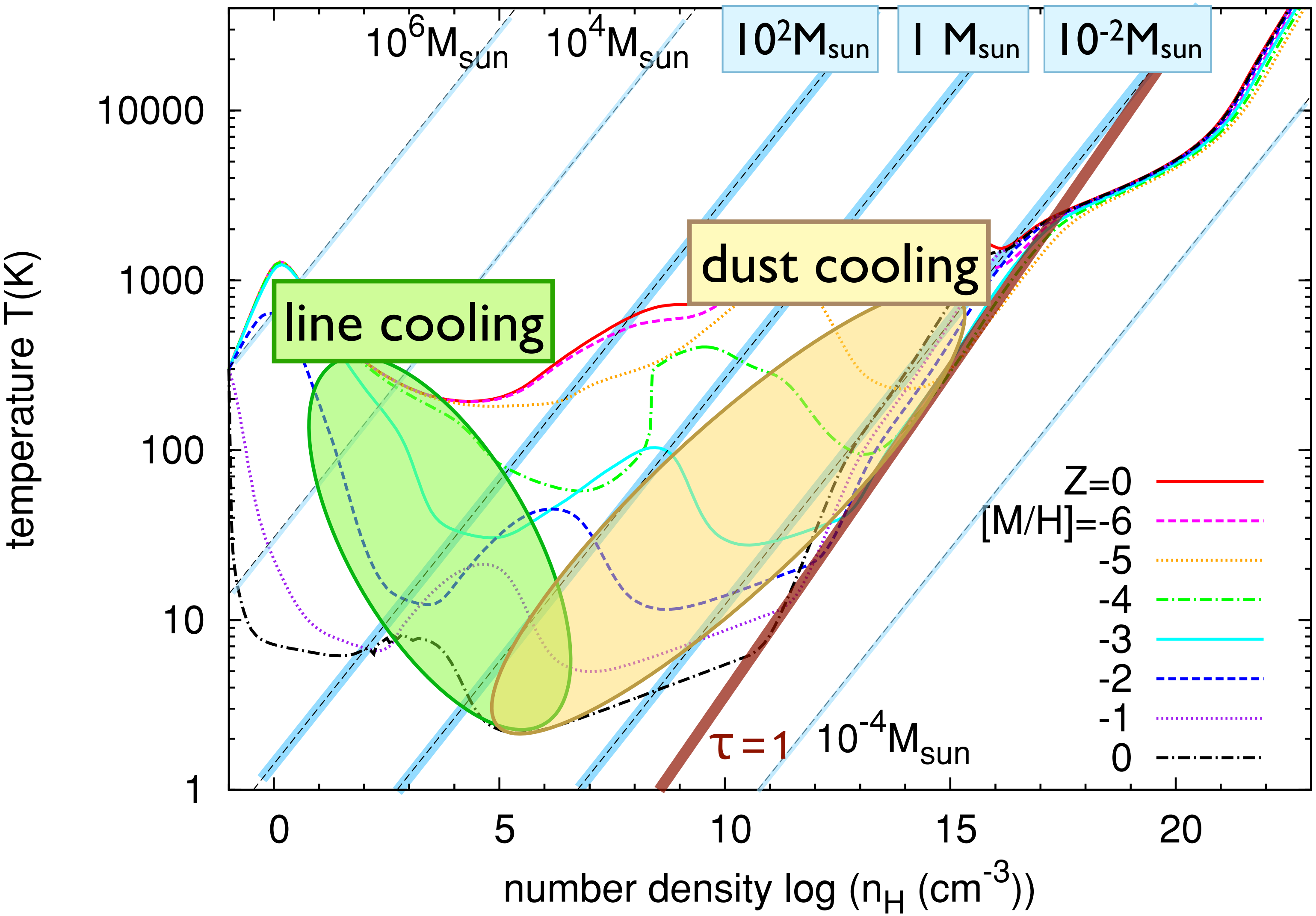
EOS as function of metallicity



Z = 0 (Larson/Elmegreen)

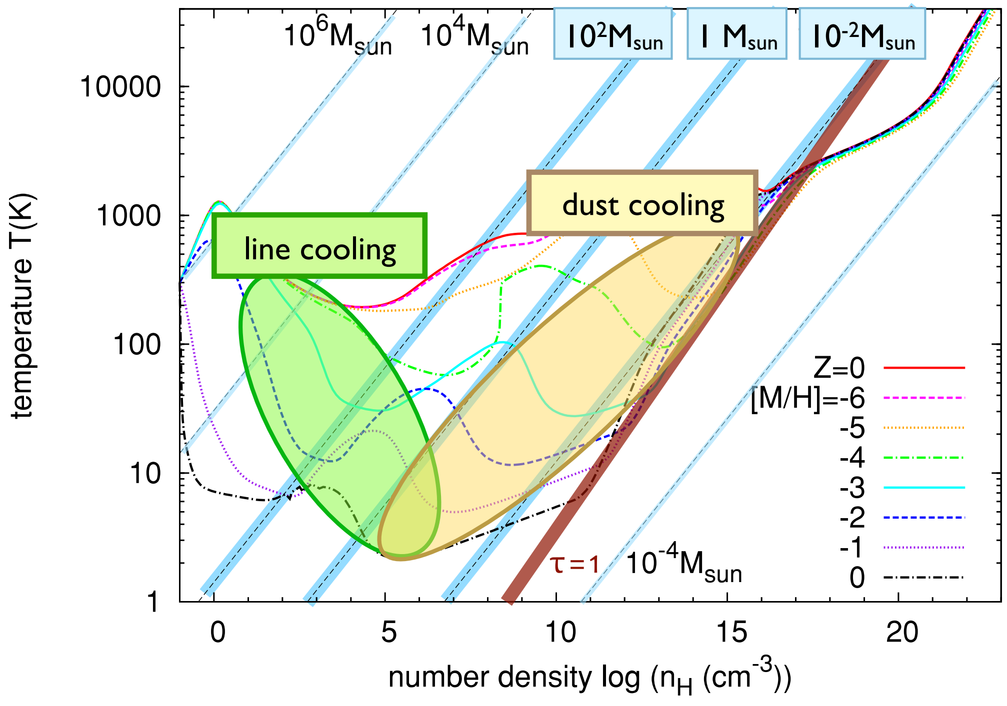
(Omukai et al. 2005, 2010)

EOS as function of metallicity



(Omukai et al. 2005, 2010)

transition: Pop III to Pop II.5



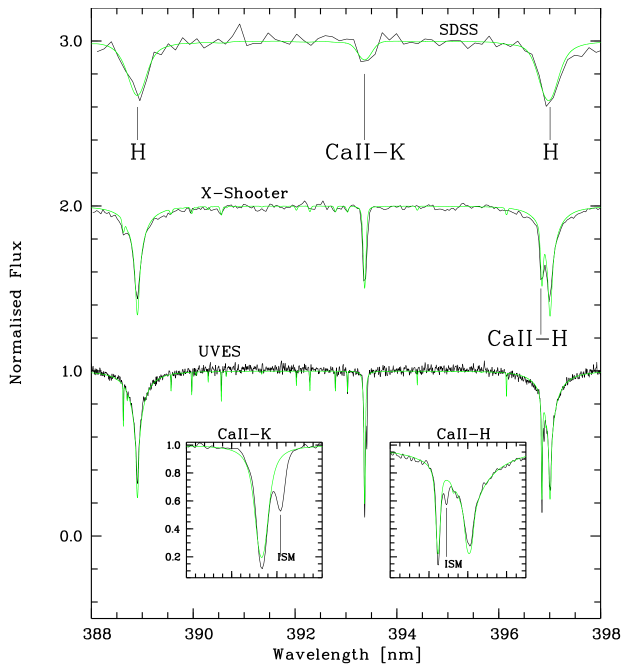
two competing models:

- cooling due to atomic fine-structure lines ($Z > 10^{-3.5}\ Z_{sun}$)
- cooling due to coupling between gas and dust ($Z > 10^{-5\ldots-6}\ Z_{sun}$)

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

(Omukai et al. 2005, 2010)

transition: Pop III to Pop II.5



SDSS J1029151+172927

- is first ultra metal-poor star with Z ~ $10^{-4.5}$ Z_{sun} for all metals seen (Fe, C, N, etc.)
  [see Caffau et al. 2011]
- this is in regime, where metal-lines cannot provide cooling
  [e.g. Schneider et al. 2011, 2012, Klessen et al. 2012]

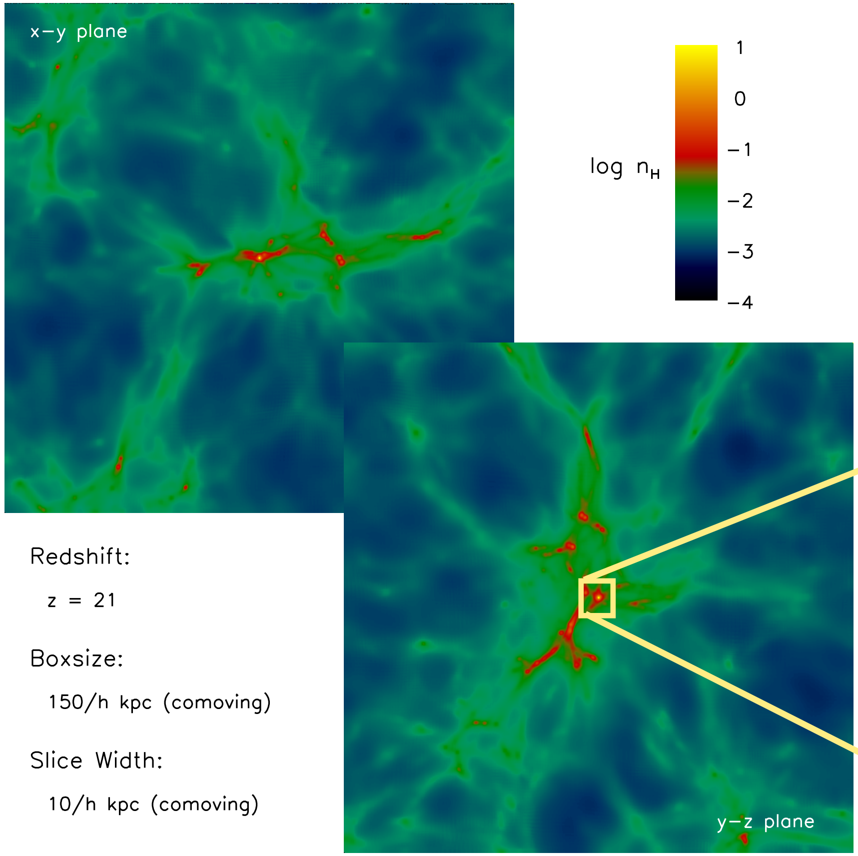
Element	$[X/H]_{1D}$	+3Dcor.	+NLTE cor.	+ 3D cor + NLTE cor	N lines	S_H	$A(X)_{\odot}$
C	≤ −3.8	≤ −4.5			G-band		8.50
N	≤ −4.1	≤ −5.0			NH-band		7.86
Mg I	−4.71 ± 0.11	−4.68 ± 0.11	−4.52 ± 0.11	−4.49 ± 0.12	5	0.1	7.54
Si I	−4.27	−4.30	−3.93	−3.96	1	0.1	7.52
Ca I	−4.72	−4.82	−4.44	−4.54	1	0.1	6.33
Ca II	−4.81 ± 0.11	−4.93 ± 0.03	−5.02 ± 0.02	−5.15 ± 0.09	3	0.1	6.33
Ti II	−4.75 ± 0.18	−4.83 ± 0.16	−4.76 ± 0.18	−4.84 ± 0.16	6	1.0	4.90
Fe I	−4.73 ± 0.13	−5.02 ± 0.10	−4.60 ± 0.13	−4.89 ± 0.10	43	1.0	7.52
Ni I	−4.55 ± 0.14	−4.90 ± 0.11			10		6.23
Sr II	≤ −5.10	≤ −5.25	≤ −4.94	≤ −5.09	1	0.01	2.92

- TOPoS: ESO large program to find more of these stars (120h x-shooter, 30h UVES) [PI E. Caffau]
- first paper out, more come soon . . .

(Caffau et al. 2011, 2012)

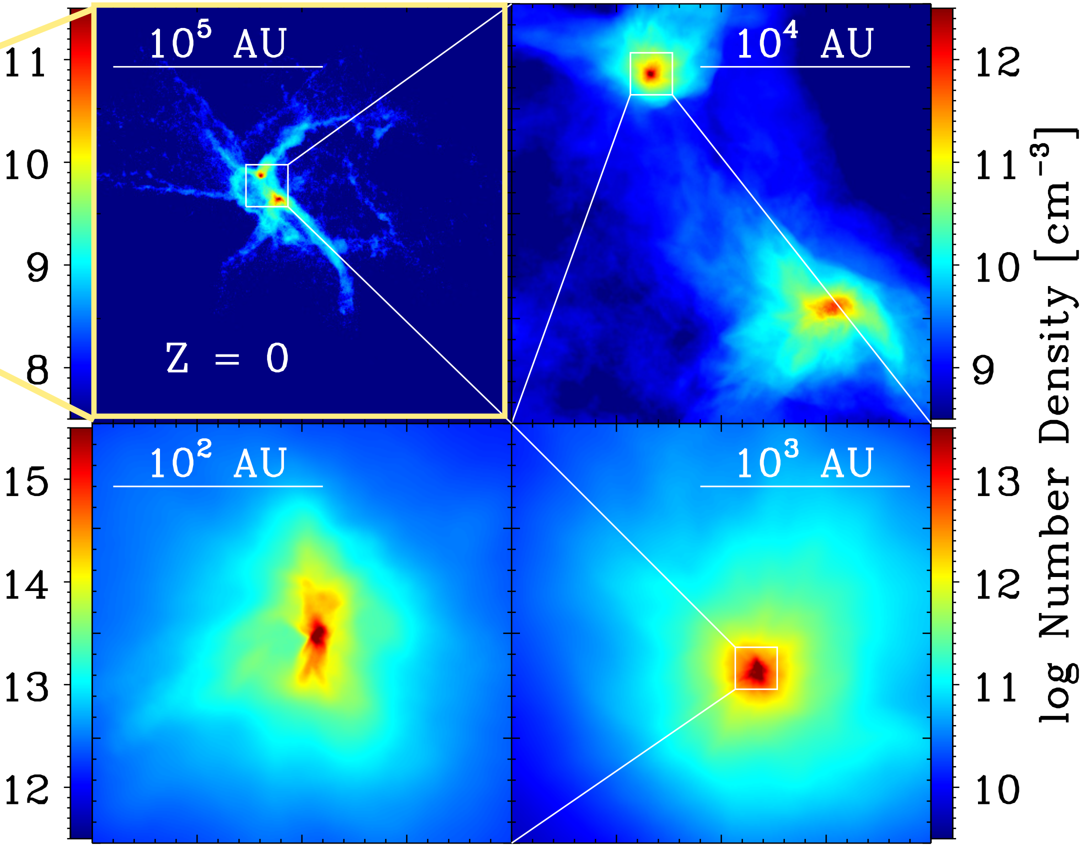
(Schneider et al. 2011,2012, Klessen et al. 2012)

modeling the formation of the first/second stares



(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)

modeling the formation of the first/second stares

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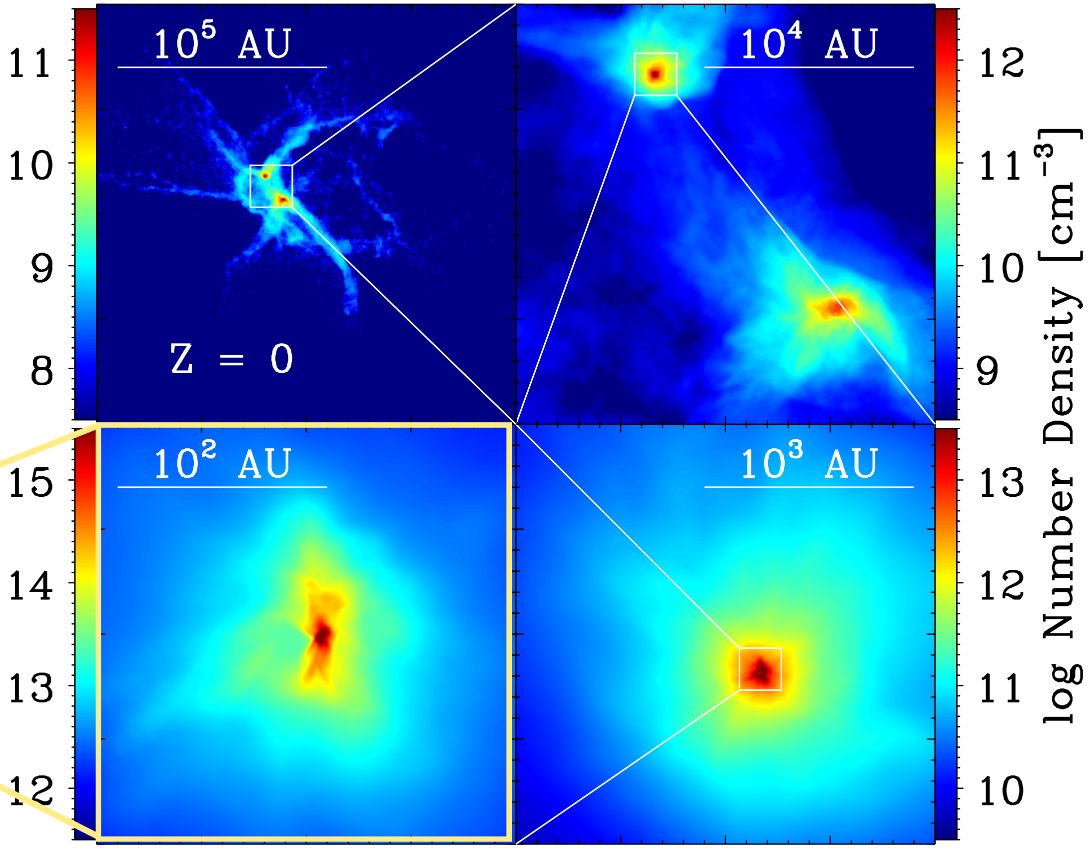
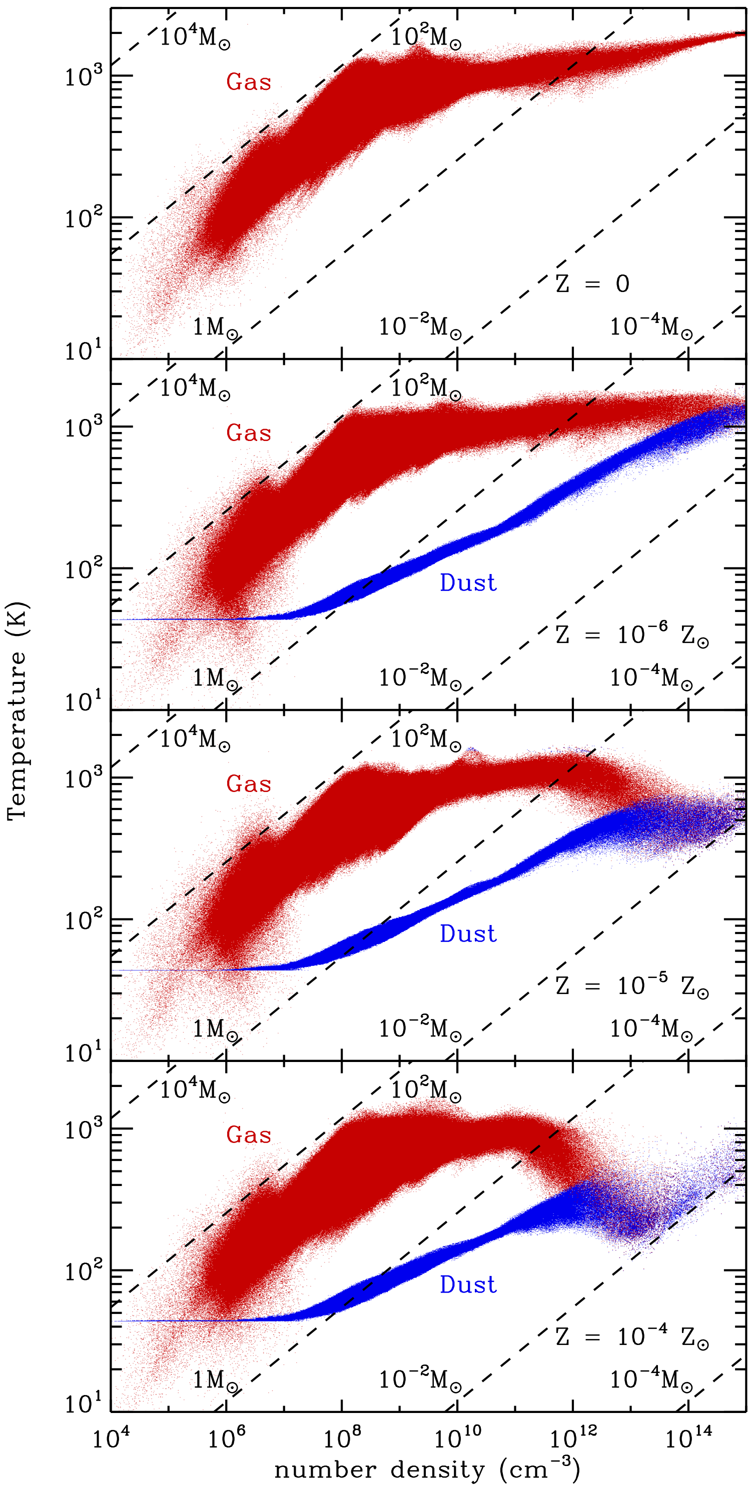


what is the time evolution of accretion disk around first star to form?

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

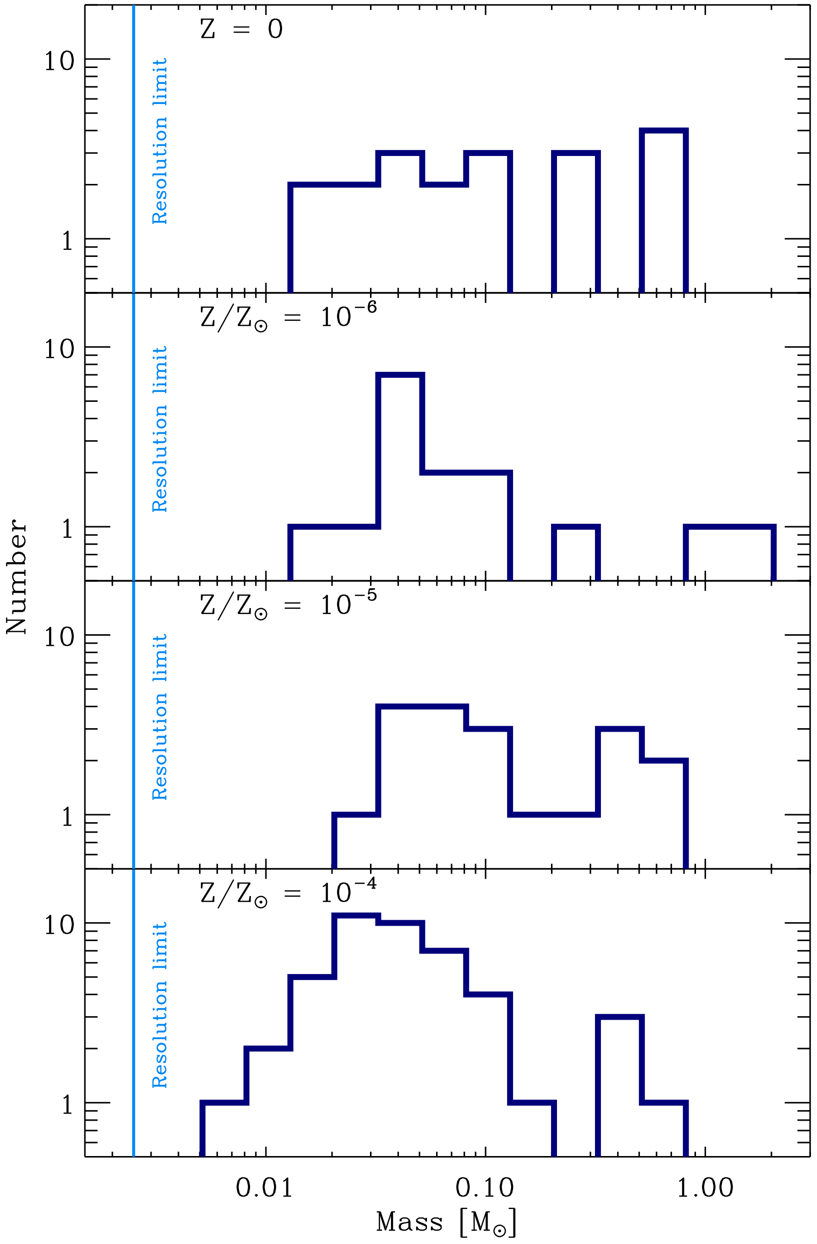


[M/H] = -ininity

[M/H] = -6

[M/H] = -5

[M/H] = -4

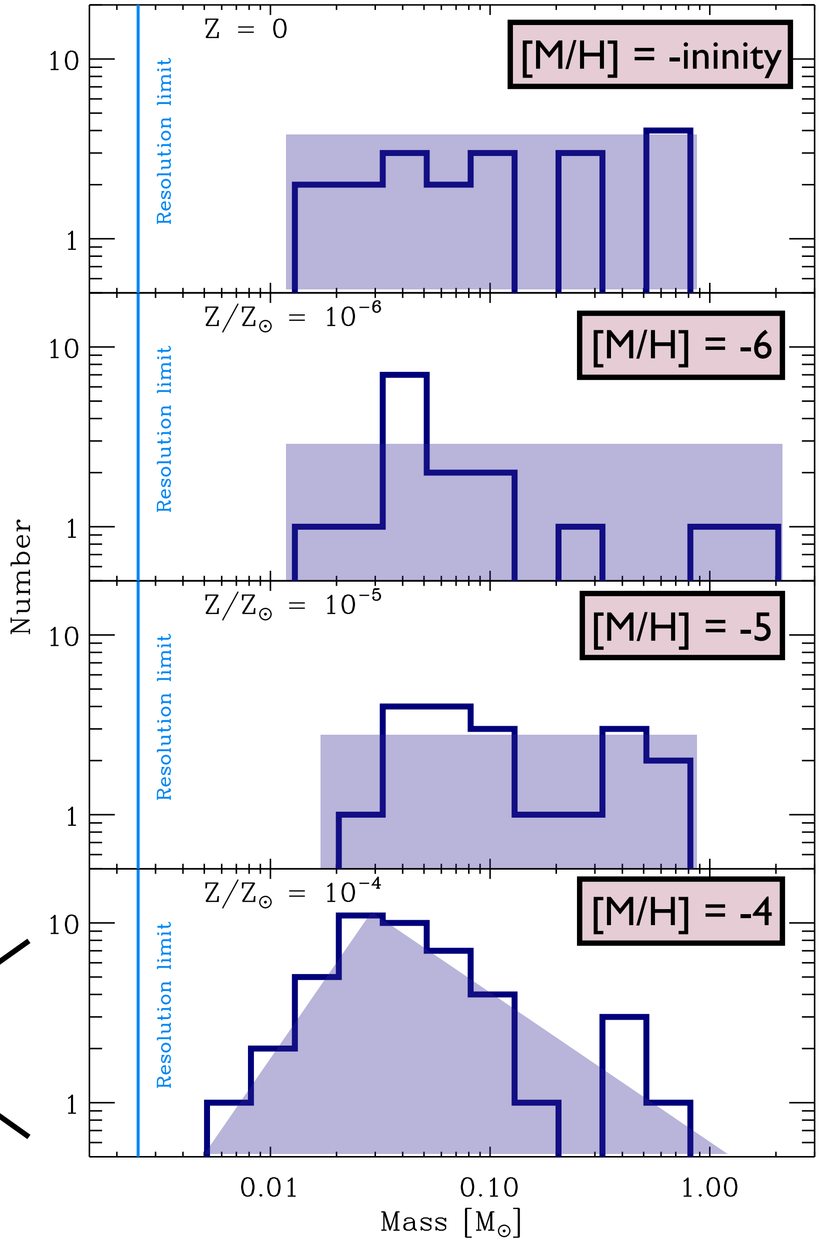


red : gas
blue: dust

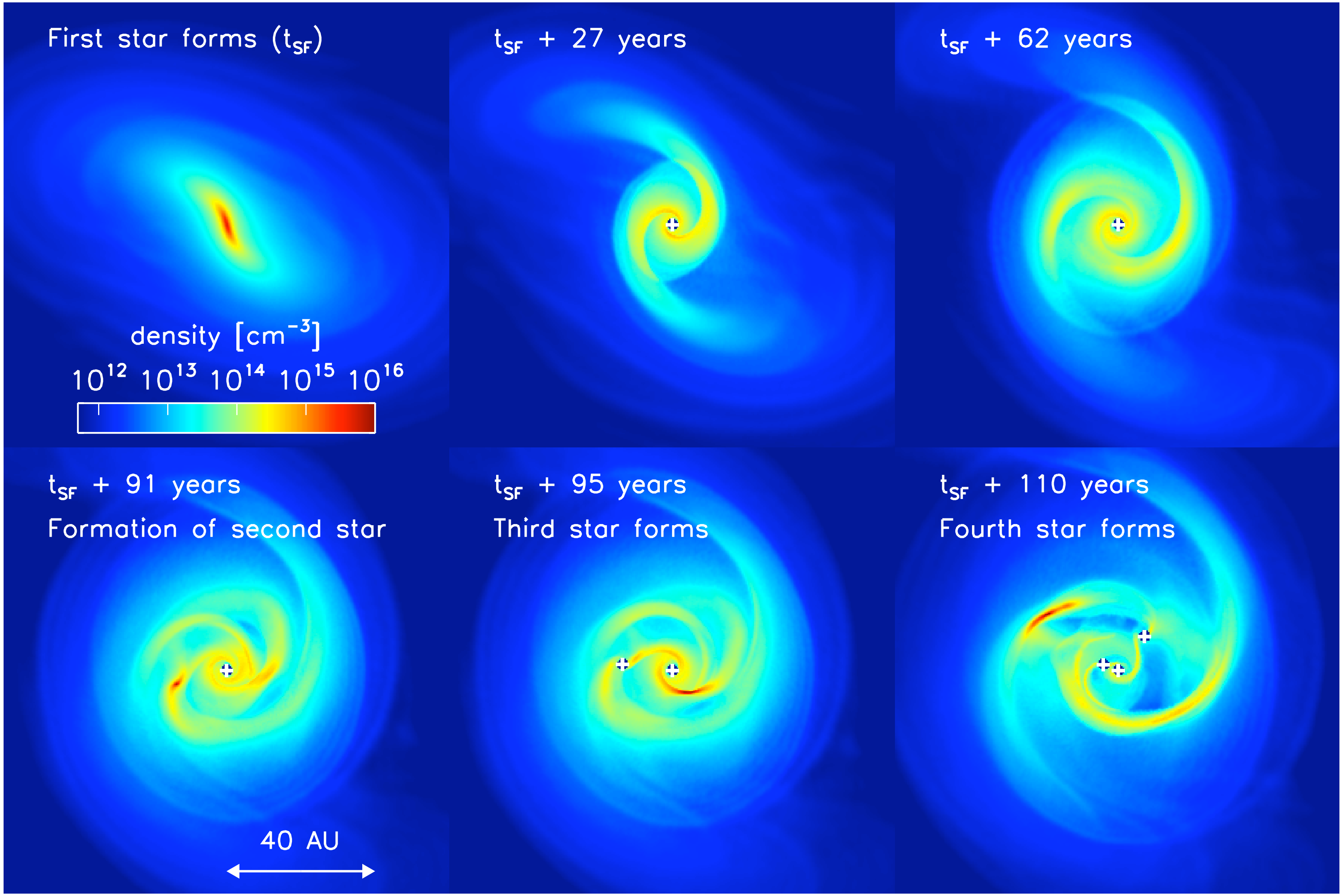
Dopcke et al., 2012, submitted to ApJ, arXiv:1203.6842) hints for differences in mass spectrum

disk fragmentation mode

gravoturbulent fragmentation mode



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

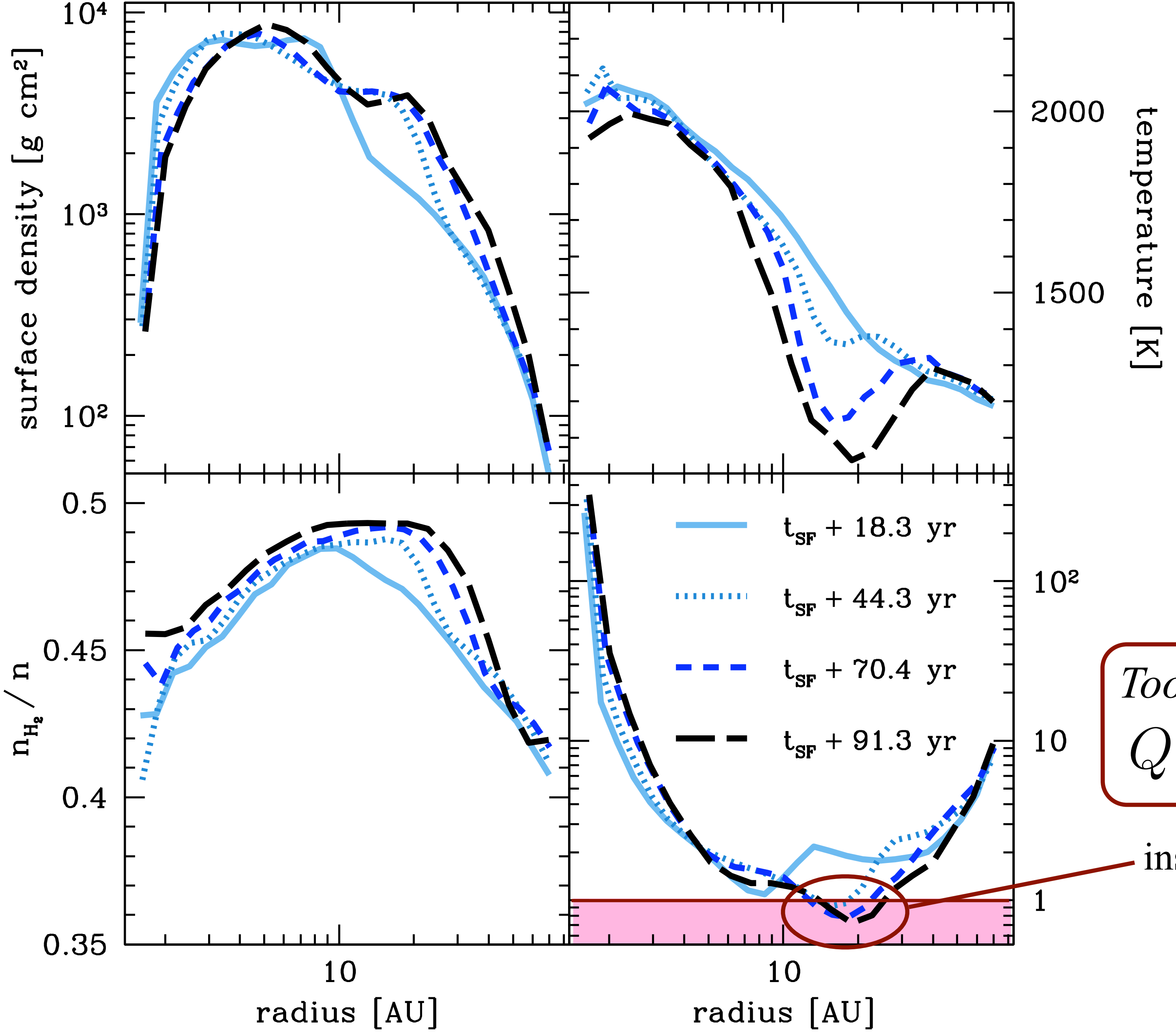


detailed look at accretion disk

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:

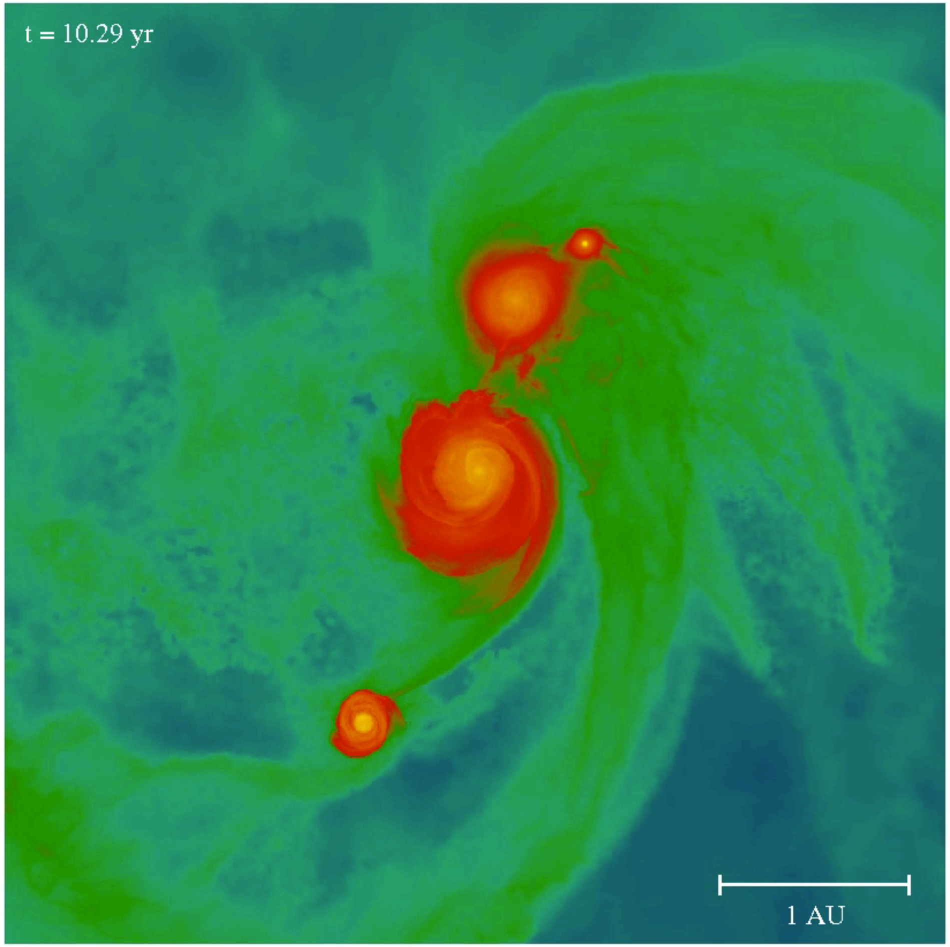
$$Q = c_s \kappa / \pi G \Sigma$$

instability for $Q<1$

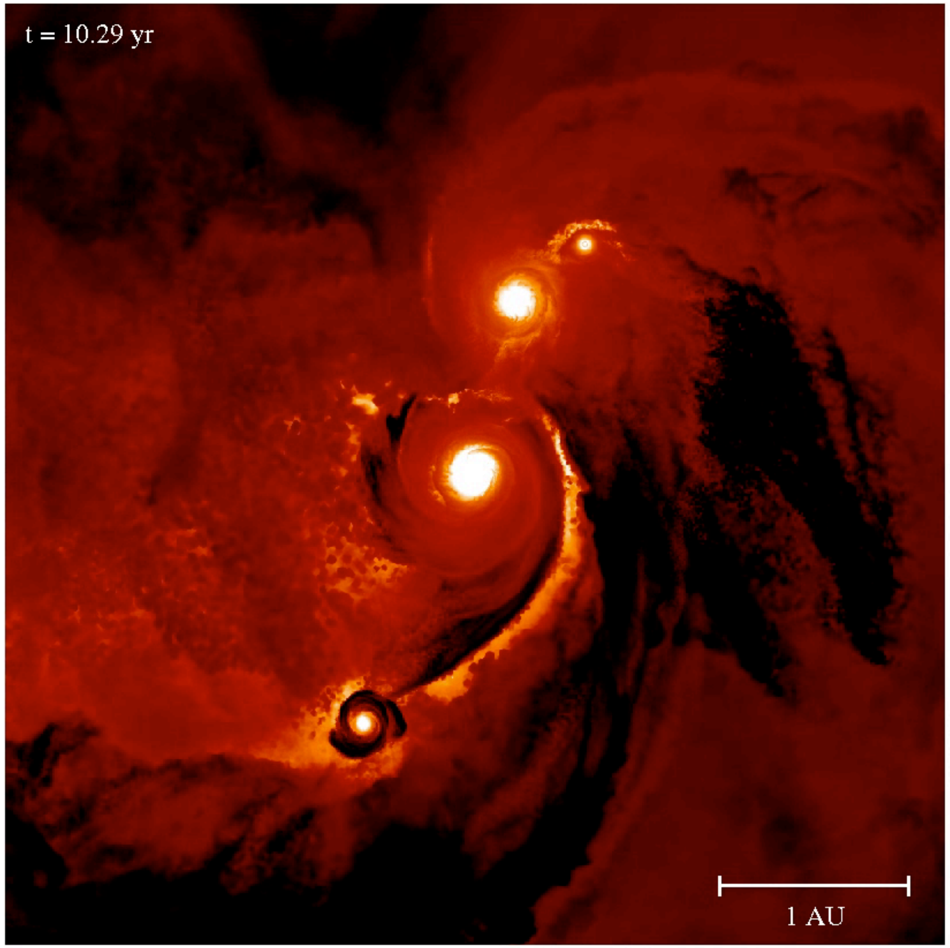
(Clark et al. 2011b, Science, 331, 1040)

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

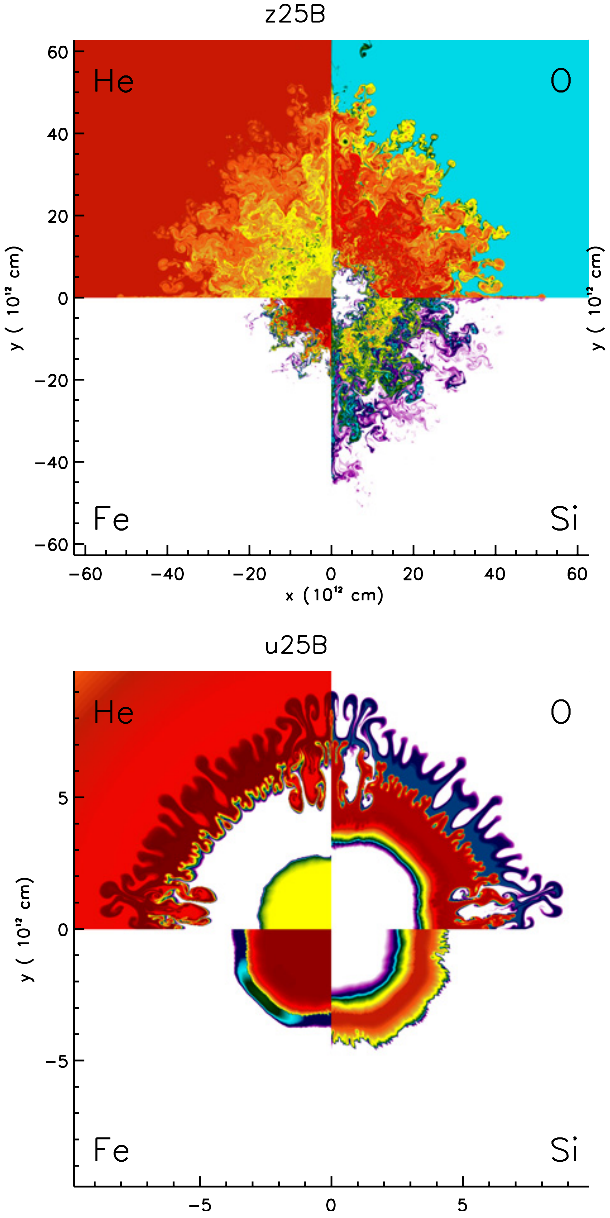


temperature

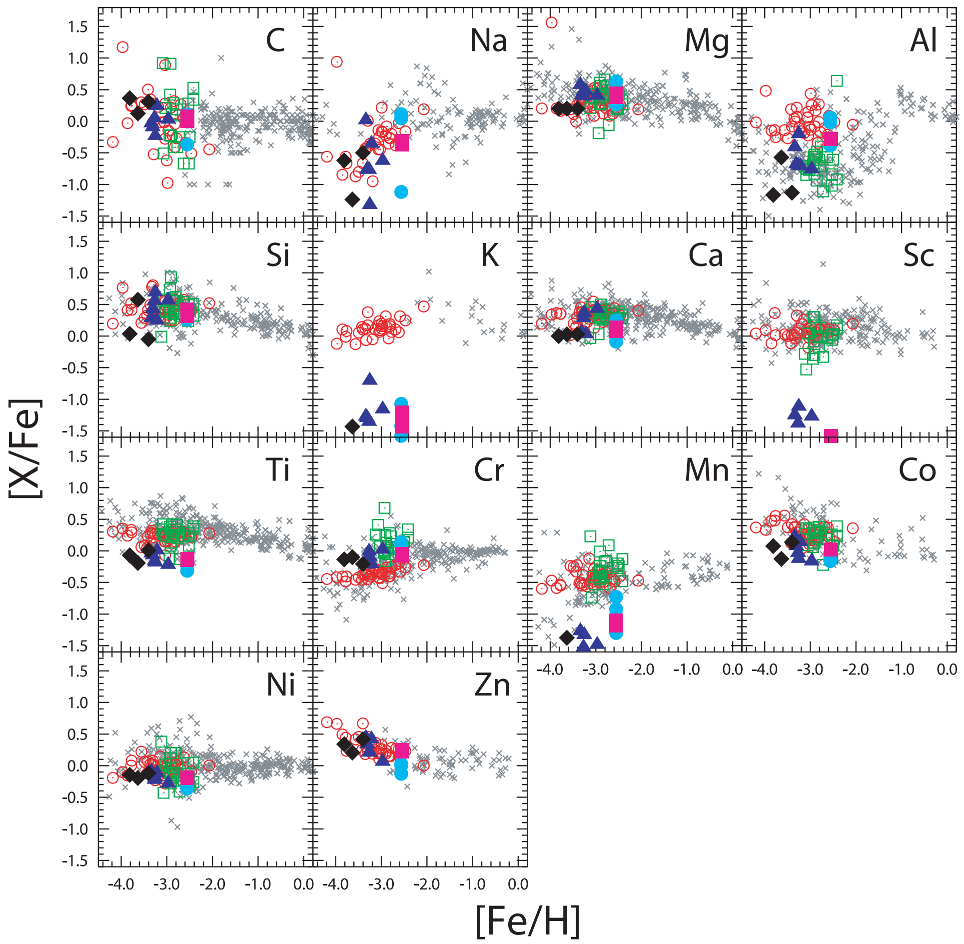
(Greif et al., 2012, MNRAS, 424, 399)

expected mass spectrum

- *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)

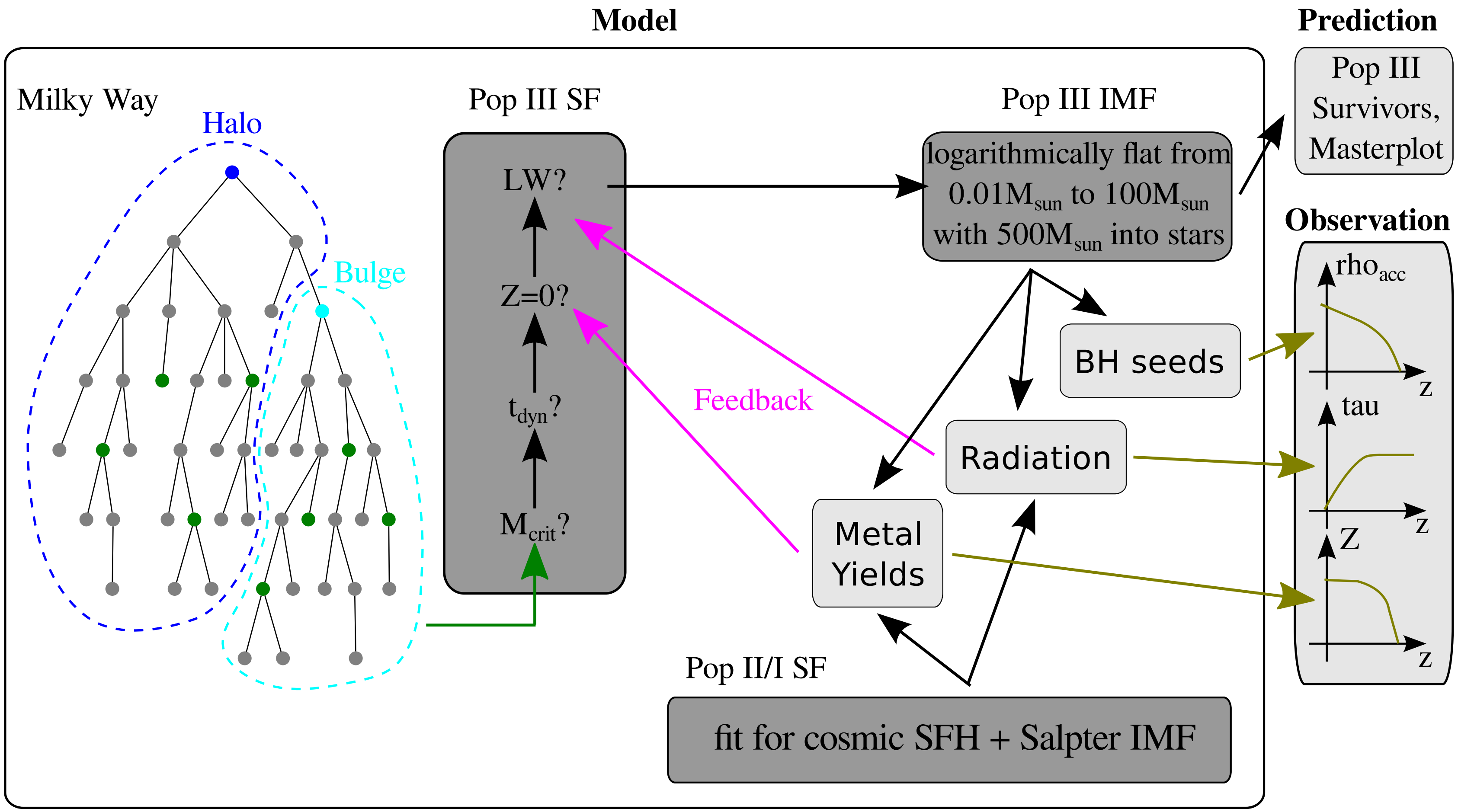


(Tominaga et al. 2007)

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)

predicting number of Pop III stars



Model

Prediction

Milky Way

Halo

Bulge

Pop III SF

LW?

Z=0?

t_{dyn}?

M_{crit}?

Pop III IMF

logarithmically flat from $0.01M_{sun}$ to $100M_{sun}$ with $500M_{sun}$ into stars

Feedback

BH seeds

Radiation

Metal Yields

Pop II/I SF

fit for cosmic SFH + Salpter IMF

Pop III Survivors, Masterplot

Observation

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

Hartwig, Bromm, Klessen (2014, in prep.)

predicting number of Pop III stars

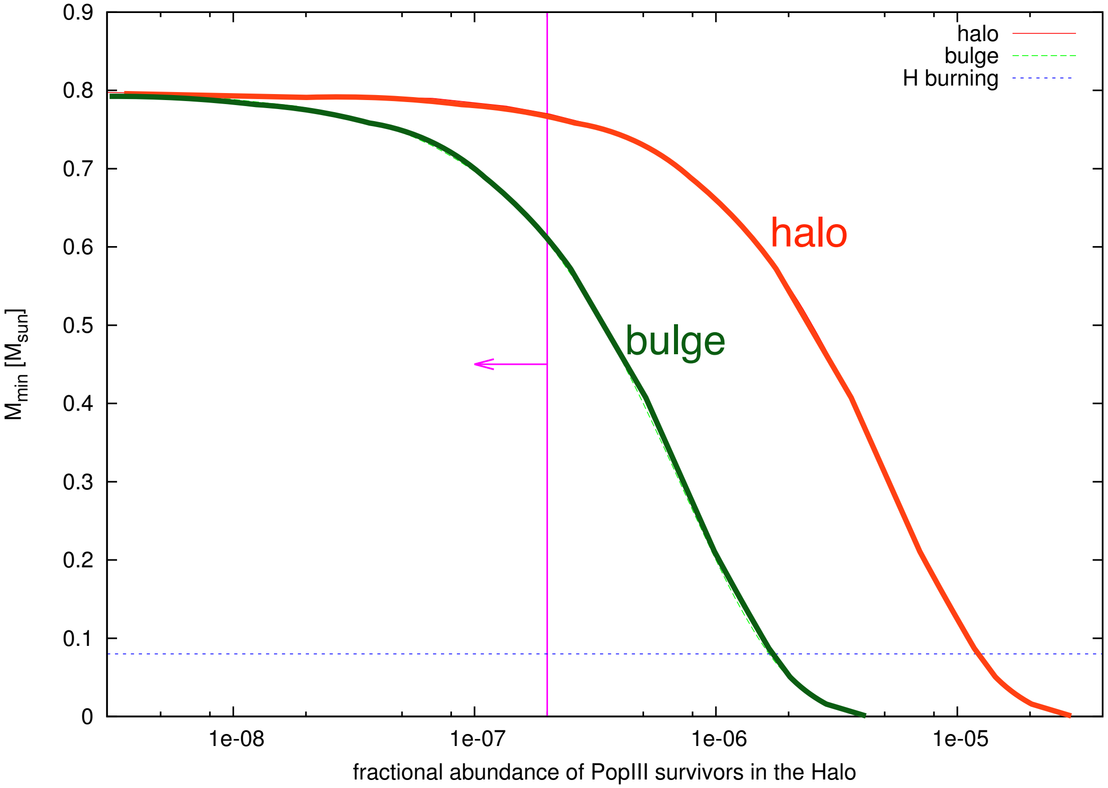


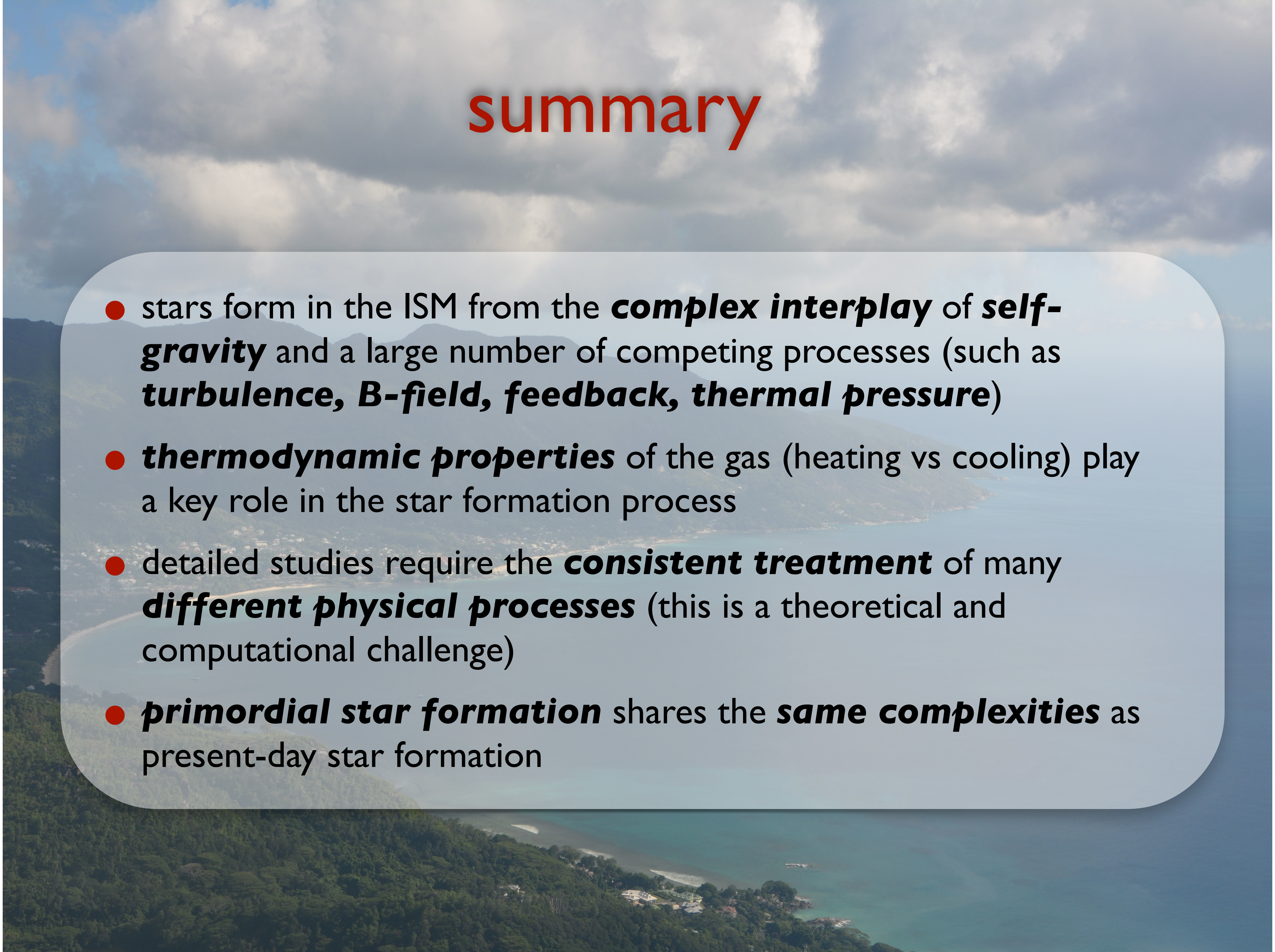
Figure 9: Expected lower mass of the primordial IMF as a function of the fractional abundance of Pop III survivors. The purple line indicates an upper limit for the fractional abundance based on current observational sample sizes. Whereas this sample only covers the halo and is therefore not valid for the bulge. Bulge values are wrong (see above)!

Hartwig, Bromm, Klessen (2014, in prep.)

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)



summary

- stars form in the ISM 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 processes*** (this is a theoretical and computational challenge)
- ***primordial star formation*** shares the ***same complexities*** as present-day star formation

thanks to ...

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

Christian Baczynski, Erik Bertram, Frank Bigiel, Paul Clark, Volker Gaibler, Simon Glover, Dimitrious Gouliermis, Tilman Hartwig, Lukas Konstandin, Mei Sasaki, Jennifer Schober, Rahul Shetty, Rowan Smith, László Szűcs

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... many collaborators abroad!

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Interstellar Medium

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Wir stiften Zukunft

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