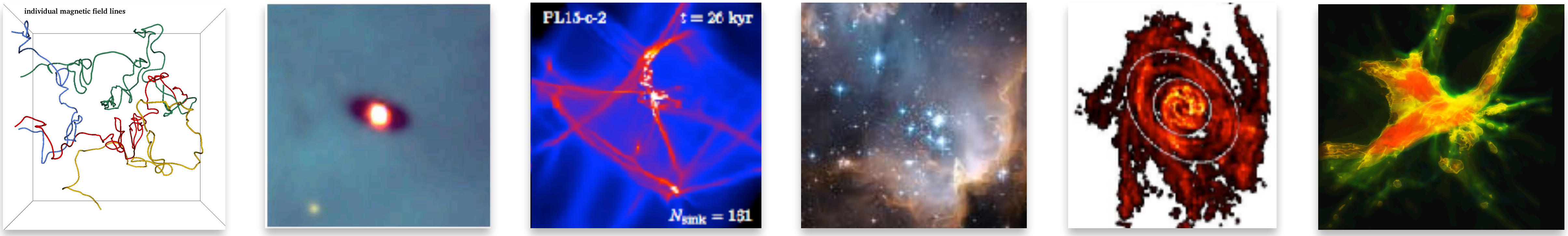
# ISM dynamics and star cluster formation



**Ralf Klessen**

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Institut für Theoretische Astrophysik

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questions rather than answers

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# thanks to …

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

*Bhaskar Agarwal, Carla Bernhard, Daniel Ceverino, Sam Geen, Simon Glover, Dimitrios Gouliermis, Lionel Haemmerle, Sacha Hony, Ondrej Jaura, Ralf Klessen, Besma Klinger-Araifa, Juan Ibanez Meija, Kiwan Park, Eric Pellegrini, Daniel Rahner, Stefan Reißl, Claes-Erik Rydberg, Anna Schauer, Mattia Sormani, Robin Treß, Katharina Wollenberg*

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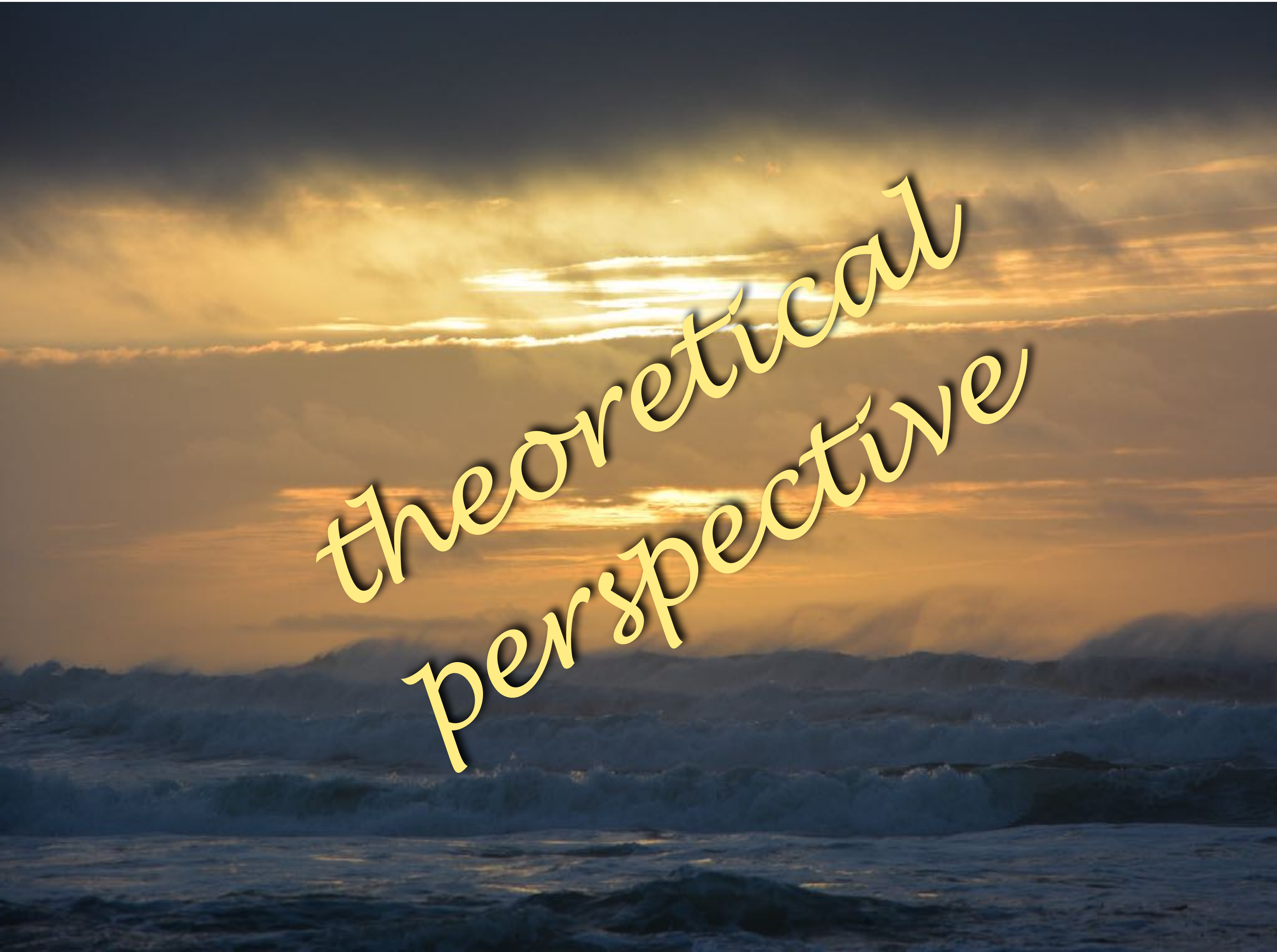
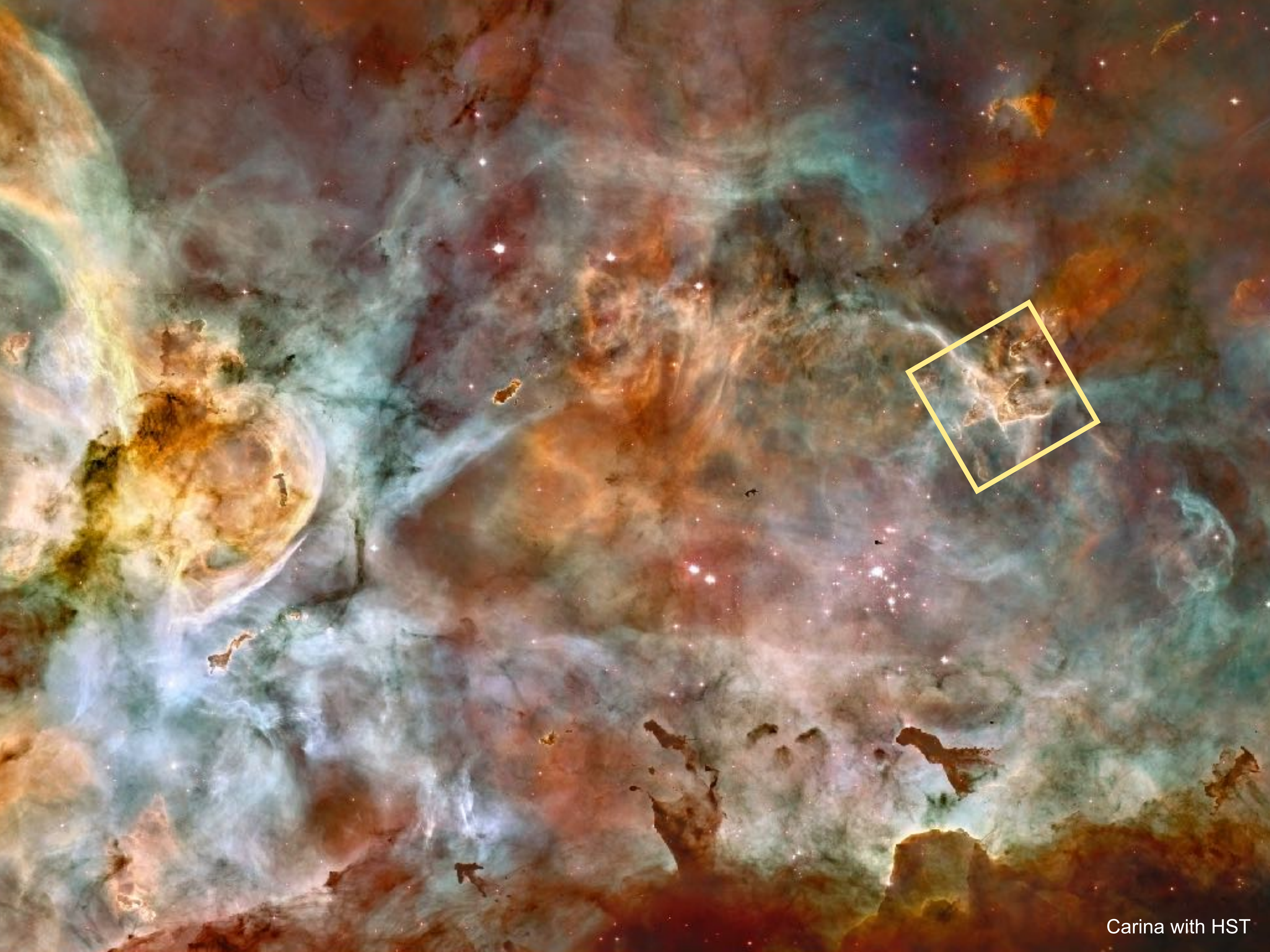
# agenda

- theoretical perspective
  - challenge
  - historic remarks
  - our current understanding and its limitations
- application
  - stellar initial mass function *(importance of thermodynamics)*
  - star cluster formation *(CAVEAT: initial conditions matter)*

NGC 3324 (Hubble, NASA/ESA)

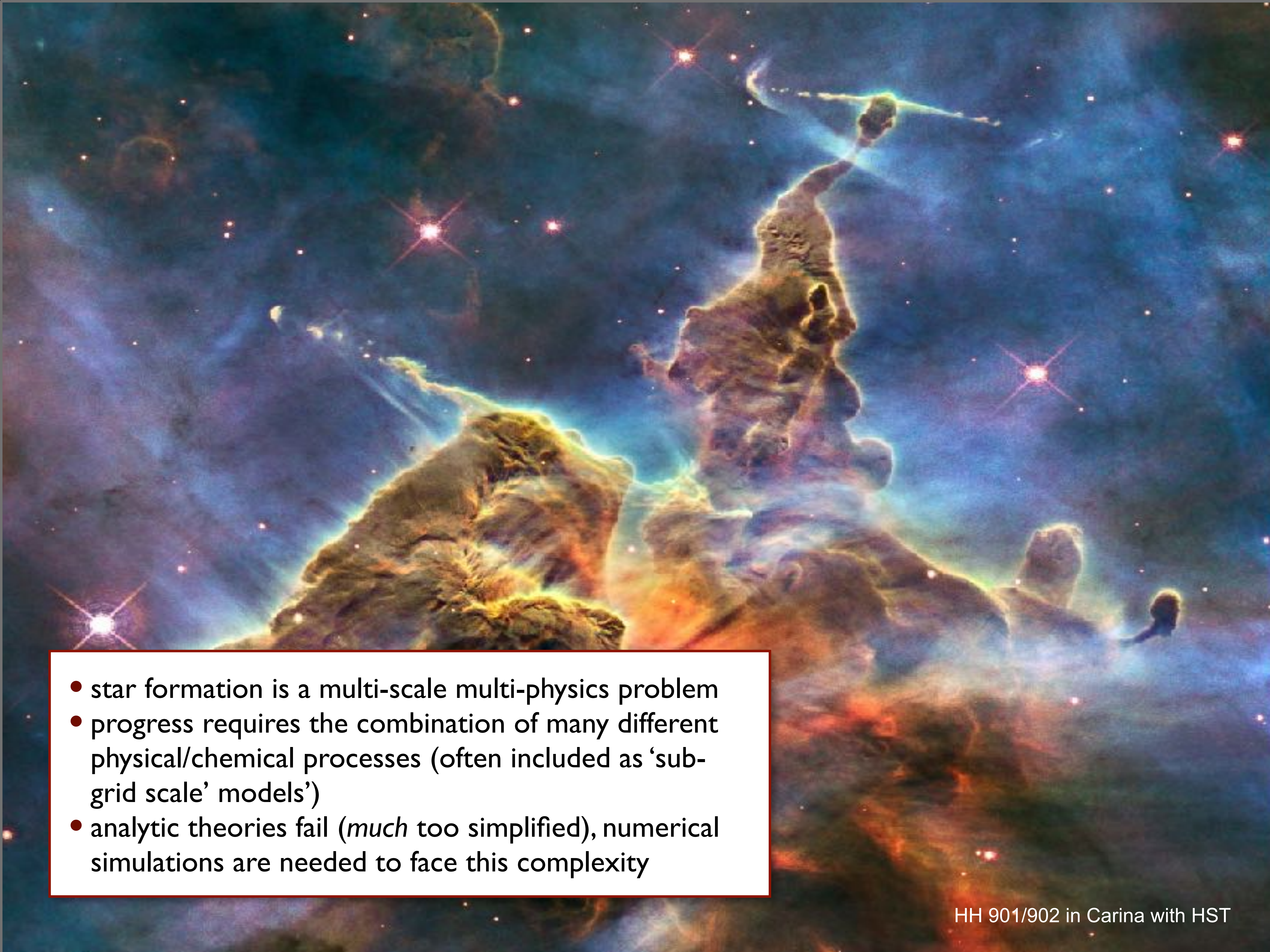


# theoretical perspective



Carina with HST

HH 901/902 in Carina with HST



- star formation is a multi-scale multi-physics problem
- progress requires the combination of many different physical/chemical processes (often included as ‘sub-grid scale’ models’)
- analytic theories fail (*much* too simplified), numerical simulations are needed to face this complexity

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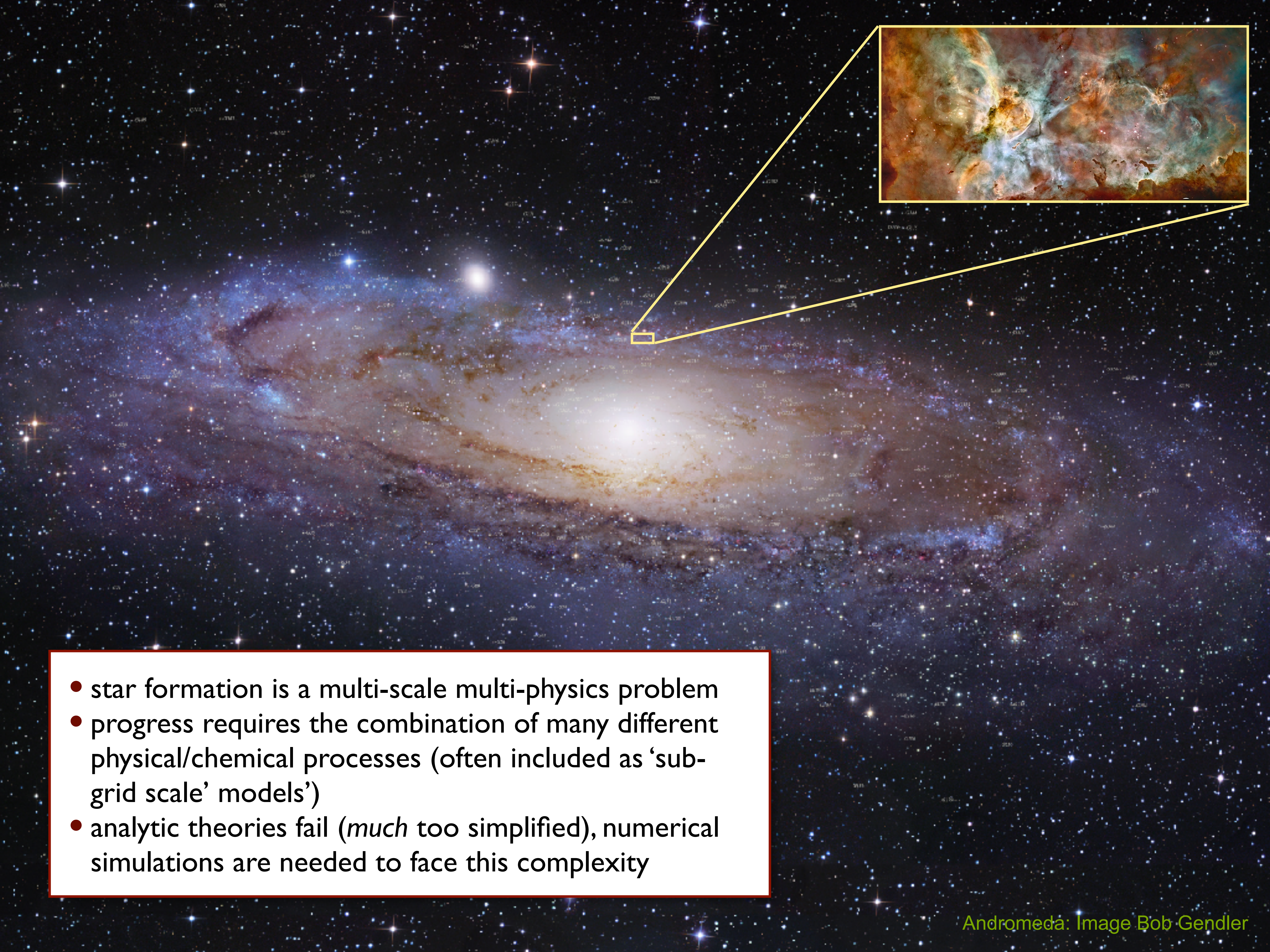

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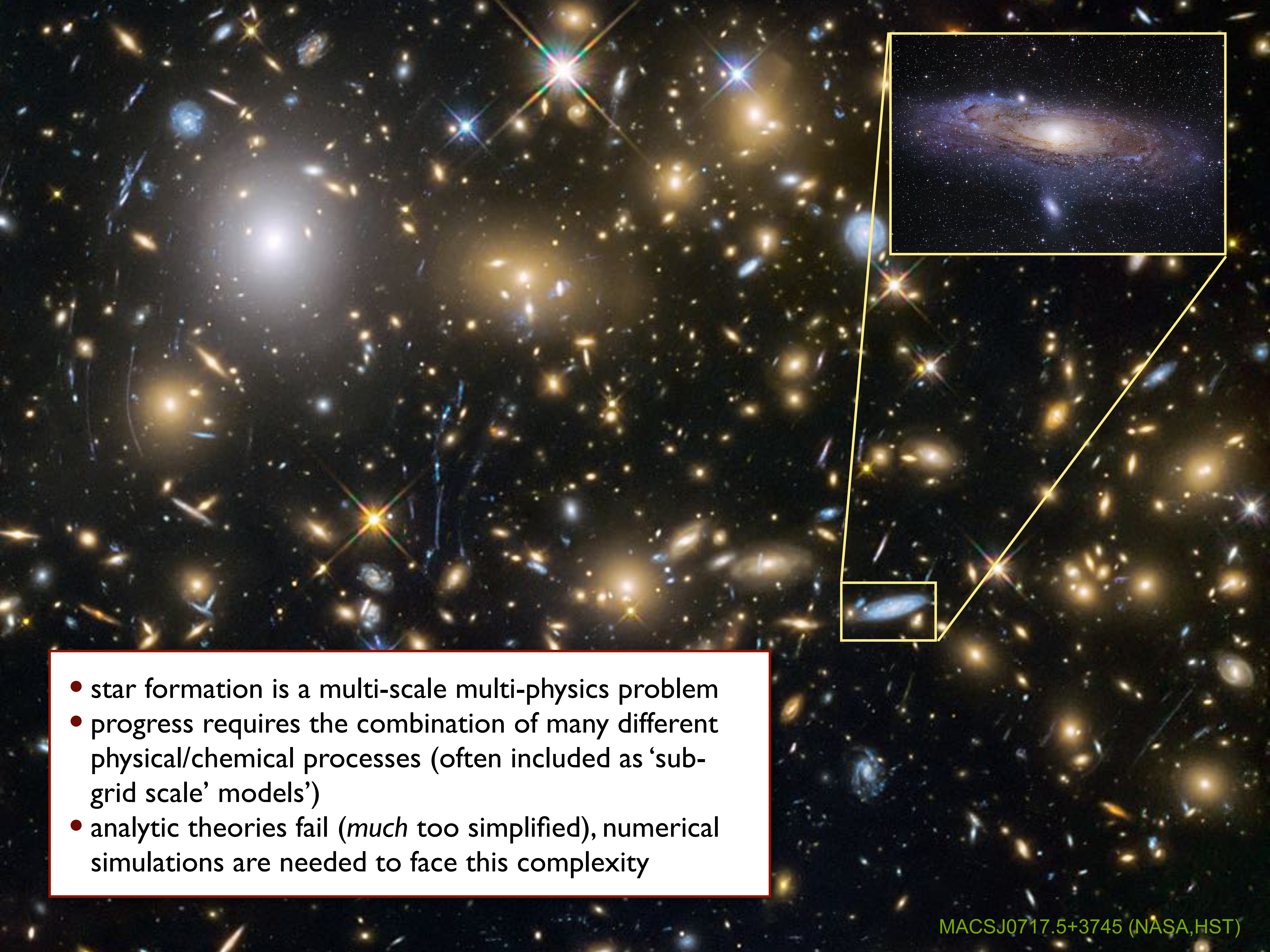
Andromeda: Image Bob Gendler



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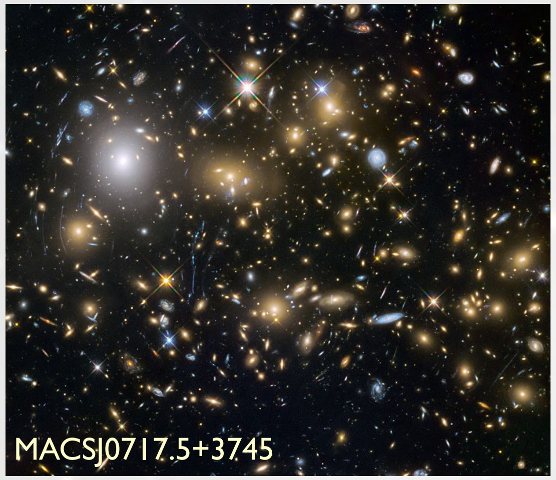
MACSJ0717.5+3745 (NASA,HST)

decrease in spatial scale / increase in density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Andromeda (R. Gendler)


NGC 602 in LMC


Proplyd in Orion


Sun


Earth

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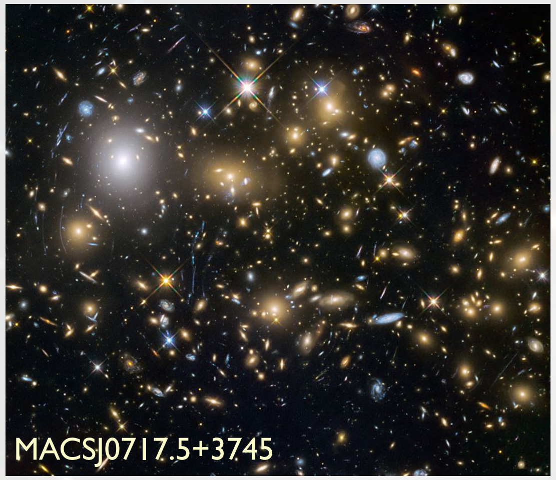
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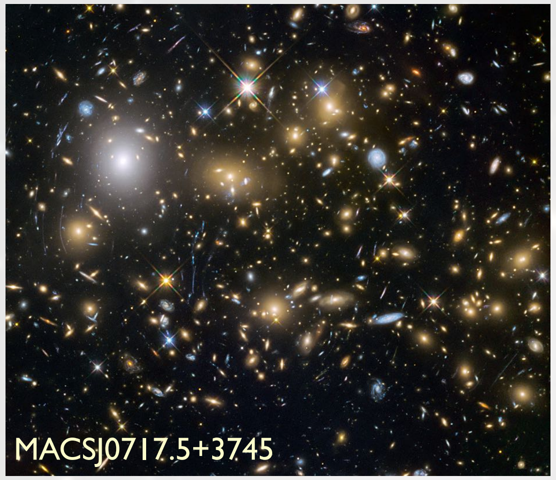
Sun


Earth

- density
  - density of ISM: few particles per cm$^3$
  - density of molecular cloud: few 100 particles per cm$^3$
  - density of Sun: 1.4 g/cm$^3$
- spatial scale
  - size of molecular cloud: few 10s of pc
  - size of young cluster: ~ 1 pc
  - size of Sun: 1.4 x 10$^{10}$ cm

MACSJ0717.5+3745 (NASA,HST)

decrease in spatial scale / increase in density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NGC 602 in LMC


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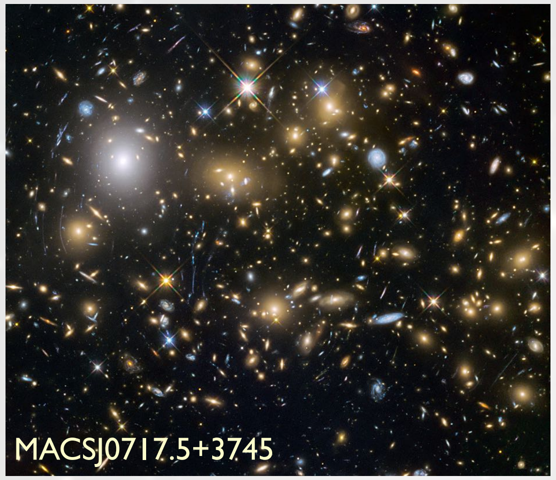
Sun


Earth

- contracting force
  - only force that can do this compression is ***GRAVITY***
- opposing forces
  - there are several processes that can oppose gravity
  - ***GAS PRESSURE***
  - ***TURBULENCE***
  - ***MAGNETIC FIELDS***
  - ***RADIATION PRESSURE***

MACSJ0717.5+3745 (NASA,HST)

decrease in spatial scale / increase in density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Proplyd in Orion


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  - ***RADIATION PRESSURE***

Modern star formation theory is based on the complex interplay between *all* these processes.

MACSJ0717.5+3745 (NASA,HST)

# early theoretical models

- *Jeans (1902):* Interplay between self-gravity and thermal pressure
  - stability of homogeneous spherical density enhancements against gravitational collapse
  - dispersion relation:

$$\boxed{\omega^2 = c_s^2 k^2 - 4\pi G\rho_0}$$

  - instability when $\omega^2 < 0$
  - minimal mass: $\boxed{M_J = \tfrac{1}{6}\pi^{-5/2} G^{-3/2} \rho_0^{-1/2} c_s^3 \propto \rho_0^{-1/2} T^{+3/2}}$

Sir James Jeans, 1877 - 1946

# first approach to turbulence

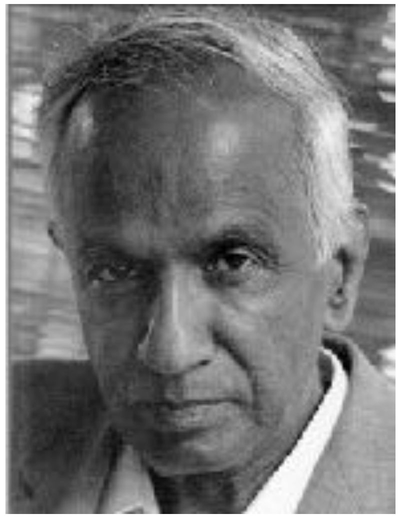
- *von Weizsäcker (1943, 1951)* and *Chandrasekhar (1951):* concept of ***MICROTURBULENCE***
  - BASIC ASSUMPTION: separation of scales between dynamics and turbulence

    $\ell_{\rm turb} \ll \ell_{\rm dyn}$
  - then turbulent velocity dispersion contributes to effective soundspeed:

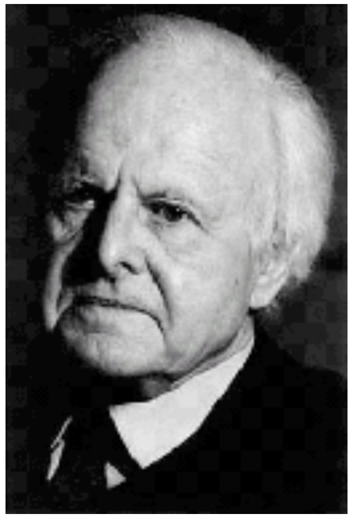
$$\boxed{c_c^2 \mapsto c_c^2 + \sigma_{rms}^2}$$

  - → Larger effective Jeans masses → more stability
  - BUT: *(1) turbulence depends on k:* $\sigma_{rms}^2(k)$

    *(2) supersonic turbulence* → $\sigma_{rms}^2(k) >> c_s^2$ *usually*



S. Chandrasekhar, 1910 - 1995



C.F. von Weiszäcker, 1912 - 2007

# problems of early dynamical theory

- molecular clouds are *highly Jeans-unstable,*
  yet, they do *NOT* form stars at high rate
  and with high efficiency (Zuckerman & Evans 1974 conundrum)
  (the observed global SFE in molecular clouds is *~5%*)
  → *something prevents large-scale collapse.*
- all throughout the early 1990's, molecular clouds had been thought to be long-lived quasi-equilibrium entities.
- molecular clouds are *magnetized*

# magnetic star formation

- *Mestel & Spitzer (1956):* Magnetic fields can prevent collapse*!!!*
  - Critical mass for gravitational collapse in presence of B-field

$$M_{cr} = \frac{5^{3/2}}{48\pi^2}\frac{B^3}{G^{3/2}\rho^2}$$

  - Critical mass-to-flux ratio (Mouschovias & Spitzer 1976)

$$\left[\frac{M}{\Phi}\right]_{cr} = \frac{\zeta}{3\pi}\left[\frac{5}{G}\right]^{1/2}$$

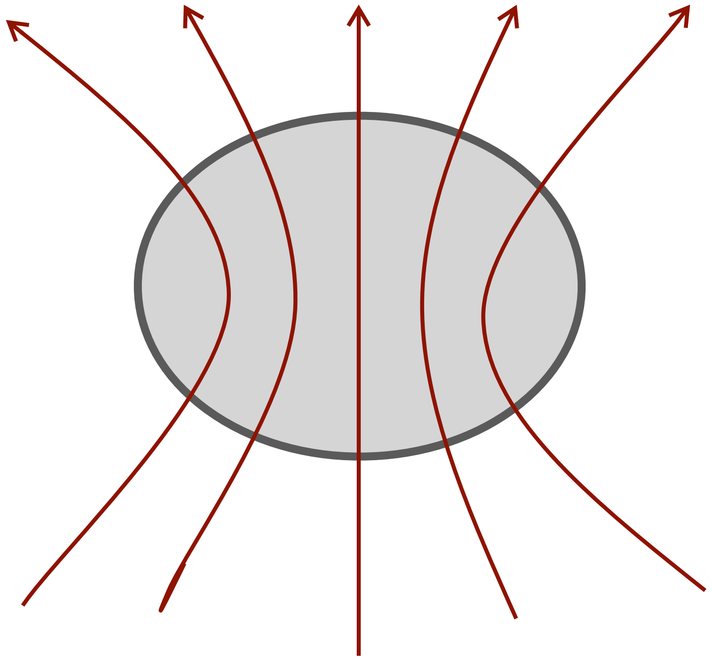
  - Ambipolar diffusion can initiate collapse

Lyman Spitzer, Jr., 1914 - 1997

# “standard theory” of star formation

- BASIC ASSUMPTION: Stars form from magnetically highly subcritical cores
- Ambipolar diffusion slowly increases ($M/\Phi$): $\tau_{AD} \approx 10\tau_{ff}$
- Once $(M/\Phi) > (M/\Phi)_{crit}$ : dynamical collapse of SIS
  - Shu (1977) collapse solution
  - $dM/dt = 0.975\ c_s^3/G = \text{const.}$
- Was (in principle) only intended for isolated, low-mass stars

Frank Shu, 1943 -



# problems of “standard theory”

- Observed B-fields are weak, at most marginally critical (Crutcher 1999, Bourke et al. 2001)
- Magnetic fields cannot prevent decay of turbulence
  (Mac Low et al. 1998, Stone et al. 1998, Padoan & Nordlund 1999)
- Structure of prestellar cores
  (e.g. Bacman et al. 2000, Alves et al. 2001)
- Strongly time varying dM/dt
  (e.g. Hendriksen et al. 1997, André et al. 2000)
- More extended infall motions than predicted by the standard model
  (Williams & Myers 2000, Myers et al. 2000)
- Most stars form as binaries
  (e.g. Lada 2006)
- As many prestellar cores as protostellar cores in SF regions (e.g. André et al 2002)
- Molecular cloud clumps are chemically young
  (Bergin & Langer 1997, Pratap et al 1997, Aikawa et al 2001)
- Stellar age distribution small ($\tau_{ff} << \tau_{AD}$)
  (Ballesteros-Paredes et al. 1999, Elmegreen 2000, Hartmann 2001)
- Strong theoretical criticism of the SIS as starting condition for gravitational collapse
  (e.g. Whitworth et al 1996, Nakano 1998, as summarized in Klessen & Mac Low 2004)
- Standard AD-dominated theory is incompatible with observations
  (Crutcher et al. 2009, 2010ab, Bertram et al. 2011)

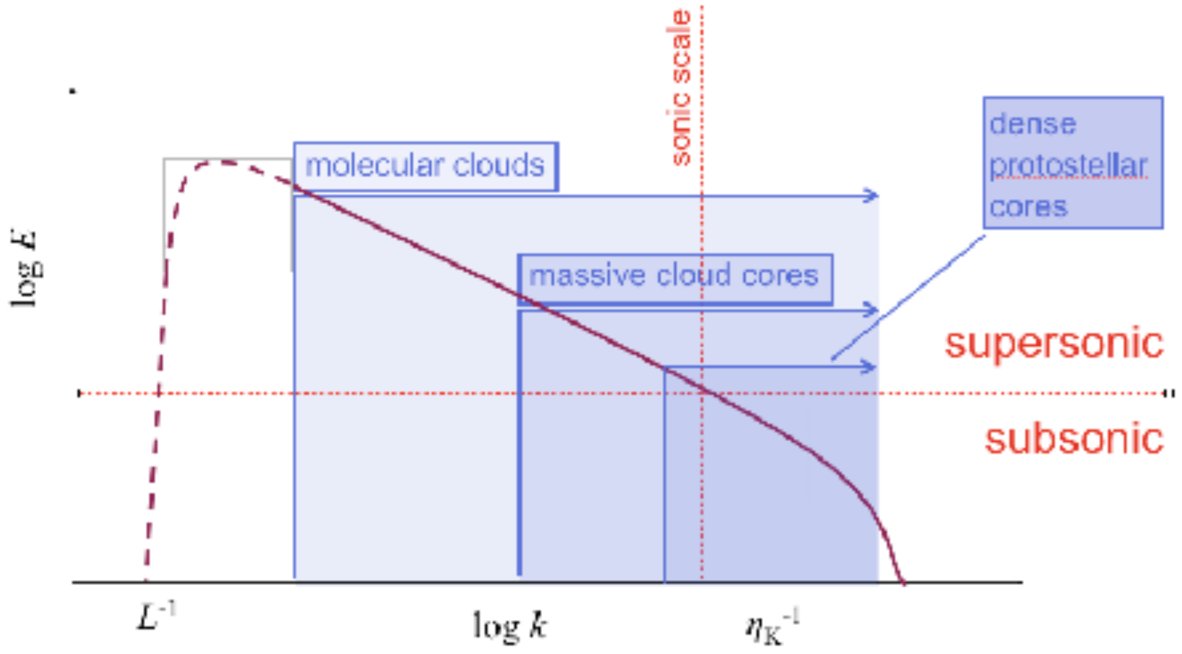
(see e.g. Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194
Klessen & Glover, 2014, Saas Fee Lecture, arXiv:1412.5182 )

# gravoturbulent star formation

- BASIC ASSUMPTION:

star formation is controlled by interplay between supersonic turbulence and self-gravity

- turbulence plays a *dual role*:
  - on *large scales* it *provides support*
  - on *small scales* it can *trigger collapse*
- some predictions:
  - dynamical star formation timescale $\tau_{ff}$
  - high binary fraction
  - complex spatial structure of embedded star clusters
  - and many more . . .

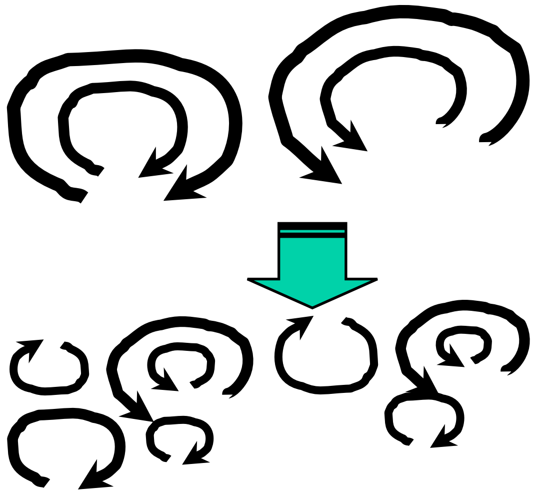


Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194
McKee & Ostriker, 2007, ARAA, 45, 565
Klessen & Glover, 2016, Saas Fee Lecture, 43, 86, arXiv:1412.5182 )

# properties of turbulence

- laminar flows turn *turbulent* at *high* *Reynolds* numbers

$$Re = \frac{\text{advection}}{\text{dissipation}} = \frac{VL}{\nu}$$



$V$= typical velocity on scale $L$, $\nu = \eta/\rho$ = kinematic viscosity, turbulence for Re > 1000 → typical values in ISM $10^8$-$10^{10}$

- Navier-Stokes equation (transport of momentum)

$$\rho\frac{d\vec{v}}{dt} = \rho\left(\frac{\partial\vec{v}}{\partial t} + (\vec{v}\cdot\vec{\nabla})\vec{v}\right) = -\vec{\nabla}P + \eta\,\vec{\nabla}^2\vec{v} + \left(\frac{\eta}{3} + \zeta\right)\vec{\nabla}(\vec{\nabla}\cdot\vec{v})$$

shear viscosity

bulk viscosity

$$\sigma_{ij} \equiv \eta\left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial v_k}{\partial x_k}\right) + \zeta\delta_{ij}\frac{\partial v_k}{\partial x_k}$$

viscous stress tensor

# properties of turbulence

- laminar flows turn *turbulent* at *high* *Reynolds* numbers

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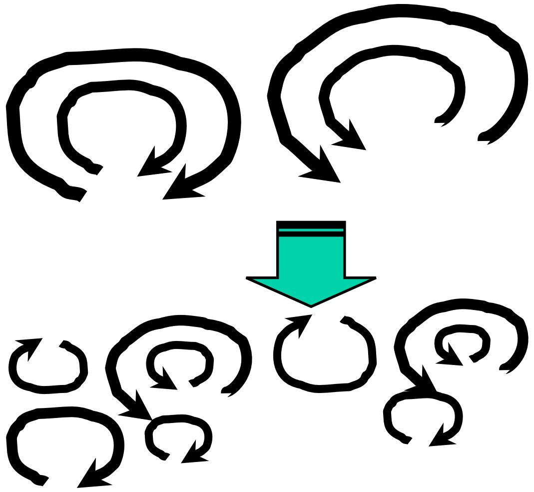


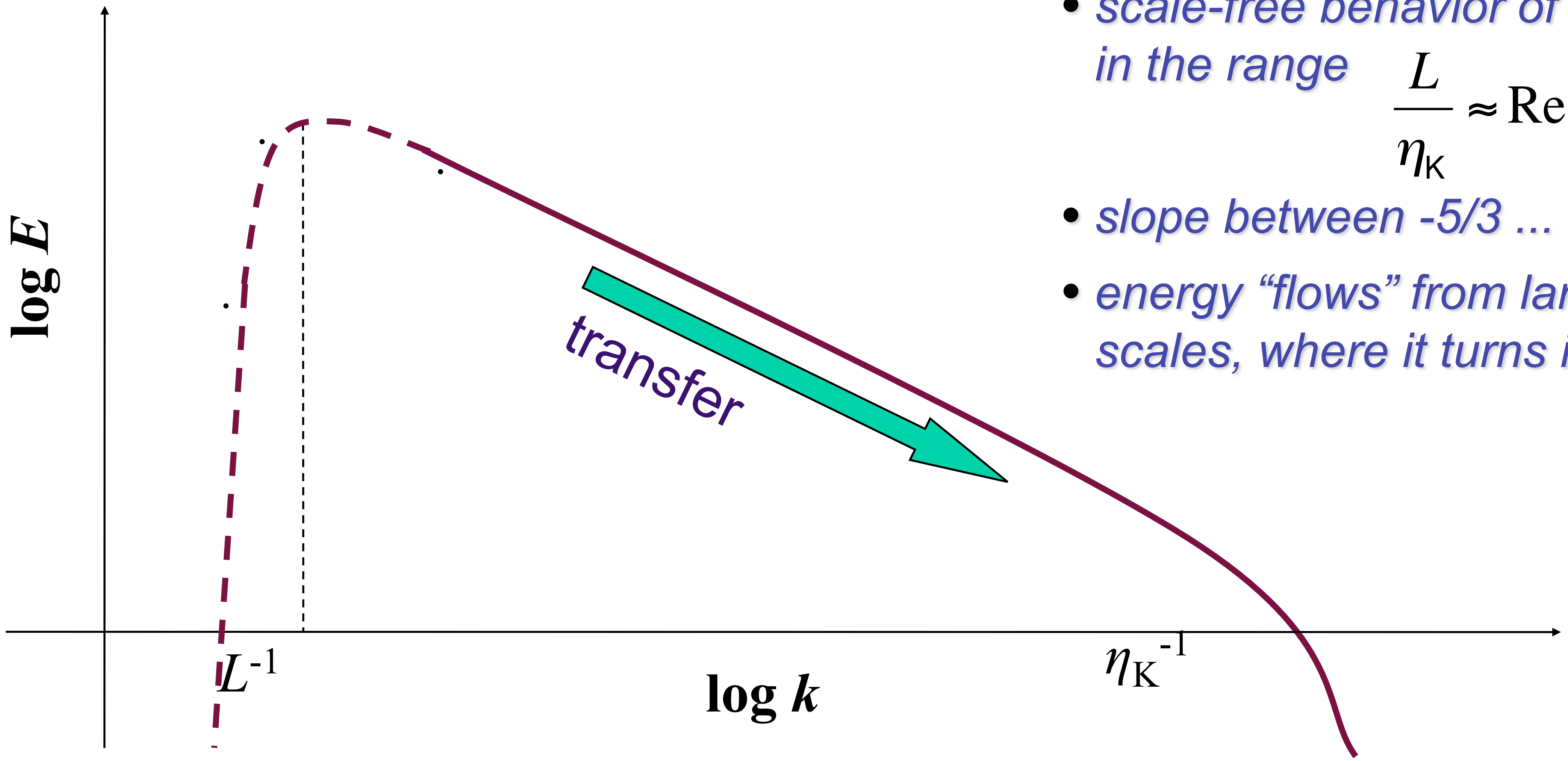
$V$= typical velocity on scale $L$, $\nu = \eta/\rho$ = kinematic viscosity,
turbulence for Re > 1000 → typical values in ISM $10^8$-$10^{10}$

- vortex streching --> turbulence is intrinsically anisotropic
  (only on large scales you may get
  homogeneity & isotropy in a statistical sense;
  see Landau & Lifschitz, Chandrasekhar, Taylor, etc.)

  (BUT: ISM turbulence: shocks & B-field
  cause additional inhomogeneity)

Tornado over Portofino

# turbulent cascade in the ISM

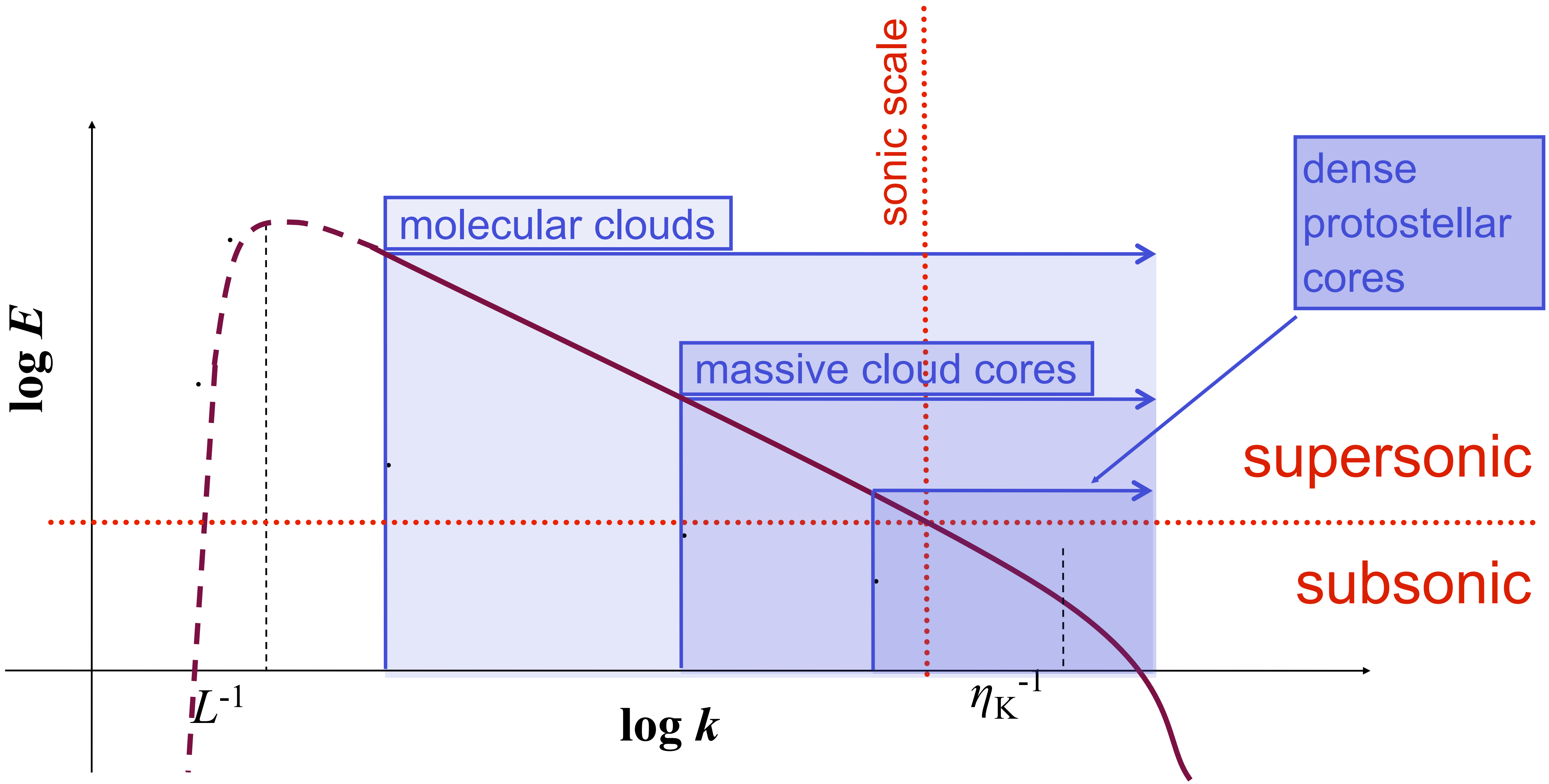


- *scale-free behavior of turbulence in the range* $\frac{L}{\eta_K} \approx \mathrm{Re}^{3/4}$
- *slope between -5/3 ... -2*
- *energy "flows" from large to small scales, where it turns into heat*

energy source & scale
*NOT known*
(supernovae, winds,
spiral density waves?)

dissipation scale not known
(ambipolar diffusion,
molecular diffusion?)

# turbulent cascade in the ISM



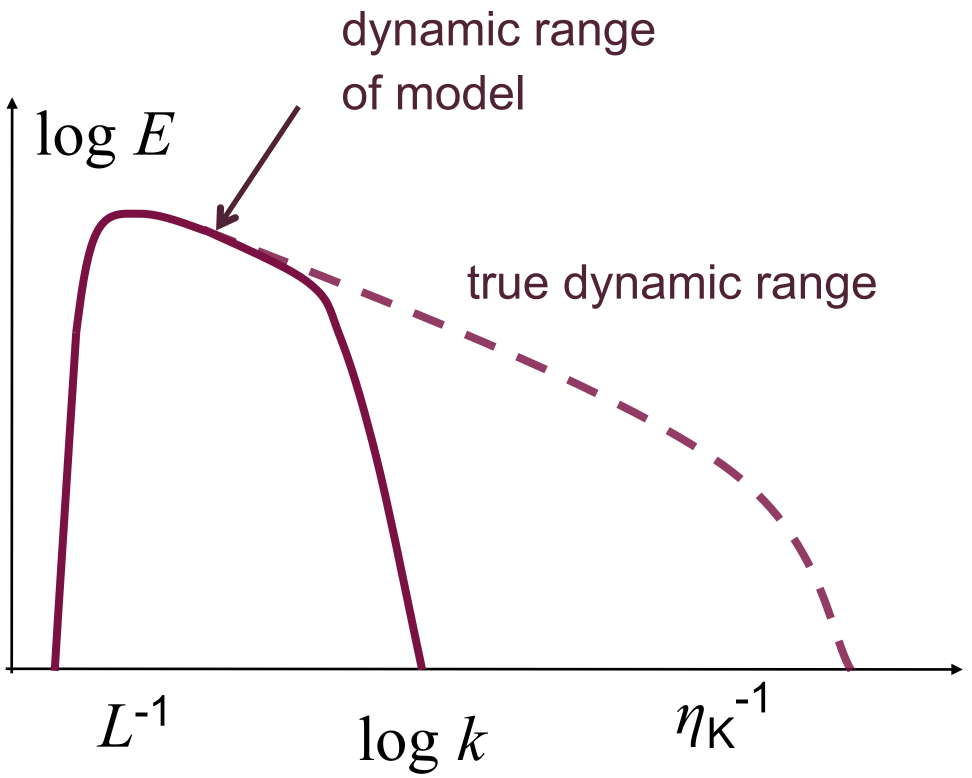
energy source & scale *NOT known* (supernovae, winds, spiral density waves?)

$\sigma_{rms} << 1$ km/s
$M_{rms} \leq 1$
$L \approx 0.1$ pc

dissipation scale not known (ambipolar diffusion, molecular diffusion?)

# large eddie simulations - caveats!

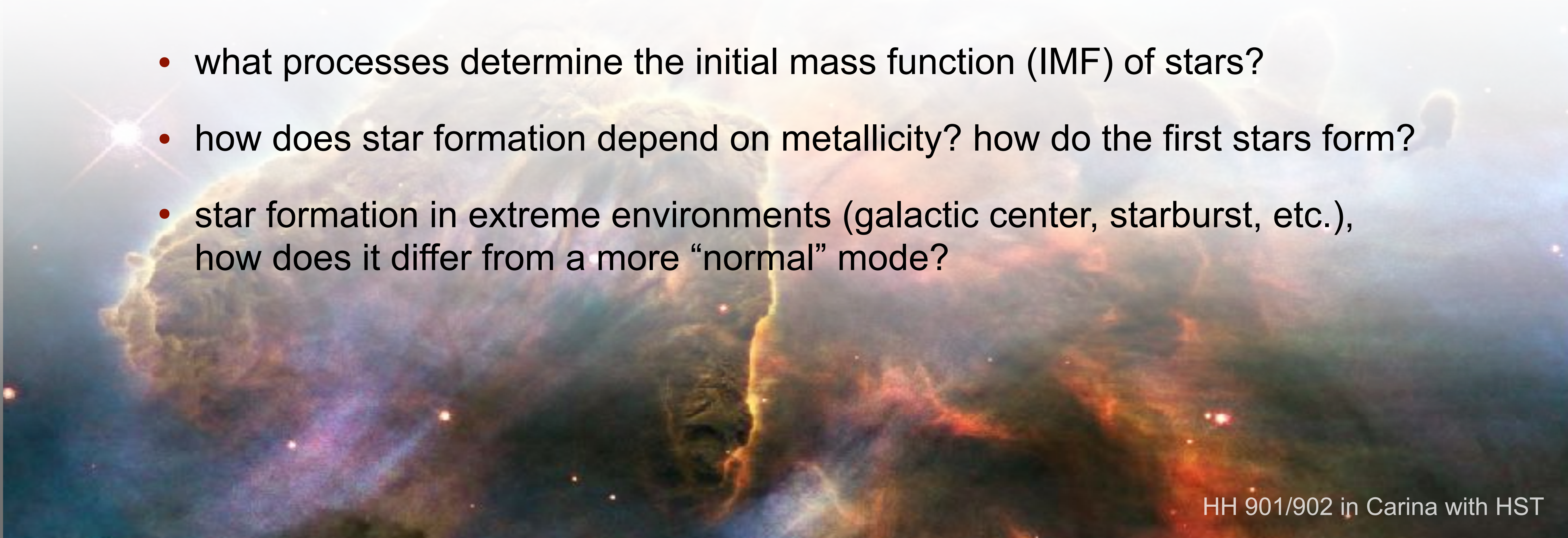
- We use ***LES*** to model the large-scale dynamics
- Principal problem: only large scale flow properties
  - Reynolds number: Re = LV/ν ***($Re_{nature}$ >> $Re_{model}$)***
  - dynamic range much smaller than true physical one
  - need *subgrid model* (in our case simple: only dissipation)
  - but what to do for more complex when processes on subgrid scale determine large-scale dynamics (chemical reactions, nuclear burning, etc)
  - Turbulence is "space filling" --> difficulty for AMR (don't know what criterion to use for refinement)
- How *large* a Reynolds number do we need to catch basic dynamics right?



# applications …

# selected open questions

- what regulates star formation on galactic scales? global SF relations?
- what drives interstellar turbulence turbulence?
- how do molecular clouds form and evolve?
  is there unaccounted (molecular) gas in galaxies?
- what are the initial conditions for star cluster formation?
  how does cloud structure translate into cluster structure?
- what processes determine the initial mass function (IMF) of stars?
- how does star formation depend on metallicity? how do the first stars form?
- star formation in extreme environments (galactic center, starburst, etc.),
  how does it differ from a more “normal” mode?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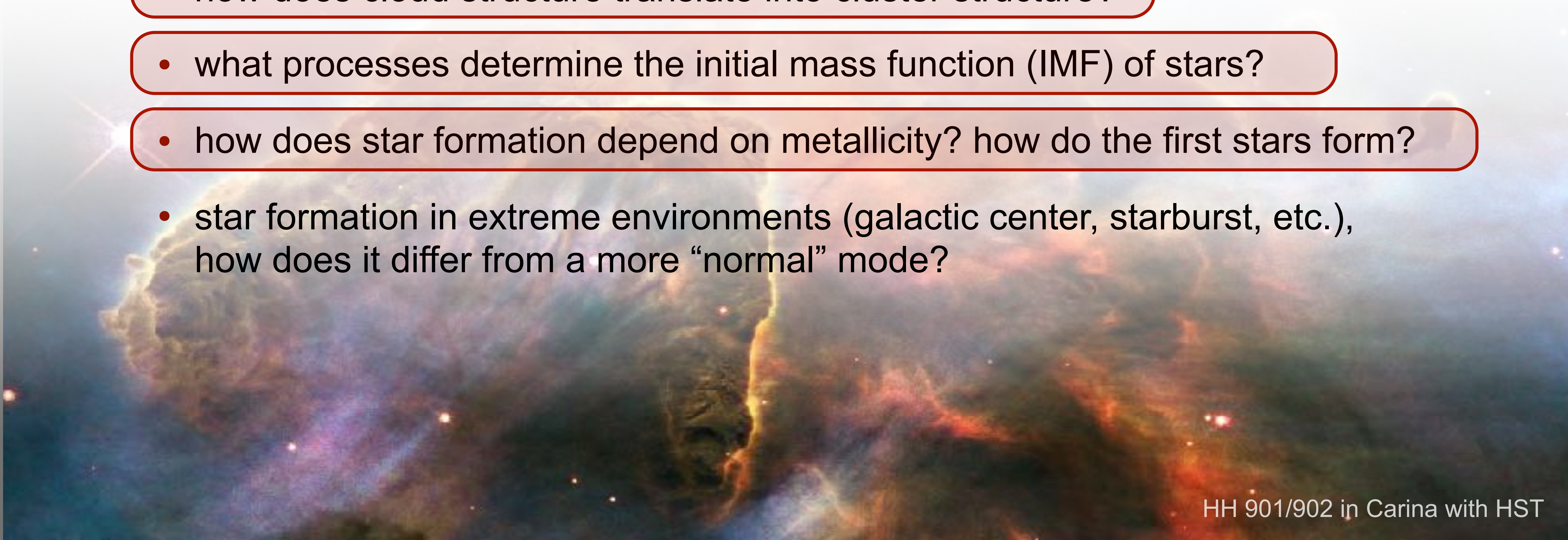

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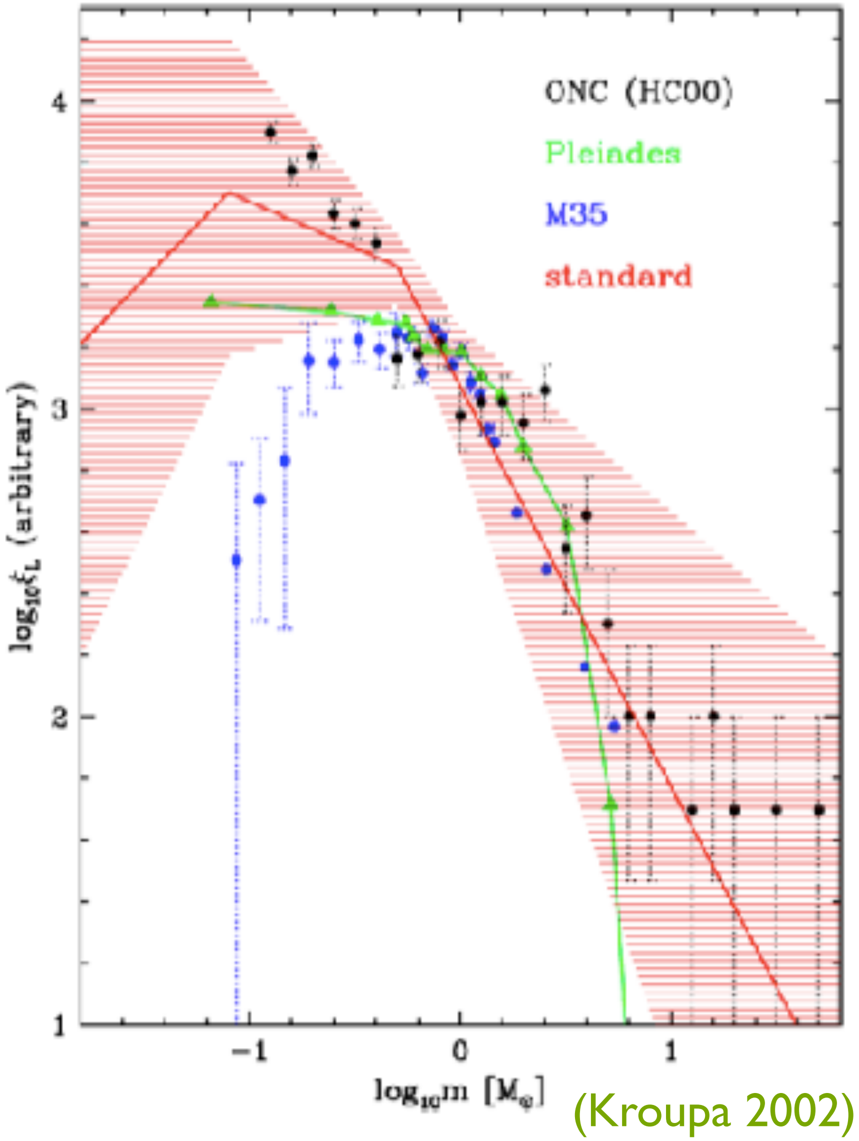
# stellar mass fuction

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

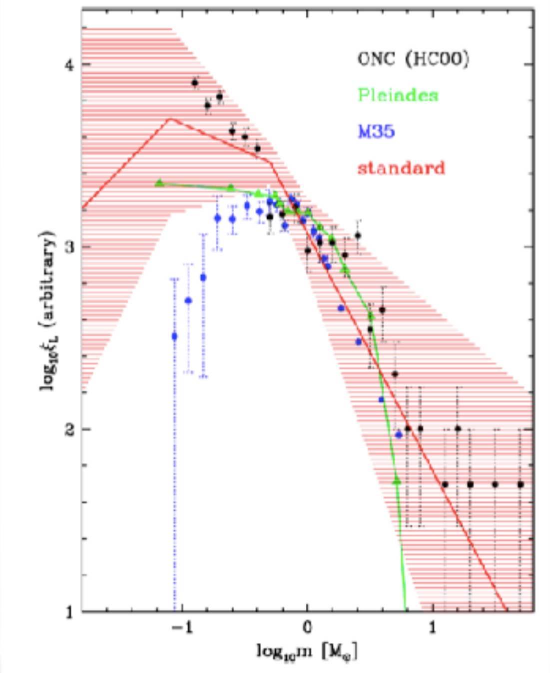


(Kroupa 2002)

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

# stellar mass function

- 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.



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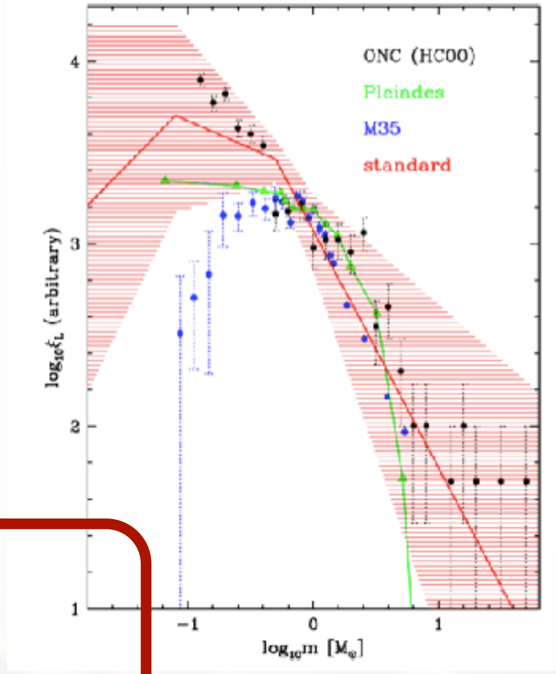


application to early star formation

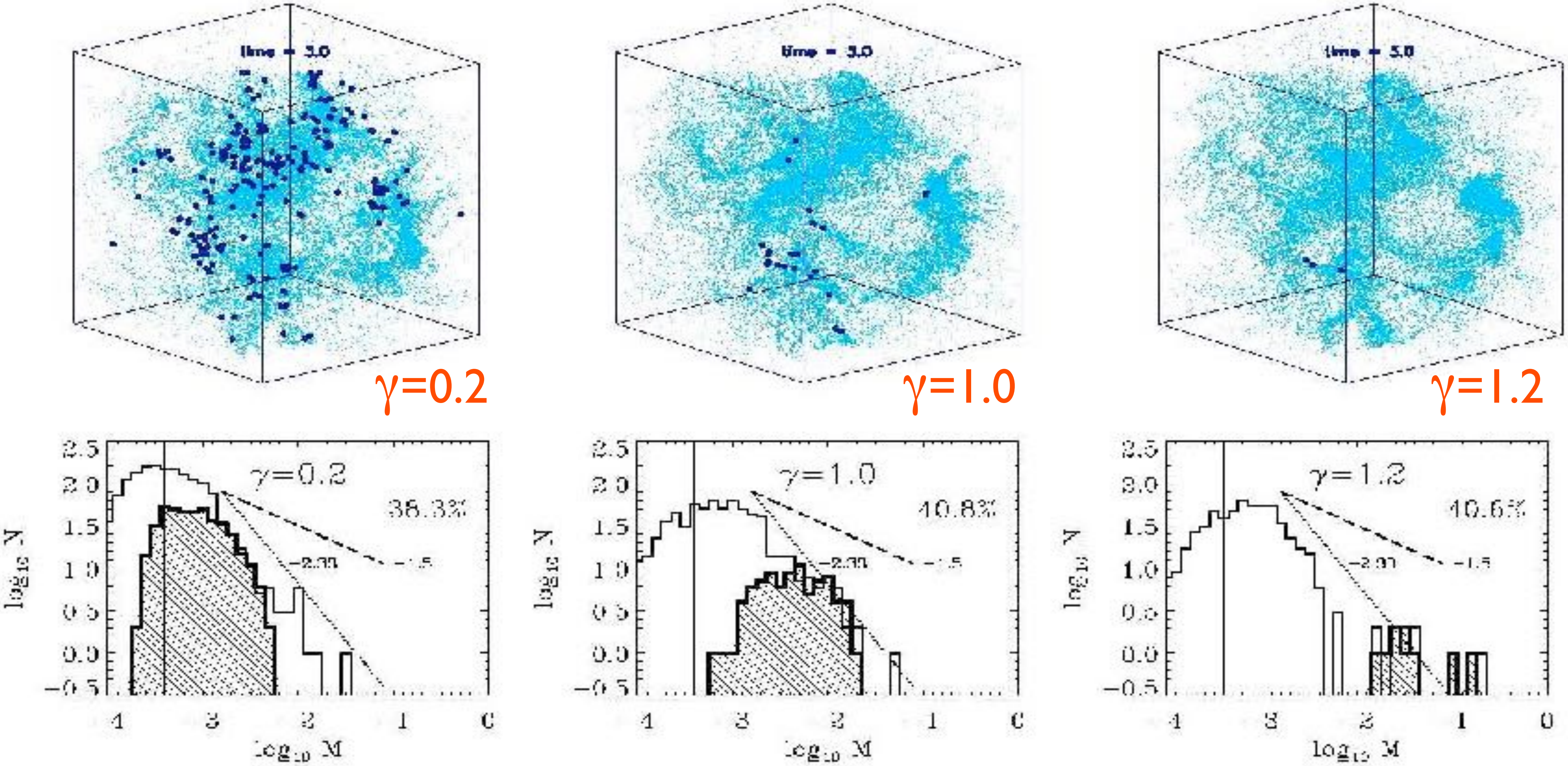
# thermodynamics & fragmentation

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

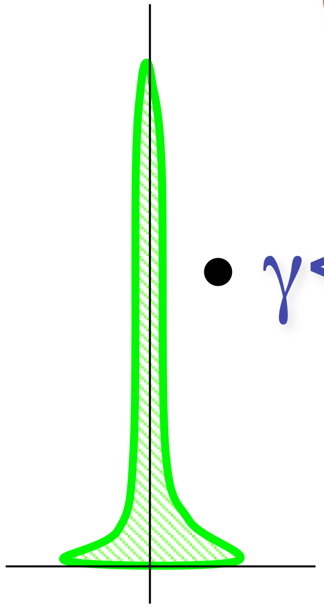
for $\gamma>1$ it is suppressed → *isolated massive stars*

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

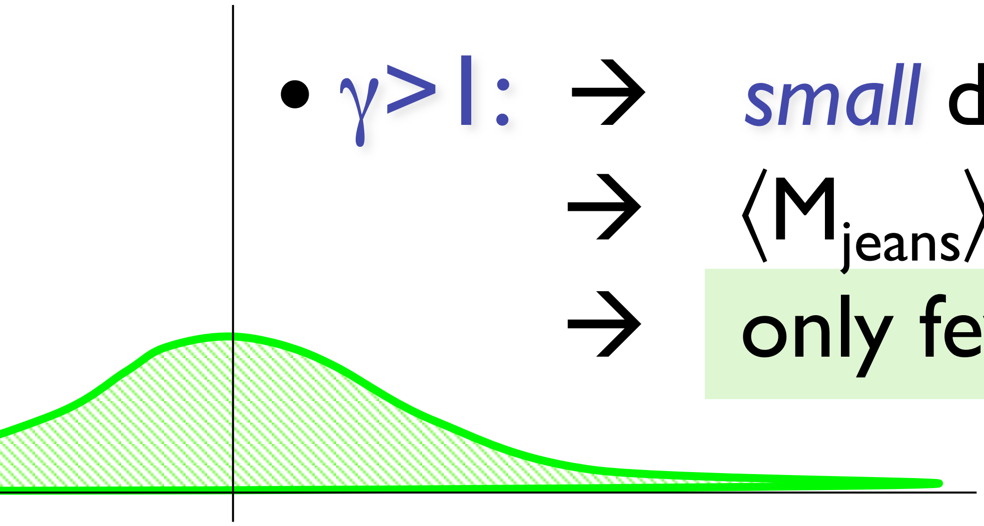
# how does that work?

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

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

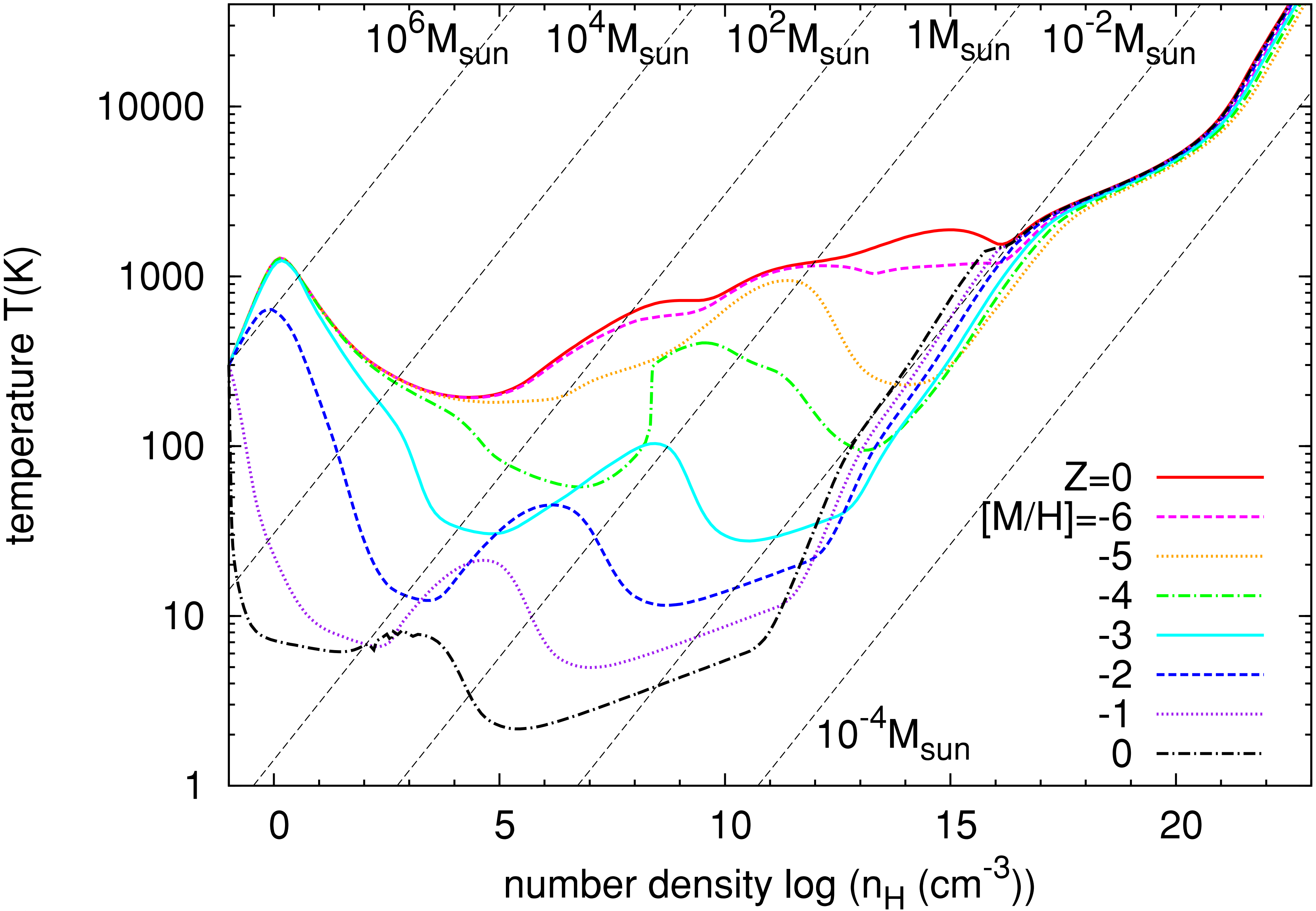


- $\gamma<1$: → *large* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ becomes small
  → number of fluctuations with $M > M_{jeans}$ is large



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

# EOS as function of metallicity



(Omukai et al. 2005, 2010)

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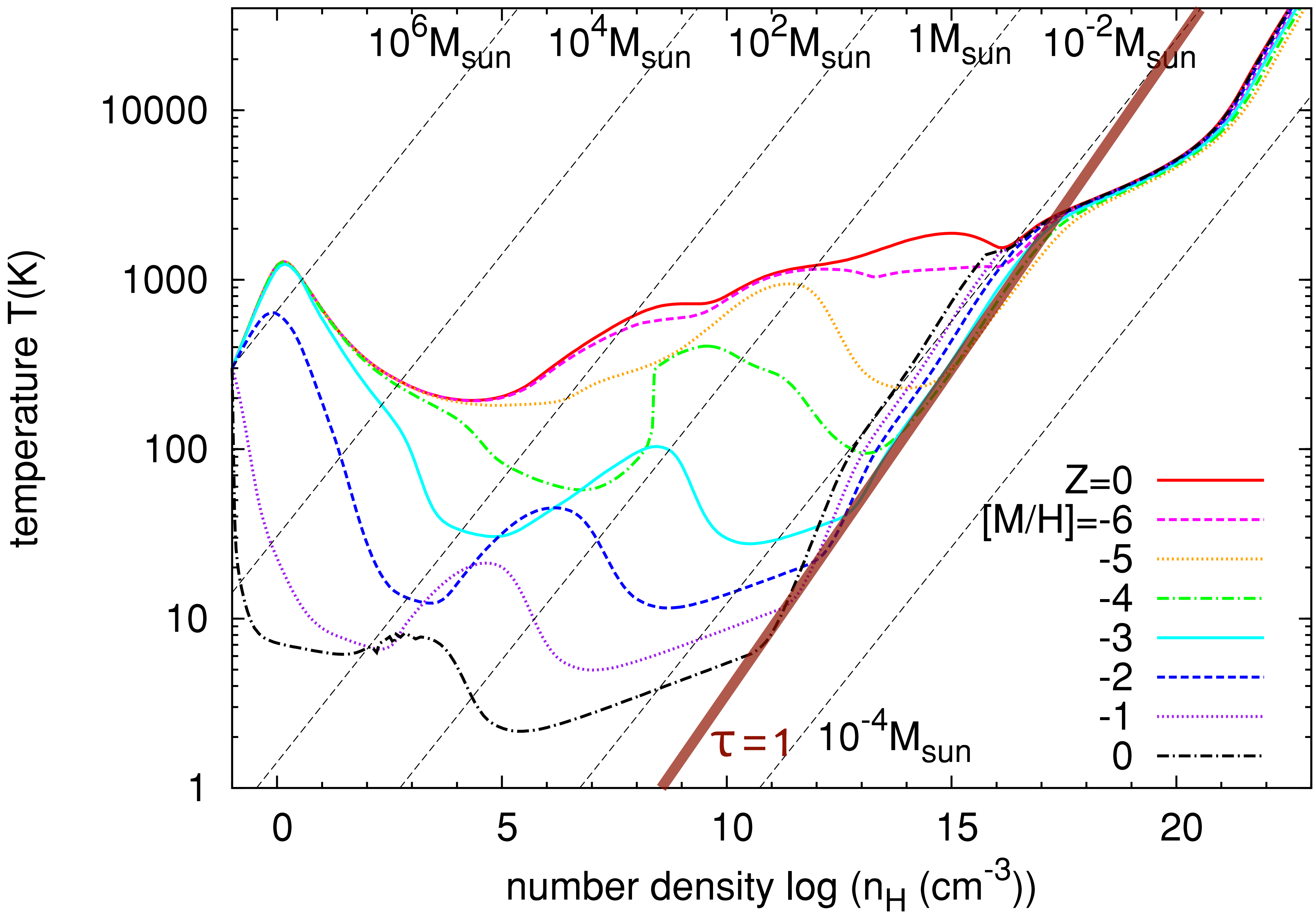

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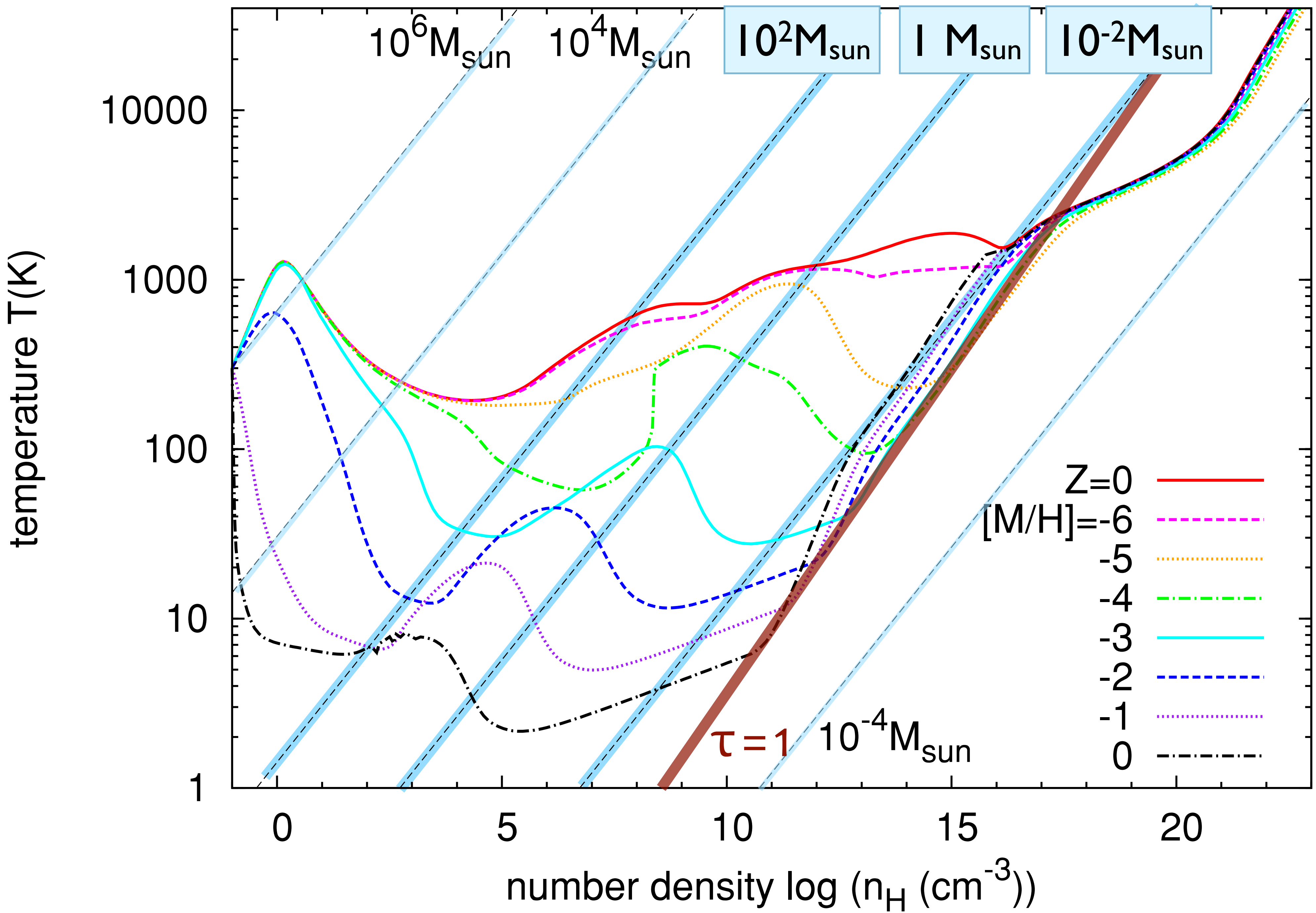

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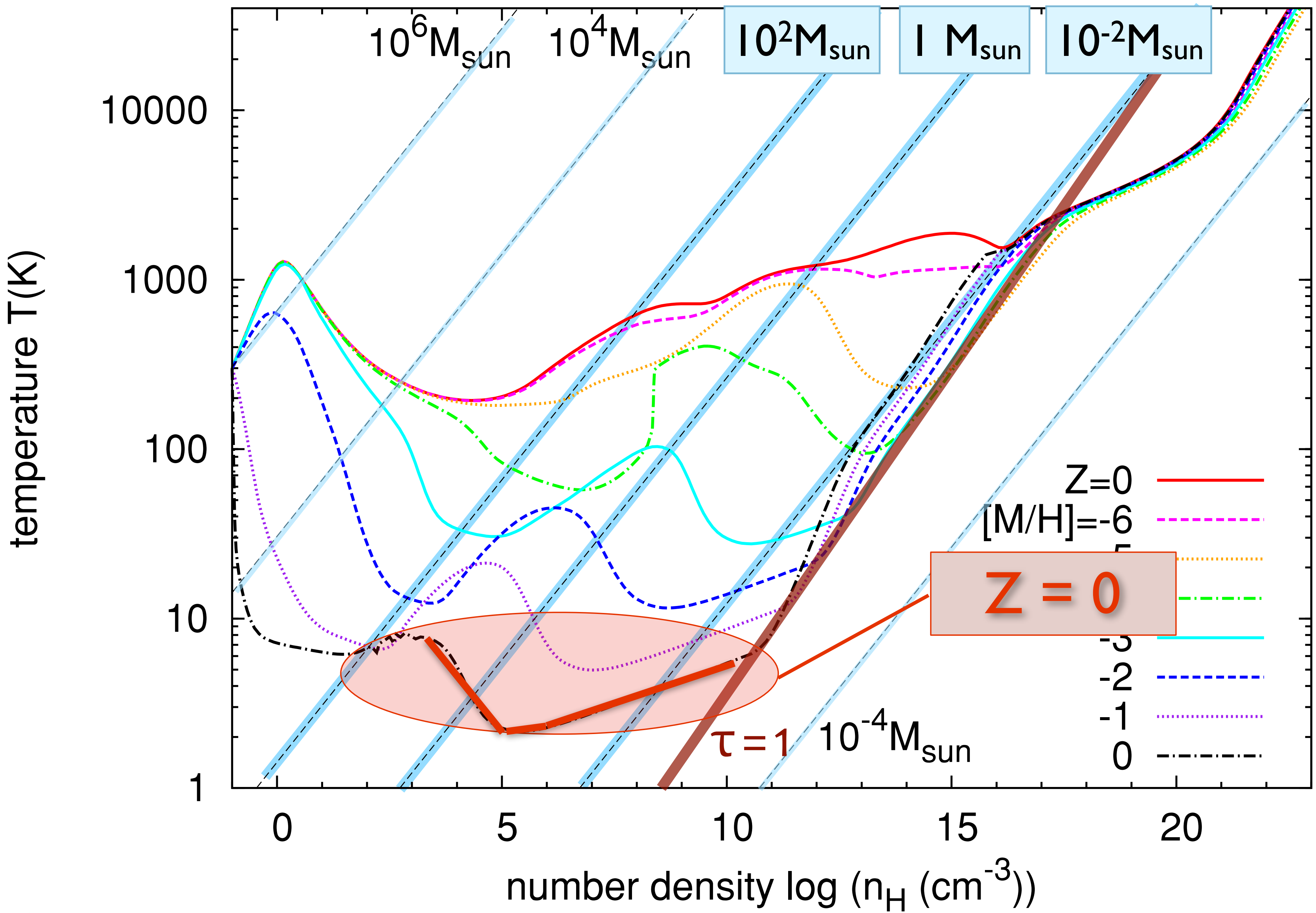
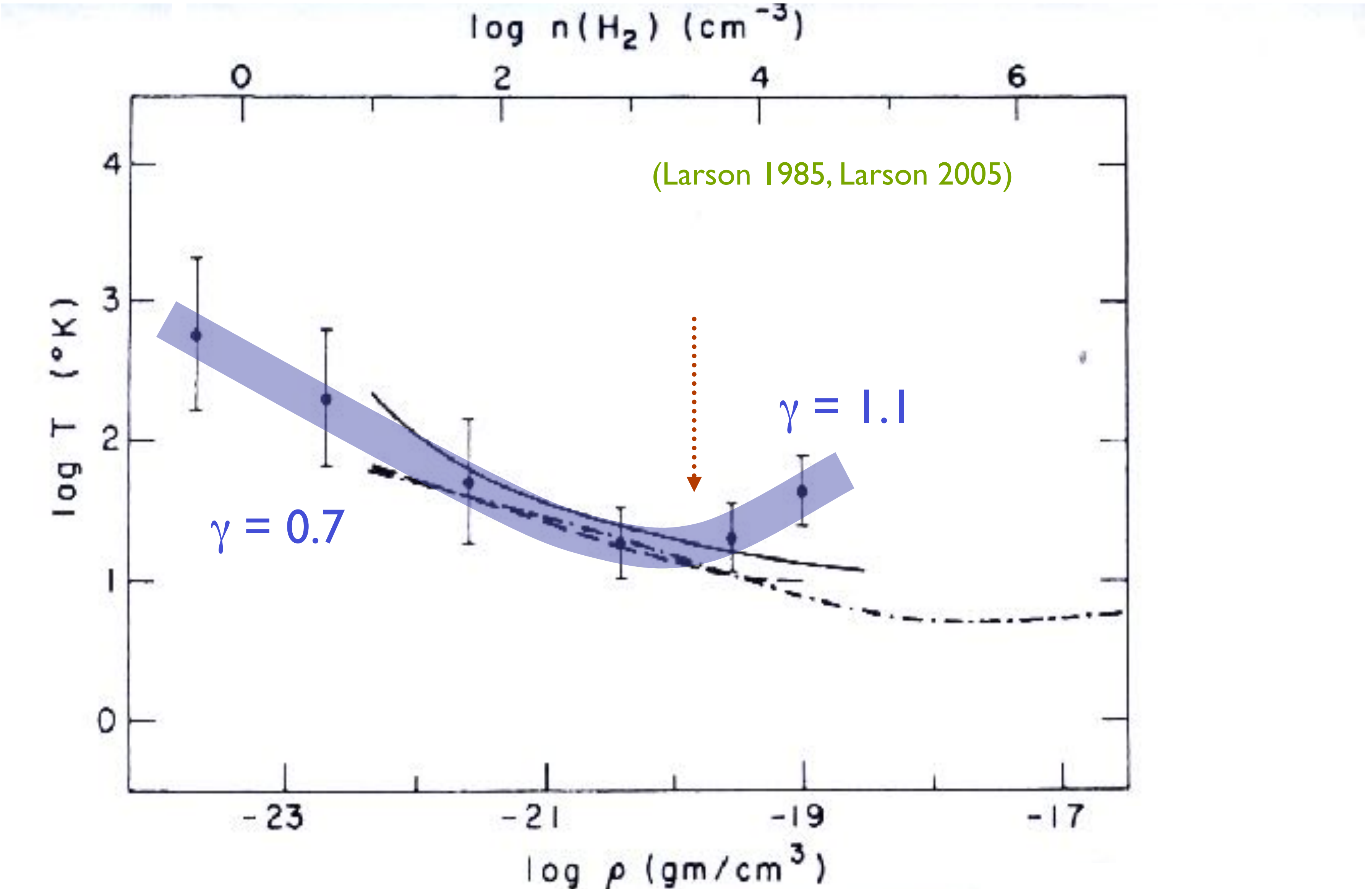


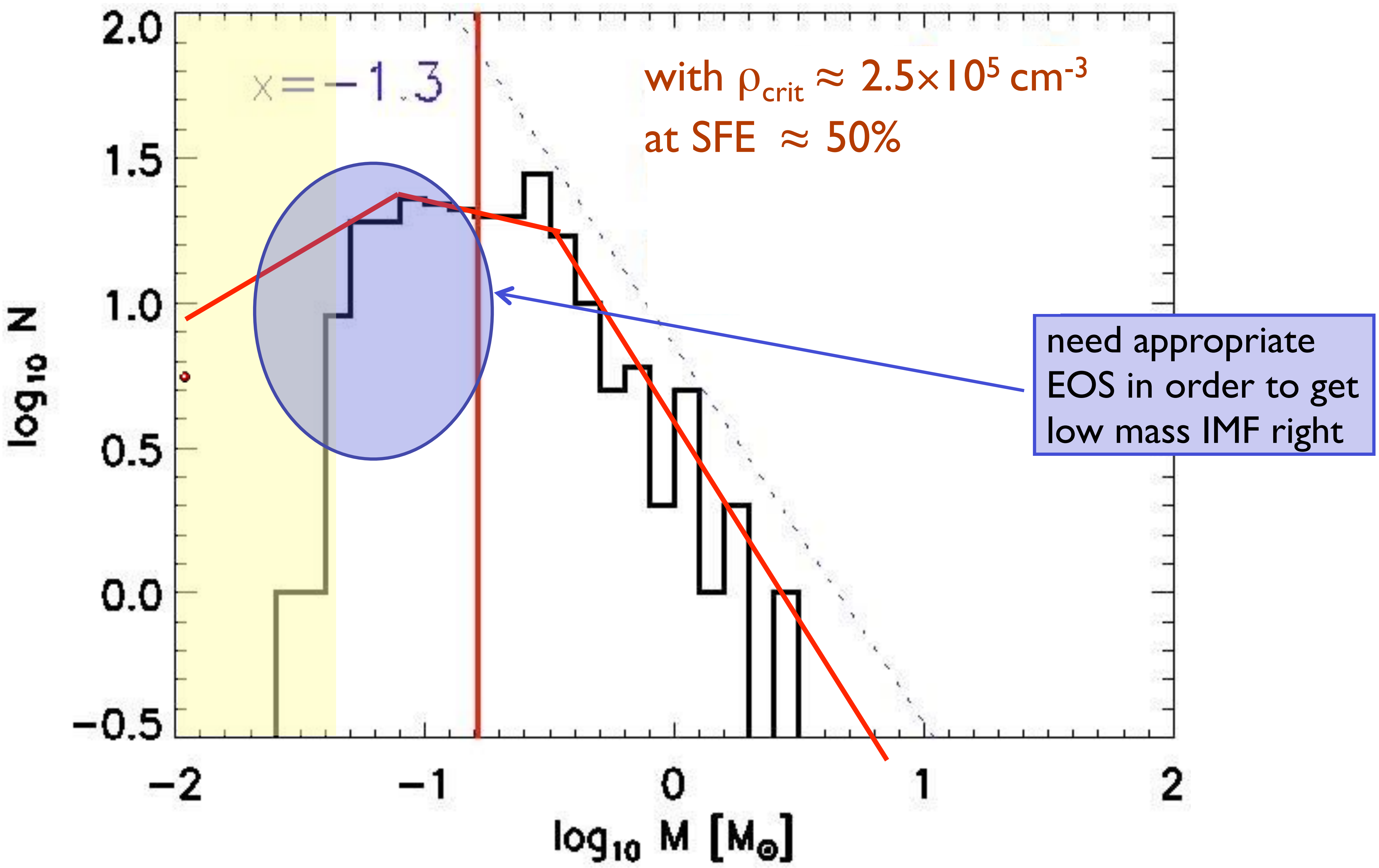
(Omukai et al. 2005, 2010)

# present-day star formation



(Larson 1985, Larson 2005)

# IMF in nearby molecular clouds



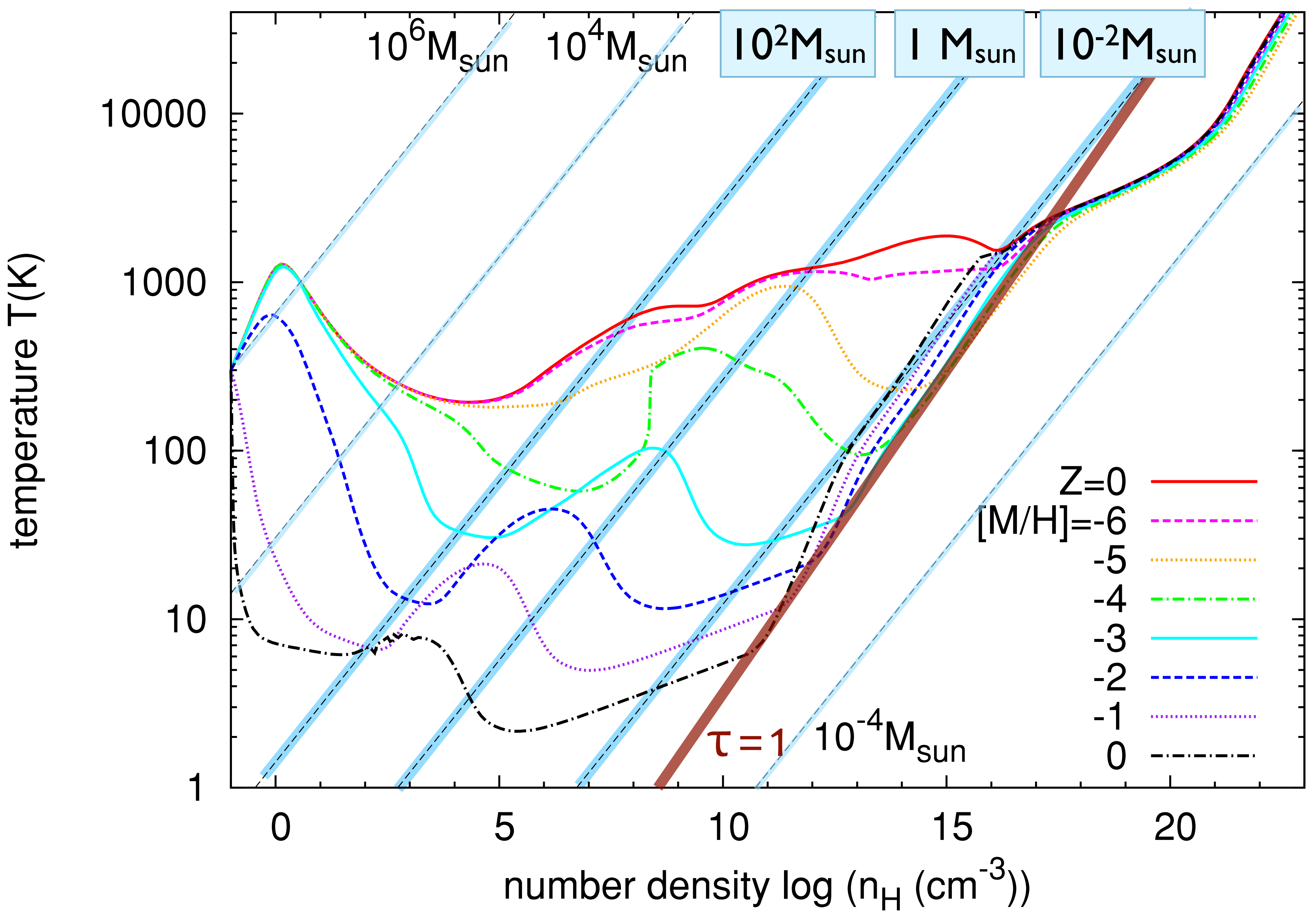
with $\rho_{crit} \approx 2.5\times10^5$ cm$^{-3}$

at SFE ≈ 50%

need appropriate EOS in order to get low mass IMF right

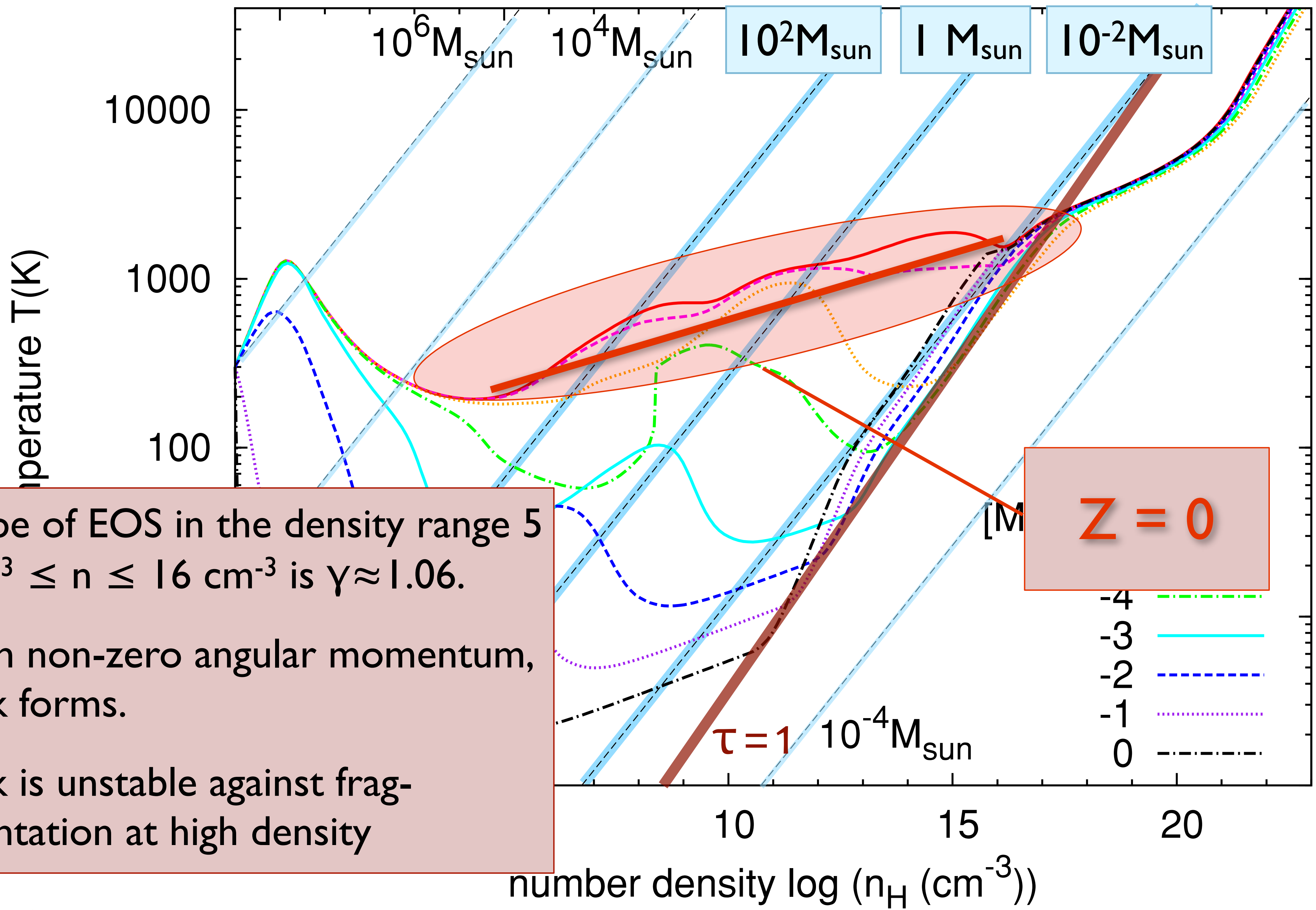
(Jappsen et al. 2005, A&A, 435, 611)

# EOS as function of metallicity



(Omukai et al. 2005, 2010)

# EOS as function of metallicity

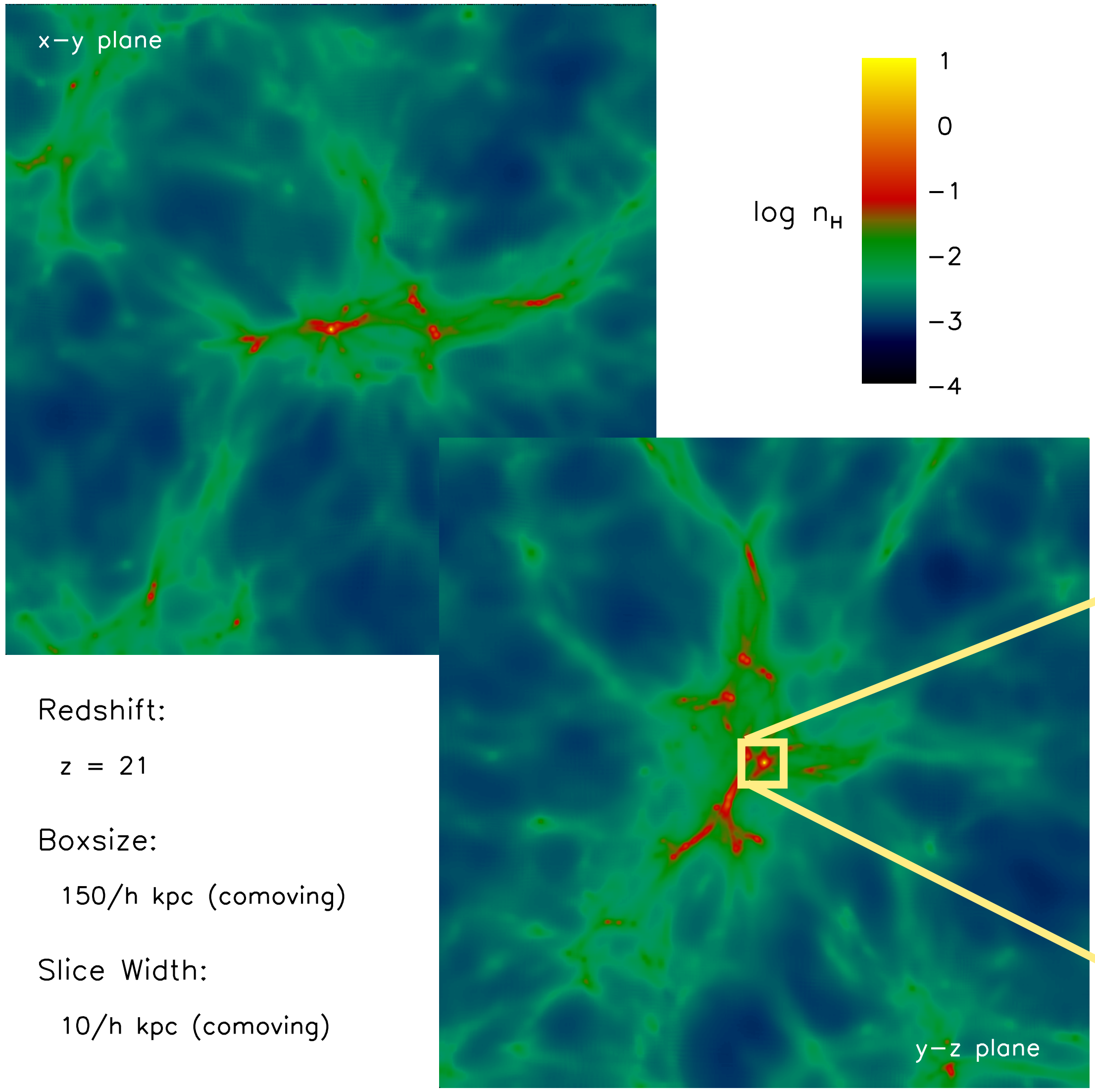


Z = 0

- 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

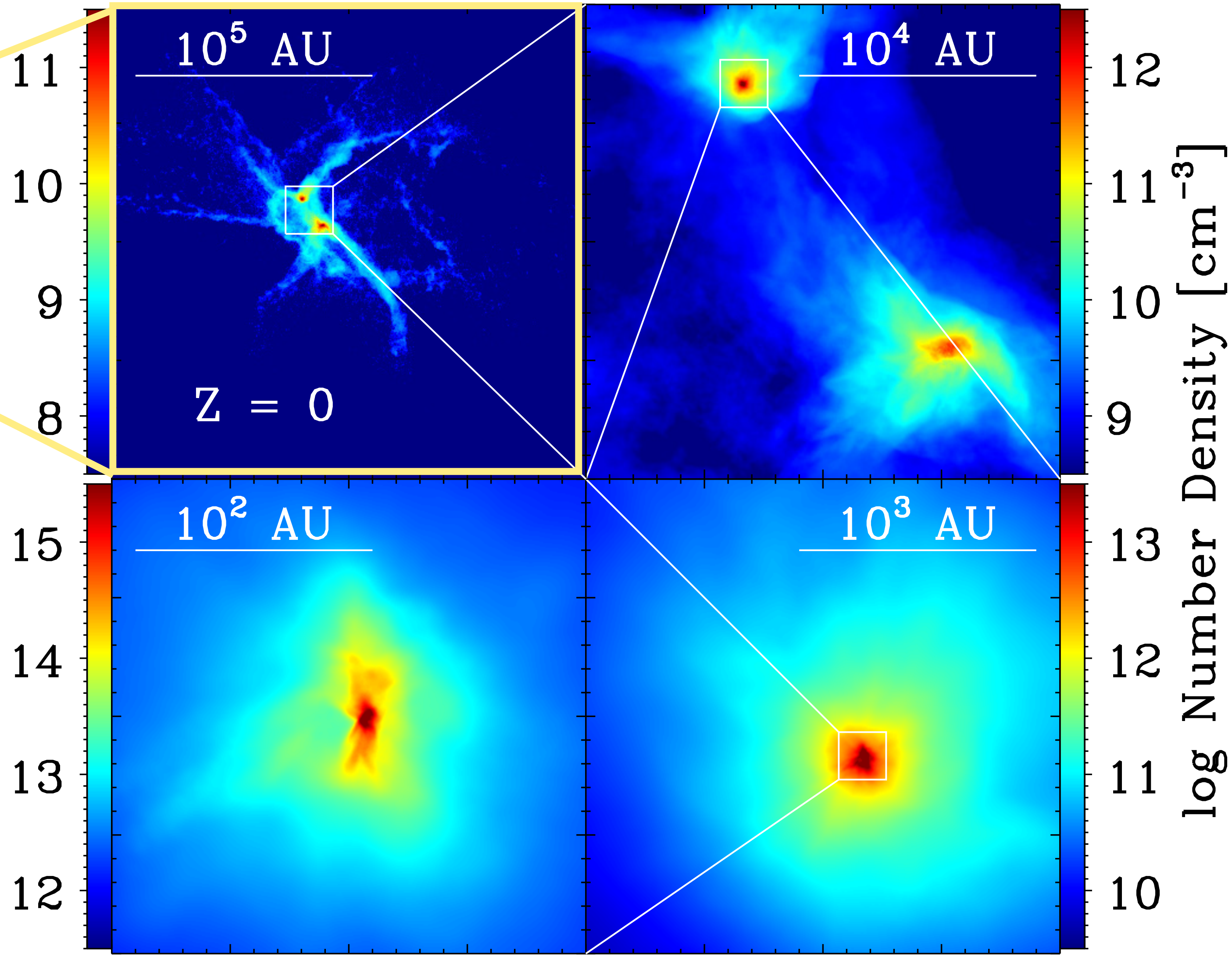
(Omukai et al. 2005, 2010)

# detailed look at accretion disk around first star



(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, Tanaka & Omukai, 2014, MNRAS, 439, 1884, Nakauchi et al. 2014, MNRAS, 442, 2667)

# detailed look at accretion disk

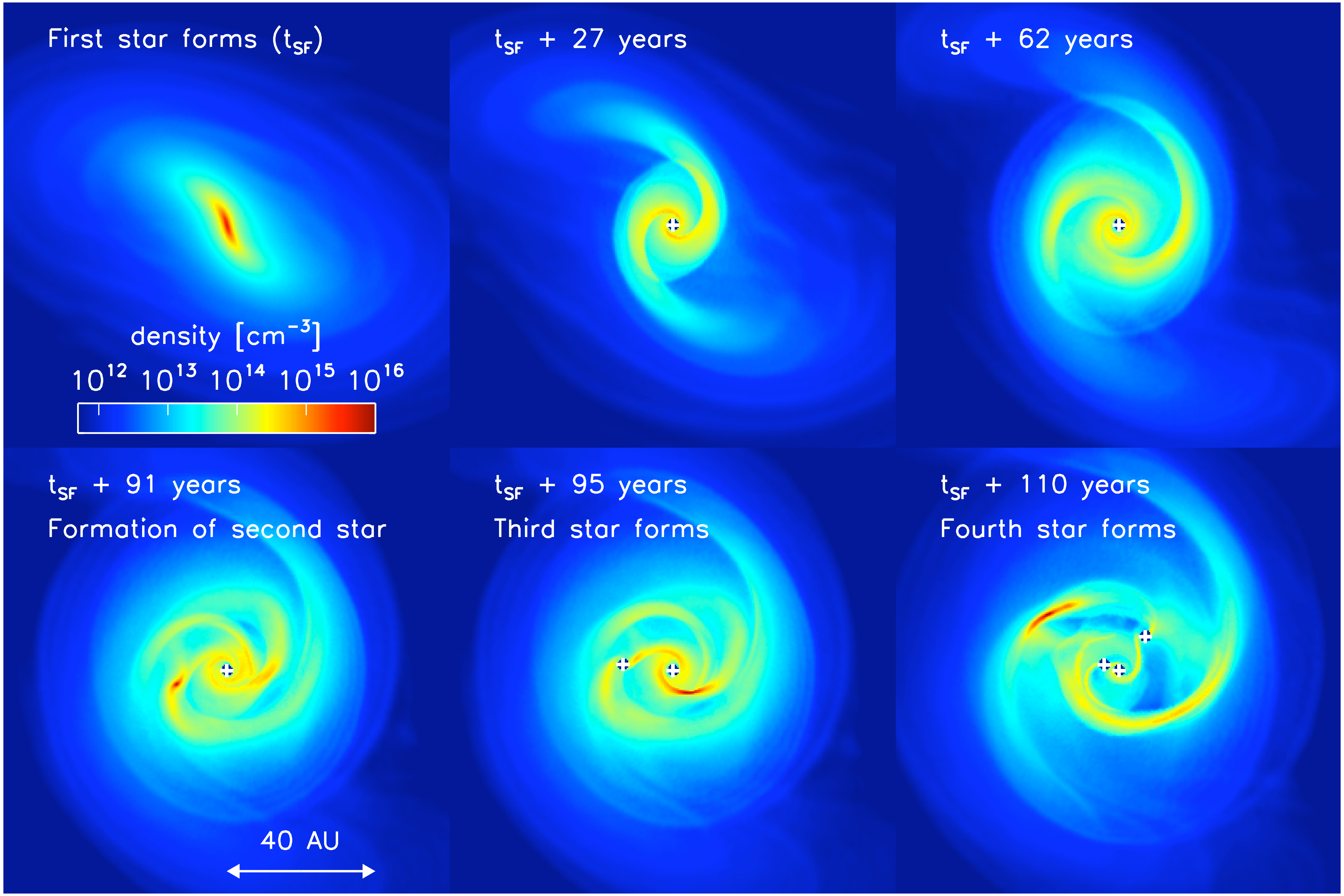
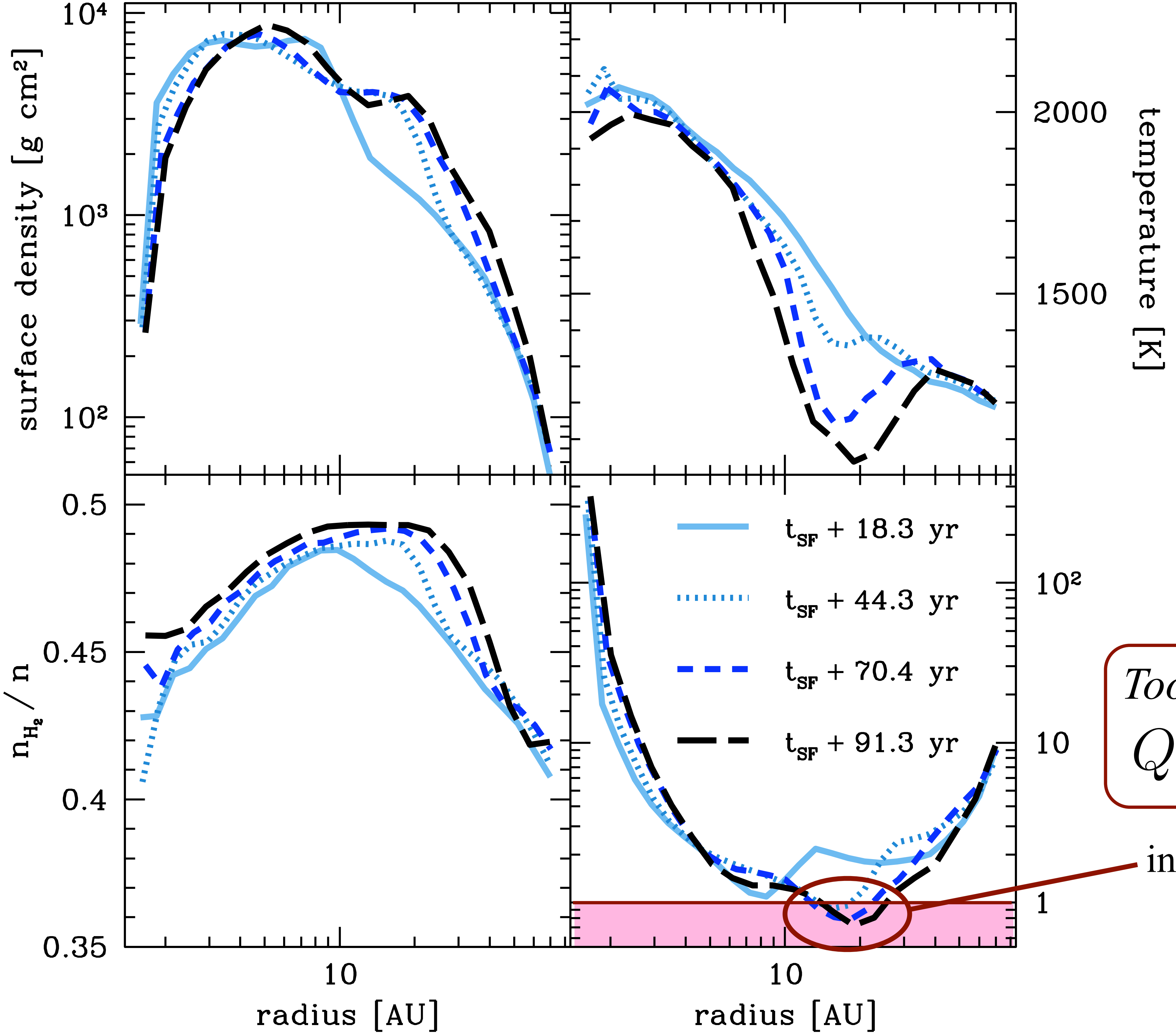


Figure 1: Density evolution in a 120 AU region around the first protostar, showing the build-up of the protostellar disk and its eventual fragmentation. We also see 'wakes' in the low-density regions, produced by the previous passage of the spiral arms.

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

# important disk parameters



*Toomre Q:*

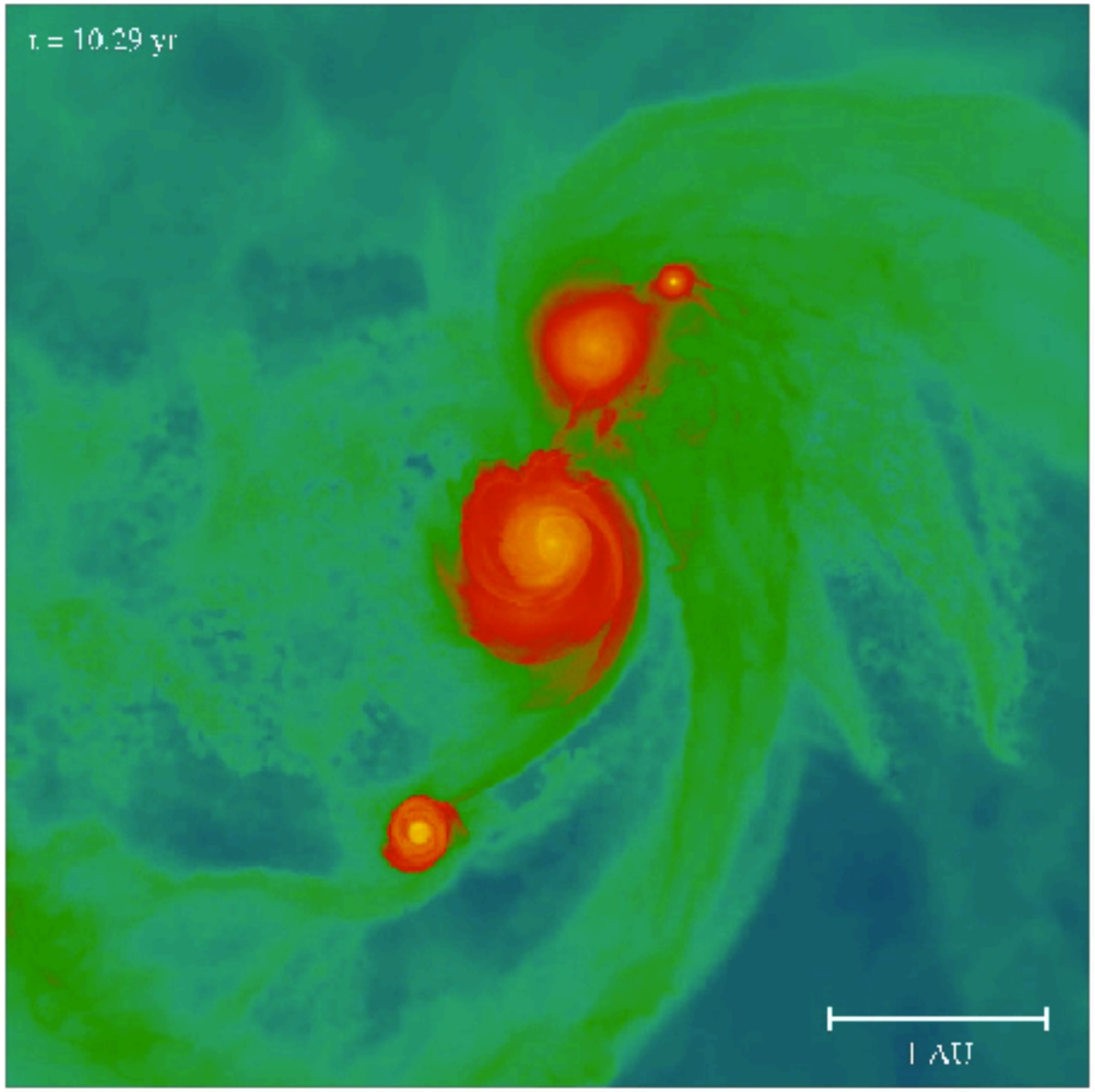
$$Q = c_s \kappa / \pi G \Sigma$$

instability for $Q<1$

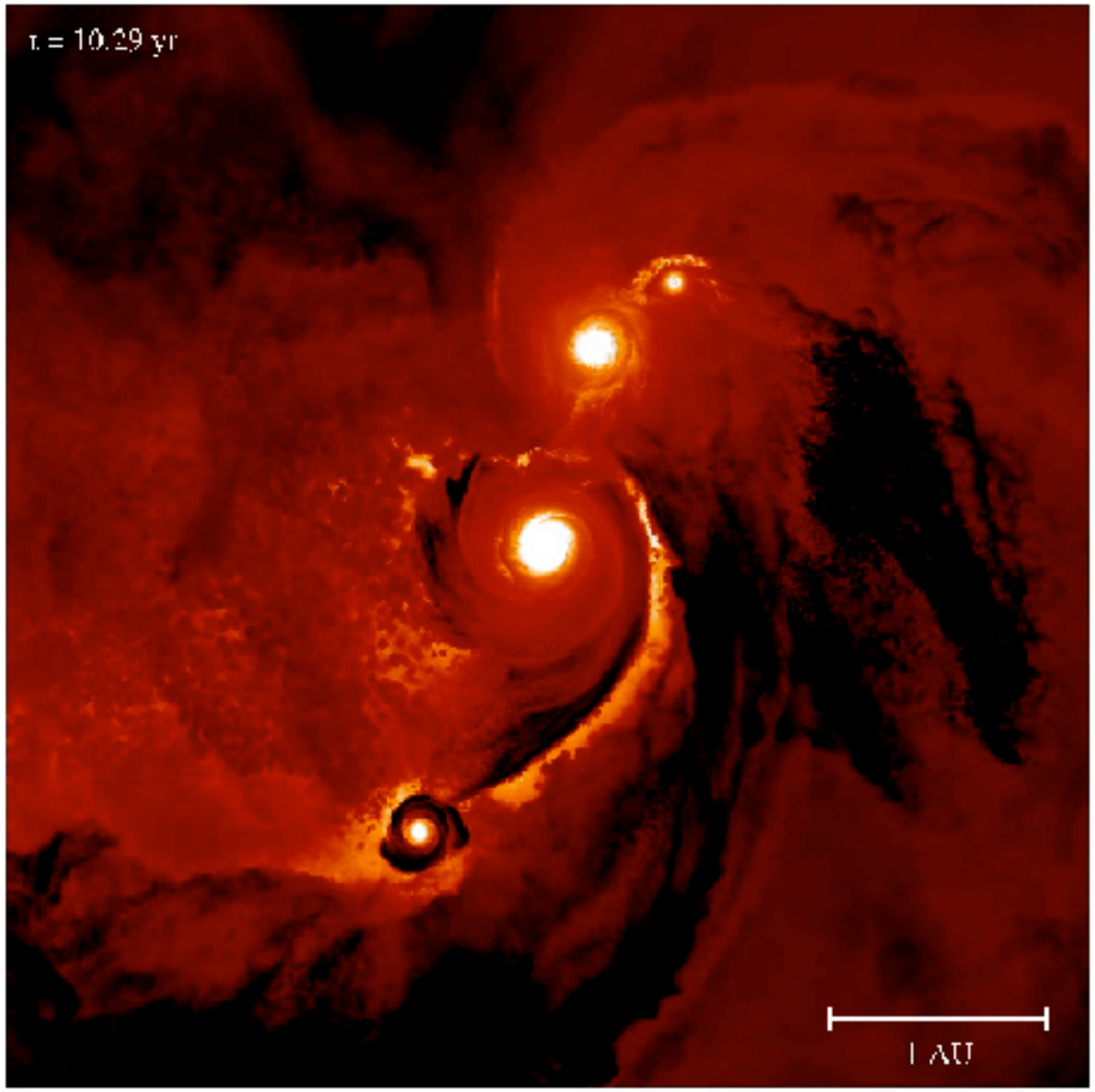
(Clark et al. 2011b, Science, 331, 1040)

# highest resolution 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)

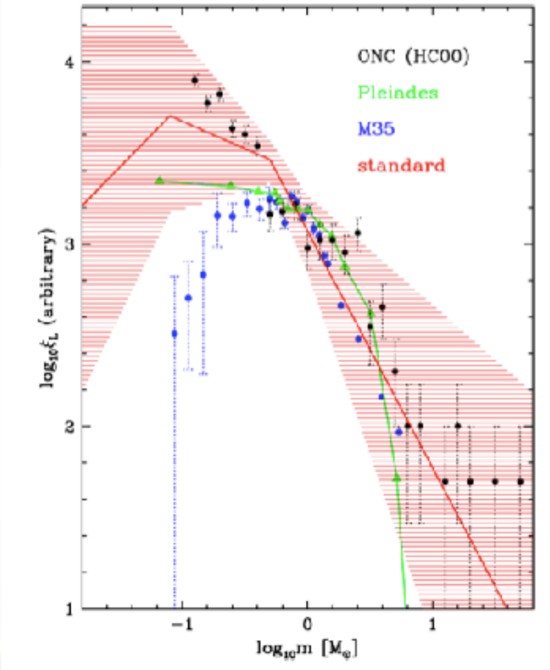
# expected mass spectrum

- *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

# stellar masses

- distribution of stellar masses depends on
  - turbulent initial conditions
    --> mass spectrum of prestellar cloud cores
  - collapse and interaction of prestellar cores
    --> accretion and *N*-body effects
  - thermodynamic properties of gas
    --> balance between heating and cooling
    --> EOS (determines which cores go into collapse)
  - (proto) stellar feedback terminates star formation
    ionizing radiation, bipolar outflows, winds, SN

(Kroupa 2002)



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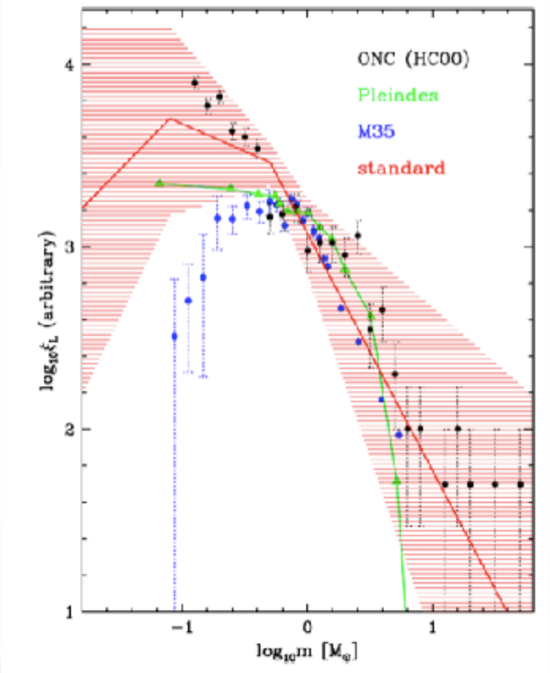


# model for Orion

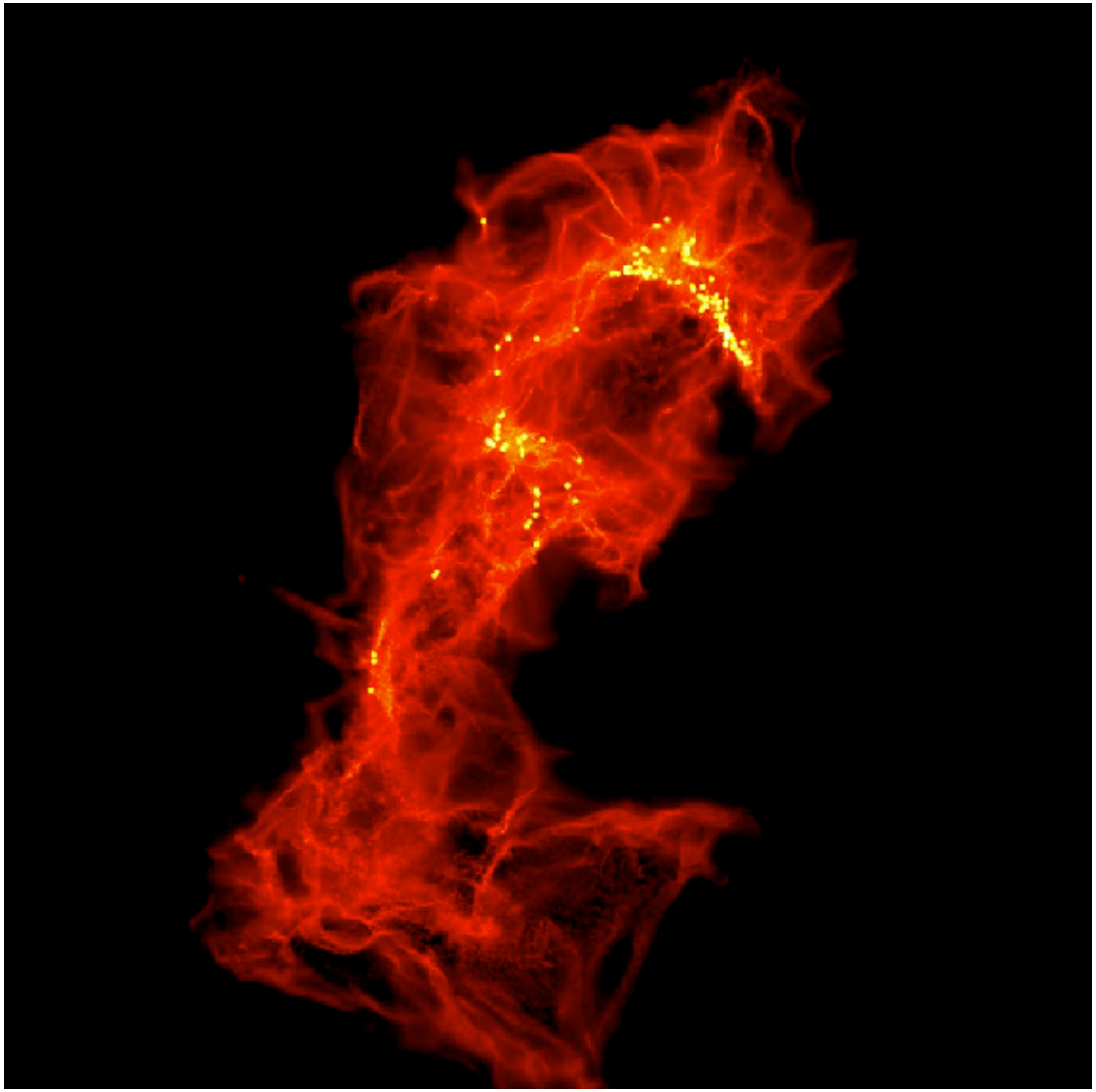
„model“ of Orion cloud:
15.000.000 SPH particles,
$10^4$ $M_{sun}$ in 10 pc, mass resolution 0,02 $M_{sun}$, forms ~2.500 „stars“ (sink particles)

isothermal EOS, top bound, bottom unbound

has clustered as well as distributed „star“ formation

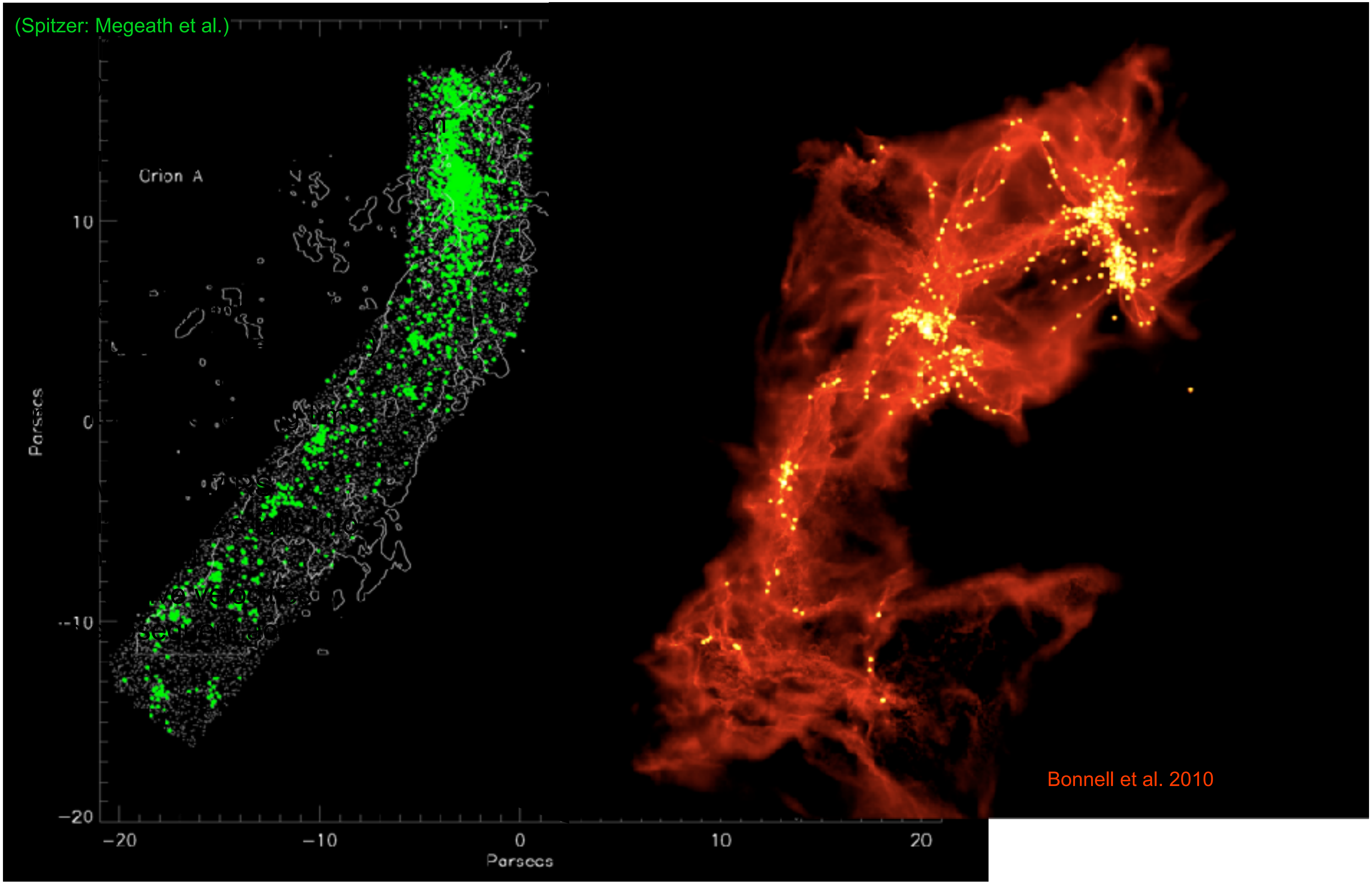
efficiency varies from 1% to 20%

develops full IMF
(distribution of sink particle masses)



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

# model for Orion

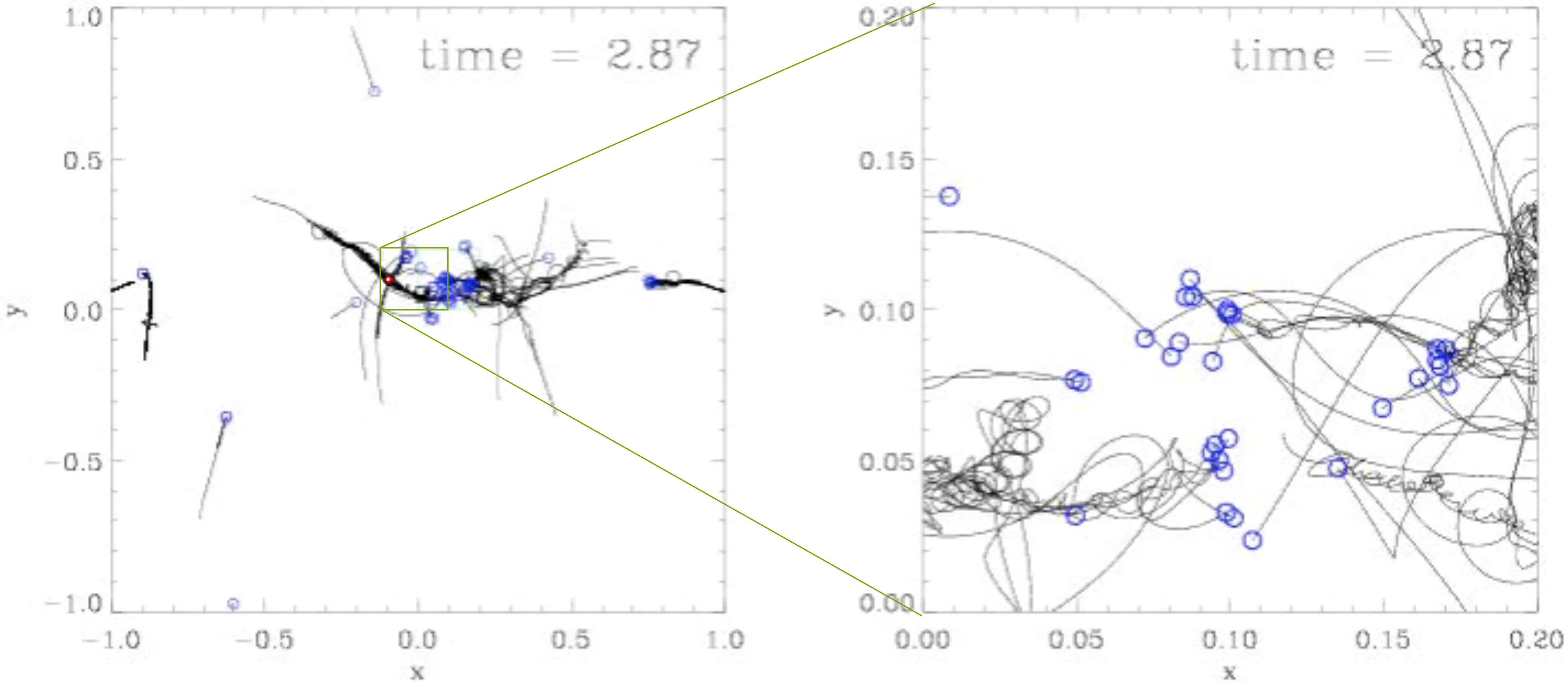


(Spitzer: Megeath et al.)

Bonnell et al. 2010

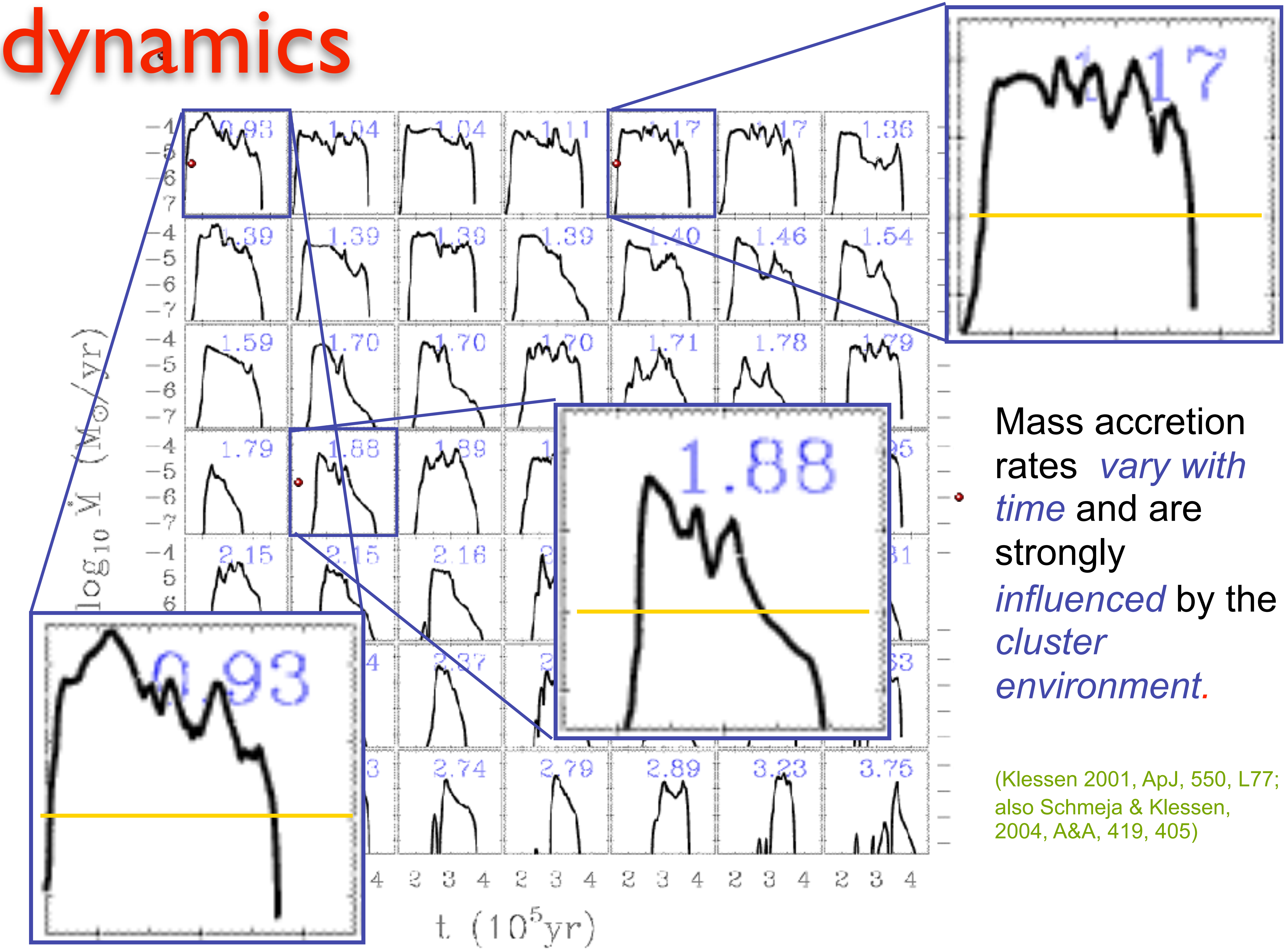
# dynamics of nascent star clusters

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)

# dynamics



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)

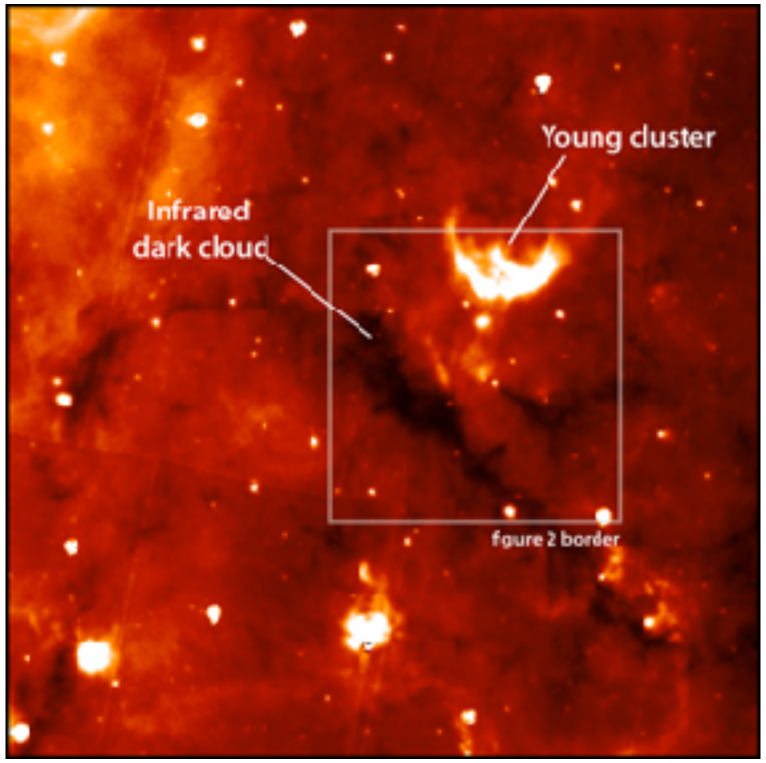
# initial conditions of star clusters

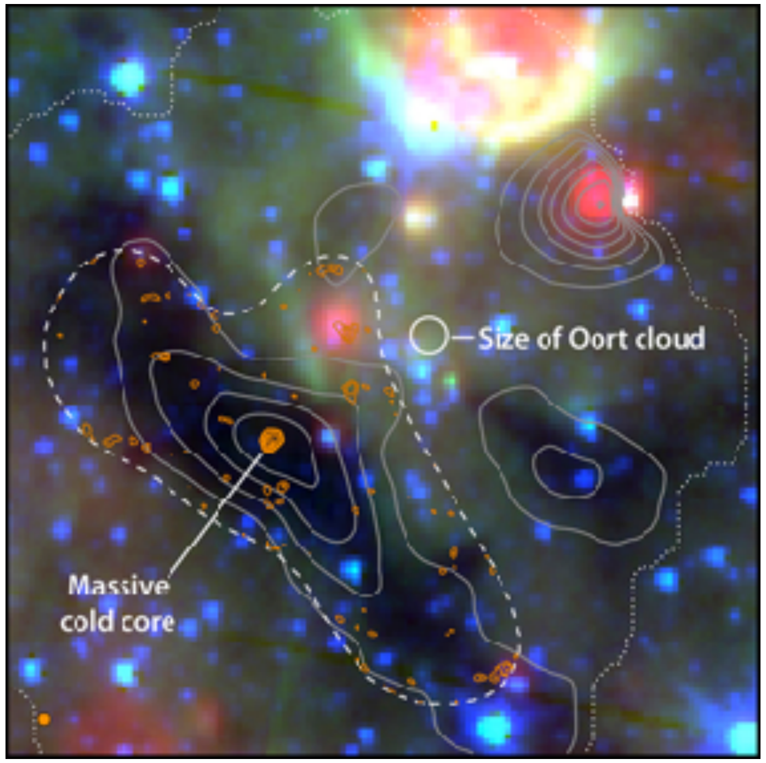
- key question:
  - what is the initial density profile of cluster forming cores? how does it compare low-mass cores?
- observers answer:
  - very difficult to determine!

clipartkid.com

# initial conditions of star clusters

- 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

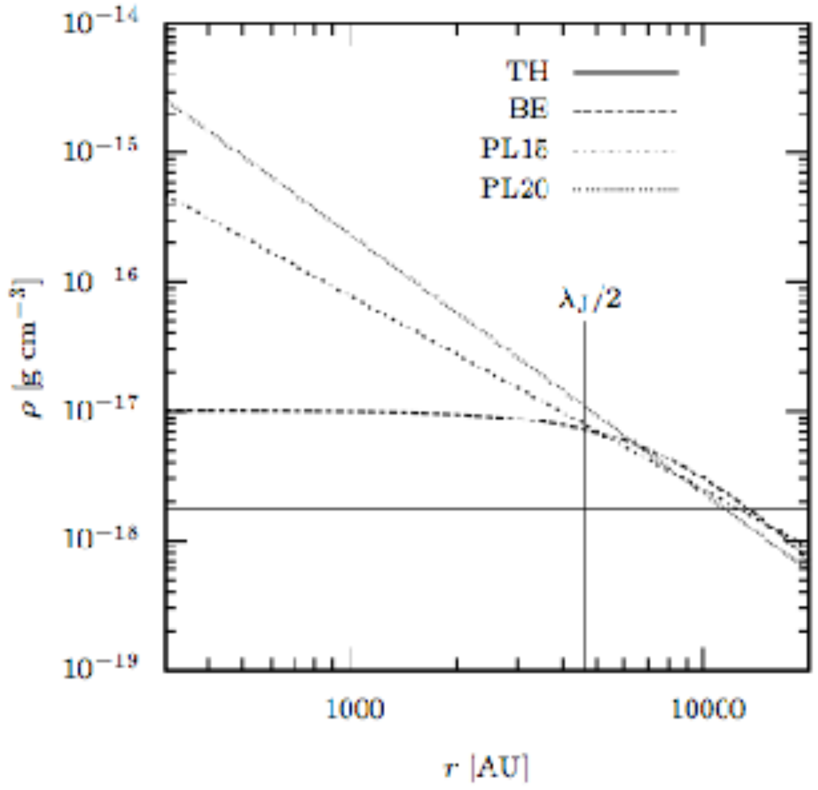




IRDC near Aquila rift, studied with the SMA: J. Swift & E. Churchwell

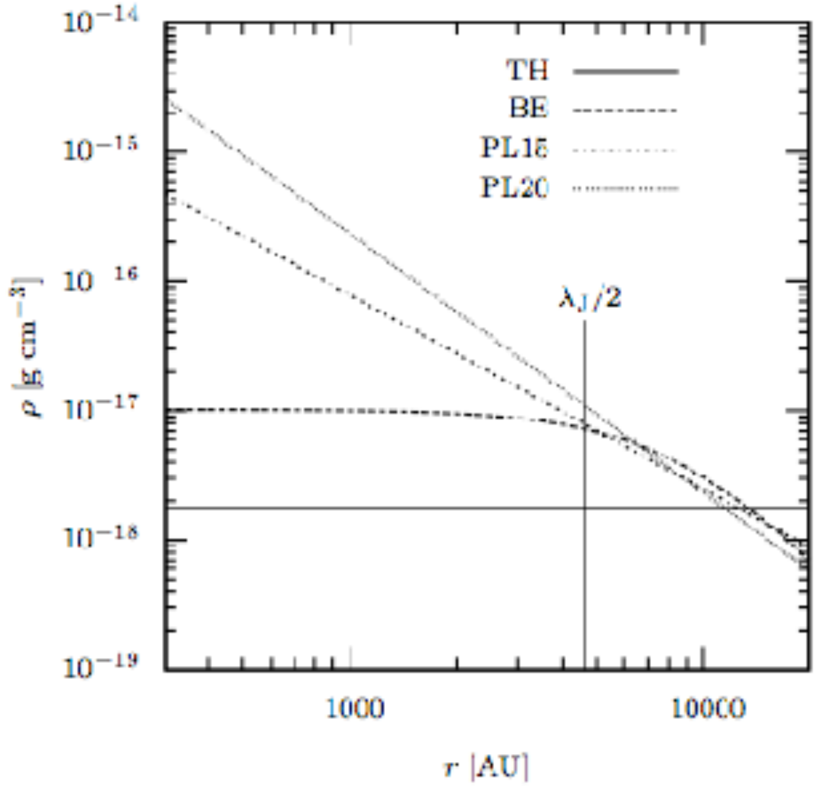
# initial conditions of star clusters

- 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



# initial conditions of star clusters

- 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)



Girichidis et al. (2011, MNRAS, 413, 2741)
Girichidis et al. (2012, MNRAS, 420, 613)
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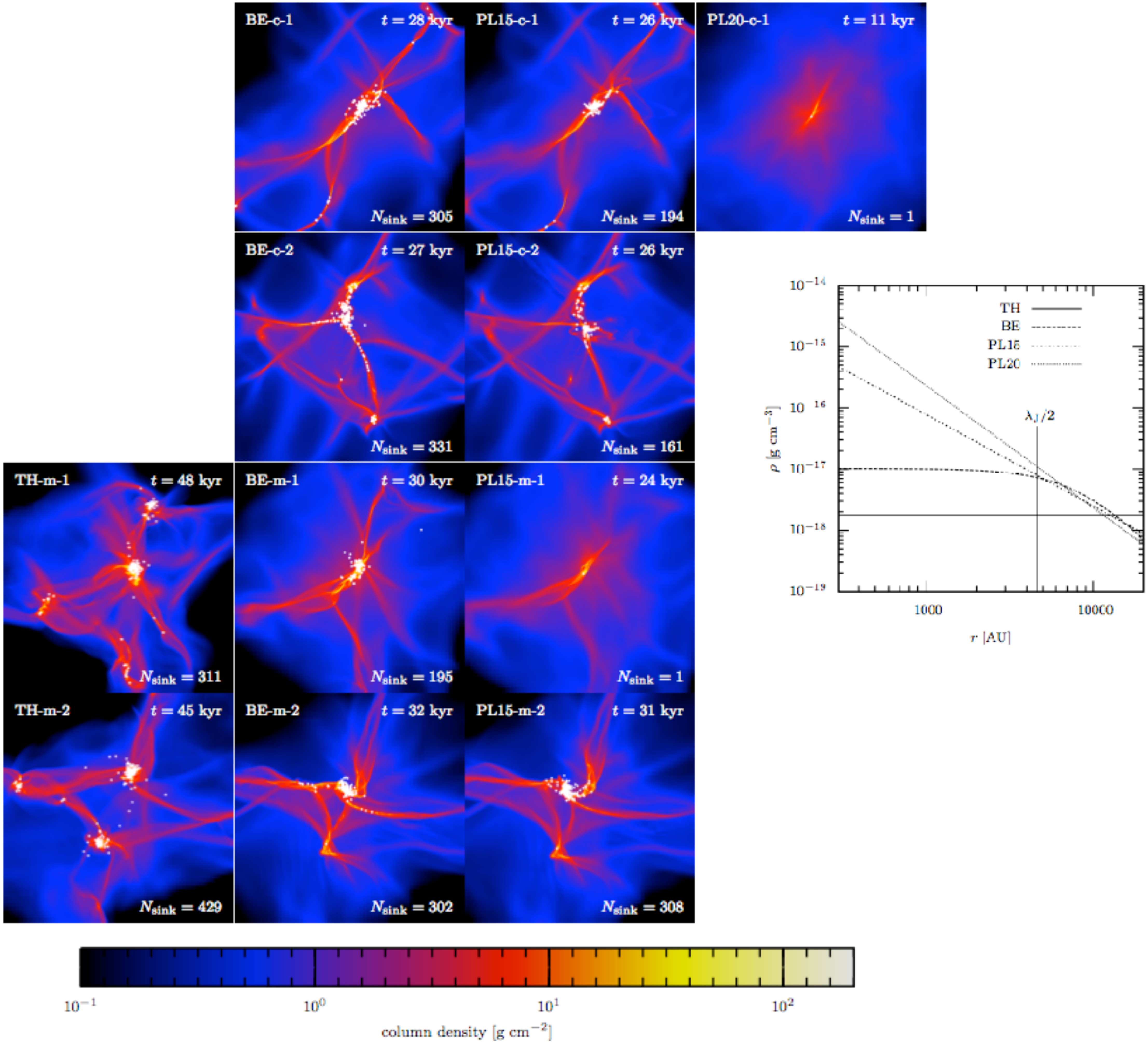

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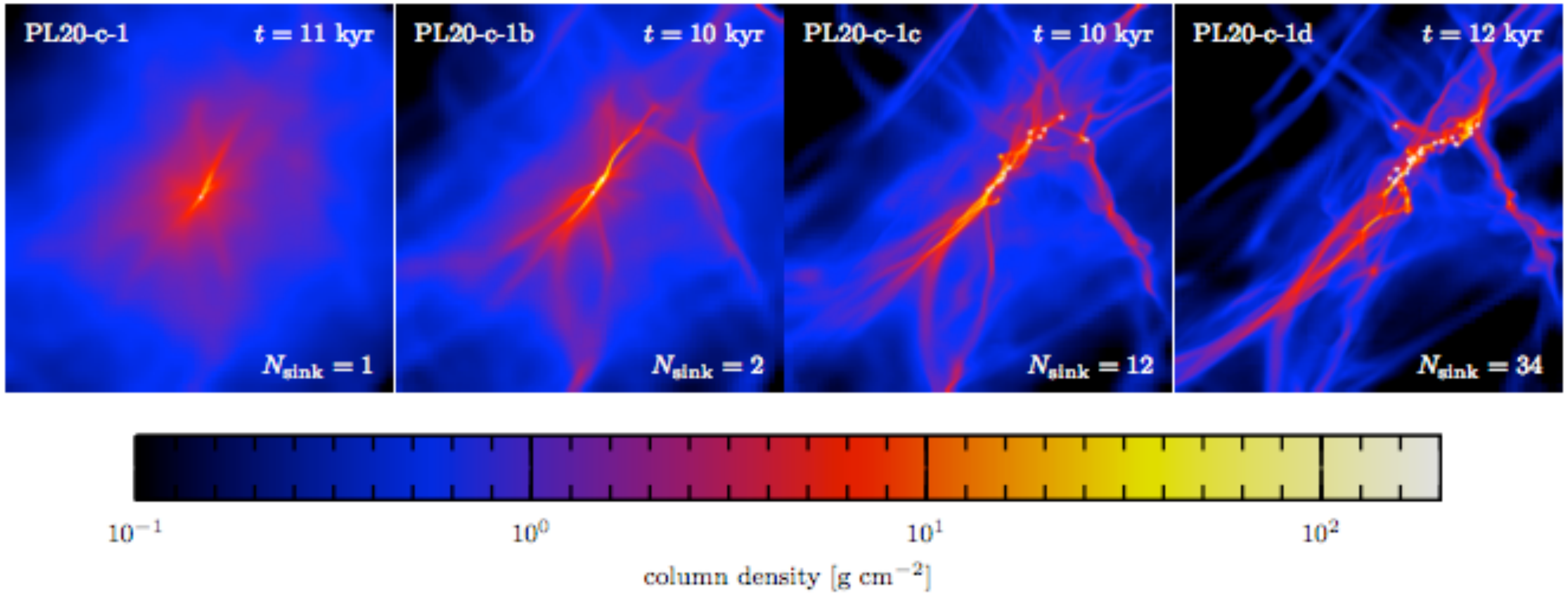

M=3 M=6 M=12 M=18

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

Girichidis et al. (2011, MNRAS, 413, 2741)
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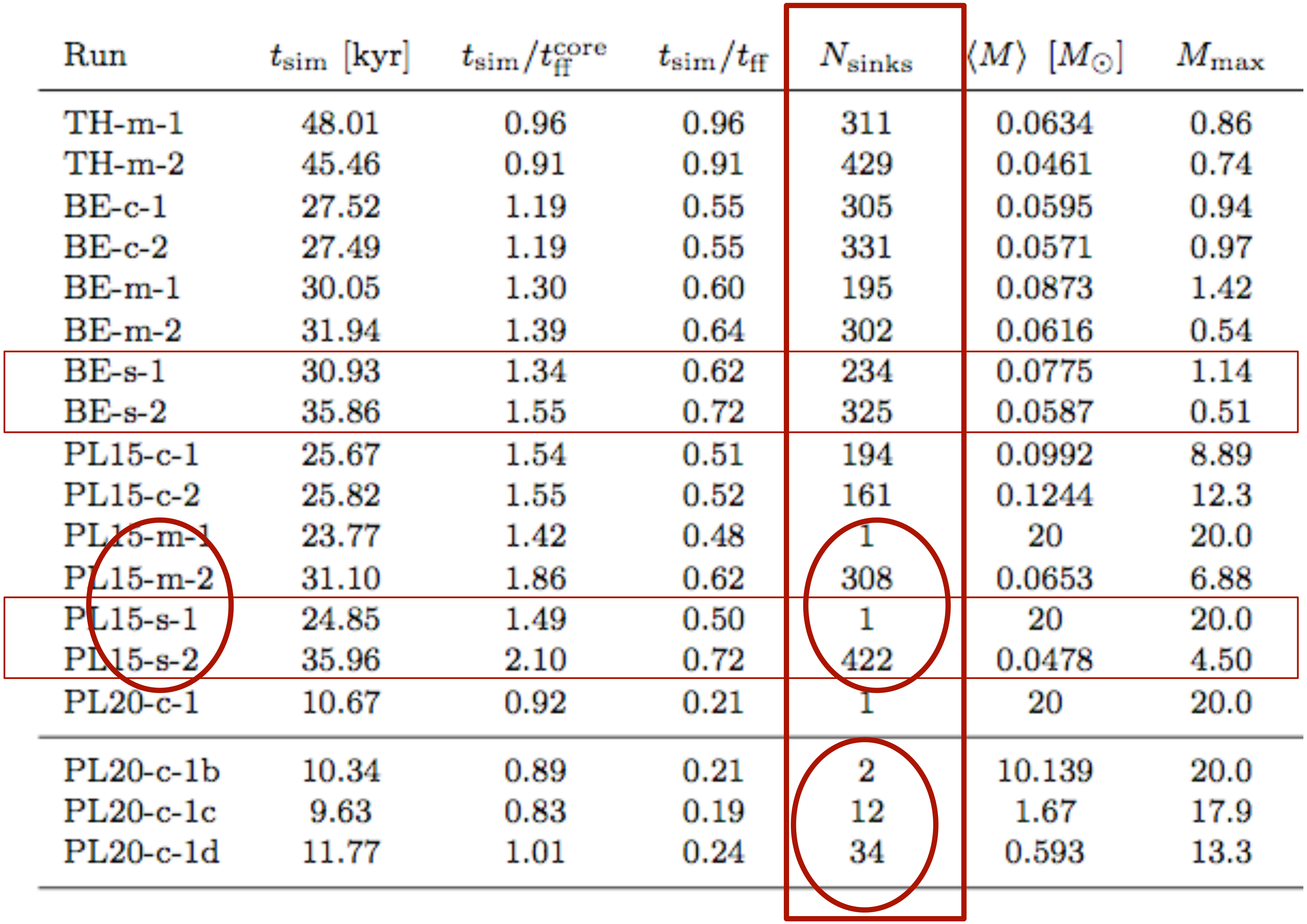
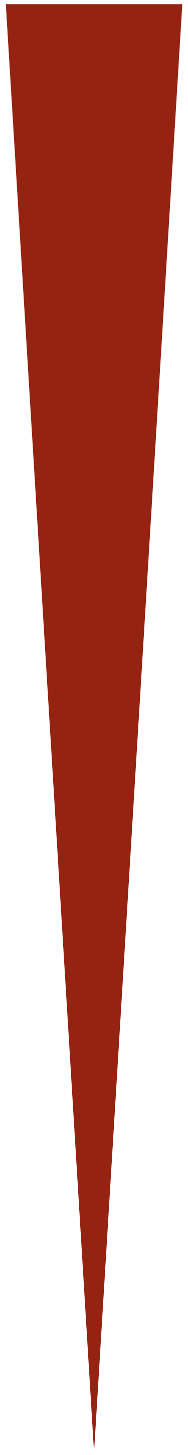


| Run | $t_{\rm sim}$ [kyr] | $t_{\rm sim}/t_{\rm ff}^{\rm core}$ | $t_{\rm sim}/t_{\rm ff}$ | $N_{\rm sinks}$ | $\langle M \rangle$ [$M_\odot$] | $M_{\rm max}$ |
|---|---|---|---|---|---|---|
| TH-m-1 | 48.01 | 0.96 | 0.96 | 311 | 0.0634 | 0.86 |
| TH-m-2 | 45.46 | 0.91 | 0.91 | 429 | 0.0461 | 0.74 |
| 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

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

very high Mach numbers are needed to make SIS fragment

Girichidis et al. (2011, MNRAS, 413, 2741), Girichidis et al. (2012, MNRAS, 420, 613), Girichidis et al. (2012, MNRAS, 420, 3264)

# initial conditions of star clusters

- 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.

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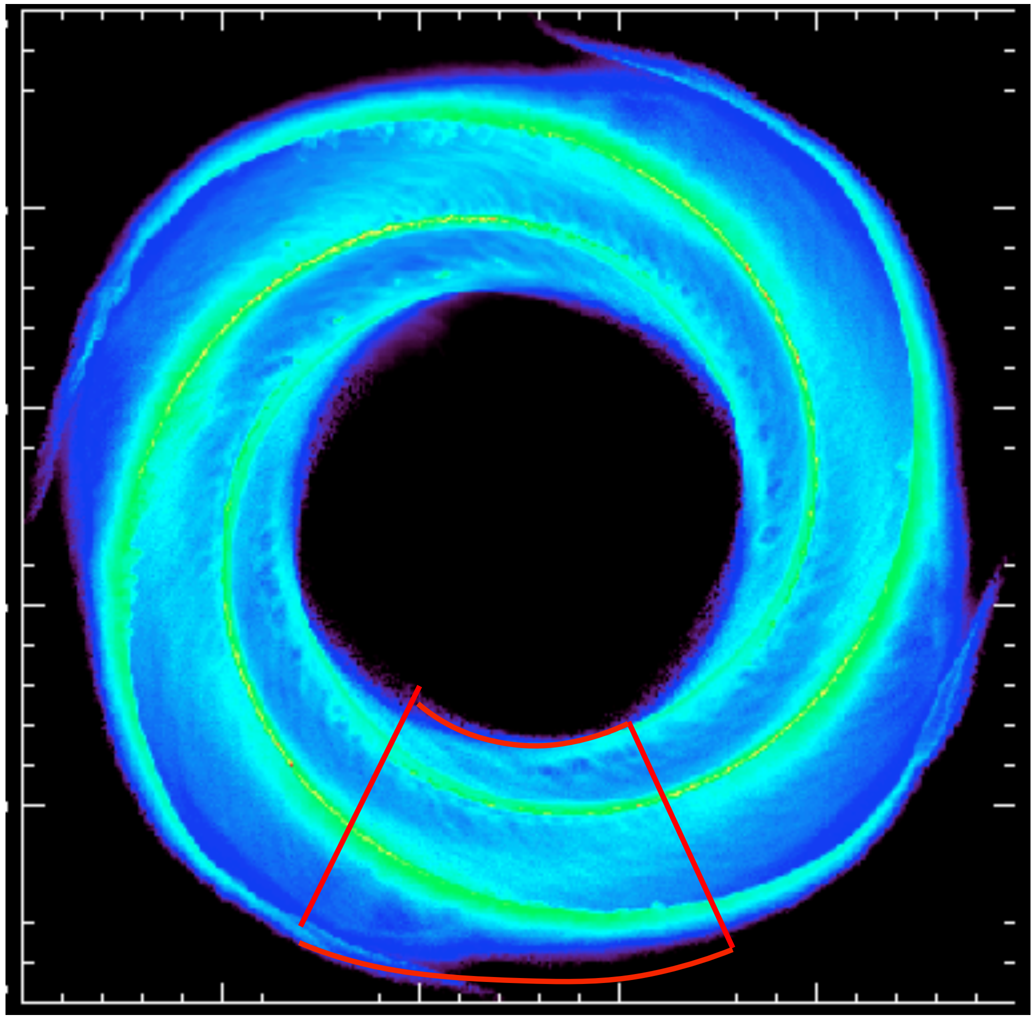
what you put in,
you get out !!!!

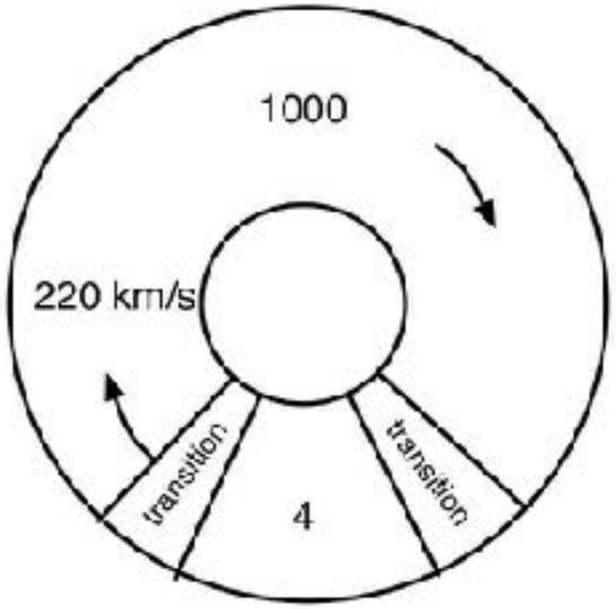
Girichidis et al. (2011, MNRAS, 413, 2741), Girichidis et al. (2012, MNRAS, 420, 613), Girichidis et al. (2012, MNRAS, 420, 3264)

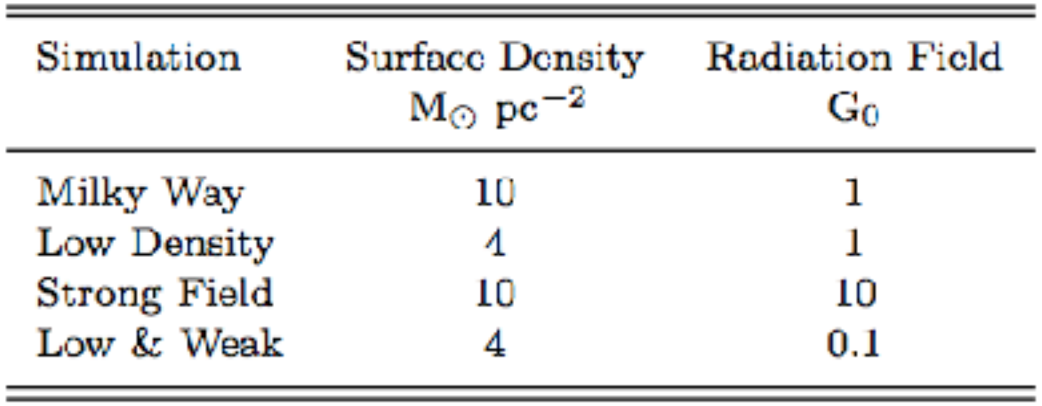
# some current developments

# modeling molecular cloud formatior

current developments





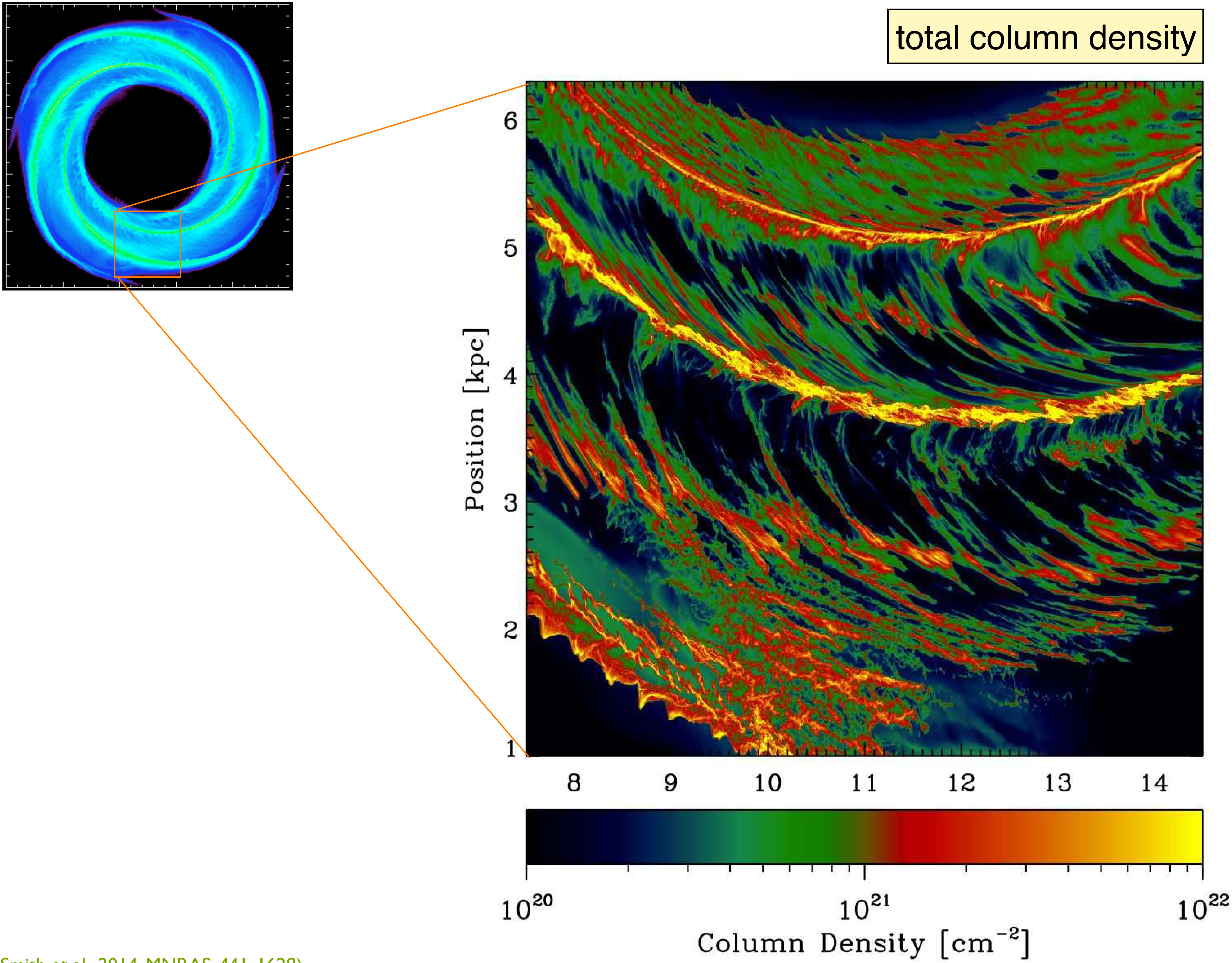


| Simulation | Surface Density $M_\odot\ pc^{-2}$ | Radiation Field $G_0$ |
|---|---|---|
| Milky Way | 10 | 1 |
| Low Density | 4 | 1 |
| Strong Field | 10 | 10 |
| Low & Weak | 4 | 0.1 |

- 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)*

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

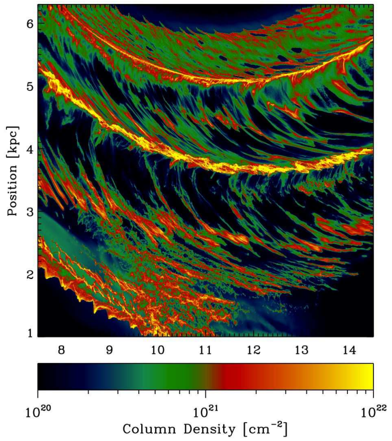
# current developments



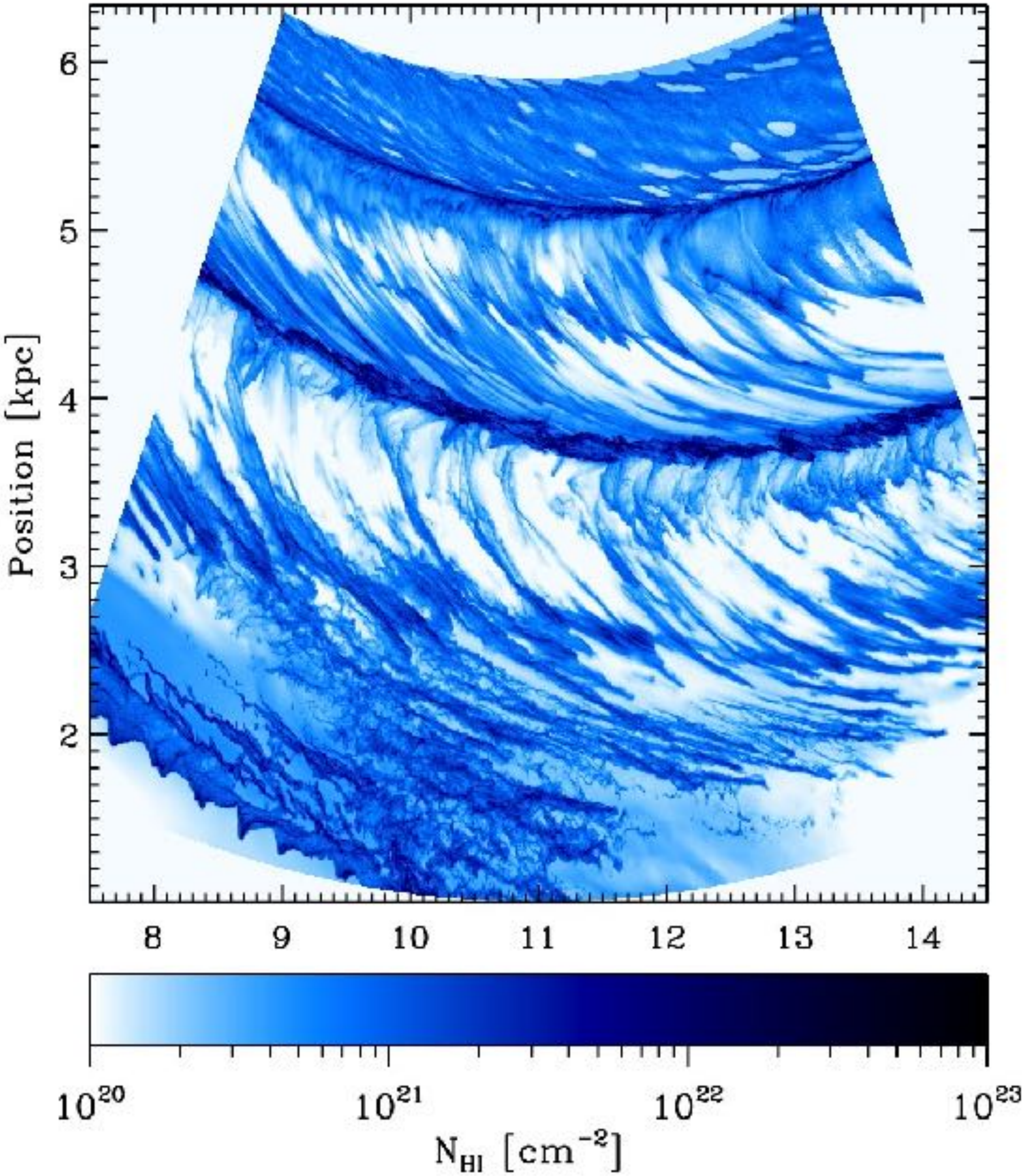
total column density

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

# current developments

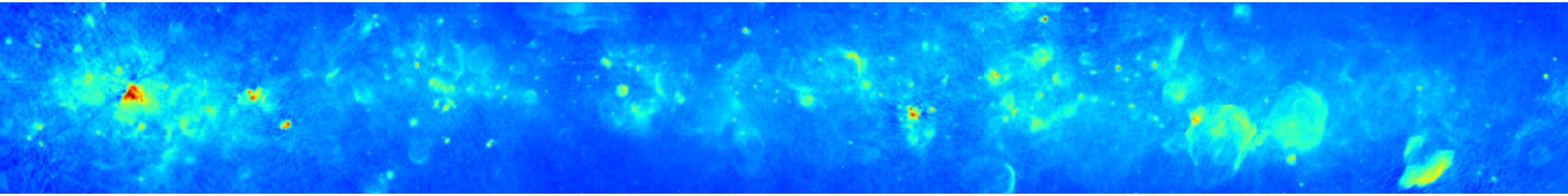


HI column density



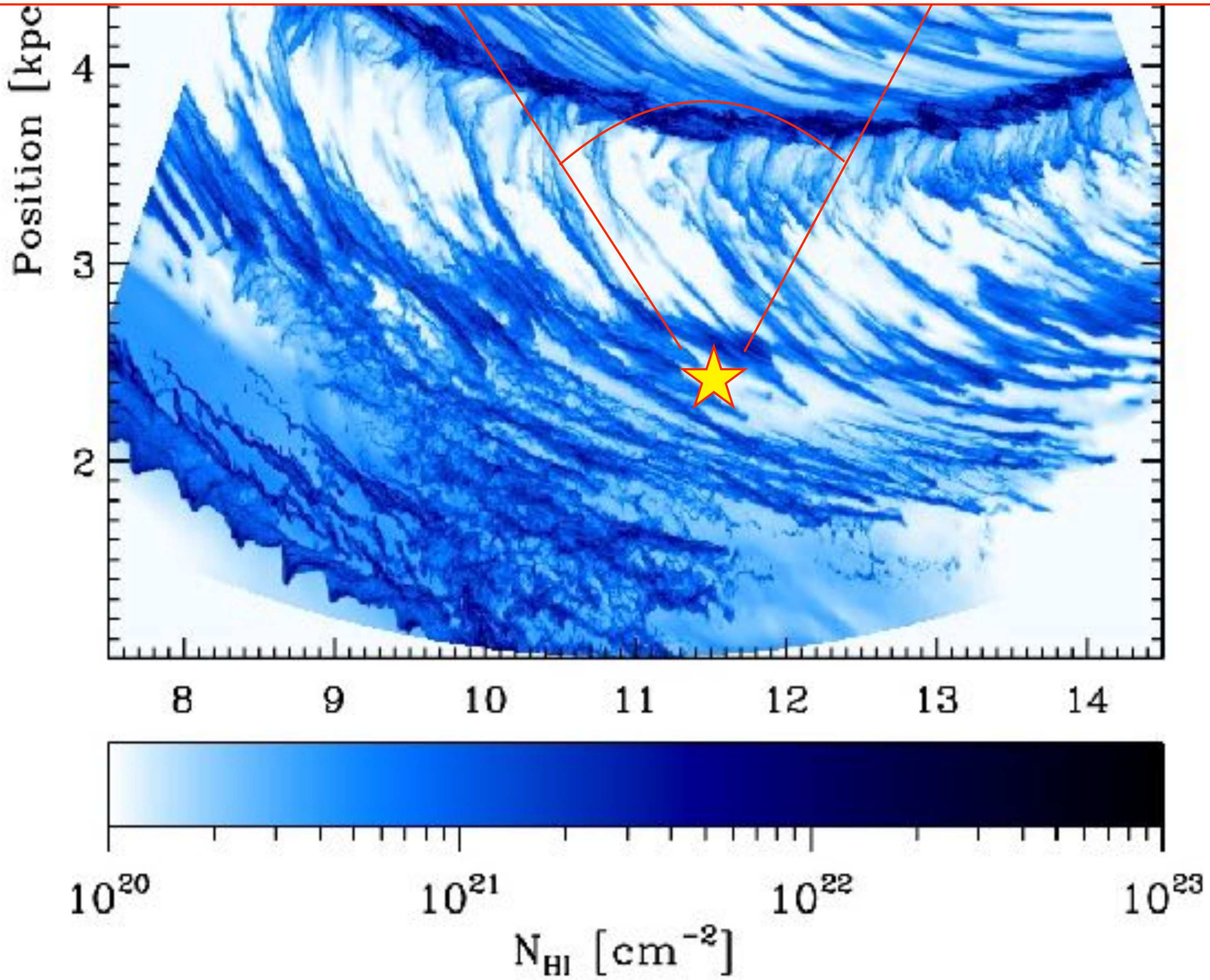
(Smith et al., 2014, MNRAS, 441, 1628)

image from THOR Galactic plane survey (PI H. Beuther): continuum emission around 21 cm



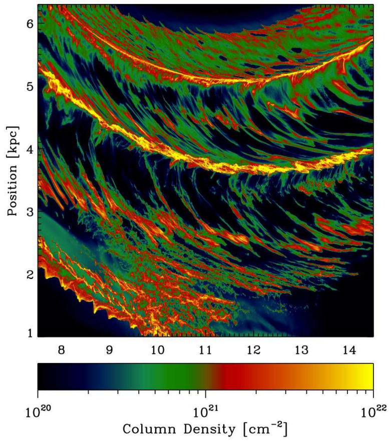
next step: produce all sky maps at various positions in the model galaxy (use RADMC-3D)

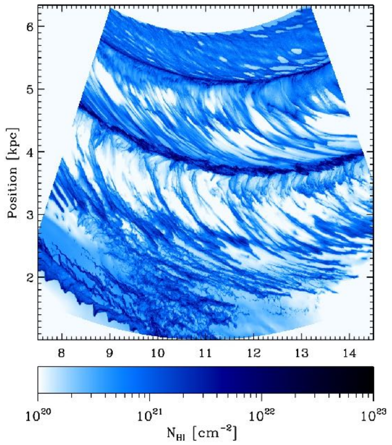
(Beuther et al., 2016, A&A, in press, arXiv:1609.03329, Bihr et al. 2016, A&A, 588, A97)



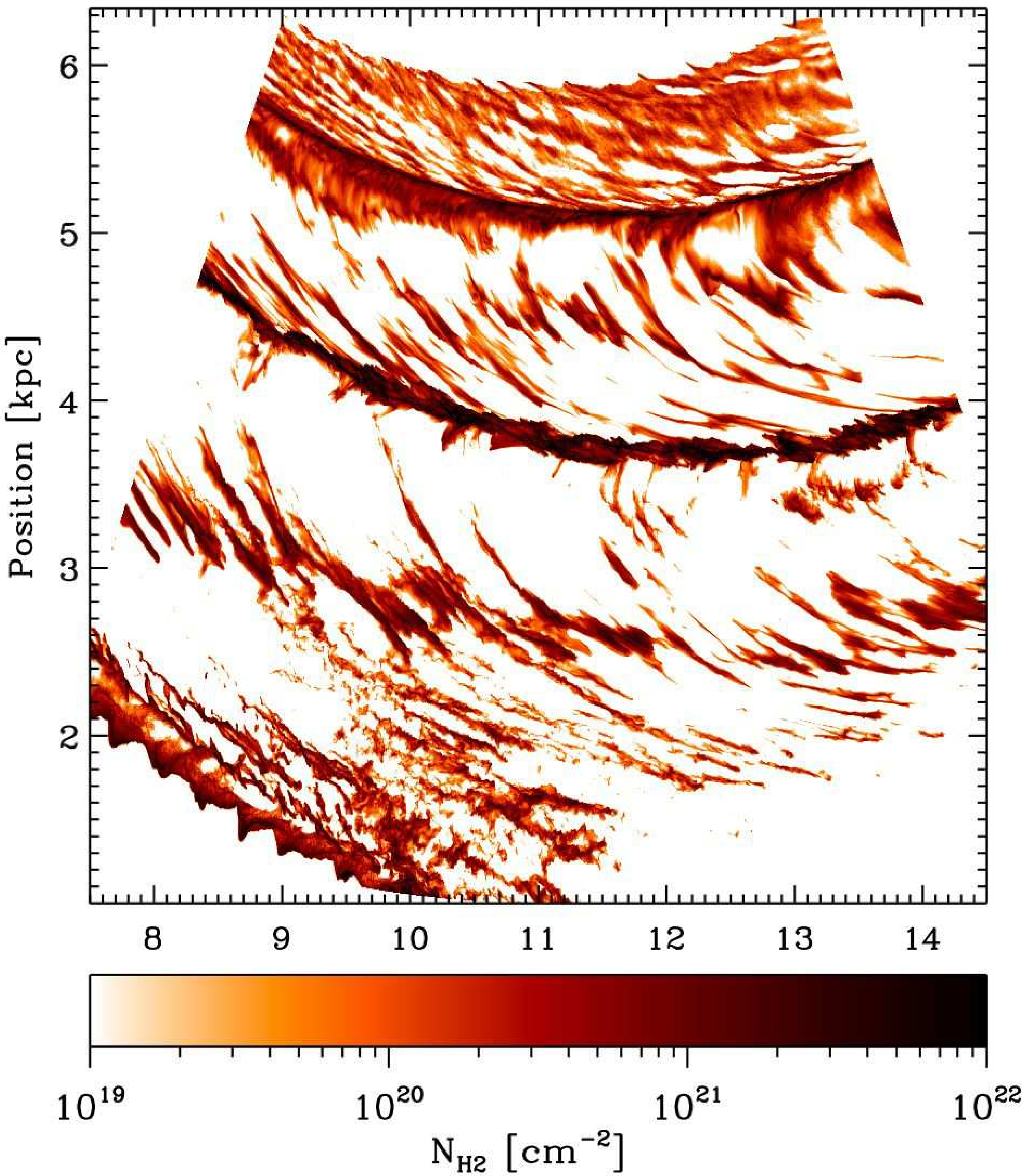
(Smith et al., 2014, MNRAS, 441, 1628)

evelopments





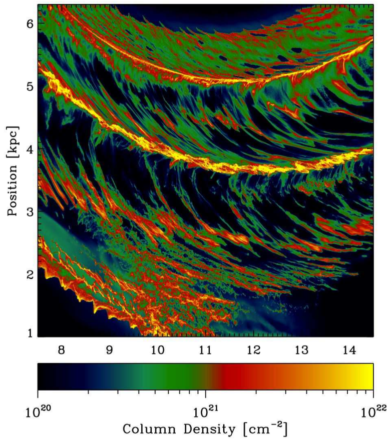
H$_2$ column density

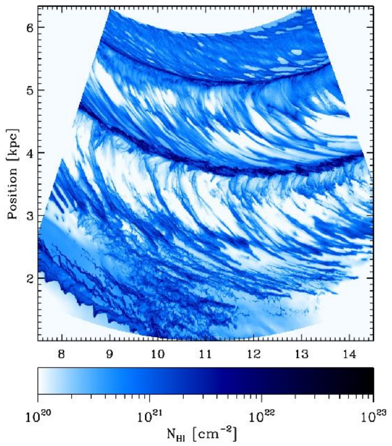


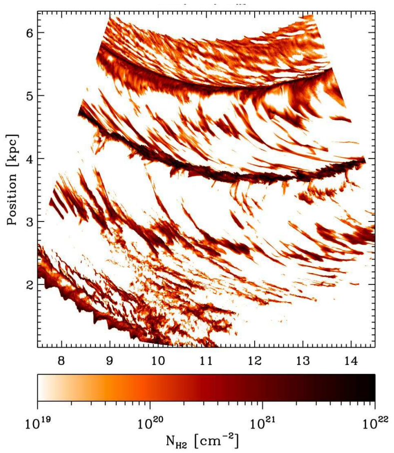
(Smith et al., 2014, MNRAS, 441, 1628)

current developments

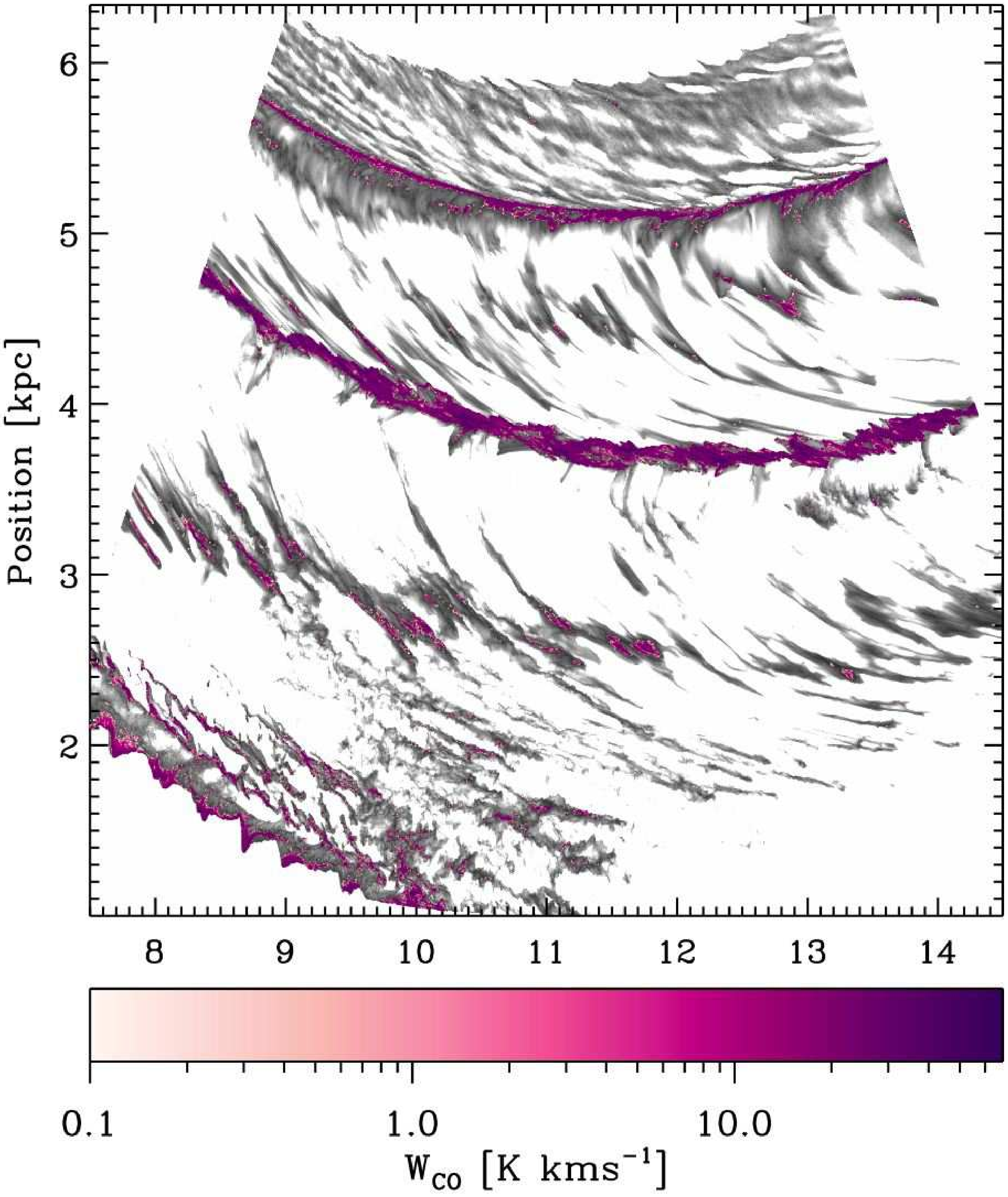
# current developments





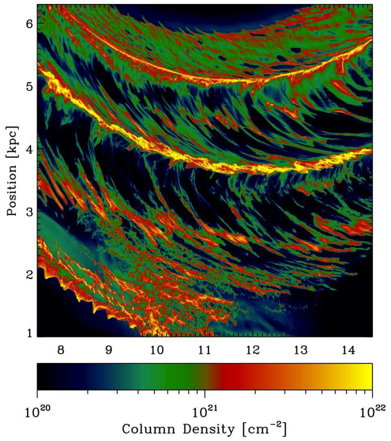


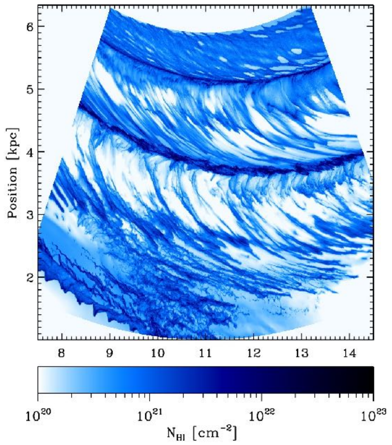
CO column density

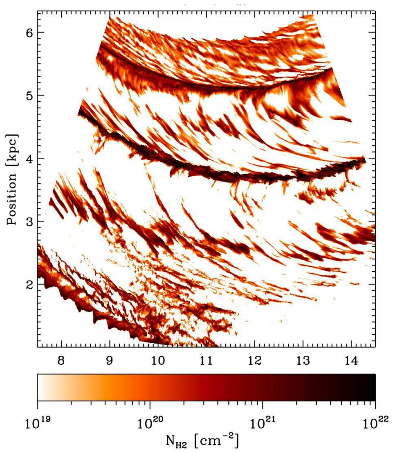


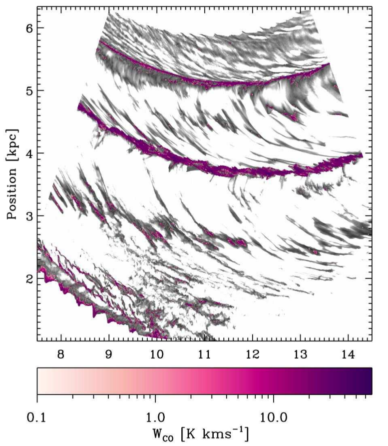
(Smith et al., 2014, MNRAS, 441, 1628)

# current developments

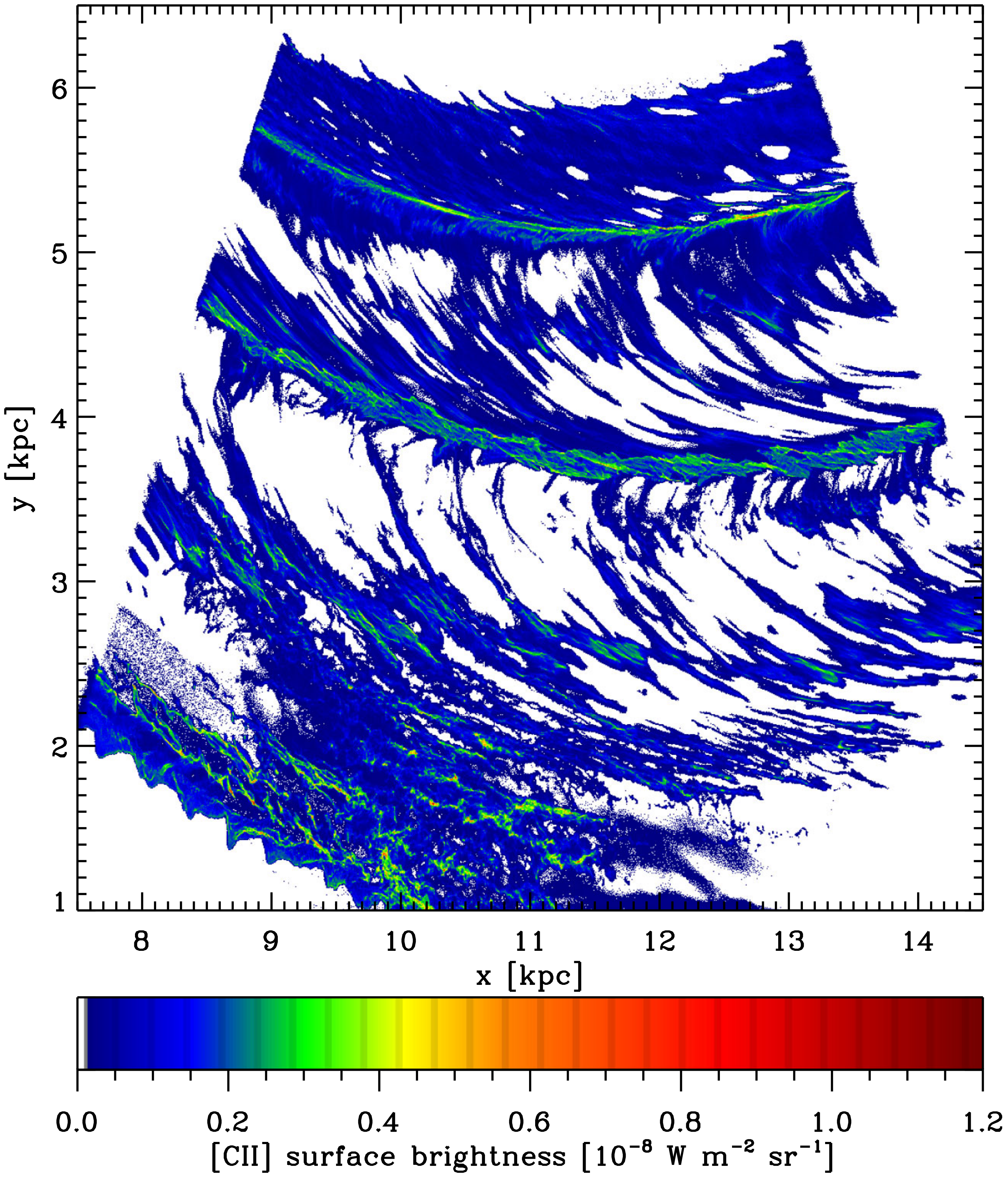






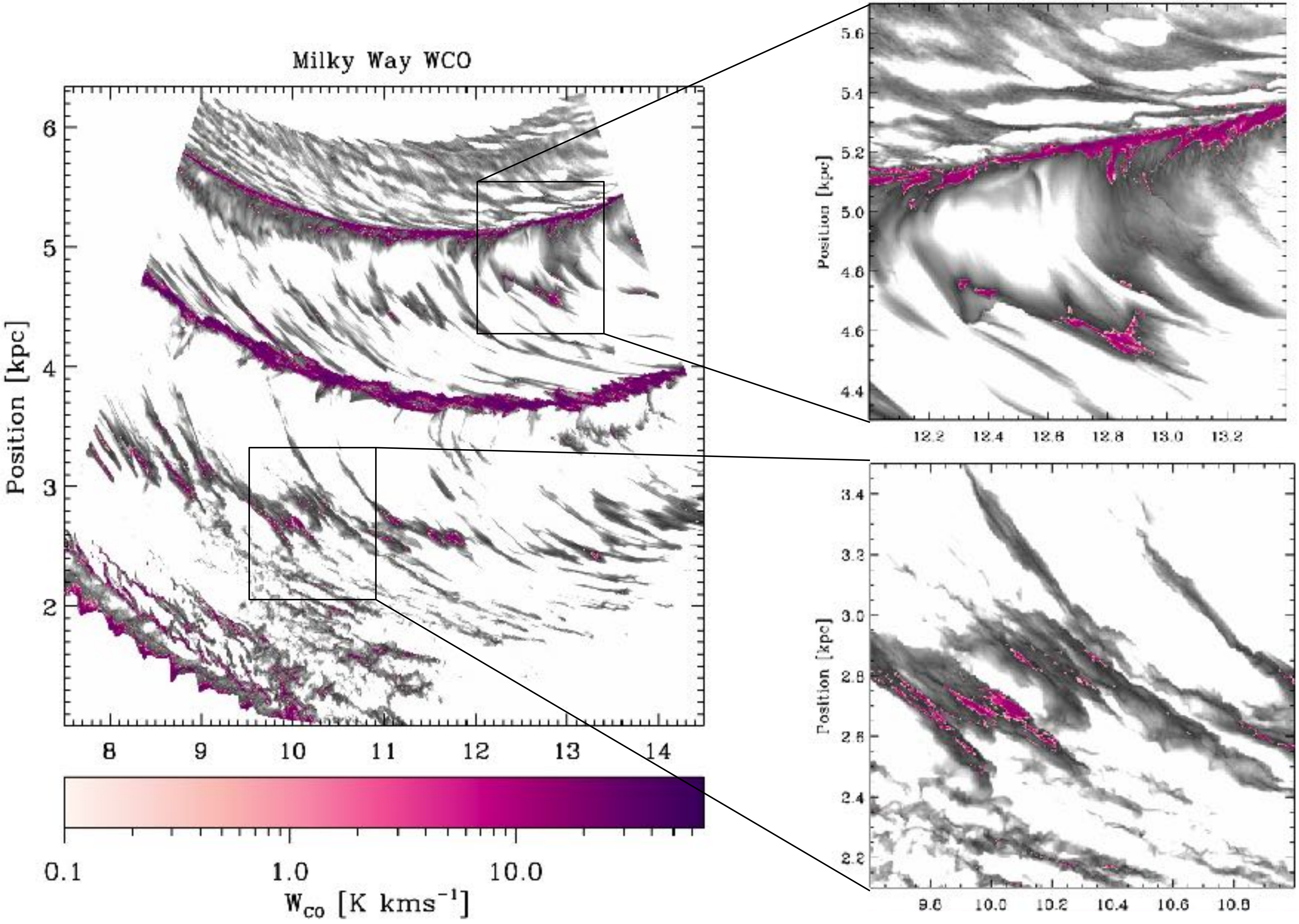


[CII] surface brightness



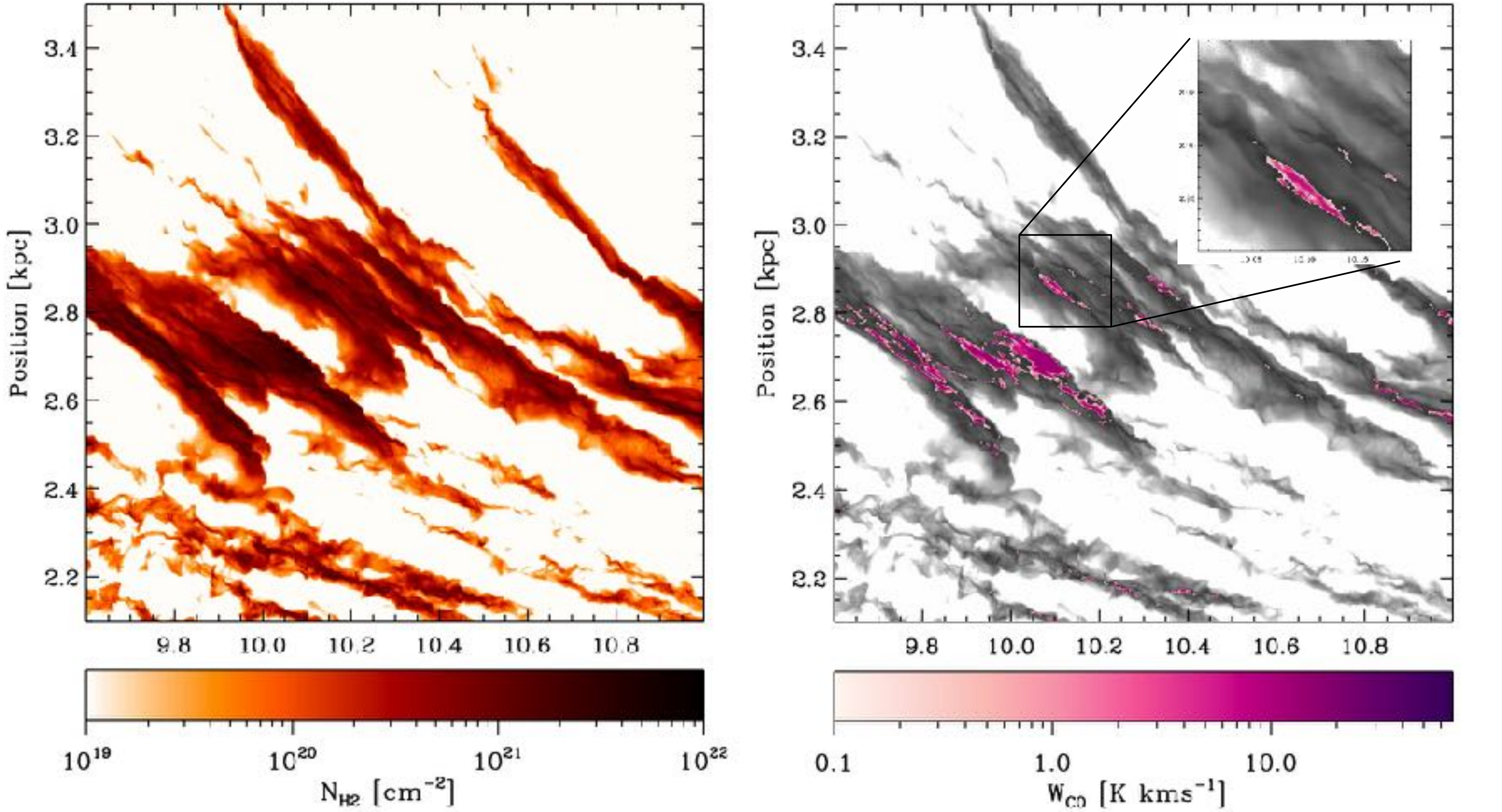
(Smith et al., 2014, MNRAS, 441, 1628, Glover & Smith, 2016, 462, 3011)

# details of CO emission



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

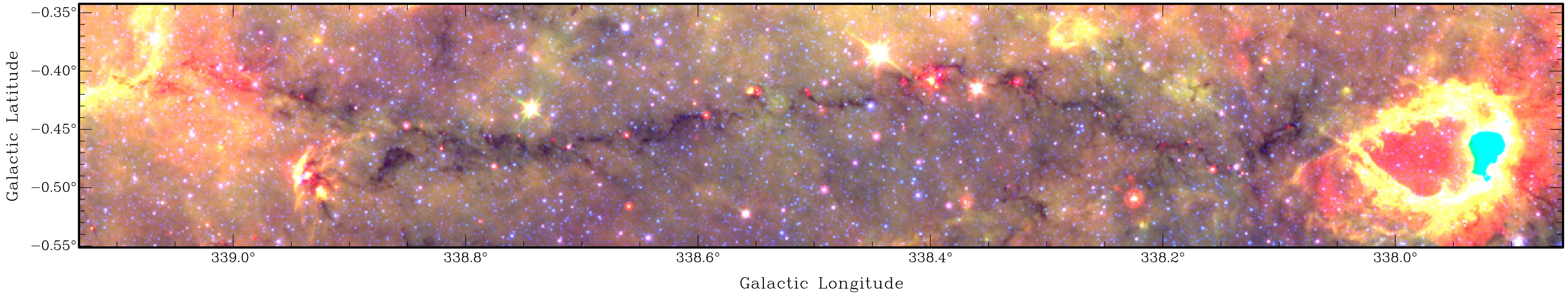
# relation between CO and $H_2$

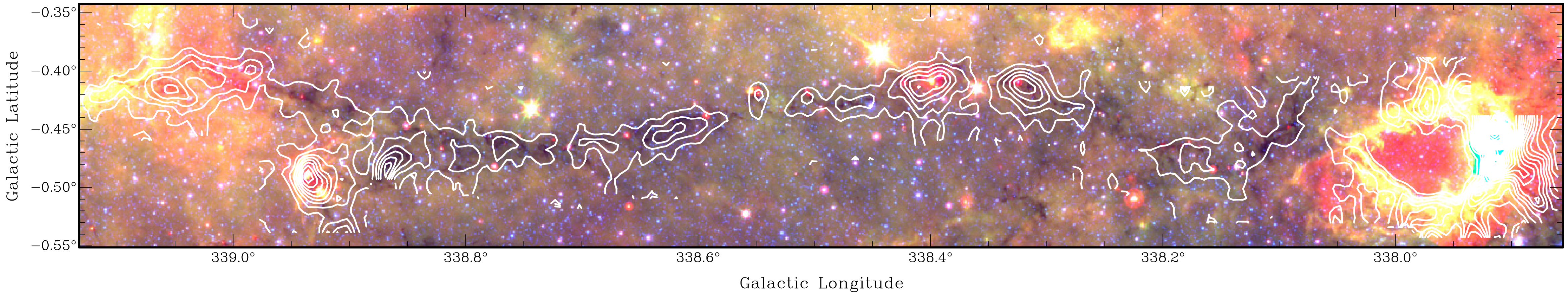


Filamentary molecular clouds in inter-arm regions are likely only the observable parts of much larger structures.

current developments

current developments





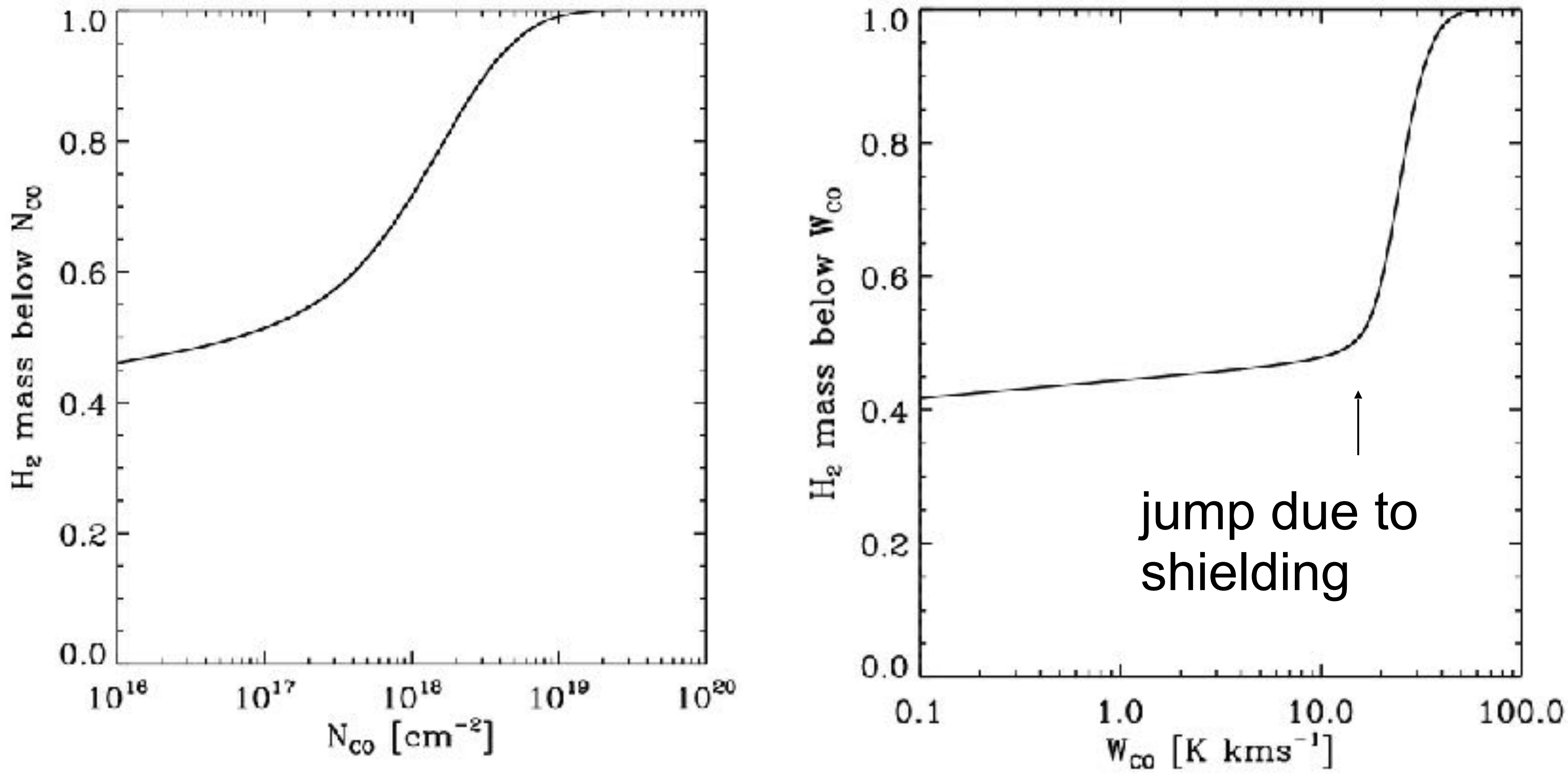
***Nessie filament*** (Jackson et al. 2010, Goodman et al, 2014)

Jackson et al. (2010, ApJ, 719, L185)

also Ragan et al. (2014 A&A 568, A73)

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

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

current developments

# further evidence form detailed colliding flow calculations

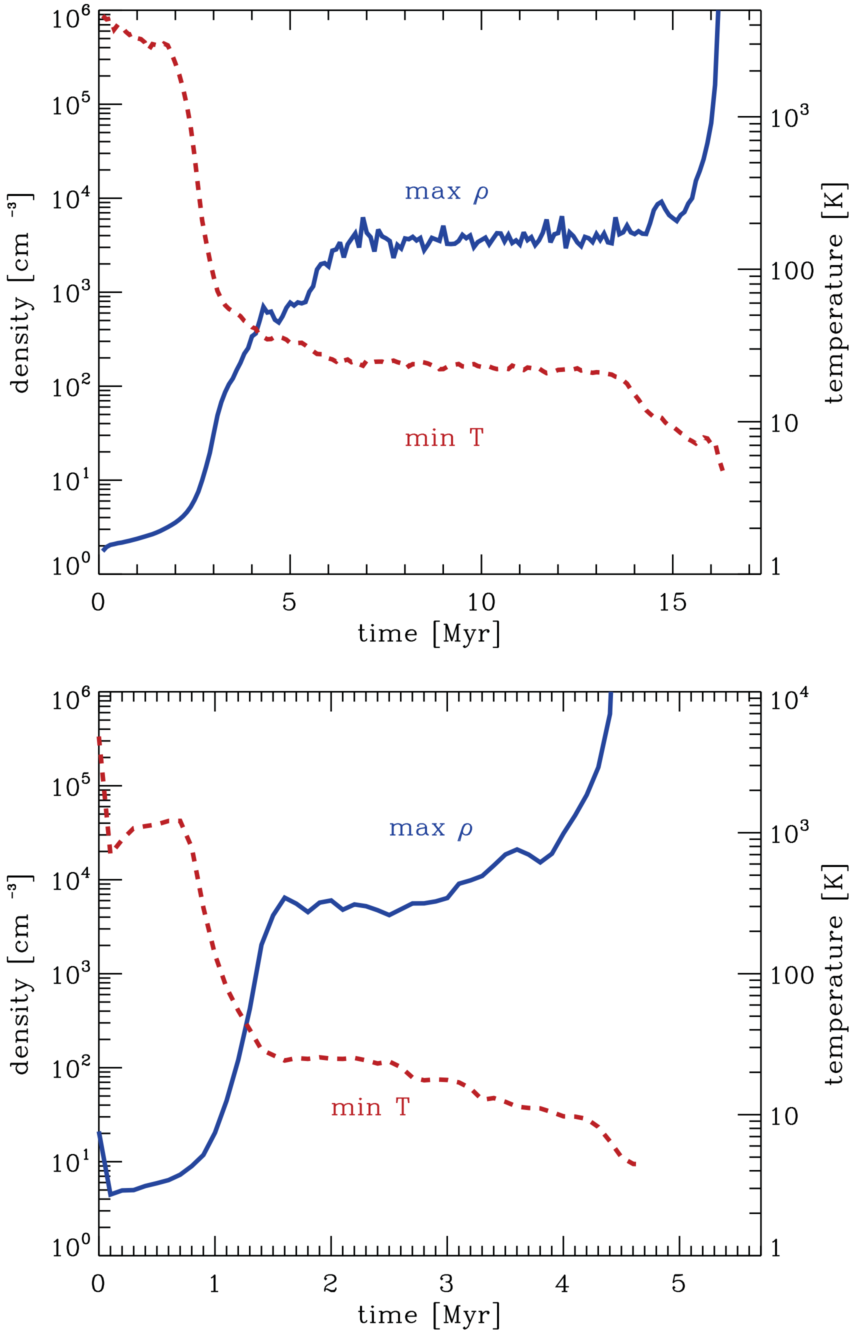
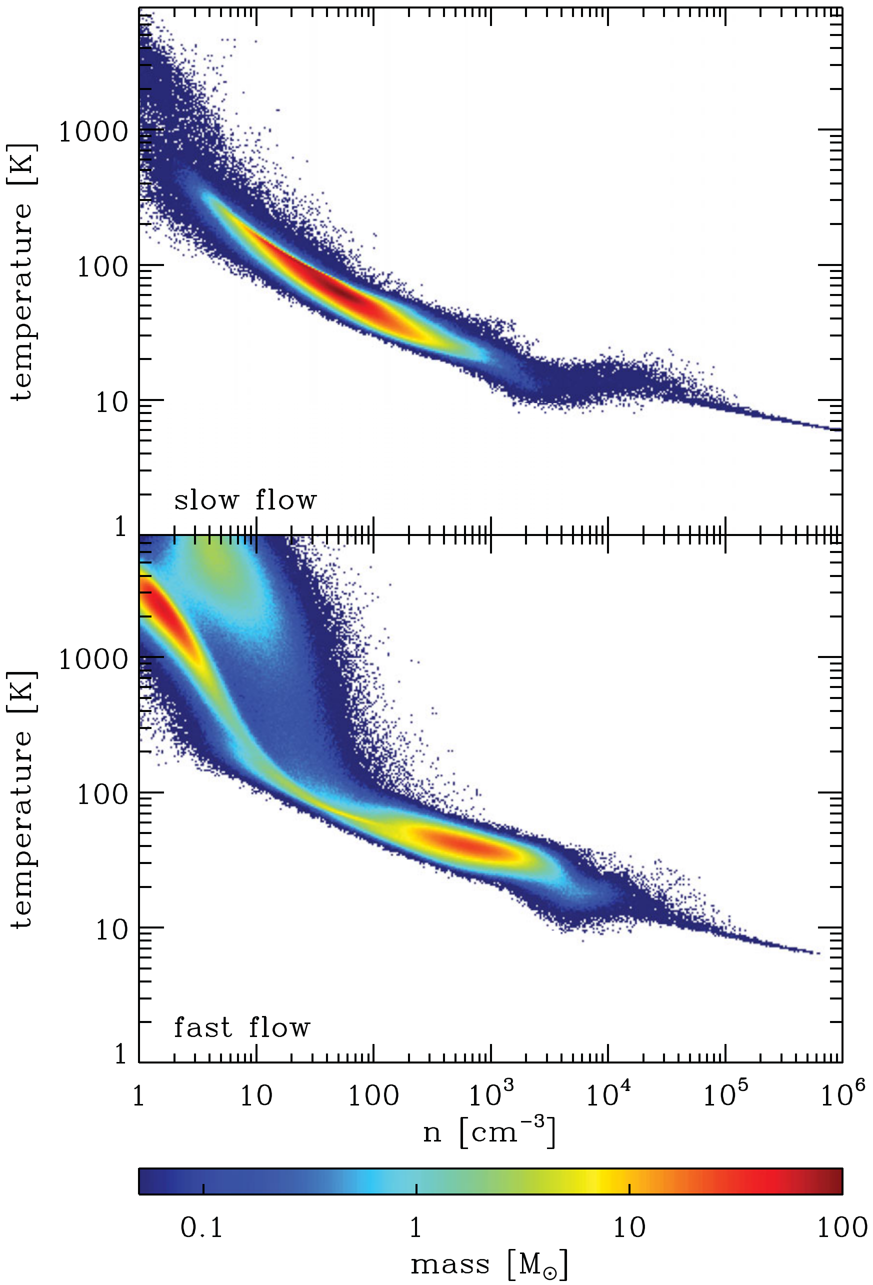


**Figure 3.** Evolution with time of the maximum density (blue, solid line) and minimum temperature (red, dashed line) in the slow flow (top panel) and the fast flow (bottom panel). Note that at any given instant, the coldest SPH particle is not necessarily the densest, and so the lines plotted are strictly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



slow flow

fast flow

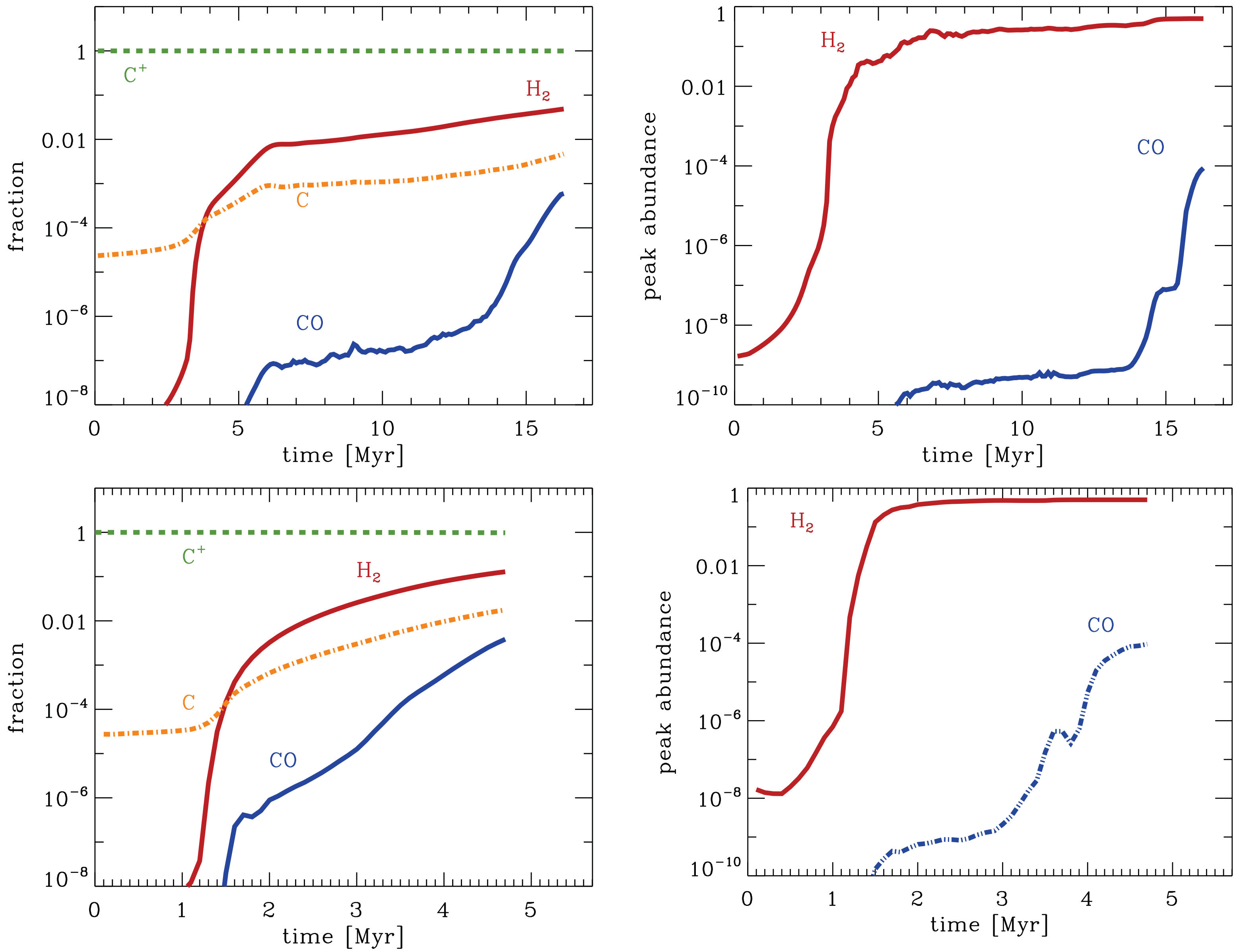
**Figure 5.** The gas temperature–density distribution in the flows at the onset of star formation.

Clark et al. (2012,MNRAS, 424, 2599)

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

# further evidence form detailed colliding flow calculations

current developments



slow flow

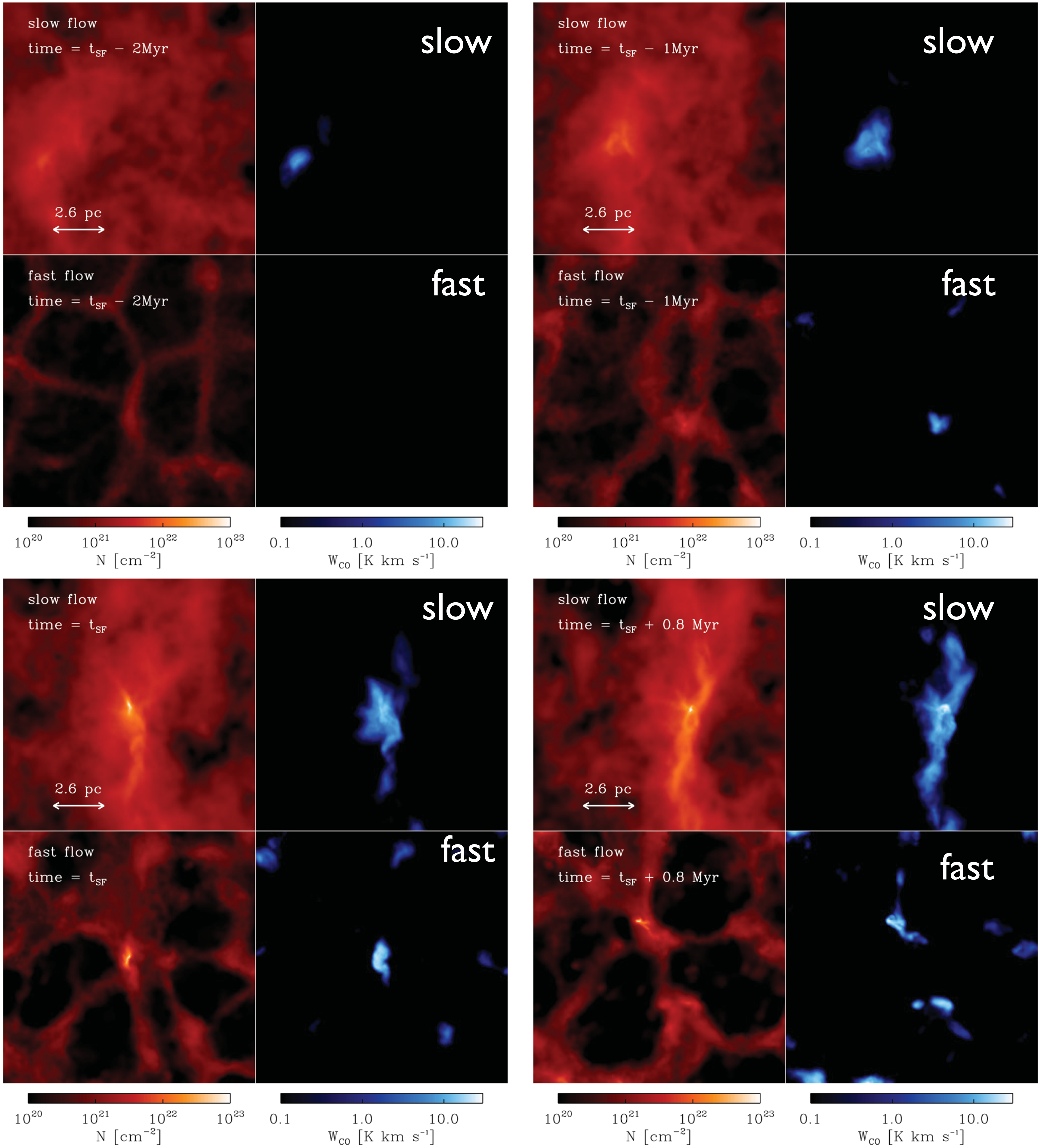
fast flow

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

t al. (2012,MNRAS, 424, 2599)

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

# current developments



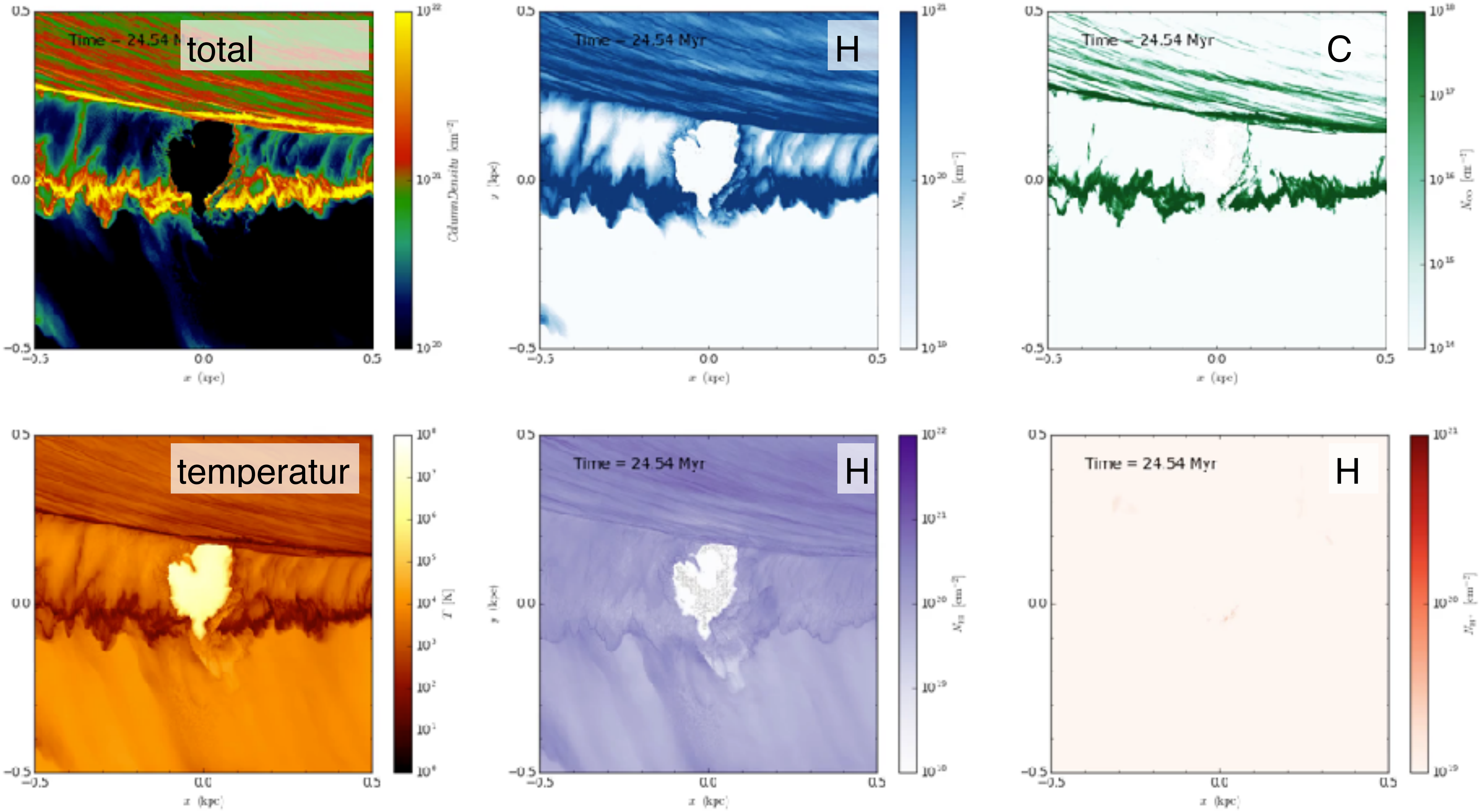
$H_2$ column

CO emission

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

Clark et al. (2012,MNRAS, 424, 2599)

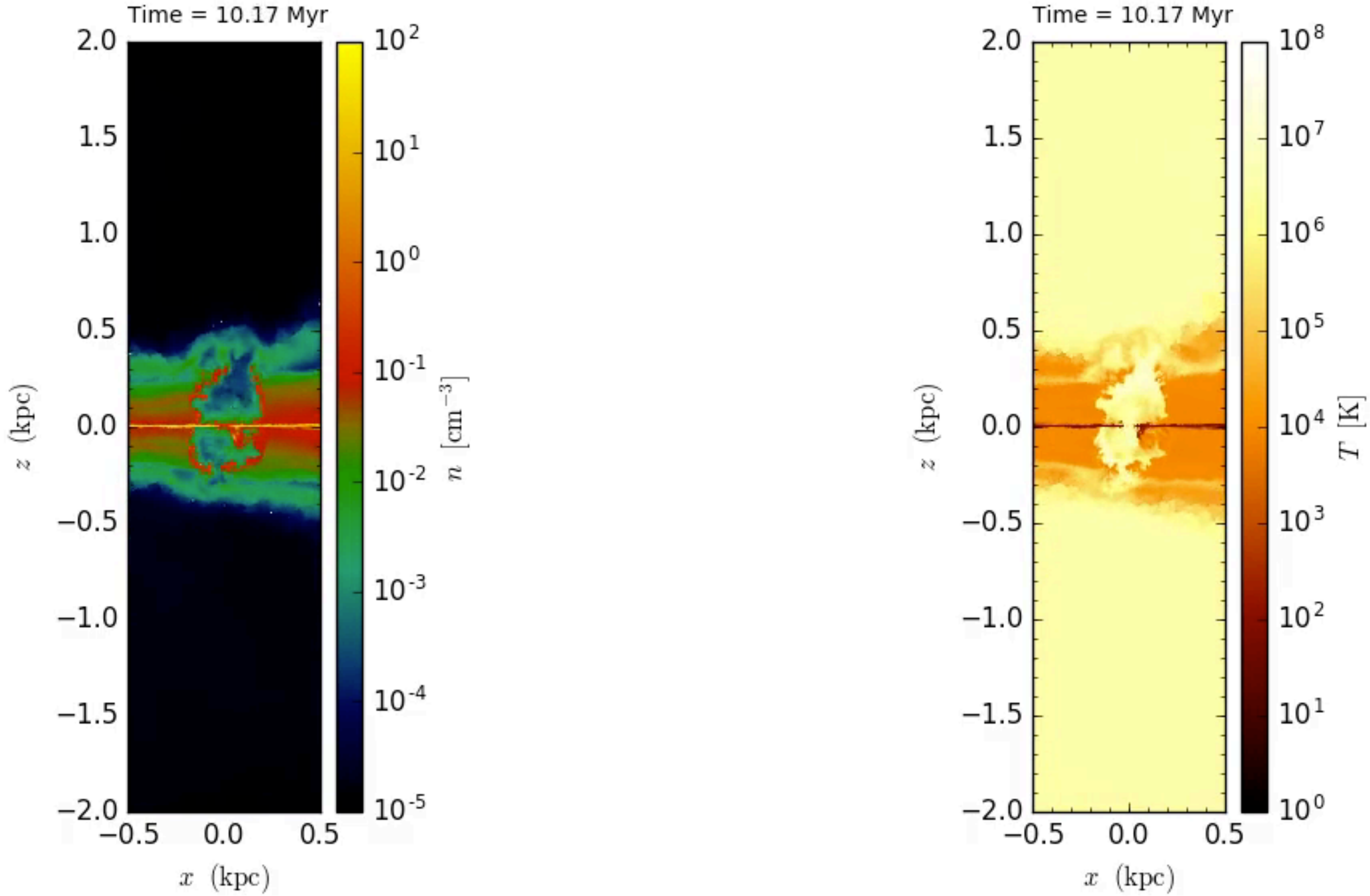
# current developments



new models that include self-consistent star formation

Treß et al. (in preparation)

# current developments



new models that include self-consistent star formation

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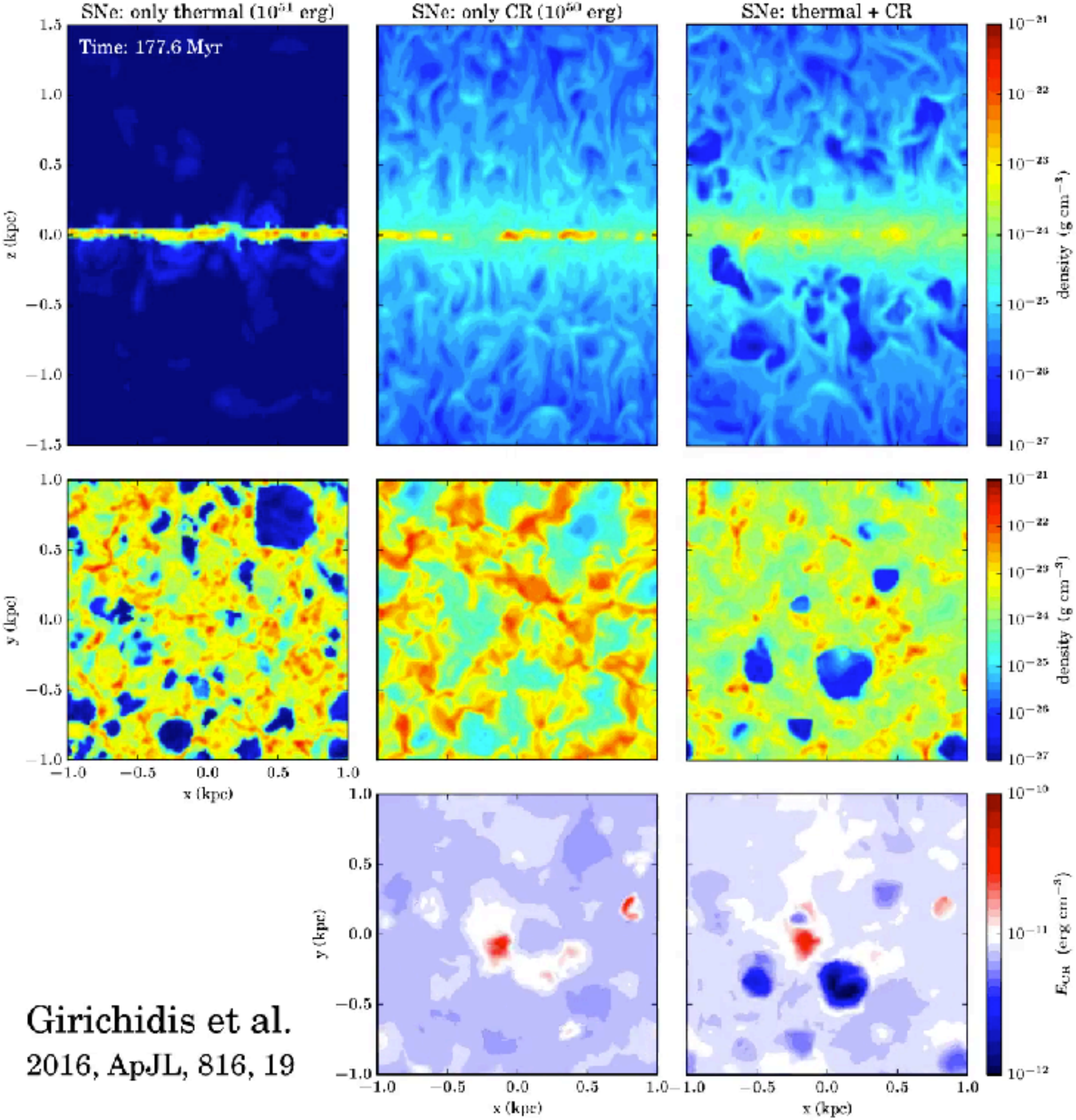
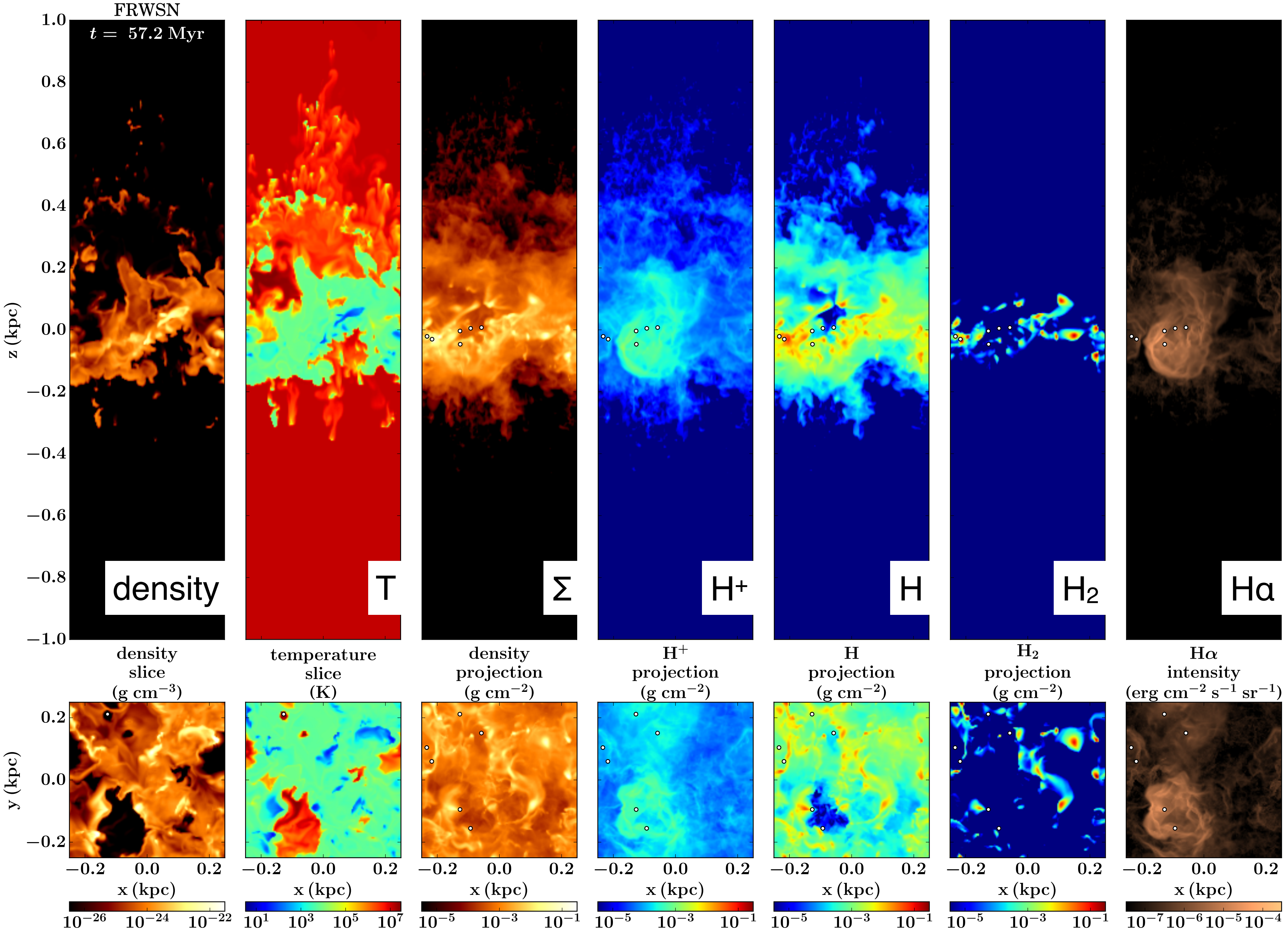


Girichidis et al.
2016, ApJL, 816, 19

see also:
Walch et al. 2015, MNRAS, 454, 238, Gatto et al. 2015, MNRAS, 449, 1057, Girichidis et al. 2016, MNRAS, 456, 3432

current developments

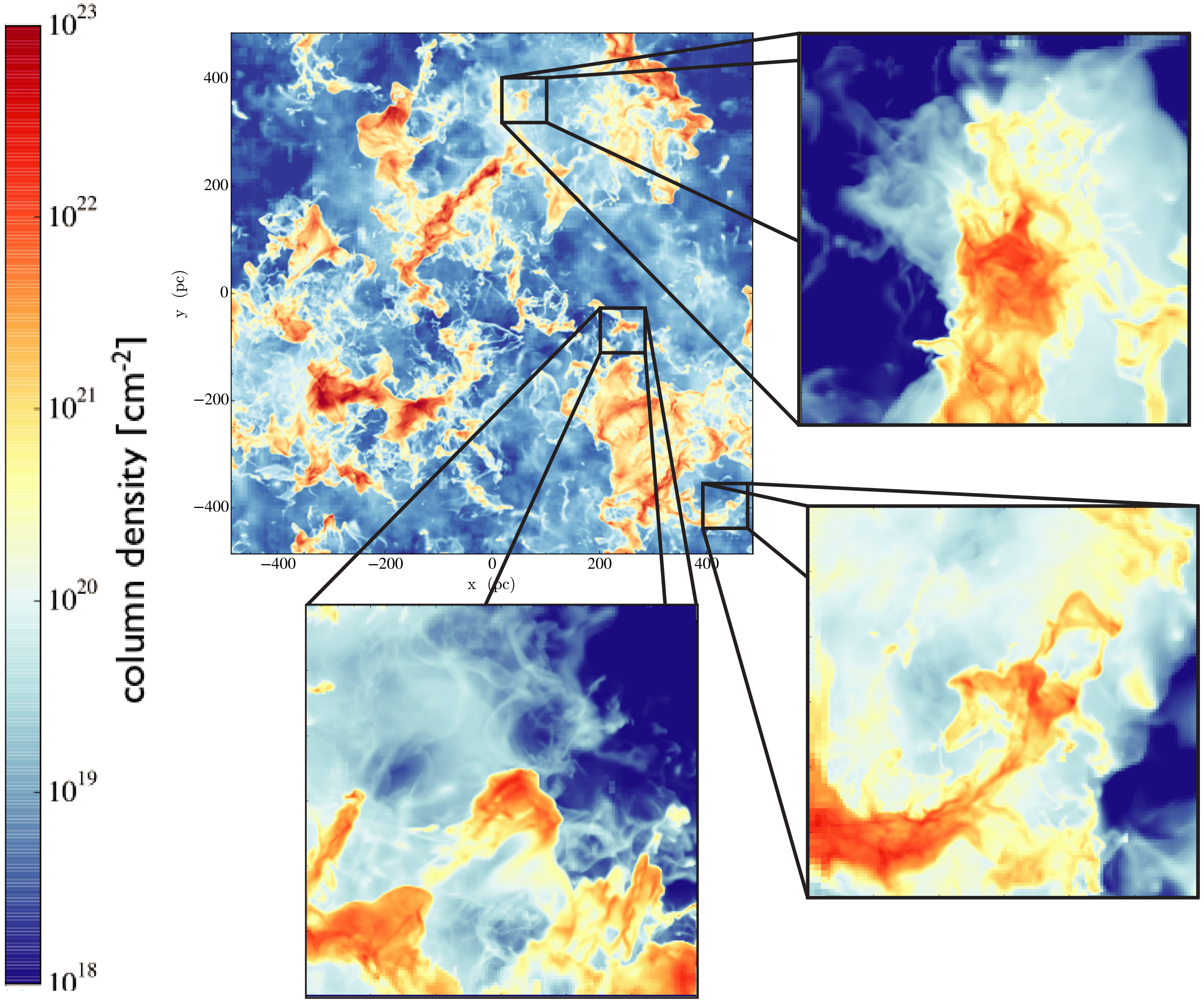


Peters et al. (2016, in prep)

synthetic maps in further observables: HI, Halpha, other radio recombination lines

SILCC collaboration: http://hera.ph1.uni-koeln.de/~silcc/

# current developments

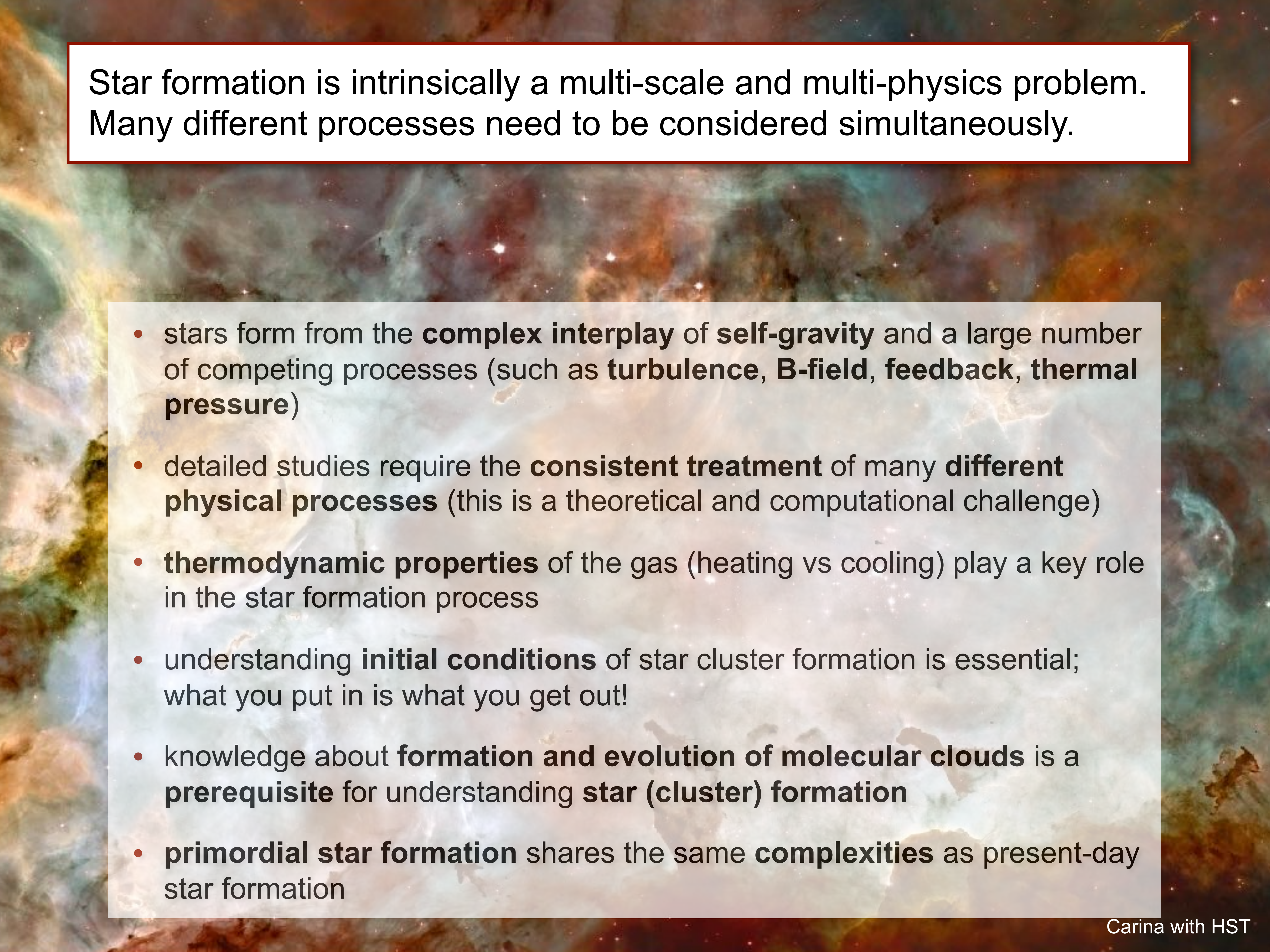


zoom-in calculations to provide better boundary conditions for star cluster formation simulations

Ibanez Mejia et al. (2016, ApJ, 824, 41), Ibanez Mejia et al. (2016, in prep.), Seifried et al. (2016, in prep.)

# summary

Carina with HST



Carina with HST

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

- stars form from the **complex interplay** of **self-gravity** and a large number of competing processes (such as **turbulence**, **B-field**, **feedback**, **thermal pressure**)
- detailed studies require the **consistent treatment** of many **different physical processes** (this is a theoretical and computational challenge)
- **thermodynamic properties** of the gas (heating vs cooling) play a key role in the star formation process
- understanding **initial conditions** of star cluster formation is essential; what you put in is what you get out!
- knowledge about **formation and evolution of molecular clouds** is a **prerequisite** for understanding **star (cluster) formation**
- **primordial star formation** shares the same **complexities** as present-day star formation

# thanks