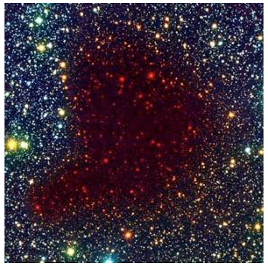
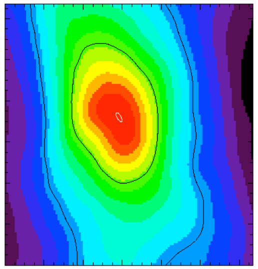
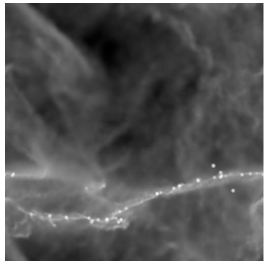
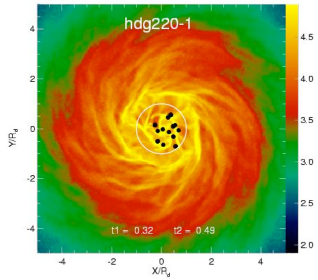
Understanding the ISM: Theoretical Aspects

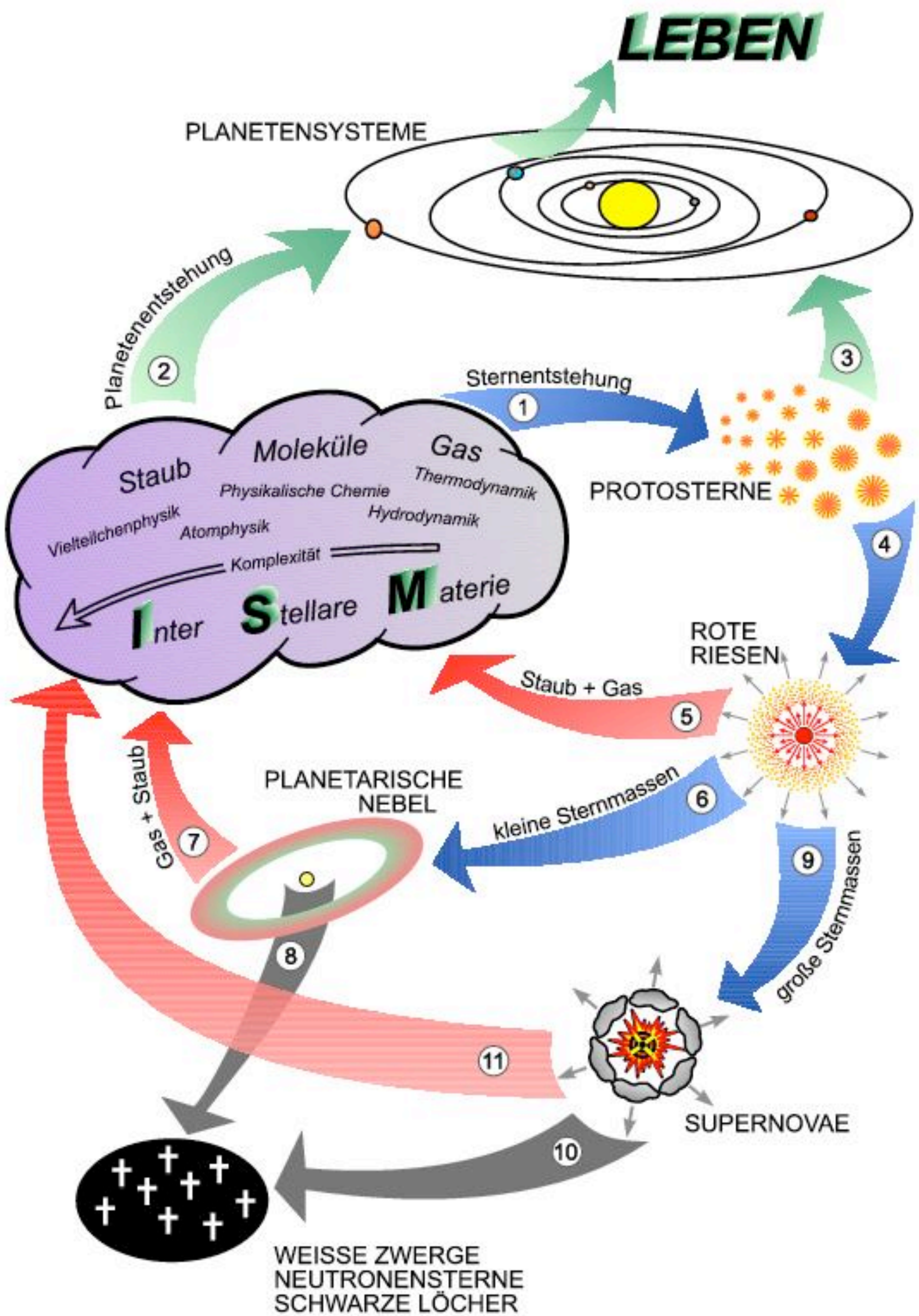





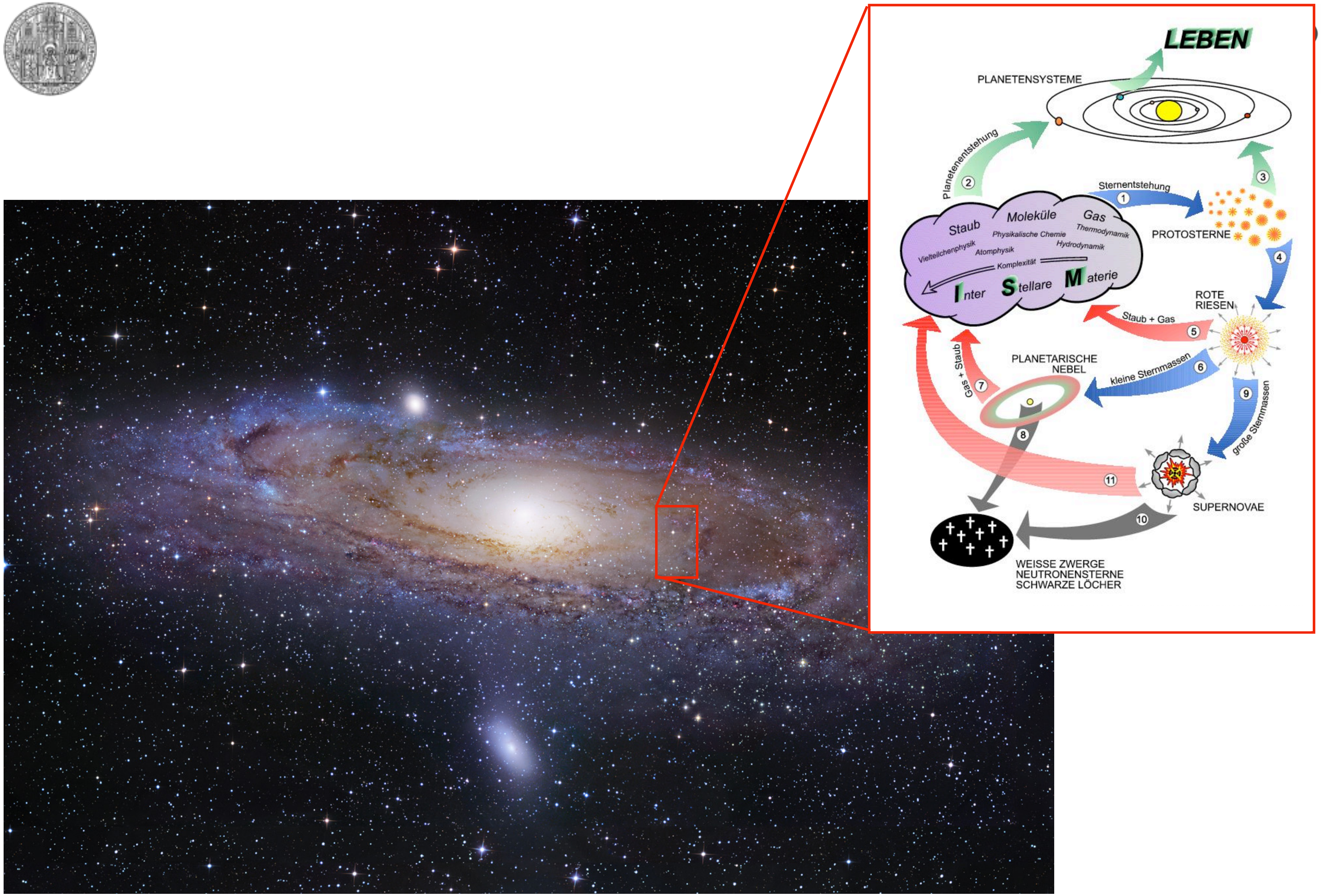


Ralf Klessen

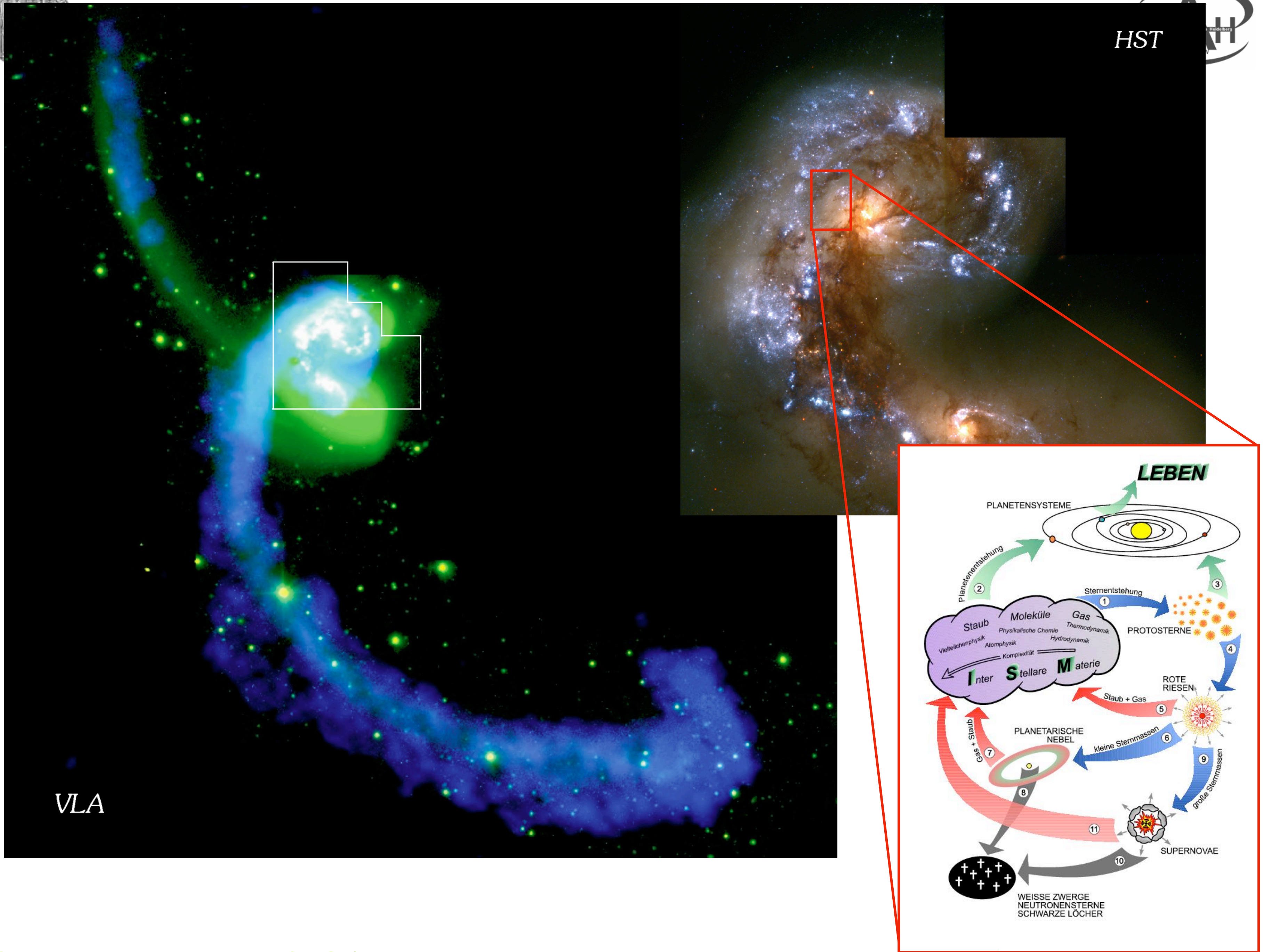
Zentrum für Astronomie der Universität Heidelberg
Institut für Theoretische Astrophysik



(from AG meeting in Berlin 2002)



(Andromeda galaxy – Bob Gendler)



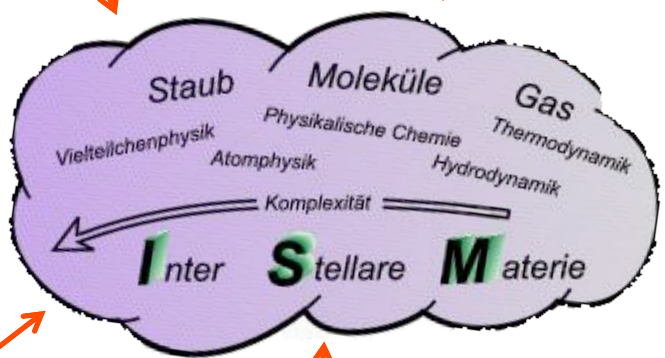
(the Antennae galaxy – VLA & HST)

Why study ISM physics?

physical processes
- turbulence theory
- ISM: laboratory for plasm physics
- ISM: laboratory for extreme chemistry

planets
- initial conditions for planet formation (chemical composition)
- diversity of planetary systems
- habitability (life)

extreme environments
- galactic center
- starburst galaxies
- primorial universe

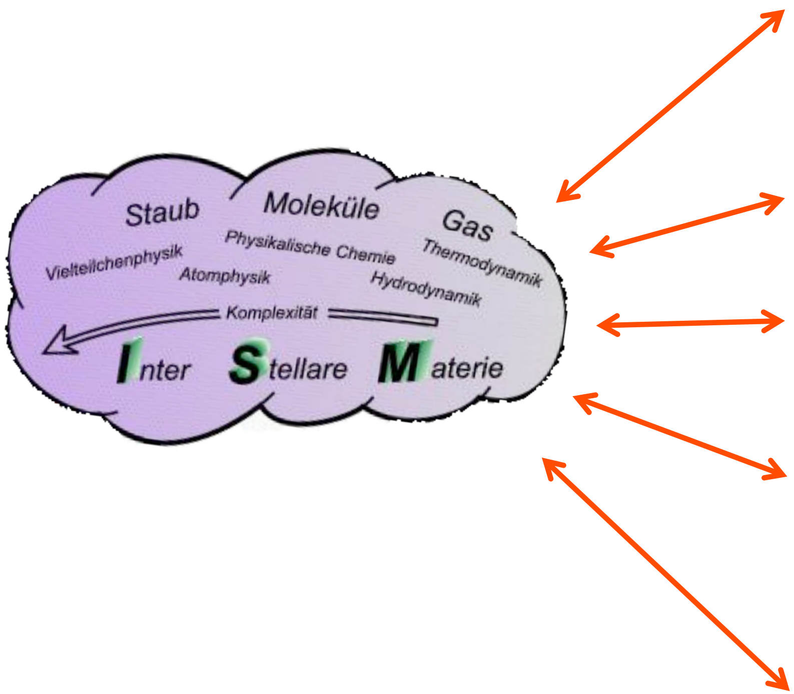


stars & star clusters
- ISM: environment for star formation
- IMF
- feedback from stars (winds, radiation, SN)
- MC turbulence

cosmology & galaxy formation
- cooling properties of high-z halos
- primordial star formation
- relation between visible and dark matter

galactic structure & evolution
- chemical enrichment
- global star formation history (Milky Way)
- interrelation between SF and galactic structure

What do we need to study ISM?



magneto-hydrodynamics
(multi-phase, non-ideal MHD, turbulence)

chemistry (gas + dust, heating + cooling)

radiation (continuum + lines)

stellar dynamics
(collisional: star clusters, collisionless: galaxies, DM)

stellar evolution
(feedback: radiation, winds, SN)

\+ **laboratory work**
(reaction rates, cross sections, dust coagulation properties, etc.)

What do we need to study ISM?

- massive parallel codes
- particle-based: SPH with improved algorithms (XSPH with turb. subgrid model, GPM, particle splitting, MHD-SPH?)
- grid-based: AMR (FLASH, ENZO, RAMSES, Nirvana3, etc), subgrid-scale models (FEARLESS)
- BGK methods

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(collisional: star clusters, collisionless: galaxies, DM)

stellar evolution
(feedback: radiation, winds, SN)

\+ **laboratory work**
(reaction rates, cross sections, dust coagulation properties, etc.)

What do we need to study ISM?

- ever increasing chemical networks
- working reduced networks for time-dependent chemistry in combination with hydro-dynamics
- improved data on reaction rates (laboratory + quantum mechanical calculations)

magneto-hydrodynamics
(multi-phase, non-ideal MHD, turbulence)

chemistry (gas + dust, heating + cooling)

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stellar dynamics
(collisional: star clusters, collisionless: galaxies, DM)

stellar evolution
(feedback: radiation, winds, SN)

\+ **laboratory work**
(reaction rates, cross sections, dust coagulation properties, etc.)

What do we need to study ISM?

- continuum vs. lines
- Monte Carlo, characteristics
- approximative methods
- combine with hydro

↔

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(multi-phase, non-ideal MHD, turbulence)

chemistry (gas + dust, heating + cooling)

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stellar dynamics
(collisional: star clusters, collisionless: galaxies, DM)

stellar evolution
(feedback: radiation, winds, SN)

\+ **laboratory work**
(reaction rates, cross sections, dust coagulation properties, etc.)

What do we need to study ISM?

- statistics: number of stars (collisional: 10^6, collisionless: 10^{10})
- transition from gas to stars
- binary orbits
- long-term integration

magneto-hydrodynamics
(multi-phase, non-ideal MHD, turbulence)

chemistry (gas + dust, heating + cooling)

radiation (continuum + lines)

stellar dynamics
(collisional: star clusters, collisionless: galaxies, DM)

stellar evolution
(feedback: radiation, winds, SN)

\+ **laboratory work**
(reaction rates, cross sections, dust coagulation properties, etc.)

What do we need to study ISM?

- very early phases (pre main sequence tracks)
- massive stars at late phases
- role of rotation
- primordial star formation

magneto-hydrodynamics
(multi-phase, non-ideal MHD, turbulence)

chemistry (gas + dust, heating + cooling)

radiation (continuum + lines)

stellar dynamics
(collisional: star clusters, collisionless: galaxies, DM)

stellar evolution
(feedback: radiation, winds, SN)

\+ **laboratory work**
(reaction rates, cross sections, dust coagulation properties, etc.)

What do we need to study ISM?

methods need to be combined!

magneto-hydrodynamics
(multi-phase, non-ideal MHD, turbulence)

chemistry (gas + dust, heating + cooling)

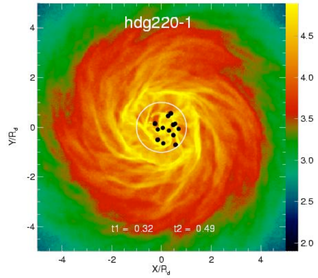
radiation (continuum + lines)

stellar dynamics
(collisional: star clusters, collisionless: galaxies, DM)

stellar evolution
(feedback: radiation, winds, SN)

\+ **laboratory work**
(reaction rates, cross sections, dust coagulation properties, etc.)

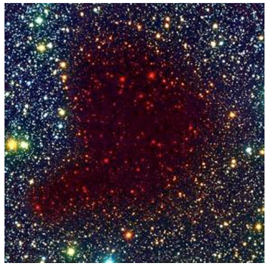
Three examples

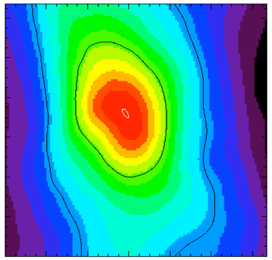


modeling star formation in galactic disk + molecular cloud formation

(hydrodynamics, stellar dynamics, chemistry, feedback [radiation, outflows])

(Schmidt law, star-formation history, relation between global dynamics and SF)

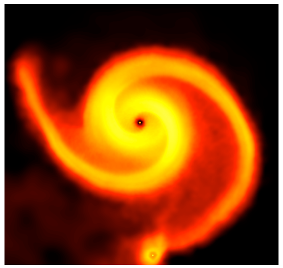




cloud fragmentation & prestellar cores

(MHD, chemistry, radiation)

(initial conditions of star formation,)

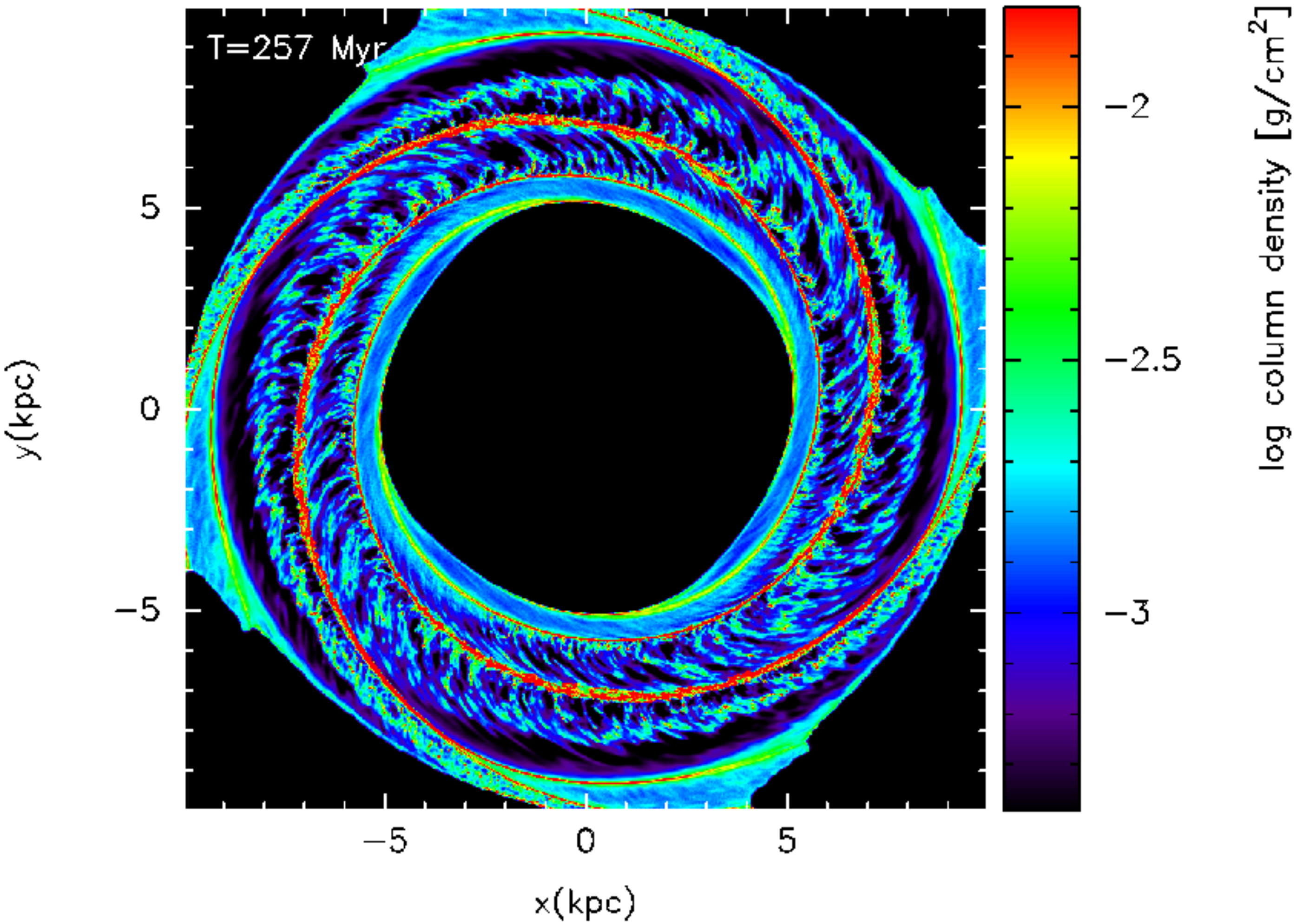


transition to stars

(MHD, stellar feedback, chemistry, radiation

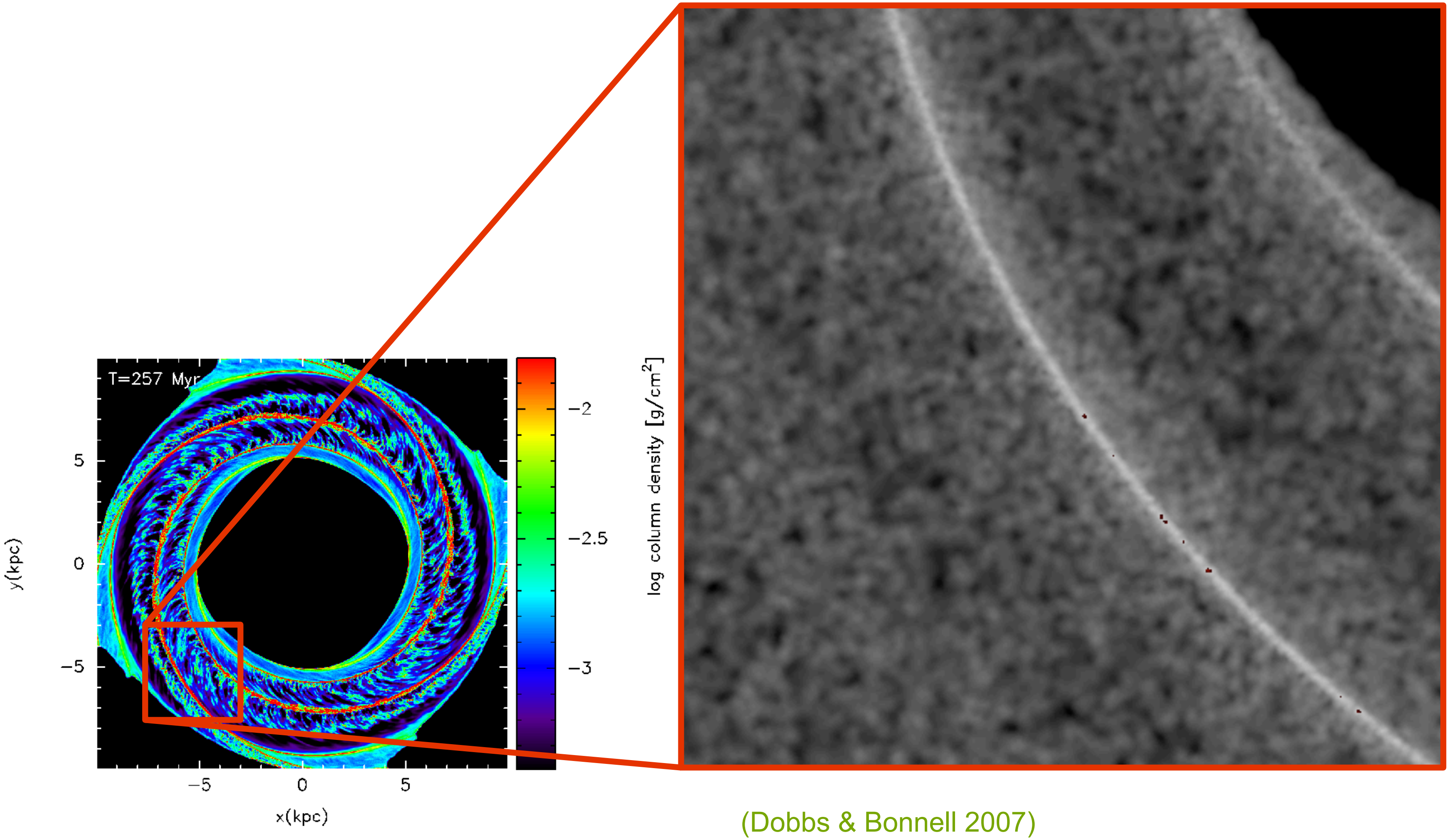
(IMF, multiplicity, planet formation, etc.)

molecular cloud formation



(from Dobbs, Glover, Clark, Klessen 2008)

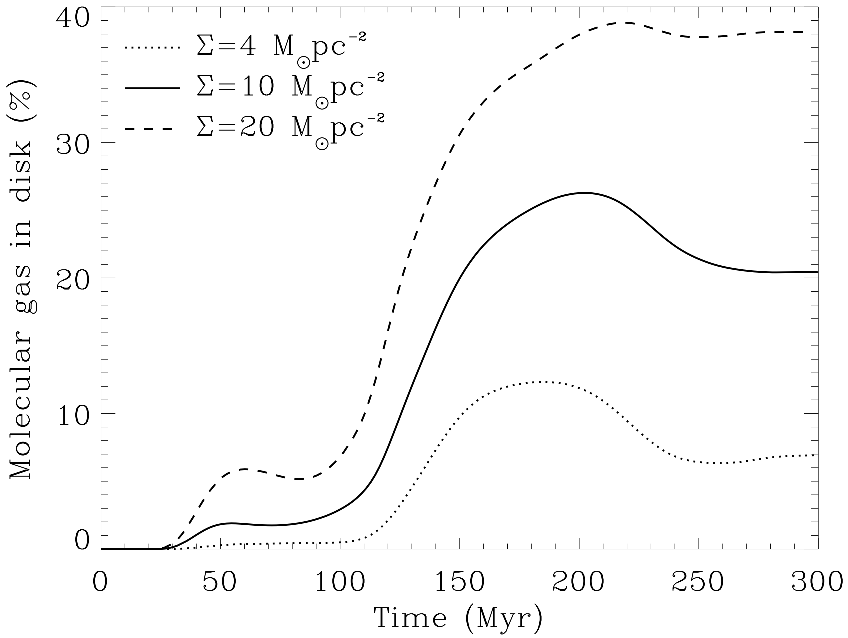
molecular cloud formation



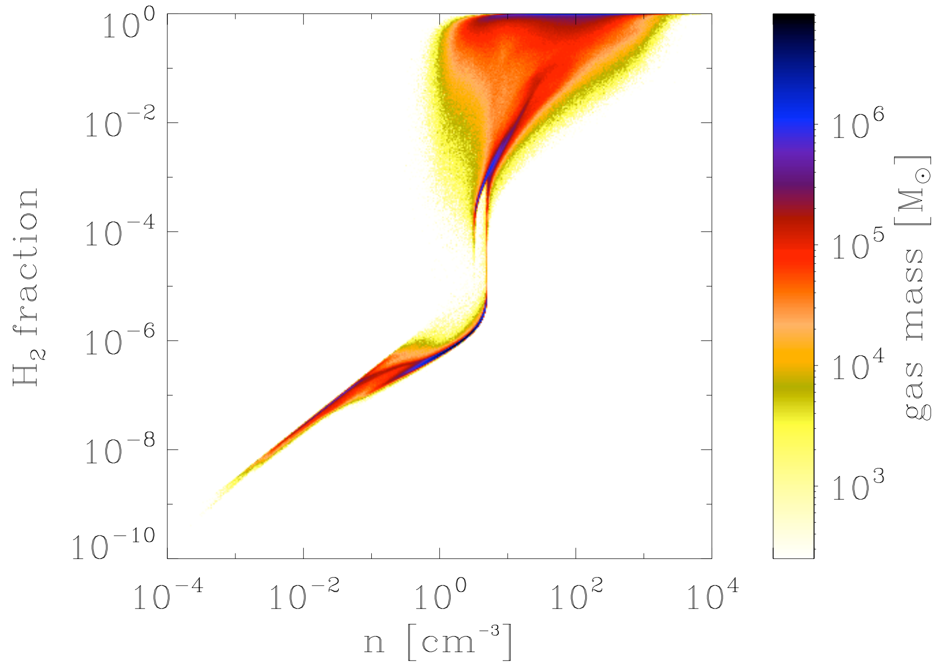
(Dobbs & Bonnell 2007)

molecular cloud formation

molecular gas fraction as function of time



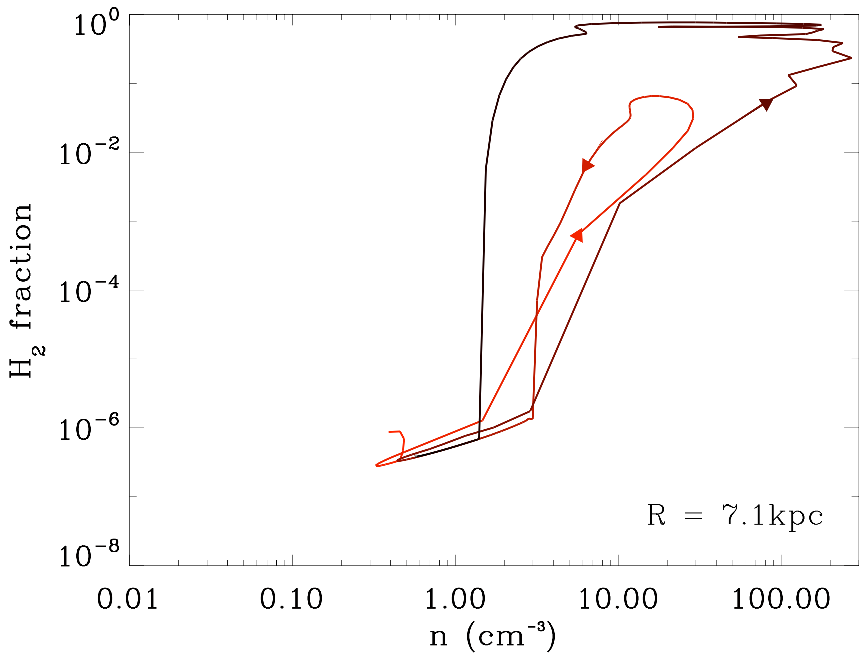
molecular gas fraction as function of density



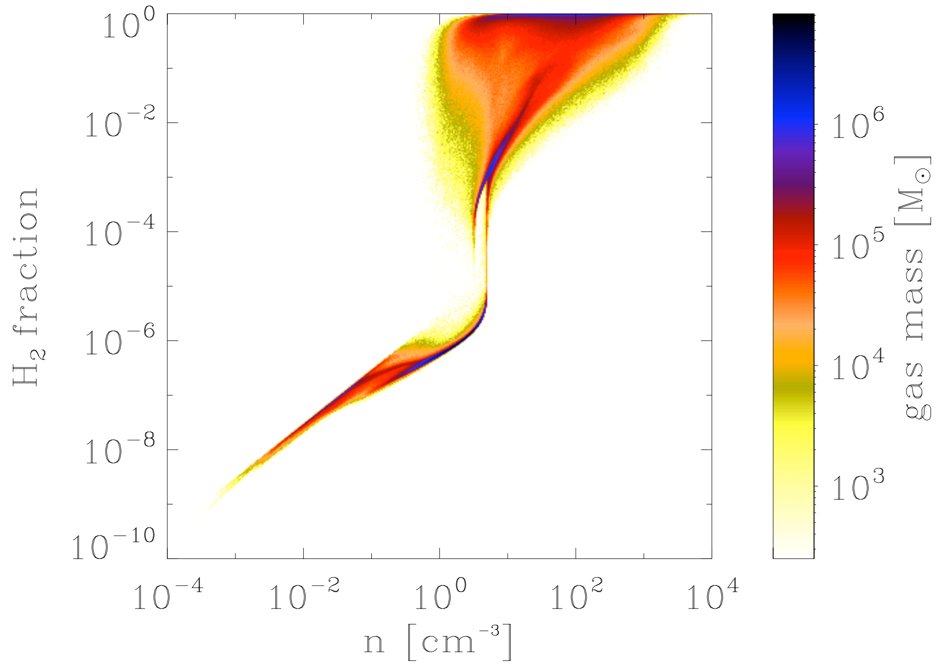
(Dobbs et al. 2008)

molecular cloud formation

molecular gas fraction of fluid element as function of time

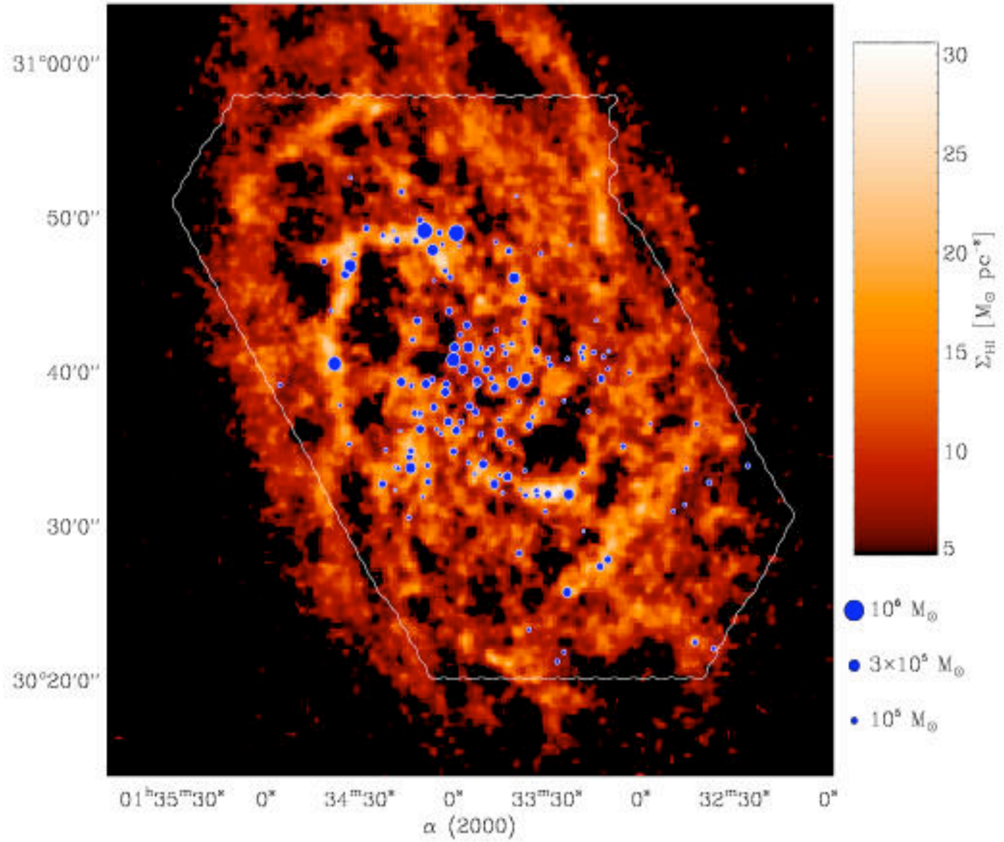


molecular gas fraction as function of density



(Dobbs et al. 2008)

observations



Compare H_2 – HI in M33:

- H_2: BIMA-SONG Survey
- HI: Westerbork Radio Telescope

(Deul & van der Hulst 1987, Blitz et al. 2004)

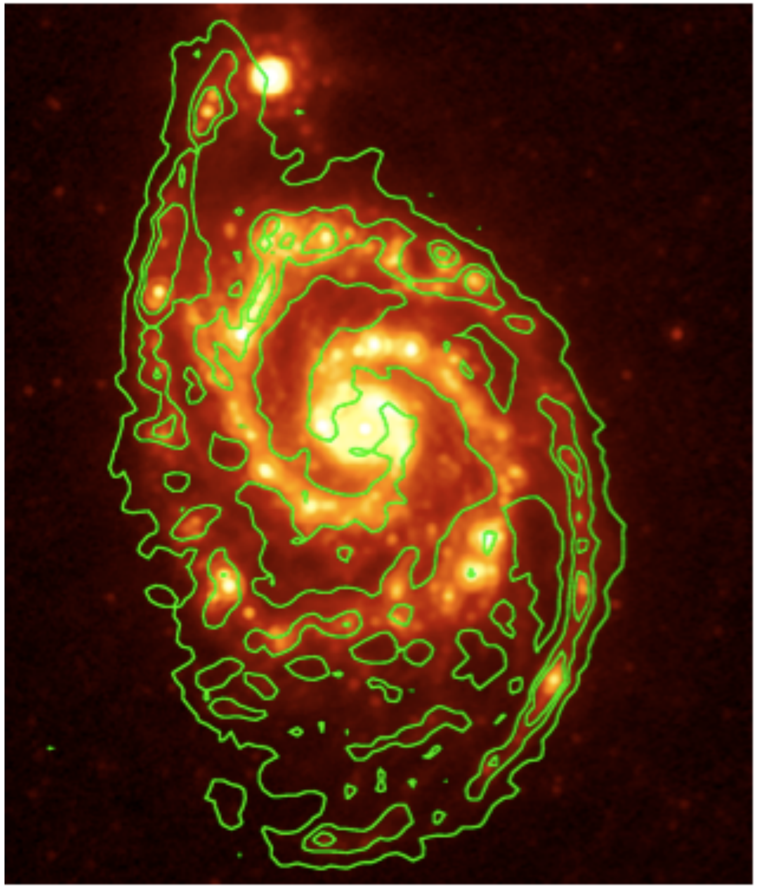


Fig. 1.— NGC 5194: the 24 μm band image is plotted in color scale; the H I emission map is overlayed with green contours.

(Tamburro et al. 2009)

molecular cloud scales

from atomic gas to molecular clouds

- hypothesis: *cold molecular clouds can form rapidly in high-density regions at stagnation points of convergent large-scale flows*
  - chemical phase transition: atomic → molecular
  - process is modulated by large-scale dynamics in galaxy
- questions
  - are molecular clouds truly “multi-phase” media?
  - turbulence? dynamical & morphological properties?
  - what is relation to initial & environmental conditions?
  - magnetic field structure?

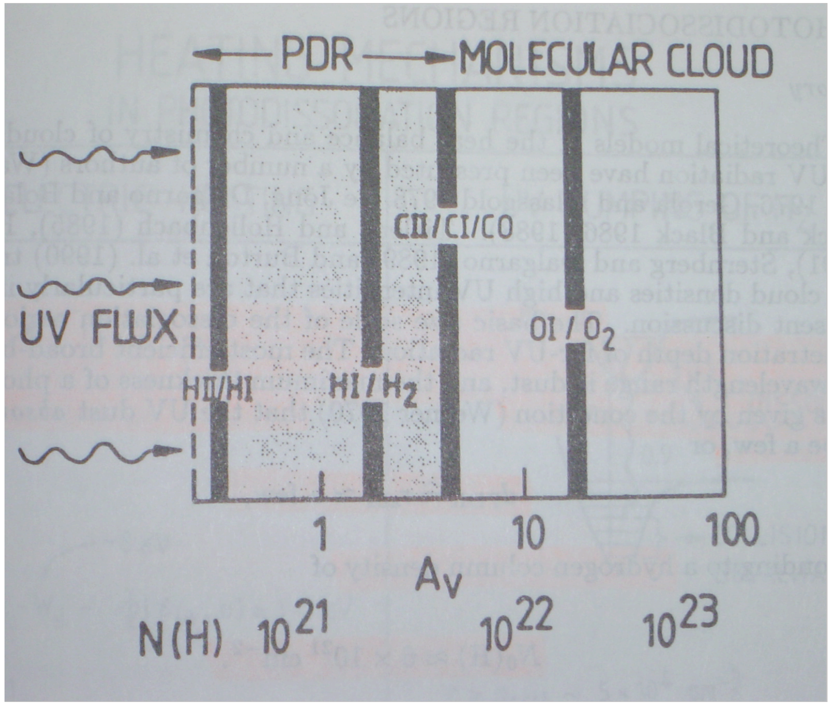
Interstellar Matter: ISM

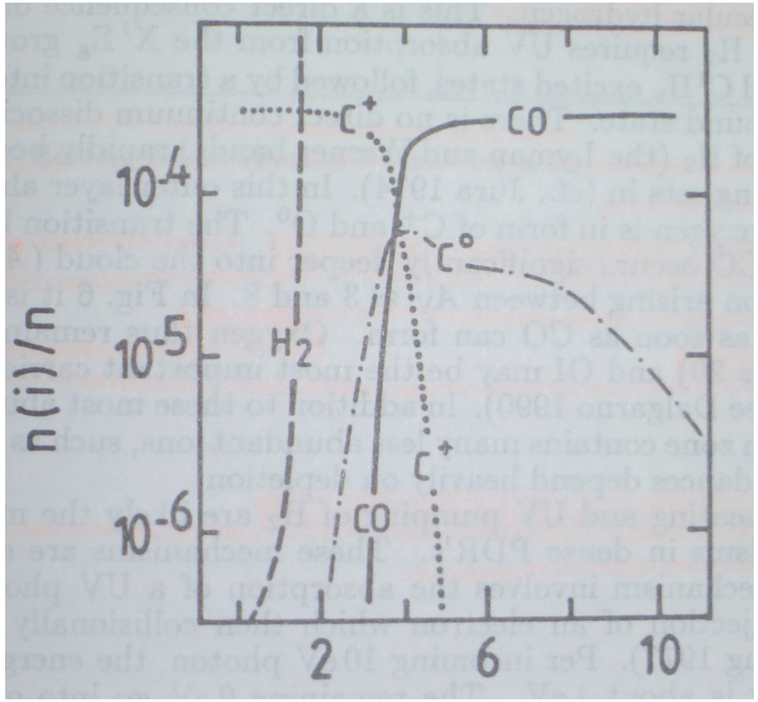
Abundances, scaled to 1.000.000 H atoms

element	atomic number		abundance
Wasserstoff	H	1	1.000.000
Deuterium	$_1H^2$	1	16
Helium	He	2	68.000
Kohlenstoff	C	6	420
Stickstoff	N	7	90
Sauerstoff	O	8	700
Neon	Ne	10	100
Natrium	Na	11	2
Magnesium	Mg	12	40
Aluminium	Al	13	3
Silicium	Si	14	38
Schwefel	S	16	20
Calcium	Ca	20	2
Eisen	Fe	26	34
Nickel	Ni	28	2

Hydrogen is by far the most abundant element (more than 90% in number).

Phases of the ISM





A_V

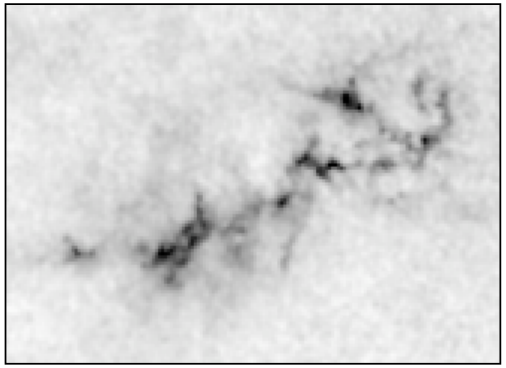
HII HI H_2

Dichte- / Säulendichte nimmt zu

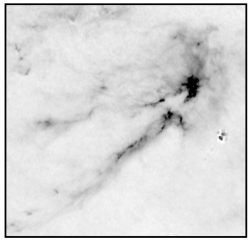
A_V bezeichnet die Extinktion, dh. die Abschwächung der einfallenden Strahlung.

nearby clouds

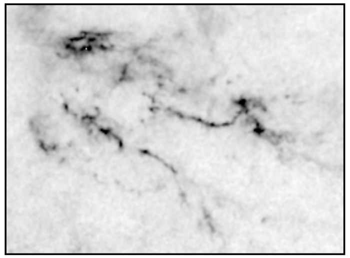
- Perseus



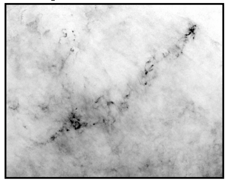
- Ophiuchus



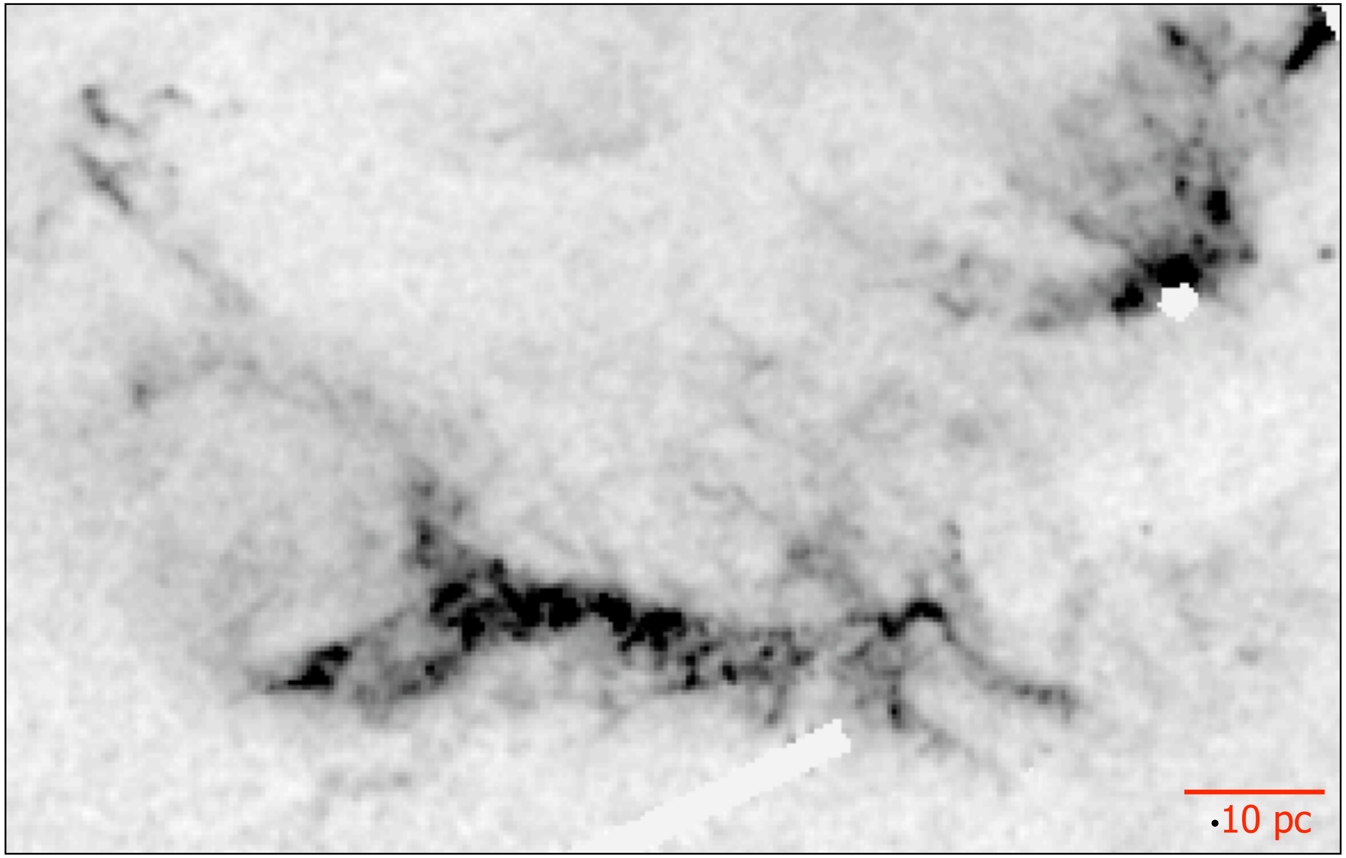
- Taurus



- Pipe

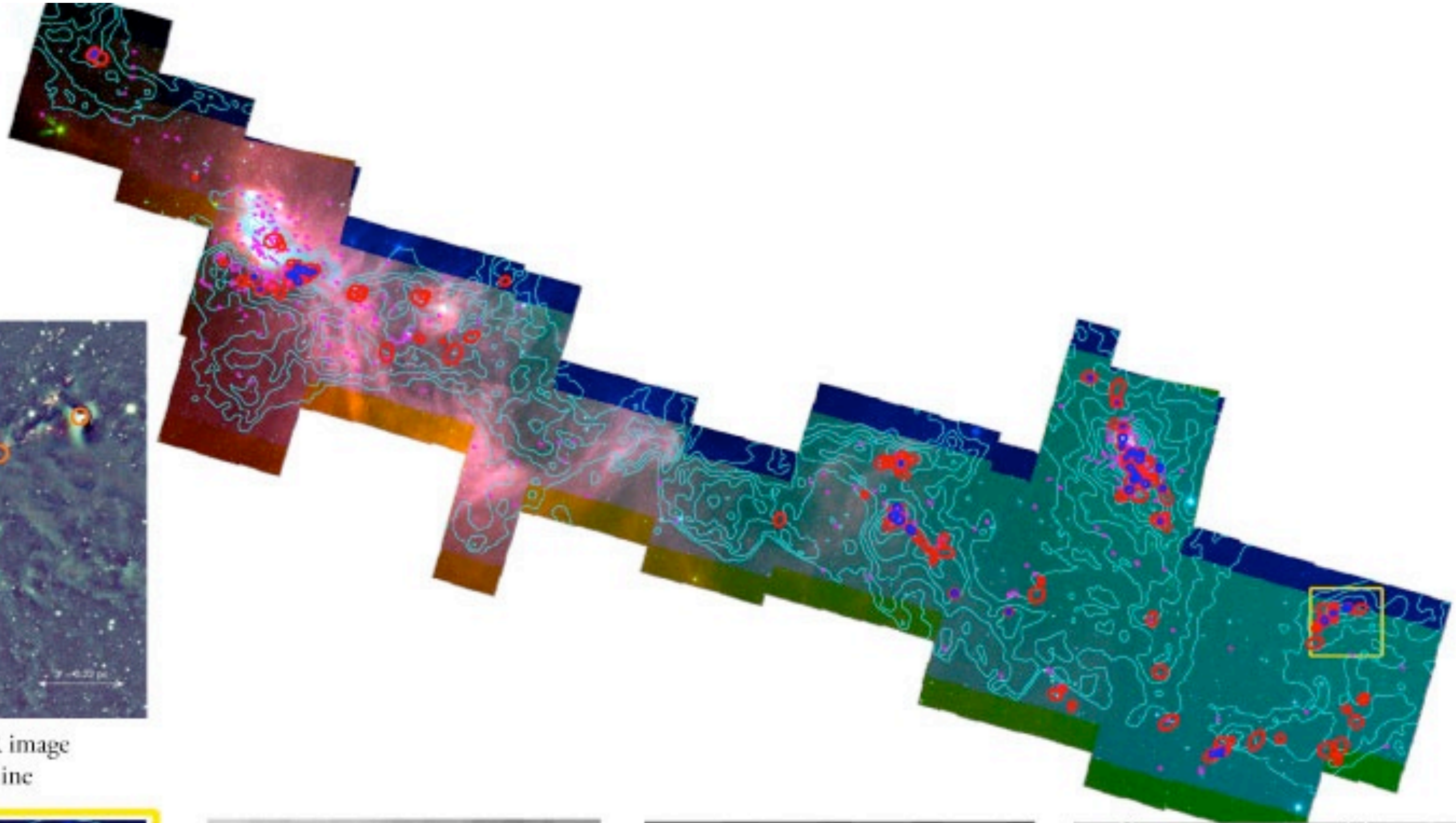


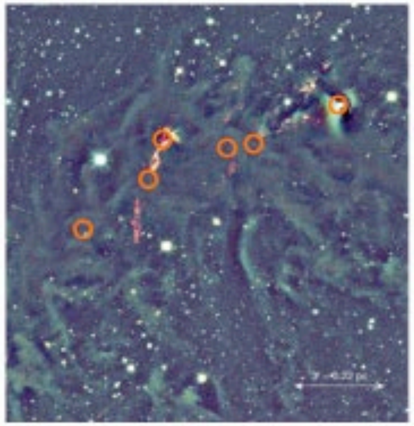
scales to same scale



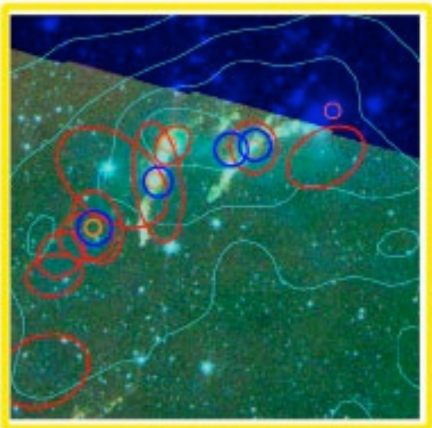
- Orion

(from A. Goodman)

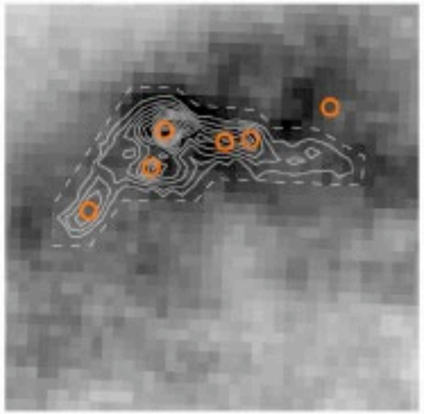




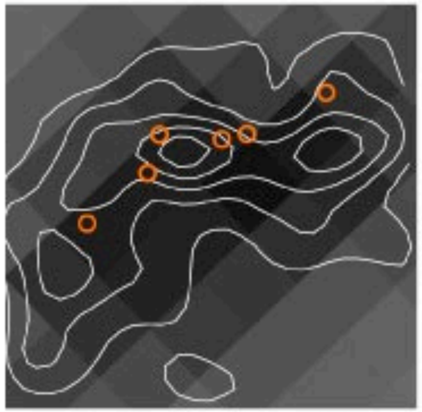
J,H,K Near-IR image
of Cloudshine



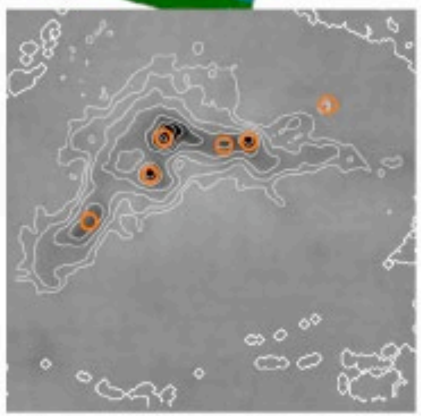
C O 850 micron and 1.1 mm clumps on a c2d IRAC 3-color image



MPL N_2H^+ on ^{13}CO integrated intensity



E Deep NIR Extinction on 2MASS Extinction



TE 1.2 mm (IRAM) on 850 micron (SCUBA) continuum

images from Alyssa Goodman

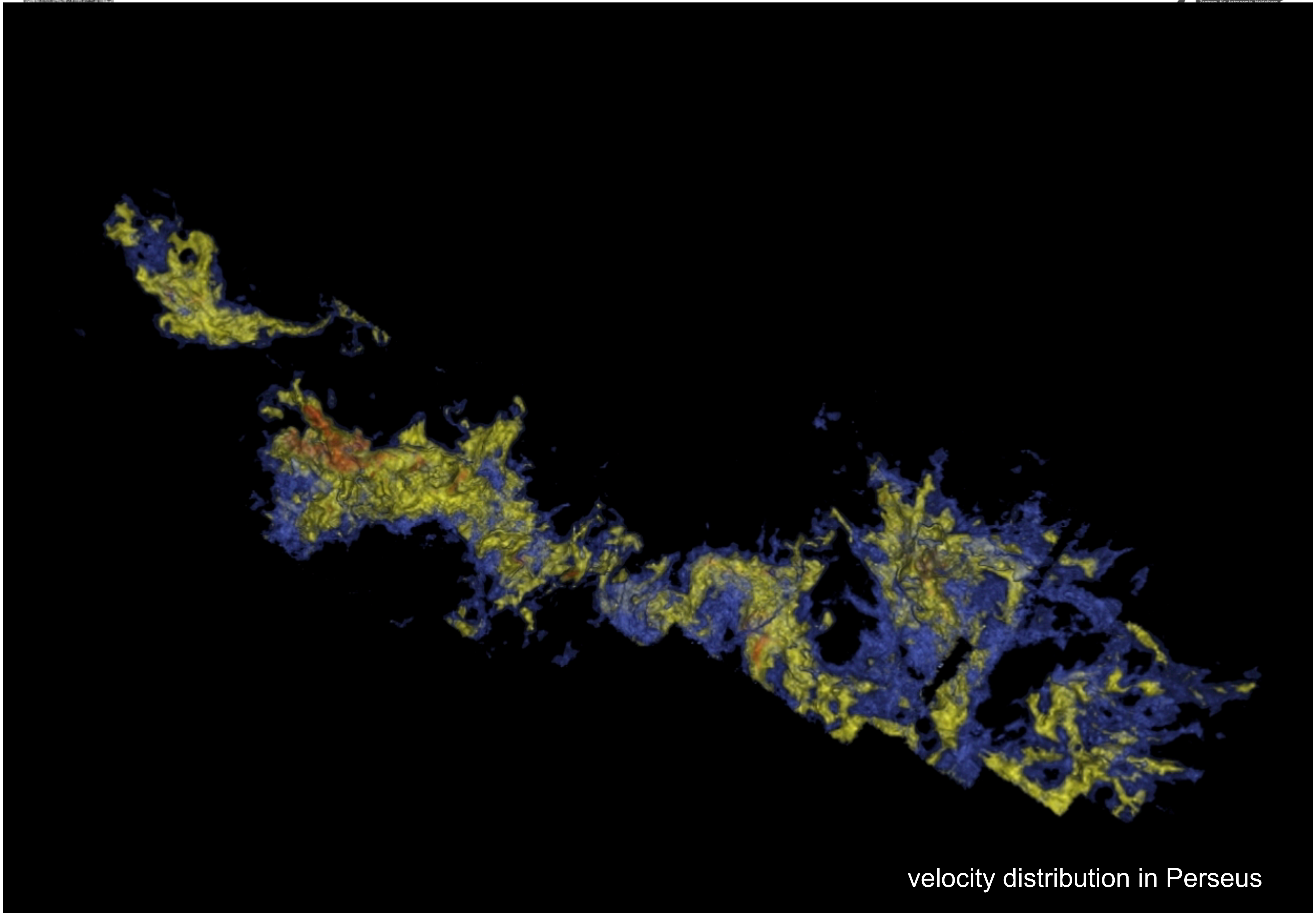
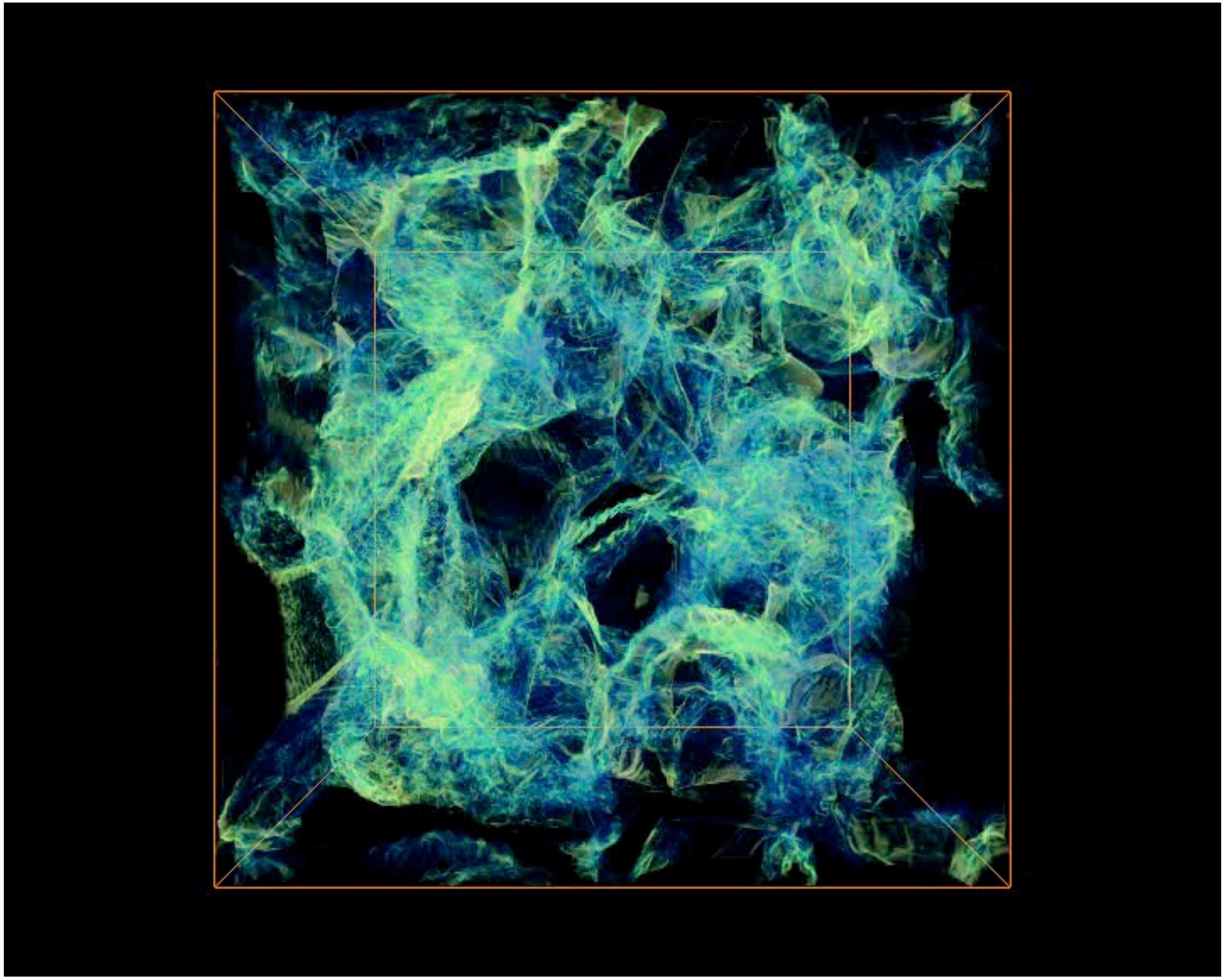
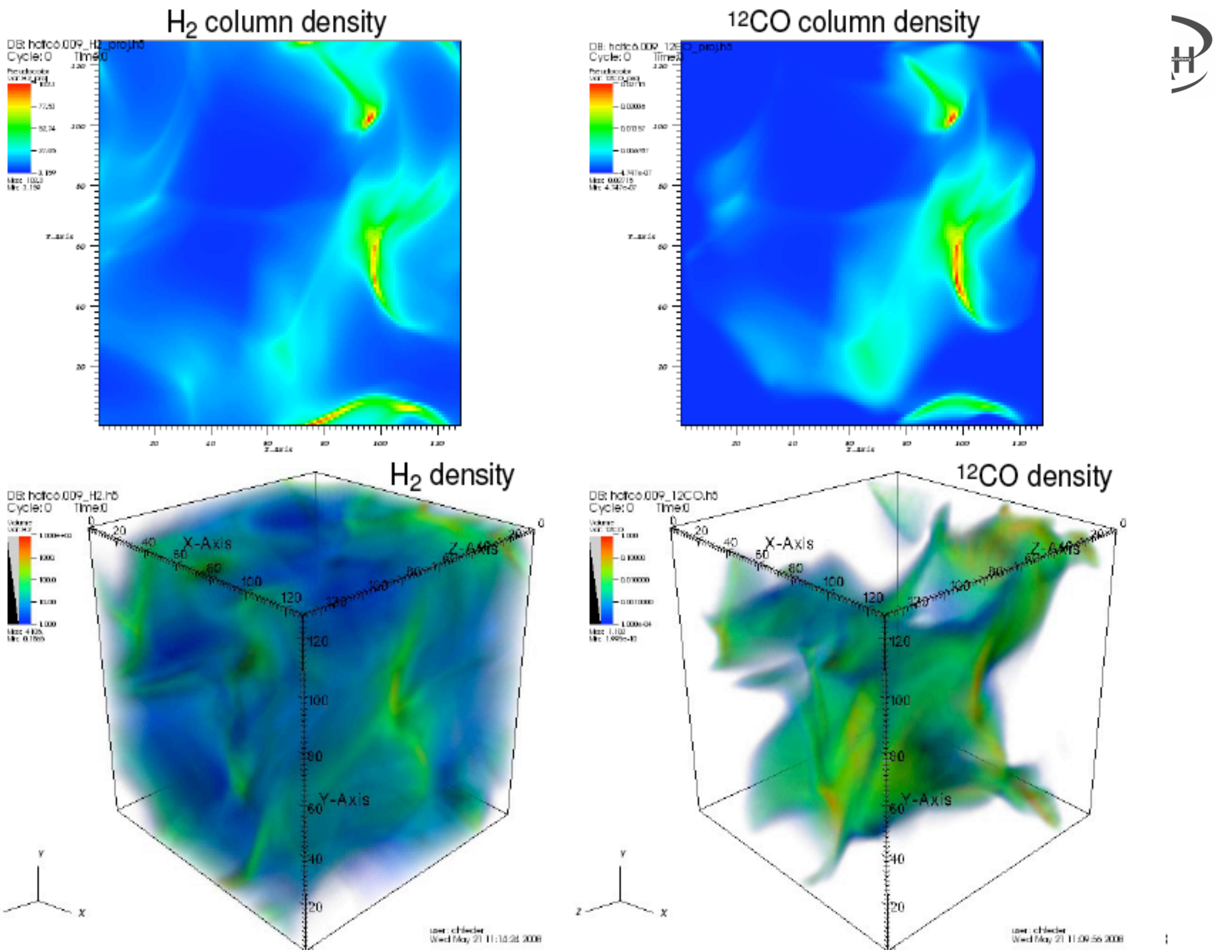


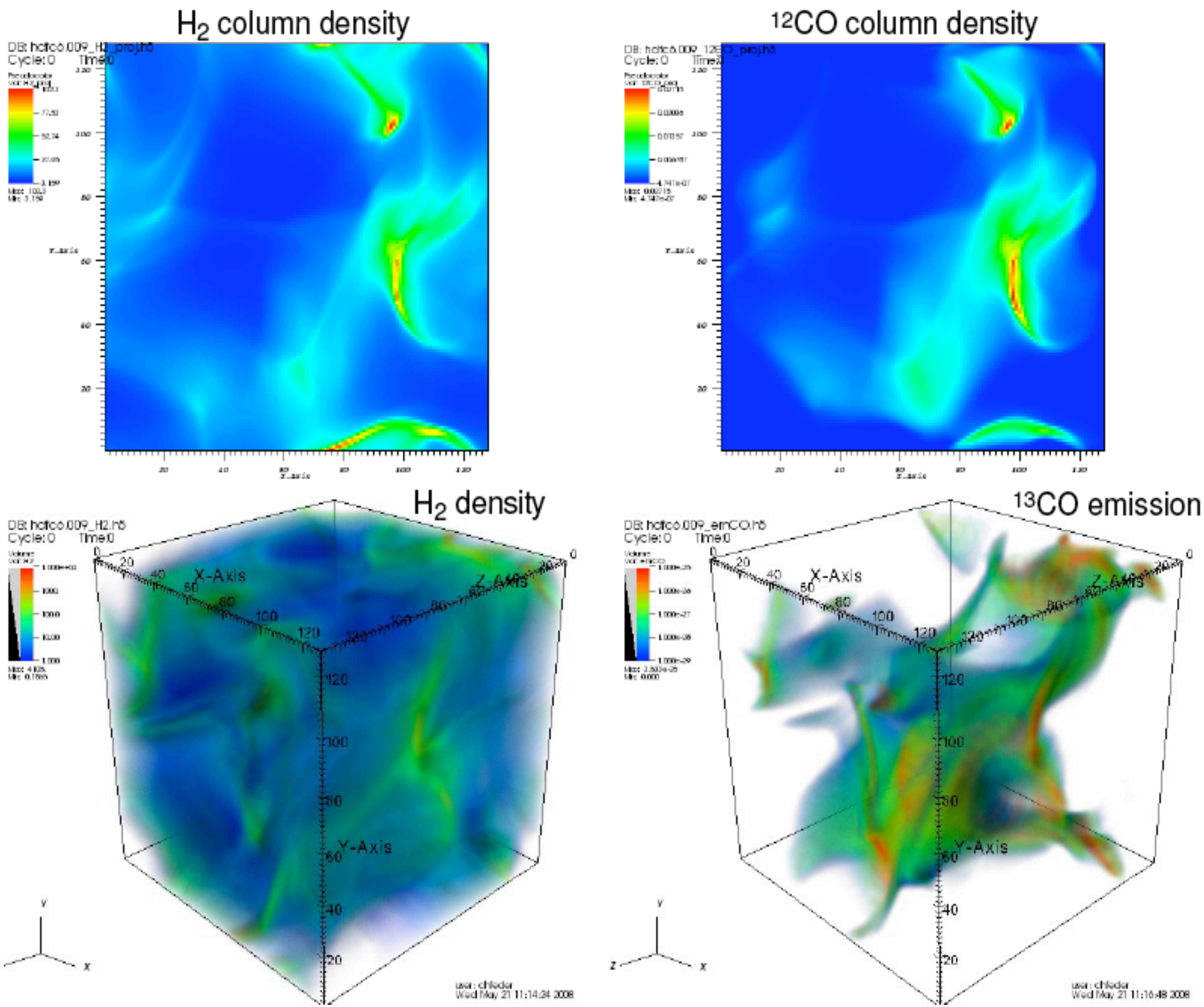
image from Alyssa Goodman: COMPLETE survey



(movie from Christoph Federrath)



(Glover, Federrath, et al.)



(Glover, Federrath, et al.)

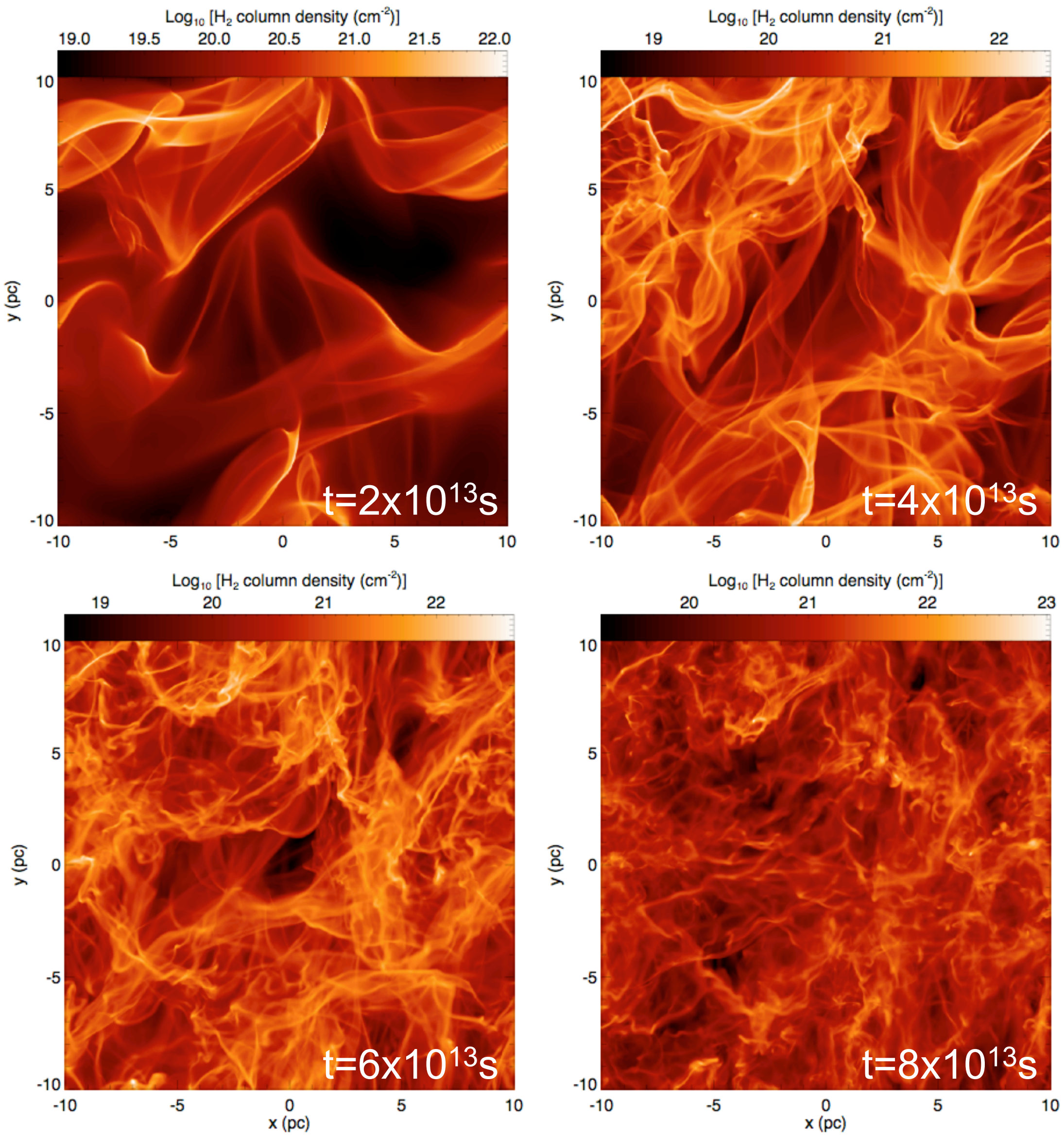
ISM: transition HI to H_2

consistent models of ISM dynamics require to go beyond the simple models!

- magnetohydrodynamics (account for large-scale dynamics + turbulence)
- time-dependent chemistry (reduced network, focus on few dominant species, e.g. H_2)
- radiation (currently simple assumptions)

H2 forms rapidly in shocks / transient density fluctuations / H2 gets destroyed slowly in low density regions / result: turbulence greatly enhances H2-formation rate

(Glover & Mac Low 2007ab:)



Reduced chemical network

Table 1. The set of chemical reactions that make up our model of non-equilibrium hydrogen chemistry.

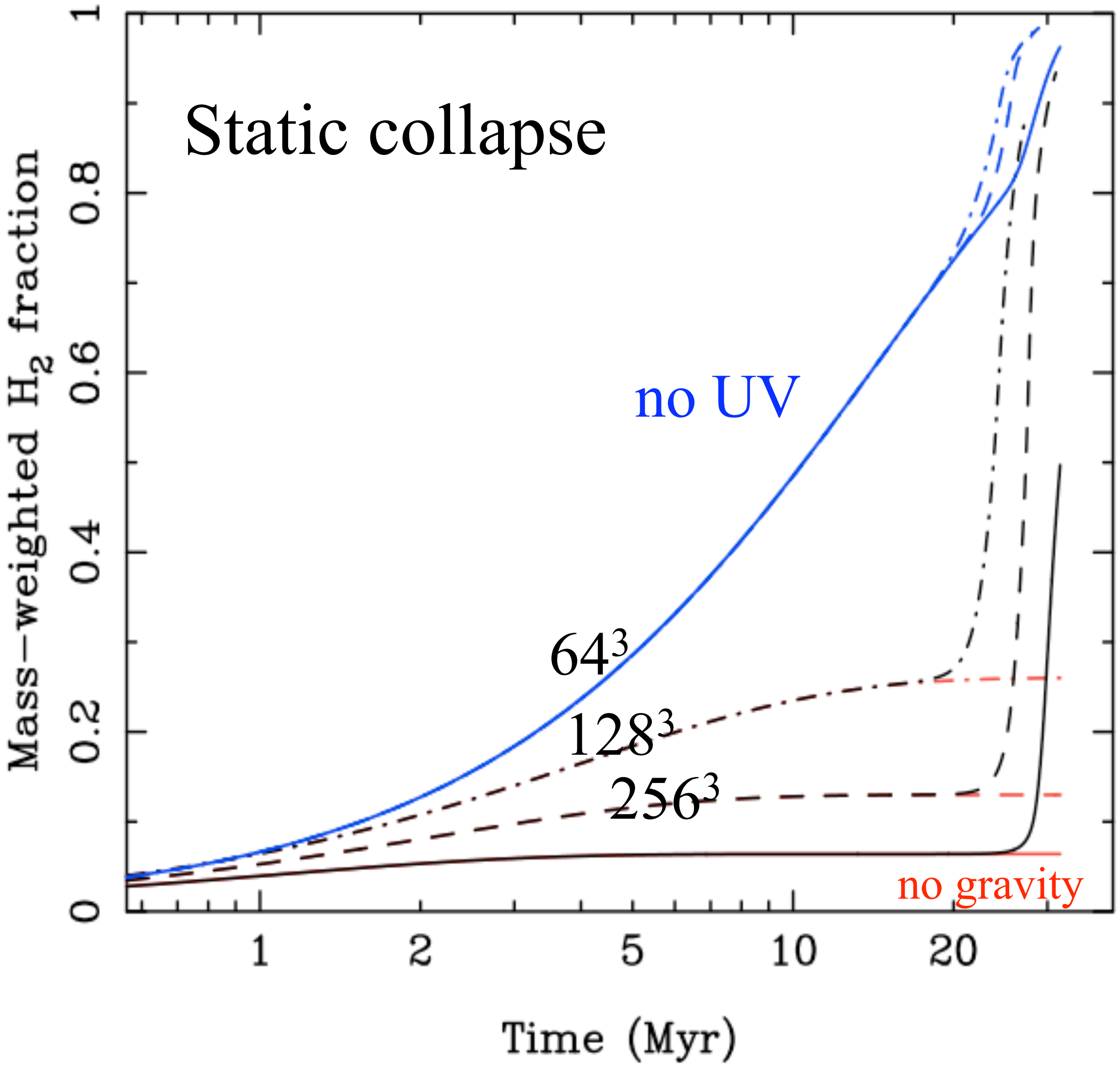
Reaction	Reference
1. $H + H + grain \rightarrow H_2 + grain$	Hollenbach & McKee (1979)
2. $H_2 + H \rightarrow 3H$	Mac Low & Shull (1986) (low density), Lepp & Shull (1983) (high density)
3. $H_2 + H_2 \rightarrow 2H + H_2$	Martin, Keogh & Mandy (1998) (low densit Shapiro & Kang (1987) (high density)
4. $H_2 + \gamma \rightarrow 2H$	See § 2.2.1
5. $H + c.r. \rightarrow H^+ + e$	Liszt (2003)
6. $H + e \rightarrow H^+ + 2e$	Abel *et al.* (1997)
7. $H^+ + e \rightarrow H + \gamma$	Ferland *et al.* (1992)
8. $H^+ + e + grain \rightarrow H + grain$	Weingartner & Draine (2001)

Table 2. Processes included in our thermal model.

Process	References
Cooling:	
C II fine structure lines	Atomic data – Silva & Viegas (2002)
	Collisional rates (H_2) – Flower & Launay (1977)
	Collisional rates (H, $T < 2000$ K) – Hollenbach & McKee (1989)
	Collisional rates (H, $T > 2000$ K) – Keenan *et al.* (1986)
	Collisional rates (e^-) – Wilson & Bell (2002)
O I fine structure lines	Atomic data – Silva & Viegas (2002)
	Collisional rates (H, H_2) – Flower, priv. comm.
	Collisional rates (e^-) – Bell, Berrington & Thomas (1998)
	Collisional rates (H^+) – Pequignot (1990, 1996)
Si II fine structure lines	Atomic data – Silva & Viegas (2002)
	Collisional rates (H) – Roueff (1990)
	Collisional rates (e^-) – Dufton & Kingston (1991)
H_2 rovibrational lines	Le Bourlot, Pineau des Forêts & Flower (1999)
Gas-grain energy transfer[1]	Hollenbach & McKee (1989)
Recombination on grains	Wolfire *et al.* (2003)
Atomic resonance lines	Sutherland & Dopita (1993)
H collisional ionization	Abel *et al.* (1997)
H_2 collisional dissociation	See Table 1
Heating:	
Photoelectric effect	Bakes & Tielens (1994); Wolfire *et al.* (2003)
H_2 photodissociation	Black & Dalgarno (1977)
UV pumping of H_2	Burton, Hollenbach & Tielens (1990)
H_2 formation on dust grains	Hollenbach & McKee (1989)
Cosmic ray ionization	Goldsmith & Langer (1978)

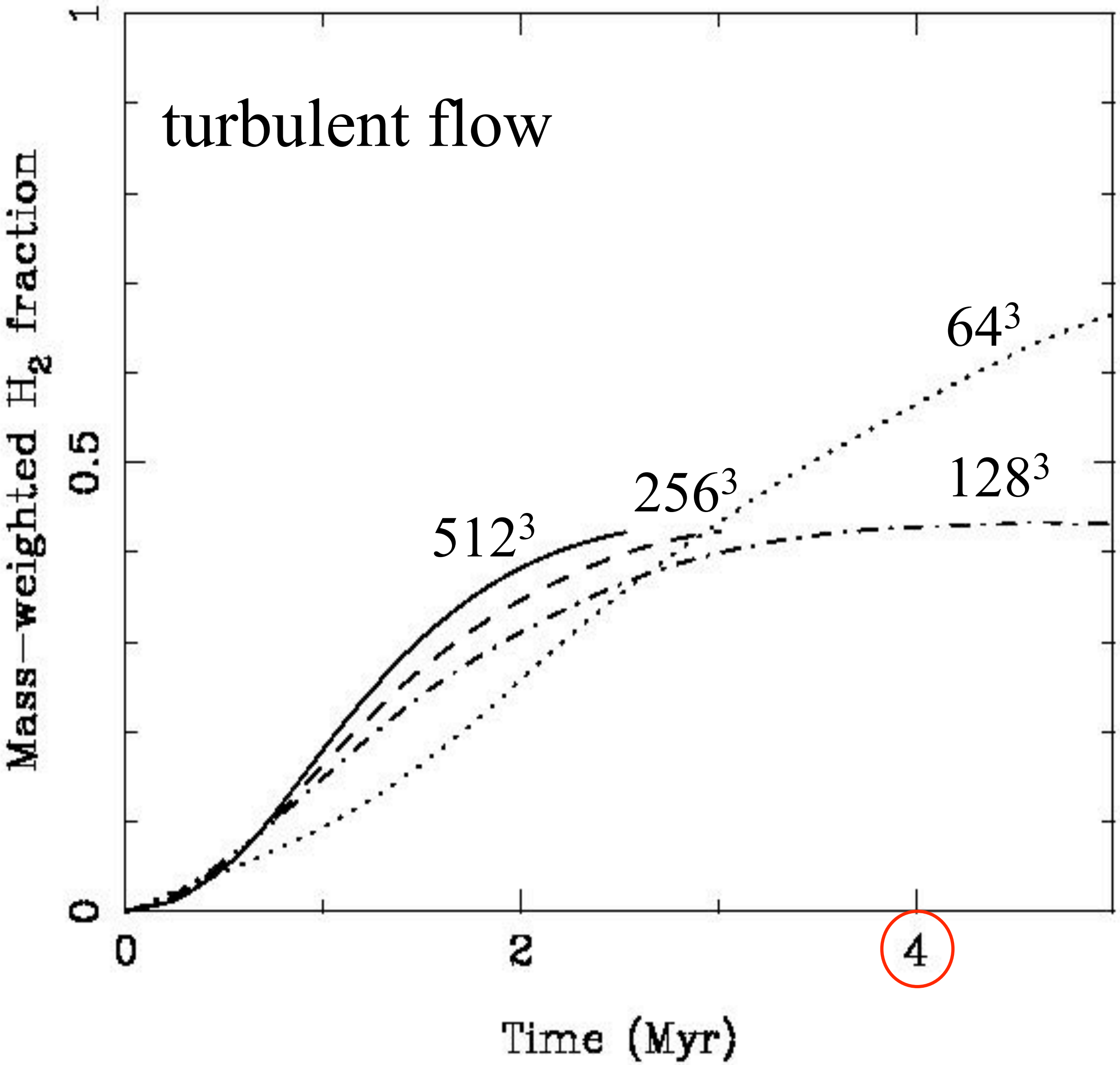
here: e^-, H^+, H, H_2
in primordial gas we do:
e^-, H^+, H, H^-, H_2^+, H_2, C, C^+, O, O^+

(Glover & Mac Low 2007ab)



L = 40 pc, n_0 = 100 cm-3, B_0 = 5.85 mG, v_{rms} = 0.0

(Glover & Mac Low 2007a)

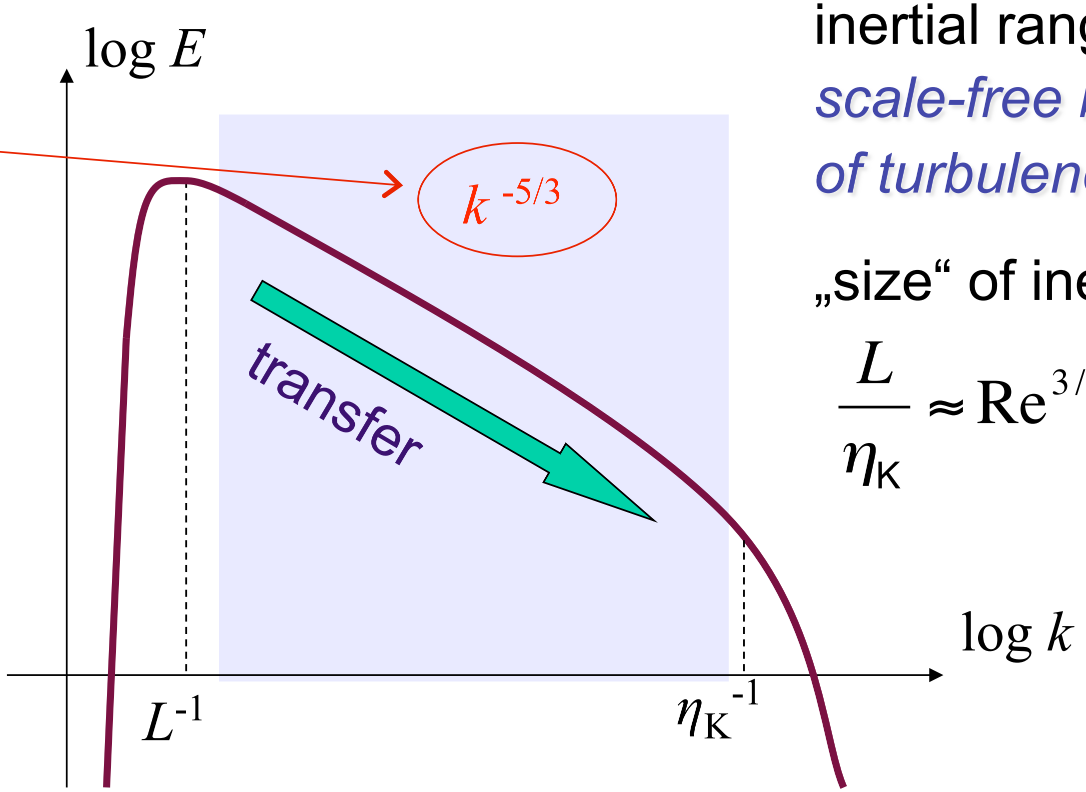


L = 20 pc, B_0 = 5.85 μG, v_{rms} = 10 km/s

(Glover & Mac Low 2007a)

turbulent cascade

Kolmogorov (1941) theory
incompressible turbulence



inertial range:
scale-free behavior of turbulence

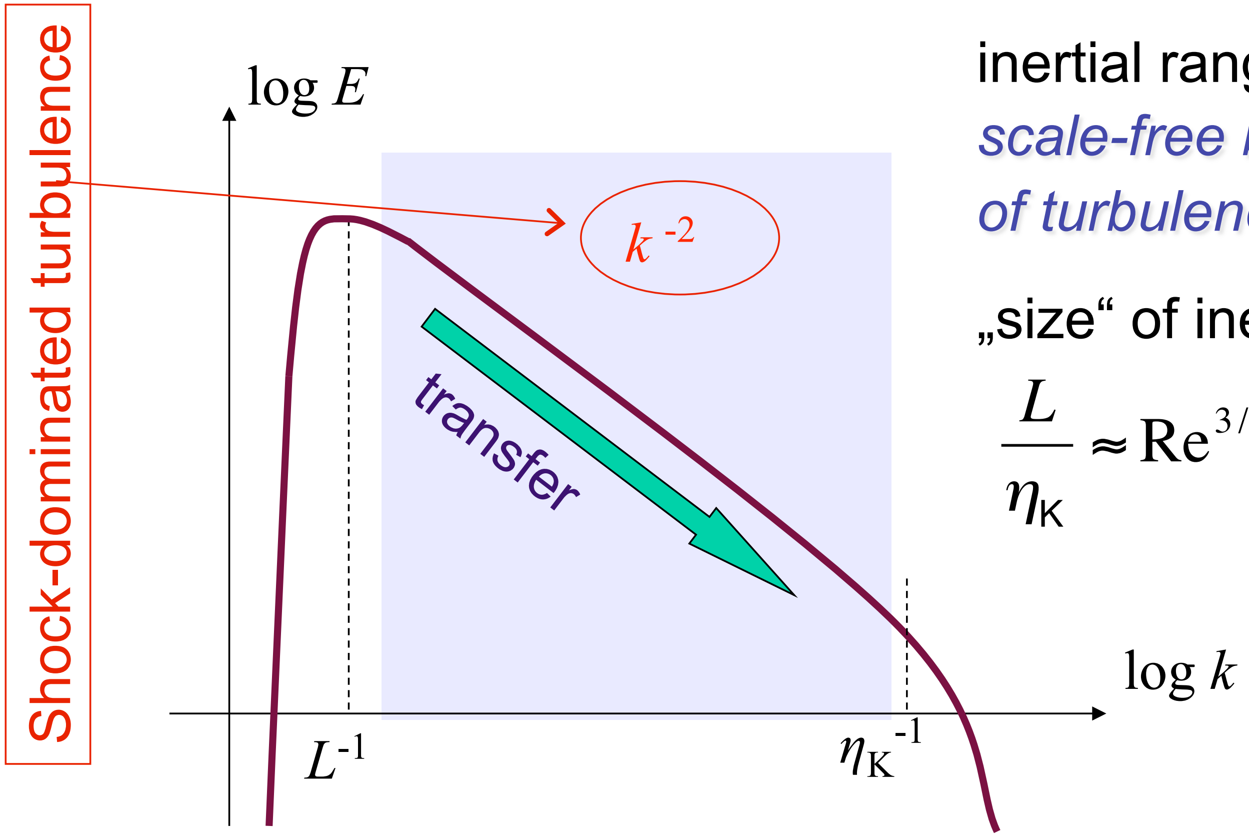
„size“ of inertial range:

$$\frac{L}{\eta_K} \approx \mathrm{Re}^{3/4}$$

energy input scale

energy dissipation scale

turbulent cascade



energy
input
scale

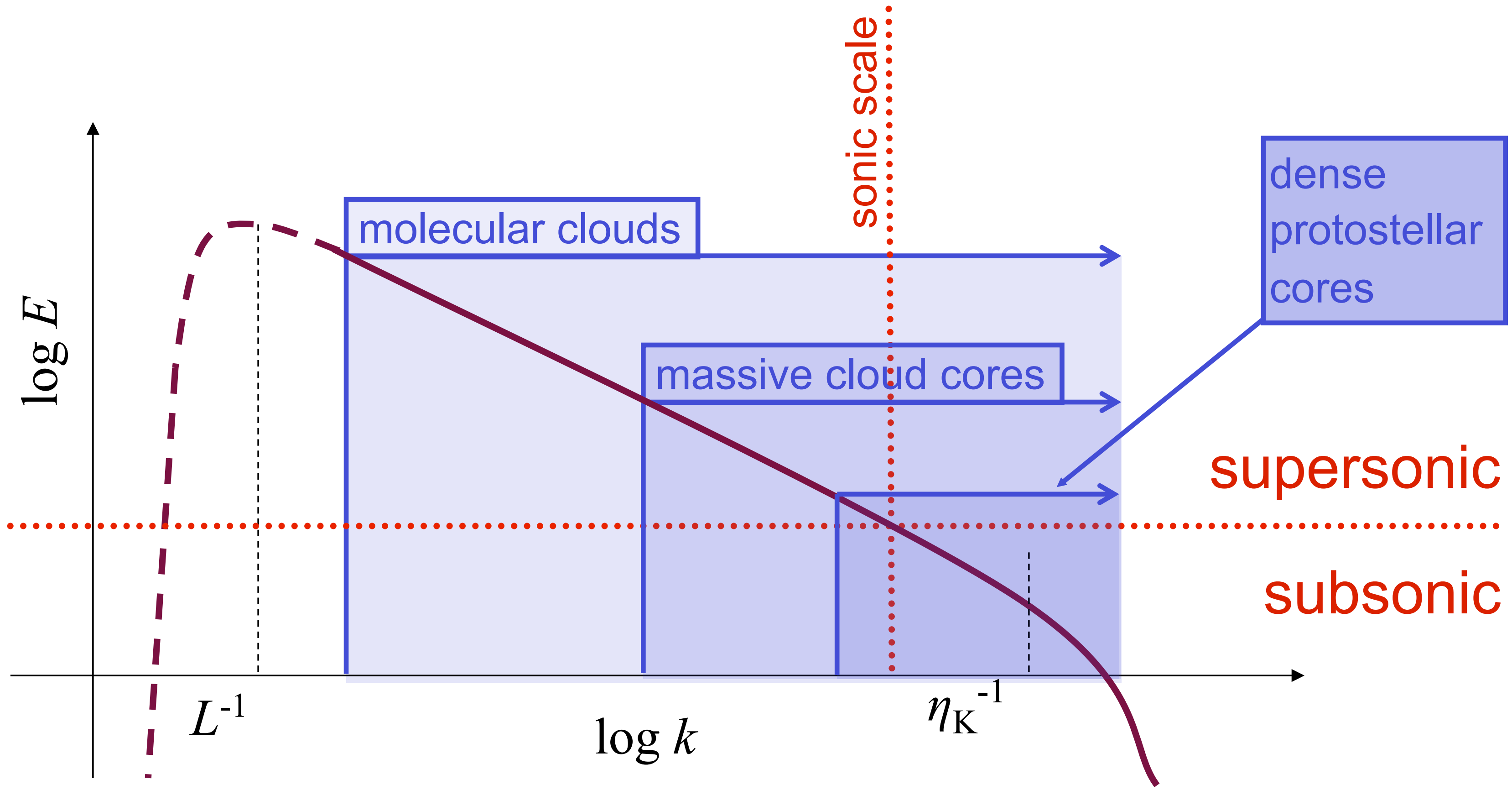
energy
dissipation
scale

inertial range:
scale-free behavior of turbulence

„size" of inertial range:

$$\frac{L}{\eta_K} \approx \mathrm{Re}^{3/4}$$

turbulent cascade in ISM



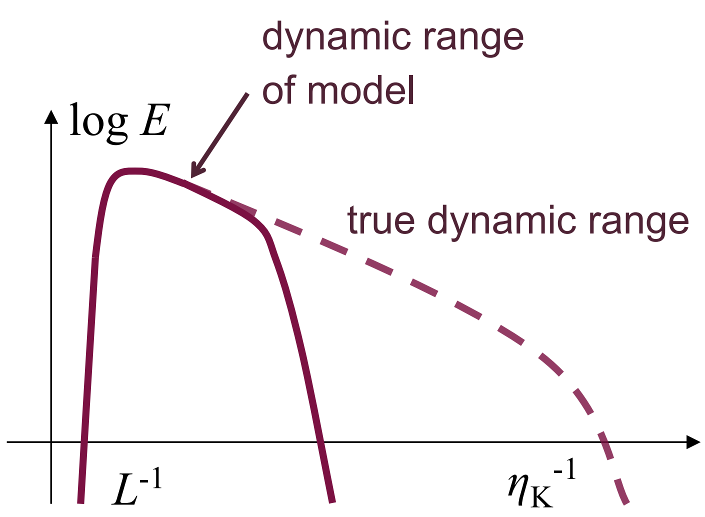
energy source & scale
NOT known
(supernovae, winds,
spiral density waves?)

σ_{rms} << 1 km/s'sm/s
$M_{rms} \leq 1$
L ≈ 0.1 pc

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

Large-eddy simulations

- 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?



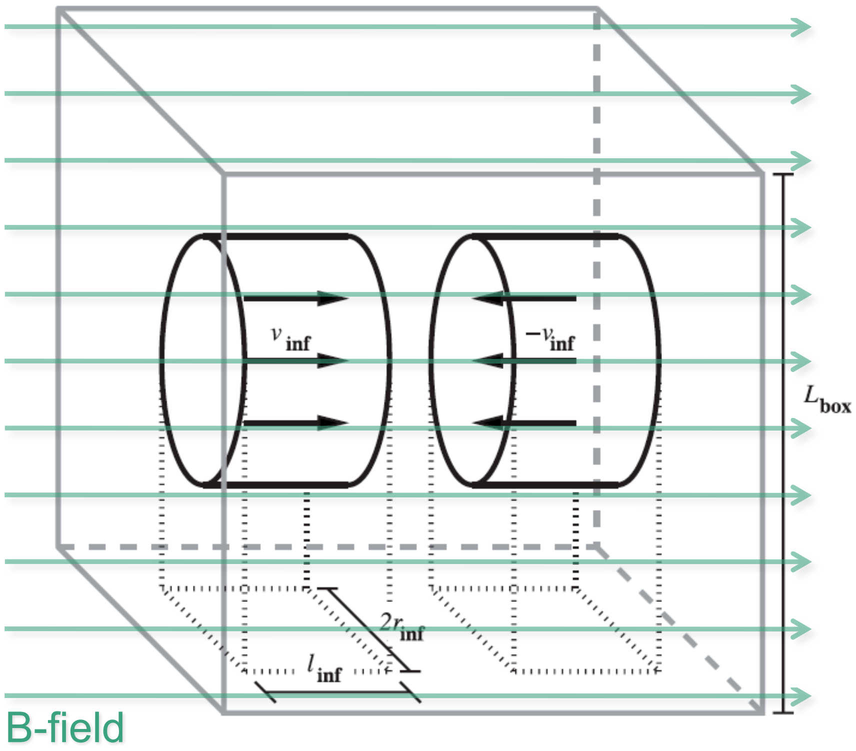
cloud core scales

fragmentation of molecular clouds

- fragmentation of molecular clouds and relation to stellar birth
- some questions
  - how does the turbulence generated by cloud formation influence cloud fragmentation?
  - how important if turbulence from internal feedback? (is that consistent with observations?)
  - interplay between gravity and turbulence?
    → role of turbulence for star formation

convergent flows: set-up

numerical set-up



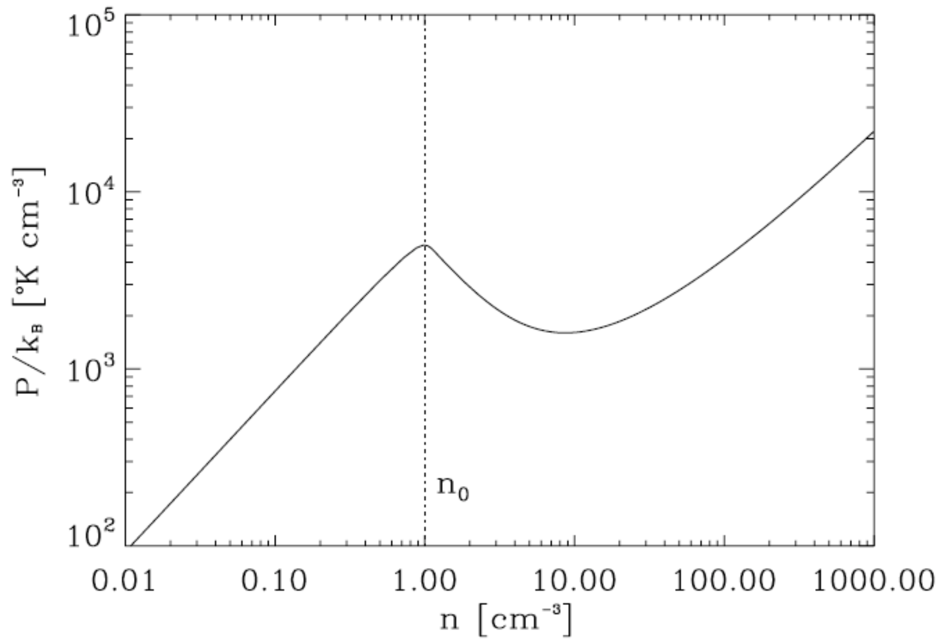
from Vazquez-Semadeni et al. (2007)

- convergent flow studies
  - atomic flows collide
  - cooling curve (soon chemistry)
  - gravity
  - magnetic fields
  - numerics: AMR, BGK, SPH

see studies by Banerjee et al., Heitsch et al., Hennebelle et al., Vazquez-Semadeni et al.

convergent flows: set-up

adopted cooling curve



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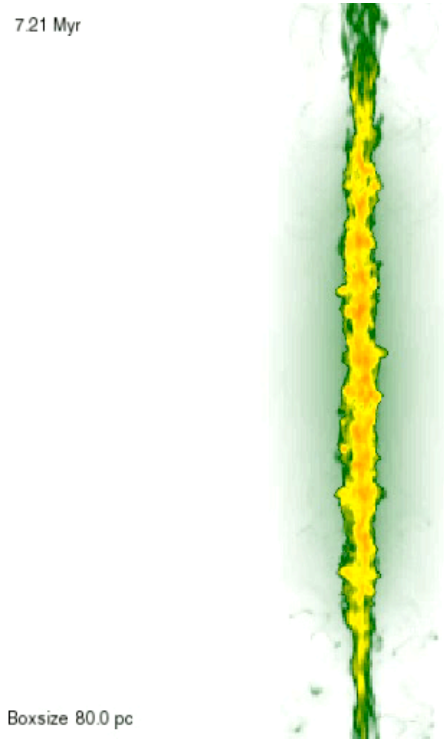
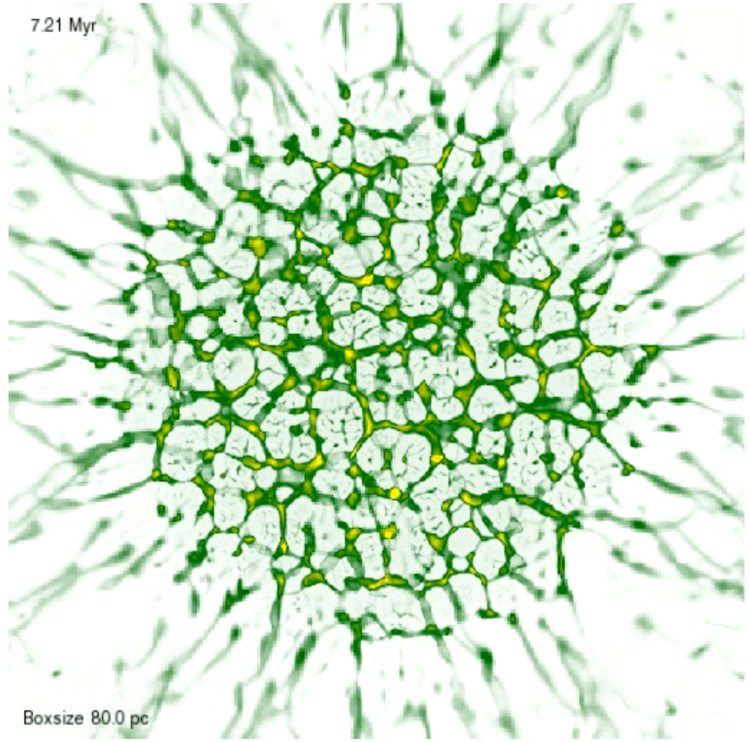
MC formation in convergent flows

thermal instability + gravity creates complex molecular cloud structure:





from Banerjee et al. (2008)
(see also studies by Hennebelle et al. and Vazquez-Semadeni et al. and Heitsch et al.)

MC formation in convergent flows

thermal instability + gravity creates complex molecular cloud structure:

0.00 Myr

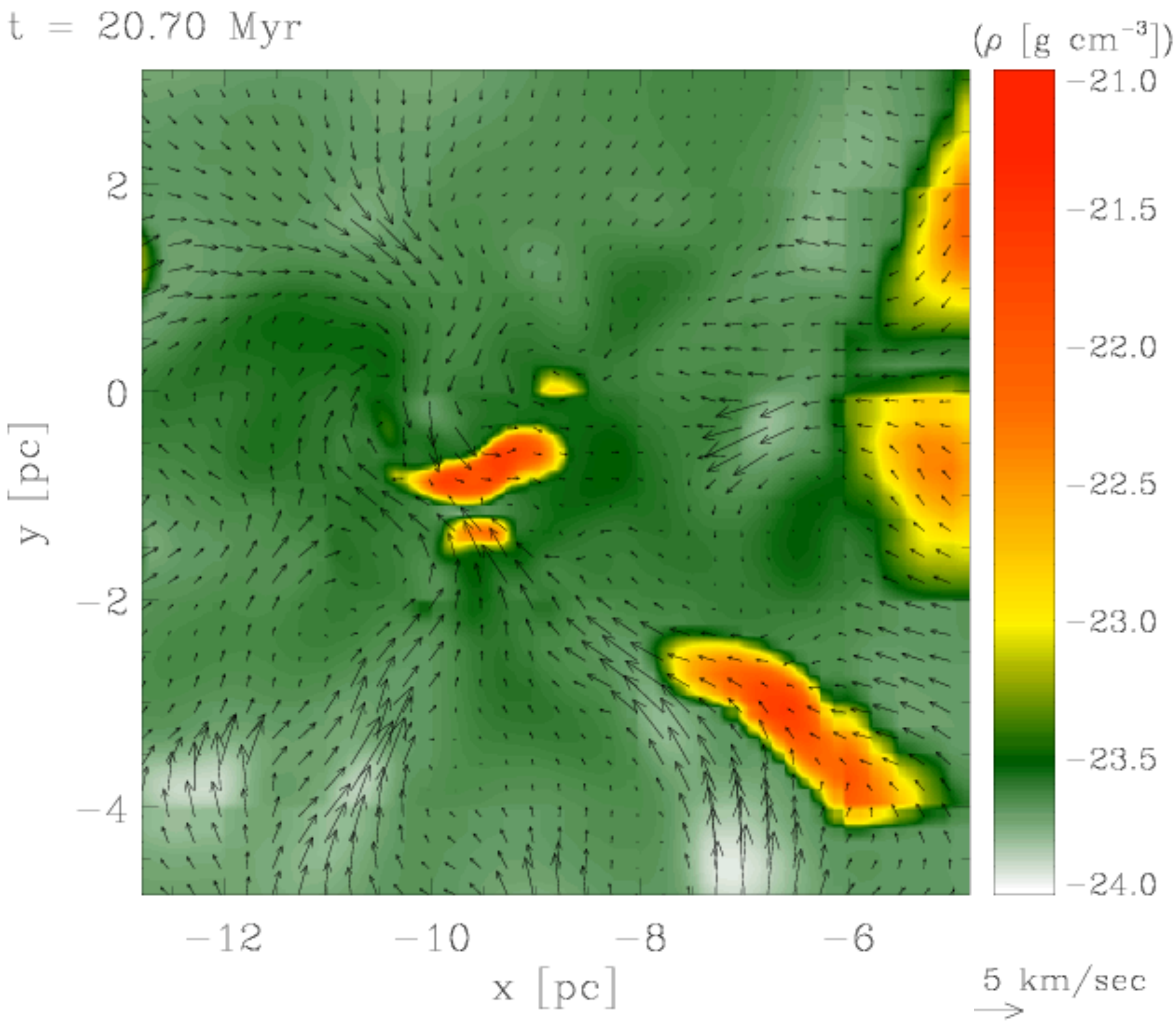
Boxsize 80.0 pc

0.00 Myr

Boxsize 80.0 pc

from Banerjee et al. (2008)
(see also studies by Hennebelle et al. and Vazquez-Semadeni et al. as well as talk by Fabian Heitsch)

density and velocity



from Banerjee et al. (2008)

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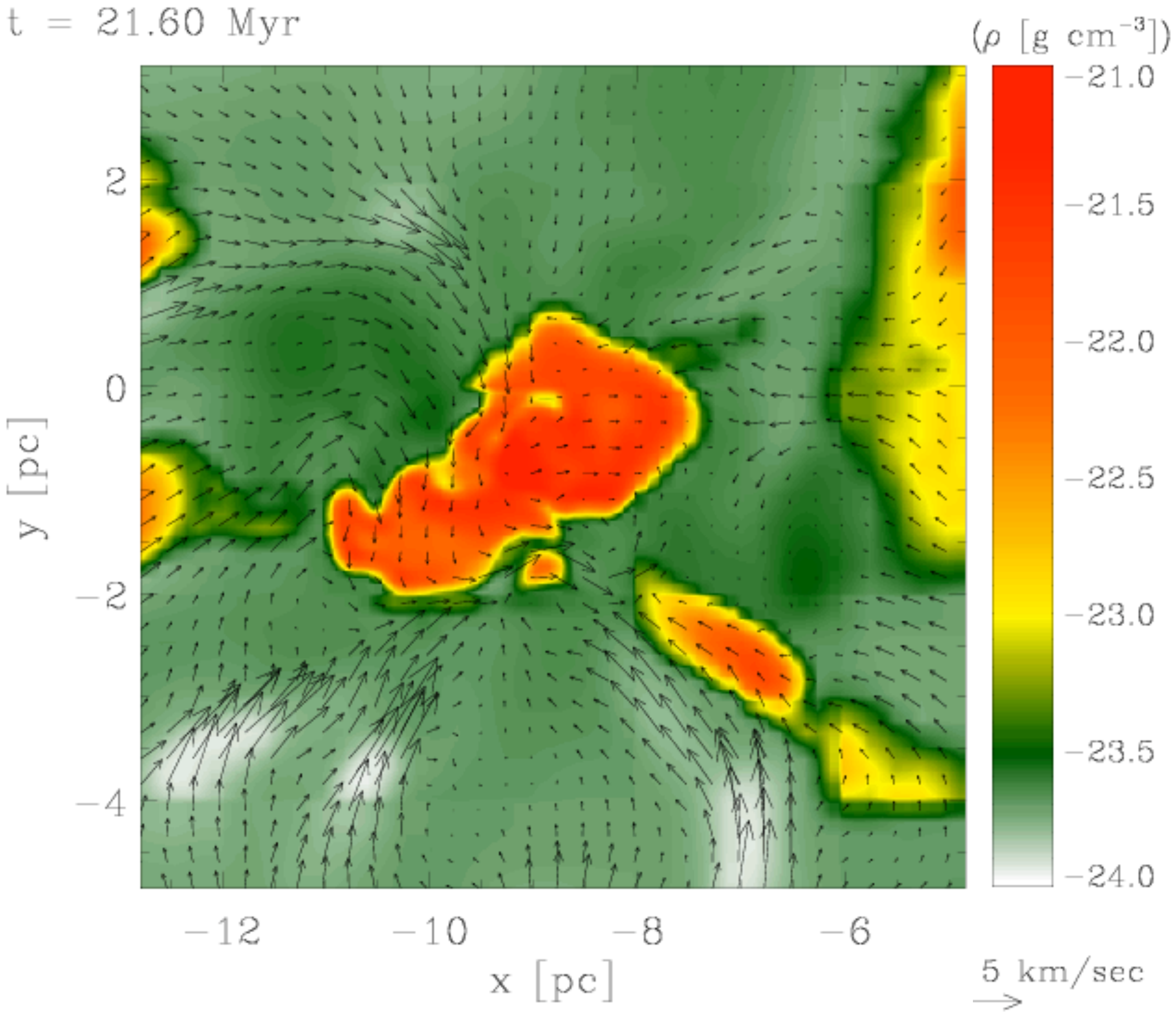

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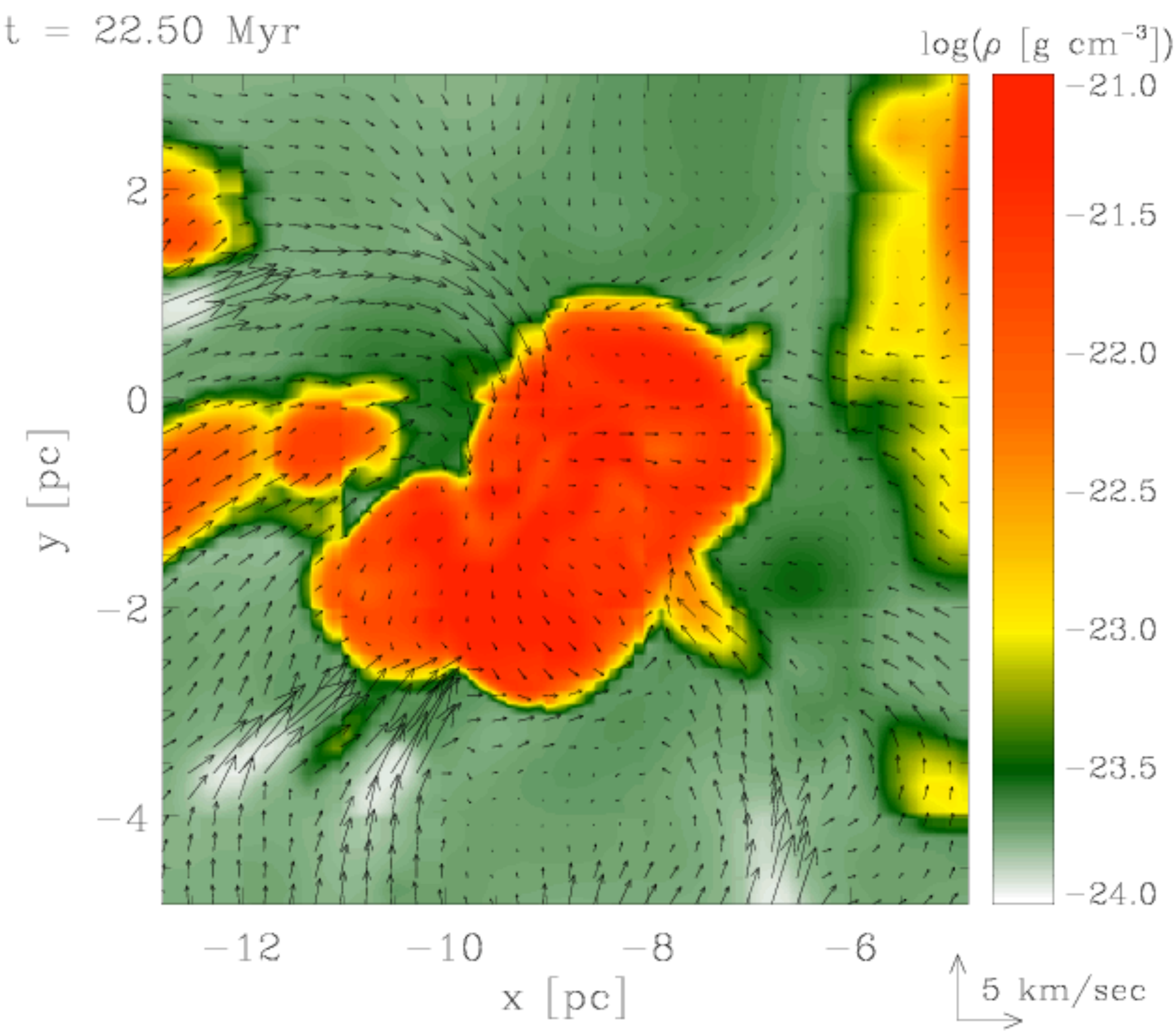


from Banerjee et al. (2008)

some results: growth of cores

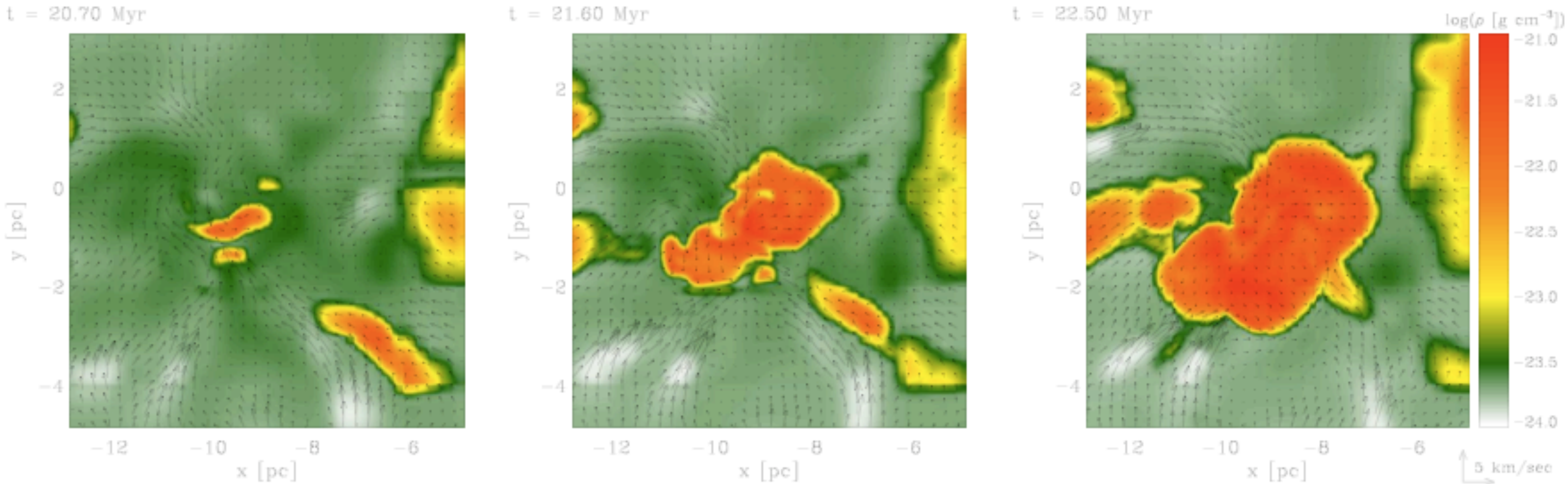


Figure 2. Shows the time evolution of a typical clump which initially develops out of the thermally unstable WNM in shock layers of turbulent flows. A small cold condensate grows by outward propagation of its boundary layer. Coalescence and merging with nearby clumps further increases the size and mass of these clumps. The global gravitational potential of the proto-cloud enhances the merging probability with time. The images show 2D slices of the density (logarithmic colour scale) and the gas velocity (indicated as arrows) in the plane perpendicular to the large scale flows.

two phases of core growth:

(1) by *outward propagation* of *boundary layer* → Jeans sub-critical phase

(2) *core mergers* → super-Jeans → gravitational collapse & star formation

example: *Pipe nebula* ???

from Banerjee et al. (2008)

some results: growth of cores

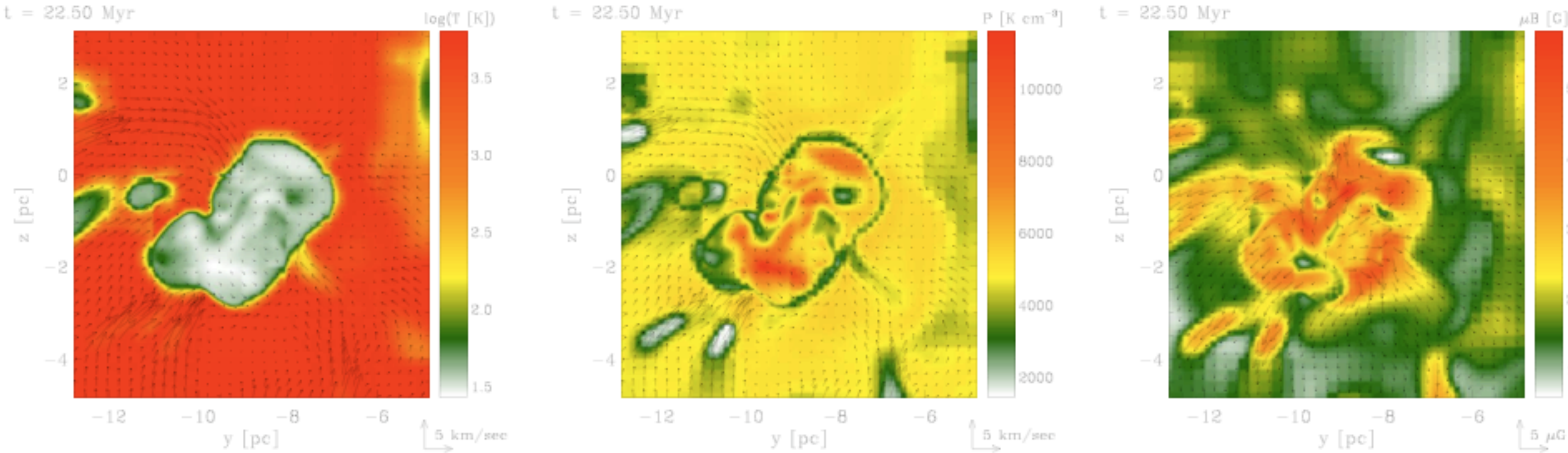


Figure 3. Shows the structure of one typical clump which forms in the thermally unstable WNM gas. The images show 2D slices of the temperature (left, log scale), thermal pressure (middle, linear scale), and magnetic field strength (right, linear scale). The arrows in the temperature and pressure plots indicate the velocity field and, in the right panel, the magnetic stream lines. The cold ($T \sim 30 - 50$ K), dense ($n \sim 2 - 5 \times 10^3\,\mathrm{cm}^{-3}$) molecular clump is embedded in the warm atomic gas ($T \sim 5 \times 10^3$ K) and has a well defined boundary. Due to the thermal properties of the ISM (see Fig. 2 of Vázquez-Semadeni et al. 2007, for the equilibrium pressure), such clumps are almost in pressure equilibrium with their surrounding. The overdense clumps exert a gravitational force on the low density environment where gas continues to stream into the clump predominately anti-parallel to the magnetic flux lines (see also Fig. 2).

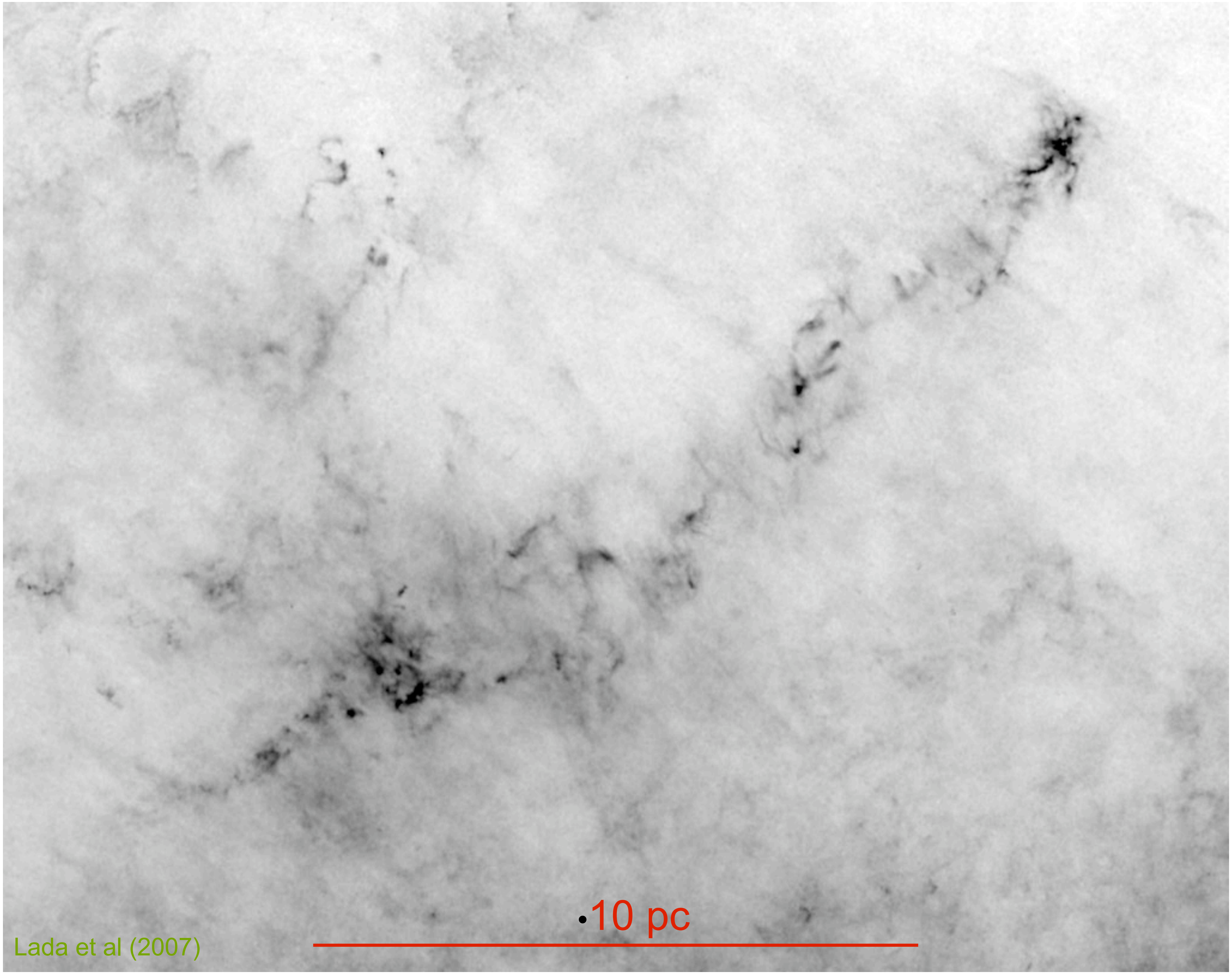
some properties of cores:

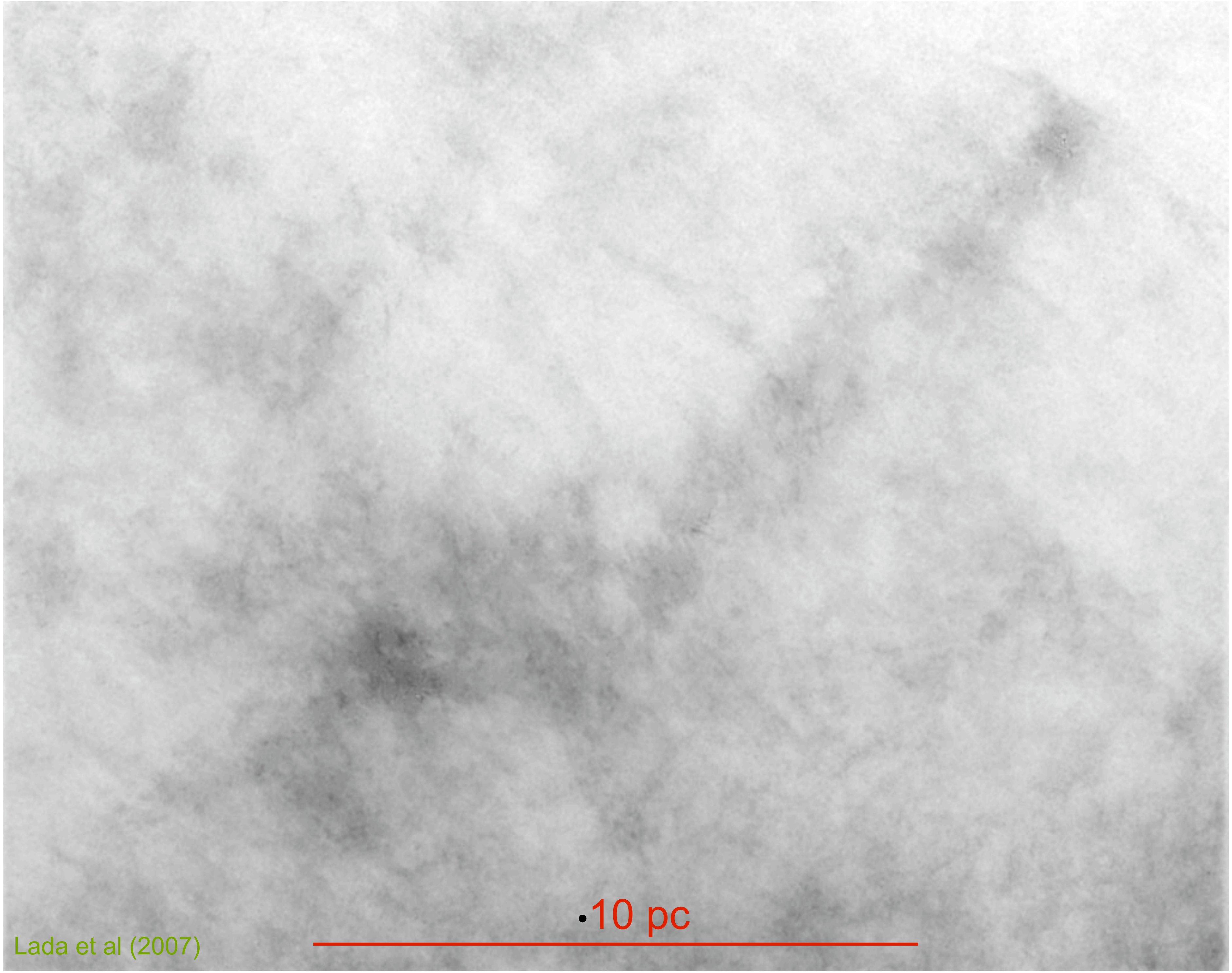
(1) cores are in approximate *pressure equilibrium* with surrounding

(2) accretion / mass flow mostly along magnetic field lines

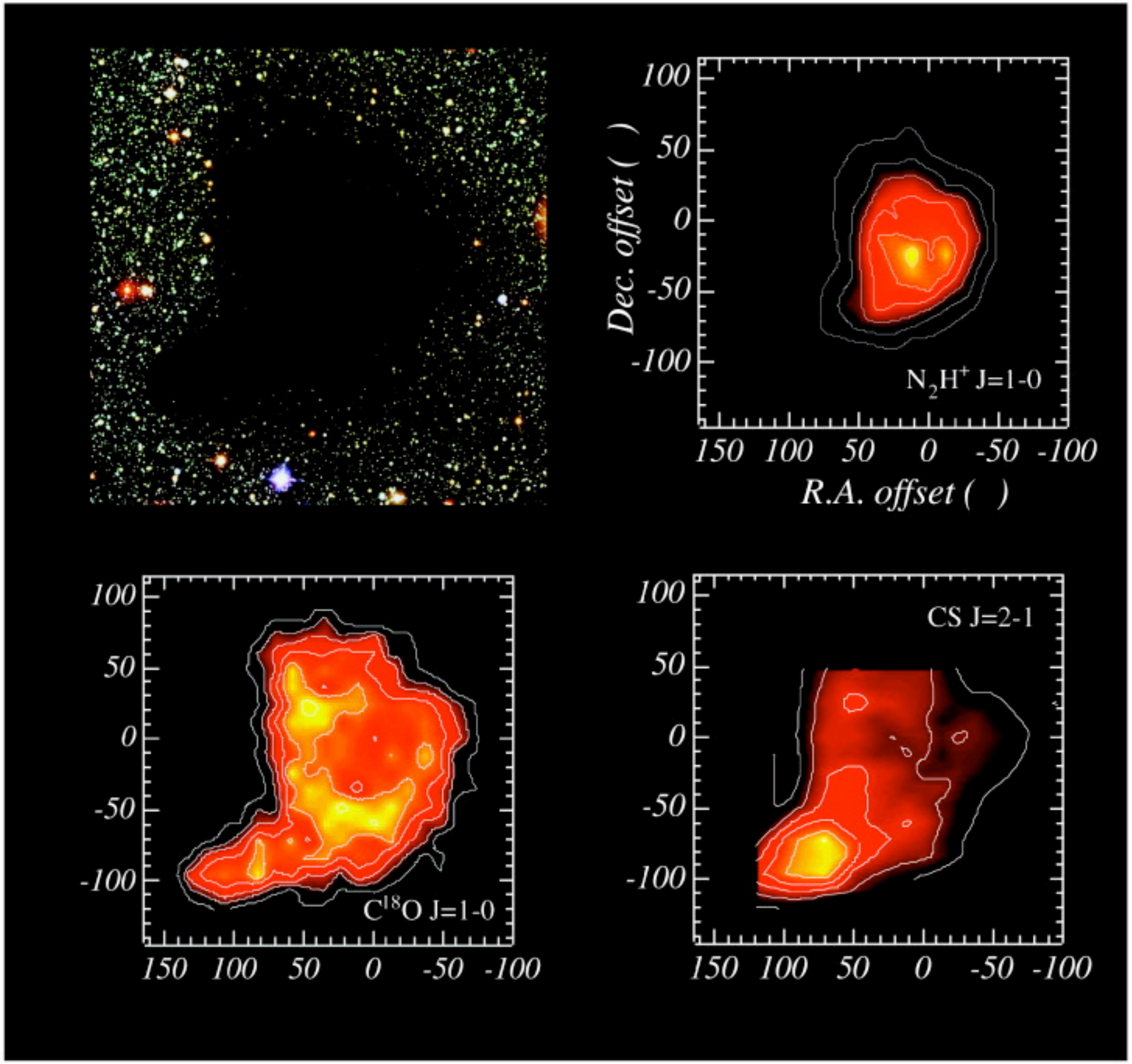
(2) core densities $n \sim 2 - 5 \times 10^3\ cm^{-3}$, core temperature $T \sim 30 - 50\ K$

from Banerjee et al. (2008)


10 pc
Lada et al (2007)

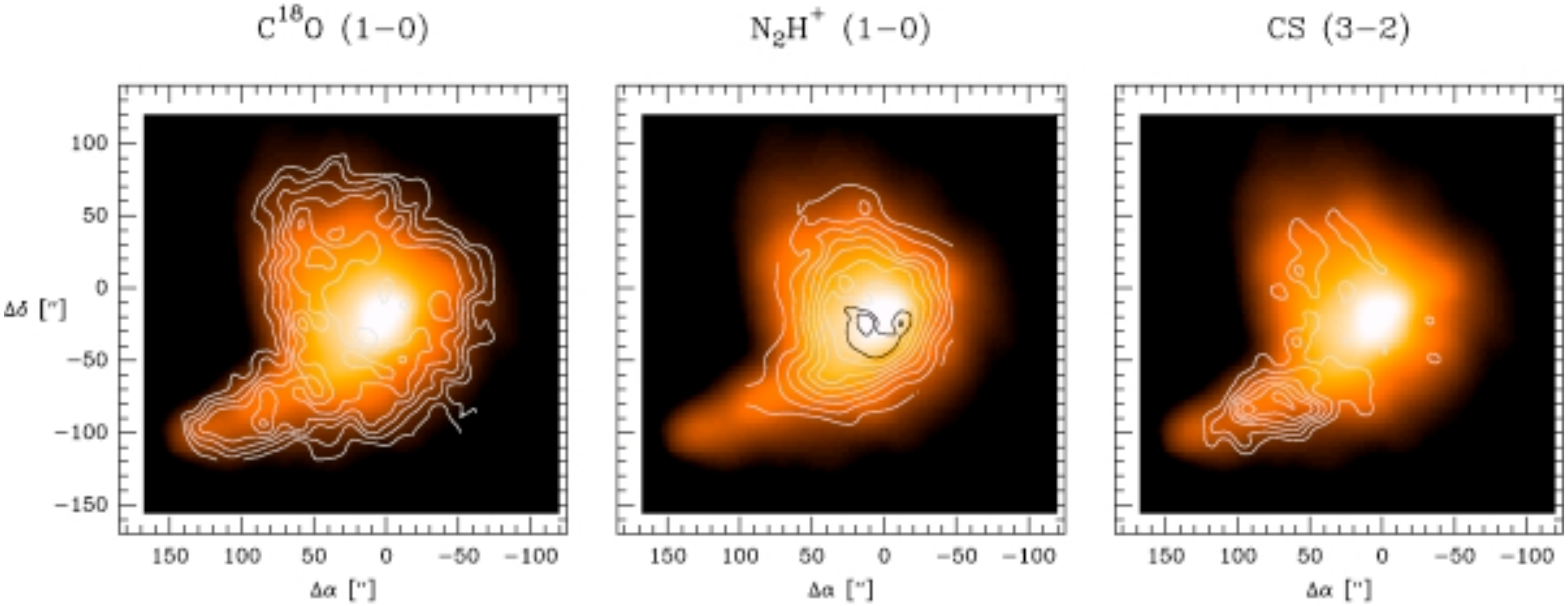

10 pc
Lada et al (2007)

Barnard 68: a well-studied isolated prestellar core



(Lada et al. 2003)

Barnard 68



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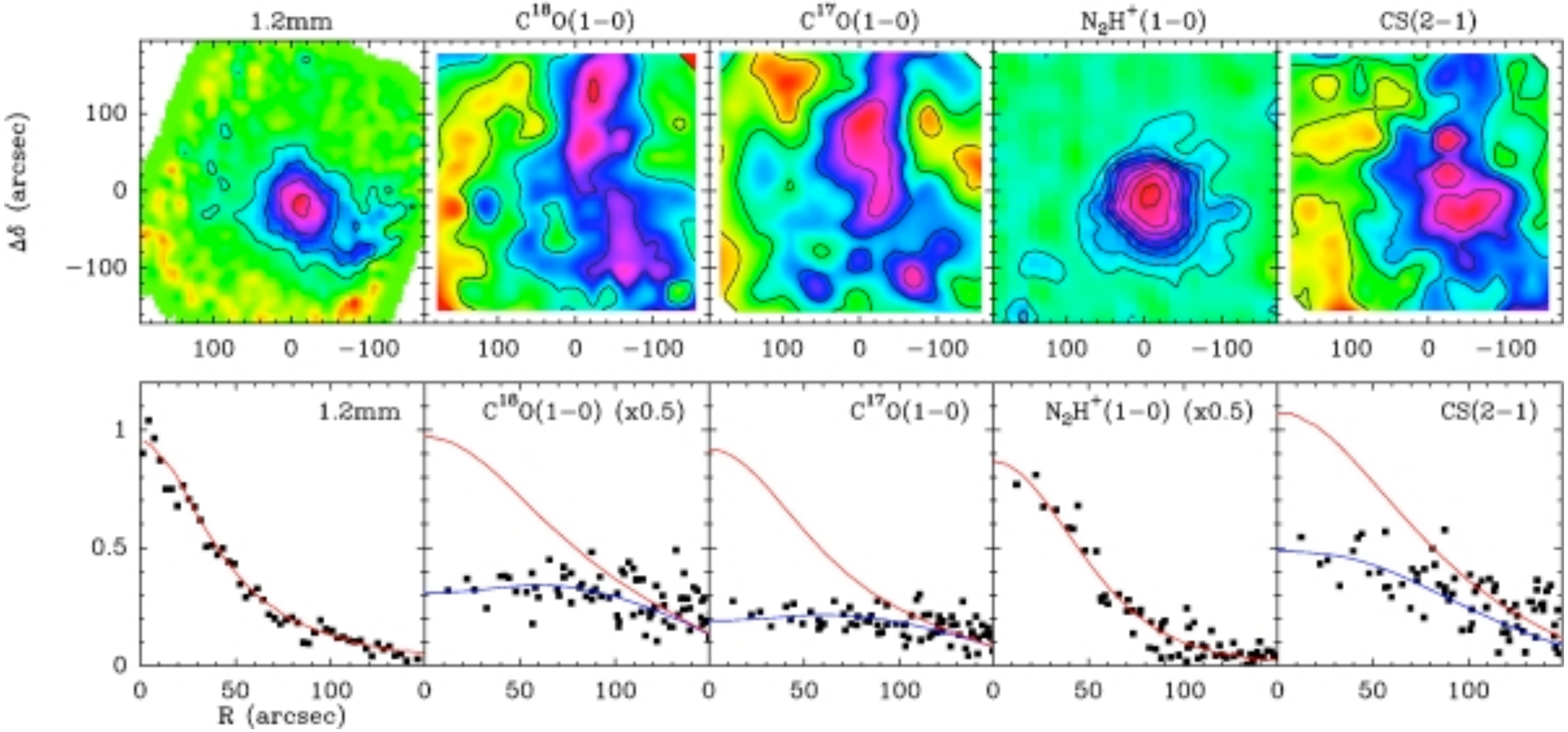


1.2mm
C^{18}O(1−0)
C^{17}O(1−0)
N$_2$H$^+$(1−0)
CS(2−1)
Δδ (arcsec)
100
0
−100
1.2mm
C^{18}O(1−0) (x0.5)
C^{17}O(1−0)
N$_2$H$^+$(1−0) (x0.5)
CS(2−1)
1
0.5
0
50
100
R (arcsec)

transition to stars

example: model of Orion cloud

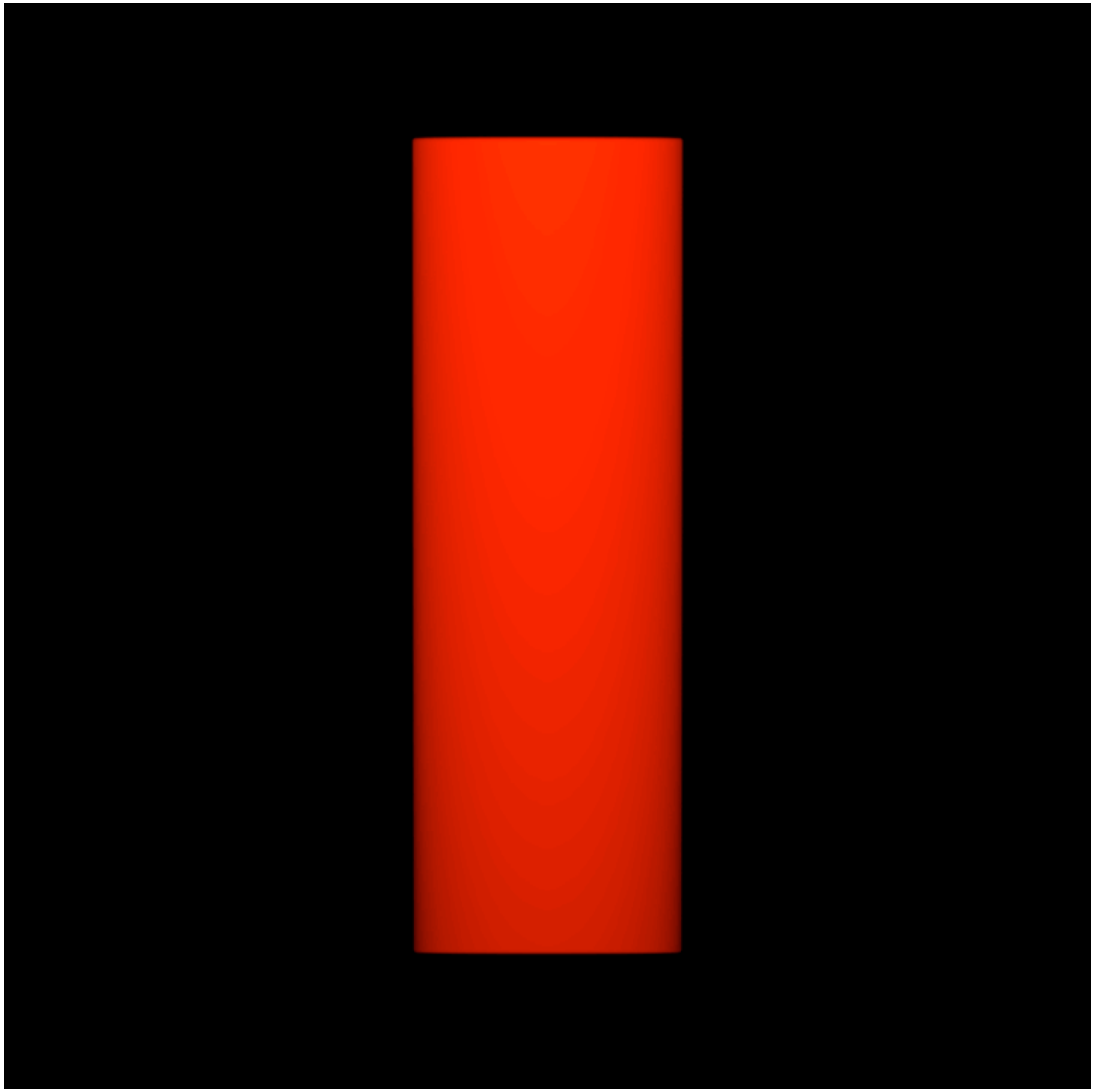
„model“ of Orion cloud: 15.000.000 SPH particles, 10^4 M_{sun} in 10 pc, mass resolution 0,02 M_{sun}, forms ~2.500 „stars“ (sink particles)

isothermal EOS, top bound, bottom unbound

has clustered as well as distributed „star“ formation

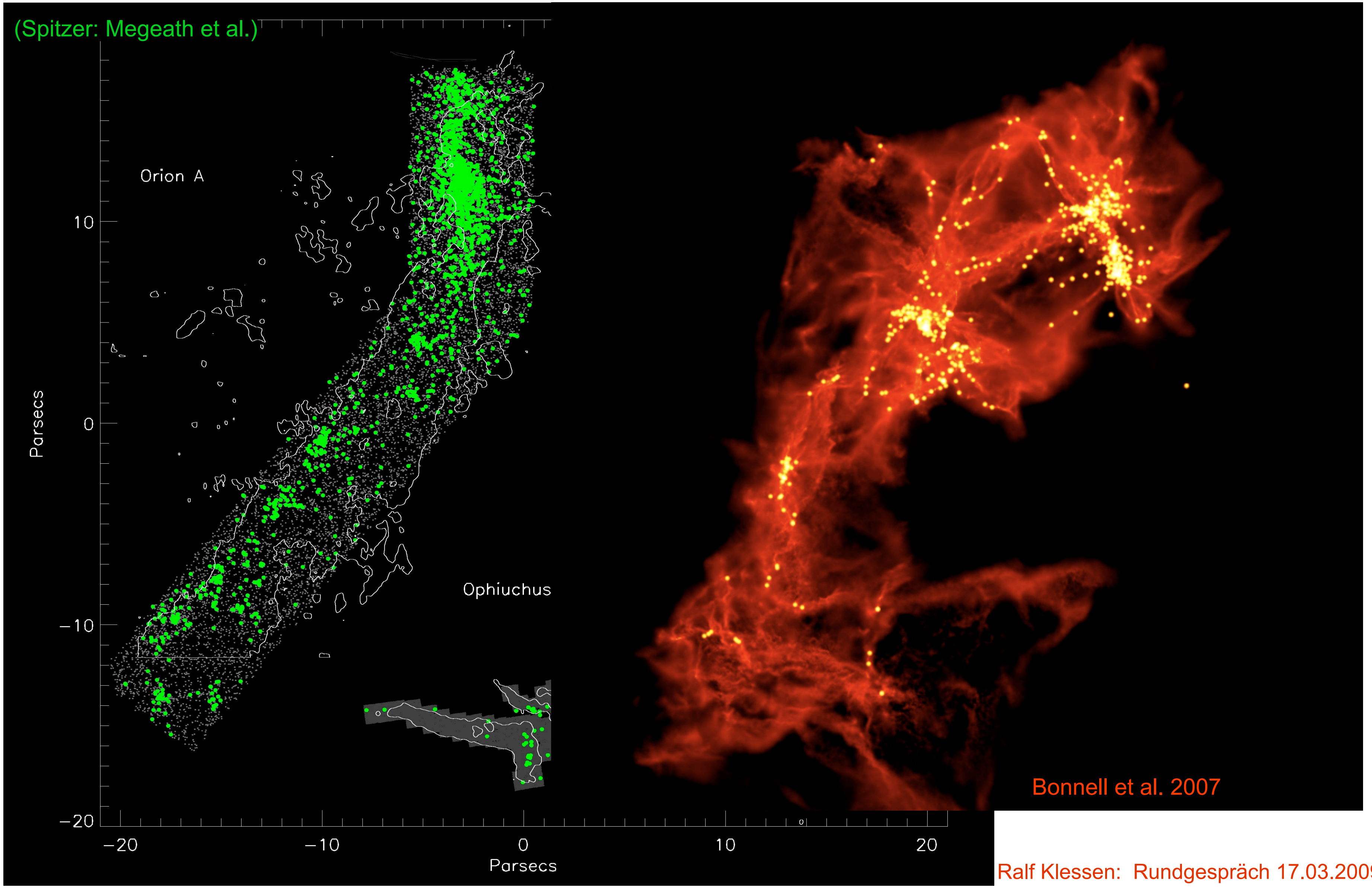
efficiency varies from 1% to 20%

develops full IMF
(distribution of sink particle masses)



(Bonnell et al. 2007)

example: model of Orion cloud



IMF

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

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

IMF

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(e.g. Larson 2003; Mac Low & Klessen, 2004; McKee & Ostriker 2007, Klessen, Krumholz, & Heitsch 2009)

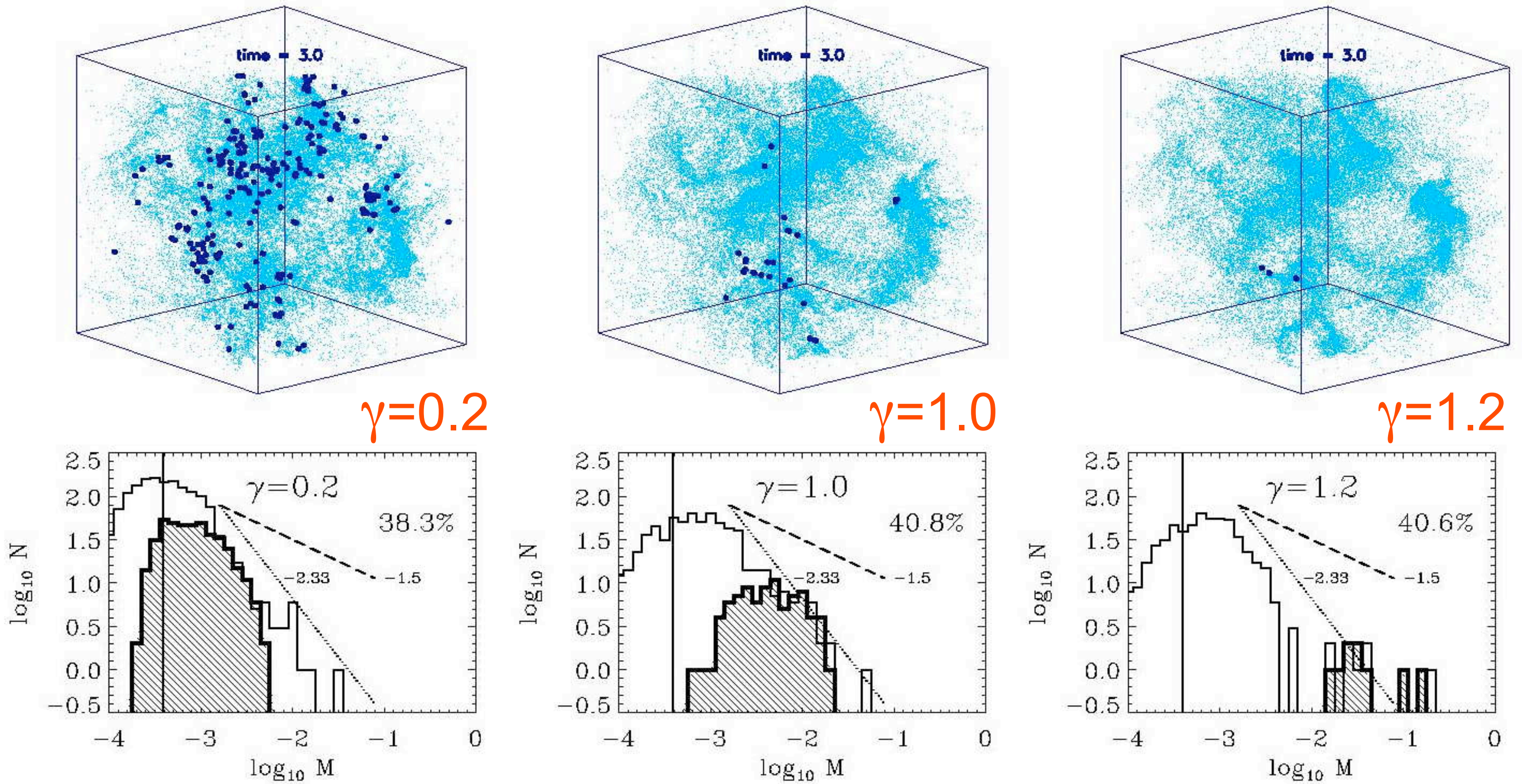
dependency on EOS

- 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, Klessen, & Mac Low 2003, ApJ, 592, 975; also Kawachi & Hanawa 1998, Larson 2003)

dependency on EOS



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

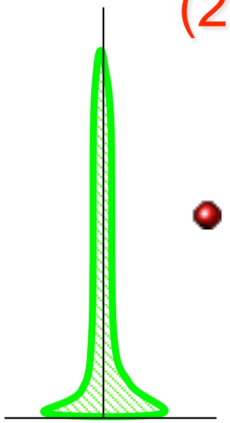
for $\gamma>1$ it is suppressed → formation of *isolated massive stars*

(from Li et al. 2003, ApJ, 592, 975)

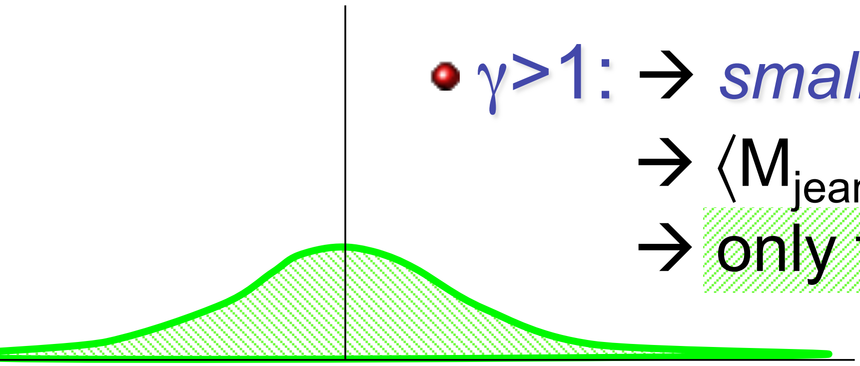
how does that work?

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

(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

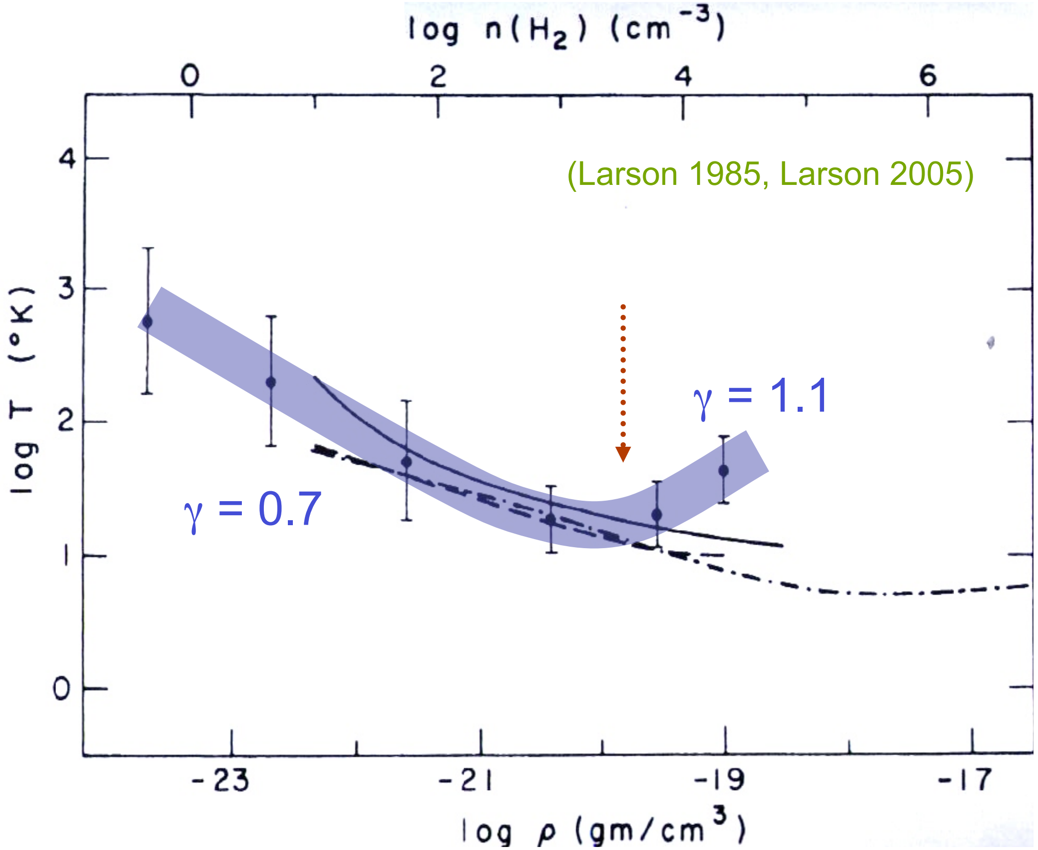


- $\gamma>1$: → *small* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ is large
  → only few and massive clumps exceed M_{jeans}

EOS for solar neighborhood

below 10^{-18} gcm^{-3}: ρ ⬆ ⇒ T ⬇

above 10^{-18} gcm^{-3}: ρ ⬆ ⇒ T ⬆



$P \propto \rho^{\gamma}$

$P \propto \rho T$

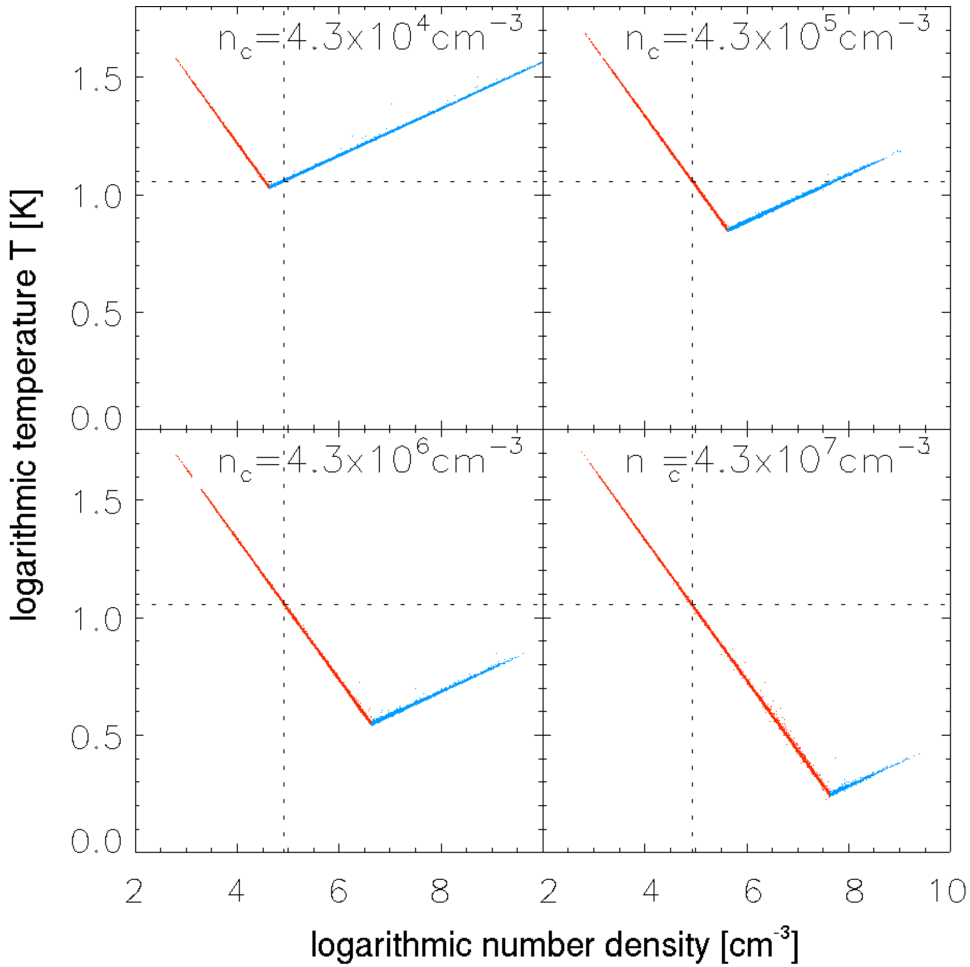
$\rightarrow \gamma = 1 + d\ln T / d\ln \rho$

IMF from simple piece-wise polytropic EOS

$\gamma_1 = 0.7$

$\gamma_2 = 1.1$

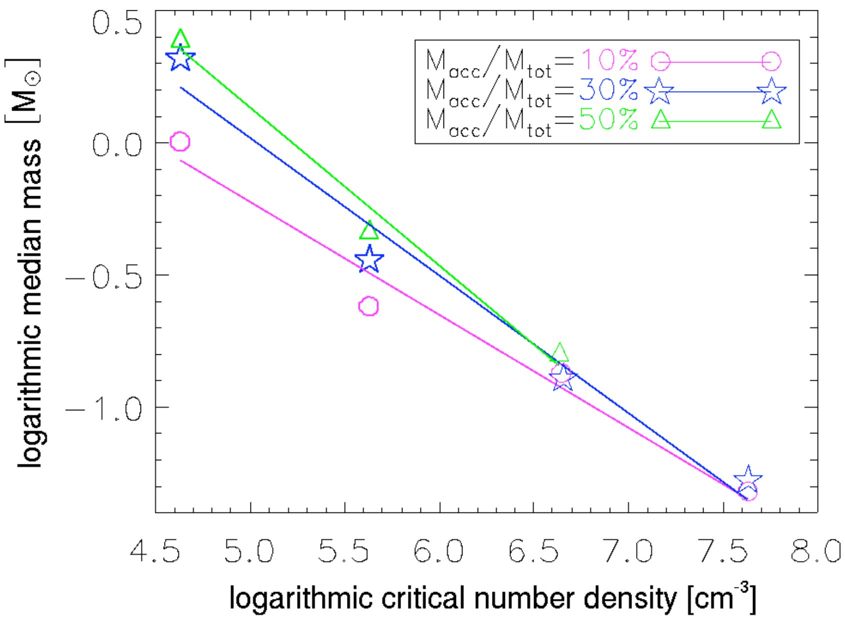
$$T \sim \rho^{\gamma-1}$$



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

IMF from simple piece-wise polytropic EOS

critical density ↑ ⟹ median mass ↓



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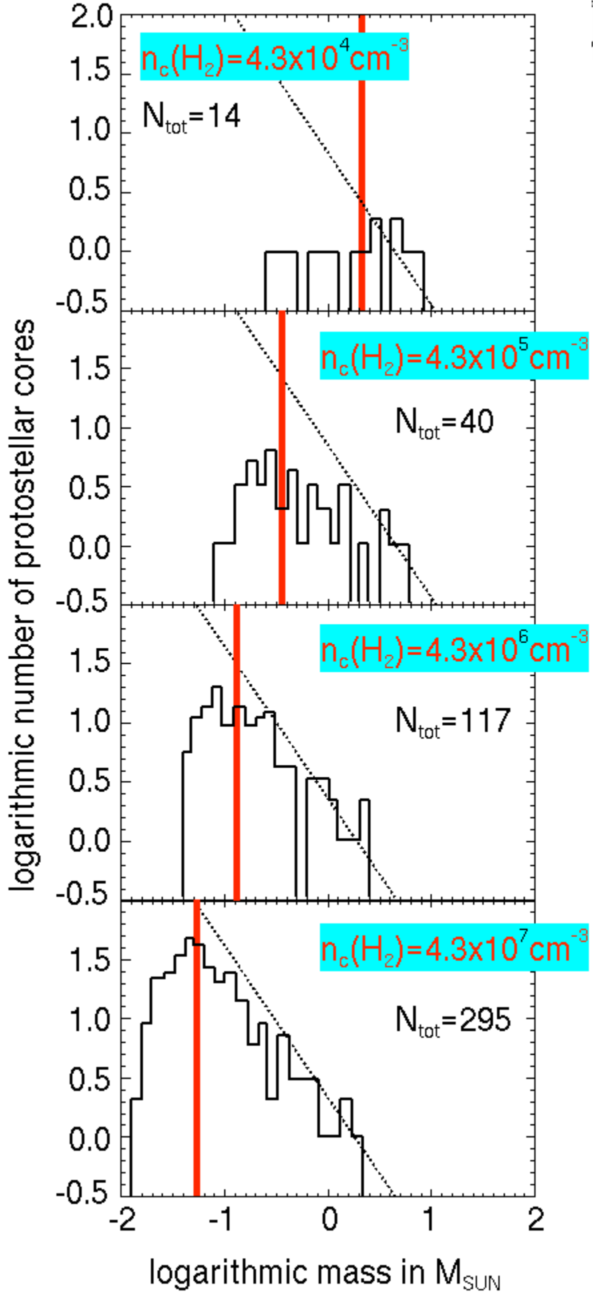
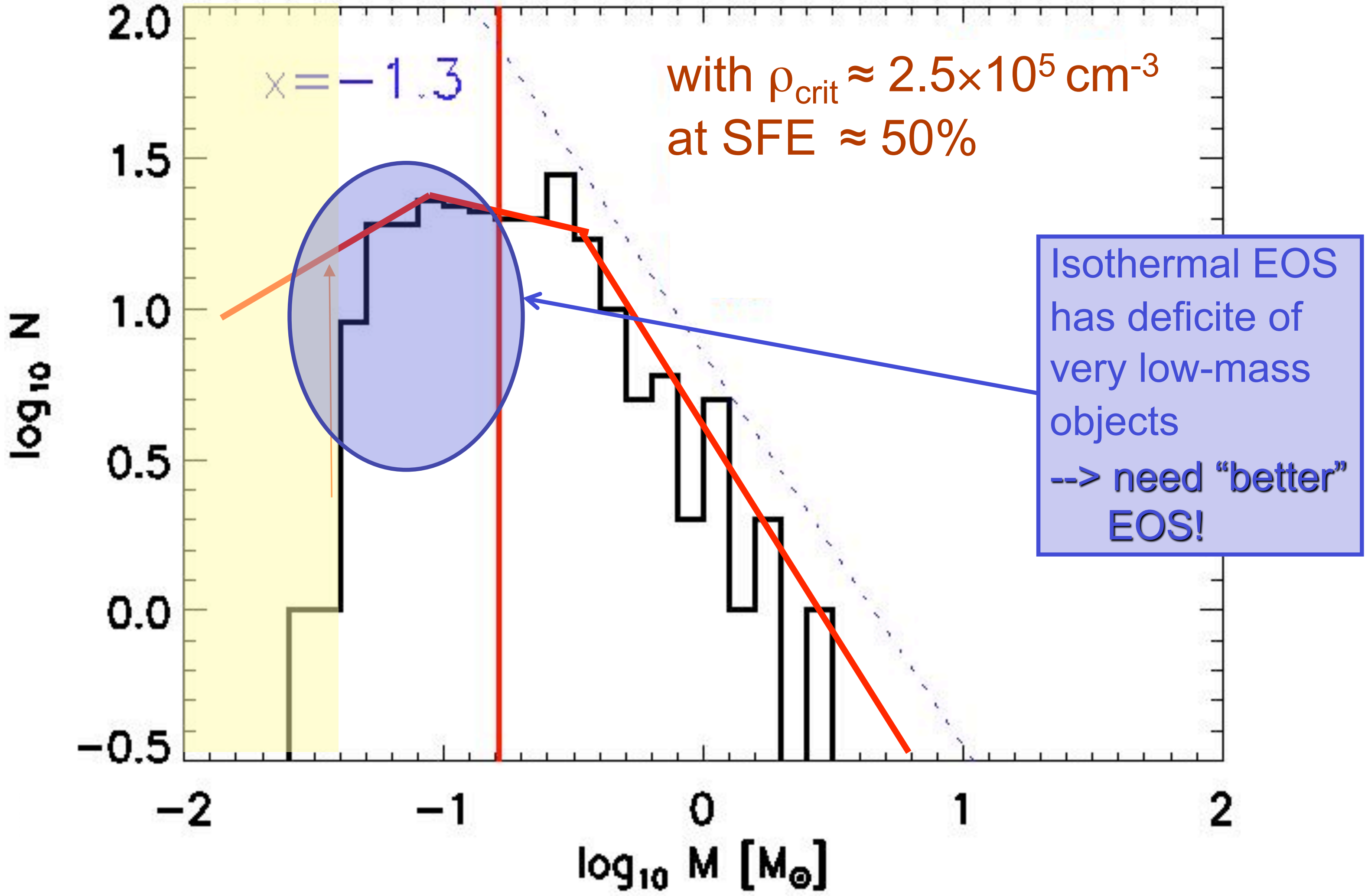
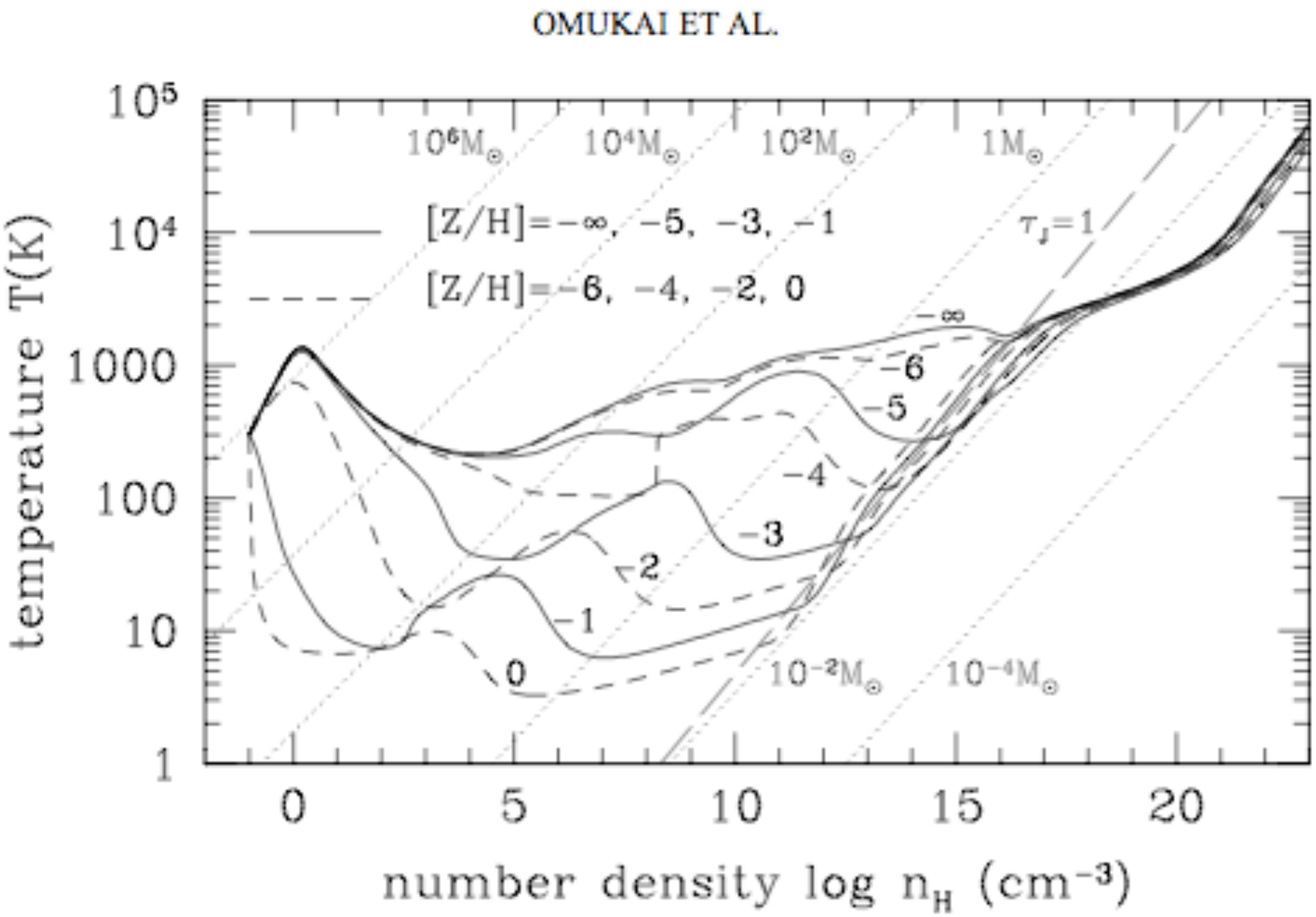


IMF in nearby molecular clouds



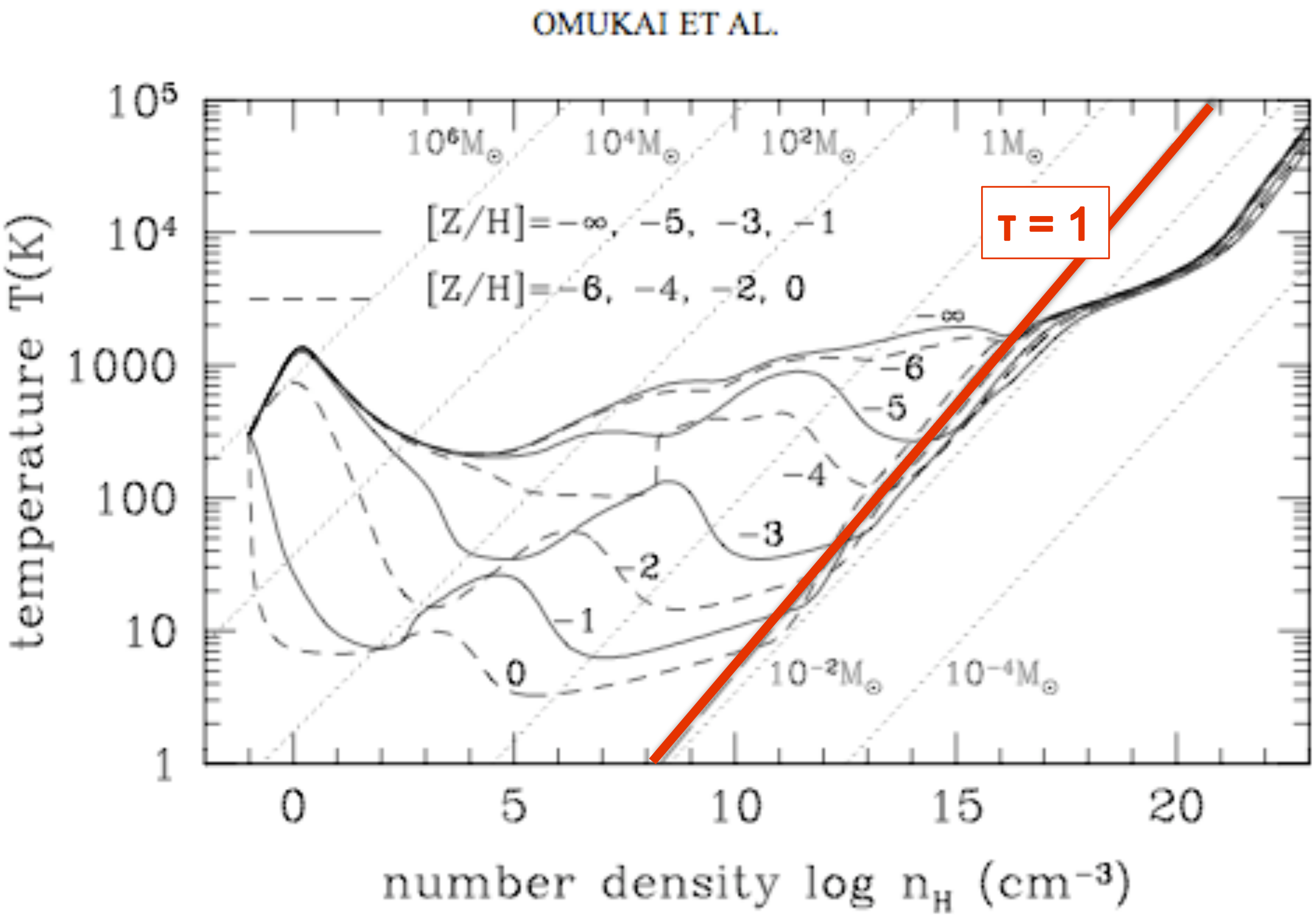
(Jappsen et al. 2005, A&A, 435, 611)

EOS as function of metallicity



(Omukai et al. 2005)

EOS as function of metallicity



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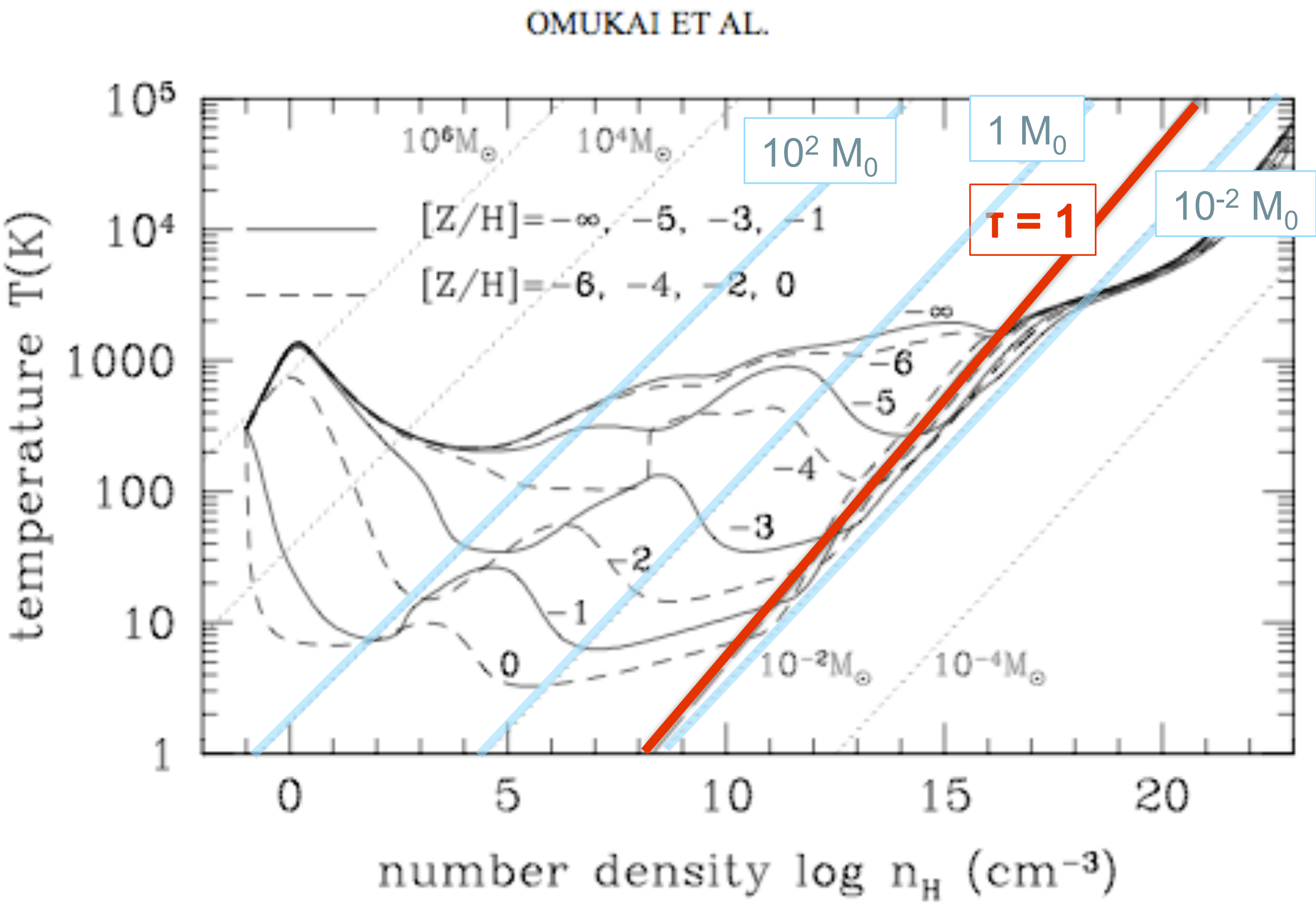
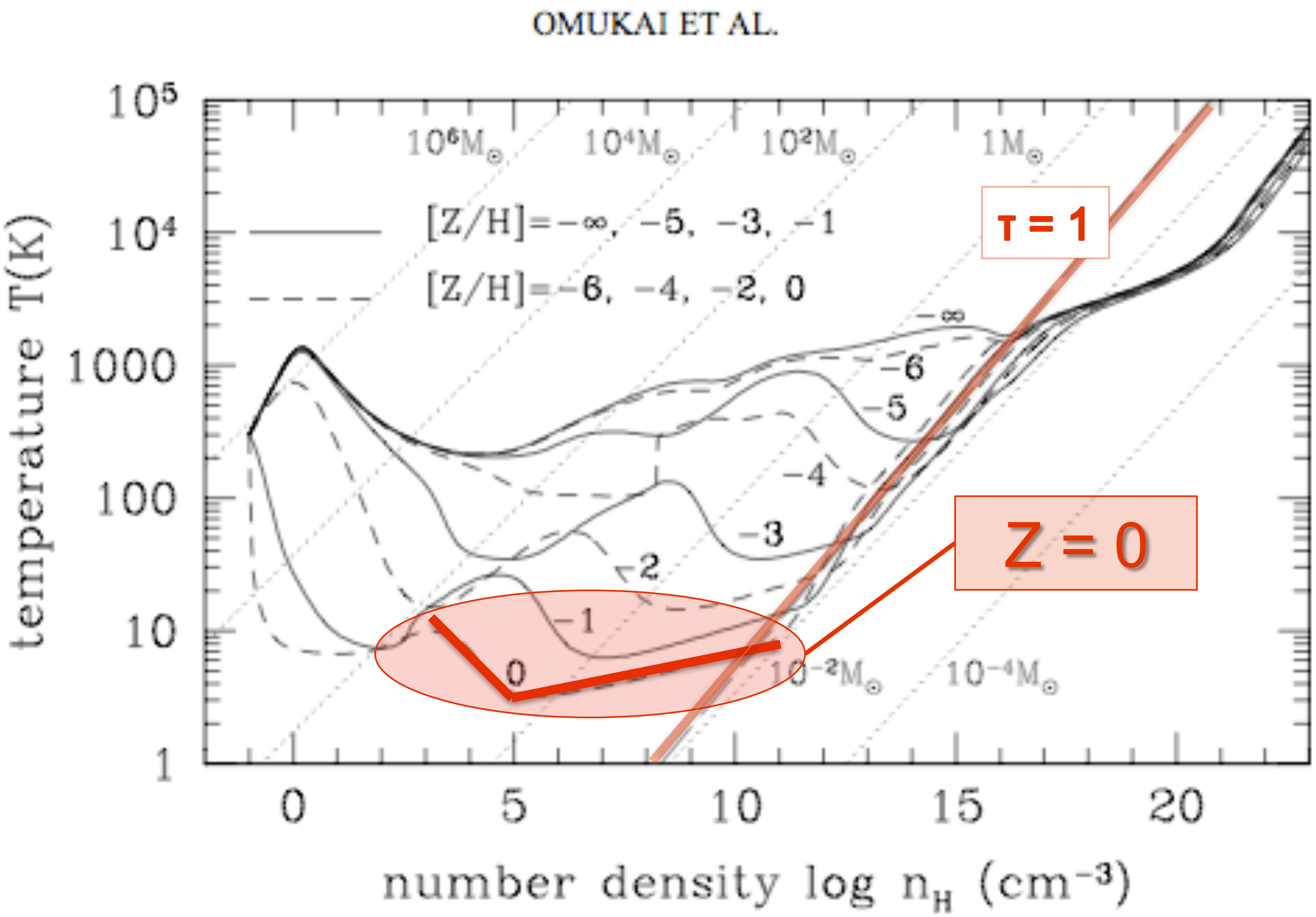
EOS as function of metallicity



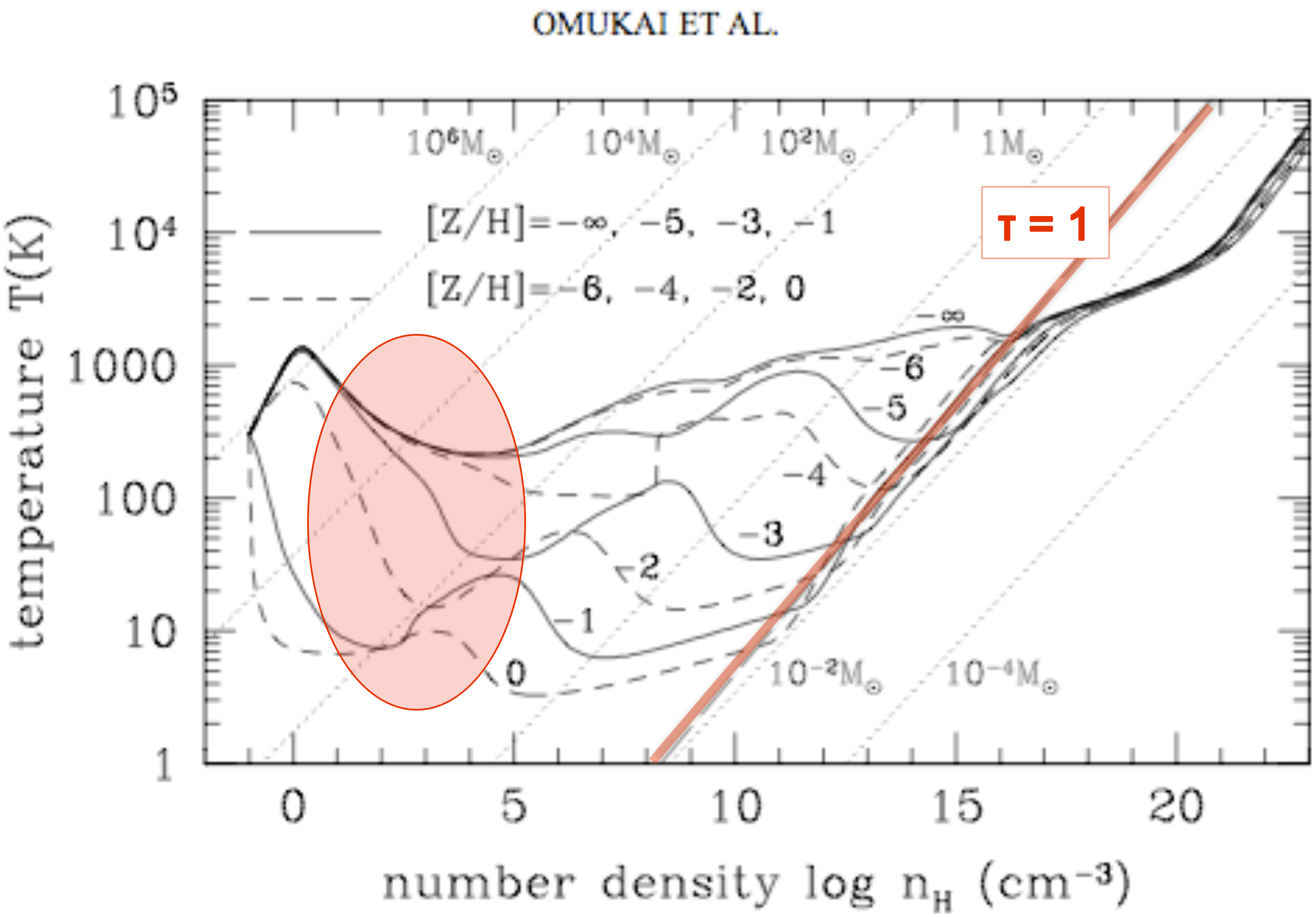
(Omukai et al. 2005)

present-day star formation



(Omukai et al. 2005)

dependence on Z at low density

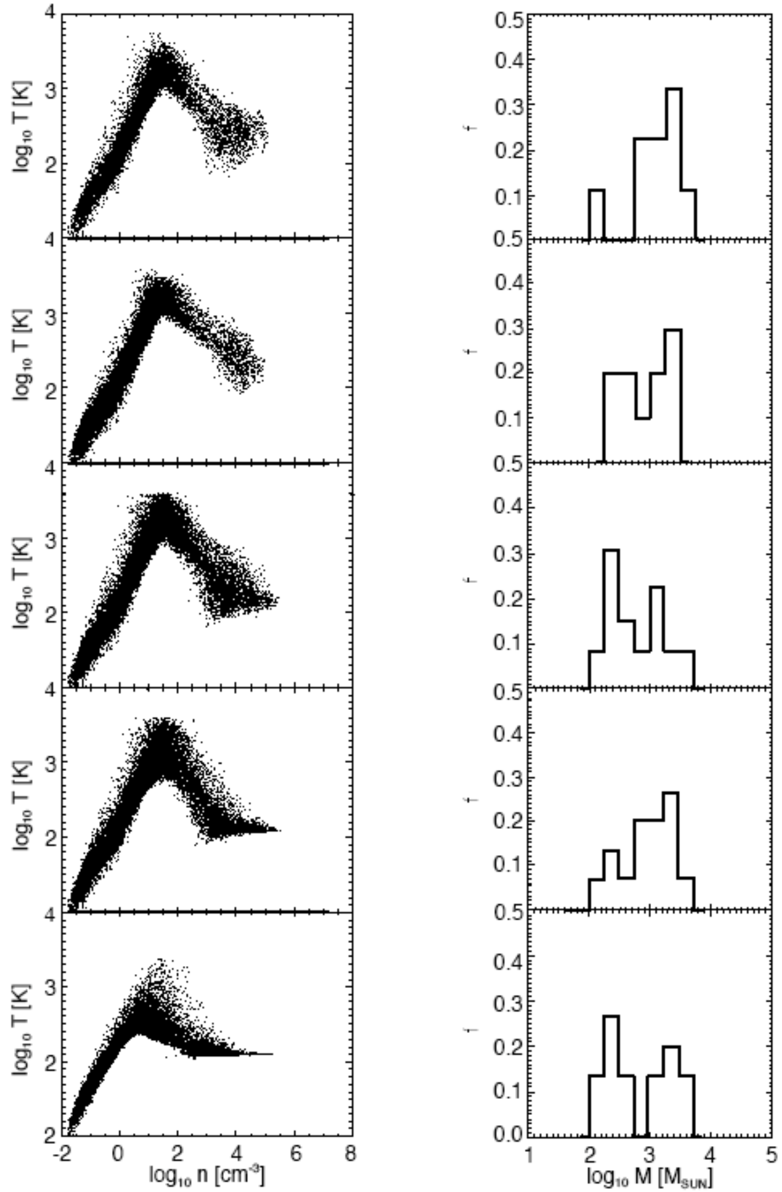


(Omukai et al. 2005)

dependence on Z at low density

- at densities below n ≈ 10^2 cm^{-3} H_2 *cooling* dominates the behavior. (Jappsen et al. 2007)
- fragmentation depends on *initial conditions then*
  - example: solid-body rotating top-hat initial conditions with dark matter fluctuations (a la Bromm et al. 1999) fragment no matter what metallicity you take (in regime n ≤ 10^6 cm^{-3})
    → because unstable disk builds up
    (Jappsen et al. 2008a)

dependence on Z at low density



Z = 0

Z = -4

Z = -3

Z = -2

Z = -1

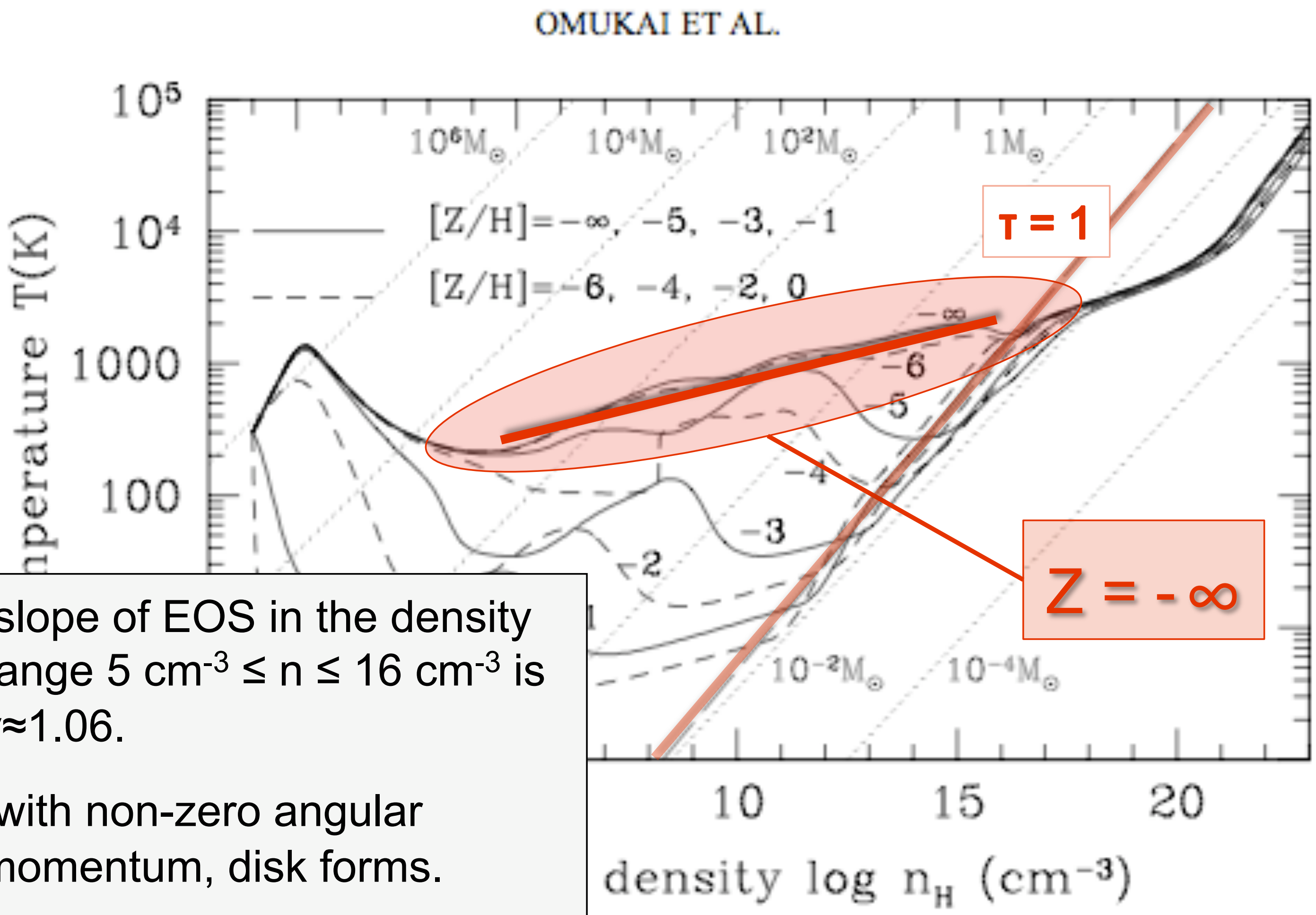
rotating top-hat with dark matter fluctuations fragments, no matter what

(Jappsen et al. 2008a, see poster by Jappsen et al, see also Clark et al. 2008)

dependence on Z at low density

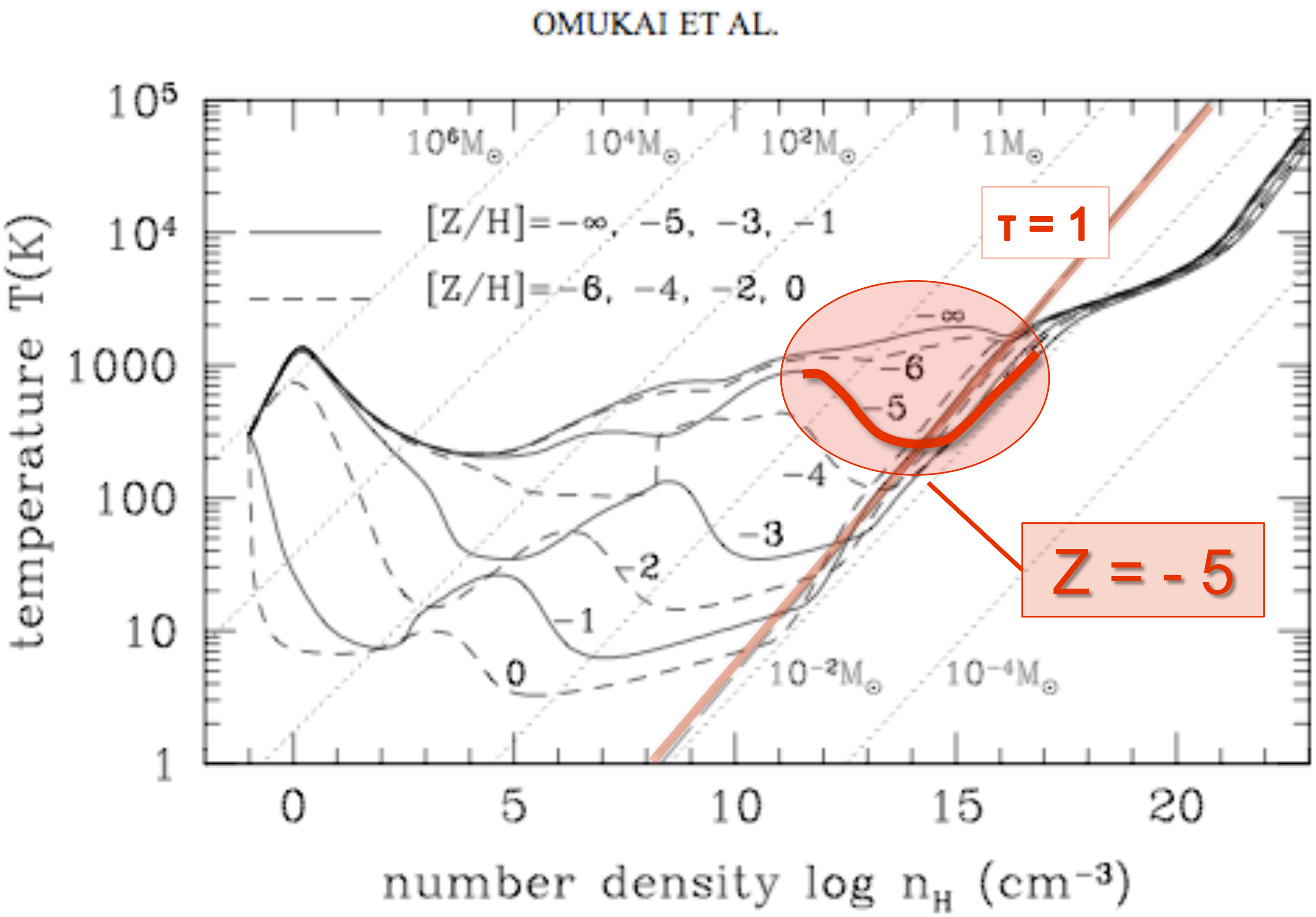
- fragmentation depends on *initial conditions then*
  - example: centrally concentrated halo does not fragment up to densities of $n \approx 10^6$ cm^{-3} up to metallicities $Z \approx -1$
    (Jappsen et al. 2008b)

metal-free star formation



- 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.
- this disk will be unstable against fragmentation

transition: Pop III to Pop II.5



(Omukai et al. 2005)

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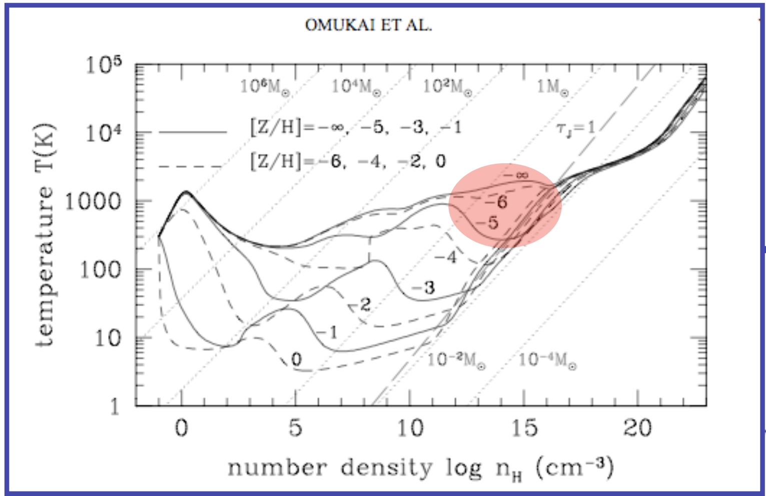
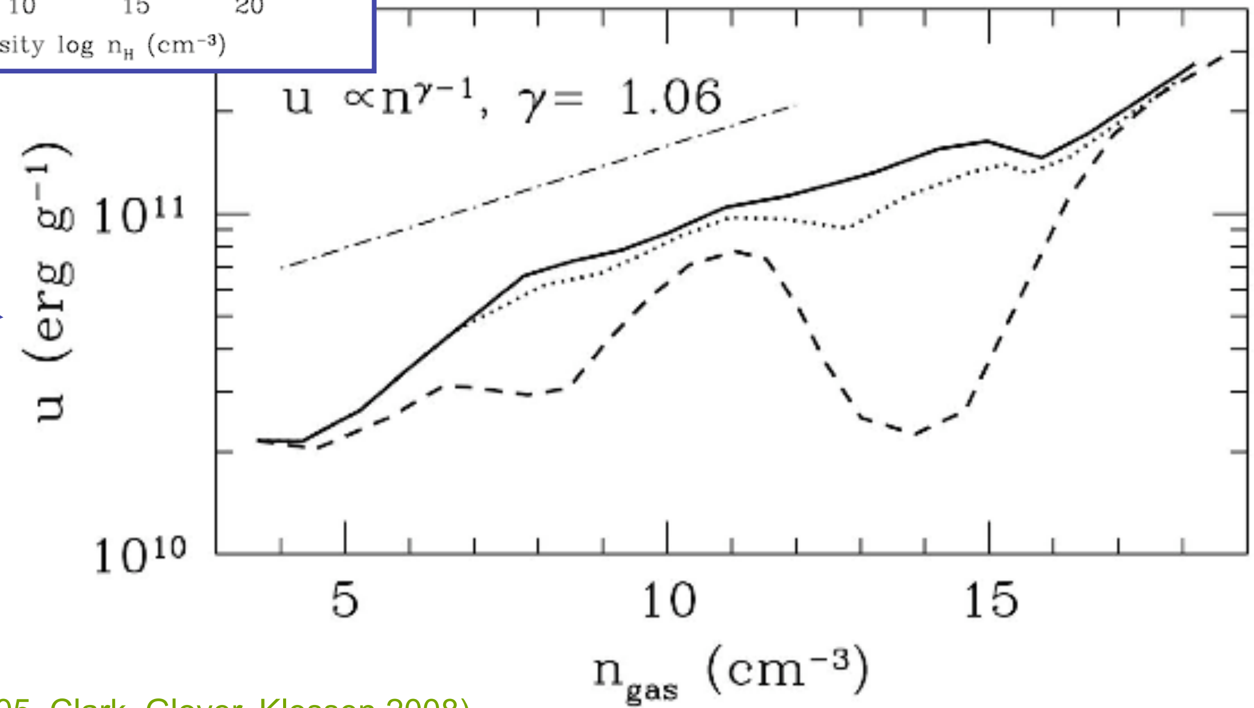
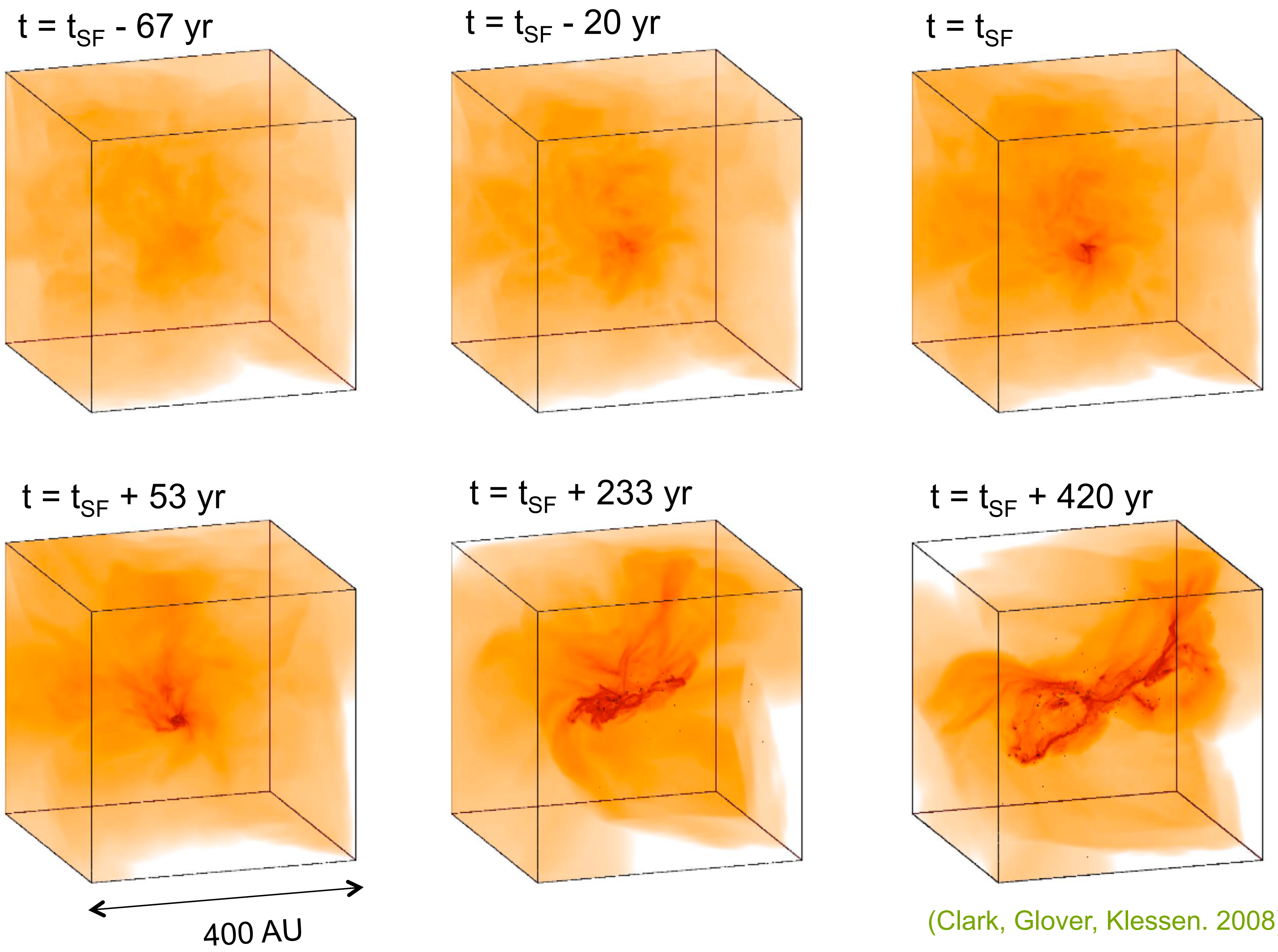




(Omukai et al. 2005, Clark, Glover, Klessen 2008)

dust induced fragmentation at $Z=10^{-5}$



(Clark, Glover, Klessen. 2008)

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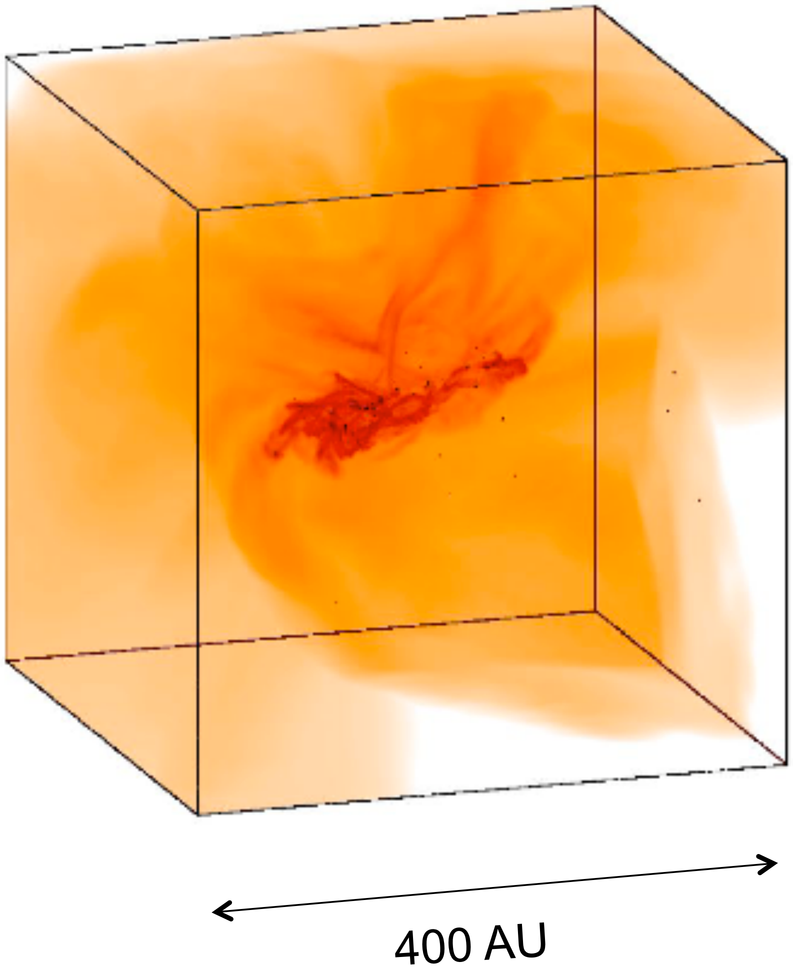


dense cluster of low-mass protostars builds up:

- mass spectrum peaks below 1 M_{sun}
- cluster VERY dense $n_{stars} = 2.5 \times 10^9\ pc^{-3}$
- fragmentation at density $n_{gas} = 10^{12} - 10^{13}\ cm^{-3}$

(Clark et al. 2008)

cluster build-up

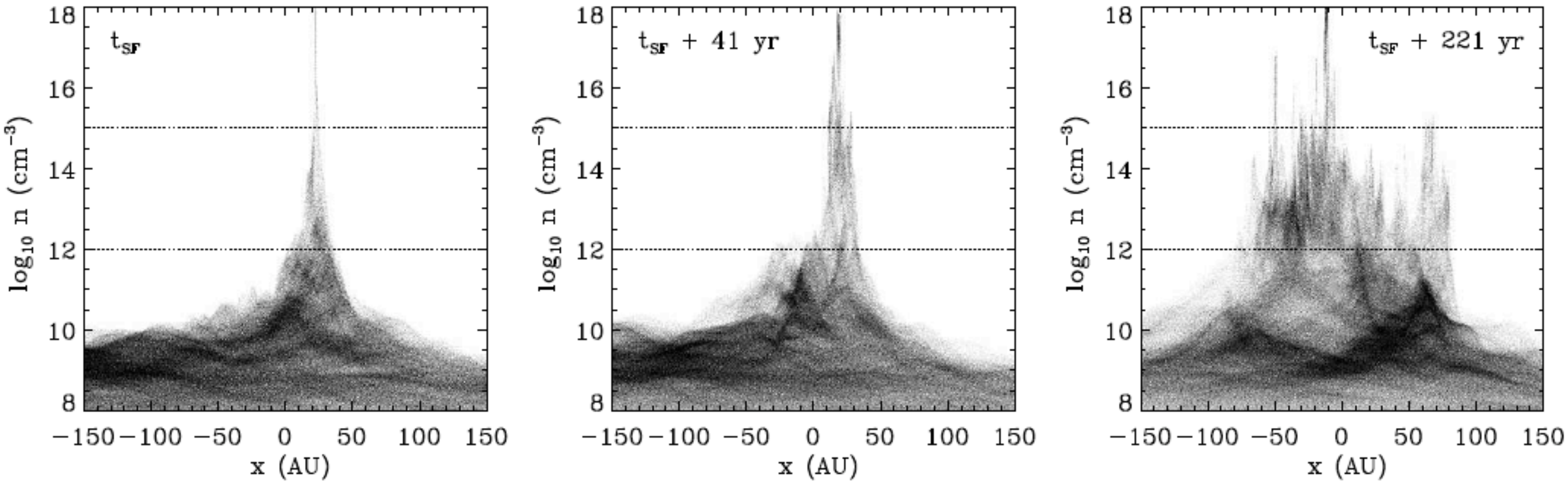
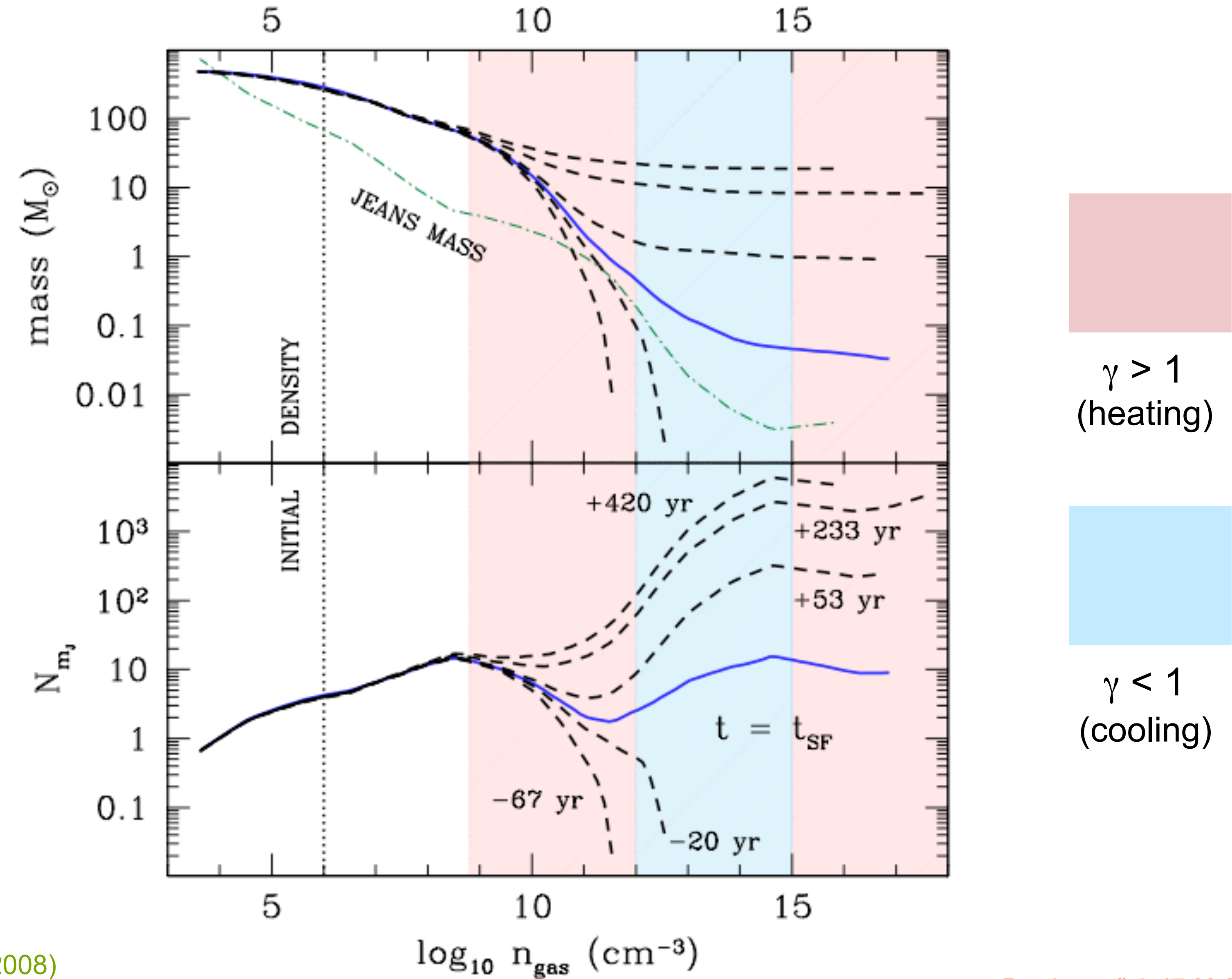


FIG. 3.— We illustrate the onset of the fragmentation process in the high resolution $Z = 10^{-5}\, Z_{\odot}$ simulation. The graphs show the densities of the particles, plotted as a function of their x-position. Note that for each plot, the particle data has been centered on the region of interest. We show here results at three different output times, ranging from the time that the first star forms (t_{sf}) to 221 years afterwards. The densities lying between the two horizontal dashed lines denote the range over which dust cooling lowers the gas temperature.

(Clark et al. 2008)

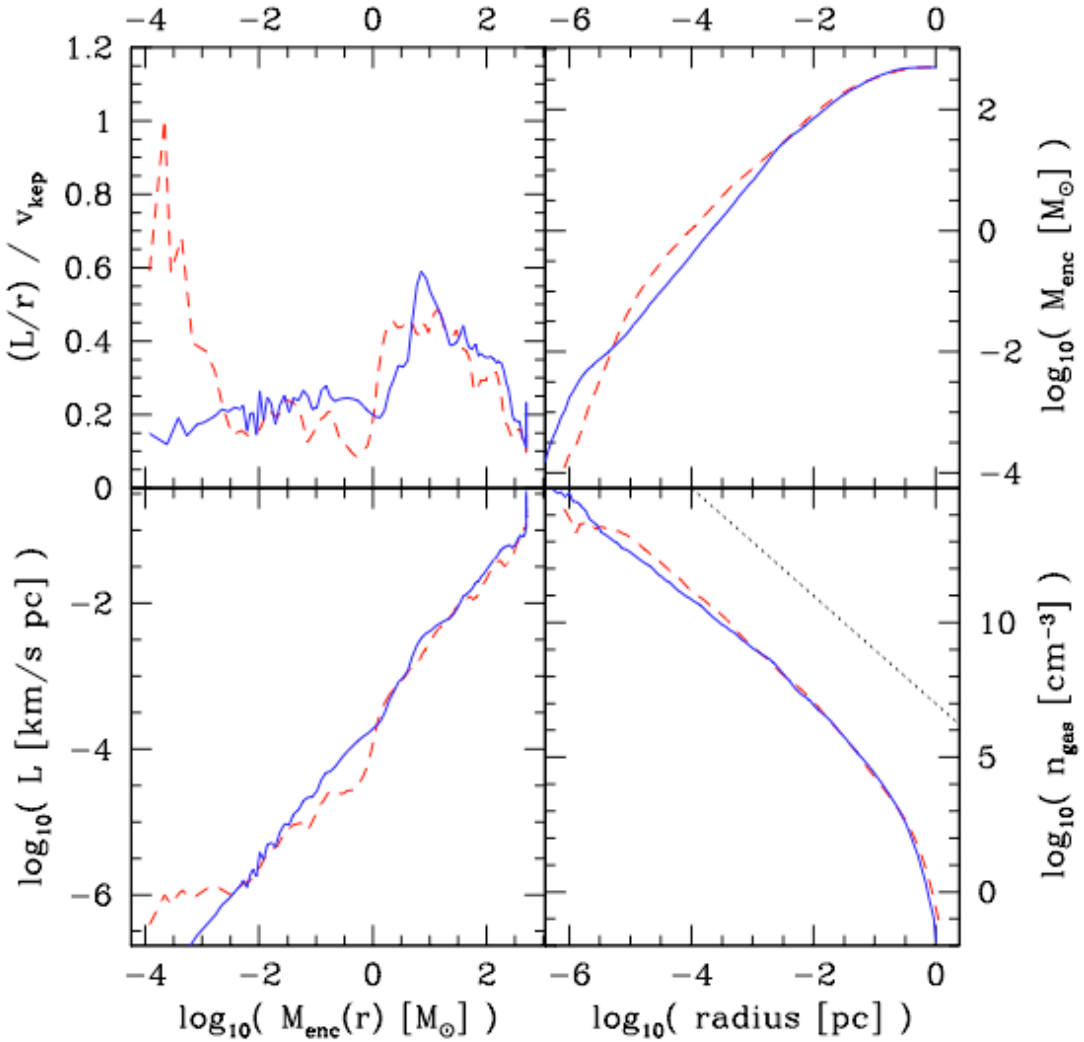
cluster build-up



(Clark et al. 2008)

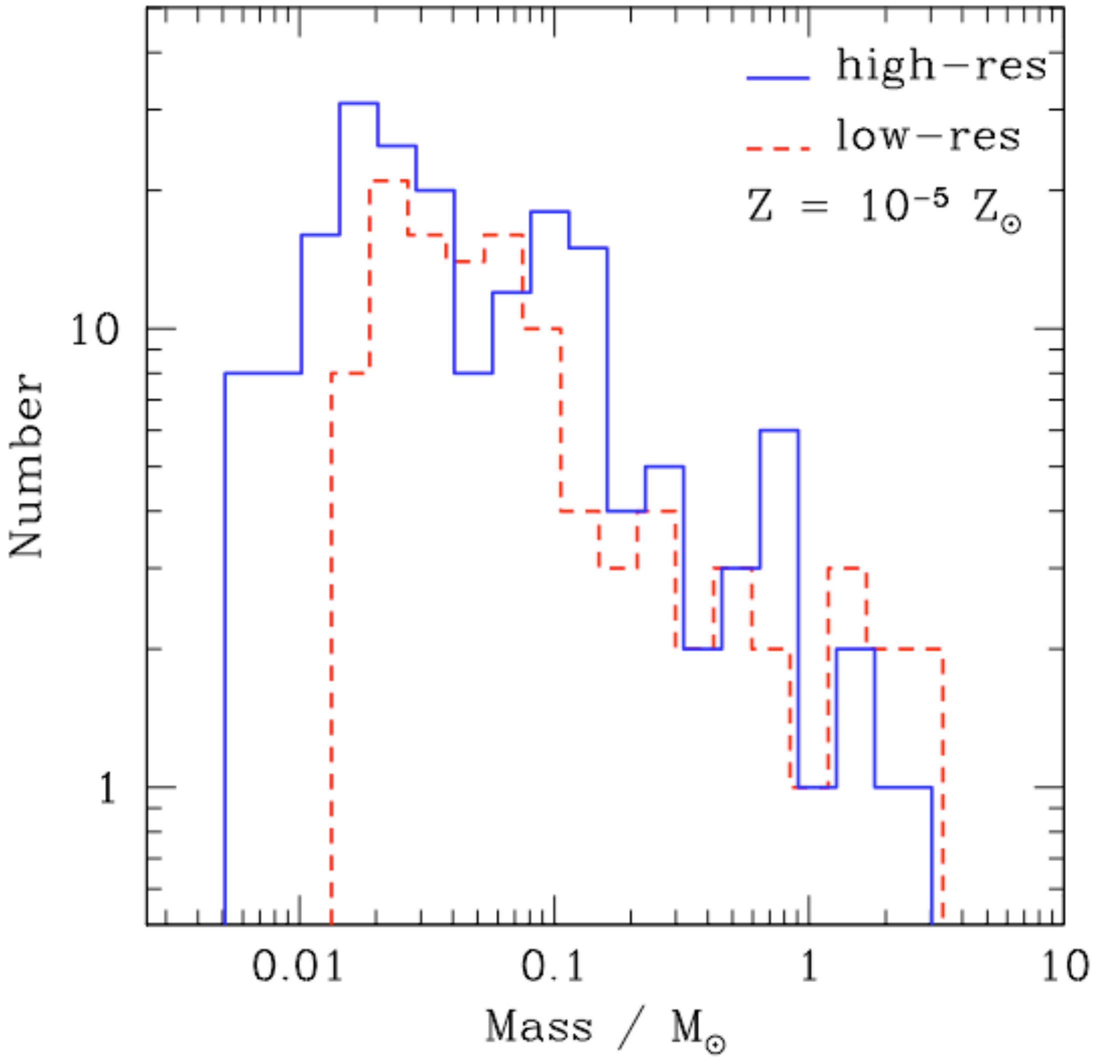
gas properties

gas properties at time when first star forms



(Clark et al. 2008)

dust induced fragmentation at $Z=10^{-5}$



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(Clark et al. 2008)

comparison for different Z

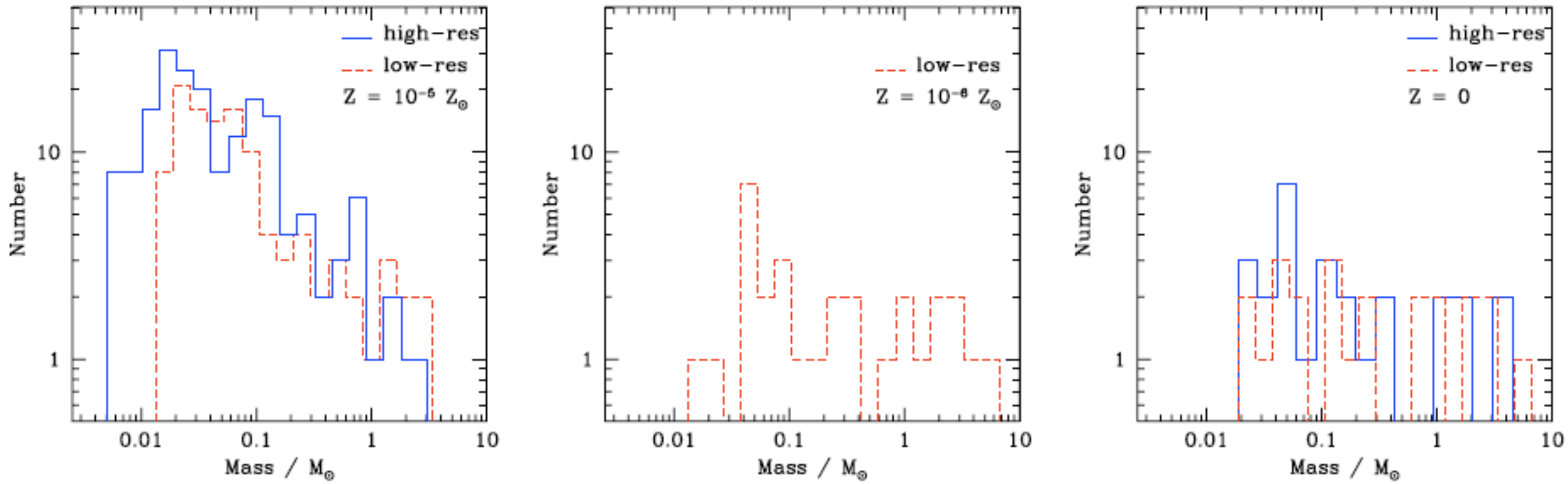


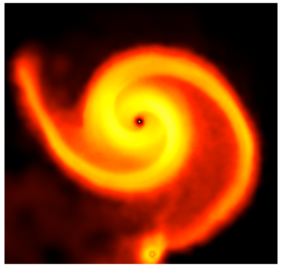
FIG. 4.— Mass functions resulting from simulations with metallicities $Z = 10^{-5}\ Z_\odot$ (left-hand panel), $Z = 10^{-6}\ Z_\odot$ (center panel), and $Z = 0$ (right-hand panel). The plots refer to the point in each simulation at which 19 $M_\odot$ of material has been accreted (which occurs at a slightly different time in each simulation). The mass resolutions are 0.002 $M_\odot$ and 0.025 $M_\odot$ for the high and low resolution simulations, respectively. Note the similarity between the results of the low-resolution and high-resolution simulations. The onset of dust-cooling in the $Z = 10^{-5}\ Z_\odot$ cloud results in a stellar cluster which has a mass function similar to that for present day stars, in that the majority of the mass resides in the lower-mass objects. This contrasts with the $Z = 10^{-6}\ Z_\odot$ and primordial clouds, in which the bulk of the cluster mass is in high-mass stars.

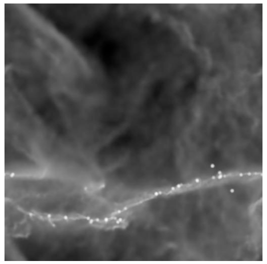
even zero-metallicity case fragments
(although much more weakly)

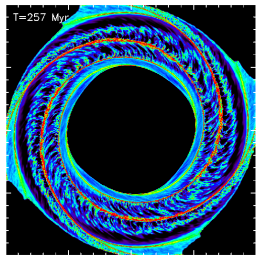
(Clark et al. 2008)

studying ISM dynamics

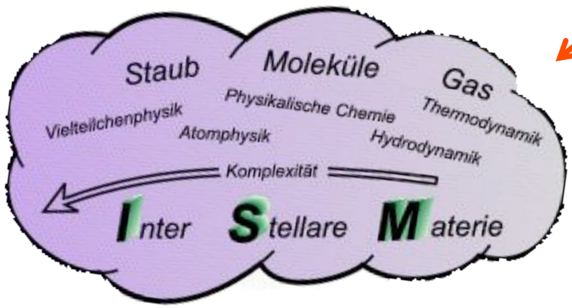
- understanding the *physical* and *chemical processes* the shape the behavior of the interstellar medium is important for *many aspects* of modern astrophysics





what do we need to study ISM?



magneto-hydrodynamics
(multi-phase, non-ideal MHD, turbulence)

chemistry (gas + dust, heating + cooling)

radiation (continuum + lines)

stellar dynamics
(collisional: star clusters, collisionless: galaxies, DM)

stellar evolution
(feedback: radiation, winds, SN)

\+ **laboratory work**
(reaction rates, cross sections, dust coagulation properties, etc.)

what do we need to study ISM?

methods need to be combined!

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(multi-phase, non-ideal MHD, turbulence)

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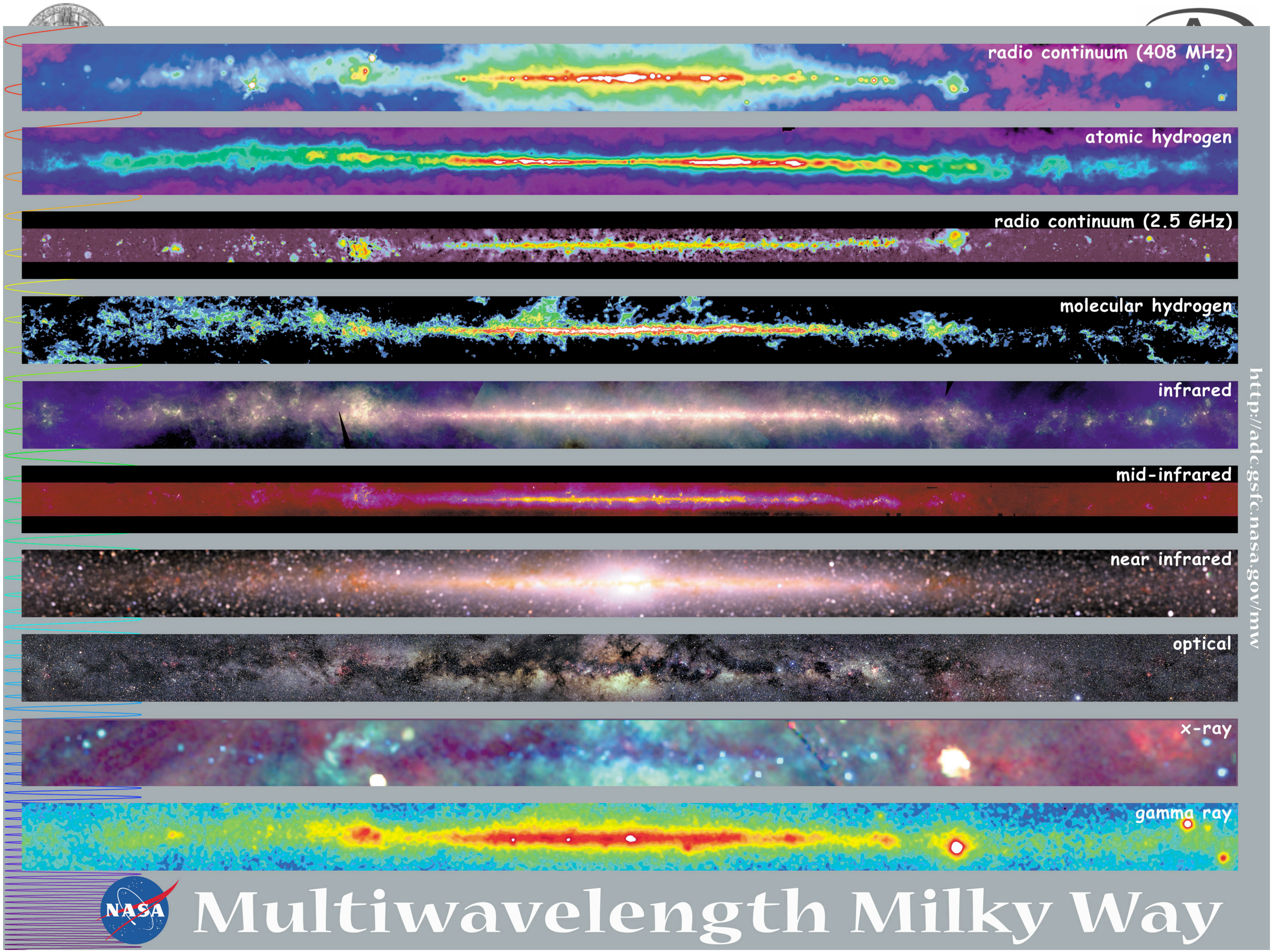
current initiatives

- DFG:
  - SFB in Köln/Bonn
  - SFB in Heidelberg
- ASTRONET
  - CATS
  - ARTIST
  - STAR FORMAT
- in Austria (Univ. Vienna)
  - Graduiertenkolleg *Cosmic Matter Circuit*

discussion

- do we want an SPP on ISM / IGM?
- what shall be included in the SPP?
  - intergalactic medium
  - interstellar medium
    - which processes are important?
  - relation of ISM / IGM to other aspects of astrophysics
    - star formation on different scales
    - chemical enrichment
    - observables at different wavelengths
  - laboratory experiments
  - intrumentation
- who will do it?


radio continuum (408 MHz)
atomic hydrogen
radio continuum (2.5 GHz)
molecular hydrogen
infrared
mid-infrared
near infrared
optical
x-ray
gamma ray
http://adc.gsfc.nasa.gov/mw
NASA
Multiwavelength Milky Way