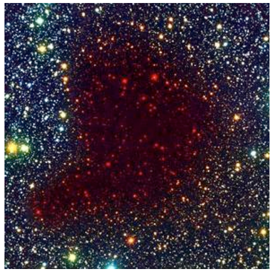
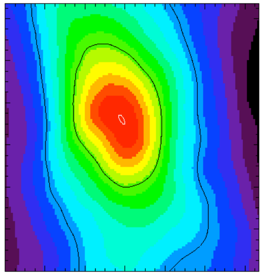
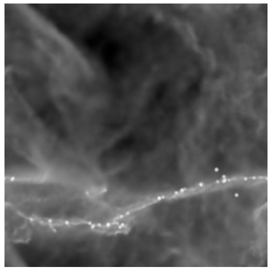
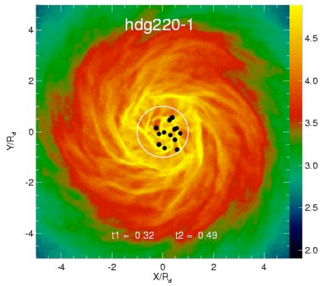
Recent Insight and Future Challenges in Theoretical Models of the ISM









Ralf Klessen

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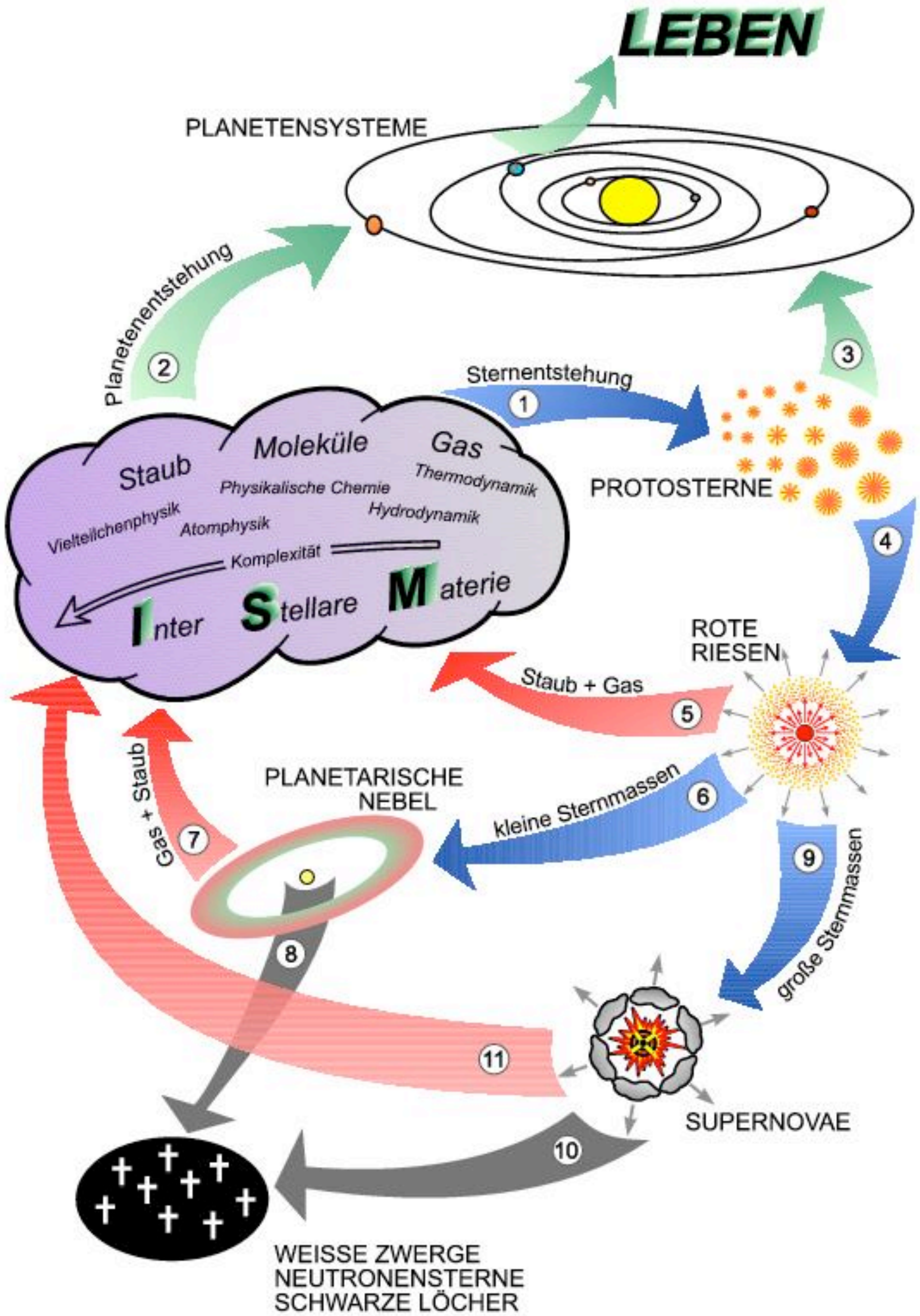
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Sternentstehung
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3
PROTOSTERNE
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Staub
Moleküle
Gas
Thermodynamik
Physikalische Chemie
Hydrodynamik
Vielteilchenphysik
Atomphysik
Komplexität
Inter Stellare Materie
ROTE
RIESEN
Staub + Gas
5
Gas + Staub
7
PLANETARISCHE
NEBEL
kleine Sternmassen
6
9
große Sternmassen
8
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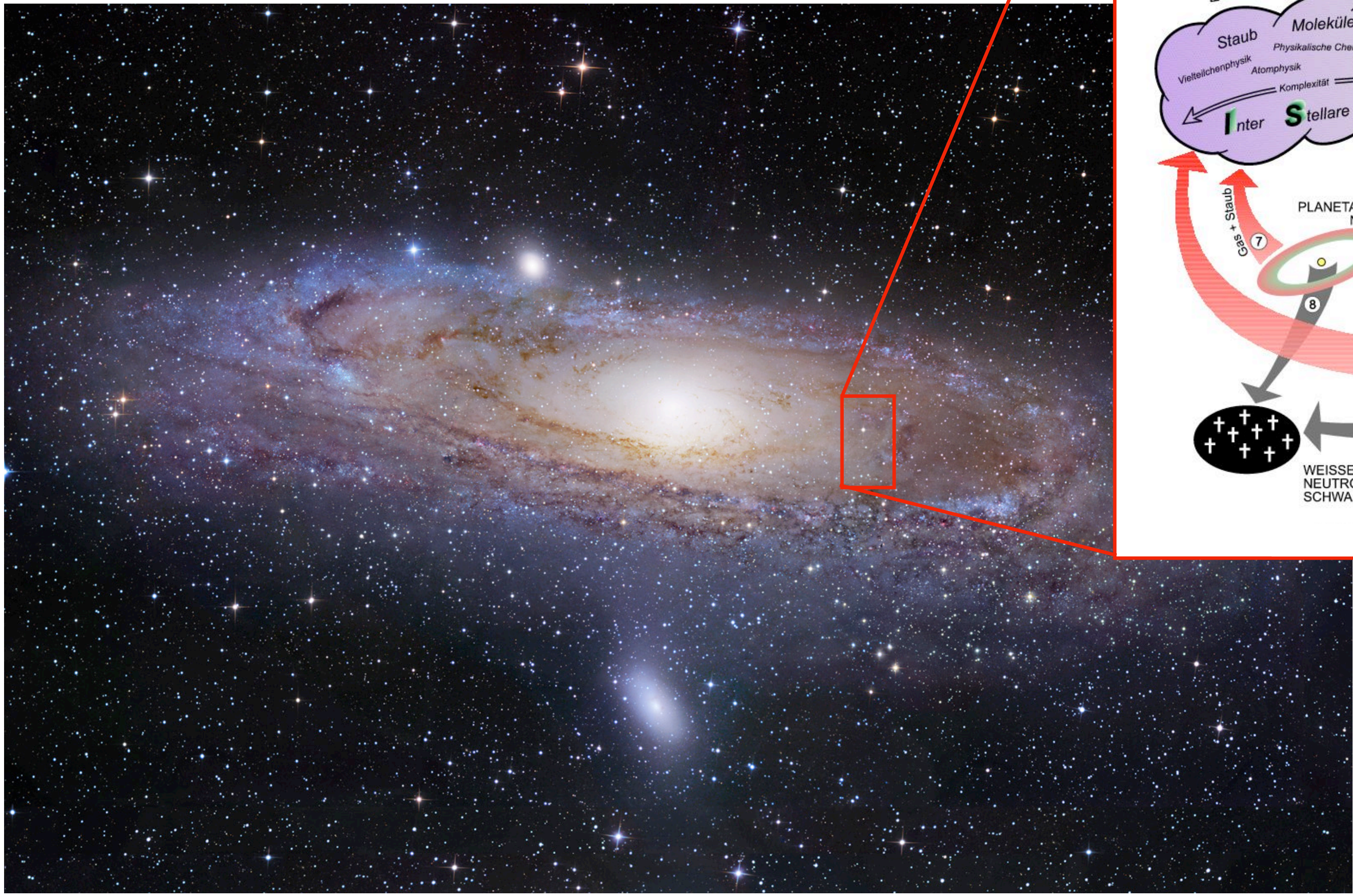
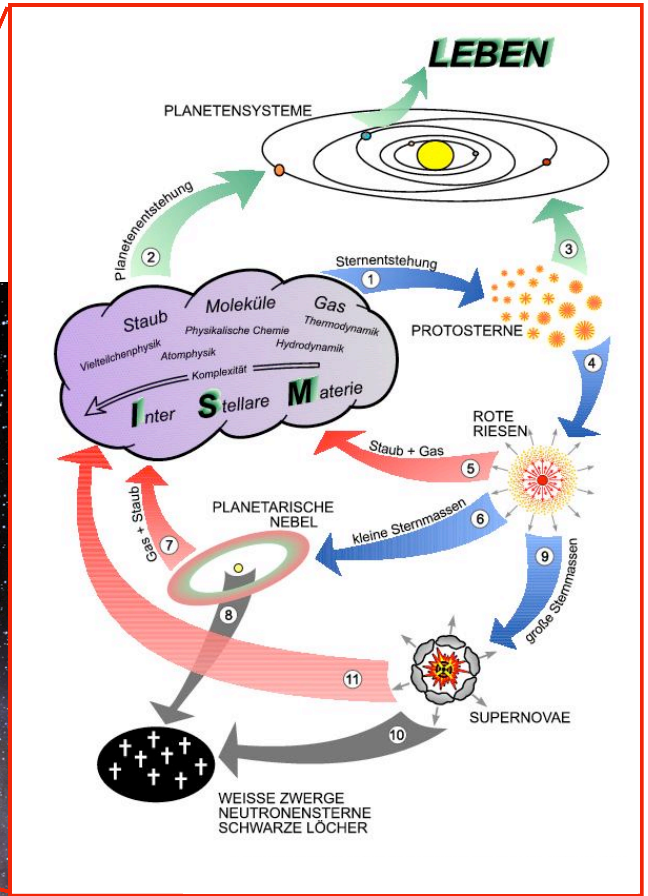
SUPERNOVAE
10
WEISSE ZWERGE
NEUTRONENSTERNE
SCHWARZE LÖCHER





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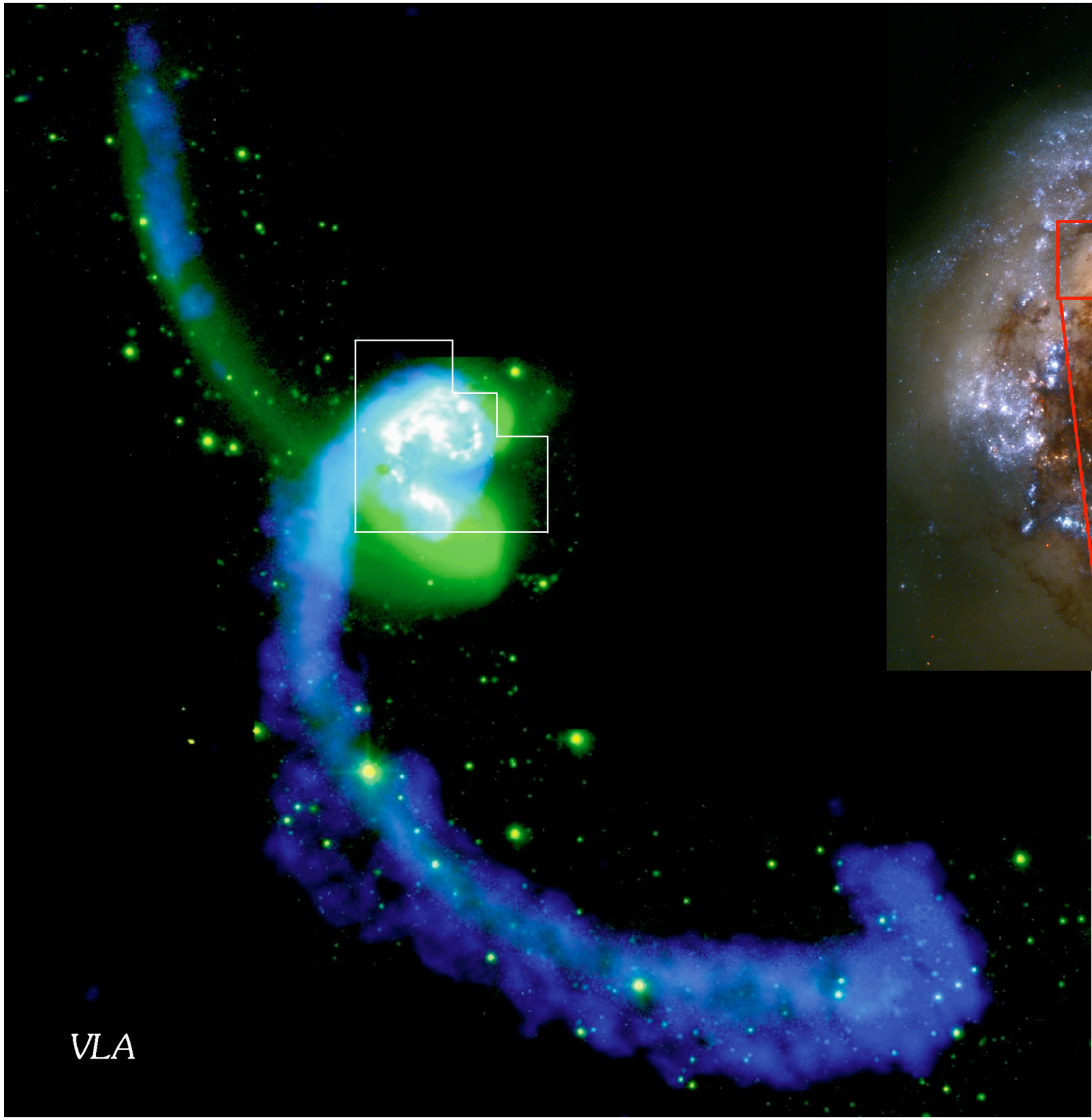
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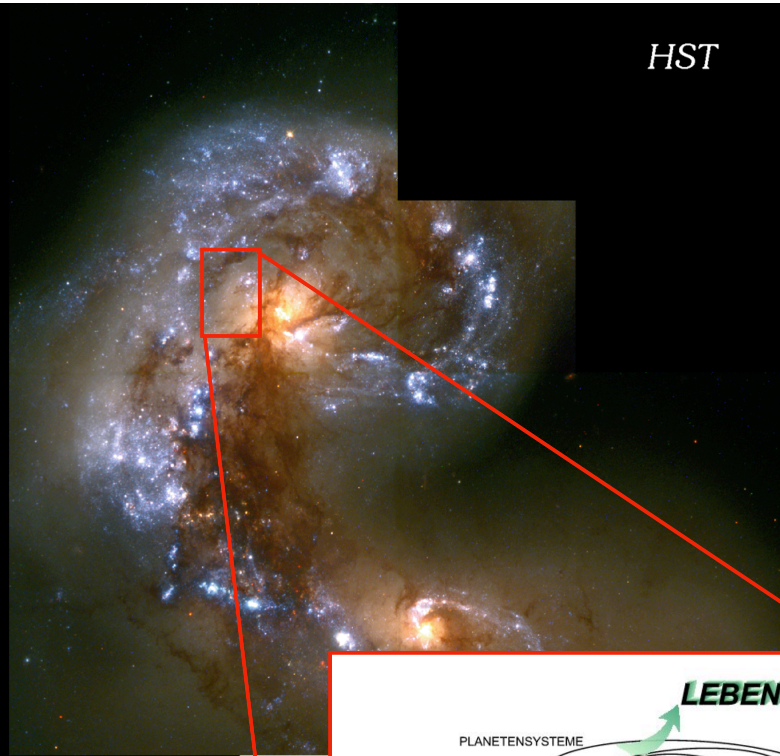
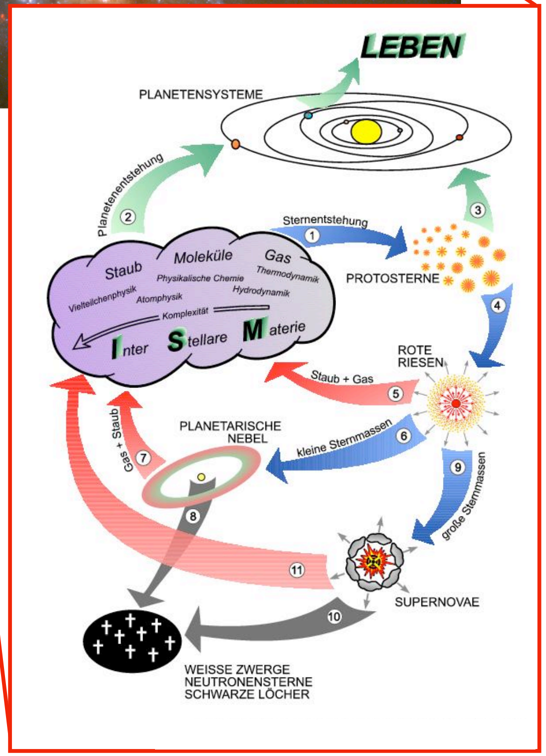

HST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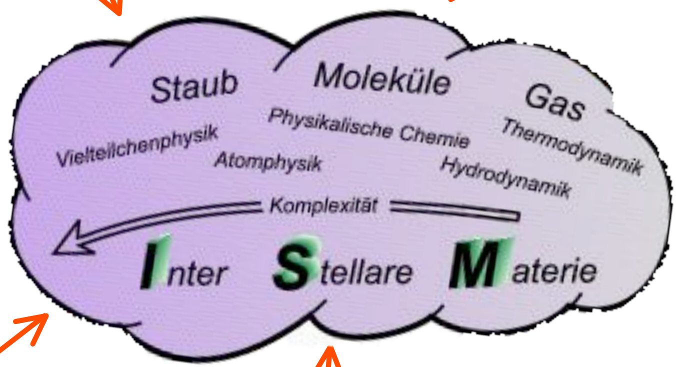
Why study ISM physics?

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

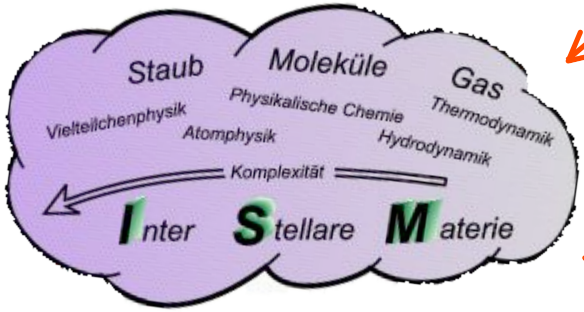


stars & star clusters
- ISM: environment for star formation
- IMF
- feedback from stars (winds, radiation, SN)
- MC turbulence

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

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

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

stellar evolution
(feedback: radiation, winds, SN)

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)

What do we need to study ISM?

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

↔

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)

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)

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)

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)

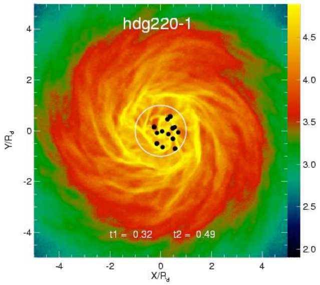
radiation (continuum + lines)

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

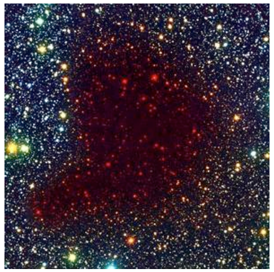
stellar evolution
(feedback: radiation, winds, SN)

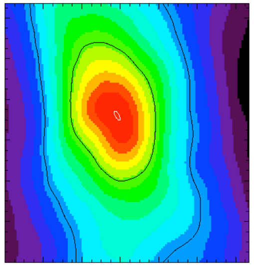
\+ **laboratory work**
(reaction rates, cross sections, dust coagulation properties, etc.)

Three examples

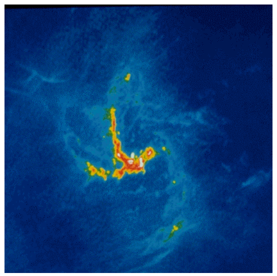


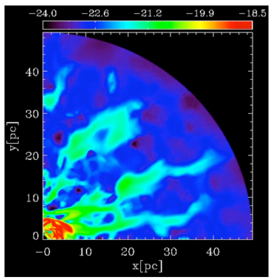
modeling star formation in galactic disk + molecular cloud formation
(hydrodynamics, stellar dynamics, chemistry, feedback [radiation, outflows])
(Schmidt law, star-formation history, relation between global dynamics and SF)





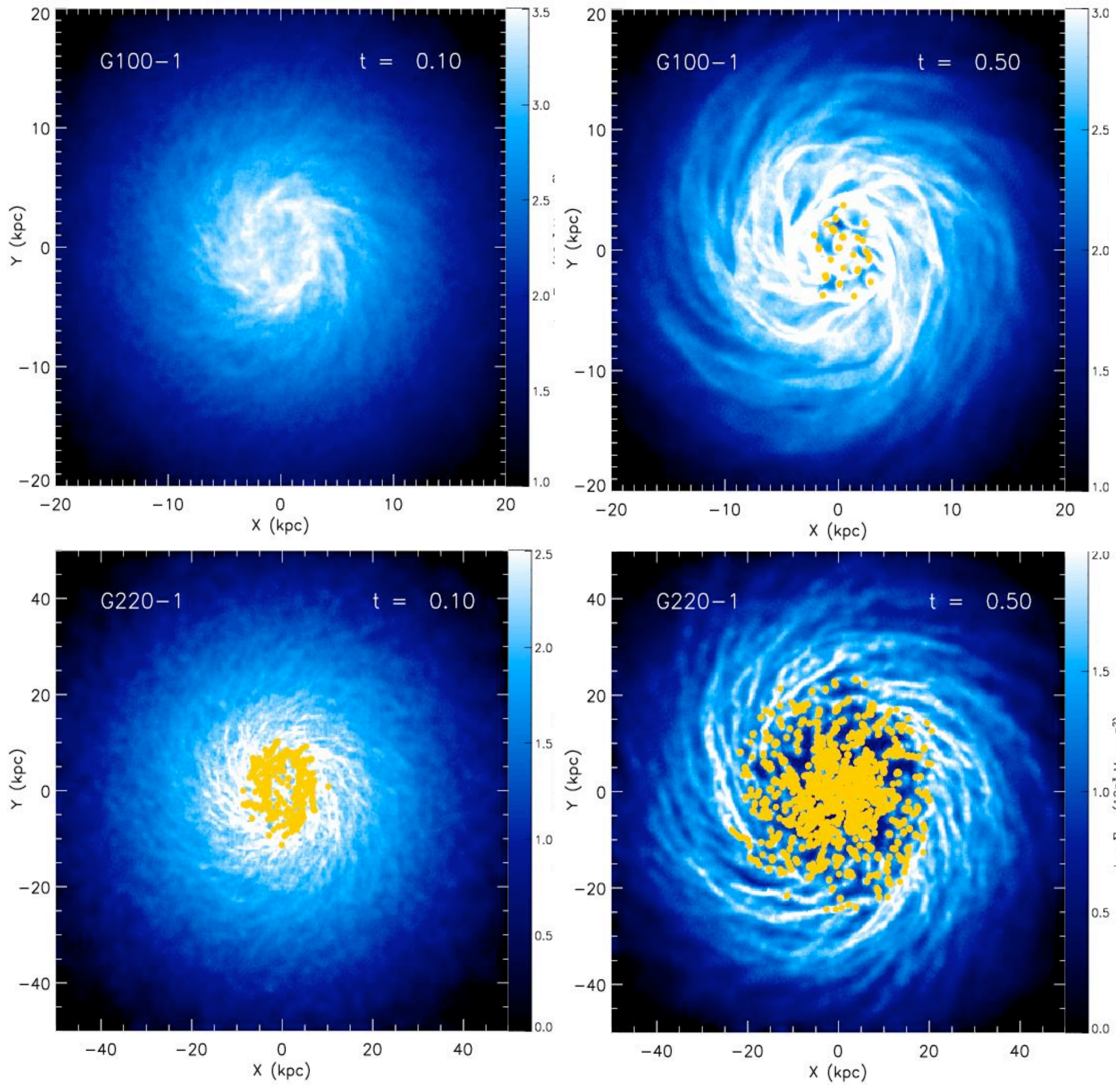
modeling properties of prestellar cores
(MHD, chemistry, radiation)
(initial conditions of star formation, IMF, multiplicity, planet formation, etc.)





modeling extreme environments: cold, dusty AGN tori
(hydrodynamics, stellar feedback, EOS + cooling)
(AGN properties + evolution, central BH)

Modeling galactic SF



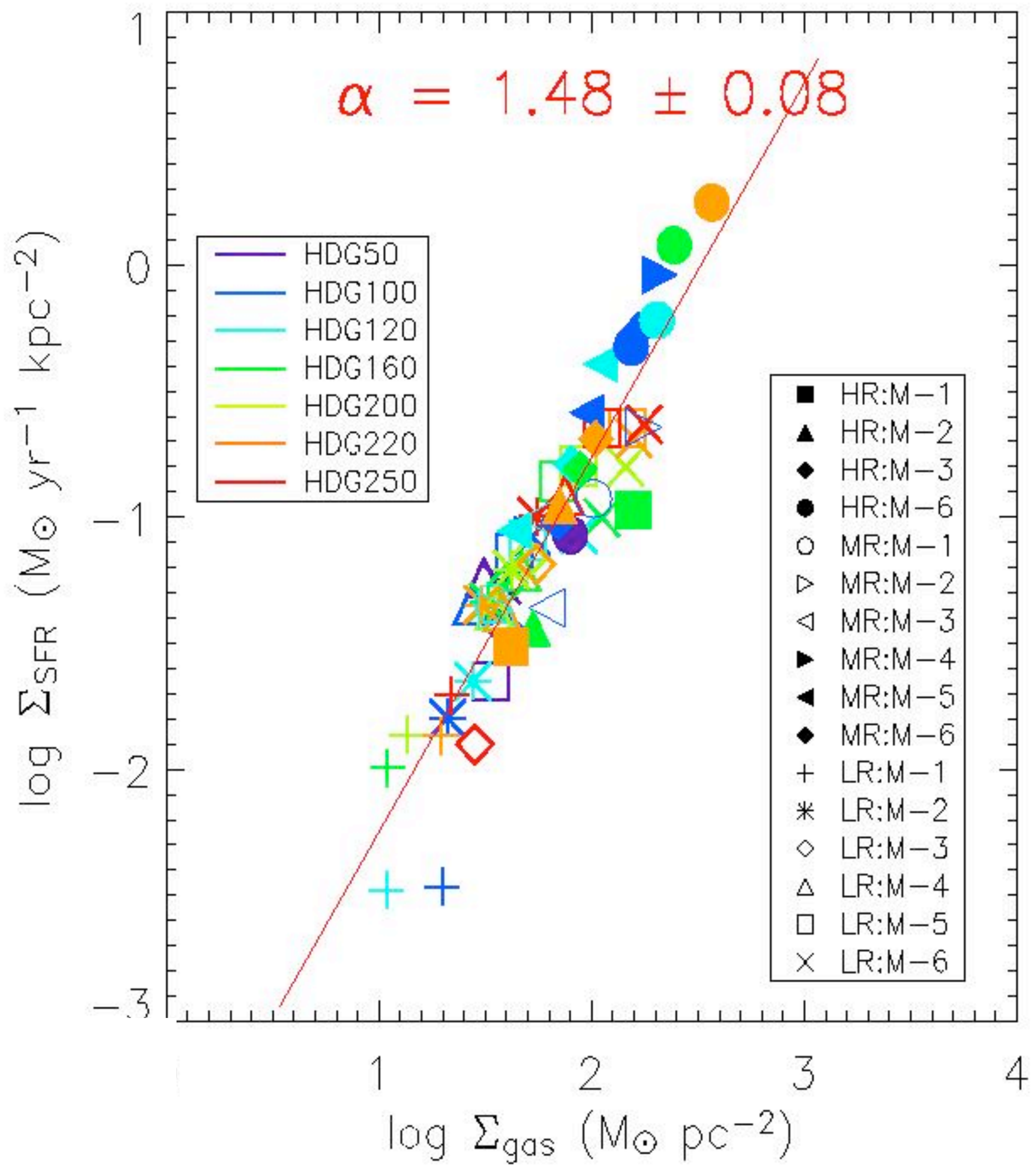
(Li et al 2005, 2006)

SPH + stars + DM models of isolated disk galaxies with several million particles

→ begin to resolve individual molecular clouds

→ we need to care about „small-scale“ physics (i.e. *transition* from *atomic gas* to *molecular*)

(simple physics: gravity + hydrodynamics (isothermal EOS) + stellar dynamics [stars + DM])



Result:
gravitational instability alone leads to the *Schmidt law* (power-law correlation between star formation and surface denstiy)

$$\Sigma_{SFR} \propto \Sigma_{gas}^{1.5}$$

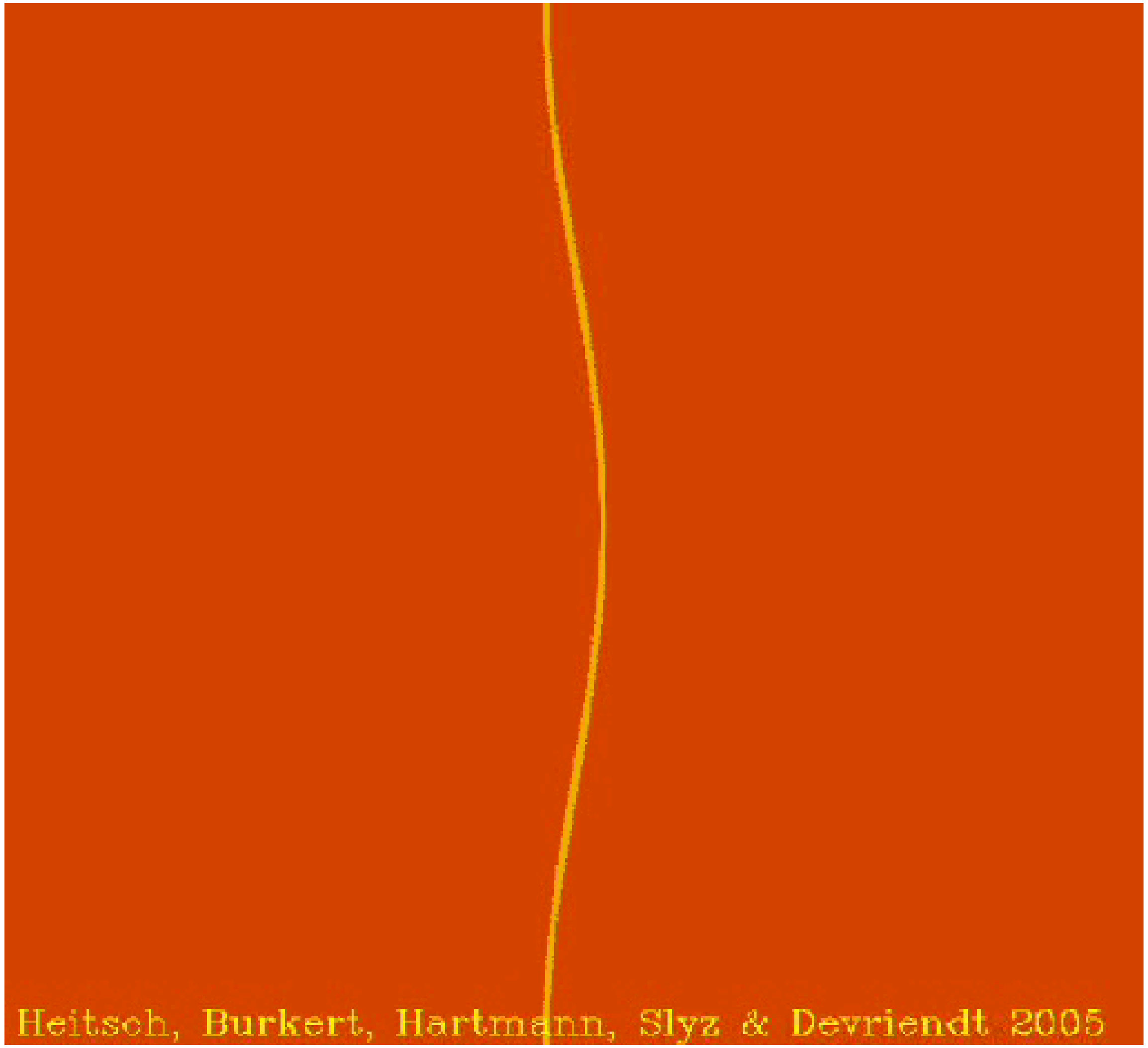
(Li et al 2005, 2006)

Molecular cloud formation

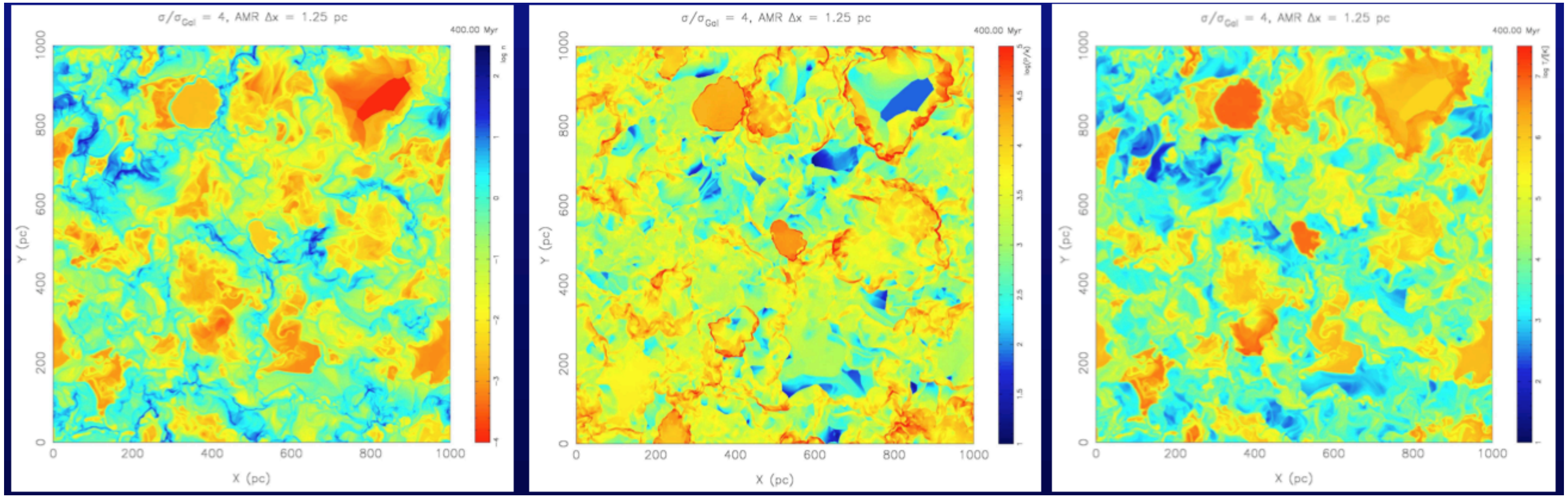
... in *convergent large-scale flows*

... setting up the *turbulent cascade*

- Mach 3 colliding flow
- Vishniac instability + thermal instability
- compressed sheet *breaks up* and builds up *cold, high-density* „blobs“ of gas
- --> *molecular cloud formation*
- cold cloud motions correspond to supersonic turbulence



(e.g. Koyama & Inutsuka 2002, Heitsch et al., 2005, Vazquez-Semadeni et al. 2004; also posters 8577, 8302)



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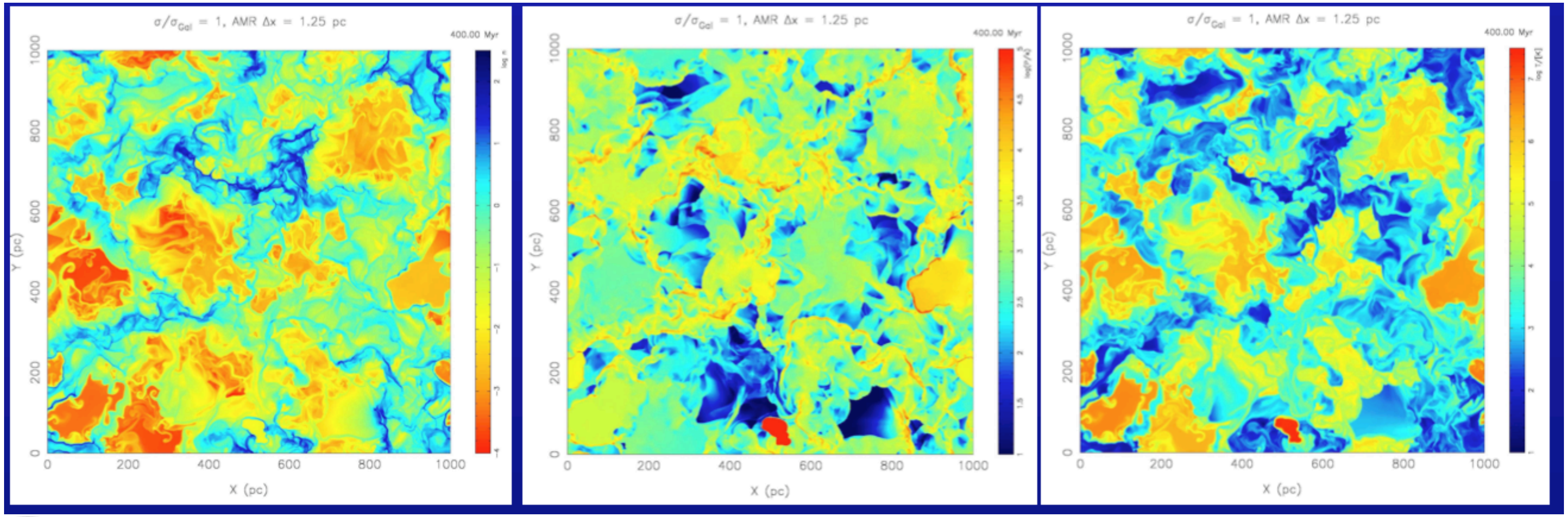


(de Avillez & Breitschwerdt)

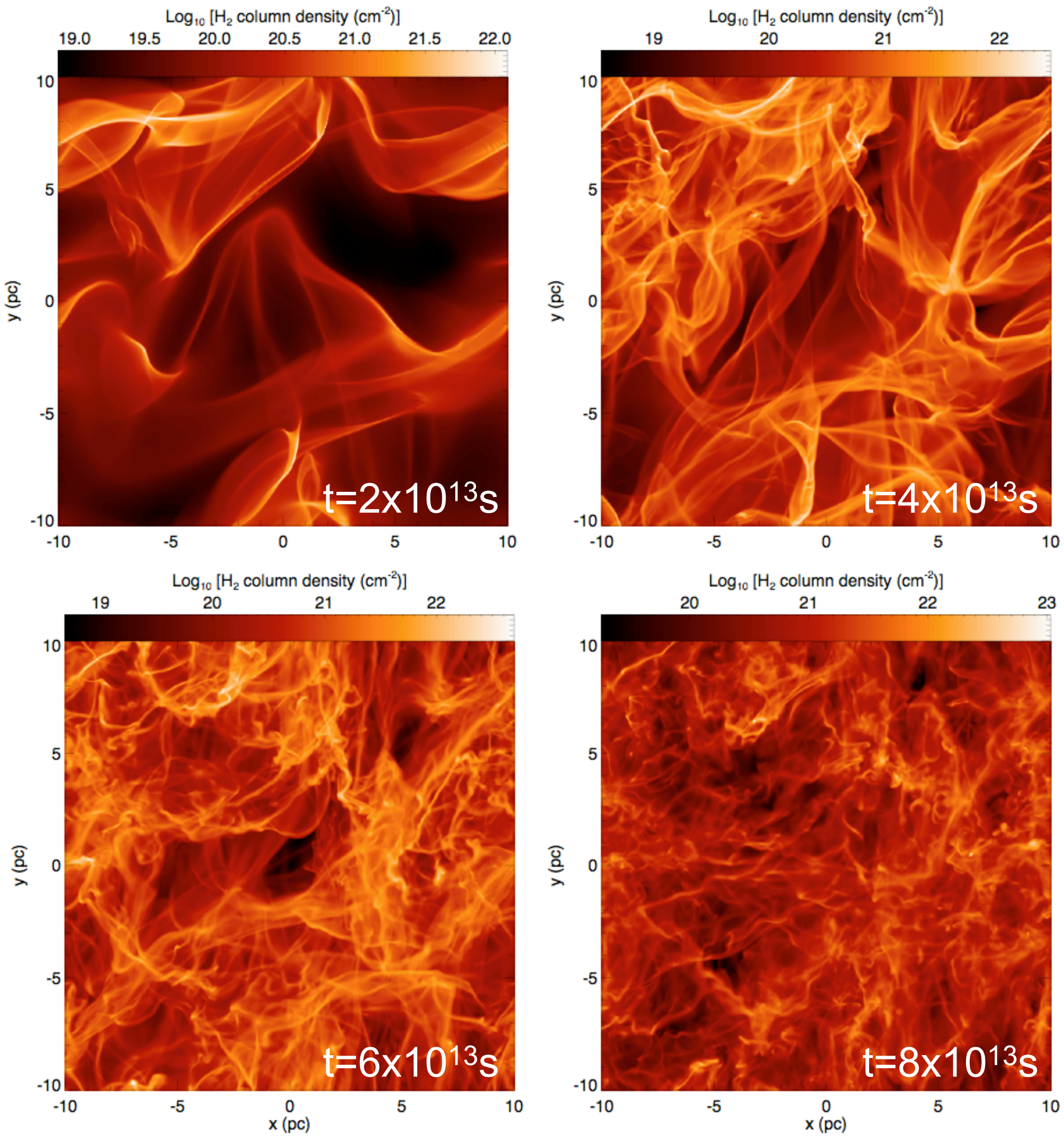
ISM: transition HI to H_2

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 2006ab:)



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[y]), 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^+

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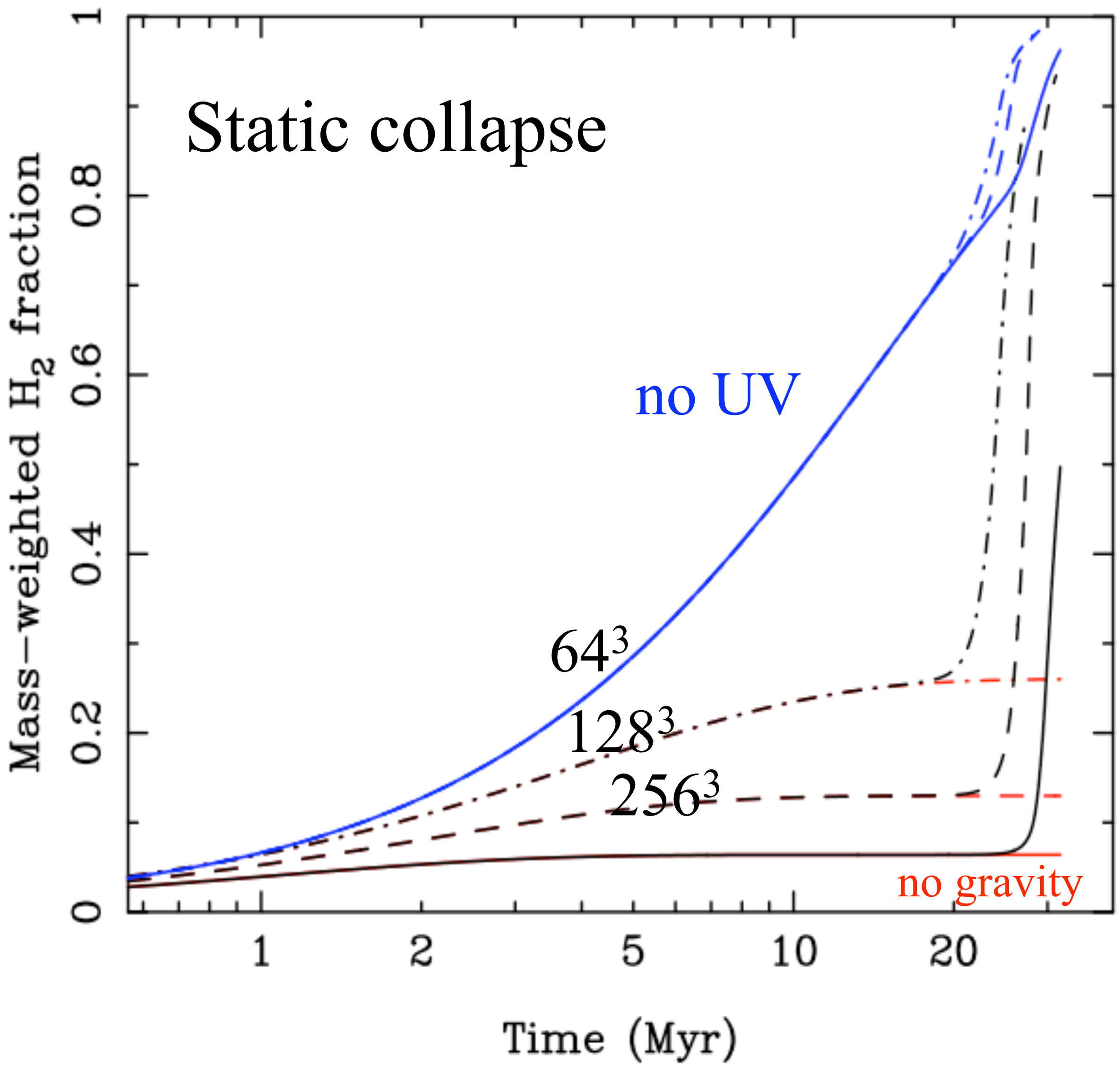
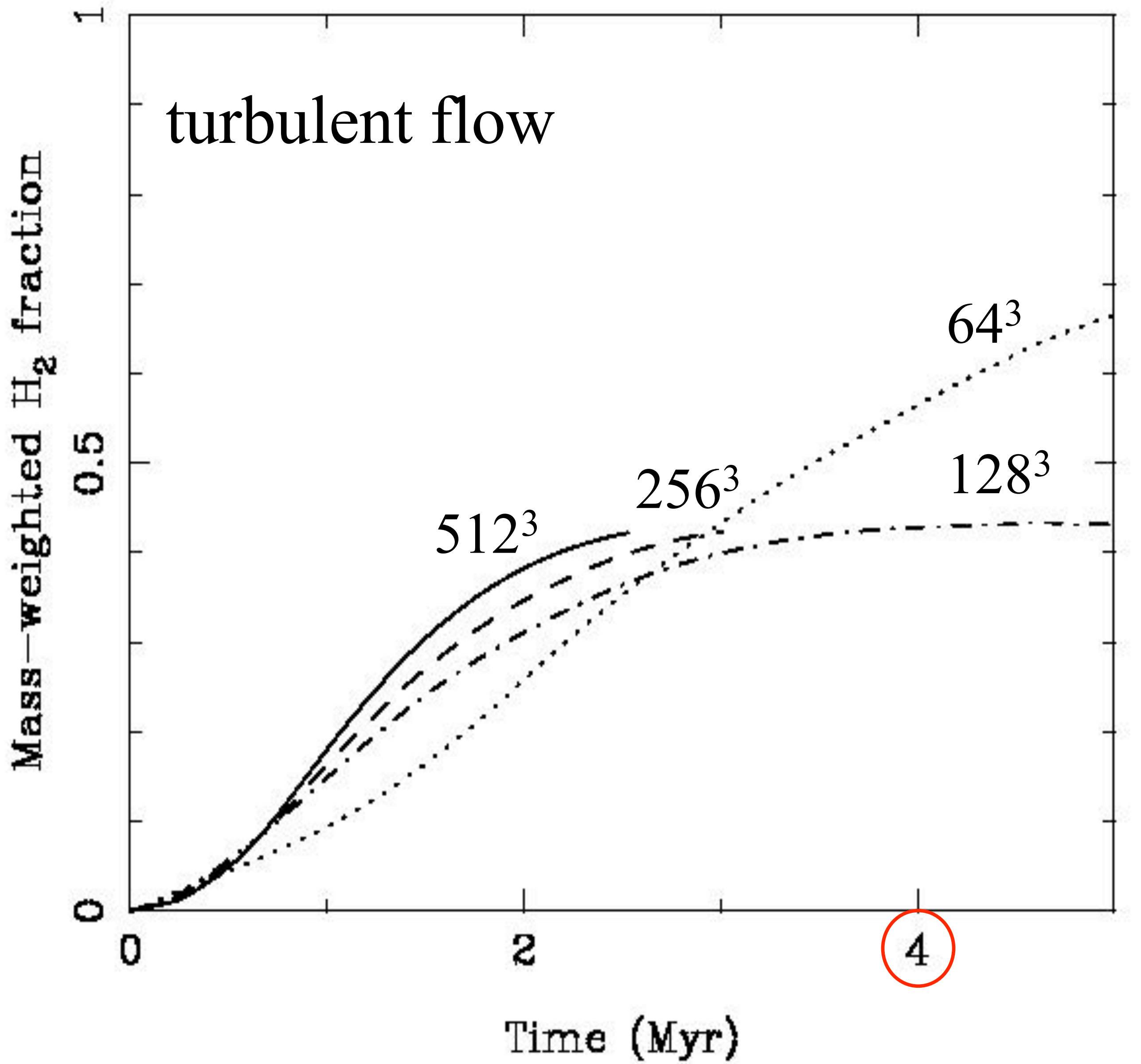
(Glover & Mac Low 2006ab)



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

(Glover & Mac Low 2006a)



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

(Glover & Mac Low 2006a)

Gravitational collapse within MCs

state of the art 5 years ago: SPH with N ≤ 10^6 particles

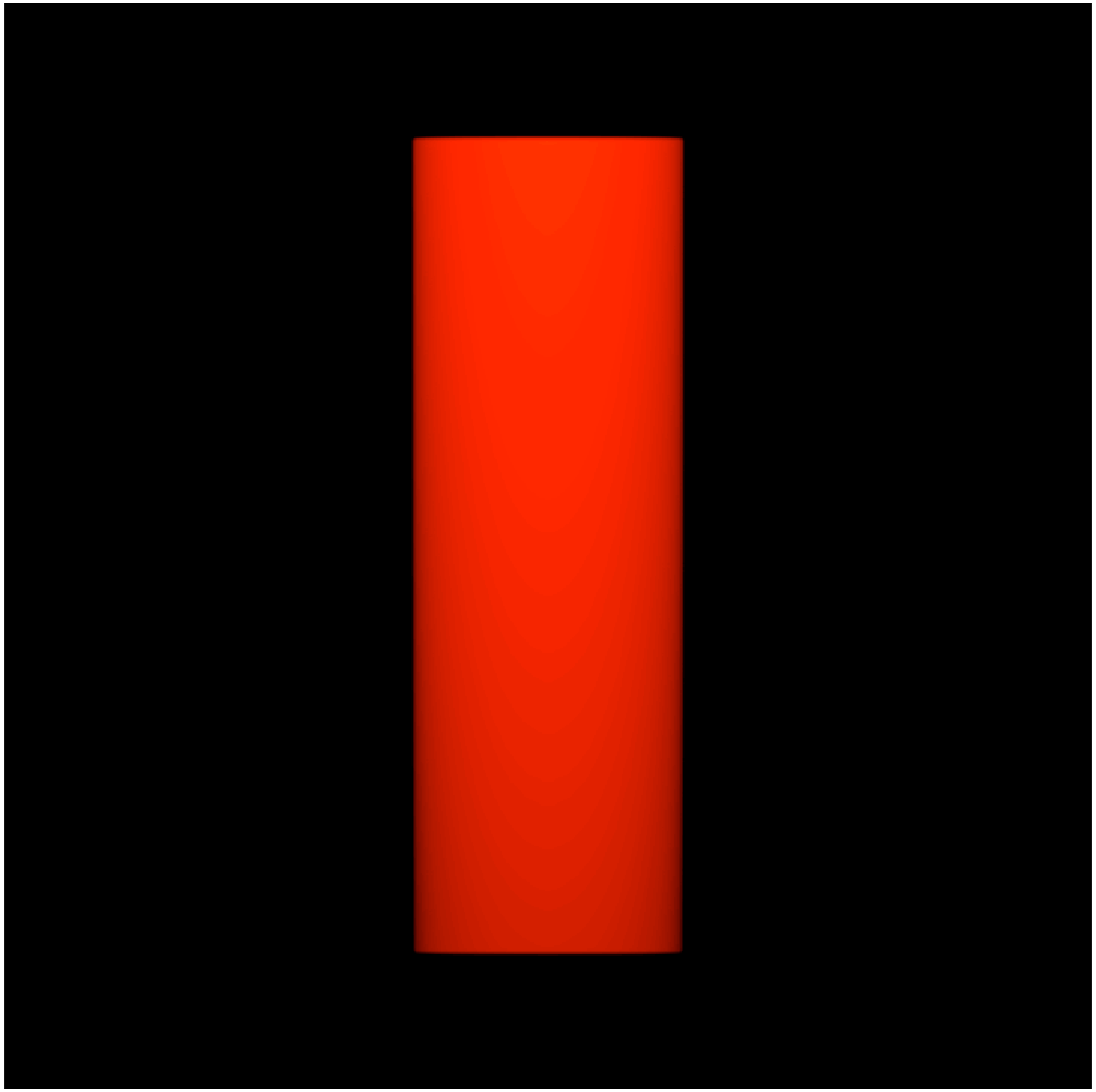
(Klessen et al.)

Gravitational collapse within MCs

today: SPH with
$N > 10^7$ particles

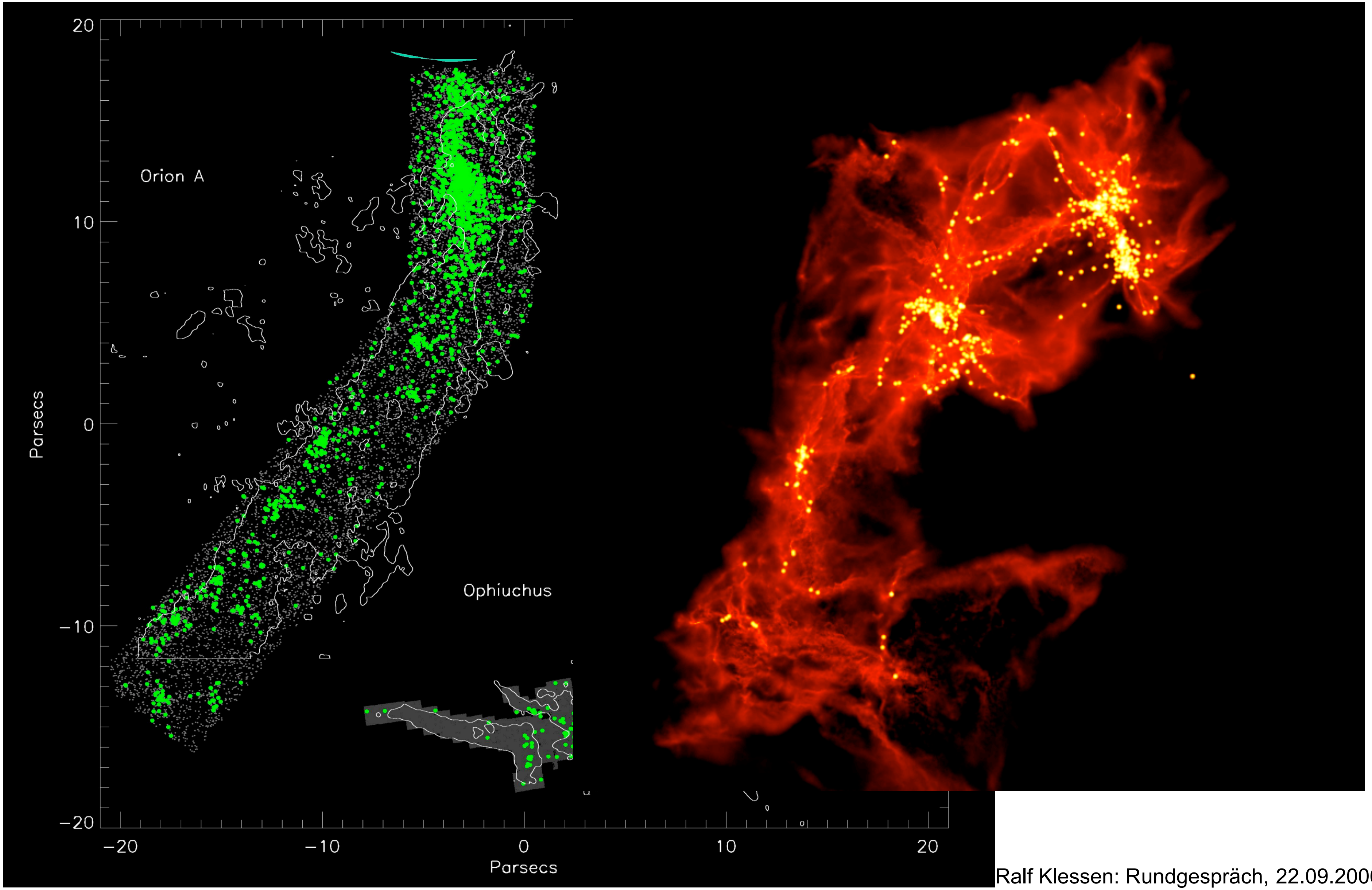
model for the Orion cloud:
$M = 10^4\ M_{sun}$, isothermal
EOS

still no *chemistry*, no
stellar feedback, no
radiation



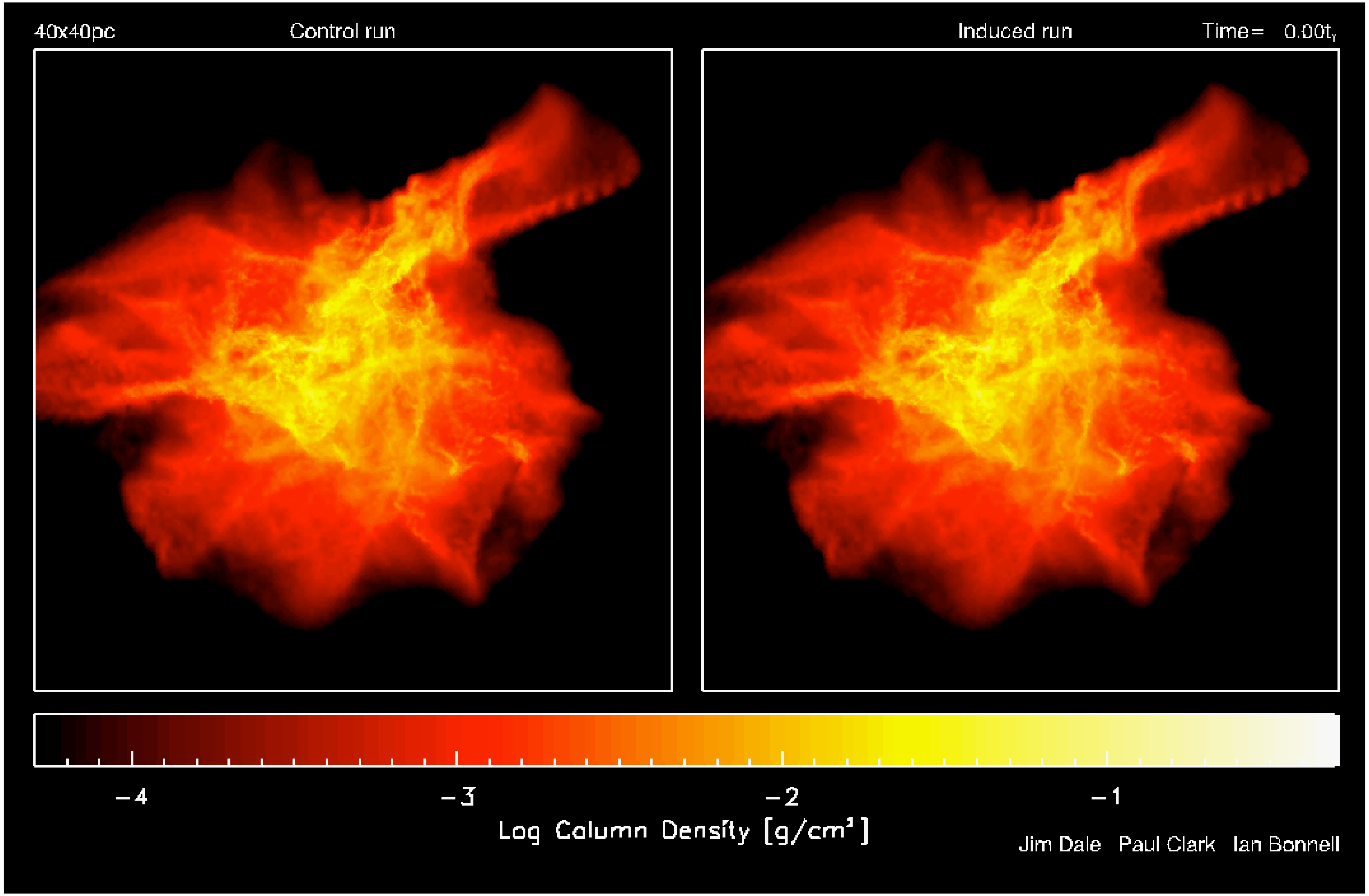
(Bonnell et al. 2006)

Gravitational collapse within MCs



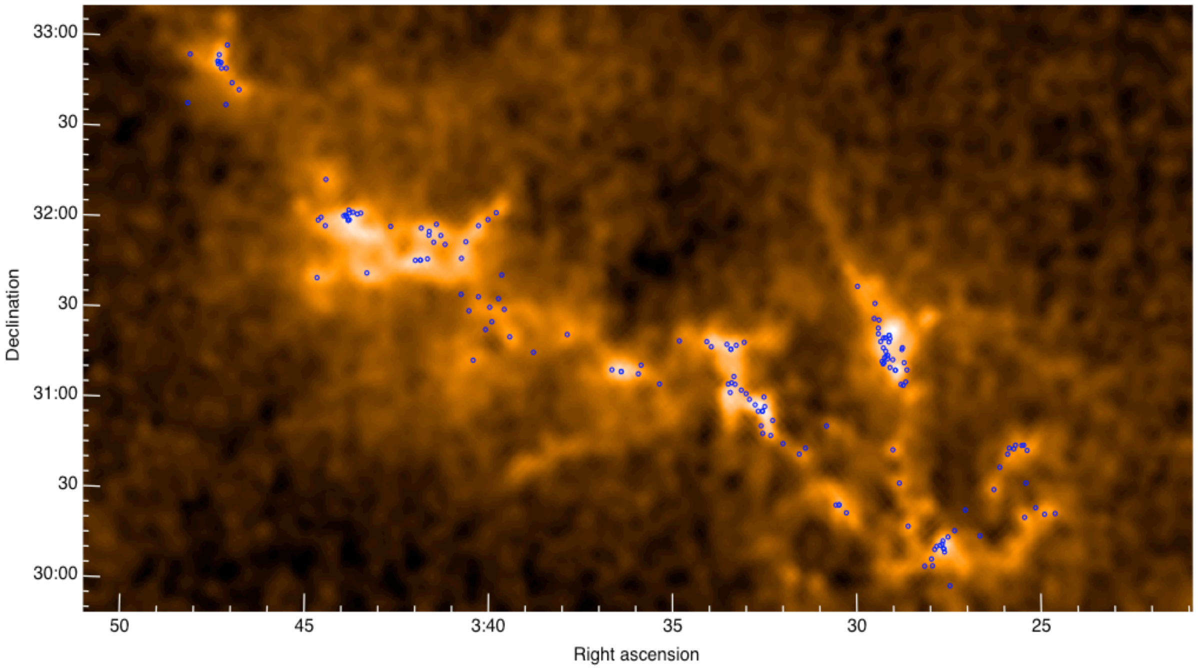
Gravitational collapse within MCs

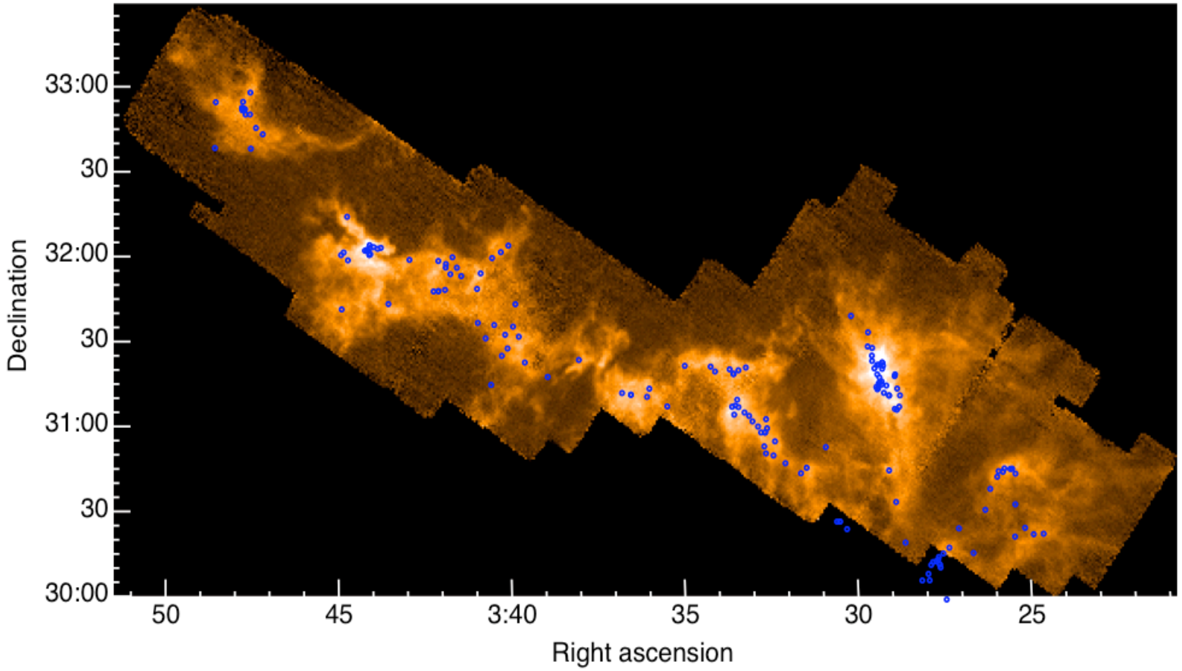
immediate future: SPH with radiation feedback (first validation runs)



IRAM Observations

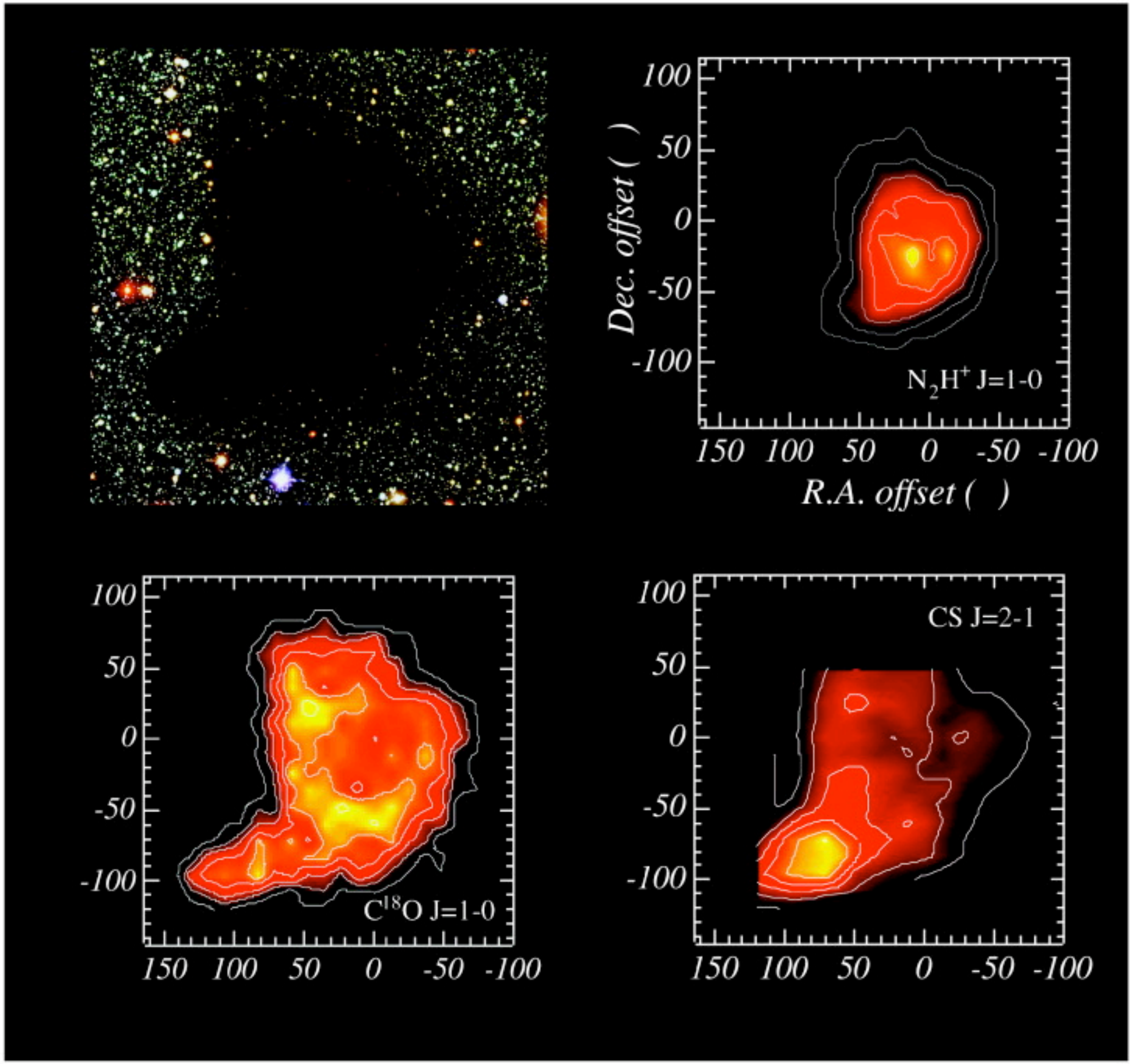
- N_2H^+ and $C^{18}O$
- 15 arcsecond res.
  - ~3000 AU
- N_2H^+ dense gas tracer
  - Most SCUBA
  - Few extinction!





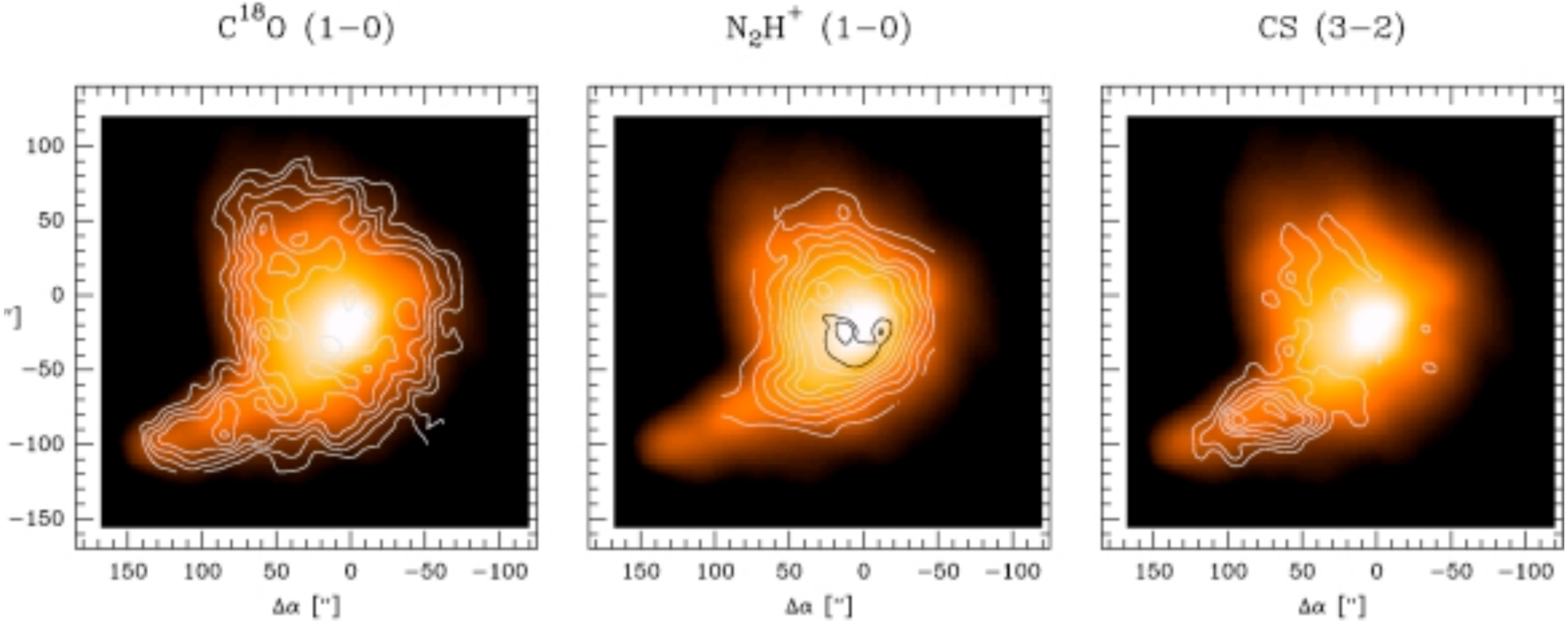
(Perseus: Johnstone et al.)

Barnard 68: a well-studied isolated prestellar core



(Lada et al. 2003)

Barnard 68



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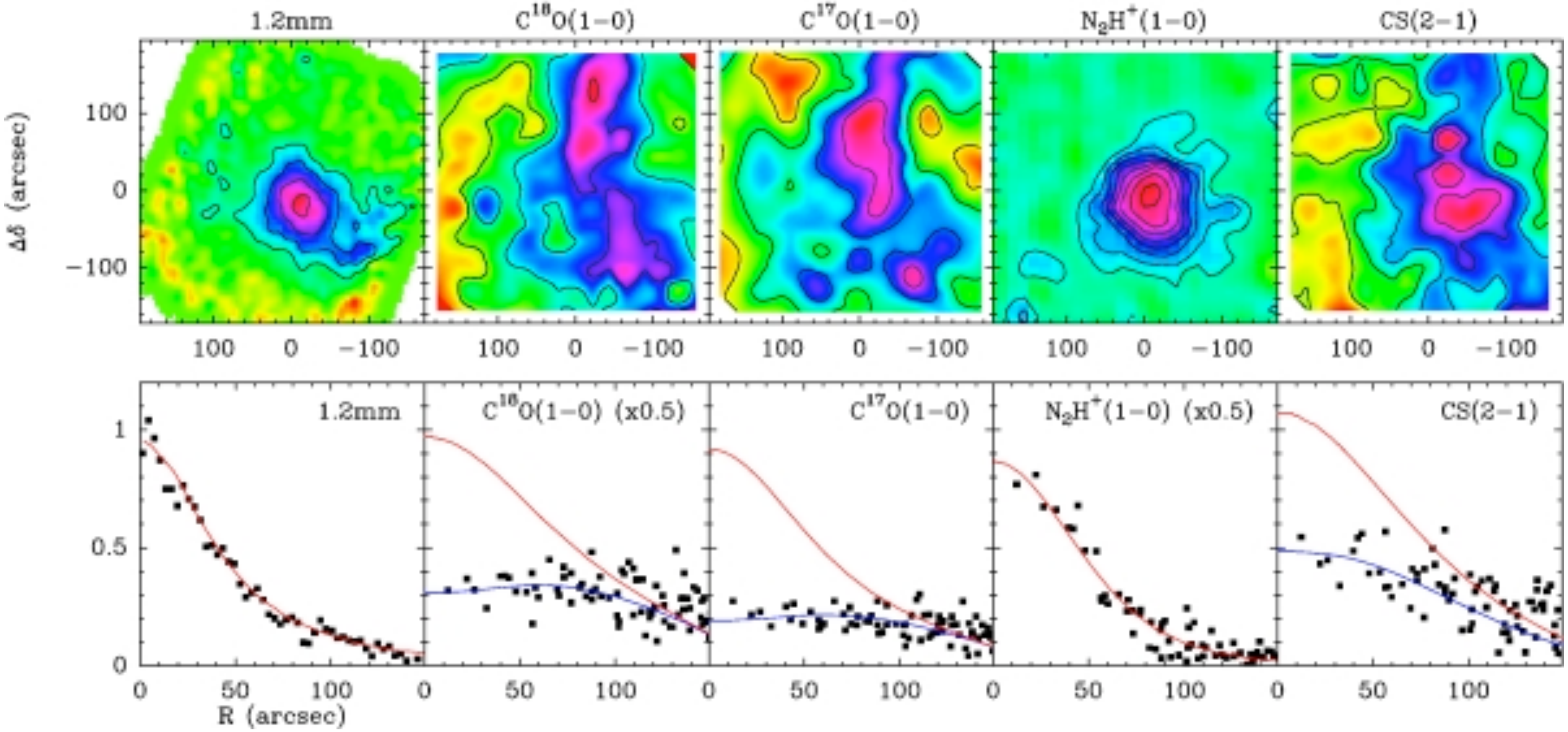
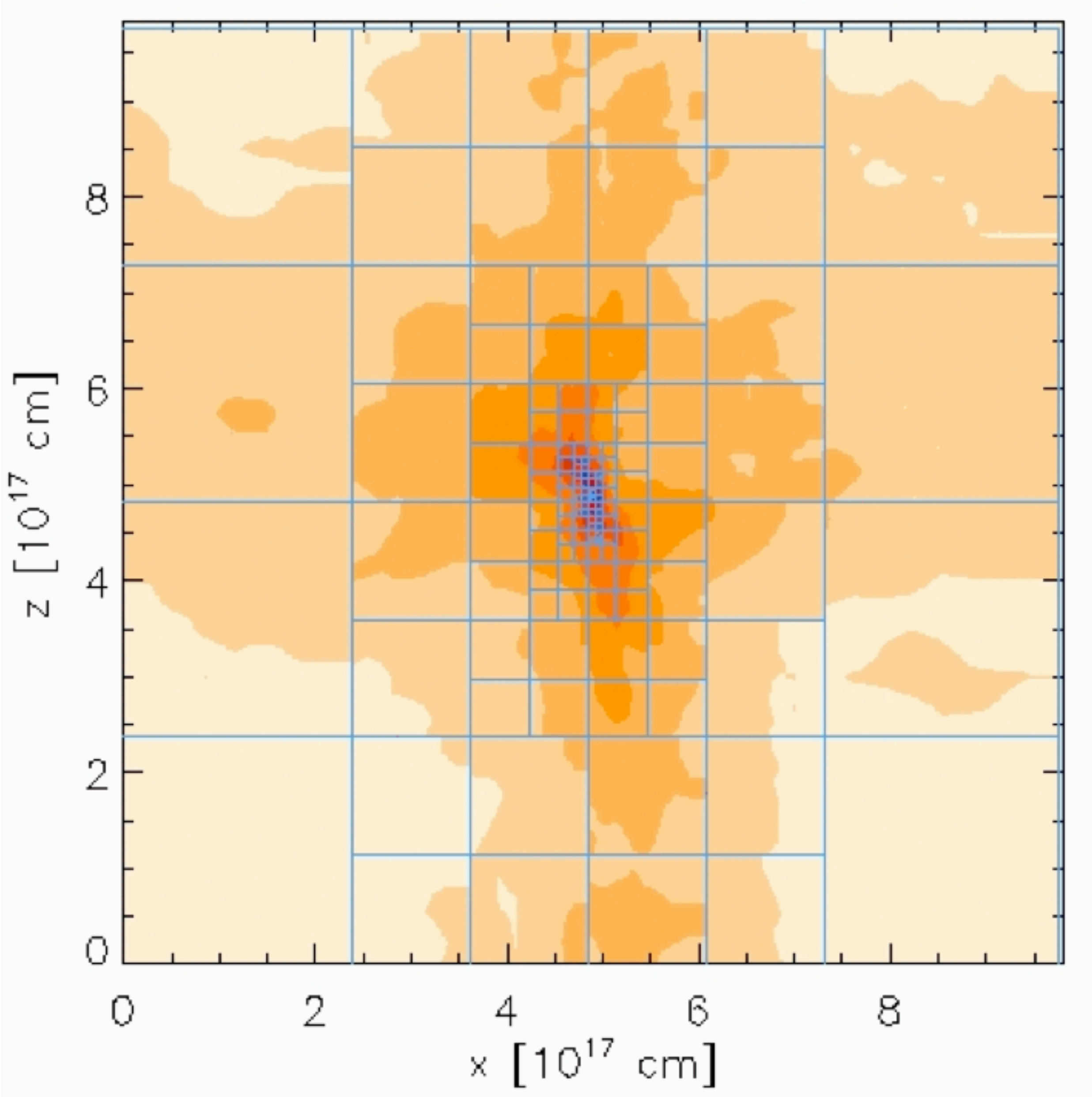


1.2mm
$C^{18}O(1-0)$
$C^{17}O(1-0)$
$N_2H^+(1-0)$
CS(2-1)
Δδ (arcsec)
100
0
−100
1.2mm
$C^{18}O(1-0)$ (x0.5)
$C^{17}O(1-0)$
$N_2H^+(1-0)$ (x0.5)
CS(2-1)
1
0.5
0
50
100
R (arcsec)

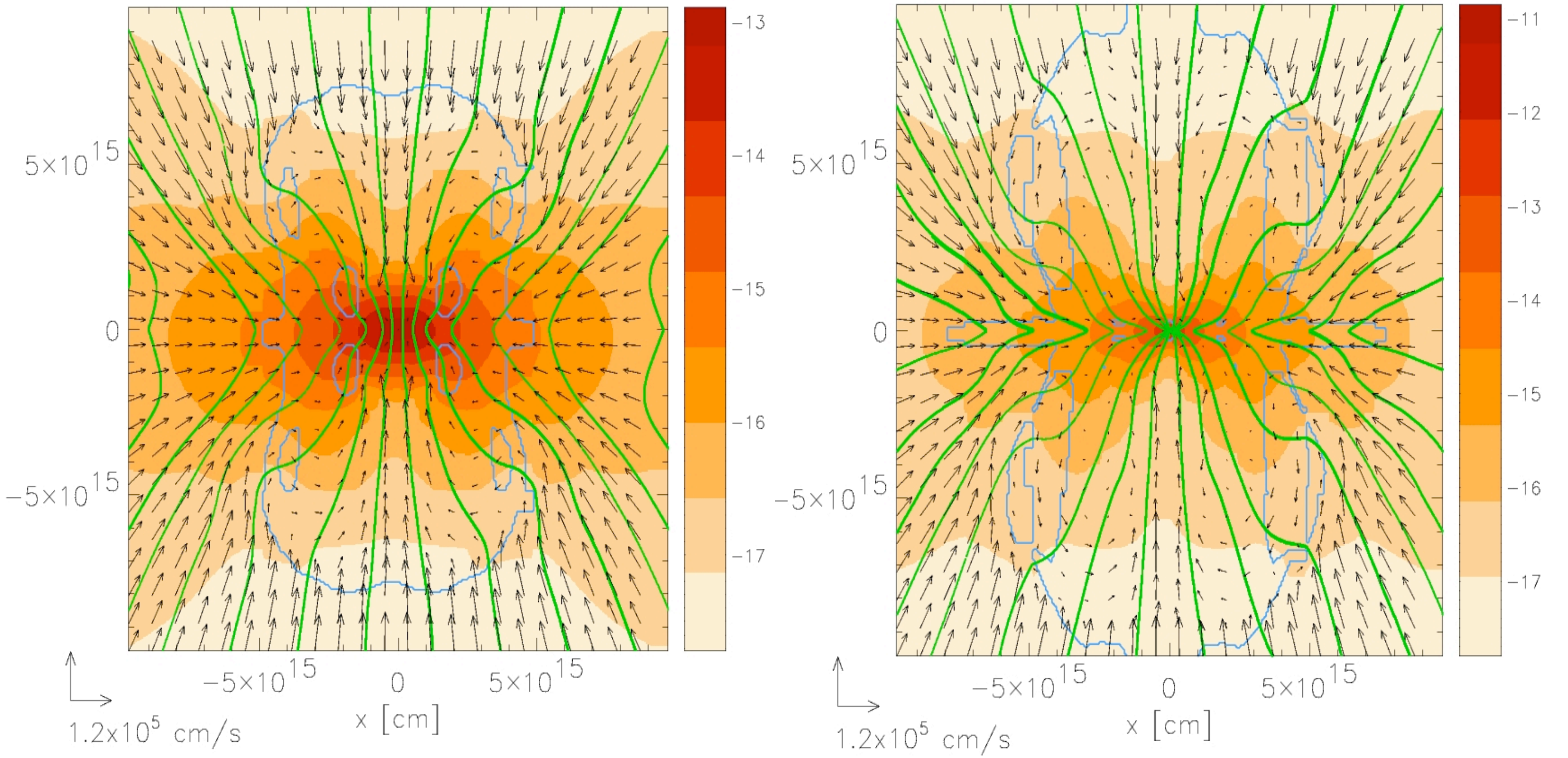


adaptive mesh refinement:

computational grid gets refined in regions of high interest (e.g. protostellar cores)

formation of 30 M_{sun} core in turbulent molecular cloud (FLASH with appropriate cooling curve module and turbulent driving)

(Banerjee & Pudritz 2006)



These 2D snapshots show the onset of the **large scale outflow**. After ca. 70.000 years into the collapse a strong toroidal magnetic field builds up whose magnetic pressure reverses the gas flow and drives an outflow (time difference between these snapshots: 1400 years).

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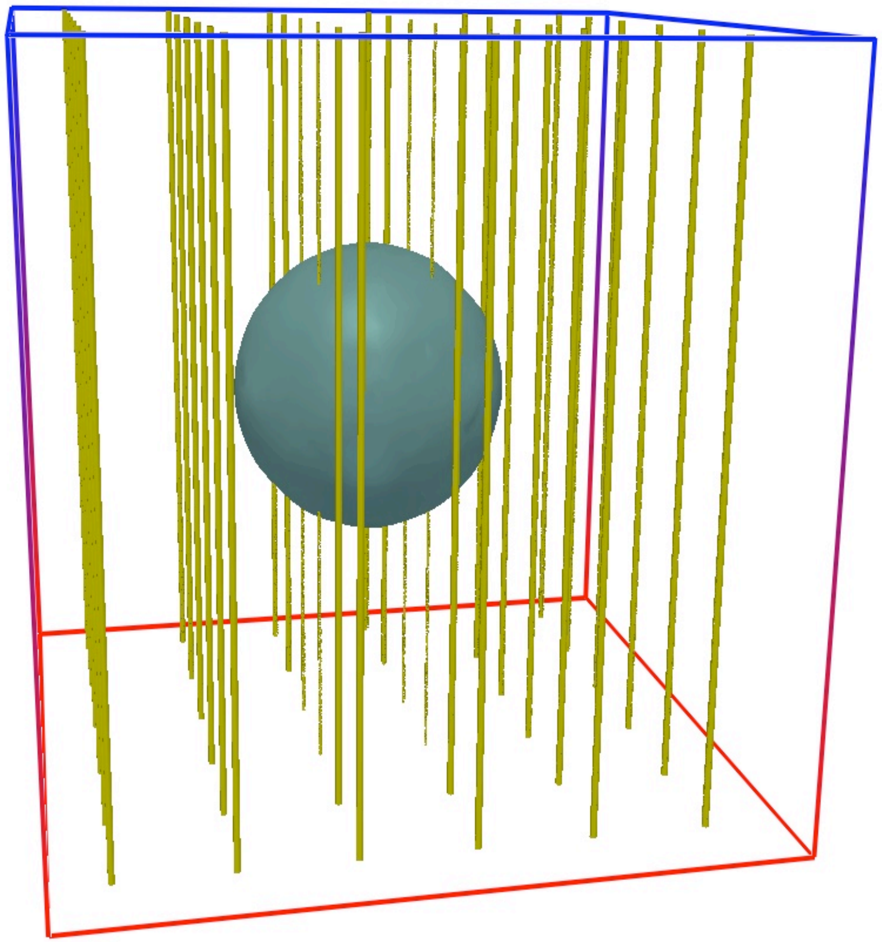
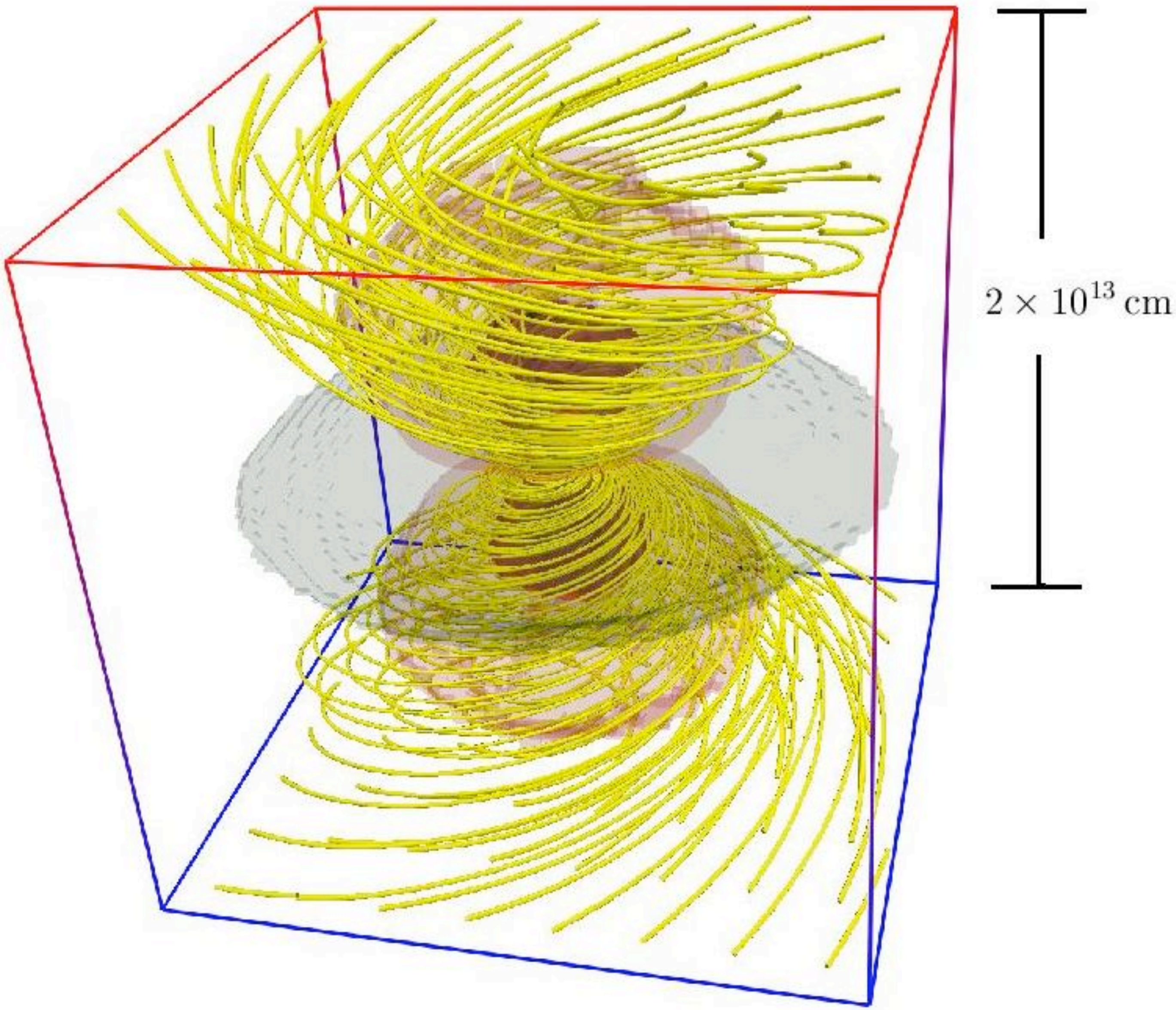
(Banerjee & Pudritz 2006)



Initially a magnetic field aligned with the rotation axis of the cloud core threads the entire simulation box. The field strength varies slightly (3.4 – 14 micro Gauss) along the equatorial plane to maintain a constant plasma b = 8pp/B2. In this configuration, prior to the gravitational collapse the sphere loses a considerable amount of angular momentum from 'magnetic braking' (Mouschovias & Paleologou, 1980).

(Banerjee & Pudritz 2006)

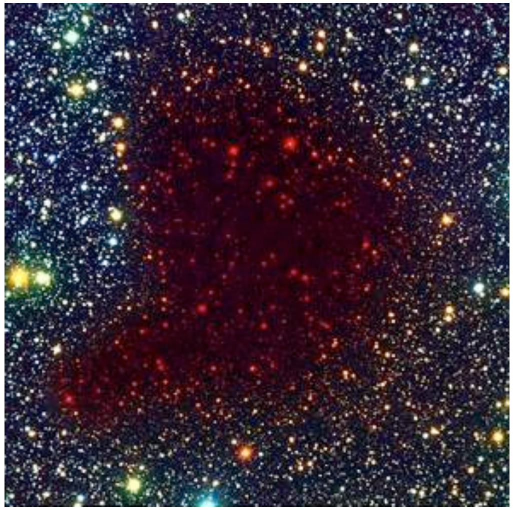


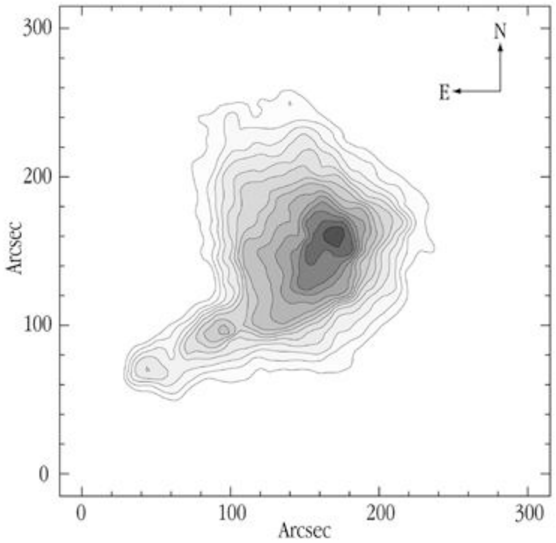
The 3D structure of the magnetic field line configuration in the **jet** launching region.

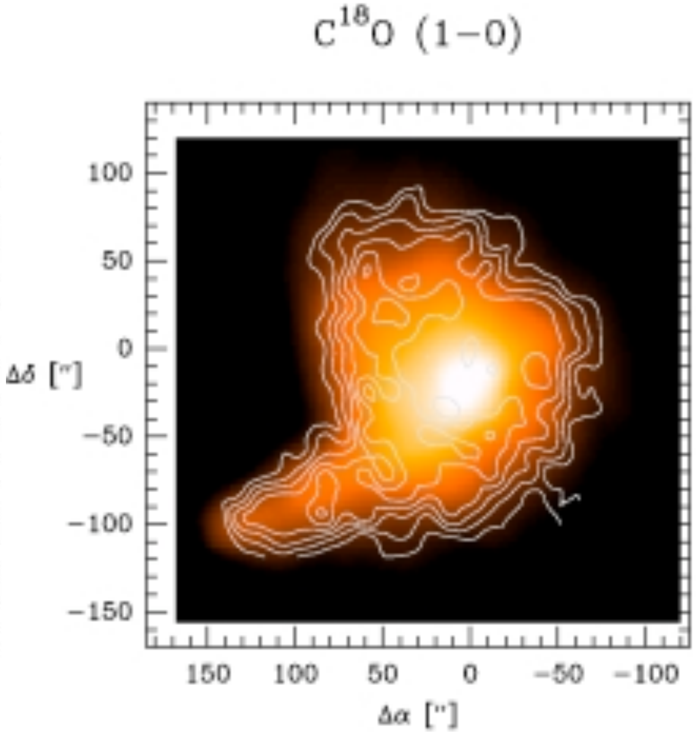
As predicted by analytics the magneto-centrifugally driven disk jet is faster in the inner region (dark red) than further away from the outflow axis (light red).

(Banerjee & Pudritz 2006)

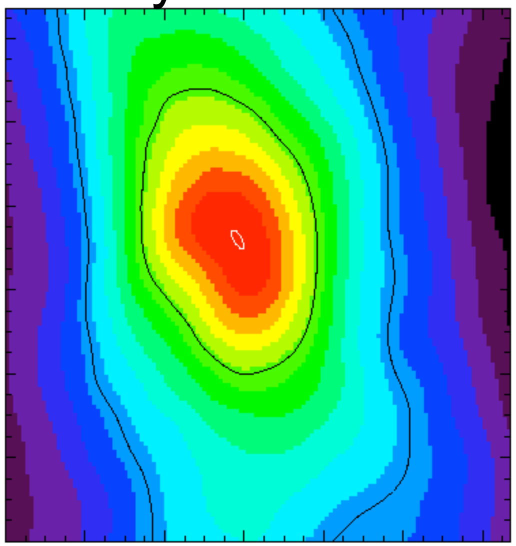
observations







theory



MHD model with proper heating and cooling terms (EOS)

+

chemical model

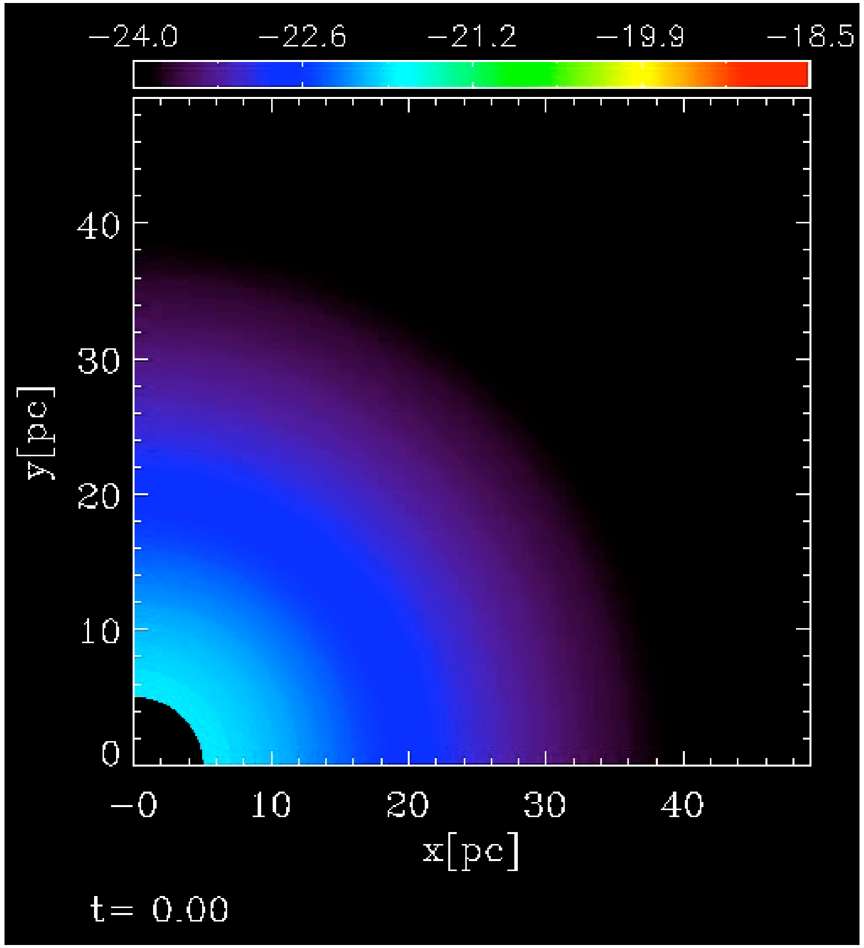
→ line radiative transfer → synthetic images of model cores

↕ compare

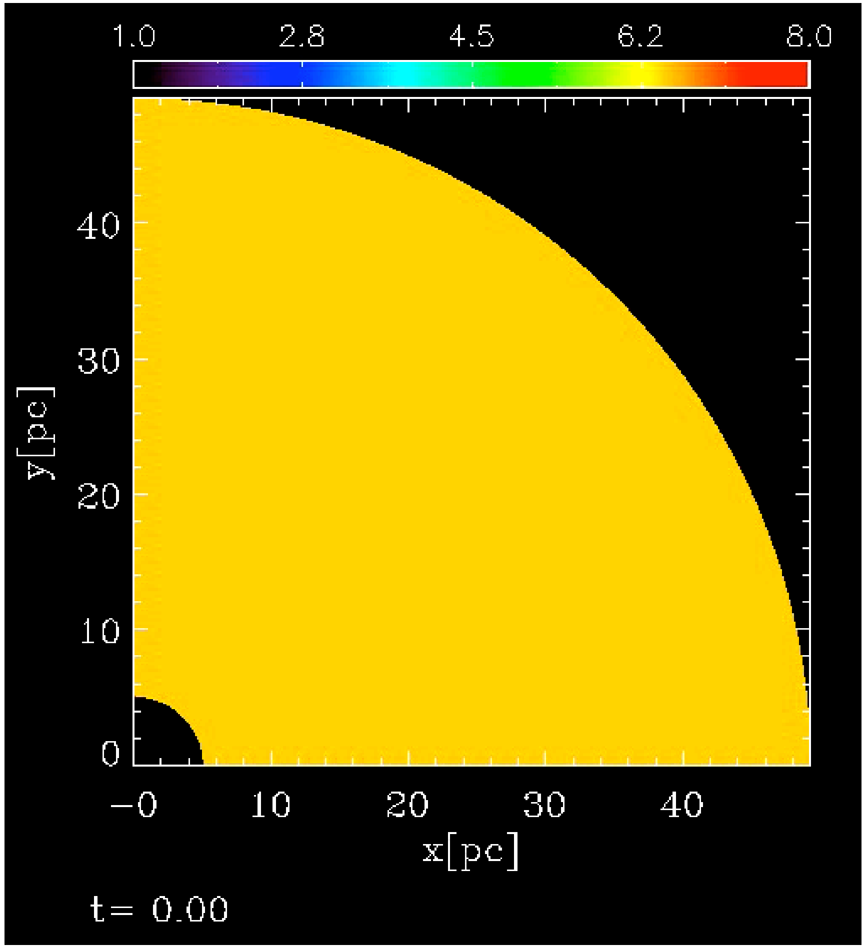
(e.g. Semenov & Pavlyuchenkov)

(3D core structure: Steinacker)

cold, dusty AGN tori



density evolution

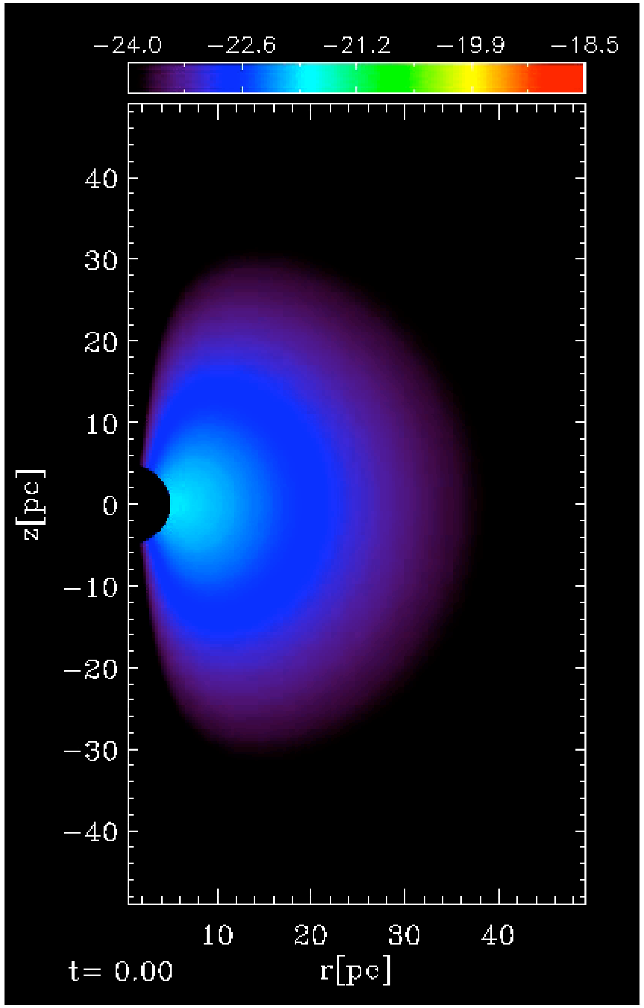


temperature distribution

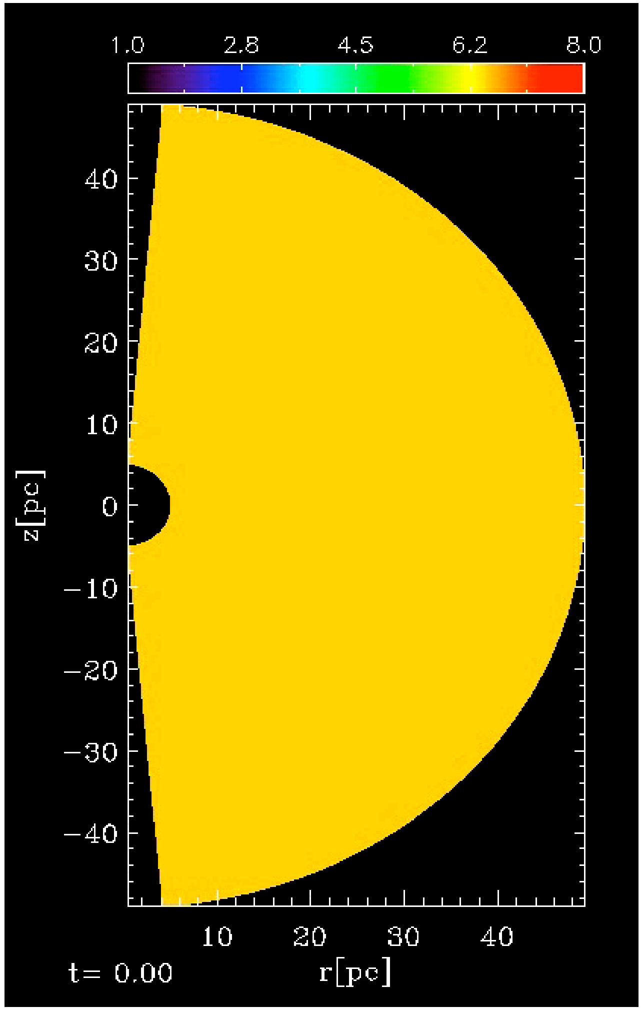
ZAH Zentrum für Astronomie Heidelberg ARI•ITA•LSW

(Schartmann, Klahr, Meisenheimer, Camenzind)

cold, dusty AGN tori



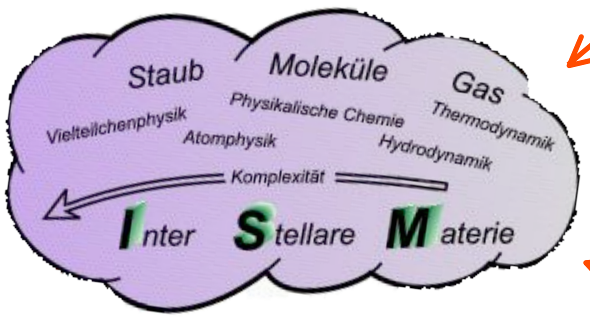
density evolution



temperature distribution

(Schartmann, Klahr, Meisenheimer, Camenzind)

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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