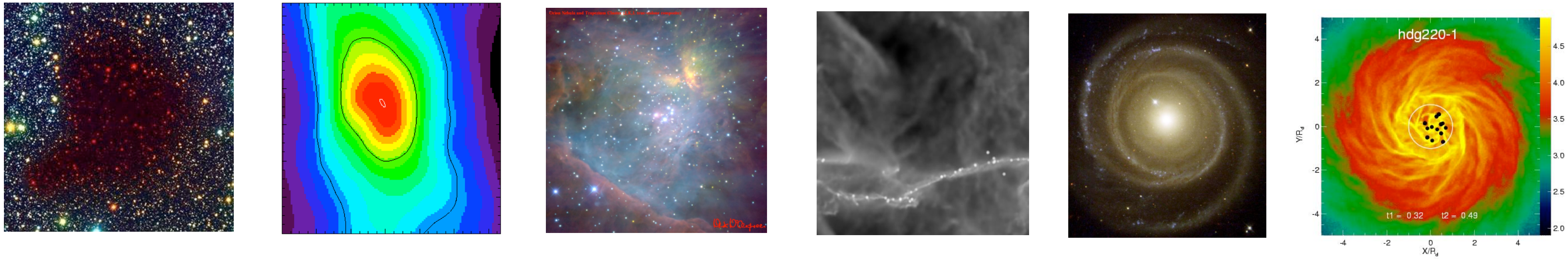
Modeling ISM Dynamics: Star Formation



Ralf Klessen

Zentrum für Astronomie der Universität Heidelberg
Institut für Theoretische Astrophysik

Structure

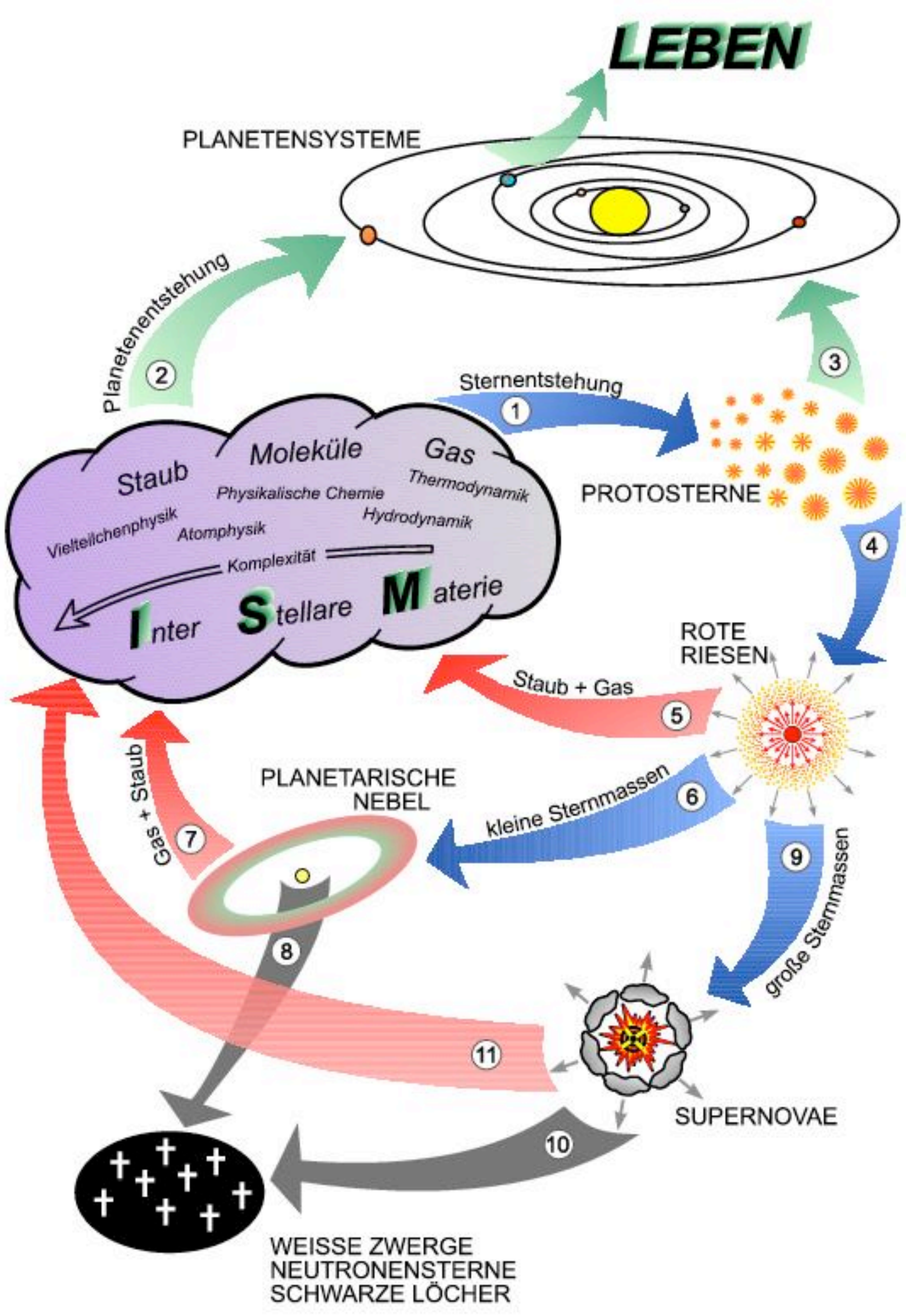
ISM overview

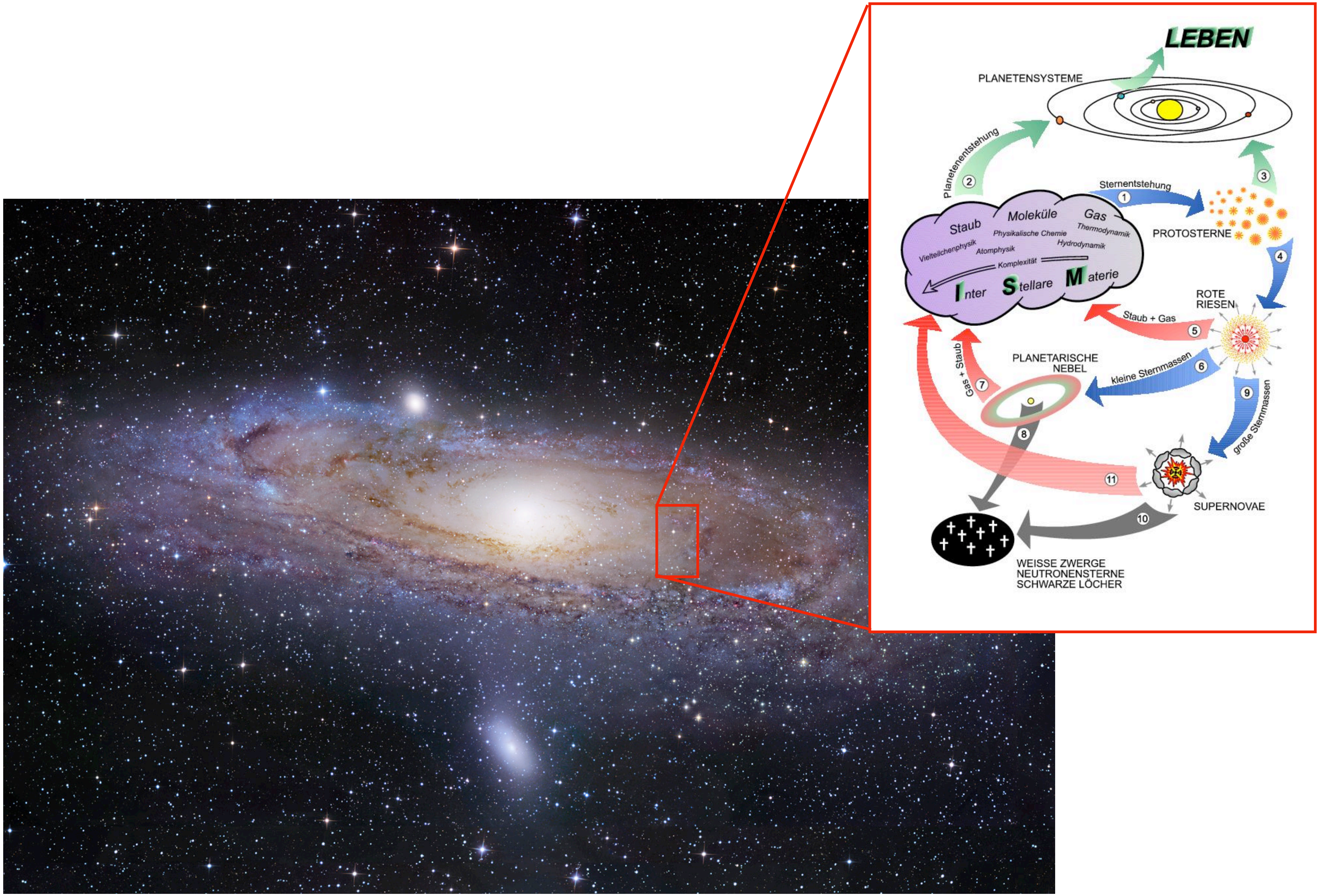
what do we need to study the ISM?

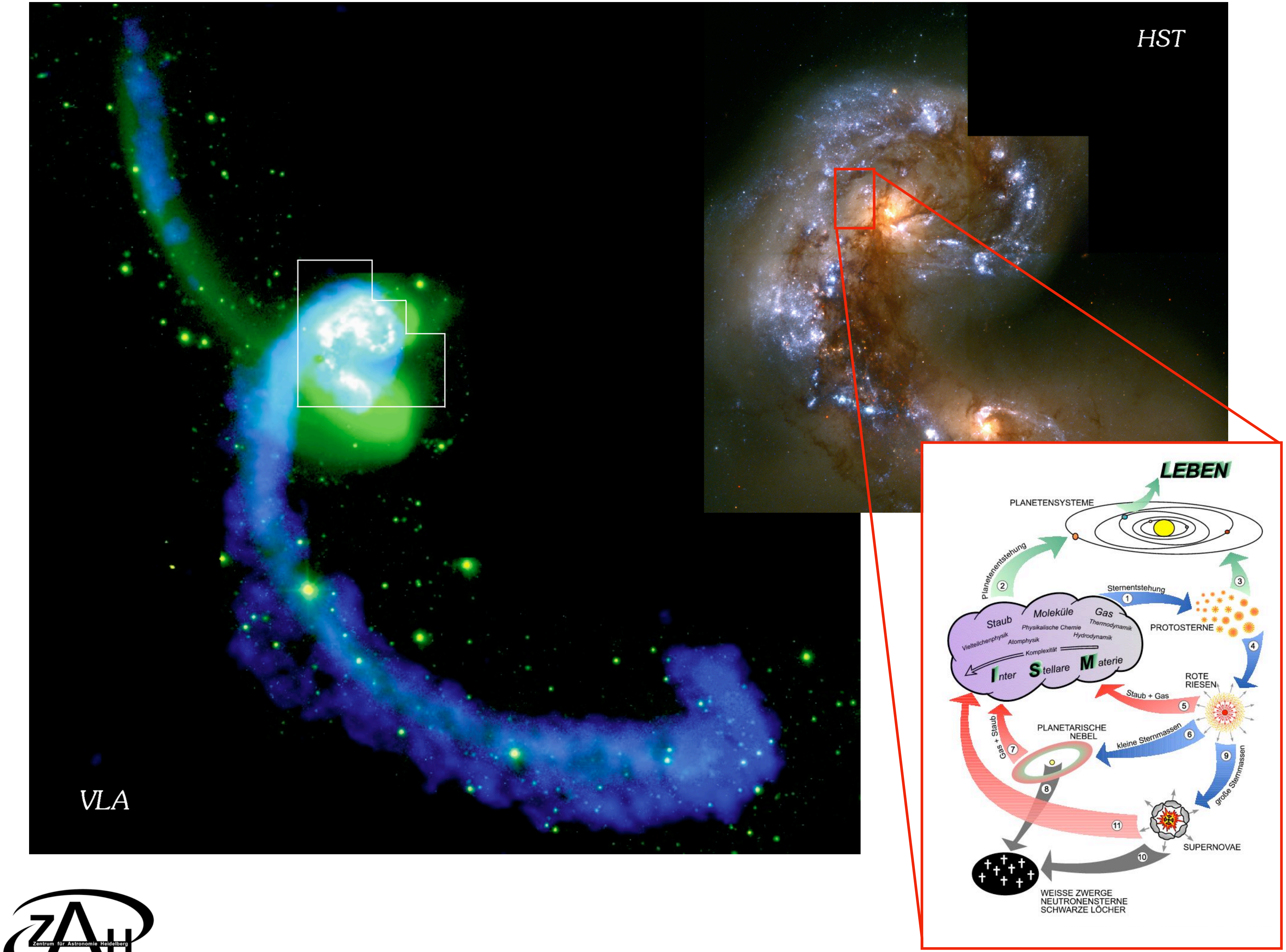
concept of ***gravoturbulent fragmentation*** and ***star formation***.

applications to star cluster formation

ISM overview


LEBEN
PLANETENSYSTEME
② Planetenentstehung
Sternentstehung ①
③
PROTOSTERNE
④
Staub
Moleküle
Gas
Physikalische Chemie
Thermodynamik
Vielteilchenphysik
Atomphysik
Hydrodynamik
Komplexität
Inter Stellare Materie
ROTE RIESEN
Staub + Gas ⑤
kleine Sternmassen ⑥
PLANETARISCHE NEBEL
Gas + Staub ⑦
⑧
⑨ große Sternmassen
⑪
SUPERNOVAE
⑩
WEISSE ZWERGE
NEUTRONENSTERNE
SCHWARZE LÖCHER


LEBEN
PLANETENSYSTEME
Planetenentstehung
2
3
Sternentstehung
1
PROTOSTERNE
Staub
Moleküle
Gas
Physikalische Chemie
Thermodynamik
Vielteilchenphysik
Atomphysik
Hydrodynamik
Komplexität
Inter Stellare Materie
4
ROTE RIESEN
Staub + Gas
5
Gas + Staub
7
PLANETARISCHE NEBEL
kleine Sternmassen
6
9
große Sternmassen
8
11
SUPERNOVAE
10
WEISSE ZWERGE
NEUTRONENSTERNE
SCHWARZE LÖCHER

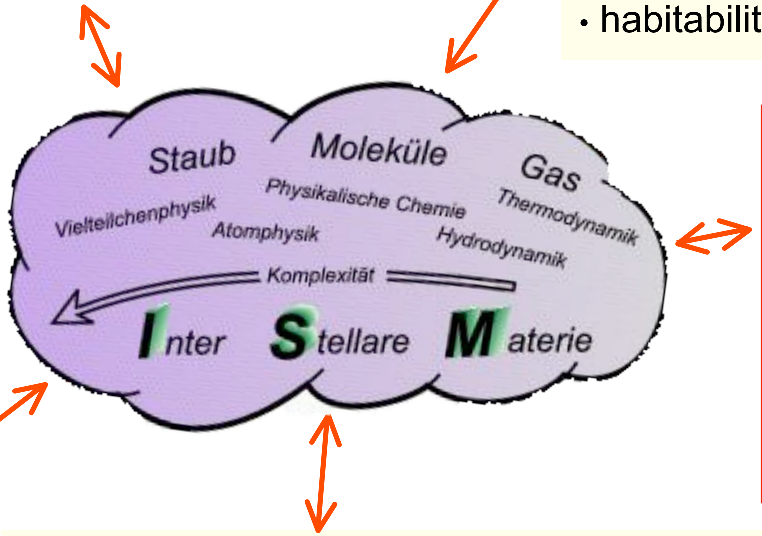

HST
VLA
LEBEN
PLANETENSYSTEME
Planetenentstehung
2
Sternentstehung
1
3
PROTOSTERNE
4
Staub
Moleküle
Gas
Physikalische Chemie
Thermodynamik
Vielteilchenphysik
Atomphysik
Hydrodynamik
Komplexität
Inter Stellare Materie
ROTE RIESEN
Staub + Gas
5
PLANETARISCHE NEBEL
kleine Sternmassen
6
Gas + Staub
7
8
9
große Sternmassen
11
SUPERNOVAE
10
WEISSE ZWERGE
NEUTRONENSTERNE
SCHWARZE LÖCHER

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

historic overview

Early dynamical theory

- *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: $\boxed{M_J = \frac{1}{6}\pi^{-5/2} G^{-3/2} \rho_0^{-1/2} c_s^3 \propto \rho_0^{-1/2} T^{3/2}}$

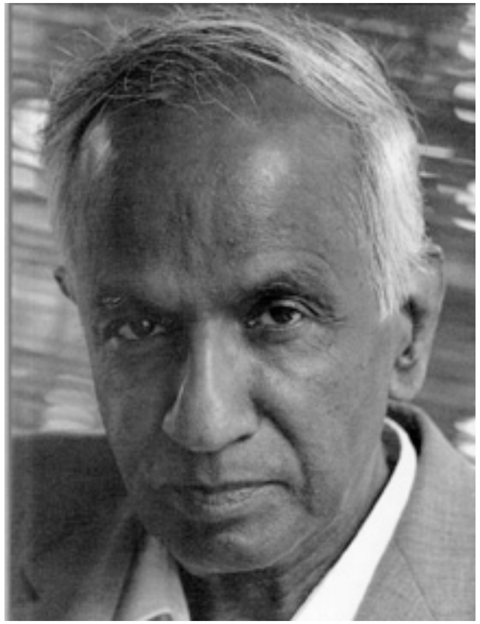
Sir James Jeans, 1877 - 1946

(full detail in Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194)

First approach to turbulence

- *von Weizsäcker (1943, 1951)* and *Chandrasekhar (1951):* concept of **MICROTURBULENCE**
  - BASIC ASSUMPTION: separation of scales between dynamics and turbulence
    $\ell_{\mathrm{turb}} \ll \ell_{\mathrm{dyn}}$
  - then turbulent velocity dispersion contributes to effective soundspeed:

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



S. Chandrasekhar, 1910 - 1995

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

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

(full detail in Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194)

Properties of IMS turbulence

ISM turbulence is:

- Supersonic (rms velocity dispersion >> sound speed)
- Anisotropic (shocks & magnetic field)
- Driven on large scales (power in mol. clouds always dominated by largest-scale modes)

Microturbulent approach is NOT valid in ISM

- No closed analytical/statistical formulation known --> necessity for numerical modeling

Problems of early dynamical theory

- Molecular clouds are *highly Jeans-unstable*
  Yet, they do *NOT* form stars at high rate
  and with high efficiency.
  (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-equilitrium entities.
- Molecular clouds are *magnetized.*

(full detail in Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194)

Magnetic star formation

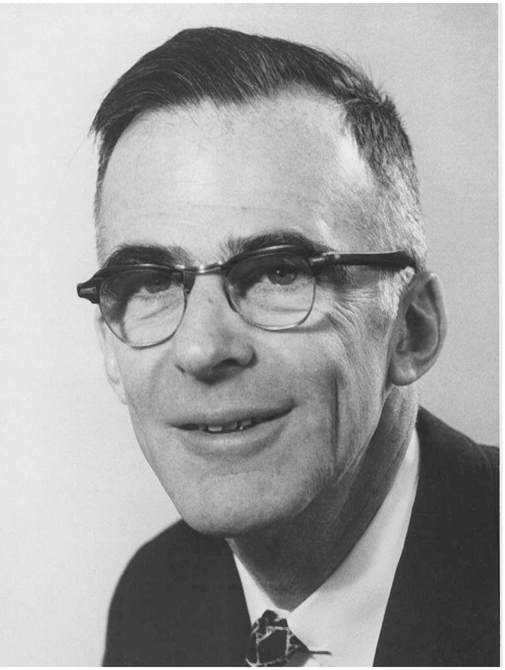
- *Mestel & Spitzer (1956):* Magnetic fields can prevent collapse*!!!*
  - Critical mass for gravitational collapse in presence of B-field

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

  - 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

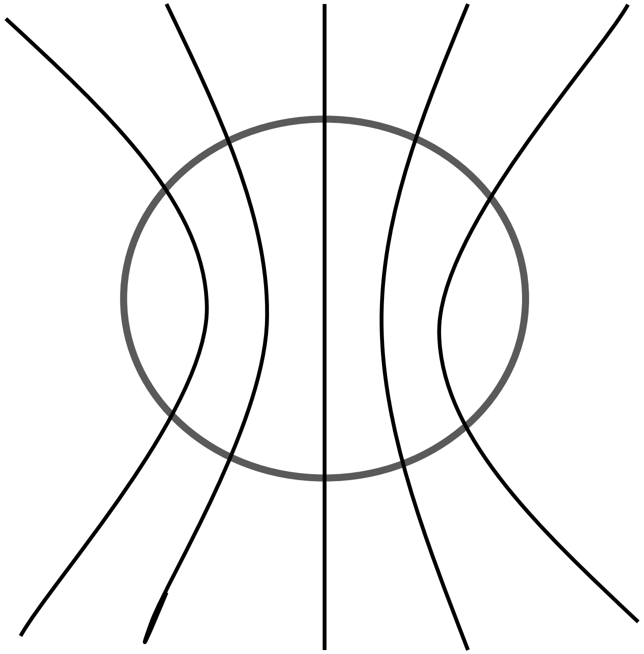


Lyman Spitzer, Jr., 1914 - 1997

(full detail in Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194)

The "standard theory" of star formation:

- BASIC ASSUMPTION: Stars form from magnetically highly subcritical cores
- Ambipolar diffusion slowly increases (M/Φ): $\tau_{AD} \approx 10\tau_{ff}$
- 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



Problems of magnetic SF

- 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
  (Bacman et al. 2000, e.g. Barnard 68 from 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)

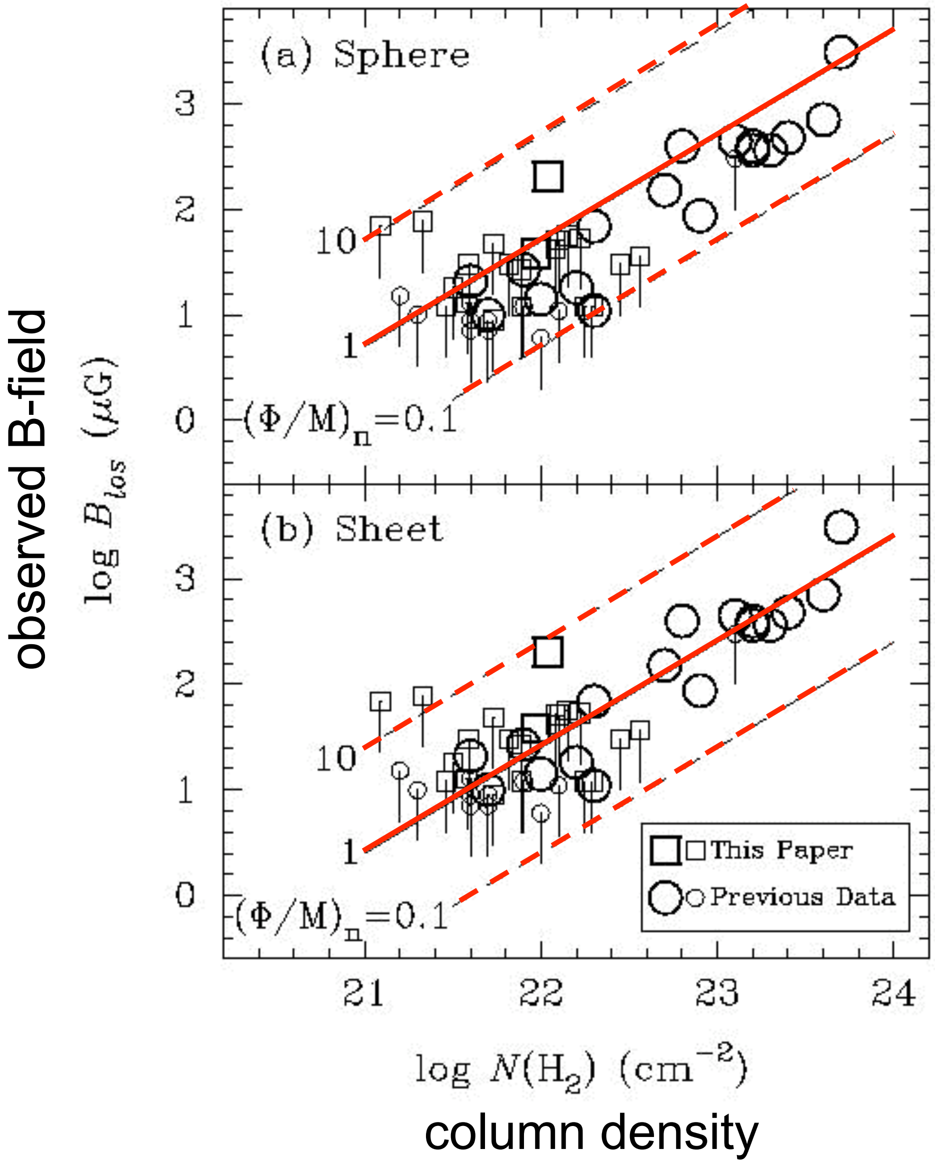
Problems of magnetic SF

- As many prestellar cores as protostellar cores in SF regions
  (e.g. André et al 2002)
- Molecular cloud clumps seem to be 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)
- Most stars form as binaries

Observed B-fields are weak

B versus $N(H_2)$ from *Zeeman measurements*.
(from Bourke et al. 2001)

→ cloud cores are marginally magnetically supercritical**!!!**



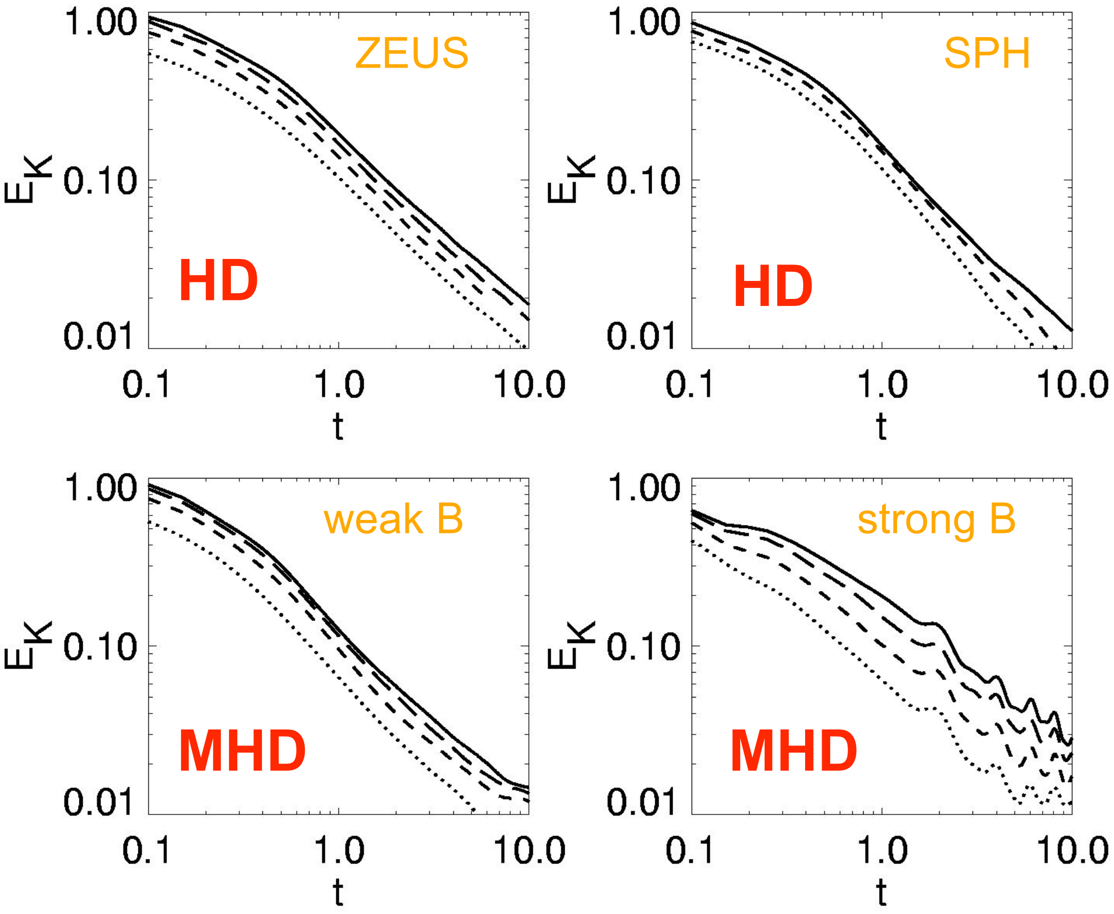
$(\Phi/M)_n > 1$ no collapse

$(\Phi/M)_n < 1$ collapse

Molecular cloud dynamics

- **Timescale problem:** Turbulence *decays* on timescales *comparable to the free-fall time* τ_{ff} ($E \propto t^{-\eta}$ with $\eta \approx 1$).

(Mac Low et al. 1998,
Stone et al. 1998,
Padoan & Nordlund 1999)



(Mac Low, Klessen, Burkert, & Smith, 1998, PRL)

- Magnetic fields (static or wave-like) *cannot* prevent loss of energy.

Problems of magnetic SF

- As many prestellar cores as protostellar cores in SF regions (e.g. André et al 2002)
- Molecular cloud clumps seem to be 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)
- Most stars form as binaries

Gravoturbulent star formation

- more recent suggestions:

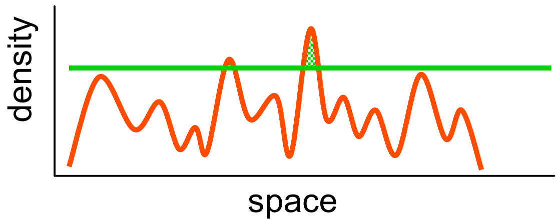
Star formation is controlled
by interplay between
gravity and
supersonic turbulence + B-field !

- dual role of turbulence:
  - *stability on large scales*
  - *initiating collapse on small scales*

- B-field:
  - *adds stability*
    on all scales

(e.g., Larson, 2003, Rep. Prog. Phys, 66, 1651;
or Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125)

Gravoturbulent star formation



- interstellar gas is highly *inhomogeneous*
  - *thermal instability*
  - *gravitational instability*
  - *turbulent compression* (in shocks $\delta\rho/\rho \propto \mathcal{M}^2$; in atomic gas: $\mathcal{M} \approx 1...3$)
- 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 the galaxy
- inside *cold clouds:* turbulence is highly supersonic ($\mathcal{M} \approx 1...20$)
  → *turbulence* creates large density contrast,
  gravity selects for collapse

→ ***GRAVOTUBULENT FRAGMENTATION***

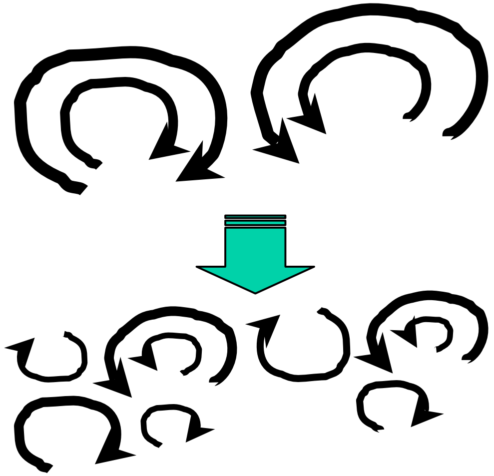
- *turbulent cascade:* local compression *within* a cloud provokes collapse → formation of individual *stars* and *star clusters*

(e.g. Mac Low & Klessen, 2004, Rev. Mod. Phys., 76, 125-194)

turbulence

Properties of turbulence

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



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

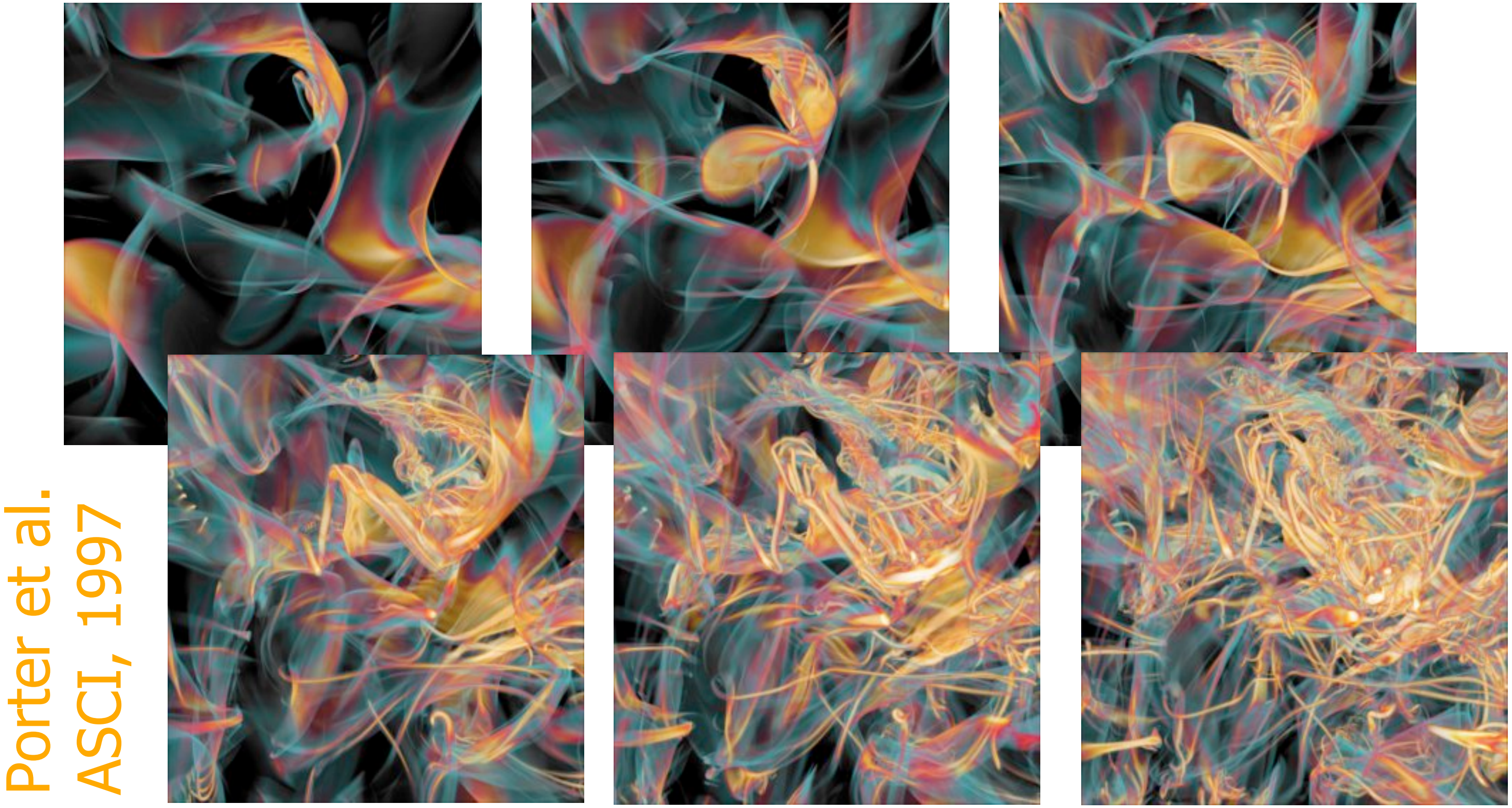
V= typical velocity on scale L, ν = viscosity, Re > 1000

- *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.)

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

Ralf Klessen: IMPRS School, 25.09.2006

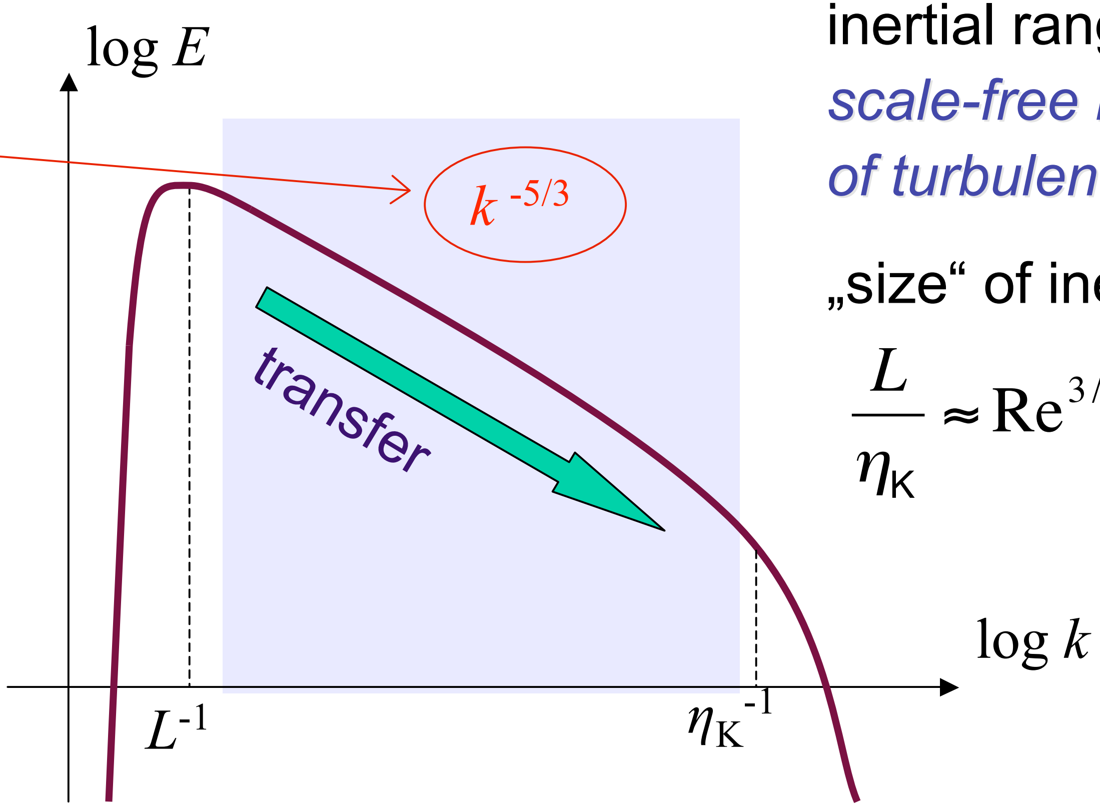
Vortex Formation



Vortices are streched and folded in three dimensions

Turbulent cascade

Kolmogorov (1941) theory
incompressible turbulence



inertial range:
scale-free behavior of turbulence

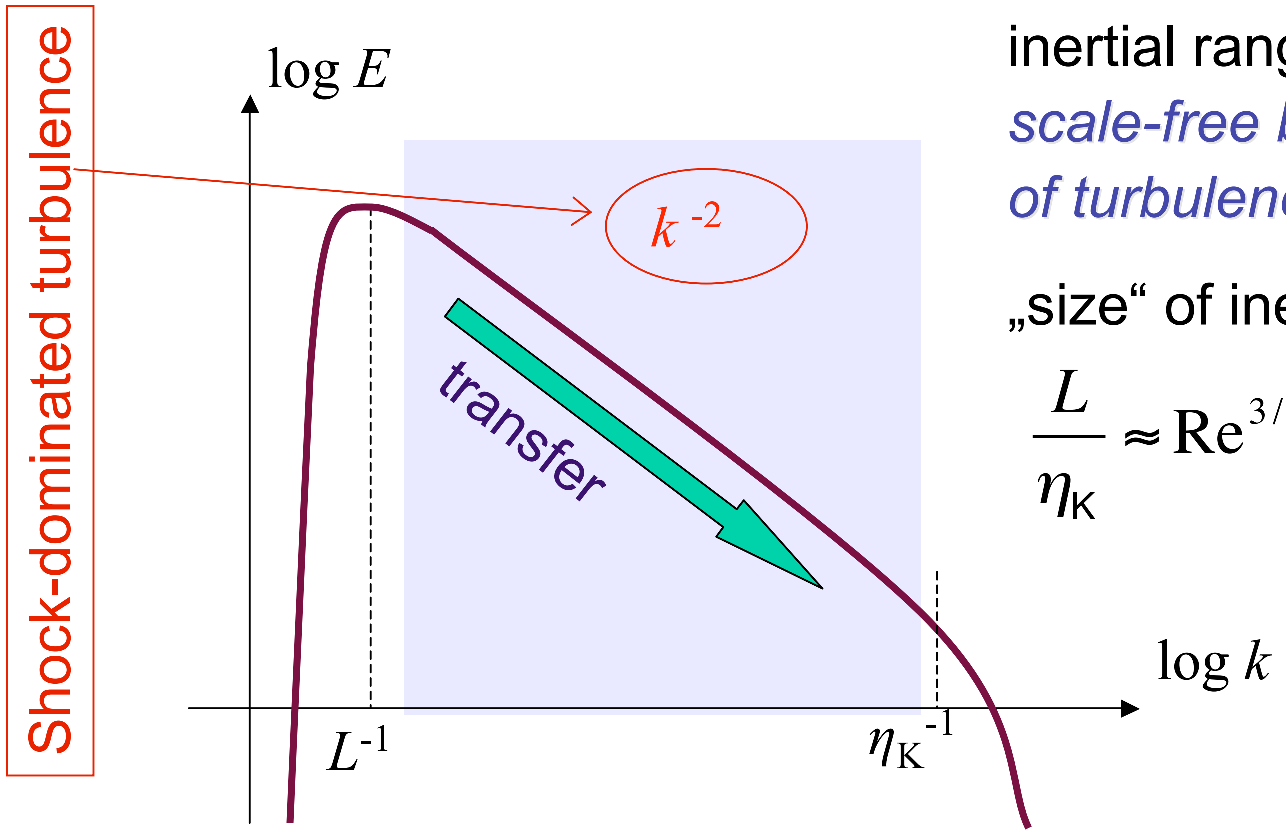
„size“ of inertial range:

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

energy
input
scale

energy
dissipation
scale

Turbulent cascade



inertial range:

scale-free behavior of turbulence

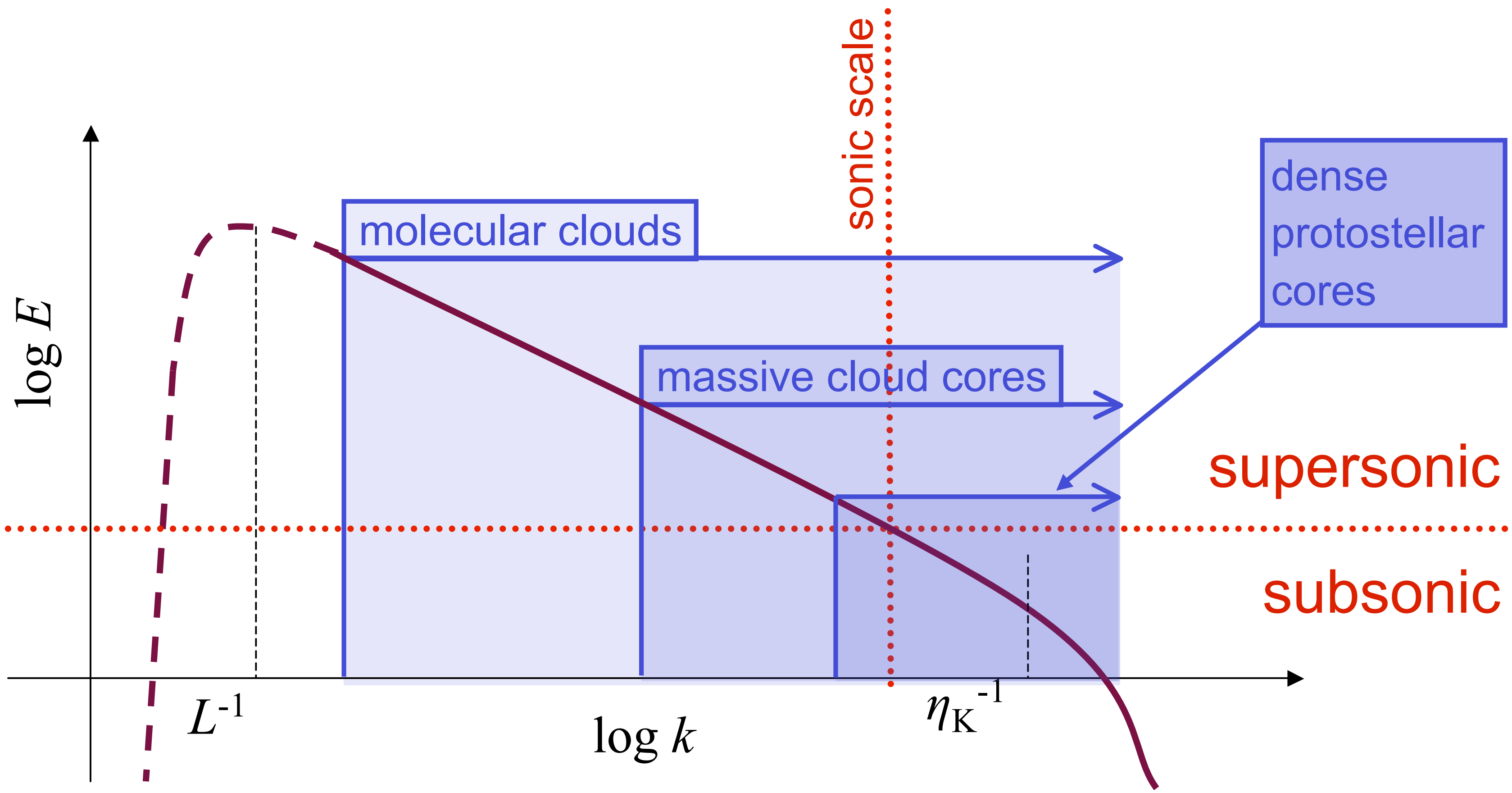
„size“ of inertial range:

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

energy input scale

energy dissipation scale

Turbulent cascade in ISM



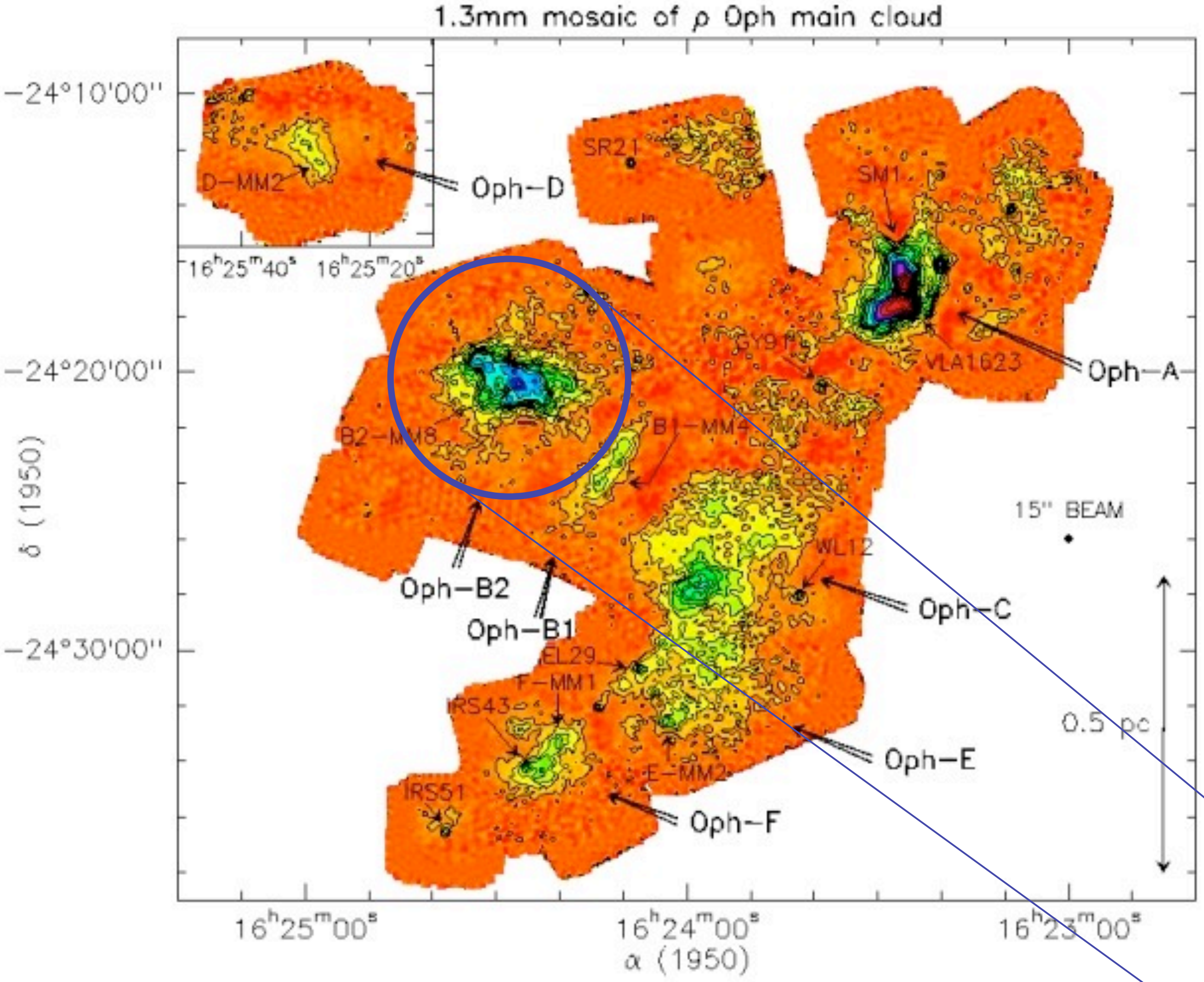
energy source & scale
NOT known
(supernovae, winds,
spiral density waves?)

$\sigma_{rms} \ll 1$ km/s
$\mathcal{M}_{rms} \leq 1$
$L \approx 0.1$ pc

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

scenario

Density structure of MC's



(Motte, André, & Neri 1998)

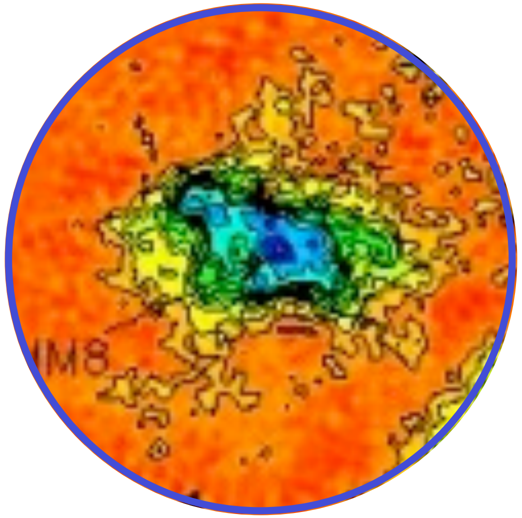
molecular clouds are highly inhomogeneous

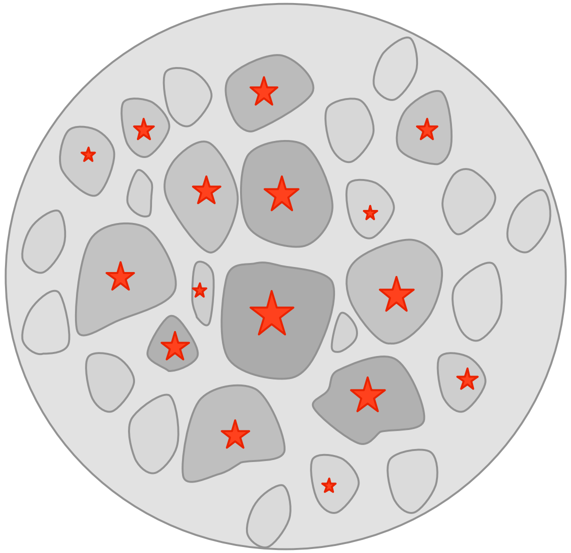
stars form in the densest and coldest parts of the cloud

ρ-Ophiuchus cloud seen in dust emission

let‘s focus on a cloud core like this one

Evolution of cloud cores

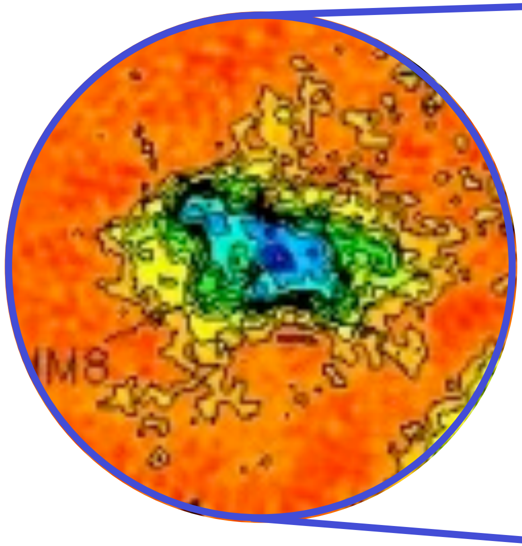


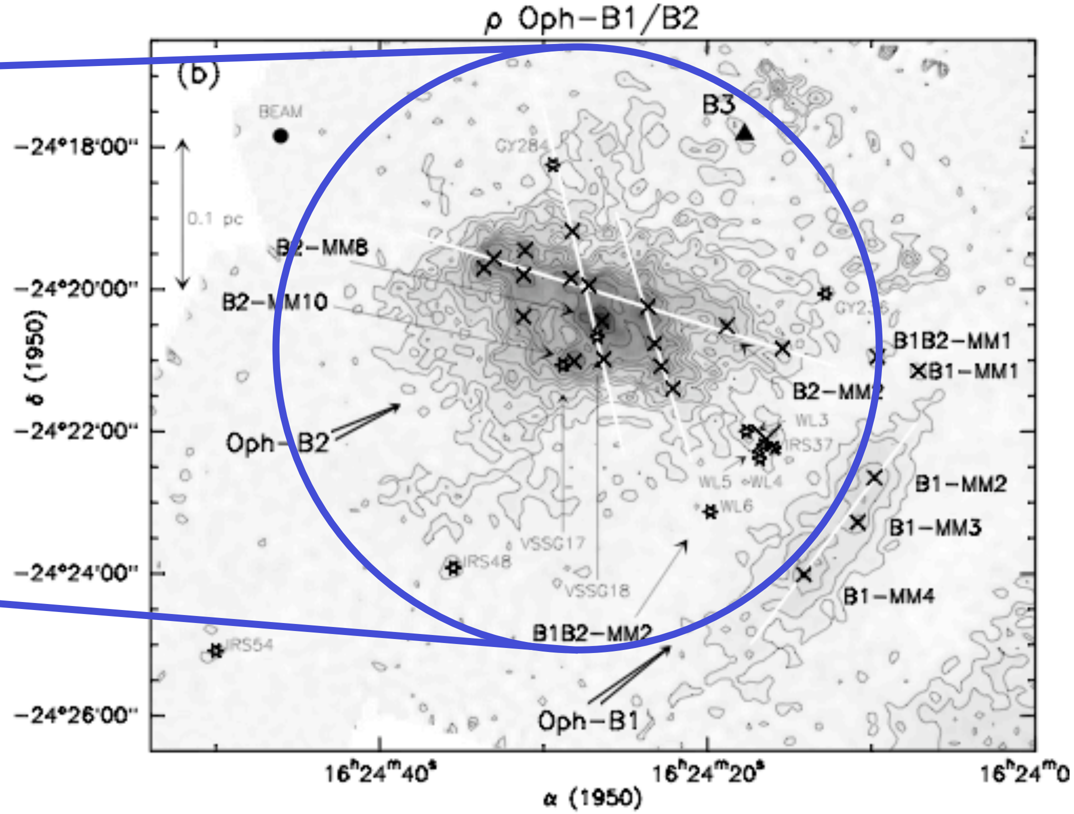


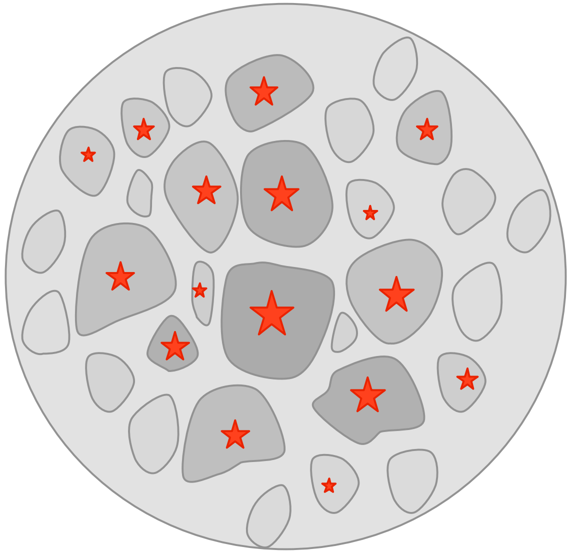
- Does core form single massive star or cluster with mass distribution?

- Turbulent cascade „goes through“ cloud core
  --> NO *scale separation* possible
  --> NO *effective sound speed*
- Turbulence is supersonic!
  --> produces strong density contrasts:
  $\delta\rho/\rho \approx \mathcal{M}^2$
  --> with typical $\mathcal{M} \approx 10$ --> $\delta\rho/\rho \approx 100$!
- many of the shock-generated fluctuations are Jeans unstable and go into collapse
- --> *core breaks up and forms a cluster of stars*

Evolution of cloud cores



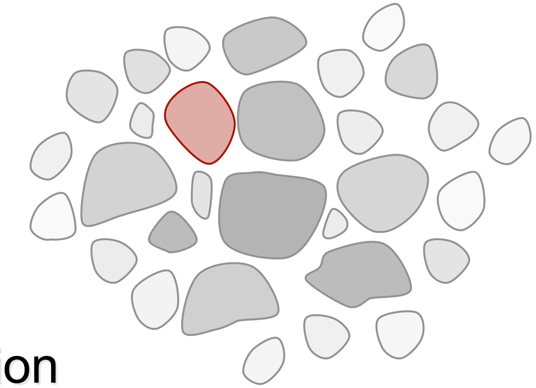




indeed ρ-Oph B1/2 contains several cores ("starless" cores are denoted by ×, cores with embedded protostars by ☆)

(Motte, André, & Neri 1998)

Formation and evolution of cores



- protostellar cloud cores form at the *stagnation points* of *convergent turbulent flows*
- if $M > M_{\mathrm{Jeans}} \propto \rho^{-1/2}\,T^{3/2}$: collapse and star formation
- if $M < M_{\mathrm{Jeans}} \propto \rho^{-1/2}\,T^{3/2}$: reexpansion after external compression fades away

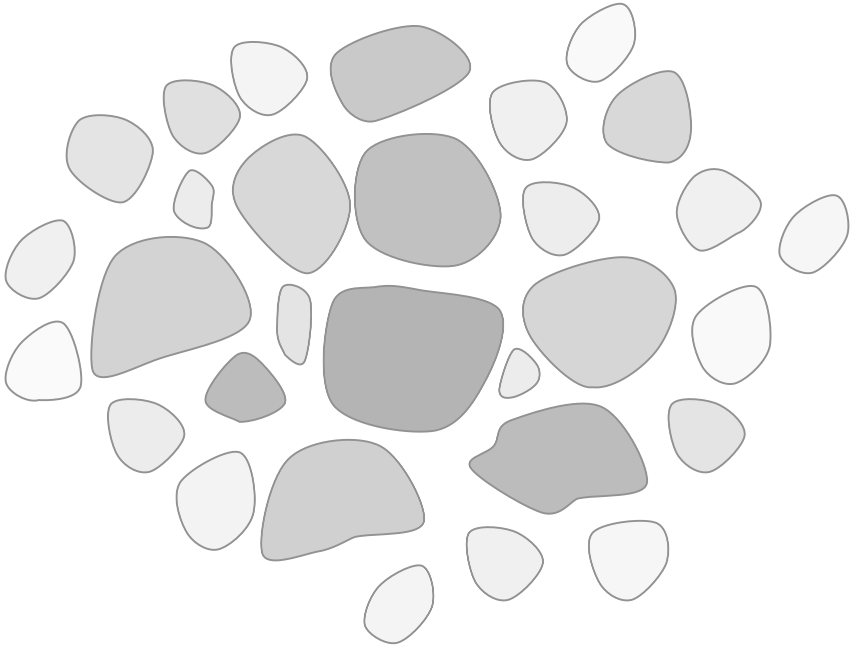
(e.g. Vazquez-Semadeni et al 2005)

- typical timescales: $t \approx 10^4 \ldots 10^5$ yr
- because *turbulent* ambipolar diffusion time is *short*, this time estimate still holds for the presence of magnetic fields, in *magnetically critical cores*

(e.g. Fatuzzo & Adams 2002, Heitsch et al. 2004)

Formation and evolution of cores

What happens to distribution of cloud cores?



Two exteme cases:

(1) turbulence dominates energy budget: $\alpha = E_{kin}/|E_{pot}| > 1$

--> individual cores do *not* interact

--> *collapse* of *individual* cores dominates *stellar mass growth*

--> *loose cluster of low-mass stars*

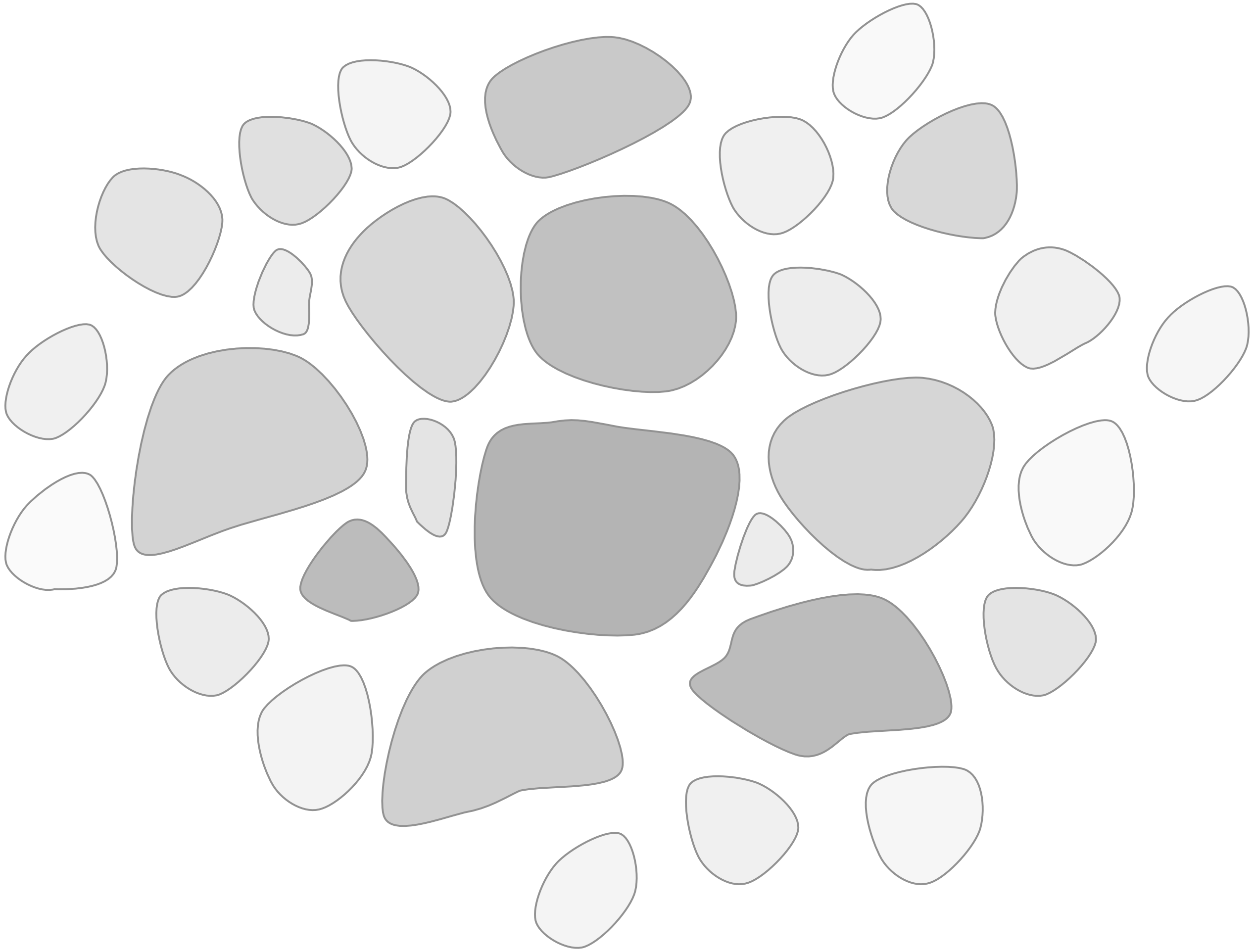
(2) turbulence decays, i.e. gravity dominates: $\alpha = E_{kin}/|E_{pot}| < 1$

--> *global contraction*

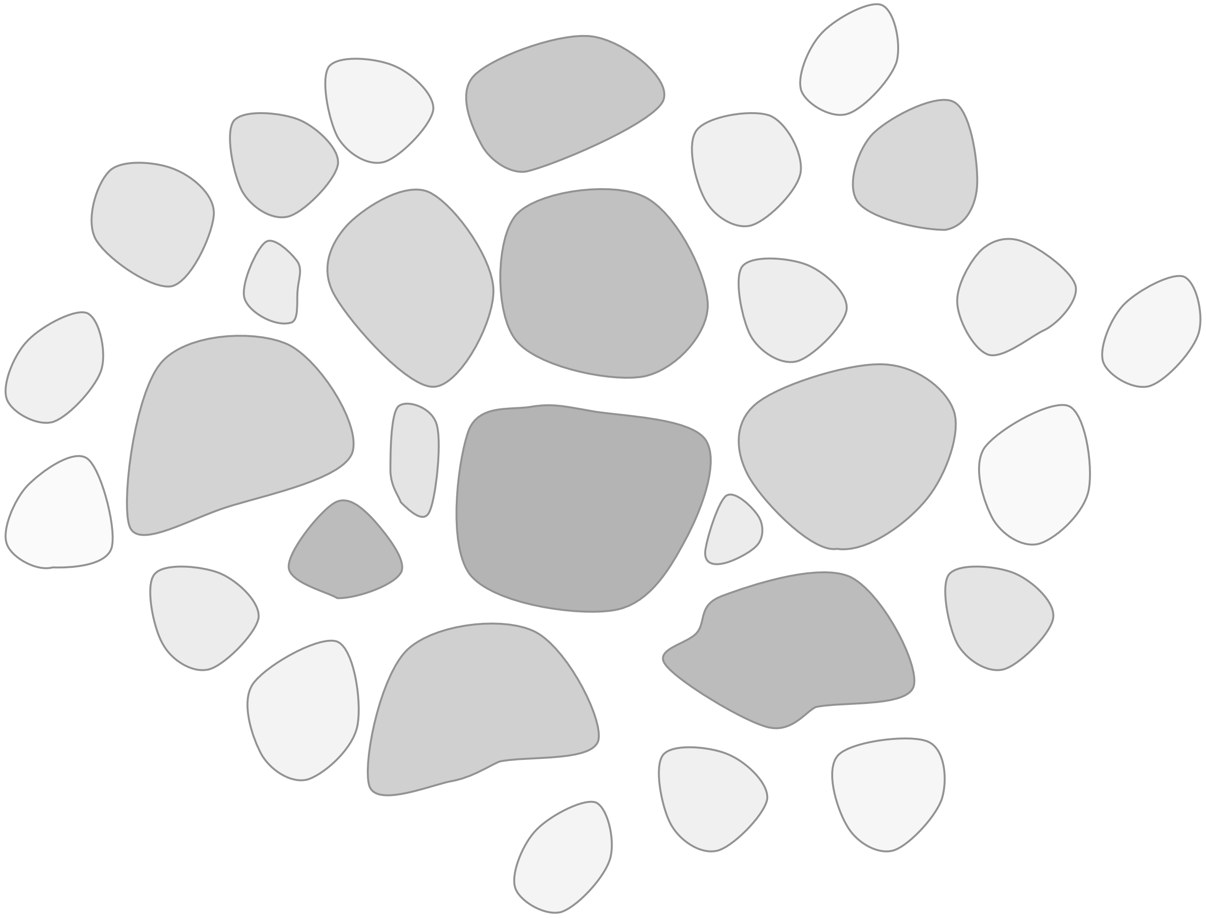
--> core do *interact* while collapsing

--> *competition* influences *mass growth*

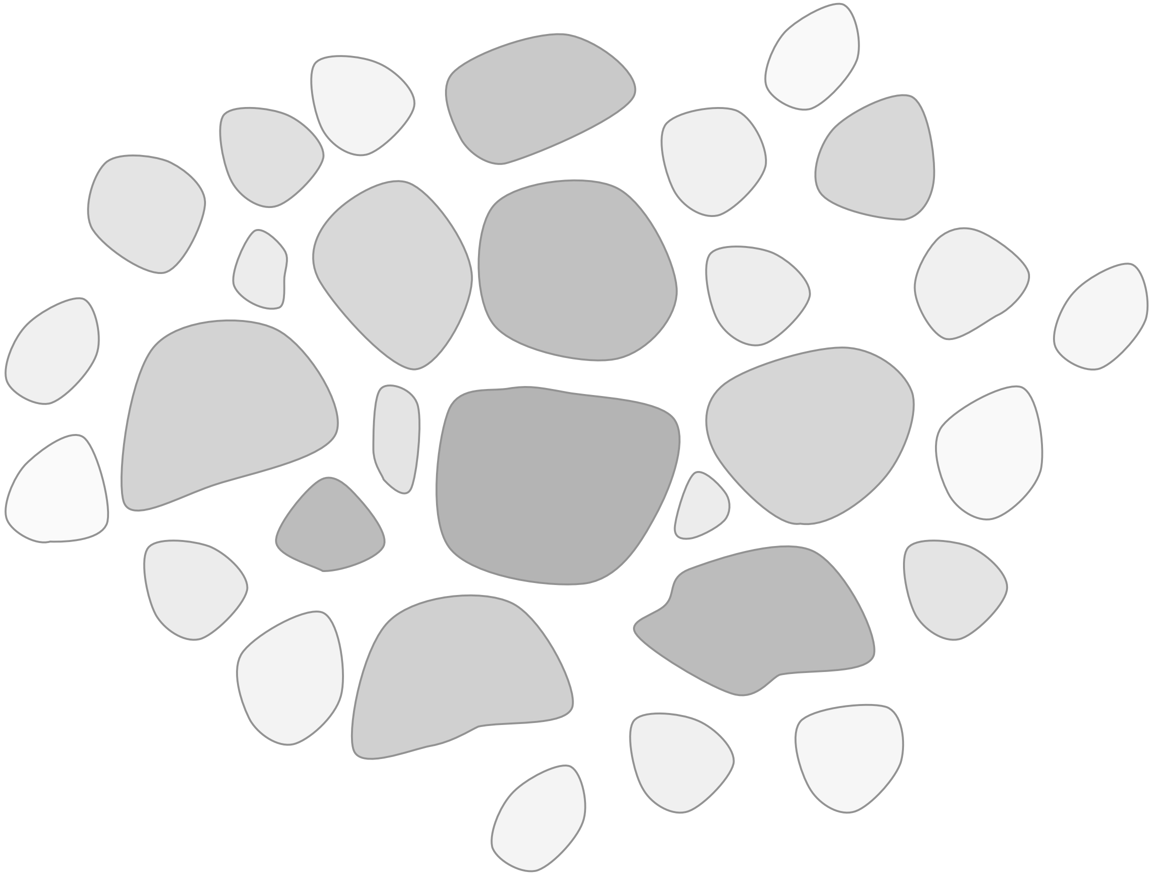
--> *dense cluster with high-mass stars*



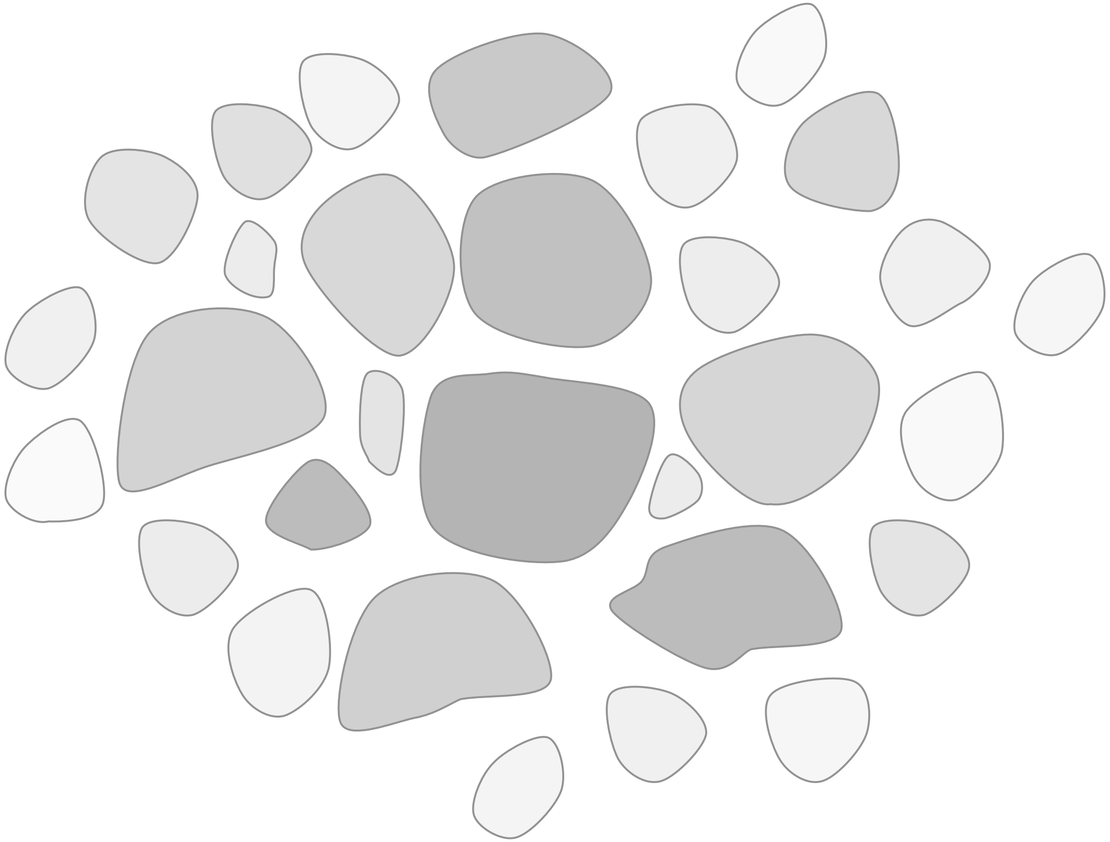
turbulence creates a hierarchy of clumps



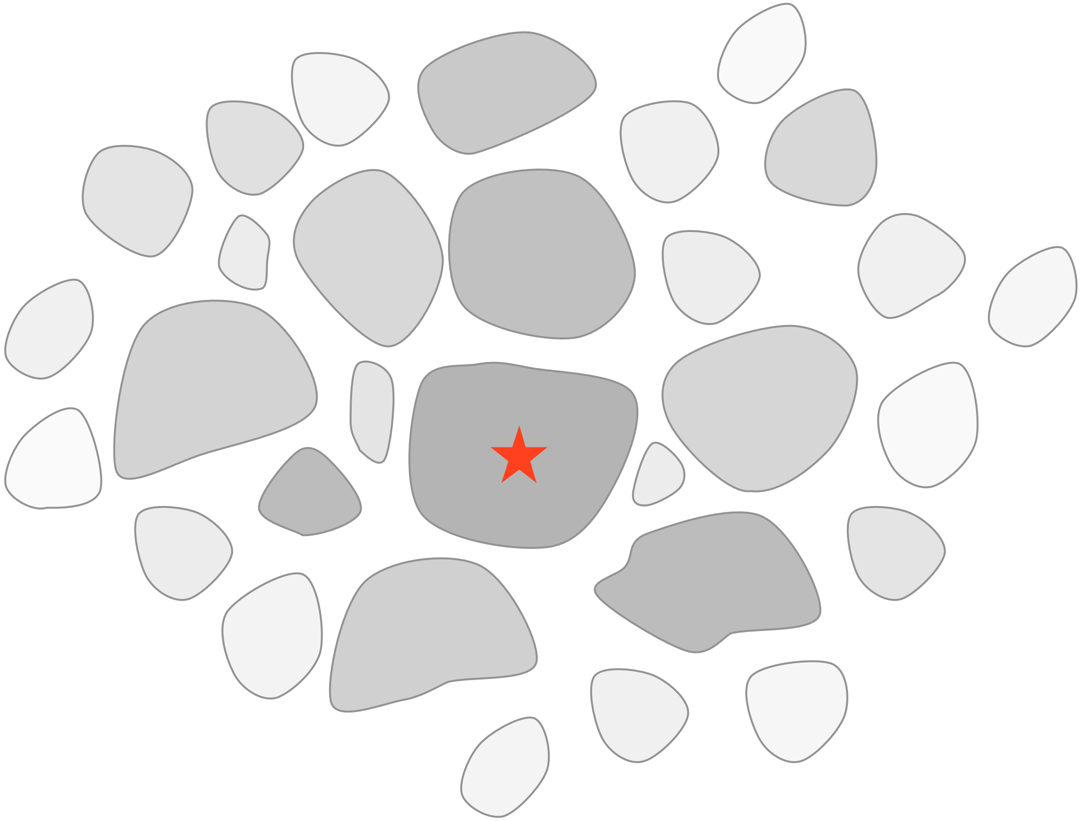
as turbulence decays locally, contraction sets in



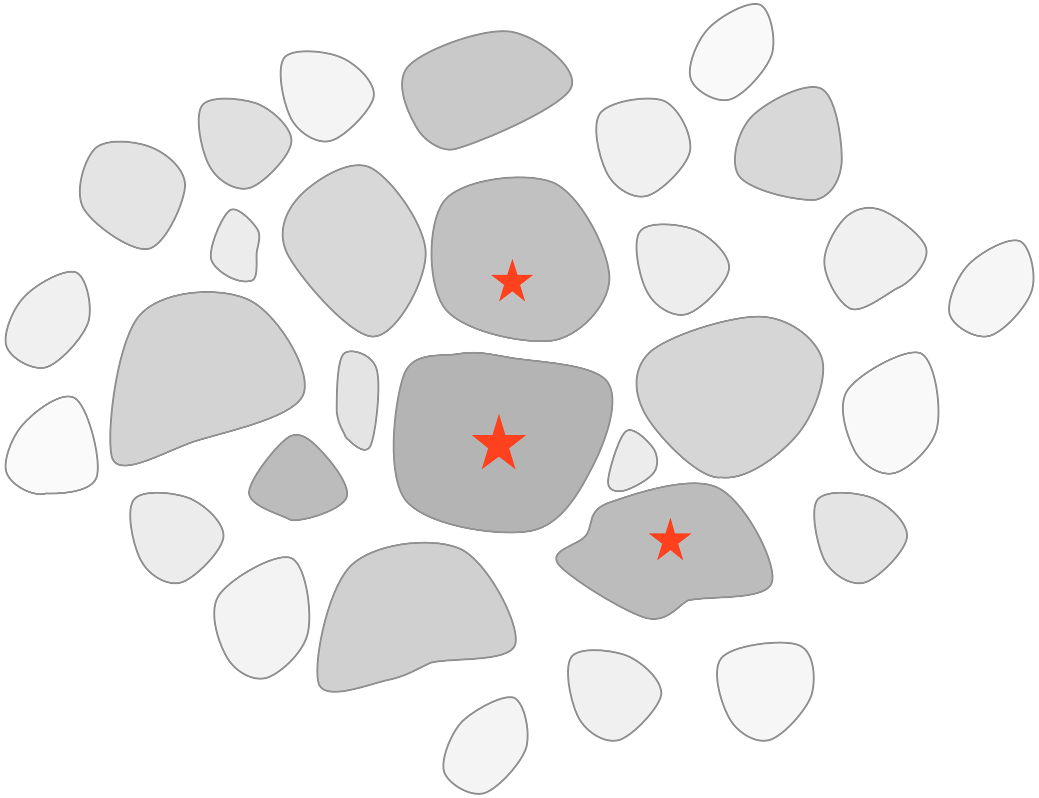
as turbulence decays locally, contraction sets in



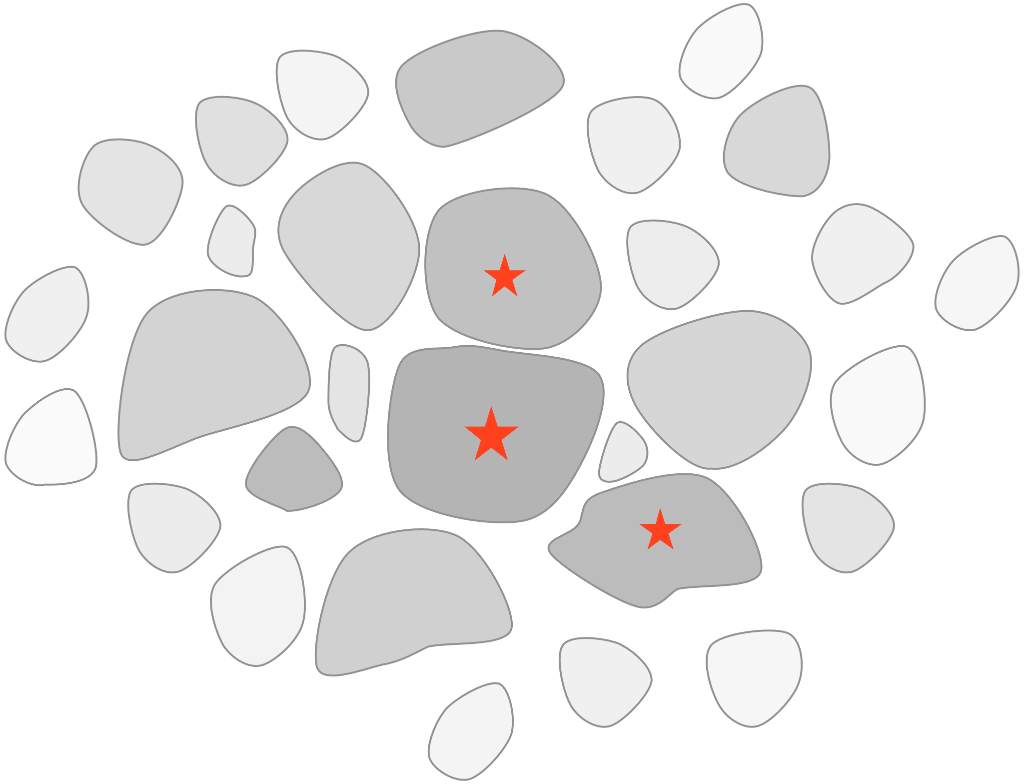
while region contracts, individual clumps collapse to form stars



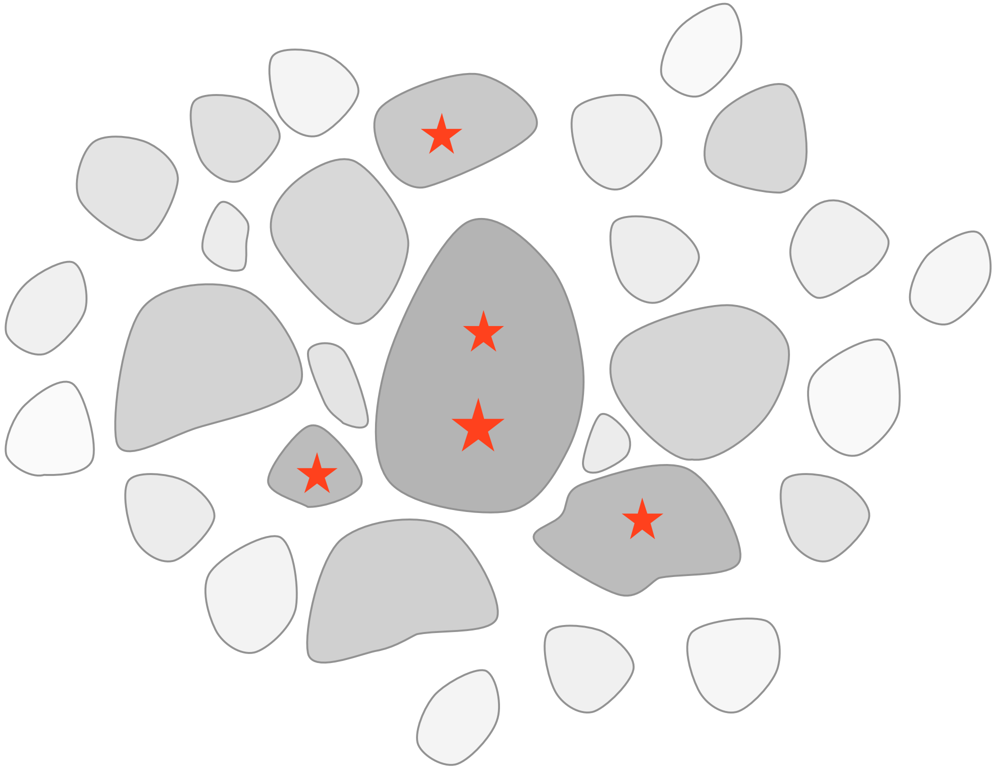
while region contracts, individual clumps collapse to form stars



individual clumps collapse to form stars

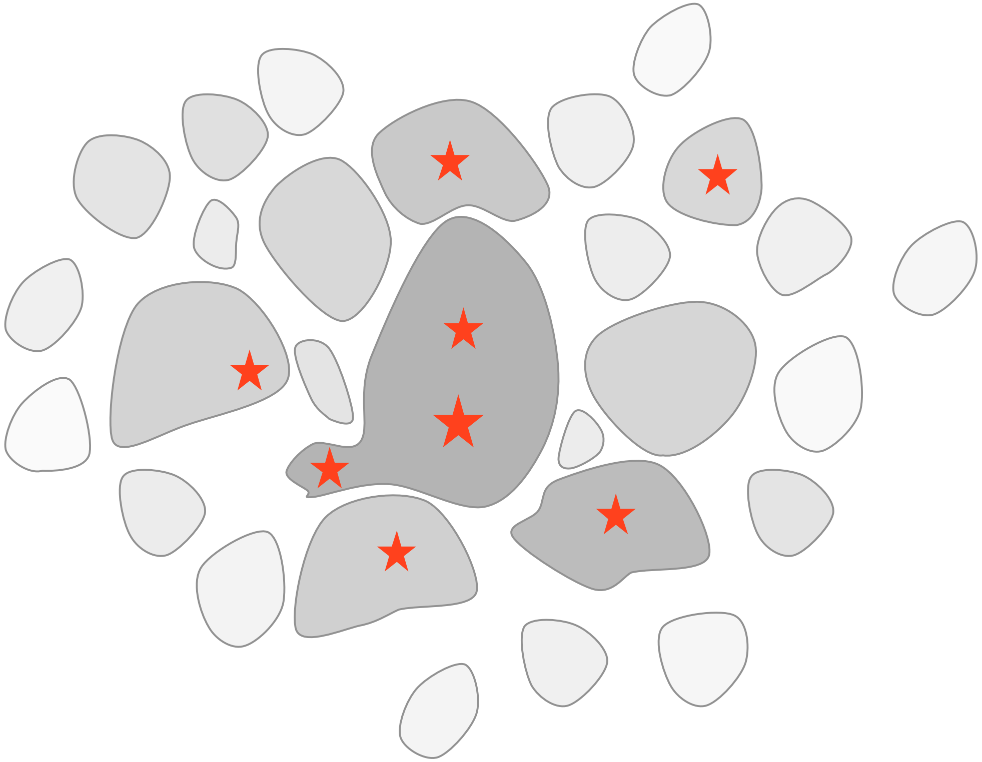


individual clumps collapse to form stars

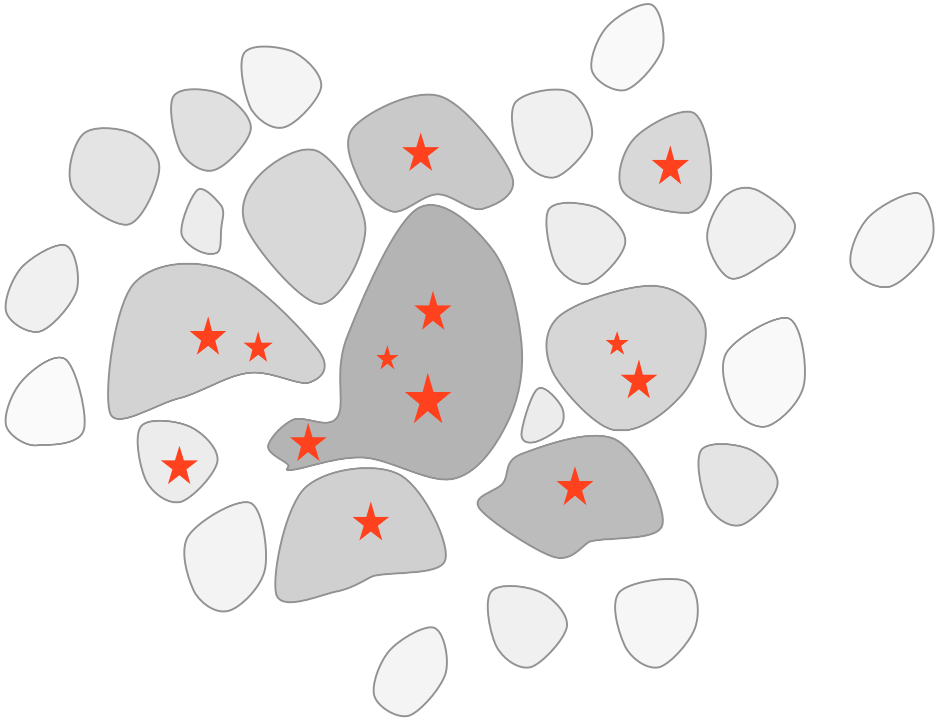


$\alpha = E_{kin}/|E_{pot}| < 1$

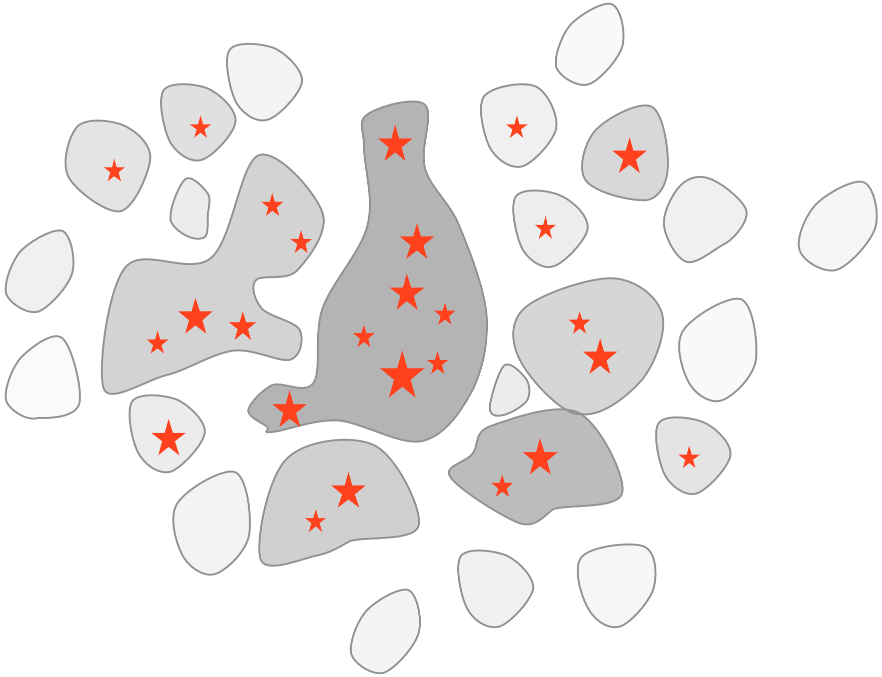
in *dense clusters*, clumps may merge while collapsing
--> then contain multiple protostars



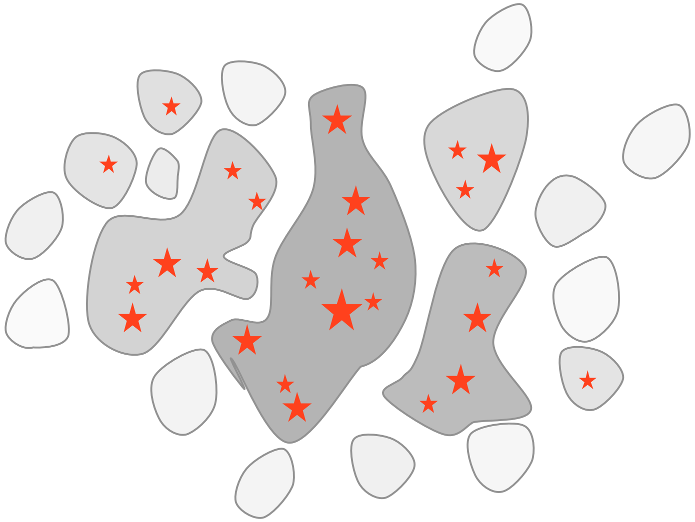
in *dense clusters*, clumps may merge while collapsing
--> then contain multiple protostars



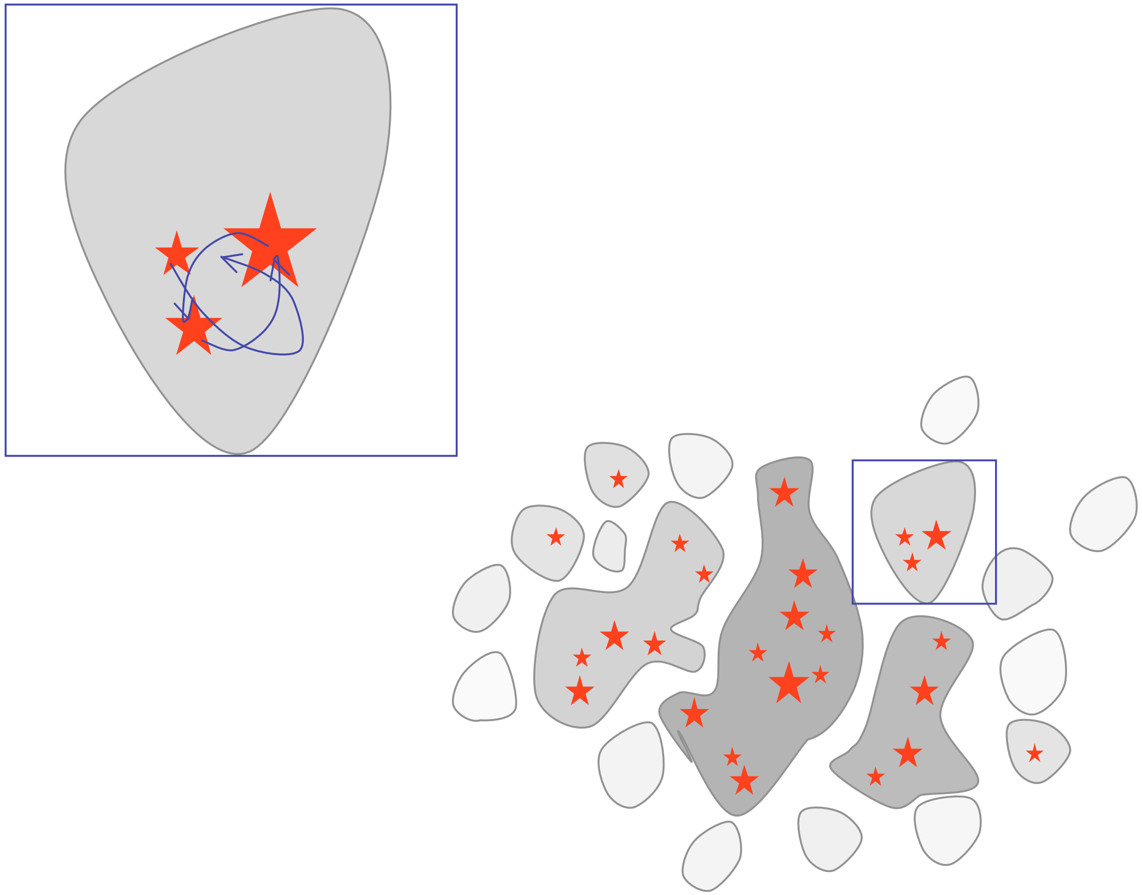
in *dense clusters*, clumps may merge while collapsing
--> then contain multiple protostars



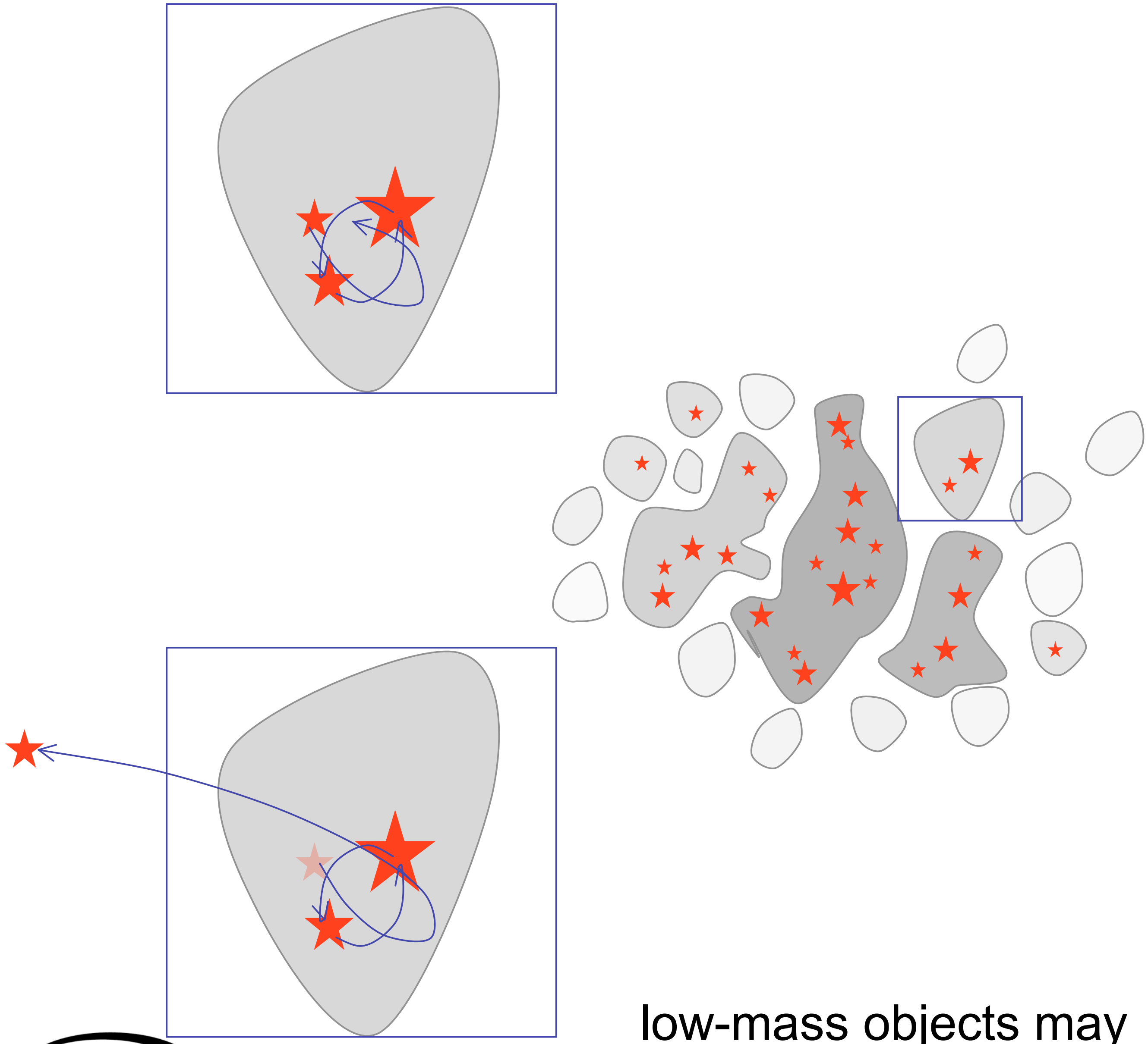
in *dense clusters*, competitive mass growth becomes important



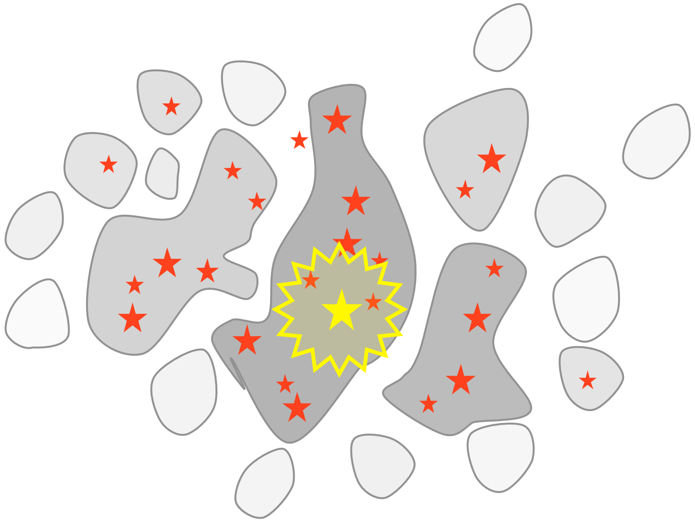
in *dense clusters*, competitive mass growth becomes important



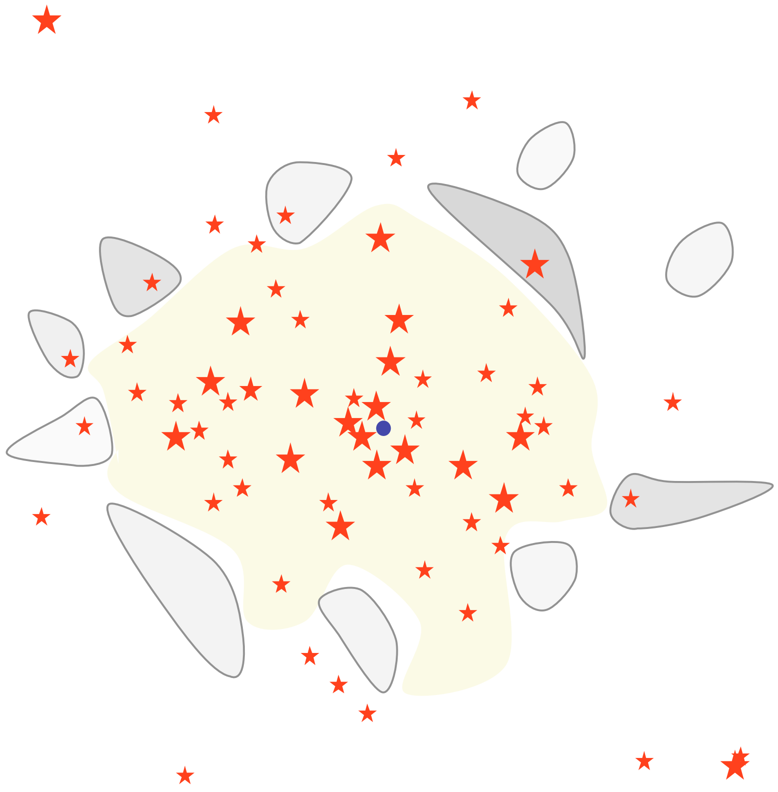
in *dense clusters*, *N*-body effects influence mass growth



low-mass objects may
become ejected --> accretion stops



feedback terminates star formation

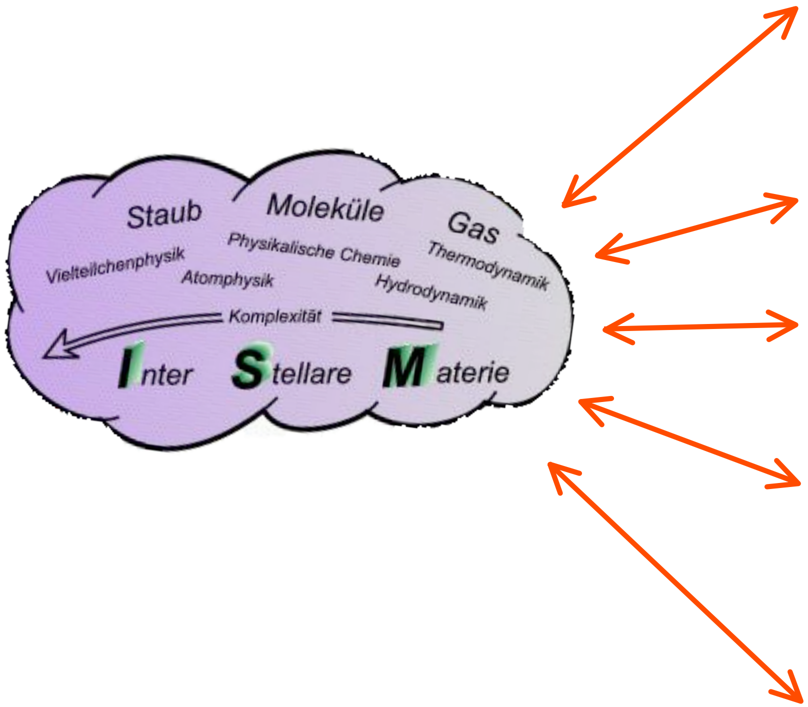


result: *star cluster*, possibly with HII region

quantitative approach

what do we need?

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)

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?

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

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?

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

chemistry (gas + dust, heating + cooling)

radiation (continuum + lines)

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

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?

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)

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

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)

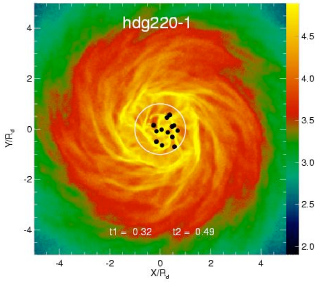
stellar dynamics
(collisional: star clusters,
collisionless: galaxies, DM)

stellar evolution
(feedback: radiation, winds, SN)

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

predictions

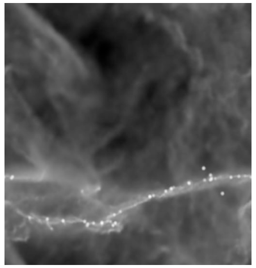
Three examples



modeling star formation in galactic disk

(hydrodynamics, stellar dynamics)

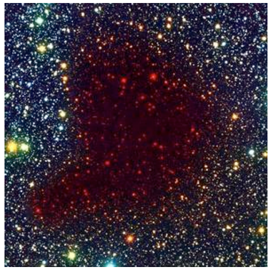
(Schmidt law, star-formation history, relation between global dynamics and SF)

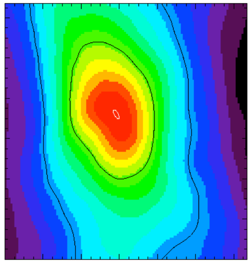


molecular cloud formation

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

(molecular cloud dynamics, star cluster formation)



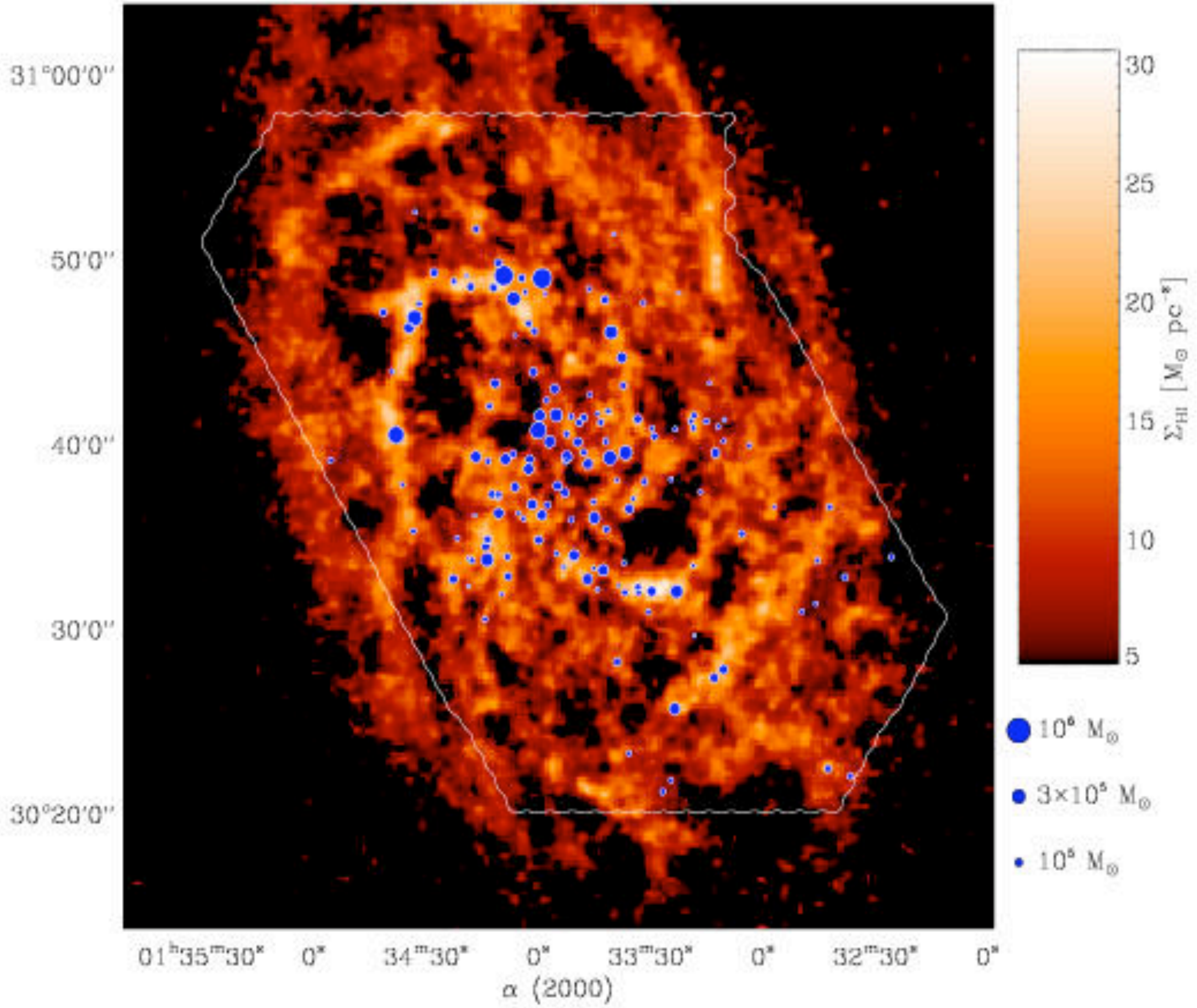


modeling properties of prestellar cores

(MHD, chemistry, radiation)

(initial conditions of star formation, IMF, multiplicity, planet formation, etc.)

Correlation between H_2 and HI



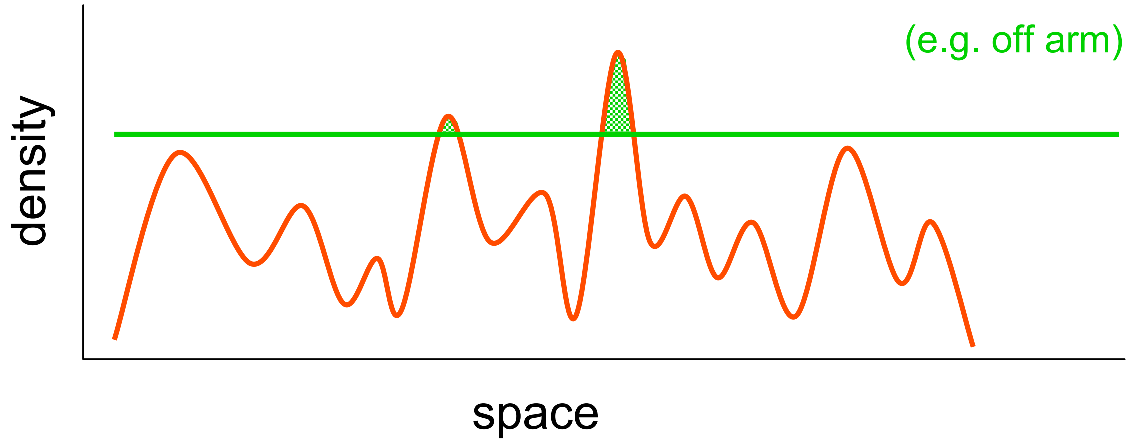
Compare H_2 - HI in M33:

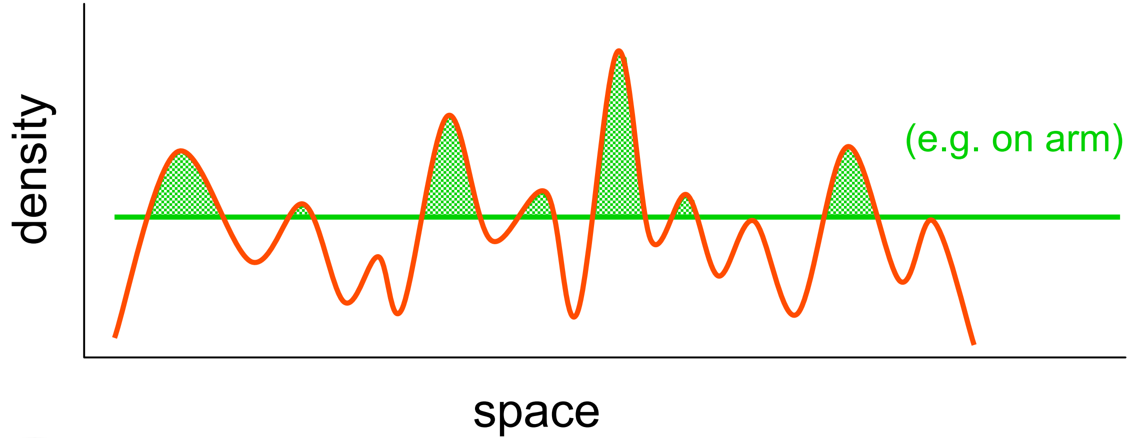
- H_2: BIMA-SONG Survey, see Blitz et al.
- HI: Observations with Westerbork Radio T.

H_2 clouds are seen in regions of high HI density (in spiral arms and filaments)

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

Correlation with large-scale perturbations





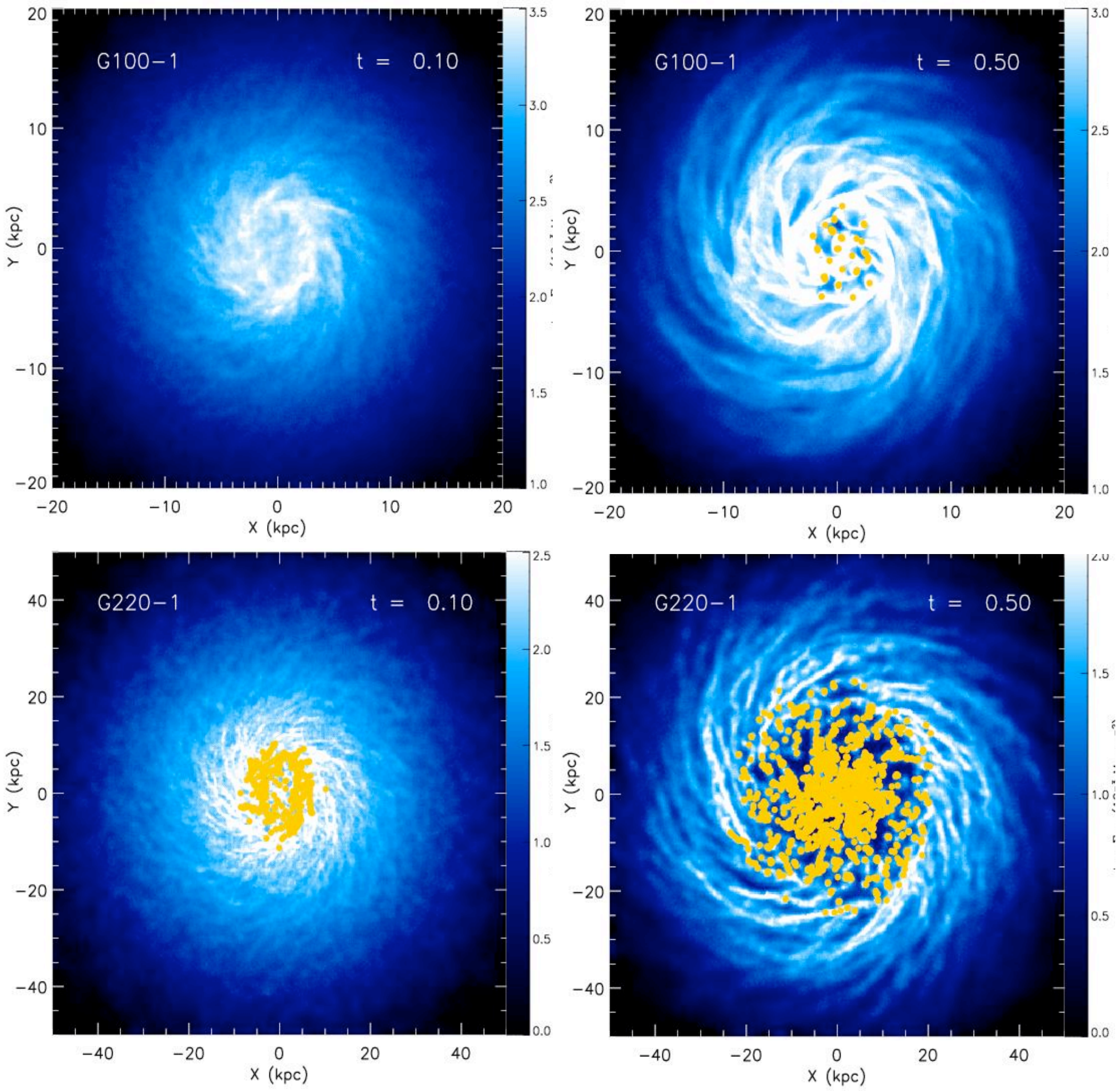
density/temperature fluctuations in warm atomar ISM are caused by *thermal/gravitational instability* and/or *supersonic turbulence*

some fluctuations are *dense* enough to *form* H_2 within "*reasonable time*"

→ *molecular cloud*

external perturbations (i.e. potential changes) *increase* likelihood

Modeling galactic SF



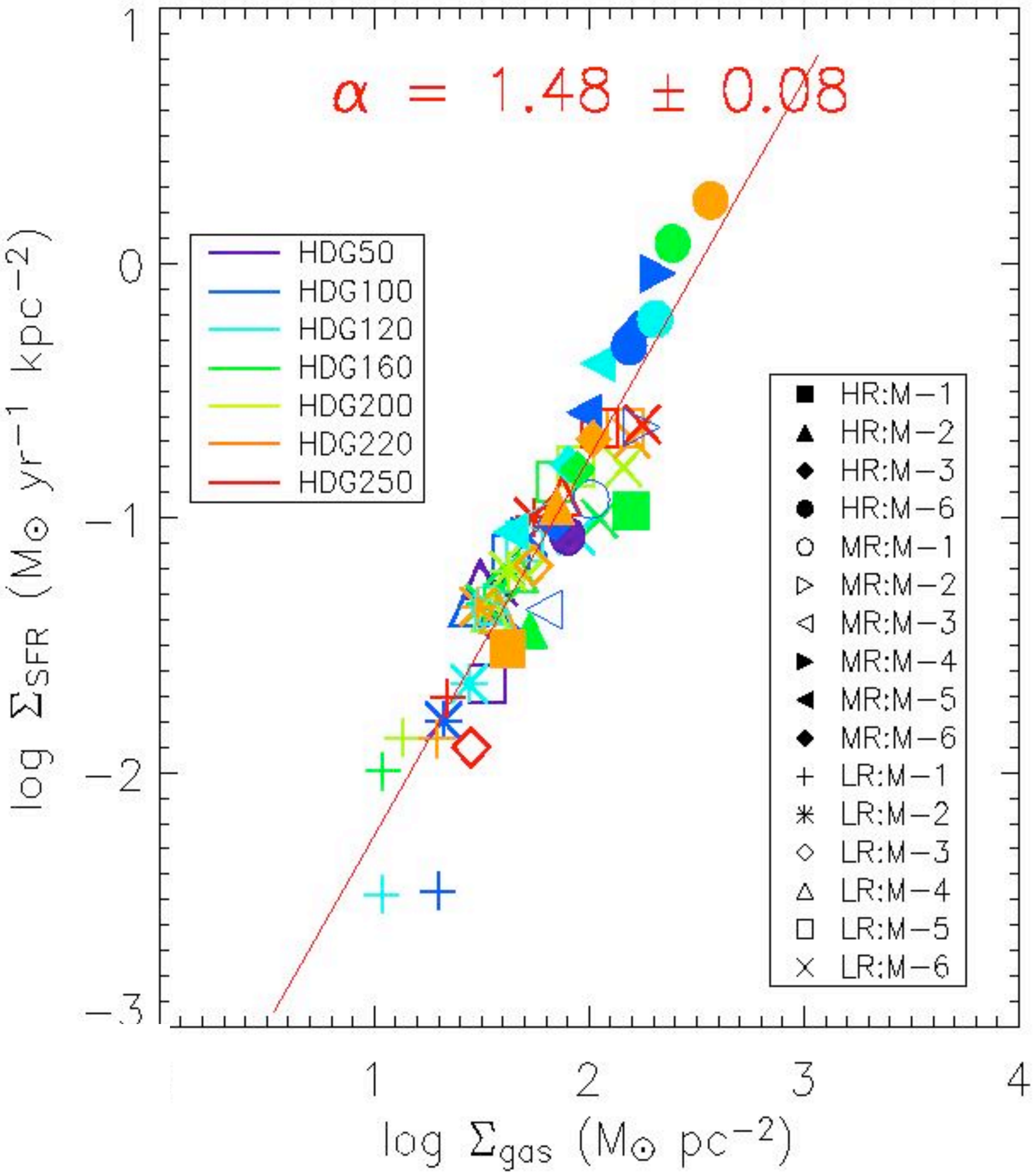
(Li et al 2005, 2006)

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)

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

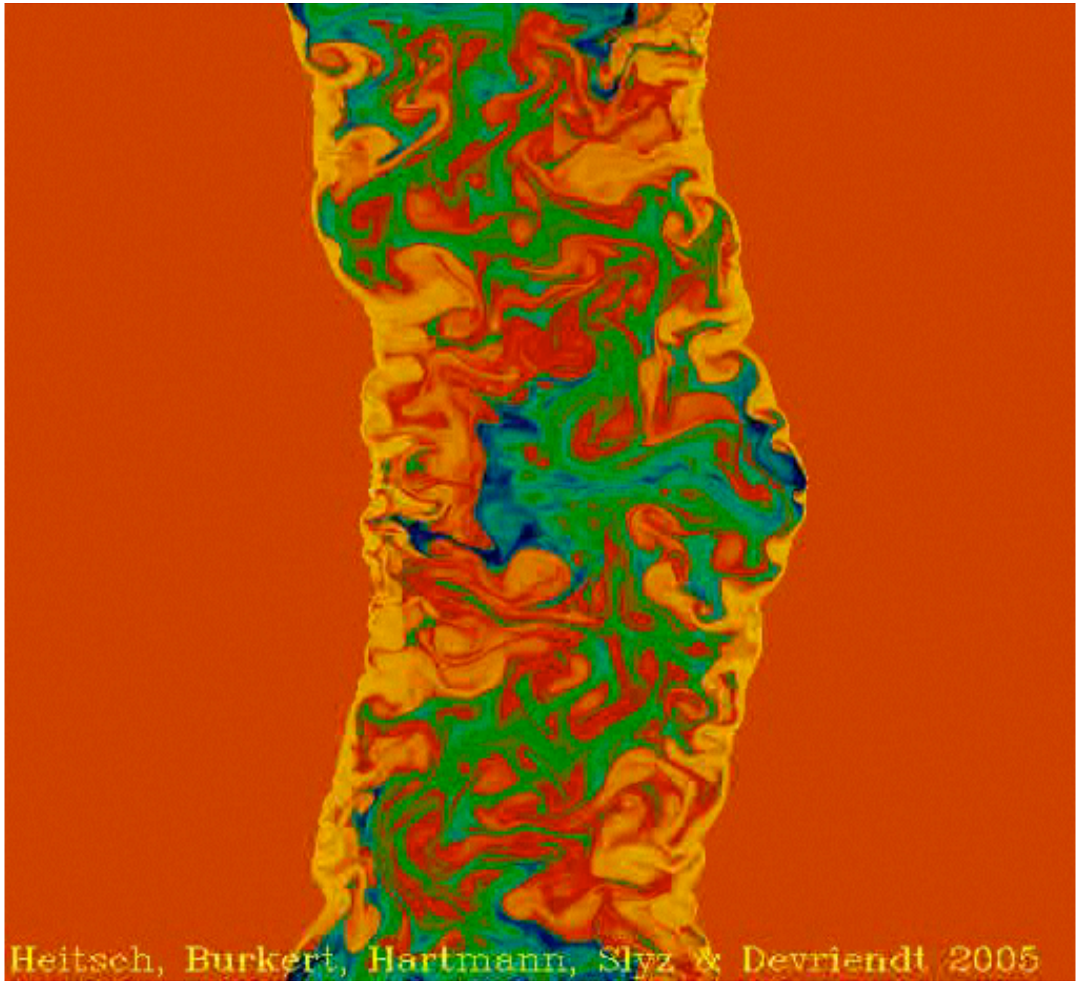
(Li et al 2005, 2006)

Molecular cloud formation

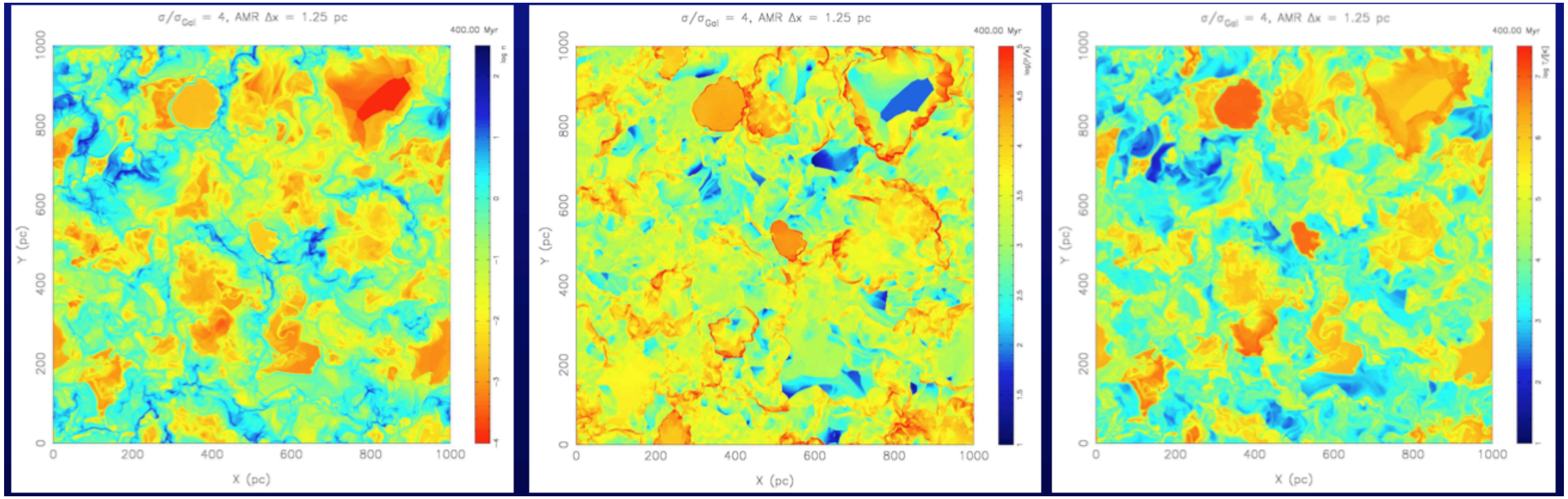
... in *convergent large-scale flows*

... setting up the *turbulent cascade*

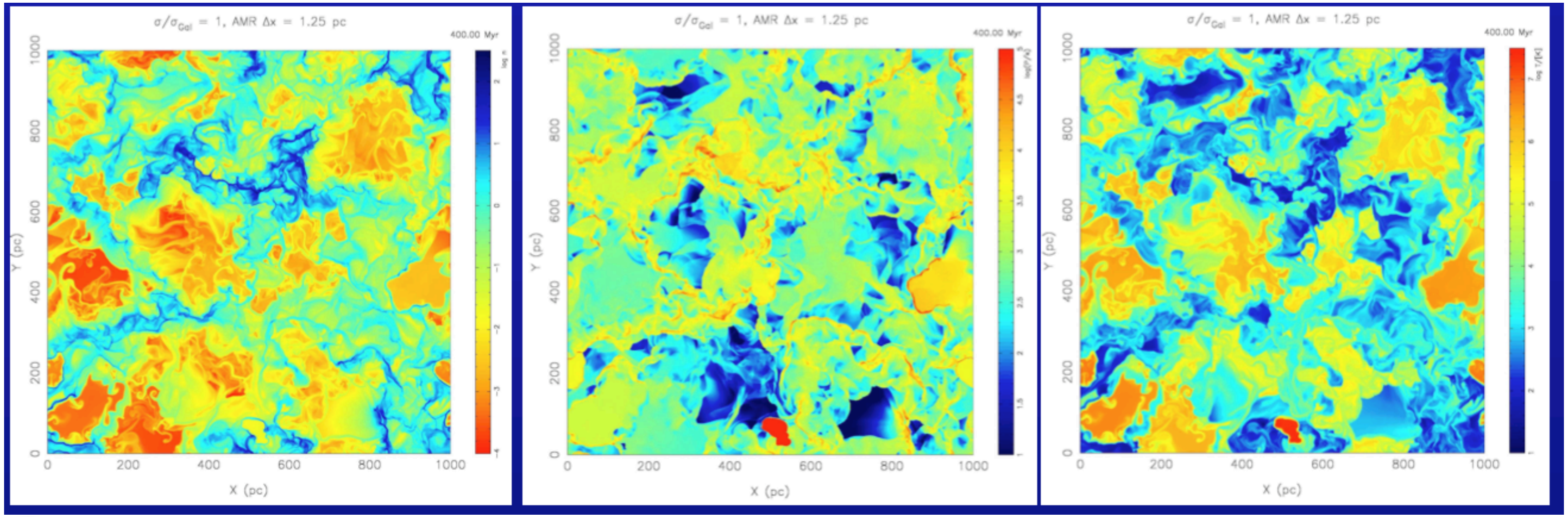
- Mach 3 colliding flow
- Vishniac instability + thermal instability
- compressed sheet *breaks up* and builds up *cold, high-density* „blobs“ of gas
- --> *molecular cloud formation*
- cold cloud motions correspond to supersonic turbulence



(e.g. Koyama & Inutsuka 2002, Heitsch et al., 2005, Vazquez-Semadeni et al. 2004)



n P/k T



Zentrum für Astronomie Heidelberg
ARI+ITA+LSW

(de Avillez & Breitschwerdt)

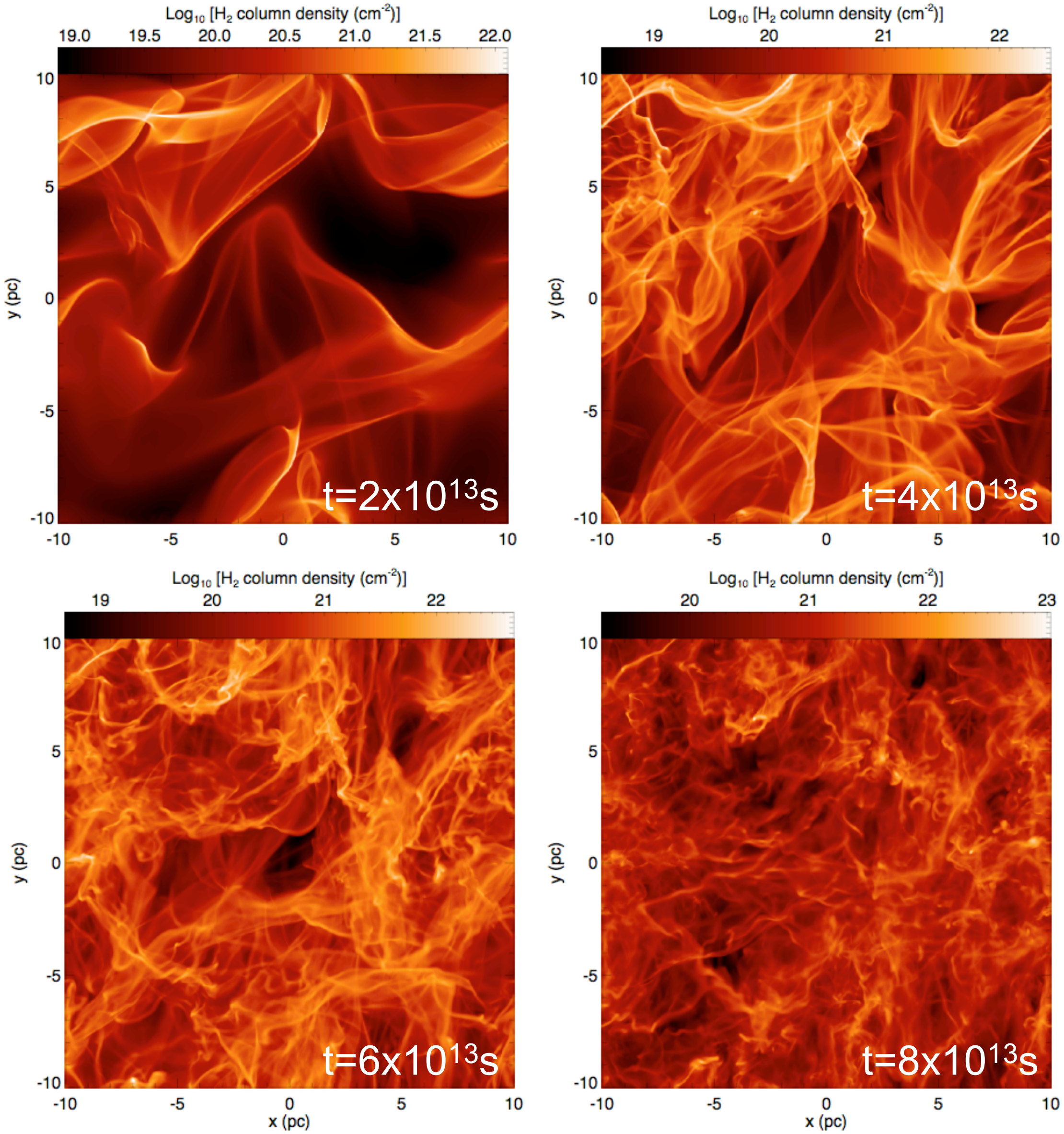
ISM: transition HI to H_2

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

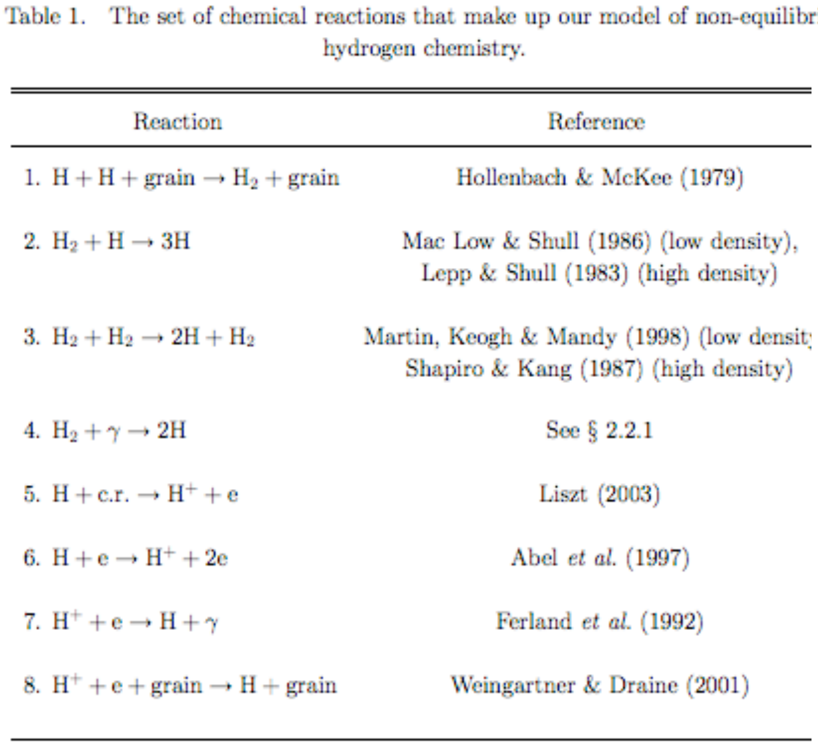


Table 1. The set of chemical reactions that make up our model of non-equilibrium hydrogen chemistry.

Reaction	Reference
1. $H + H + \mathrm{grain} \rightarrow H_2 + \mathrm{grain}$	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. $H + \mathrm{c.r.} \rightarrow H^+ + e$	Liszt (2003)
6. $H + e \rightarrow H^+ + 2e$	Abel *et al.* (1997)
7. $H^+ + e \rightarrow H + \gamma$	Ferland *et al.* (1992)
8. $H^+ + e + \mathrm{grain} \rightarrow H + \mathrm{grain}$	Weingartner & Draine (2001)

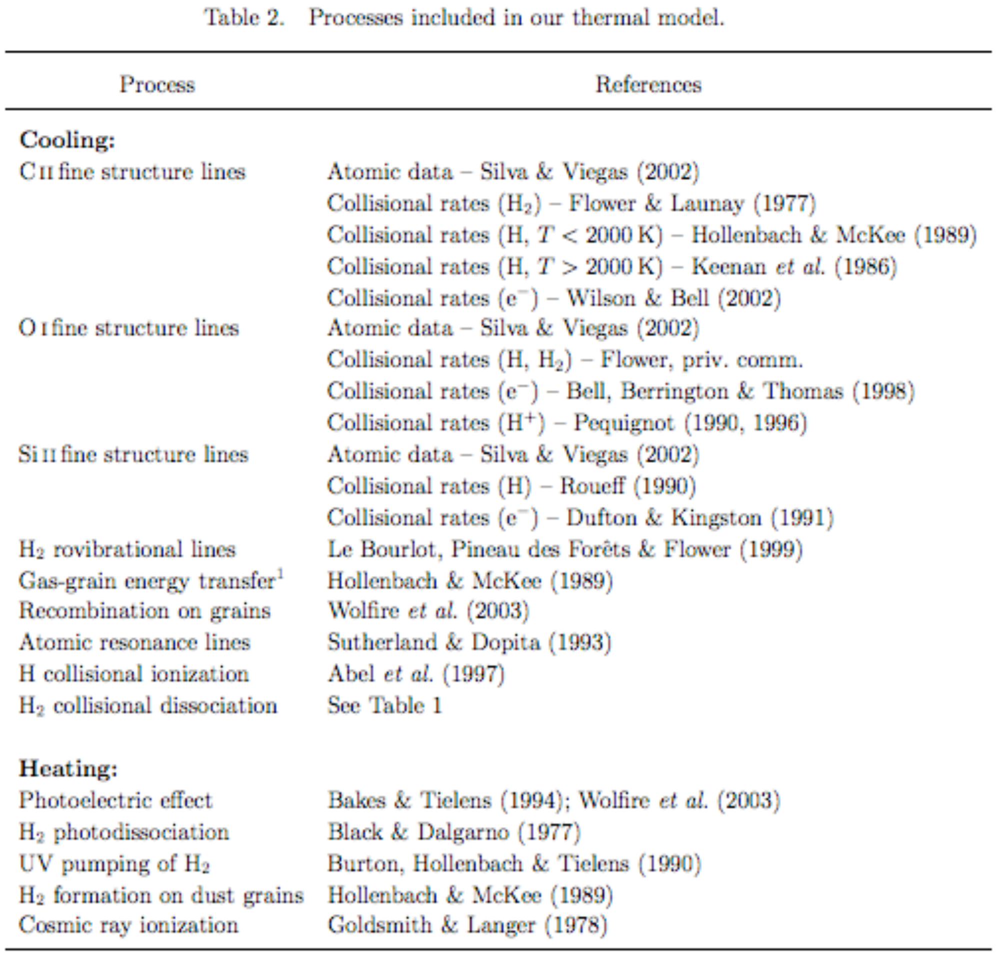


Table 2. Processes included in our thermal model.

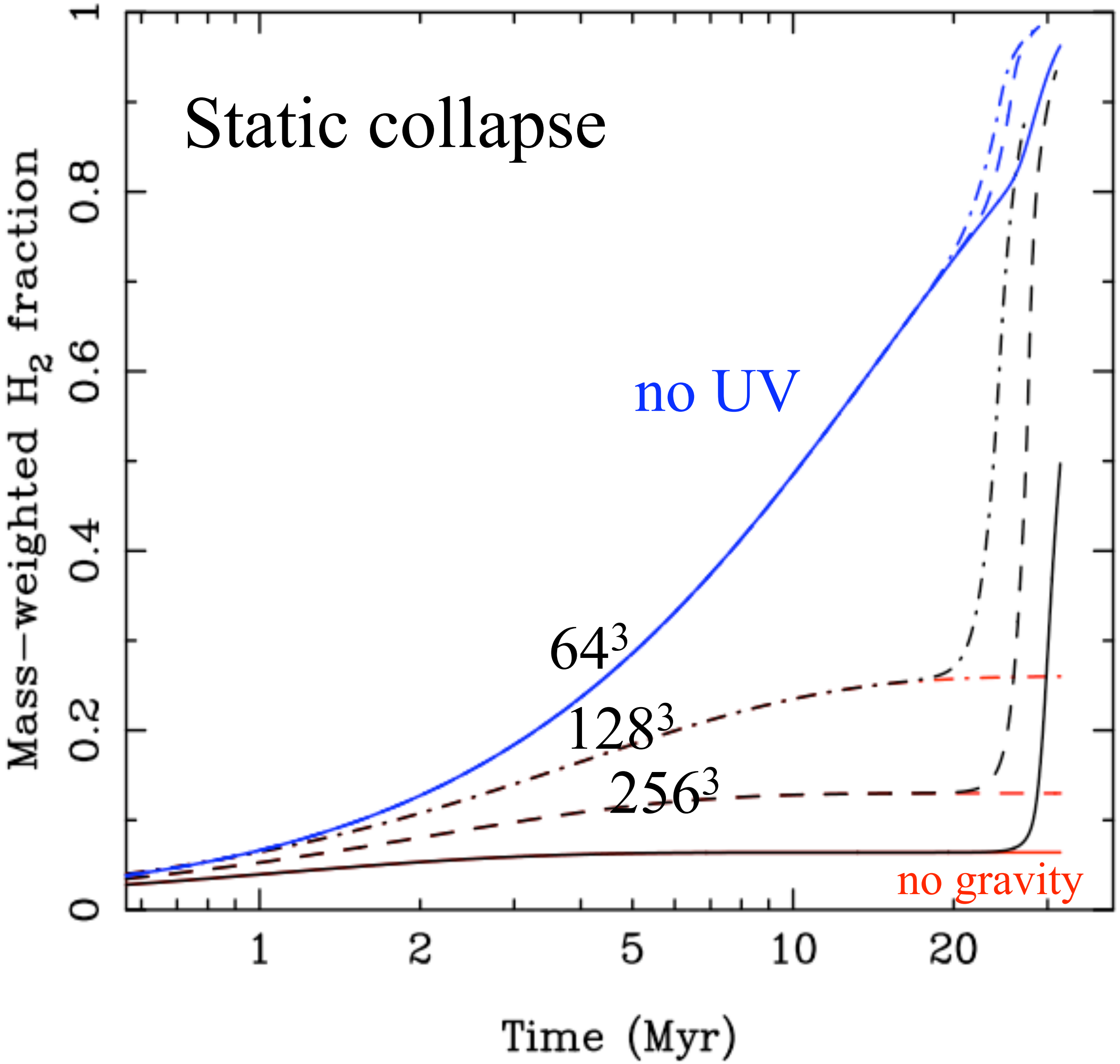
Process	References
Cooling:	
C II fine structure lines	Atomic data – Silva & Viegas (2002)
	Collisional rates (H_2) – Flower & Launay (1977)
	Collisional rates (H, $T < 2000$ K) – Hollenbach & McKee (1989)
	Collisional rates (H, $T > 2000$ K) – Keenan *et al.* (1986)
	Collisional rates (e^-) – Wilson & 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:

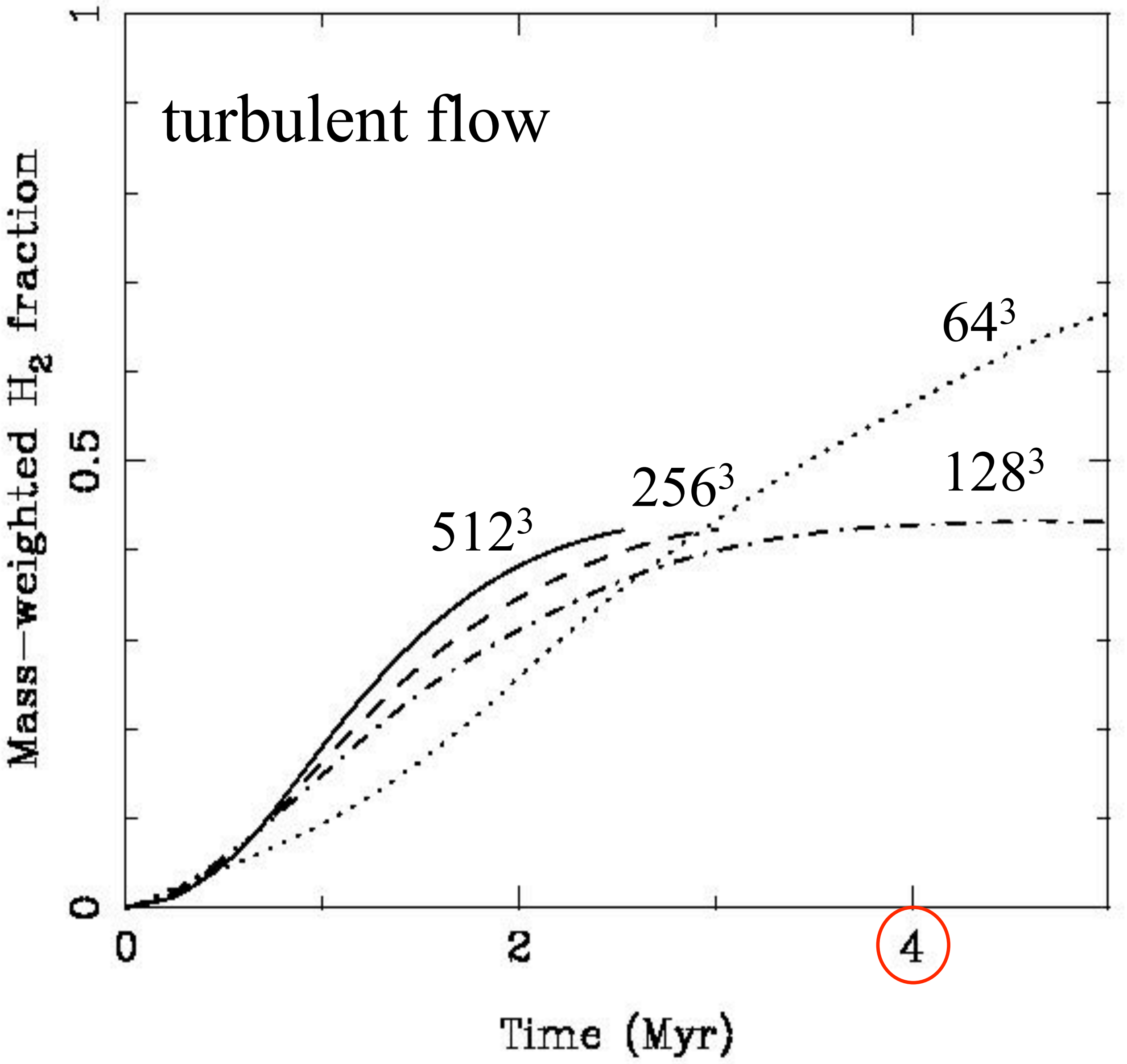
e^-, H^+, H, H^-, H_2^+, H_2, C, C^+, O, O^+

(Glover & Mac Low 2006ab)



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

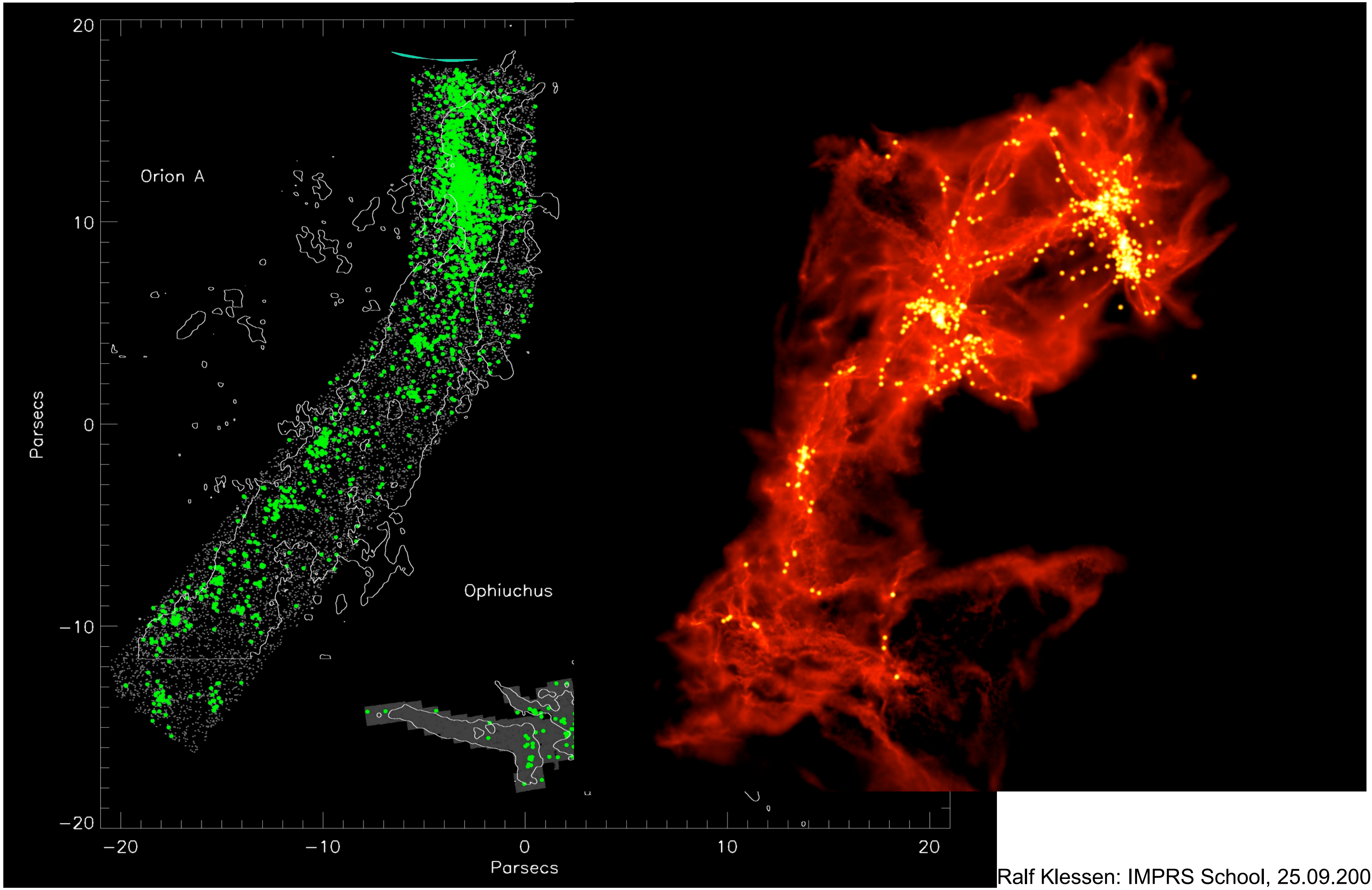
(Glover & Mac Low 2006a)



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

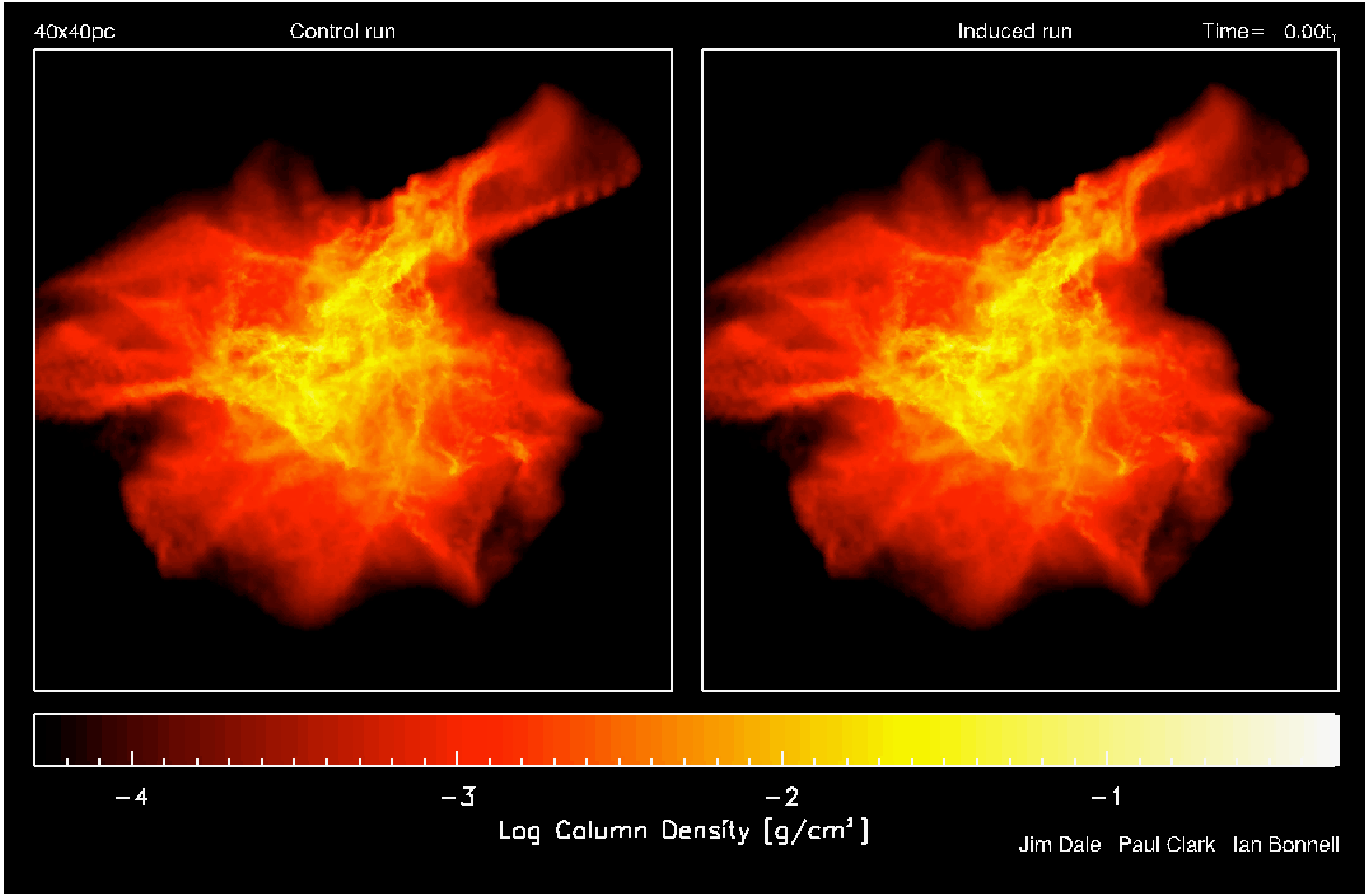
(Glover & Mac Low 2006a)

Gravitational collapse within MCs



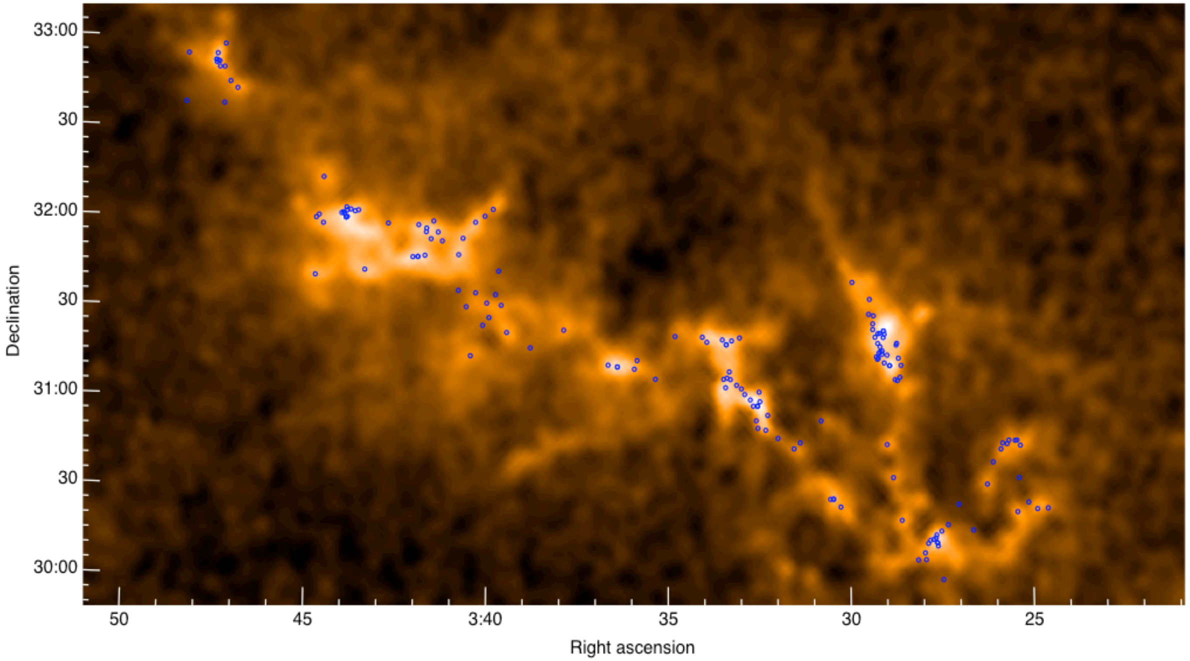
Gravitational collapse within MCs

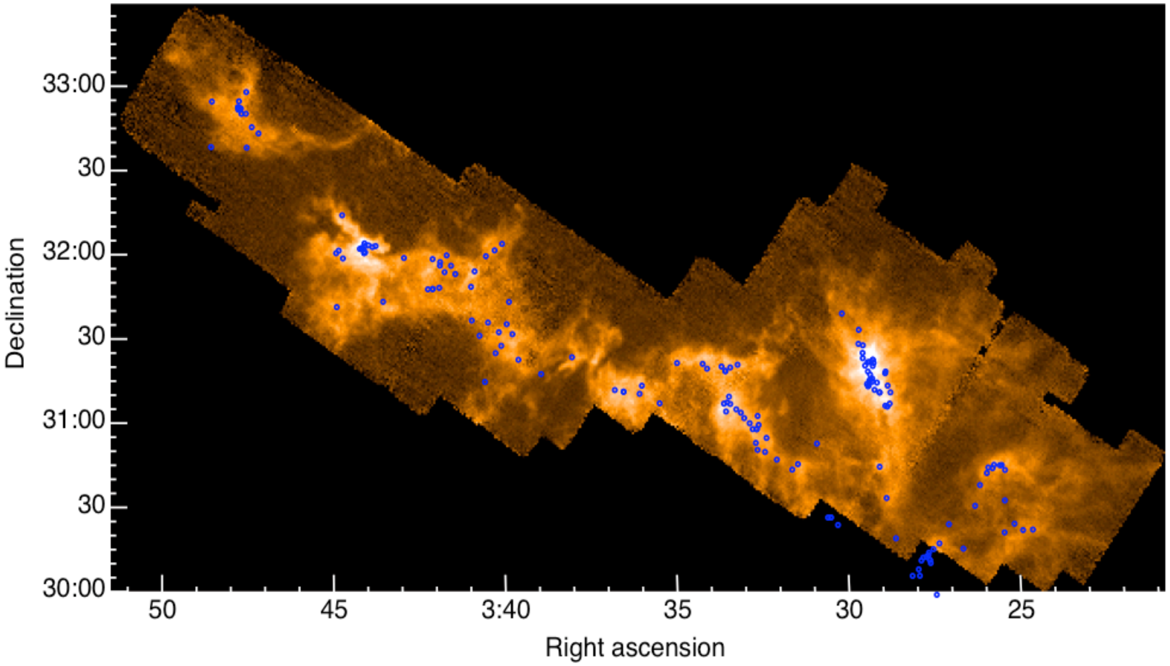
immediate future: SPH with radiation feedback (first validation runs)



IRAM Observations

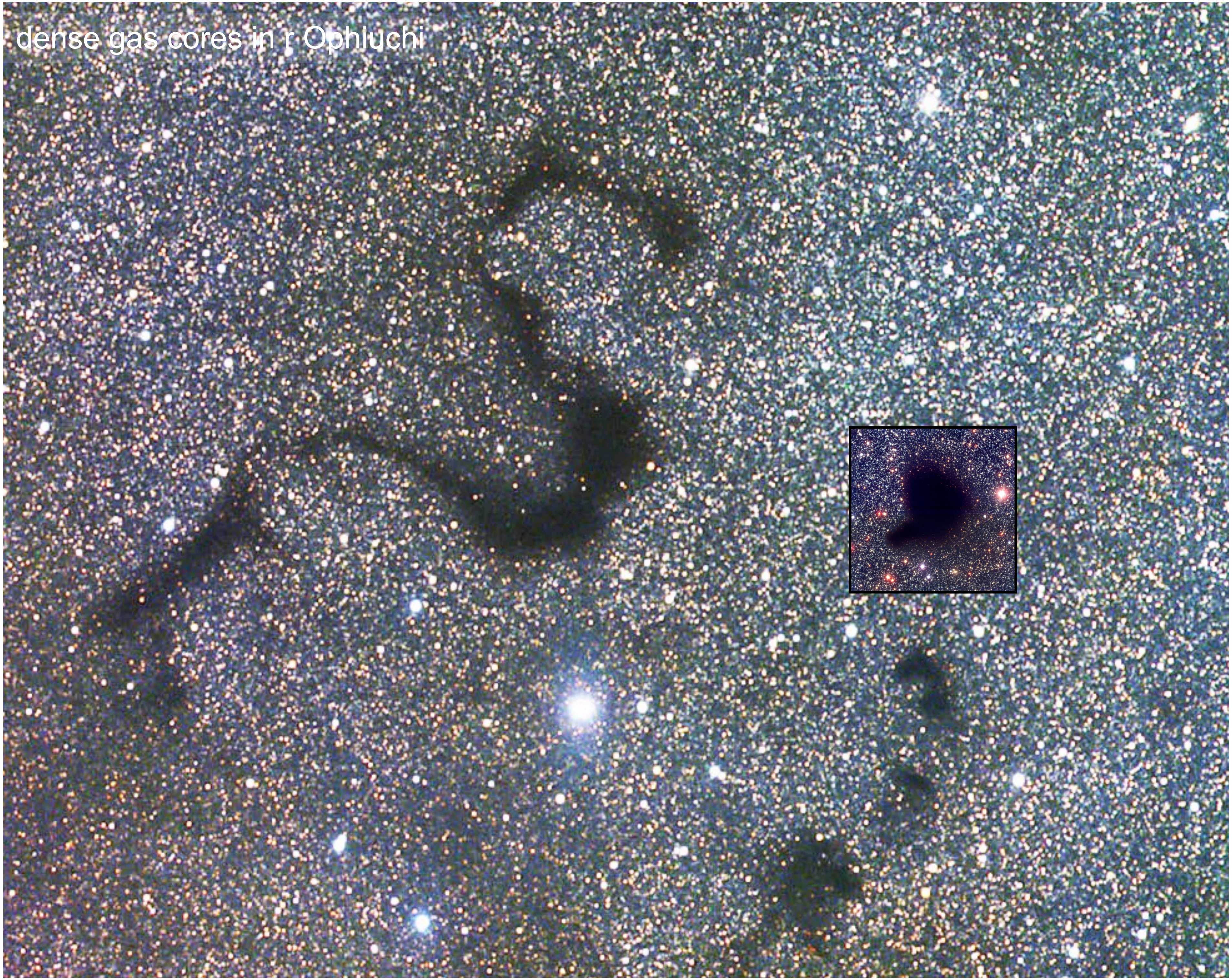
- N_2H^+ and $C^{18}O$
- 15 arcsecond res.
  - ~3000 AU
- N_2H^+ dense gas tracer
  - Most SCUBA
  - Few extinction!





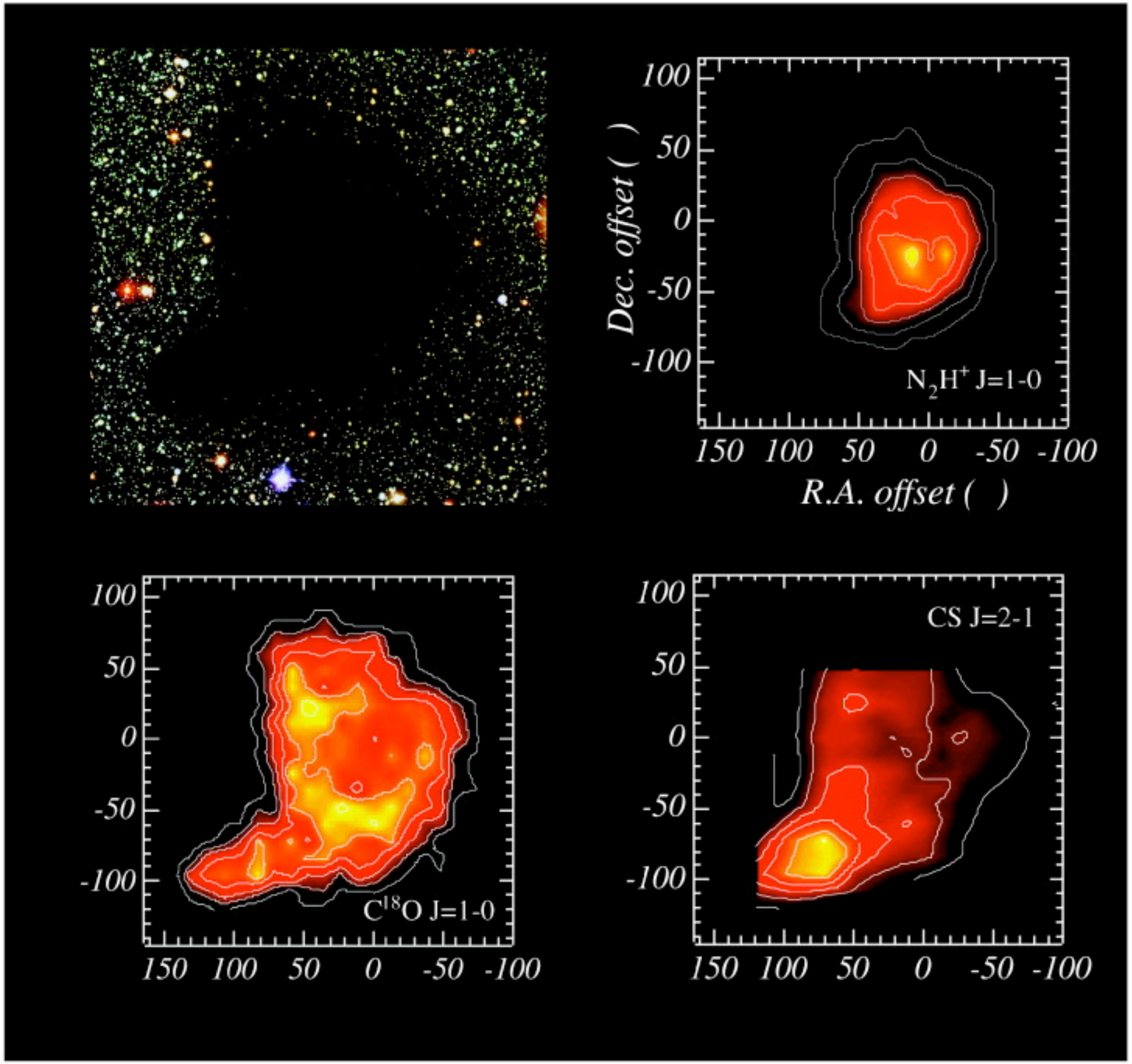
(Perseus: Johnstone et al.)

dense gas cores in r Ophiuchi



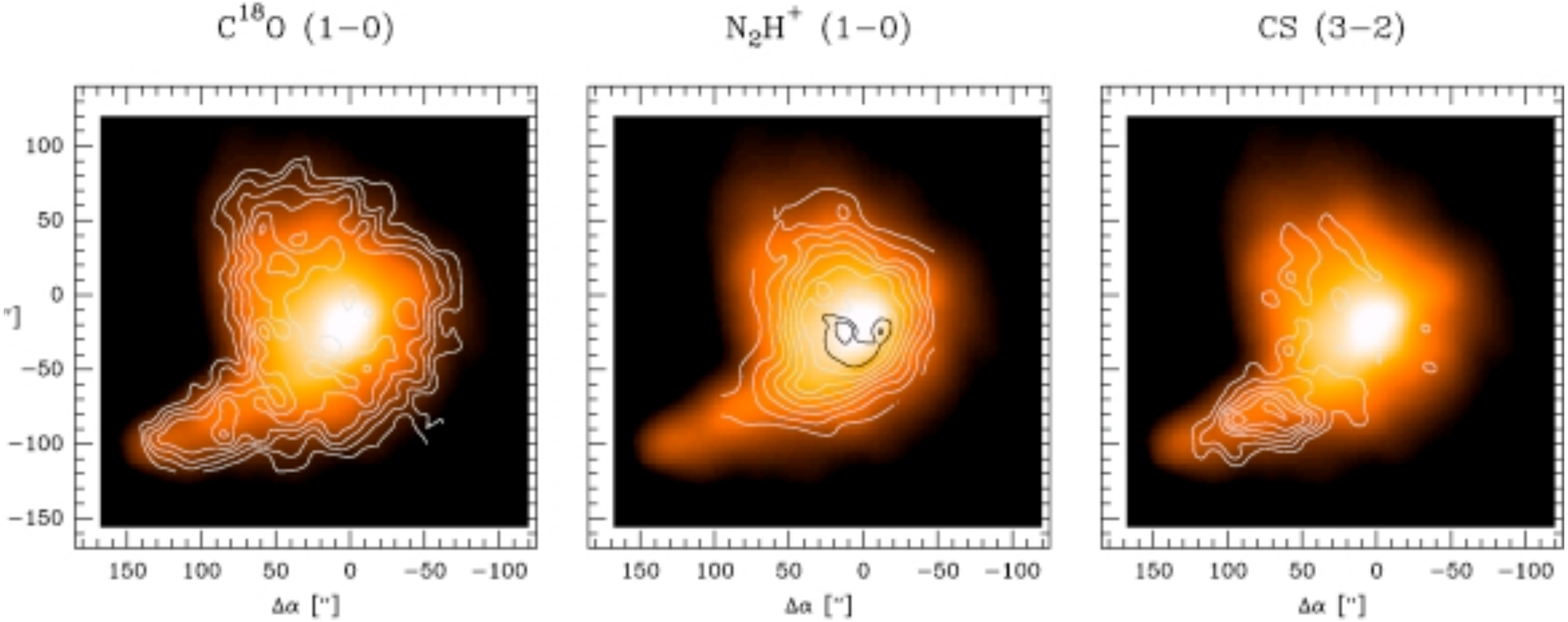

B68

Barnard 68: a well-studied isolated prestellar core



(Lada et al. 2003)

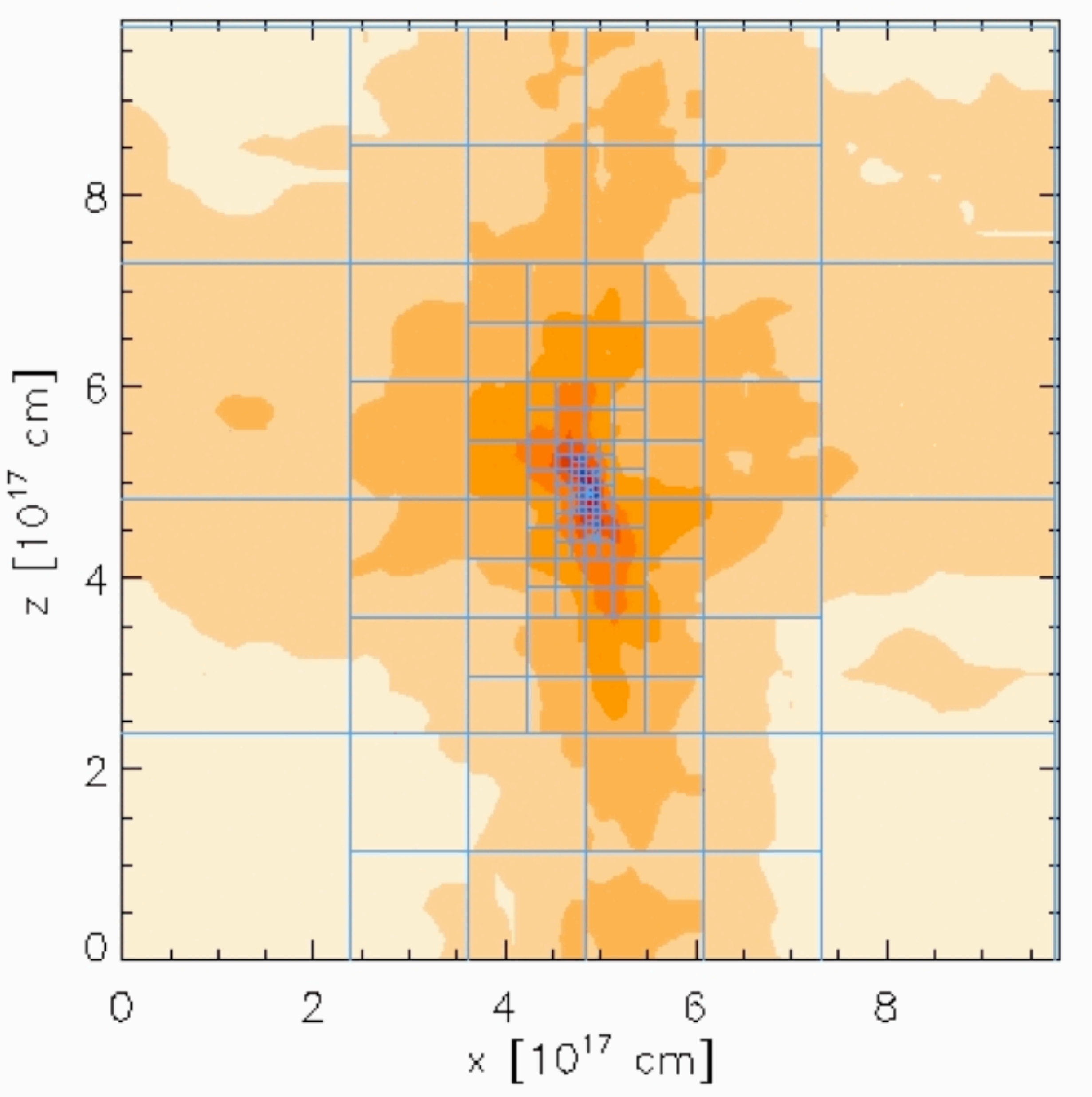
Barnard 68



$C^{18}O$ (1−0)

N_2H^+ (1−0)

CS (3−2)

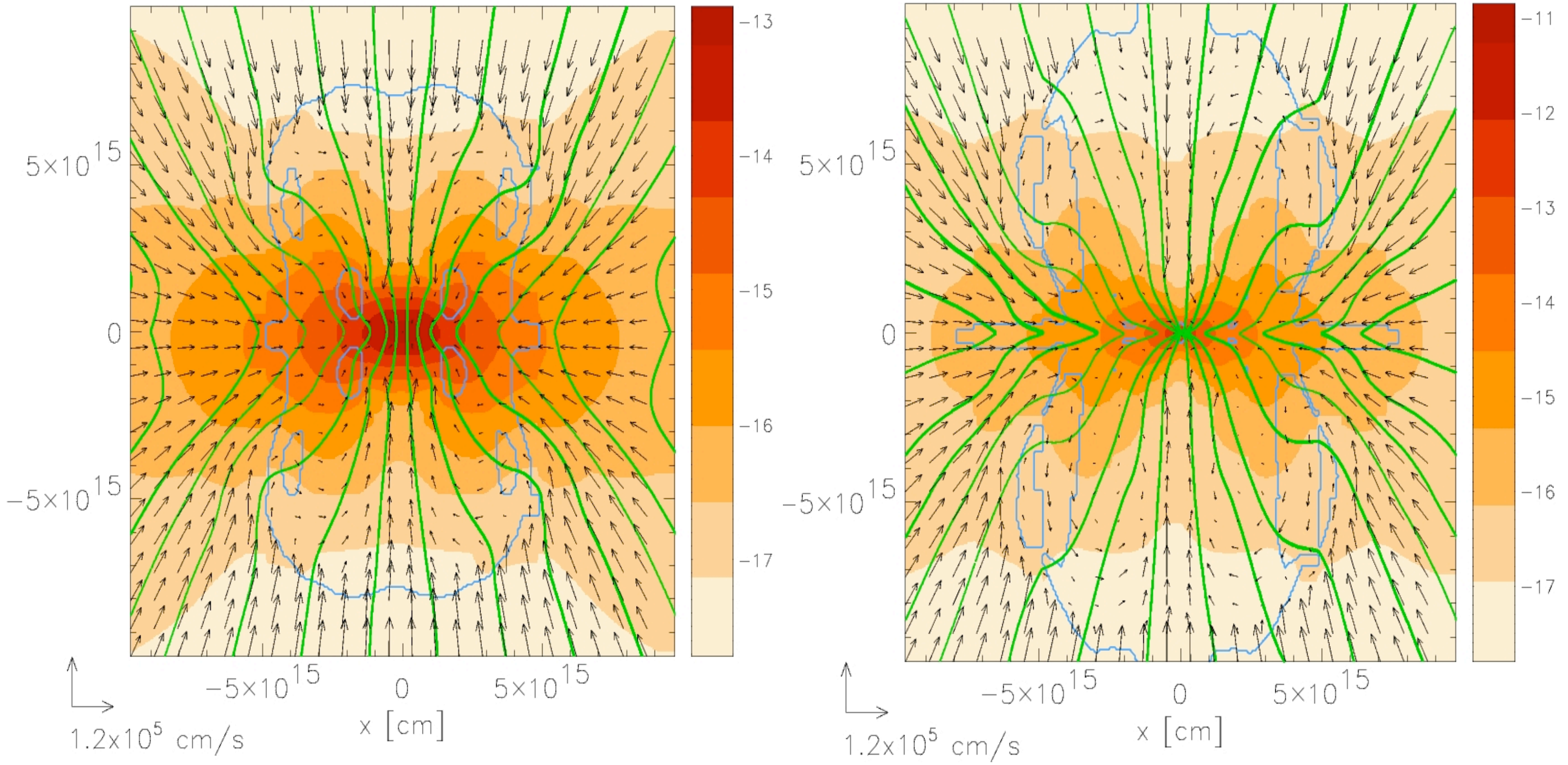


adaptive mesh refinement:

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

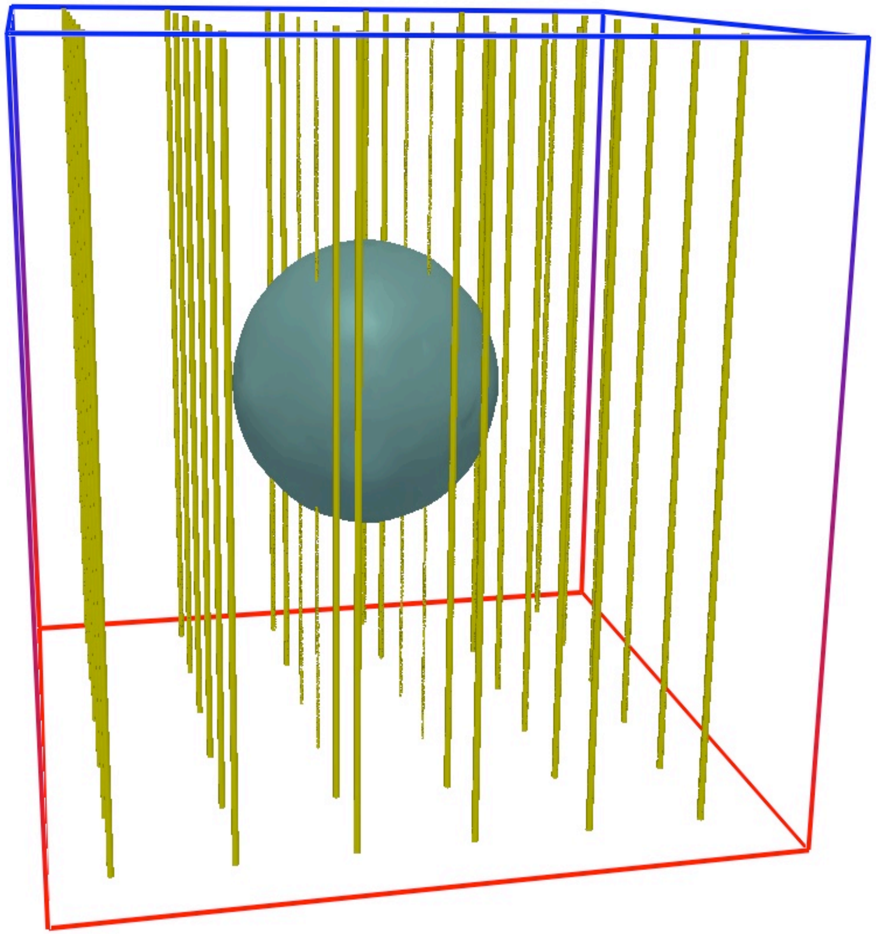
formation of 30 M_{sun} core in turbulent molecular cloud (FLASH with appropriate cooling curve module and turbulent driving)

(Banerjee & Pudritz 2006)



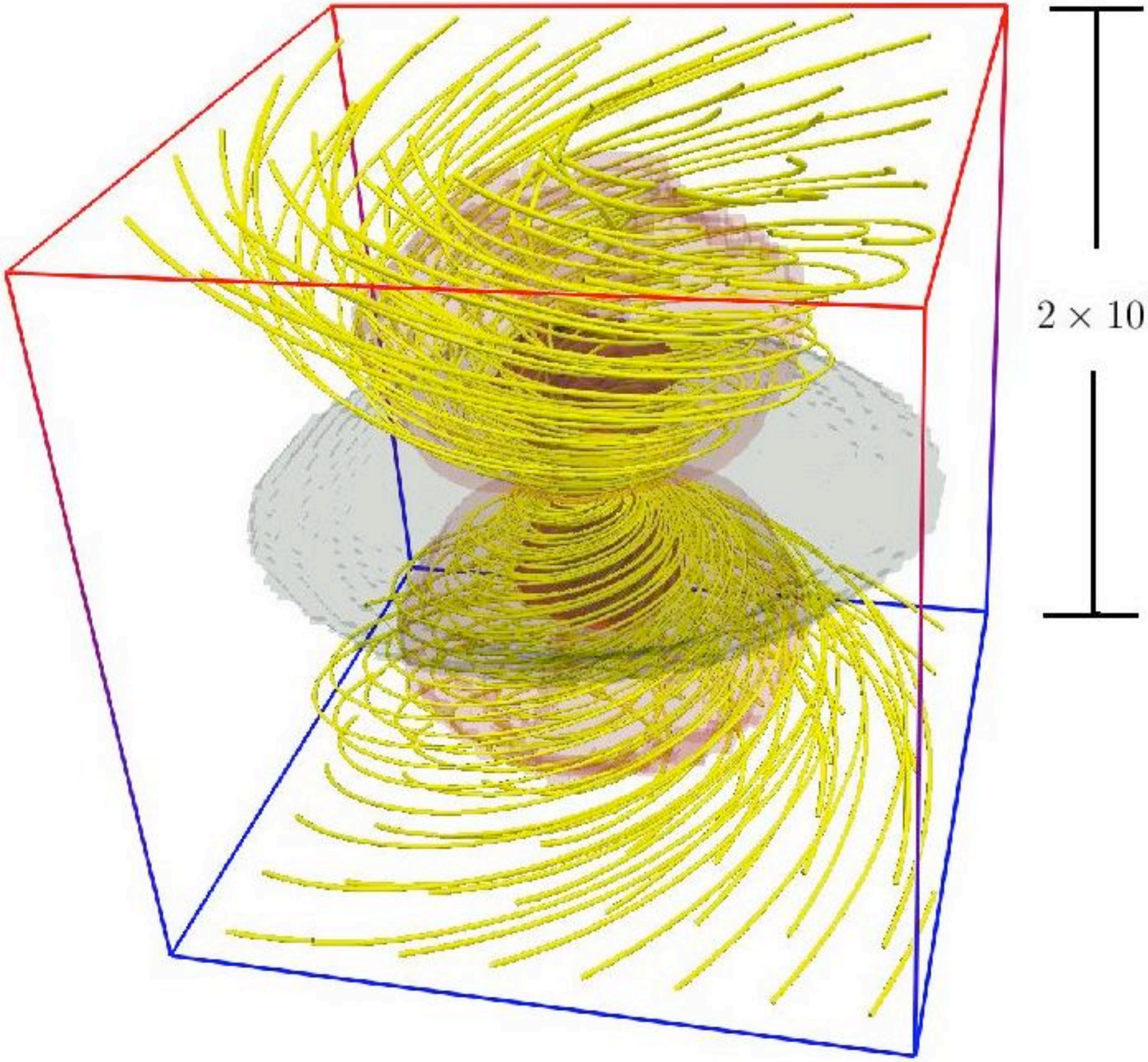
These 2D snapshots show the onset of the **large scale outflow**. After ca. 70.000 years into the collapse a strong toroidal magnetic field builds up whose magnetic pressure reverses the gas flow and drives an outflow (time difference between these snapshots: 1400 years).

(Banerjee & Pudritz 2006)



(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).

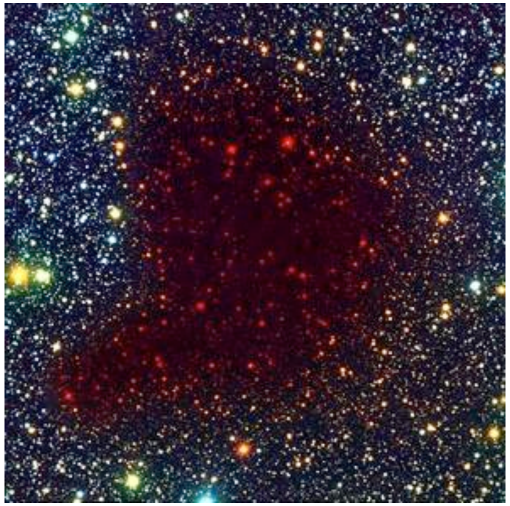


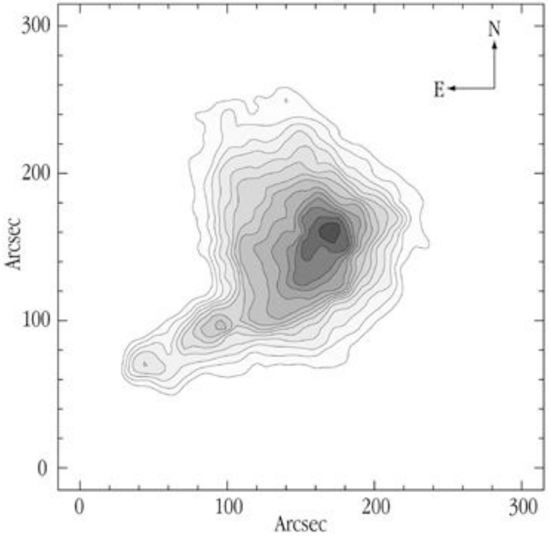
The 3D structure of the magnetic field line configuration in the **jet** launching region.

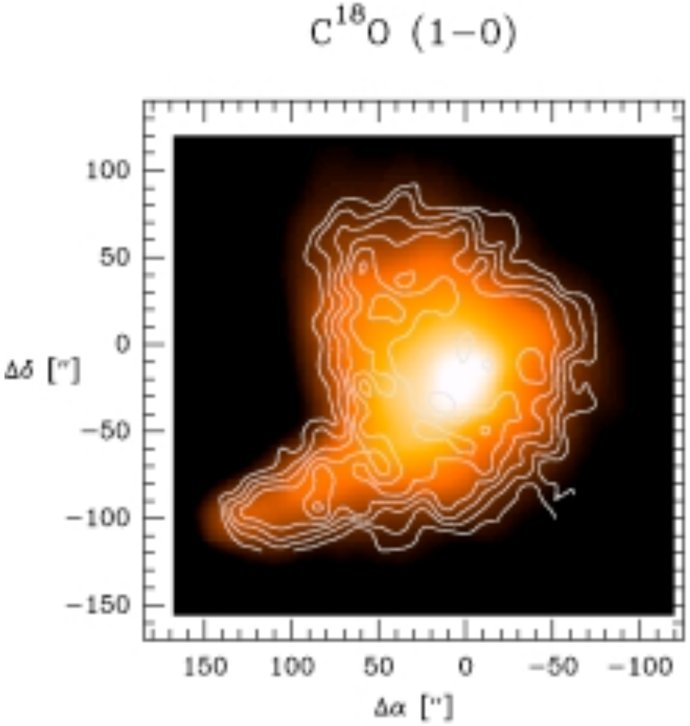
As predicted by analytics the magneto-centrifugally driven disk jet is faster in the inner region (dark red) than further away from the outflow axis (light red).

(Banerjee & Pudritz 2006)

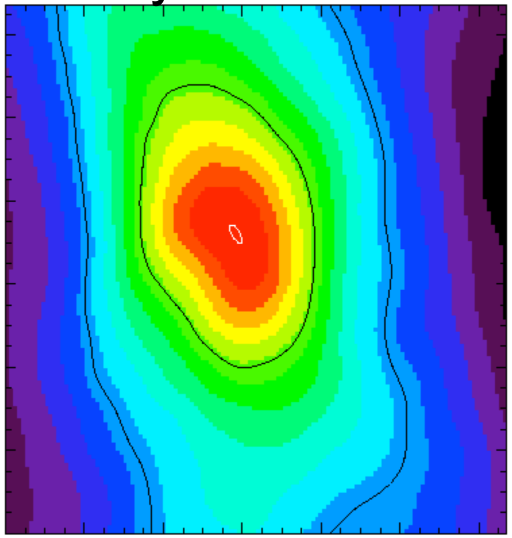
observations

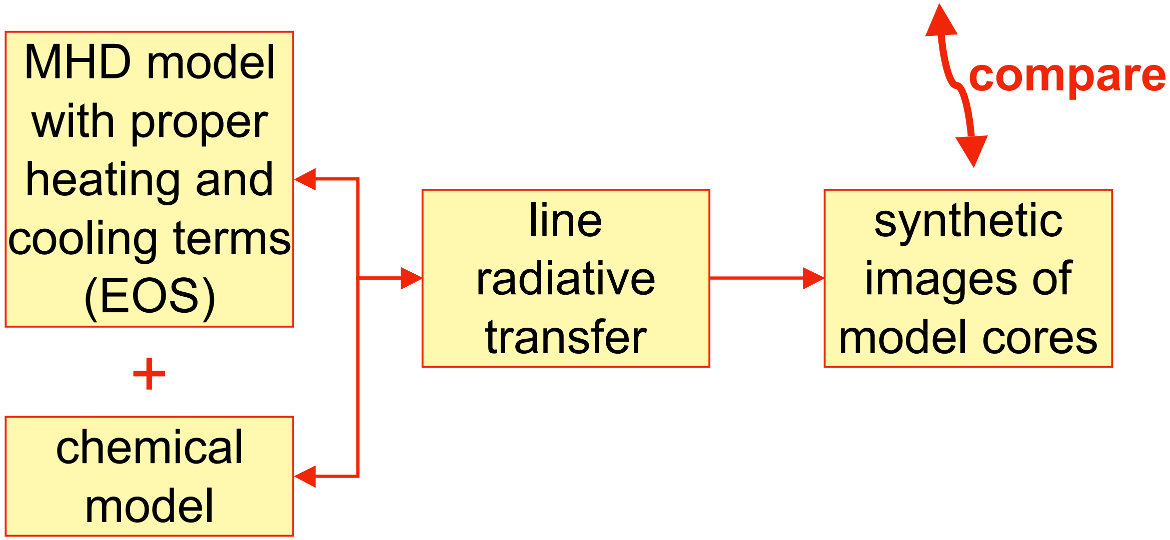






theory





MHD model with proper heating and cooling terms (EOS)

\+

chemical model

line radiative transfer

synthetic images of model cores

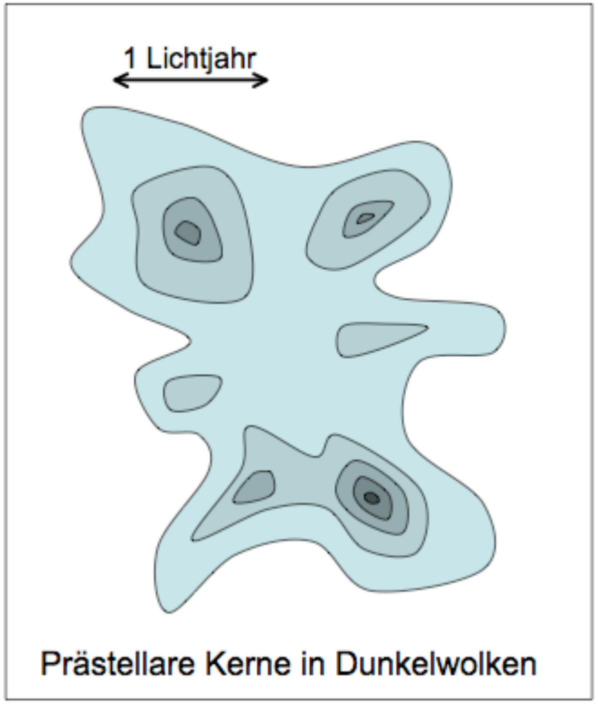
compare

(e.g. Semenov & Pavlyuchenkov)

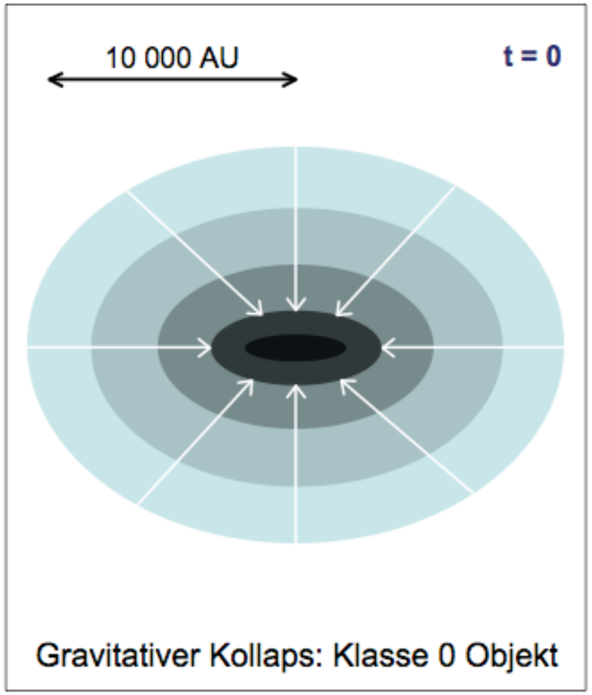
(3D core structure: Steinacker)

final cartoons

Protostellar collapse

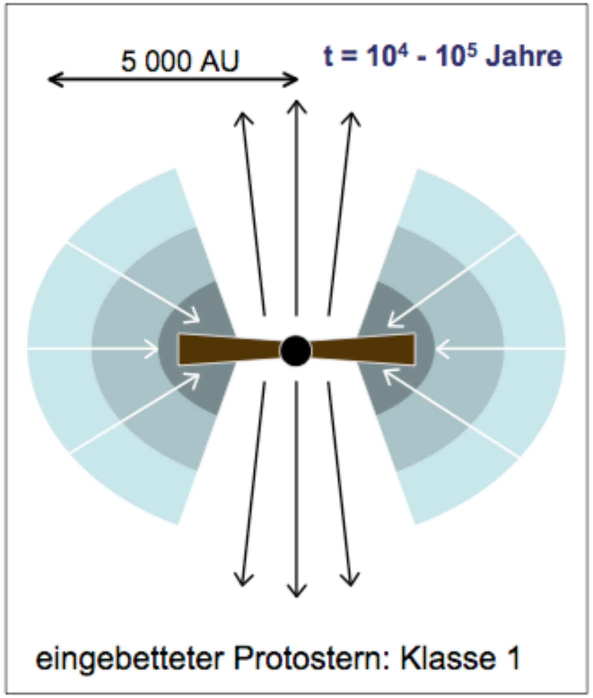


Prästellare Kerne in Dunkelwolken

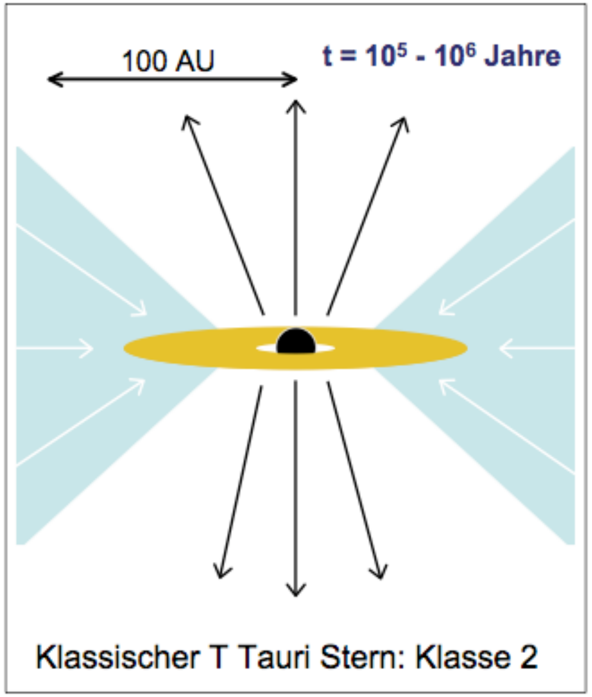


Gravitativer Kollaps: Klasse 0 Objekt

Protostellar collapse

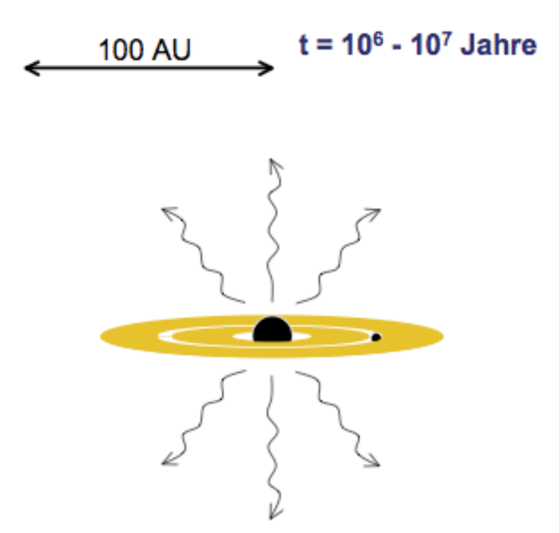


eingebetteter Protostern: Klasse 1

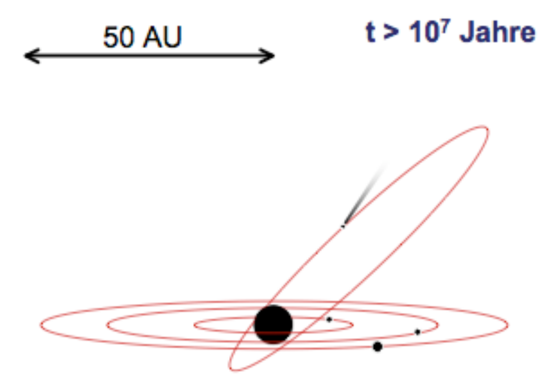


Klassischer T Tauri Stern: Klasse 2

Protostellar collapse



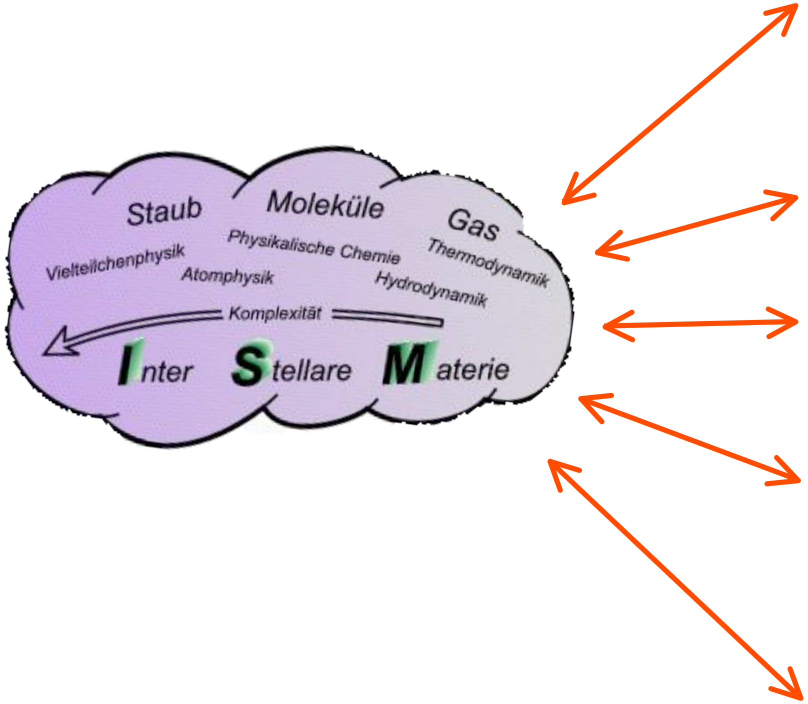
Vorhauptreihenstern mit Debris-Scheibe, sichtbar im Optischen



Stern auf Hauptreihe (Kernfusion im Zentrum) mit Planetensystem

the future…

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!

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.)

THANKS