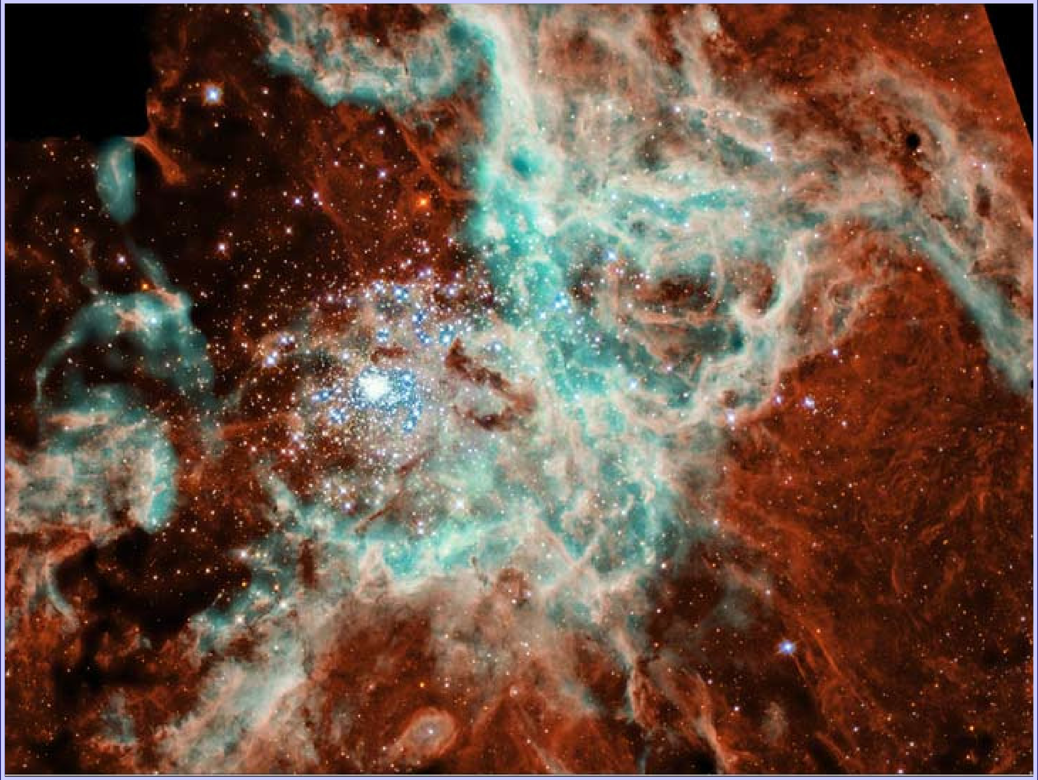
The Puzzle of Star Formation



In collaboration with: F. Heitsch, L. Hartmann, S. Dib,
M. Gritschneder, A. Slyz, J. Devriendt

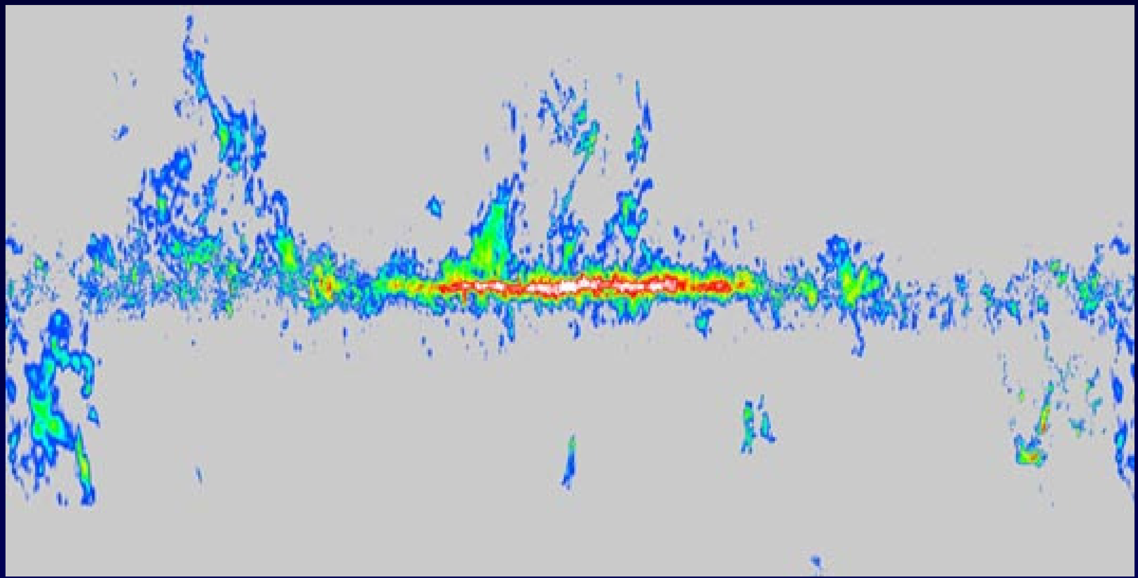
Munich University Observatory
CAST
Computational Astrophysics Group

$$SFR = \eta_{sf} \frac{M_{H2}}{\tau_{sf}}$$

Distribution of Molecular Hydrogen

Galactic
CO-distribution

(Dame, 2000)



- Most of H_2 is found in molecular clouds with $M \approx 10^4 - 10^6\ M_\odot$
- Total mass of molecular hydrogen: $1-2 \cdot 10^9\ M_\odot$
- $T \approx 10K$ and $n \approx 100\ cm^{-3} \rightarrow M_{Jeans} \approx 20\ M_\odot$
- Collapse timescale: $\tau_{ff} = 2 \cdot 10^6\ yrs$

$$SFR = \eta_{sf} \frac{M_{H2}}{\tau_{sf}}$$

$$SFR = \eta_{sf} \frac{M_{H2}}{\tau_{sf}} \approx 50 \, {M_\odot}/{yr}$$

$10^9 \; M_\odot$

10%

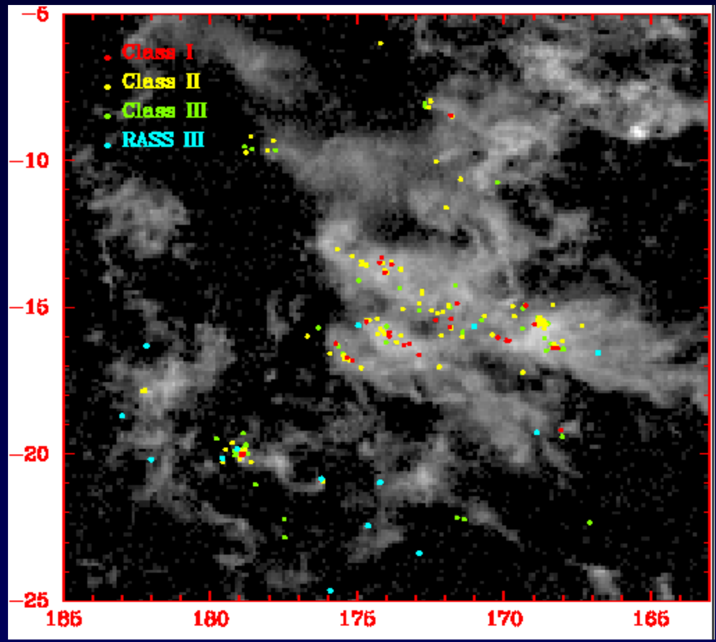
$2 \cdot 10^6$ yrs

The Timescale Puzzle

<u>The Post T-Tauri Problem</u>

- Age spread of stars in Taurus: $1-3$ Myrs
- Almost all clouds in the solar neighborhood form stars

→ MC lifetimes are short (few Myrs)



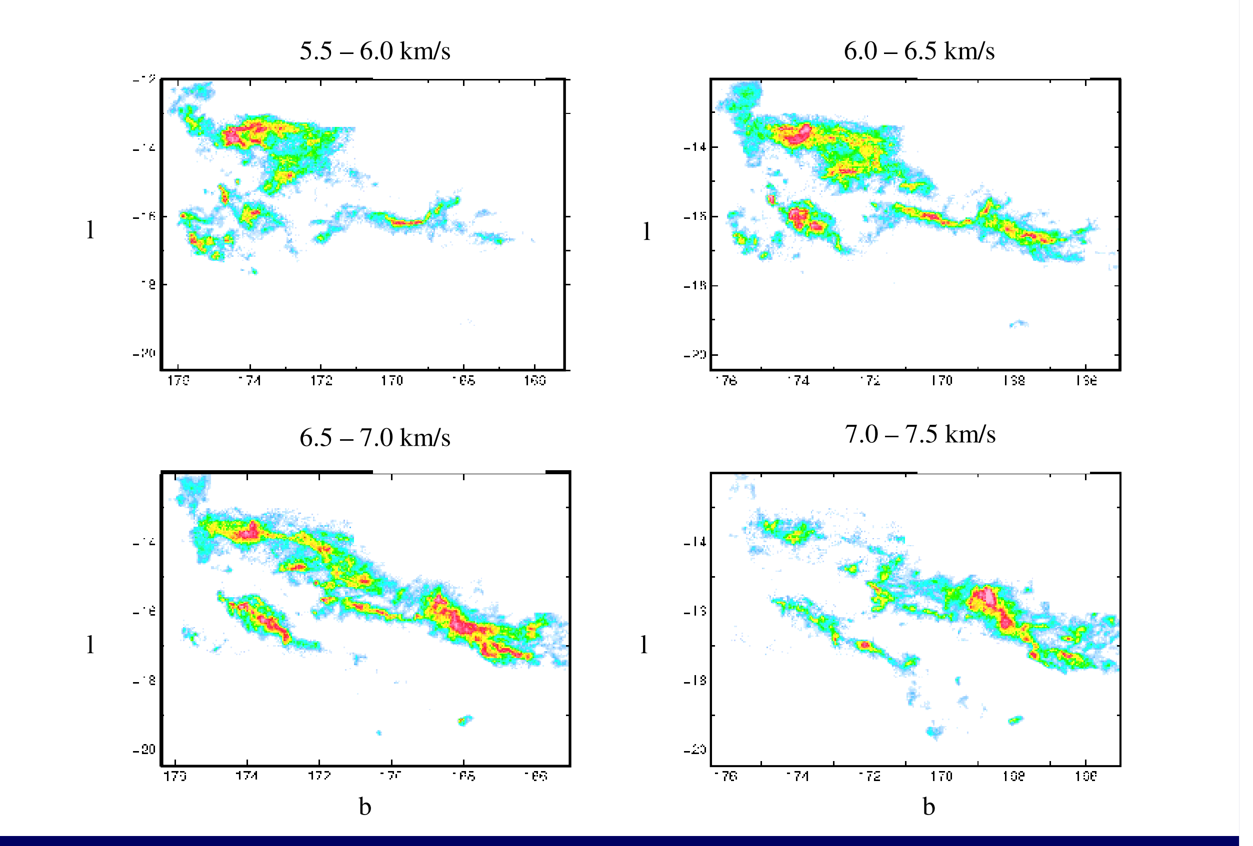
(Hartmann 2000, 2001)

- However Palla et al. find a larger age spread
- THINGS team(Adam Leroy): Fast star formation in a few Myrs

Internal Structure of Molecular Clouds

Taurus-GMC

(Mizuno et al. 1995)



- Clumpy substructure
- Velocity dispersion:

$$\sigma \approx 3\ km/s \approx 10\, c_s$$

- Turbulent Jeans mass:

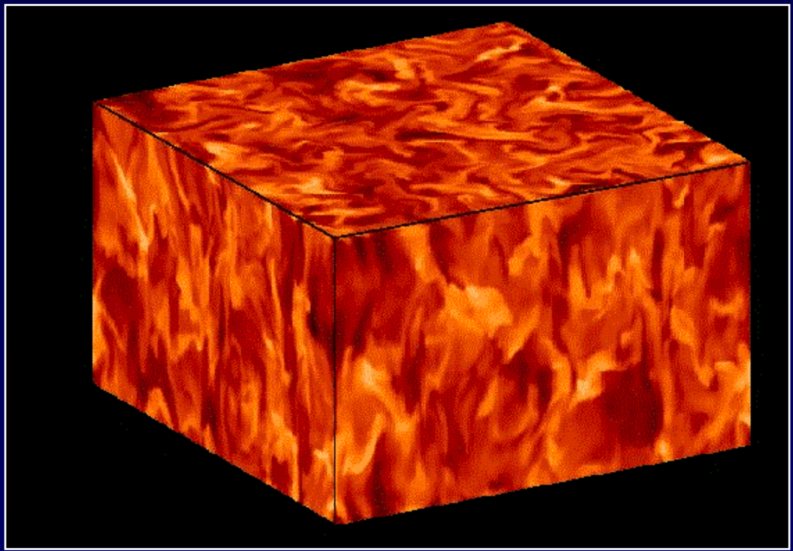
$$M_{Jeans} \approx 2 \cdot 10^4 \mathrm{M}_\odot$$

Molecular clouds are stabilized by their turbulent velocity field.

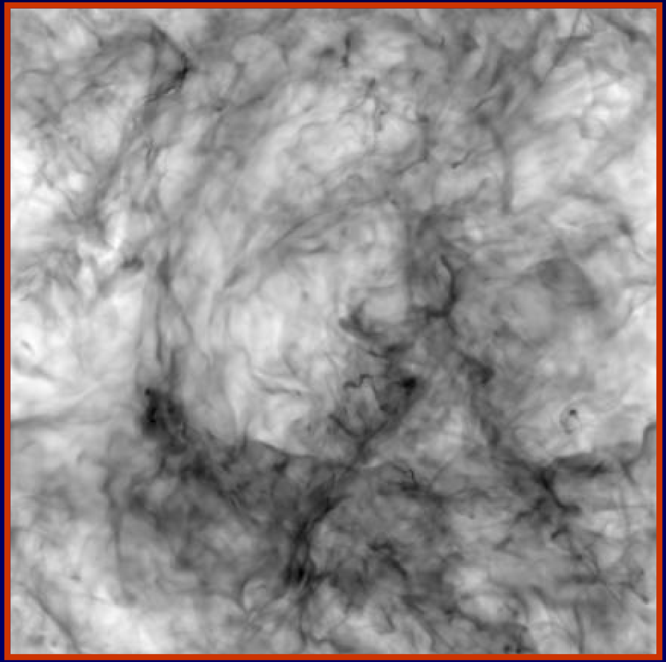
Structure of a Driven Turbulent Gas Cloud

- Continuous energy input on large scales only (k=1-2)
- Turbulent cascade of energy to smaller scales

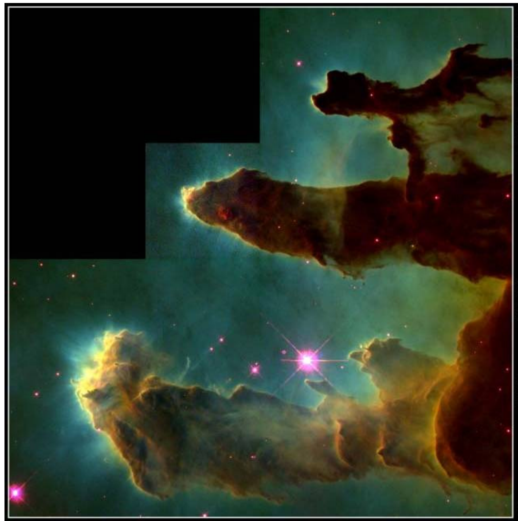
Surface density distribution of a driven turbulent gas cloud (M=5)

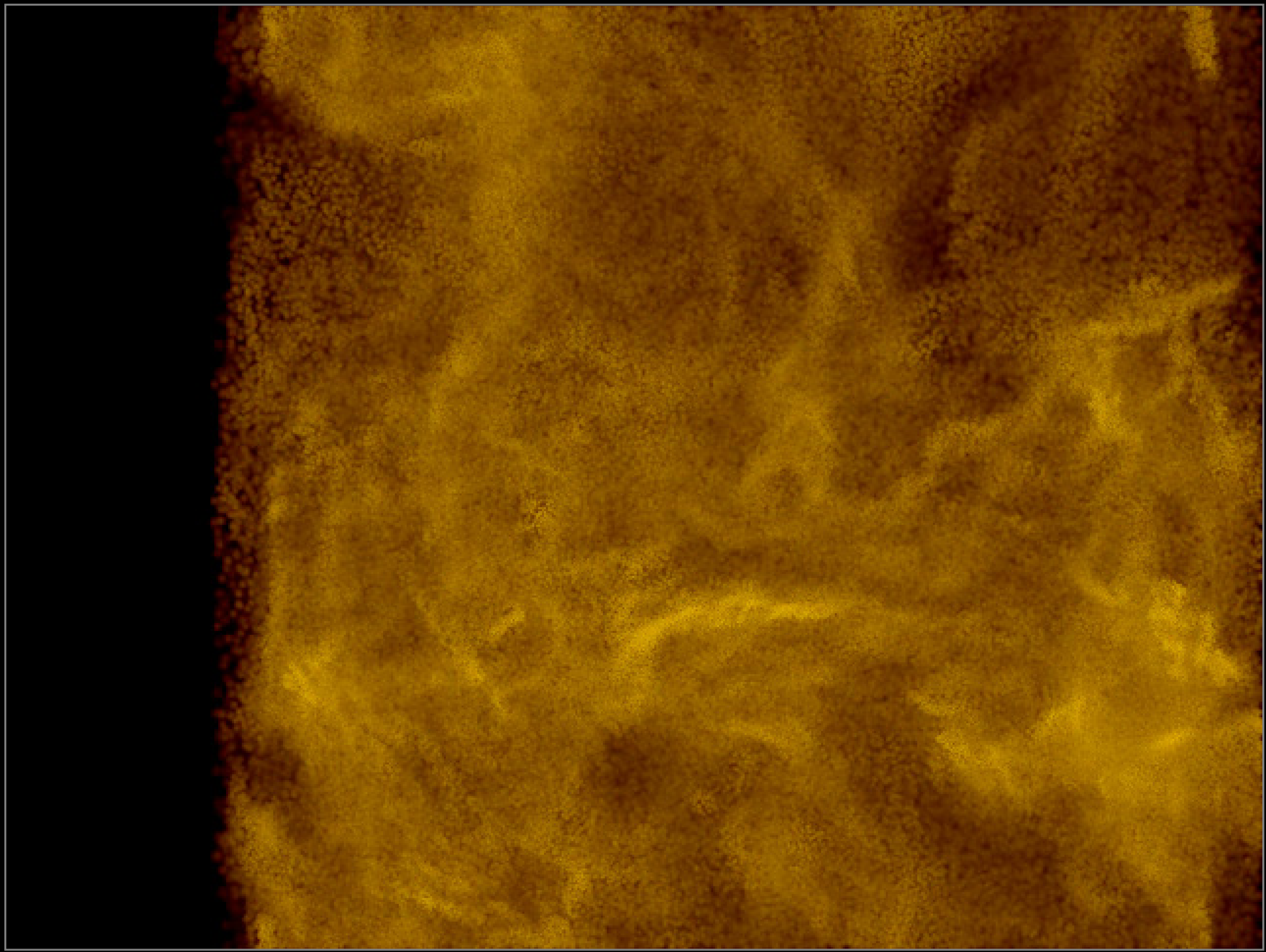


(Mac Low et al.)



(Heitsch et al.)





(Gritschneder et al. 2007)

The Decay of Turbulence in Molecular Clouds

- Numerical simulations show that the turbulent velocity field is dissipated on timescales of τ_{ff}

Kinetic energy dissipation

a) Grid code

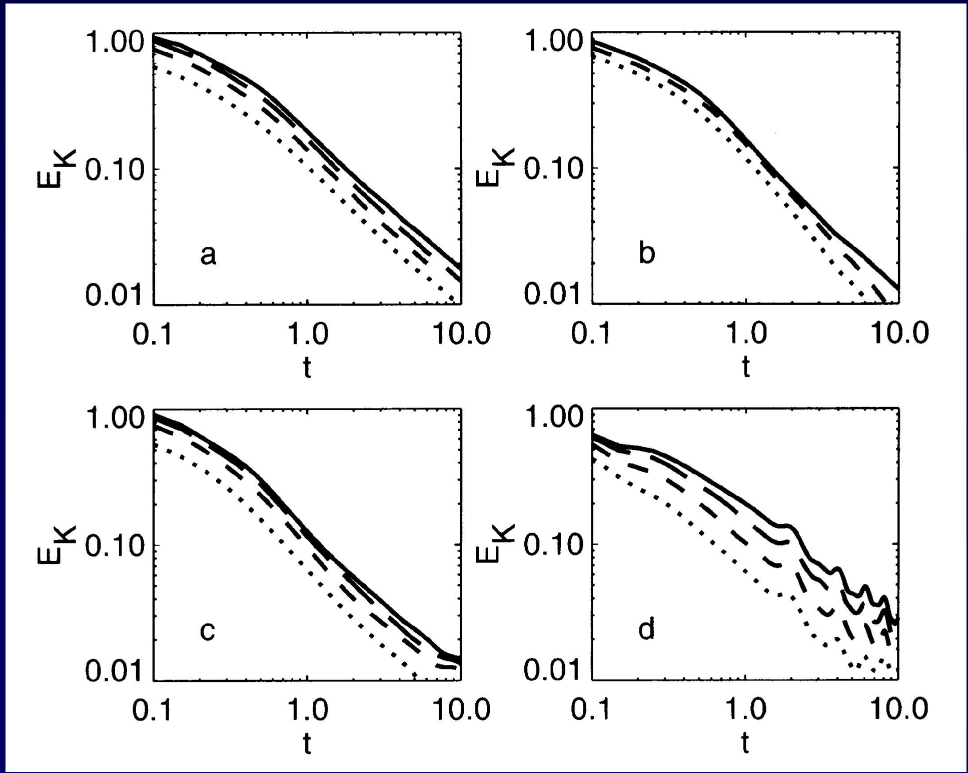
b) SPH-Code

c) Weak magnetic field

$$\beta = \frac{p_{th}}{p_{mag}} = \frac{2\mu_0 \rho c_s^2}{B^2} = 5$$

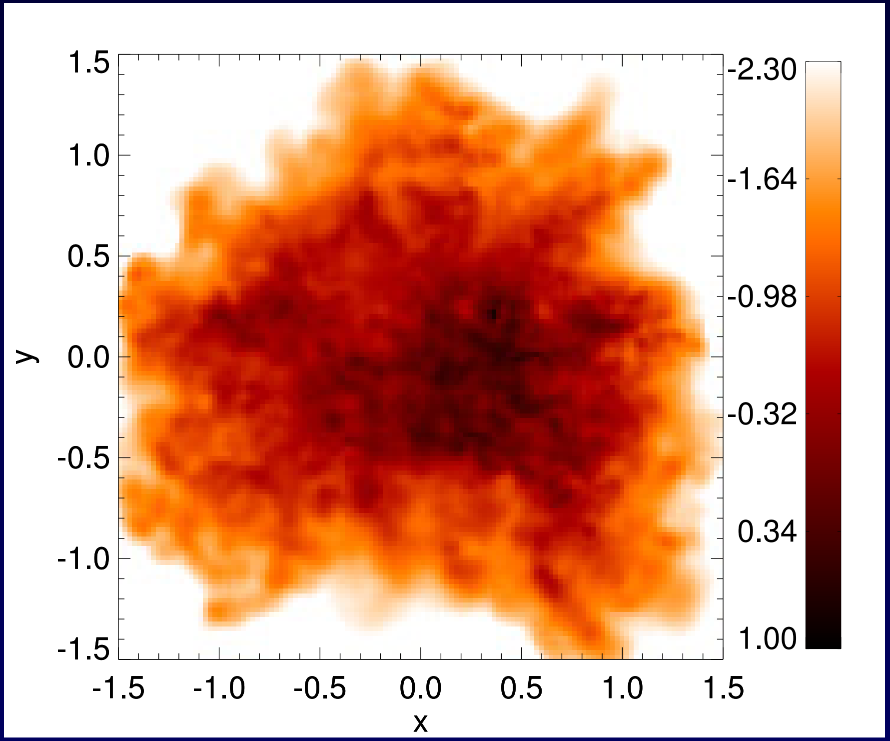
d) Strong magnetic field

$$\beta = 0.5$$



(Mac Low, Klessen, Burkert & Smith 1998)

Star formation and cloud disruption



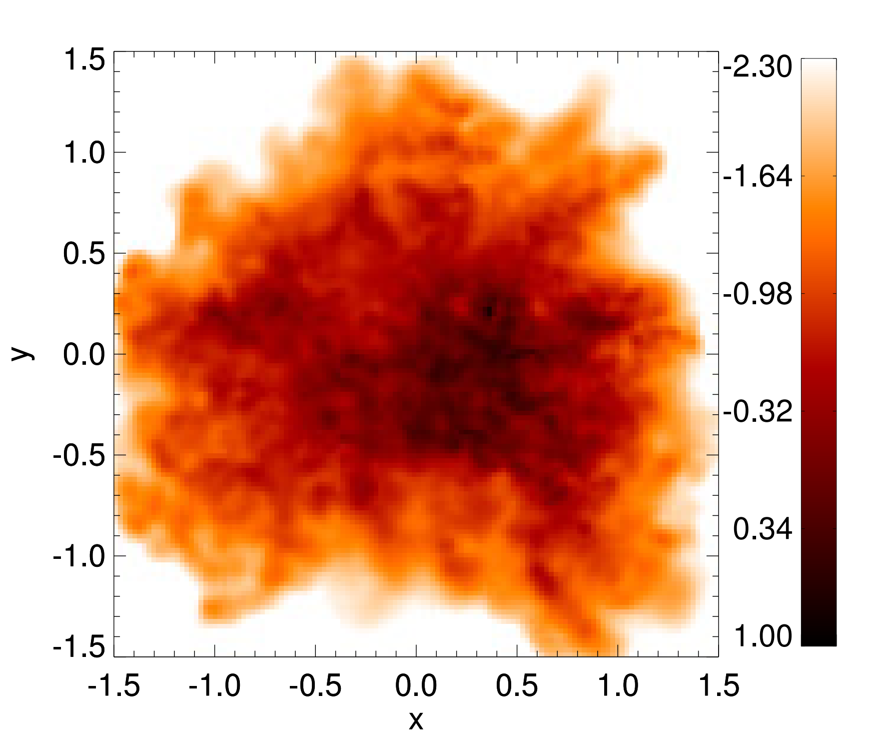
(Geyer & Burkert)

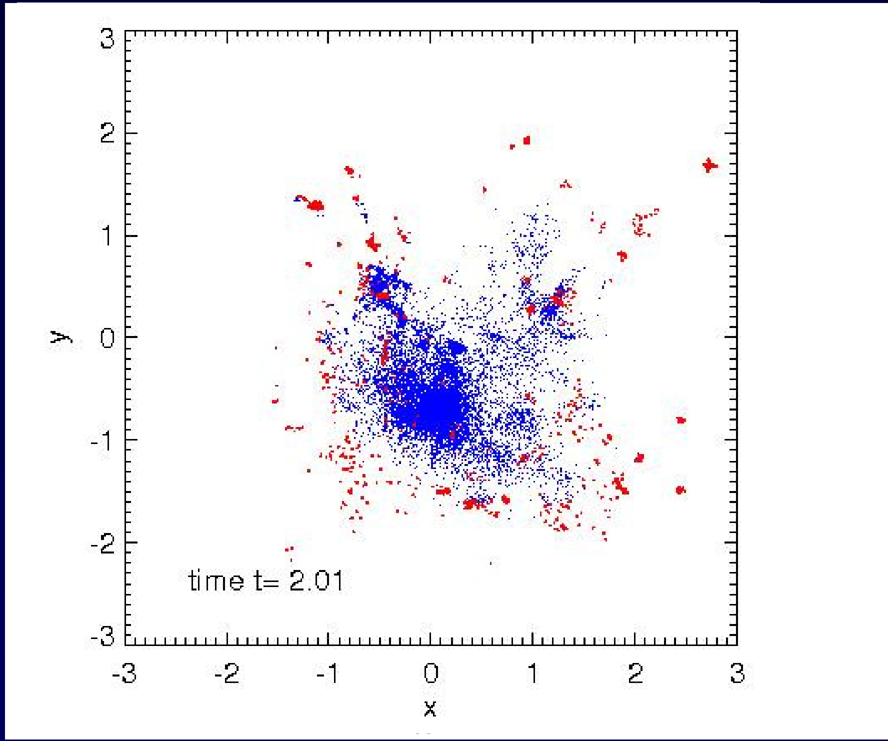
A group of stars, represented by a stellar particle forms if

- converging gas flow $\vec{\nabla} \cdot \vec{v} < 0$
- Jeans unstable region $M > M_{Jeans}$
- density threshold $n_g > n_{sf}$

Massive stars are allowed to heat the surrounding gas.

- Cut out a spherical region and remove periodic boundary condition

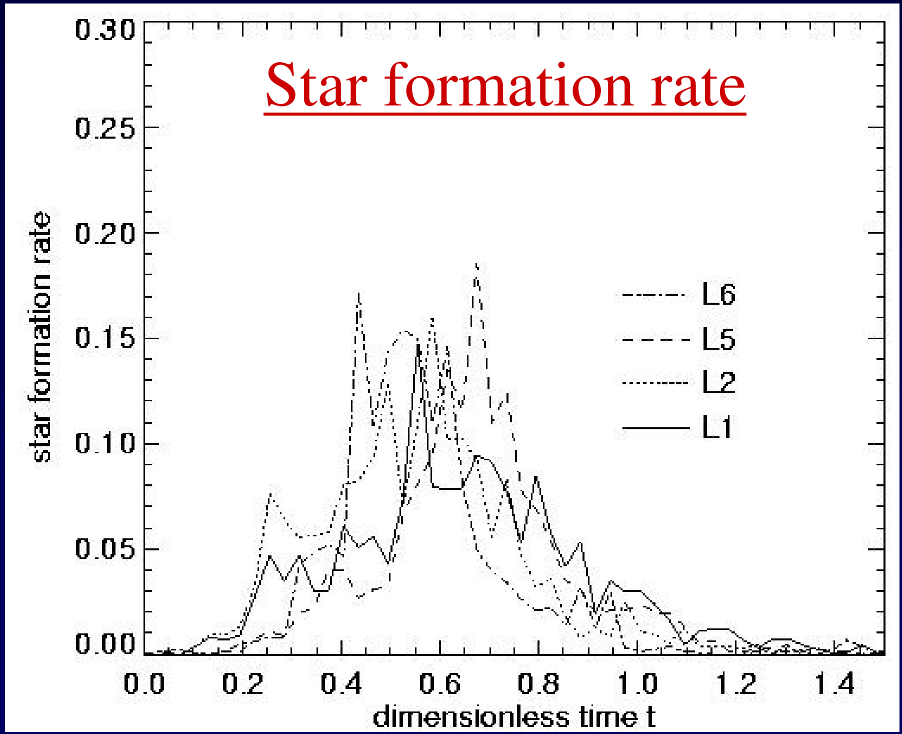


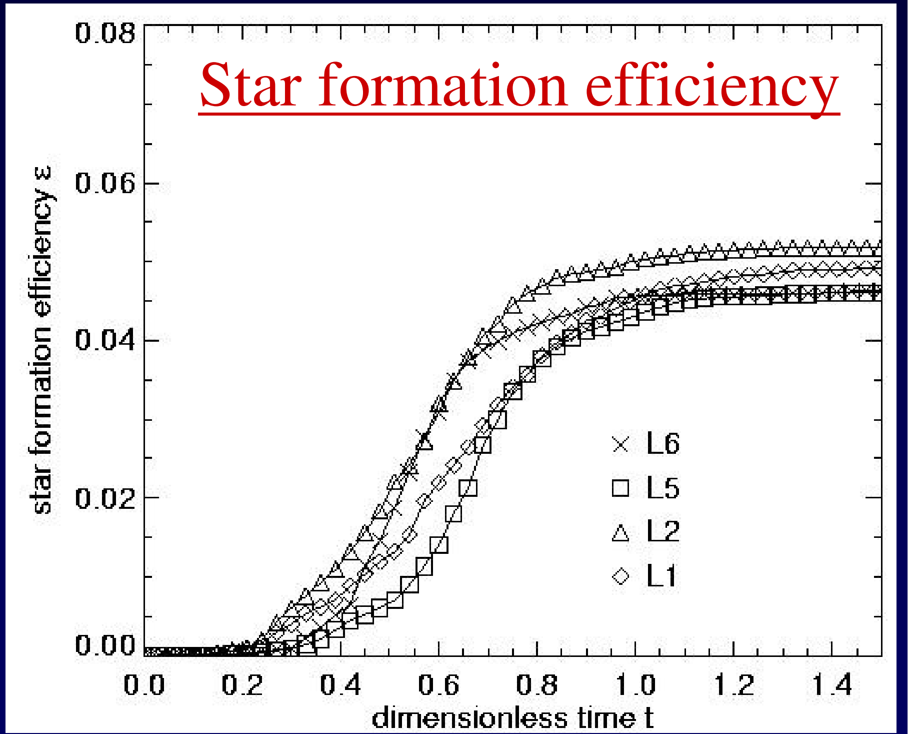


Massive stars are allowed to heat the surrounding gas.

Star Formation Rate and Efficiency

Units: $0.01\,M_{\odot}\,/\,yr$





Heating by massive star: L1: $2 \cdot 10^{32}$ erg/s L2: $2 \cdot 10^{34}$ erg/s

L1,2: $n_{sf} = 0$ L5,6: $n_{sf} = 100\,cm^{-3}$

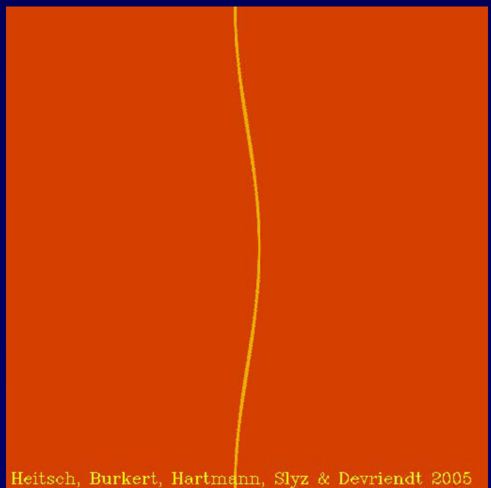
Star Formation: An Initial Condition Problem

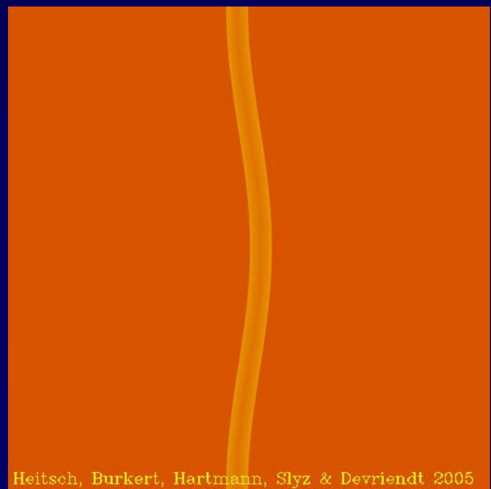
(Heitsch et al 05a,b, 06; Vazquez-Semadeni et al.)

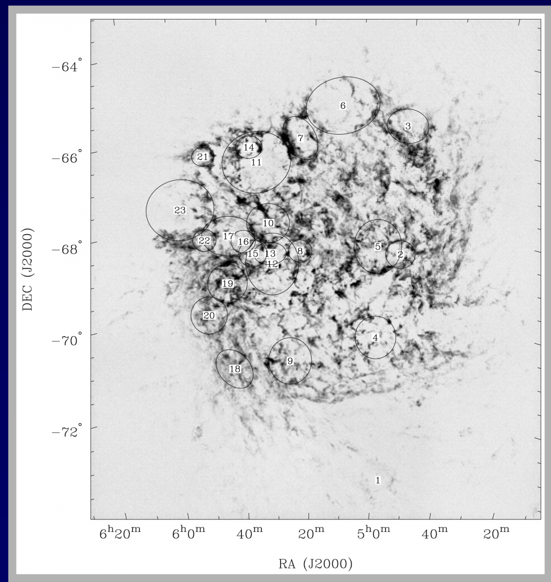
- The turbulent, clumpy structure of molecular clouds is imprinted atnd driven during time of formation.

- Star formation starts as soon as $10^3 - 10^5\ M_{\odot}$ of H_2 are accumulated

<u>Cloud formation in shock compressed layers:</u>







(Kim et al. 1998, 1999)

The Timescale Puzzle

$$M_{cloud} = 5000\,M_{\odot} \left(\frac{d}{30\,pc}\right)^2 \left(\frac{v}{10\,km/s}\right)\left(\frac{n}{1\,cm^{-3}}\right)\left(\frac{t}{10^7\,yrs}\right)$$

- It takes a few 10^7 yrs to generate a typical molecular cloud.
- H_2 forms as soon as $\Sigma_{HI} \approx 10^{21}\,cm^{-2}$ → Turbulent HI slabs

→ *Talk by Robert Braun*

- For inflow speeds of 10 km/s and inflow densities of $1-3\,cm^{-3}$ it takes of order $1-3\cdot 10^7$ yrs before the HI slab becomes molecular.

(Larson relation)

However

Equilibrium between HI and H_2 :

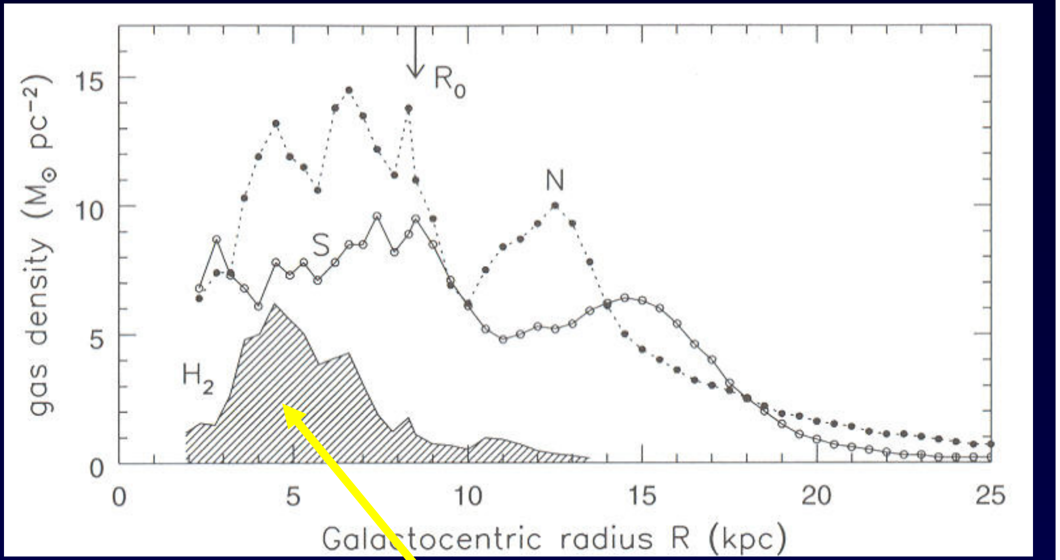
$$\dot{M}_{HI \to H_2} = \dot{M}_{H_2 \to HI} \quad \to \quad \frac{M_{H_2}}{M_{HI}} = \frac{\tau_{H_2 \to HI}}{\tau_{HI \to H_2}} \approx 0.1 \quad \to \quad M_{H_2} \approx 0.1\, M_{HI}$$

This is not in agreement with the observations:

$$M_{H_2} \approx M_{HI}$$

→ HI inflow from halo?

Distribution of HI and H2 in the Milky Way



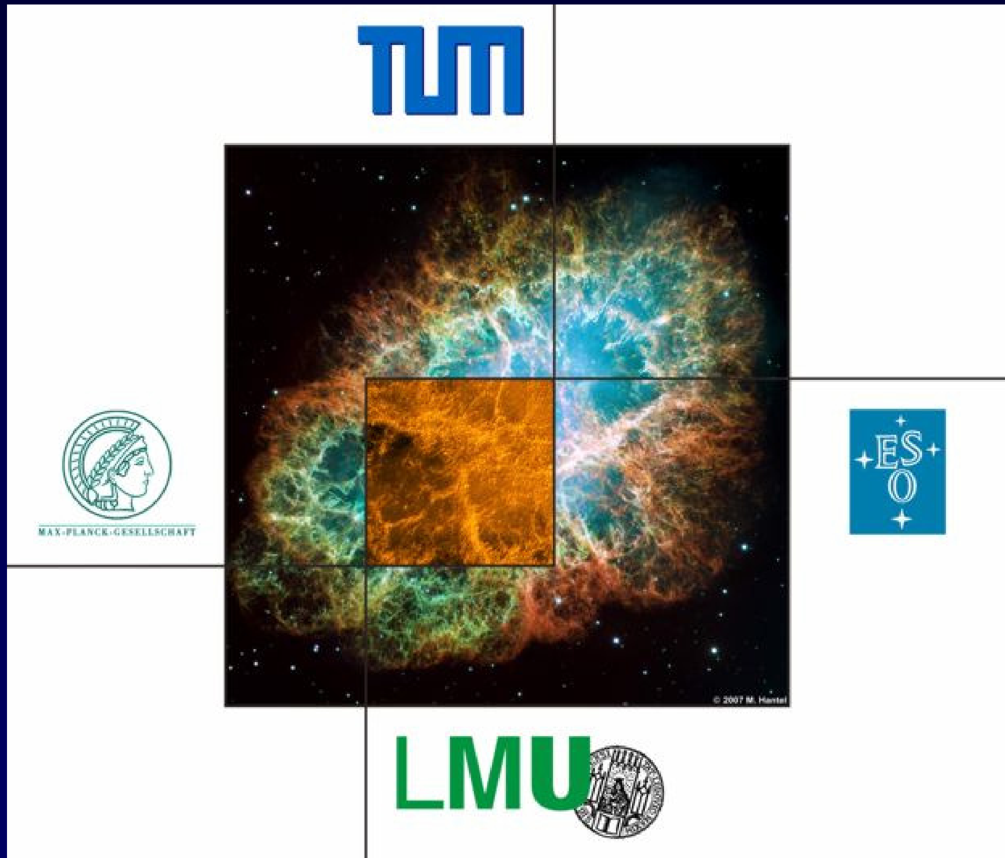
How is the molecular ring stabilized?

A Scenario of Molecular Cloud and Star Formation

- Turbulent HI Clouds form on timescales of order 10 Myrs
- As soon as they become optically thick ($\Sigma \approx 10^{21}$ cm^{-2}) they turn into molecular clouds and form stars on a dynamical timescale.
- According to this scenario, most of the gas in the solar neighborhood should be atomic.
- The large fraction of molecular gas in the Milky Way is a result of its molecular ring that might be stirred by the galactic bar, suppressing efficient star formation.

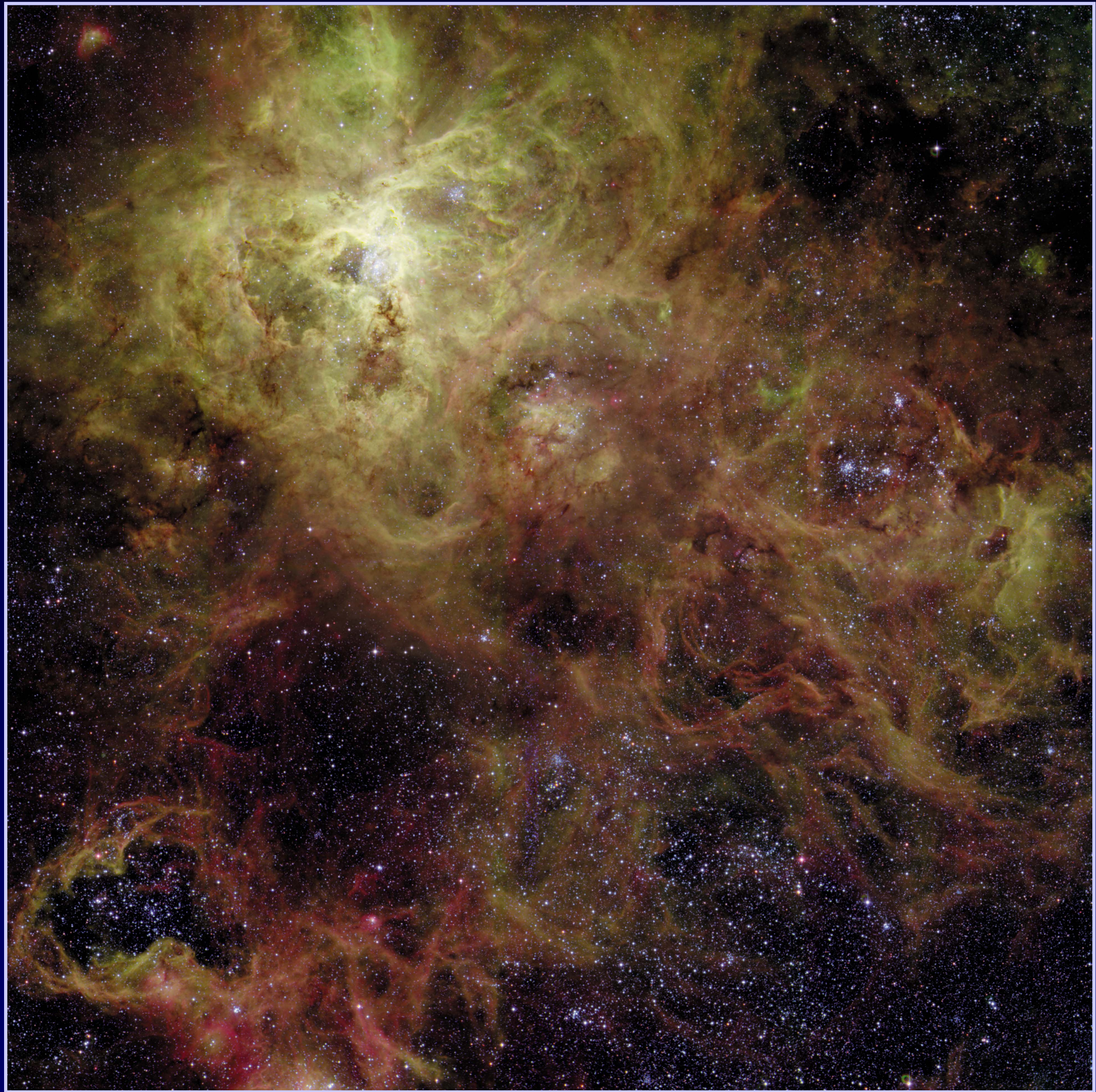
Origin and Structure of the Universe

The Cluster of Excellence for Fundamental Physics



http://www.universe-cluster.de

The End



Global Properties of Molecular Clouds

Molecular clouds are part of the most massive objects in the Galaxy.

- mass: $10^4 - 10^6 \, M_\odot$
- density: $100 \, cm^{-3}$ $\rightarrow$ $M_{Jeans} \approx 20 M_\odot$
- temperature: $10 - 30 \, K$ $\rightarrow$ $c_s = 0.3 \, km/s$
- magnetic field strength: $\sim 10^{-5} \, G$
- collapse timescale: $\tau_{ff} = 2 \cdot 10^6 \, yrs$

Number distribution of molecular clouds: $N(m) \sim m^{-2}$

Clouds with masses of $10^5 M_\odot - 10^6 M_\odot$ contain most of the molecular mass in the Galaxy.

The Puzzling Molecular Cloud Lifetimes

Star formation rate:

$$SFR = \eta_{sf} \cdot \left(\frac{2 \cdot 10^9 M_{\odot}}{\tau_{ff}} \right) \approx 100 \ \ M_{\odot} / yr$$

10% (η_{sf})

$2 \cdot 10^6$ yrs (τ_{ff})

Observations:

$\eta_{sf} \approx 1\% - 10\%$

$$SFR = 1 \ \ M_{\odot} / yr \longrightarrow \tau_{sf} \approx 5 \cdot 10^7 \ \ yr \approx 25 \cdot \tau_{ff}$$

- Molecular clouds should have long lifetimes

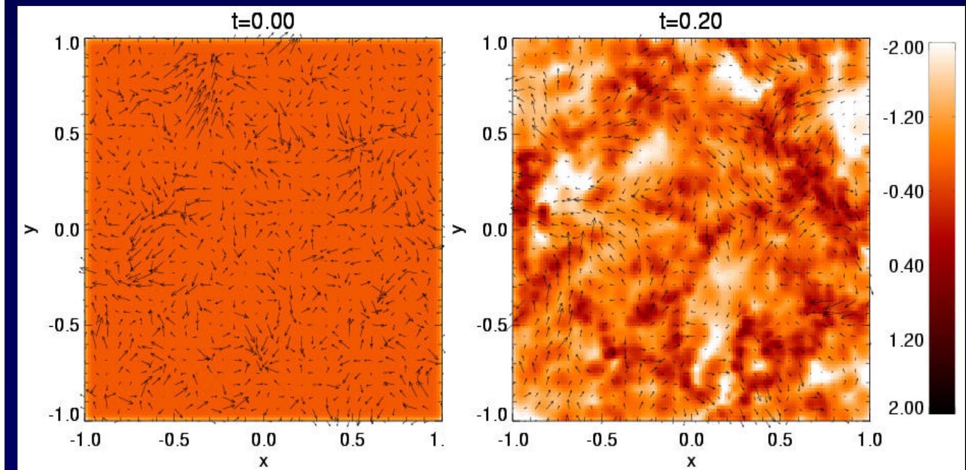
What stabilizes molecular clouds against gravitational collapse?

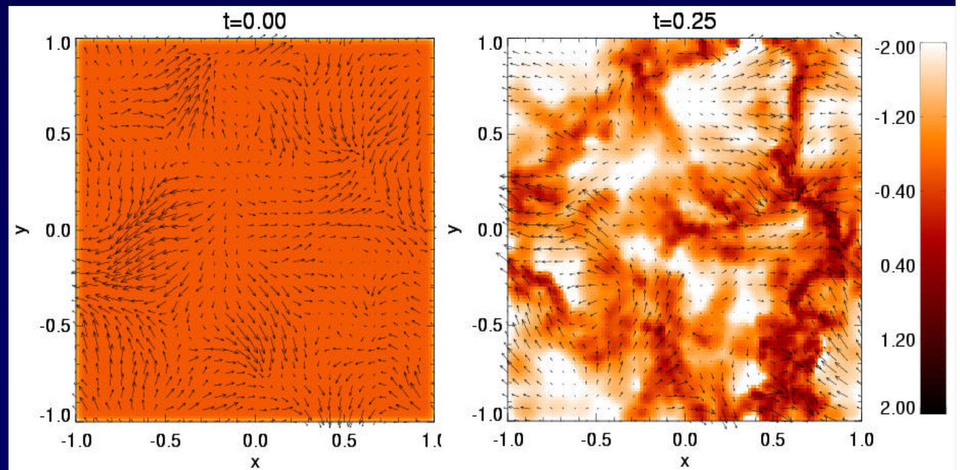
Numerical Simulations of Turbulent Molecular Clouds

Initial conditions:

- Homogeneous density distribution
- Gaussian random velocity field with $P(k) \propto k^{-n}$

$P(k) \sim k^{-2}$ Mach = 5 $P(k) \sim k^{-4}$





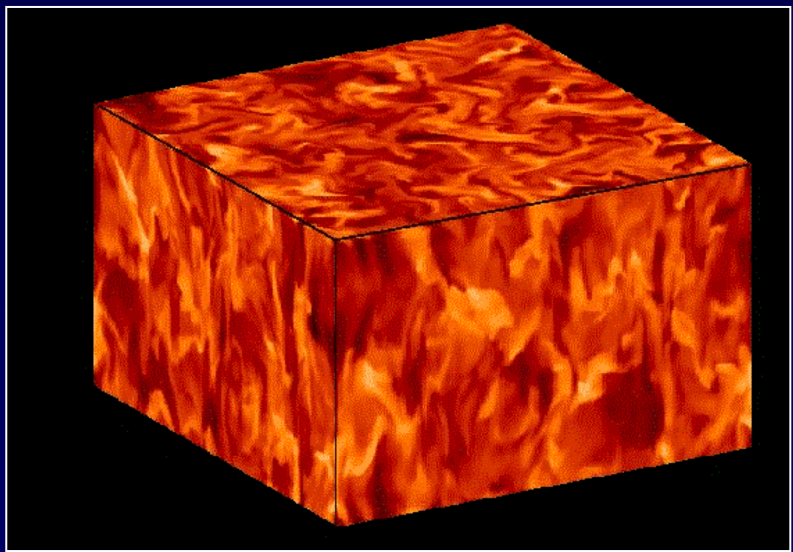
(Geyer & Burkert, 2001, 05)

Problem: Dependence on initial conditions and loss of turbulent energy

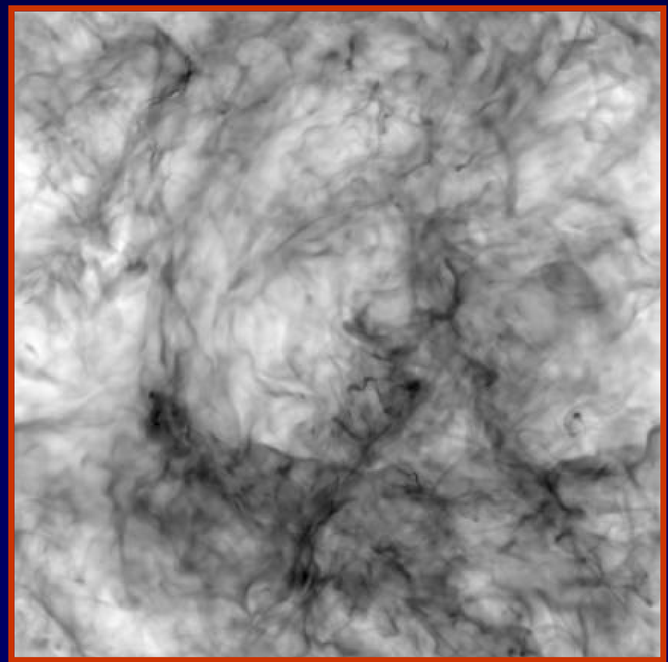
Structure of a Driven Turbulent Gas Cloud

- Continuous energy input on large scales only (k=1-2)
- Turbulent cascade of energy to smaller scales

Surface density distribution of a driven turbulent gas cloud (M=5)



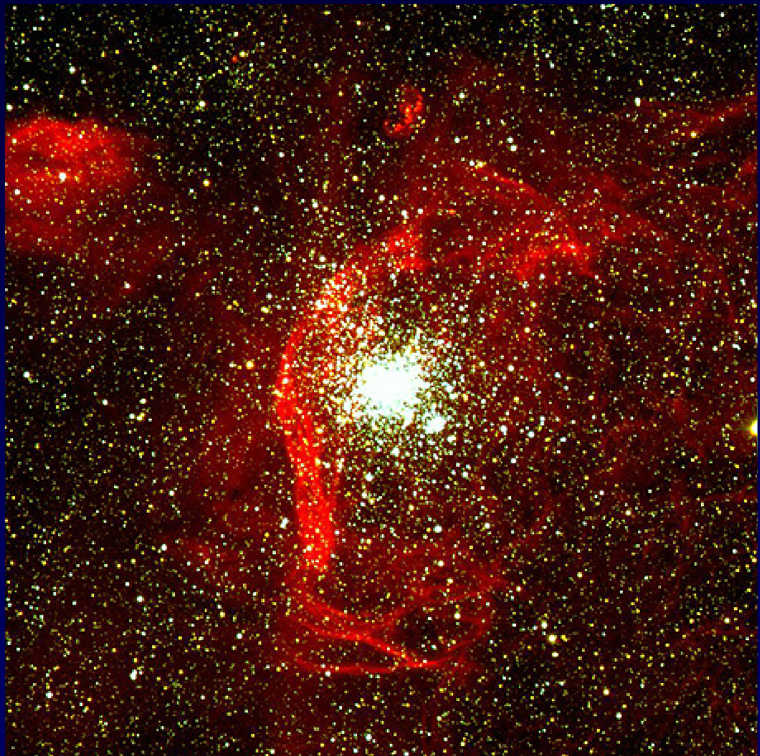
(Mac Low et al.)



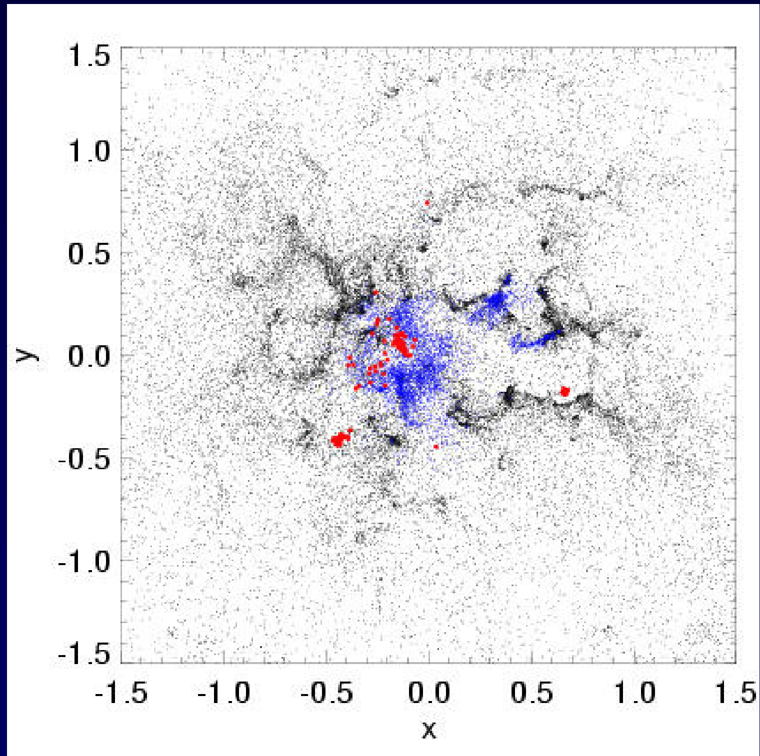
(Heitsch et al.)

Structure of the Star Cluster

NGC 1850



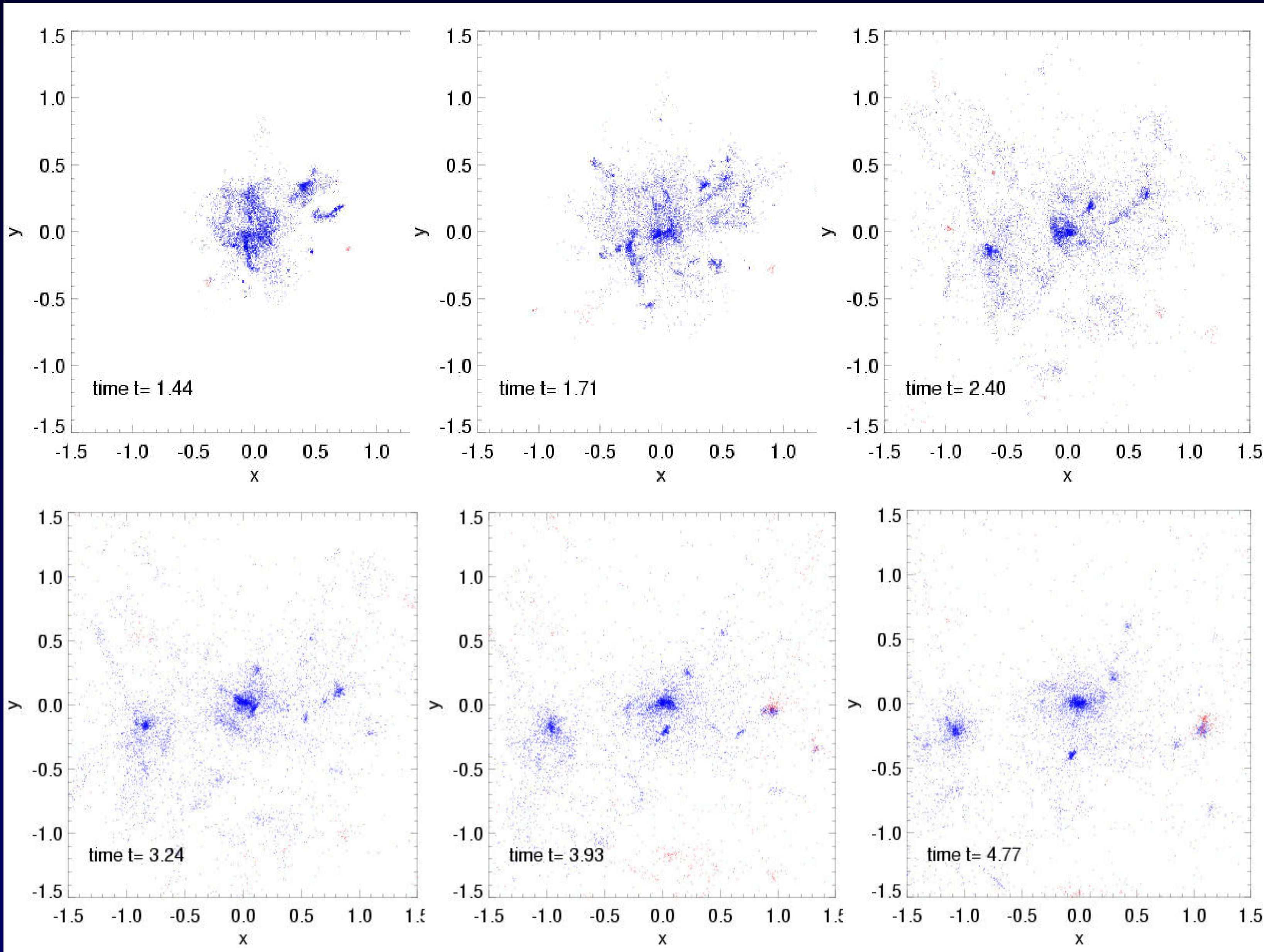
Numerical Simulation



blue: grav. bound stars

red: unbound stars

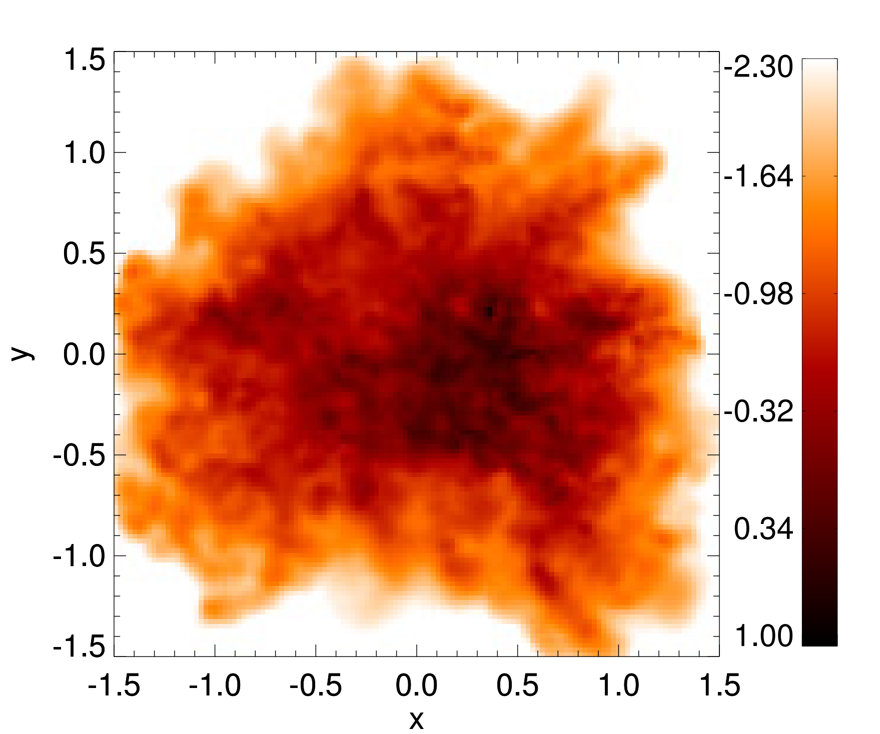
black: gas

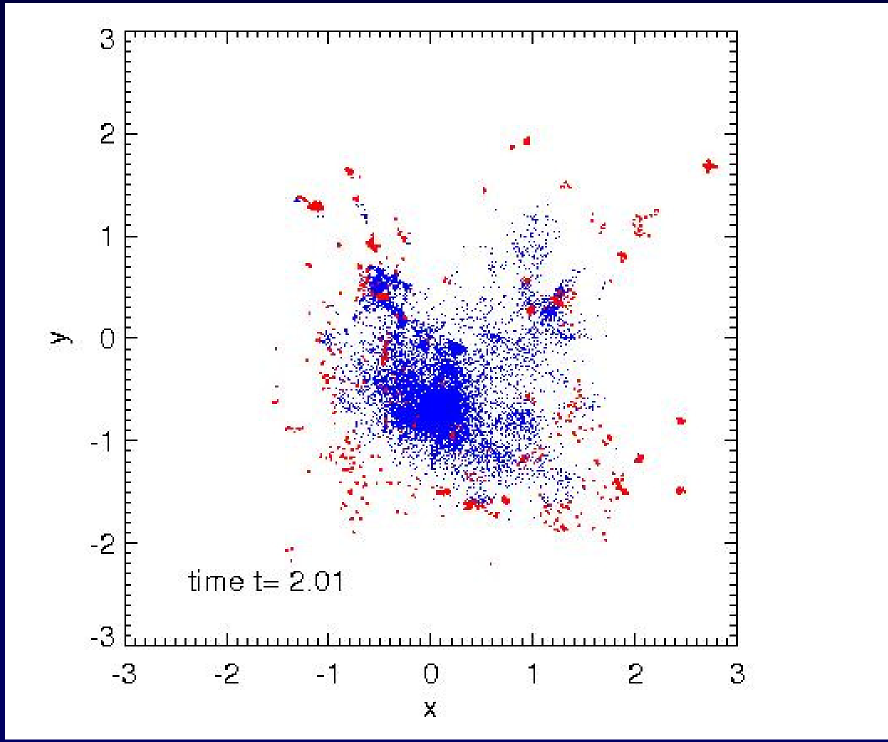


Structure similar to Faint Fuzzies (Brodie & Larsen)

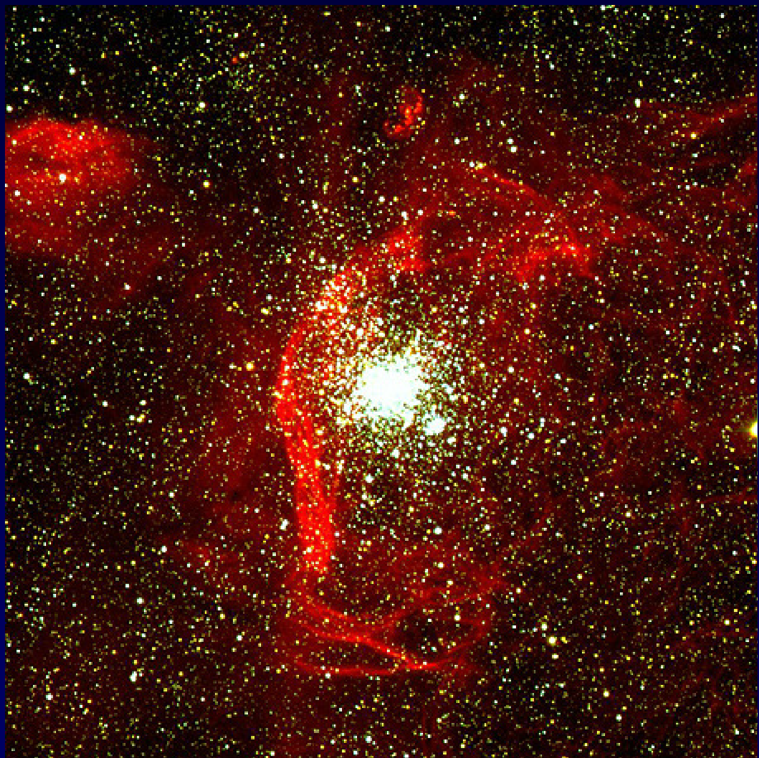
- Cut out a spherical region and remove periodic boundary condition

Massive stars are allowed to heat the surrounding gas.

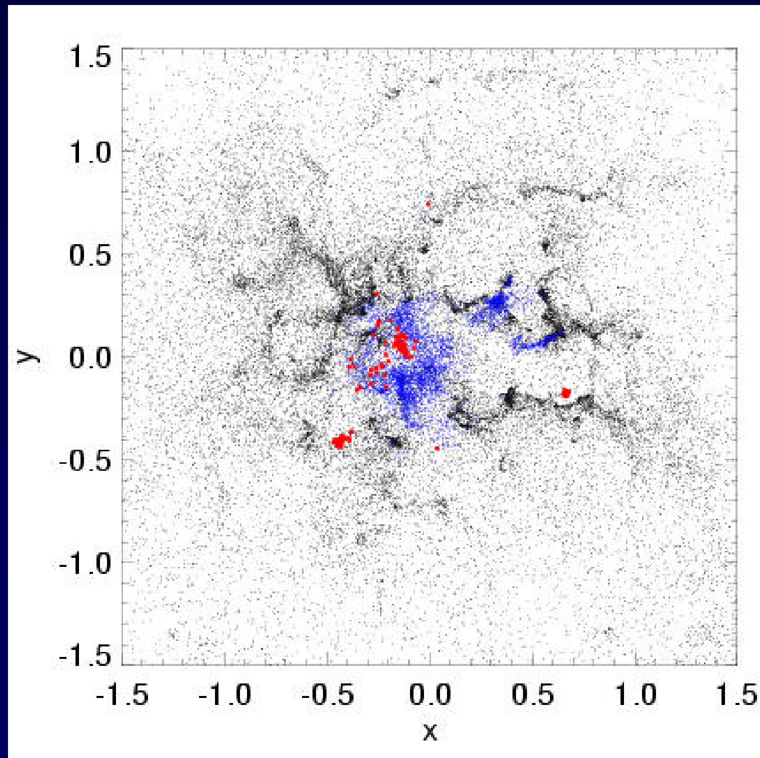




NGC 1850



Numerical Simulation



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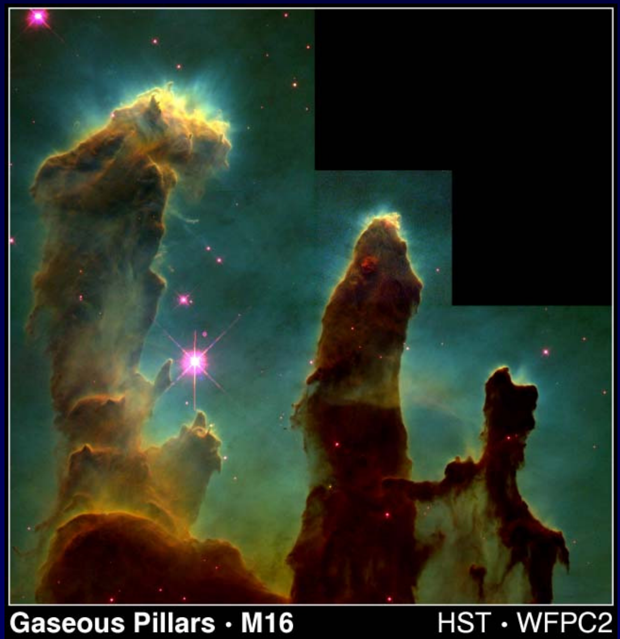
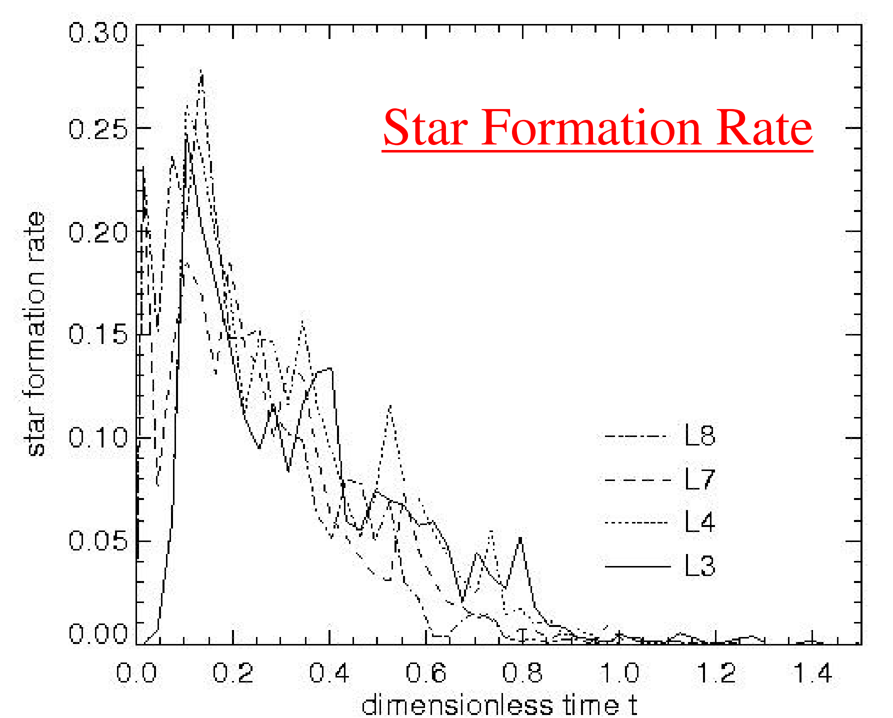
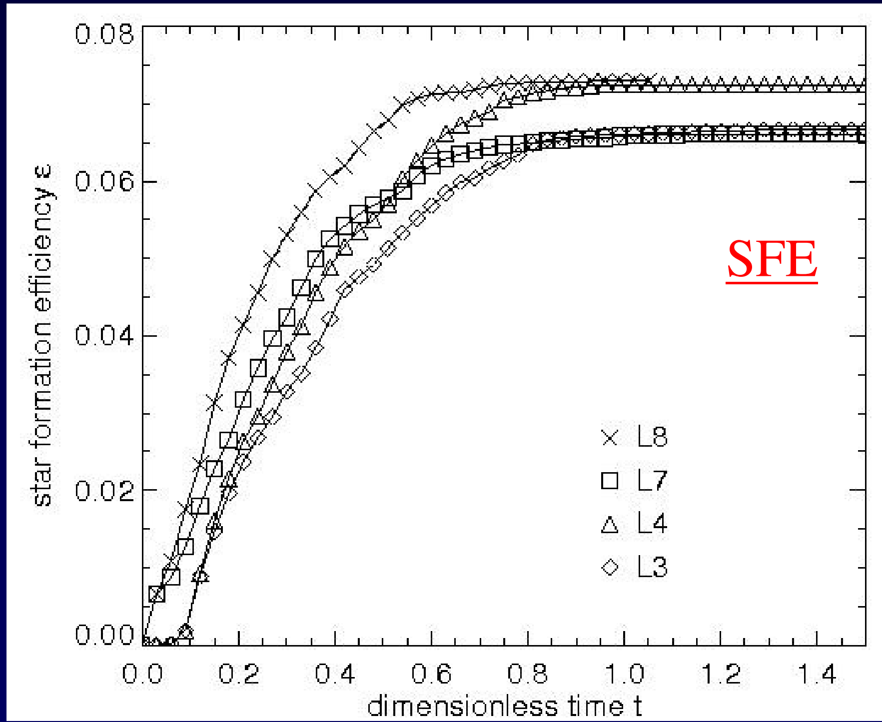

Gaseous Pillars · M16
HST · WFPC2

Star Formation Rate and Efficiency

$P(k) \propto k^{-4}$

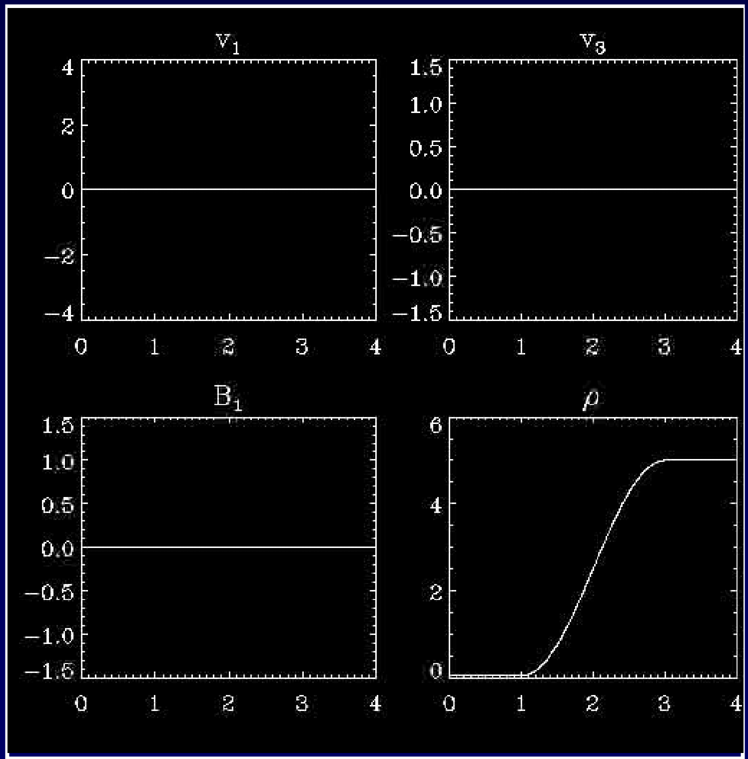


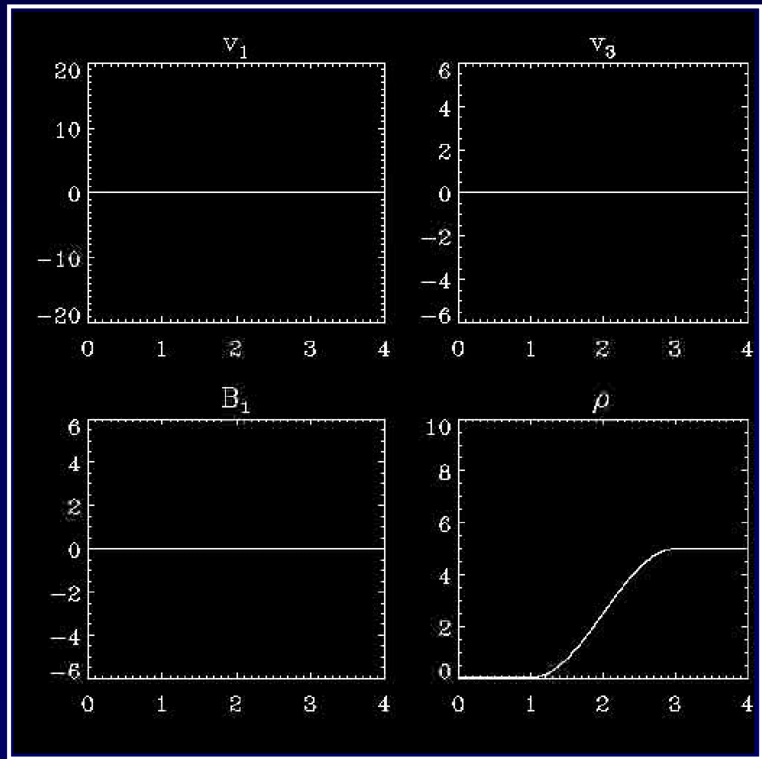


Which Mechanisms Drive Turbulence inside Molecular Clouds?

- Internal drivers can be ruled out (Klessen et al. 2001).
- Interaction with the turbulent, diffuse environment by Alvén waves.

  Problem: Efficient energy dissipation at the cloud boundary.





Mach=4

(Heitsch & Burkert, 2001)

Mach=10

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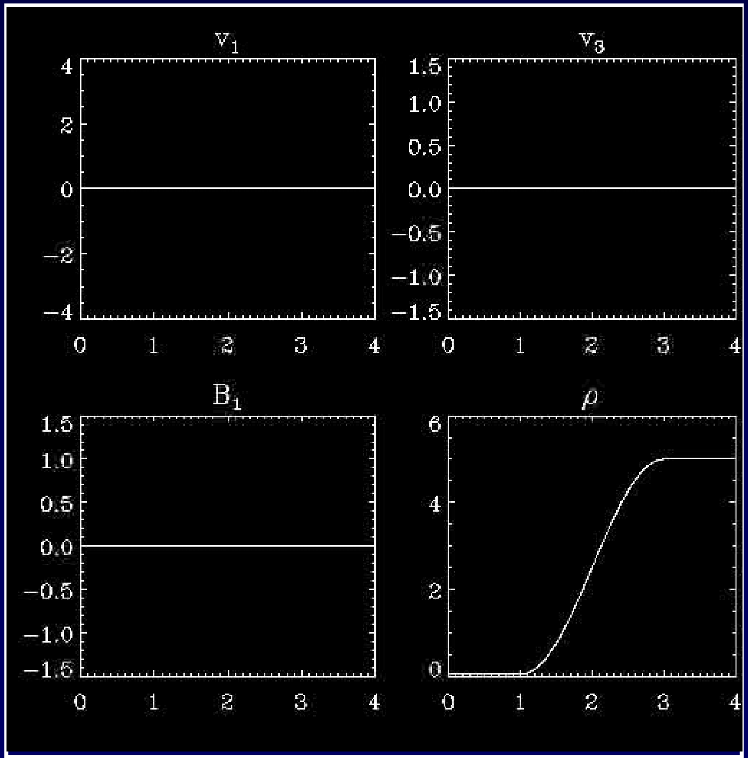

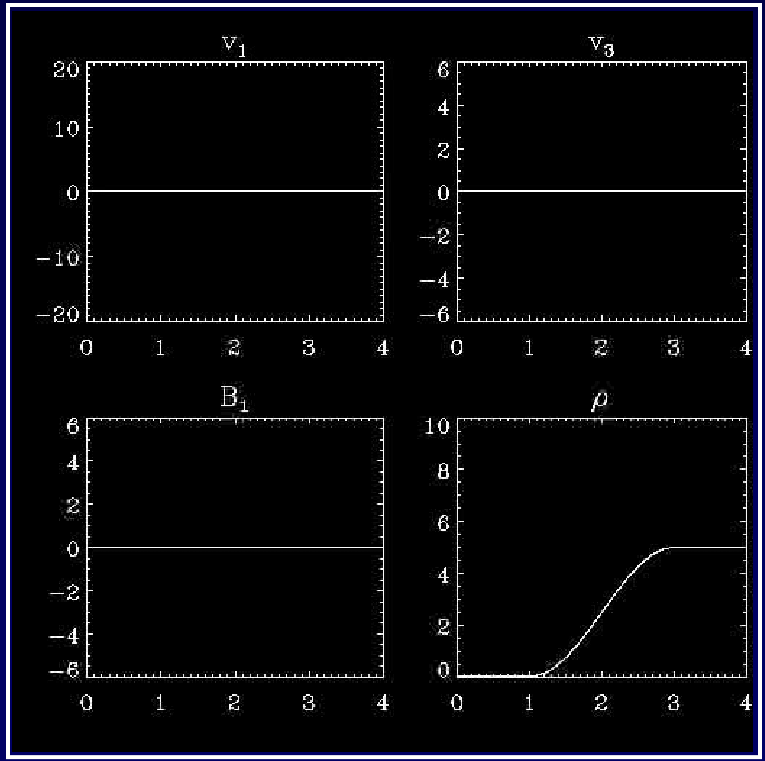

Mach=4

(Heitsch & Burkert, 2001)

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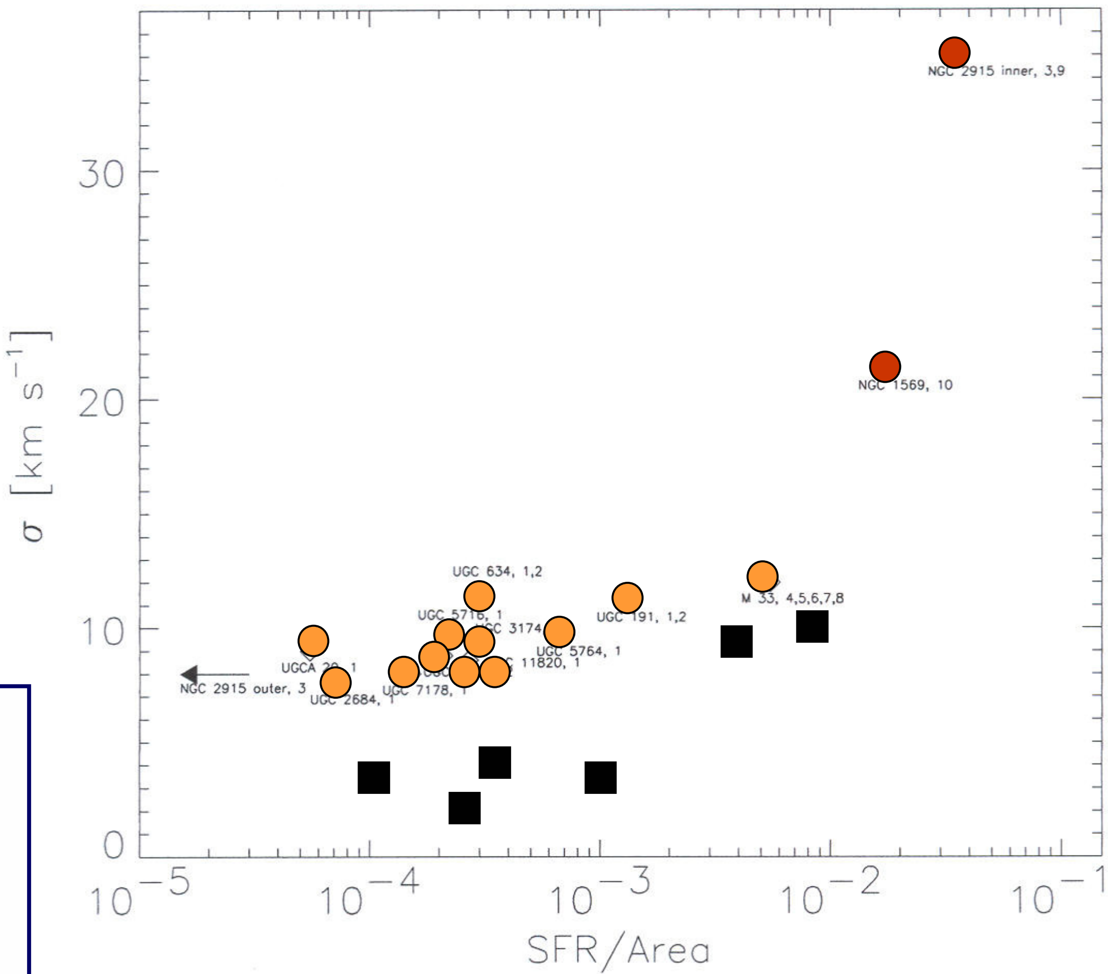
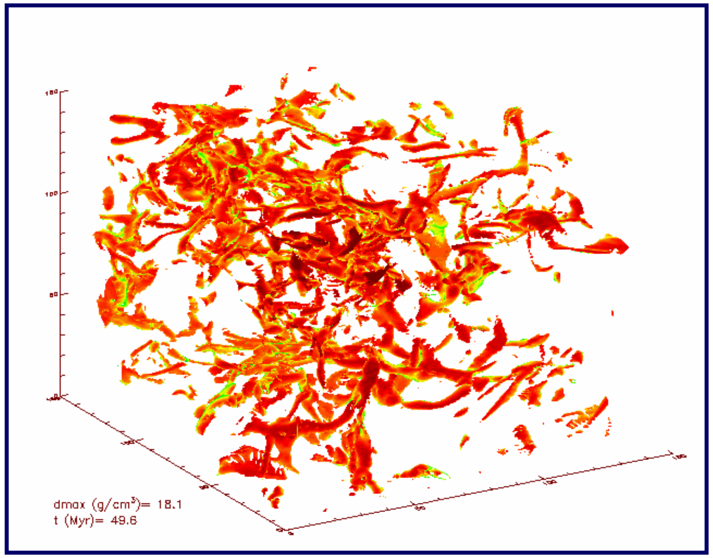
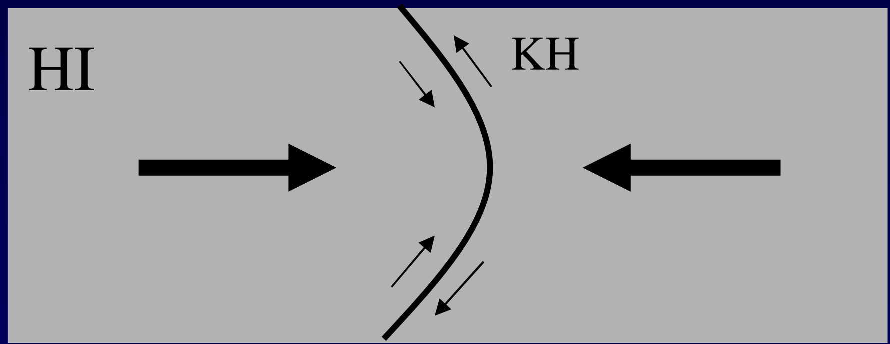


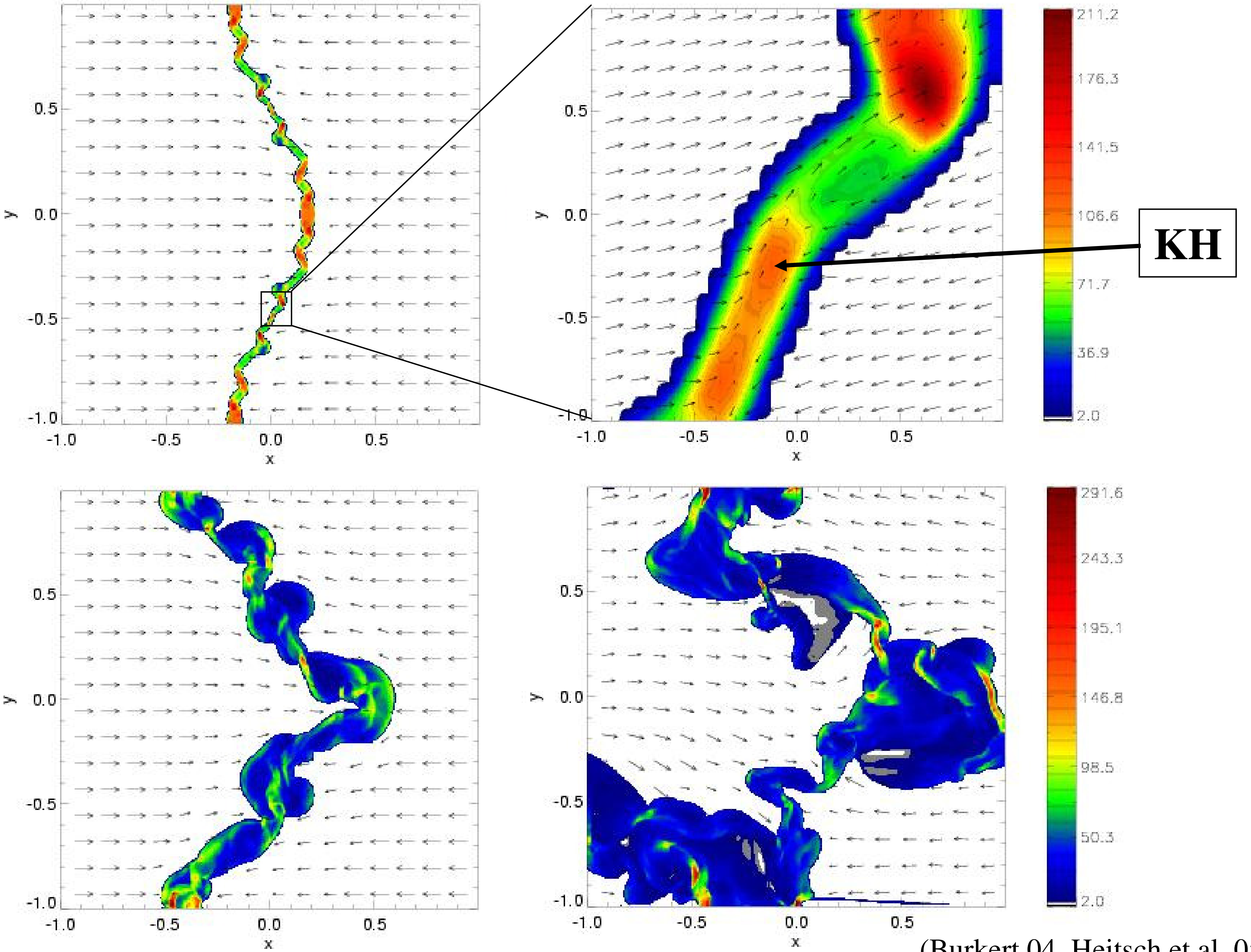


(Dib, Bell & Burkert 2006)

Cloud Formation in Shock Compressed Layers

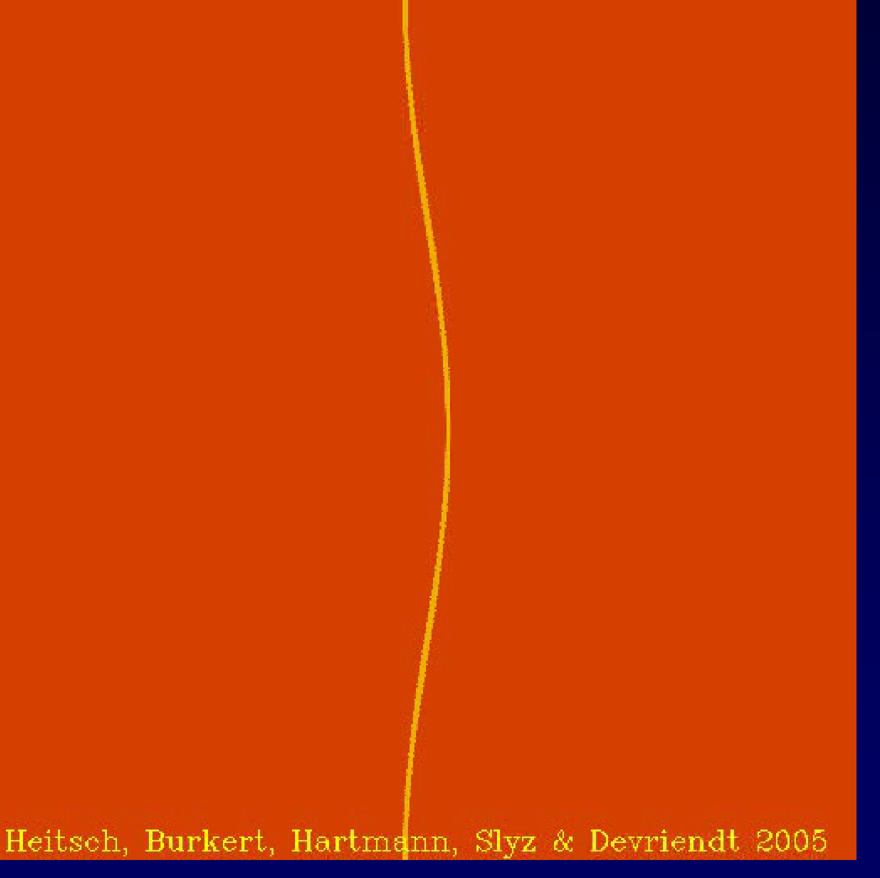
Non-linear Thin Shell Instability





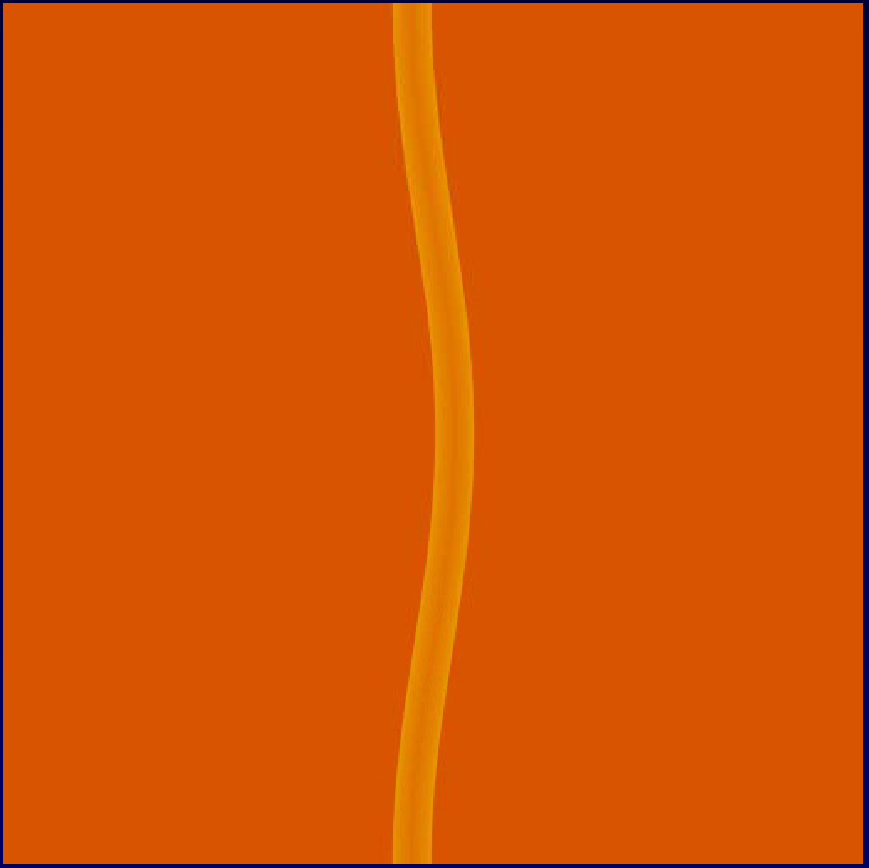
(Burkert 04, Heitsch et al. 05)

NTSI Instability



low density, high velocity

Kelvin-Helmholtz Instability



Heitsch et al. (05)

low density, low velocity

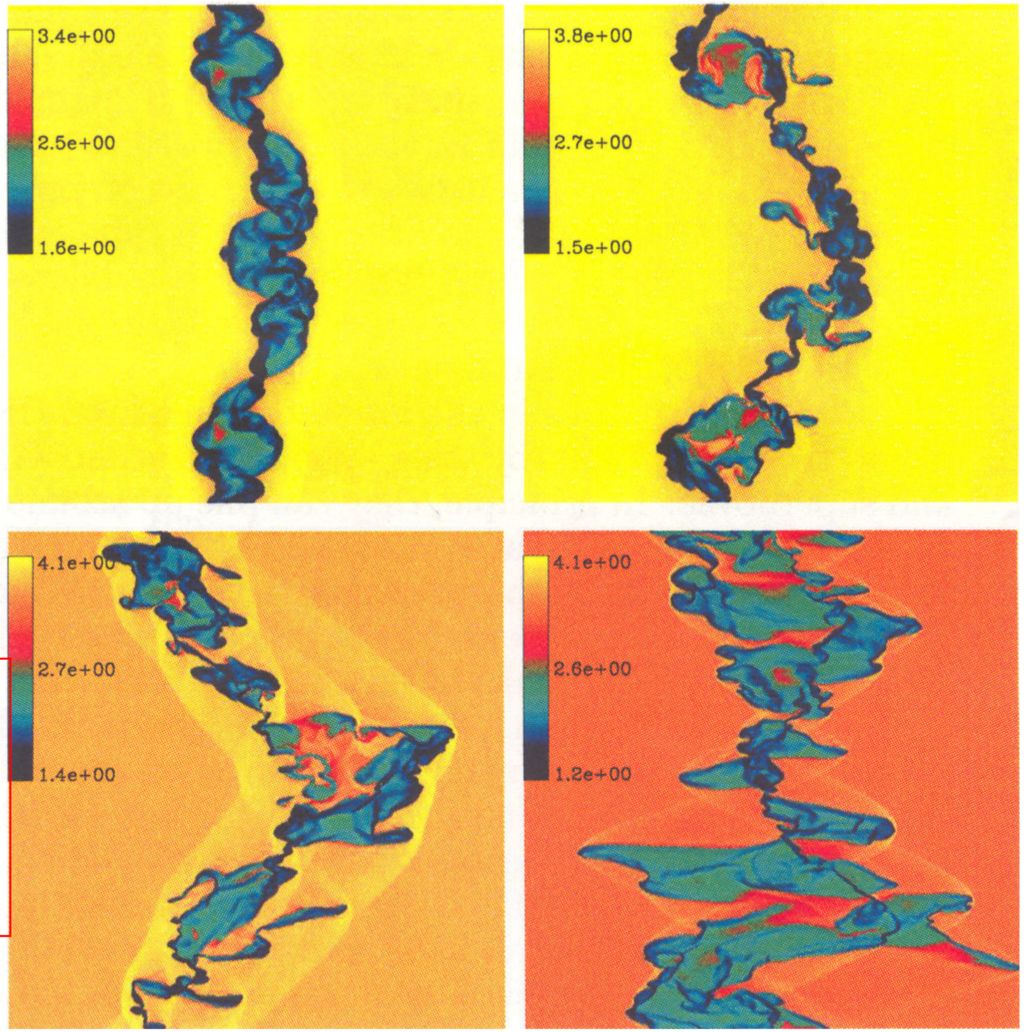
Dominant Instabilities

high density, low velocity

low density, low velocity

Thermal Instability

Kelvin Helmholz Instabiliy

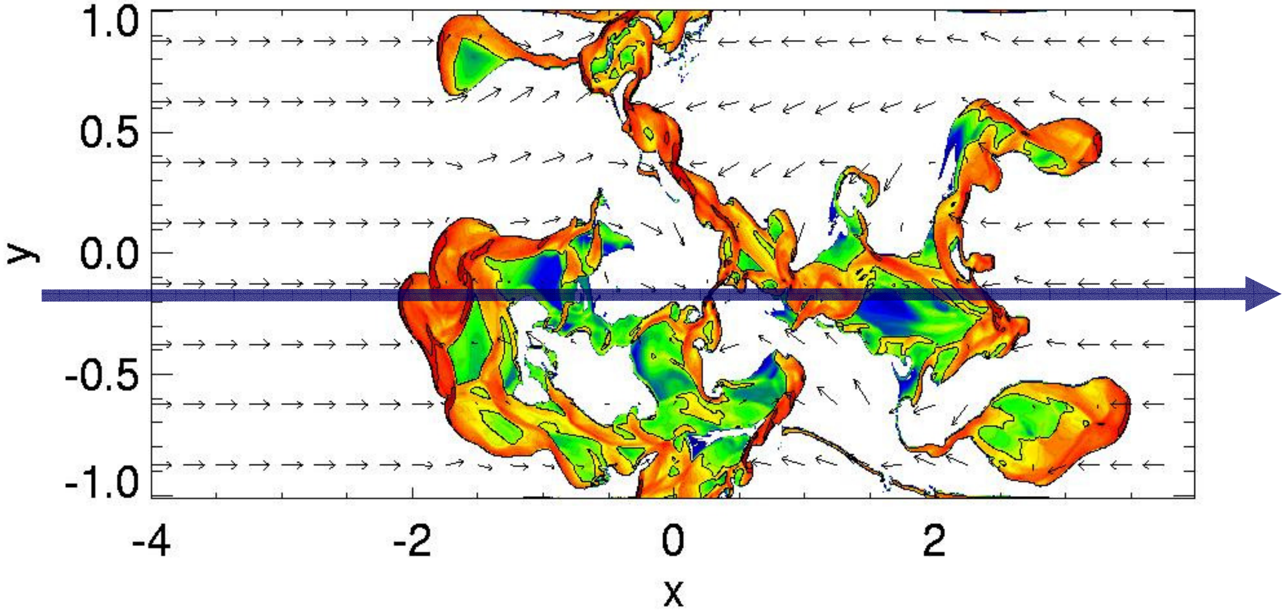


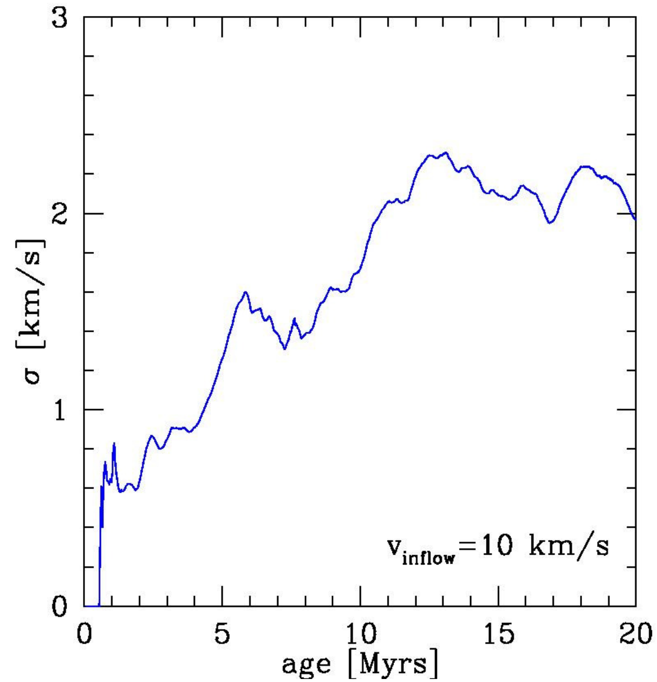
Kelvin Helmholz + NTSI Instability

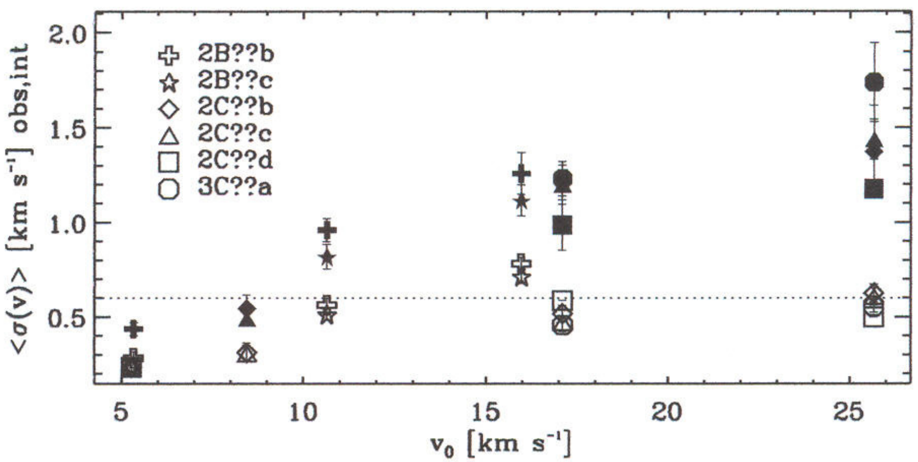
NTSI Instabiliy

high density, high velocity

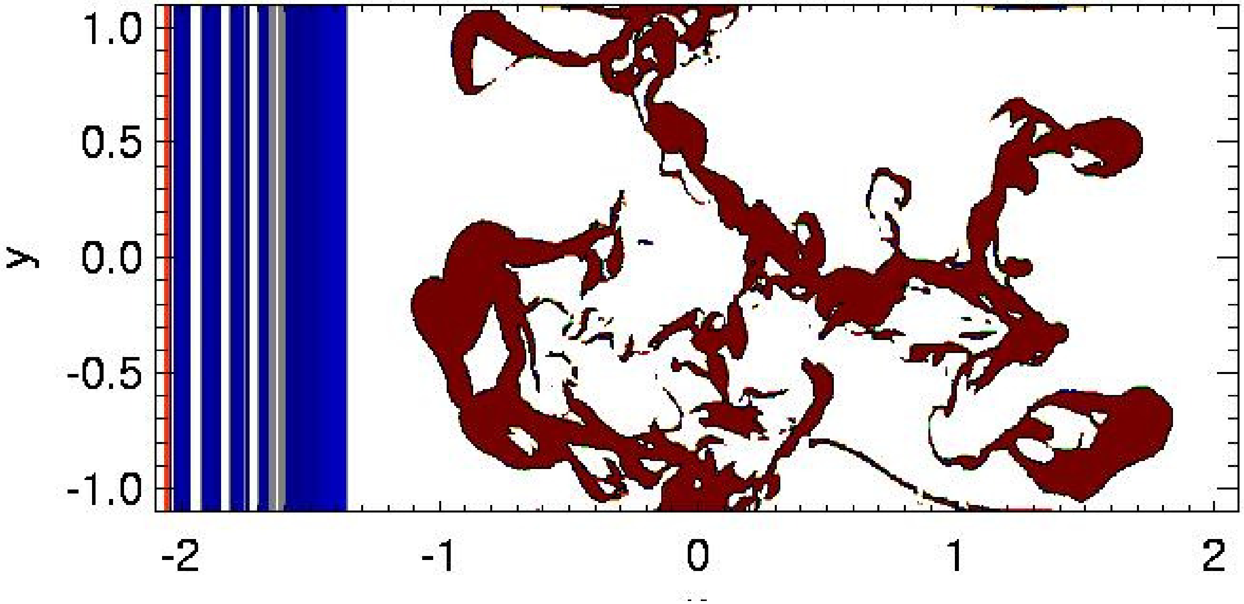
low density, high velocity

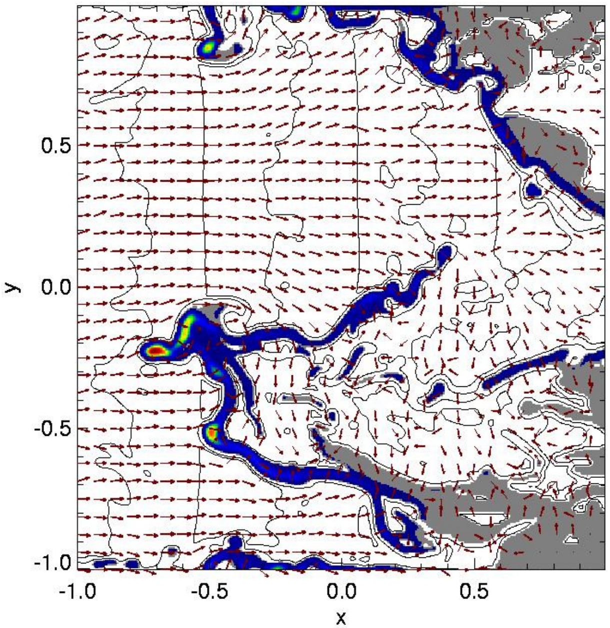






(Heitsch et al. 2006)

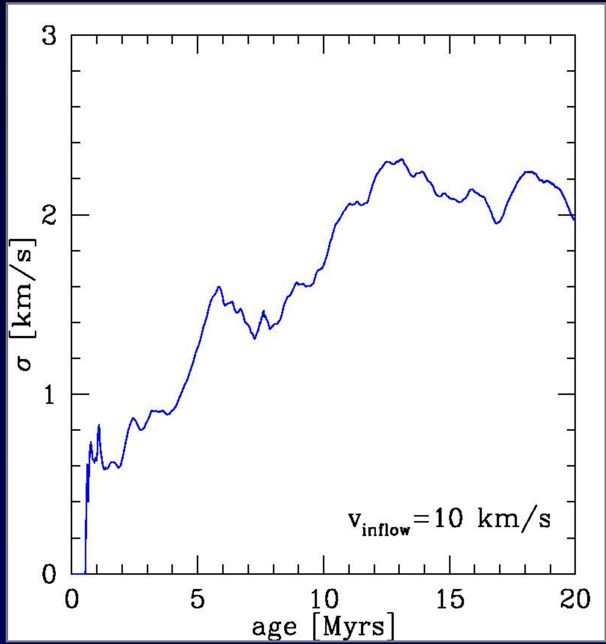




(Burkert & Heitsch 07)

The Efficiency of Molecular Cloud Disruption and Formation

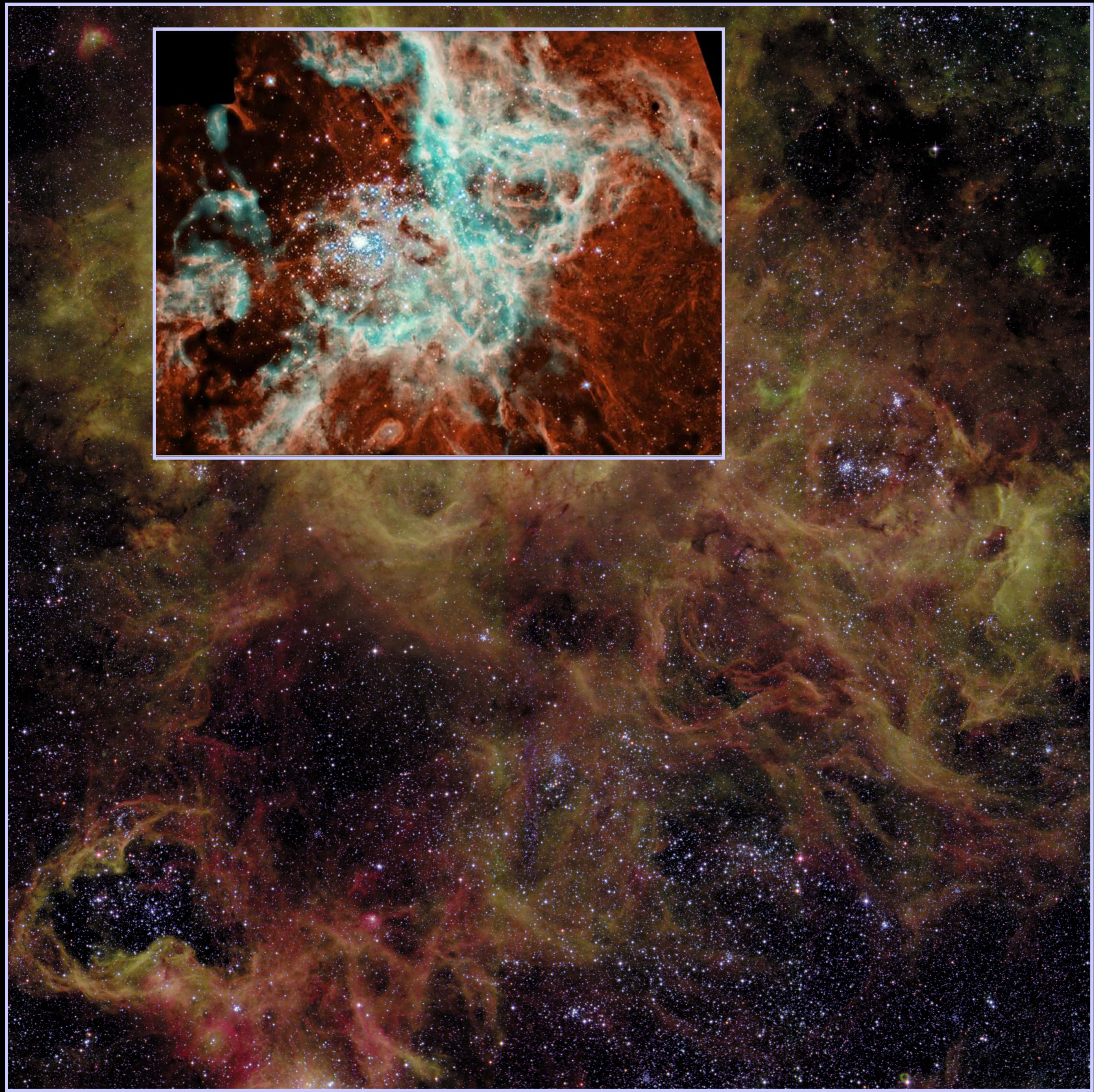
Age spread of stars in Taurus: 1 – 3 Myrs



→ Molecular clouds are dispersed after ~ 4 Myrs

Almost all molecular clouds in the solar neighborhood form stars (Hartmann 03)

→ Molecular clouds form as quickly as they are dispersed.



Summary I

- Stars form in dense, clumpy molecular clouds.
- Supersonic turbulence suppresses global collapse and generates a clumpy density distribution.
- This turbulence was generated on large scales.
- Due to turbulent energy dissipation molecular clouds should condense into stars within a free falltime.

Is there a yet unknown large-scale driver of MC turbulence?

- Star formation is likely to be an initial condition problem and the molecular cloud structure is imprinted at the time of formation.

Which processes lead to clouds with supersonic turbulence?

Summary II

- Molecular cloud disruption by the newly formed stars still keeps most of the dispersed gas in a molecular state.

Where is all that molecular cloud debris?

- The dispersed molecular gas needs to be swept up again on timescales of order a few Myrs.

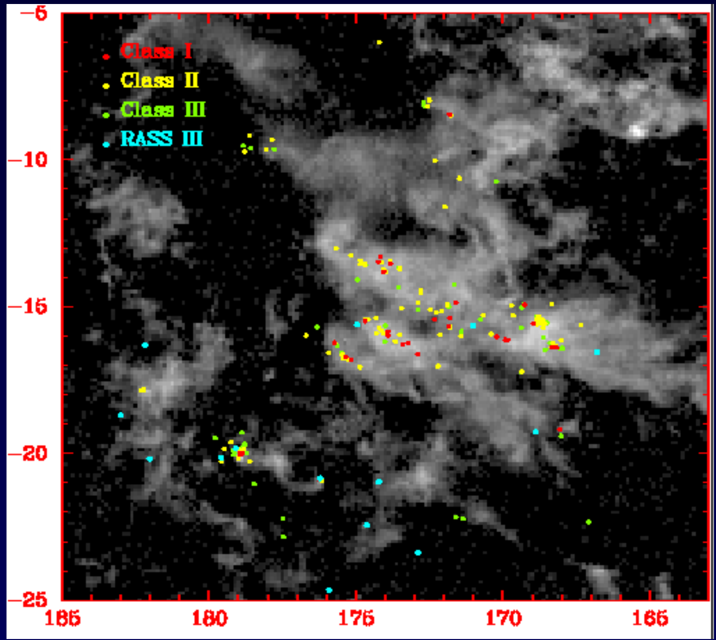
Which processes are that efficient?

- The star formation efficiency is in general very small $\eta_{sf} \approx 0.5\%$

Is this in agreement with observations?

The Post T-Tauri Problem

- Age spread of stars in Taurus: $1-3$ Myrs
- Lateral crossing timescale: $20-30$ Myrs



(Hartmann 2000, 2001)

Which processes coordinated star formation in Taurus?

Clumpy Substructure of Molecular Clouds

Clumps are unbound turbulent density fluctuations

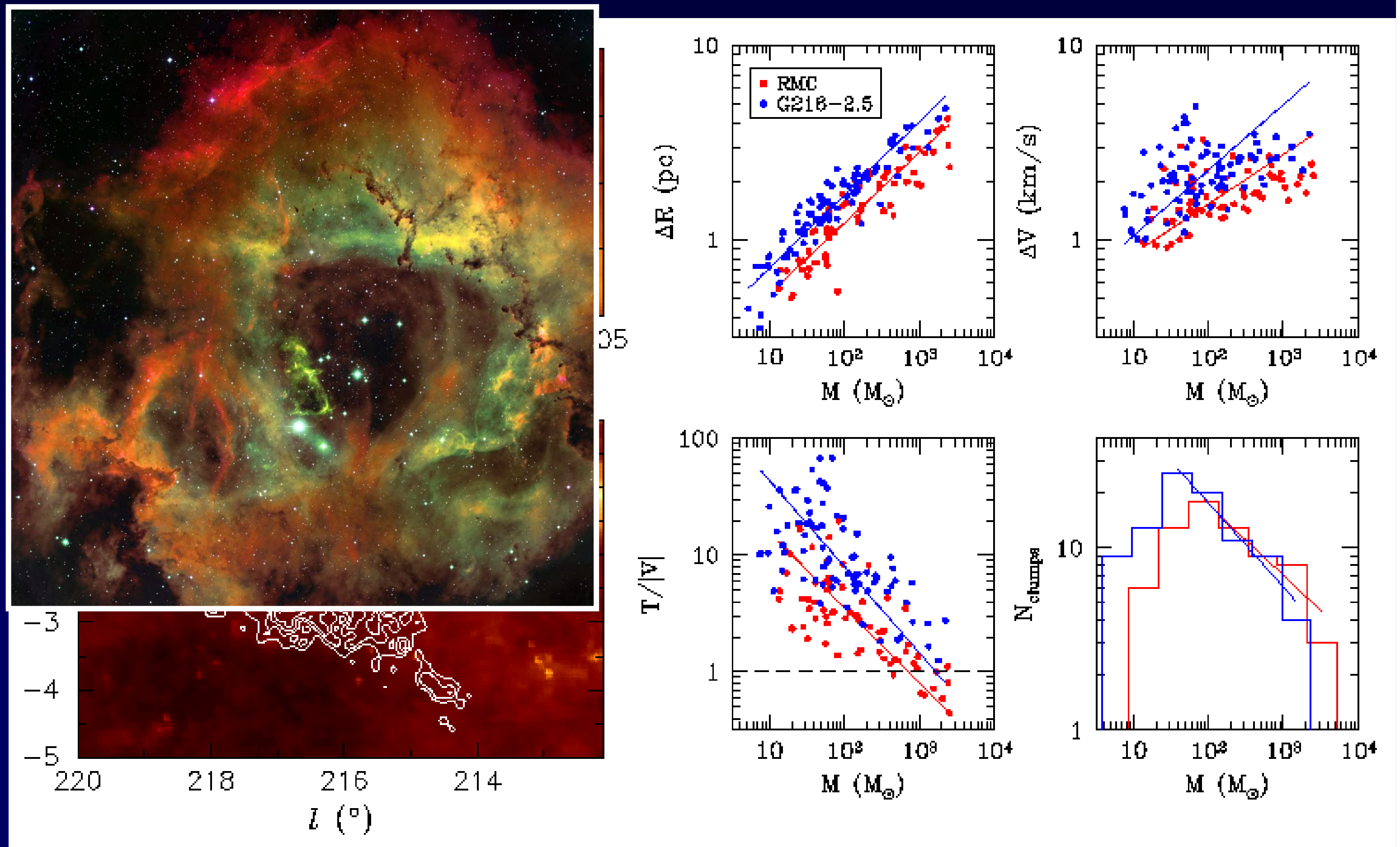
Scaling Relations:

$R \propto M^{0.5}$

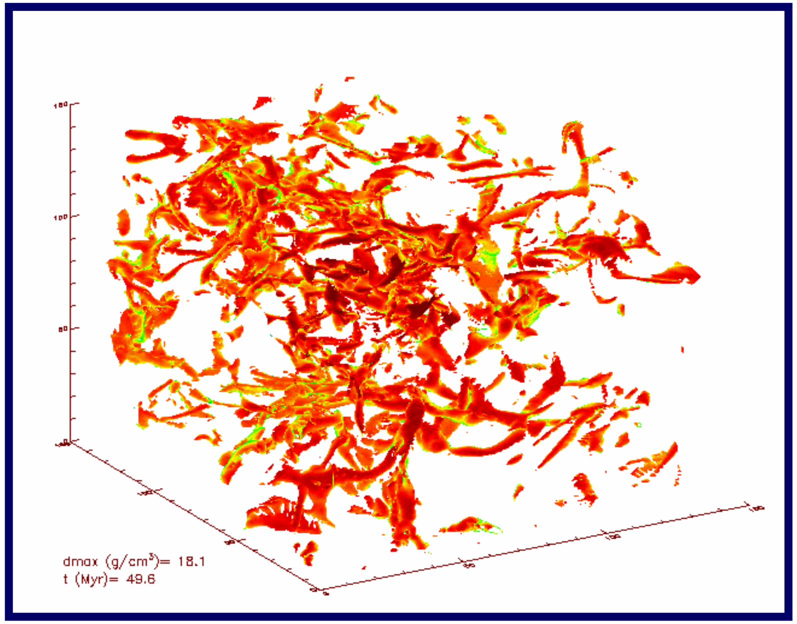
$\sigma \propto M^{0.3}$

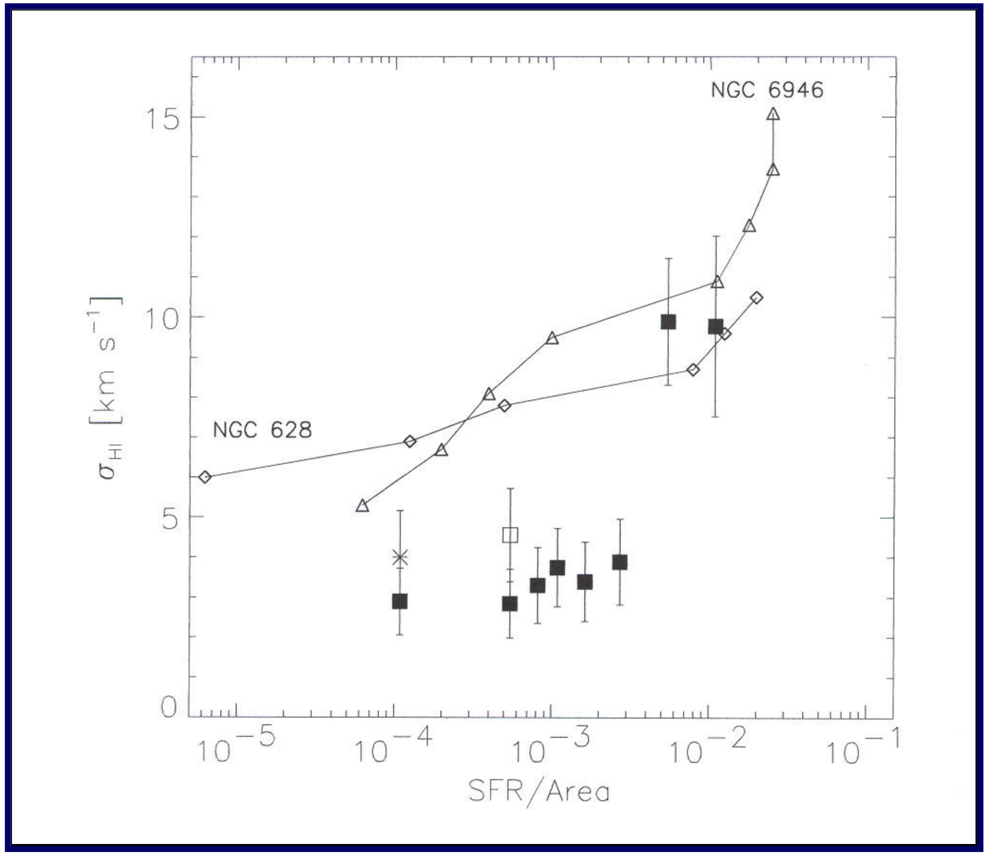
$N \propto M^{-2}$

(Larson 81)

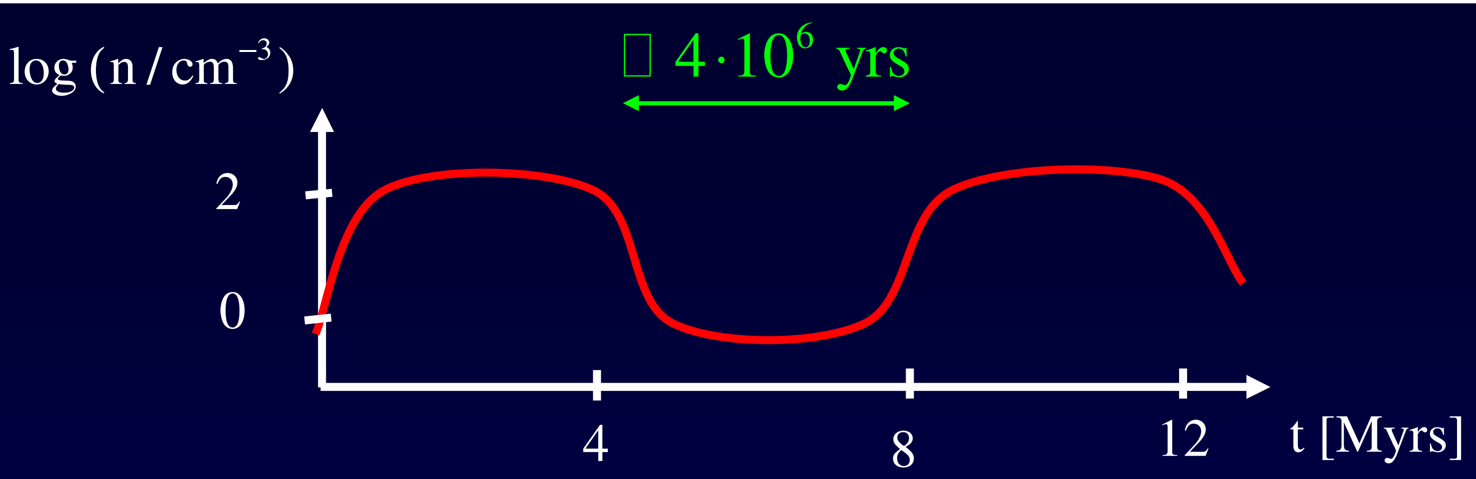


(Williams et al. 2000)





(Dib et al. 2006)



For most of the dispersed molecular gas to be in clouds, the dispersed molecular material needs to be swept up into new clouds on timescales of

$$\tau \approx 4\cdot 10^6 \text{ yrs}$$

In addition, star formation must be very inefficient:

$$SFR = \eta_{sf}\frac{2\cdot 10^9\, M_\odot}{4\cdot 10^6 \text{ yrs}} \approx 500\,\eta_{sf}\, M_\odot/\text{yr} \quad \rightarrow \quad \eta_{sf} \approx 0.002$$

Star Formation

The formation of stars is yet an unsolved astrophysical problem.

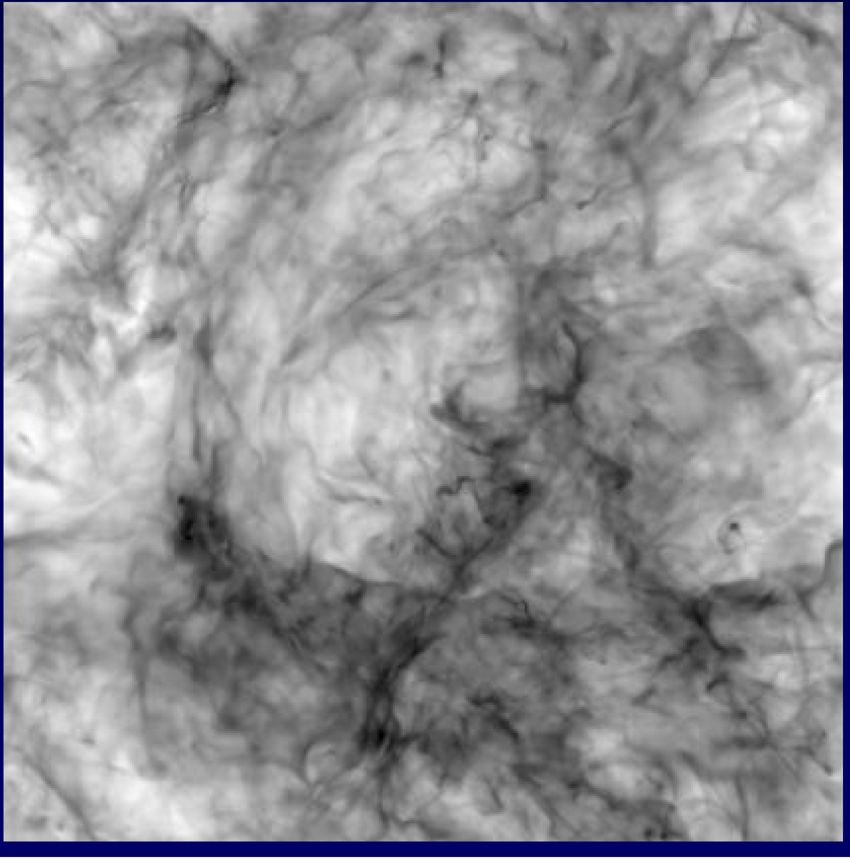
<u>Observations:</u>

- Stars form in turbulent, clumpy giant molecular clouds.
- Stars form on short timescales and in clusters.
- The star formation efficiency is low.
- The stellar initial mass function is universal.
- Stars form preferentially as binaries with a very broad period distribution.

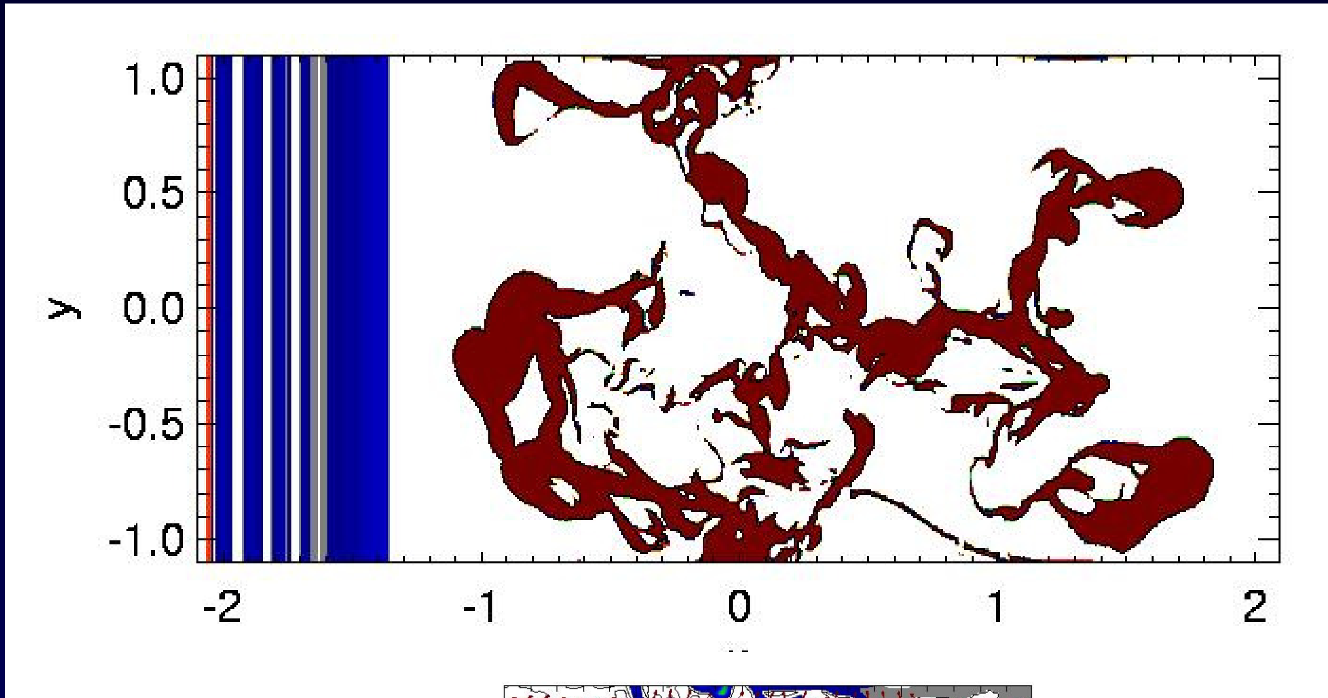
Structure of a Driven Turbulent Gas Cloud

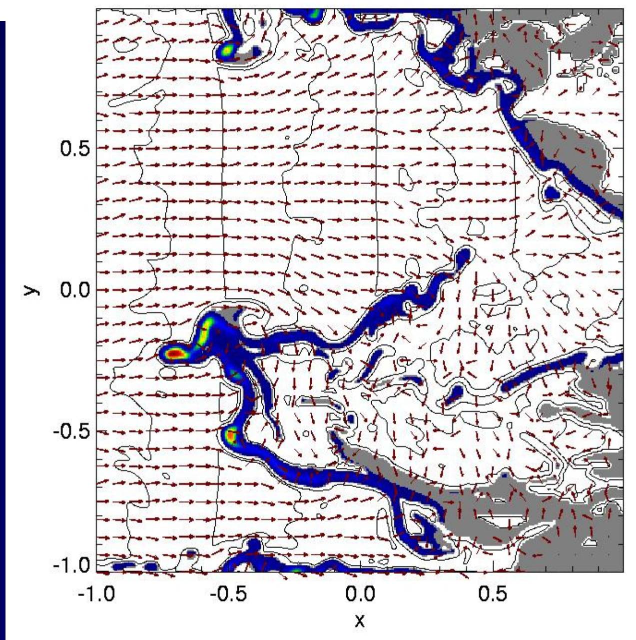
- Continuous energy input on large scales only (k=1-2)
- Turbulent cascade of energy to smaller scales

Surface density distribution of a driven turbulent gas cloud (M=5)



(Heitsch)



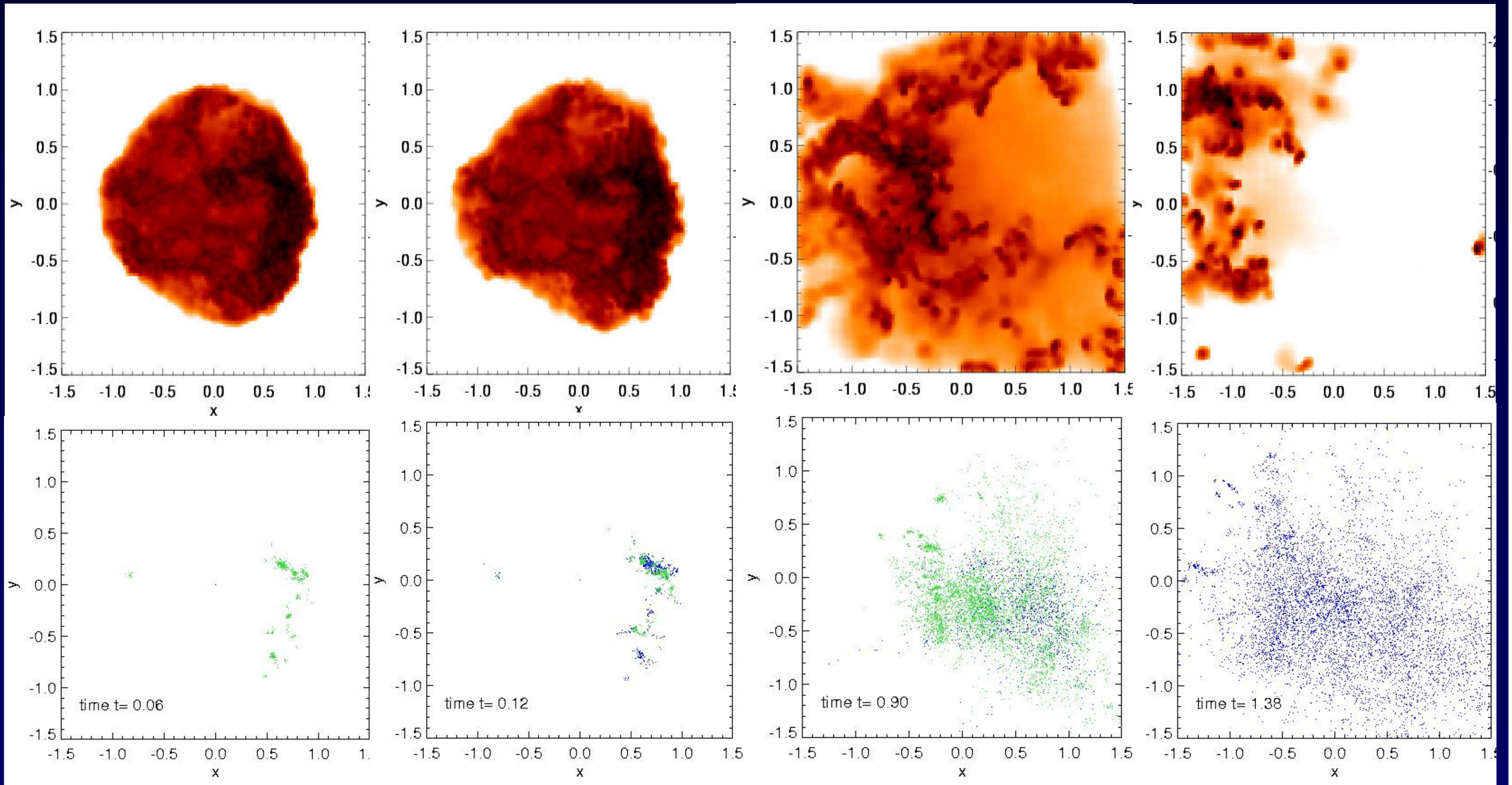


(Burkert & Heitsch 06)

Star Formation with a Low Density Threshold

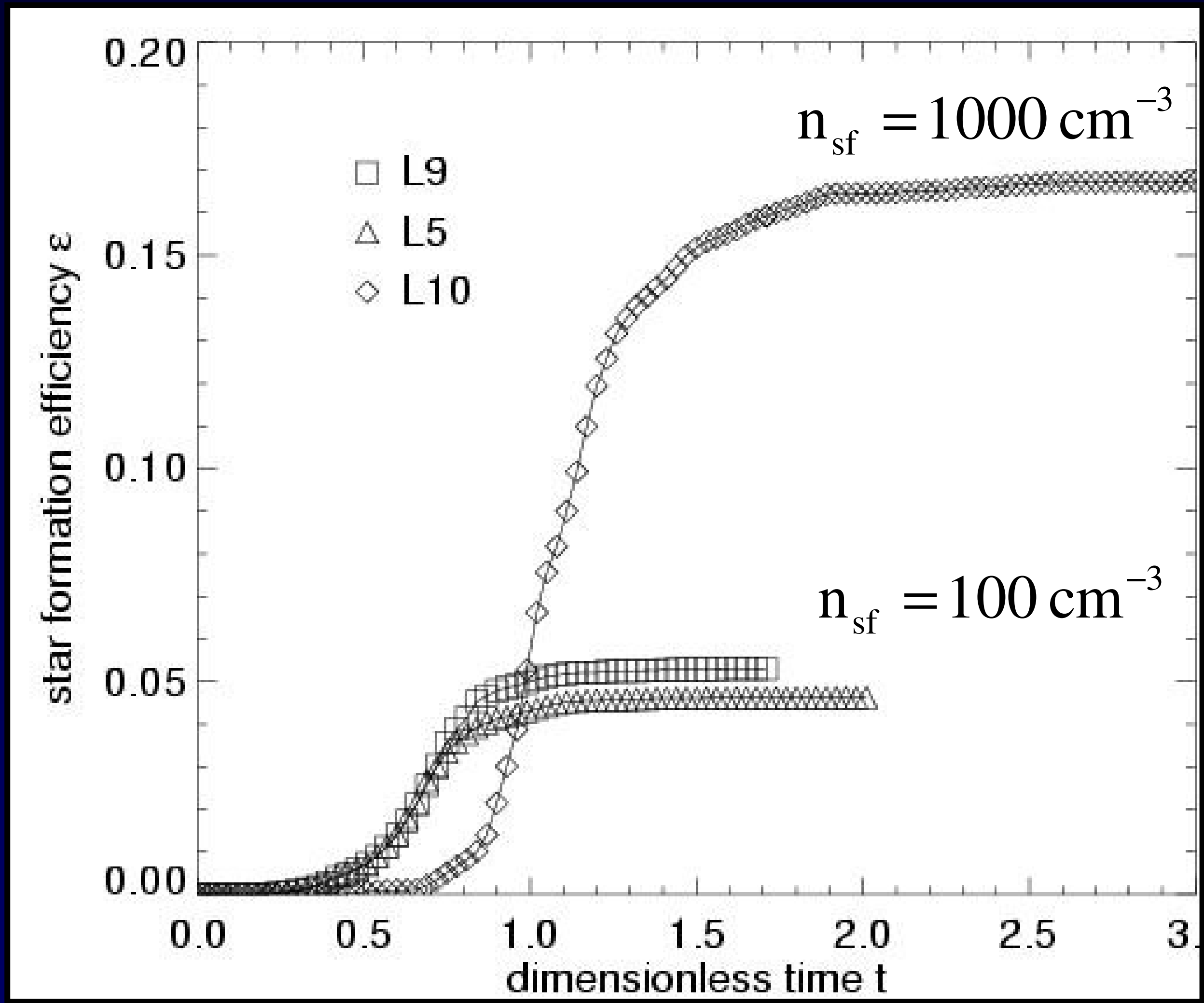
Gas

$n_{sf} = 100\,cm^{-3}$



Stars

(Geyer & Burkert, 2007)



0.20
0.15
0.10
0.05
0.00
star formation efficiency ε
$n_{sf} = 1000\,cm^{-3}$
$n_{sf} = 100\,cm^{-3}$
L9
L5
L10
0.0
0.5
1.0
1.5
2.0
2.5
3.
dimensionless time t