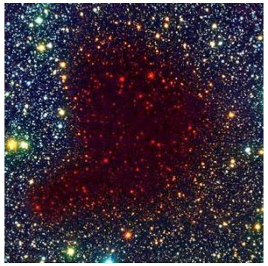
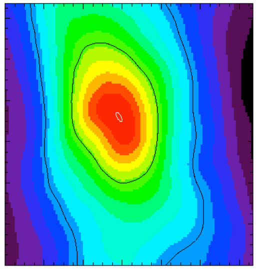
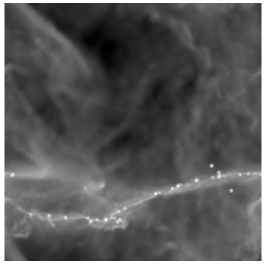
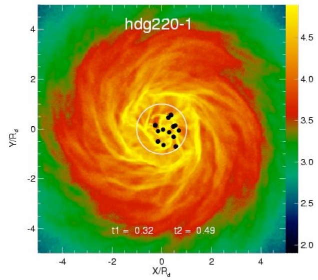
star formation in disk galaxies









Ralf Klessen

Zentrum für Astronomie der Universität Heidelberg
Institut für Theoretische Astrophysik

agenda

- phenomenology
  - stars
  - gas
- interplay between gravity and turbulence
- examples and predictions
  - transient cloud structure
  - stellar initial mass function

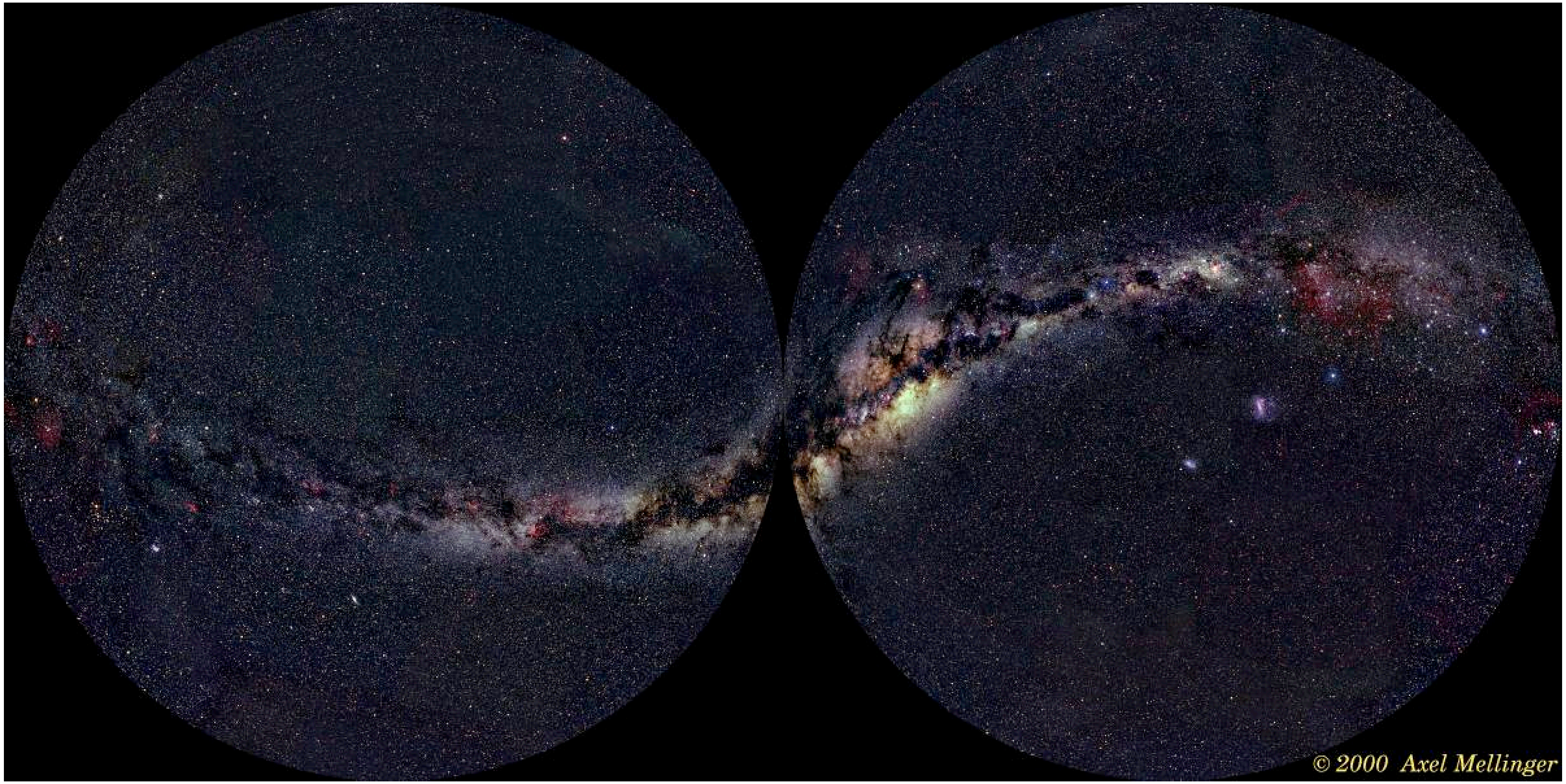
stars

young stars in spiral galaxies

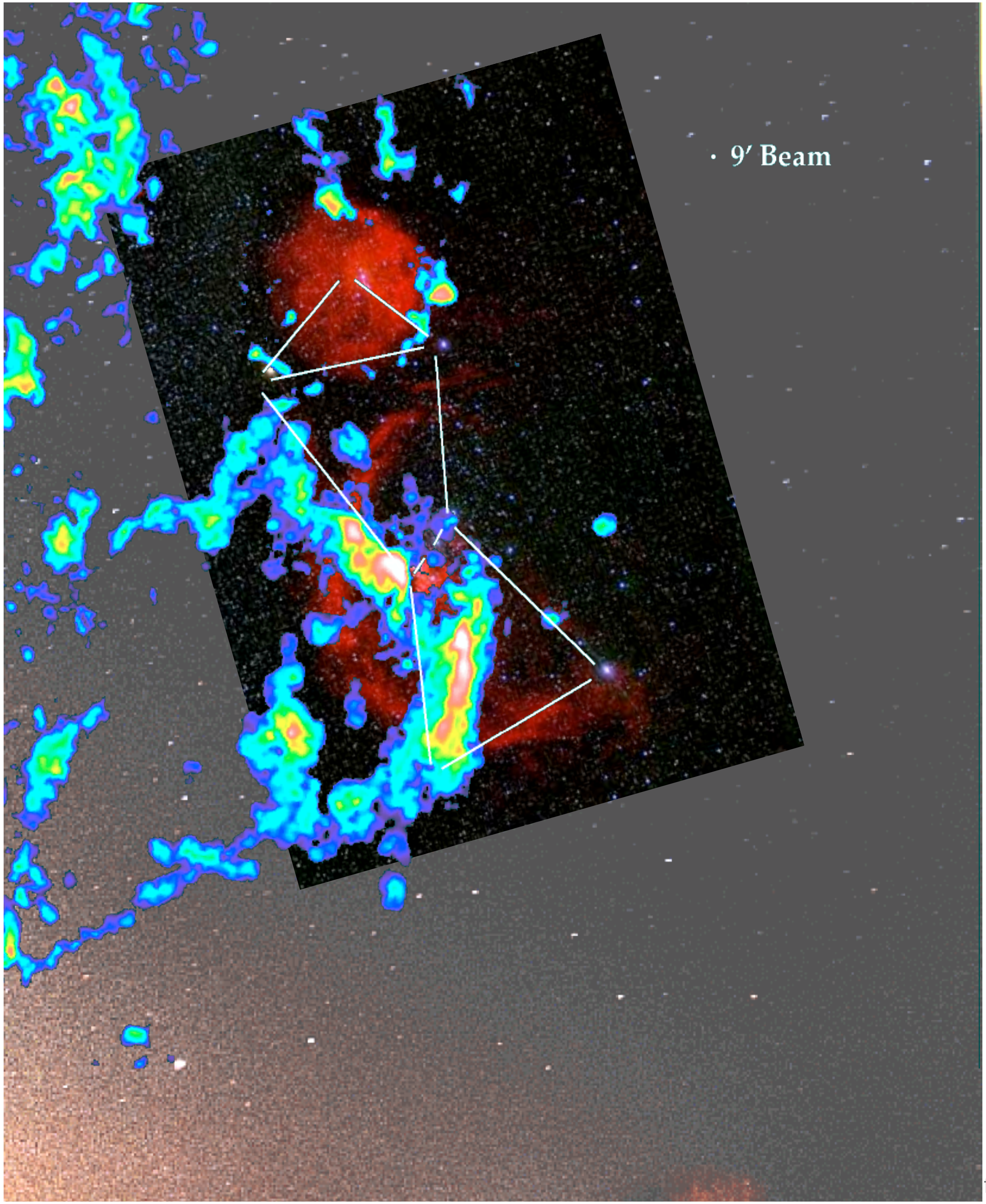
(NGC 4622 from the Hubble Heritage Team)

- Star formation *always* is associated with *clouds of gas and dust*.
- Star formation is essentially a *local phenomenon* (on ~pc scale)
- HOW is star formation is *influenced* by *global* properties of the galaxy?

young stars in the Milky Way



On the night sky, you see ***stars*** and ***dark clouds***:
The brightest stars are massive and therefore young.
→ Star formation is important for understanding the structure of our Galaxy

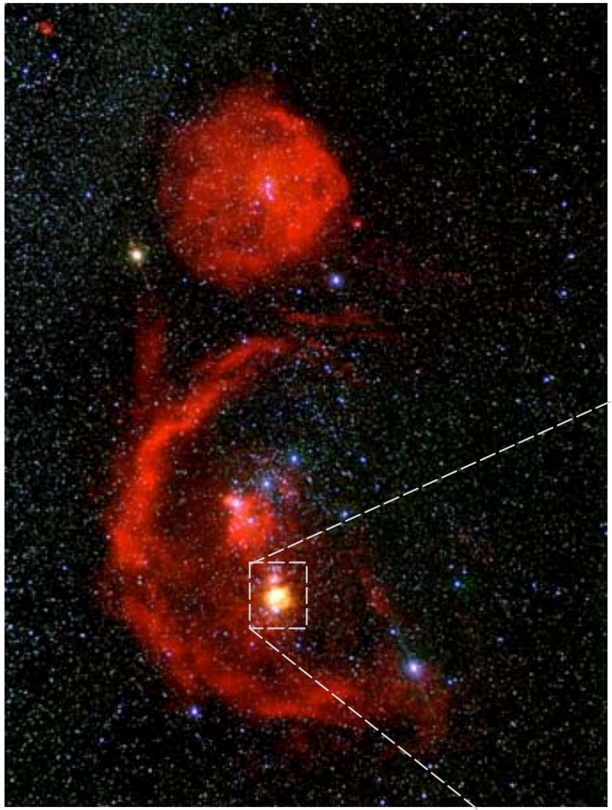


star formation in Orion

We see

- *Stars* (in visible light)
- Atomic hydrogen (in Hα -- red)
- Molecular hydrogen H_2 (radio emission -- color coded)

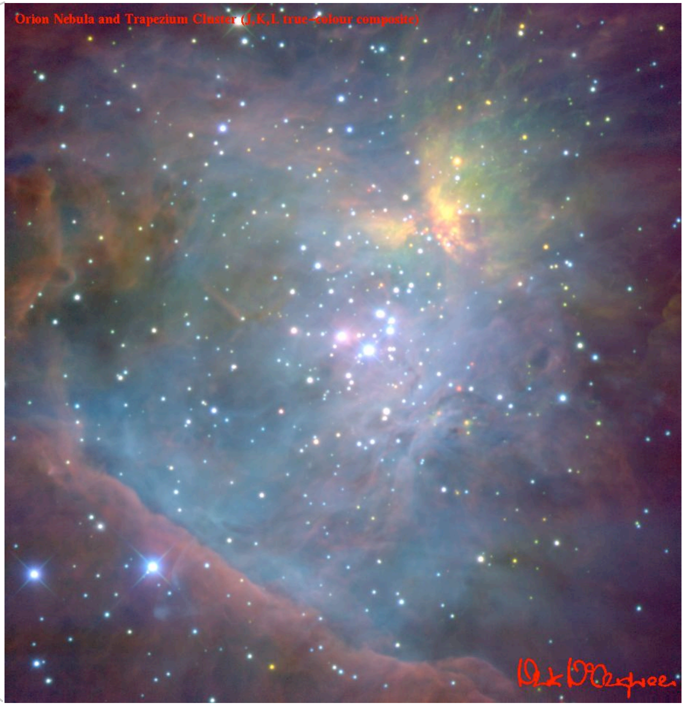
local star forming region: ONC - Orion nebula cluster



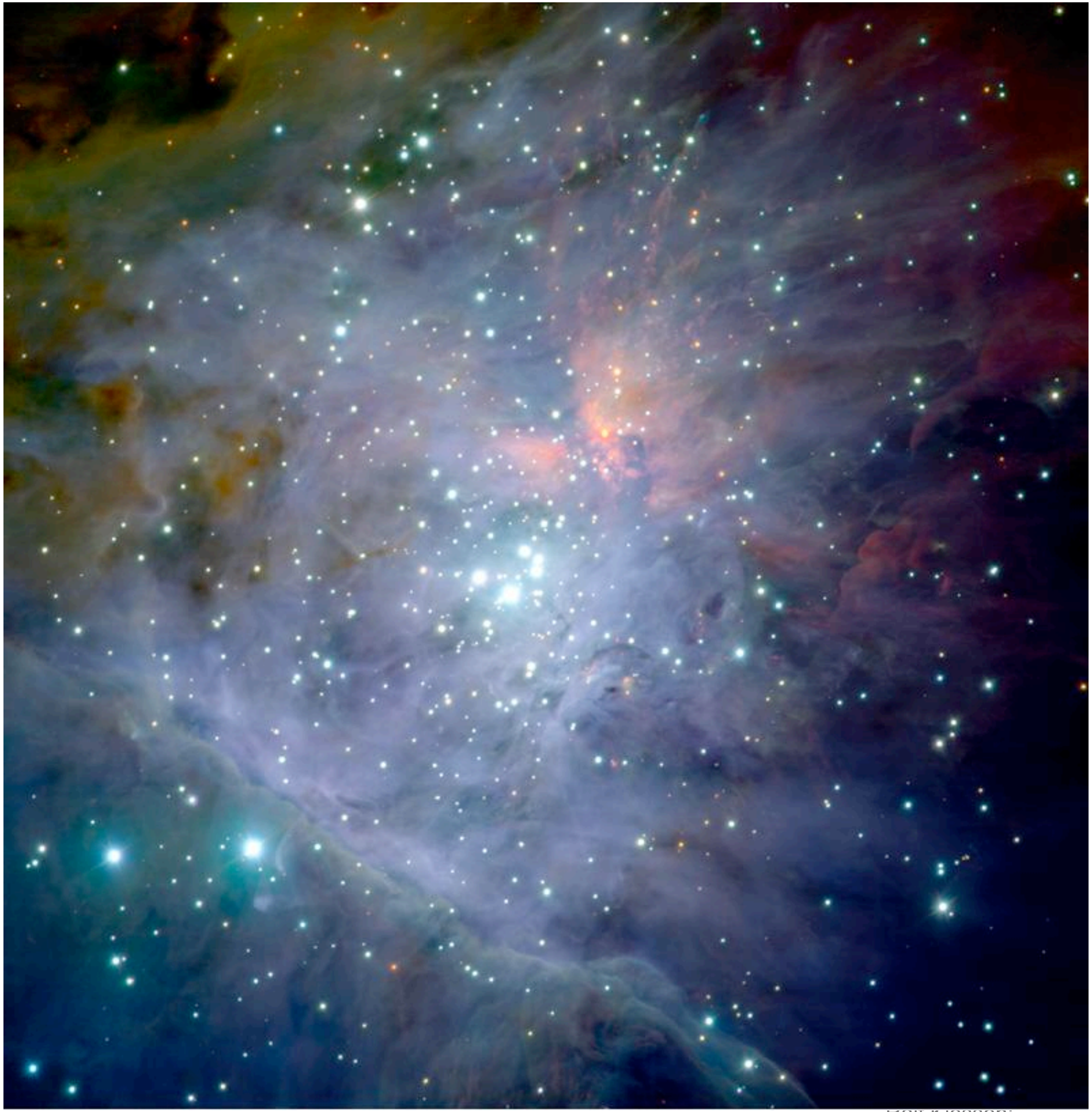
Orion molecular cloud

The Orion molecular cloud is the birth- place of several young embedded star clusters.

The Trapezium cluster is only visible in the IR and contains about 2000 newly born stars.



Trapezium cluster



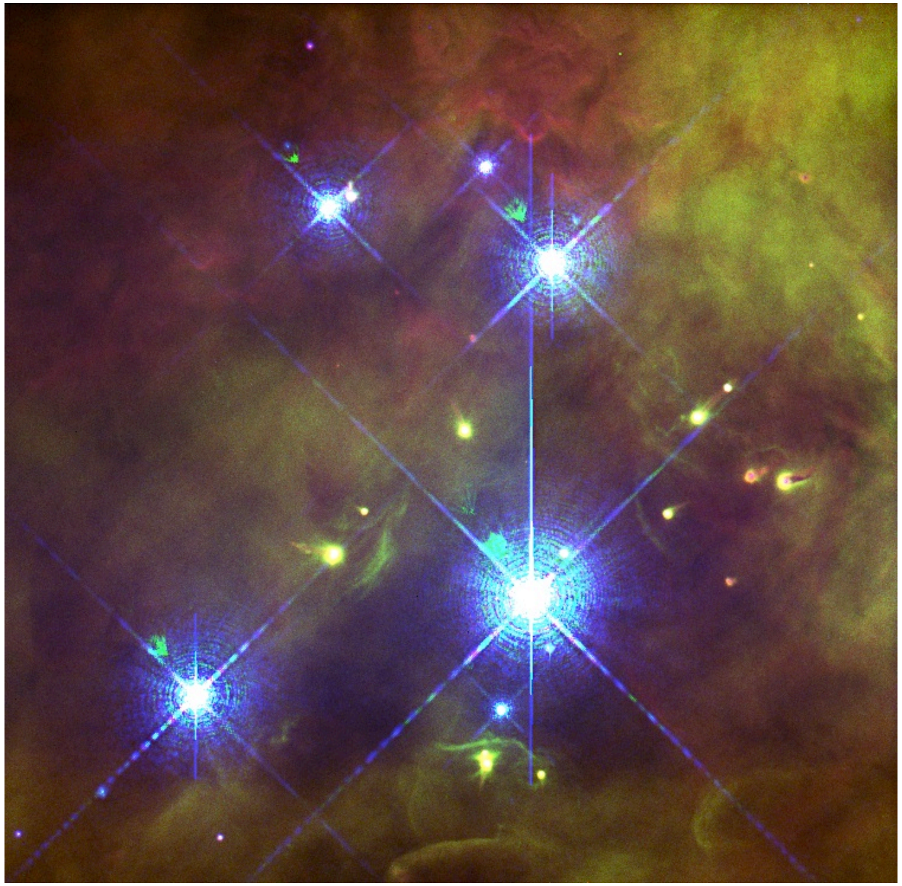
ONC
(detail)

- stars form in clusters
- stars form in molecular clouds
- (proto)stellar feedback is important

(color composite J,H,K by M. McCaughrean, VLT, Paranal, Chile)

center of ONC: the trapezium

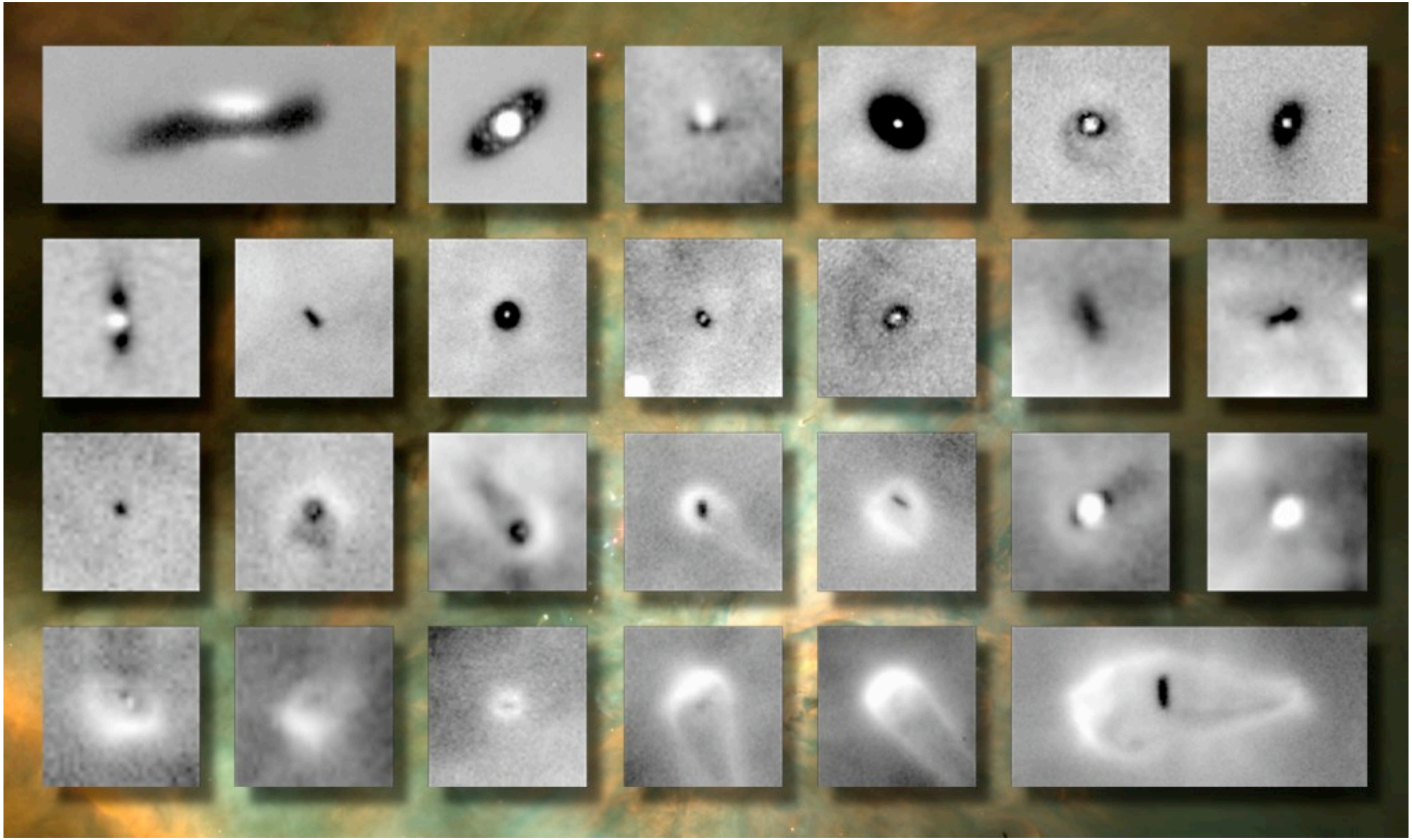
Ionizing radiation from central star **Θ1C Orionis**



Proplyds: Evaporating ``protoplanetary´´ disks around young low-mass protostars

(images: Doug Johnstone et al.)

siluette disks in Orion



protostellar disks: dark shades in front of the photodissociation region in the background. Each image is 750 AU x 750 AU.

(data: Mark McCaughrean)

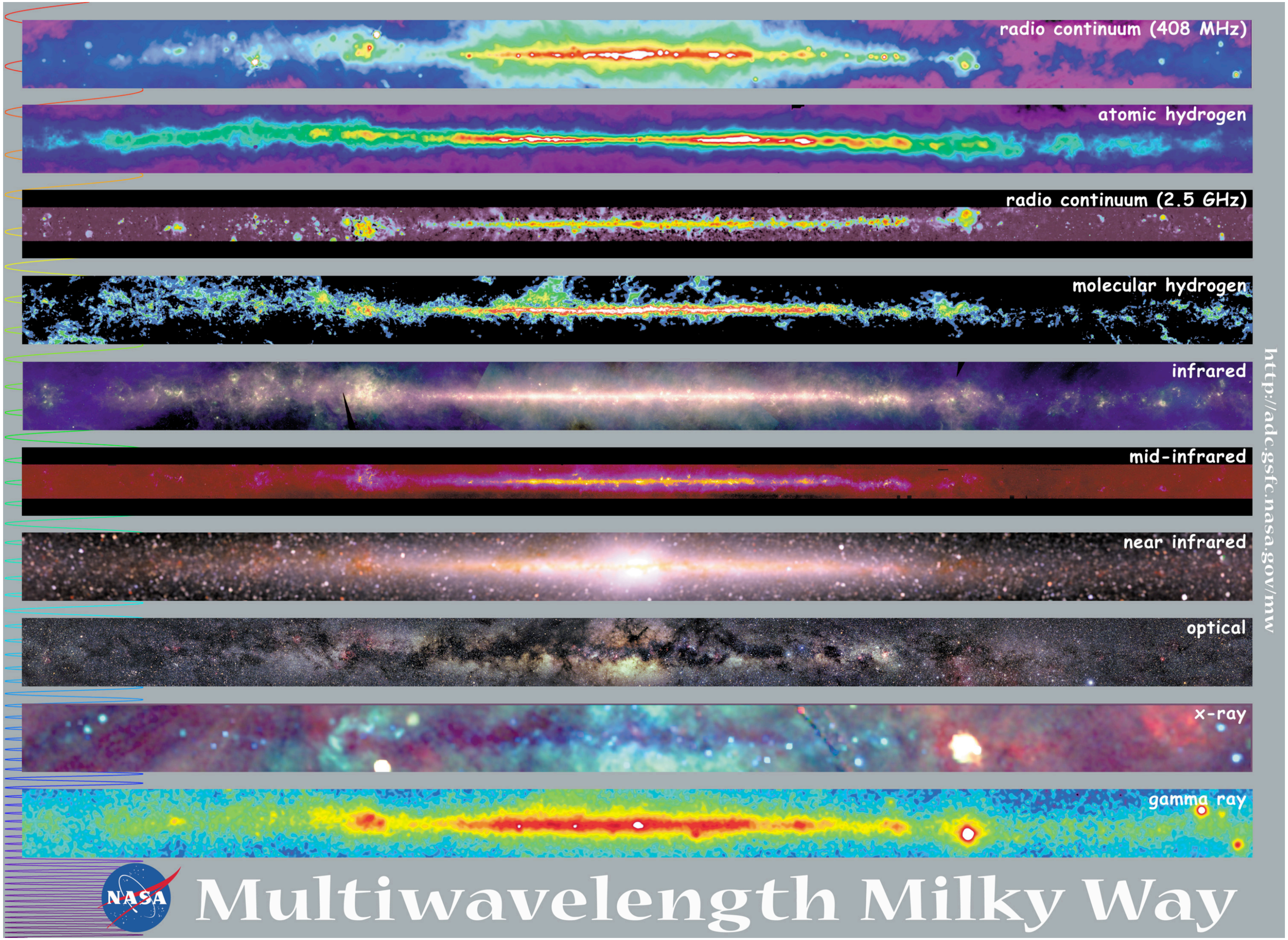
gas

how to observe star forming clouds?

Different wavelength give different information.

→astronomer use the full electromagnetic spectrum

• Radio:	interstellar gas (line emission -> velocity information)
• sub-mm range:	dust (thermal emission)
• infrared & optical:	stars
• x-rays:	stars (coronae), supernovae remnants (very hot gas)
• γ-rays:	supernovae remnants (radioactive decay, e.g. ^{26}Al), compact objects, merging of neutron stars (γ-ray burst)


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

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

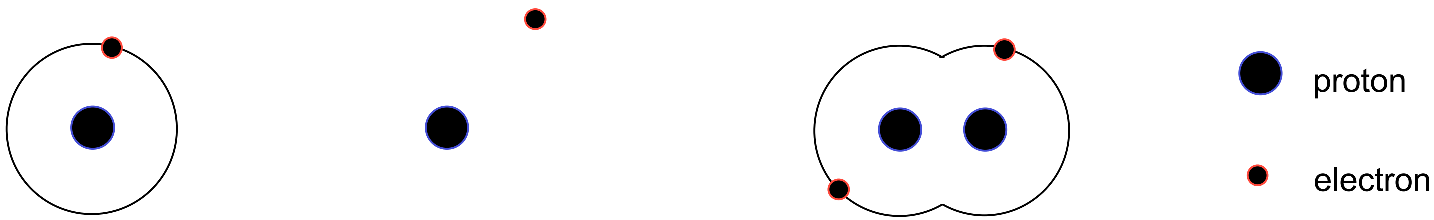
Because hydrogen is the dominating element, the classification scheme is based on its chemical state:

ionized atomic hydrogeN	*HII (H^+)*
neutraler atomic hydrogen	*HI (H)*
molecular hydrogen	*H_2*

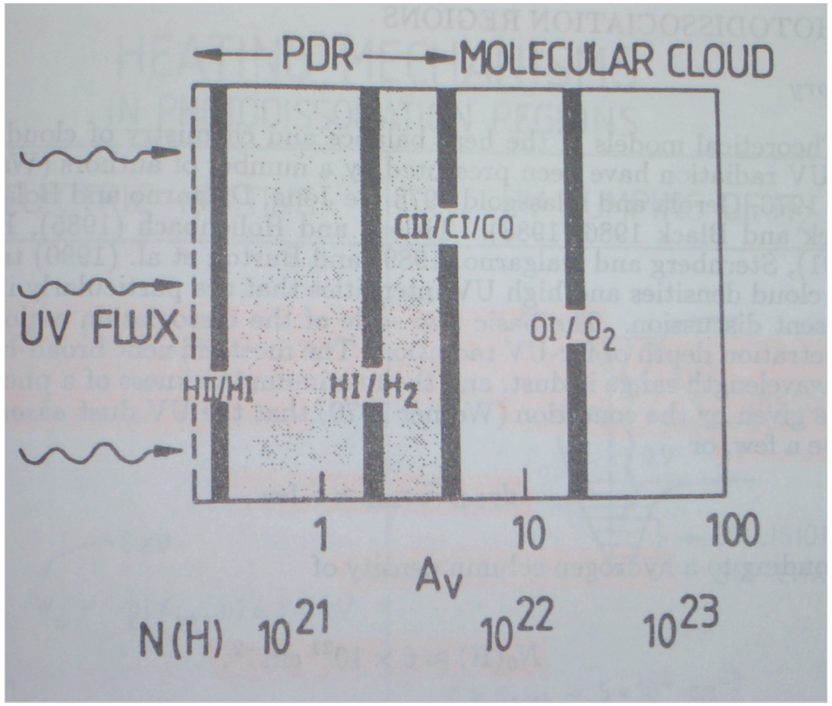
Ionisation
Phasenübergang

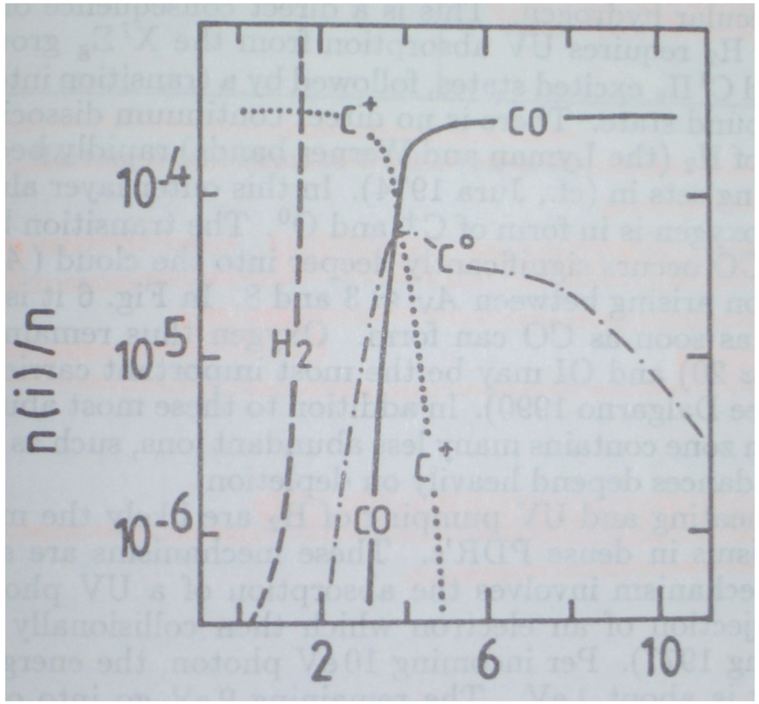
different regions consist of almost 100% of the appropriate phase, the transition regions between HII, H and H_2 are very thin.

star formation always takes place in dense and cold molecular clouds.



phases of the ISM





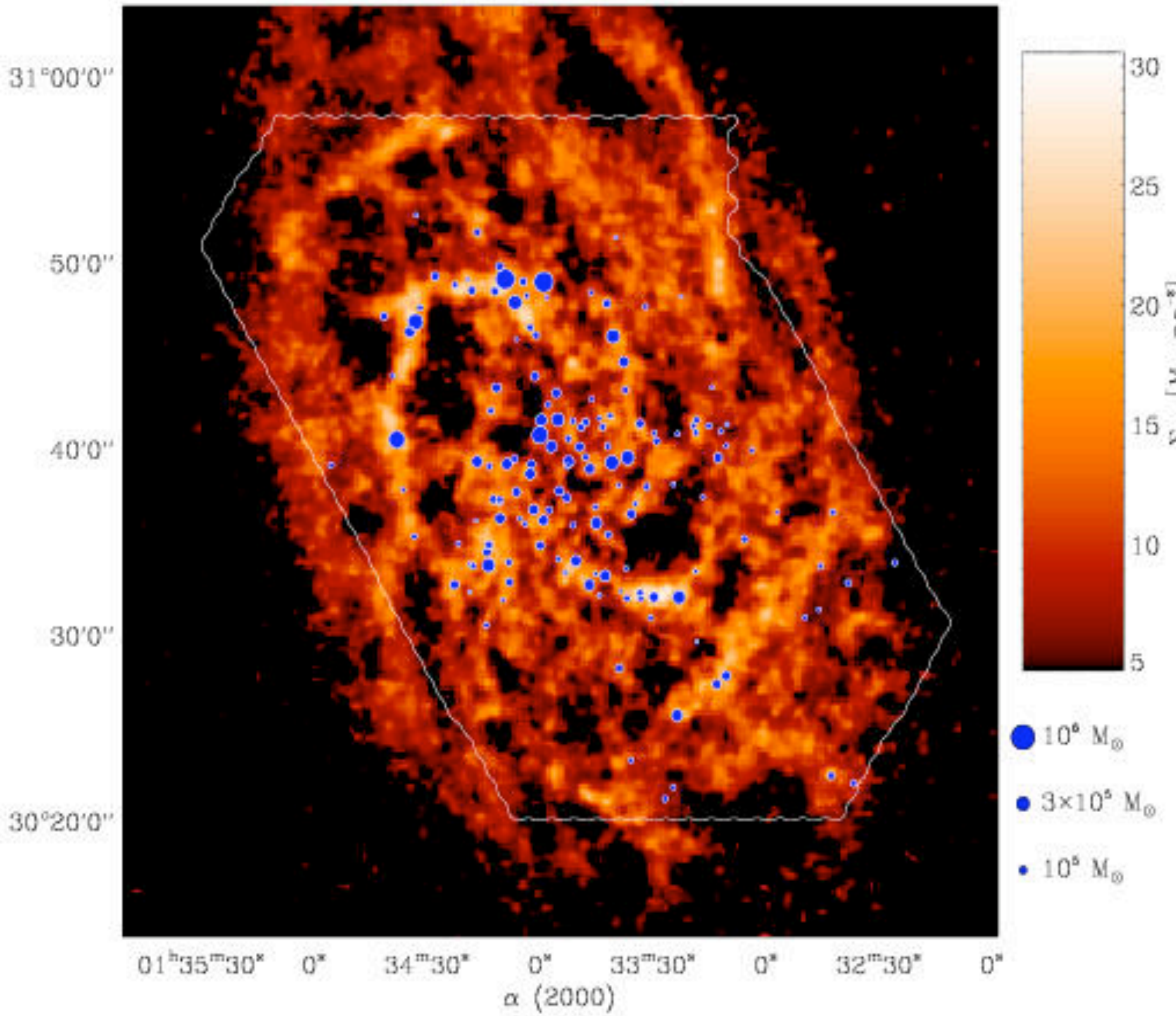
A_V

HII HI H_2

Dichte- / Säulendichte nimmt zu

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

correlation between H_2 and HI



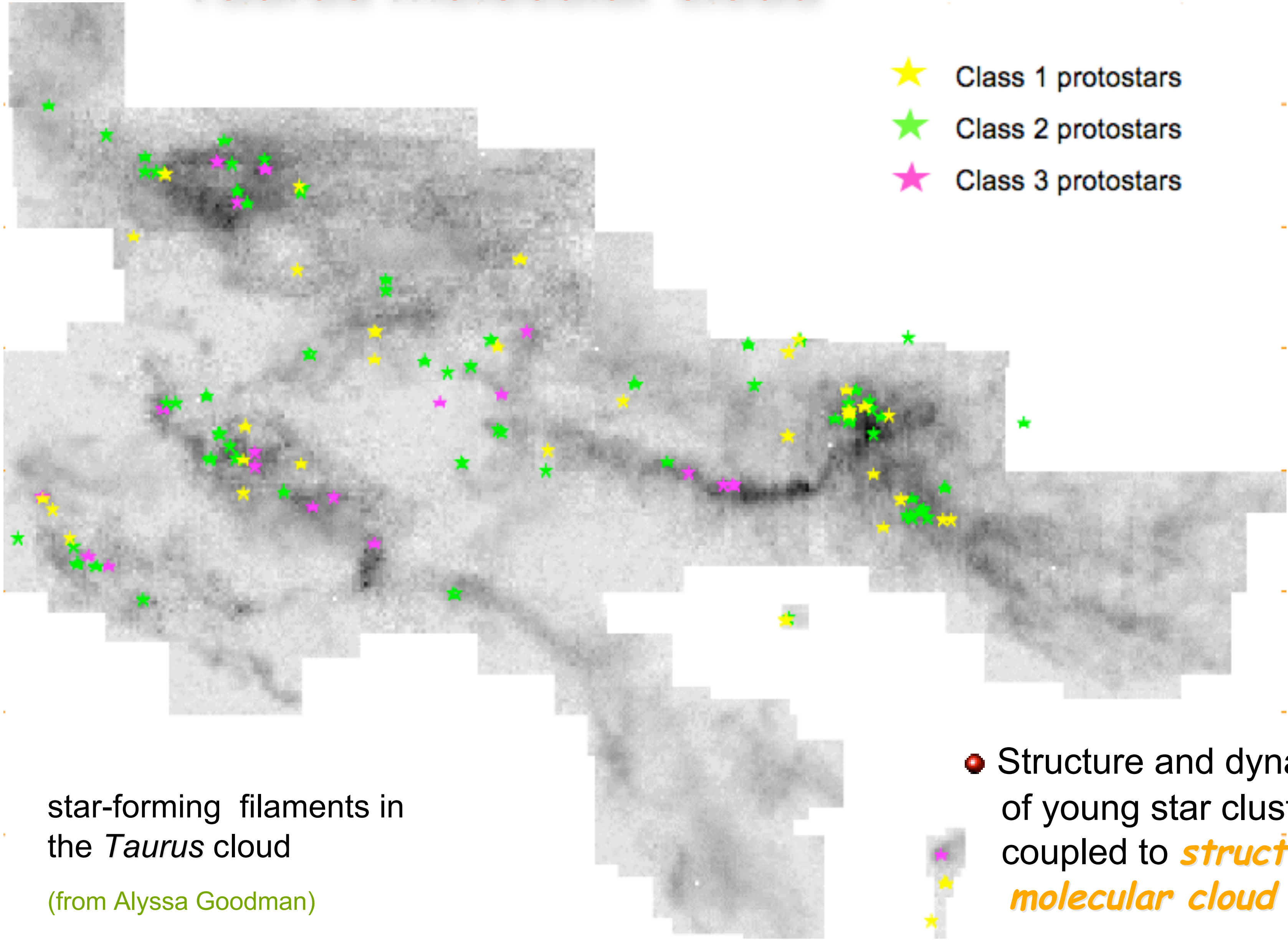
Compare H_2 - HI in M33:

- 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)

Taurus molecular cloud

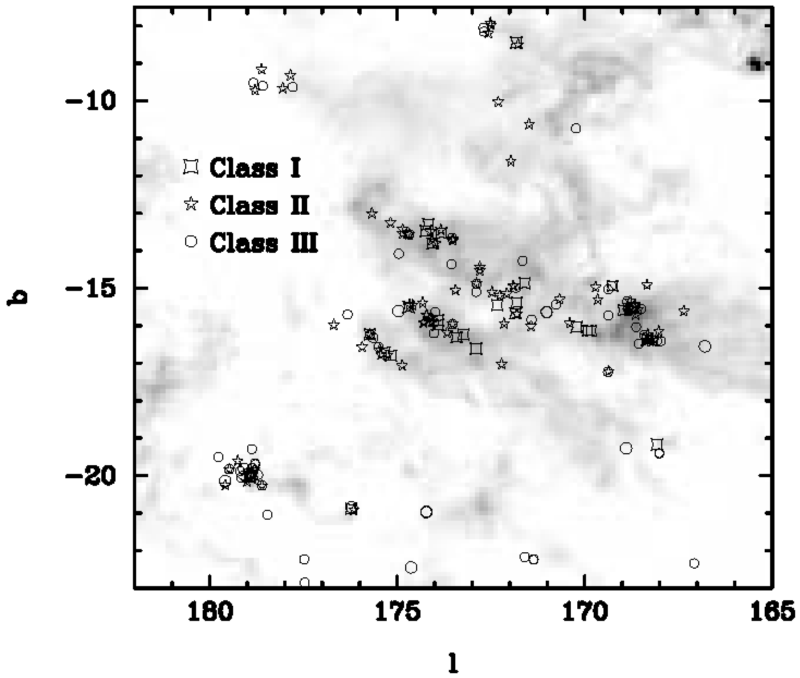


star-forming filaments in the *Taurus* cloud

(from Alyssa Goodman)

- Structure and dynamics of young star clusters is coupled to ***structure of molecular cloud***

Taurus molecular cloud

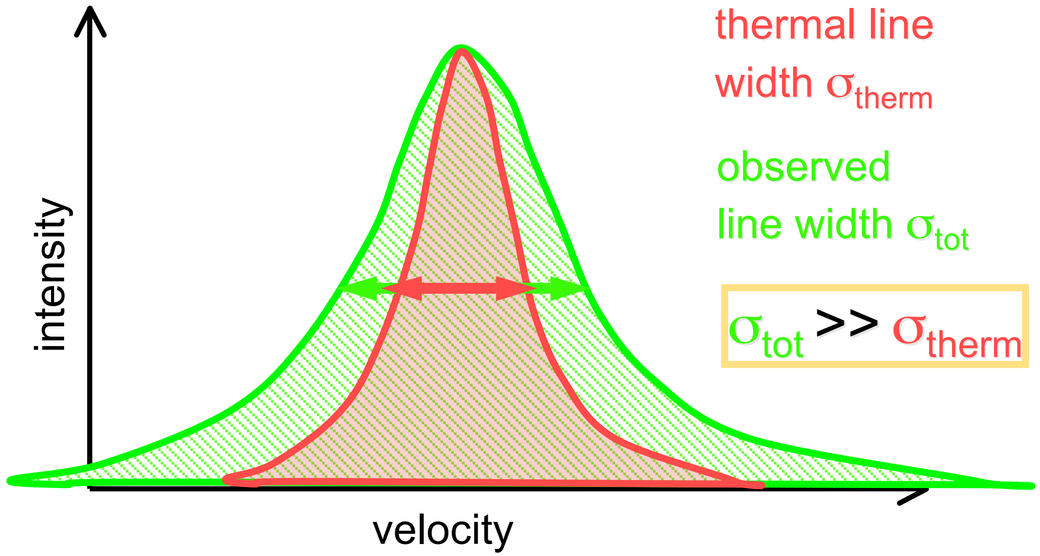


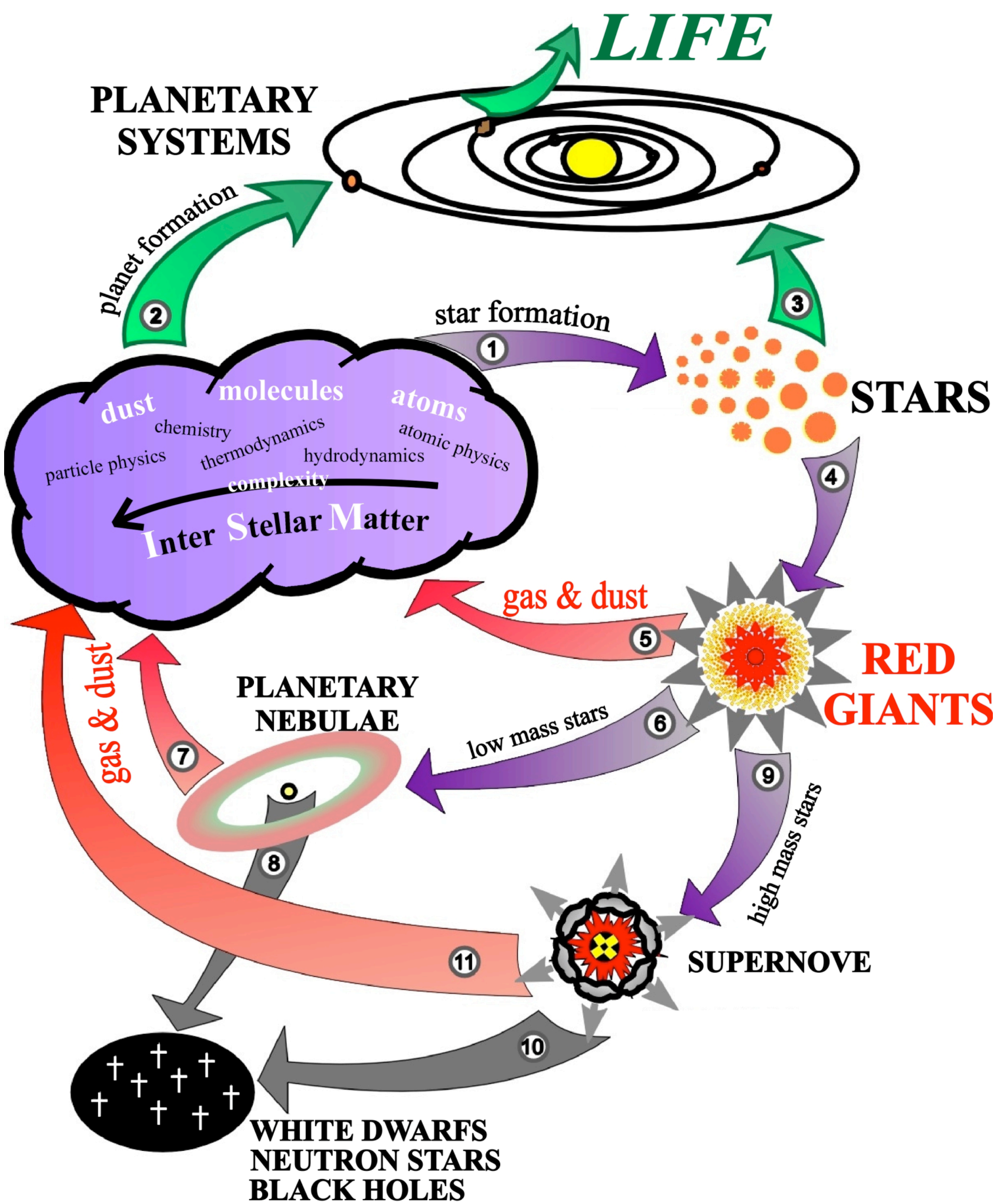
Star-forming filaments in *Taurus* cloud

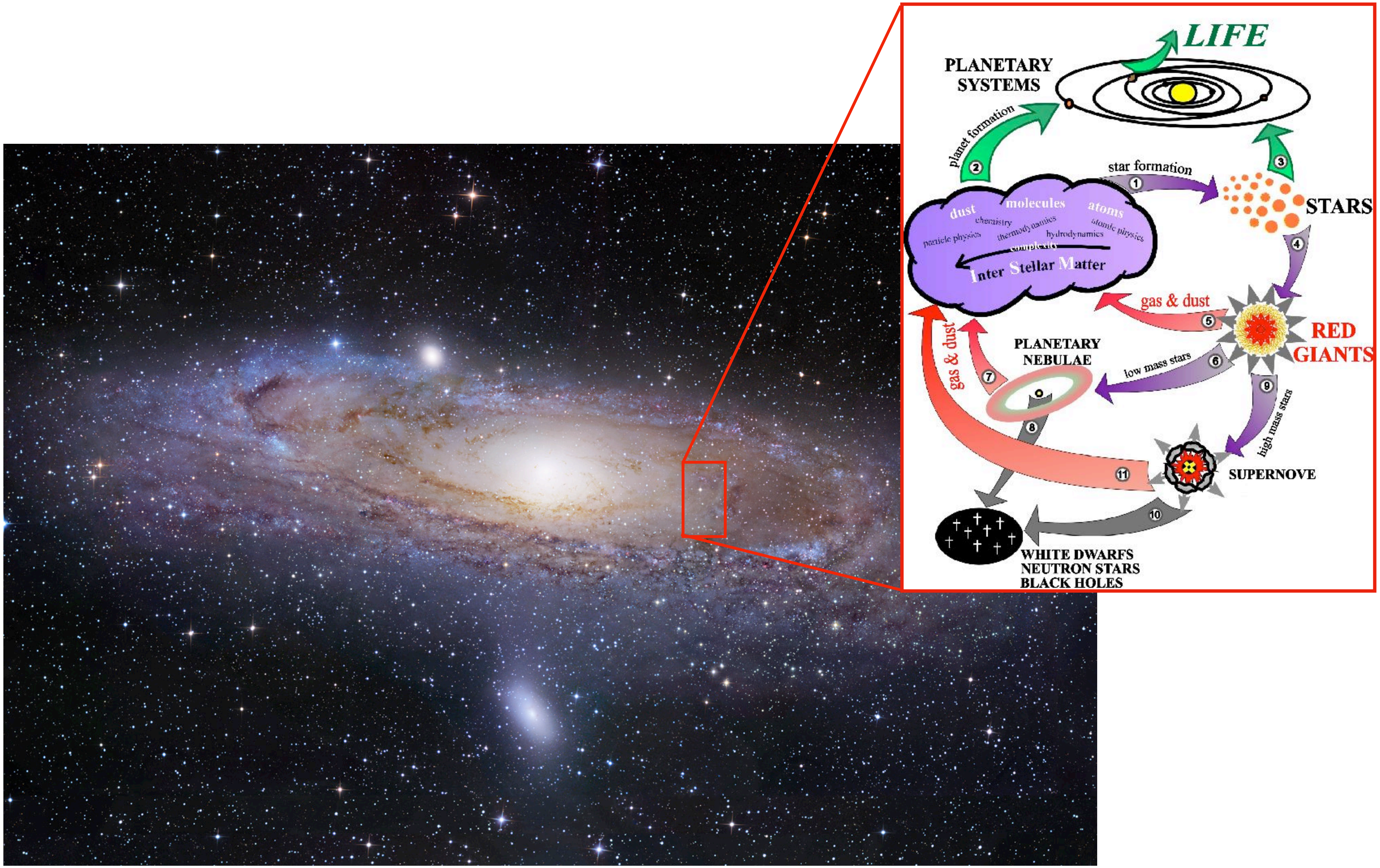
(from Hartmann 2002)

- Strukture and dynamics of ***molekular cloud*** is determined by ***supersonic turbulence***

- Structure and dynamics of young star clusters is coupled to ***structure of molecular cloud***




LIFE
PLANETARY SYSTEMS
planet formation
2
star formation
1
3
STARS
dust
molecules
atoms
chemistry
thermodynamics
atomic physics
particle physics
hydrodynamics
complexity
Inter Stellar Matter
4
gas & dust
5
RED GIANTS
gas & dust
PLANETARY NEBULAE
low mass stars
6
7
9
high mass stars
8
SUPERNOVE
11
10
WHITE DWARFS
NEUTRON STARS
BLACK HOLES


LIFE
PLANETARY SYSTEMS
planet formation
star formation
STARS
dust
molecules
atoms
chemistry
thermodynamics
hydrodynamics
atomic physics
particle physics
Inter Stellar Matter
gas & dust
RED GIANTS
PLANETARY NEBULAE
low mass stars
gas & dust
high mass stars
SUPERNOVE
WHITE DWARFS
NEUTRON STARS
BLACK HOLES

idea

gravotuturbulent star formation

- idea:

> ***Star formation is controlled by interplay between gravity and supersonic turbulence!***

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

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

gravotuturbulent star formation

- idea:

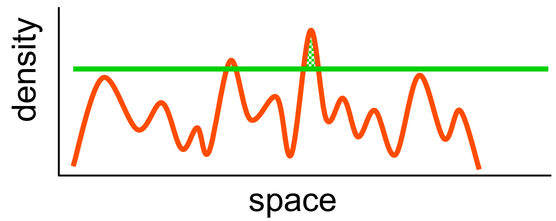
> *Star formation is controlled by interplay between gravity and supersonic turbulence!*

- validity:

This hold on *all* scales and applies to build-up of stars and star clusters within molecular clouds as well as to the formation of molecular clouds in galactic disk.

(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

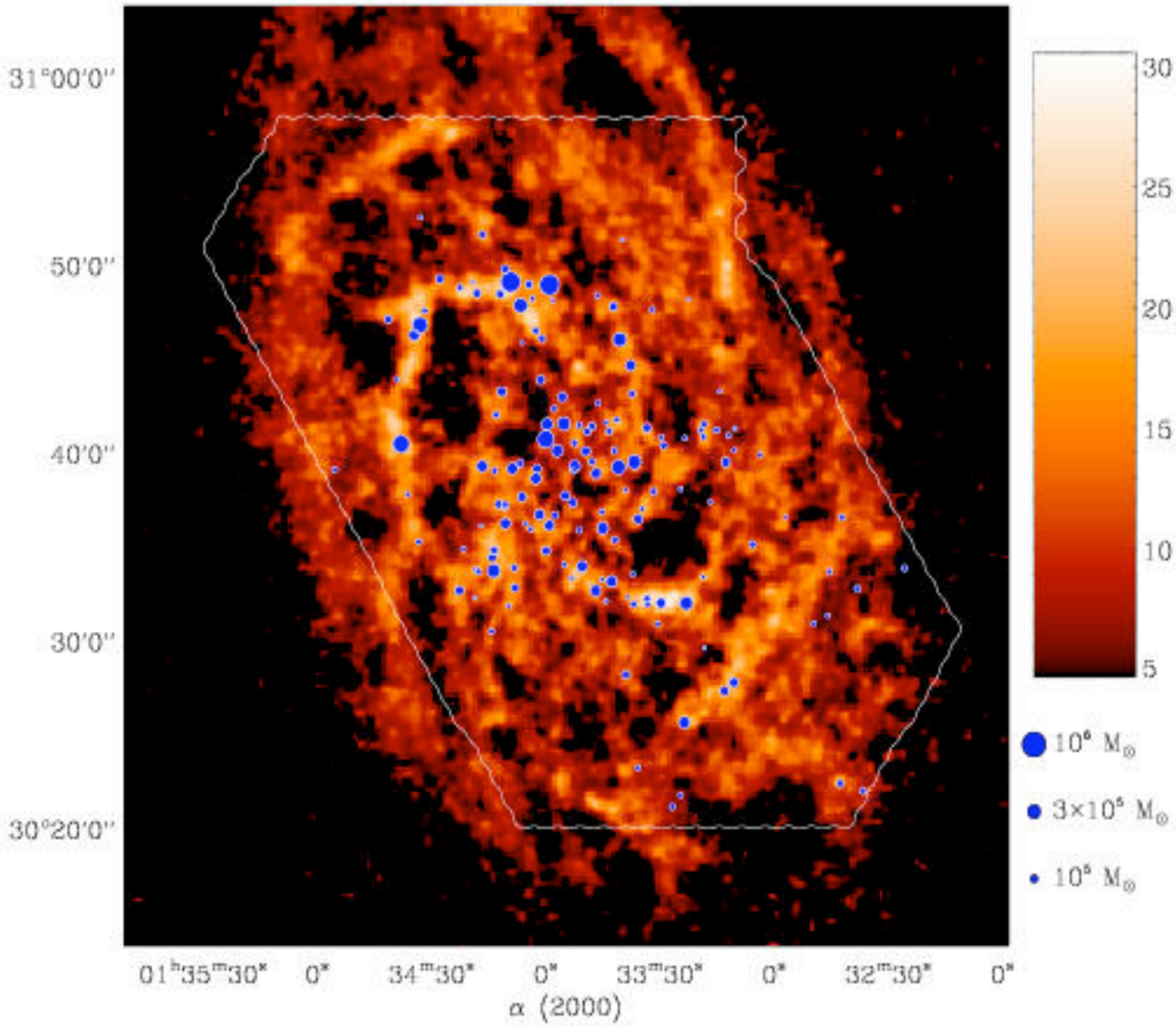
→ ***GRAVOTUBULENT FRAGMENTATION***

- *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)

modeling large scales

molecular cloud formation

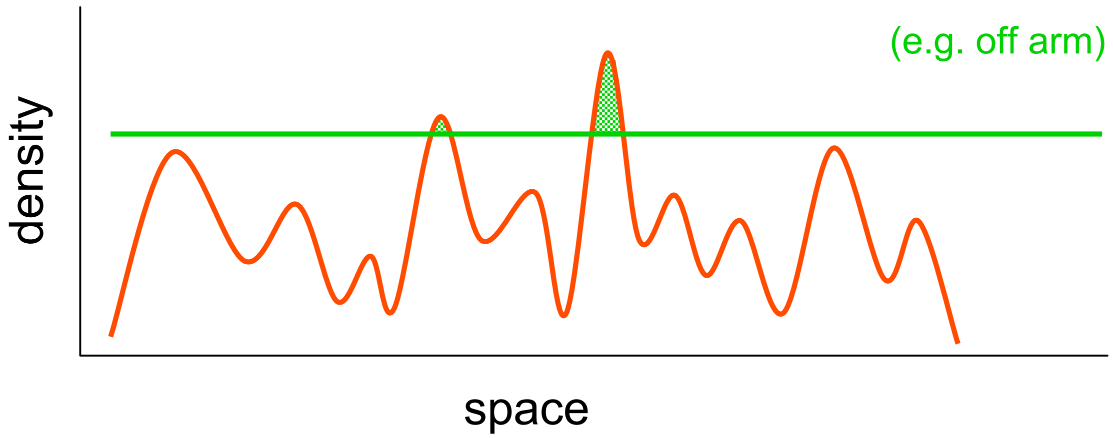


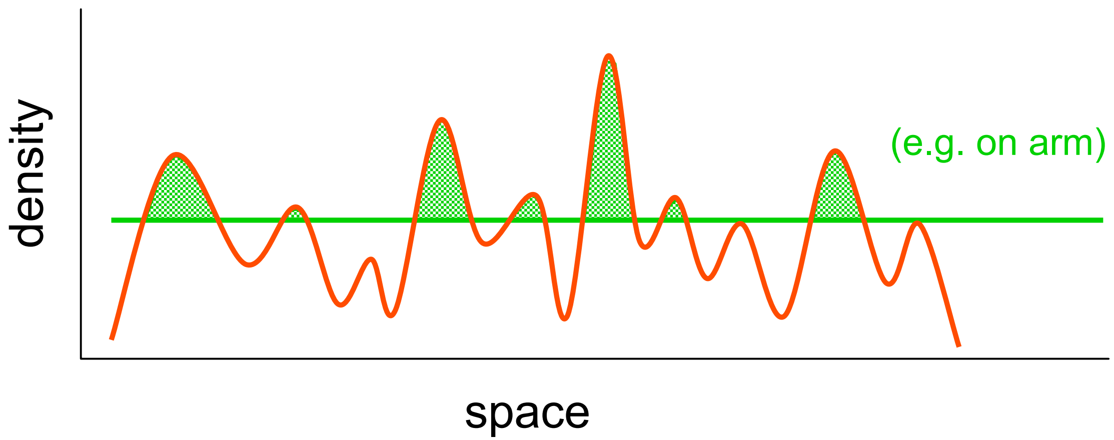
Thesis:

Molecular clouds form at *stagnation points* of large-scale convergent flows, mostly triggered by global (or external) perturbations.

(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*"

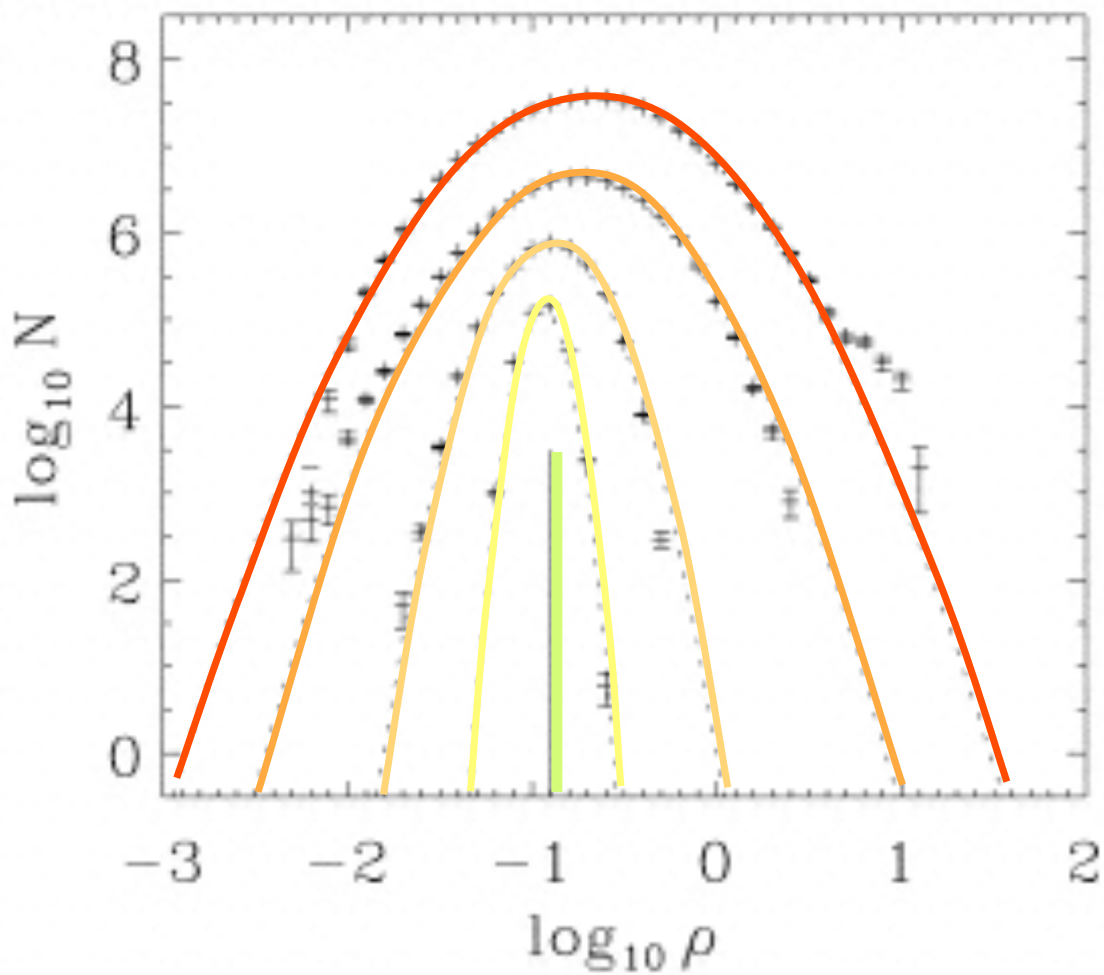
→ *molecular cloud*

(Glover & Mac Low 2007a,b)

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

(Dobbs & Bonnell 2006)

star formation on *global* scales



mass weighted ρ-pdf, each shifted by ΔlogN=1

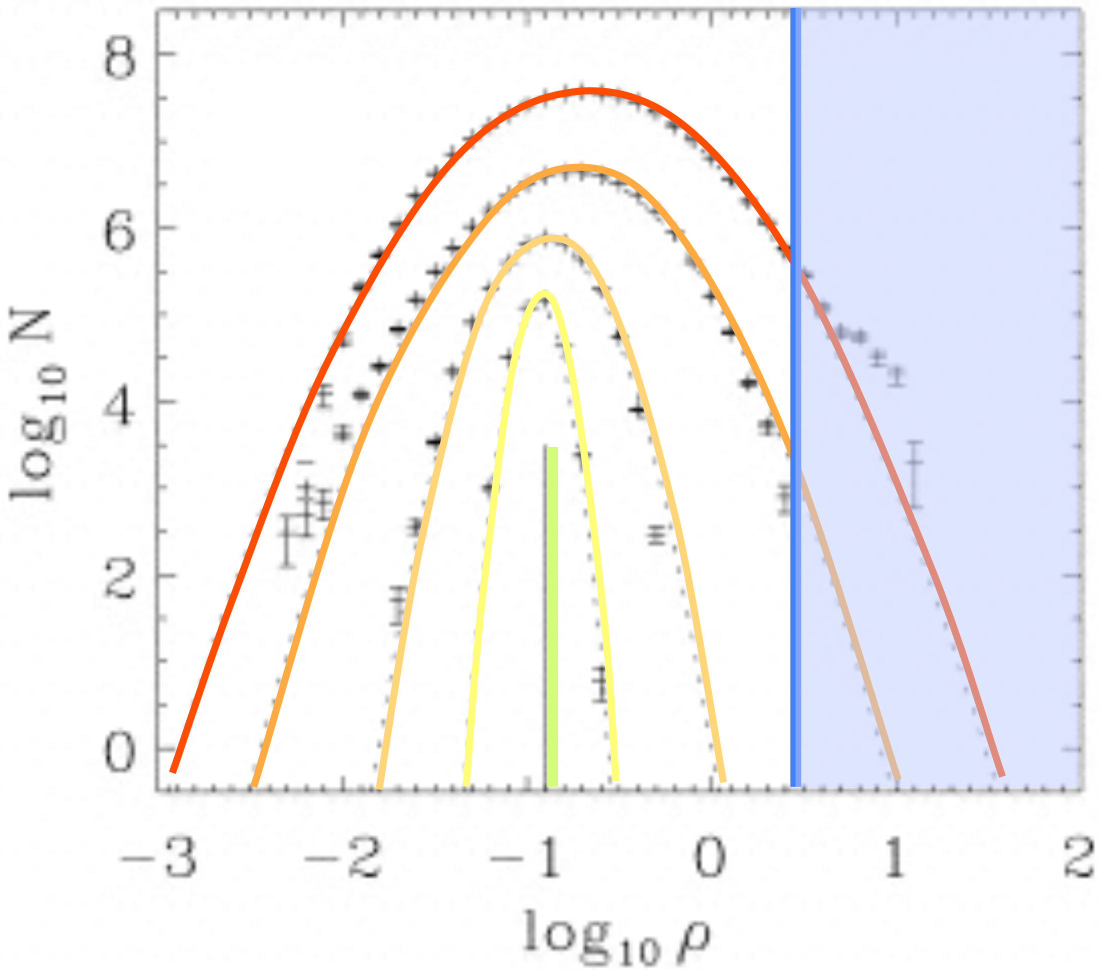
(from Klessen, 2001; also Gazol et al. 2005, Mac Low et al. 2005)

probability distribution function of the density *(ρ-pdf)*

varying rms Mach numbers:

M1 > M2 > M3 > M4 > 0

star formation on *global* scales



mass weighted ρ-pdf, each shifted by $\Delta \log N = 1$

(rate from Hollenback, Werner, & Salpeter 1971)

H_2 formation rate:

$$\tau_{H_2} \approx \frac{1.5\,\mathrm{Gyr}}{n_H / 1\mathrm{cm}^{-3}}$$

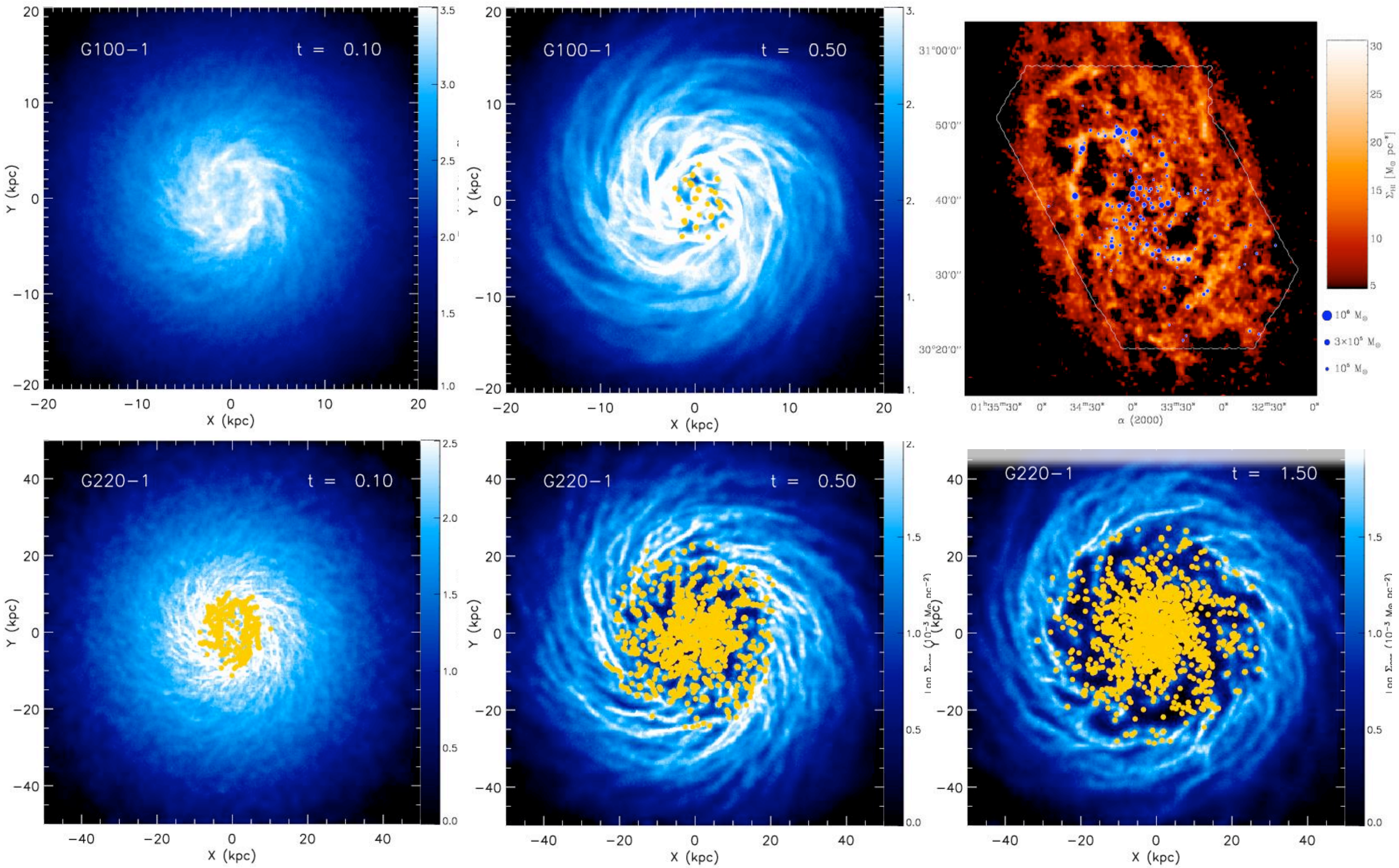
for $n_H \geq 100\ \mathrm{cm}^{-3}$, H_2 forms within 10Myr, this is about the lifetime of typical MC's.

in turbulent gas, the H_2 fraction can become very high on short timescale

(for models with coupling between cloud dynamics and time-dependent chemistry, see Glover & Mac Low 2007a,b)

modeling galactic SF

SPH calculations of self-gravitating disks of stars and (isothermal) gas in dark-matter potential, sink particles measure local collapse --> star formation



(Li, Mac Low, & Klessen, 2005, ApJ, 620,L19 - L22)

Modeling galactic SF

- Evolution of 42 isolated disk galaxies
  - DM halo, stellar disk & gas disk
  - SPH code GADGET with accretion particles
    (resolution: 5×10^5 to 3×10^6 gas particles)
  - $50\ \mathrm{km/s} \leq v_{circ} \leq 250\ \mathrm{km/s}$
  - fraction of disk mass: $m_d = 5\% - 10\%$
  - gas fraction in disk: $f_d = 20\%, 50\%, \& \ 90\%$
  - total mass: $4.15\times10^{10}\ M_\odot \leq M_{200} \leq 357.14\times10^{10} M_\odot$

    (corresponds to mass resolution of $138\ M_\odot \leq M_{SPH} \leq 10^5\ M_\odot$ in models with $3\mathrm{x}10^6$ gas particles)

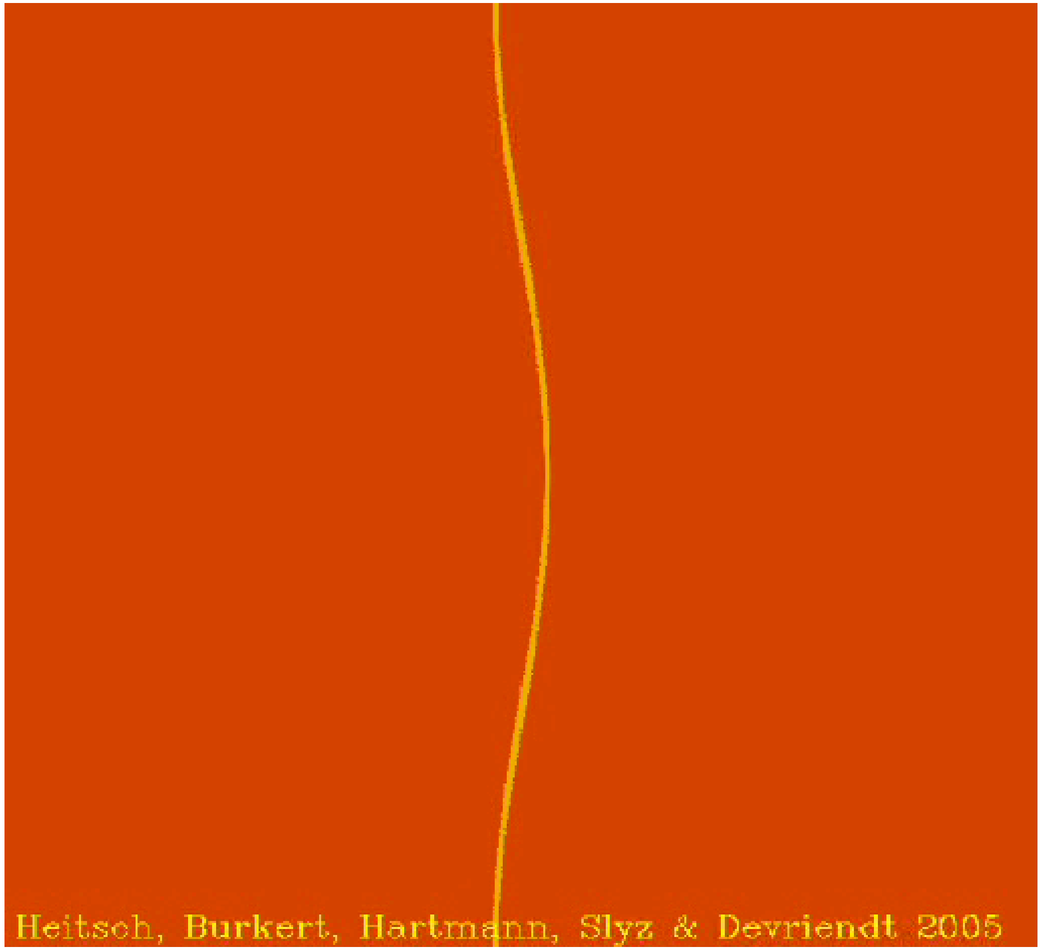
(Li, Mac Low, & Klessen, 2005, 2006a,b, ApJ)

Molecular cloud formation

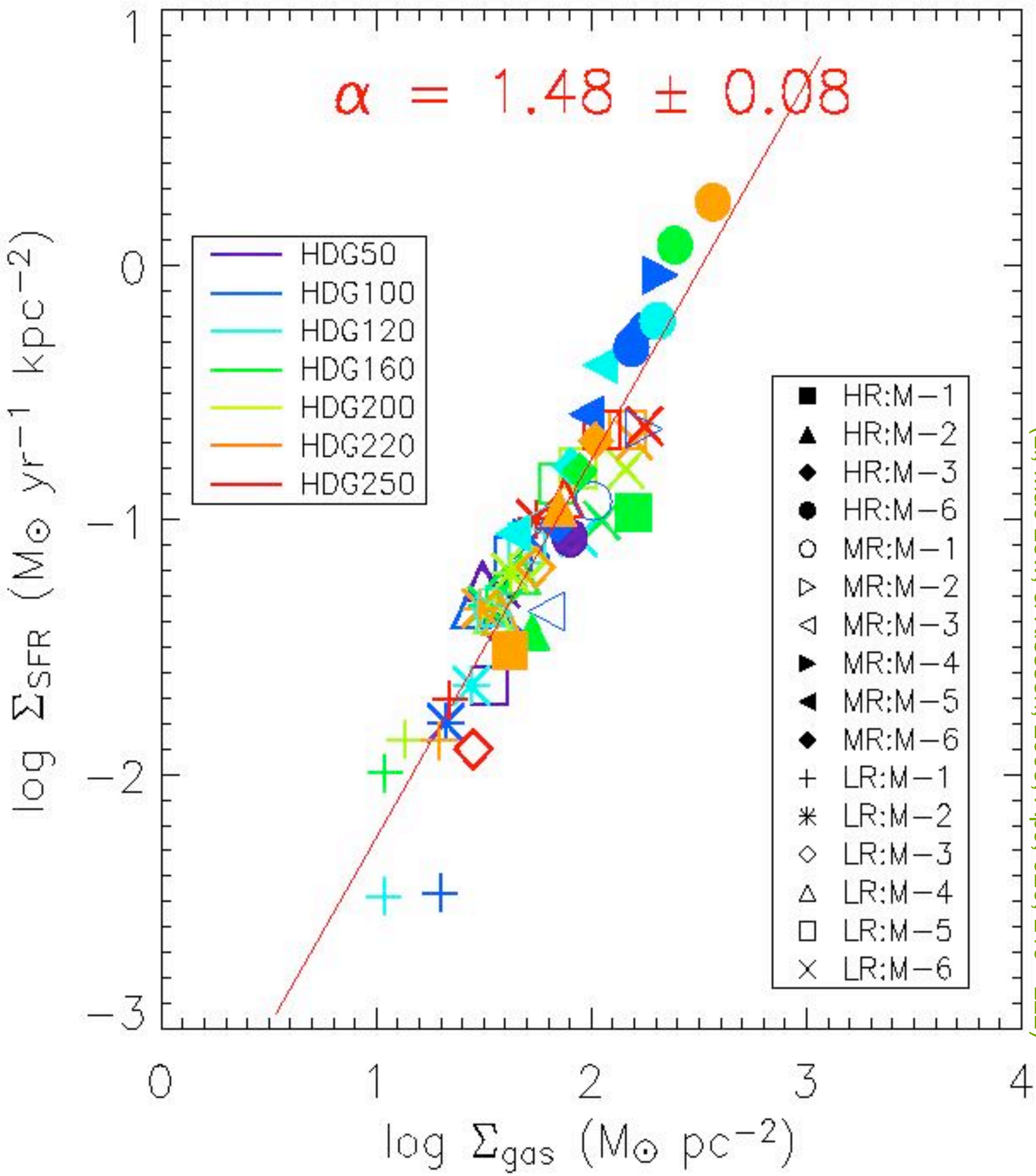
... in *convergent large-scale flows*

... 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)



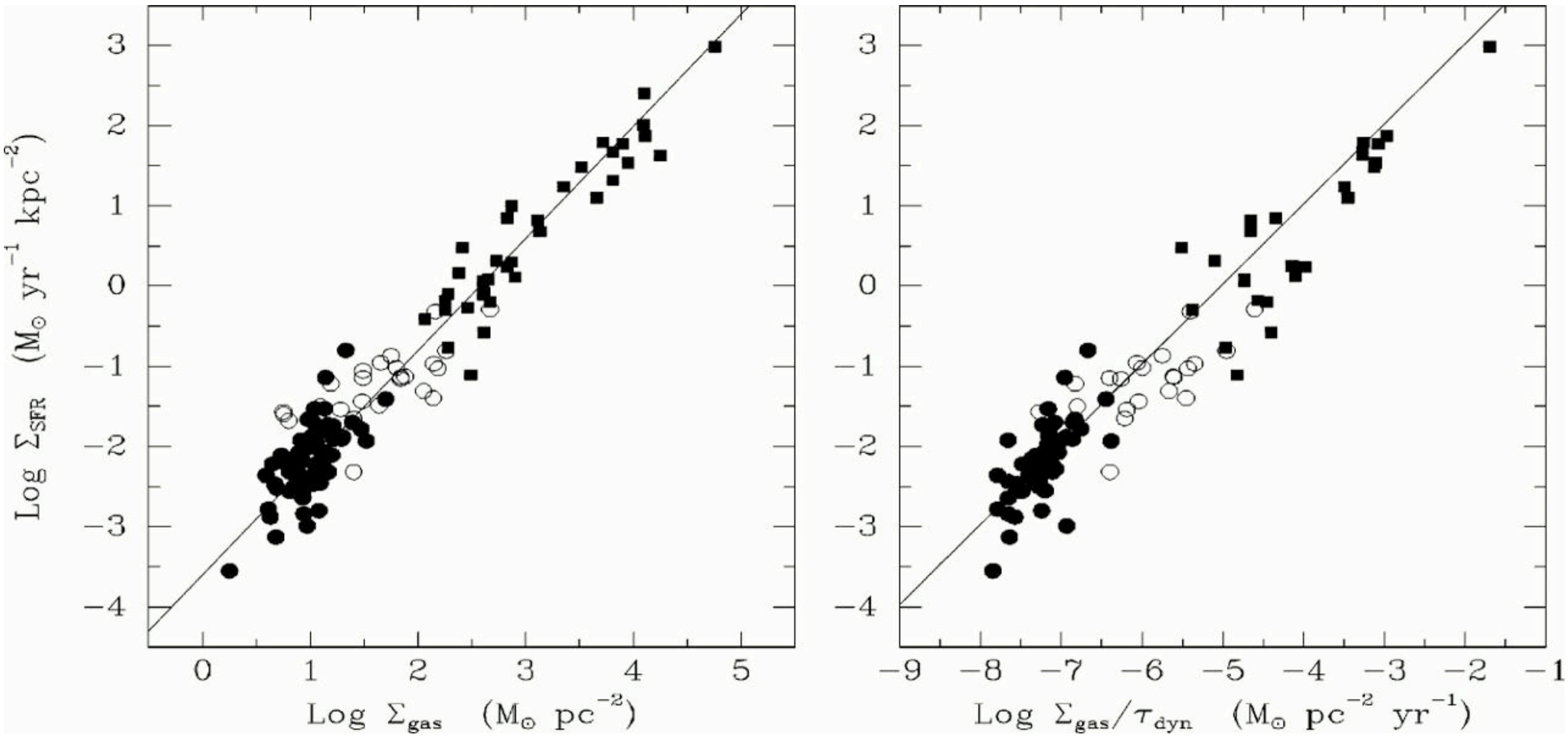
(Li, Mac Low, & Klessen, 2005, ApJ, 620, L19 - L22)

We find correlation between *star formation rate* and *gas surface density:*

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

global Schmidt law

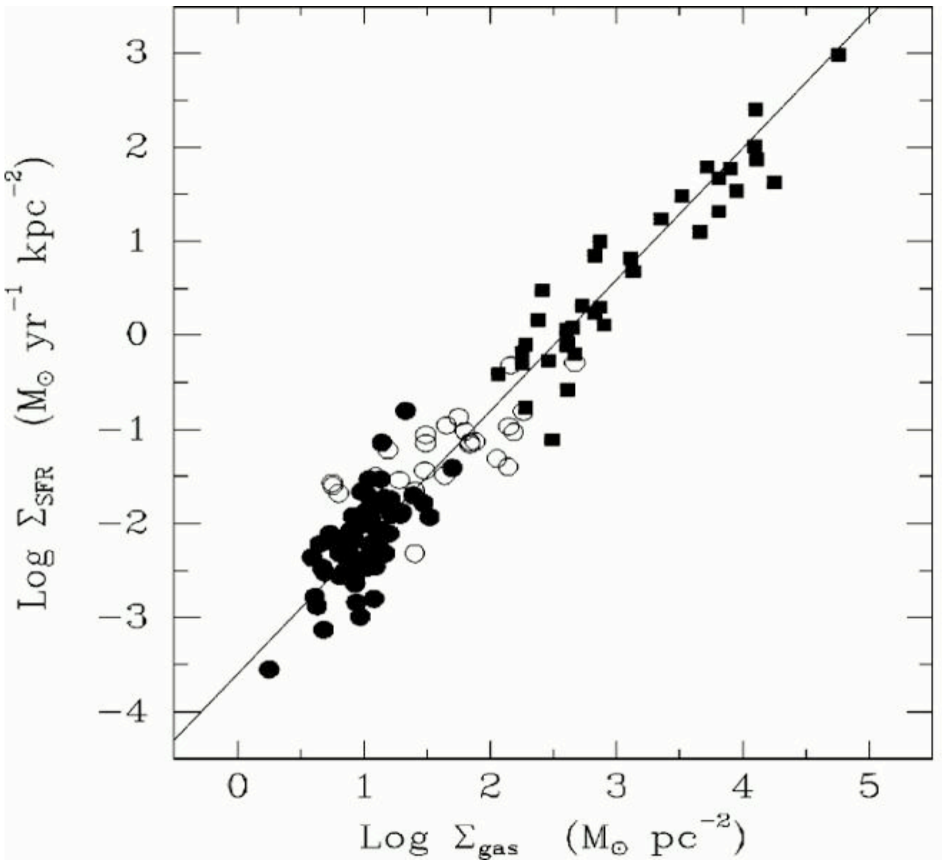
Observed Schmidt law

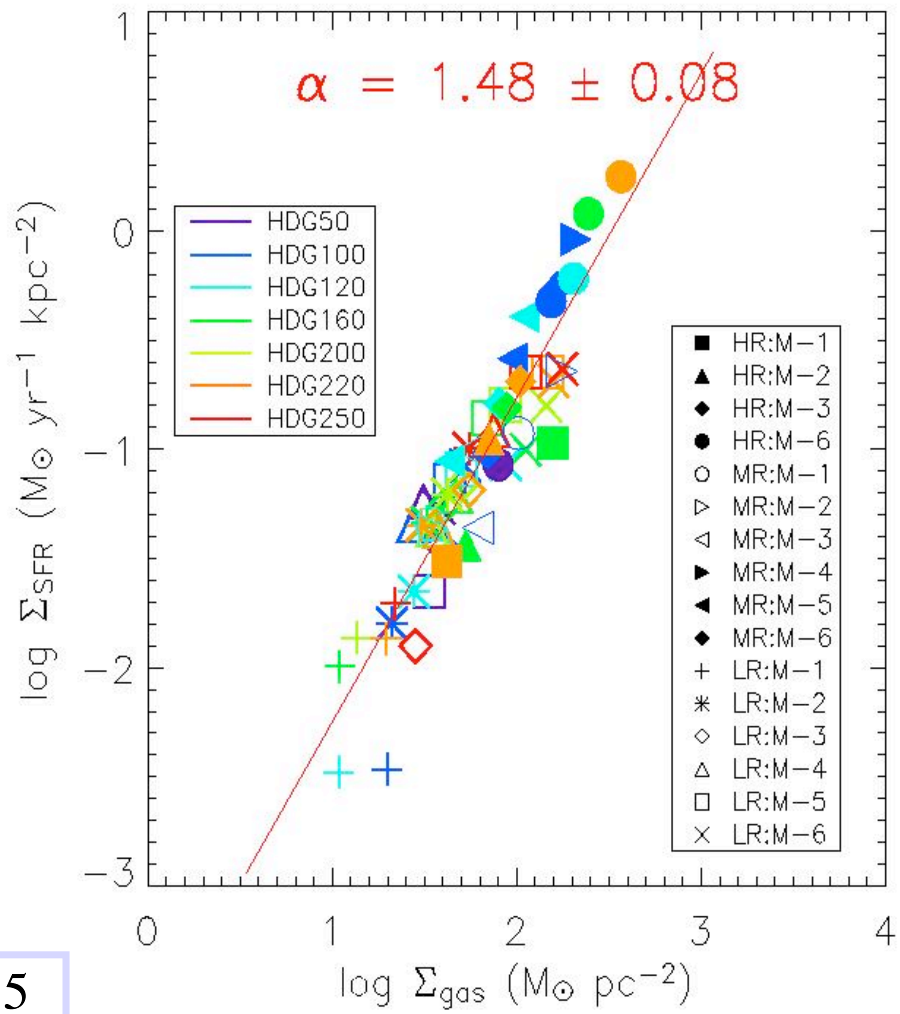


$$\Sigma_{SFR} = (2.5 \pm 0.7) \times 10^{-4} \left(\frac{\Sigma_{gas}}{1\ M_\odot\ \mathrm{pc}^{-2}} \right)^{1.4 \pm 0.15} M_\odot\ \mathrm{year}^{-1}\,\mathrm{kpc}^{-2},$$

(from Kennicutt 1998)

observed Schmidt law





in both cases: $\Sigma_{SFR} \propto \Sigma_{gas}^{1.5}$

(from Kennicutt 1998)

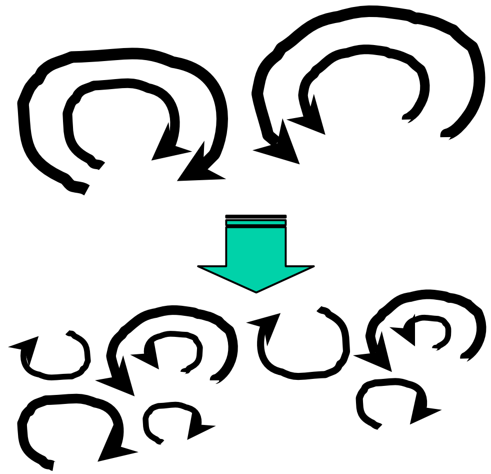
modeling small scales

Properties of turbulence

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

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

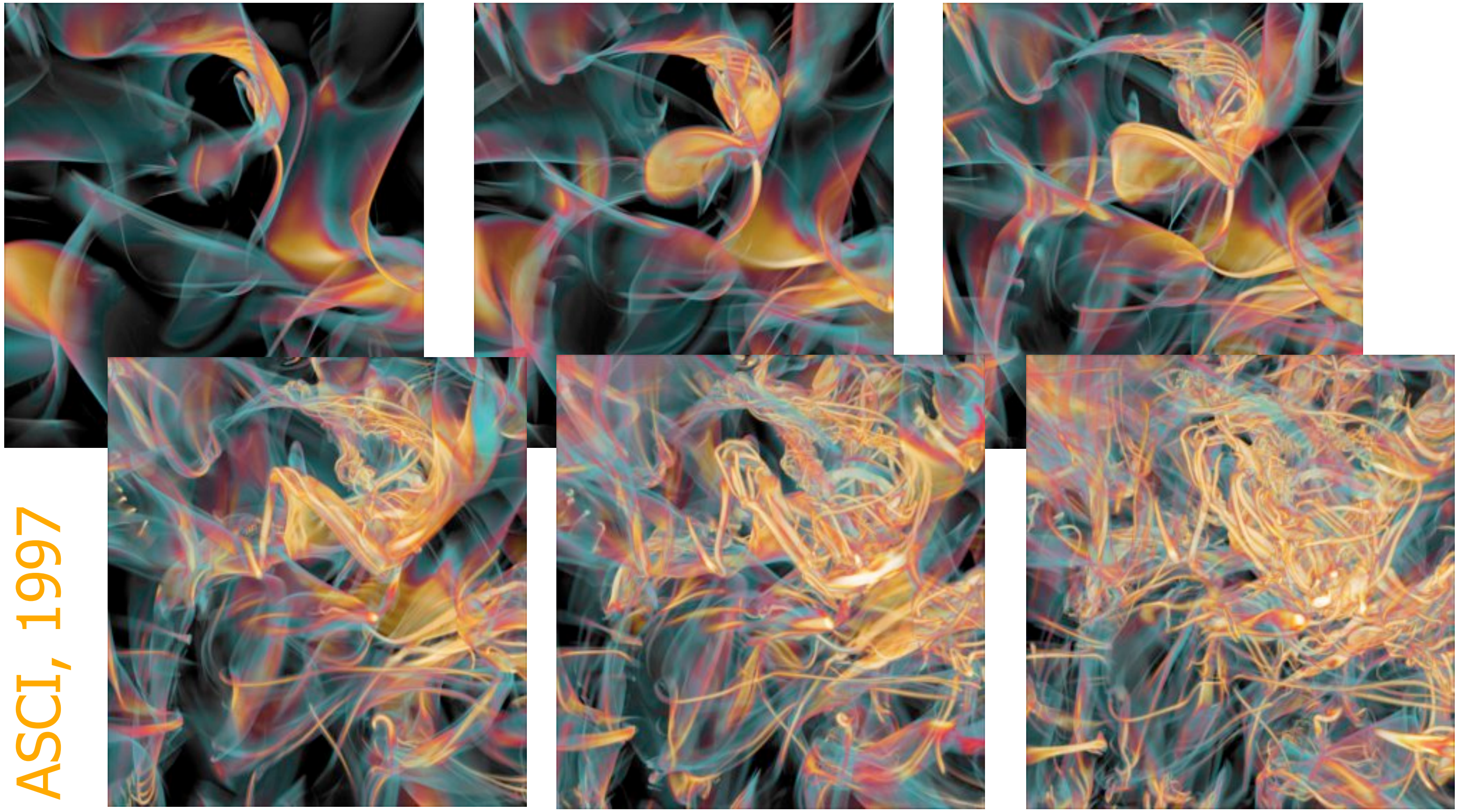
V= typical velocity on scale L, ν = viscosity, Re > 1000



- *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)

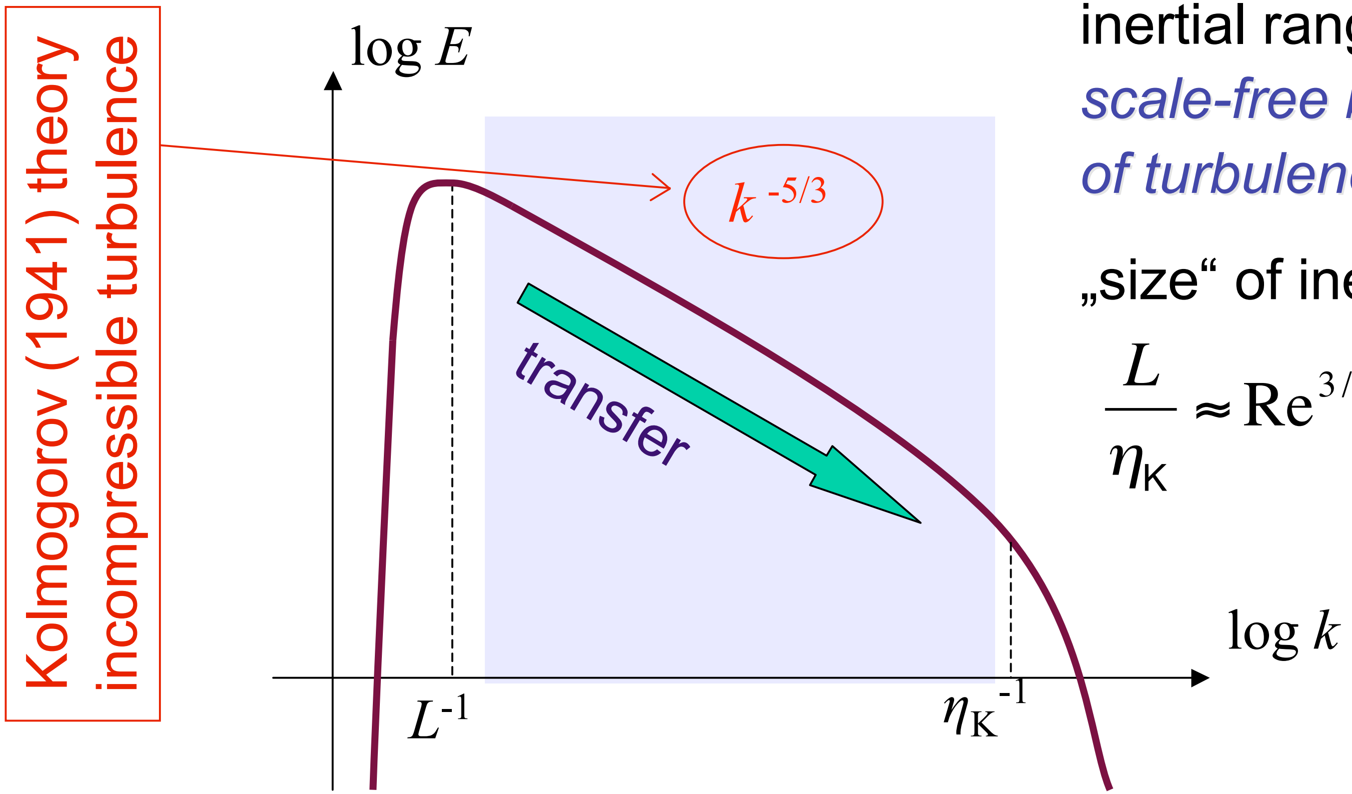
Vortex Formation



Porter et al.
ASCI, 1997

Vortices are streched and folded in three dimensions

turbulent cascade



inertial range:

scale-free behavior of turbulence

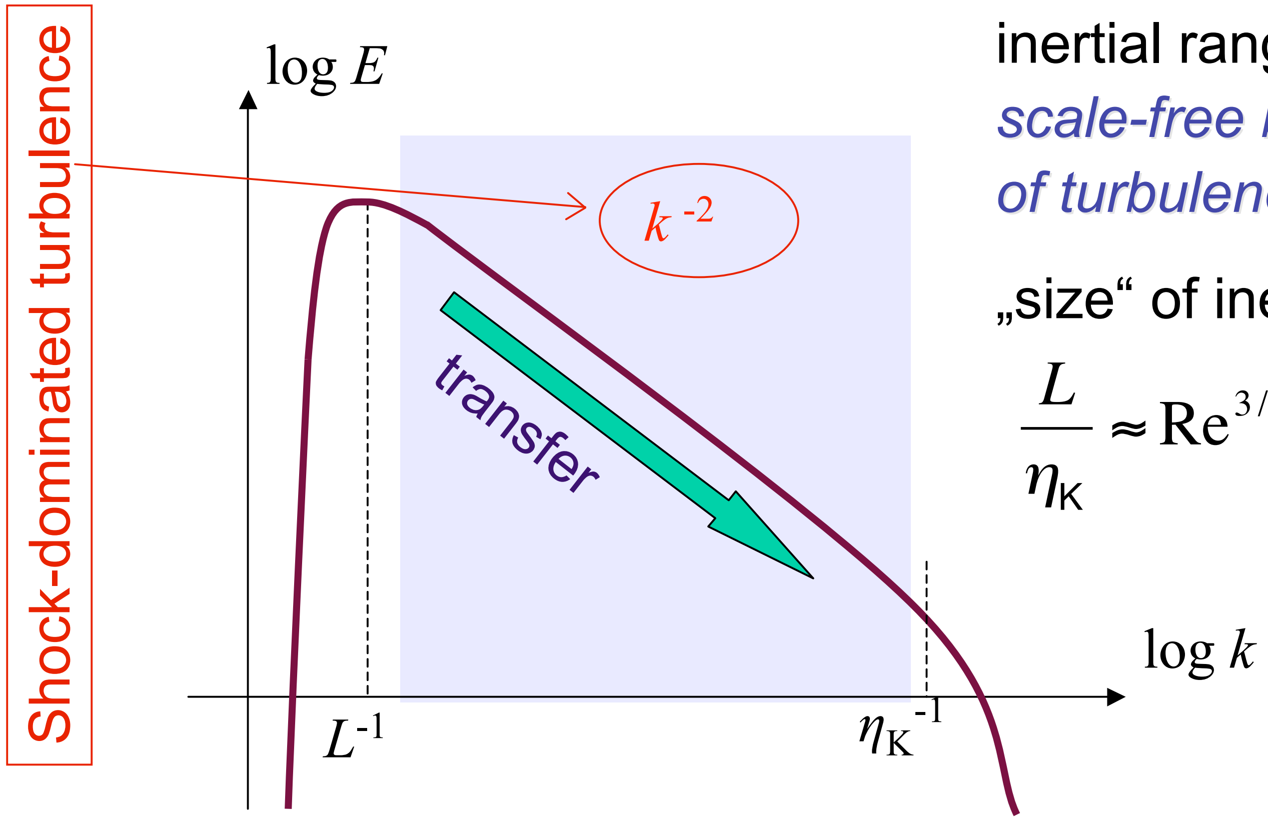
„size“ of inertial range:

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

energy input scale

energy dissipation scale

turbulent cascade



energy
input
scale

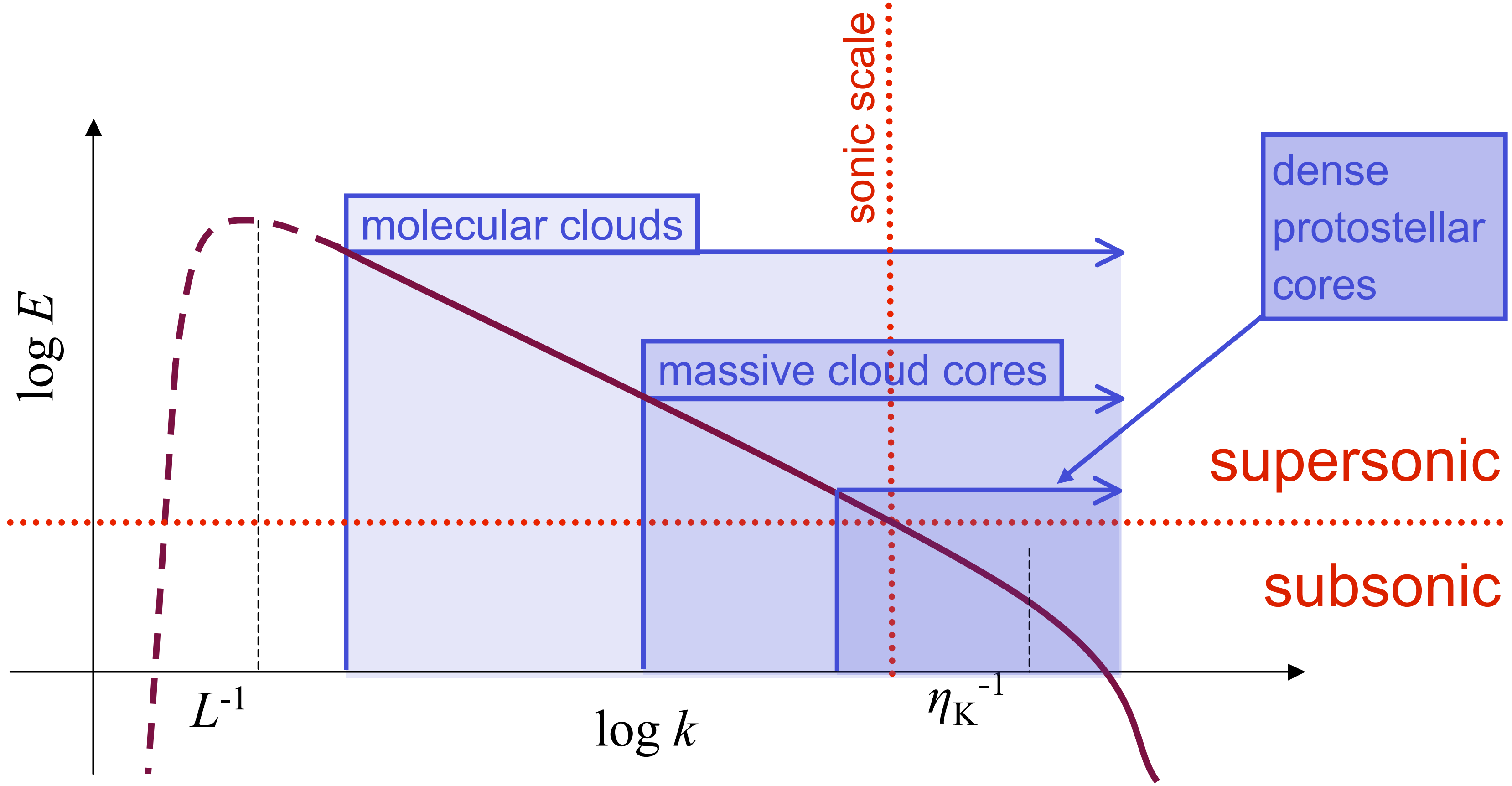
energy
dissipation
scale

inertial range:
scale-free behavior of turbulence

„size“ of inertial range:

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

turbulent cascade in ISM

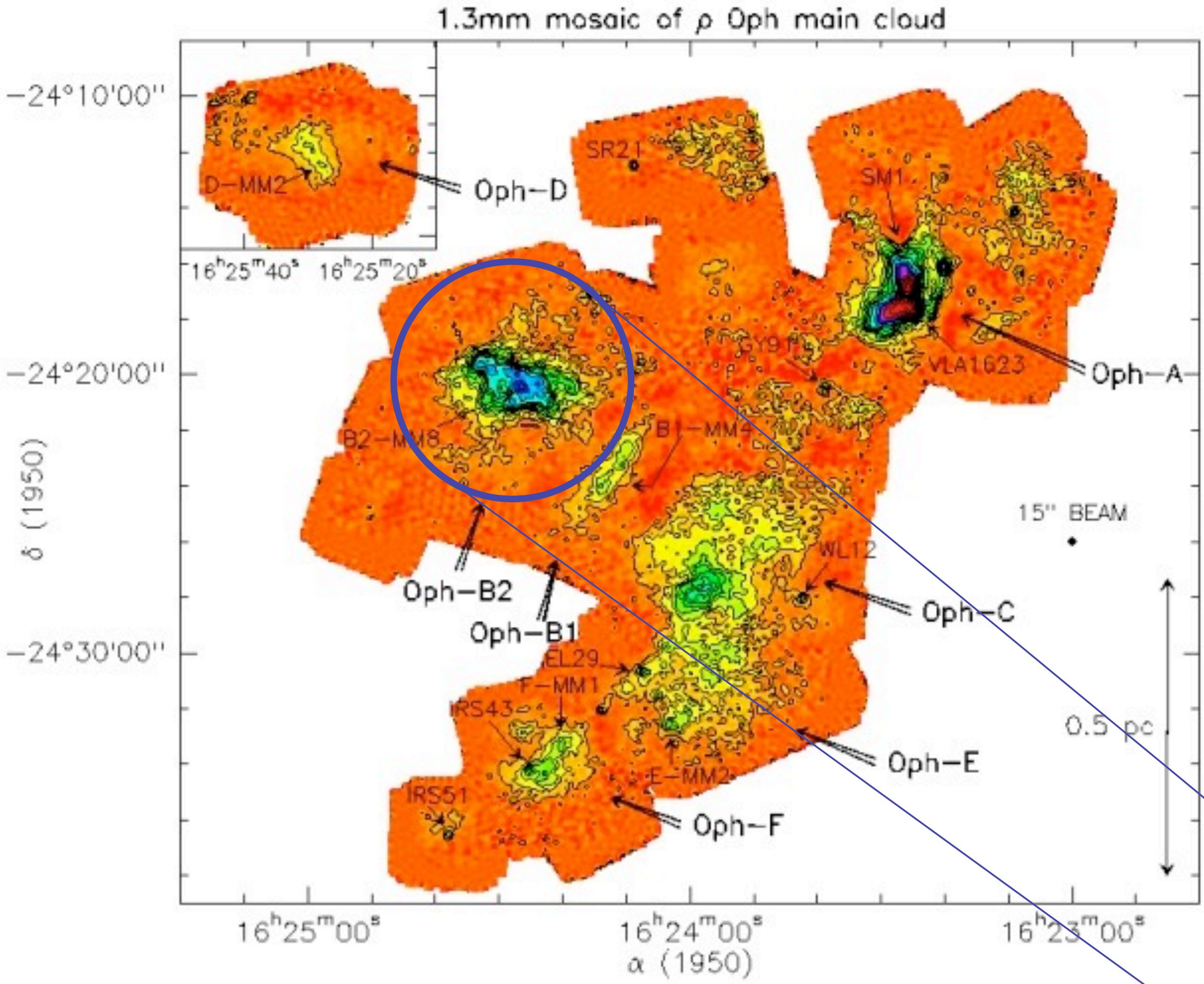


energy source & scale *NOT known* (supernovae, winds, spiral density waves?)

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

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

density structure of MCs



(Motte, André, & Neri 1998)

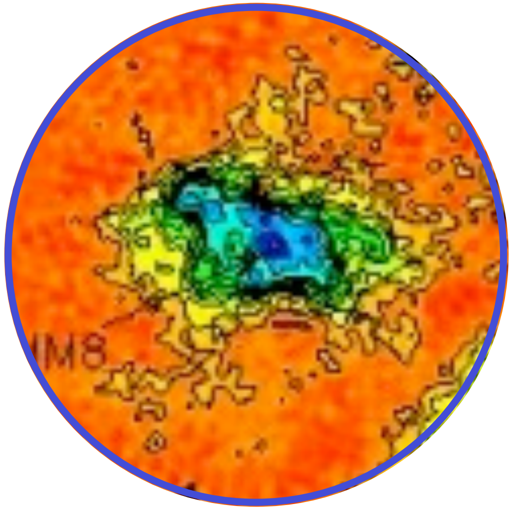
molecular clouds are highly inhomogeneous

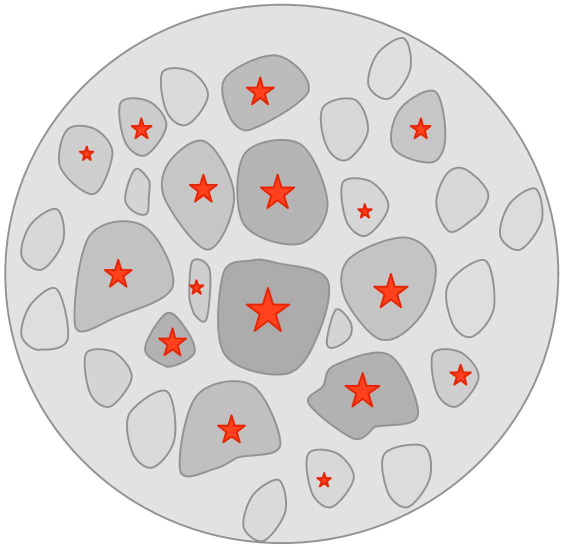
stars form in the densest and coldest parts of the cloud

ρ-Ophiuchus cloud seen in dust emission

let's focus on a cloud core like this one

evolution of cloud cores

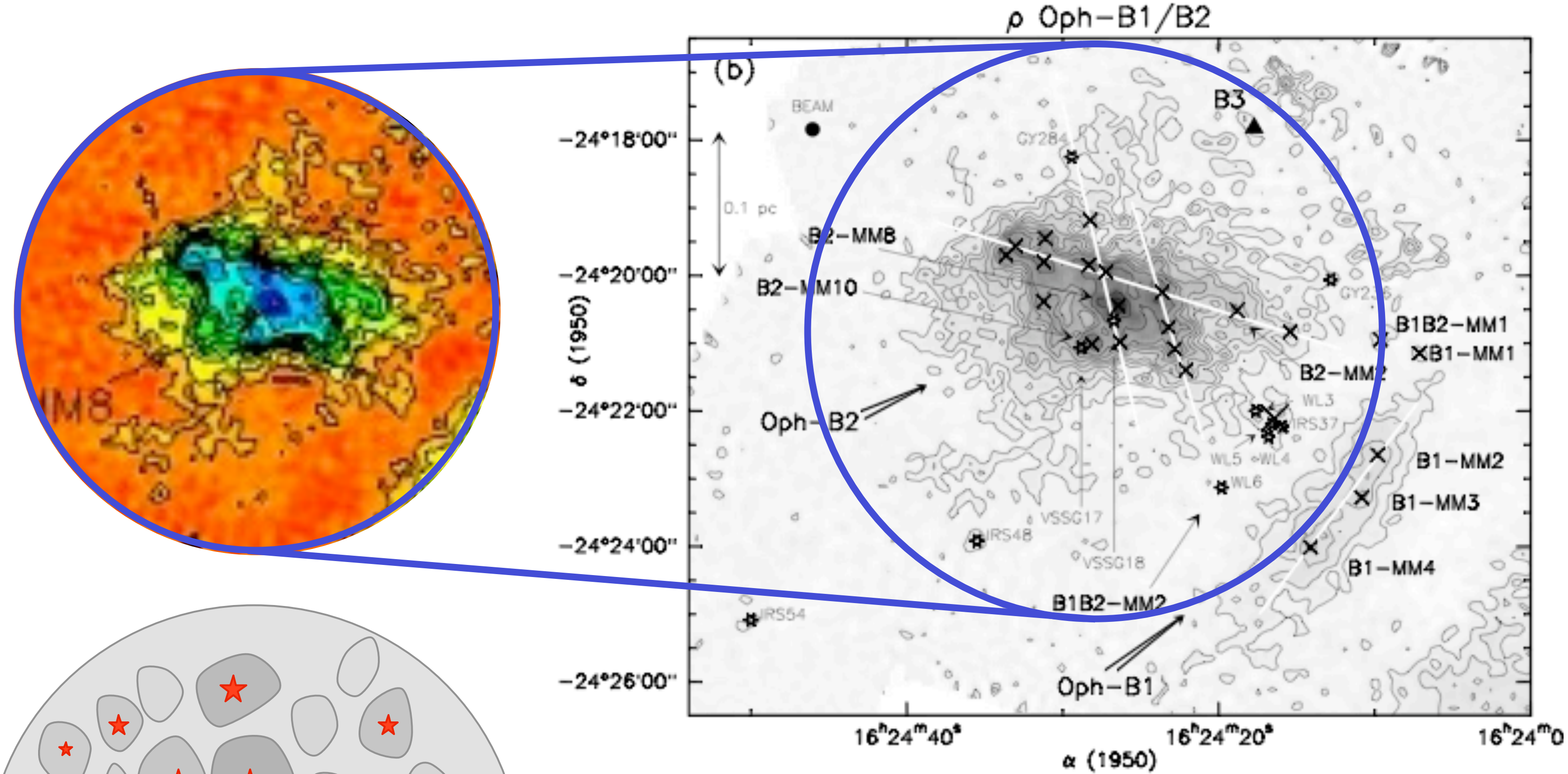


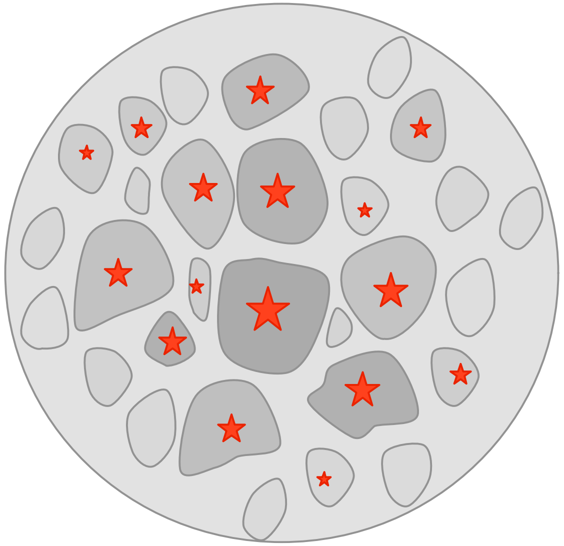


- Does core form single massive star or cluster with mass distribution?

- 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

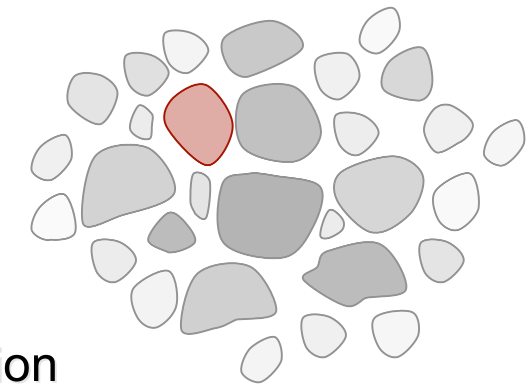




indeed ρ-Oph B1/2 contains several cores (“starless” cores are denoted by ×, cores with embedded protostars by ☆)

(Motte, André, & Neri 1998)

formation and evolution of cores



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

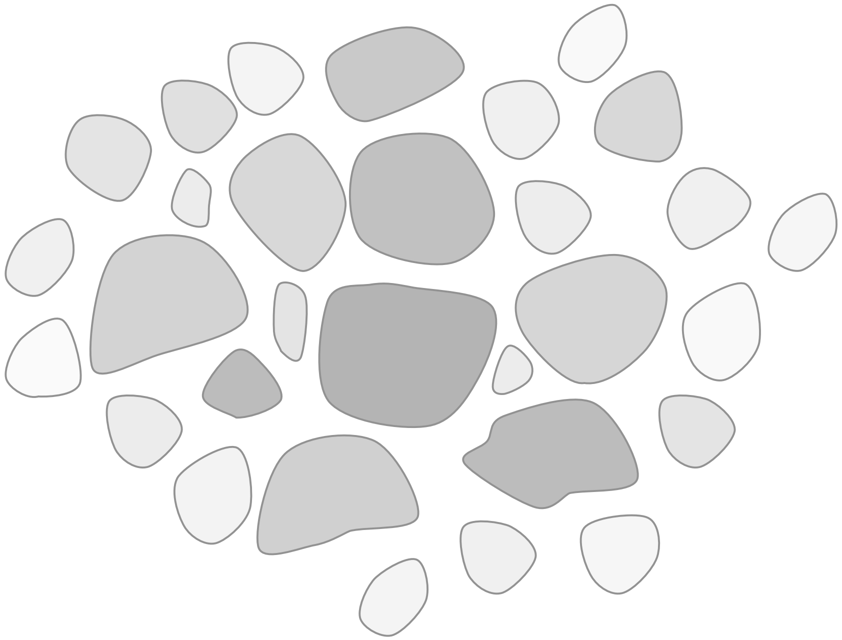
(e.g. Vazquez-Semadeni et al 2005)

- 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*

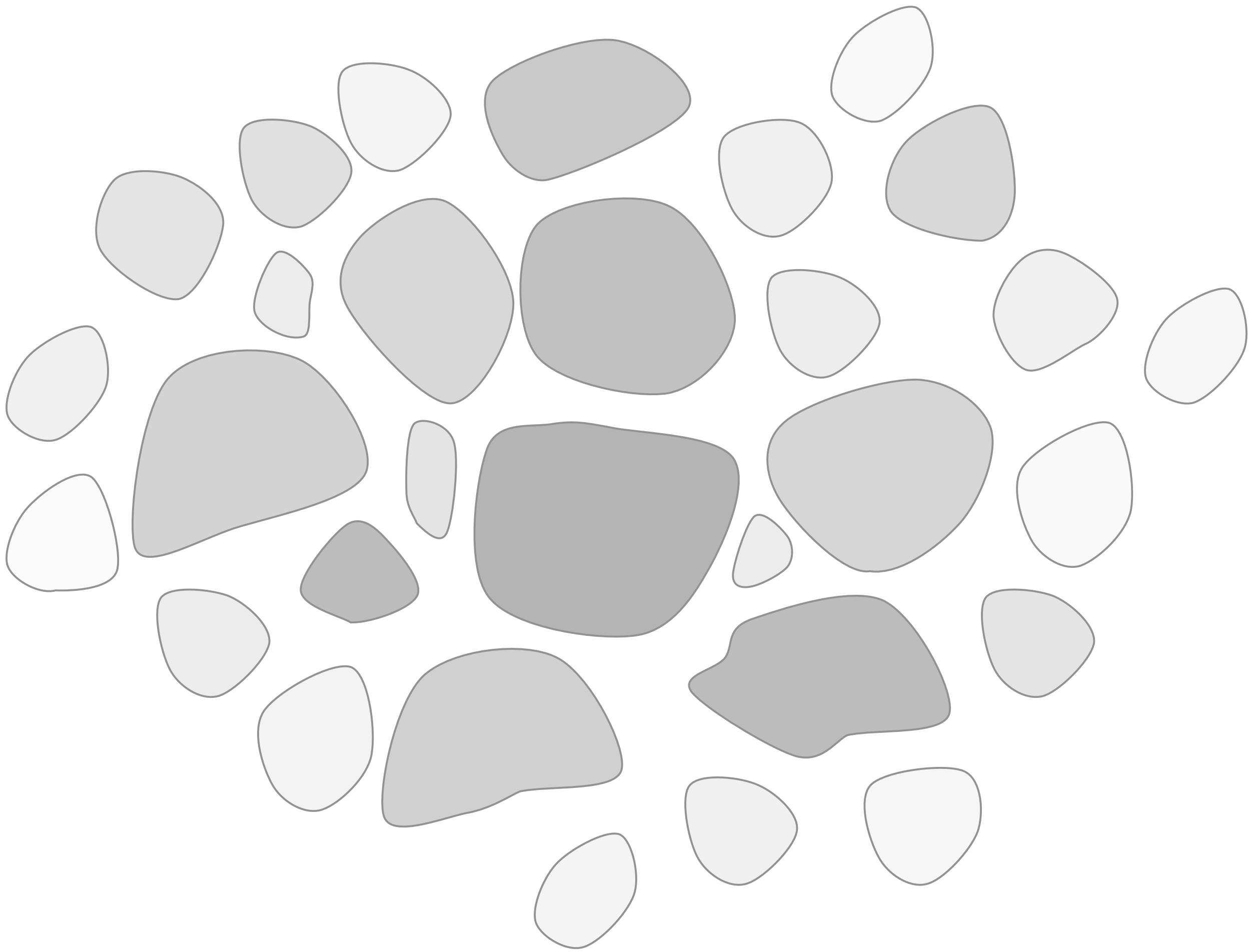
(2) turbulence decays, i.e. gravity dominates: $\alpha = E_{kin}/|E_{pot}| < 1$

--> *global contraction*

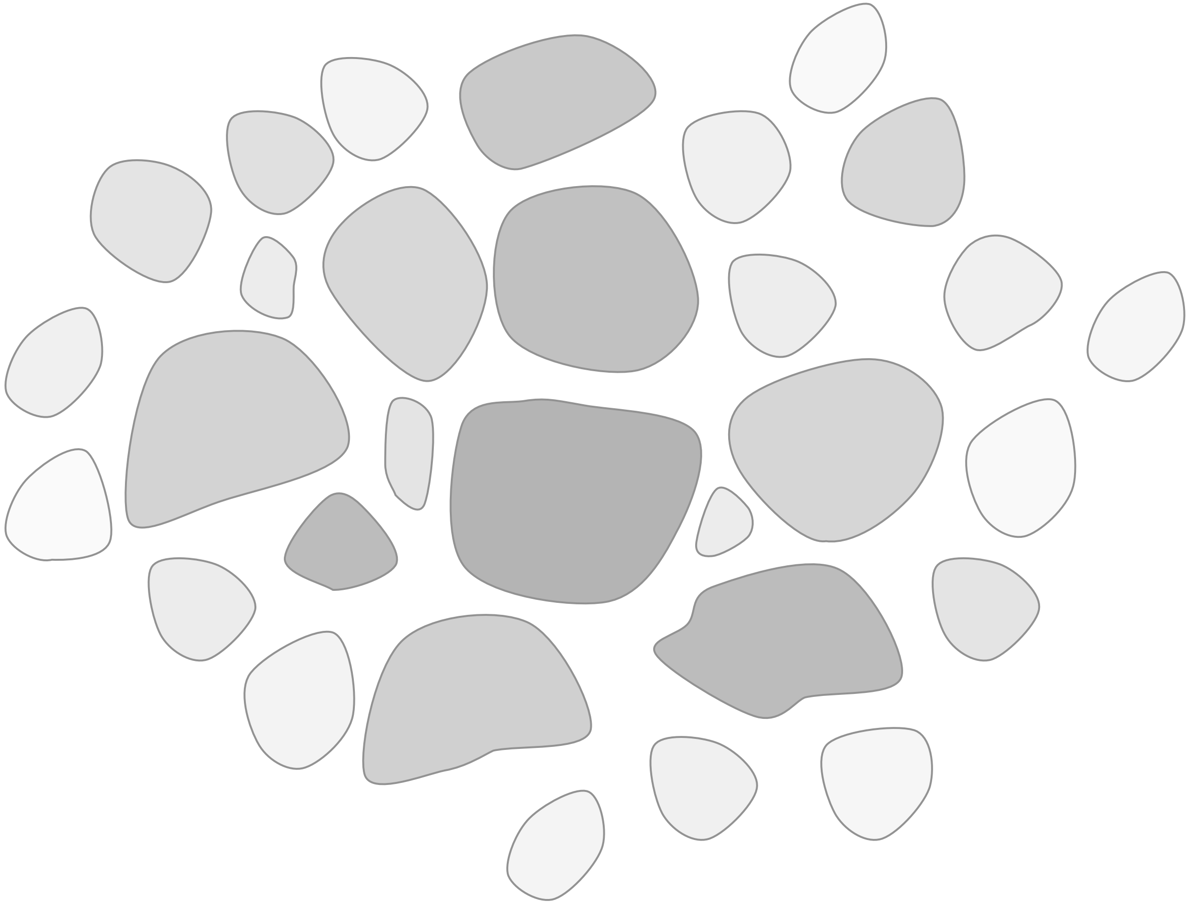
--> core do *interact* while collapsing

--> *competition* influences *mass growth*

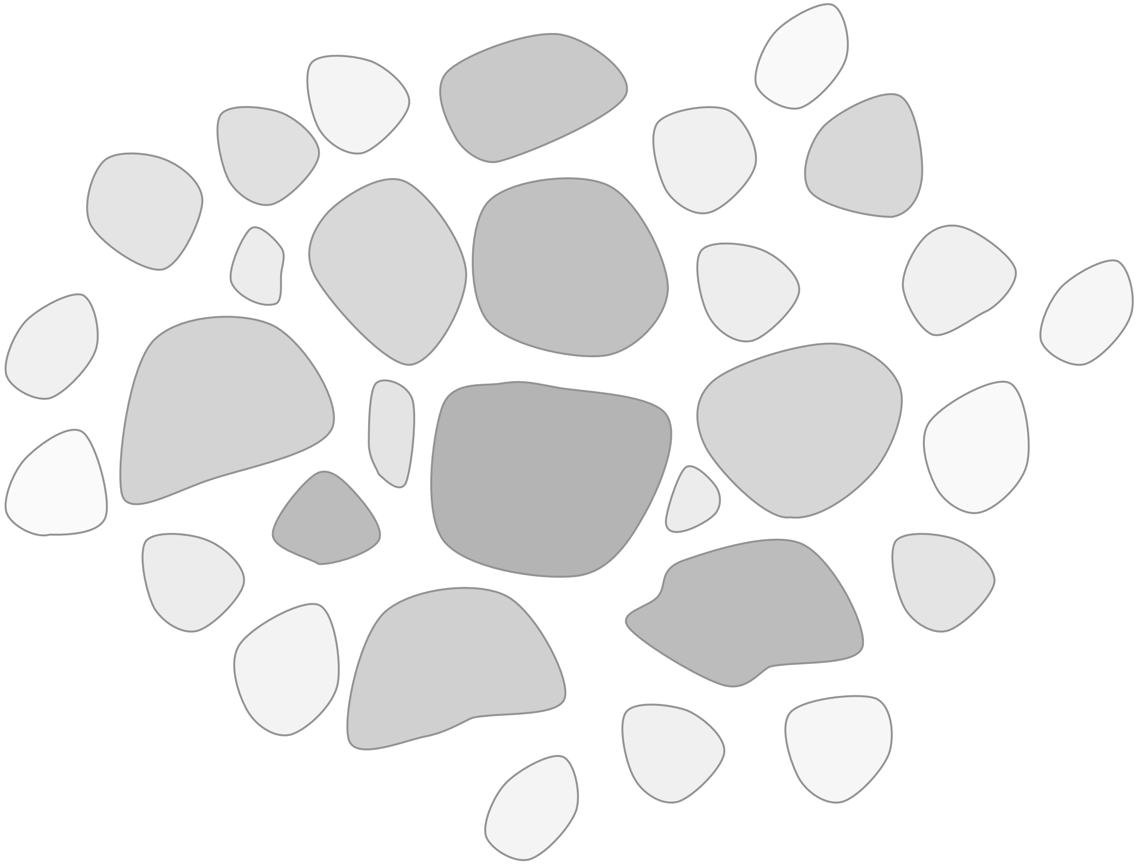
--> *dense cluster with high-mass stars*



turbulence creates a hierarchy of clumps



as turbulence decays locally, contraction sets in



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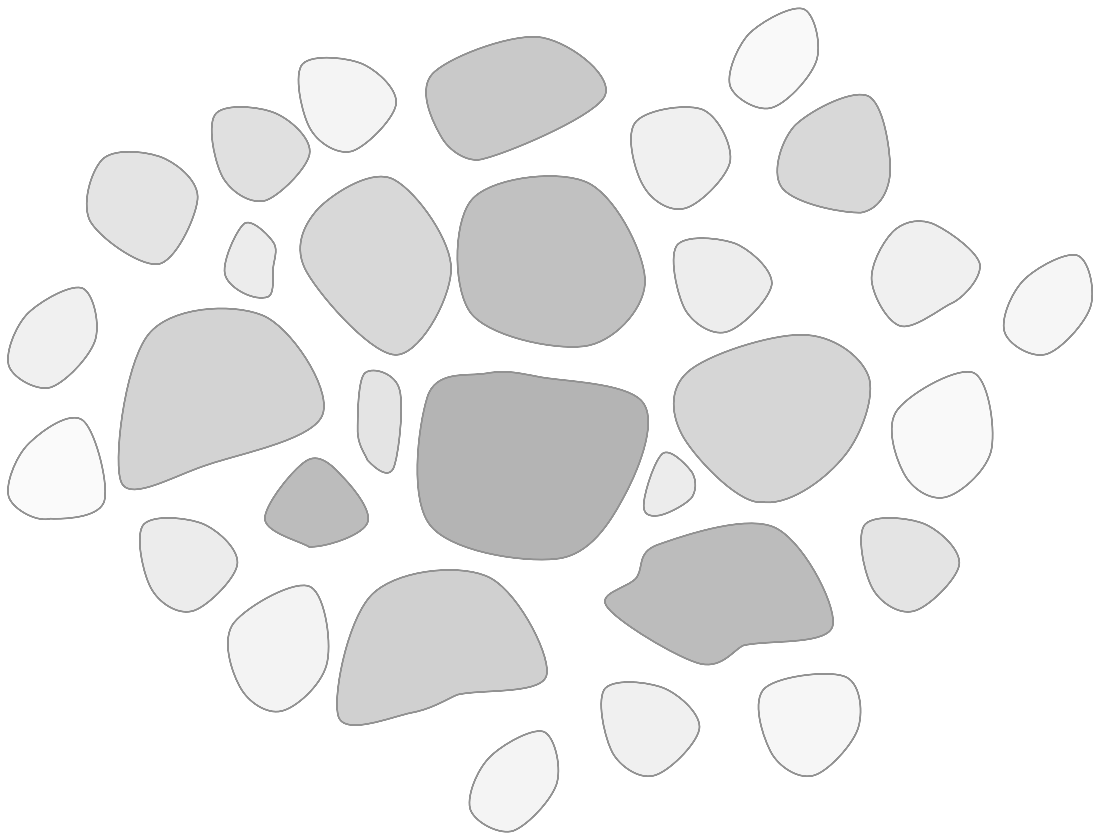
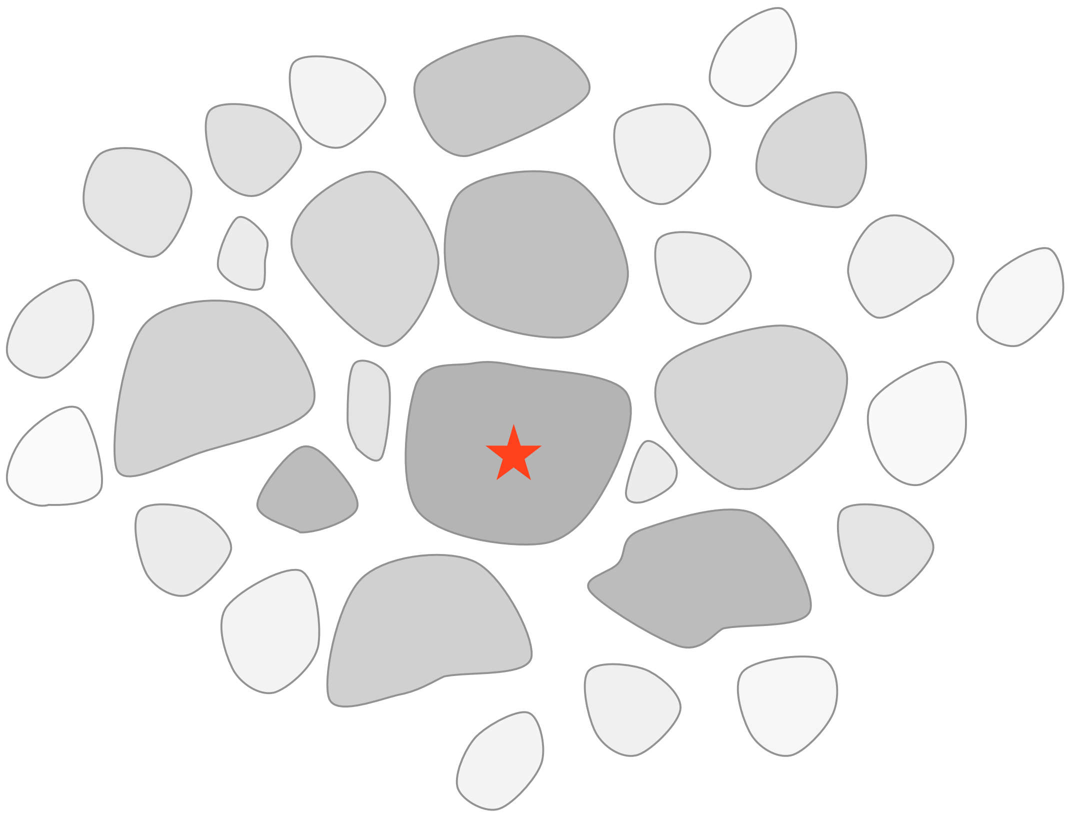


while region contracts, individual clumps collapse to form stars



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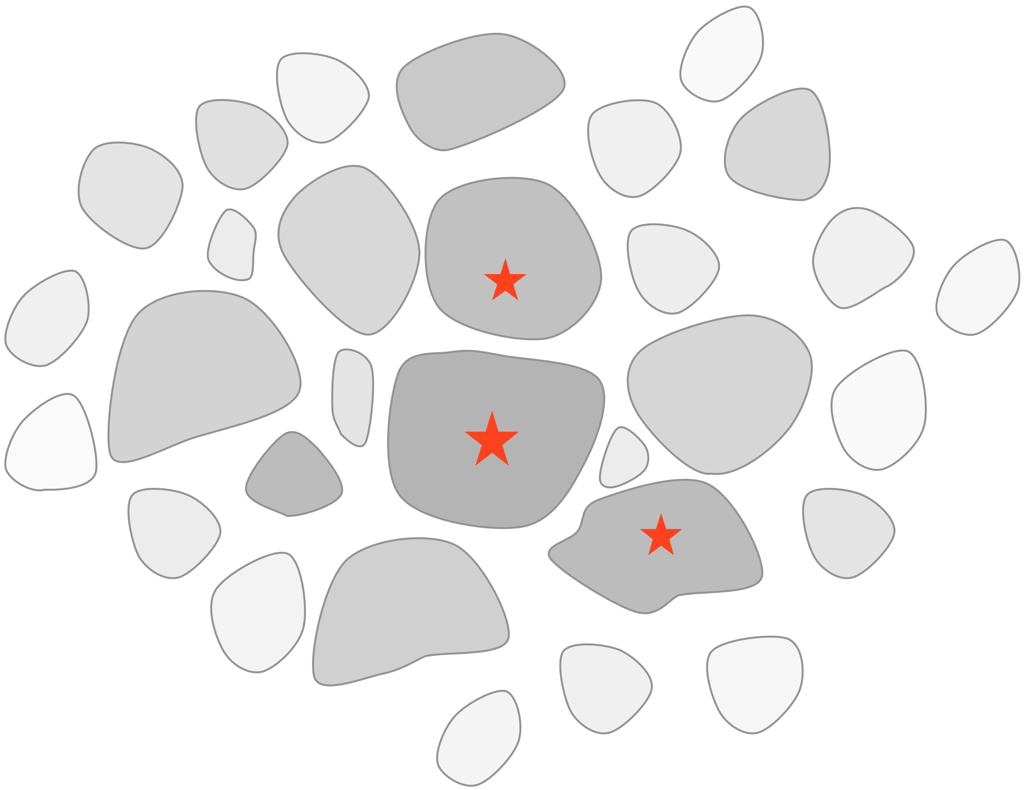
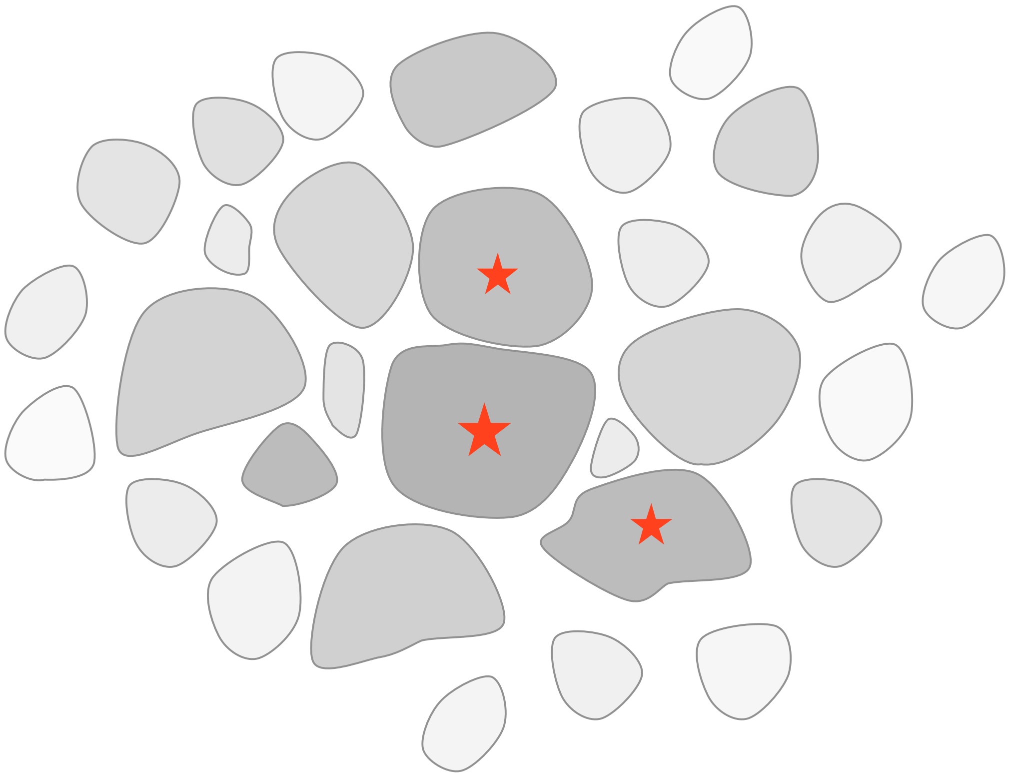


individual clumps collapse to form stars



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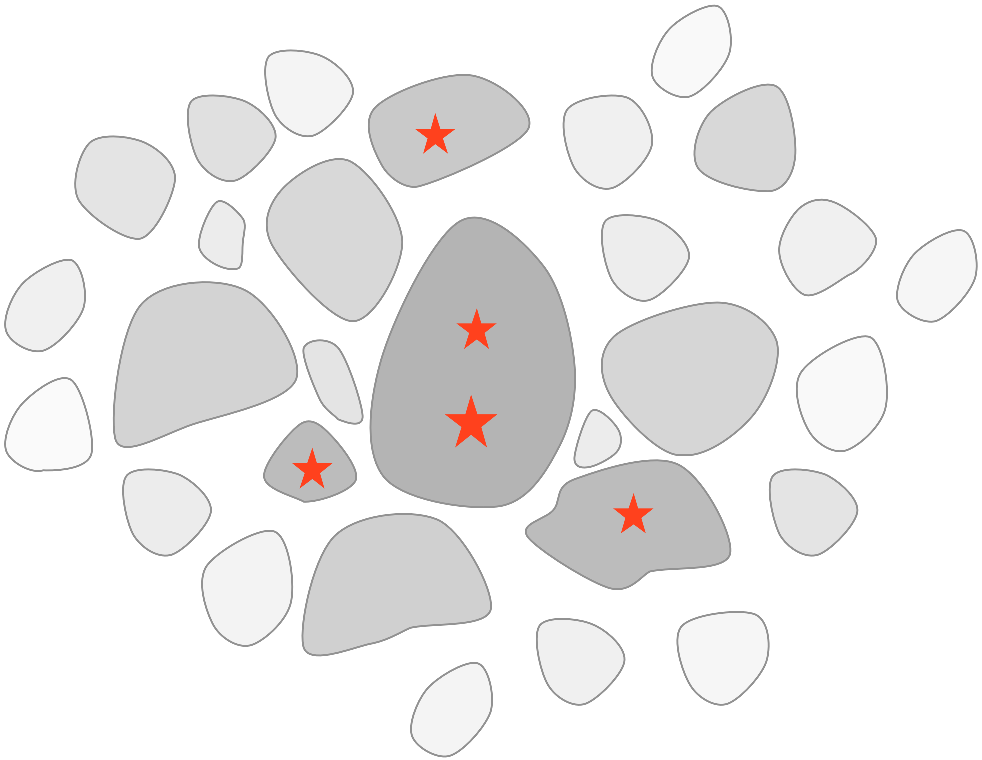
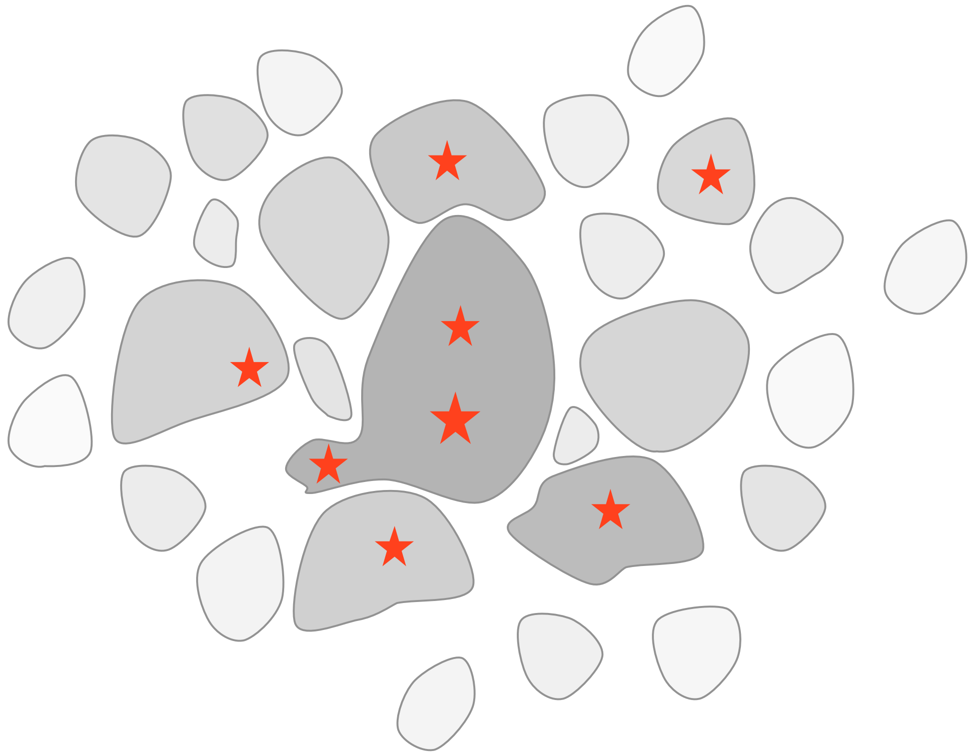


$\alpha = E_{kin}/|E_{pot}| < 1$

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



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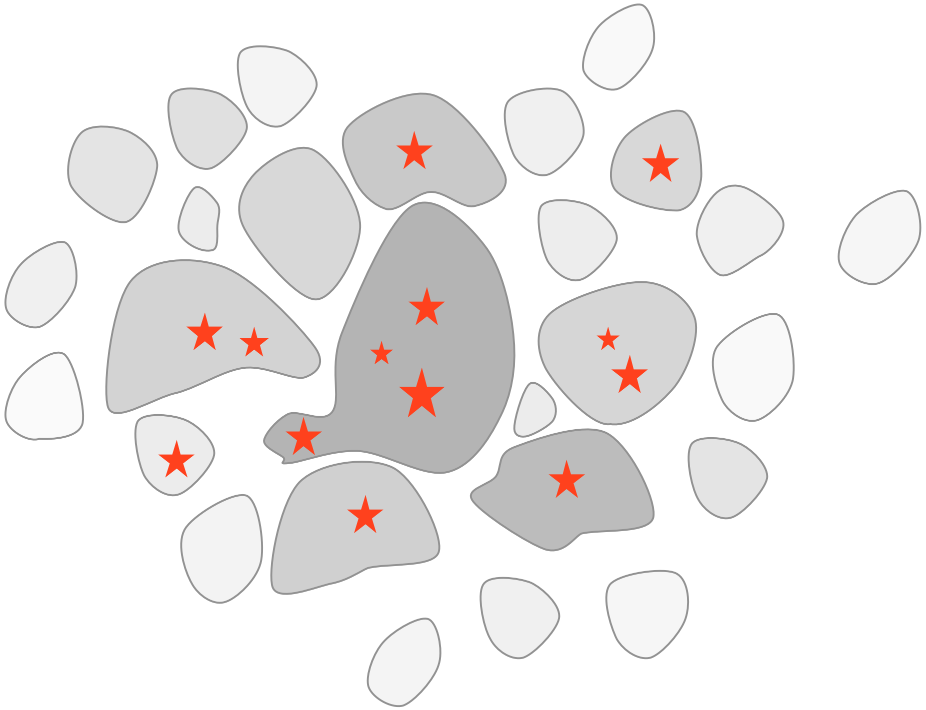

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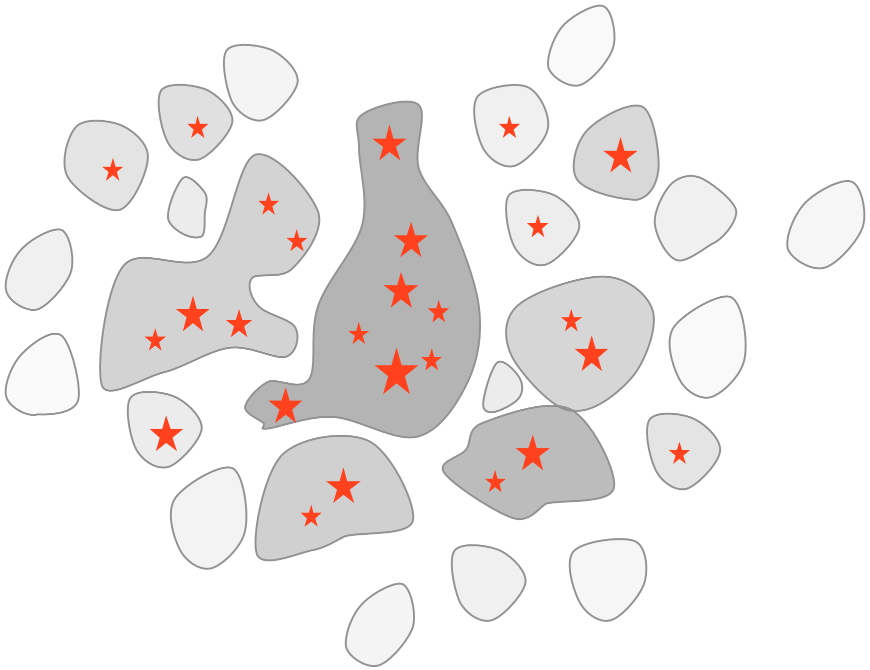
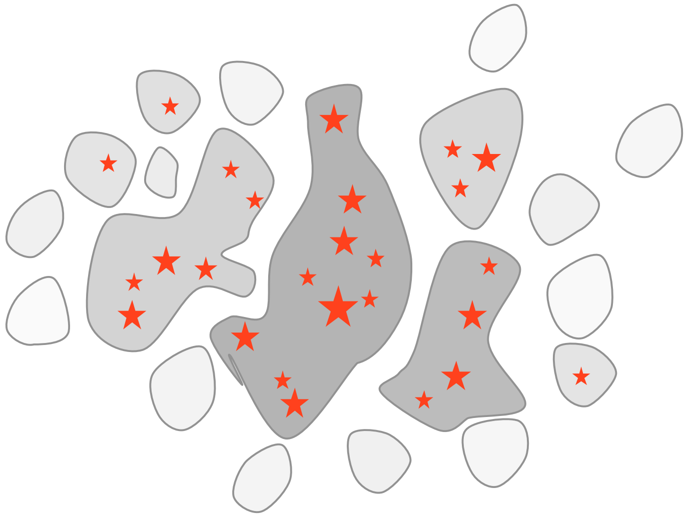


in *dense clusters*, competitive mass growth becomes important



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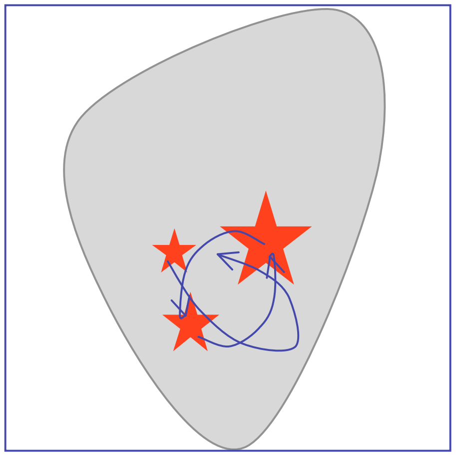
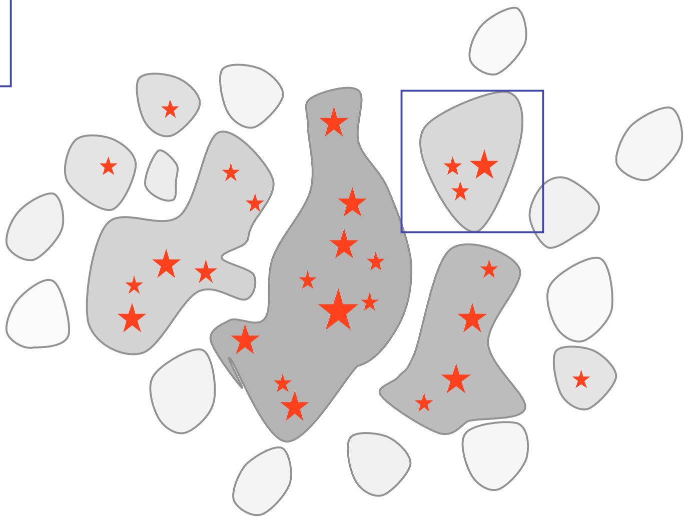
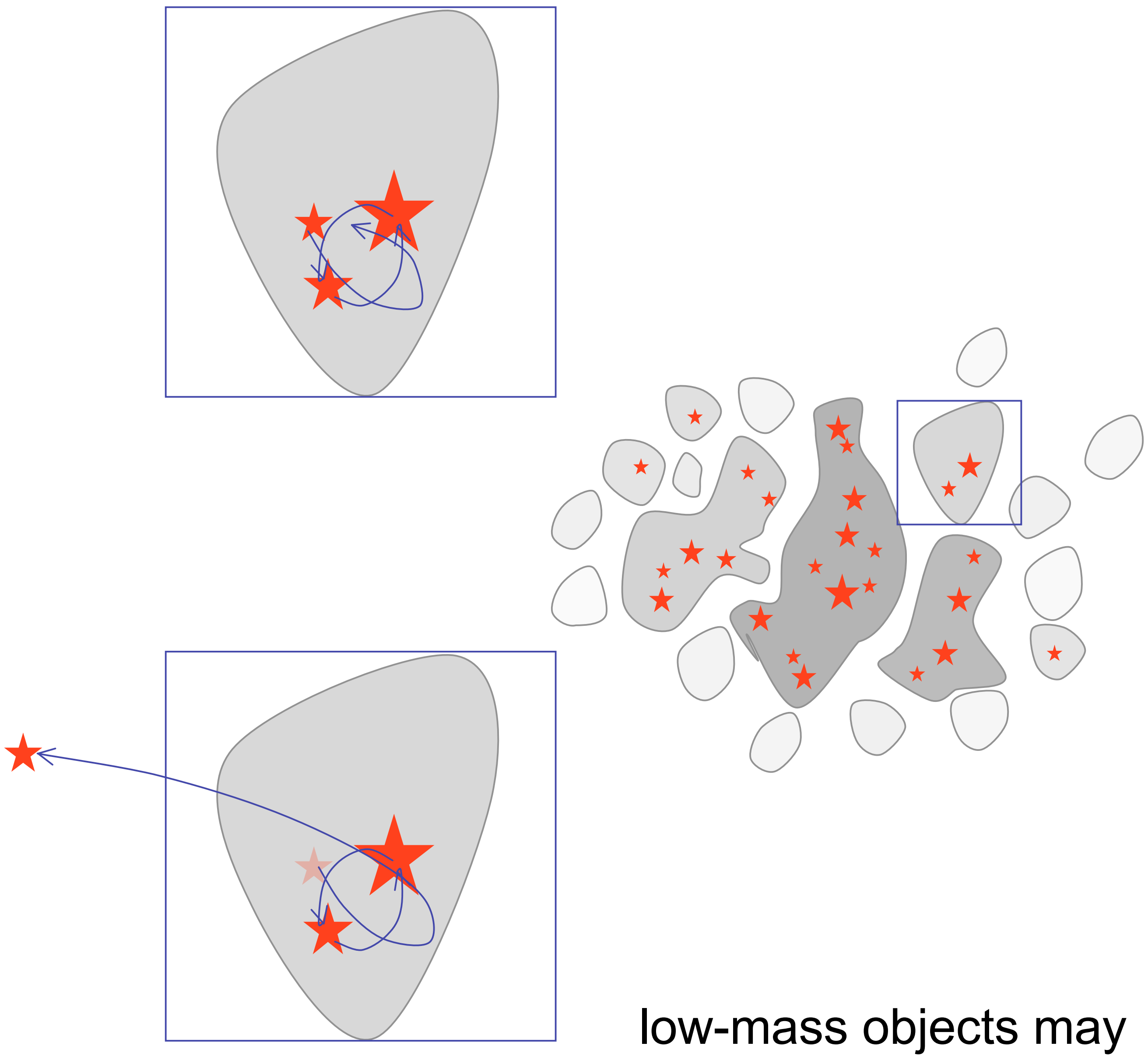
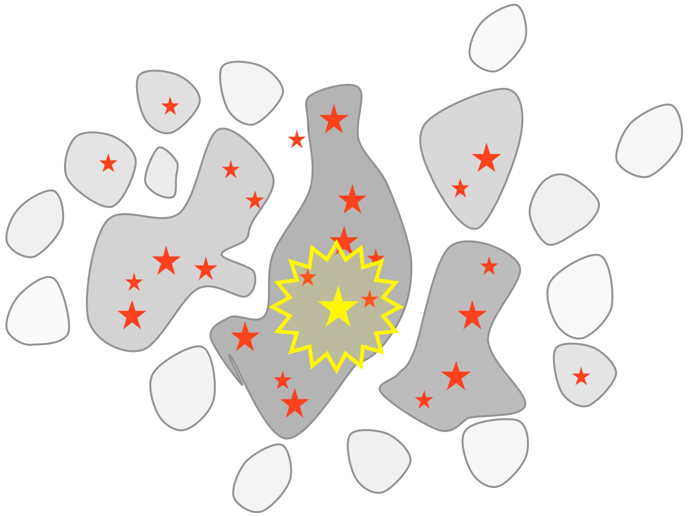




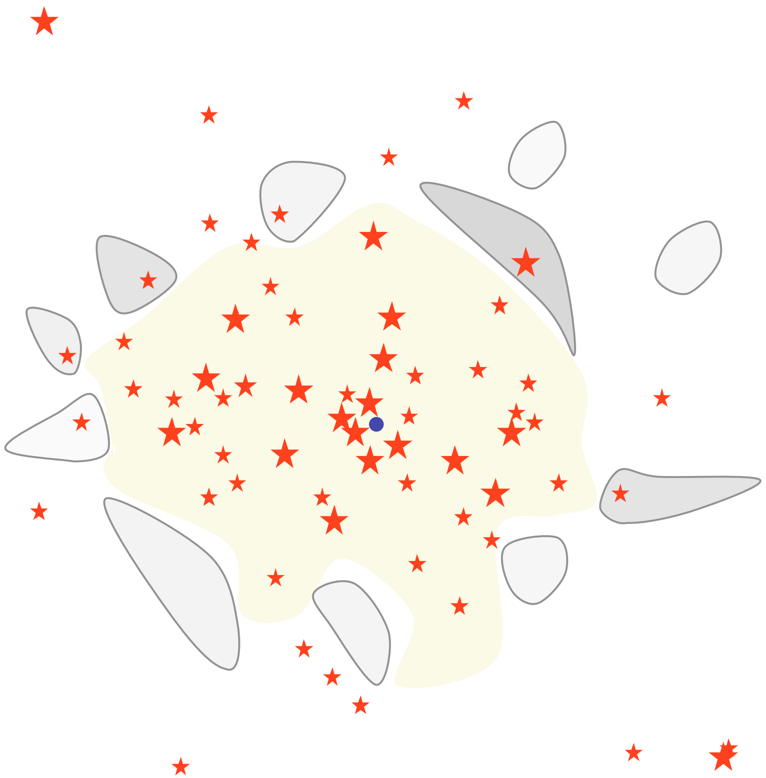
in *dense clusters*, *N*-body effects influence mass growth



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



feedback terminates star formation



result: *star cluster*, possibly with HII region predictions

predictions

- *global properties* (statistical properties)
  - SF efficiency and timescale
  - stellar mass function -- IMF
  - dynamics of young star clusters
  - description of self-gravitating turbulent systems (pdf's, Δ-*var.)*
  - chemical mixing properties
- *local properties* (properties of individual objects)
  - properties of individual clumps (e.g. shape, radial profile, lifetimes)
  - accretion history of individual protostars (dM/dt vs. t, j vs. t)
  - binary (proto)stars (eccentricity, mass ratio, etc.)
  - SED's of individual protostars
  - dynamic PMS tracks: T_{bol}-L_{bol} evolution

examples and predictions

example 1: transient structure of turbulent clouds

example 2: speculations on the origin of the stellar mass spectrum (IMF) example 1

Transient cloud structure

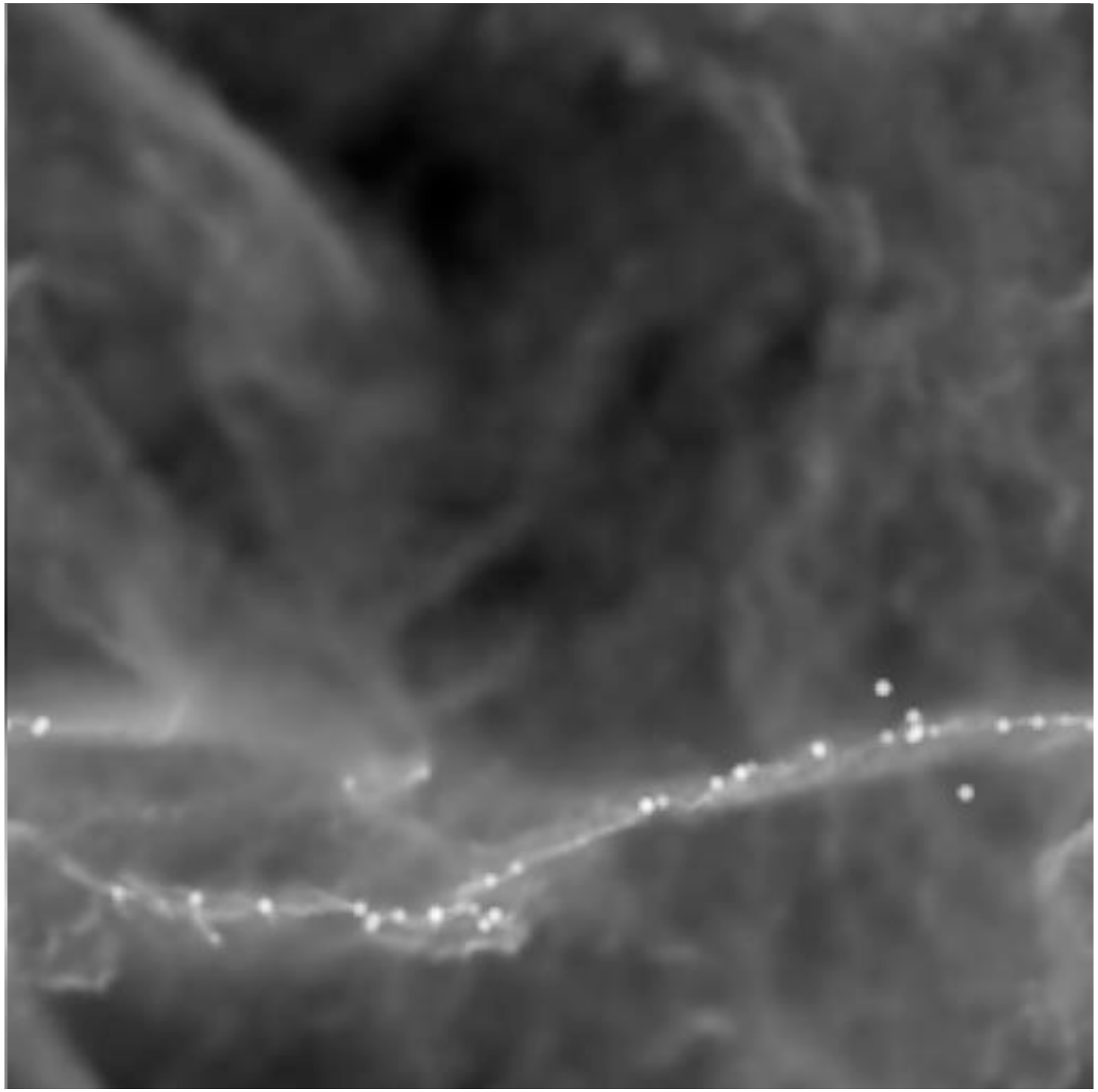
Gravoturbulent fragmentation of turbulent self-gravitating clouds

xy projection *xz projection* *yz projection*

- SPH model with $1.6 \mathrm{x} 10^6$ particles
- large-scale driven turbulence

- Mach number $\mathcal{M} = 6$
- periodic boundaries
- physical scaling: “Taurus”

Gravoturbulent fragmentation



Gravoturbulent fragmentation in molecular clouds:

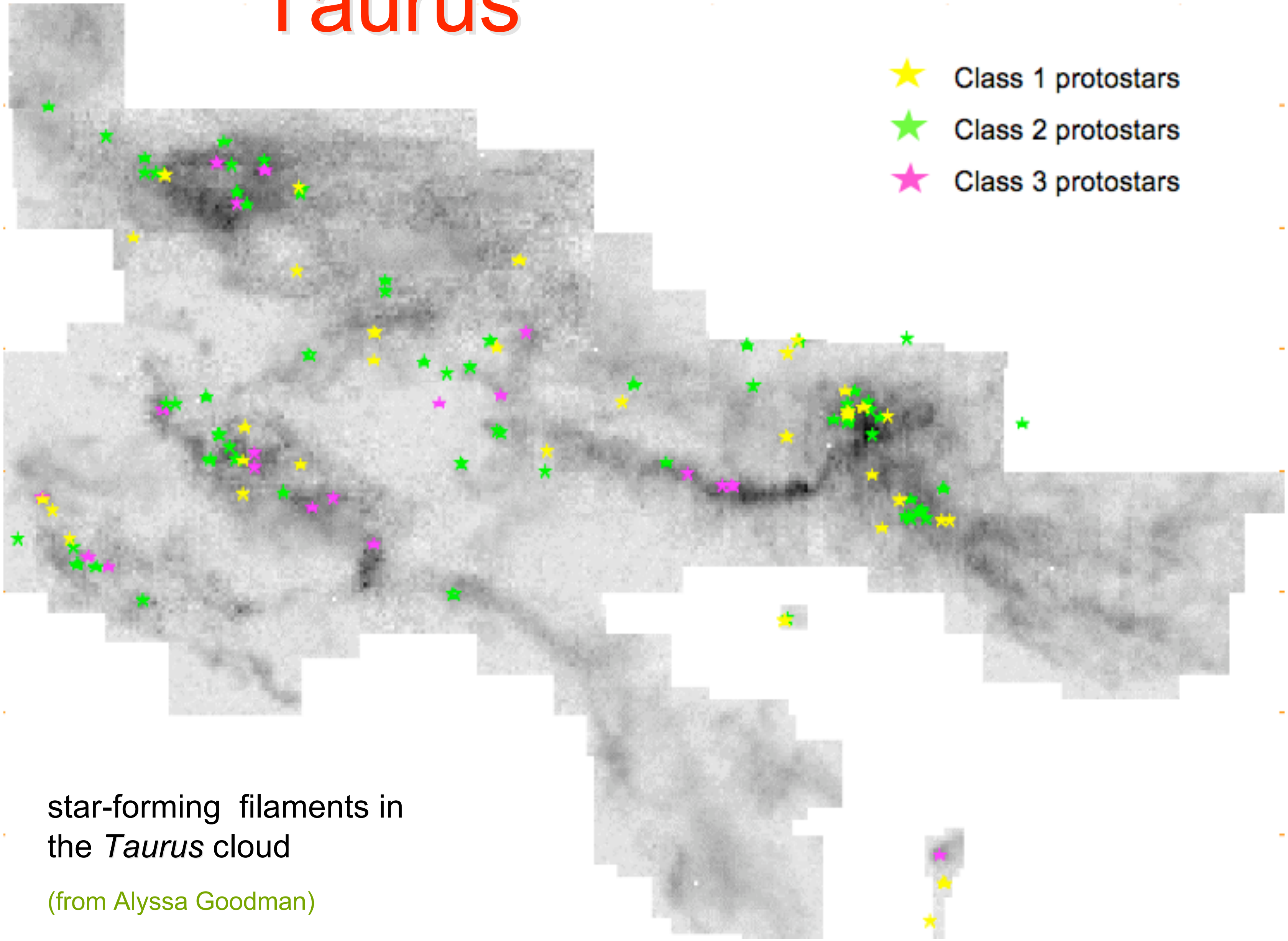
- SPH model with 1.6×10^6 particles
- large-scale driven turbulence
- Mach number $\mathcal{M} = 6$
- periodic boundaries
- physical scaling:

"Taurus":

→ density $n(H_2) \approx 10^2\,cm^{-3}$

→ $L = 6\,pc$, $M = 5000\,M_\odot$

Taurus



star-forming filaments in
the *Taurus* cloud

(from Alyssa Goodman)

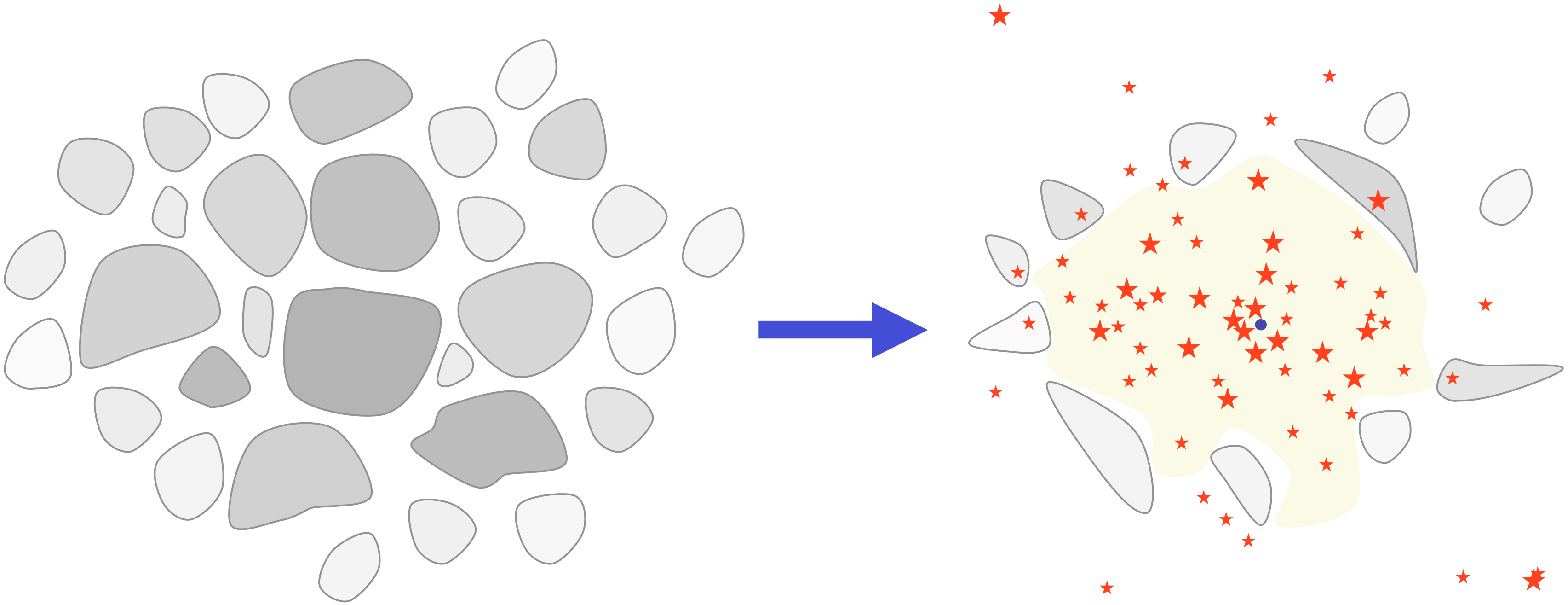
example 2

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

Star cluster formation

Most stars form in clusters → *star formation = cluster formation*

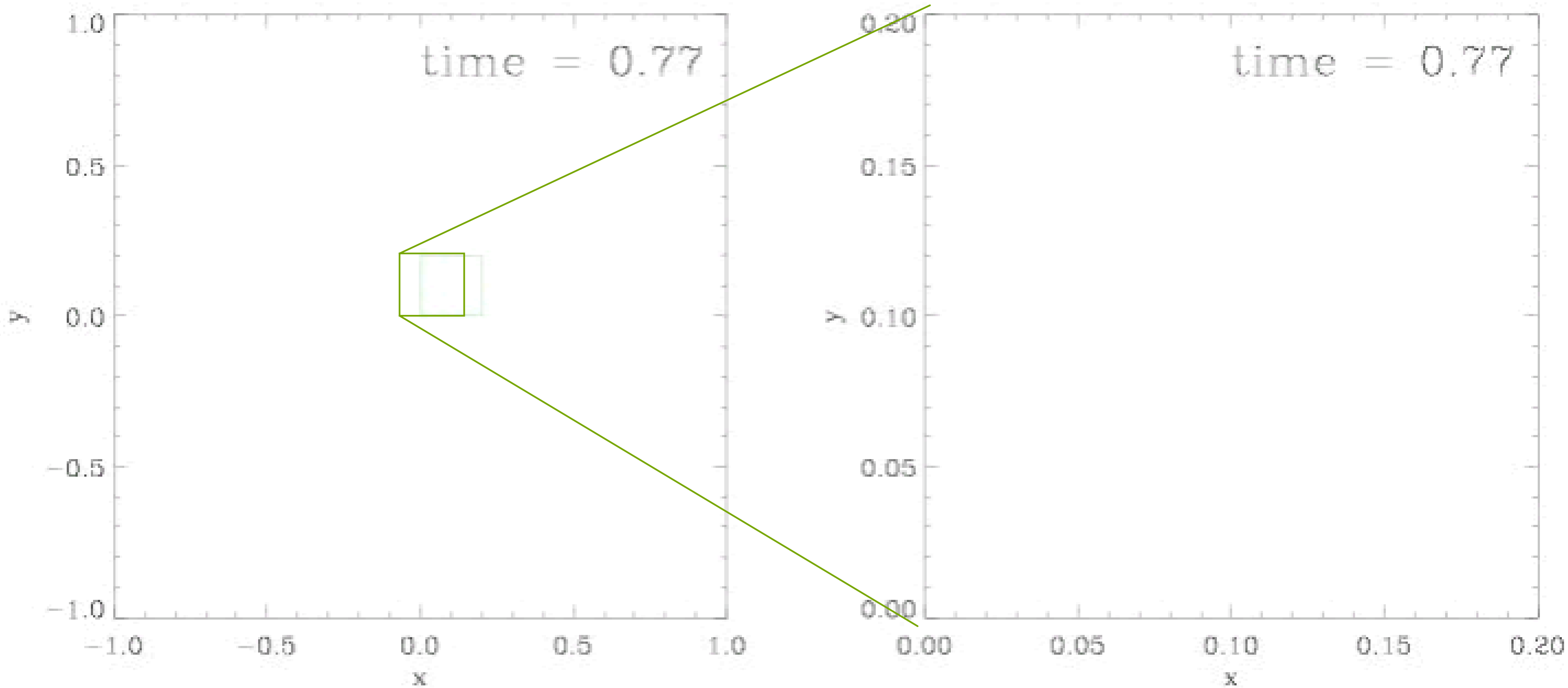


How to get from cloud cores to star clusters?

How do the stars acquire mass?

Star cluster formation

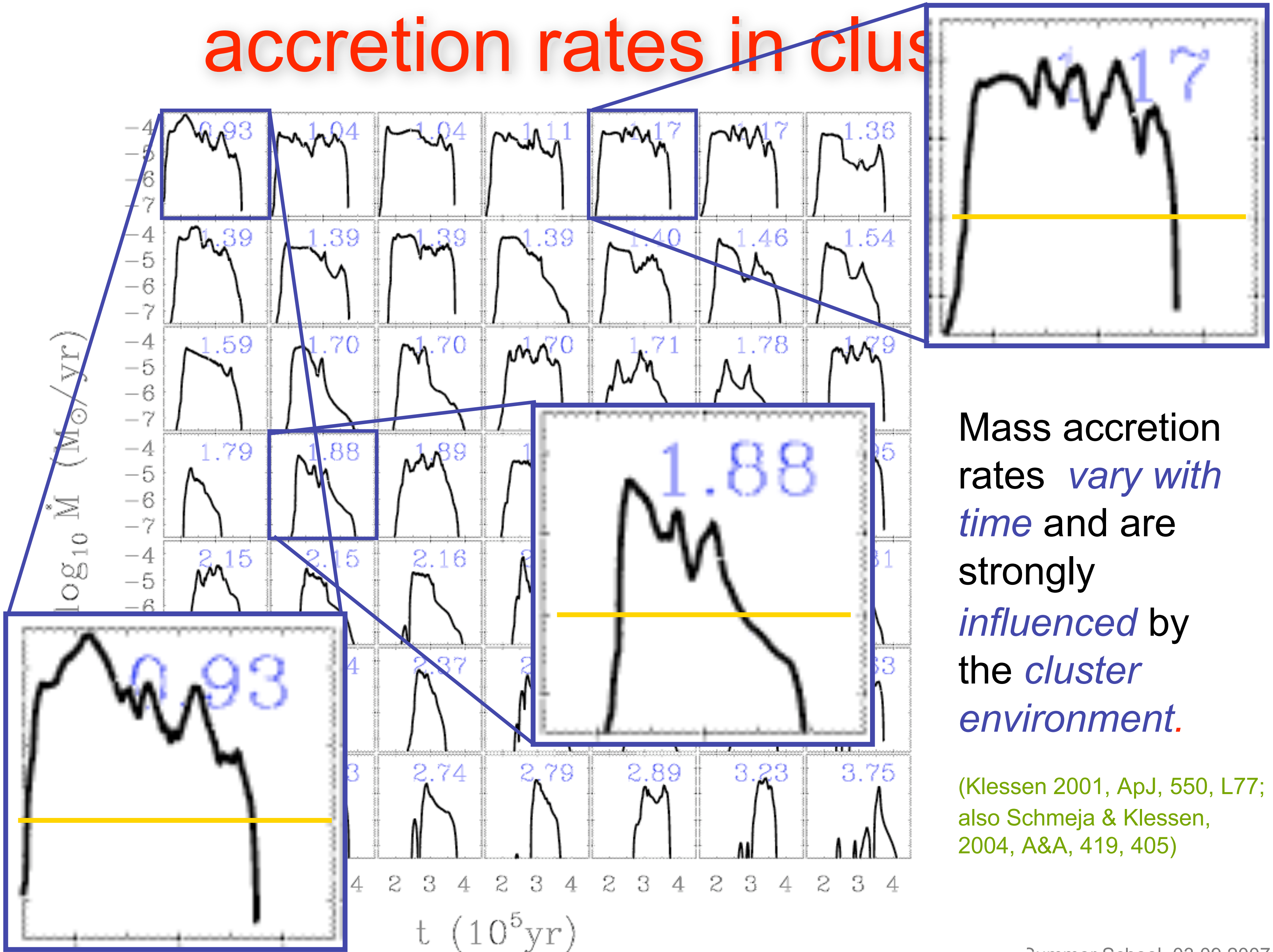
in dense clusters protostellar interaction may be come important!



Trajectories of protostars in a nascent dense cluster created by gravoturbulent fragmentation

(from Klessen & Burkert 2000, ApJS, 128, 287)

accretion rates in clus



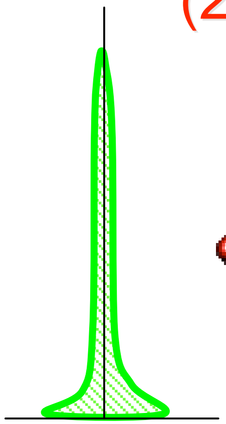
Mass accretion rates *vary with time* and are strongly *influenced* by the *cluster environment*.

(Klessen 2001, ApJ, 550, L77; also Schmeja & Klessen, 2004, A&A, 419, 405)

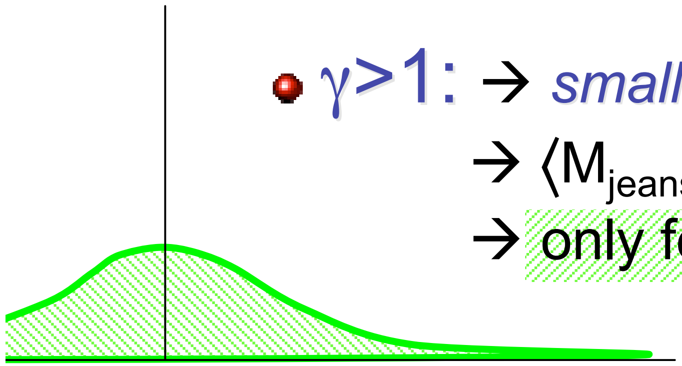
fragmentation depends on EOS

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

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

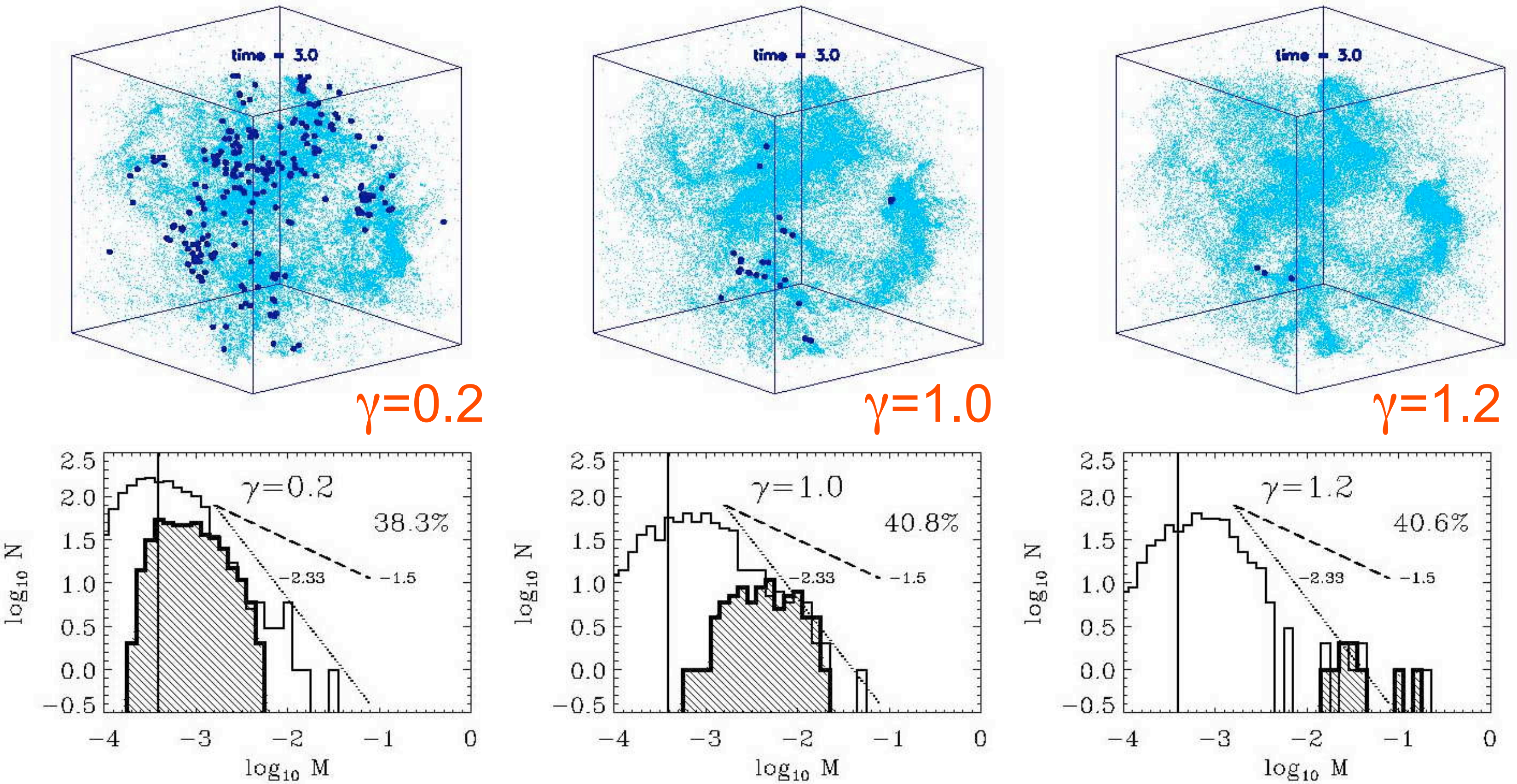


- $\gamma<1$: → *large* density excursion for given pressure
  → $\langle M_{jeans} \rangle$ becomes small
  → number of fluctuations with $M > M_{jeans}$ is large



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

fragmentation depends on EOS



for γ<1 fragmentation is enhanced → *cluster of low-mass stars*

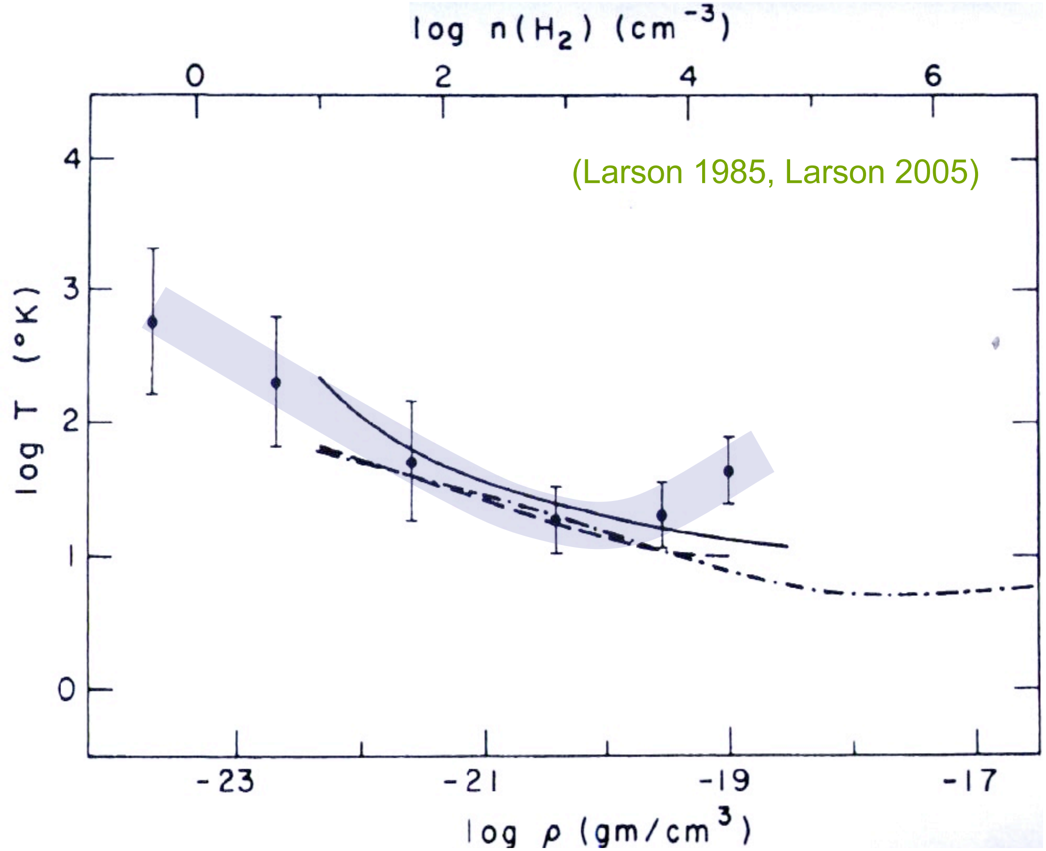
for γ>1 it is suppressed → formation of *isolated massive stars*

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

EOS for solar neighborhood

below 10^{-18} gcm^{-3}: ρ ⬆ ⟹ T ⬇

above 10^{-18} gcm^{-3}: ρ ⬆ ⟹ T ⬆

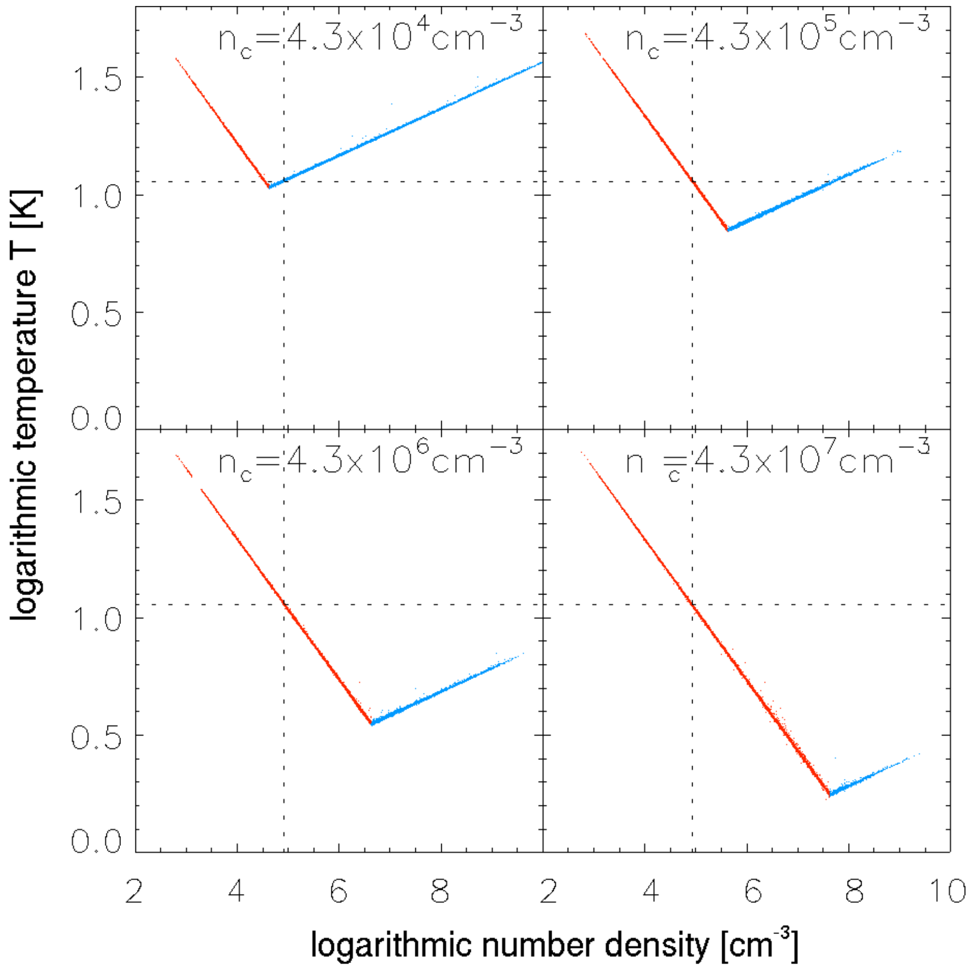


IMF from simple piece-wise polytropic EOS

$\gamma_1 = 0.7$

$\gamma_2 = 1.1$

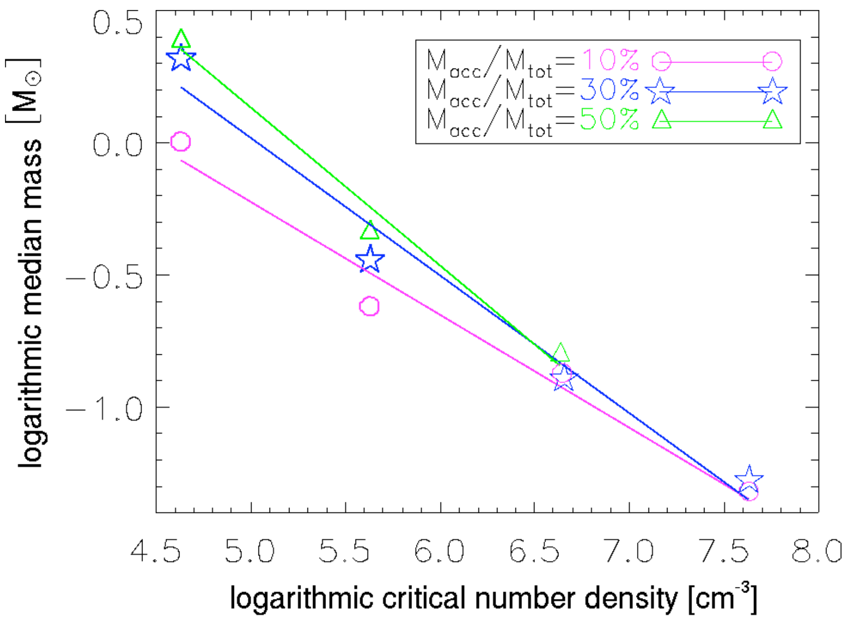
$$T \sim \rho^{\gamma-1}$$



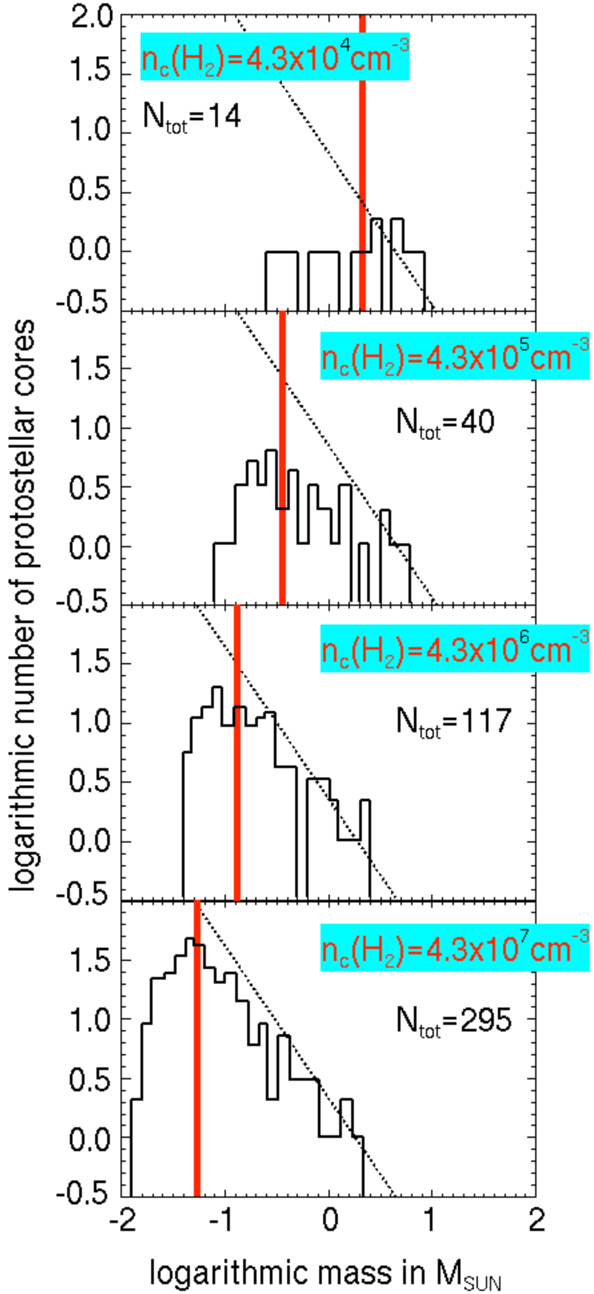
(Jappsen et al. 2005)

IMF from simple piece-wise polytropic EOS

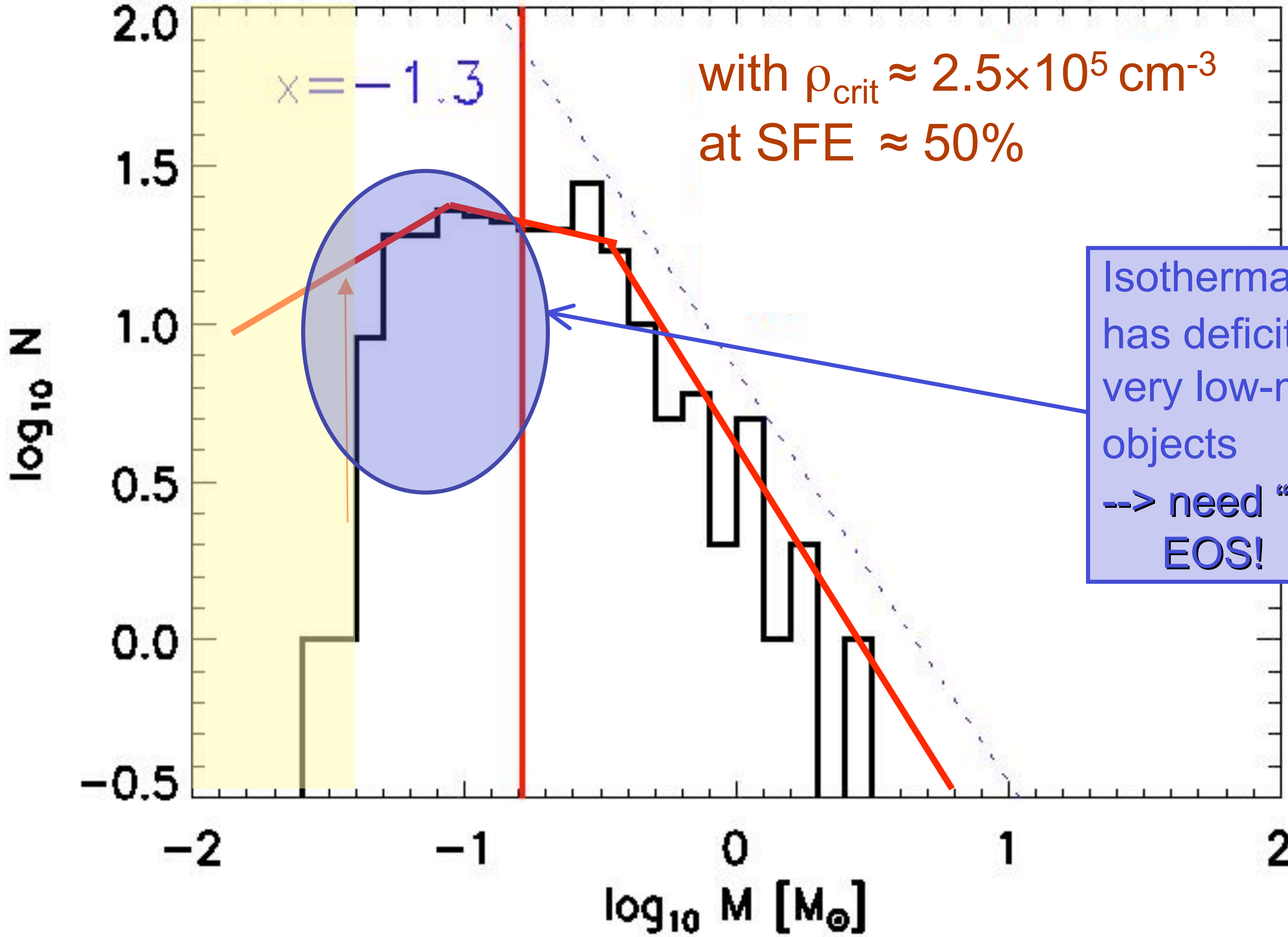
critical density ⬆ ⇨ median mass ⬇



(Jappsen et al. 2005)



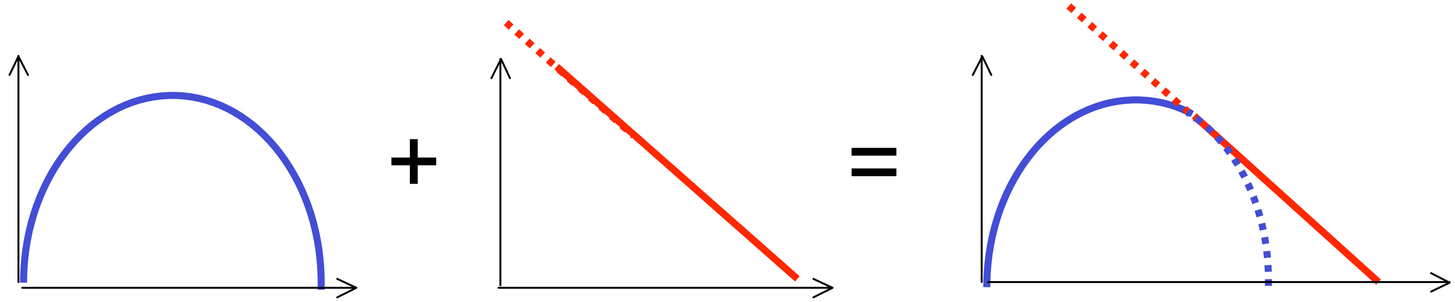
IMF in nearby molecular clouds



Isothermal EOS has deficite of very low-mass objects
--> need "better" EOS!

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

Plausibility argument for shape



- Supersonic turbulence is scale free process

  → *POWER LAW BEHAVIOR*

- *But also:* turbulence and fragmentation are highly stochastic processes → central limit theorem

  → *GAUSSIAN DISTRIBUTION*

Summary

summary

- interstellar gas is highly inhomogeneous
  - *thermal instability*
  - *gravitational instability*
  - *turbulent compression* (in shocks $\delta\rho/\rho \approx \mathcal{M}^2$; in atomic gas: $\mathcal{M} \approx 1...3$)
- cold *molecular clouds* form rapidly in high-density regions
  - 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 density structure, *gravity* selects for collapse

  ⟶ ***GRAVOTUBULENT FRAGMENTATION***
- *turbulent cascade:* local compression *within* a cloud provokes collapse
- individual *stars* and *star clusters* form through *sequence* of highly *stochastic* events:
  - *collapse* of cloud cores in turbulent cloud (cores change during collapse)
  - plus mutual *interaction* during collapse (importance depends on ratio of potential energy to turbulent energy) (buzz word: *competitive accretion*)

(Larson 2003, PRP; Mac Low & Klessen 2004, RMP, 76, 125-194, Ballesteros-Paresed et al. PPV)

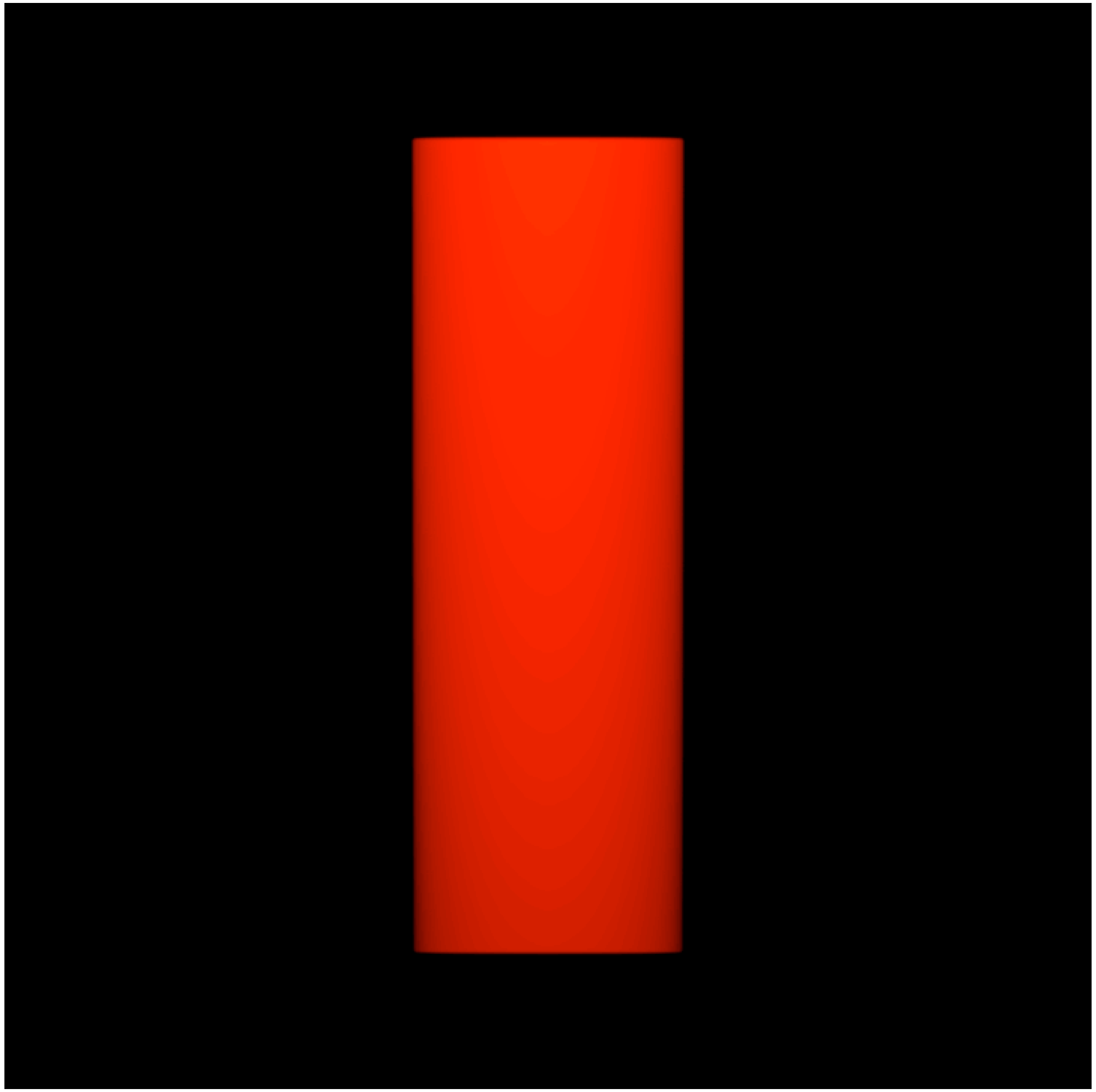
Thanks!

Gravitational collapse within MCs

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

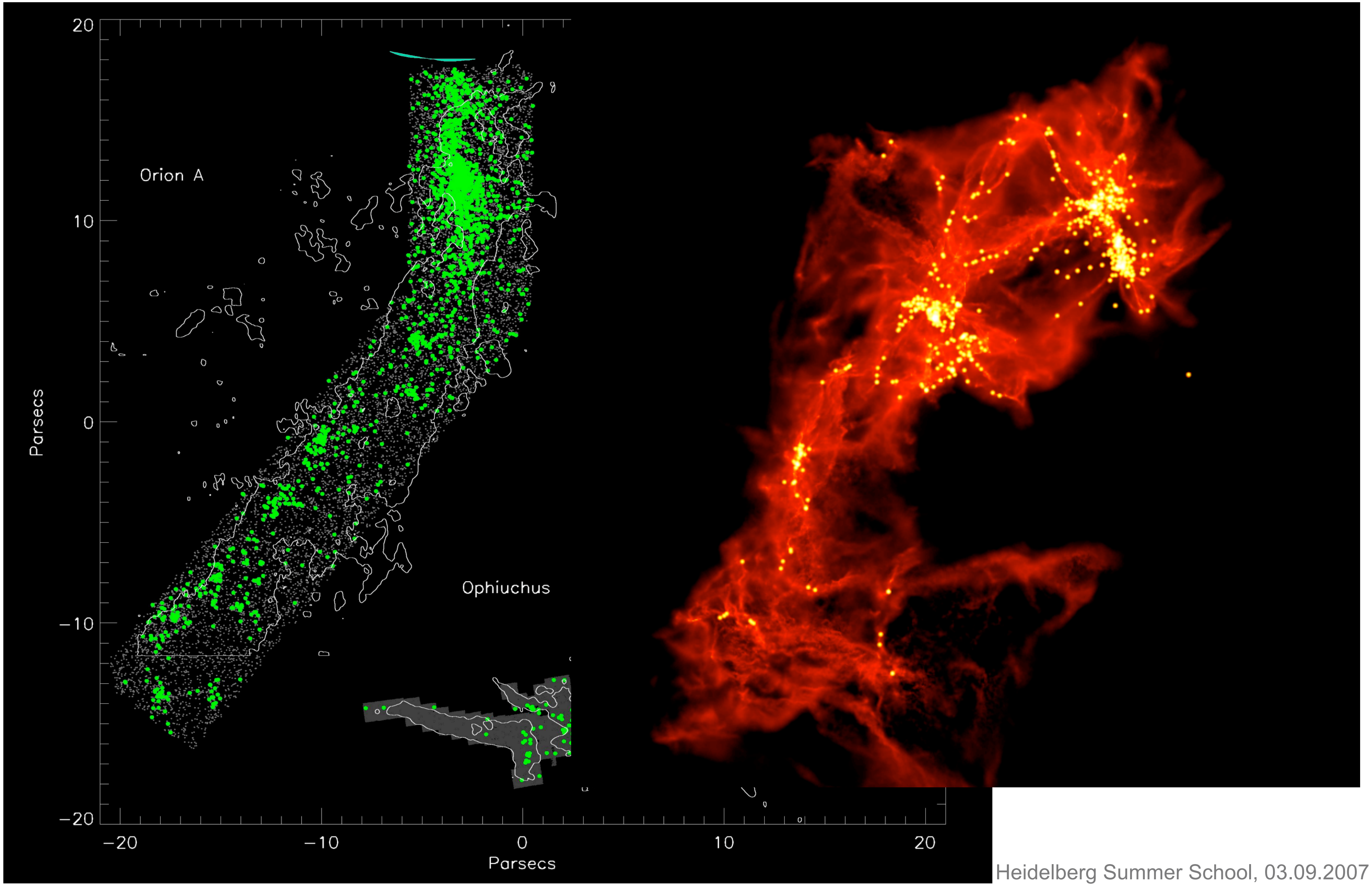
model for the Orion cloud:
$M = 10^4\ M_{sun}$, isothermal
EOS

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)