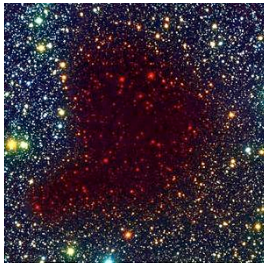
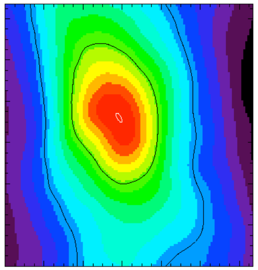
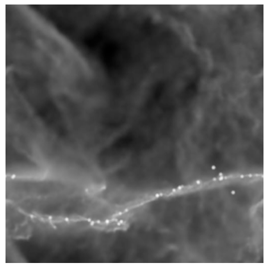
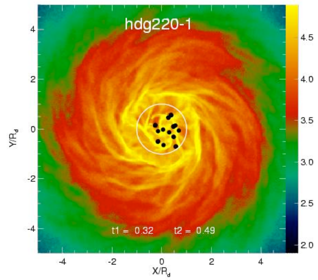
HOW DO STARS FORM?
the turbulent birth of stellar clusters





Ralf Klessen

Zentrum für Astronomie der Universität Heidelberg
Institut für Theoretische Astrophysik

Collaborators

many thanks to...

- Javier Ballesteros-Paredes (UNAM, Morelia)
- Peter Bodenheimer (UC Santa Cruz)
- Andreas Burkert (Uni. München)
- Simon Glover (AIP, Potsdam)
- Fabian Heitsch (Uni. München)
- Dirk Froebrich (Dublin University)
- Katharina Jappsen (AIP, Potsdam)
- Richard Larson (Yale University)
- Yuexing Li (CfA)
- Doug Lin (UC Santa Cruz)
- Mordecai Mac Low (ANMH, New York)
- Stefan Schmeja (AIP, Potsdam)
- Michael Smith (Kent University)
- Marco Spaans (Kapteyn Institute)
- Enrique Vazquez-Semadeni (Morelia)
- Hans Zinnecker (AIP, Potsdam)

Structure

Phenomenology and motivation

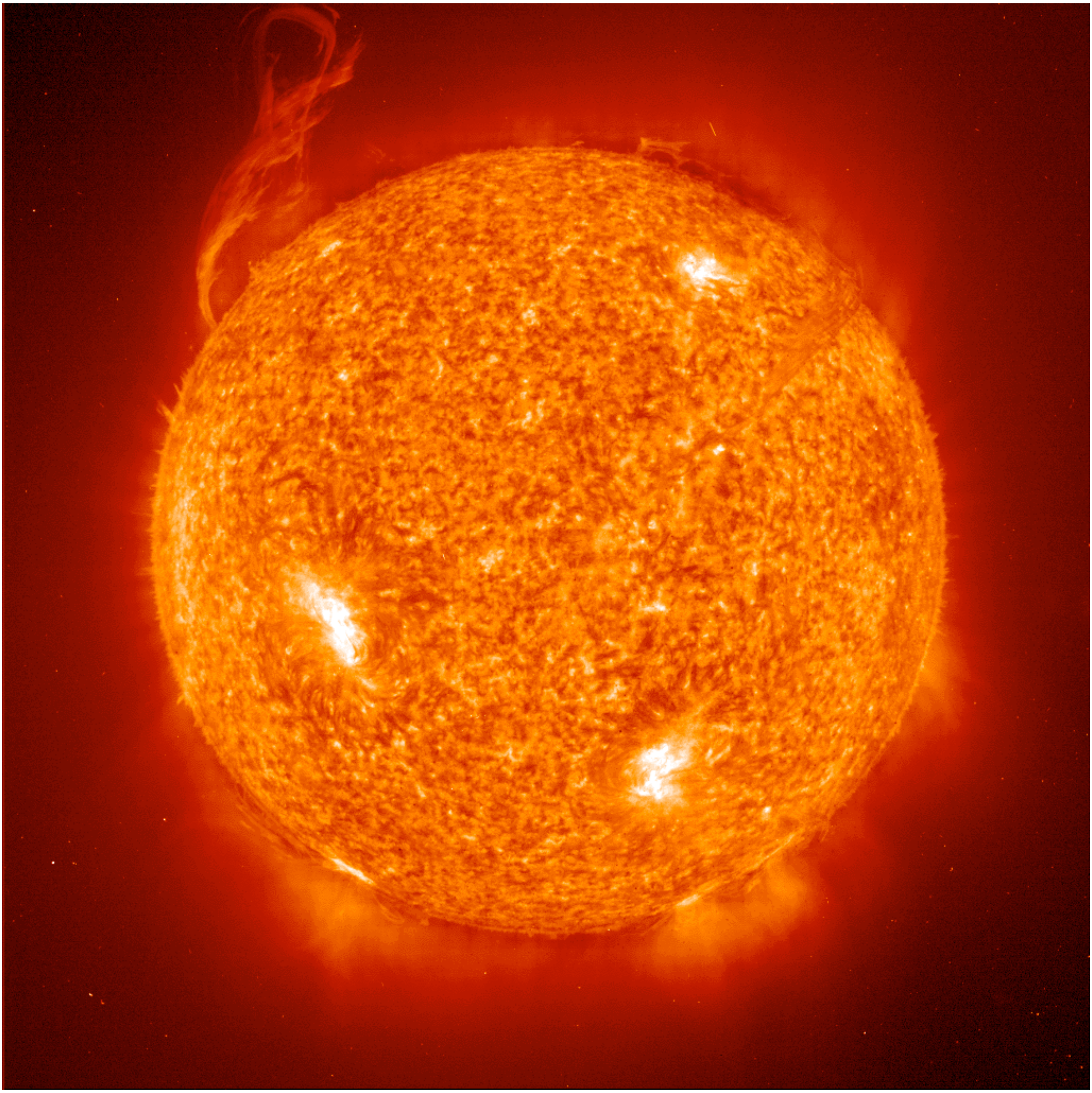
Historic overview of star formation

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

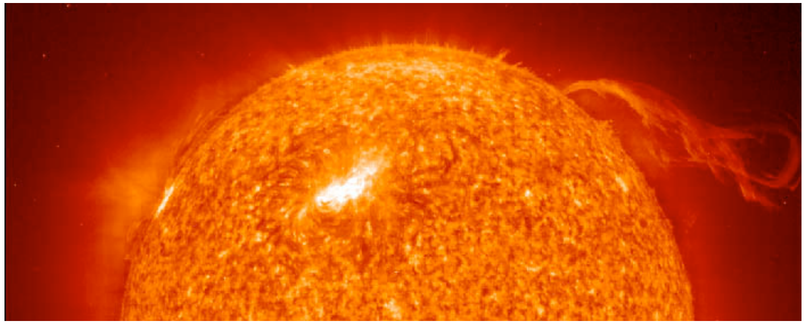
Applications to star cluster formation

what is a star?

Our Sun



Stars: Our Sun



Properties of stars
(stellar parameters):

Our Sun ⊙ as reference star

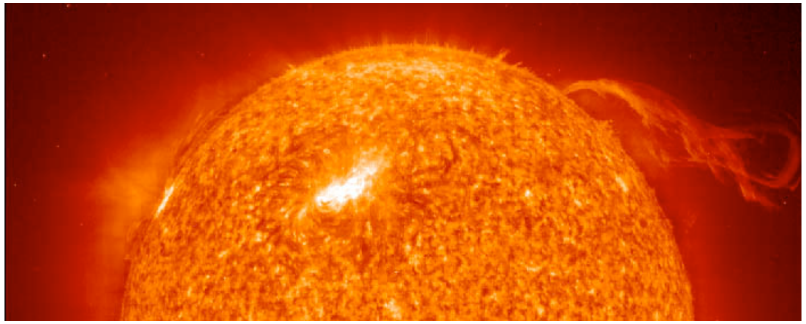
radius	$R_\odot$	696 000 km	
mass	$M_\odot$	$1{,}989 \times 10^{30}$ kg	
luminosity	$L_\odot$	$3{,}86 \times 10^{26}$ W	← on Earth: solar constant 1.37 kW/m^2
effective temperature	T_{eff}	5800 K (surface)	
central temperature	$T_{zentral}$	15×10^6 K	
age	$t_\odot$	4.5×10^9 yr	

spectral type G2
luminosity class V

chemical composition (mass fraction)

73% hydrogen X
25% helium Y
2% metals Z

Stars: Our Sun



Properties of stars
(stellar parameters):

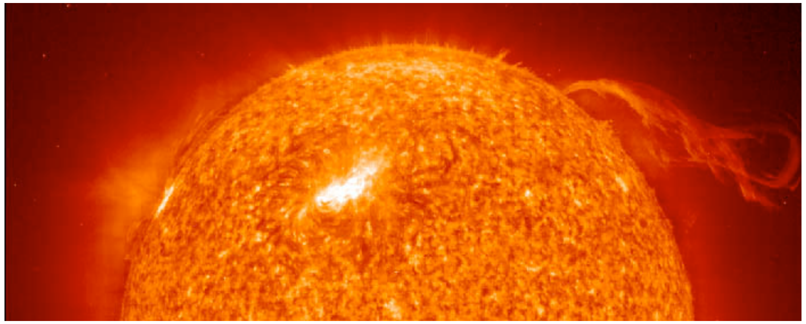
Our Sun ⊙ as reference star

radius	$R_\odot$	7×10^{10} cm
mass	$M_\odot$	2×10^{33} g
luminosity	$L_\odot$	4×10^{33} erg/s
effective temperature	T_{eff}	5800 K (surface)
central temperature	$T_{zentral}$	15×10^6 K
age	$t_\odot$	1.7×10^{17} s

in cgs units

spectral type G2
luminosity class V
chemical composition (mass fraction)
73% hydrogen X
25% helium Y
2% metals Z

Stars: some further numbers

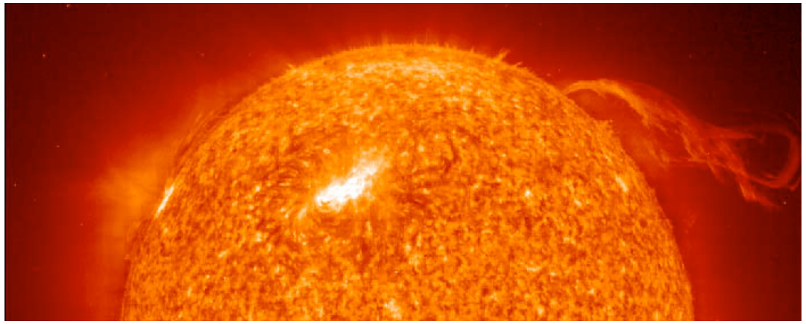


stellar density in solar vicinity $n_* \approx 0{,}05\ \mathrm{pc}^{-3}$
stellar density in dense star cluster $n_* \approx 10^3\ \mathrm{pc}^{-3}$
stellar density in starburst regionen $n_* \approx 10^4\ \mathrm{pc}^{-3}$

$1\ \mathrm{pc} = 3{,}086 \times 10^{18}\ \mathrm{cm}$

number of stars in Milky Way: $\approx 10^{11}$
star formation rate: $\approx 2\ M_\odot/\mathrm{yr}$

Stars: some further numbers



stellar density in solar vicinity	$n_* \approx 0{,}05\ pc^{-3}$
stellar density in dense star cluster	$n_* \approx 10^3\ pc^{-3}$
stellar density in starburst regionen	$n_* \approx 10^4\ pc^{-3}$

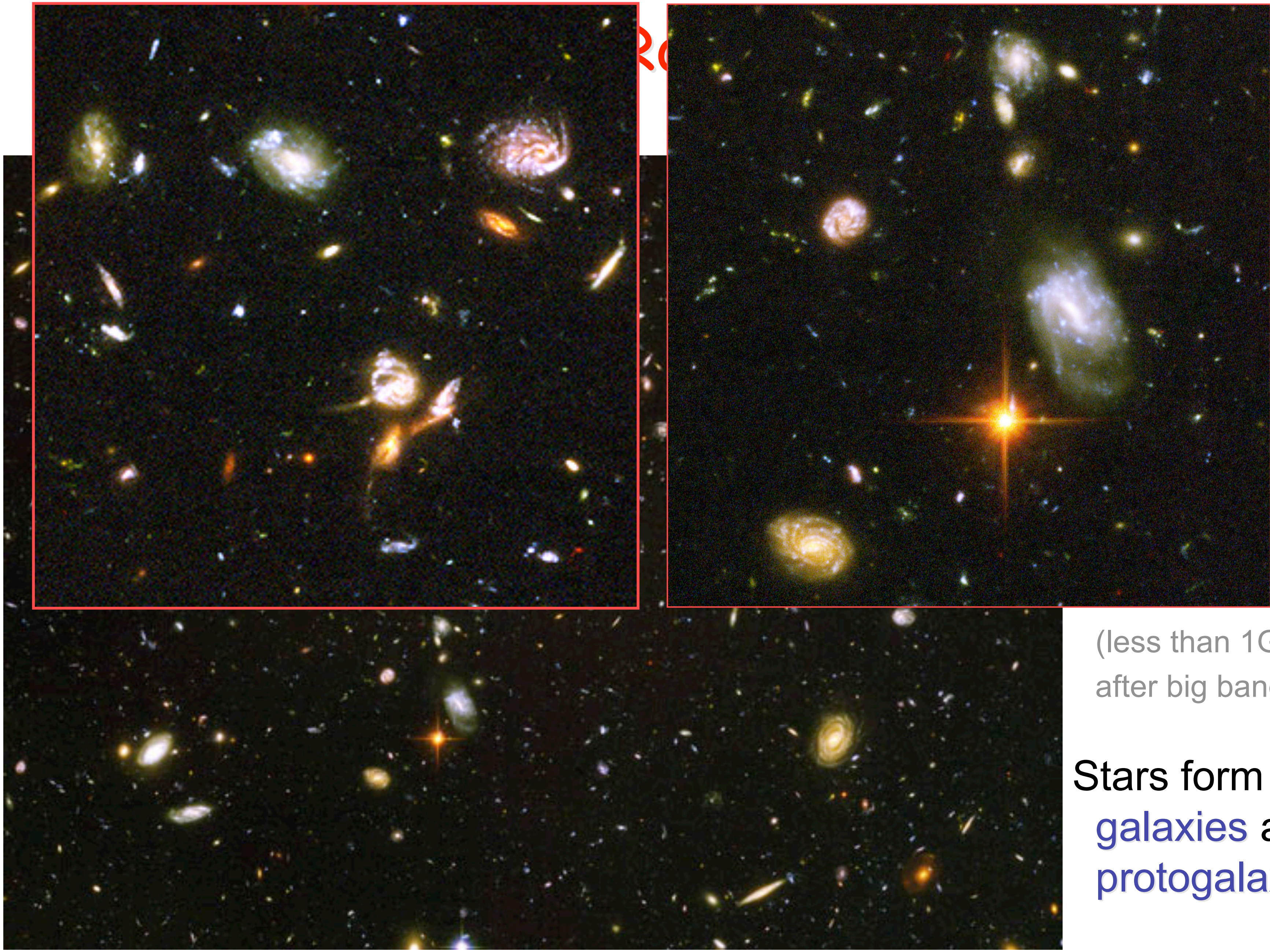
$1\ pc = 3{,}086 \times 10^{18}$ cm

number of stars in Milky Way:	**$\approx 10^{11}$**
star formation rate:	**$\approx 2\ M_\odot/yr$**

scales:

Milky Way	$\varnothing \approx$ 30 kpc $\approx 10^{23}$ cm $\approx$ 100.000 light years
solar system (Pluto orbit)	$\varnothing \approx$ 80 AU $\approx 10^{15}$ cm $\approx$ 11 light years
Earth orbit	$\varnothing \approx$ 2 AU $\approx 3 \times 10^{15}$ cm $\approx$ 17 light years
diameter of Sun	$\varnothing \approx 1{,}4 \times 10^{11}$ cm
diameter of Earth	$\varnothing \approx 1{,}3 \times 10^{9}$ cm

observations

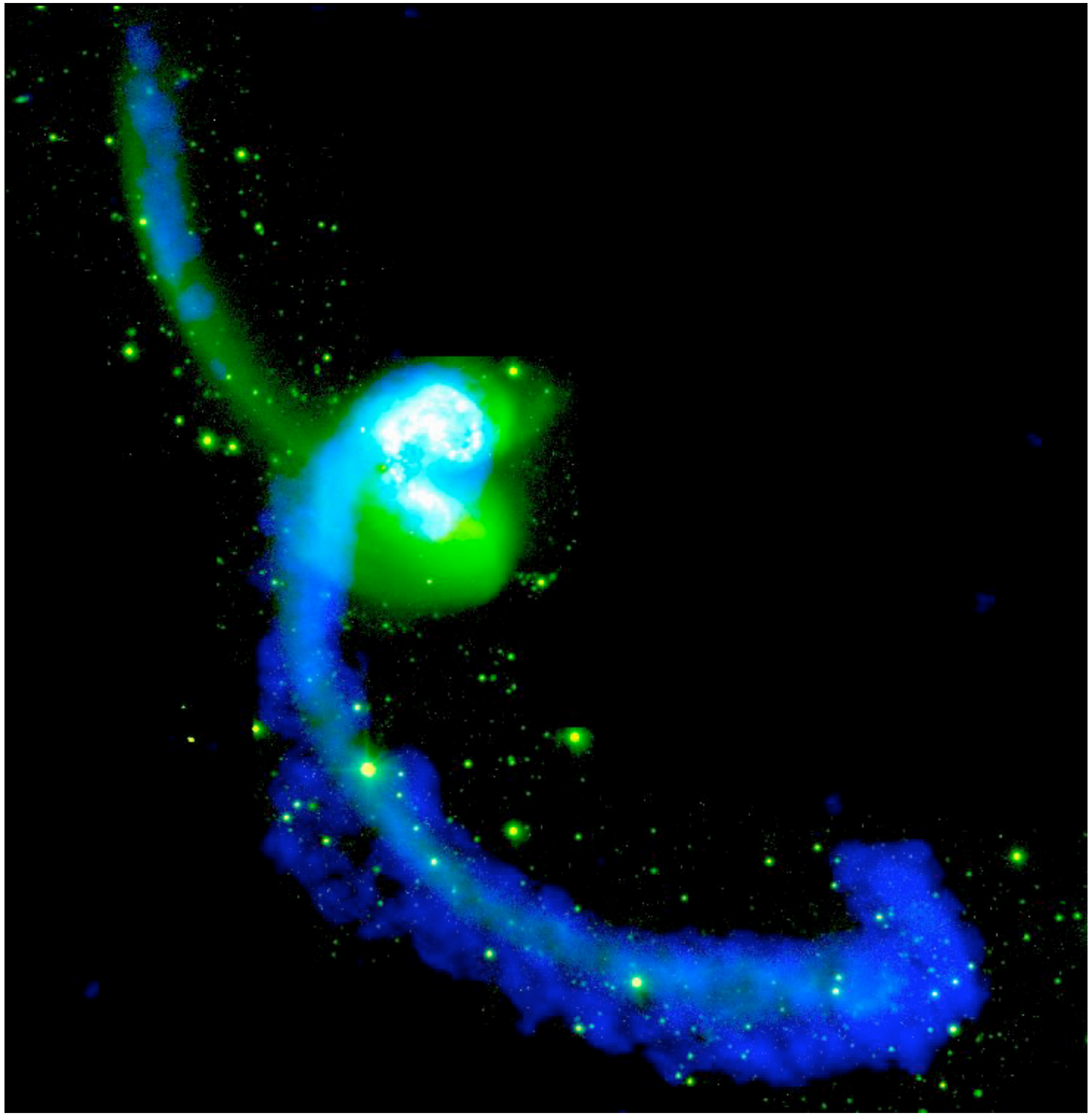


(less than 1Gyr after big bangl)

Stars form in galaxies and protogalaxies

(Hubble Ultra-Deep Field, from HST Web site)

Star formation in interacting galaxies:

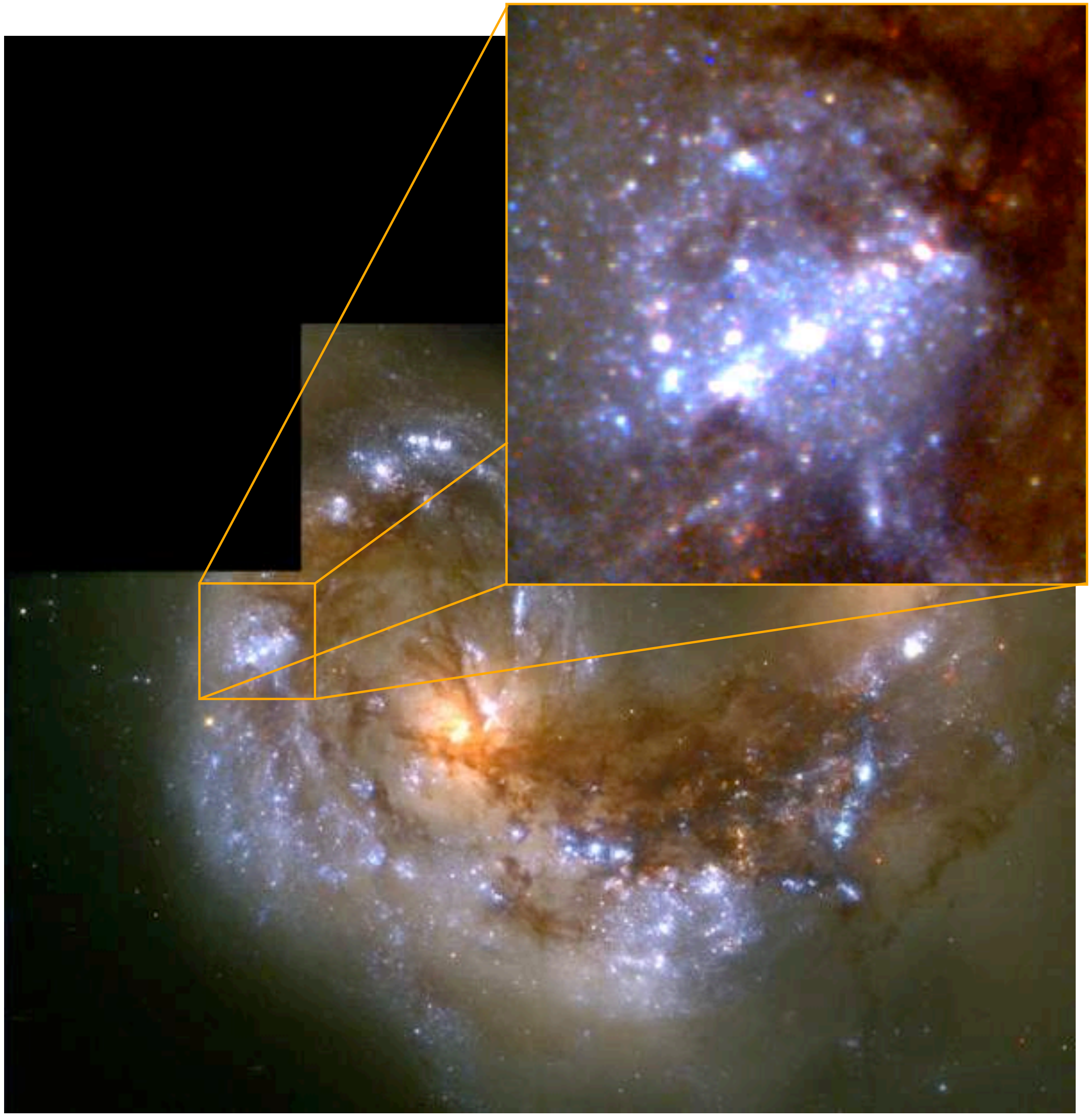


(from the Chandra Webpage)

Antennae galaxy

- *NGC4038/39*
- *distance: 19.2Mpc*
- *vis. Magn: 11.2*
- *optical: white, green*
- *radio: blue*

Star formation in interacting galaxies:



(HST: Whitmore & Schweizer 1997)

Antennae galaxy

- Star formation burst in interacting (merging) galaxies
- Strong perturbation SF in tidal “tales”
- Large-scale gravitational motion determines SF
- Stars form in “knobs” (i.e. superclusters)

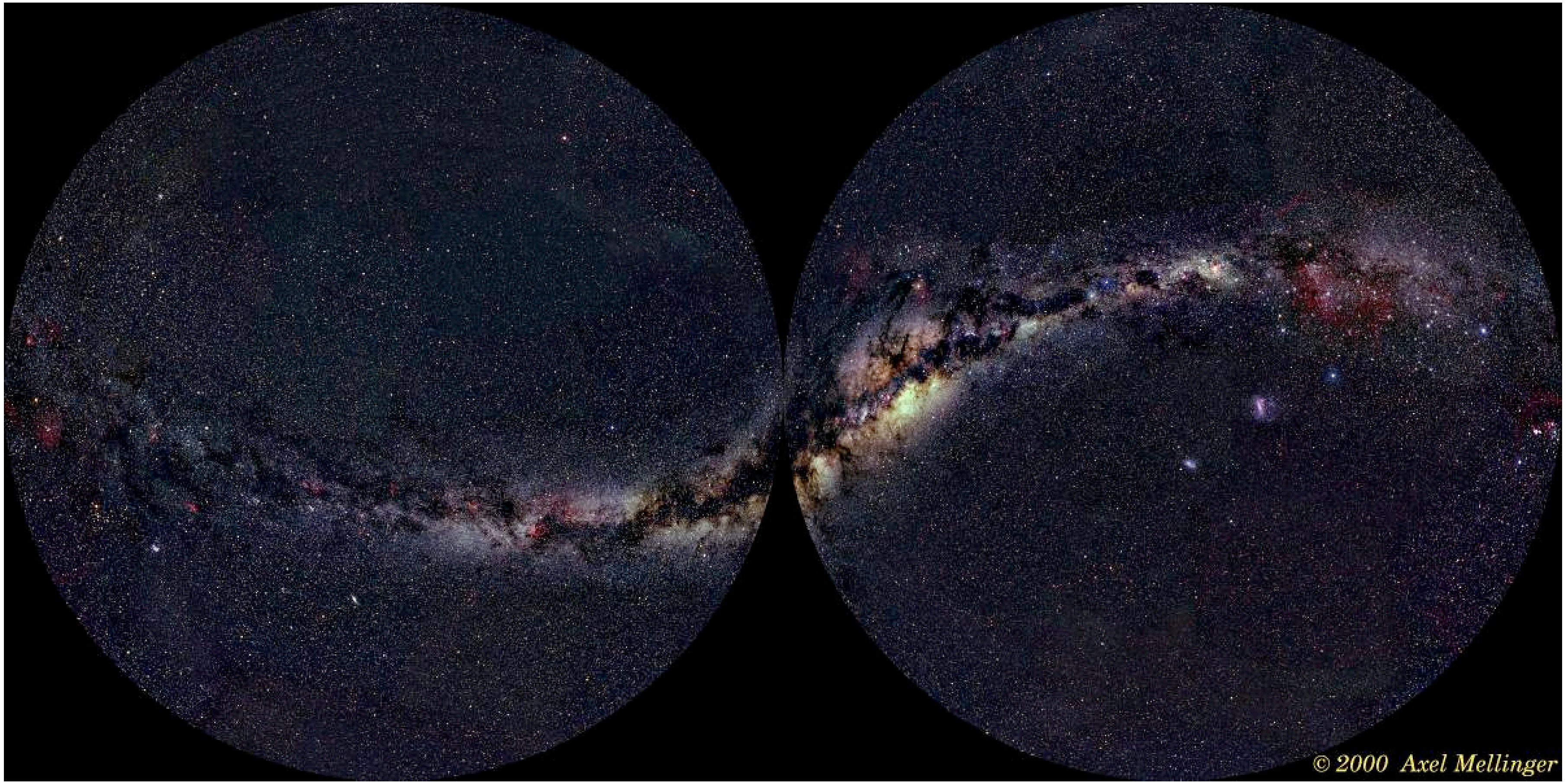
Star formation in "typical" spiral:

(from the Hubble Heritage Team)

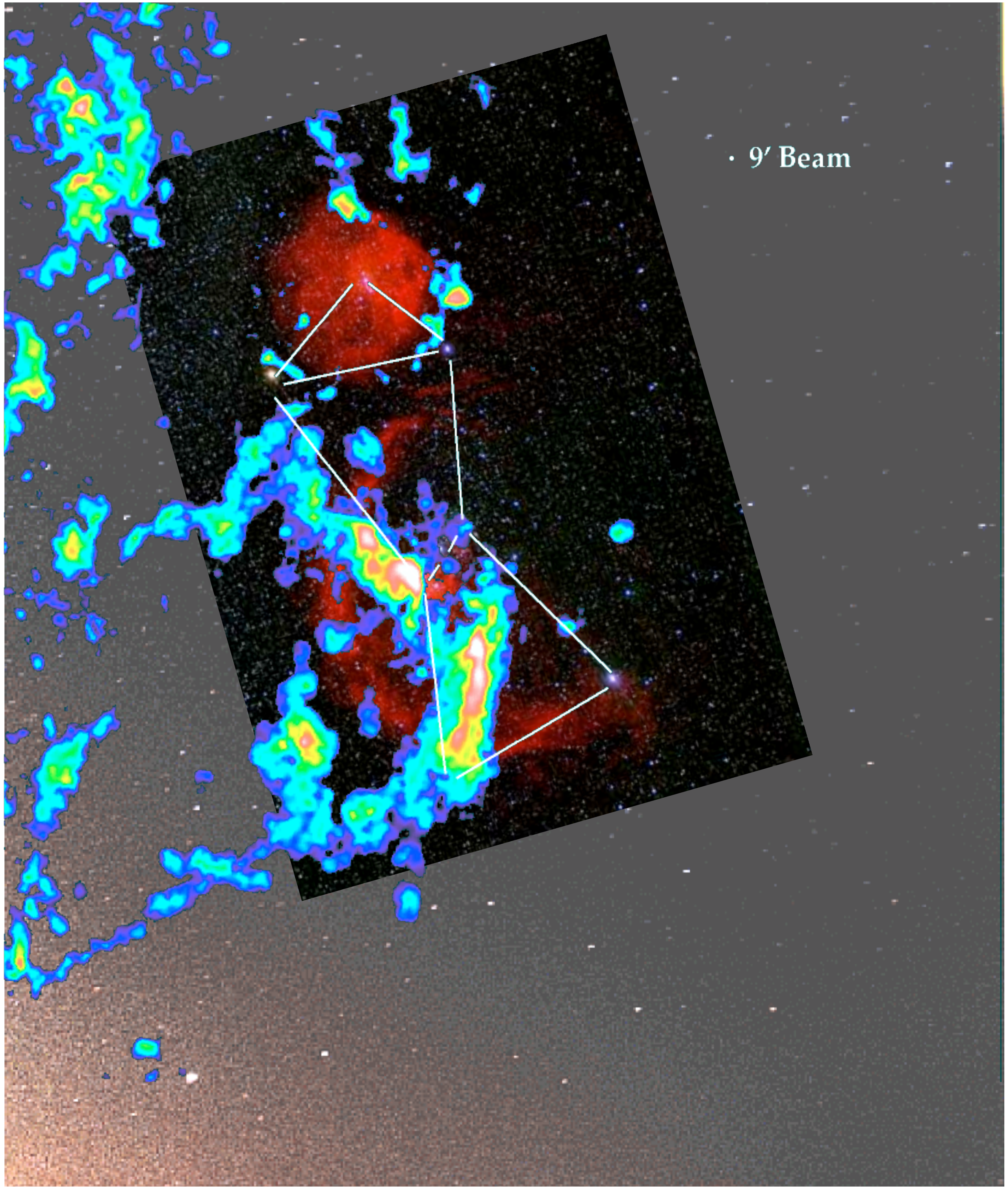
NGC4622

- 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?

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

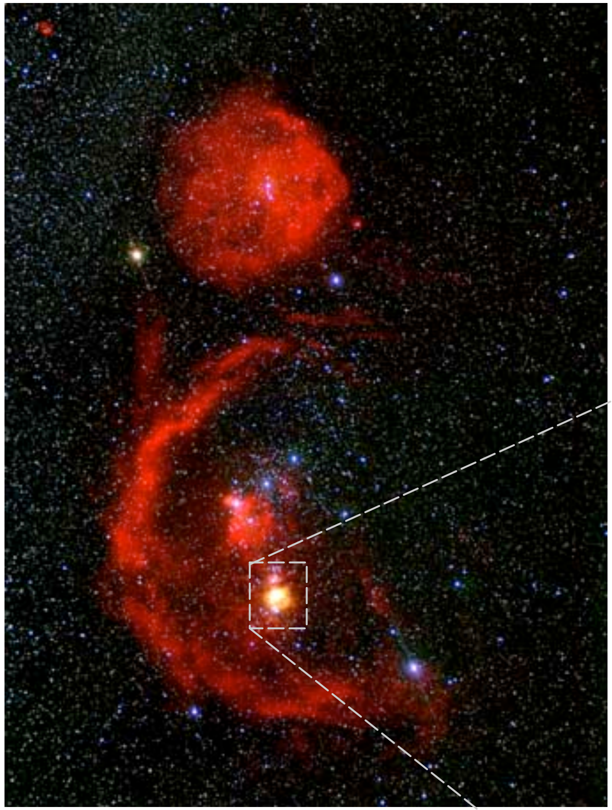


Star formation in Orion

We see

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

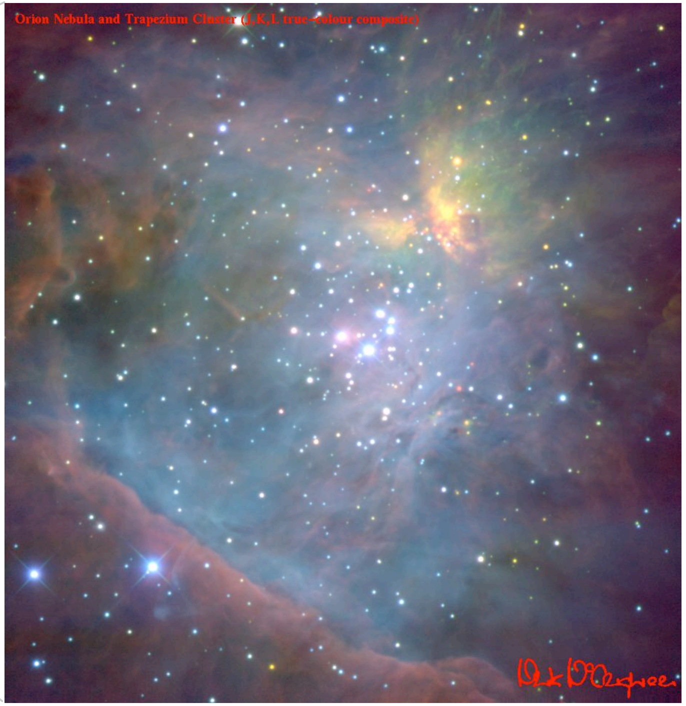
Local star forming region: The Trapezium Cluster in Orion



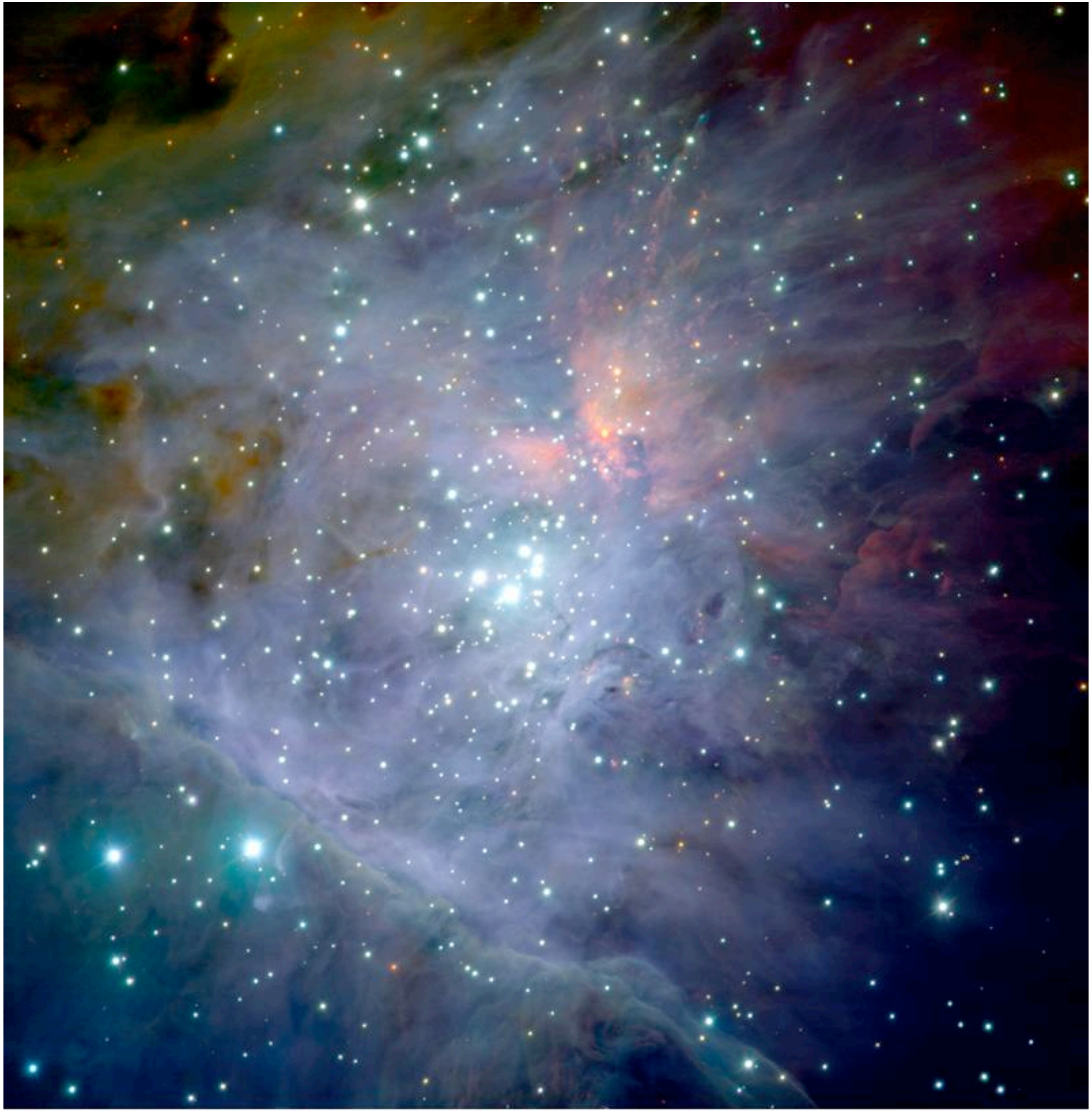
Orion molecular cloud

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



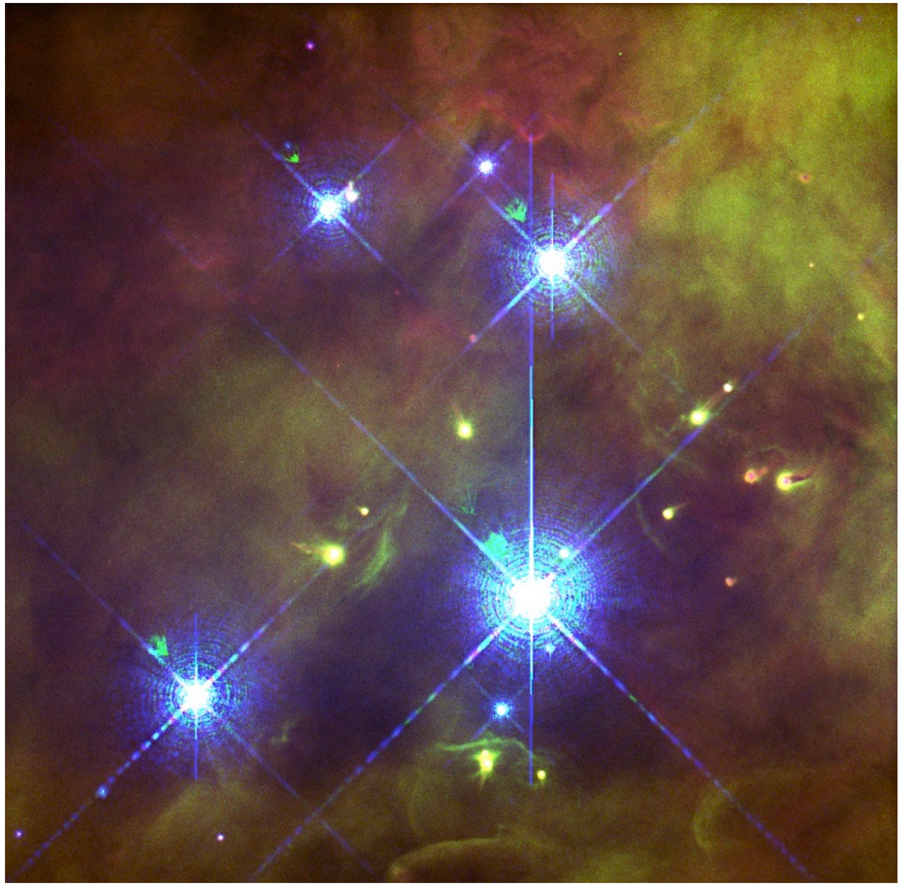
Trapezium Cluster

(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)

Trapezium Cluster: Central Region

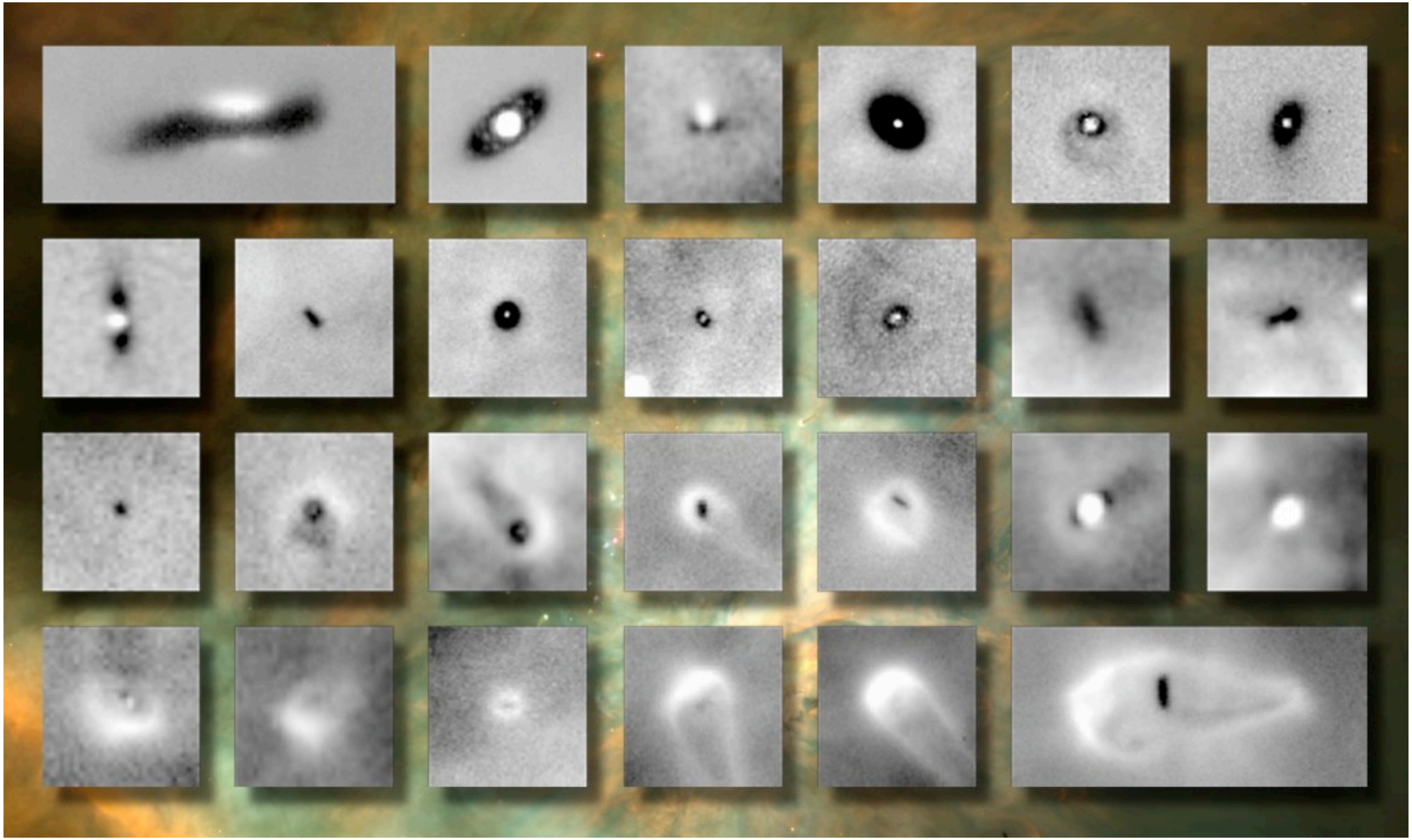


Ionizing radiation from central star **Θ1C Orionis**

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

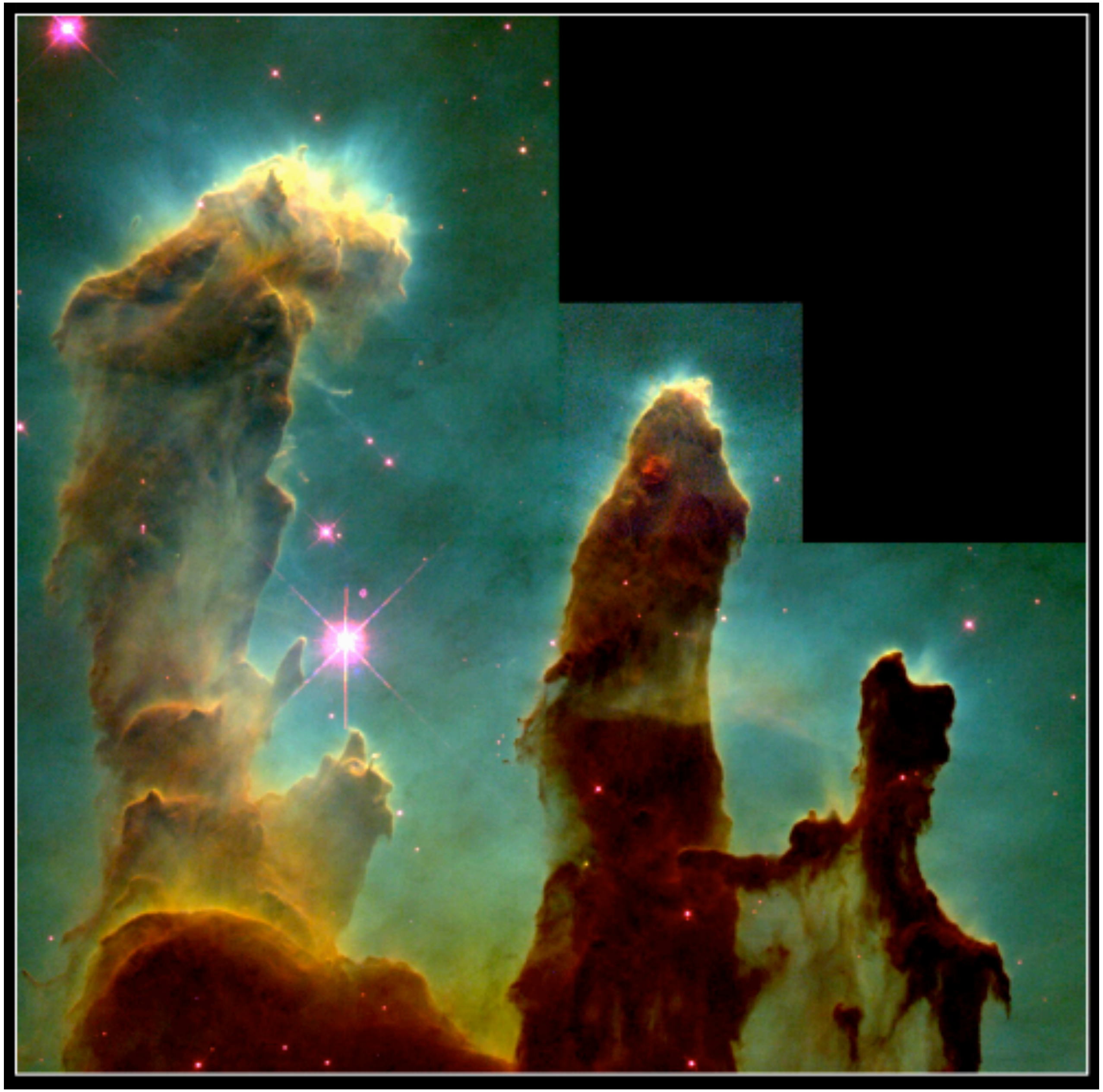
(images: Doug Johnstone et al.)

Futher Details: 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)



Pillars of God (in Eagle Nebula): Formation of small groups of young stars in the tips of the columns of gas and dust ….

Infrared observation

IR observation with ESO-VLT

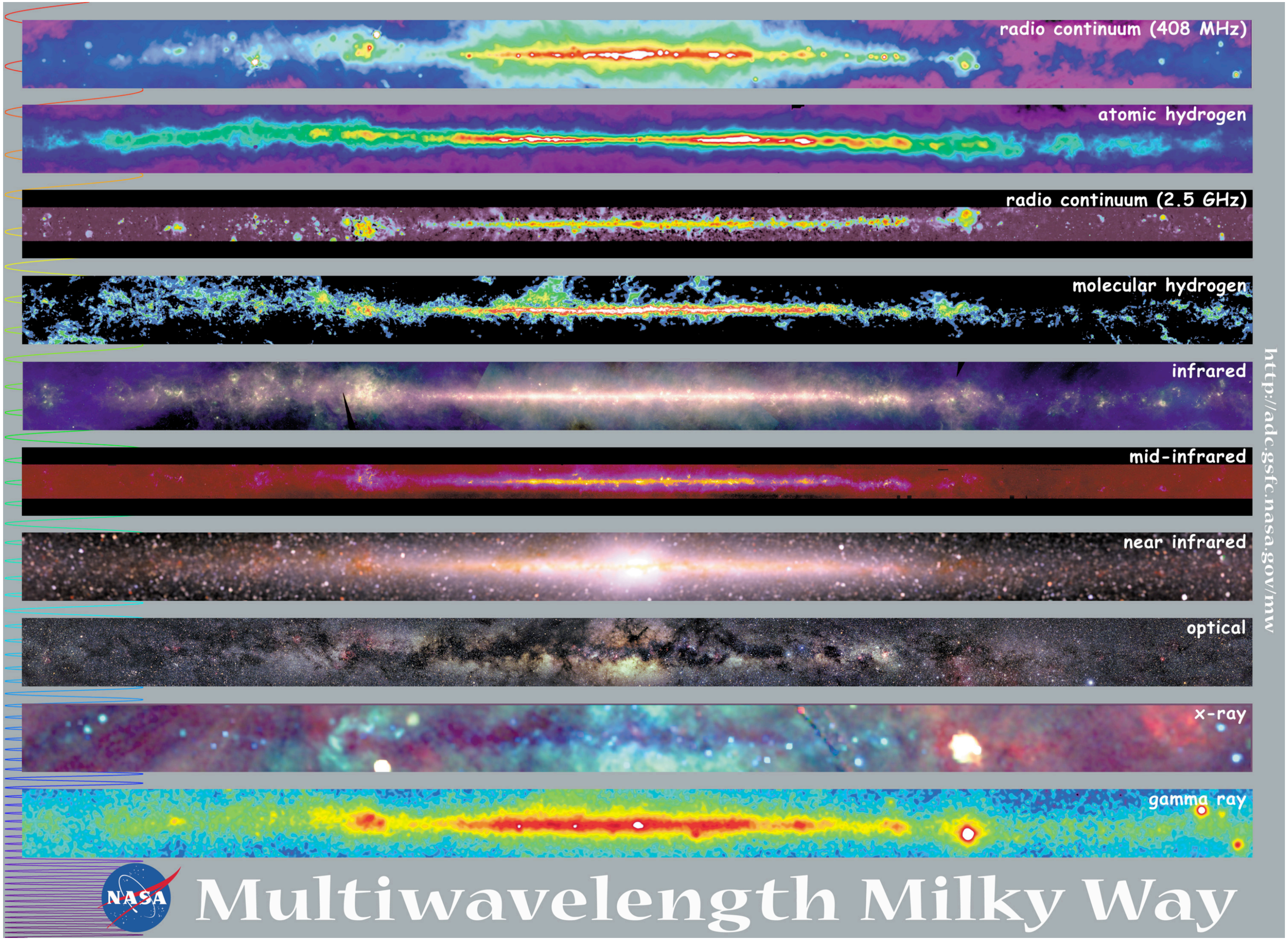
Pillars of God (in Eagle Nebula): Formation of small groups of young stars in the tips of the columns of gas and dust ….

How do we 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

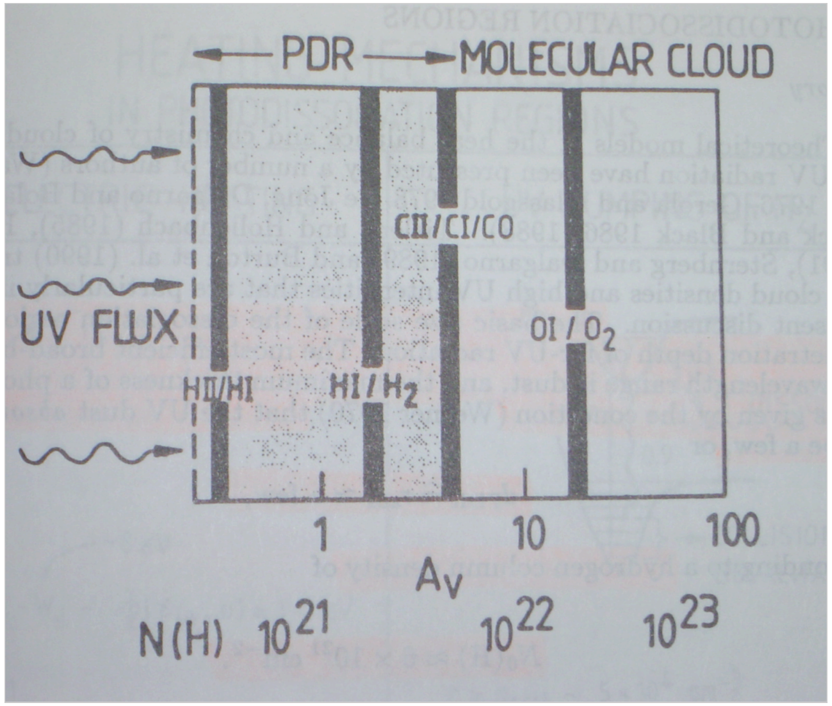
Because hydrogen is the dominating element, the classification scheme is based on its chemical state:

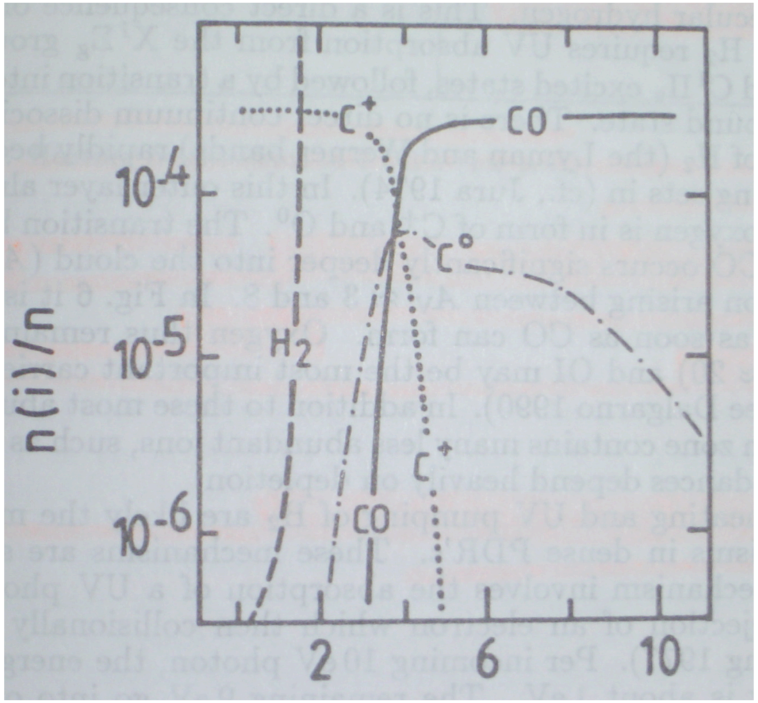
ionized atomic hydrogeN	*HII (H^+)*	Ionisation
neutraler atomic hydrogen	*HI (H)*	Phasenübergang
molecular hydrogen	*H_2*	

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

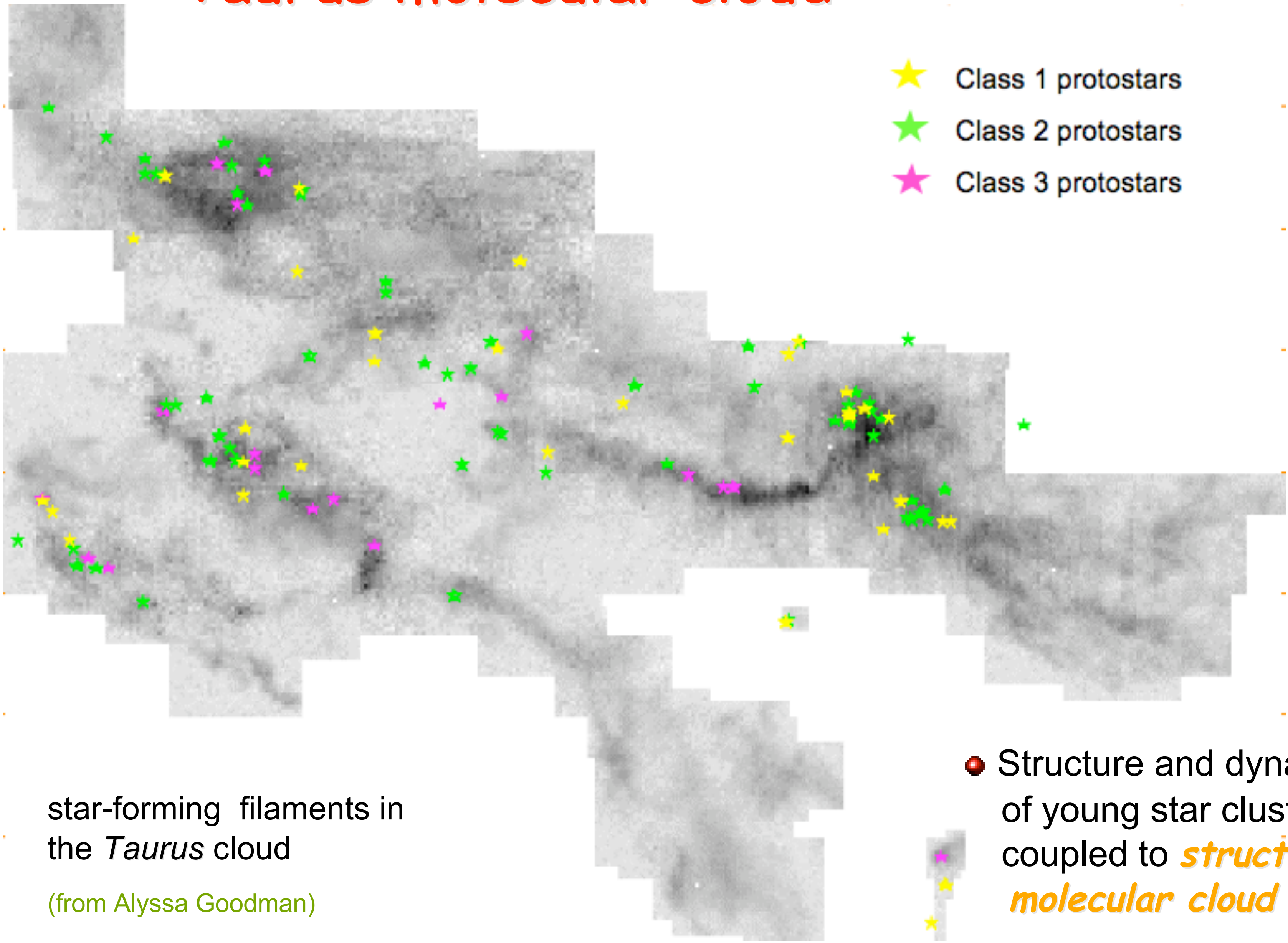
Dichte- / Säulendichte nimmt zu

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

ISM-Properties

- most important for star formation: **molecular hydrogen**
- most important wavelength: **IR and Radio emission** (dust continuum and molecular lines: CO, NH_3, CS, etc.) (more than 170 different molecules identified)
- Problem: only projection along the line of sight (real 3d structure of molecular clouds illusive)
- column density from intensity of line emission
- LOS velocity by Doppler shift of observed lines

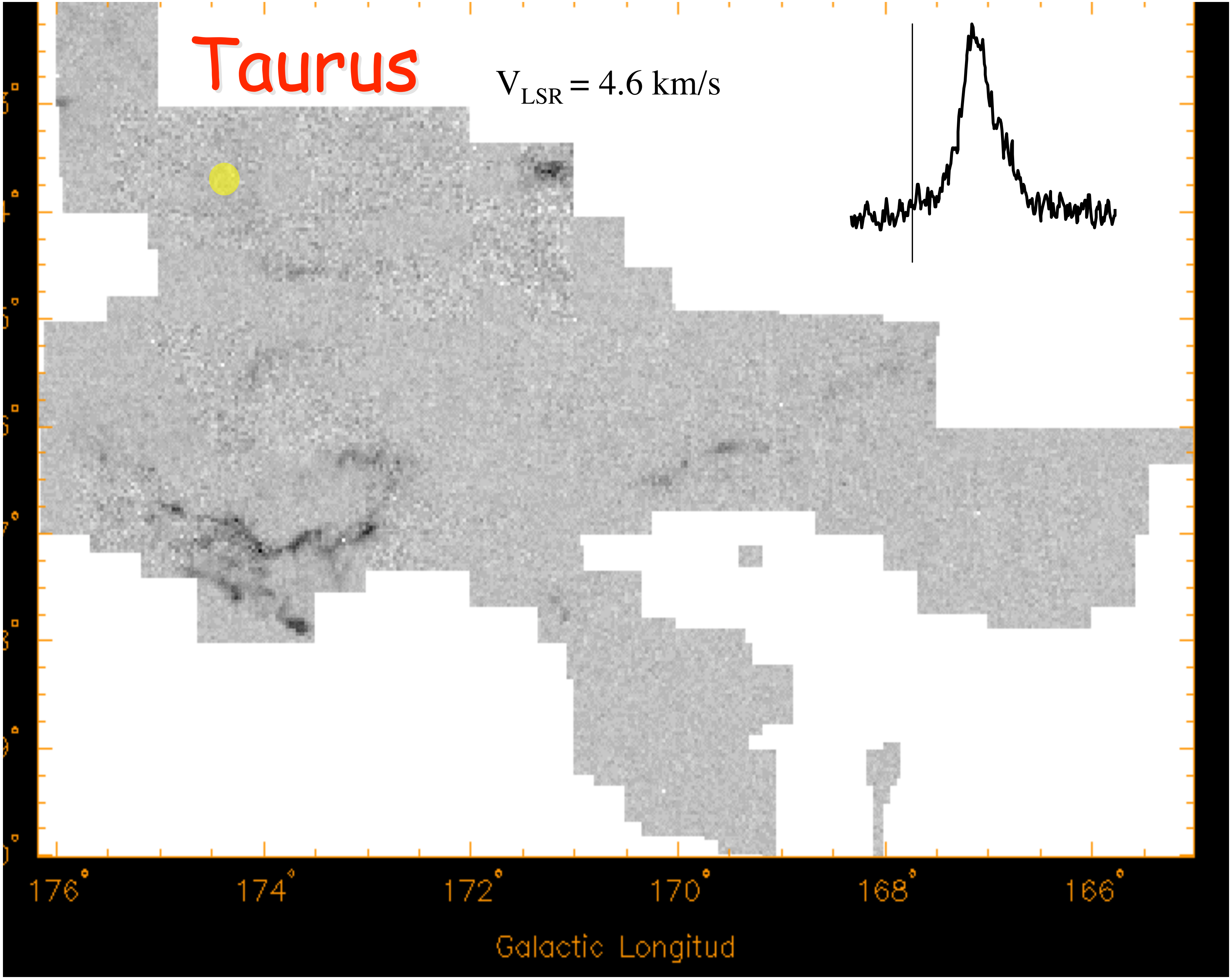
Taurus molecular cloud

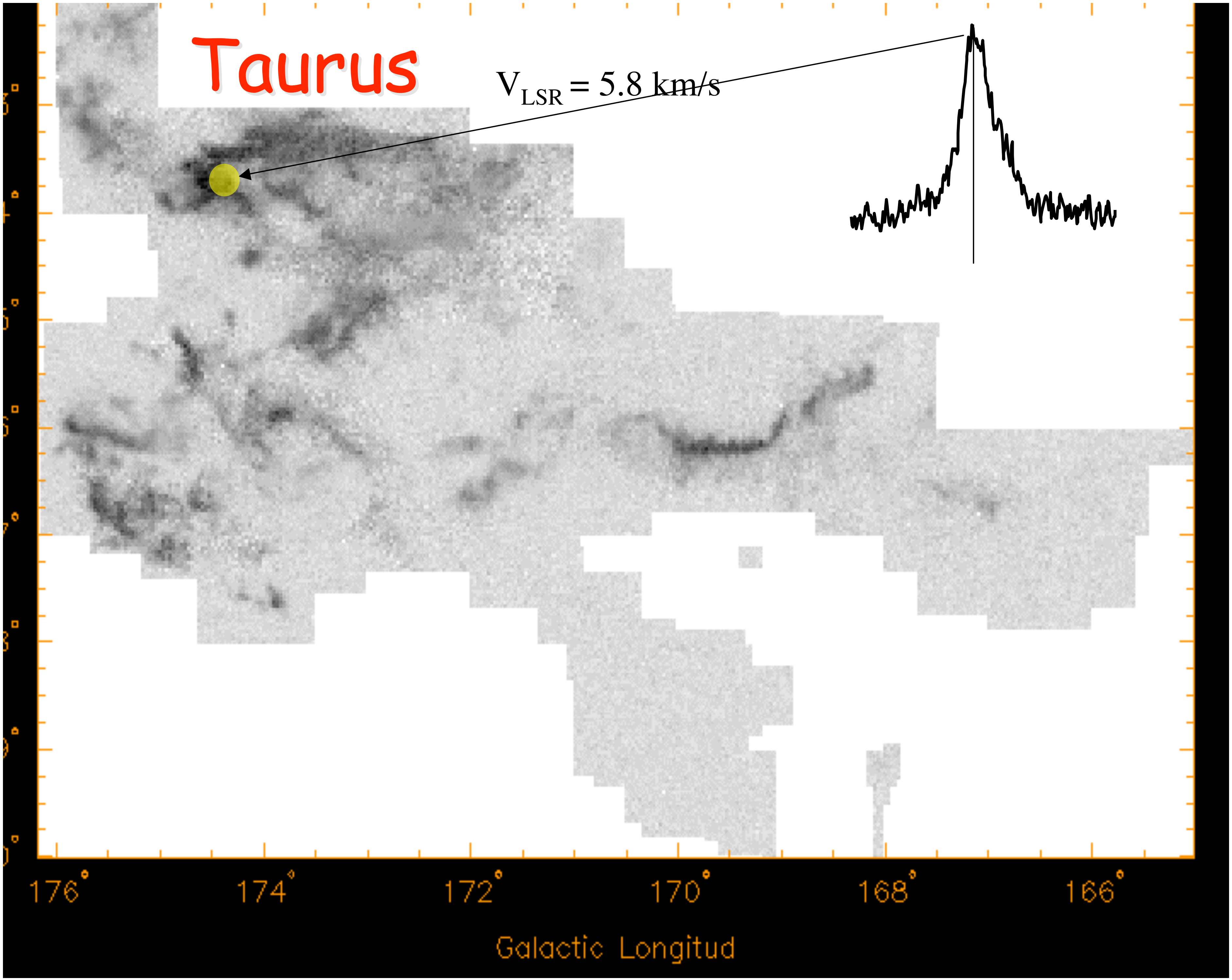


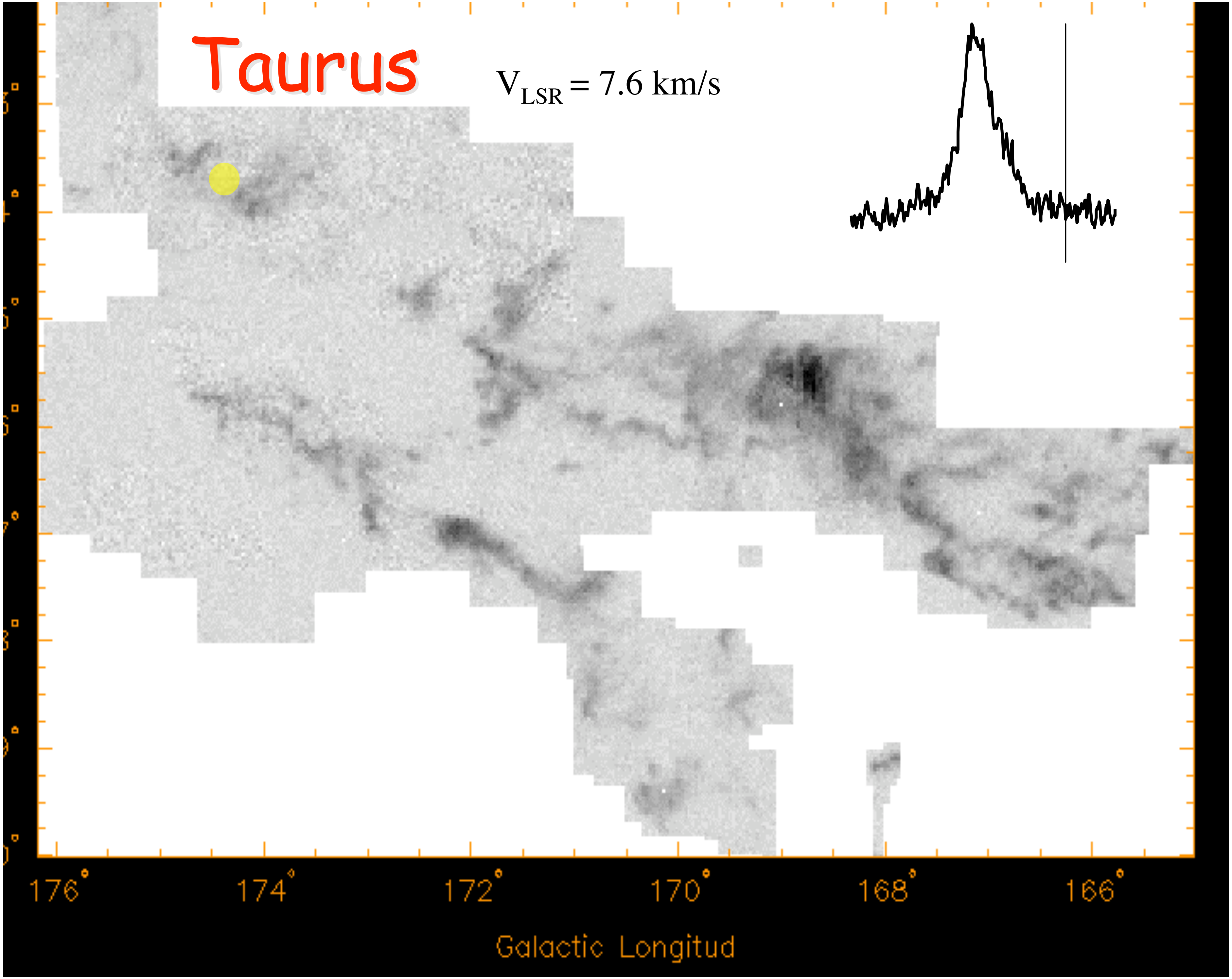
star-forming filaments in the *Taurus* cloud

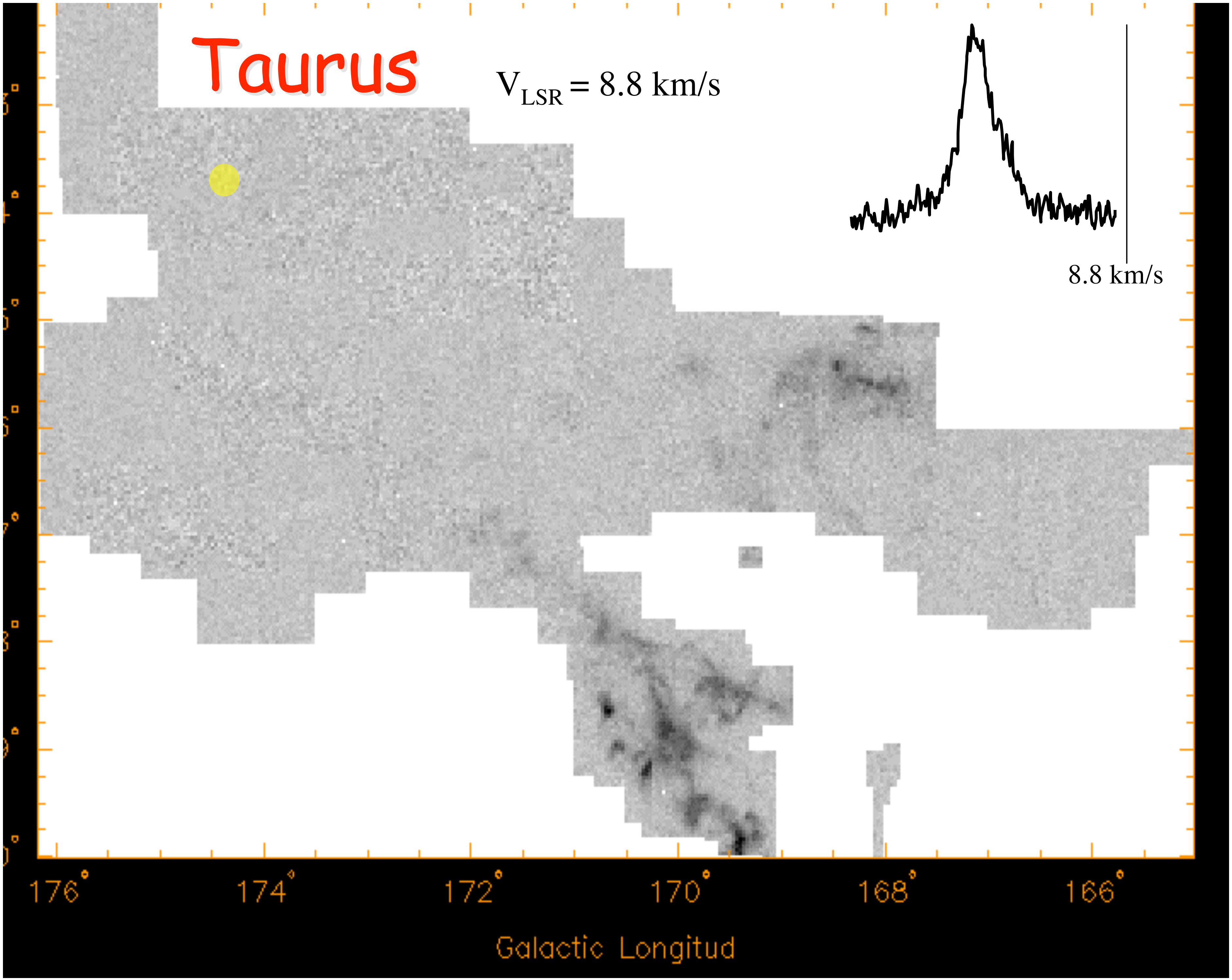
(from Alyssa Goodman)

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

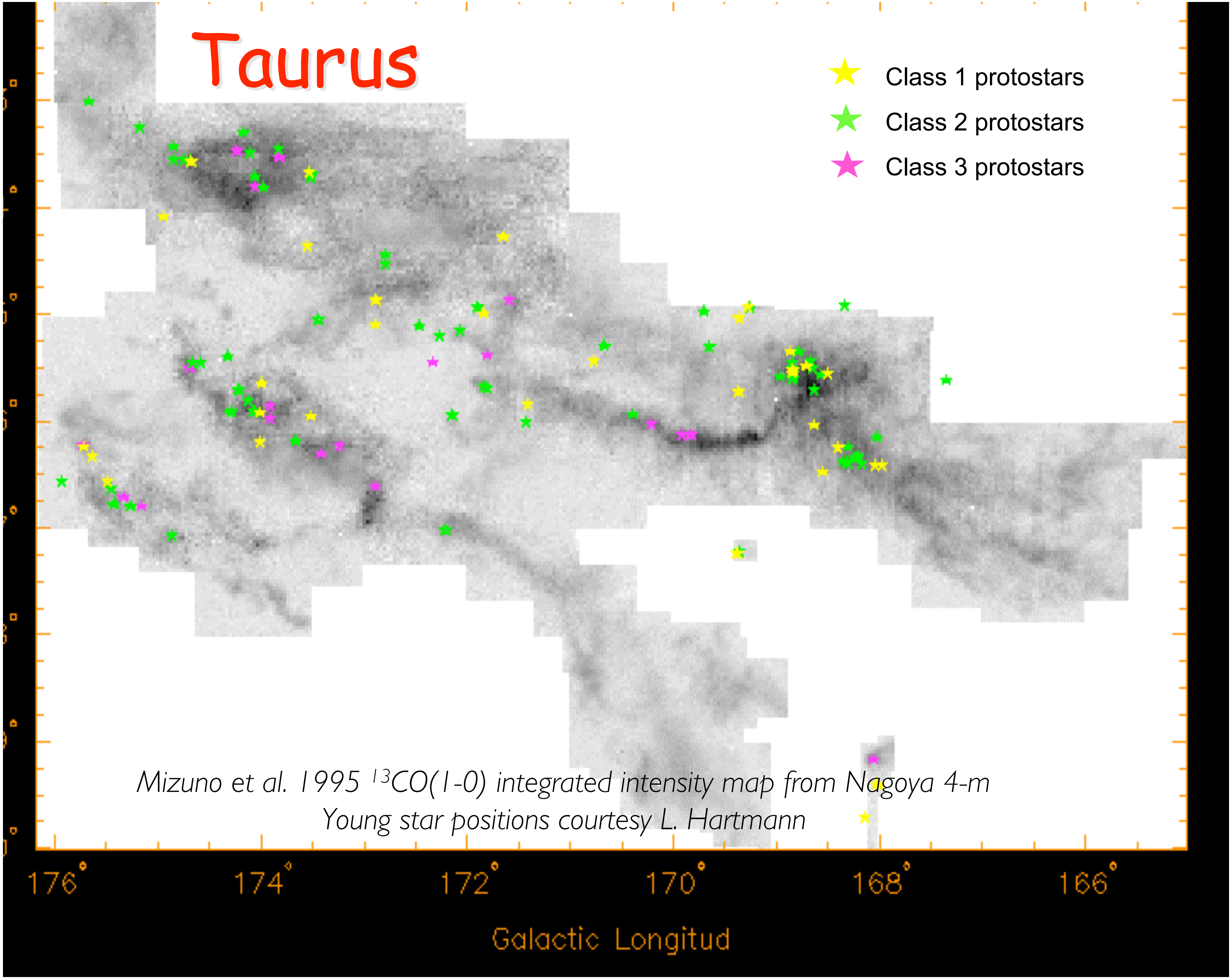

Taurus
V_LSR = 4.6 km/s
176°
174°
172°
170°
168°
166°
Galactic Longitud


Taurus
V_LSR = 5.8 km/s
176°
174°
172°
170°
168°
166°
Galactic Longitud


Taurus
V$_{LSR}$ = 7.6 km/s
176°
174°
172°
170°
168°
166°
Galactic Longitud



Taurus
V_LSR = 8.8 km/s
8.8 km/s
176°
174°
172°
170°
168°
166°
Galactic Longitud



Mizuno et al. 1995 $^{13}CO(1-0)$ integrated intensity map from Nagoya 4-m
Young star positions courtesy L. Hartmann

the questions

The star formation process

- *How* do stars form?
- What determines *when* and *where* stars form?
- What *regulates* the process and determines its *efficiency*?
- How do *global* properties of the galaxy influence star formation (a *local* process)?
- Are there different *modes* of SF? (Starburst galaxies vs. *LSBs*, *isolated* SF vs. *clustered* SF)

→ ***What physical processes initiate and control the formation of stars?***

the idea

Gravoturbulent 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)

Gravoturbulent star formation

- Idea:

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

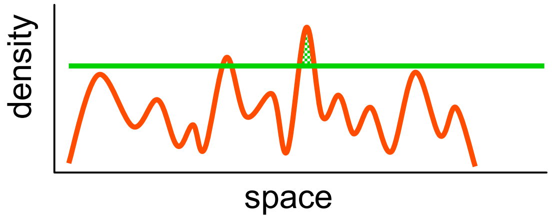
- Validity:

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***

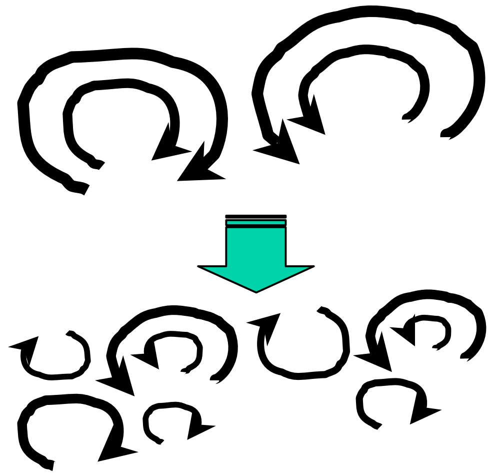
- *turbulent cascade:* local compression *within* a cloud provokes collapse
  → formation of individual *stars* and *star clusters*

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

turbulence

Properties of turbulence

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



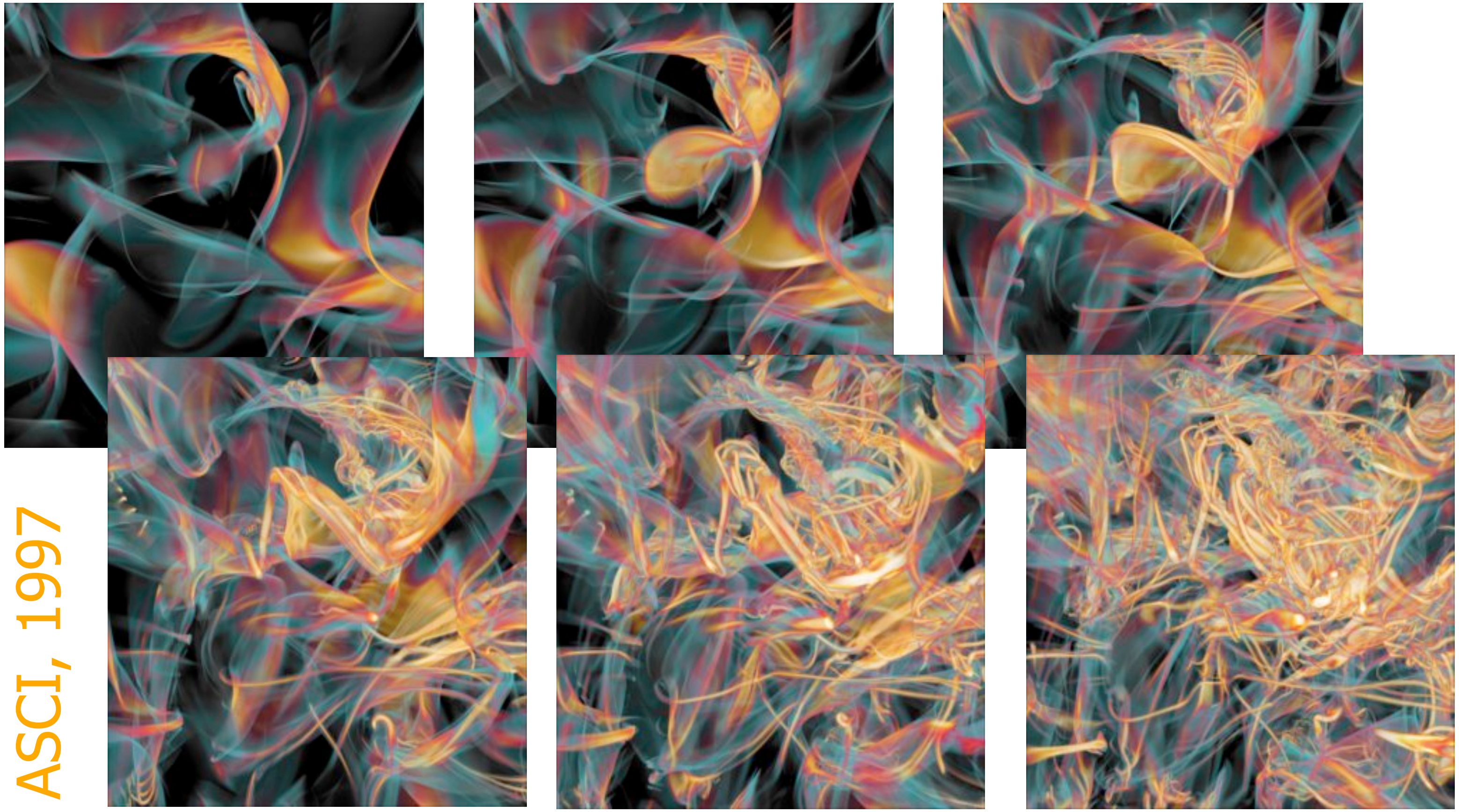
$$\mathrm{Re} = \frac{\text{advection}}{\text{dissipation}} = \frac{VL}{\nu}$$

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)

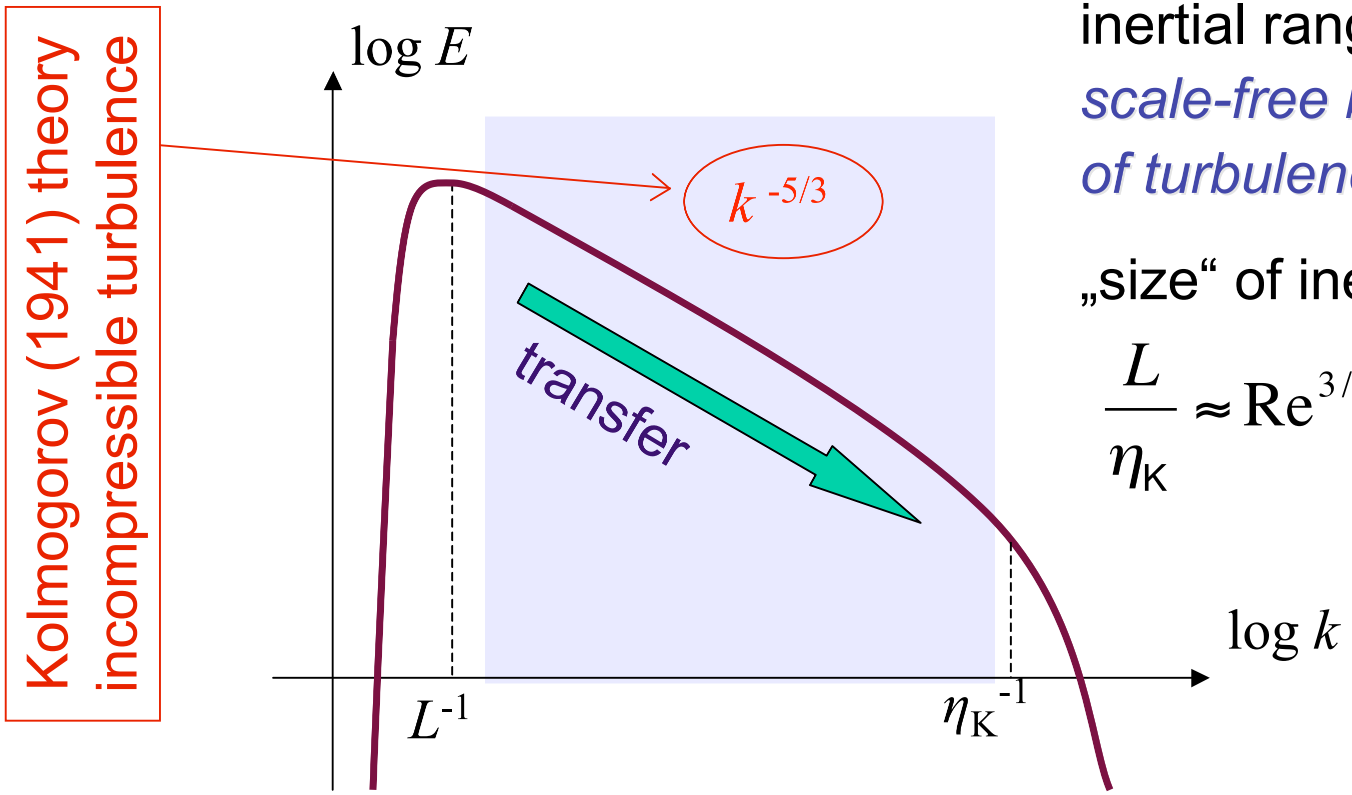
Vortex Formation



Porter et al.
ASCI, 1997

Vortices are streched and folded in three dimensions

Turbulent cascade



inertial range:
scale-free behavior of turbulence

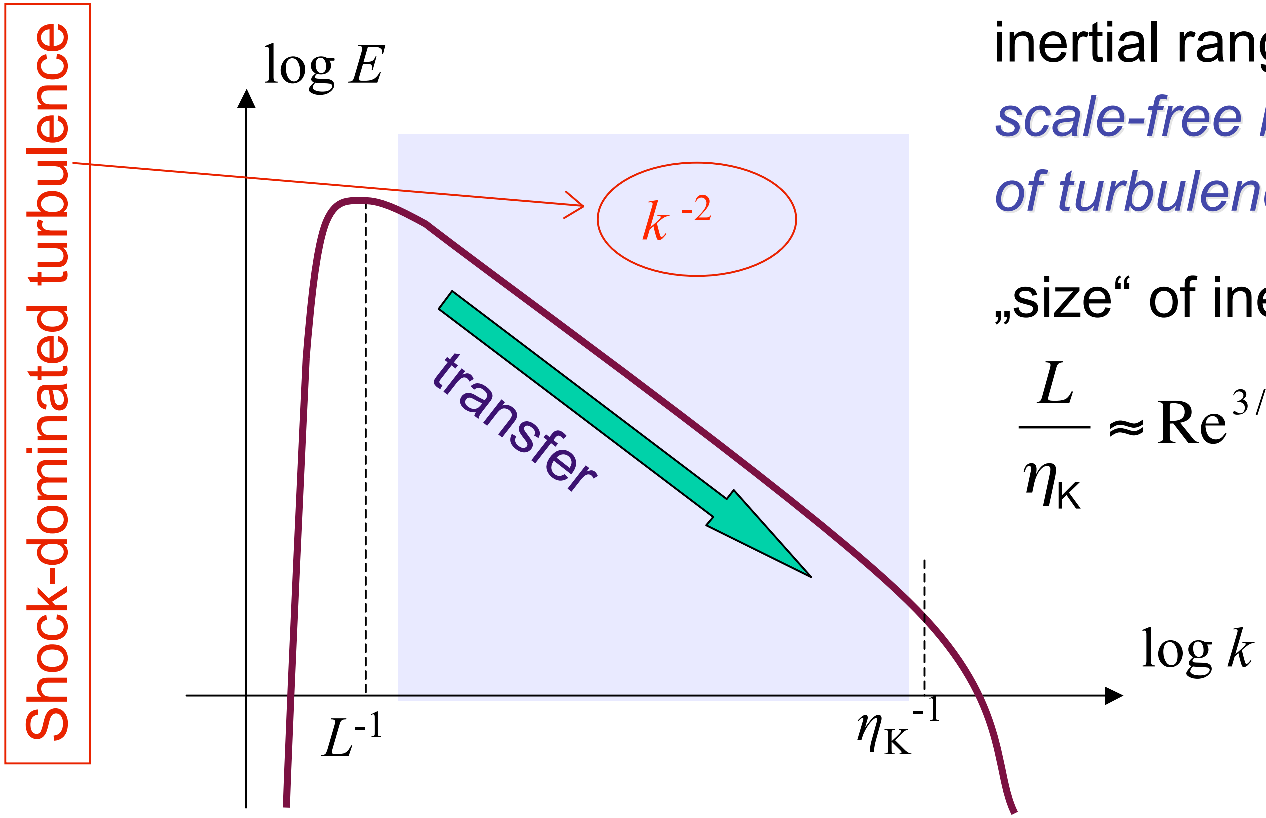
„size“ of inertial range:

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

energy input scale

energy dissipation scale

Turbulent cascade



energy
input
scale

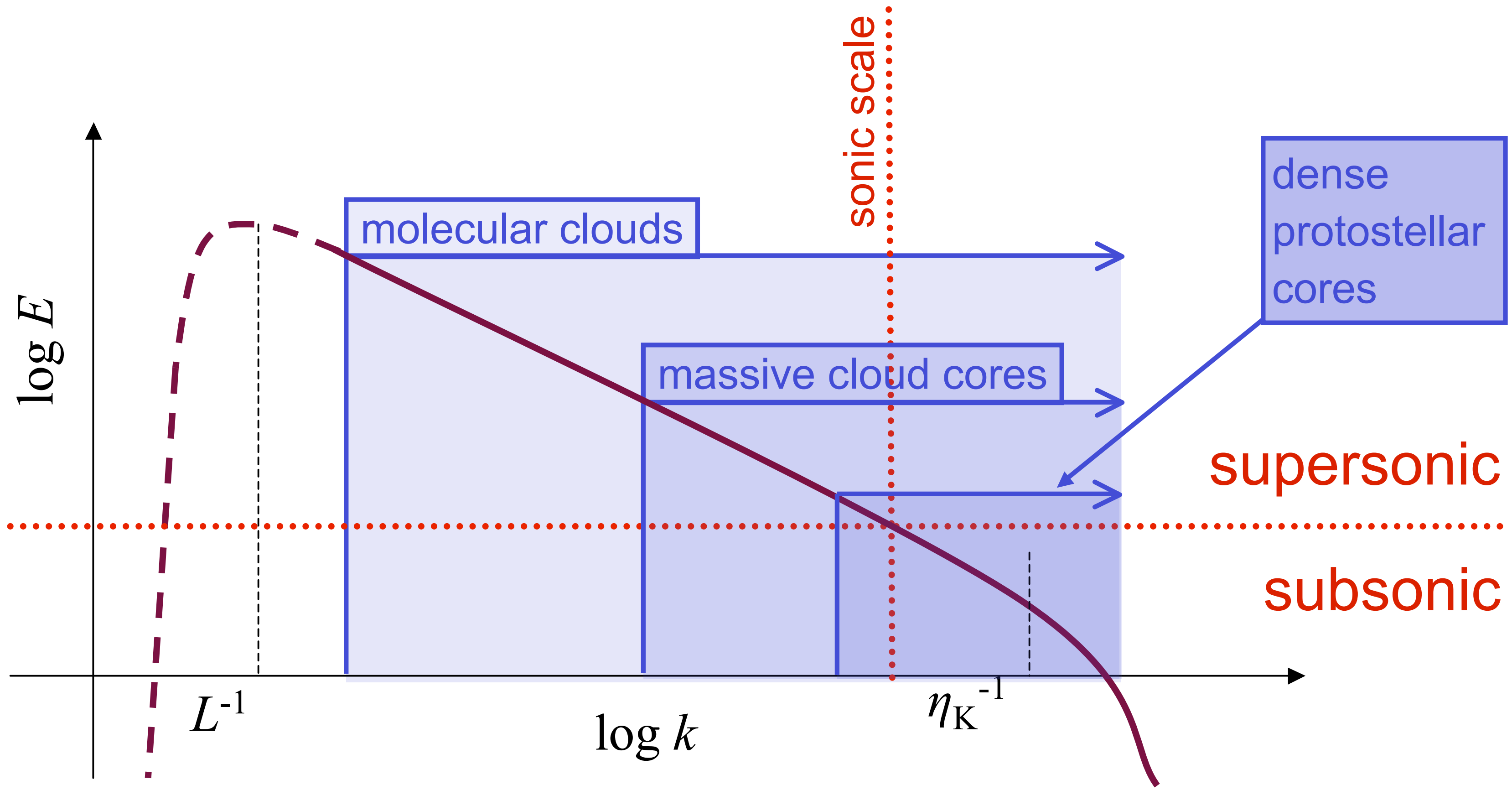
energy
dissipation
scale

inertial range:
scale-free behavior of turbulence

„size" of inertial range:

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

Turbulent cascade in ISM

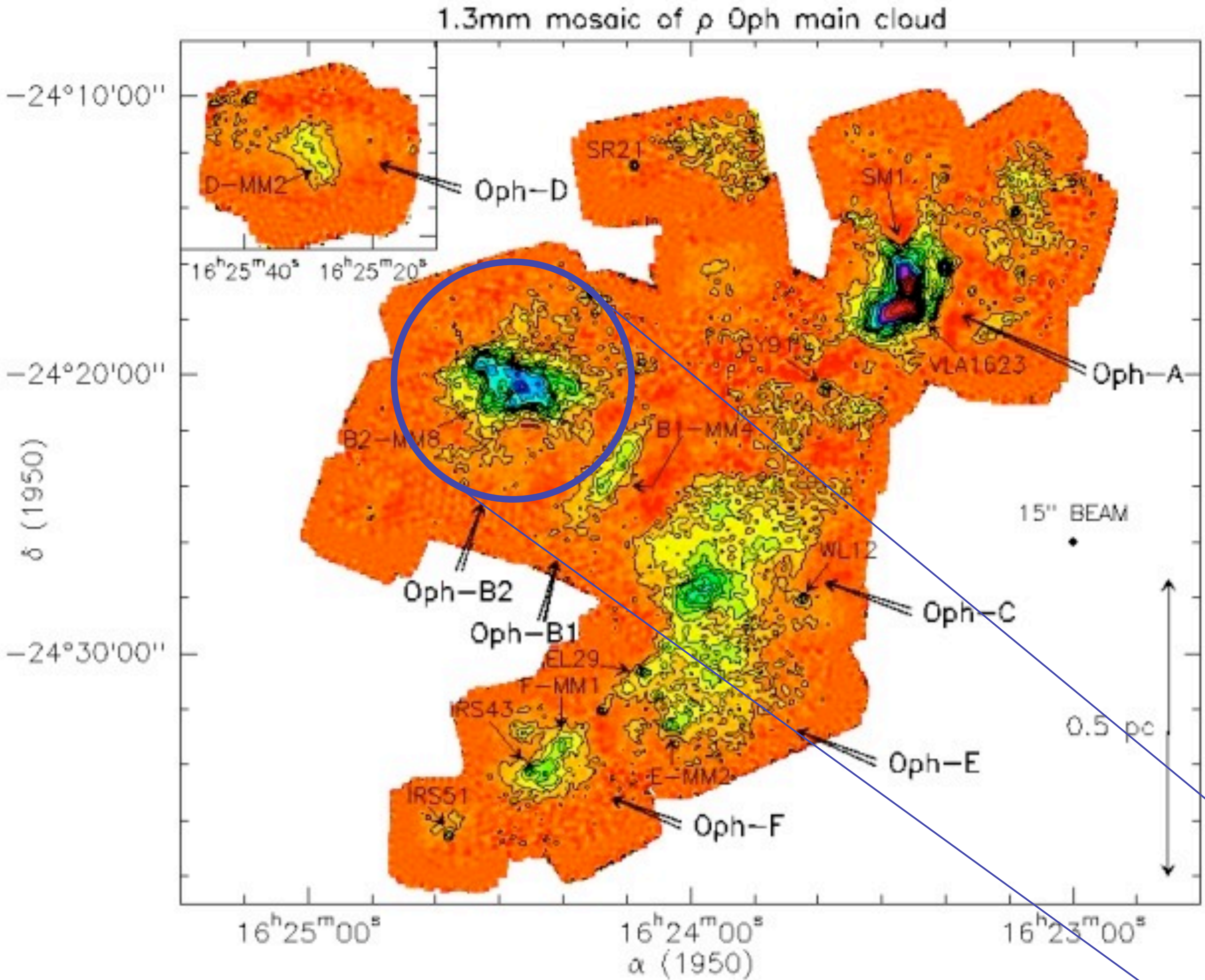


energy source & scale
NOT known
(supernovae, winds,
spiral density waves?)

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

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

Density structure of MC's



(Motte, André, & Neri 1998)

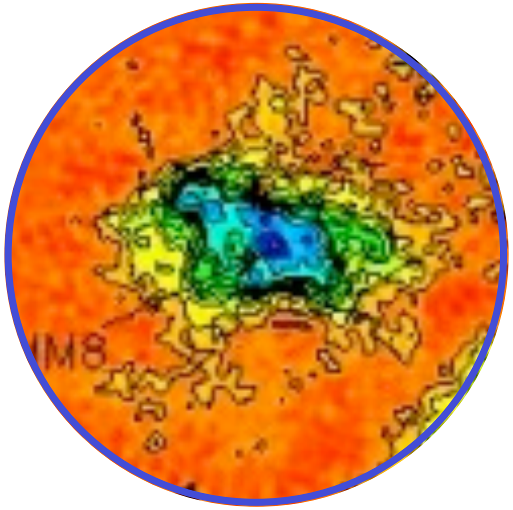
molecular clouds are highly inhomogeneous

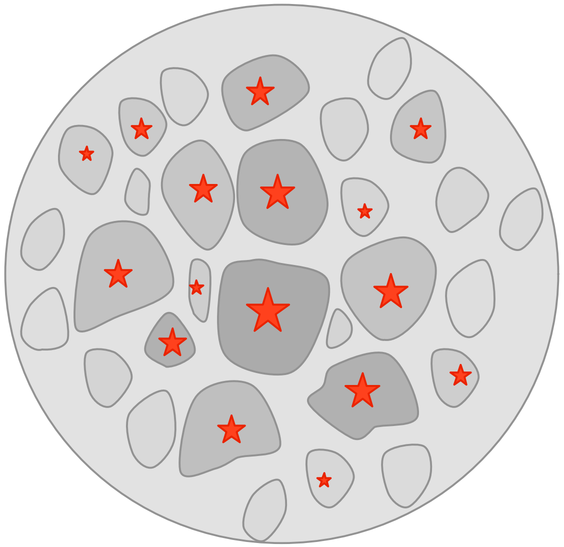
stars form in the densest and coldest parts of the cloud

ρ-Ophiuchus cloud seen in dust emission

let's focus on a cloud core like this one

Evolution of cloud cores

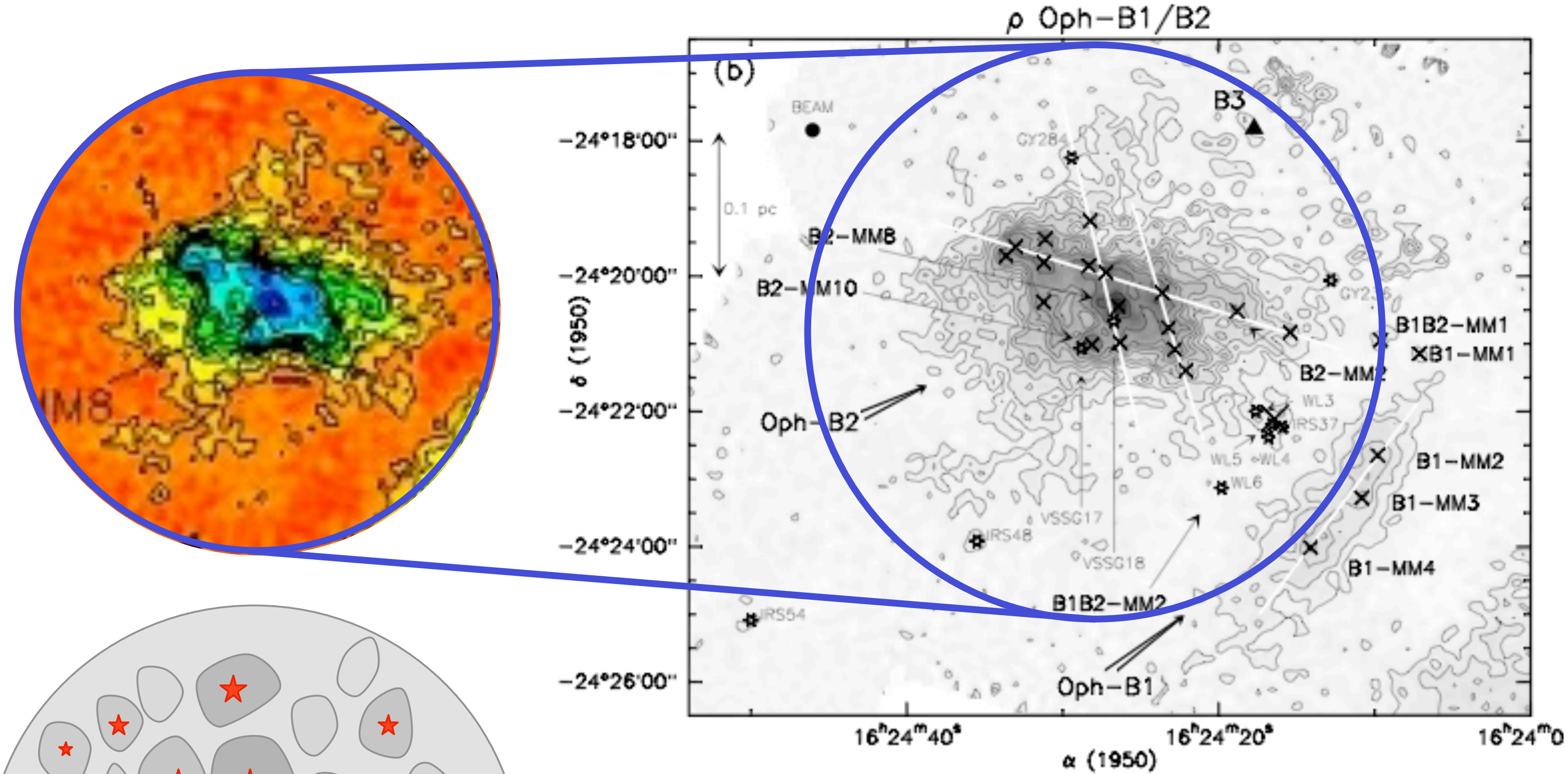


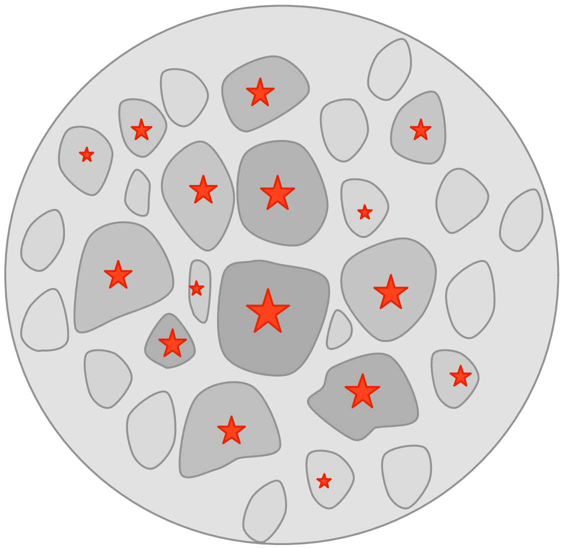


- How does this core evolve?
  Does it form one single massive star
  or cluster with mass distribution?

- 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
- --> expectation: *core breaks up and forms a cluster of stars*

Evolution of cloud cores

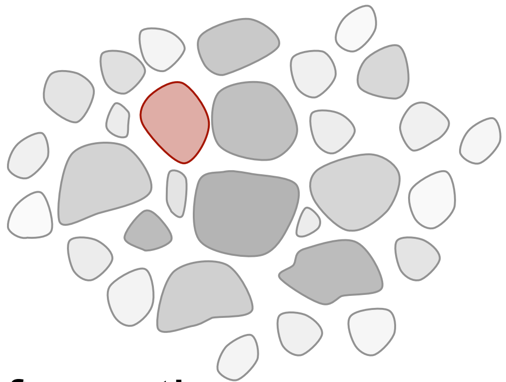




indeed ρ-Oph B1/2 contains several cores ("starless" cores are denoted by ×, cores with embedded protostars by ☆)

(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

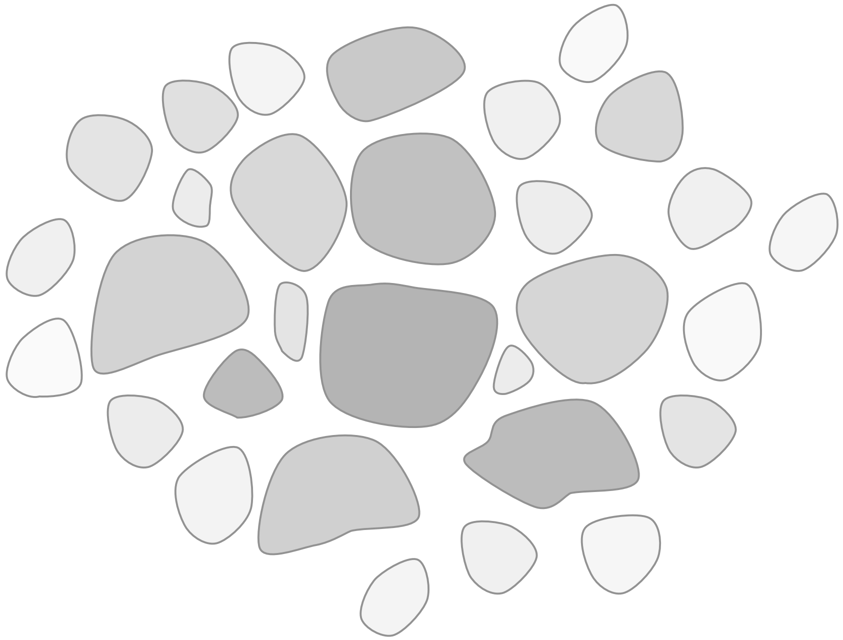
  (e.g. Vazquez-Semadeni et al 2005)

- 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

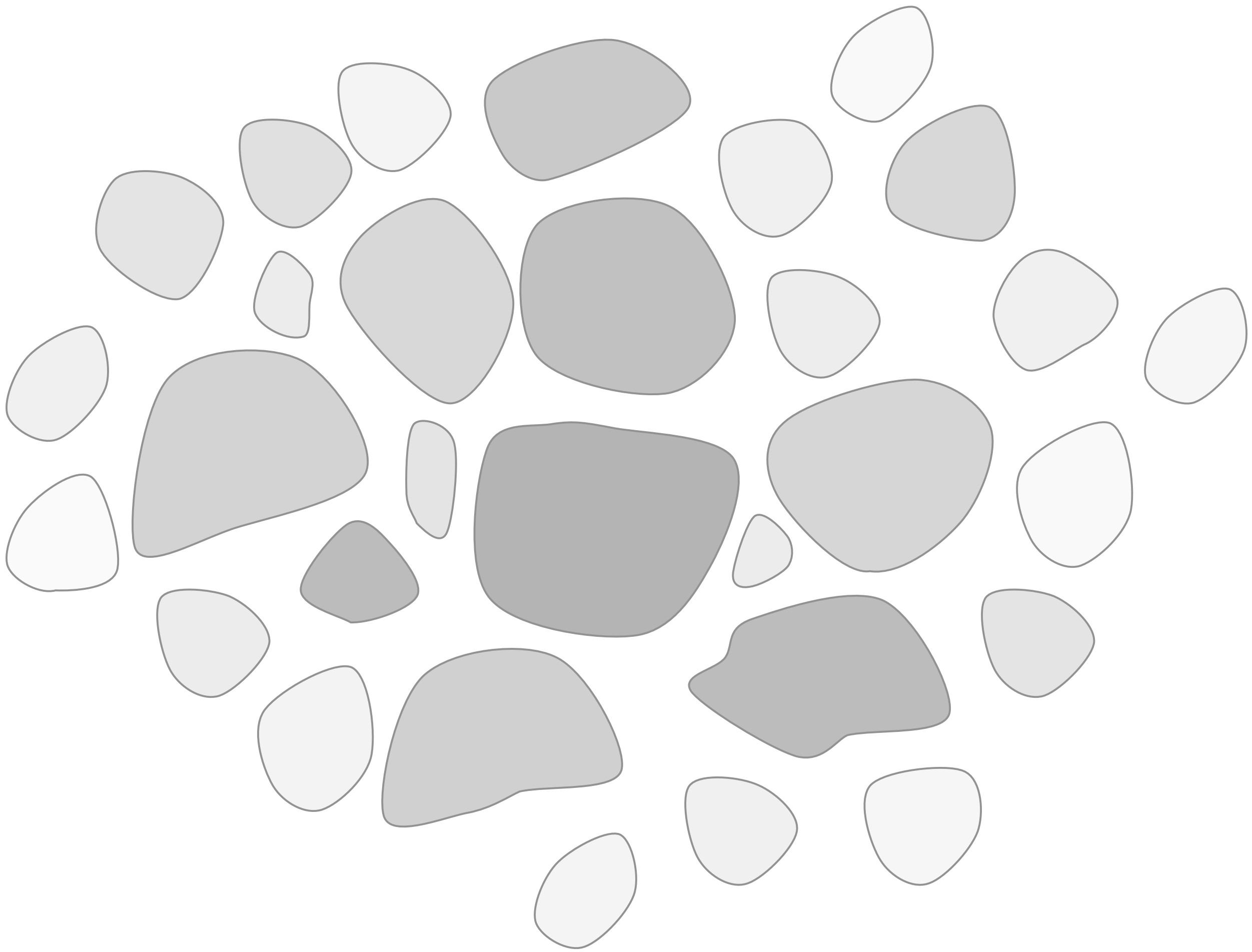
What happens to distribution of cloud cores?



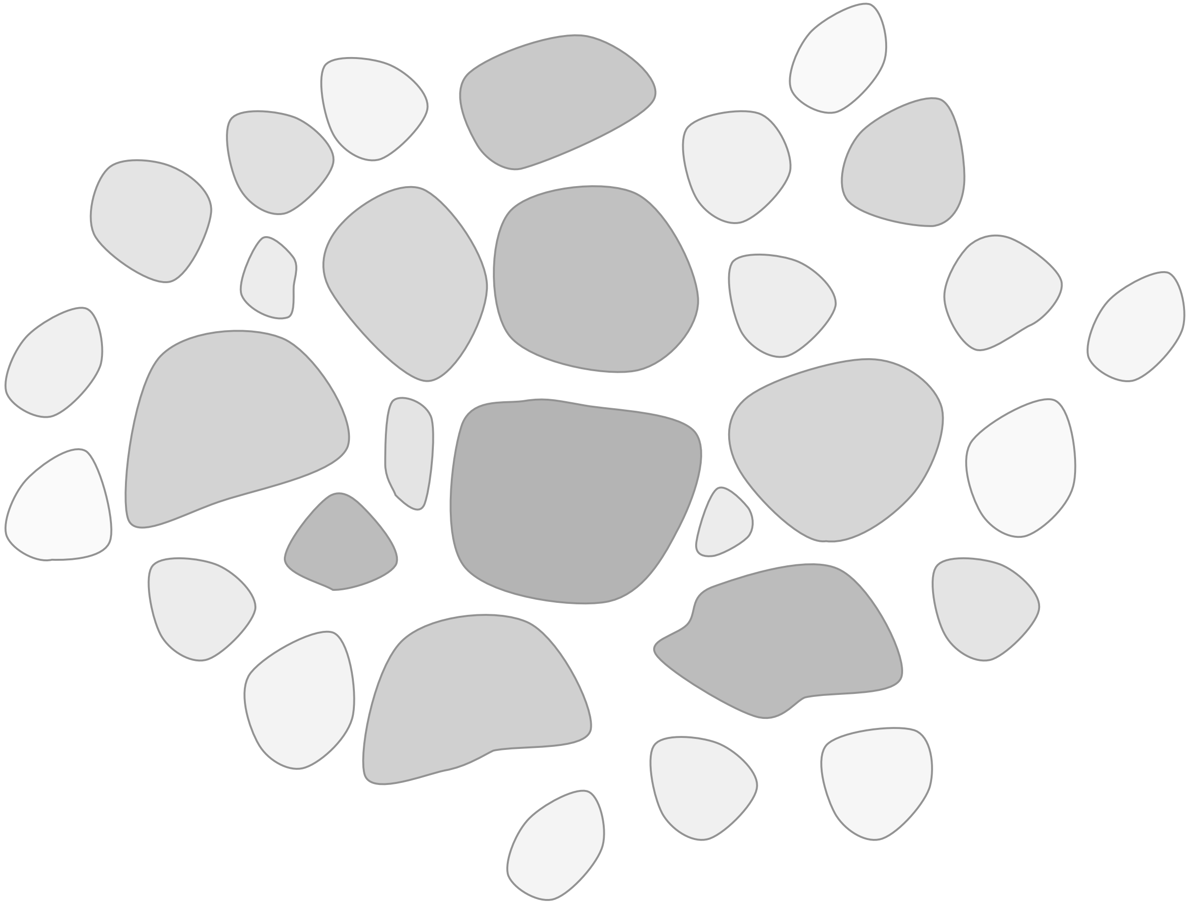
Two exteme cases:

(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*

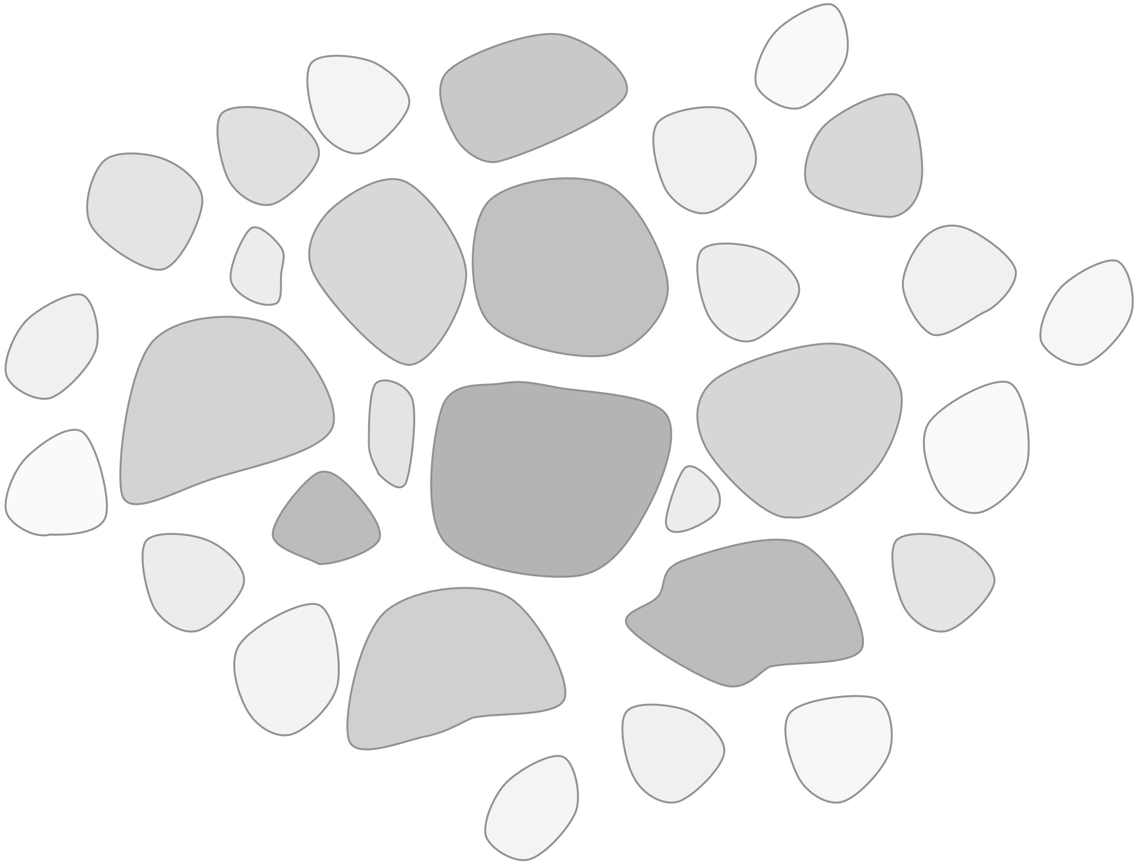
(2) turbulence decays, i.e. gravity dominates: $\alpha = E_{kin}/|E_{pot}| < 1$
--> *global contraction*
--> core do *interact* while collapsing
--> *competition* influences *mass growth*
--> *dense cluster with high-mass stars*



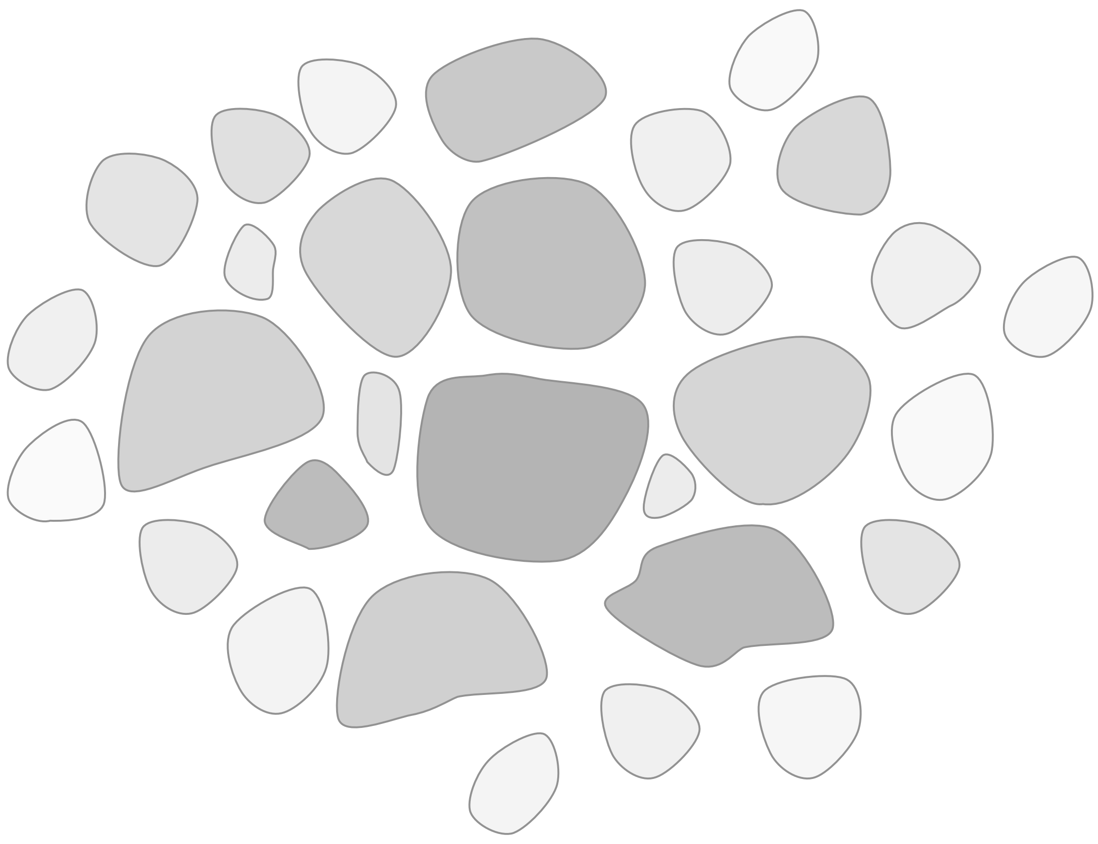
turbulence creates a hierarchy of clumps



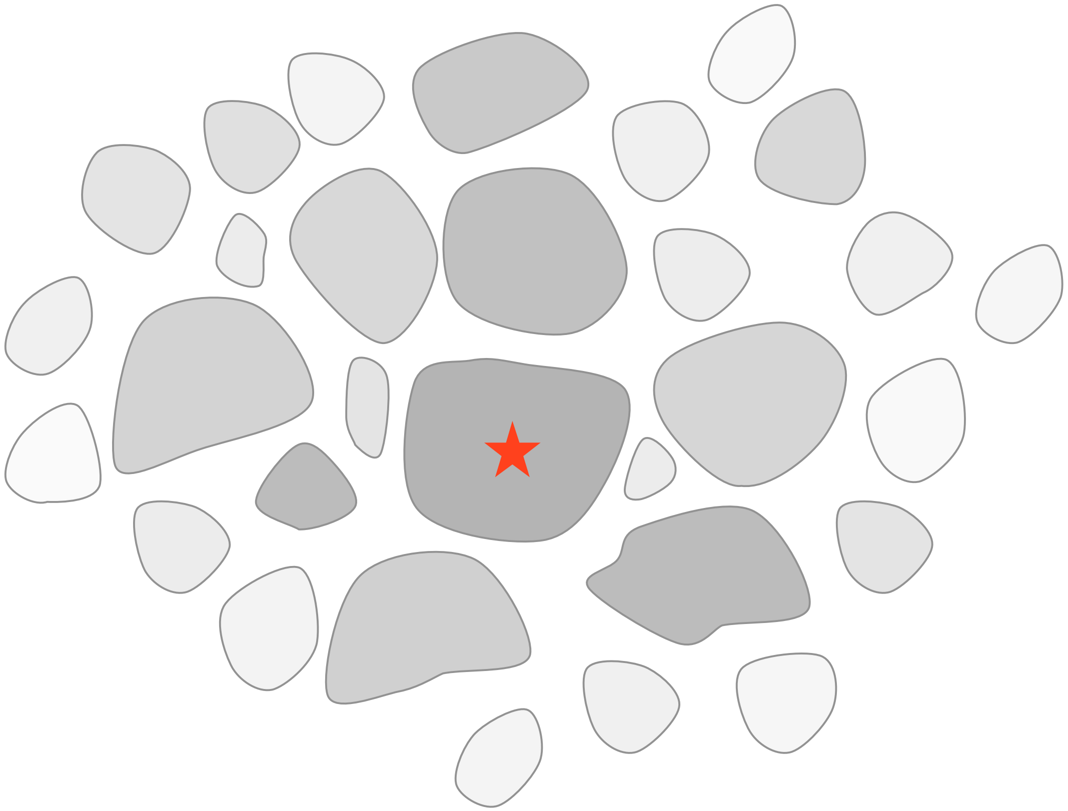
as turbulence decays locally, contraction sets in



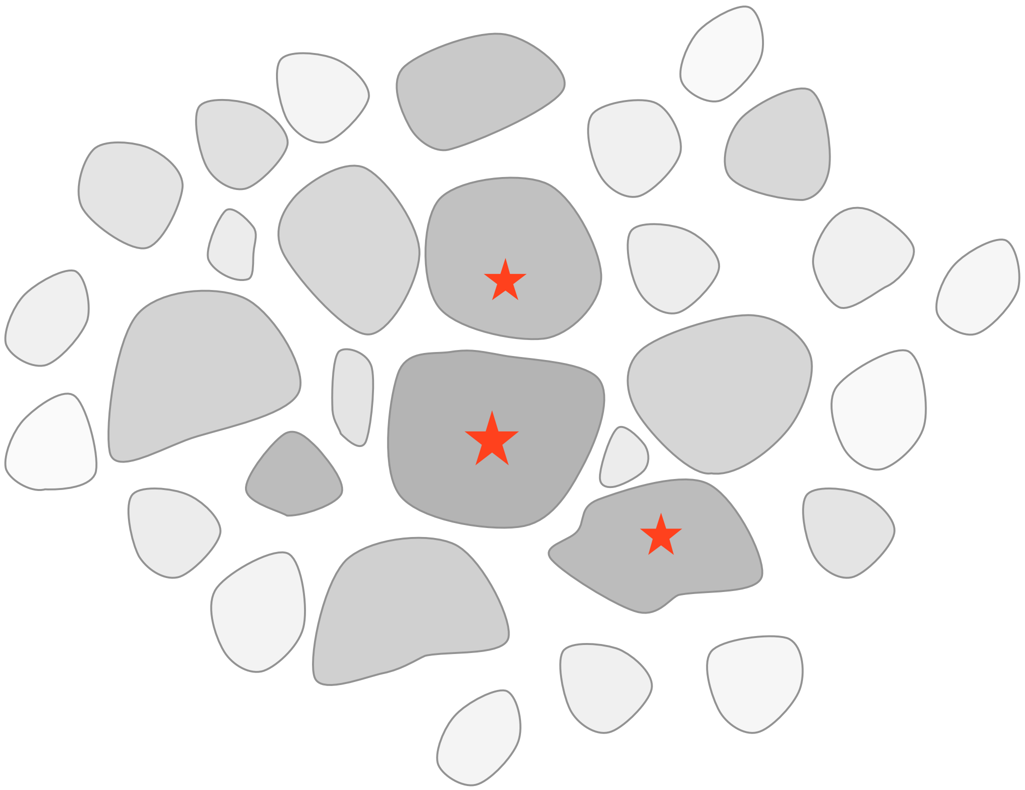
as turbulence decays locally, contraction sets in



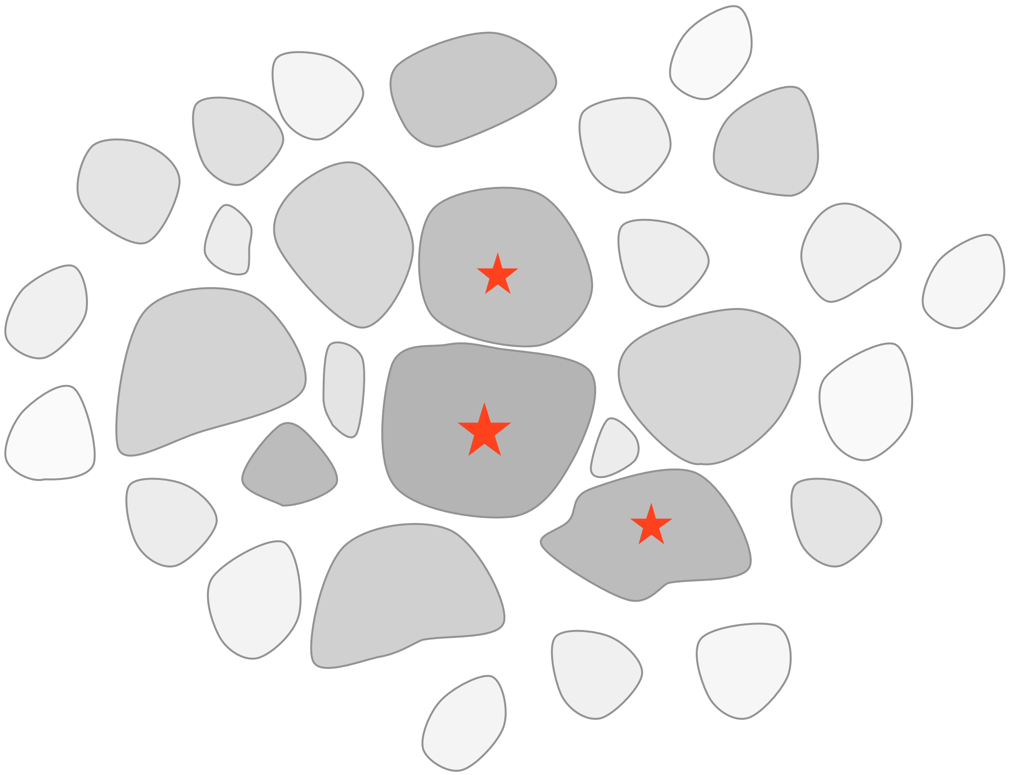
while region contracts, individual clumps collapse to form stars



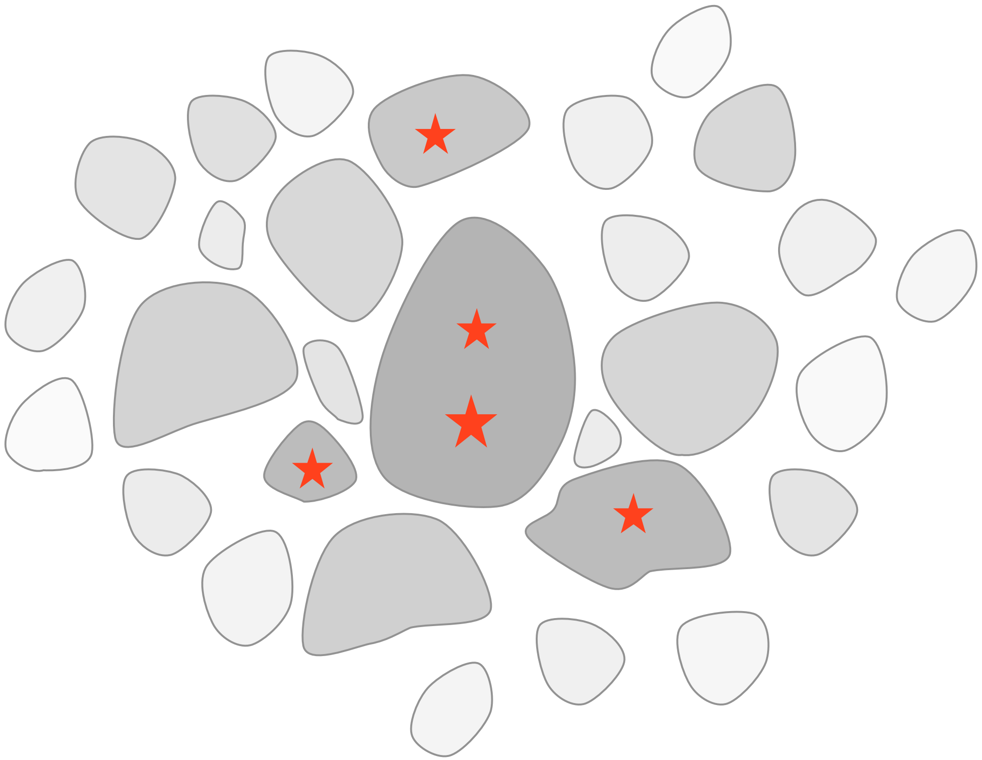
while region contracts, individual clumps collapse to form stars



individual clumps collapse to form stars

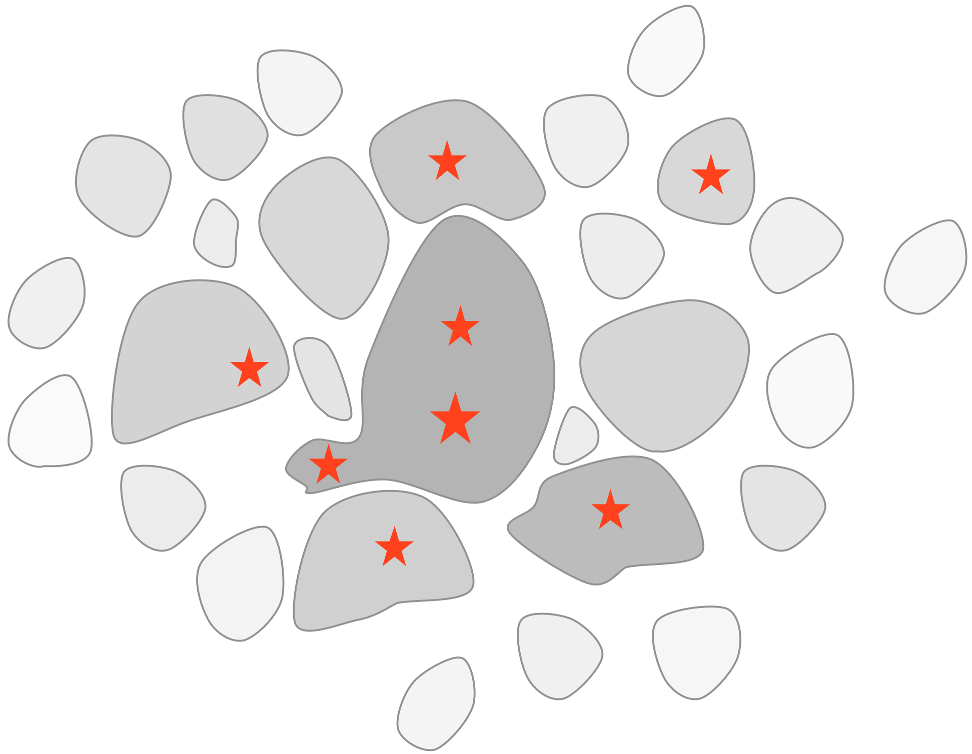


individual clumps collapse to form stars

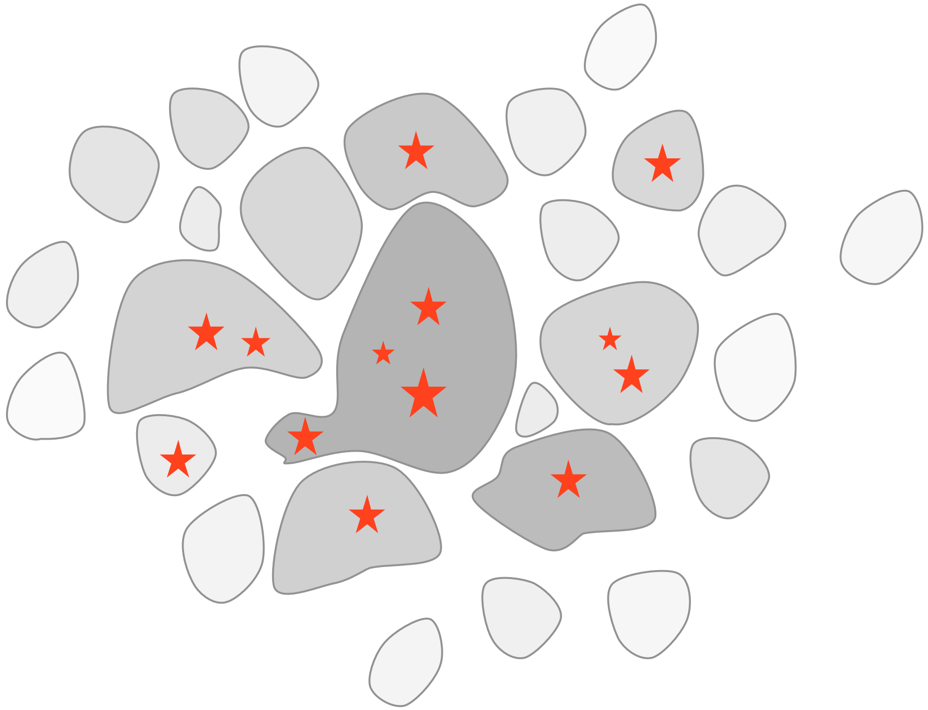


$\alpha = E_{kin}/|E_{pot}| < 1$

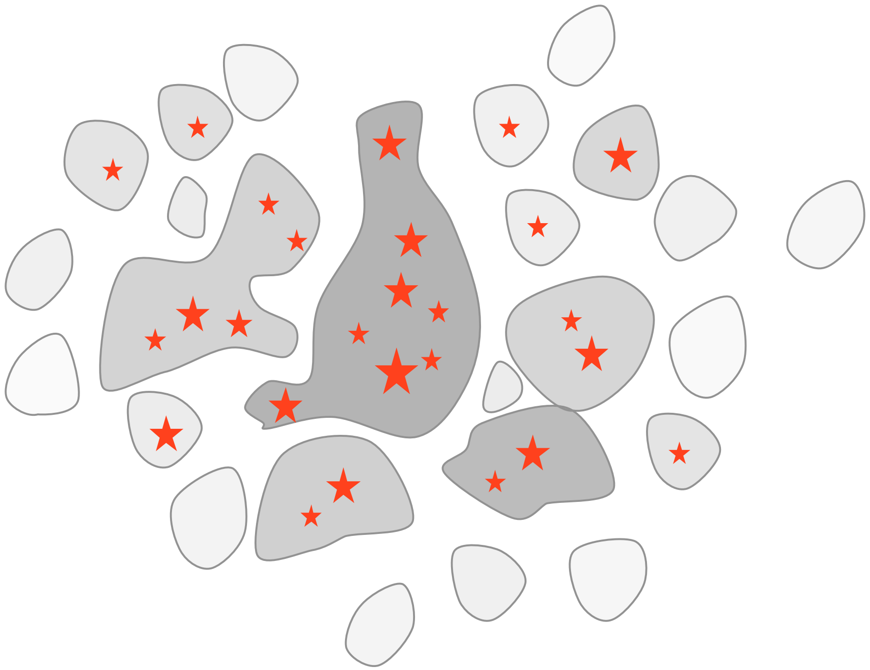
in *dense clusters*, clumps may merge while collapsing
--> then contain multiple protostars



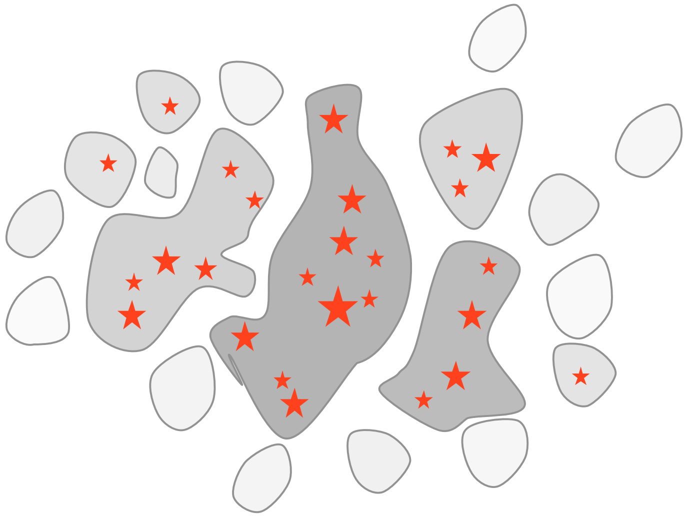
in *dense clusters*, clumps may merge while collapsing
--> then contain multiple protostars



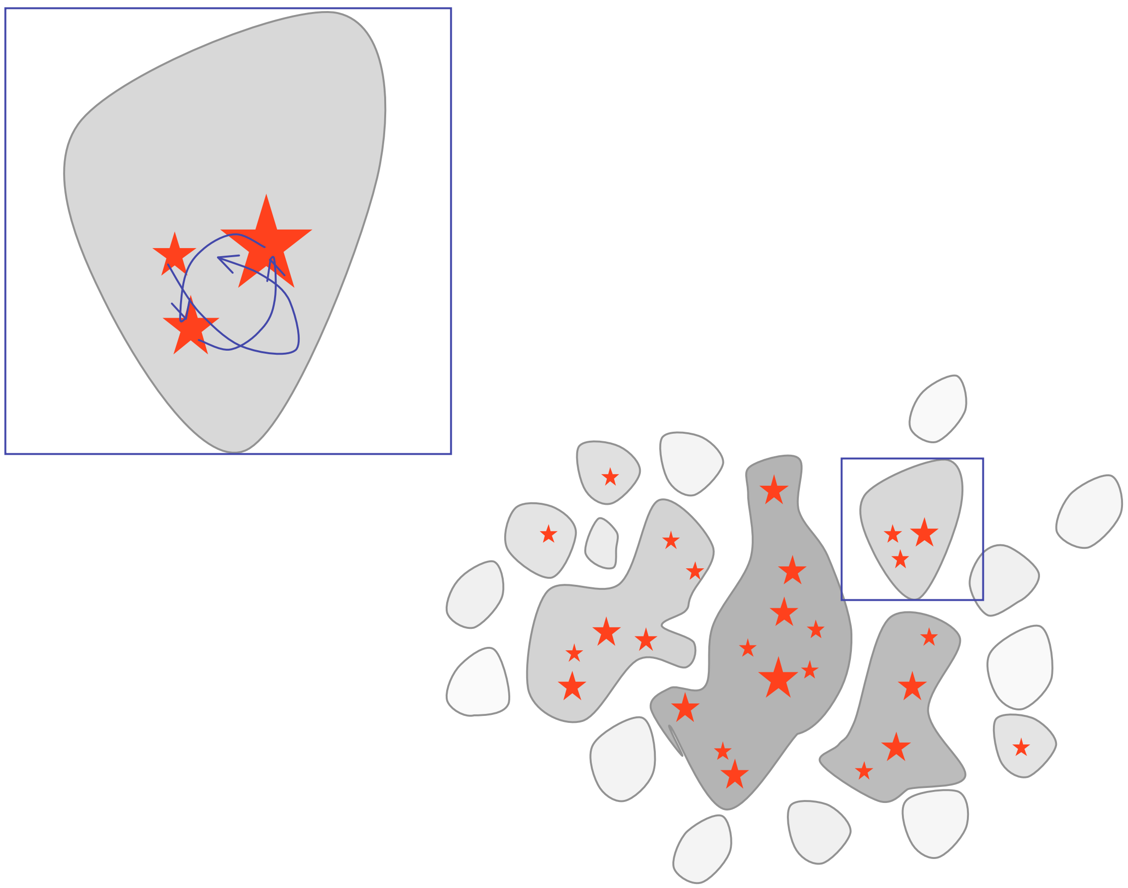
in *dense clusters*, clumps may merge while collapsing
--> then contain multiple protostars



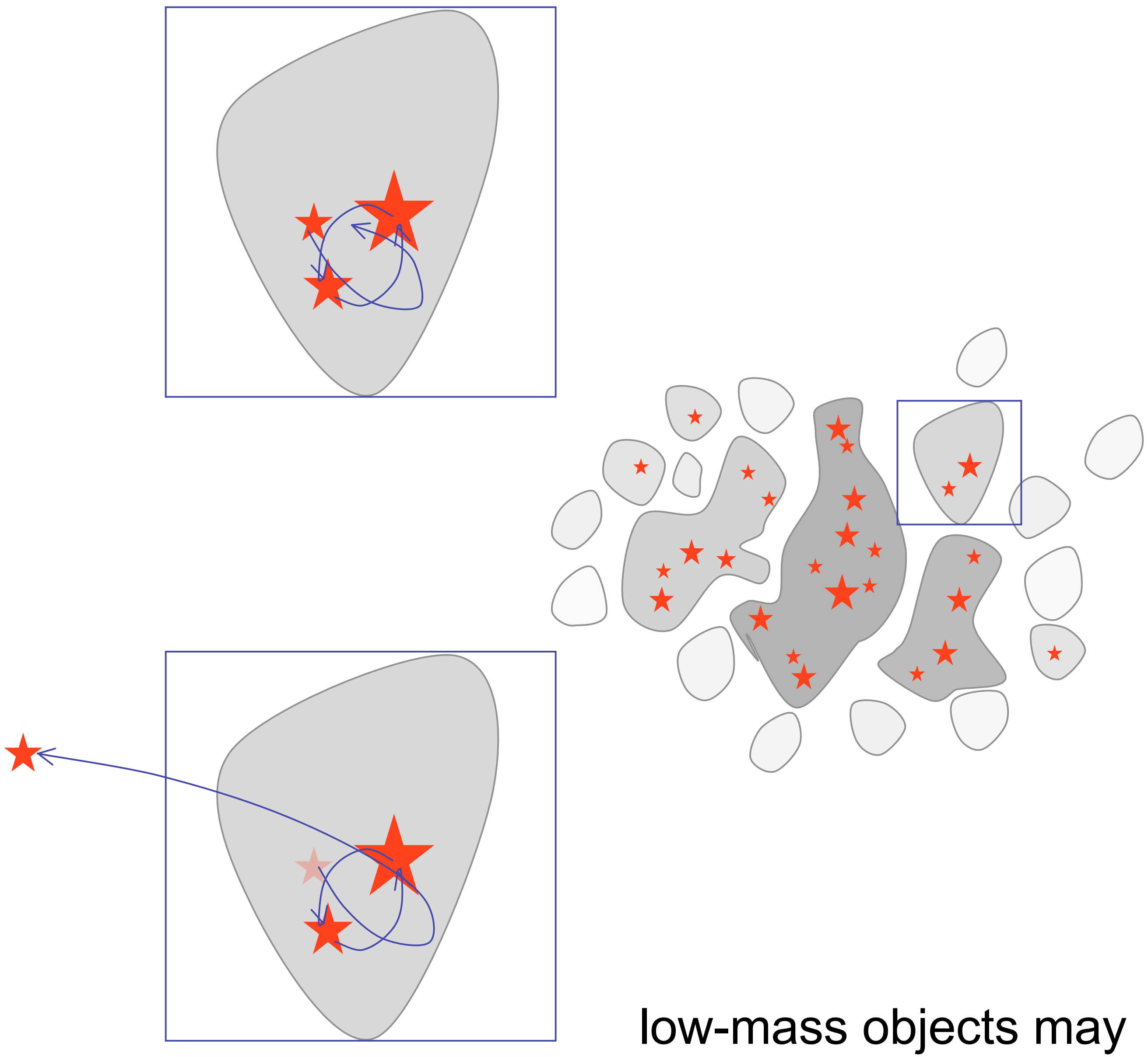
in *dense clusters*, competitive mass growth becomes important



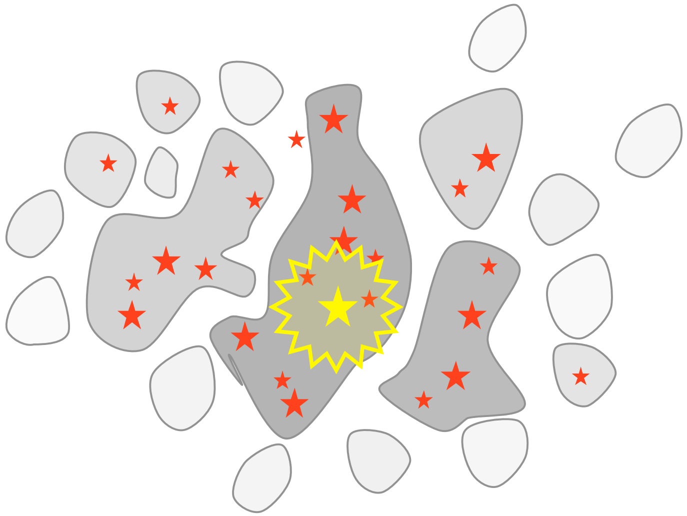
in *dense clusters*, competitive mass growth becomes important



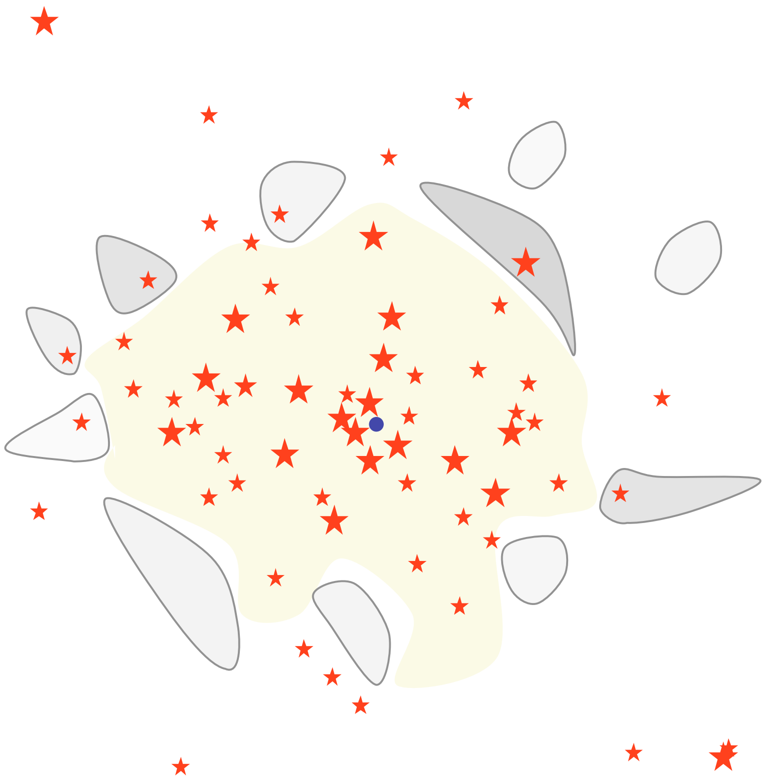
in *dense clusters*, *N*-body effects influence mass growth



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



feedback terminates star formation



result: *star cluster*, possibly with HII region

predictions

Predictions

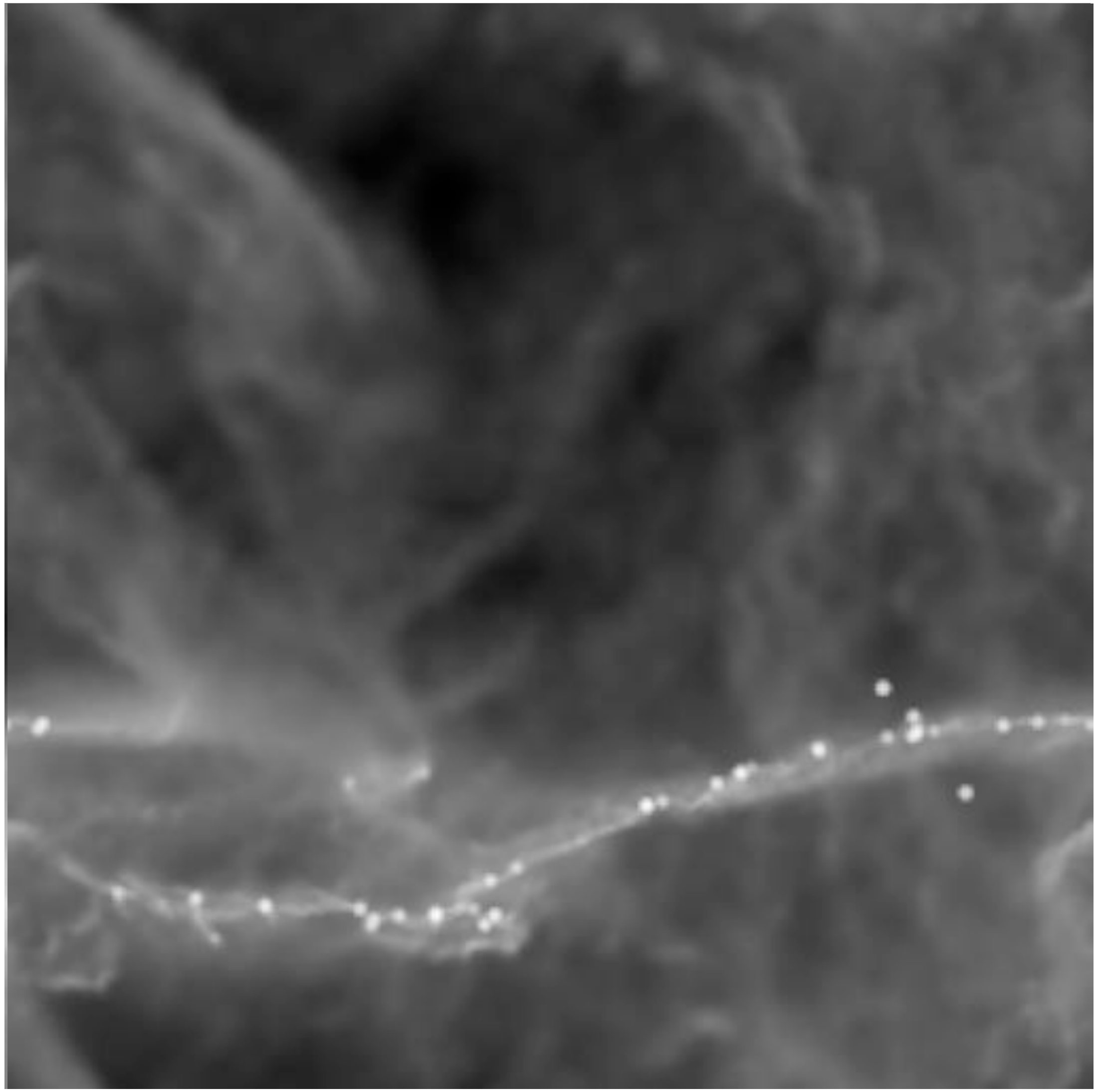
- *global properties* (statistical properties)
  - SF efficiency and timescale
  - stellar mass function -- IMF
  - dynamics of young star clusters
  - description of self-gravitating turbulent systems (pdf's, Δ-*var.)*
  - chemical mixing properties
- *local properties* (properties of individual objects)
  - 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

Gravoturbulent fragmentation



<u>Gravoturbulent fragmentation in molecular clouds:</u>

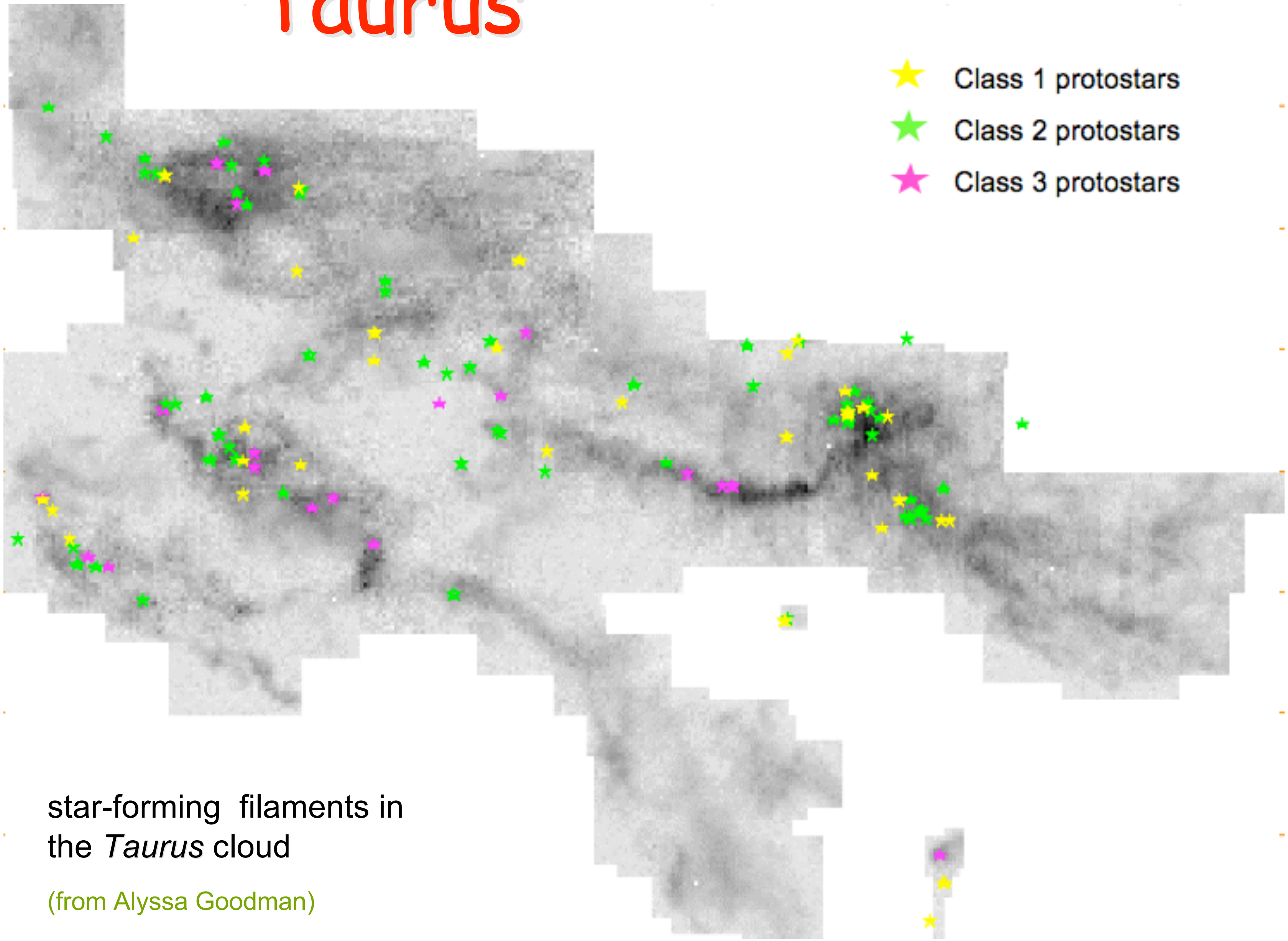
- SPH model with 1.6×10^6 particles
- large-scale driven turbulence
- Mach number $\mathcal{M} = 6$
- periodic boundaries
- physical scaling:

"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

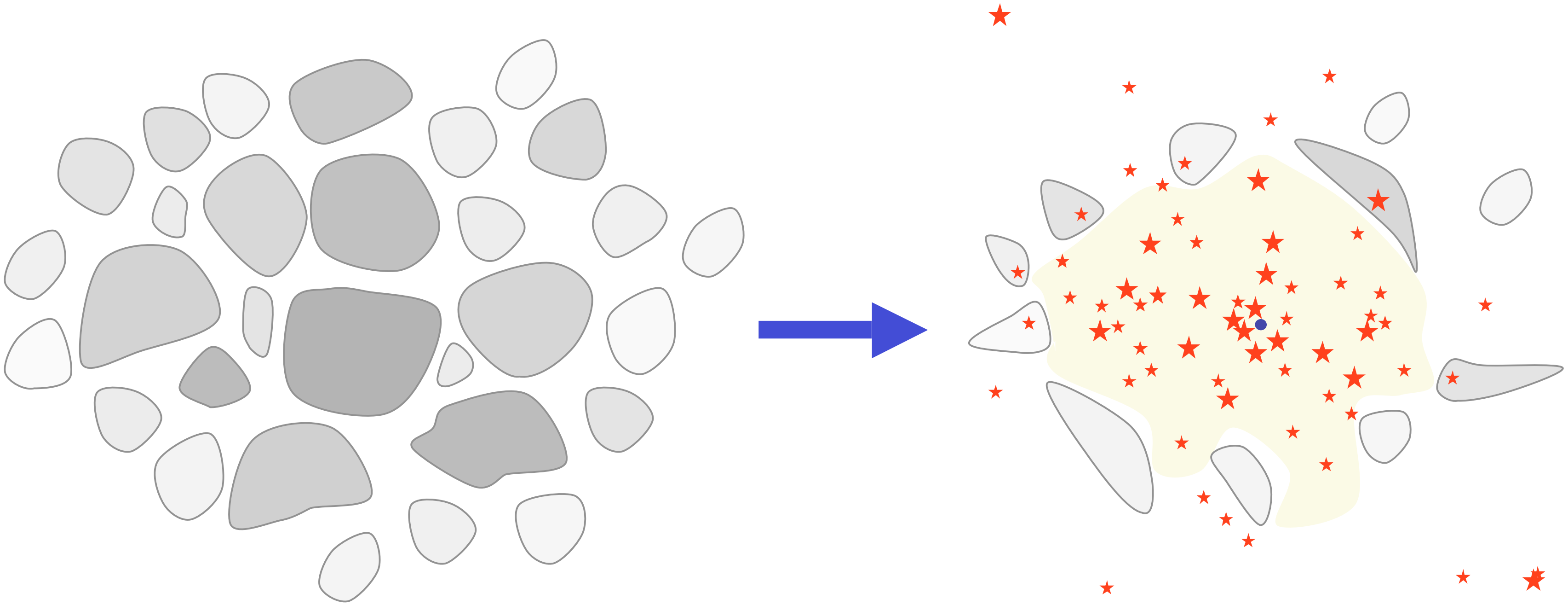
IMF

- 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

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

Star cluster formation

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



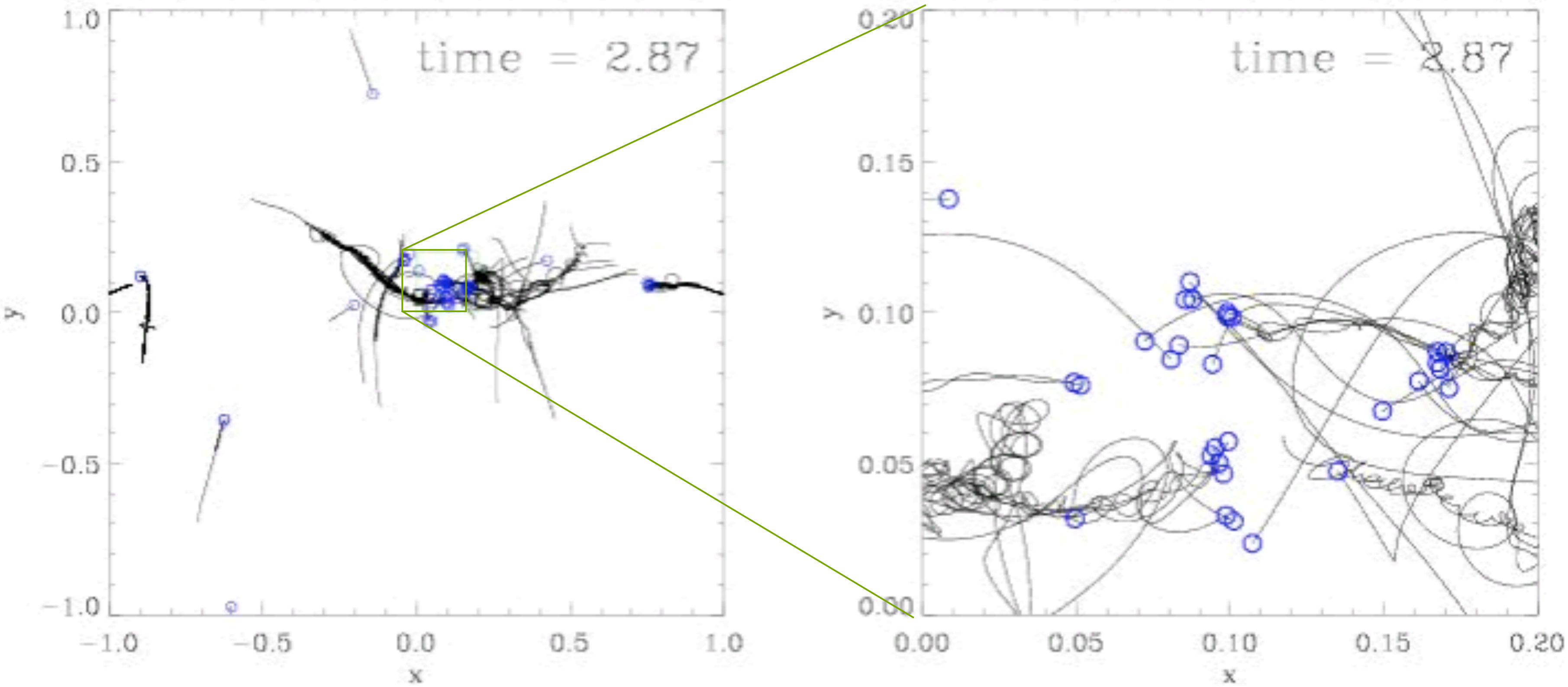
How to get from cloud cores to star clusters?

How do the stars acquire mass?

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

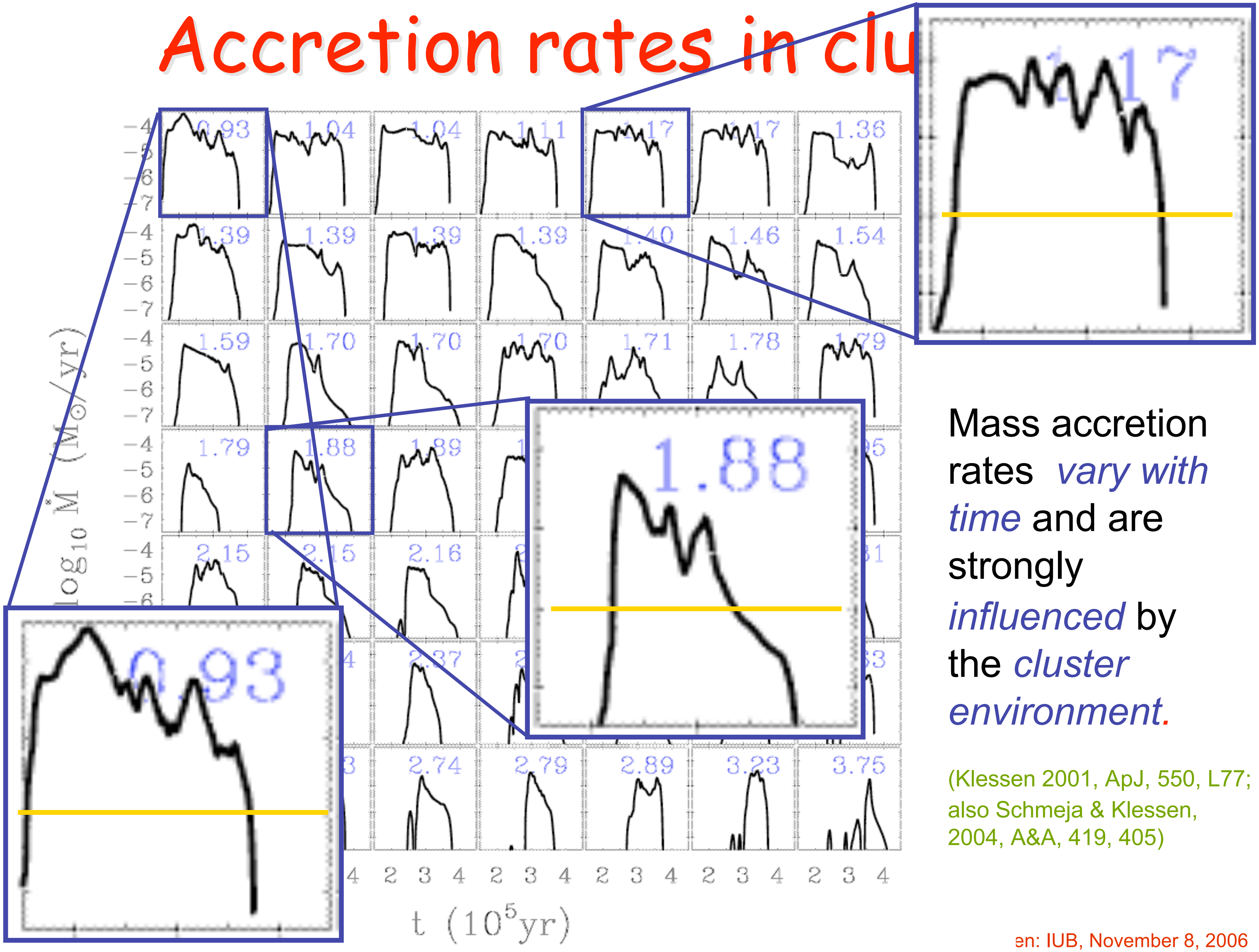
Star cluster formation

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



Trajectories of protostars in a nascent dense cluster created by gravoturbulent fragmentation
(from Klessen & Burkert 2000, ApJS, 128, 287)

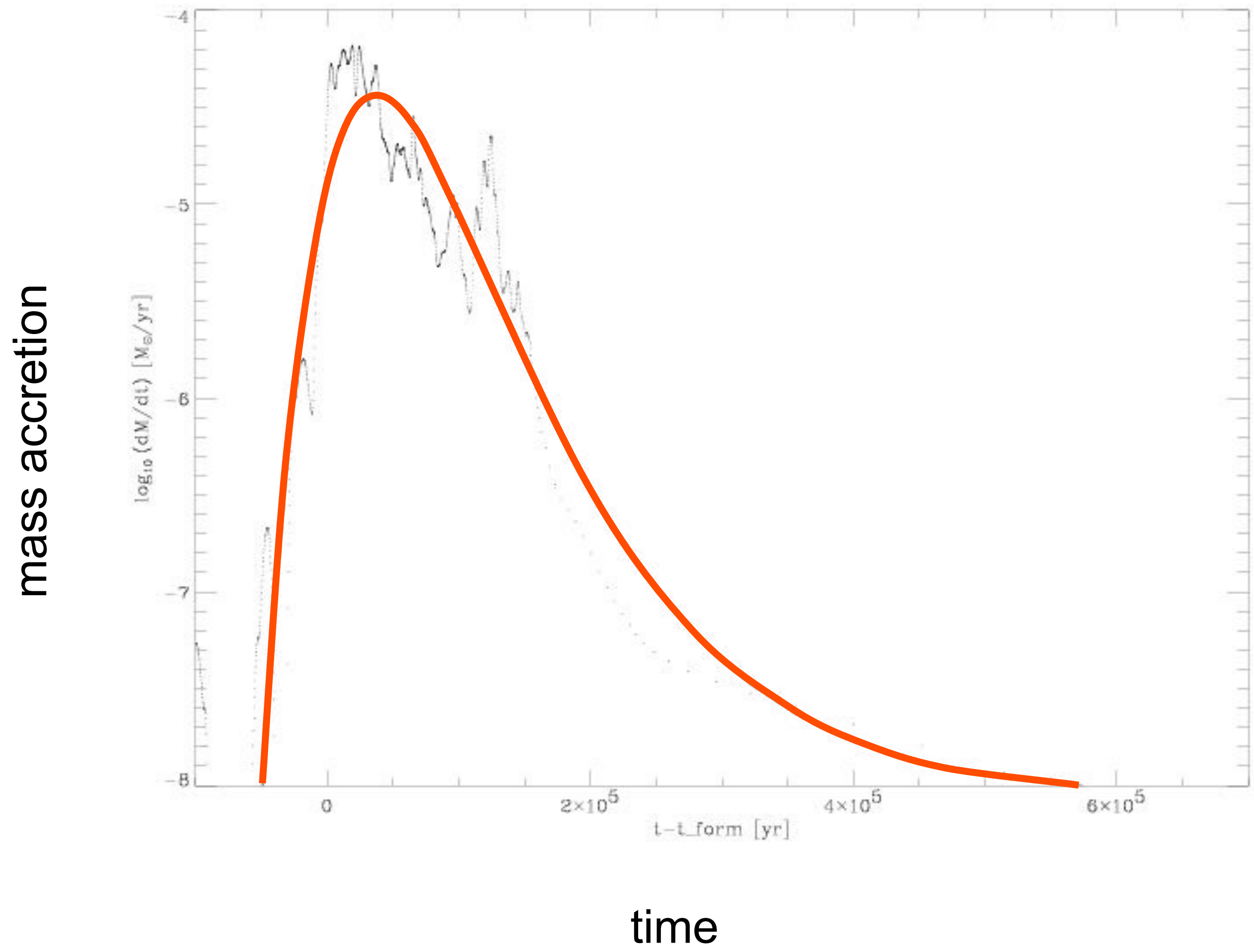
Accretion rates in clu



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)

“Empirical” mass accretion law



Simple analytic formula for individual mass accretion rates: $dM/dt = At \bullet \exp(-t/\tau)$

(Schmeja & Klessen, 2004 -- A&A, 419, 405 - 417)

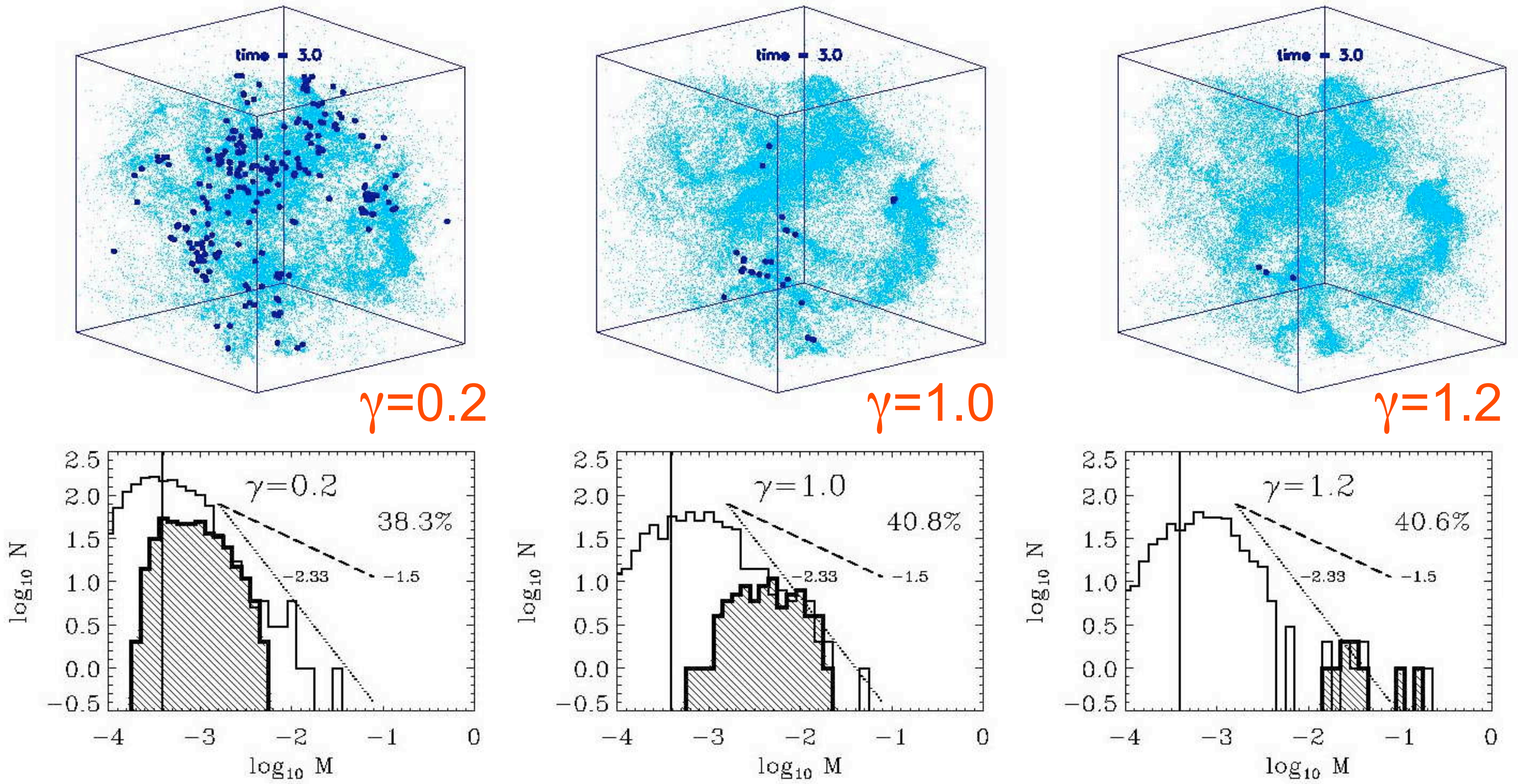
Dependency on EOS

- degree of fragmentation depends on *EOS!*

- polytropic EOS: $p \propto \rho^{\gamma}$
- $\gamma<1$: dense cluster of low-mass stars
- $\gamma>1$: isolated high-mass stars

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

Dependency on EOS



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

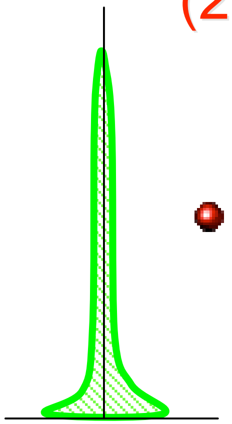
for $\gamma>1$ it is suppressed → formation of *isolated massive stars*

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

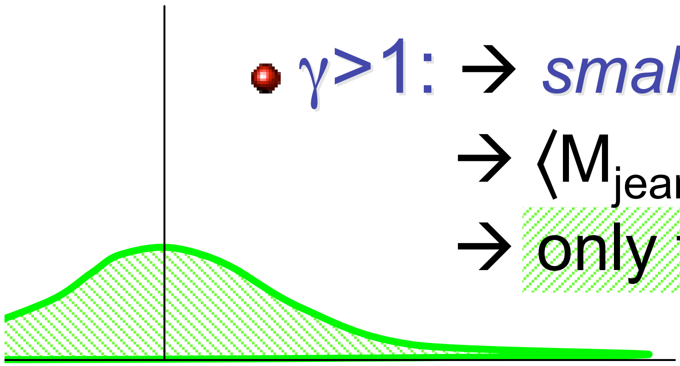
How does that work?

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

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



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



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

Implications

- degree of fragmentation depends on *EOS!*

- polytropic EOS: $p \propto \rho^{\gamma}$
- $\gamma<1$: dense cluster of low-mass stars
- $\gamma>1$: isolated high-mass stars

  (see Li, Klessen, & Mac Low 2003, ApJ, 592, 975; Kawachi & Hanawa 1998; Larson 2003; also Jappsen, Klessen, Larson, Li, Mac Low, 2005, 435, 611)

- implications for extreme environmental conditions
  - expect Pop III stars to be massive and form in isolation
  - expect IMF variations in warm & dusty starburst regions

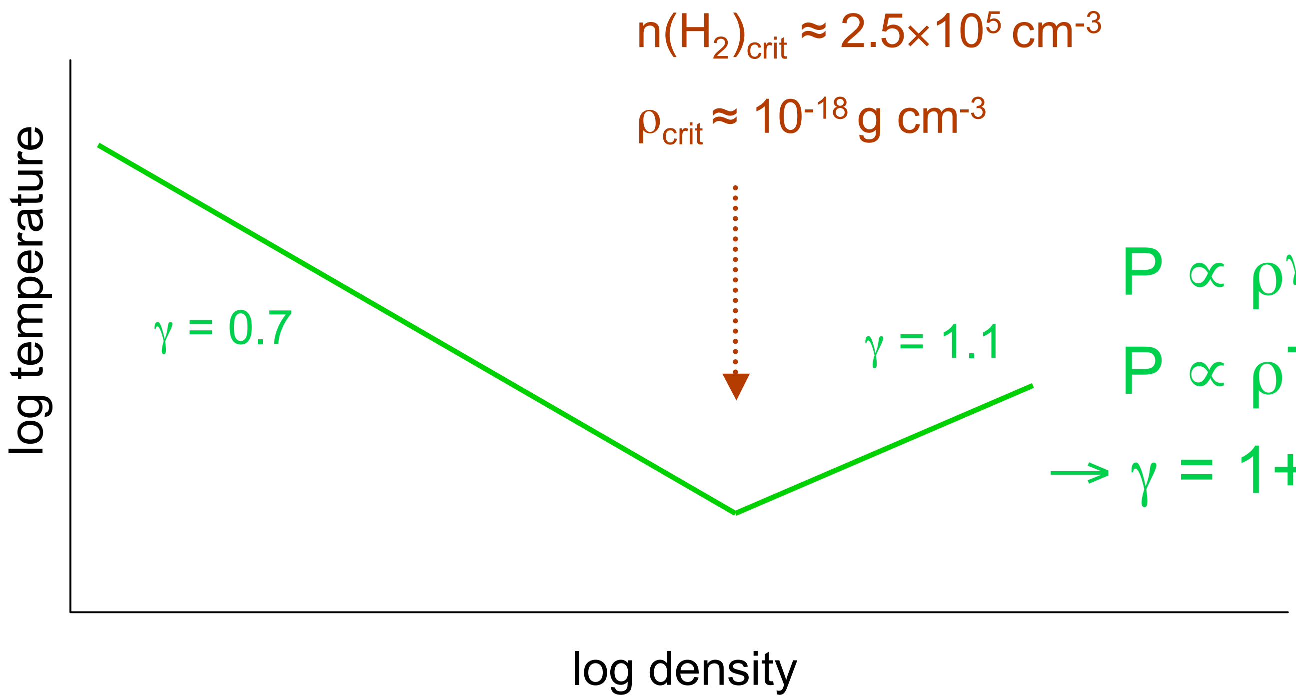
  (Spaans & Silk 2005; Klessen, Spaans, & Jappsen 2005)

- Observational findings: isolated O stars in LMC (and M51)?

  (Lamers et al. 2002, Massey 2002; see however, de Witt et al. 2005 for Galaxy)

More realistic EOS

- But EOS depends on *chemical state*, on *balance* between *heating* and *cooling*



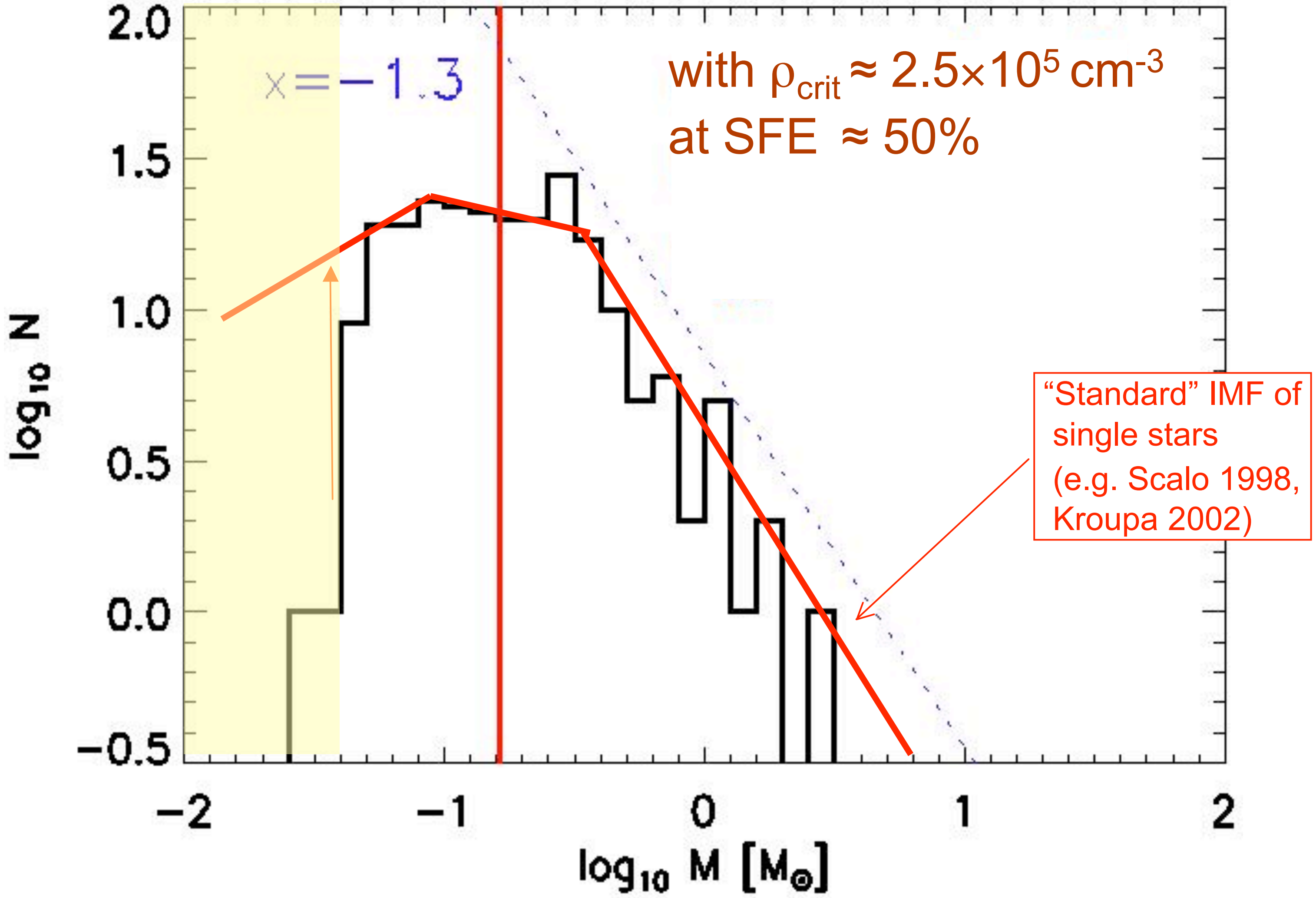
$P \propto \rho^\gamma$

$P \propto \rho T$

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

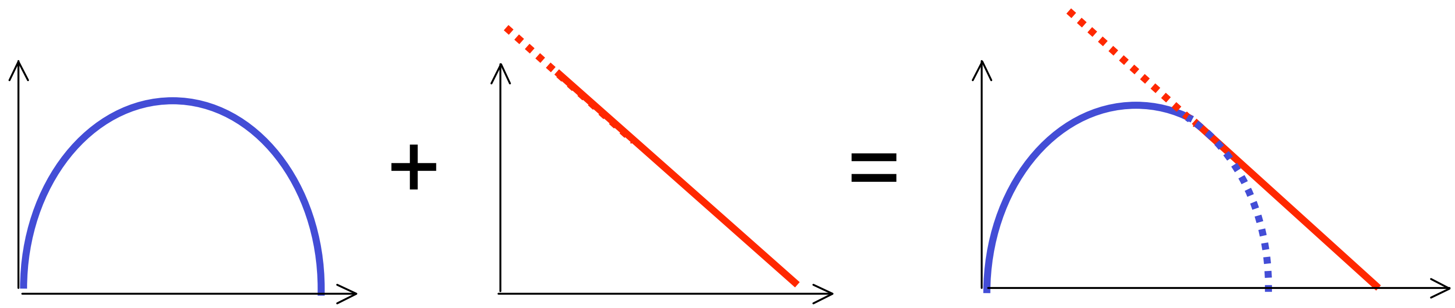
(Larson 2005; Jappsen et al. 2005, A&A, 435, 611)

IMF in nearby molecular clouds



(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***

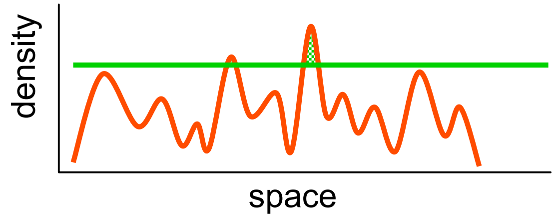
- *turbulent cascade:* local compression *within* a cloud provokes collapse

- 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)

Summary

- 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)

Thanks!