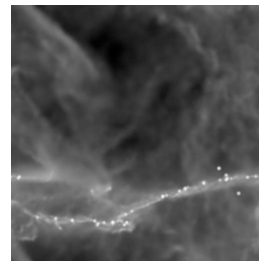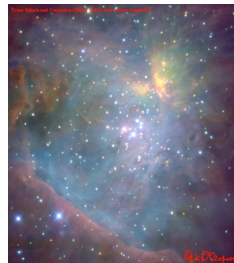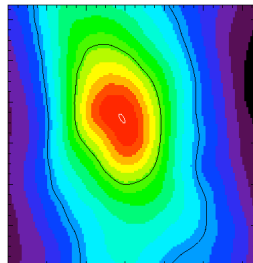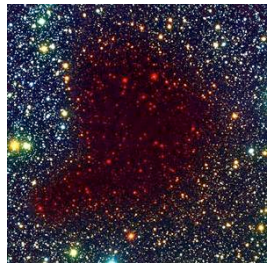# Star Formation



**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)

# Agenda

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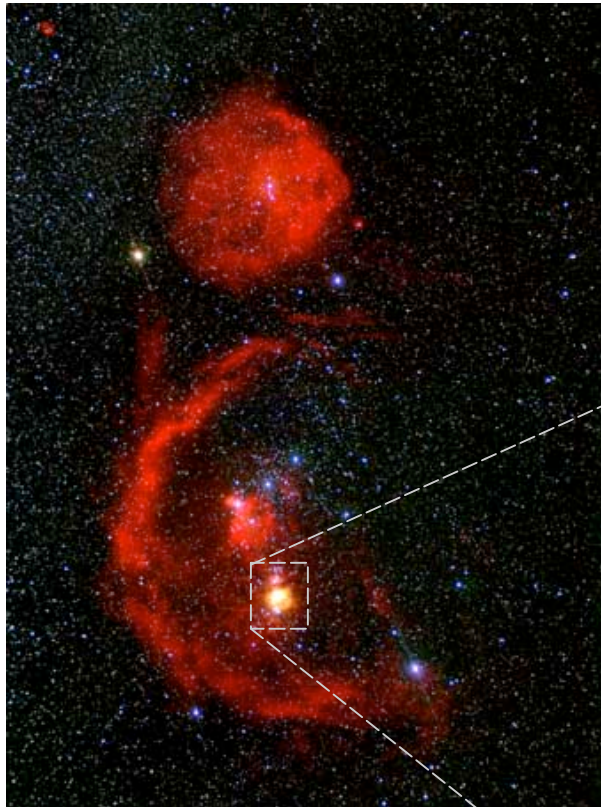  - stellar initial mass function

phenomenology

Ralf Klessen:  Capri, September 2007
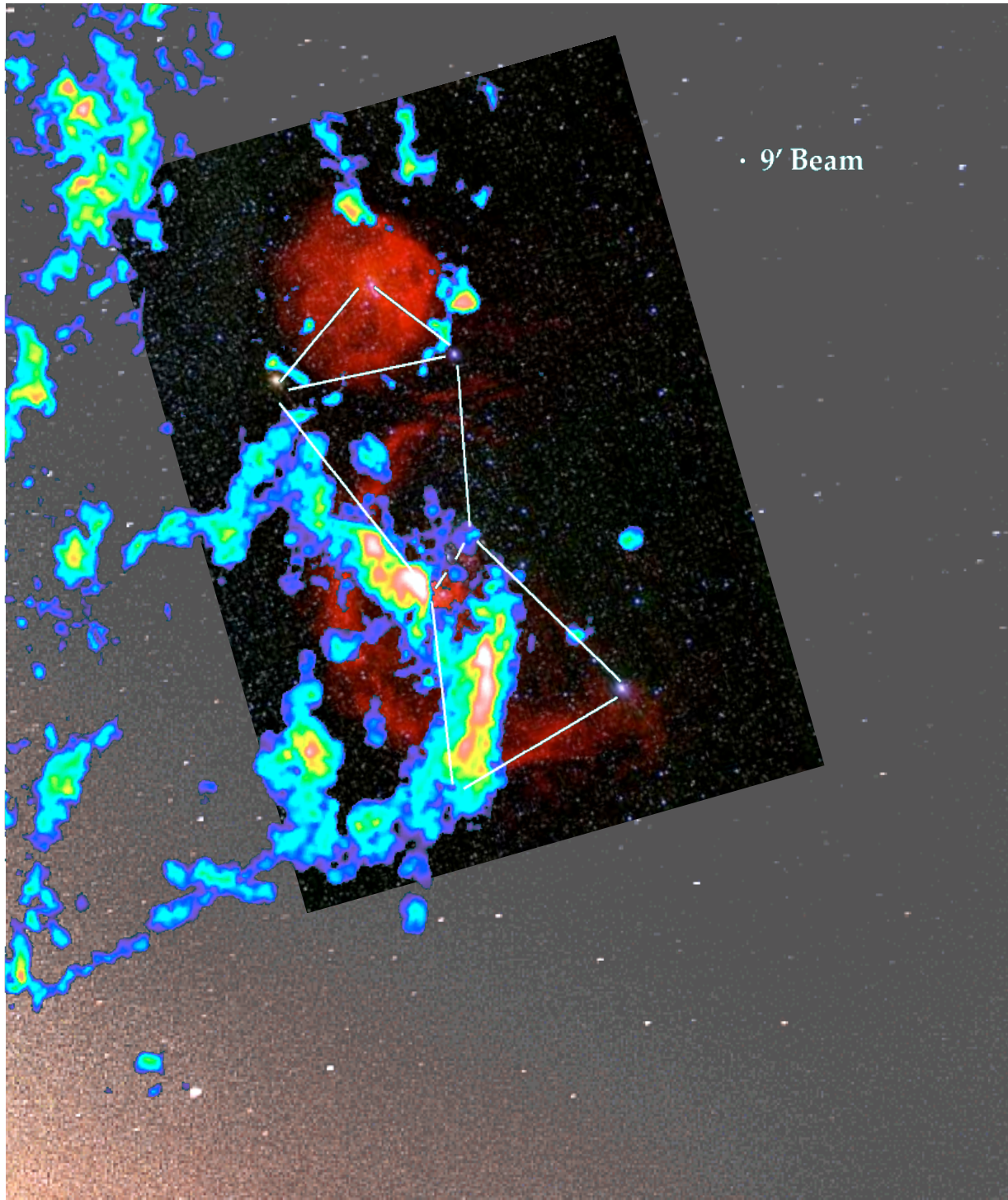
# Star formation in Orion

9' Beam

We see

- *Stars* (in visible light)

- Atomic hydrogen (in Hα -- red)

- Molecular hydrogen $H_2$ (radio emission -- color coded)

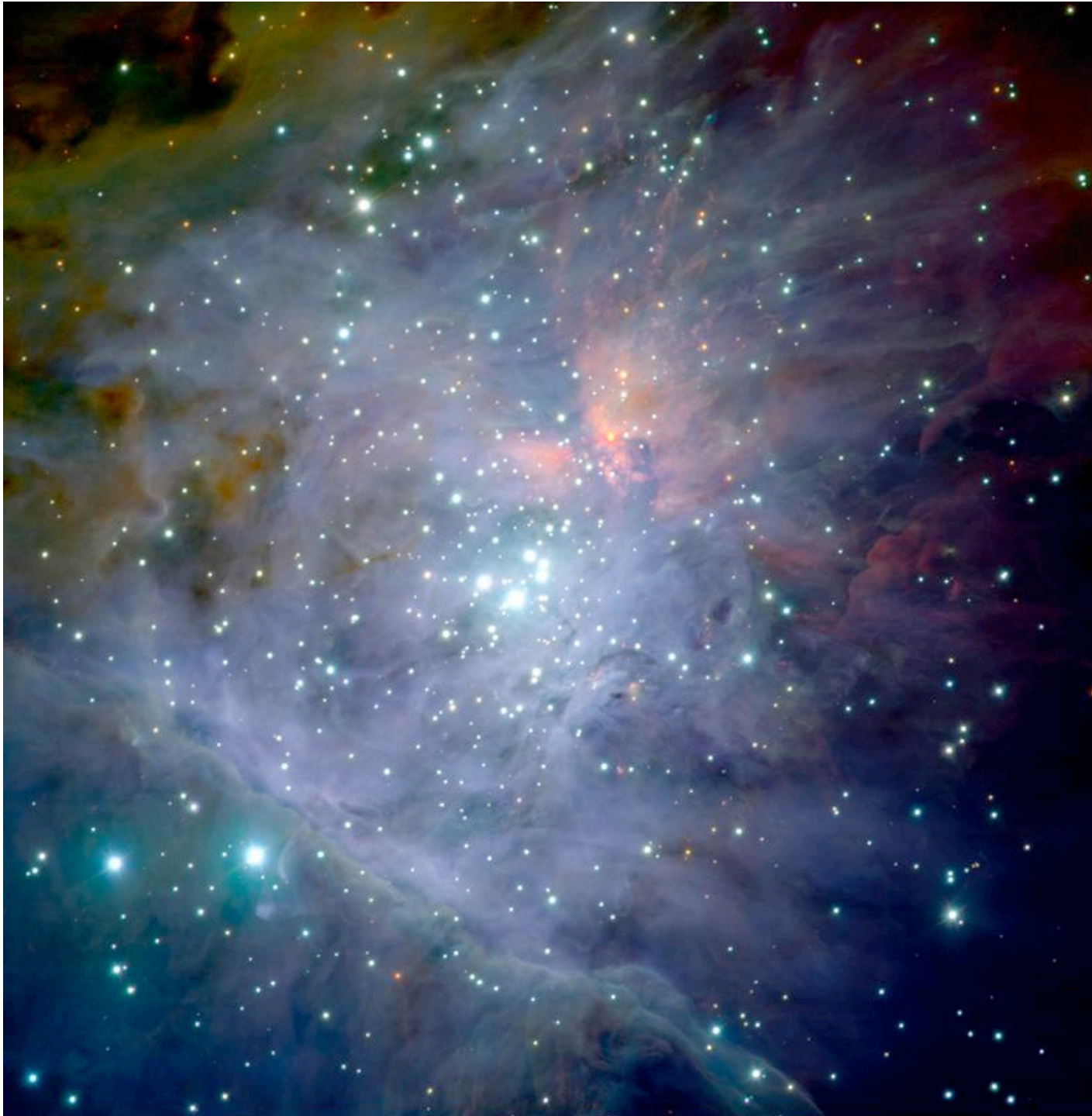# Local star forming region: The Trapezium Cluster in Orion



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.



Orion Nebula and Trapezium Cluster (J,K,L true colour composite)
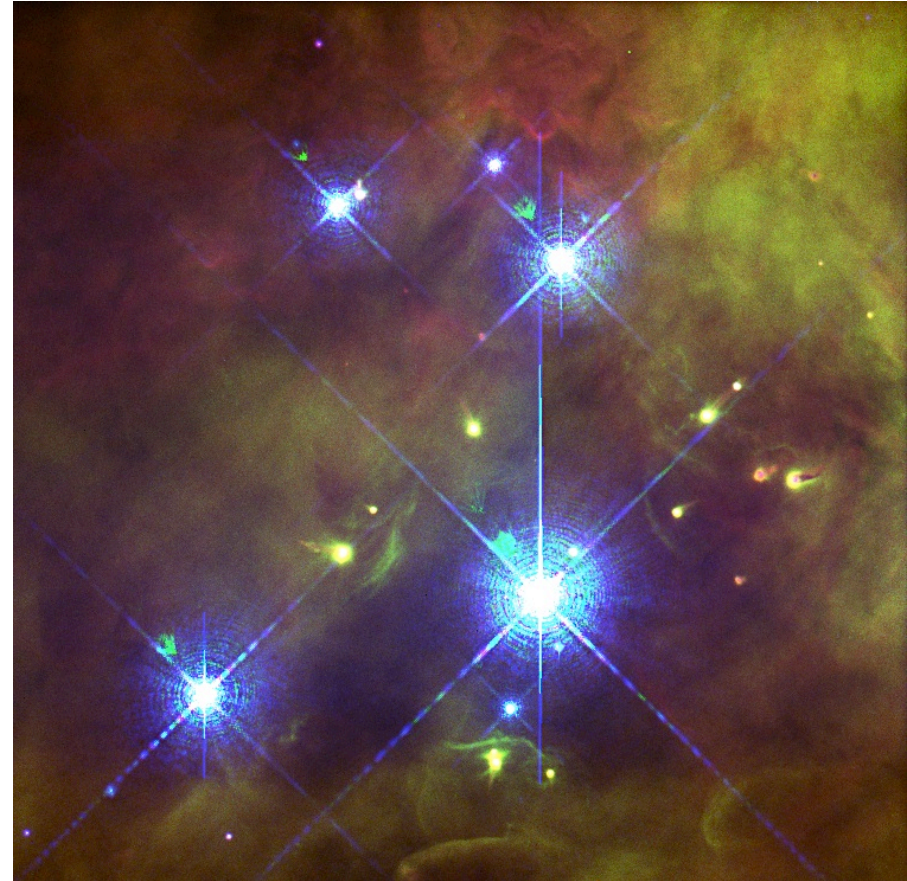
Trapezium cluster

# 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)
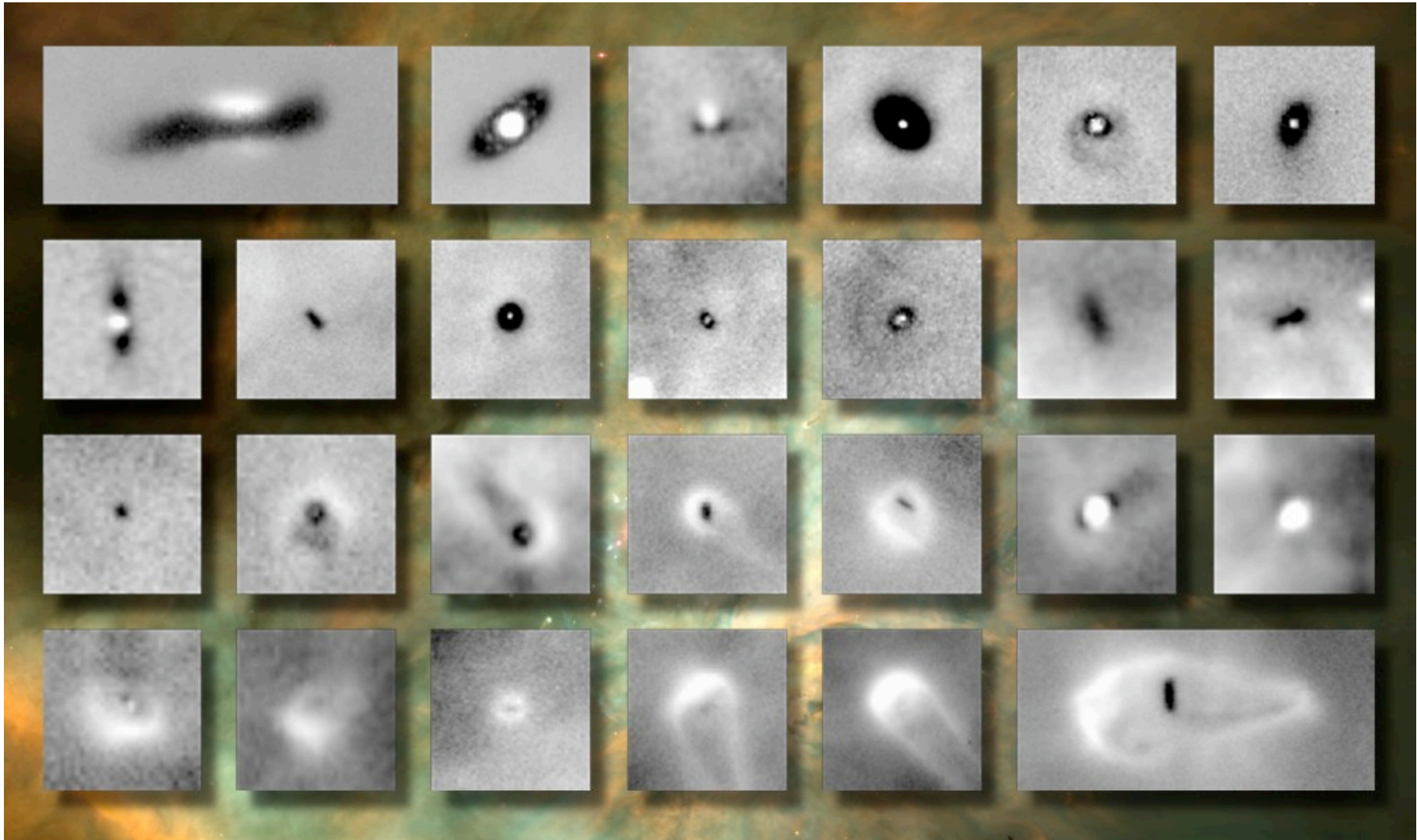
# Trapezium Cluster: Central Region



Ionizing radiation from central star
**Θ1C Orionis**

**Proplyds:** Evaporating ``protoplanetary´´ disks around young low-mass protostars
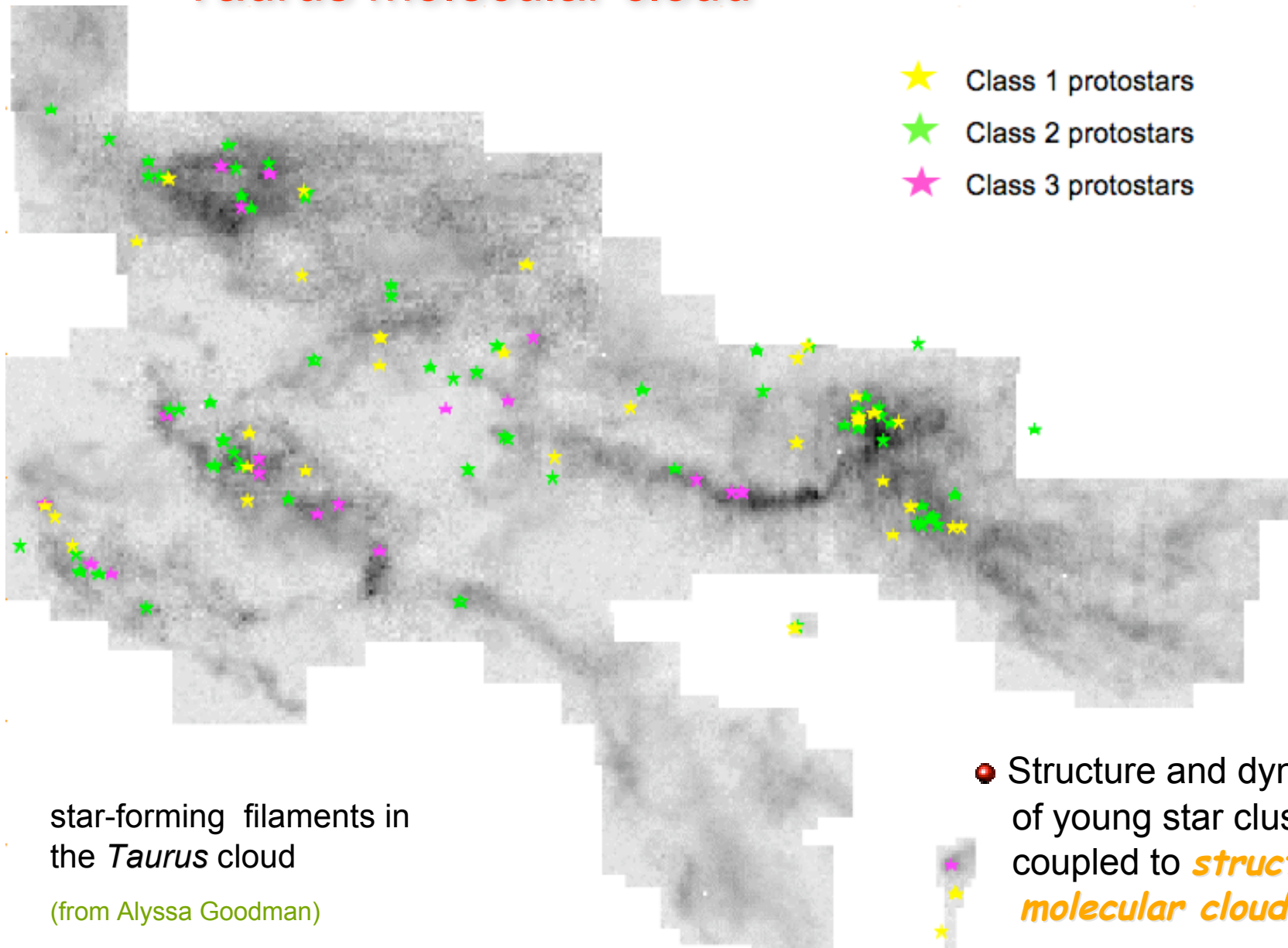
(images: Doug Johnstone et al.)

# 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)

# Taurus molecular cloud



★ Class 1 protostars
★ Class 2 protostars
★ Class 3 protostars

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

$V_{LSR} = 3.4$ km/s

3.4 km/s

Galactic Longitud

Taurus

$V_{LSR} = 3.8$ km/s

Galactic Longitud
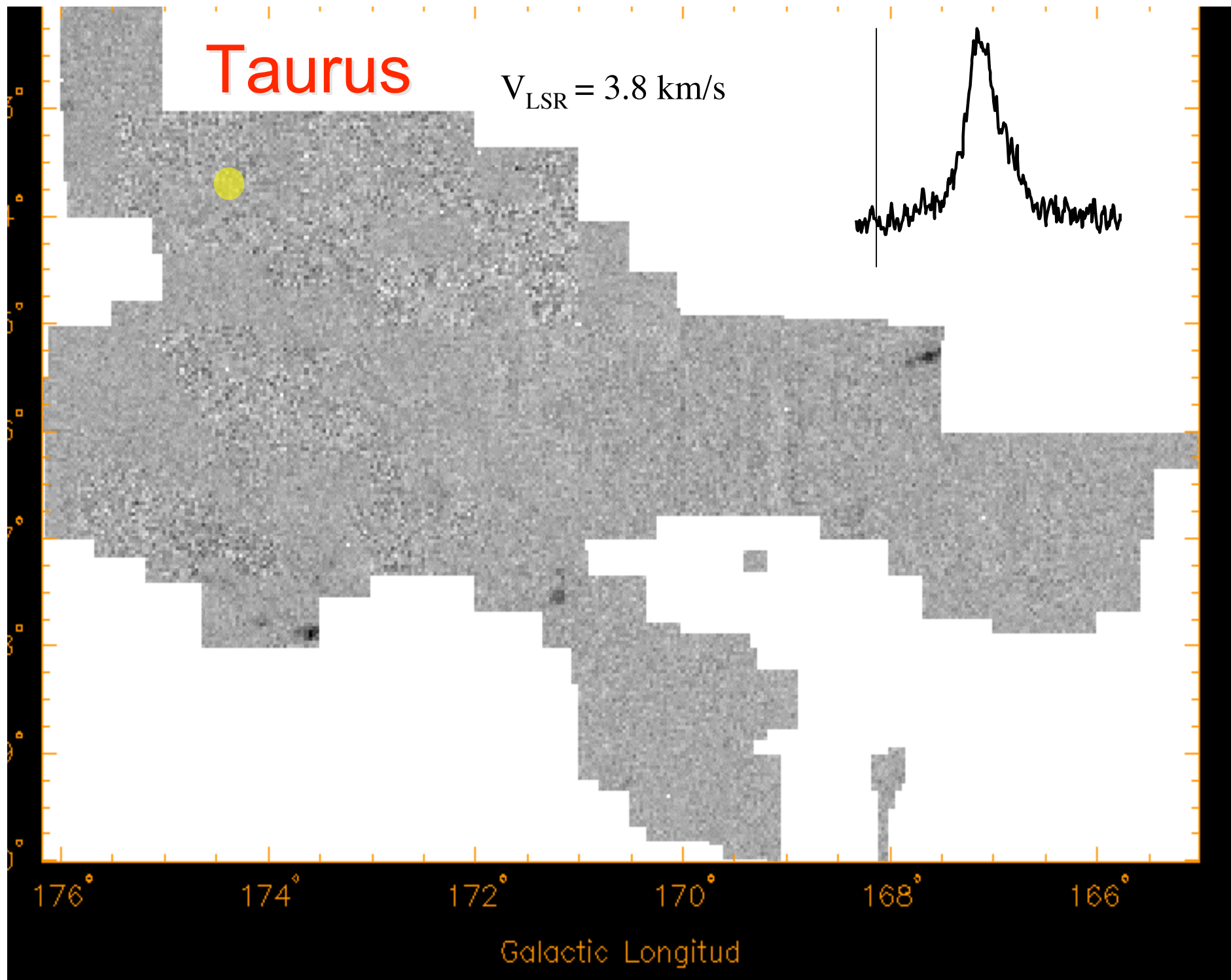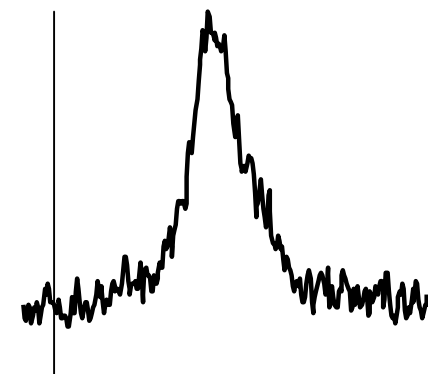
Taurus

$V_{LSR} = 4.2$ km/s
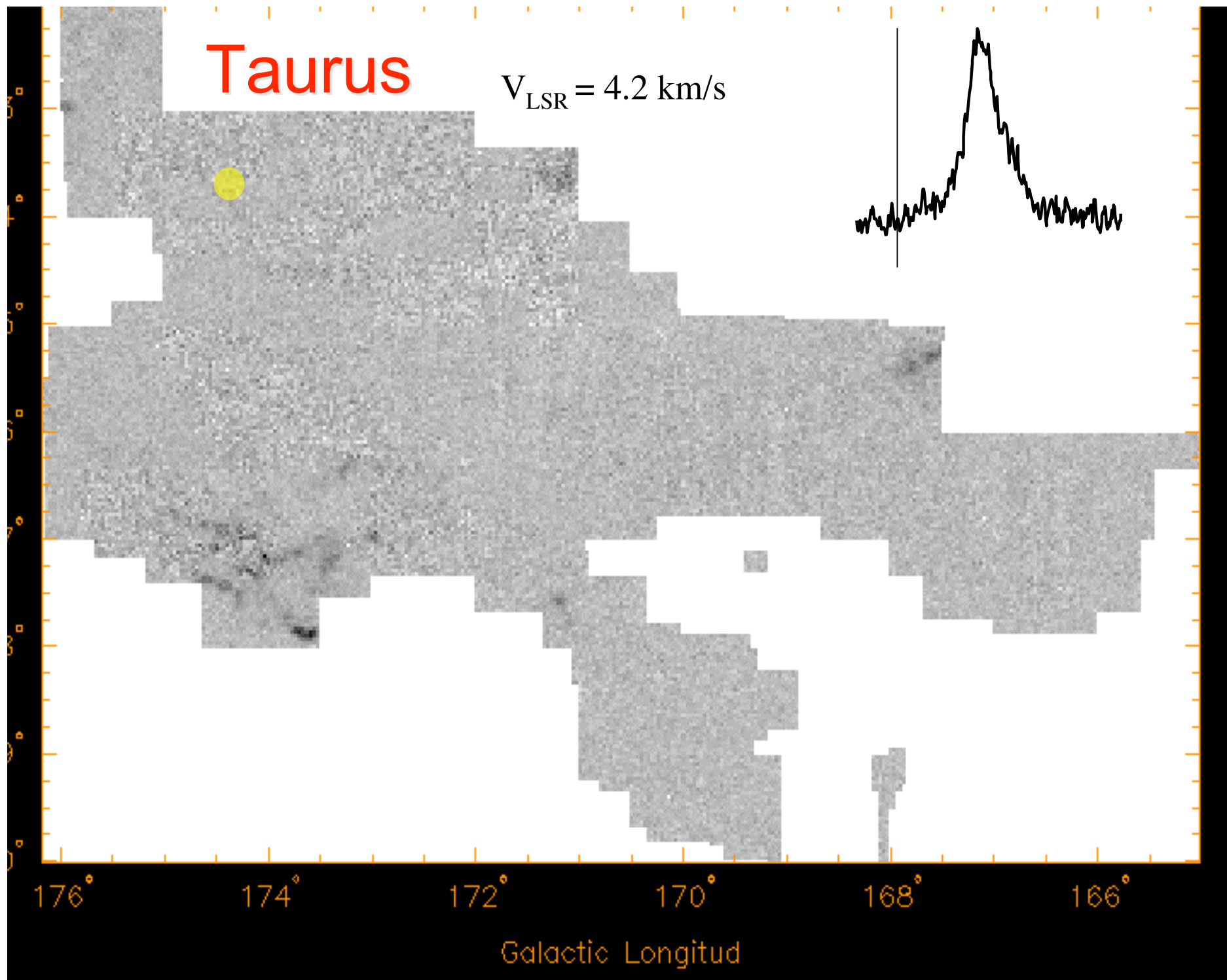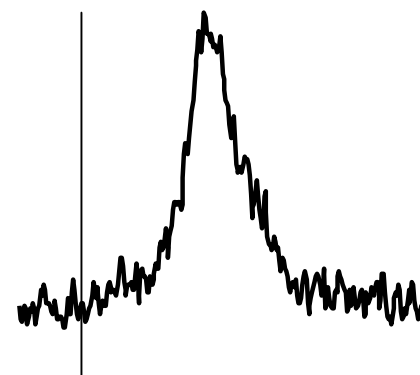
Galactic Longitud

Taurus

$V_{LSR} = 4.6$ km/s
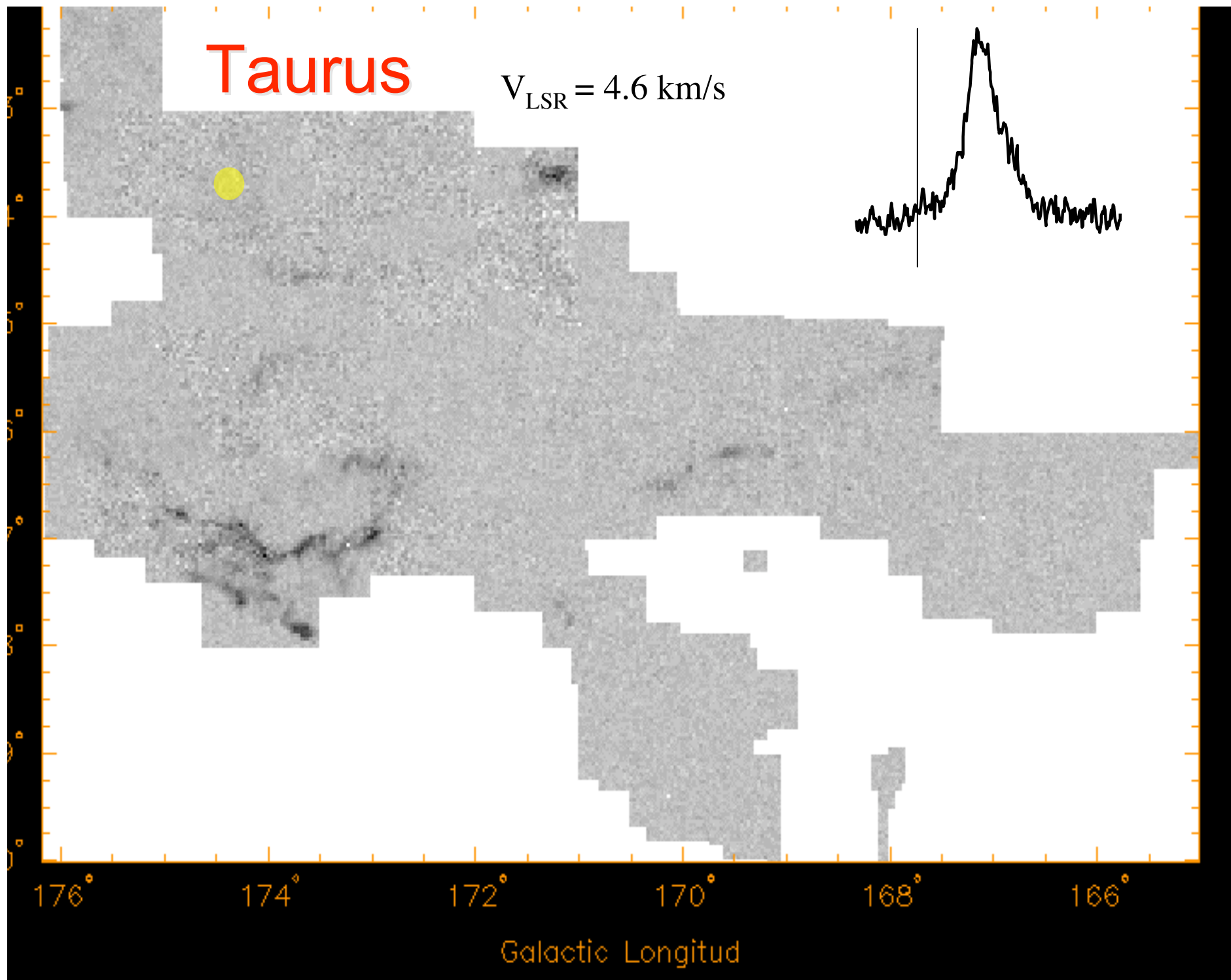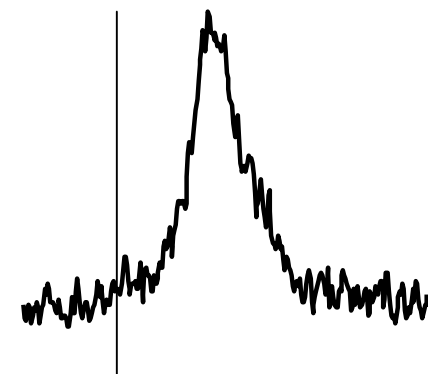
Taurus

$V_{LSR} = 5.0$ km/s
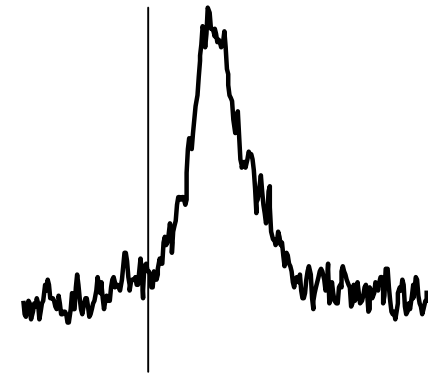
Galactic Longitud

Taurus

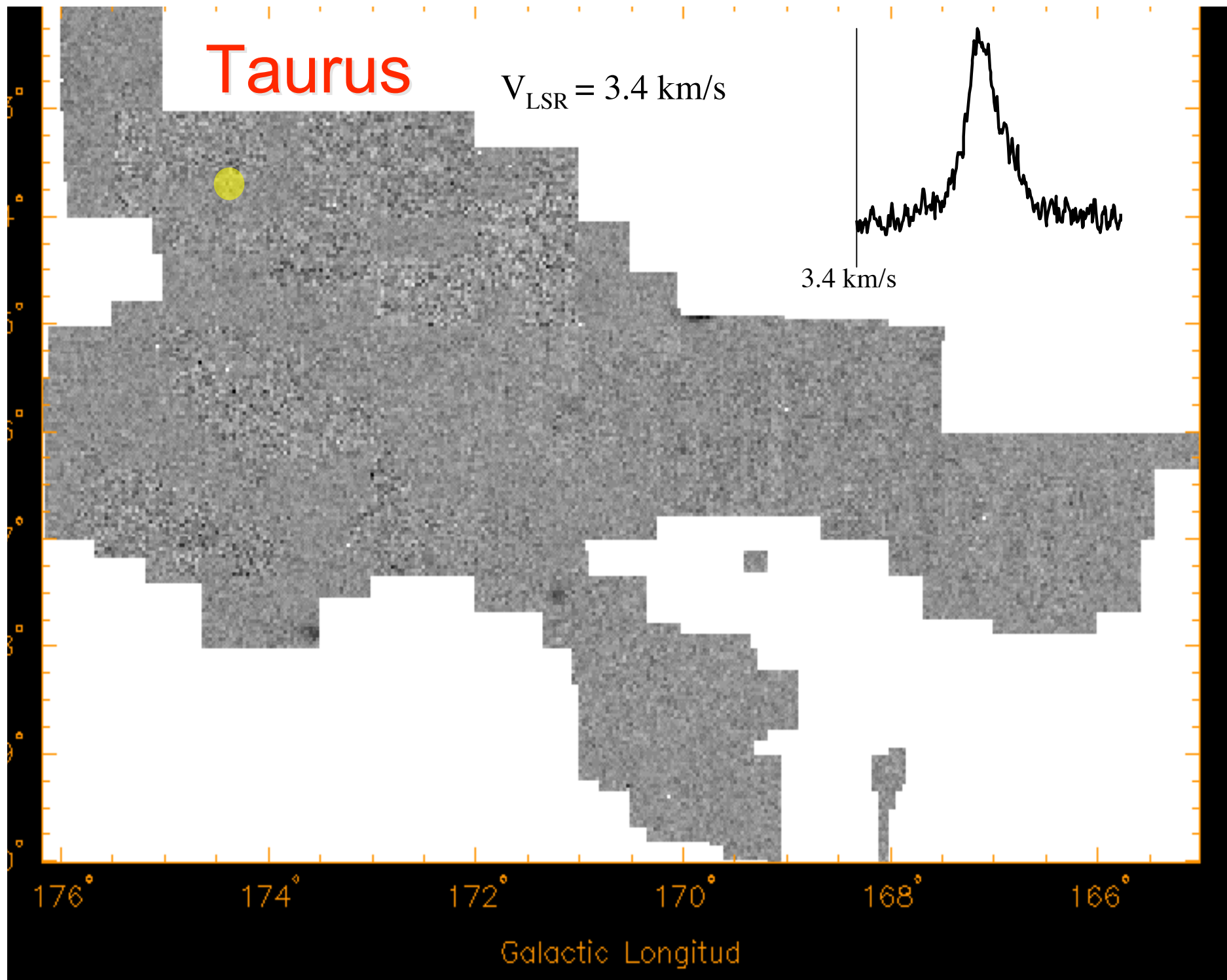$V_{LSR} = 5.4$ km/s
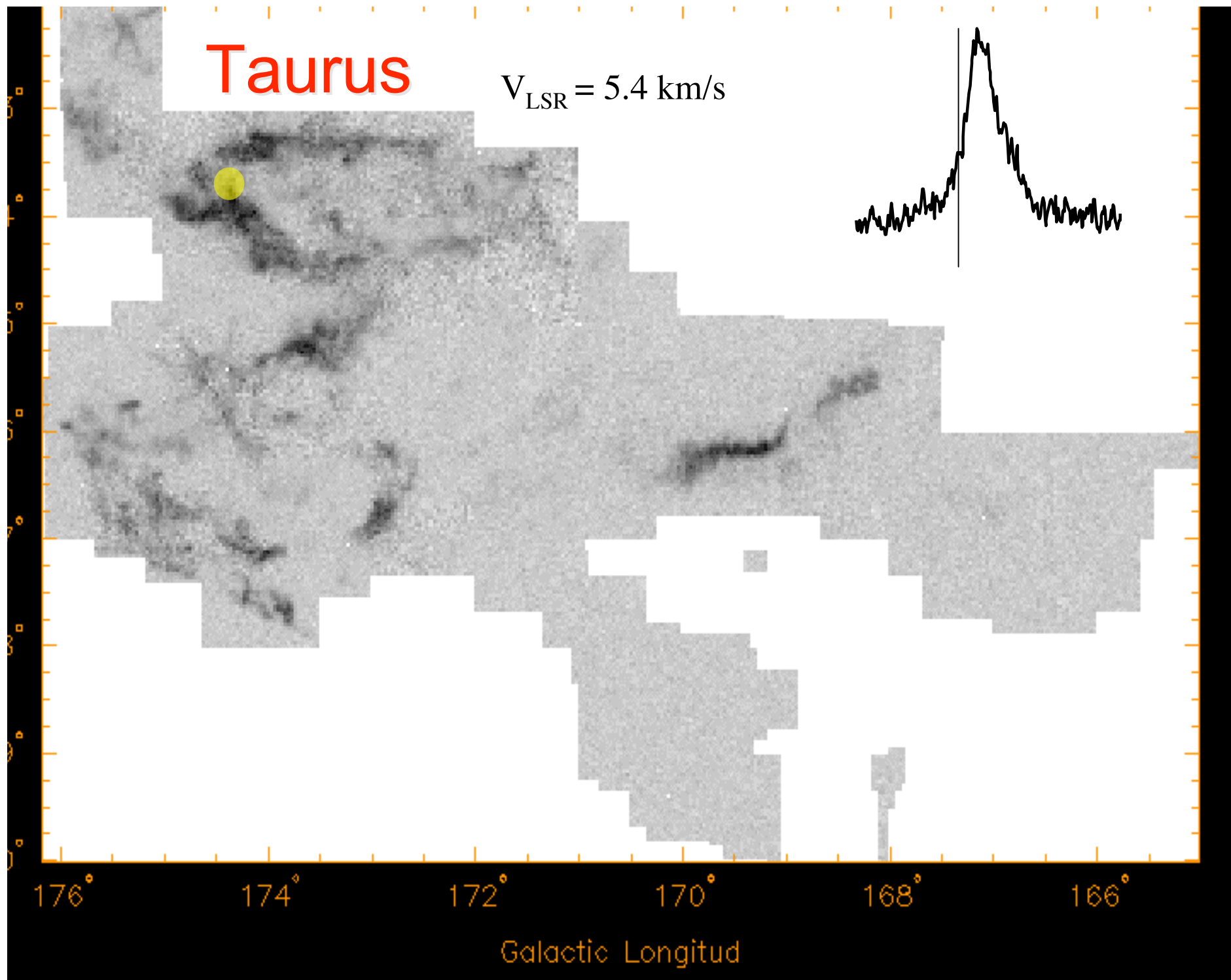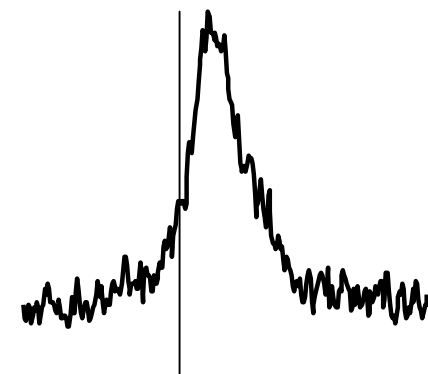
Galactic Longitud

Taurus

$V_{LSR} = 5.8$ km/s
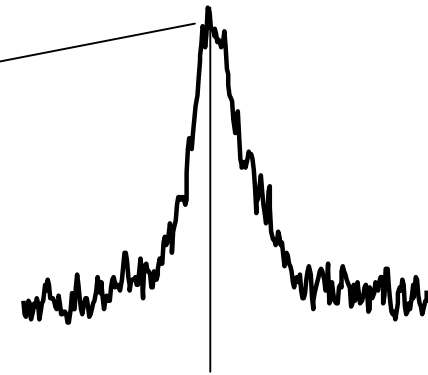
176° 174° 172° 170° 168° 166°

Galactic Longitud

Taurus

$V_{LSR} = 6.2$ km/s

Galactic Longitud
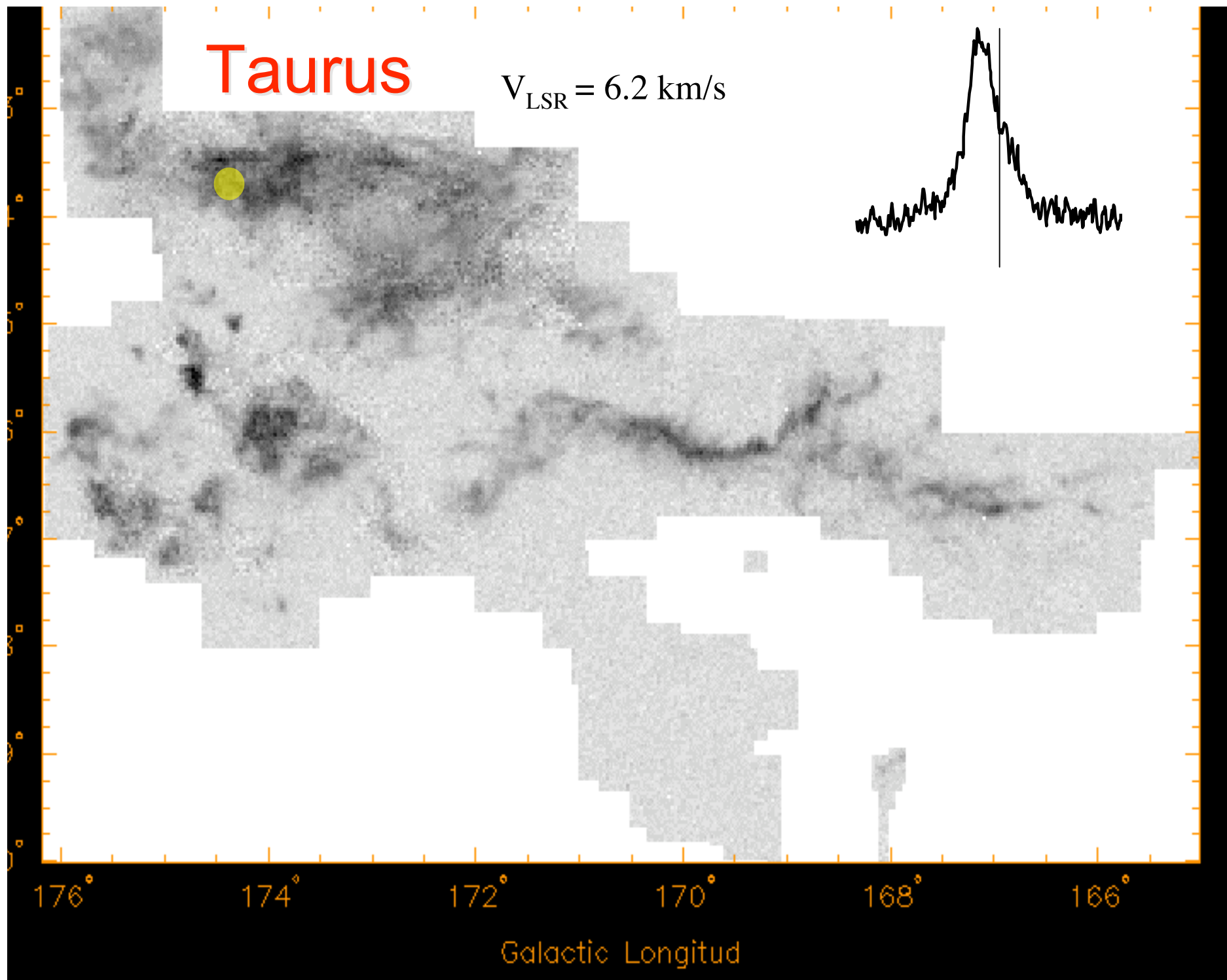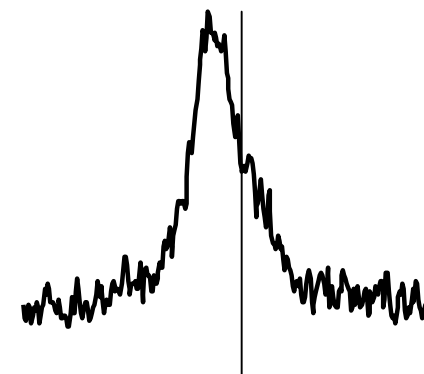
Taurus

$V_{LSR} = 6.6$ km/s
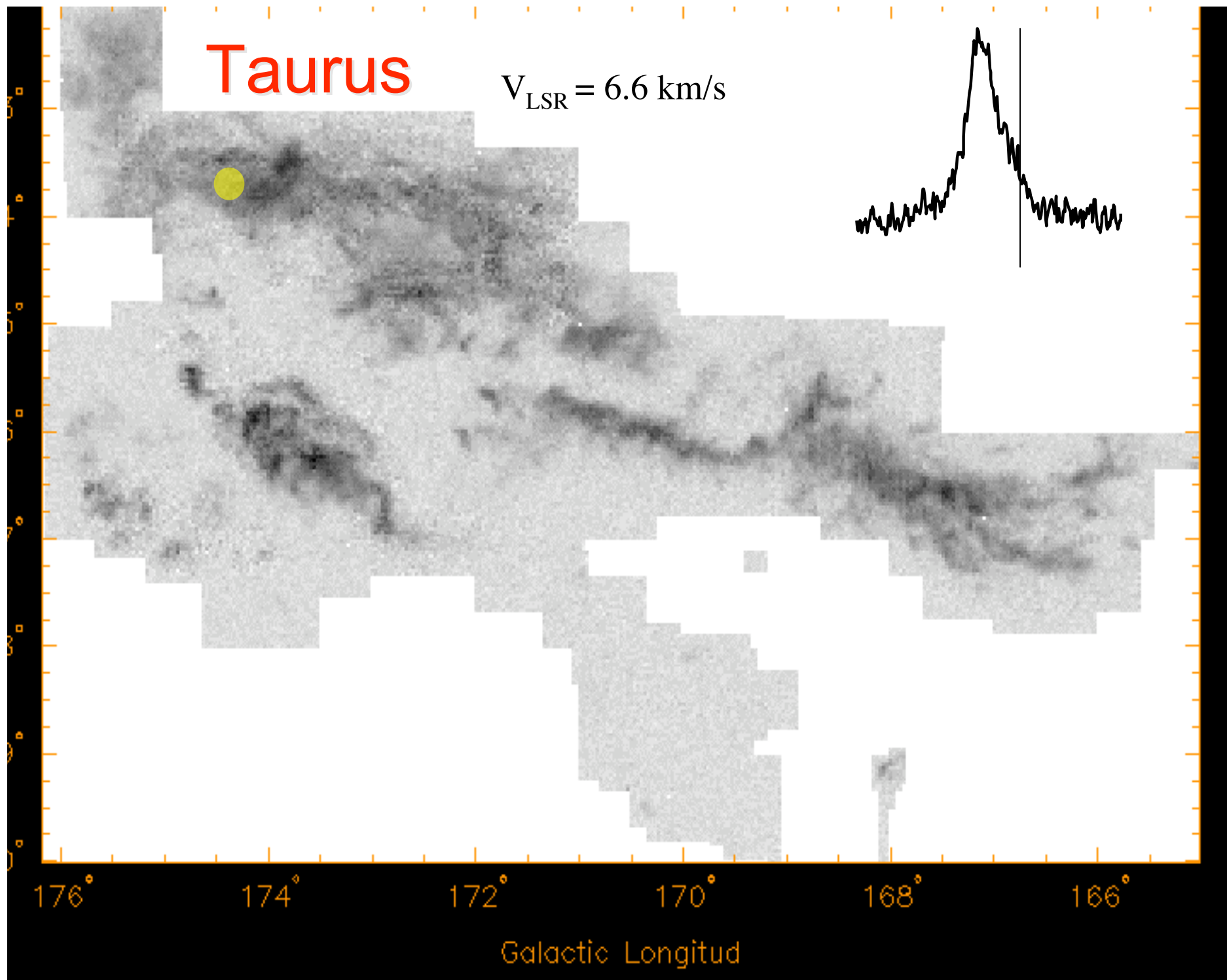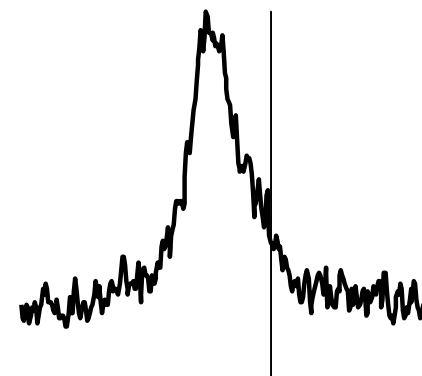
Taurus

$V_{LSR} = 7.0$ km/s
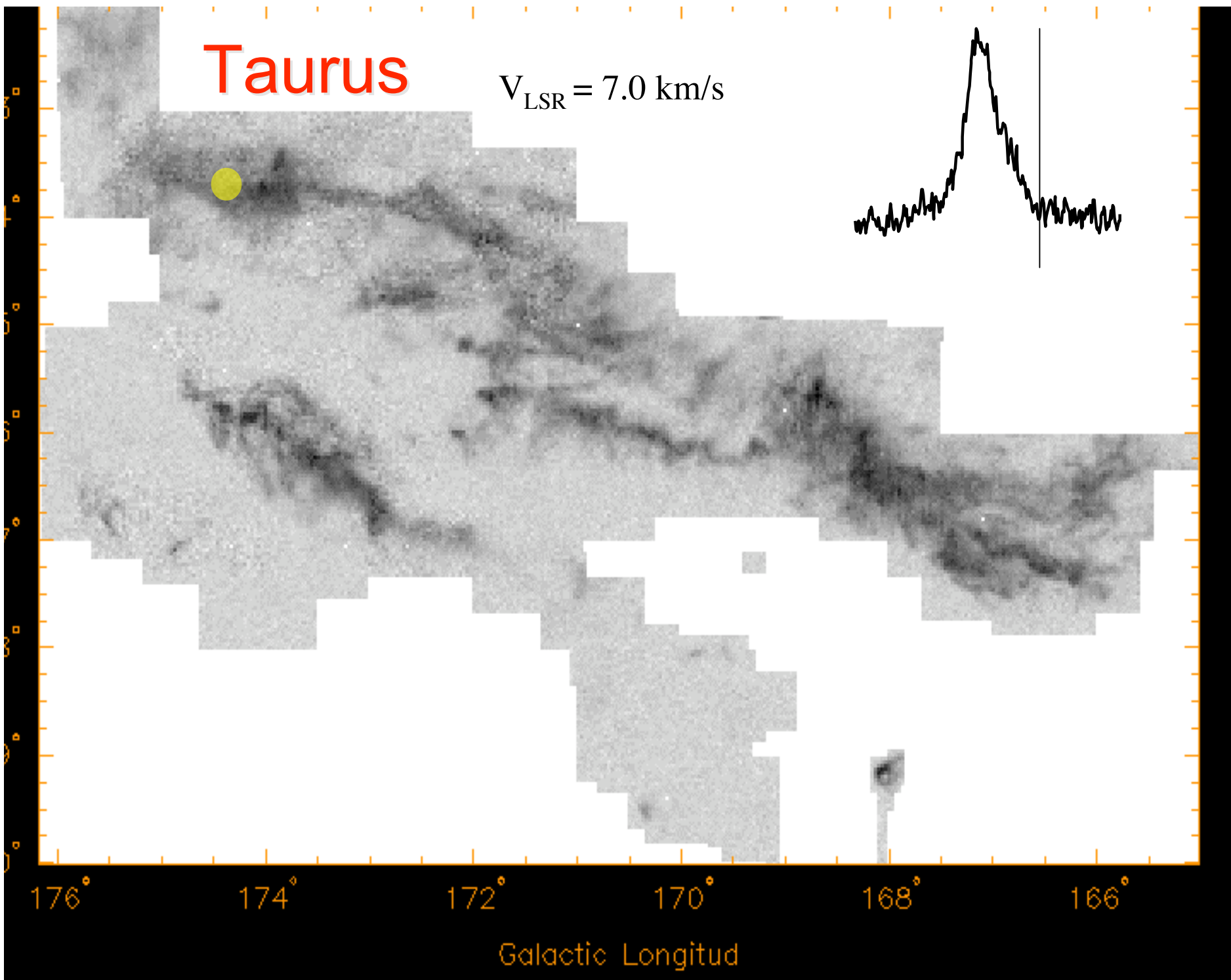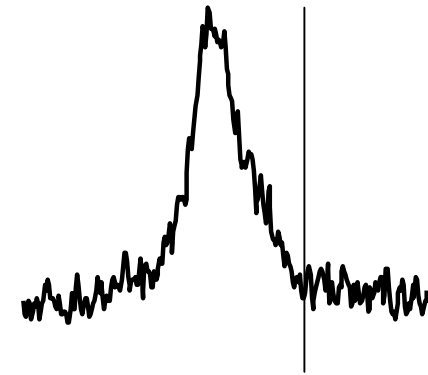
Taurus

$V_{LSR} = 7.4$ km/s
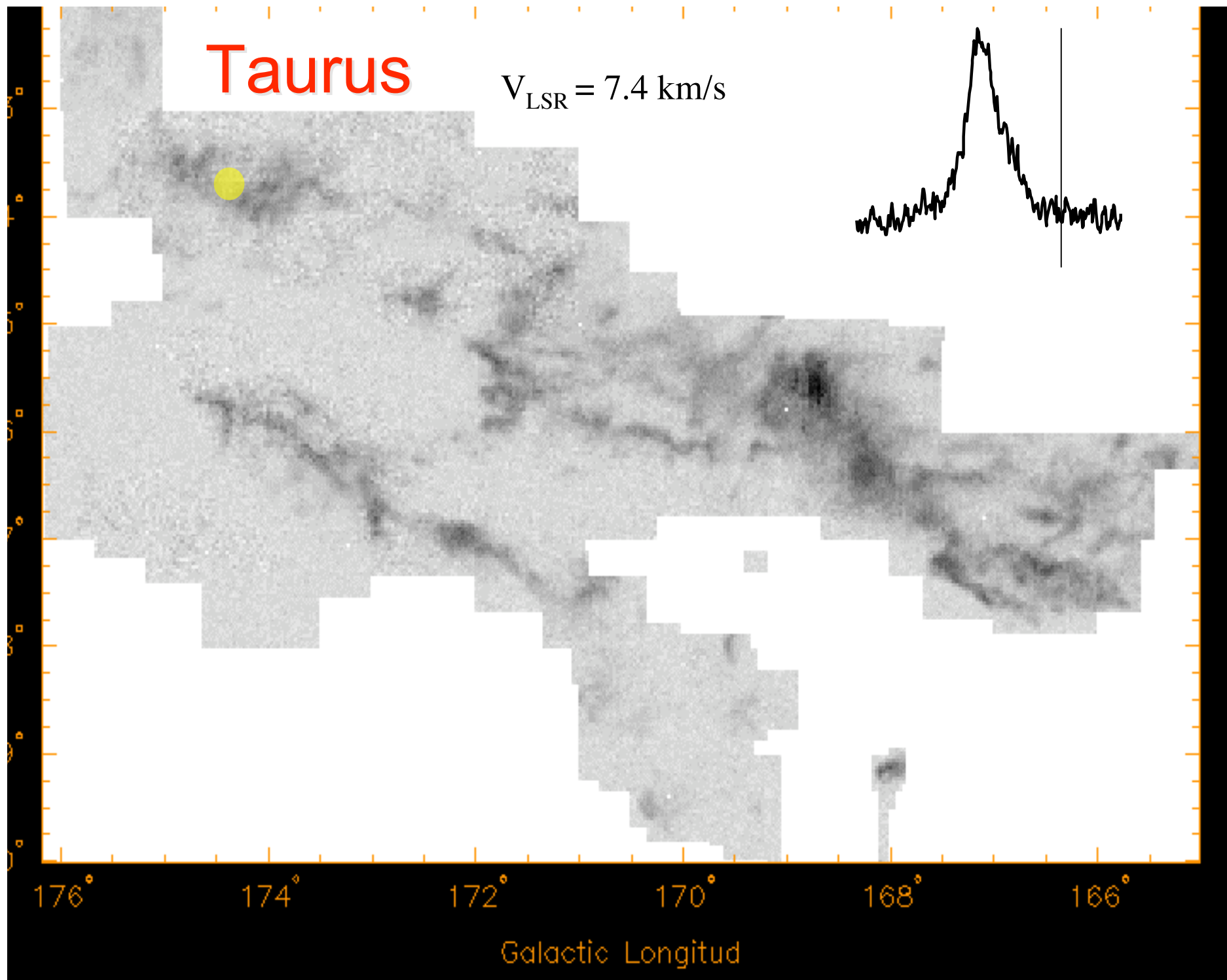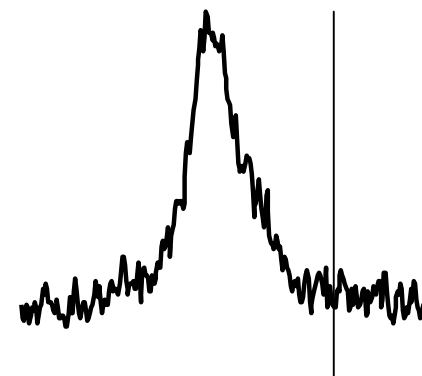
Taurus
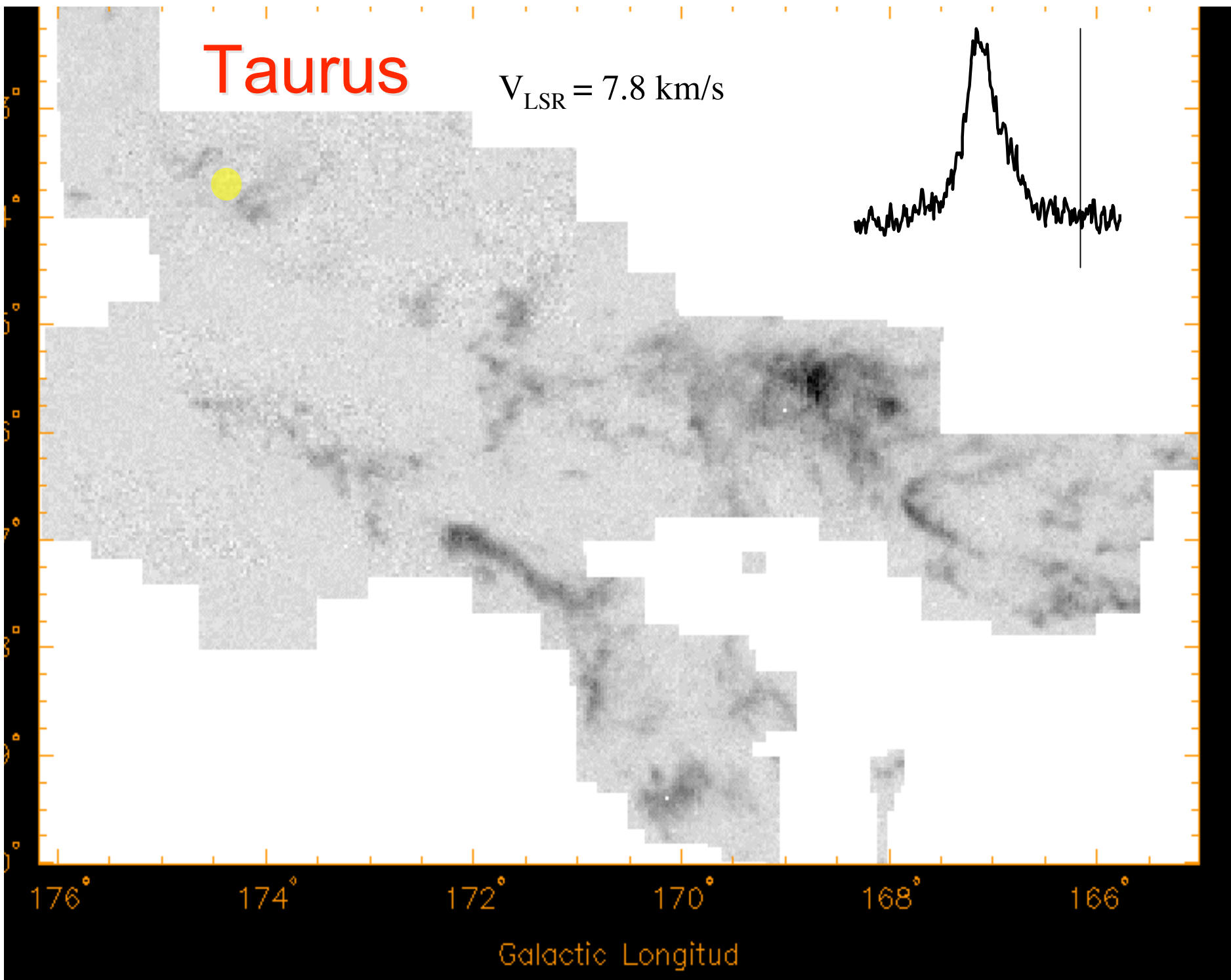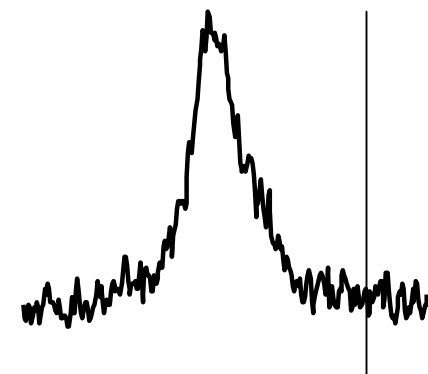
$V_{LSR} = 7.8$ km/s

Taurus
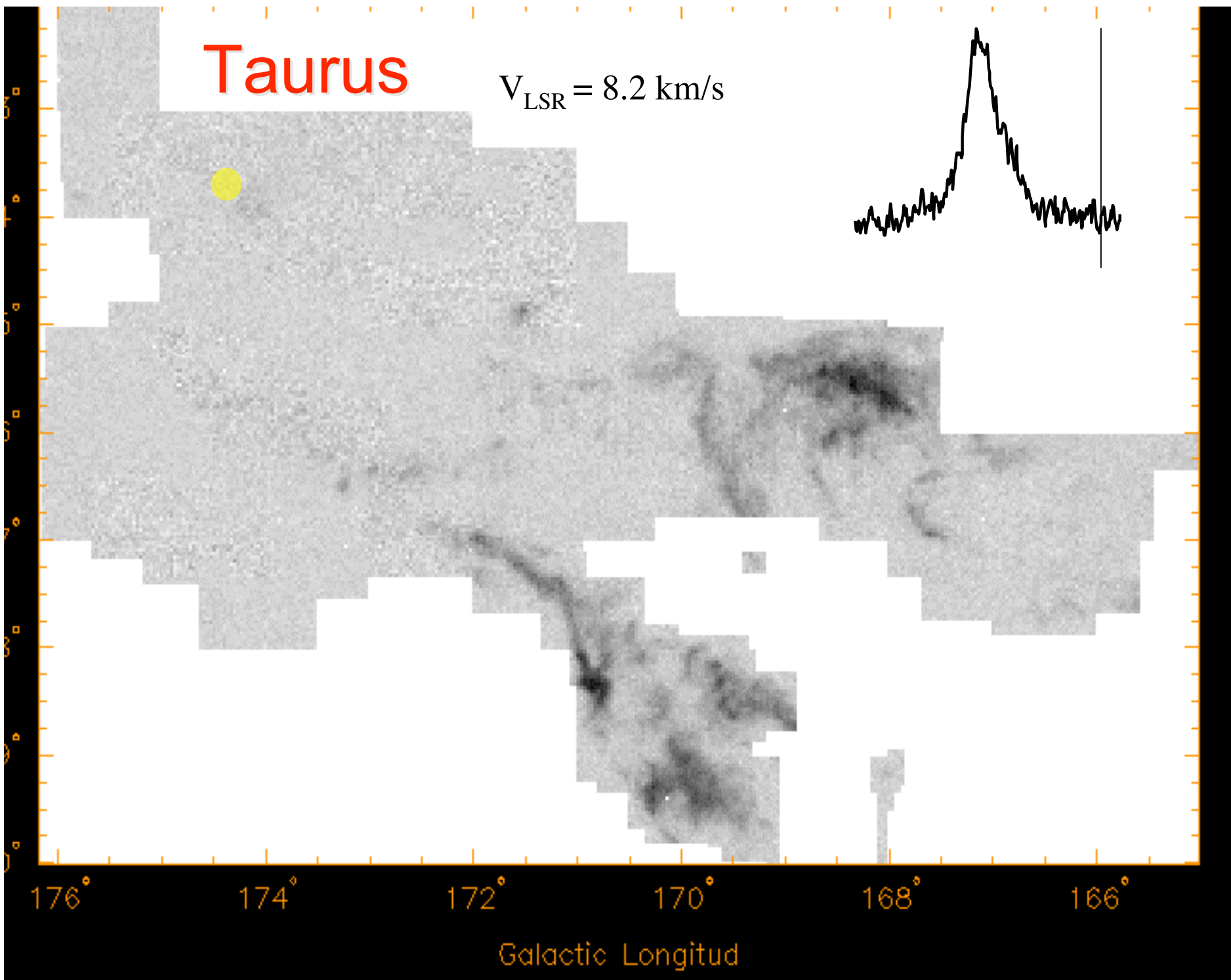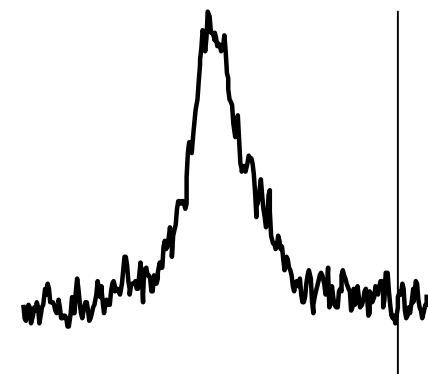
Class 1 protostars
Class 2 protostars
Class 3 protostars
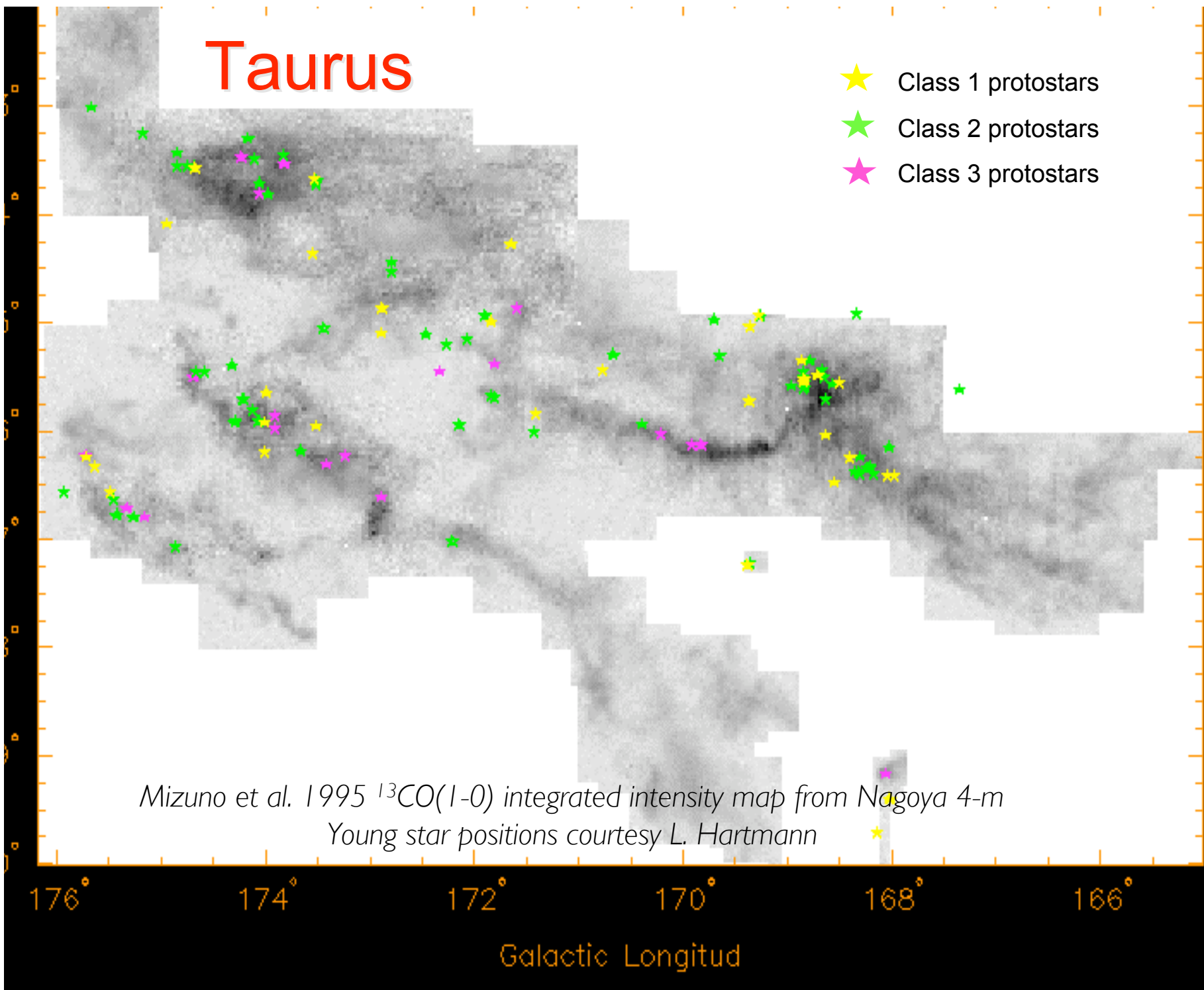
*Mizuno et al. 1995 ¹³CO(1-0) integrated intensity map from Nagoya 4-m*
*Young star positions courtesy L. Hartmann*

176°  174°  172°  170°  168°  166°

Galactic Longitud

theoretical
approach

# 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 $\delta\rho/\rho \propto M^2$; in atomic gas: $M \approx 1...3$)

- 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 ($M \approx 1...20$)
  → *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

Ralf Klessen:  Capri, September 2007

# Properties of turbulence

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

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

V = typical velocity on scale L,   $\nu$ = 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)
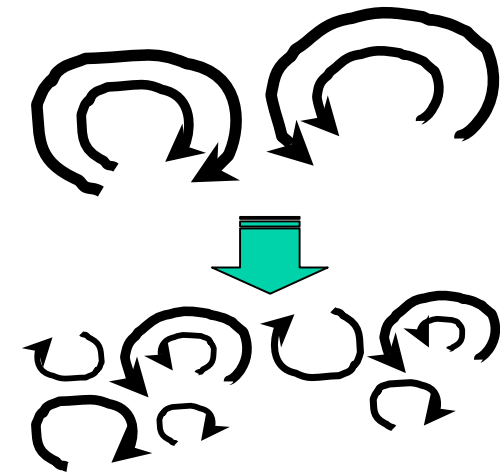
# Vortex Formation



Porter et al. ASCI, 1997
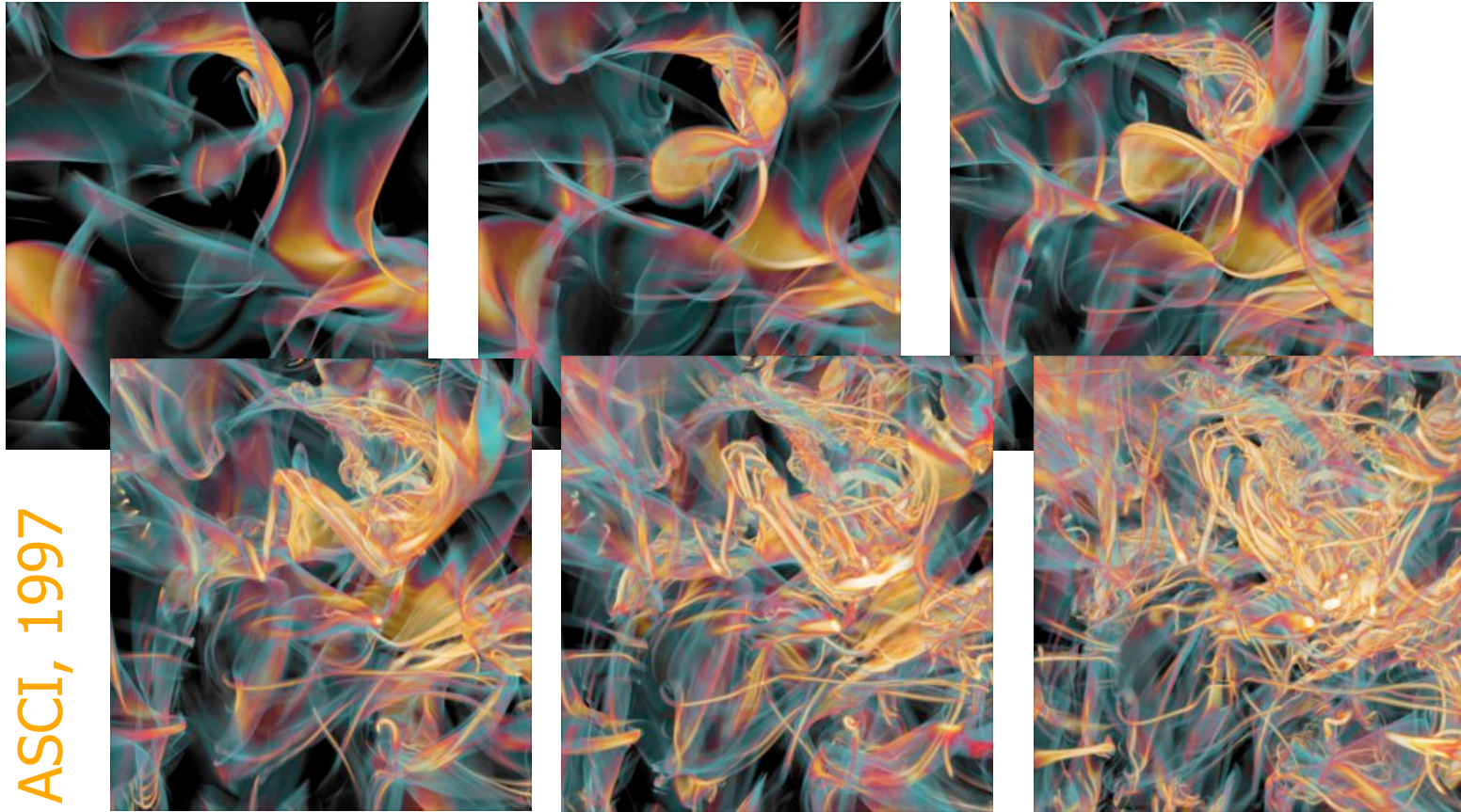
Vortices are streched and folded in three dimensions

Ralf Klessen:  Capri, September 2007

# Turbulent cascade



Kolmogorov (1941) theory
incompressible turbulence

$\log E$

$k^{-5/3}$

transfer

$L^{-1}$

$\eta_{K}^{-1}$

$\log k$

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

Shock-dominated turbulence

$\log E$

$k^{-2}$

transfer

$\log k$

$L^{-1}$

$\eta_{\text{K}}^{-1}$
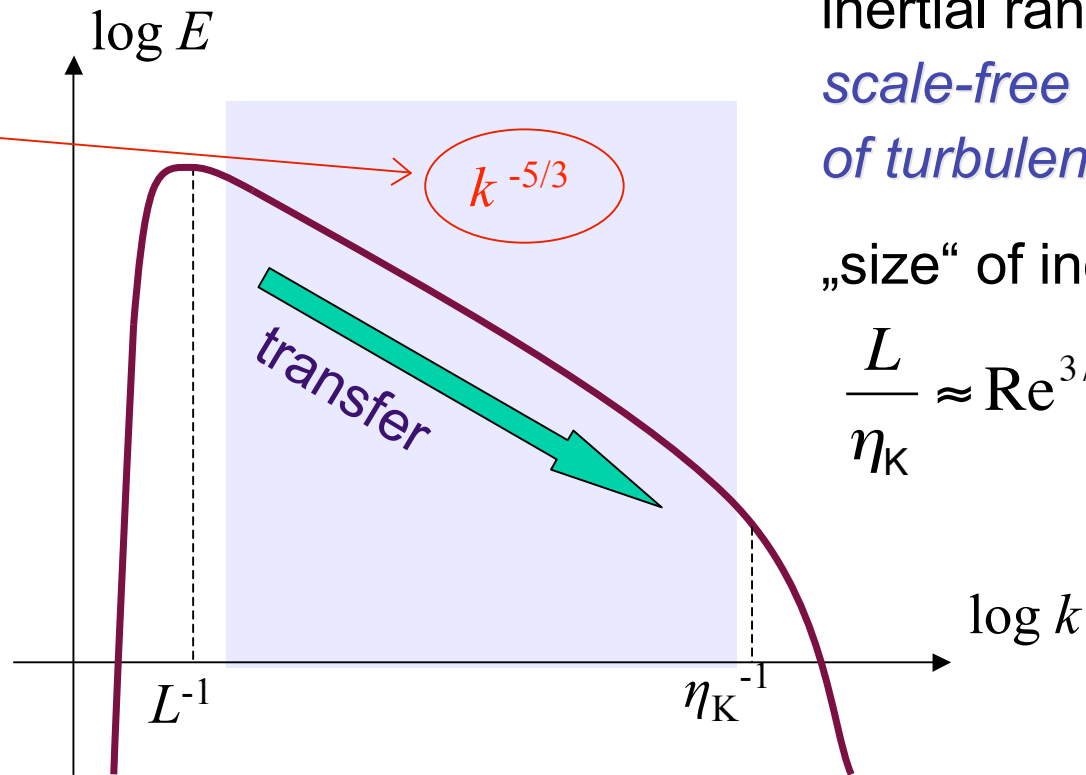
inertial range:
*scale-free behavior of turbulence*

„size" of inertial range:

$$\frac{L}{\eta_{\text{K}}} \approx \text{Re}^{3/4}$$

energy
input
scale

energy
dissipation
scale

# Turbulent cascade in ISM



energy source & scale
*NOT known*
(supernovae, winds,
spiral density waves?)
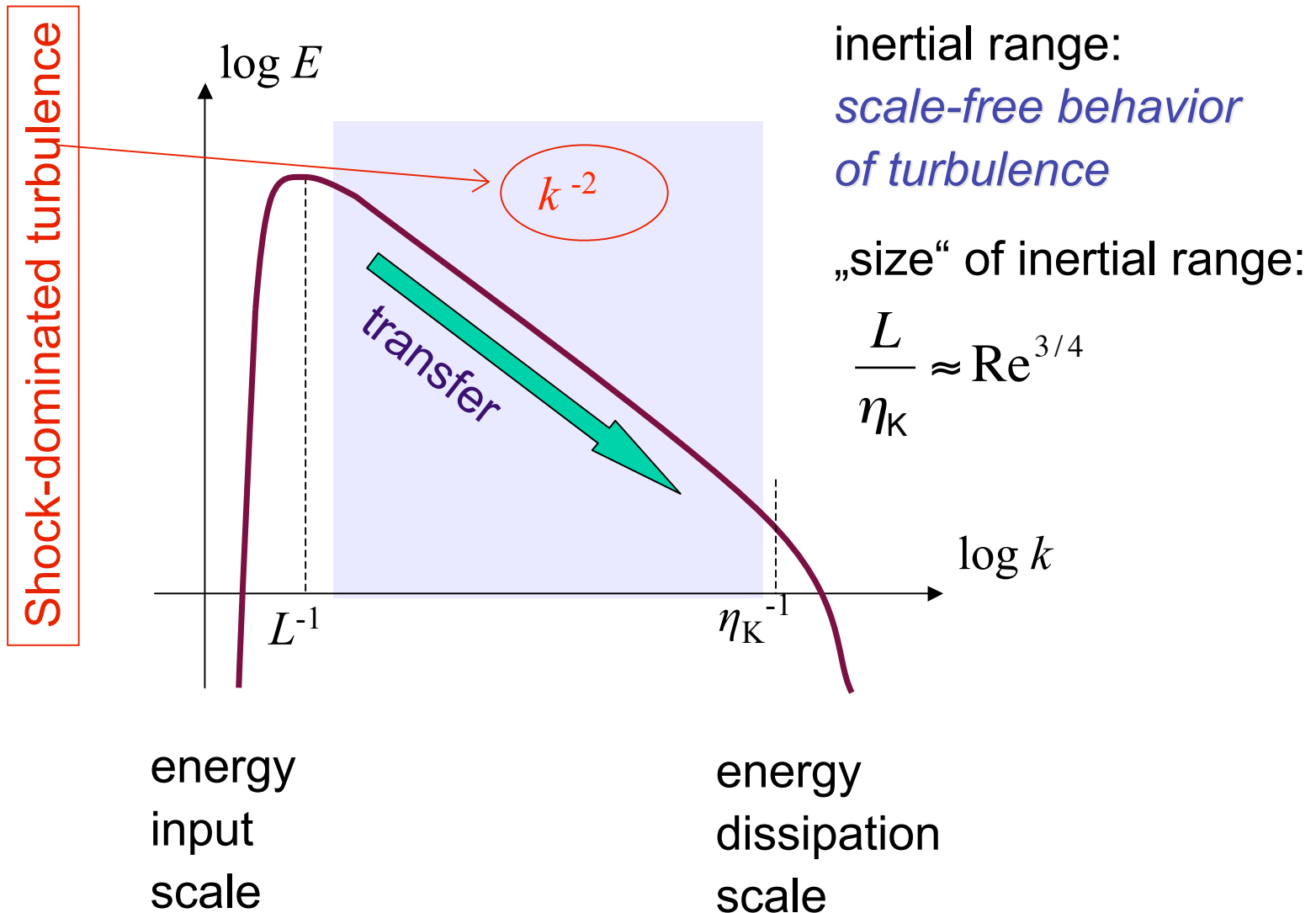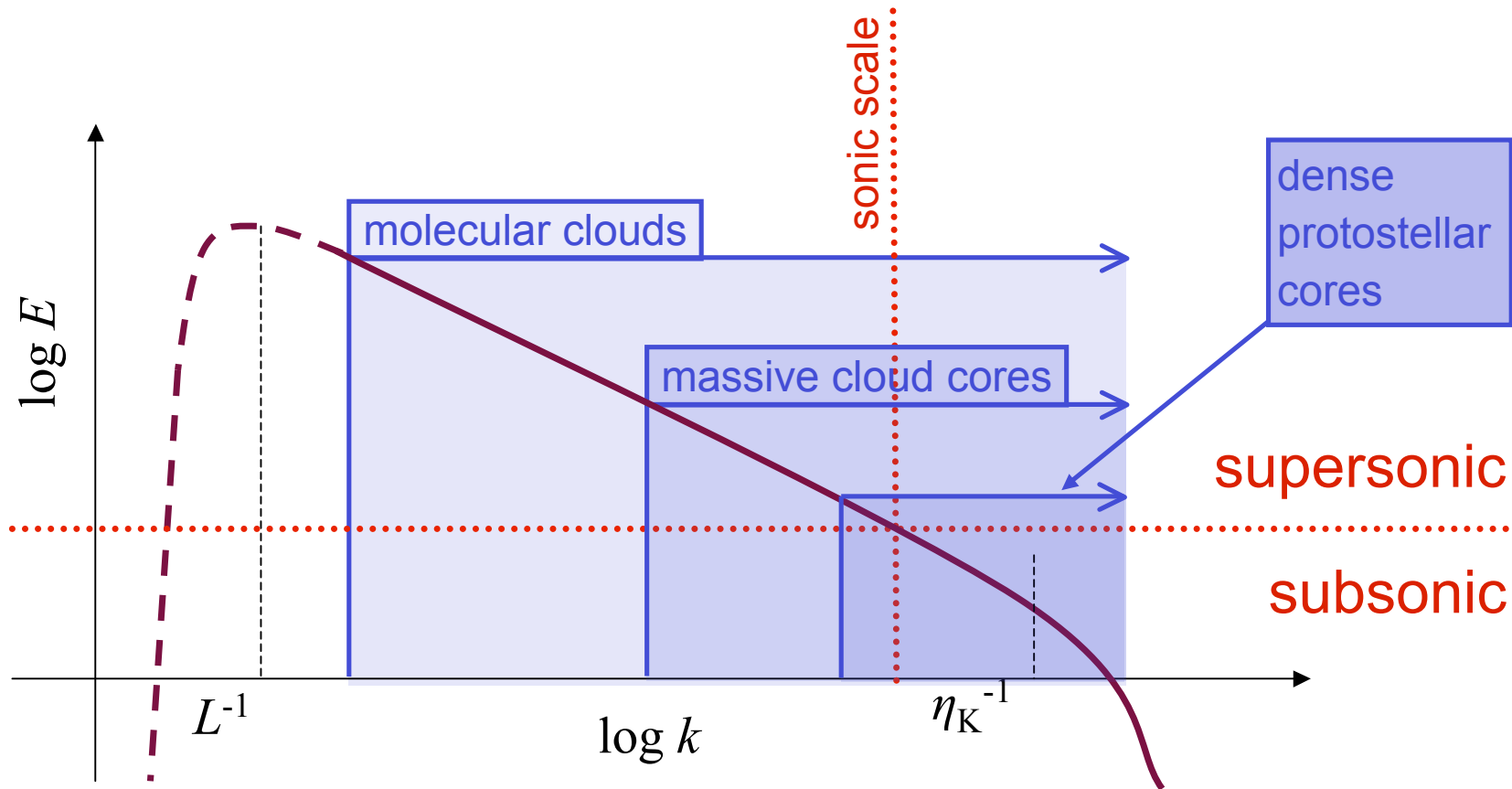
$\sigma_{rms}$ << 1 km/s
$M_{rms} \leq 1$
$L \approx 0.1$ pc

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

# Density structure of MC's



1.3mm mosaic of ρ Oph main cloud

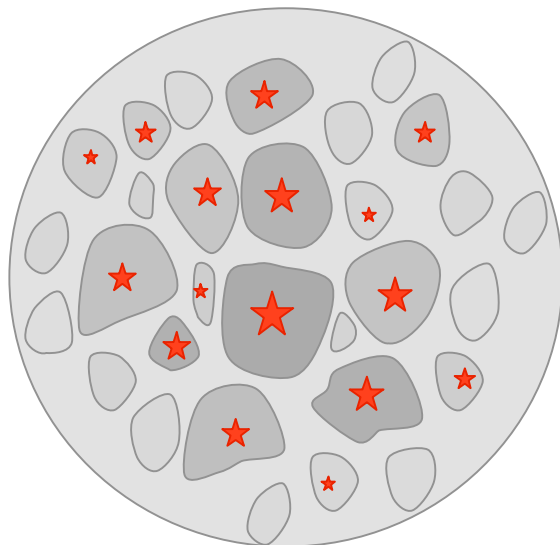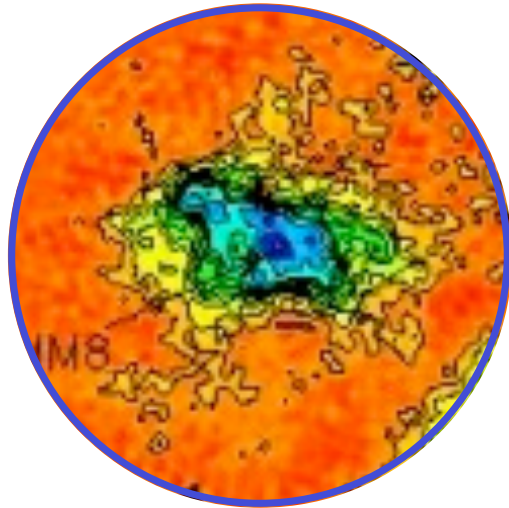(Motte, André, & Neri 1998)
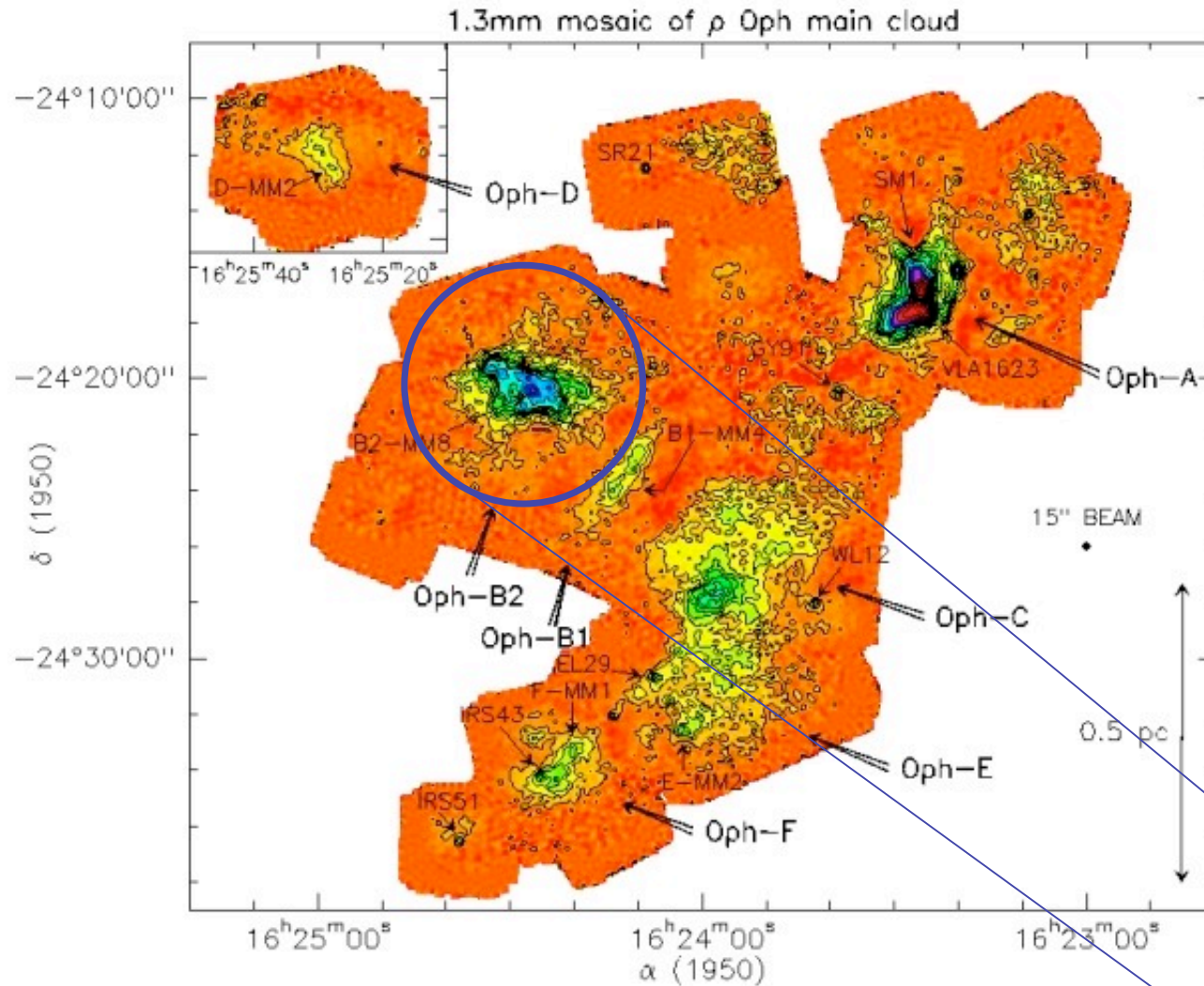
molecular clouds are highly inhomogeneous

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:
  $$\delta\rho/\rho \approx M^2$$
  --> with typical $M \approx 10$ --> $\delta\rho/\rho \approx 100$!

- 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



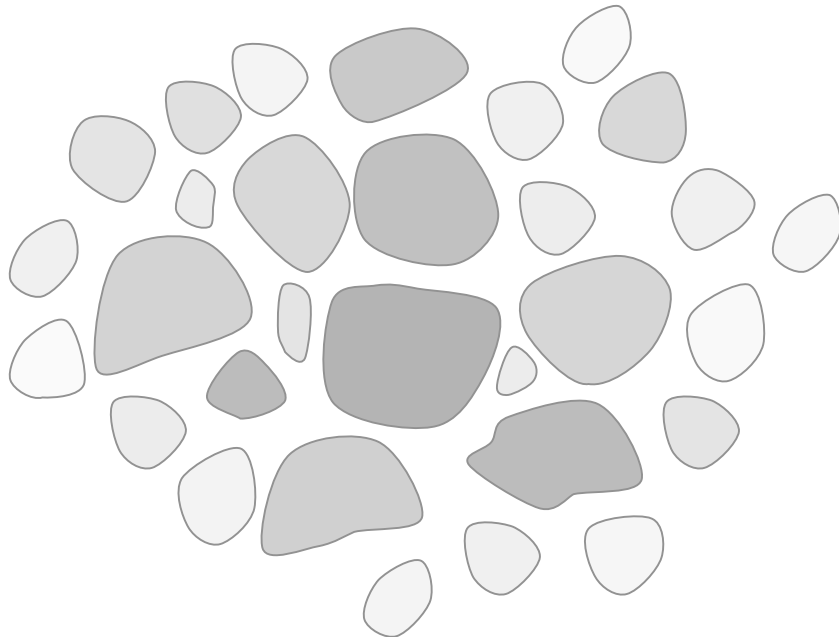ρ Oph−B1/B2

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

(Motte, André, & Neri 1998)
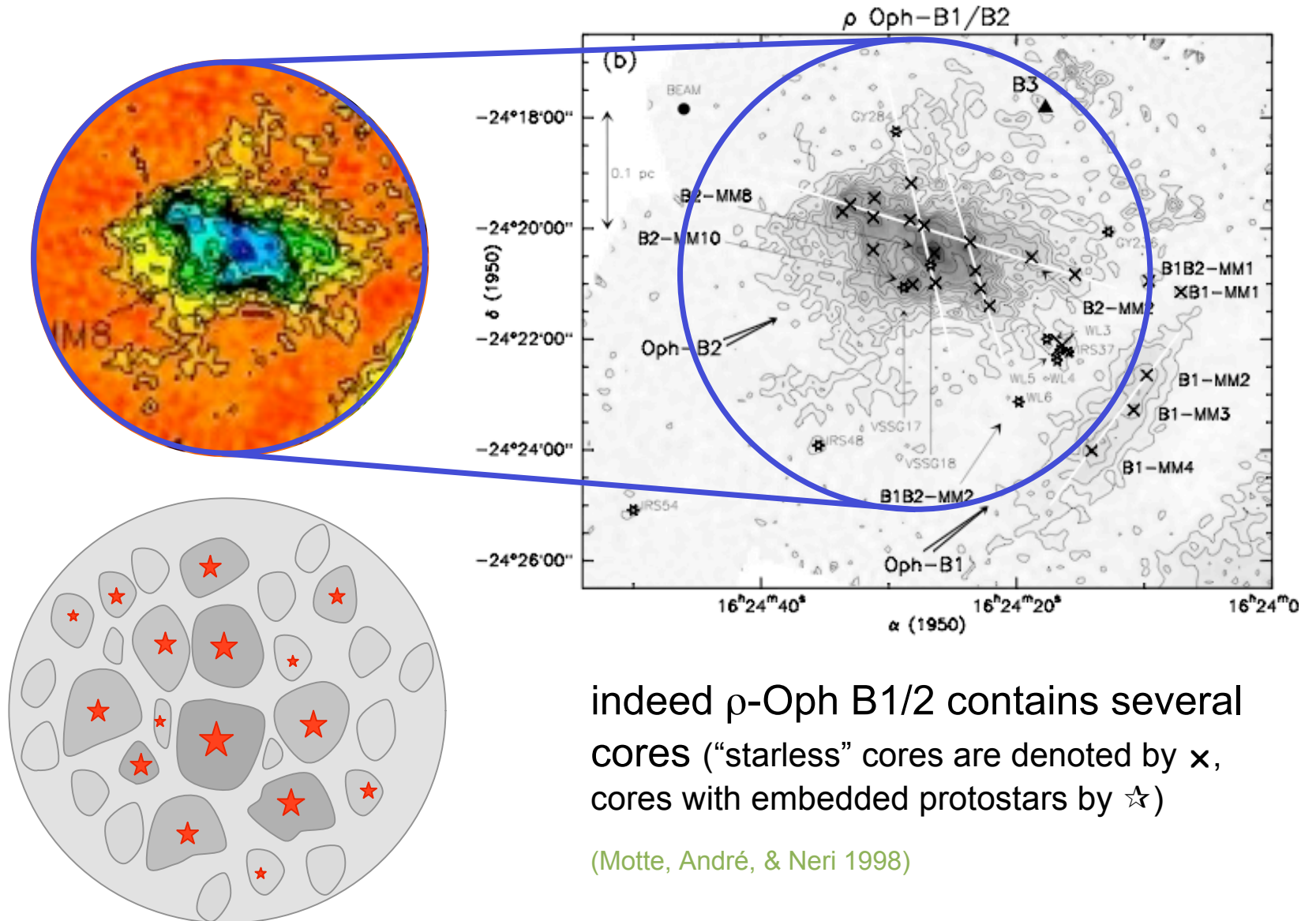
# Formation and evolution of cores

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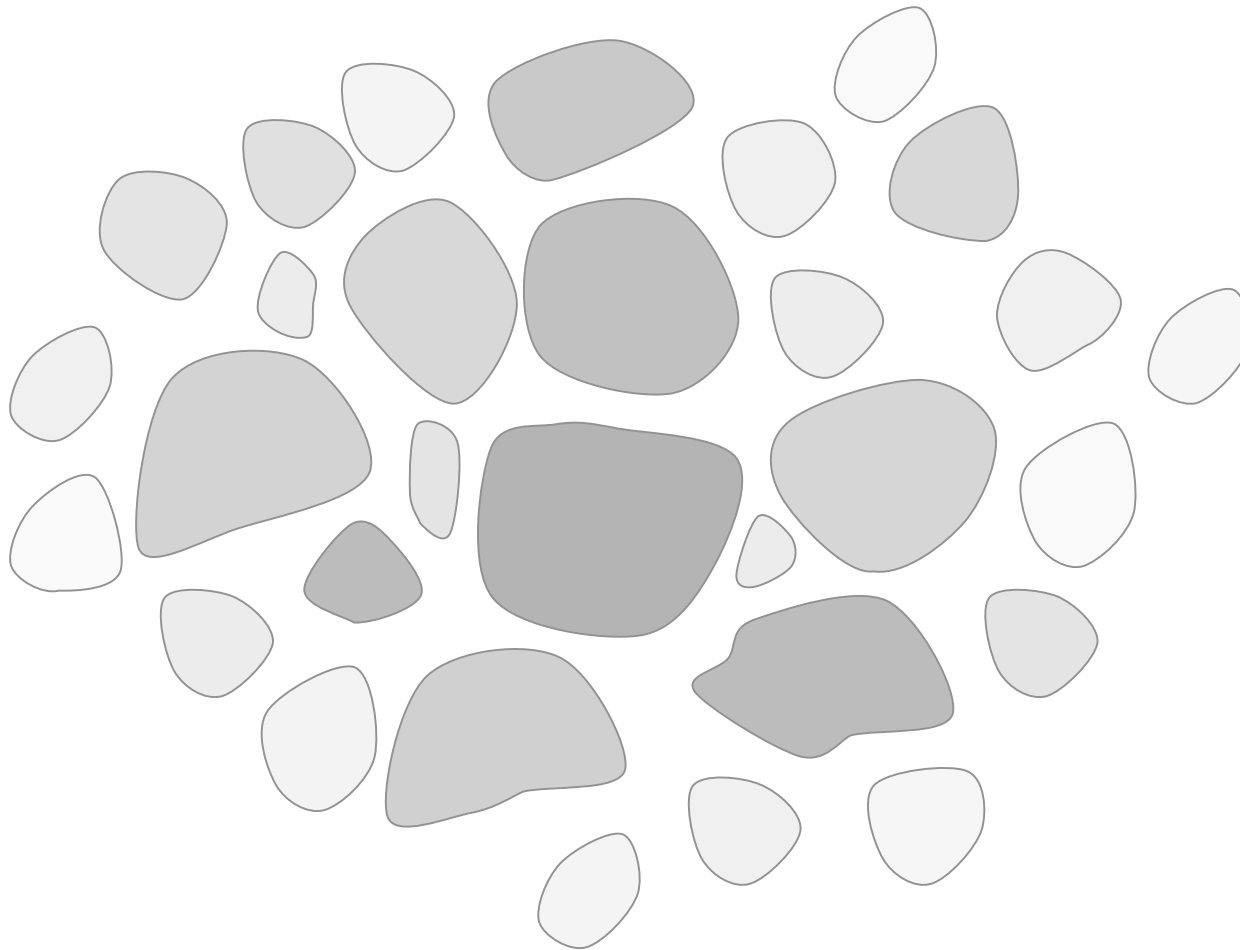
(2) turbulence decays, i.e. gravity
    dominates: $\alpha = E_{kin}/|E_{pot}| < 1$
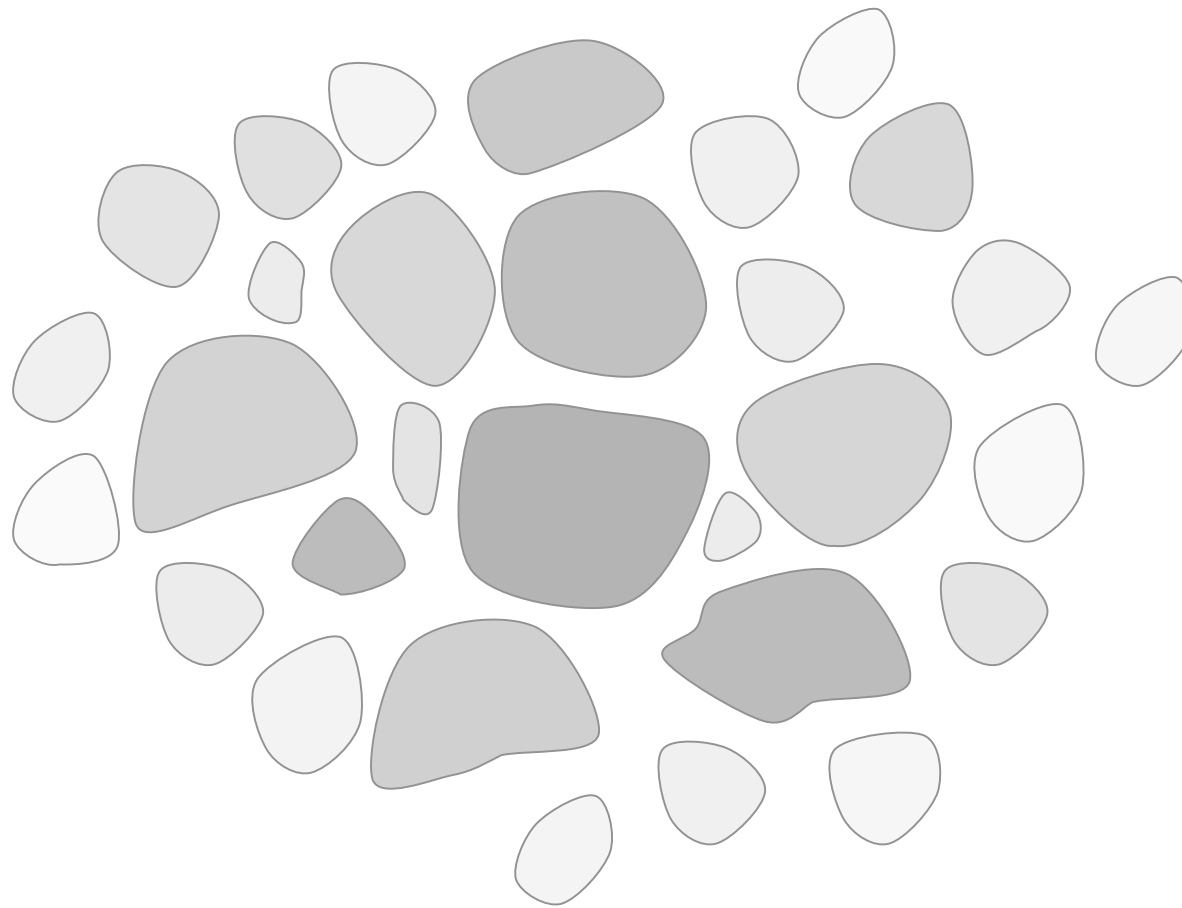--> *global contraction*
--> core do *interact* while collapsing
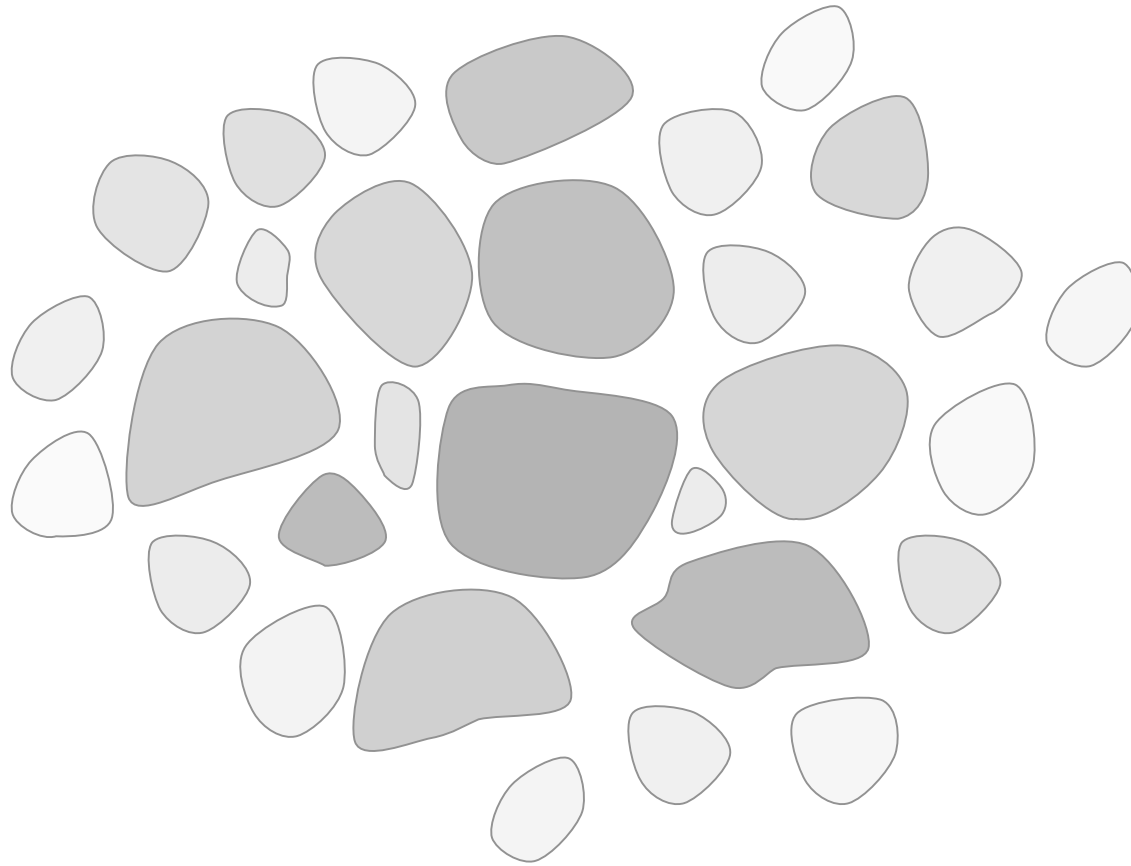--> *competition* influences *mass growth*
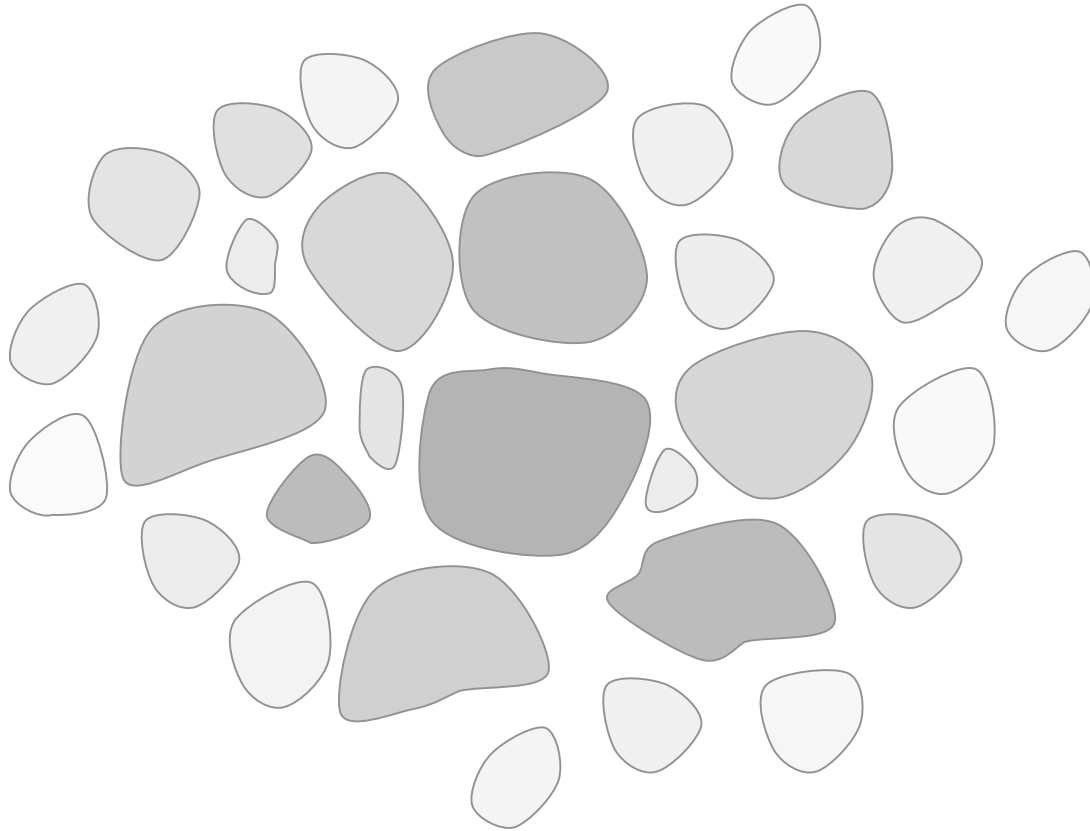--> *dense cluster with high-mass stars*

turbulence creates a hierarchy of clumps

as turbulence decays locally, contraction sets in

as turbulence decays locally, contraction sets in

Ralf Klessen:  Capri, September 2007

while region contracts, individual clumps collapse to form stars
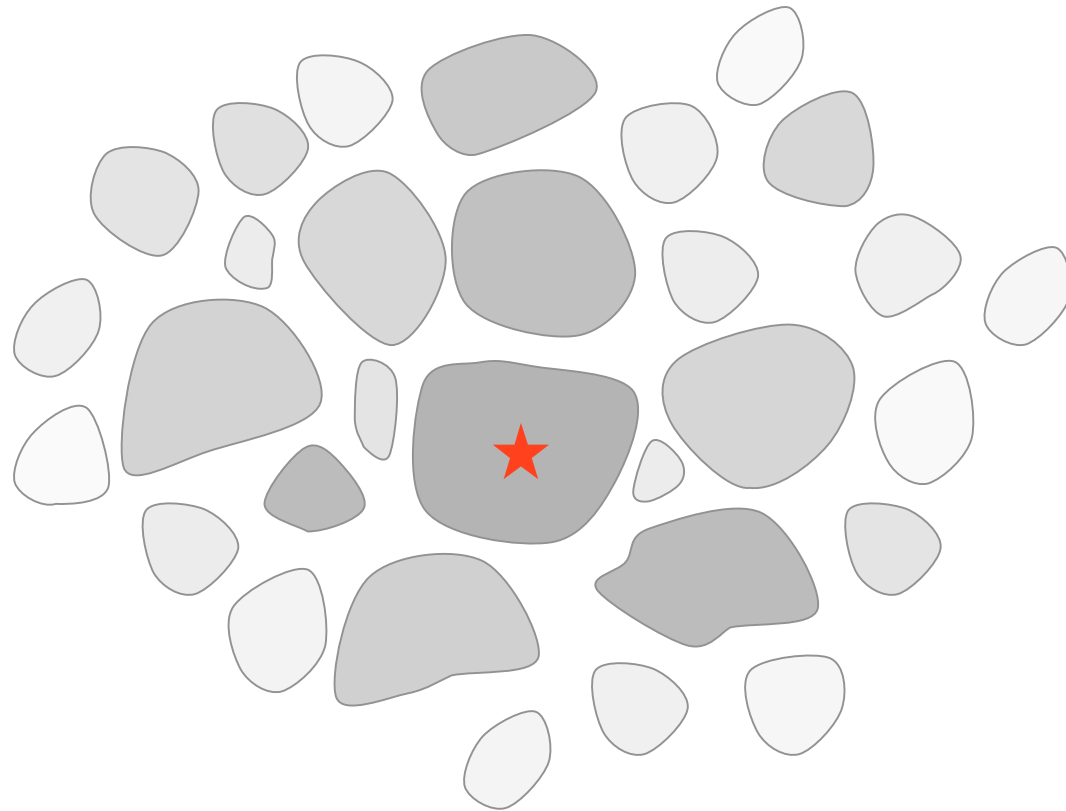
while region contracts, individual clumps collapse to form stars
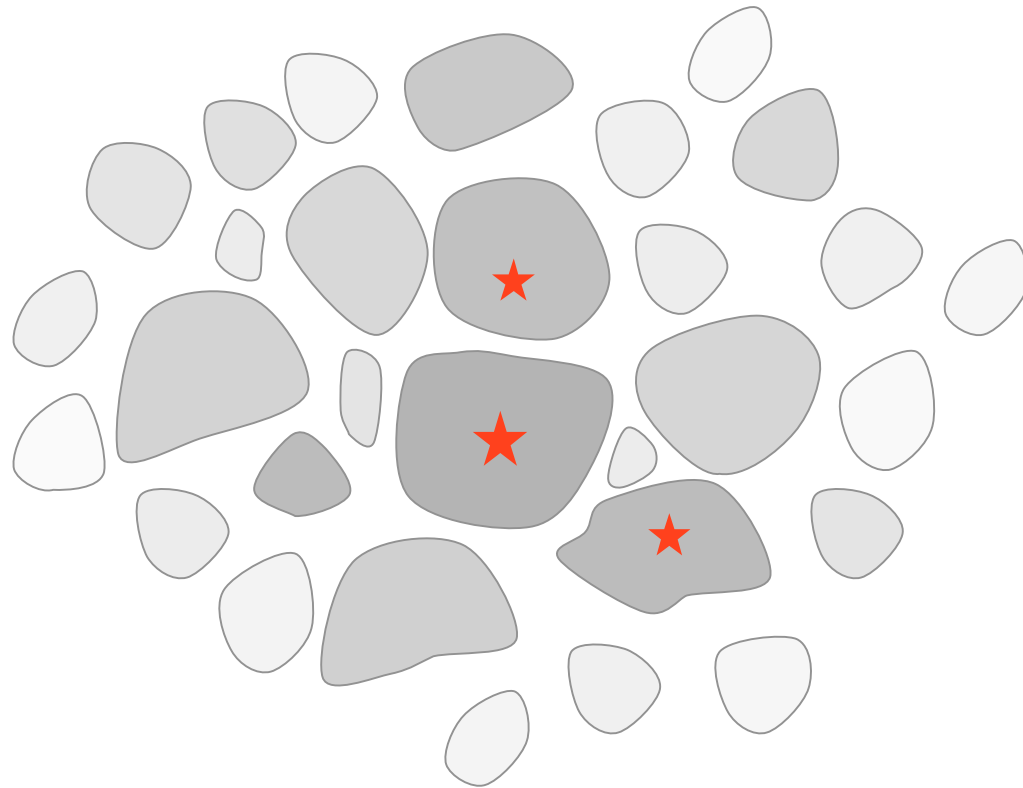
individual clumps collapse to form stars
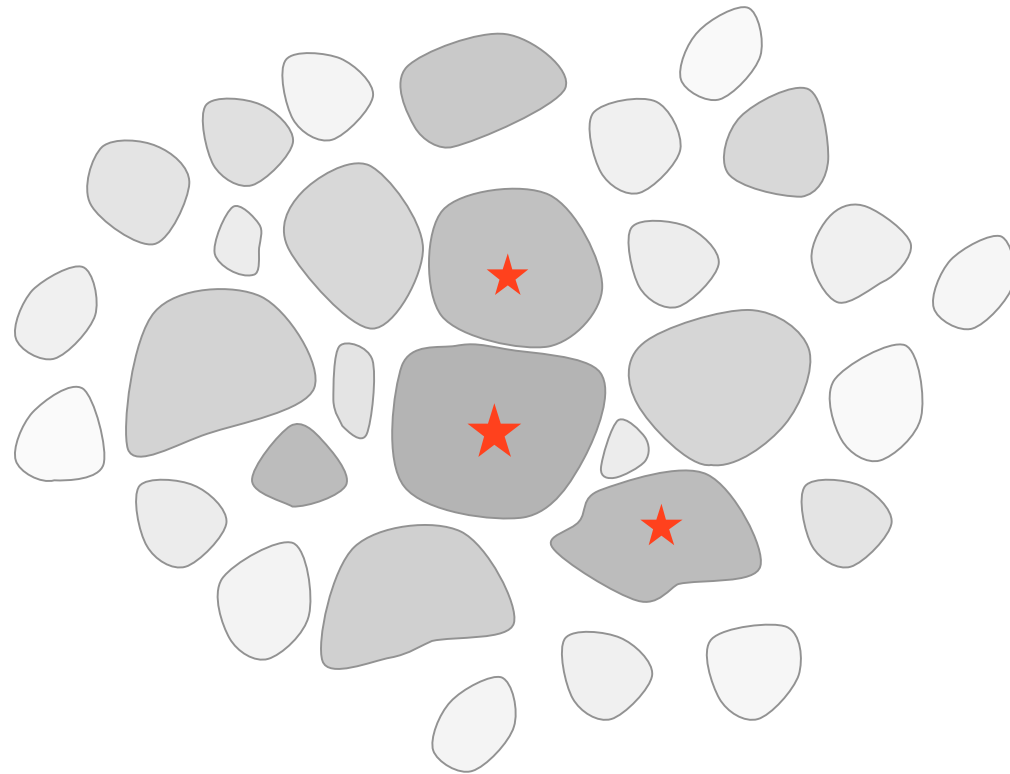
individual clumps collapse to form stars
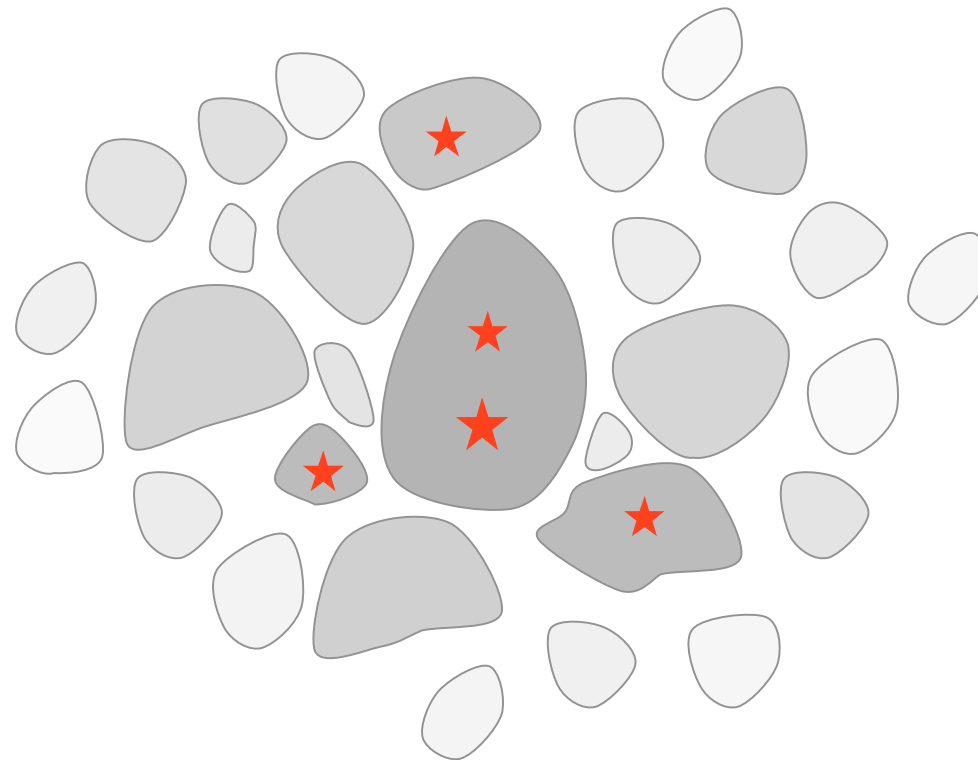
$\alpha = E_{kin}/|E_{pot}| < 1$

in *dense clusters*, clumps may merge while collapsing
--> then contain multiple protostars
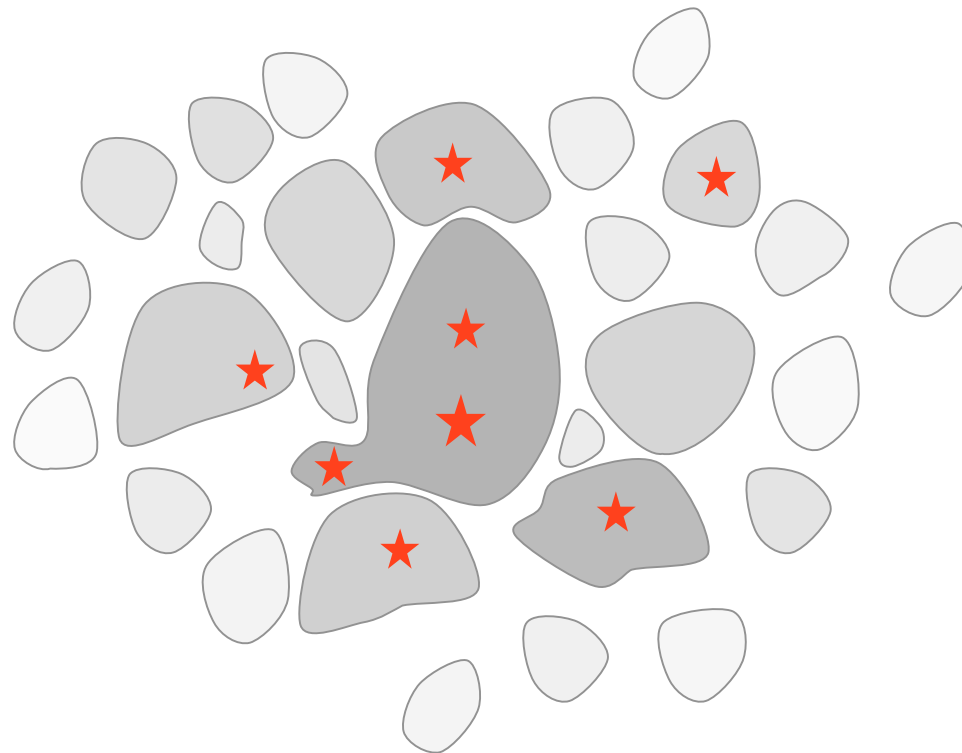
in *dense clusters*, clumps may merge while collapsing
--> then contain multiple protostars
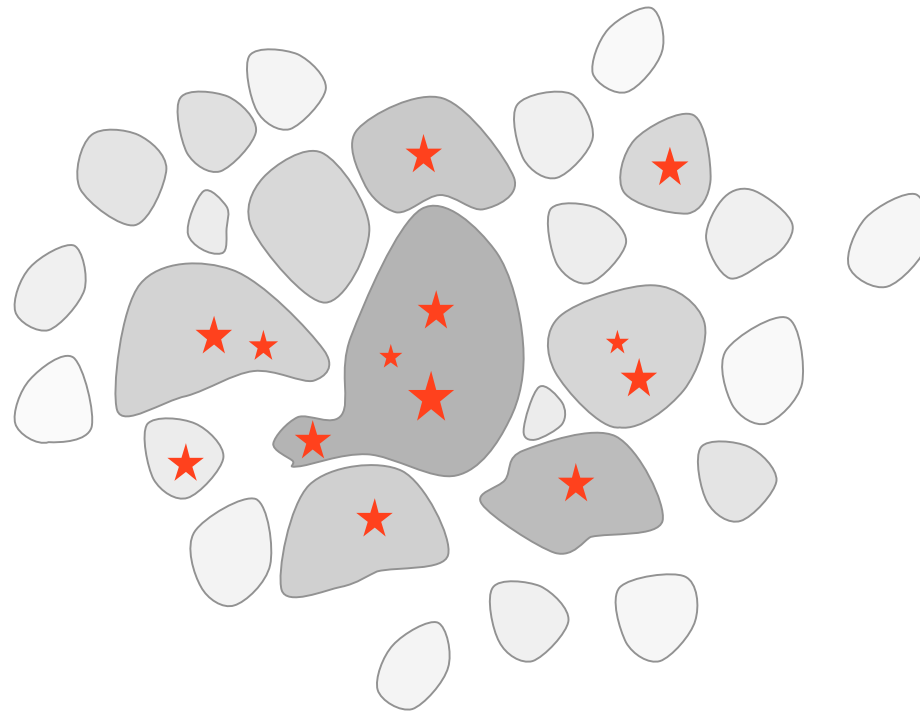
in *dense clusters*, clumps may merge while collapsing
--> then contain multiple protostars
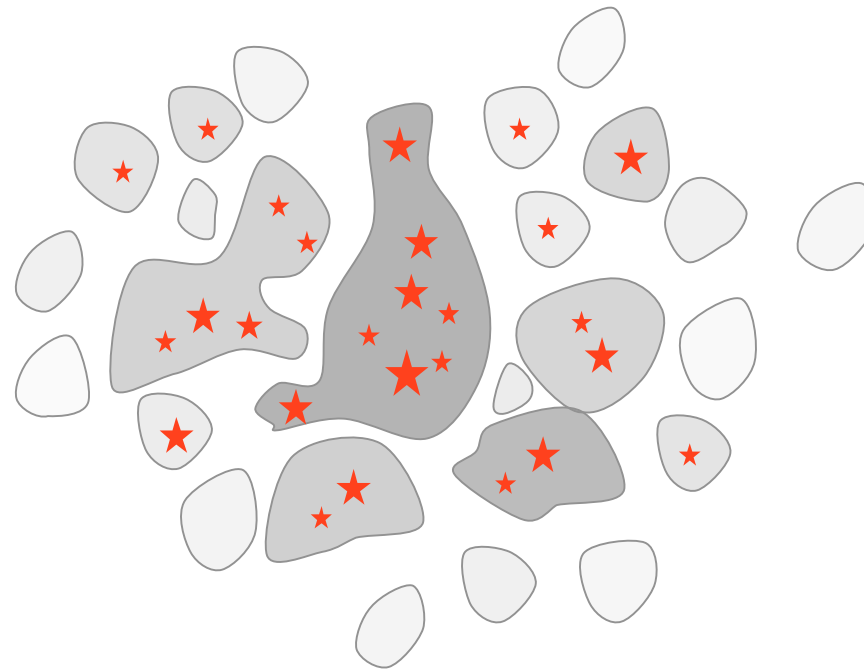
in *dense clusters*, competitive mass growth
becomes important
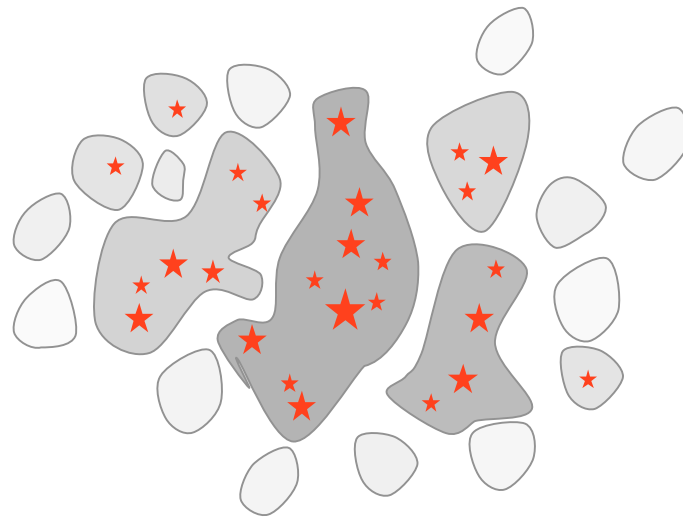
in *dense clusters*, competitive mass growth
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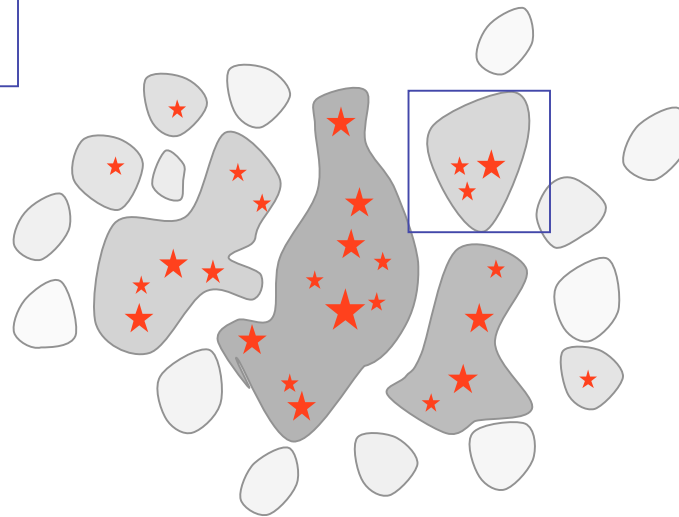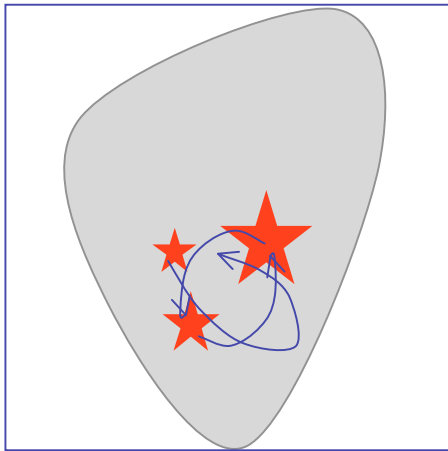
in *dense clusters*, *N*-body effects influence mass growth
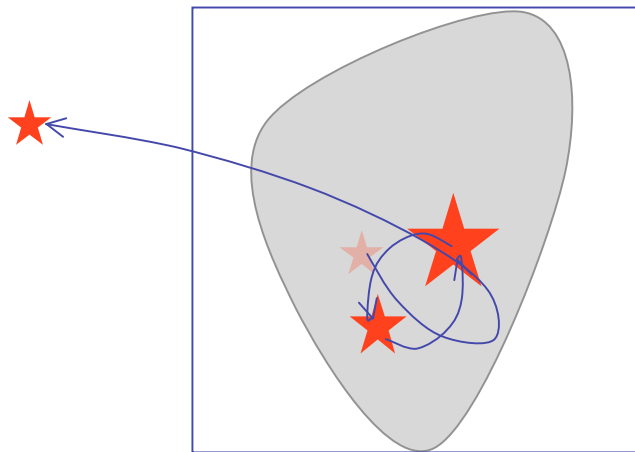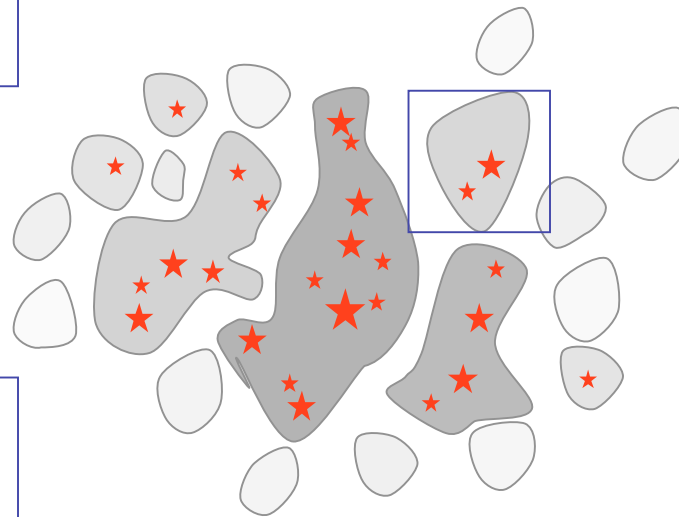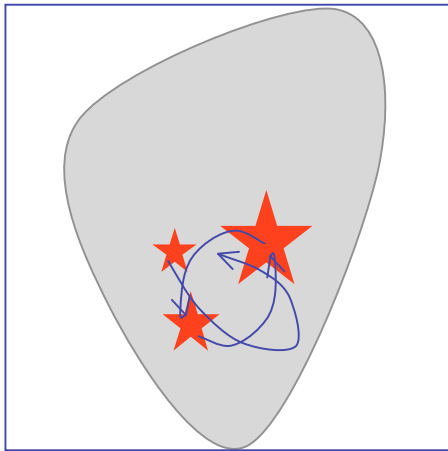
low-mass objects may
become ejected --> accretion stops
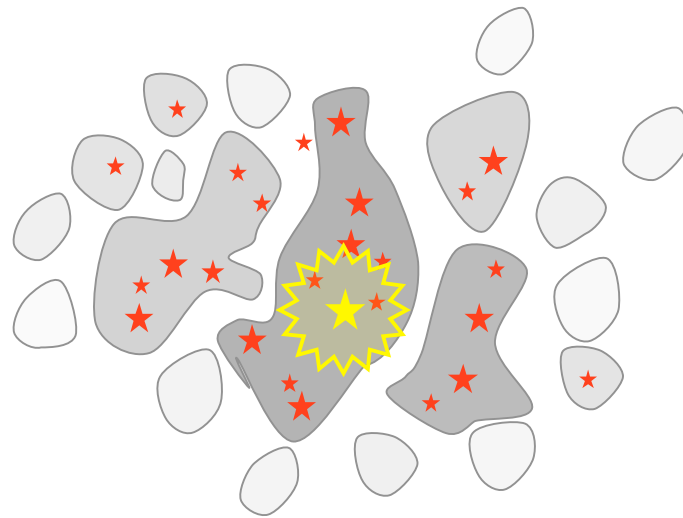
feedback terminates star formation
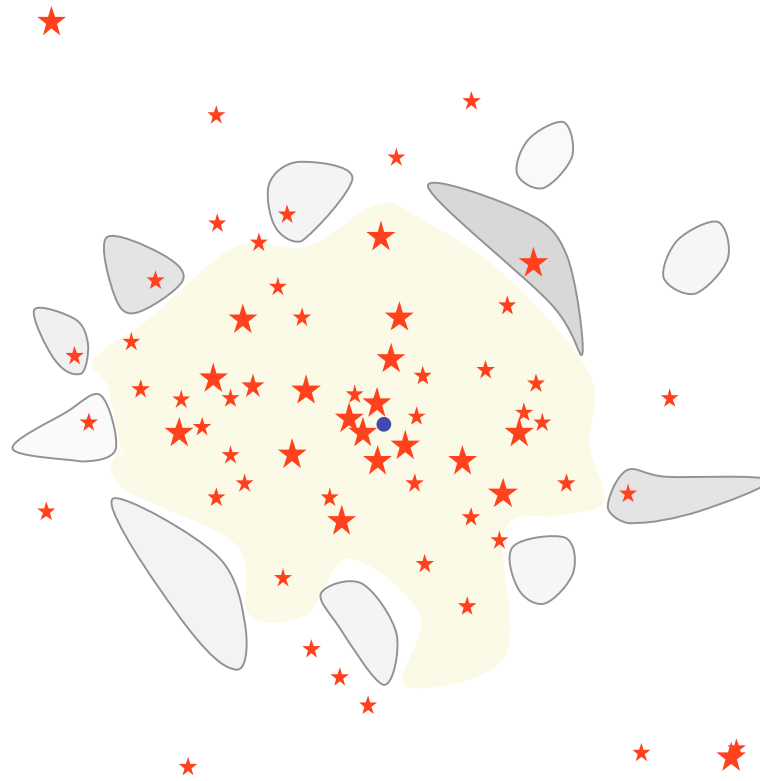
result: *star cluster*, possibly with HII region

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, $\Delta$-*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

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# Transient cloud structure

*Gravoturbulent fragmentation of turbulent self-gravitating clouds*



*xy projection*          *xz projection*          *yz projection*
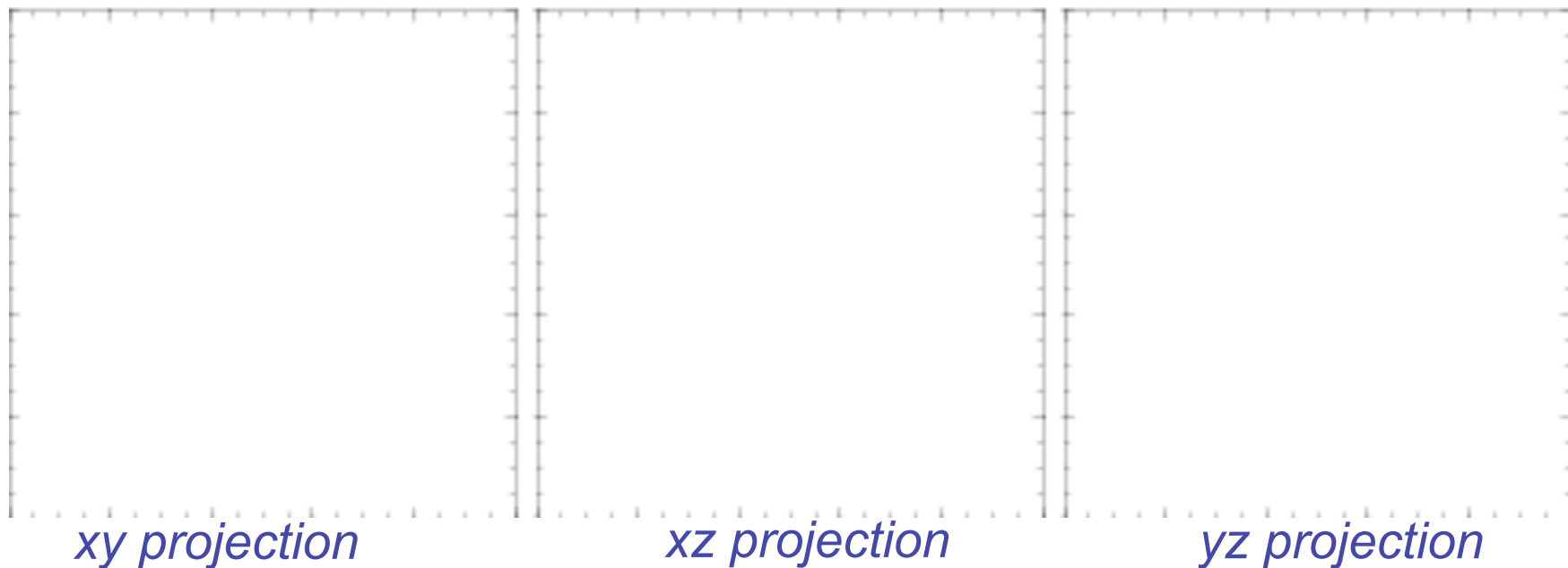
- SPH model with 1.6x10$^6$ particles
- large-scale driven turbulence

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

# Gravoturbulent fragmentation
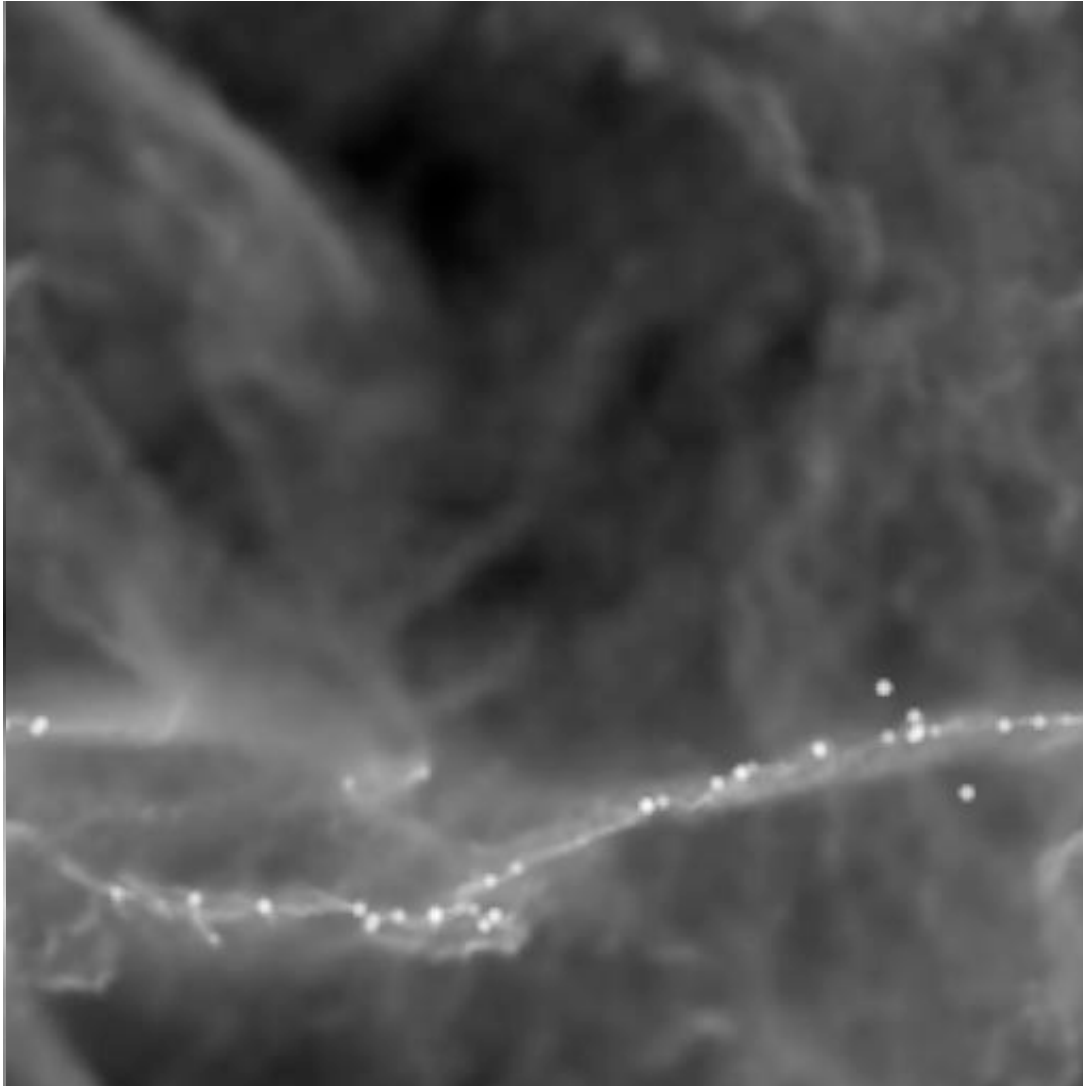


Filament generated by combination of compression and local shear:
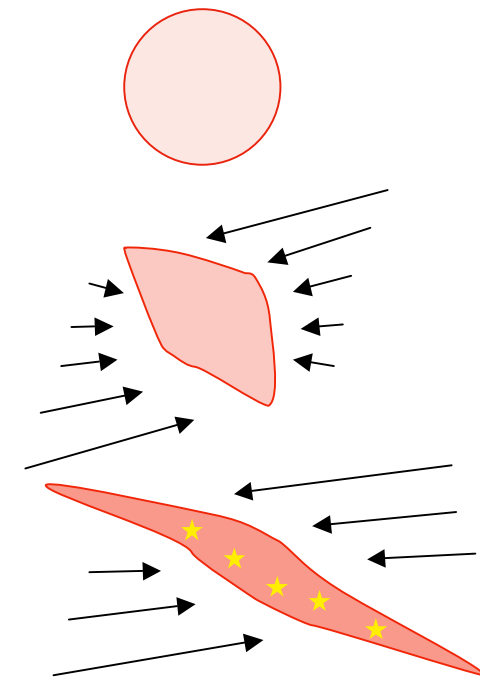
"Taurus":
→ density $n(H_2) \approx 10^2\,cm^{-3}$
→ $L = 6\,pc$, $M = 5000\,M_\odot$

# Taurus



Class 1 protostars
Class 2 protostars
Class 3 protostars

star-forming filaments in
the *Taurus* cloud

(from Alyssa Goodman)
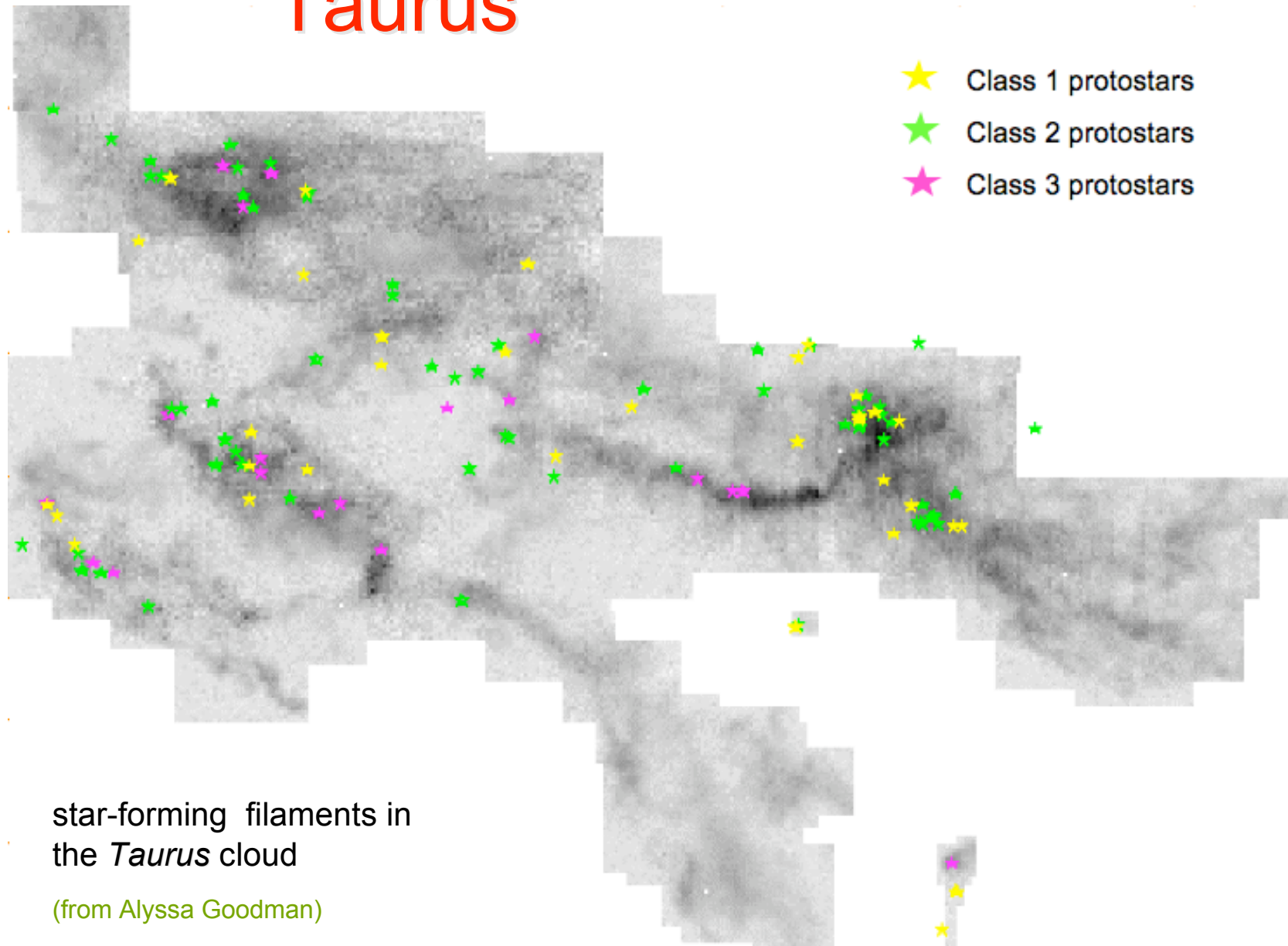
# Example: model of Orion cloud



(Spitzer: Megeath et al.)

Orion A

Ophiuchus

Parsecs

Parsecs

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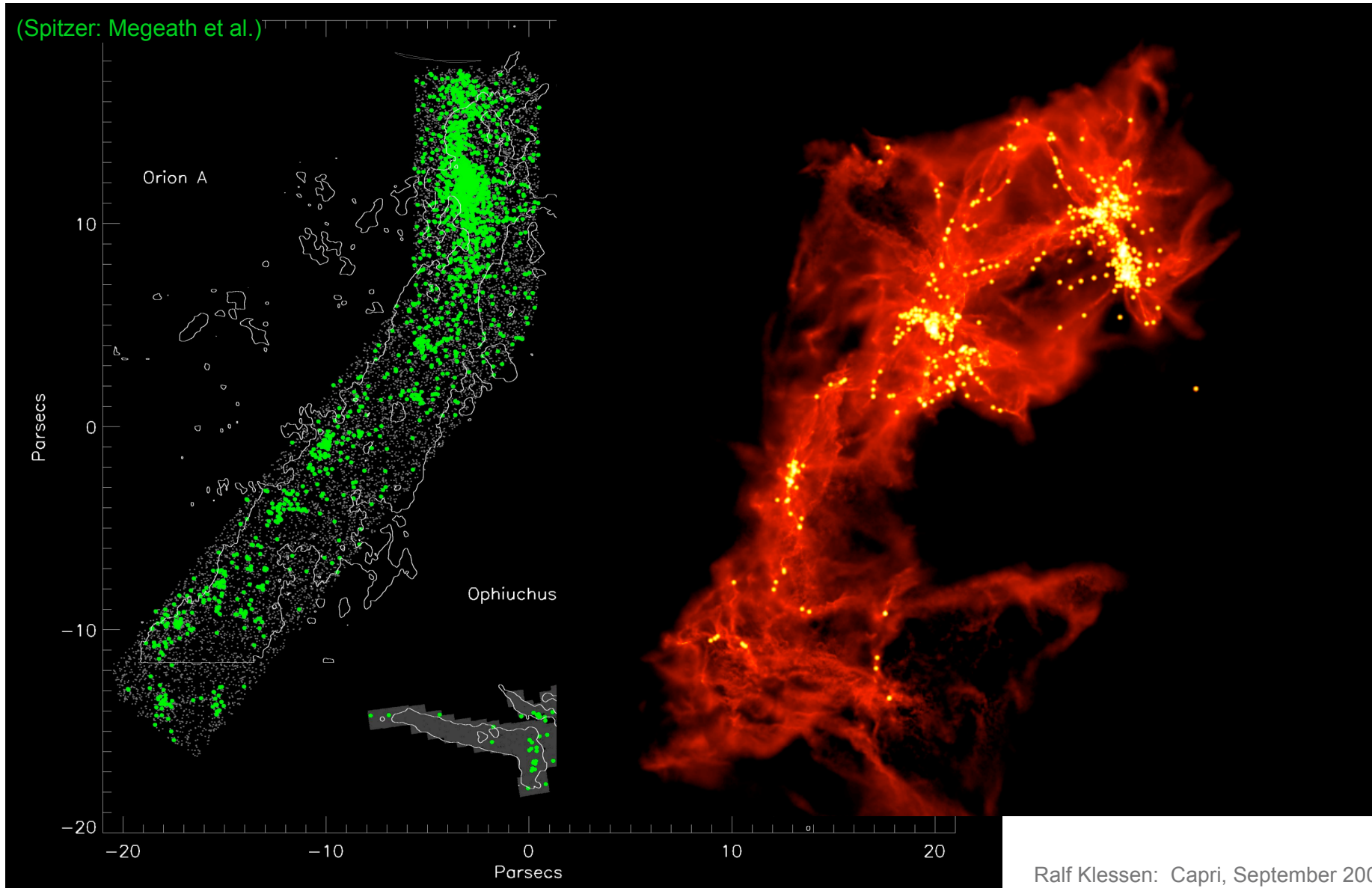
# Model with ionizing feedback

SPH with radiation feedback: first calculations of star-cluster formation with ionization
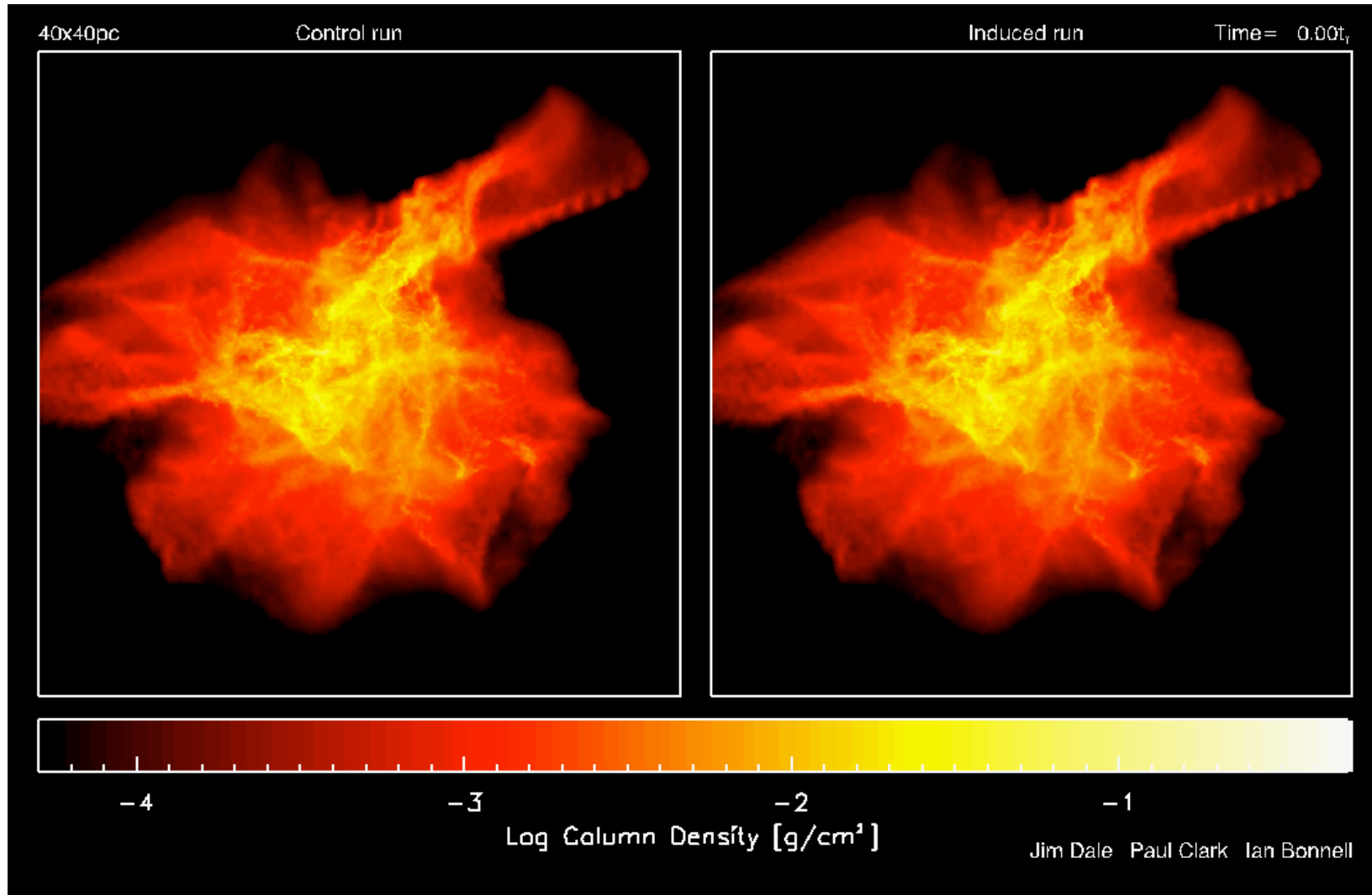
example 2

# 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*
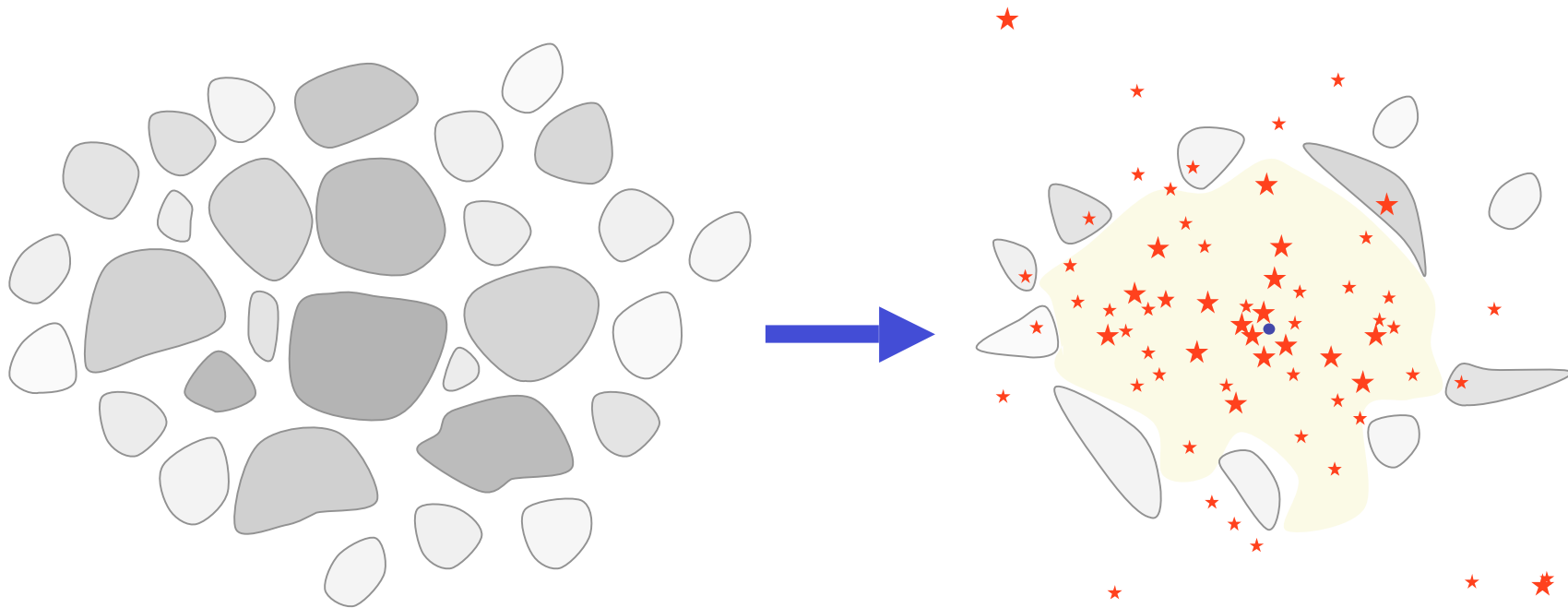


How to get from cloud cores  to star clusters?

How do the stars acquire mass?

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

# Dynamics of nascent star cluster

in dense clusters protostellar interaction may be come important!
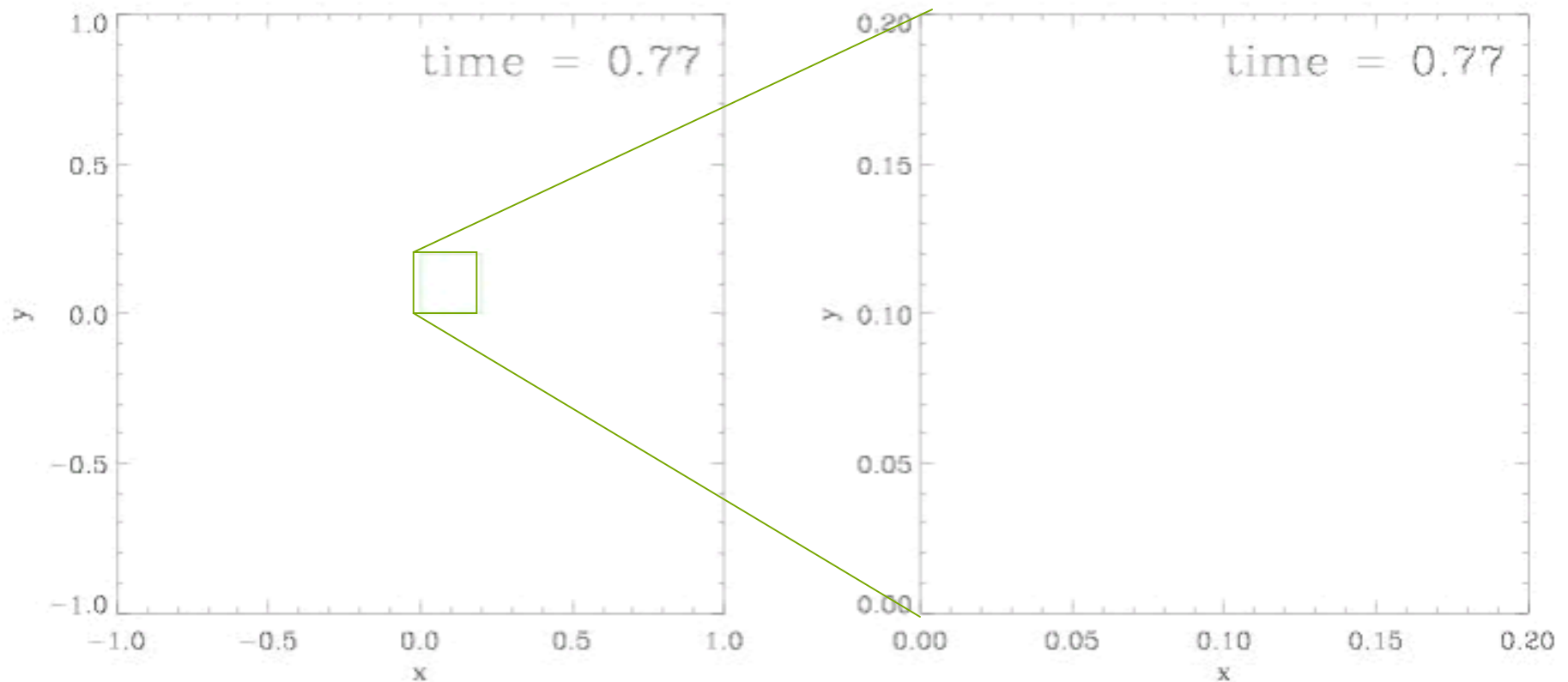


Trajectories of protostars in a nascent dense cluster created by gravoturbulent fragmentation
(from Klessen & Burkert 2000, ApJS, 128, 287)

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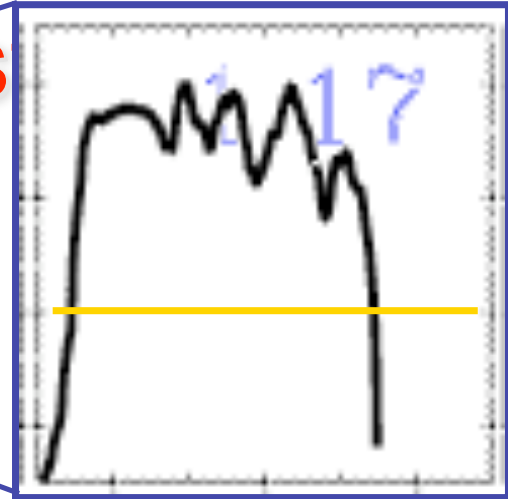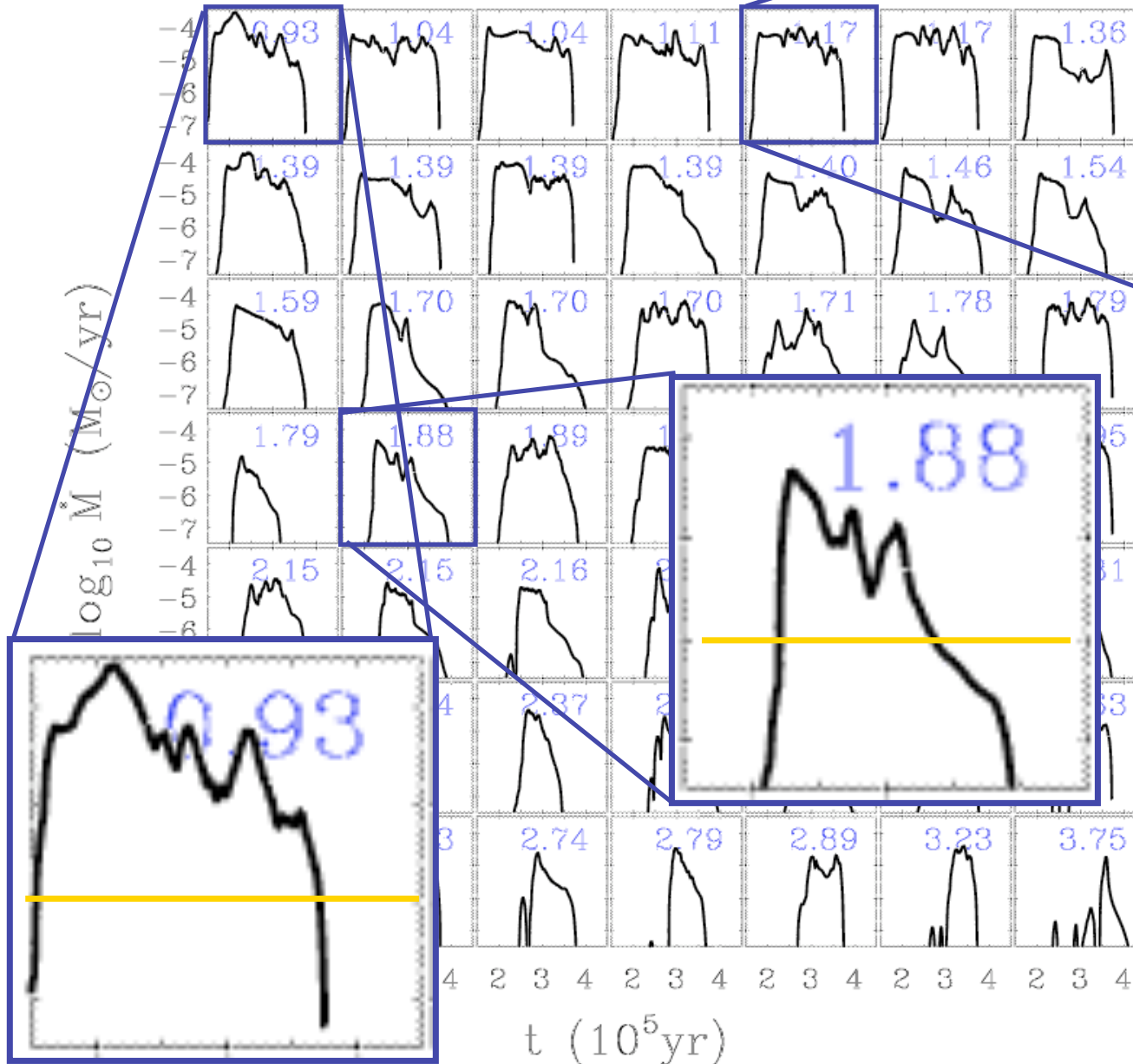
Mass accretion rates *vary with time* and are strongly *influenced* by the *cluster environment*.

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

sen: Capri, September 2007

# "Empirical" mass accretion law
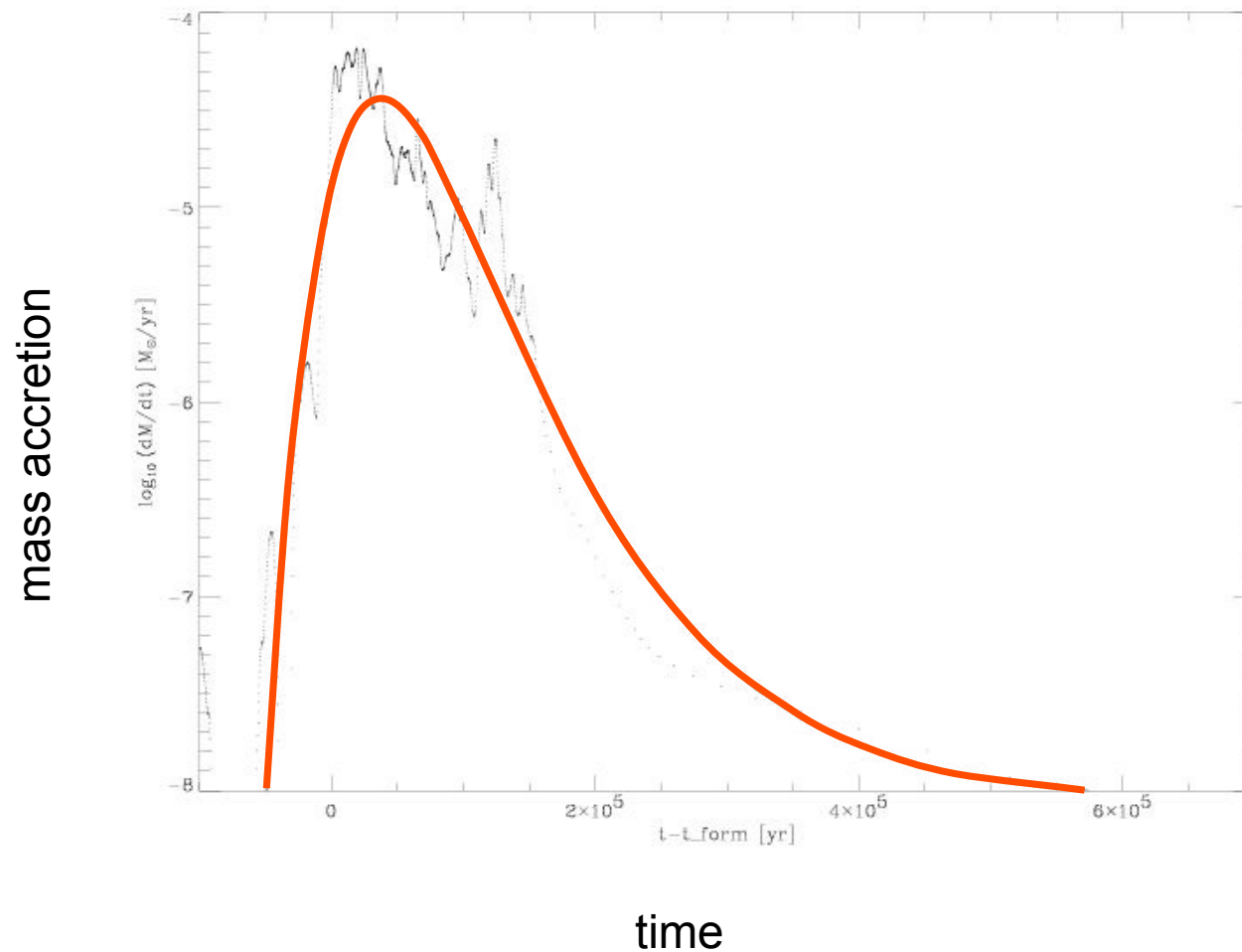


Simple analytic formula for individual mass accretion rates: $dM/dt = At \cdot \exp(-t/\tau)$

(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



γ=0.2  γ=1.0  γ=1.2
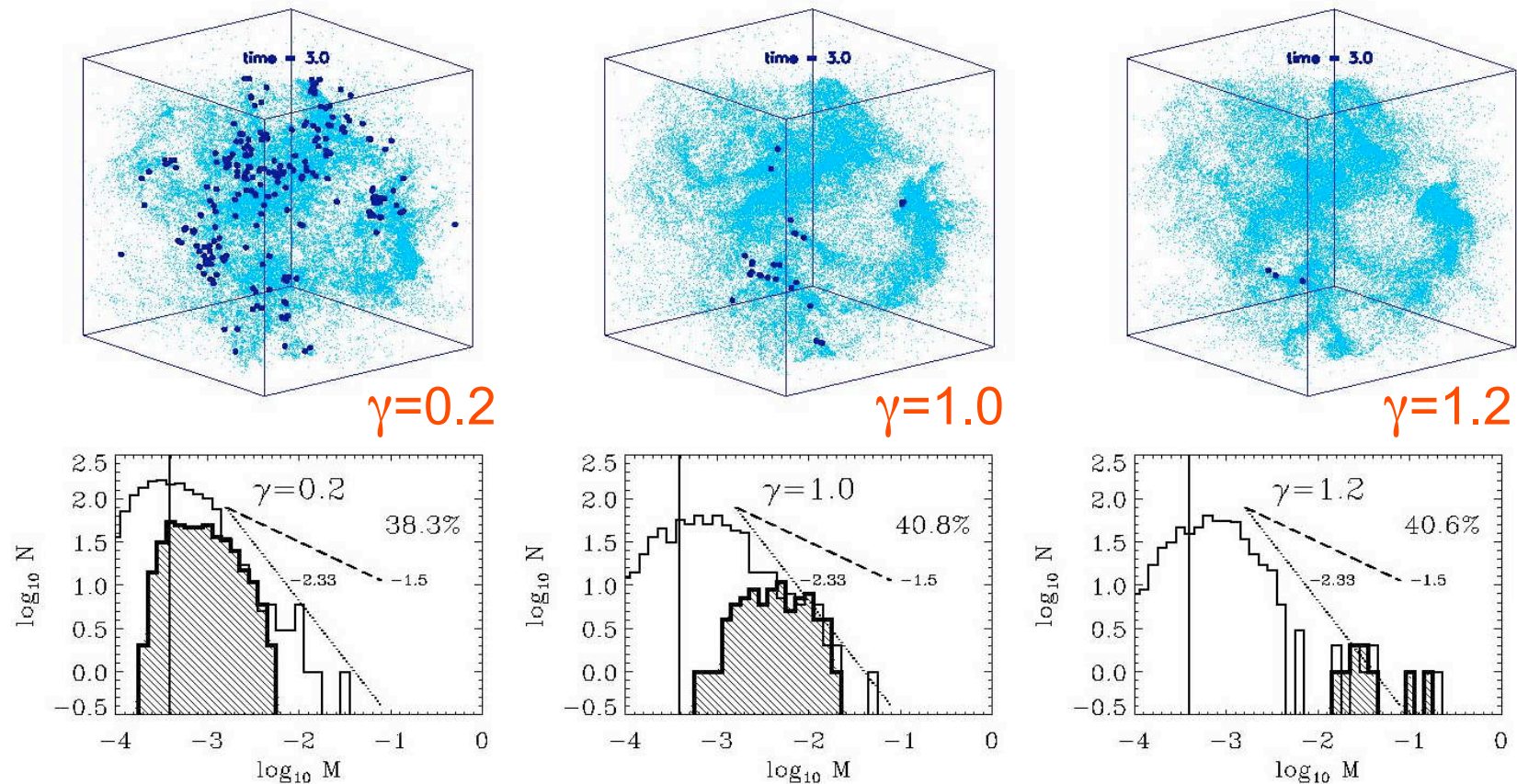
for γ<1 fragmentation is enhanced → *cluster of low-mass stars*

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

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

# How does that work?

(1) $\quad p \propto \rho^{\gamma} \quad \rightarrow \quad \rho \propto p^{1/\gamma}$
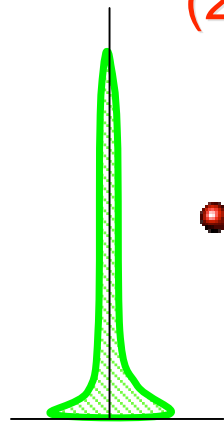
(2) $\quad M_{jeans} \propto \gamma^{3/2} \rho^{(3\gamma-4)/2}$

- $\gamma<1$: $\rightarrow$ *large* density excursion for given pressure
  - $\rightarrow \langle M_{jeans}\rangle$ becomes small
  - $\rightarrow$ number of fluctuations with $M > M_{jeans}$ is large
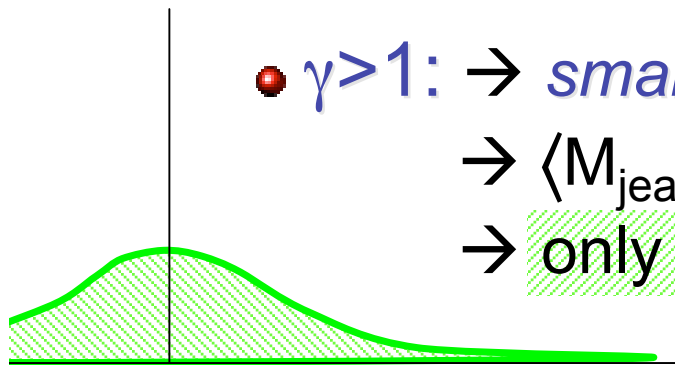
- $\gamma>1$: $\rightarrow$ *small* density excursion for given pressure
  - $\rightarrow \langle M_{jeans}\rangle$ is large
  - $\rightarrow$ only few and massive clumps exceed $M_{jeans}$

# EOS for solar neighborhood
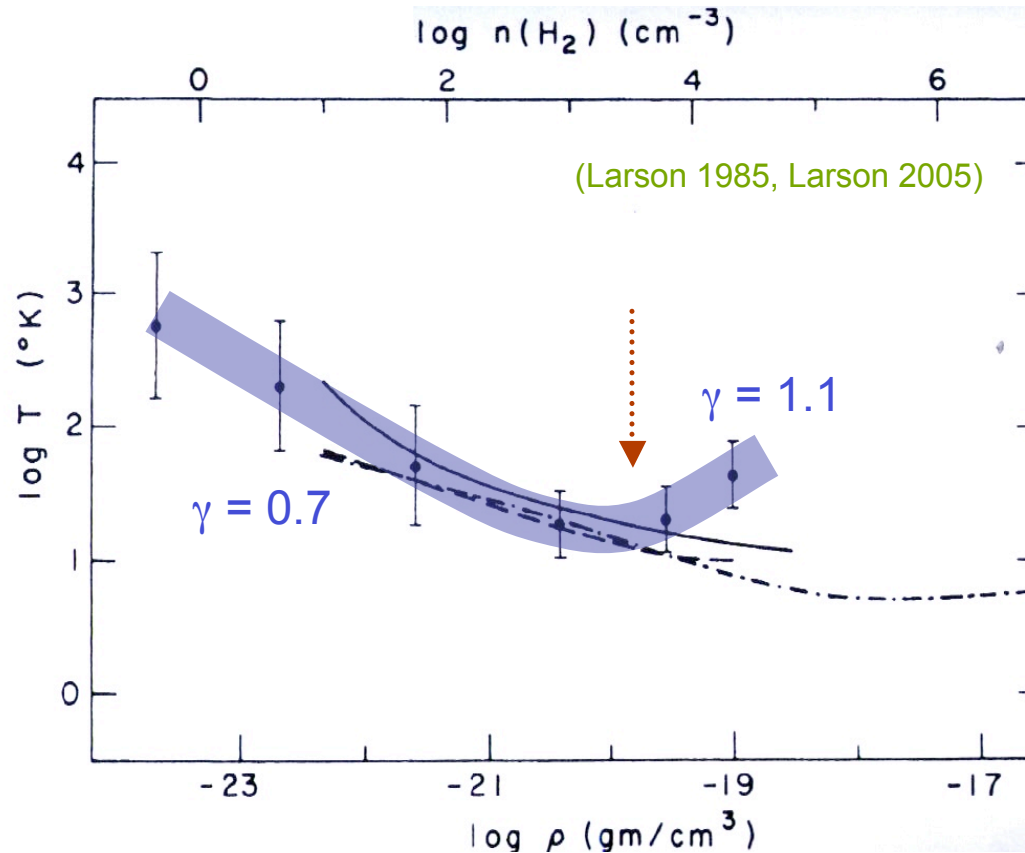
below $10^{-18}$ gcm$^{-3}$: $\rho$ ⬆  ⟹  T ⬇

above $10^{-18}$ gcm$^{-3}$: $\rho$ ⬆  ⟹  T ⬆



(Larson 1985, Larson 2005)

$\gamma = 1.1$

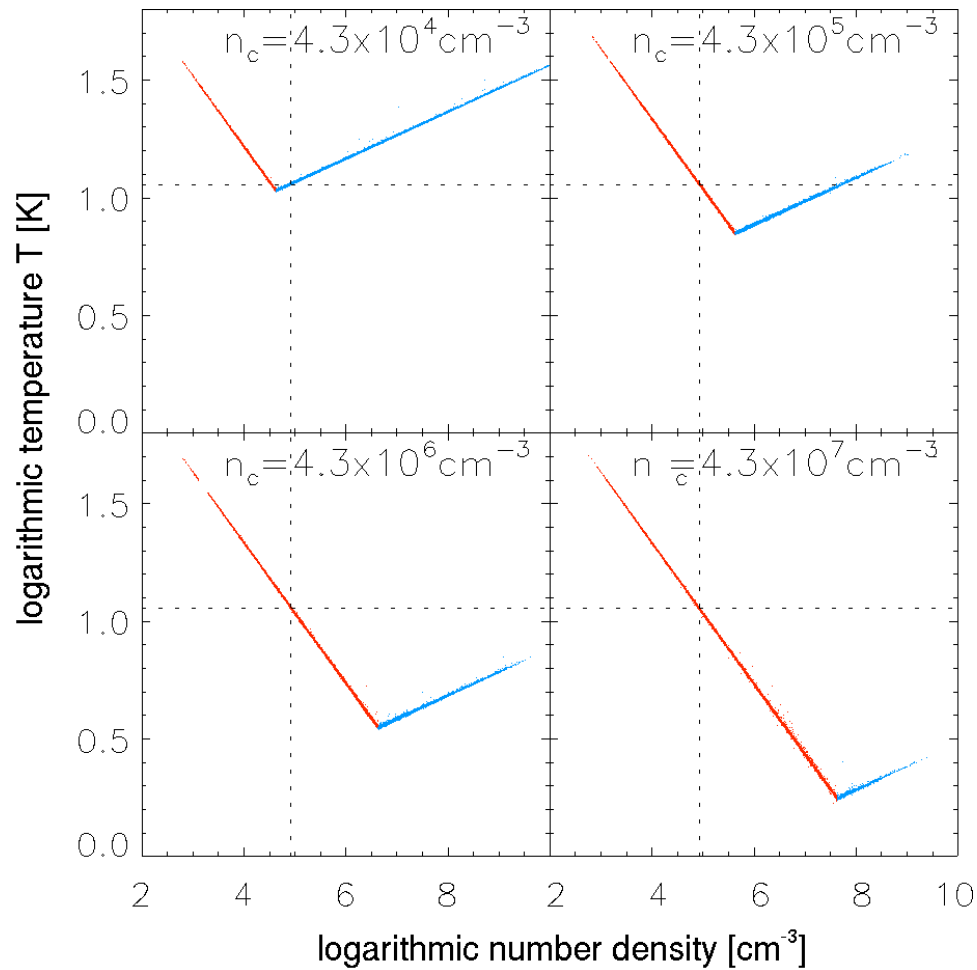$\gamma = 0.7$

$P \propto \rho^{\gamma}$

$P \propto \rho T$

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

# IMF from simple piece-wise polytropic EOS

$\gamma_1 = 0.7$
$\gamma_2 = 1.1$

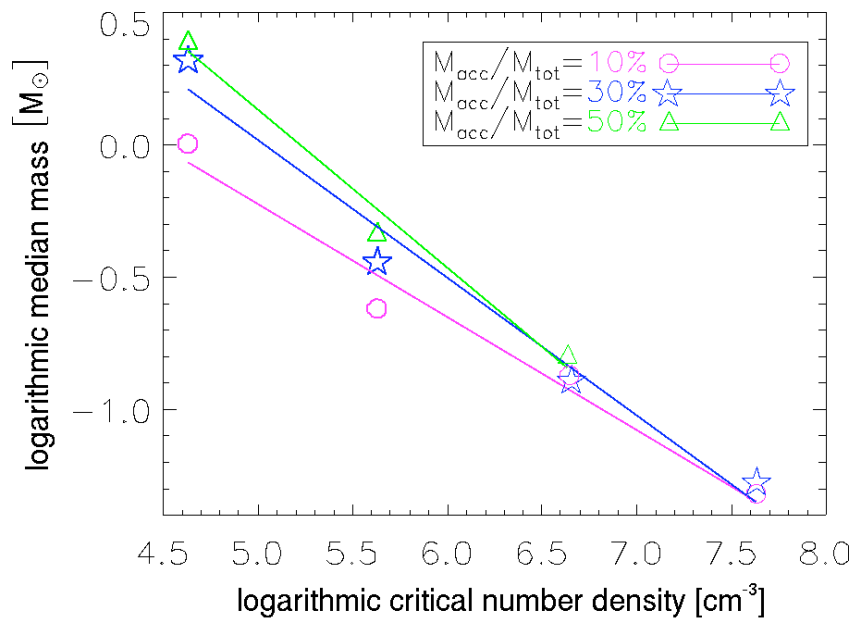$$T \sim \rho^{\gamma-1}$$



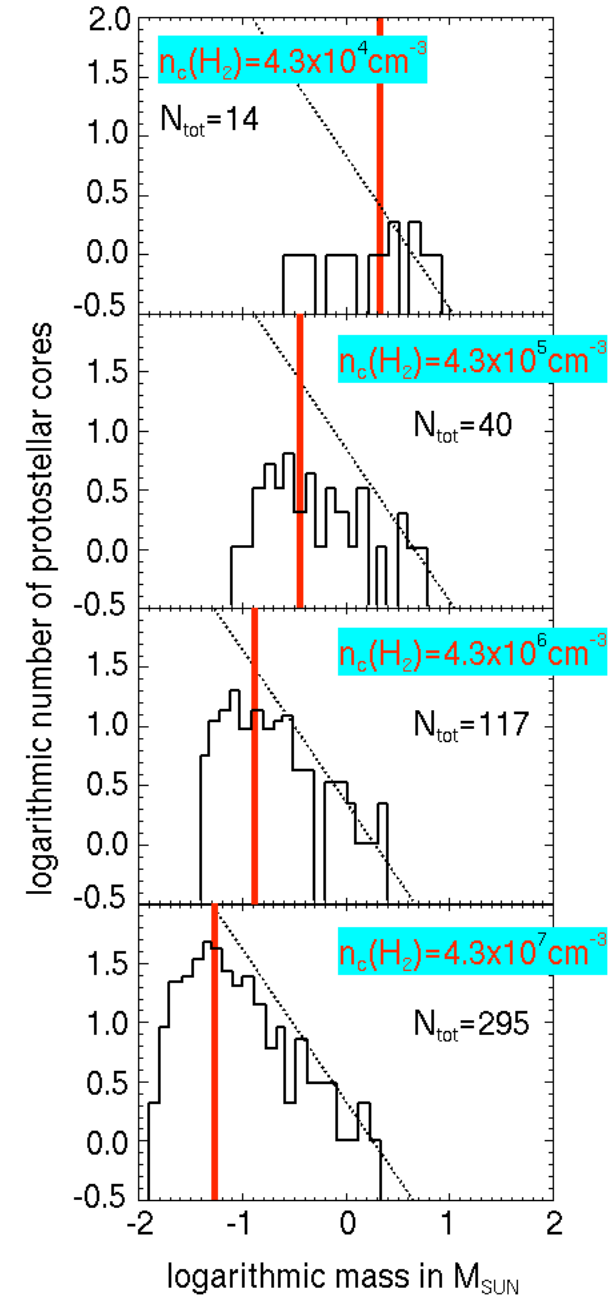(Jappsen et al. 2005)

# IMF from simple piece-wise polytropic EOS

critical density ⬆ ⟹ median mass ⬇



(Jappsen et al. 2005)

# IMF in nearby molecular clouds



$x = -1.3$

with $\rho_{crit} \approx 2.5 \times 10^5$ cm$^{-3}$
at SFE $\approx 50\%$

Isothermal EOS has deficite of very low-mass objects

--> need "better" EOS!

(Jappsen et al. 2005, A&A, 435, 611)c
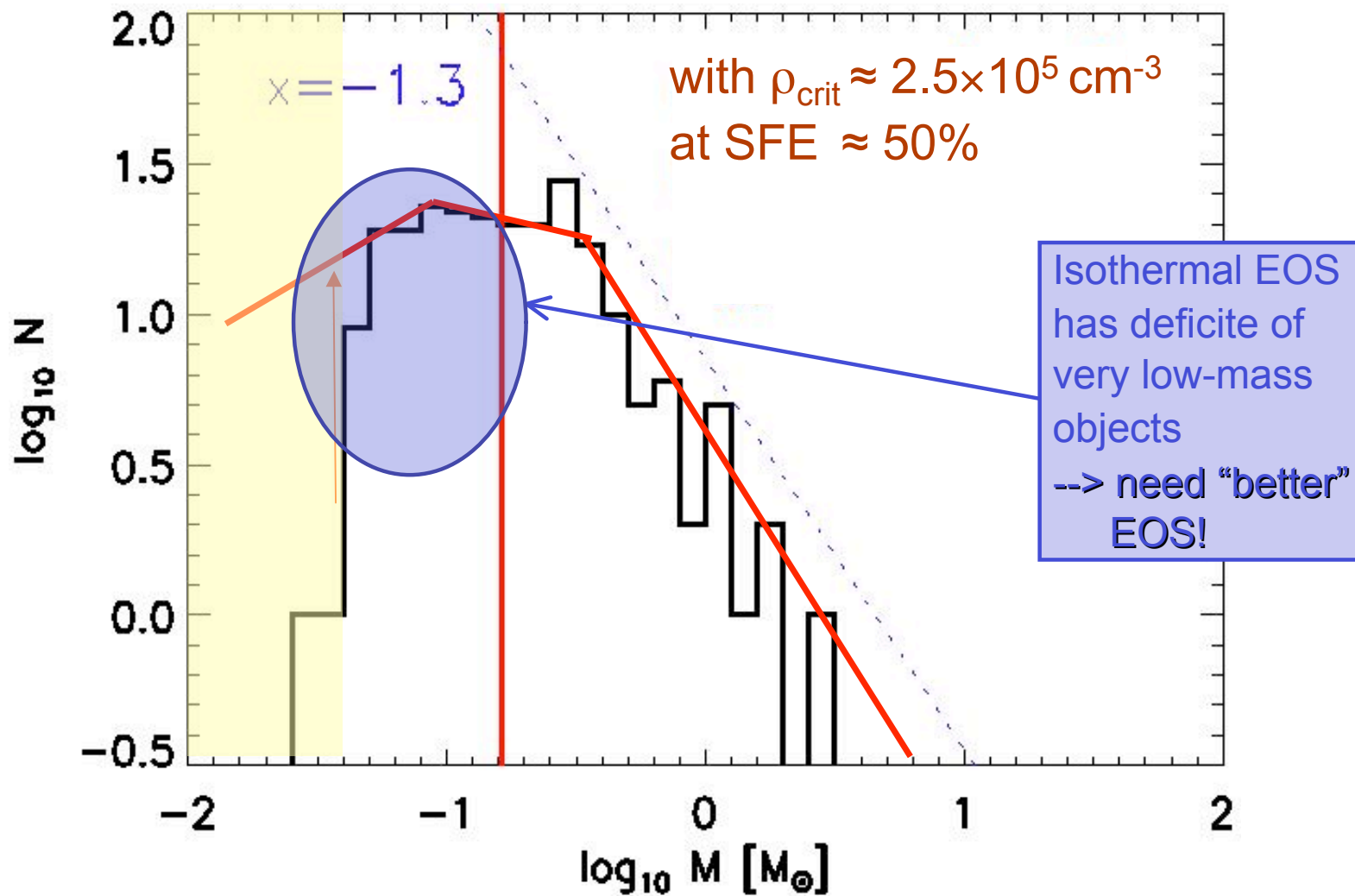
# Plausibility argument for shape



- Supersonic turbulence is scale free process

  → *POWER LAW BEHAVIOR*

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

  → *GAUSSIAN DISTRIBUTION*

# IMF in starburst galaxies

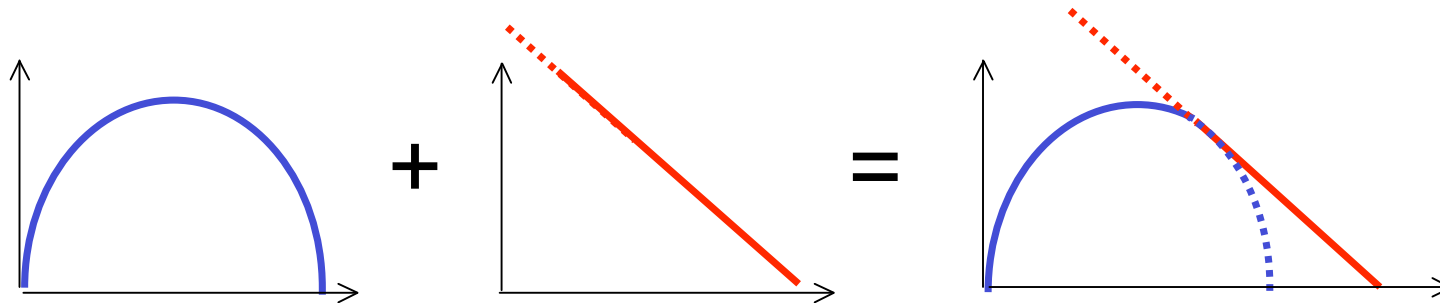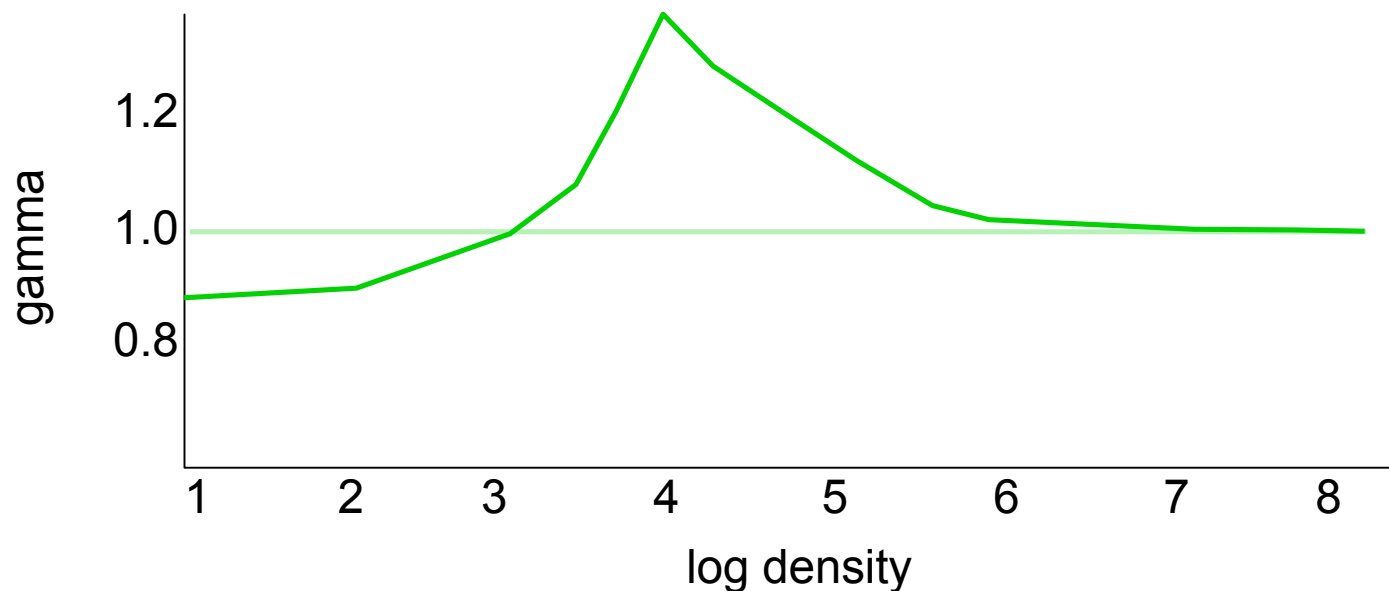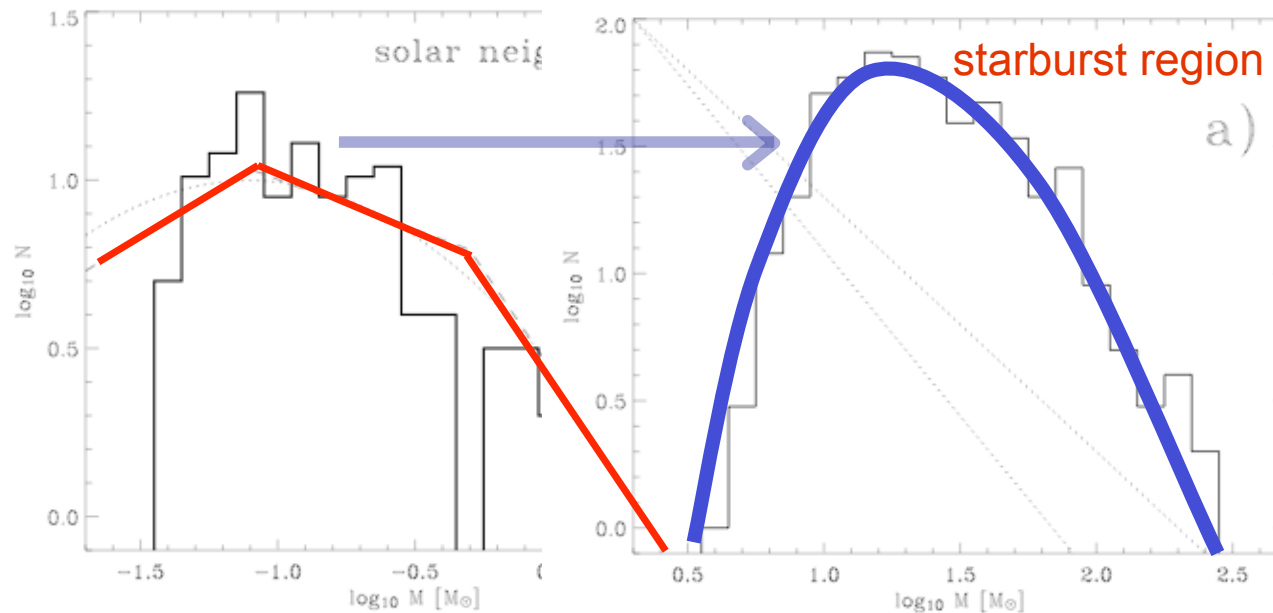- Nuclear regions of starburst galaxies are extreme:
  - hot dust, large densities, strong radiation, etc.
- Thermodynamic properties of star-forming gas differ from Milky Way --> Different EOS!
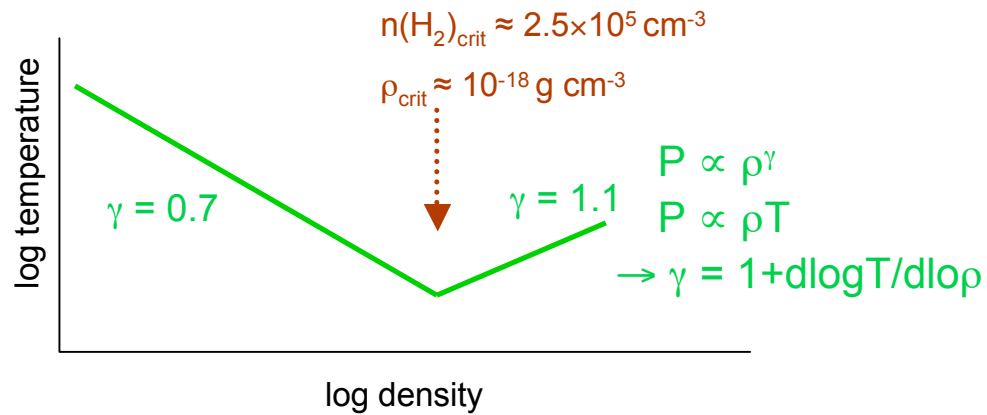  (see Spaans & Silk 2005)

# IMF in starburst galaxies

- Starburst EOS --> top-heavy IMF
  (Klessen, Spaans, Jappsen, 2007)

# fragmentation depends on EOS



$n(H_2)_{crit} \approx 2.5 \times 10^5 \, cm^{-3}$

$\rho_{crit} \approx 10^{-18} \, g \, cm^{-3}$

$\gamma = 0.7$

$\gamma = 1.1$

$P \propto \rho^\gamma$

$P \propto \rho T$

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

(Larson 2005)
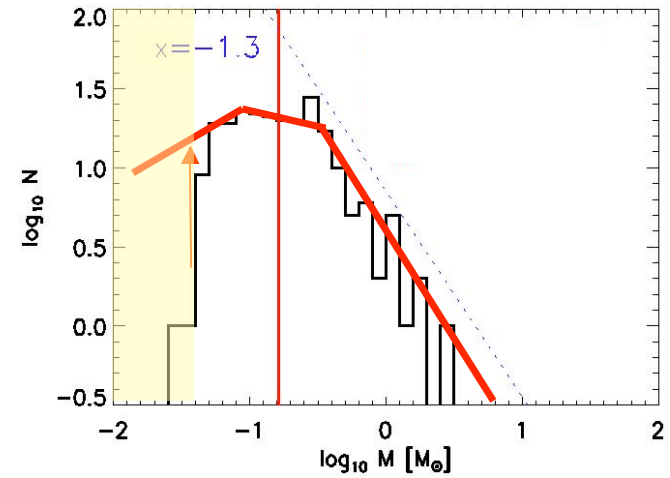
(Jappsen et al. 2005)
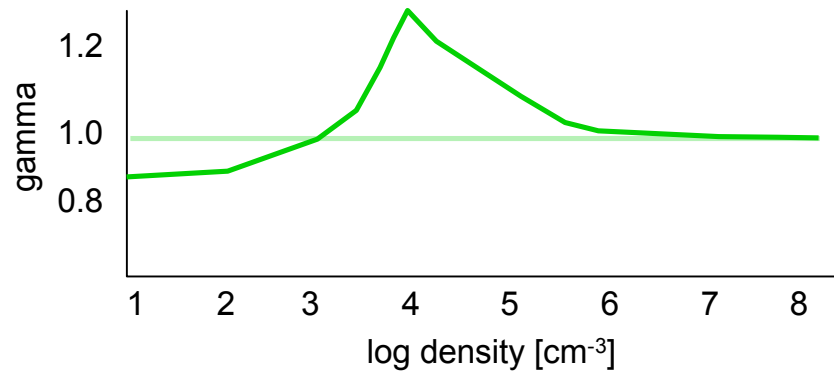
(Spaans & Silk 2005)

(Klessen et al. 2007)

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# transition: Pop III to Pop II.5
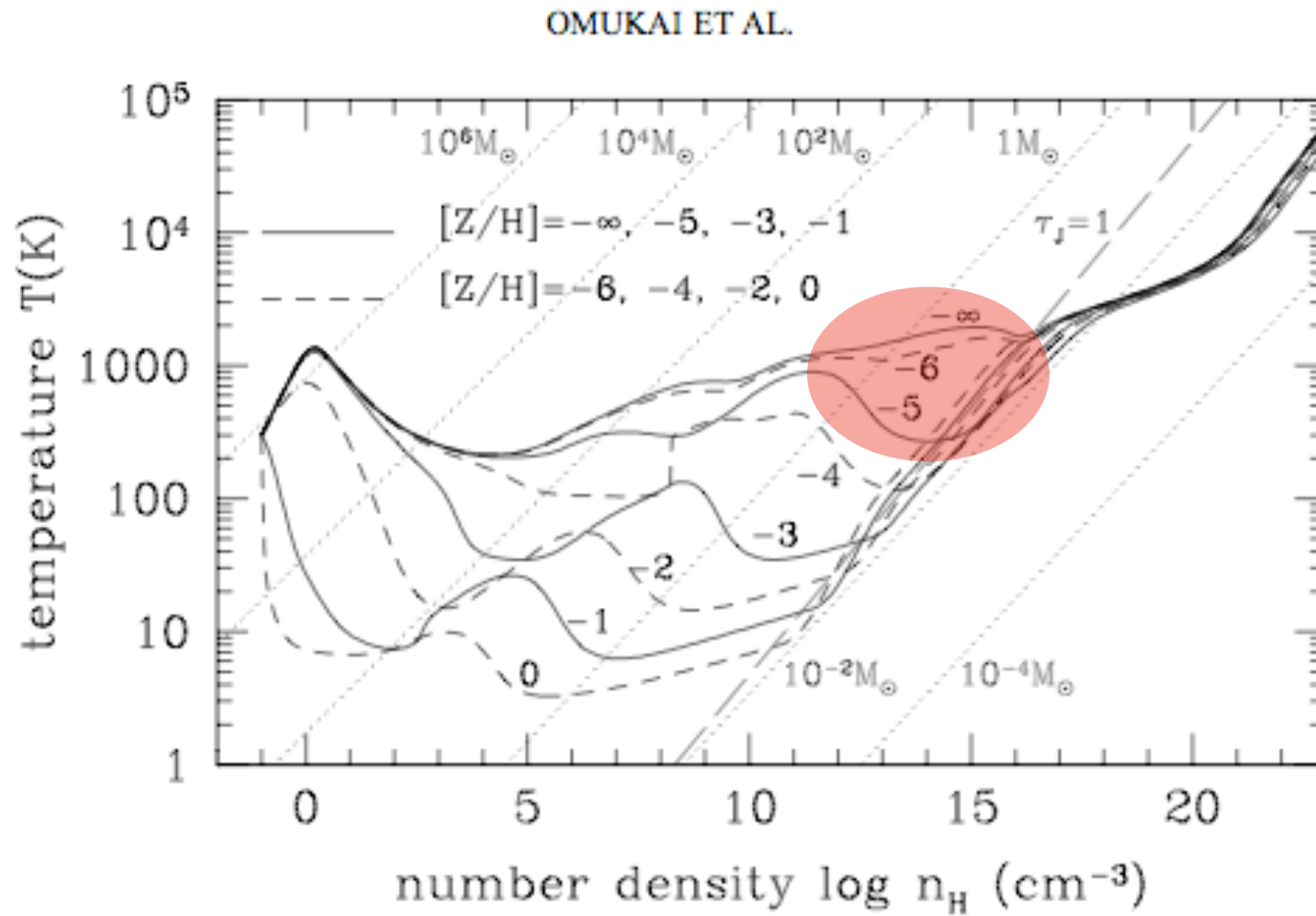


OMUKAI ET AL.

(Omukai et al. 2005)

# transition: Pop III to Pop II.5
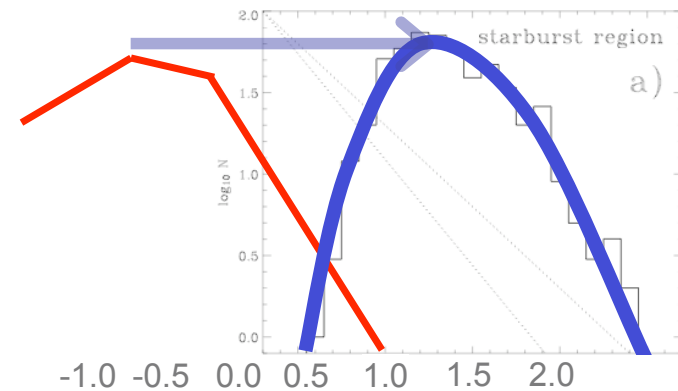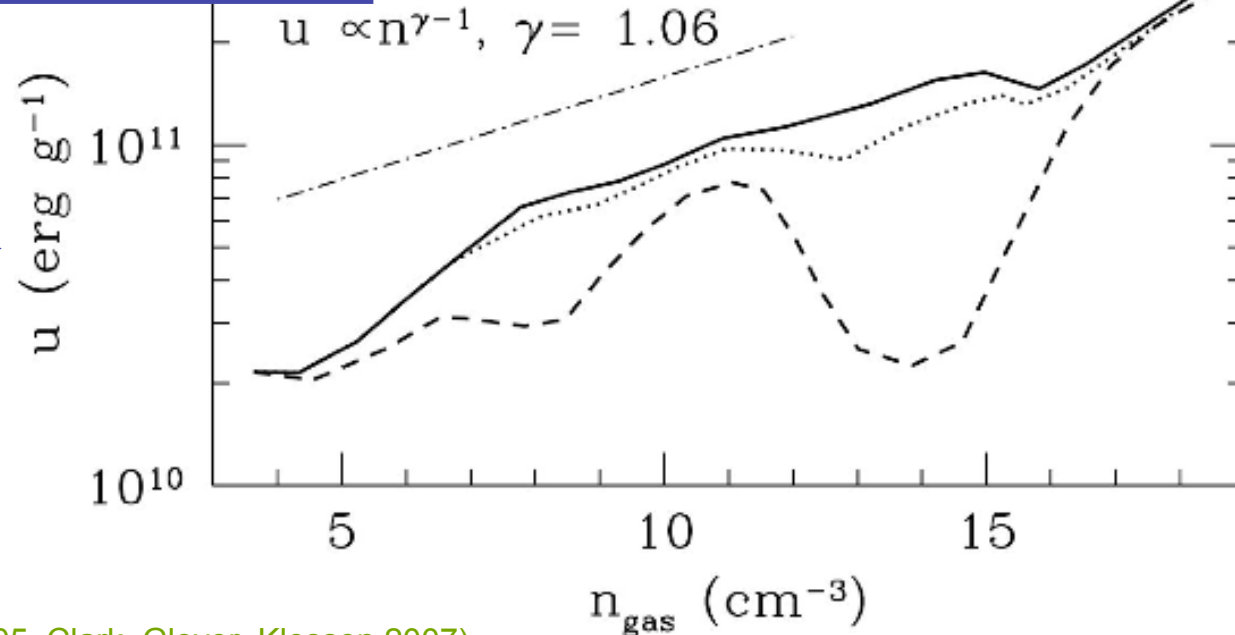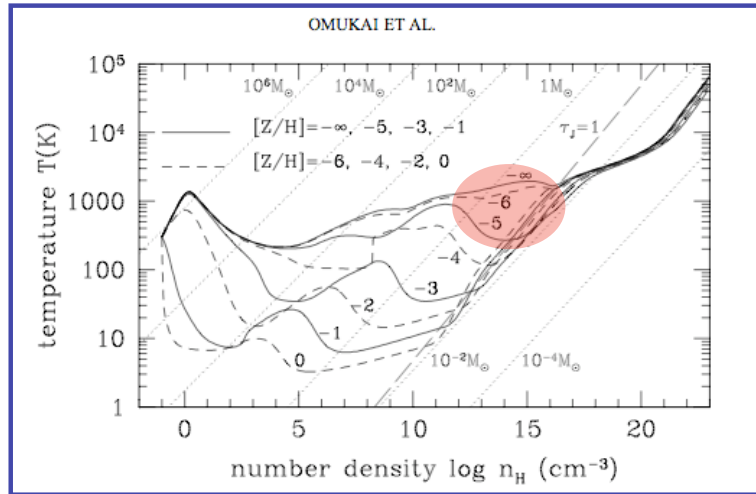


(Omukai et al. 2005, Clark, Glover, Klessen 2007)

# dust induced fragmentation at Z=10$^{-5}$

t = t$_{SF}$ - 67 yr

t = t$_{SF}$ - 20 yr

t = t$_{SF}$

t = t$_{SF}$ + 53 yr

t = t$_{SF}$ + 233 yr

t = t$_{SF}$ + 420 yr

400 AU

(Clark et al. 2007)

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# dust induced fragmentation at Z=10$^{-5}$

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(Clark et al. 2007)

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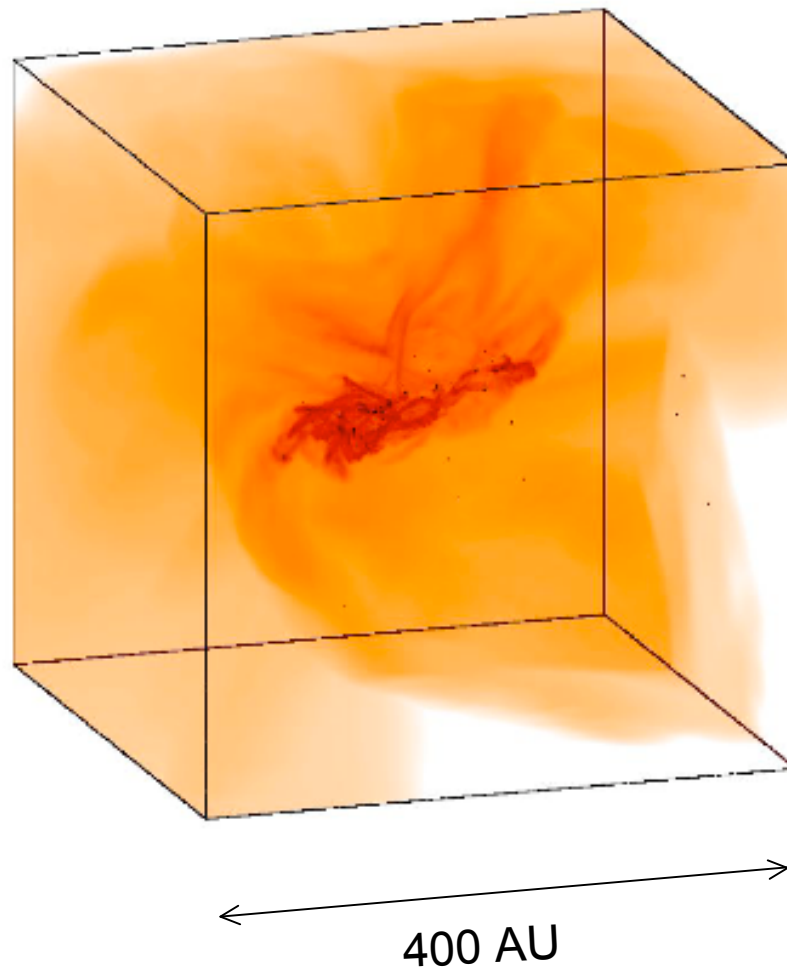


400 AU

dense cluster of low-mass protostars builds up:

- mass spectrum peaks below 1 $M_{sun}$
- cluster VERY dense $n_{stars} = 2.5 \times 10^9$ pc$^{-3}$
- fragmentation at density $n_{gas} = 10^{12} - 10^{13}$ cm$^{-3}$

(Clark et al. 2007)

# cluster build-up
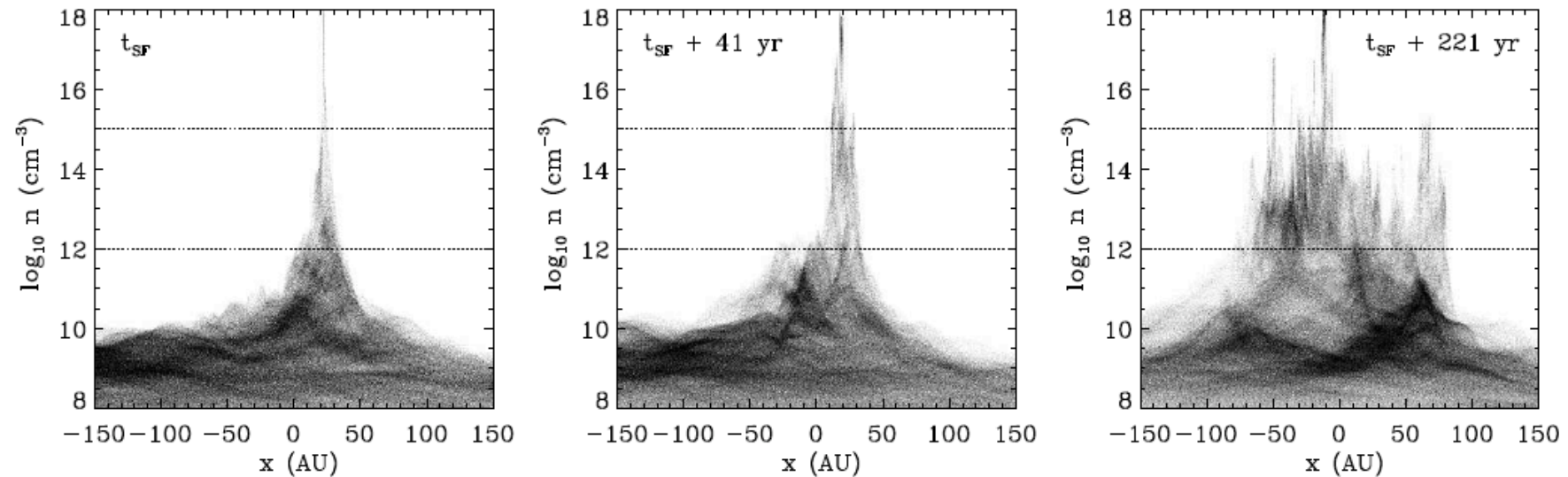


FIG. 3.— We illustrate the onset of the fragmentation process in the high resolution $Z = 10^{-5} Z_\odot$ simulation. The graphs show the densities of the particles, plotted as a function of their x-position. Note that for each plot, the particle data has been centered on the region of interest. We show here results at three different output times, ranging from the time that the first star forms ($t_{sf}$) to 221 years afterwards. The densities lying between the two horizontal dashed lines denote the range over which dust cooling lowers the gas temperature.

(Clark et al. 2007)

# cluster build-up



$\gamma > 1$
(heating)

$\gamma < 1$
(cooling)
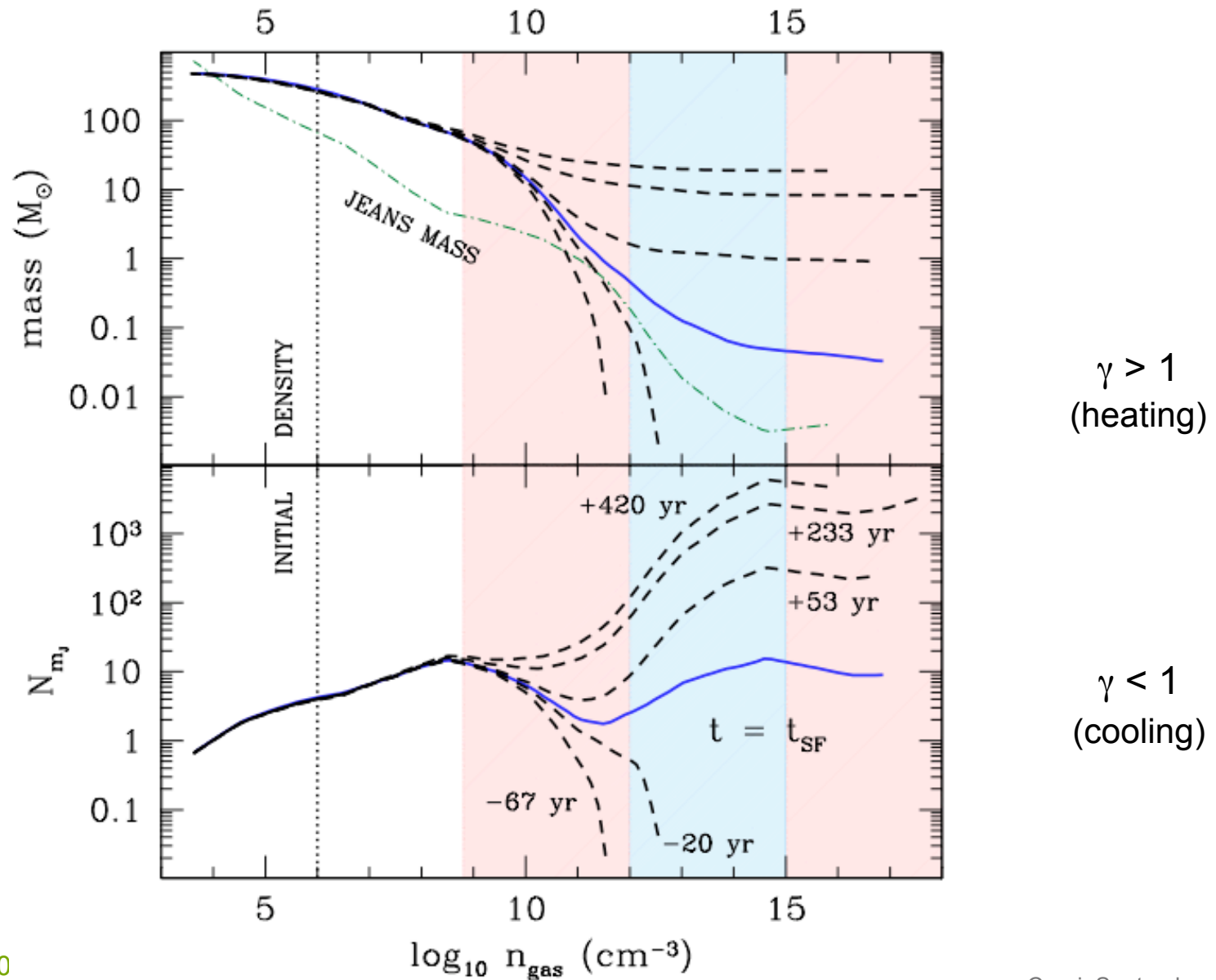
(Clark et al. 20

# dust induced fragmentation at Z=10$^{-5}$



dense cluster of low-mass protostars builds up:

- mass spectrum peaks below 1 M$_{sun}$
- cluster VERY dense n$_{stars}$ = 2.5 x 10$^9$ pc$^{-3}$
- fragmentation at density n$_{gas}$ = 10$^{12}$ - 10$^{13}$ cm$^{-3}$

(Clark et al. 2007)

summary

# Summary

- interstellar gas is highly inhomogeneous

  - *thermal instability*
  - *gravitational instability*
  - *turbulent compression* (in shocks $\delta\rho/\rho \approx M^2$; in atomic gas: $M \approx 1...3$)

- 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 ($M \approx 1...20$)
  → *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*)
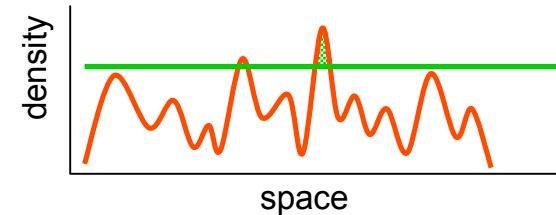
# Summary

- interstellar gas is highly *inhomogeneous*

  - *thermal instability*

  - *gravitational instability*

  - *turbulent compression* (in shocks $\delta\rho/\rho \propto M^2$; in atomic gas: $M \approx 1...3$)



- 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 ($M \approx 1...20$)
  → *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!

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