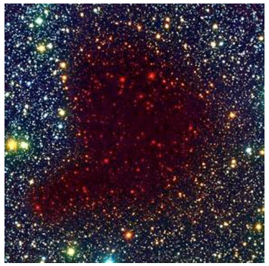
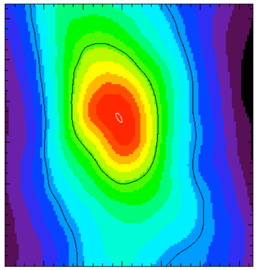
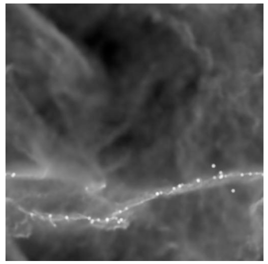
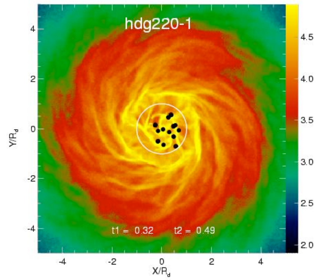
Star Formation









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ARI+ITA+LSW

ISM fragmentation: star formation

- theoretical approach to star formation
  (historic overview + recent developments)
- interplay between turbulence and gravity
  (properties of interstellar turbulence)
- application to star formation in Galactic molecular clouds

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?***

historic overview

Early dynamical theory

- *Jeans (1902):* Interplay between self-gravity and thermal pressure
  - stability of homogeneous spherical density enhancements against gravitational collapse
  - dispersion relation:

$$\omega^2 = c_s^2 k^2 - 4\pi G \rho_0$$

  - instability when $\omega^2 < 0$
  - minimal mass: $$M_J = \tfrac{1}{6}\pi^{-5/2} G^{-3/2} \rho_0^{-1/2} c_s^3 \propto \rho_0^{-1/2} T^{3/2}$$

Sir James Jeans, 1877 - 1946

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

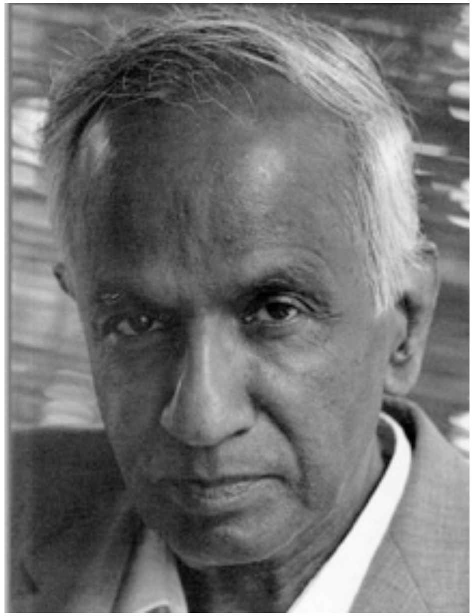
First approach to turbulence

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

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

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

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



S. Chandrasekhar, 1910 - 1995

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

Properties of IMS turbulence

ISM turbulence is:

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

> Microturbulent approach is NOT valid in ISM

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

Problems of early dynamical theory

- Molecular clouds are *highly Jeans-unstable*
  Yet, they do *NOT* form stars at high rate
  and with high efficiency.
  (the observed global SFE in molecular clouds is *~5%*)
  → *something prevents large-scale collapse.*
- All throughout the early 1990's, molecular clouds had been thought to be long-lived quasi-equilitrium entities.
- Molecular clouds are *magnetized.*

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

Magnetic star formation

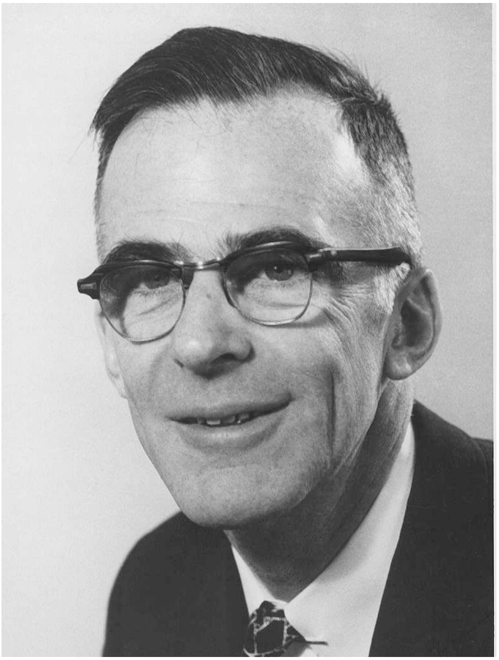
- *Mestel & Spitzer (1956):* Magnetic fields can prevent collapse*!!!*
  - Critical mass for gravitational collapse in presence of B-field

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

  - Critical mass-to-flux ratio (Mouschovias & Spitzer 1976)

$$\left[\frac{M}{\Phi}\right]_{cr} = \frac{\zeta}{3\pi}\left[\frac{5}{G}\right]^{1/2}$$

  - Ambipolar diffusion can initiate collapse

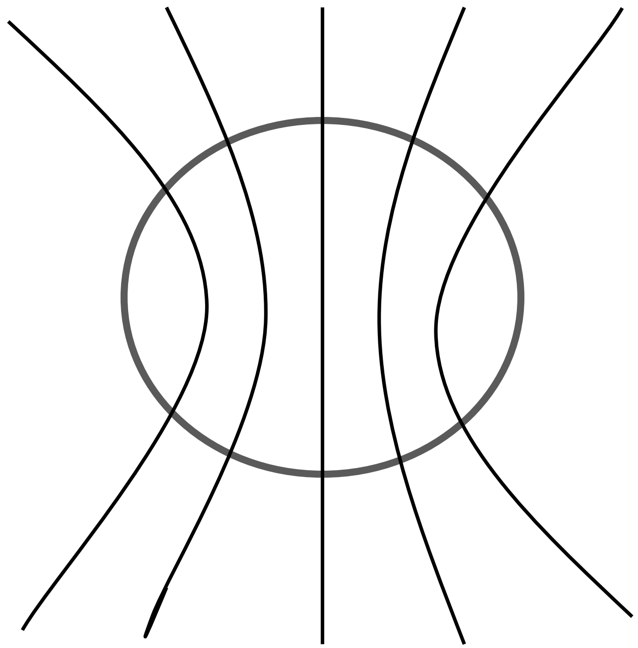


Lyman Spitzer, Jr., 1914 - 1997

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

The "standard theory" of star formation:

- BASIC ASSUMPTION: Stars form from magnetically highly subcritical cores
- Ambipolar diffusion slowly increases (M/Φ): $\tau_{AD} \approx 10\tau_{ff}$
- Once $(M/\Phi) > (M/\Phi)_{crit}$: dynamical collapse of SIS
  - Shu (1977) collapse solution
  - $dM/dt = 0.975\ c_s^3/G = \text{const.}$
- Was (in principle) only intended for isolated, low-mass stars



Problems of magnetic SF

- Observed B-fields are weak, at most marginally critical (Crutcher 1999, Bourke et al. 2001)
- Magnetic fields cannot prevent decay of turbulence
  (Mac Low et al. 1998, Stone et al. 1998, Padoan & Nordlund 1999)
- Structure of prestellar cores
  (Bacman et al. 2000, e.g. Barnard 68 from Alves et al. 2001)
- Strongly time varying dM/dt
  (e.g. Hendriksen et al. 1997, André et al. 2000)
- More extended infall motions than predicted by the standard model
  (Williams & Myers 2000, Myers et al. 2000)

Observed B-fields are weak

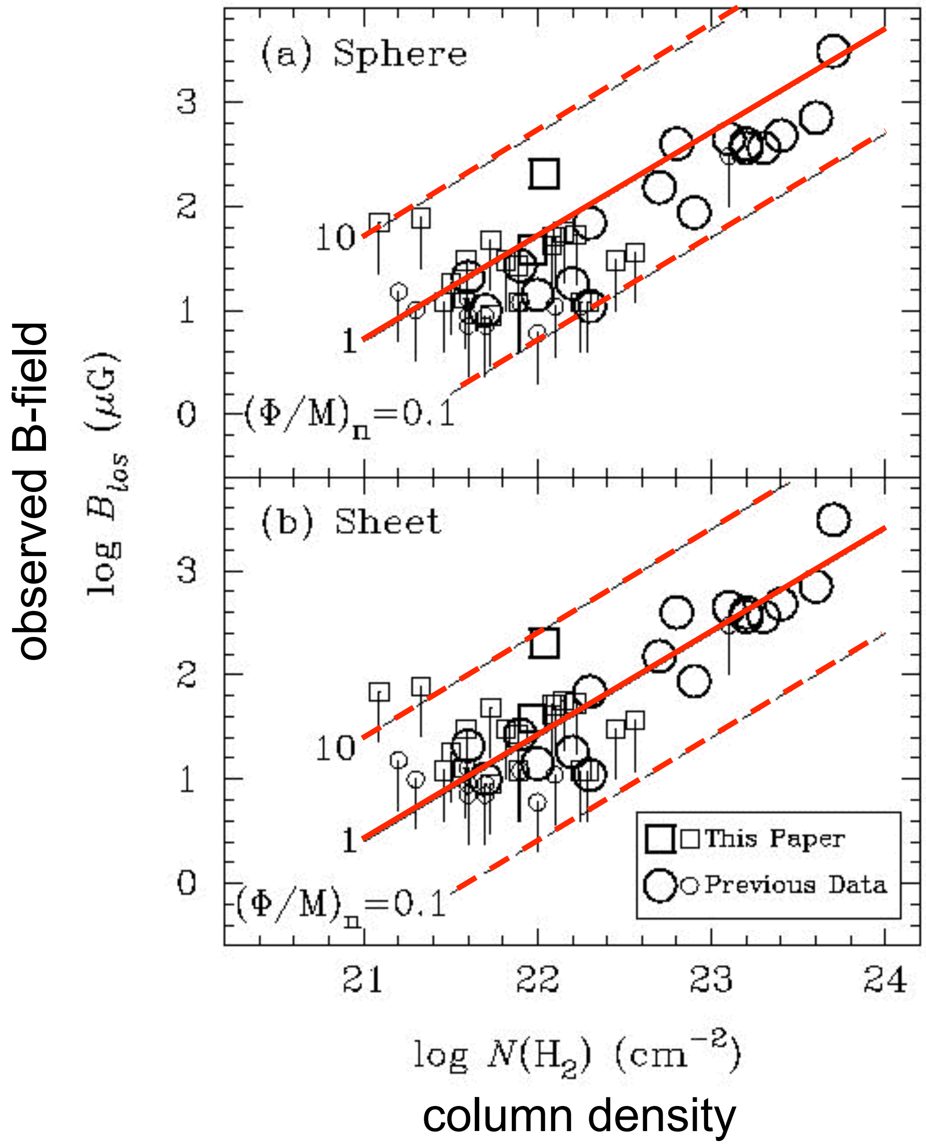
B versus ***N(H₂)*** from *Zeeman measurements*.

(from Bourke et al. 2001)

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

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

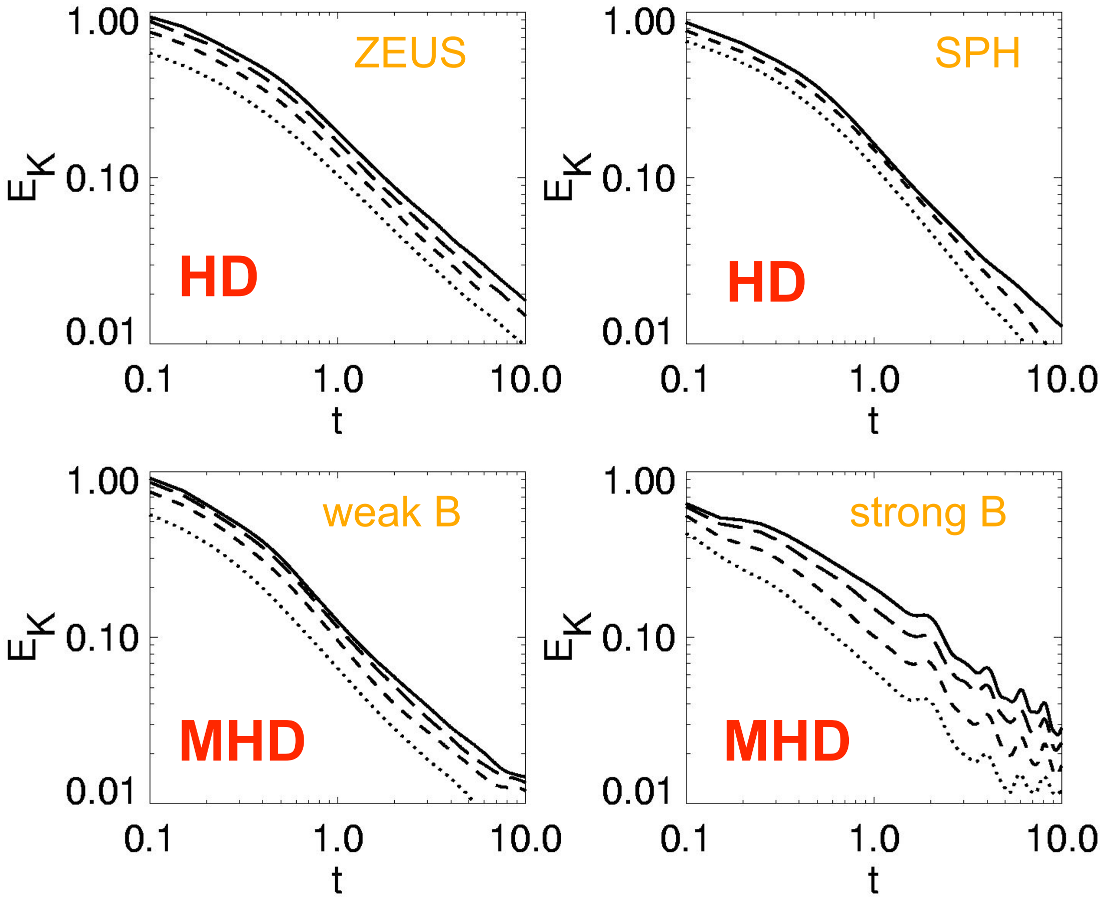
$(\Phi/M)_n < 1$ collapse



Molecular cloud dynamics

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

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



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

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

Ra

Problems of magnetic SF

- As many prestellar cores as protostellar cores in SF regions (e.g. André et al 2002)
- Molecular cloud clumps seem to be chemically young
  (Bergin & Langer 1997, Pratap et al 1997, Aikawa et al 2001)
- Stellar age distribution small ($\tau_{ff} << \tau_{AD}$)
  (Ballesteros-Paredes et al. 1999, Elmegreen 2000, Hartmann 2001)
- Strong theoretical criticism of the SIS as starting condition for gravitational collapse
  (e.g. Whitworth et al 1996, Nakano 1998, as summarized in Klessen & Mac Low 2004)
- Most stars form as binaries

modern ideas

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:

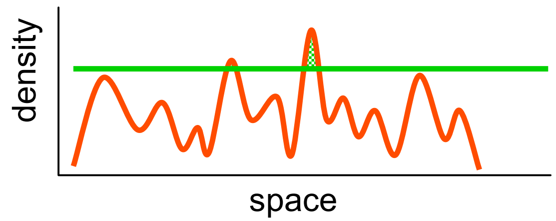
Star formation is controlled by interplay between gravity and supersonic turbulence!

- 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

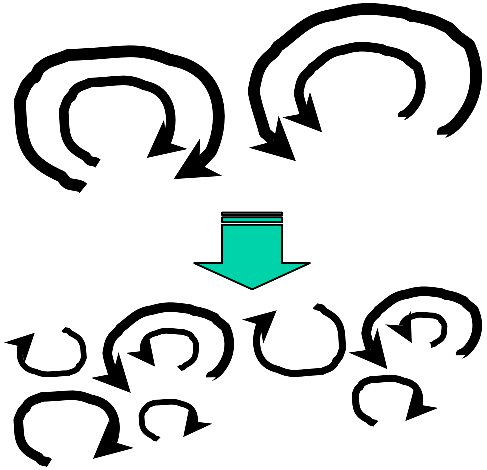
  ⟶ ***GRAVOTUBULENT FRAGMENTATION***
- *turbulent cascade:* local compression *within* a cloud provokes collapse
  → formation of individual *stars* and *star clusters*

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

turbulence

Properties of turbulence

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



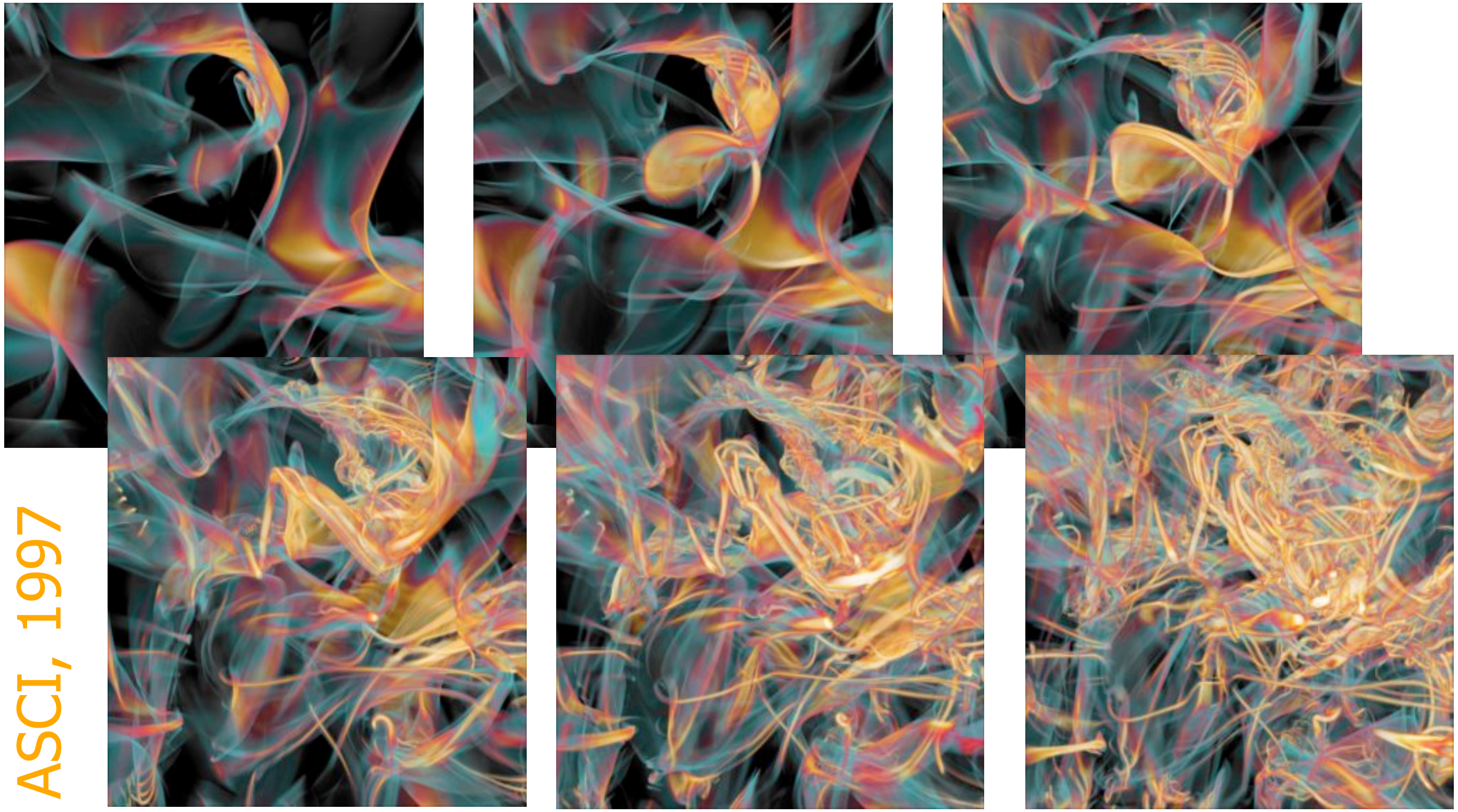
$$\mathrm{Re} = \frac{\text{advection}}{\text{dissipation}} = \frac{VL}{\nu}$$

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)

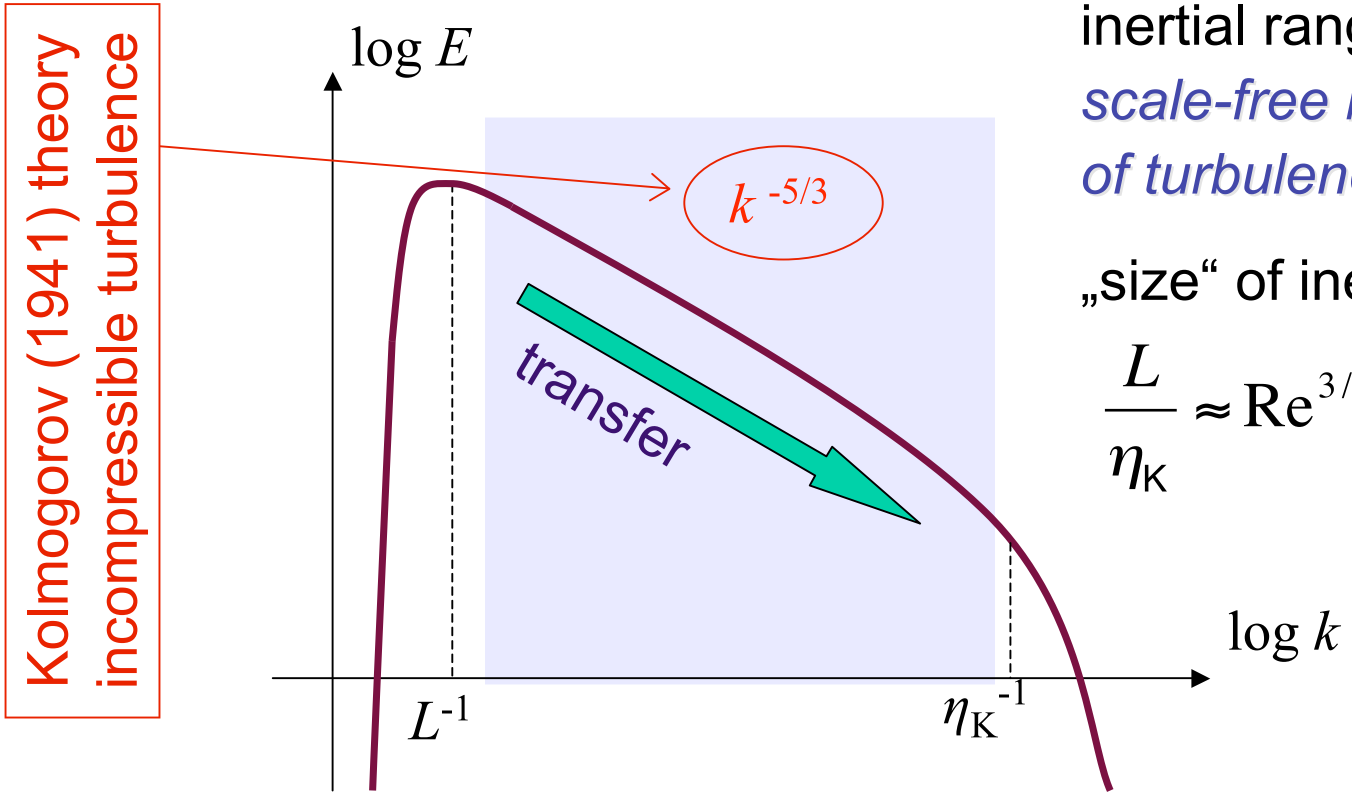
Vortex Formation



Porter et al.
ASCI, 1997

Vortices are streched and folded in three dimensions

Turbulent cascade



energy
input
scale

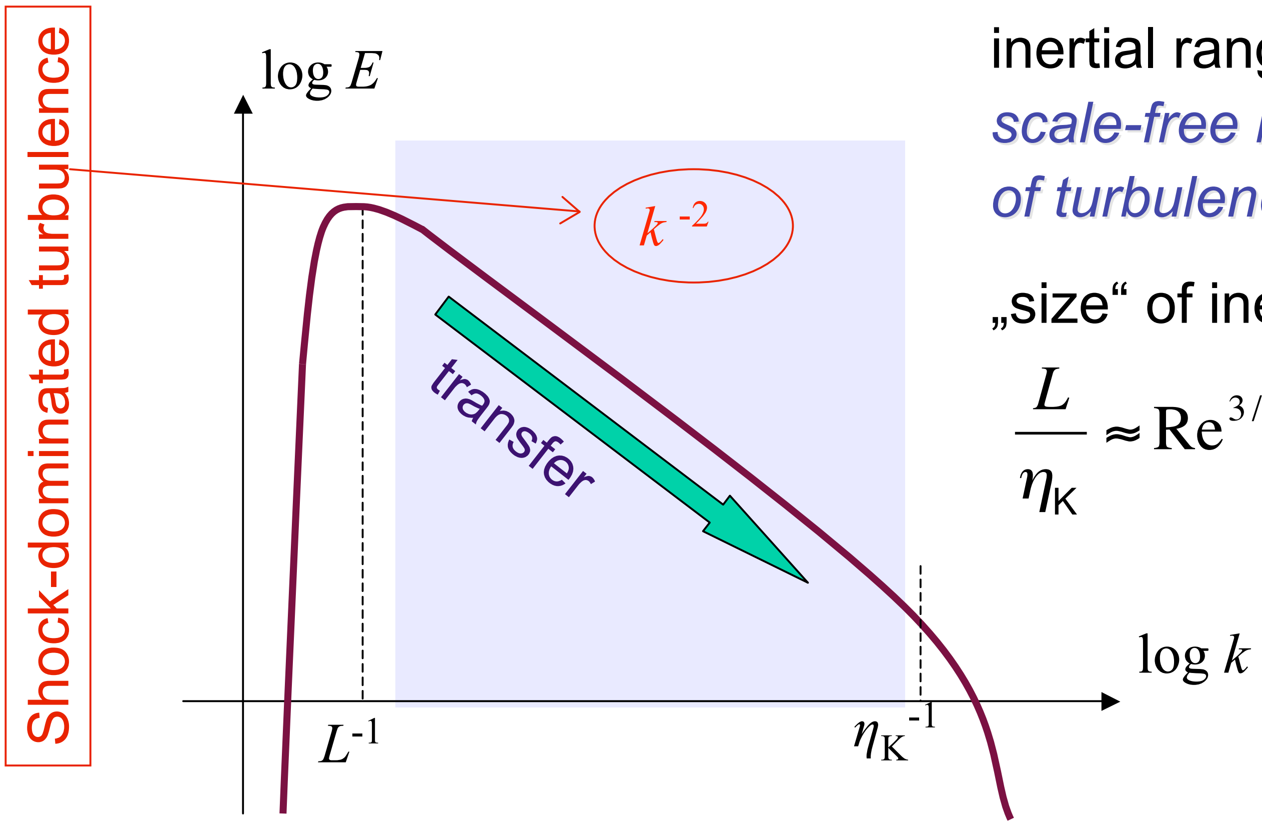
energy
dissipation
scale

inertial range:
scale-free behavior of turbulence

„size“ of inertial range:

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

Turbulent cascade



inertial range:

scale-free behavior of turbulence

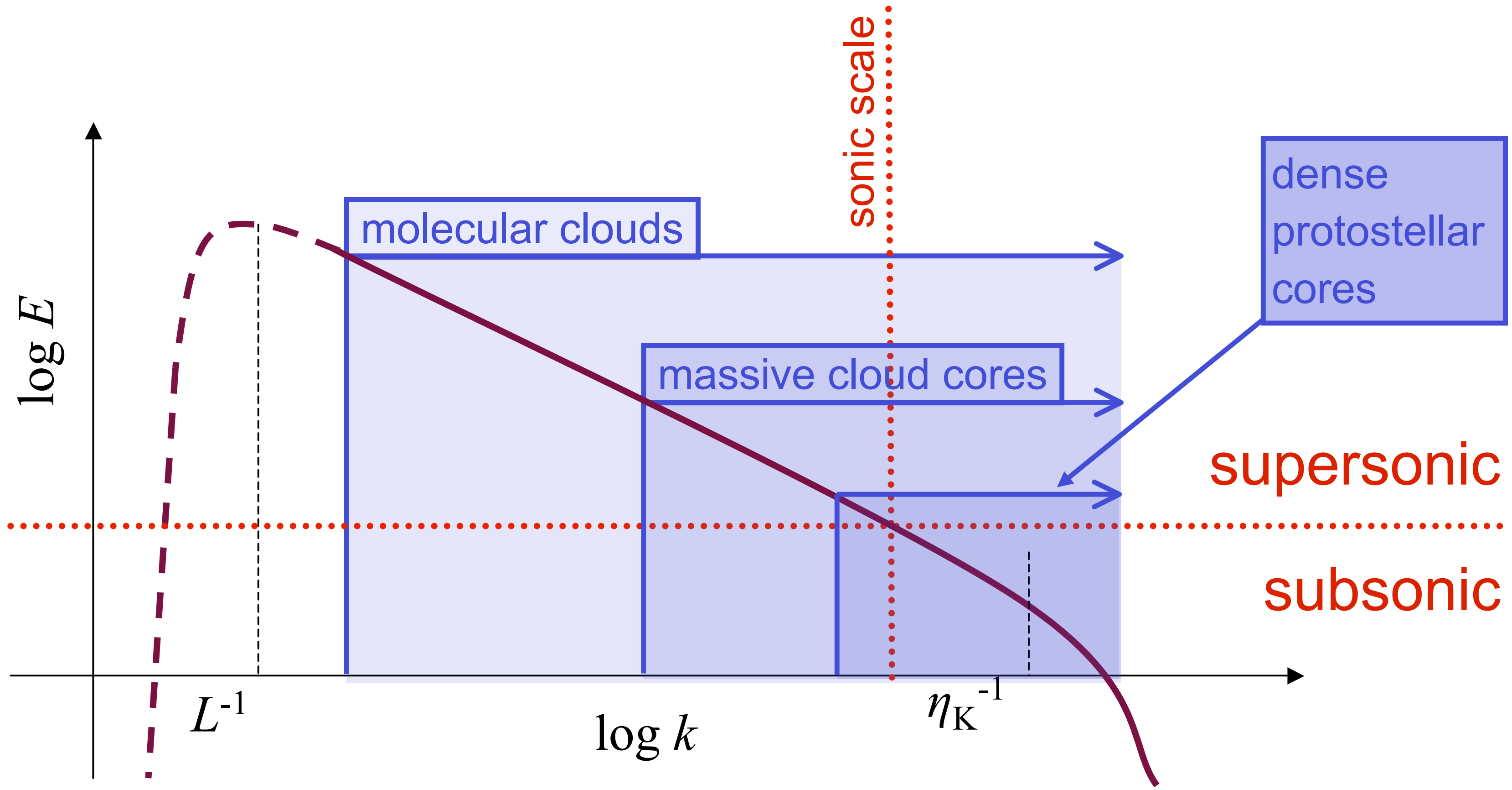
„size“ of inertial range:

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

energy input scale

energy dissipation scale

Turbulent cascade in ISM

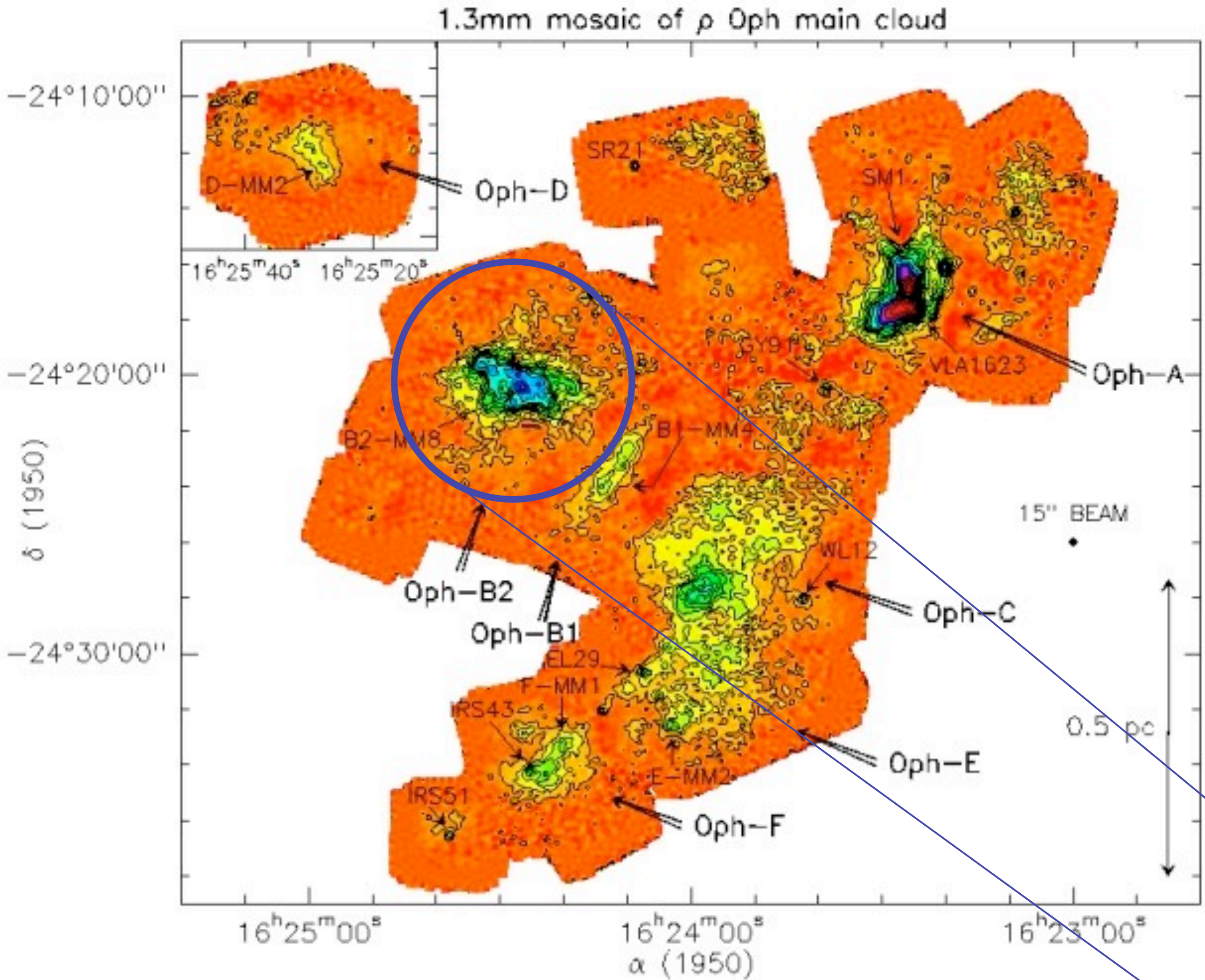


energy source & scale
NOT known
(supernovae, winds,
spiral density waves?)

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)

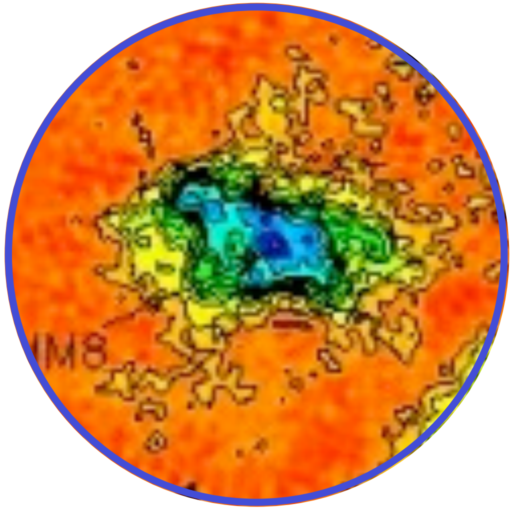
molecular clouds are highly inhomogeneous

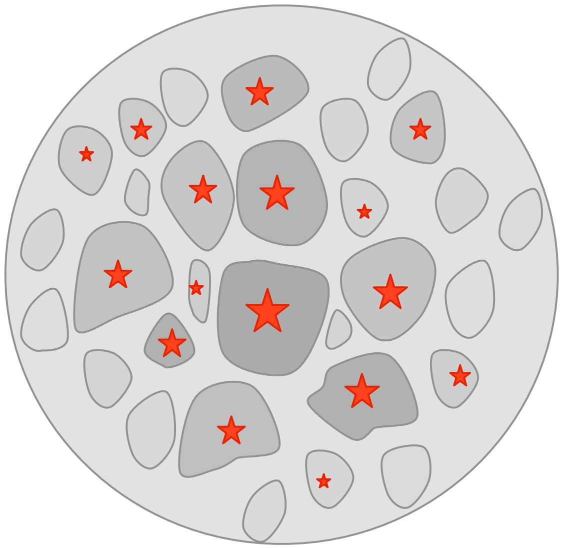
stars form in the densest and coldest parts of the cloud

ρ-Ophiuchus cloud seen in dust emission

let's focus on a cloud core like this one

Evolution of cloud cores

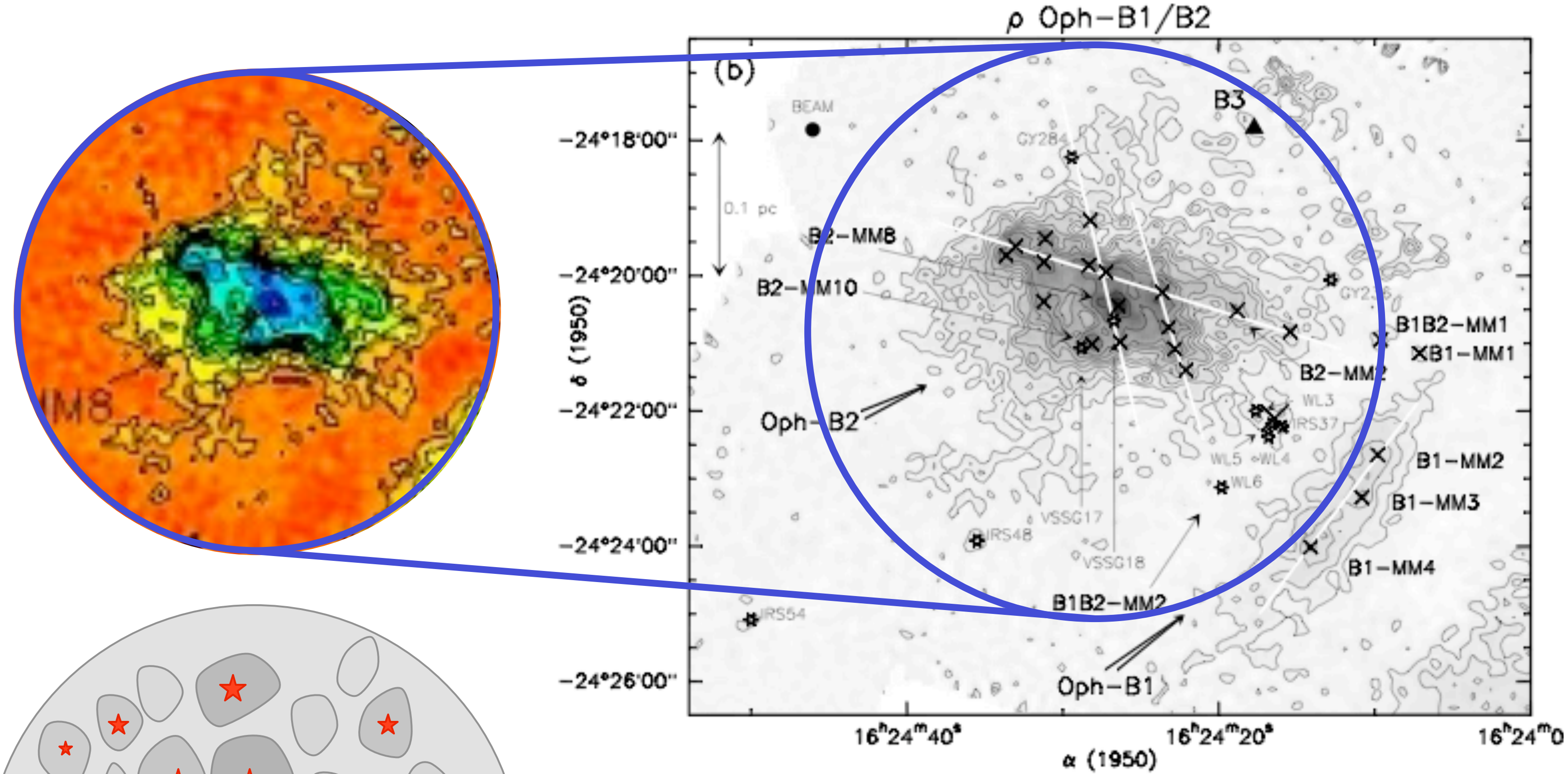


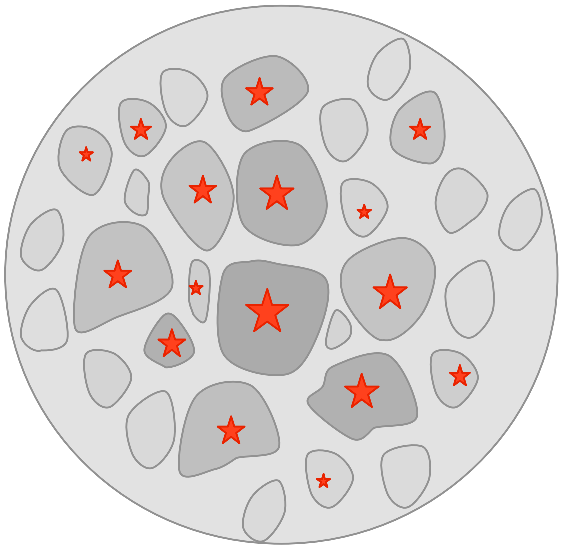


- How does this core evolve? Does it form one single massive star or cluster with mass distribution?

- 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



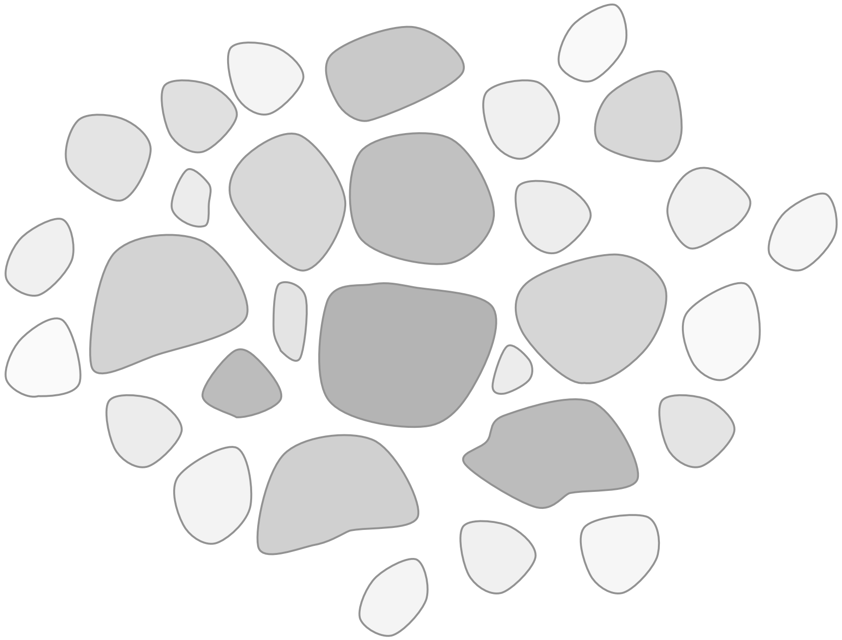


indeed ρ-Oph B1/2 contains several cores (“starless” cores are denoted by ×, cores with embedded protostars by ☆)

(Motte, André, & Neri 1998)

Formation and evolution of cores

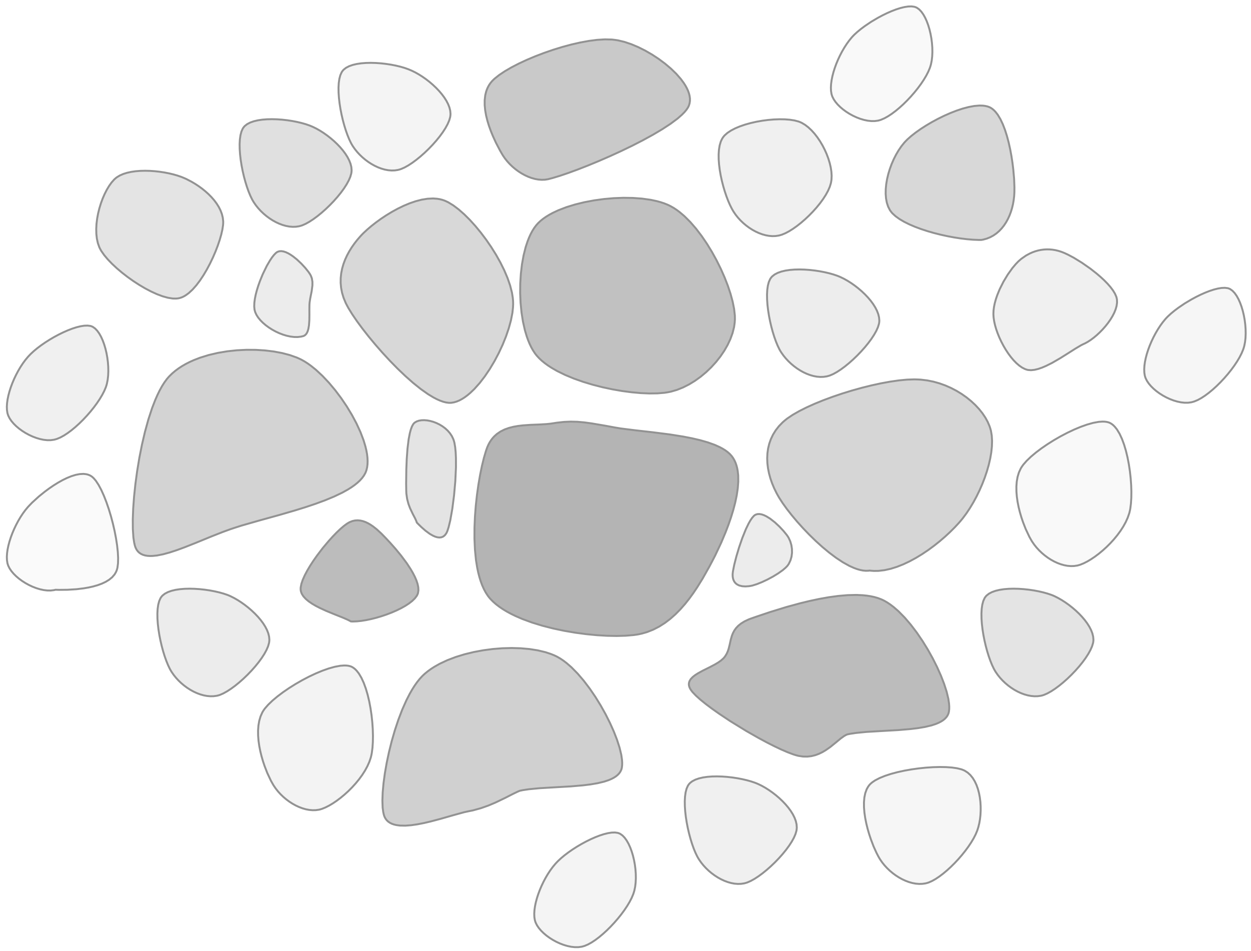
What happens to distribution of cloud cores?



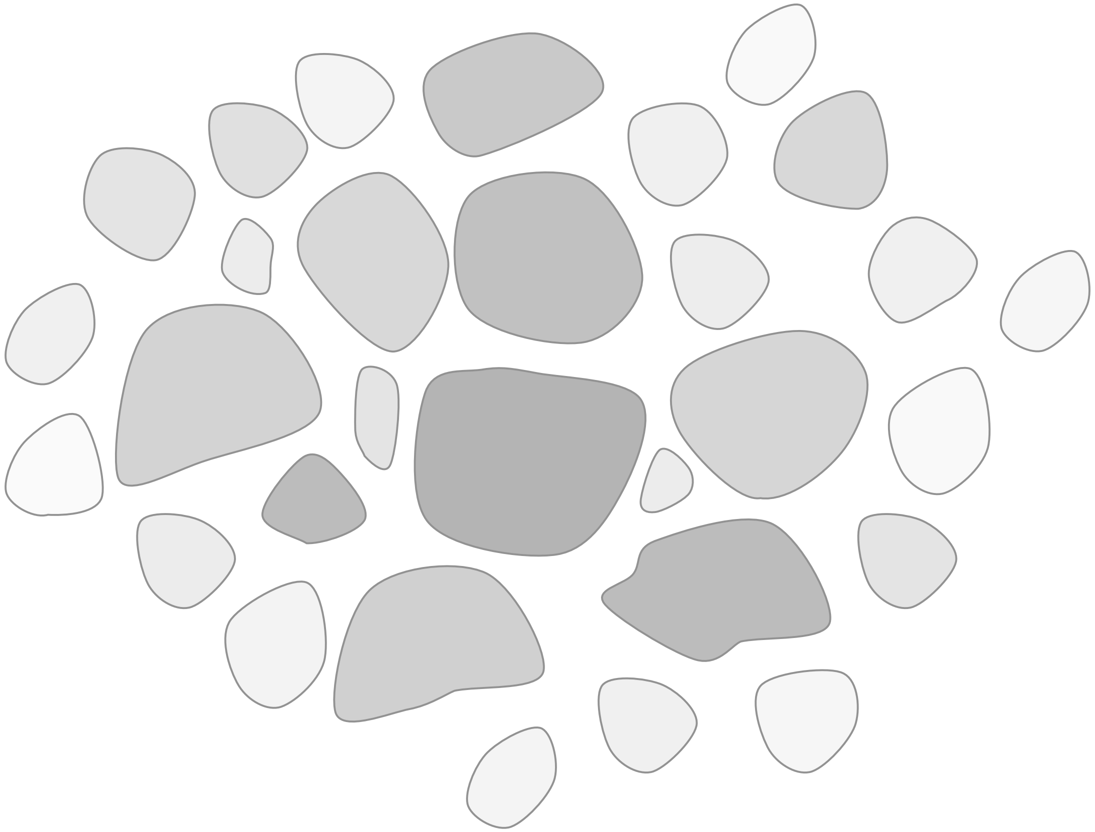
Two exteme cases:

(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*

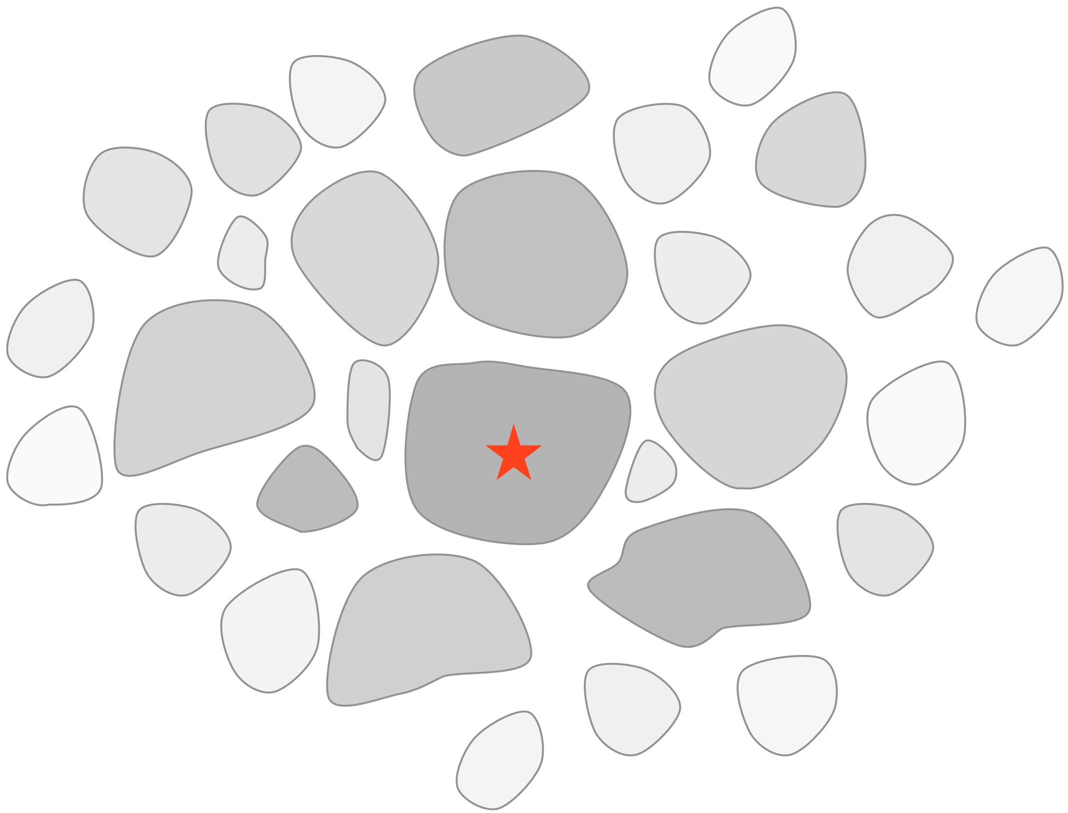
(2) turbulence decays, i.e. gravity dominates: $\alpha = E_{kin}/|E_{pot}| < 1$
--> *global contraction*
--> core do *interact* while collapsing
--> *competition* influences *mass growth*
--> *dense cluster with high-mass stars*



turbulence creates a hierarchy of clumps



while region contracts, individual clumps collapse to form stars



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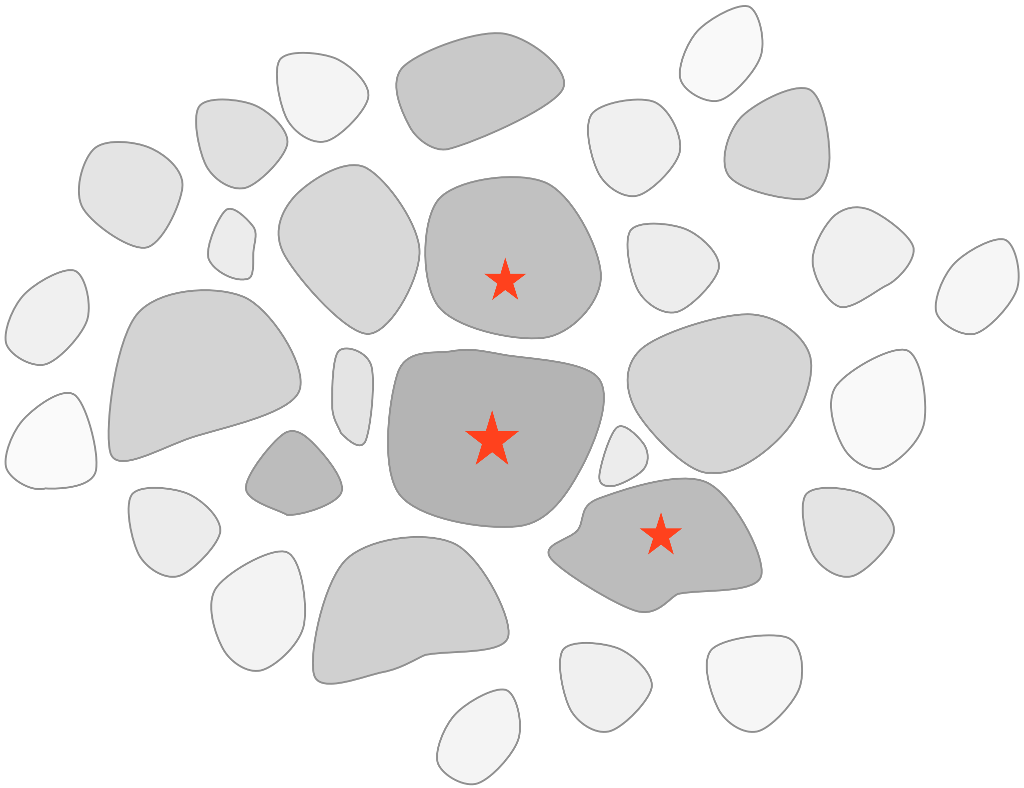
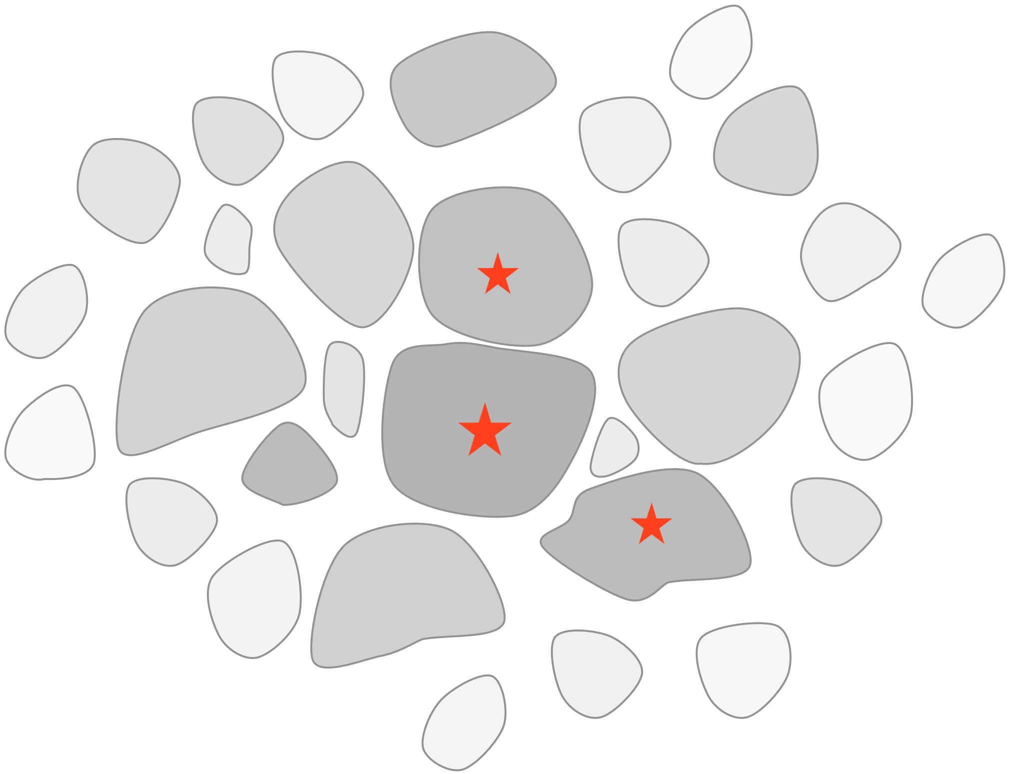
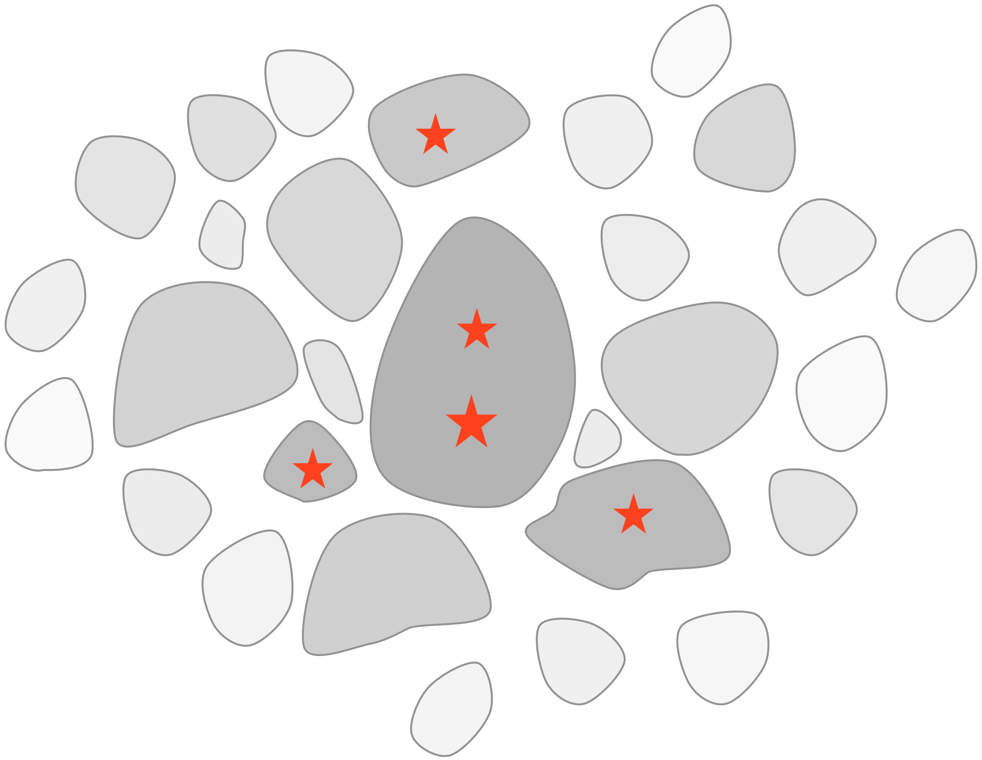


individual clumps collapse to form stars

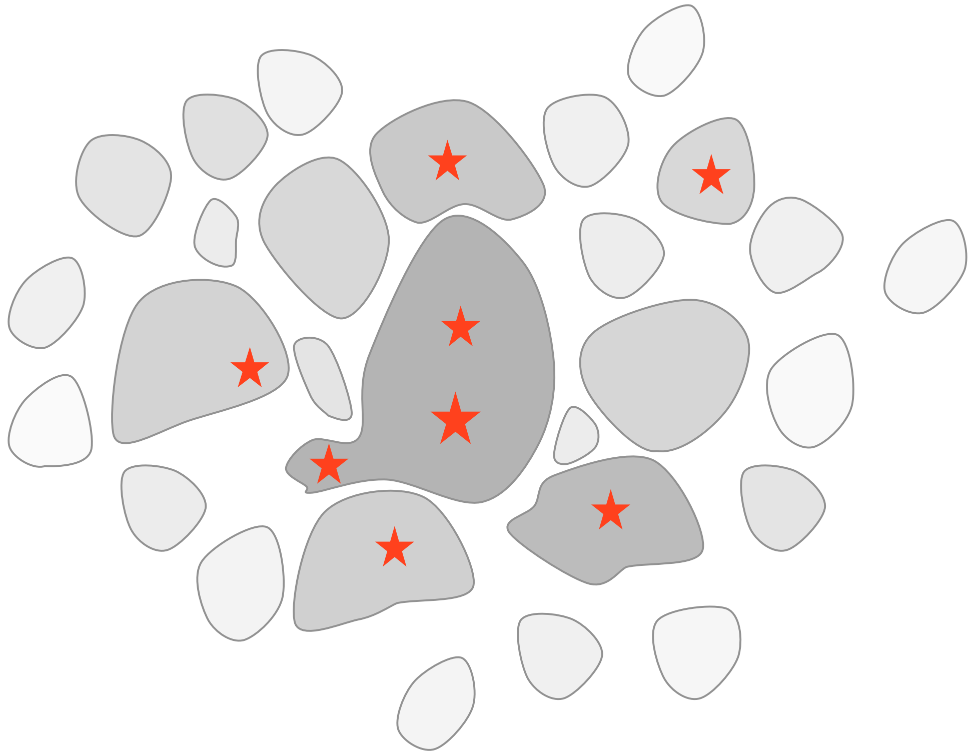


individual clumps collapse to form stars



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

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



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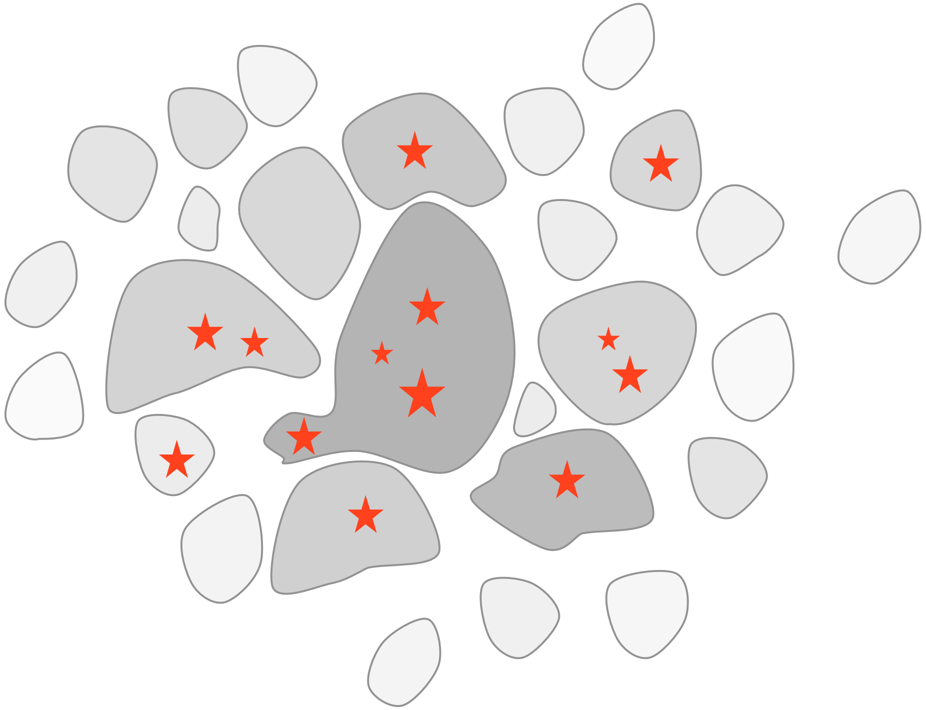

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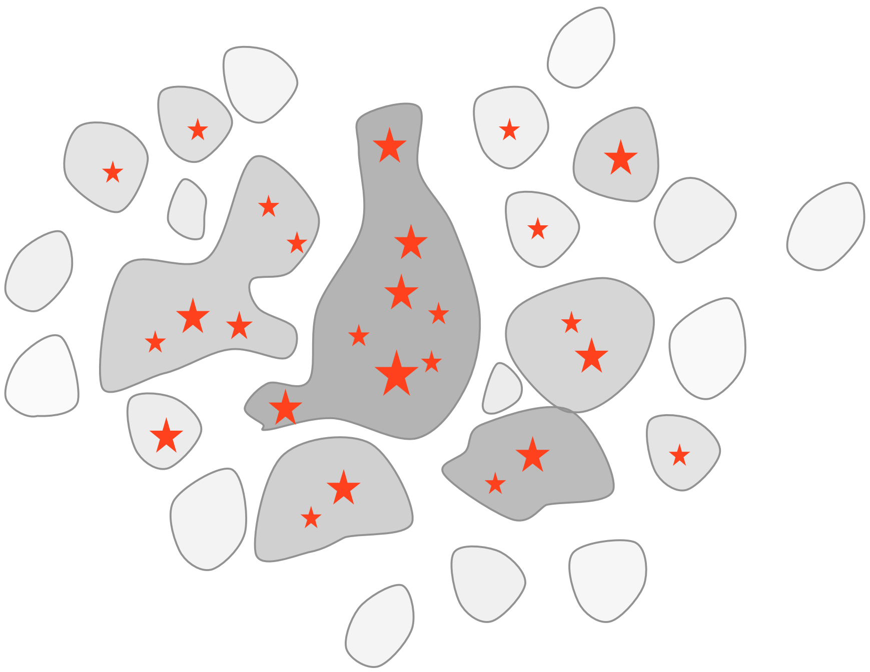
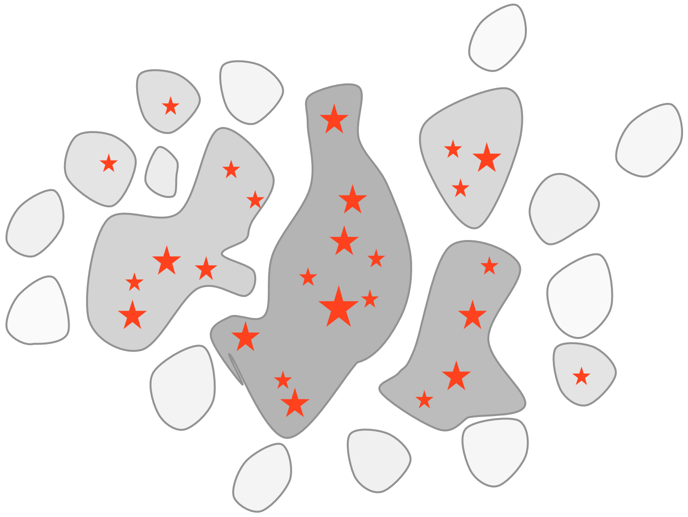


in *dense clusters*, competitive mass growth becomes important



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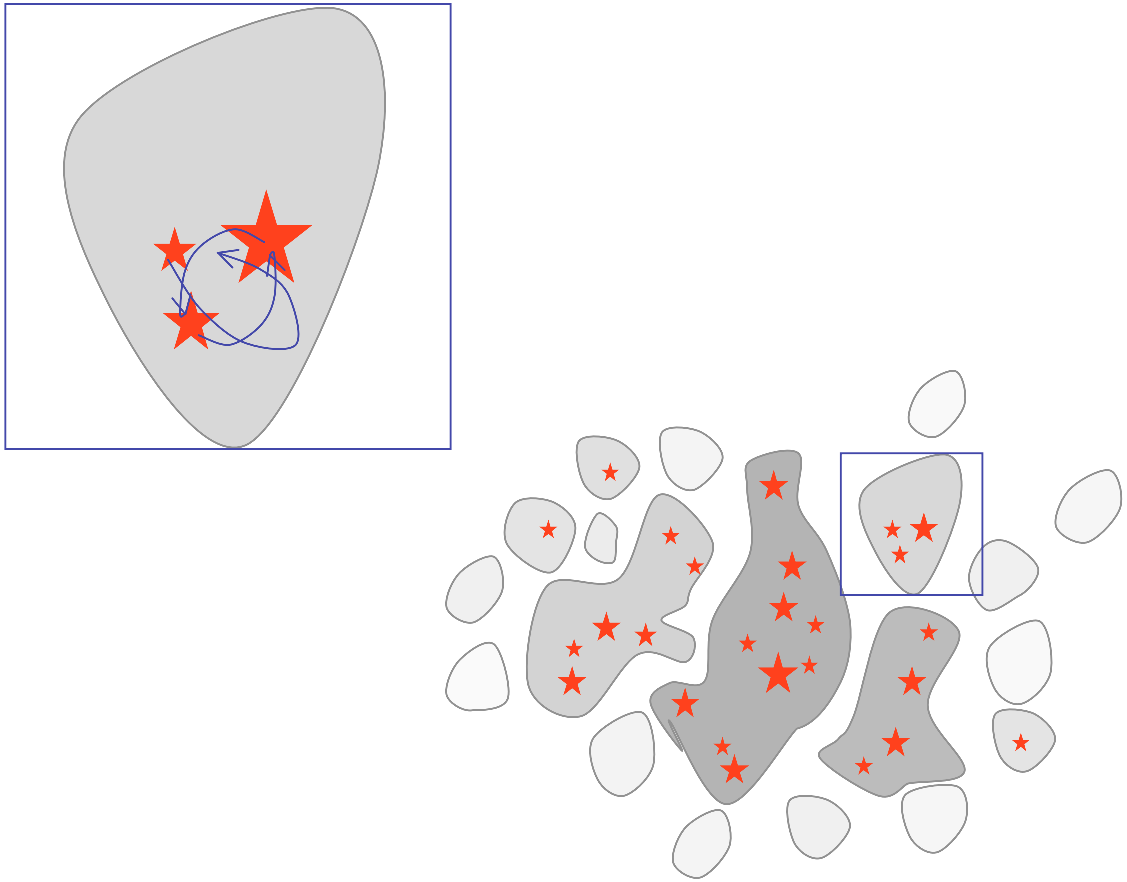
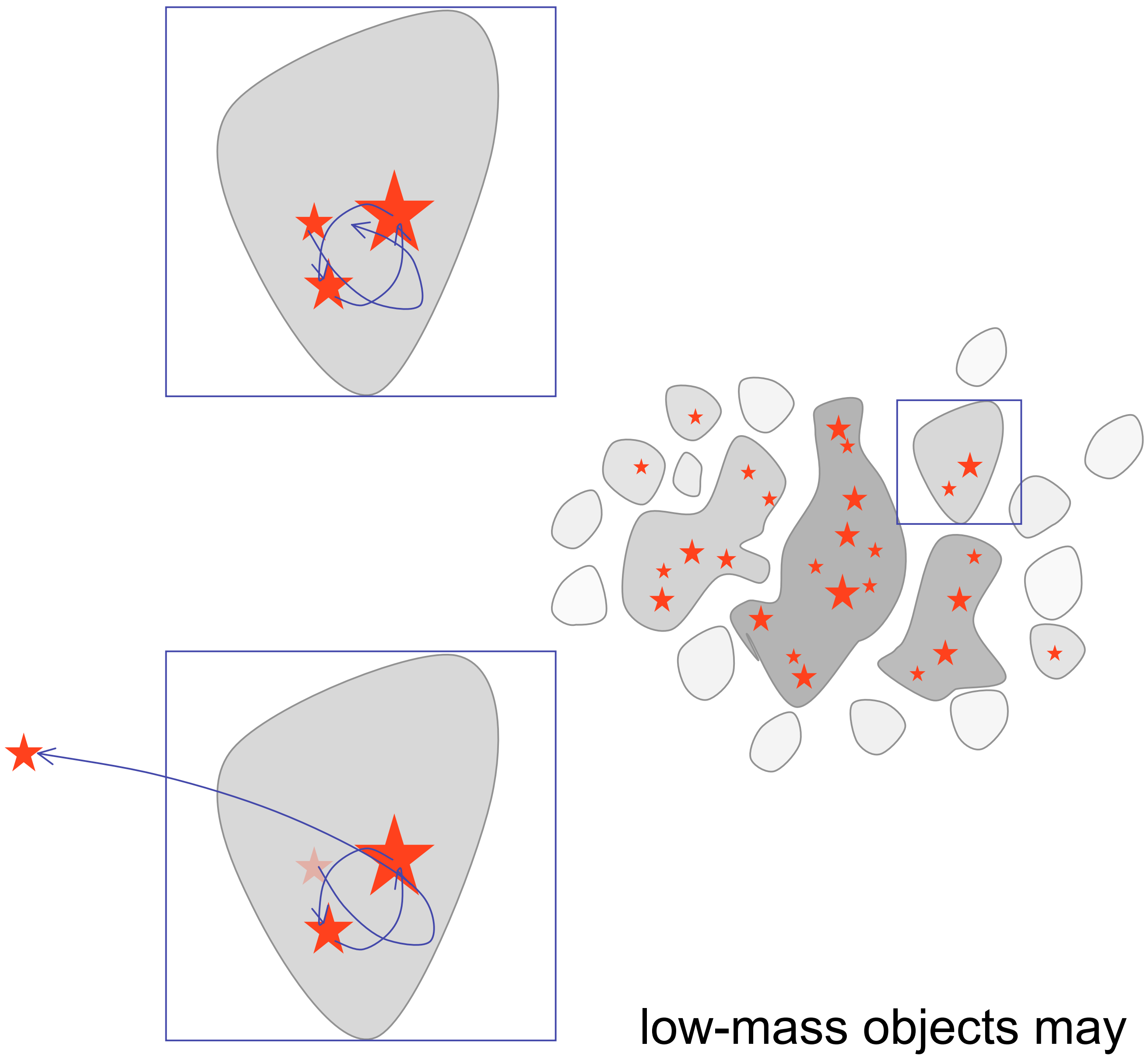
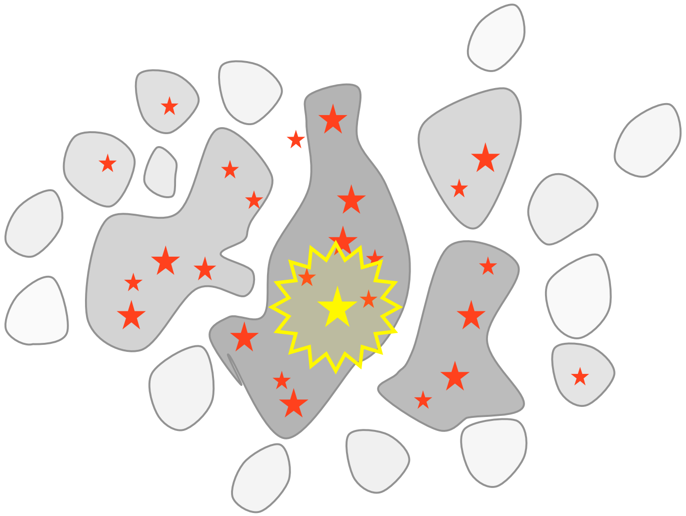


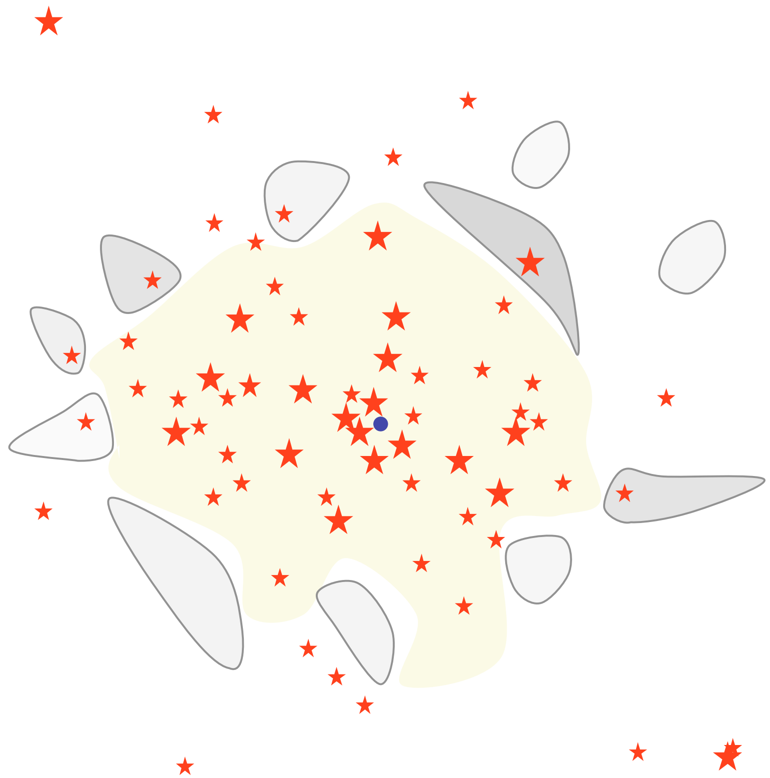
in *dense clusters*, *N*-body effects influence mass growth



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



feedback terminates star formation



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

Predictions

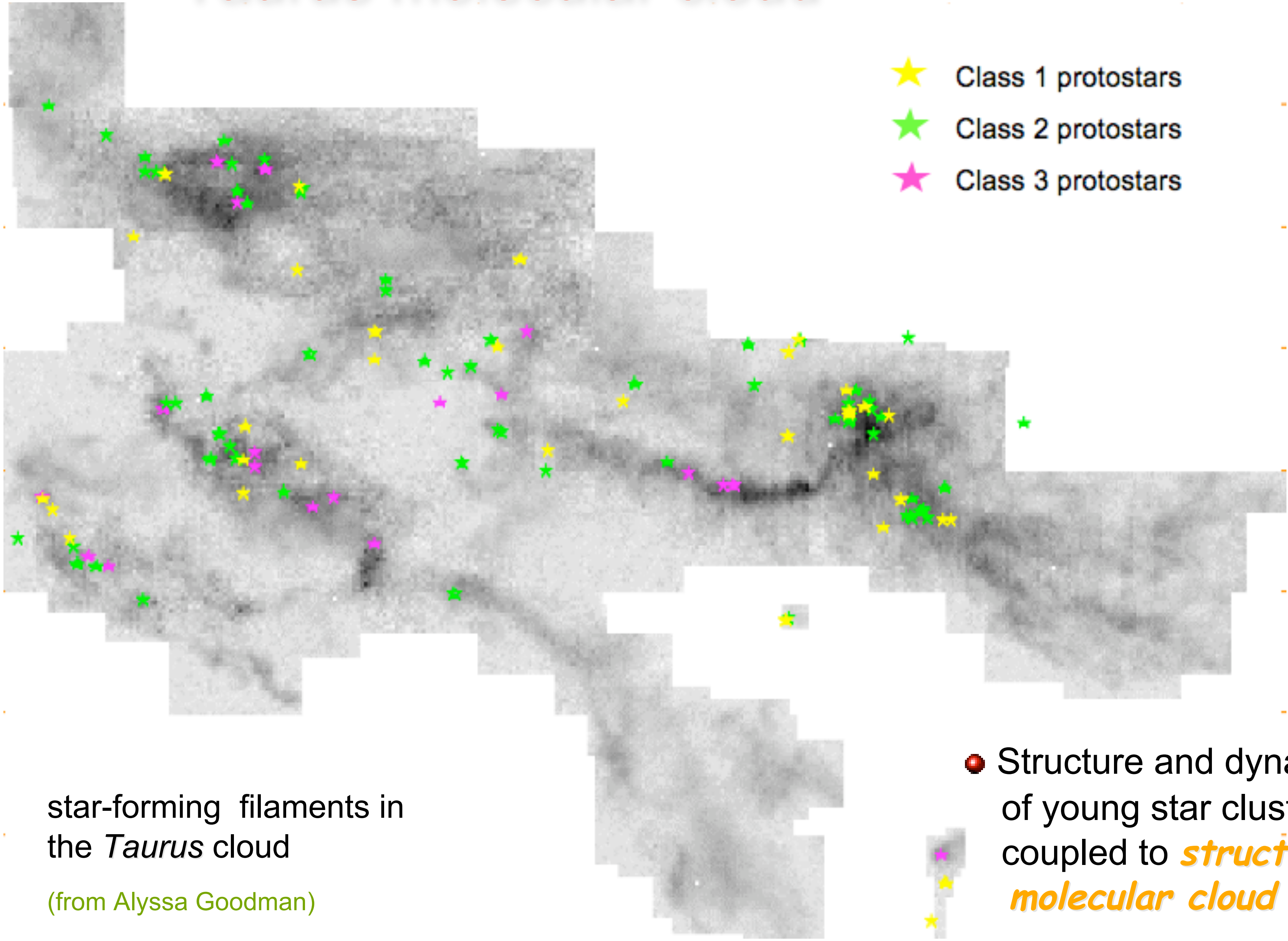
- *global properties* (statistical properties)
  - SF efficiency and timescale
  - stellar mass function -- IMF
  - dynamics of young star clusters
  - description of self-gravitating turbulent systems (pdf's, Δ-*var.)*
  - chemical mixing properties
- *local properties* (properties of individual objects)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

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

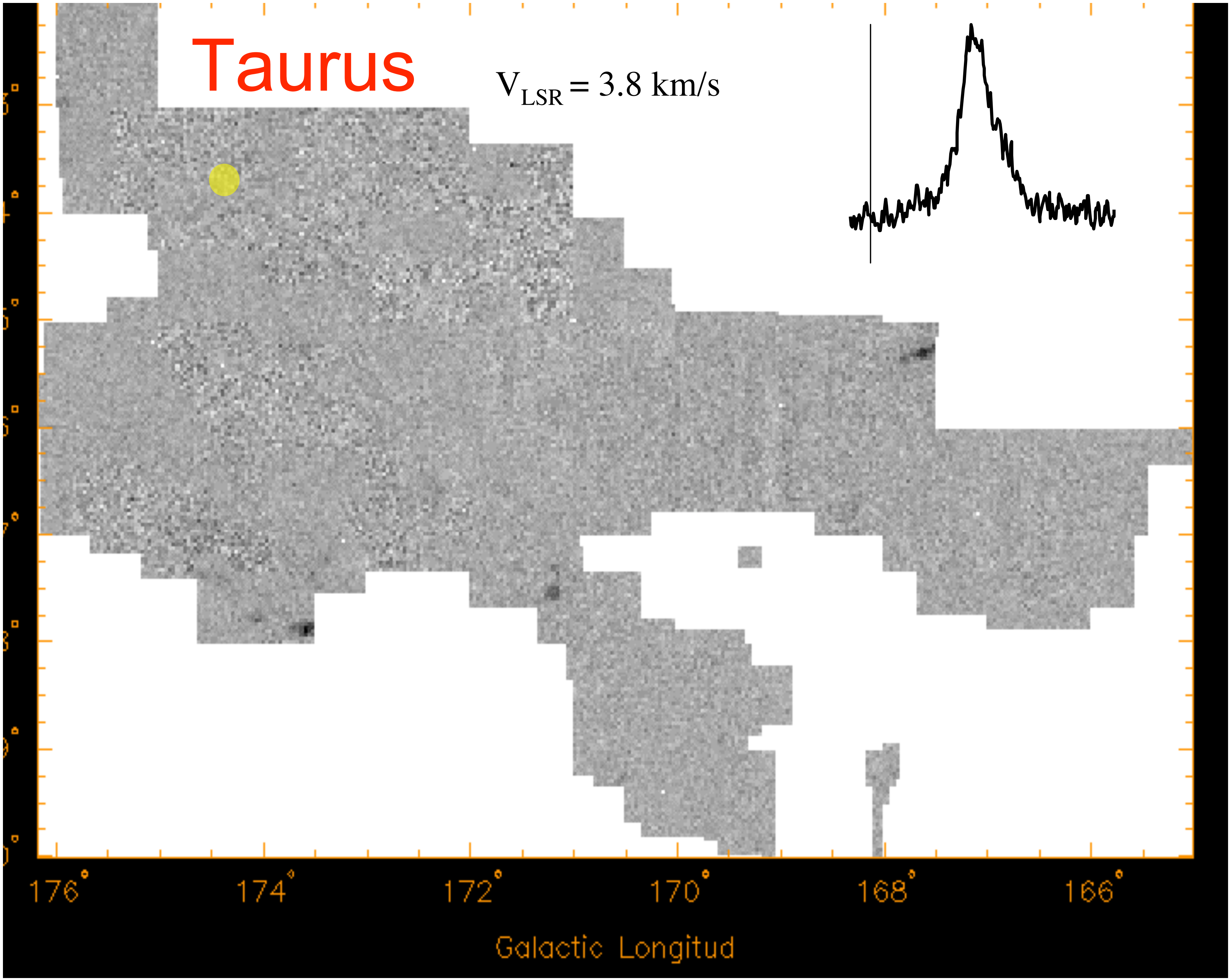
Taurus molecular cloud



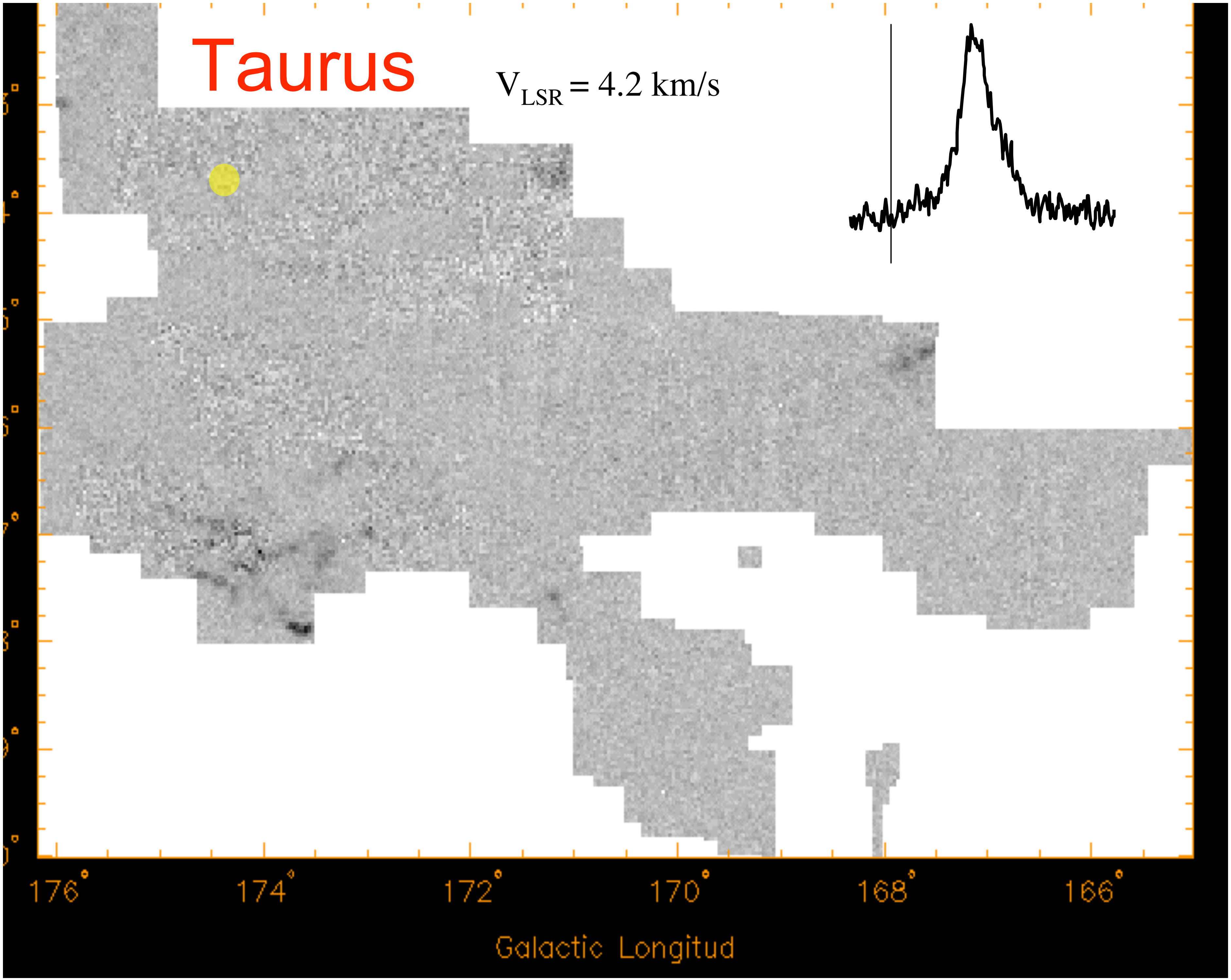
star-forming filaments in the *Taurus* cloud

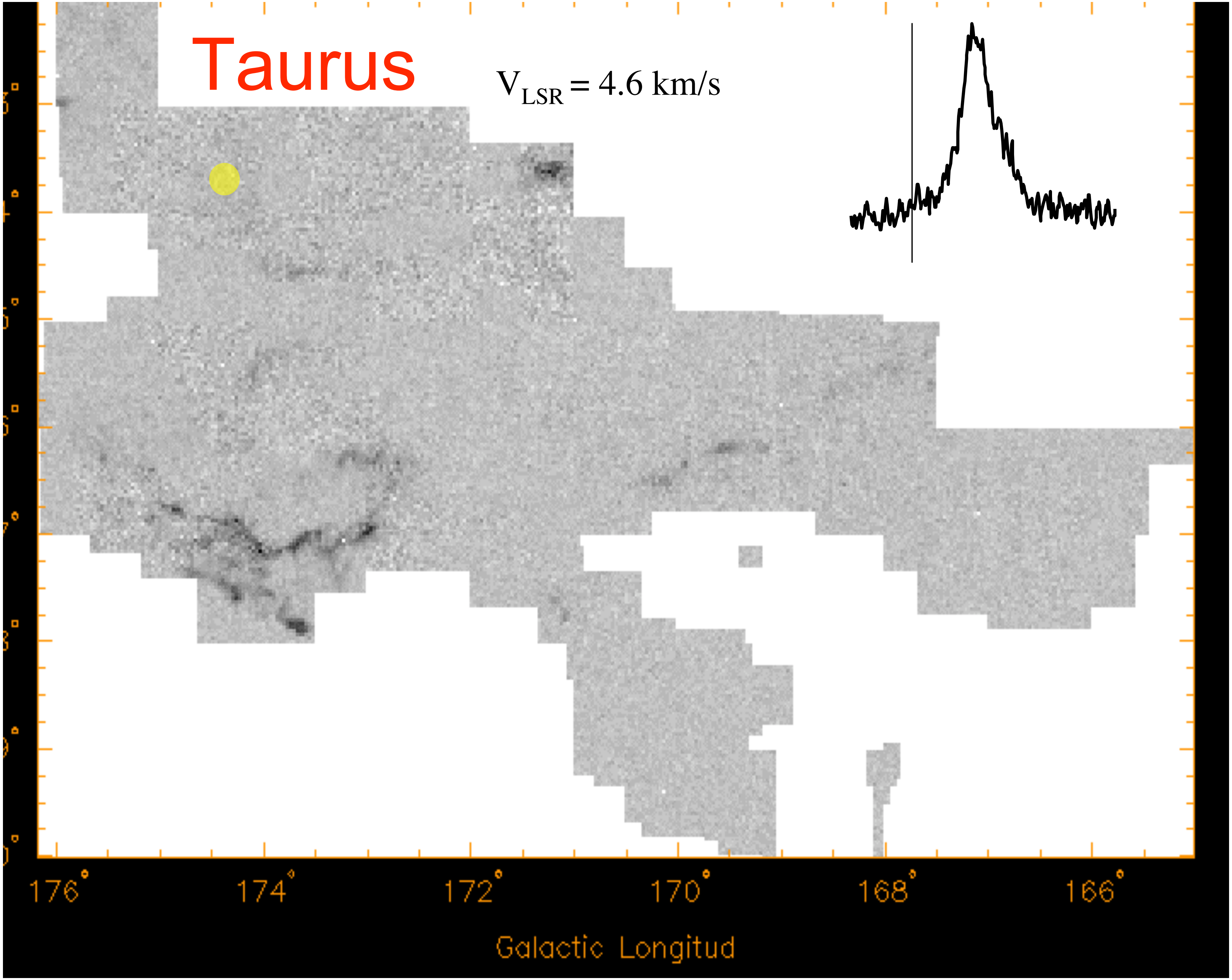
(from Alyssa Goodman)

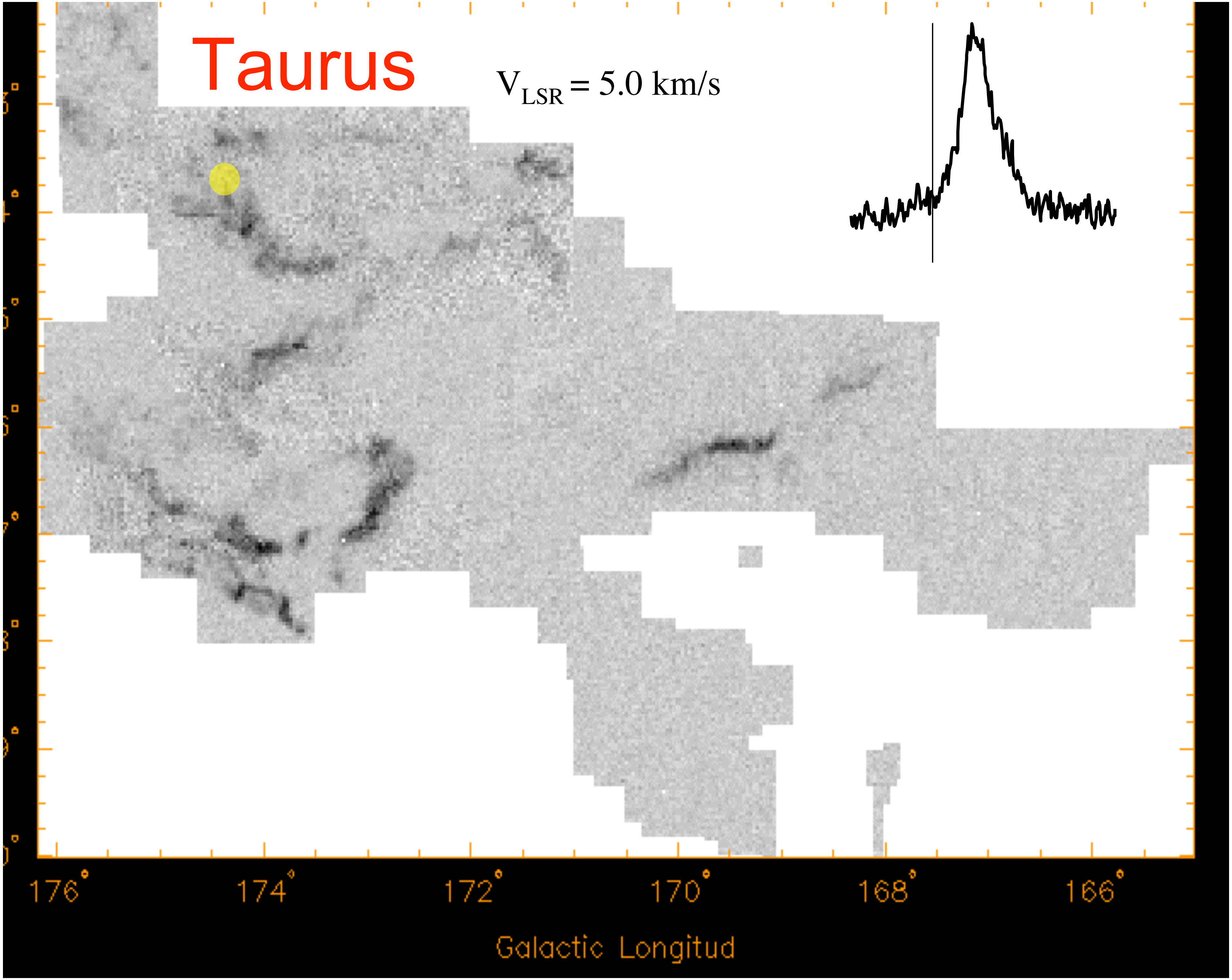
- Structure and dynamics of young star clusters is coupled to ***structure of molecular cloud***



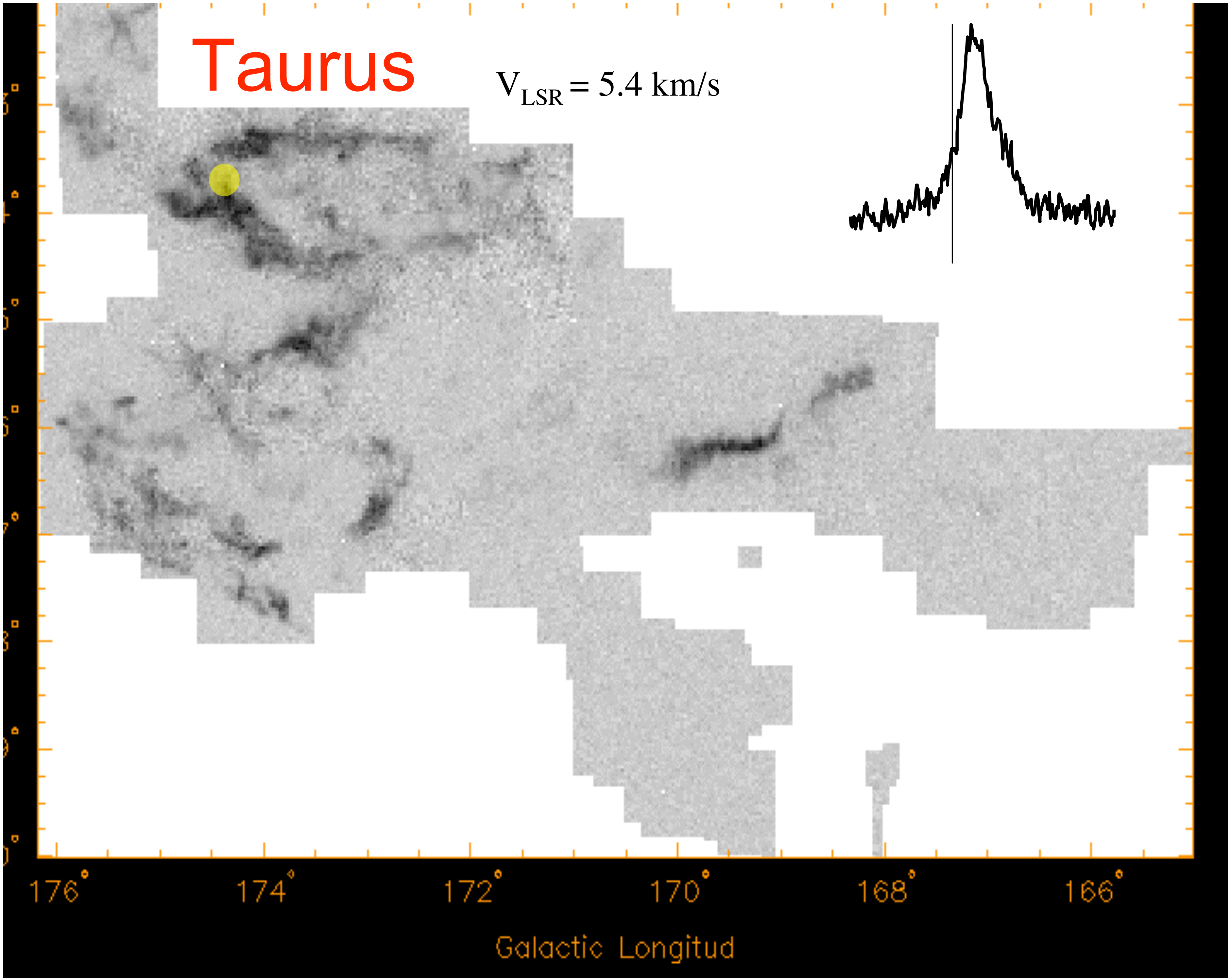
Taurus
V_LSR = 3.8 km/s
176°
174°
172°
170°
168°
166°
Galactic Longitud


Taurus
V_LSR = 4.2 km/s
176°
174°
172°
170°
168°
166°
Galactic Longitud

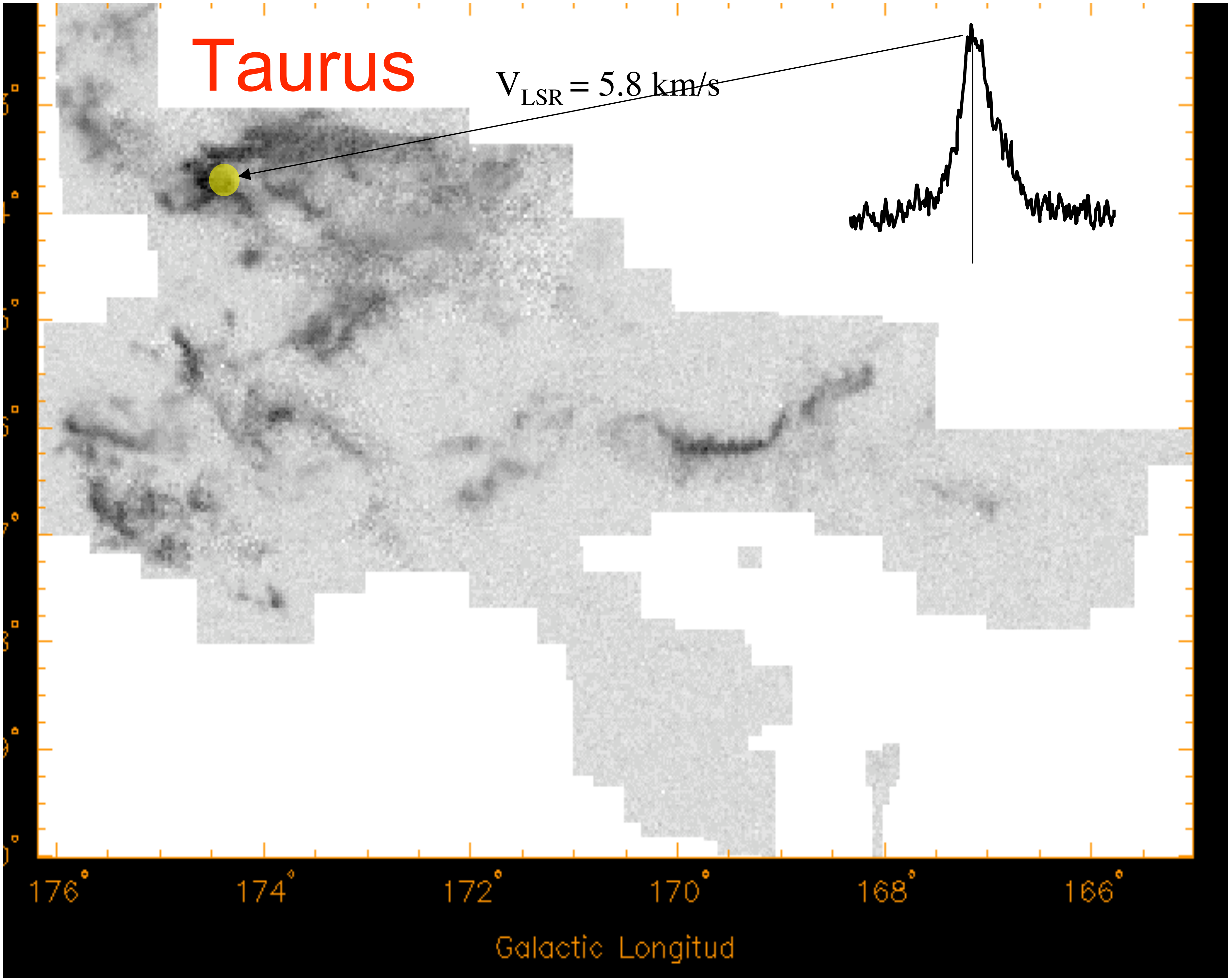

Taurus
V_{LSR} = 4.6 km/s
176°
174°
172°
170°
168°
166°
Galactic Longitud

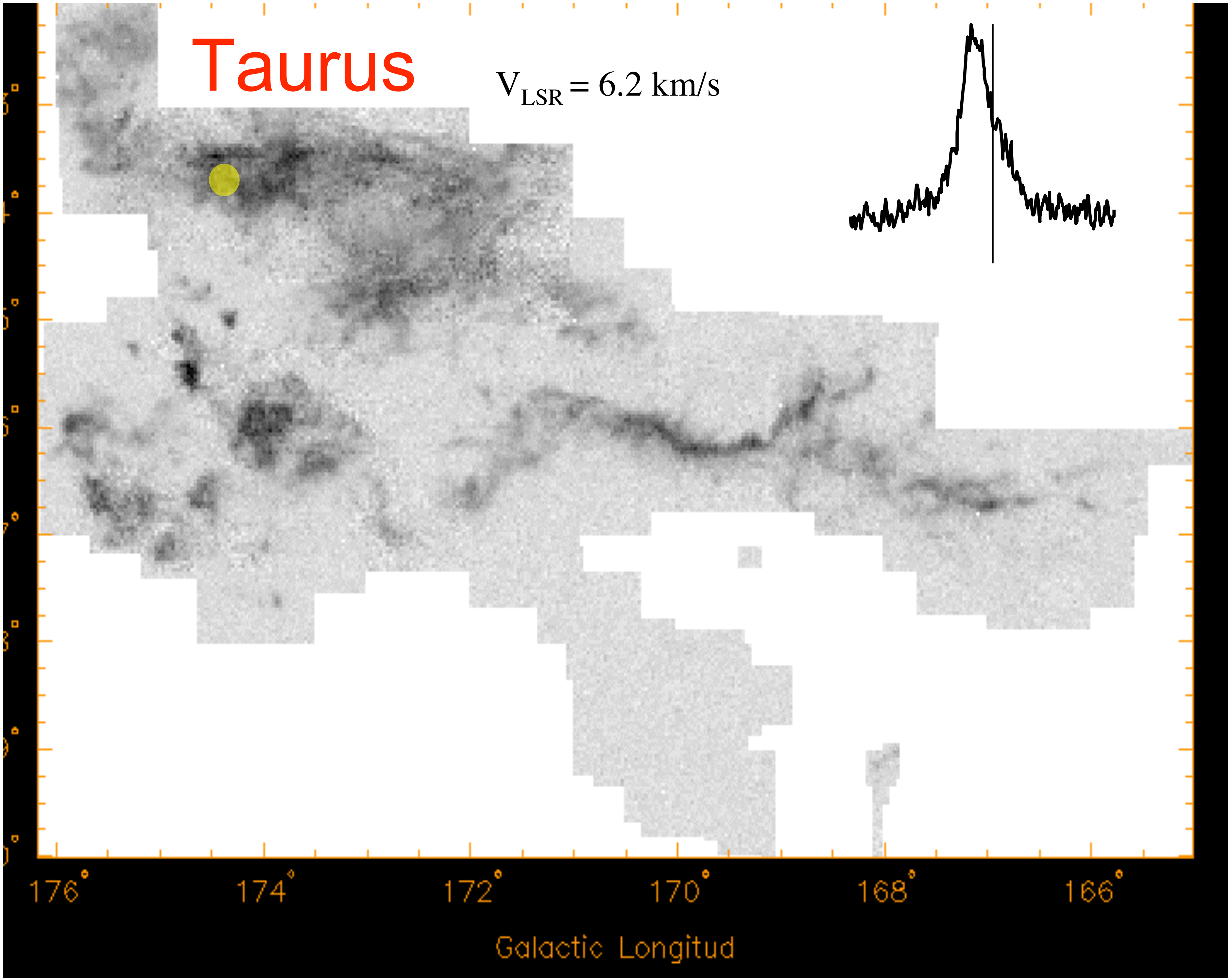


Taurus
V_{LSR} = 5.0 km/s
176°
174°
172°
170°
168°
166°
Galactic Longitud

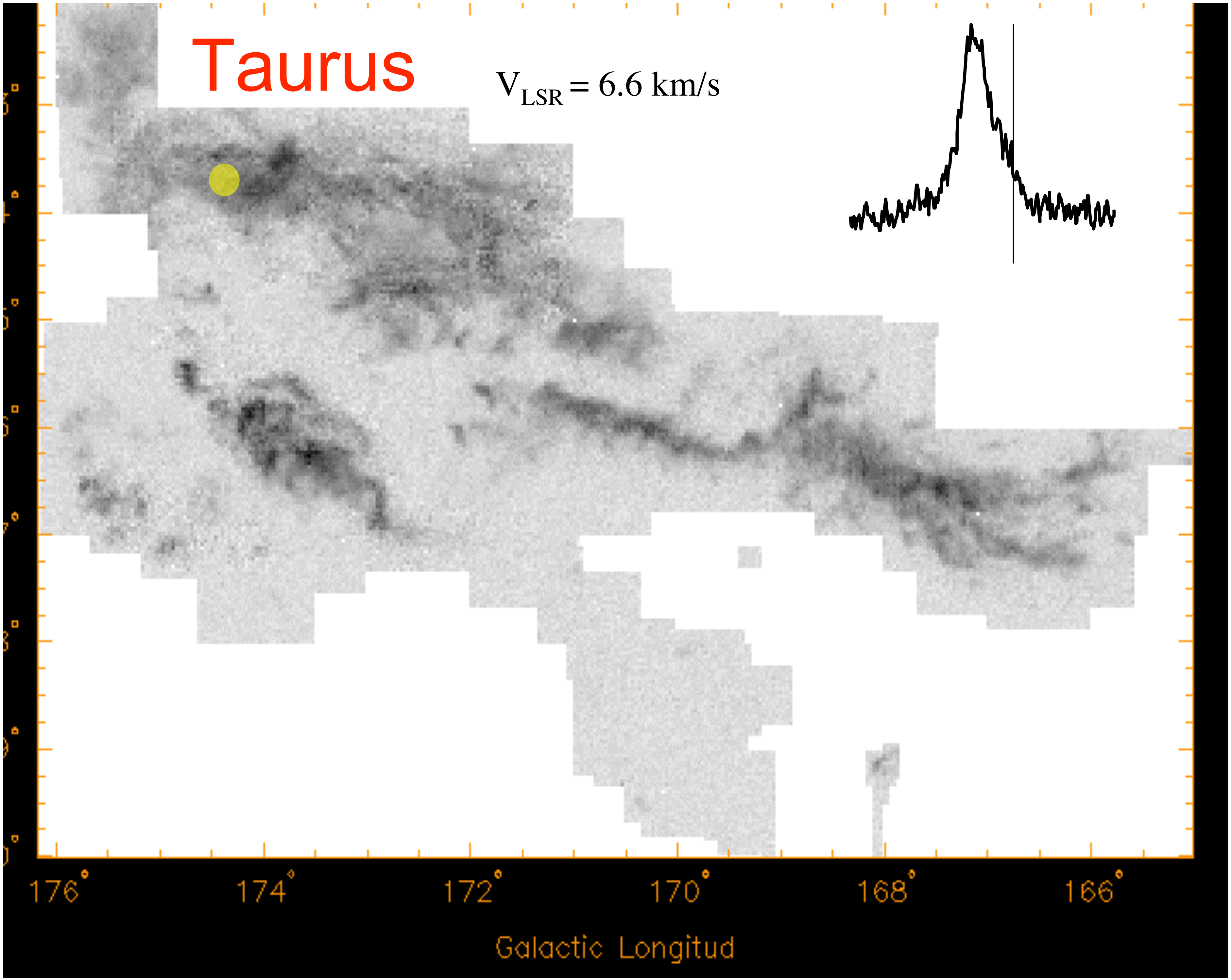


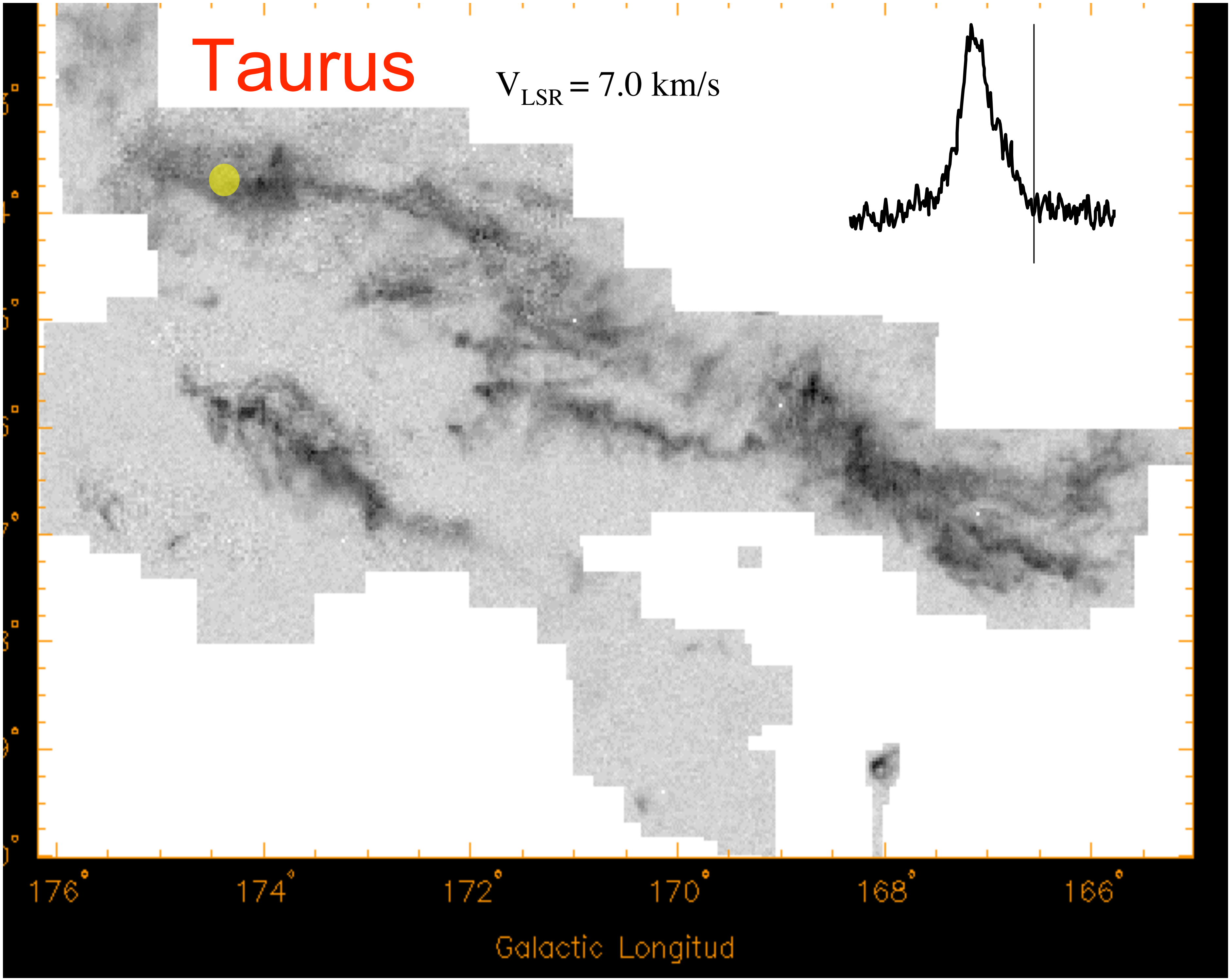
Taurus
V_LSR = 5.4 km/s
176°
174°
172°
170°
168°
166°
Galactic Longitud


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

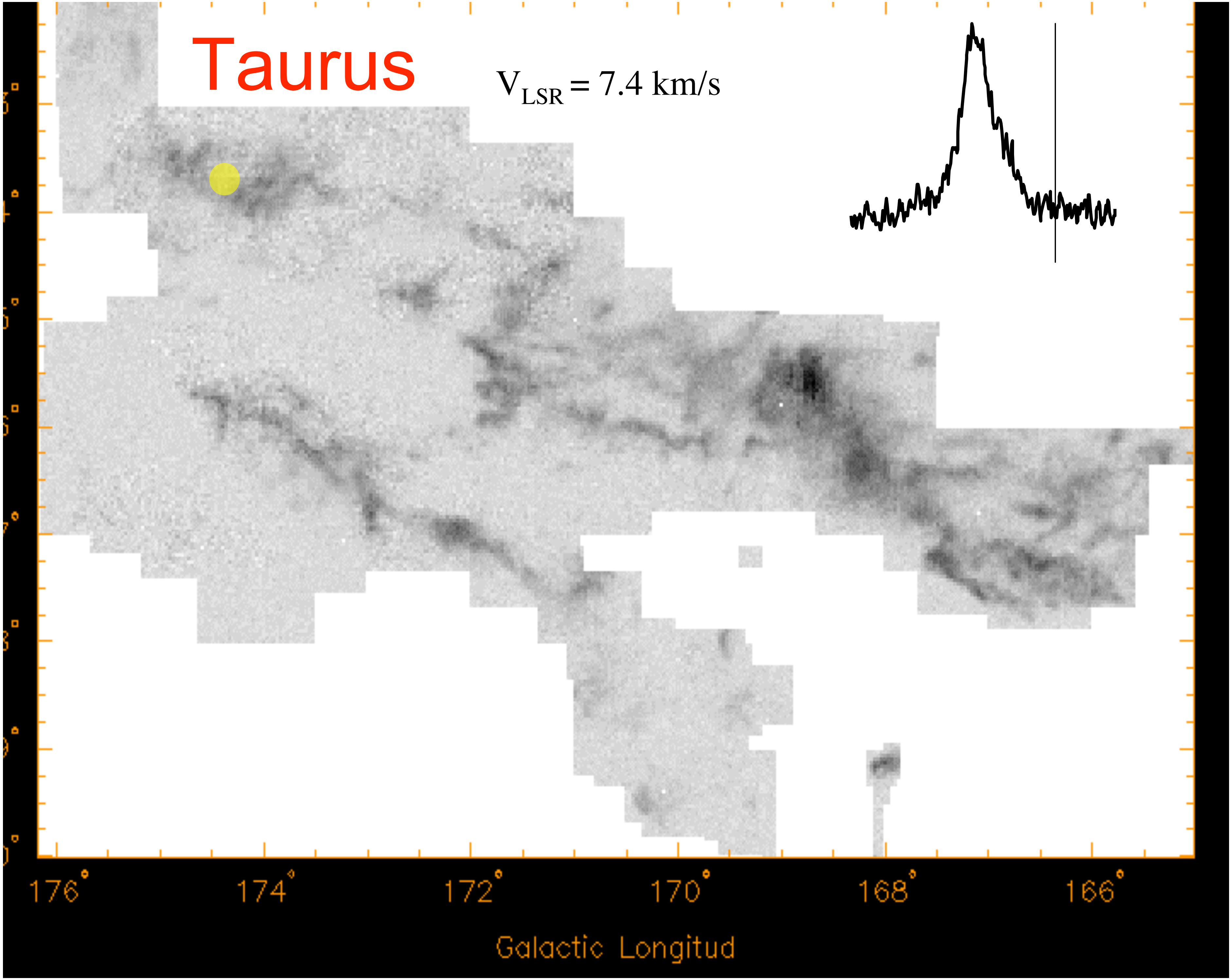


Taurus
V_LSR = 6.2 km/s
176°
174°
172°
170°
168°
166°
Galactic Longitud

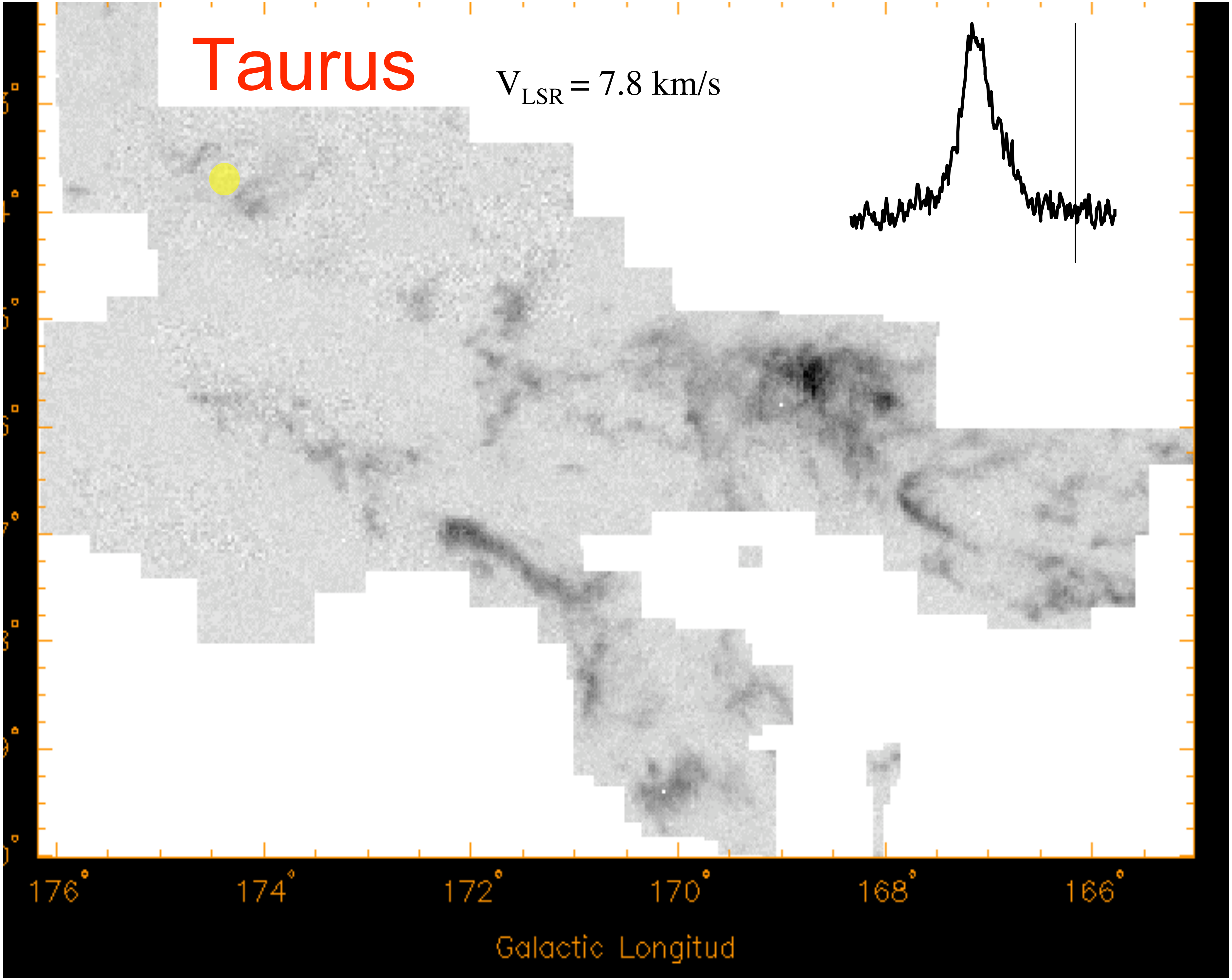

Taurus
V_LSR = 6.6 km/s
176°
174°
172°
170°
168°
166°
Galactic Longitud



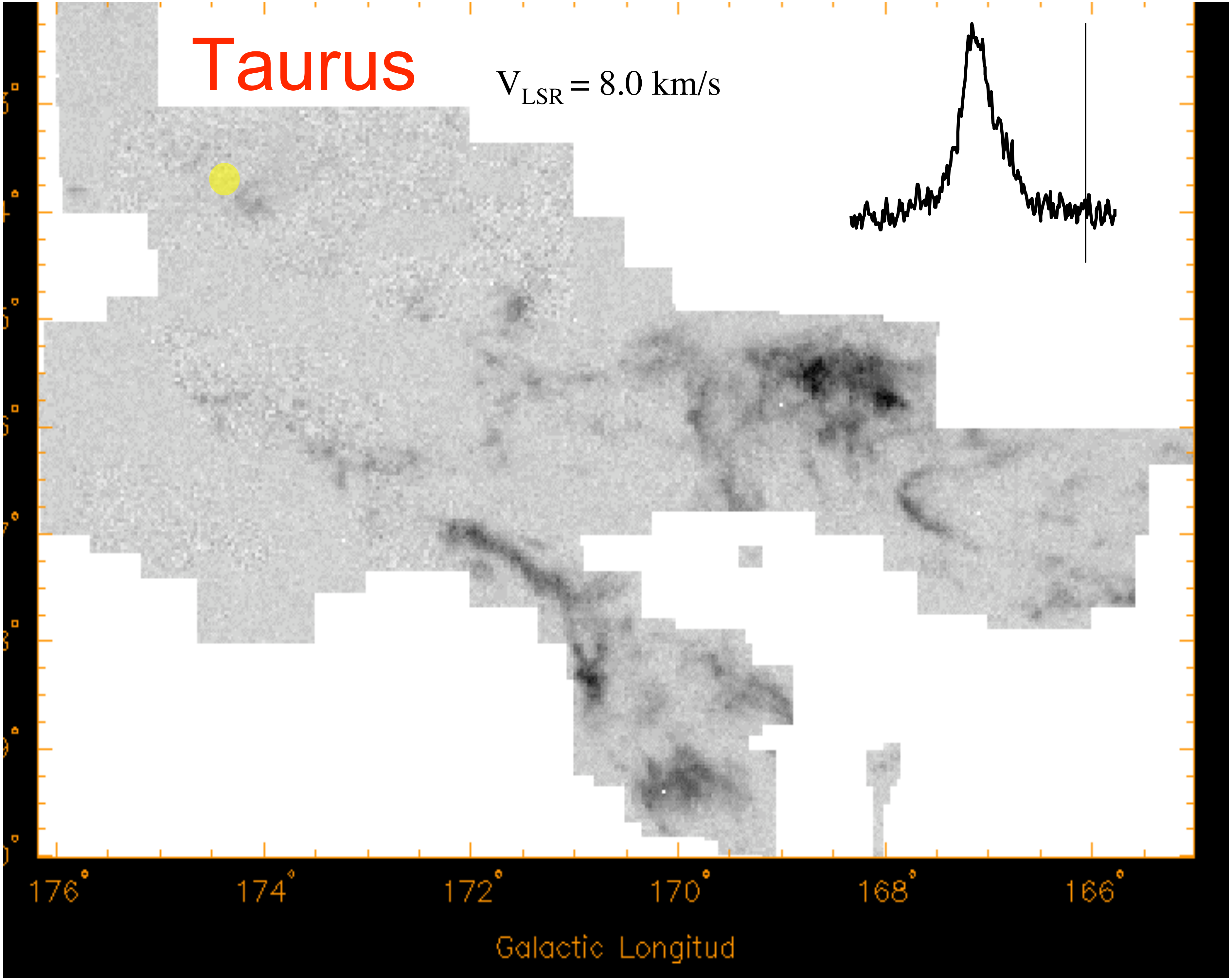
Taurus
V$_{LSR}$ = 7.0 km/s
176°
174°
172°
170°
168°
166°
Galactic Longitud



Taurus
V_LSR = 7.4 km/s
176°
174°
172°
170°
168°
166°
Galactic Longitud

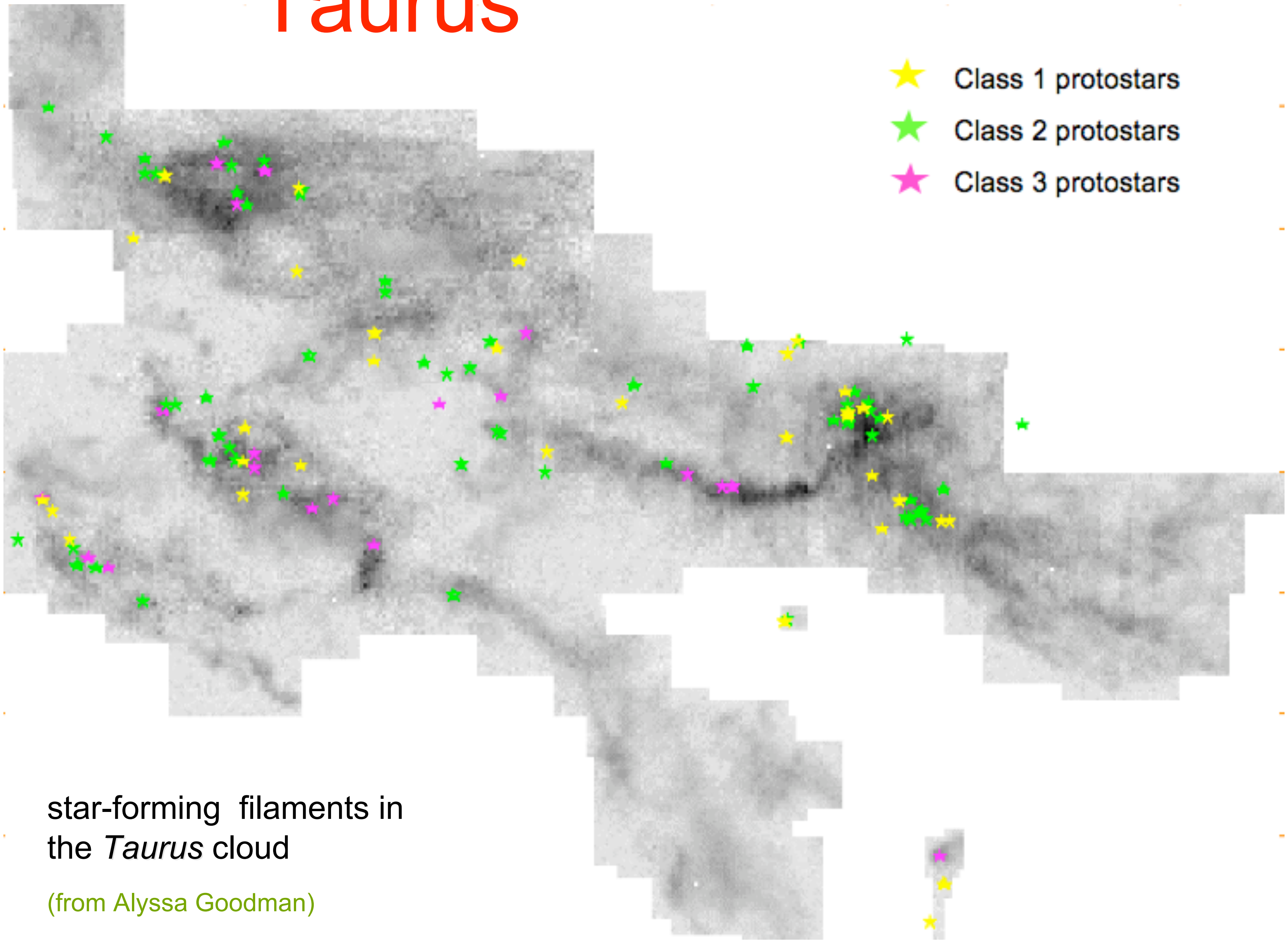


Taurus
V_{LSR} = 7.8 km/s
176°
174°
172°
170°
168°
166°
Galactic Longitud



Taurus
V_{LSR} = 8.0 km/s
176°
174°
172°
170°
168°
166°
Galactic Longitud

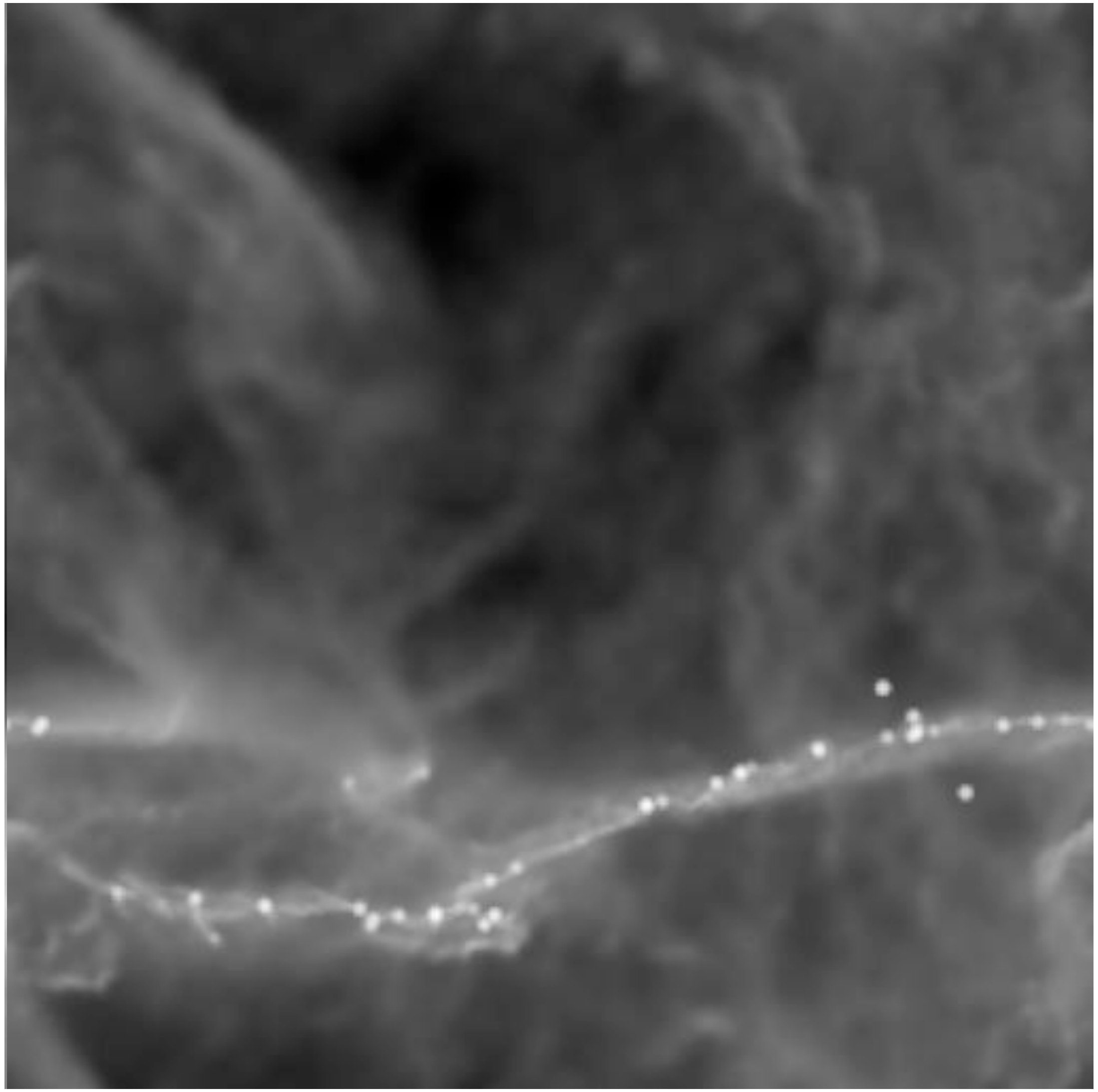
Taurus



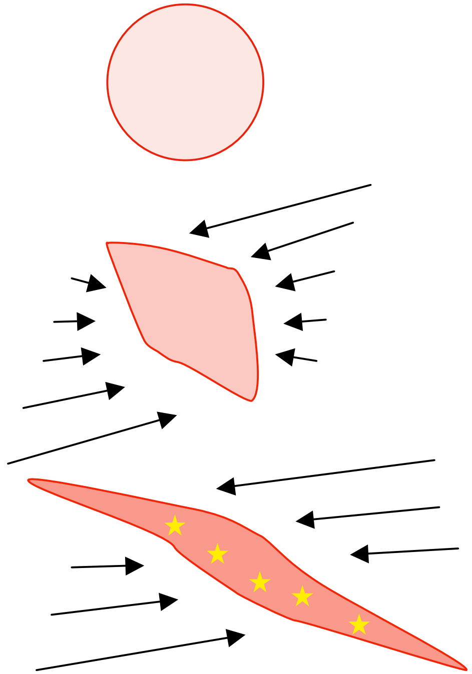
star-forming filaments in
the *Taurus* cloud

(from Alyssa Goodman)

Gravoturbulent fragmentation



Filament generated by combination of compression and local shear:

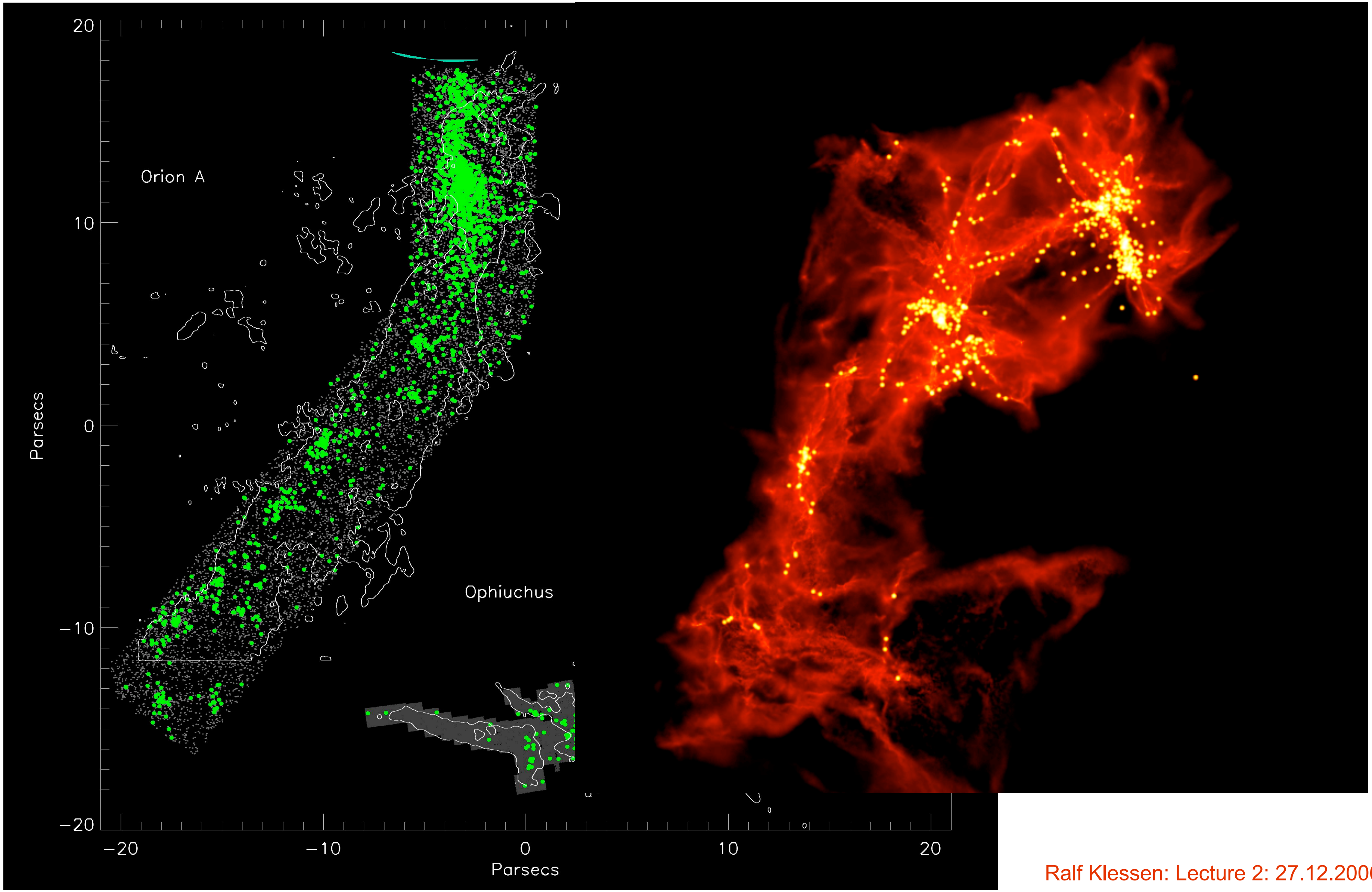


"Taurus":

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

→ $L = 6\,pc$, $M = 5000\,M_\odot$

Gravitational collapse within MCs



improvements

What do we need to study ISM?

ISM dynamics and SF

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

chemistry (gas + dust, heating + cooling)

radiation (continuum + lines)

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

stellar evolution
(feedback: radiation, winds, SN)

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

What do we need to study ISM?

- massive parallel codes
- particle-based: SPH with improved algorithms (XSPH with turb. subgrid model, GPM, particle splitting, MHD-SPH?)
- grid-based: AMR (FLASH, ENZO, RAMSES, Nirvana3, etc), subgrid-scale models (FEARLESS)
- BGK methods

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stellar evolution
(feedback: radiation, winds, SN)

What do we need to study ISM?

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

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

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What do we need to study ISM?

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

↔

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stellar evolution
(feedback: radiation, winds, SN)

What do we need to study ISM?

- statistics: number of stars (collisional: 10^6, collisionless: 10^{10})
- transition from gas to stars
- binary orbits
- long-term integration

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

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What do we need to study ISM?

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

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

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(feedback: radiation, winds, SN)

What do we need to study ISM?

methods need to be combined!

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

chemistry (gas + dust, heating + cooling)

radiation (continuum + lines)

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

stellar evolution
(feedback: radiation, winds, SN)

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

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!