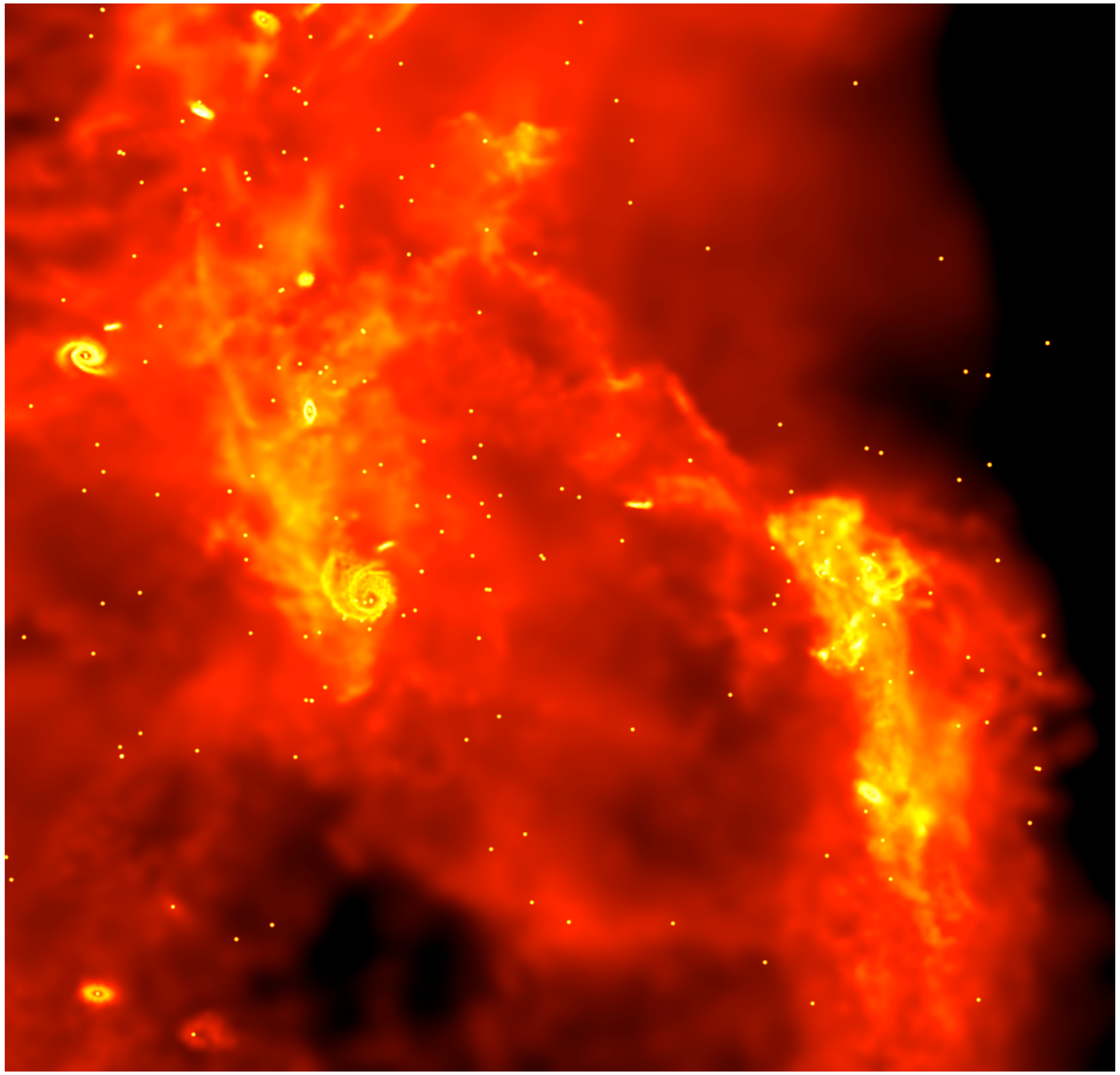
An overview of star formation



ITA:

Paul Clark

Ralf Klessen

Robi Banerjee

Simon Glover

Ian Bonnell

Clare Dobbs

Jim Dale

Why study star formation?

- Stars chemically the enrich the Universe, so star formation describes how this happens.
- Young stars influence their environment: important for galactic dynamics (where do they form?).
- Star formation is the study where the baryonic matter goes.
- Protostars allow us to study accretion discs.
- Most importantly: how did the stars get there?

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

Where do stars form?

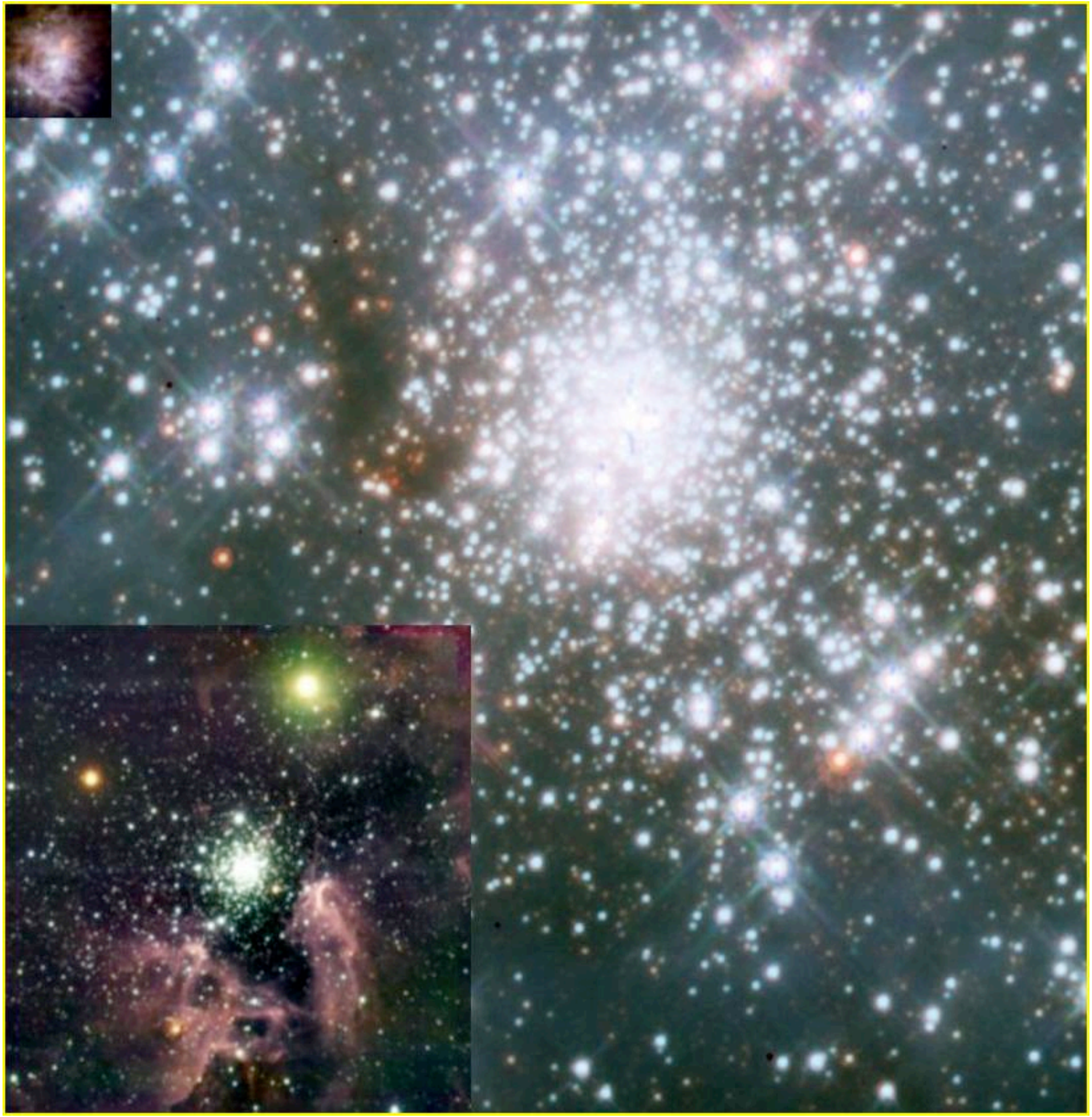
- Stars form in massive regions of cold, predominately molecular (so H_2) gas, called Giant Molecular Clouds (GMCs).
- GMCs contain up to 10^6 M_{sun}, radii of ~20pc and with temperatures ~10-30K.
- Observed to contain significant non-thermal velocities, which are supersonic ($v > c_s$). Taken for turbulence, since they are random.

Part of the Tarantula Nebula in the LMC.

NASA and The Hubble Heritage Team (STScI/AURA). Y-H. Chu (U. of Illinois), E. Grebel (U. of Washington)

Clusters

- Within GMCs, star formation is typically clustered.
- Can have just a few stars (~10) or in the local region few 1000. More rare examples can have 10,000s.

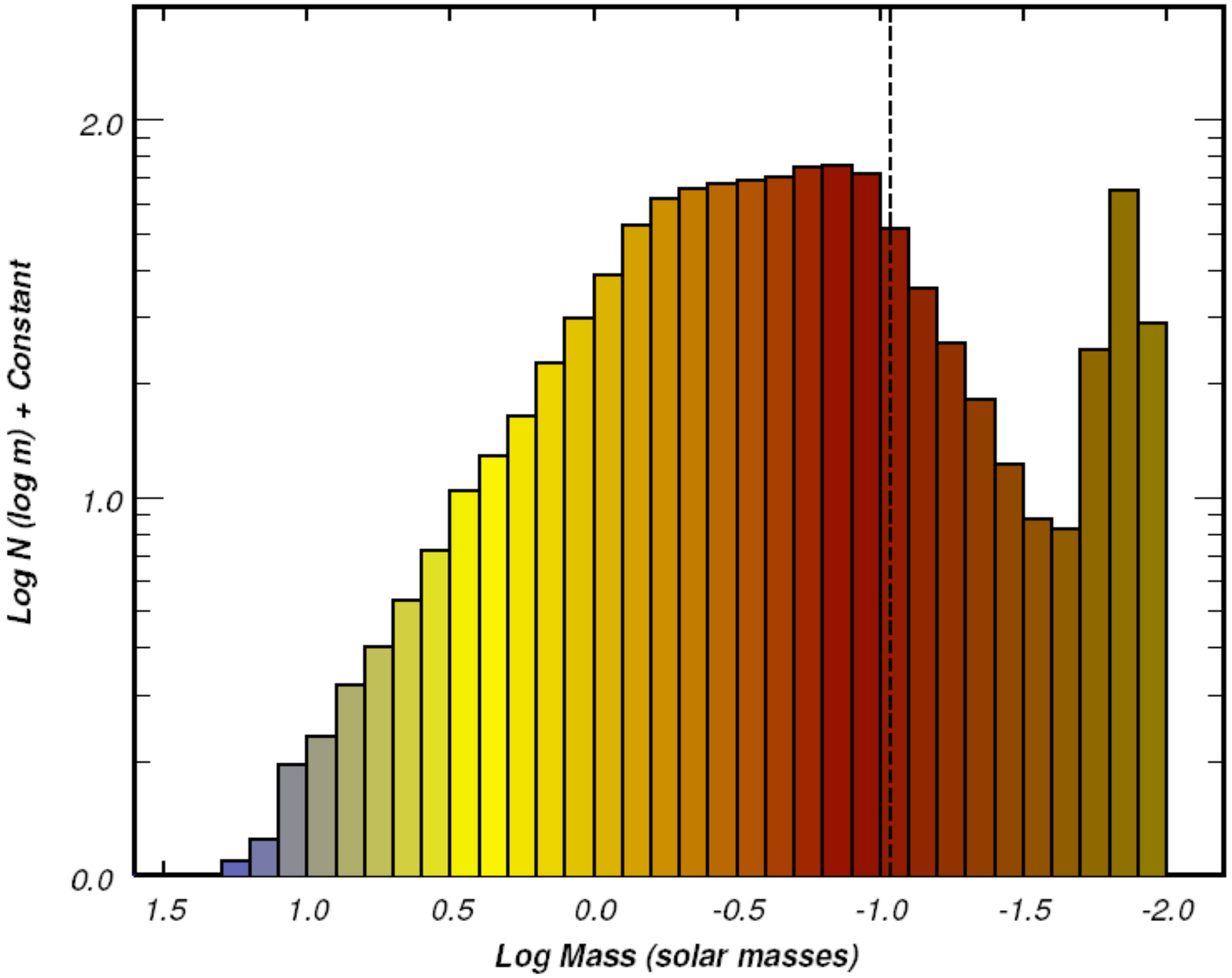


IMF

- The initial mass function (IMF) is the distribution of masses with which stars are born.
- Mass function of stars in the clusters always seems to have (roughly) the same shape.
- Normally assumed to take the form of a broken power-law:

$$dN(m) = N_0\, m^{-\xi}\, dm$$

- For masses above ~ 0.5 Msun, normally find ξ = 2.35 (Salpeter 1955)



Muench (2002): Orion Nebula cluster

Why are GMCs so cold?

At ‘low’ densities ($n<10^5$ cm^{-3}; $\rho < 10^{-19}$ gcm^{-3}):

CII, OI, SiII fine-structure cooling

CO line cooling

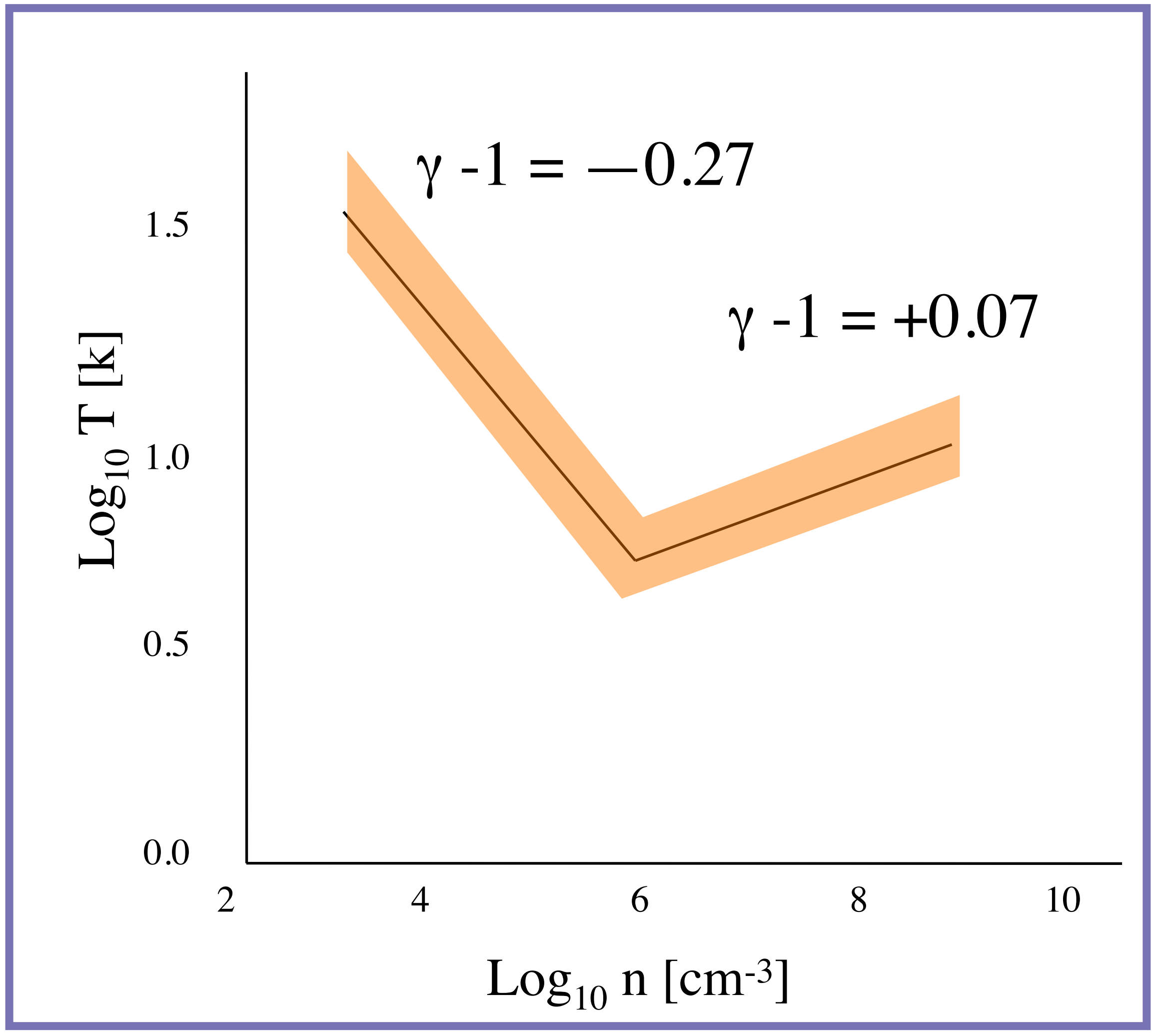
At ‘high’ densities:

Cooling by dust.

Main heating:

pdV compressional heating/shocks

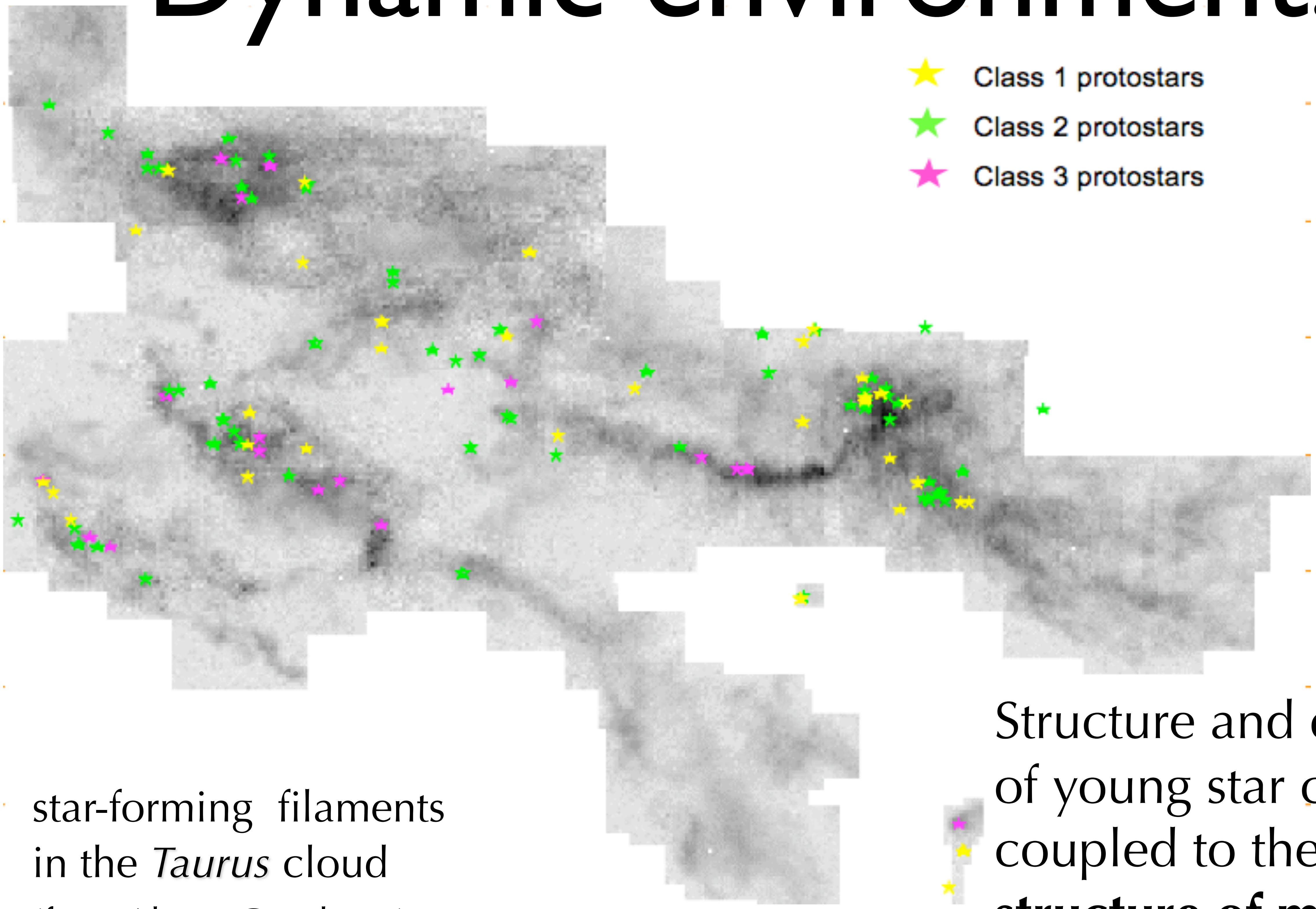
photoelectric emmision from dust



$$p = K\rho^{\gamma}$$

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

Dynamic environment...

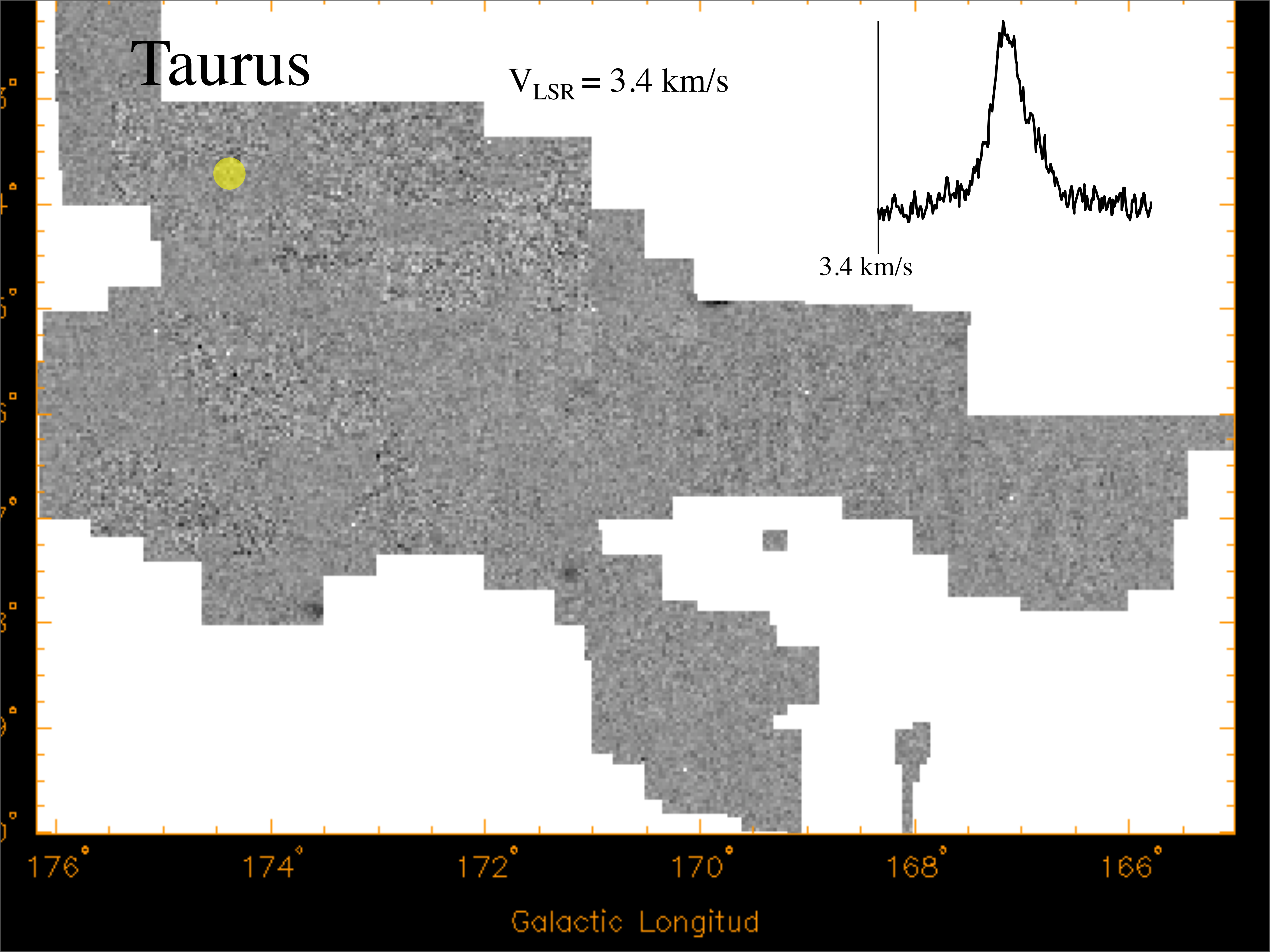


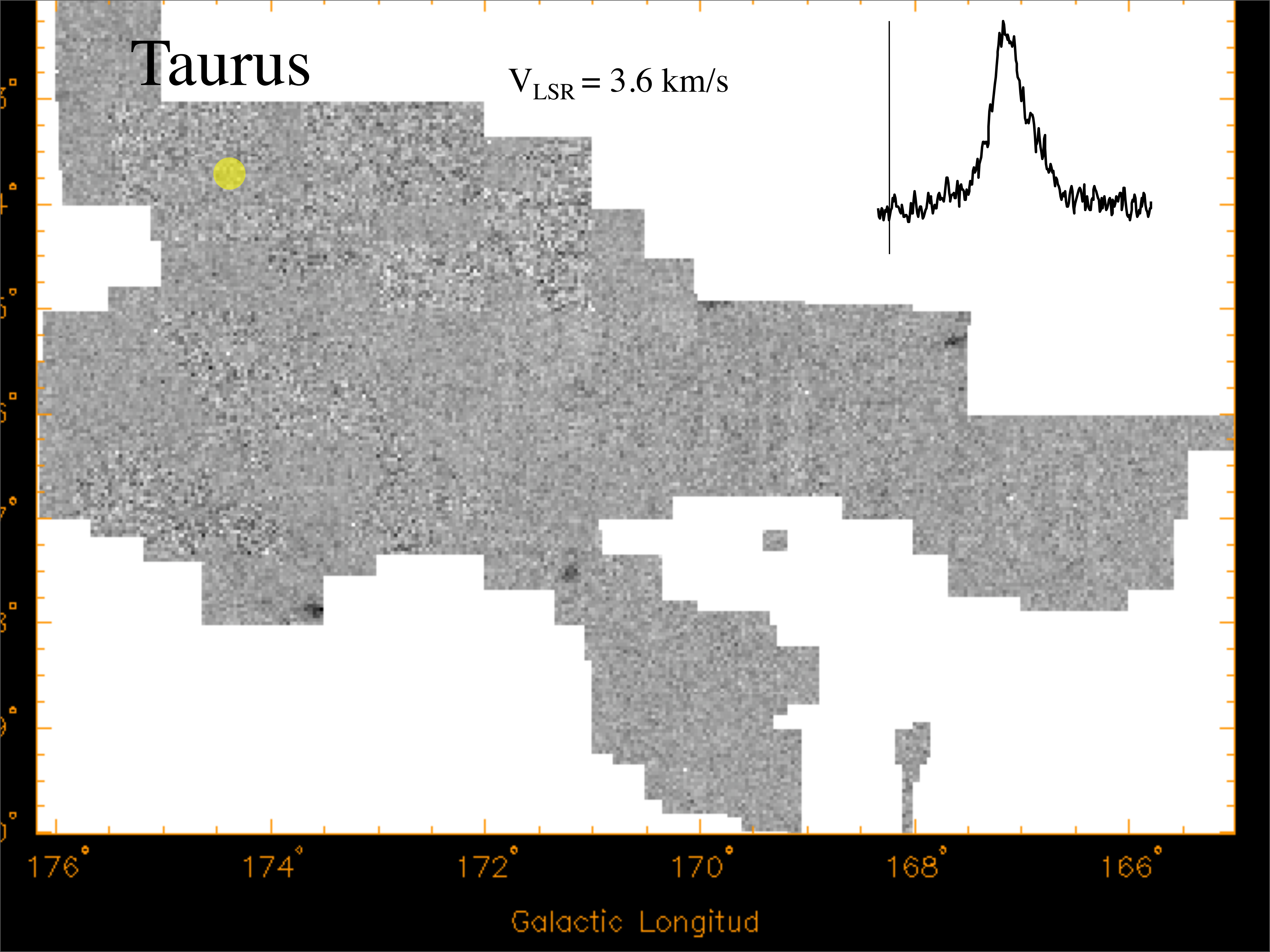
star-forming filaments
in the *Taurus* cloud
(from Alyssa Goodman)

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

Taurus

$V_{LSR} = 3.4$ km/s



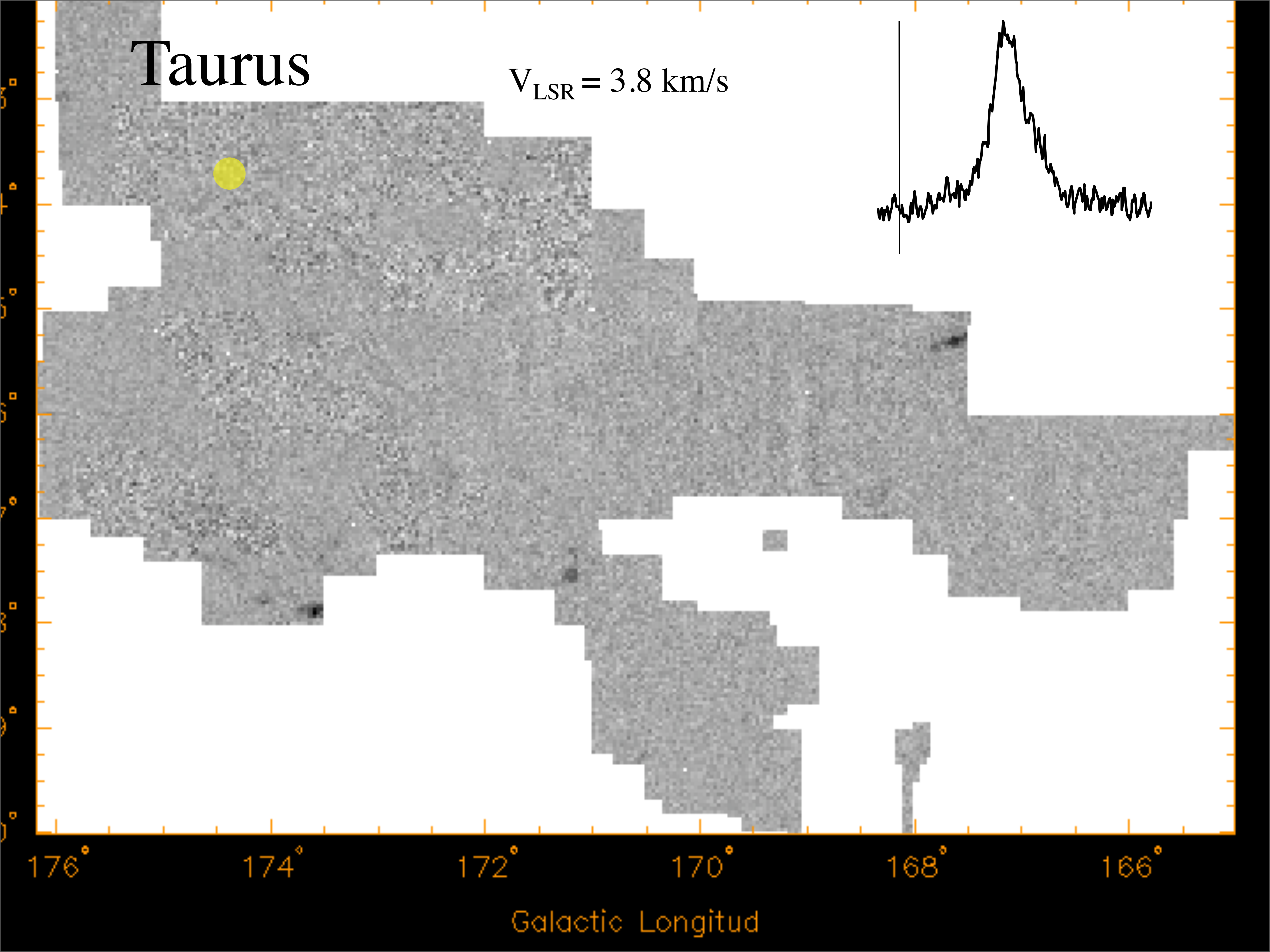


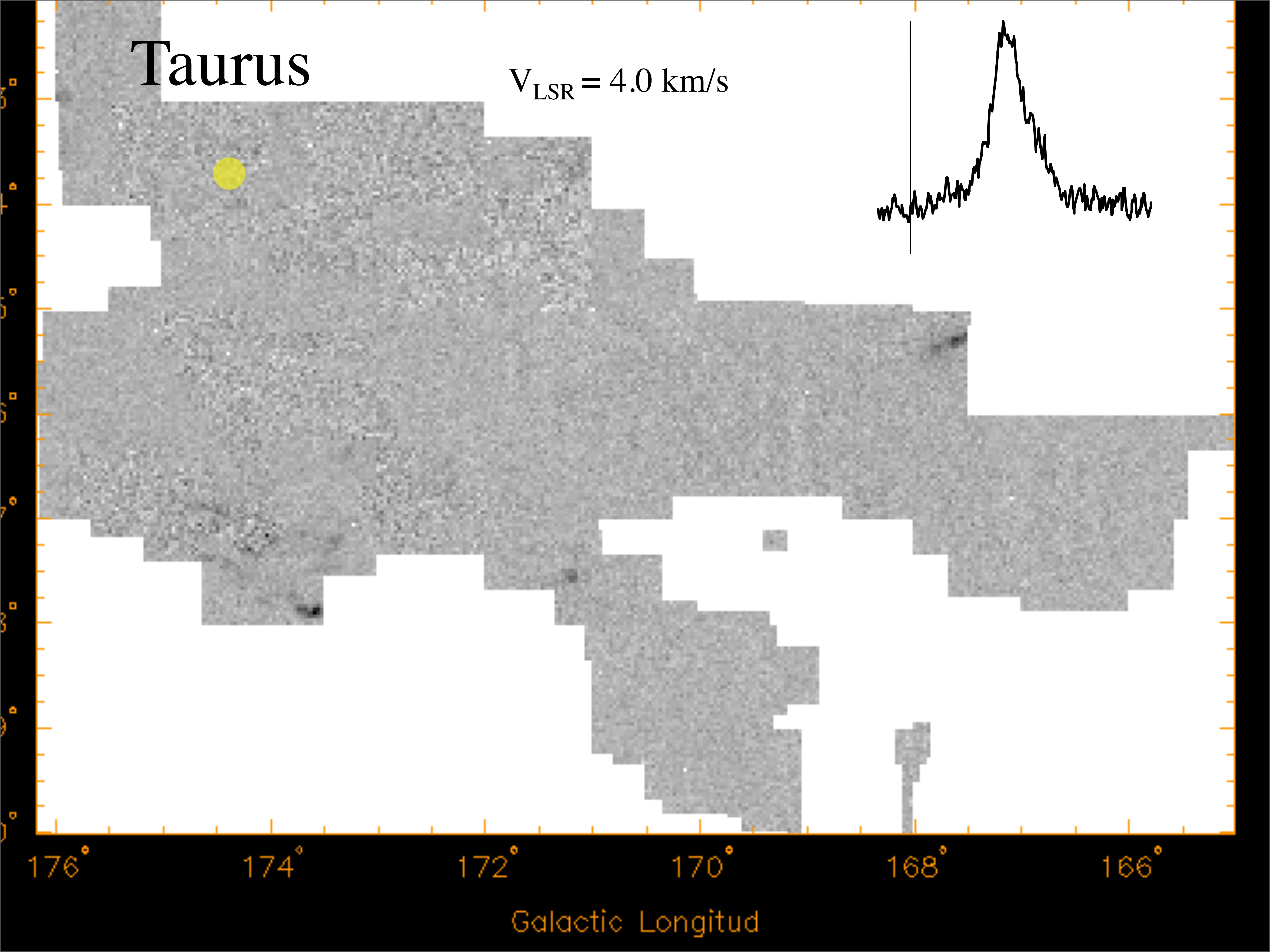
Taurus

$V_{LSR} = 3.6$ km/s

Taurus

$V_{LSR} = 3.8$ km/s

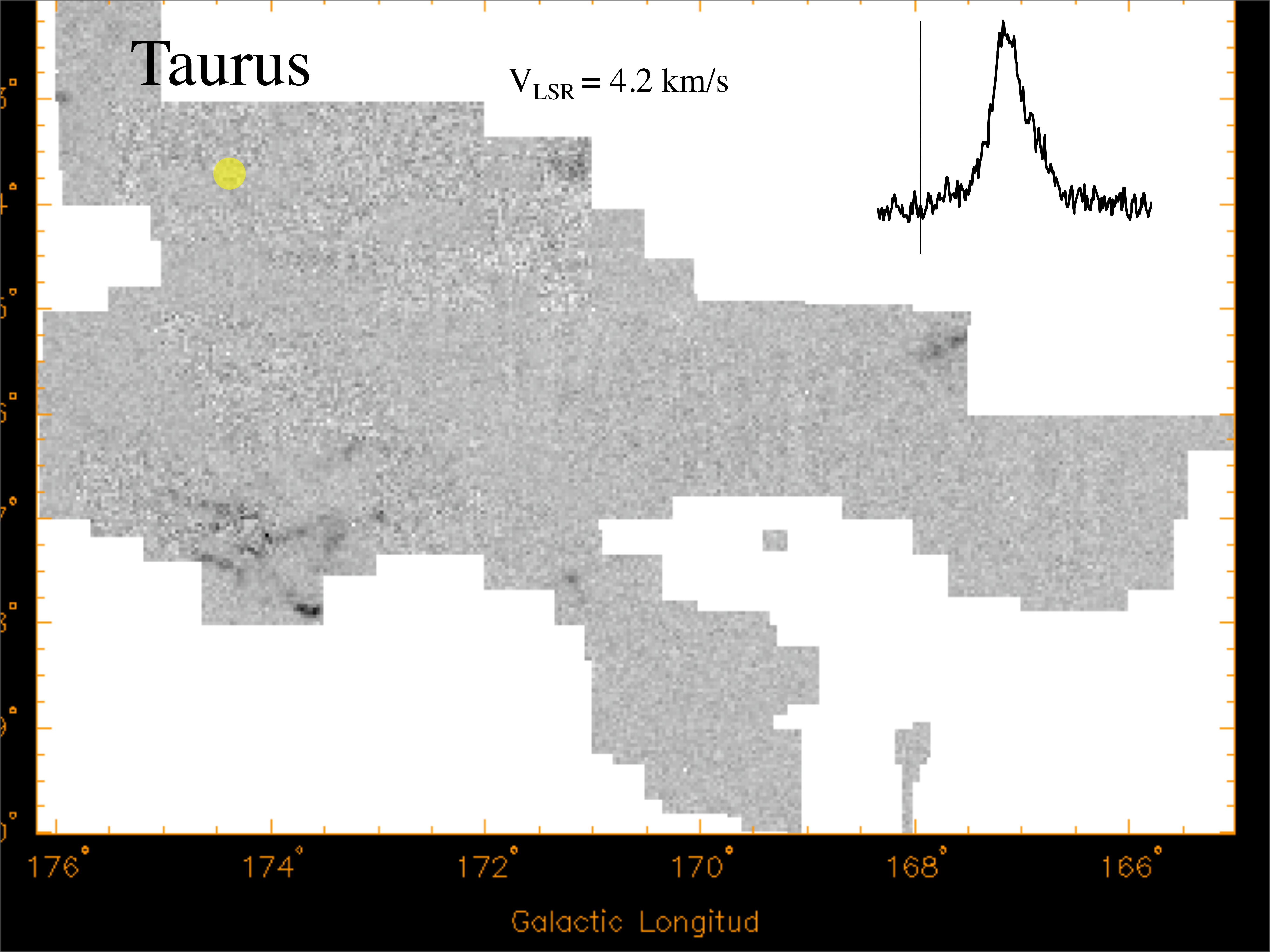




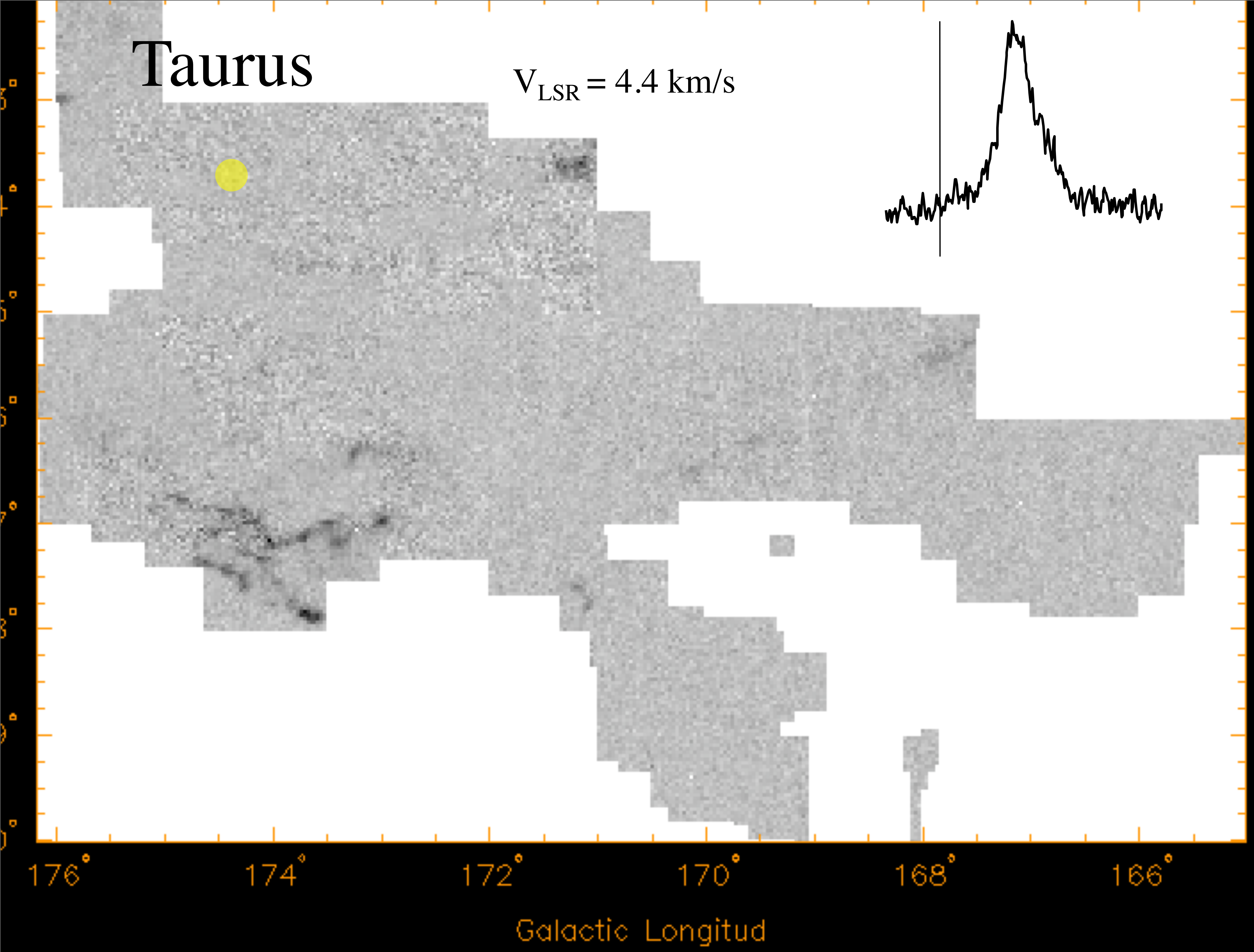
Taurus

$V_{LSR} = 4.0$ km/s

Taurus



V_{LSR} = 4.2 km/s

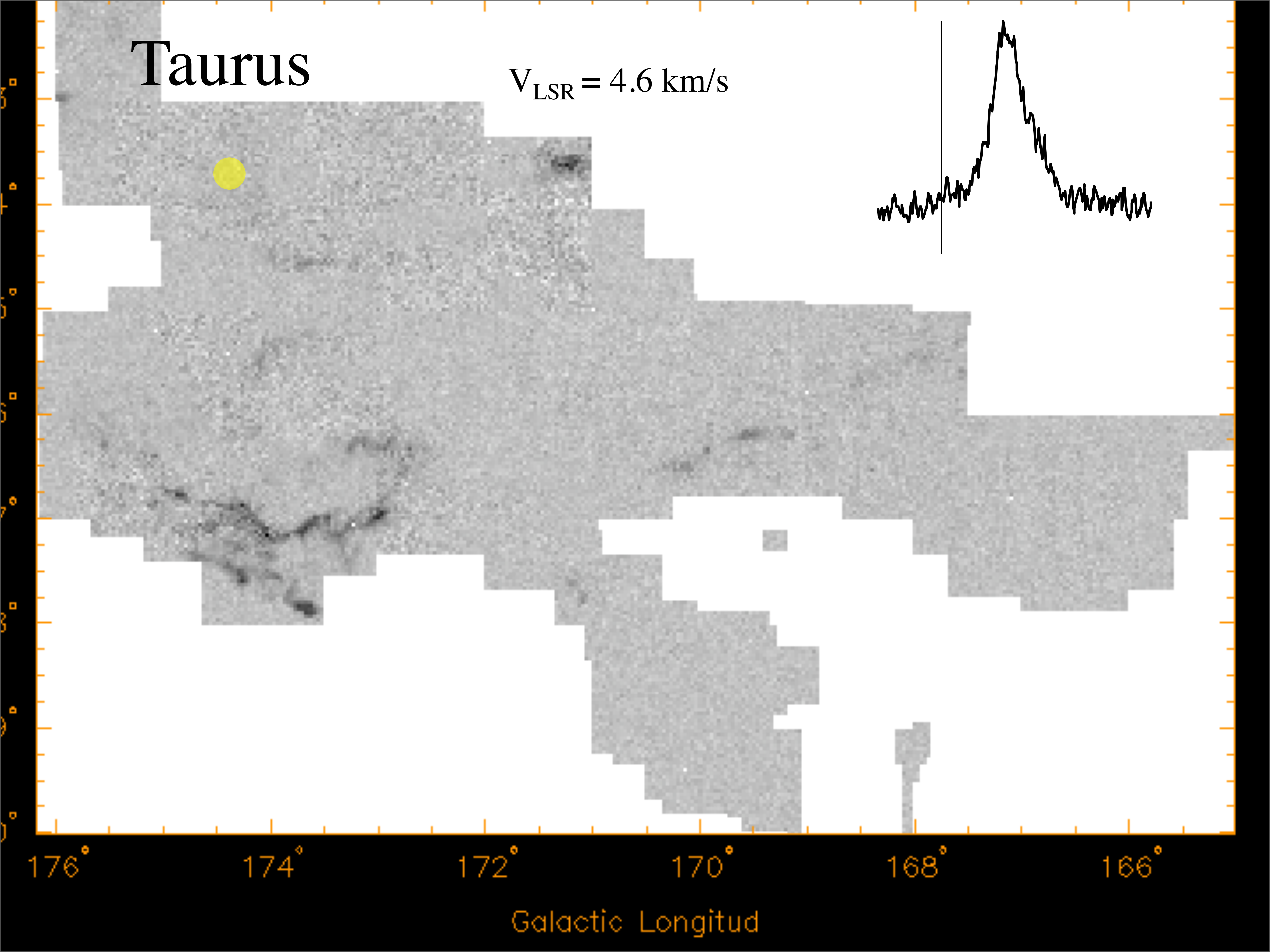


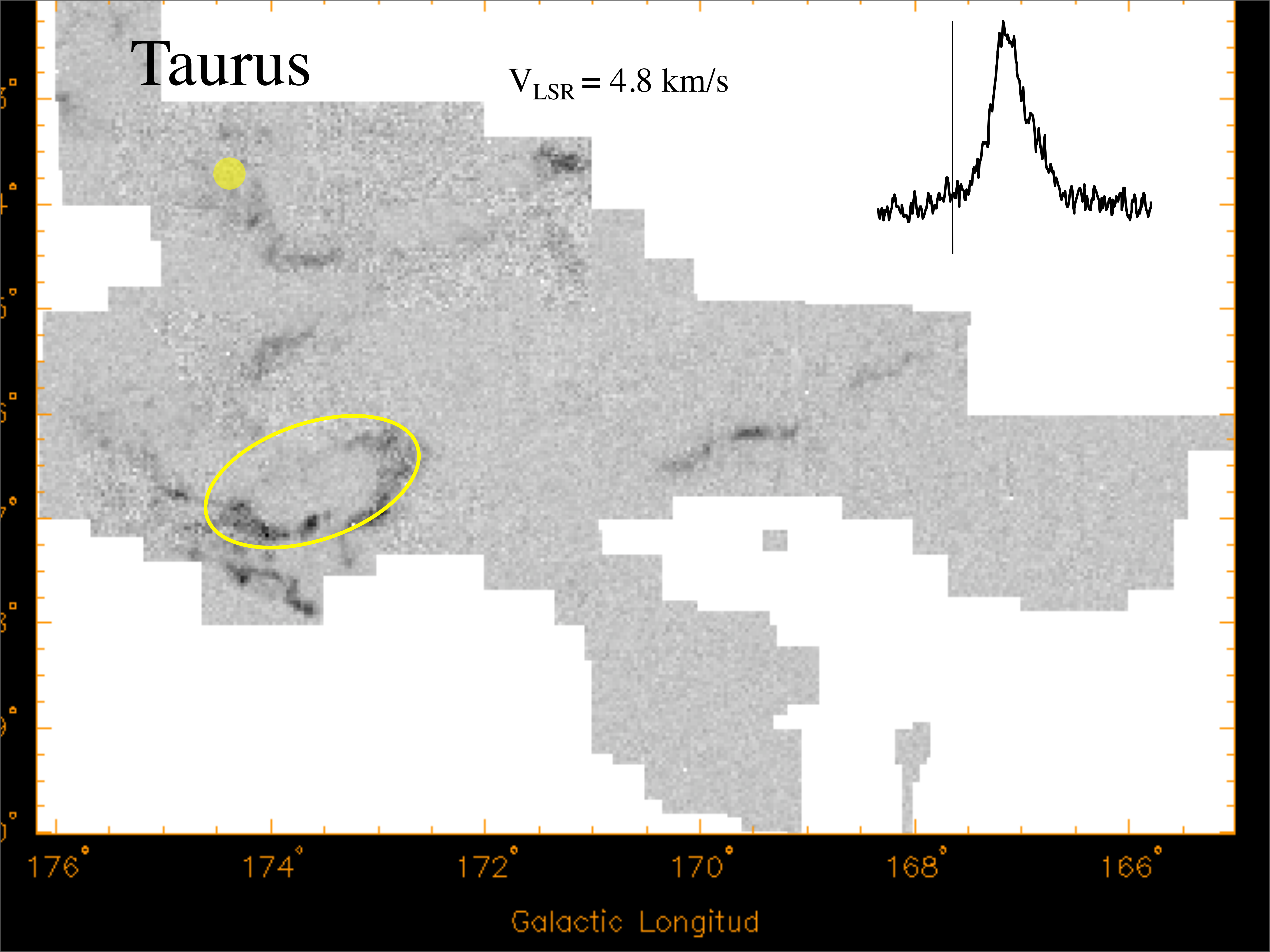
Taurus

$V_{LSR} = 4.4$ km/s

Taurus

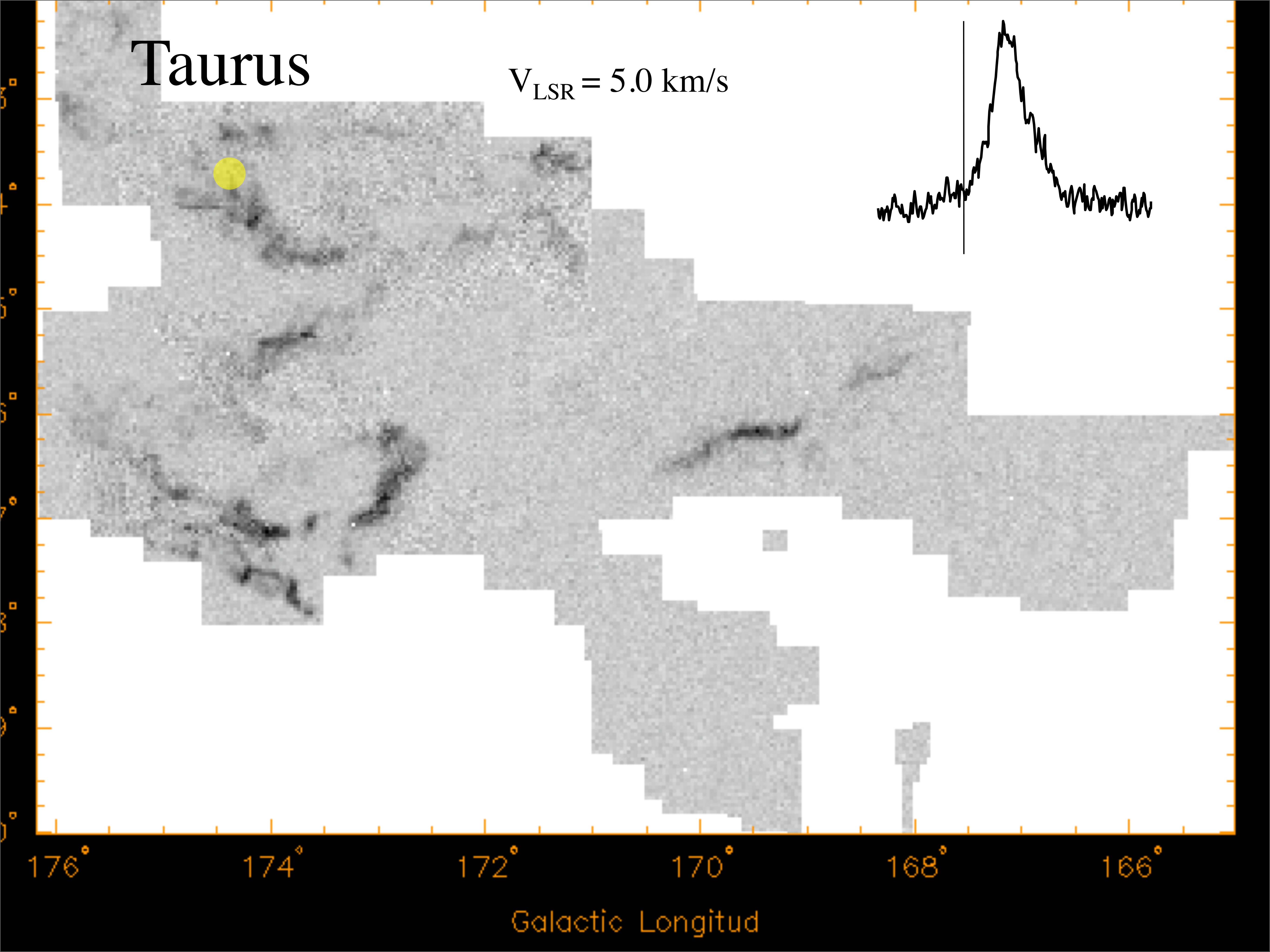
$V_{LSR} = 4.6$ km/s





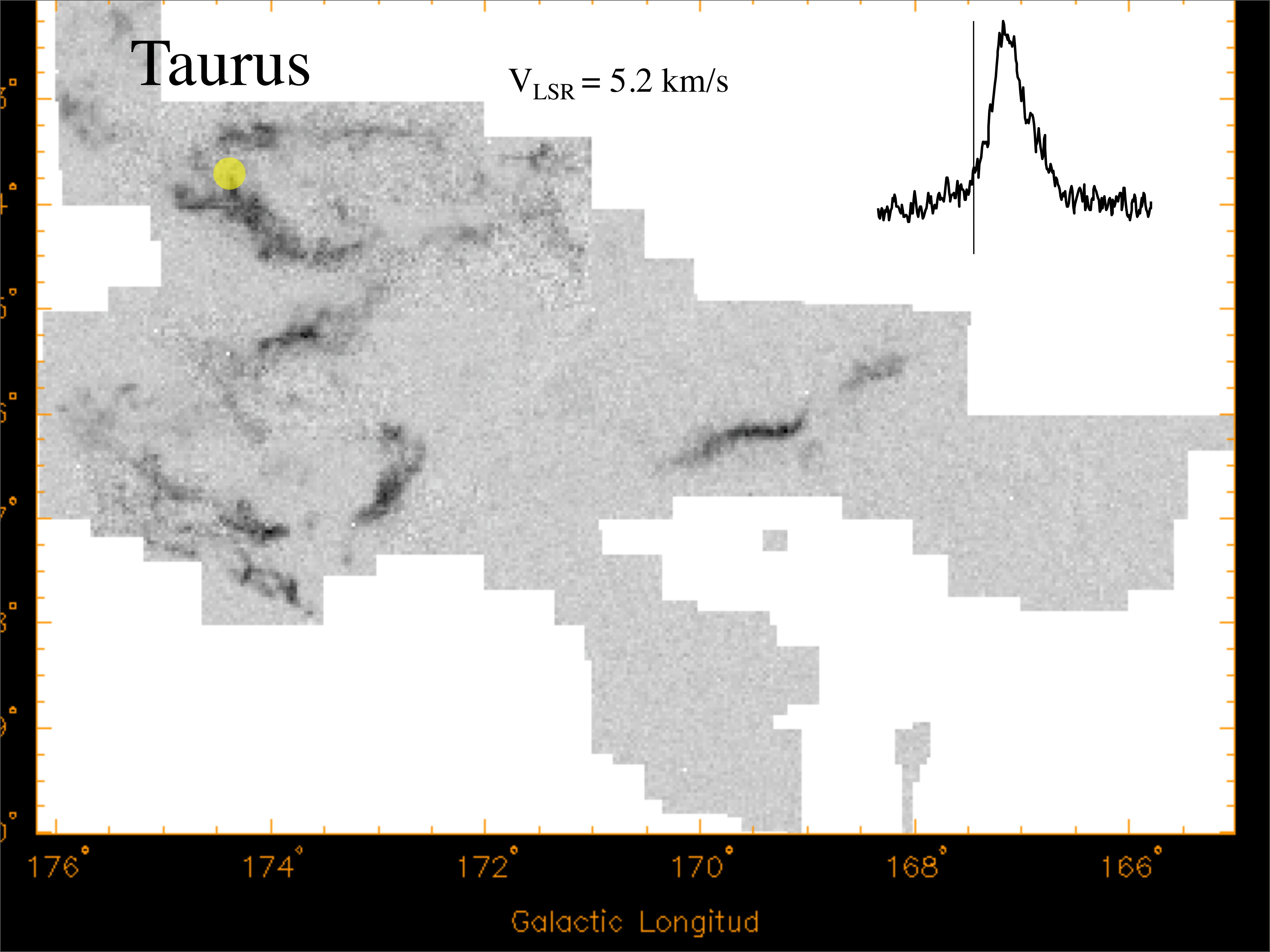
Taurus

$V_{LSR} = 4.8$ km/s



Taurus

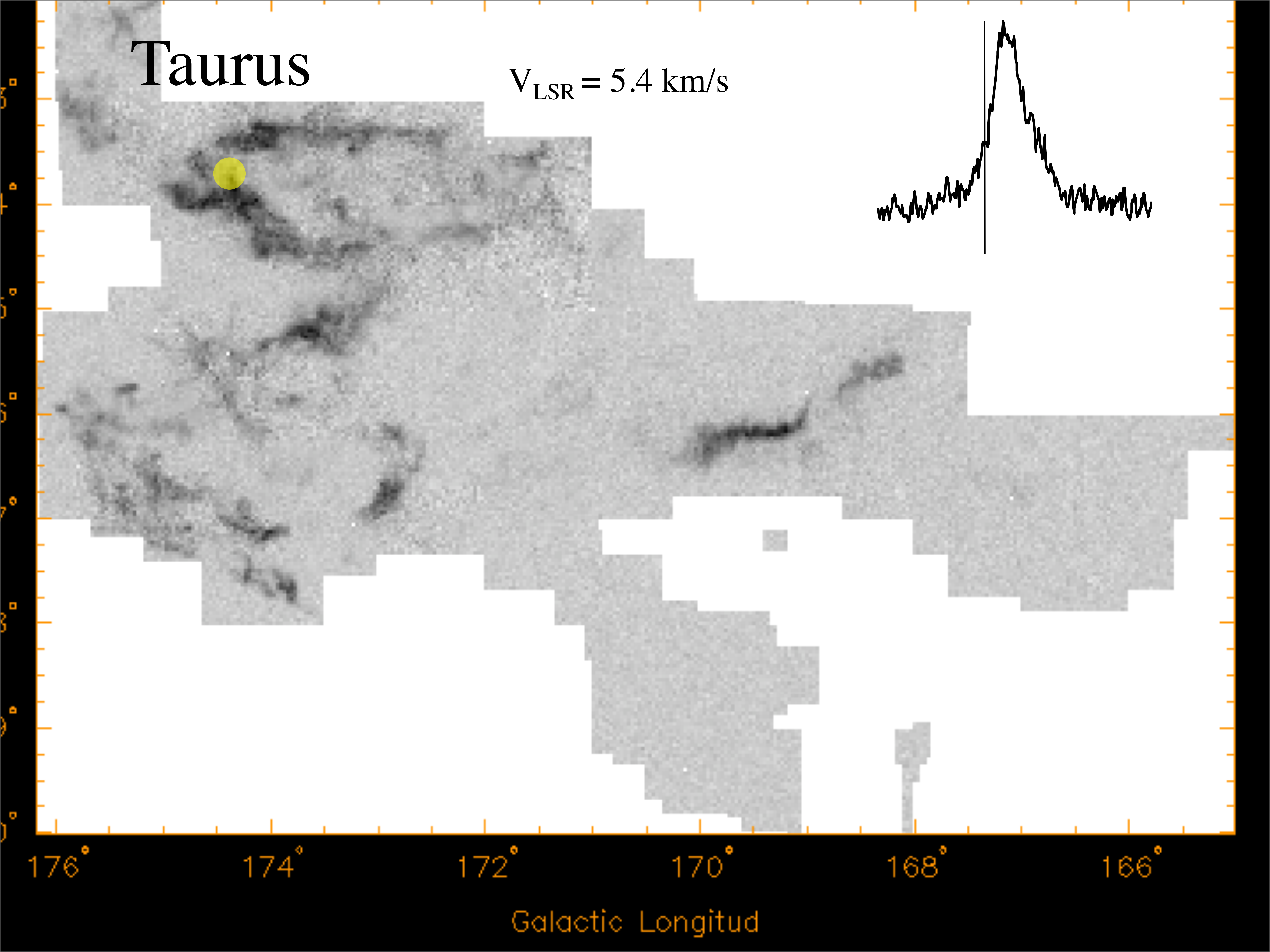
$V_{LSR} = 5.0$ km/s



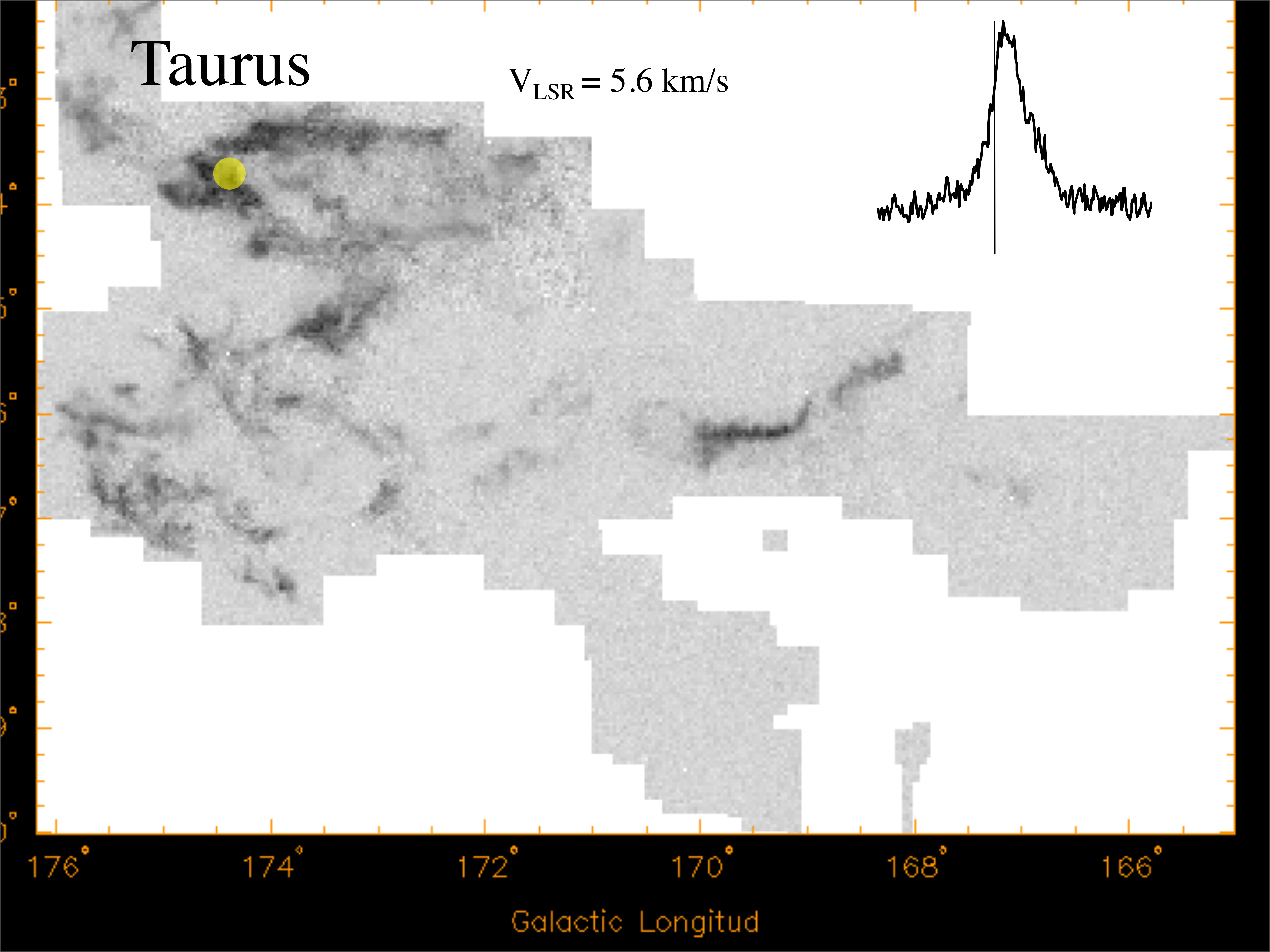
Taurus

$V_{LSR} = 5.2$ km/s

Taurus

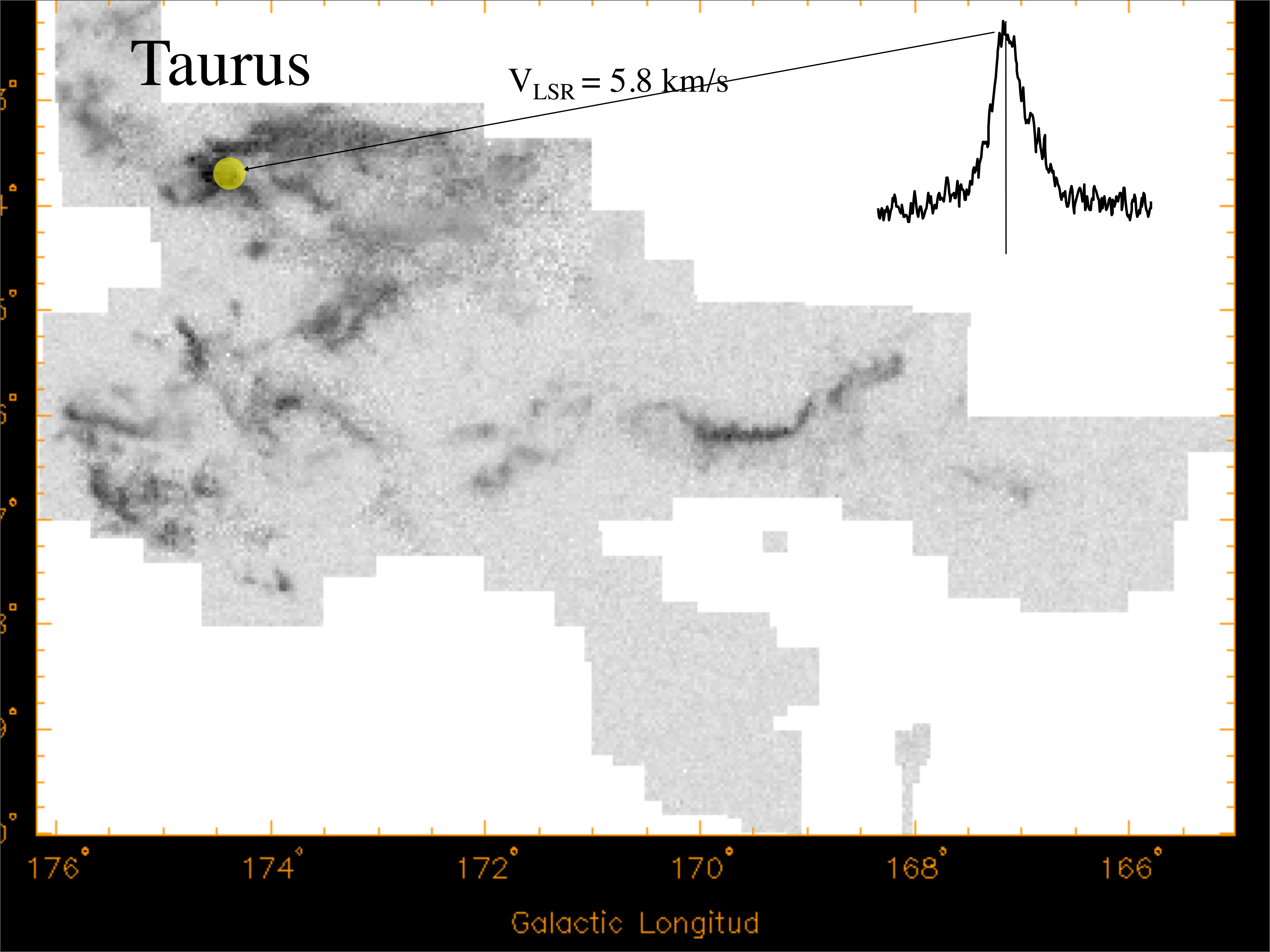


V_{LSR} = 5.4 km/s



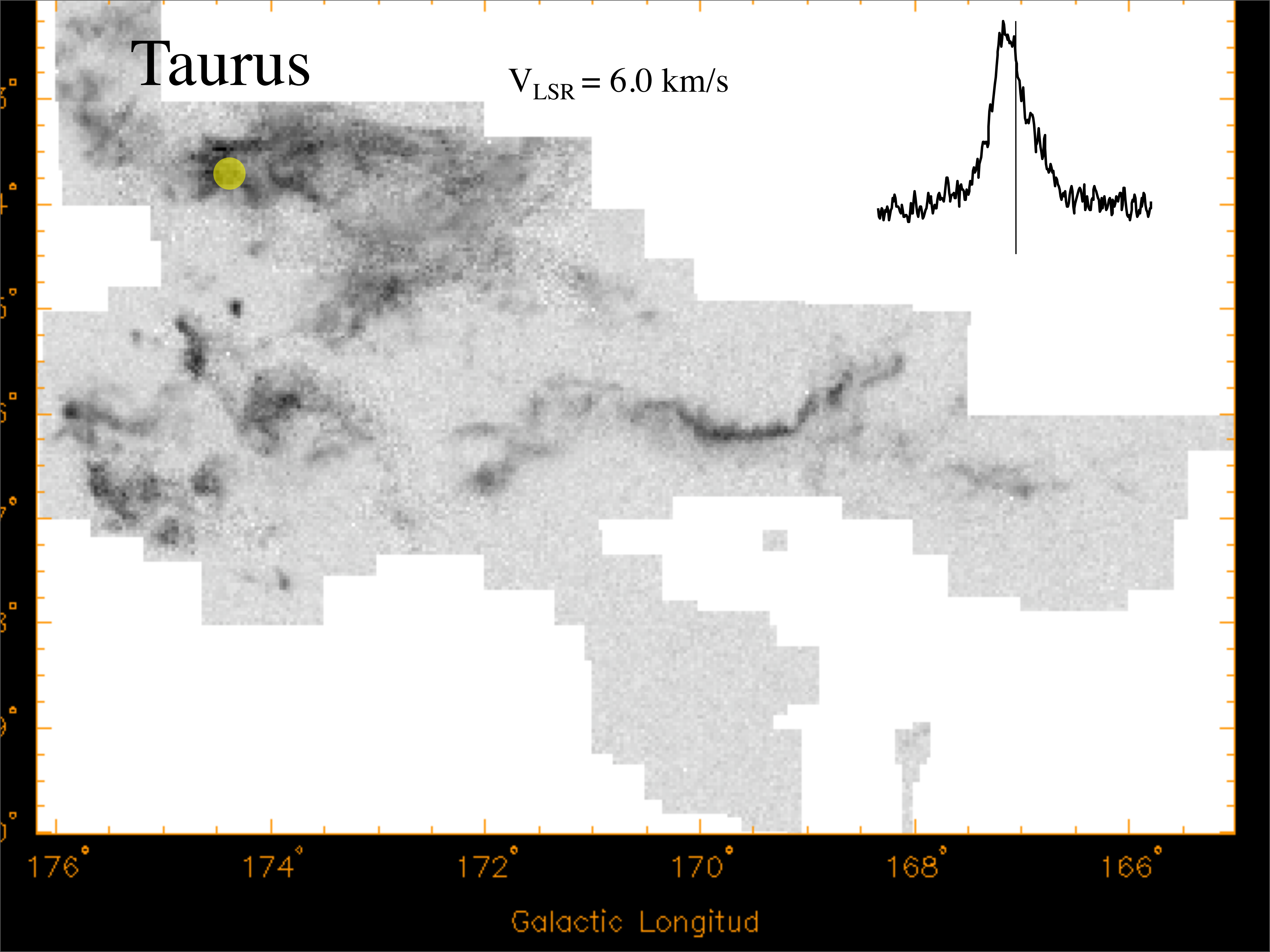
Taurus

$V_{LSR} = 5.6$ km/s



Taurus

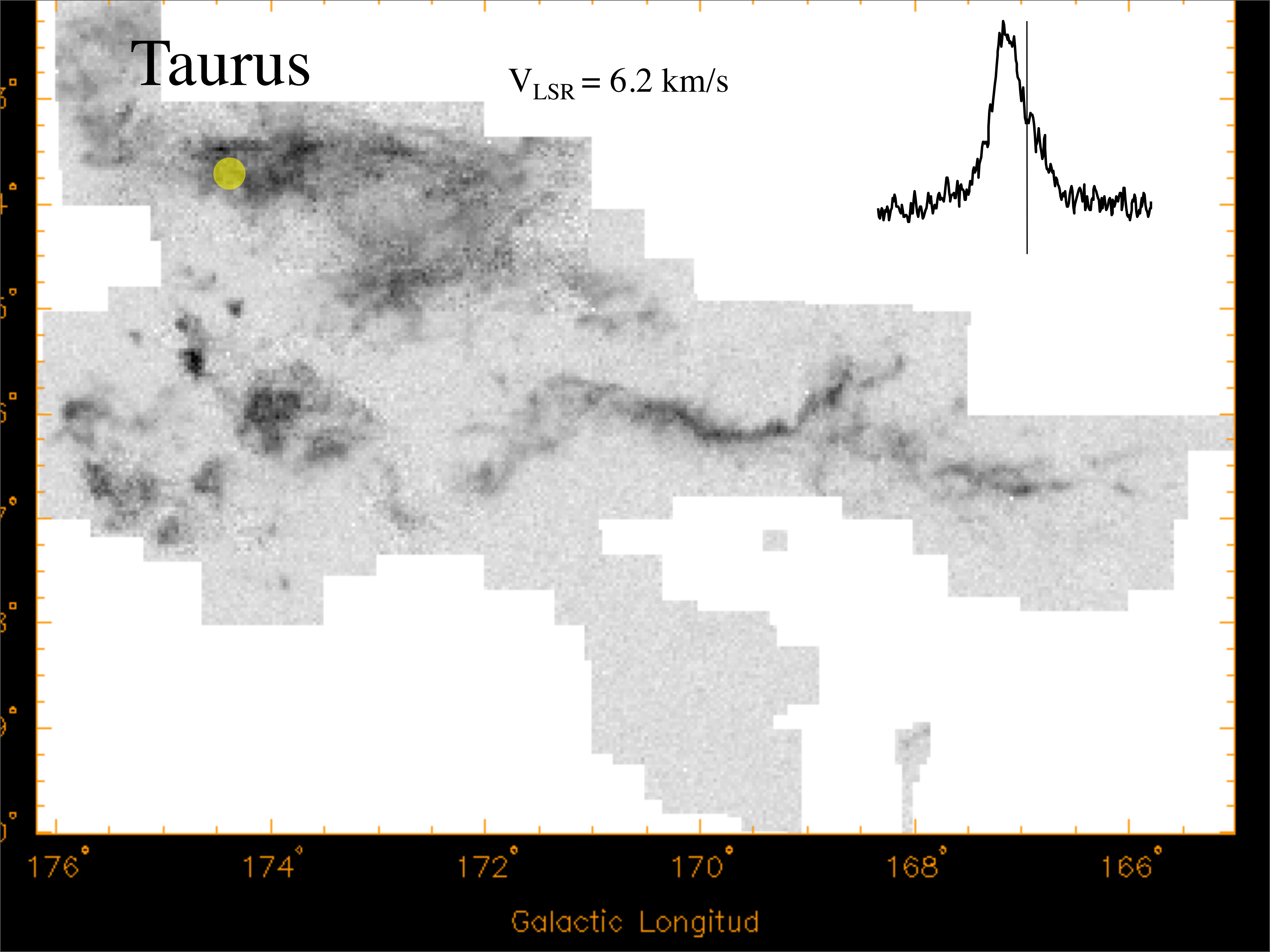
$V_{LSR} = 5.8$ km/s



Taurus

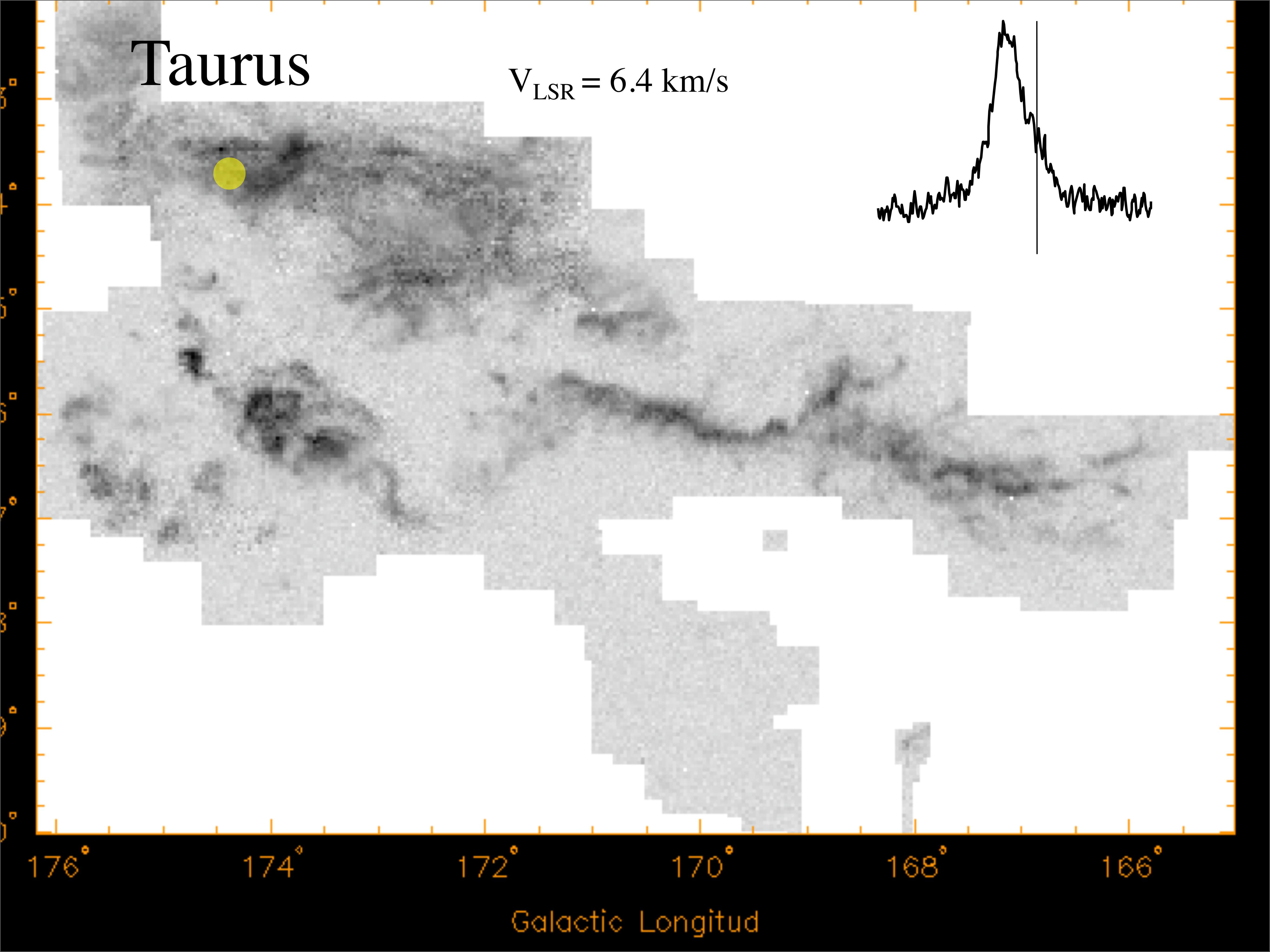
$V_{LSR} = 6.0$ km/s

Taurus



$V_{LSR} = 6.2$ km/s

Taurus



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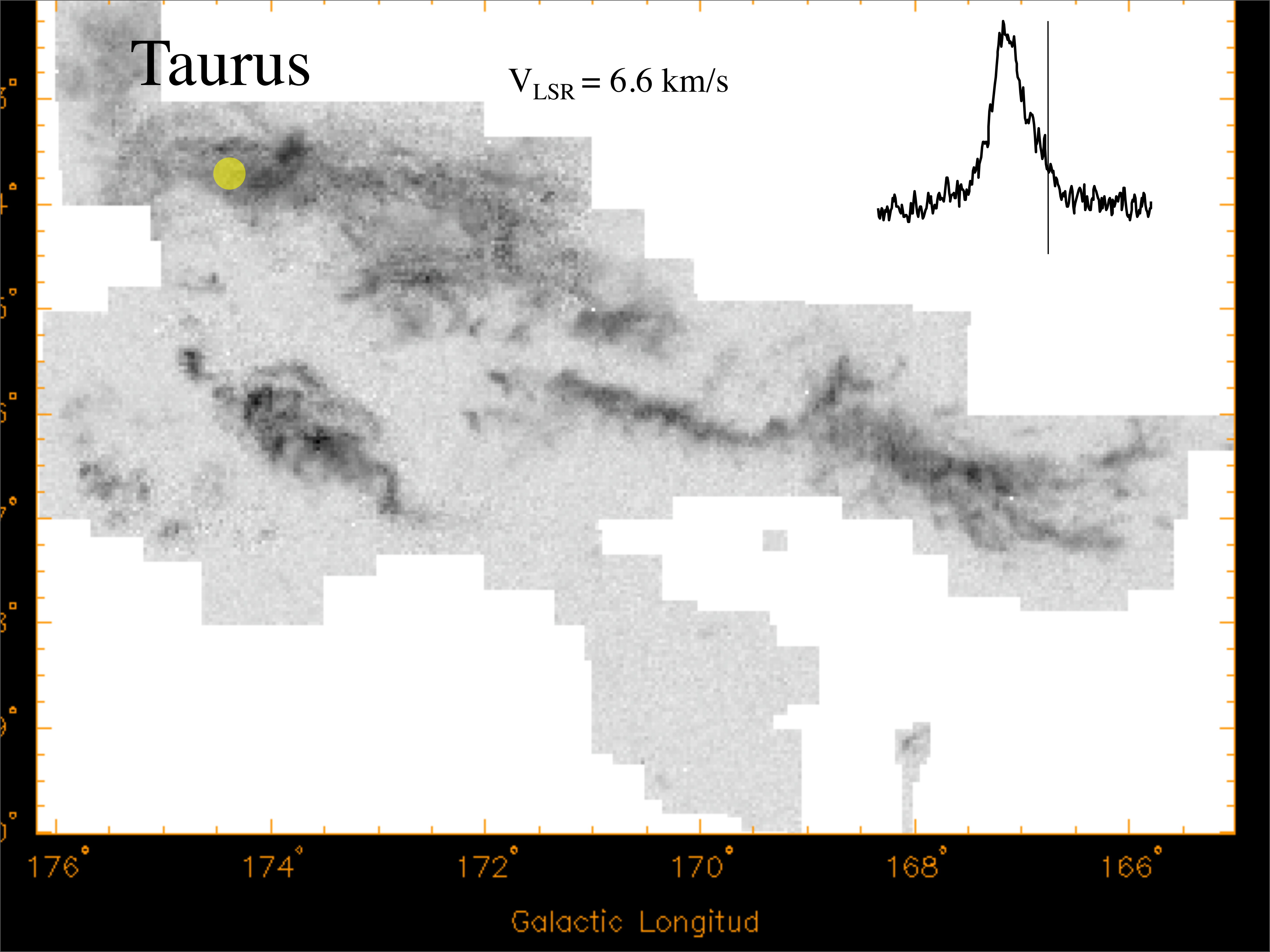
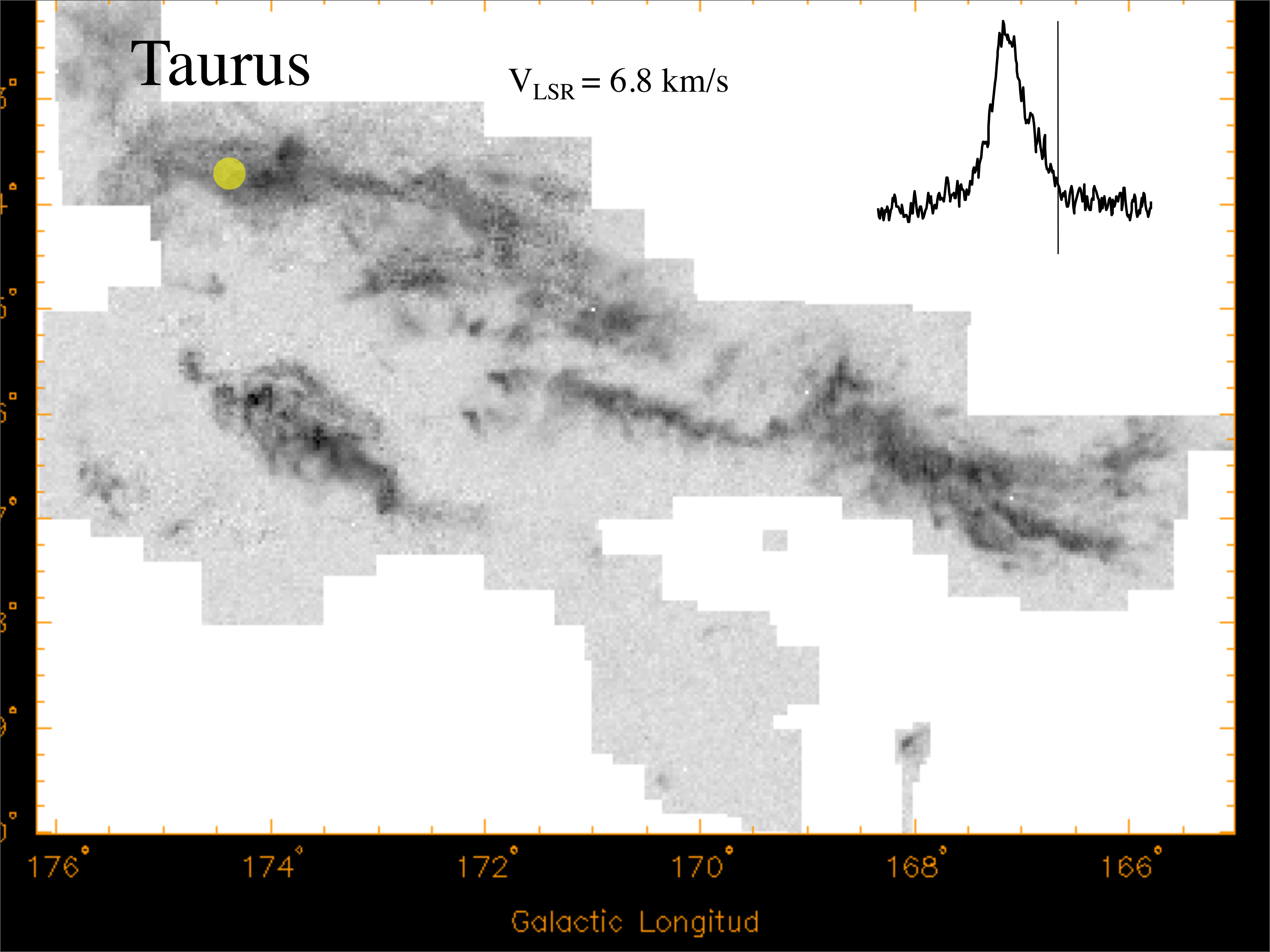
Taurus

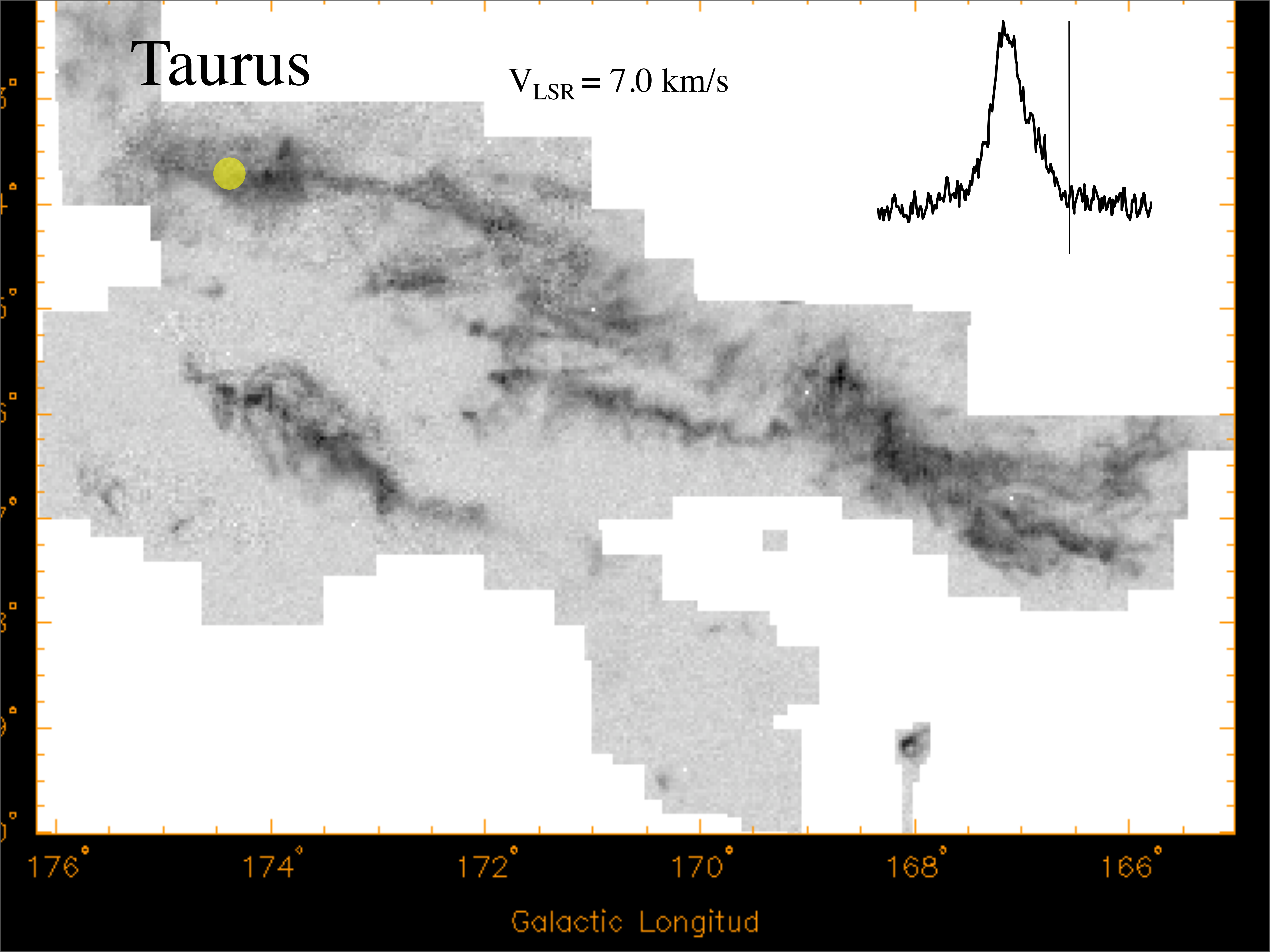


$V_{LSR} = 6.6$ km/s

Taurus

$V_{LSR} = 6.8$ km/s

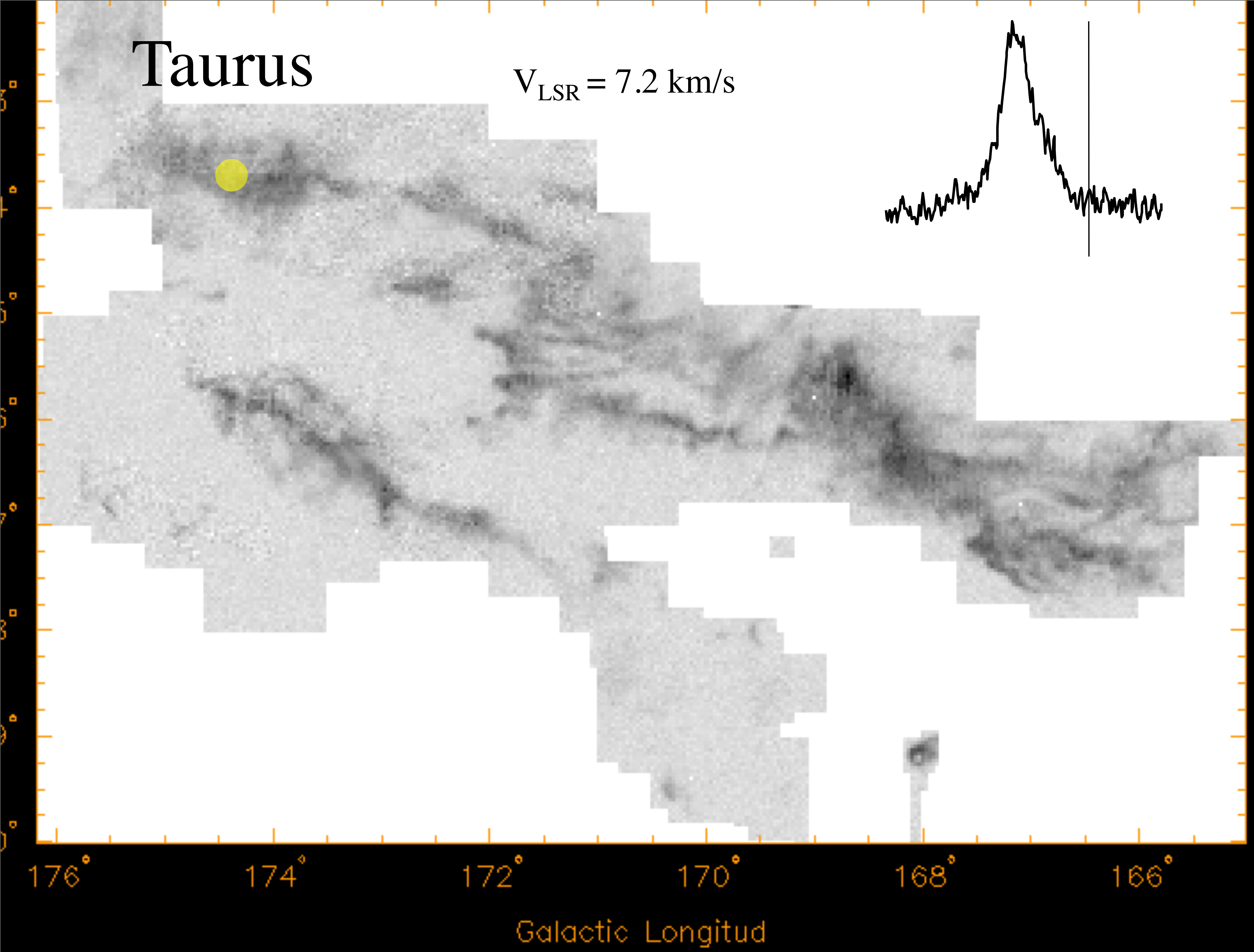




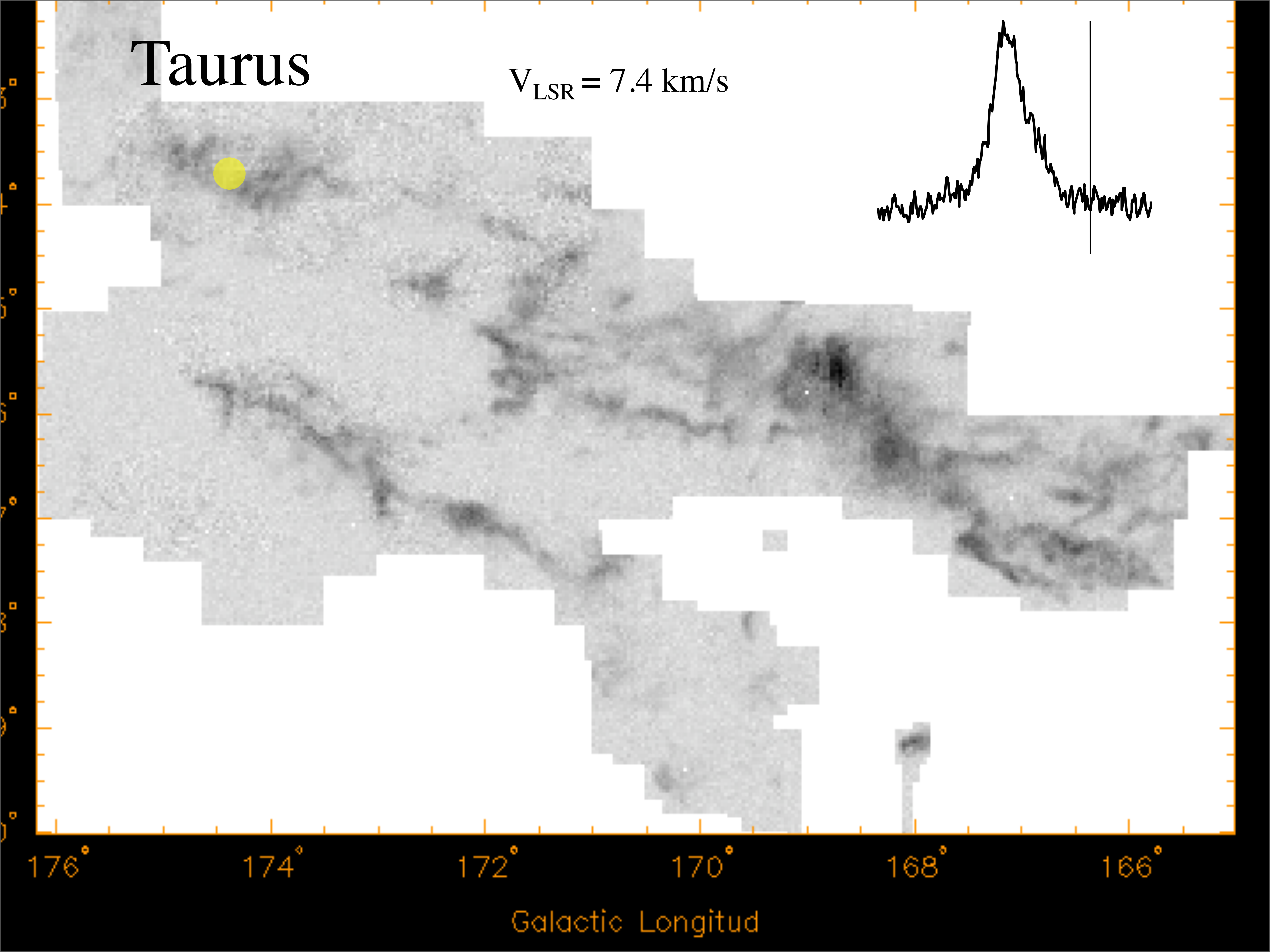
Taurus

V_{LSR} = 7.0 km/s

Taurus



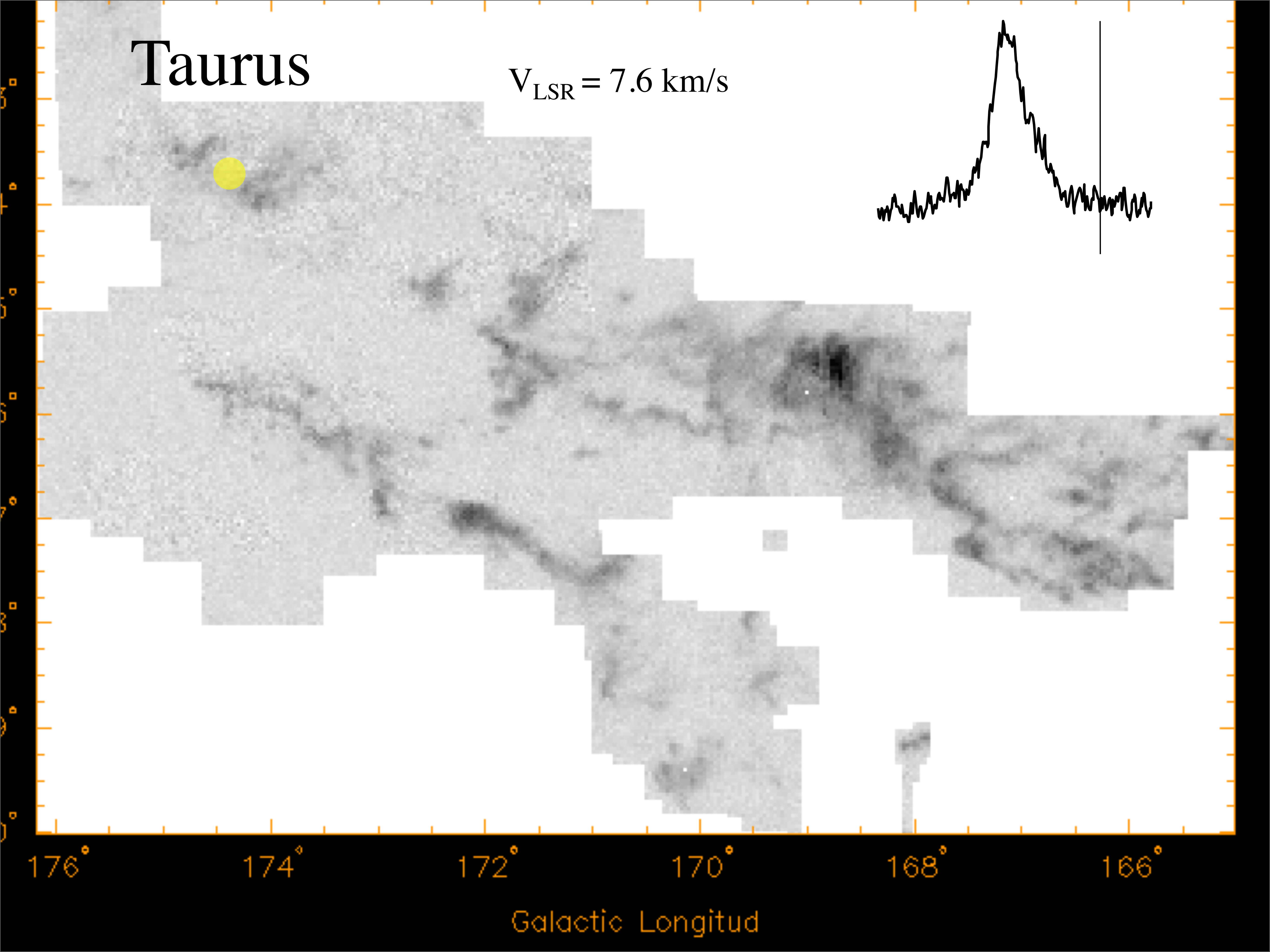
$V_{LSR} = 7.2$ km/s



Taurus

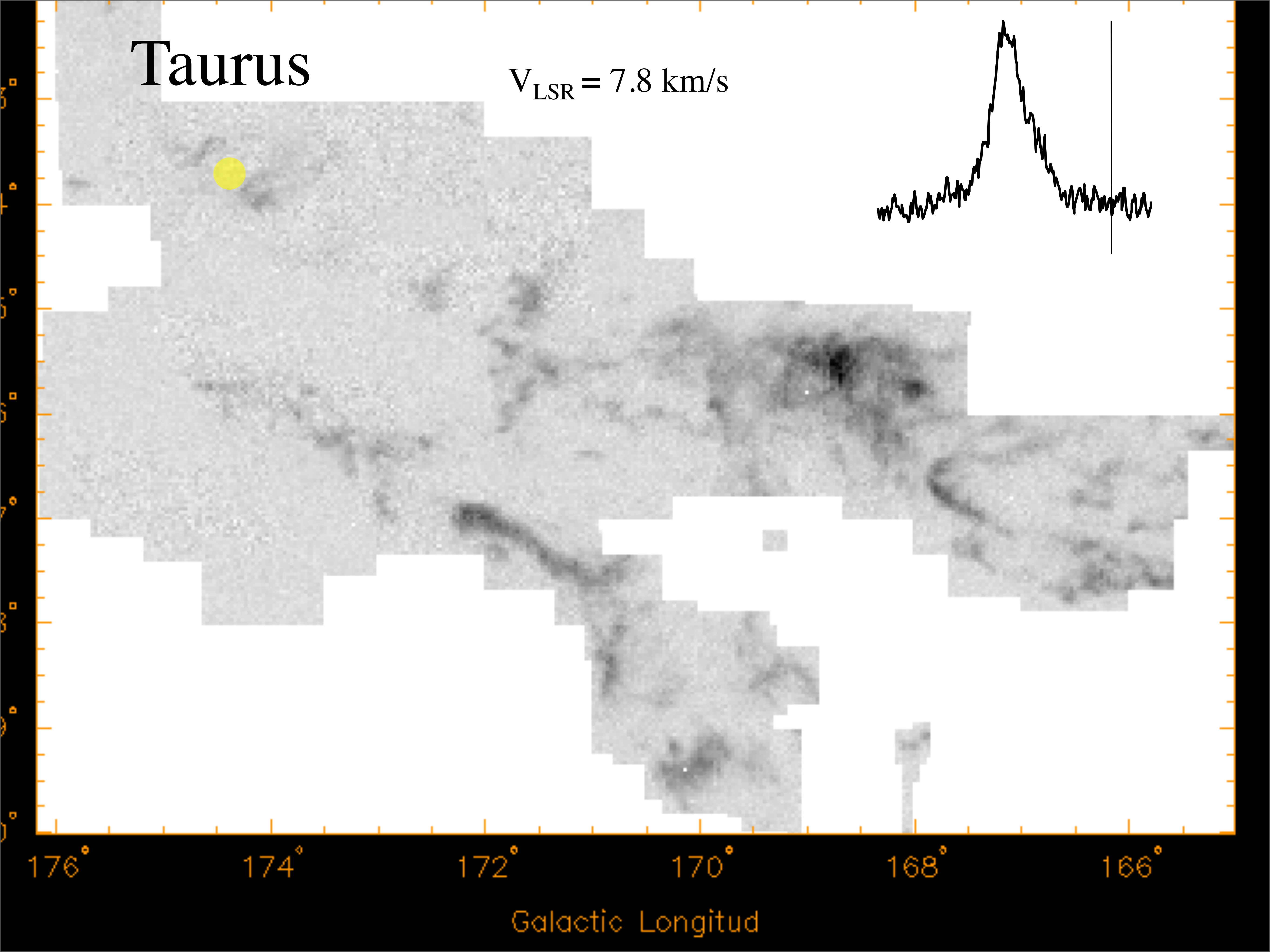
V_{LSR} = 7.4 km/s

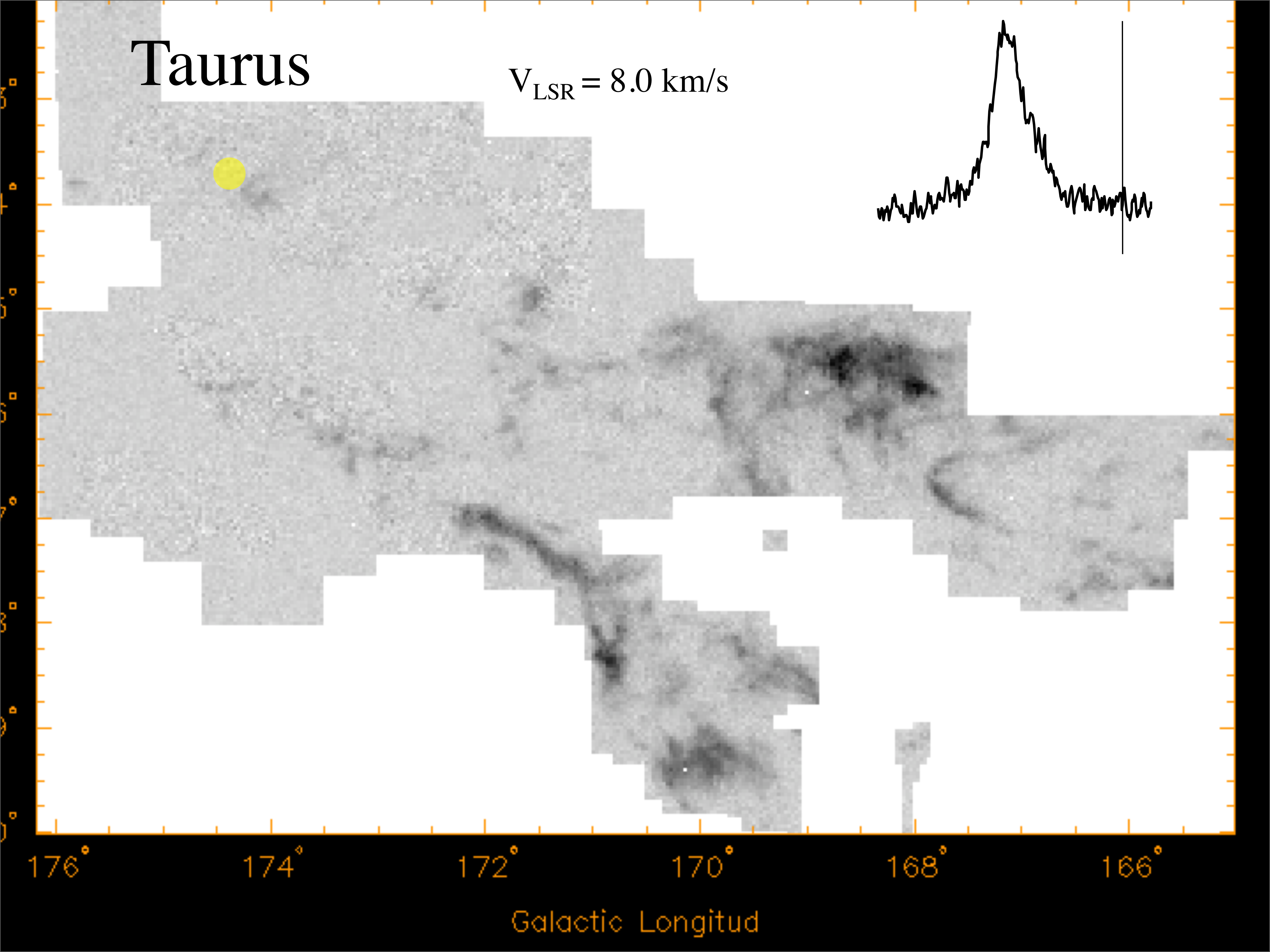
Taurus



$V_{LSR} = 7.6$ km/s

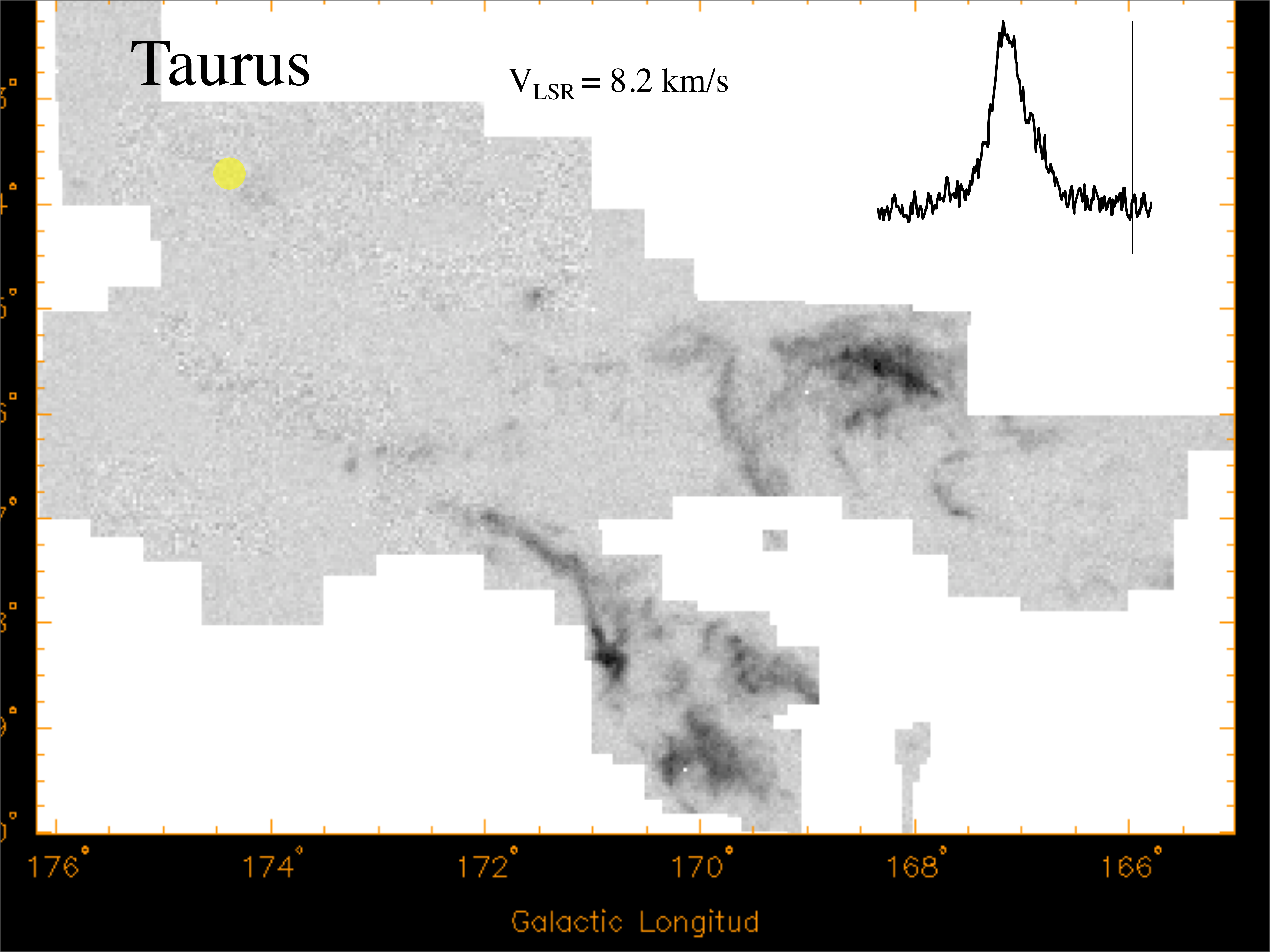
Taurus





Taurus

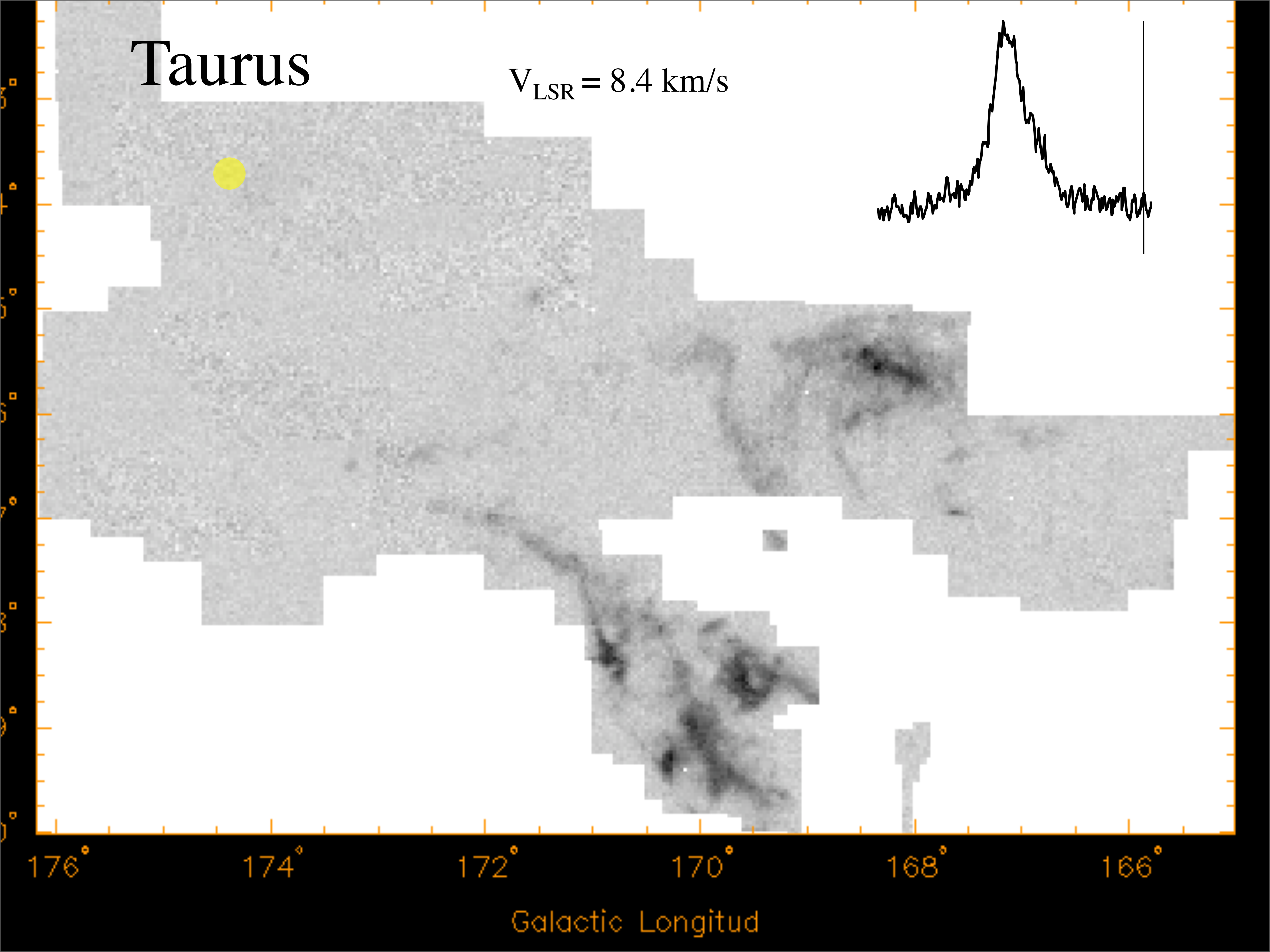
V_{LSR} = 8.0 km/s



Taurus

$V_{LSR} = 8.2$ km/s

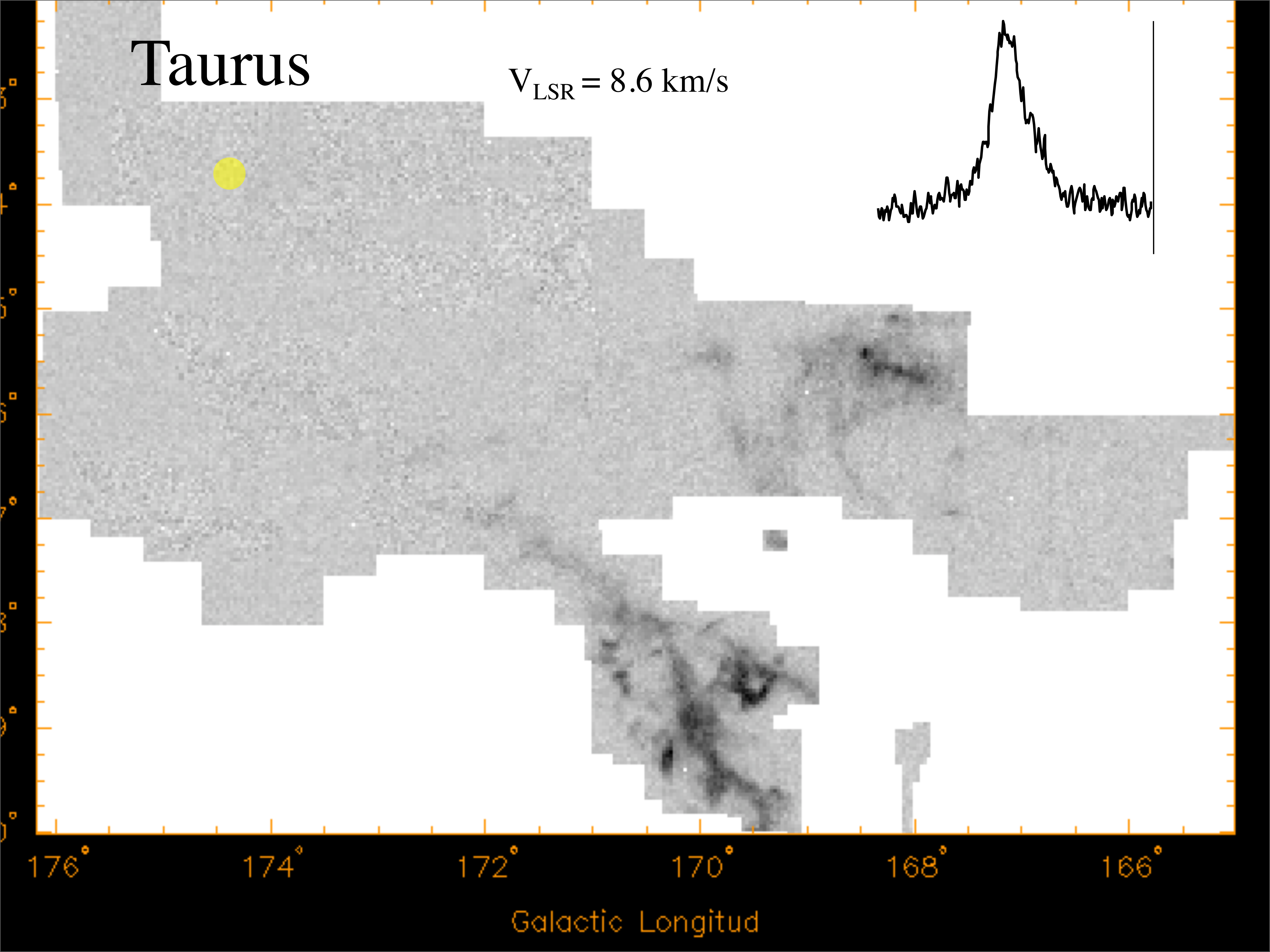
Taurus



$V_{LSR} = 8.4$ km/s

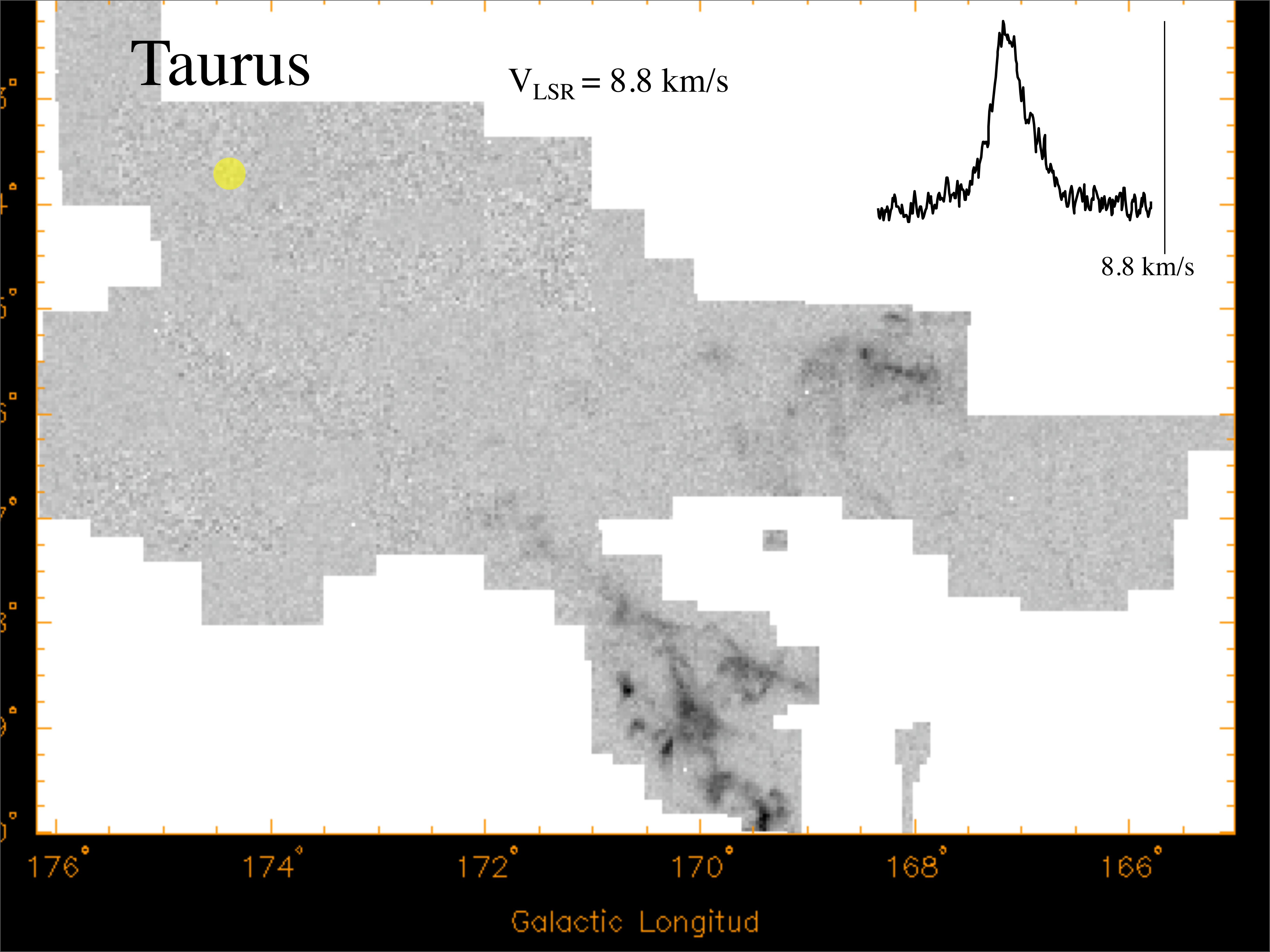
Taurus

$V_{LSR} = 8.6$ km/s

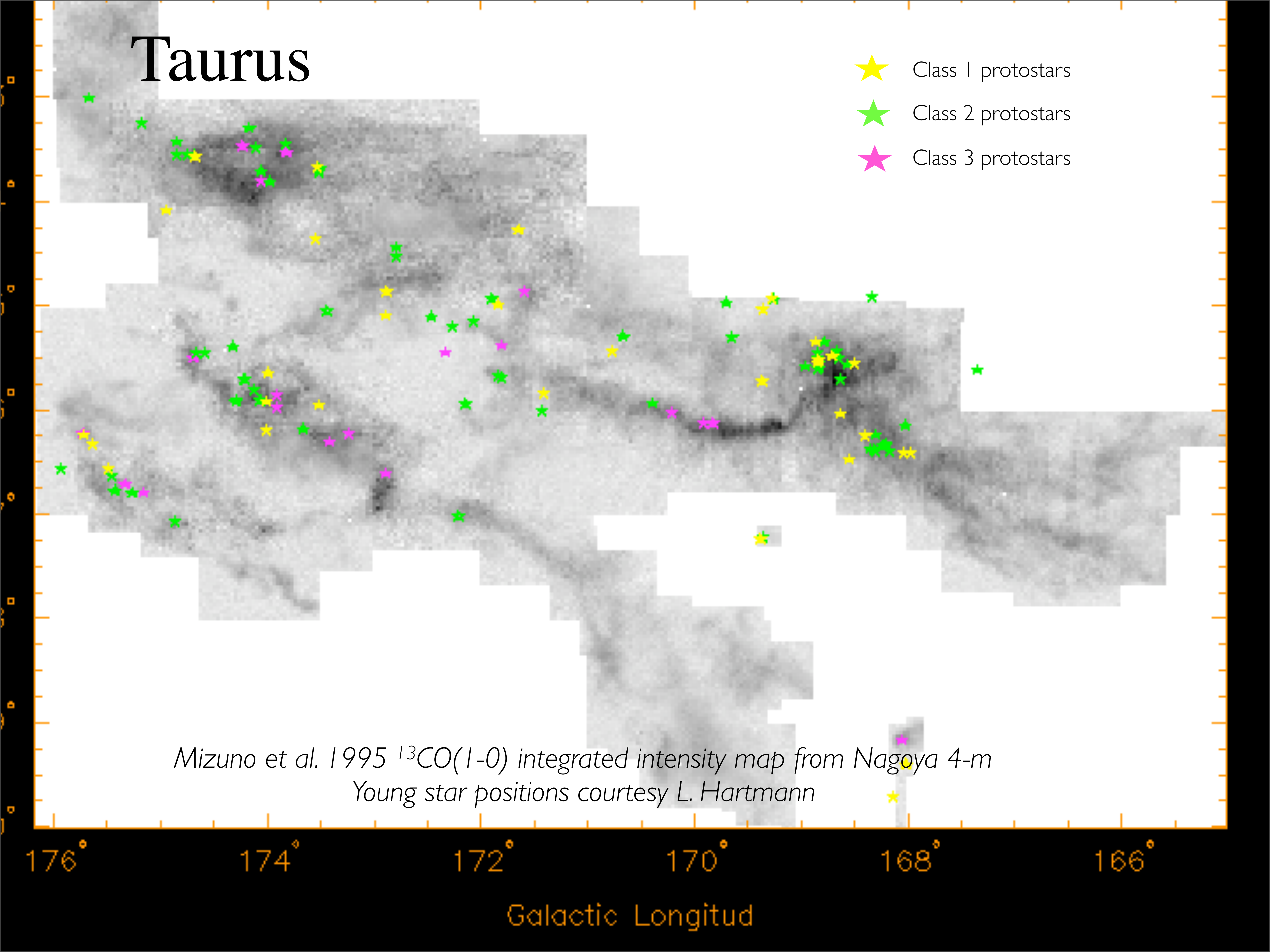


Taurus

$V_{LSR} = 8.8$ km/s



Taurus



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

What causes stars to form?

Out of the chaos, at some point:

$$2E_{grav} + E_{therm} + E_{kin} + E_{mag} < 0$$

gravity wins and collapse can proceed

Most of present day star formation research is trying to answer **why**!

The Jeans mass...

Simplest way to derive, is to just equate $E_{grav} = E_{therm}$:

For a uniform density sphere,

$$E_{grav} = \frac{3}{5}\frac{Gmm}{r} \qquad E_{therm} = \frac{3}{2}\frac{k_BT}{\mu m_p}m \qquad \rho = \frac{3m}{4\pi r^3}$$

which give,

$$m_J = \left[\frac{4\pi\rho}{3}\right]^{-1/2}\left[\frac{5k_BT}{2G\mu m_p}\right]^{3/2}$$

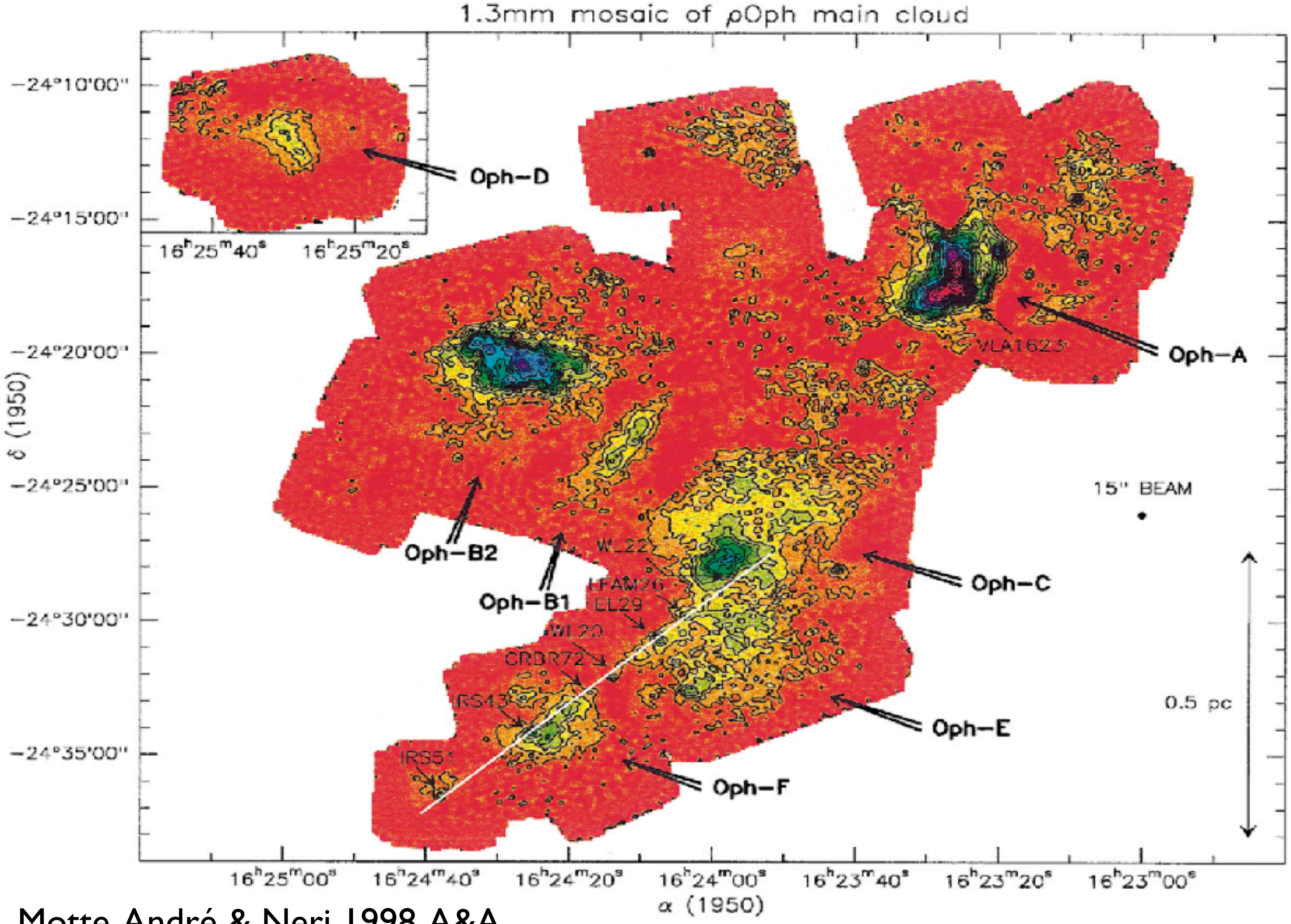
$$\lambda_J = \left[\frac{4\pi\rho}{3}\right]^{-1/2}\left[\frac{5k_BT}{2G\mu m_p}\right]^{1/2}$$

or in 'useful' units,

$$m_J = 1M_\odot\left[\frac{\rho}{10^{-19}gcm^{-3}}\right]^{-1/2}\left[\frac{T}{10K}\right]^{3/2}$$

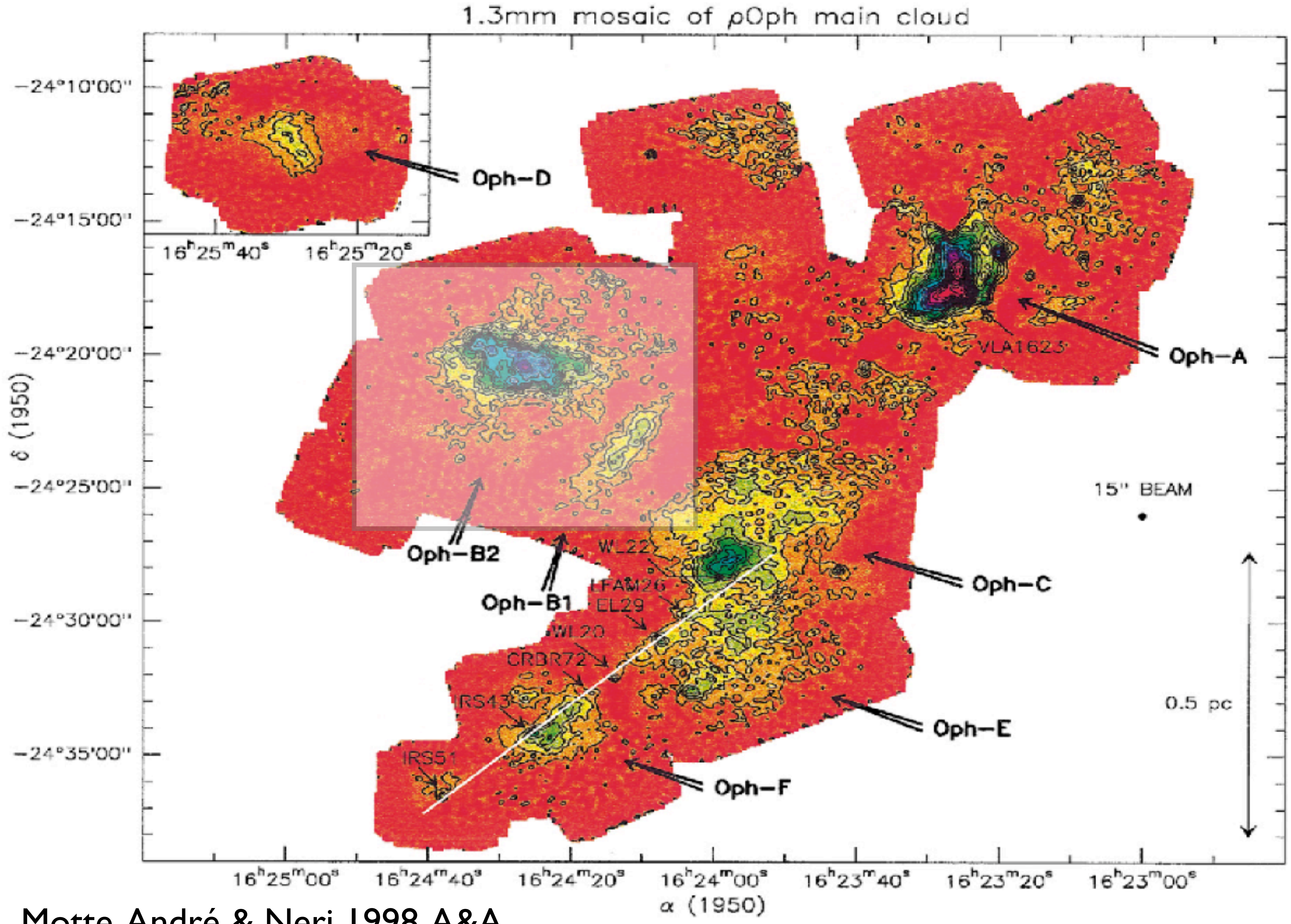
$$\lambda_J = 8500au\left[\frac{\rho}{10^{-19}gcm^{-3}}\right]^{-1/2}\left[\frac{T}{10K}\right]^{1/2}$$

The Jeans mass in action



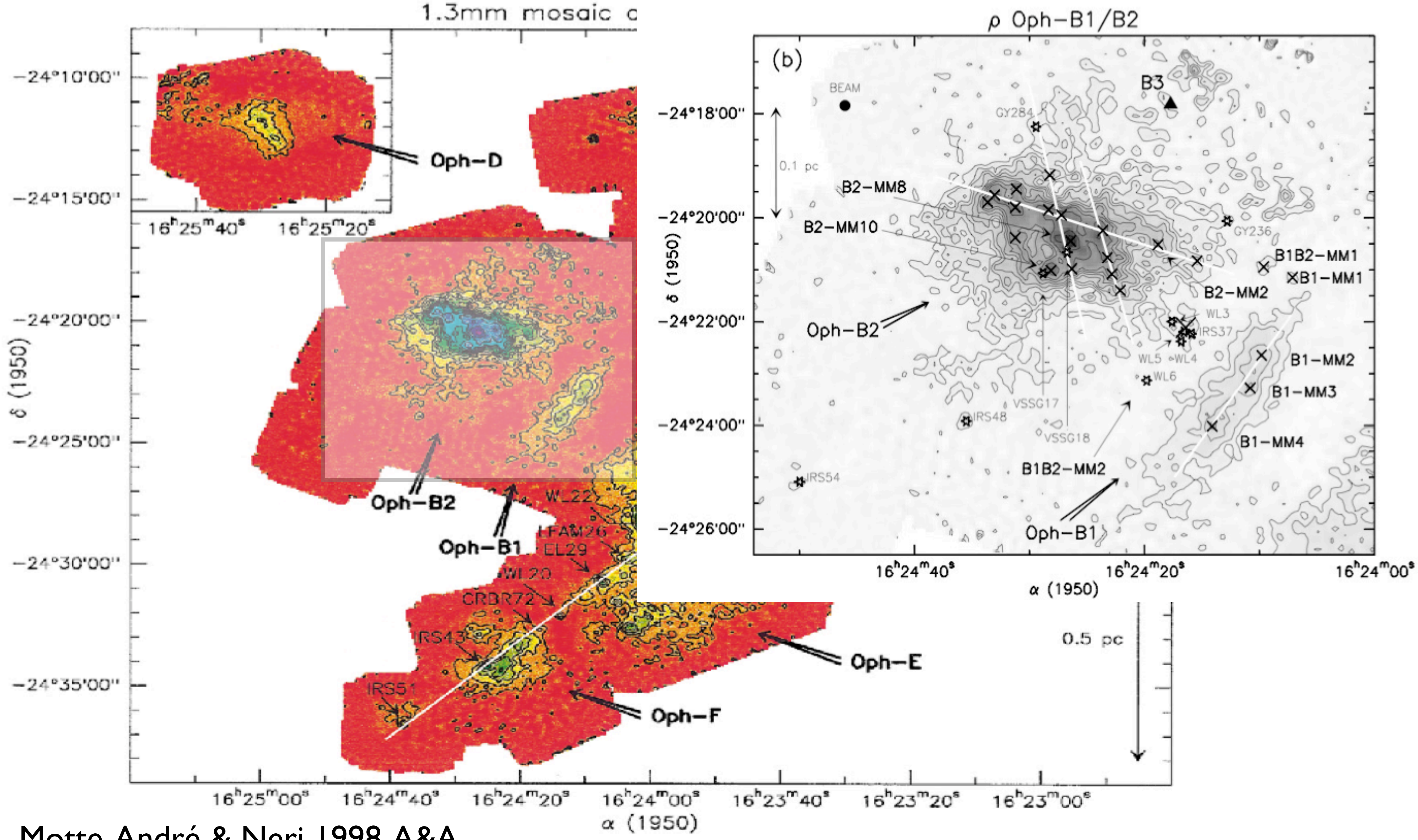
Motte, André & Neri 1998, A&A 336, 150

The Jeans mass in action



Motte, André & Neri 1998, A&A 336, 150

The Jeans mass in action



Motte, André & Neri 1998, A&A 336, 150

Now it's bound....
... what happens next?

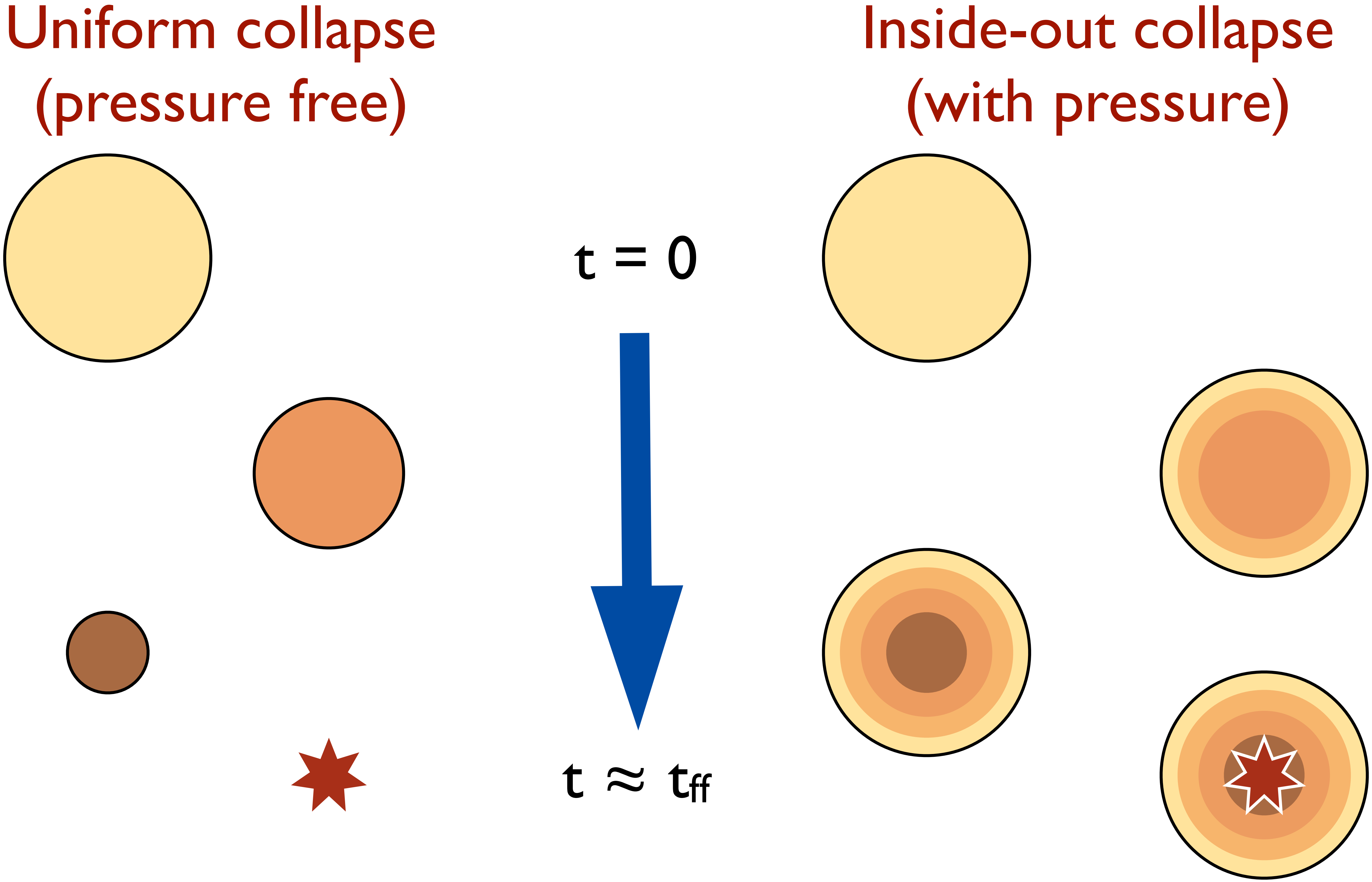
The free-fall time:

Time taken for a pressure-free fluid to collapse to a point,

$$t_{ff} = \left[\frac{3\,\pi}{32\;G\;\rho}\right]^{1/2}$$

(derivation on board)

Inside-out collapse!



The formation of a protostar (I)

R.B. Larson (1969):

mass continuity

$$\frac{\partial m}{\partial t}+\frac{4\pi r^2 u}{V}=0$$

momentum continuity

$$\frac{\partial u}{\partial t}+u\,\frac{\partial u}{\partial r}+\frac{Gm}{r^2}+V\,\frac{\partial P}{\partial r}=0$$

$$\frac{\partial E}{\partial t}+P\,\frac{\partial V}{\partial t}+u\left(\frac{\partial E}{\partial r}+P\,\frac{\partial V}{\partial r}\right)+\frac{3}{4\pi}\,V\,\frac{\partial L}{\partial r^3}=0$$

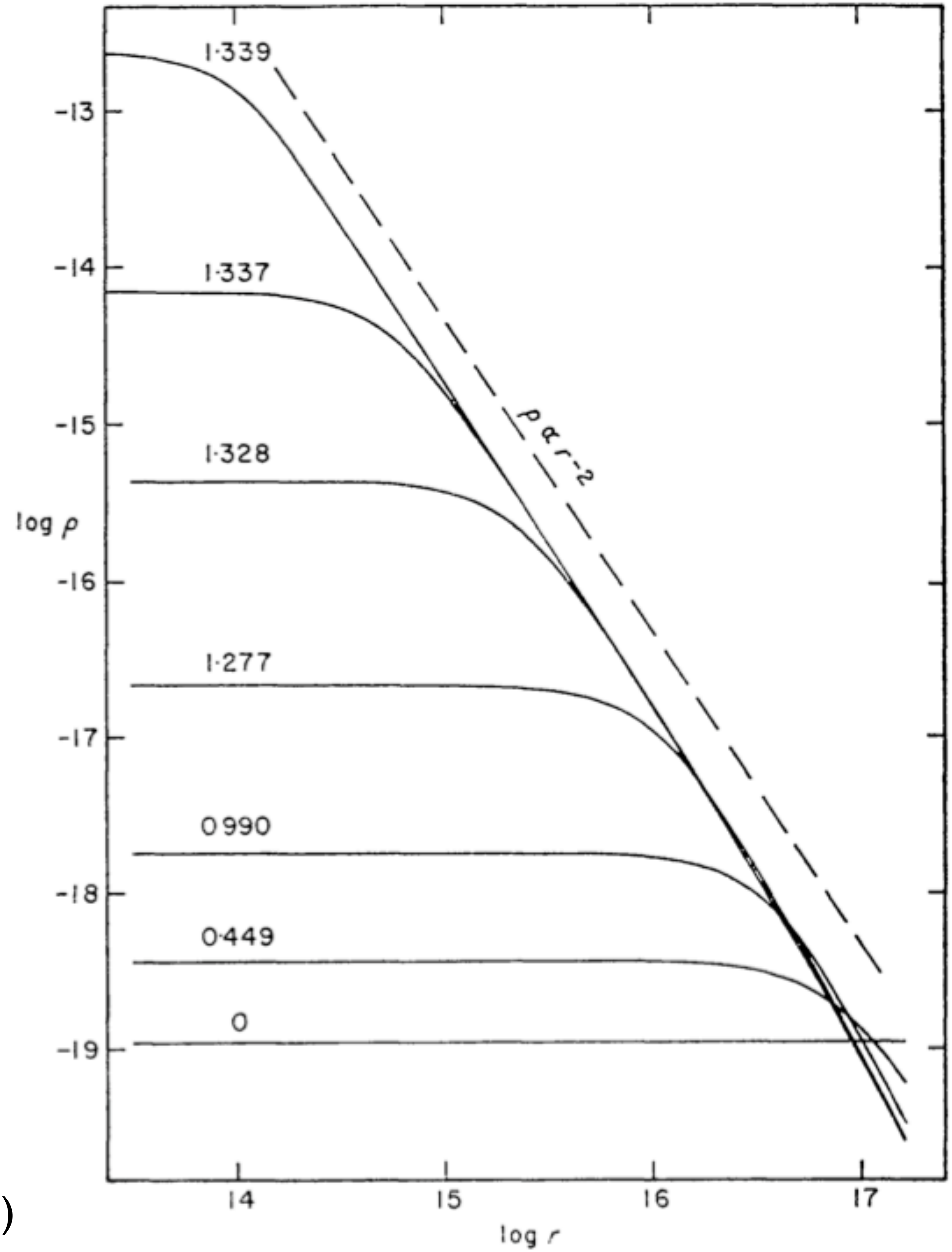
energy equation

volume / mass relation

$$\frac{1}{V}-\frac{3}{4\pi}\,\frac{\partial m}{\partial r^3}=0$$

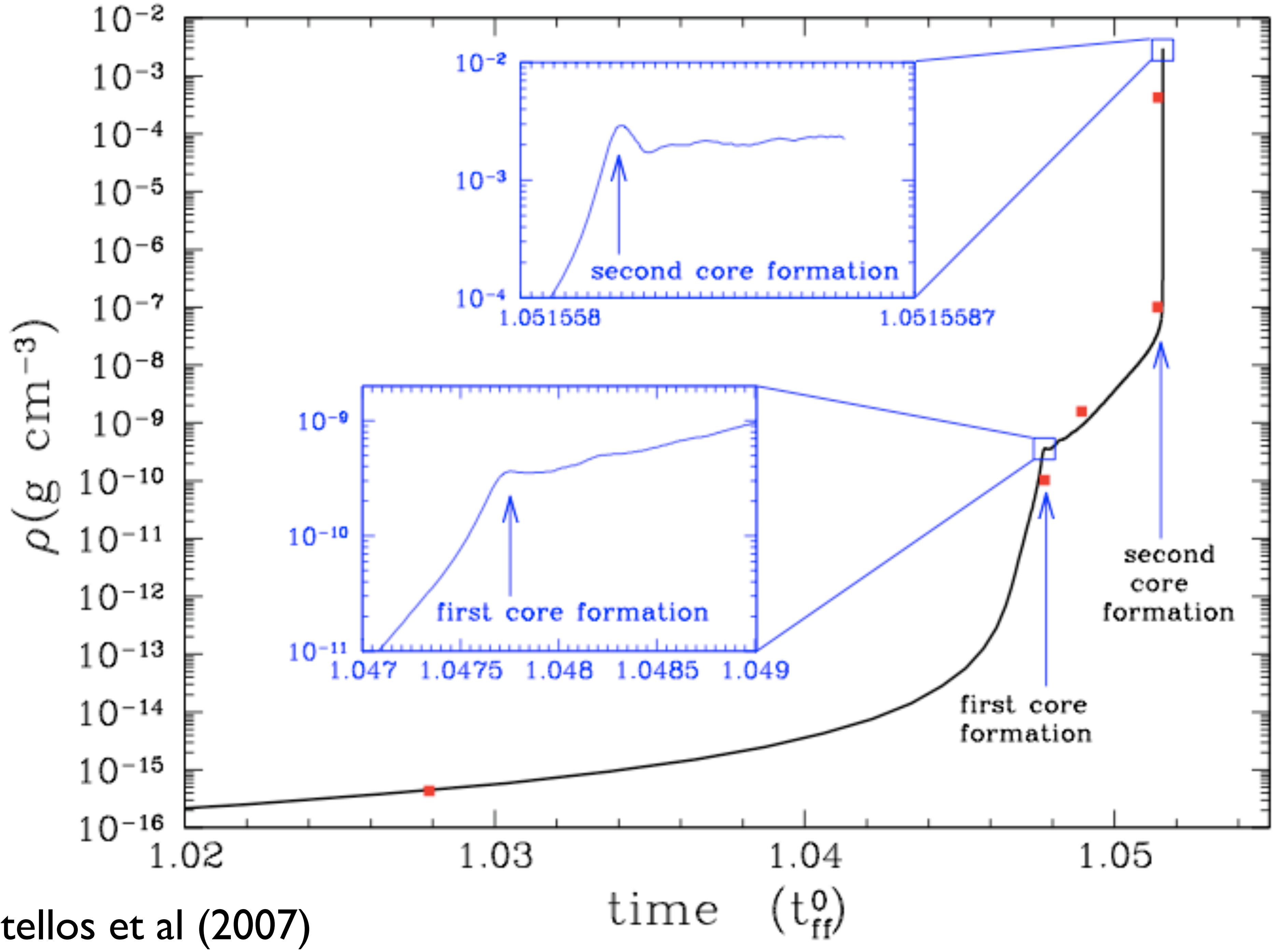
Diffusion approximation for radiative transport

$$L=-\frac{64\pi\sigma}{3}\,r^2\,\frac{VT^3}{\kappa}\,\frac{\partial T}{\partial r}.$$



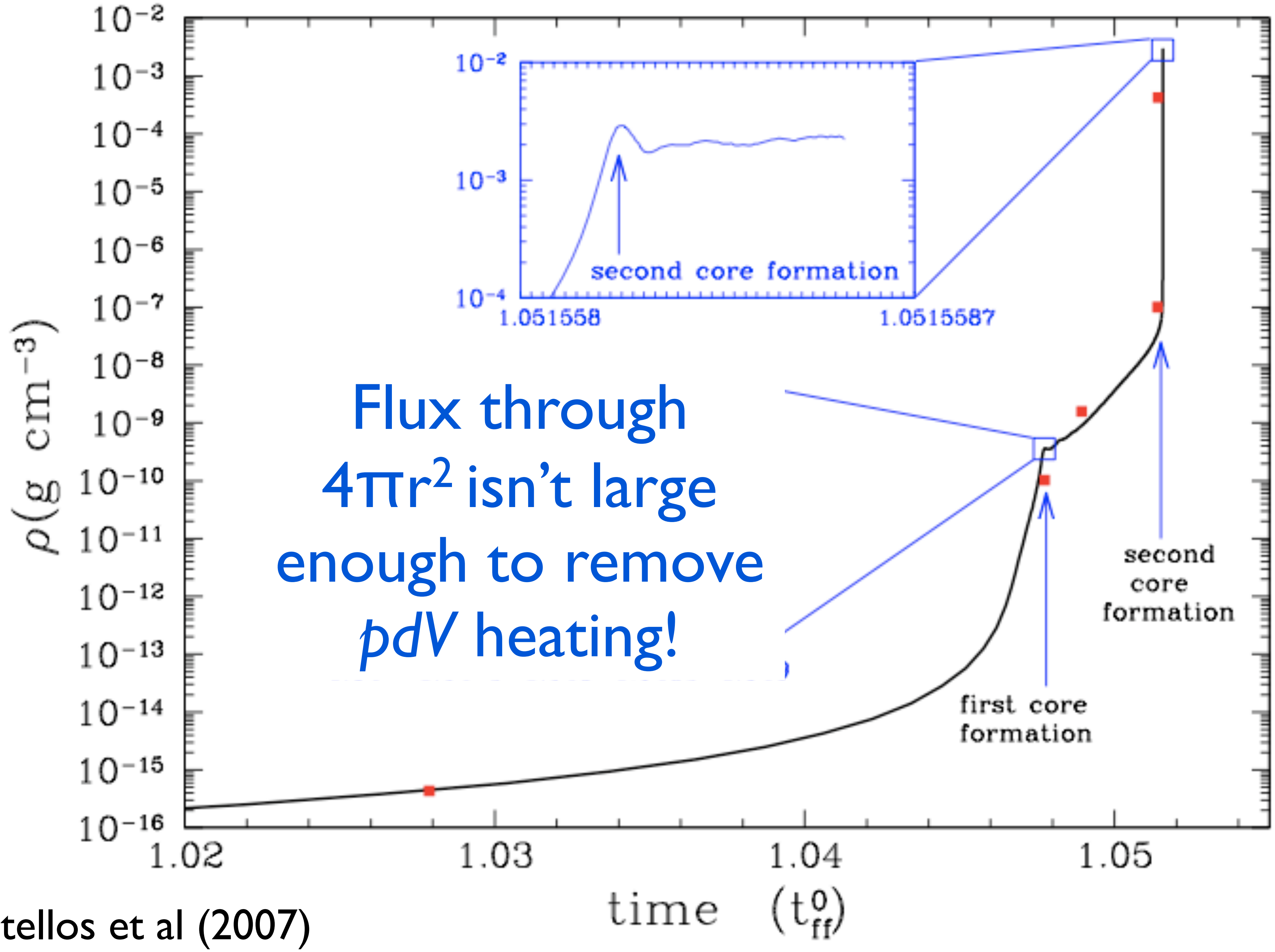
R.B. Larson (1969)

The formation of a protostar (II)



Stamatellos et al (2007)

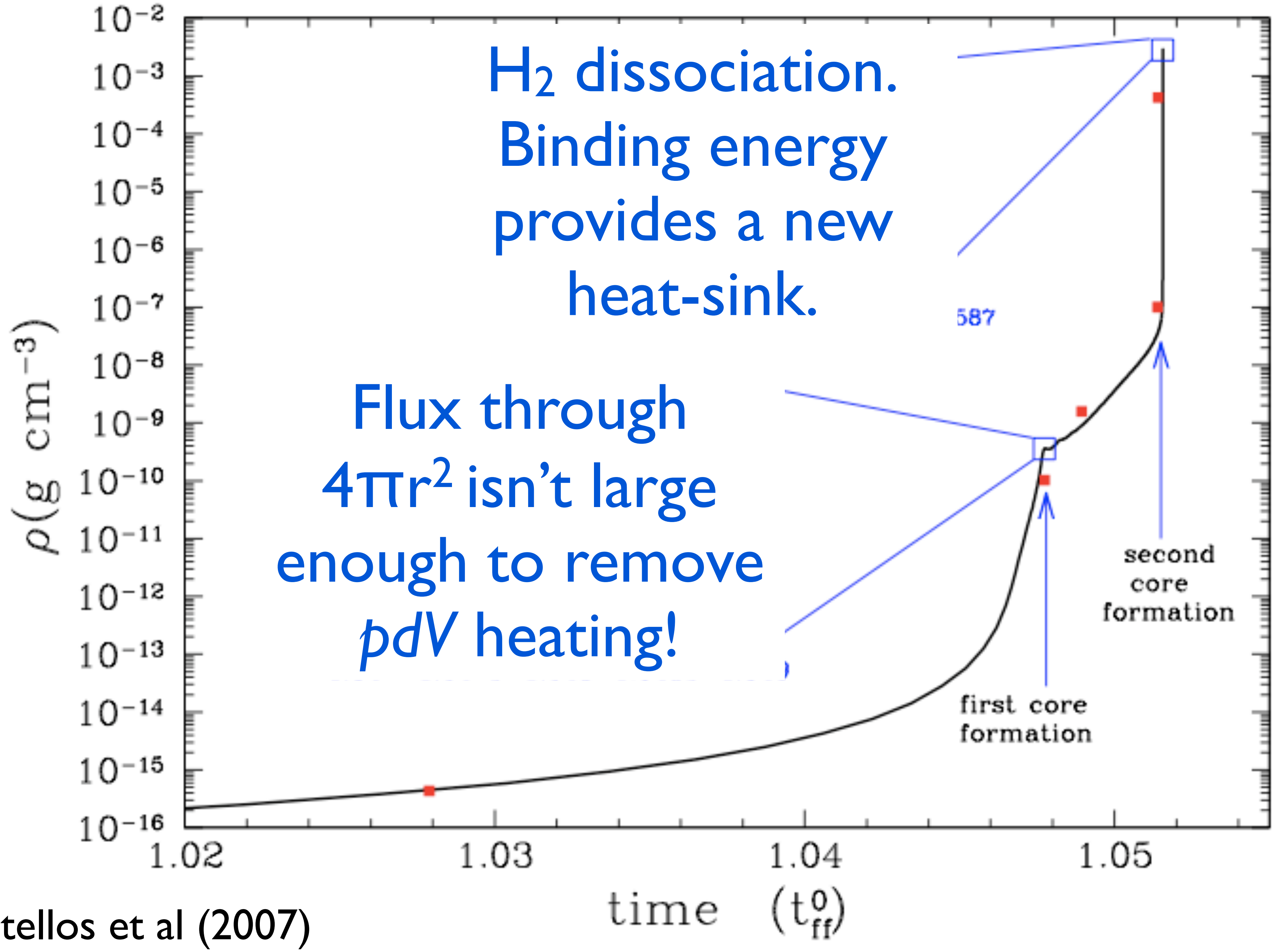
The formation of a protostar (II)



Flux through $4\pi r^2$ isn't large enough to remove *pdV* heating!

Stamatellos et al (2007)

The formation of a protostar (II)



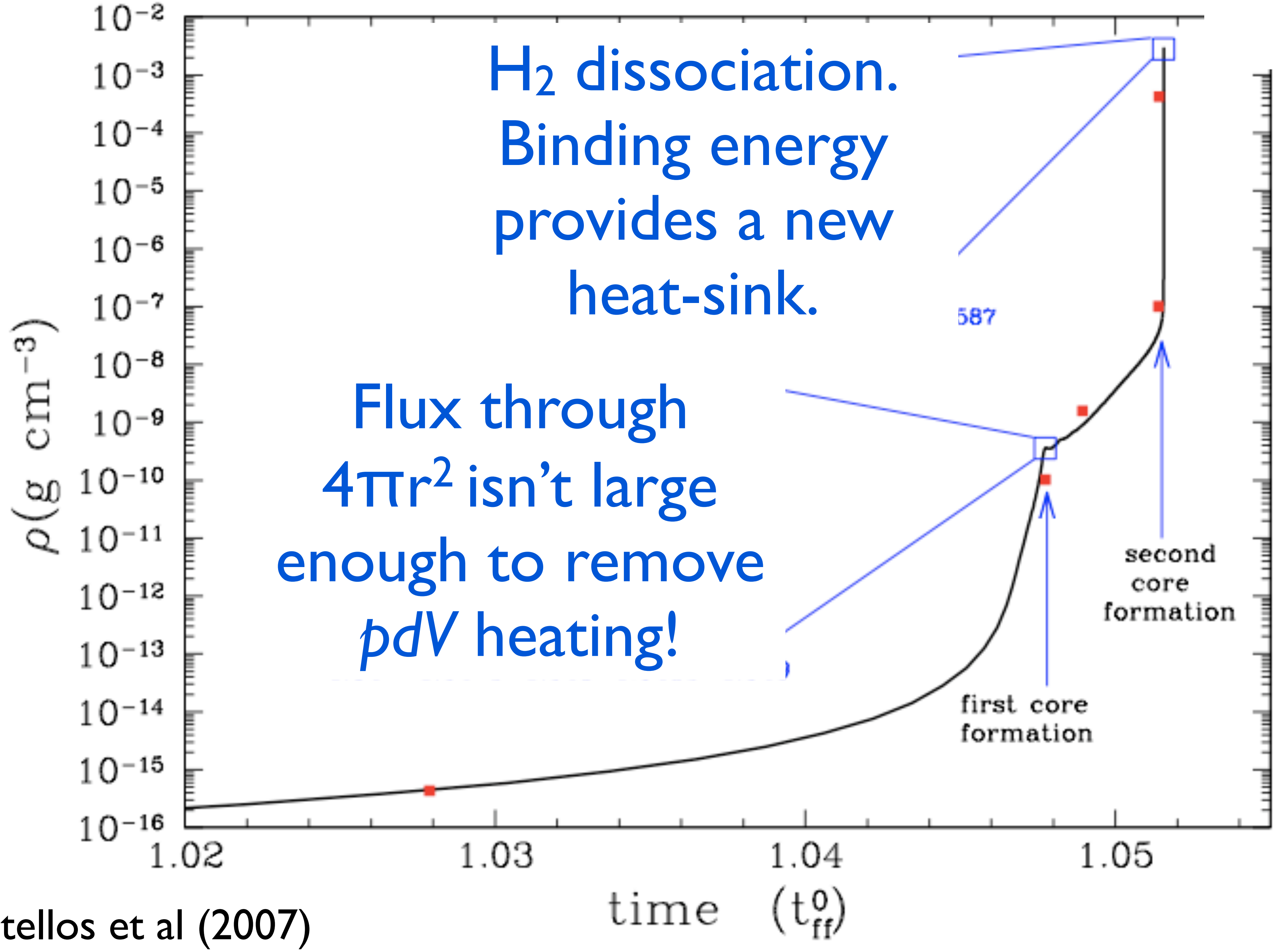
H_2 dissociation. Binding energy provides a new heat-sink.

Flux through $4\pi r^2$ isn't large enough to remove *pdV* heating!

Stamatellos et al (2007)

The formation of a protostar (II)

H_2 gone! Protostar forms



H_2 dissociation. Binding energy provides a new heat-sink.

Flux through $4\pi r^2$ isn't large enough to remove *pdV* heating!

Stamatellos et al (2007)

What happens to the infall energy?

Accretion Luminosity:

If one assumes roughly all the potential energy released is turned into heat,

$$\mathrm{L_{acc}} \approx \frac{\mathrm{G\ M_* \ \dot{m}}}{\mathrm{R_*}}$$

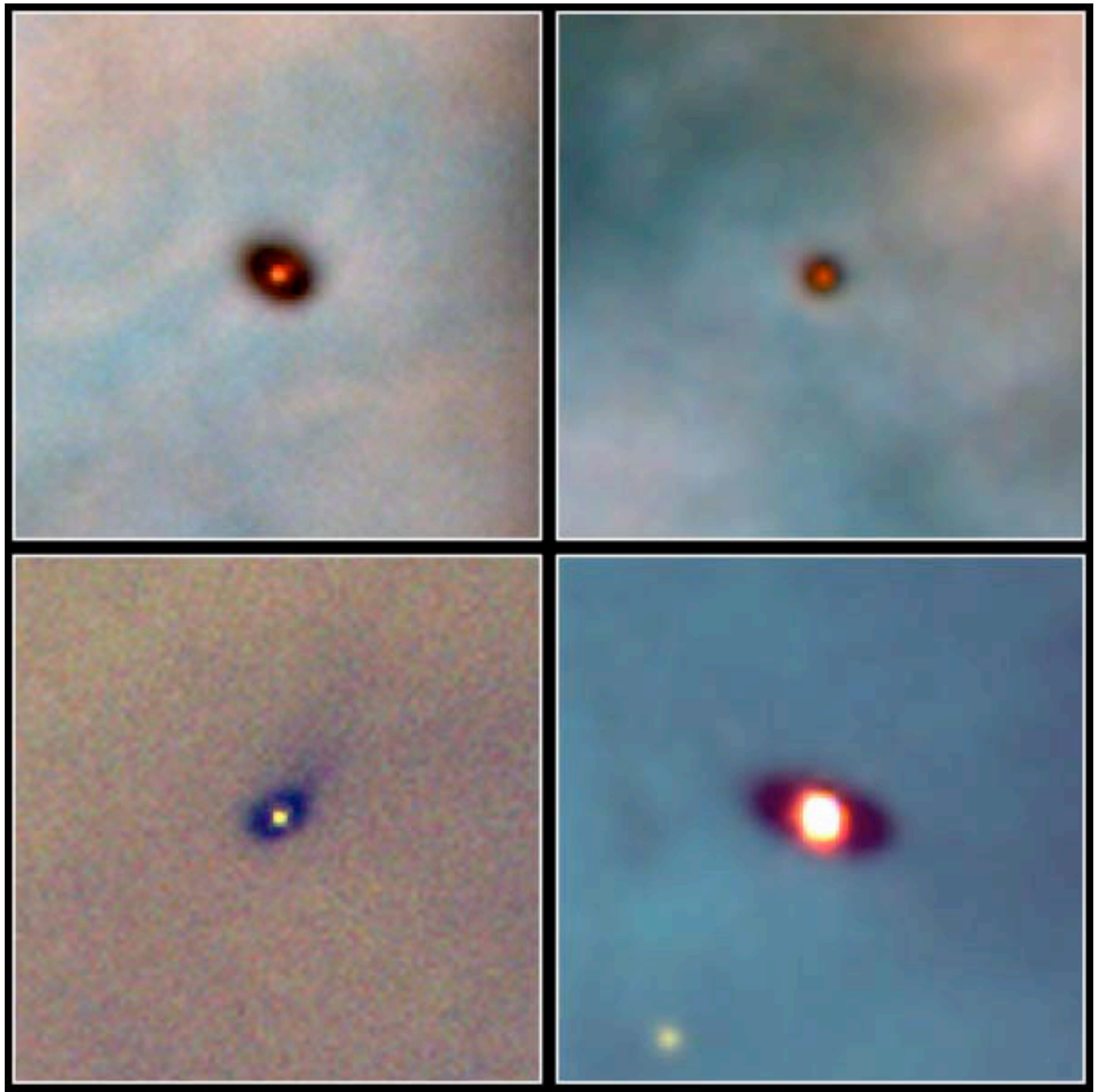
$$\mathrm{L} = 4\pi\ \mathrm{r_*^2}\ \sigma\ \mathrm{T^4}$$

$$\mathrm{T_{acc}} = \left[\frac{\mathrm{G}}{4\pi\ \sigma}\right]^{1/4} \frac{(\mathrm{M_*\ \dot{m}})^{1/4}}{\mathrm{R_*^{3/4}}}$$

Weakly depends on mass

Strong function of R*

1D is not really enough...
... need 3D!



Protoplanetary Disks
Orion Nebula

HST • WFPC2

PRC95-45b • ST ScI OPO • November 20, 1995
M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA

- Gas that undergoes gravitational instability contains angular momentum about the centre of mass

- Gas collapses into a plane, perpendicular to:

$$\mathbf{L} = m\,\mathbf{r} \times \mathbf{v}$$

How big should the discs be?

Rough estimate:

- Assume cores are uniform density spheres, in solid-body rotation.
- Can then first define the spin parameter $\beta = E_{rot} / E_{grav}$,

$$E_{rot} = \frac{1}{2} I\omega^2 \qquad I = \frac{2}{5} mr \qquad \omega = \frac{v_{rot}}{r} \qquad E_{grav} = \frac{3}{5}\frac{Gmm}{r}$$

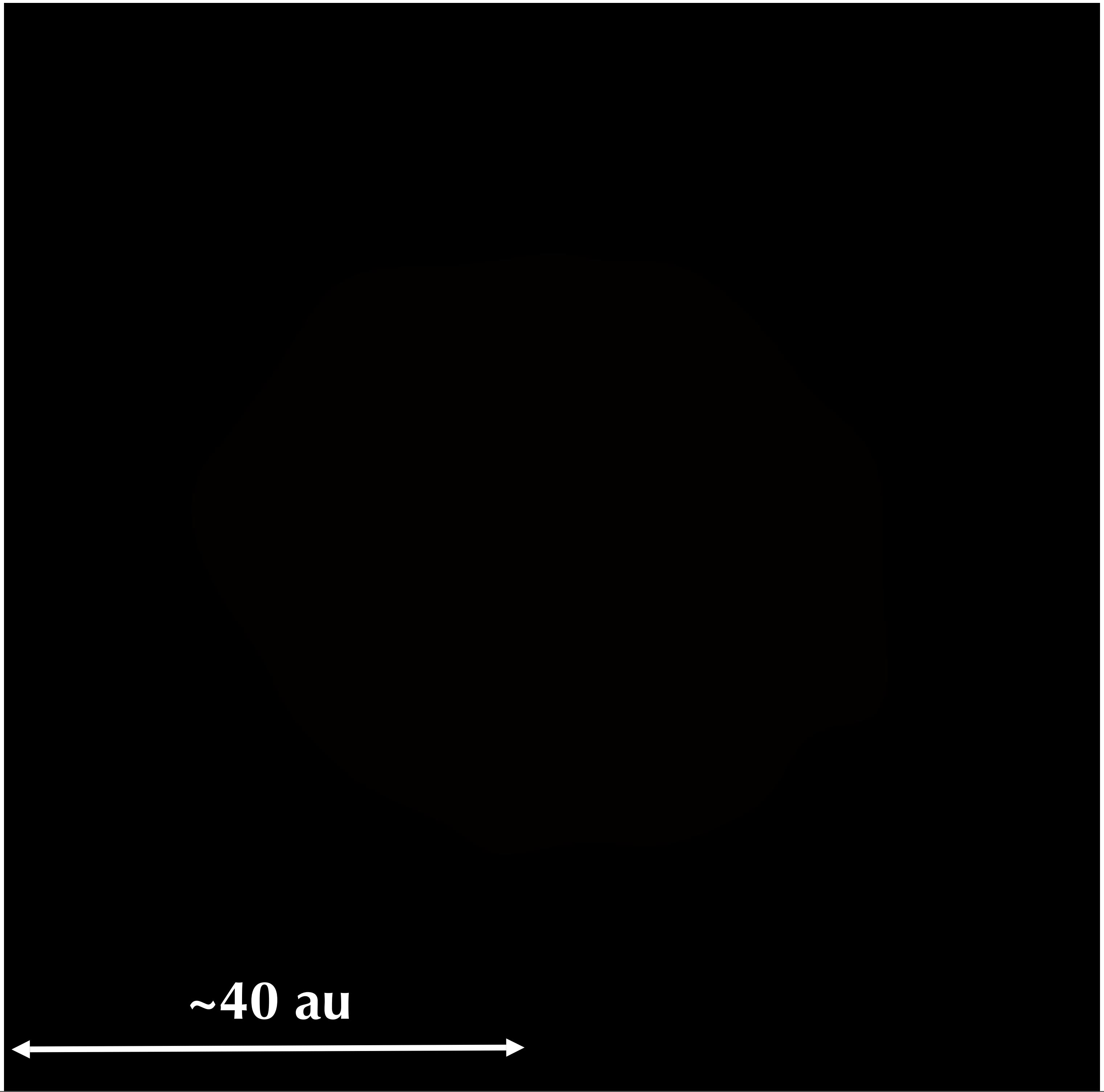
$$\beta = \frac{1}{3}\frac{r\ v_{rot}}{G\ m}$$

- This is what the observers use.
- Typical values for cores from 0.01pc to ~ 1pc is around $\beta = 0.02$ (Goodman et al 1995).

Then equate the initial cloud L/m with final orbit L/m!

Disc formation during collapse

Disc formation during collapse

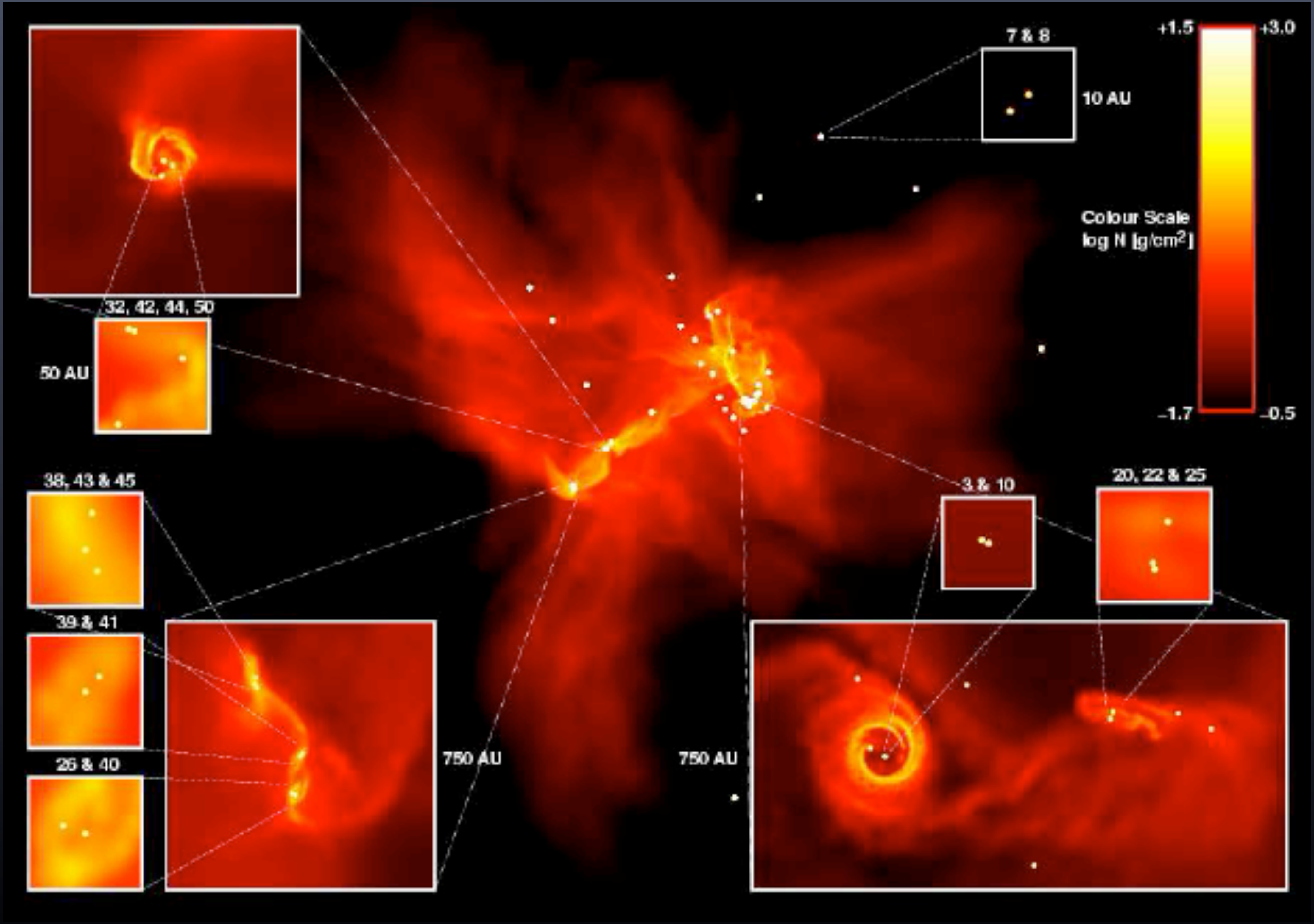


Cluster formation

Simulation: Matthew Bate, Exeter
Visualisation: Richard West, UKAFF

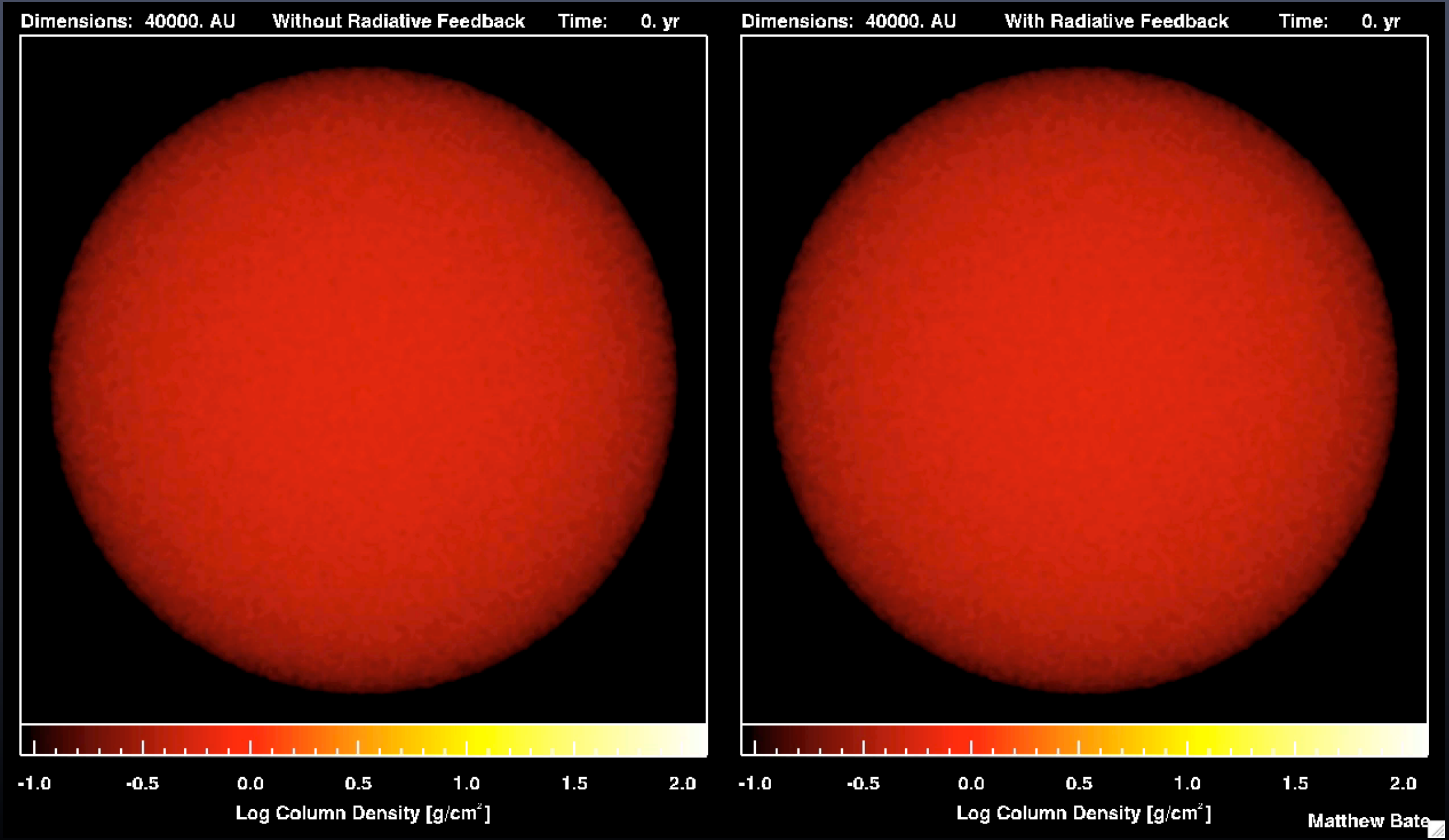
Bate, Bonnell & Bromm (2003)

Binary formation



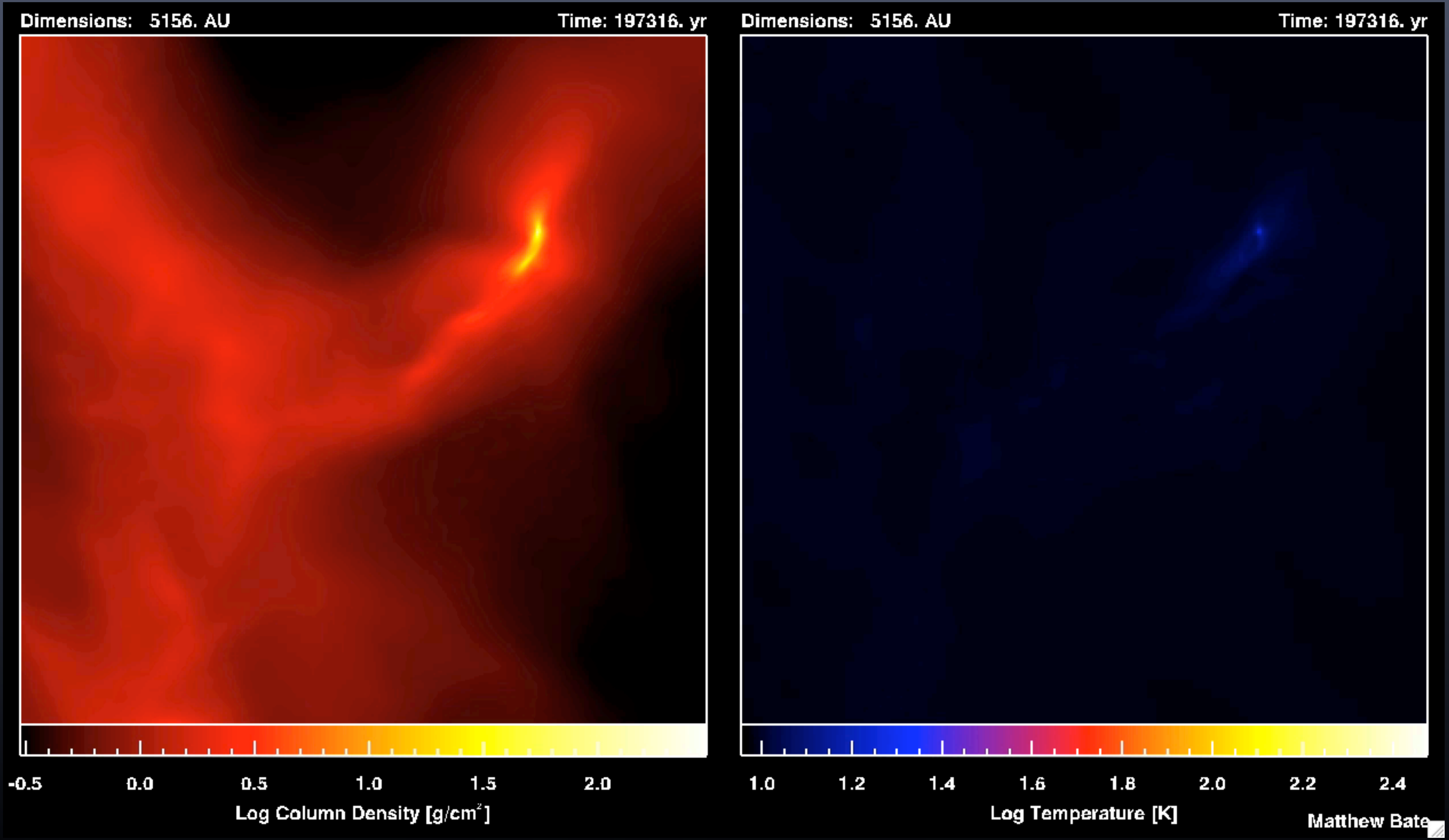
Bate, Bonnell & Bromm (2003)

With radiative transfer



M. R. Bate (2008)

Temperature structure?

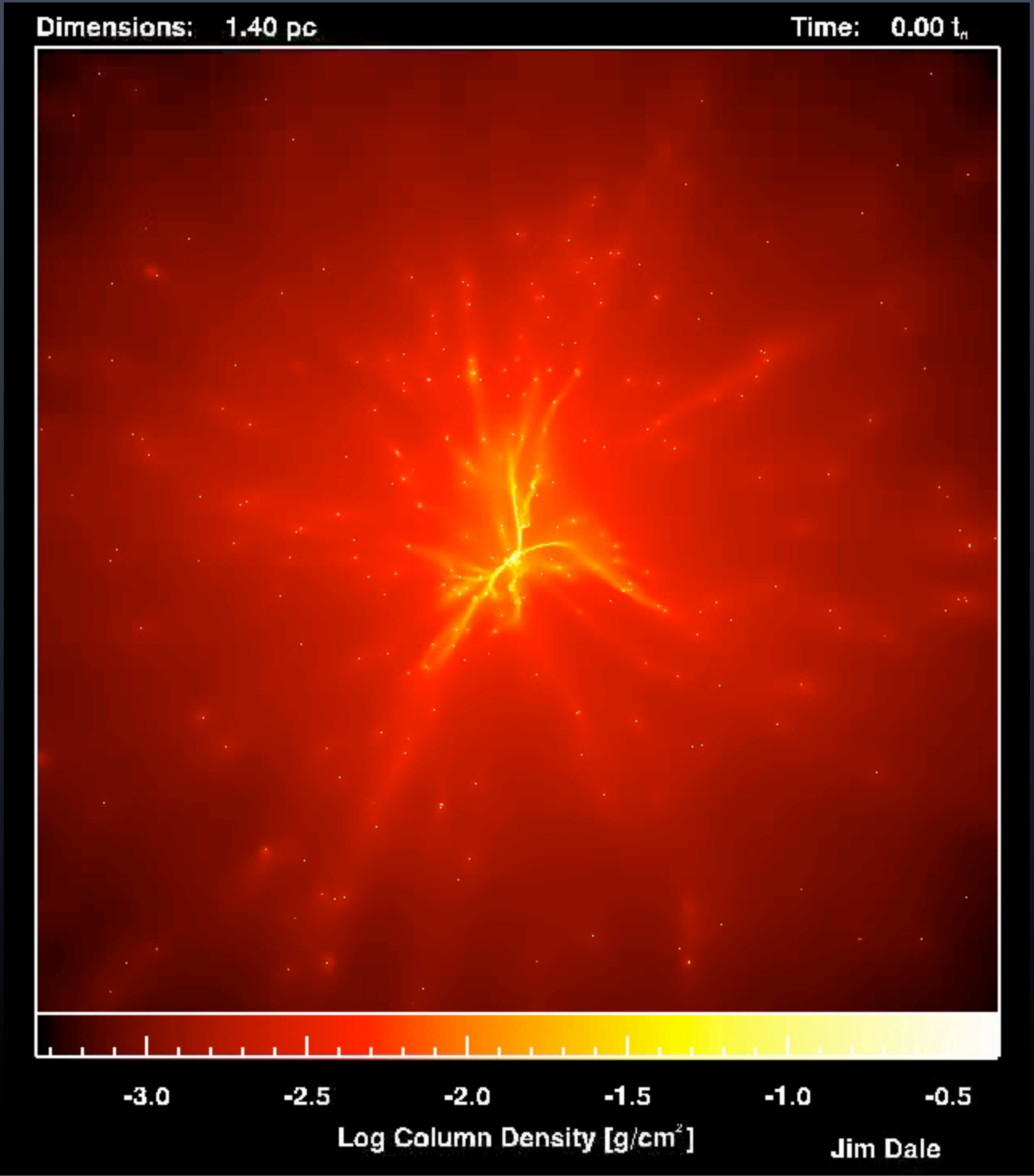


M. R. Bate (2008)

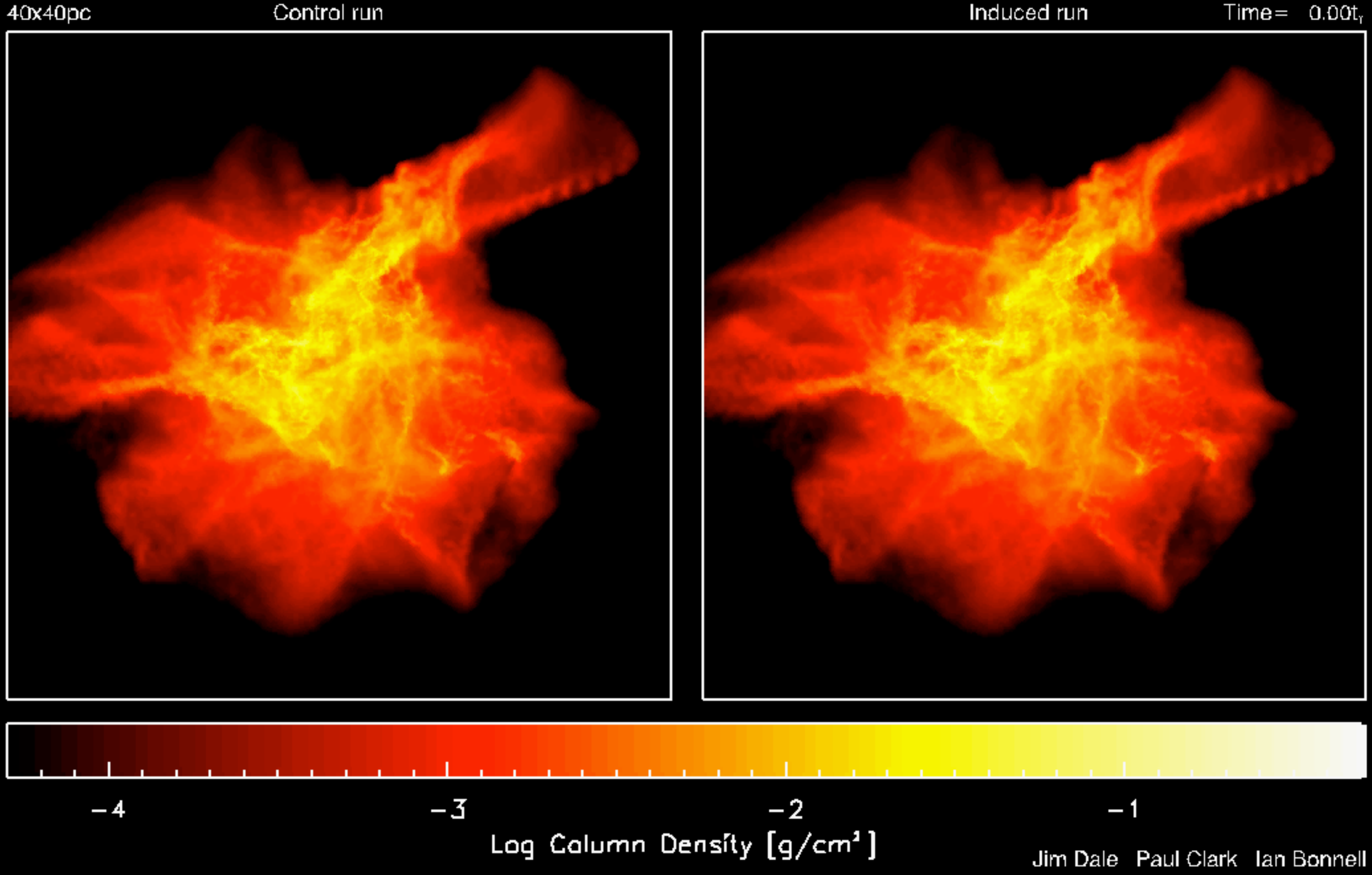
Can ionisation feedback halt SF?

- OB-type stars ionize the gas in young clusters, creating HI regions.
- Thought that this process would effectively terminate star formation (and/or accretion), by unbinding gas from the cluster.
- Dale et al (2005) show that this is not the case:

  Hot gas escapes through cavities and filaments are compressed.

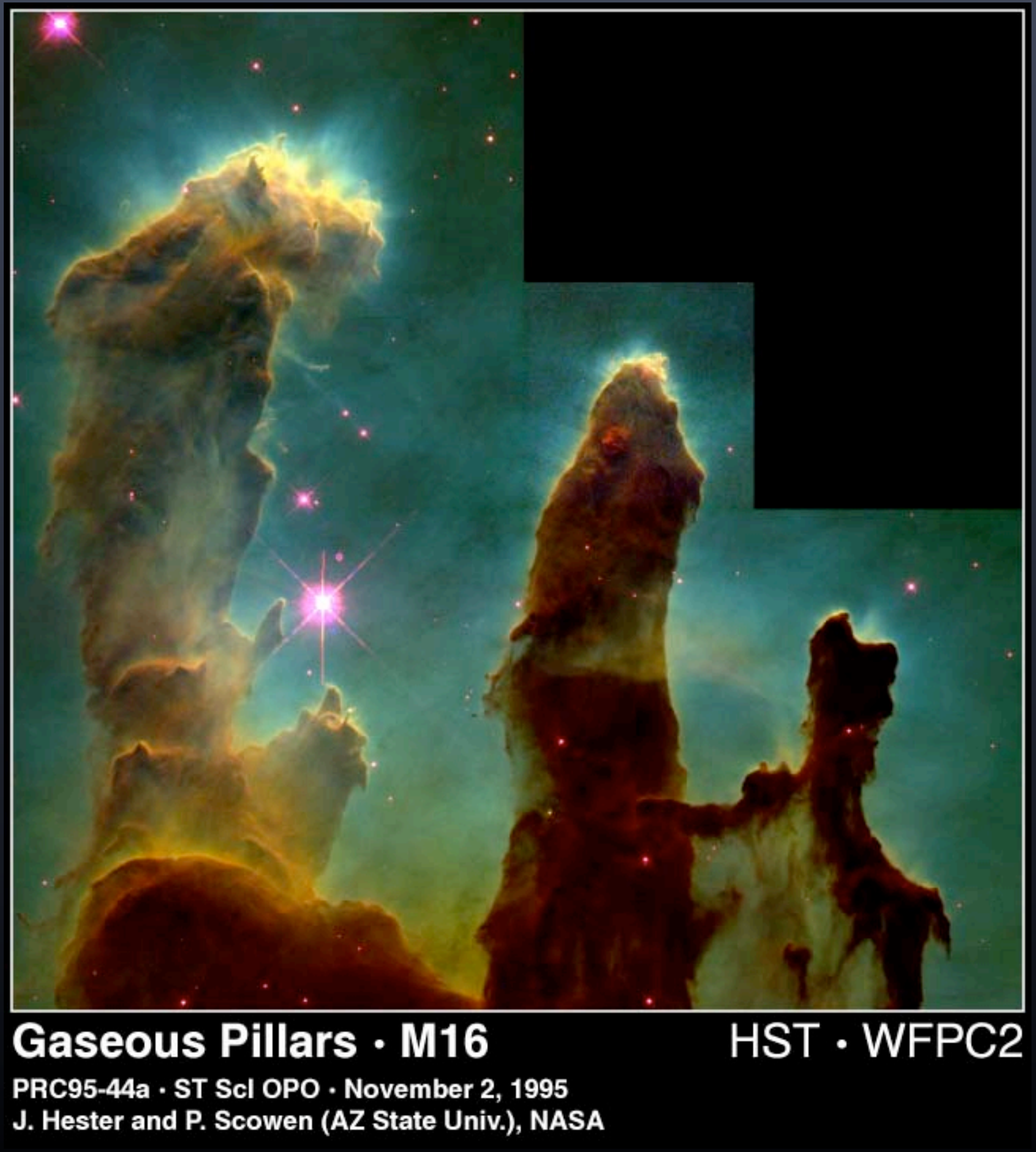


Is star formation triggered?

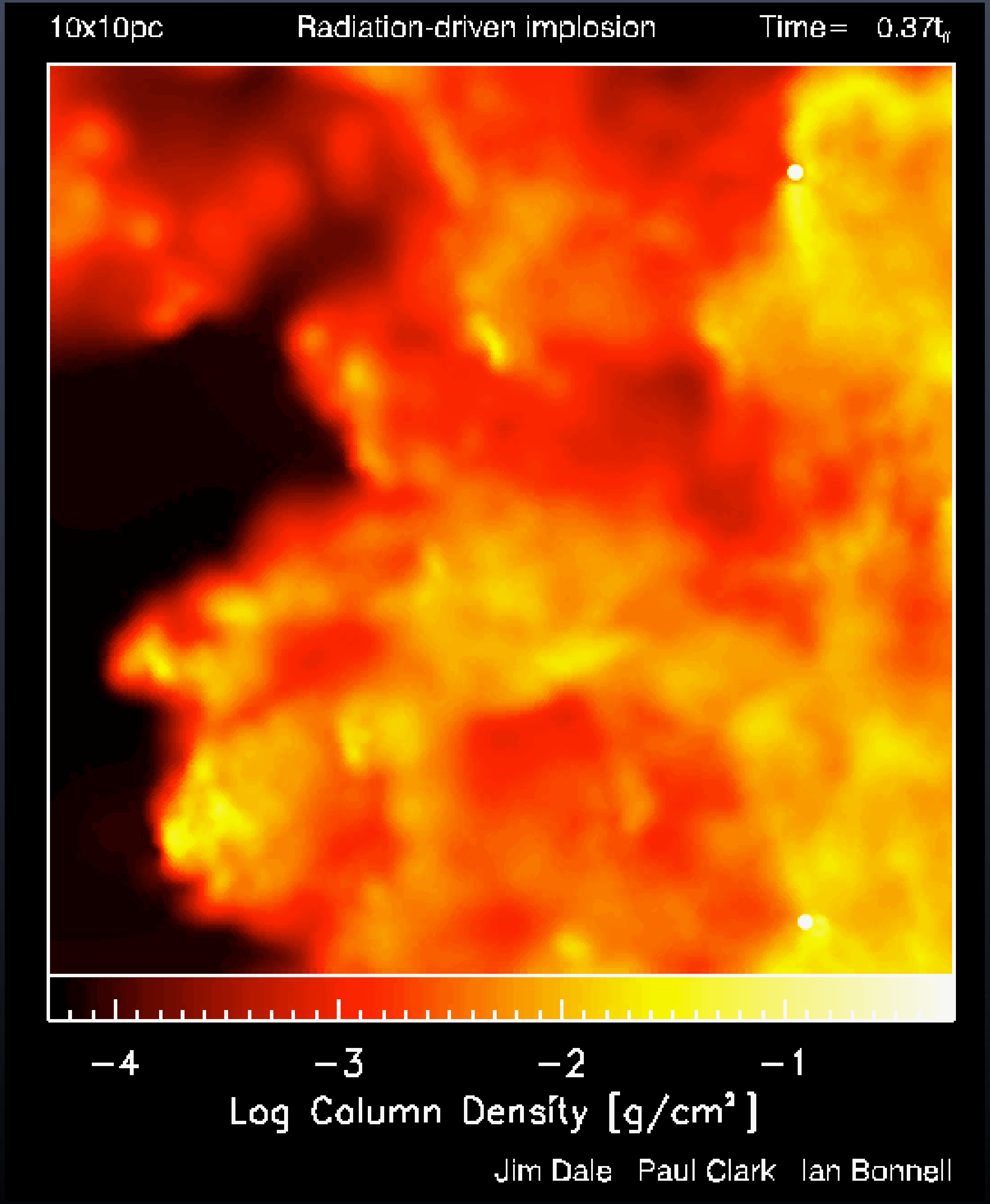


Dale, Clark & Bonnell (2007)

Pillars of creation?



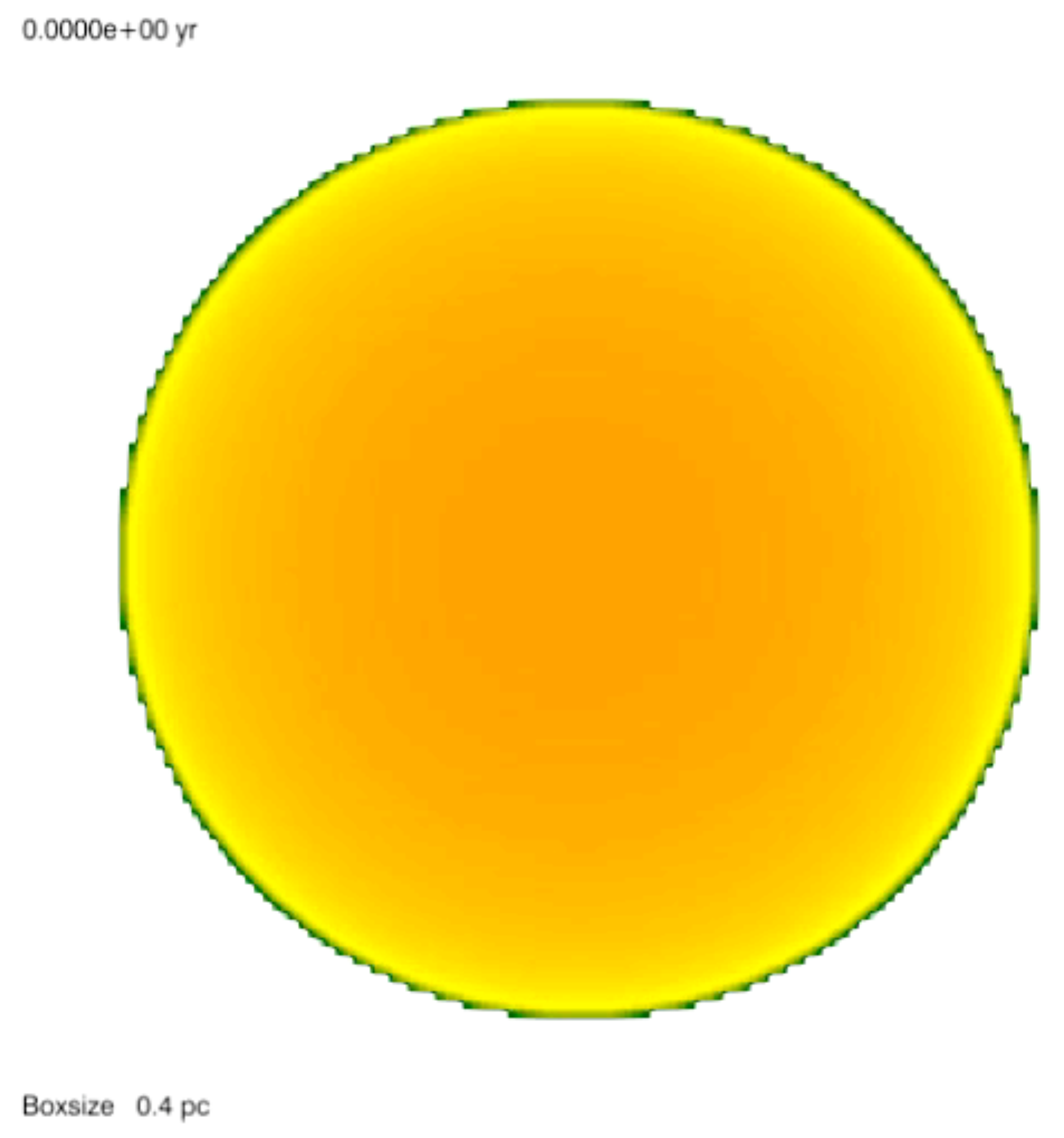
PRC95-44a • ST ScI OPO • November 2, 1995
J. Hester and P. Scowen (AZ State Univ.), NASA



Jim Dale Paul Clark Ian Bonnell

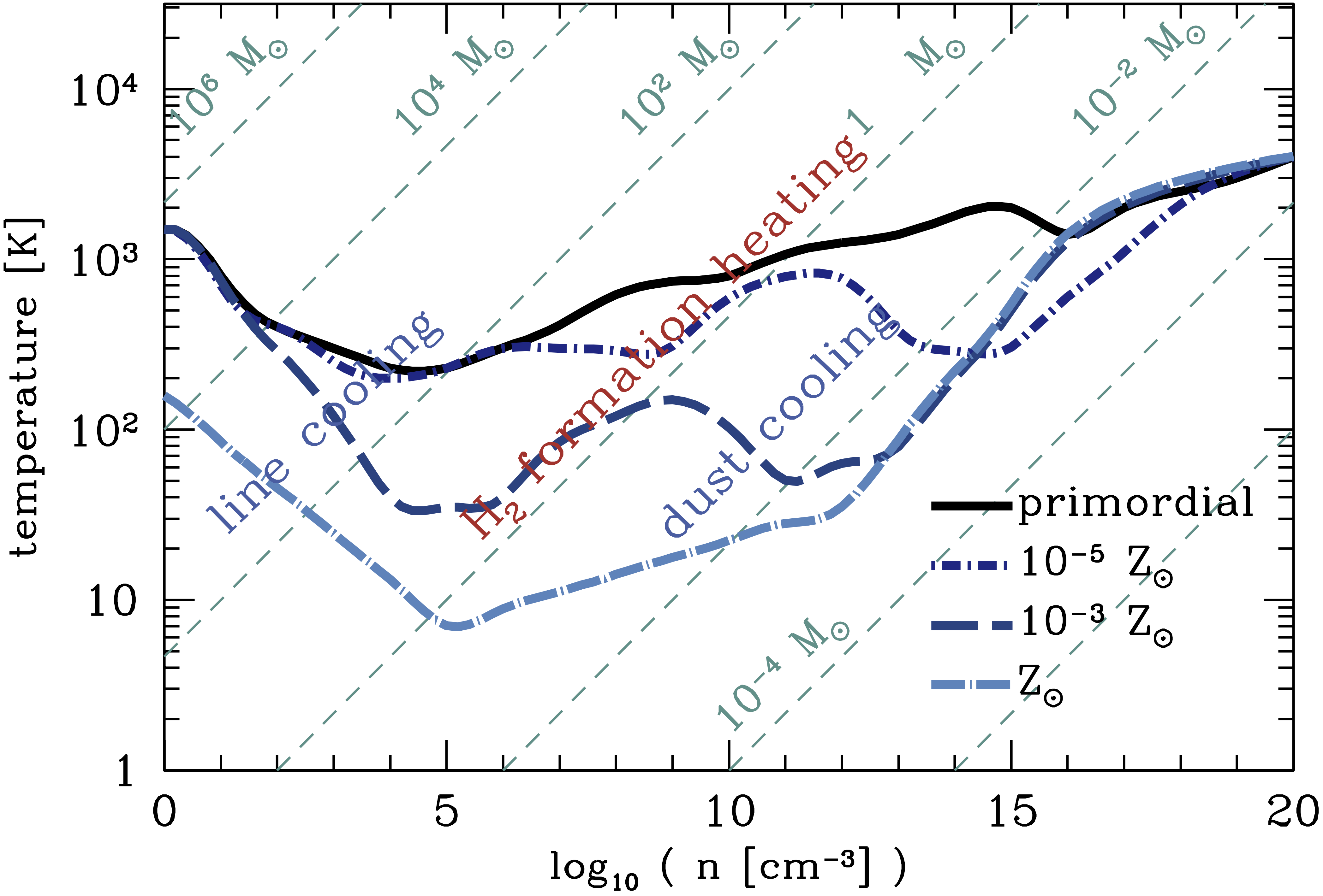
Protostellar outflows

- Banerjee, Horn & Klessen are trying to see what happens to the cluster when the outflows are modelled.
- Includes Bate-style sink particles in the AMR code FLASH.



0.1pc

T(ρ) with varying metallicity



- Dust cooling at low metallicities