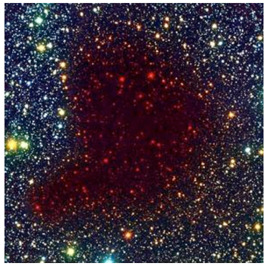
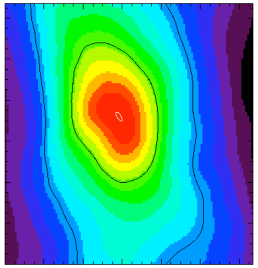
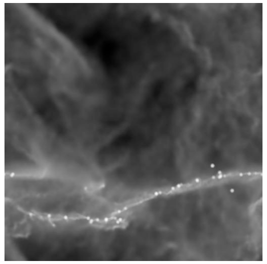
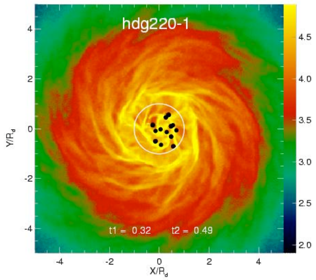
Astronomie am ITA





Ralf Klessen

Zentrum für Astronomie der Universität Heidelberg
Institut für Theoretische Astrophysik

Zentrum für Astronomie Heidelberg
ARI+ITA+LSW

Institut für Theoretische Astrophysik

- Professoren: Matthias Bartelmann, Ralf Klessen, Werner Tscharnuter
- ursprüngliches Uni-Institut

- <u>Aktuelle Forschungsgebiete:</u>
- Planetenbildung
- Sternentstehung, Galaxiendynamik
- Kosmologie: Dunkle Materie, Dunkle Energie
- numerische Astrophysik (Hydrodynamik, Strahlungstransport)

ITA

ZAH Zentrum für Astronomie Heidelberg ARI+ITA+LSW

Institut für Theoretische Astrophysik

ZENTRUM FÜR ASTRONOMIE

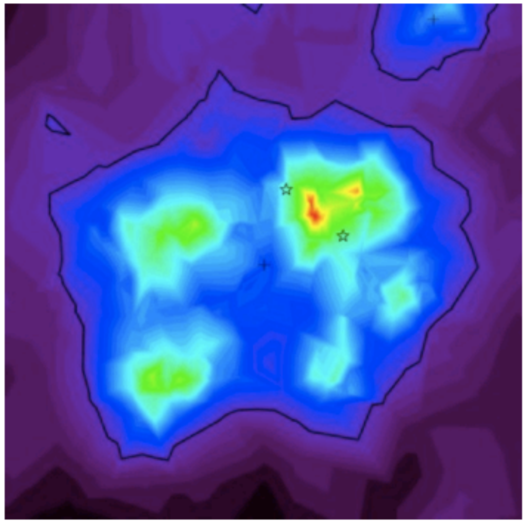
ARI ITA LSW

- **Arbeitsgruppe**
- Aktuelles
- Forschung
- Lehre
- Veröffentlichungen
- Offene Stellen
- Internes
- ITA Startseite
- Center for Astronomy

Arbeitsgruppe Sternentstehung

Wir beschäftigen uns mit verschiedenen Aspekten der Sternentstehung in der Milchstraße und im frühen Universum. Wir untersuchen interstellare Turbulenz und die Entstehung und Entwicklung von Galaktischen Gaswolken. Und versuchen die dynamische Entwicklung der Milchstraße und ihrer Satellitengalaxien zu verstehen. Da unsere Arbeit sehr stark numerisch geprägt ist, beschäftigen wir uns auch mit der Entwicklung und Verbesserung numerischer Algorithmen.

Bild des Monats: Die Struktur eines jungen Sternhaufens



Für weitere Informationen klicken Sie das Bild an.

Gruppenmitglieder

Leitung:	Ralf Klessen
Postdocs:	Robi Banerjee
	Paul C. Clark
	Stefan Schmeja
Doktoranden:	Christoph Federrath
	Thomas Greif
	Thomas Peters
	Dominik Schleicher
Diplomanden:	Susanne Horn
	Hendrik Lönngren

Forschungsthemen

Sternentstehung, Interstellare Turbulenz, Molekülwolkendynamik, Galaxiendynamik, Erste Sterne, Numerische Methoden

Lehre

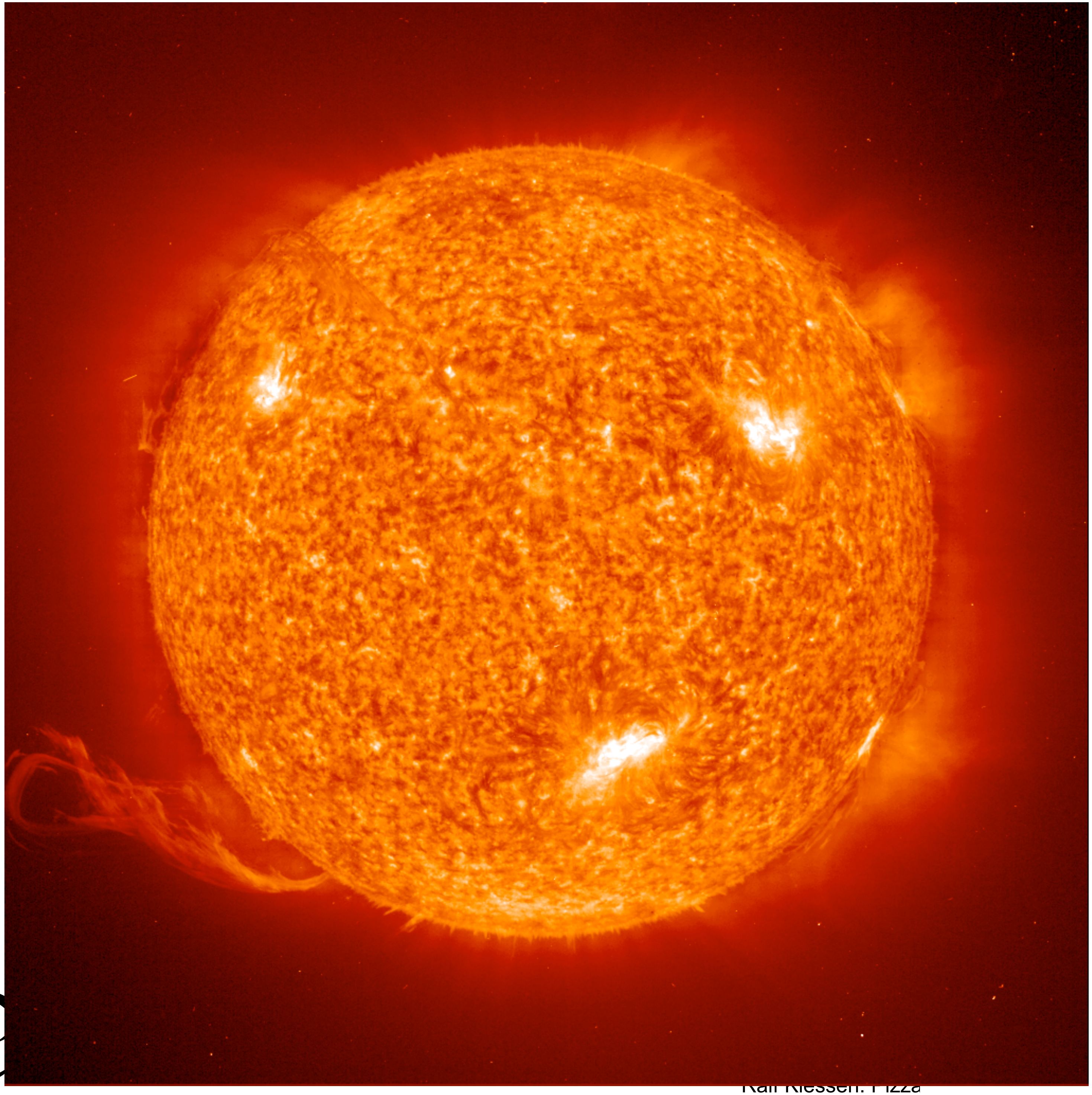
laufende und frühere Vorlesungen und Seminare

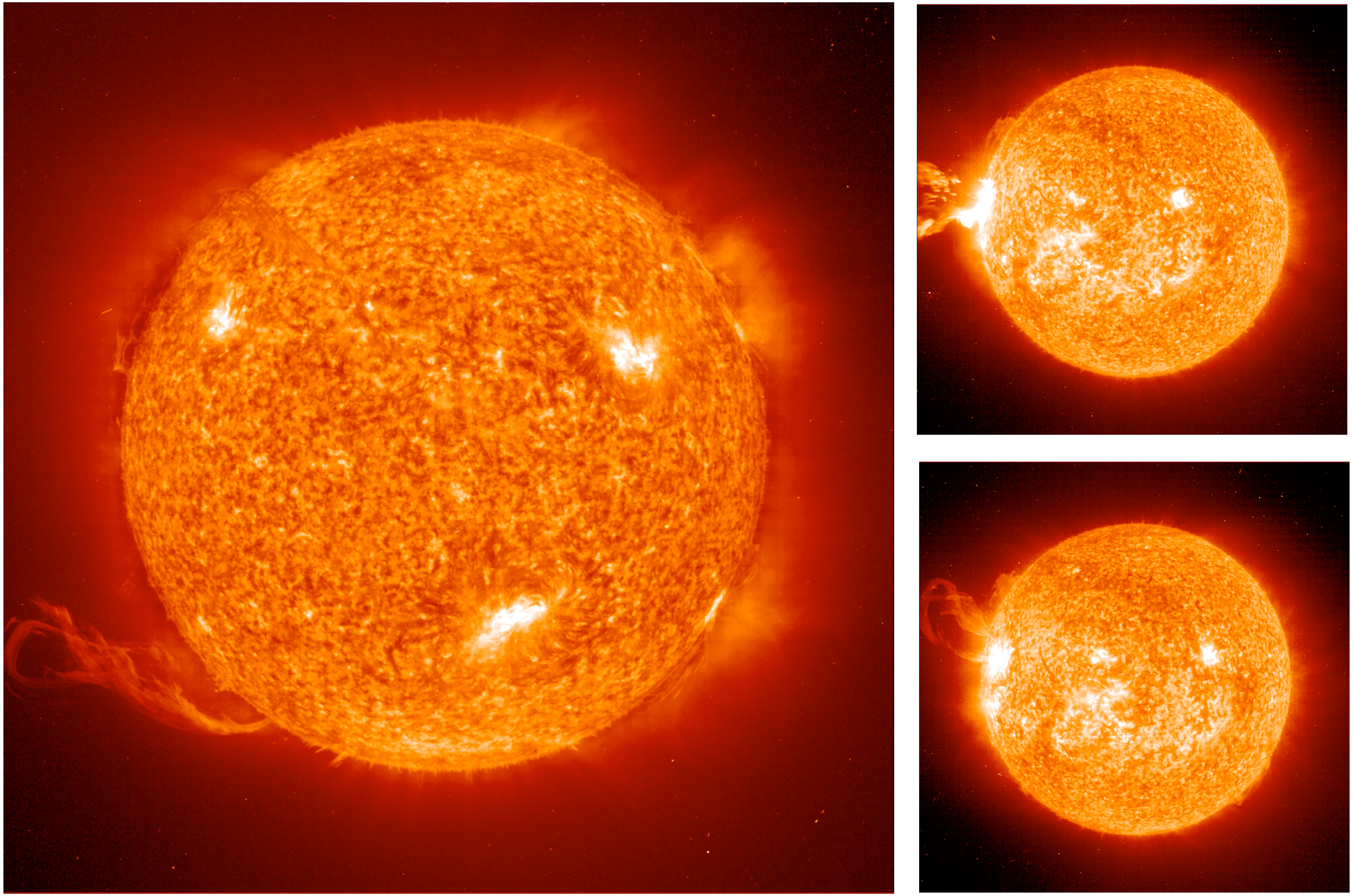
Verantwortlich: Ralf Klessen, letzte Änderung am Monday, 05-May-2008 16:10:34 CEST

Sternentstehung

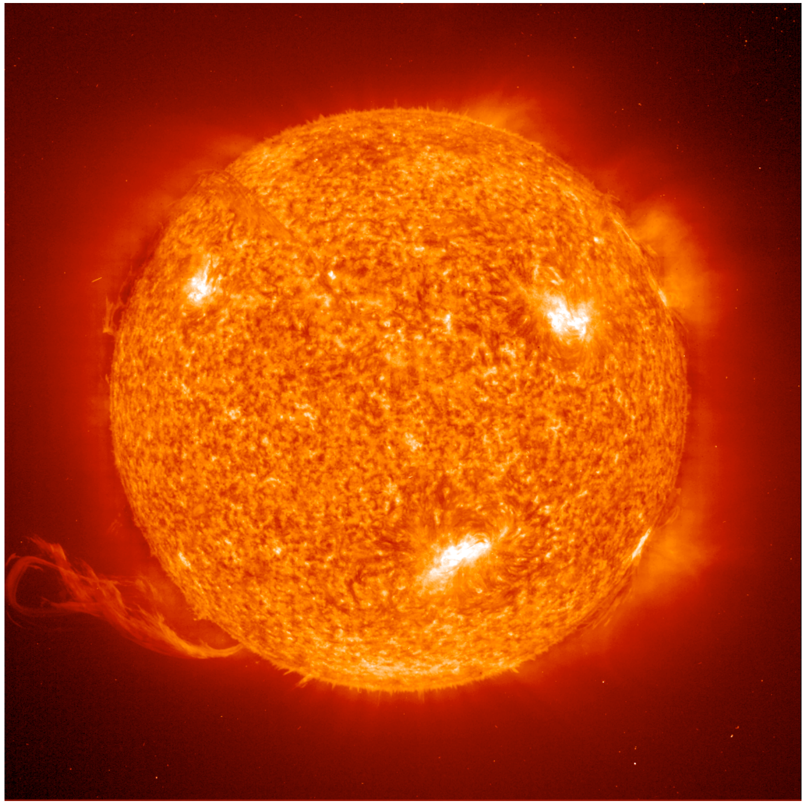
- Early Universe (reionization, 21cm line, optical depth)
- Dark Stars ...
- First Stars ...
- Second Generation of Stars ...
- Formation of First Galaxies ...
- Star Formation in the Milky Way
- Formation and Evolution of Stellar Clusters
- Formation and Evolution of Star Forming Interstellar Gas Cloud
- Protostellar Collapse: formation of individual stars and their planetary systems

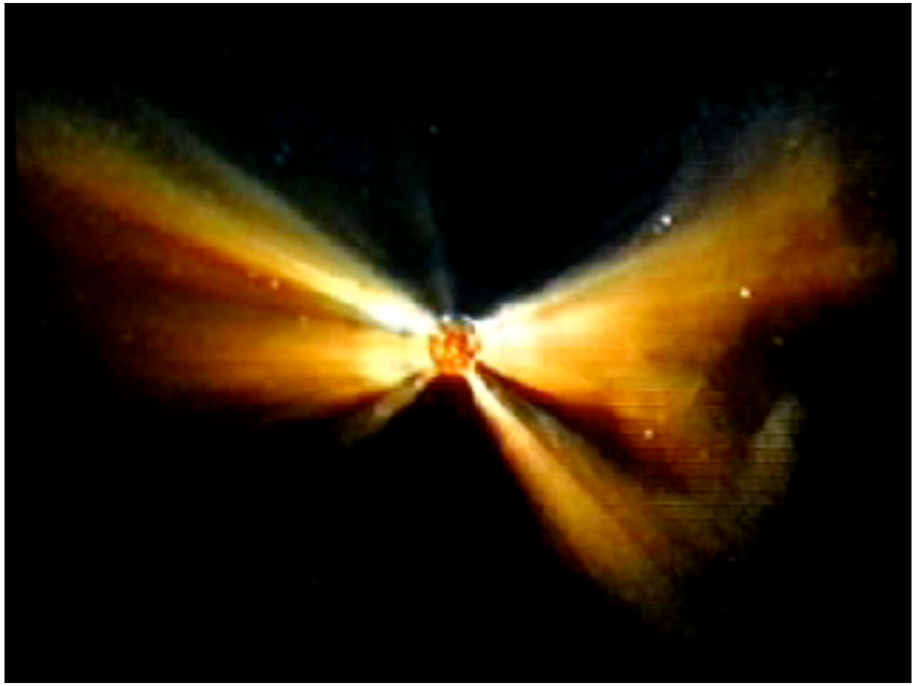
Unsere Sonne





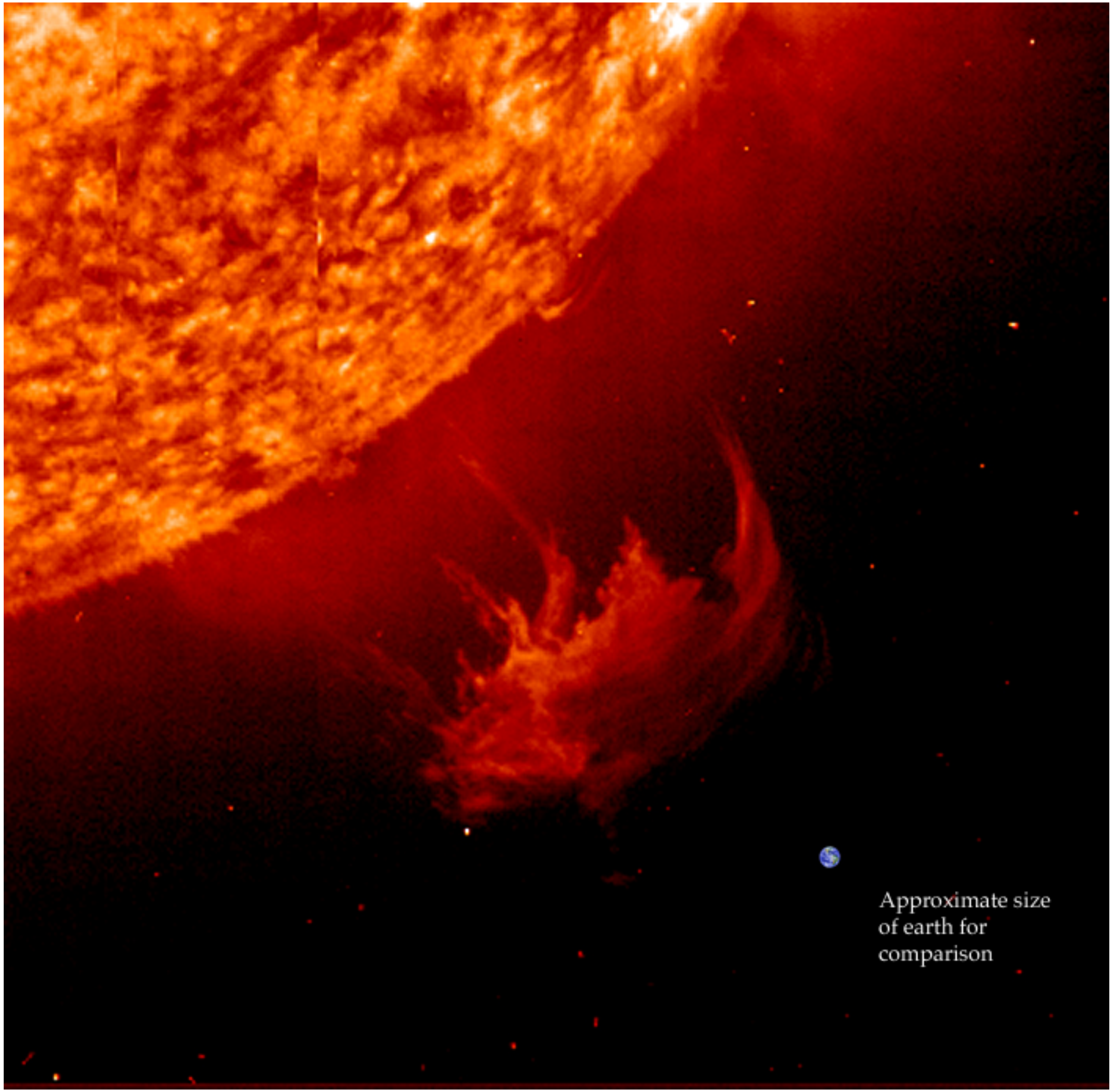
Unsere Sonne in verschiedenen Aktivitätsphasen



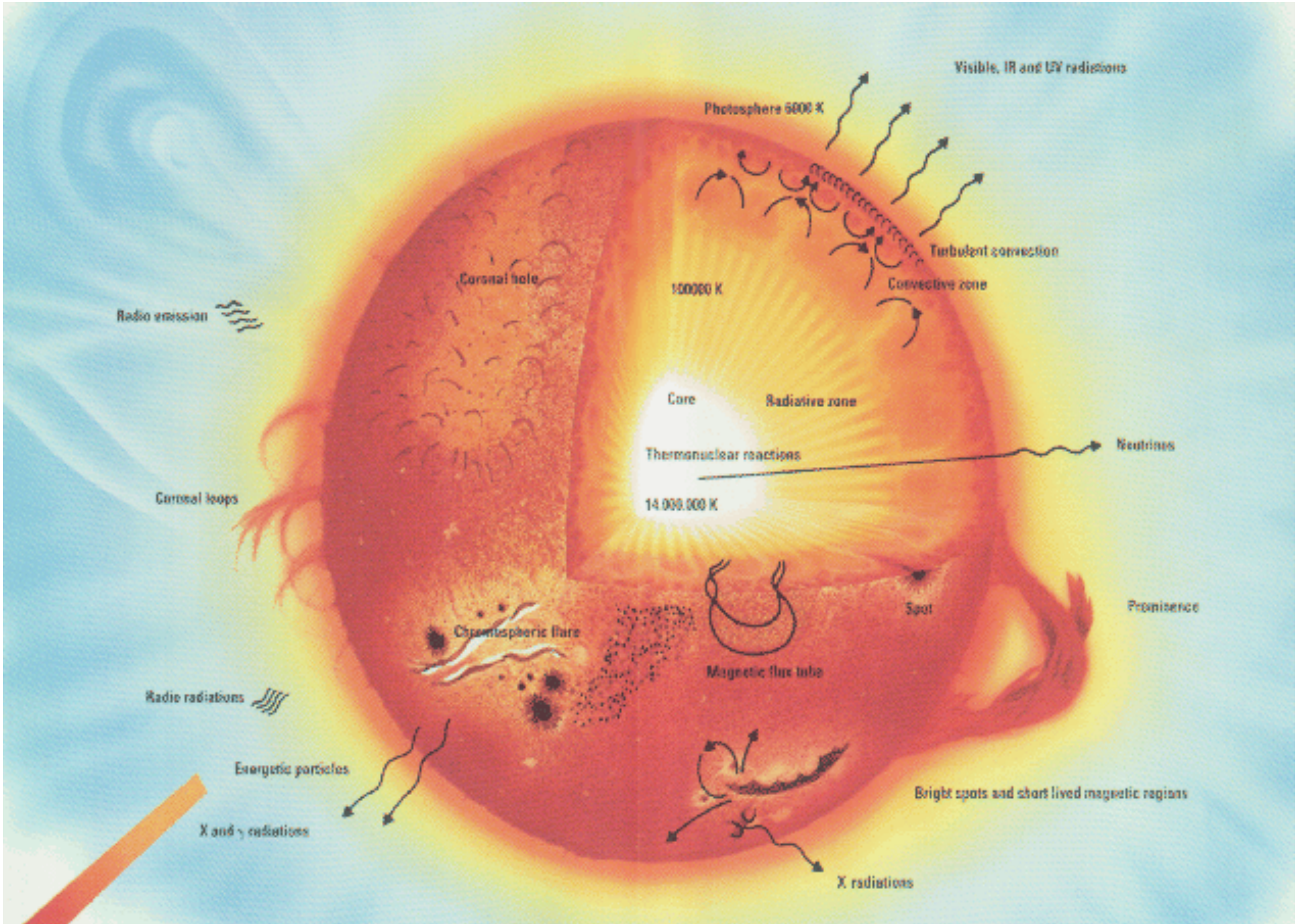


Unsere Sonne in verschiedenen Aktivitätsphasen

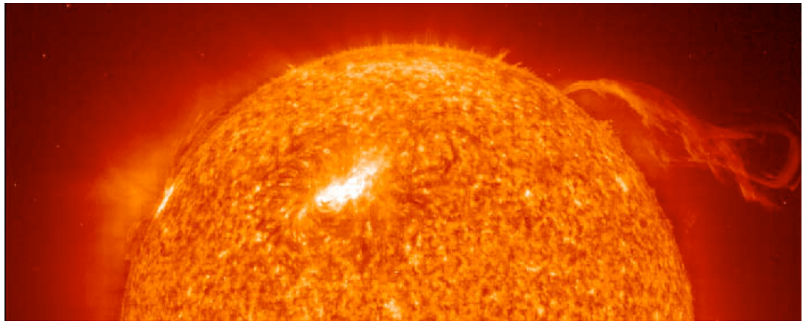
Größenvergleich: Sonne - Erde



Ralf


Visible, IR and UV radiations
Photosphere 6000 K
Turbulent convection
Coronal hole
100000 K
Convective zone
Radio emission
Core
Radiative zone
Neutrinos
Thermonuclear reactions
Coronal loops
14.000.000 K
Spot
Prominence
Chromospheric flare
Magnetic flux tube
Radio radiations
Energetic particles
Bright spots and short lived magnetic regions
X and γ radiations
X radiations

Sterne: die Sonne



Eigenschaften der Sterne
(Stellare Zustandsgrößen):

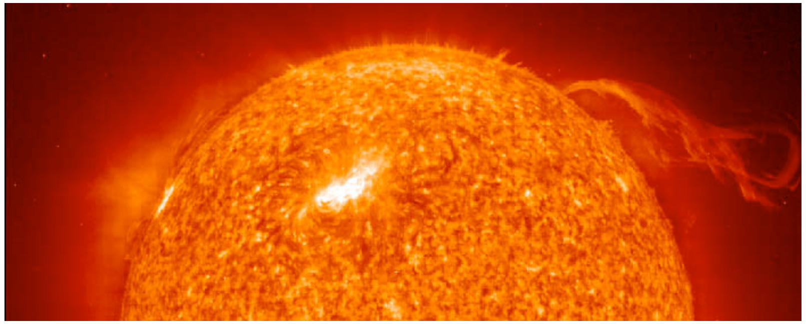
Unsere Sonne ⊙ als Referenzstern

Radius	$R_\odot$	696 000 km	
Masse	$M_\odot$	$1{,}989 \times 10^{30}$ kg	
Leuchtkraft	$L_\odot$	$3{,}86 \times 10^{26}$ W	
effektive Temperatur	T_{eff}	5800 K	(Oberfläche)
Zentraltemperatur	$T_{zentral}$	15×10^{6} K	
Alter	$t_\odot$	4.5×10^{9} a	

auf der Erde:
Solarkonstante
1.37 kW/m^2

Spektraltyp G2
Leuchtkraftklasse V
chemische Zusammensetzung (Massenanteil)
73% Wasserstoff X
25% Helium Y
2% Metalle Z

Sterne: die Sonne



Eigenschaften der Sterne
(Stellare Zustandsgrößen):

Unsere Sonne ⊙ als Referenzstern

Radius	$R_\odot$	7×10^{10} cm
Masse	$M_\odot$	2×10^{33} g
Leuchtkraft	$L_\odot$	4×10^{33} erg/s
effektive Temperatur	T_{eff}	5800 K
Zentraltemperatur	$T_{zentral}$	15×10^6 K
Alter	$t_\odot$	1.7×10^{17} s

in cgs Einheiten

Spektraltyp	G2
Leuchtkraftklasse	V

chemische Zusammensetzung (Massenanteil)

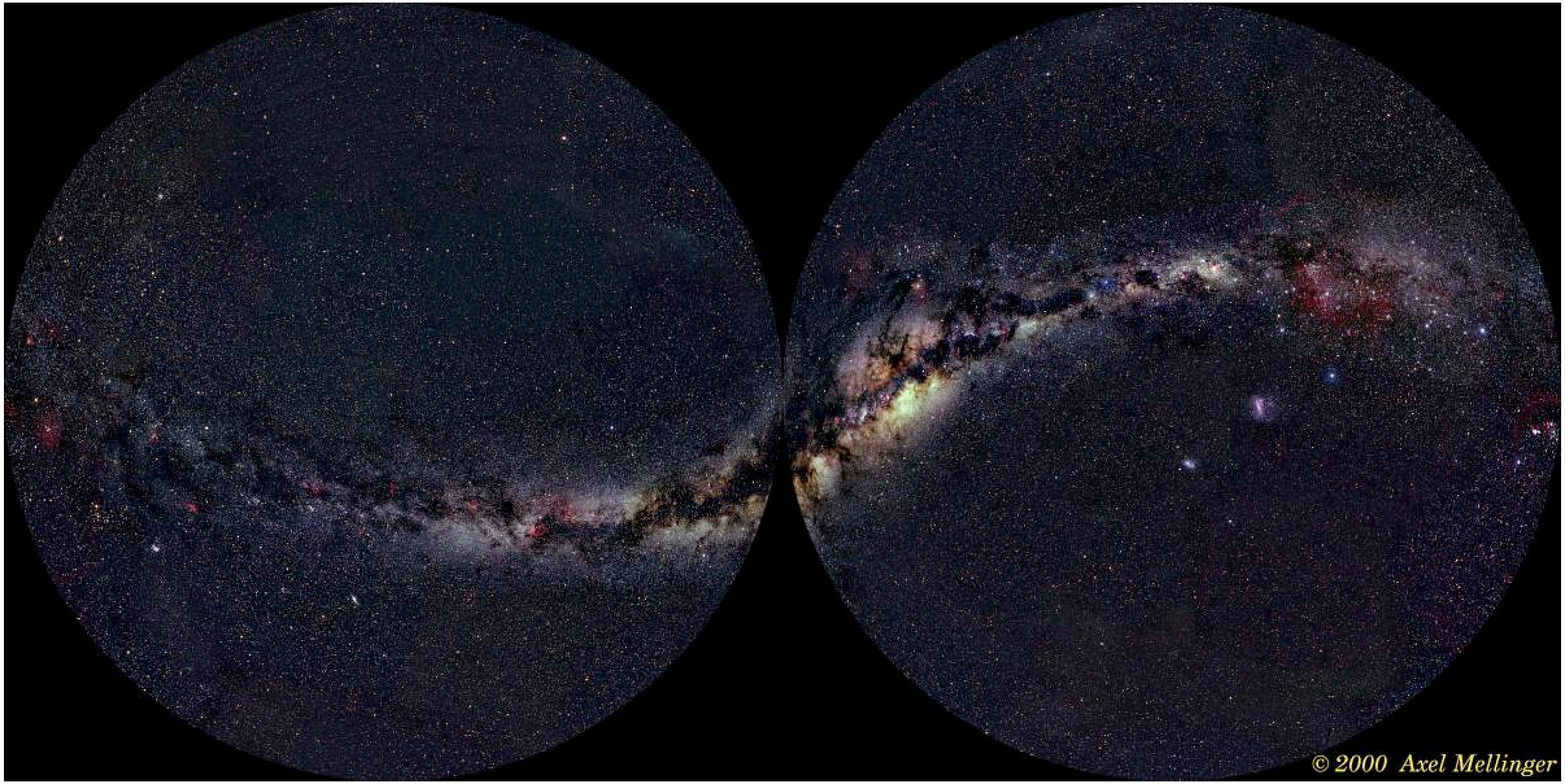
73% Wasserstoff X
25% Helium Y
2% Metalle Z

young stars in spiral galaxies

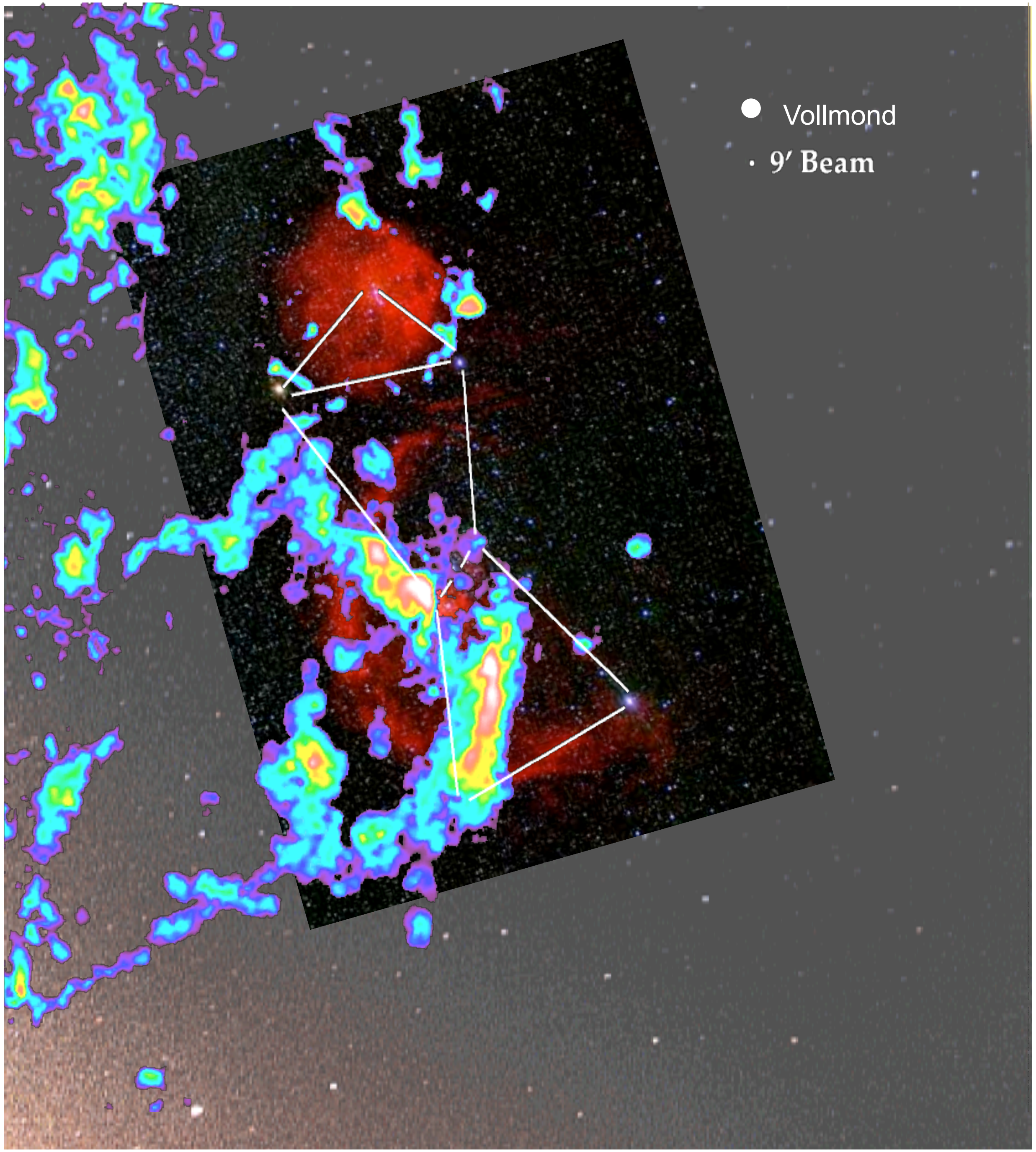
(NGC 4622 from the Hubble Heritage Team)

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

young stars in the Milky Way



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

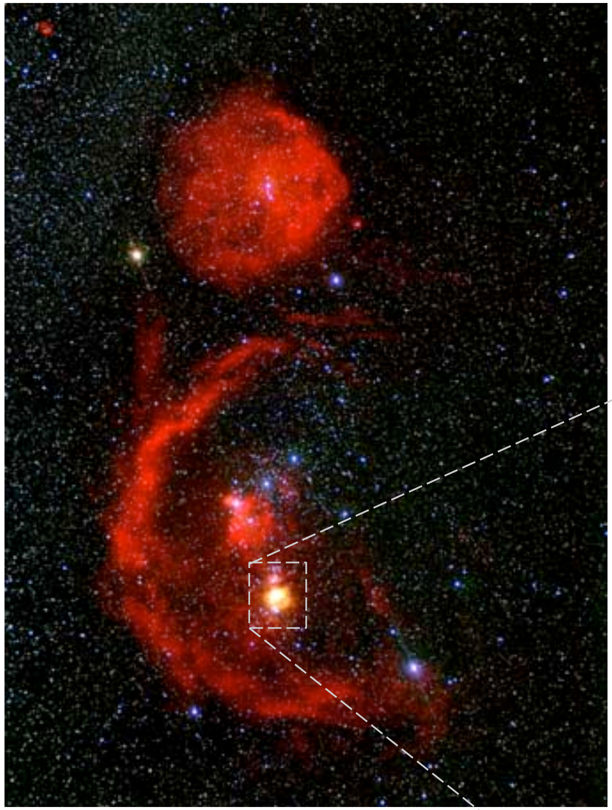


Stern-entstehung in Orion

Wir sehen

- *Sterne* (im sichtbaren Licht)
- Atomaren Wasserstoff (in Hα -- *rot*)
- Molekularen Wasserstoff H_2 (Radiostrahlung von Tracermolekül CO *farbcodiert*)

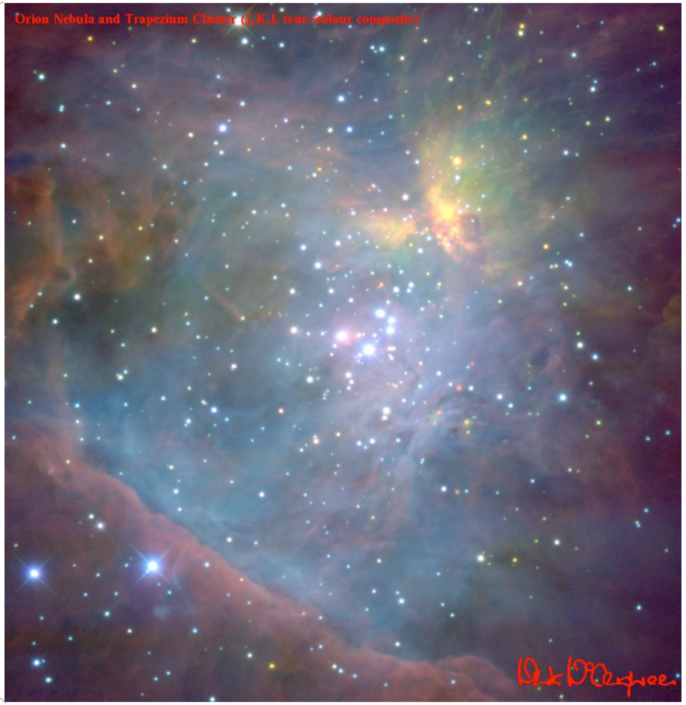
Lokales SE Gebiet: Trapezhaufen in Orion



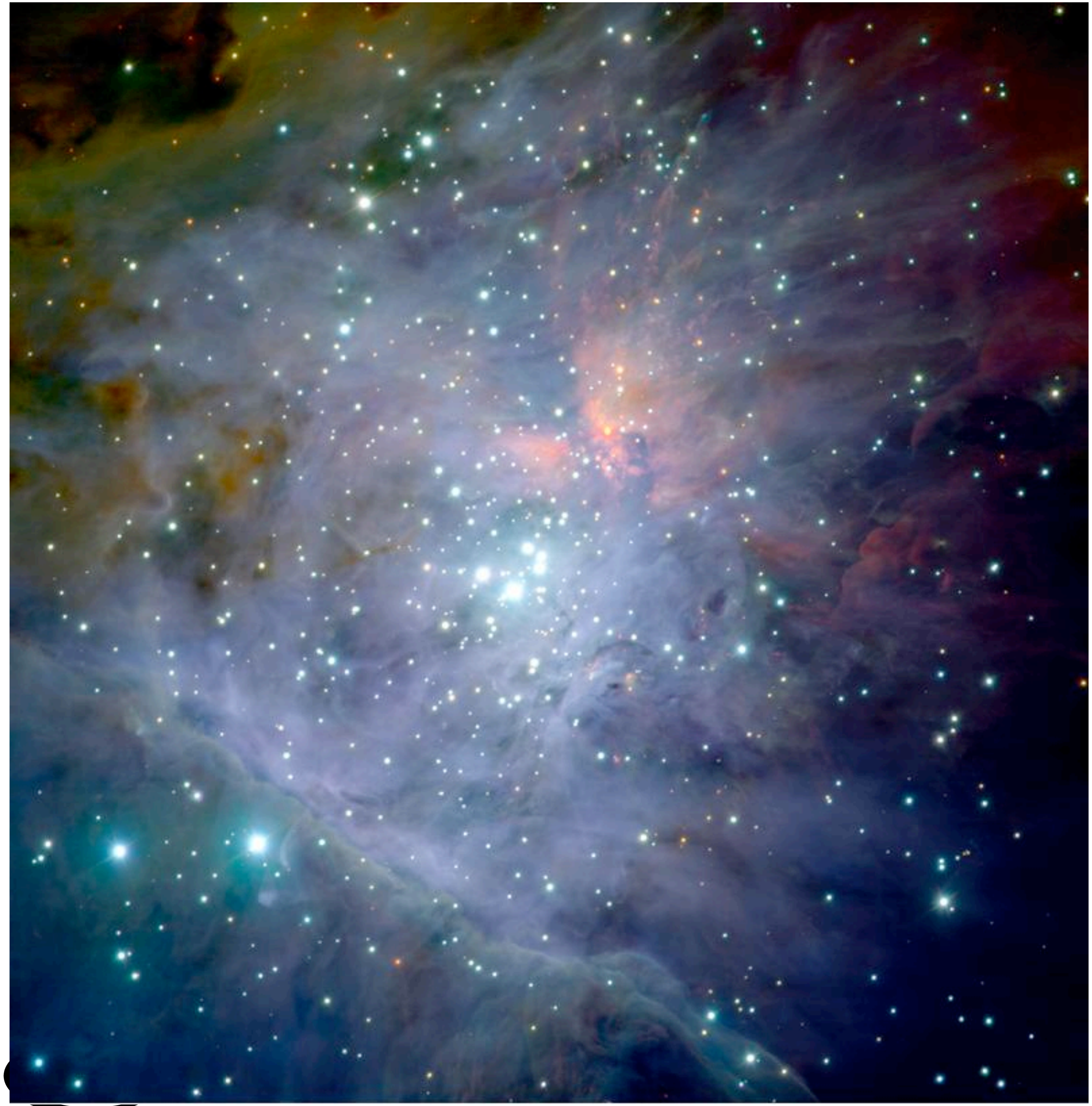
Sternbild Orion

Die Orionmolekülwolke ist die Geburtsstätte mehrer junger Sternhaufen.

Der Trapezhaufen ist noch ``eingebettet´´ und nur im IR Wellenbereich sichtbar. Der Haufen besteht aus ~2000 jungen Sternen.



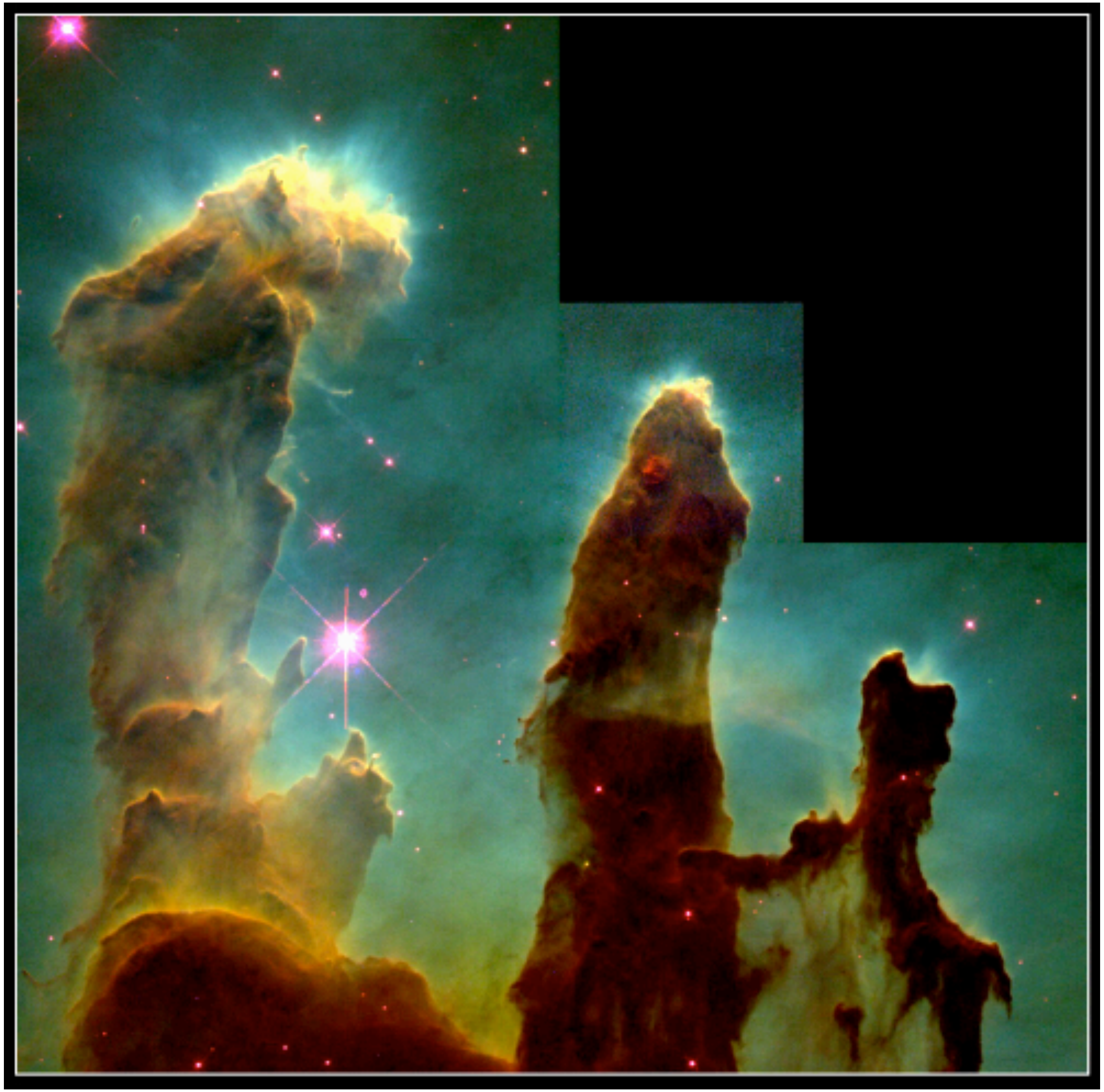
Trapez-
haufen



Trapez-haufen (Detail)

- Sterne entstehen in Haufen
- Sterne entstehen in Molekülwolken
- Rückkopplungseffekte sind wichtig

(Mehrfarbenaufnahme in J,H,K: McCaughrean, VLT, Paranal, Chile)



HST Aufnahme

Pillars of God (im Adlernebel): Entstehung kleiner Gruppen junger Sterne in den ``Spitzen´´ der Gas- und Staubsäulen….

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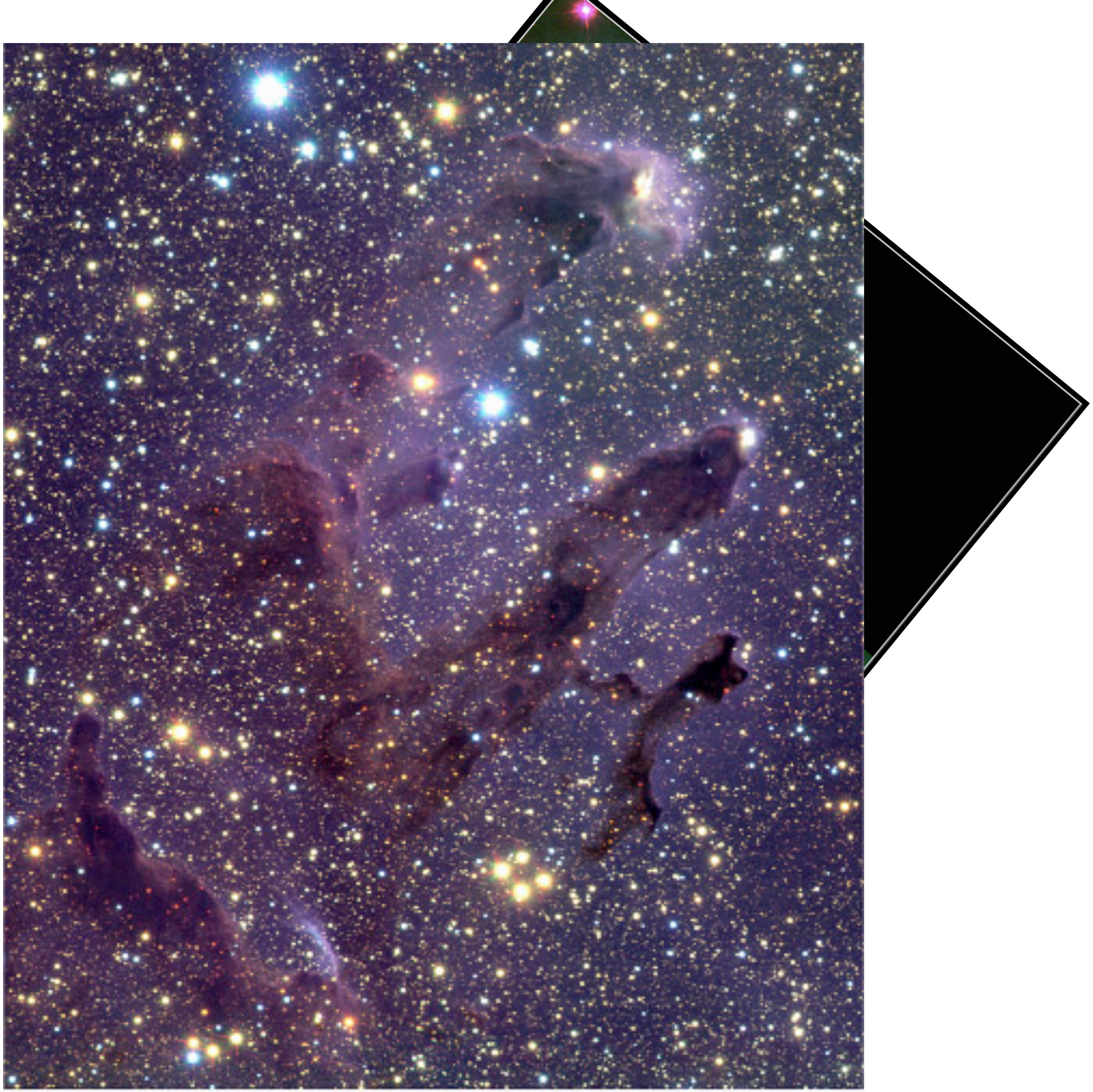
Aufnahme im
Infraroten.



IR Aufnahme mit dem ESO-VLT

Pillars of God (im Adlernebel): Entstehung kleiner Gruppen junger Sterne in den ``Spitzen´´ der Gas- und Staubsäulen….

IR Aufnahme mit dem ESO-VLT

Pillars of God (im Adlernebel): Entstehung kleiner Gruppen junger Sterne in den ``Spitzen´´ der Gas- und Staubsäulen….

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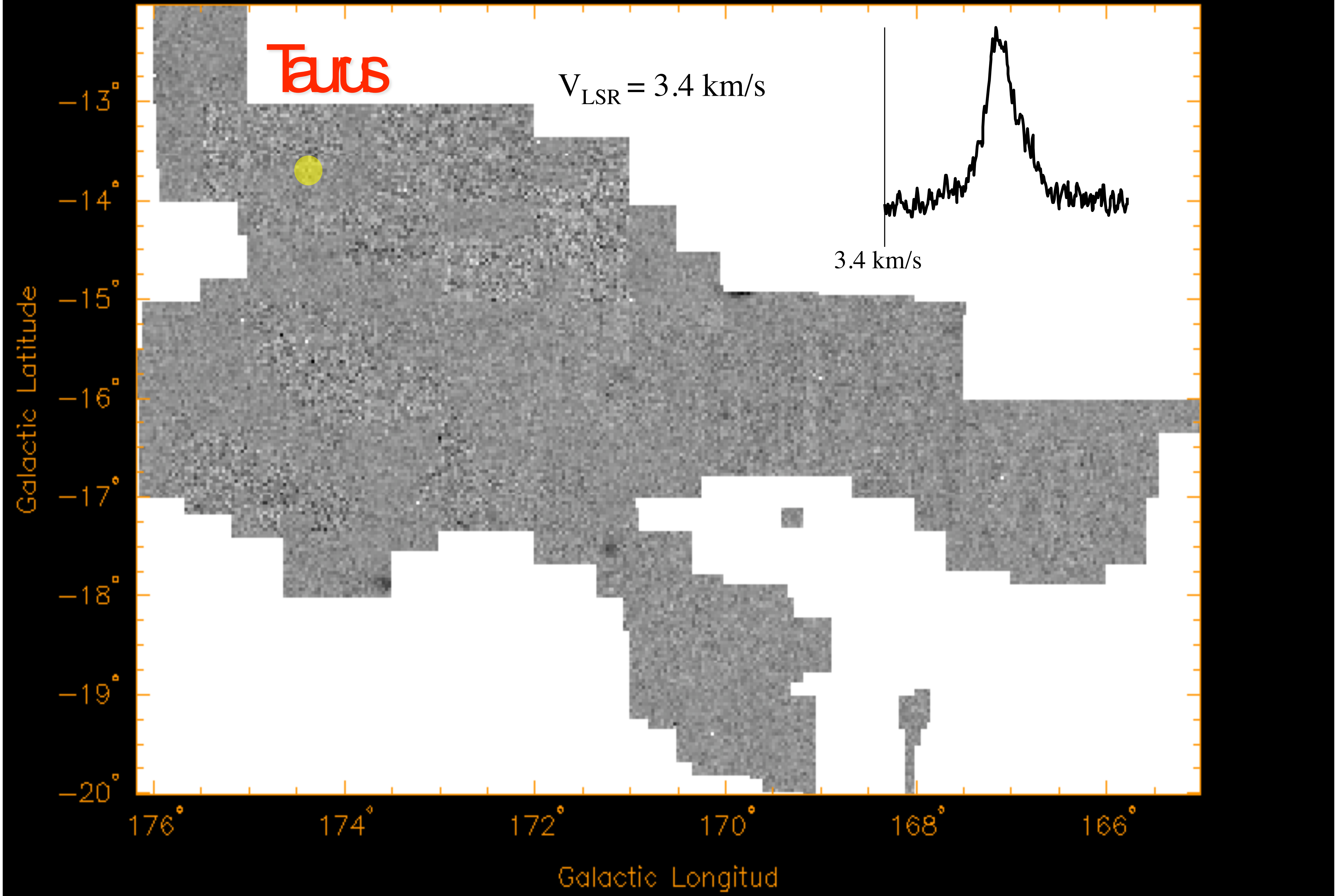

Taurus
VLSR = 3.4 km/s
3.4 km/s
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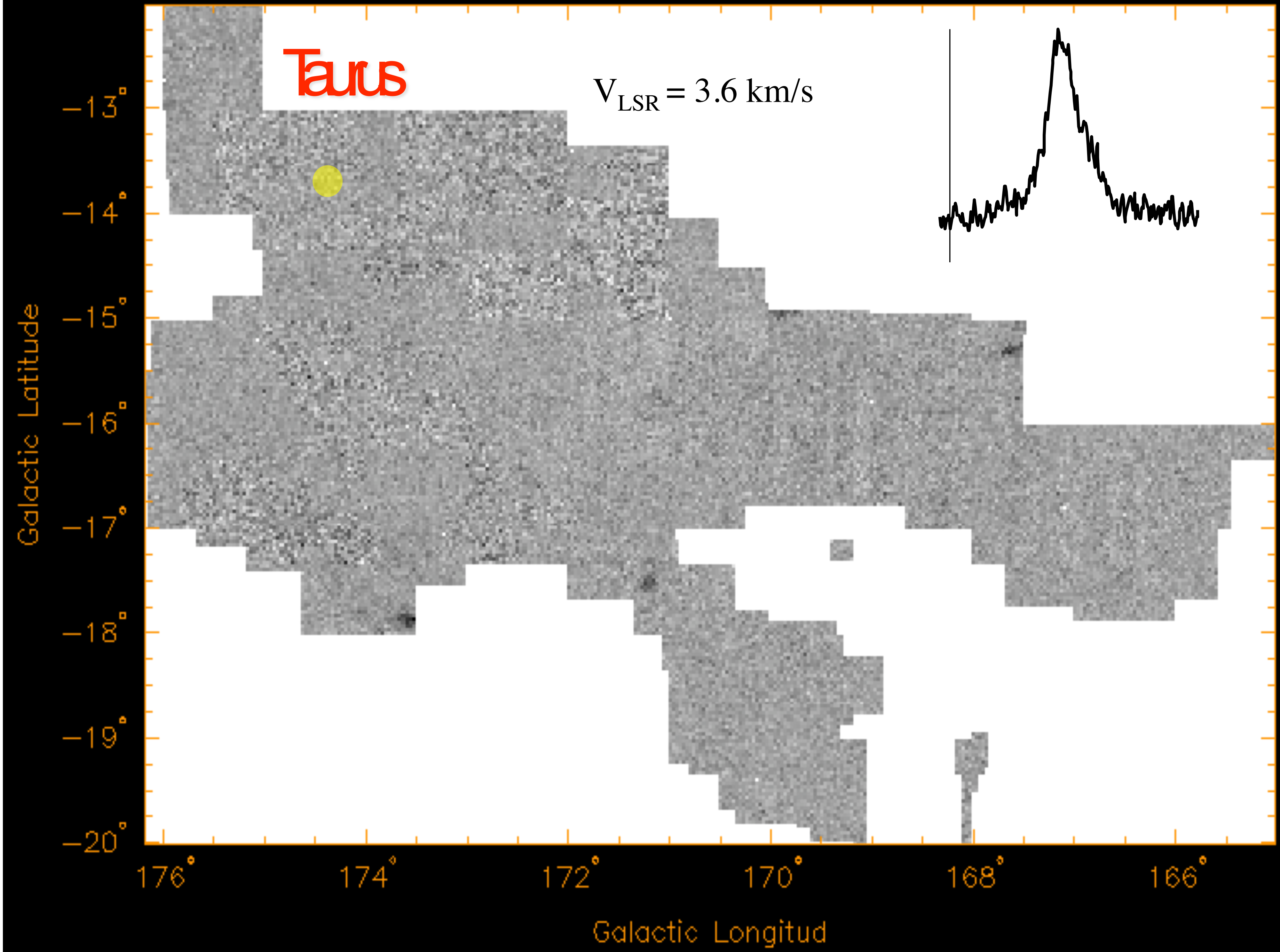
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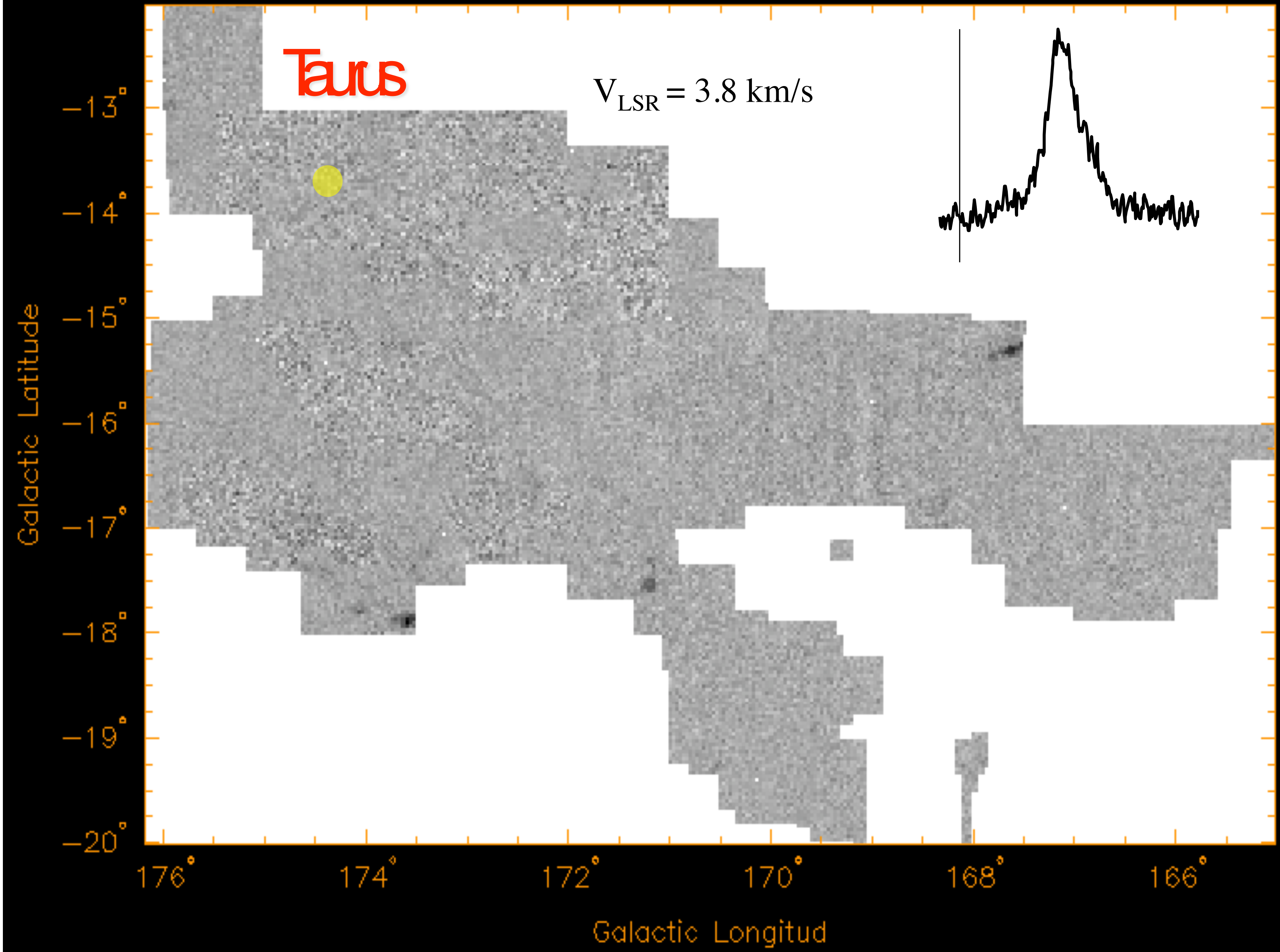

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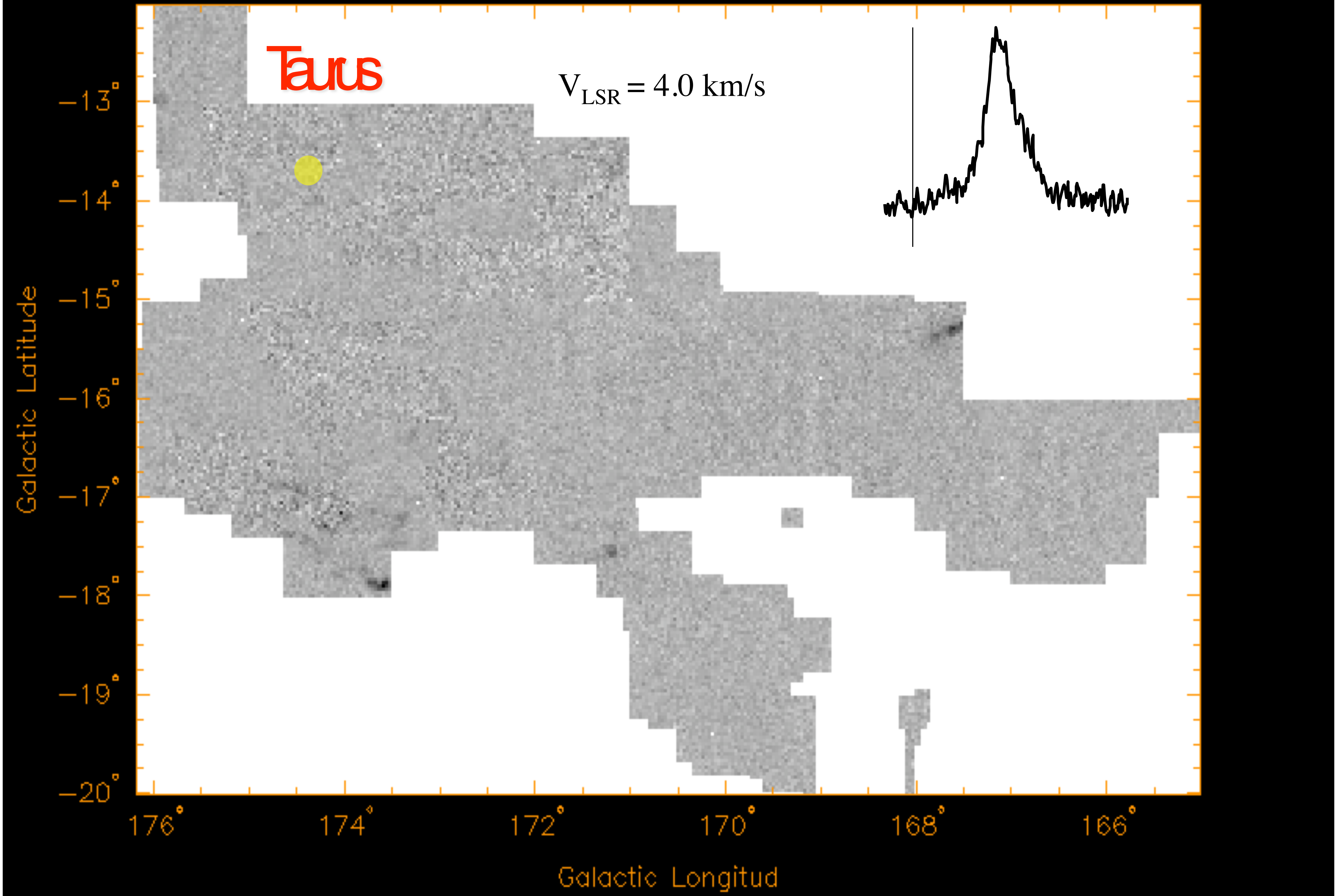

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V$_{LSR}$ = 4.0 km/s
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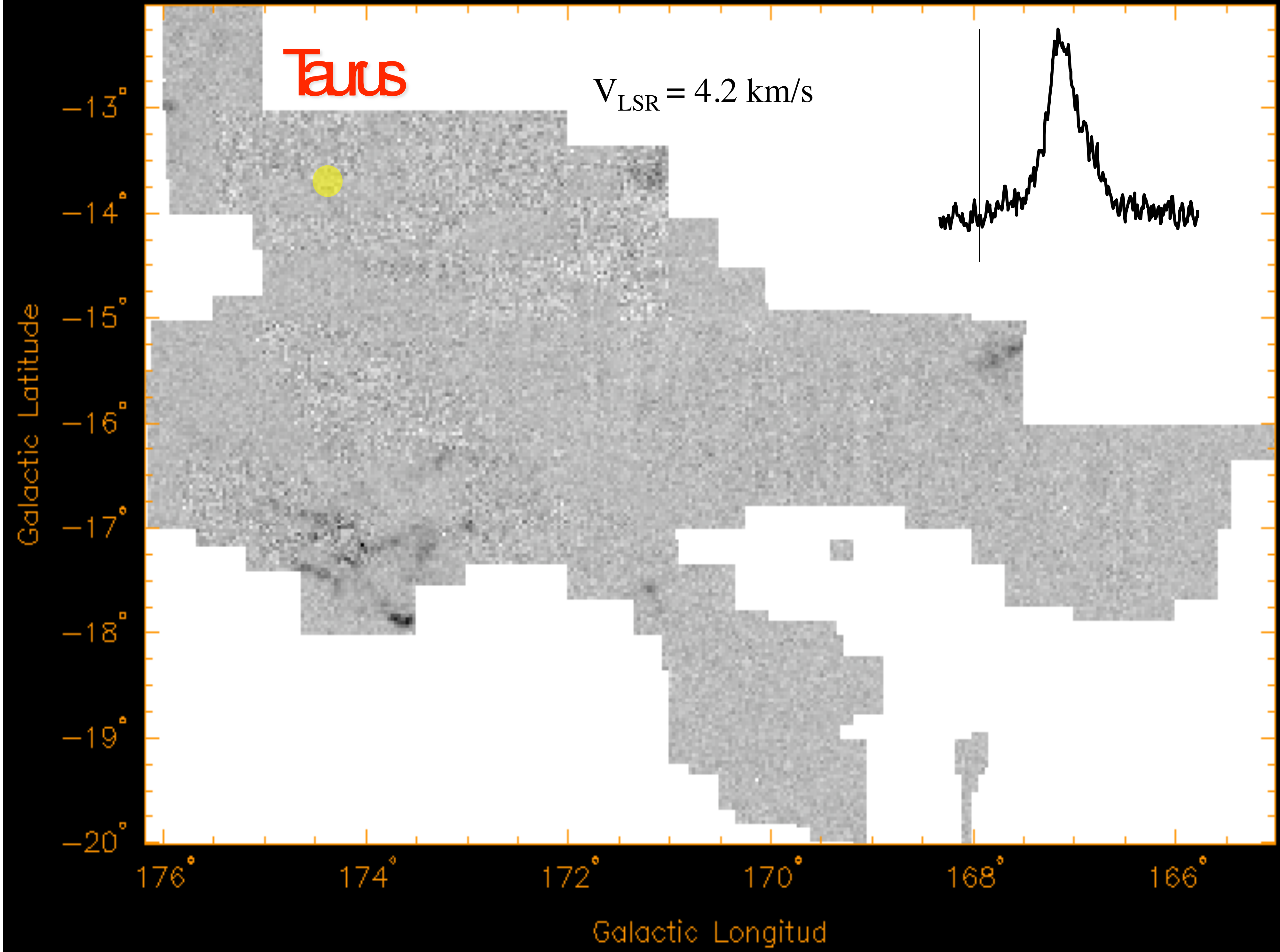
Galactic Latitude
Galactic Longitud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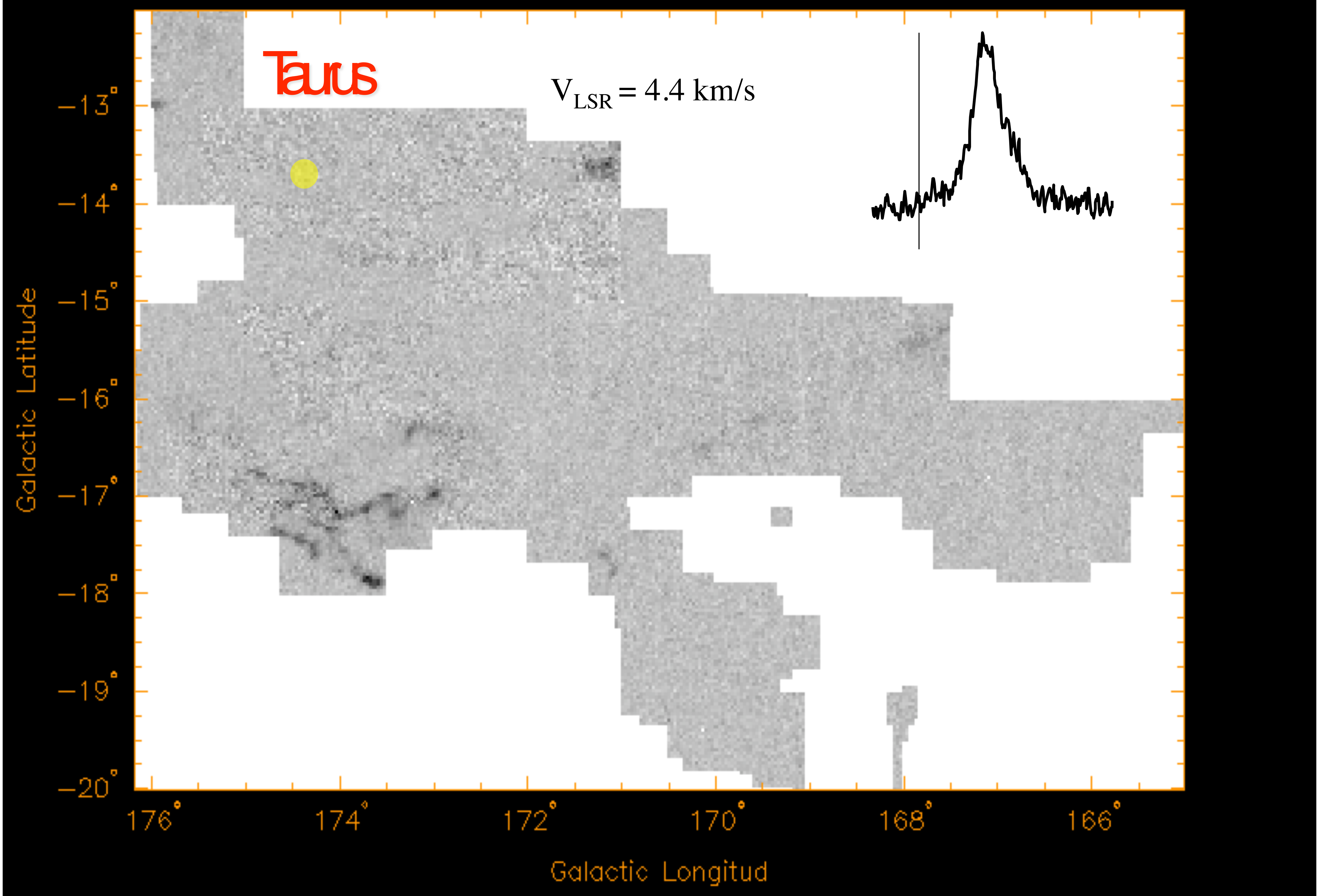
Galactic Longitud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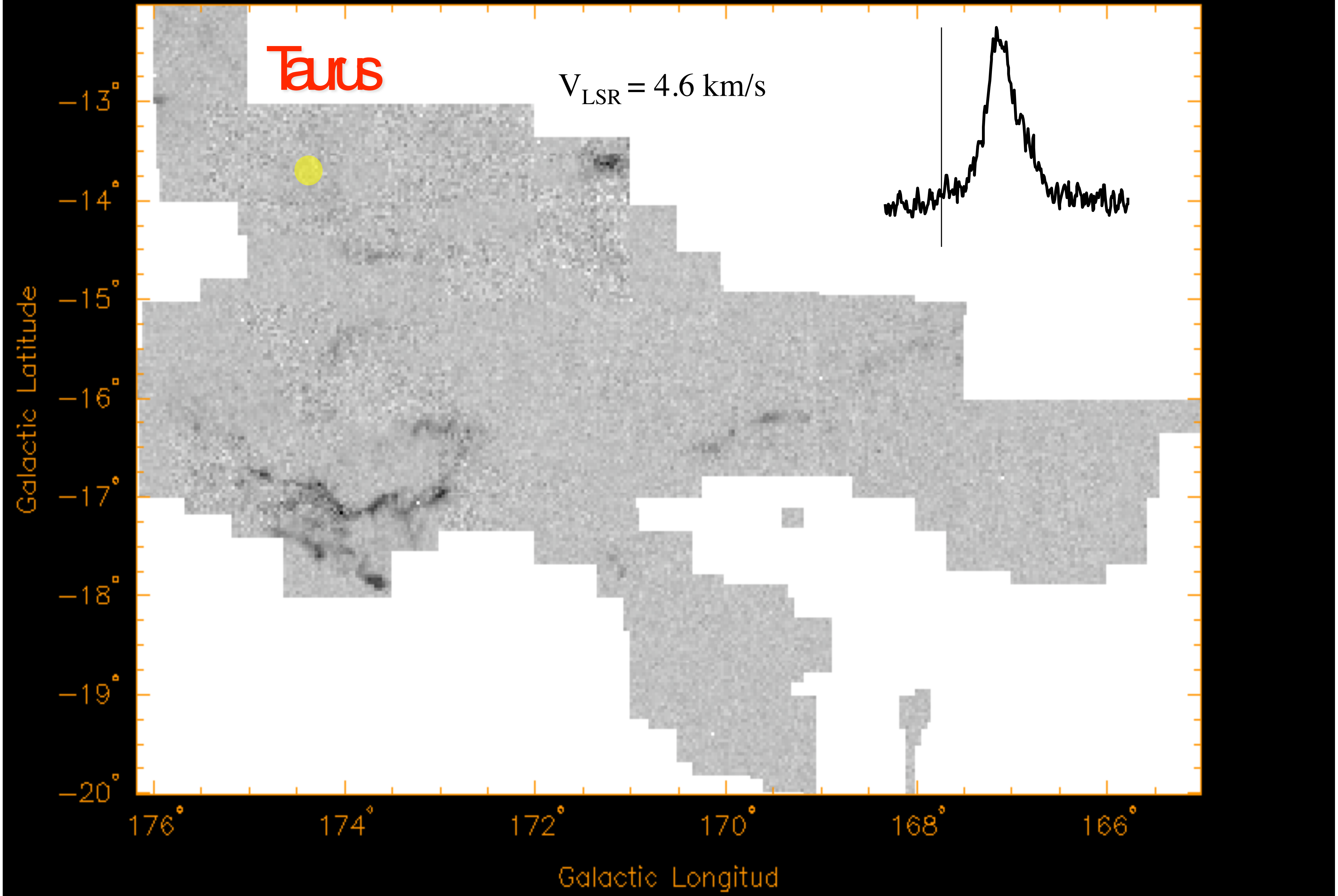
Galactic Longitud



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V_{LSR} = 4.6 km/s
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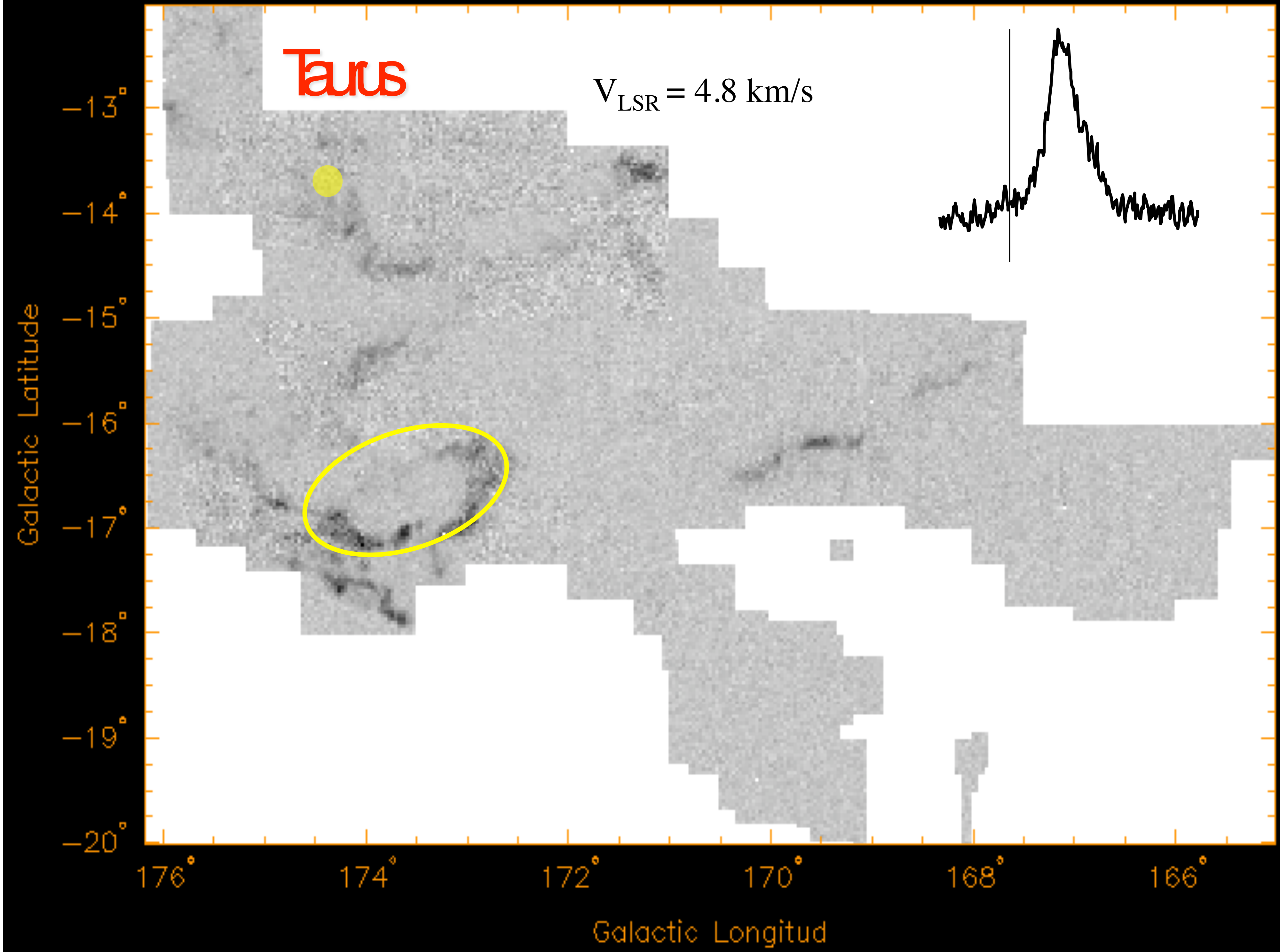
Galactic Longitud



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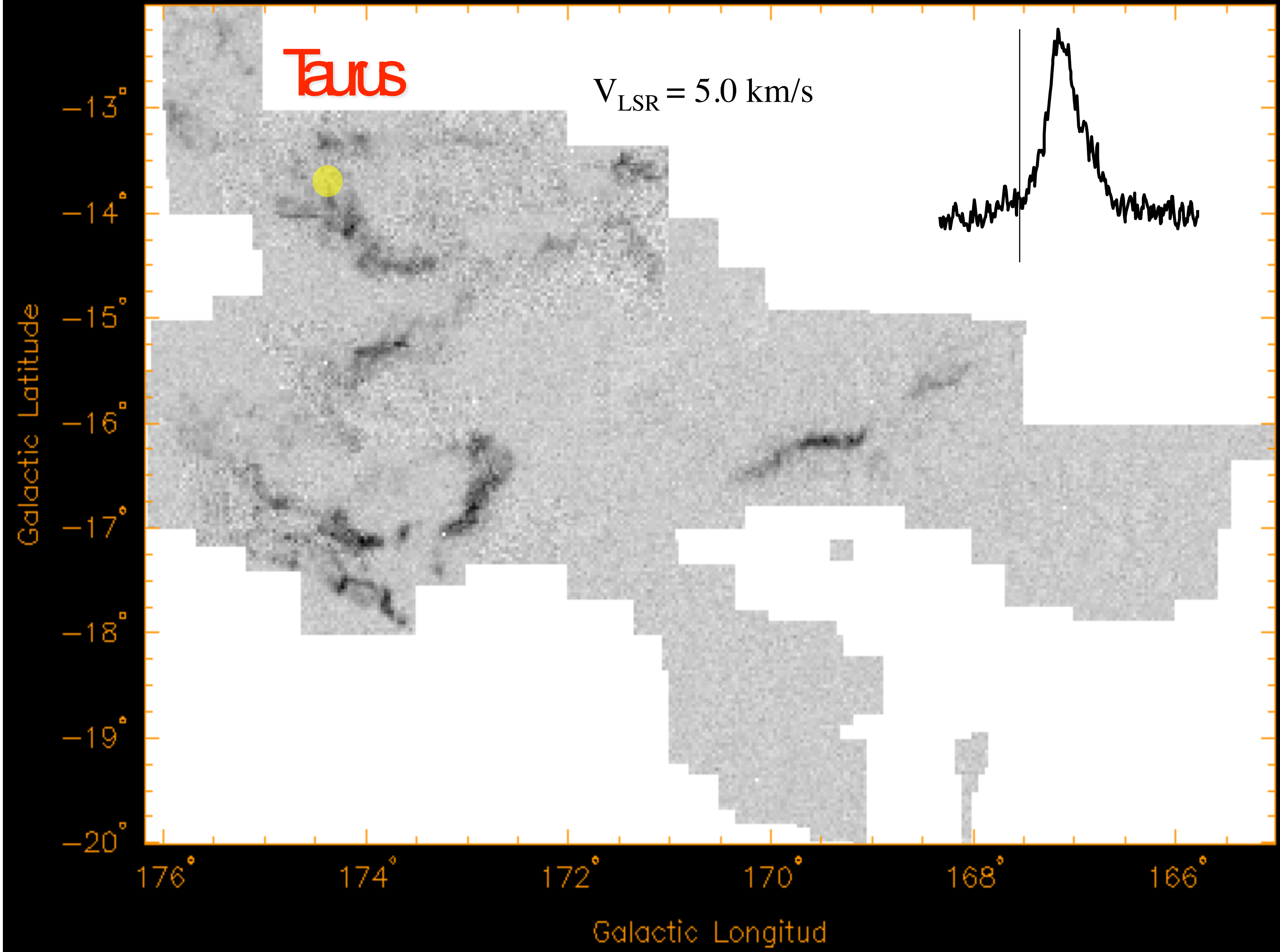

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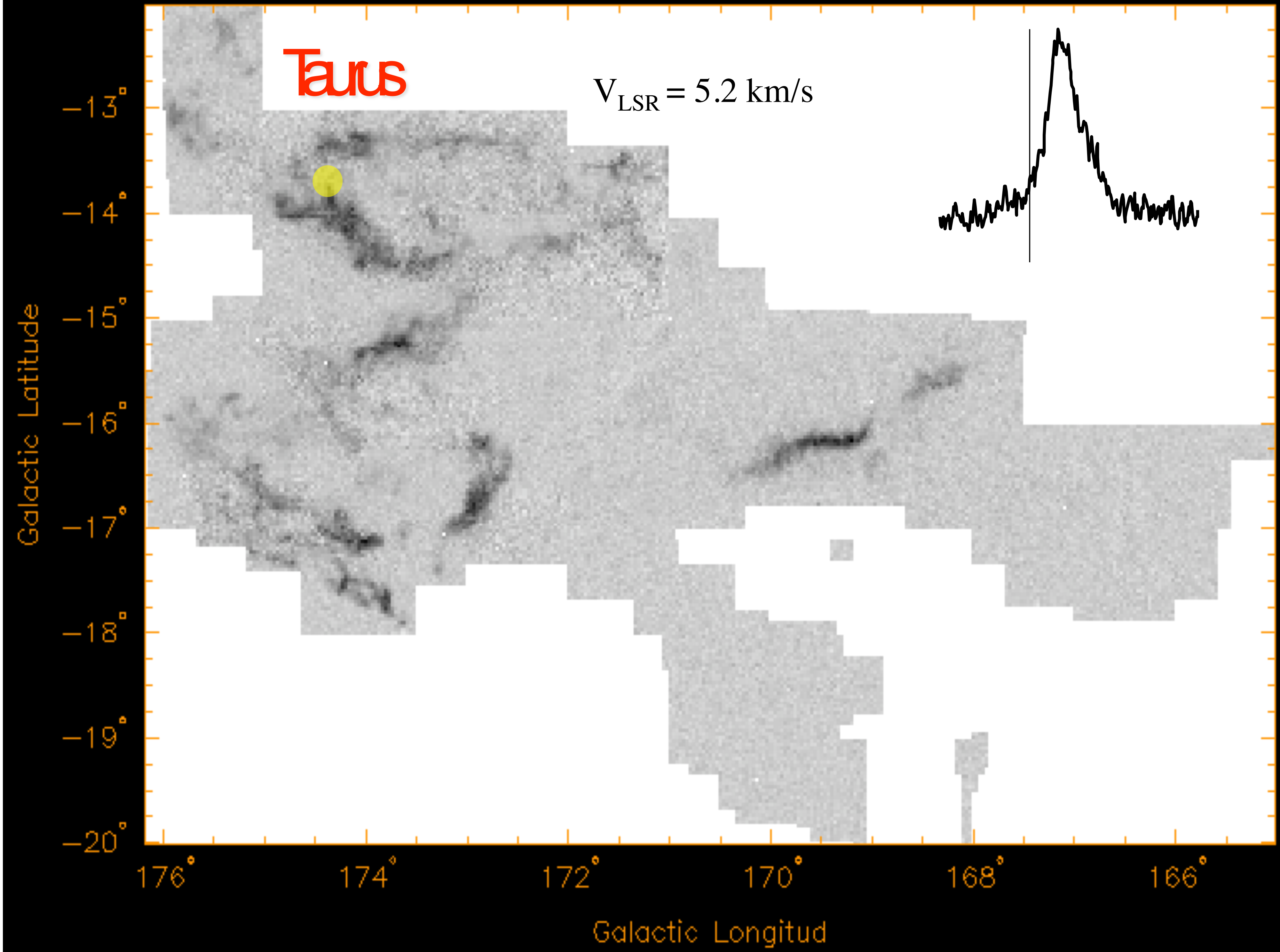

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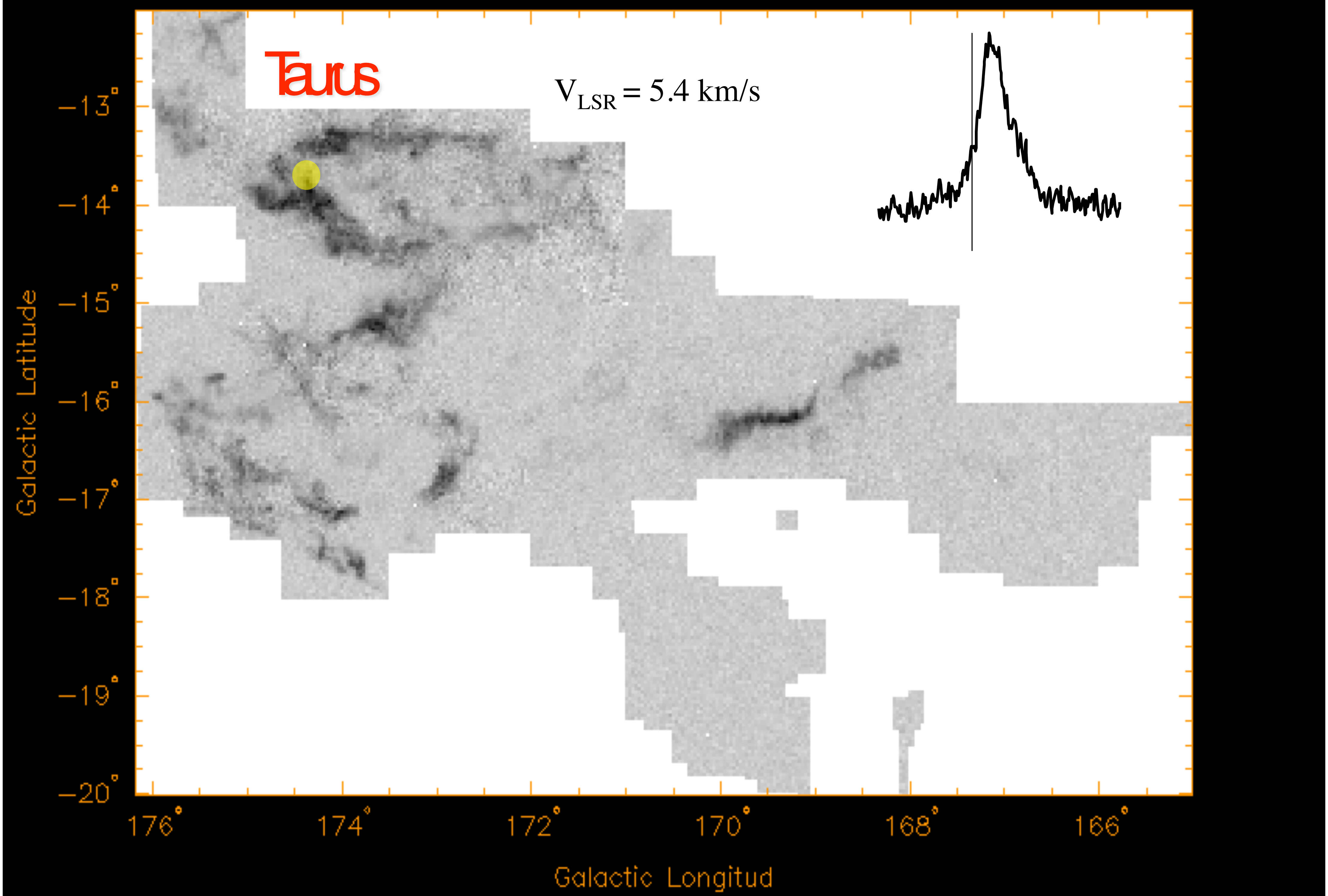

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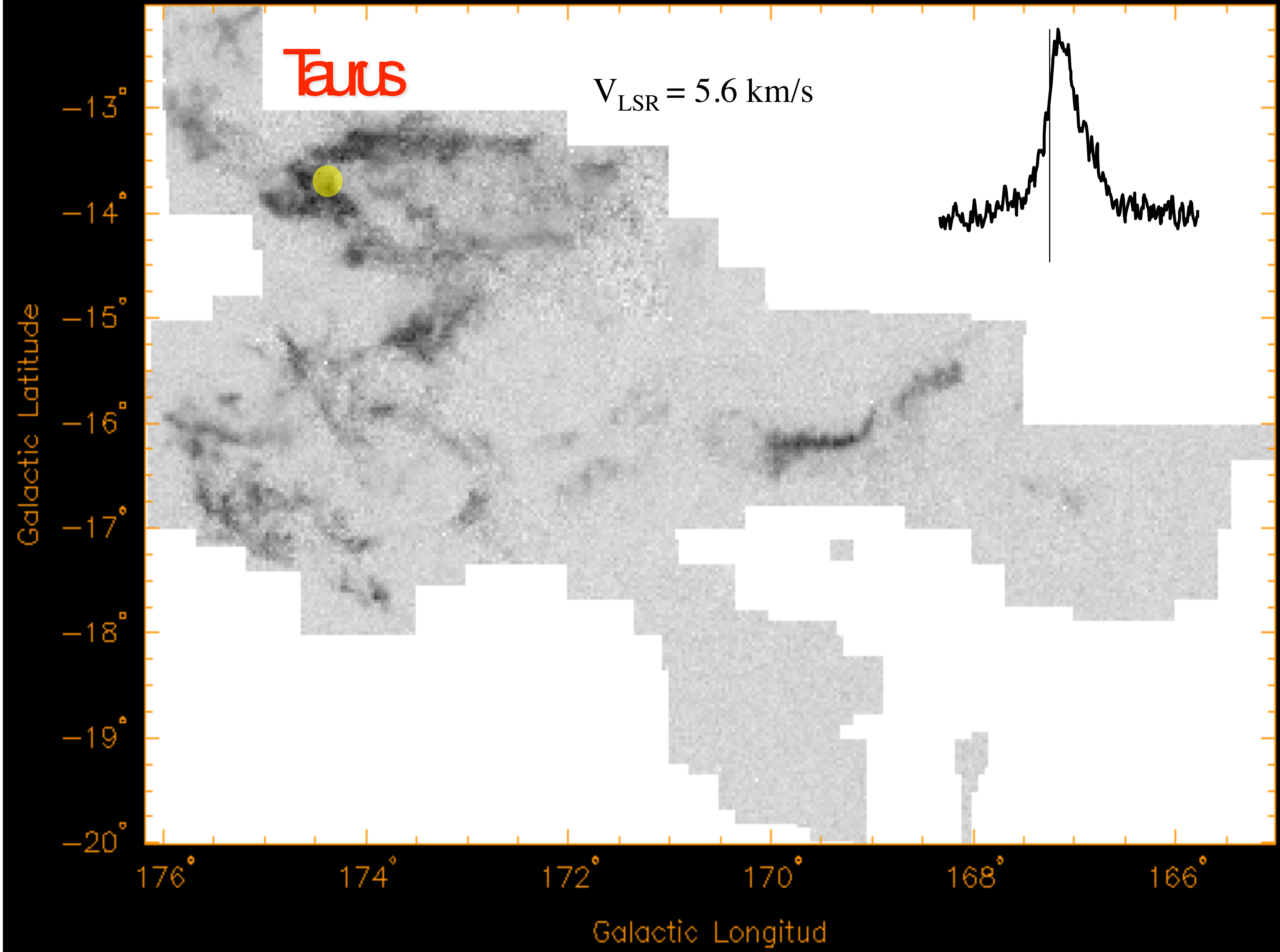
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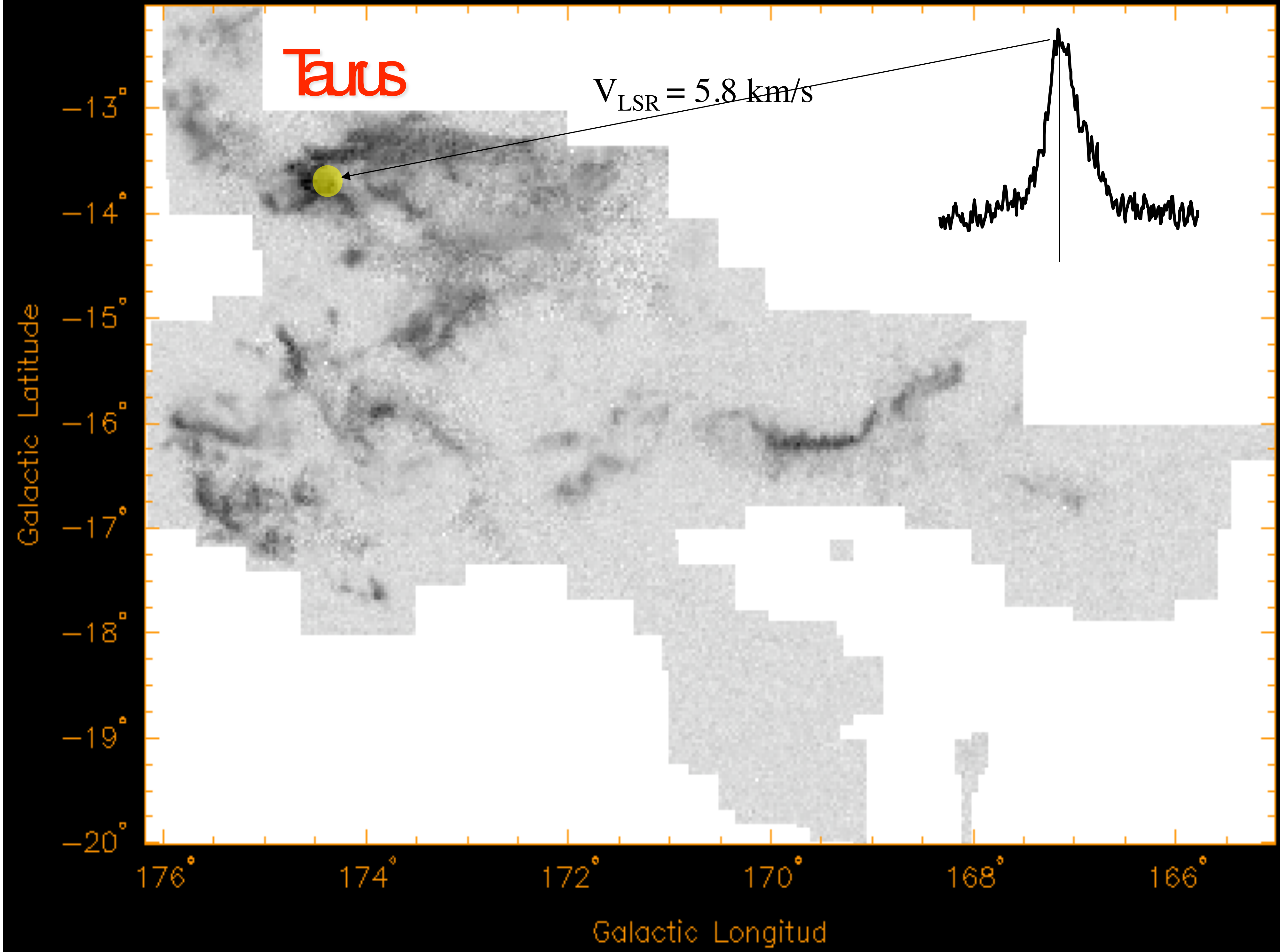

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V$_{LSR}$ = 5.8 km/s
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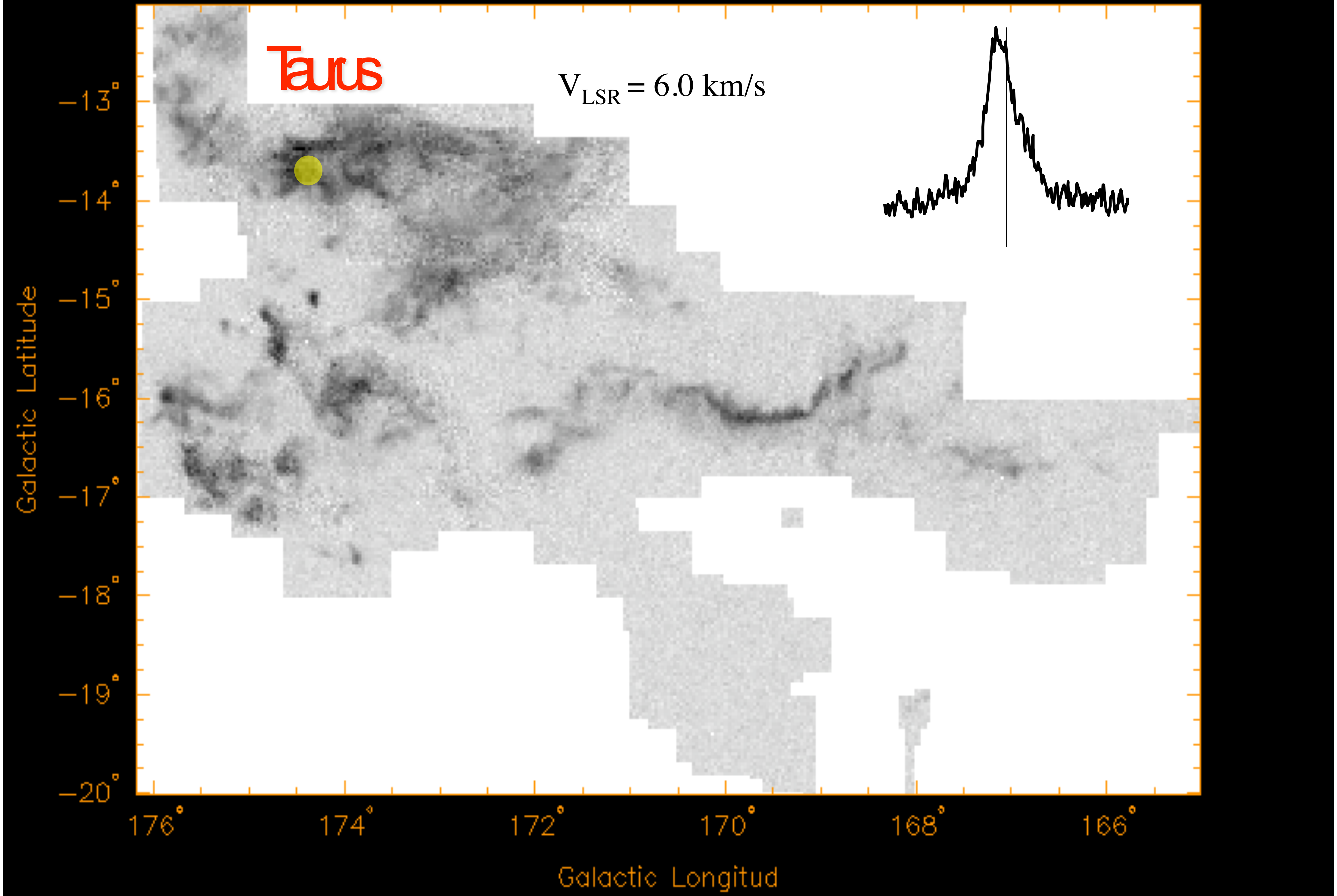

Taurus
V_{LSR} = 6.0 km/s
Galactic Latitude
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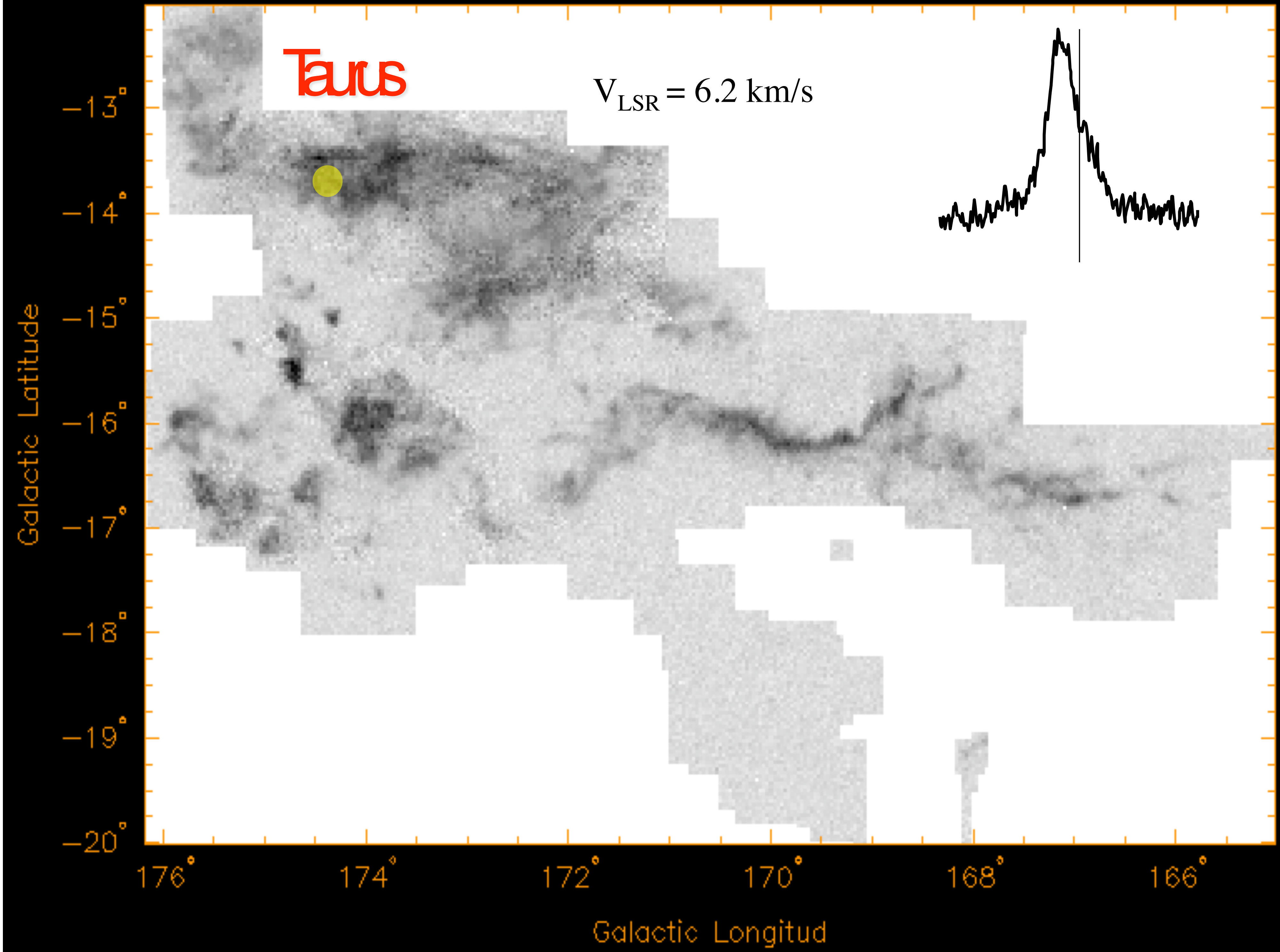

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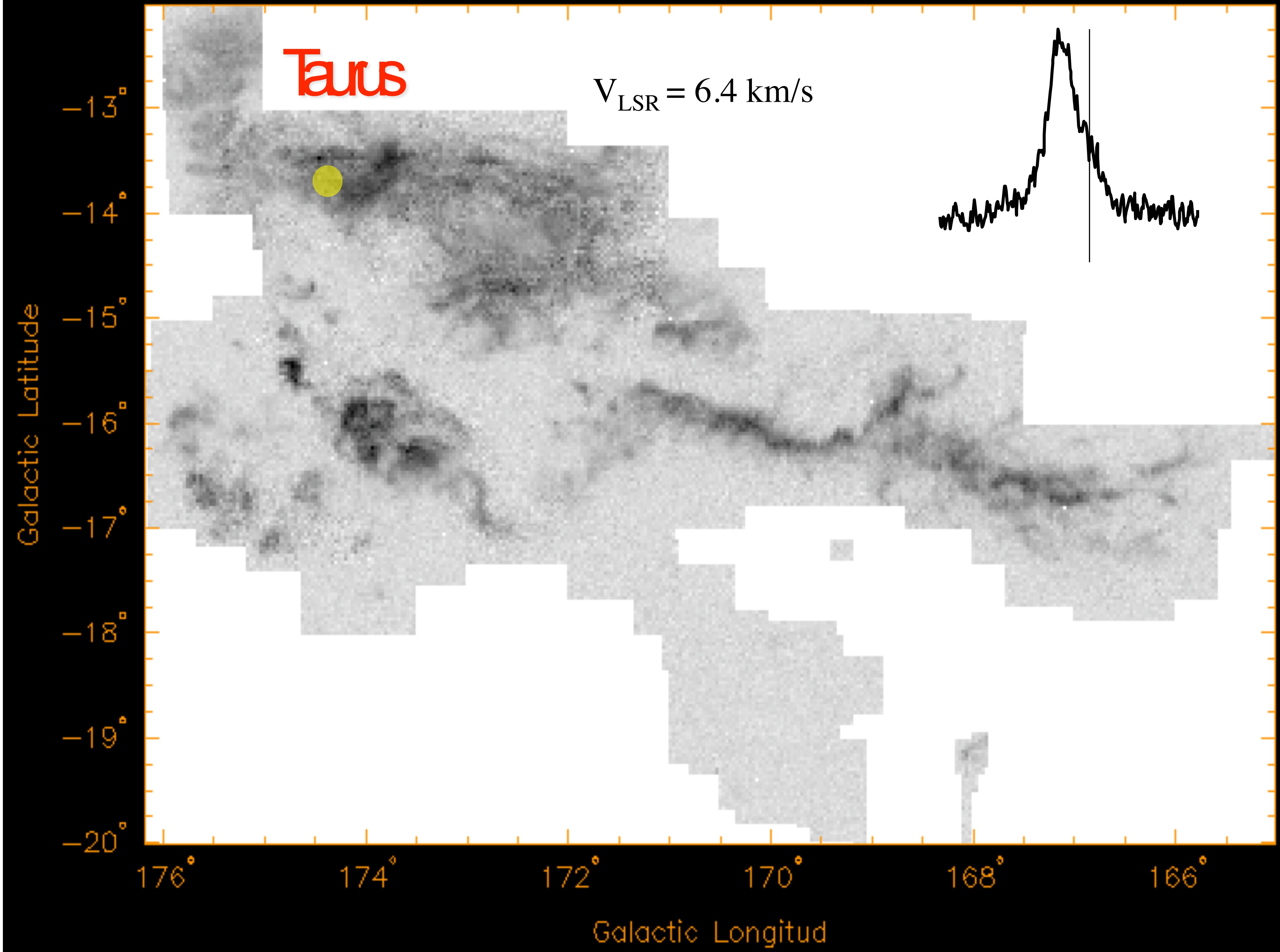

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V_{LSR} = 6.4 km/s
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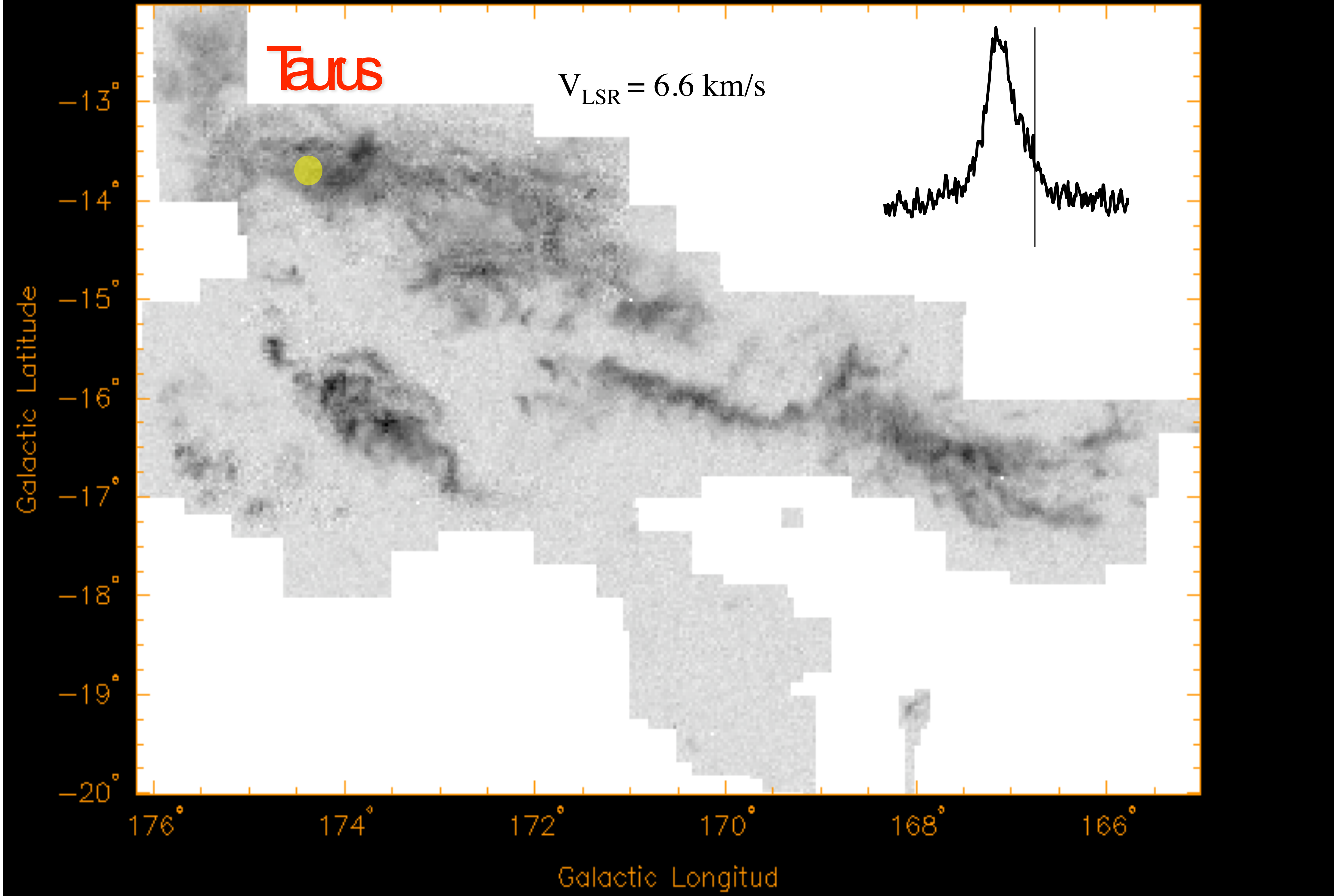
Galactic Longitud



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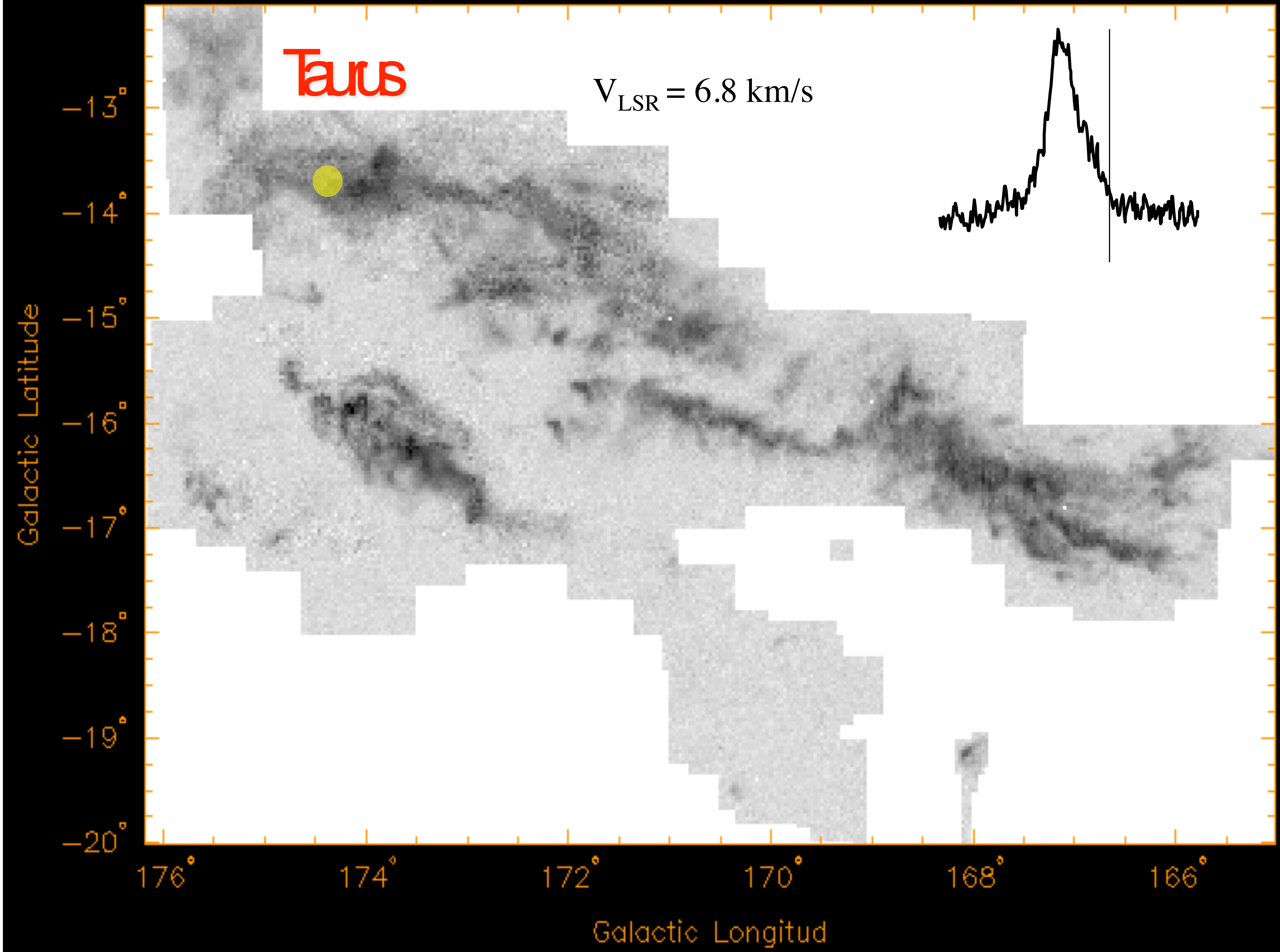

Taurus
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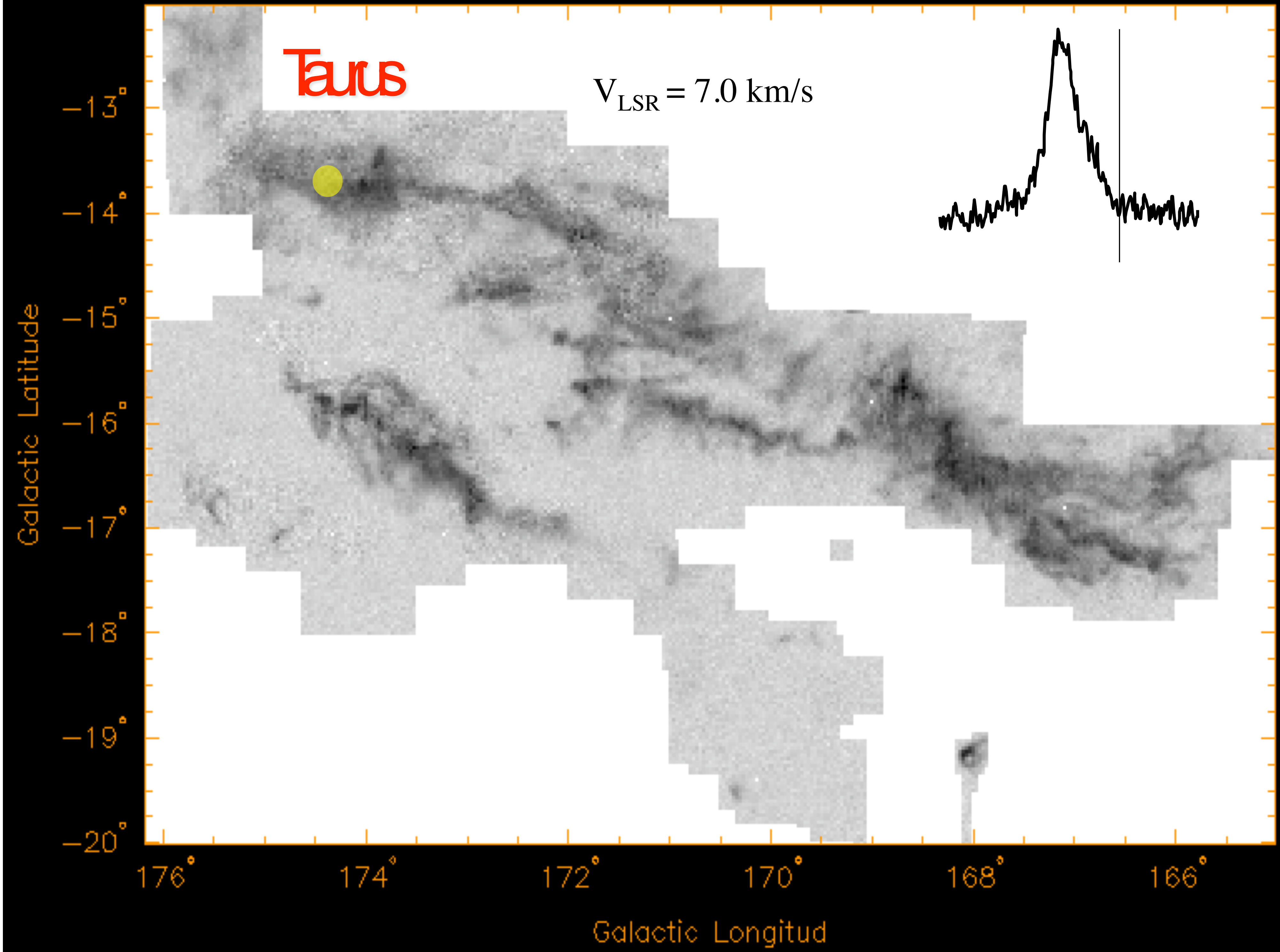
Galactic Longitud



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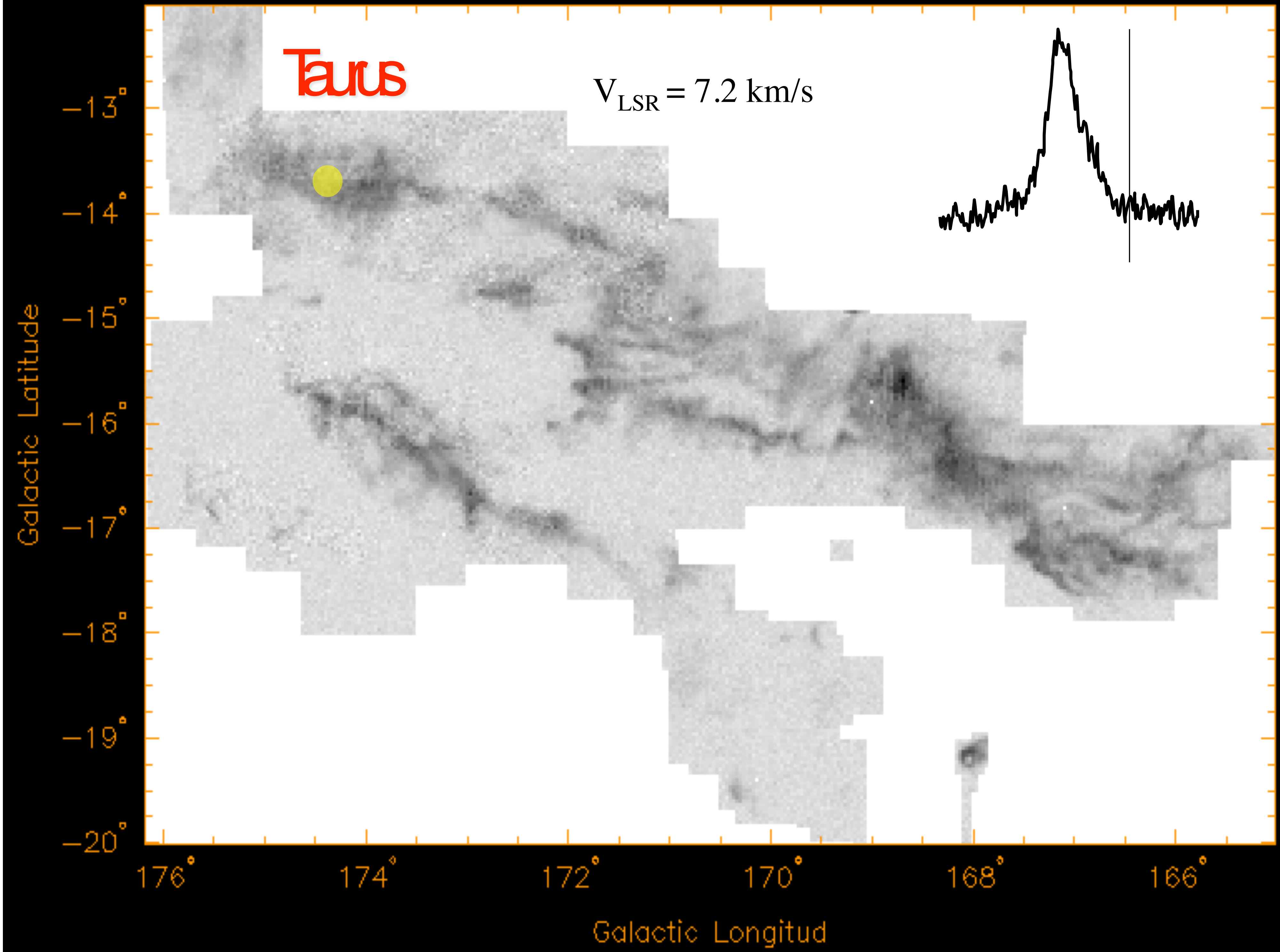
Galactic Longitud


Taurus
VLSR = 7.2 km/s
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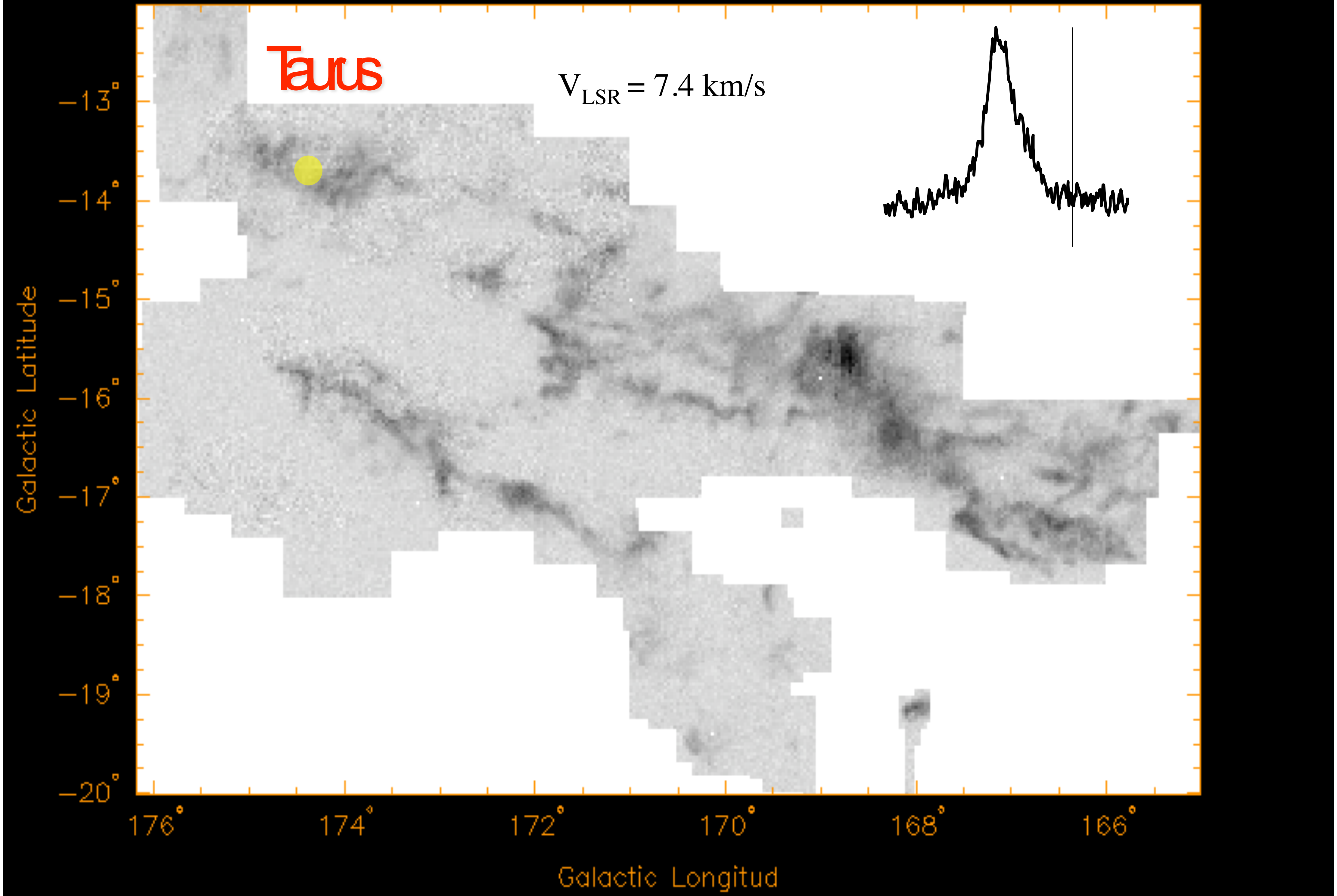
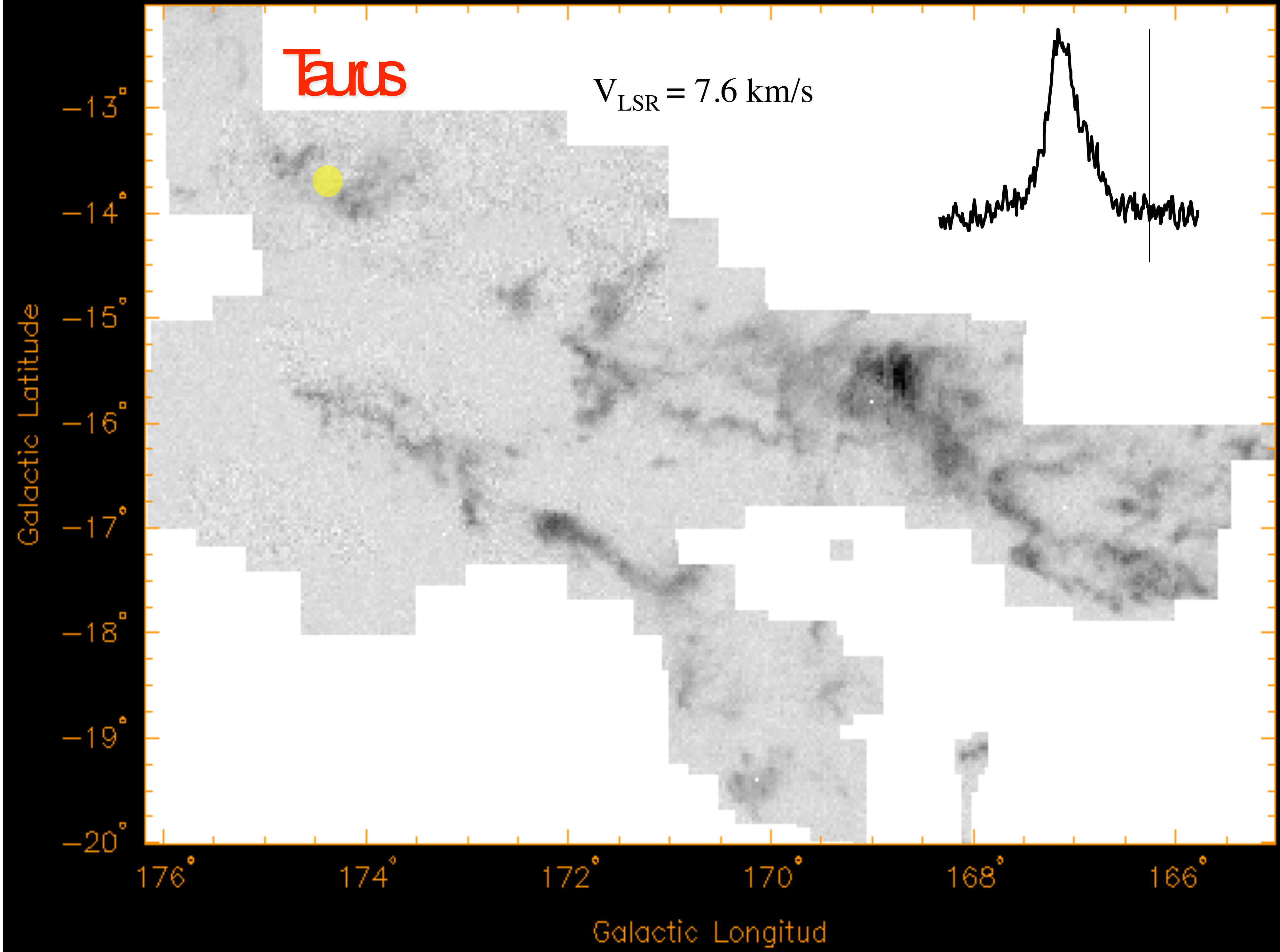
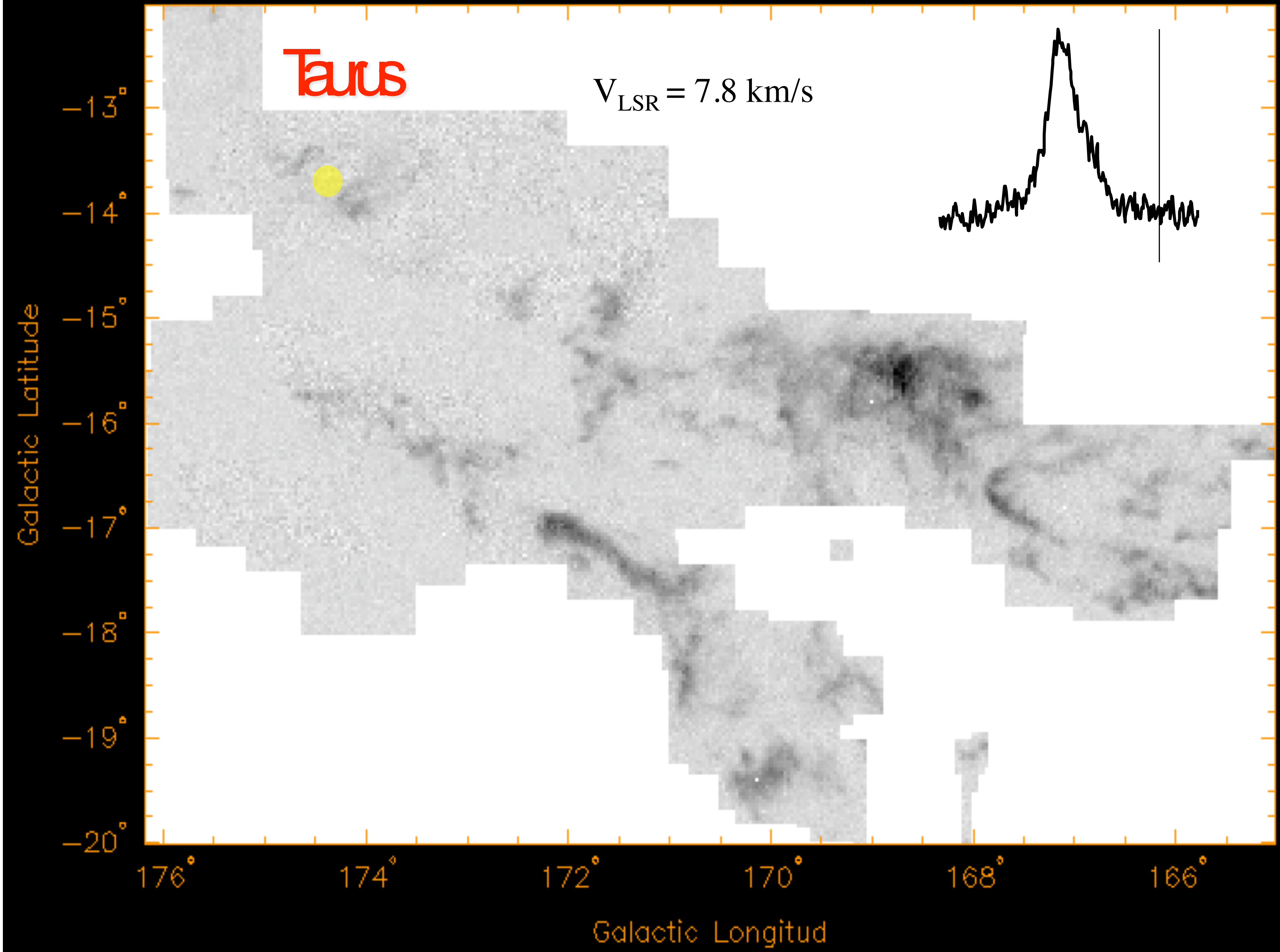
166°
Galactic Longitud

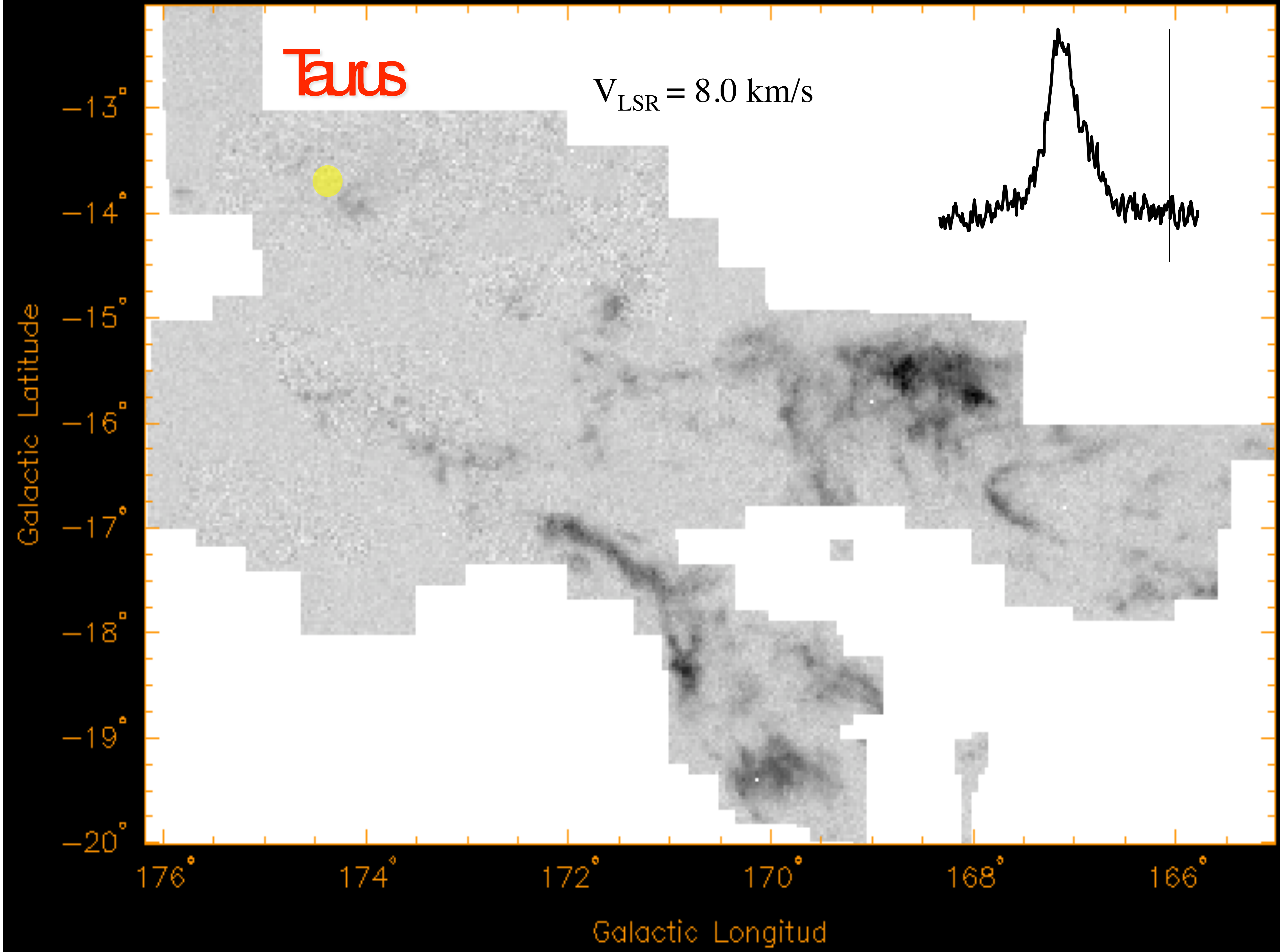

Taurus
V_{LSR} = 7.4 km/s
−13°
−14°
−15°
−16°
−17°
−18°
−19°
−20°
Galactic Latitude
176°
174°
172°
170°
168°
166°
Galactic Longitud

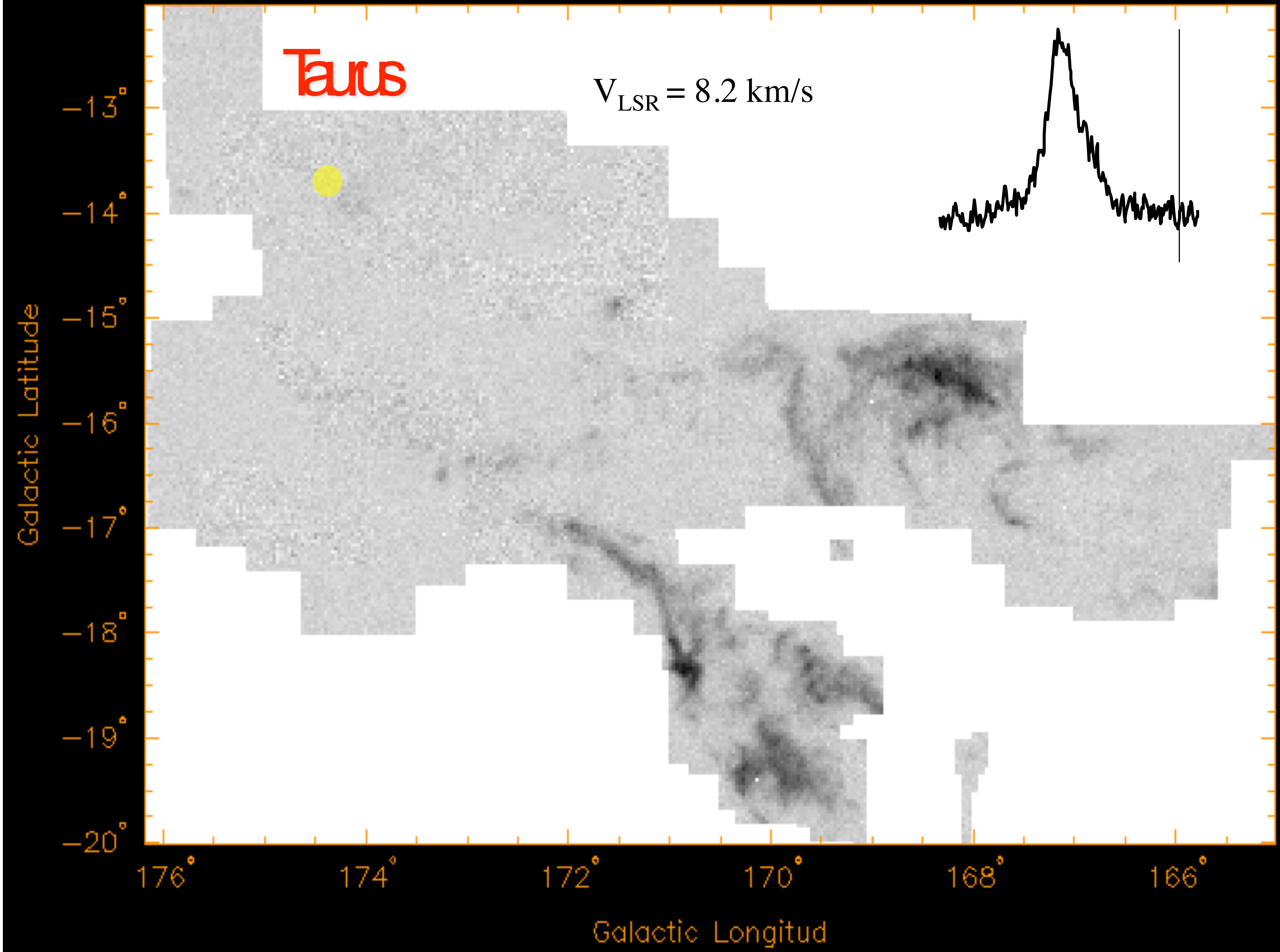


Taurus
V_LSR = 7.6 km/s
Galactic Latitude
−13°
−14°
−15°
−16°
−17°
−18°
−19°
−20°
176°
174°
172°
170°
168°
166°
Galactic Longitud

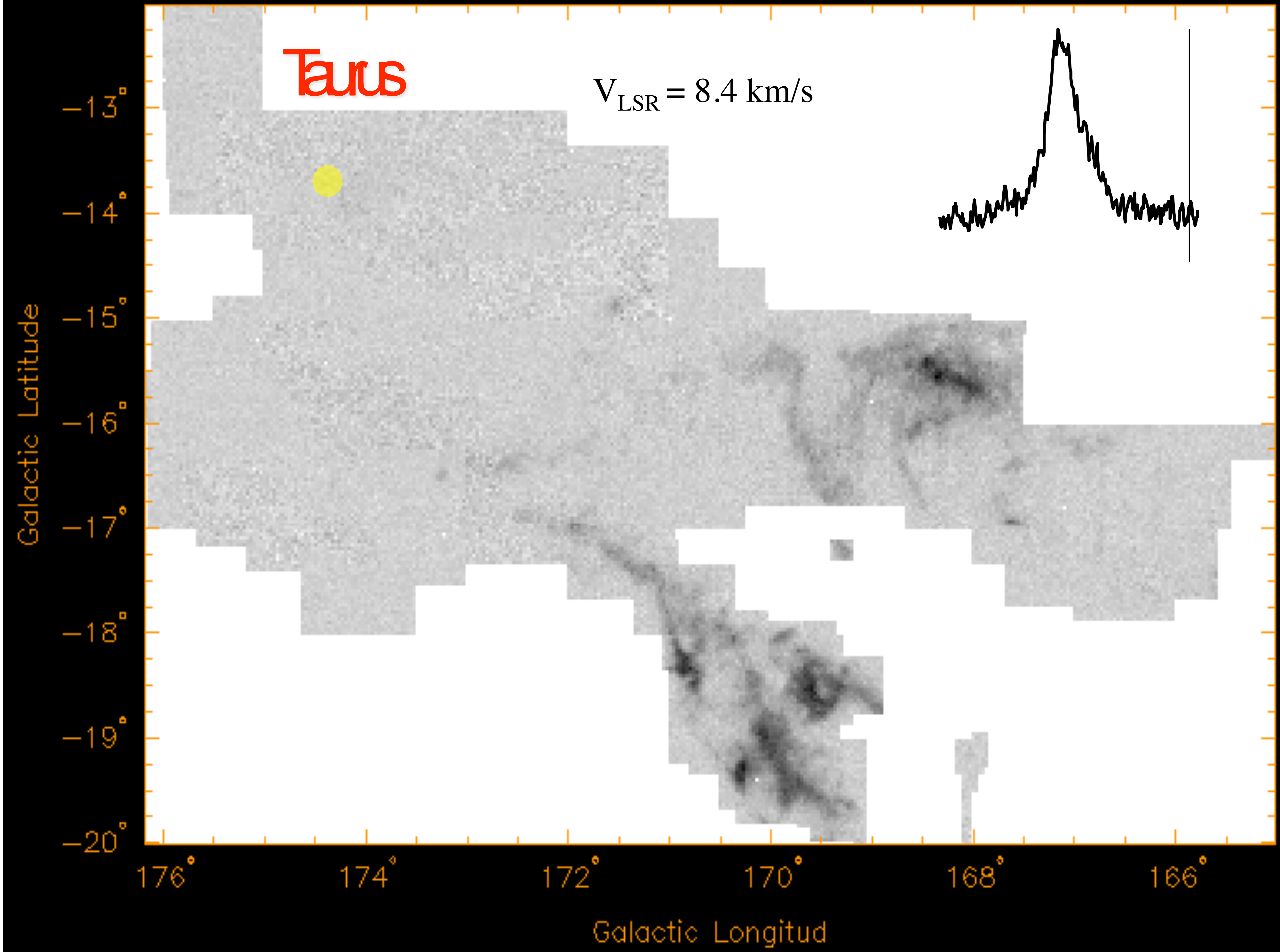


Taurus
V_{LSR} = 7.8 km/s
−13°
−14°
−15°
−16°
−17°
−18°
−19°
−20°
Galactic Latitude
176°
174°
172°
170°
168°
166°
Galactic Longitud

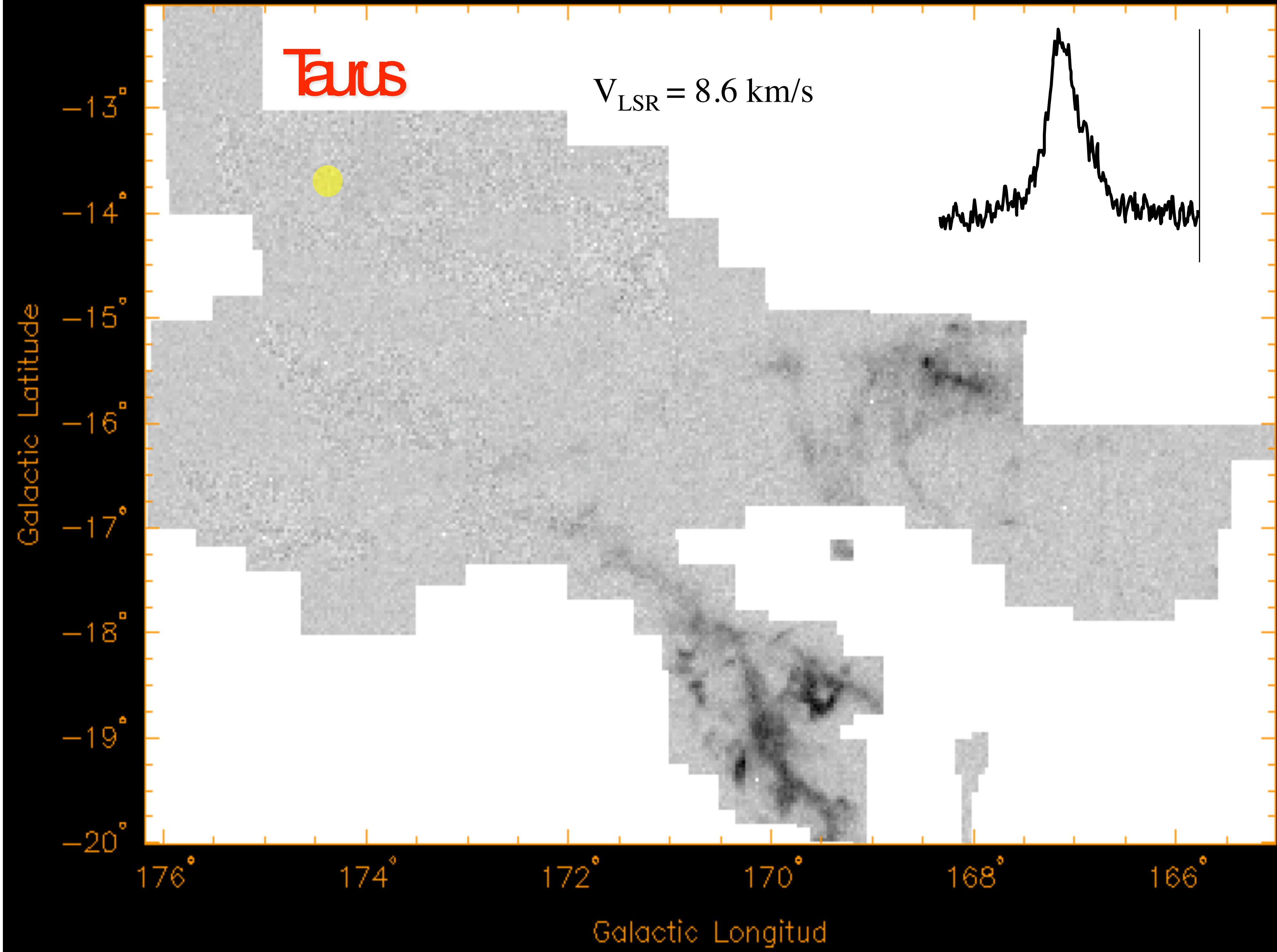

Taurus
V_LSR = 8.0 km/s
Galactic Latitude
−13°
−14°
−15°
−16°
−17°
−18°
−19°
−20°
176°
174°
172°
170°
168°
166°
Galactic Longitud



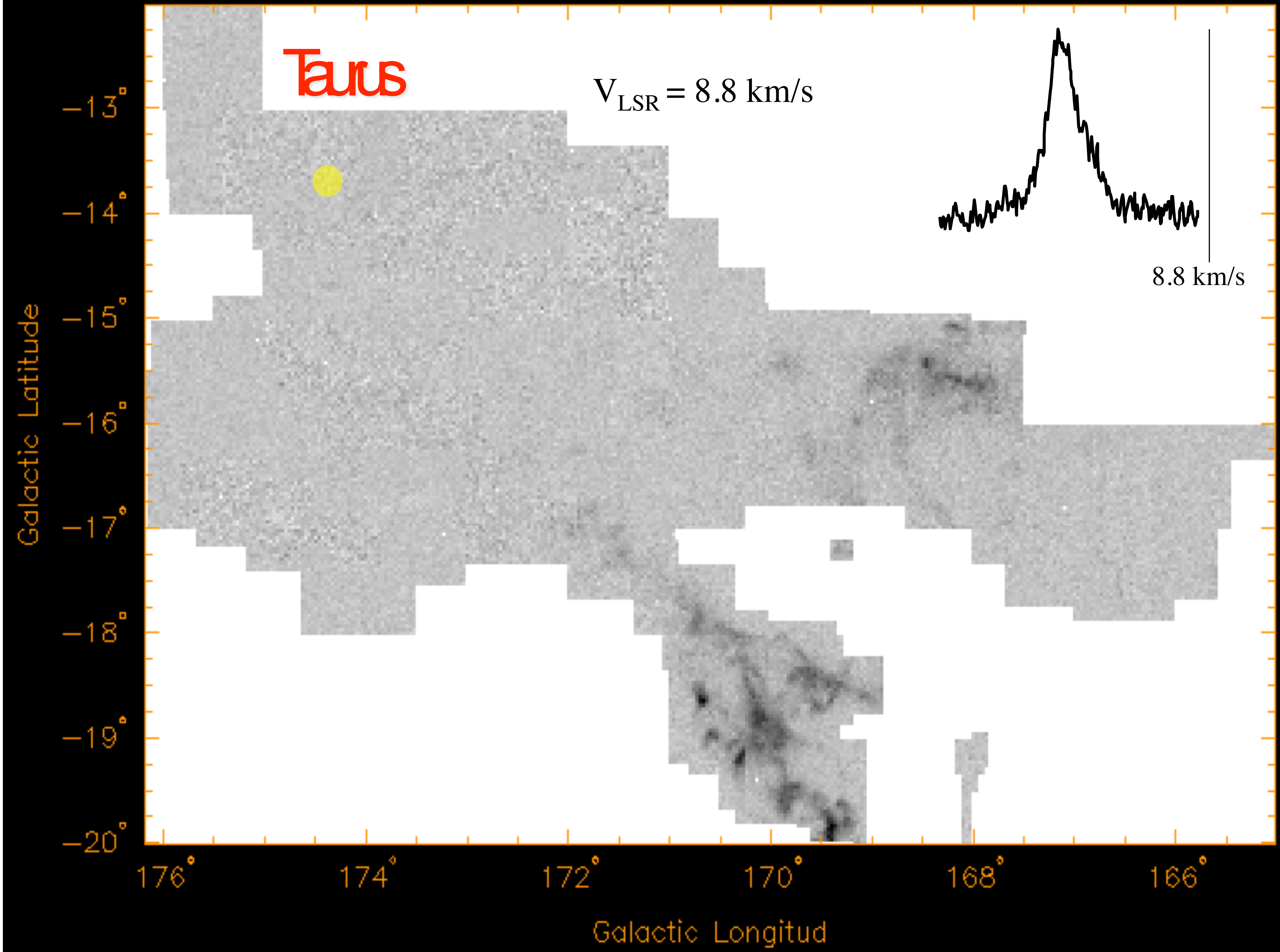
Taurus
V_LSR = 8.2 km/s
−13°
−14°
−15°
−16°
−17°
−18°
−19°
−20°
Galactic Latitude
176°
174°
172°
170°
168°
166°
Galactic Longitud



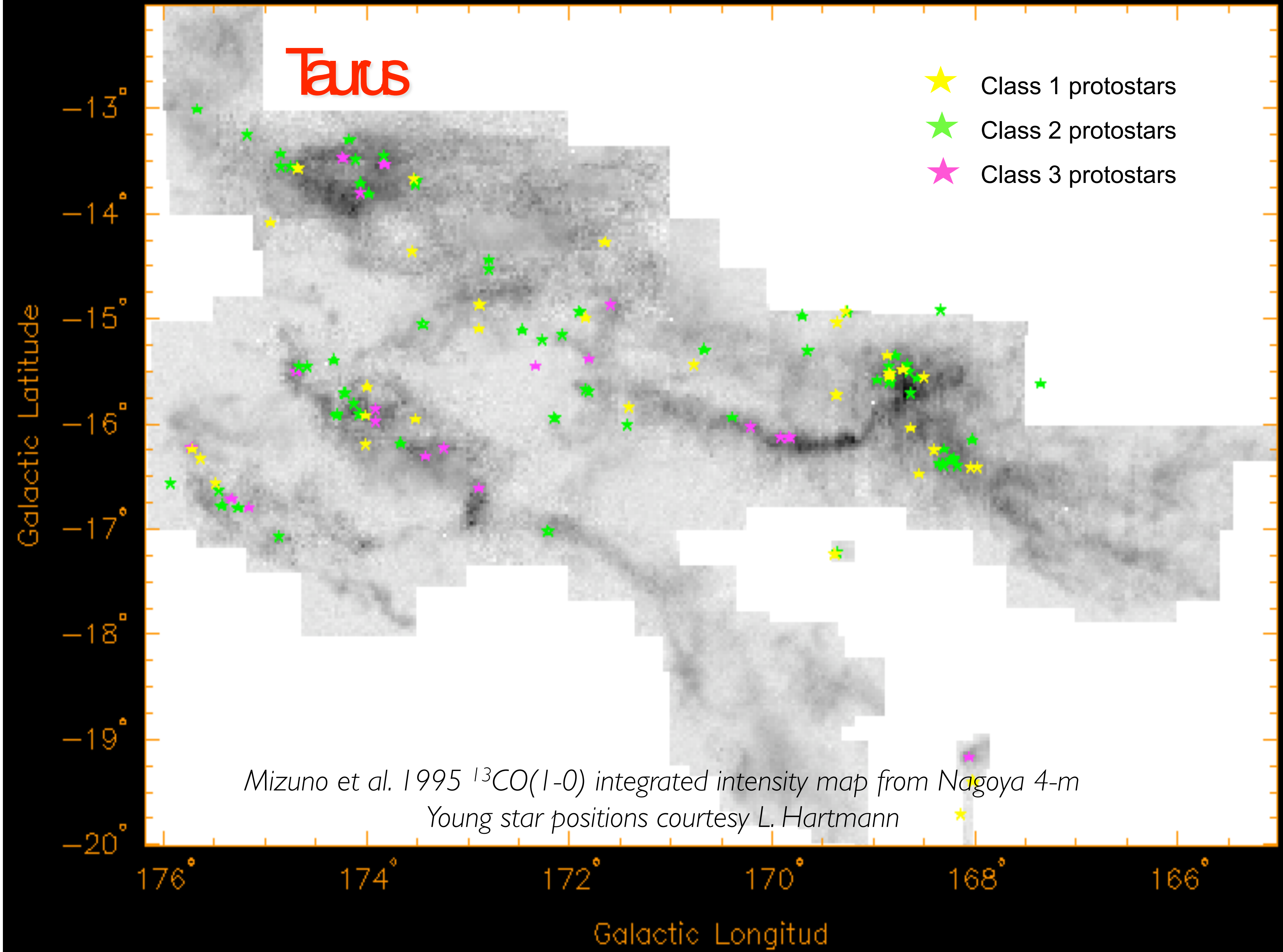
Taurus
V_{LSR} = 8.4 km/s
−13°
−14°
−15°
−16°
−17°
−18°
−19°
−20°
176°
174°
172°
170°
168°
166°
Galactic Latitude
Galactic Longitud



Taurus
V_{LSR} = 8.6 km/s
−13°
−14°
−15°
−16°
−17°
−18°
−19°
−20°
Galactic Latitude
176°
174°
172°
170°
168°
166°
Galactic Longitud



Taurus
V_{LSR} = 8.8 km/s
8.8 km/s
−13°
−14°
−15°
−16°
−17°
−18°
−19°
−20°
Galactic Latitude
176°
174°
172°
170°
168°
166°
Galactic Longitud


Taurus
Class 1 protostars
Class 2 protostars
Class 3 protostars
−13°
−14°
−15°
−16°
−17°
−18°
−19°
−20°
Galactic Latitude
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

gravoturbulent star formation

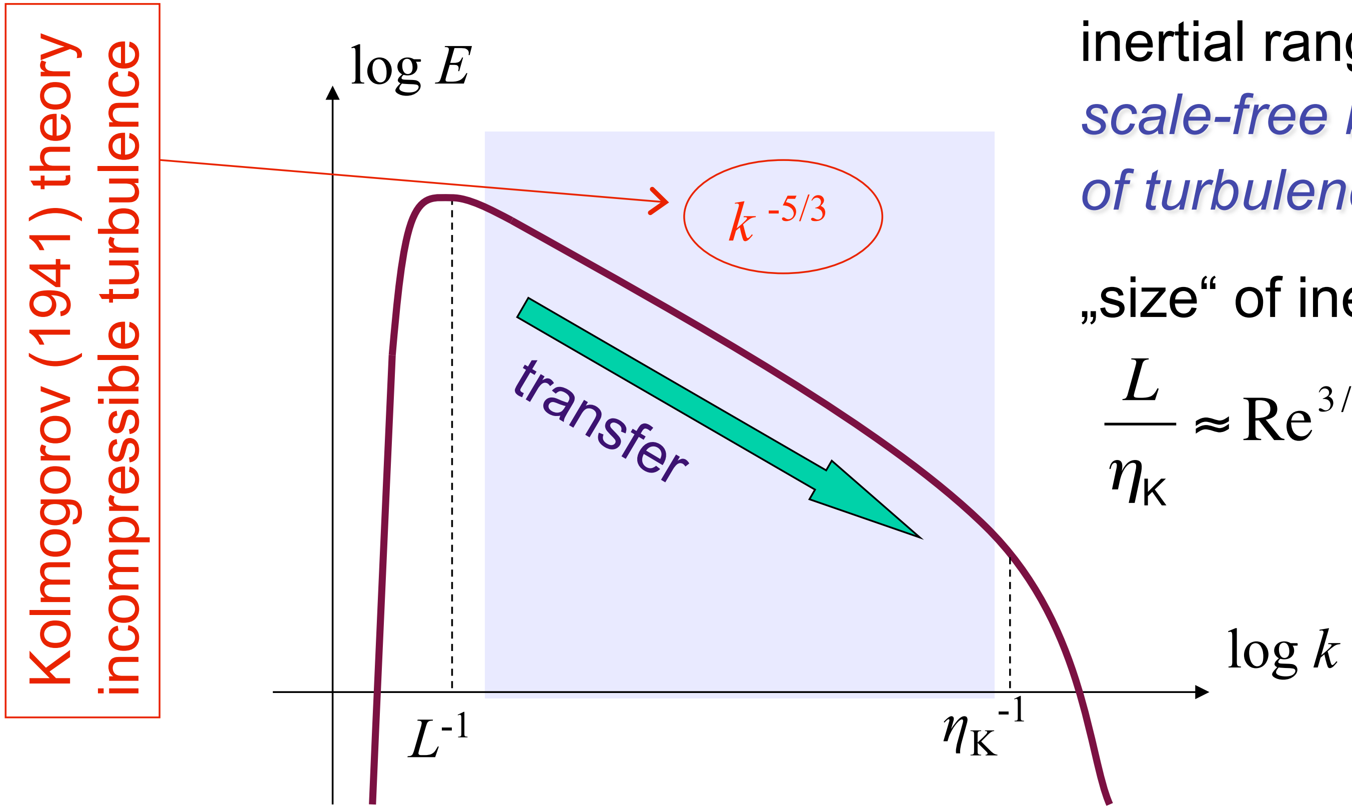
- Idea:

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)

turbulent cascade



energy
input
scale

energy
dissipation
scale

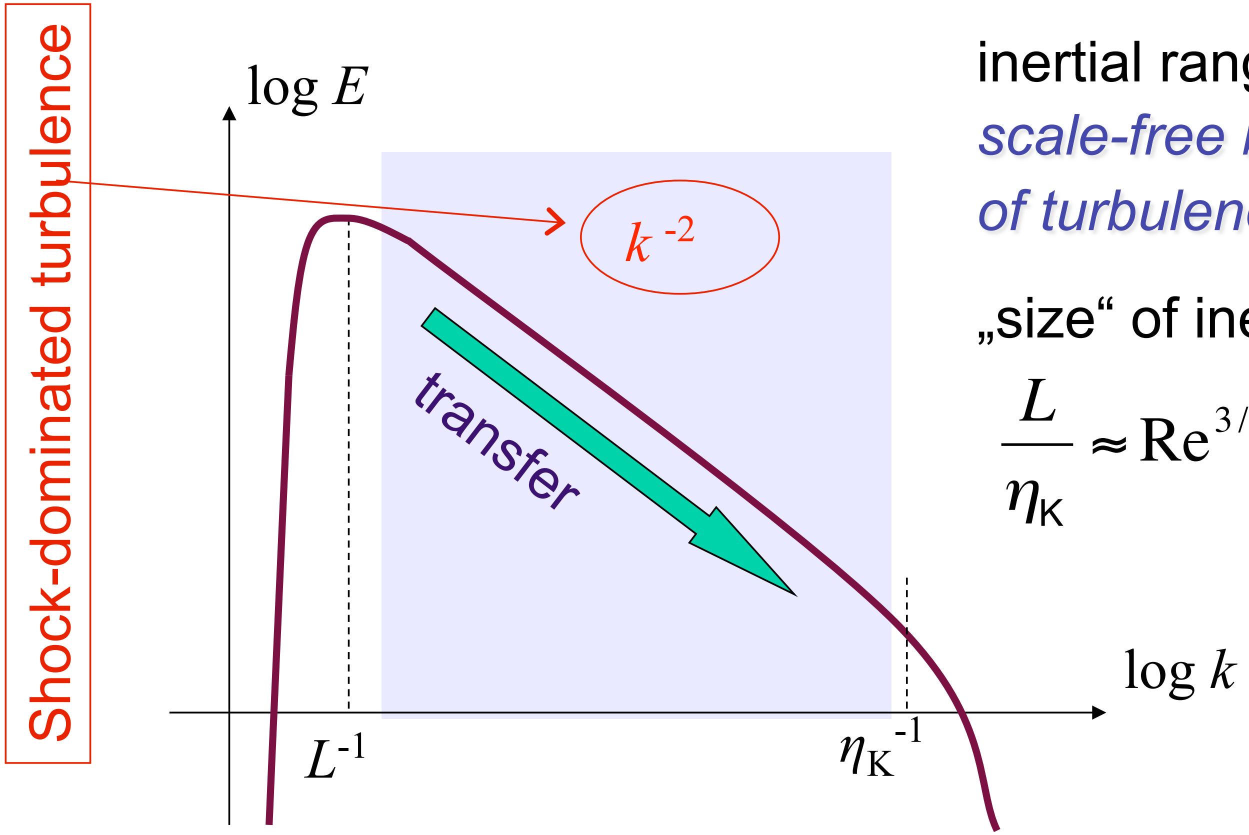
inertial range:
scale-free behavior
of turbulence

„size“ of inertial range:

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

Mac Low & Klessen 2004, Rev. Mod. Phys., 6, 125

turbulent cascade



energy
input
scale

energy
dissipation
scale

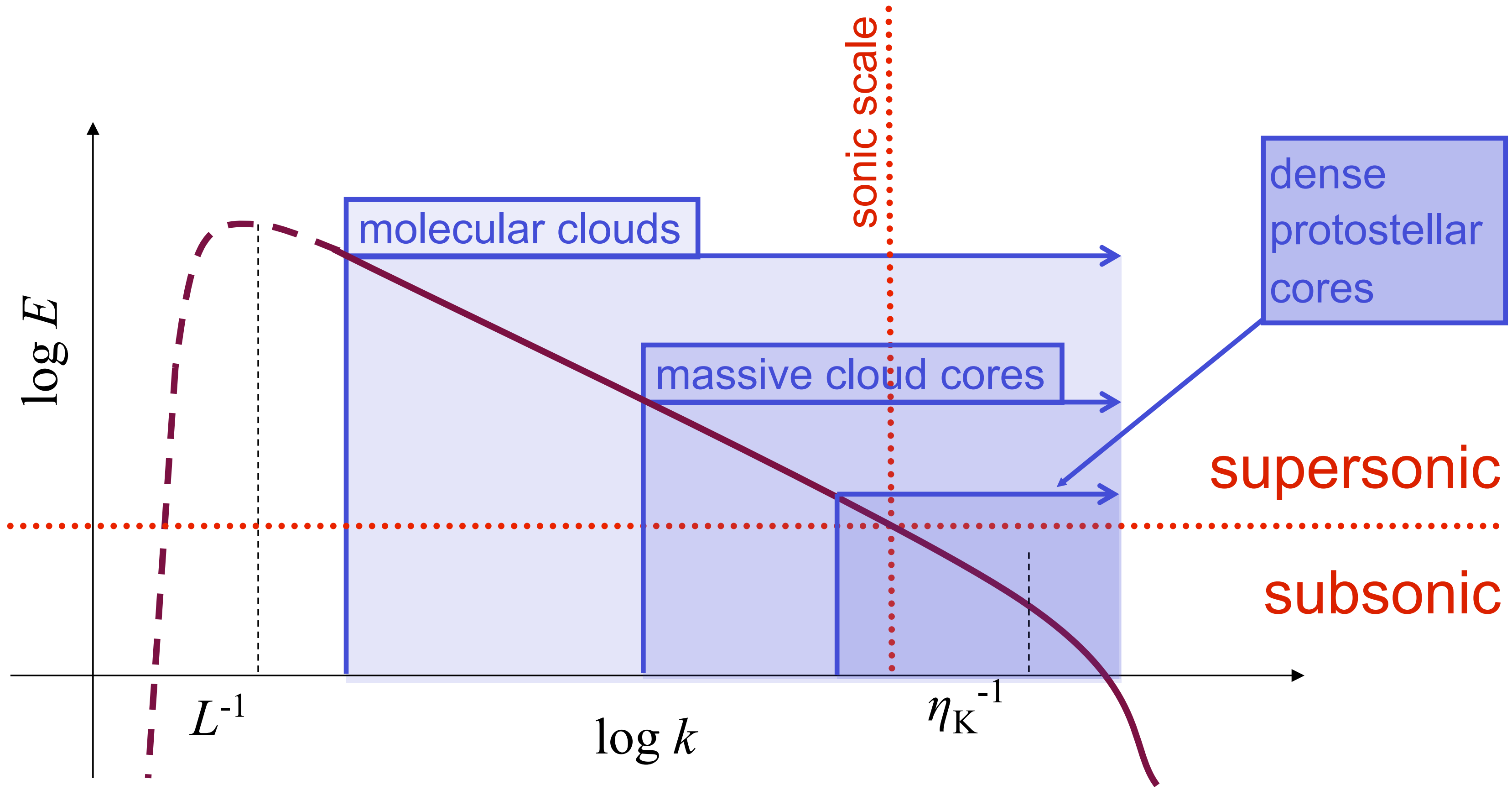
inertial range:
scale-free behavior of turbulence

„size" of inertial range:

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

Mac Low & Klessen 2004, Rev. Mod. Phys., 6, 125

turbulent cascade in ISM



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

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

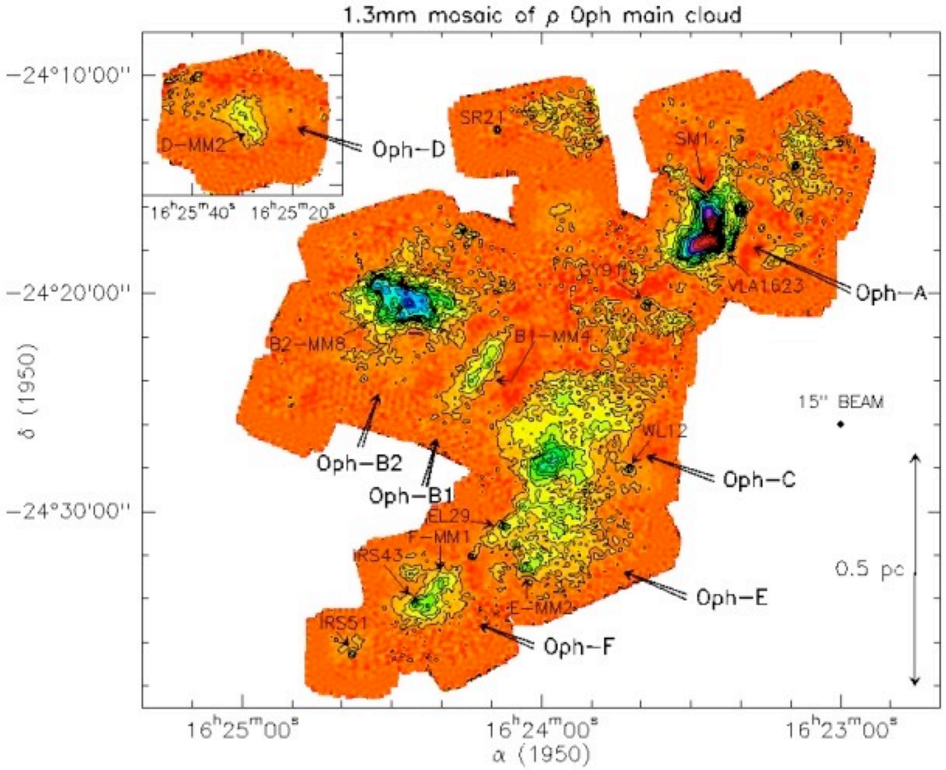
dissipation scale not known (ambipolar diffusion, molecular diffusion?)

Mac Low & Klessen 2004, Rev. Mod. Phys, 6, 125

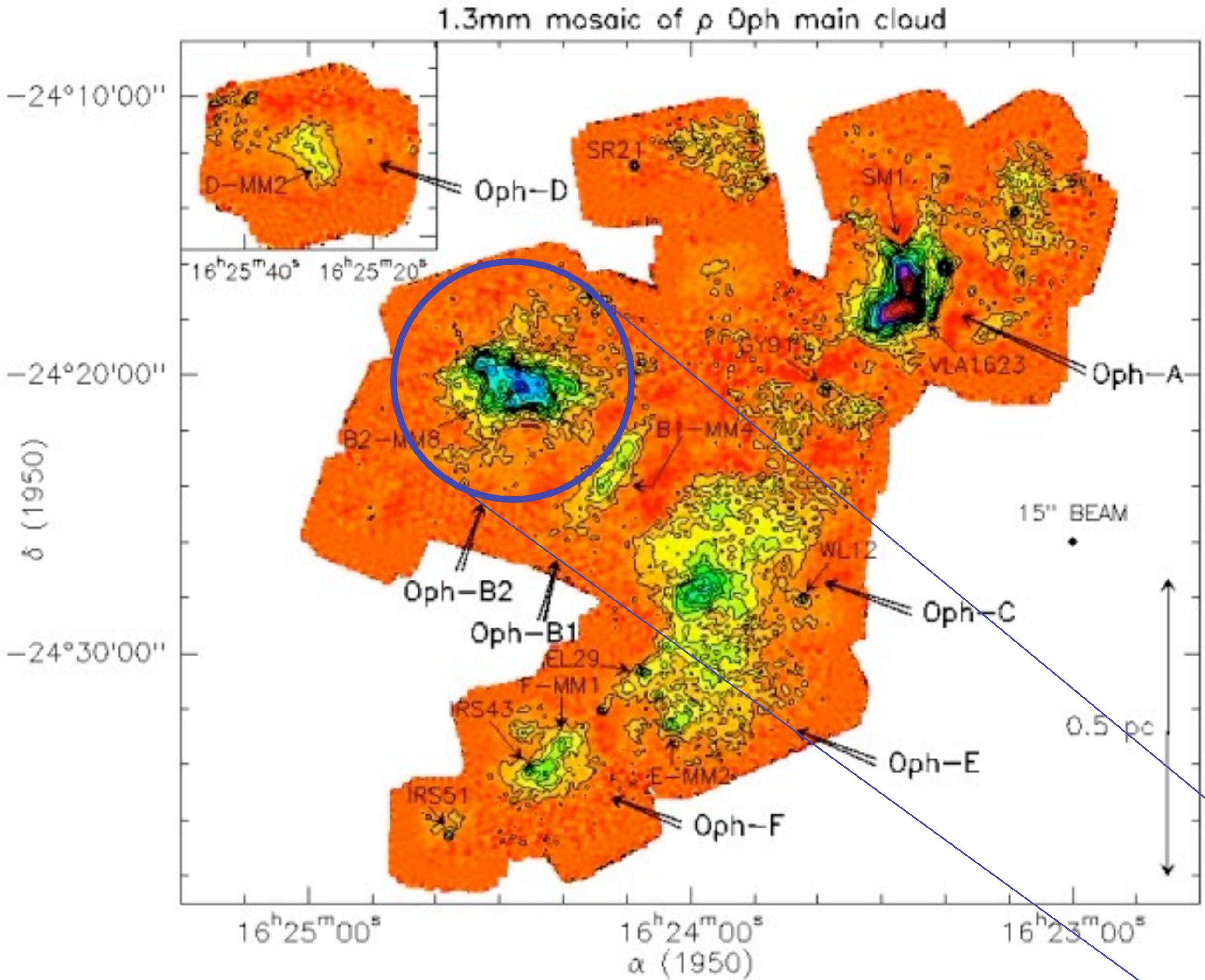
environment

- also the environment (stellar density) will effect the stellar mass distribution

  ➘ *competitive accretion* vs. *simple collapse*



density structure of MC's



(Motte, André, & Neri 1998)

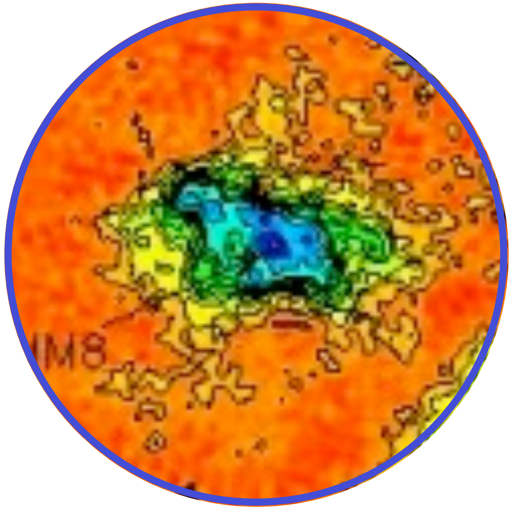
molecular clouds are highly inhomogeneous

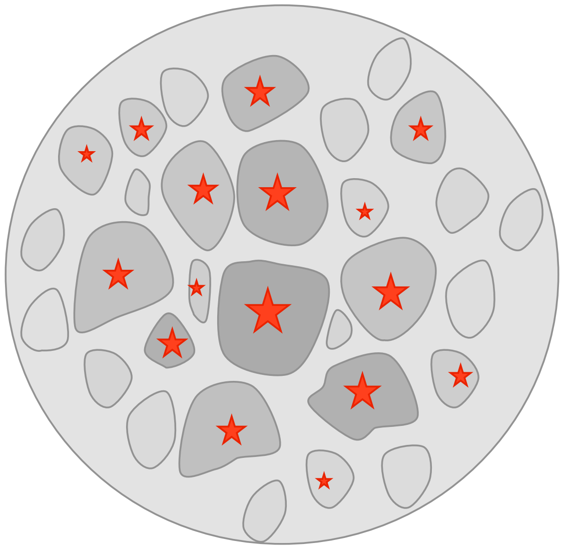
stars form in the densest and coldest parts of the cloud

ρ-Ophiuchus cloud seen in dust emission

let‘s focus on a cloud core like this one

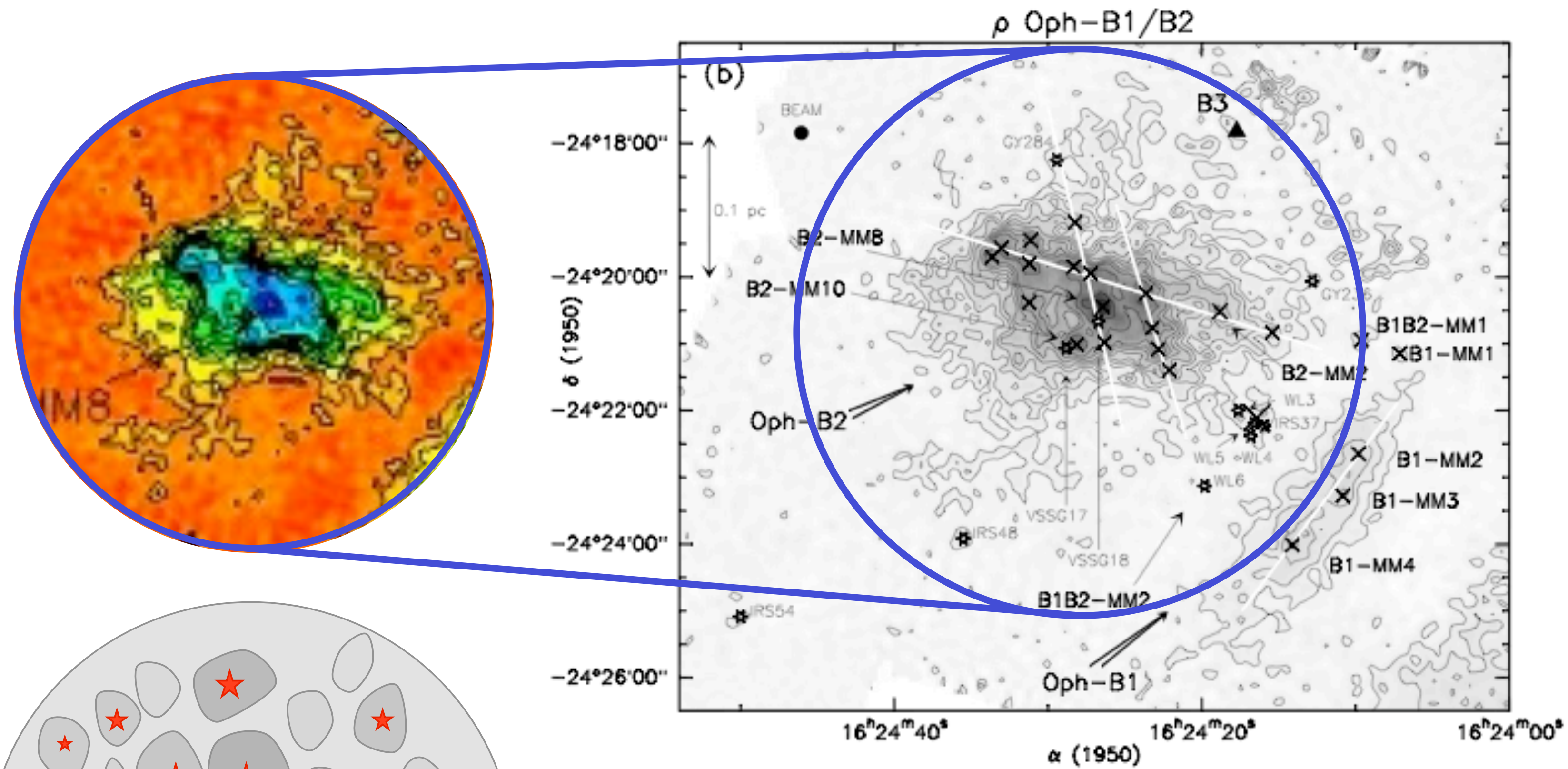
evolution of cloud cores

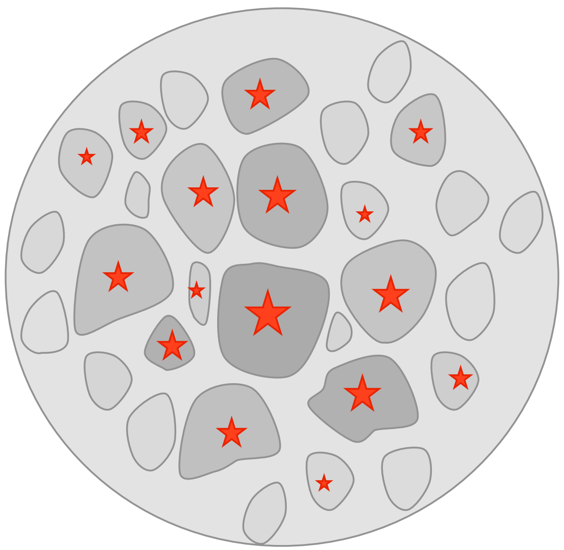




- *How does this core evolve?*
  Does it form one single massive star or cluster with mass distribution?
- Turbulent cascade „goes through“ cloud core
  --> NO *scale separation* possible
  --> NO *effective sound speed*
- Turbulence is supersonic!
  --> produces strong density contrasts:
  $\delta\rho/\rho \approx M^2$
  --> 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

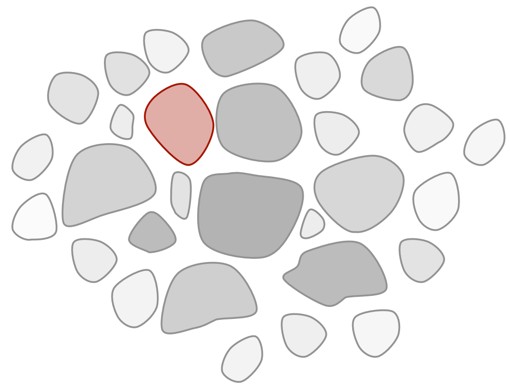




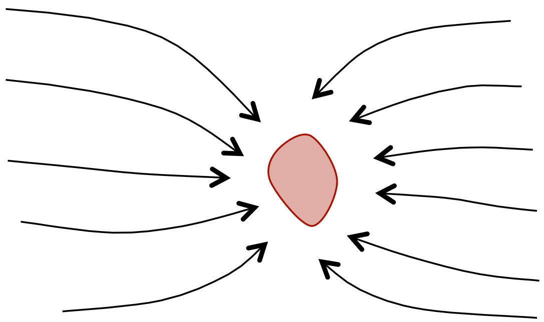
indeed ρ-Oph B1/2 contains several cores ("starless" cores are denoted by ×, cores with embedded protostars by ☆)

(Motte, André, & Neri 1998)

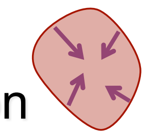
formation and evolution of cores



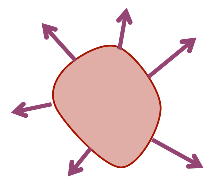
- protostellar cloud cores form at *stagnation point* in *convergent turbulent flows*



- if $M > M_{crit} \propto \rho^{-1/2}\, T^{3/2}$: collapse & star formation



- pf $M < M_{crit} \propto \rho^{-1/2}\, T^{3/2}$: reexpansion after end of external compression

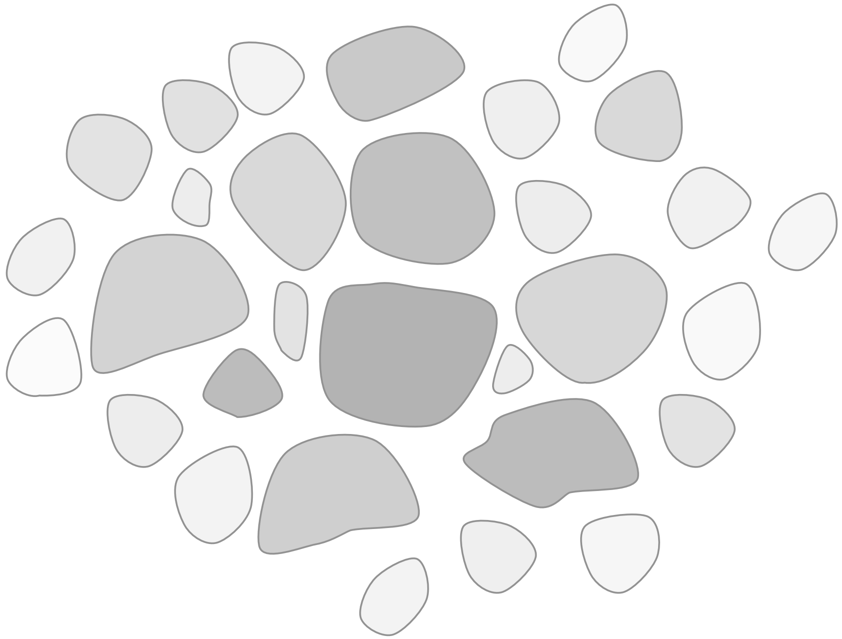


(e.g. Vazquez-Semadeni et al 2005)

- typical timescale: $t \approx 10^4 \ldots 10^5$ yr

formation and evolution of cores

What happens to distribution of cloud cores?

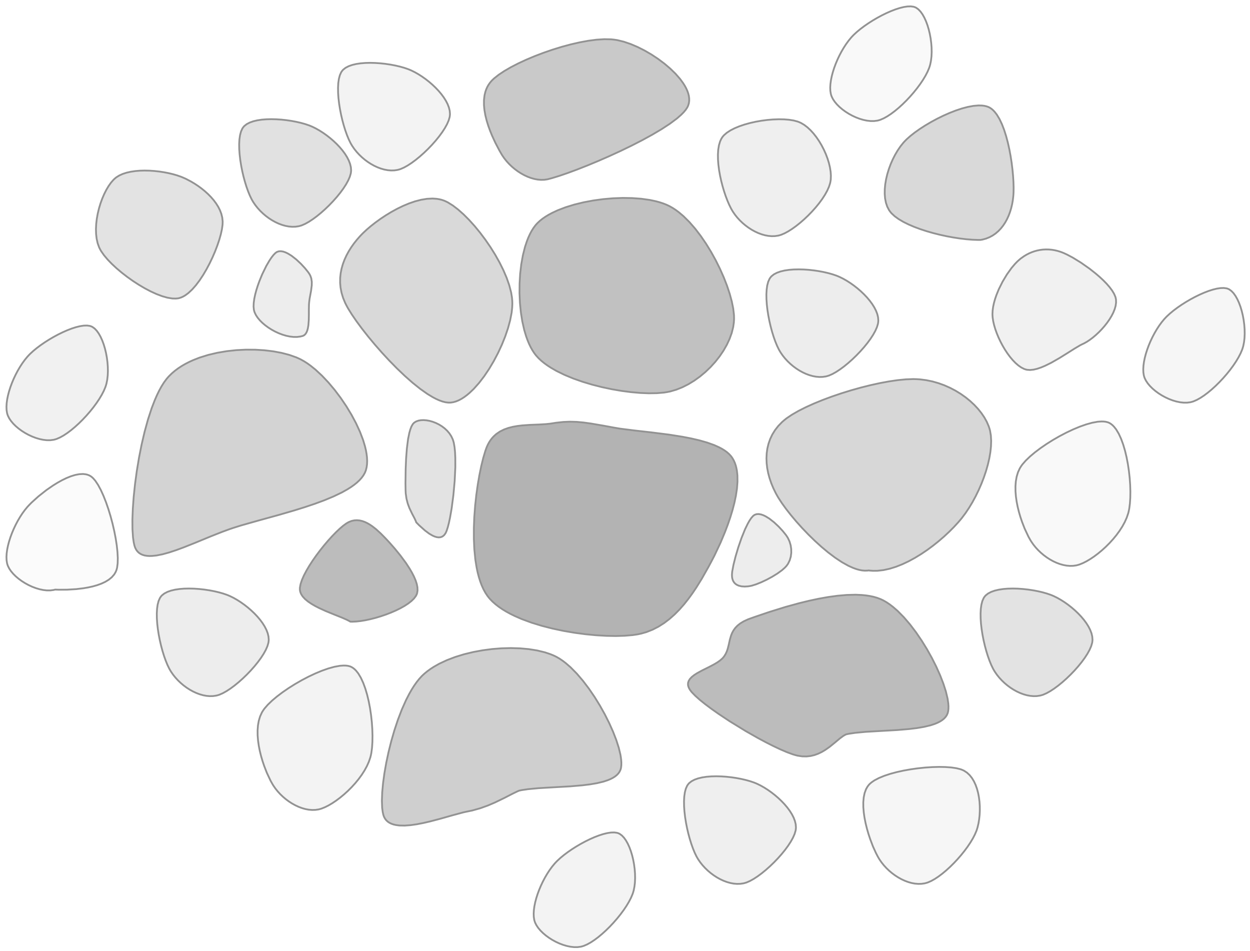


two exteme cases:

competitive accretion vs.
simple collapse

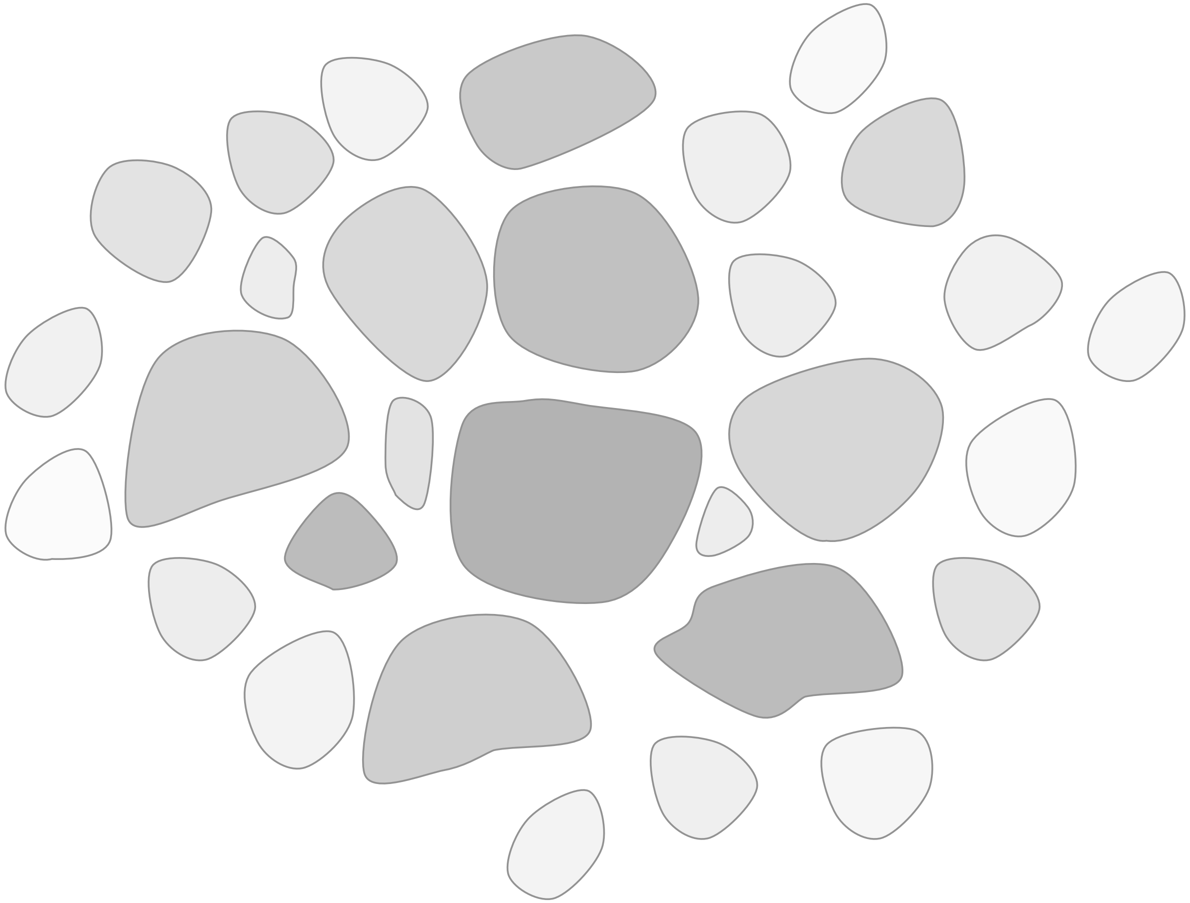
(1) turbulence dominates energy budget:
$\alpha = E_{kin}/|E_{pot}| > 1$
--> individual cores do *not* interact
--> *collapse* of *individual* cores dominates *stellar mass growth*
--> *loose cluster of low-mass stars*

(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*

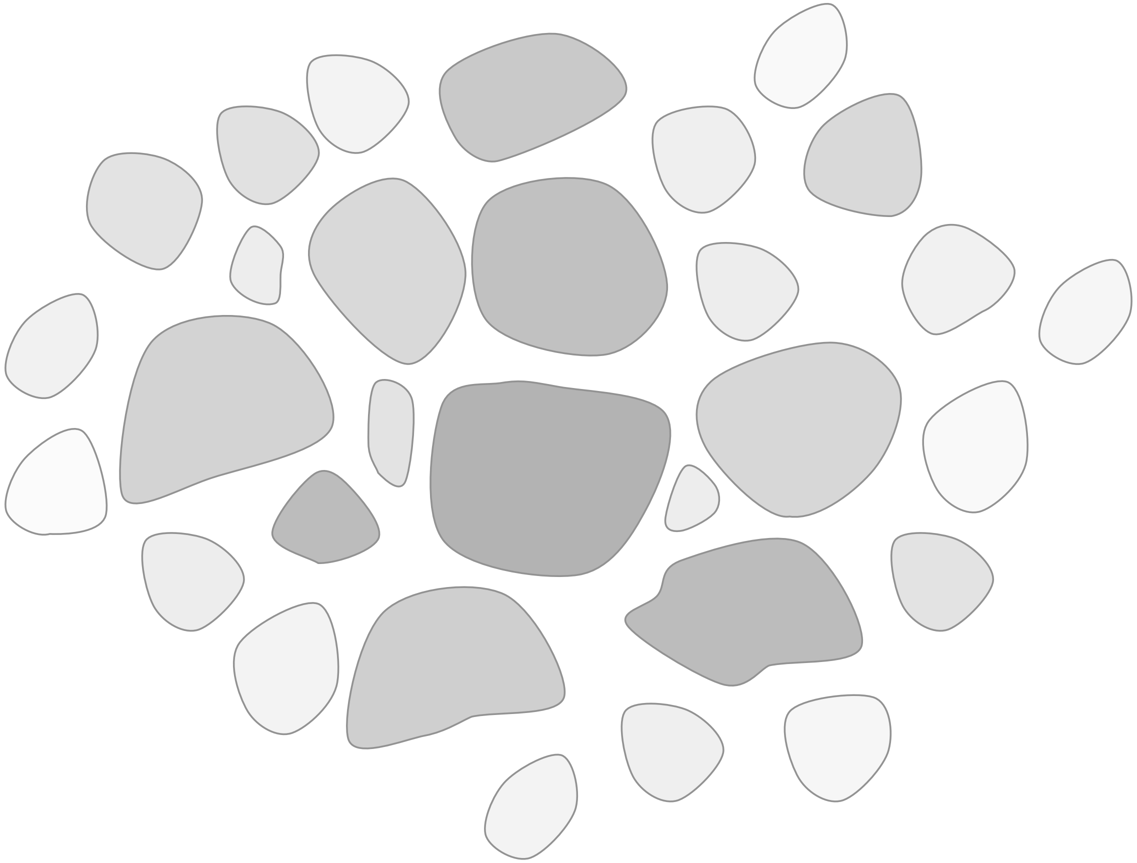


turbulence creates a hierarchy of clumps

Ralf Klessen: PizzaNight 16.07.2008



as turbulence decays locally, contraction sets in



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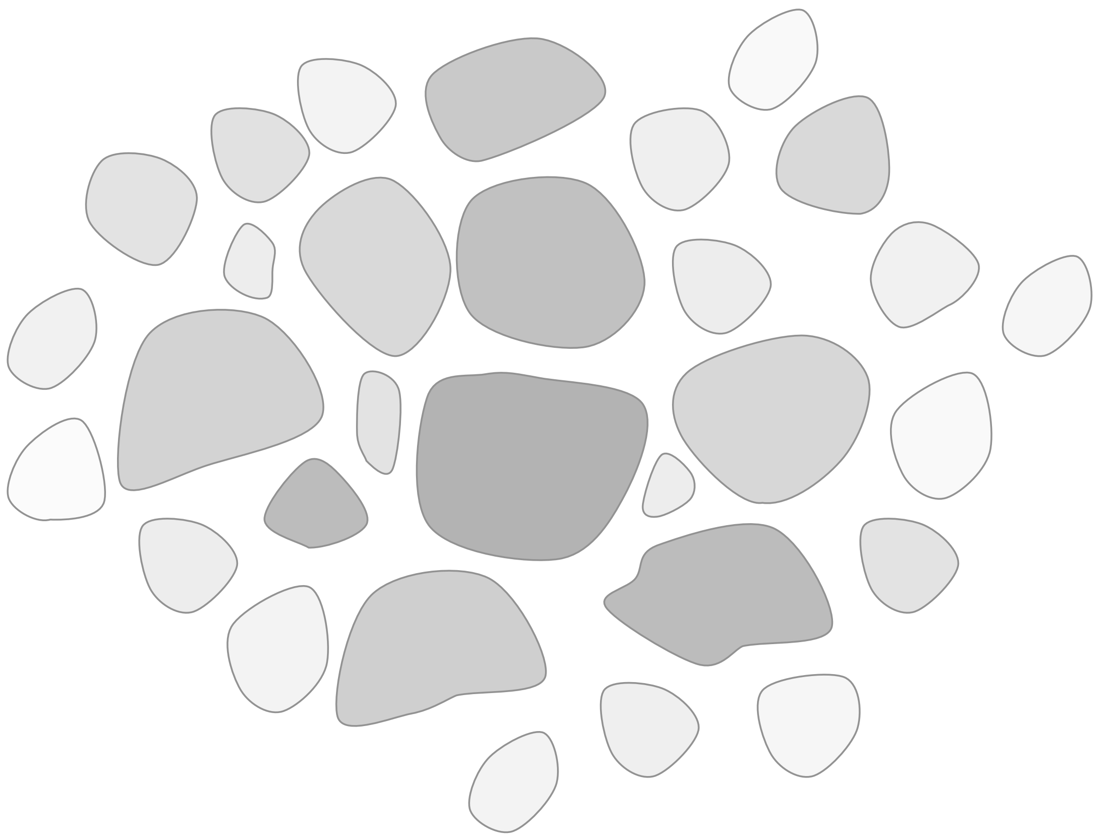
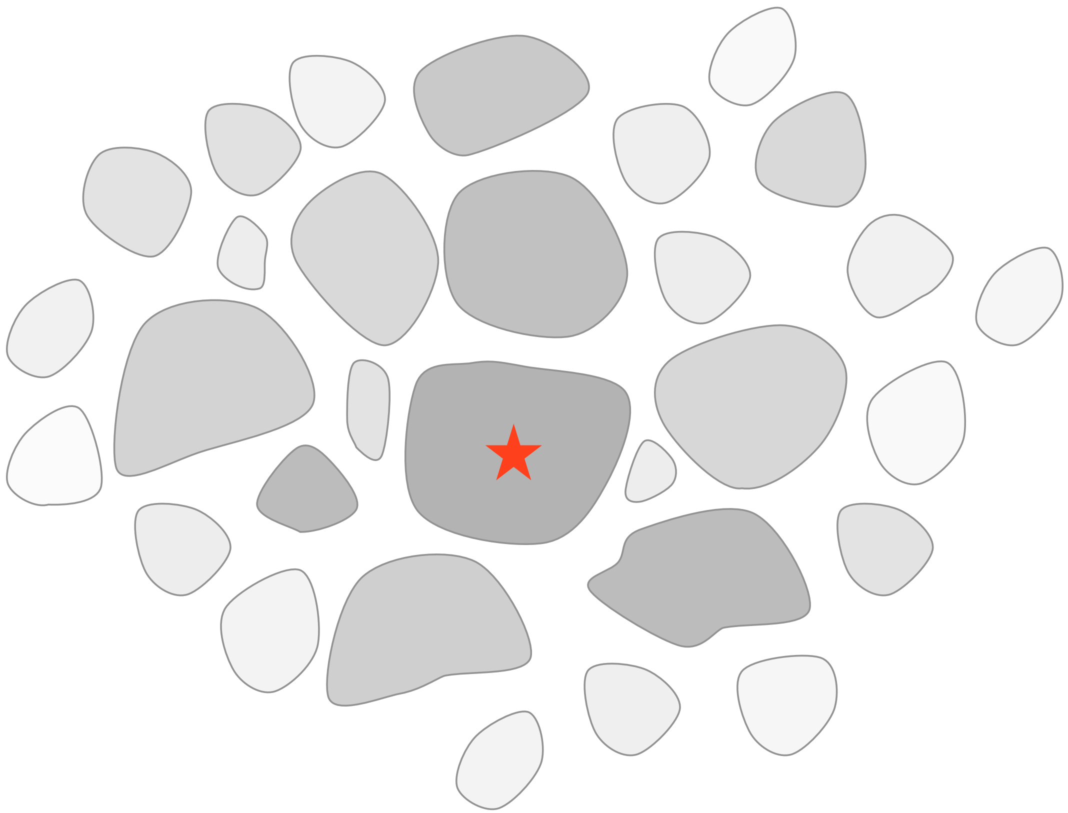


while region contracts, individual clumps collapse to form stars

Zentrum für Astronomie Heidelberg
ARI+ITA+LSW



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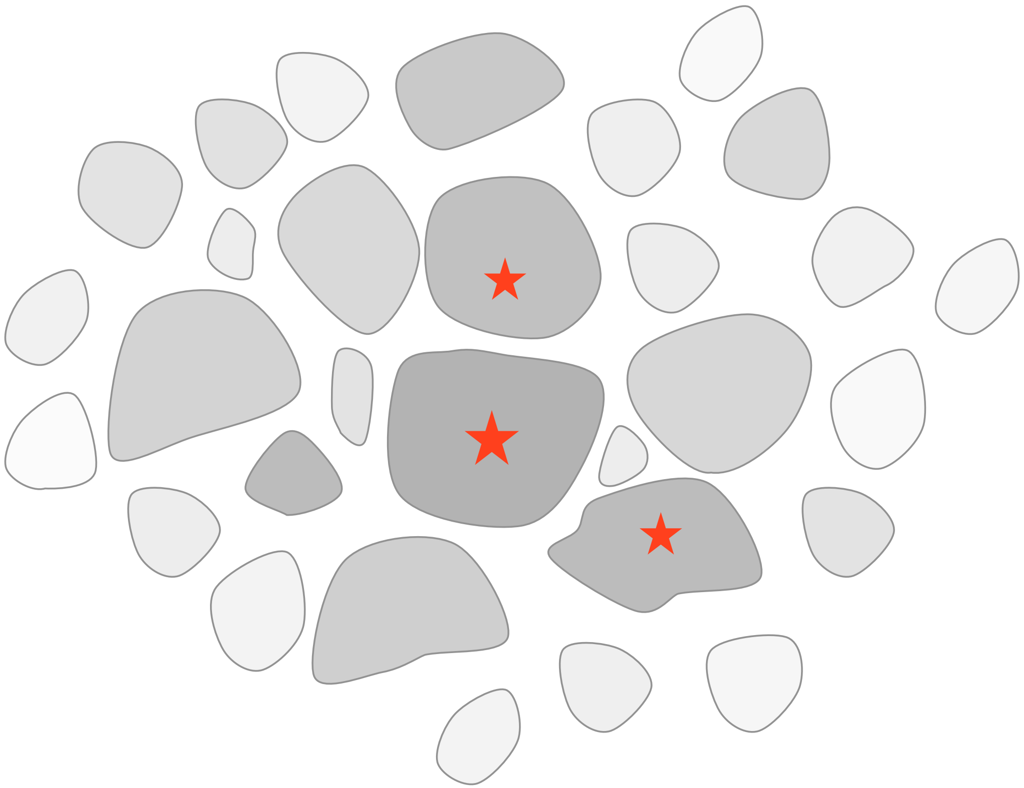

individual clumps collapse to form stars

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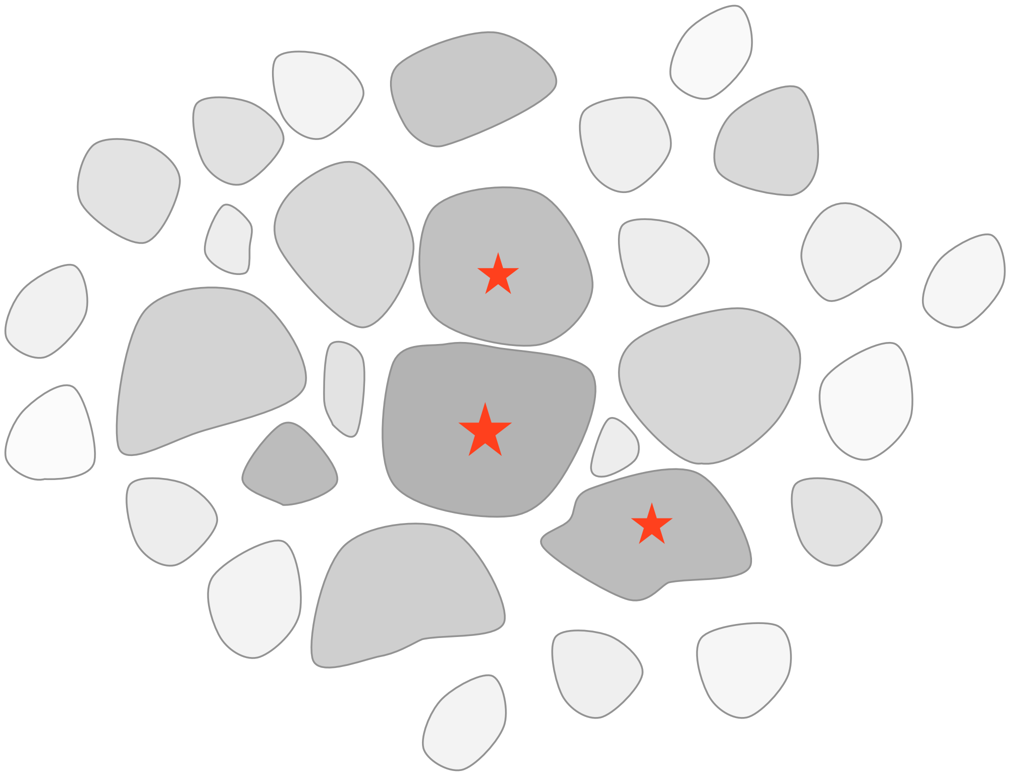
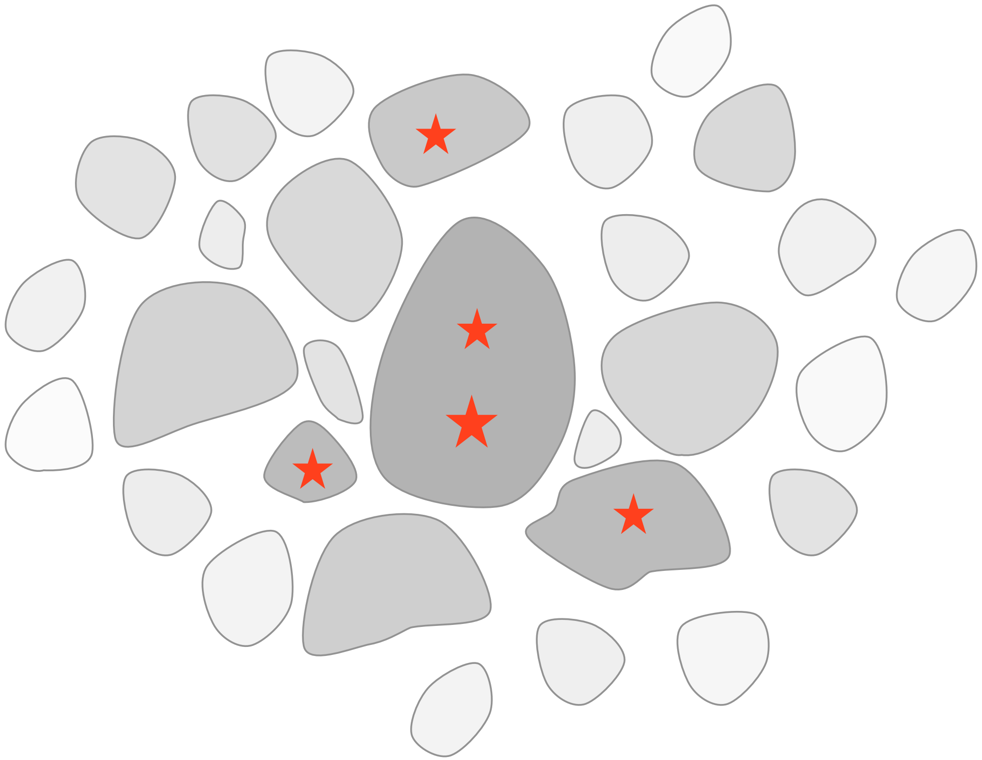
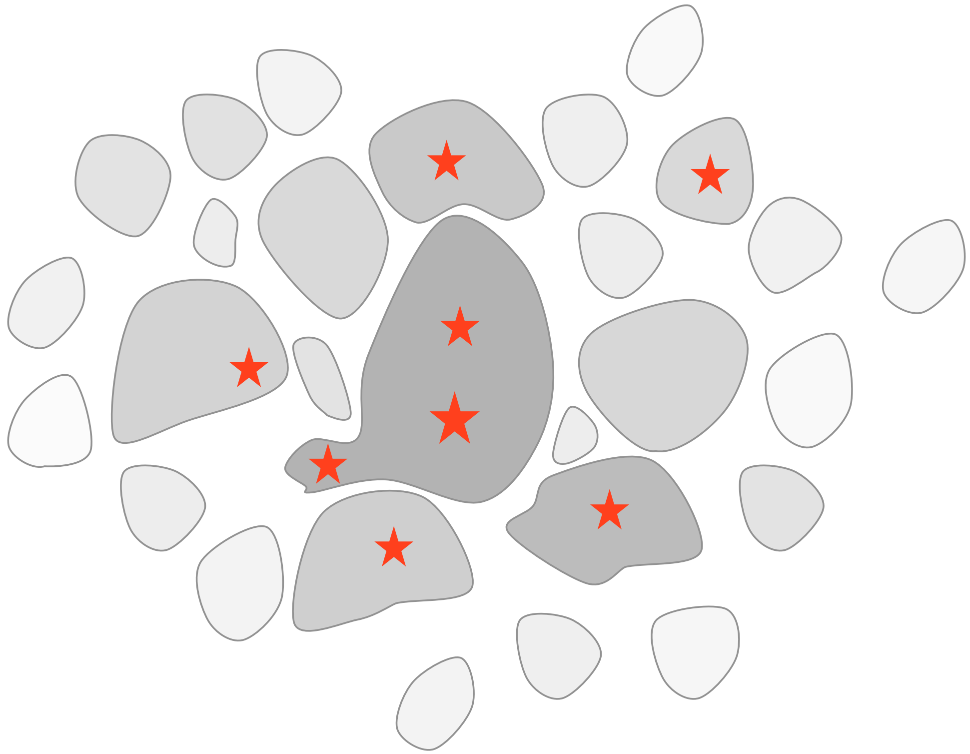


individual clumps collapse to form stars



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

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



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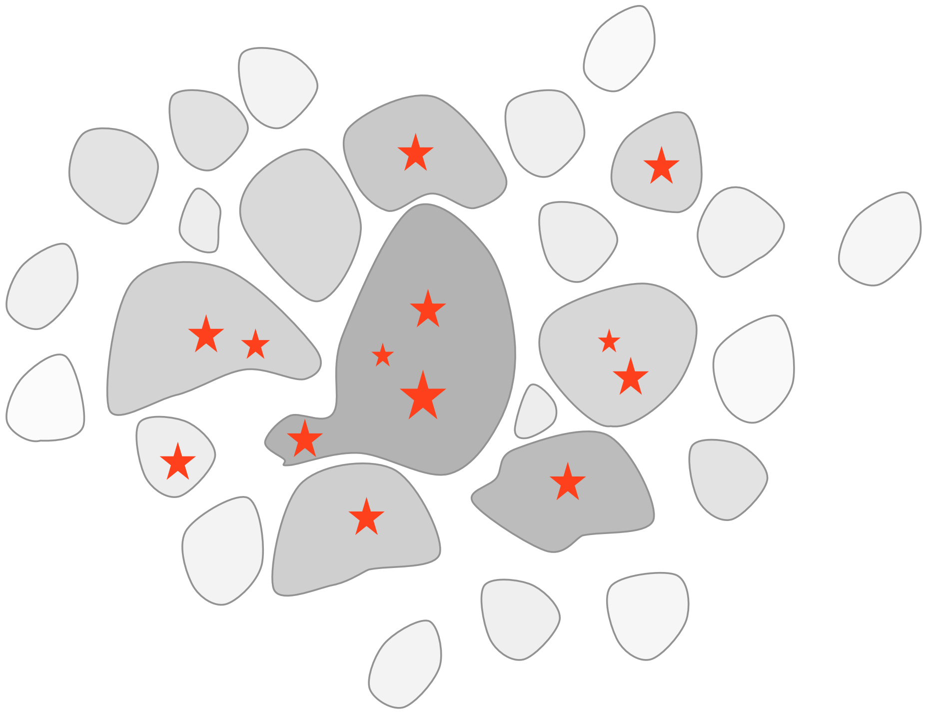

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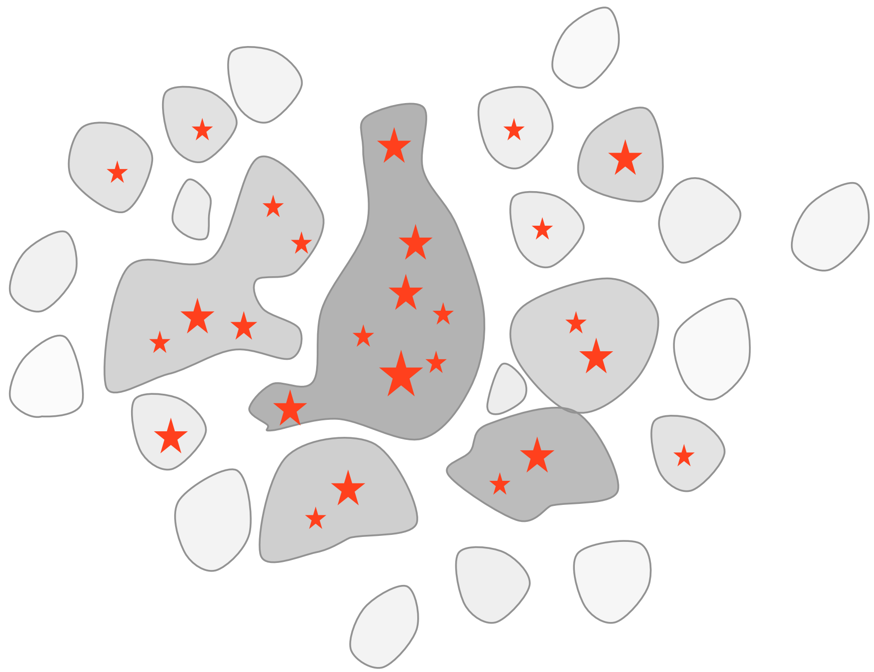
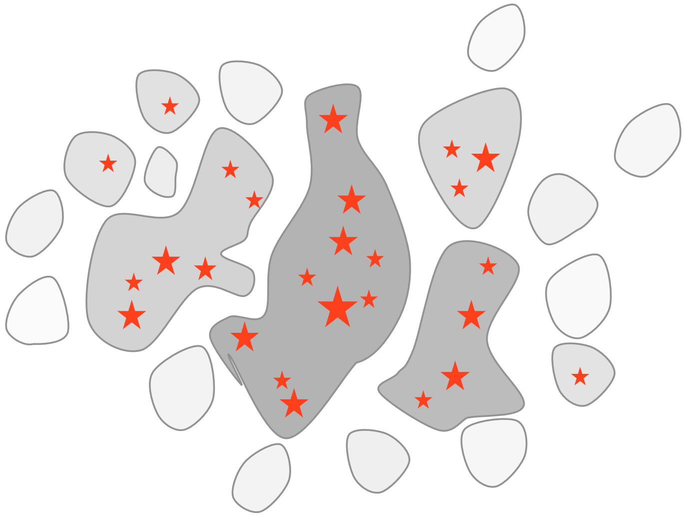


in *dense clusters*, competitive mass growth becomes important



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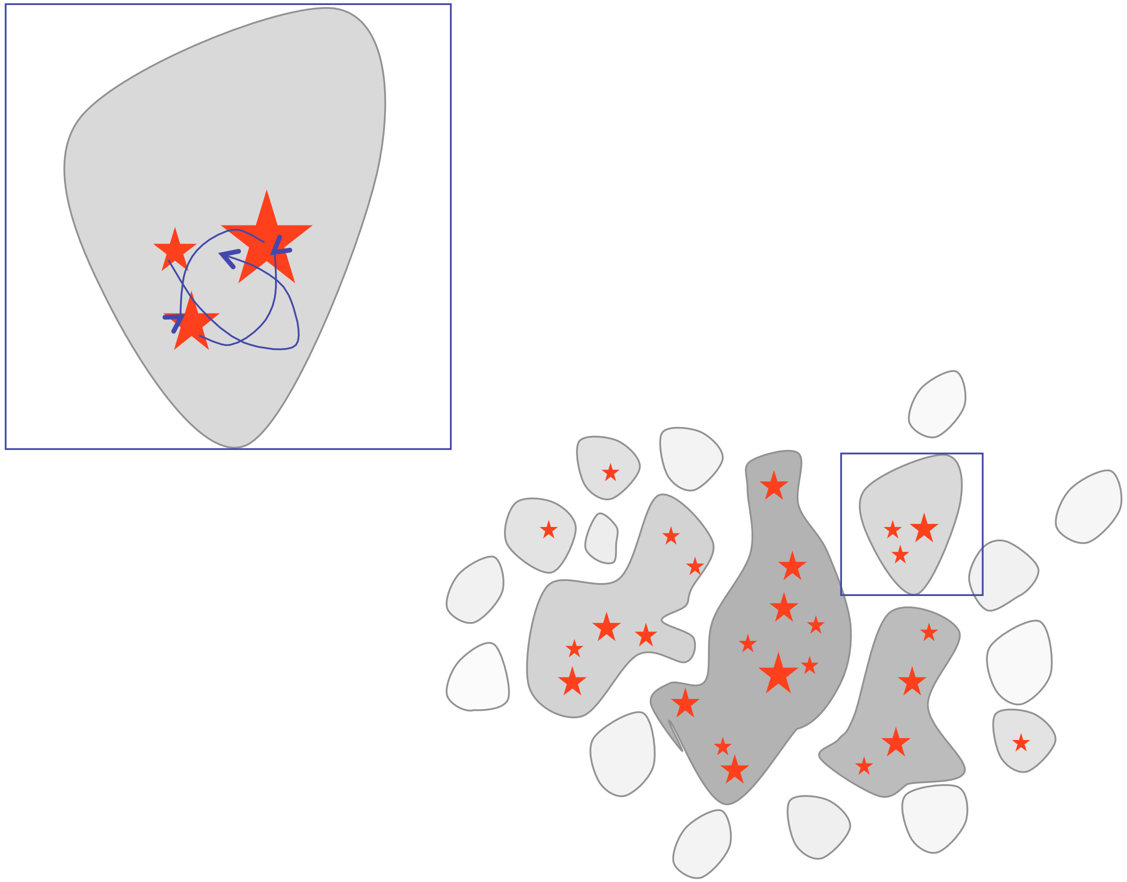
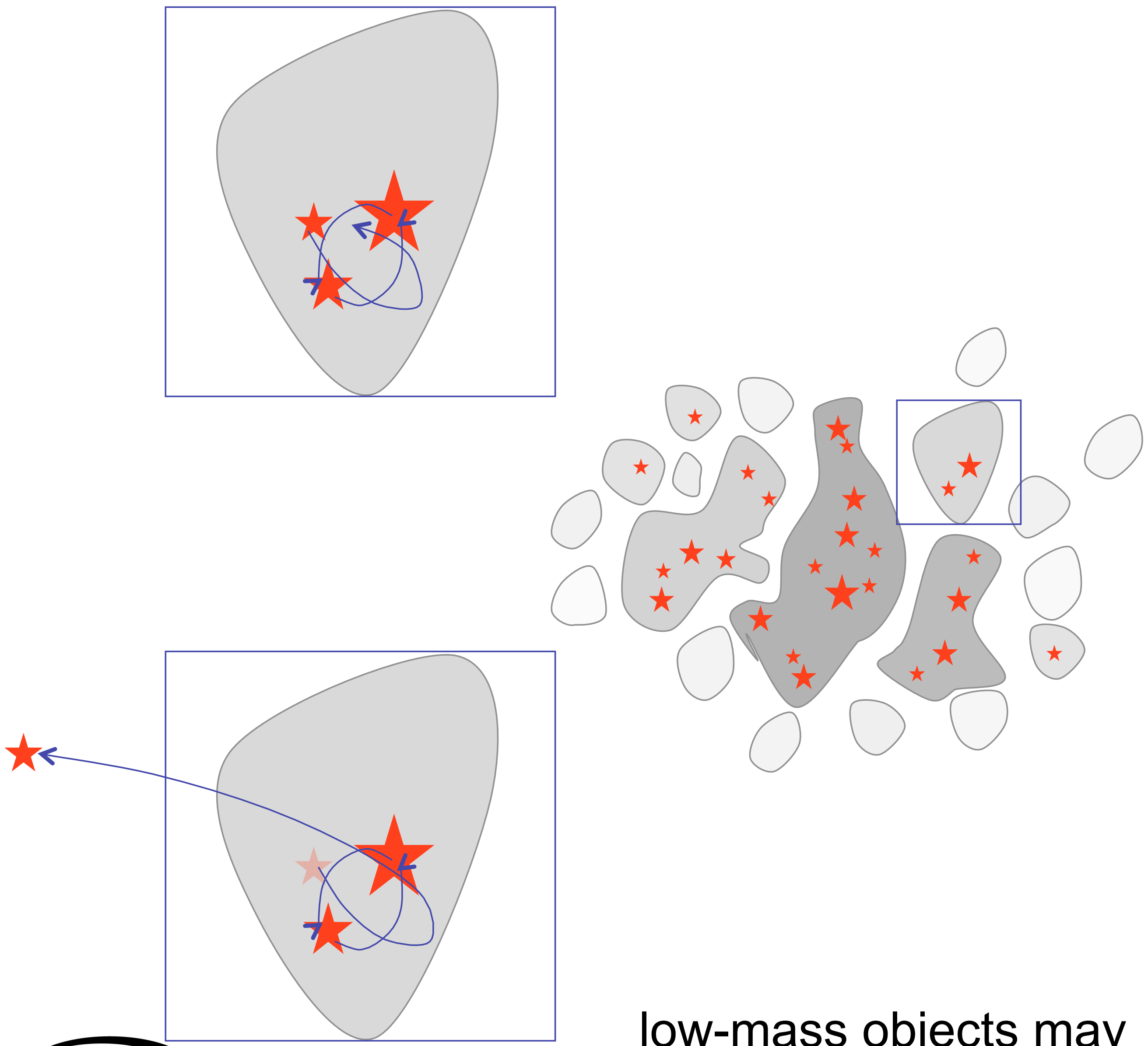
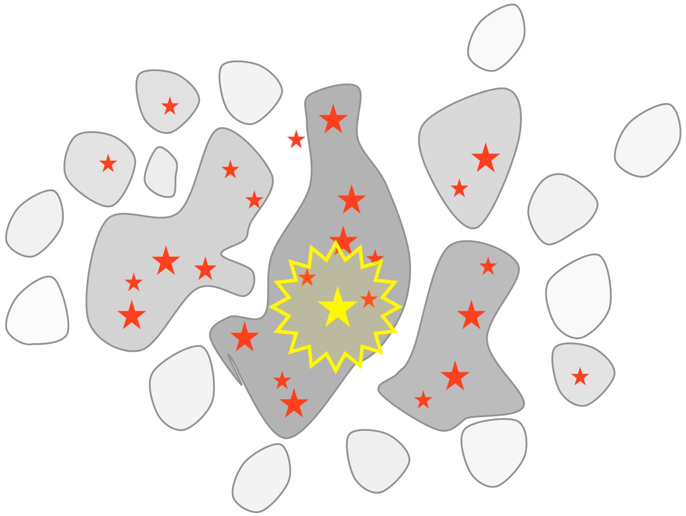


in *dense clusters*, *N*-body effects influence mass growth

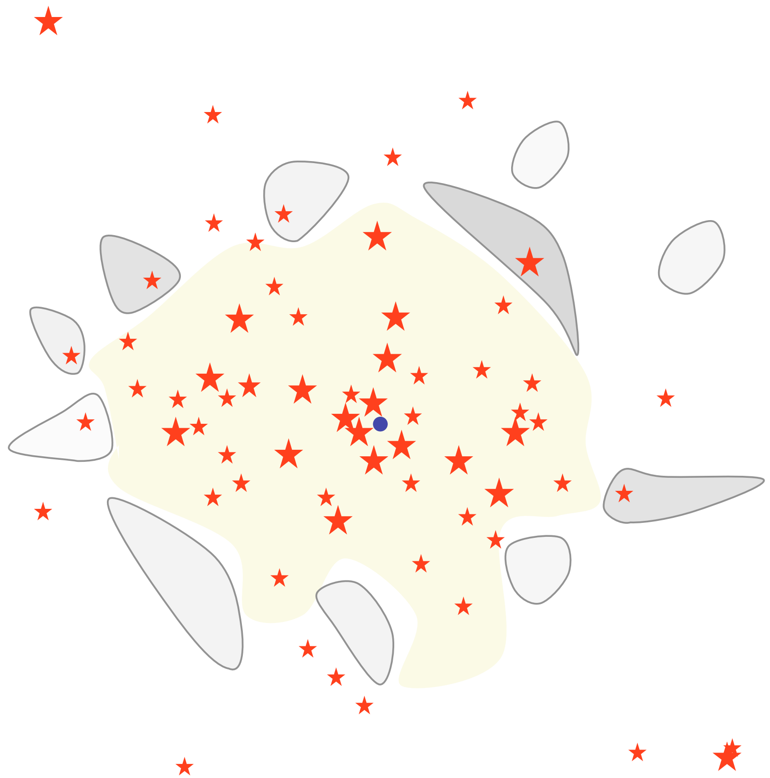


low-mass objects may
become ejected --> accretion stops



feedback terminates star formation

Ralf Klessen: PizzaNight 16.07.2008

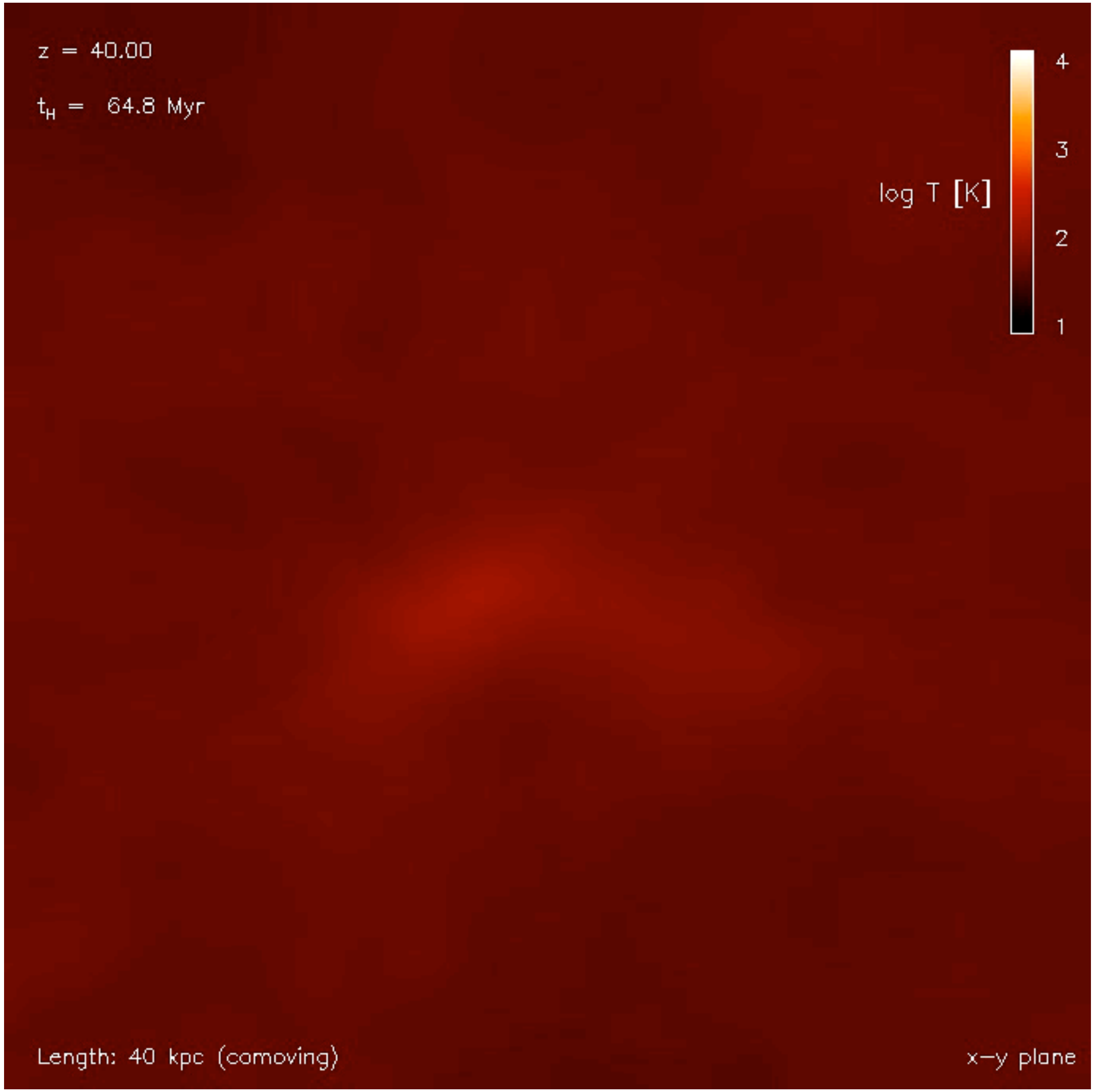


result: *star cluster*, possibly with HII region

Sternentstehung

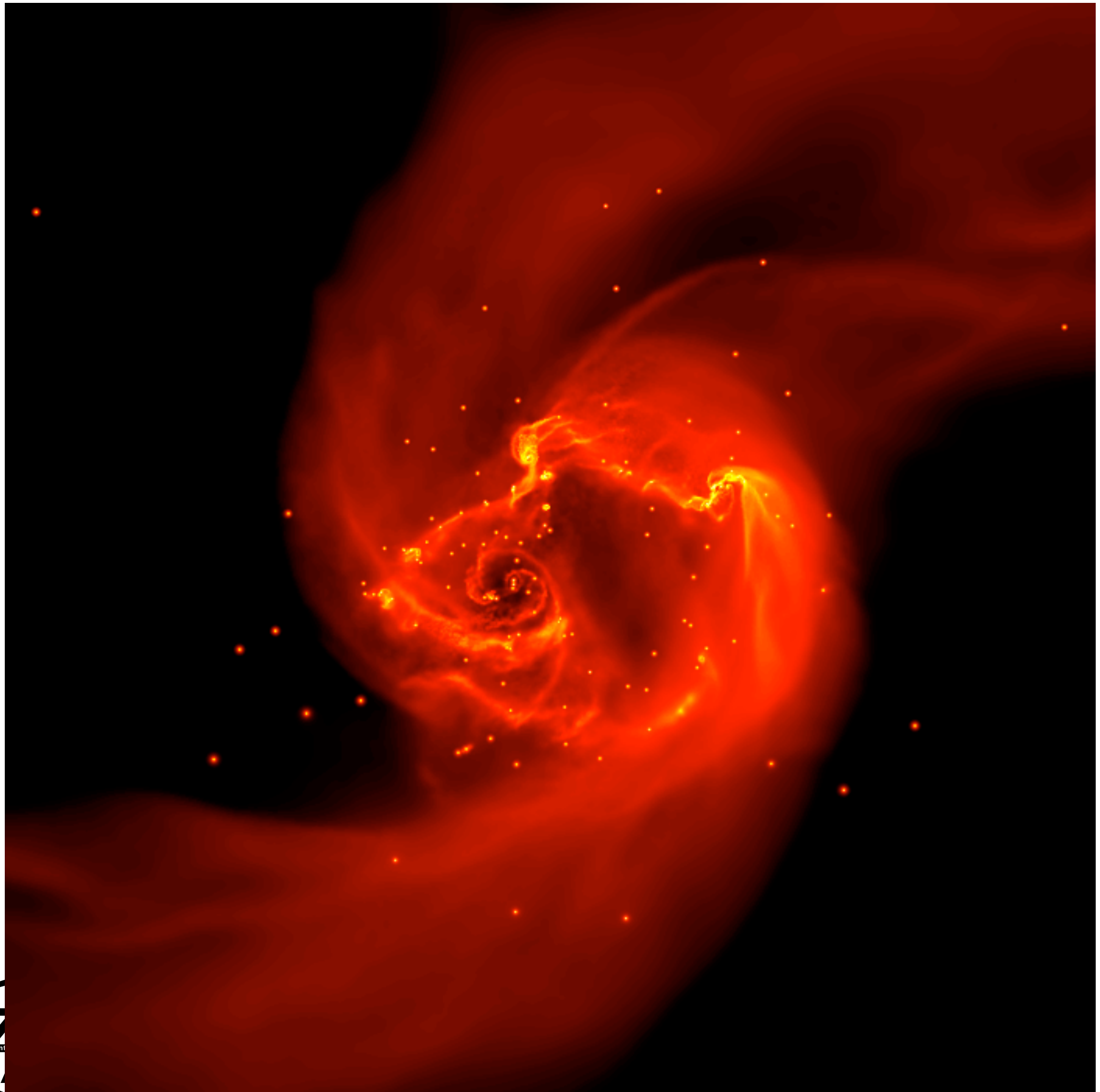
- Dark Stars ...
- First Stars ...
- Second Generation of Stars ...
- Formation of First Galaxies ...
- Star Formation in the Milky Way
- Formation and Evolution of Stellar Clusters
- Formation and Evolution of Star Forming Interstellar Gas Cloud
- Protostellar Collapse: Formation of individual stars and their planetary systems

turbulence developing in an atomic cooling halo



(Greif et al. 2008, MNRAS, 387, 1021)

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

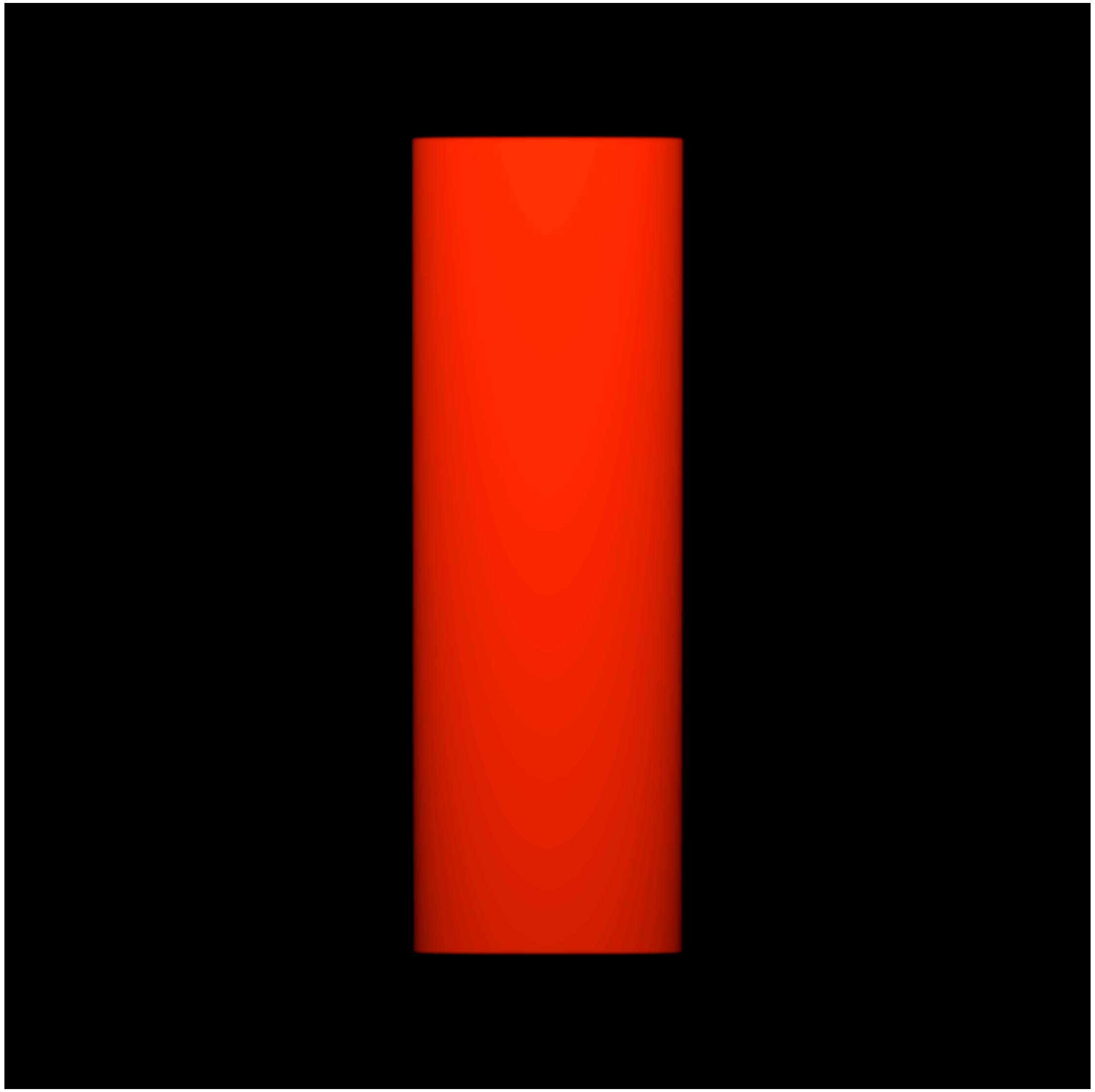


dense cluster of low-mass protostars builds up:

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

(Clark et al. 2008, ApJ 672, 757)

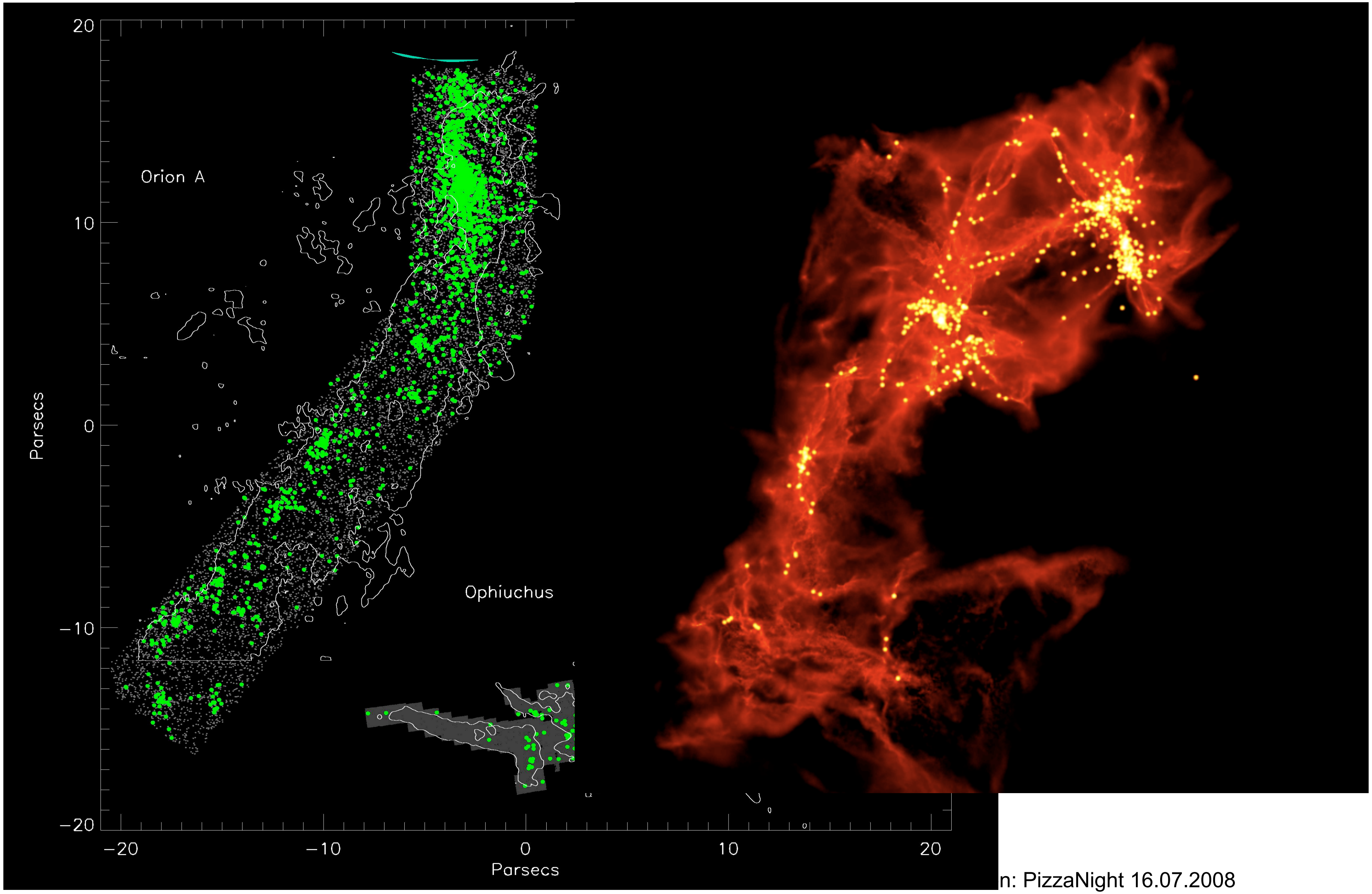
Gravitativer Kollaps in Wolken



Model für die Orion Wolke: $M = 10^4\ M_{sun}$, isotherme Zustandsgleichung, SPH Rechnung

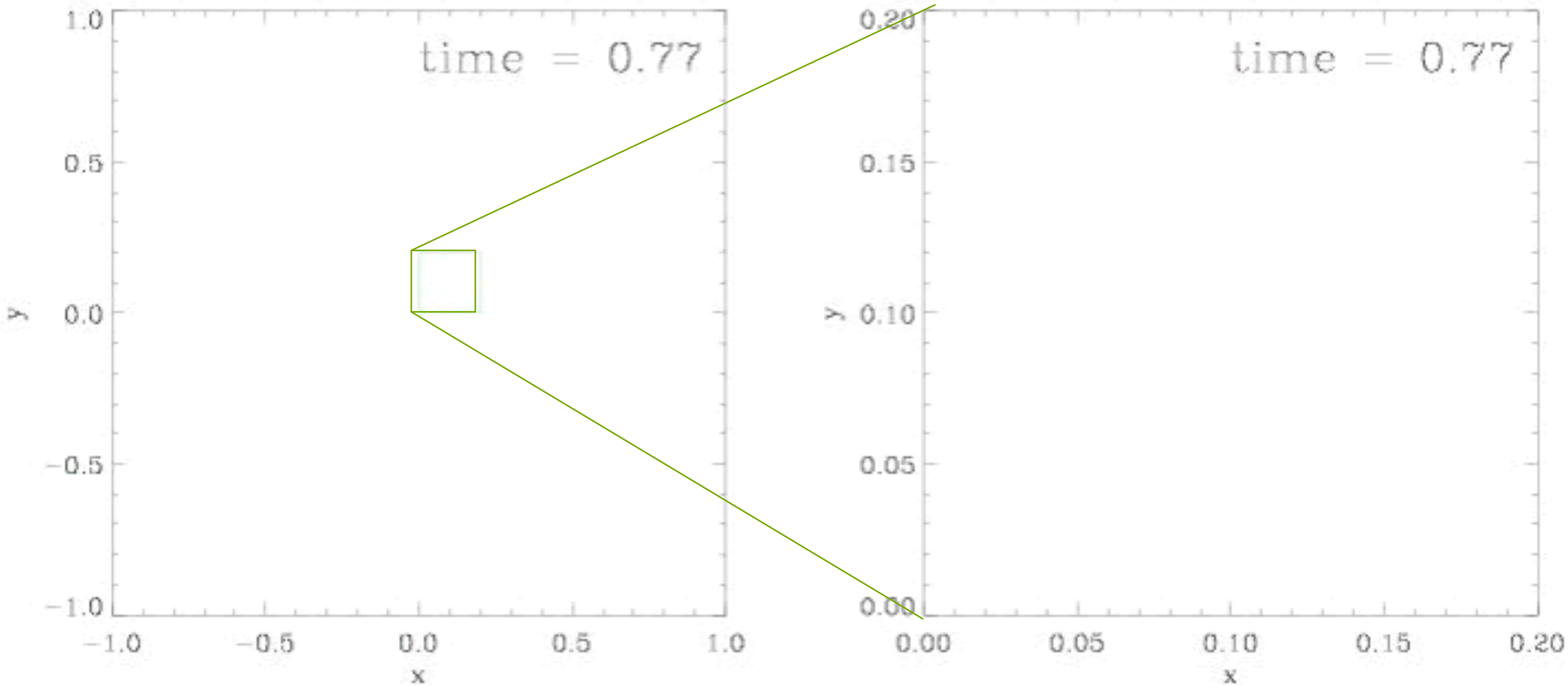
(Bonnell et al. 2006)

Gravitativer Kollaps in Wolken



Dynamics of nascent star cluster

in dense clusters protostellar interaction may be come important!

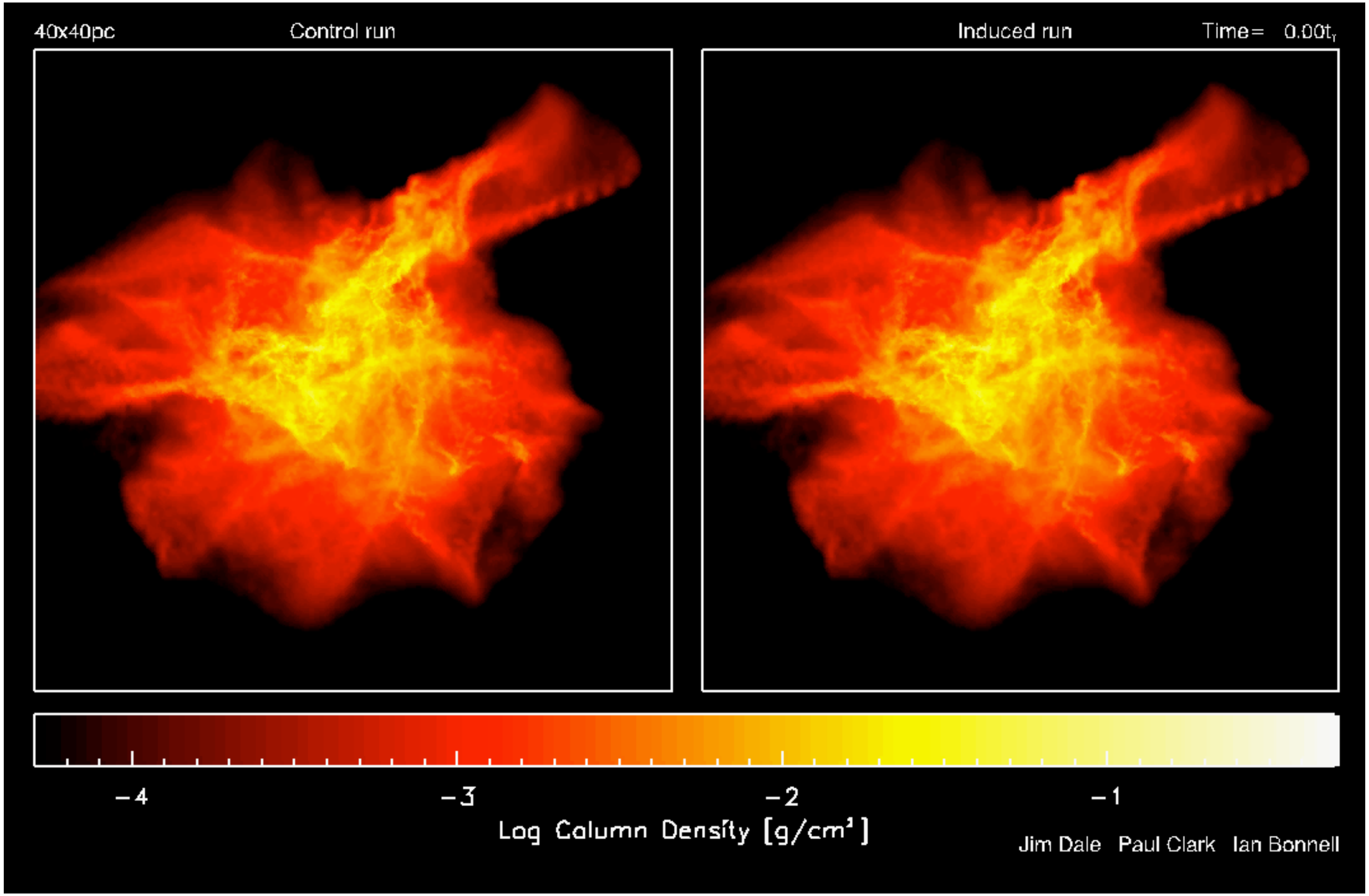


Trajectories of protostars in a nascent dense cluster created by gravoturbulent fragmentation

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

Gravitativer Kollaps in Wolken

Model mit Strahlungseffekten



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- Formation and Evolution of Star Forming Interstellar Gas Cloud
- Protostellar Collapse: Formation of individual stars and their planetary systems

Fragen und Methoden

- Fragen:
  - Wie entstehen und entwickeln sich Planeten?
  - Wie entstehen und entwickeln sich Sterne?
  - Wie entstand die Milchstraße? Was bestimmt die weitere Entwicklung?
  - Wie entstand das Universum?
- ITA:
  - Versuch diese Fragen mit Hilfe theoretischer und numerischer Modelle zu lösen.