Large-Scale Structure of the Molecular Gas in Taurus Revealed by High Spatial Dynamic Range Spectral Line Mapping

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With vital and extensive support from:

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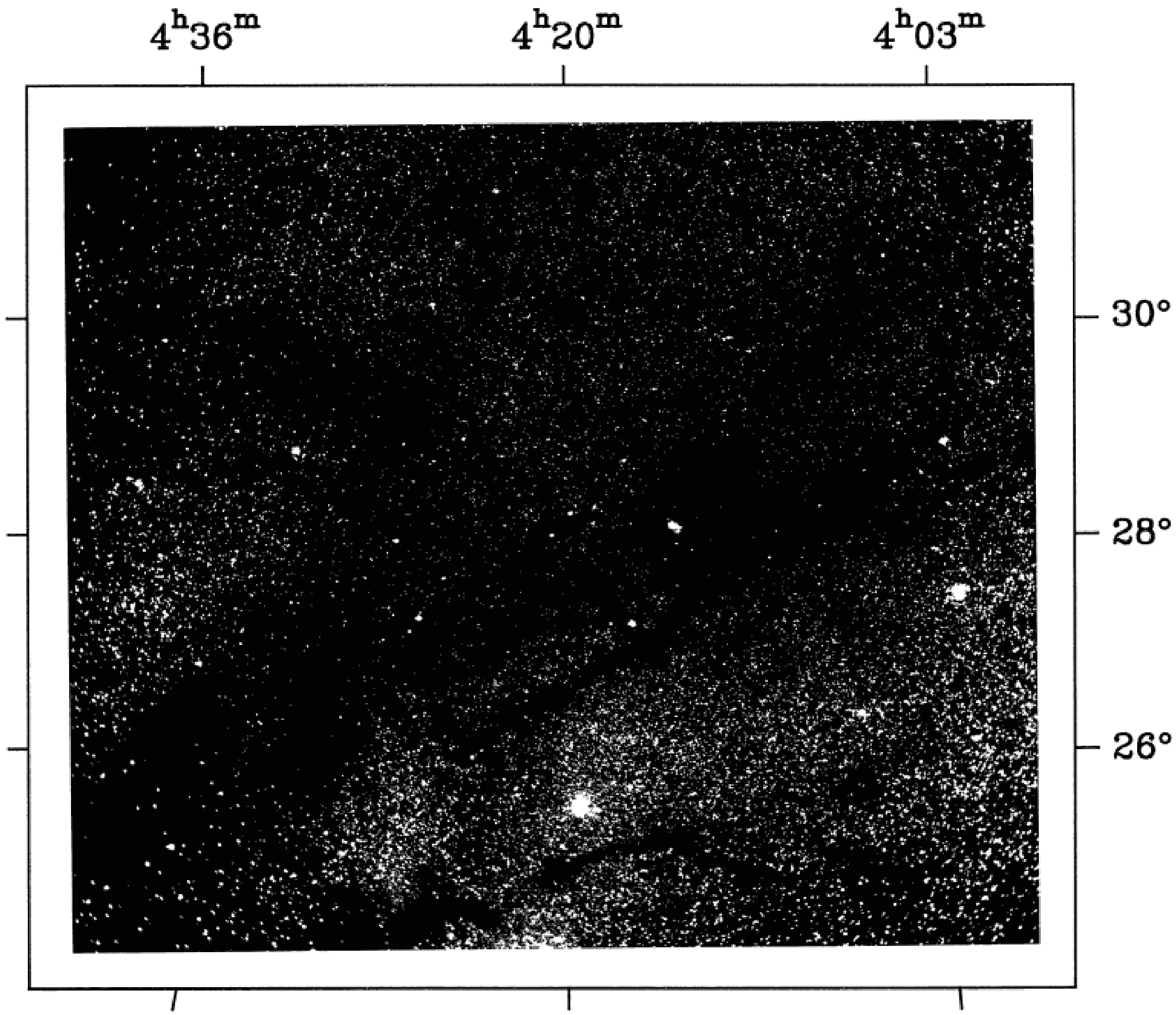
OPTICAL IMAGE OF TAURUS

Taurus has Long Been Recognized as a Nearby Region With a Large Dust Column Density



Duvert, Cernicharo, & Baudry (1986);

from

Barnard (1927)

Dust Extinction in IR Has Provided a New Tool for Probing Cloud Morphology

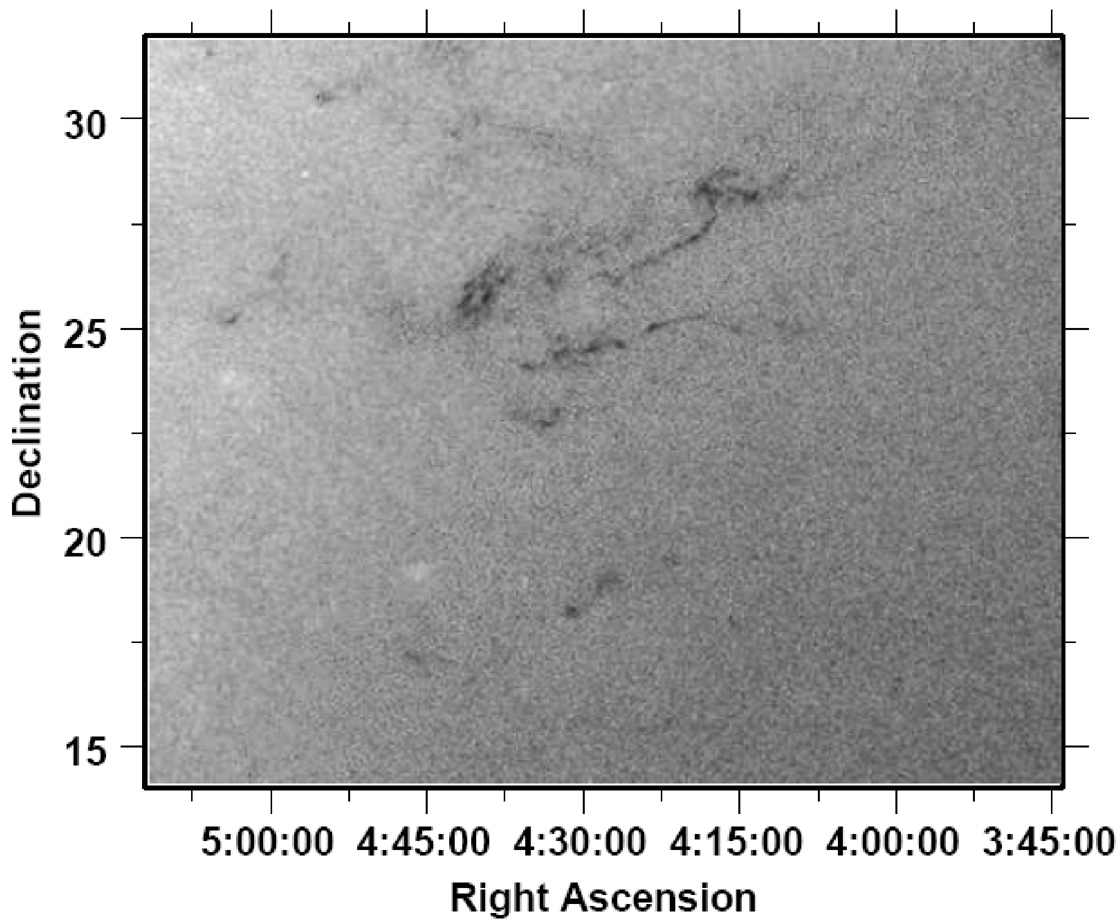


Figure 1. Star count map of the Taurus-Auriga dark clouds. This map was prepared for this paper from stars with J $\leq$ 16.5 in the 2MASS point source catalog downloaded from the IRSA archive. The intensity scale is proportional to the number of stars per square arcmin. The dark clouds are clearly visible as low density regions. Two small bright regions are the open clusters NGC 1647 (RA = 4^h46^m, Dec = 19°) and NGC 1750/1758 (RA = 5^h04^m, Dec = 24°).

Kenyon, Gómez, & Whitney (2007)

Observations of the Gas can Contribute Critical Information on

- **Gas Temperature**
- **Gas Column Density & Distribution**
- **Mass**
- **Kinematics**

Requirements

1. High Angular Resolution to Reveal Important Structures
2. Extended Coverage to Trace Connection Between Small & Large Scale Structure
3. Focal Plane Array on MM Telescopes is the Enabling Technology

The Taurus Molecular Cloud Complex: The Big Picture

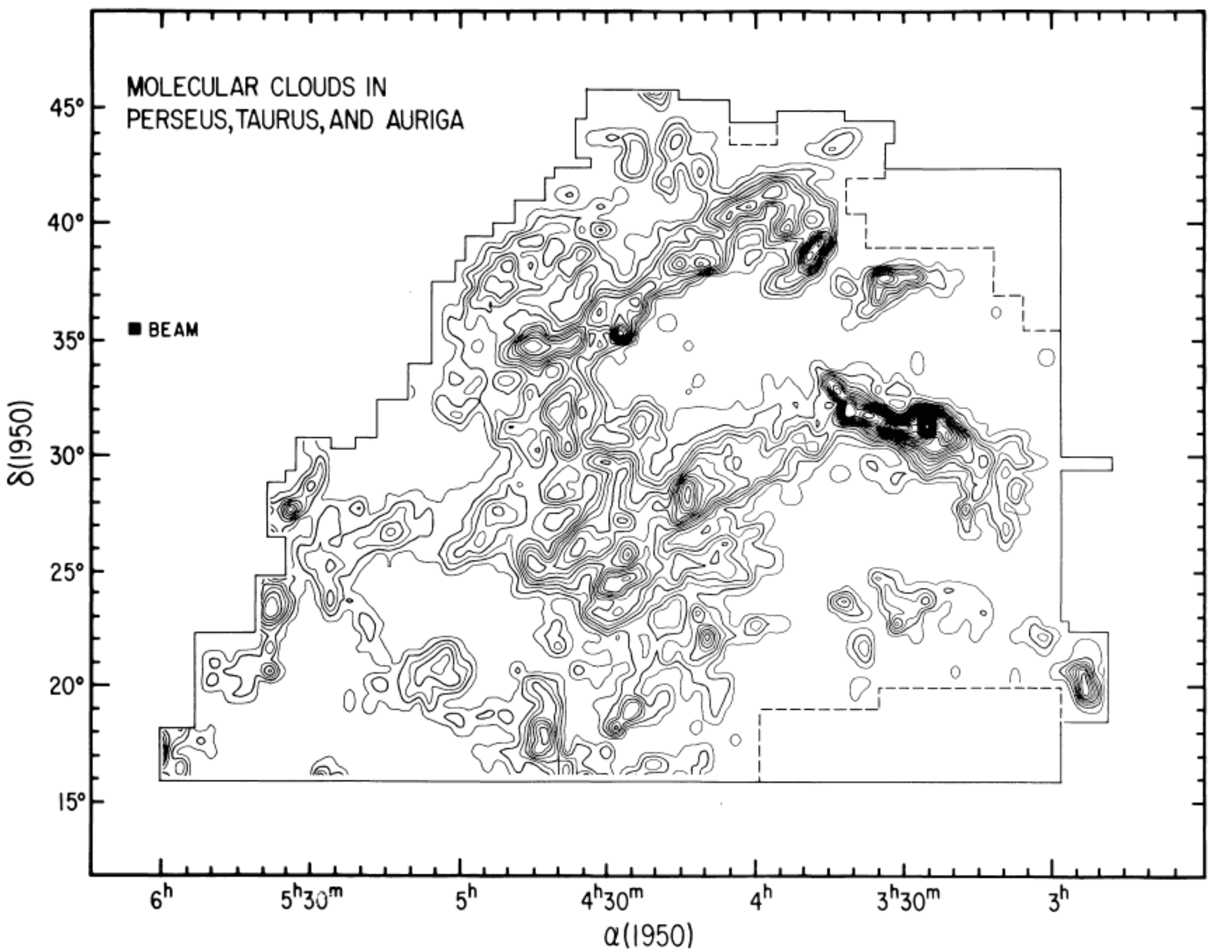
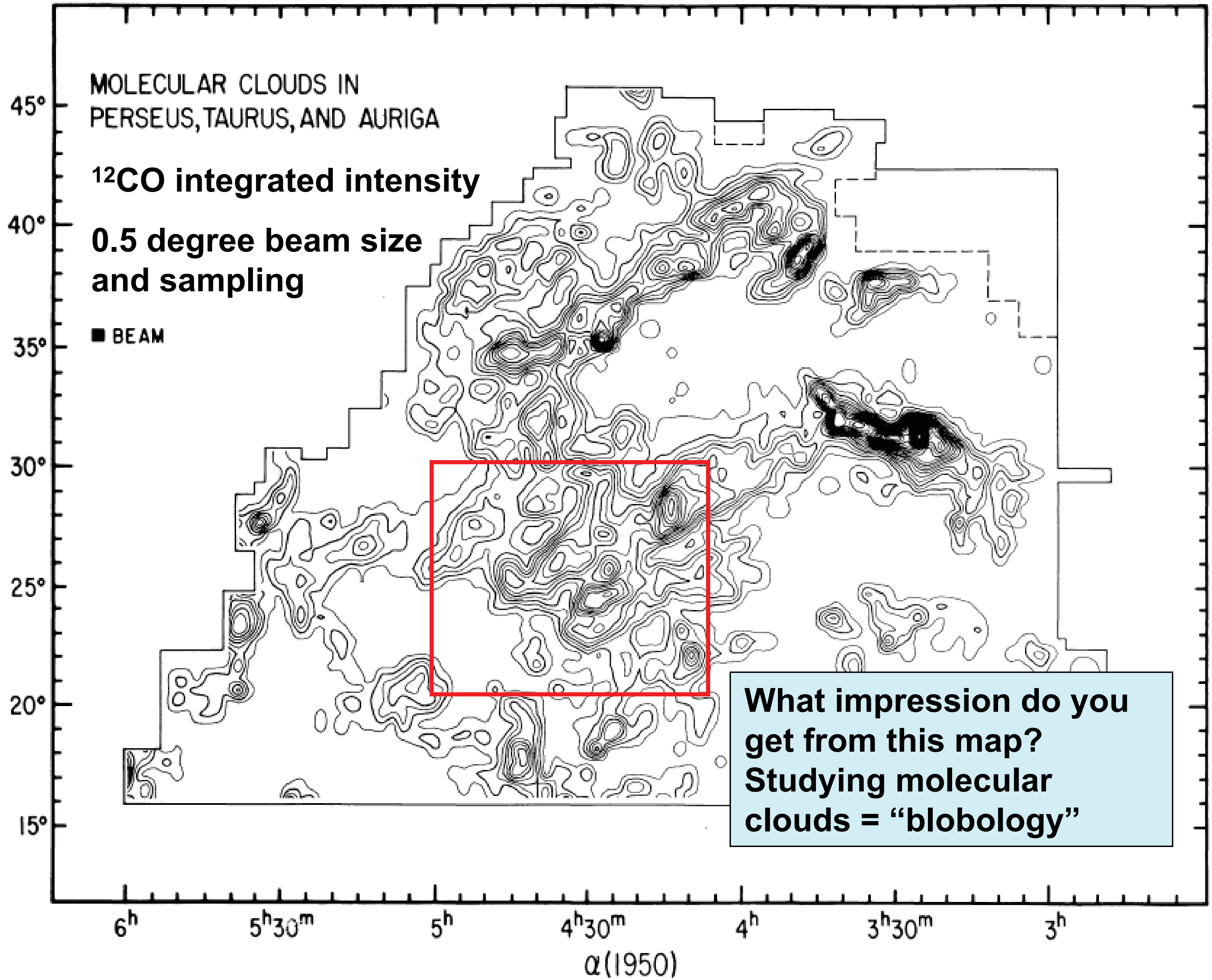


FIG. 1.—Velocity-integrated intensity of CO emission, W_{CO}. The lowest contour is 0.5 K km s^{-1}, and the separation between contours is 1.5 K km s^{-1}. The border of the surveyed region is indicated by the outer, solid line; in the small regions beyond the dashed line the map is undersampled, with a spacing of $4^m \times 1°$.

Ungerechts & Thaddeus 1987 ApJS

Distance = 140 pc

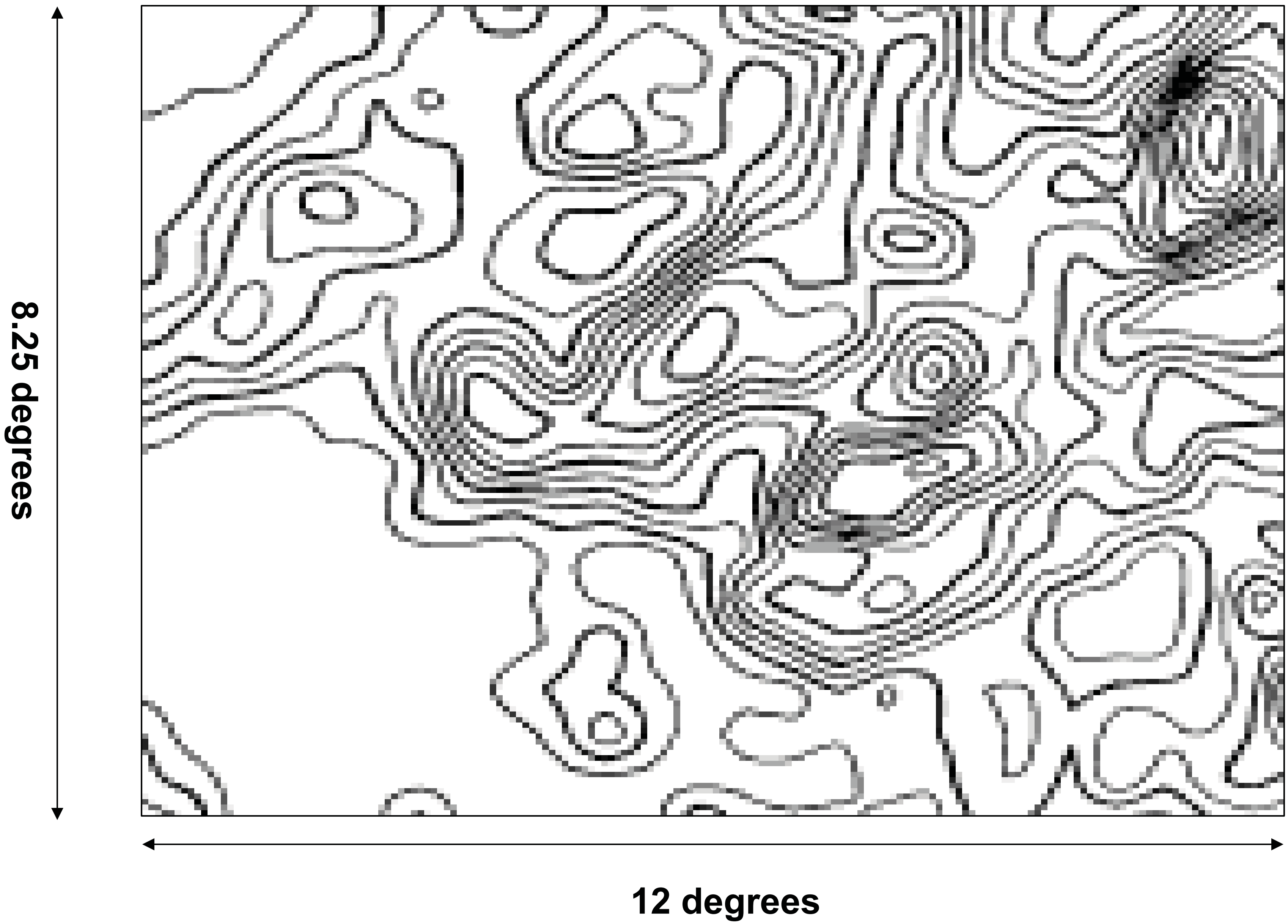
1 deg = 2.4 pc

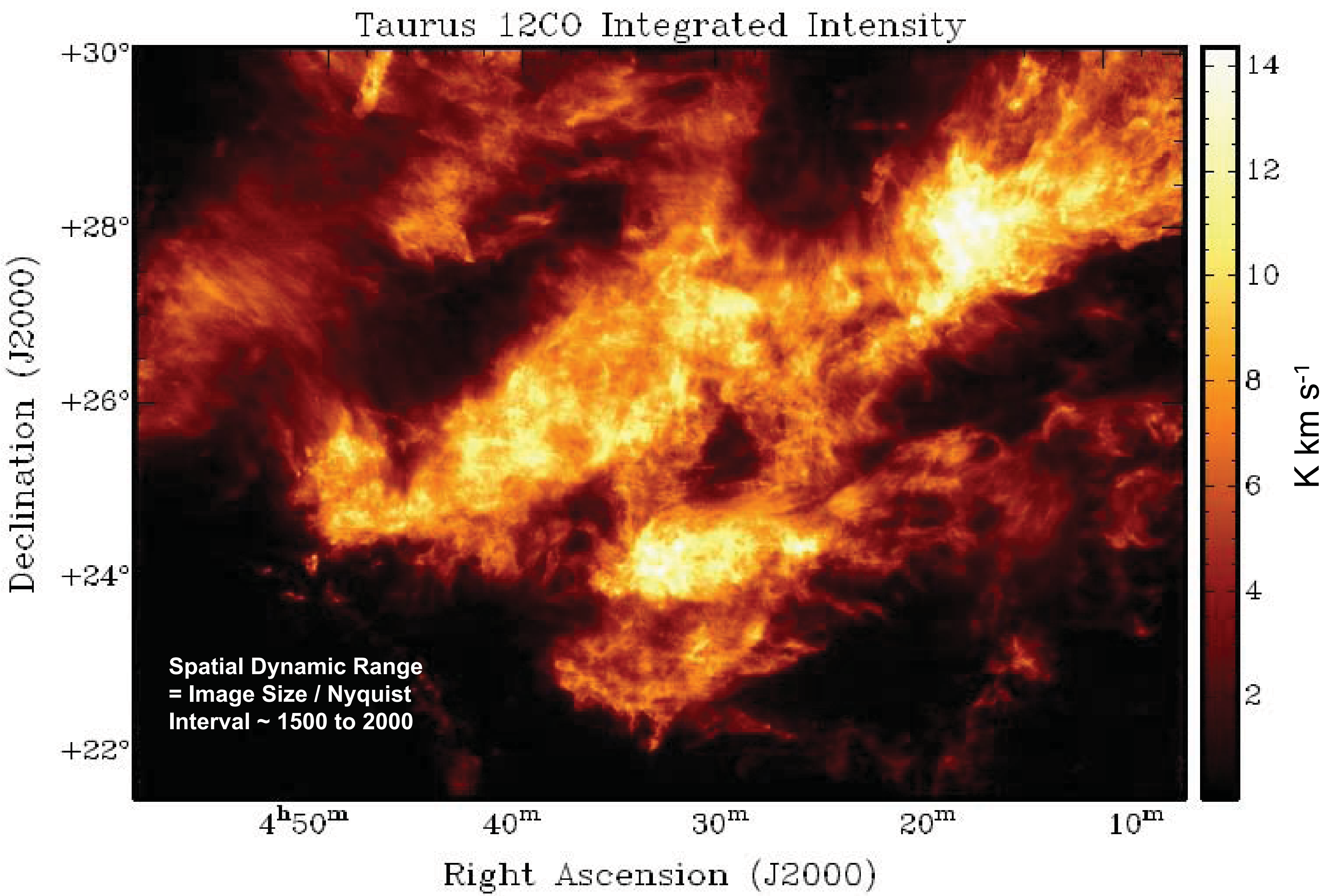


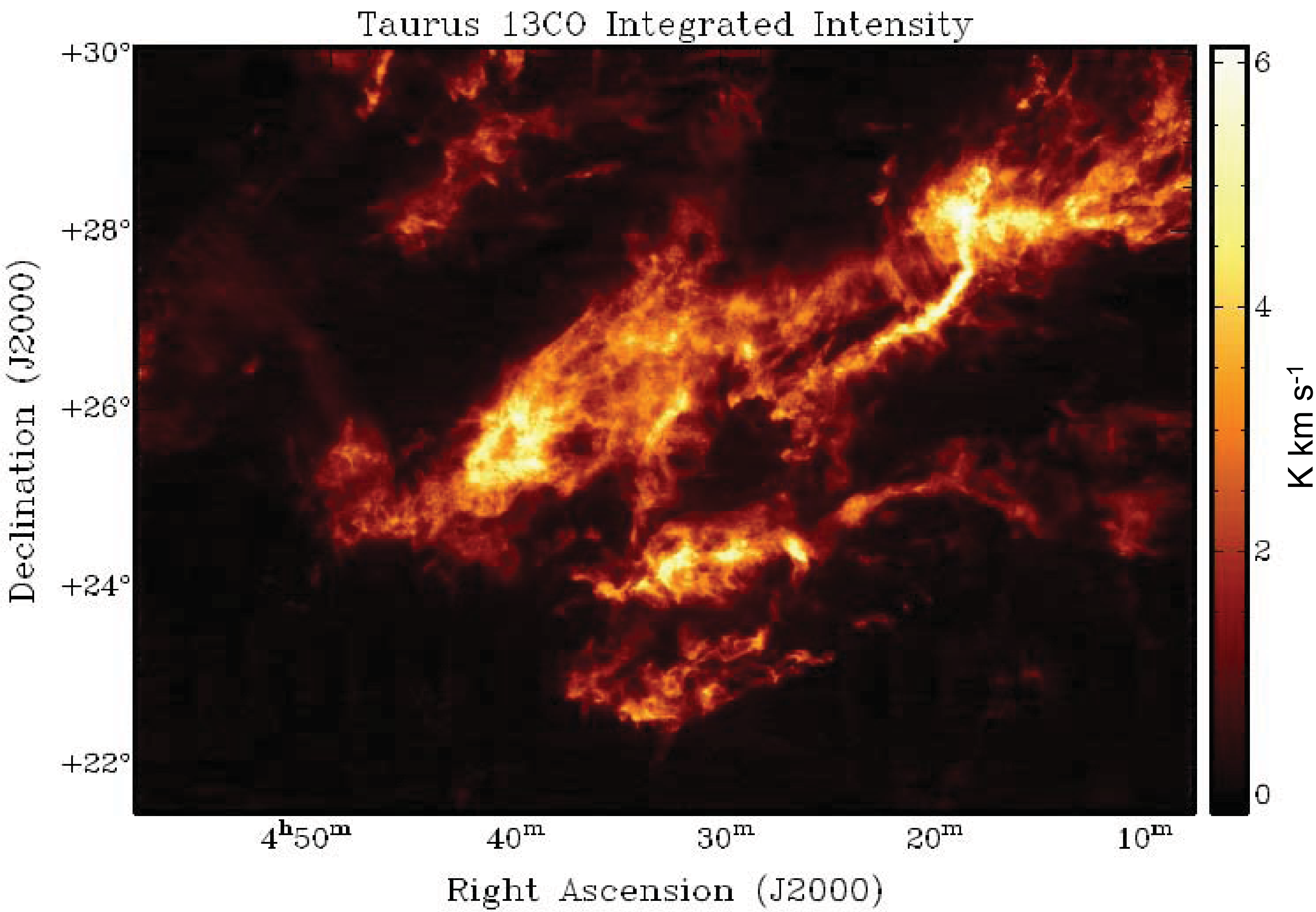
^{12}CO integrated intensity

0.5 degree beam size and sampling

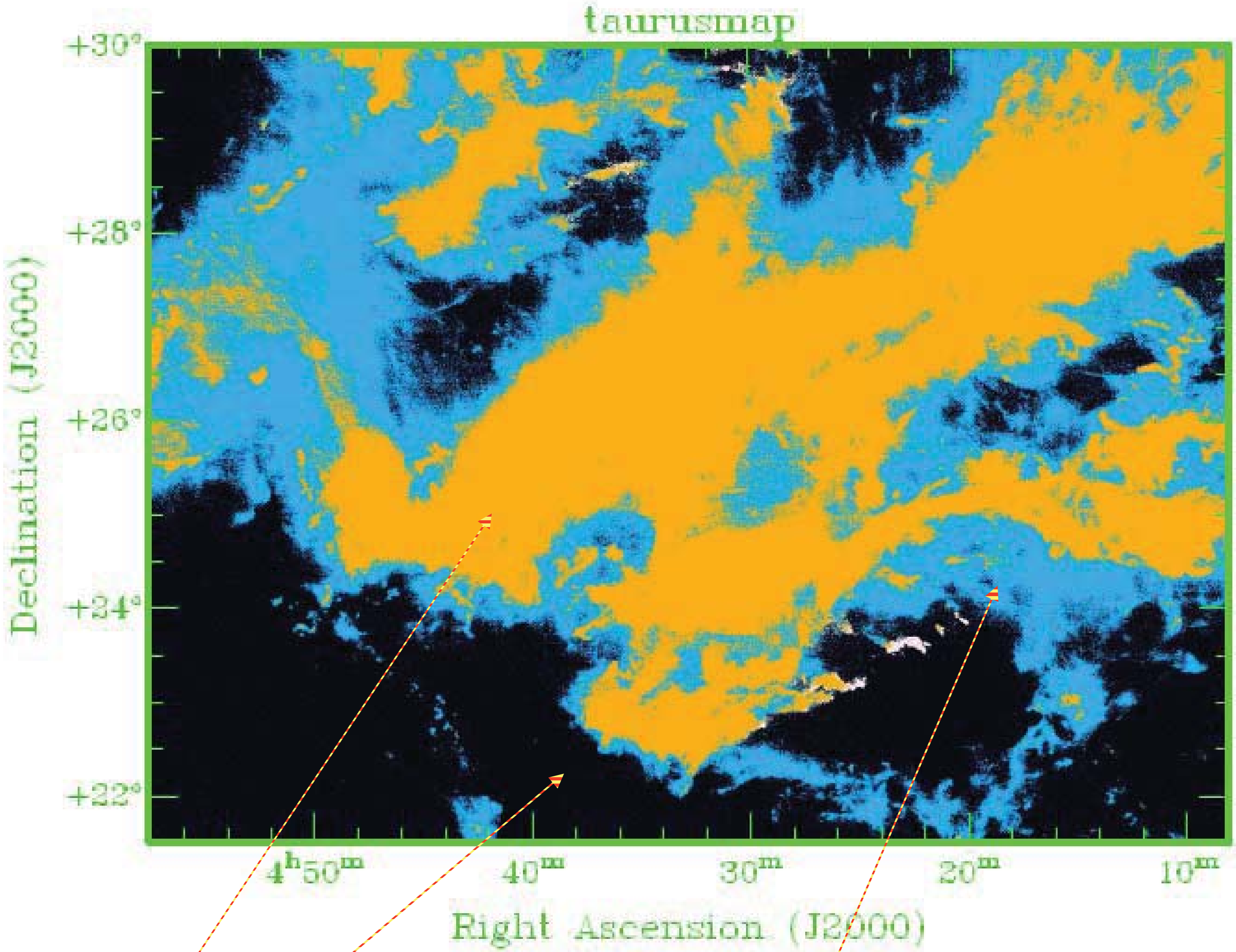
What impression do you get from this map? Studying molecular clouds = "blobology"


8.25 degrees
12 degrees


Taurus 12CO Integrated Intensity
Declination (J2000)
+30°
+28°
+26°
+24°
+22°
Right Ascension (J2000)
4h50m
40m
30m
20m
10m
K km s-1
14
12
10
8
6
4
2
Spatial Dynamic Range
= Image Size / Nyquist
Interval ~ 1500 to 2000

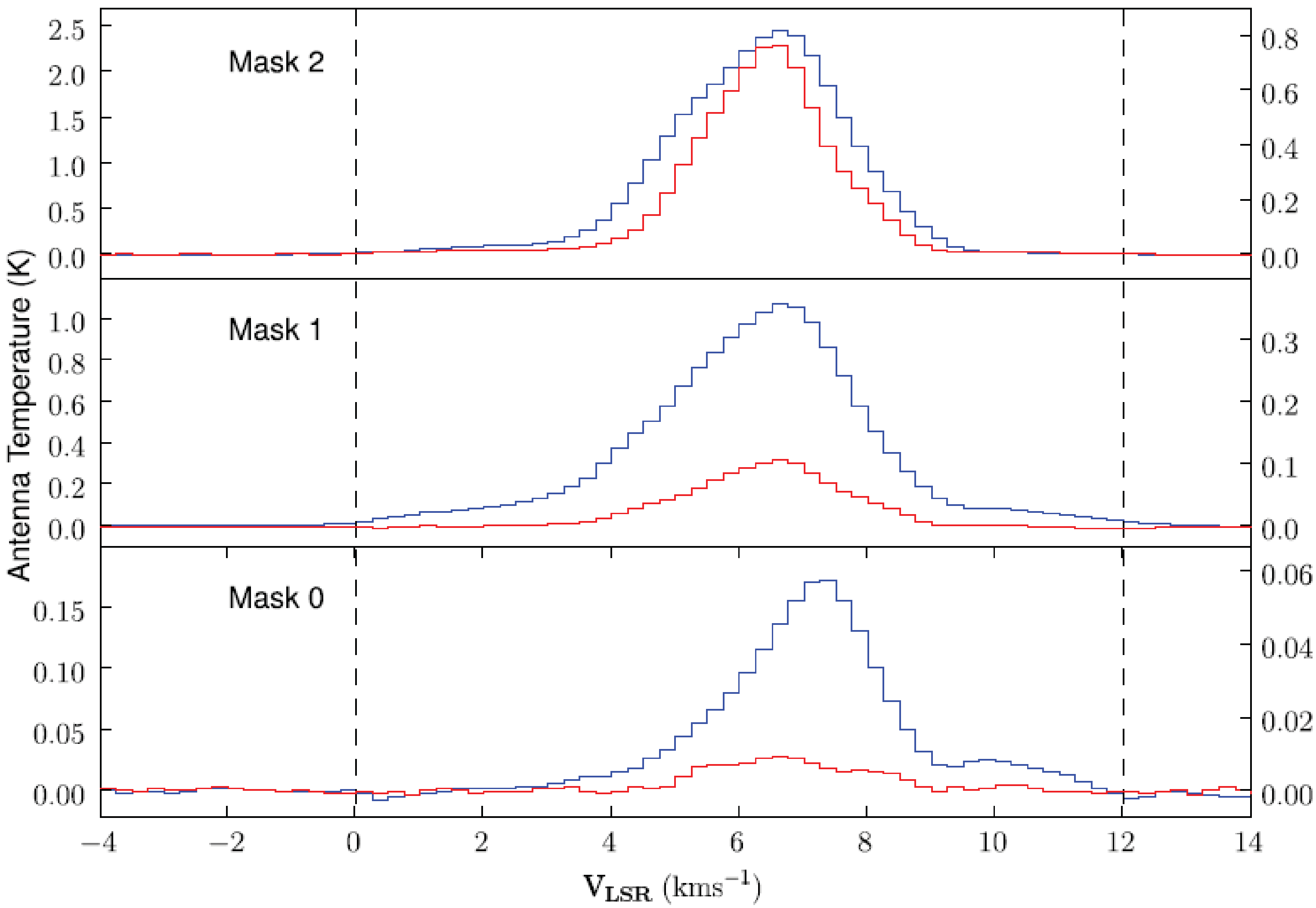


Taurus 13CO Integrated Intensity
+30°
+28°
+26°
+24°
+22°
Declination (J2000)
4h50m
40m
30m
20m
10m
Right Ascension (J2000)
6
4
2
0
K km s-1



Mask 2 ^{12}CO & ^{13}CO detected; **Mask 1** ^{12}CO but not ^{13}CO detected; **Mask 0** neither isotopologue detected in individual pixels

Average Spectra in Each Mask Region



Mask 2 Data

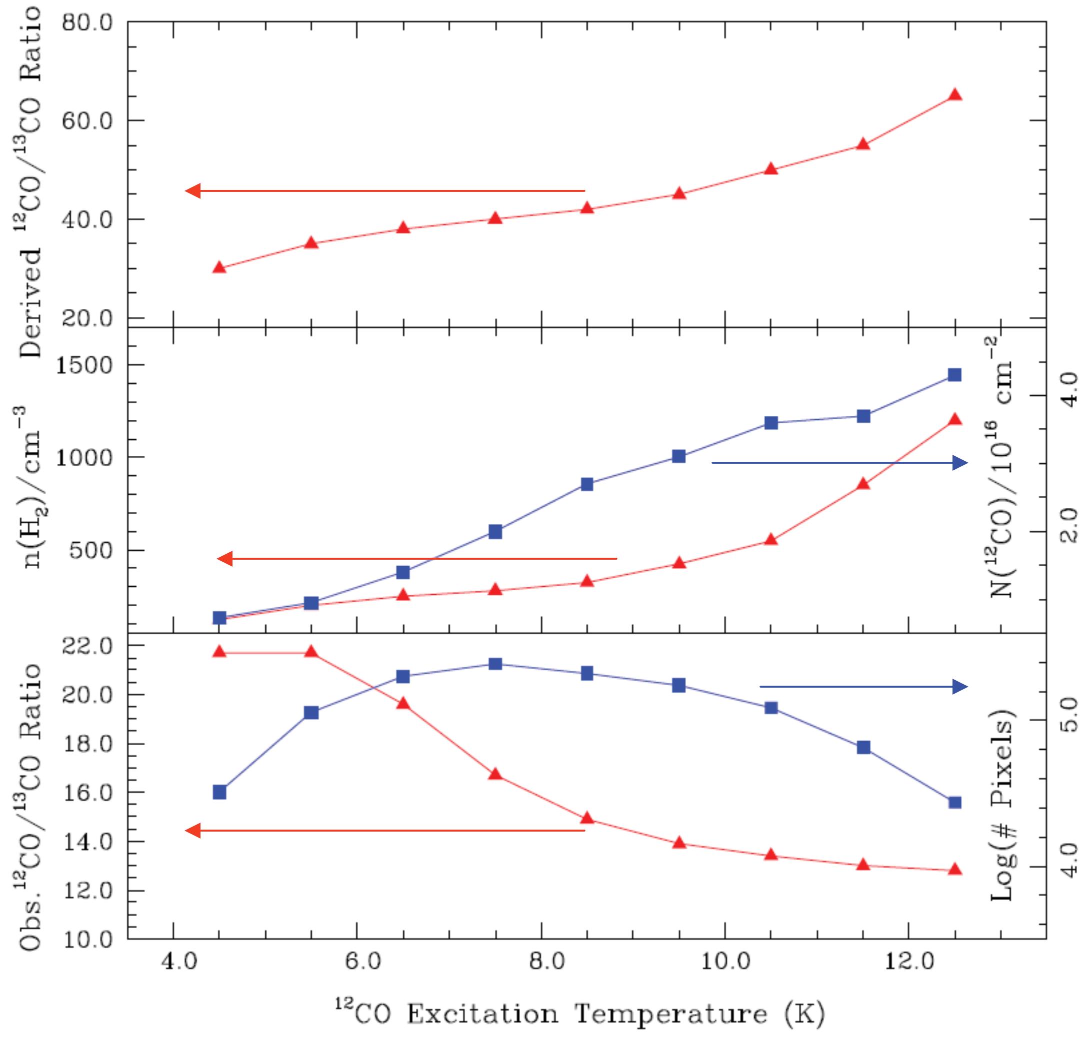
- Both isotopologues in each pixel (“standard” cloud mapping situation)
- Find T_{ex} from max $\{^{12}CO\}$
- Assume LTE so this directly yields T_{kin}
- Determine $\tau(^{13}CO)$, R $(^{12}CO/^{13}CO)$ and thus the column densities of both isotopologues

Dealing with Mask 1 Data

- **Bin** pixels by excitation temperature and average spectra within each bin
- ^{13}CO as well as ^{12}CO then detected (30,000 – 200,000 pixels in each bin)
- Use data for both isotopologues with LVG model to determine $n(H_2)$ and N(CO) per bin

  T_{kin} specified to be 15 K
- The result is a relationship between N(CO) and T_{ex} and thus between $T(^{12}CO)$ and N(CO)

Behavior of Mask 1 Pixels

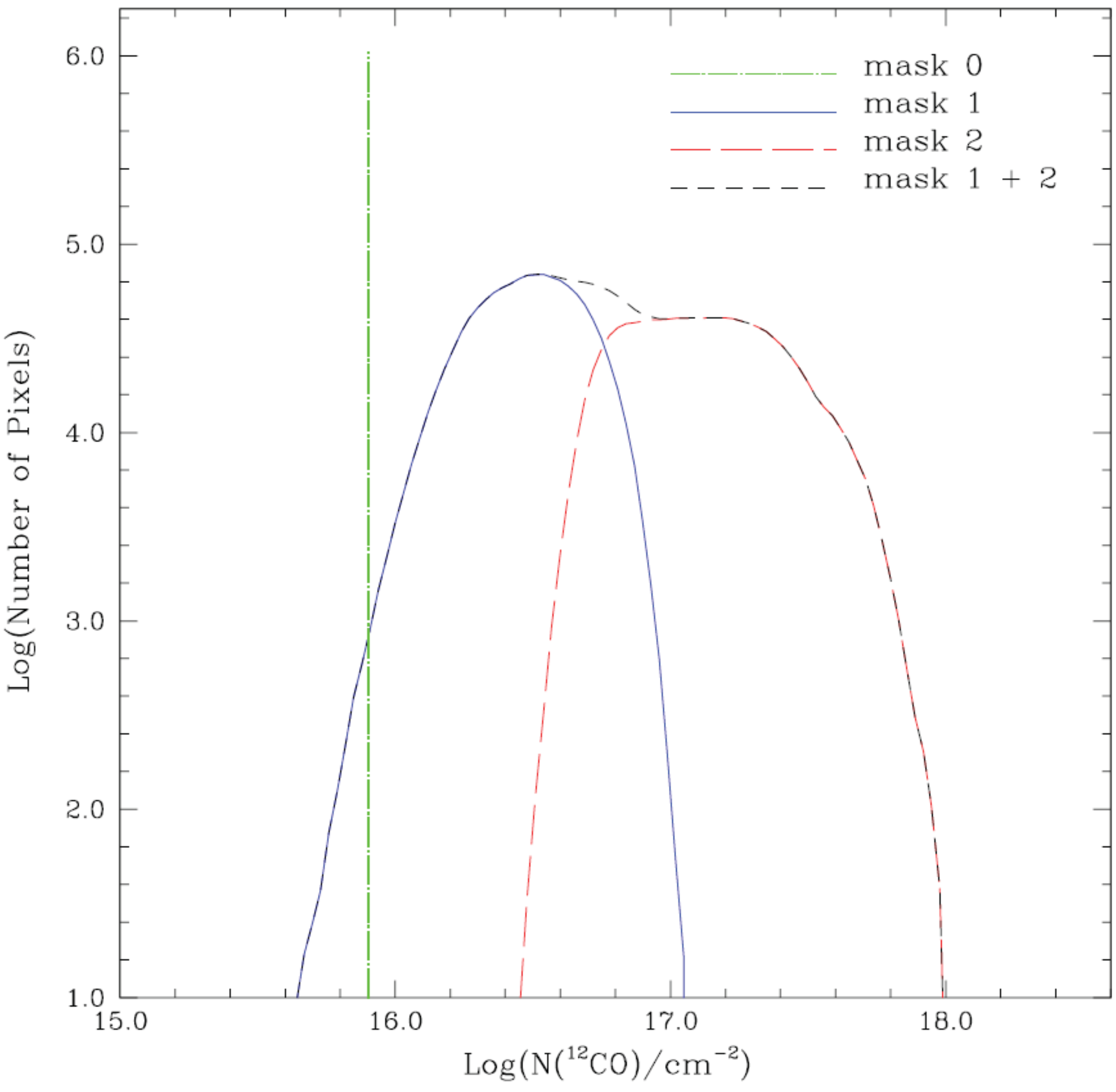


Derived $^{12}CO/^{13}CO$ ratio increases with increasing T_{ex}

$n(H_2)$ decreases for lower T_{ex} due to subthermal excitation

Observed $^{12}CO/^{13}CO$ ratio drops with increasing T_{ex}

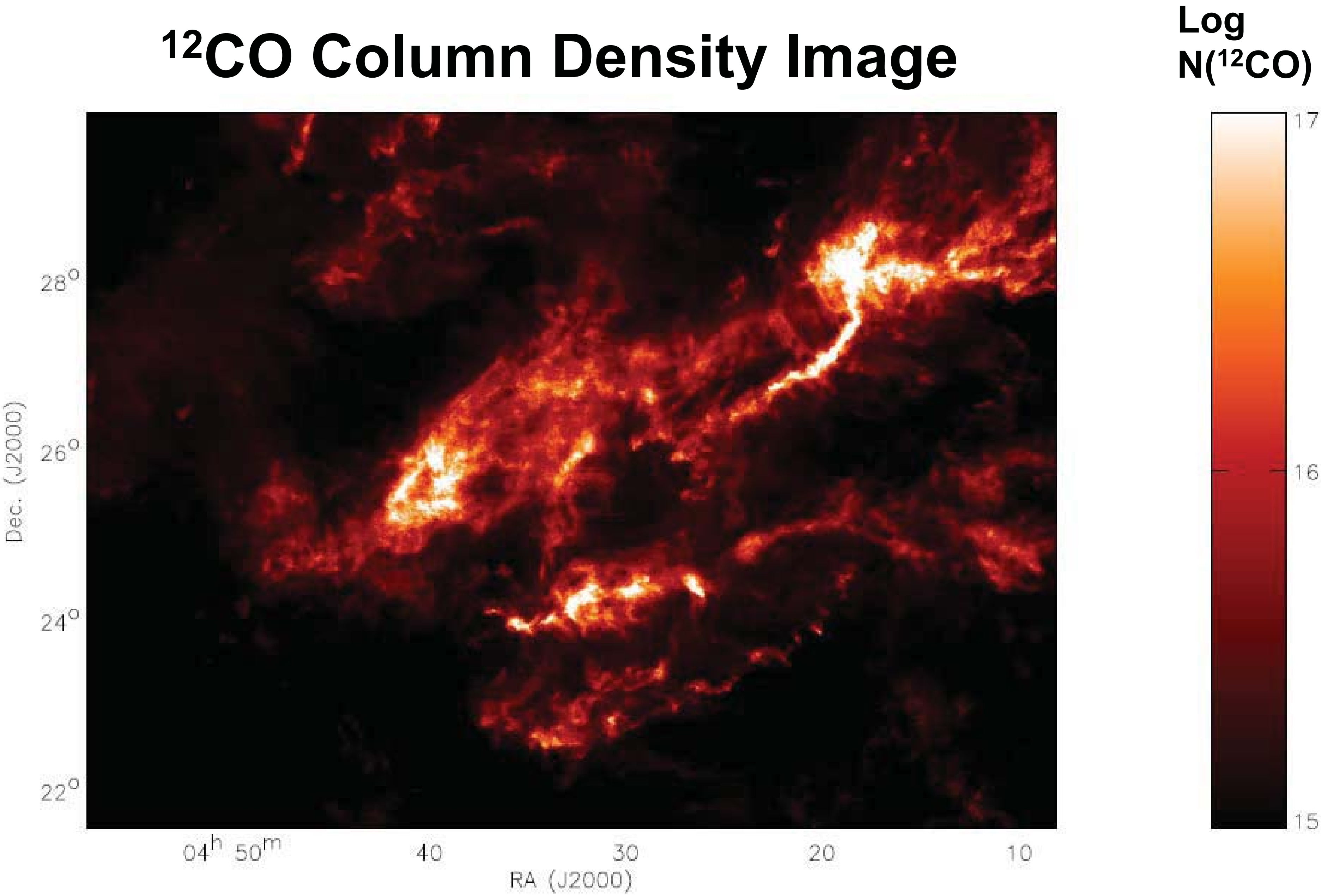
Distribution of CO Column Densities



Note: Mask 0 treated as single entity

$n(H_2) = 75\ cm^{-3}$
$N(CO) = 7.5 \times 10^{15}\ cm^{-2}$

^{12}CO Column Density Image



Conversion to H_2 Column Density

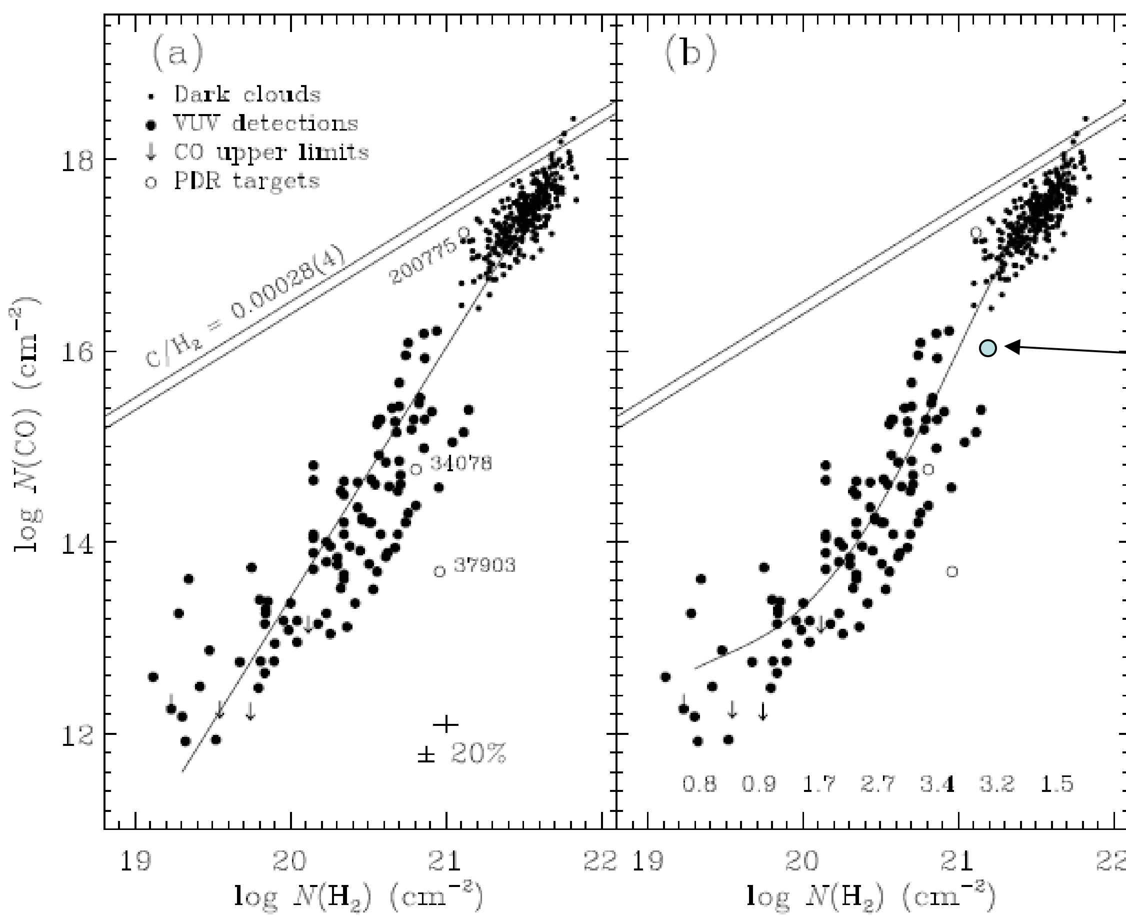
Region mapped includes a very large range of column density and thus of visual extinction

Use of single fractional abundance for CO is almost certain to be seriously in error

Adopt model from VanDishoeck & Black (1988) optimized for Taurus, which calculates N(CO) as fn. of N(H_2); we invert the process to get N(H_2) from N(CO)

X(CO) varies from ~ 10^{-6} in mask 0 to 10^{-4} in high-A_V portion of mask 2

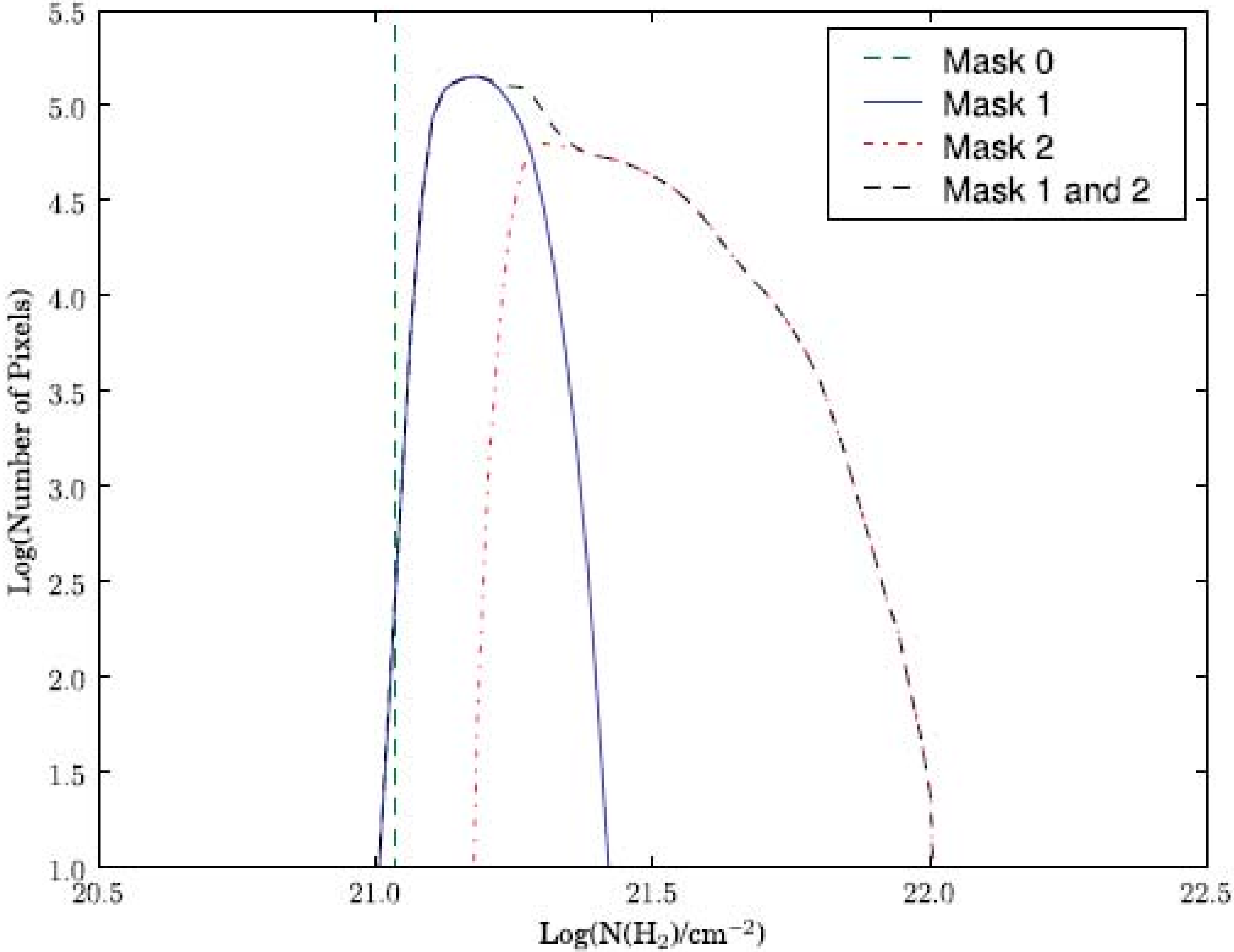
Variable CO/H_2 Ratio with Values << 10^{-4} at Low N Indicated by UV Results



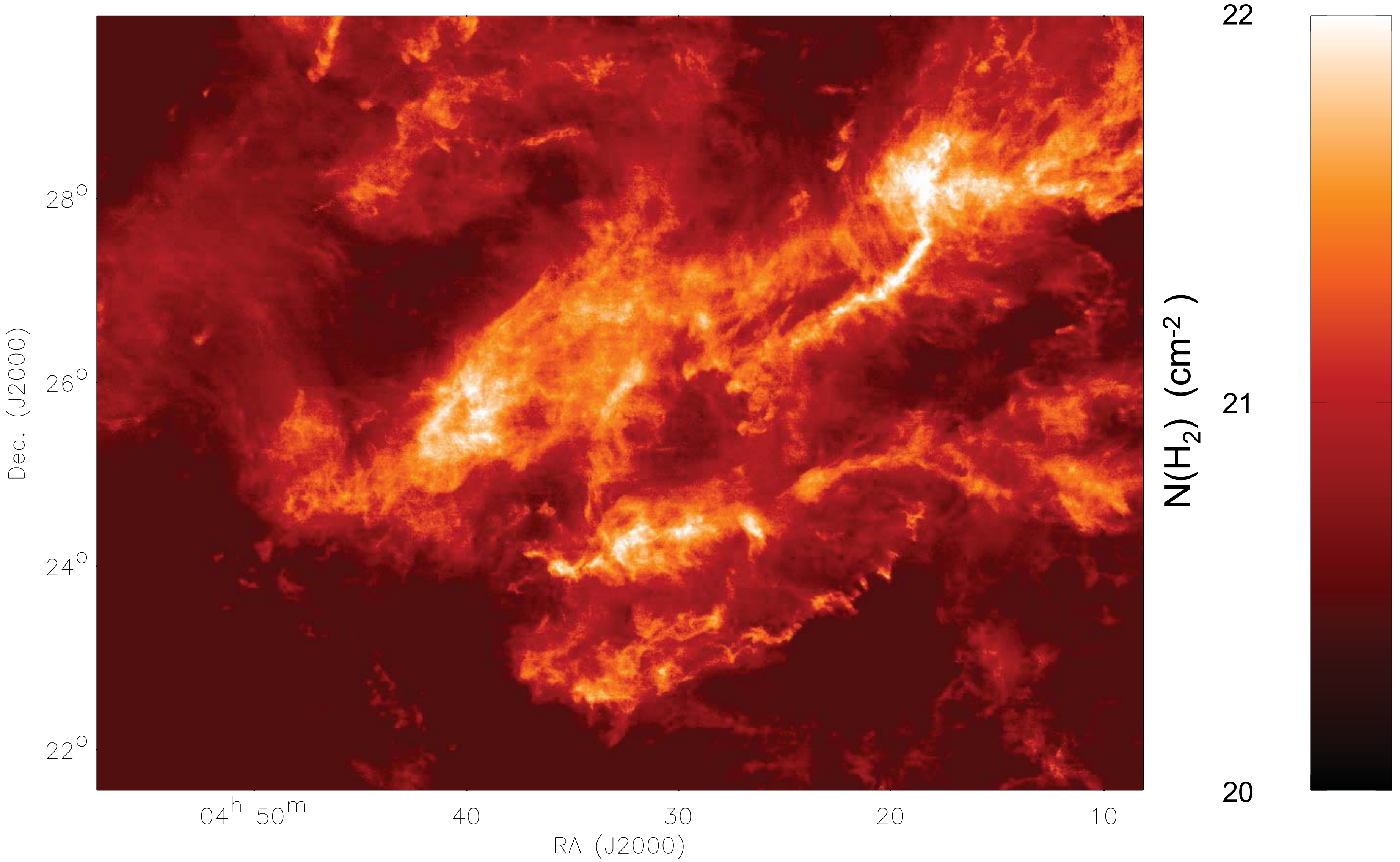
Mask 0

Sheffer et al. (2008)

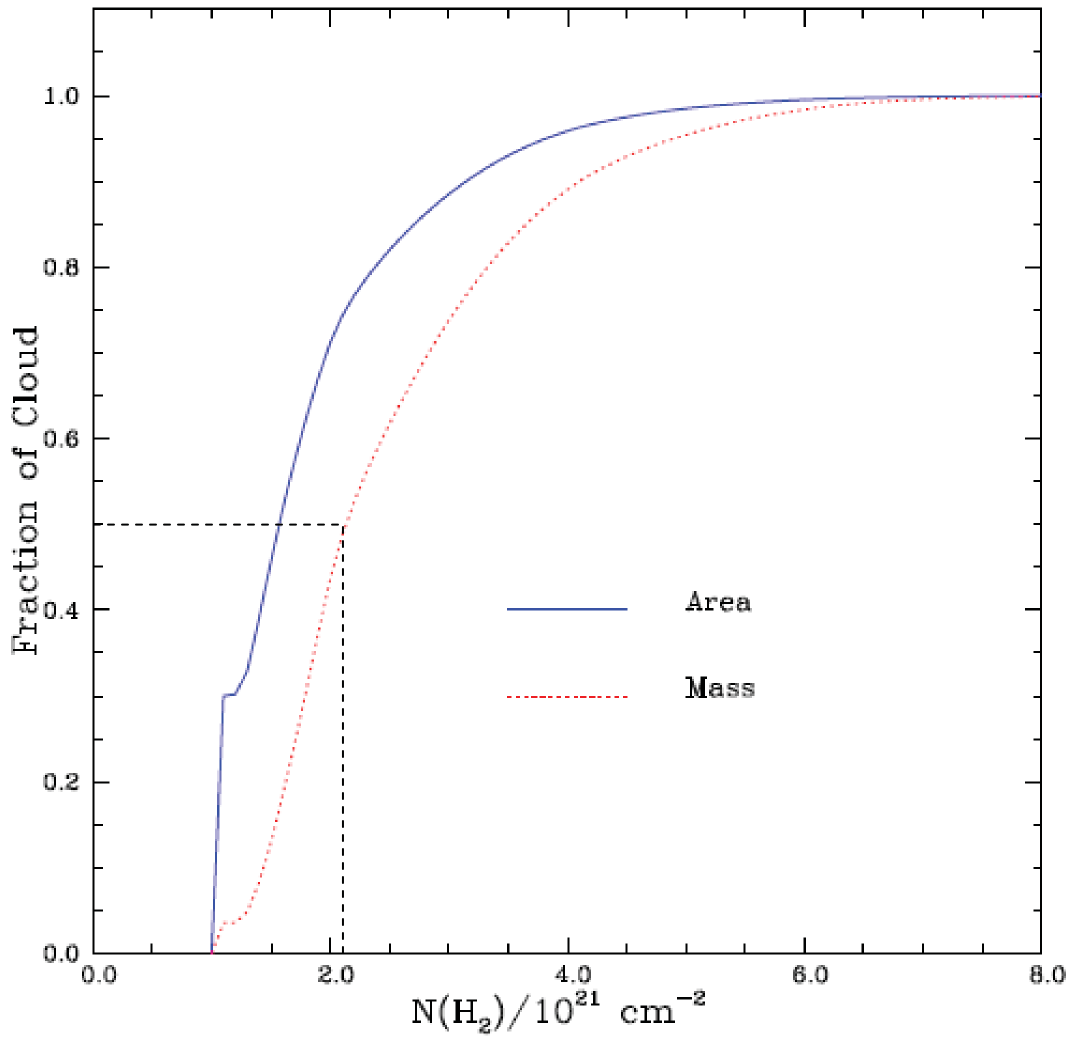
Histogram of $N(H_2)$ Distribution



H_2 Column Density Distribution in Taurus



Cumulative Distribution of Mass and Area



Half the molecular mass is at $N(H_2)$ below 2.1×10^{21} or $A_v < 2.1$ mag

Lower CO Fractional Abundance in mask 0 and 1 Regions Greatly Increases Mass Determined In Our Analysis

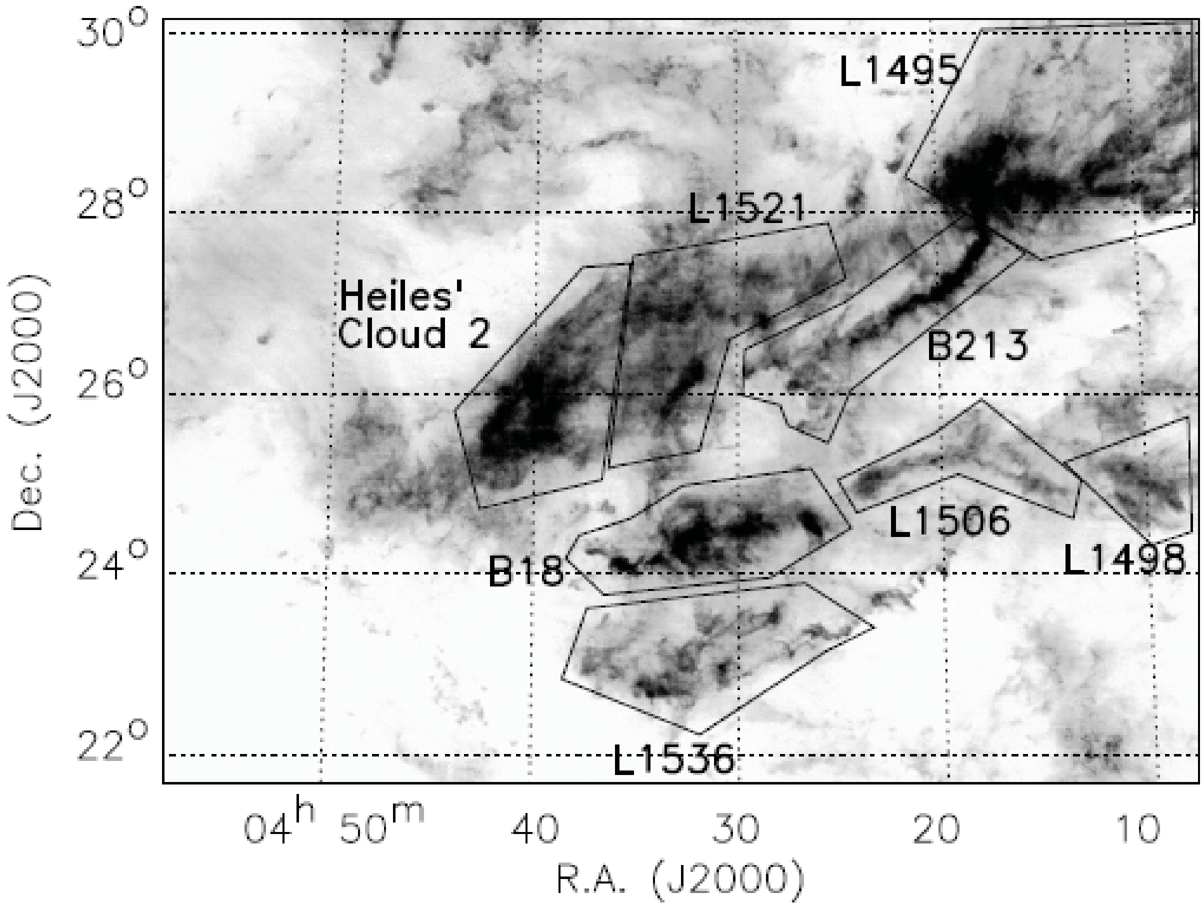
Table 3. Mass of Region in Taurus Mapped

Mask Region	Mass (10^3 $M_\odot$) a	b
0	0.1	4.1
1	1.7	7.7
2	7.8	11.8
Total	9.6	23.6

[a]Using constant H_2/CO ratio equal to 2×10^4

[b]Using H_2/CO ratio with I(UV) = 1.0 and $\delta_C = 0.1$ from Van Dishoeck & Black (1988)

Hitchiker’s Guide to Taurus and Mass of High Density Regions



Mass of High–Density Regions in Taurus[a]

Region	Mass [b] $M_\odot$	Area pc^2
L1495	2616	31.7
B213	1095	13.7
L1521	1584	17.6
HCl2	1513	15.8
L1498	373	5.7
L1506	491	7.7
B18	1157	14.5
L1536	978	16.6
Total	9807	123.3

[a]Regions defined in Figure 11

[b]Includes correction for He

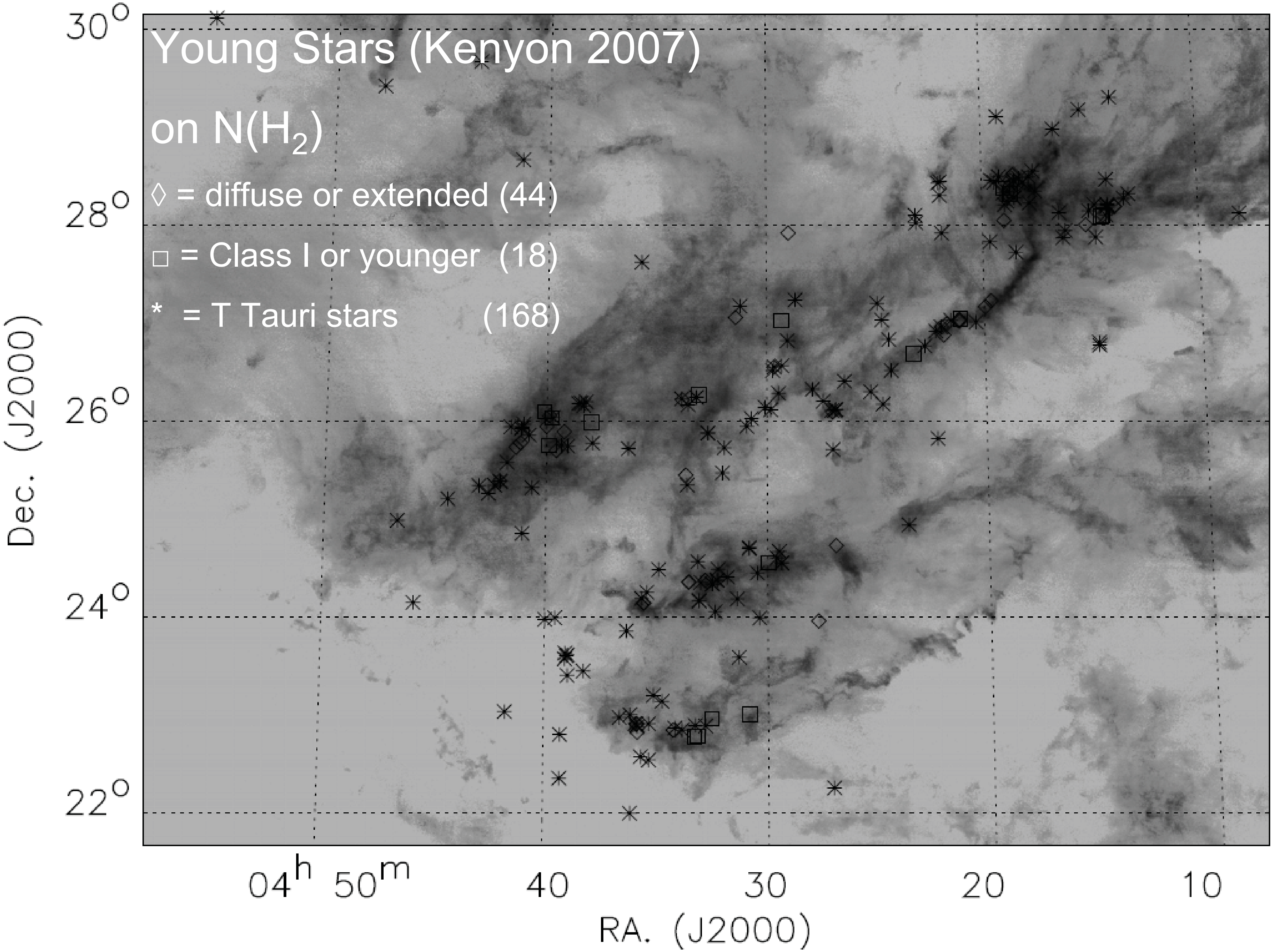
Total Cloud Mass = 2.4×10^4 Solar Masses

Masses Determined with Variable X(CO) and Including Diffuse Regions Agrees well with those Found from L(CO)

Table 5. Comparison of Masses Determined from ^{12}CO and ^{13}CO With Those Derived from CO Luminosity

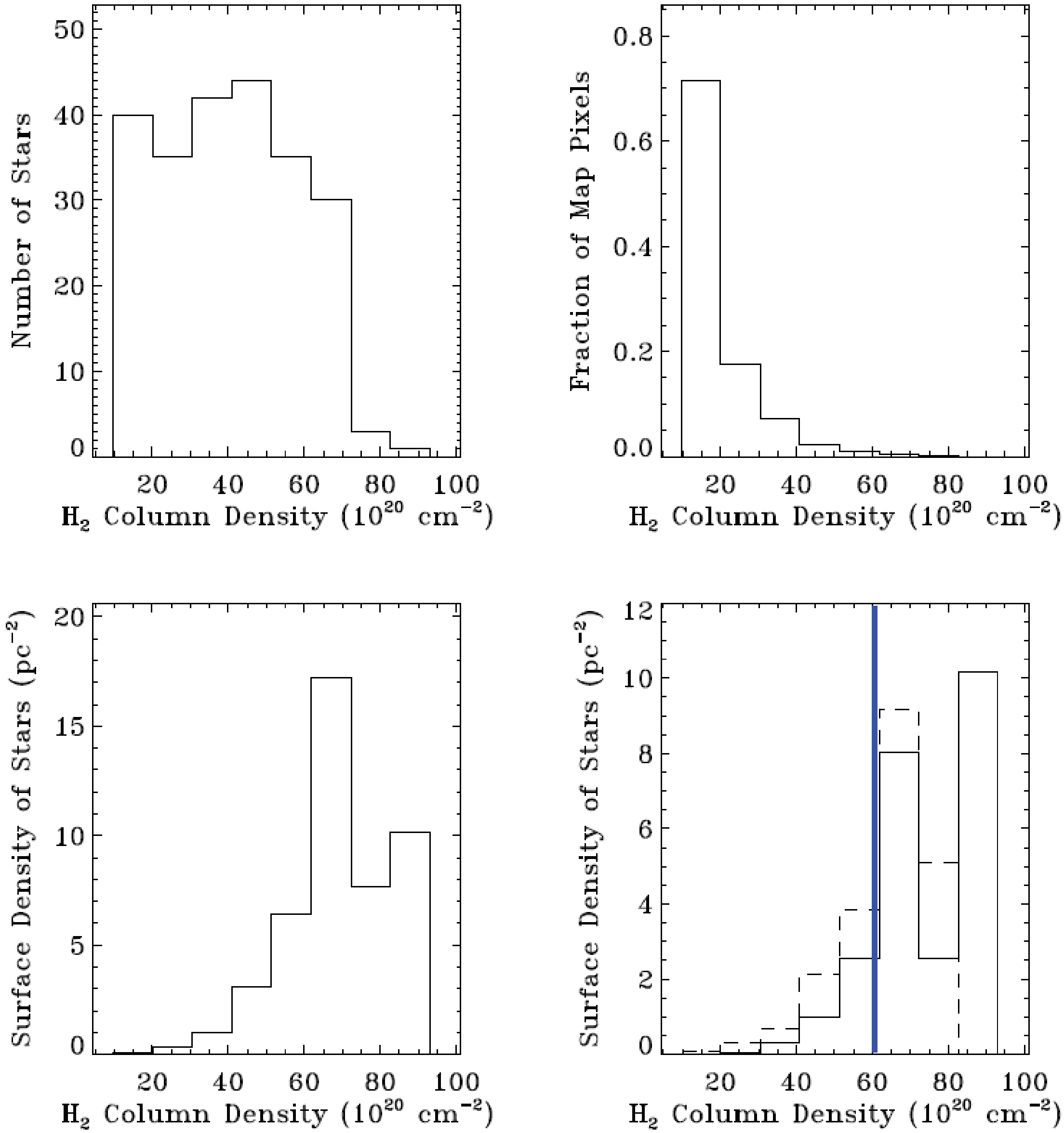
Region	Mass from ^{12}CO and ^{13}CO ($M_\odot$)	^{12}CO Luminosity ($\mathrm{K km s^{-1} pc^2}$)	Mass from ^{12}CO Luminosity ($M_\odot$)
mask 0	4081	193	791
mask 1	7699	2052	8413
mask 2	11752	3305	13550
Total	23532	5550	22754

M(solar masses) = 4.1 L_{CO} (Strong & Mattox 1996)



Young Stars (Kenyon 2007)
on N(H2)
◊ = diffuse or extended (44)
□ = Class I or younger (18)
* = T Tauri stars (168)
30°
28°
26°
24°
22°
Dec. (J2000)
04h 50m
40
30
20
10
RA. (J2000)

Distribution of Young Stars as Function of Molecular Column Density



Stars appear to be uniformly distributed as function of $N(H_2)$ but

Only a very small fraction of area has high column density so that

Surface density of stars exhibits a sharp rise for $N(H_2) \sim 6\times10^{21}$ cm^{-2}

=> Column Density Threshold for Star Formation

Star Formation Efficiency

Star Formation Efficiency

$$SFE = M_{stars}/M_{gas}$$

But what stellar mass and what gas mass?

Assume avg. mass of 230 PMS stars = 0.6 M_{solar}

1. $SFE_{total} = M_{PMS\ stars} / M_{total\ molecular\ gas} = 0.006$
2. $SFE_{current} = M_{protostars} / M_{dense\ molecular\ gas} = 0.003$
3. $SFE_{practical} = M_{PMS\ stars} / M_{dense\ molecular\ gas} = 0.012$

Star formation efficiency is low, due in part to modest fraction of gas at high density / high column density

Star Formation Rate & Gas Depletion

<Star Formation Rate> = M_{stars}/SF Timescale

Assume SF Timescale = T-Tau Star Ages ~ 3×10^6 yr

<SFR> = 138 M_{solar} / 3×10^6 yr = 5×10^{-5} M_{solar} yr^{-1}

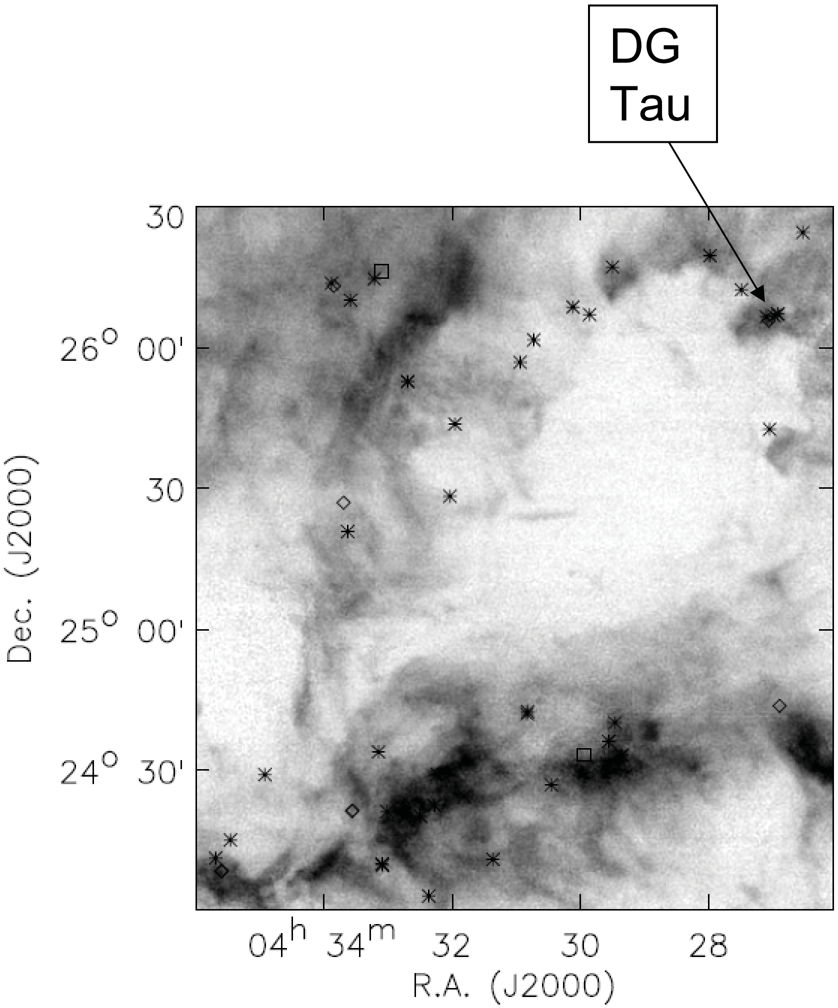
Mass Conversion Rate = <SFR> / M_{gas} = 2×10^{-9} yr^{-1}

Gas Depletion Timescale = MCR^{-1} = 5×10^8 yr

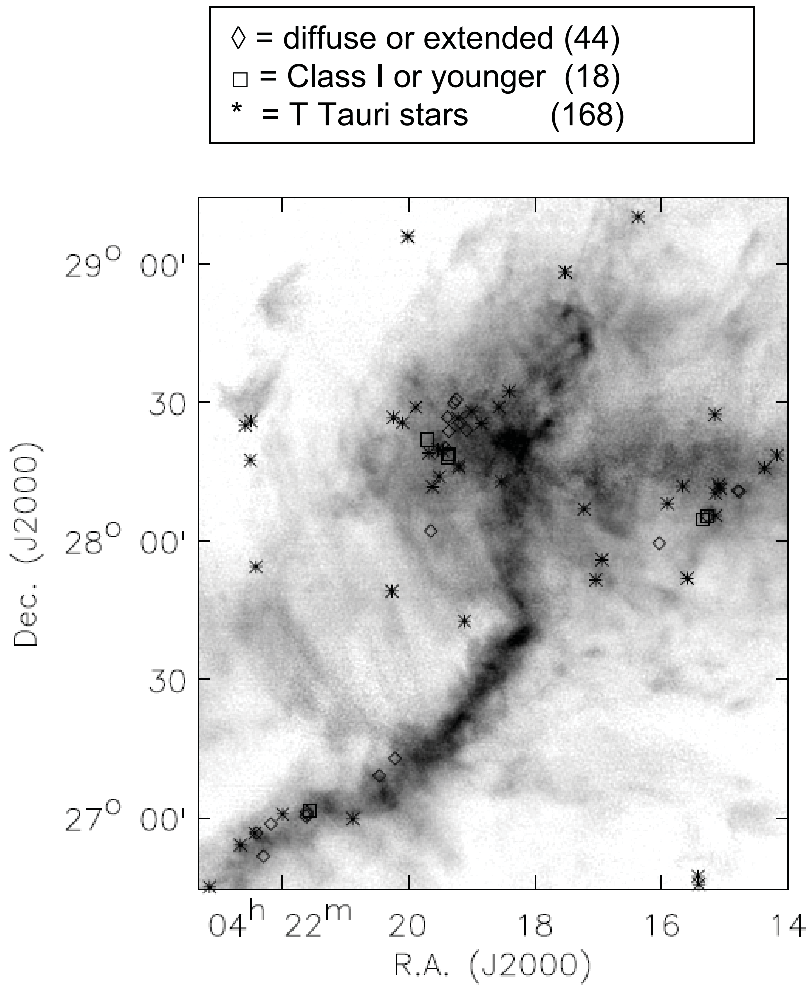
Are we seeing Taurus (& other low mass star-forming regions at onset of star formation? UNLIKELY

=>Interesting question – what terminates star formation at low SFE in regions like Taurus?

Enlarged Images of Some of the Regions with Numerous Young Stars

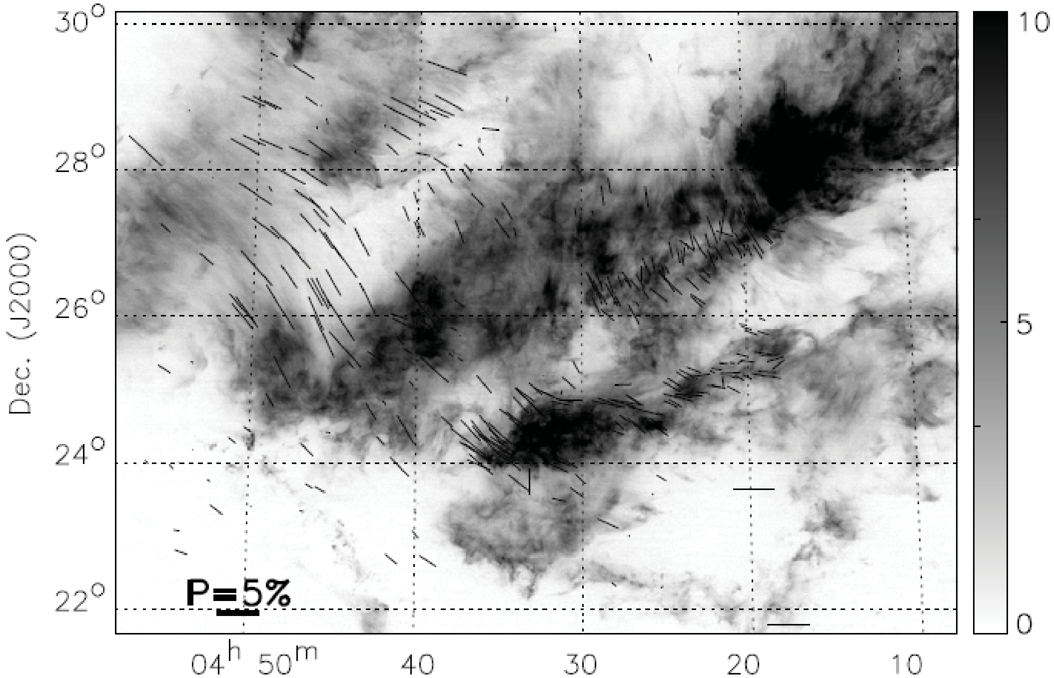


Cavity and B18

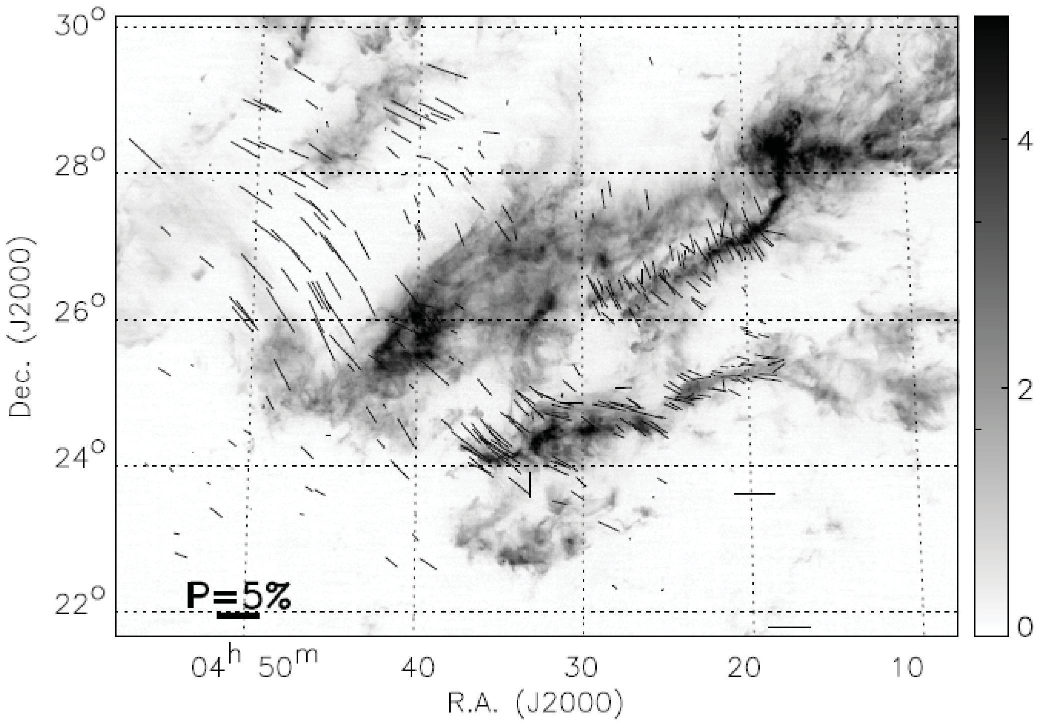


L1495 and B213

Magnetic Field Direction & Fractional Polarization

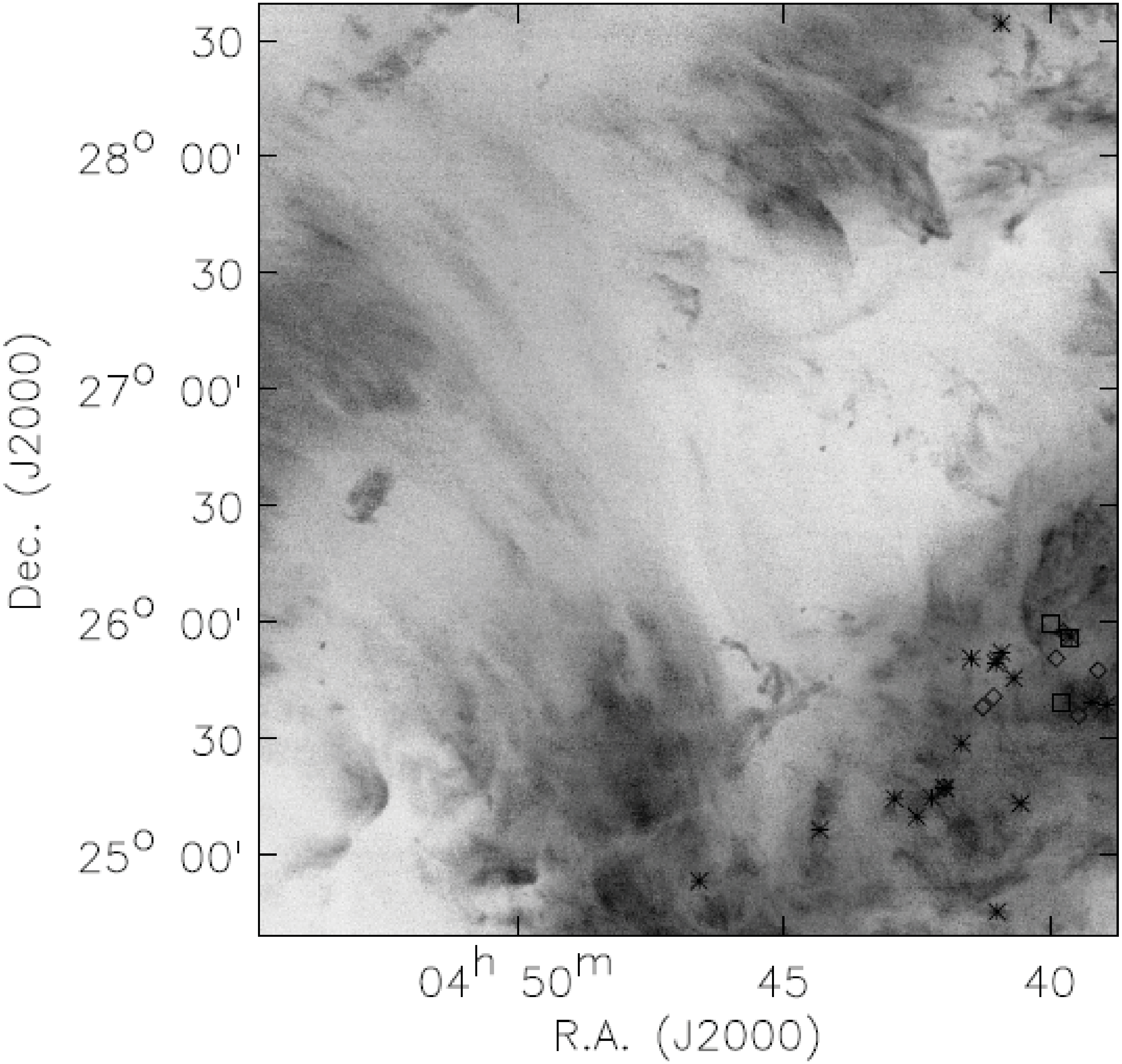


Superimposed on ^{12}CO integrated intensity (5 km s^{-1} to 8 km s^{-1})

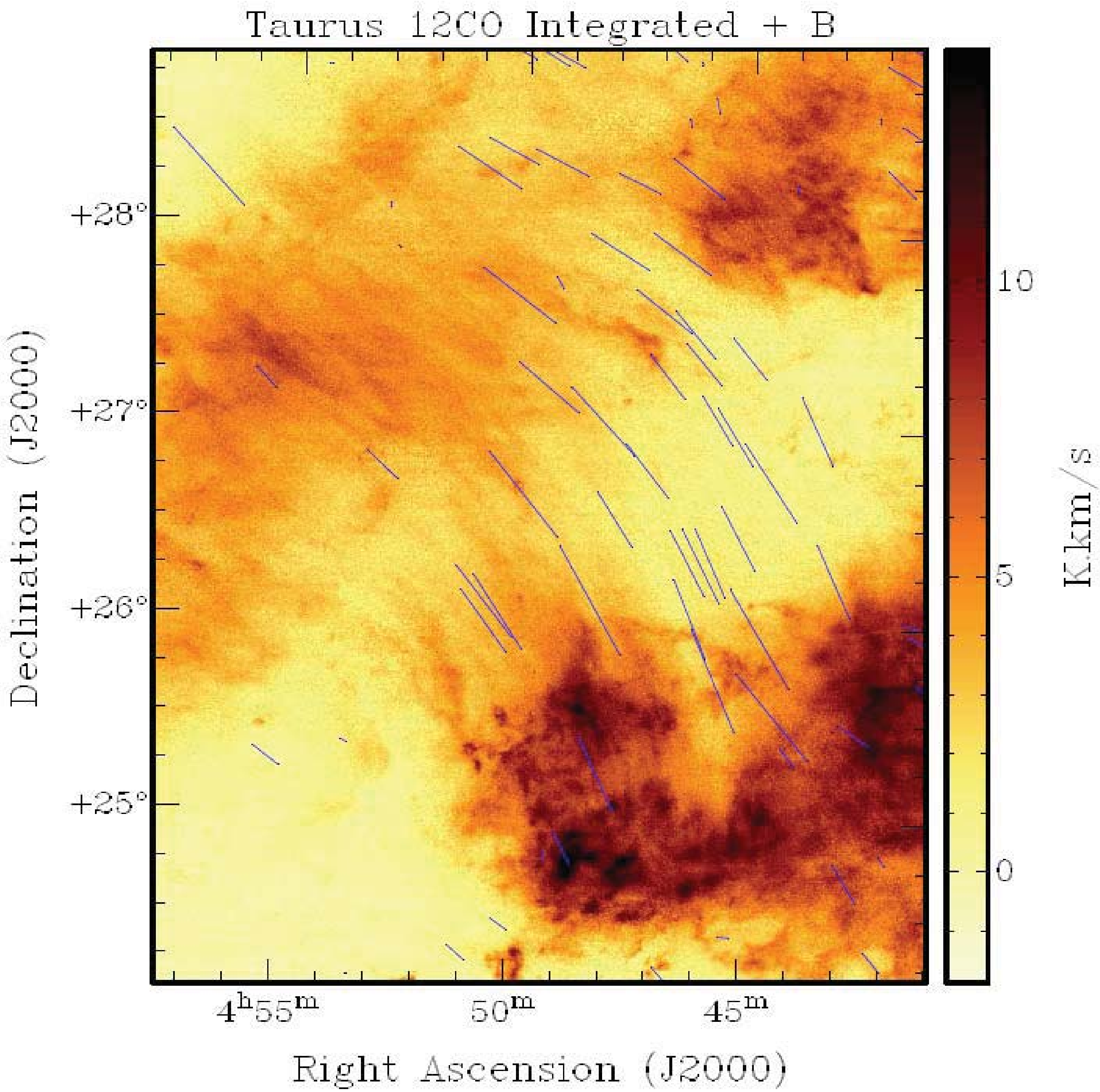


Superimposed on ^{13}CO integrated intensity (5 km s^{-1} to 8 km s^{-1})

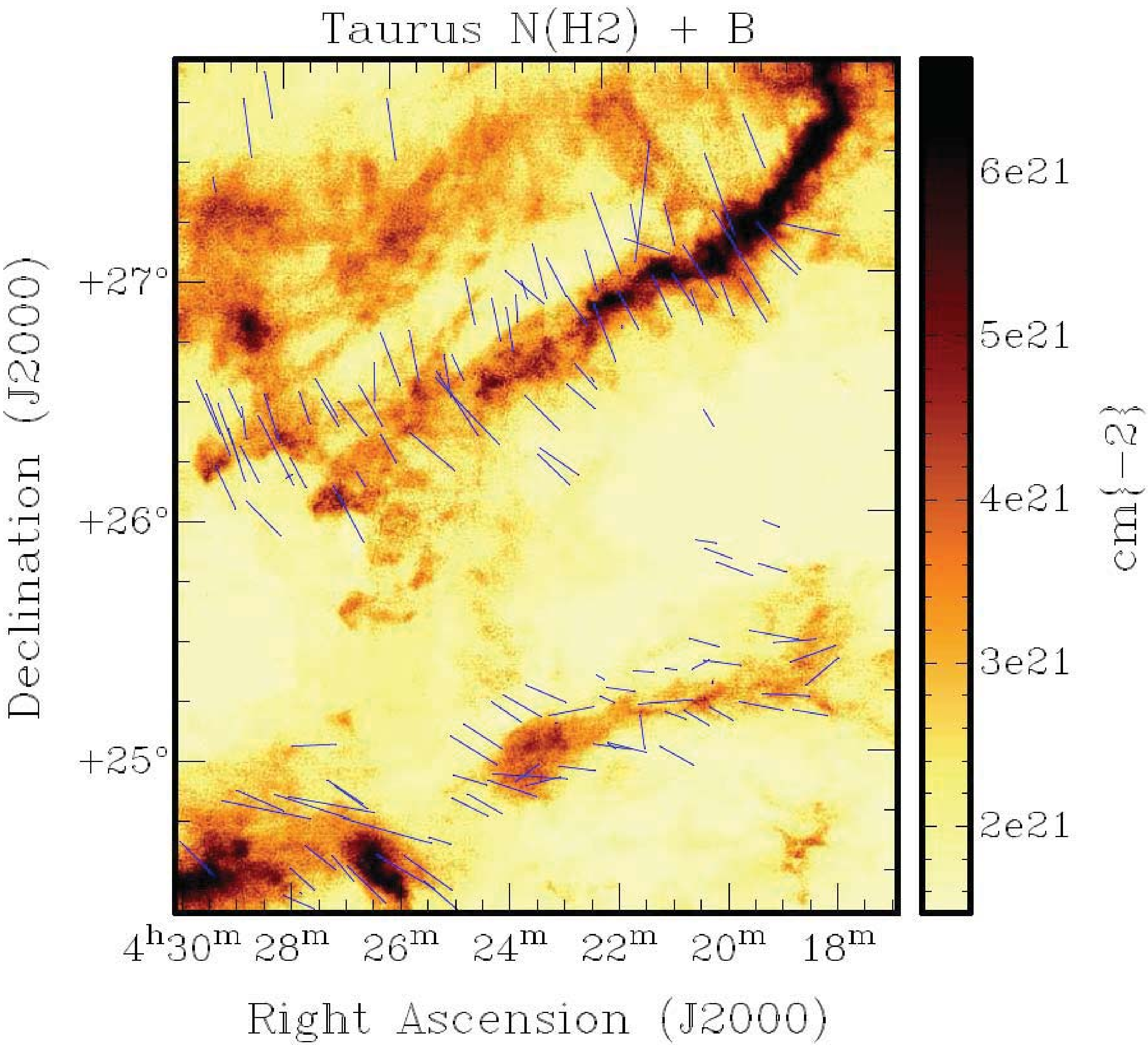
Caveat: B-field inferred from optical absorption measurements



Striations in NE Region



Low density material traced by ^{12}CO seems to have "striations" which are oriented parallel to magnetic field direction

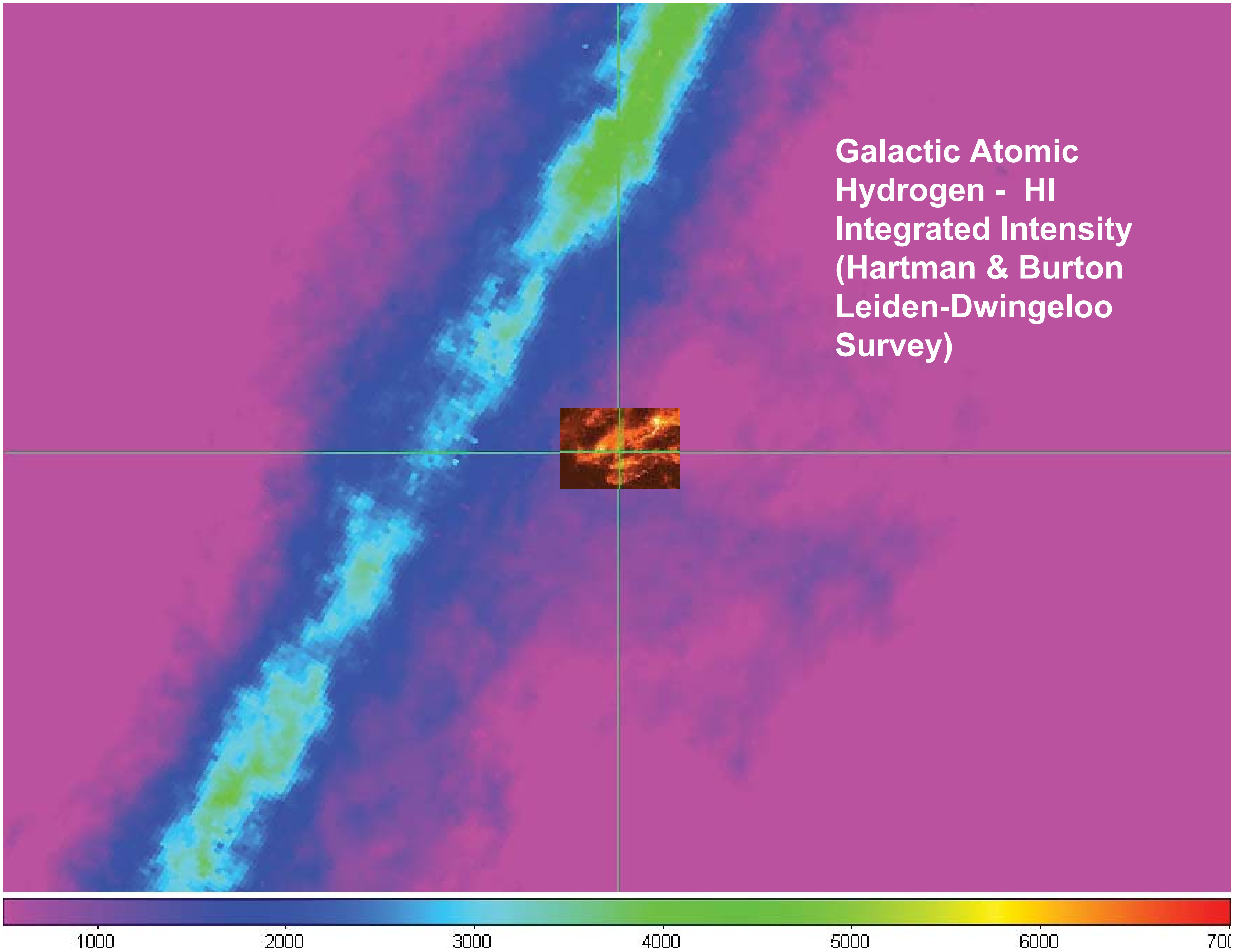


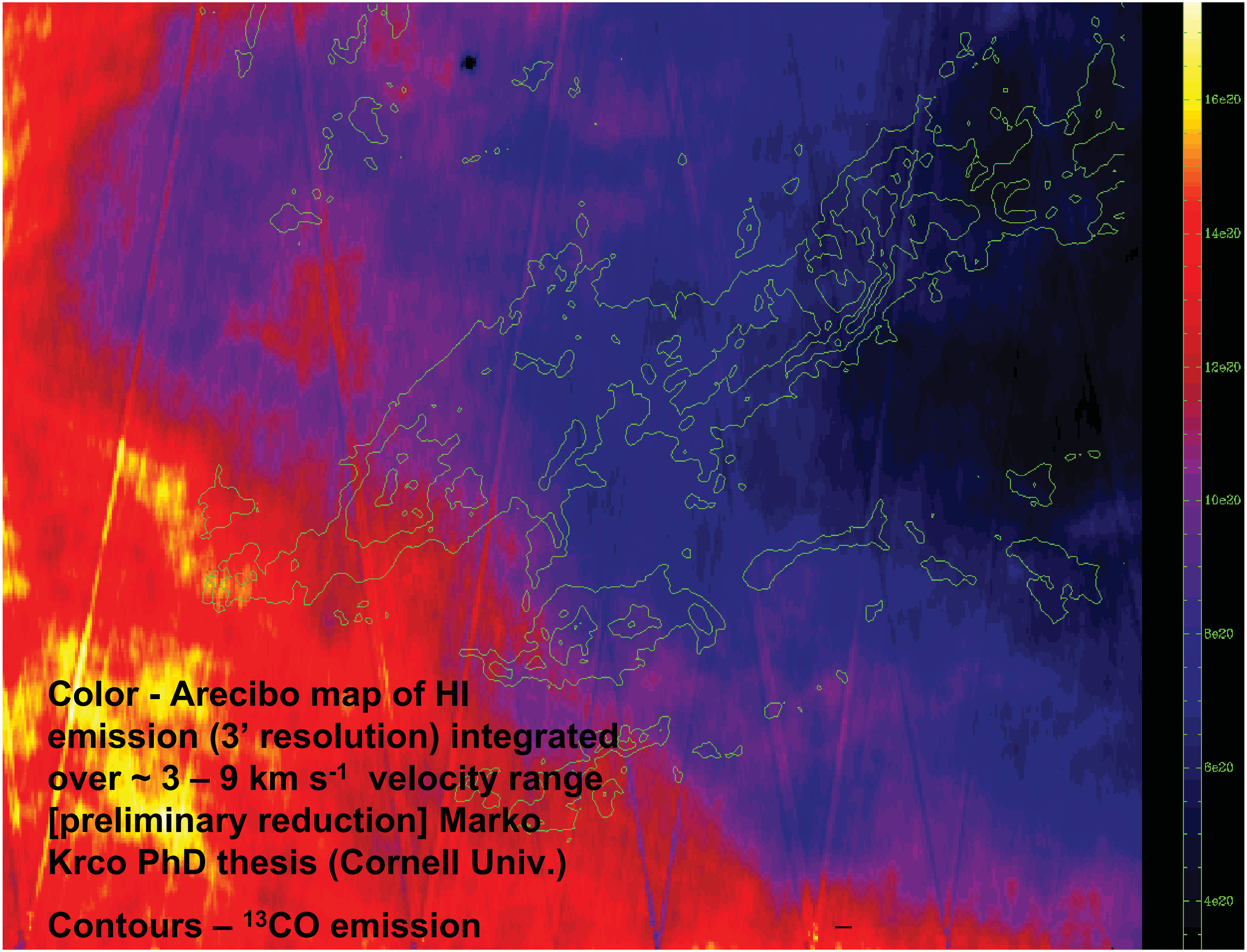
Magnetic field on periphery of B213 filament is perpendicular to filament axis

For L1506, the situation is less clear

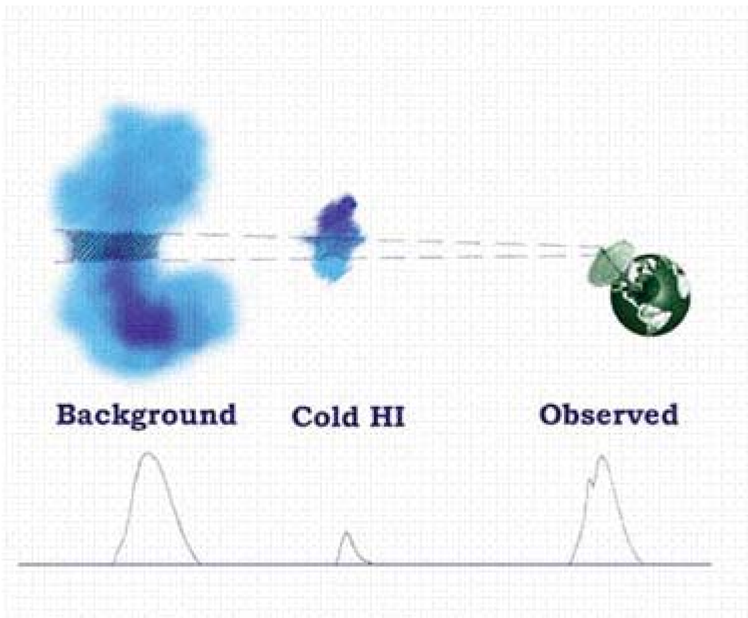
What is the Origin of the Taurus Molecular Cloud ?

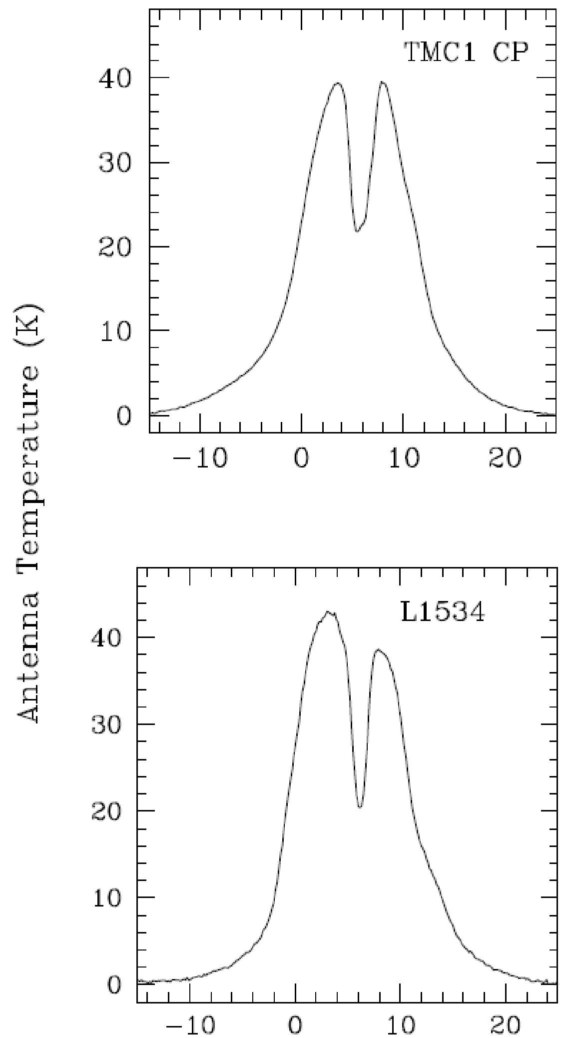
Did it Evolve from HI Gas ?
Do Kinematics Give us a Clue to its Origin?
What is Relationship to Star Formation?


Galactic Atomic
Hydrogen - HI
Integrated Intensity
(Hartman & Burton
Leiden-Dwingeloo
Survey)
1000
2000
3000
4000
5000
6000


16e20
14e20
12e20
10e20
8e20
6e20
4e20
Color - Arecibo map of HI emission (3' resolution) integrated over ~ 3 – 9 km s^{-1} velocity range [preliminary reduction] Marko Krco PhD thesis (Cornell Univ.)
Contours – ^{13}CO emission

Cold HI Mixed With Molecular Gas Can Absorb Background Signal





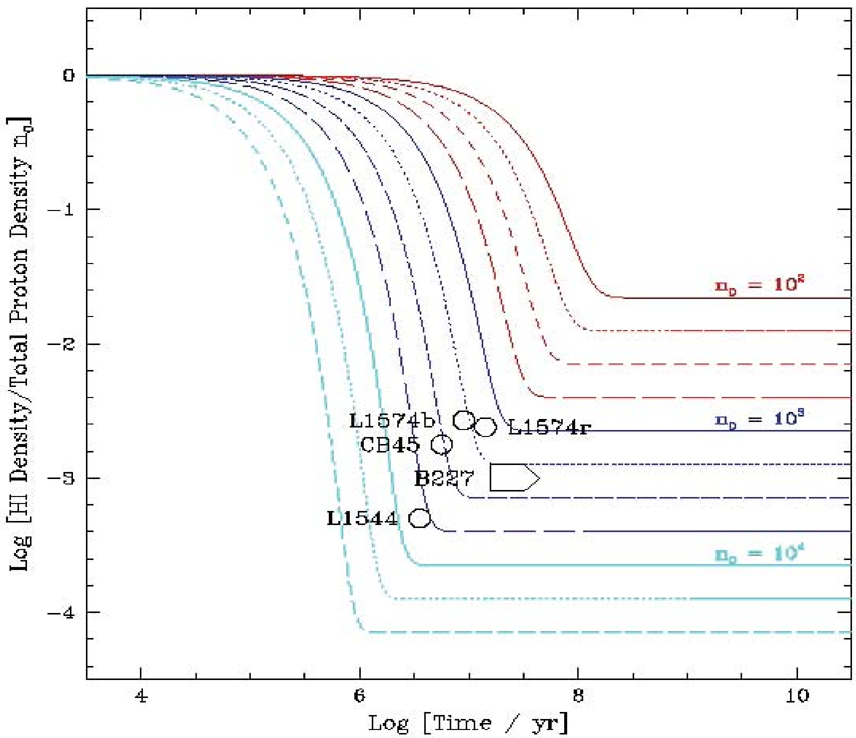
This atomic hydrogen has velocity and nonthermal linewidth similar to that of ^{13}CO and similar morphology => mixed with molecular gas

HINSA

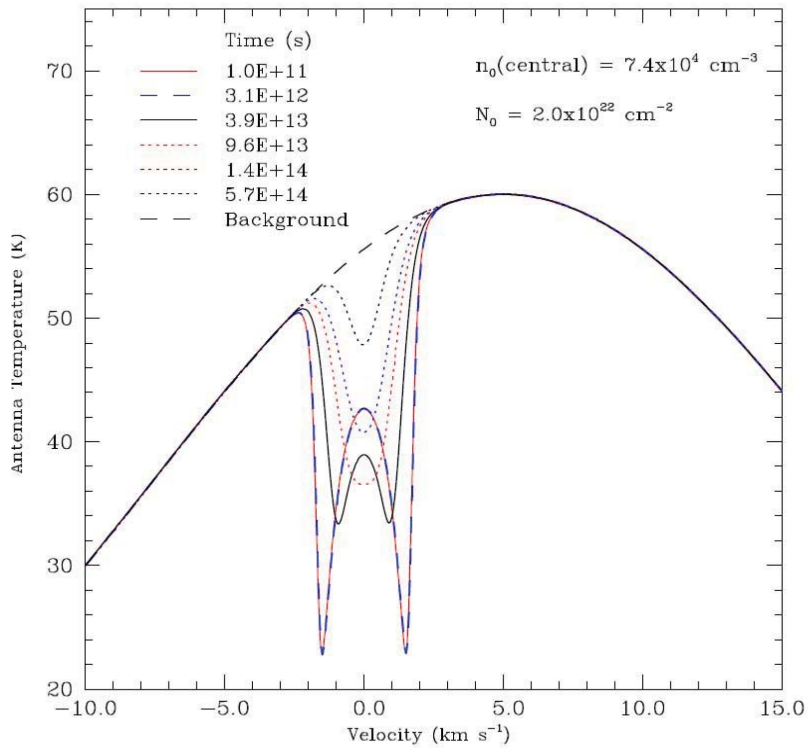
HI Narrow Self Absorption

HI/H_2 Ratio Drops as Cloud Evolves from Atomic to Molecular

Goldsmith & Li (2005)

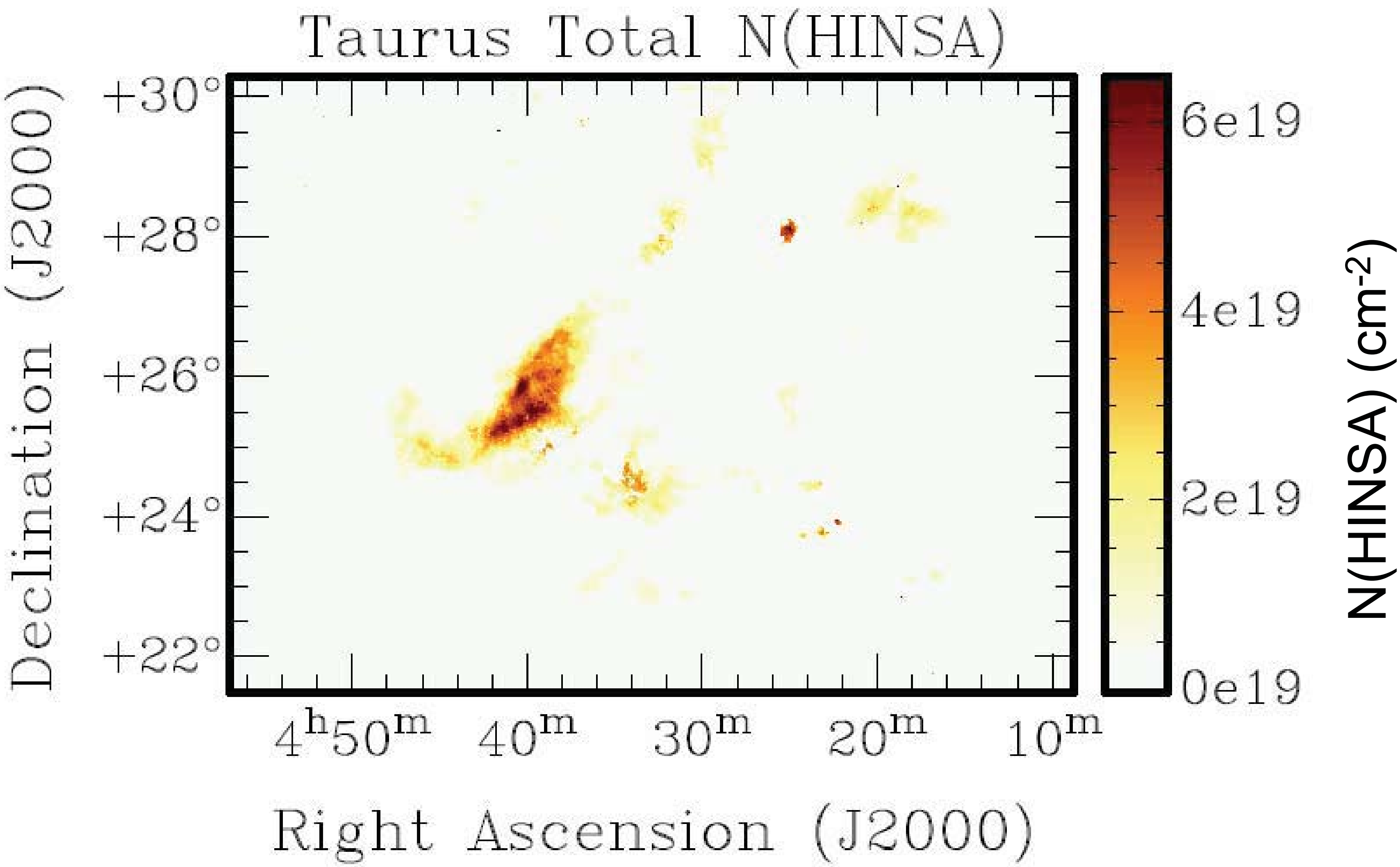


Goldsmith et al. (2007)



"Age" of nearby dark clouds including several in Taurus is few x 10^6 – 10^7 yr

HINSA Observed in Much of Dense Gas in Taurus: HCl2& B18 But Relatively Weaker in B213 & L1495



HI in Taurus

- HINSA observations suggest that individual condensations have existed for > few million years as well-shielded regions
- General kinematic correspondence between cold HI and molecular gas
- Large scale variations in HI/H_2 are currently unexplained but suggestive of complex evolution

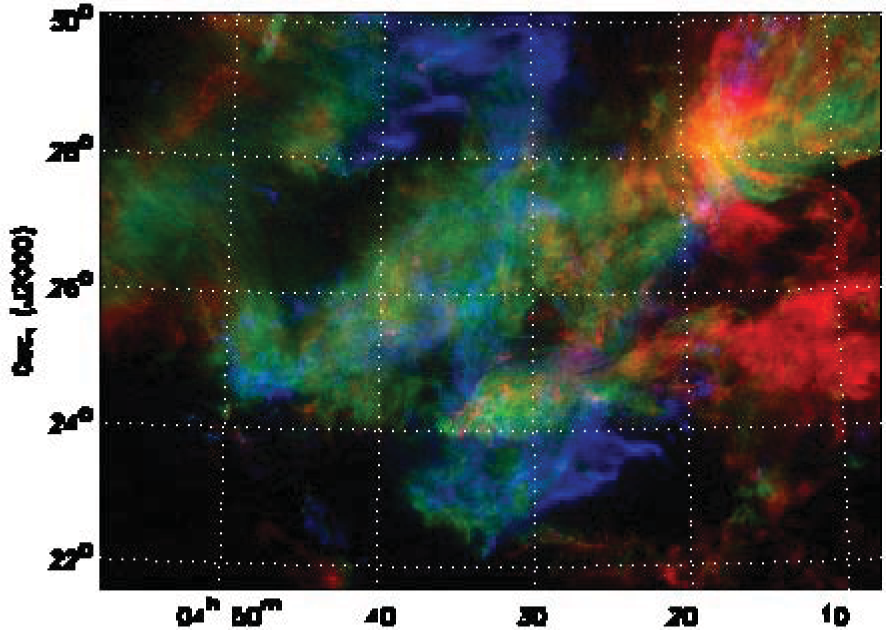
Kinematics of the Molecular Gas in Taurus

3 – 5 km s^{-1} blue

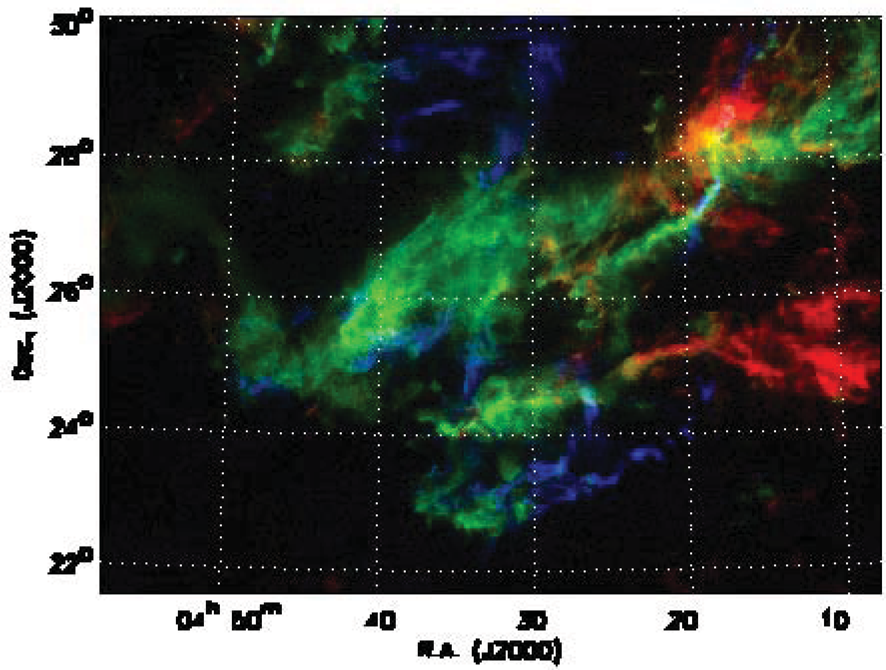
5 – 7 km s^{-1} green

7 – 9 km s^{-1} red

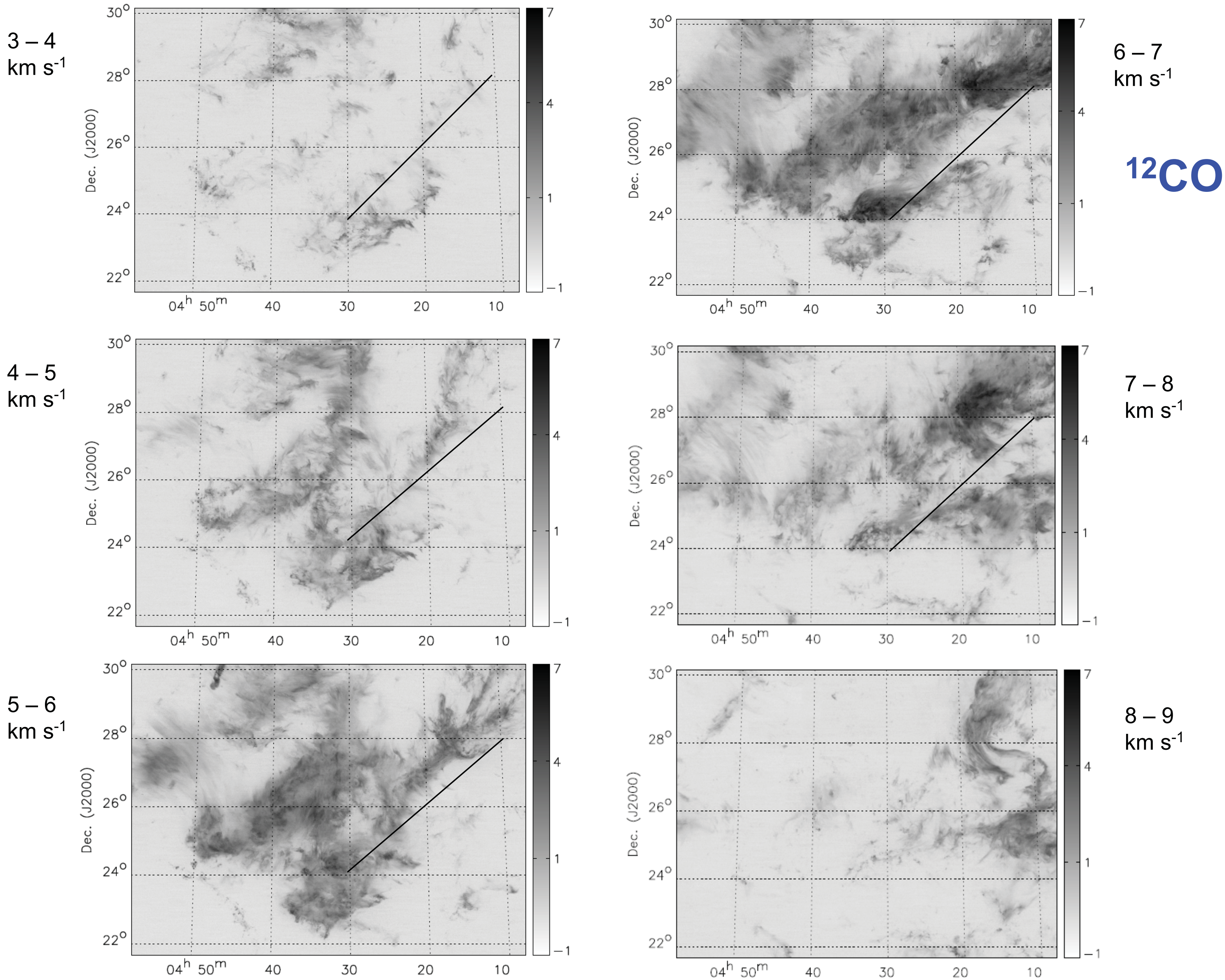
- Localized gradients
- "Extreme" velocities associated with filamentary structures



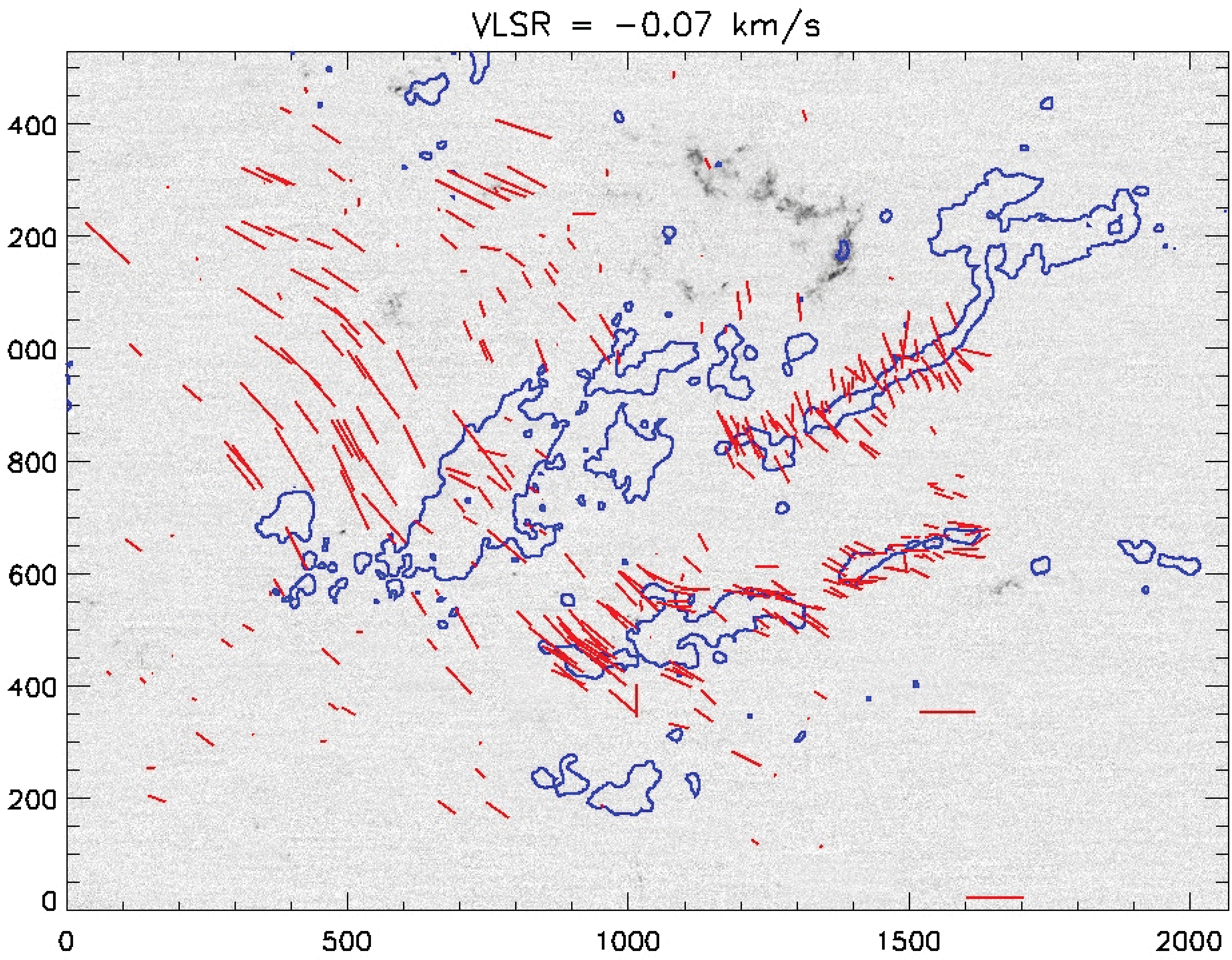
^{12}CO



^{13}CO



3 – 4 km s-1
4 – 5 km s-1
5 – 6 km s-1
6 – 7 km s-1
7 – 8 km s-1
8 – 9 km s-1
12CO
Dec. (J2000)
30° 28° 26° 24° 22°
04h 50m 40 30 20 10
7 4 1 −1


VLSR = −0.07 km/s
400
200
000
800
600
400
200
0
0
500
1000
1500
2000

Summary & Conclusions (1)

- The molecular gas in Taurus has extremely complex morphology, being composed of filaments and rings
- Gas distribution does not look “relaxed” by any usual definition
- Low column density gas is clearly present and including this in variable-abundance model results in ~3x increase in total H_2 mass to 2.4×10^4 solar masses
- Magnetic field aligned with striated low density gas and ~ perpendicular to dense molecular filaments
- The kinematics are obviously complex, with large-scale motions perhaps controlled by B field combining with local quasi-random motions

Summary & Conclusions (2)

- The young stars are concentrated in regions of large column density with “threshold” for star formation ~ $6x10^{21}$ cm^{-2}
- The star formation efficiency is 0.003 to 0.012, which is low and implies a long gas exhaustion time
- There is no obvious connection between the molecular gas and HI seen in emission
- The cold HI mixed with the molecular gas is seen in absorption throughout much of Taurus
- The HI/H_2 ratio implies a relatively long time of few x 10^6 yr since atomic-to-molecular transition began