Watching the Interstellar Medium Move

Alyssa A. Goodman

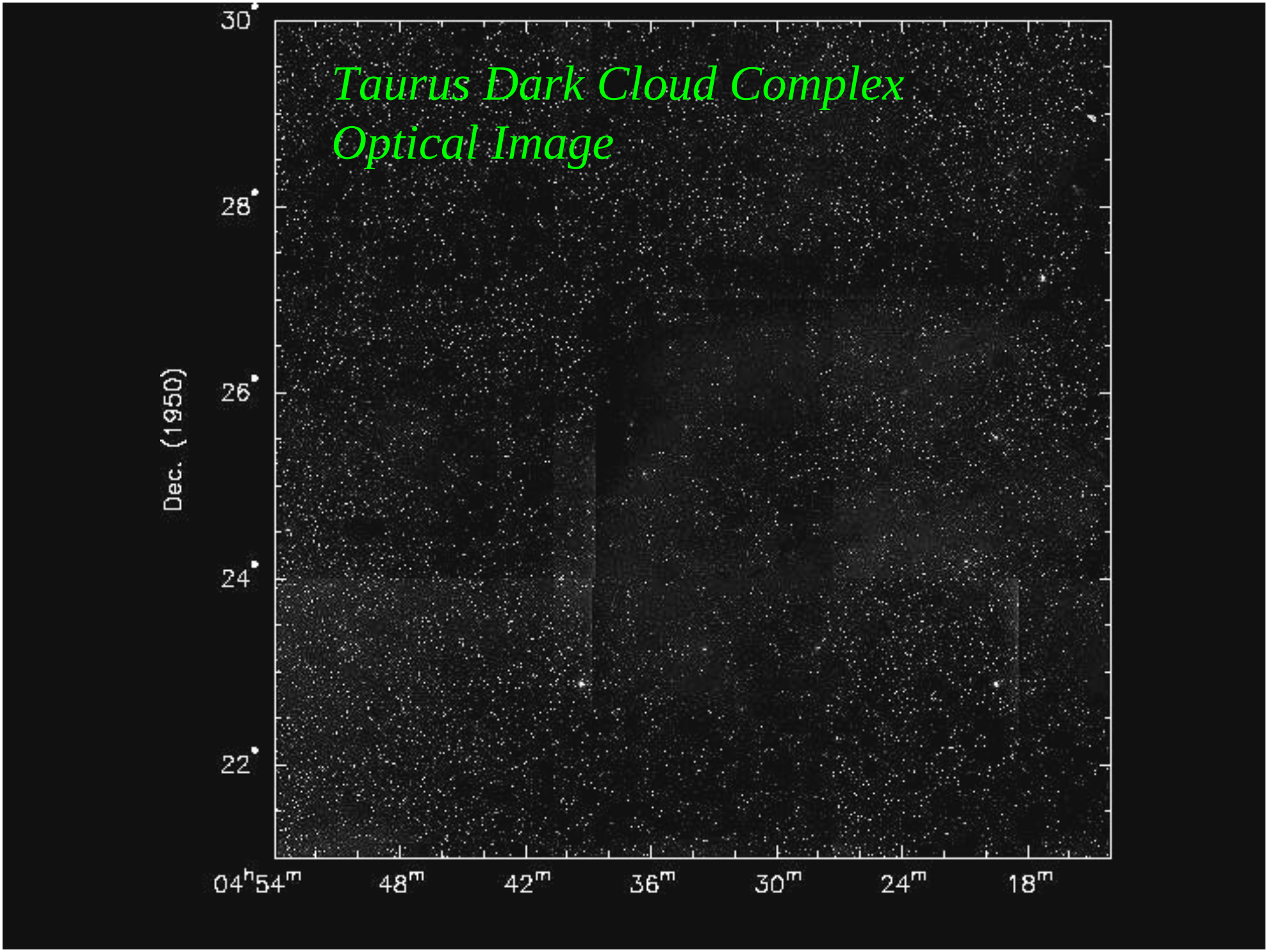
Harvard University

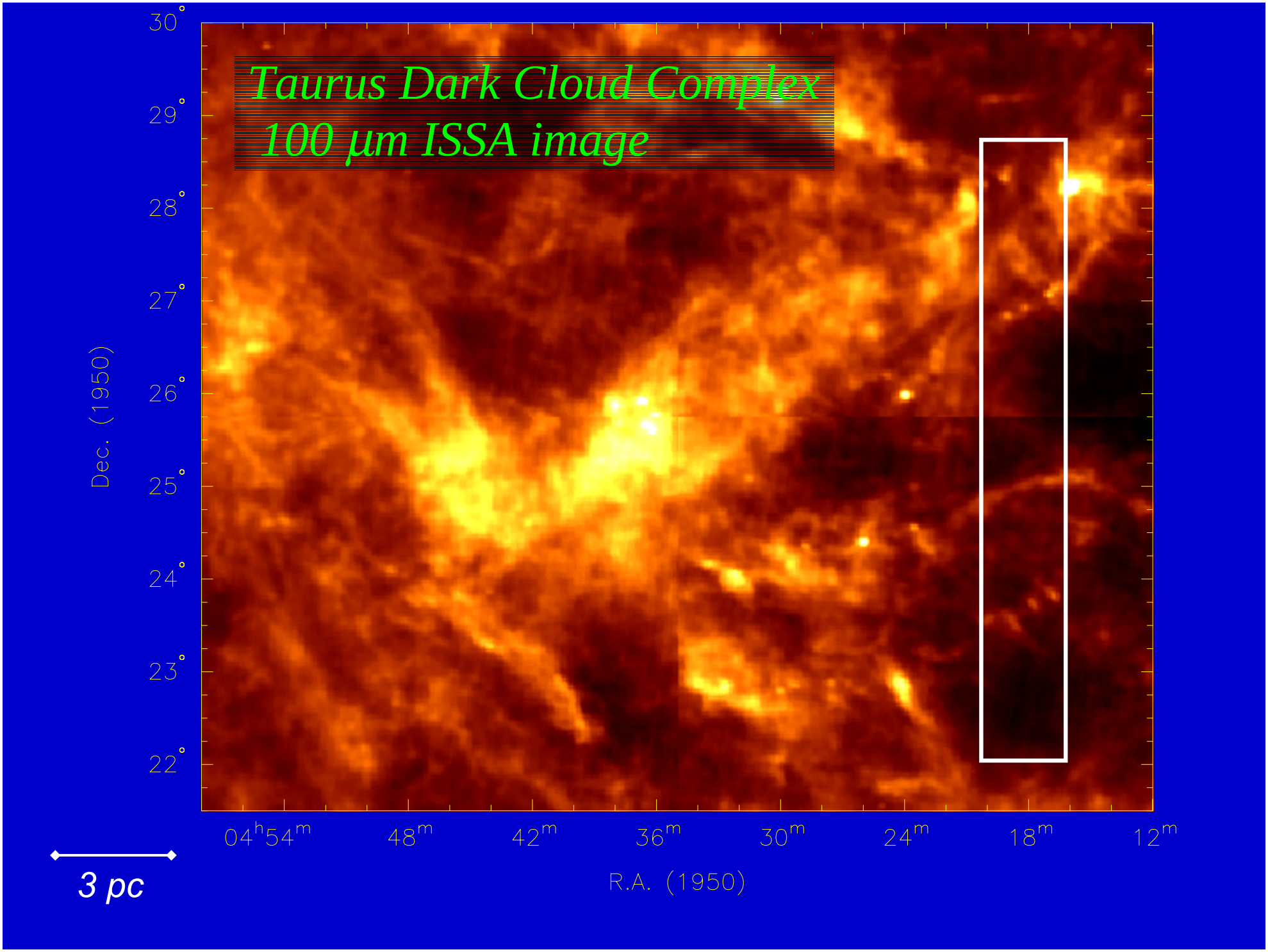
Bart Bok and the "Dark Nebulae"

"They are no good, and only a damn fool would be bothered by such a thing. A sensible person does not get involved with the dark nebulae but steers to the clear parts in between."

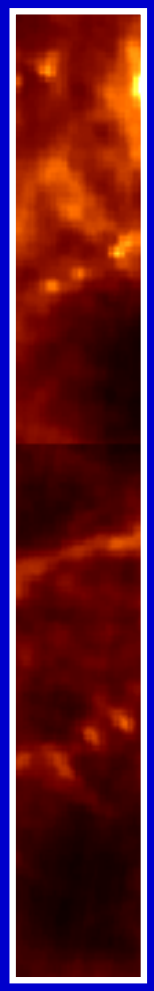
--Pieter van Rhijn, Bok's Thesis Advisor

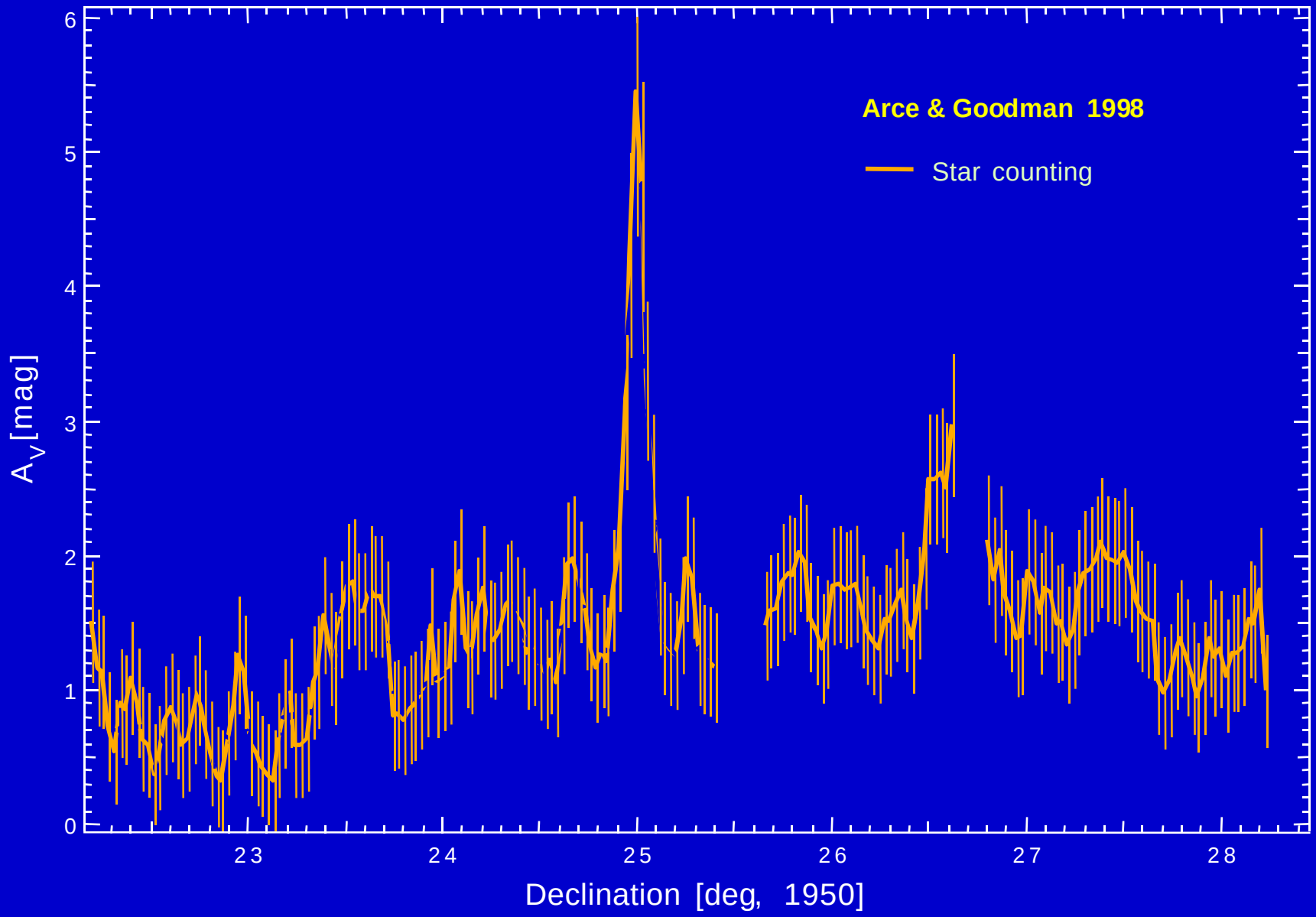
(commenting on Bok's book, "The Distribution of Stars in Space," in 1937)


Taurus Dark Cloud Complex
Optical Image
30°
28°
26°
24°
22°
Dec. (1950)
04h54m
48m
42m
36m
30m
24m
18m

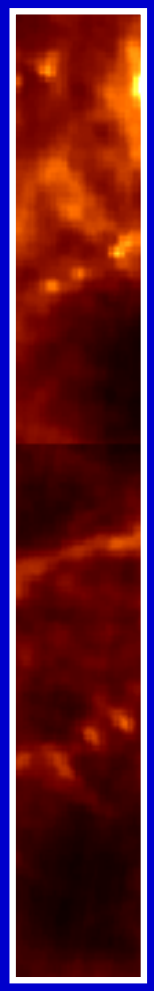

Taurus Dark Cloud Complex
100 μm ISSA image
30°
29°
28°
27°
26°
25°
24°
23°
22°
Dec. (1950)
04h54m
48m
42m
36m
30m
24m
18m
12m
R.A. (1950)
3 pc

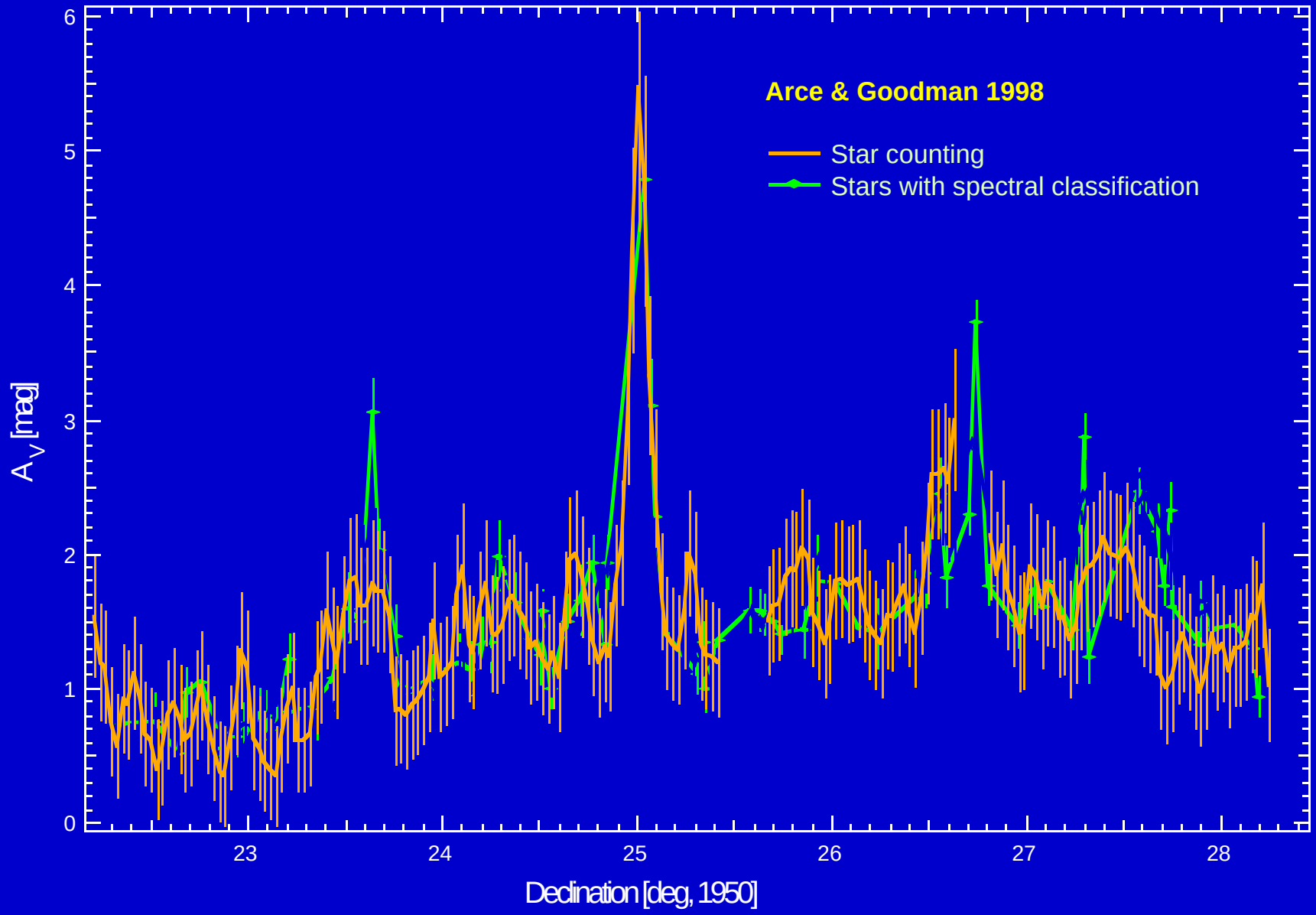
Taurus: Star Counting



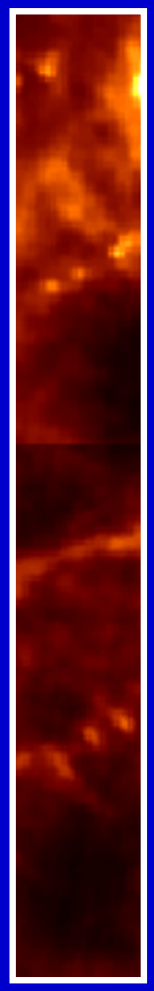


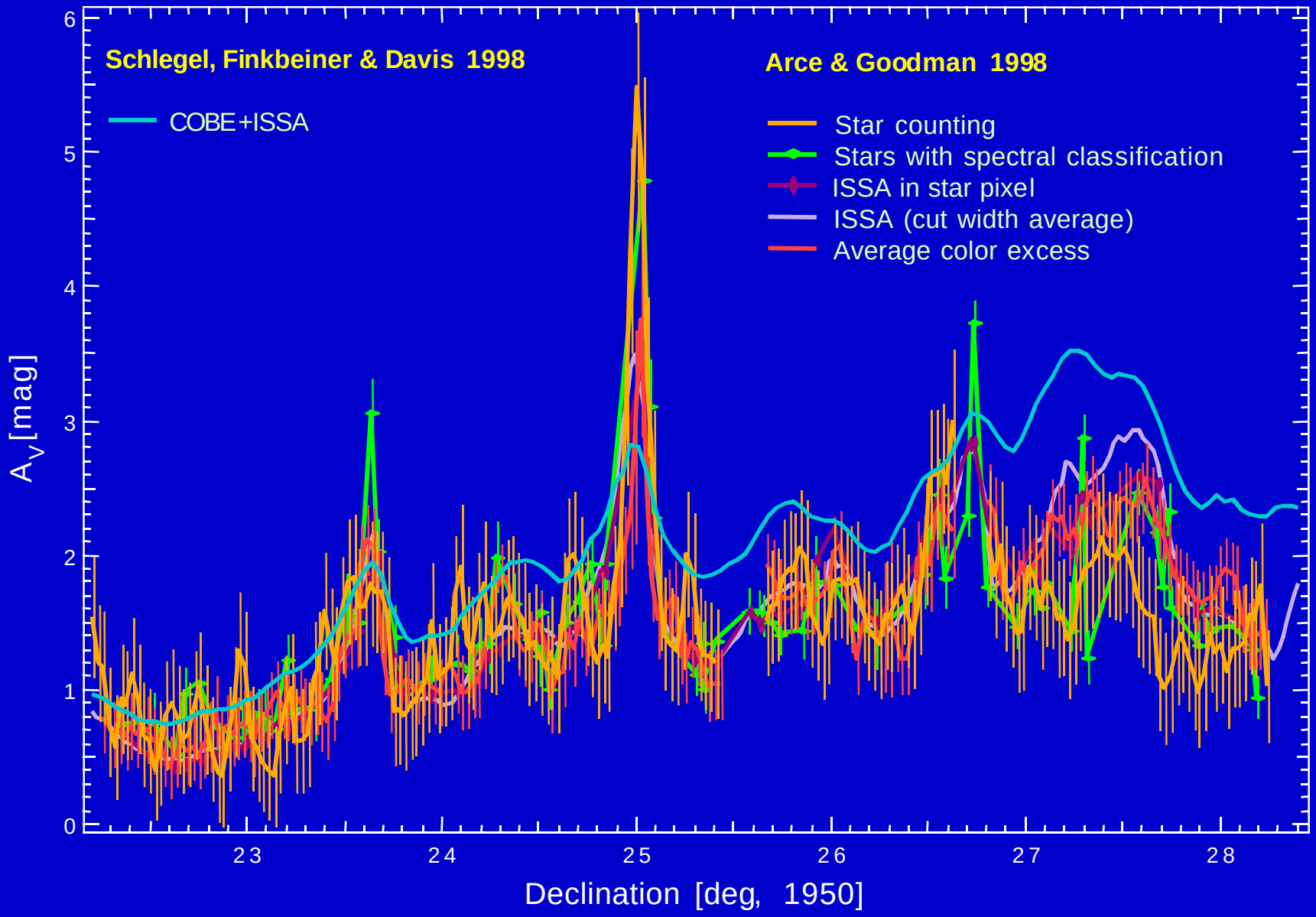
Taurus: Star Counting, Color Excess of Stars





Taurus: All Methods of Measuring Extinction



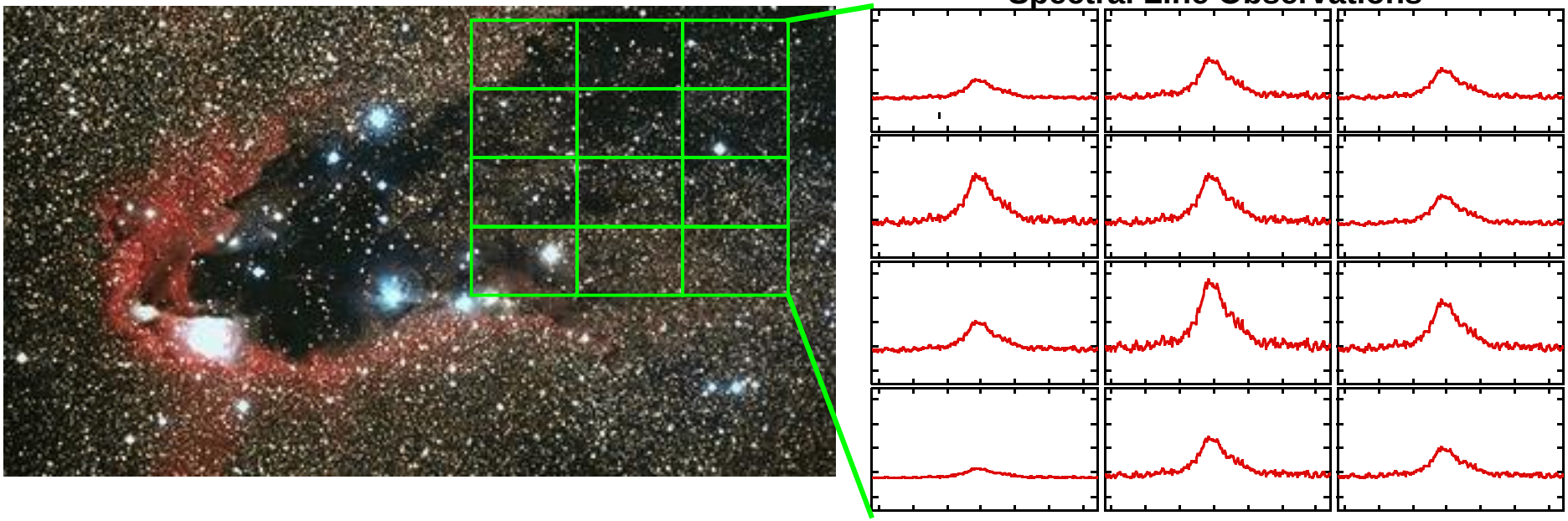


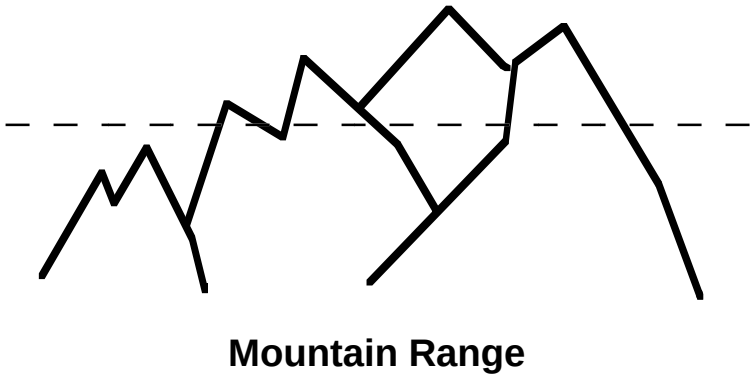
Bart Bok in 1955

"With the increased angular resolution to be provided by paraboloid antennas now under construction, and with continued emphasis on the improvement of electronic equipment, 21 cm research promises to provide increasingly useful information on the cloud structure of the interstellar medium. By continuing our efforts to blend optical and radio studies of the interstellar medium into one whole, we have real hope of greatly advancing our knowledge of the interstellar medium in years to come."

--Bart Bok, *AJ*, **60**, p. 148.

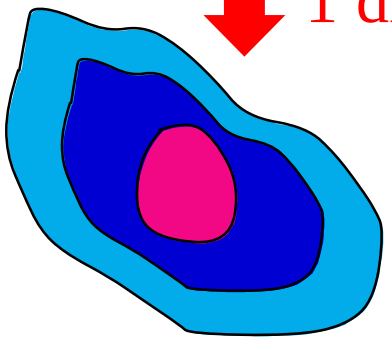
Adding a Third Dimension

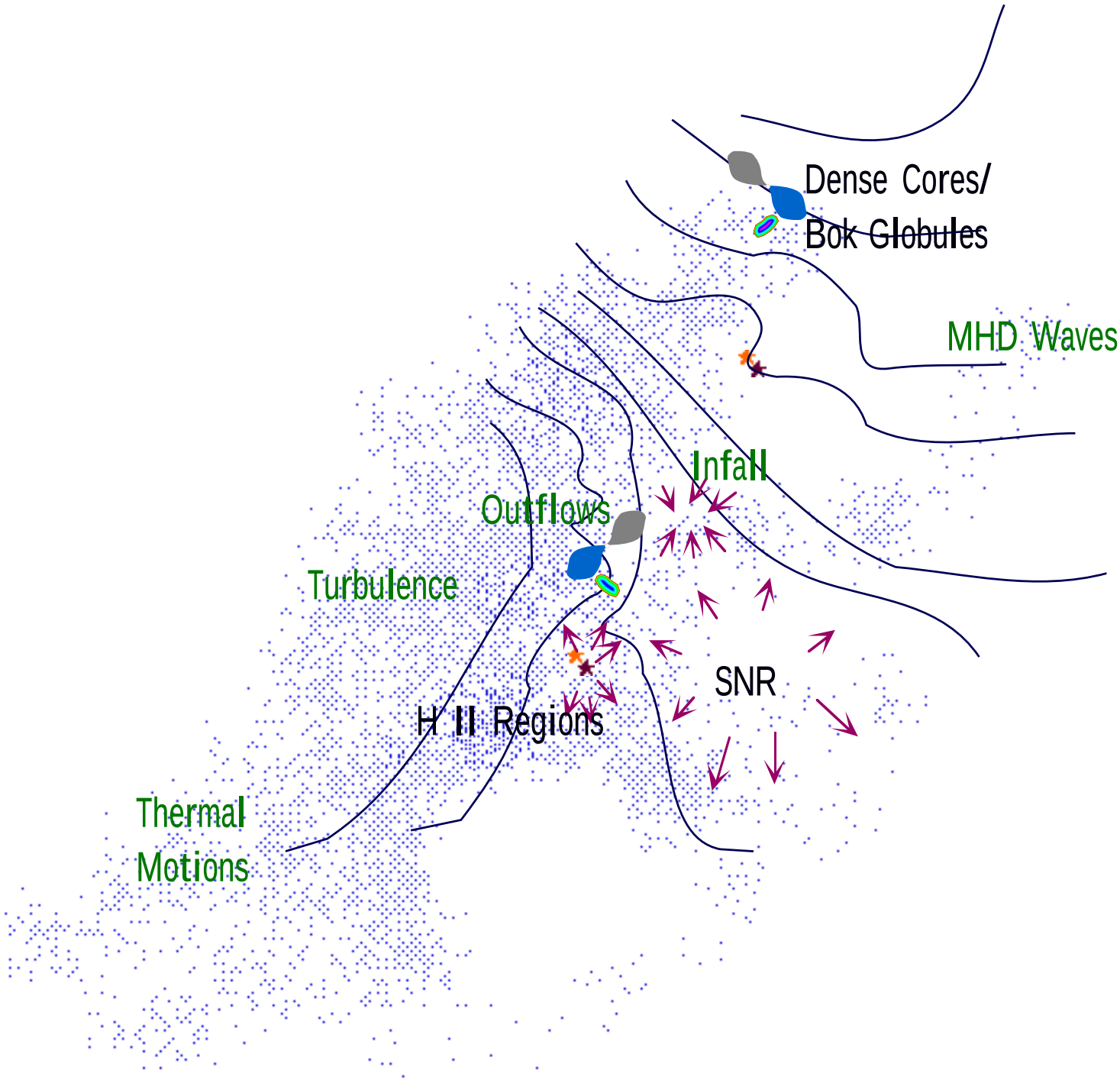




No loss of information

Loss of 1 dimension




Dense Cores/
Bok Globules
MHD Waves
Infall
Outflows
Turbulence
SNR
H II Regions
Thermal
Motions

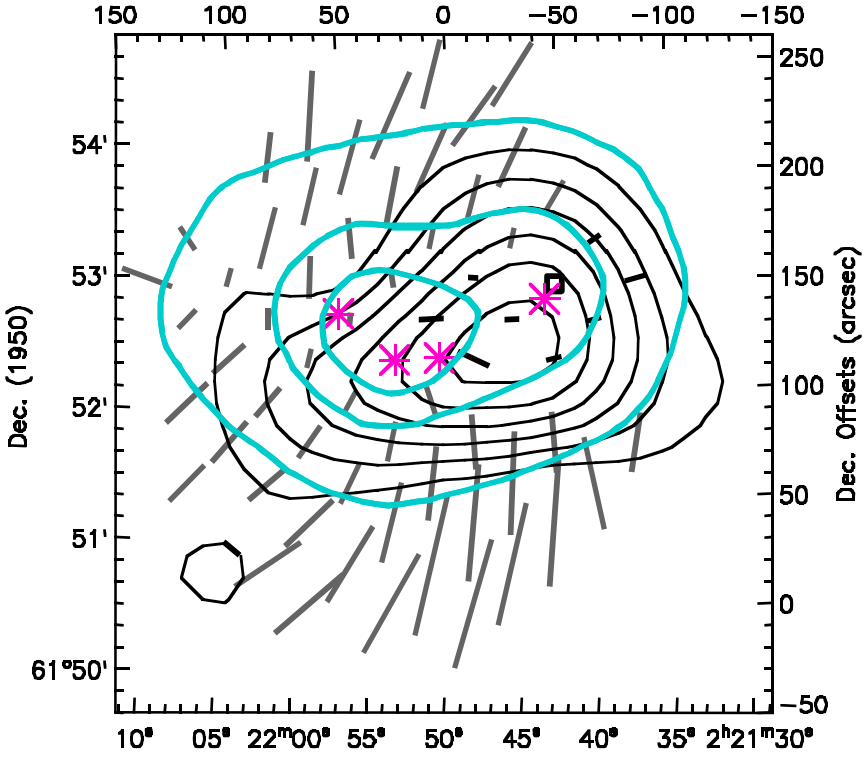
Watching the ISM Move

- W3: Massive Star-Forming Region
  - velocity information explains magnetic field geometry & star formation
- Ursa Major: High-Latitude Cloud
  - velocity analysis shows “dripping” & impact
- Dense Cores
  - velocity dimension reveals “coherence”
- Spectral Correlation Function
  - should lead to better simulations & more

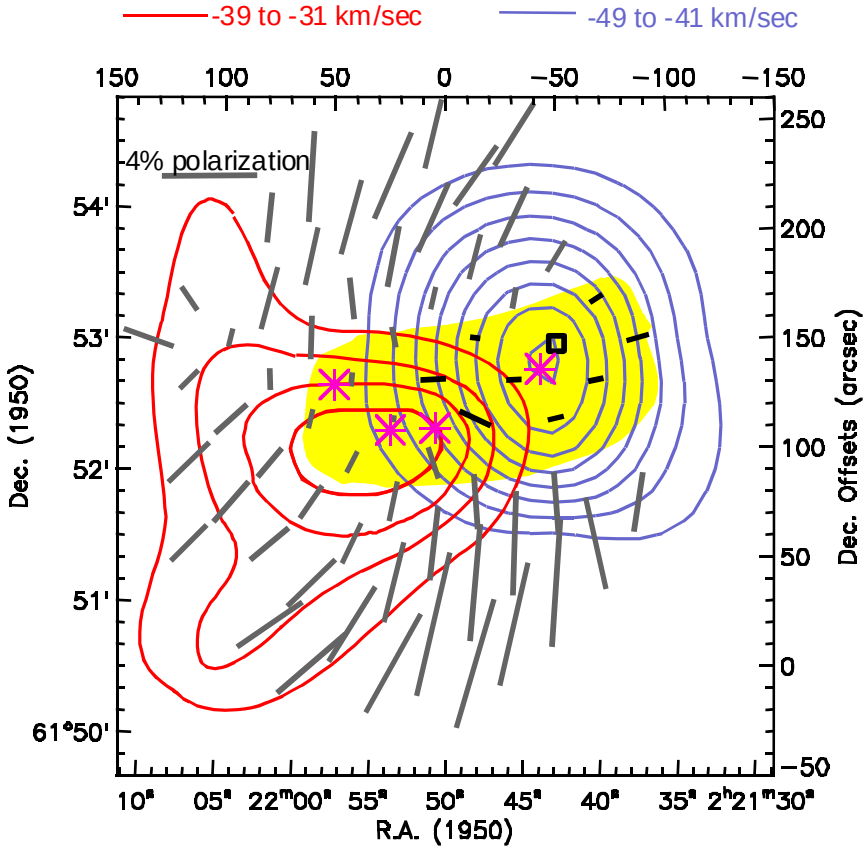
W3

^{13}CO Integrated Intensity

Dust Thermal Emission

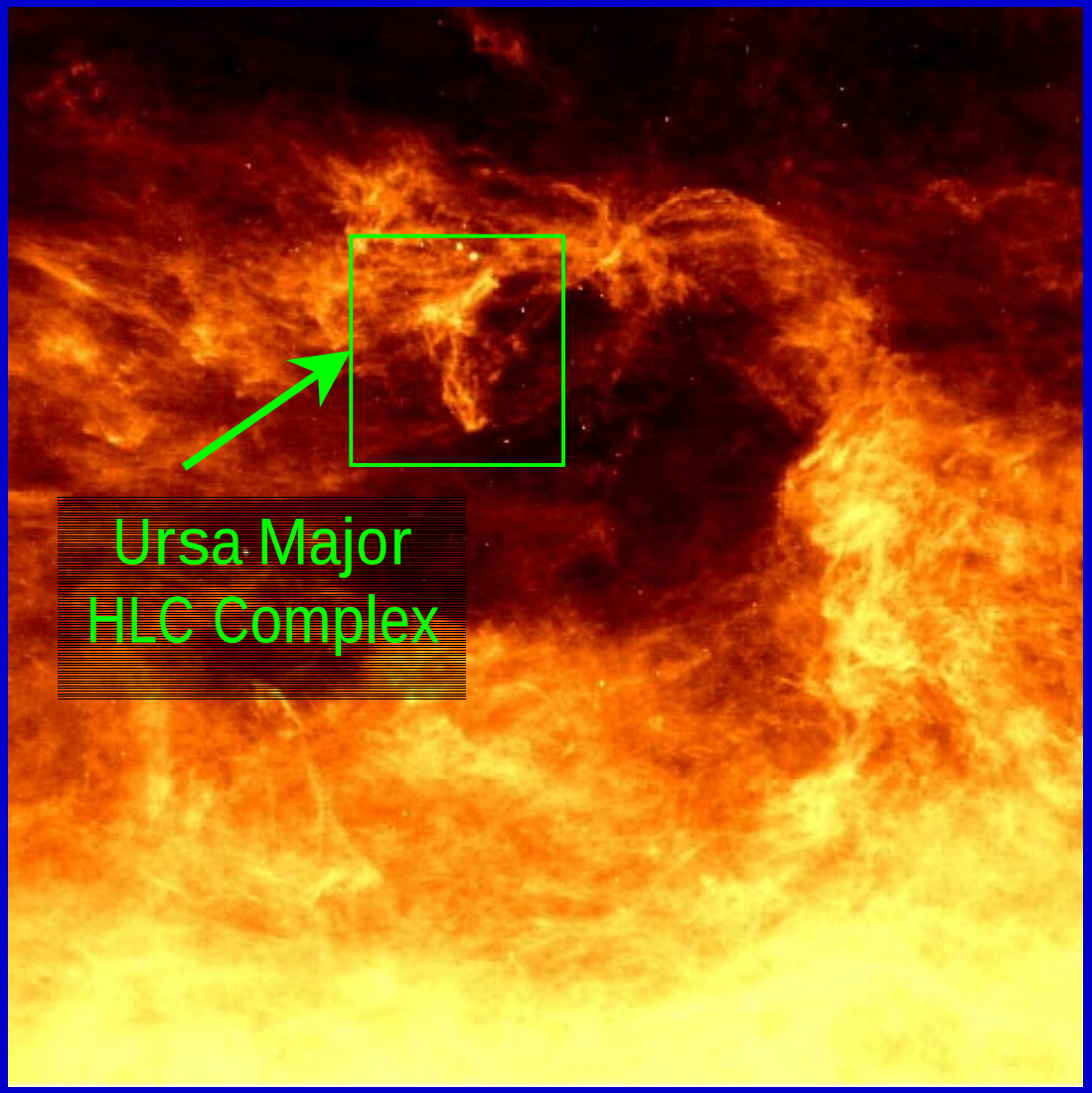


^{13}CO Channel Maps



Kannappan & Goodman 1998; Dowell 1998

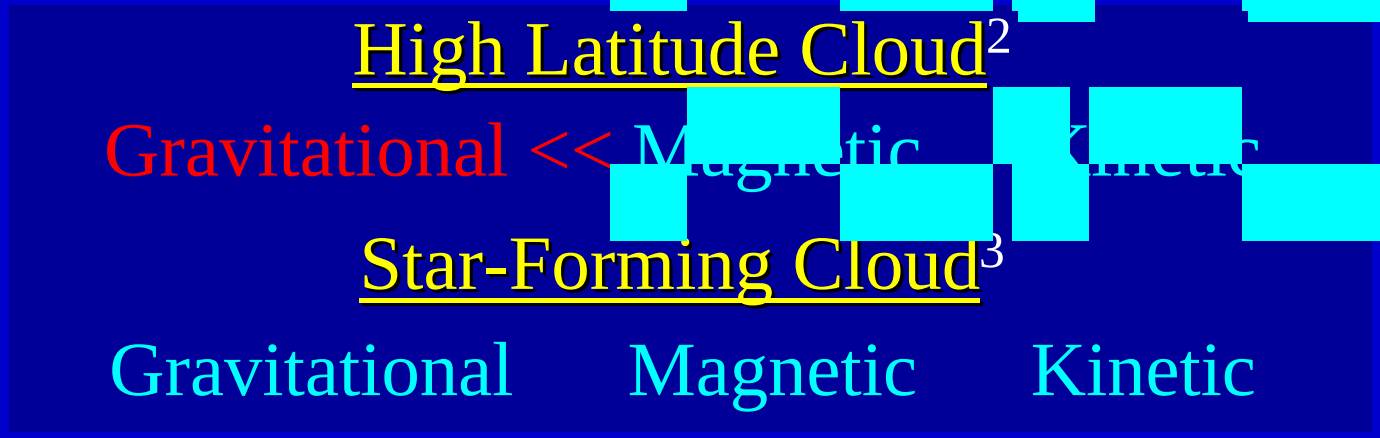
The Origin and Evolution of High-Latitude Clouds



Pound & Goodman 1997

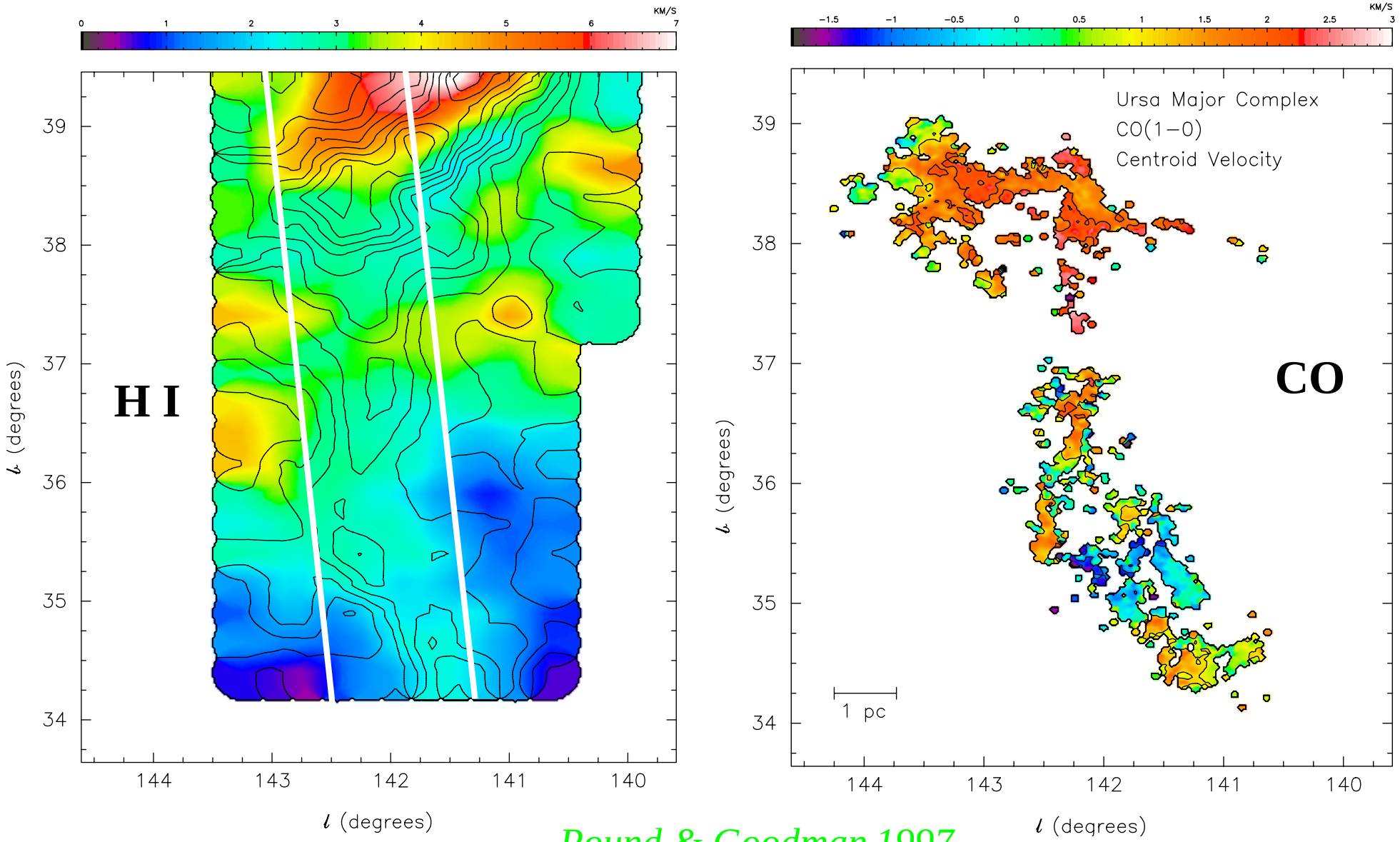
High-latitude Clouds

- "High-latitude"= very nearby (D_{UMAJ}~100 pc)
- ~No star formation[1]
- Energy distribution very different than star-forming regions

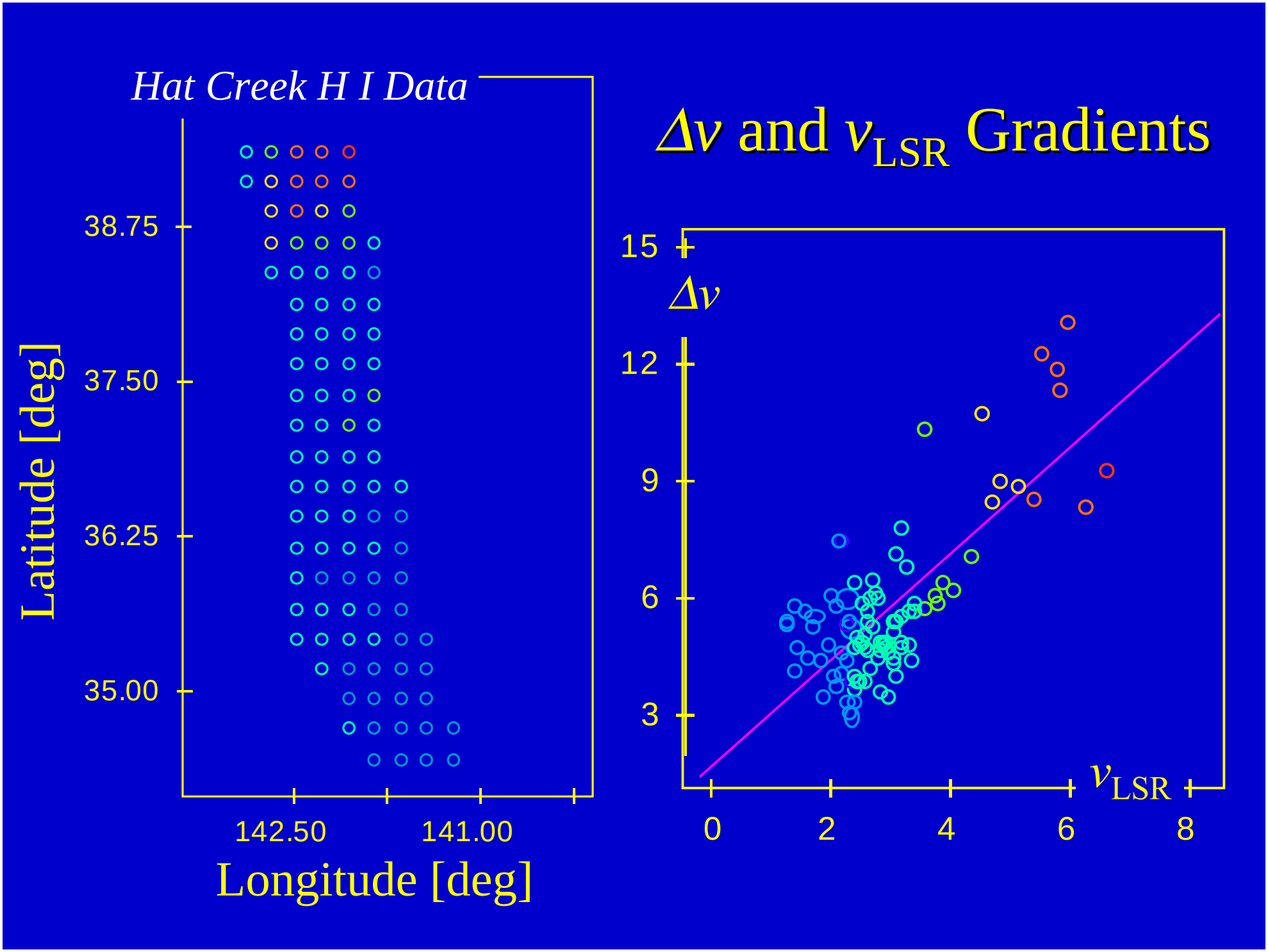


(1) Magnani et al. 1996; (2) Myers, Goodman, Güsten & Heiles 1995; (3) Myers & Goodman 1988

The Velocity Field in Ursa Major



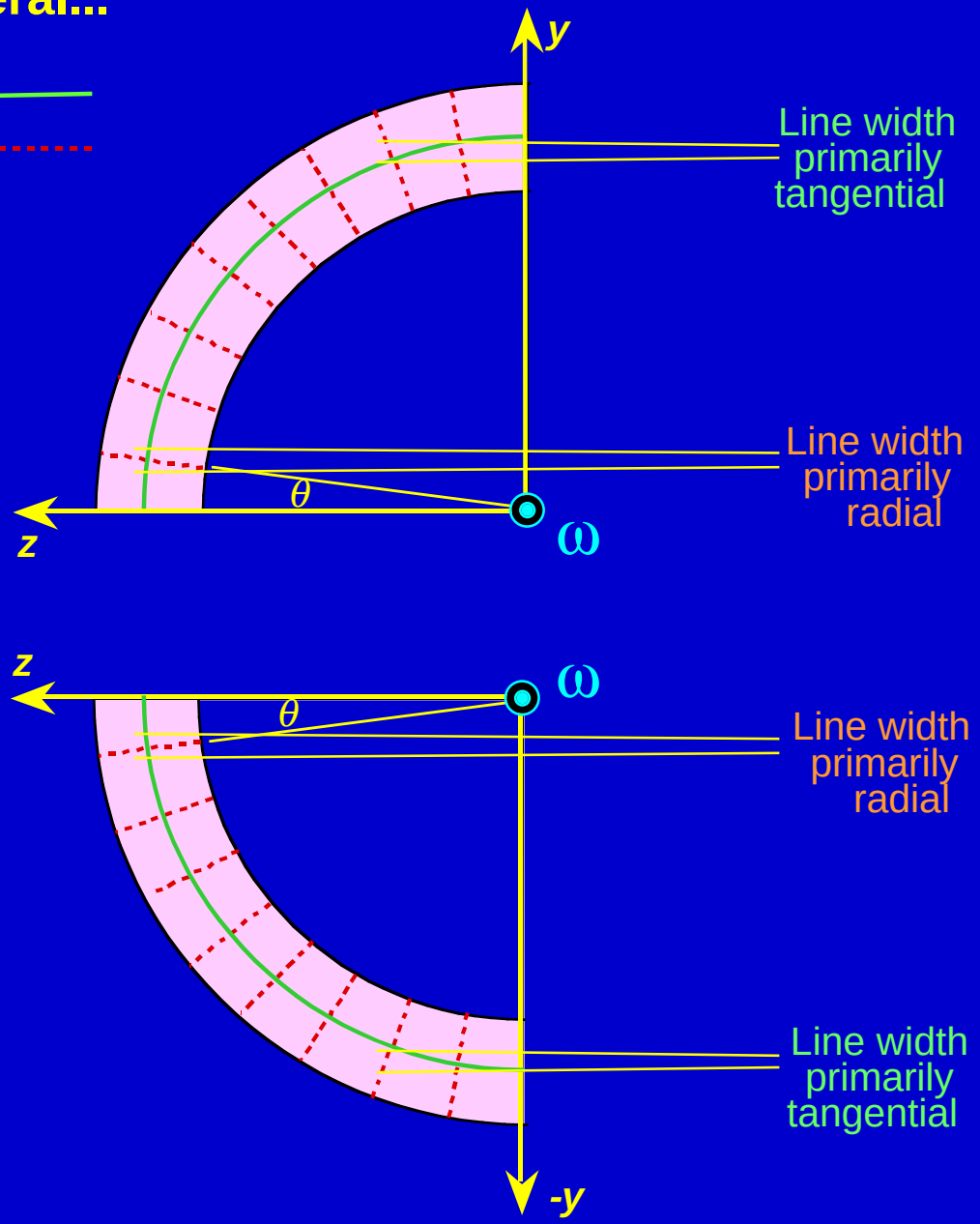
Pound & Goodman 1997


Hat Creek H I Data
38.75
37.50
36.25
35.00
Latitude [deg]
142.50
141.00
Longitude [deg]
Δv and v_LSR Gradients
15
Δv
12
9
6
3
v_LSR
0
2
4
6
8

In General...

Δv_{tan}

Δv_{rad}



...in Ursa Major

$\Delta v_{z,obs}$

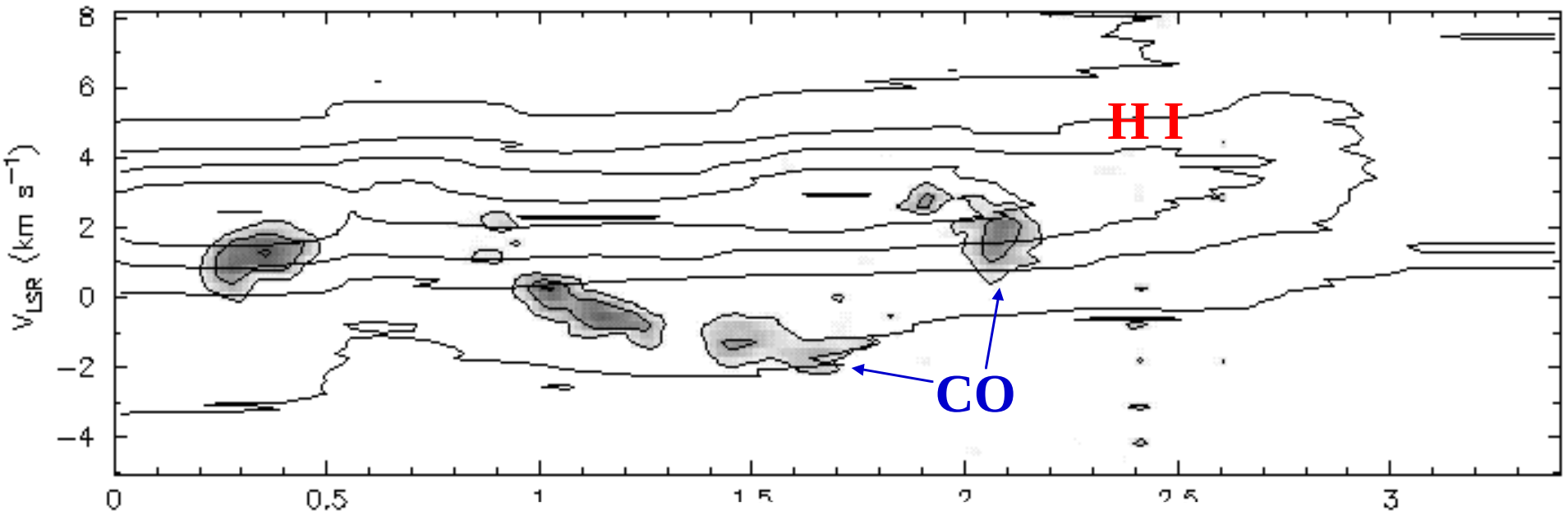
implication:

$\Delta v_{tan} \gg \Delta v_{rad}$

$\Delta v_{z,obs}$

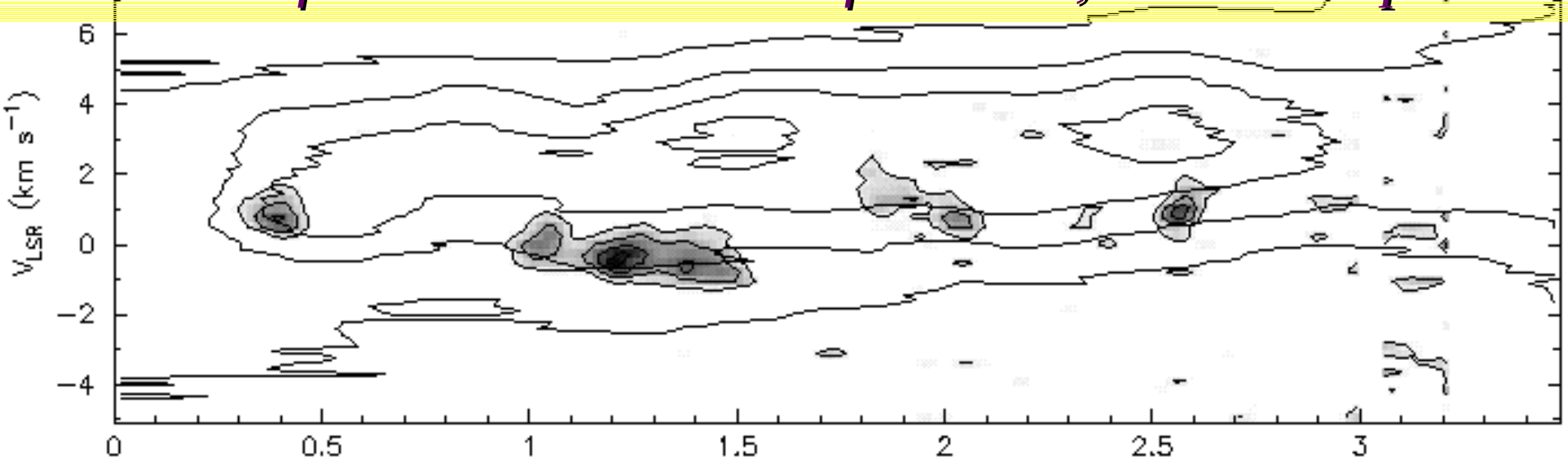
implication:

$\Delta v_{tan} \ll \Delta v_{rad}$

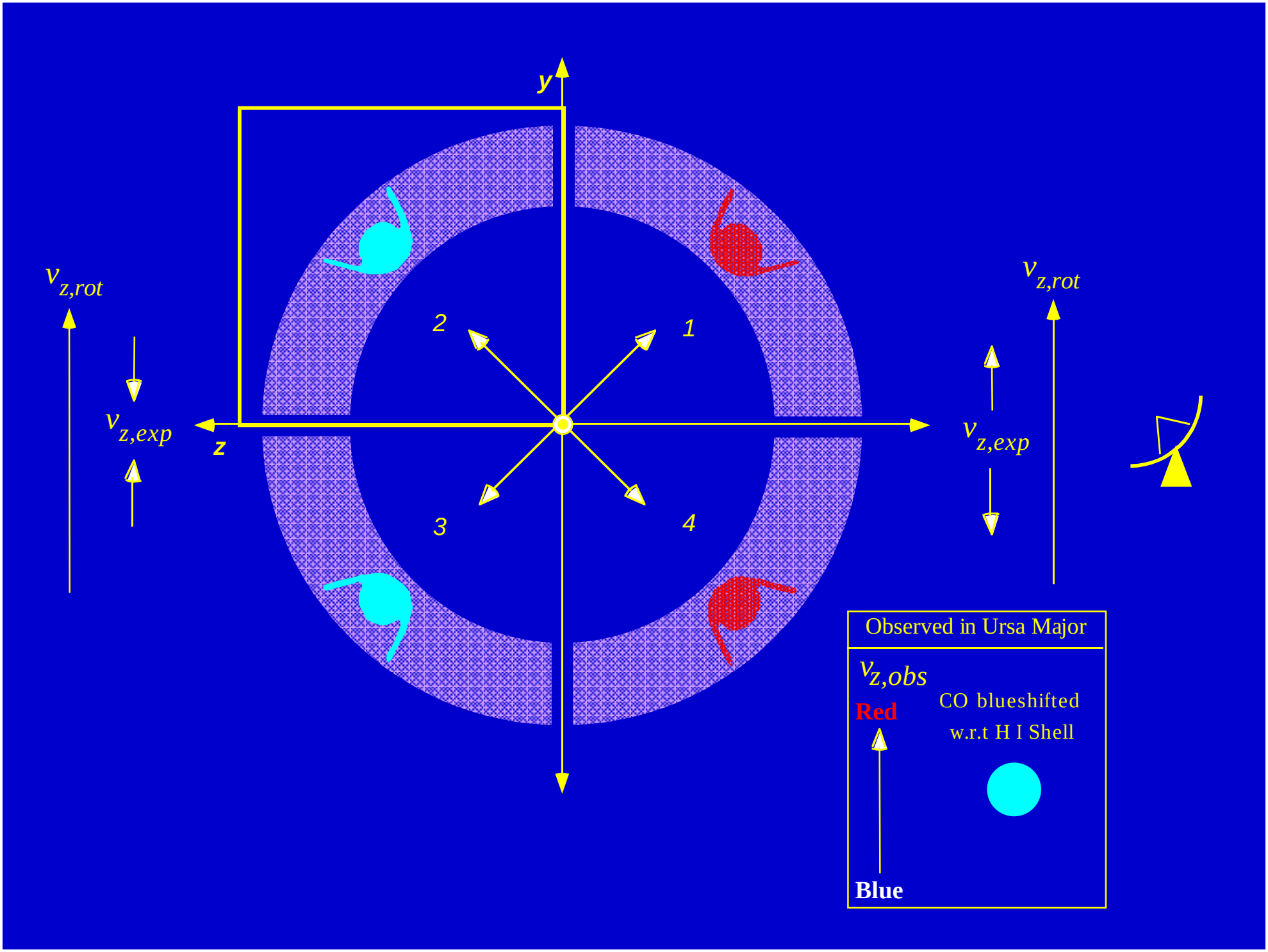


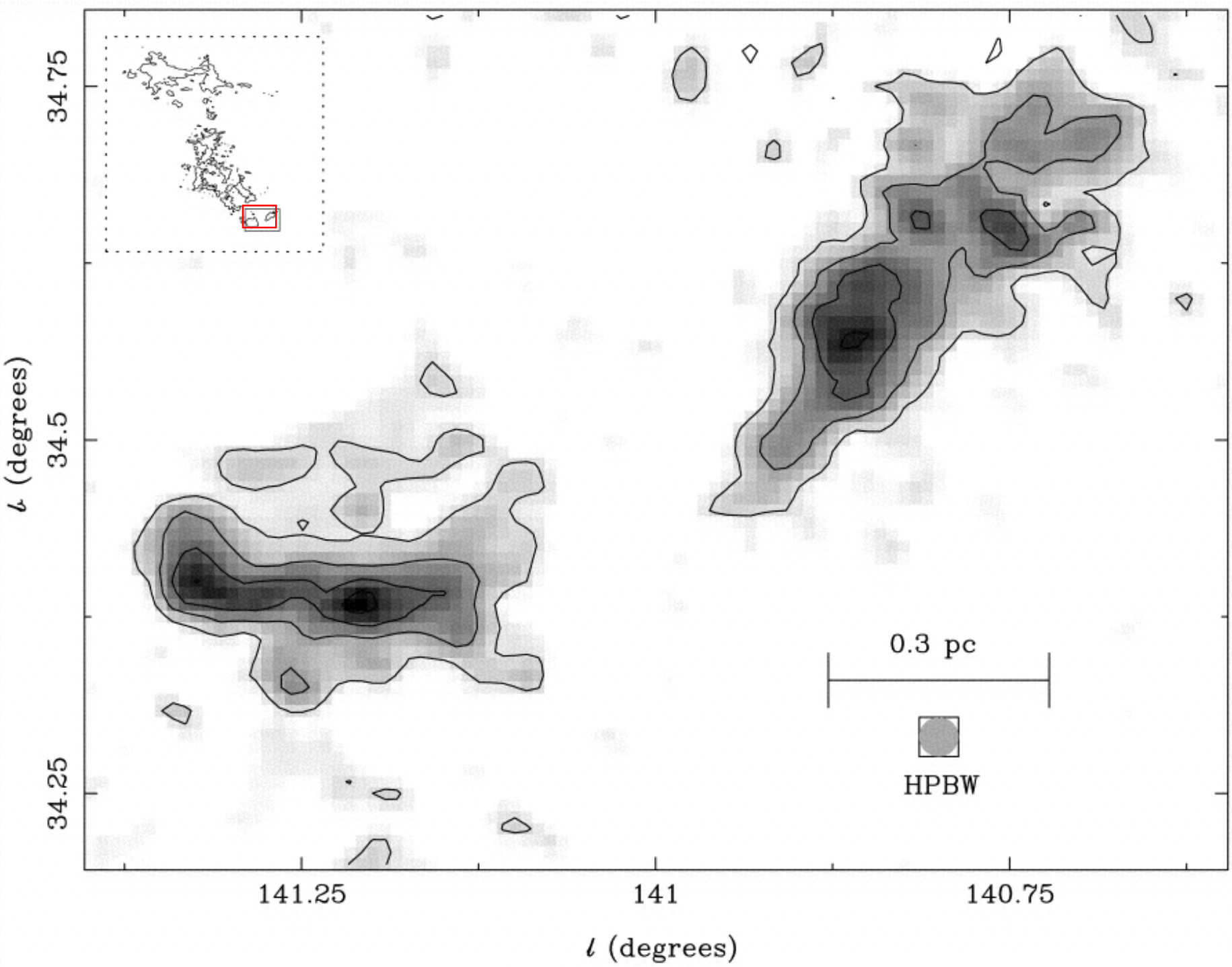
Position Along Filament 1

CO Blueshifted w.r.t. H I in both filaments, in arc-like pattern



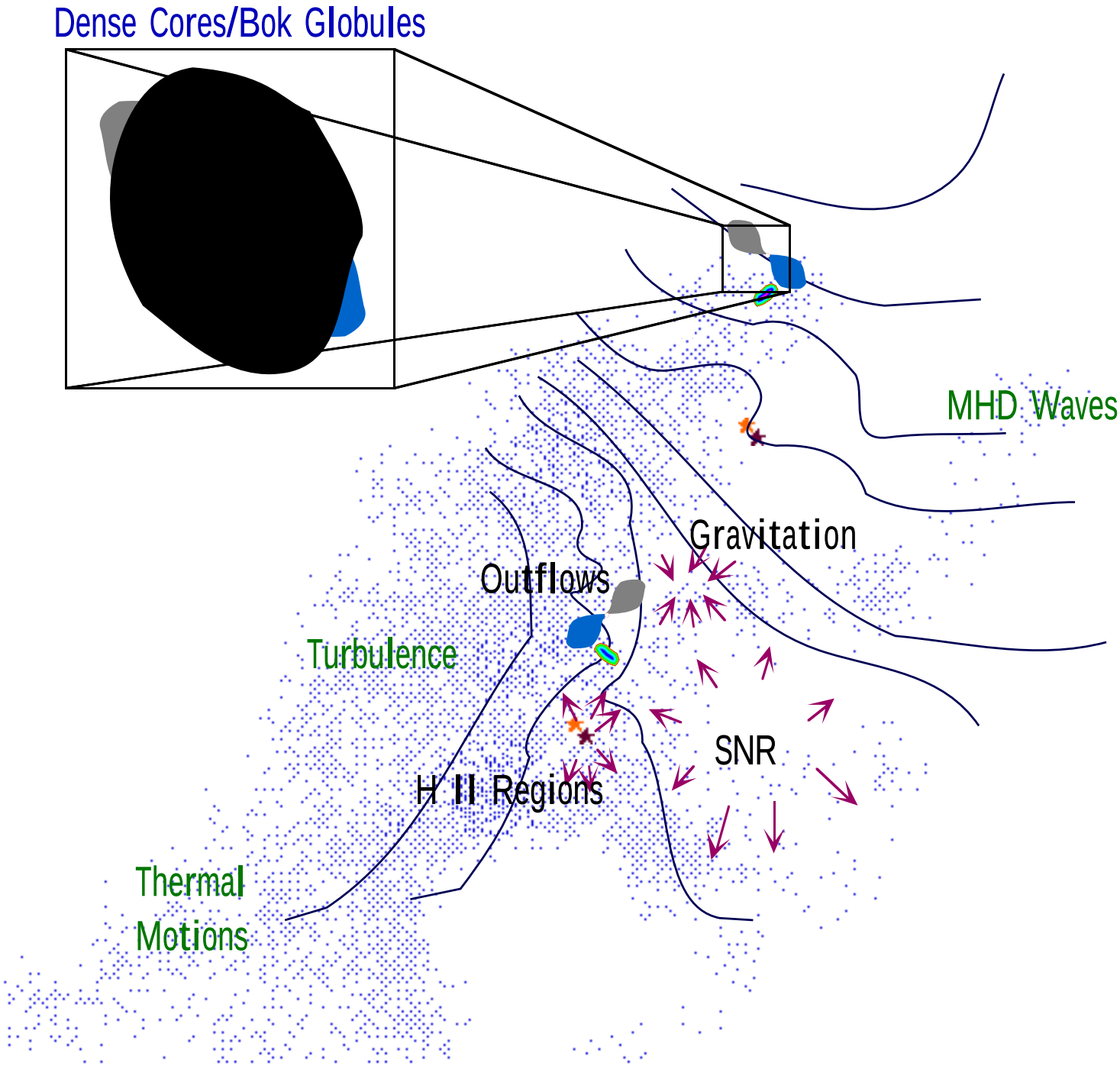
Position Along Filament 2


y
z
$v_{z,rot}$
$v_{z,exp}$
$v_{z,rot}$
$v_{z,exp}$
1
2
3
4
Observed in Ursa Major
$v_{z,obs}$
Red
Blue
CO blueshifted
w.r.t H I Shell


34.75
34.5
34.25
b (degrees)
141.25
141
140.75
l (degrees)
0.3 pc
HPBW

Implications of Ursa Major Study

- Many HLC's may be related to "supershell" structures; some shells harder to identify than NCP Loop.
- (Commonly observed) velocity offsets between atomic and molecular gas may be due to impacts, followed by conservation of momentum. Use this as a clue in other cases.


Dense Cores/Bok Globules
MHD Waves
Gravitation
Outflows
Turbulence
SNR
H II Regions
Thermal
Motions

Bok and his Globules

"In recent years several authors have drawn attention to the possibility of the formation of stars from condensations in the interstellar medium (Spitzer 1941; Whipple 1946)."

--Bok & Reilly 1947, *ApJ*, **105**, 255, opening paragraph

Bok and his Globules

"The globules are interesting objects… Every one of them merits further careful study with the largest available reflecting telescopes."

--Bok & Reilly 1947, *ApJ*, **105**, 255, closing paragraph

1990: *"Bart Bok Was Correct!"*

THE ASTROPHYSICAL JOURNAL, 365:L73–L76, 1990 December 20

STAR FORMATION IN SMALL GLOBULES: BART BOK WAS CORRECT!

JOÃO LIN YUN AND DAN P. CLEMENS
Astronomy Department, Boston University
Received 1990 August 15; accepted 1990 October 4

ABSTRACT

We have probed a large sample of optically selected, small molecular clouds (Bok globules) using *IRAS* co-added images to search for associated young stellar objects. The *IRAS* images were examined for point sources located within the boundaries of the optical and infrared extents of 248 clouds. A total of 57 of the globules (23% of the sample) show evidence for associated point sources. From a comparison of the 12 and 25 μm fluxes of these objects, we find a distribution of spectral indices consistent with the presence of circumstellar dust. Similar analysis of other point sources within the *IRAS* images, but far from the globule boundaries, shows only normal stellar spectral indices. All young stars more massive than 0.7 $M_\odot$ were likely found. However, extrapolation of a Miller-Scalo initial mass function to the hydrogen-burning limit indicates that only about 20% of the total number of stars were found. It is therefore likely that almost every Bok globule harbors a young star. The inferred star formation efficiency is about 6% again based on the Miller-Scalo initial mass function. Interestingly, this is the best test in 43 years of the conjecture made by Bart Bok that dust globules could represent the earliest stage of star formation. We are pleased to report that his conjecture was correct.

Subject headings: infrared: sources — interstellar: matter — luminosity function — nebulae: general — stars: formation — stars: luminosities — stars: pre–main-sequence

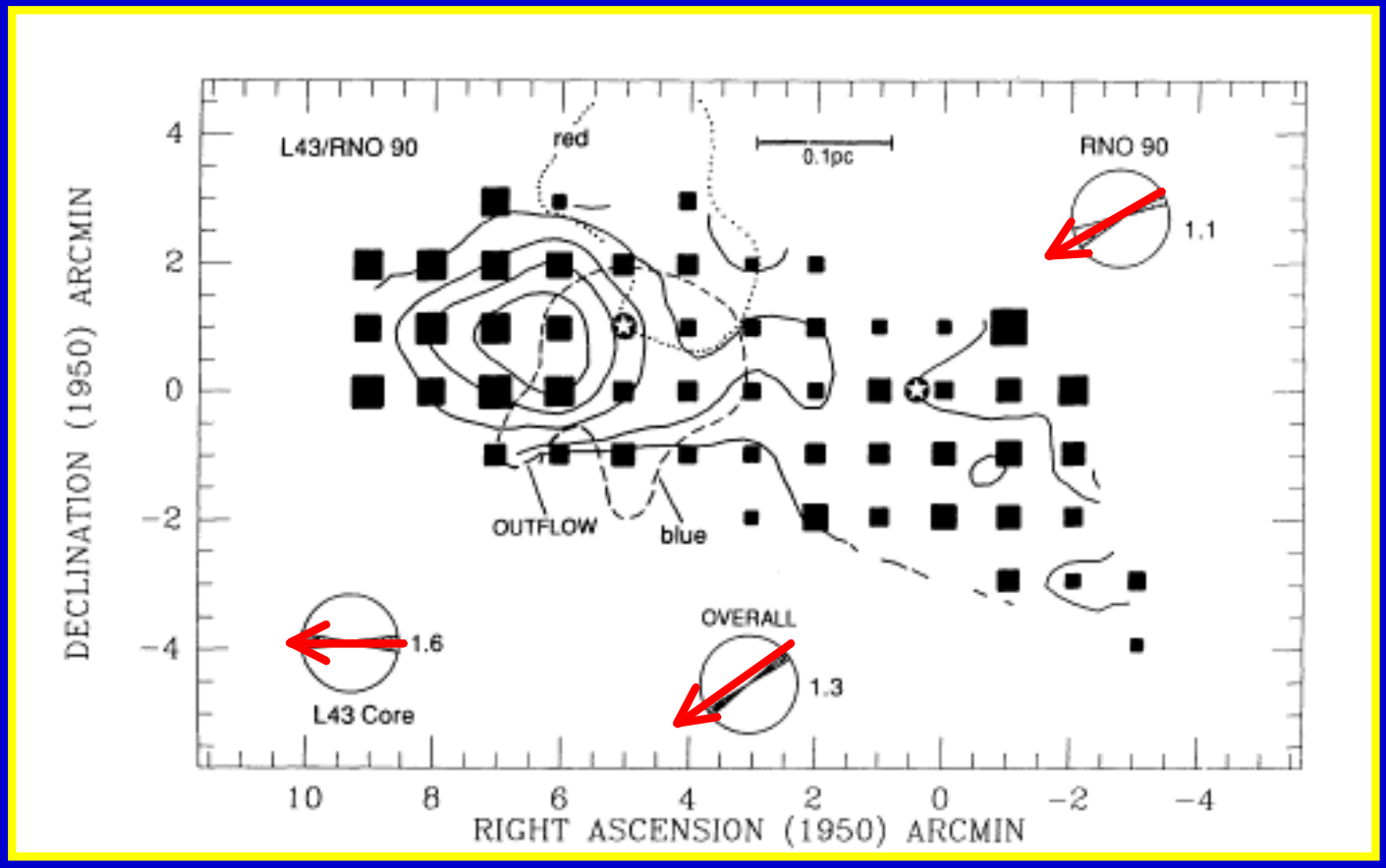
Motions *Of*, *In* and *Around* Dense Cloud Cores

- Rotation
  - β~0.04; enough to matter but not to fragment
- Velocity Coherence
  - Cores as "Islands of Calm in a Turbulent Sea"
- Bulk motion
  - Infall: see Ho, Lada, Keto, Myers, Williams, Wilner, Zhang...
  - Outflow: see Arce, Lada, Raymond...

Coherent Cores: “Islands of Calm in a Turbulent Sea”

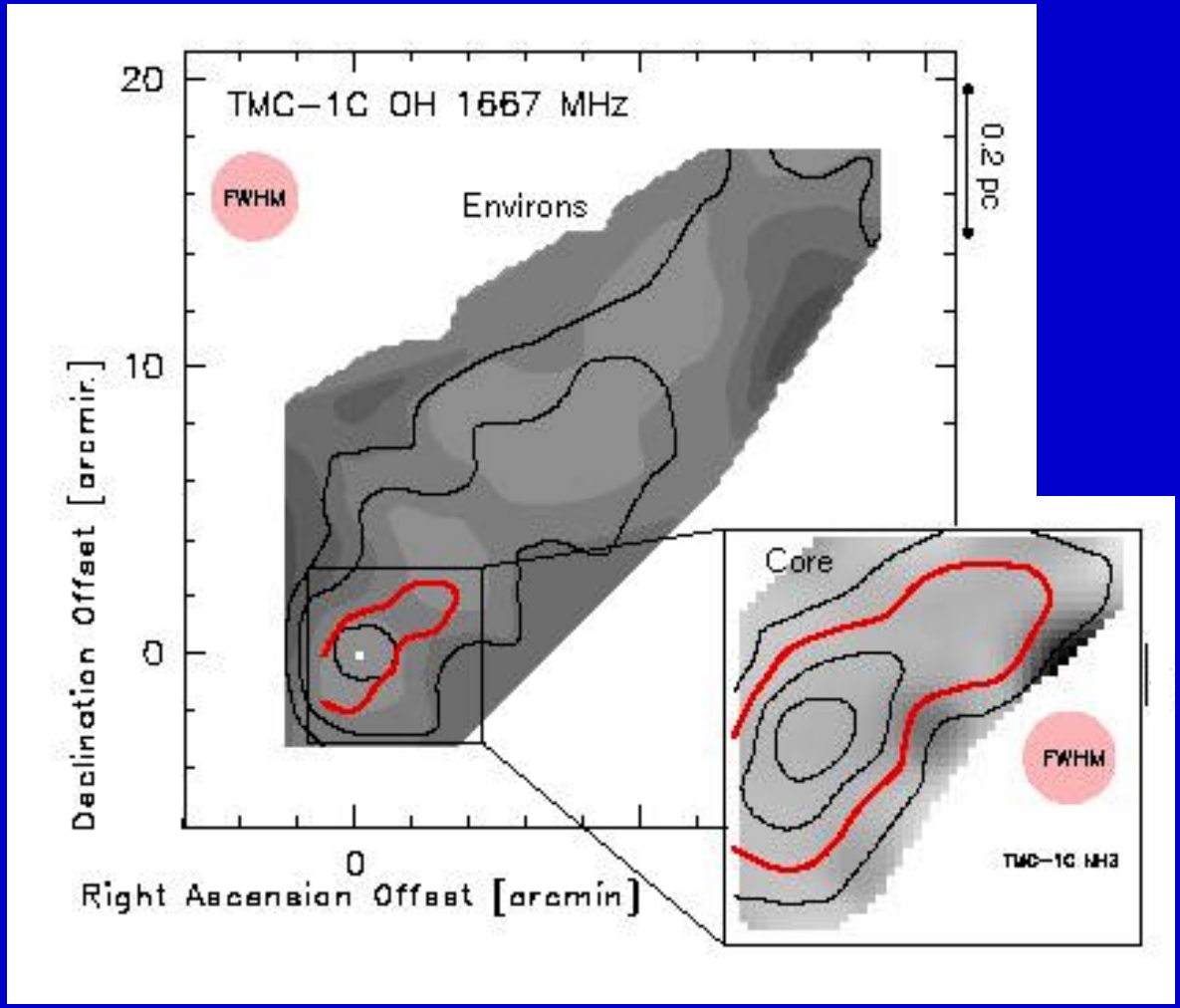
"Rolling Waves" by KanO Tsunenobu © The Idemitsu Museum of Arts.

Hint #1: Independent Core Rotation



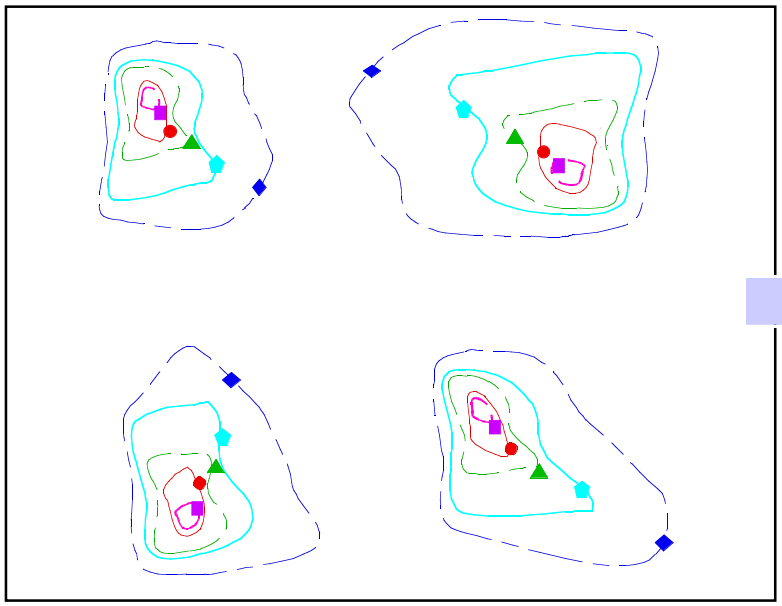
Goodman, Benson, Fuller & Myers 1993

Hint #2: Constant Line Width in Cores?



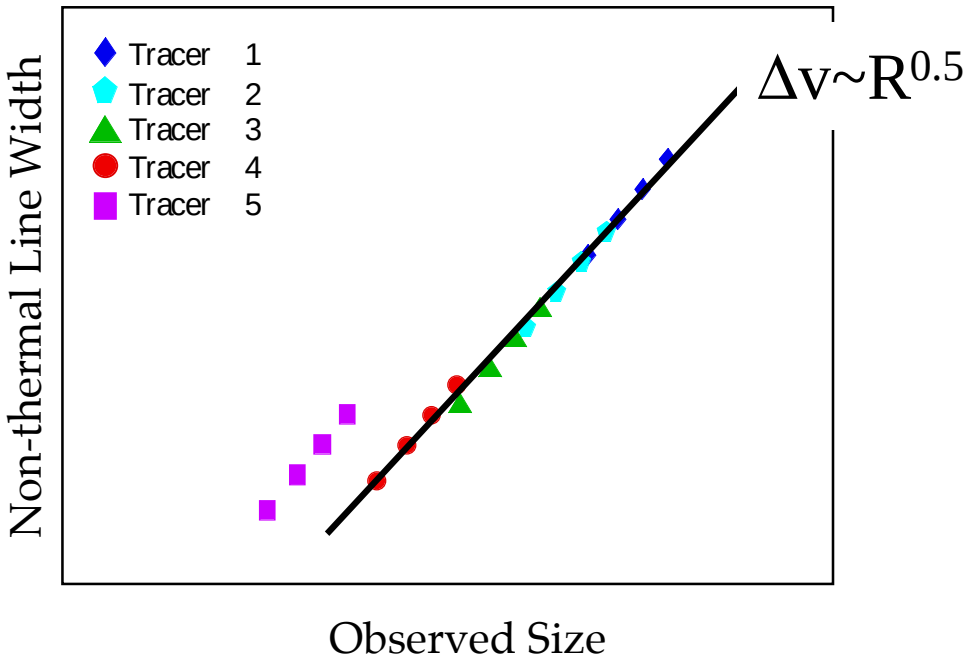
Types of Line width-Size Relations

Ensemble of Clouds



FWHM of Various Tracers Shown

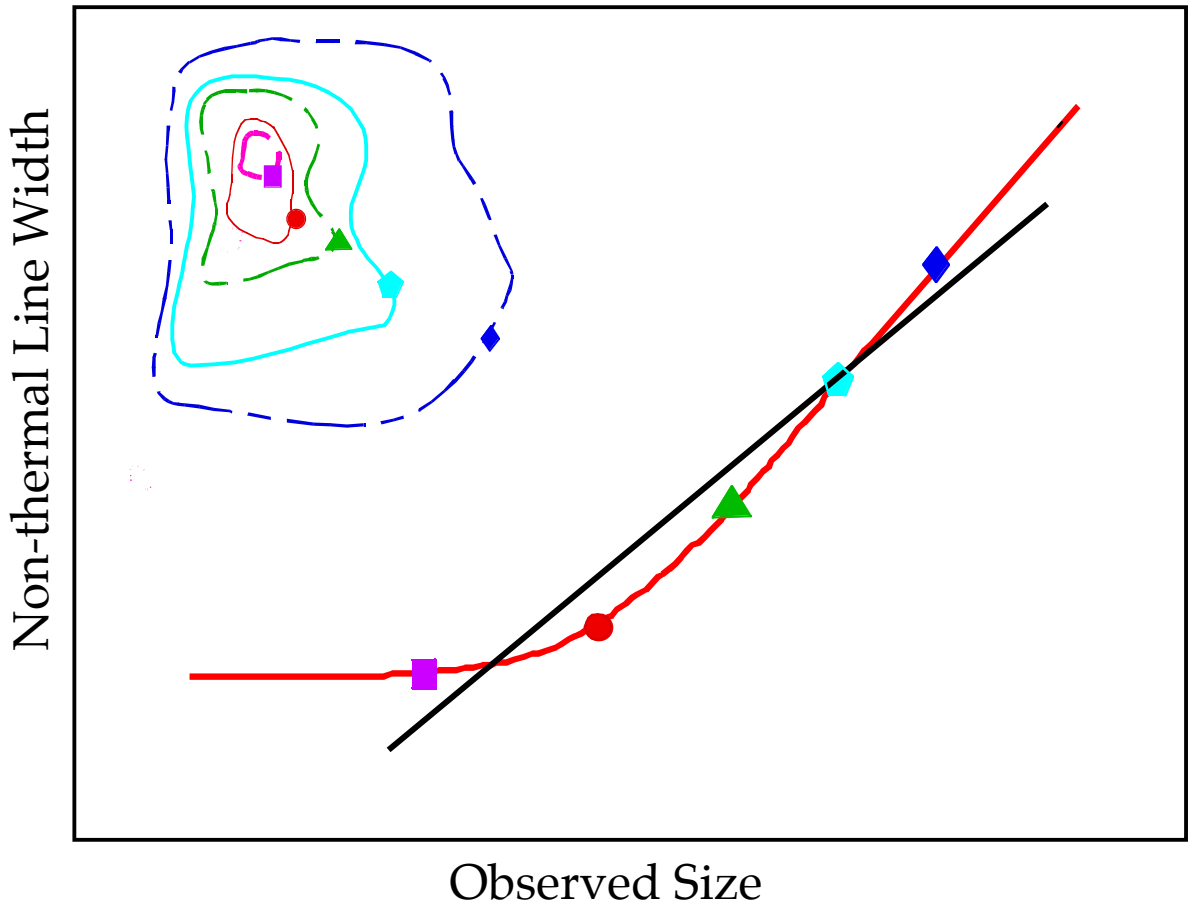
Type 1: "Larson's Law"



Gives overall state of ISM~magnetic virial equilibrium.
See Larson 1981; Myers & Goodman 1988 for examples.

Types of Line width-Size Relations

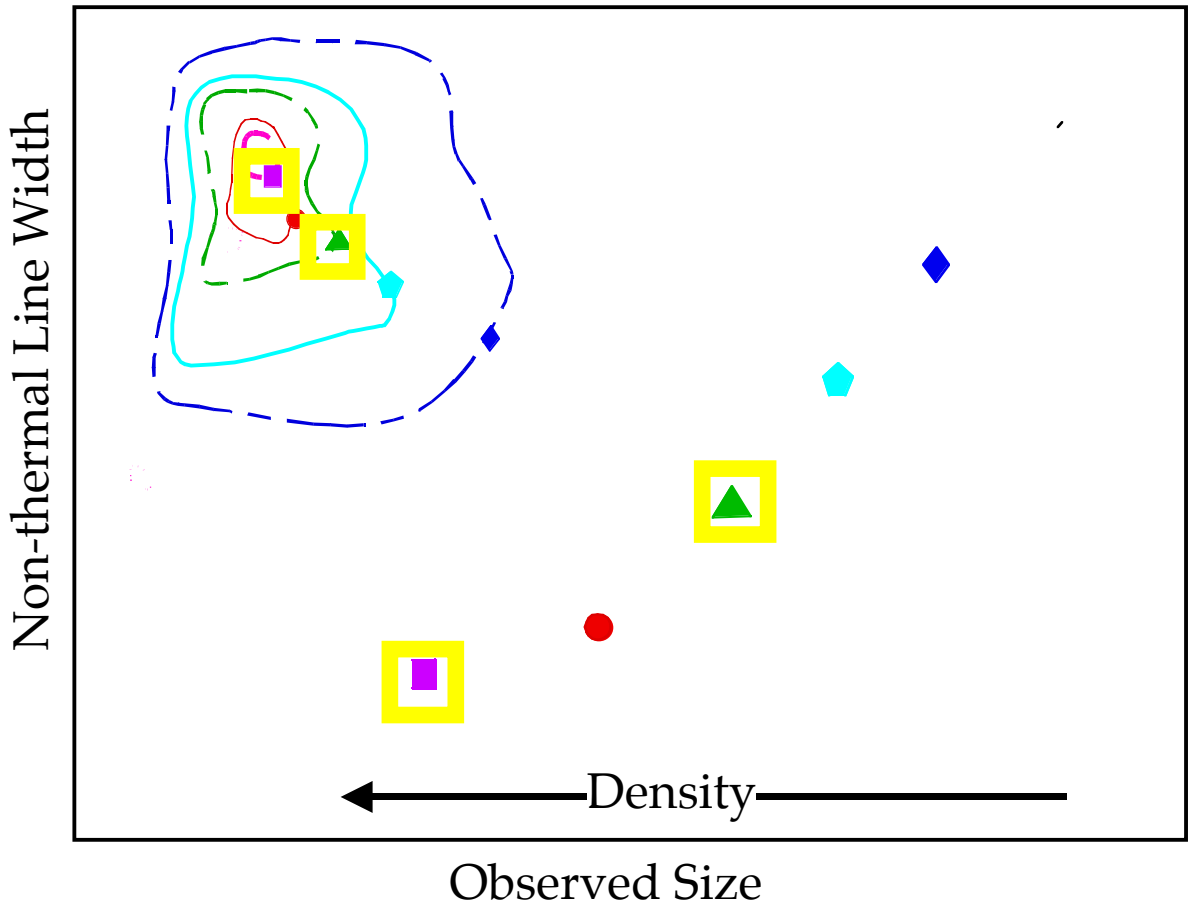
"Type 3:" Single Cloud Observed in Multiple Tracers



Gives pressure structure of an individual cloud.
See Fuller & Myers 1992.

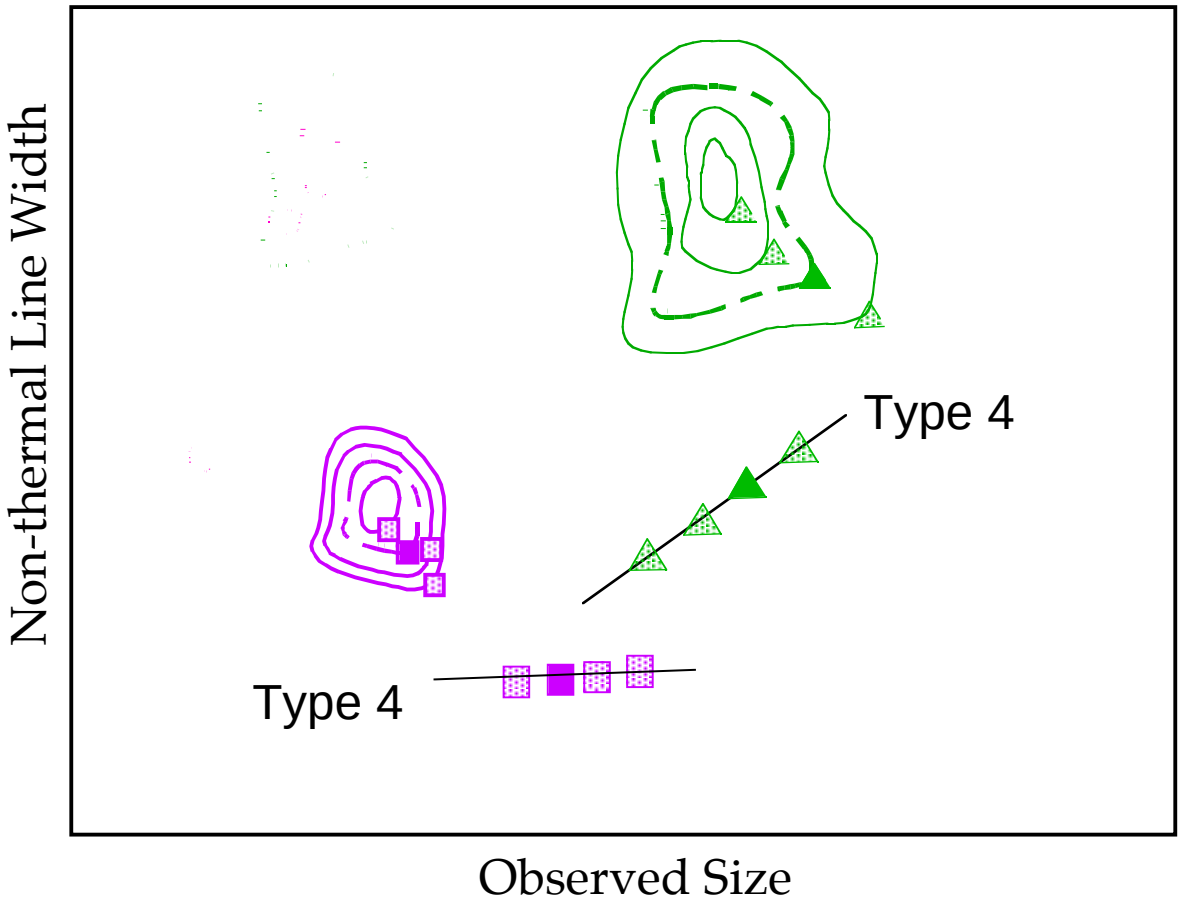
Types of Line width-Size Relations

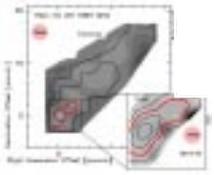
"Type 3:" Single Cloud Observed in Multiple Tracers



Types of Line width-Size Relations

"Type 4:" Single Cloud Observed in a Single Tracer



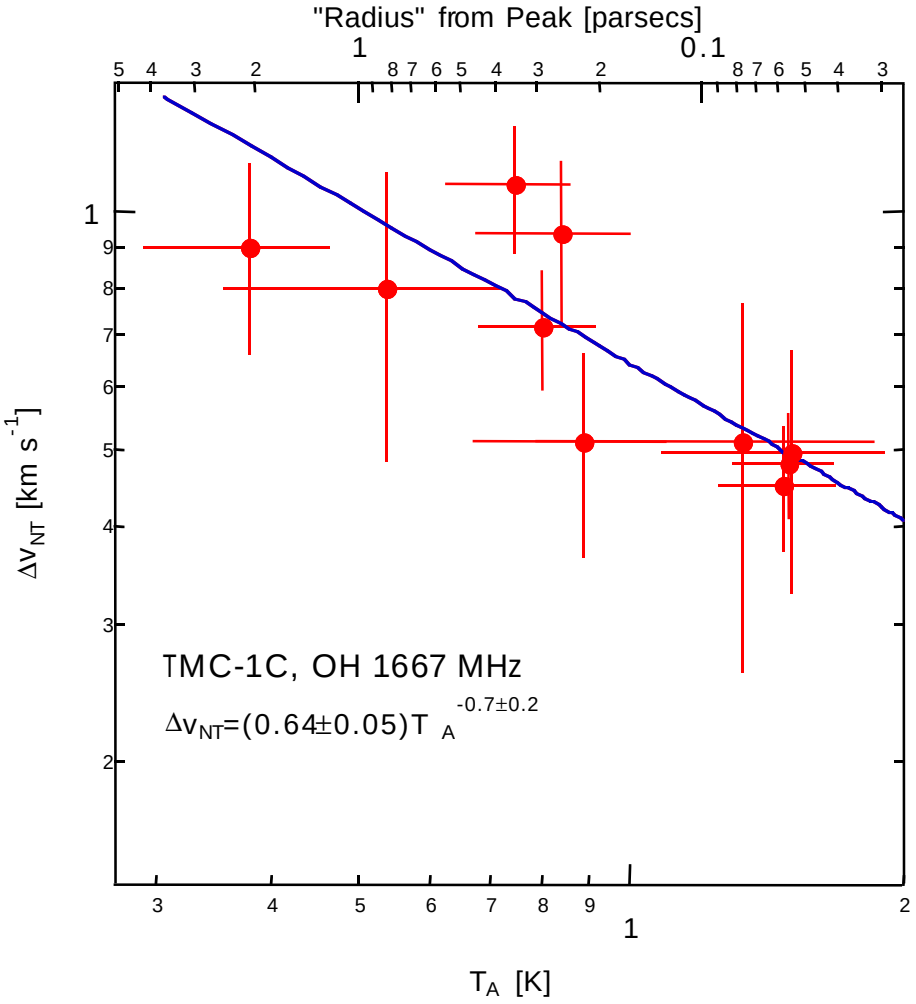


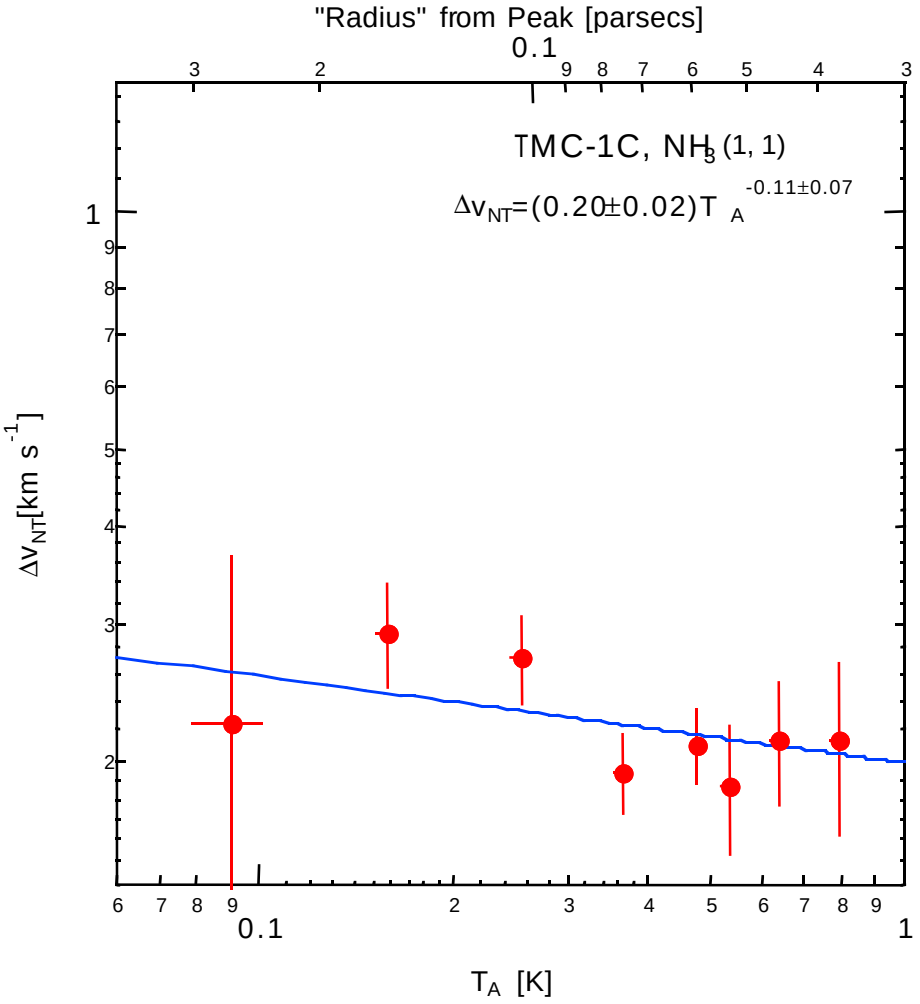
Gives information on power spectrum of velocity fluctuations.

See Barranco & Goodman 1998; Goodman, Barranco, Heyer & Wilner 1998.

An Example of the (Original) Evidence for Coherence

Type 4 Line width-"Size" Relations

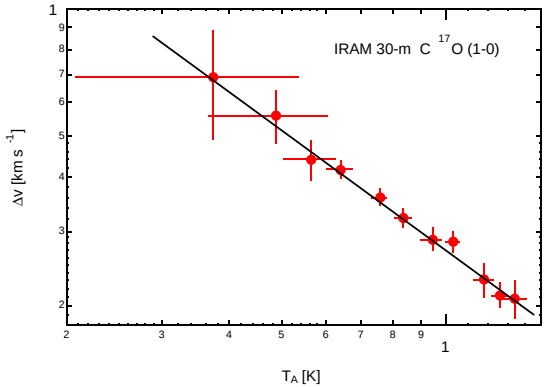


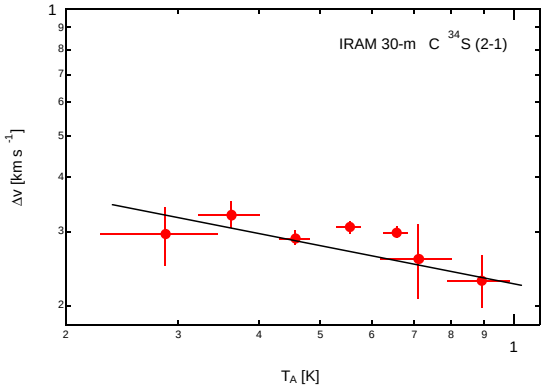


$$\Delta v_{NT} = (1.0 \pm 0.2) R^{0.27 \pm 0.08}$$

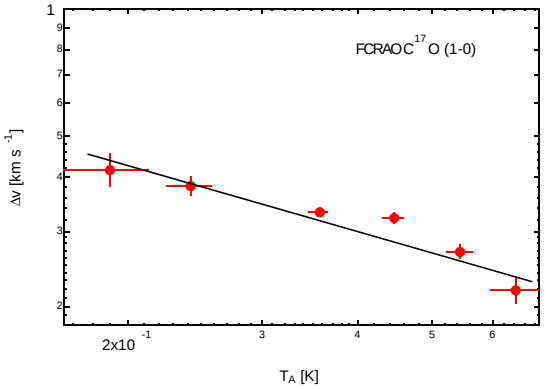
$$\Delta v_{NT} = (0.30 \pm 0.09) R^{0.12 \pm 0.08}$$

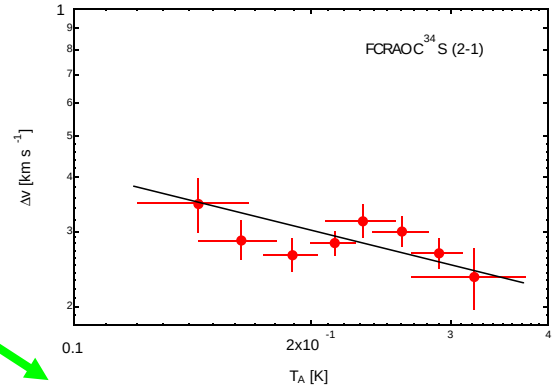
The (Newer) Evidence for Coherence

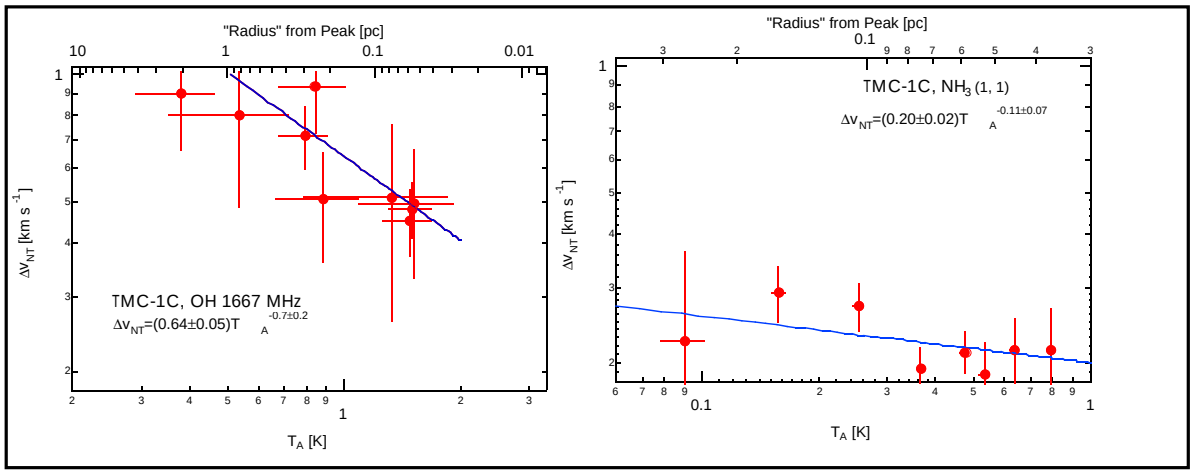


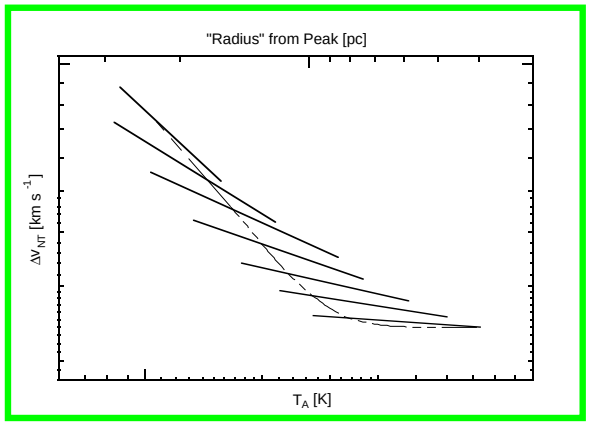


Type 4 slope appears to decrease with density, as predicted.

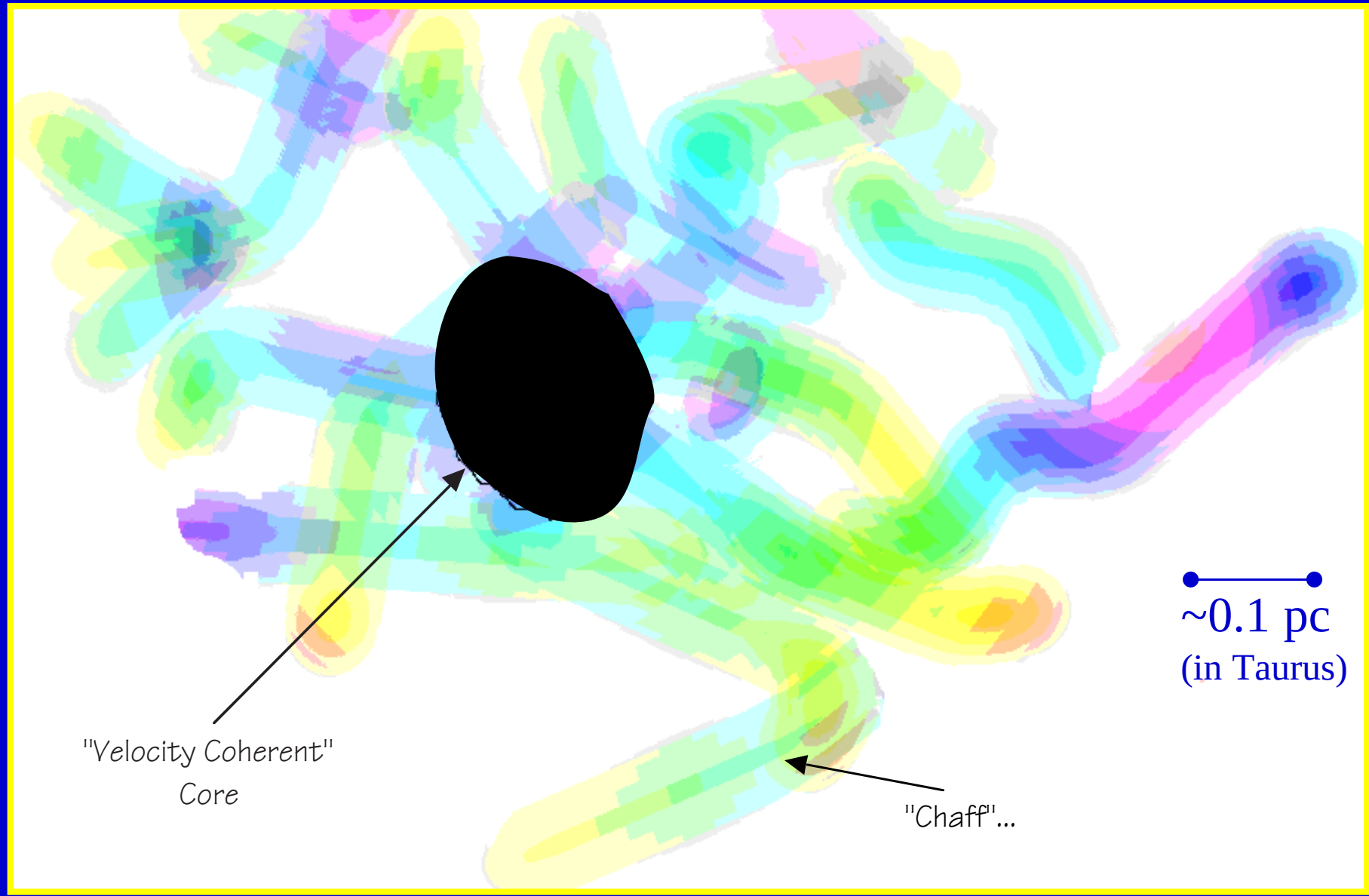




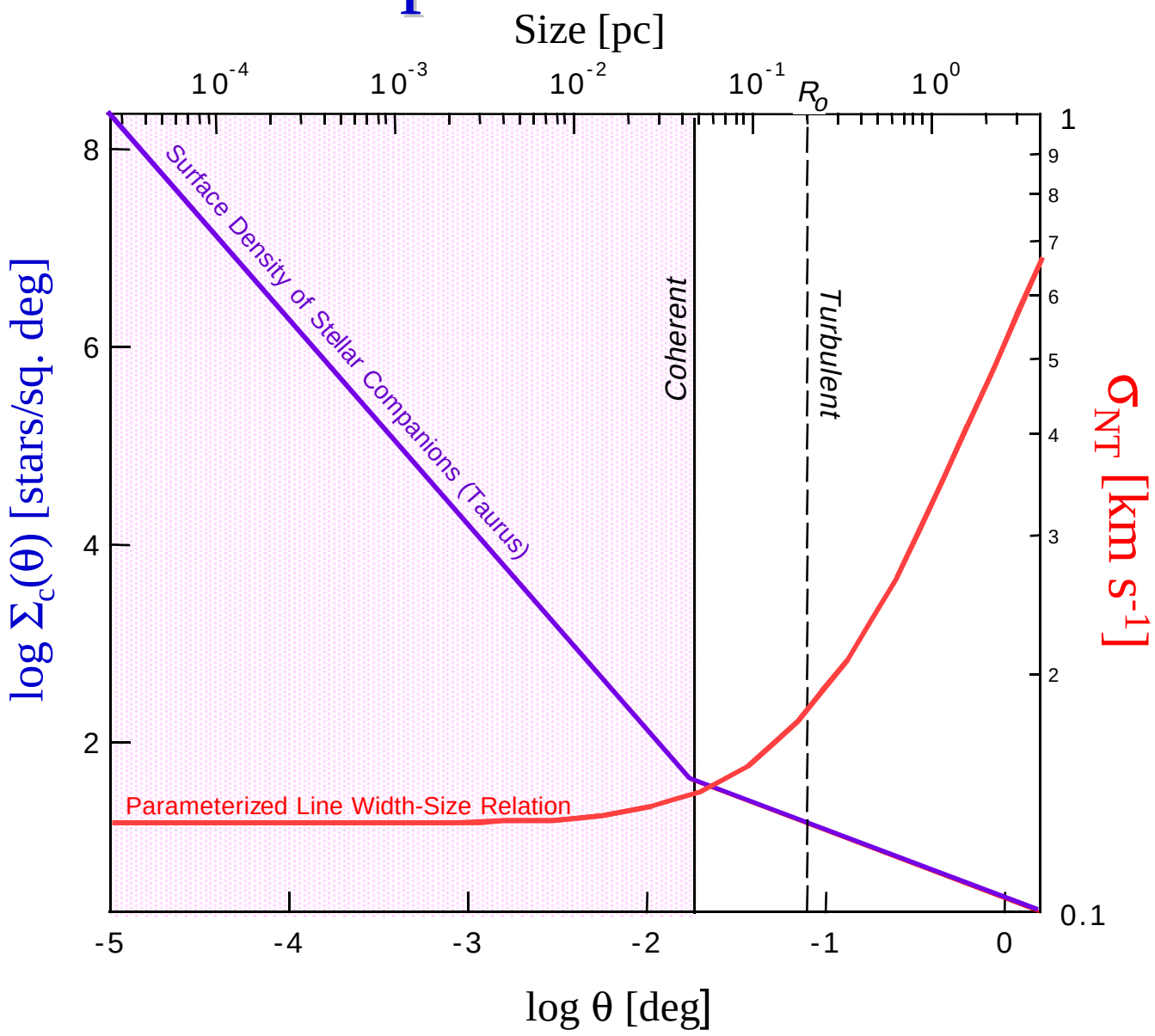




Coherent Dense Core



“Coherence” in Spatial Distribution of Stars



Goodman et al. 1998.

Larson 1995; see also Gomez et al. 1993; Simon 1997

The Cause of Coherence?

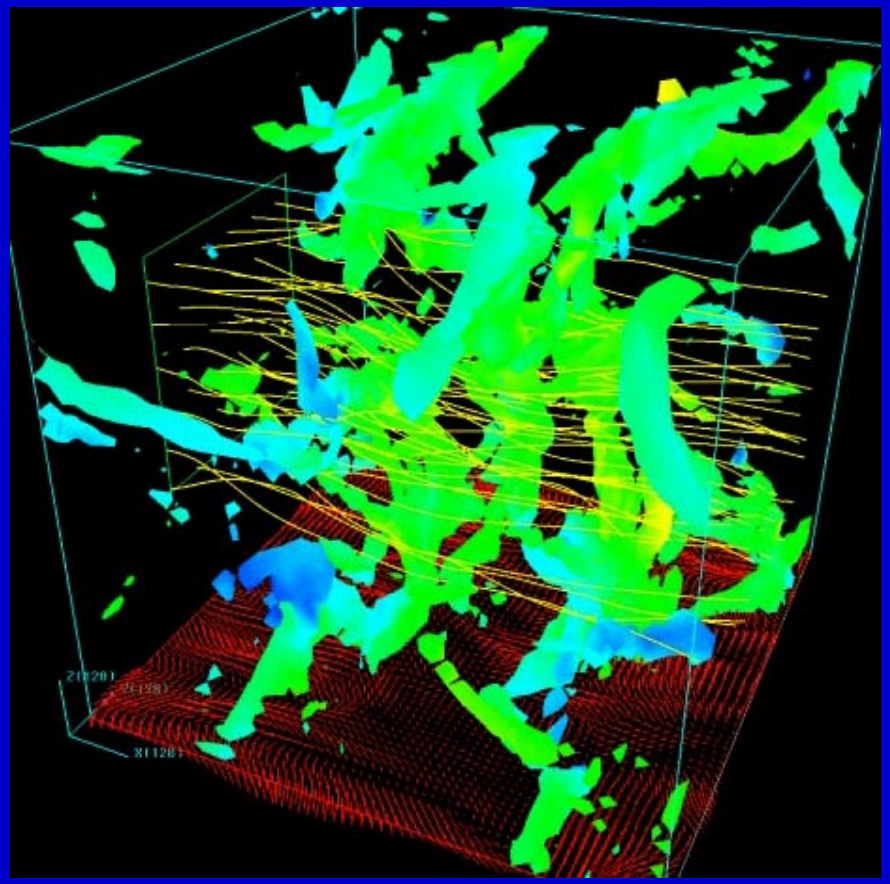
3D MHD simulation of Ostriker, Gammie & Stone (in prep.)

Most likely suspect:

- Loss of magnetic support due to reduced ionization fraction in core. (Scale gives clues.)

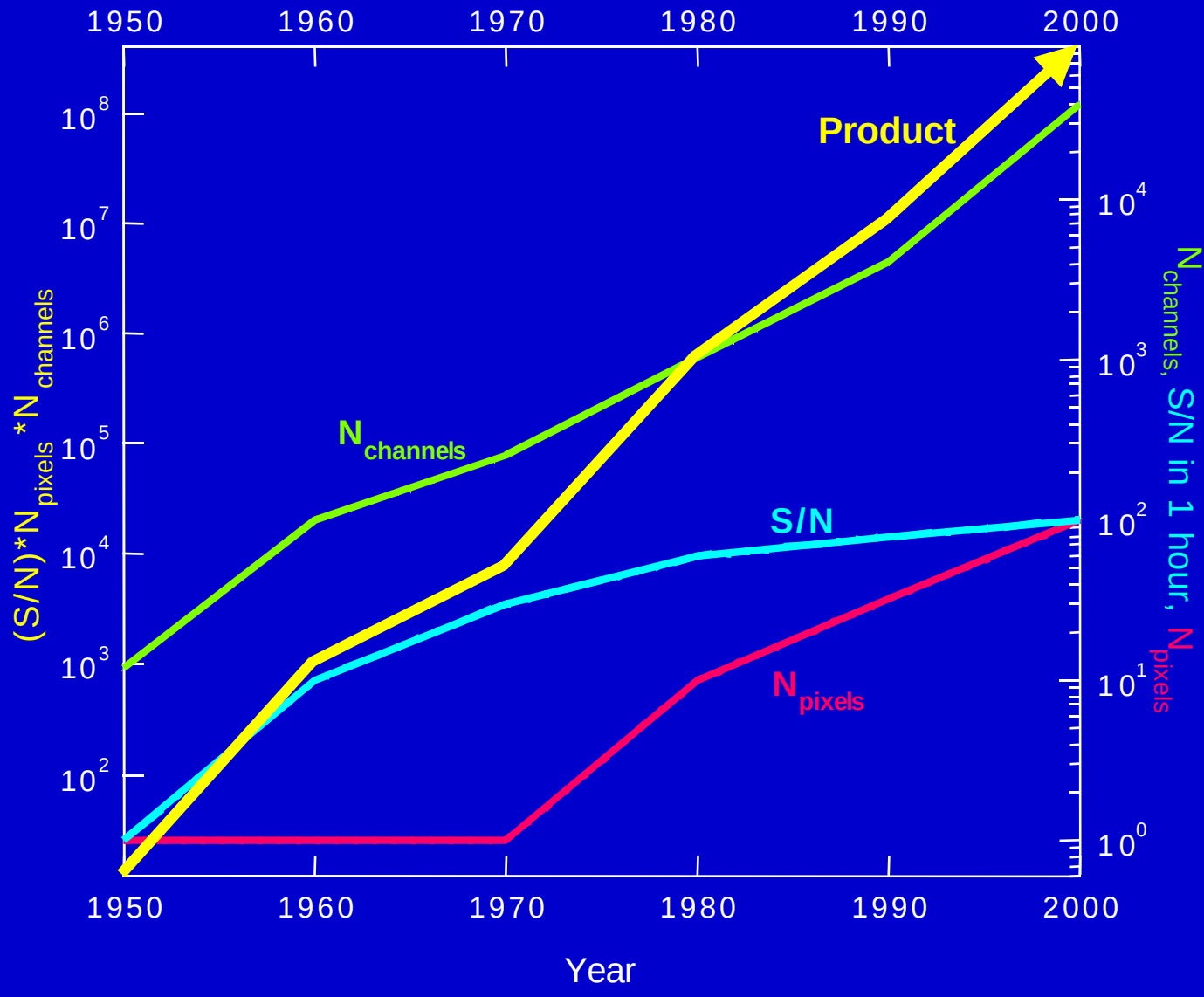
Interesting question raised:

- What causes residual non-thermal line width?



No ambipolar diffusion yet…

Learning More from “Too Much” Data



The Spectral Correlation Function

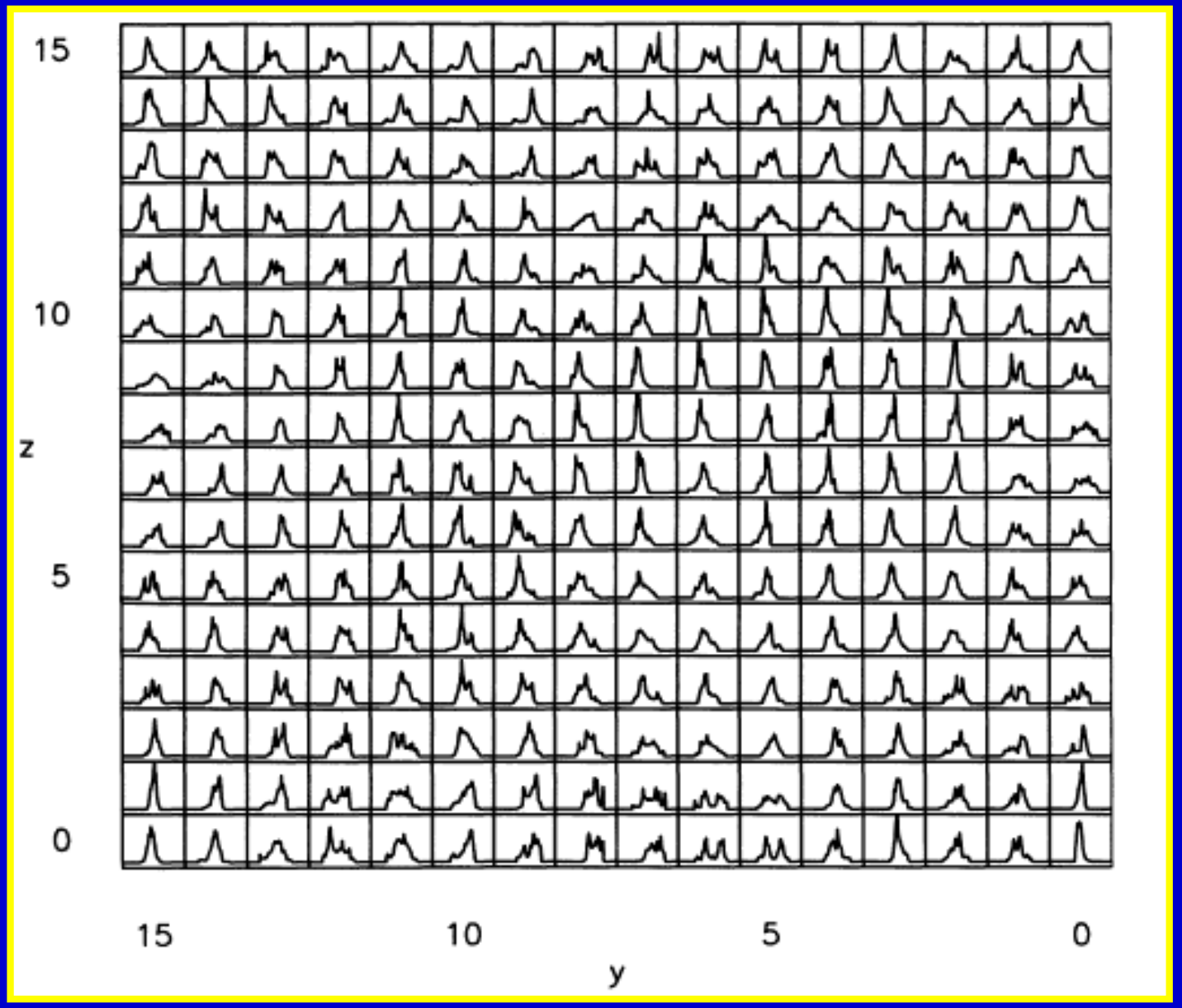


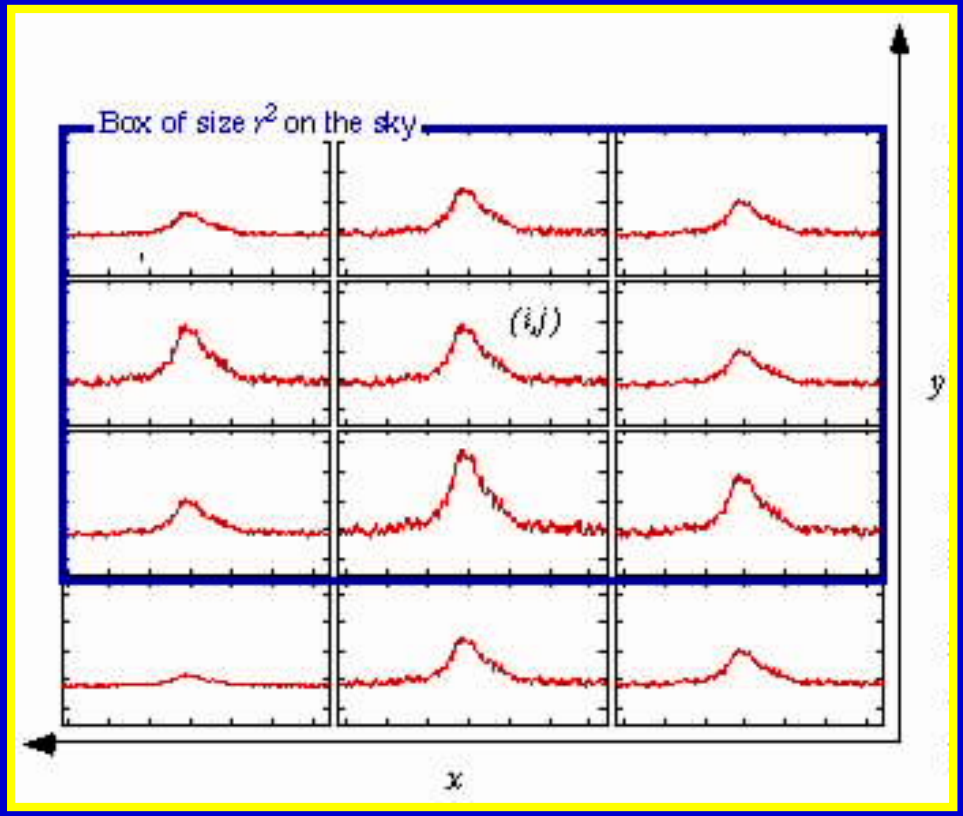
Figure from Falgarone et al. 1994 Simulation

Goals of “SCF” Project

- Develop a “sharp tool” for statistical analysis of ISM, using as much data of a data cube as possible
- Compare information from this tool with other tools (e.g CLUMPFIND, GAUSSCLUMPS, ACF, Wavelets), applied to same cubes
- Use best suite of tools to compare “real” & “simulated” ISM
- Adjust simulations to match, understanding physical inputs

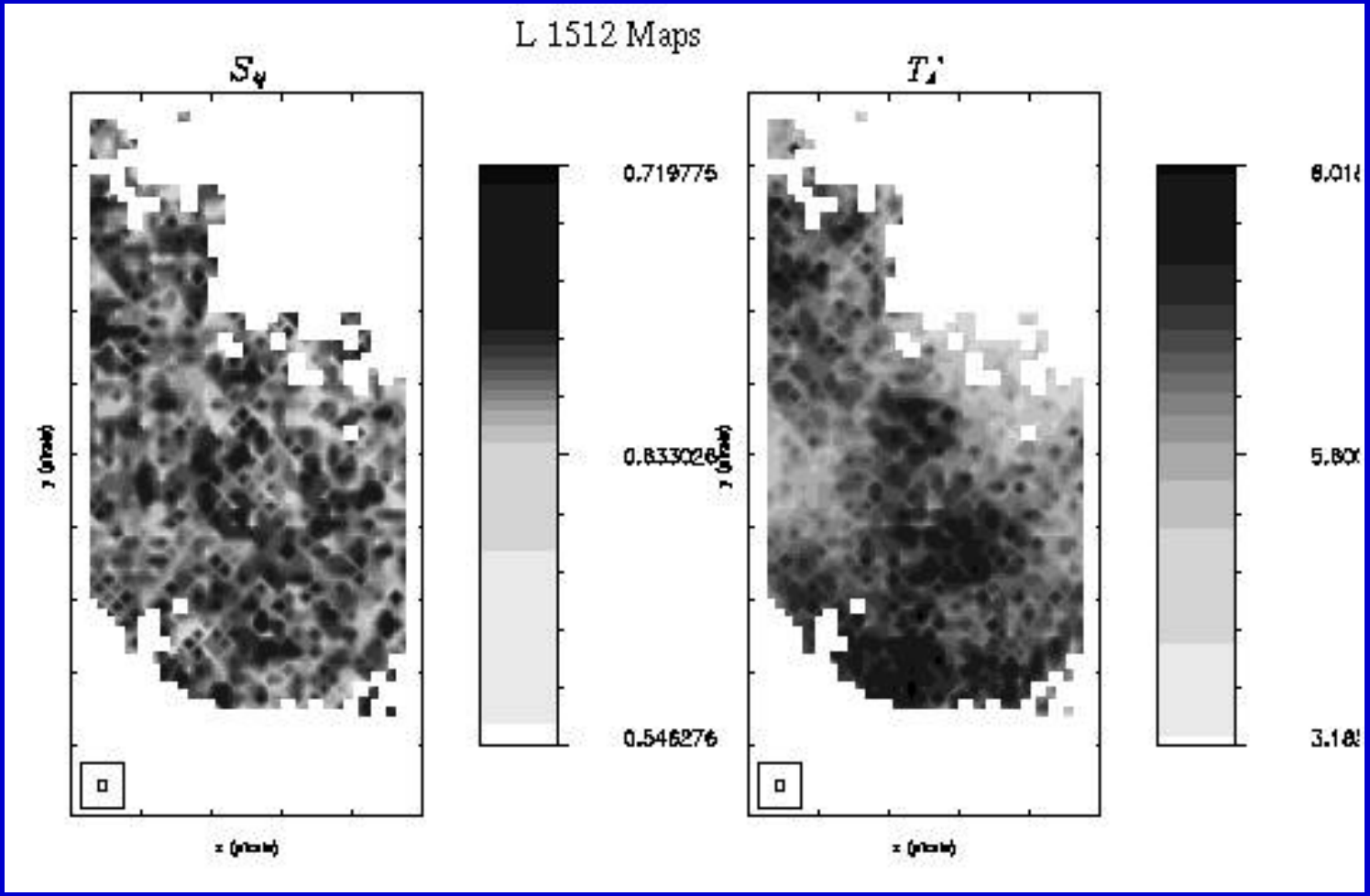
How the SCF Works

- Measures similarity of neighboring spectra within a specified "beam" size
  - lag & scaling adjustable
  - signal-to-noise equalized



See: Rosolowsky, Goodman, Wilner & Williams 1998.

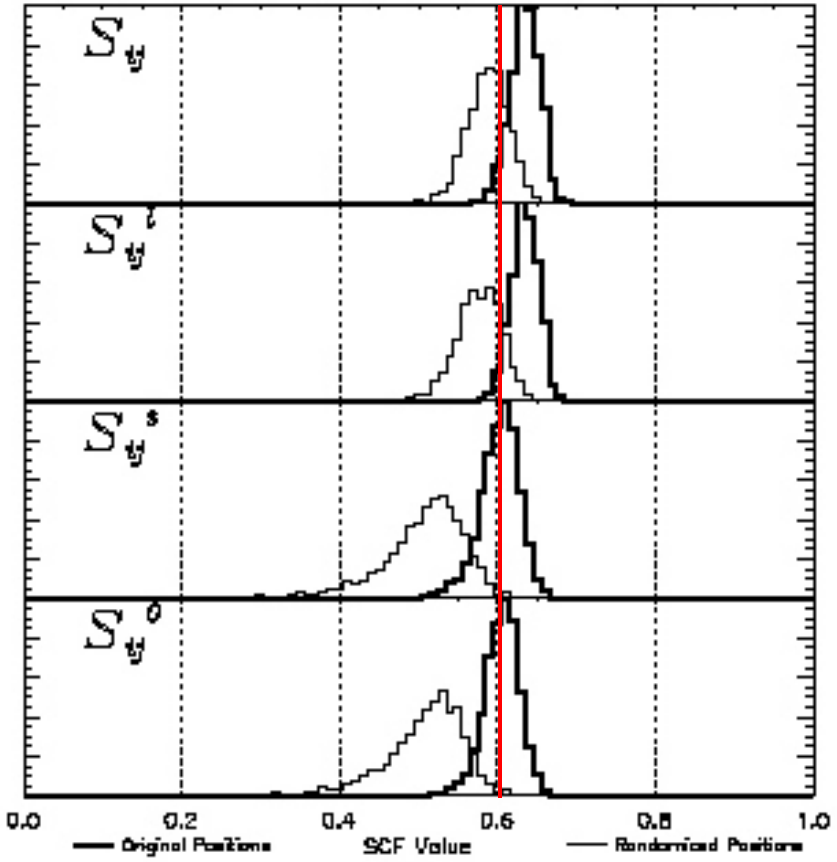
A “Real” Molecular Cloud



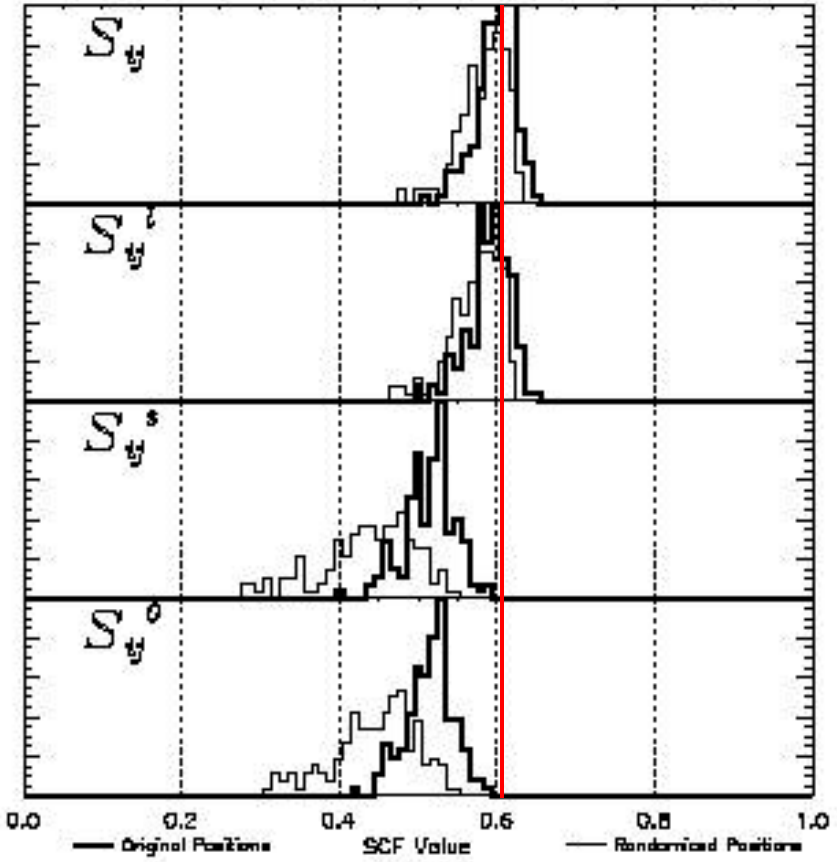
IRAM Key Project Data

Initial Comparisons using the SCF

L1512 (Real Cloud)



"Matching?" Turbulence Simulation

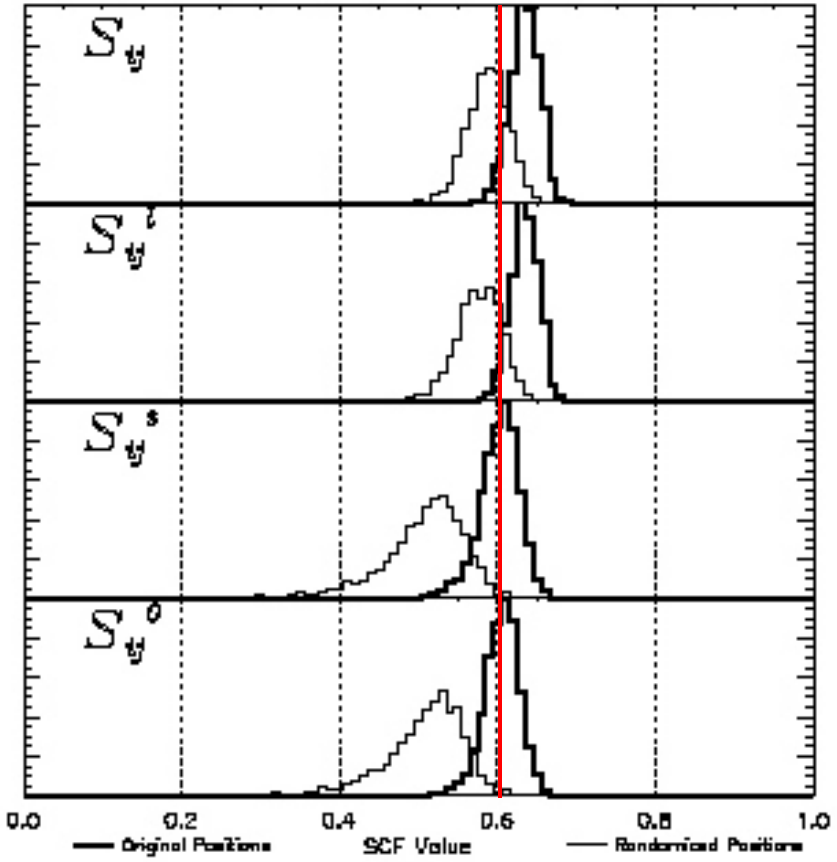


IRAM Key Project Data

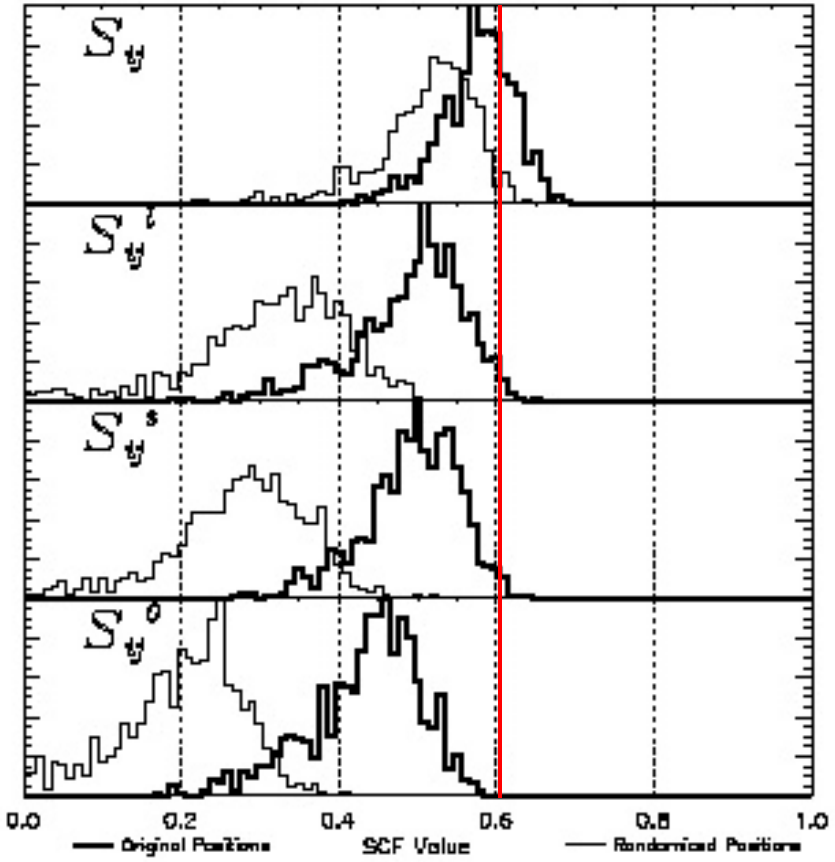
Falgarone et al. 1994

Initial Comparisons using the SCF

L1512 (Real Cloud)



Better? MHD Simulation



IRAM Key Project Data

Gammie, Ostriker & Stone 1998

Goals of “SCF” Project

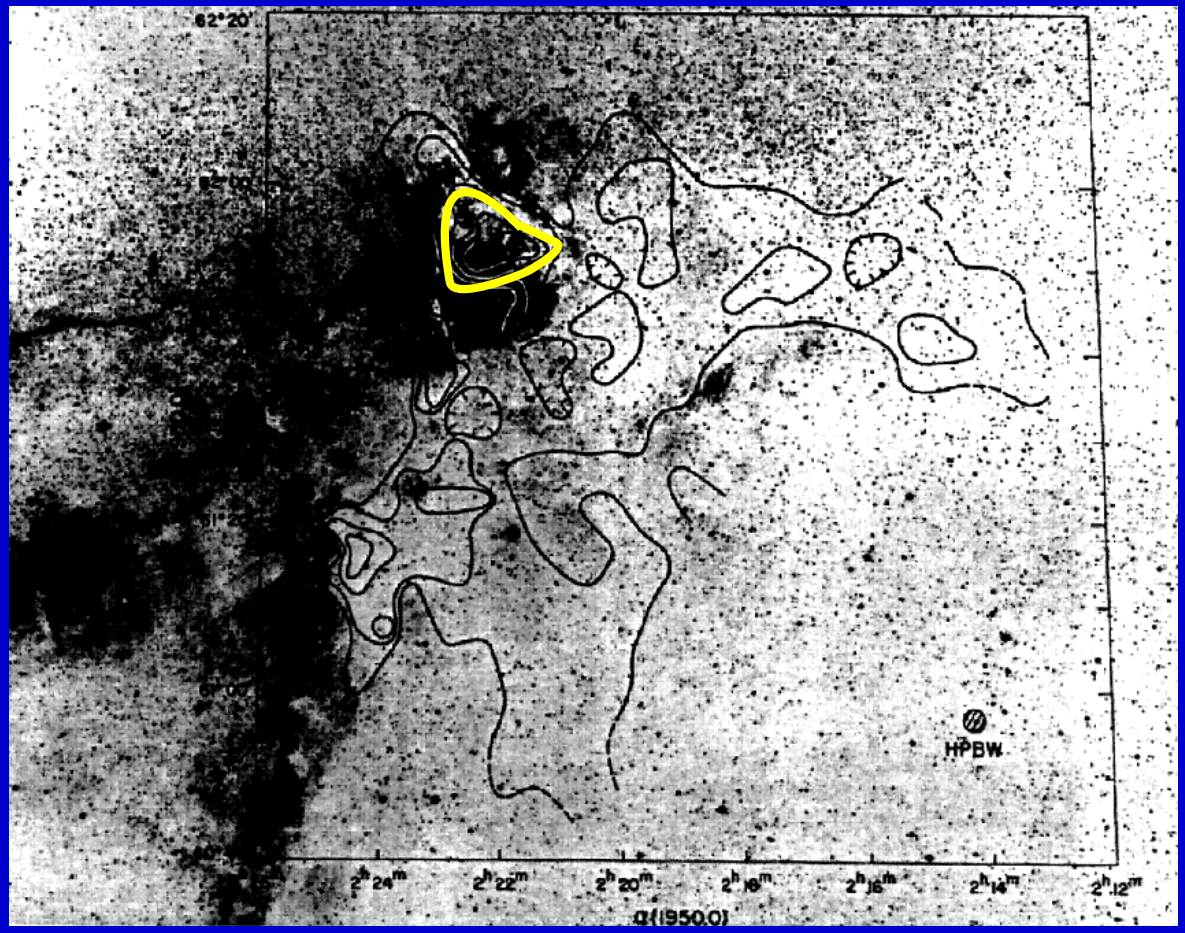
- Develop a “sharp tool” for statistical analysis of ISM, using as much data of a data cube as possible
- Compare information from this tool with other tools (e.g CLUMPFIND, GAUSSCLUMPS, ACF, Wavelets), applied to same cubes
- Use best suite of tools to compare “real” & “simulated” ISM
- Adjust simulations to match, understanding physical inputs

Watching the ISM Move

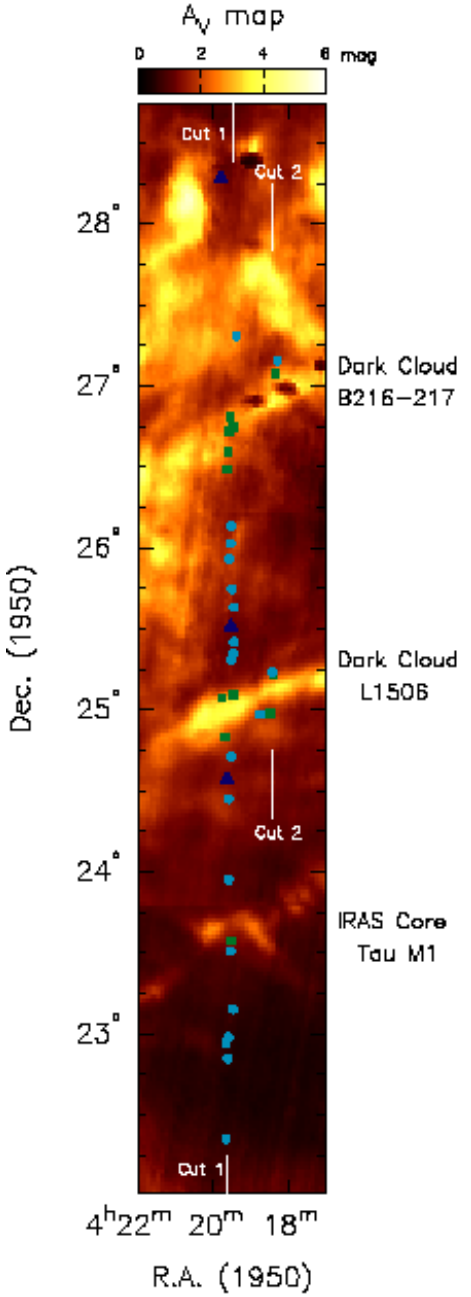
- W3: Massive Star-Forming Region
  - velocity information explains field geometry & star formation
- Ursa Major: High-Latitude Cloud
  - velocity analysis shows “dripping” & impact
- Dense Cores
  - velocity dimension reveals “coherence”
- Spectral Correlation Function
  - should lead to better simulations & more

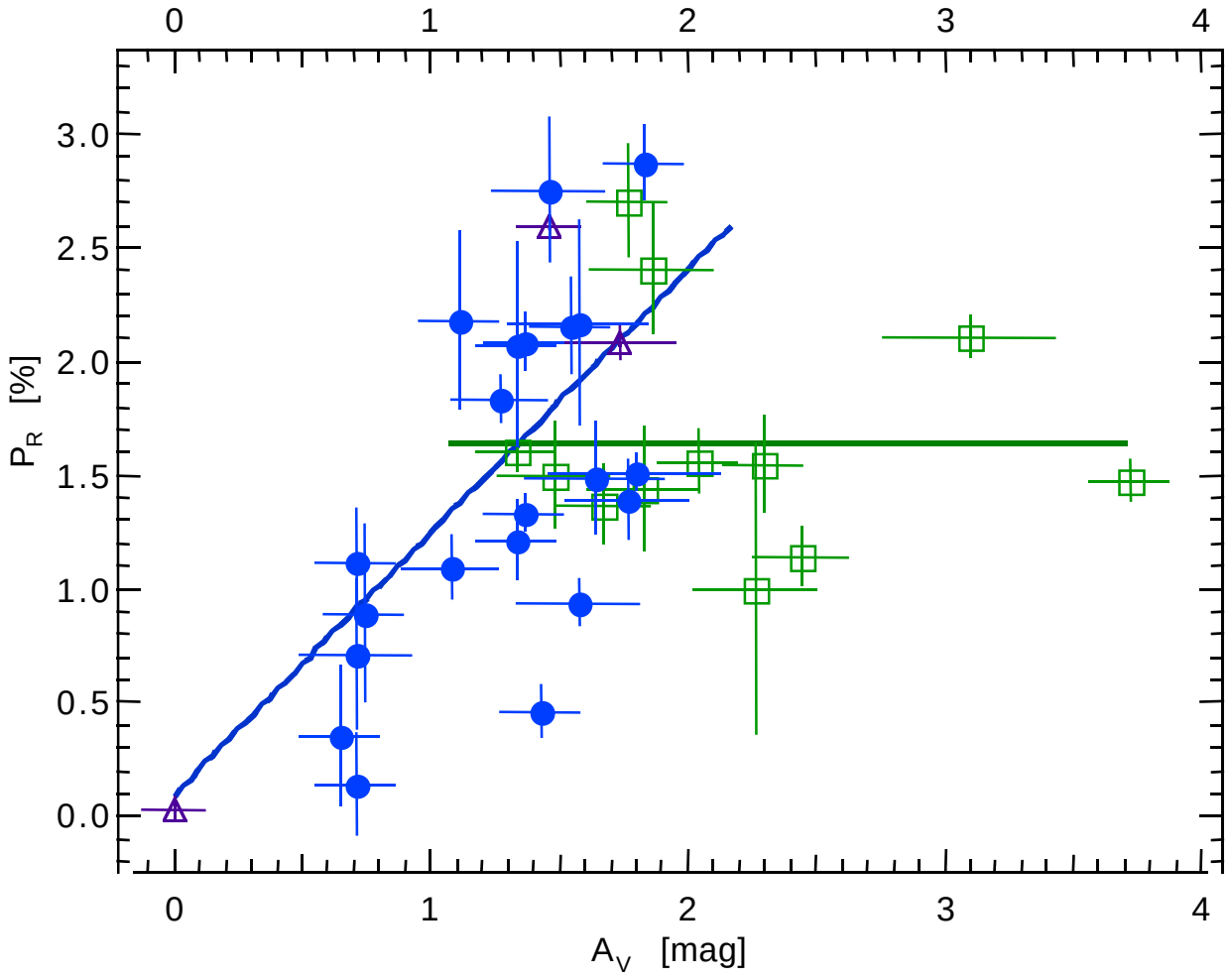
Extra slides follow...

Optical View of W3 Region



"Go no further than A_V~1.3 mag."





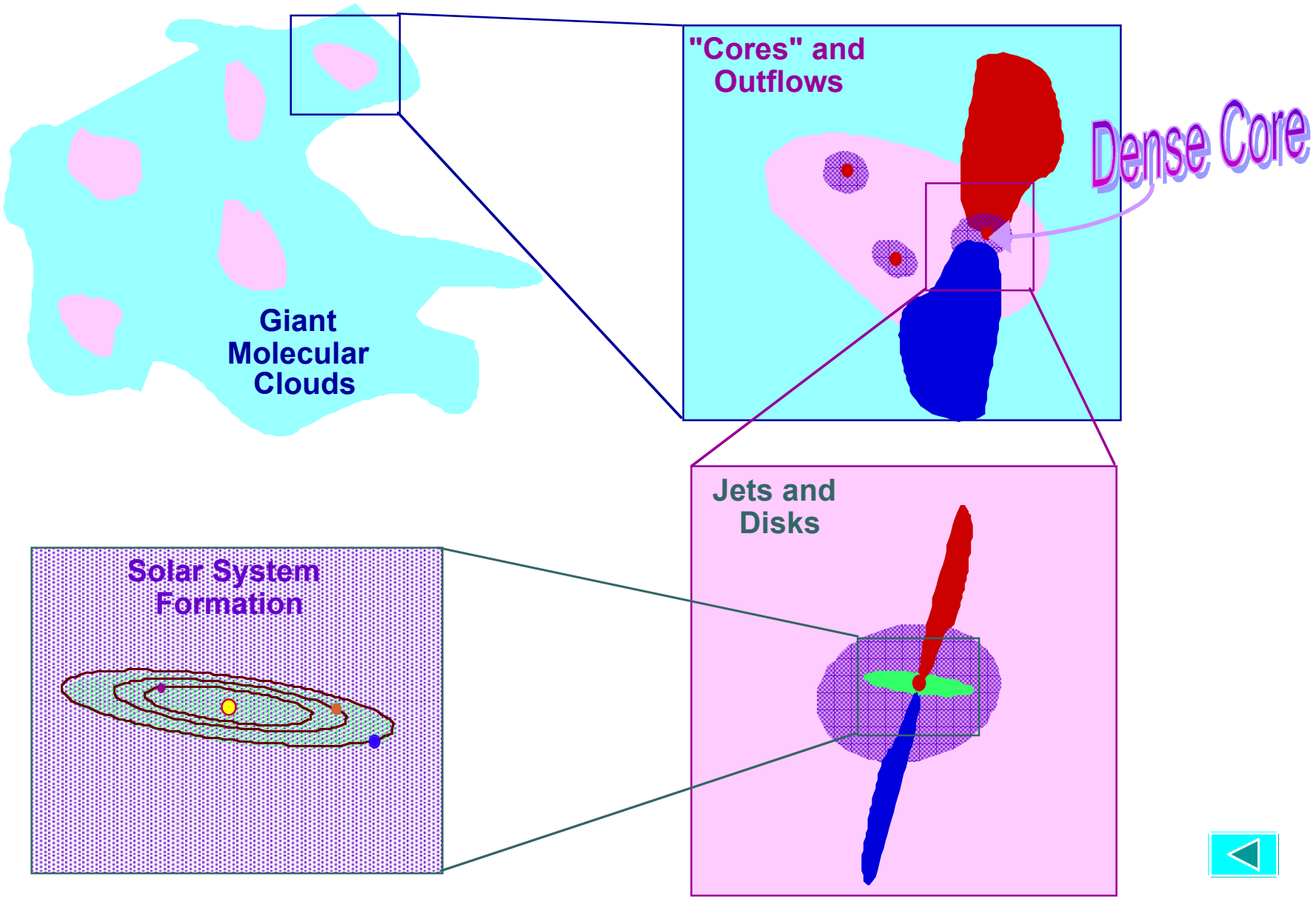
Arce et al. 1998

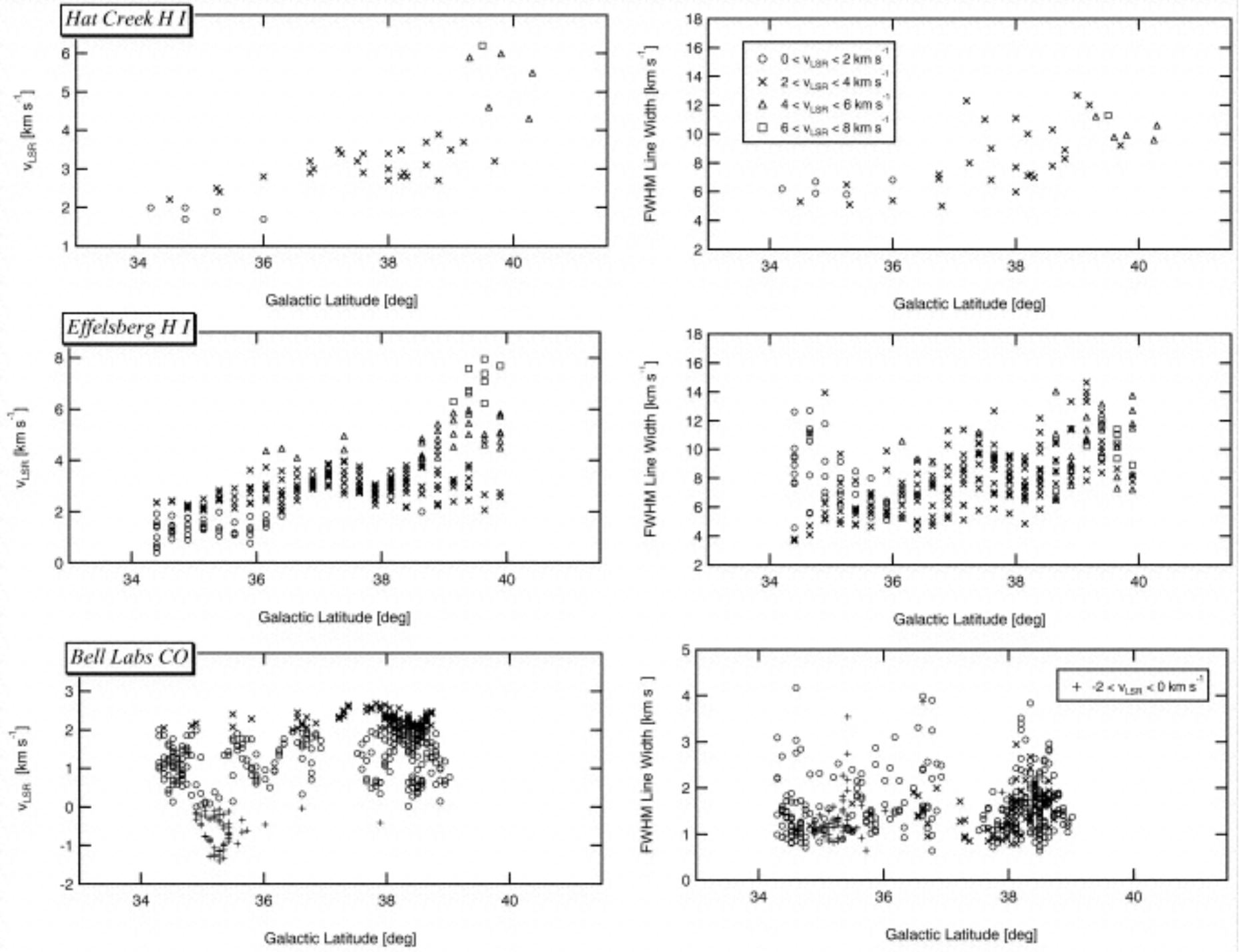
□ Background to Cold Dark Cloud

● Background to General ISM

Magnetic Fields

“Star and Planet Formation”




Hat Creek H I
Effelsberg H I
Bell Labs CO
v_{LSR} [km s^{-1}]
FWHM Line Width [km s^{-1}]
Galactic Latitude [deg]
0 < v_{LSR} < 2 km s^{-1}
2 < v_{LSR} < 4 km s^{-1}
4 < v_{LSR} < 6 km s^{-1}
6 < v_{LSR} < 8 km s^{-1}
-2 < v_{LSR} < 0 km s^{-1}