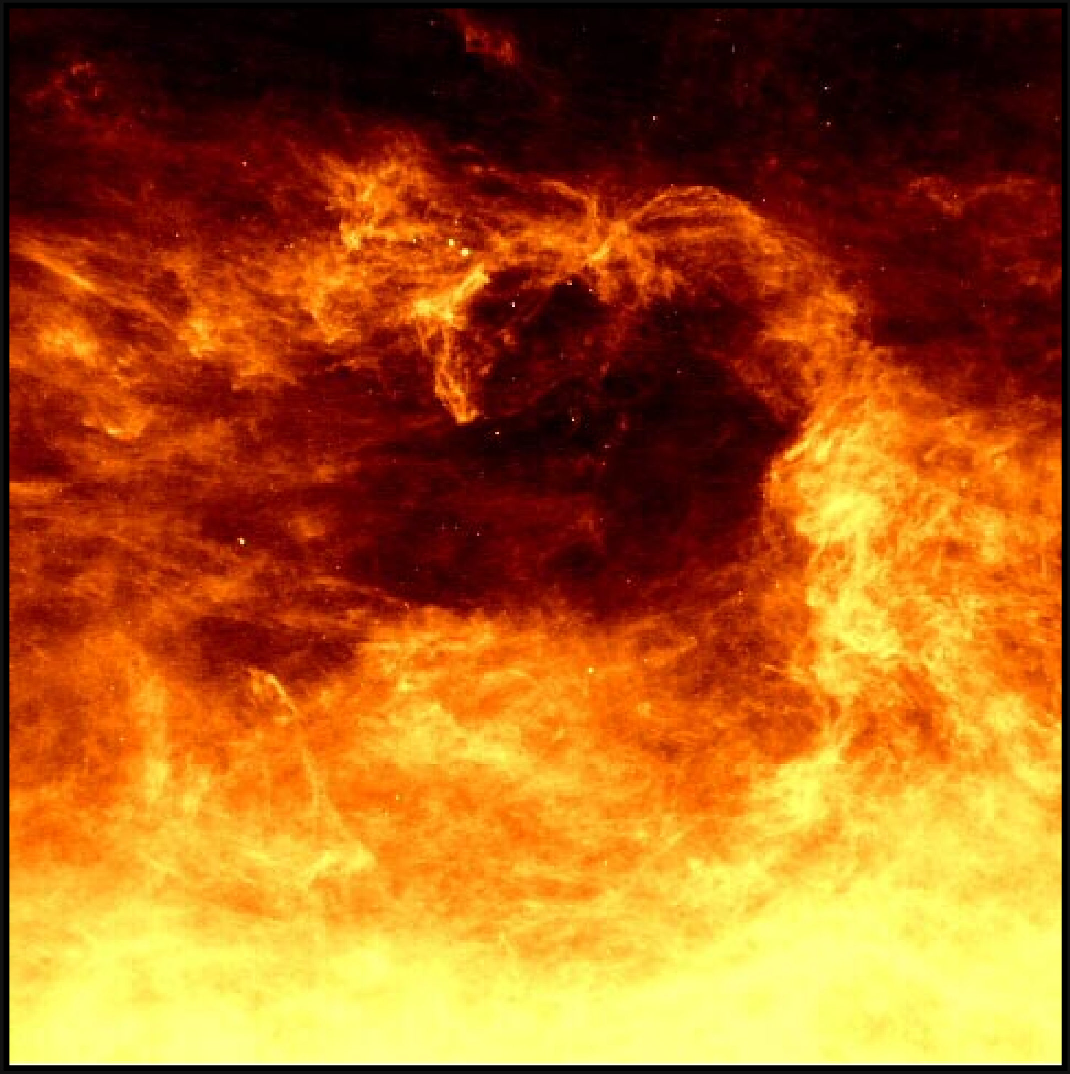
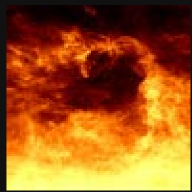
What Sculpts the Interstellar Medium?

Alyssa A. Goodman

Harvard University



Galaxies & Museums



Galaxies & Museums

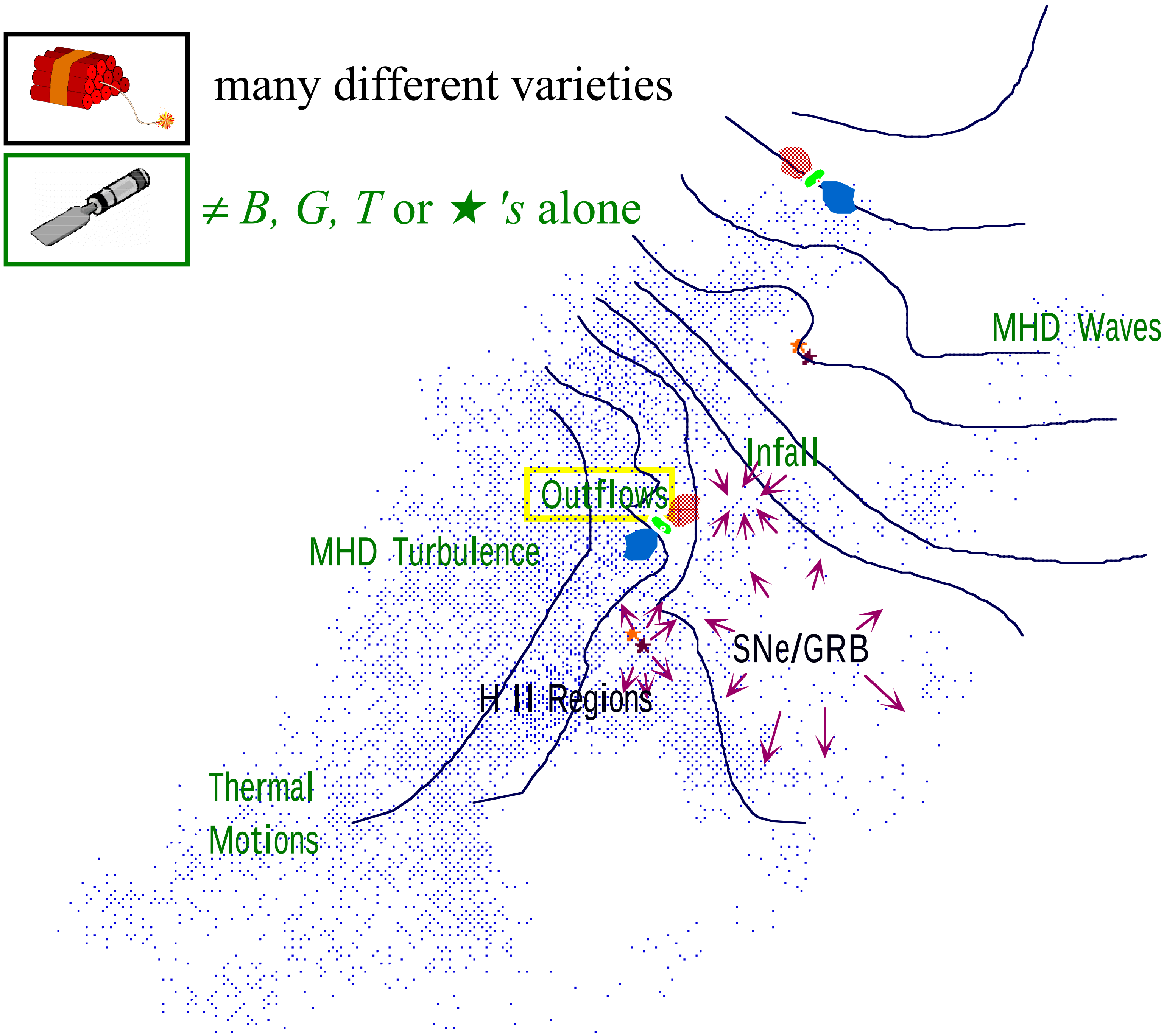
- Galactic Rotation + Gravity
  - GMCs (10^5=10^6 $M_\odot$)
- SNe, GRBs, OB ★ winds
  - Cloud complex (sub-GMC)
- MHD waves, MHD turbulence, shocks
  - More "internal structure,"
  - sometimes resulting in "cores"
- Star-Formation, Evaporation
  - Eventual disappearance of gas

"Blasting"

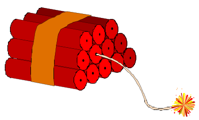
"Chiseling"

"Weathering"

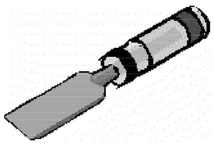
- Geology
  - Deposit of Marble
- Saws & Dynamite
  - Block with specific aspect ratio
- Series of chisels
  - Head, Arms, Legs, then Fingers, Toes, Eyes, Mouth
  - sometimes human form
- Wars, Wind
  - Eventual disappearance of art



many different varieties
≠ B, G, T or ★ 's alone
MHD Waves
Infall
Outflows
MHD Turbulence
SNe/GRB
H II Regions
Thermal
Motions



Tools for finding the tools



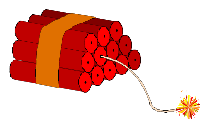
Key Method: Use the velocity field

- third (really fourth) dimension
- valuable information on energetics

Tools for finding the tools

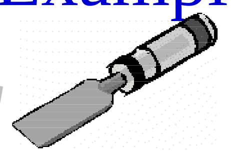
-Introduction to measuring velocity structure

-Blasting



- UMaj Example: Specialized Velocity Analysis

-Chiseling

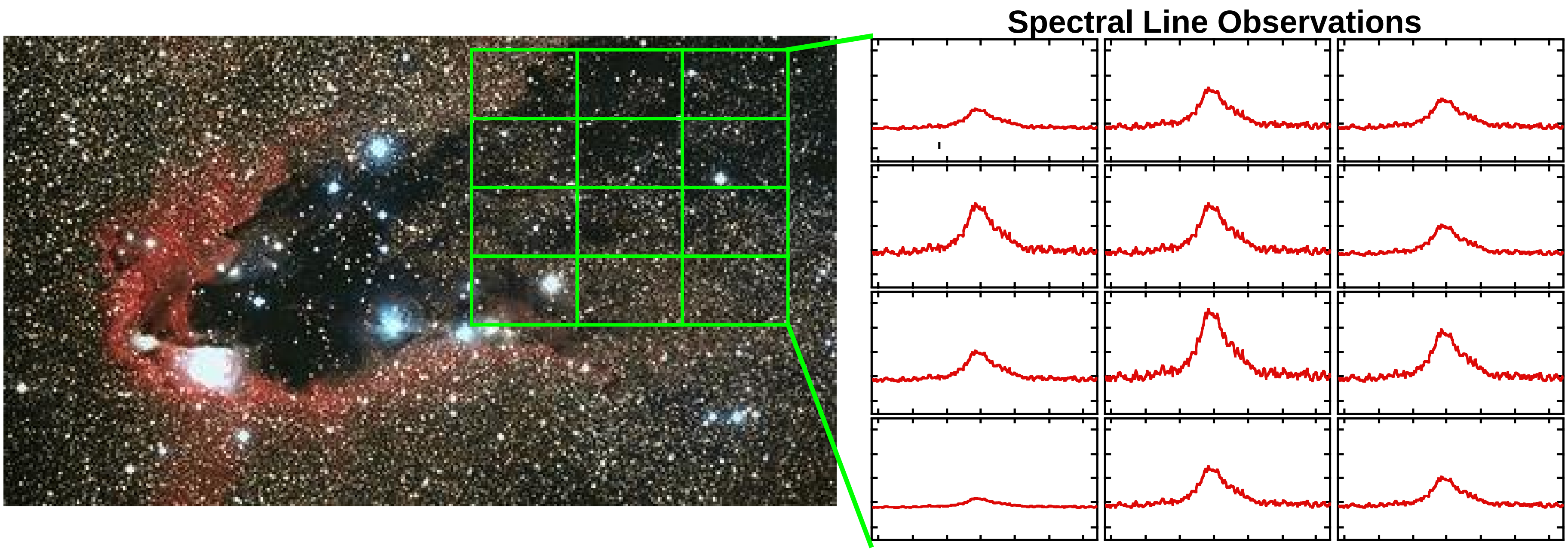


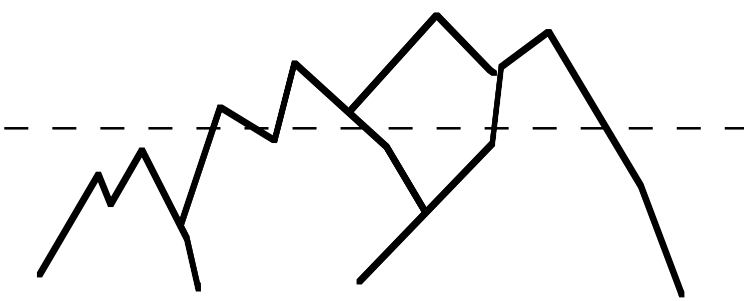
- Generic chiseling: Line width-Size relations
- "In our own image": Coherent Dense Cores
- Quality Control: The Spectral Correlation Function

-"Weathering"

- Sandblasting? Extinction Studies

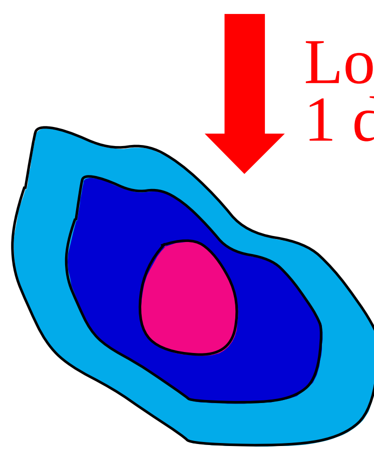
Velocity as a "Fourth" Dimension





Mountain Range

No loss of information

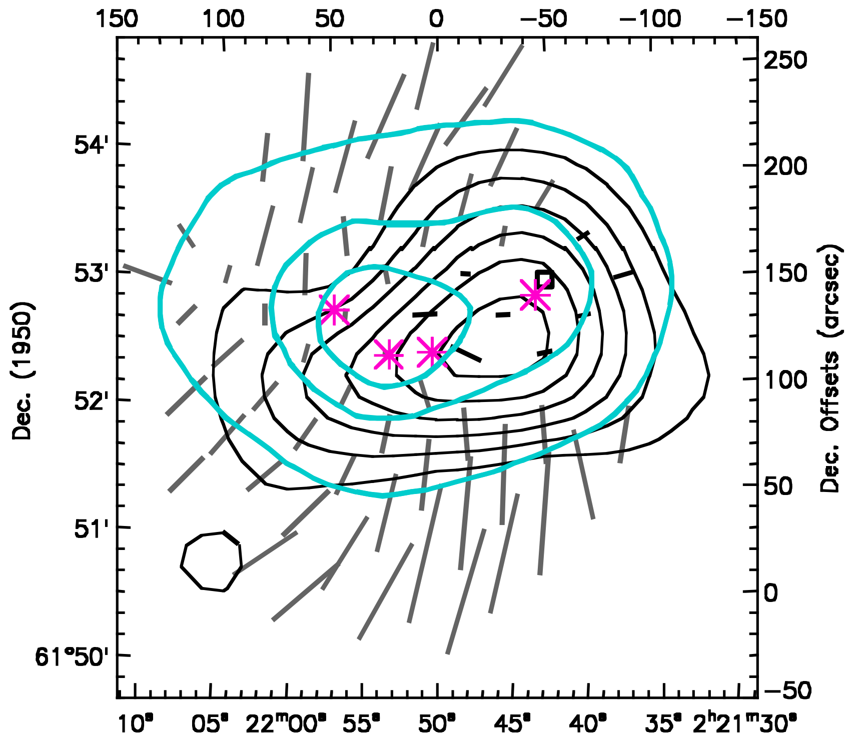


Loss of 1 dimension

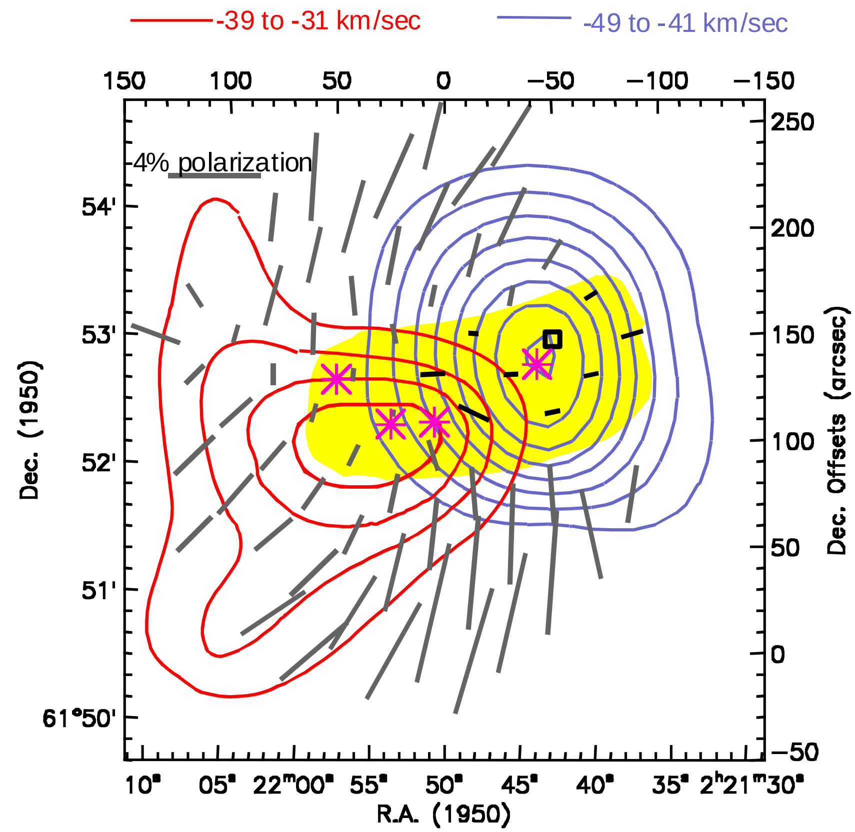
W3

^{13}CO Integrated Intensity

Dust Thermal Emission

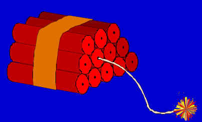


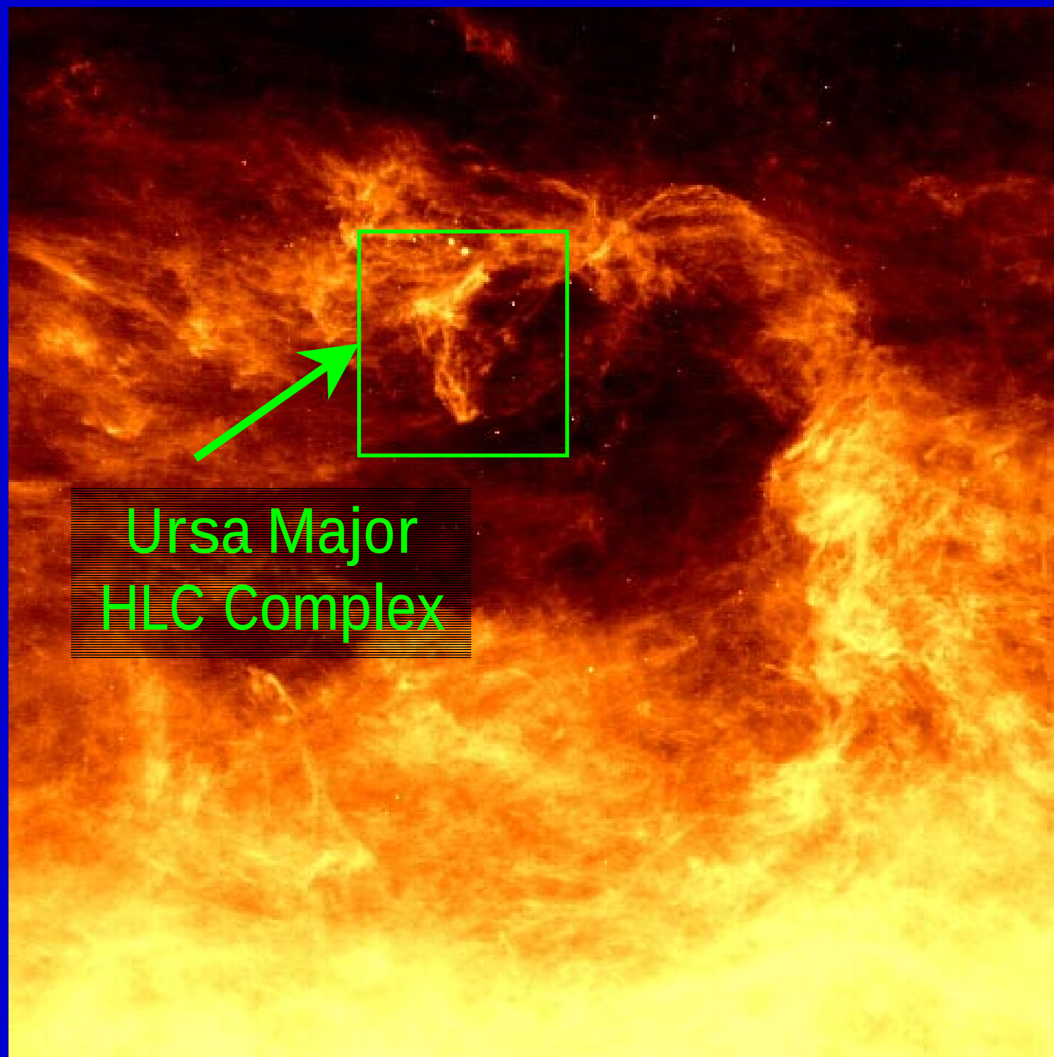
^{13}CO Channel Maps



Kannappan & Goodman 1999 & Dowell 1998

Blasting





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

<u>High Latitude Cloud</u>[2]

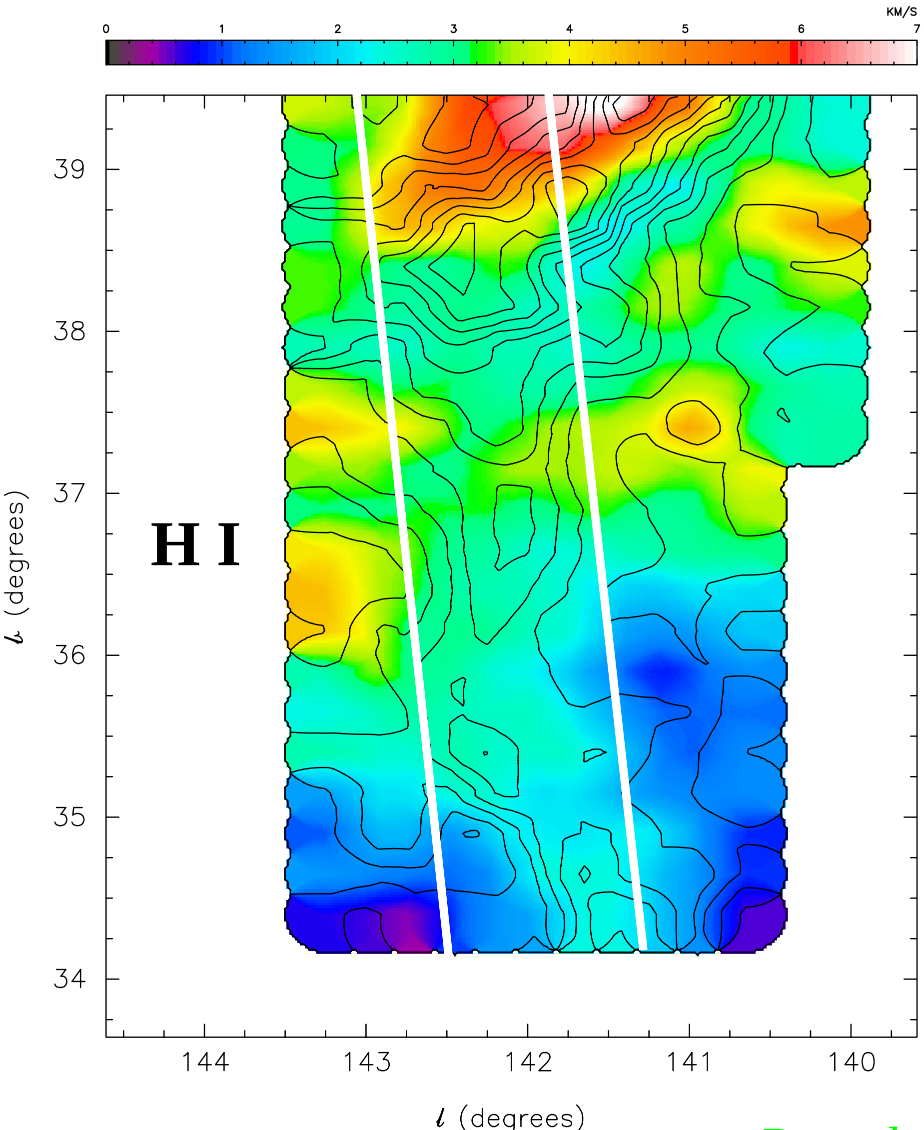
Gravitational << Magnetic ≈ Kinetic

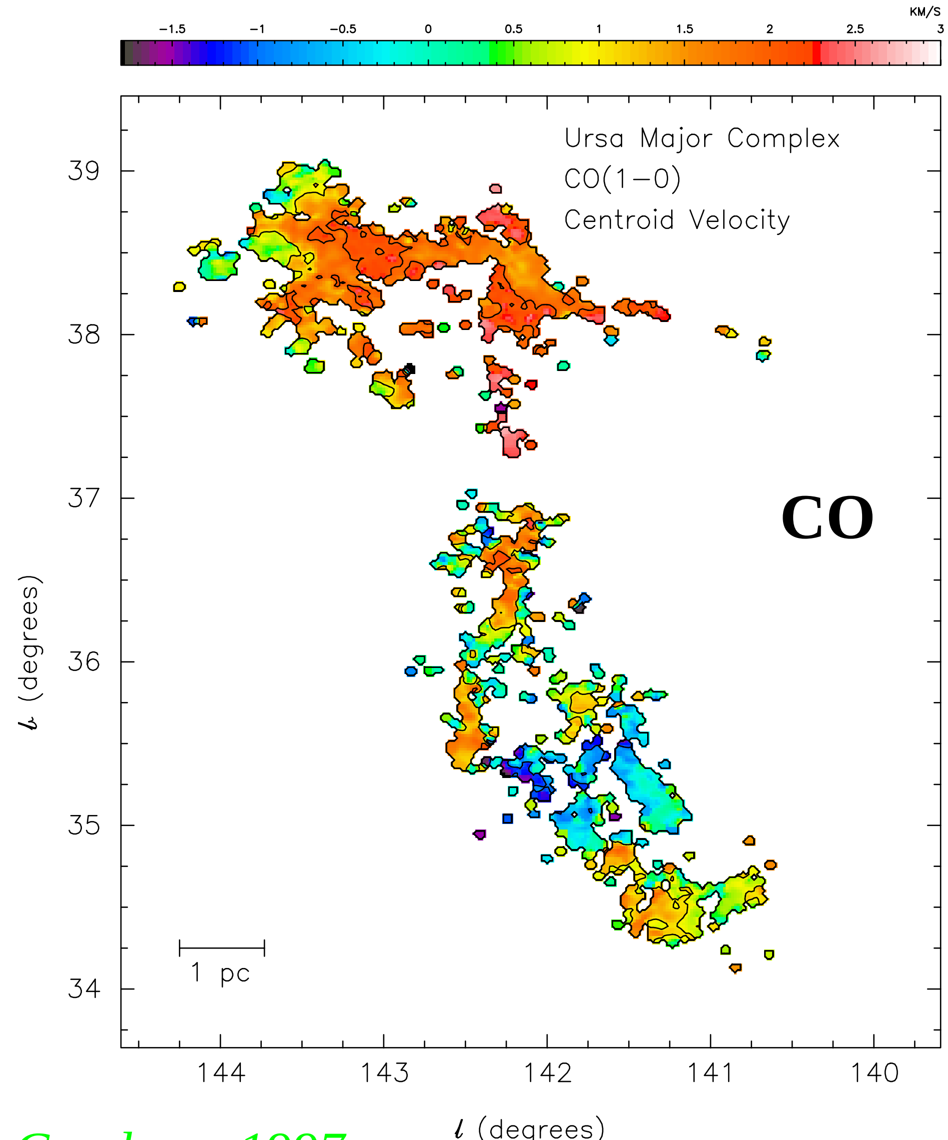
<u>Star-Forming Cloud</u>[3]

Gravitational ≈ Magnetic ≈ Kinetic

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

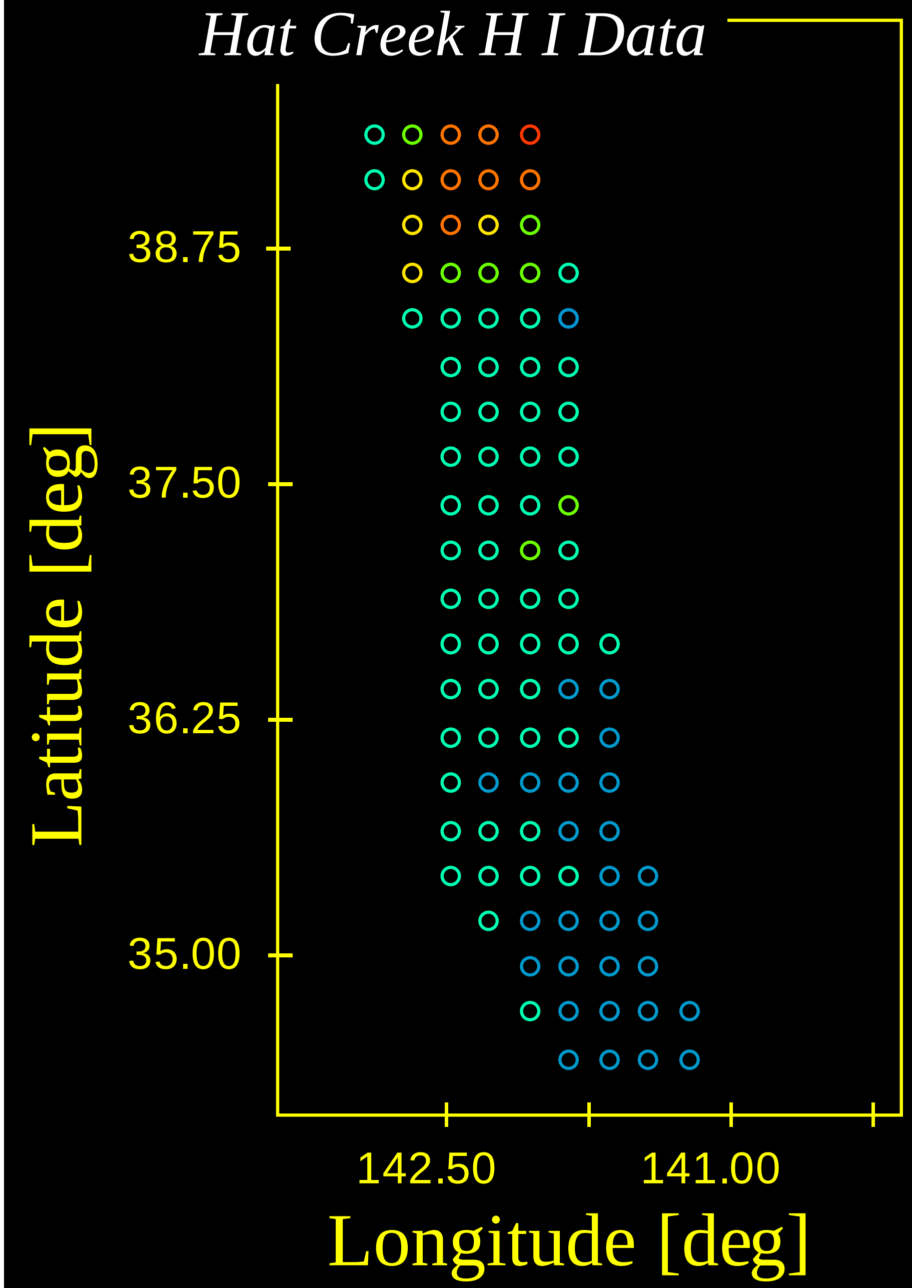
The Velocity Field in Ursa Major

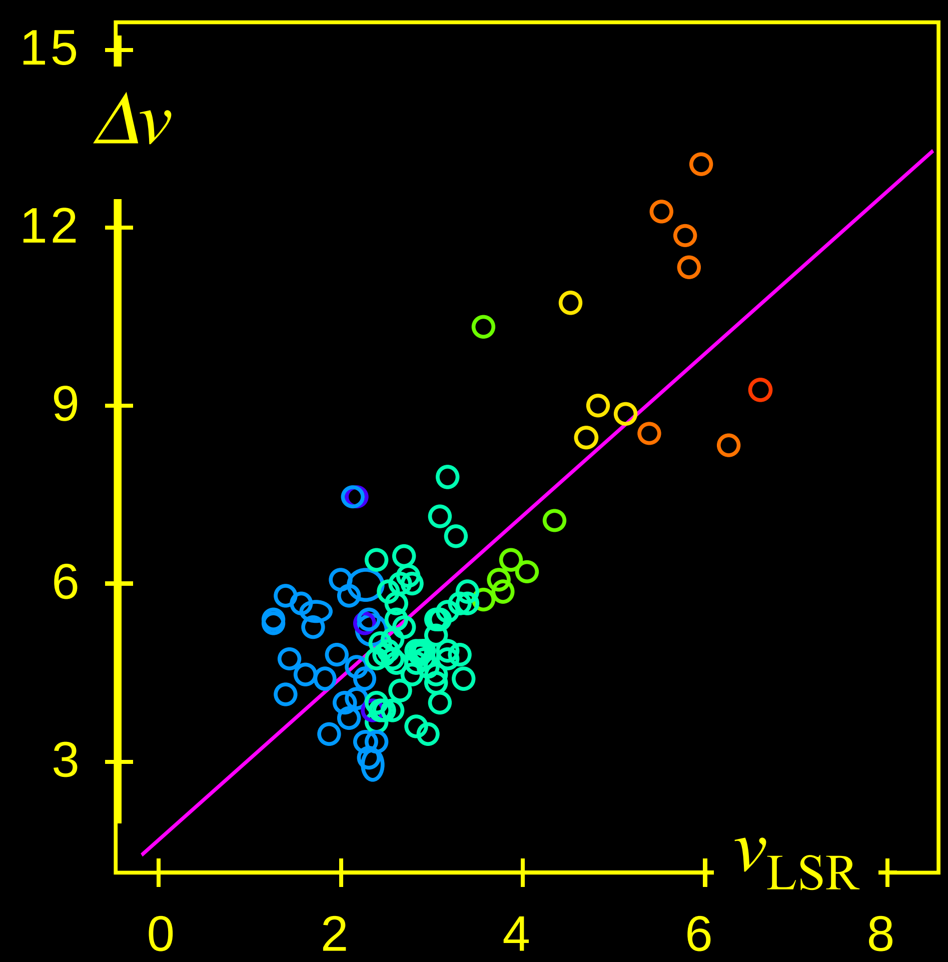


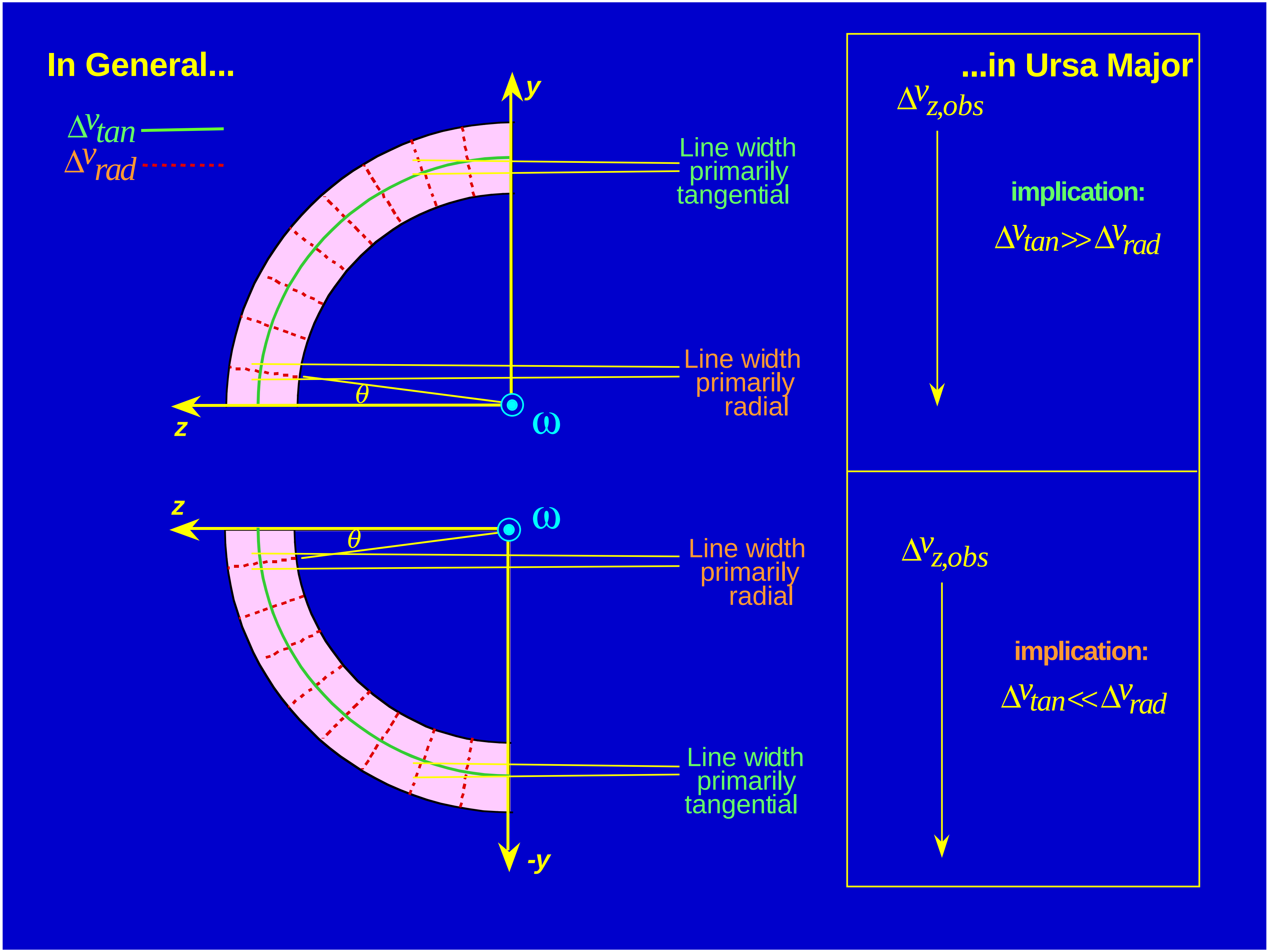


Pound & Goodman 1997

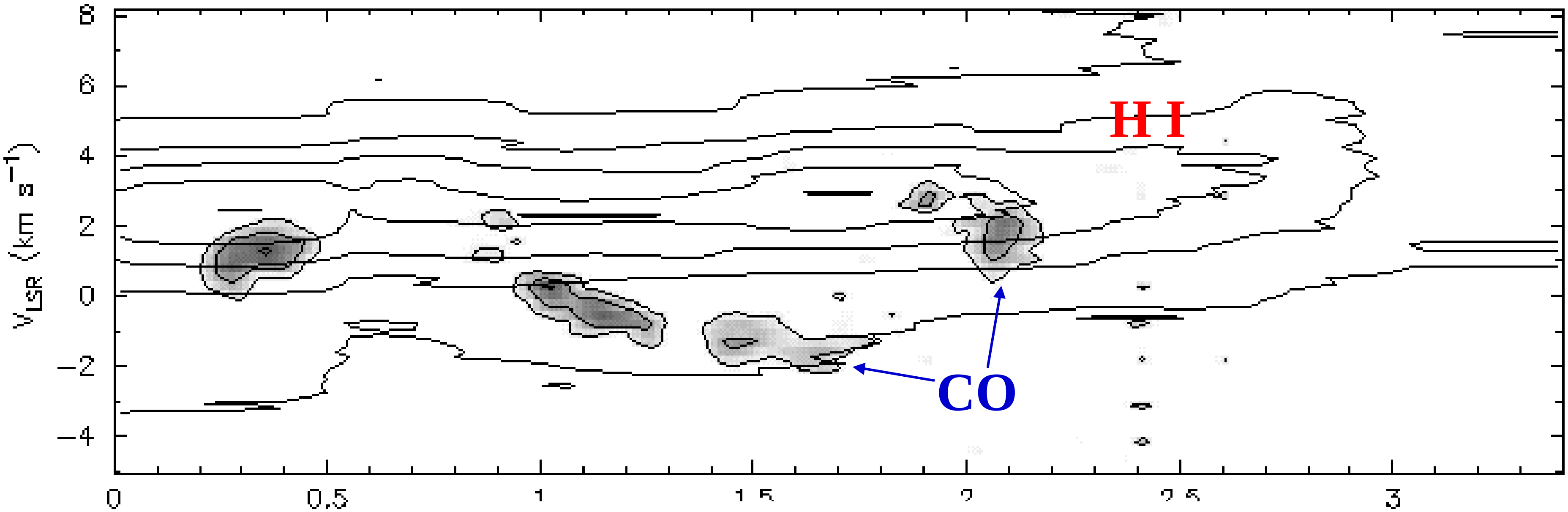
Δv and v_{LSR} Gradients





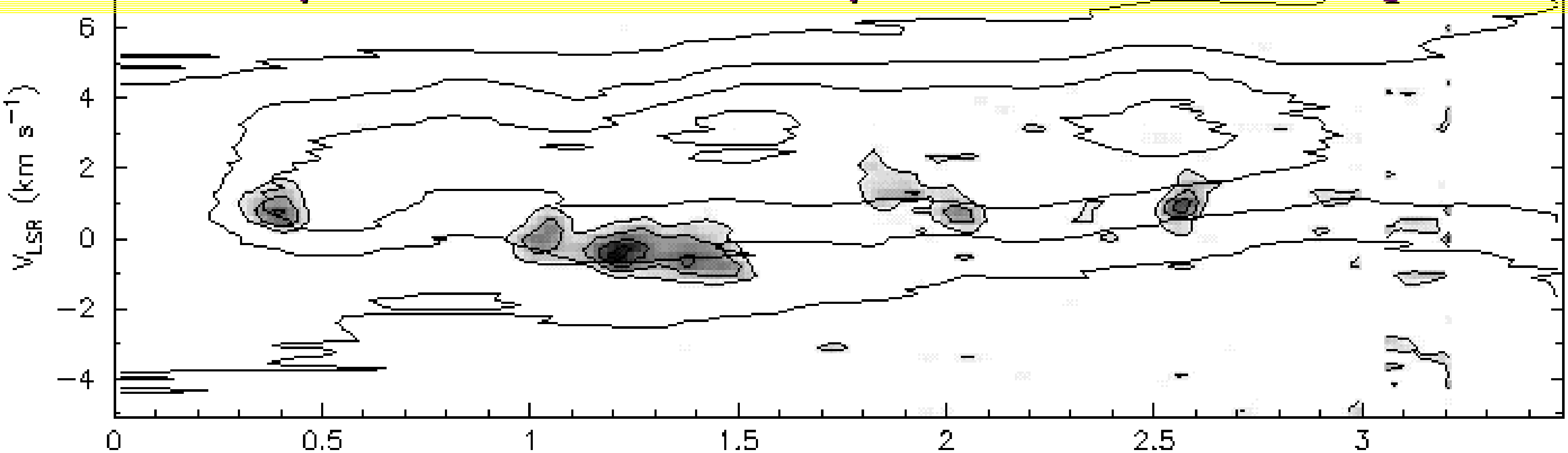


In General...
Δv tan
Δv rad
y
z
θ
ω
Line width primarily tangential
Line width primarily radial
z
θ
ω
Line width primarily radial
Line width primarily tangential
-y
...in Ursa Major
Δv z,obs
implication:
Δv tan >> Δv rad
Δv z,obs
implication:
Δv tan << Δv rad

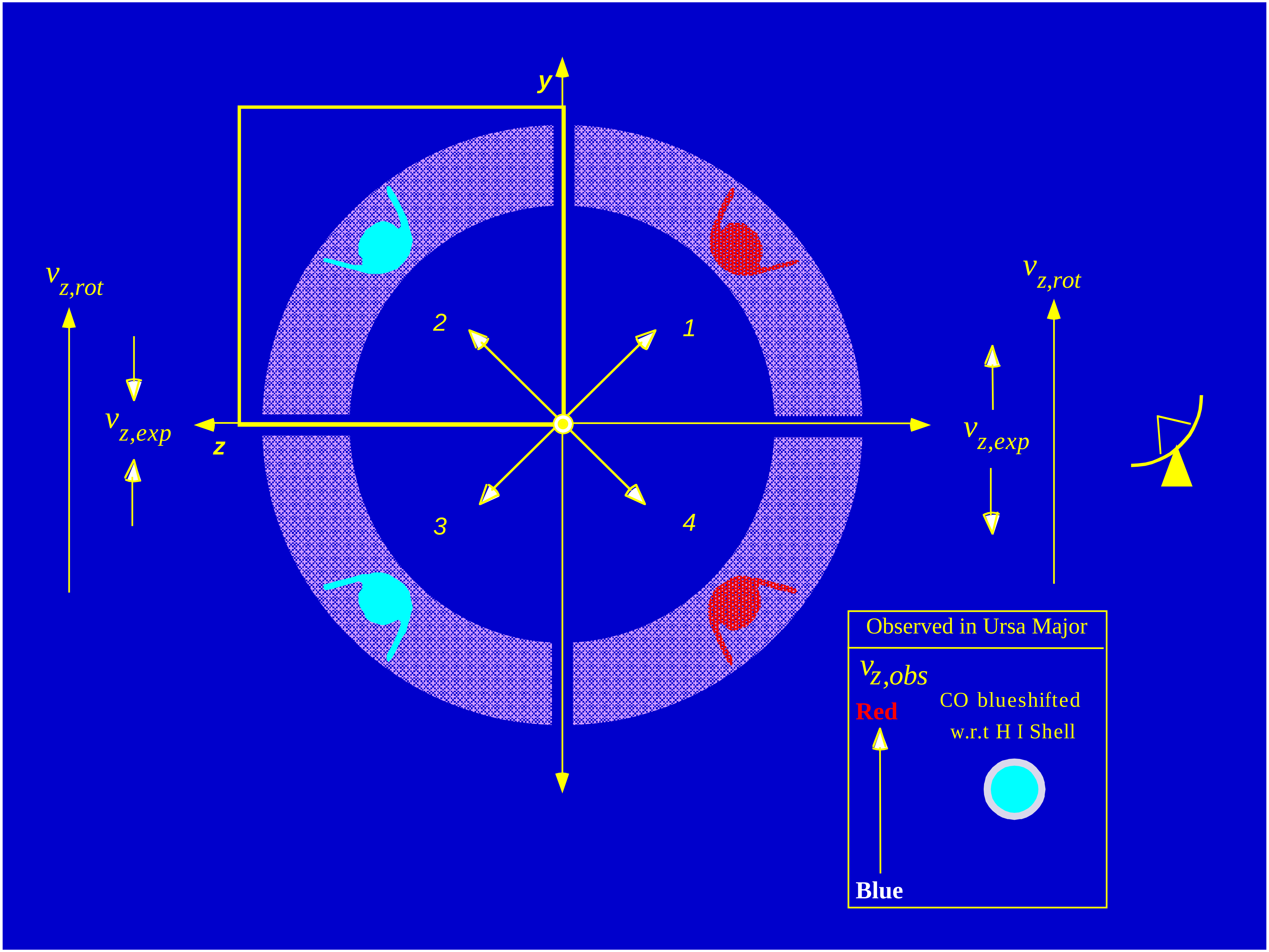


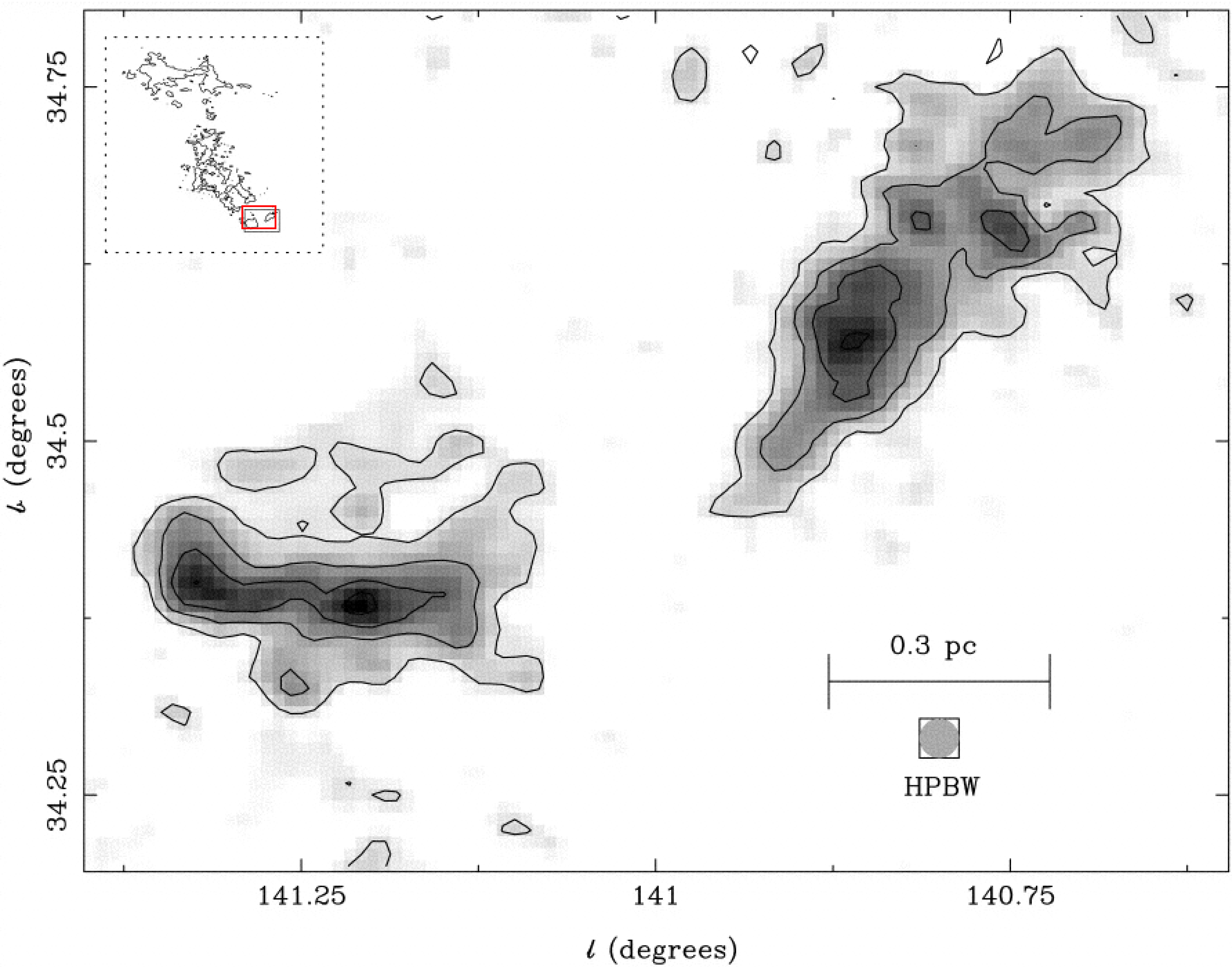
Position Along Filament 1

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



Position Along Filament 2


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



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

Implications of Ursa Major Study

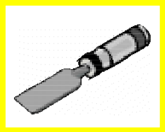
- Many HLC's may be related to "supershell" structures; some shells harder to identify than NCP Loop.
- (Commonly observed) velocity offsets between atomic and molecular gas may be due to impacts, followed by conservation of momentum. Use this as a clue in other cases.

Chiseling

Generic Chiseling (Π(*B*, *G*, *T*, ★'*s*))

Self-similar structure

Line width-Size Relations ($\Delta v \sim R^a$)



"In our own image"

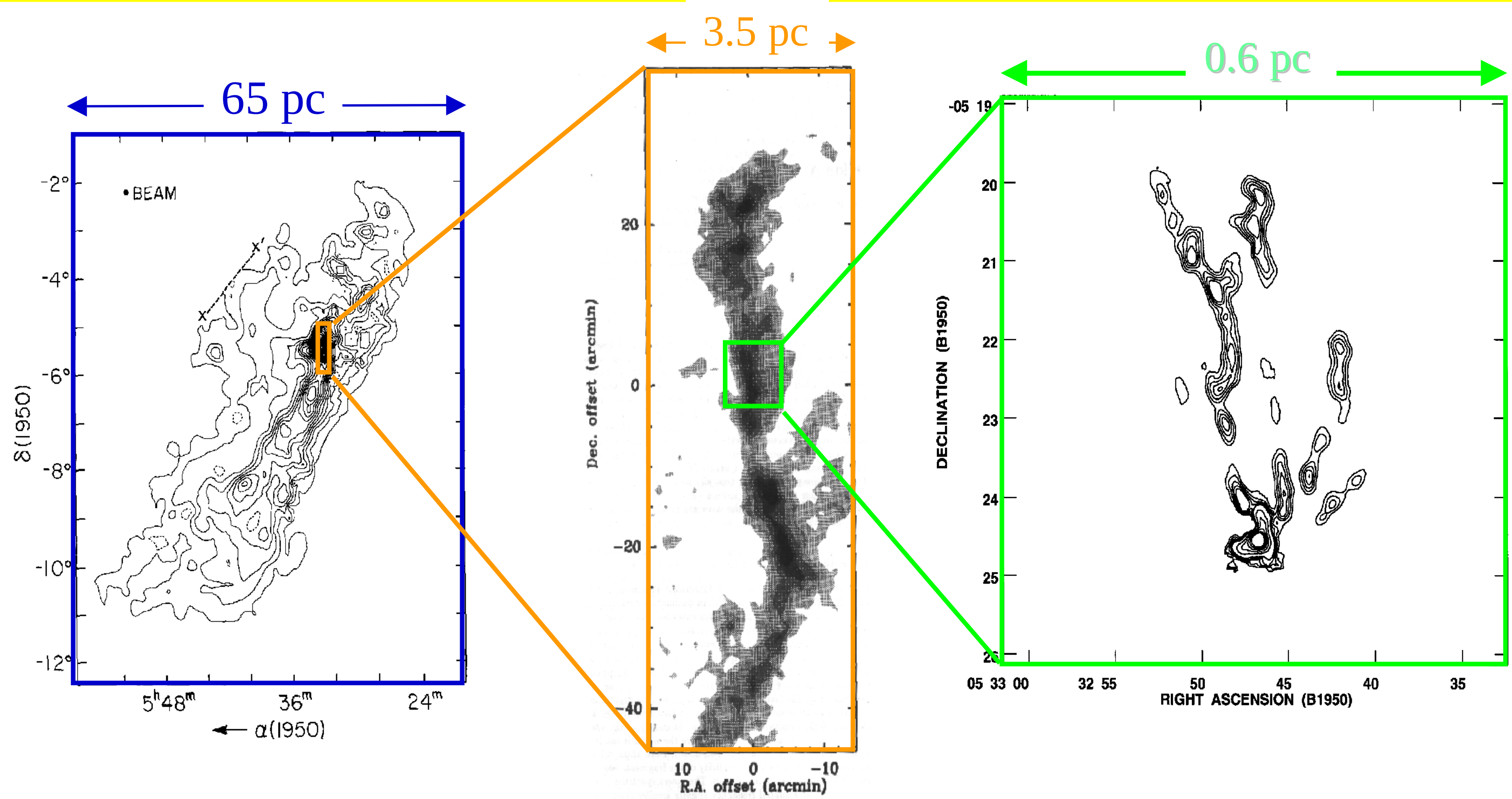
Putting down the chisel: Coherent Dense Cores

Quality Control

The Spectral Correlation Function [which Π(*B*, *G*, *T*, ★'*s*)?]

Self-similar Structure

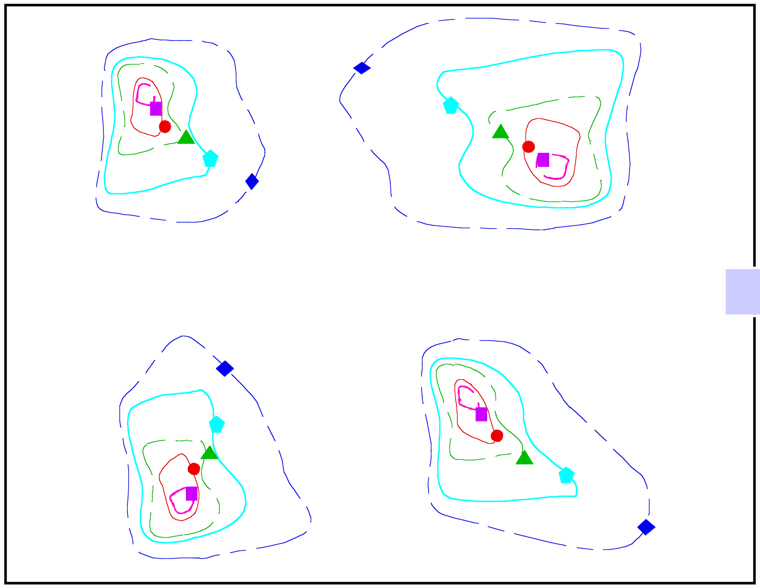
on scales from 100 pc to 0.1 pc...in Orion



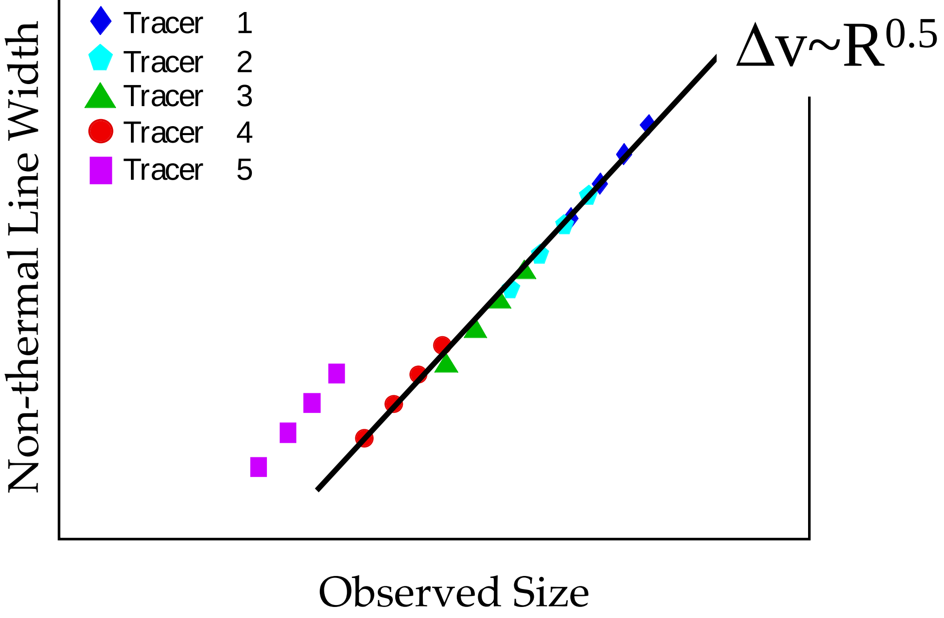
Maddalena et al. 1986	Dutrey et al. 1991	Wiseman 1995
CO Map, 8.7 arcmin resolution	$C^{18}O$ Map, 1.7 arcmin resolution	NH_3 Map, 8 arcsec resolution
Columbia-Harvard "Mini"	*AT&T Bell-Labs 7-m*	VLA

Types of Line width-Size Relations

Ensemble of Clouds



Type 1: "Larson's Law"



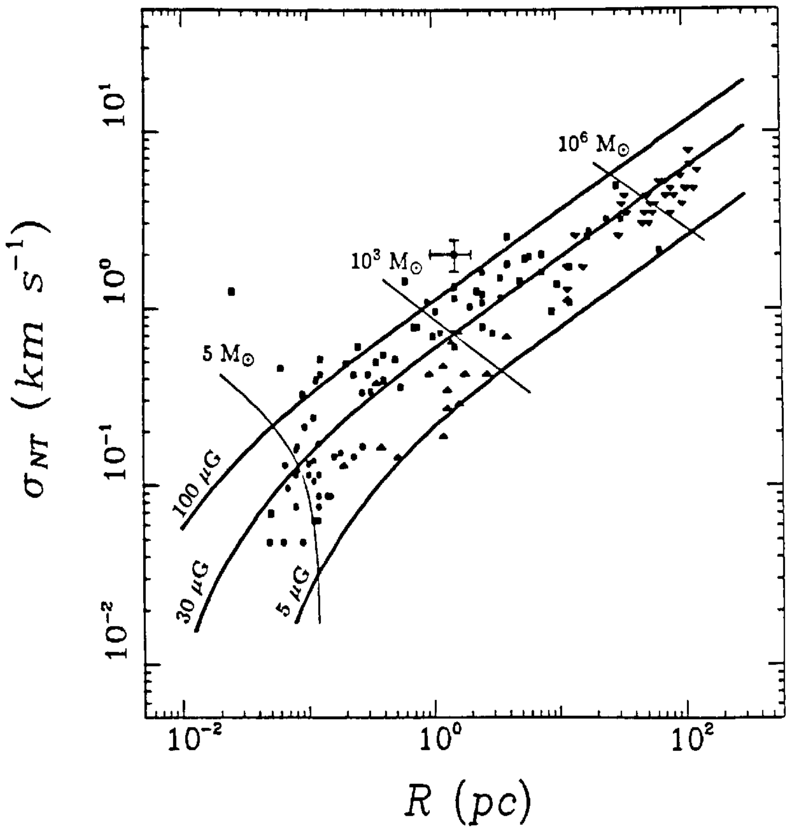
FWHM of Various Tracers Shown

Gives overall state of ISM~magnetic virial equilibrium.

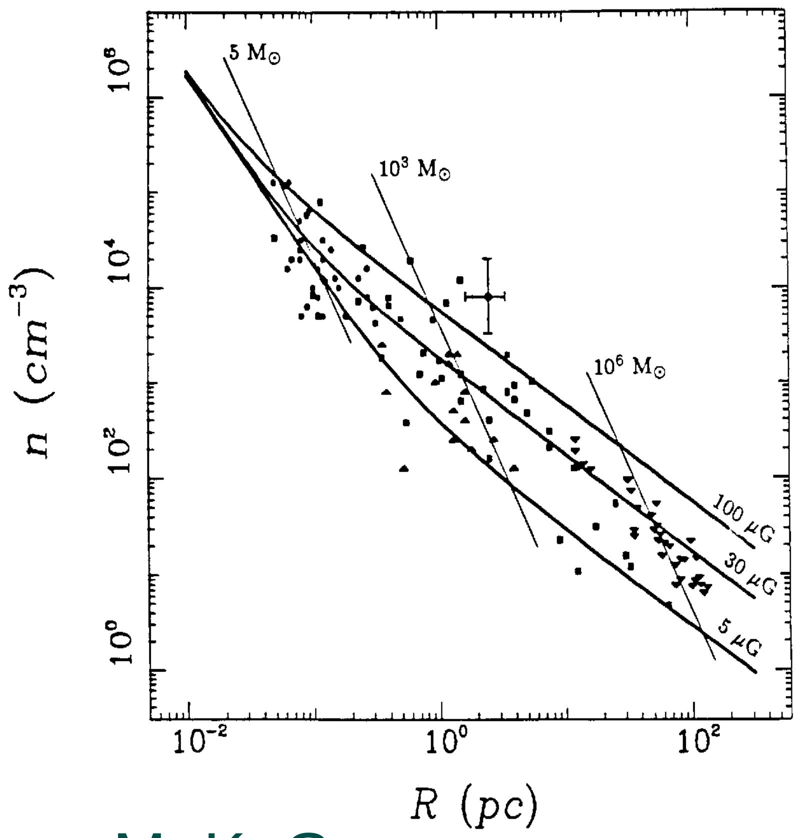
See Larson 1981; Myers & Goodman 1988 for examples.

"Larson's Law" Scaling Relations (1981)

(line width)~(size)$^{1/2}$



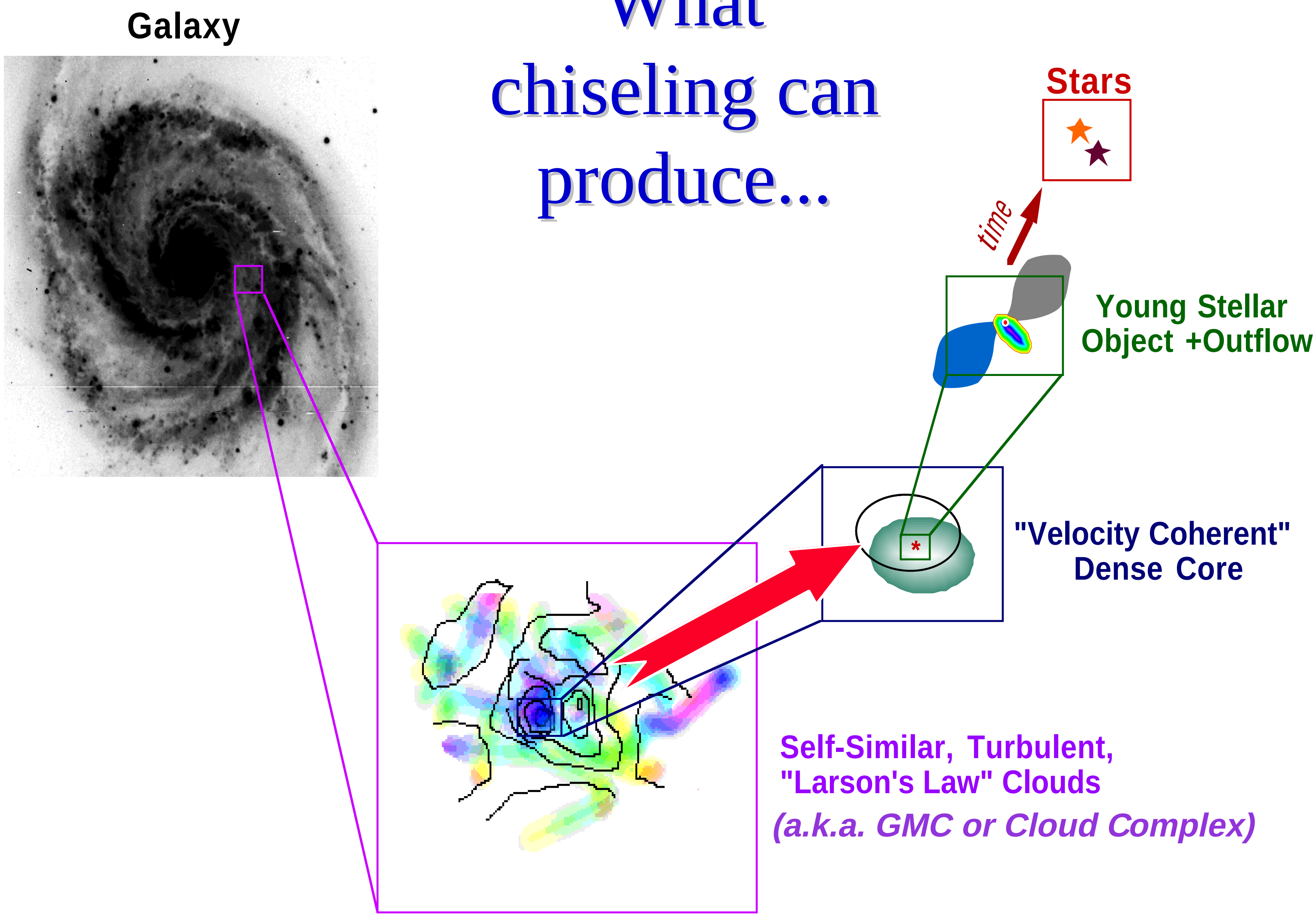
(density)~(size)$^{-1}$



Curves assume M=K=G

(Myers & Goodman 1988)

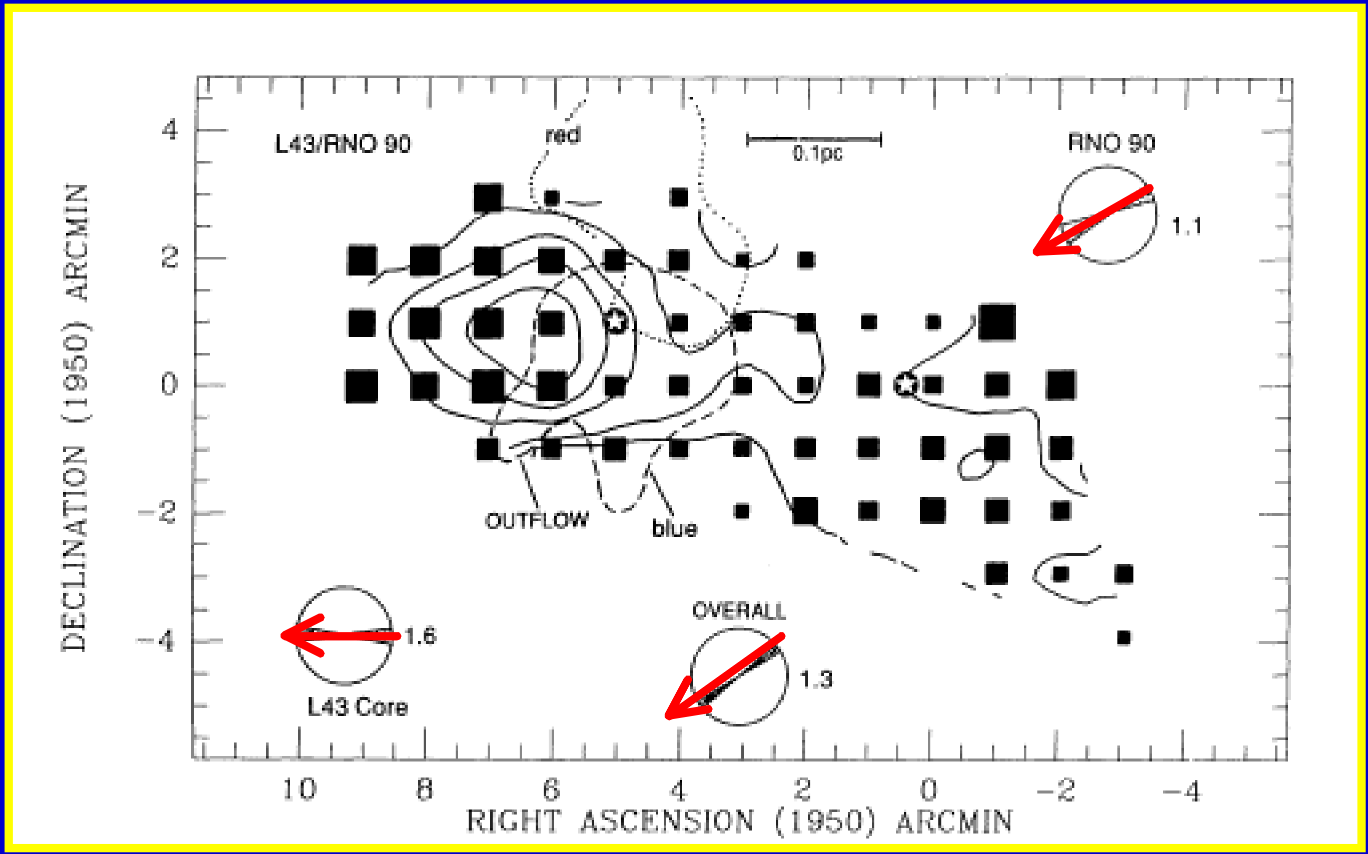
What chiseling can produce...



Coherent Cores: "Islands of Calm in a Turbulent Sea"

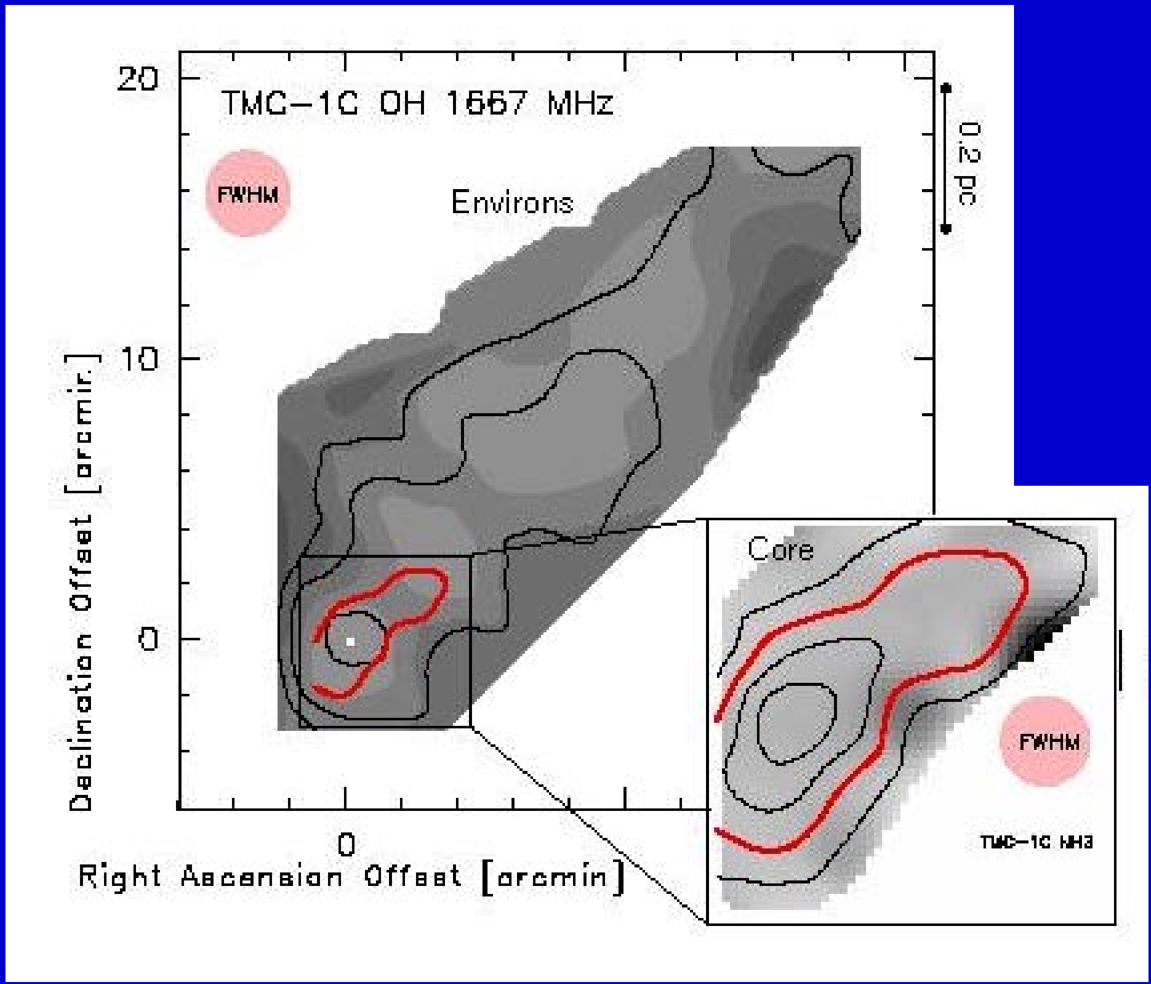
"Rolling Waves" by KanO Tsunenobu © The Idemitsu Museum of Arts.

Hint #1: Independent Core Rotation



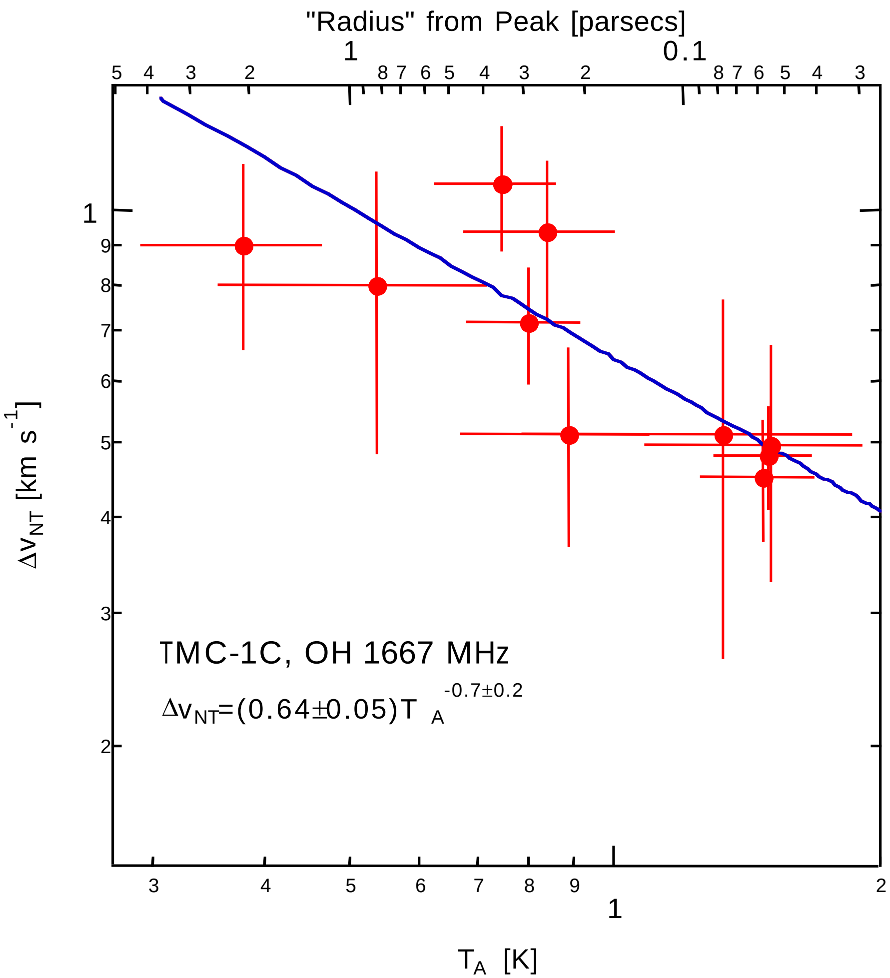
Goodman, Benson, Fuller & Myers 1993

Hint #2: Constant Line Width in Cores?

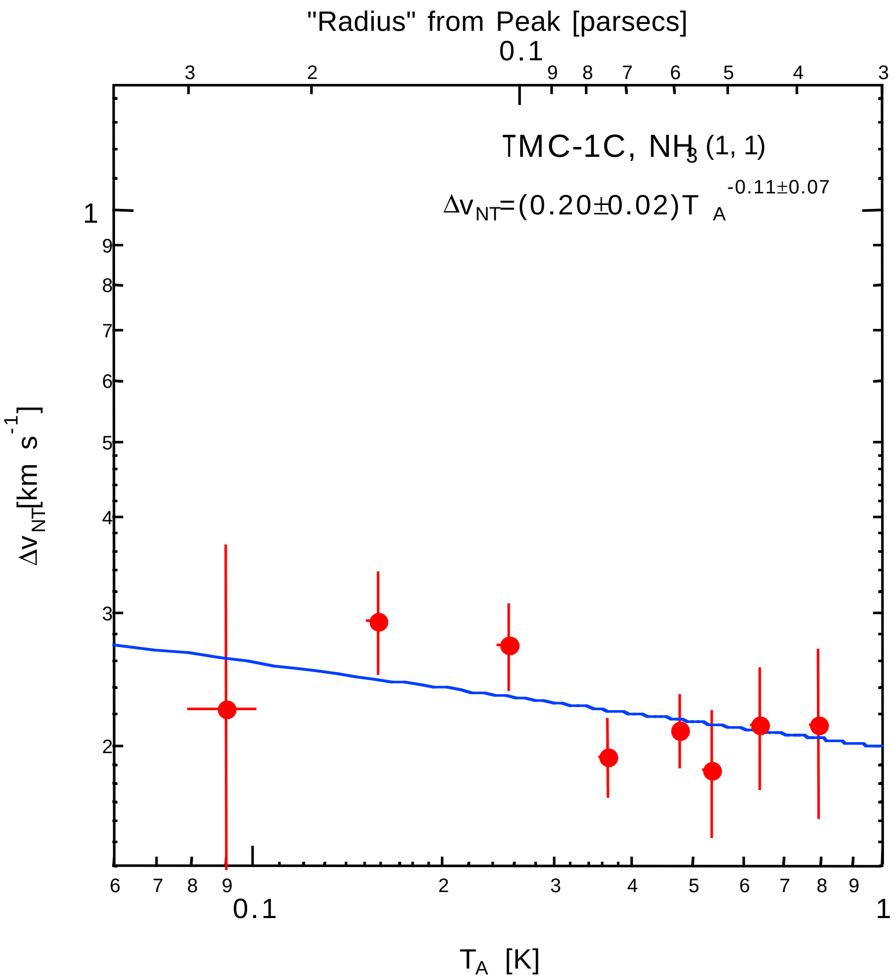


Example of the (Original) Evidence for Coherence

Type 4 Line width-“Size” Relations



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

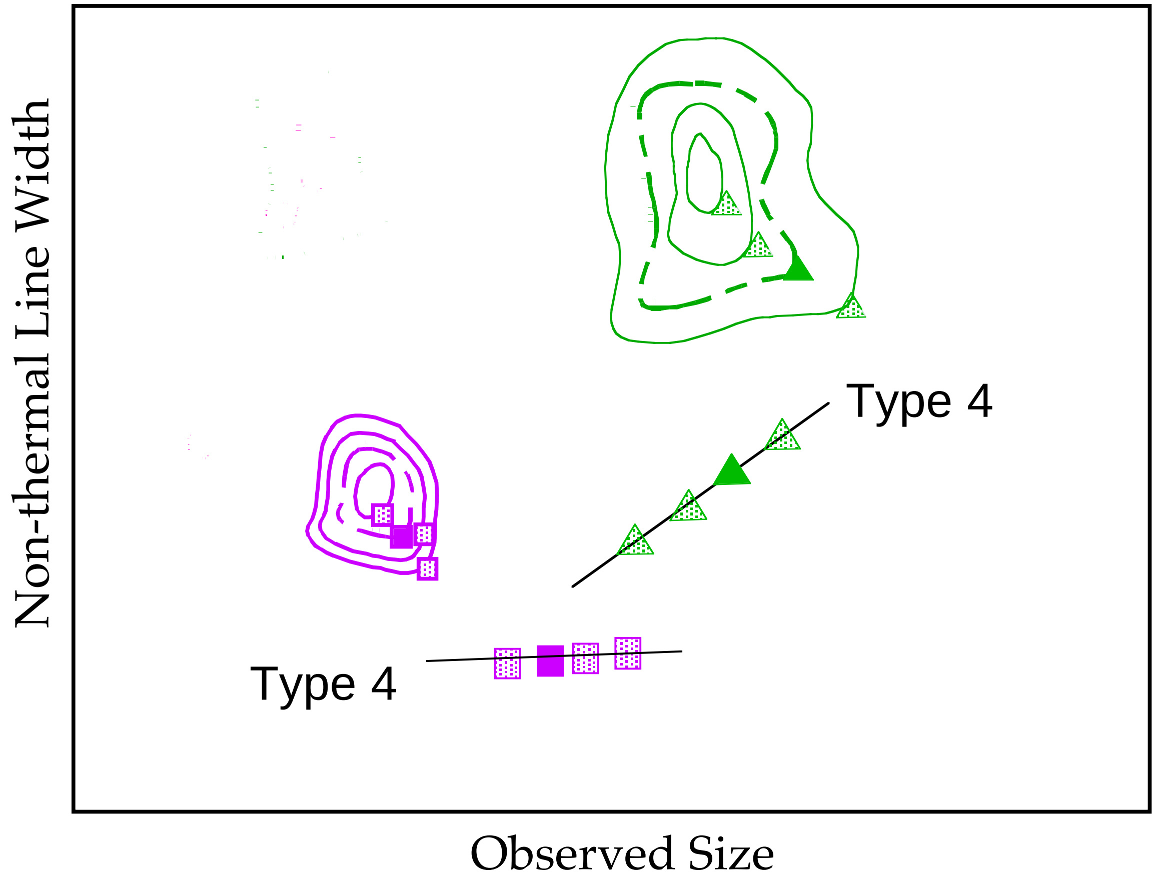


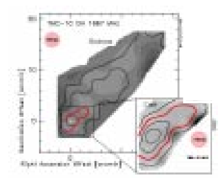
$$\Delta v_{NT} = (0.30 \pm 0.09) R^{0.12 \pm 0.08}$$

Goodman, Barranco, Heyer & Wilner 1998

Types of Line width-Size Relations

"Type 4:" Single Cloud Observed in a <u>Single</u> Tracer



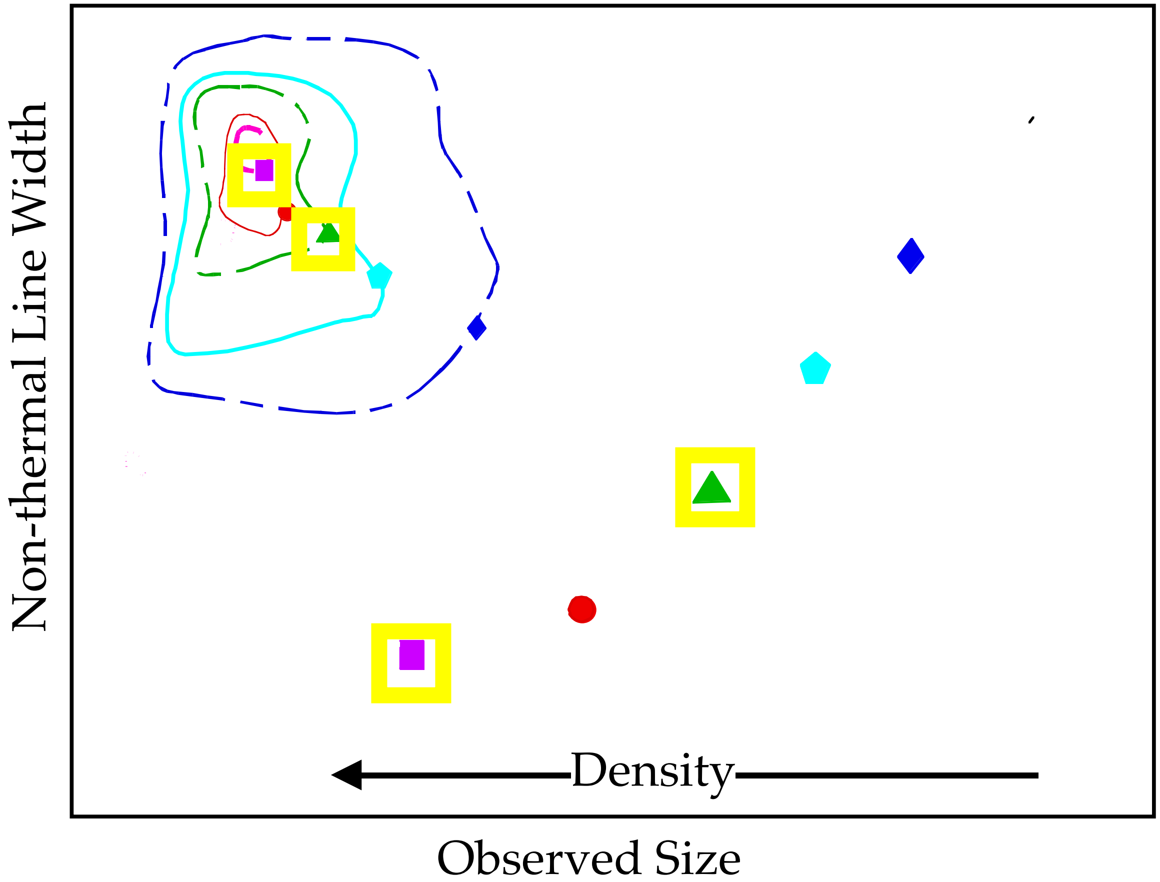


Gives information on power spectrum of velocity fluctuations.

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

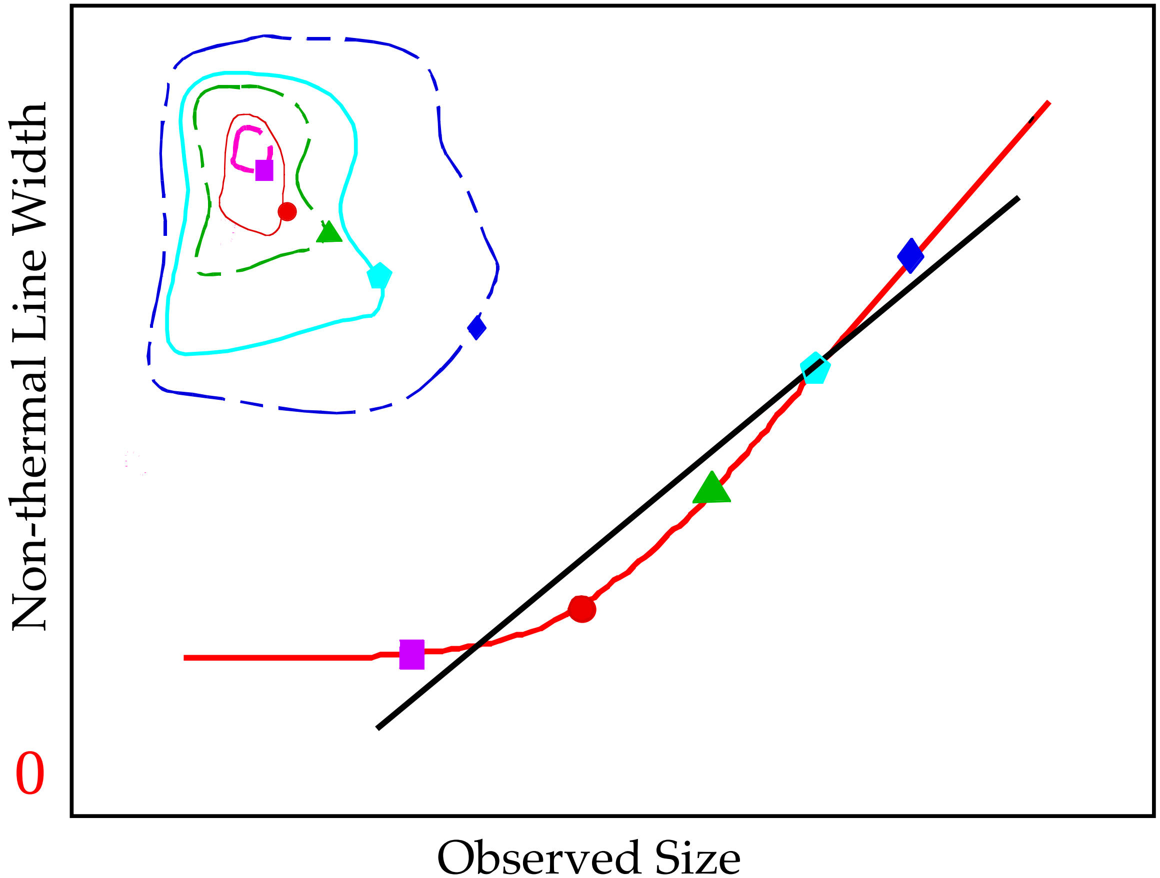
Types of Line width-Size Relations

"Type 3:" Single Cloud Observed in Multiple Tracers



Types of Line width-Size Relations

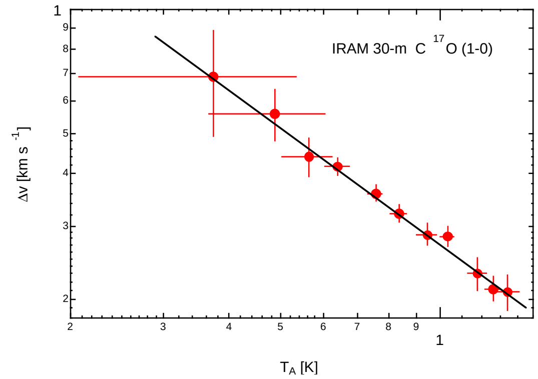
"Type 3:" Single Cloud Observed in Multiple Tracers

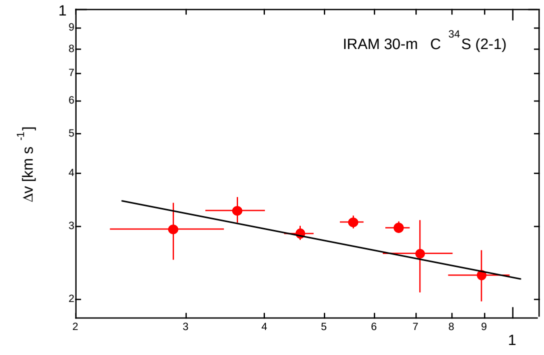


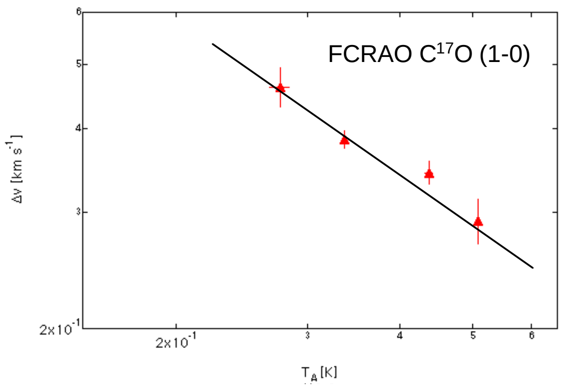
Gives pressure structure of an individual cloud.

See Fuller & Myers 1992.

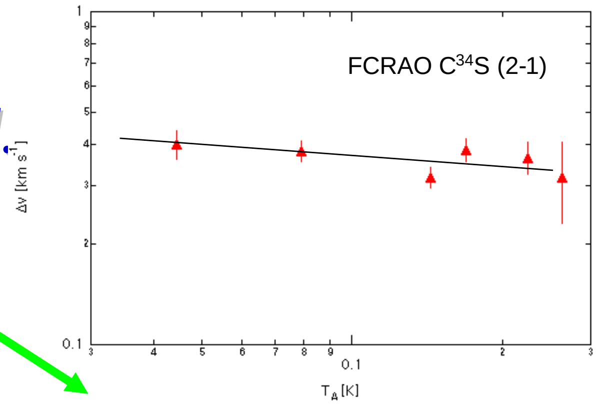
The (Newer) Evidence for Coherence

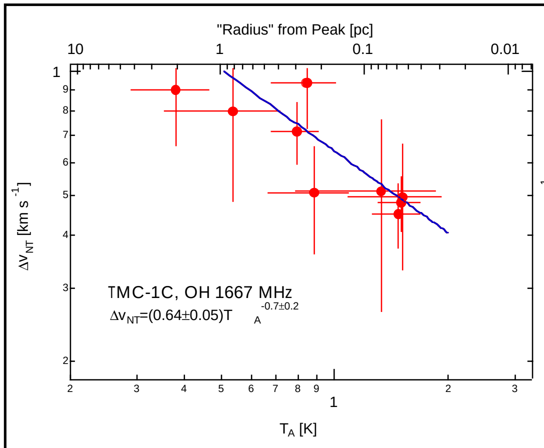


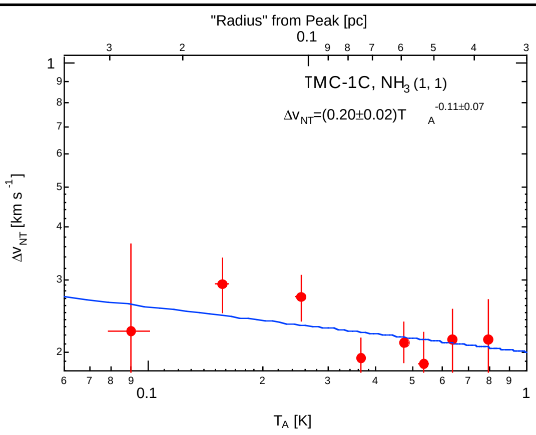


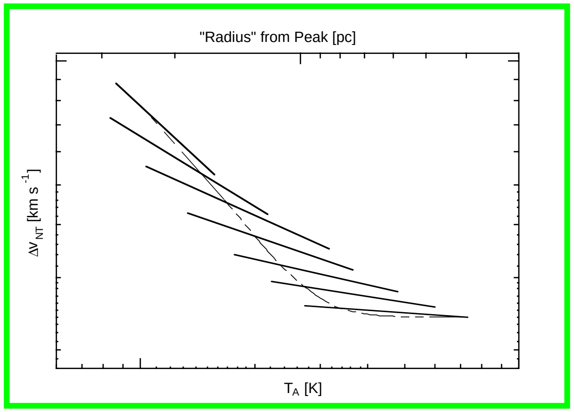


Type 4 slope appears to decrease with density, as predicted.



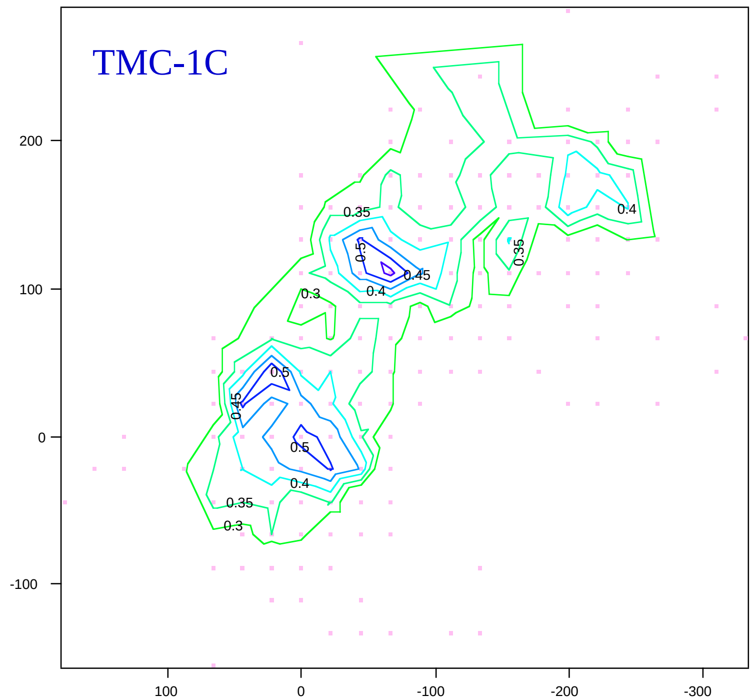


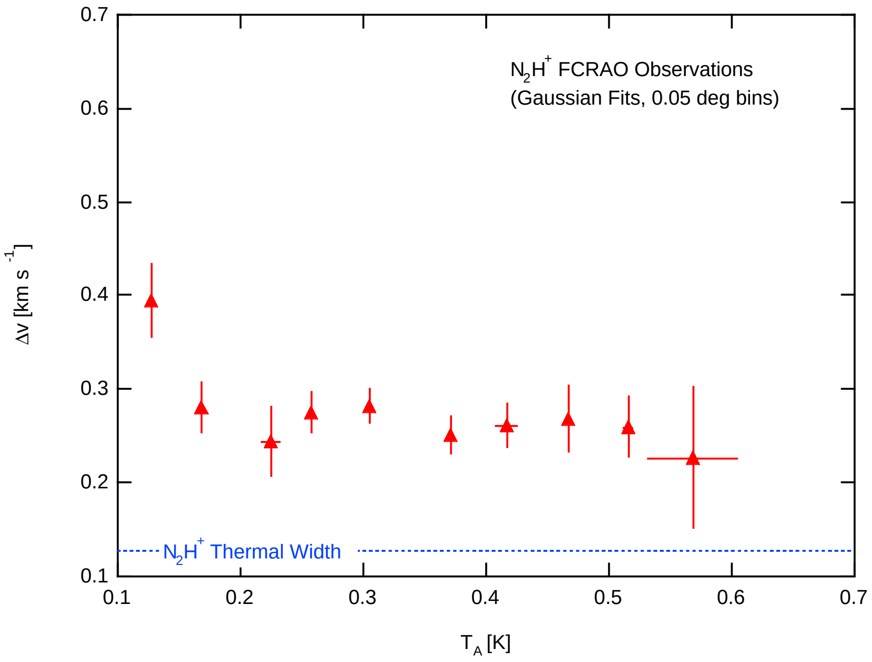




The Newest Evidence for Coherence

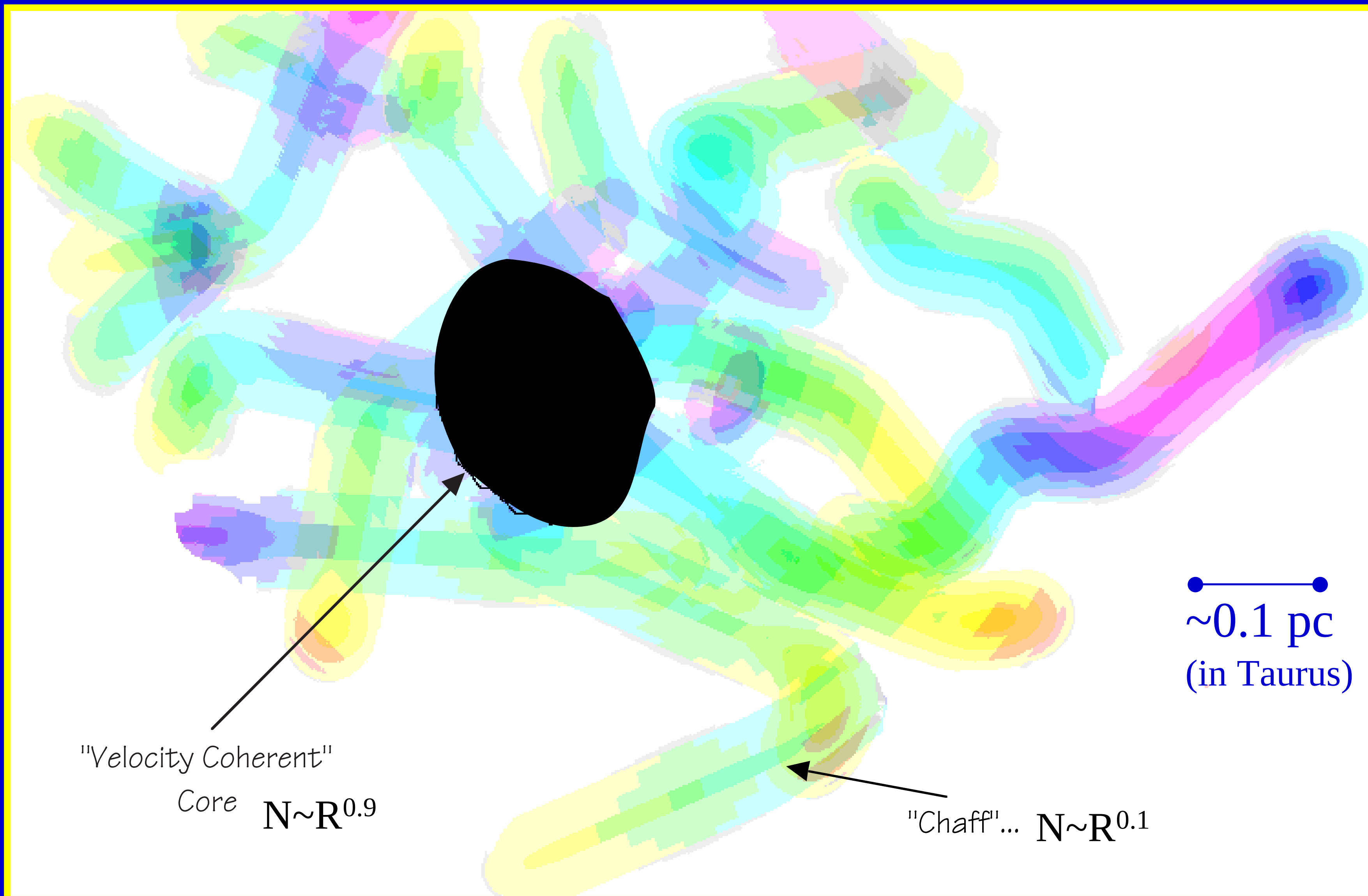
N_2H^+: Coherence in the Ionized Gas



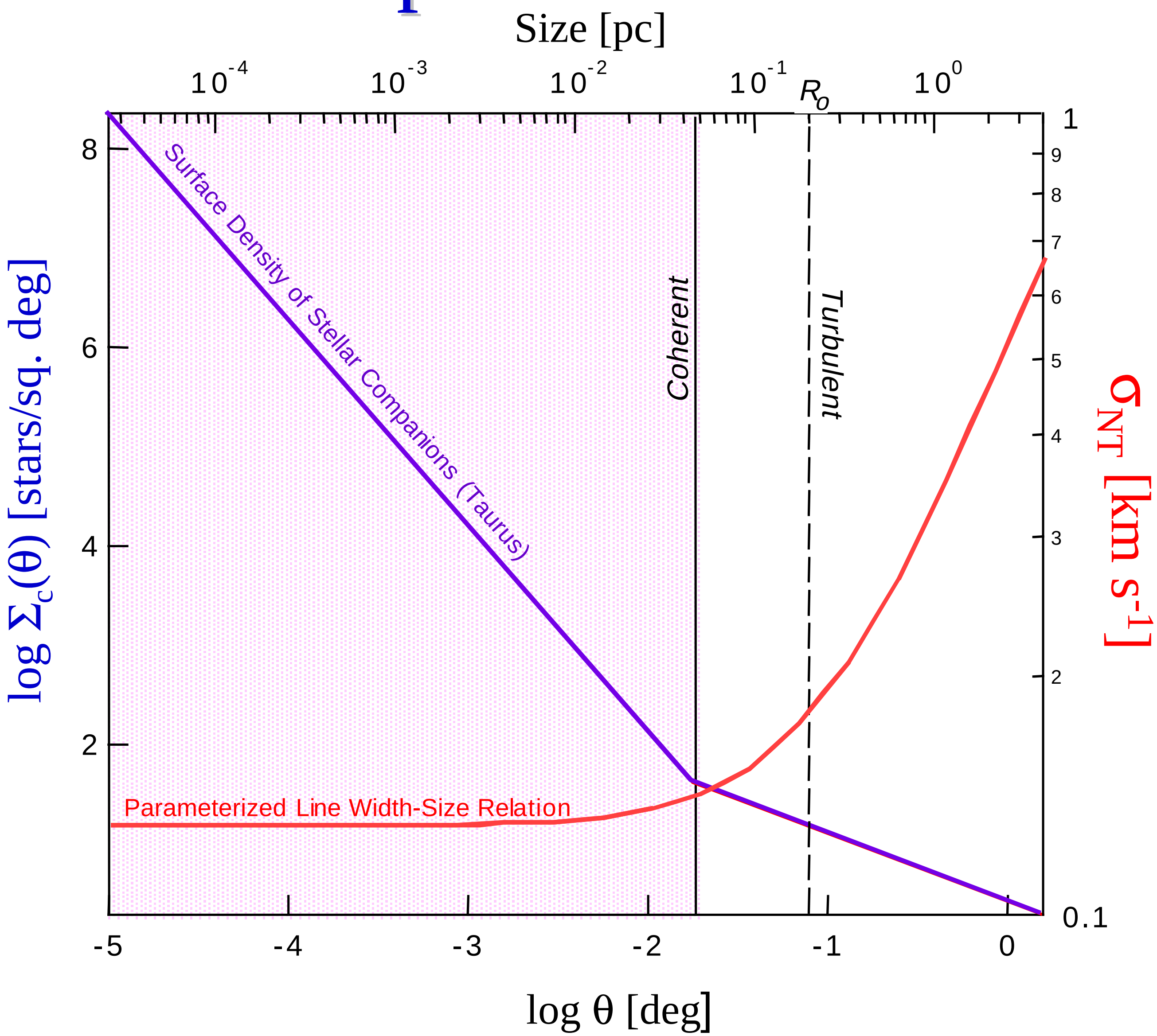


Goodman, Arce, Caselli, Heyer, Williams & Wilner 1999

Coherent Dense Core



“Coherence” in Spatial Distribution of Stars

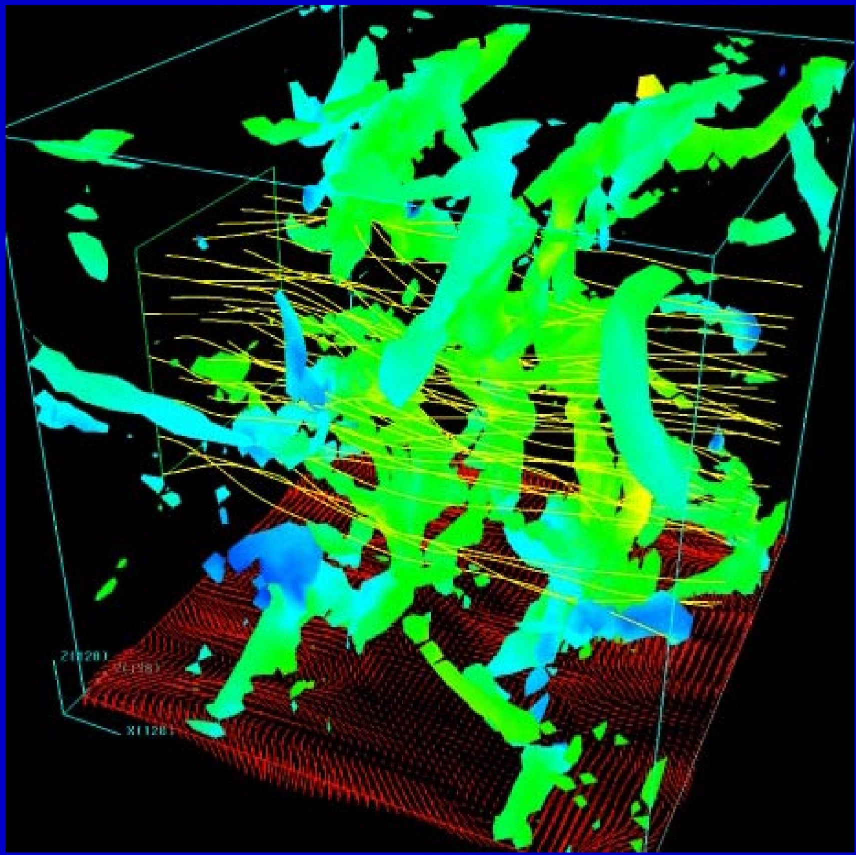


Goodman et al. 1998

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

The Cause of Coherence?

3D MHD simulation of Ostriker, Gammie & Stone (1998)



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?

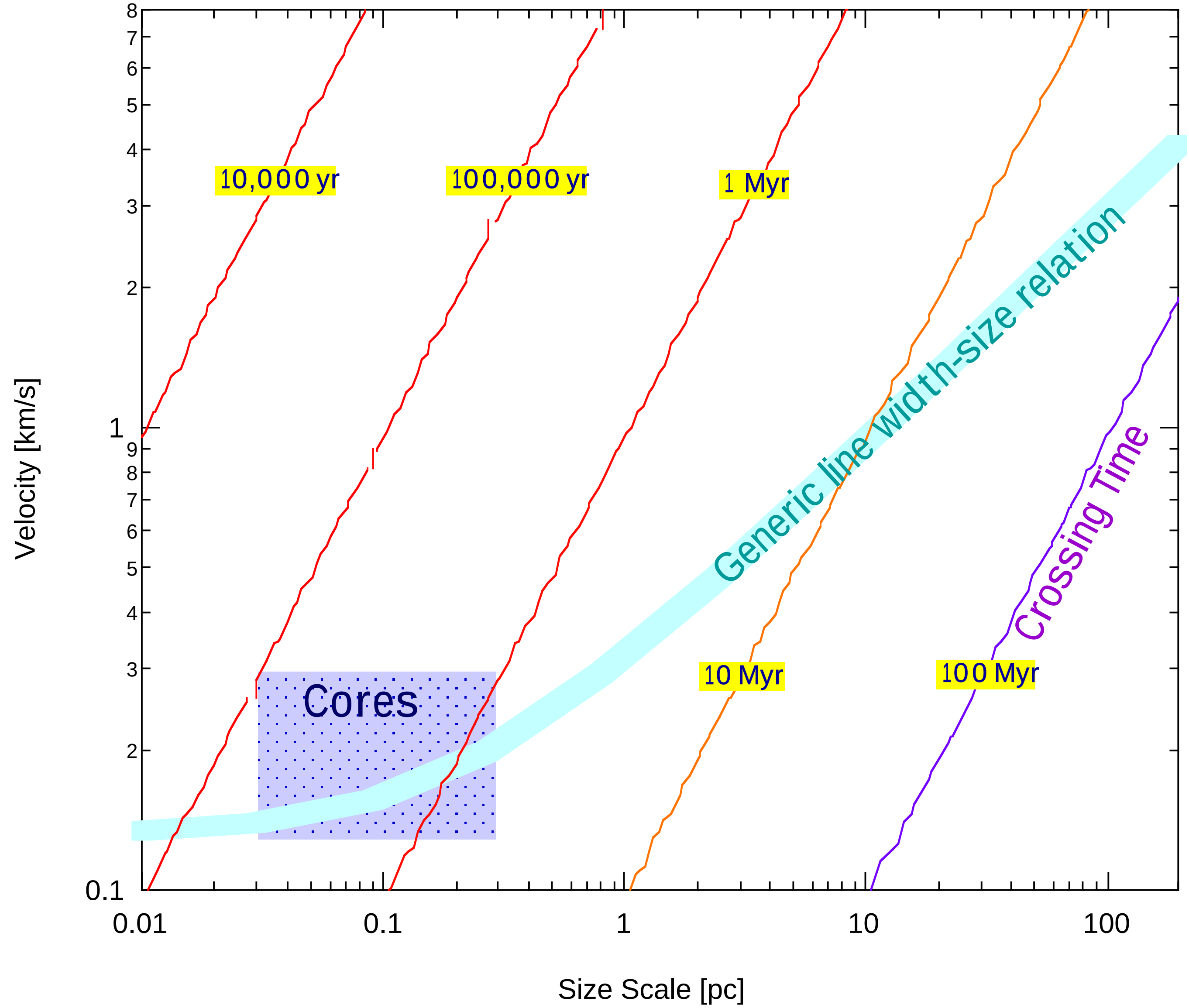
No ambipolar diffusion yet...

Length Scales Relevant to Coherence

For the Conditions: $n = 5 \times 10^3 \text{ cm}^{-3}$; $B = 20\ \mu\text{G}$; $T = 10$ K; $\mu = 2.33$ amu; $\Delta v = 1 \text{ km s}^{-1}$; $x_i = 10^{-7}$

Length Scale	Expression	Estimate [pc]	Comments
Alfvén Wave Cutoff	$R_{cut} = \frac{\pi^{1/2}}{4} \frac{B}{\rho^{3/2} x_i \gamma}$	0.3	$\sim R_{coh}$
Inner Scale of *Non-Magnetic* Turbulent Flow	$\lambda_\circ \approx \left[\frac{n \Delta v \sigma_{nn}}{(kT/\mu)^{1/2} \mathcal{R}_{cr}} \right]^{-3/4} L^{1/4}$	1×10^{-3}	for $L = 100$ pc; $\mathcal{R}_{cr} = 1000$; $\sigma_{nn} = 6 \times 10^{-16} \text{ cm}^{-2}$
Inner Scale of *Magnetic* Turbulent Flow	$\lambda_{\circ,B} \approx \lambda_\circ \left(\frac{\mathcal{R}_M}{\mathcal{R}} \right)^{-3/4}$	~0.3	$\sim R_{coh}$; assuming $\mathcal{R}/\mathcal{R}_M \approx 1500$
Thermal & Non-thermal Motions Equal	$R_{TNT} = \sqrt{\frac{90}{G} \frac{kT}{\mu B}}$	0.2	$\sim R_{coh}$; assuming magnetic, kinetic & gravitational equipartition
Ambipolar Diffusion in a Smooth Medium	$R_{AD} \approx R_{TNT}$	0.2	$\sim R_{coh}$; assuming predominantly cosmic ray ionization

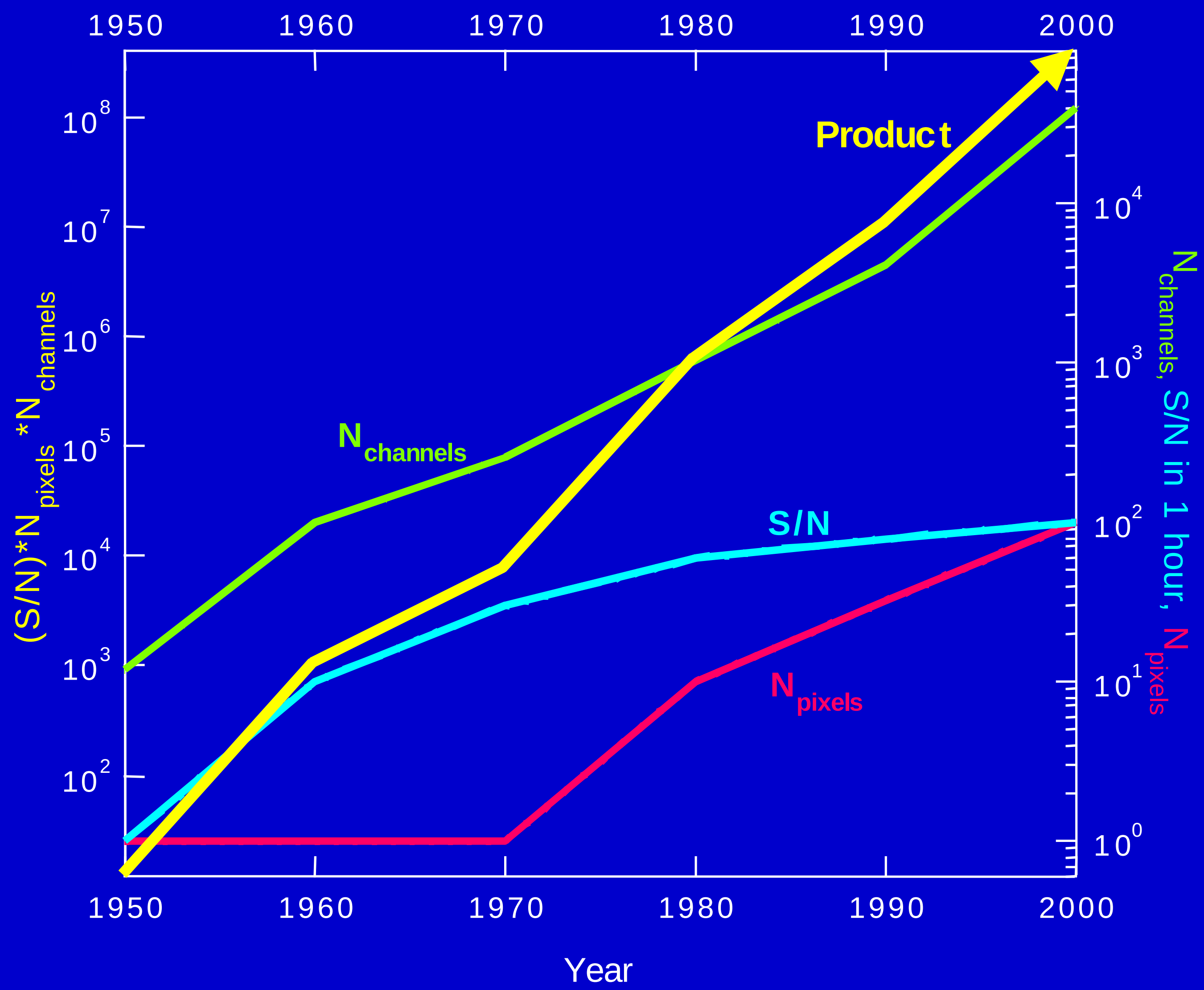
Timescales



10,000 yr
100,000 yr
1 Myr
10 Myr
100 Myr
Cores
Generic line width-size relation
Crossing Time
Velocity [km/s]
Size Scale [pc]
0.01
0.1
1
10
100
0.1
1

Quality Control

Learning More from "Too Much" Data



The Spectral Correlation Function

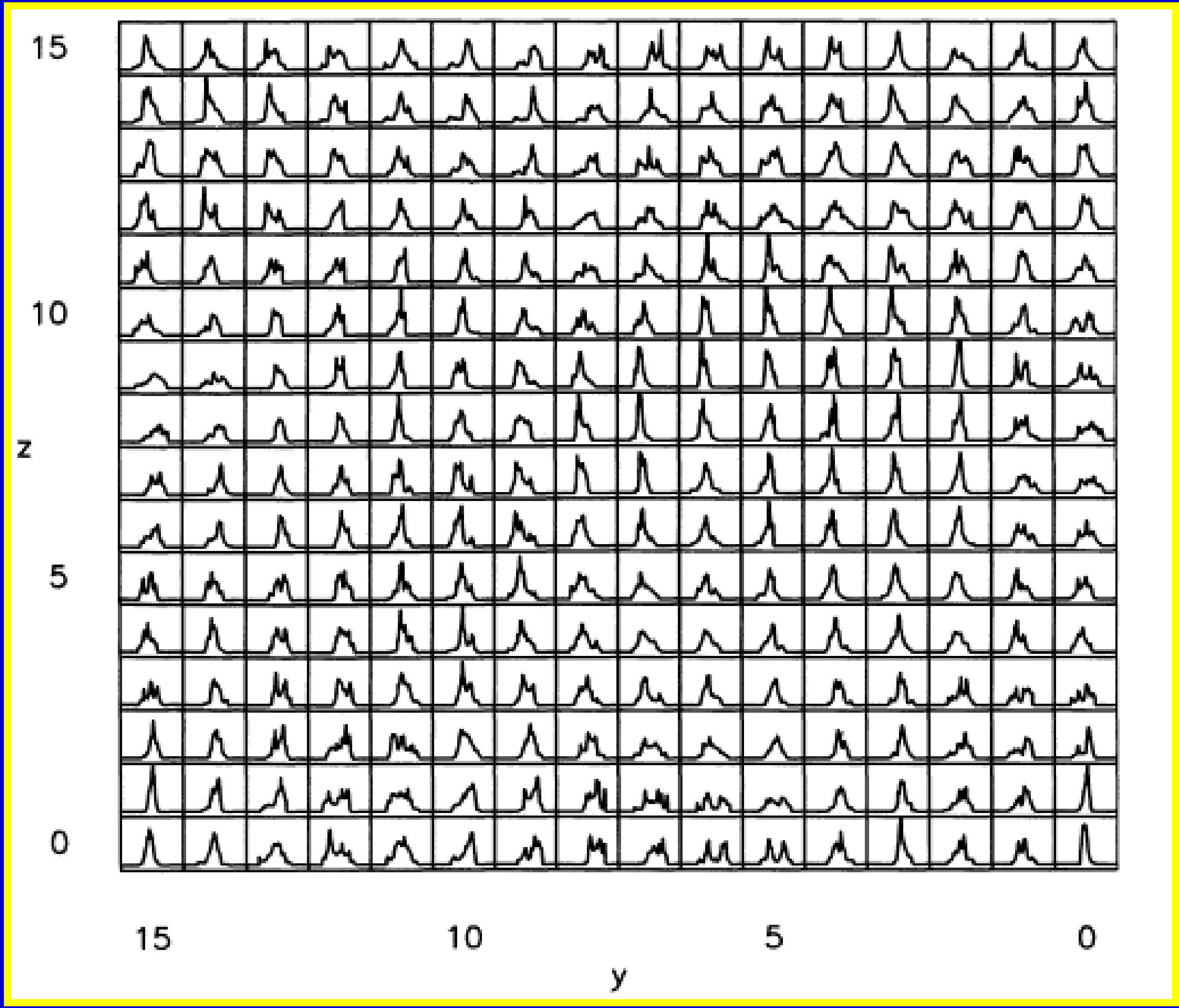


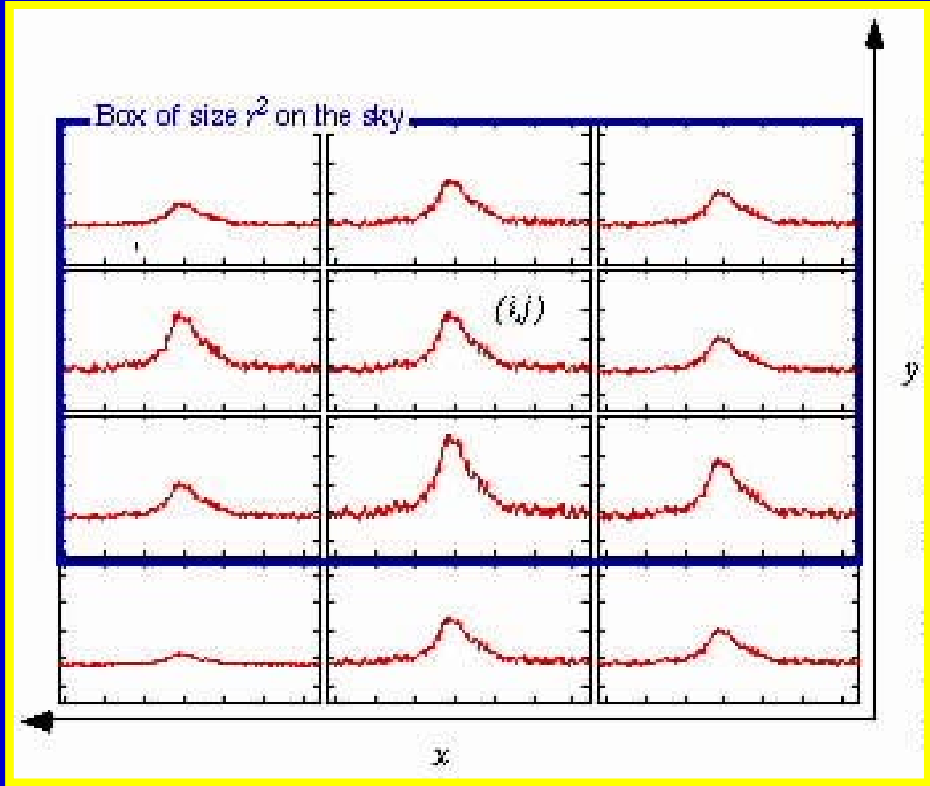
Figure from Falgarone et al. 1994 Simulation

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

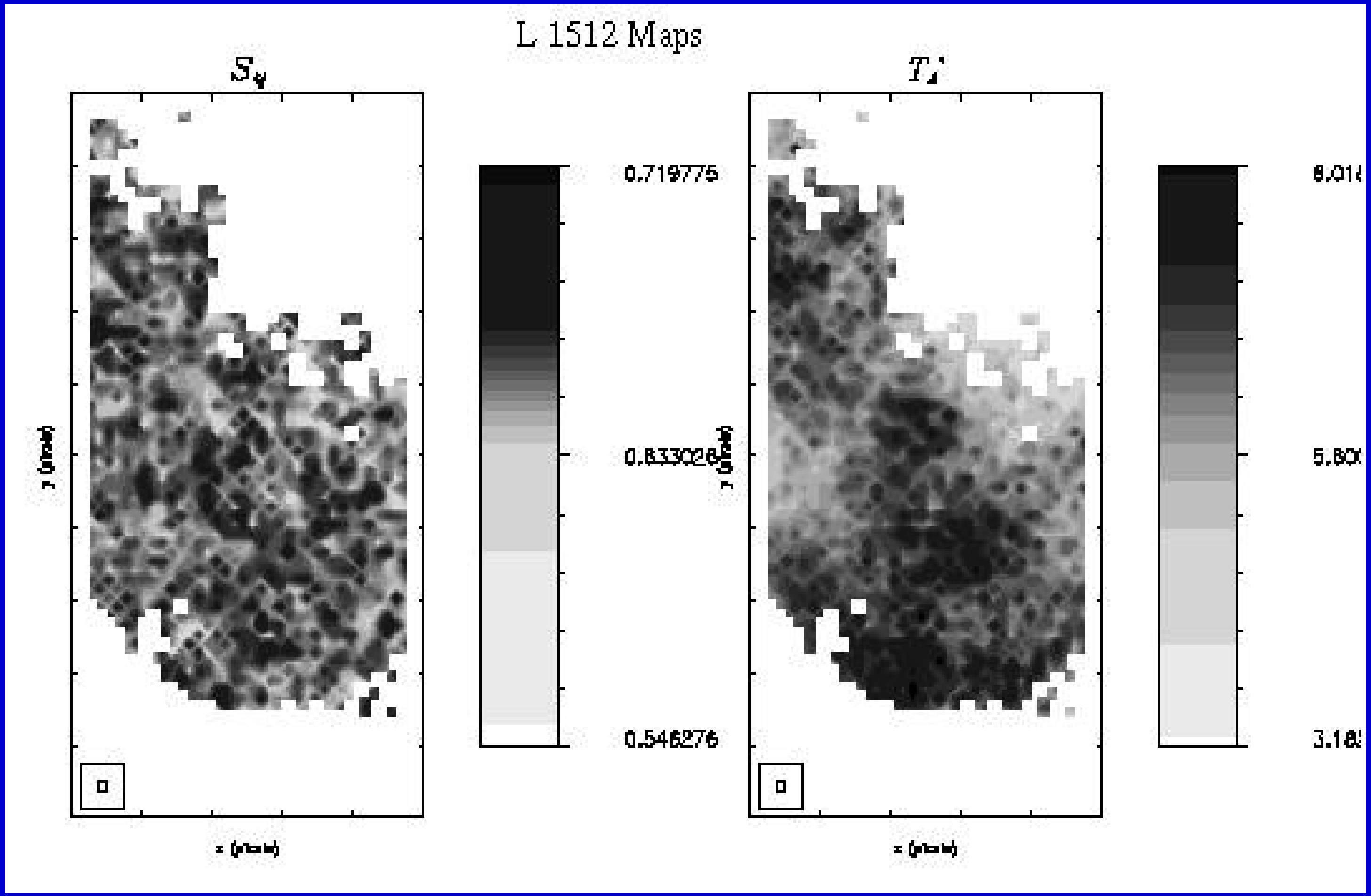
How the SCF Works

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



See: Rosolowsky, Goodman, Wilner & Williams 1999.

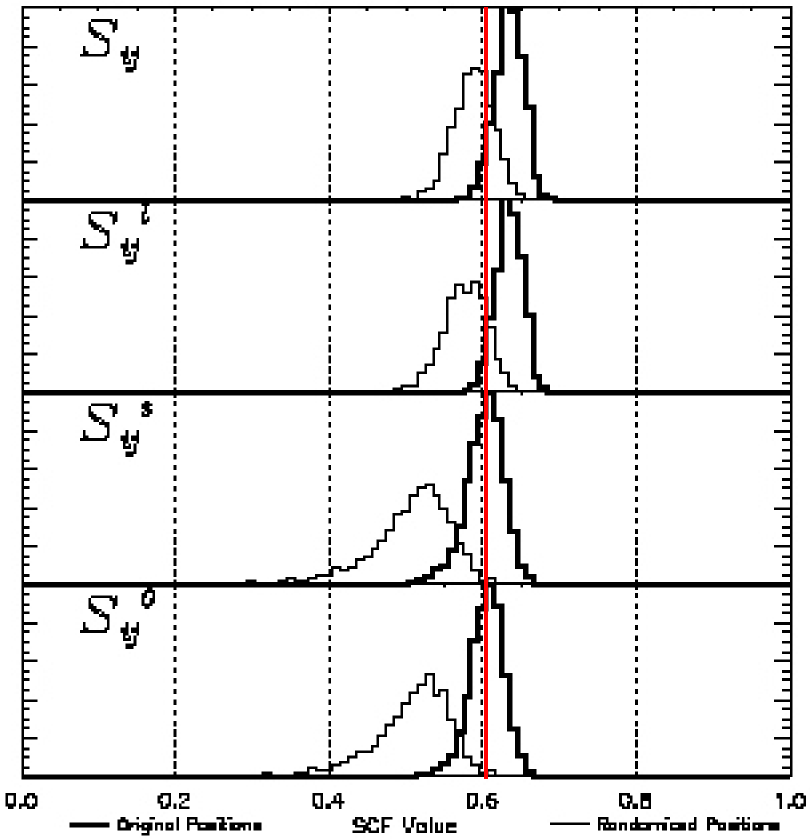
A "Real" Molecular Cloud



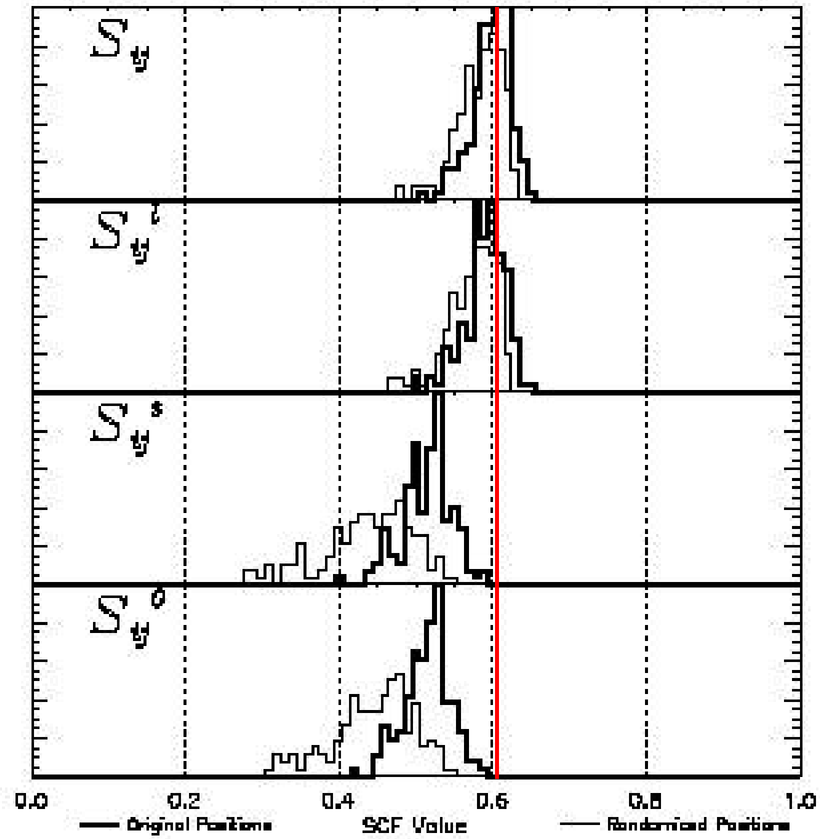
IRAM Key Project Data

Initial Comparisons using the SCF

L1512 (Real Cloud)



"Matching?" Turbulence Simulation

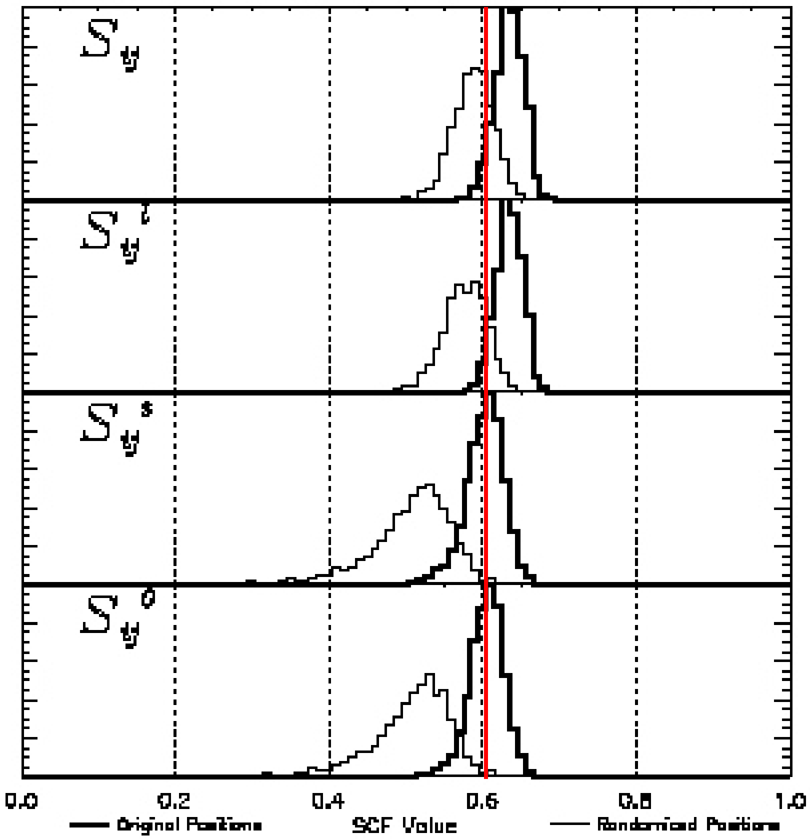


IRAM Key Project Data

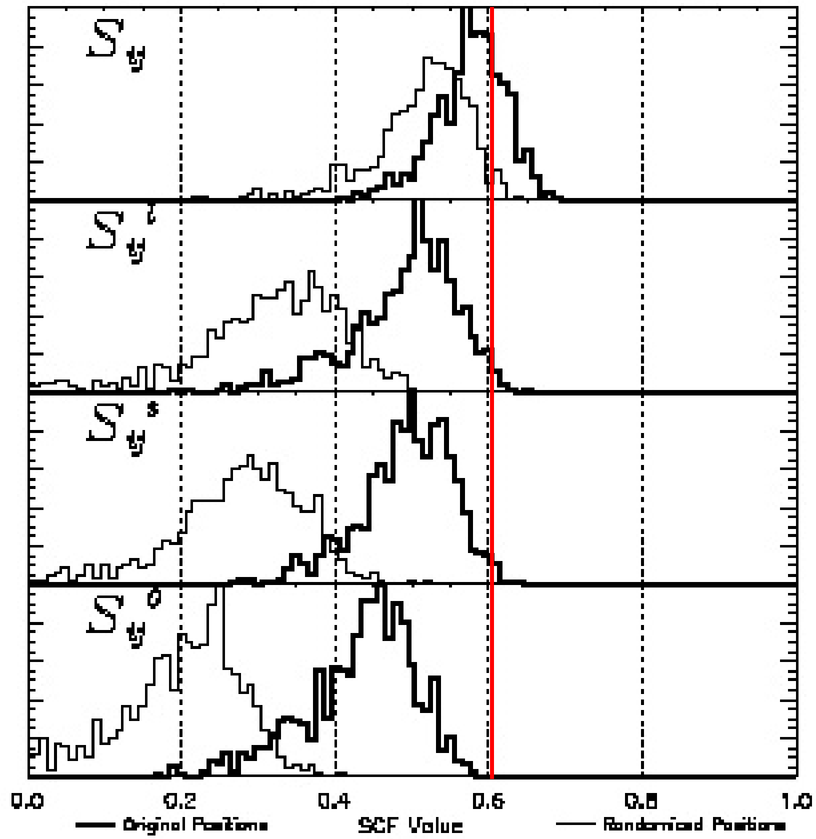
Falgarone et al. 1994

Initial Comparisons using the SCF

L1512 (Real Cloud)



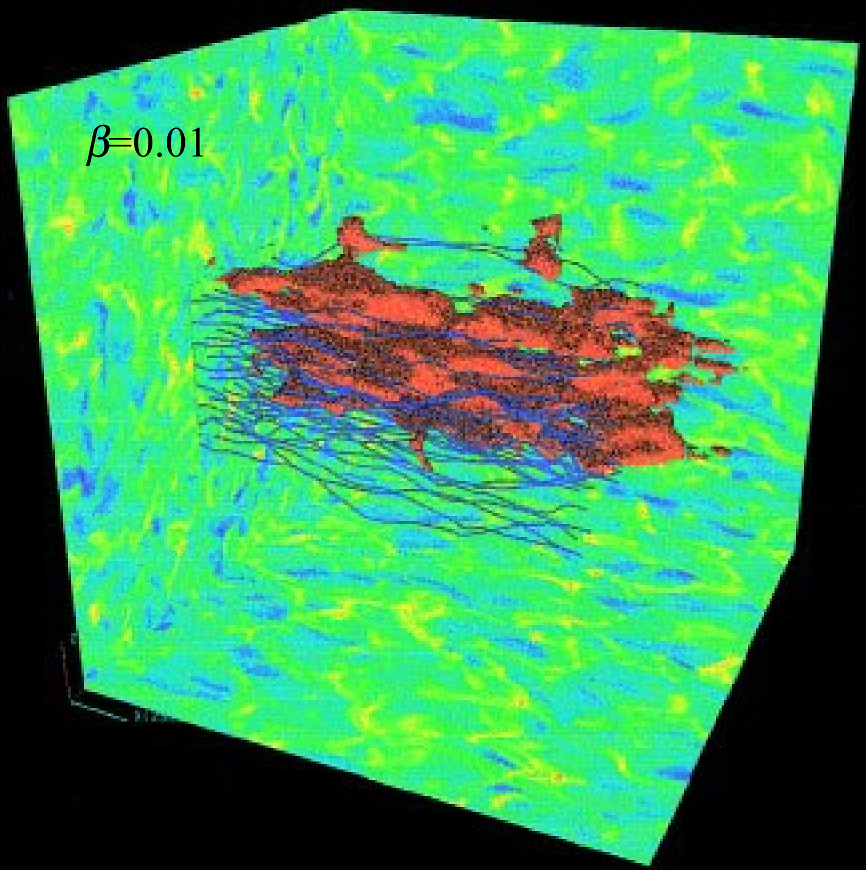
Better? MHD Simulation

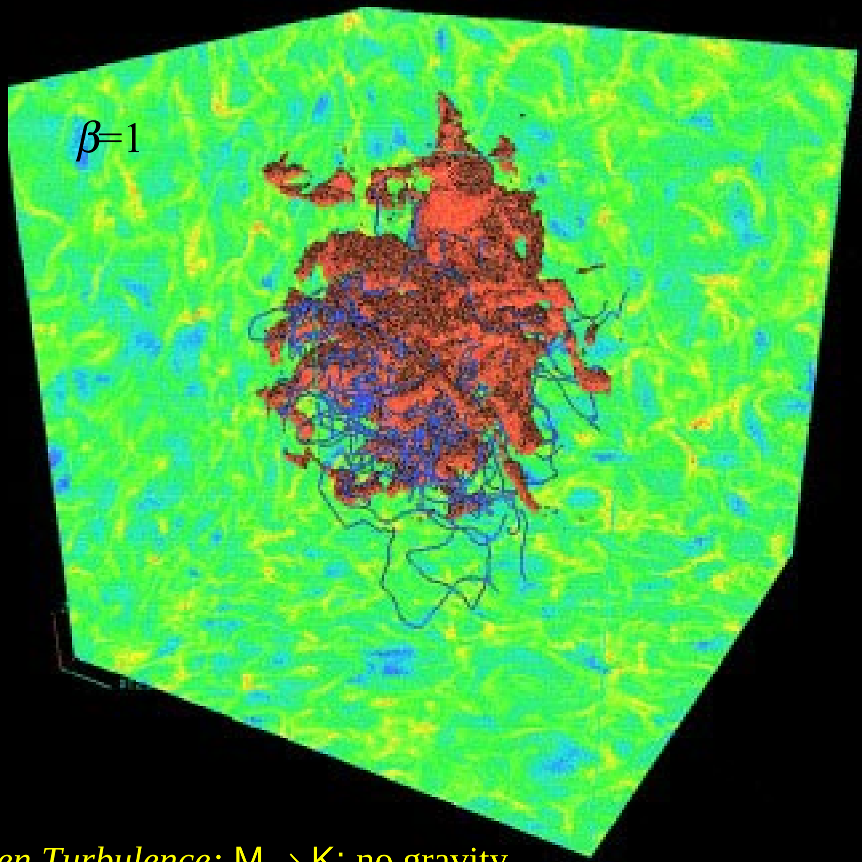


IRAM Key Project Data

Gammie, Ostriker & Stone 1998

Strong vs. Weak Field





Stone, Gammie & Ostriker 1999

$$\beta = \frac{[T / 10\ \mathrm{K}]}{[n_{H_2} / 100\ \mathrm{cm}^{-3}][B / 1.4\ \mu\mathrm{G}]^2}$$

- *Driven Turbulence;* M→ K; no gravity
- *Colors: log density*
- *Computational volume: 256^3*
- *Dark blue lines: B-field*
- *Red : isosurface of passive contaminant after saturation*

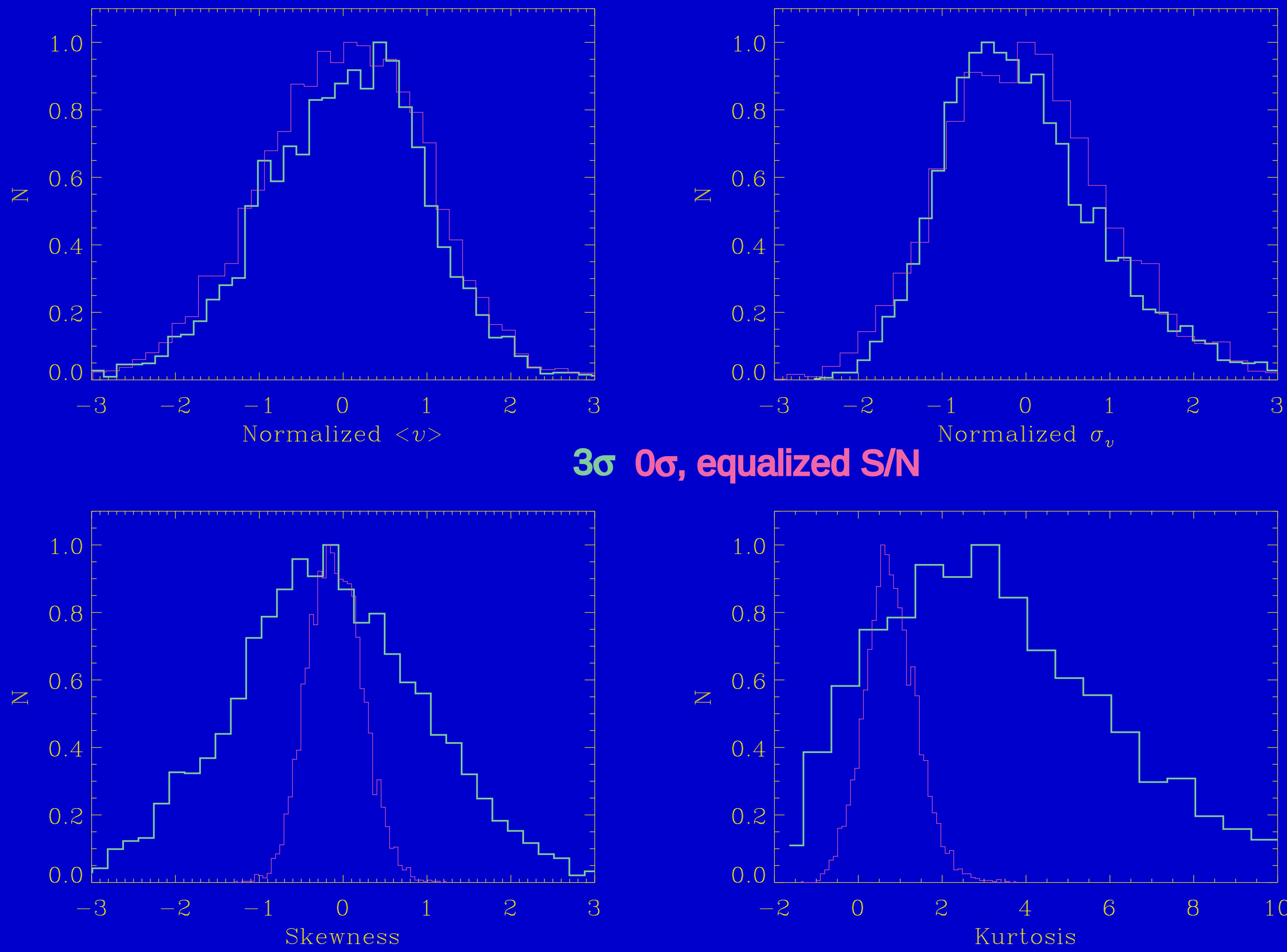
Goals of "SCF" Project

- 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

Results from SCF Project, 3/99

- Some simulations do match quantitatively better than others *(Goodman & Padoan 1999)*
  - compared so far: Padoan et al.; Ostriker, Gammie & Stone; Vazquez, Porter, Pouquet et al; MacLow et al.
- Comparison with moment analysis shows SCF more discriminating (*Rosolowsky et al. 1999*)
- Noise analysis is critical for ALL methods
  - S/N cutoffs, corrections
  - Window size
- SCF used on Galactic H I can identify shells automatically (see *Ballesteros, Vazquez & Goodman 1999*)

The Effects of Noise



What Sculpts the ISM?

Blasting

Origin of High-Latitude Clouds

Generic Chiseling

Line width-Size Relations ($\Delta v \sim R^a$)

"In our own image"

Coherent Dense Cores

Quality Control

The Spectral Correlation Function

Which Π(*B, G, T,* ★*'s*)?

To be discussed:

The Role of Clay

- *Agglomeration, Tidal Stripping, the IMF*

Weathering

- *Museum Destroyed on 100,000 yr time scale*
- *Longest lifetime of Galactic ISM Structures?*

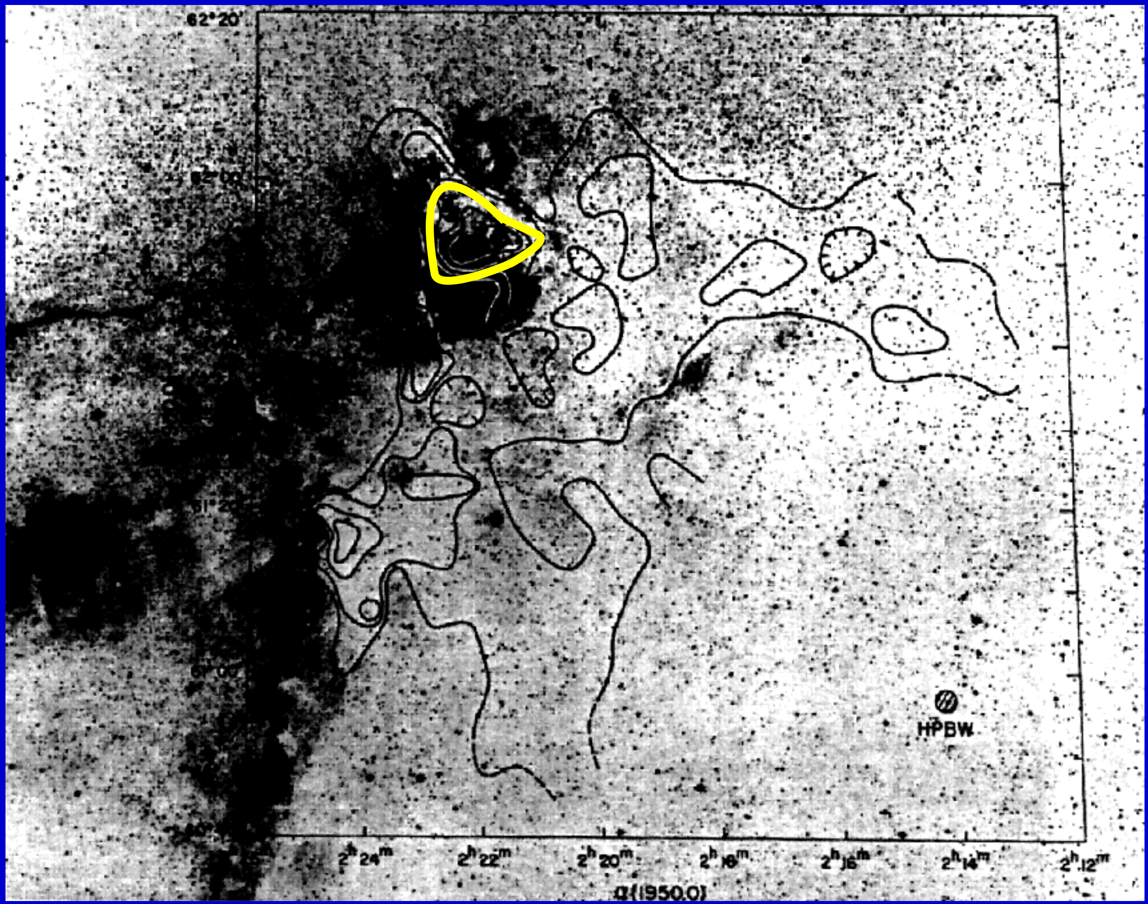
The Role of Chemistry

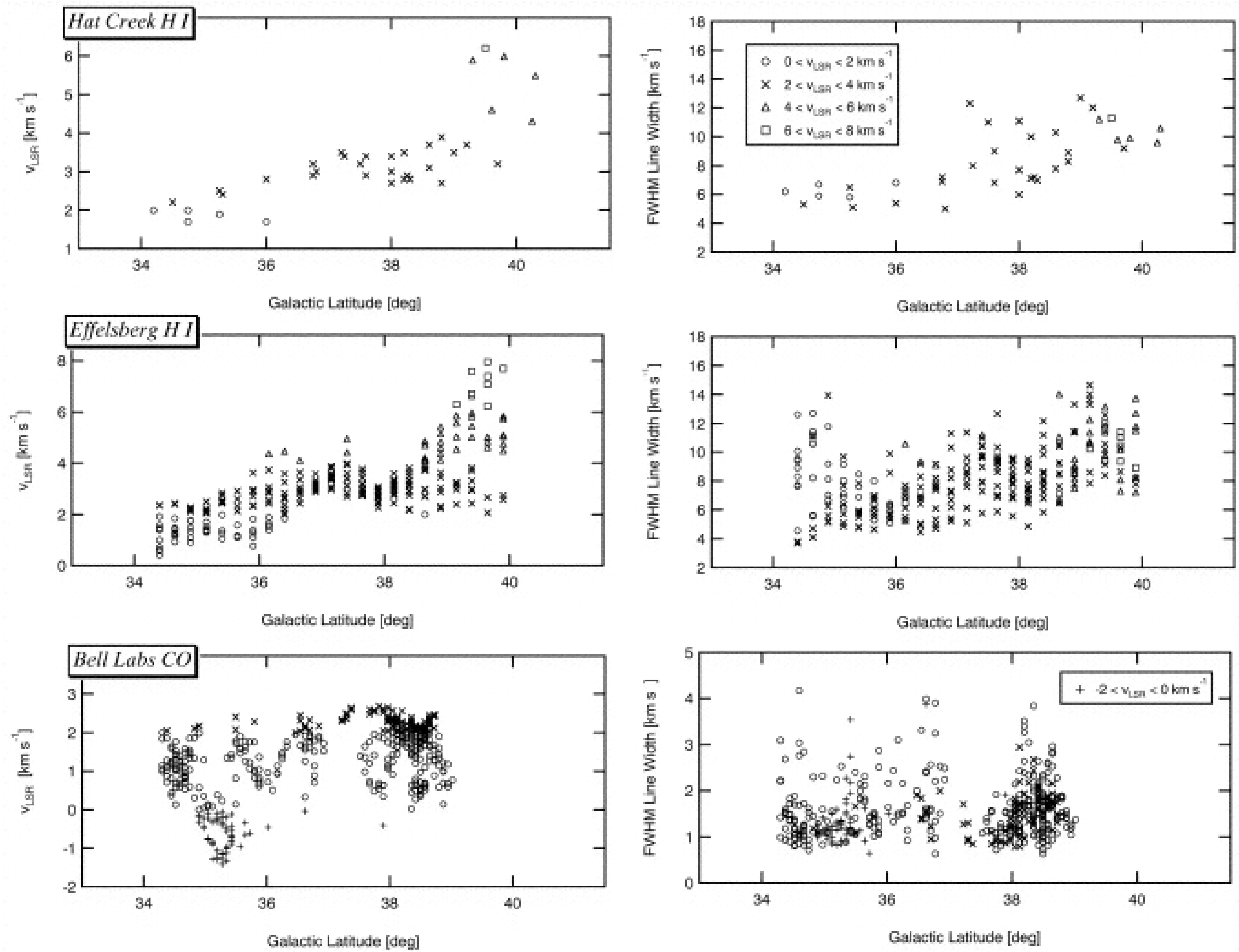
- *How much structure is density, how much chemistry?*

Very Small-Scale Structure

- *Interferometric Observations*
- *Extinction surveys & Pencil-beam Observations*

Optical View of W3 Region





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