Magnetic Fields & Turbulence: Observations

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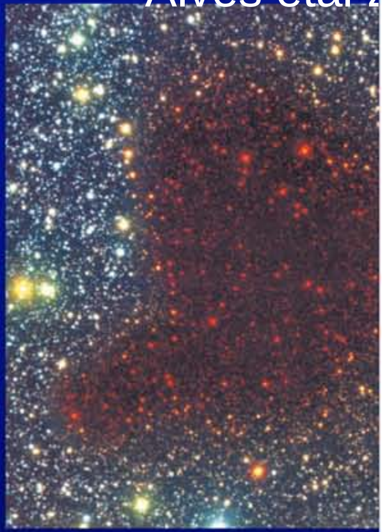
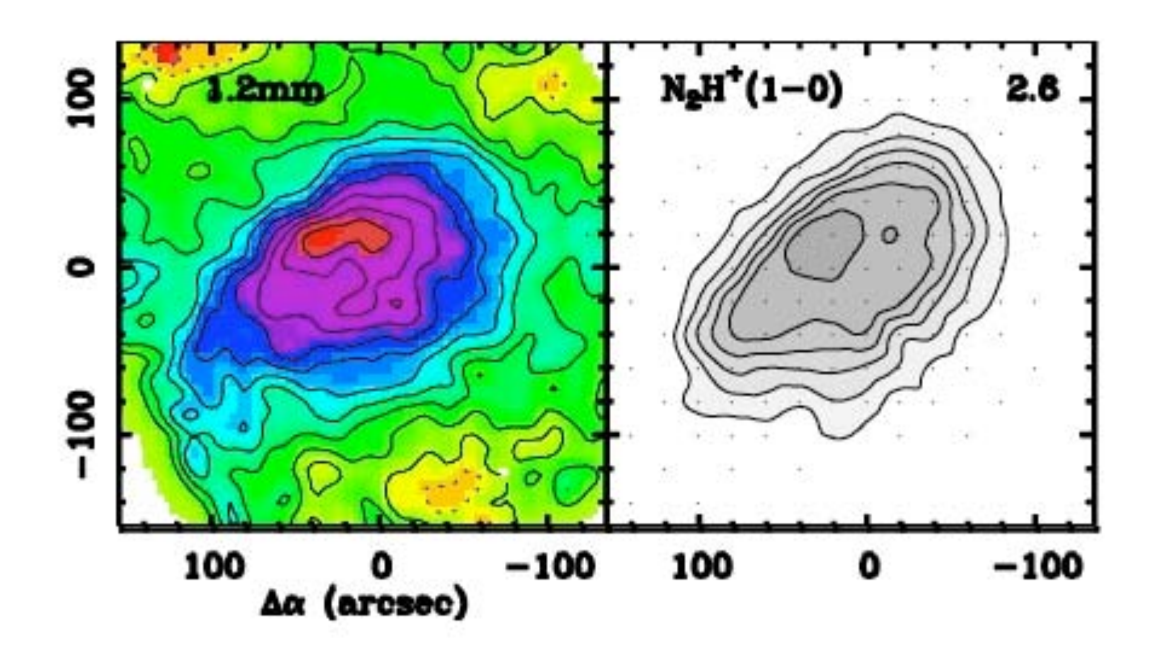
University of Massachusetts

Star Formation: Near & Far
14 August 2007

Protostellar/Cluster Cores

Alves etal 2

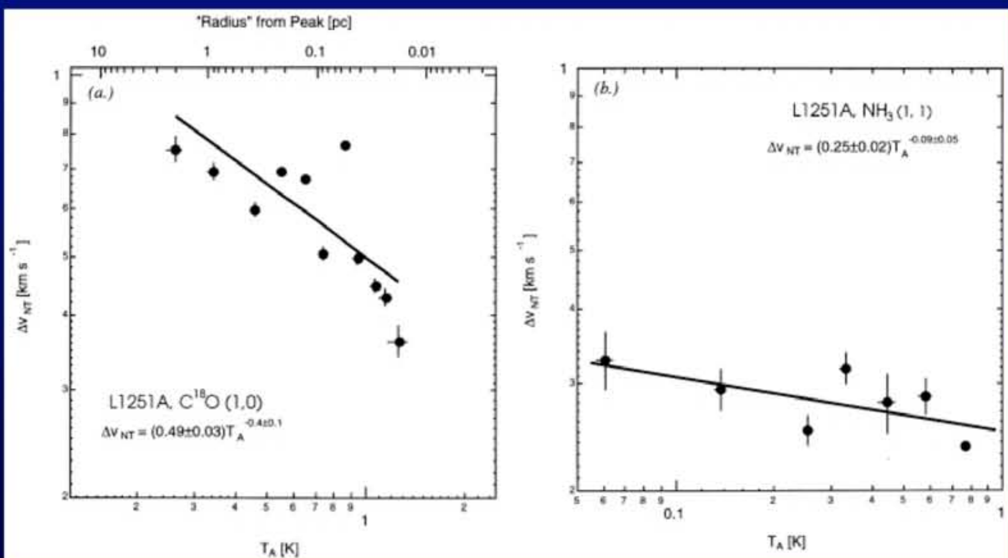




Tafalla etal 2006

Decoupled Cores

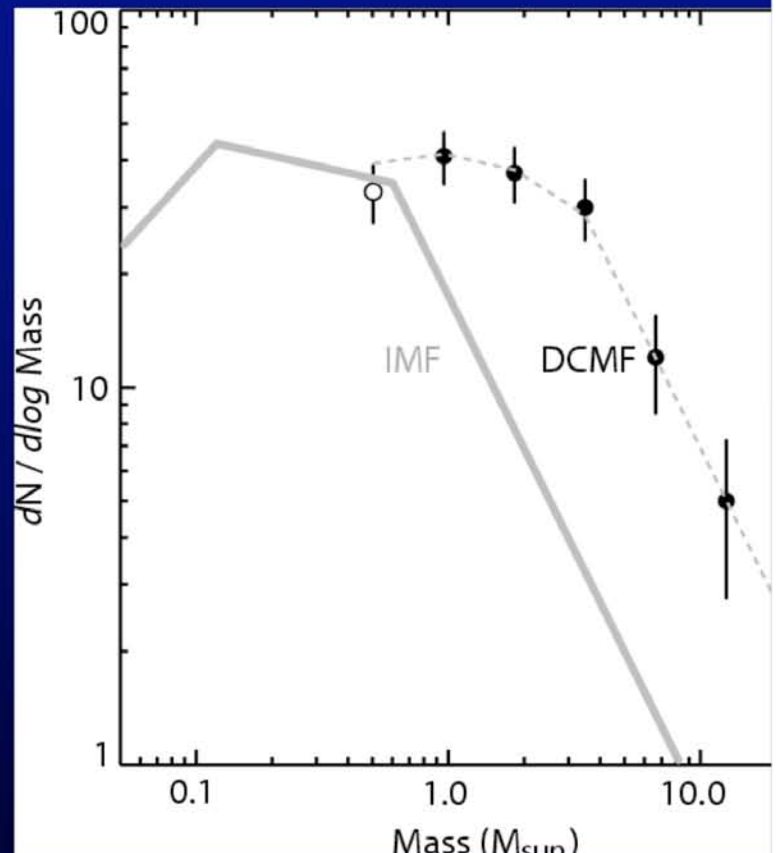
Goodman etal 1998



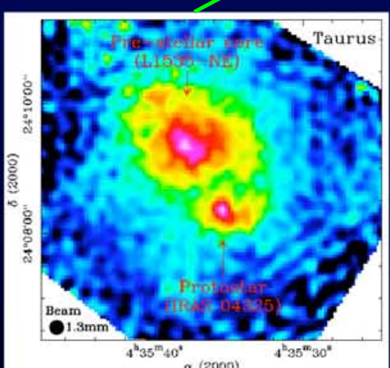
SIZE

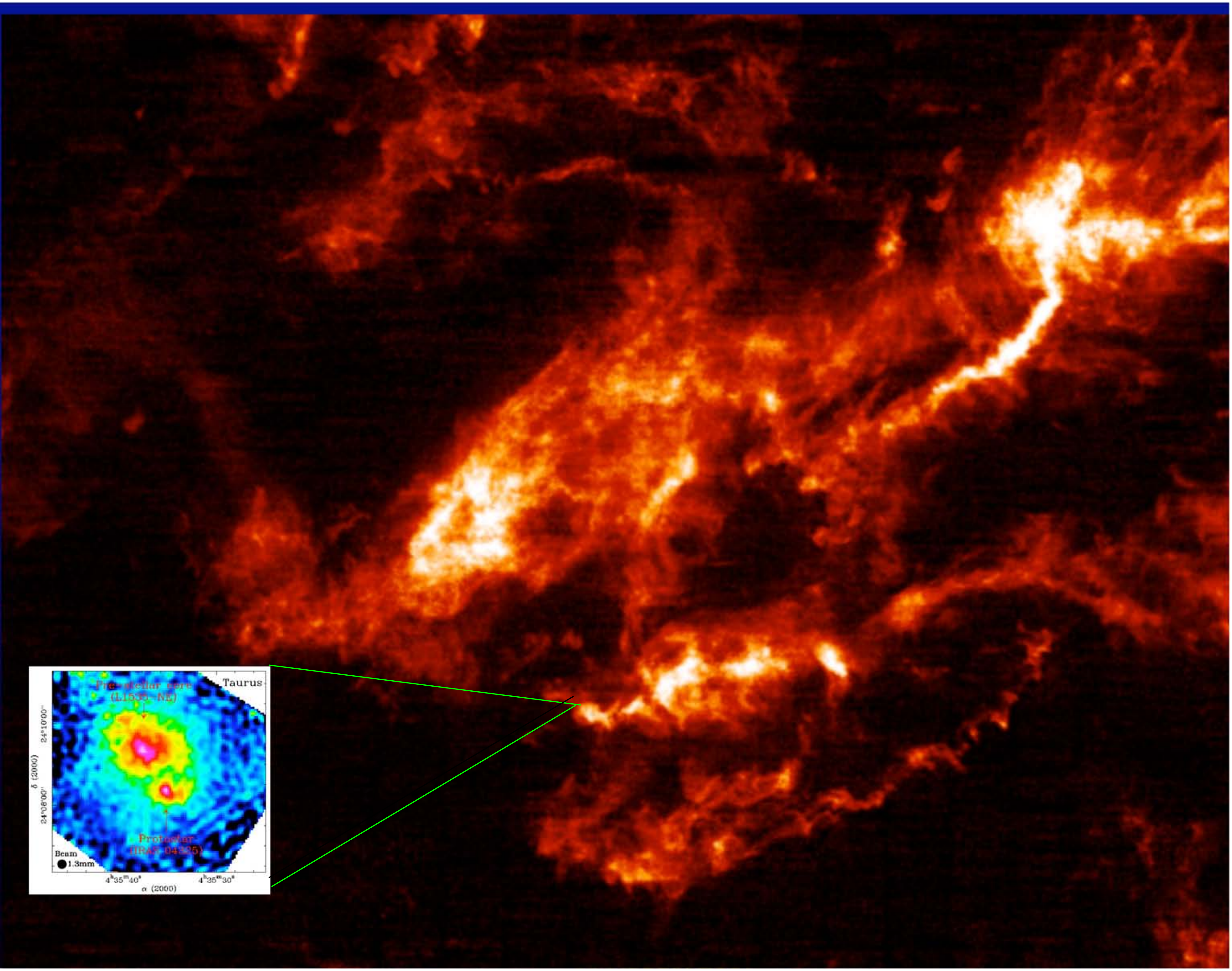
SIZE

Lombardi etal 2006



L1535 Protostellar core
Thermal Dust Continuum Emission
Motte etal 2001

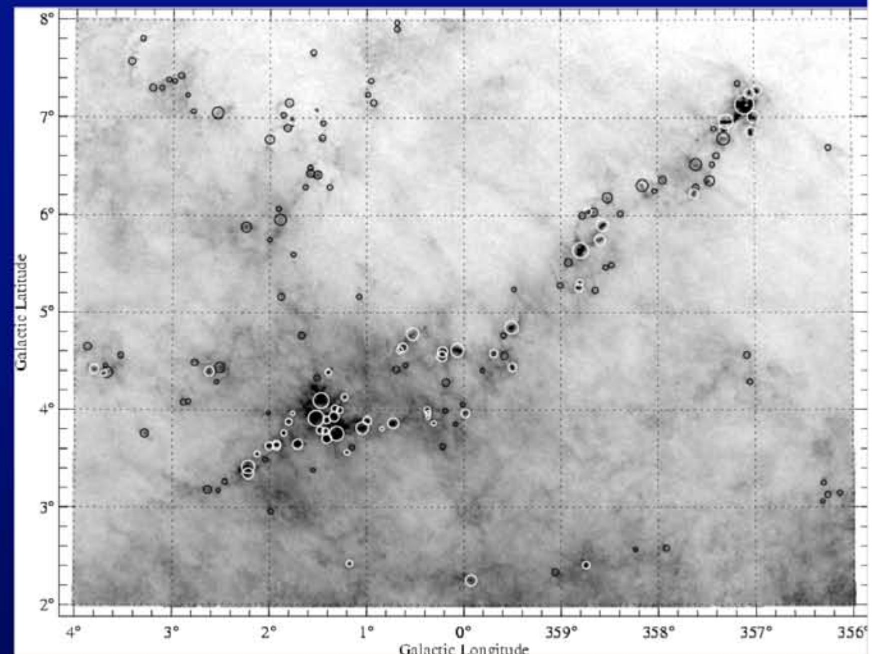



Taurus
Pre-stellar core
(L1535-NE)
Protostar
(IRAS 04325)
Beam
1.3mm
δ (2000)
24°10'00''
24°08'00''
4h35m40s
4h35m30s
α (2000)

- **New views of Galactic Molecular Clouds**
- **Dynamical Properties of Molecular Clouds**
  - **Velocity Correlation Spectrum**
  - **Energy Sources/Driving Scale of Turbulence**
  - **Magnetic Criticality**

Extended Cloud Component

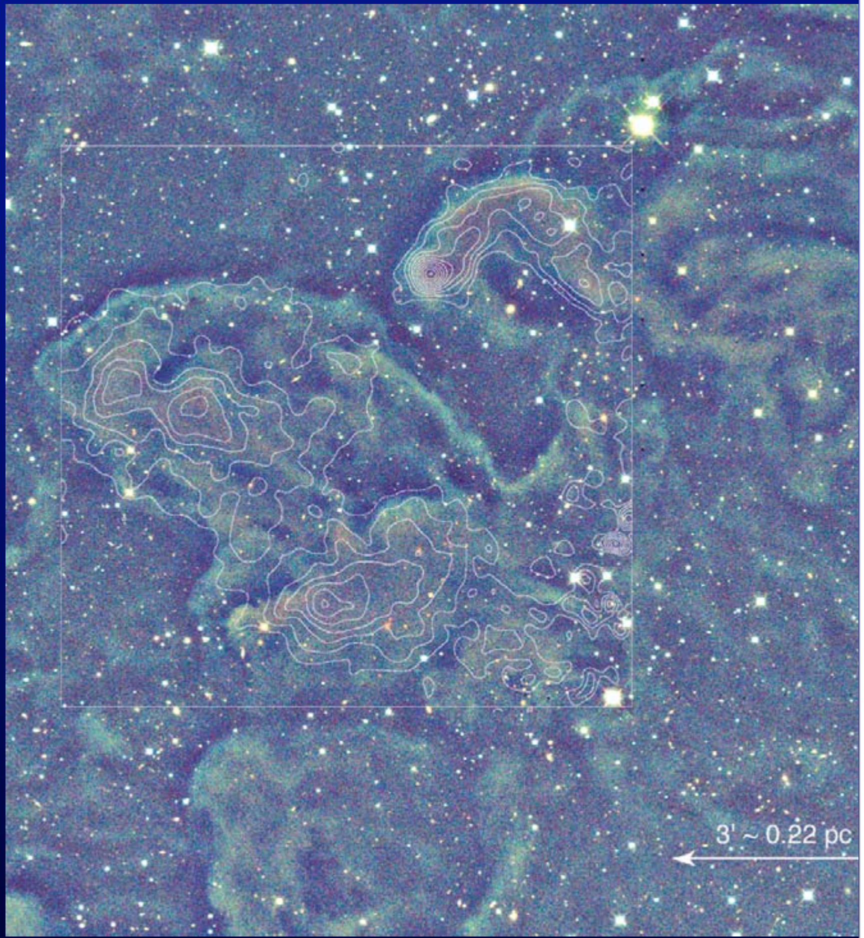
- Infrared Extinction



Lombardi etal 2006

Extended Cloud Component

- Infrared Extinction
- Scattered Light

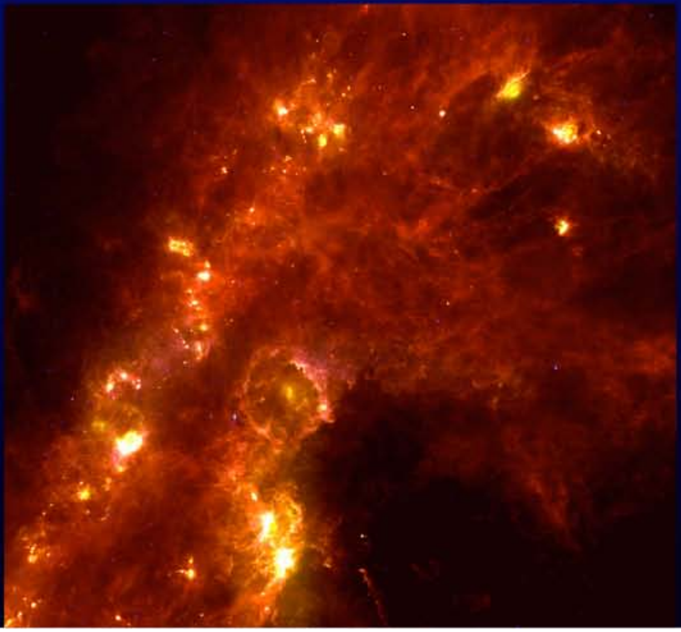


Foster & Goodman 2006

Extended Cloud Component

- Infrared Extinction
- Scattered Light
- Dust/PAH Emission

Spitzer/GLIMPSE

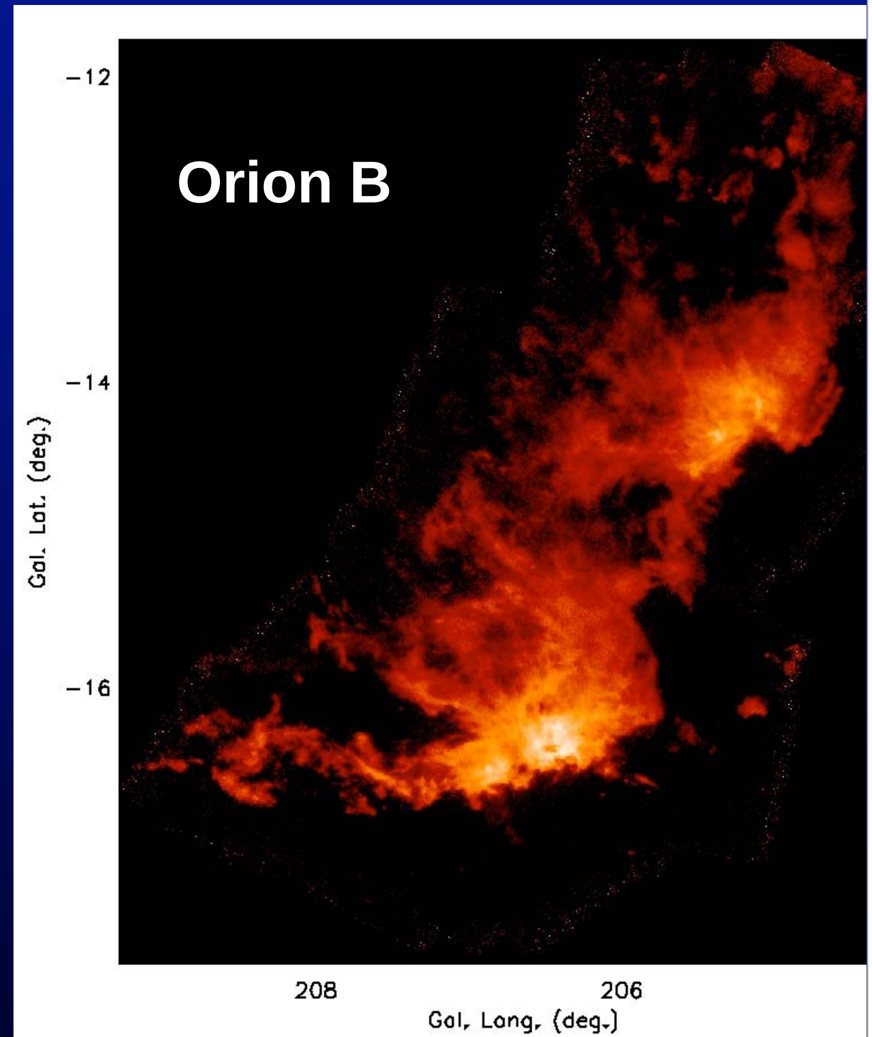


Extended Cloud Component

- Infrared Extinction
- Scattered Light
- Dust/PAH Emission
- Molecular Line Emission

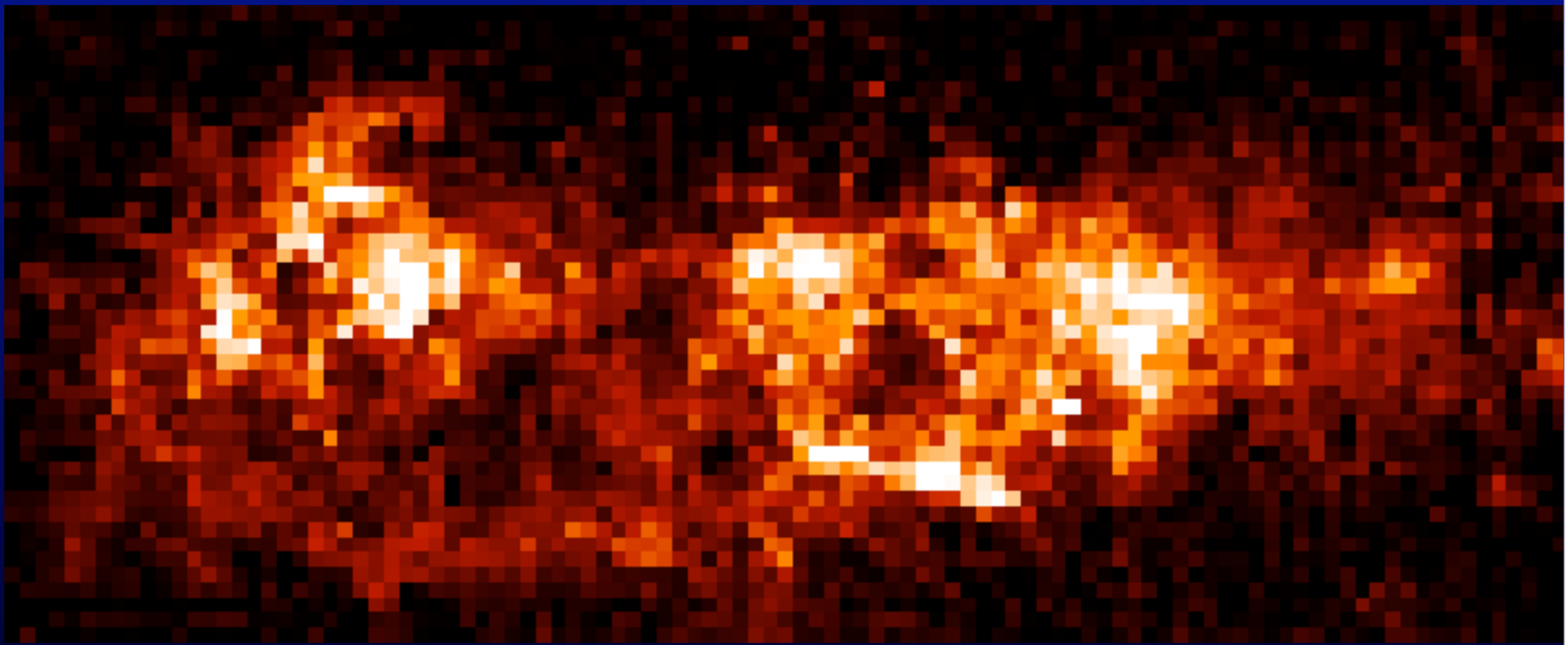
(low rotational transitions of

^{12}CO, ^{13}CO)



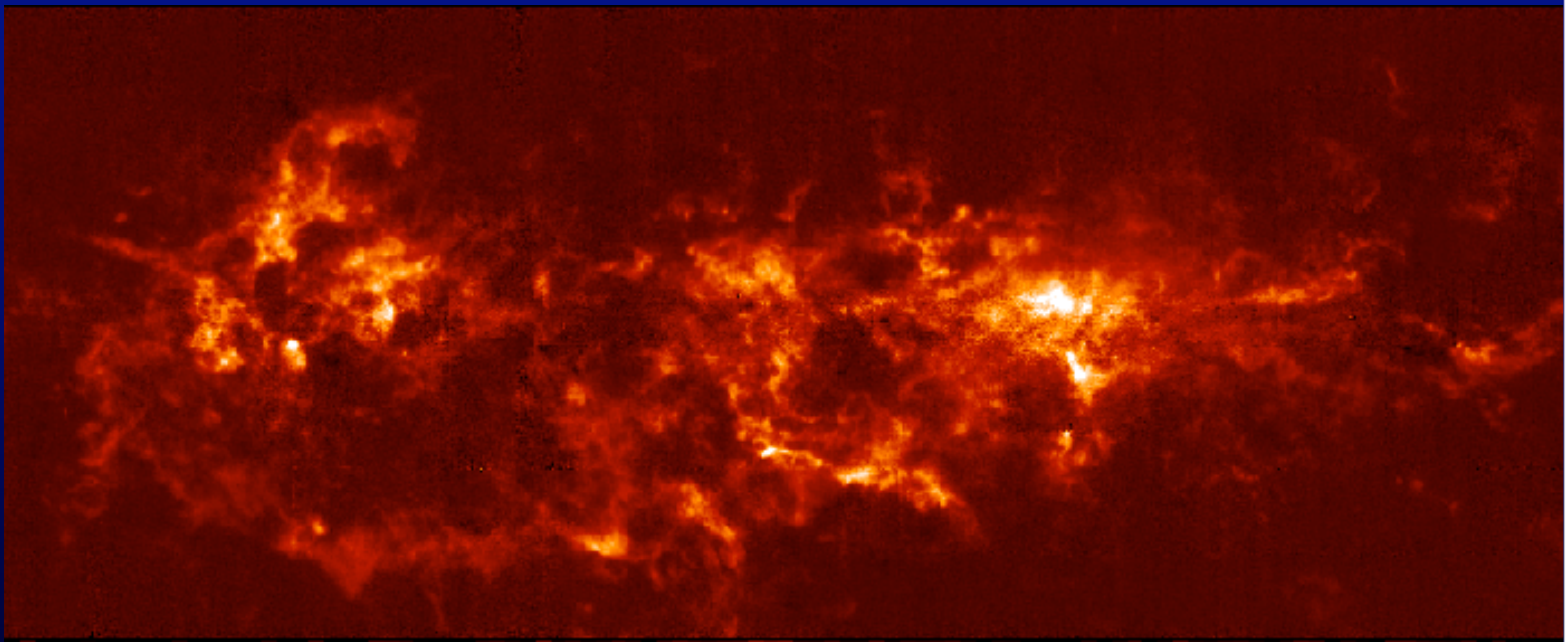
GMCs- Then

Massachusetts-Stony Brook Survey (Sanders etal 1985)

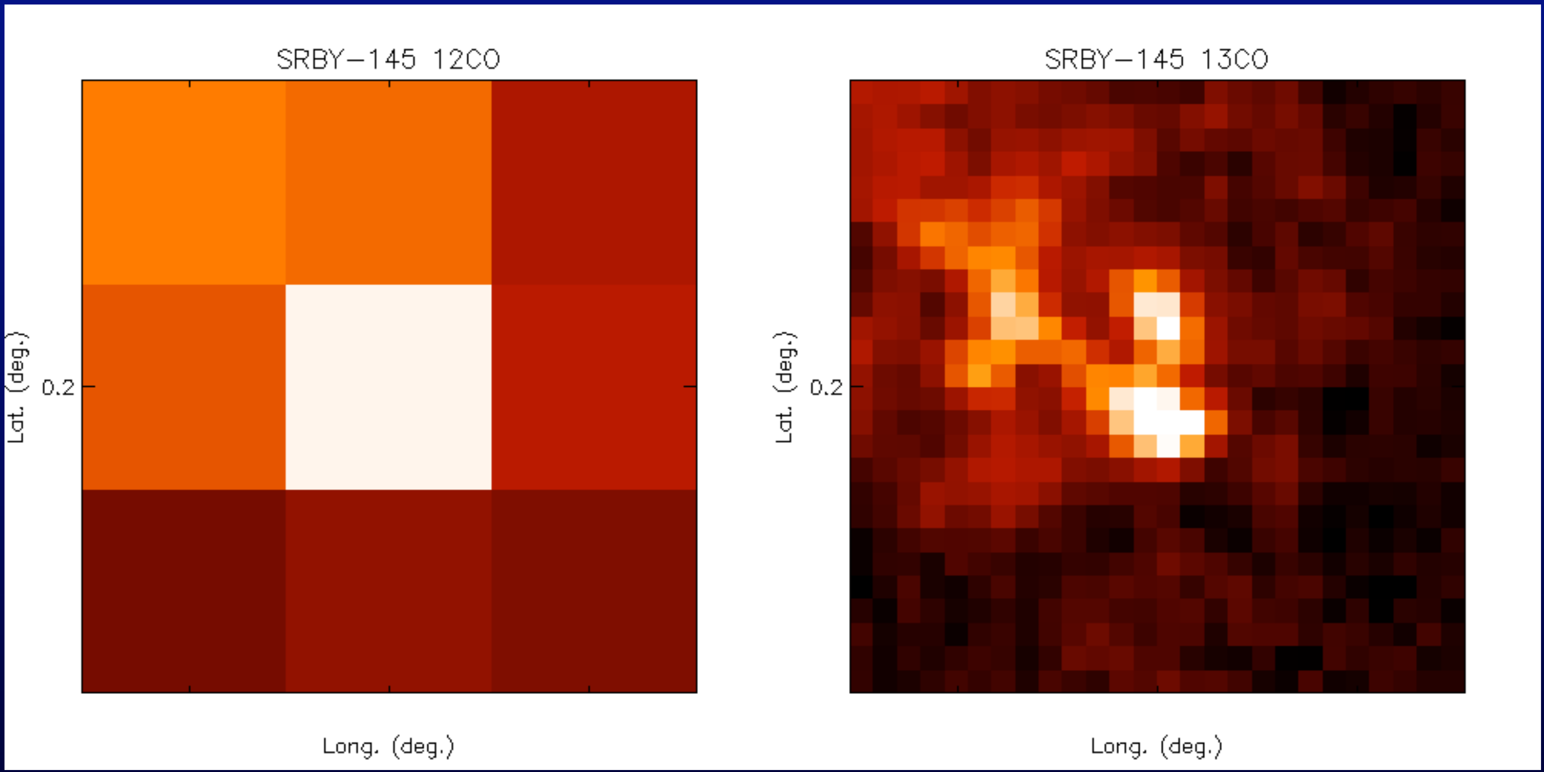


GMCs- Now

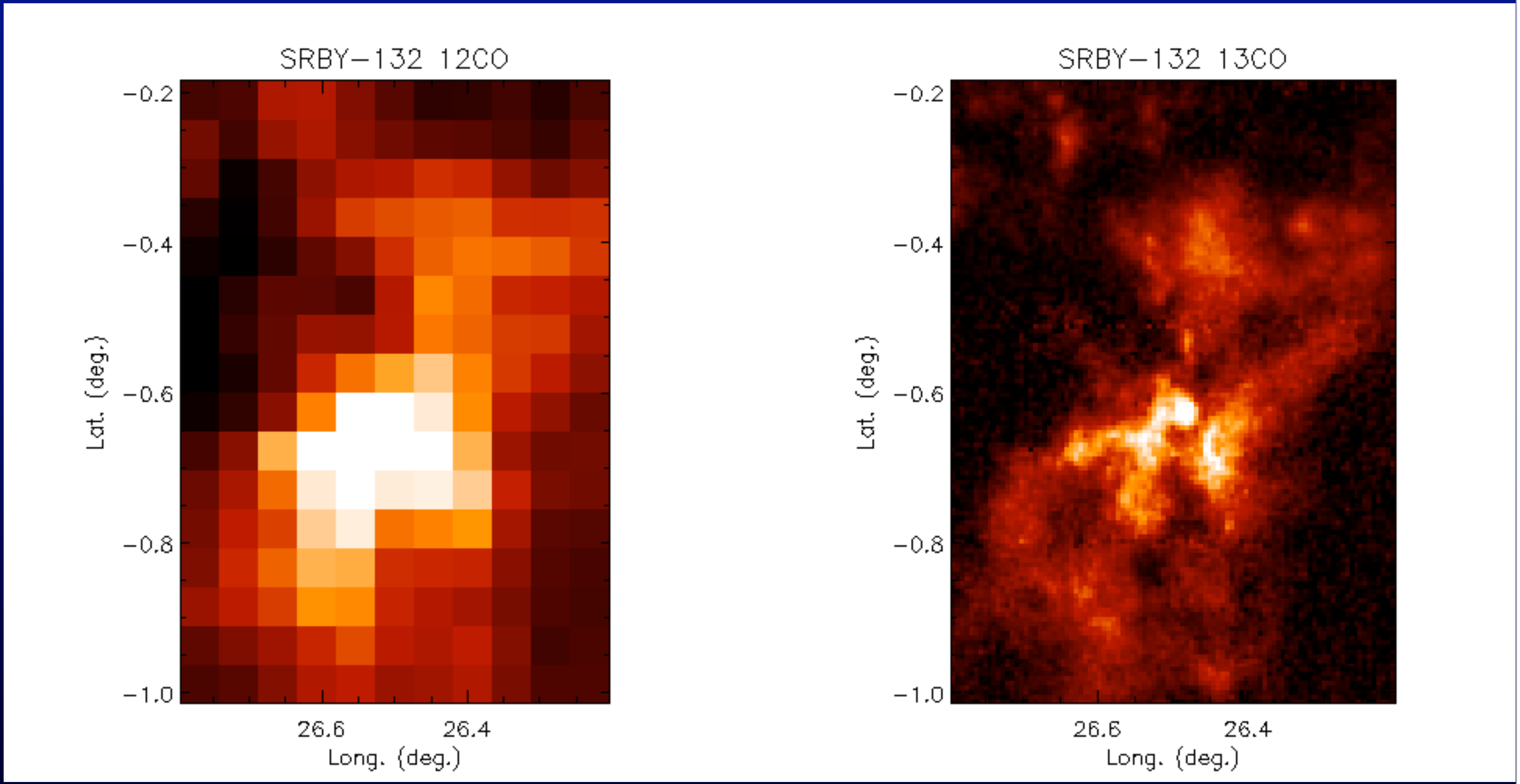
Boston University-FCRAO Galactic Ring Survey (Jackson etal 2006)



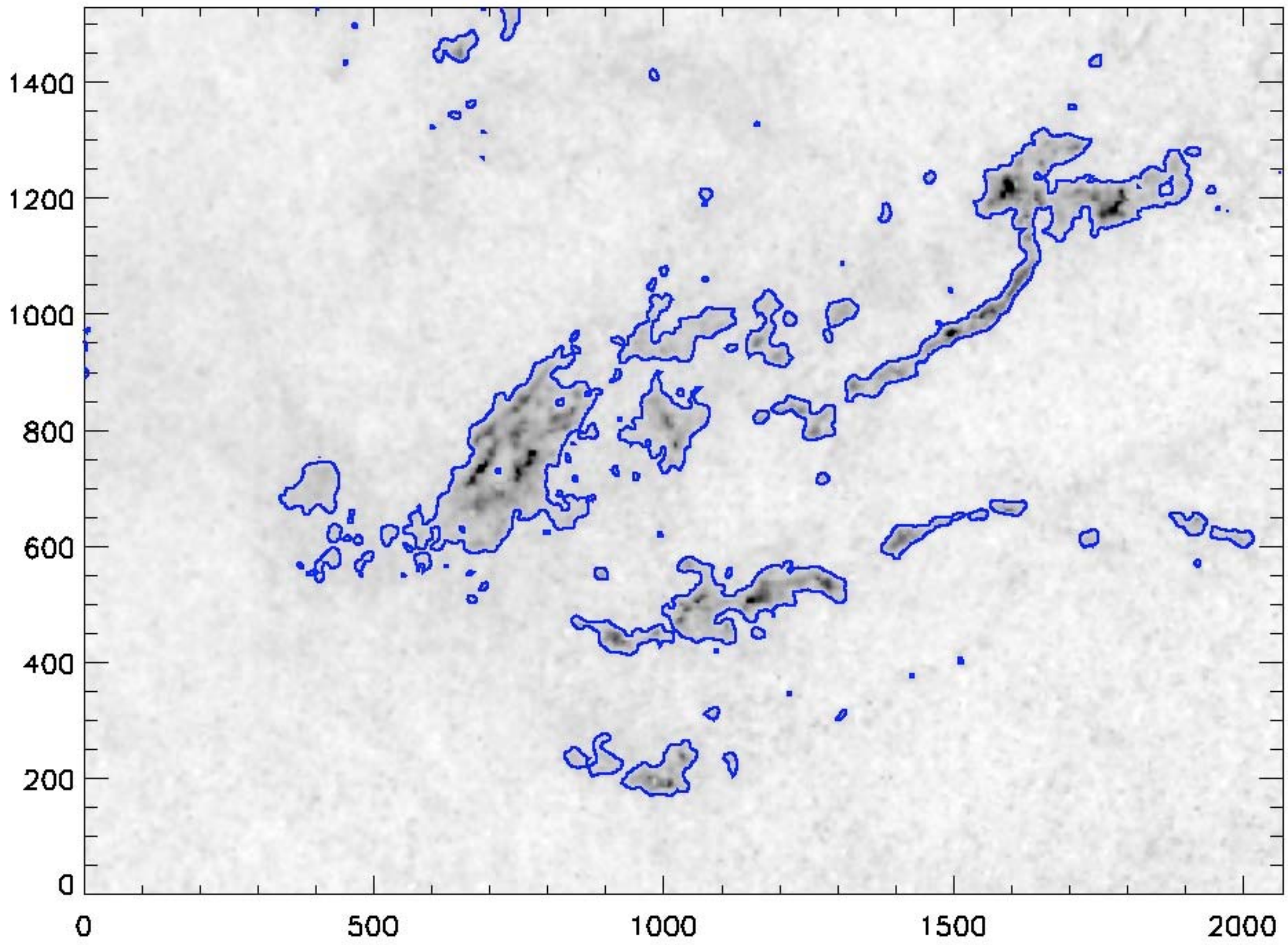
GMCs- Then and Now



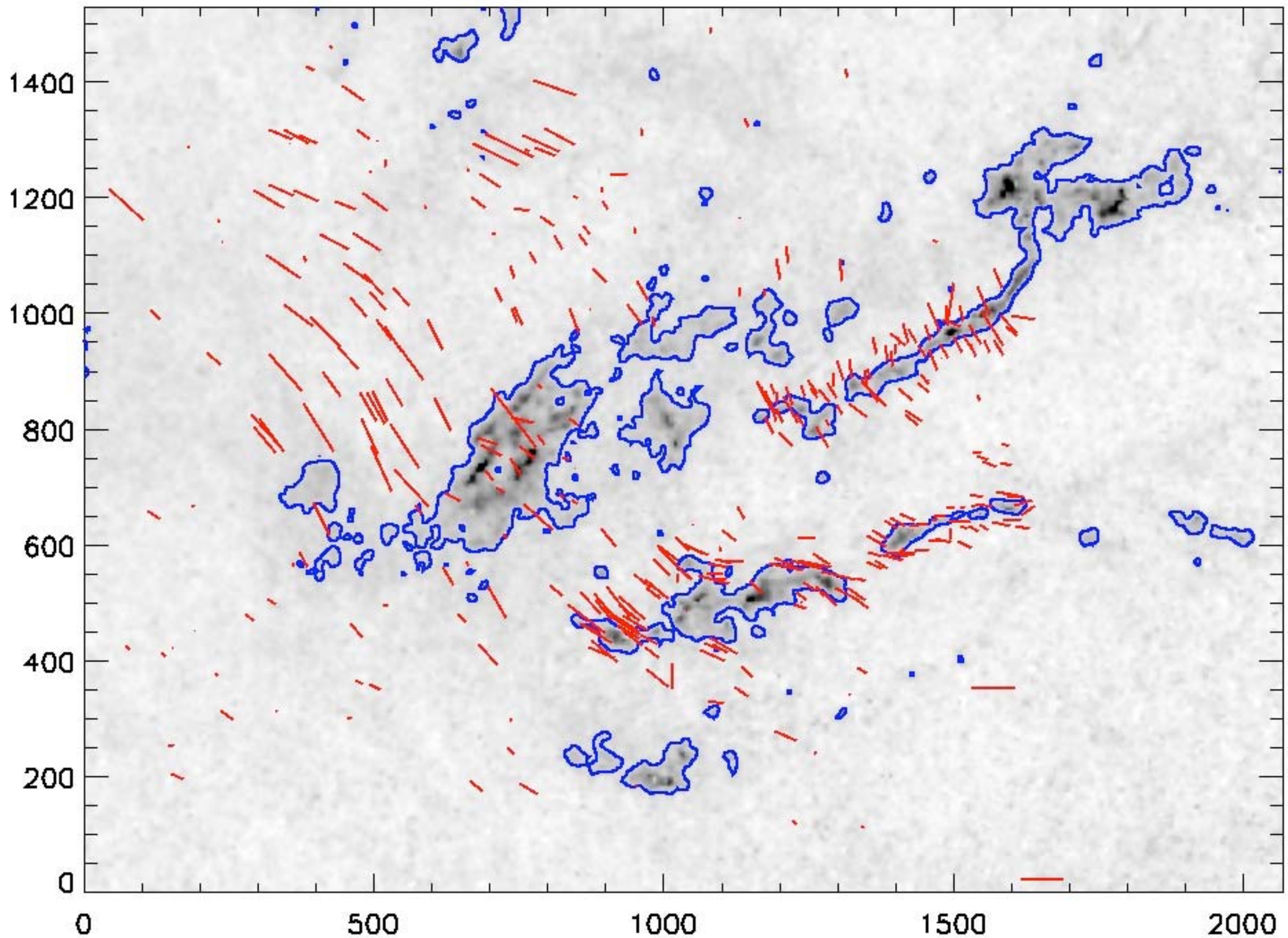
GMCs- Then and Now



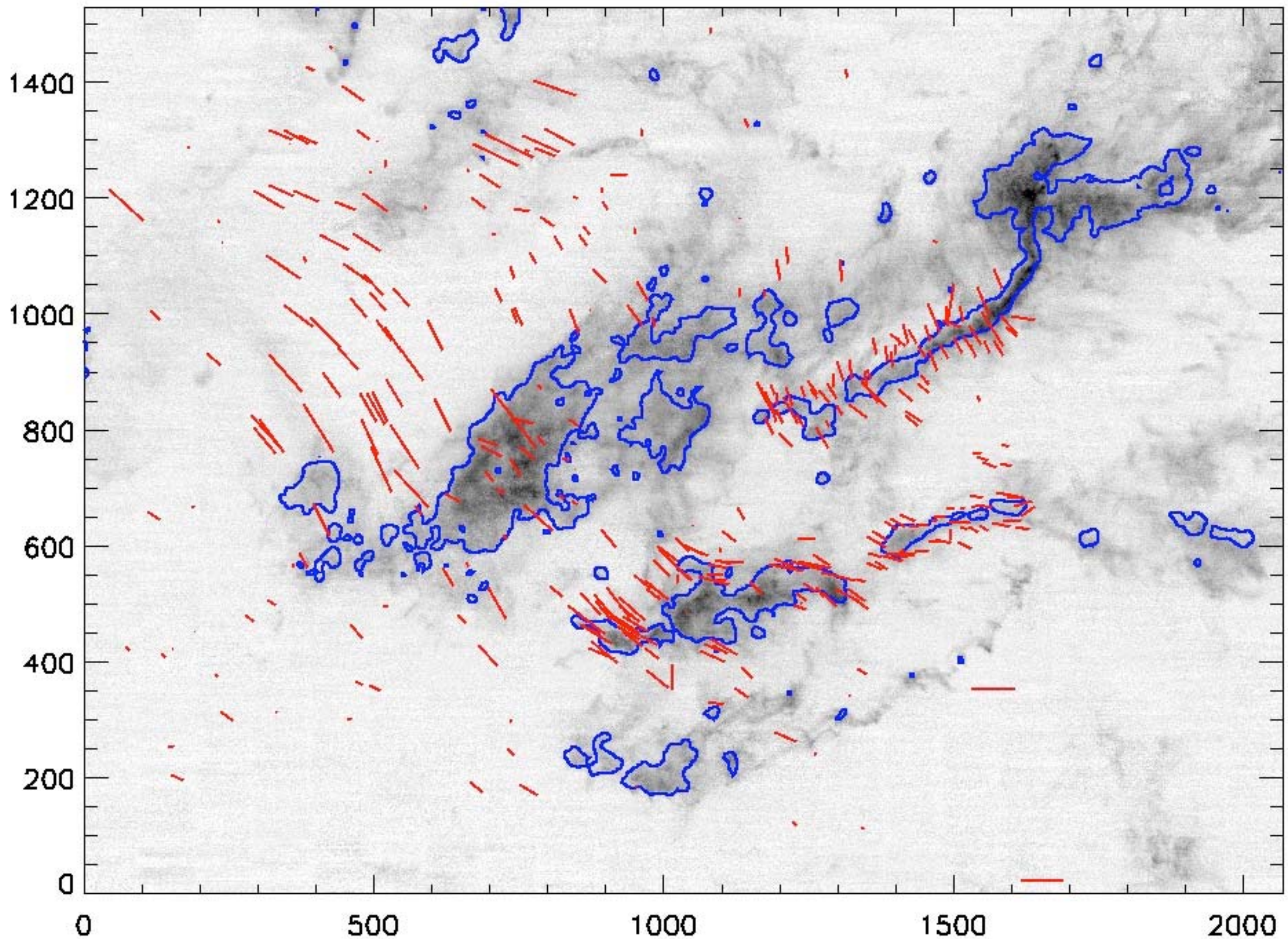
2MASS Extinction Image

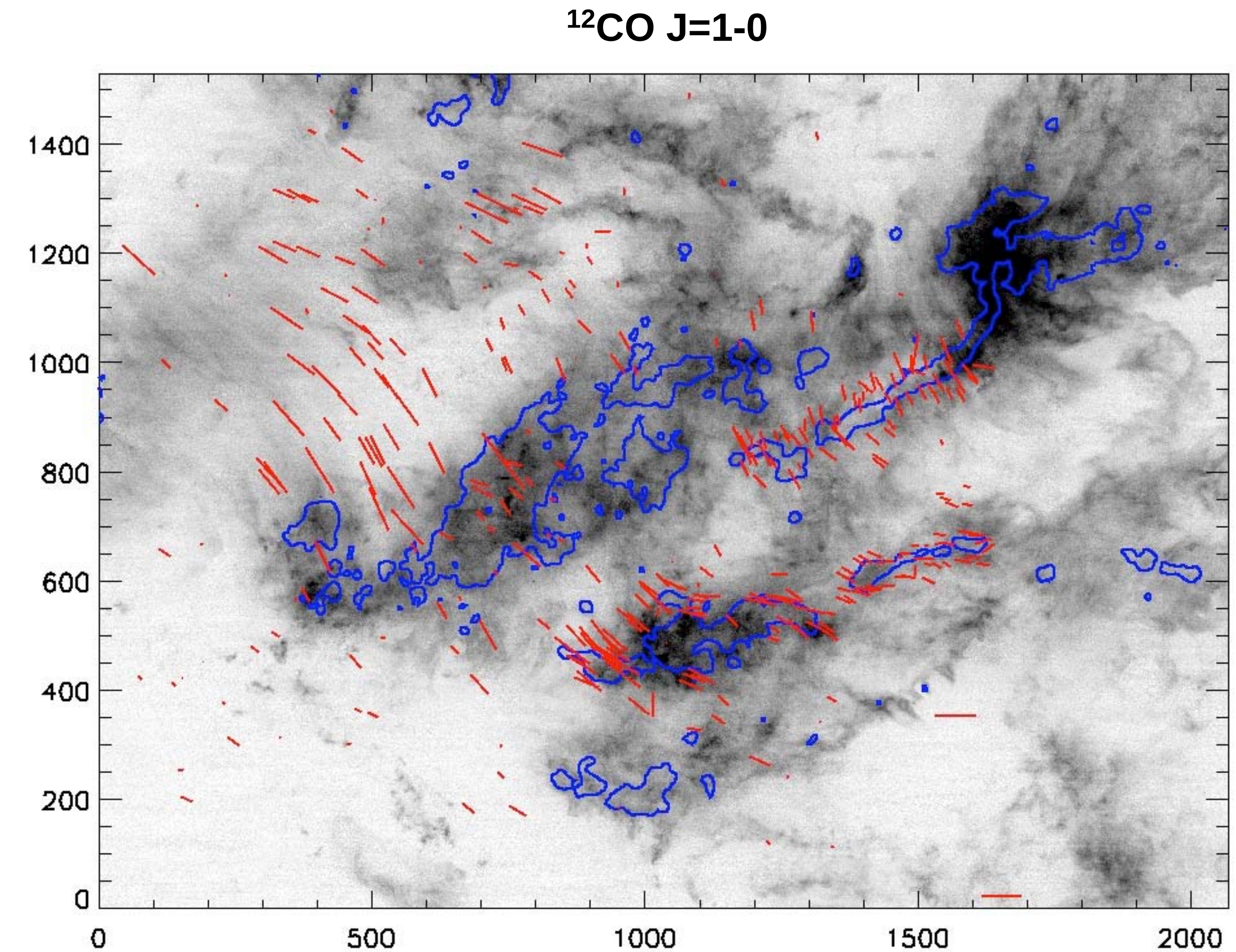


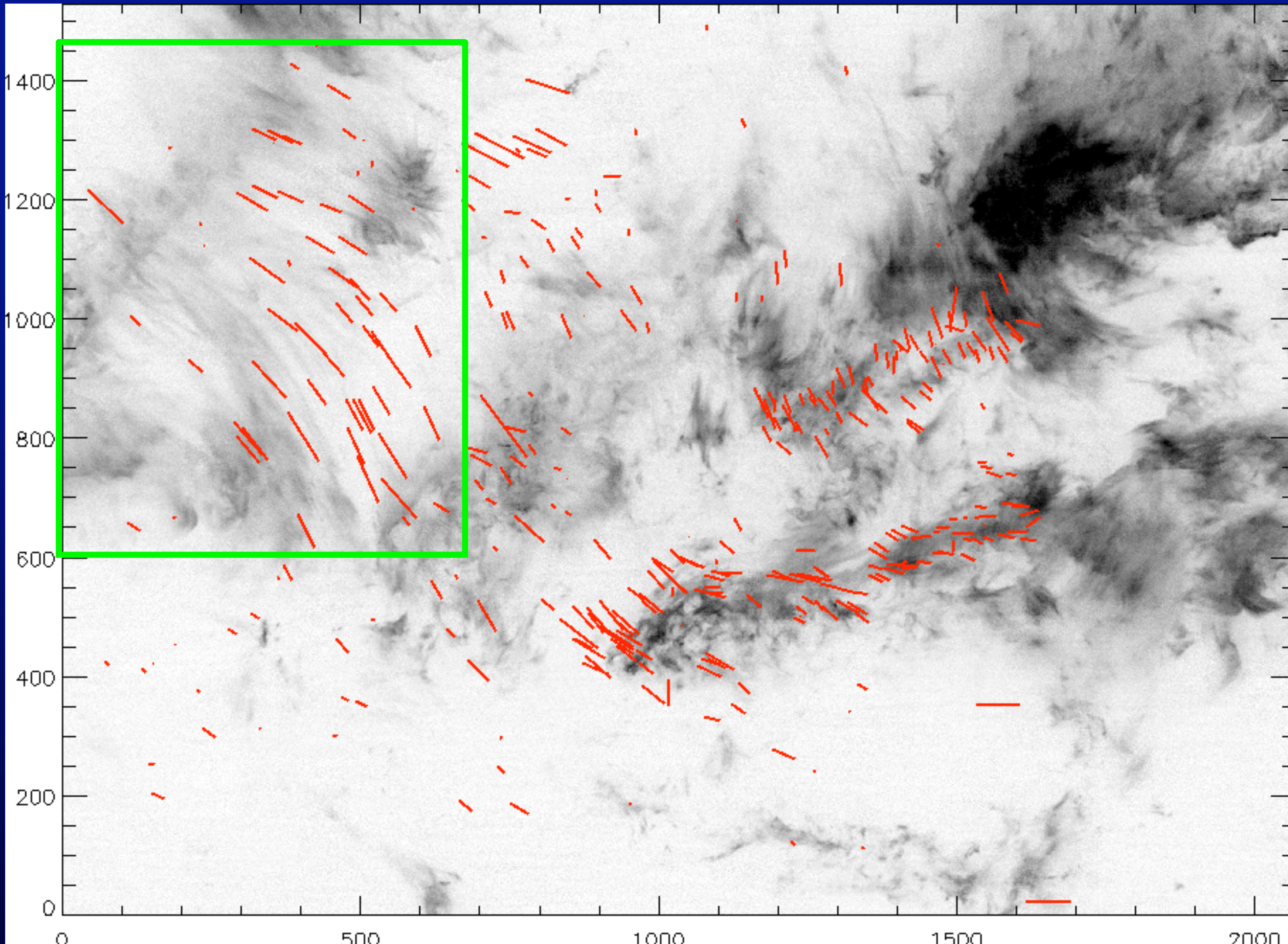
Extinction and Polarization Vectors



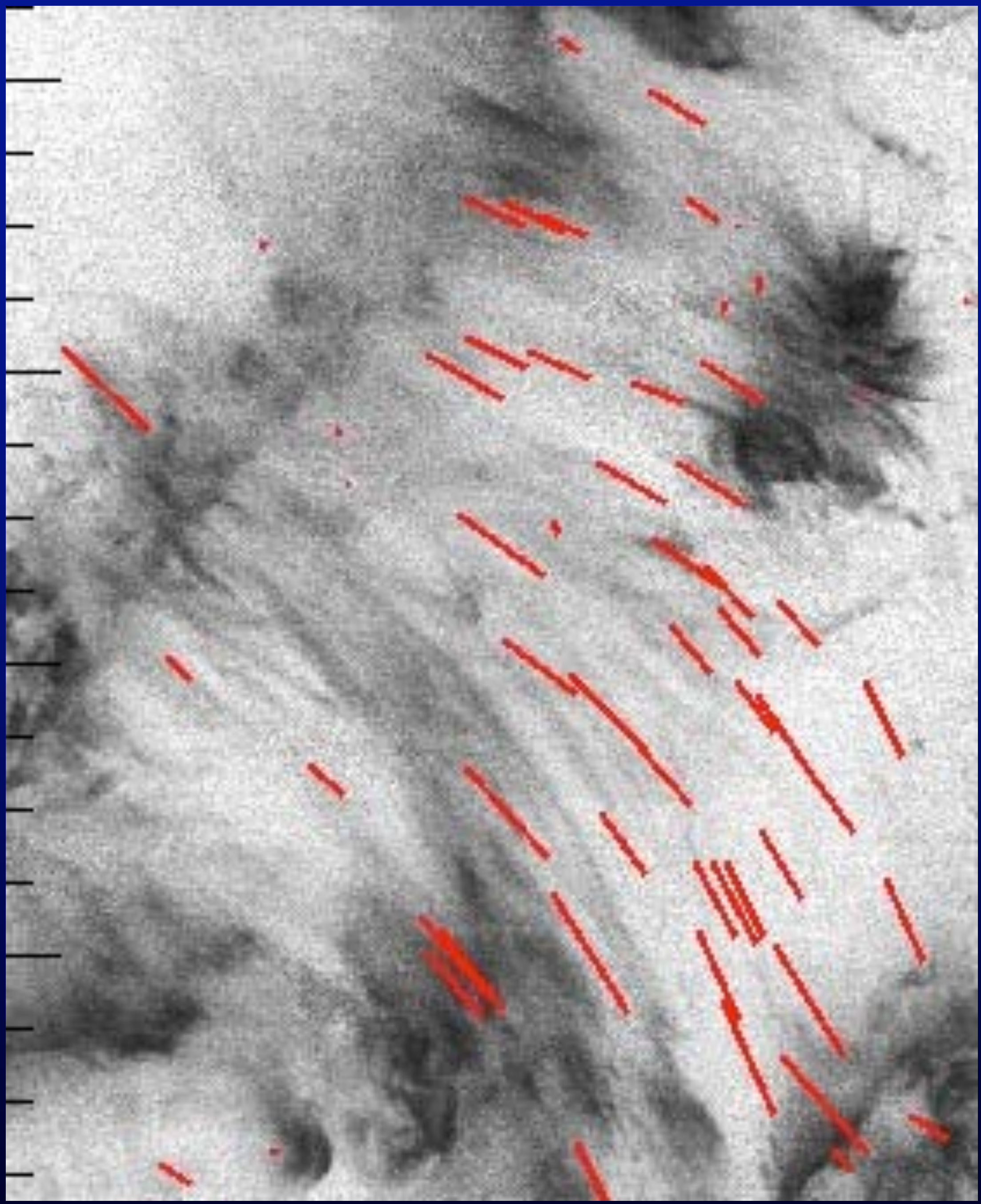
^{13}CO J=1-0




^{12}CO J=1-0
1400
1200
1000
800
600
400
200
0
0
500
1000
1500
2000



1400
1200
1000
800
600
400
200
0
0
500
1000
1500
2000



Star Formation: Near & Far
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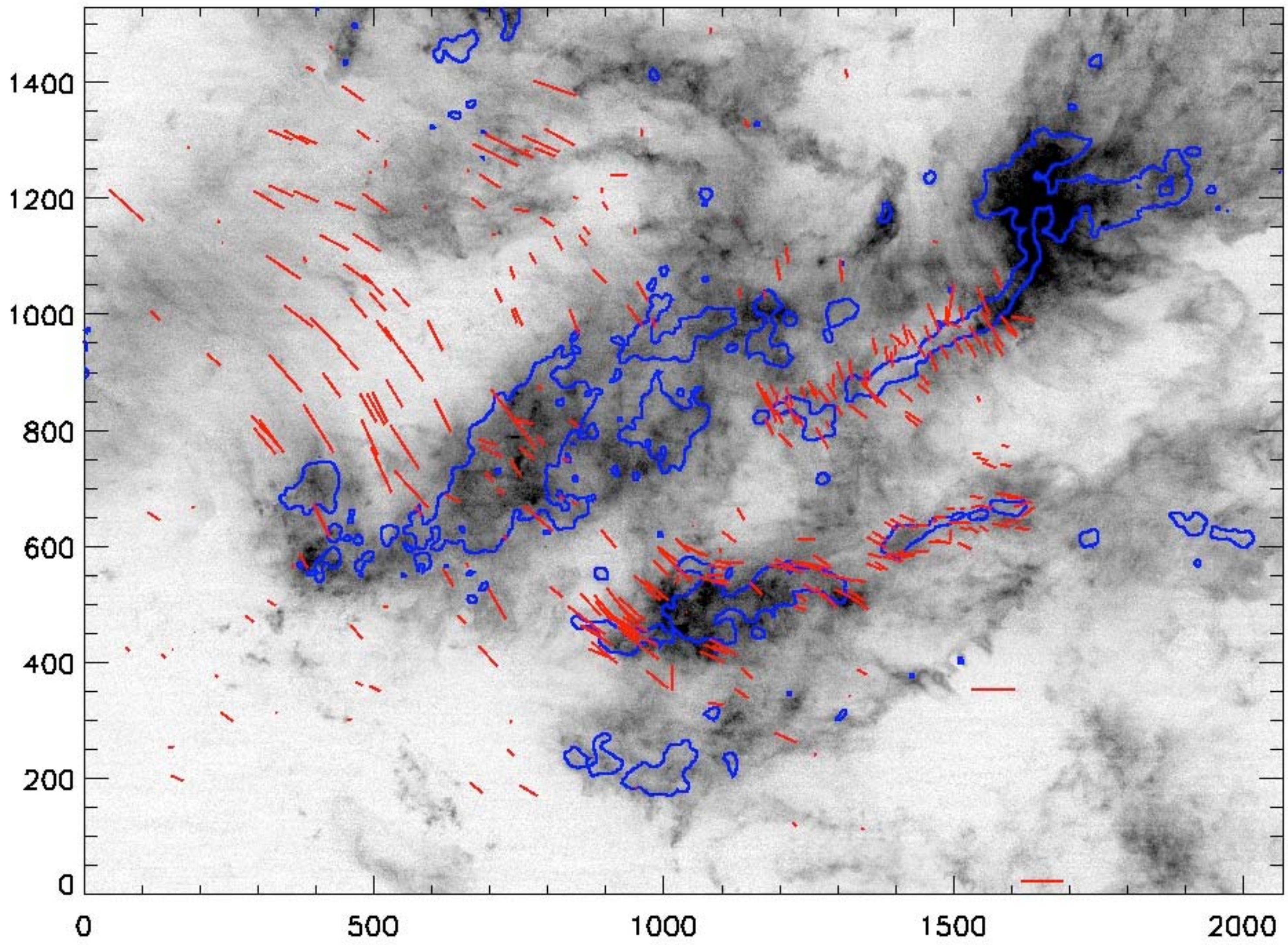
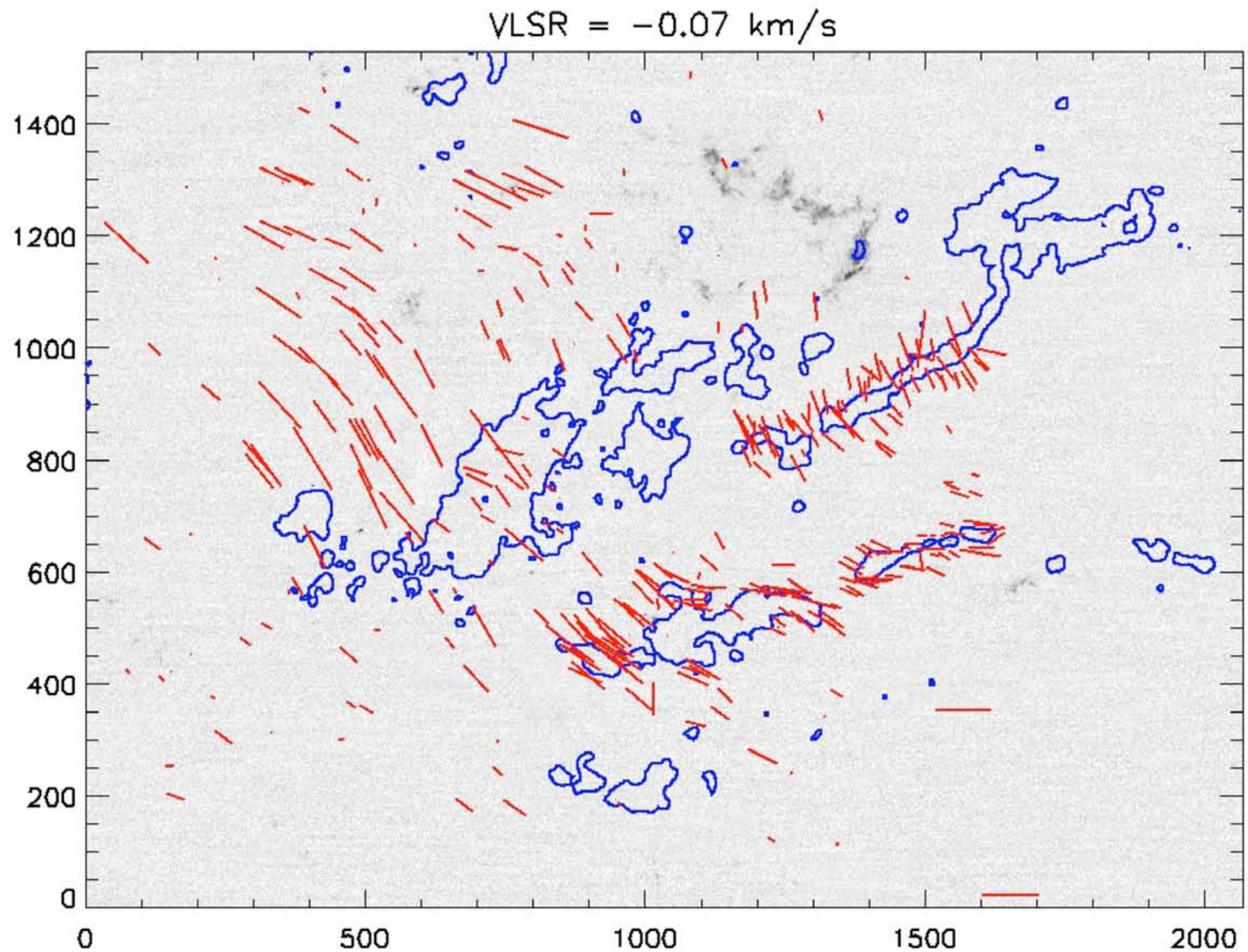
Sequence of Channel Images




VLSR = −0.07 km/s
1400
1200
1000
800
600
400
200
0
0
500
1000
1500
2000

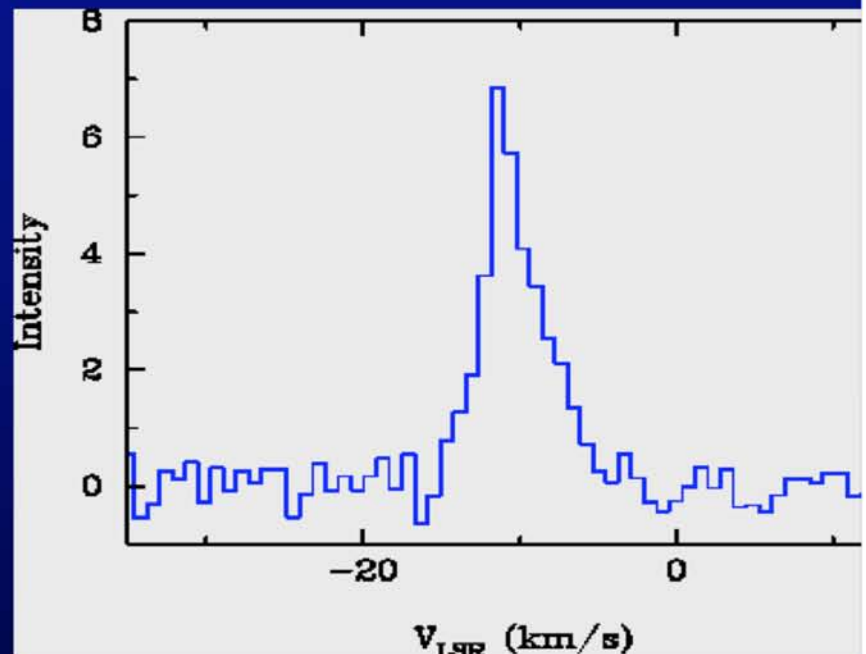
A Molecular Line Spectrum

ISM Fields

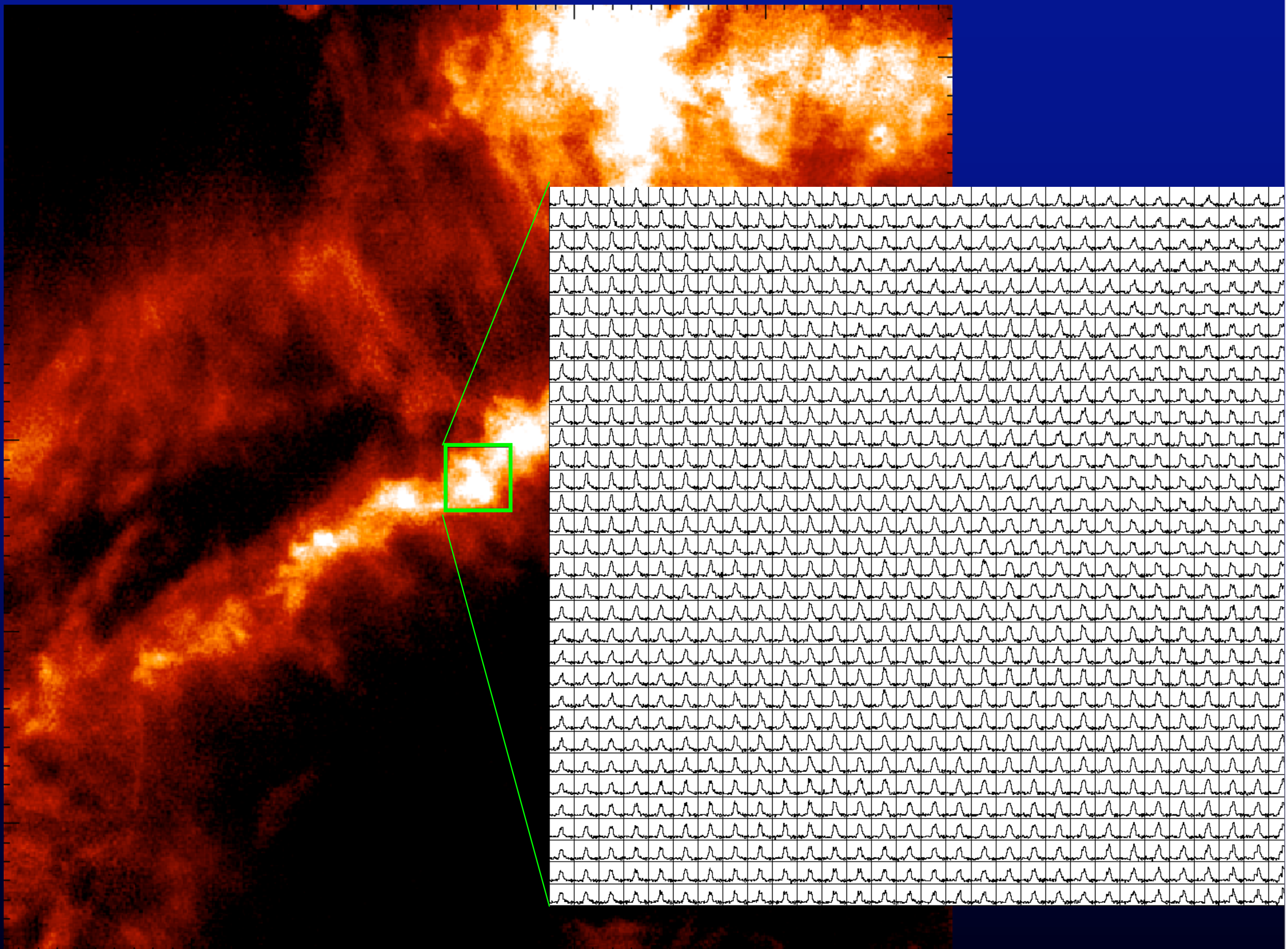
$\vec{\mathbf{v}}(x,y,z), \rho(x,y,z),$

$T(x,y,z), X(x,y,z),$

$U_{rad}(x,y,z), \vec{B}(x,y,z)$



Complex, non-linear convolution of density, velocity, temperature, abundance fields along the line of sight



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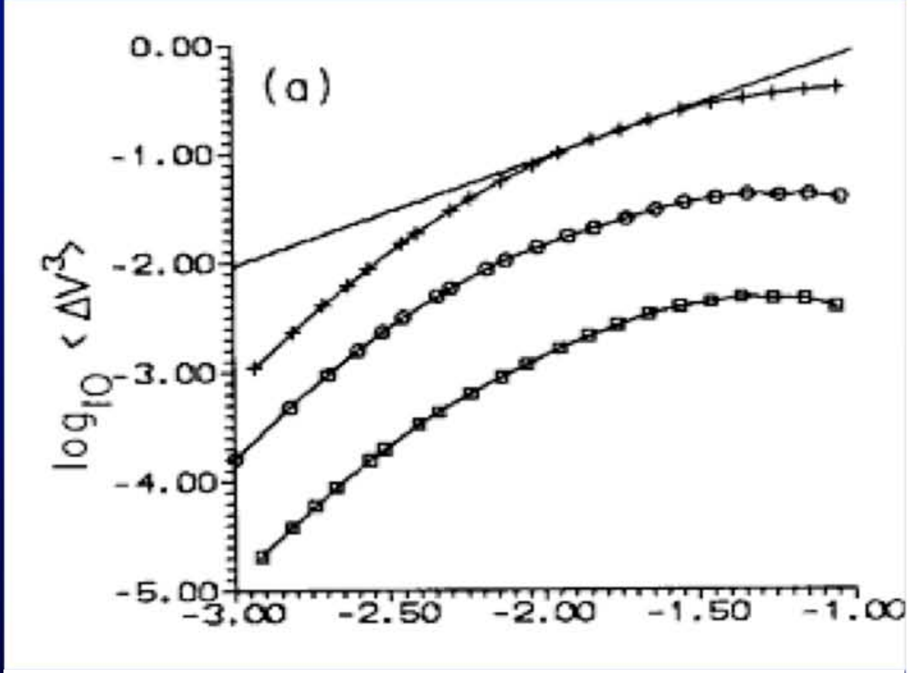
Velocity Correlation Spectrum

$$S_n(\tau) = \langle |v(r+\tau) - v(r)|^n \rangle \sim \tau^{\zeta(n)}$$

Measuring $\zeta(n)$ is difficult given small inertial range



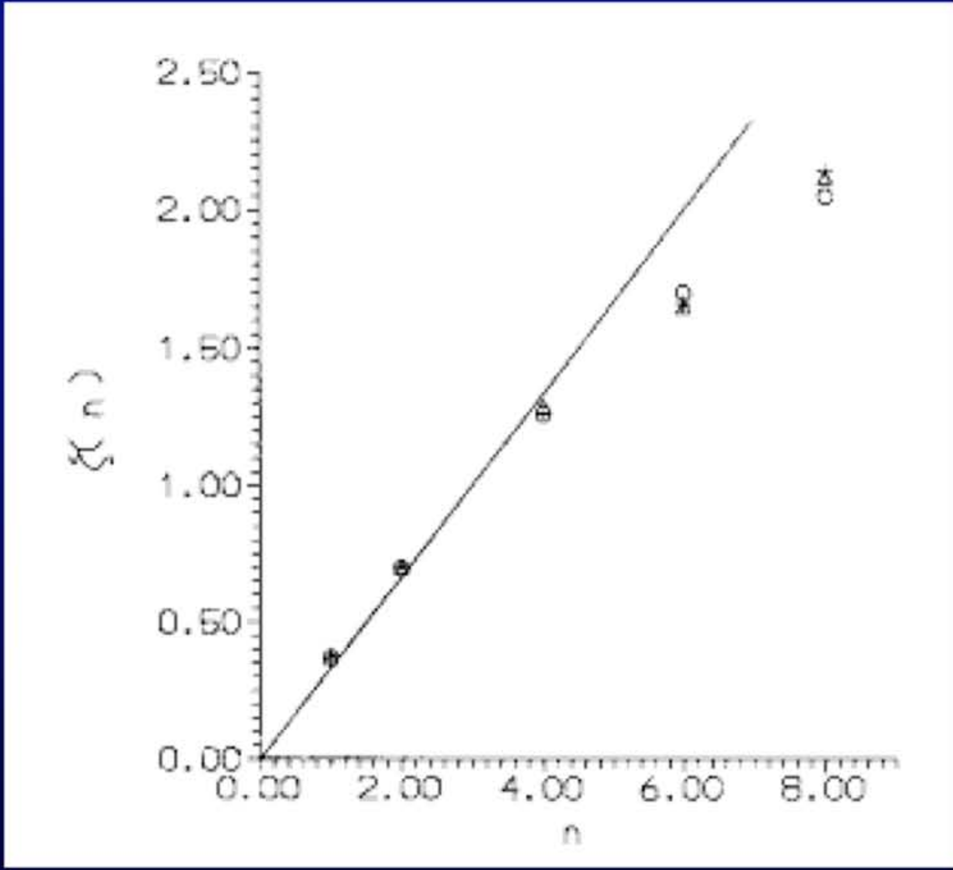
log10 r

Extended Self-Similarity (ESS)

$$S_n(\tau) = B_n\ S_3(\tau)^{\ \zeta(n)/\zeta(3)}$$

- ***extends into dissipation range***

- enables more accurate derivation of ζ(n) (given ζ(3))

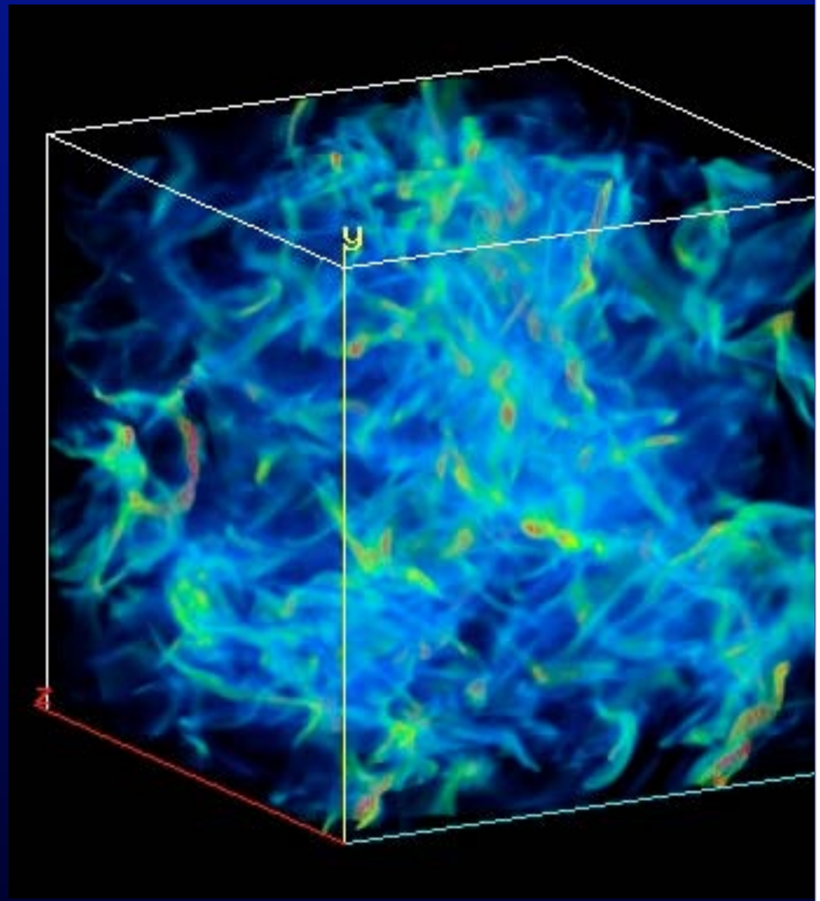


Velocity Spectrum

$$S_q(\tau) = \langle\, |v(r+\tau) - v(r)|^q \,\rangle \sim \tau^{\zeta(q)}$$

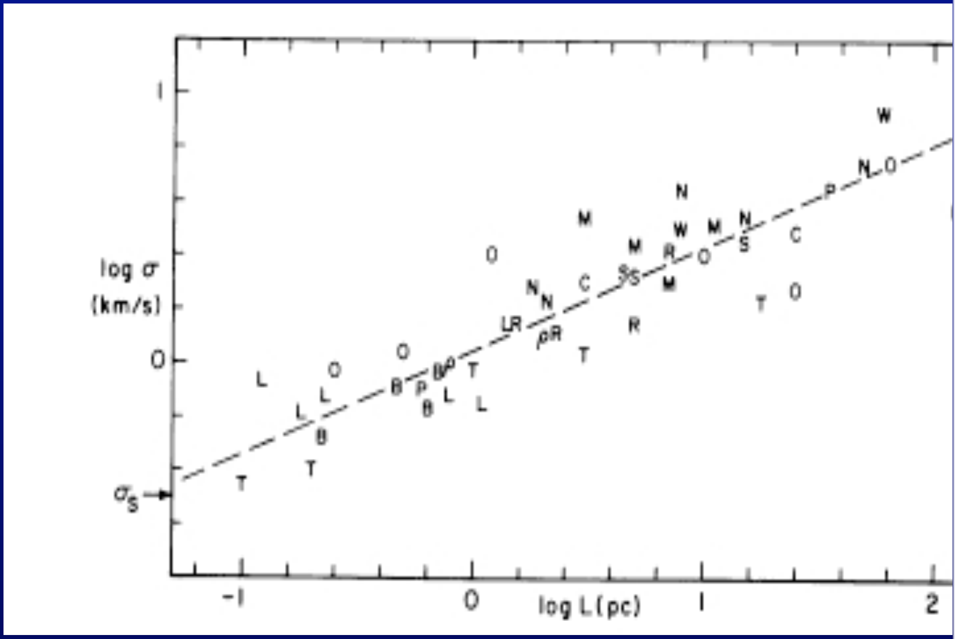
$$\delta v = v_o \tau^{\gamma}$$

Model	γ
Kolmogorov	1/3
Supersonic turbulence	1/2
Micro-turbulence	0
Solid body rotation	1



Larson (1981)

- Multi tracer/multi cloud
- $\sigma_v = 1.1\ L^{0.38}$



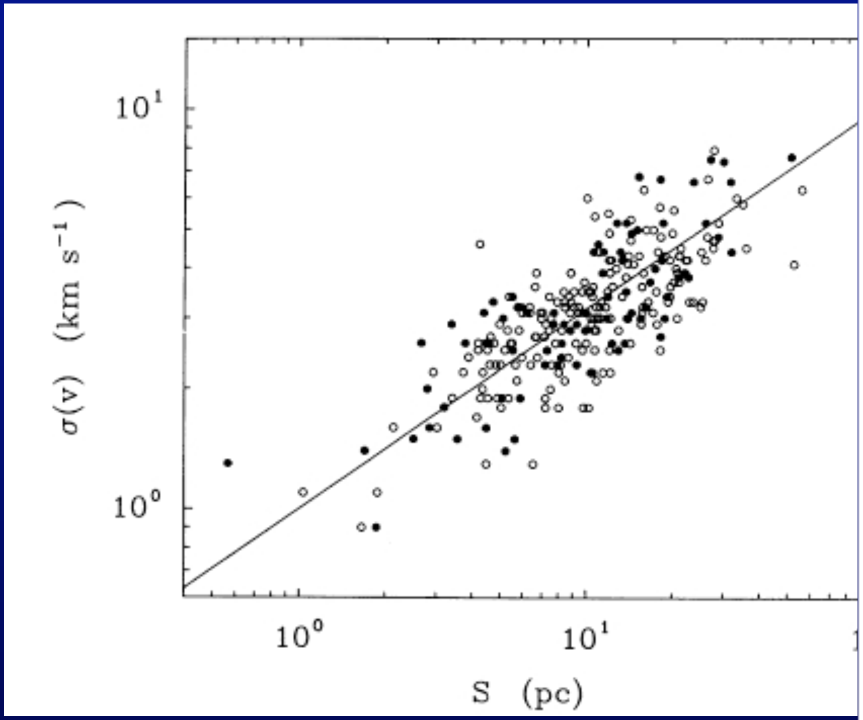
"common hierarchy of interstellar turbulent motions"

Solomon etal (1987)

- Single tracer/multi cloud
- $\sigma_v = 1.0\ S^{0.5}$

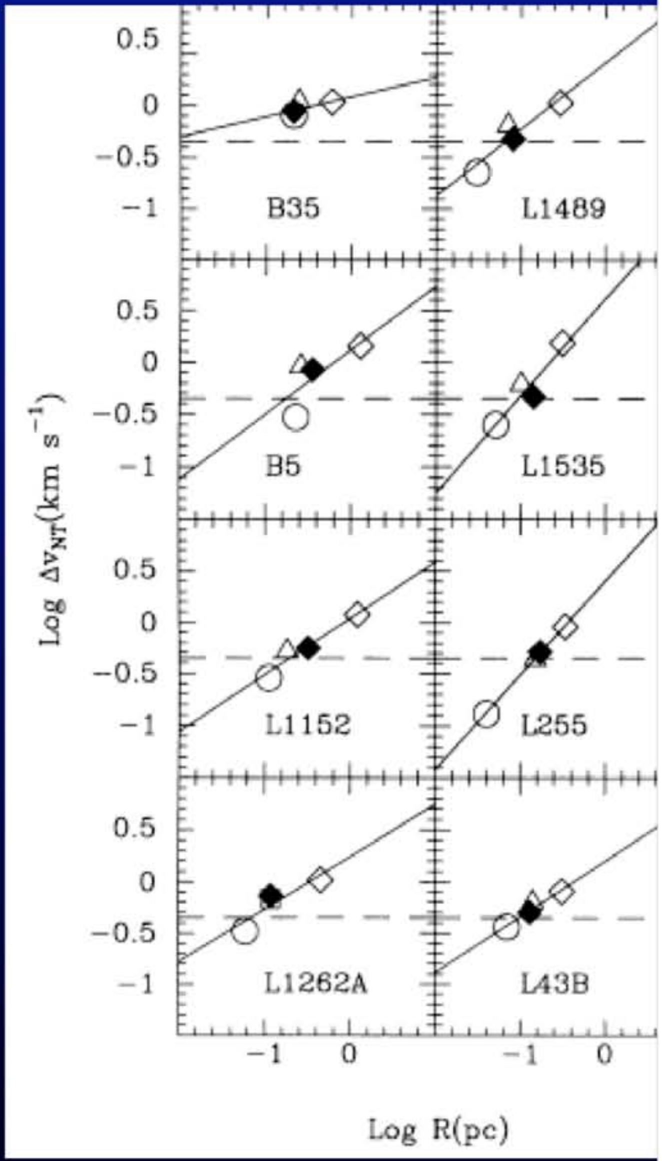
  $\Sigma \sim$ constant

  $M_{virial}/M \sim 1$



Fuller & Myers (1992)

- Multi tracer/single cloud
- $\Delta v_{NT} \sim R^{0.2 - 0.7}$



Single Tracer/Single Cloud

Velocity Centroid statistics

Munch 1958, Scalo 1984; Kleiner & Dickman 1985; Miesch & Bally 1994; Lis etal 1996; I

& Falgarone 2003; Lazarian & Esquivel 2003; Ossenkopf etal 2006

(q=1,2,3,4,...)

Velocity Channel Analysis (VCA)

Lazarian & Pogosyan 2000; Padoan etal 2006

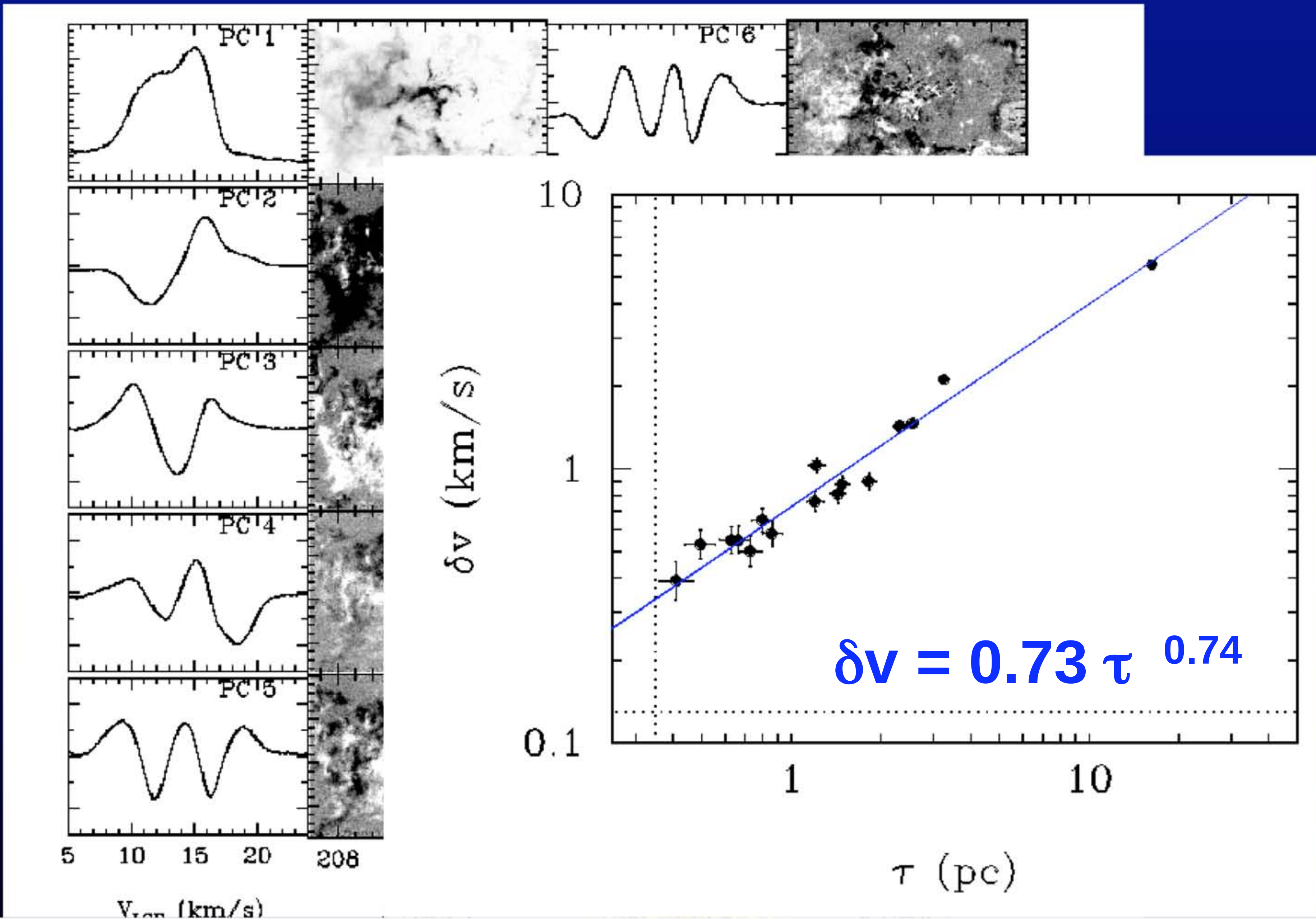
(q=2)

Principal Component Analysis (PCA)

Heyer & Schloerb 1997; Brunt & Heyer 2002; Brunt etal 2003; Heyer & Brunt 2004

(q~1)

Structure Functions from PCA

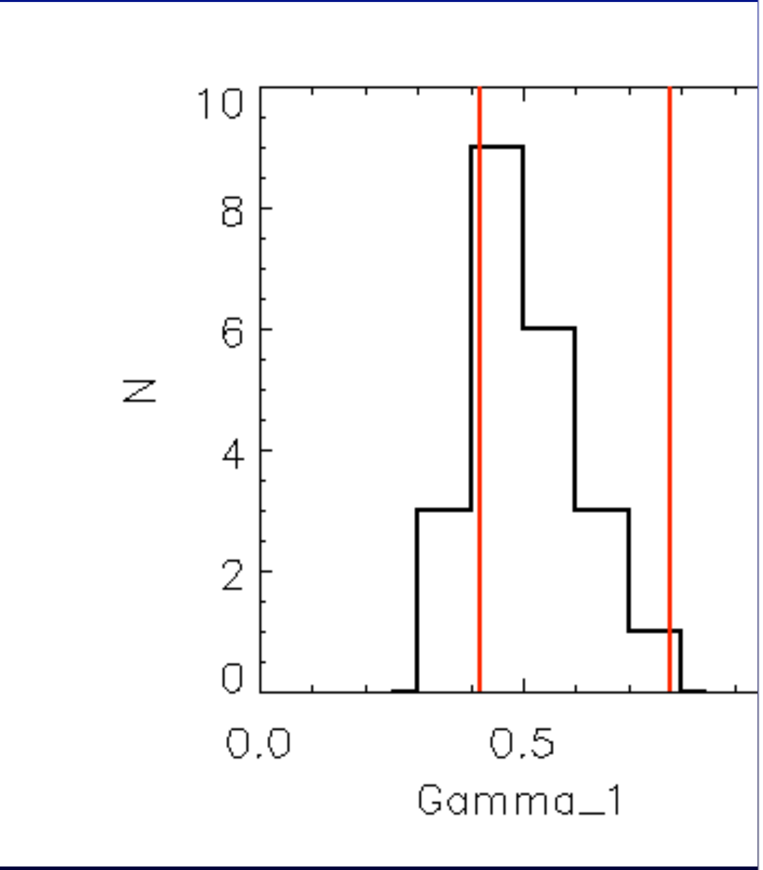


Distribution of $\gamma_1 = \zeta(1)$

$\langle\gamma_1\rangle = 0.5 \pm 0.1$

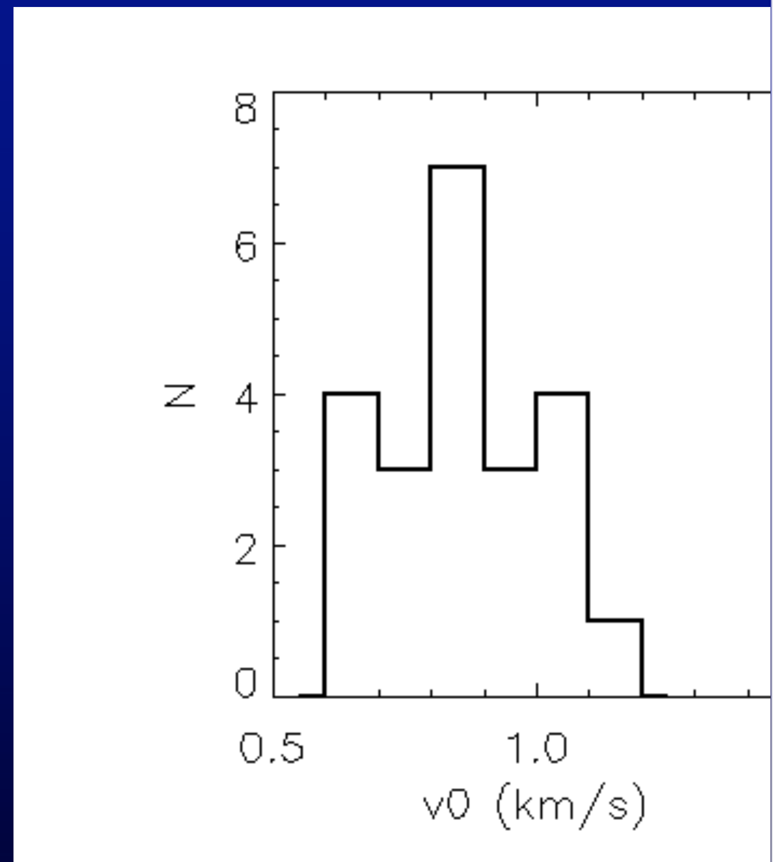
Kolmogorov-Burgers' Model
Boldyrev etal 2002

$0.42 < \gamma_1 < 0.78$



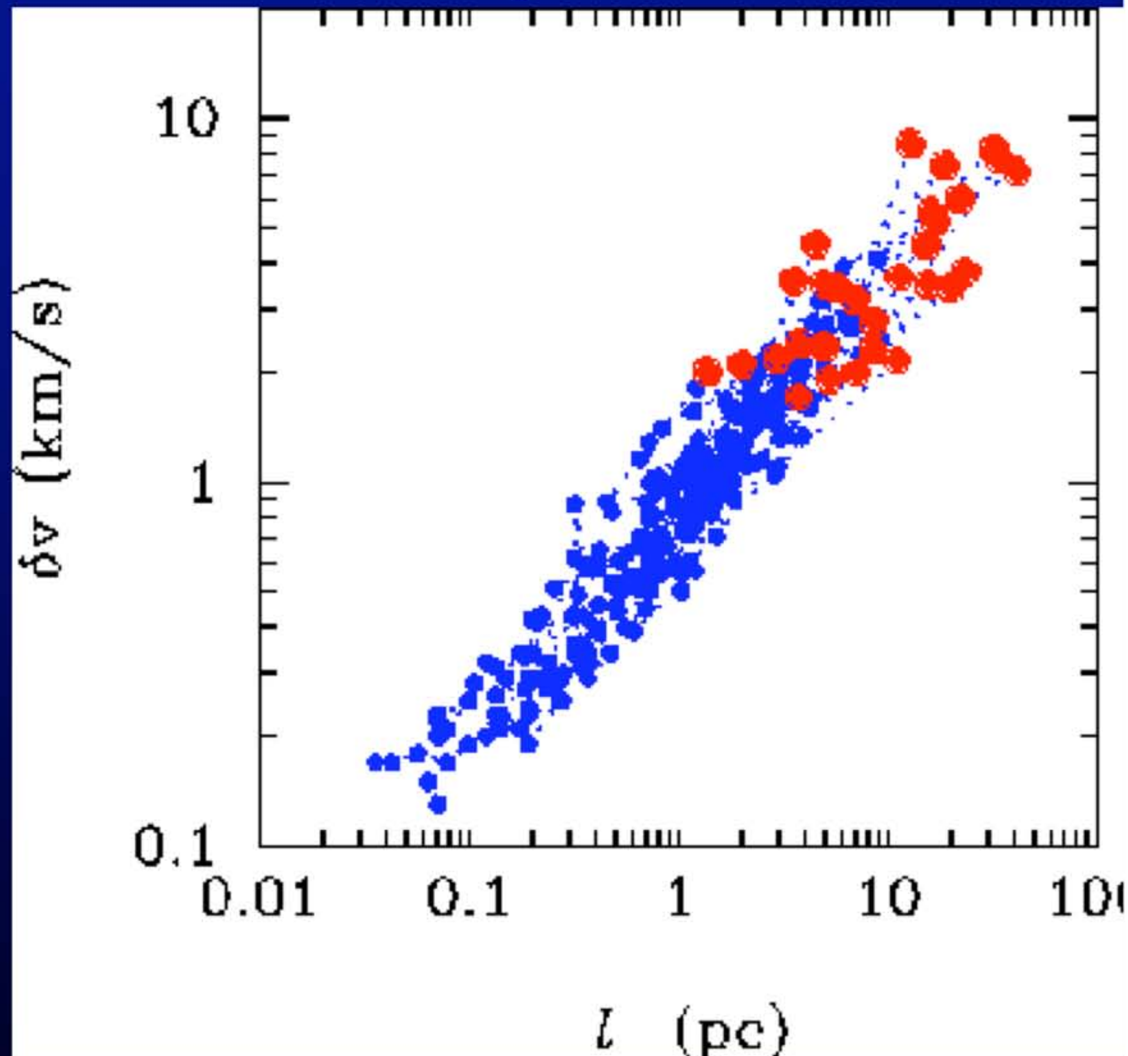
Distribution of v_0

$\langle v_0 \rangle = 0.9$ +/- 0.1 km/s

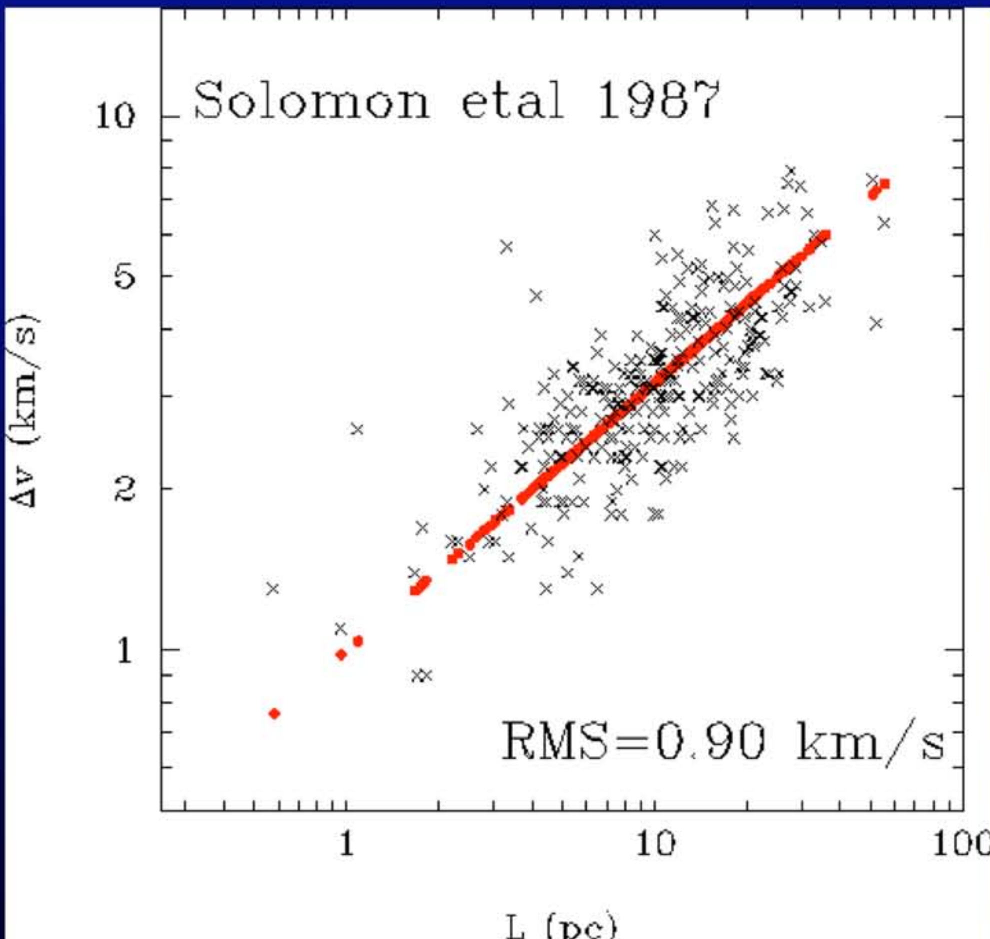


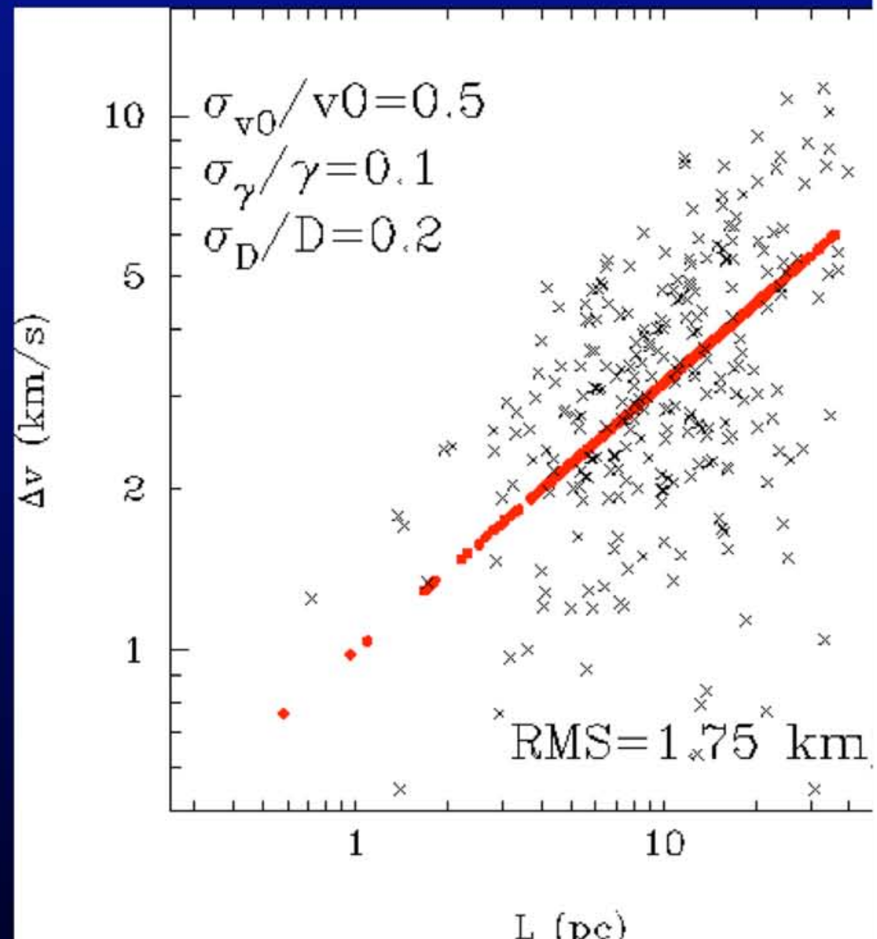
Structure functions are universal!

Heyer & Brunt 2004



Universality and Larson's Scaling Law





Source of Turbulent Energy in Molecular Clouds

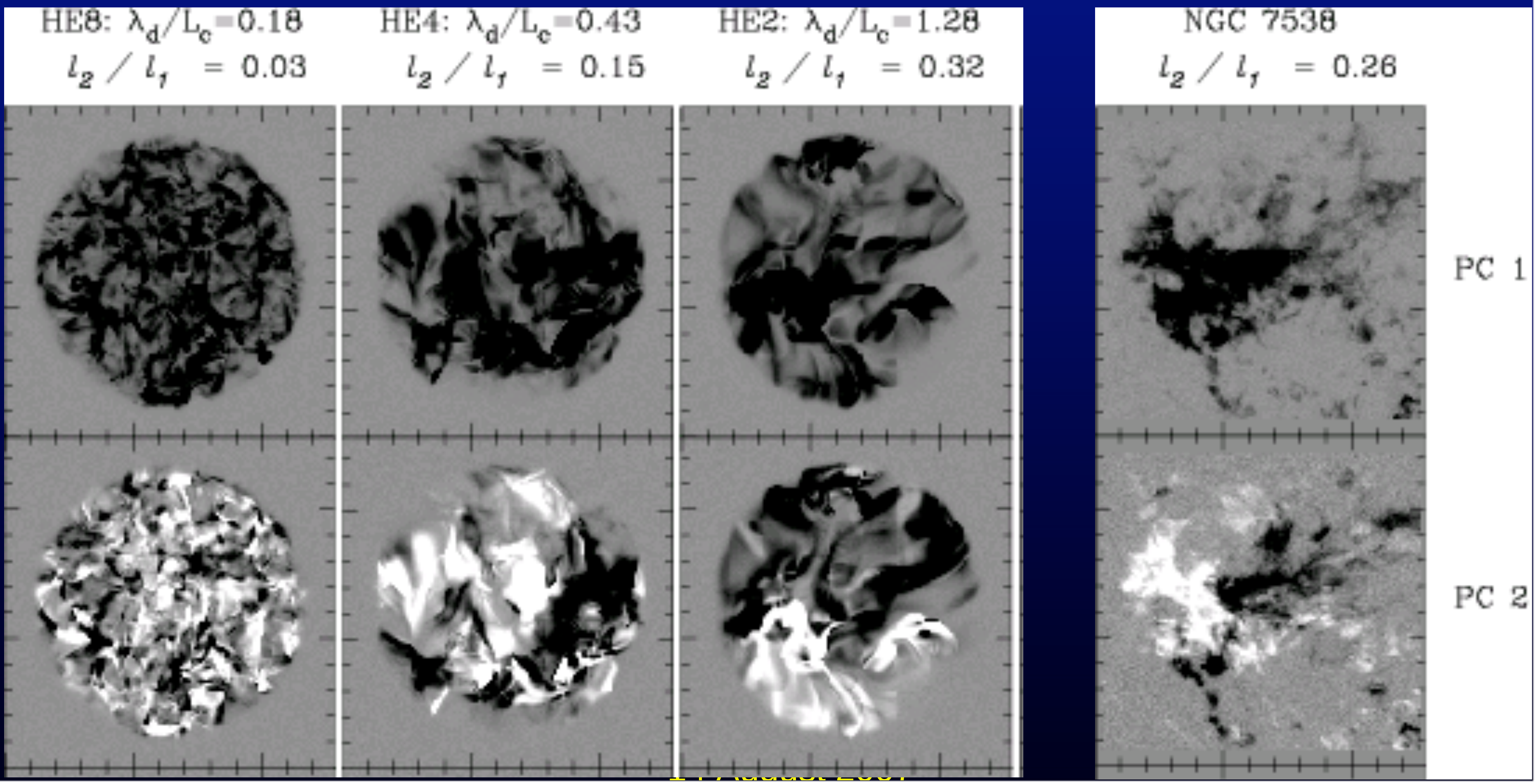
Supersonic turbulence should rapidly dissipate UNLESS driven by some energy source

Source	Scale (pc)
Bipolar Outflows	0.1-1
HII regions	0.01-20
Isolated supernovae	1-20
Stellar Winds	1-50
Supershells	150-200
UV Radiation	L_{cloud}
Galactic shear	L_{cloud}
Spiral density Waves	L_{cloud}
Grav. torques	L_{cloud}

Observational Constraints to λ_D

Simulations **Real Data**

Small **Intermediate** **Large**



Magnetic Criticality

Magnetic Field Strength

- Zeeman Measurements
- Indirect Measures

Magnetic Criticality:

$\lambda = 2\pi G^{1/2} (\Sigma / B_{tot})$

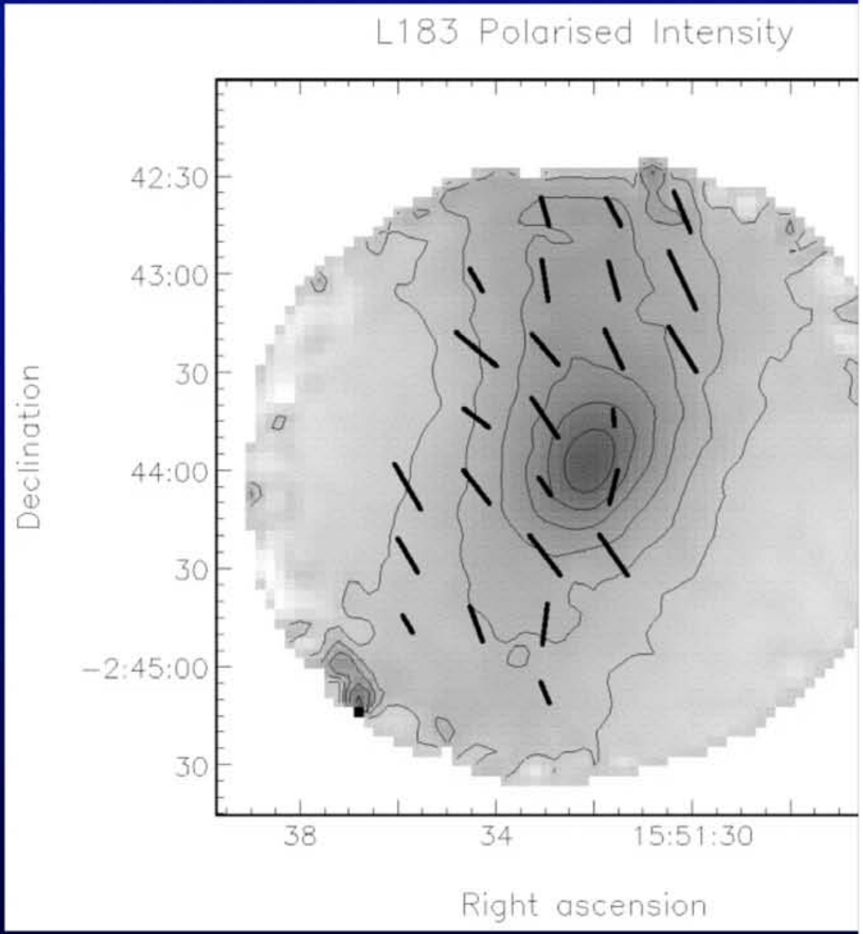
$\lambda = 7.6\times10^{-21} (N(H_2) / B_{tot})$

Chandrasekhar-Fermi (1953) Effect

$$\delta B/B_p = |\delta v| / v_A$$

$$\sigma_{pol} = f\,(4\pi\rho_o)^{1/2}\,\sigma_v / B_p \qquad (f \sim 0.5)$$

Submillimeter Polarimetry



Crutcher etal 2004

Taurus Cloud Envelope

σ_{pol} = 0.16 radians

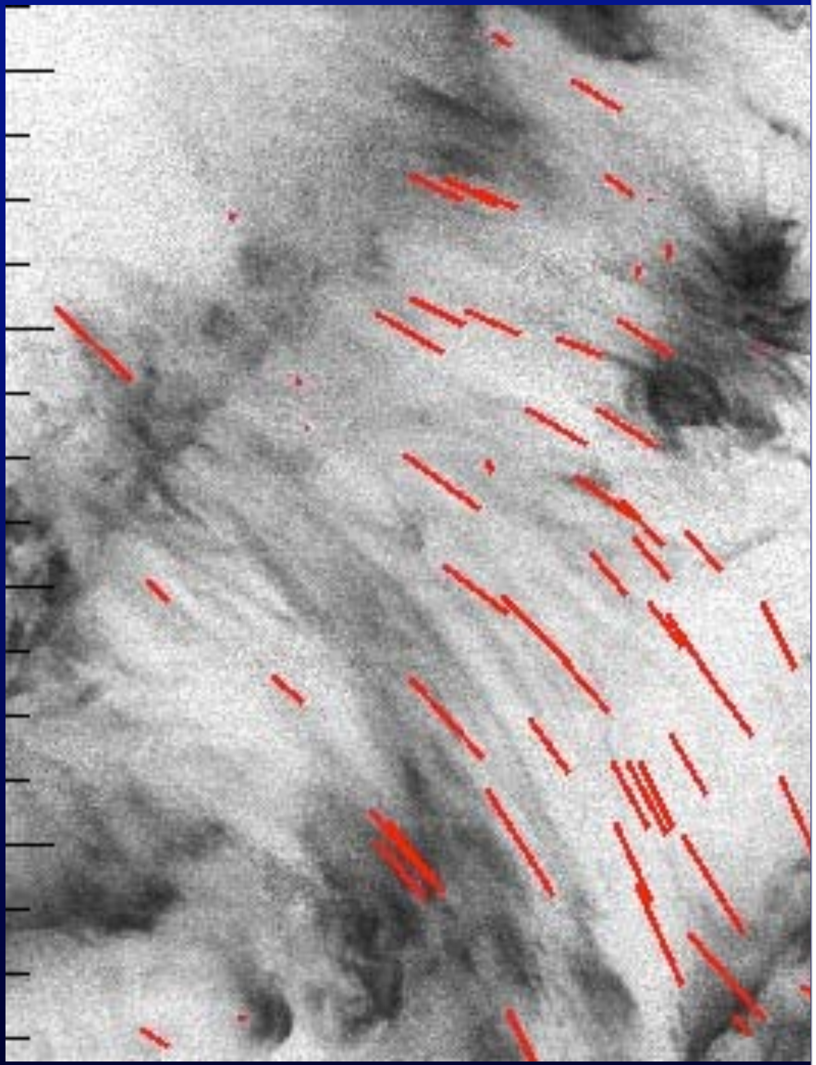
σ_v = 0.38 km/s (^{13}CO)

<n> = 250 cm^{-3}

$N(H_2)$ = 1.5x10^{21} cm^{-2}

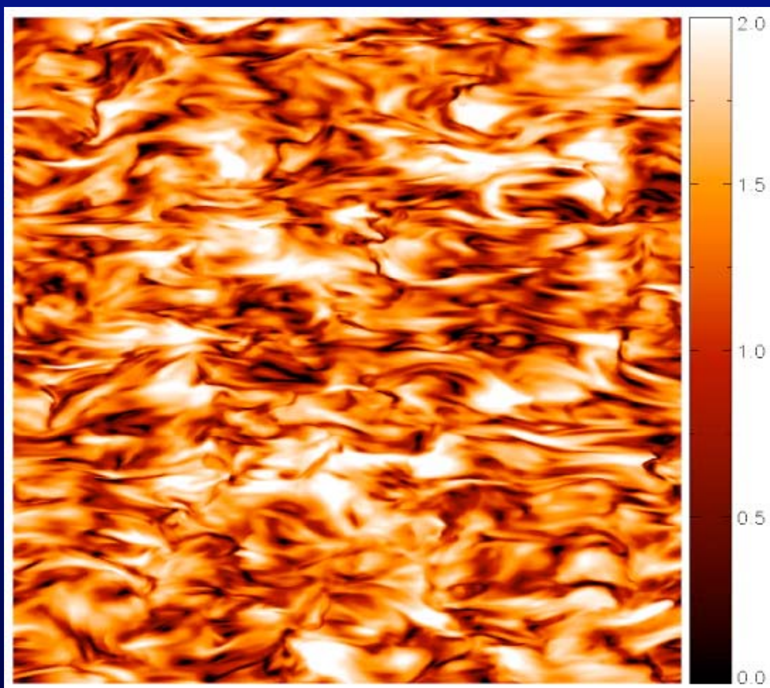
B_{CF} = 14 μG

λ_{obs} = 0.8



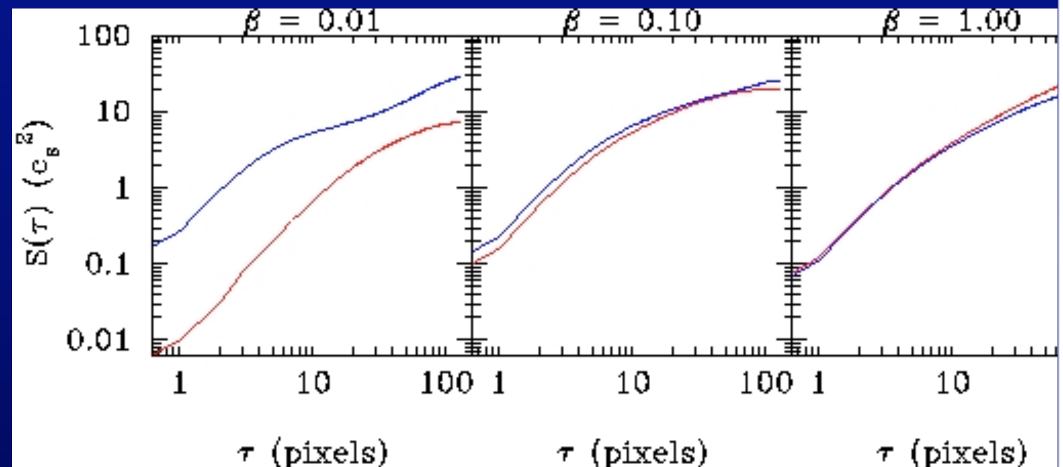
MHD Velocity Anisotropy (Goldreich-Sridhar 1995)

Vestuto, Ostriker, & Stone 2003



B →

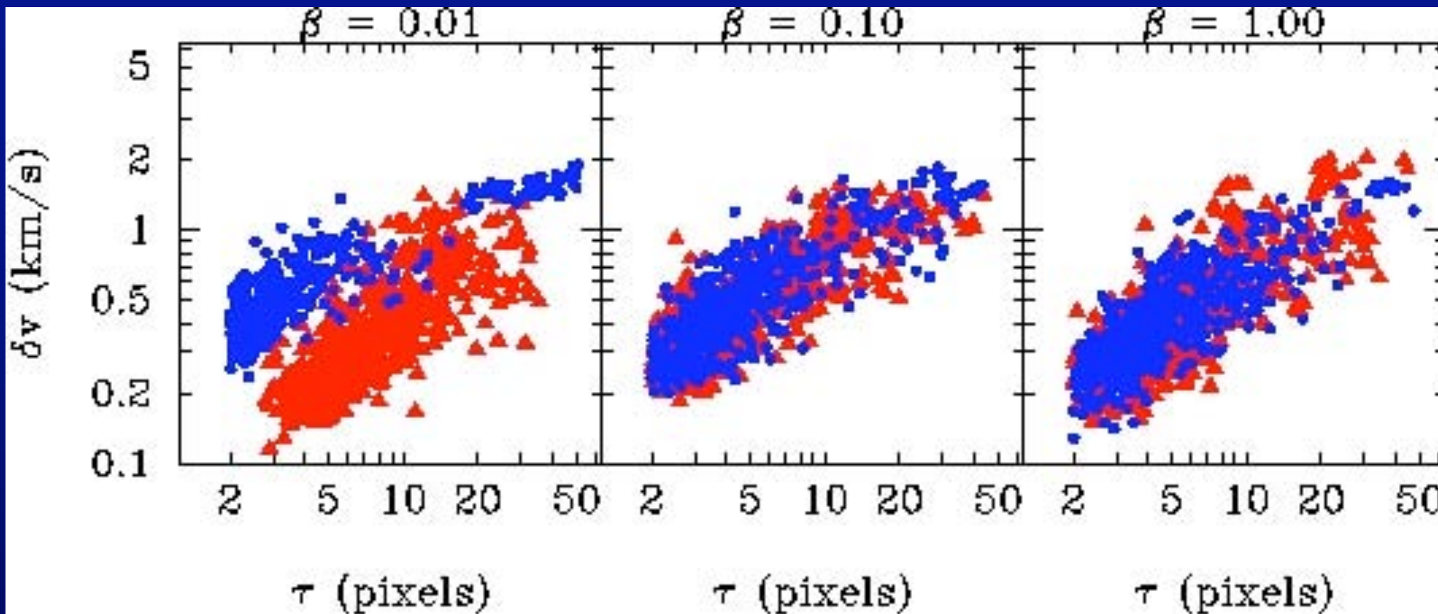
RED: Parallel BLUE: Perp.



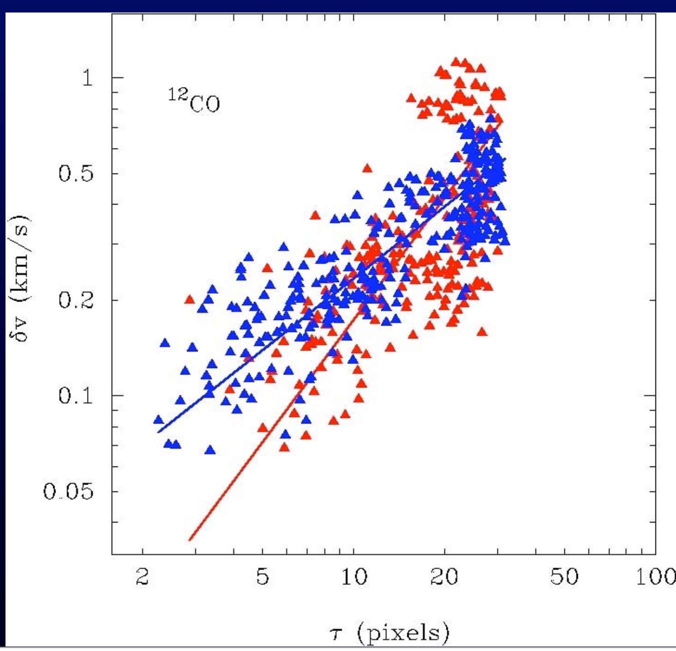
<u>Degree of anisotropy</u> is an indirect probe of dynamical importance of the magnetic field.

Axis-Constrained PCA (Heyer etal 2007)

RED: Parallel   BLUE: Perp.



Applied to Mode



Applied to Taurus

$\beta \sim 0.03$ (T_k=15,n=250 cm^{-3}

B = 15 μG

Open Questions

- Why are Structure Functions of molecular clouds universal?
- Are cloud envelopes magnetically sub-critical?
- What is the ***observed*** dependence of star formation properties (rate, efficiency, IMF) on turbulent and/or magnetic properties?