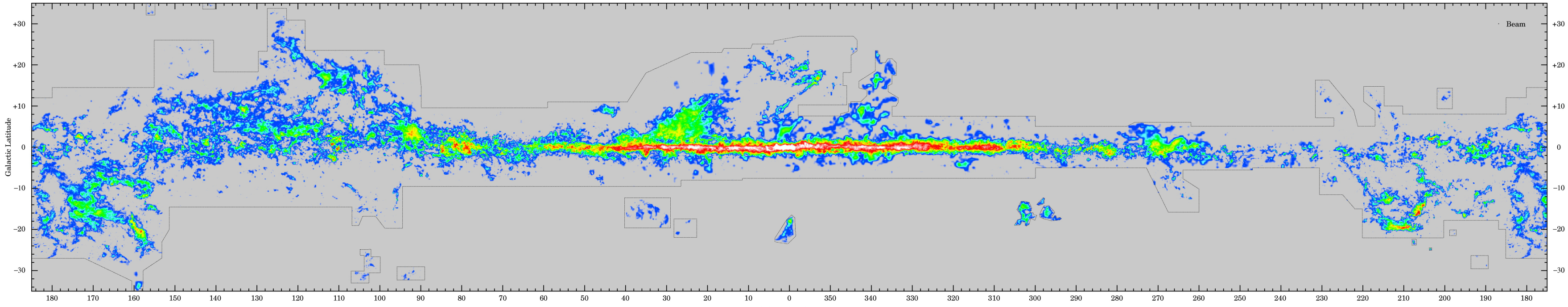


The Structure and Organization of the Molecular ISM. The Galactic Perspective

Mark Heyer

University of Massachusetts, USA

Regulation of Star Formation in Molecular Gas: from galactic to sub-cloud scales
Ringberg Workshop 24 June 2013

Motivate the importance of Milky Way

- our own Galaxy:
- baseline knowledge to compare with results from other galaxies both near and far
- Spatial Resolution: ability to resolve but super-resolve (100s resolution elements across target) -- ALMA (0.1 arcsec -→ 0.5 pc at Mpc)
  - *to reveal gas distribution (dust, gamma rays, and spectral lines) and kinematics (spectral lines)*
  - *Comparisons to theory and simulations*
  - *identify key physical process of GMCs and star formation*

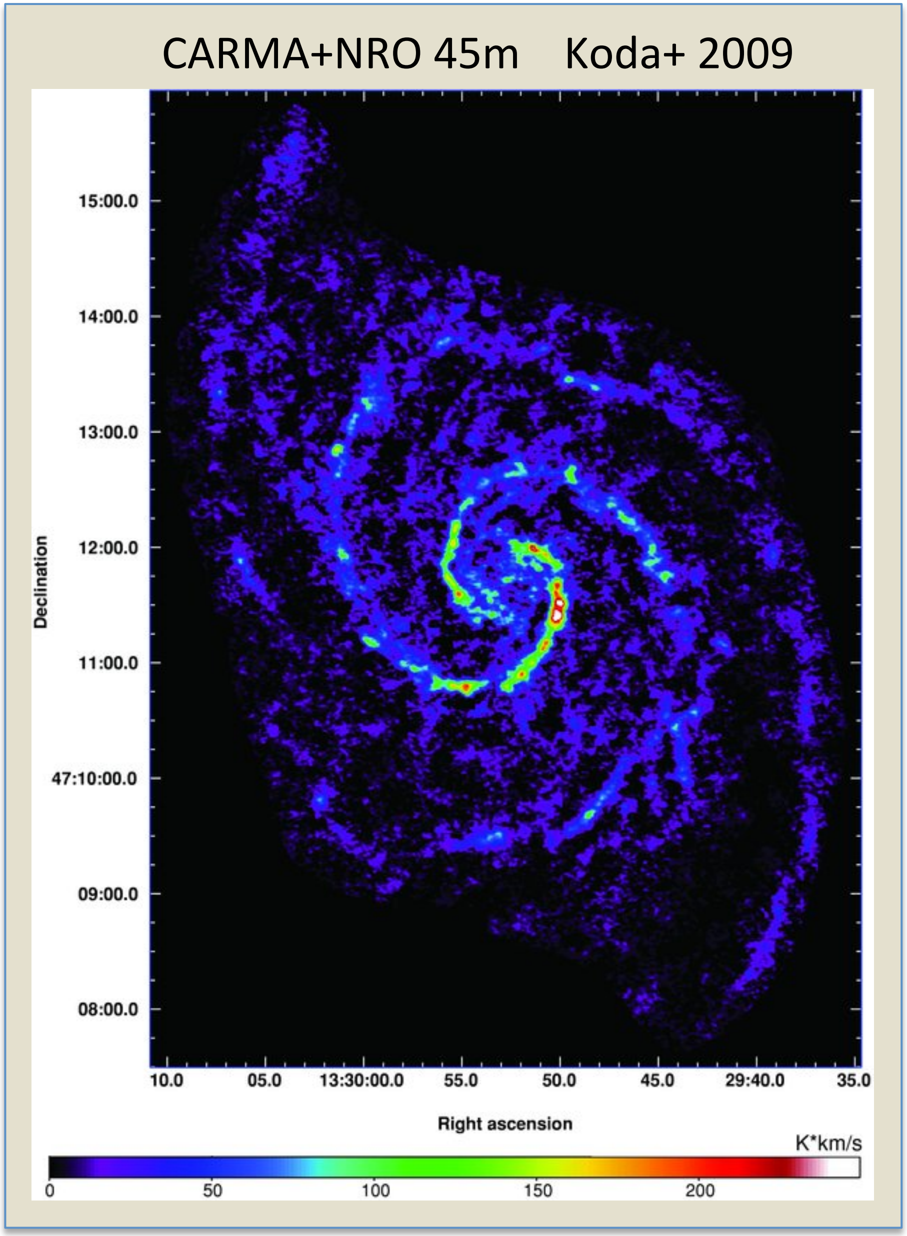
Outline

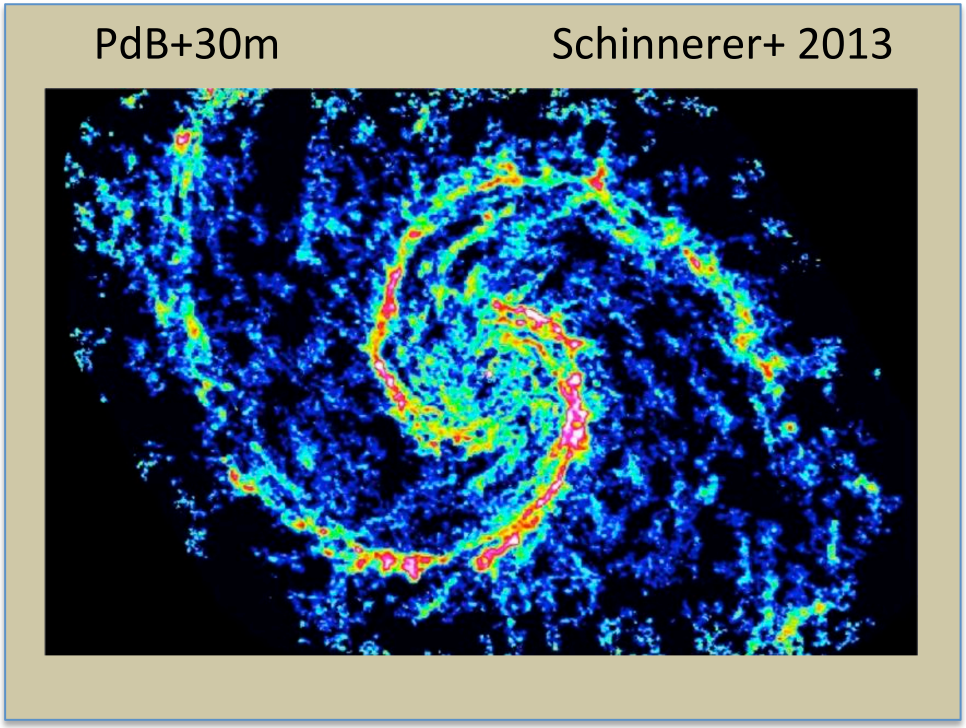
- The distribution of H_2 inferred from CO surveys
- Column density and velocity fields of GMCs

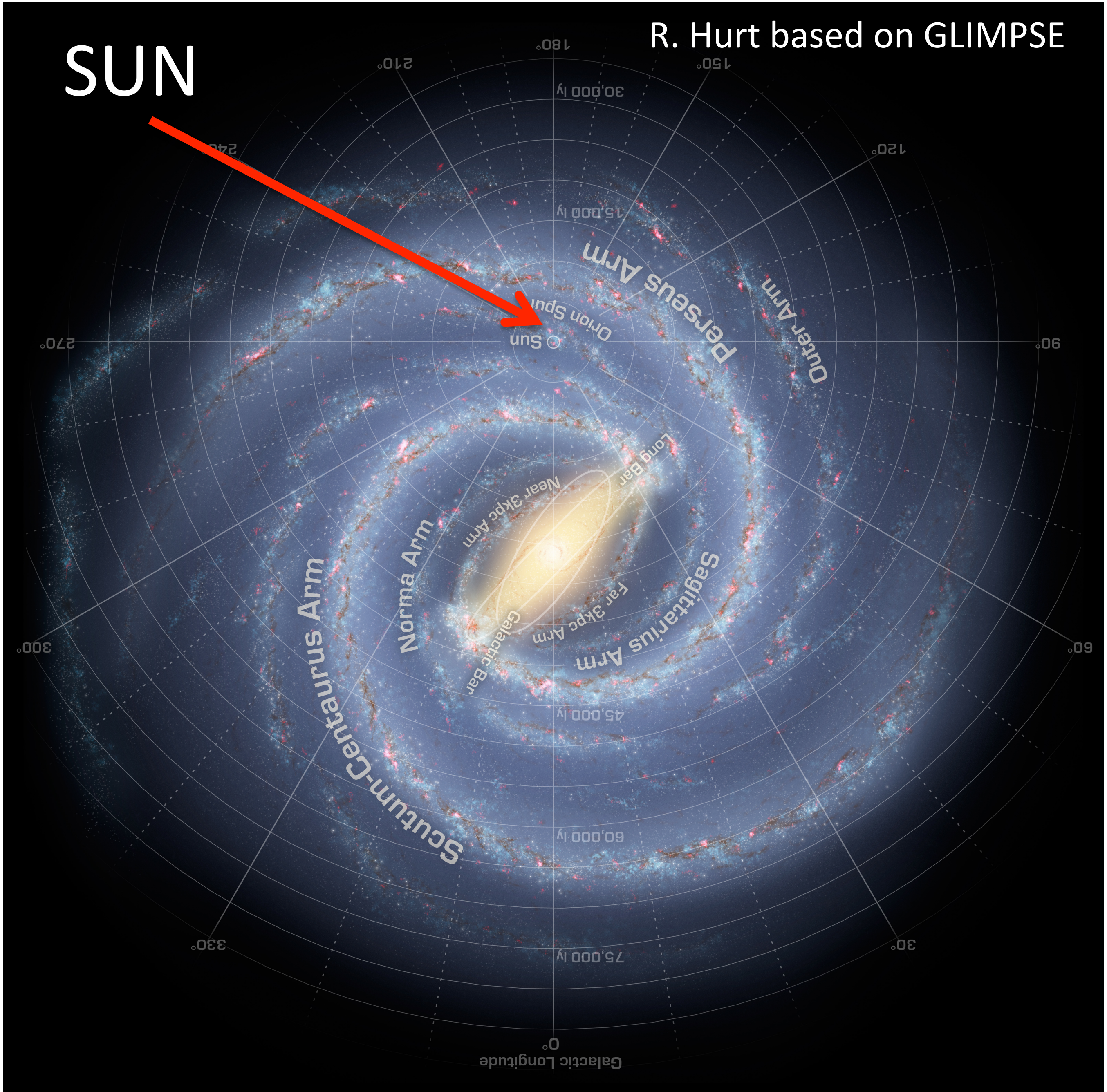
I will ***NOT*** talk in depth about:

- XCO and its variation
- Properties of GMCs: (see Julia's and Alyssa's talks)
- Star Formation: See tomorrow's presentations

M51 in CO

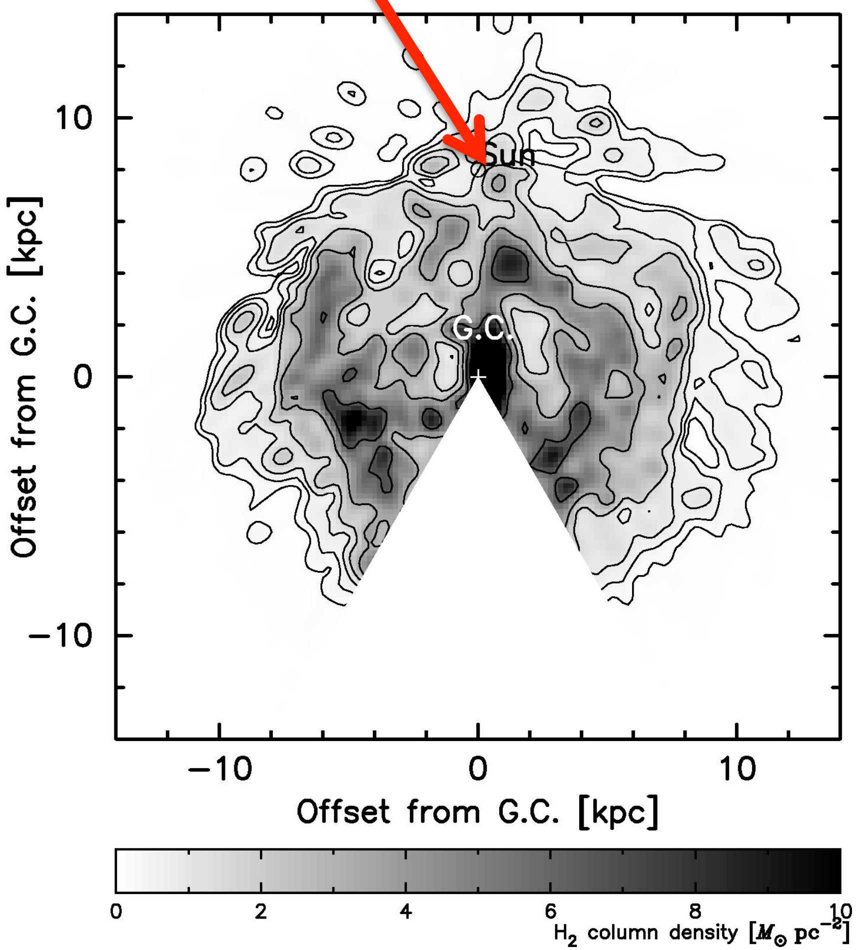

CARMA+NRO 45m Koda+ 2009
15:00.0
14:00.0
13:00.0
12:00.0
11:00.0
47:10:00.0
09:00.0
08:00.0
Declination
10.0
05.0
13:30:00.0
55.0
50.0
45.0
29:40.0
35.0
Right ascension
K*km/s
0
50
100
150
200

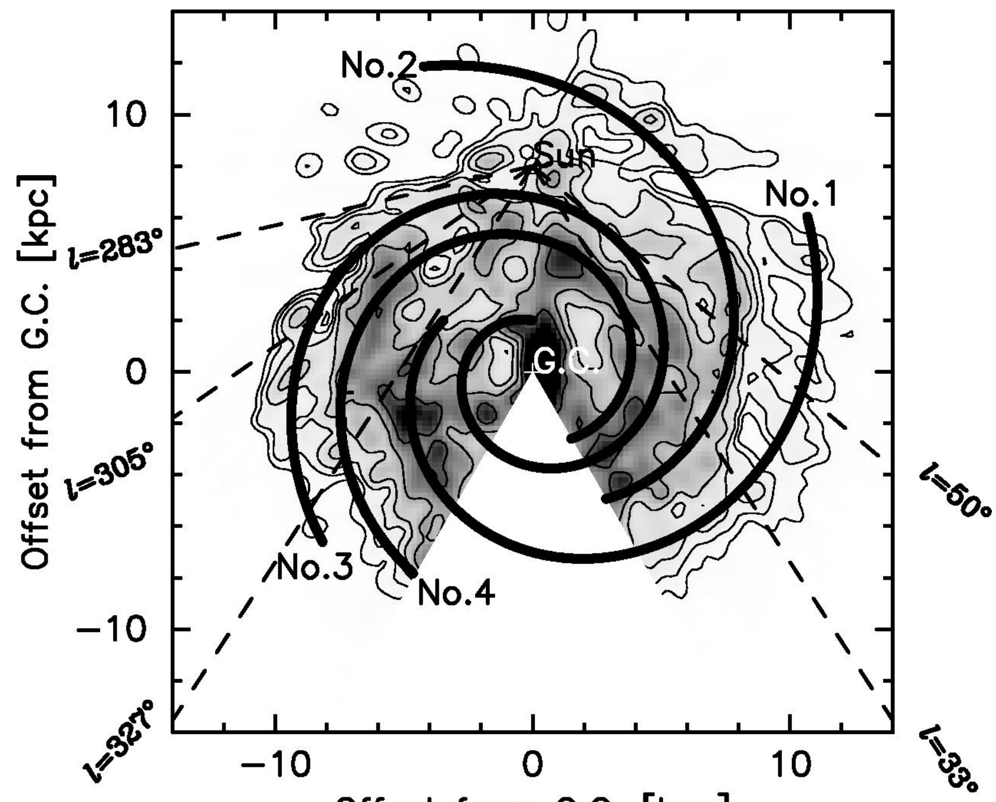

PdB+30m Schinnerer+ 2013


SUN
R. Hurt based on GLIMPSE
Sun
Orion Spur
Perseus Arm
Outer Arm
Long Bar
Near 3kpc Arm
Norma Arm
Scutum-Centaurus Arm
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Galactic Longitude

Sun

Nakanishi & Sofue 2006



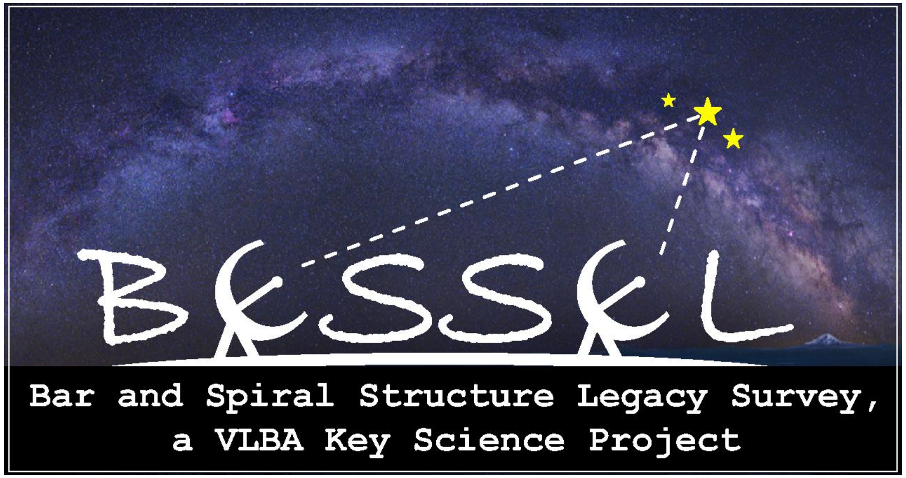


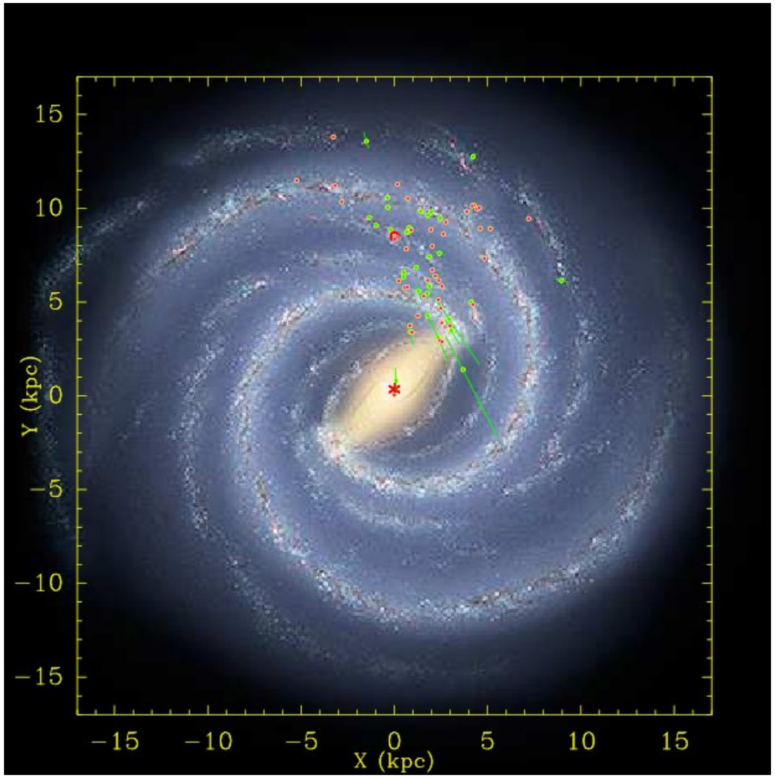
Trigonometric Parallax Measurements with VLBA of methanol and H_2O masers

Accurate distances for ~400 high mass star forming regions in the Milky Way

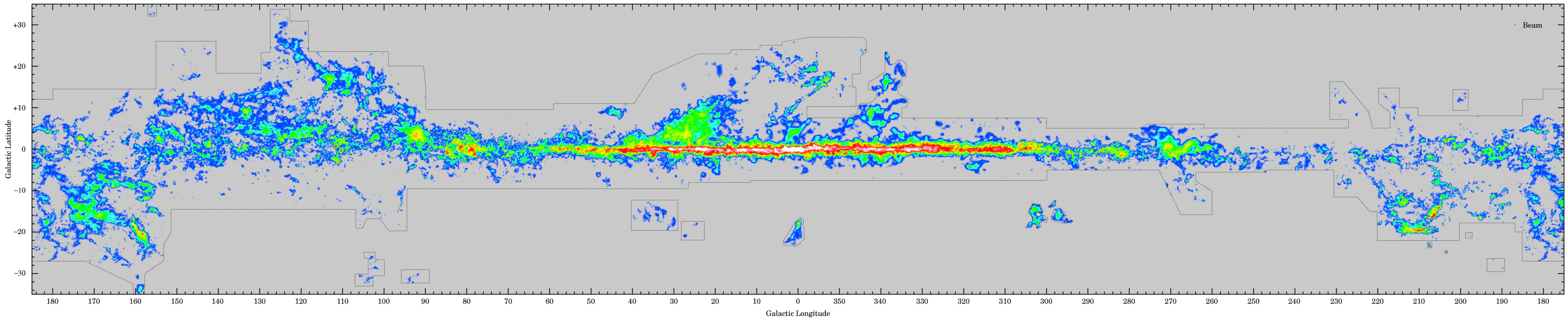
- Improved rotation curve
- Improved kinematic distance estimates
- Identify streaming motions induced by local gravitational potential (SDW, bar)

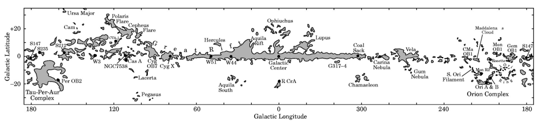
See also VERA





Dame, Hartmann, Thaddeus 2001





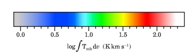
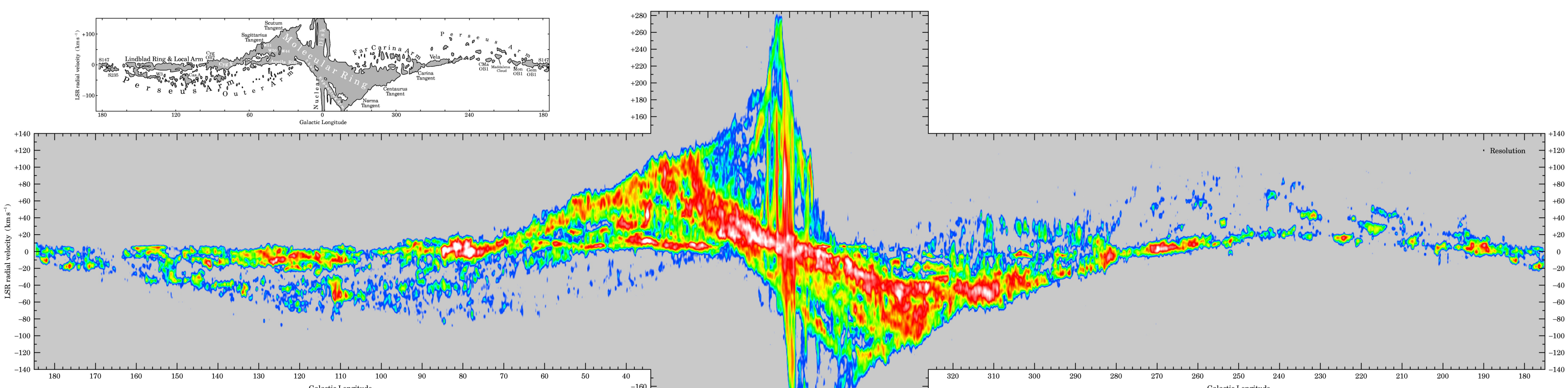
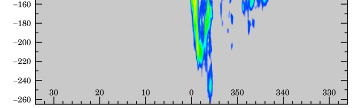


FIG. 2.–Velocity-integrated CO map of the Milky Way. The angular resolution is 9′ over most of the map, including the entire Galactic plane, but is lower (15′ or 30′) in some regions out of the plane (see Fig. 1 & Table 1). The sensitivity varies somewhat from region to region, since each component survey was integrated individually using moment masking or clipping in order to display all statistically significant emission but little noise (see §2.2). A dotted line marks the sampling boundaries, given in more detail in Fig. 1.





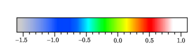


FIG. 3.—Longitude-velocity map of CO emission integrated over a strip ~4° wide in latitude centered on the Galactic plane (see §2.2)—a latitude range adequate to include essentially all emission beyond the Local spiral arm (*i.e.*, at $|v| > 20$ km s^{-1}). The map has been smoothed in velocity to a resolution of 2 km s^{-1} and in longitude to a resolution of 12′. The sensitivity varies somewhat over the map, since each component survey was integrated individually using moment masking at the 3-s level (see §2.2).

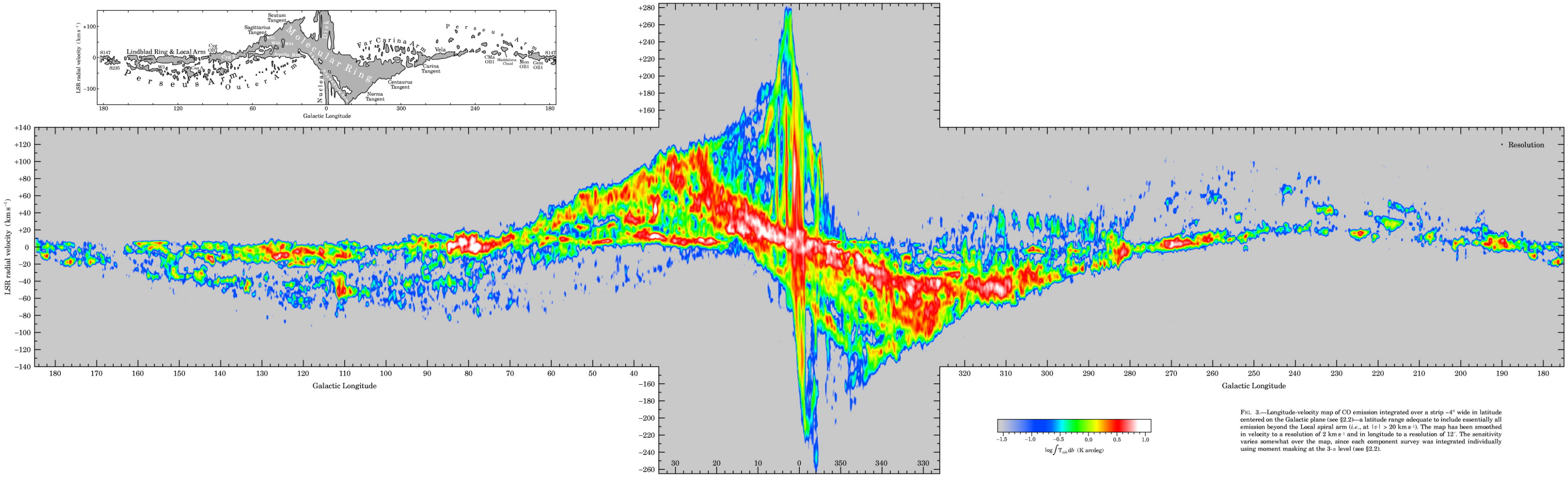
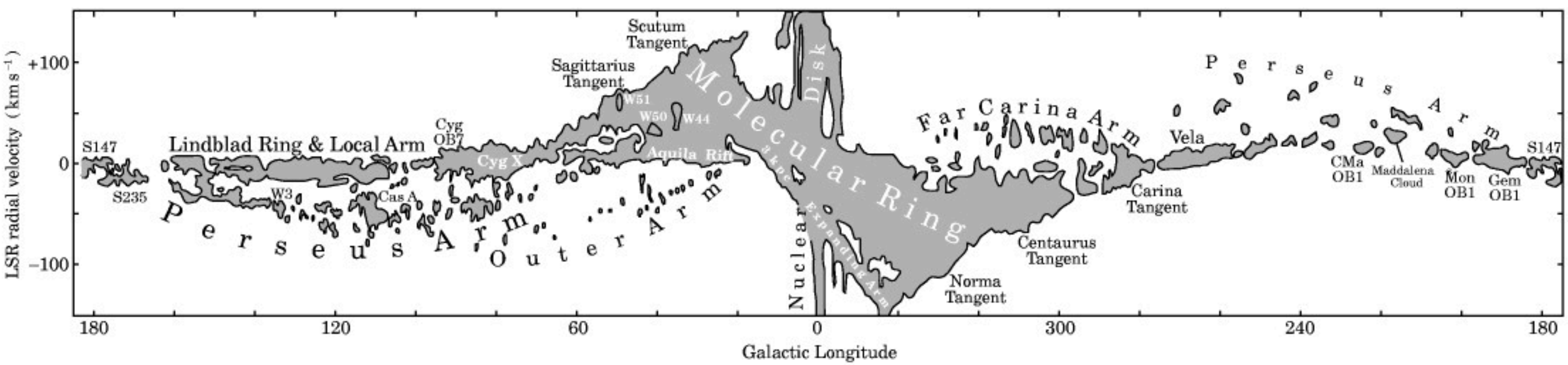
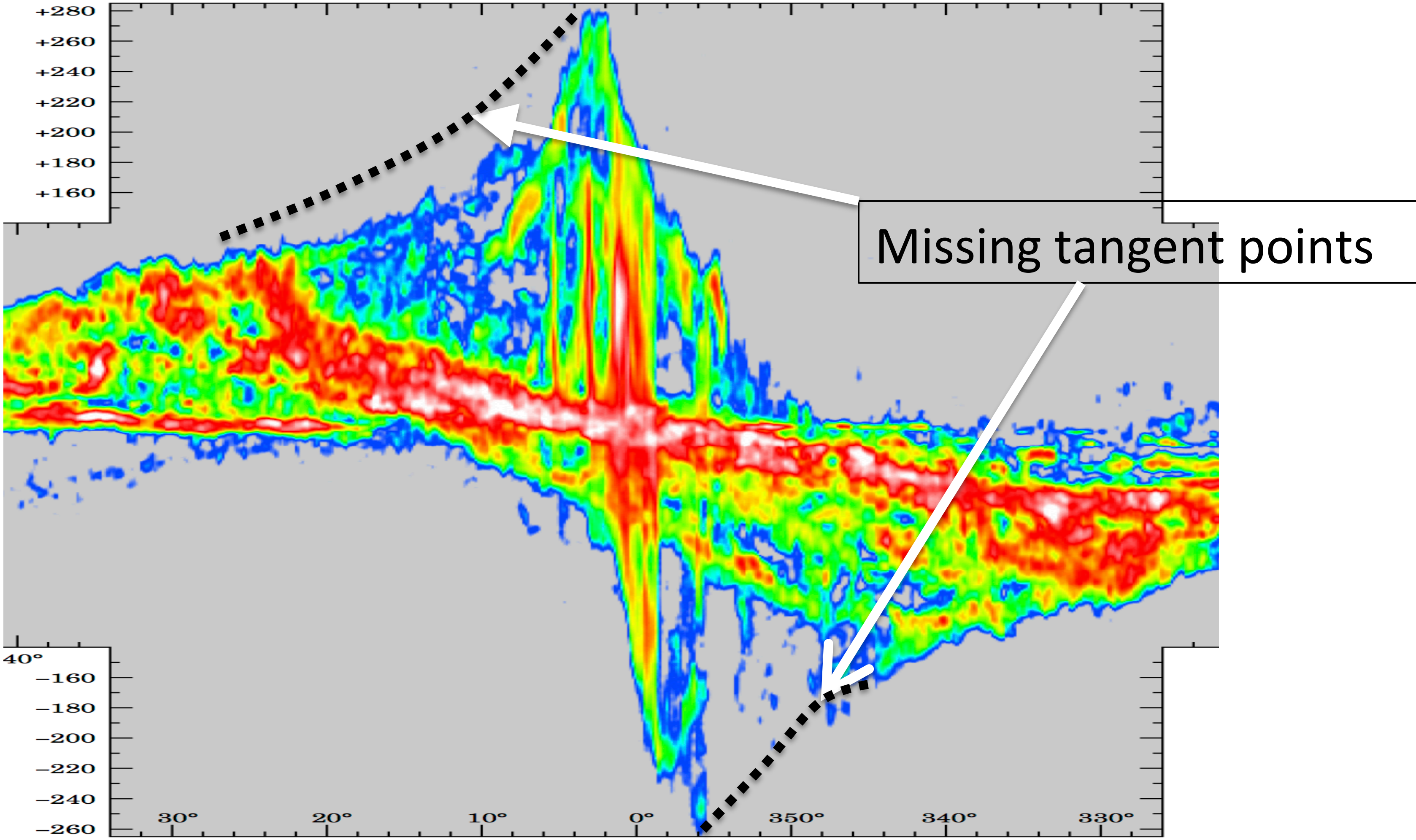


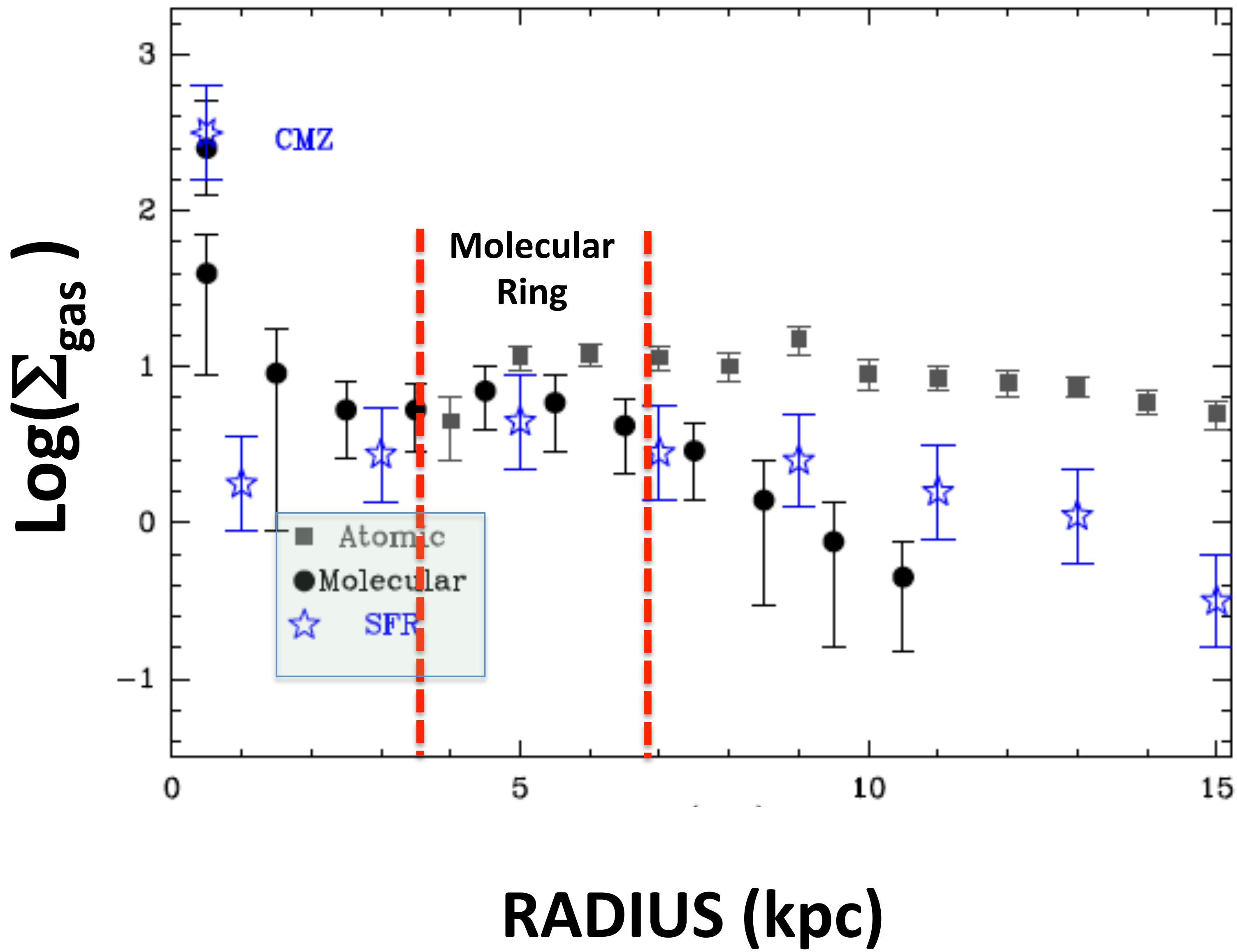
FIG. 3.—Longitude-velocity map of CO emission integrated over a strip ~4° wide in latitude centered on the Galactic plane (see §2.2)—a latitude range adequate to include essentially all emission beyond the Local spiral arm (*i.e.*, at $|v| > 20$ km s^{-1}). The map has been smoothed in velocity to a resolution of 2 km s^{-1} and in longitude to a resolution of 12′. The sensitivity varies somewhat over the map, since each component survey was integrated individually using moment masking at the 3-s level (see §2.2).



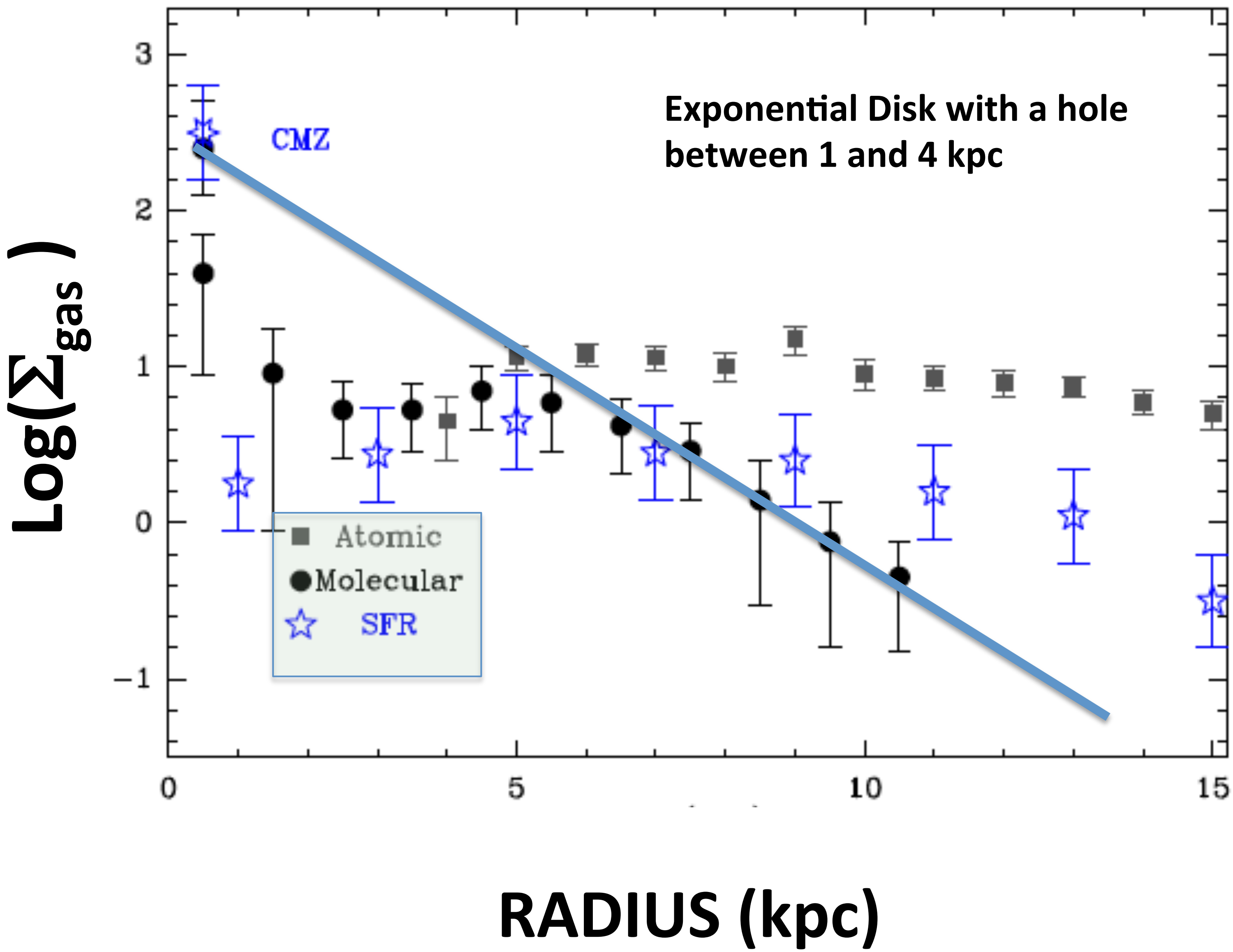


Molecular Ring (Scoville & Solomon 1975; Gordon & Burton 1976)
5 < l < 25: absence of CO tangent points: no CO related molecular 1 < R < 3.5 kpc **in circular orbits**

Kennicutt & Evans 2012 adapted from Nakanishi & Sofue 2006 and Kalberla & Dedes 2008

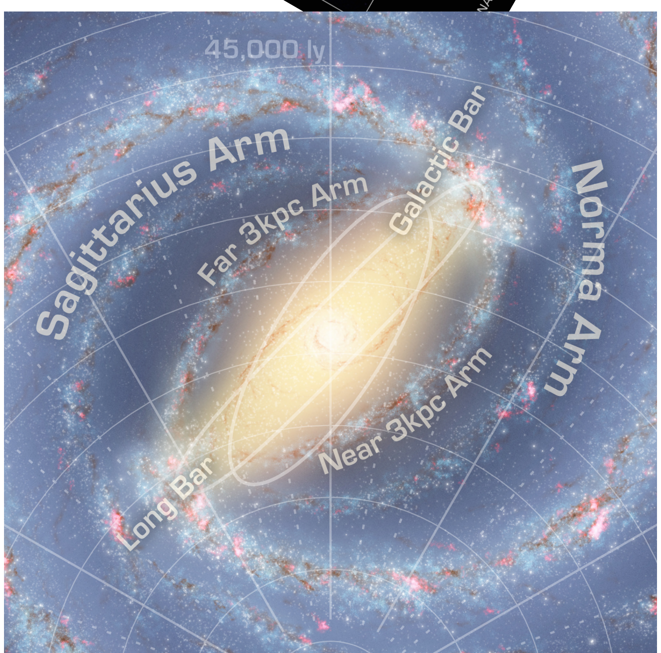


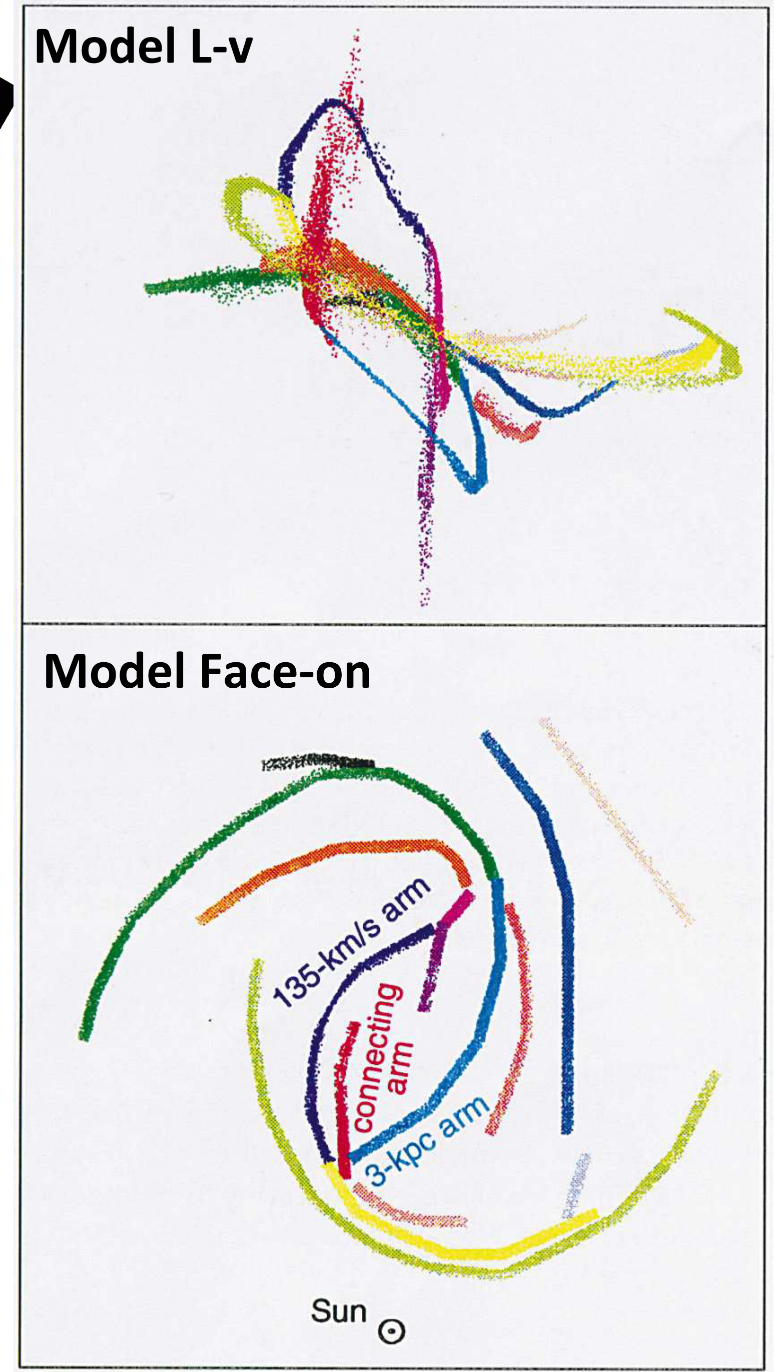
Kennicutt & Evans 2012 adapted from Nakanishi & Sofue 2006 and Kalberla & Dedes 2008



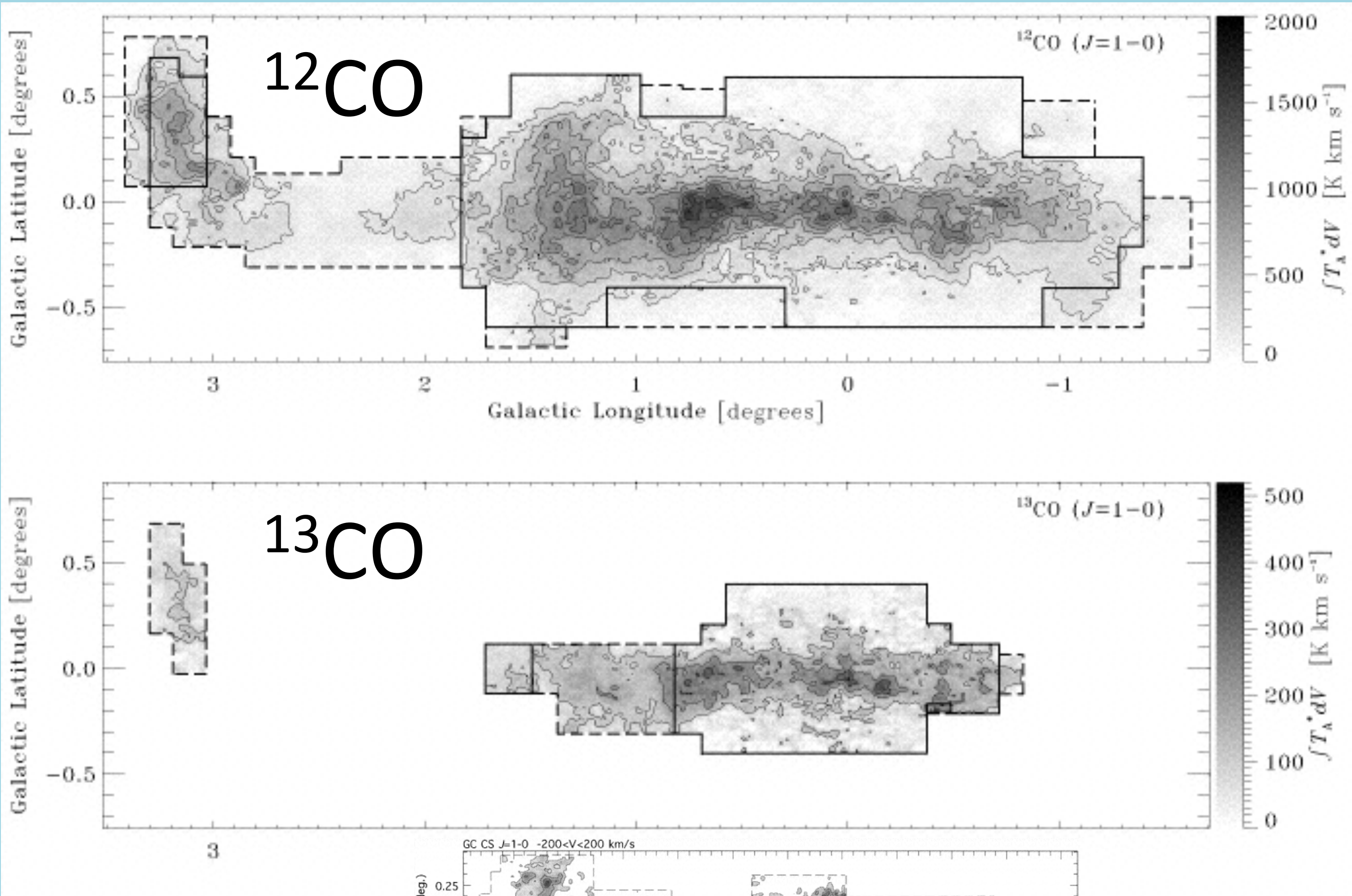
Fux 1999


Barred Spiral Galaxy NGC 1300
Hubble Heritage
NASA, ESA, and The Hubble Heritage Team (STScI/AURA) • Hubble Space Telescope ACS • STScI-PRC05-01

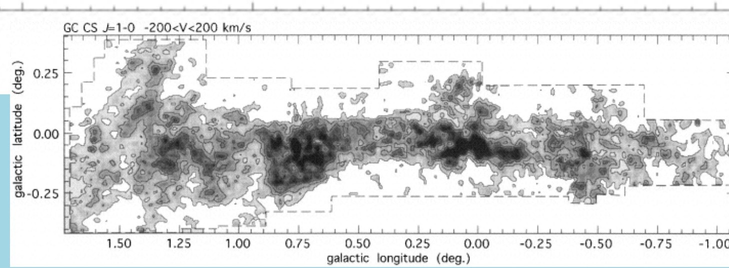

45,000 ly
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Norma Arm
Near 3kpc Arm
Long Bar


Model L-v
Model Face-on
135-km/s arm
connecting arm
3-kpc arm
Sun

Central 600 pc of MW



Oka+ 1998



CS J=1-0

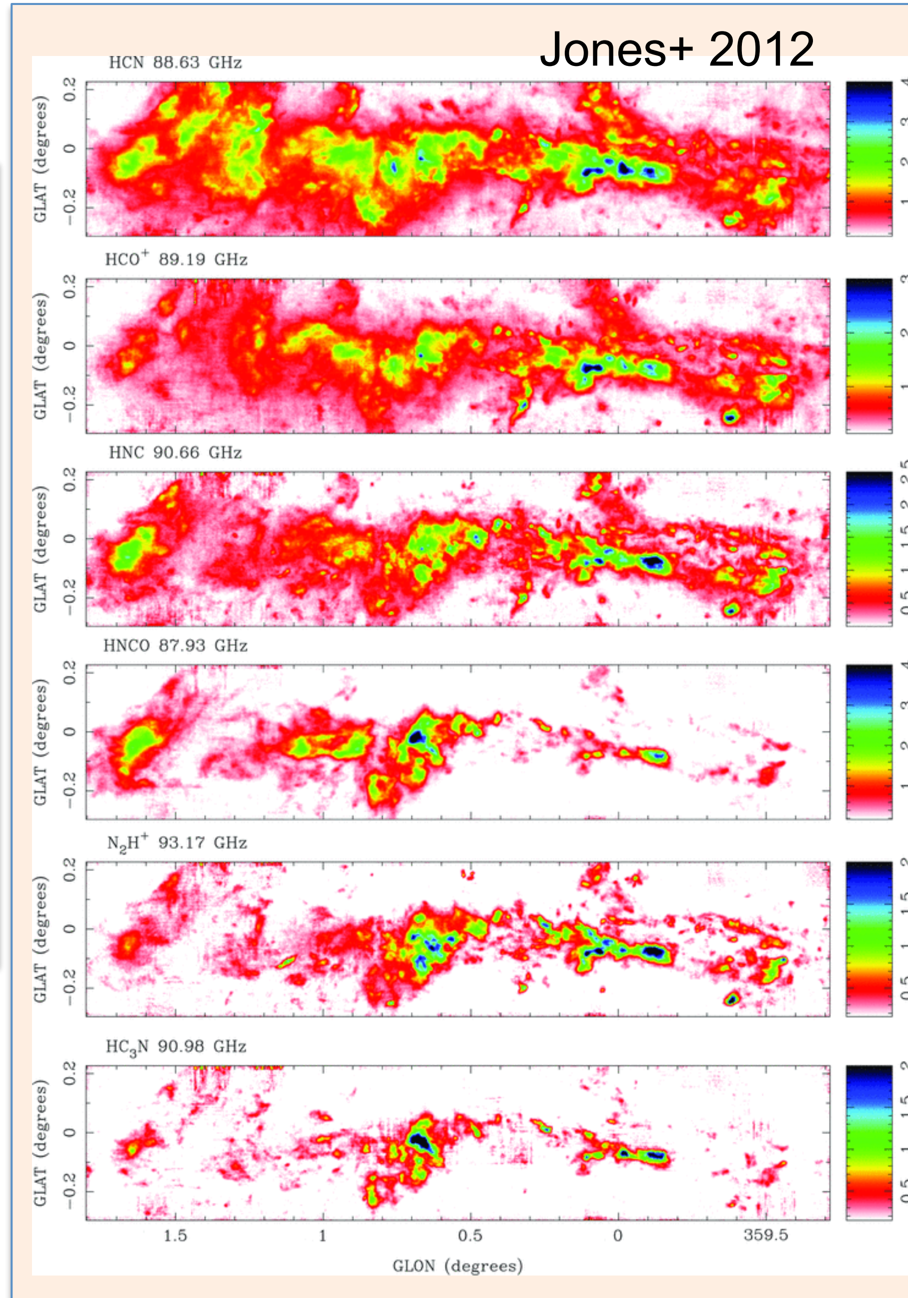
Tsuboi 1999

Central 600 pc of MW

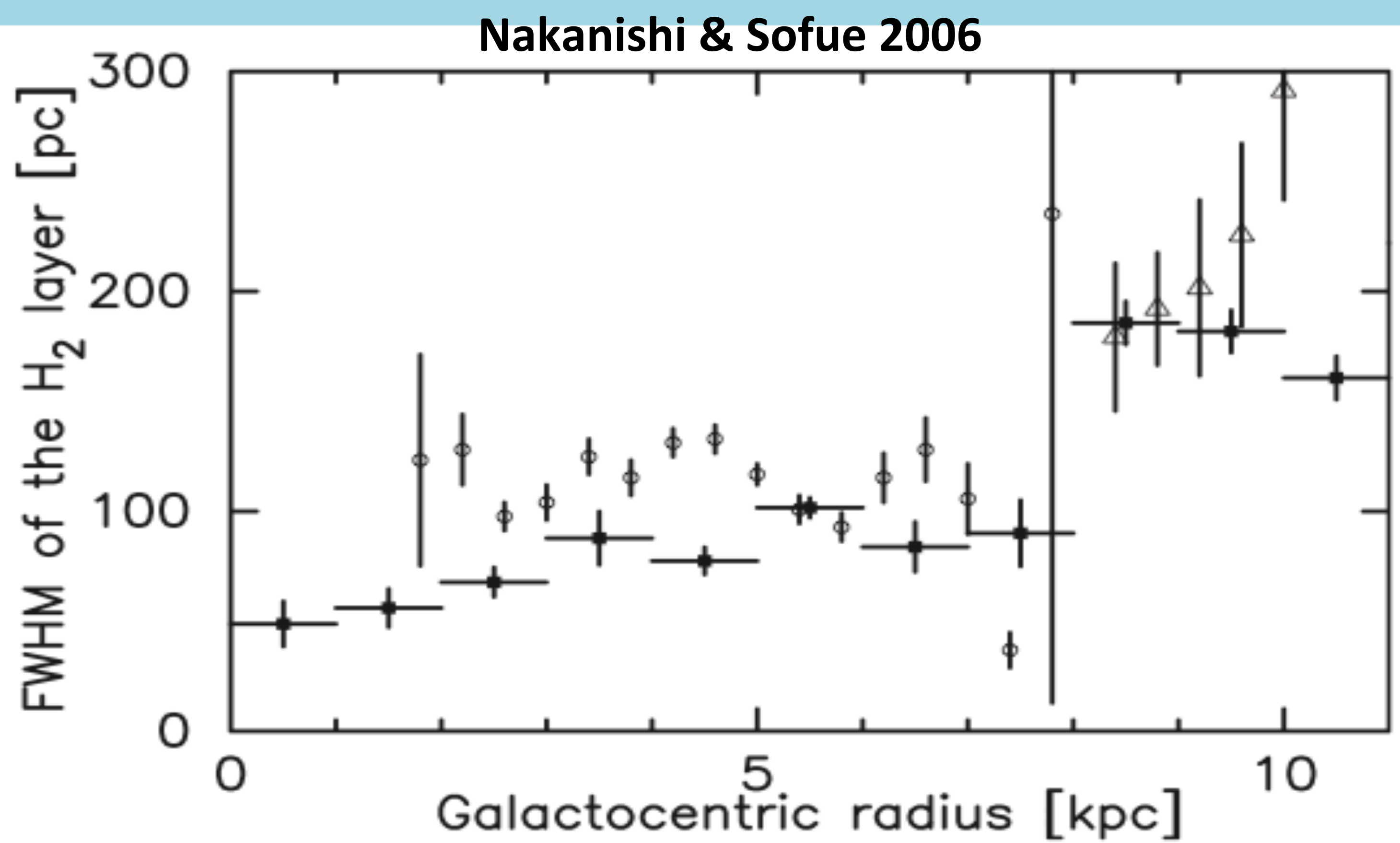
GC GMCs:

- are dense ($\langle n \rangle \sim 10^5$ cm^{-3})
- large filling factors
- larger velocity dispersions $\sigma_v/R^{1/2} = 5$ kms $^{-1}$ pc$^{-1/2}$
- Possibly Pressure bounded

Bally+ 1988; Jackson+1996; Oka+2001; Shetty+ 2012



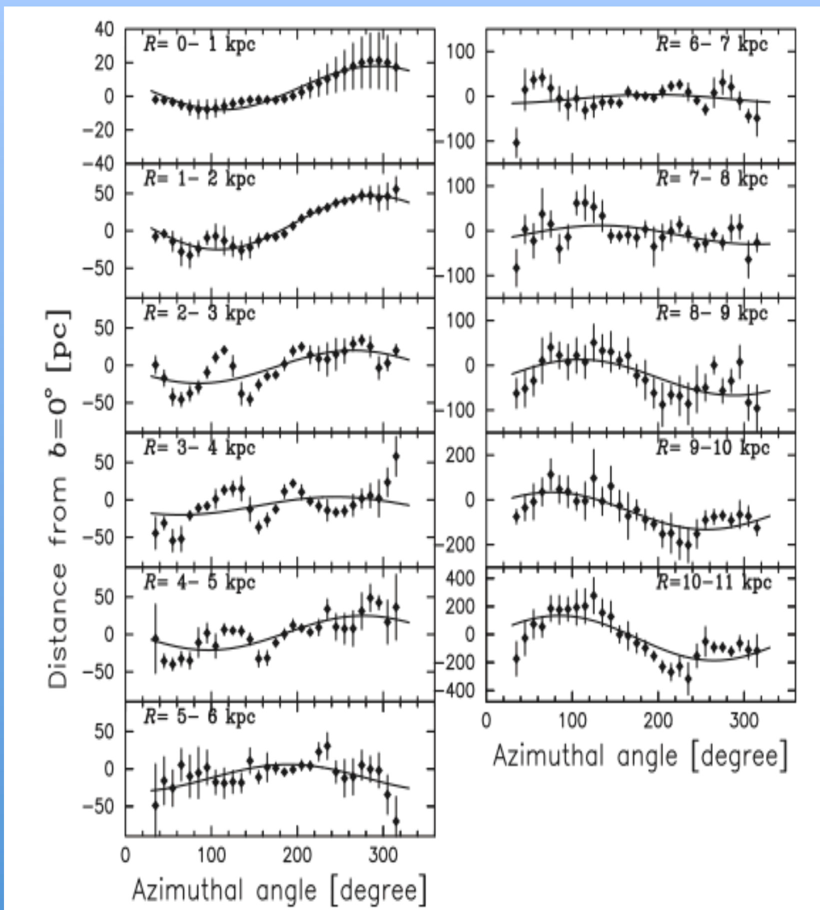
Vertical Distribution of CO Emission: Layer Thickness

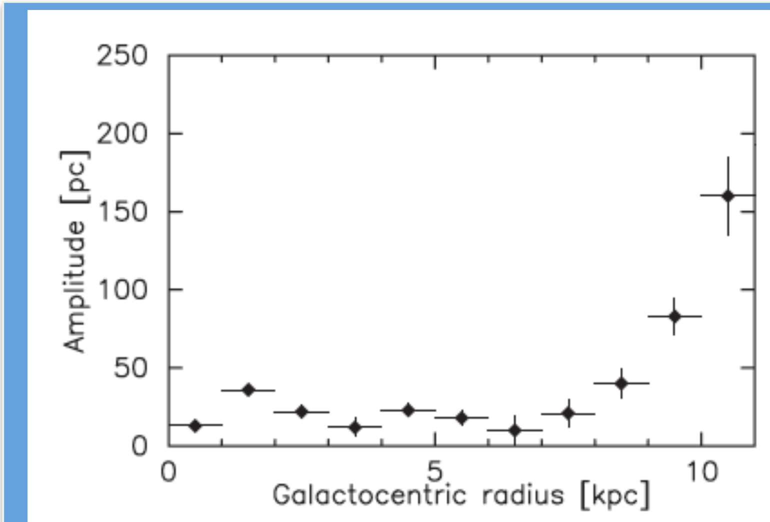


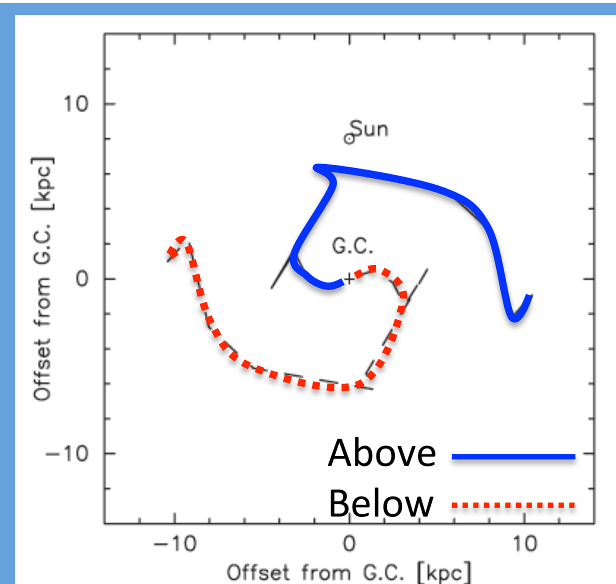
Flaring Disk at large radii

Vertical Distribution of CO Emission: Mid-plane displacement

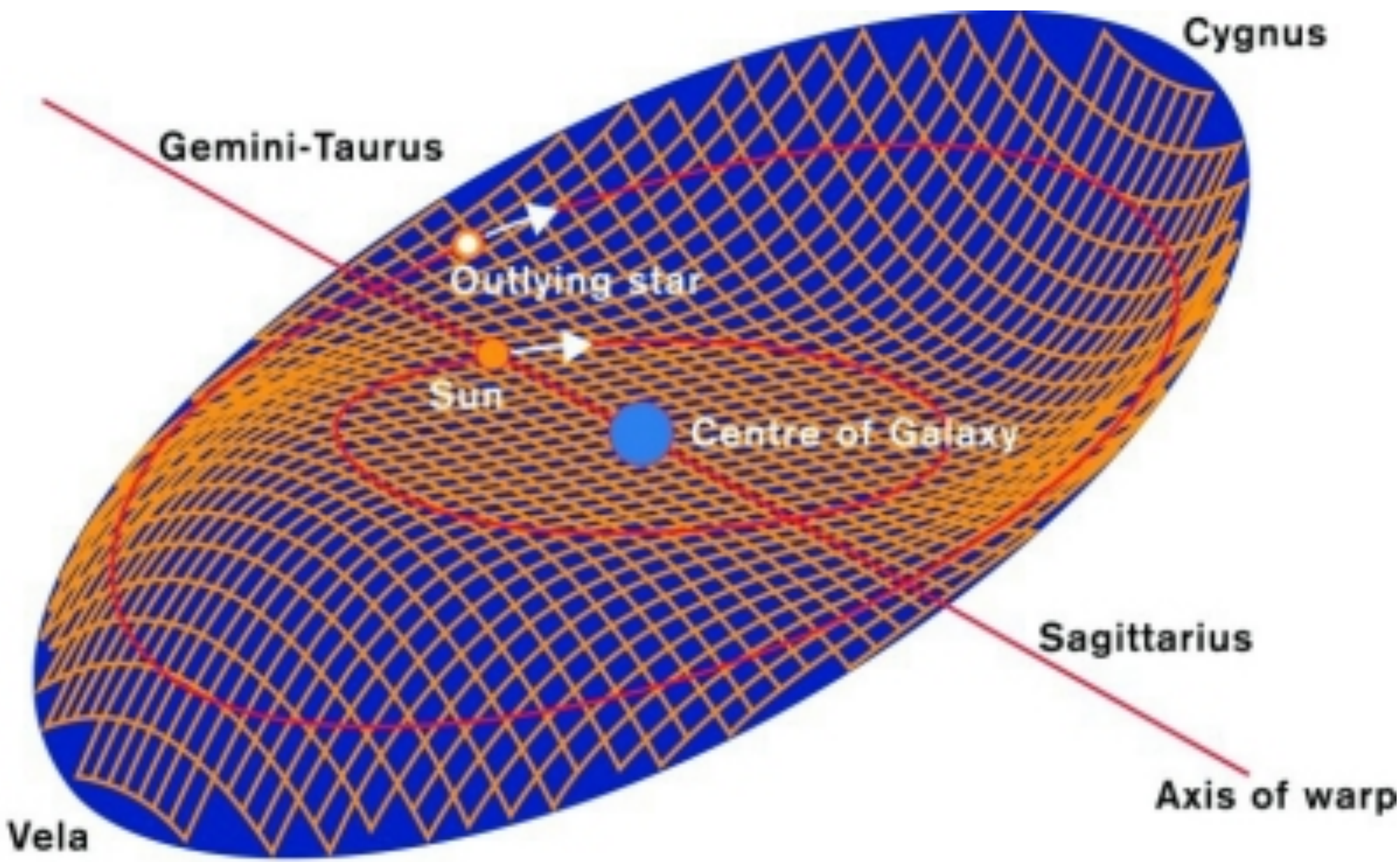
Nakanishi & Sofue 2006





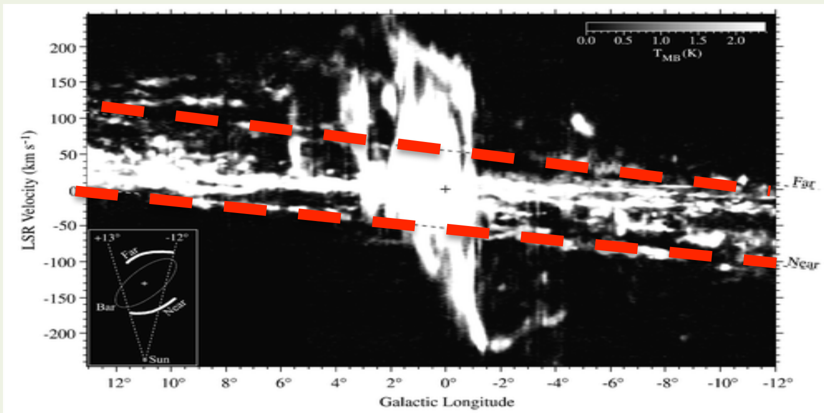


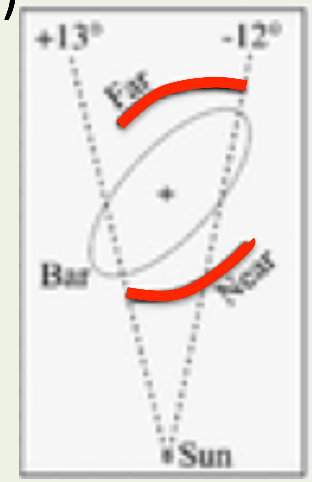
Molecular Disk is warped


Cygnus
Gemini-Taurus
Outlying star
Sun
Centre of Galaxy
Sagittarius
Axis of warp
Vela

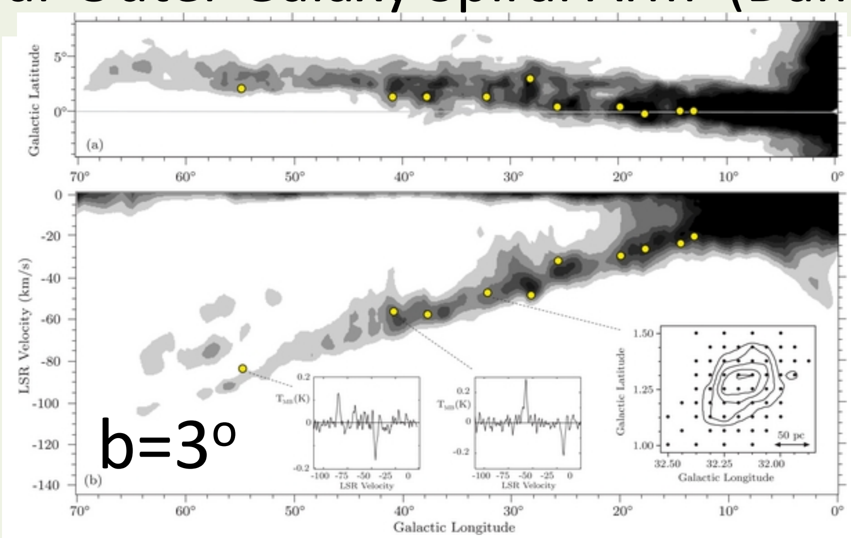
Recently Uncovered Large Scale Molecular Features

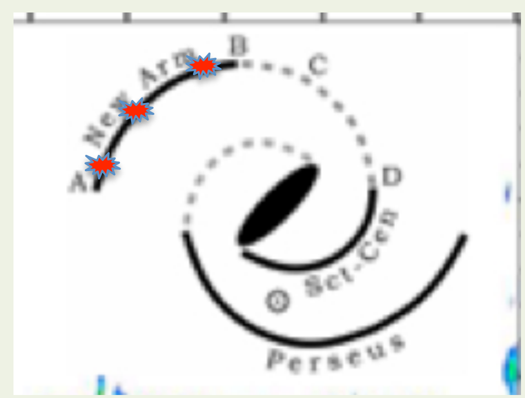
Far side 3 kpc arm (Dame & Thaddeus 2008)





Far Outer Galaxy Spiral Arm (Dame & Thaddeus 2011)



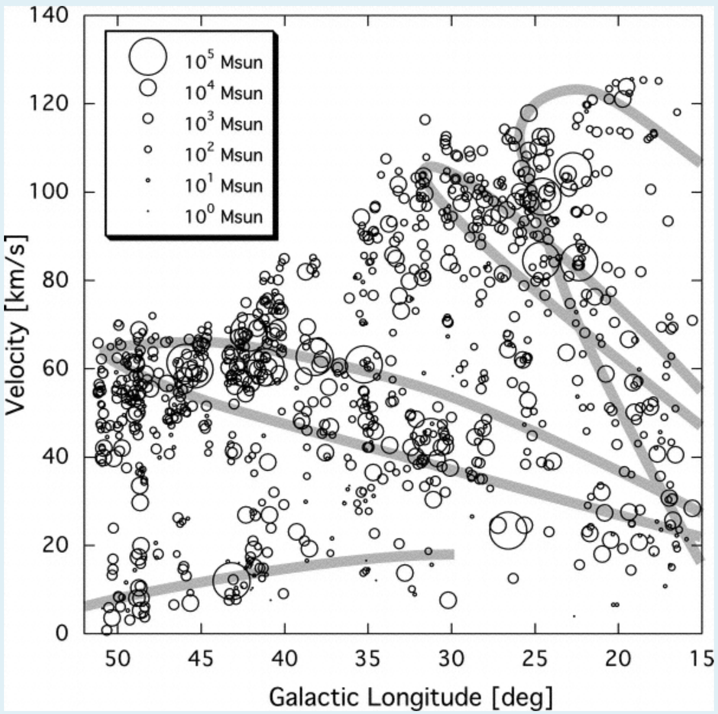


Molecular Spiral Structure

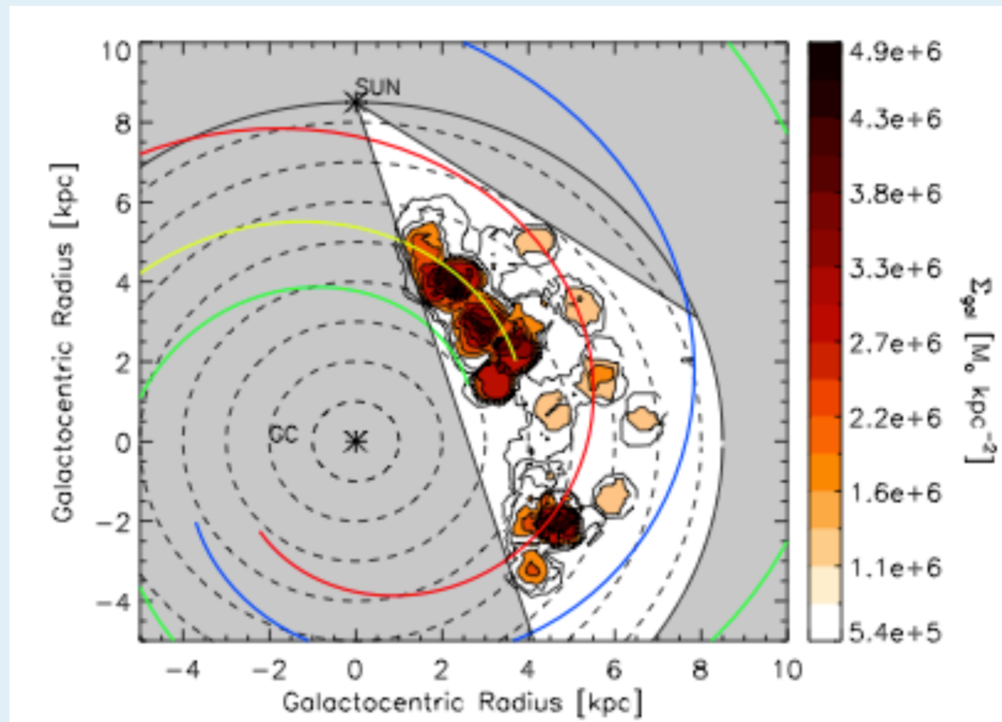
Are GMCs ***exclusively*** located in spiral arms?
Important constraint to formation and lifetime of GMCs

Analyses of BU-FCRAO Galactic Ring Survey

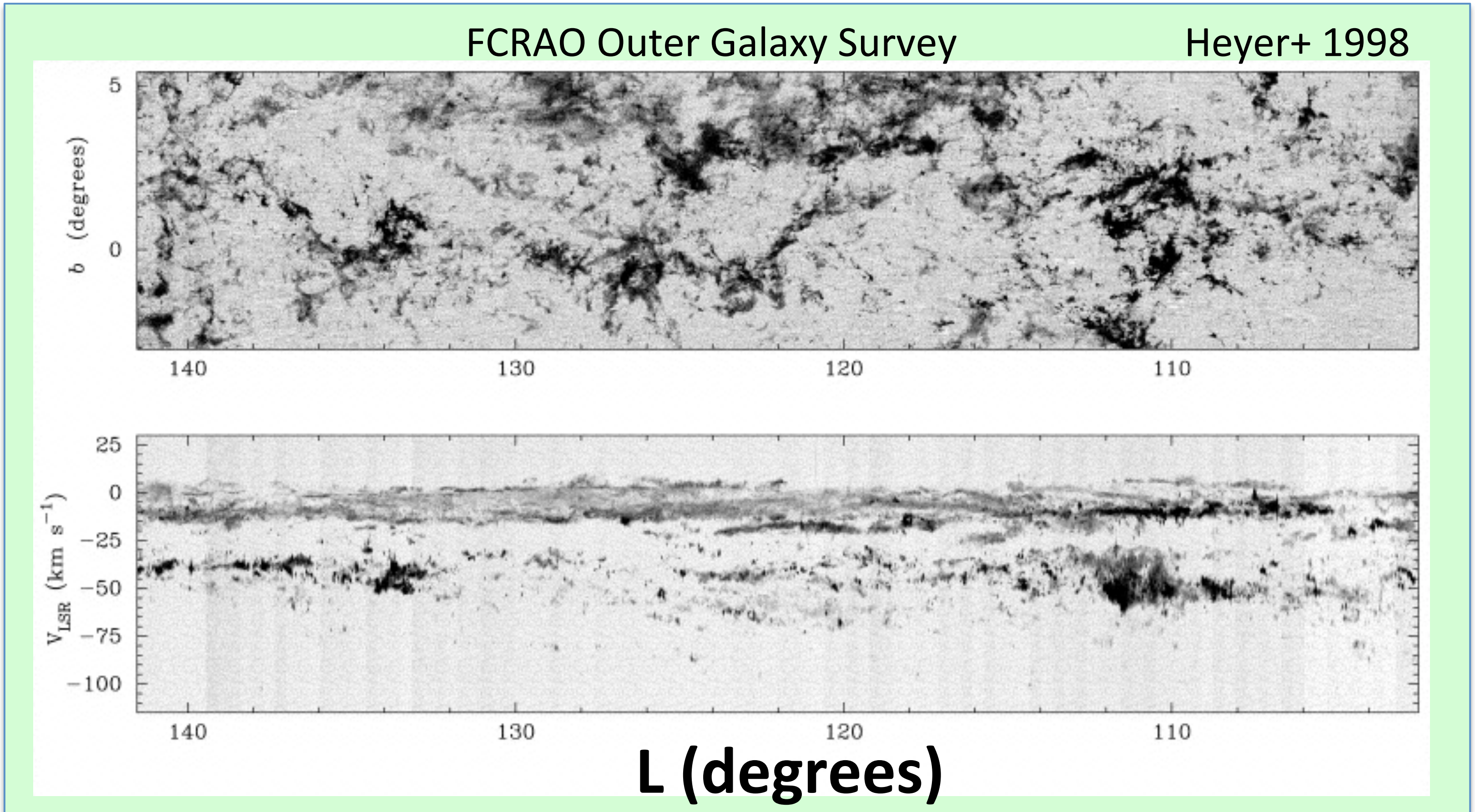
Koda+ 2006



Roman-Duval+ 2010

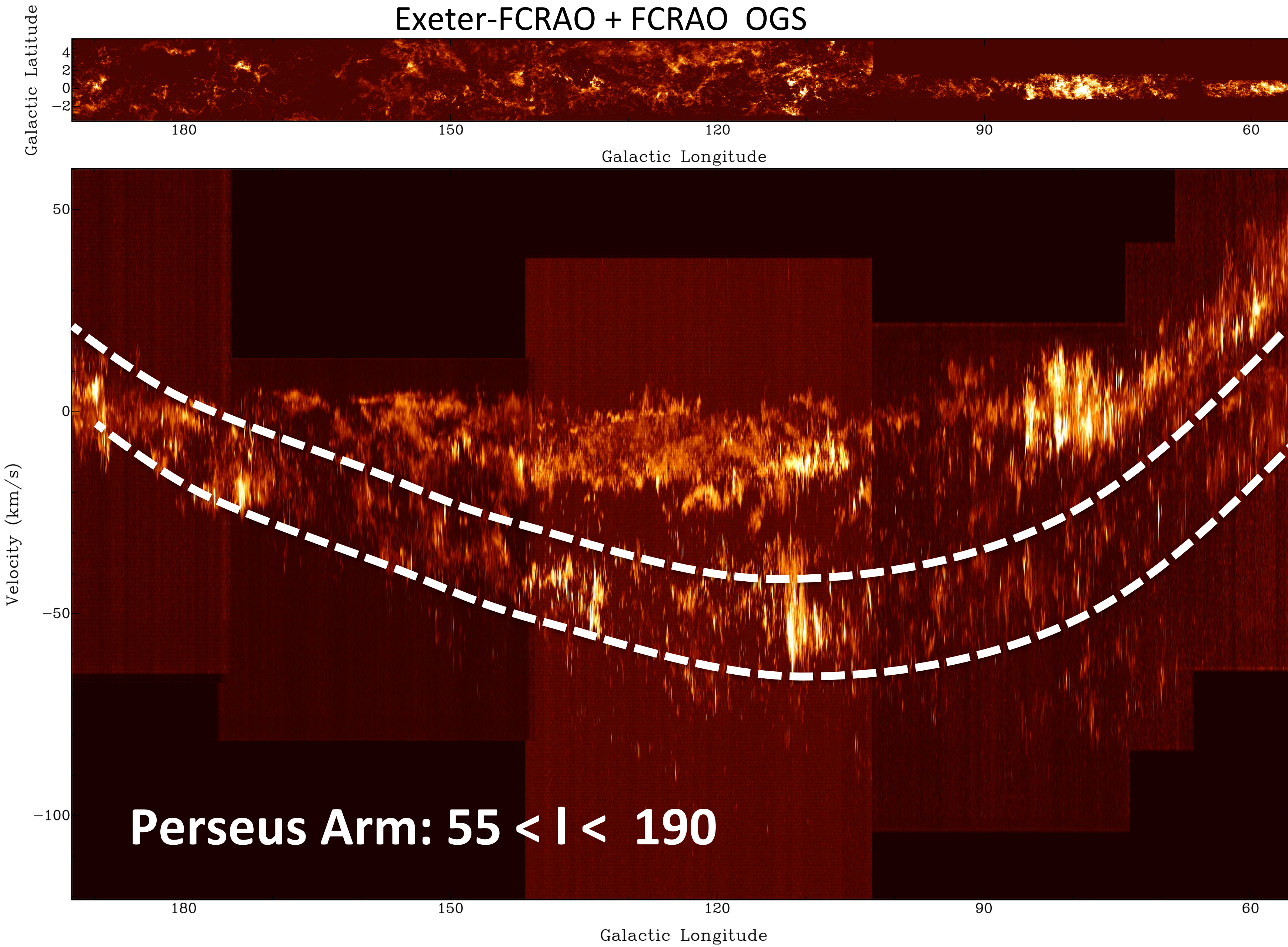


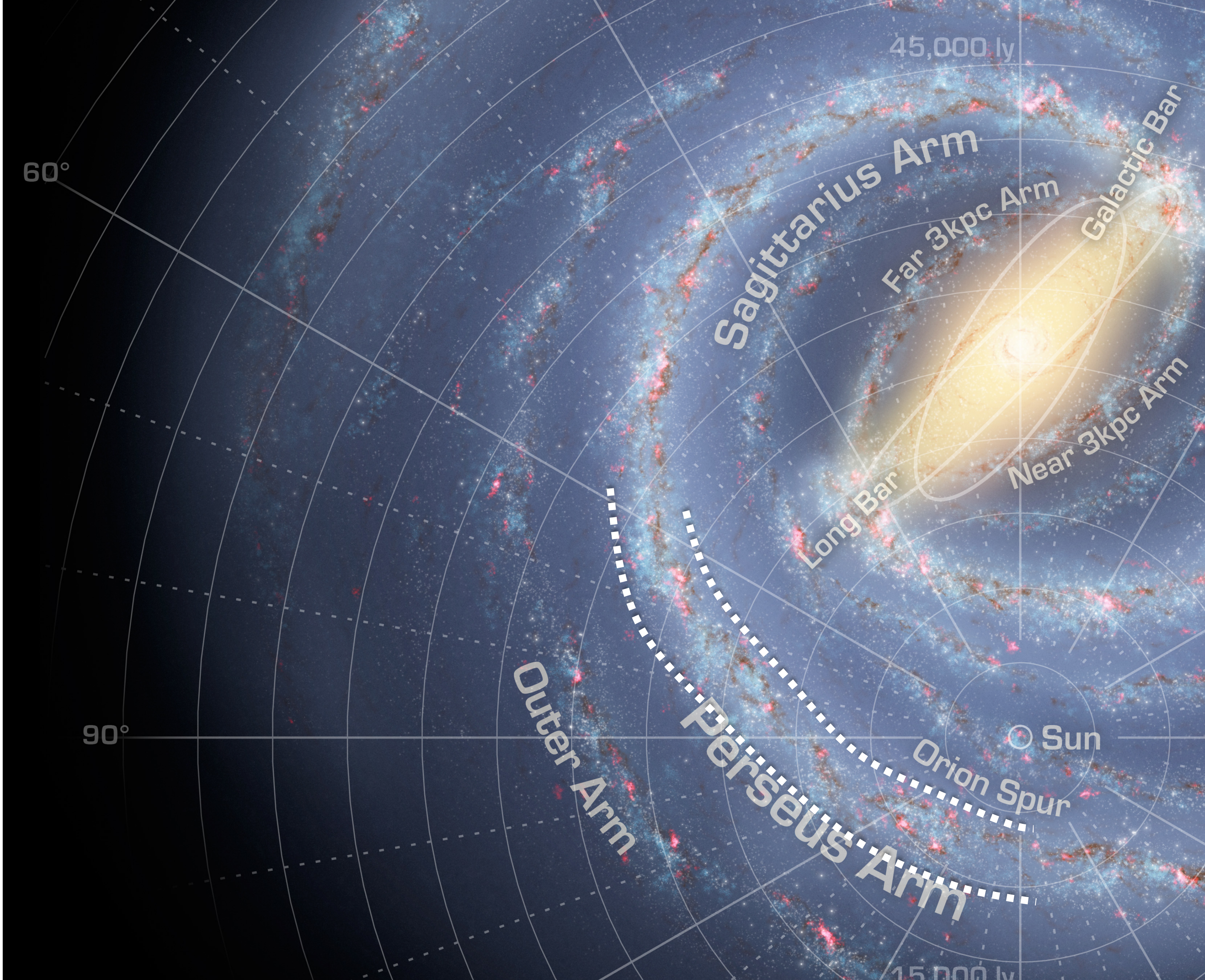
Outer Galaxy: Negligible CO emission within interarm velocity intervals

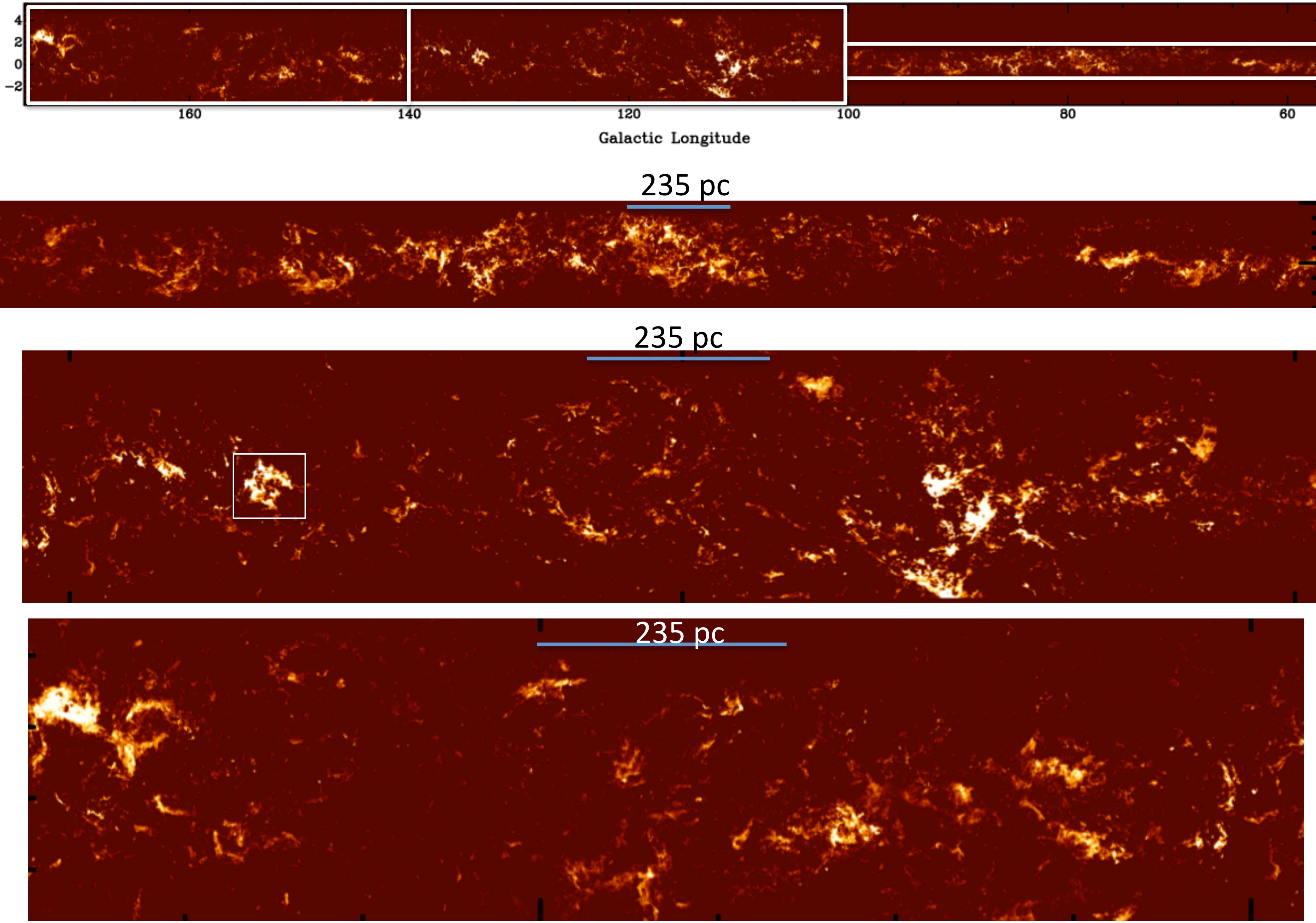


Non-circular motions are severe in 2nd quadrant
Trigonometric parallax distances are essential

Exeter-FCRAO + FCRAO OGS



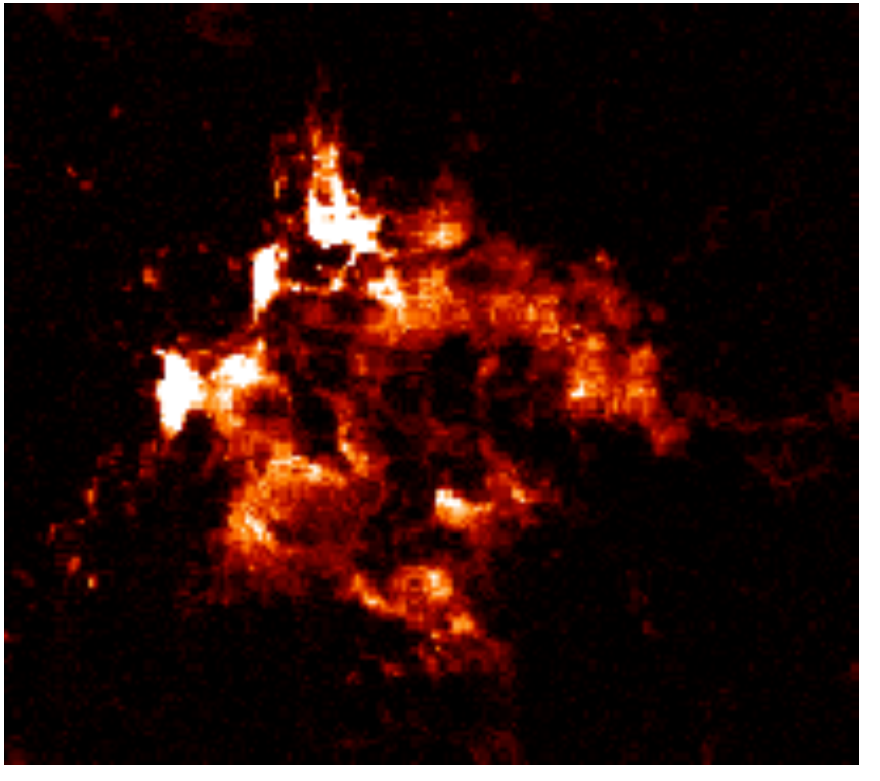

45,000 ly
60°
Sagittarius Arm
Far 3kpc Arm
Galactic Bar
Near 3kpc Arm
Long Bar
Outer Arm
Perseus Arm
90°
Sun
Orion Spur
15,000 ly


4
2
0
−2
160
140
120
100
80
60
Galactic Longitude
235 pc
235 pc
235 pc

W3 GMC: Rivera-Ingraham+ 2013

Herschel View of GMCs

- Filaments everywhere
- Illuminated surfaces

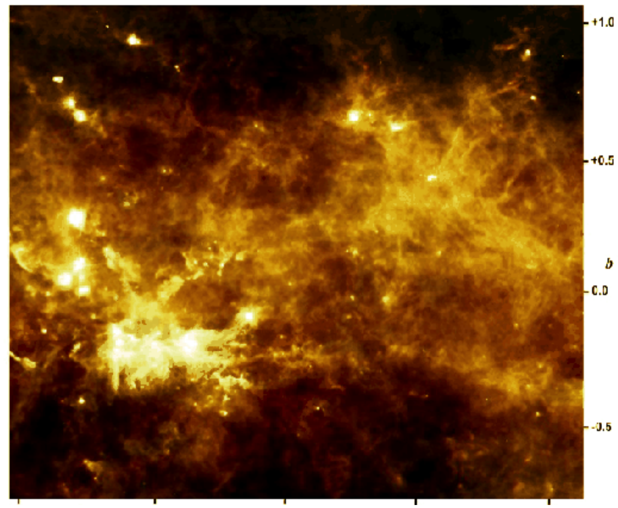


Herschel View of GMCs

- Filaments everywhere
- Illuminated surfaces

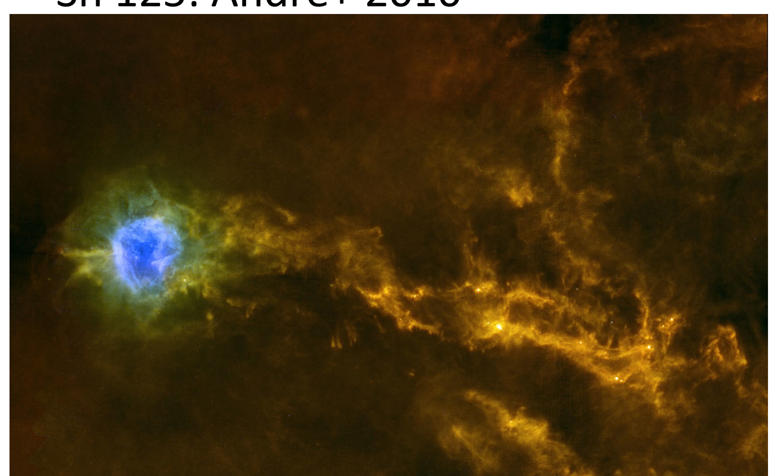
W3 GMC: Rivera-Ingraham+ 2013

G59.5: Molinari+ 2010

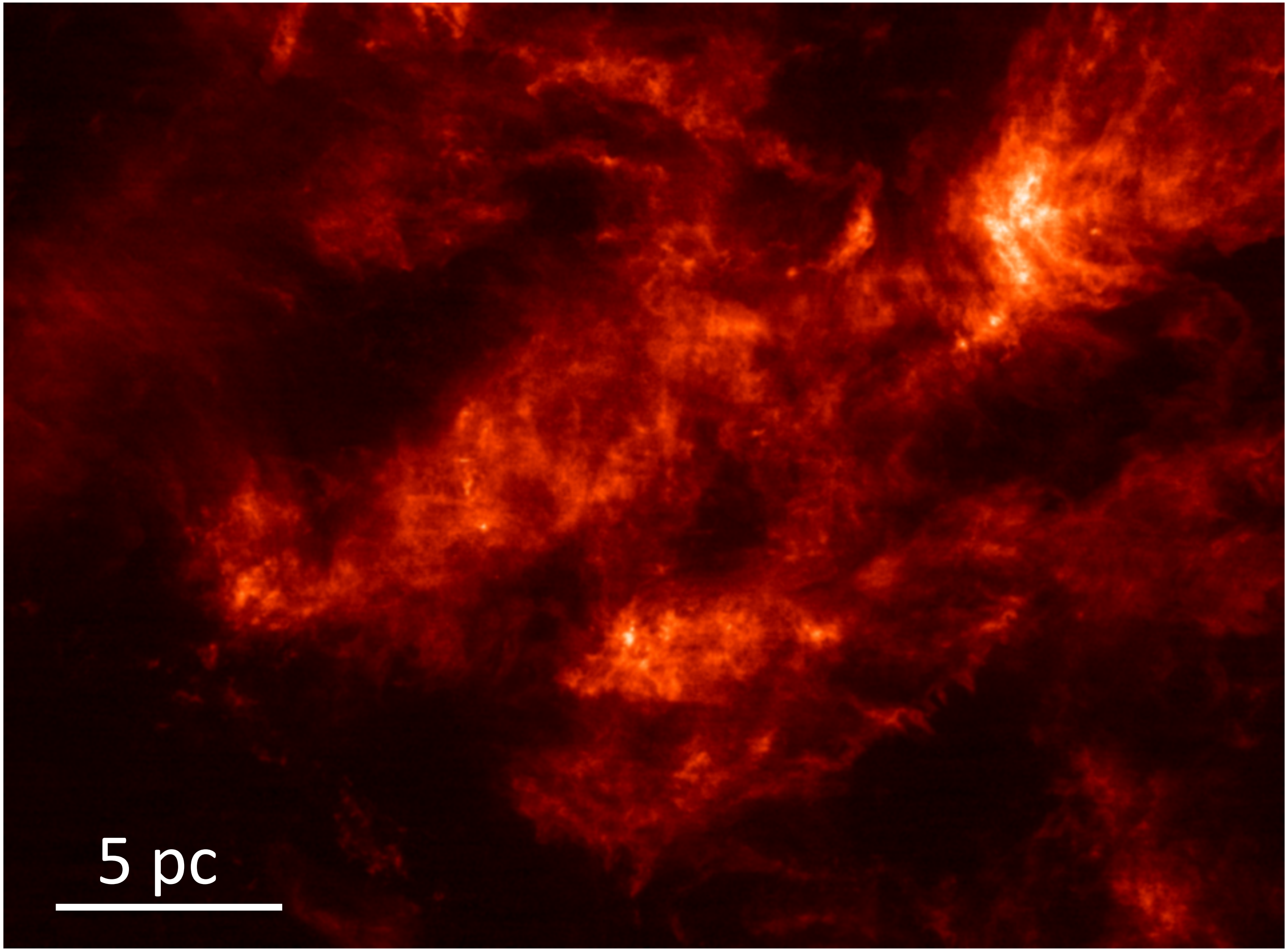


Rosette GMC: Schneider+ 2010

Sh 125: Andre+ 2010

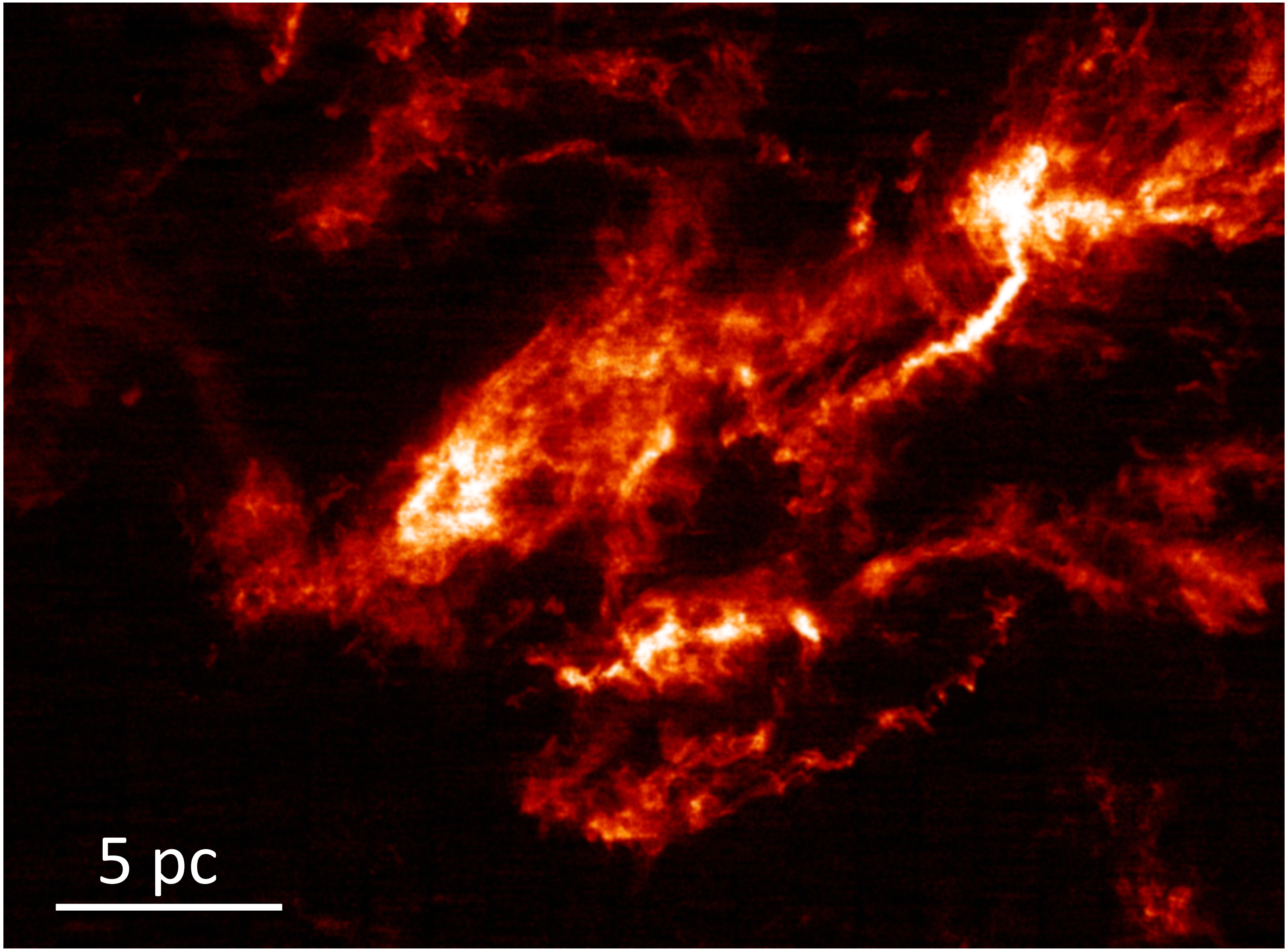


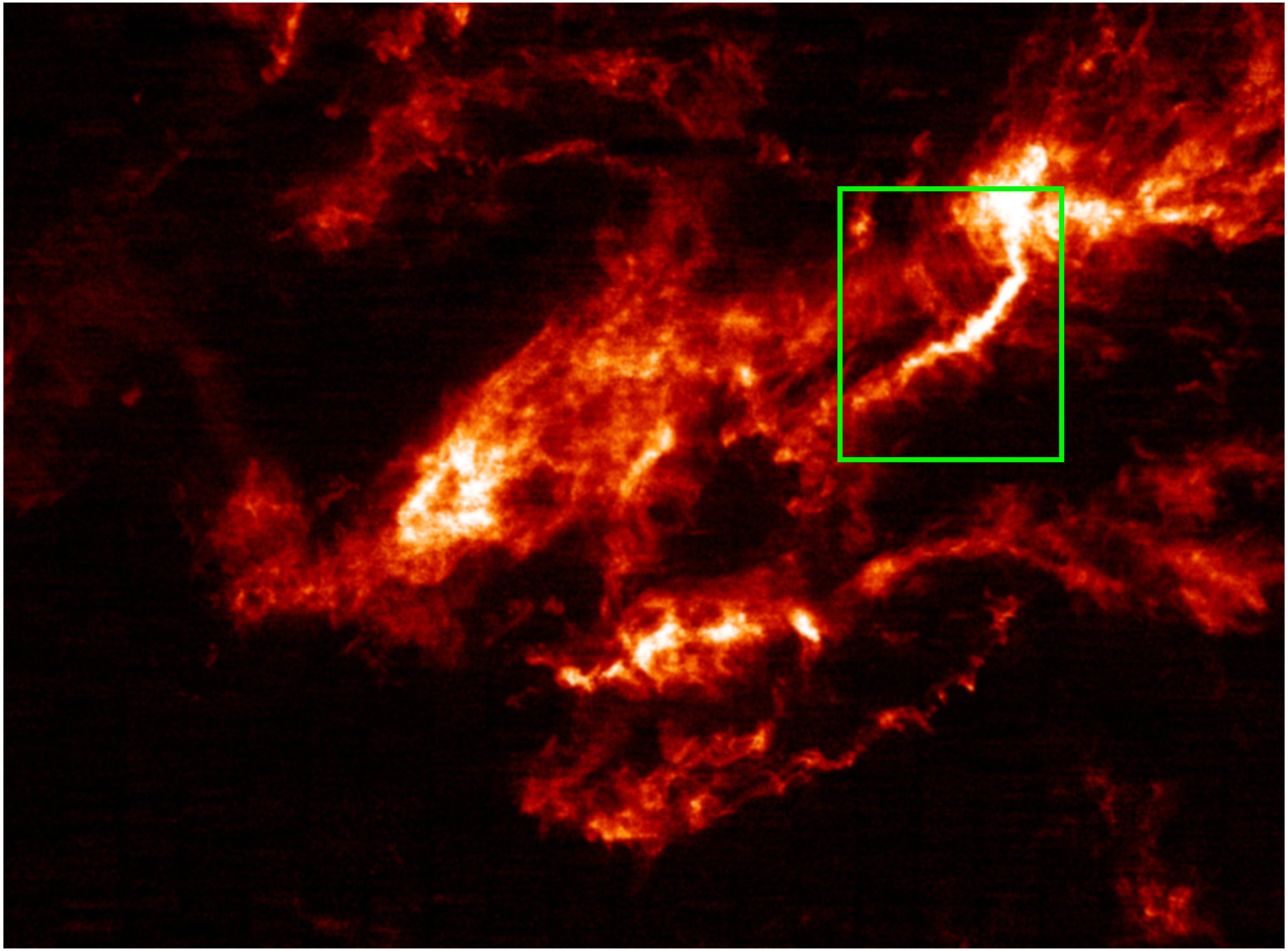
Taurus Molecular Cloud: ^{12}CO J=1-0

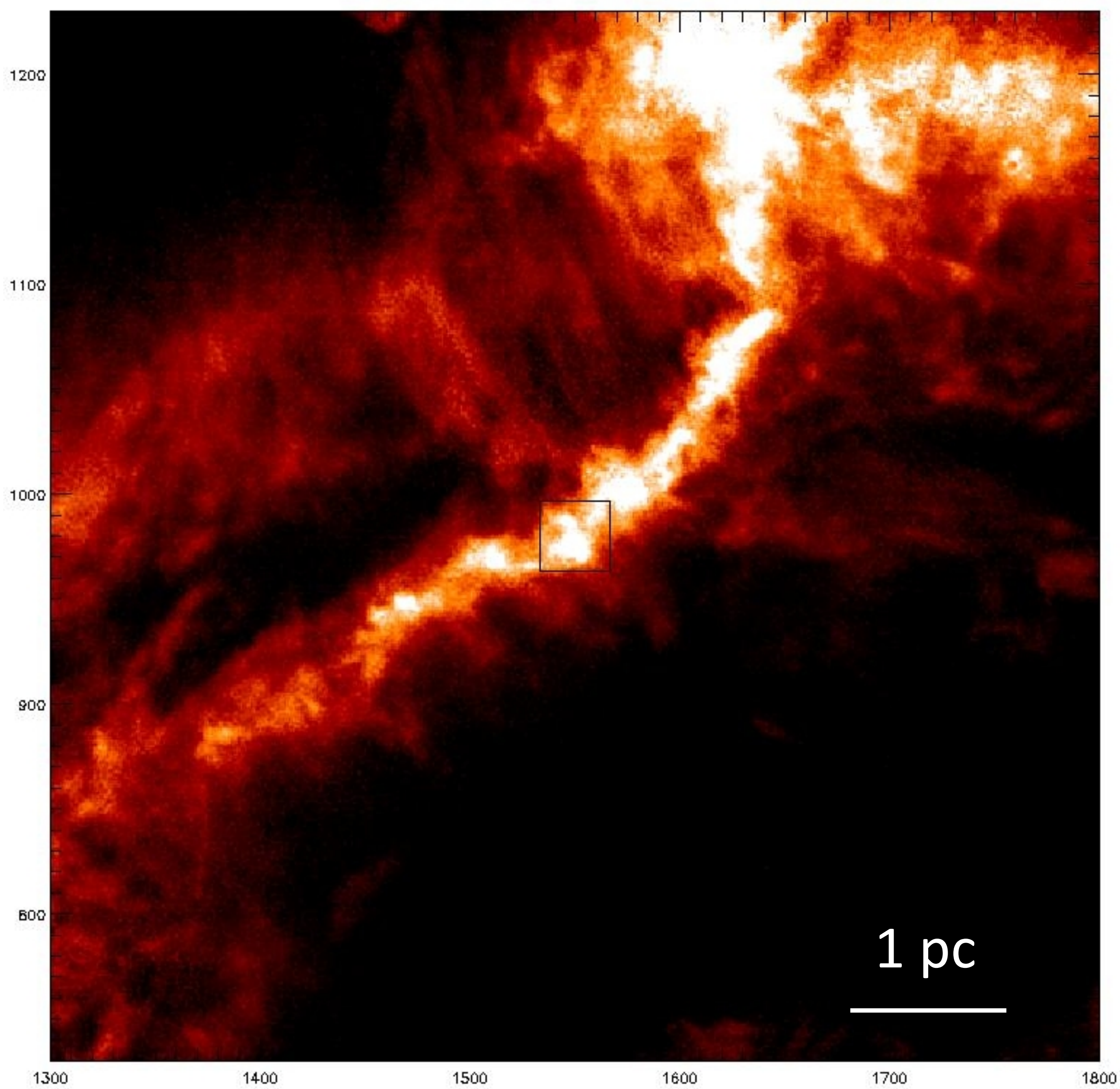


Goldsmith+ 2008; Narayanan+ 2008

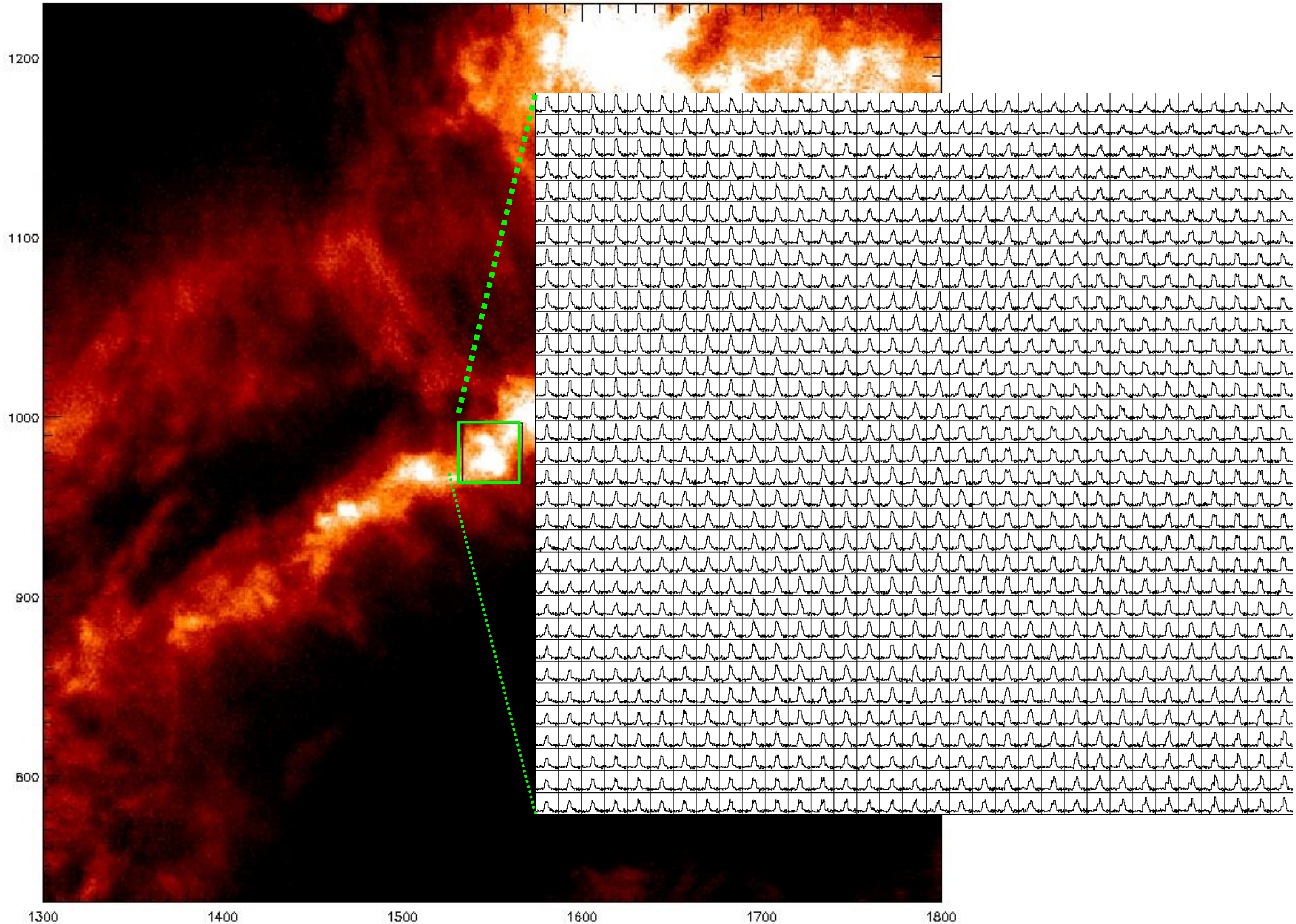
Taurus Molecular Cloud: ^{13}CO J=1-0



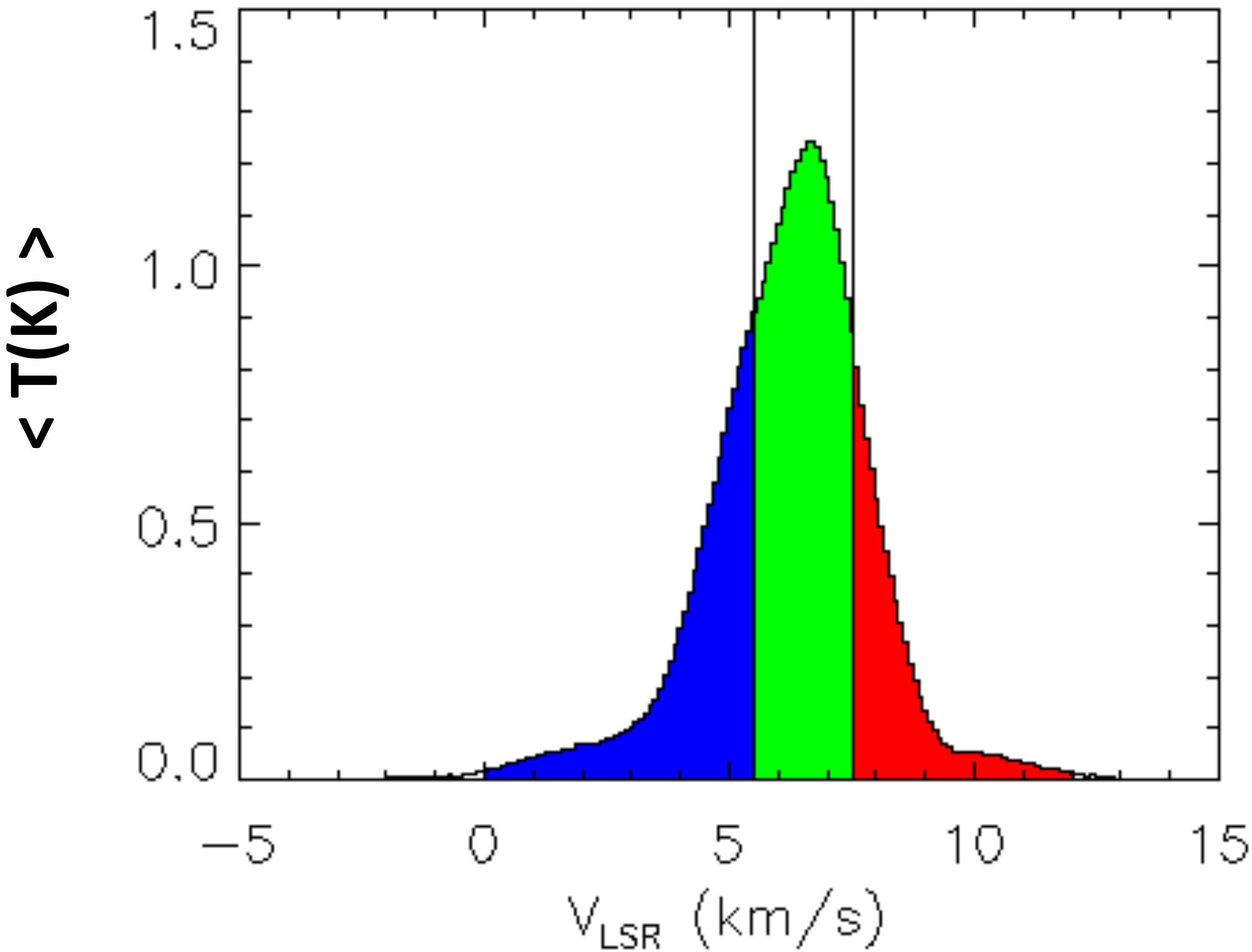




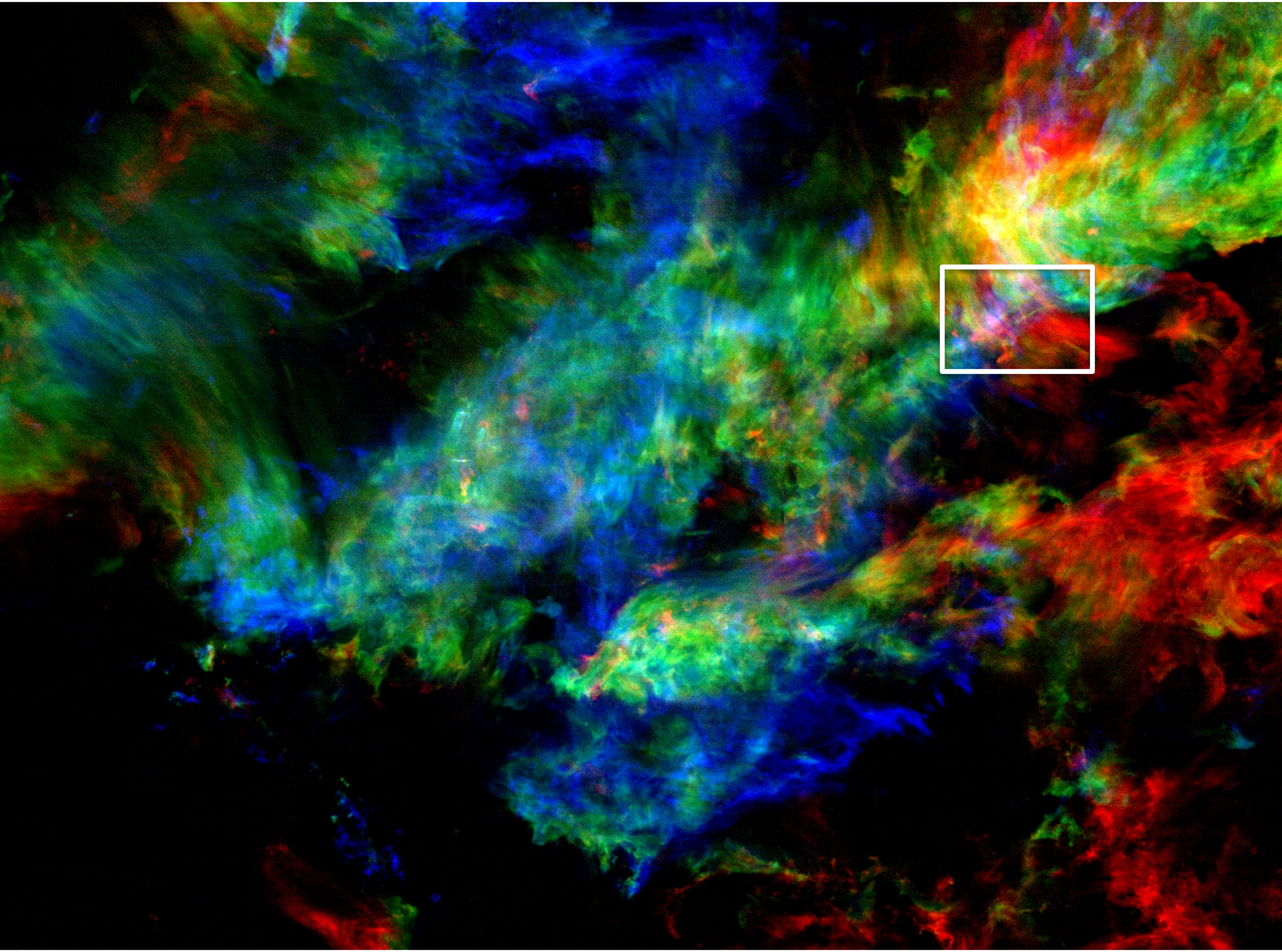
1200
1100
1000
900
800
1300
1400
1500
1600
1700
1800
1 pc

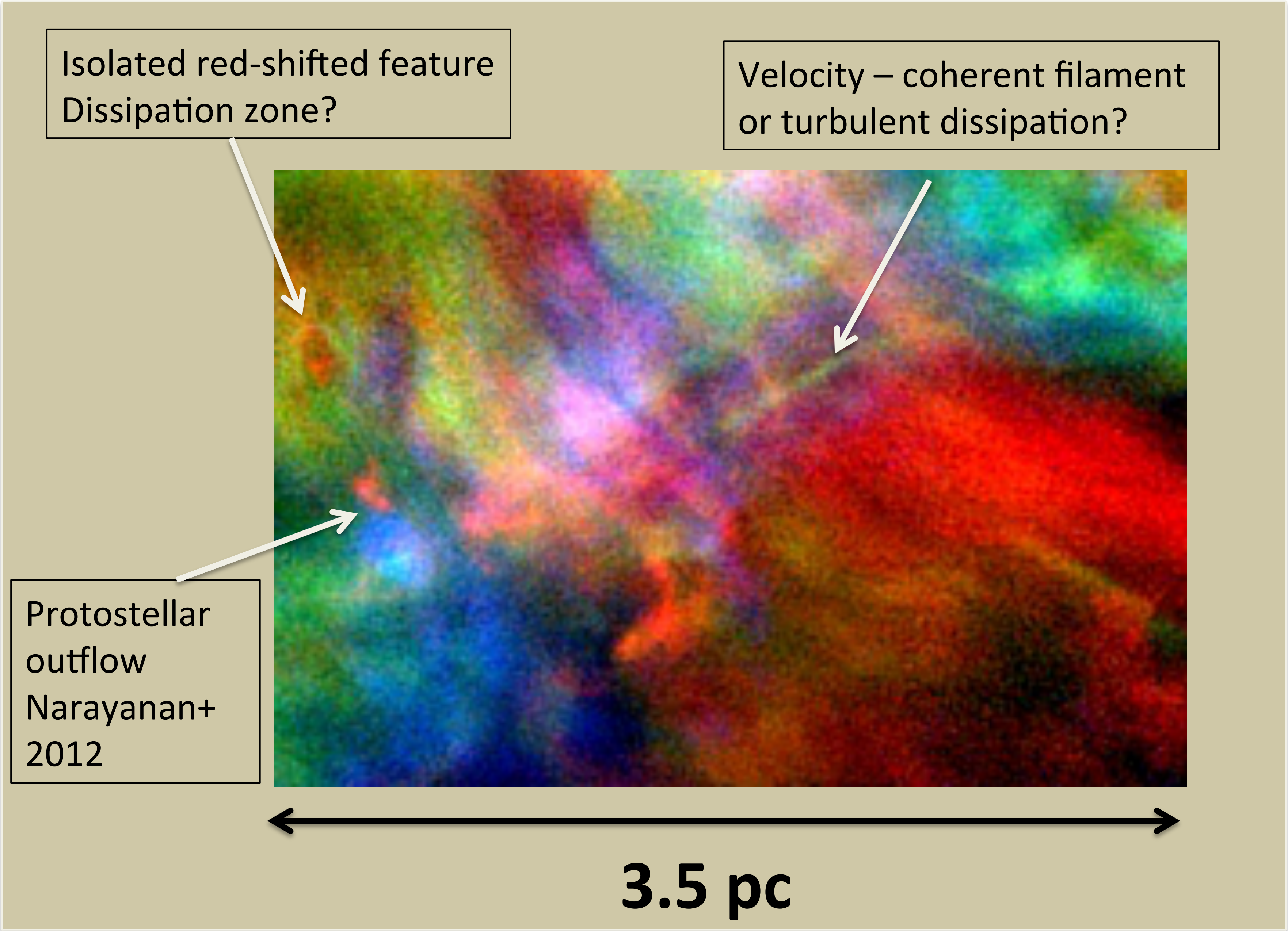


1200
1100
1000
900
800
1300
1400
1500
1600
1700
1800

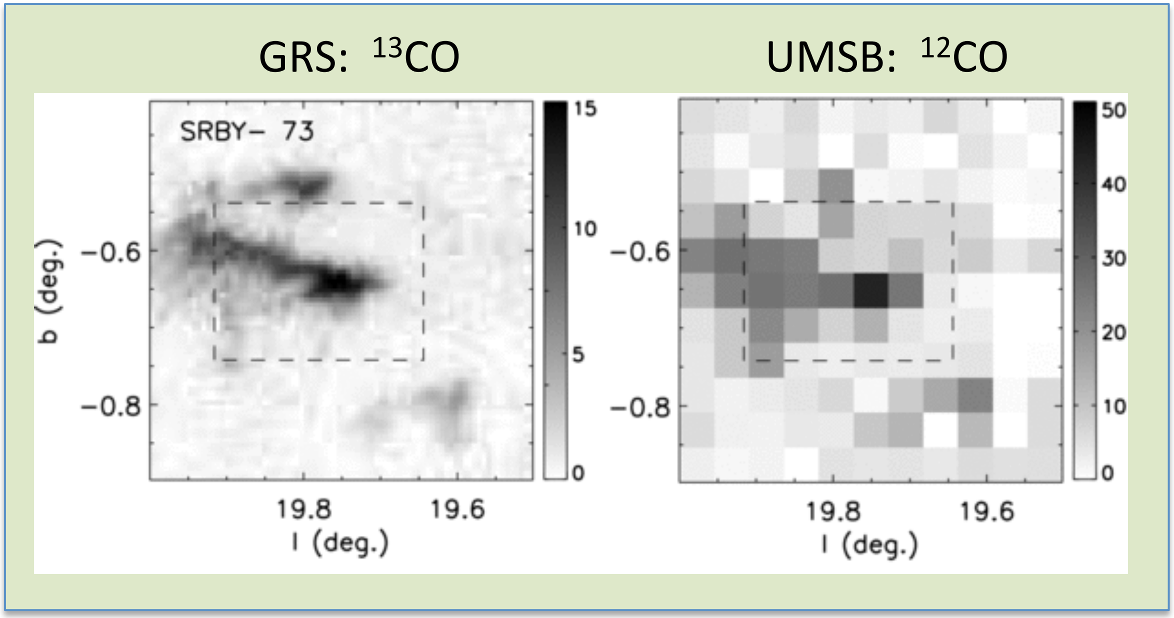


1.5
1.0
0.5
0.0
< T(K) >
−5
0
5
10
15
V_LSR (km/s)




Isolated red-shifted feature
Dissipation zone?
Velocity – coherent filament
or turbulent dissipation?
Protostellar
outflow
Narayanan+
2012
3.5 pc

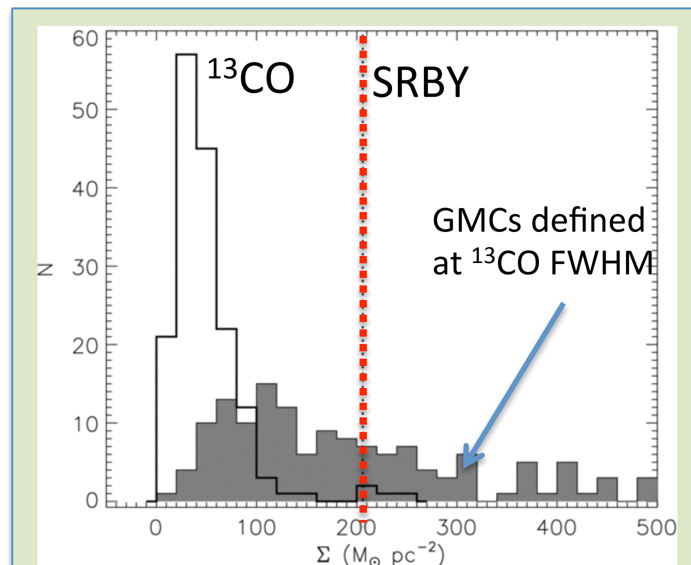
Heyer+ 2009: Re-analysis of Solomon+ 1987 GMC catalog



Measured:
$<\Sigma_{GMC}> = 40\ M_{sun}/pc^2$

^{13}CO Abundance variations in GMC envelope

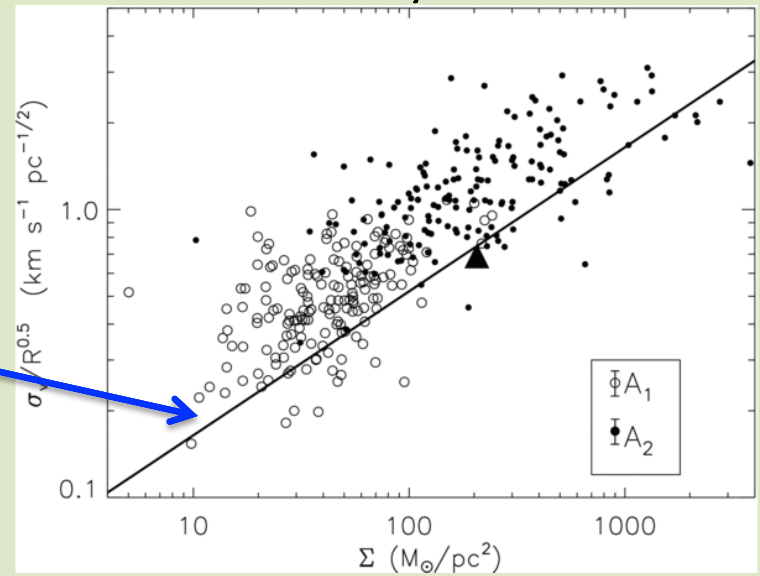
$<\Sigma_{GMC}>_{Biased} = 80\text{-}100\ M_{sun}/pc^2$



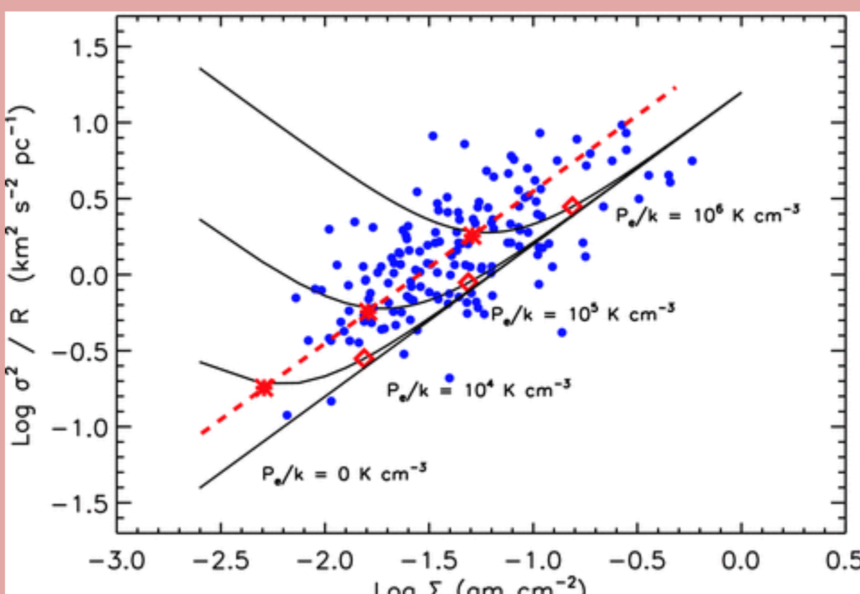
Self-gravitating GMC in virial equilibrium

$$\sigma_v/R^{1/2} = (\pi G\Sigma/5)^{1/2}$$

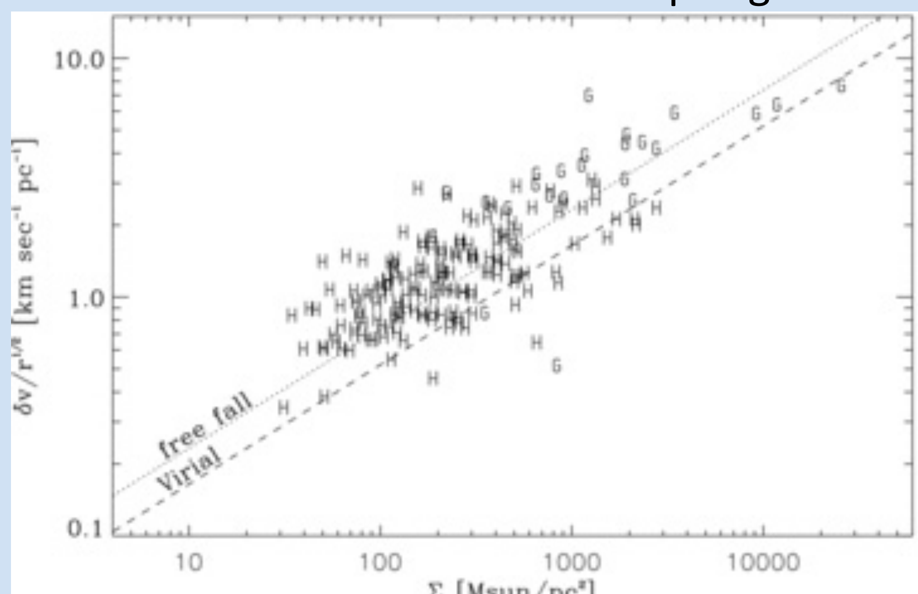
Heyer+ 2009



Field+ 2011: Pressure confined GMCs



Ballesteros-Paredes+ 2011: Collapsing GMCs



Dense Gas Mass Fraction

Newborn stars and clusters form in the dense (> 10^4 cm^{-3}), localized regions within GMCs

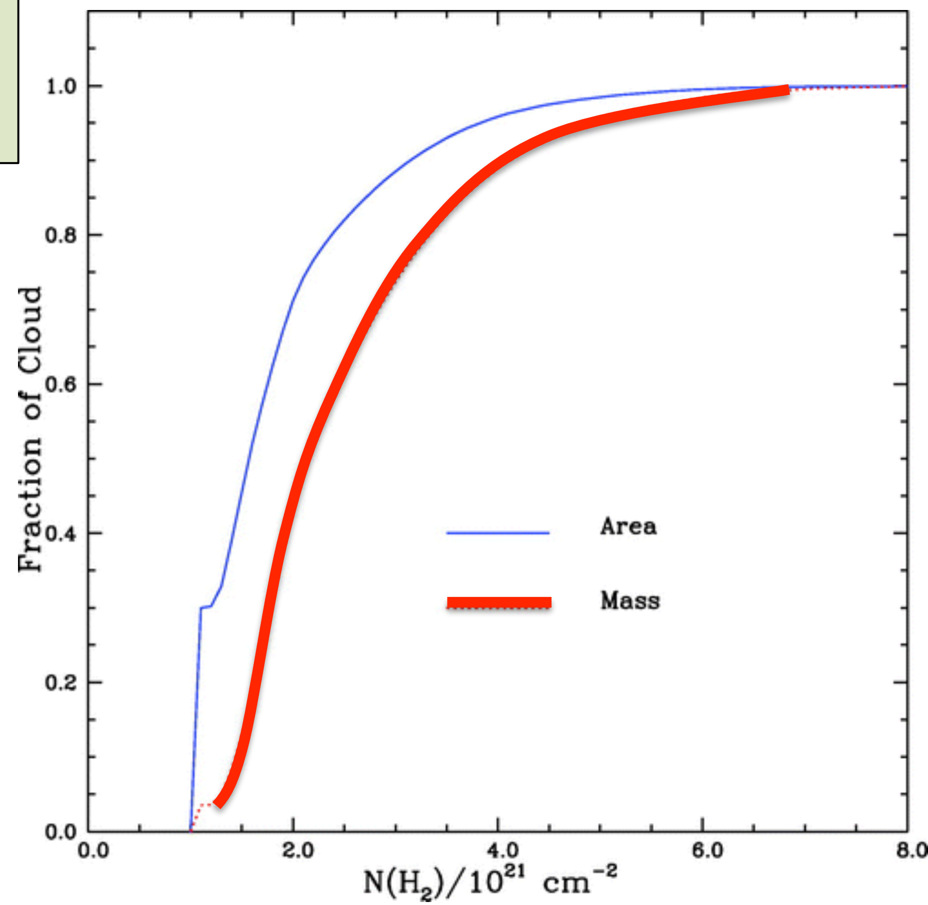
Heiderman+ 2010; Lada+ 2012; Kainulainen+ 2009, 2013

$$SFR \;\alpha\; M_{dense} = f_{DG}\, M_{GMC}$$

$$SFE \;\alpha\; f_{DG}$$

Value of f_{DG}?

Taurus: Goldsmith+ 2008



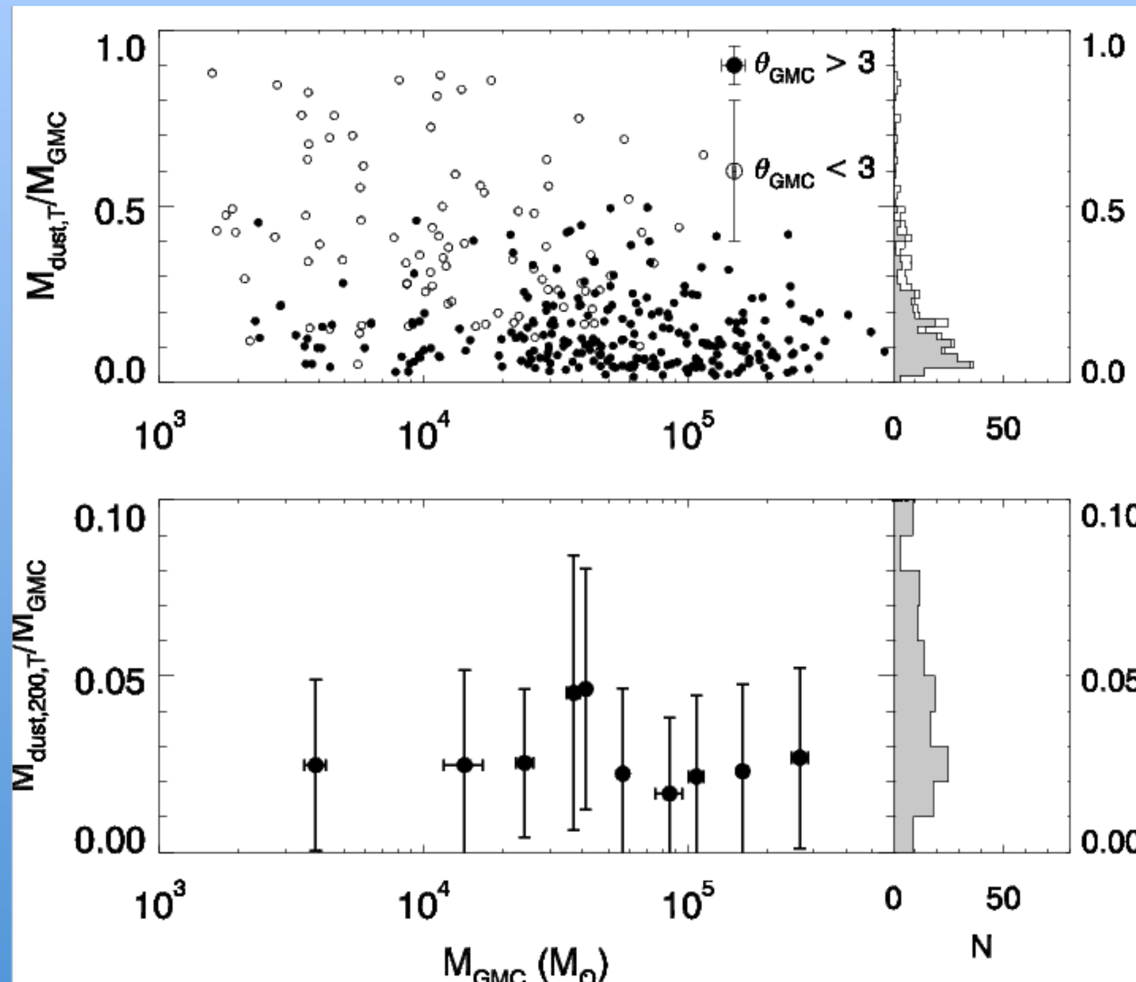
Bolocam Galactic Plane Survey 1.1mm dust sources to measure mass of dense gas

FCRAO ^{13}CO Surveys to derive M_{GMC}

High column density fragments of clouds account for < 2-3% of the GMC mass

f_{DG} is independent of GMC mass

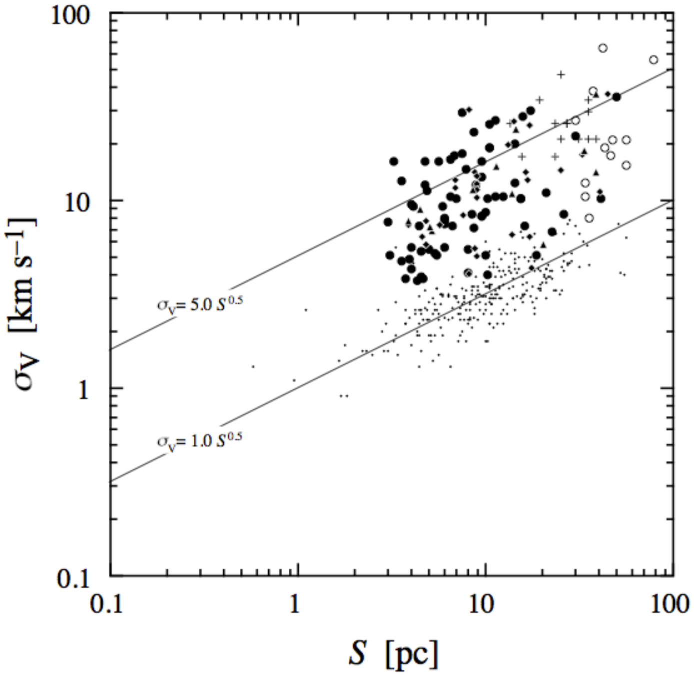
Battisti & Heyer 2013



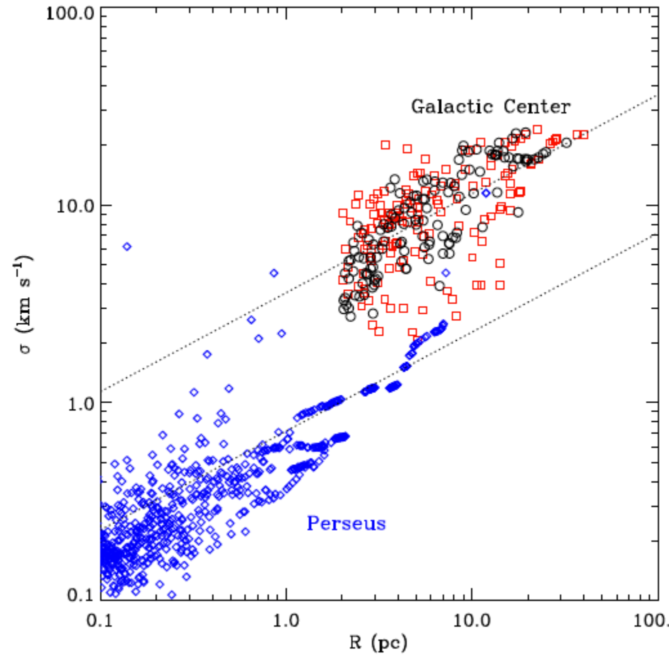
Key Sequential Steps to Star Formation

- Formation of GMCs from the diffuse, atomic medium? ***Challenging from a Galactic perspective***

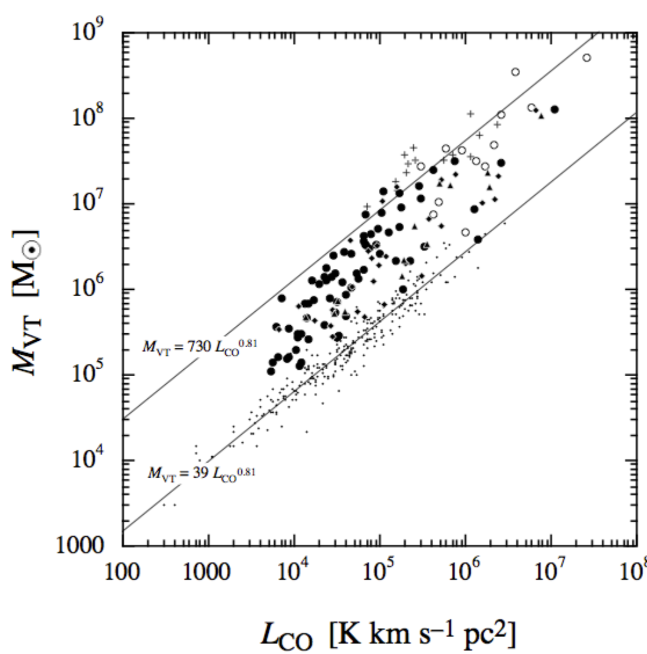
- Development of dense, gravitationally unstable fragments from the low density substrate of the GMC? ***Consider kinematics of low density gas with respect to high density fragments***



100
10
1
0.1
0.1
1
10
100
σ_V [km s^{-1}]
S [pc]
$\sigma_V = 5.0\, S^{0.5}$
$\sigma_V = 1.0\, S^{0.5}$



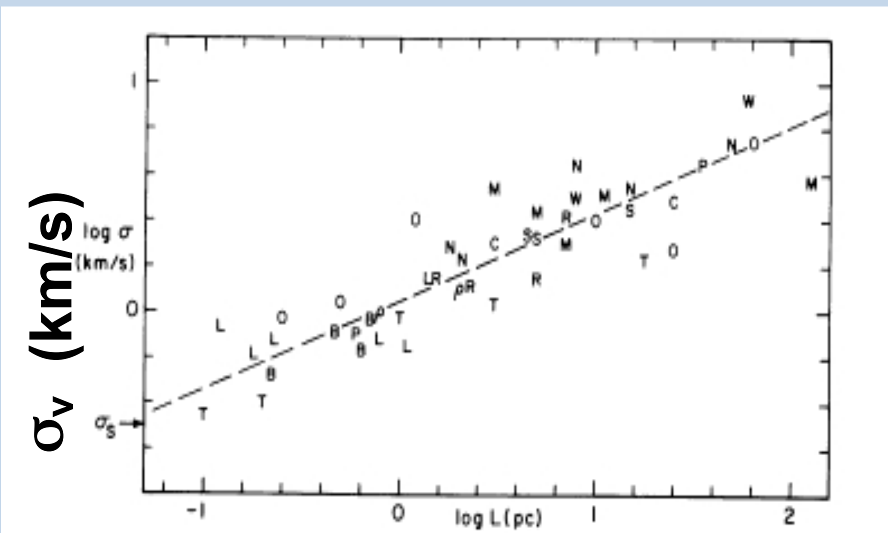
100.0
10.0
1.0
0.1
0.1
1.0
10.0
100.0
Galactic Center
Perseus
σ (km s^{-1})
R (pc)



10^9
10^8
10^7
10^6
10^5
10^4
1000
100
1000
10^4
10^5
10^6
10^7
10^8
M_{VT} [M$_\odot$]
L_{CO} [K km s^{-1} pc2]
$M_{VT} = 730\, L_{CO}^{0.81}$
$M_{VT} = 39\, L_{CO}^{0.81}$

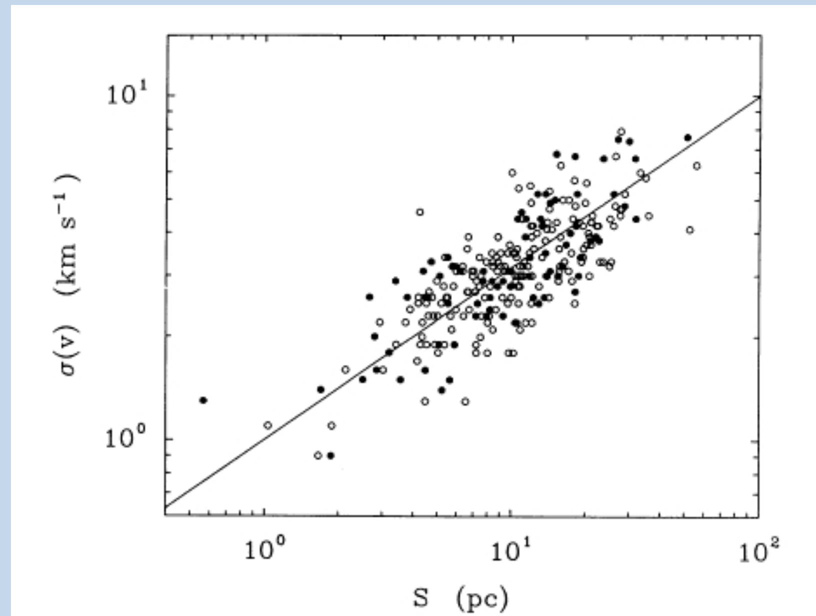
Size-velocity dispersion relationship

Larson (1981)



Size (pc)

Solomon etal (1987)



“Common hierarchy of interstellar turbulent motions”

Velocity Spectrum/Structure Function

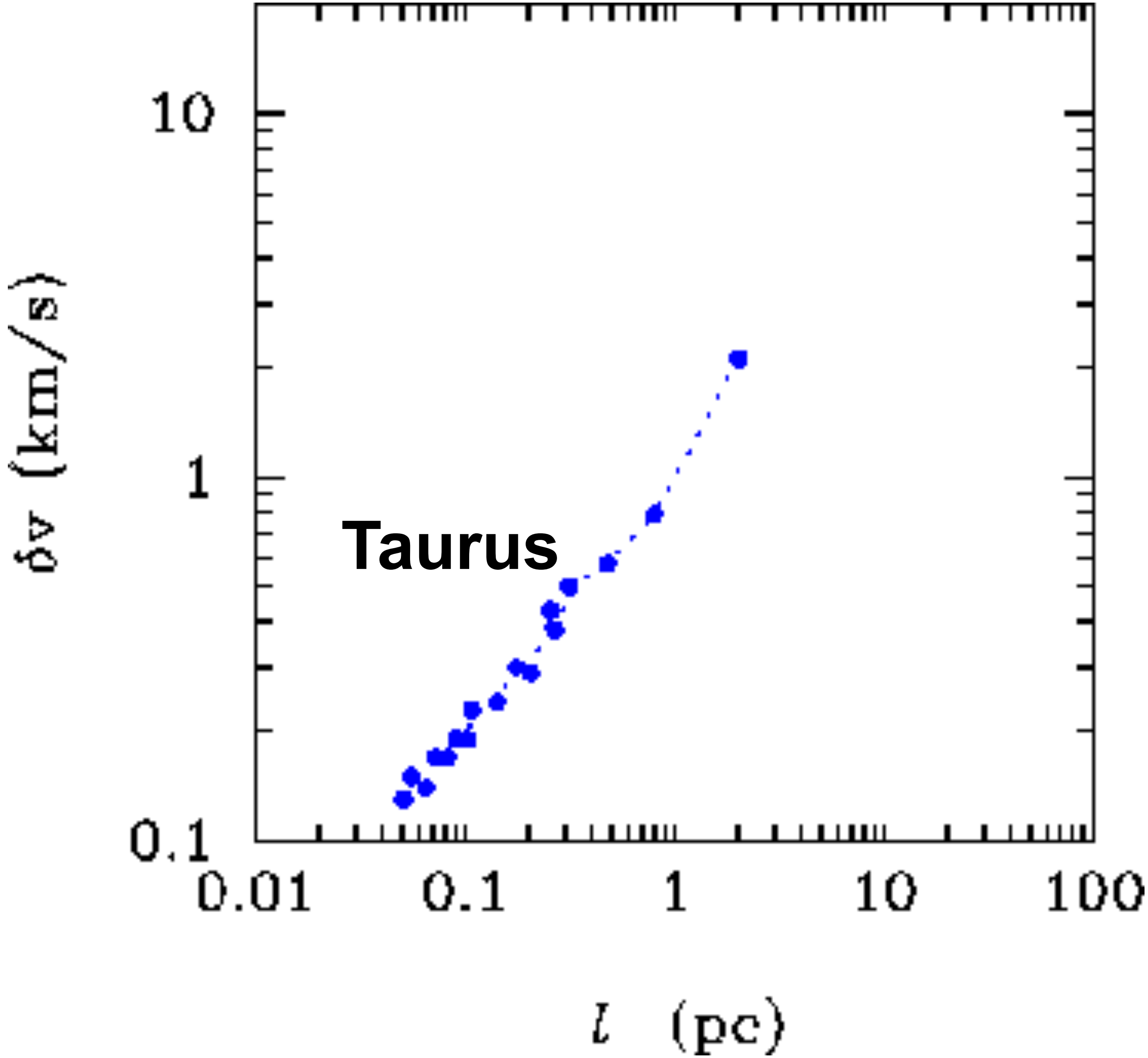
$$S_p(\Delta x) = <|v(x) - v(x+\Delta x)|^p> \sim \Delta x^{\zeta(p)}$$

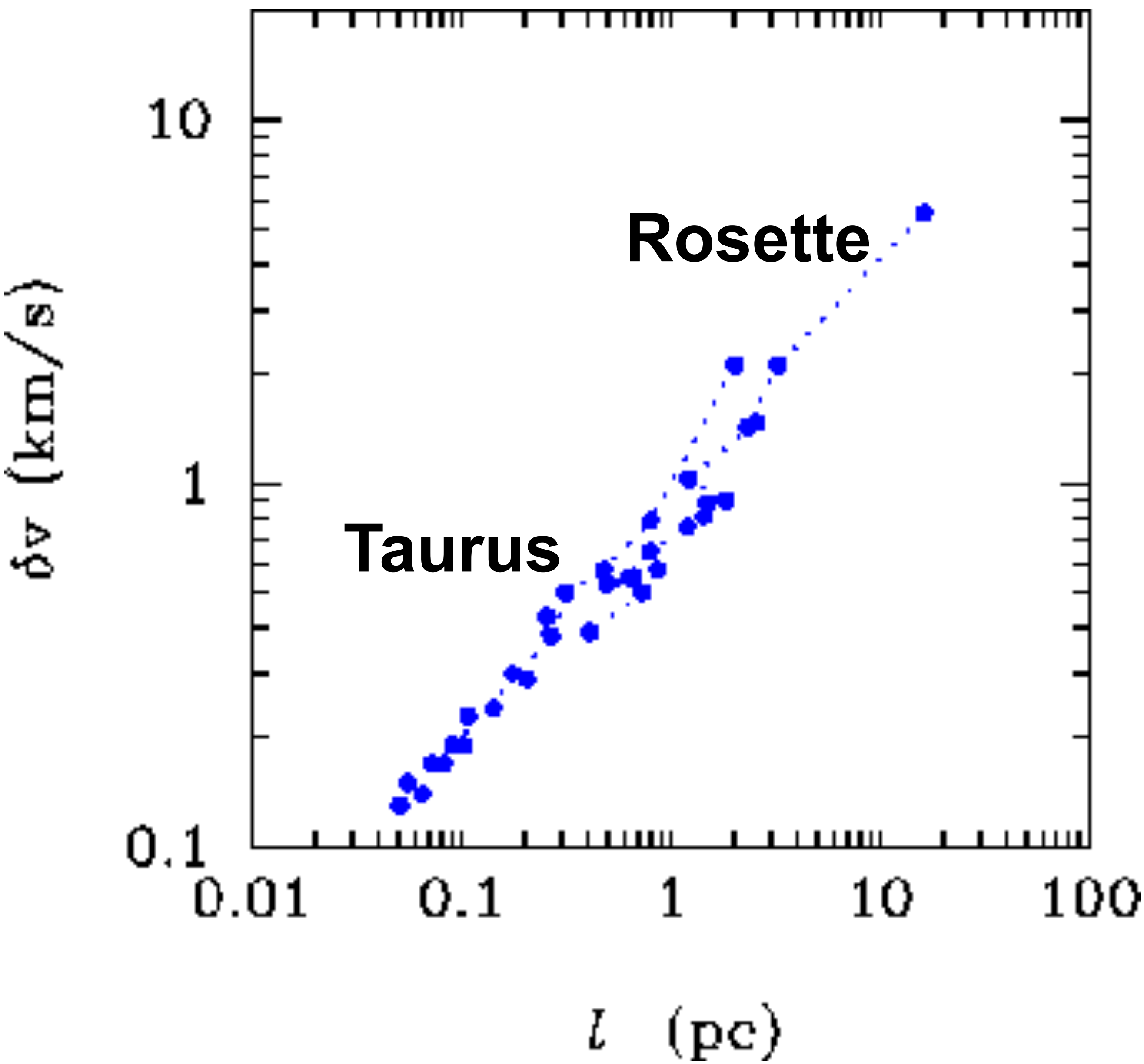
$$\delta v = v_0 \, (\Delta x)^{\gamma(p)} \qquad \gamma(p)=\zeta(p)/p$$

V_0 = amplitude of velocity fluctuations at fixed scale
γ = measures degree of spatial correlation

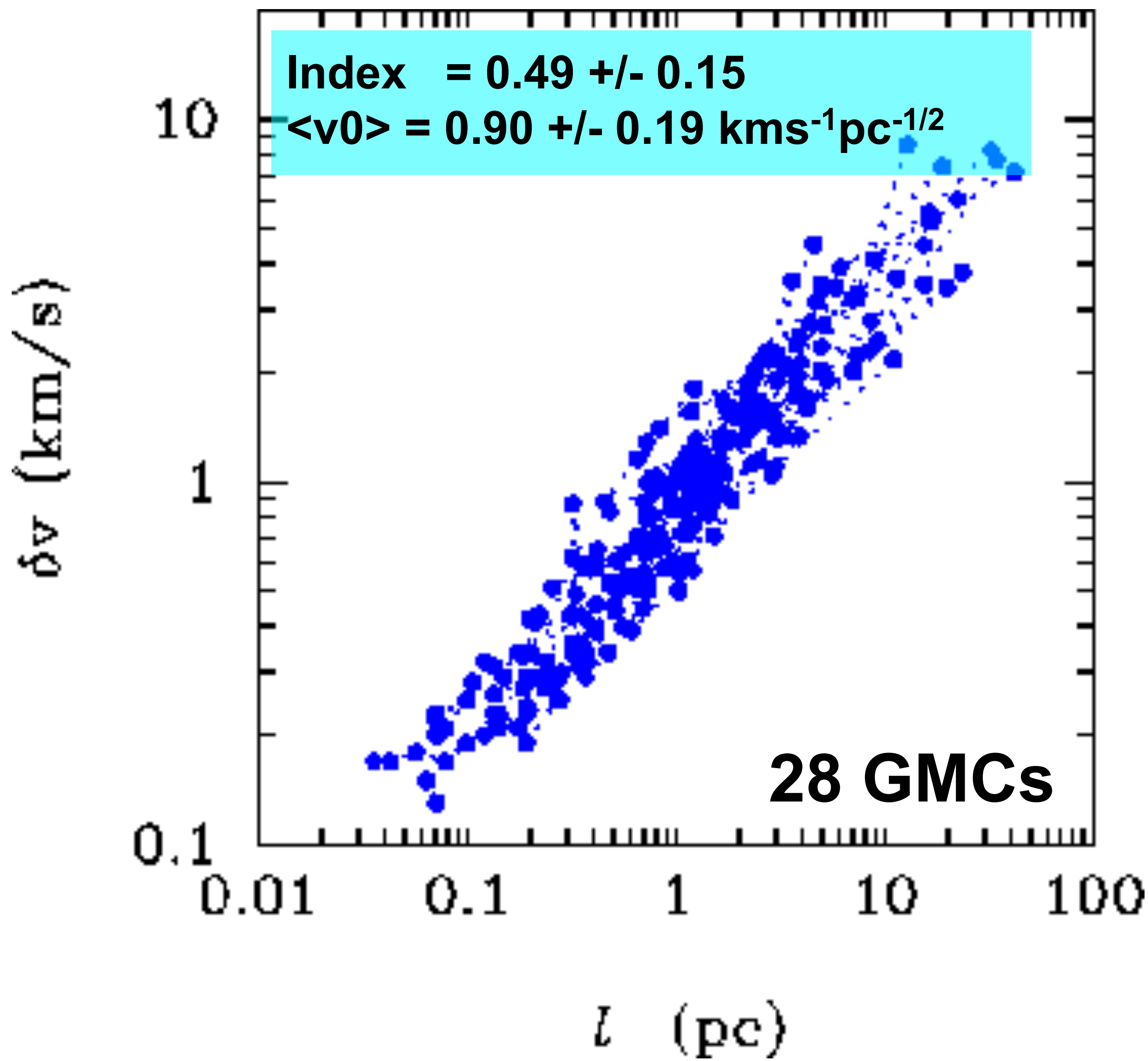
Micro-turbulence:	$\gamma << 1$
MHD Turbulence:	$\gamma = 1/$
Kolmogorov:	$\gamma = 1/3$
Supersonic/Alfvenic:	$\gamma = 1/2$

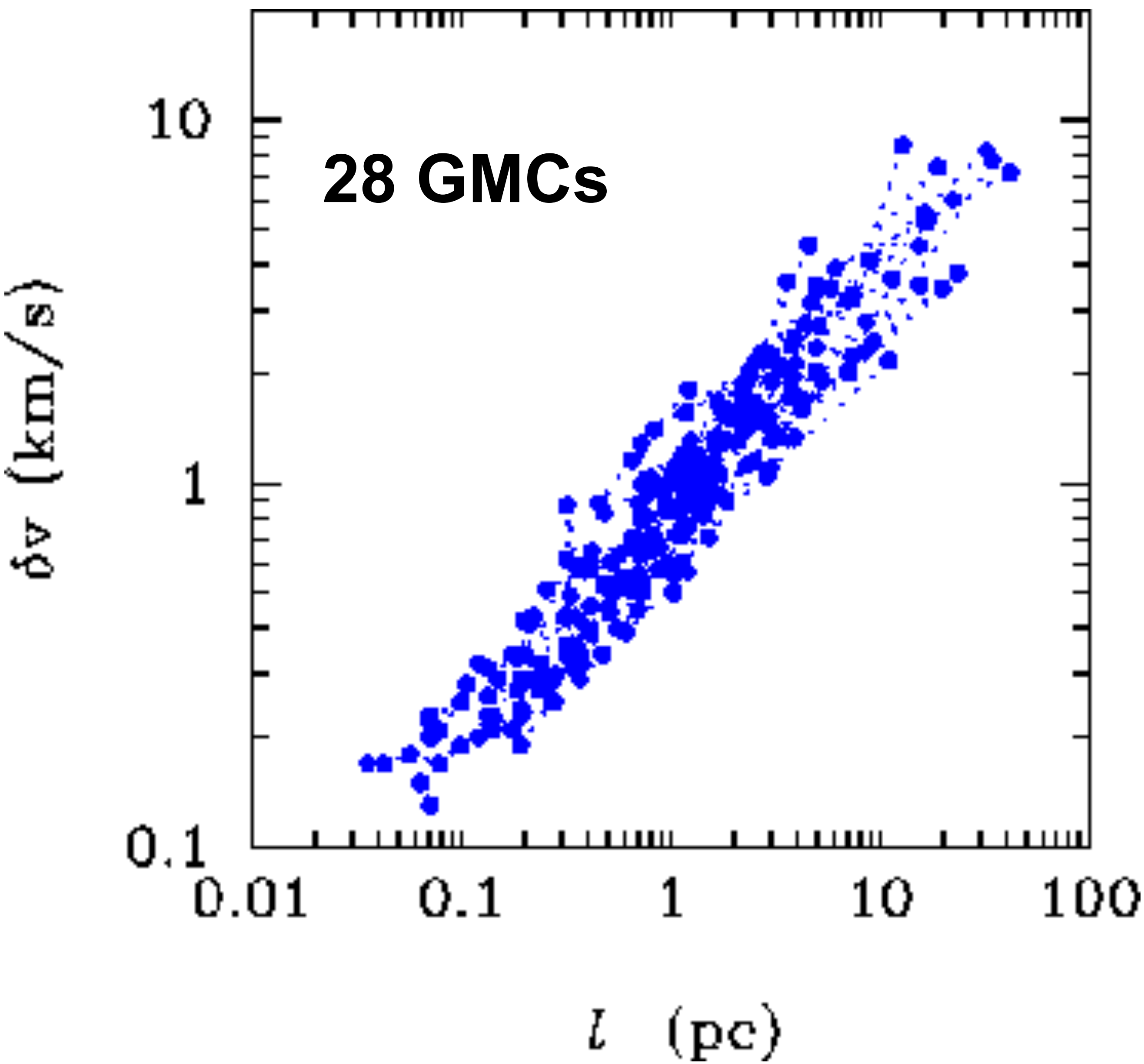
Pseudo-Structure Functions





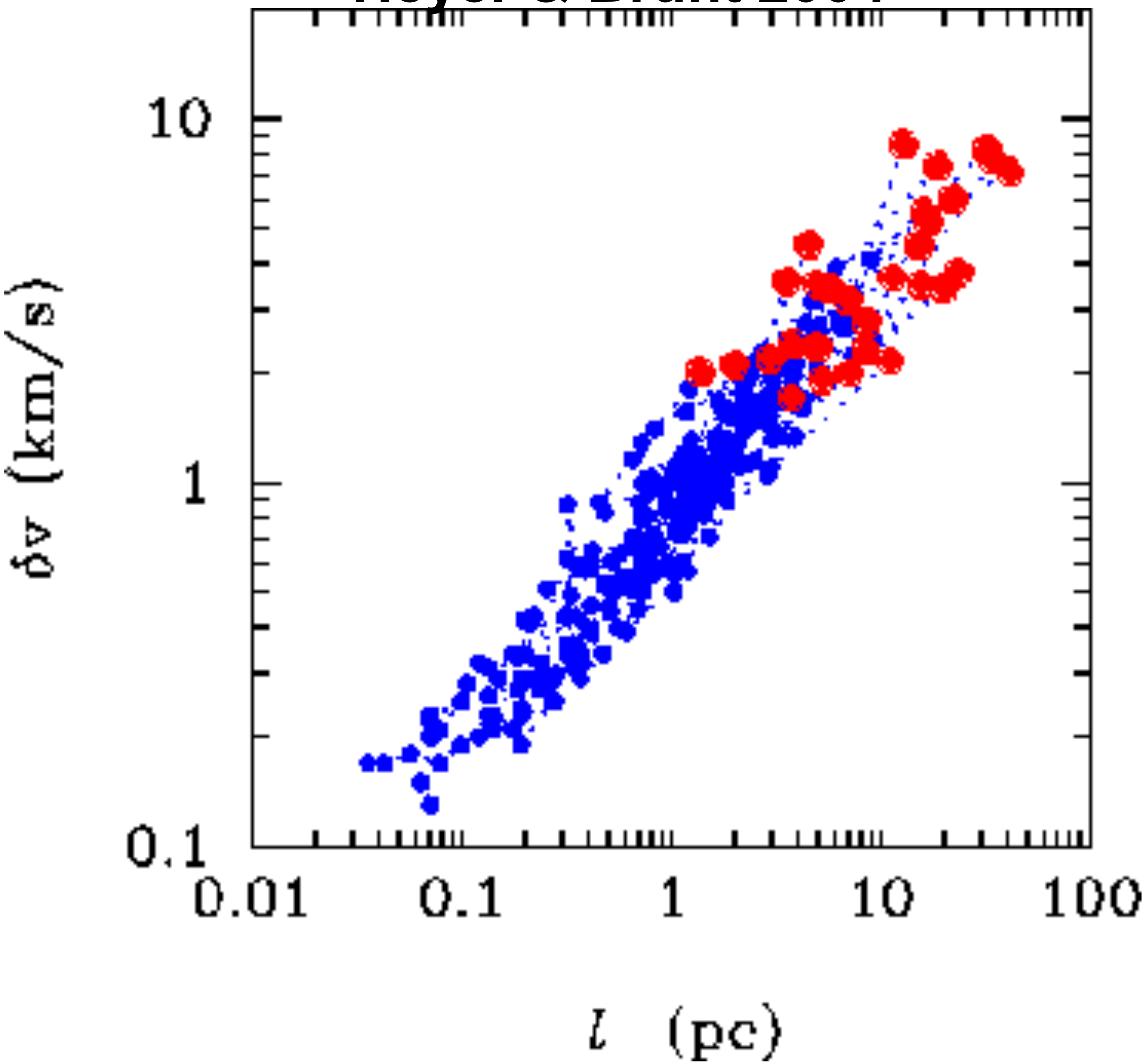
Rosette
Taurus
δv (km/s)
10
1
0.1
0.01
0.1
1
10
100
l (pc)


Index = 0.49 +/- 0.15
<v0> = 0.90 +/- 0.19 kms-1pc-1/2
28 GMCs
δv (km/s)
l (pc)
10
1
0.1
0.01
0.1
1
10
100



28 GMCs
10
1
0.1
0.01
0.1
1
10
100
δv (km/s)
l (pc)

Heyer & Brunt 2004



Implications of near universality of velocity structure functions

Cloud sample spans a large range of GMC masses, sizes, and star formation activity

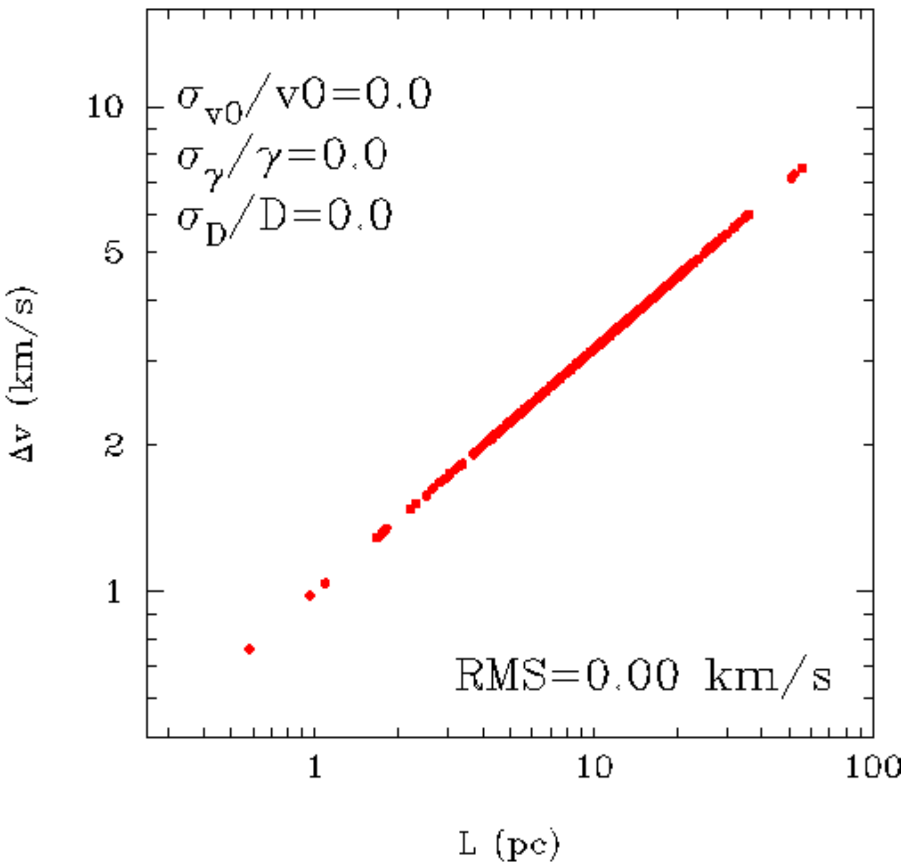
GMCs need to satisfy equipartition to exist

Turbulent fragmentation is not the exclusive regulatory process of star formation

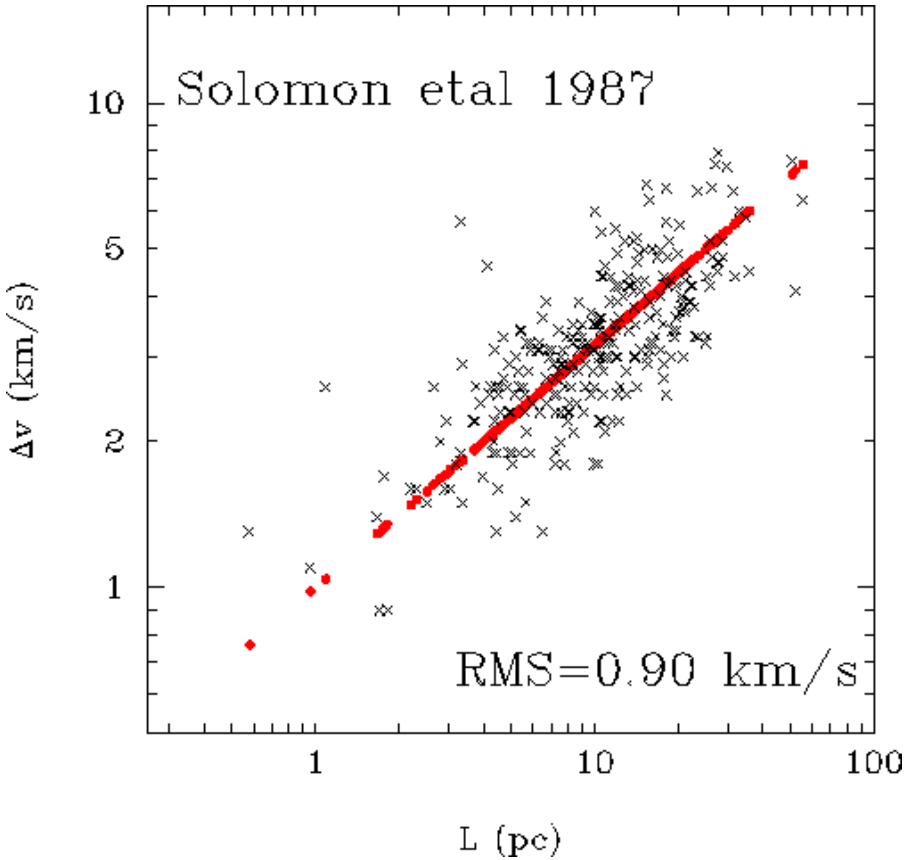
External driving source of turbulent energy

(not protostellar outflows,HII regions)

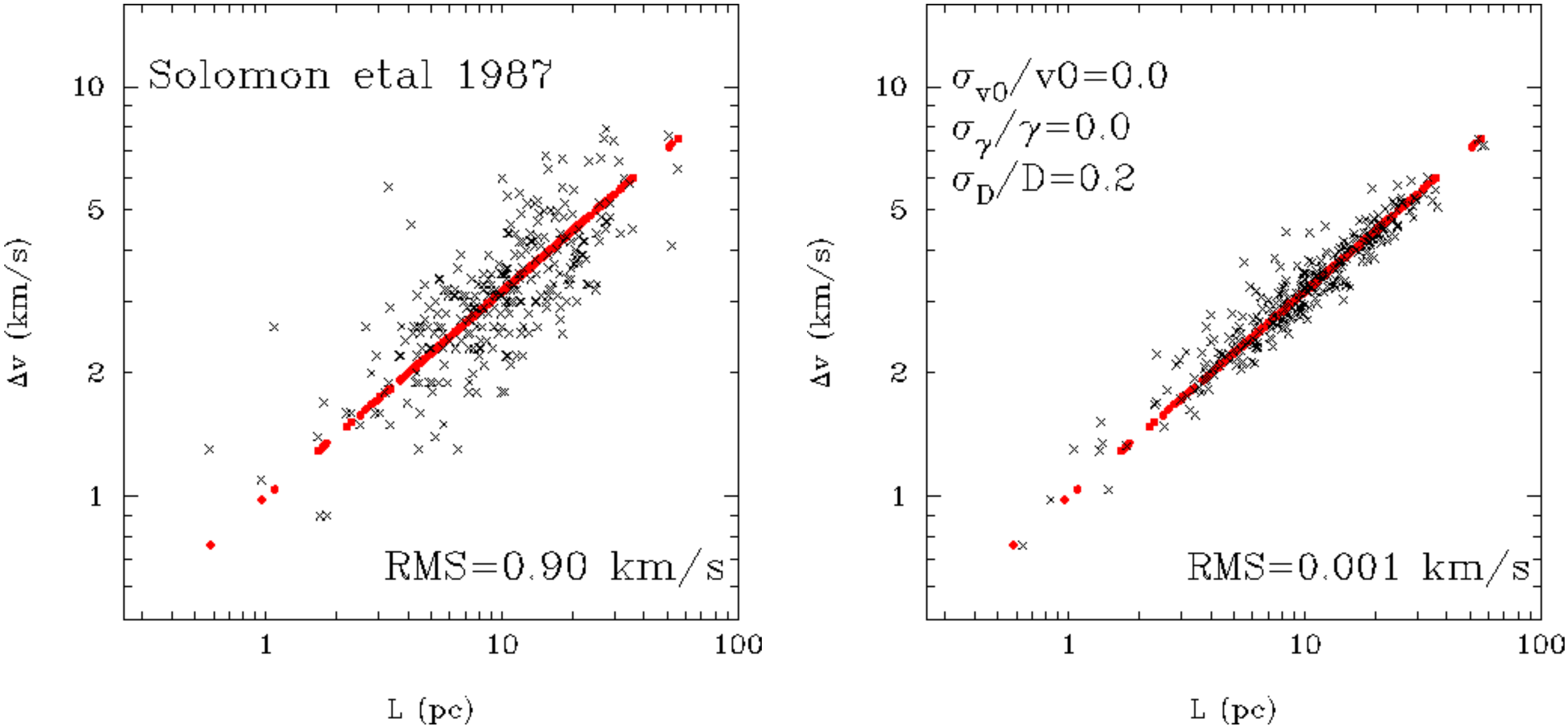
Universality and Larson's Scaling Law



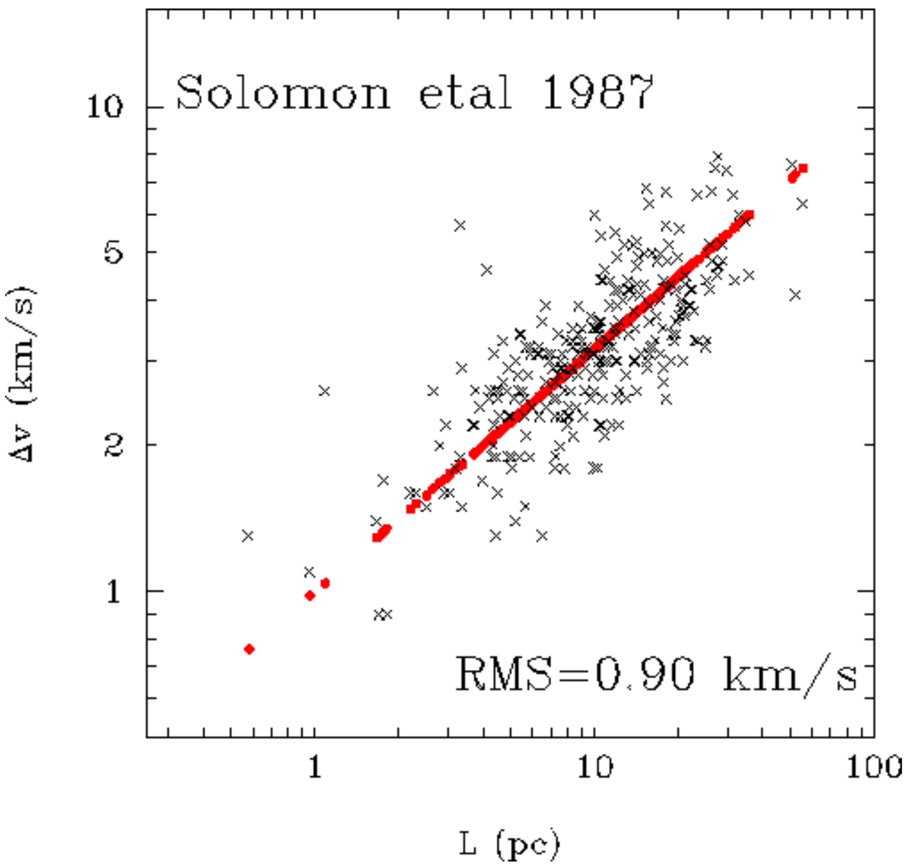
Universality and Larson’s Scaling Law

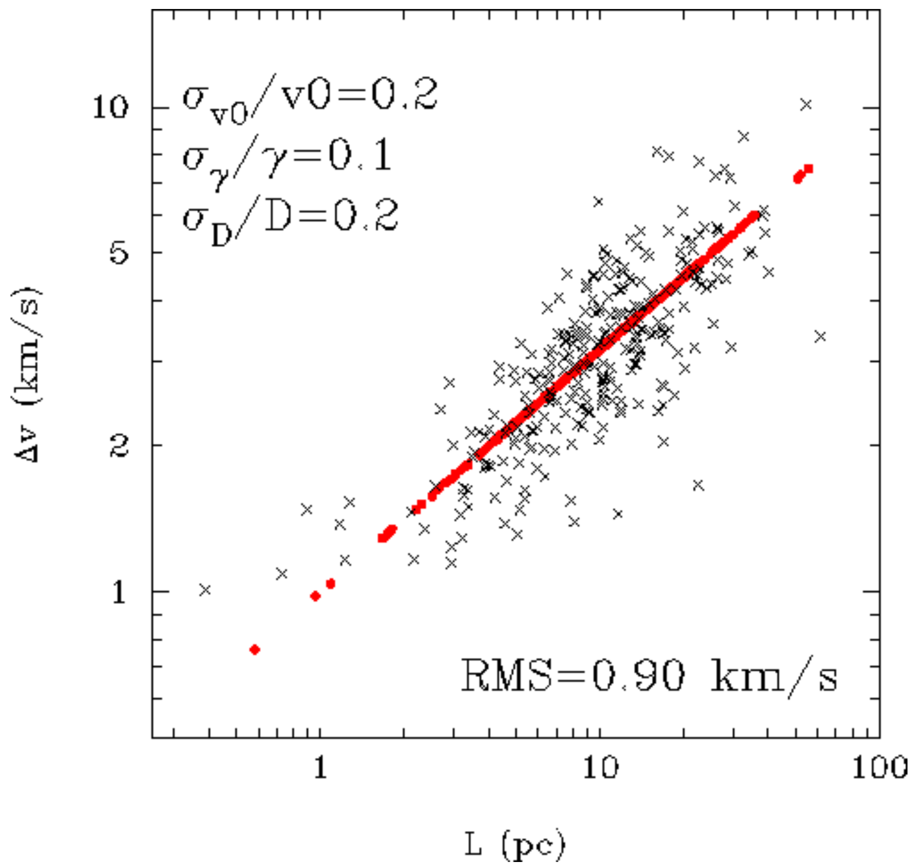


Universality and Larson's Scaling Law



Universality and Larson’s Scaling Law





Universality and Larson's Scaling Law