PROPERTIES AND DISTRIBUTION OF MOLECULAR CLOUDS IN THE MILKY WAY

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RINGBERG WORKSHOP 2013

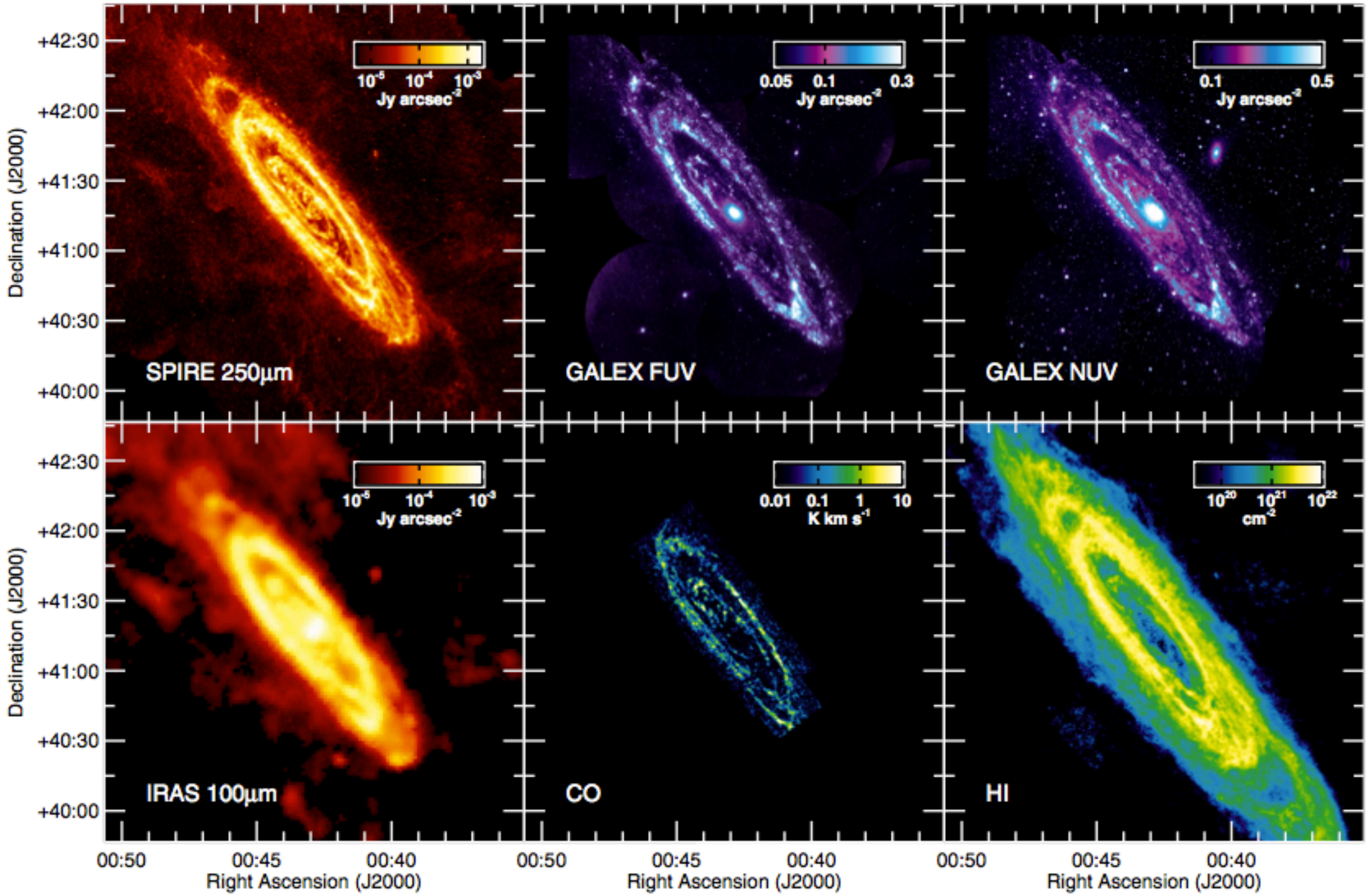
QUESTIONS

- **How do molecular clouds form?**
  - Cloud collisions in spiral arms?
  - Compression in spiral arms?
  - Flow collisions?
  - Transient density enhancements in the overall turbulent flow?
- **What is the lifetime of a molecular cloud?**
  - What are the processes that destroy MCs?
- **How are molecular clouds supported?**
  - Effects of magnetic fields?
  - Are they bound, or transient over-densities in a turbulent flow?
- **What is the process that leads from molecular clouds to star formation?**
  - How does the mass function of molecular clouds relate to the IMF?

=> *The distribution and properties of molecular clouds, along with theoretical models, can help answer those questions*

MOLECULAR CLOUDS AND STAR FORMATION

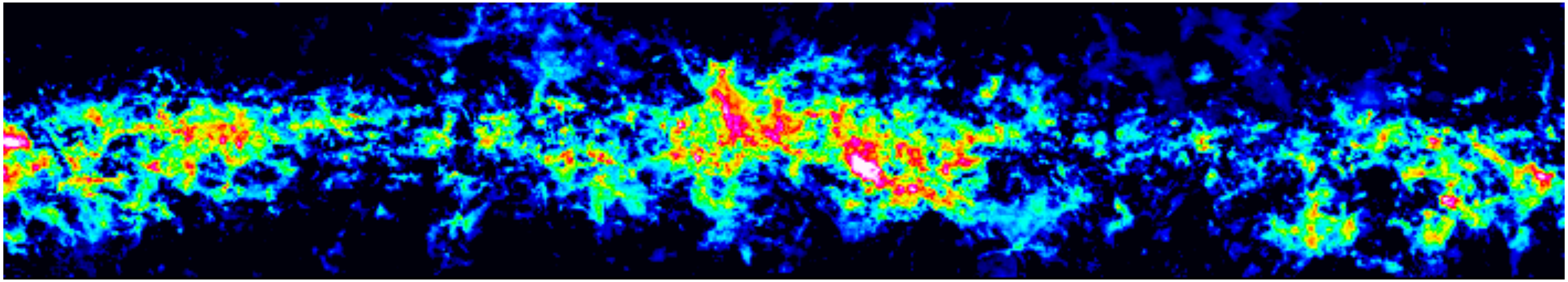
Fritz et al. 2012



DATA SETS

Galactic Ring Survey (GRS) (*Jackson et al.* 2006):

- ^{13}CO survey of the first quadrant of the Galaxy (18° < l < 55°, |b| < 1°)
- Resolution of 48” (sampled on 22” grid), 0.2 km/s
- *Rathborne et al.* (2009) identified 829 clouds in the GRS using CLUMPFIND



University of Massachusetts Stony Brook Survey (UMSB):

- ^{12}CO survey of the first quadrant
- Resolution of 44” sampled on 3’ grid (velocity resolution 1 km/s)

Very Large Array (VLA) Galactic Plane Survey (VGPS)

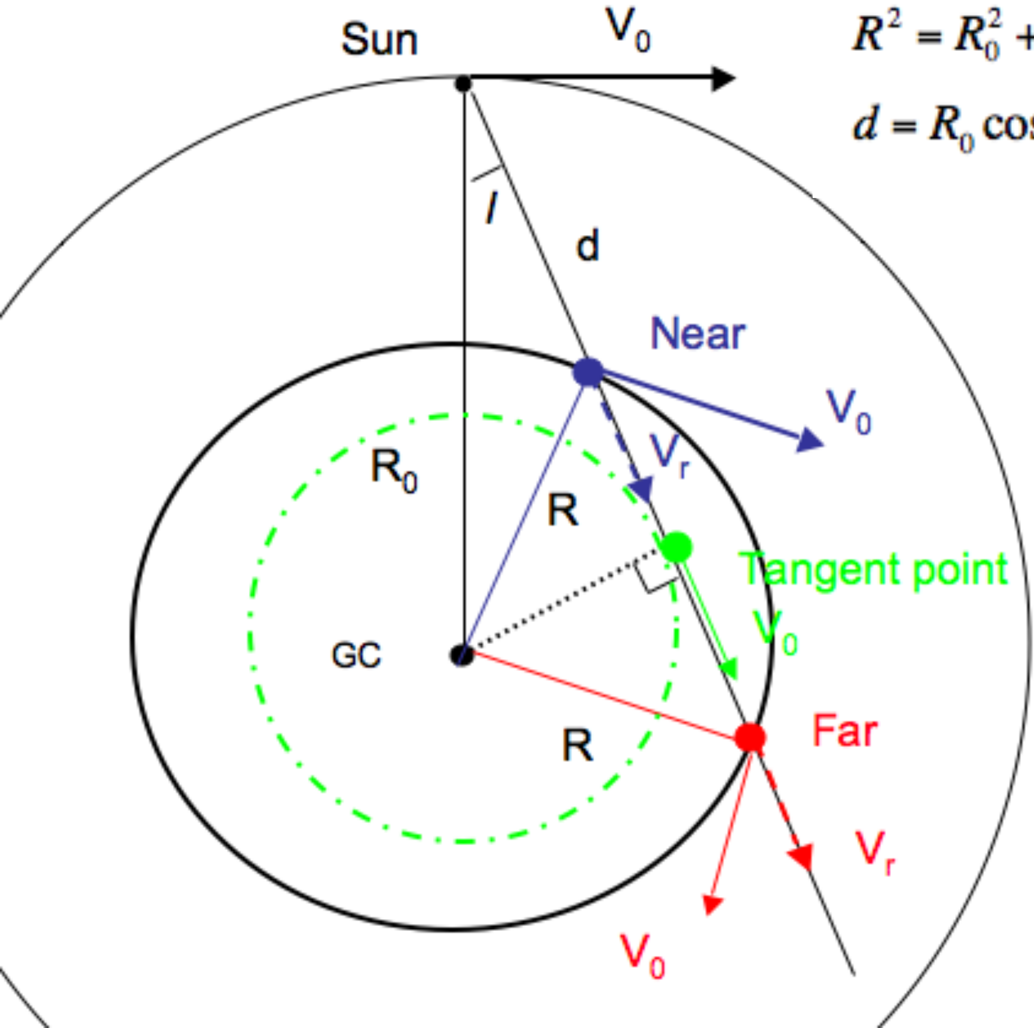
- HI 21 cm survey of the first quadrant (18° < l < 67°, |b| < 2°)
- Resolution of 1’ sampled on 0.3’ grid; spectral resolution of 1.2 km/s sampled on 0.8 km/s grid

DISTANCES TO MOLECULAR CLOUDS

$$V_{radial} = V_0 \sin l \left(\frac{R_0}{R} - 1\right)$$

$$R^2 = R_0^2 + d^2 - 2Rd\cos l$$

$$d = R_0 \cos l \pm \sqrt{R^2 - R_0^2 \sin^2 l} = R_0 \cos l \pm \sqrt{R^2 - R_{min}^2}$$



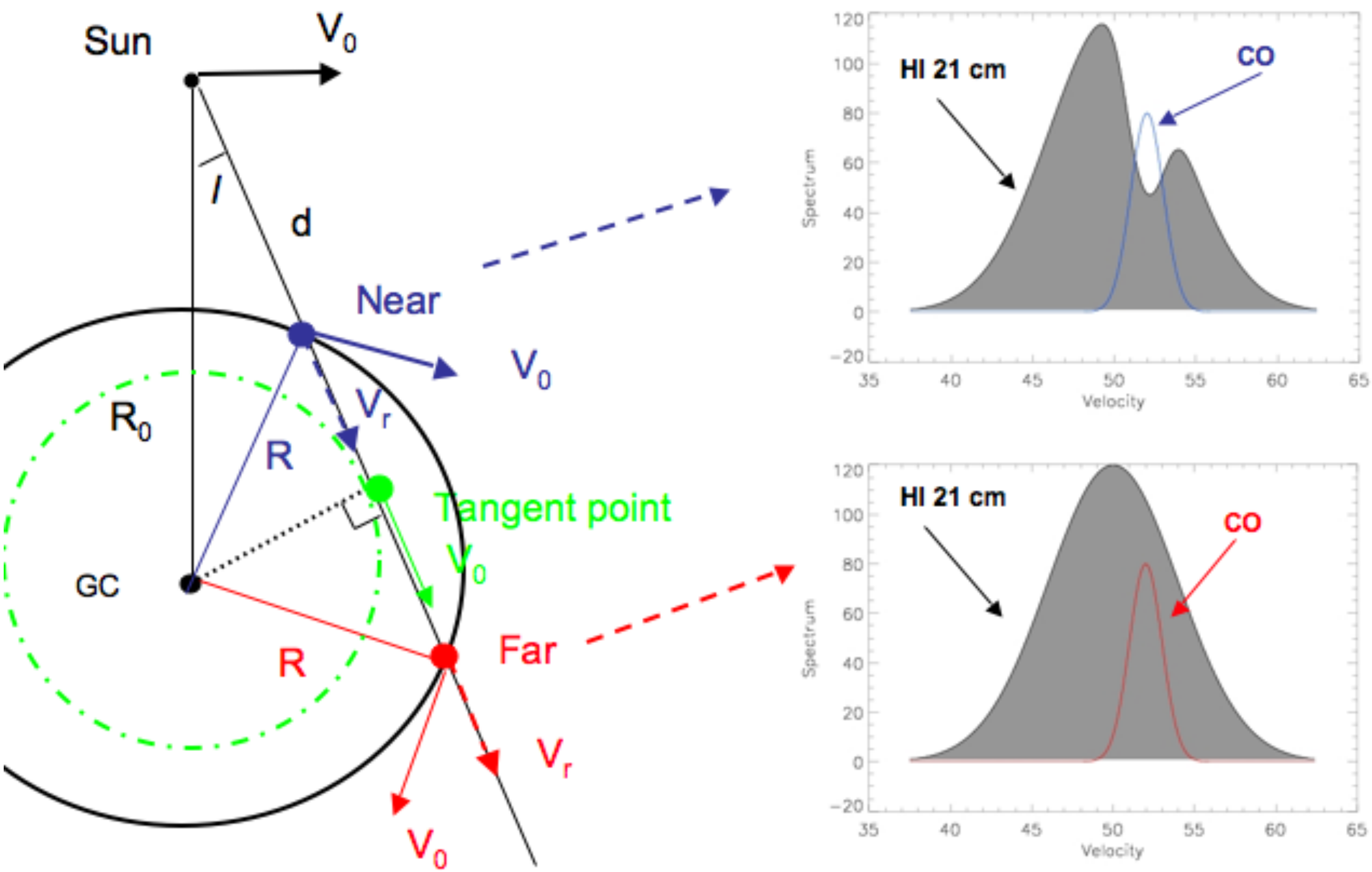
- Based on a rotation curve model
- Large errors where non-circular motions (spiral arms….)
- Unique solution for the galactocentric radius
- Two solutions for the distance (with respect to the tangent point)
  - "Near"
  - "Far"

⇒ Kinematic Distance Ambiguity (KDA)

BREAKING THE KDA

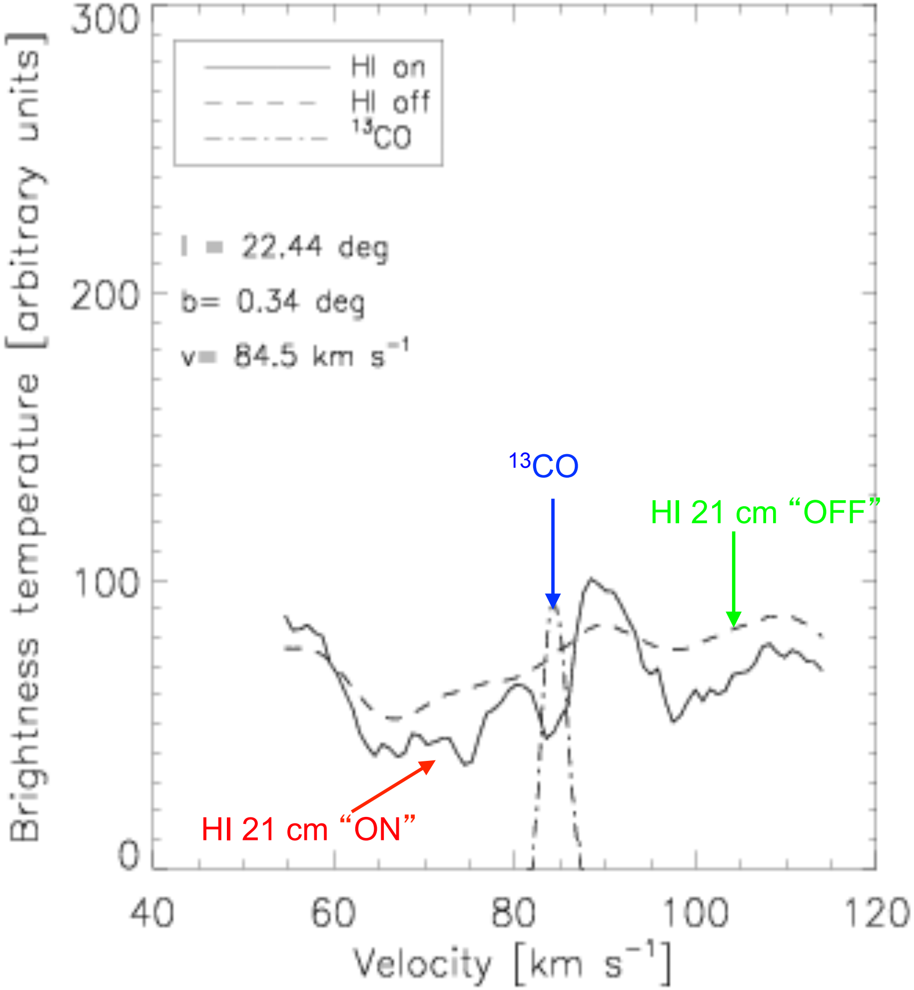
Warm HI (T_{ex} ~100 - 10000K) everywhere in the Galaxy

T_{ex} ~ 10 K for HI in clouds + high column density => cold clouds absorb background 21 cm radiation from warm HI

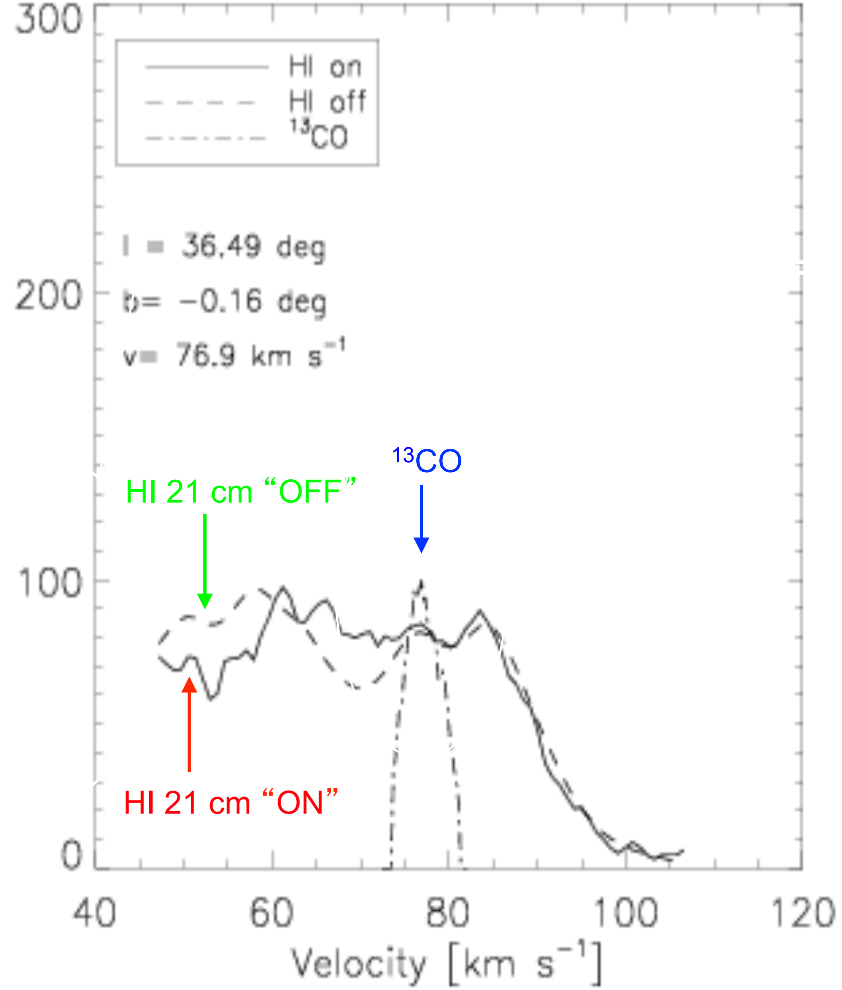


EXAMPLE

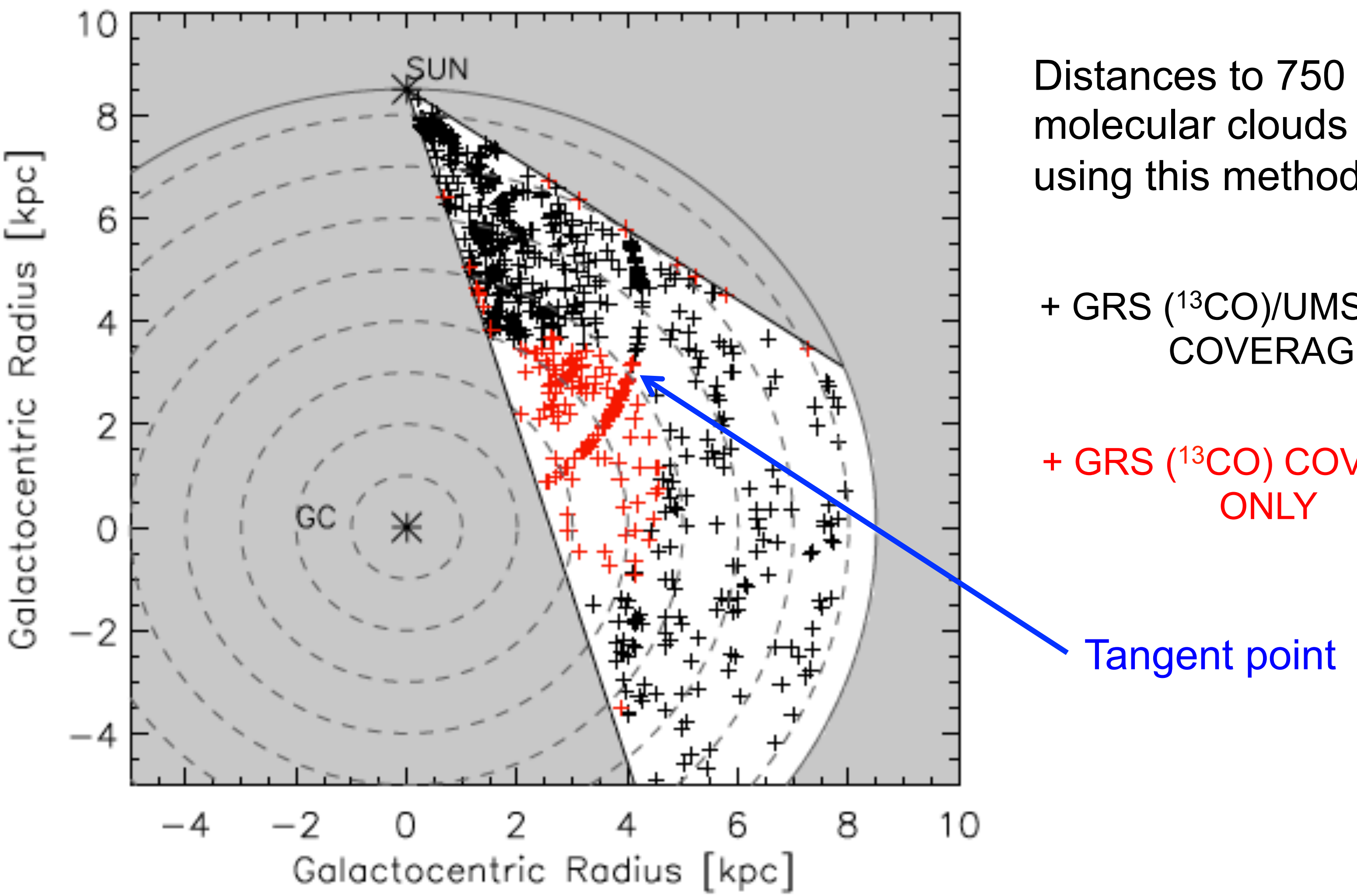
NEAR



FAR



WHERE ARE THEY?



Distances to 750 GRS molecular clouds derived using this method

+ GRS (^{13}CO)/UMSB (^{12}CO) COVERAGE

+ GRS (^{13}CO) COVERAGE ONLY

DERIVING MC PROPERTIES

CO excitation temperature from ^{12}CO data

From ^{12}CO (UMSB)

$$T_{ex} = \frac{5.53}{ln(1 + \frac{5.53}{T_{12}+0.837})}$$

^{13}CO optical depth

From ^{13}CO (GRS)

$$\tau_{13}(\ell, b, v) = -ln\left(1 - 0.189\, T_{13}(\ell, b, v)\left(\frac{1}{\frac{1}{e^{\frac{5.3}{T_{ex}(\ell,b,v)}}-1} - 0.16}\right)\right)$$

Mass of H_2 + He (assume abundance $^{13}CO/H_2$)

$$\frac{M}{M_{\odot}} = 0.27\,\frac{d^2}{kpc^2}\int_{\ell}\int_{b}\int_{v}\frac{T_{ex}(\ell, b, v)}{1 - e^{\frac{-5.3}{T_{ex}(\ell,b,v)}}}\,\tau_{13}(\ell, b, v)\frac{dv}{km\ s^{-1}}\,\frac{d\ell}{arcmin}\,\frac{db}{arcmin}$$

MC PROPERTIES

- **Properties are derived inside 4σ isophot, or T_b > 1 K**
- **Radius: Count positions N_{pix} where the ^{13}CO integrated intensity is > 4σ ~ 0.2 K km/s**

$$A = N_{pix} d^2 \Delta l \Delta b \qquad R = \sqrt{\frac{A}{\pi}}$$

- **Virial parameter: Describes the ratio of kinetic energy to gravitational energy (α =M_{vir}/M)**

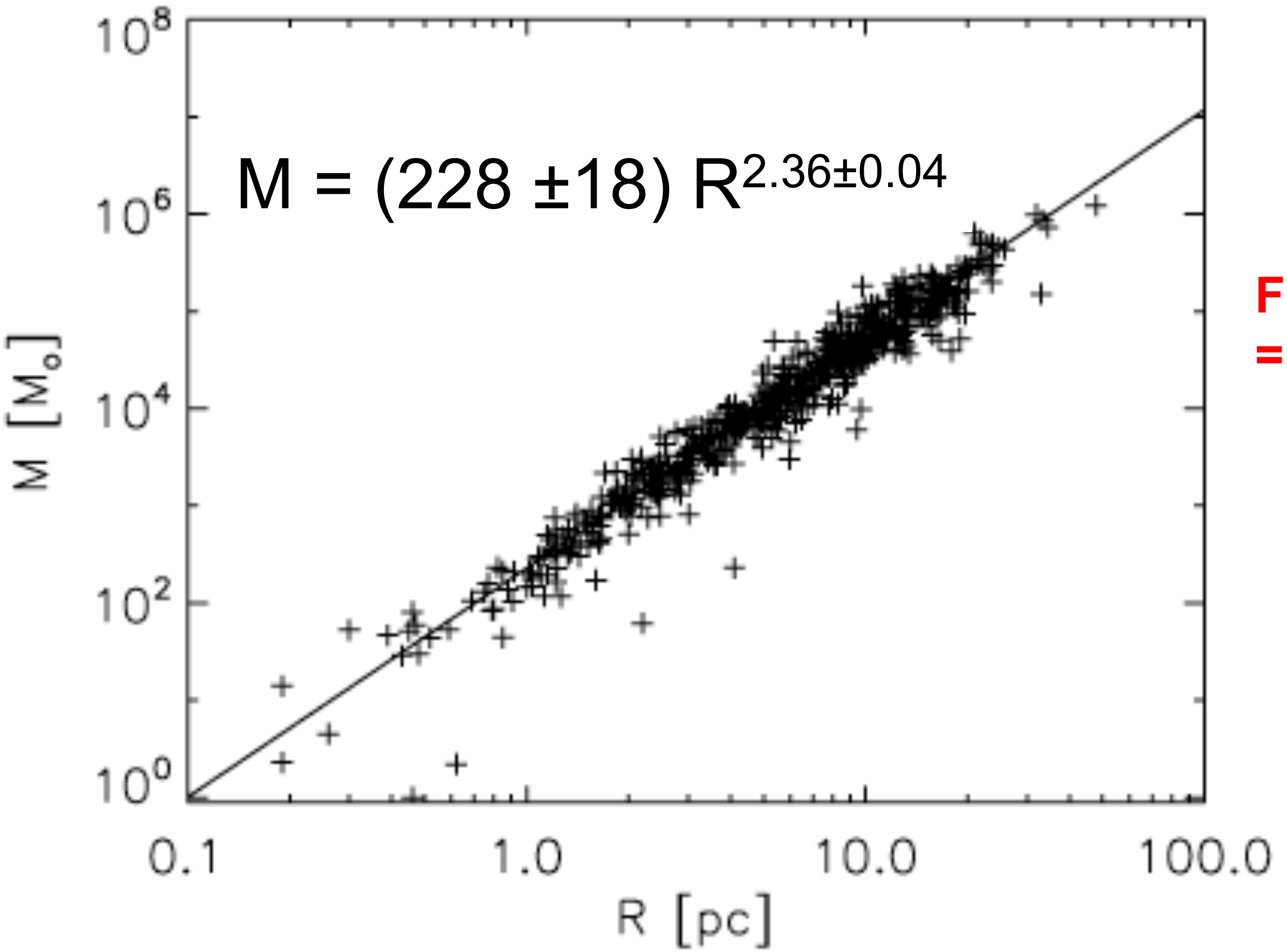
$$\alpha = \frac{5\sigma_v^2 R}{GM} = 1160\left(\frac{\sigma_{v_{1D}}^2}{km^2 s^{-2}}\right)\left(\frac{R}{pc}\right)\left(\frac{1M_o}{M}\right)$$

- **Surface mass density:**

$$\Sigma = \frac{M}{\pi R^2}$$

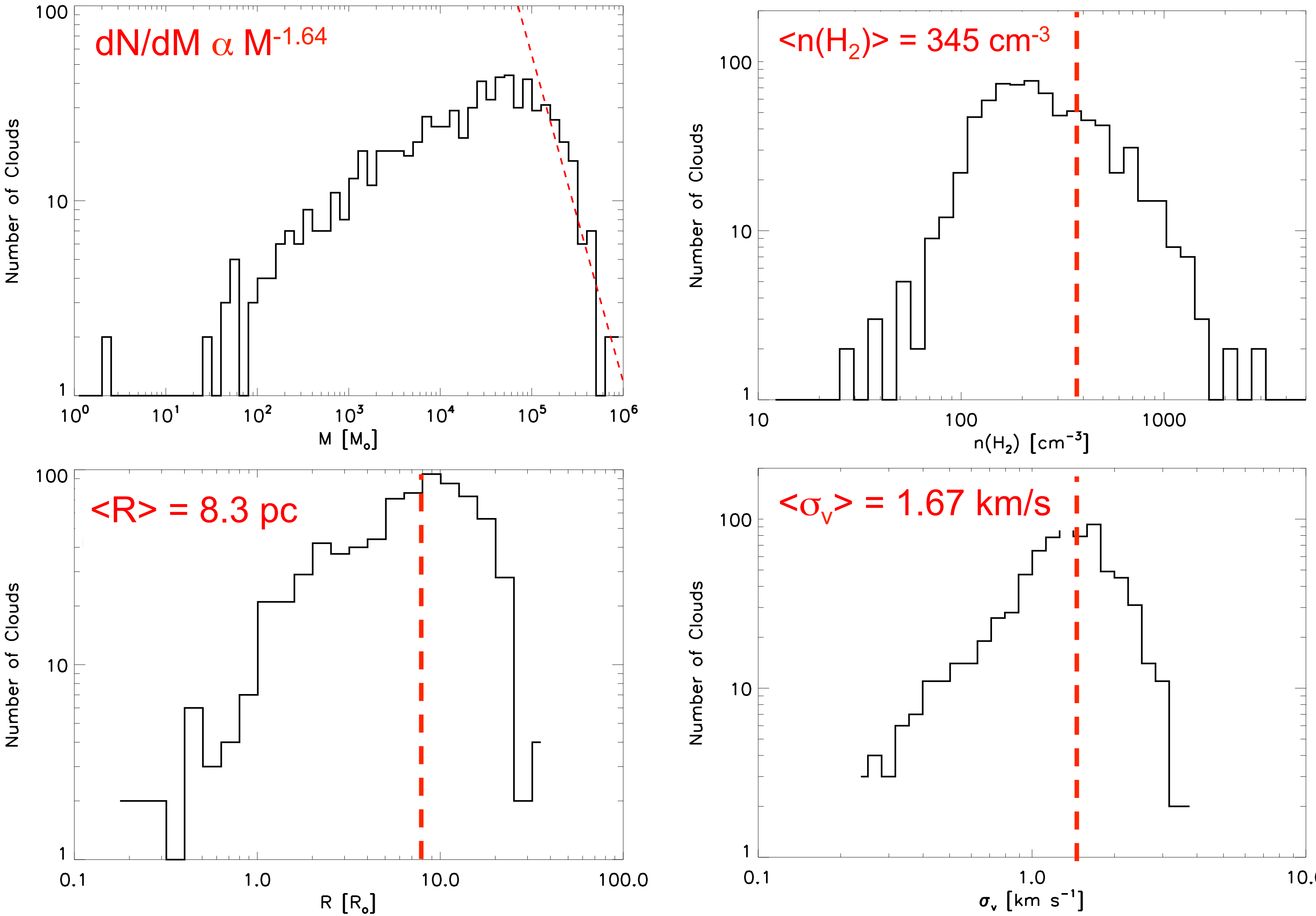
RADIUS/MASS CORRELATION

- M can only be derived for clouds covered by both GRS and UMSB (580 clouds)
- Use tight R/M correlation to derive masses of clouds outside UMSB coverage (170)

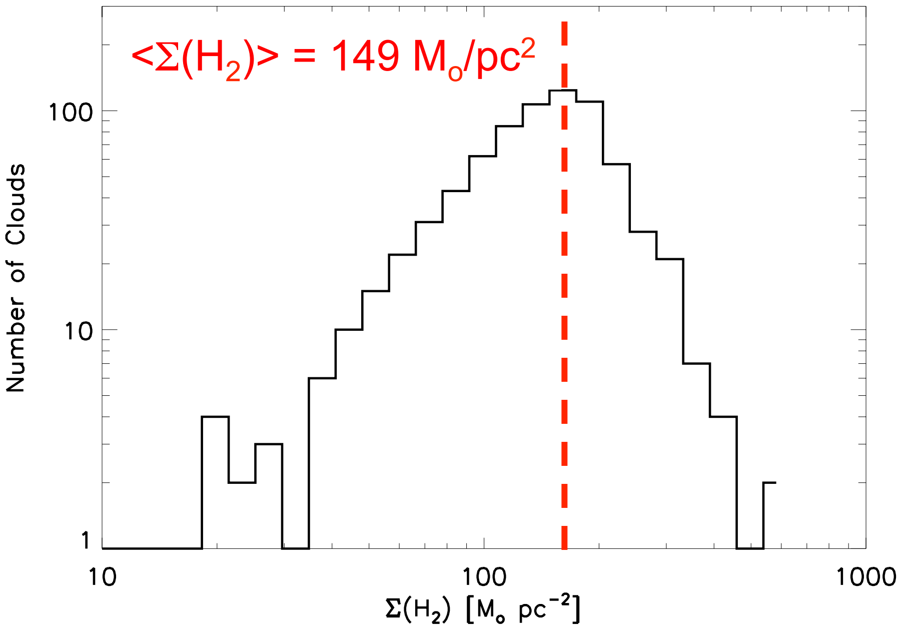


Fractal dimension = 2.36?

PROPERTIES OF MW ^{13}CO CLOUDS



PROPERTIES OF MW ^{13}CO CLOUDS



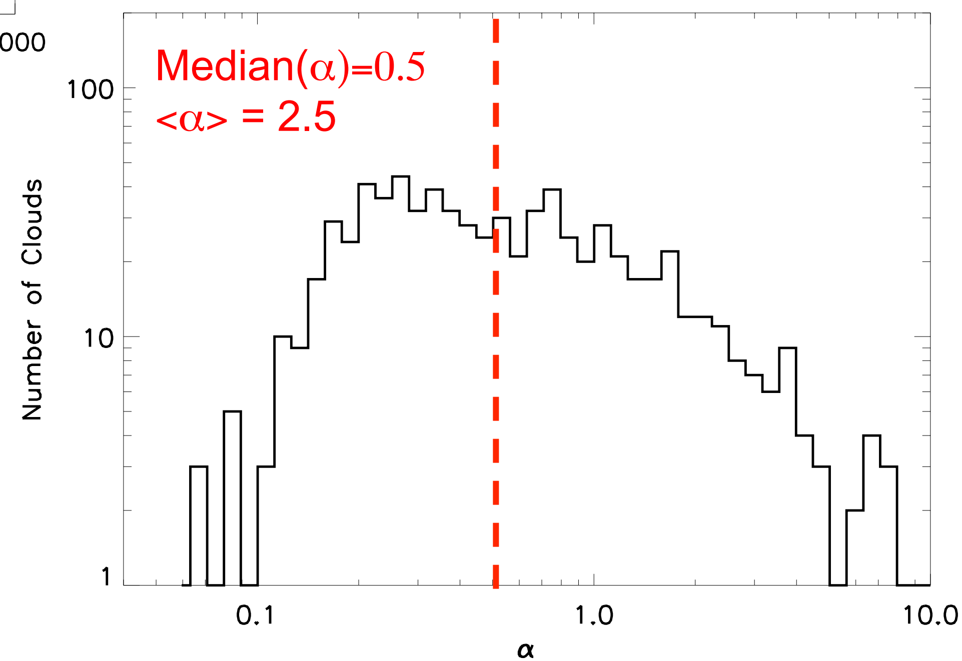
WARNING:

THESE PROPERTIES ARE DERIVED IN THE ^{13}CO CLOUDS ONLY!

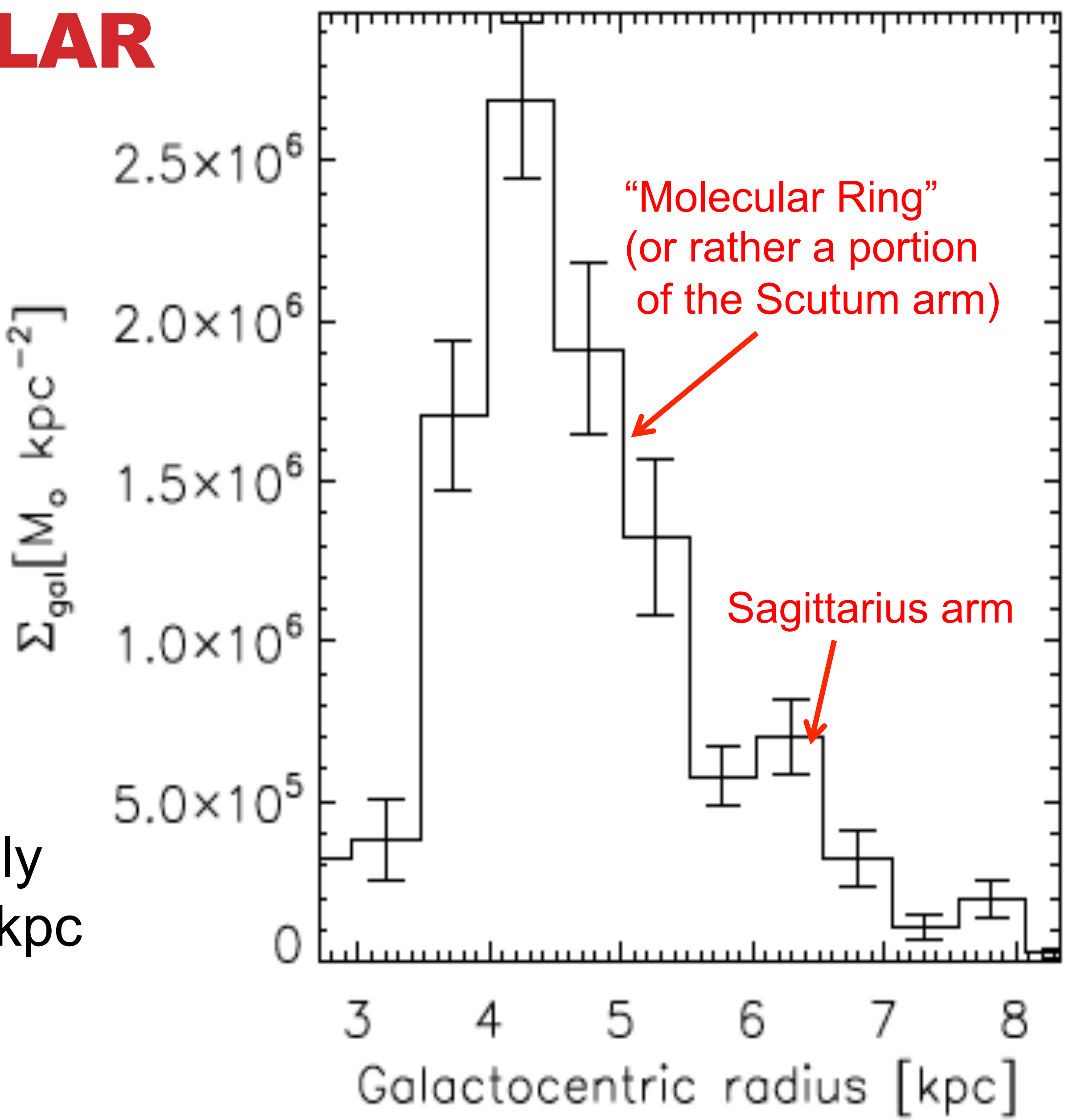
Lower <n> and <Σ> will be found in the area encompassing ^{12}CO clouds, or H_2 (from dust)

$$\alpha = \frac{M_{vir}}{M}$$

$$M_{vir} = \frac{5\sigma_v^2 R}{G}$$



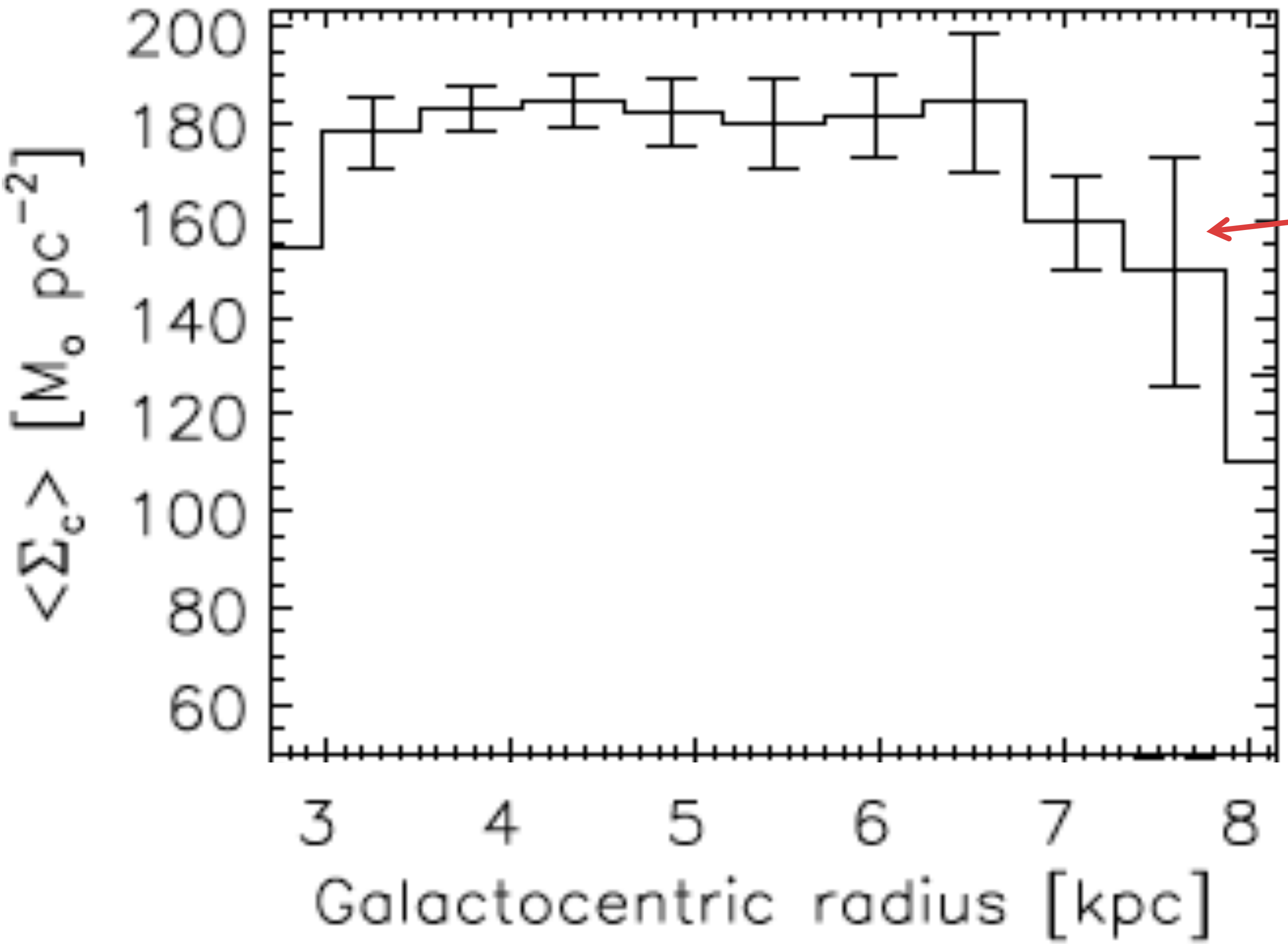
DISTRIBUTION OF MOLECULAR CLOUDS



Surface density of molecular gas strongly peaked at R_{gal} = 4-5 kpc

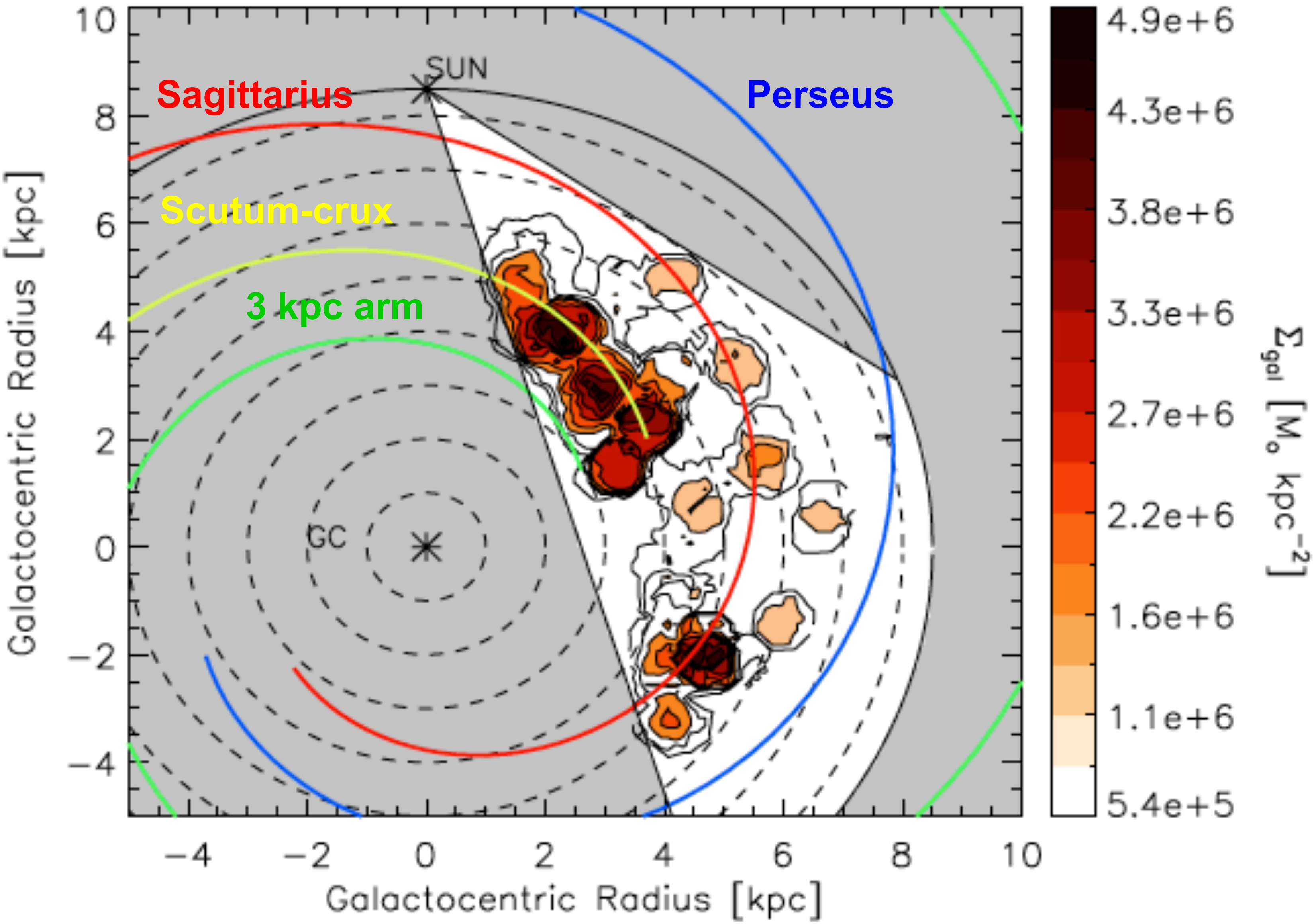
➔"Molecular Ring"

SURFACE DENSITY IN MOLECULAR CLOUDS

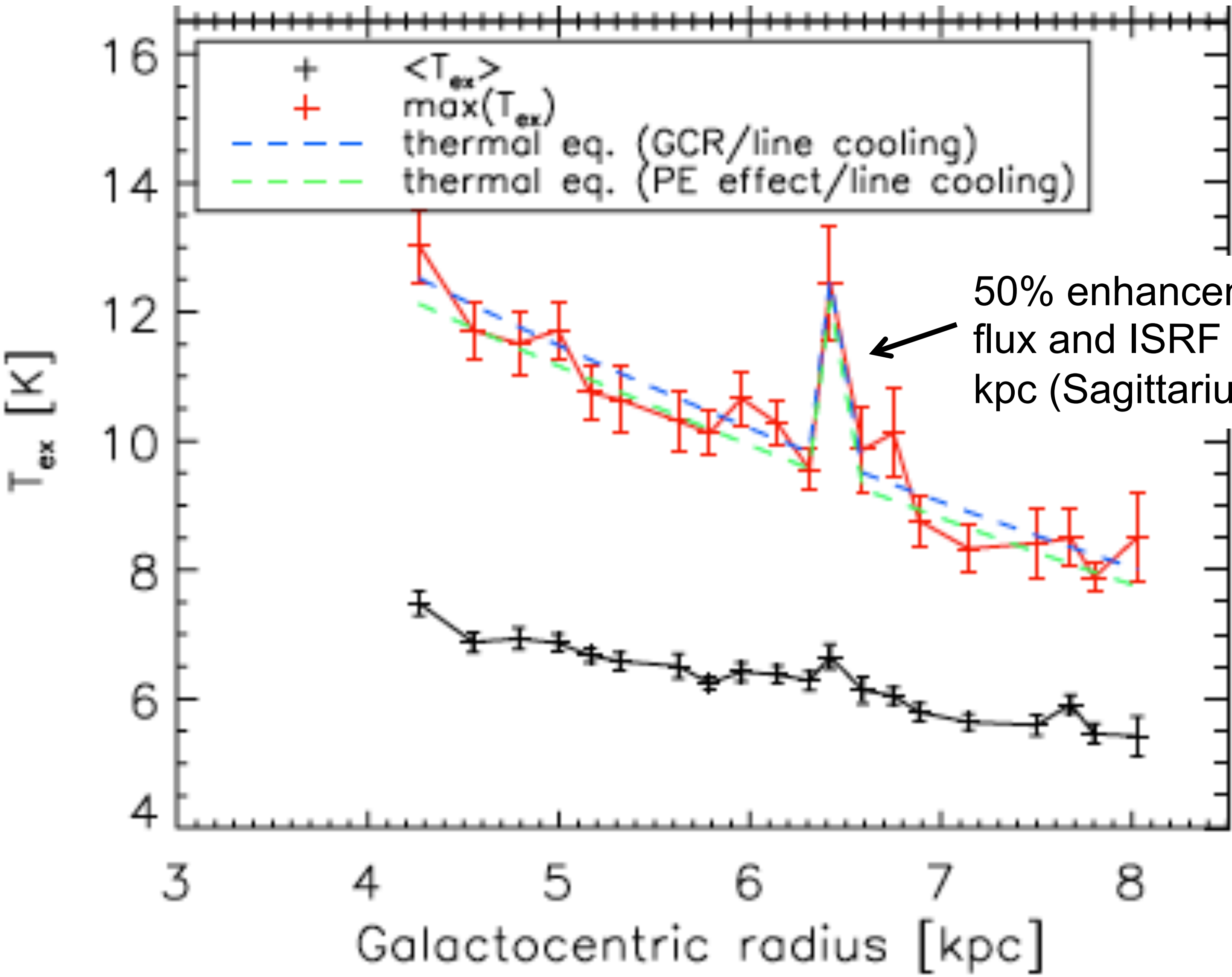


Poor stats
(V > 0, inner
galaxy only)

DISTRIBUTION OF MCS



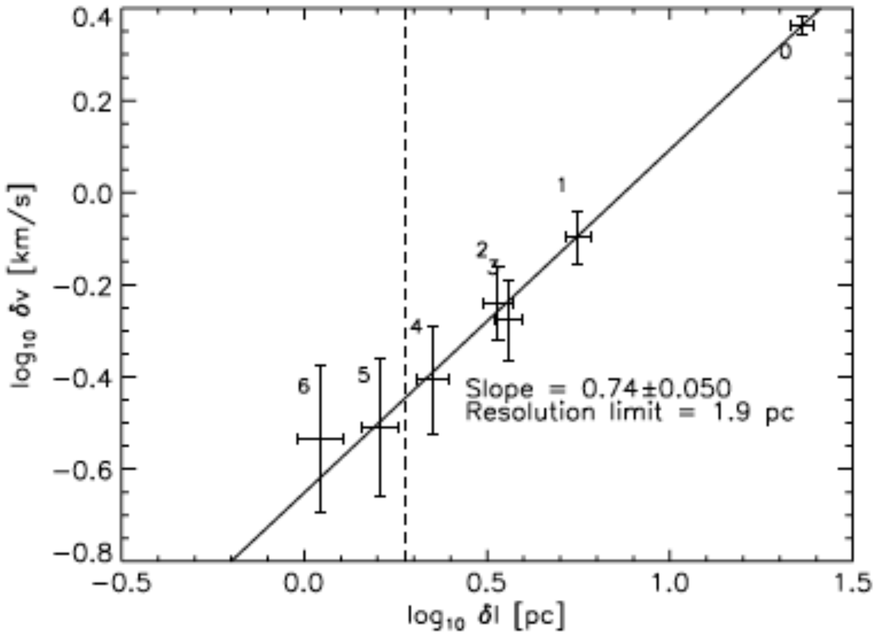
EXCITATION CONDITIONS

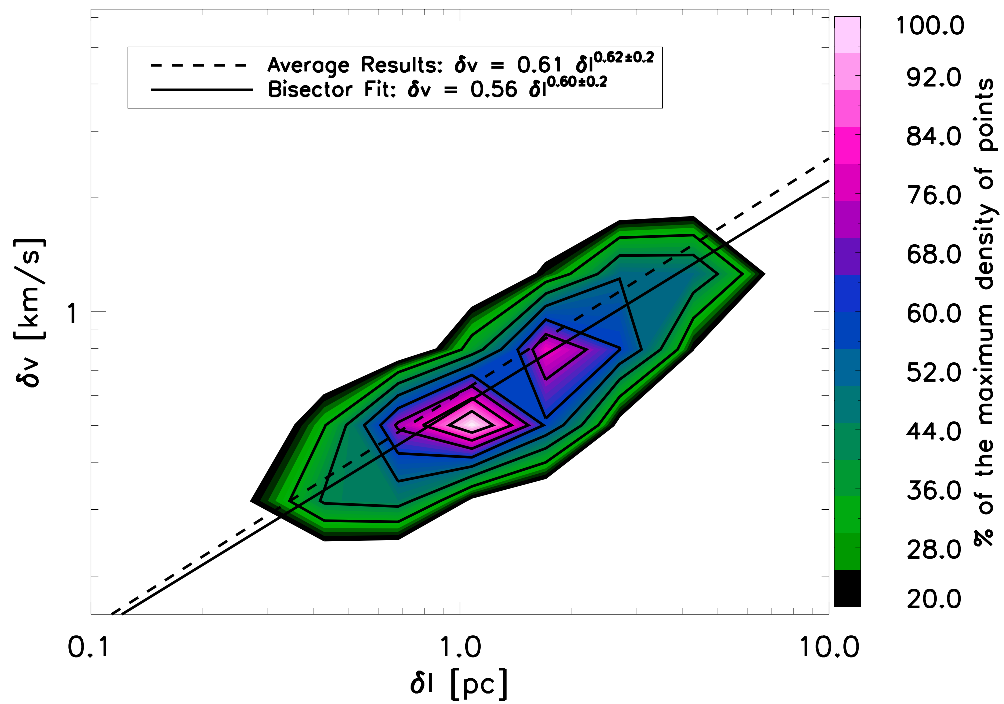


50% enhancement in GCR flux and ISRF at R_{gal} = 6.4 kpc (Sagittarius)

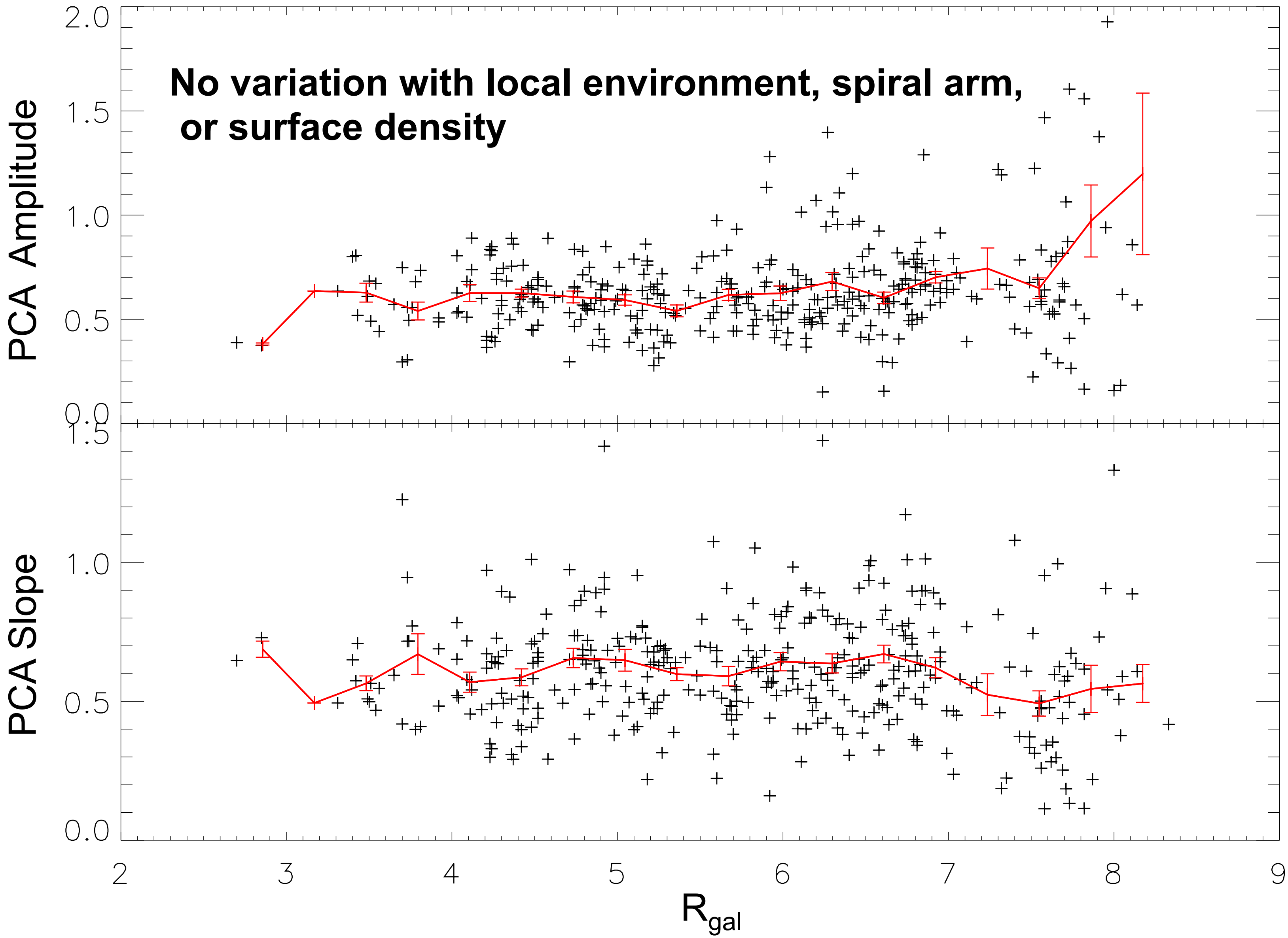
TURBULENCE

- **Composite structure function includes all scales detected by PCA in all ~350 GRS clouds**
- **Constant slope and intercept**
  - turbulence is universal
  - Properties of turbulence (compressible, intermittent) could determine the slope of the IMF
- **Slope of the PCA composite structure function (0.62) compatible with intermittent compressible turbulence**





UNIVERSALITY OF TURBULENCE



TAKE AWAY

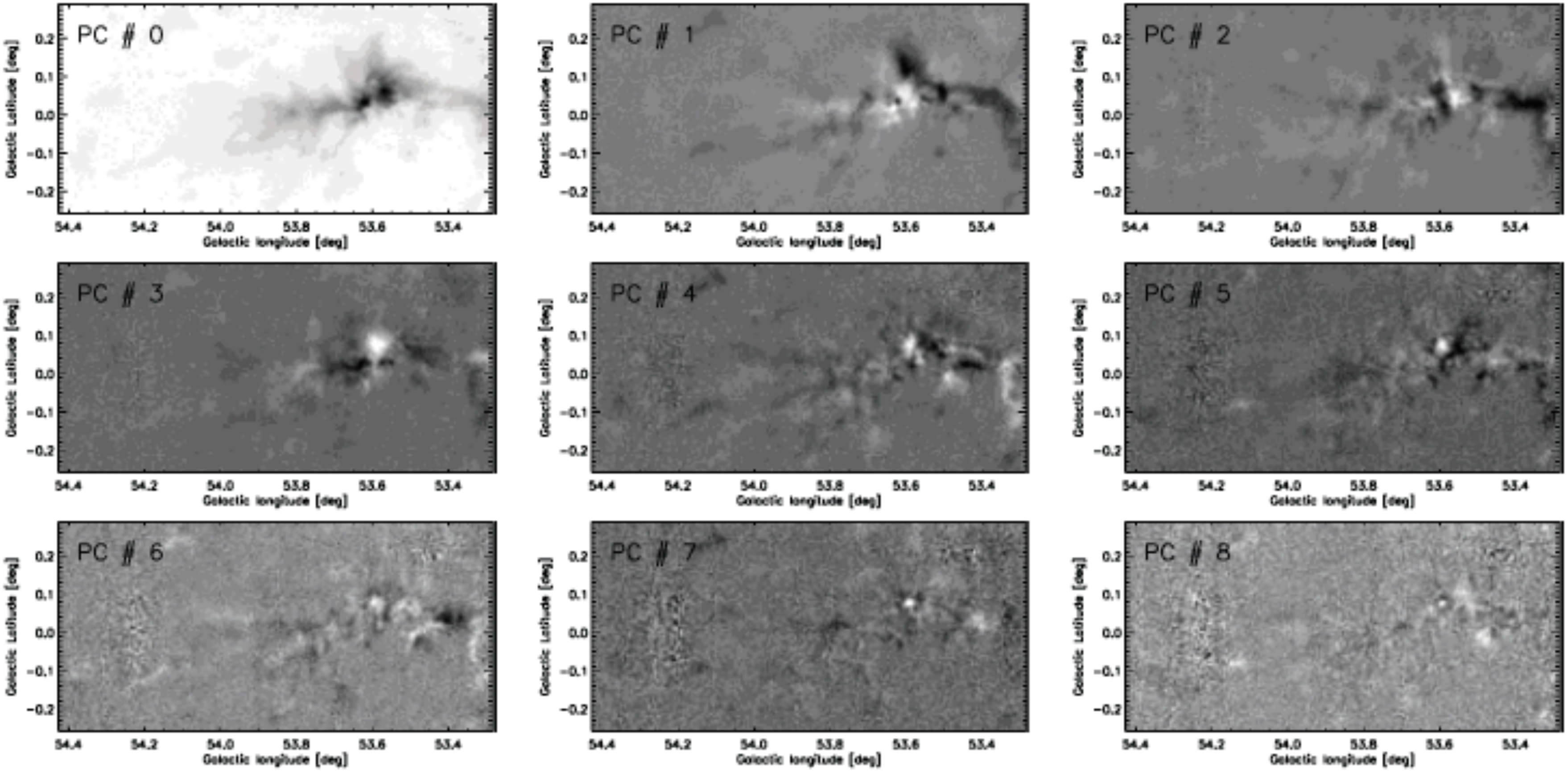
- Kinematic distances to ~ 750 ^{13}CO clouds in the Milky Way (20° < l < 55°) are derived using HI self-absorption method (and/or continuum absorption for select cases)

- Properties and galactic distribution of ^{13}CO clouds are derived with GRS (^{13}CO), UMSB (^{12}CO), HI 21 cm (VGPS)
  - $<\Sigma> \sim 150\ M_o\ pc^{-2}$, $<n> \sim 300\ cm^{-3}$, $R \sim 10$ pc, $\sigma_v \sim 1.5$ km/s
  - $M \alpha\ R^{2.36}$
  - $\Sigma(H_2)$ peaks around 5 kpc (“molecular ring”)
  - Spiral arm or ring requires more longitude coverage
  - T_{ex} seems to directly trace ISRF/SFR

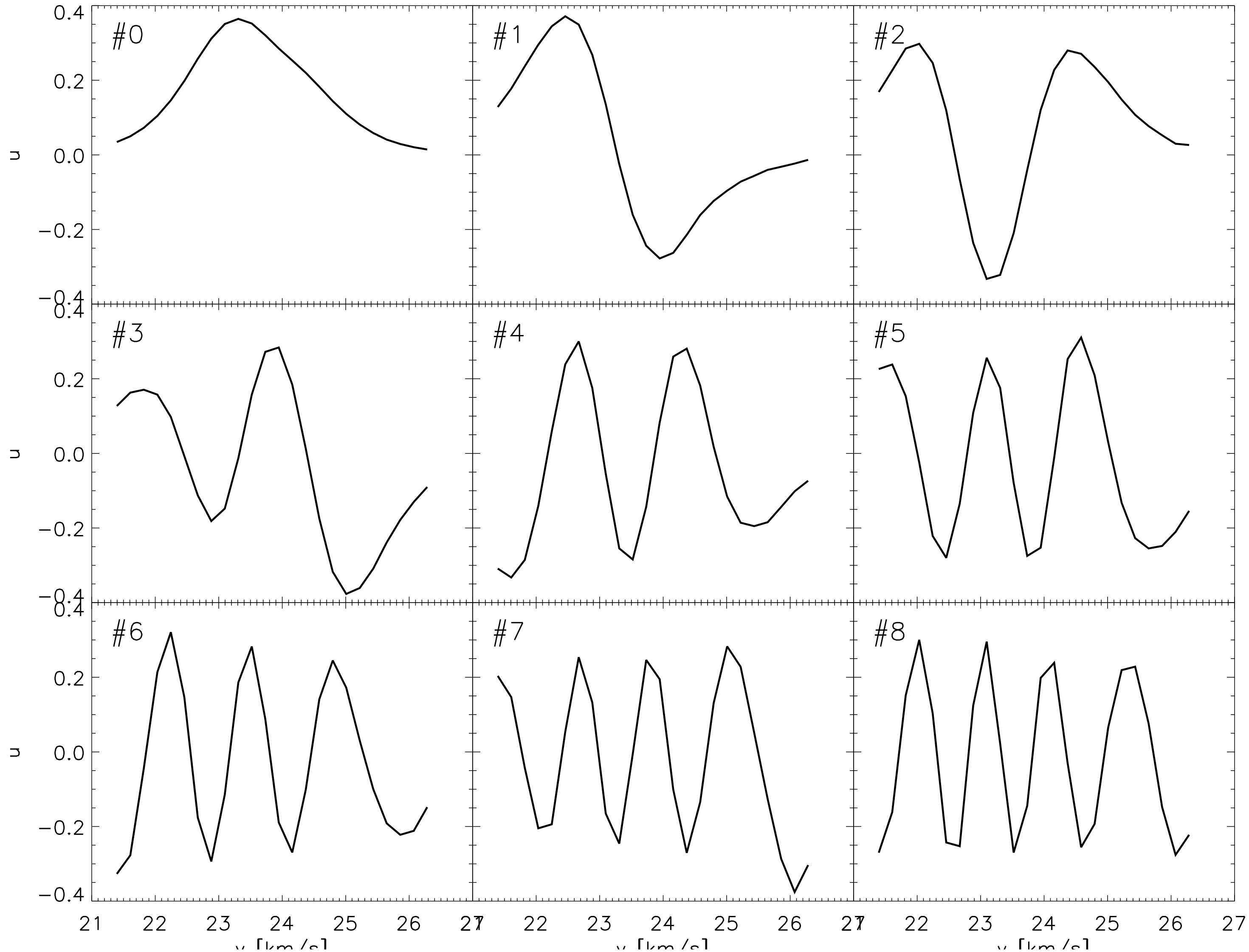
- Principal component analysis of spectral cubes of MCs:
  - Turbulence energy spectrum consistent with intermittent, compressible flows
  - Slope and amplitude of structure function remarkably uniform
  - Turbulence must be driven on large scales, by processes external to MCs that are uniform in the MW.

BACK UP SLIDES

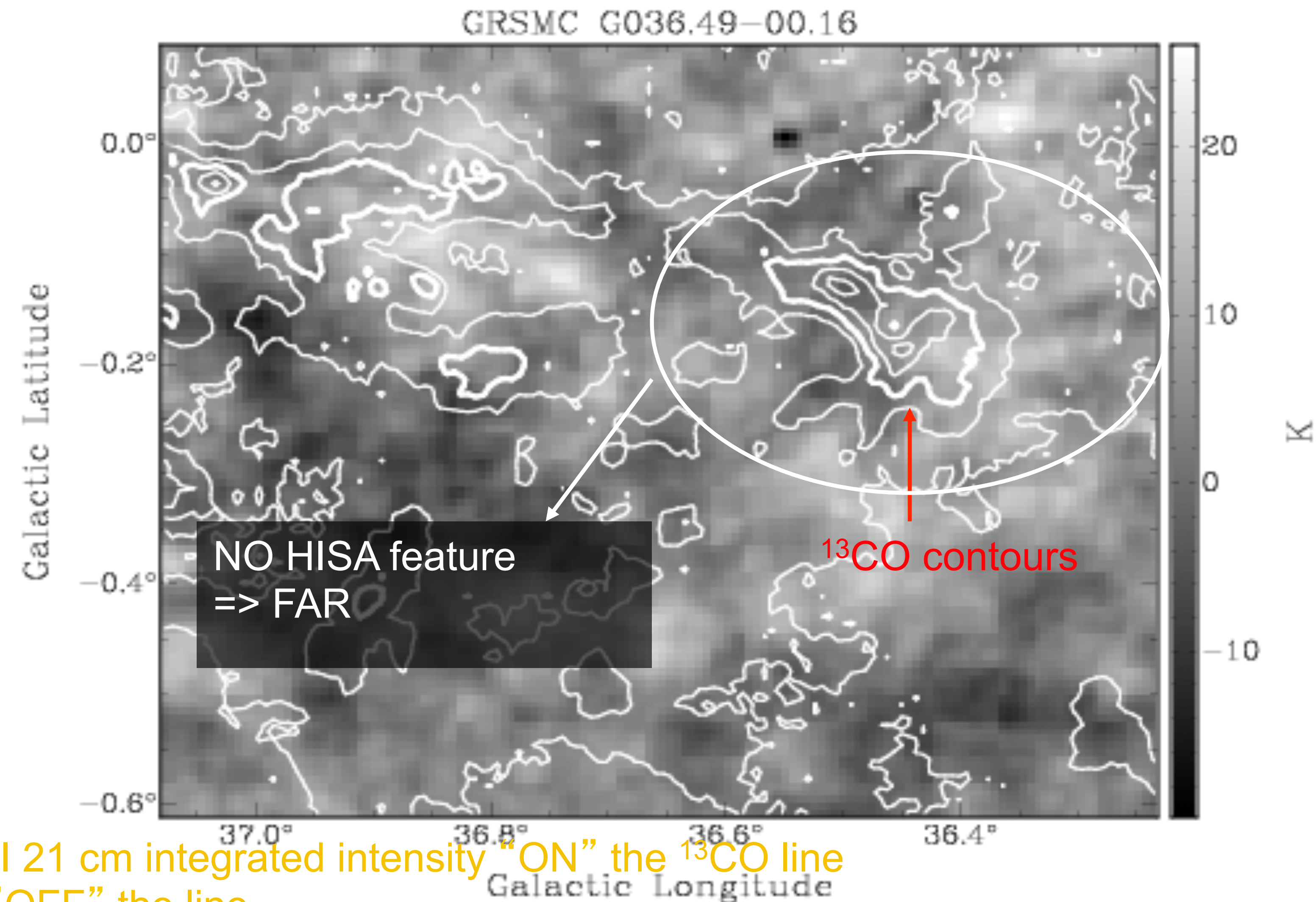
PCA


PC # 0
PC # 1
PC # 2
PC # 3
PC # 4
PC # 5
PC # 6
PC # 7
PC # 8
Galactic Latitude [deg]
Galactic longitude [deg]
0.2
0.1
0.0
−0.1
−0.2
54.4
54.2
54.0
53.8
53.6
53.4

PCA

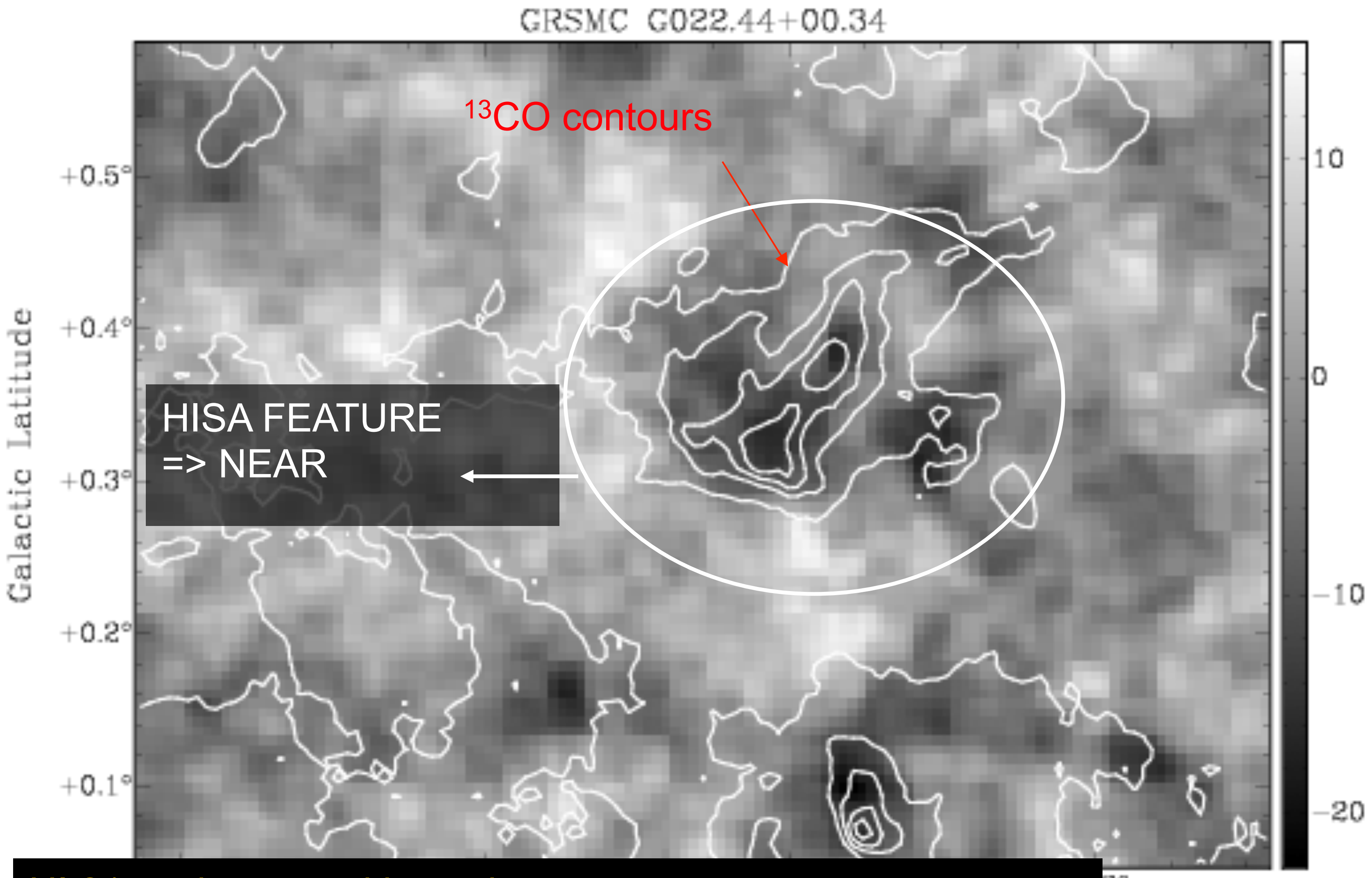


EXAMPLE OF HISA FOR A FAR CLOUD



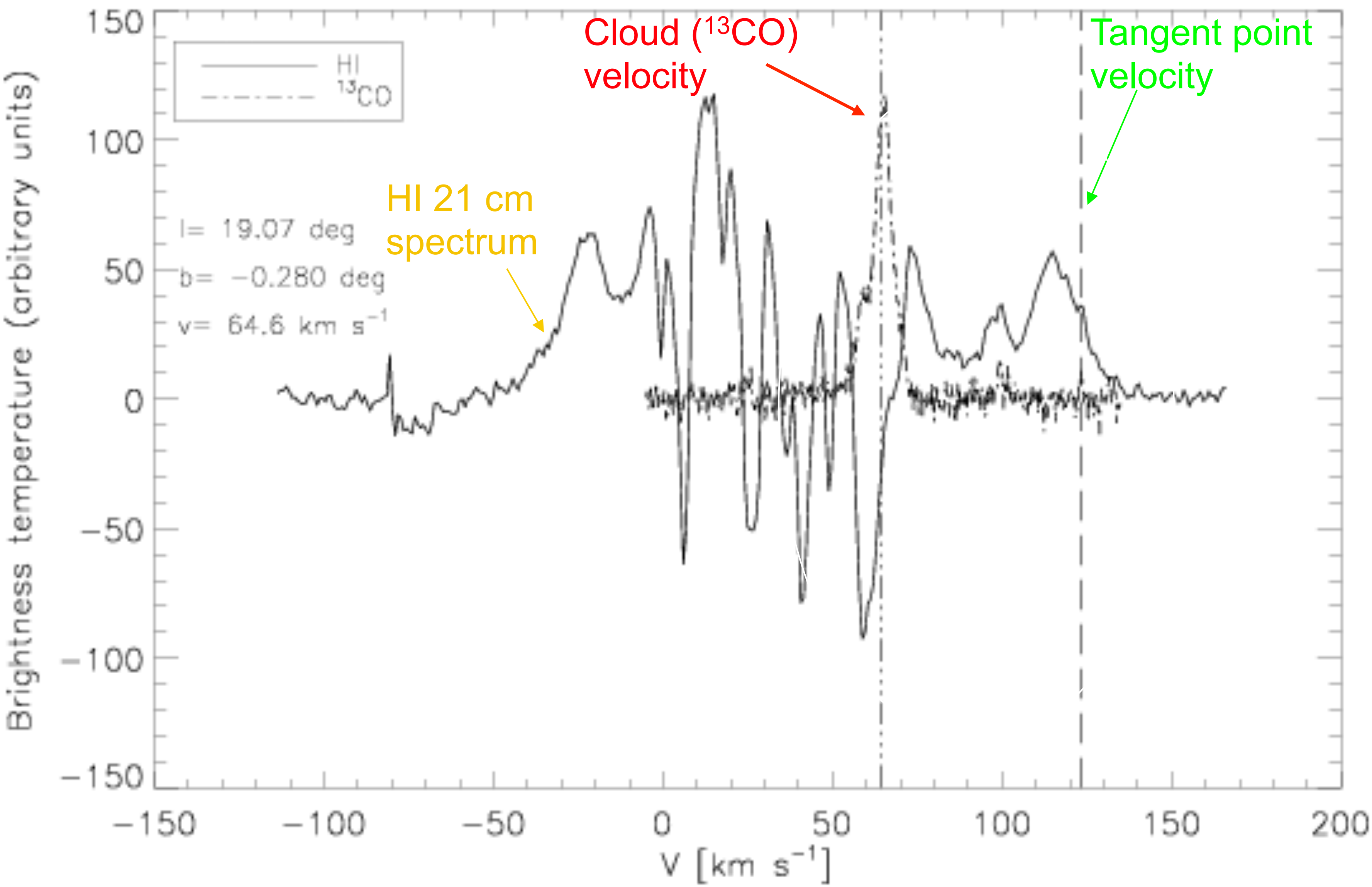
HI 21 cm integrated intensity "ON" the ^{13}CO line -"OFF" the line

EXAMPLE OF HISA FOR A NEAR CLOUD

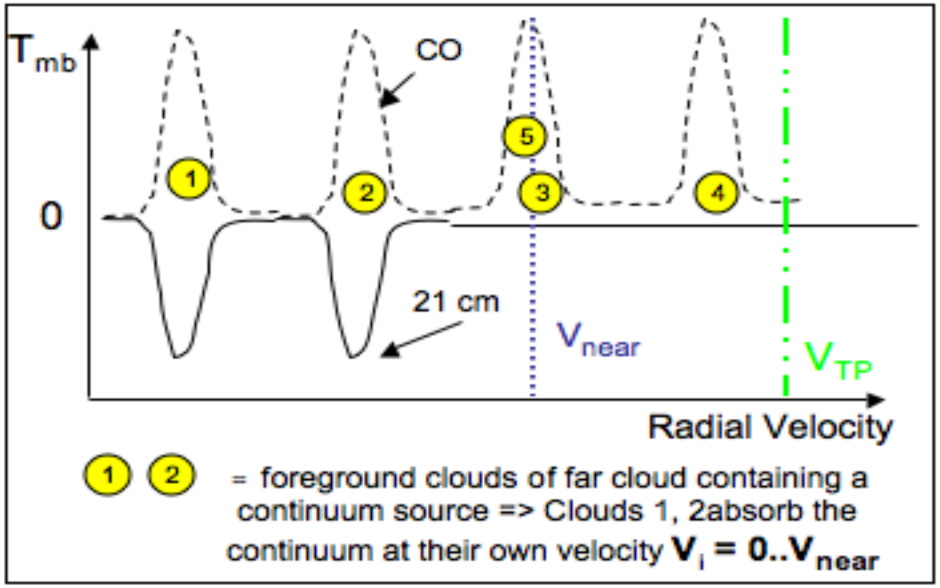


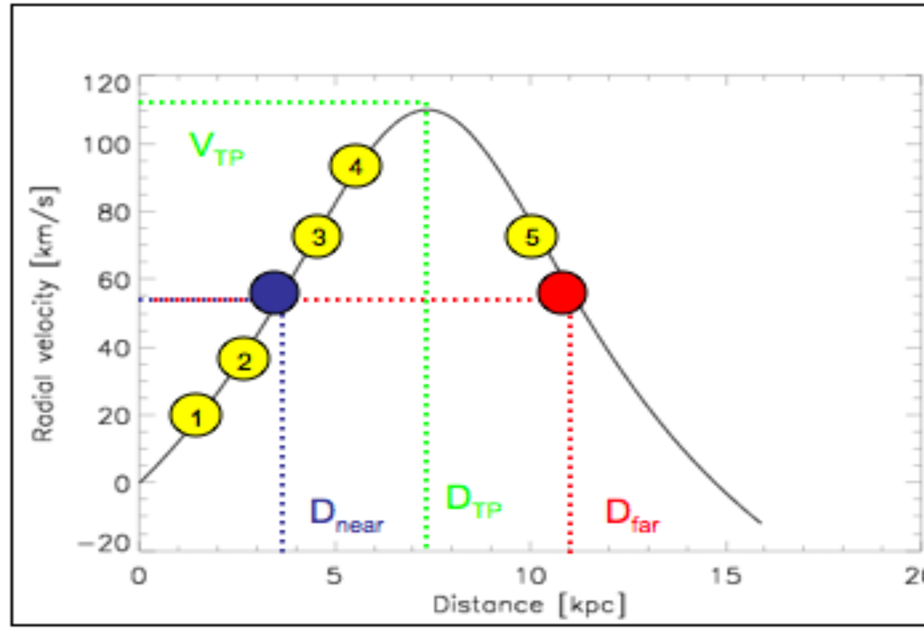
HI 21 cm integrated intensity
"ON" the ^{13}CO line - "OFF" the ^{13}CO line

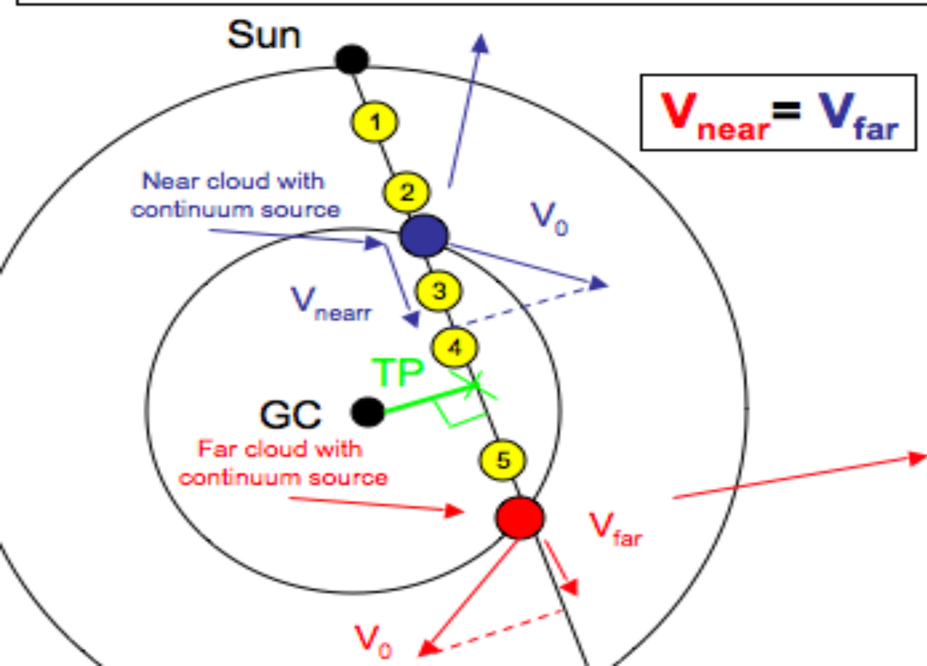
EXAMPLE OF NEAR CLOUD WITH 21 CM CONTINUUM

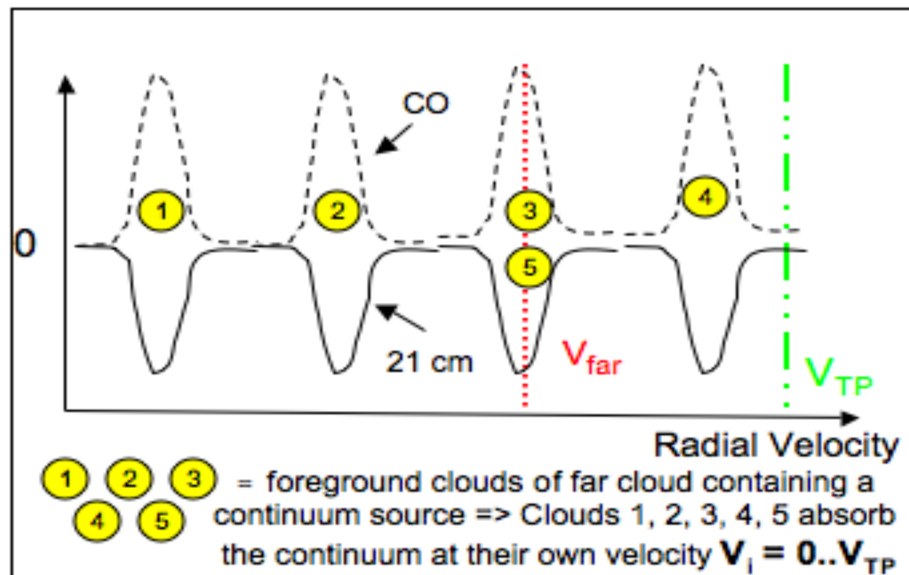


ABSORPTION IN THE 21 CM CONTINUUM

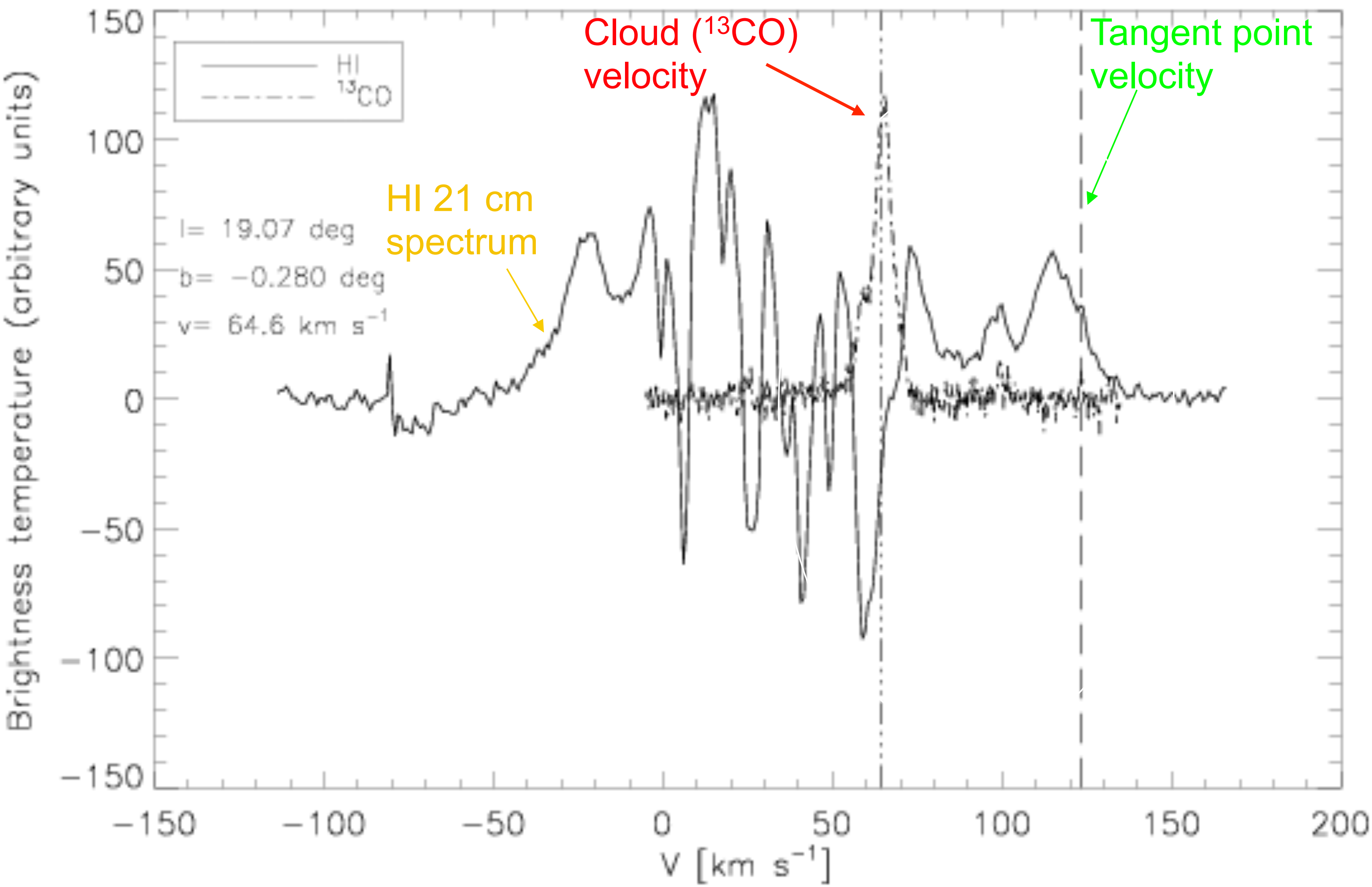




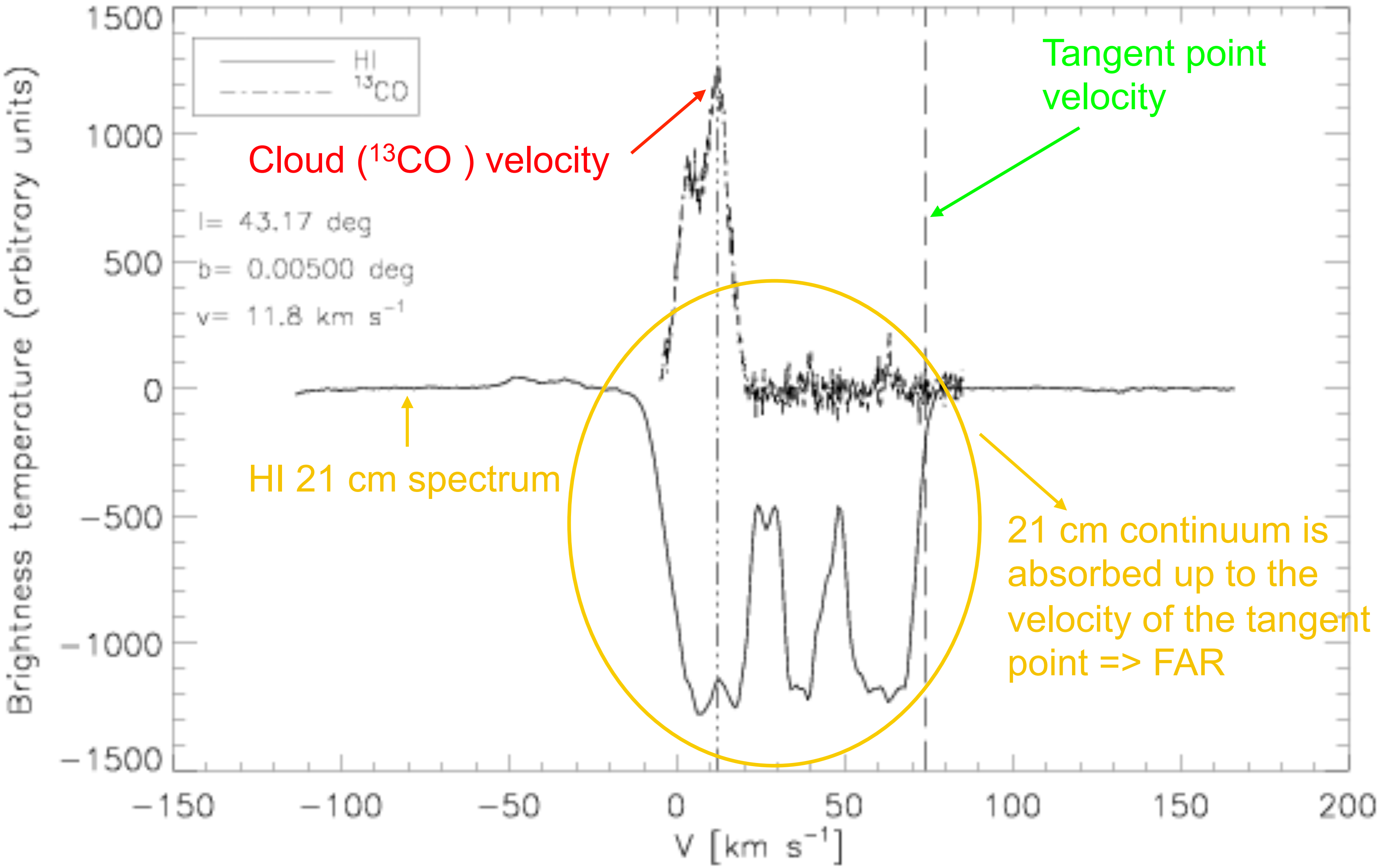




EXAMPLE OF NEAR CLOUD WITH 21 CM CONTINUUM



EXAMPLE OF FAR CLOUD WITH 21 CM CONTINUUM



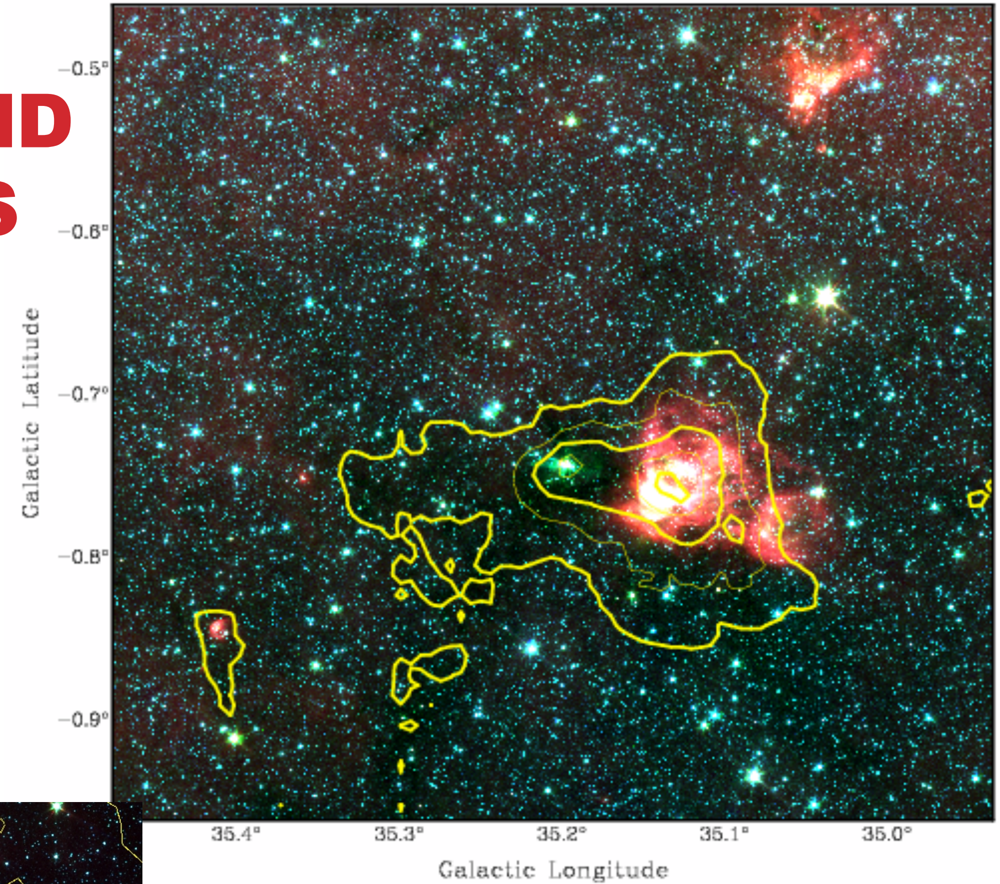
DISTANCES TO MILKY WAY MOLECULAR CLOUDS

Our view of the Milky Way is very confused

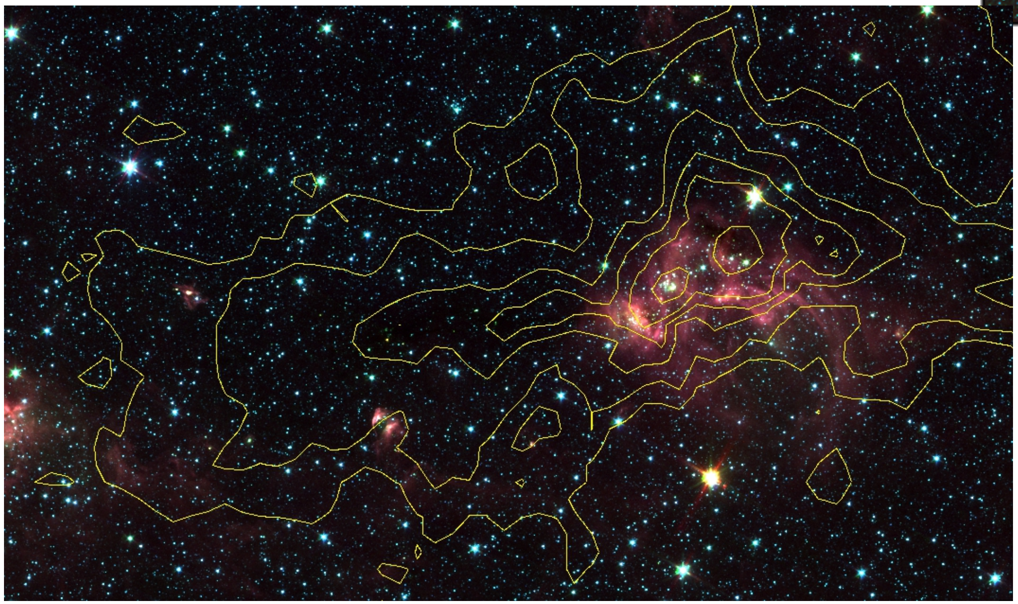
STAR FORMATION AND MOLECULAR CLOUDS

GLIMPSE:
Red = 8 μm
Green = 4.5 μm
Blue = 3.8 μm

GALACTIC RING SURVEY (GRS):
13COJ=1-0



GRSMC G035.14-00.76



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