Spectroscopic Surveys of CO Emission in the Milky Way

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Umass / KOSMA

Formation and Development of Molecular Clouds

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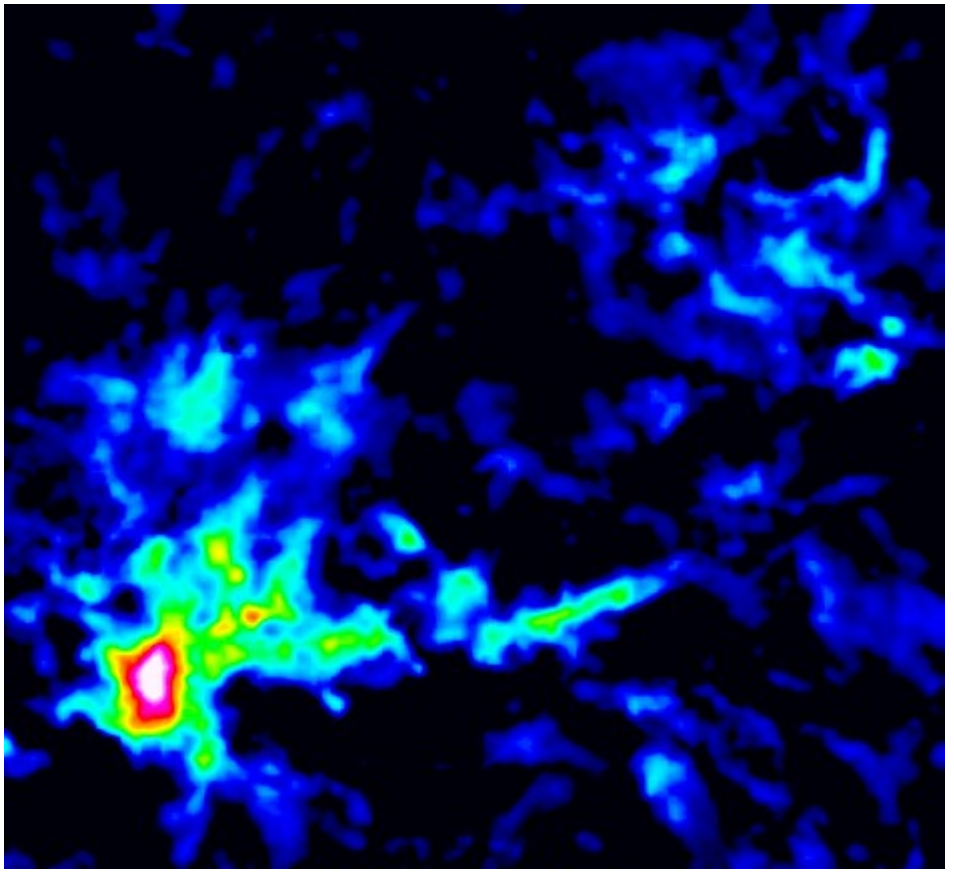
Value of Galactic Plane Surveys

- CO spectroscopic imaging enables views of GMCs **<u>across</u>** the Galaxy
- **ISM Diversity:** need for large sample sizes
- **GMCs are complex objects**:

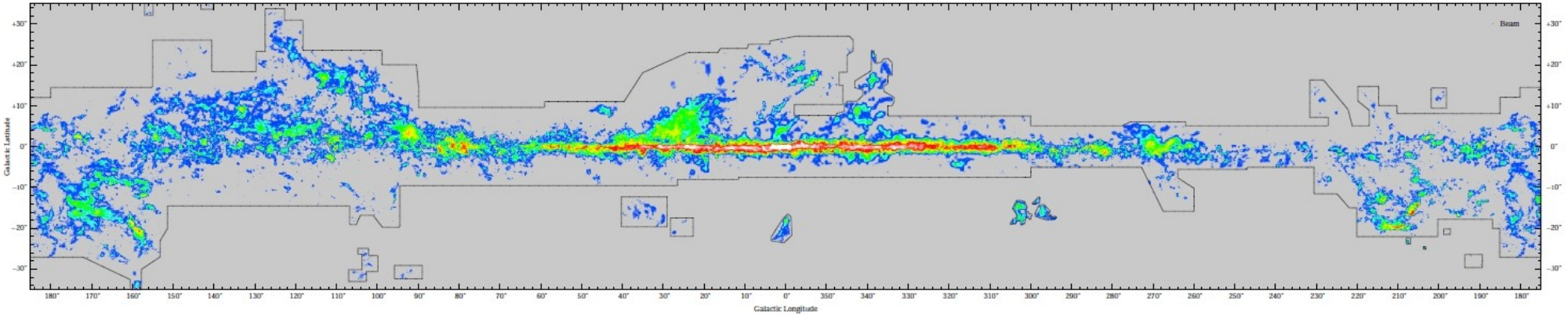
High spatial dynamic range is essential

- **Velocity information:** best diagnostic for dynamical systems



Complete Survey of CO in MW

Dame, Hartmann & Thaddeus 2001



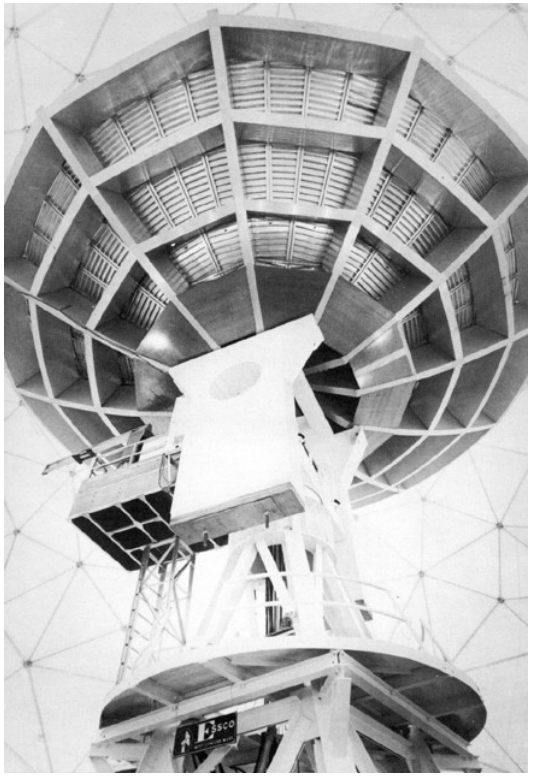
- Excellent calibration
- Complete survey of the MW molecular disk

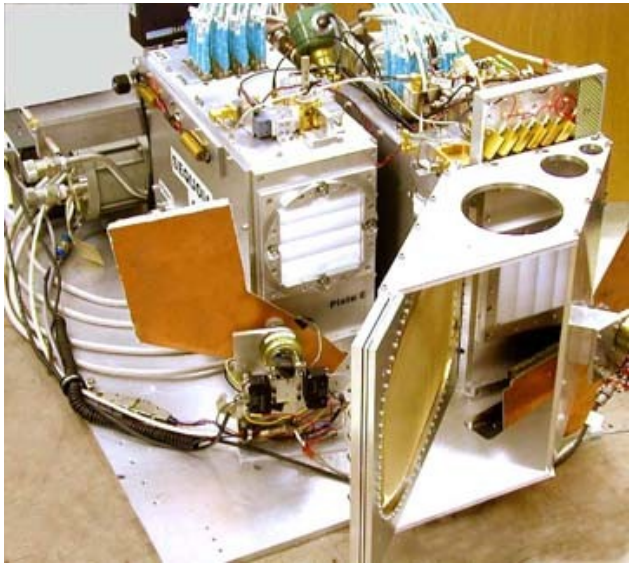
Limitations:

- 8.7 arcmin resolution
- ^{12}CO: opacity >>1

FCRAO 14m Telescope (1976-2006)

- 14m antenna 45” at 115 Ghz
- SEQUOIA – 32 pixel, focal plane array
- Autocorrelation spectrometers
- On-the-Fly Mapping
- Stable, efficient control systems



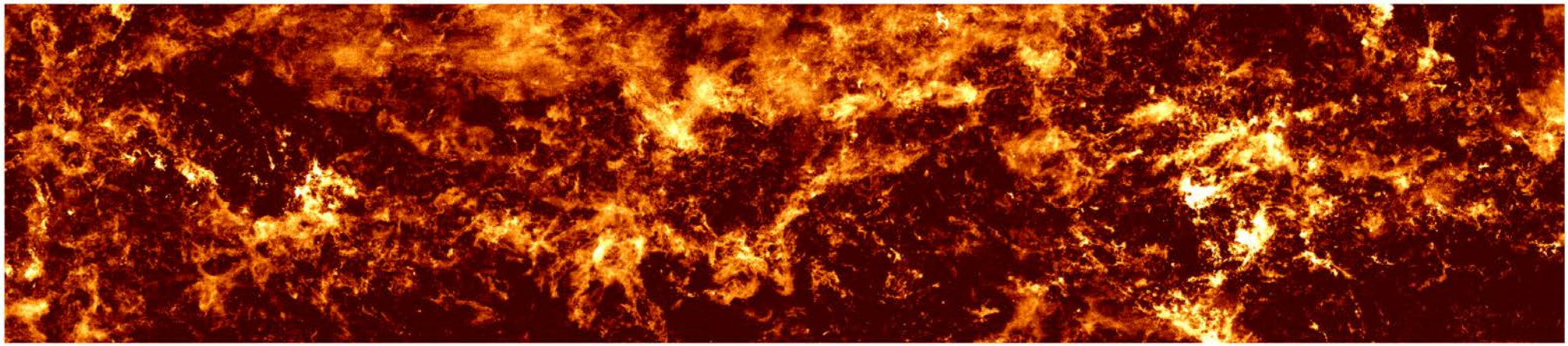


FCRAO Galactic Plane Coverage: 1115 deg^2

Survey	Coverage	Mol.	Sampling	Sensitivity (T_{MB})	Publication	Data Access
Outer Galaxy Survey	102 < l < 141 -3 < b < 5.5	^{12}CO	50.2” 0.82 km/s	0.93	Heyer etal 1998	Yes
BU-FCRAO Galactic Ring Survey	18.5 < l < 55.5 |b| < 1	^{13}CO	22.2” 0.13 km/s	0.21	Jackson etal 2006	Yes
Anti-Center Survey	175 < l < 192 -3.5 < b < 5.5	^{12}CO ^{13}CO	22.5” 0.13 km/s	2.02 0.88	Brunt etal 2012	June 2012
Extended Outer Galaxy Survey	141 < l < 175 -3.5 < b < 5.5	^{12}CO ^{13}CO	22.5” 0.13 km/s	2.00 0.83	Brunt etal 2012	June 2012
Vulpecula Survey	55.7 < l < 65 |b| < 1.0	^{12}CO ^{13}CO C^{18}O	22.5” 0.13 km/s	1.87 0.46 0.44	Brunt etal 2012	June 2012
Cygnus Survey	65 < l < 102.5 -1.0 < b < 1.5	^{12}CO ^{13}CO	22.5” 0.13 km/s	2.11 0.83	Brunt etal 2012	June 2012
Cepheus Flare Survey	101 < l < 116 5.5 < b < 17	^{12}CO ^{13}CO	22.5” 0.13 km/s	0.9 0.4	Brunt & Heyer 2012	January 2013

FCRAO Outer Galaxy Survey

(QUARRY 15 element Schottky array)

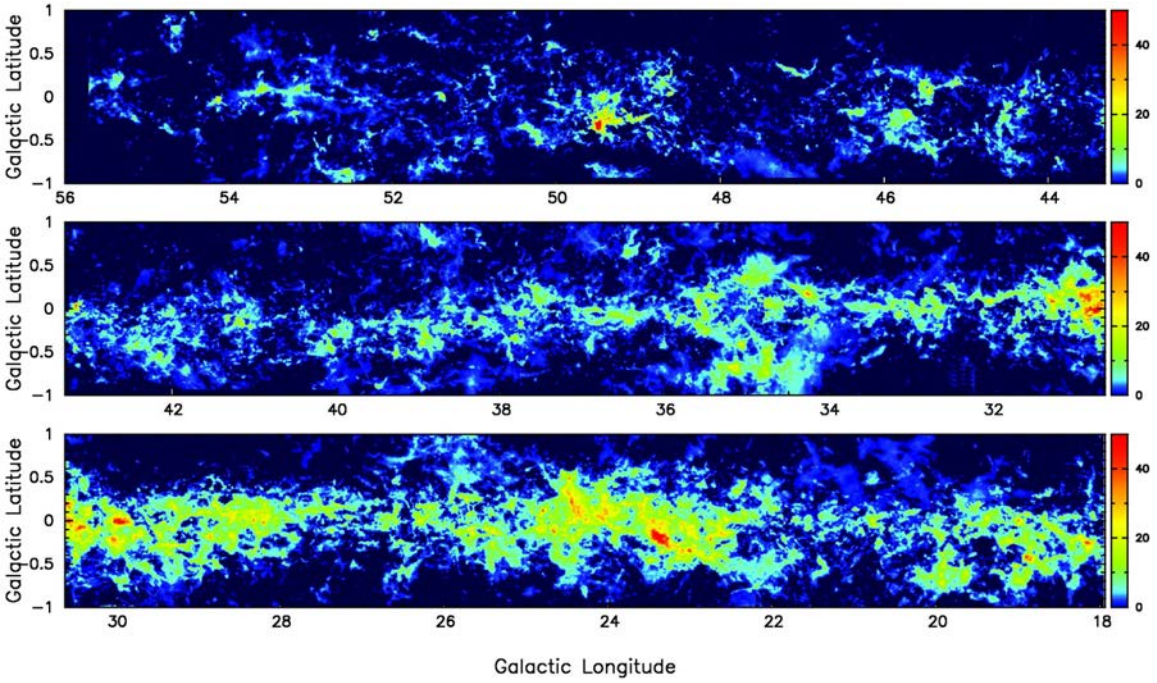


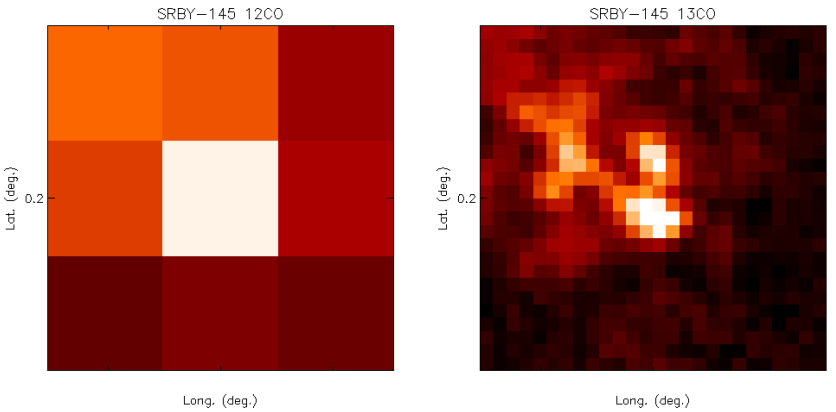
Primary Results

- Confinement of CO to spiral arm features to much more sensitive limits (Heyer & Terebey 1998)
- Equilibrium State of GMCs (Heyer etal 2001)
- Universality of Turbulence (Brunt 2003; Heyer & Brunt 2004)
- HI Self-Absorption-CO Connection (Gibson etal 2000)

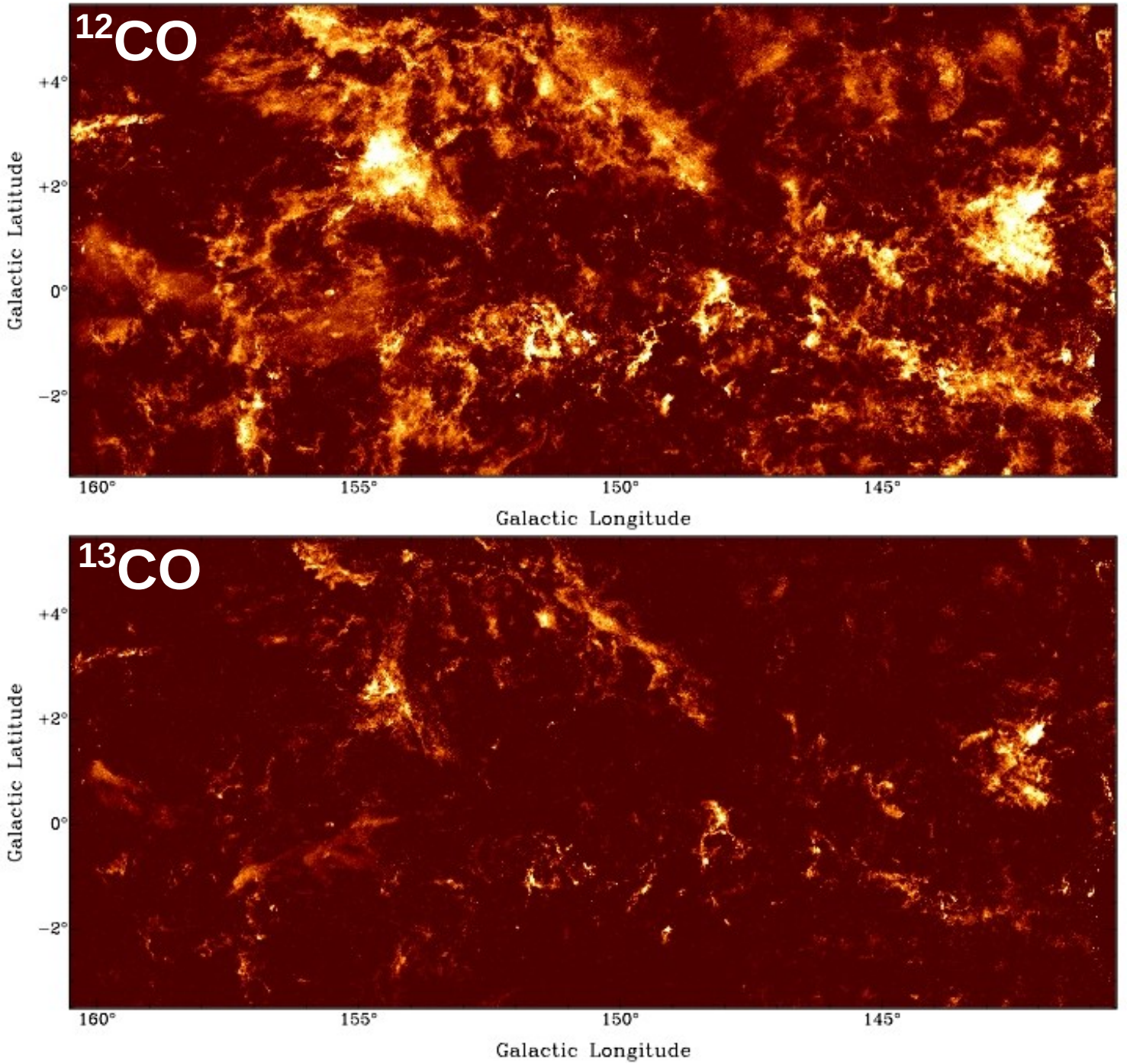
BU-FCRAO Galactic Ring Survey

- Established HI self-absorption to discriminate near-far ambiguity
- Equilibrium of inner Galaxy GMCs (Simon et al 2001)
- Infrared Dark Cloud Distribution (Simon et al 2006; Jackson et al 2008)
- GMCs Properties with HII regions (Andersson et al 2009)
- Reduced surface density of GMCs with respect to SRBY (Heyer et al 2009)
- Dependence of turbulent velocity amplitude on surface density (Heyer et al 2009)

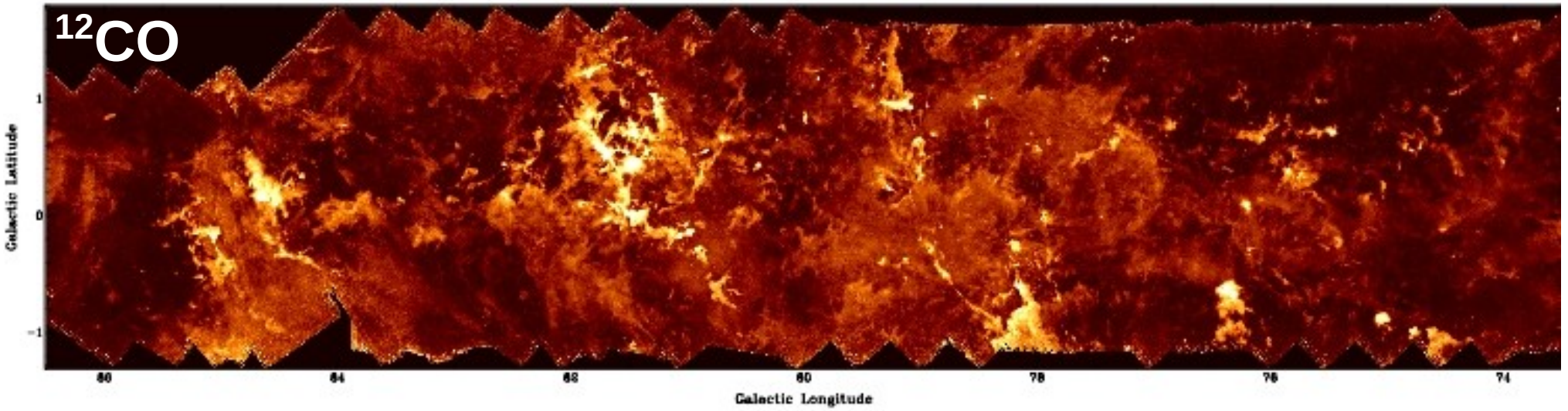


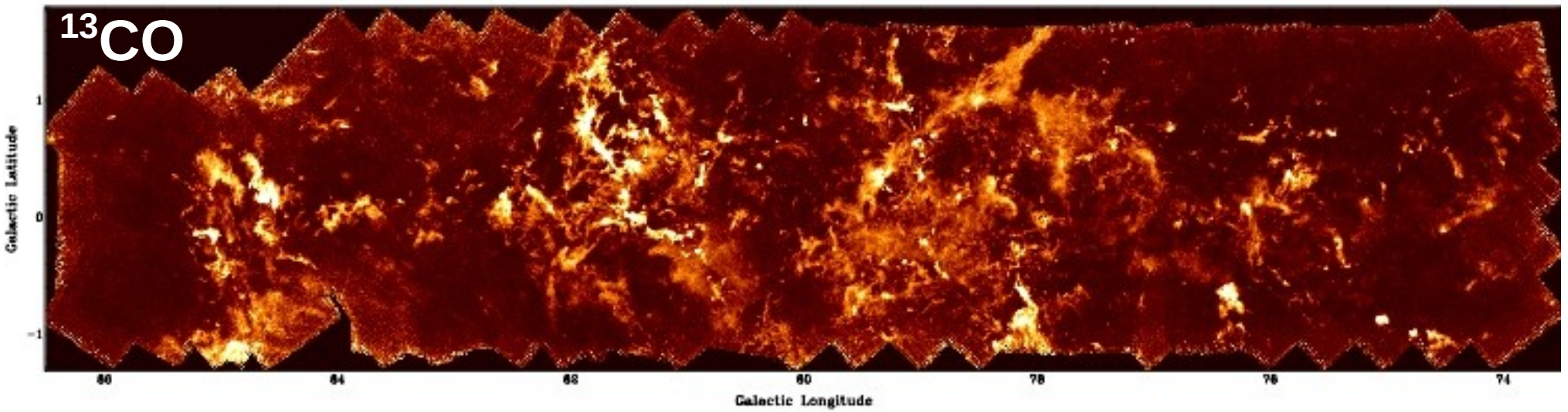


FCRAO Extended Outer Galaxy Survey



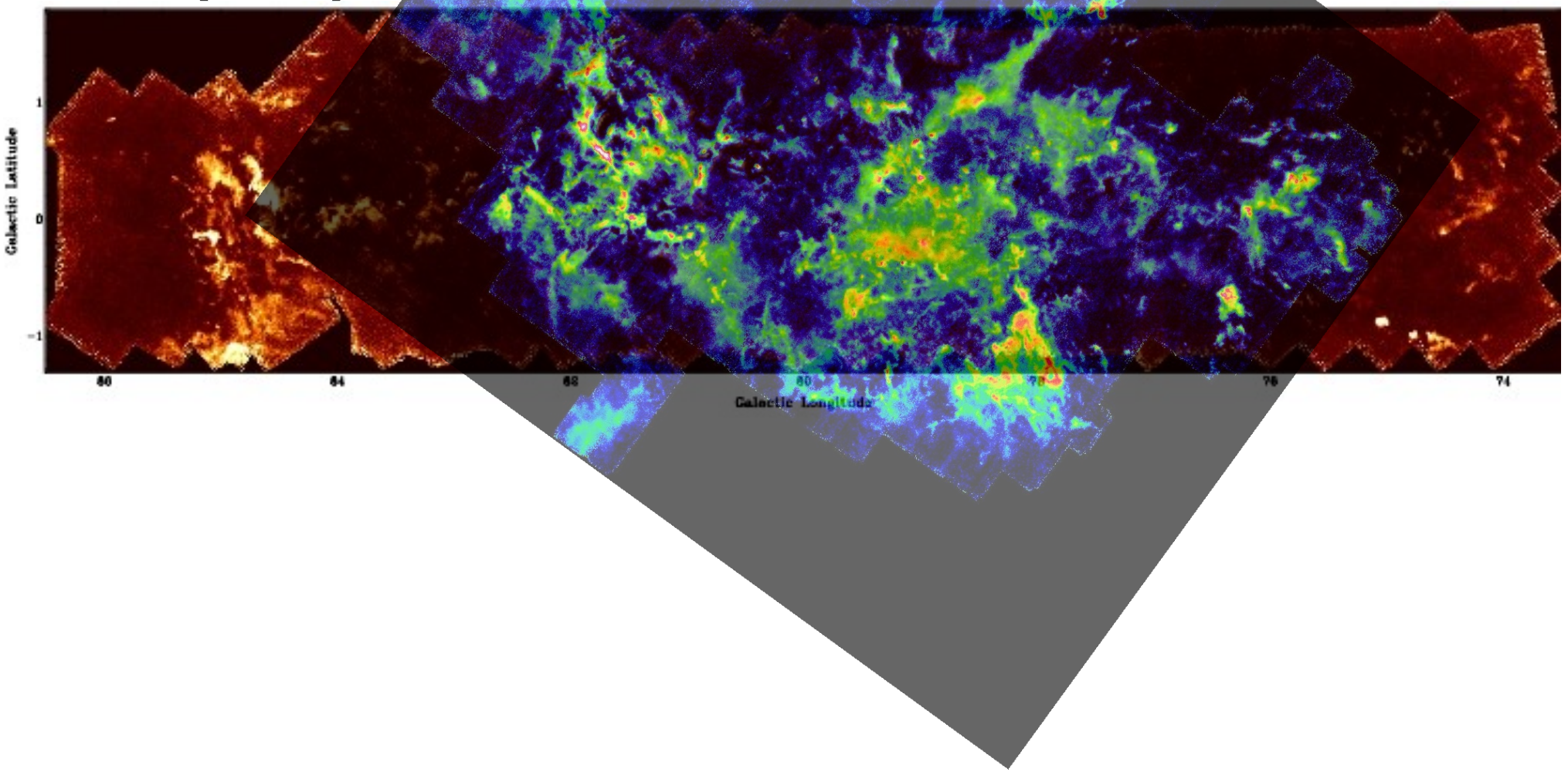
Cygnus:
74 < Longitude < 86





Cygnus X survey

^{13}CO ($C^{18}O$)



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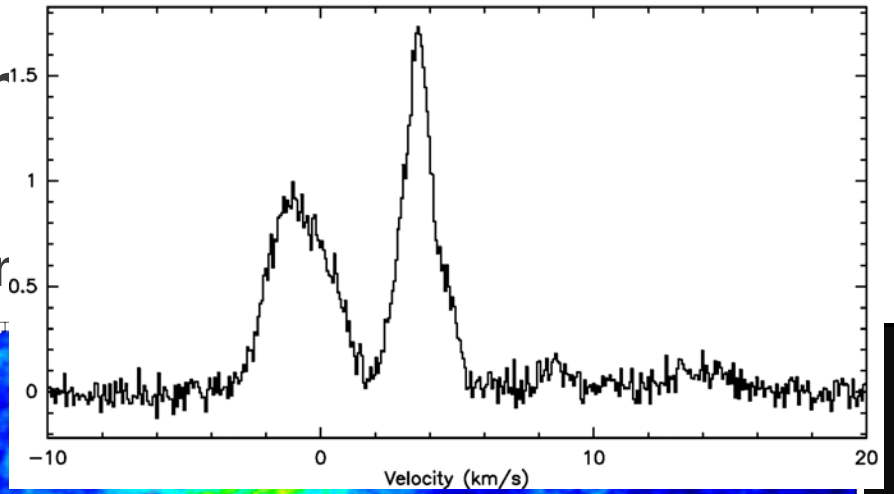
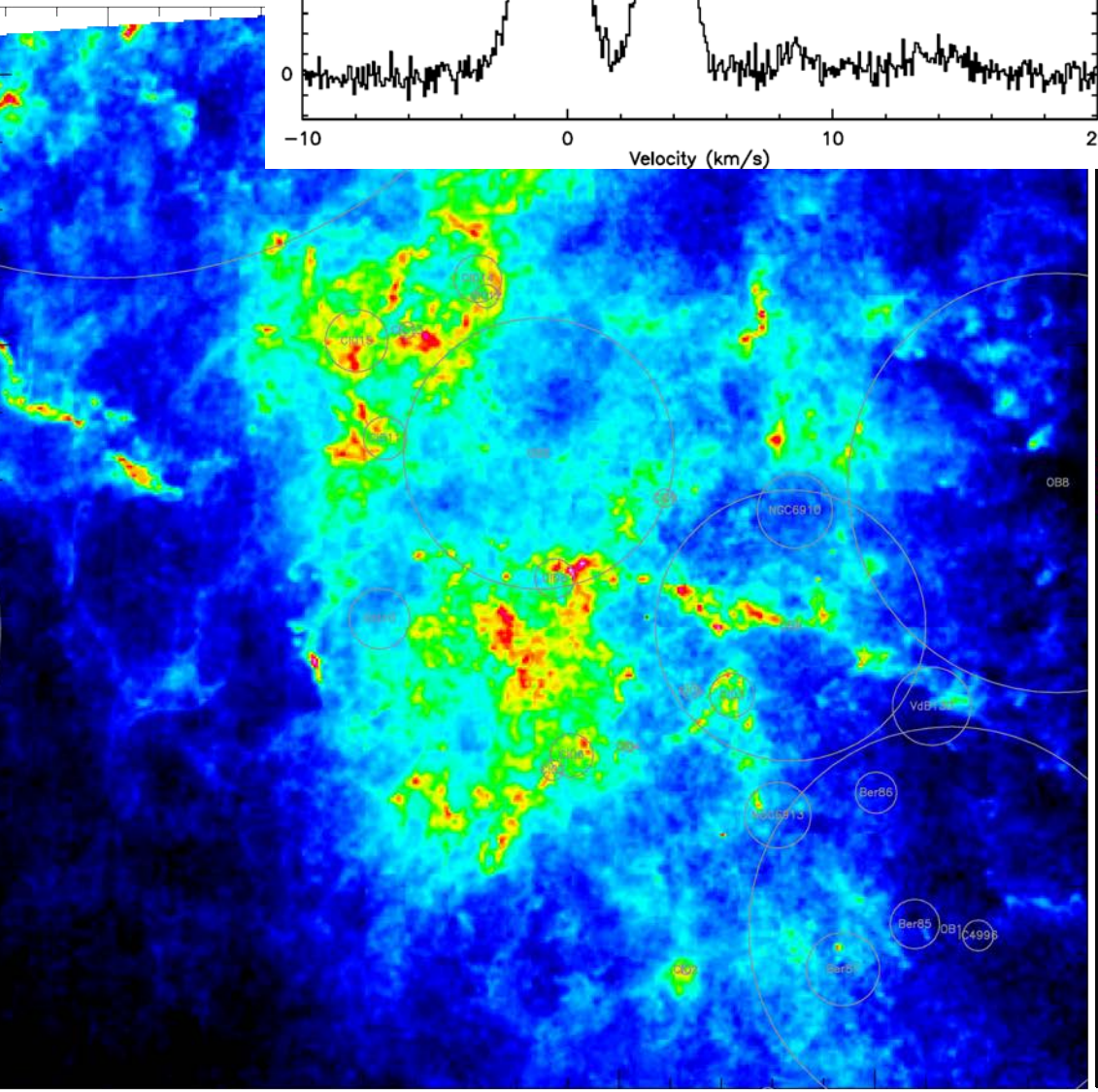
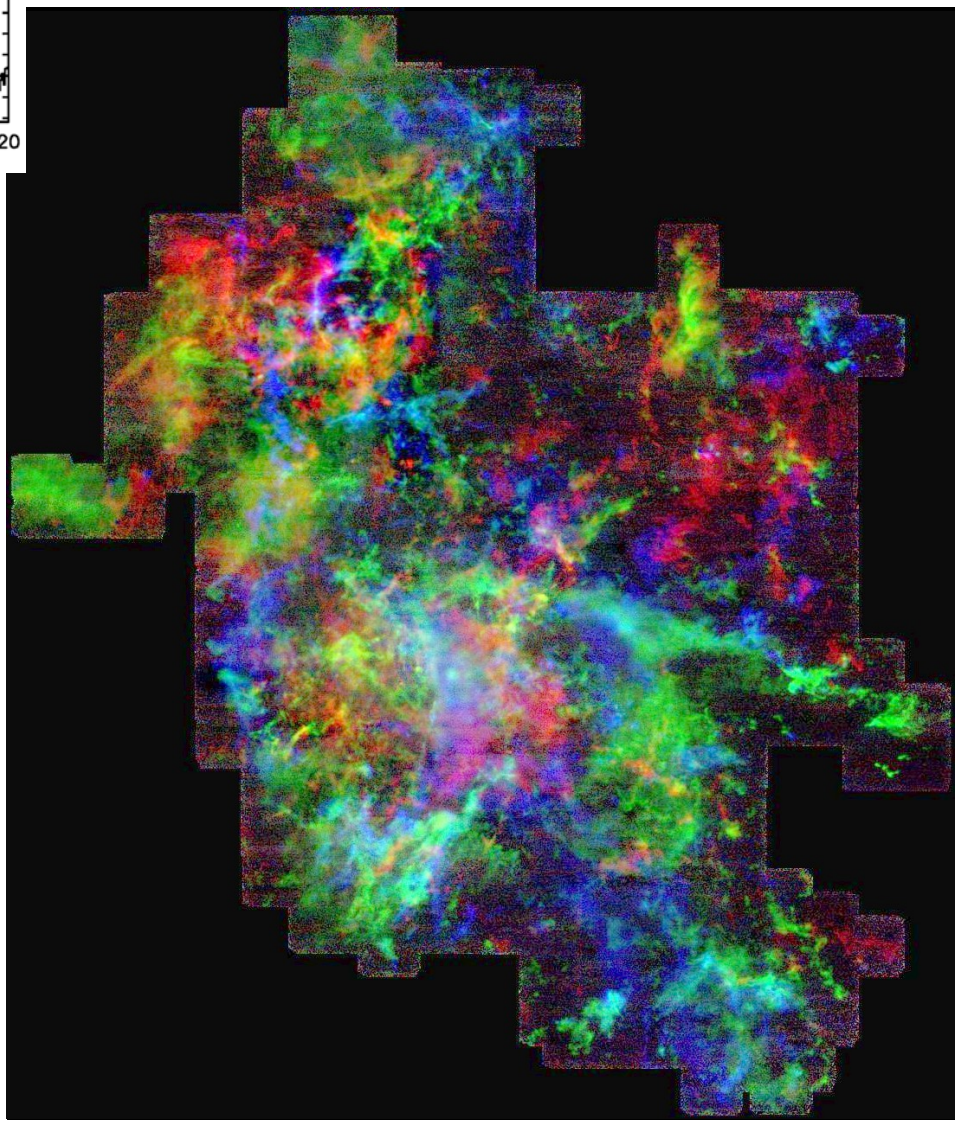




^{13}CO ($C^{18}O$)



Limitations of Milky Way CO Surveys

- Rely on rotation curve to place GMC in disk
- Confusion near tangent point
- Non-circular motions (5 – 30 km/s) in spiral potentials
- Challenging to relate observations to large-scale processes that introduce non-circular motions

- CO likely misses a significant fraction of H_2 mass

- CCAT role?

Constraining the Physics of GMC Formation

Theory

- Formation rate of H_2 is slow (~$10^9/n_H$ yr)
- Top-down processes from diffuse ISM
  - Instabilities: Jeans', Parker, magneto-rotational
  - GMC formation in expanding shells
  - Turbulent, converging HI flows
- Bottom-up process
  - Coagulation of smaller pre-existing molecular clouds
- What is the role of spiral density waves? Catalyst for both?
- Link GMCs to larger structures (spiral arms, shells, HI streams) → nearby galaxies

Constraining the Physics of GMC Formation

- Imaging of so called “Dark H_2” gas is key to understanding GMC formation: (0.1 < Av < 3 mag)
- Planck/FERMI results: extended reservoir of H_2 gas not traced by CO. Distribution?
- CCAT can image a fraction of this component with the 492 GHz CI fine structure line
- Advantage over ALMA: Low surface brightness sensitivity, large scale imaging

Probing the Atomic-Molecular Transition with CCAT

CCAT imaging of 492 GHz CI line

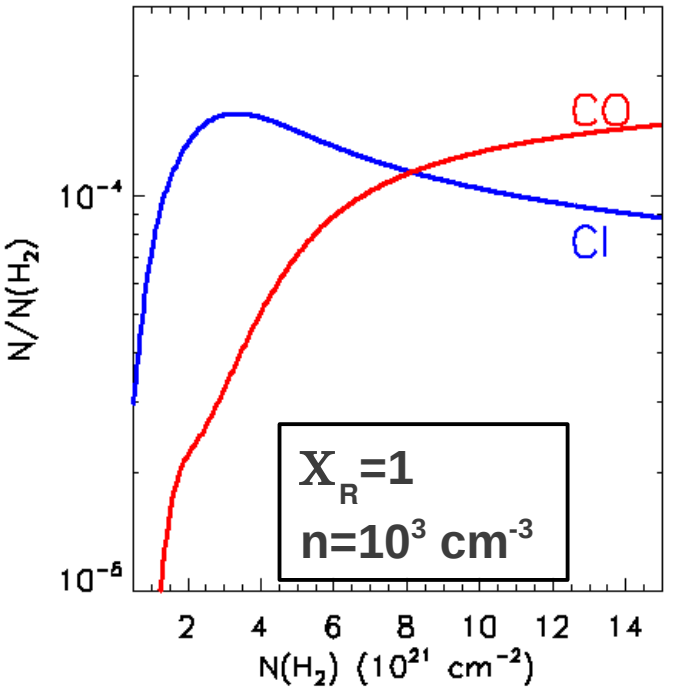
What phase is the gas entering spiral potential?

- Image the spiral structure of CI emission in nearby galaxies

Are CO GMCs located at the interface of converging gas streams?

- Image CI emission that circumscribes a GMC. Analyze velocity field for large scale, converging motions centered on GMC

Meudon PDR Model



Constraining the Physics of Star Formation

Theory: linking cloud dynamics to star forming cores

- Probe kinematics of dense gas in GMCs
    - Angular momentum structure
    - Role of magnetic fields, polarimetry
- Turbulent Fragmentation:
    - Measures of turbulent velocity spectrum: sonic scale

- Still need lower excitation line emission to challenge current theories of star formation that focus on the role of turbulence in the low density gas to produce star forming cores/filaments

Conclusions

- Focal plane array development essential
  - Frequencies?
  - CO 3-2 not as useful as 1-0/2-1 for GMC formation studies
  - CI potentially more useful; it may be difficult to distinguish dark H_2 gas in envelope from residual CI deeper inside
- Galactic plane surveys not worthwhile for CCAT
  - Rather focus on nearby galaxy imaging to address GMC formation complementary to ALMA