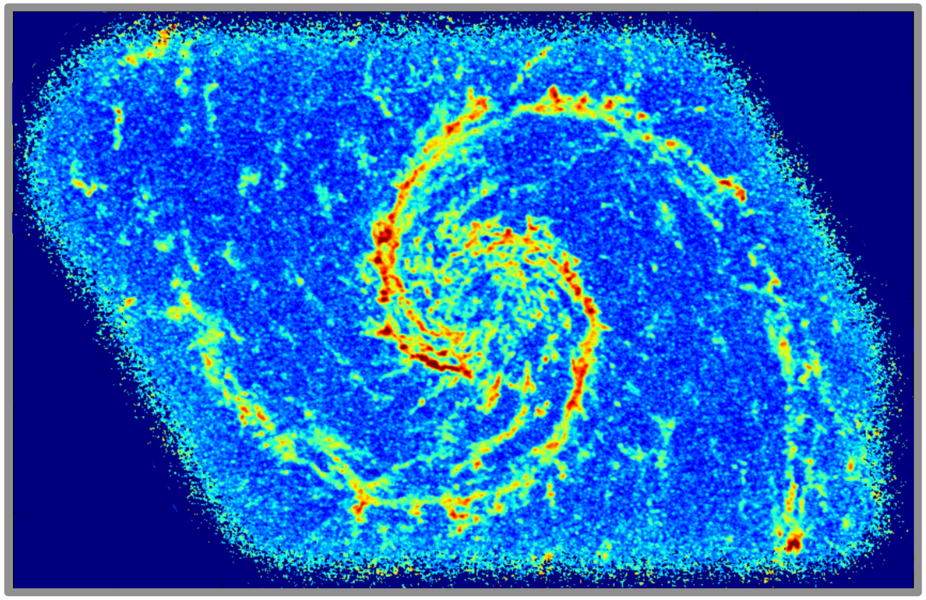
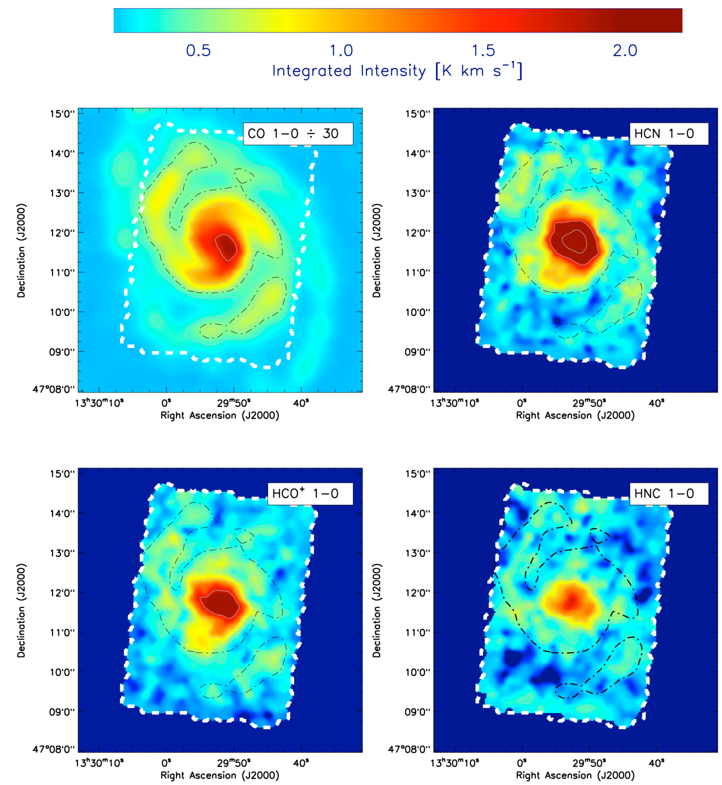
Sensitive mm-Wave Spectroscopy as an Essential Complement to High Resolution Imaging



Cloud-scale interferometric CO map of M51 – Schinnerer+ '13



Sensitive single dish multi-line maps of M51 – Bigiel+ in prep.

Adam Leroy (Ohio State University)

Amanda Kepley and the Green Bank dense gas collaboration

Antonio Usero, Fabian Walter and the HERACLES dense gas collaboration

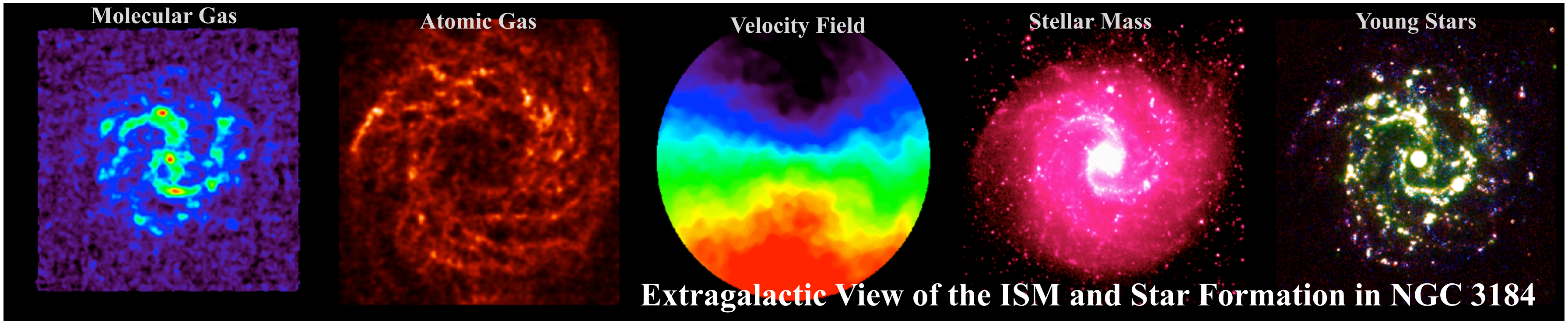
Frank Bigiel, Maria Jesus Jimenez Donaire and the EMPIRE collaboration

Annie Hughes, Eva Schinnerer, Sharon Meidt and the PAWS collaboration

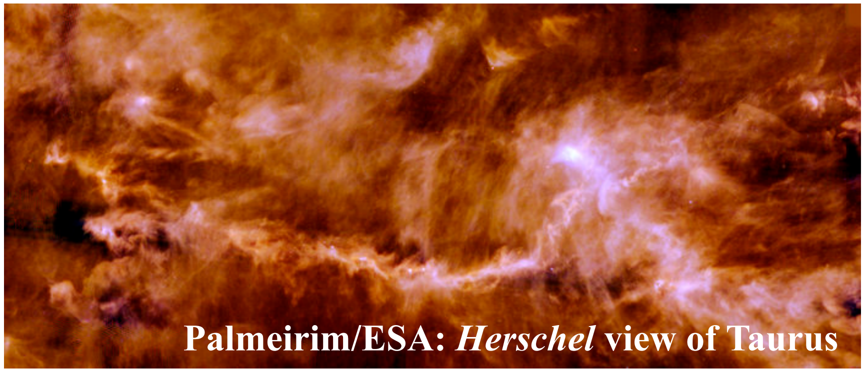
Incl.: Alberto Bolatto, Santiago Garcia-Burillo,, Erik Rosolowsky, Karin Sandstrom, Andreas Schruba

How To Link These Two Views of Star Formation?

Complete multiwavelength views of star formation and gas on ~ kpc scales

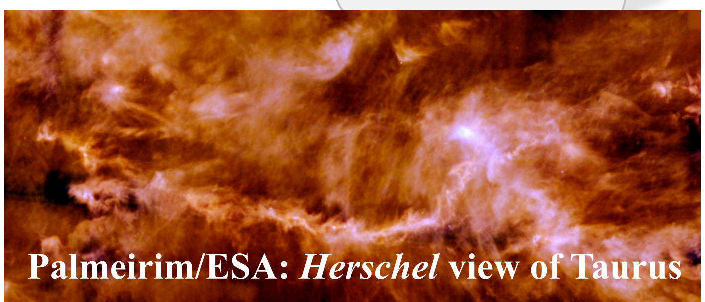


Detailed views of young stars and gas structure inside individual Milky Way clouds.

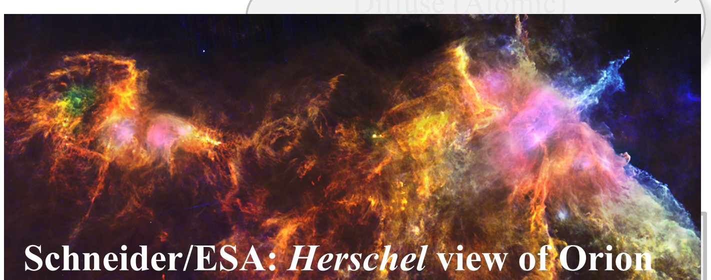


Star Formation in Galaxies and Small Scale Physics

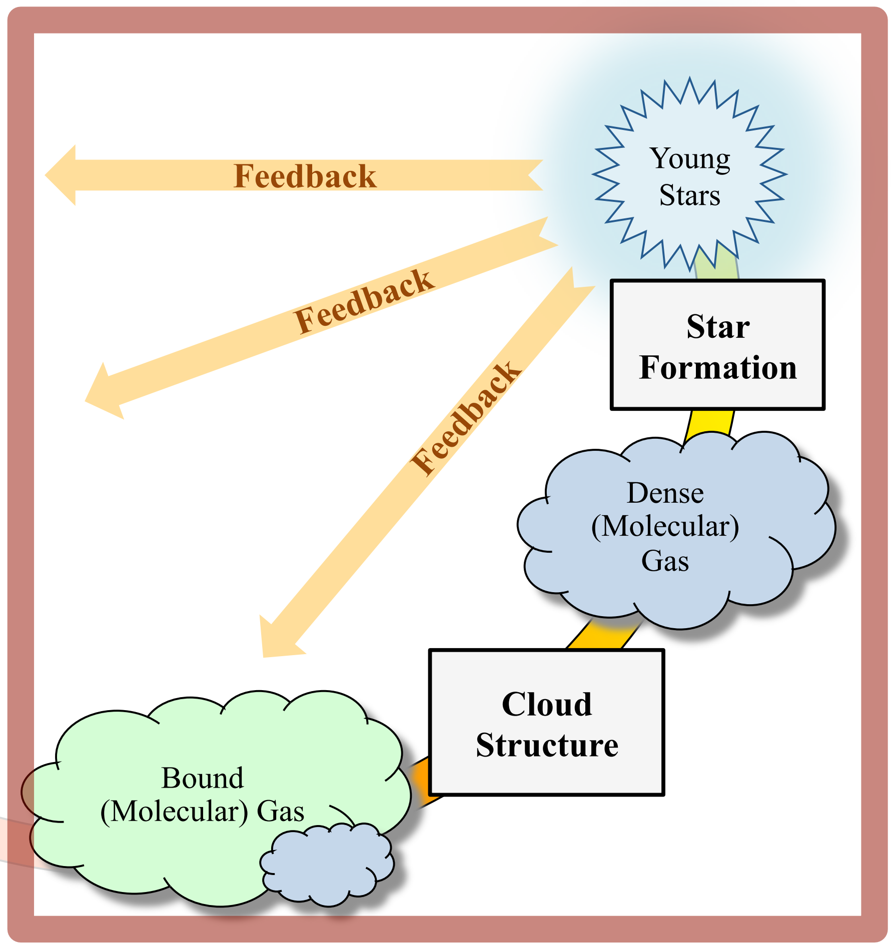
Stars form at very small scales. Large scale variations in the SFR-per-H_2 ***require*** *a link between large scale environment and physical conditions in the gas.*



Palmeirim/ESA: *Herschel* view of Taurus



Schneider/ESA: *Herschel* view of Orion



Linking SFR/H_2 to Local Physics

*How are **local physical conditions** set by galactic environment, how do they influence SFR per H_2?*

(1) Dense gas mass: locally, stars form out of high column, high density material.

e.g., Heiderman+ '10, Lada+ '10, '12, Andre+ '14, Evans+ '14; also Gao & Solomon '04, Wu+ '05, '10

How does the **dense gas mass fraction** depend on conditions in a galaxy?

Is the **rate of star formation in dense gas** universal?

(2) Cloud scale (~30 pc) structure: in turbulent models, cloud-scale conditions drive SFR.

e.g., Padoan & Nordlund '02, Krumholz+ '05, '12, Hennebelle & Chabrier '08, Hopkins+ '12, Federrath & Klessen '12

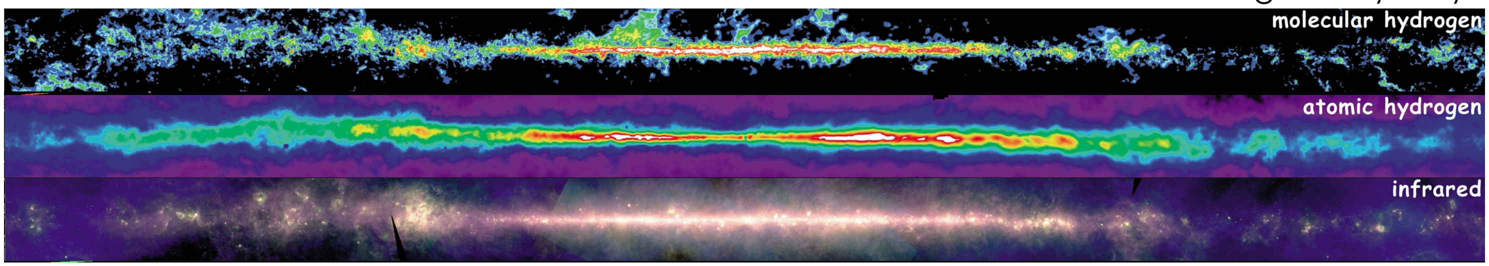
How do the cloud-scale **density**, **Mach number**, and **gravitational boundedness** affect SFR/H_2?

How do these quantities depend on conditions in a galaxy?

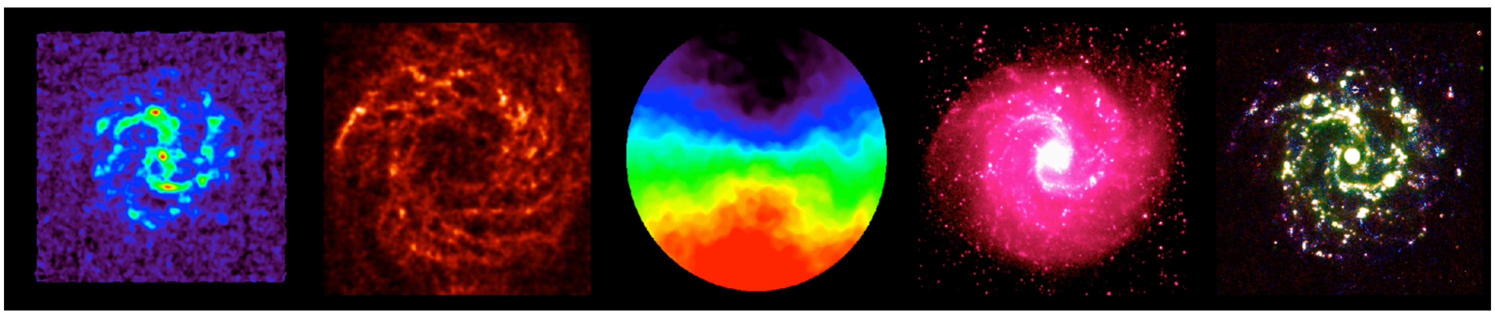
*We would like **observational** answers to these questions from a diverse set of galaxies.*

Other Galaxies: Perspective, Diversity, Statistics

NASA's Multiwavelength Milky Way



THINGS/HERACLES/SINGS view of NGC 3184

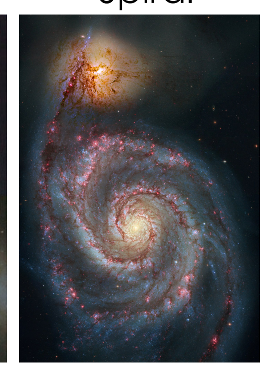


I Zw 18
Primitive starburst

M81
Quiescent Disk

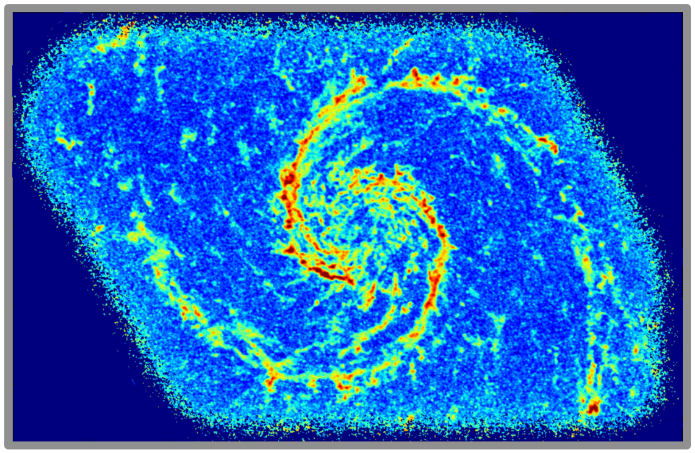
M82
Gas-Rich Starburst

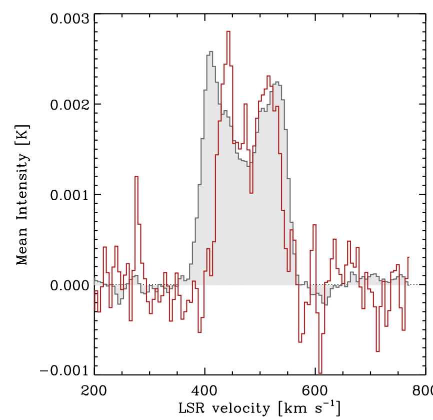
M51
Spiral



The Take Away Point

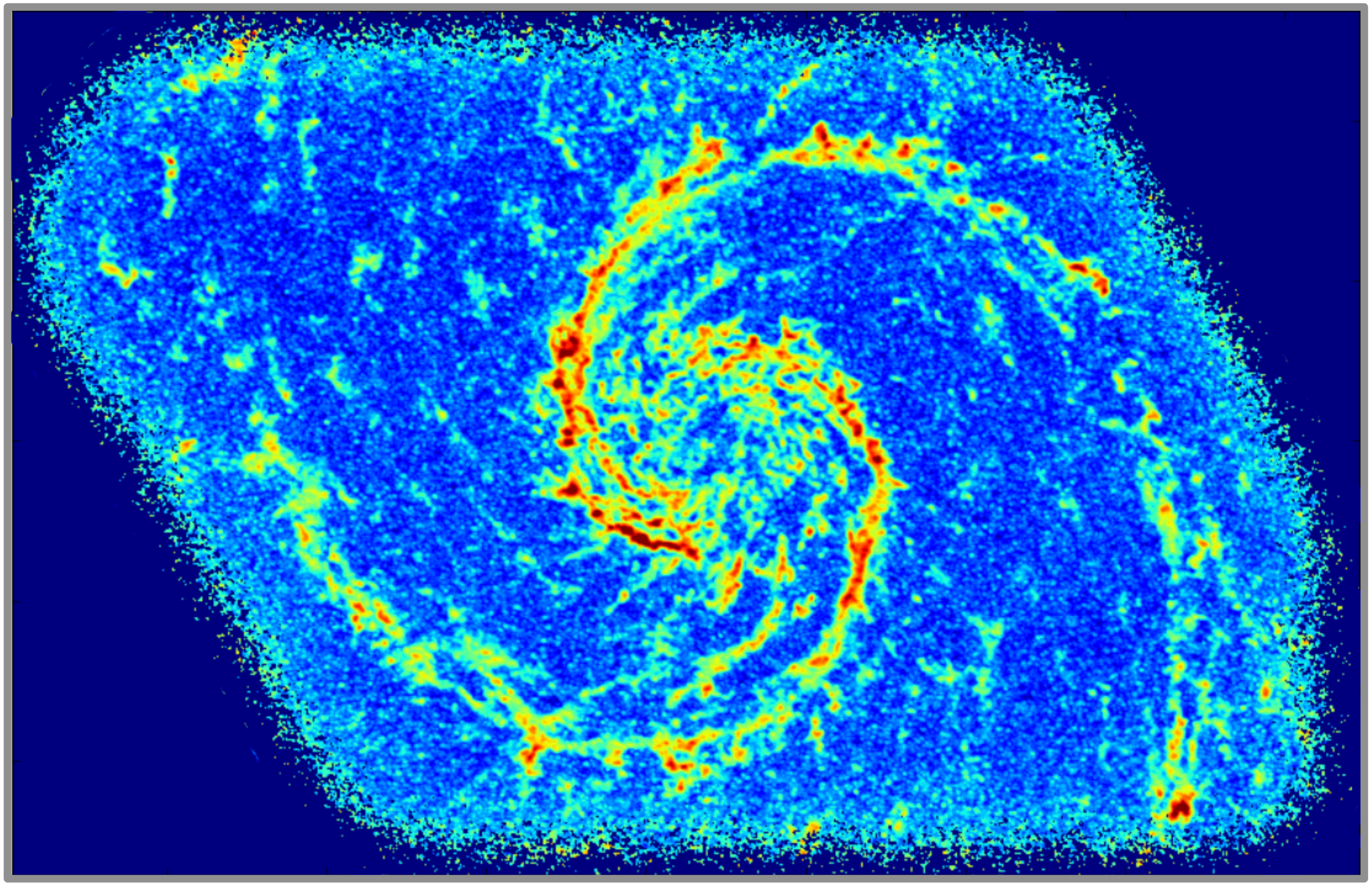
Sensitive mm-wave spectroscopy (a forte of the GBT) is an essential complement to high resolution imaging to understand the physics of star formation in a galactic context.





Cloud-Scale Structure from Interferometric Imaging

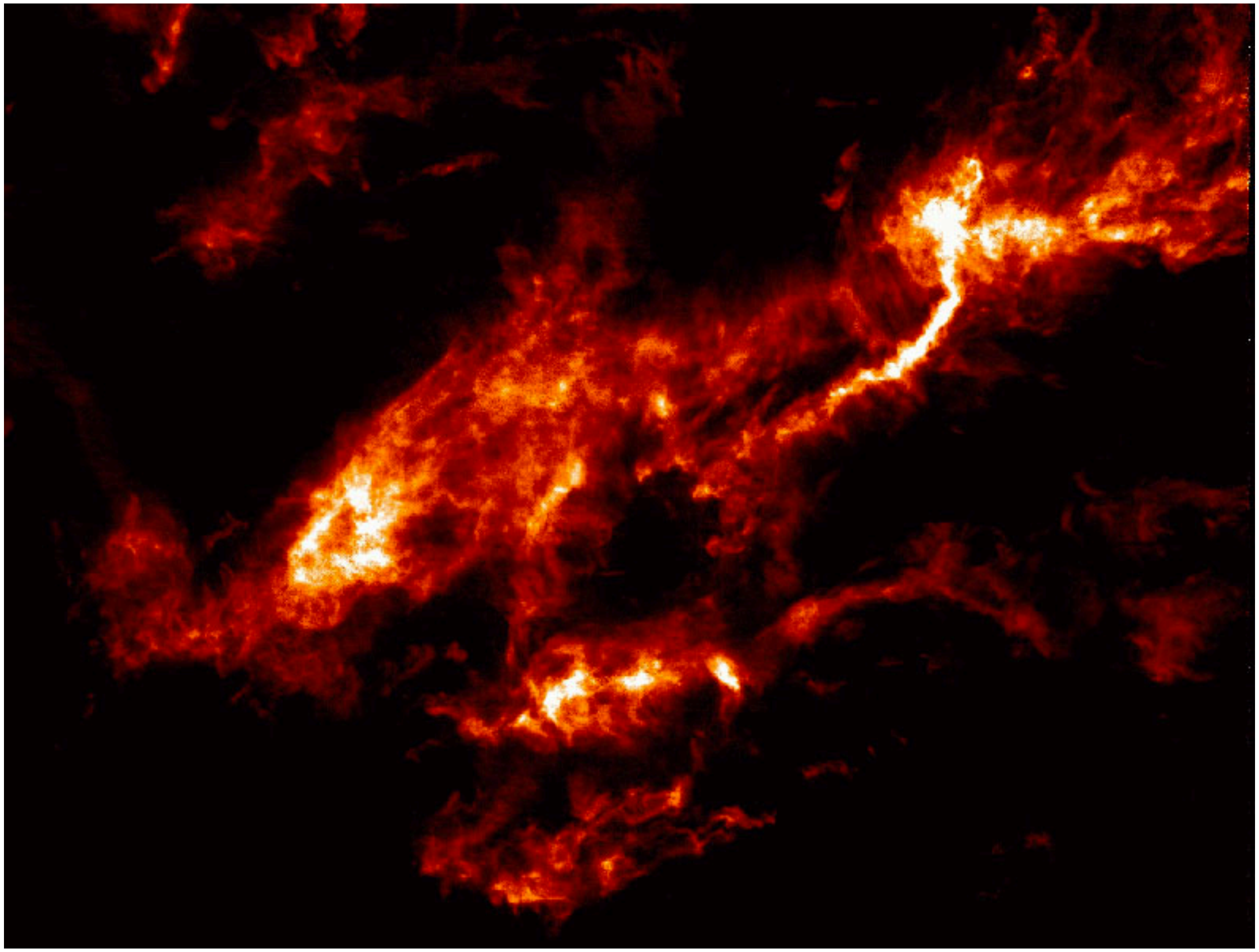
Cloud scale surface density, turbulent dispersion, boundedness – can be directly observed in galaxies out to ~ 15 Mpc. Here the PdBI PAWS view of M51 in CO.



M51 at 40 pc : *Schinnerer+ '13, Pety+ '13, Meidt+ '13, Hughes+ '13ab*

Cloud-Scale Structure from Interferometric Imaging

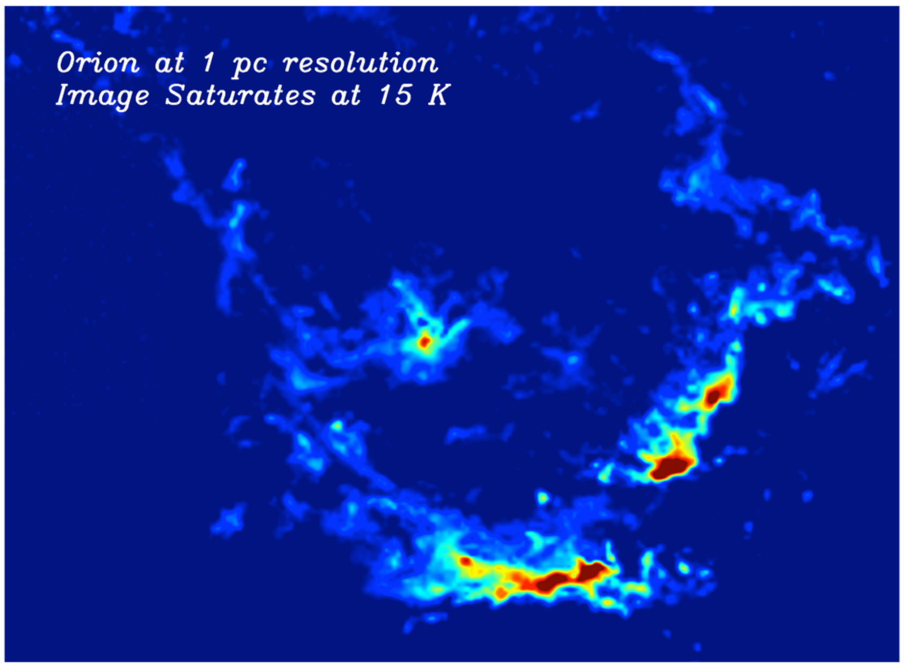
The dense star-forming superstructure (filaments) ***within*** *local star-forming molecular clouds are ~ 0.1 pc across.*

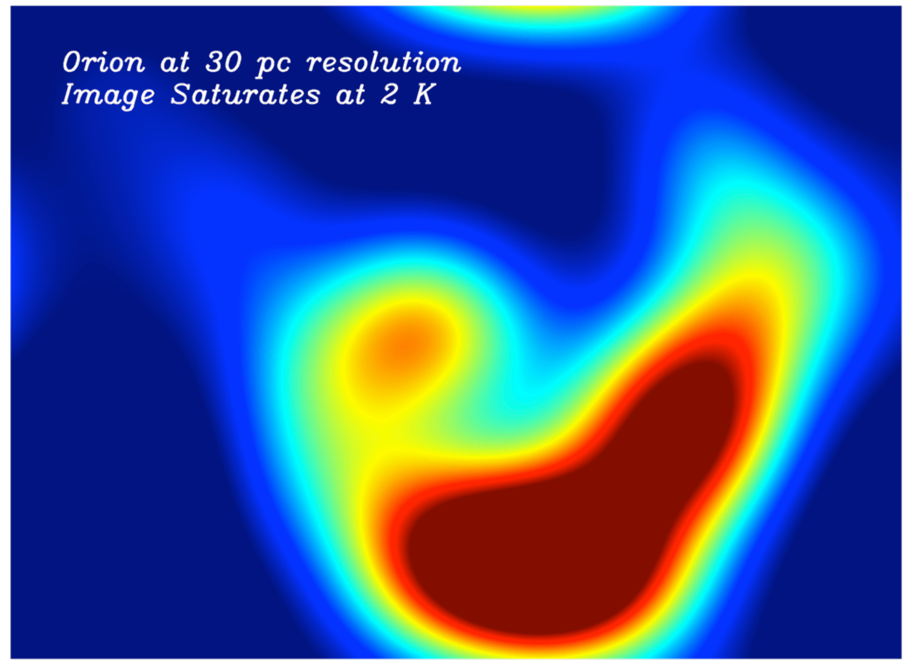


Filaments in Taurus from CO mapping – peak ^{13}CO intensity: *NARAYANAN+ '08*

Cloud-Scale Structure from Interferometric Imaging

*Achieving resolutions matched (even within ~ an order of magnitude) of these star-forming substructures using interferometers targeting other galaxies is **extremely** challenging.*





This is what Orion looks like in the PAWS M51 CO map.

Orion at 1 and 30 pc: *WILSON+ '05*

The Challenge of High Physical Resolution at Distance

Resolving dense substructure is <u>very</u> hard – even with ALMA.

Substructure Mapping:

- For a fixed array + brightness:

$$\tau_{\mathrm{int}} \propto \theta^{-4}$$

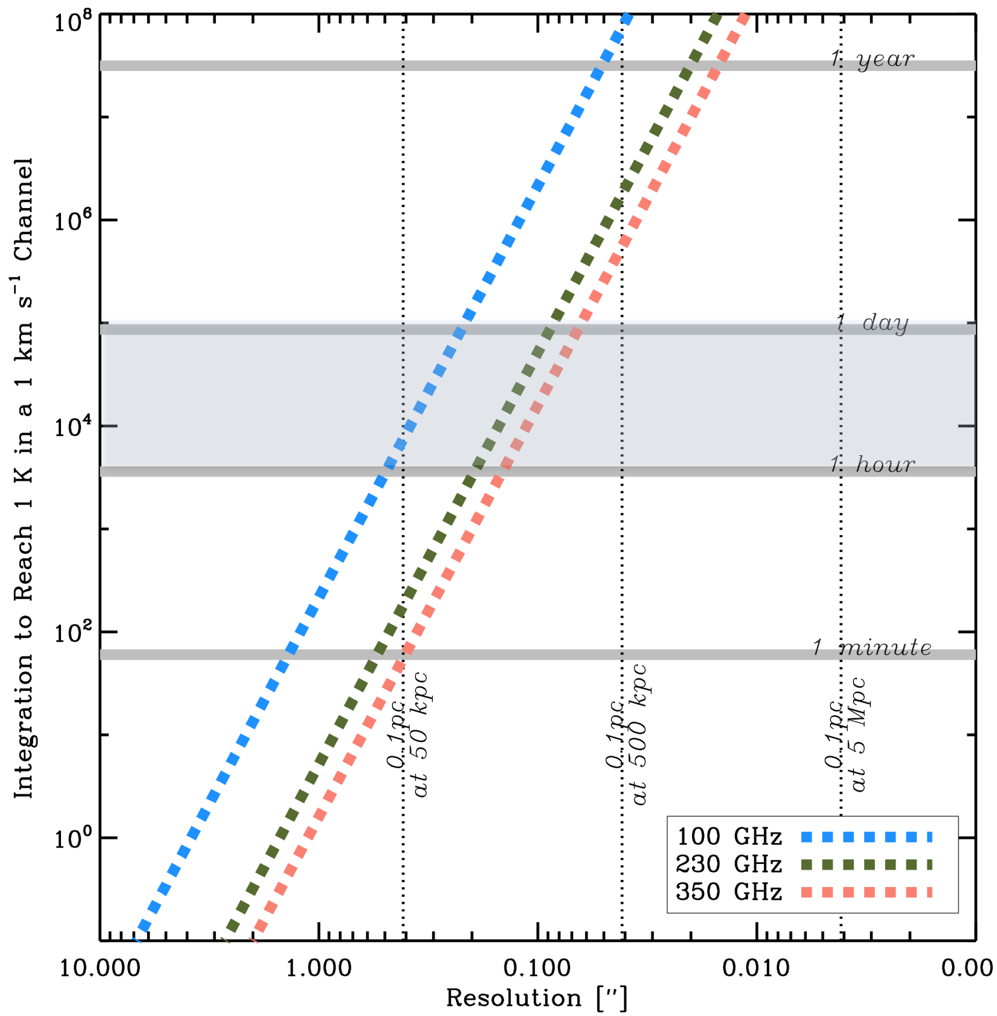
- So for fixed (e.g., 0.1 pc) res.:

$$\tau_{\mathrm{int}} \propto d^{4}$$

- Gains in field of view:

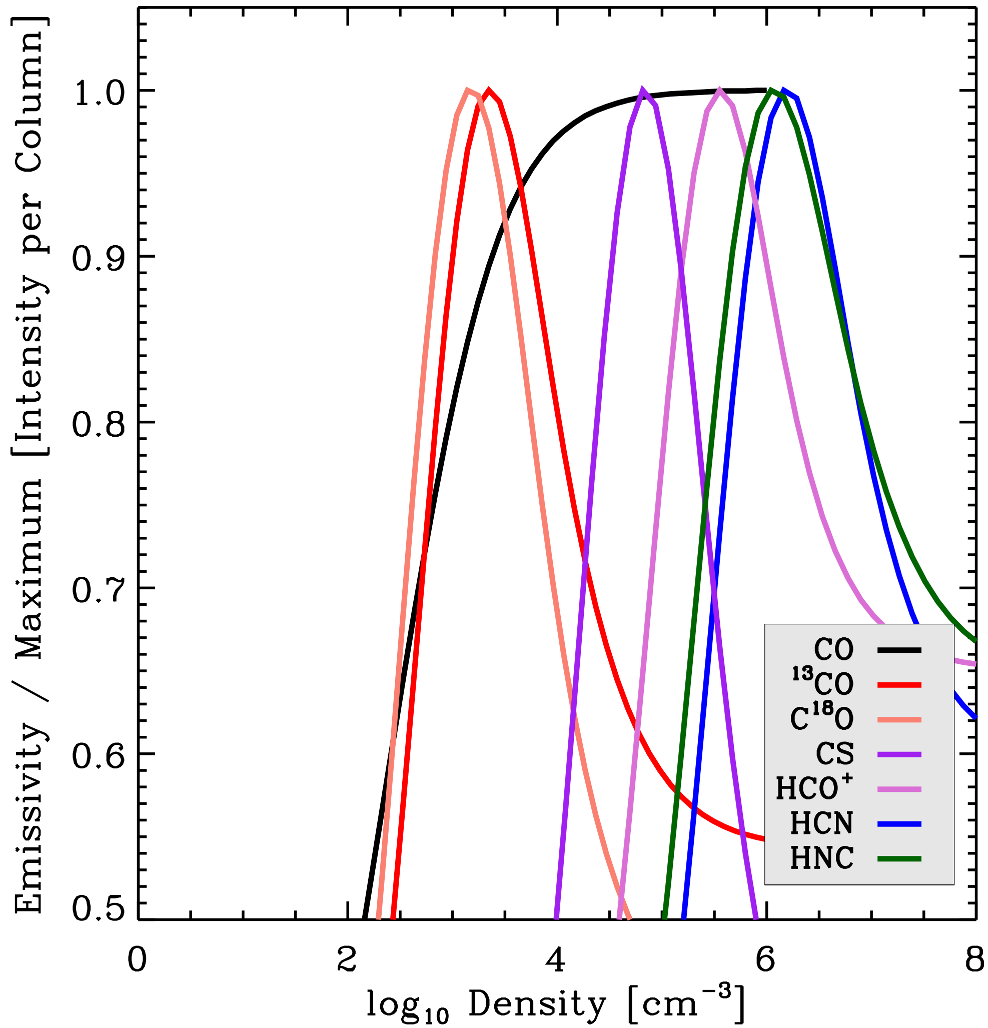
$$A_{FOV} \propto d^{2}$$

ALMA Time to Reach Fixed Sensitivity



Spectroscopic Tracers of Substructure

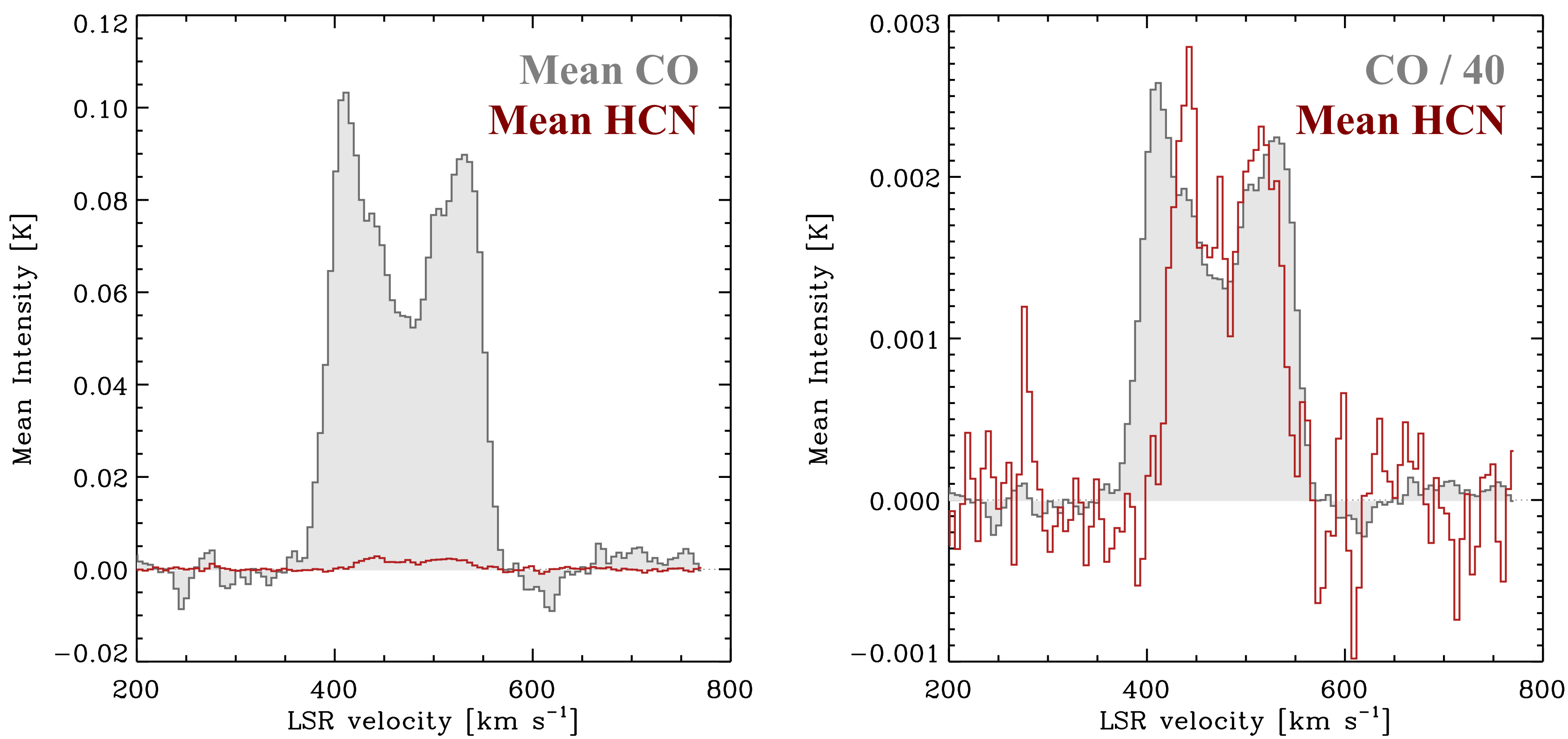
GBT-observable molecular species in the 3mm window emit effectively at different densities. Comparing them gives a handle on the density distribution within a beam.



RADEX (VAN DER TAK '07) CALCULATIONS AT N_{H2} ~ 1E22 CM^{-2} AND ~30 K

Faintness of Dense Gas Tracers

Dense gas tracers are still faint – here is the disk-integrated mean spectrum of M51. CO is on average 30-40 times fainter. This means ~1000 times longer for a matched quality map.

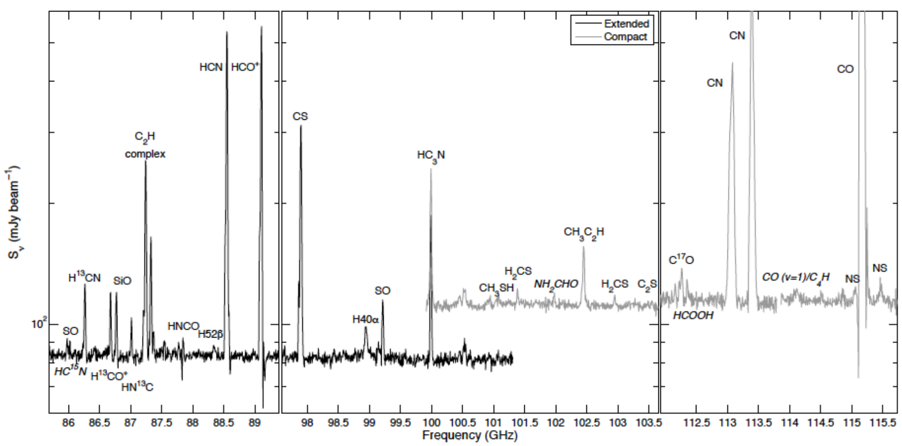


Maps integrated from Pety et al. (2013), Bigiel et al. in prep.

mm-wave Spectroscopy with Current Facilities

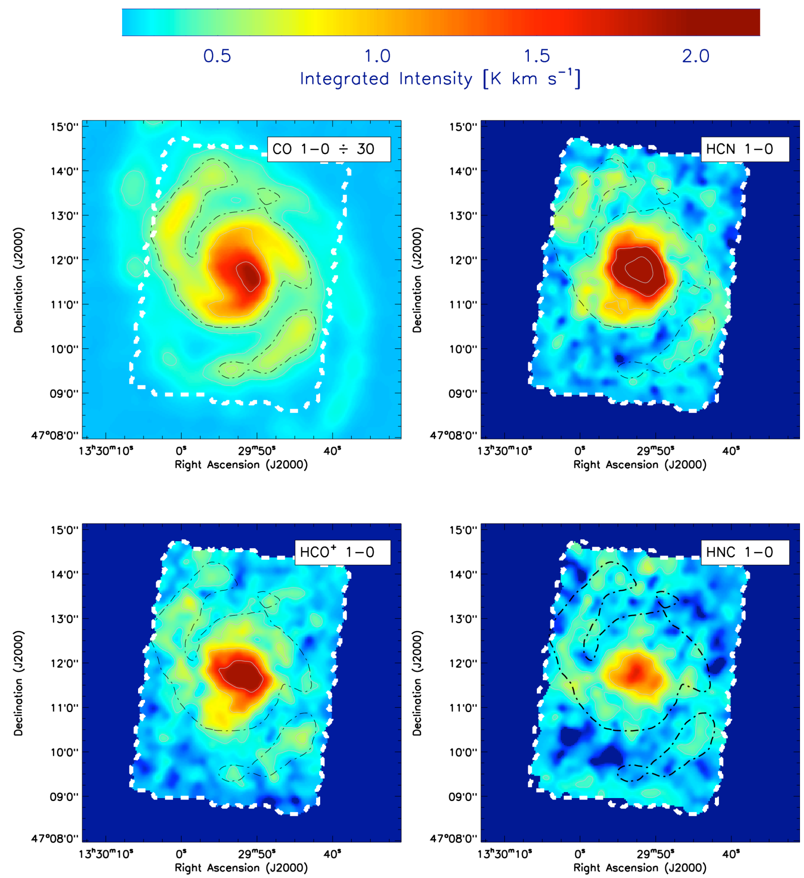
We can do this now in a systematic way (building on earlier case studies) – though it still takes a lot of effort. New instrumentation and significant time commitments.

ALMA spectrum of the inner region of NGC 253



MEIER ET AL. (2015); C.F. LEROY ET AL. (2015), BOLATTO ET AL. (2013)

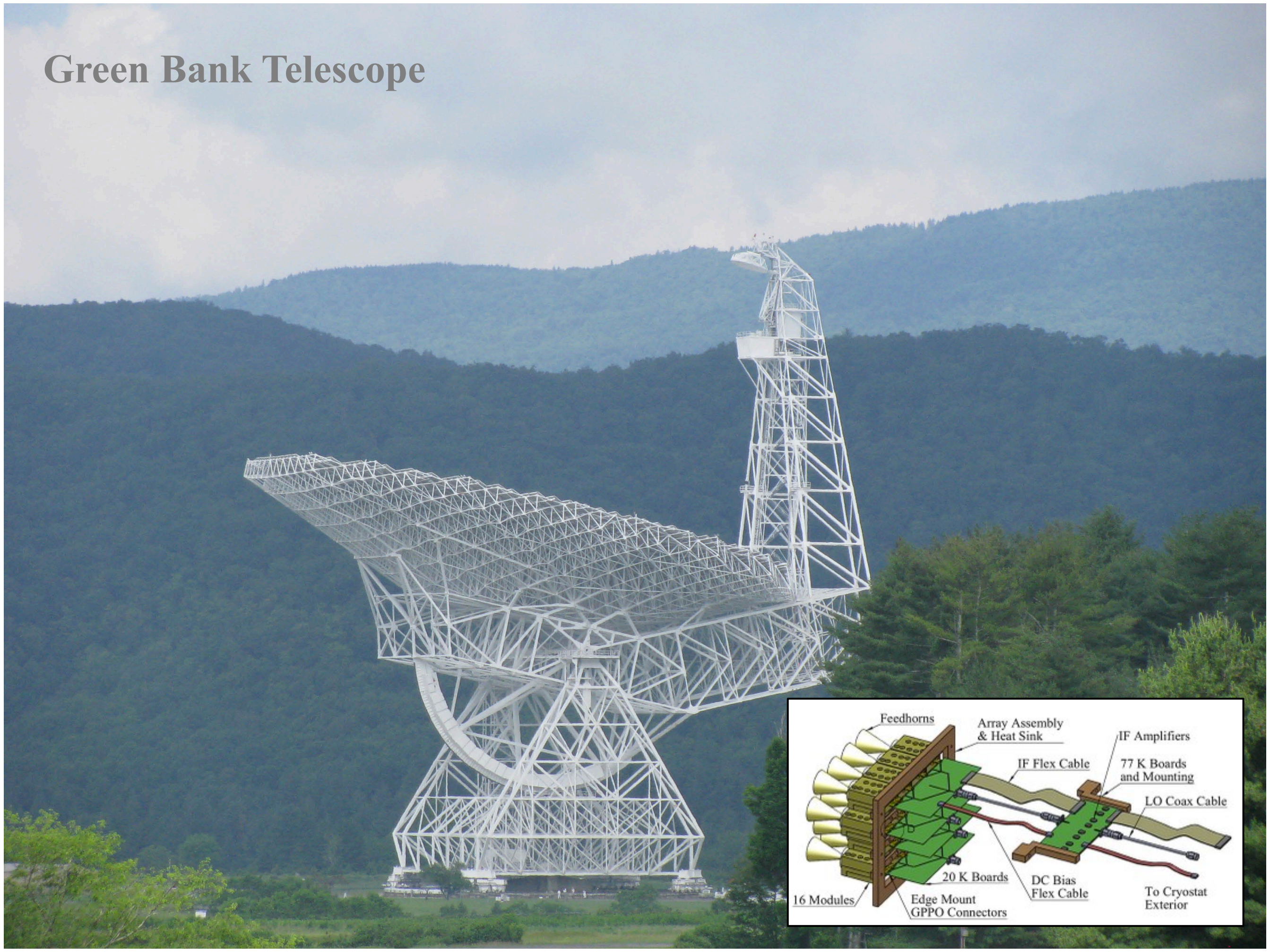
IRAM 30-m maps of HCN, HCO^{+}, HNC for M51 – "EMPIRE"



BIGIEL ET AL. IN PREP. – IRAM EMPIRE LARGE PROGRAM

The GBT as a Spectroscopy Machine

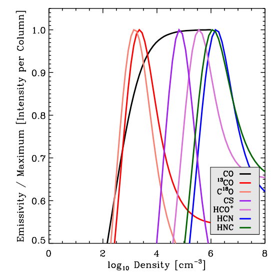
Sensitive mm-wave spectroscopy (a forte of the GBT) is an essential complement to high resolution imaging to understand the physics of star formation in a galactic context.



Observing the Link Between SFR/H_2 and Local Physics

How does the ***dense gas mass fraction*** *depend on conditions in a galaxy?*

Is the ***rate of star formation in dense gas*** *universal?*



$$\frac{\mathrm{SFR}}{\mathrm{M_{H2}}} \sim \frac{\mathrm{IR}}{\mathrm{CO}}$$

How good is <u>all</u> molecular gas at forming stars?

$$\frac{\mathrm{M_{dense}}}{\mathrm{M_{H2}}} \sim \frac{\mathrm{HCN}}{\mathrm{CO}}$$

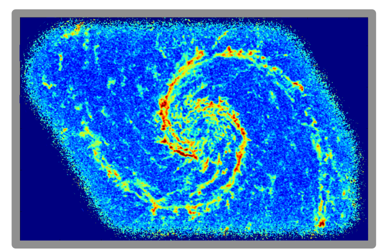
What fraction of molecular gas is dense?

$$\frac{\mathrm{SFR}}{\mathrm{M_{Dense}}} \sim \frac{\mathrm{IR}}{\mathrm{HCN}}$$

How good is <u>dense</u> molecular gas at forming stars?

How do the ***dense gas mass fraction*** *depend on* ***cloud scale structure****?*

Especially the cloud-scale ***surface density****,* ***dispersion****, and* ***boundedness****.*



$$\frac{\mathrm{M_{dense}}}{\mathrm{M_{H2}}} \sim \frac{\mathrm{HCN}}{\mathrm{CO}}$$

What fraction of molecular gas is dense?

$$\langle \Sigma \rangle_{50\,\mathrm{pc}} \quad \langle \sigma \rangle_{50\,\mathrm{pc}}$$

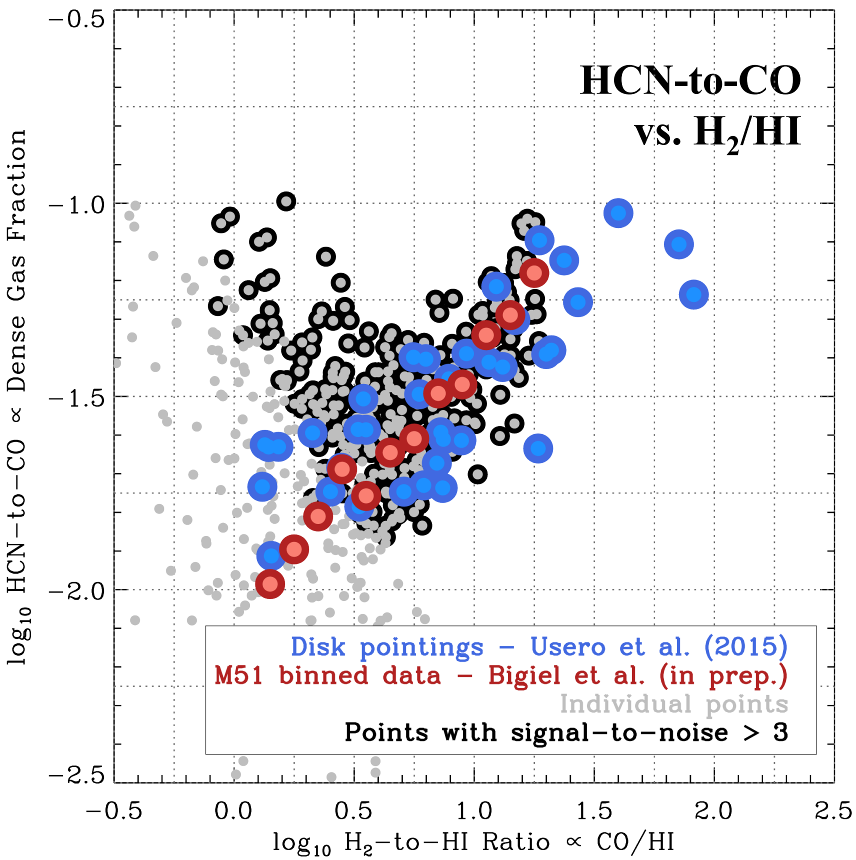
Surface density and velocity dispersion at the scale of a cloud.

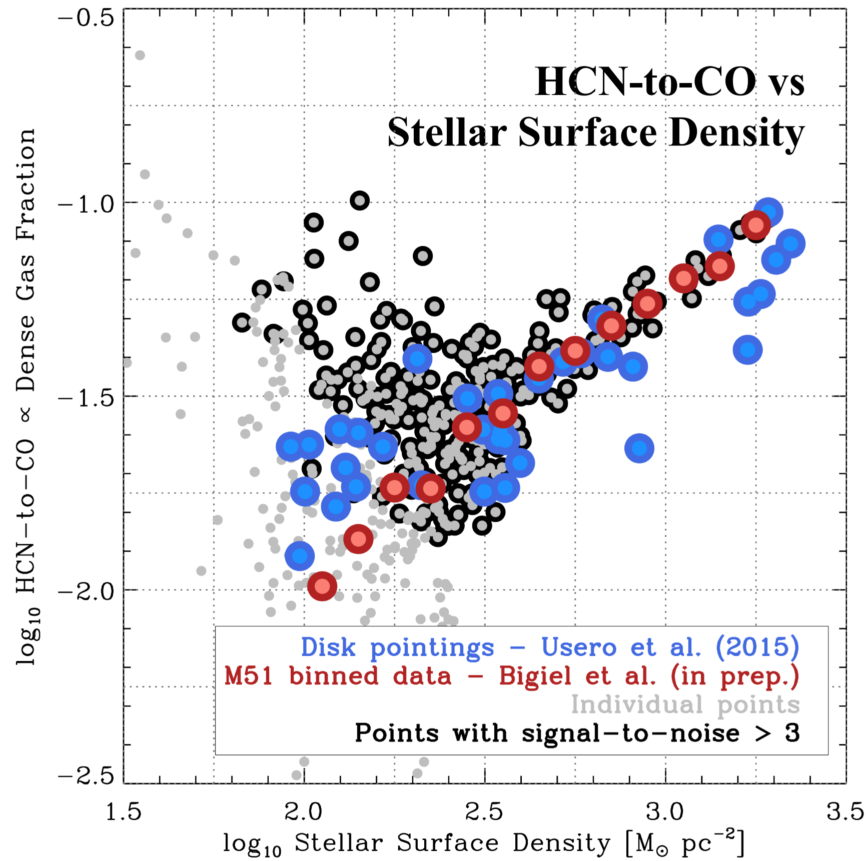
$$\frac{\langle \Sigma \rangle_{50\,\mathrm{pc}}}{\langle \sigma \rangle^2_{50\,\mathrm{pc}}}$$

Gravitational boundedness at the scale of a cloud

HCN-to-CO Rises With Increasing Surface Density

Apparent dense gas fraction a clear function of surface density inside galaxy disks.

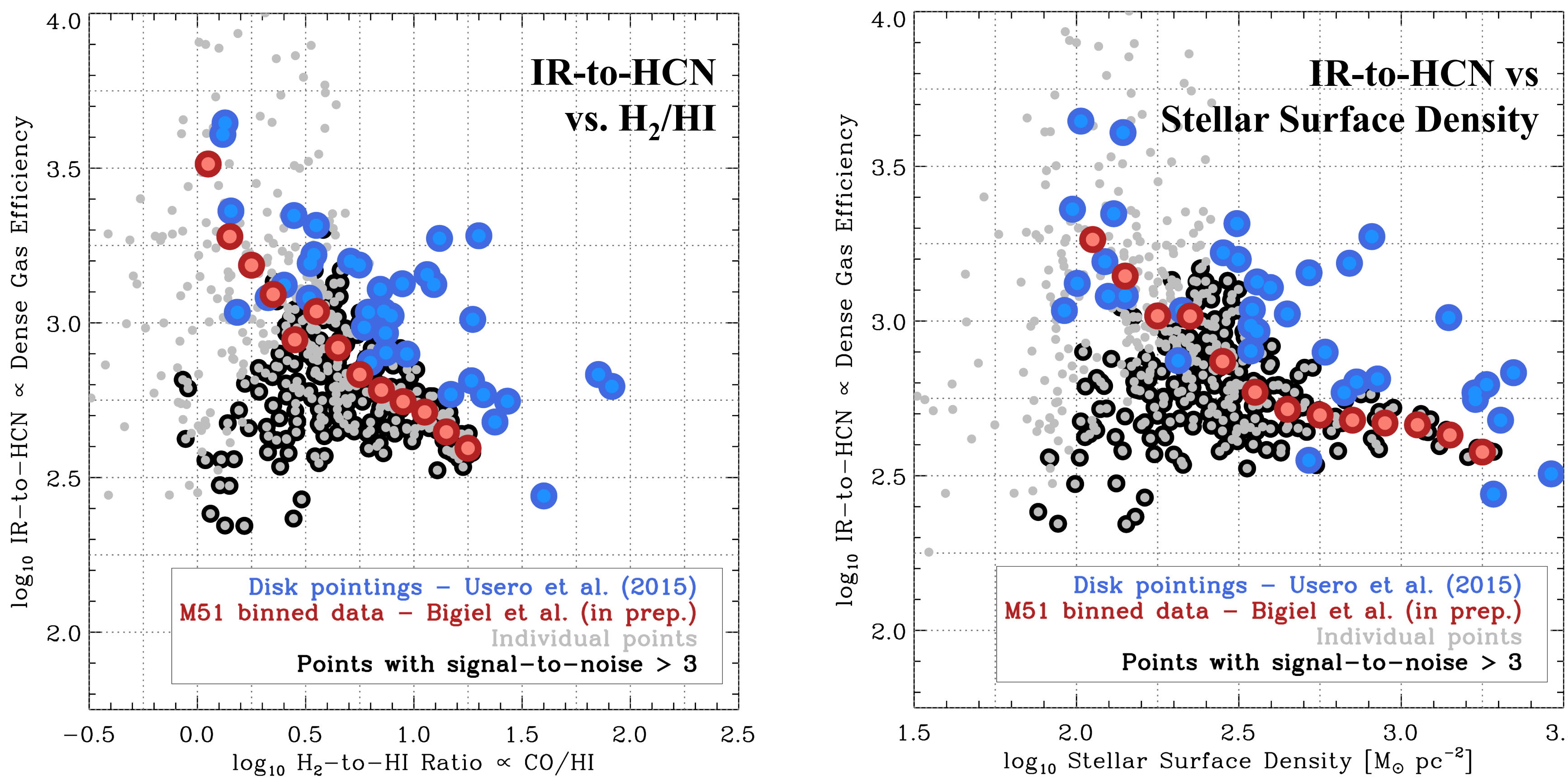




Usero, Leroy et al. (incl. Walter, Bigiel) 2015; Bigiel et al. (in prep.); see also Helfer & Blitz '97

IR-to-HCN Drops With Increasing Surface Density

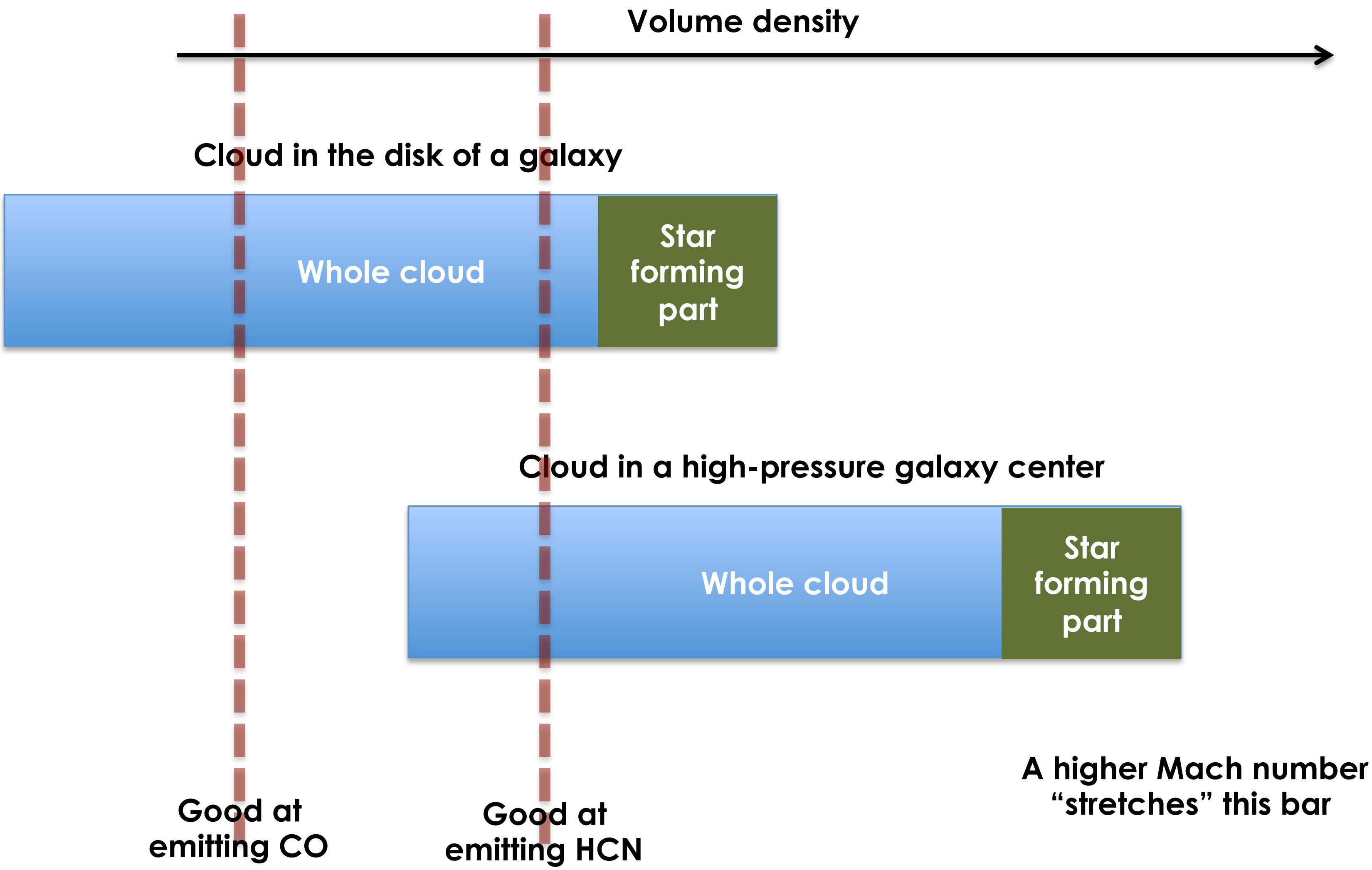
Apparent dense gas efficiency a clear function of surface density inside galaxy disks.



USERO, LEROY ET AL. (INCL. WALTER, BIGIEL) 2015; BIGIEL ET AL. (IN PREP.); see also GARCIA-BURILLO+ '12
MILKY WAY CENTER: LONGMORE+ '13, RATHBORNE+ '14, KAUFFMAN+ '13

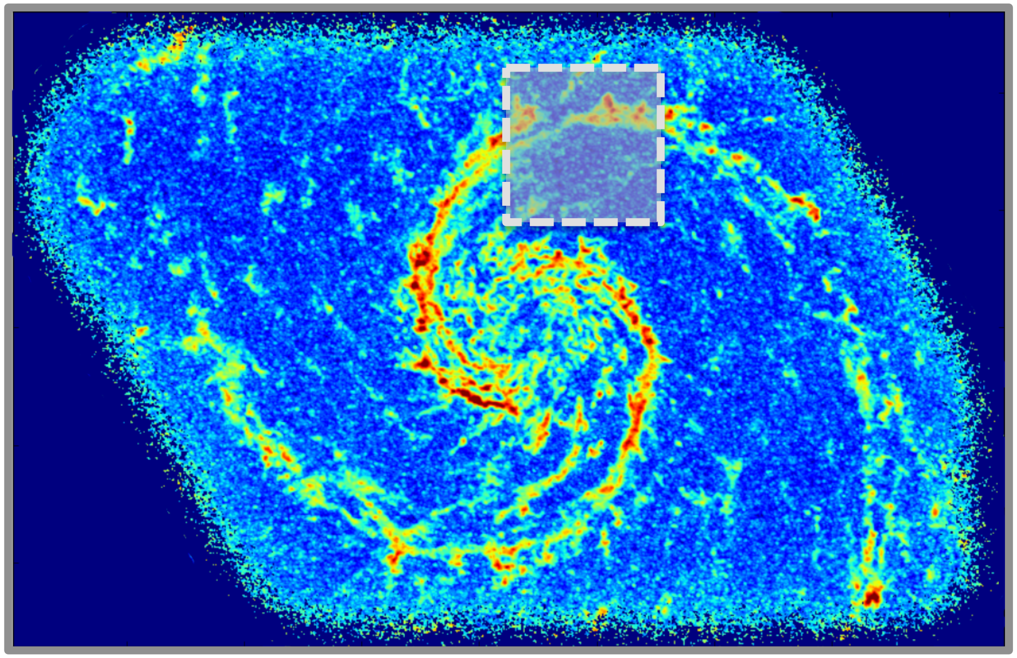
Density Thresholds and Whole Cloud Physics

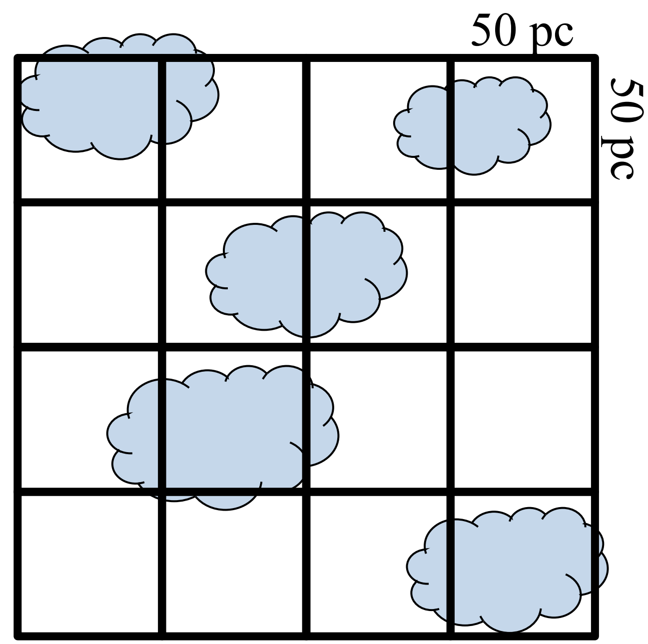
"Whole cloud" idea vastly (vastly) simplified:



Cloud Scale Conditions

SCHINNERER+ '13



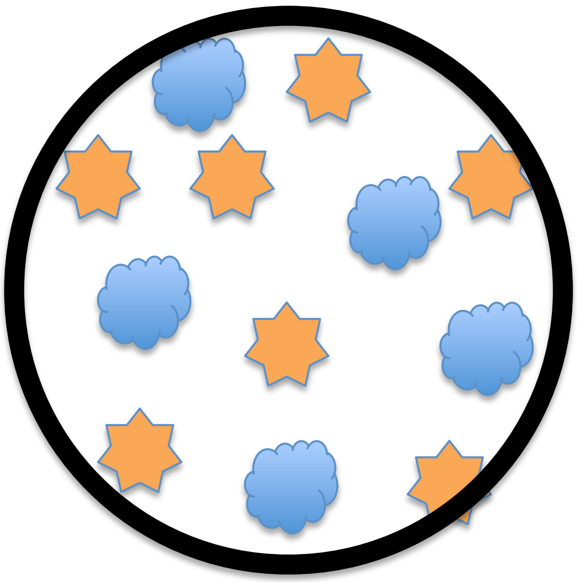


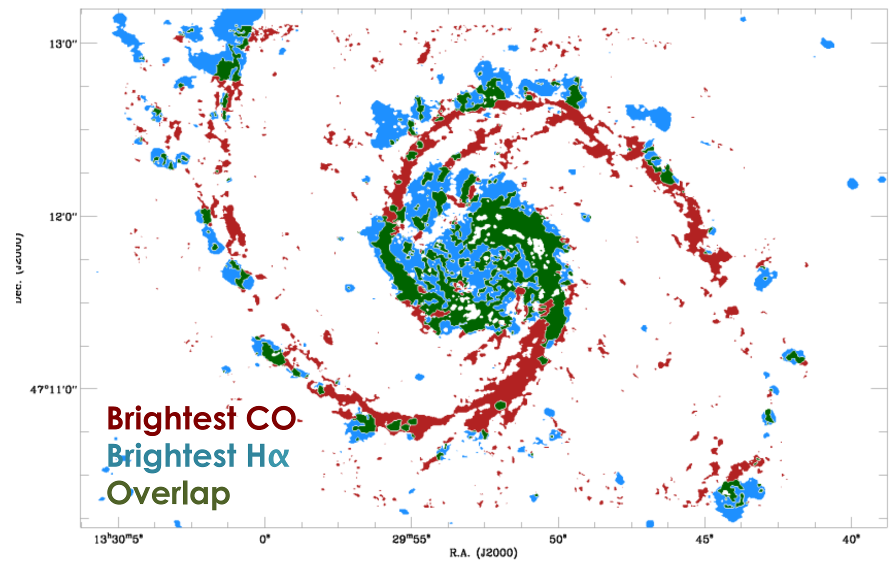
Measure ratio of molecular gas to star formation over a large (~ kpc) part of a galaxy that is still small enough to roughly isolate local conditions.

The integral over an area is needed to capture the time-cycling of gas phases and stars.

*Within this large area, measure the cloud scale properties of the gas, integrated to measure the mass-weighted **surface density**, **velocity dispersion** (Mach number), and **boundedness**.*

Cloud-Scale Conditions and Large-Scale Cycling



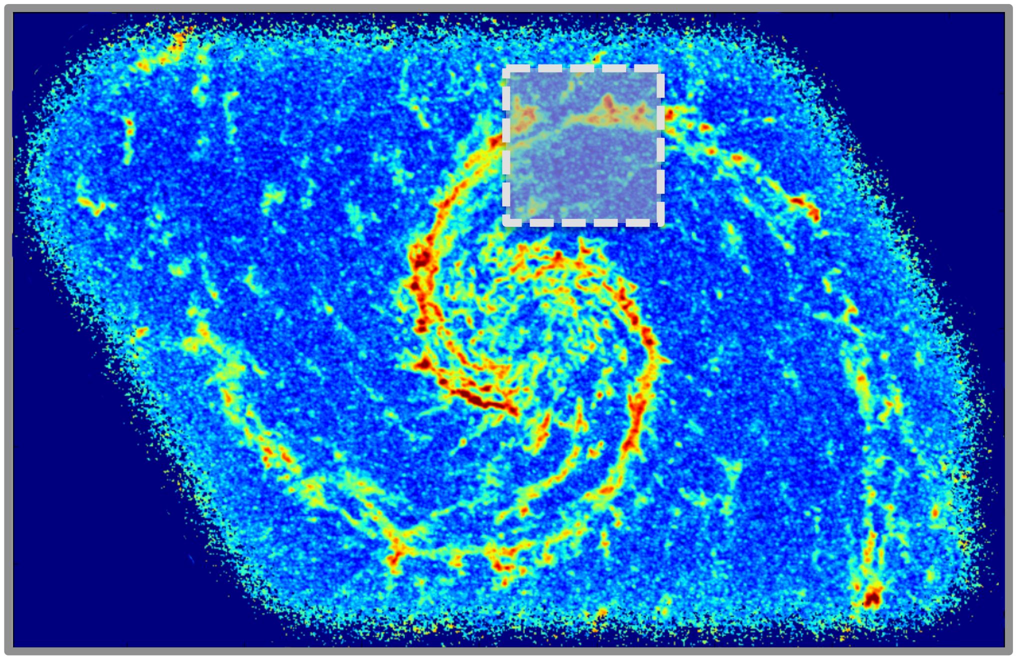


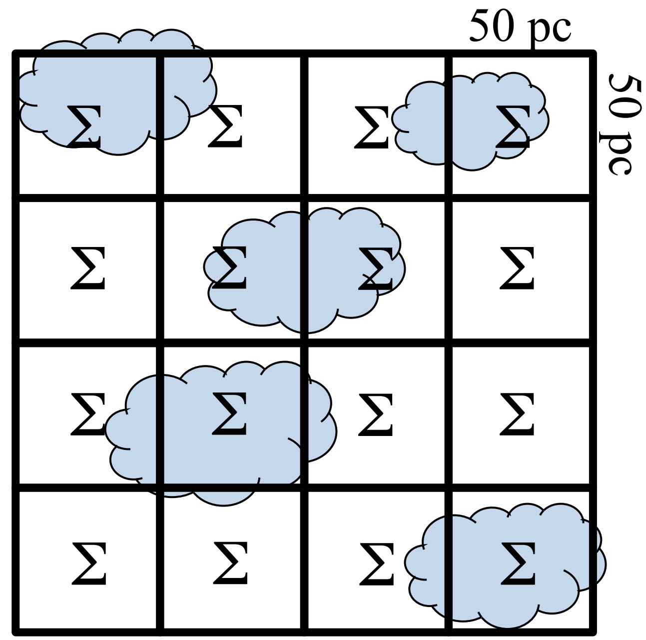
Capture large scale processes (like time-averaged SF) with:

$$\tau_{\mathrm{Dep}}^{\mathrm{H2}} = \frac{M_{H2}}{SFR}$$

measured at large (~kpc, GBT) scales capture the time-averaged process. This zoomed out approach avoids resolving the galaxy into discrete evolutionary stages.

Cloud Scale Conditions





Over the area, the time (space) averaged ability of gas to form stars is captured by:

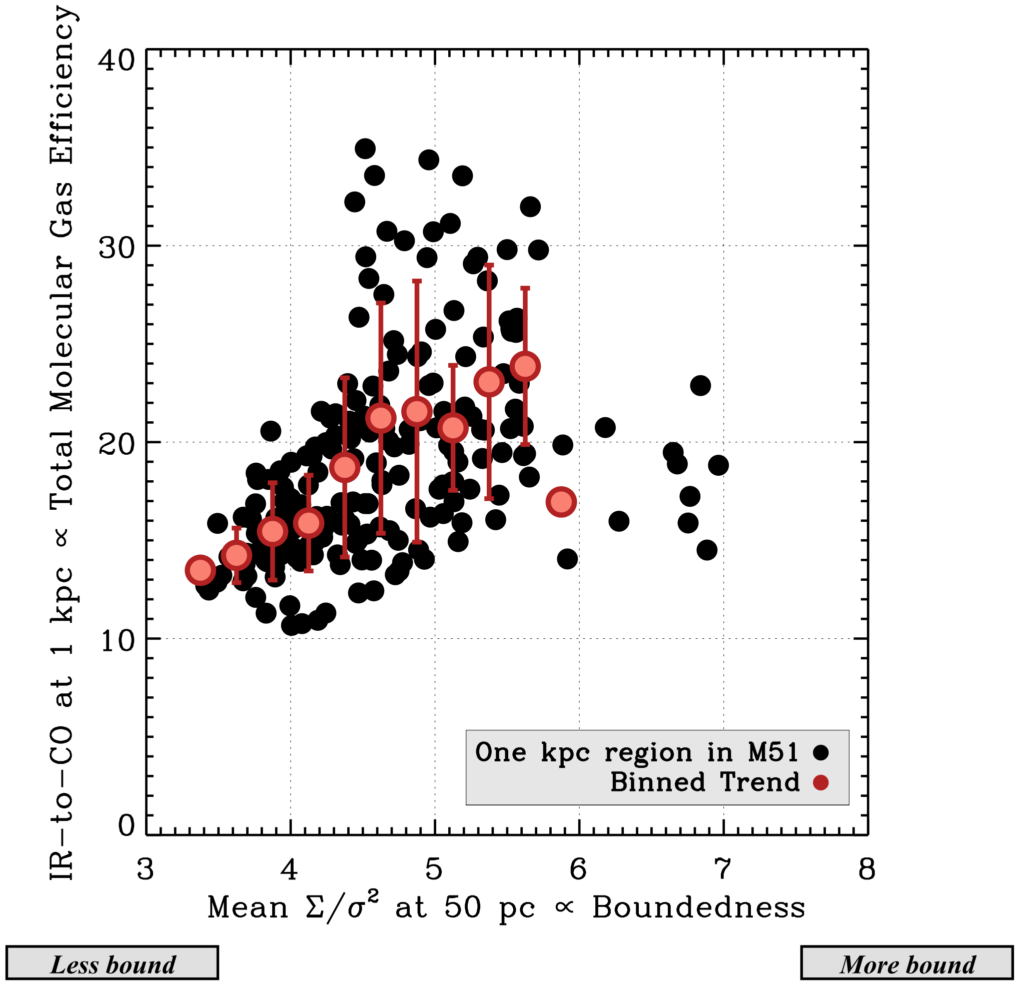
$$\frac{\mathrm{SFR}}{\mathrm{M_{H2}}} \sim \frac{\mathrm{IR}}{\mathrm{CO}}$$

The mass-weighted local conditions (here surface density) are captured by:

$$\langle\Sigma\rangle^{\mathrm{M}} = \frac{\int_A \Sigma \times \Sigma \, dA}{\int_A \Sigma \, dA} = \frac{\int_A \Sigma^2 \, dA}{\int_A \Sigma \, dA}$$

Cloud Scale Conditions and SFR-per-H_2

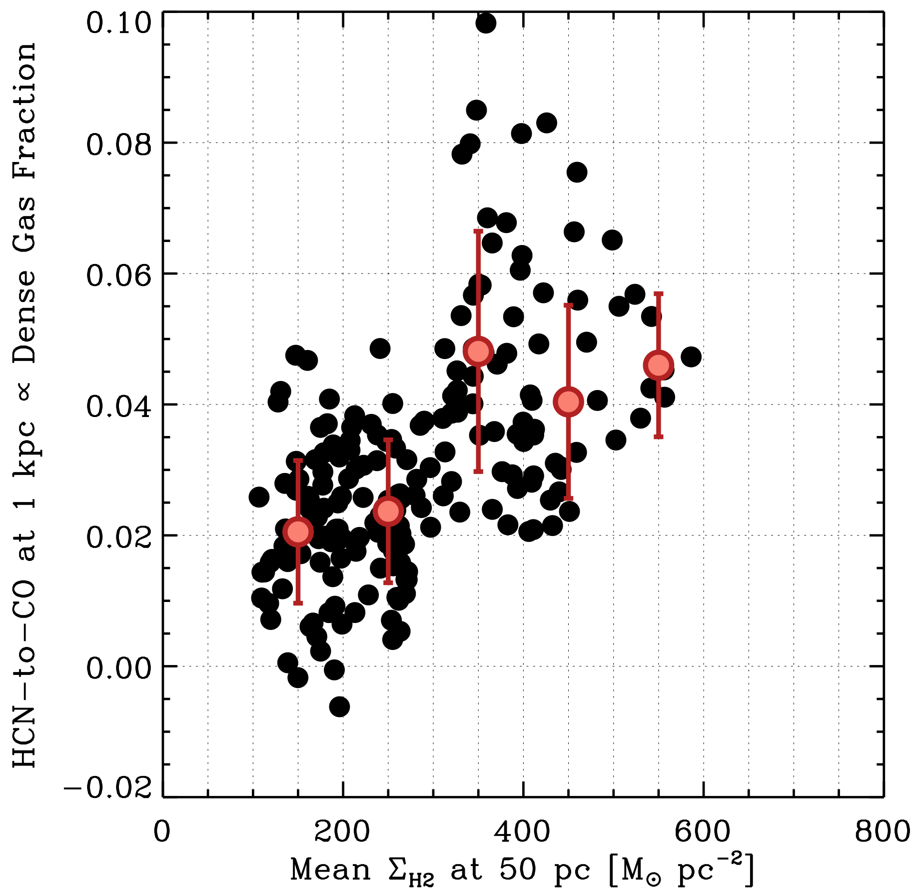
In M51, the ability of the ISM to form stars (IR-to-CO) correlates with the self-gravity of the gas at cloud (50 pc) scales – gas that is more bound appears better at forming stars.

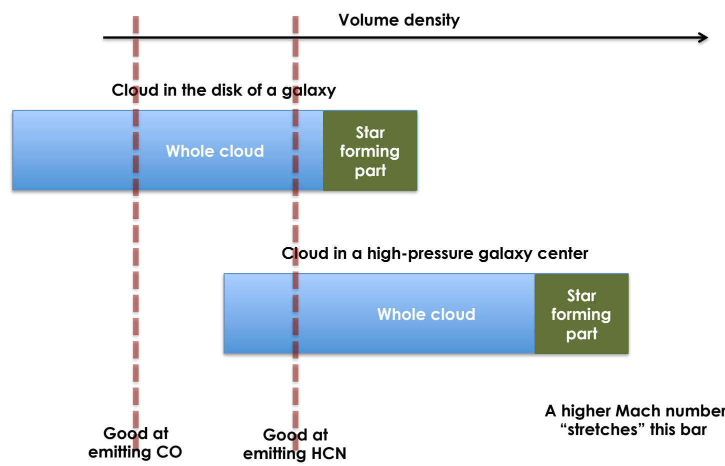


LEROY, HUGHES, BIGIEL, SCHINNERER ET PAWS IN PREP.

Cloud Scale Conditions and Dense Gas Mass Fraction

In M51, the average small scale surface density over a kpc correlates with the apparent fraction of the molecular gas mass that is dense. The y-axis is a GBT observable.

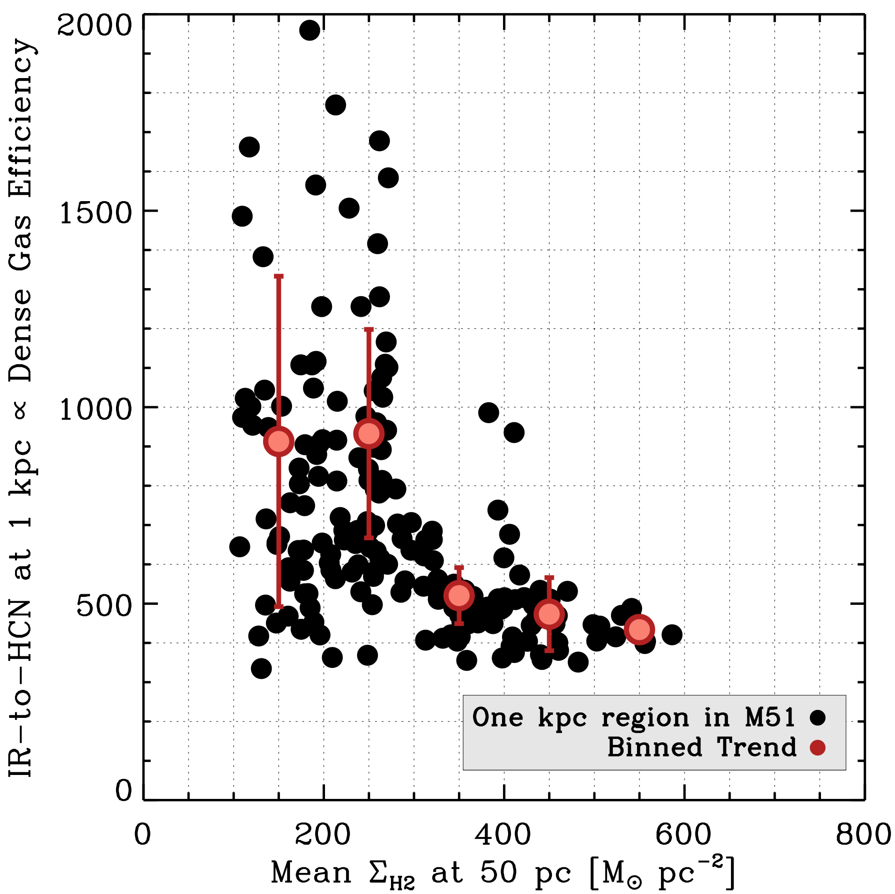


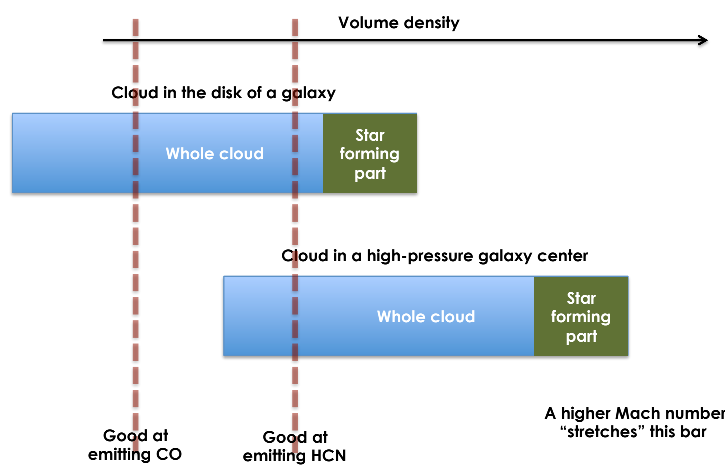


LEROY, HUGHES, BIGIEL, SCHINNERER ET PAWS IN PREP.

Cloud Scale Conditions and SFR-per-Dense Gas

In the inner part of M51, higher cloud-scale surface densities also lead to lower ratios of star formation per unit dense gas. The y-axis is a GBT observable.

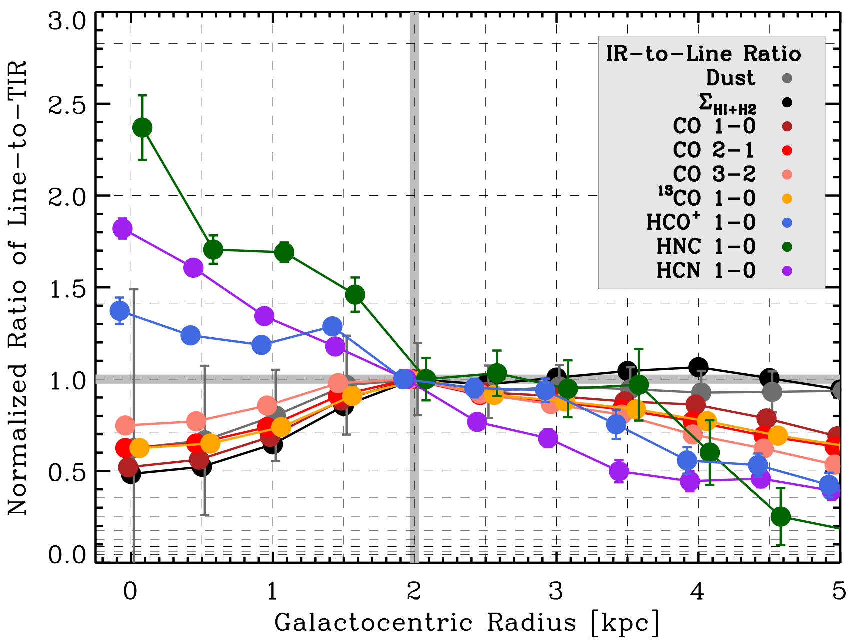


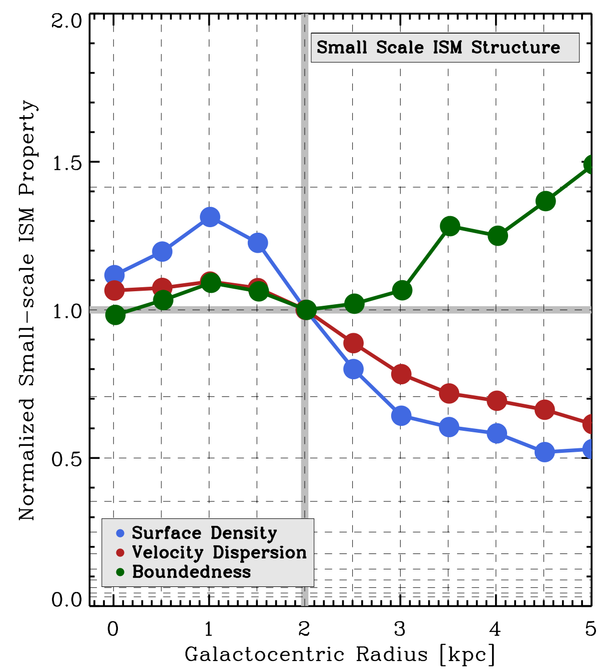


LEROY, HUGHES, BIGIEL, SCHINNERER ET PAWS IN PREP.

Multi-Line Spectroscopy and Cloud-Scale Conditions

The combination of high resolution structure and (lower resolution) multiline spectroscopy (something the GBT can now achieve very efficiently) links galaxy-scale conditions to the multi-scale structure of the ISM and star formation.





LEROY, HUGHES, BIGIEL, SCHINNERER ET PAWS IN PREP.

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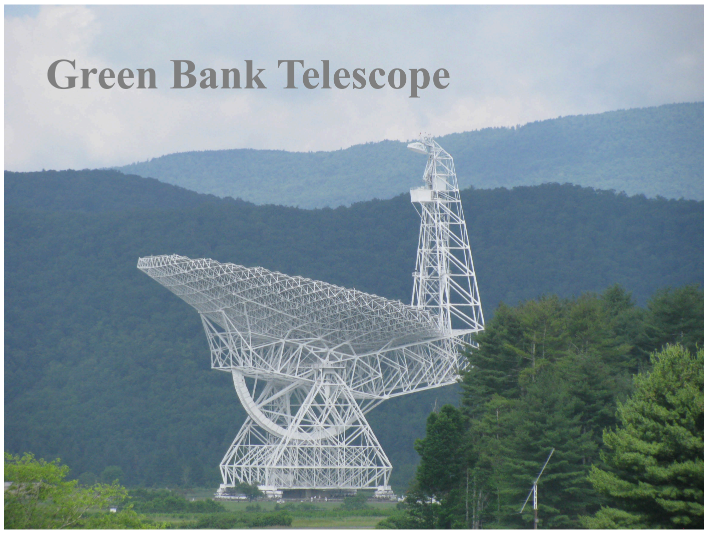

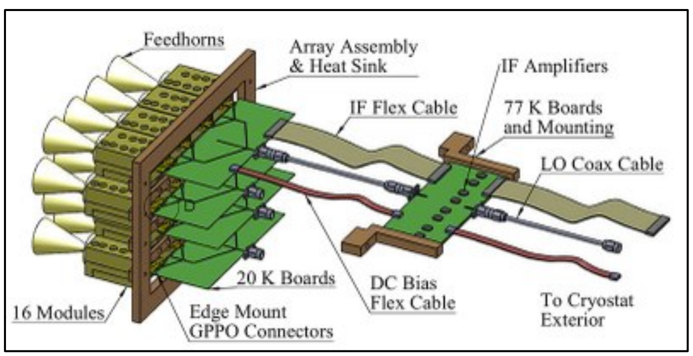

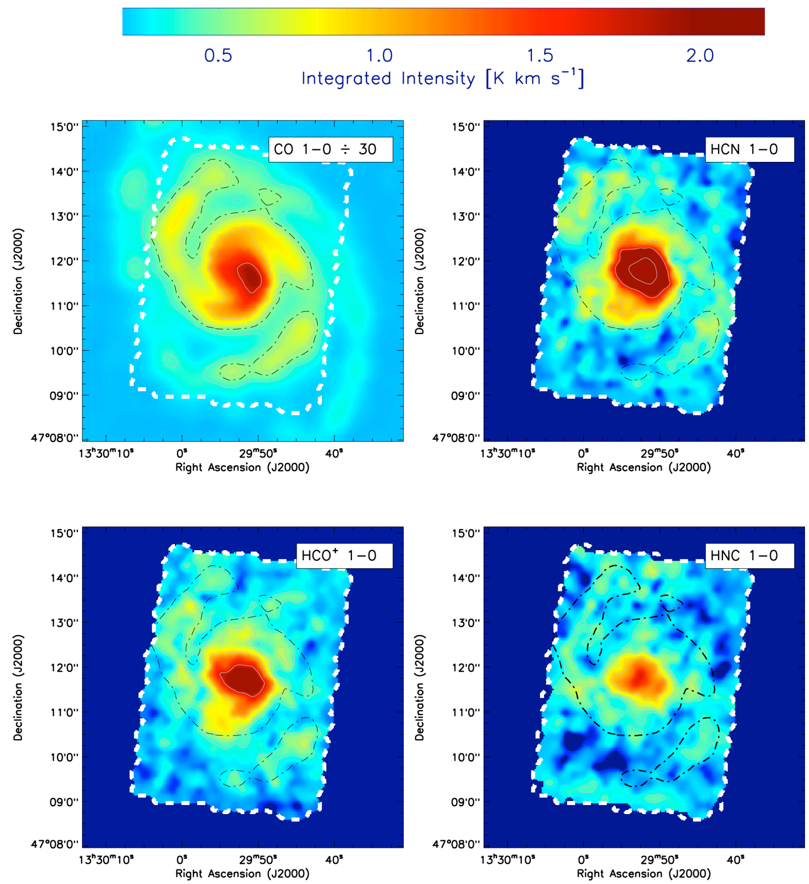

BIGIEL ET AL. IN PREP.