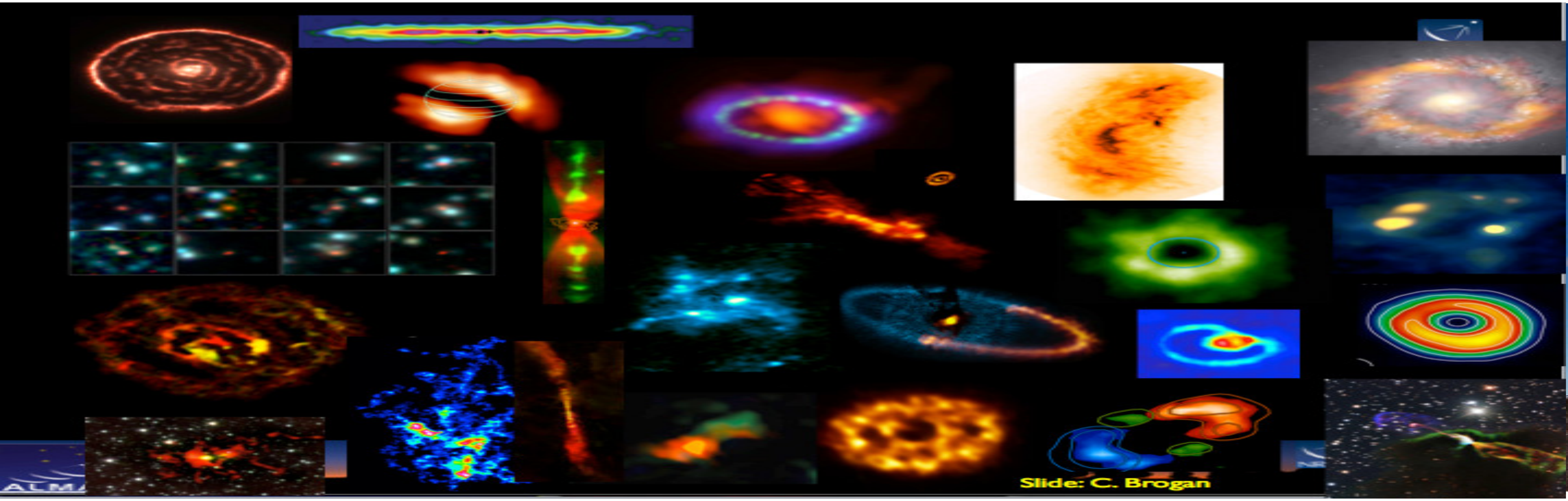
# ALMA/GBT Band 2 Science

## Workshop, Goteborg, May 2016




## A Short Overview

Al Wootten

Atacama Large Millimeter/submillimeter Array
Karl G. Jansky Very Large Array
Robert C. Byrd Green Bank Telescope
Very Long Baseline Array

# Highest Level Science Goals

***Bilateral Agreement Annex B:***

"ALMA has three level-1 science requirements:

- ❖ The ability to detect spectral line emission from CO or C+ in a normal galaxy like the Milky Way at a redshift of z = 3, in less than 24 hours of observation.
- ❖ The ability to image the gas kinematics in a solar-mass protostellar/ protoplanetary disk at a distance of 150 pc (roughly, the distance of the star-forming clouds in Ophiuchus or Corona Australis), enabling one to study the physical, chemical, and magnetic field structure of the disk and to detect the tidal gaps created by planets undergoing formation.
- ❖ The ability to provide precise images at an angular resolution of 0.1". Here the term *precise image* means accurately representing the sky brightness at all points where the brightness is greater than 0.1% of the peak image brightness. This requirement applies to all sources visible to ALMA that transit at an elevation greater than 20 degrees.

These requirements drive the technical specifications of ALMA. "

**A detailed discussion of them may be found in the ESA publication *Dusty and Molecular Universe* on ALMA and Herschel.**

# ALMA Top Science cases

- The first high-level science goal is directly about ALMA Band 2, as the lower CO lines in the Milky Way are the strongest, and the J=3-2 line lies at 86 GHz. This sets the sensitivity target for Band 2. The goal was to detect 'normal' galaxies, if they existed, at z=3.
- BUT…since the high-level goals were set (see Baker, 2009, private note)
  - ALMA became not 64x12m antennas but 54x12m + 12x7m antennas, with the equivalent surface area of 58x12m antennas.
  - Measurements, mainly from the VLBA, have shrunk the Milky Way and lowered the absolute intensity of its CO lines.
  - Cosmology has changed, making the MW at z=3 fainter. $D_L$ increased from 15 to 26 Gpc
  - We're measuring Tsys daily
  - Andrew estimated $\mathbf{S}_{CO(3-2)} = 36.3\ \mu$Jy.

# MW at z=3

- Tsys
  - Andrew used Tsys=67K for B3. The B2 specs would give us Tsys=50K.
  - B3 datasets suggest Tsys=50K for recent datasets in good weather.
  - The requirement aims at Trx=30K for B2, the current requirement, which I calculate should provide Tsys <50K on the sky.

# What are the numbers?

$$\frac{\Delta S}{\mathrm{mJy}} = 2.6 \times 10^6 \left(\frac{T_{\mathrm{sys}}}{\mathrm{K}}\right) \left(\frac{\eta_a}{1}\right)^{-1} \left(\frac{N D^2}{\mathrm{m}^2}\right)^{-1} \left(\Delta\nu\Delta t\right)^{-1/2}$$

Assuming

- **T**sys = 50K
- aperture efficiency $\boldsymbol{\eta}_a$ = 0.74 for Band 3,
- **ND**$^2$ = 58x 12$^2$ = 8352m$^2$
- 75 kms$^{-1}$ channel (which at **v** = **v**0/(1 + **z**) = 86.449GHz corresponds to 21.6MHz)

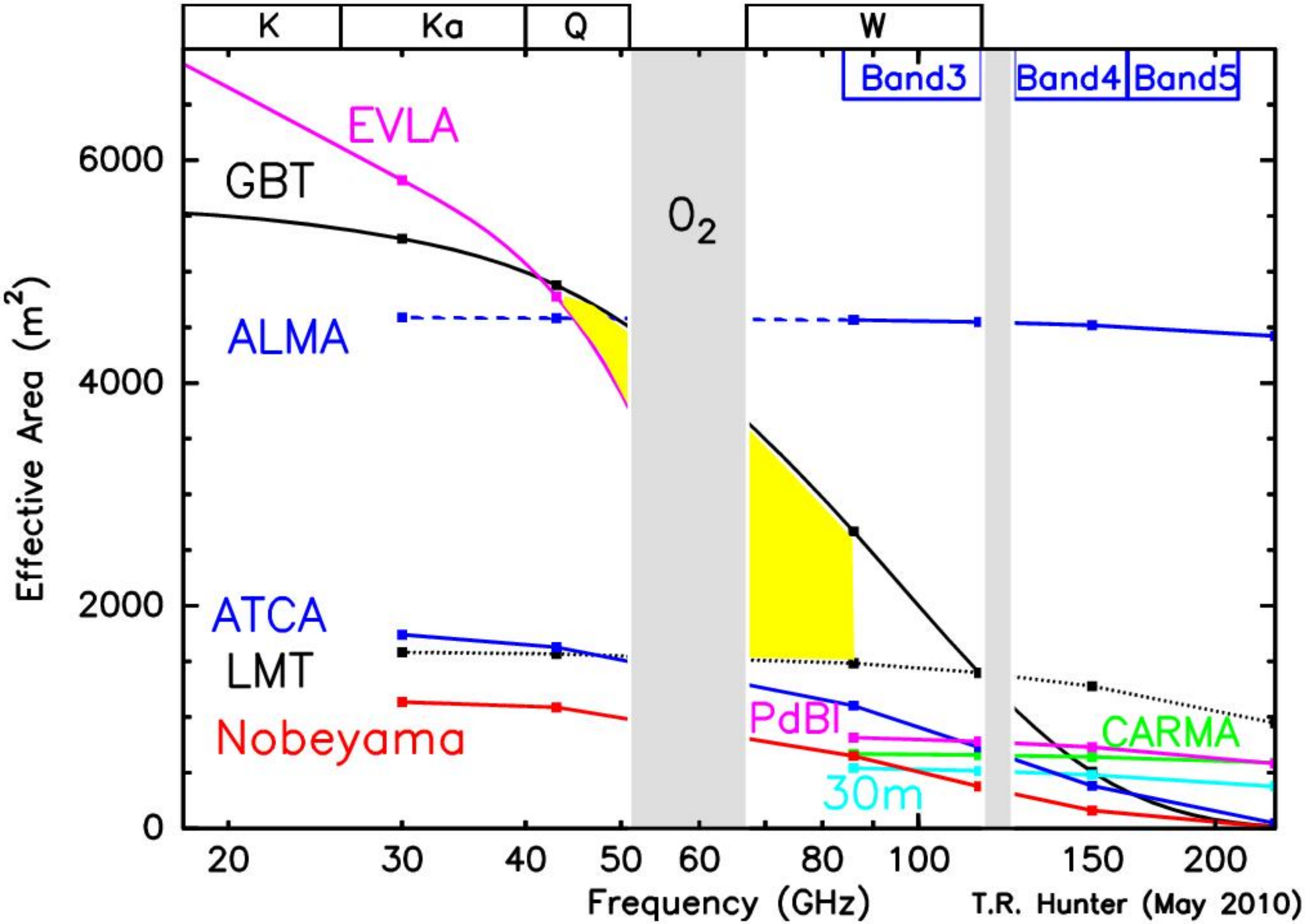
Then in 1 day of integration, one reaches **ΔS~15μJy, for a 2 σ** detection per channel. One could use an (uncommissioned so far) 4bit correlator mode to gain another small factor of sensitivity.

One concludes that the detection is ***just*** feasible with the current specs. *Maintaining specified sensitivity* is important for reaching this goal.

ALMA sensitivity ~GBT sensitivity at 4mm→survey GBT science

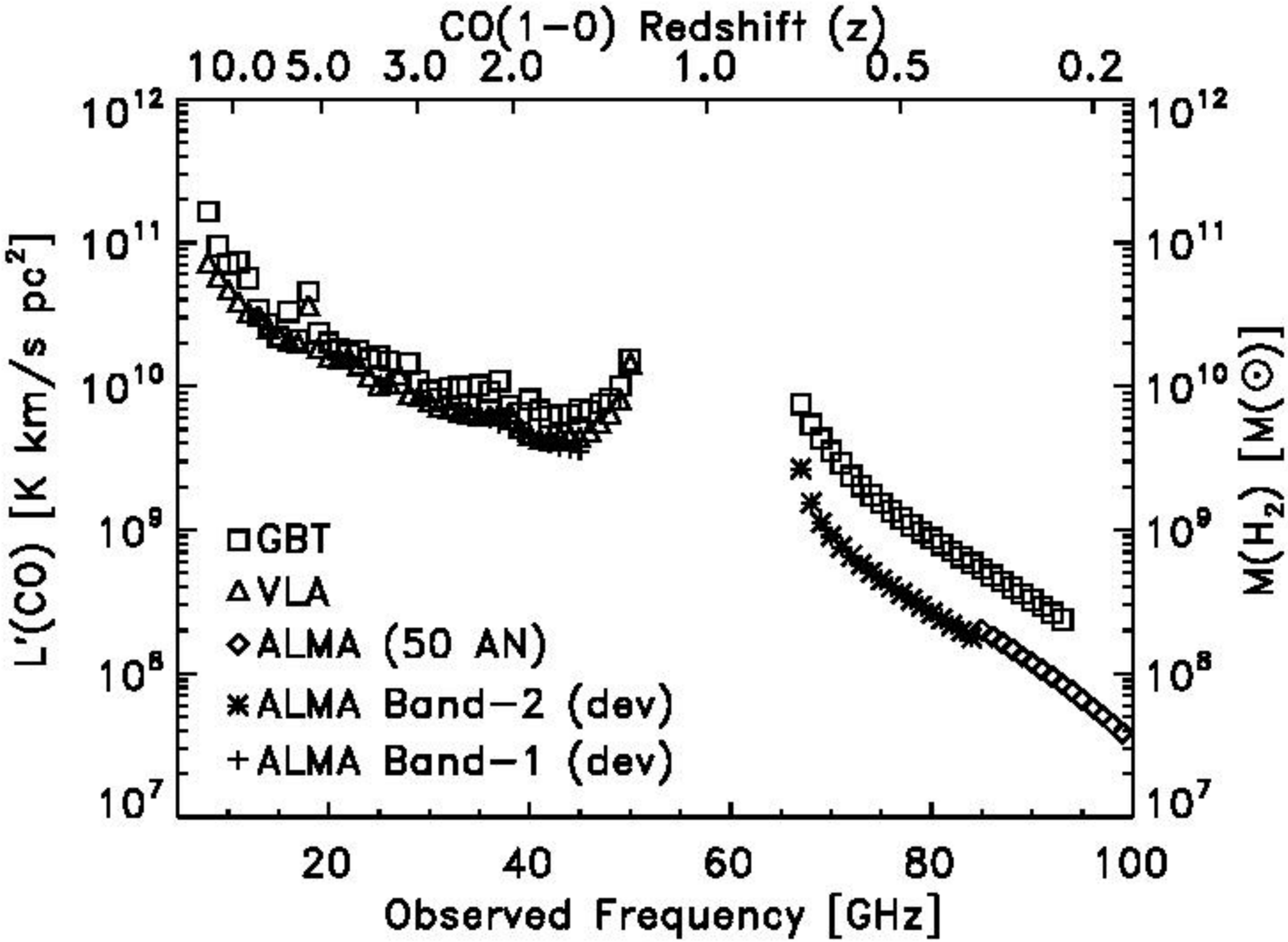
# Effective Collecting Area ( $\eta_a$ * Area)

ALMA potential sensitivity exceeds that of other telescopes; GBT is closest now. Use current GBT science as a guide to ALMA science.



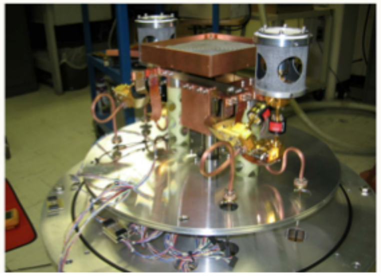
# Comparison of ALMA,VLA, and the GBT for redshifted CO(1-0)

Detection levels for same amount of observing time

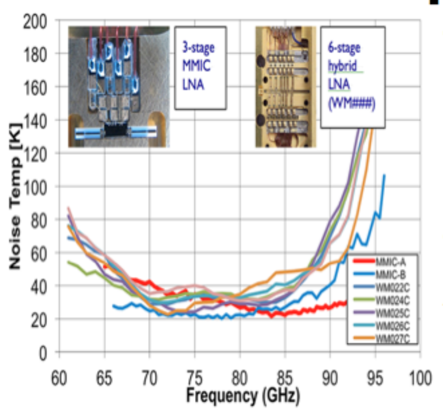



Plot made in Aug 2012, before GBT 4mm upgrade

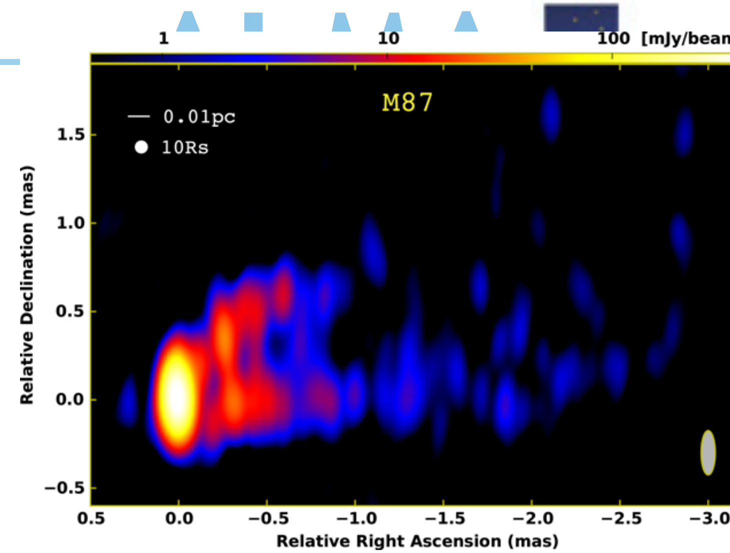
# GBT 4mm Receiver



- Commission in 2012
- Operates from 67—93 GHz
- Dual feed, dual linear polarization
- Has ¼ wave-plate that provides circular polarization for VLBI
- Only instrument in the world that can currently observe the key (1-0) deuterated transitions in the cold proto-stellar cores

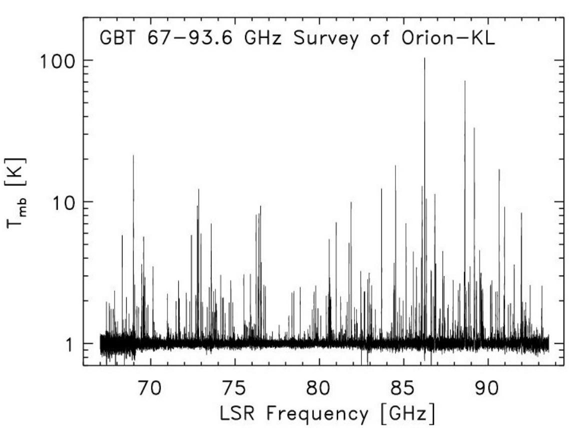



(Left) The performance of different cold amplifier designs measured in the lab. The GBT 4mm system has better receiver temperatures than ALMA Band-3.

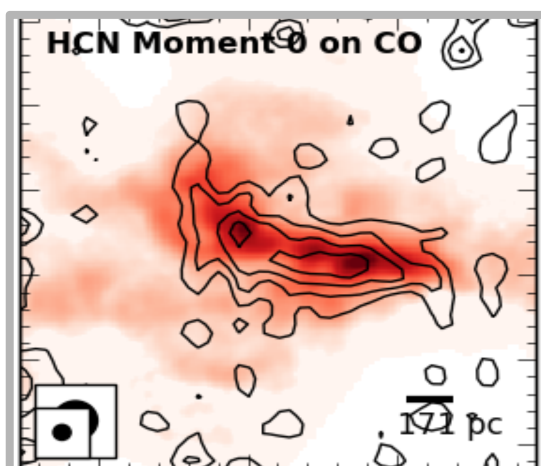



VLBI observations using the GBT at 3.5mm that measured the base of the jet of M87 at a resolution of 10 Schwarzschild radii (Hada et al. 2016, ApJ, 817,131).

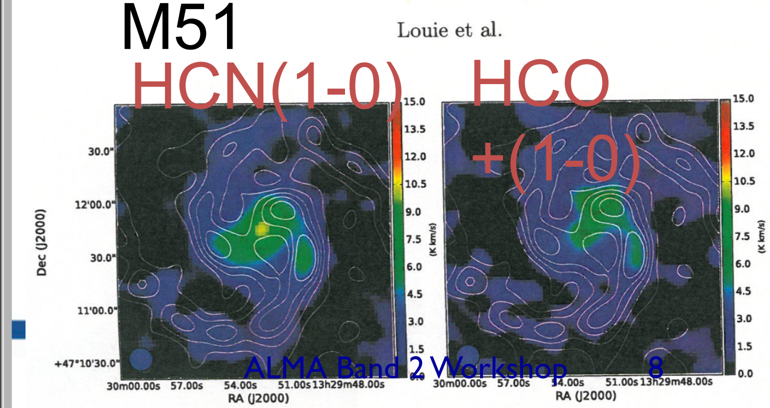
**Orion-KL Spectral Line Survey 67-93.6 GHz**
(Frayer et al. 2015)




Mapping Dense Gas in nearby Galaxies: M82 HCN(1-0) contours (16 hrs) on CO image (A. Kepley et al.)




M. Louie PhD Thesis: M51

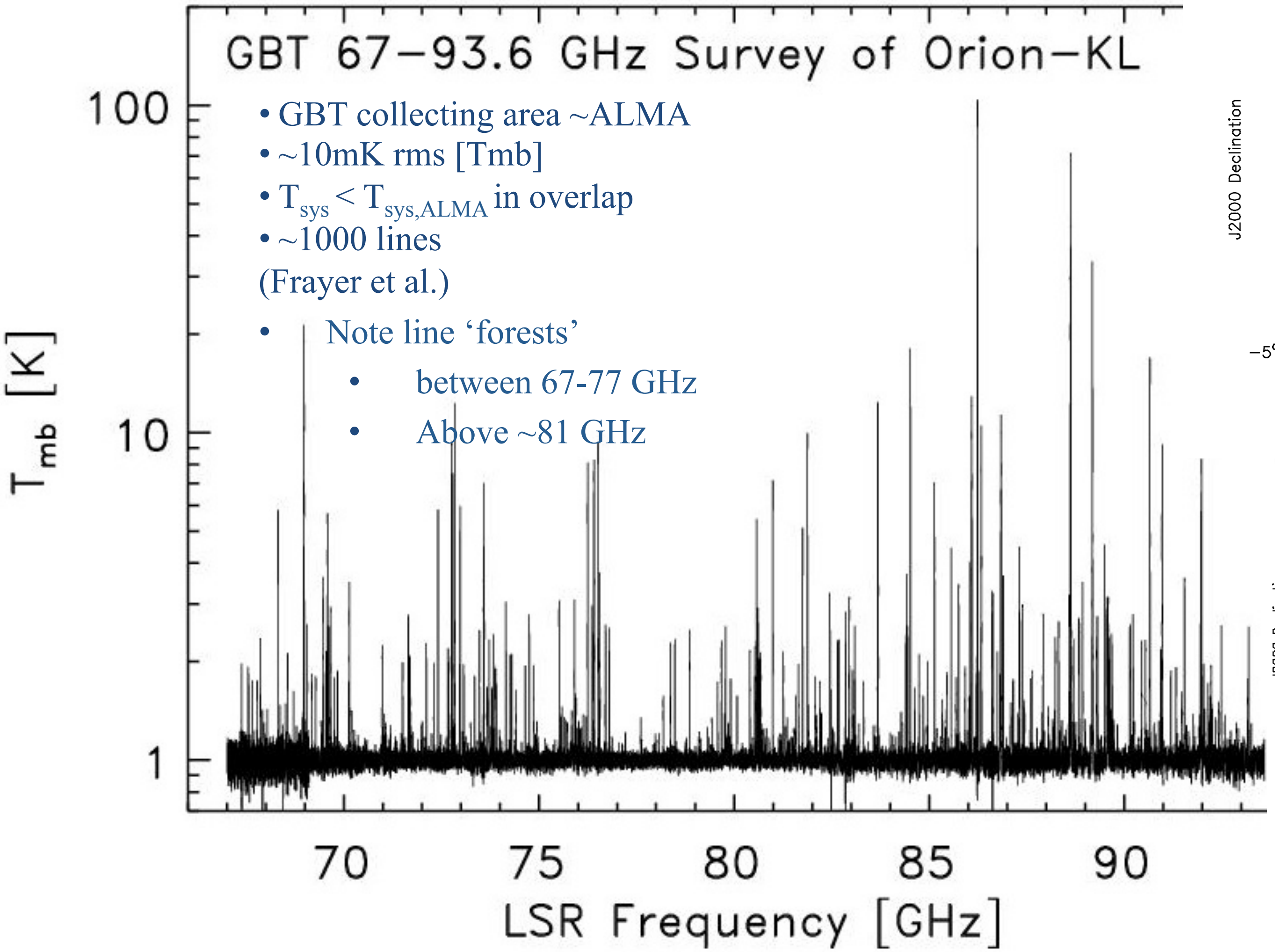


# ALMA Band 2 Science Case Summary

- **The Context of Star Formation** – Deuterium species and dense gas tracers key for studies of cold cloud cores from which stars form.
- **Galaxies Across Cosmic Time** – CO(1-0) at intermediate redshifts where the evolution of galaxies is proceeding rapidly and dense gas tracers, such as HCN and HCO+, in local star-forming galaxies.
- **Origin of Life** – Complex organic molecules and pre-biotic molecules in the ISM and comets which are key for studying the conditions from which life eventually forms (unexplored frequencies --- lots of discovery potential in astro/bio-chemistry).
- **Fundamental Physics** – With VLBI, probe the physics near the base of black hole jets in nearby galaxies {and measure the size of the galaxy via parallax of SgrA*}.

# Orion-KL Spectral Line Survey 67-93.6 GHz

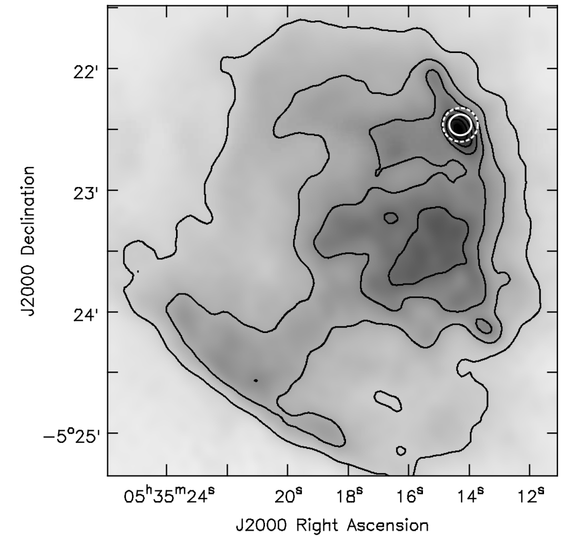
**(Frayer +15; single pixel)**

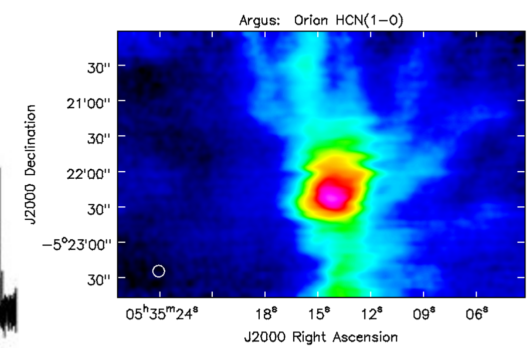



- GBT collecting area ~ALMA
- ~10mK rms [Tmb]
- $T_{sys} < T_{sys,ALMA}$ in overlap
- ~1000 lines

(Frayer et al.)

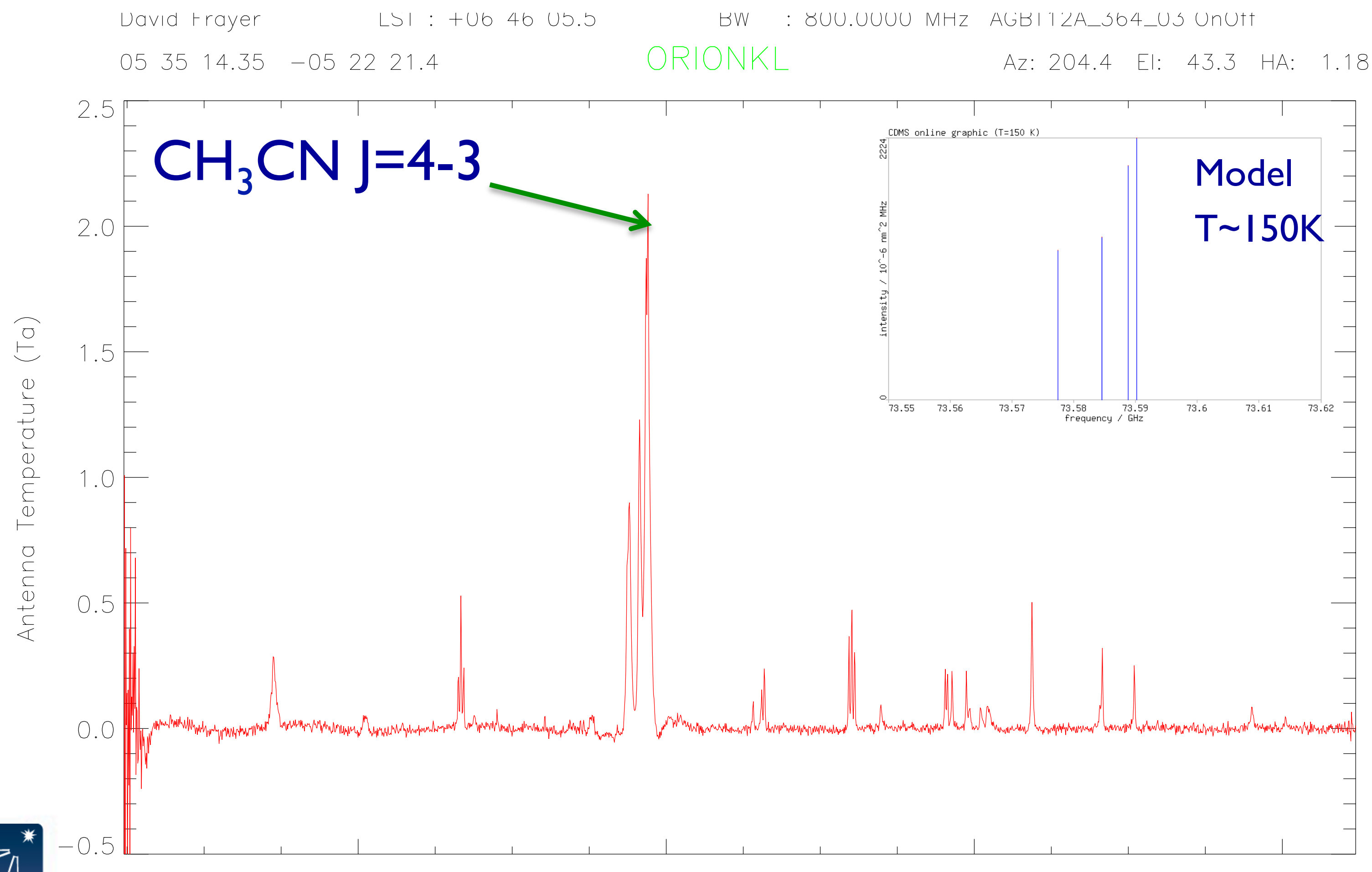
- Note line 'forests'
  - between 67-77 GHz
  - Above ~81 GHz



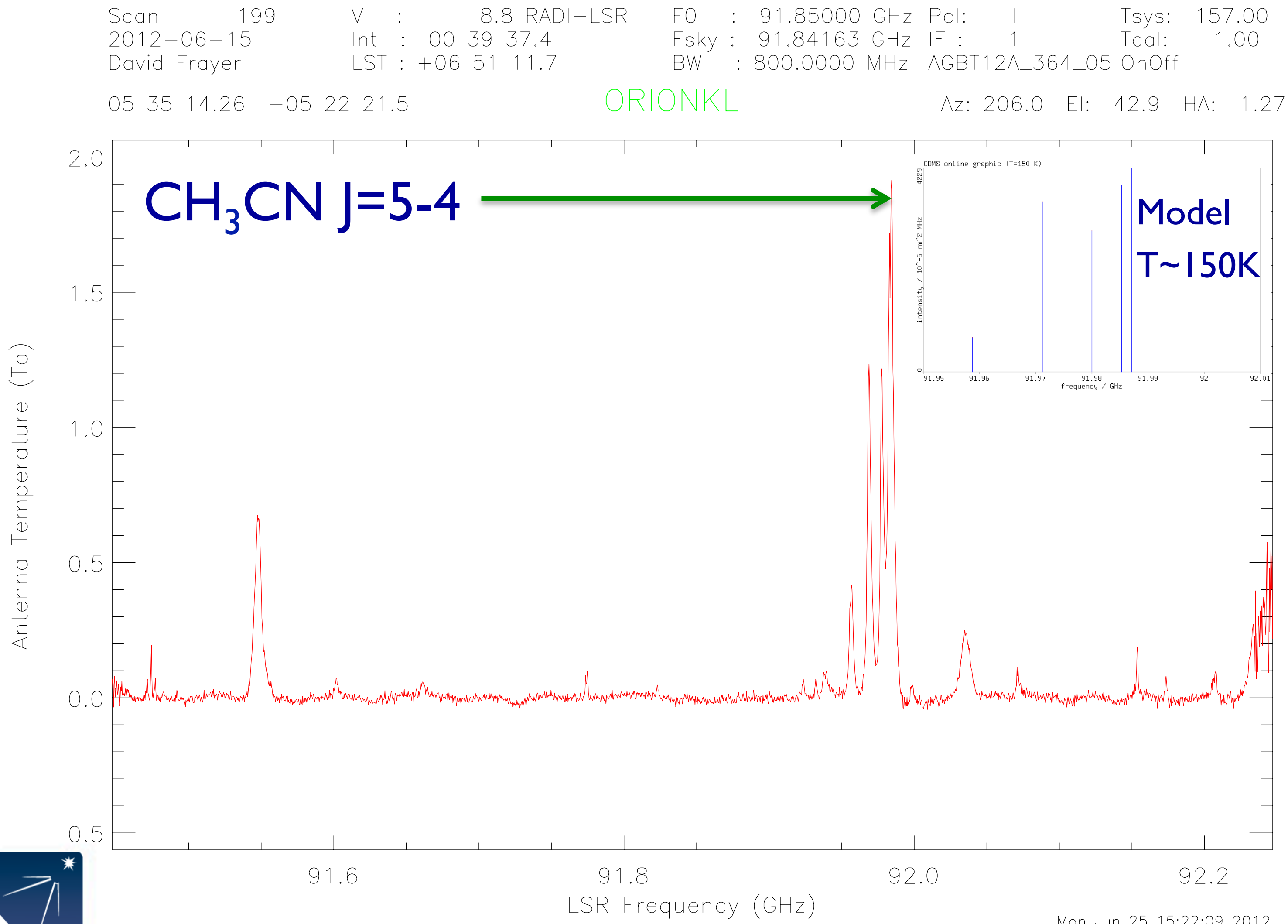




HCN image with new multibeam receiver

# Orion Temperature Probe



# Second in-band transition

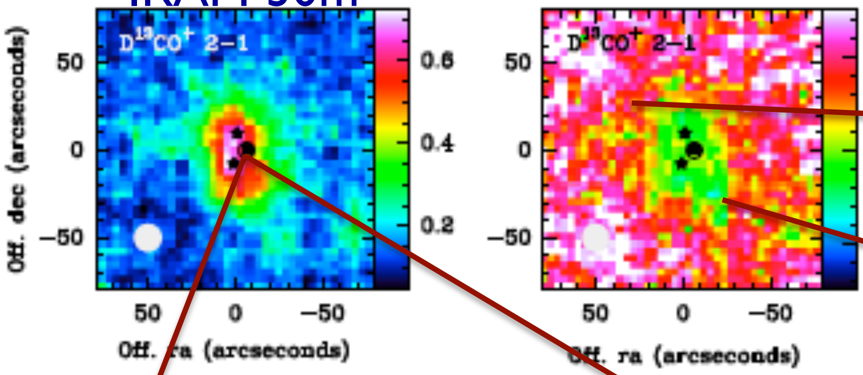


# Core, Disk Studies Need ALMA Band 2

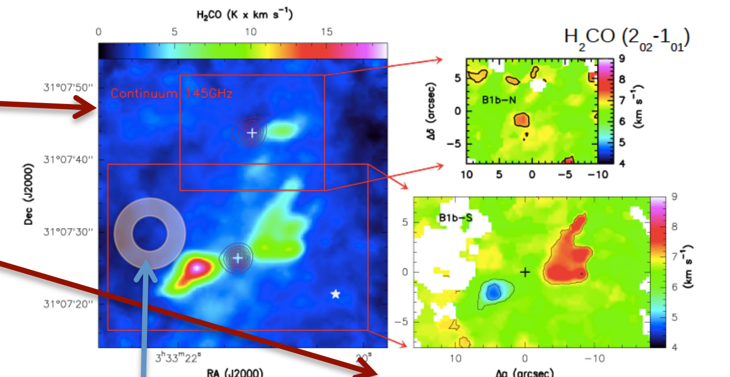
- Lines of Deuterium isotopomers of many molecules lie in this band.
  - $NH_2D$, $DCO^+$, DCN, $N_2D^+$, $C_2D$, HDO & $CH_2D^+$
  - Deuterated lines are faint requiring sensitivity
    - $T_B < 1K$ for e.g. $N_2D^+$ (1-0) at 77.1 GHz and similar lines
    - Only the resonance line 1-0 probes the entire core
  - Line strength varies across core requiring good angular resolution
    - Intensity is a strong function of density / temperature
    - Within the core at high density higher J transitions are produced
  - Deuterated lines are narrow requiring sensitivity
    - $\Delta v \sim 0.3$ km/s, lines have nearly thermal FWHM
- Emission at 4mm is very useful for measuring $\beta$ a measure of grain growth in cold dense cores
  - Optically thin
  - On RJ tail of emission offering a large wavelength range for comparison
  - Useful for cores and disks
    - For cores, need to recover emission on large angular scales
    - For disks, need fine angular scales
  - ALMA needed for sensitivity
    - $S_\nu \sim \nu^{-(2+\beta)}$
- Need sensitivity, angular resolution, velocity resolution
    - ALMA Band 2!

# Per B1b: A First Hydrostatic Core?

IRAM 30m




PdBI Observations

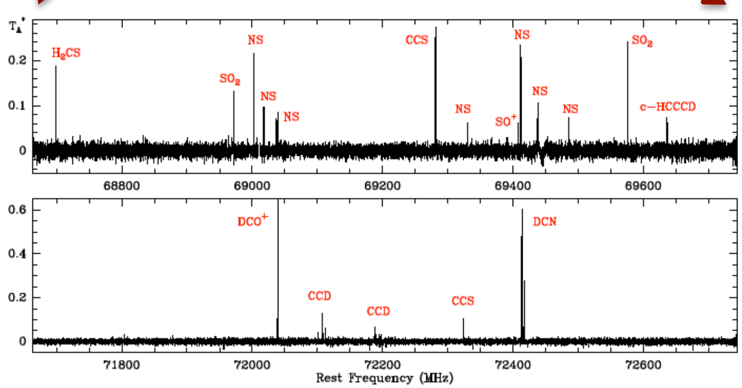



7-field mosaic in C+D configurations at 145GHz + IRAM-30m short spacings
Beam : 2.2 x 2.3" (500 AU) PA = 108°
$H_2CO$ $(2_{02}-1_{01})$ ; $CH_3OH$ $(3_K-2_K)$ ; $c\text{-}C_3H_2$ $(3_{12}-2_{21})$ ; $DCO^+(2-1)$ ; DCN (2 - 1) ; Continuum

GBT beam

Gerin et al 2015

GBT 100m



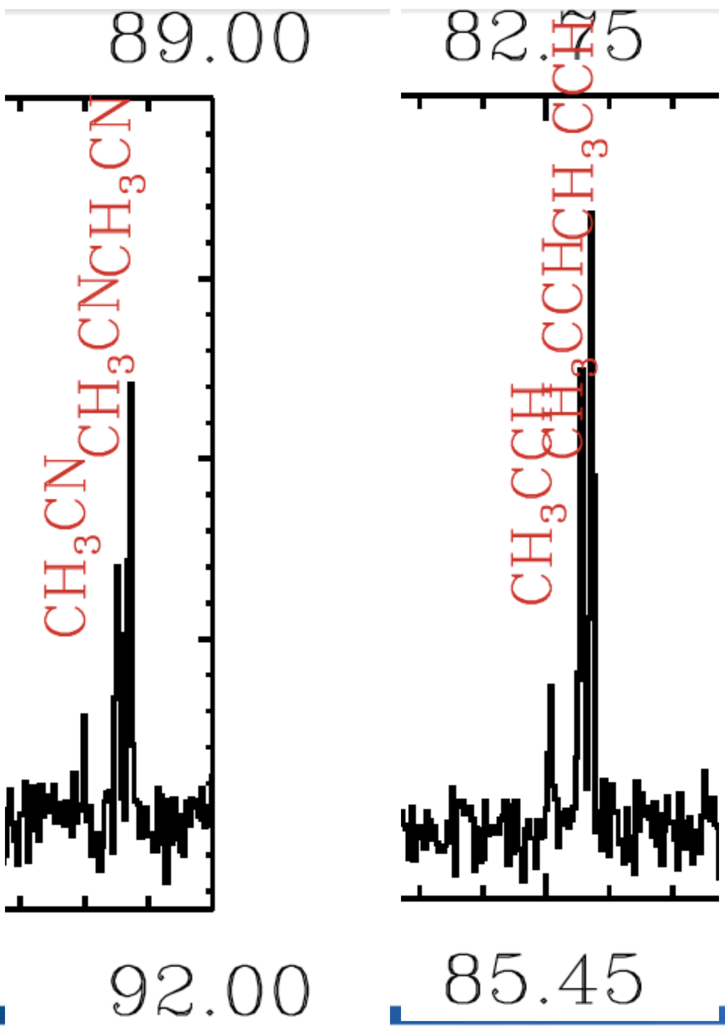

Marcelino et al in prep

- Two close D-enhanced cores, differ in evolutionary stage
  - B1nS shows clear outflow
  - B1nN more compact: 1st hydrostatic core?
- GBT beam separates them
- ARGUS array will image them

# Temperature probe: cold cores

ALMA

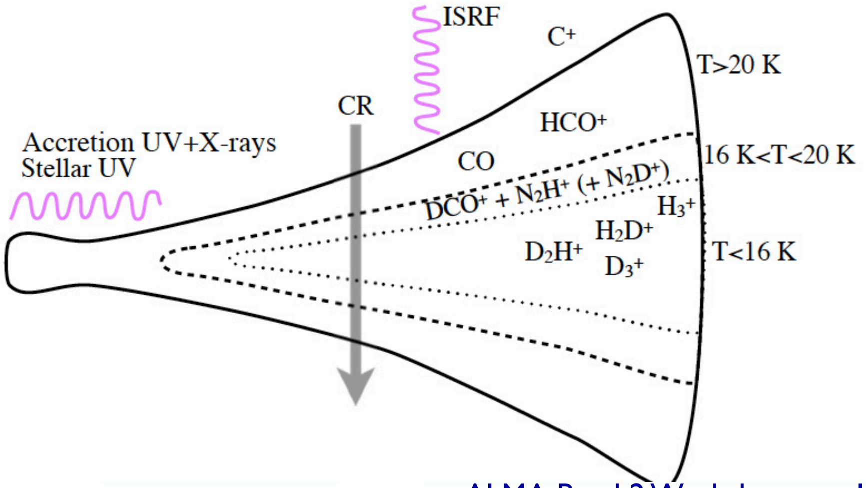
- Marcelino et al Survey of the B1b core shows emission from $CH_3CN$, $CH_3CCH$ lines at tenth K level. Temperature fit suggests ~15K, agrees with $NH_3$
- Note chemically. $CH_3CN$ is 'hot' species, $CH_3CCH$ is 'cool' species
- J=5-4 and J=4-3 can be observed simultaneously with other lines with broadband receivers (e.g. GBT, ALMA Band2).
- Relative intensities of different J lines provide a measure of density over a range $10^4$ to $10^6$ $cm^{-3}$; they lie near excitation peak




NRAO

# J=1-0 Lines Critical for PPD Midplane Study

- Disk midplanes are the sites of planet formation, the main reservoirs of mass and probable sources of complex organics
- Disk midplanes are cold
- To characterize disk midplanes requires access to range of low-energy lines of ions, deuterated molecules, isotopologues and organics
- ALMA Band 2 is will provide spatially resolved observations of key J=1-0 lines in disks.



# Star Formation in the Nearby Universe at Band 2

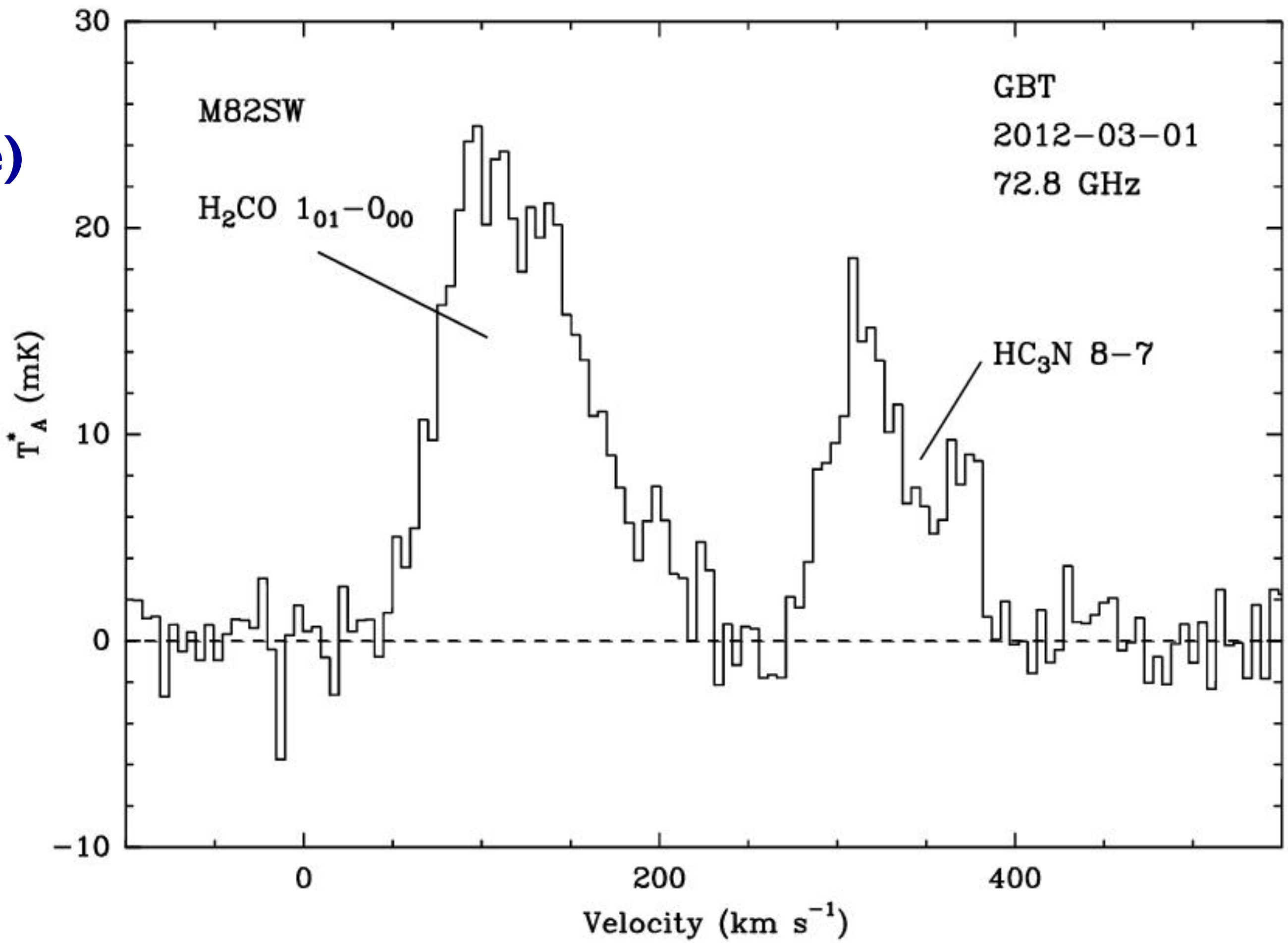
- Trace extragalactic star formation heating processes (HCN/HNC, D isotopomers)
- Measure spatial density and kinetic temperature ($H_2CO$ K-doublets, $CH_3CN$ J=5-4 and 4-3; $CH_3C_2H$ J=5-4 and J=4-3) (also other bands)
- Trace UV penetration into dense environments ($C_2H$, $HCO^+$, $DCO^+$)
- Identify shock environments (SiO)

# 4mm: Dense gas and Molecular Diversity in Nearby Galaxies: Sensitive Spectroscopy

ALMA

## M82

**H2CO (formaldehyde) & HC3N (J. Mangum)**



# The GBT produces deep 4mm images

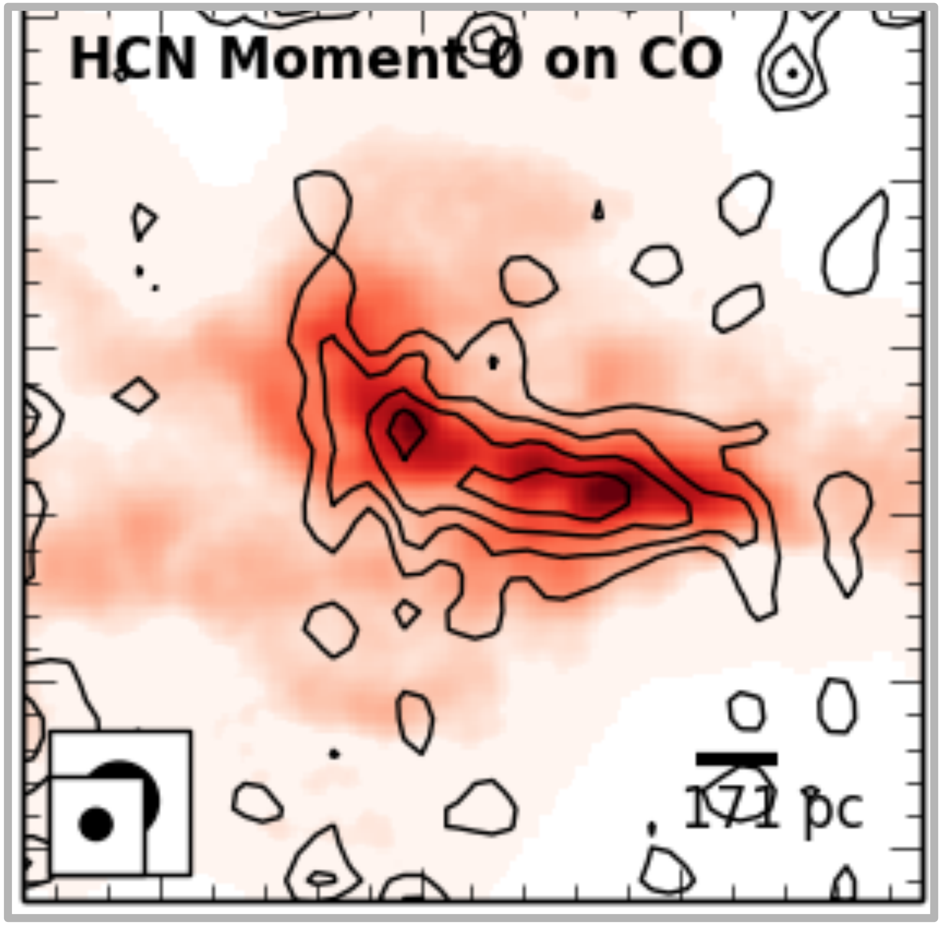
ALMA

For dense gas, GBT sensitivity to HCN, HCO+ is similar to that of IRAM 30m to CO.

Image of the starburst galaxy M82 in the dense gas tracers HCN/HCO+.

16 hours total time with existing effectively single pixel receiver.

The commissioned 16-pixel ARGUS instrument will increase observing efficiency by an order of magnitude.



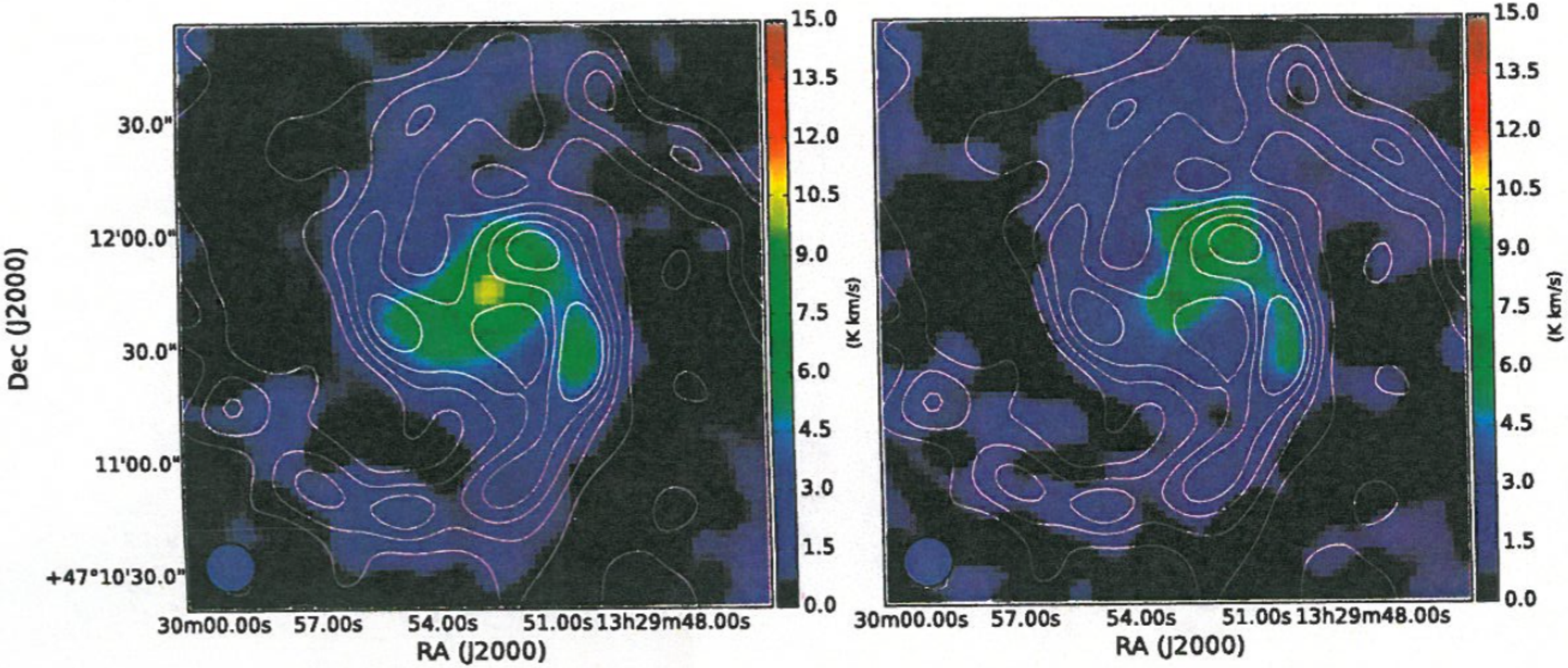

Kepley, Leroy, Frayer + 2014

# HCN and HCO+ in M51

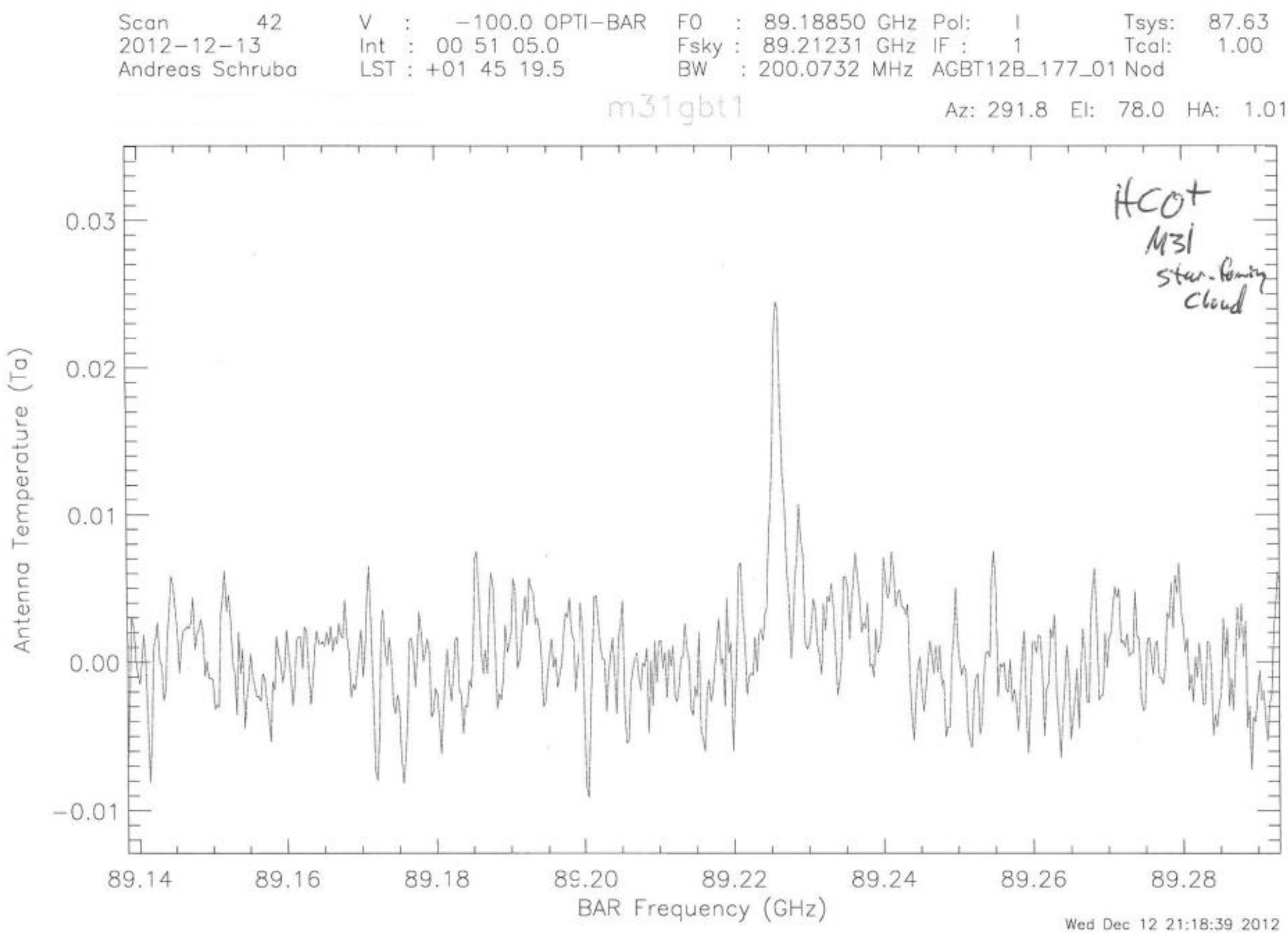
## (M. Louie Ph.D. Thesis with J. Koda)

Color is HCN left and HCO+ right with CO contours

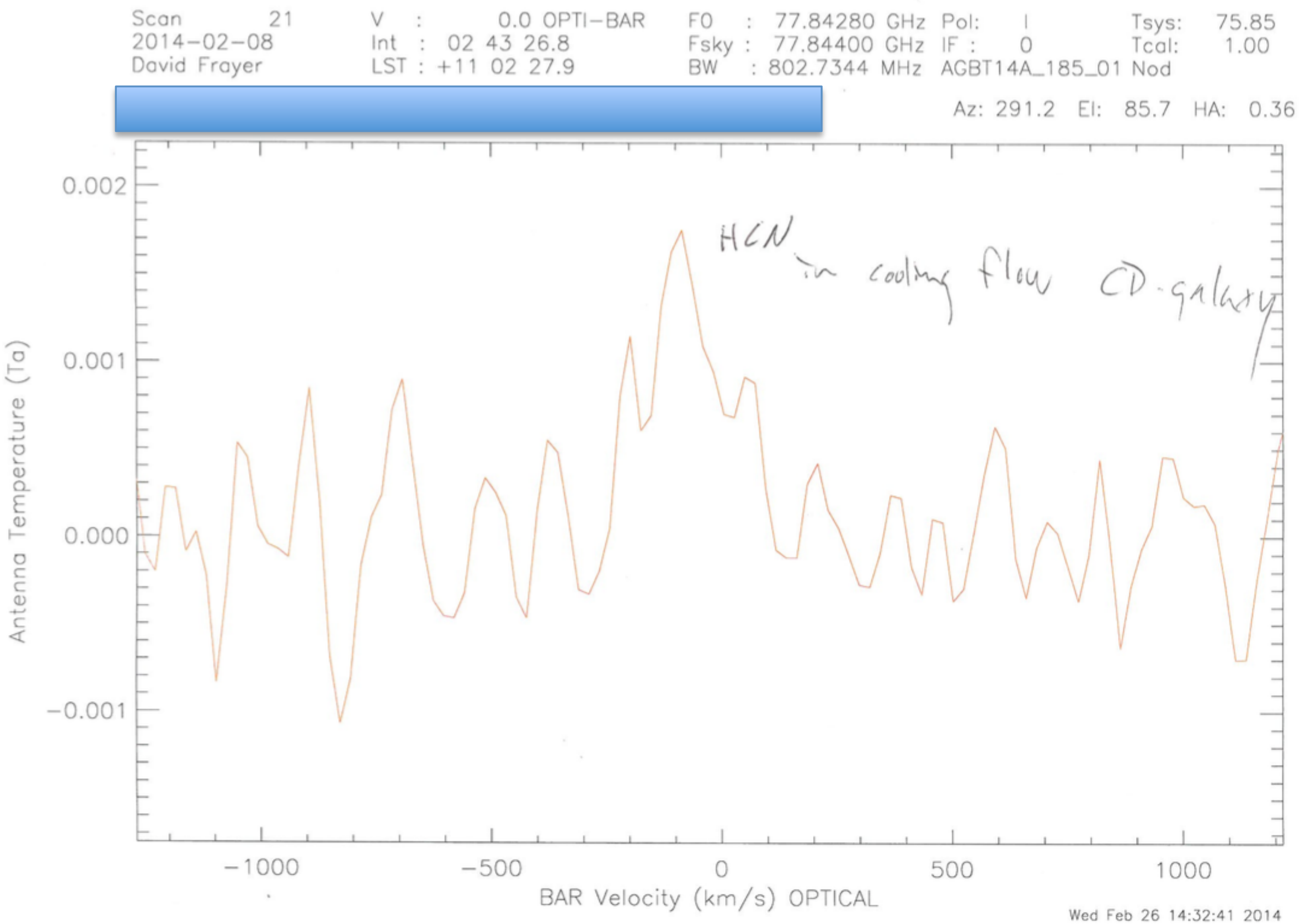
Louie et al.



# HCN/HCO+ in M31 Molecular Clouds, A. Schruba et al.

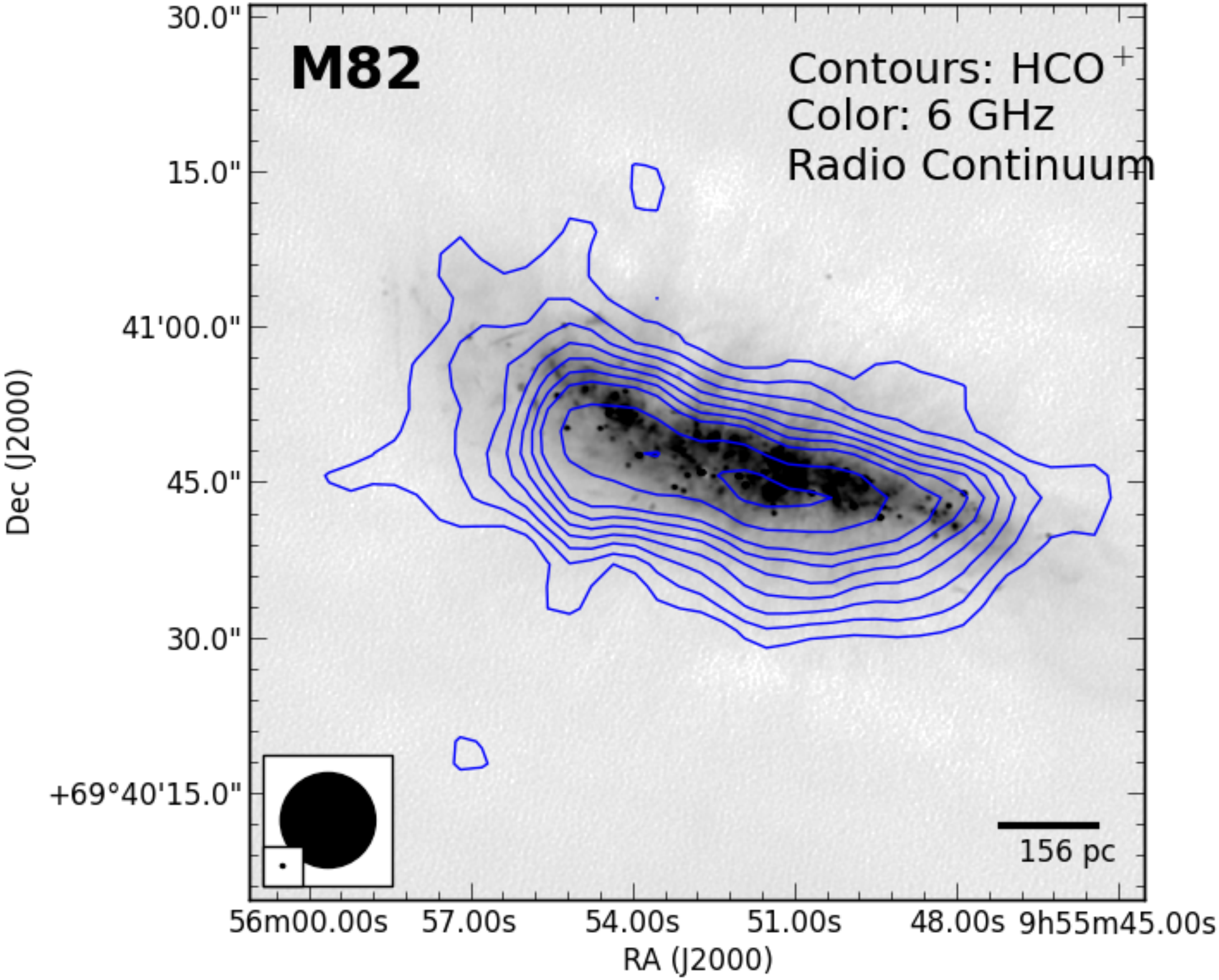


# HCN and HCO+ in Cluster Cooling Flows (Oonk, Edge, Frayer)



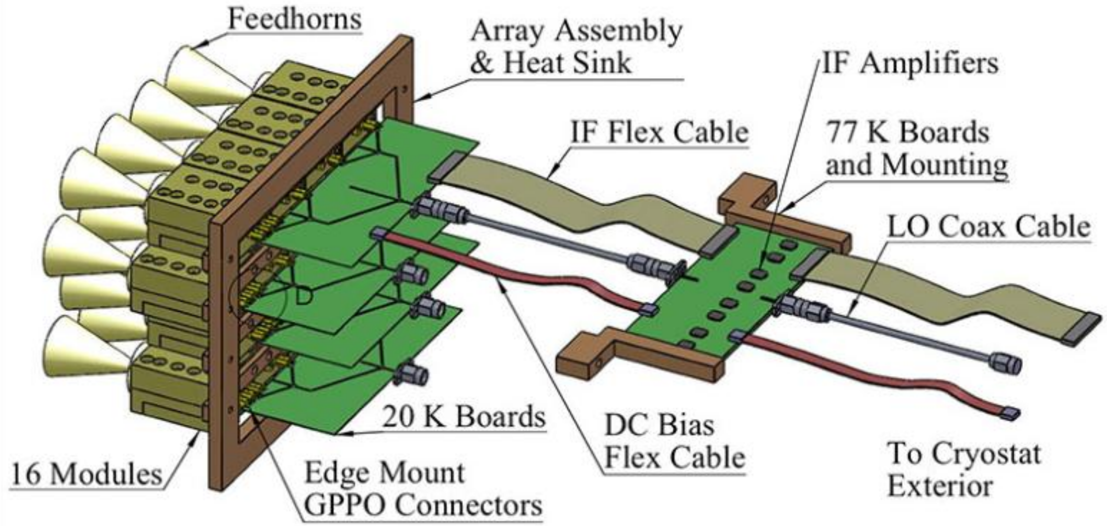
# 4mm Mapping of dense gas in nearby Galaxies:

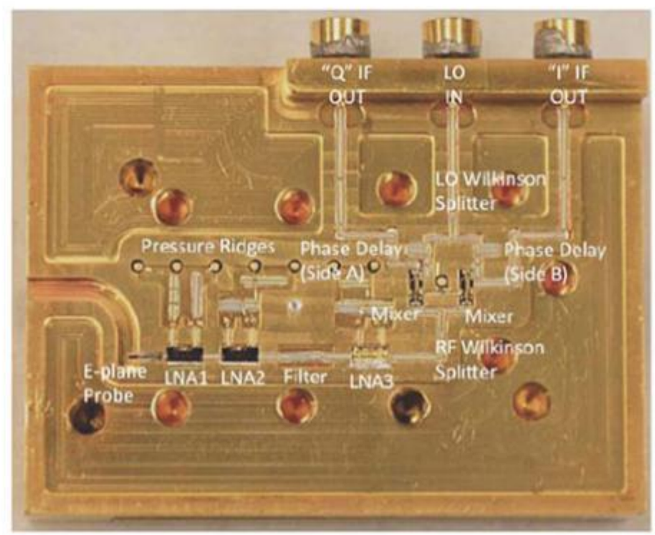
M82 HCO+(1-0) contours on VLA 6cm image (A. Kepley et al.)



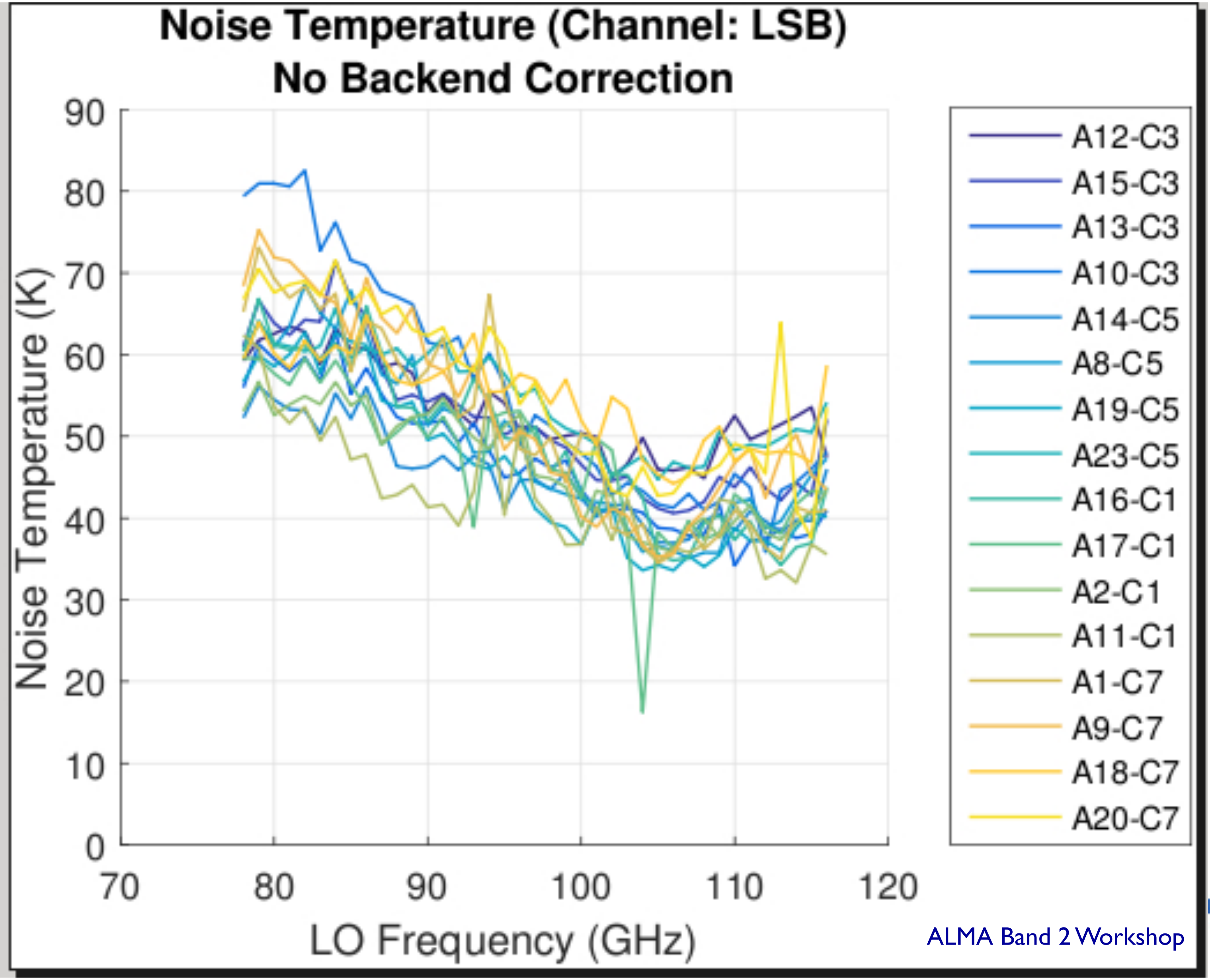
# 16 element scalable W-band FPA for the GBT

Tsys~75K

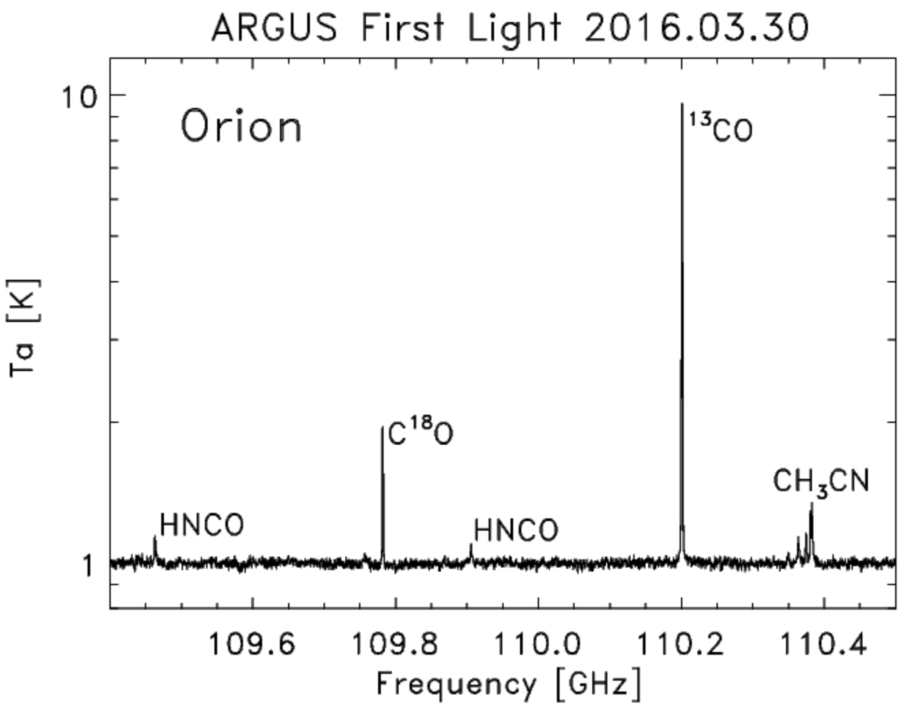


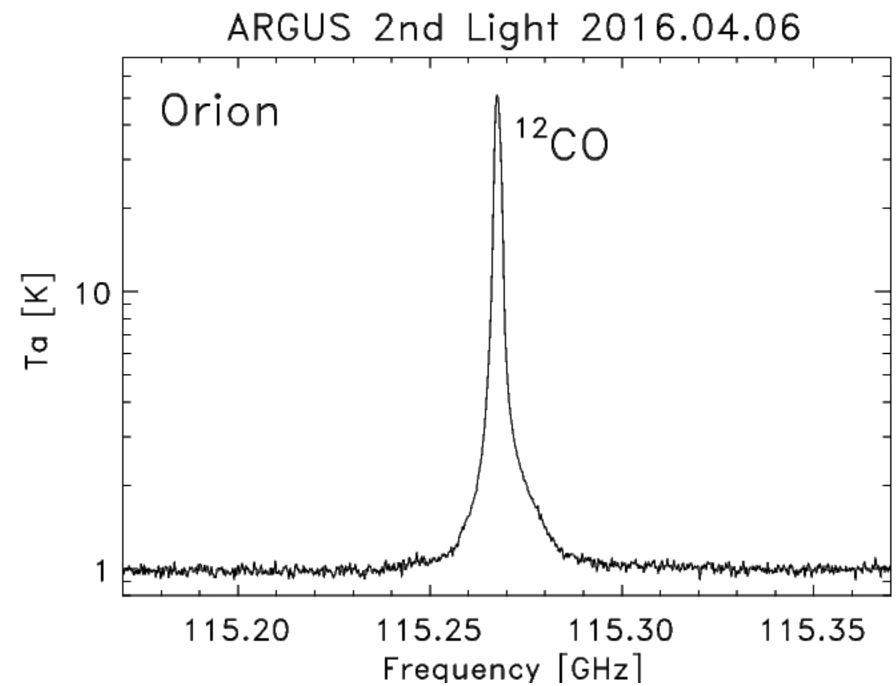



# Argus GB-Lab Performance – Matt Sieth (Stanford)

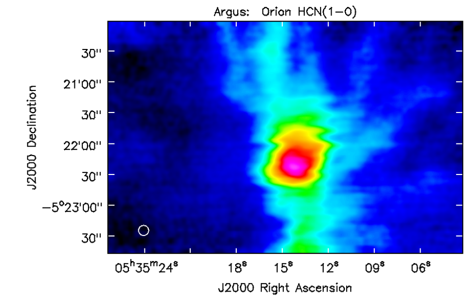


# Argus First Light




Excellent baselines, small beam

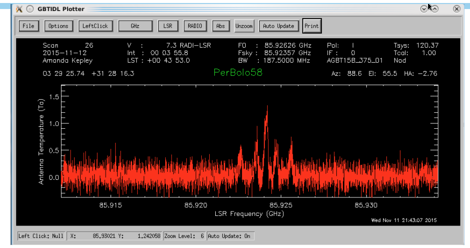



HCN image (commissioning)

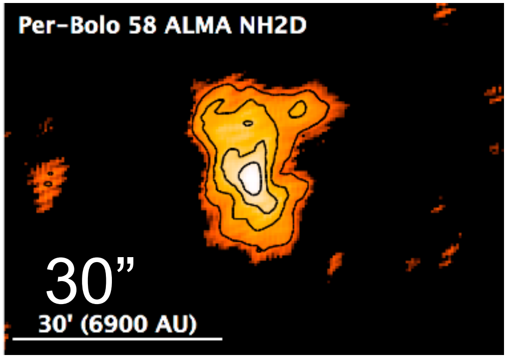
# GBT as a Complement to ALMA

- Problem: ALMA TP observations are costly in time
- GBT solution: For sources overlapping in frequency and celestial position, the GBT could provide a more efficient TP imaging alternative.
  - Time requirement: GBT, especially with ARGUS can be faster
  - GBT provides better uv overlap (100m vs 12m) and sensitivity (10x) owing to larger diameter
- Sky coverage overlap:
  - ALMA is designed to observe to Dec +42, so there is considerable sky overlap with the GBT.
  - At the high declinations, the GBT is particularly useful as ALMA observations must be carried out in a short temporal window at low elevations compared to the time window and elevation available to the GBT (though the sky may still be better at ALMA).
  - We have identified public domain ALMA datasets for which either Total Power was not requested or has not yet been delivered, and gotten DDT time on GBT for total power observations for comparison in a combined dataset.
  - Result: Coming soon!

# Example 2




GBT spectrum




- Comparing GBT and ALMA TP Short-Spacing Corrections
  - GBT DDT proposal to obtain 3 mm observations as a total power complement to data from an ALMA cycle 1 program (M. Dunham) as a proof of concept for using the GBT in this capacity.
  - W-band receiver with VEGAS to observe the line $NH2D(1_{11}-1_{01})$ at 85.92626GHz
  - GBT achieves higher channel resolution and larger bandwidth 2m 15s per beam
  - Map a region 1.5 x 1.5 arcmin across. This region was chosen to map the entire FOV of the ALMA Band 3 data (~1arcmin). Need 6hr, 8s per beam. With calibration overhead, 12 hr needed.
- Results: Awaiting further analysis

ALMA NH2D (86GHz) integrated intensity map for Per-Bolo 58, one of the candidate first cores observed in our cycle 1 program. The contours start at 5s and increase by 3s. The scale bar shows that the 12-m array data only recover a small fraction of the total core emission, which is known to have a diameter of approximately 1’.

# Comparison

## GBT, ALMA, ngVLA at 86 GHz

### Spectroscopy

### Time to map a 3'x3' field to 20 mK rms

| GBT 2015 1 pixel 9" | GBT 2016 16 pixels 9" | ALMA 50x12m 3" | ALMA 50x12m 1" | ALMA 10x7m 24" | GBT 2020 50 pixels 9" | ngVLA 500x18m 1" |
|---|---|---|---|---|---|---|
| $56^h$ | $8.3^h$ | $15^h$ | $1,250^h$ | $0.5^h$ | $1.1^h$ | $17,500^h$ |

*1 km/s ch. -- GBT 2,000 hr/year weather -- ngVLA tapered to 1"*

# Design and Testing of a Prototype Band-2 Cartridge

**Award**: $1,493,969

**Investigators**: Eric W. Bryerton (NRAO), Kieran Cleary (Caltech/JPL), David T. Frayer (NRAO), Matthew A. Morgan (NRAO), Marian W. Pospieszalski (NRAO), Kamaljeet S. Saini (NRAO), Scott Schnee (NRAO), Sivasankaran Srikanth (NRAO), Anthony C. S. Readhead (Caltech/JPL), Lorene Samoska (JPL)

**Science Objectives**:

- To cover the largely unexplored 4 mm band, previously available only on the 12 m Kitt Peak telescope (ARO) and very recently on the GBT (NRAO).
- Access the $J = 1 \rightarrow 0$ transitions of the deuterium analogs of common, abundant interstellar molecules, including $DCO^+$, DCN, $N_2D^+$ & $C_2D$, as well as $H_2{}^{13}CO$, $^{13}C_2H$, $H^{13}CO^+$, $HC^{18}O$, $H^{13}CN$, $HC^{15}N$, $H_2CO$, $HCNH^+$ and $C_2H$.
- "Cold chemistry", using the lowest energy transitions of simple deuterated species to trace the coldest and densest areas of star-forming cores and proto-planetary disks.
- Study galaxies and clusters at low intermediate redshifts – this is currently unavailable with the present ALMA bands for the important CO($1 \rightarrow 0$), HCN($1 \rightarrow 0$), $HCO^+$($1 \rightarrow 0$), HNC($1 \rightarrow 0$), and SiO($2 \rightarrow 1$) transitions.

**Bottom Line**: Technology is ready for ALMA, informed by European NA and other Studies

- Workshops held in March 2014, May 2016 for exchange of information by NA, EU and EA.

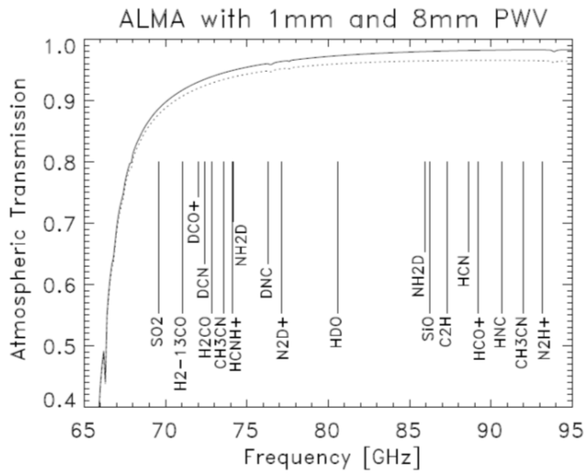
# Design and Testing of a Prototype Band-2 Cartridge

## SCIENCE CASE

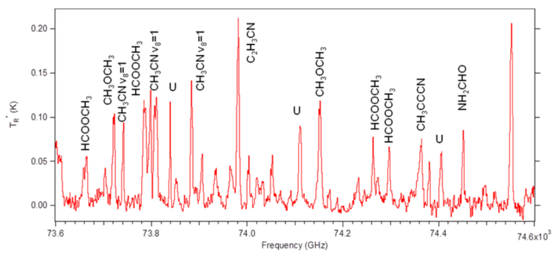
- The 67 – 90 GHz region of the electromagnetic spectrum has been largely unexplored, though recently NRO 45m, IRAM 30m, GBT 100m have addressed this.
- High sensitivity and resolution offered by ALMA will yield exciting new results.
- J = 1 → 0 transitions of several molecules in the frequency range allow investigation of:
  - The evolution of gas in galaxies and clusters at low and intermediate redshifts.
  - Galactic Evolution
  - Formation of stars and proto-planetary discs.
  - Chemistry of the Universe.
  - Origin of Life.

Science case has been further developed as part of our collaboration with the ESO funded Band-2/(2+3) consortium.

ALMA's high sensitivity will allow detection of many ***new*** weak transitions of complex species (in the sense of small line strengths or small dipole components).




*(ABOVE) 4 mm atmospheric window from the ALMA site showing important astronomical spectral-line transitions. (Band-2 is 67 – 90 GHz.)*




*(ABOVE) Rich spectral lines measured towards SgrB2(N) at 74 GHz, using the ARO 12 m telescope & with 1 GHz of bandwidth (from Halfen et al. 2012).*


20-23 September 2016, Indian Wells, CA (near Palm Springs)

More information: http://go.nrao.edu/ALMA5years

- ***Galaxy Formation and Evolution I: Cosmic Evolution*** Caitlin Casey U.Tx at Austin
- ***Galaxy Formation and Evolution II: Gas & Star Formation Properties*** Linda Tacconi Max Planck Institute for extraterrestrial Physics
- ***Galactic Centers (<1 kpc): Star formation, AGN, Black Holes & ULIRG*** Masatoshi Imanishi National Astronomical Observatory of Japan
- ***Nearby Galaxies I: Normal Galaxies*** Karin Sandstrom U. California San Diego
- ***Nearby Galaxies II: Starburst & Super Star Clusters*** Kazushi Sakamoto ASIAA
- ***Massive Star Formation*** Jill Rathborne CSIRO Astronomy and Space Science
- ***Low Mass Star formation*** Adele Plunkett ESO Santiago
- ***Chemical Evolution During Star and Planet Formation*** Jeong-Eun Lee Kyung Hee University
- ***Protostellar Disks & Planet Formation*** Laura Perez U. de Chile
- ***Debris Disks*** Brenda Matthews NRC-HIA
- ***Stars and Stellar Evolution*** Leen Decin KU Leuven
- ***Solar System*** Arielle Moullet NRAO
- ***Synergy between ALMA and JWST*** Klaus Pontoppidan STScI
- ***ALMA after 5 Years*** Pierre Cox JAO
- ***Future ALMA*** John Carpenter (JAO), Al Wootten (NRAO), Neal Evans (U.Texas at Austin
- ***Conference Summary*** Anneila Sargent Caltech

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