ALMA Band 2$^+$ Science

Summary from Workshops at NAASC, Firenze, PDR

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

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) and NRO 45m.
- Access the J = 1 → 0 transitions of the deuterium analogs of common, abundant interstellar molecules, including DCO^+, DCN, N_2D^+, C_2D & NH_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 and low excited states of HDO, NH_2D and CH_2D^+
- "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 → 0), HCN(1 → 0), HCO^+(1 → 0), HNC(1 → 0), and SiO(2 → 1) transitions.

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

– This Workshop planned for exchange of information by NA, EU and EA.

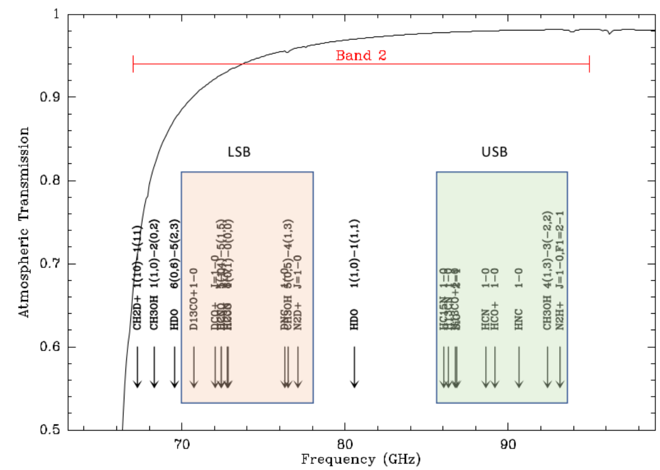
Design and Testing of a Prototype Band-2 Cartridge

SCIENCE CASE

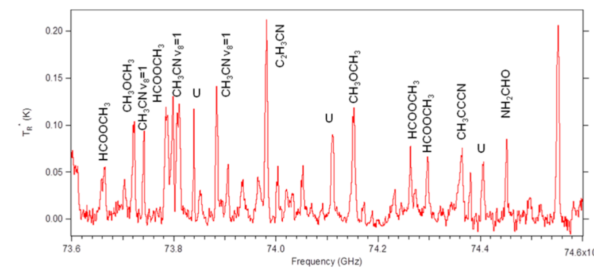
- The 67 – 95 GHz region of the electromagnetic spectrum is largely unexplored.
  - Will have 2x8GHz x 2 polzns of bandwidth
- High sensitivity and resolution offered by ALMA will yield exciting new results.
- J = 1 → 0 transitions of several molecules in the frequency range allow investigation of:
  - 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 will be 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).

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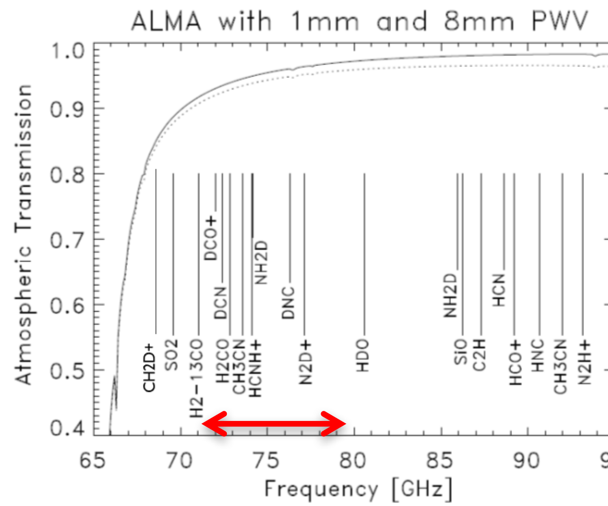
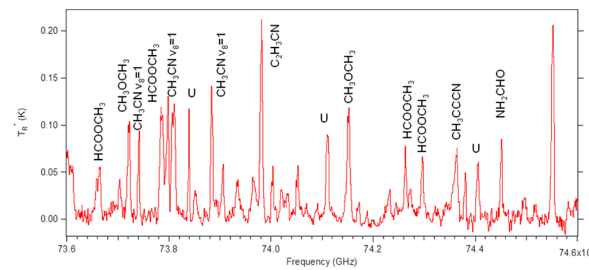


(ABOVE) 4 mm atmospheric window from the ALMA site showing important astronomical spectral-line transitions. (Band-2 is 67 – 90 GHz.) NA Project IF is 8 GHz (marked).



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ALMA's 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 updated by Baker (2009).

The first two of these speak directly to requirements for Band 2 receivers.

ALMA

ALMA Top Science case #1

- The first high-level science goal ***is directly about ALMA Band 2***, as the lower CO lines in the Milky Way are the strongest & the J=3-2 line at 86 GHz is ***the only ALMA-accessible line***. This ***sets*** a sensitivity target for Band 2. The goal is to detect 'normal' galaxies, if they exist, 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 somewhat 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
  - 2009: Andrew Baker et al. estimated $\mathbf{S}_{CO(3-2)}$ = **36.3 μ**Jy.
  - 2014: We're measuring Tsys daily in B3 and preparing to build Band 2

Milky Way at z=3

- Tsys
  - Andrew used Tsys=67K for B3. The B2 specs would give us Tsys≤50K.
  - As the B3 datasets shown later suggest, Tsys=50K for recent datasets in good weather is in fact obtainable for some B3 systems.
  - The proposal aims at Trx=30K for B2, the current requirement, which 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

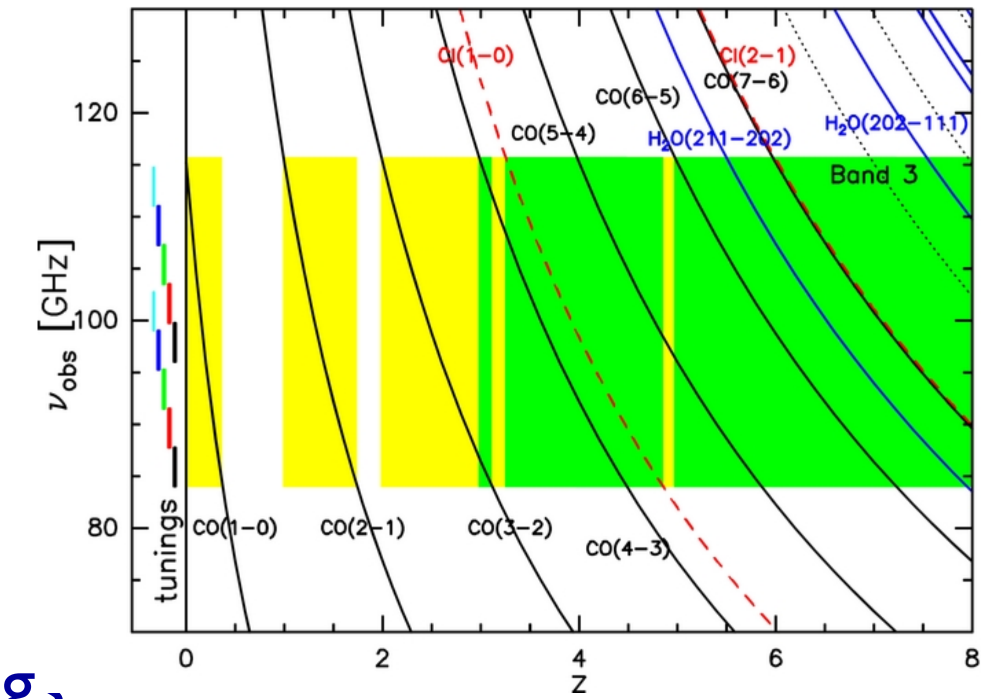
- **T**sys = 50K
- aperture efficiency $\boldsymbol{\eta}_a$ = 0.74 for Band 3,
- **ND**^{2} = 58x 12^2 = 8352m^2 For the combined array
- 75 kms^{-1} channel (which at $v = v_0/(1 + \mathbf{z})$ = 86.449GHz corresponds to 21.6MHz)

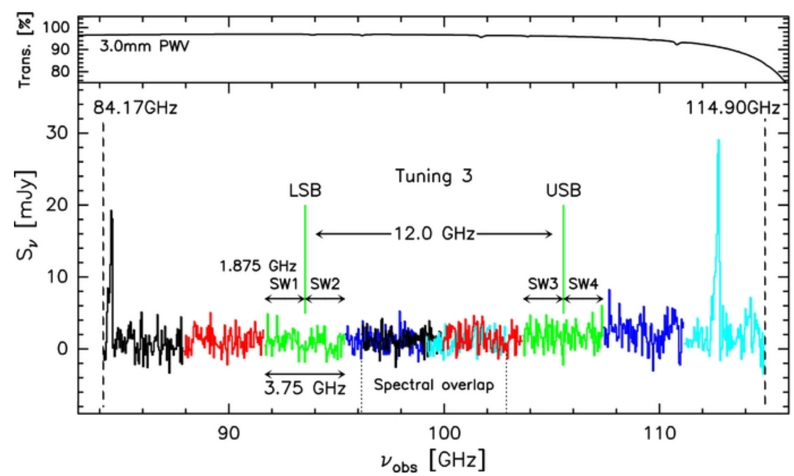
Then in 1 day of integration, one reaches **ΔS~15μJy, for a 2 σ** detection per channel; if line is e.g. Δv=300 km/s, one could achieve 4σ.

One concludes that the detection is ***just*** feasible with the current specs.

B23 Xgal Science

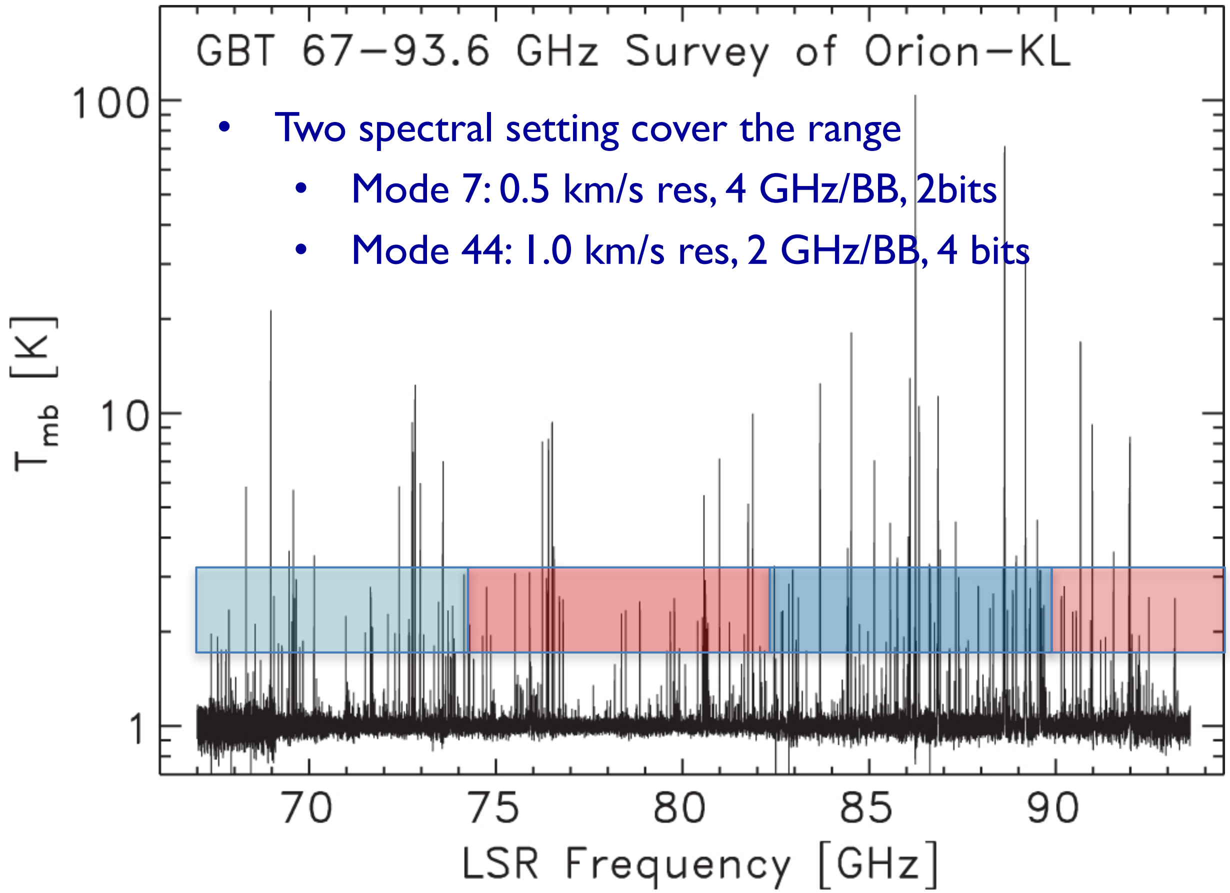
- MW at z=3
- LIRGS at z~0.2 to 0.7
  - No CO 1-0 z>0.2 in B3; 2-1 z~1
  - Galaxies ran out of gas?
  - Low J XCO tractable
- Spectral searches: 2 settings
- Dense tracers
  - Now only z<0.05; B2^{+} gets to z<0.3
  - Lines in Band 1 only for z>1
  - Scales 1-4''/kpc.
  - FOV ~70-90''





Band 2+: Rapid Spectral Surveys

- Two spectral setting cover the range
  - Mode 7: 0.5 km/s res, 4 GHz/BB, 2bits
  - Mode 44: 1.0 km/s res, 2 GHz/BB, 4 bits

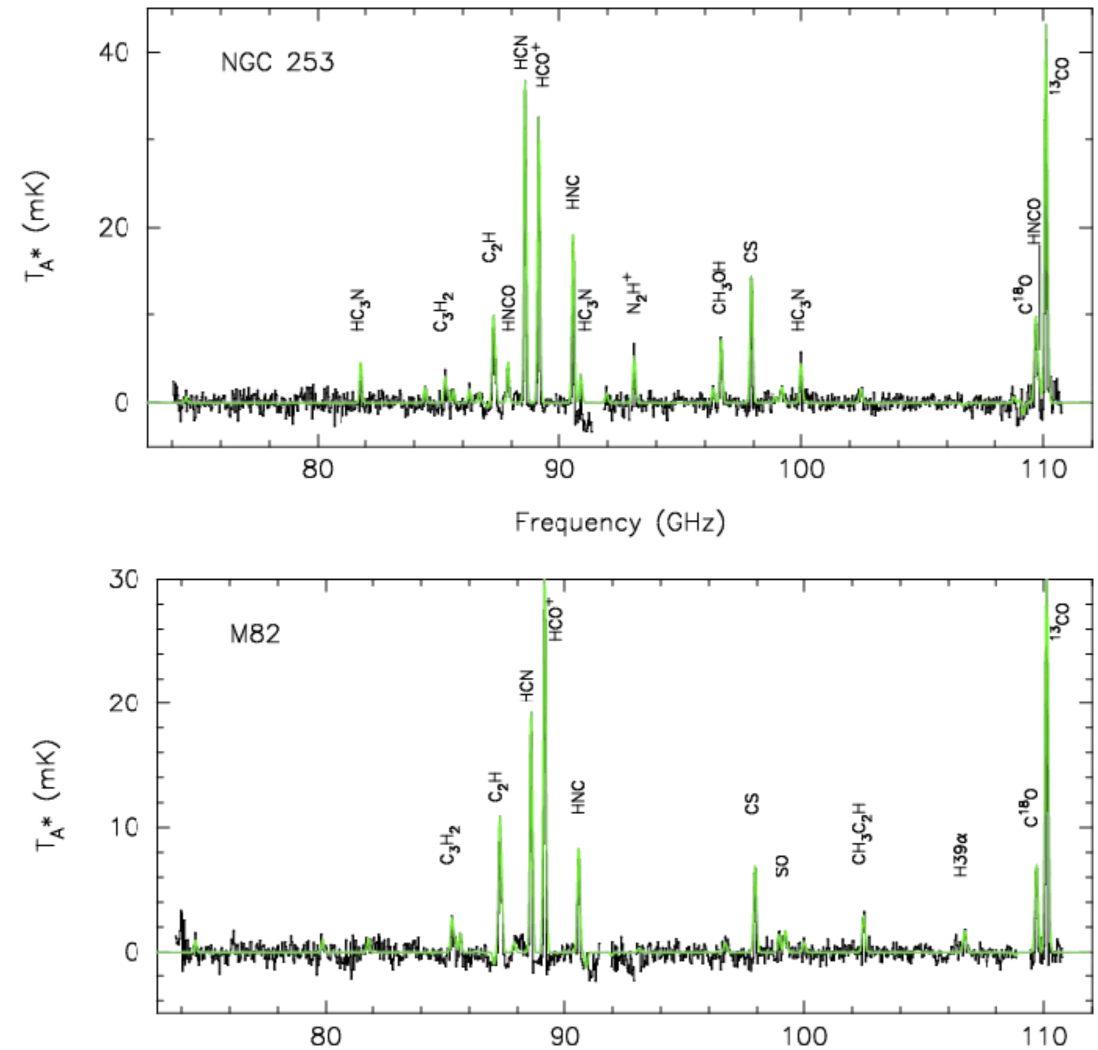


What are the Bright Extragalactic Lines?

FCRAO 14m RSR: NGC253+M82

ALMA Band-2 (67-90 GHz)

Line	Redshift Range
^{12}CO:	0.28<z<0.72
^{13}CO:	0.2<z<0.64
HCN:	0<z<0.32
HCO^+:	0<z<0.33



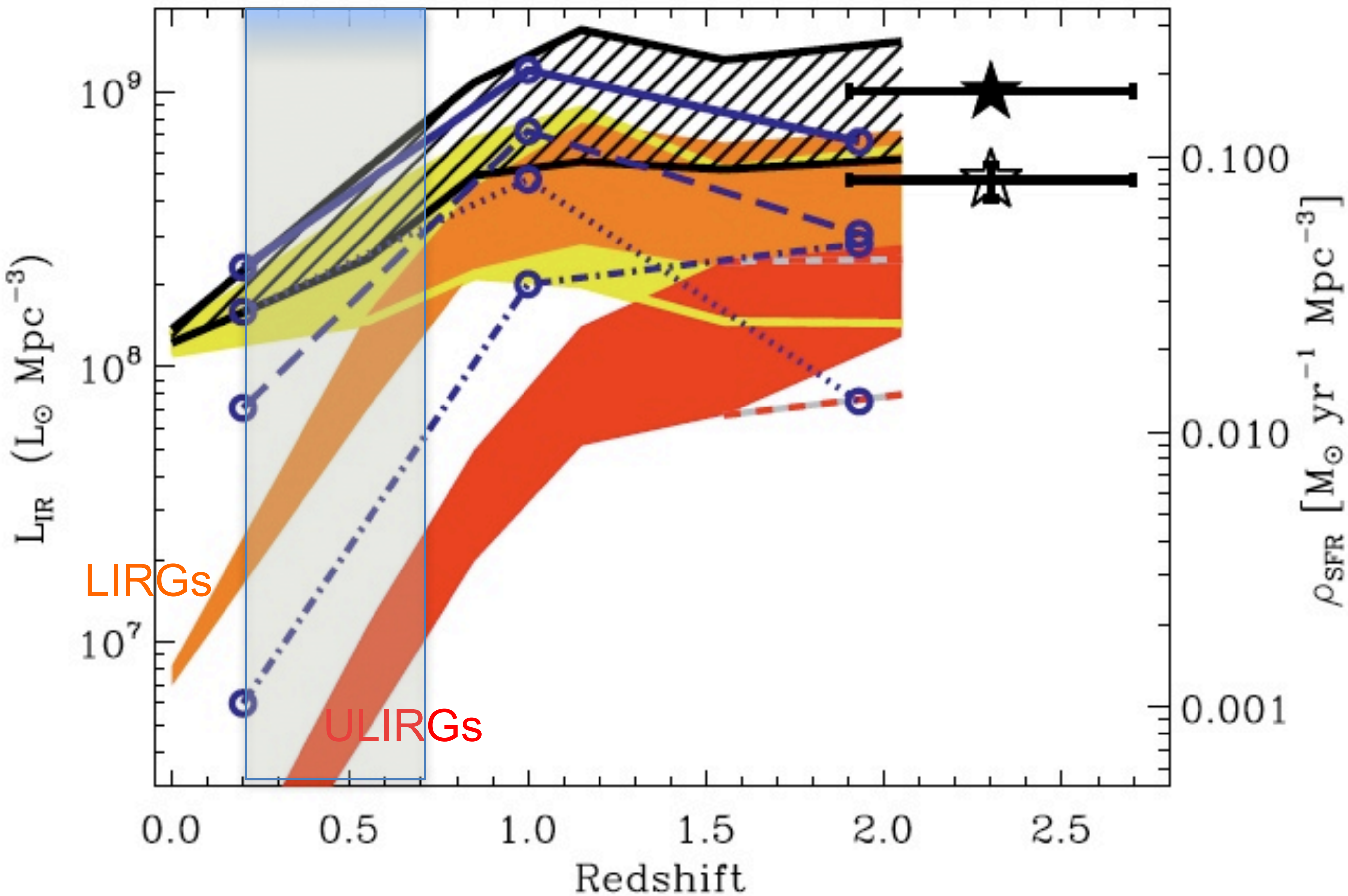
Intermediate redshift galaxies and (1-0) transitions are important for understanding galaxy evolution

Lines are typically 1/20 as strong as CO or less.

Star-Formation History from IR

Why are LIRGs important?

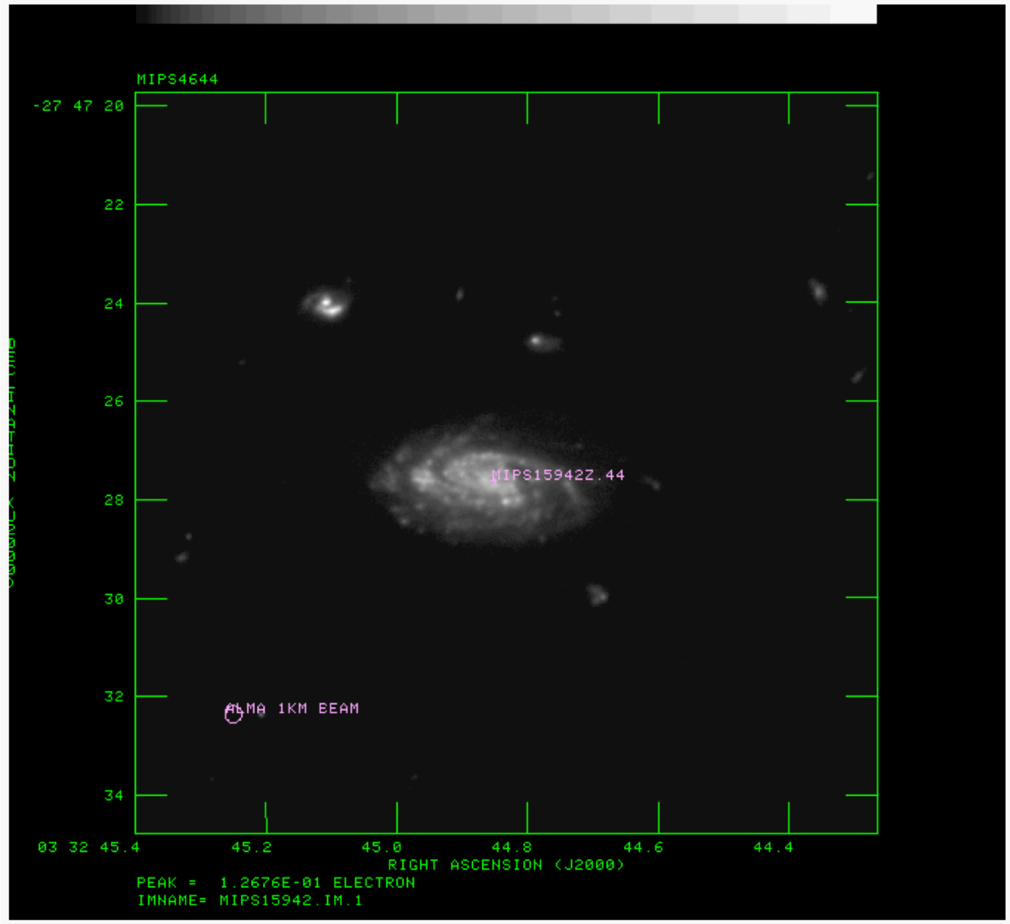
The bulk of the infrared EBL is at z~1, and the rapid evolution from now to z~1 is associated with luminous infrared star-forming galaxies (LIRGs). Herschel and Spitzer Surveys found large numbers of z~0.2-1 LIRGS.
➔ CO at intermediate z key



Magnelli, et al. 2009 (Spitzer FIDEL-70um result)

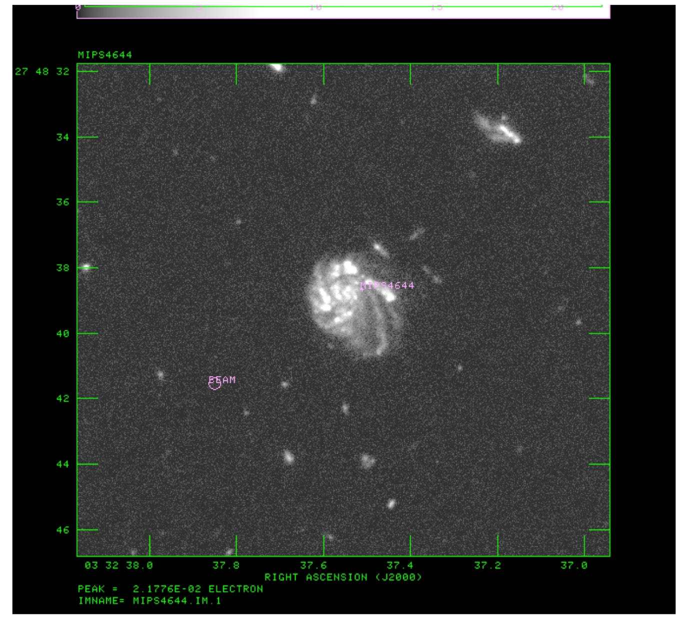
CO in LIRGs $0.2<z<0.7$

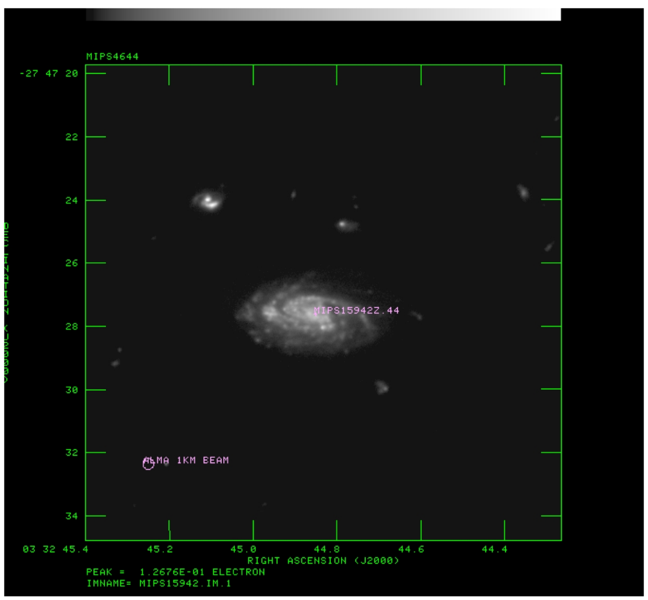
- How did galaxies evolve to their current form?
- Image is MIPS15942, z=0.44, D_L=2420Mpc
  - 'modern-looking'
  - ~5L* similar to NGC7331, NGC4321
- Assume $L(CO)_{1\text{-}0}$~5 $L(CO)_{1\text{-}0, MW}$
- T_{sys}~50K SSB
- 5σ 1 hr could detect this .8 mJy75 km/s line
  - 1"~6kpc
  - Rotation curve survey just possible



Examples

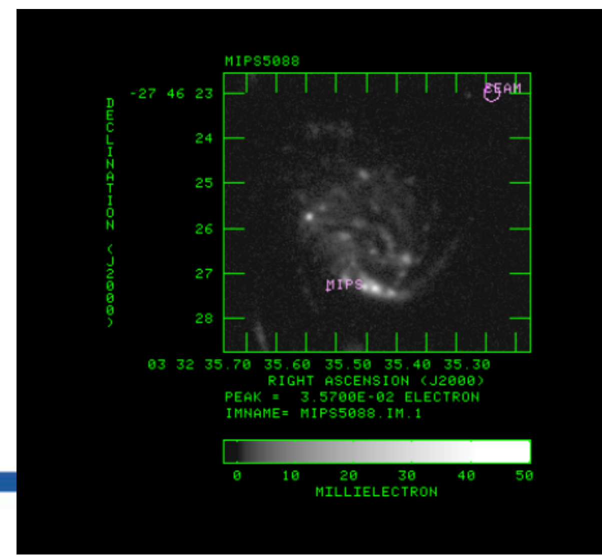
- MIPS4644. Image of the LIRG galaxy MIPS4644, at a distance of z=0.67 in the Hubble UltraDeep Field. The visible structure in this galaxy subtends about 4", or 20 kpc or so.





- MIPS15942 at z=0.44, another LIRG in the UDF

- MIPS5088, another LIRG in the UDF



What are the Bright Extragalactic Lines?

ALMA Band-2+ (67-95 GHz)

Line	Redshift Range
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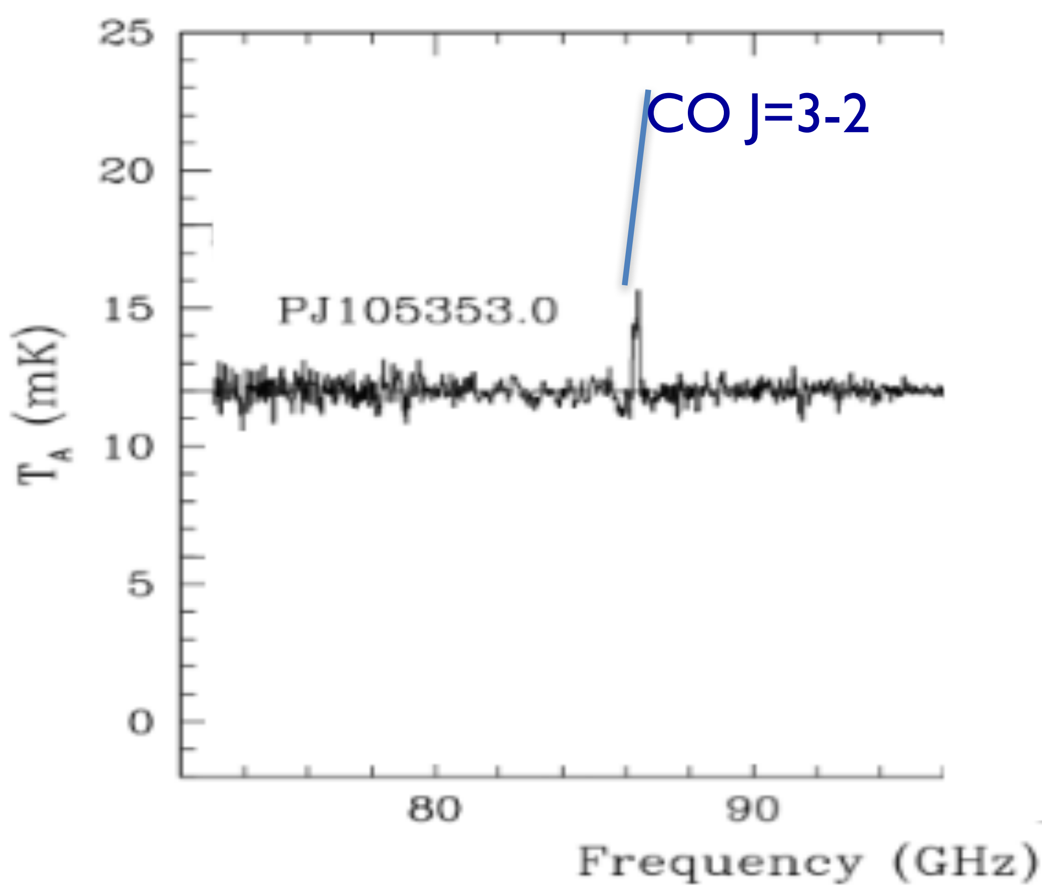
^{13}CO:	$0.2<z<0.64$
HCN:	$0<z<0.32$
HCO^{+}:	$0<z<0.33$

FCRAO 14m RSR @LMT: PJ105353.0



Clusters of Galaxies (Band 1/Band2)

- Sunyaev-Zel'dovich Effect Observations of Galaxy Clusters
  - Studies of Shocks
    - natural tool for detecting and characterizing the pressure discontinuity at a shock
    - In high-z clusters cosmological dimming of X-ray surface brightness makes X-ray observations challenging and expensive
  - Studies of AGN-driven Radio Bubbles / X-ray Cavities
  - Studies of ICM Turbulence through Pressure Fluctuations
  - Joint SZ/X-ray Surface Brightness Constraints on Cluster Temperature

ALMA Top Science case #2: Protoplanetary Disk at 150pc

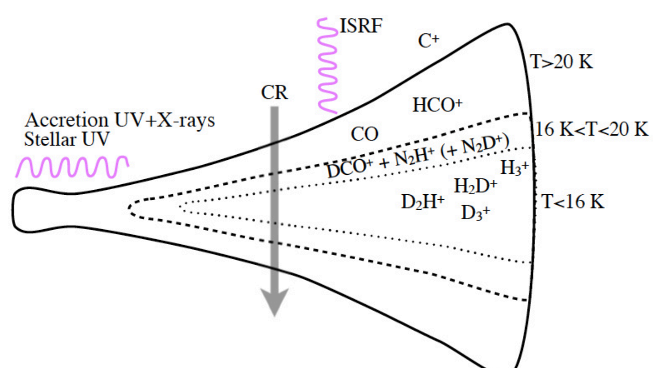
- 'to study the physical, chemical, and magnetic field structure of the disk and to detect the tidal gaps created by planets undergoing formation.'
- J=1-0 transitions are needed to constrain
  - midplane distributions
    - Disk midplanes are cold, best traced by lines with low energy levels
- To constrain temperatures 1-0 and e.g. 3-2 transitions are needed (6-5 will typically not be populated)
- J=1-0 lines of key molecules are in ALMA Band 2:
  - Ions: DCO^+, N_2D^+,
  - Deuterated molecules: DCO^+, N_2D^+ ,C_2D, DCN, NH_2D
  - Other isotopologues: $H_2{}^{13}CO$, $^{13}C_2H$, $H^{13}CO^+$, $HC^{18}O^+$, $H^{13}CN$, $HC^{15}N$
  - Small organics: H_2CO, C_2H
- Other lines of important D-bearing molecules NH_2D, CH_2D^+ and HDO
  - T probes (CH_3CN, CH_3CCH)

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)

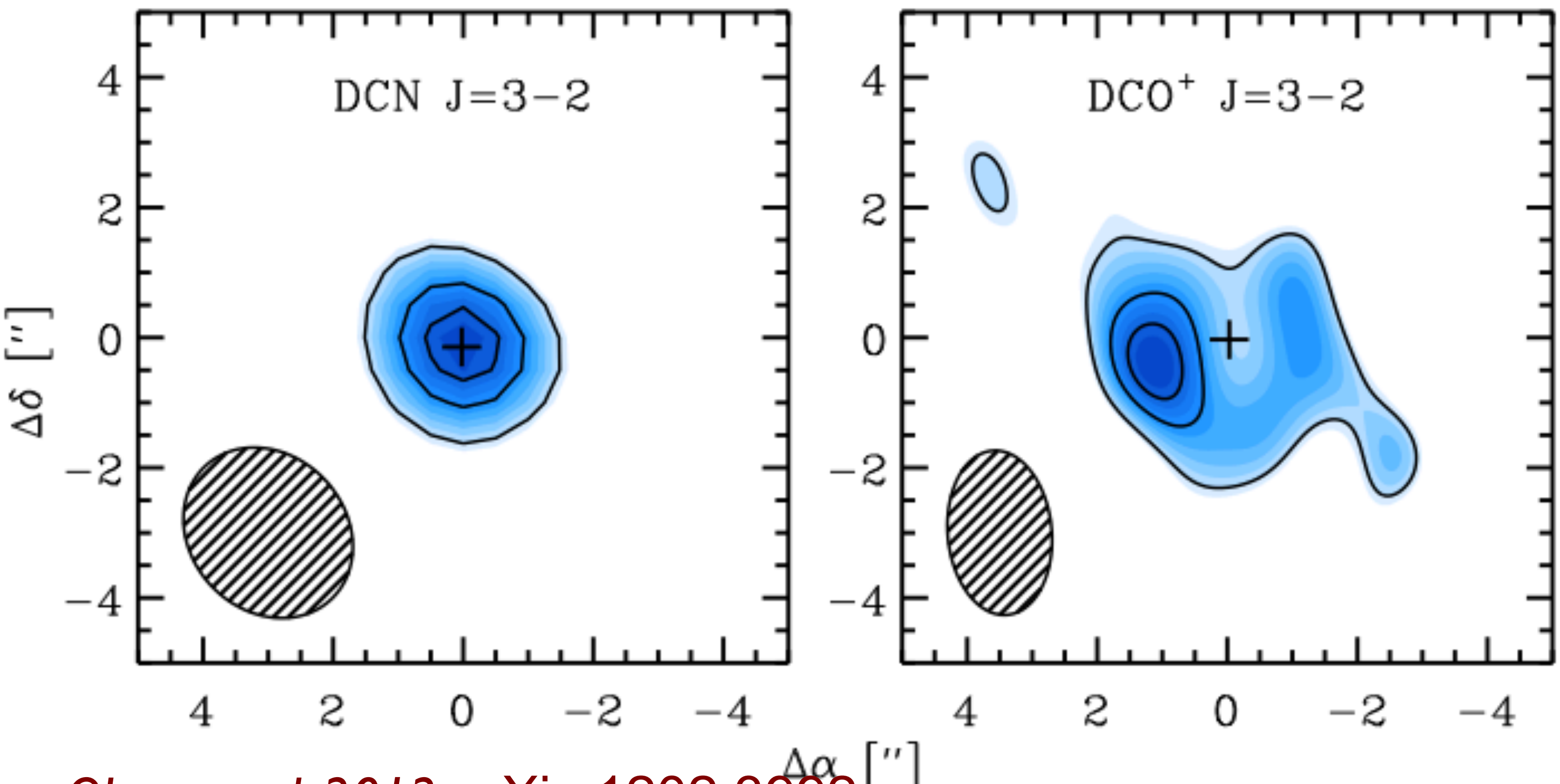
J=1-0 Lines Critical for PPD Midplane Study

- Disk midplanes are the sites of planet formation, the main reservoirs of mass and probable sources of complex organics
- Disk midplanes are cold—ices form; ices are sticky; good larger body seeds
- To characterize disk midplanes requires access to range of low-energy lines of ions, deuterated molecules, isotopologues and organics
- ALMA Band 2 is the only observatory that would provide spatially resolved observations of key J=1-0 lines.
- The NA Project's 8 GHz IF would encompass all of the important D-molecule resonance lines, unique frequency!



ALMA SV Data: Protoplanetary Disk TW Hya

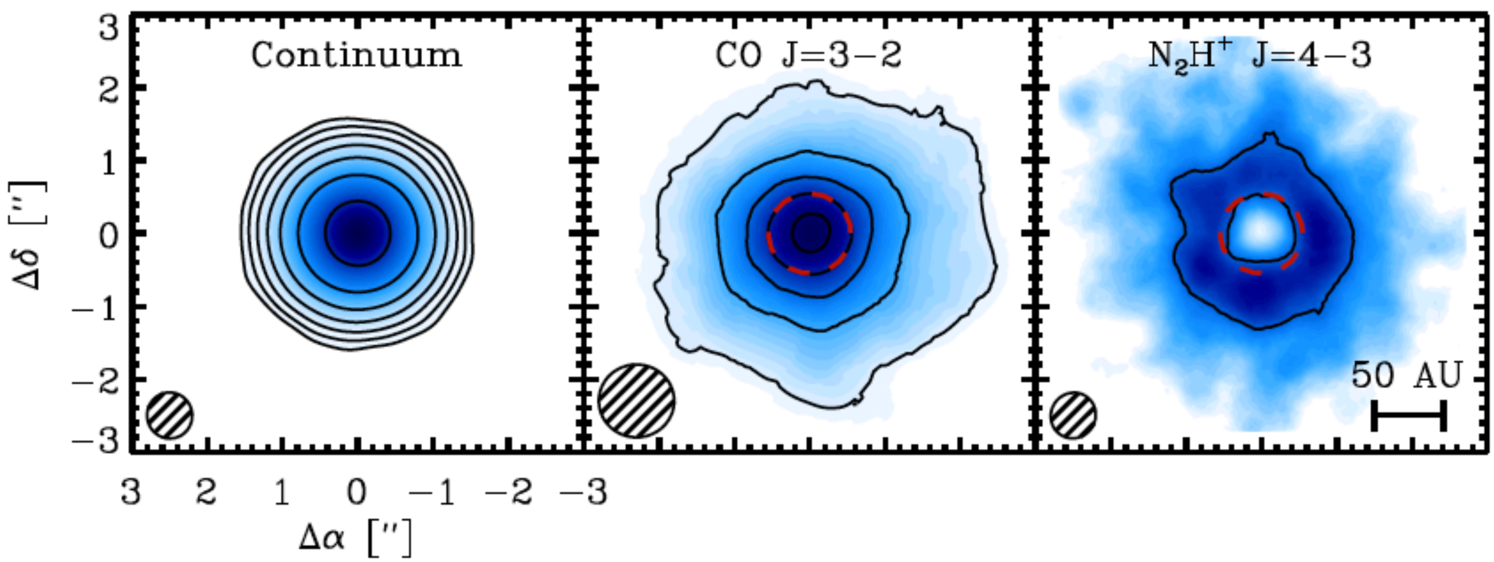
- The different radial distributions of DCN and DCO^+ suggests the presence of different formation pathways for these species and support a model in which DCN is mainly formed through reactions with CH_2D^+ while DCO+ is dominantly formed from H_2D^+



Oberg et al. 2012 arXiv:1202.3992

Imaging of the CO Snow Line in a Solar Nebula Analog

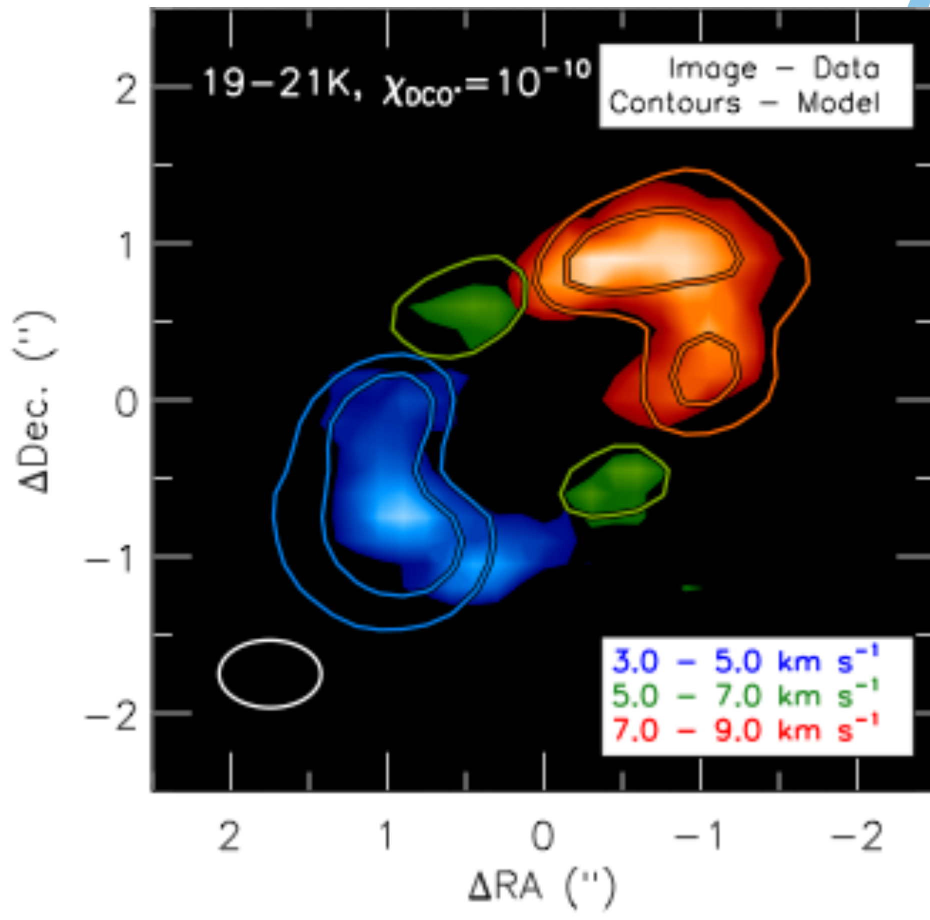
ALMA has imaged the CO ‘snow line’ around TW Hya, an analog of the solar nebula. Planets form in the disks around young stars. Their formation efficiency and composition are intimately linked to the protoplanetary disk locations of "snow lines" of abundant volatiles. The chemical imaging used high spatial and spectral resolution observations of N_2H^+, a reactive ion present in large abundance only where CO is frozen out. The N_2H^+ emission is distributed in a large ring, with an inner radius that matches CO snow line model predictions. The extracted CO snow line radius of ~ 30 AU is a key parameter in constraining models of the formation dynamics of planetary systems.

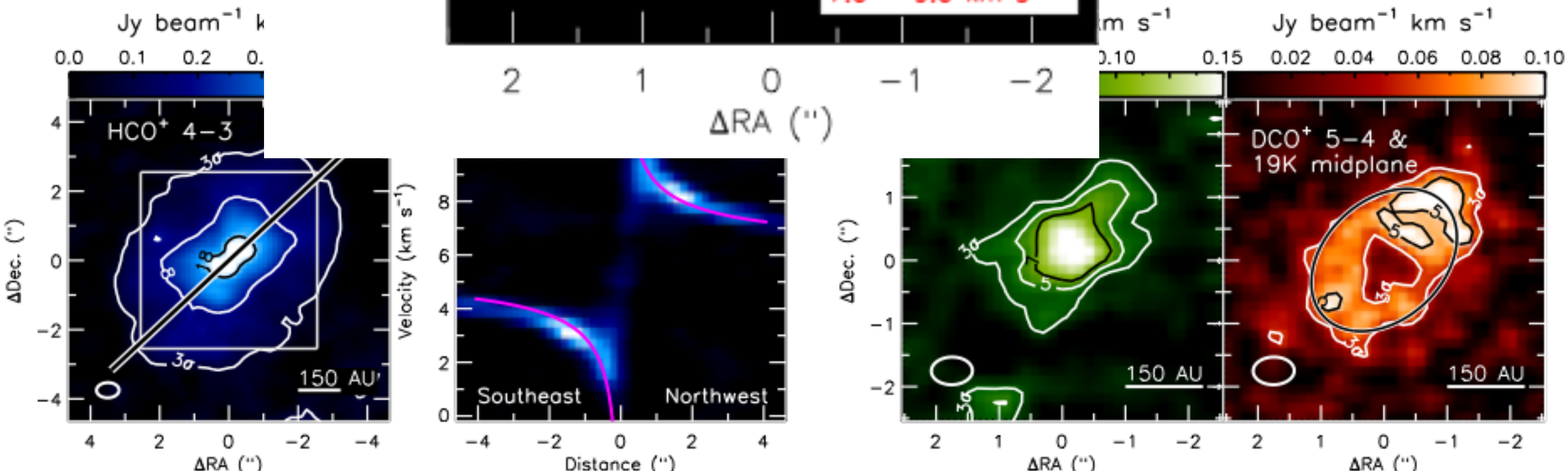


ALMA and SMA images of dust, CO and N_2H^+ emission toward TW Hya. The red circle is the CO snow line prediction.

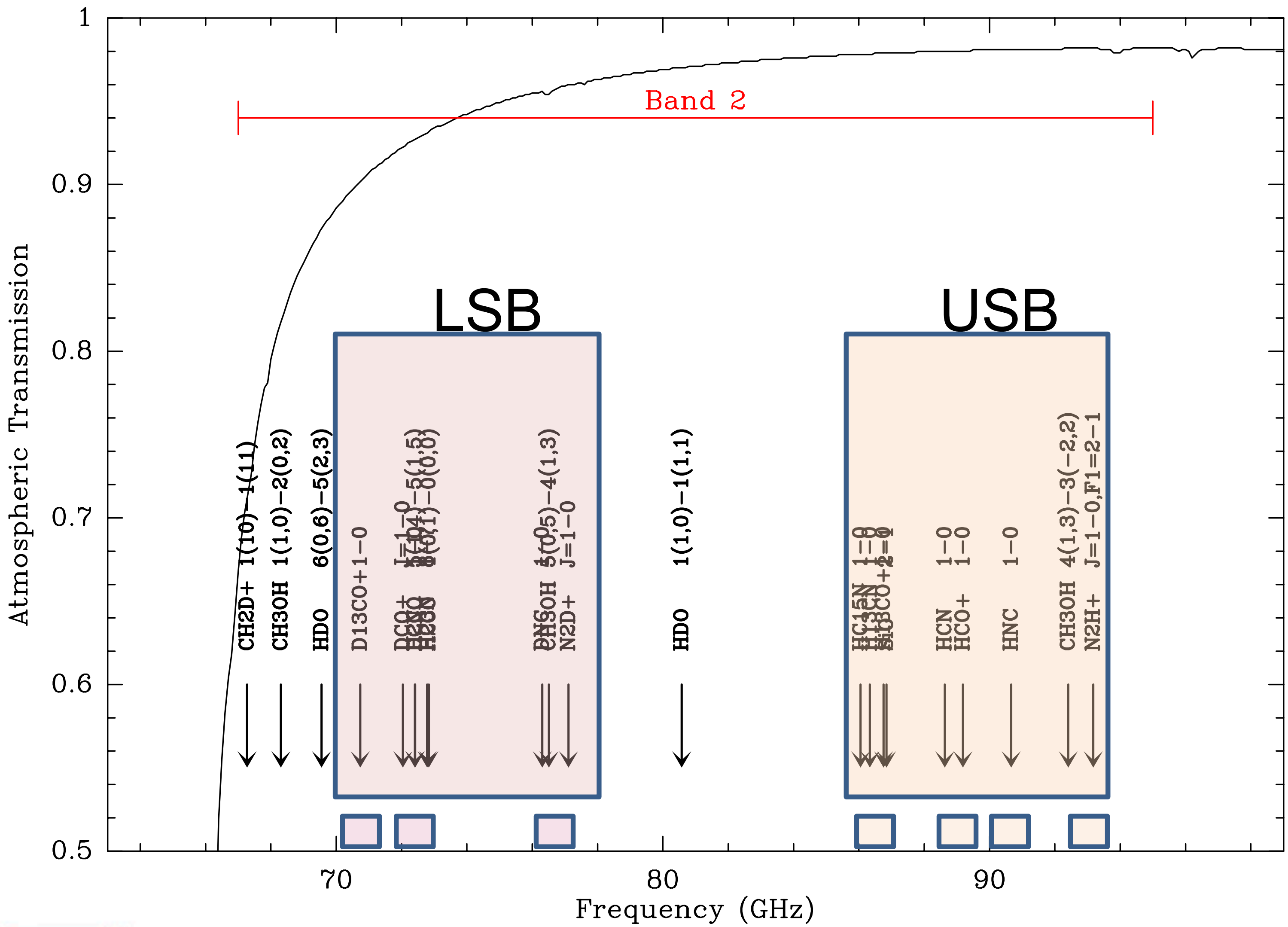
The CO-S ... 96

- HD16329
- Luminous: ... lumn of gas
  - Qi et a ... ^{13}CO SMA data
  - Mathe ... mages snowline.
    - DC ... D enhancement
    - Pr ... H_2D^+?
    - Ex





ALMA

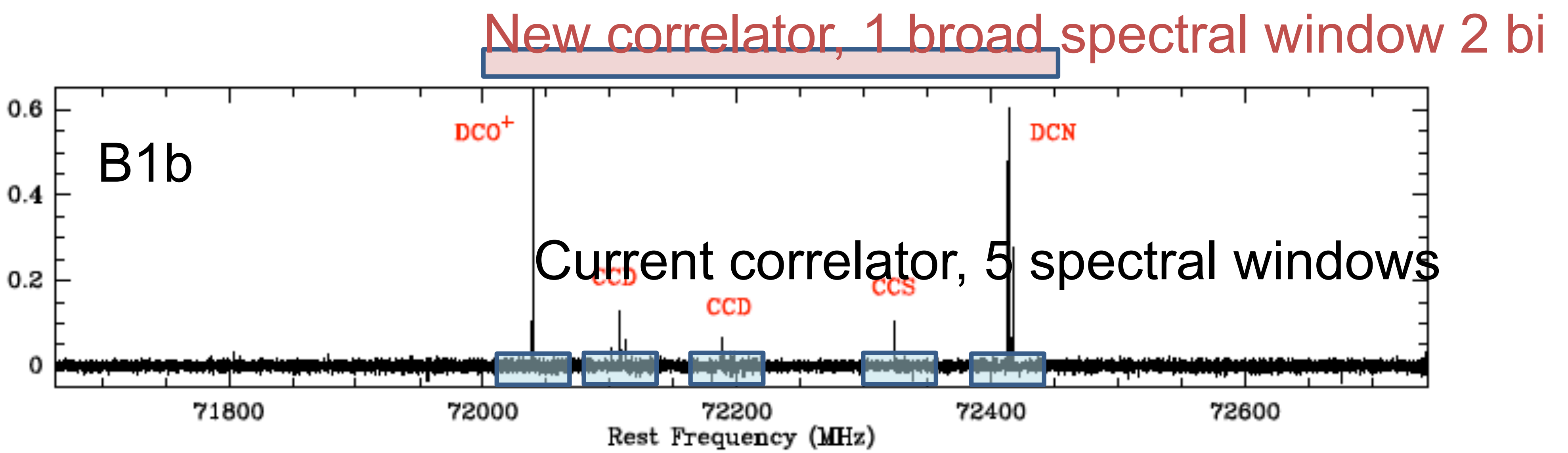


Example Deuterium Setting

- Assumes correlator upgrade
  - Mode 46
  - 500MHz
  - Dual pol
  - 8192 channels
  - 61kHz spacing
    - (0.25 km/s)
  - 4bits (99% efficiency)
  - Critical lines fit in 7 of 16 windows, or more higher resolution windows
- Also Digitizer upgrade

NRAO

- Band2 setup: current correlator, limited to 58.6 MHz high resolution chunks: Mode 12: 15.3 kHz resolution over 58.6 MHz 3840 channels
- Upgraded correlator: Mode 60: 15.3kHz (0.06 km/s) resolution over 469 MHz, 30720 channels per window 2bits
  - Or Mode 62: 30.5 kHz (0.12 km/s) resolution over 117 MHz, 3840 channels per window, 4 bits
  - 4bits provides 13% higher efficiency



Core, Disk Studies Need ALMA Band 2

- 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 βa 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!

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 and planets 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* and other sources.

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