Astronomical Spectroscopy at Millimeter and Submillimeter Wavelengths

Keck Institute for Space Studies
WORKSHOP ON MMIC ARRAY RECEIVERS AND SPECTROGRAPHS

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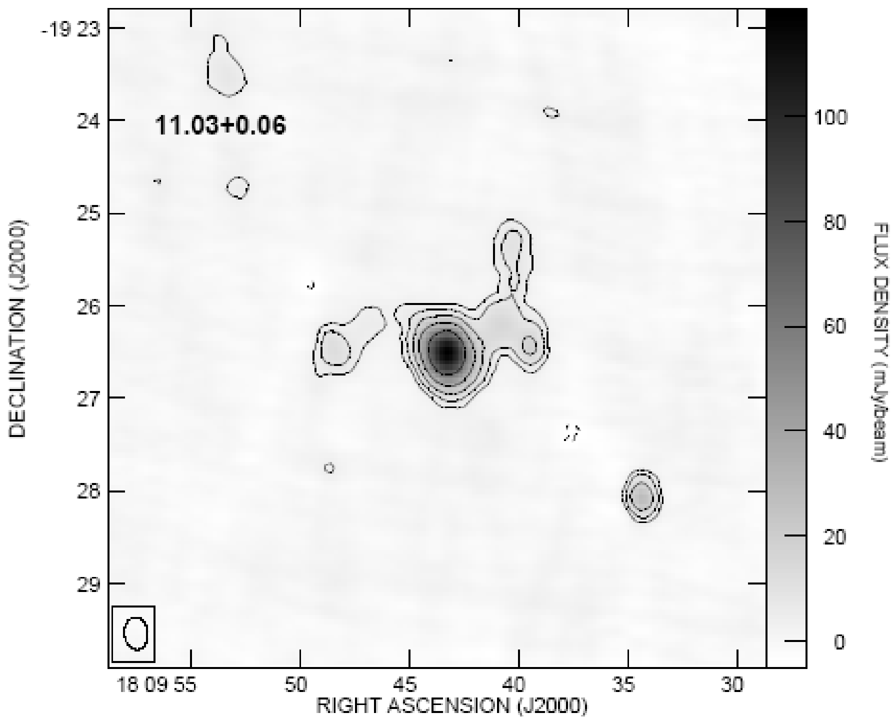
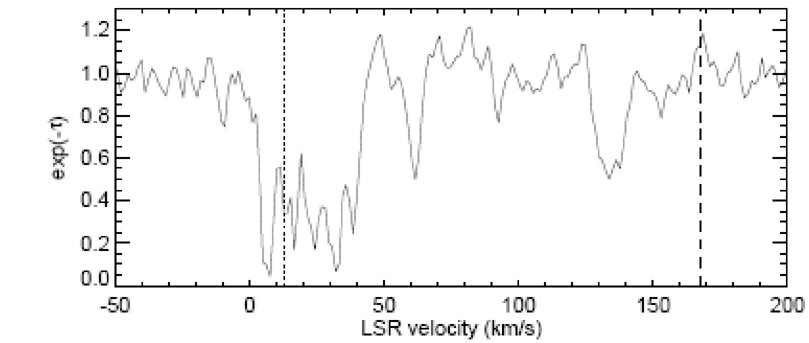
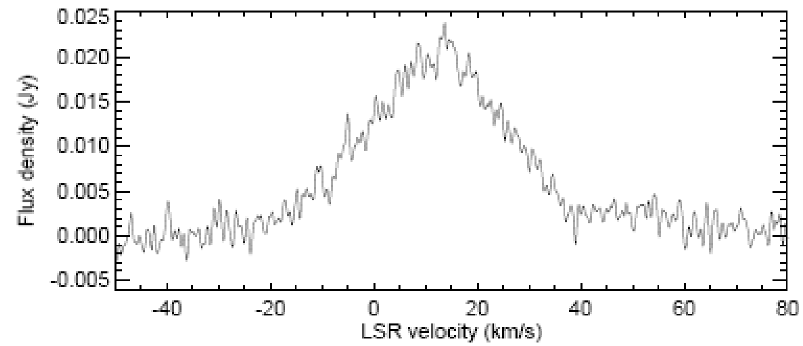
Atomic Recombination Lines are Important Probes of Ionized Regions

Continuum Emission (21cm)



HI Optical Depth





H - Recombination Line; Average of H103α to H110α

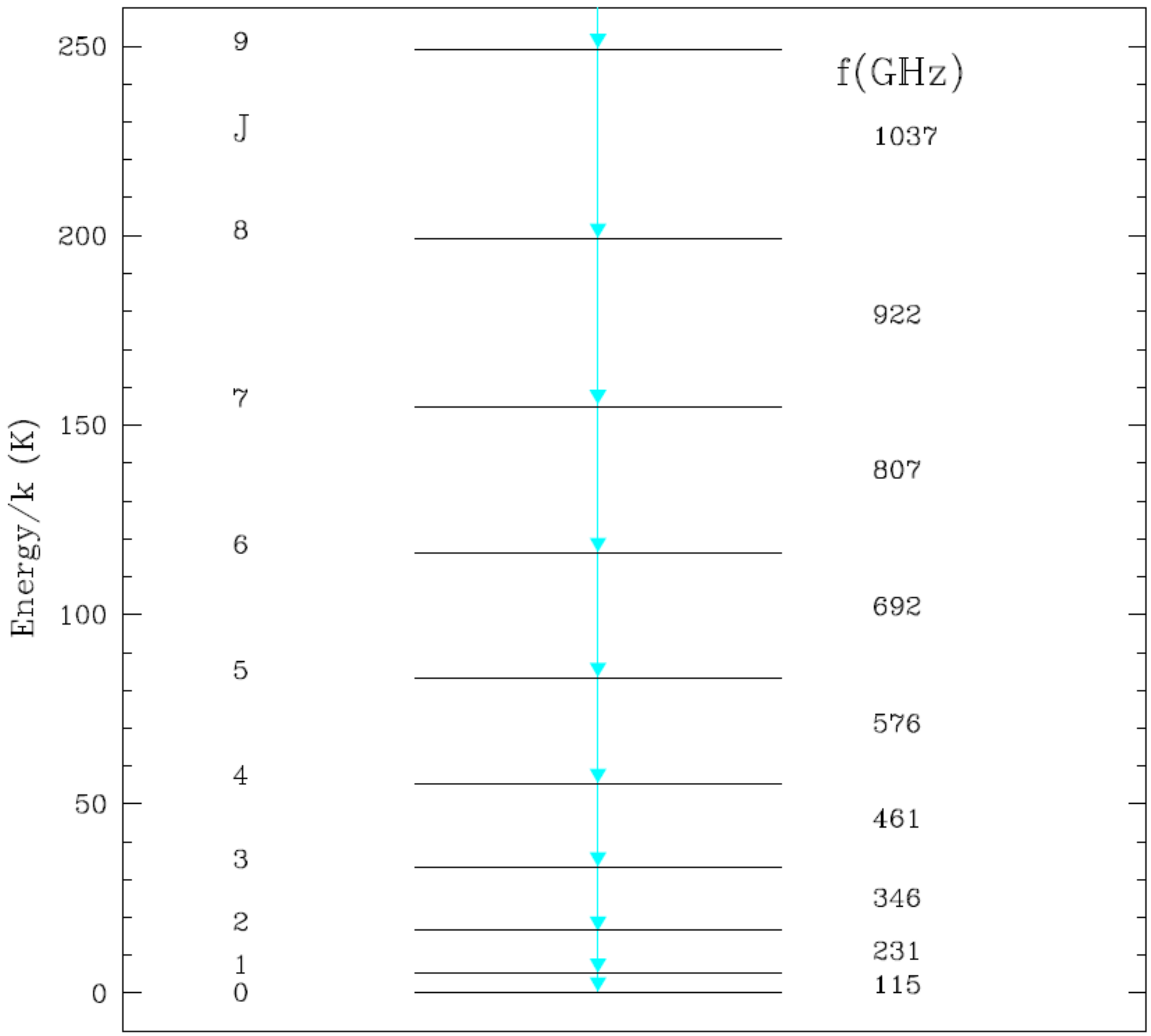
» Throughout cm and mm range

Molecular Lines Dominate Millimeter-λ Spectrum of Interstellar Medium

Energy Levels and Transitions of Simple Rotor

- Classical Rotational Energy $E = |J|^2/2I$
- Moment of Inertia $I = \mu r^2$
- Quantum Mechanics: $|J|^2 \rightarrow (h^2/4\pi^2)\, J(J+1)$
  $J = 0, 1, 2, 3\ldots$
- Energy Levels $E(J) = hB_0J(J+1)$
  $B_0 = h/8\pi^2\mu r^2$
- Selection rules $\Delta J = \pm 1$ => set of equally spaced transitions with $\nu = 2B_0J$
- $B_0 \sim \mu^{-1} \sim m_1^{-1}+m_2^{-1}$ for a diatomic molecule, so that isotope shifts are large and different isotopologues are readily resolved (unlike atomic lines)

Lower Rotational Energy Levels of ^{12}CO – Simple Diatomic Molecule

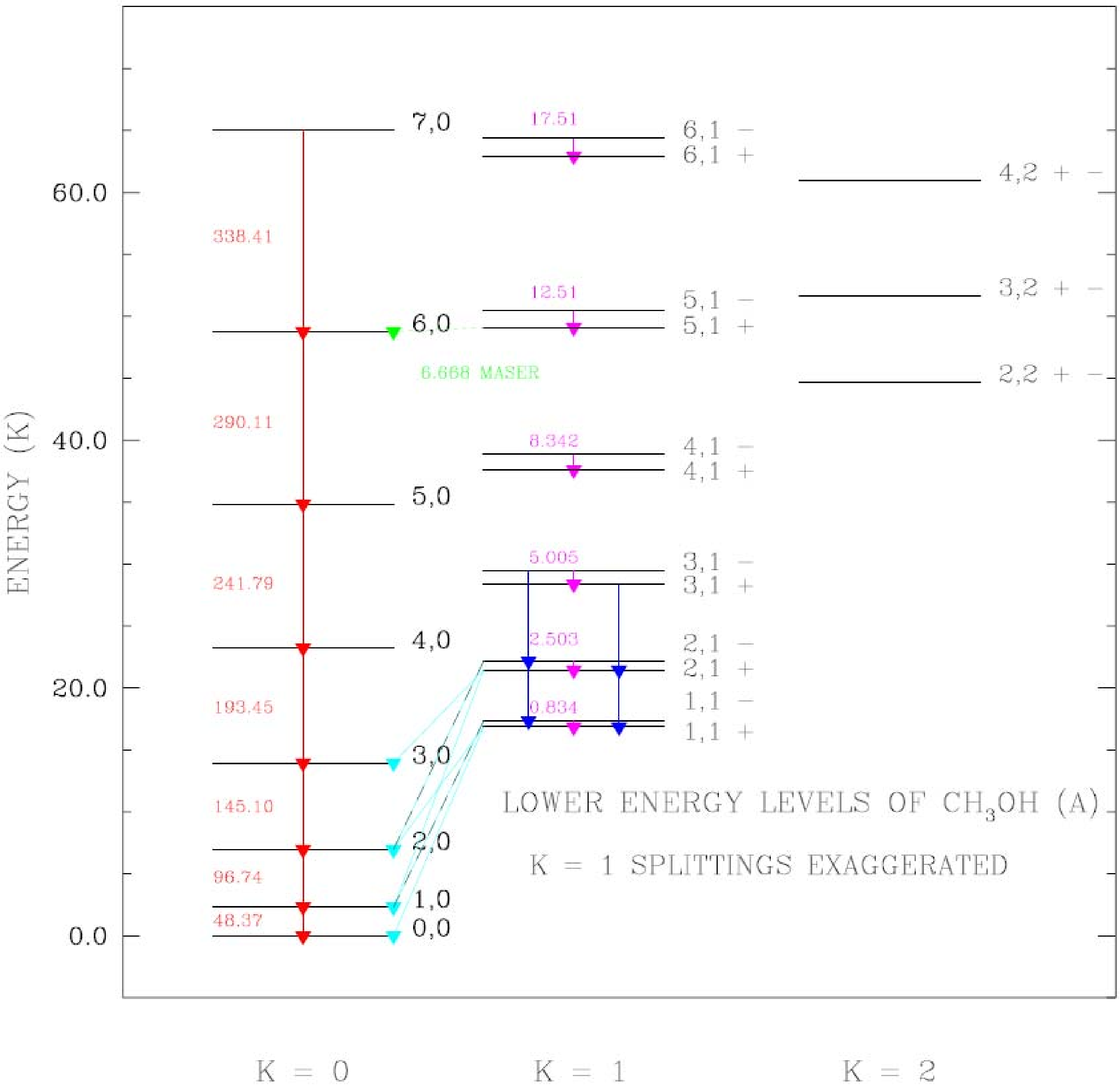


Carbon monoxide is very important because of its large abundance and numerous transitions => it is an important cloud COOLANT

It is also is a good tracer of molecular gas over wide range of conditions

^{12}CO is optically thick - traces gas temperature

Less abundant opticall thin isotopologues such as ^{13}CO trace column density of clouds



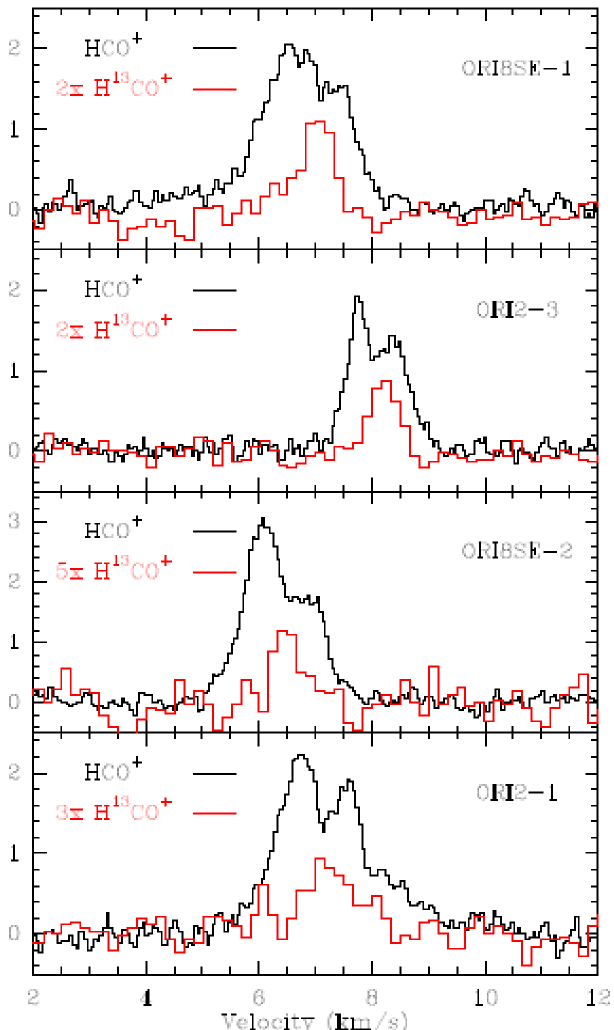
Methanol:

Despite having only 6 atoms, methanol is an asymmetric top molecule with internal hindered rotation

Its spectrum is complex

This figure gives only a hint – in the submm, things are yet far worse

High Velocity Resolution is Essential for Studying Dynamics of Cloud Cores



Velusamy et al. 2009, in preparation

Sound speed: $v_a = 7.7\text{x}10^3\ T^{0.5}$ cm s^{-1}

$= 0.25$ km s^{-1} @ 10 K

Δv_{FWHM} (thermal) = $(8\ln 2kT/m_{mol})^{0.5}$

$= 0.68/\sqrt{\mu}$ km s^{-1} @ 10 K

$= 0.7$ km s^{-1} for HI; 0.09 for CCS

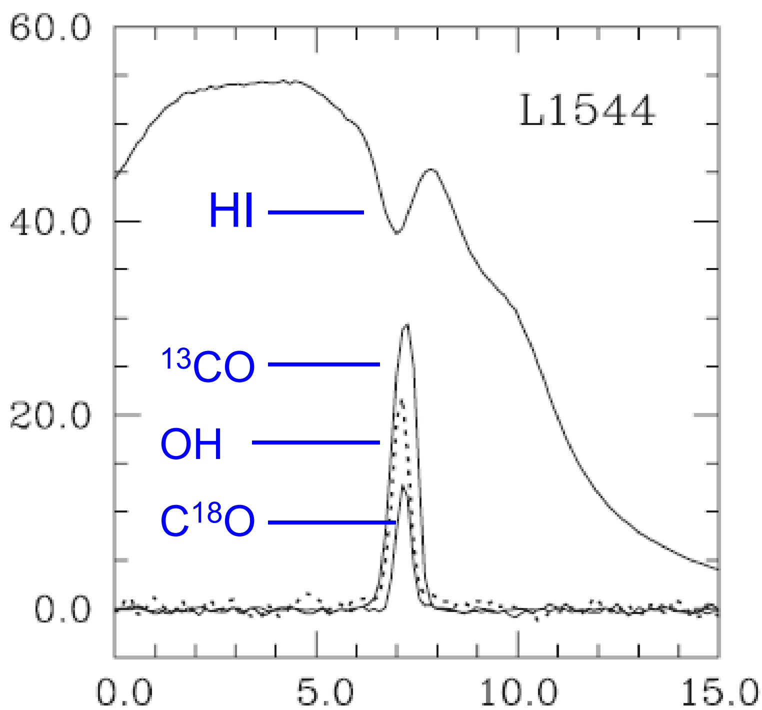
Resolution of 0.1 kms^{-1} is necessary to resolve structure in line profiles

Ratio of different components may give critical information on dynamical state of cores – whether collapsing, static, or expanding.

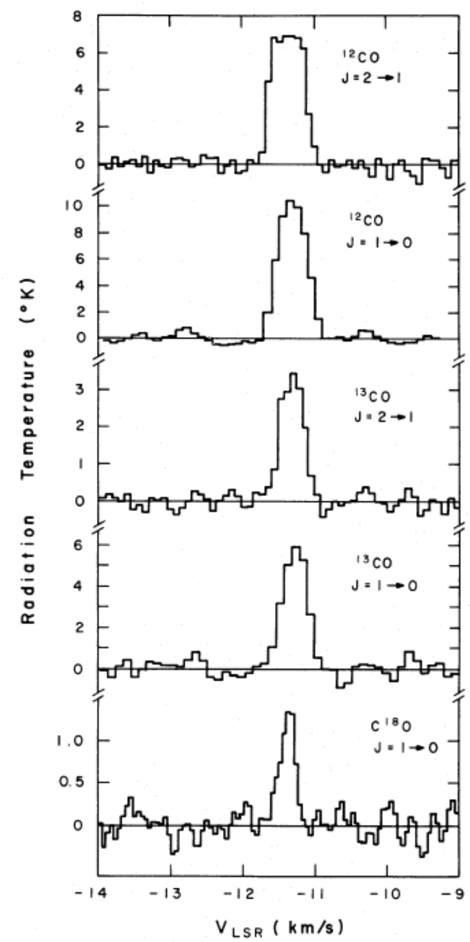
0.1 kms^{-1} corresponds to 0.03 MHz at λ = 3 mm, 0.1 MHz at λ = 1 mm, and 0.3 MHz at λ = 0.3 mm

Heterodyne systems are **uniquely capable** of this frequency resolution

Line Profiles Provide Vital Information



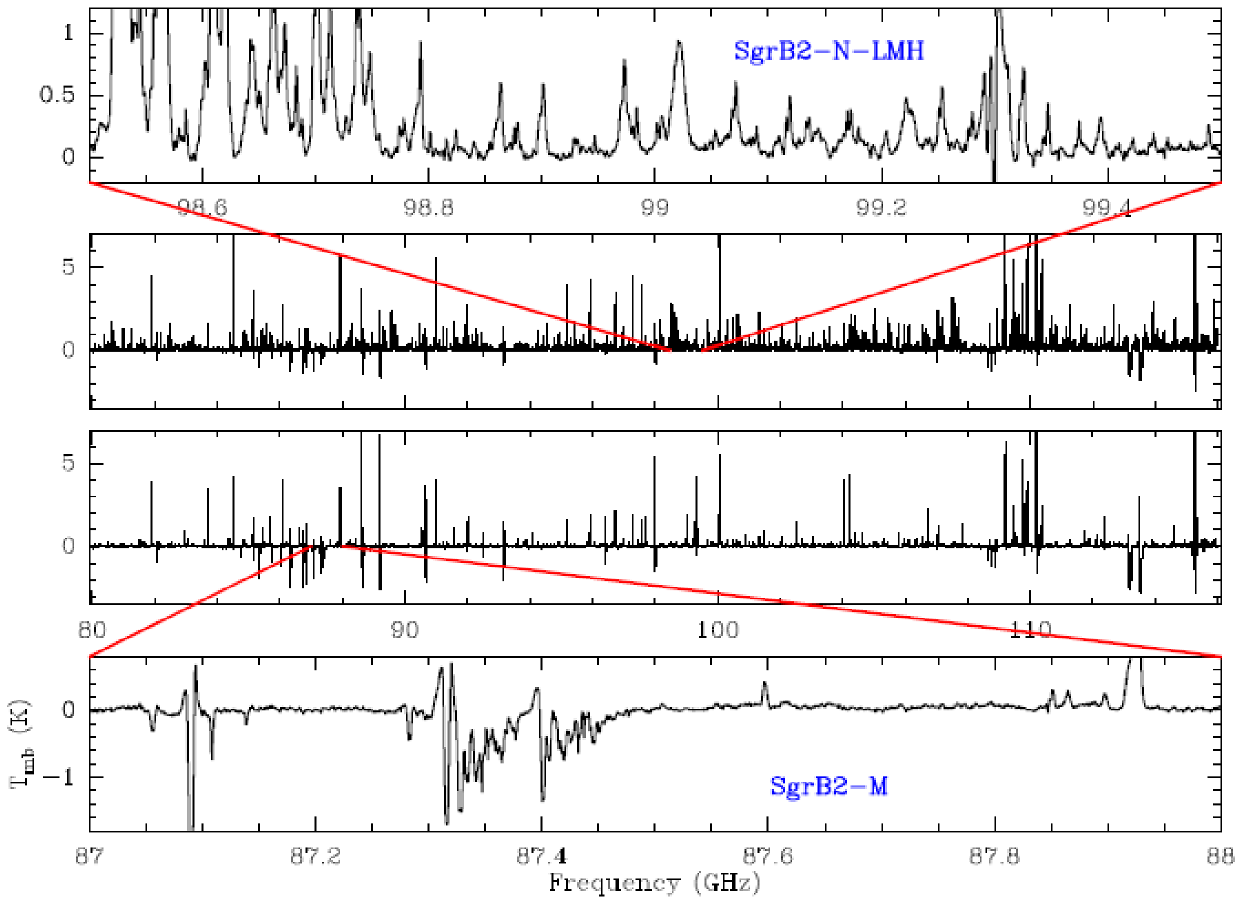
Goldsmith & Li 2005



Dickman & Clemens 1983

Various effects can increase observed line widths including large-scale velocity gradients and saturation

Spectra of "Hot Cores" – Regions Close to Massive Young Stars – are Particularly Complex



From Belloche et al. 2008 in *Molecules in Space & Laboratory, pp. 65 - 68*

Broad spectral coverage with high resolution ESSENTIAL to

- Determine accurate column densities
- Identify **all** lines of common molecules ("weeds") to allow detection of weak lines of new ("flower") species

Mapping the ISM in the Milky Way

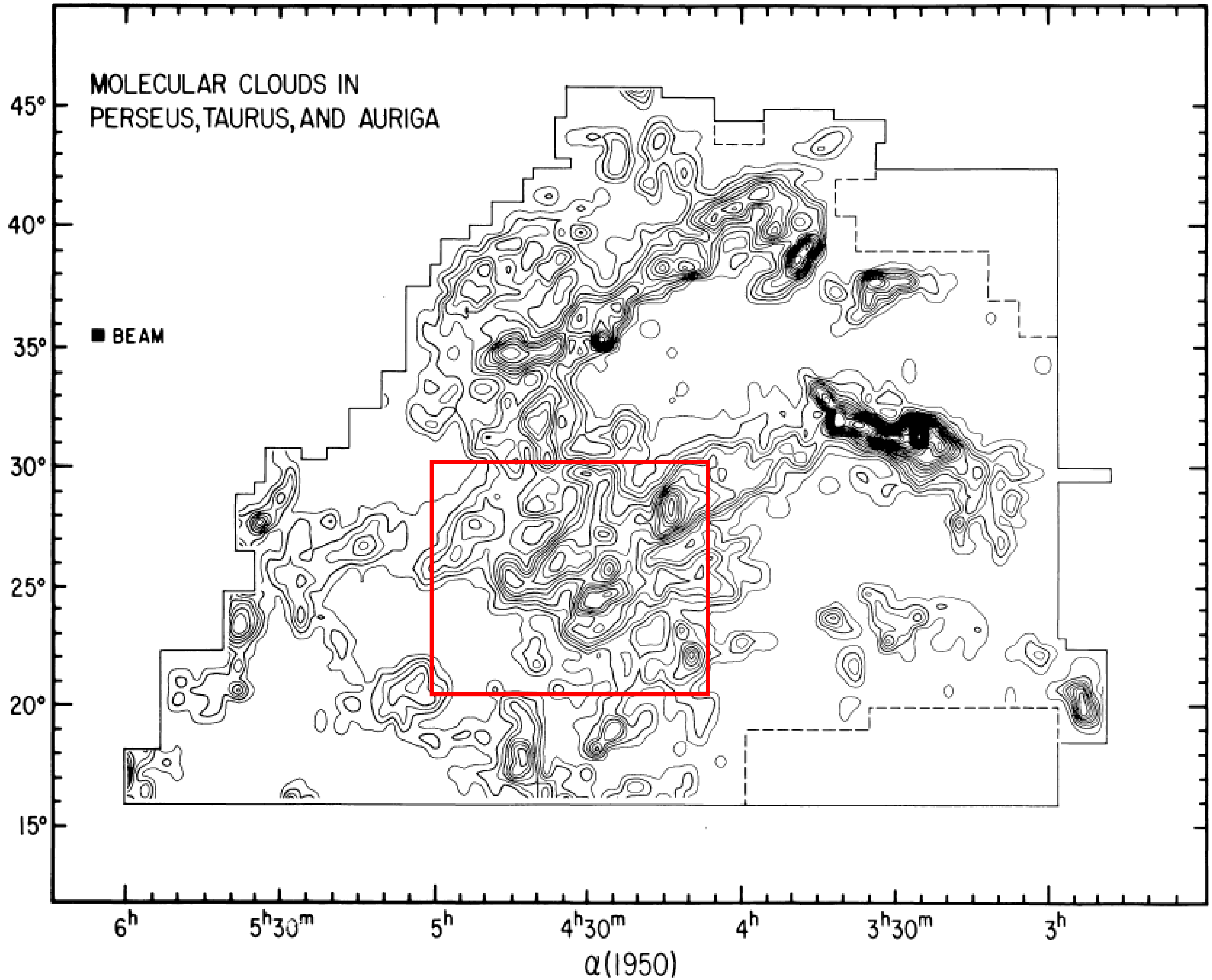
- Spectral resolution characteristic of individual line studies is required
- Interesting possibility is simultaneous mapping of multiple lines
  - Not a simple issue because very different line intensities reduce effectiveness
  - e.g. $C^{18}O$ a factor of ~5 weaker than ^{13}CO
  - Definitely positive if spectrometer can handle multiple lines without sacrificing resolution/coverage
- Issue must be examined for specific frequencies/lines

Spectral Line Mapping of the ISM

Linear Spatial Dynamic Range

LSDR defined as Map dimension/Angular resolution

- Early molecular line maps had LSDR of 10's to 100's
- Adequate for determining overall size and mass, but -
- Lost important aspects of small-scale structure and/or missed important large scale features
- Connection of large and small scales is essential for understanding formation and evolution of clouds, star formation, and feedback processes
- Importance of LSDR > 1000 illustrated by study of Taurus molecular cloud by Goldsmith et al. (2008) using FCRAO 14m telescope with 32 pixel SEQUOIA HEMT MMIC focal plane array in ^{12}CO and ^{13}CO simultaneously

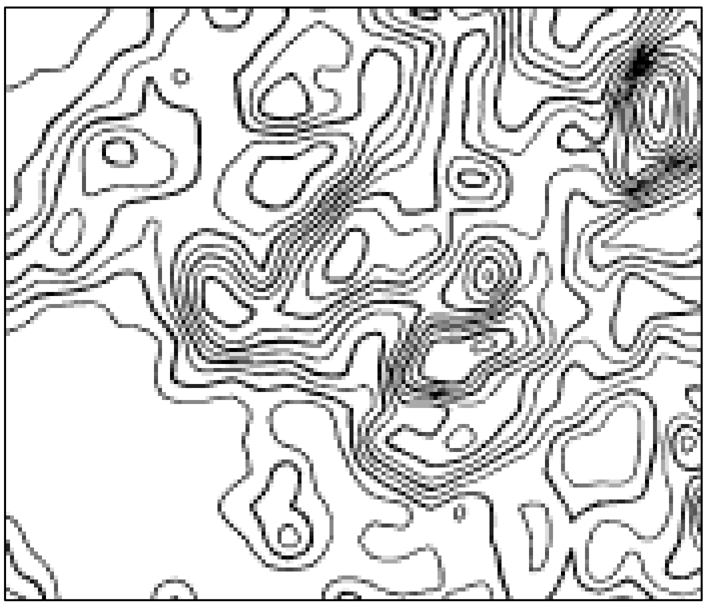


MOLECULAR CLOUDS IN
PERSEUS, TAURUS, AND AURIGA
BEAM
45°
40°
35°
30°
25°
20°
15°
6h
5h30m
5h
4h30m
4h
3h30m
3h
α(1950)

~100 Square Degree Area of Taurus

selected from Ungerechts & Thaddeus (1987)

8.25 degrees



12 degrees

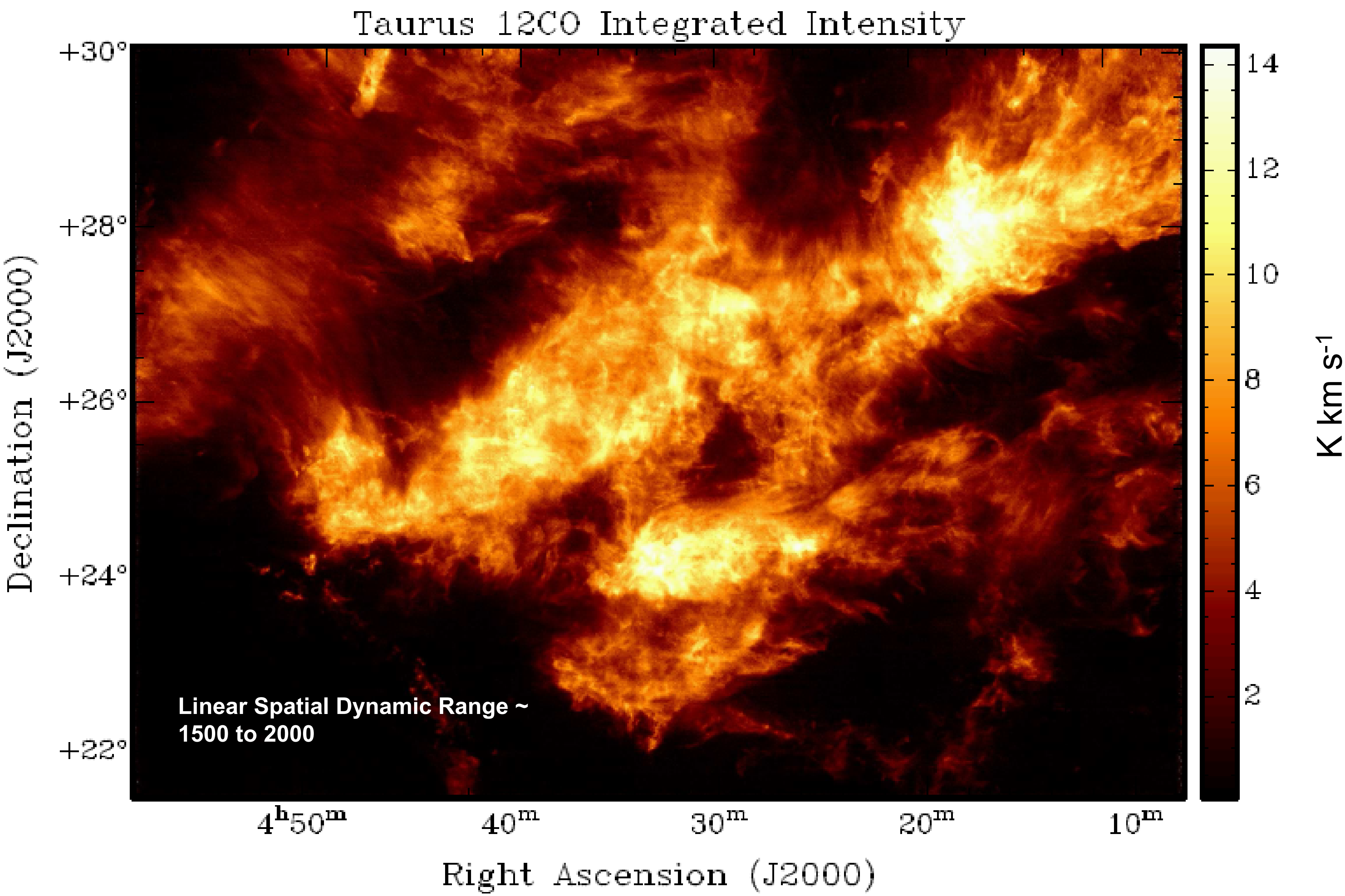
^{12}CO integrated intensity shown

0.5 degree beam size and sampling

What impression do you get from this map?

Studying molecular clouds = “blobology”

3×10^6 spectra



Spectral Lines Averaged over 1 degree square boxes in Taurus

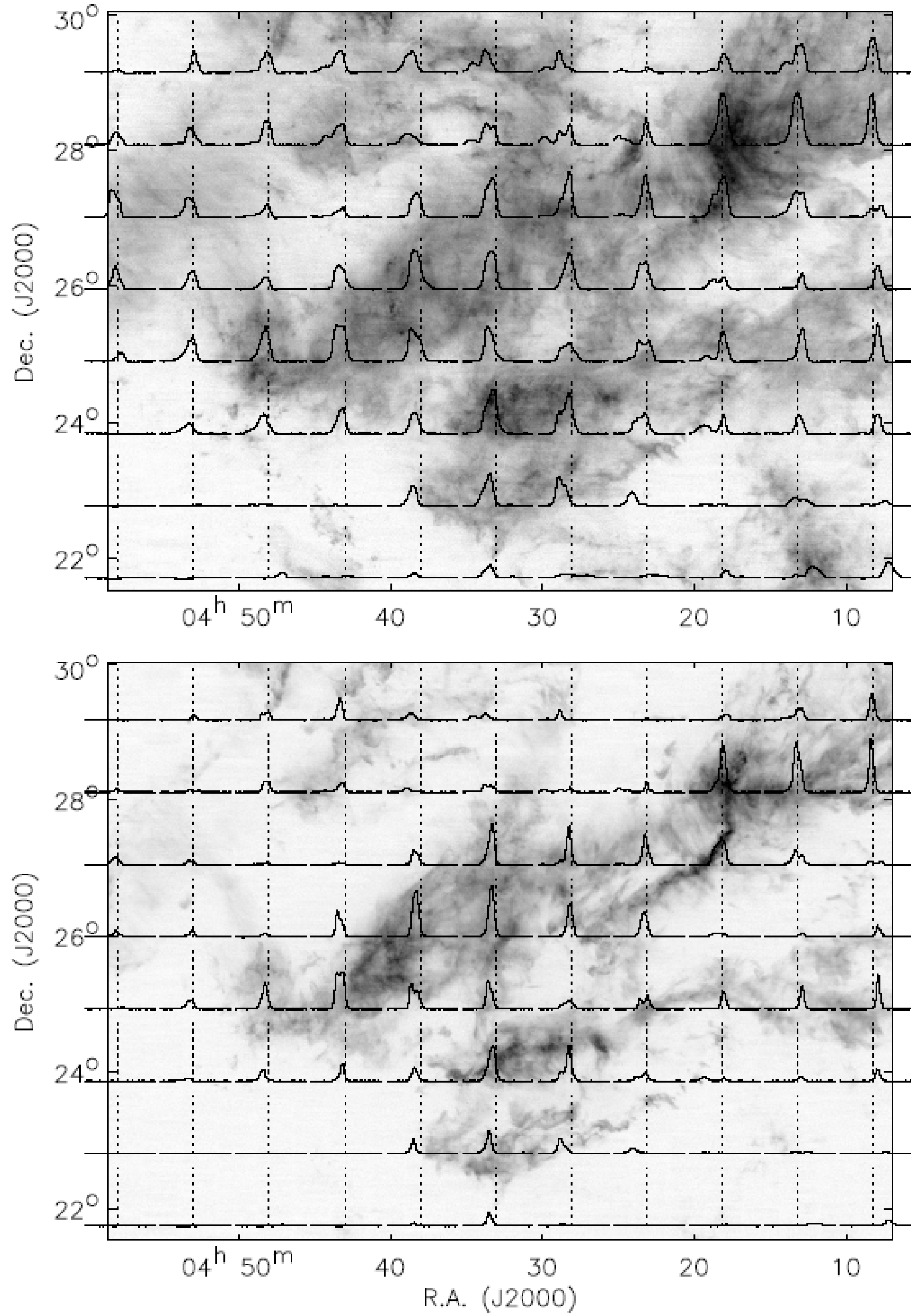
(32,400 spectra per box)

Show large scale kinematic structure

^{12}CO considerably more spatially extended

Outflows in ^{12}CO at low level over extended velocity range

Considerable kinematic structure on small scales associated with prominent filaments

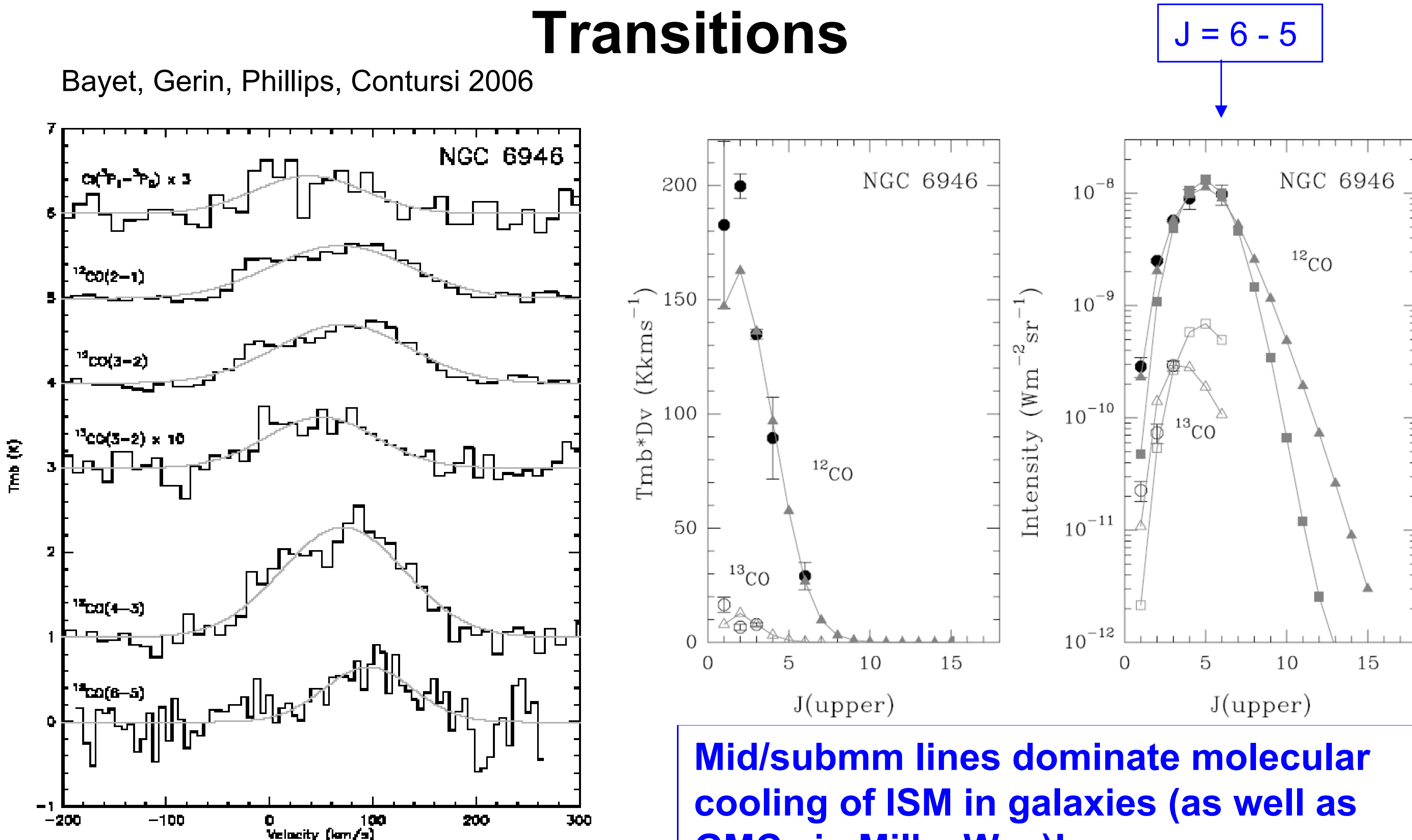


^{12}CO

^{13}CO

Nearby Galaxies: Submm CO Lines Probe Different Phase of ISM in than do Low-J Transitions

Bayet, Gerin, Phillips, Contursi 2006



Mid/submm lines dominate molecular cooling of ISM in galaxies (as well as GMCs in Milky Way)!

^{12}CO J = 6 - 5 Map of M82

Ward, Zmuidzinas, Harris, Isaak 2003

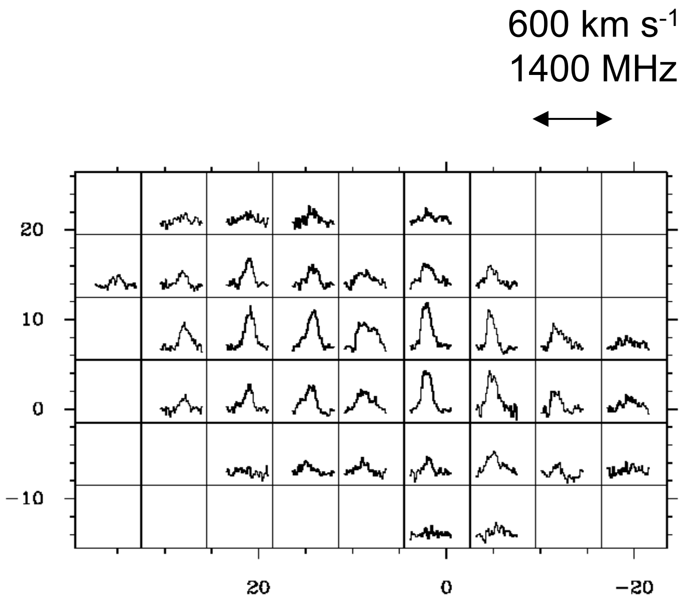


Fig. 1.—Spectra of ^{12}CO $J = 6$–5 in M82. The map has been rotated such that the horizontal offsets are approximately along the major axis. Offsets are in arcsec from an arbitrary center. The vertical scale ranges from T_{MB} of −1 to 4.5 K, and the horizontal scale ranges from −80 to 520 km s^{-1}.

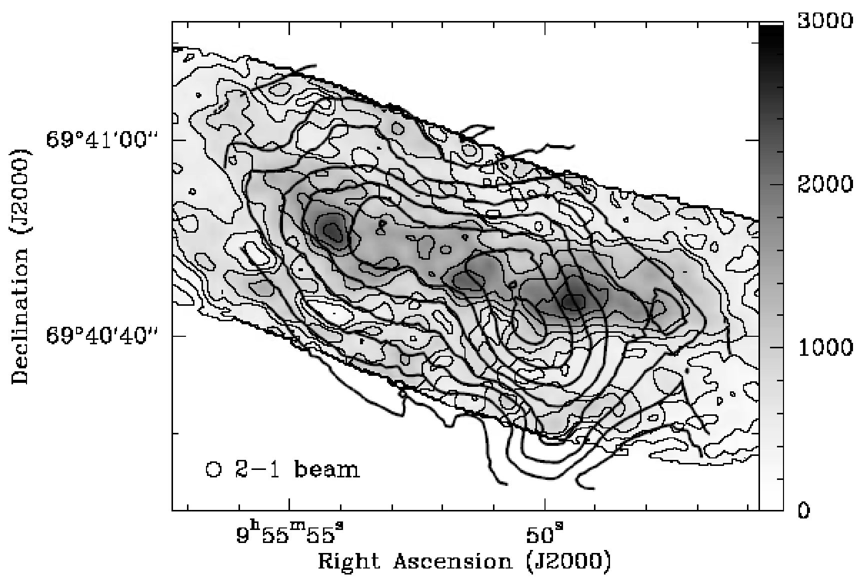


Fig. 5.—M82 ^{12}CO $J = 6$–5 integrated intensity contours superimposed on ^{12}CO $J = 2$–1 integrated intensity from Weiss et al. (2001). Contours are 50, 100, 150, 200, 250, 300, 350, and 400 K km s^{-1}.

CSO Beam FWHM = 14”
Peak T_{MB} = 4 K

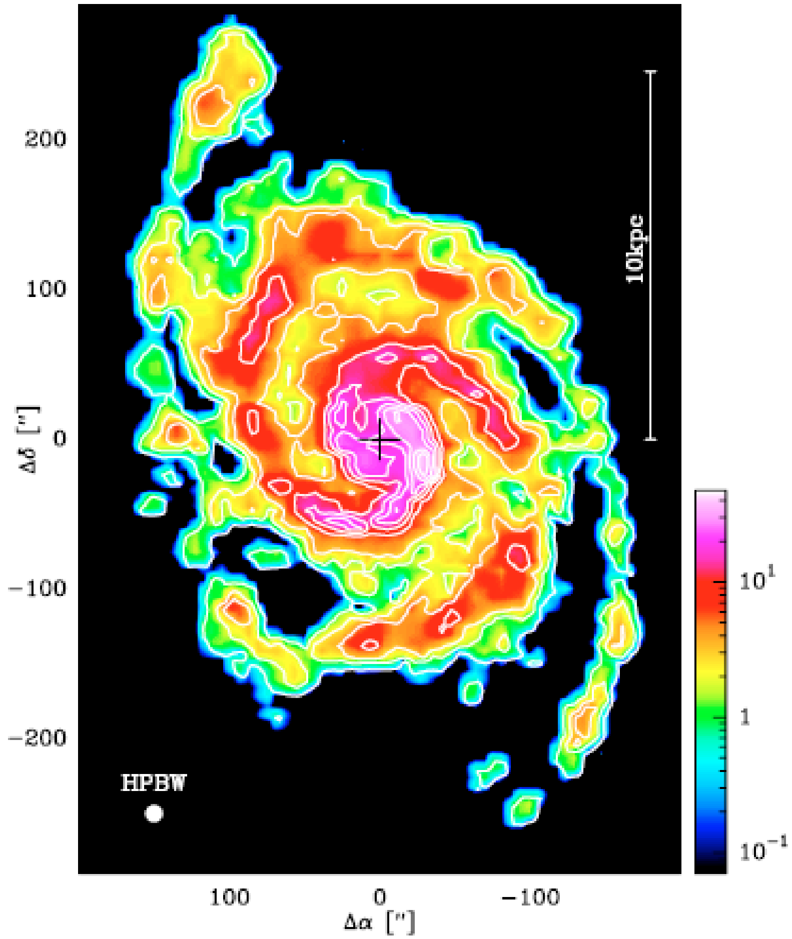
J=6 - 5 / J=2 -1 line ratio is as large as 0.5

Multiple components required to fit set of CO lines including warm (>50 K), low density gas

J= 6 - 5 has quite different distribution than J = 2 - 1

Mapping Nearby Galaxies – ^{12}CO J = 2-1 Image of M51 (D = 8.4 Mpc)

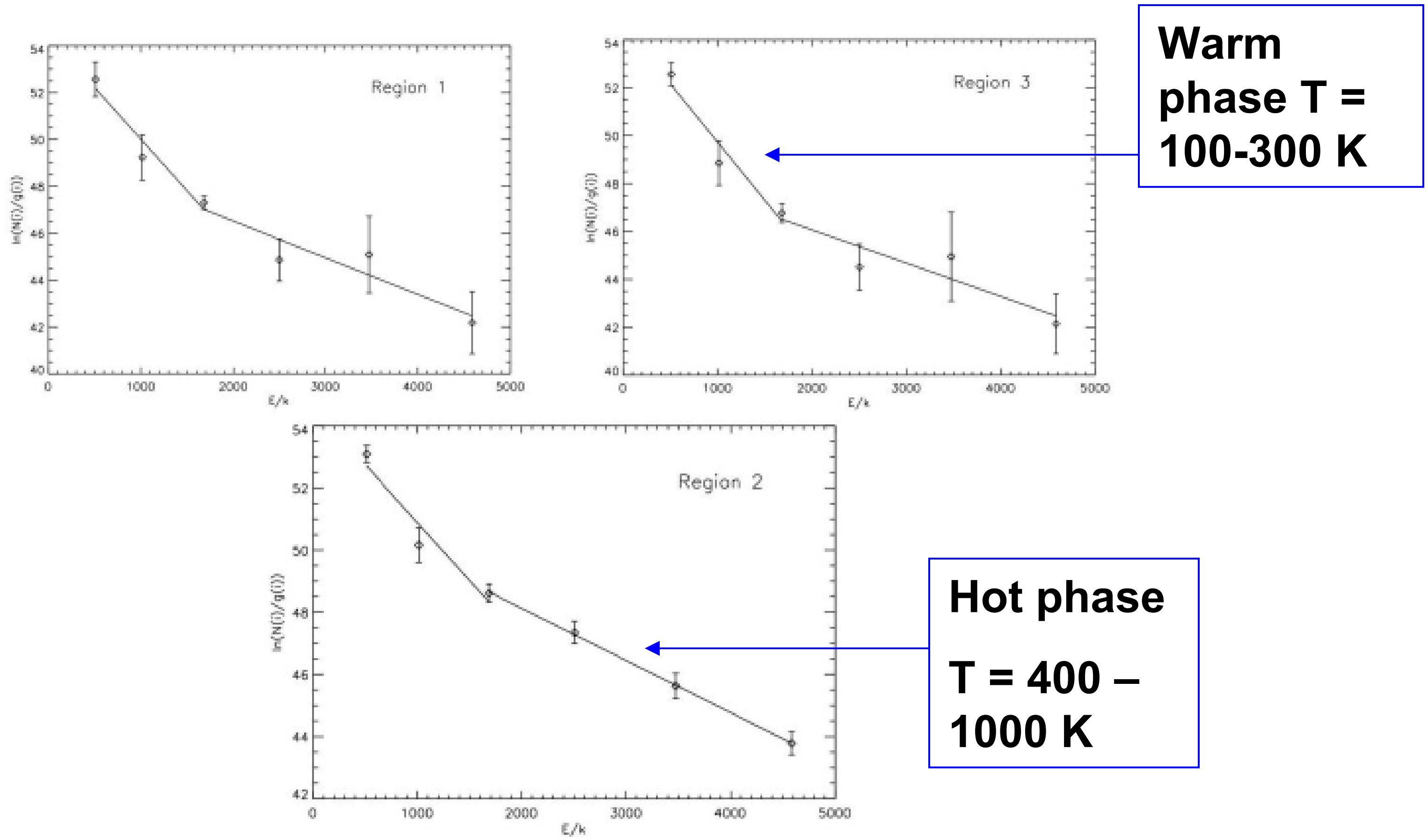
Schuster et al. A&A 2007



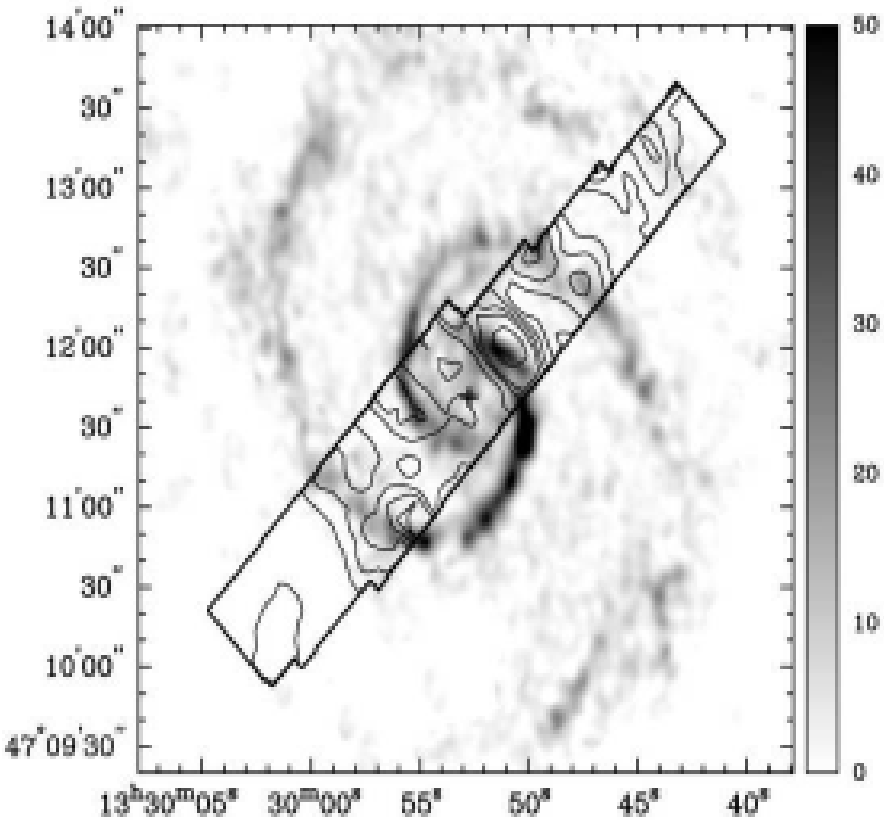
- Angular resolution = 11" (450 pc) with the IRAM 30 m telescope @ 230 GHz
- Employed 18-element HERA focal plane array
- Total H_2 mass = 1.9×10^9 M_{solar}
- Atomic/Molecular gas density = 0.1 in center rising to 20 in outer regions
- Velocity dispersion in CO drops from ~28 kms^{-1} in center to ~6 kms^{-1} at 7-9 kpc and then rises to ~8 kms^{-1}
- CCAT angular resolution = 4.3" @ 690 GHz; 10x smaller beam solid angle
- 4×10^4 Nyquist-sampled pixels => Time = 1000 hr / N_{pix} @ 90s integ. time per pointing

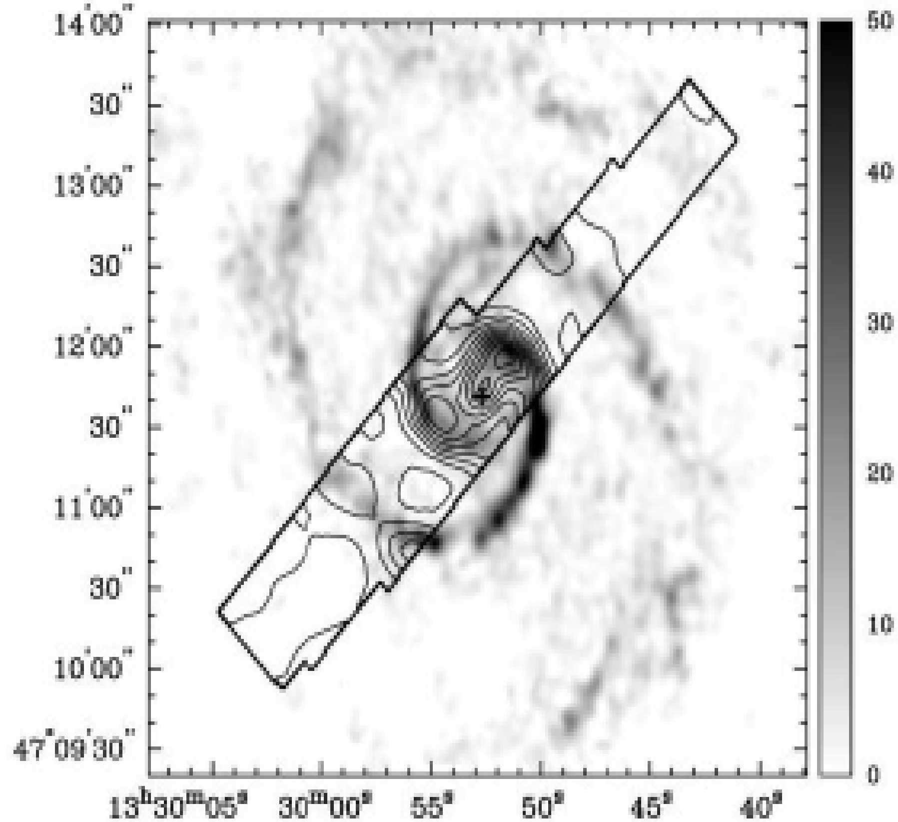
FOCAL PLANE ARRAY REQUIRED!

Surprise in M51 – Warm & Hot H_2 Detected by Spitzer



Brunner, Sheth, Armus, et al. 2008





Warm (left) and hot (right) H_2 overplotted on J = 1 – 0 CO (BIMA SONG) in M51

- Both are strongest in nucleus but warm phase is appreciable in spiral arms
- What is keeping the H_2 at these high temperatures?
- Can it be traced by e.g. warm component of CO observed in submm lines?

Frequency Resolution and Coverage for Observations of the Local Universe

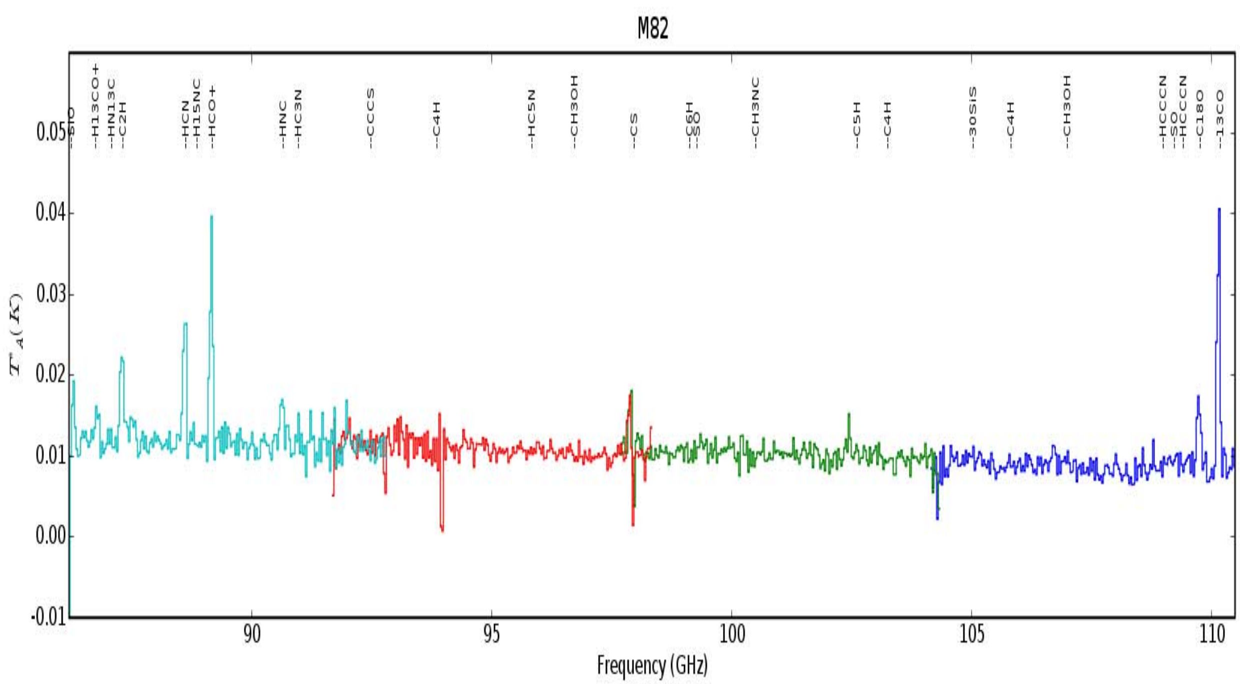
- For Galactic sources, frequency resolution of 0.1 kms^{-1} ⇔ 0.03 MHz can be beneficial
- An individual spectral line may cover up to 300 kms^{-1} ⇔ 100 to 300 MHz in nearby galaxies
- Wide frequency coverage gives important benefits including
  - Secure molecular identifications
  - Accurate column density determinations
  - Increased astrochemical comprehensiveness
  - Reduction of telescope time for many projects

Measurement of Redshift of Photometrically Detected Galaxy

- Surveys with large-format continuum cameras will identify many mm/submm galaxies, about which almost nothing is known
- An important step is to measure redshift
- This obviously requires broad frequency coverage
- Prime candidates are lower rotational transitions of CO

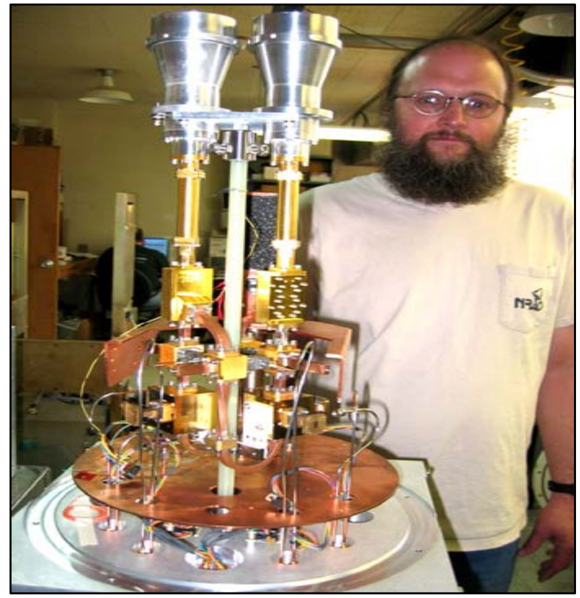
Red Shift Machine

- Developed by N. Erickson & G. Narayanan at University of Massachusetts.
- Intended for use on LMT (30m/50m) but tested on FRCAO 14m telescope
- Covers 70 to 110 GHz. HEMT amplifier frontend and analog autocorrelator backend with resolution ~50 MHz.
- Two polarizations in each of two channels.
- Very rapid beam switching using ferrite polarization rotator.

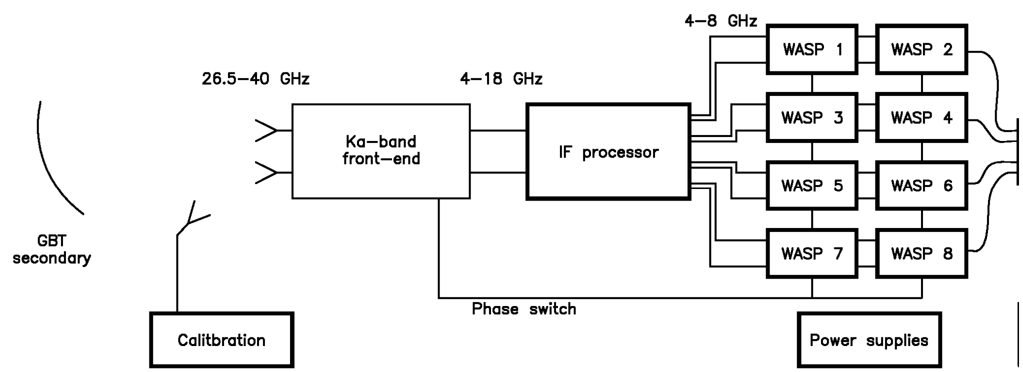


Zpectrometer

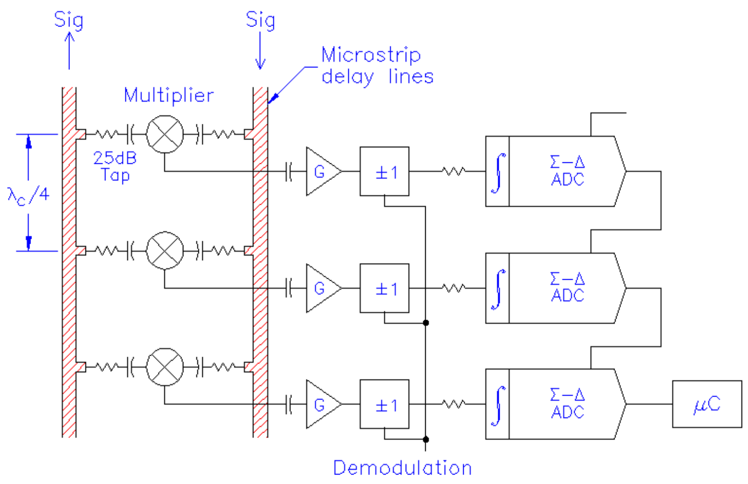
- Developed by A. Harris & A. Baker at Univ. Maryland
- HEMT amplifiers followed by analog correlator
- Used on GBT (100m)
- Covers 26 to 38 GHz with resolution of 32 MHz
- Corresponds to CO *J* = 1-0 line at redshifts of 1.9 to 3.4
- Two channels with separate feed horns. Beam switching by subreflector motion.
- Tsys ~ 45 K but noise typically 2 to 3 x that predicted from the radiometer equation

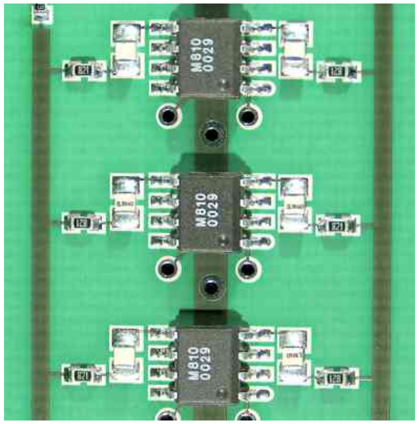


GBT's Ka-band continuous comparison radiometer

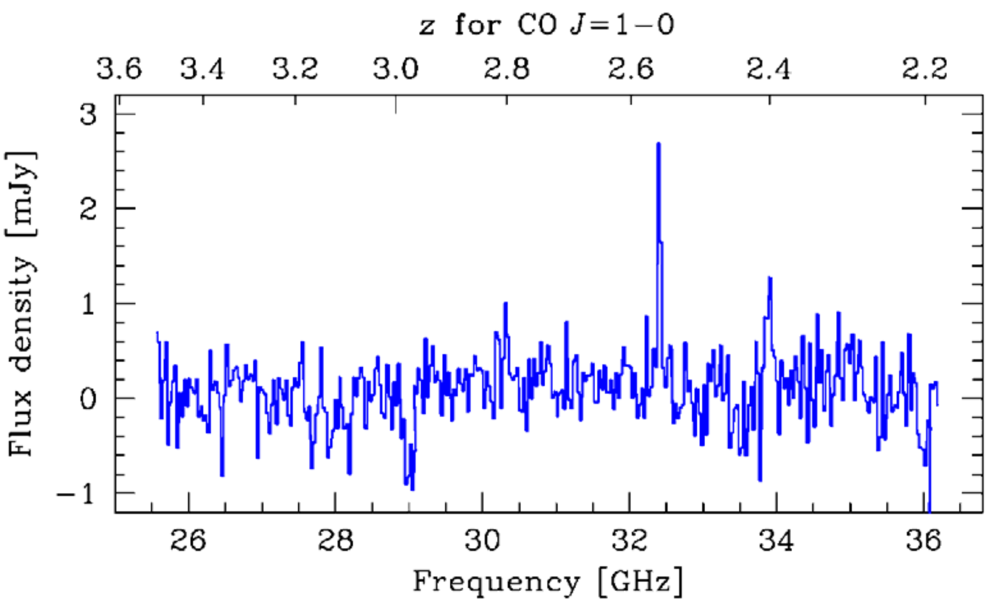


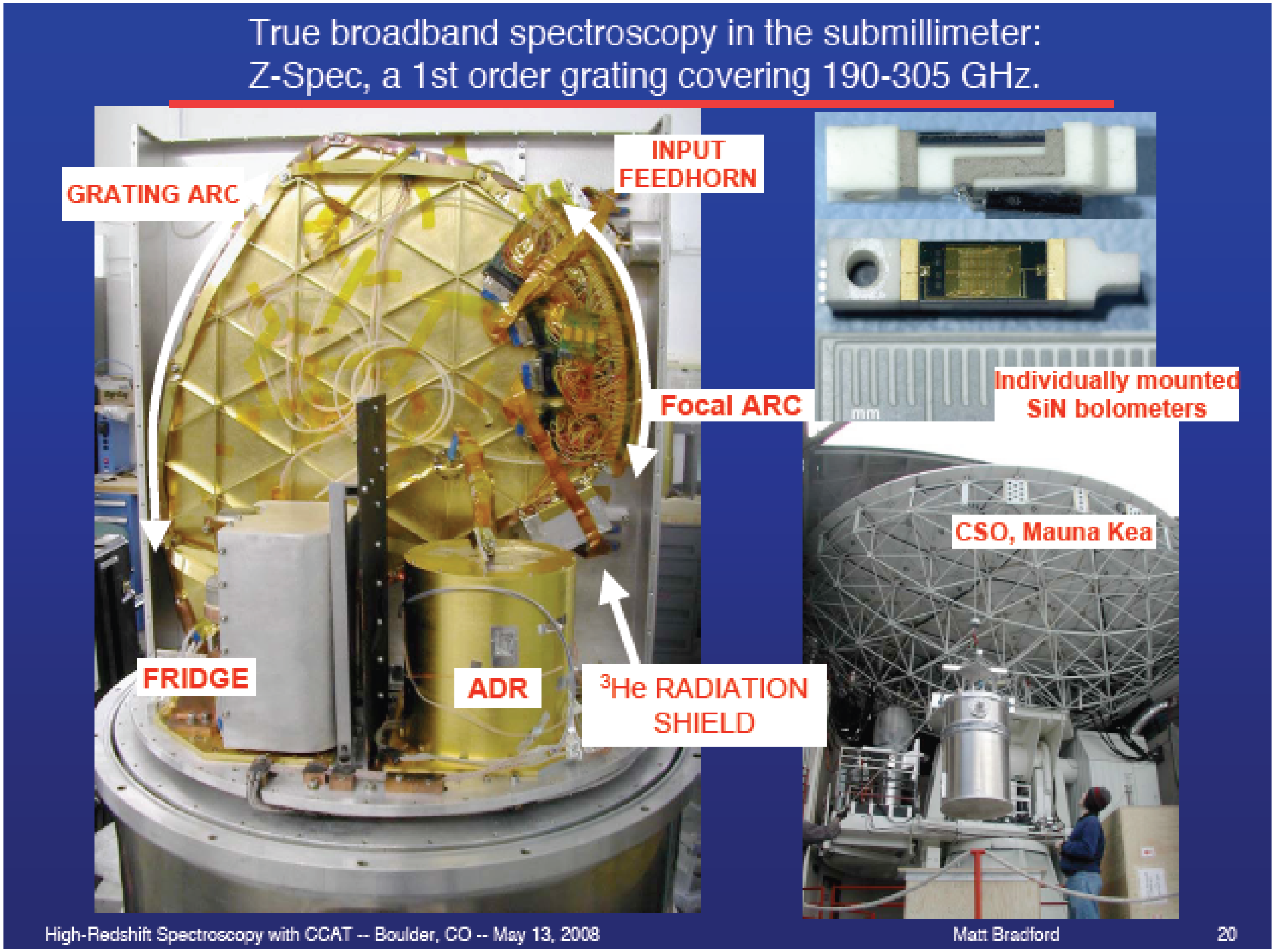
Zpectrometer (2)





Zpectrometer spectrum of CO J=1-0 from the Cloverleaf galaxy at *z* = 2.56. 1.3 hours on sky with GBT, no baseline corrections





Z-Spec

Curved diffraction grating in parallel plate waveguide

Feedhorn input – single mode

Array of bolometer detectors

R~300 (0.8 GHz)

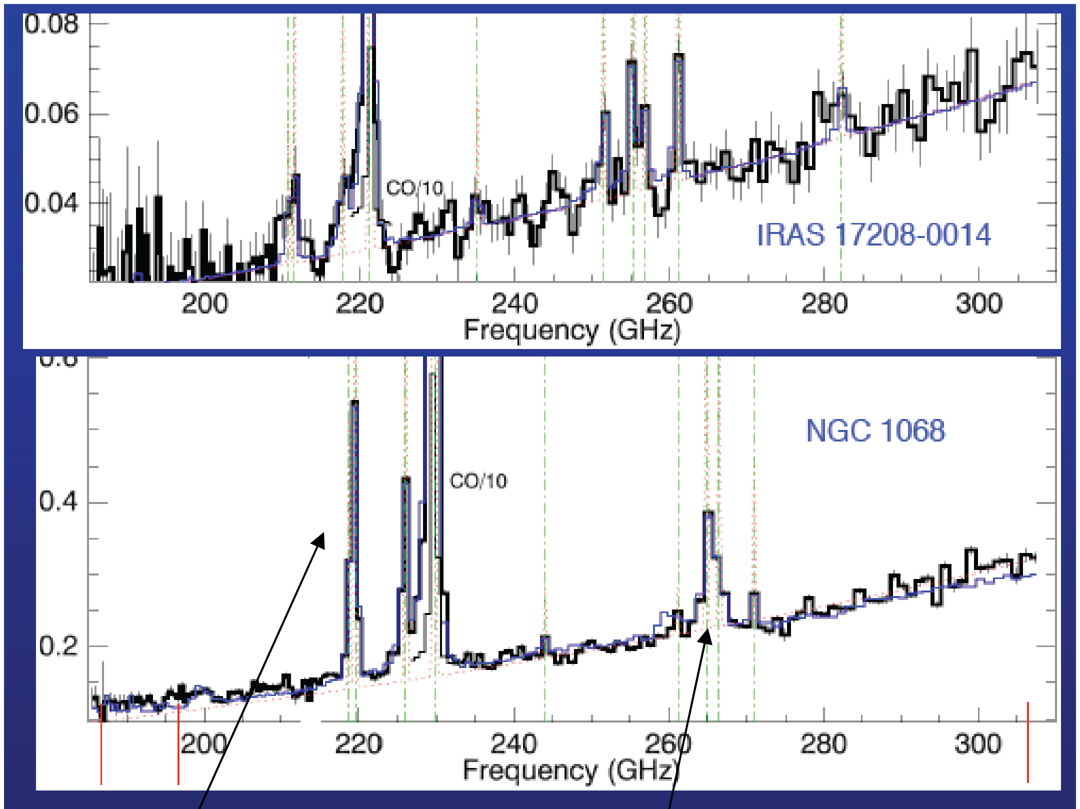
Z-Spec Team

JPL / Caltech
- M. Bradford
- J. Bock
- B. Naylor
- J. Zmuidzinas
- H. Nguyen

Colorado
- J. Glenn
- J. Aguirre (also NRAO)
- L. Earle

ISAS / JAXA
- H. Matsuhara

Z-Spec Direct Detection Spectroscopy

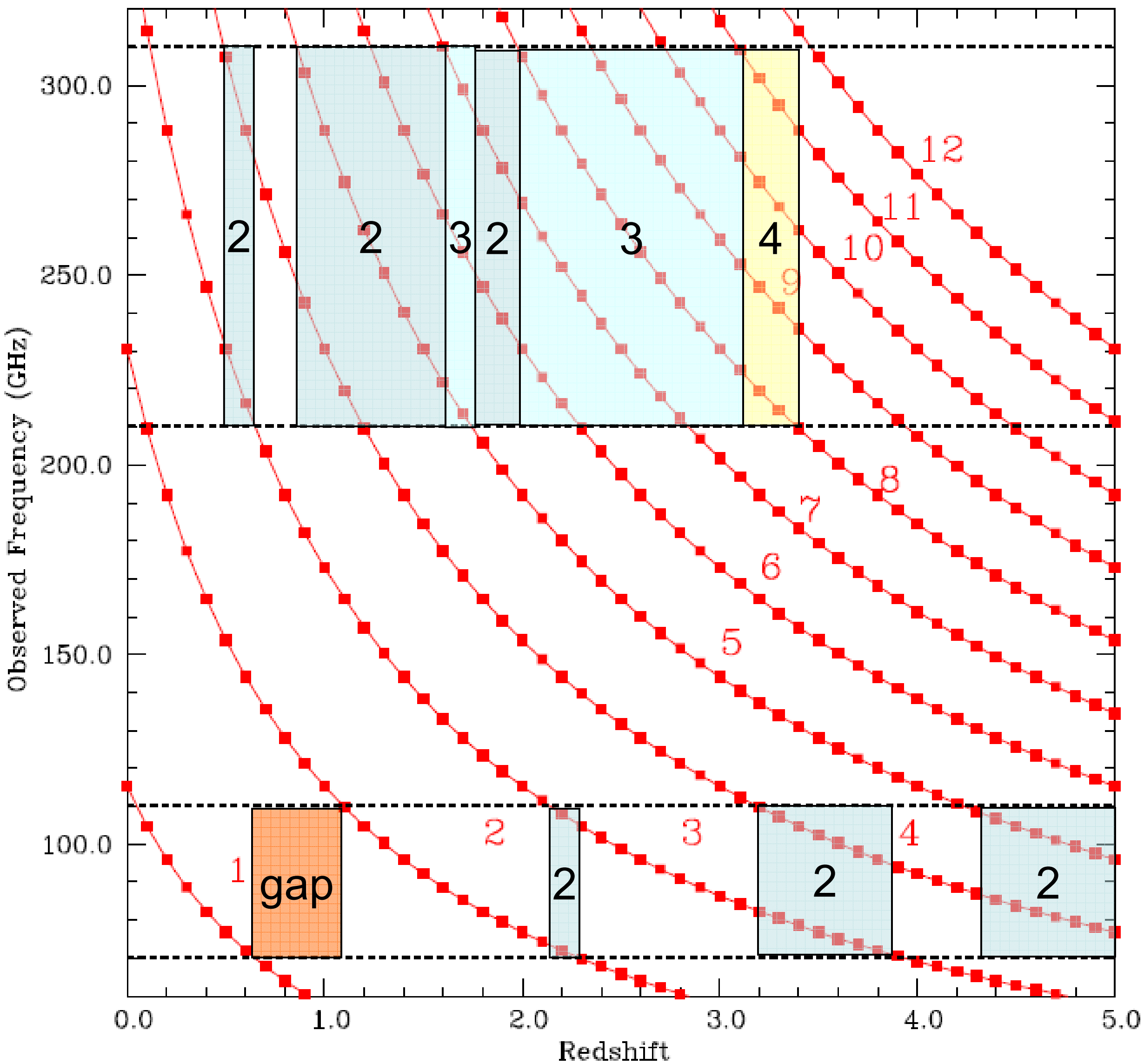


^{13}CO J = 2-1

HNC J = 3-2

Z-Spec covers 190 - 305 GHz with R = 300

Corresponds to Δz = .003, which is quite good for identification and calculation of luminosity



1 mm

3 mm

Redshift Survey Machine Basics

J = Rotational quantum number of upper level of the transition J → J - 1

Freq. coverage determined by atmosphere

Reconfigurable Focal Plane Array Spectrometer aka Multi Object Spectrograph

For study of distant galaxies it is inefficient to populate focal plane with densely packed array

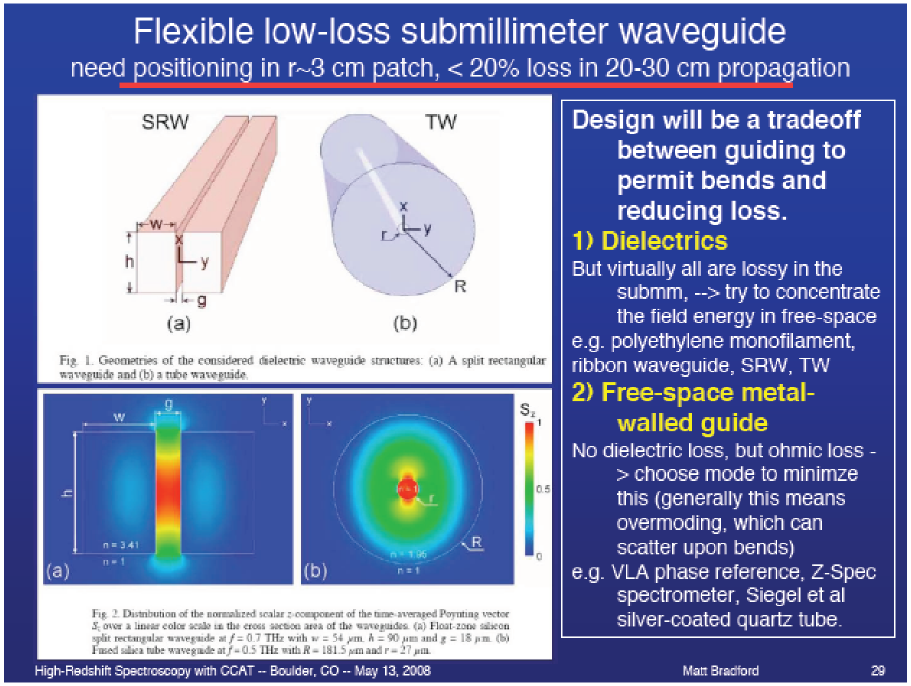
Need low-loss reconfigurable transmission means to connect set of spectrographs to specified points in focal plane

Highest source density is CO J = 6-5 peaking at z~1.6 (270 GHz) [Blain et al. 2000]

In 20’ FOV expect 10’s of galaxies @ > 10^{-20} Wm^{-2} level

Brighter galaxies (few x 10^{-20} Wm^{-2}) detectable in few hrs with CCAT and T_{sys} = 200 K

Focal plane MOS using MMICs could compete with direct detection in terms of sensitivity and resolve lines in brighter sources



J. Glenn et al.

Space Missions and Spectral Line Astrophysics

- Elimination of atmosphere enables observations of key molecular and atomic species
  - H_2O (low-lying lines start at 557 GHz; others @ 183.3 GHz, 325, 380 GHz)
  - O_2 (lines at 50-60 GHz, 118.8, 369. 425, 487 GHz,…)
  - HD (2675 GHz)
  - C^+ (1901 GHz)
  - H_2D^+ (ground state line at 1372 GHz, 1112 GHz)
- Many, but not all, of these will be covered by Herschel (e.g. not ground state line of H_2D^+), and most are deep in submm and hence not candidates for MMIC technology at the present time
- There are a few exceptions which include lines of H_2O and O_2 that may be observed in future space missions at mm wavelengths
- Specific lines may be observed from sub-orbital platforms which can push technology and astronomy together (STO balloon; SOFIA)
- Long duration observing, multi pixel systems, and simplicity may offer a niche for MMIC systems in mm/submm regime if sensitivity continues to improve

Conclusions

- High resolution spectroscopy is fundamental for study of the gas in the Milky Way and nearby galaxies
- Future systems will demand
  - Broad instantaneous frequency coverage of at least ~ 10 GHz and ideally 10s of GHz
  - Rapid aerial coverage with maps containing millions of voxels (spectral line pixels)
- Redshift surveys in 1.3 mm window can exploit > 100 GHz instantaneous frequency coverage, ideally with ~10 MHz frequency resolution and minimum of 100 MHz resolution
- Next-generation systems should consider having several hundred spatial pixels with single sideband coverage of 24 GHz
- Looking ahead we should be pushing towards kilopixel high resolution arrays offering good focal plane sampling