Heterodyne Receivers for CCAT – Selected Astronomical Perspectives

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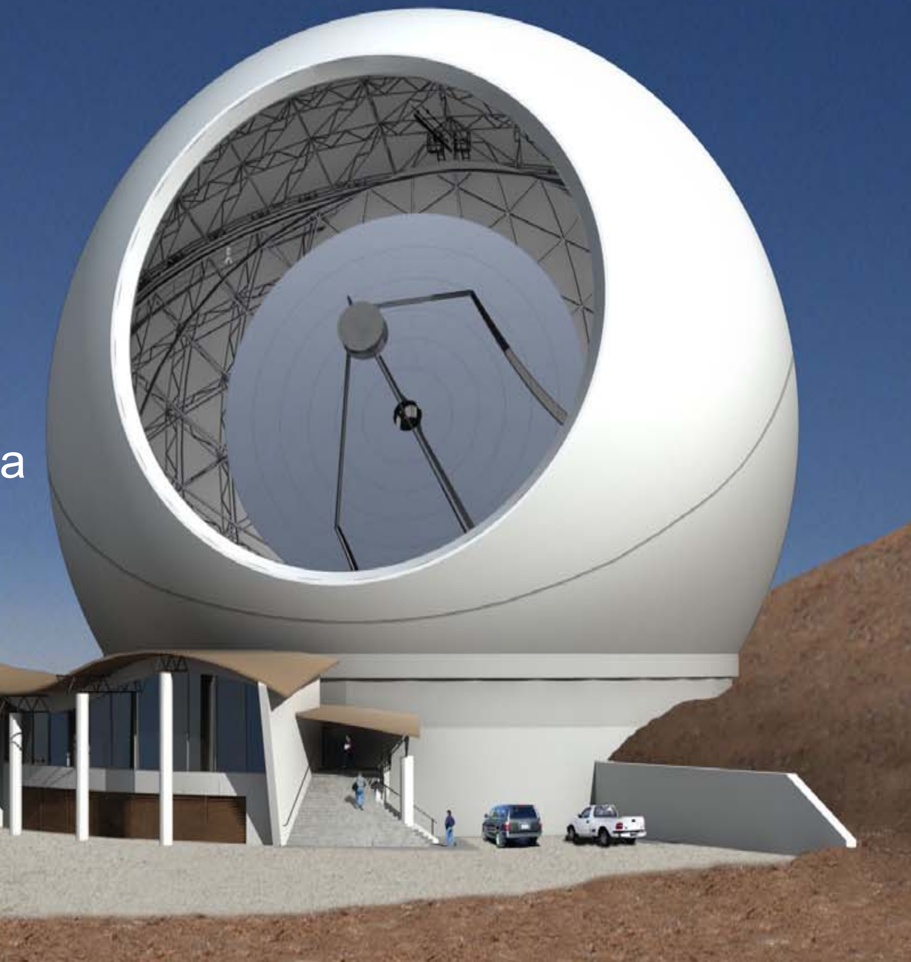
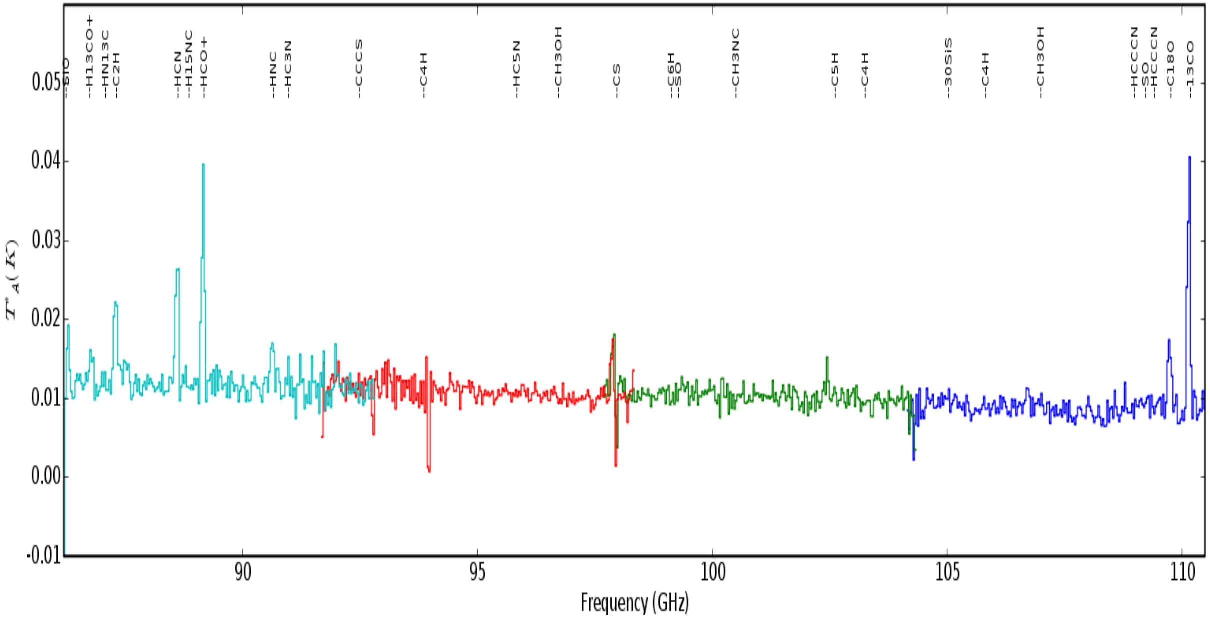
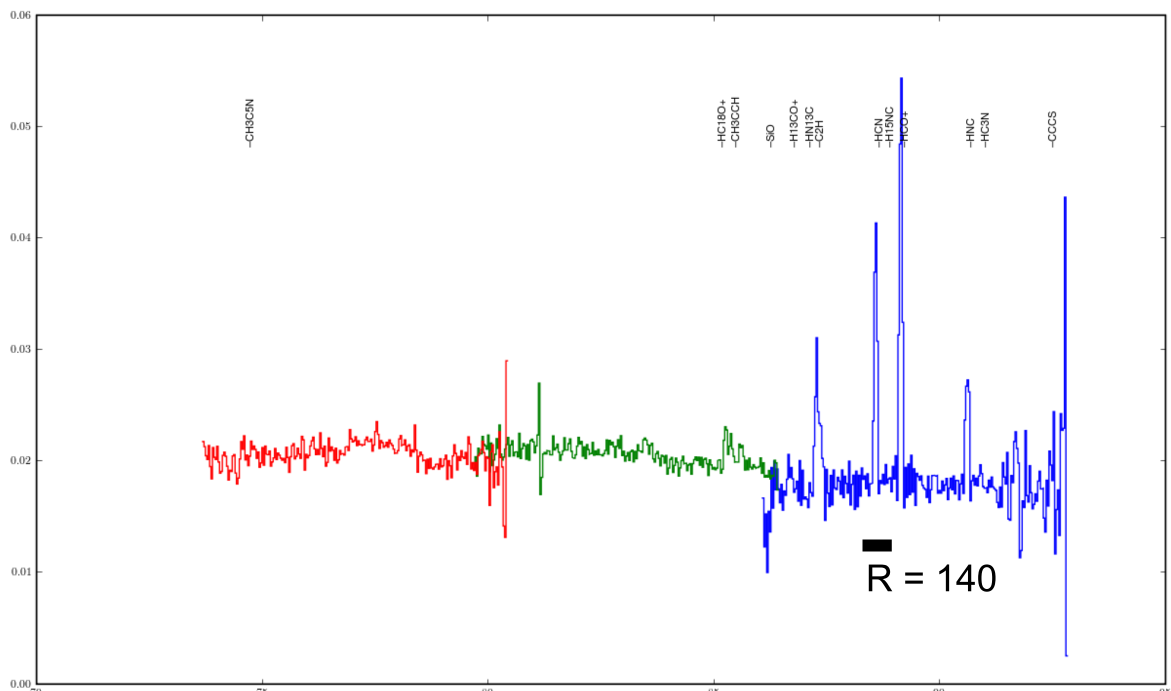
With thanks to Neal Erickson, John Ward,
Imran Mehdi, Eric Murphy, and Jorge Pineda



Why Heterodyne Receivers?

- High frequency resolution
  - Essential when detailed study of kinematics gives critical information
  - Necessary to disentangle rich spectra in which line confusion is potential problem
- *Heterodyne* and *High Resolution Spectroscopy* are basically interchangeable for submm wavelengths
- Focal plane arrays are practical and costs of backend spectral processing are dropping dramatically





3mm Spectra of M82

- Obtained with the FCRAO 14m ($\Delta\theta$ = 50") telescope
- Used broadband heterodyne receiver with HEMT amplifiers

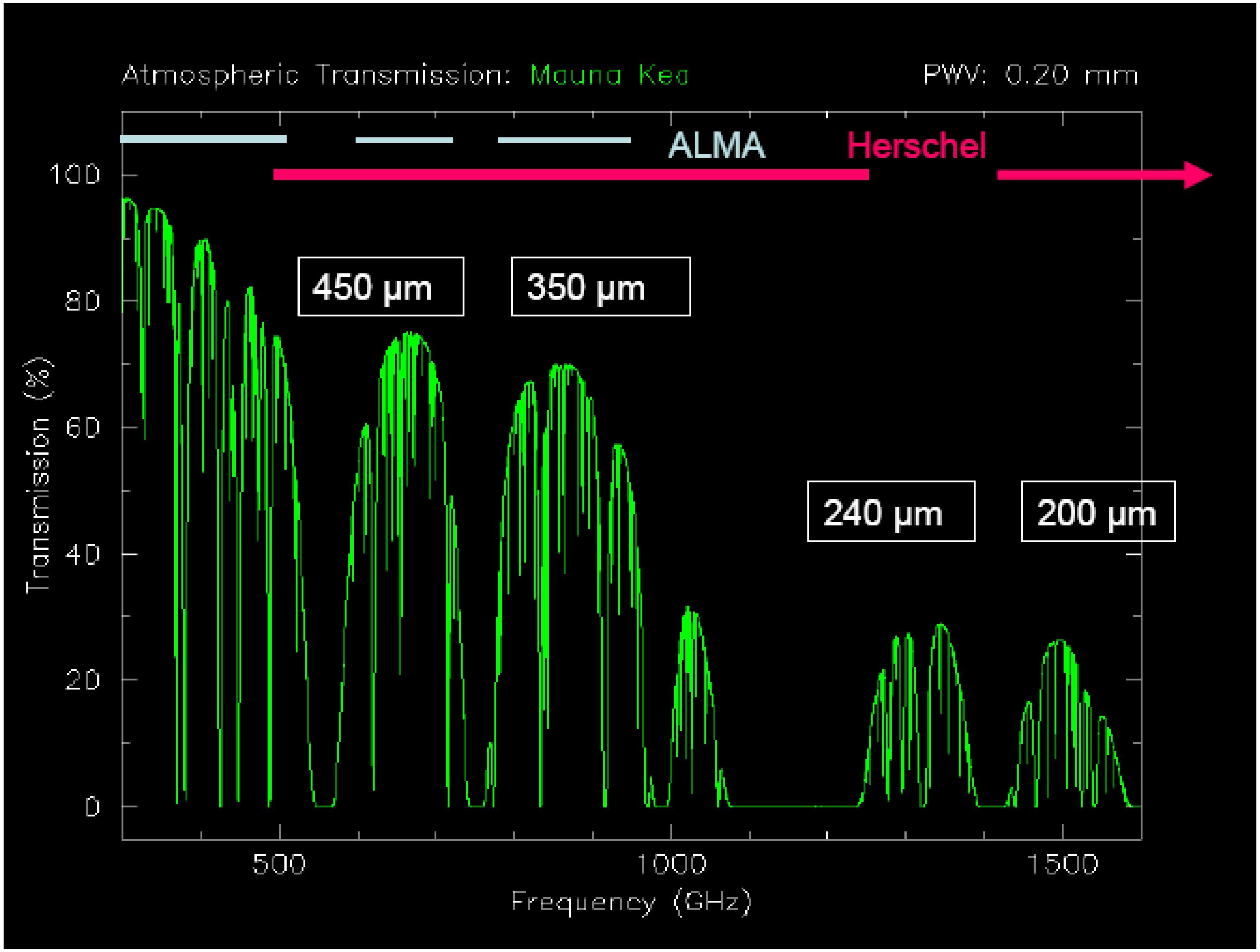
(N. Erickson, G. Narayanan, et al.)

- Now covers 75 GHz to 115 GHz in single spectrum and in two polarizations

$f/\delta f$ = 160 for HCN-HCO^+

Moderate spectral resolution necessary even for extragalactic observations

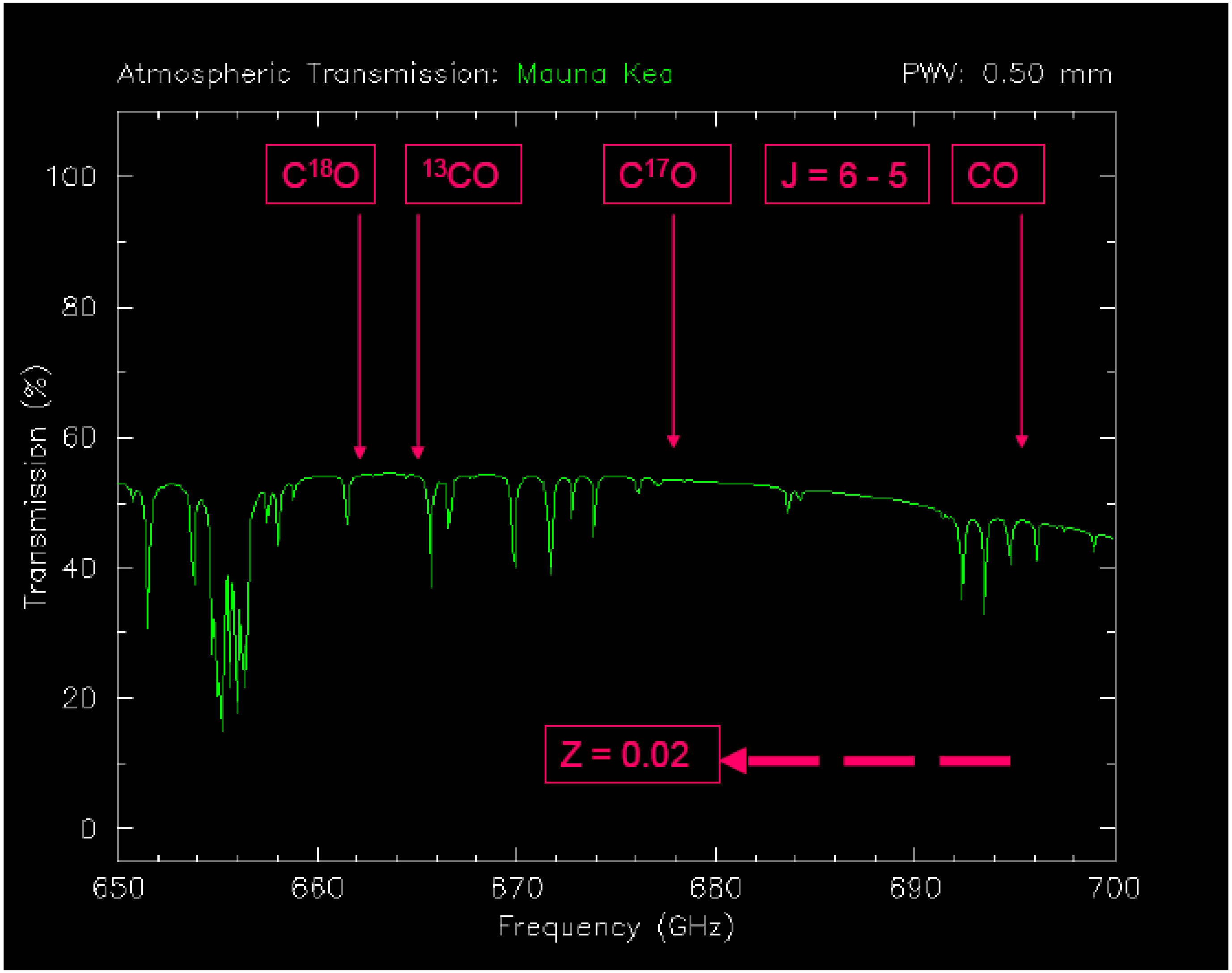
Submillimeter Windows



Valuable Spectral lines In Each Atmospheric Window

- Long-submillimeter (850 μm) window – ideal for less than optimum PWV. Includes J = 3-2 CO and CI fine structure line (492 GHz; not a good frequency)
- 450 μm window includes CI fine structure line (810 GHz) and CO J = 7-6 line (807 GHz; transmission not so good)
- 200 μm window – important tracer of diffuse ISM (NII fine structure line at 1.46 THz) but requires minimum PWV
- Important astrochemical lines throughout submillimeter (G. Fuller & D. Lis talks)

Focus on 650-700 GHz Window – Powerful Tracers of Warm Molecular ISM



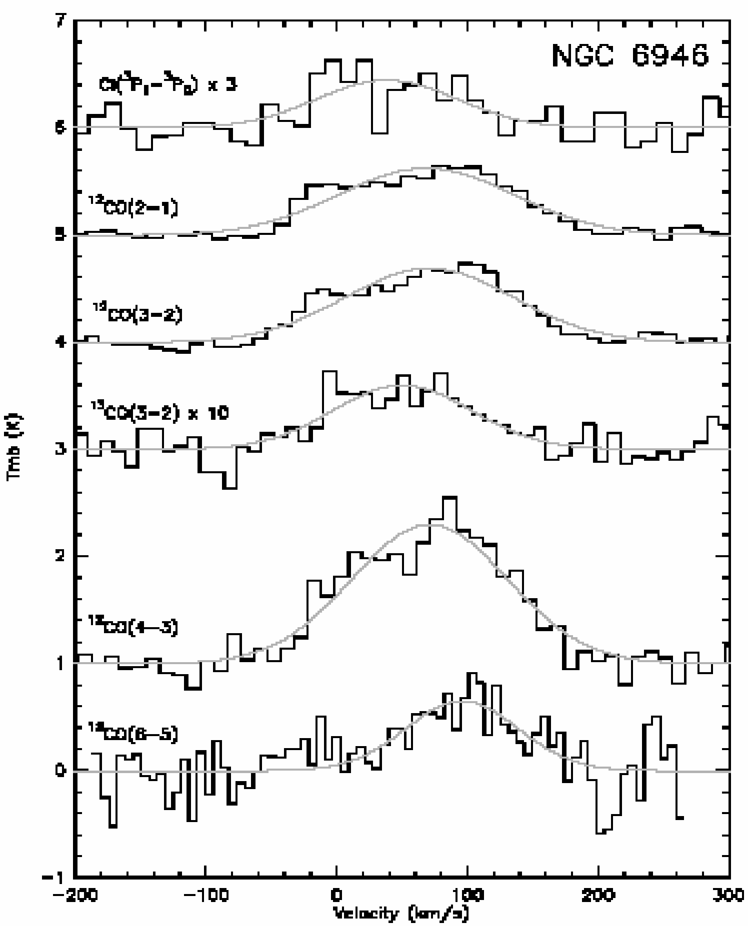
J = 6 – 5 carbon monoxide isotopologues

CO	**691473.**
$C^{17}O$	**674009.**
^{13}CO	**661067.**
$C^{18}O$	**658553.**

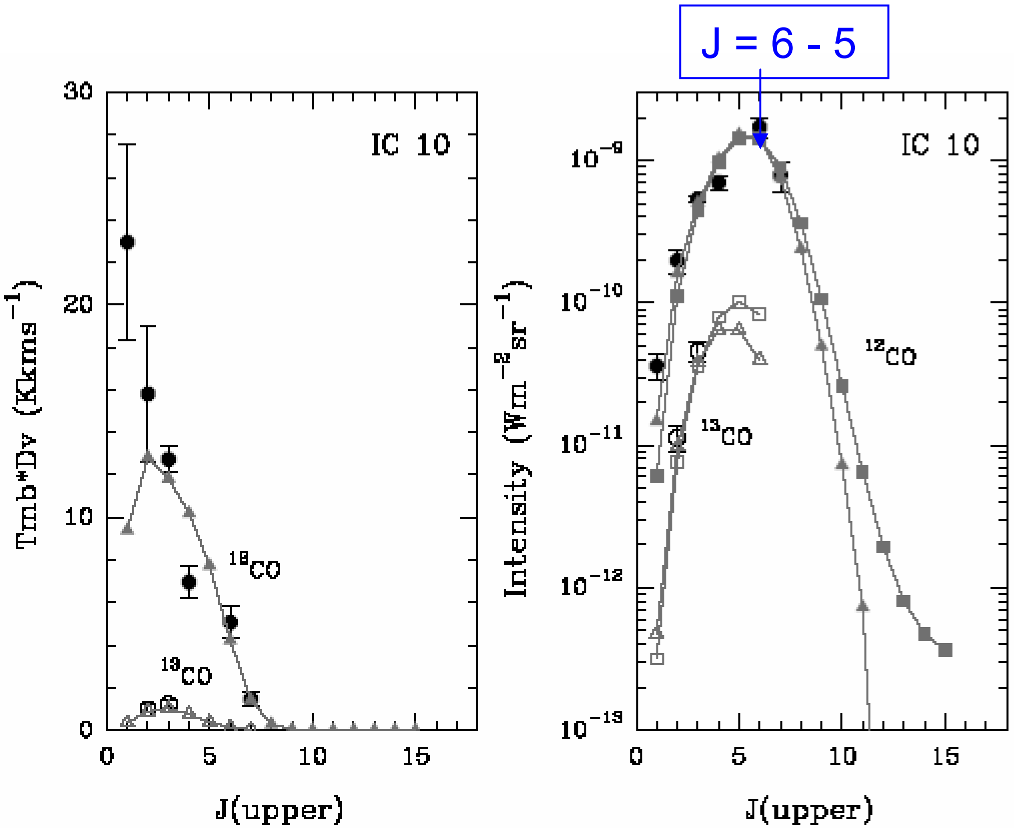
Submm Spectral Line Studies of Nearby Galaxies

- Require high spectral resolution
- Submm lines give different view of ISM and star formation activities than e.g. low-J carbon monoxide transitions
- Sources can be many arcminutes in size and 4” CCAT resolution offers possibility of resolving important features (ALMA follow up)
- Requires array (heterodyne camera) for reasonable observing time

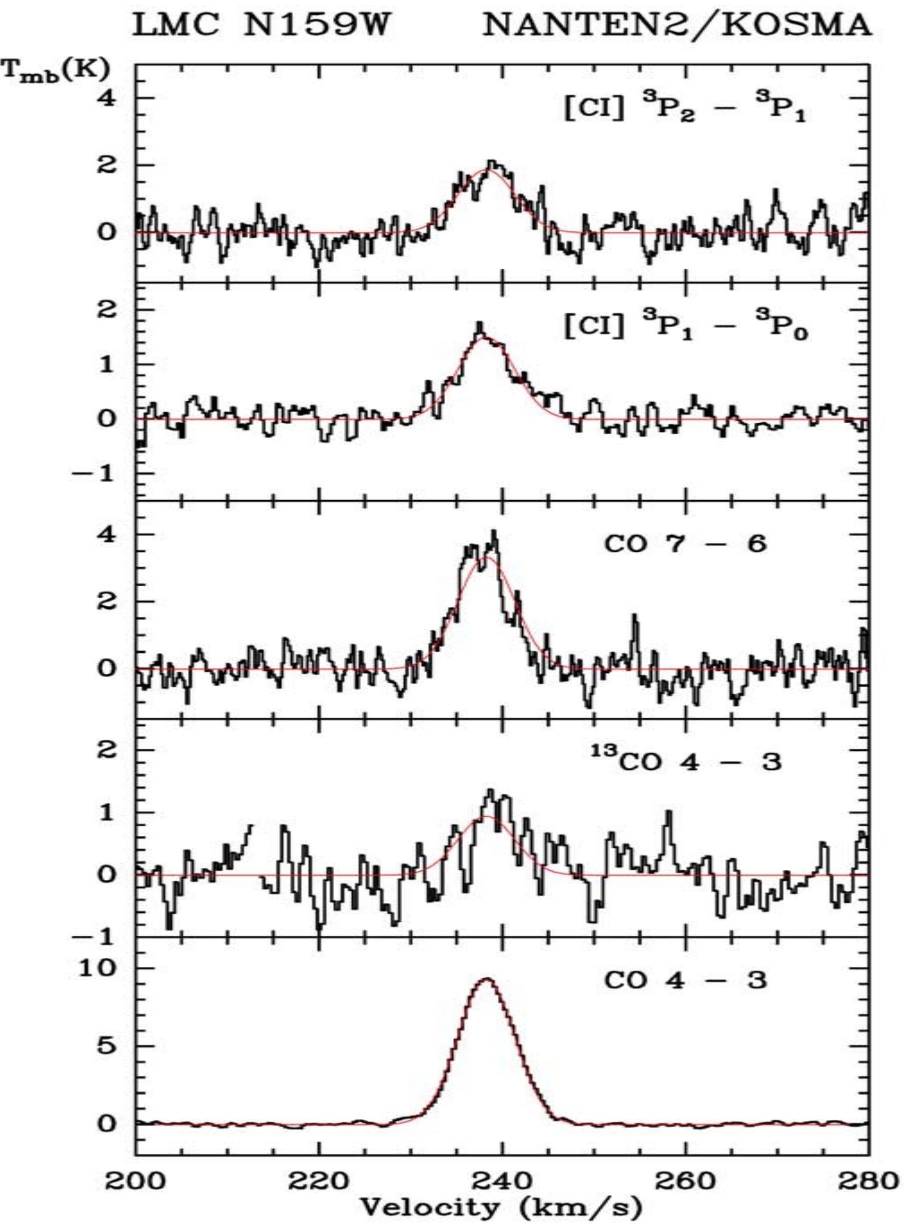
Mid-submm CO Lines Probe Different Phase of ISM than do Low - J Transitions



Bayet, Gerin, Phillips, Contursi 2006



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

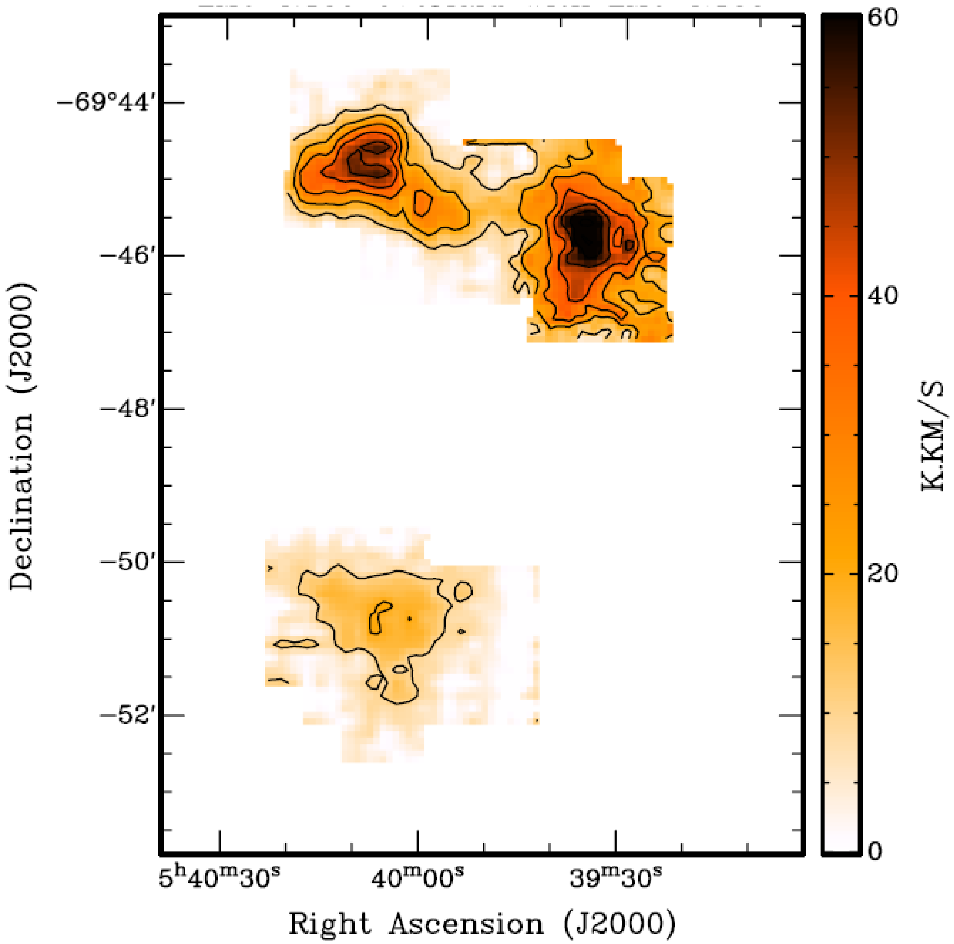


J. Pineda et al. A&A 2008 submitted

Submm Spectra from PDR in LMC

- C/CO Abundance Ratio ~ 1
- Consistent with large C^+ and C abundances relative to CO in low-metallicity PDRs
- Modeling requires highly clumped PDR structure

Molecular Clouds in LMC



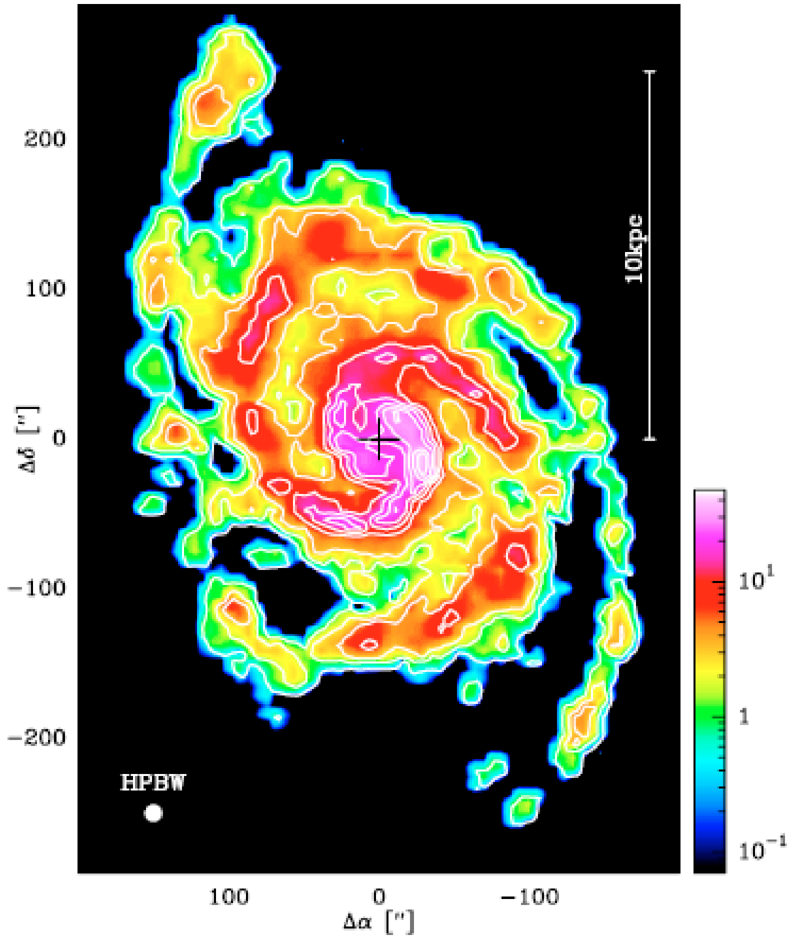
CO J = 4 - 3

Submm mapping of multiple CO lines suggests molecular cloud temperatures are ~60K, much hotter than Galatic GMCs

Effect of lower metallicity?

Nanten2 Collaboration

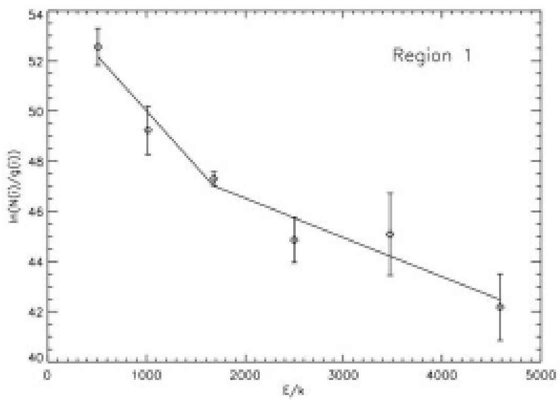
Large-Scale Study of Nearby Galaxies – ^{12}CO J = 2-1 Map of M51 (D = 8.4 Mpc)

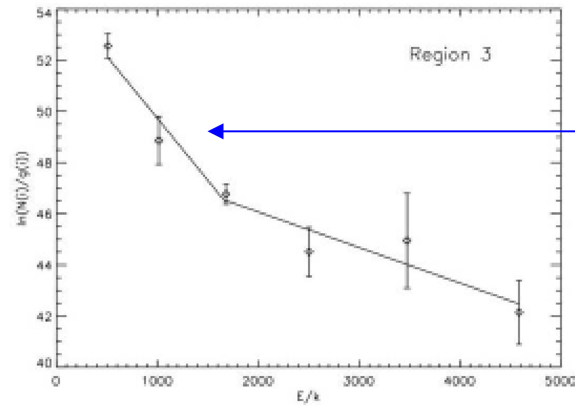


Schuster et al. A&A 2007

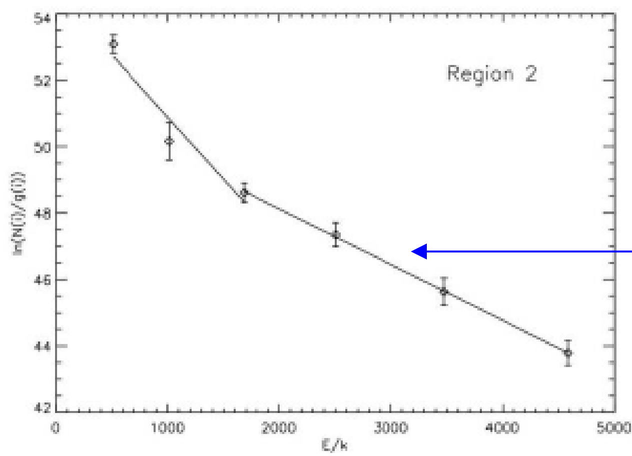
- Angular resolution = 11” (450 pc)
- Total H_2 mass = 1.9×10^9 M_{solar}
- Atomic/Molecular gas density = 0.1 in center rising to 20 in outer regions
- Velocity dispersion in CO drops from ~28 kms^{-1} in center to ~6 kms^{-1} at 7-9 kpc and then rises to ~8 kms^{-1}
- CCAT angular resolution = 4.3” @ 690 GHz; 10x smaller beam solid angle
- 4×10^4 Nyquist-sampled pixels => Time = 1000 hr / N_{pix} @ 90s integ. Time/ptg

Surprise in M51 – Warm & Hot H_2 Detected by Spitzer





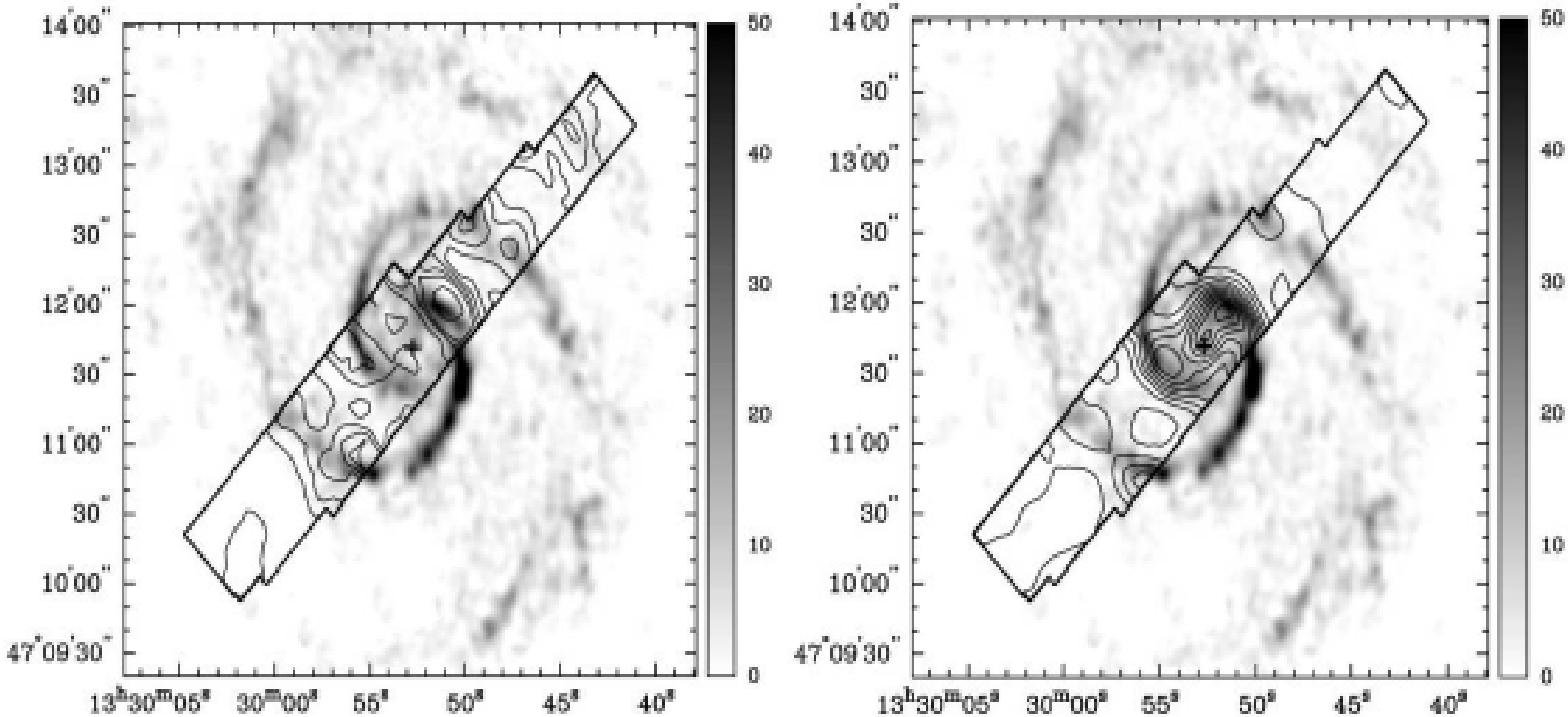
Warm phase T = 100-300 K



Hot phase

T = 400 – 1000 K

Brunner, Sheth, Armus, et al. 2008



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

•Both strongest in nucleus

•Wam phase 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?

^{12}CO J = 6 - 5 Emission from M82

Ward, Zmuidzinas, Harris, Isaak 2003

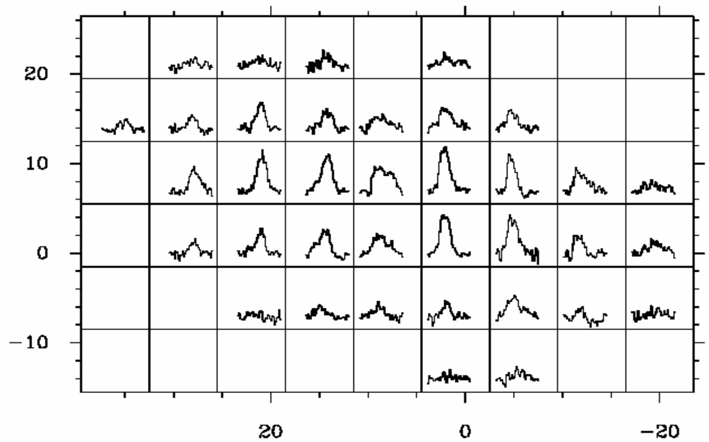


FIG. 1.—Spectra of ^{12}CO $J = 6$–5 in M82. The map has been rotated such that the horizontal offsets are approximately along the major axis. Offsets are in arcsec from an arbitrary center. The vertical scale ranges from T_{MB} of −1 to 4.5 K, and the horizontal scale ranges from −80 to 520 km s^{-1}.

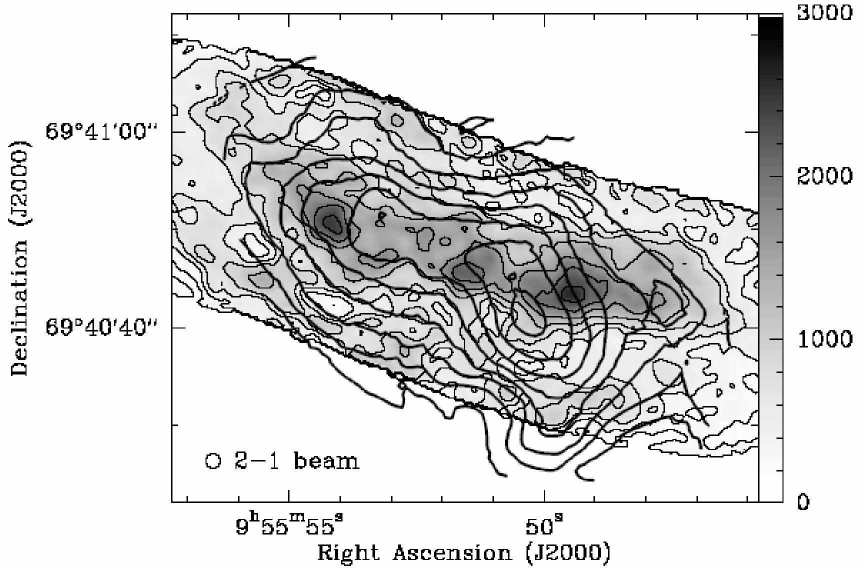


FIG. 5.—M82 ^{12}CO $J = 6$–5 integrated intensity contours superimposed on ^{12}CO $J = 2$–1 integrated intensity from Weiss et al. (2001). Contours are 50, 100, 150, 200, 250, 300, 350, and 400 K km s^{-1}.

CSO Beam FWHM = 14”
Peak TMB = 4 K

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

Multiple components are 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

Higher resolution needed

Mapping Nearby Galaxies is a Challenge: NGC 6946 (D = 3 Mpc)

133 CCAT beams at 690 GHz

10’ x 10’ region includes ~72,000 Nyquist sampled CCAT pixels @ 690 GHz

→ 550 pointings with 144 element array (use OTF)

For T_R = 500 K τ = 0.5; T_{out} = 1000 K

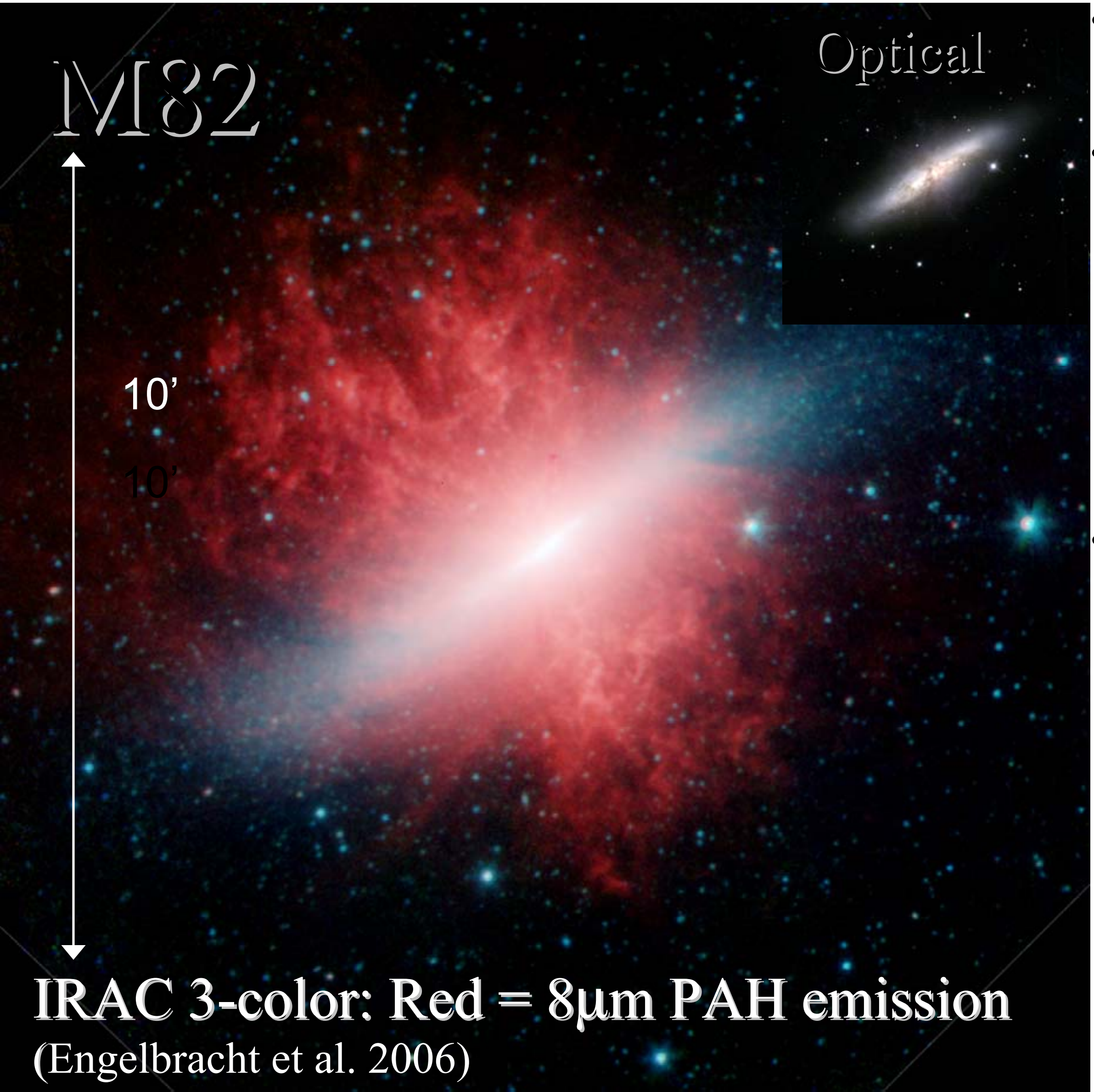
Use δv = 10 km/s δf = 23 MHz

ΔT = 0.02 K in 100 s

15 hr time (nominal) to map the region

Larger array is faster and would open possibility of ^{13}CO and other tracers

Vertical Structure & Velocity of Warm Molecular Gas in Nearby Galaxies

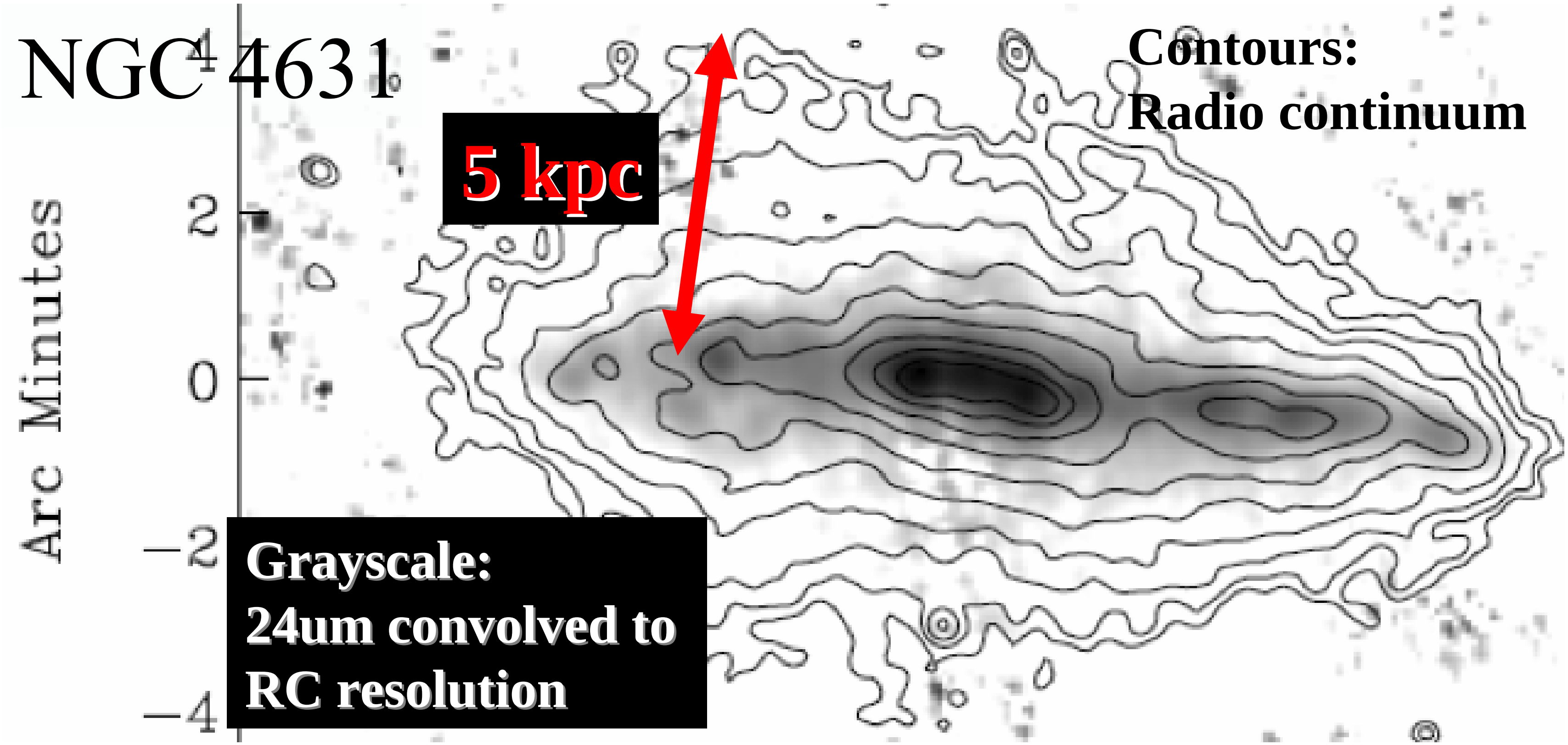


IRAC 3-color: Red = 8μm PAH emission
(Engelbracht et al. 2006)

- Does warm molecular gas reach escape velocity to enrich the IGM?
- Velocity of outflows:
  - Are phase dependent
    - Hot X-ray gas: v~500-800 km/s
    - Cooler material 1 to 100’s of km/s
  - Increase with increasing SFR/area
- **CCAT** is only feasible way to map high *J* transitions of CO for large haloes of nearby galaxies at sub-kpc resolution
  - Map *J*=6-5: ~100K mol. Gas
  - Spatial res ~4.5”
  - comparison with atomic and radio haloes on large scale is essential

Eric Murphy (IPAC)

Studying Negative Feedback Effects by Mapping Warm Molecular Gas in Nearby Galaxies w/ CCAT



- Starburst winds are multiphase (e.g. Large synchrotron haloes):
  - Arise from advected cosmic-ray electrons in large-scale magnetic field
  - Implications for negative feedback effects: Is SF quenched by galactic CR winds (e.g. Socrates et al. 2008)?
    - Need direct comparison w/ distribution/kinematics of warm molecular gas
    - => for high-z ULIRGs where we cannot study these processes in detail

Notional CCAT Heterodyne Spectrometer

- Must be large array with N_{pix} > 100 to be significantly faster than ALMA when mapping extended sources
  - ALMA is not well-matched to this type of astronomy and time is not likely to be devoted to it, even if technical problems of large-area mosaics (1000's of pointings) and obtaining zero spacing flux are solved
- Large format arrays eminently practical at submillimeter wavelengths
  - Small feedhorn size reduces footprint size of array and thus cooling is not a major problem
  - LO generation is straightforward at least to 1000 GHz

General Considerations for Large-Format Submm Heterodyne Array

- Gaussian beam for illuminating telescope
  - $w_0 = 0.22\ [T_E(\mathrm{dB})]^{0.5}\ (f/D)\lambda$
  - For f/D = 8; λ = 0.434 mm; T_E = 11 dB (optimum illumination); w_0 = 2.5 mm
  - Feedhorn diameter = 3 w_0 = 7.5 mm
  - Minimum spacing ~ 10 mm (10.6")
  - This is probably as small as can accommodate IF amplifier, connectors, etc. => large f/D ratio is required
- With f/D = 8 we have ~12cm x 12cm array physical dimension which is OK from optics, thermal, and mechanical viewpoints

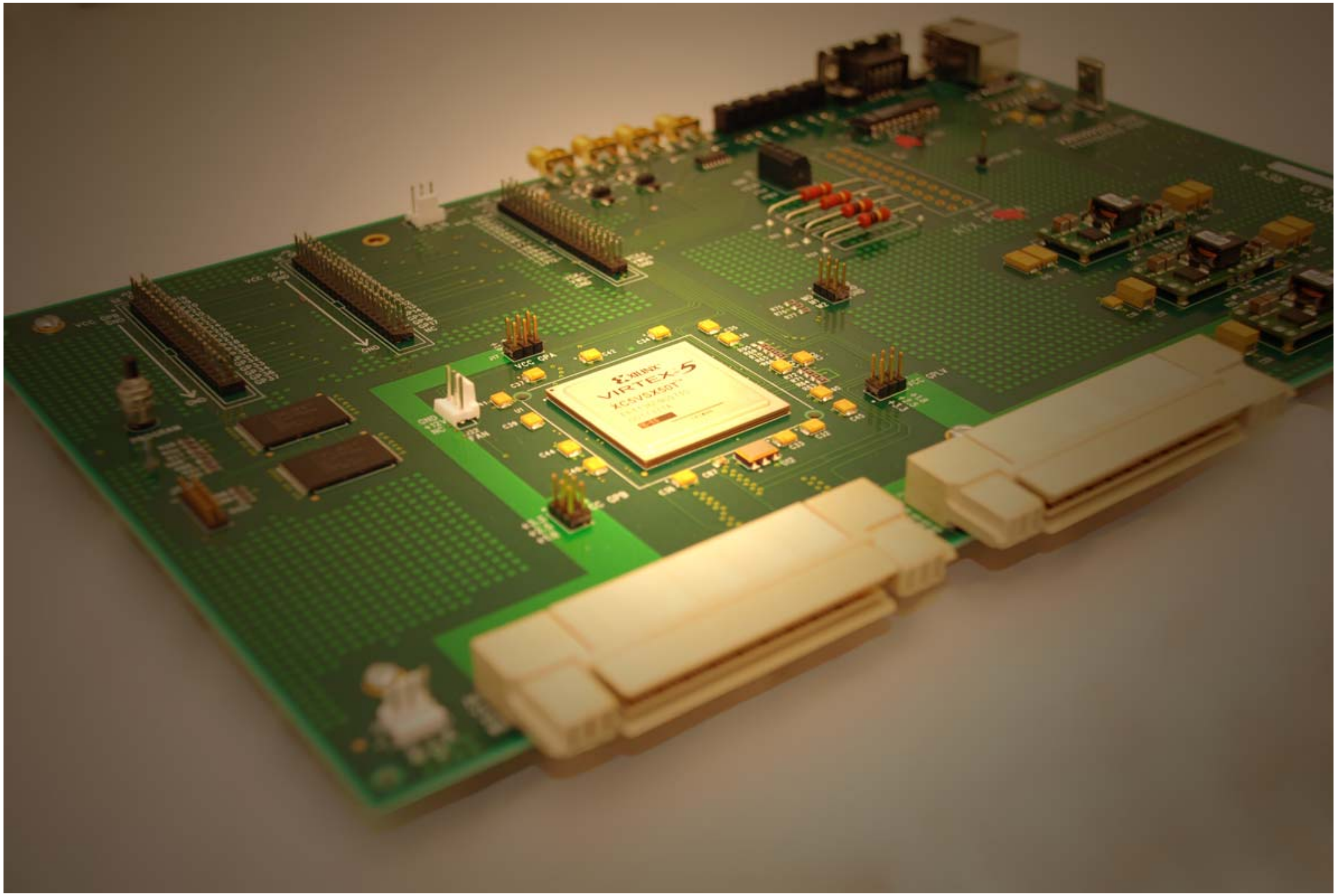
CCAT Heterodyne Array for Mapping (CHARM)

- 12x12 array of 2SB SIS mixers covering 640 – 700 GHz (more if possible)
- ~2' x 2' FOV with 4 pointings required for beam sampling and 16 for Nyquist sampling. OTF mapping may be popular
- 8 GHz BW per sideband; IF bandpass TBD: 4 – 12 GHz plausible
  - ^{13}CO, $C^{18}O$, $C^{17}O$ simultaneously
- Single polarization array with upgrade path to 288 pixel dual polarization array
- LO power requirement ~ 50 μW for 2SB mixer. Total power of 7 mW is significant step from what is available today (1-2 mW), but not major obstacle if distribution is efficient

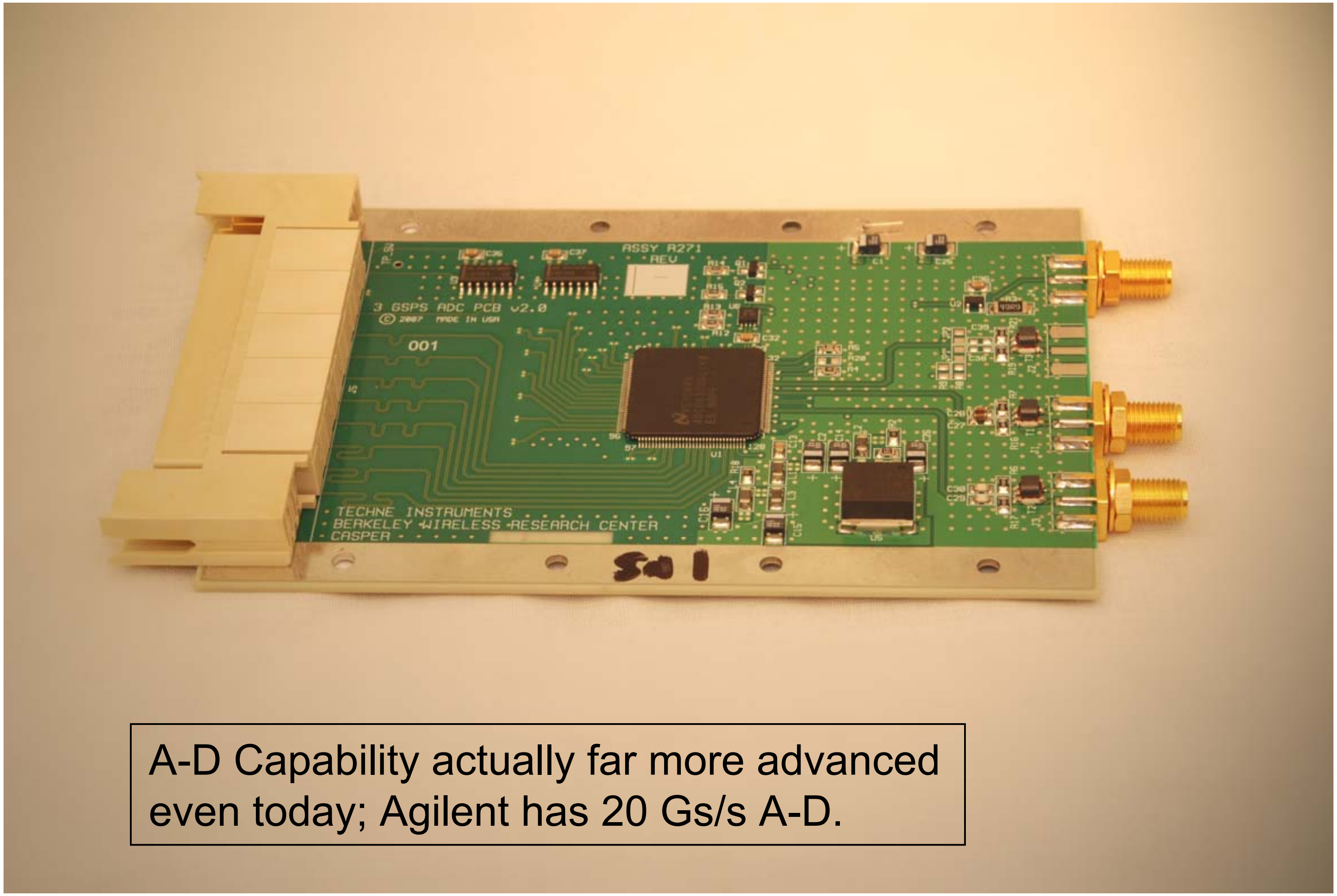
Digital Spectrometers – Moore's Law!

- Current board from D. Werthimer uses Virtex 5 chip:
- 2 GHz bandwidth; 30 W power; $5K cost
- D.W. indicates that time scale for generation is about 1 year and each generation means 2X reduction in power OR 2x greater speed. Software reused
- 4 generations to CCAT early observations (min.)
- 16 GHz bandwidth 15 W power $5K cost
- 144 pixel array of sideband separating mixers with 8 GHz BW per sideband requires 144 boards consuming 2.2 kW and costing $700K (not complete system cost)
- One such backend serves multiple frontends for different windows
- Put the backend in shielded, cooled enclosure near the receiver!
- JPL (and likely others) are working on ASIC which will have dramatically lower power consumption but less flexibility.

FPGA Spectrometer Board Developed by D. Werthimer Giving 2 GHz Bandwidth



3 Gs/s ADC Board: Two Together Give 2 GHz Bandwidth



A-D Capability actually far more advanced even today; Agilent has 20 Gs/s A-D.