Heterodyne Systems for Astronomy with CCAT

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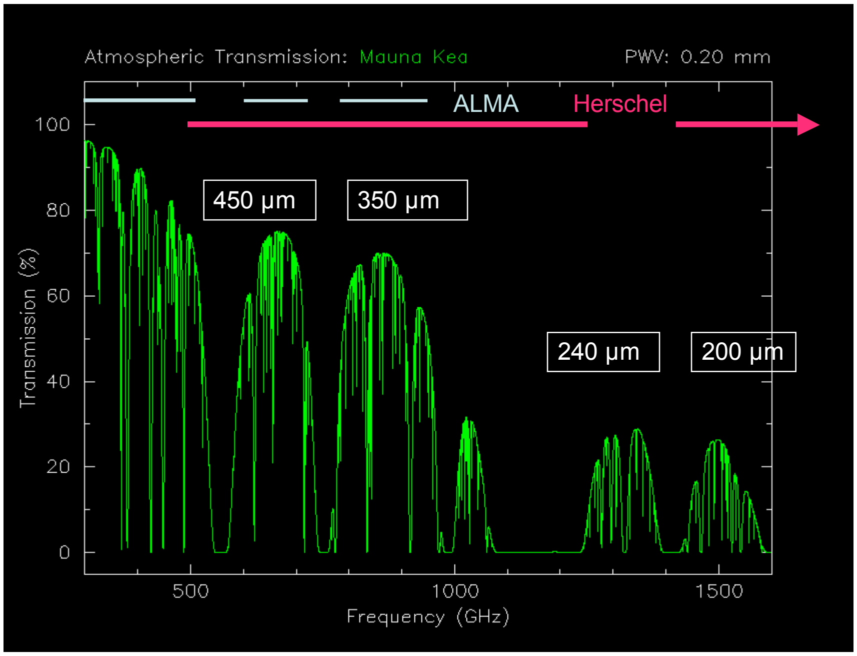
Why Heterodyne Systems for Submillimeter Astronomy ?

- Only proven method of achieving the spectral resolution to resolve atomic and molecular lines in the Milky Way and nearby galaxies
- Frequency multiplexing advantage – multiple resolution elements on the line + baseline simultaneously
- Amenable to spatial multiplexing thanks to recent technological developments



The Context for High Resolution Spectroscopy with CCAT

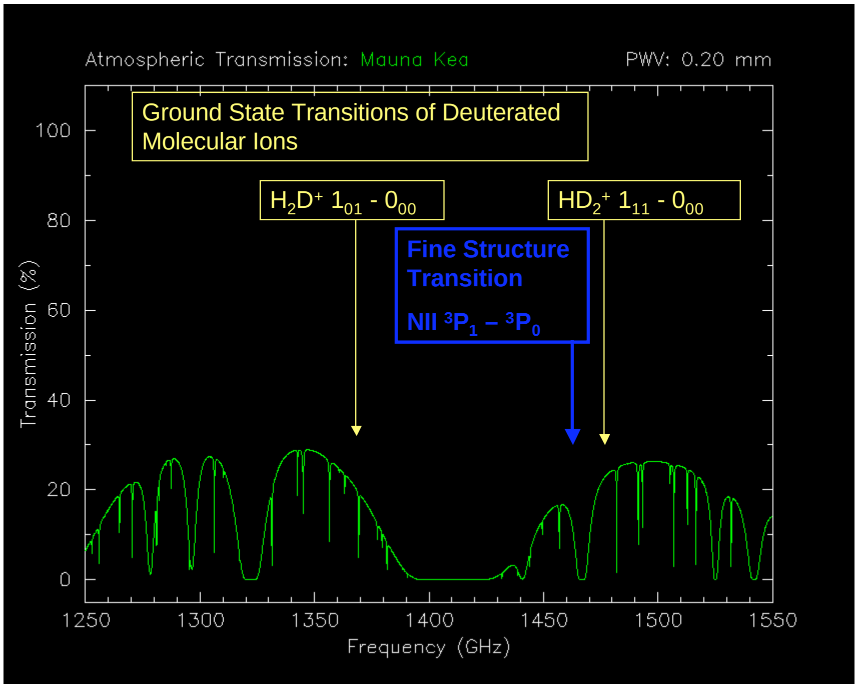
- APEX (12 m; λ ≤ 350 μm)
  - 5x less effective area than CCAT
  - worse atmospheric transmission
  - 2x larger beam size
- LMT (50m; λ ≤ 1.3 mm)
  - Good complementarity at lower frequencies
  - ~2x larger beam size
- ALMA (50 x 12m + Compact)
  - Band 8 = 385-500 GHz; Band 9 = 602-720 GHz; Band 10 = 787-950 GHz
  - Covers major submm windows but schedule for higher bands uncertain
- A variety of smaller telescopes

Three Categories of Application of Heterodyne Receivers

1. Individual “target of opportunity” lines
2. Operation with ALMA
3. Large-scale surveys

Lines of Opportunity

- There are some spectral lines of particular interest whose properties are little known at present
- They may become valuable probes of e.g. core evolution, thermal balance, grain and gas chemistry
- Examples include NII fine structure line, lines of key deuterated molecular ions, …

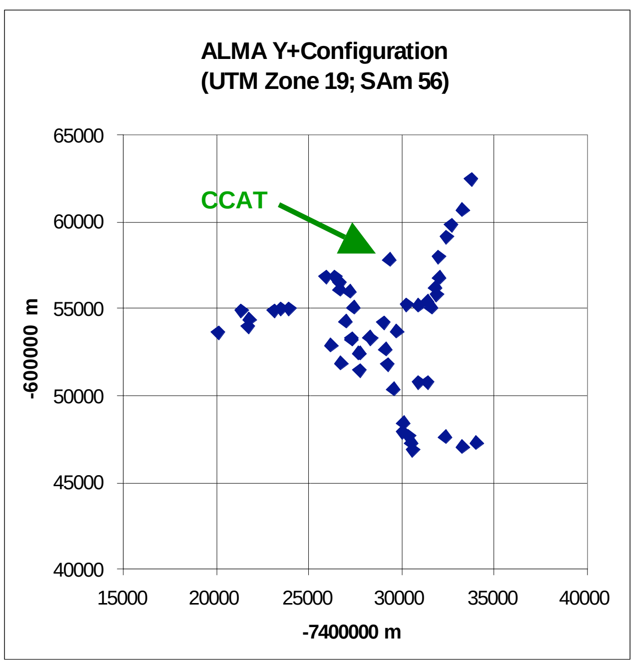


Lines of Opportunity (2)

- APEX will certainly have done some of this work, but CCAT will be much more powerful
- Need to have ability to put special purpose receivers in place to advance the field
- Probably not a major driver in terms of optics, telescope, or infrastructure but should be kept in mind

CCAT + ALMA

- The most efficient approach would be to have ALMA receiver package on CCAT
- All baselines to CCAT have sensitivity doubled
- ALMA f/D = 8, identical to current CCAT design
- Detailed issues including polarization & antenna switching speed need study
- Infrastructure impact – receiver package, compressors, electronics package
- Connection via fiber link (4 fibers)



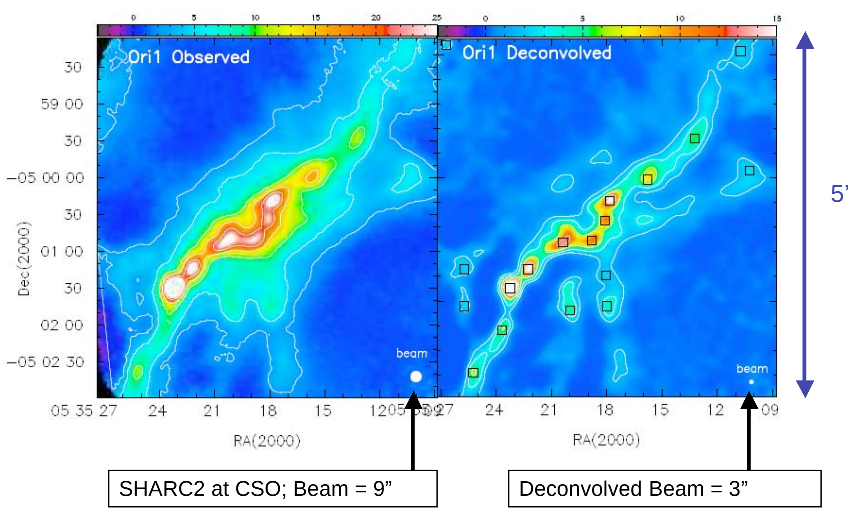
Galactic Surveys

Large –scale surveys of Galactic molecular clouds, especially cloud cores, are envisioned as part of key CCAT science

Initial surveys will be carried out with short wavelength camera observing continuum emission from dust

There is a major need for follow up observations to reap scientific benefit

(Beam) Size Matters!



- The CCAT beam size at 350 μm will be 3.5”, similar to the deconvolved beam size obtained from CSO observations
- It is plausible that with good signal to noise ratio, reliable pointing, and constant beam shape, we can deconvolve CCAT data to 1” angular resolution
- This should be of enormous value in determining the masses and structure of cloud cores

Cloud Core Mass Function

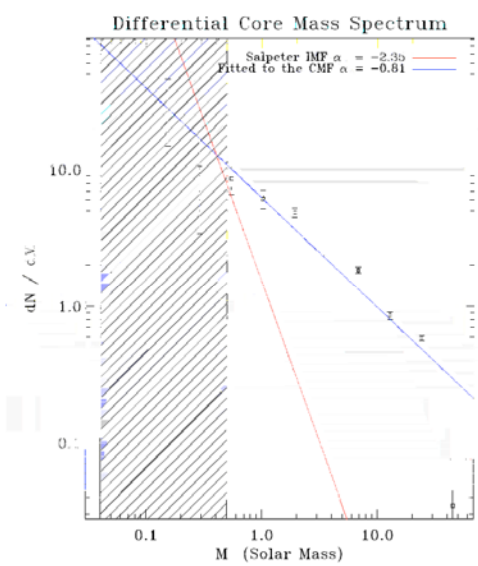
The Core Mass Function (CMF) is a important and interesting descriptor

Relationship to stellar IMF gives vital information on how stars form

We want to know in addition the dynamical state of these sites of potential star formation

Which cores are going to do what?

Observations of dust can give us mass, but we need more!

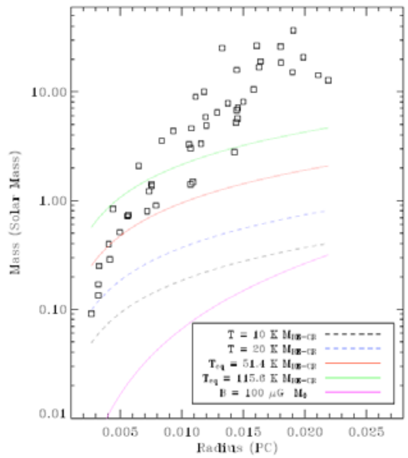


Evolution of Cloud Cores

Cloud core masses appear greater than can be supported by thermal pressure, or kinetic (turbulent) pressure, or the magnetic field

These calculations need extensive detailed observational verification

For this we need information on internal motions, i.e. **linewidths** of tracers of the core material. This requires heterodyne observations of appropriate tracer on angular scale comparable to that of dust continuum observations

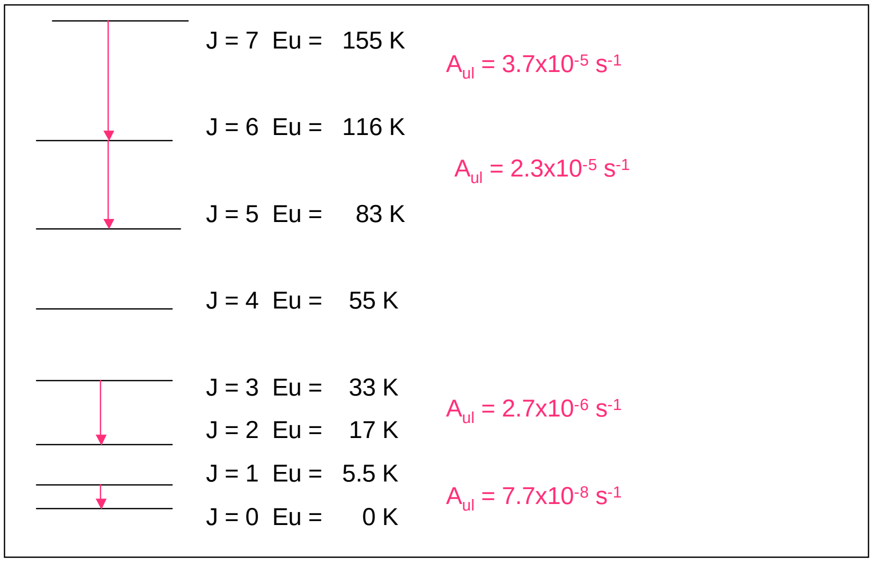


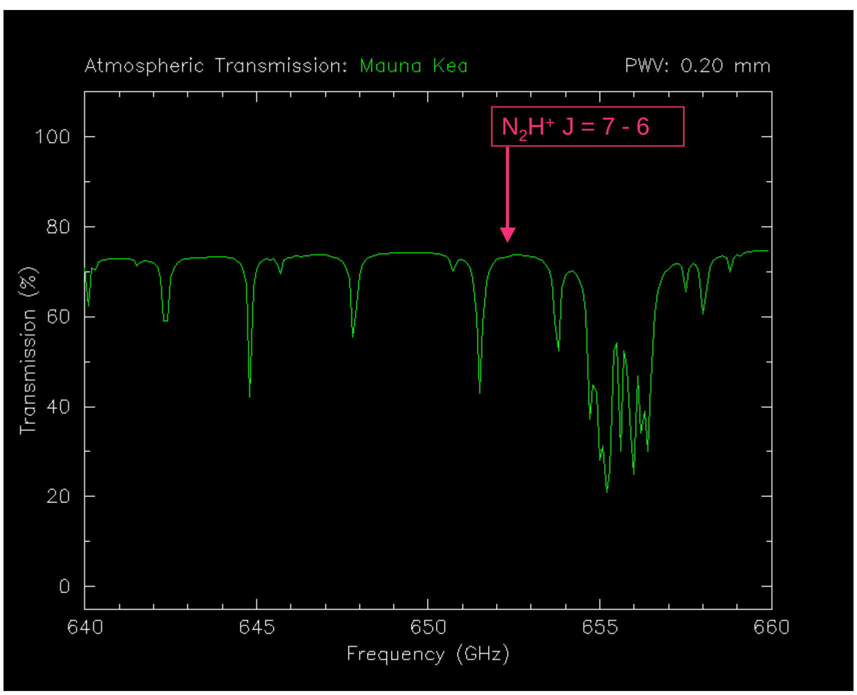
Li, Velusamy, Goldsmith, & Langer 2006

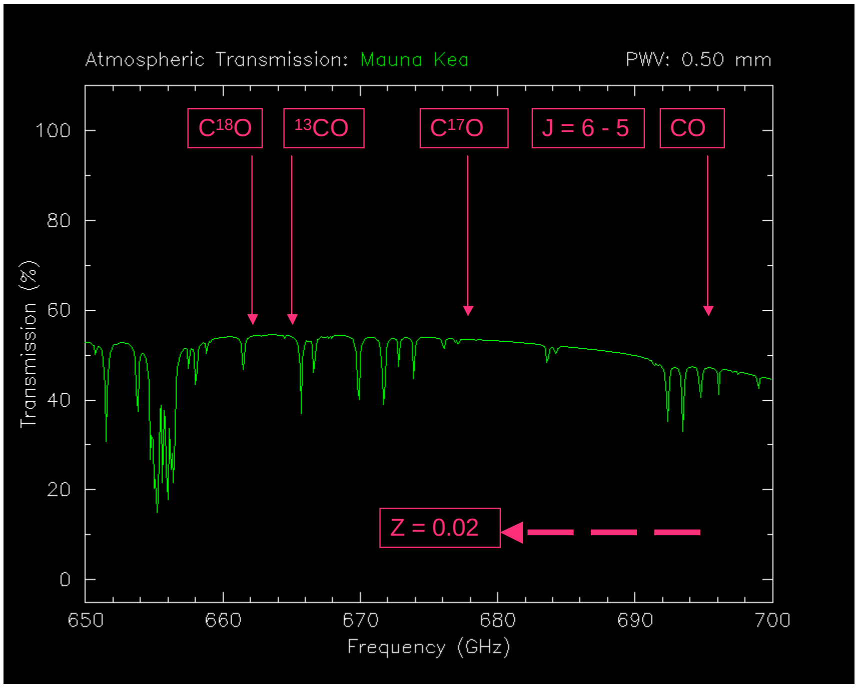
Probing Cloud Core Kinematics, Structure, and Star Formation

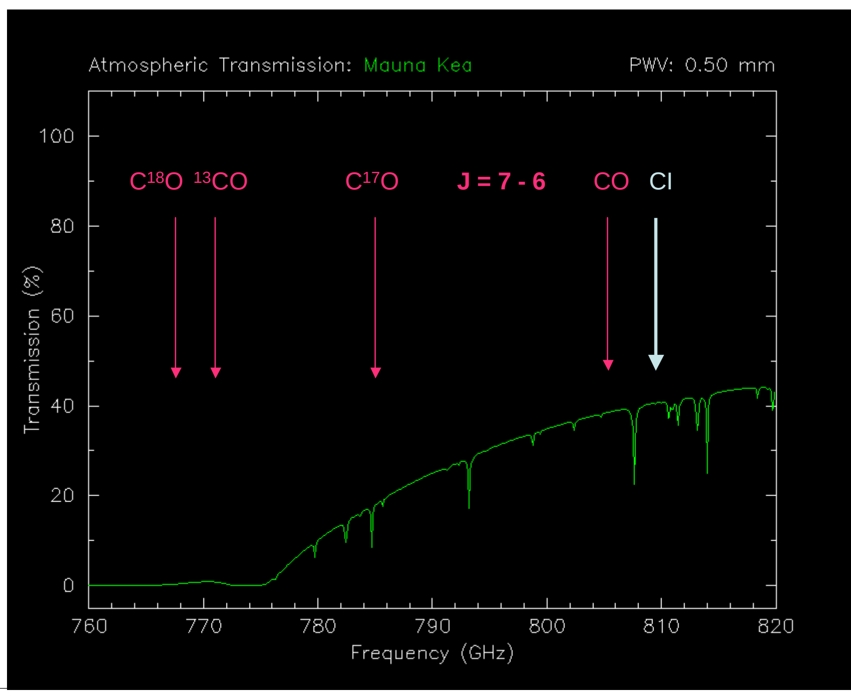
- N_2H^+ J = 7 - 6 at 652.1 GHz could be a powerful probe for very dense, moderately warm gas
- CO J = 6 - 5 (E_u /k = 116 K) and CO J = 7 - 6 E_u /k = 155 K) are possibilities to probe very warm gas
- With isotopologues ^{13}CO and $C^{18}O$ will be excellent tracers of core kinematics.
- Can trace mass of warm gas where depletion is not likely to be severe
- Excellent discrimination of warmer vs. cooler cores (in conjunction with e.g. CO J = 2 - 1)
- Potentially powerful probe of outflows

Lower Rotational Levels of ^{12}CO



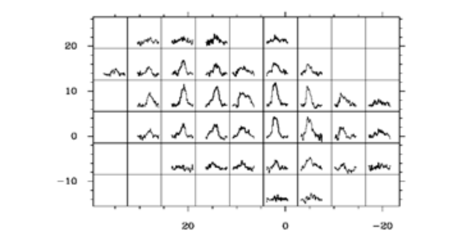


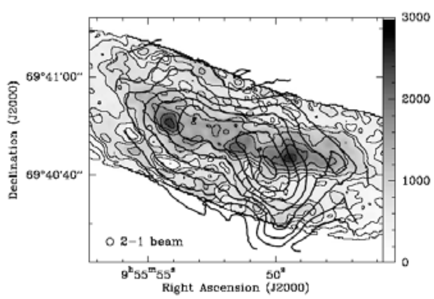

Atmospheric Transmission: Mauna Kea
PWV: 0.50 mm
C18O
13CO
C17O
J = 6 - 5
CO
Z = 0.02
Transmission (%)
Frequency (GHz)


Atmospheric Transmission: Mauna Kea
PWV: 0.50 mm
C18O
13CO
C17O
J = 7 - 6
CO
CI
Transmission (%)
Frequency (GHz)

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





^{12}CO J = 6 - 5 Map of M82
Ward, Zmuidzinas, Harris, Isaak 2003

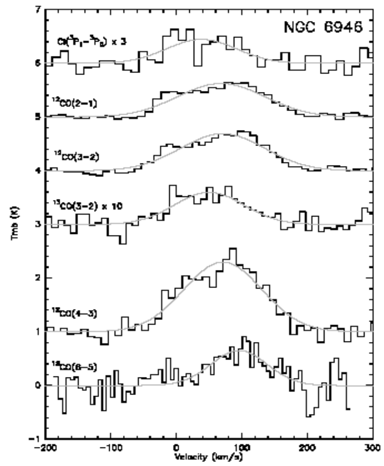
CSO Beam FWHM = 14”
Peak TMB = 4 K

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

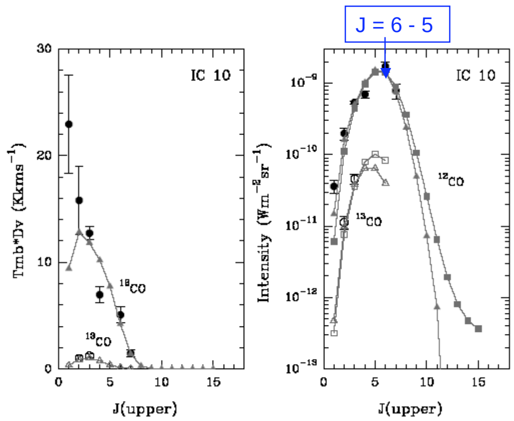
Multiple components required to fit set of CO lines including warm (>50 K), low density gas

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

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)!

An Example of Mapping Nearby Galaxy: NGC 6946 (D = 3 Mpc)

280 CCAT pixels at 690 GHz

10' x 10' region includes ~78,00 Nyquist sampled pixels

→ 1225 pointings with 64 element array (use OTF)

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

For δv = 10 km/s δf = 23 MHz

ΔT = 0.02 K in 100 s

34 hr time to map the region w/ 64 pixel array; 8.5 hr w/ 256 pixel array

Note: representative nearby galaxy not likely CCAT source due to decl.

Submillimeter Feedhorn Coupling to CCAT

- Gaussian beam for illuminating telescope
  - $w_0 = 0.22\ [T_E(dB)]^{0.5}\ (f/D)\lambda$
  - For f/D = 8; λ = 0.46 mm; T_E = 11 dB (optimum illumination); w_0 = 2.7 mm [no reimaging optics]
- Feedhorn diameter = 3 w_0 = 8.1 mm
- Total array footprint = 9 cm x 9 cm for 8x8 single polarization array
- Close packed array of "good" feed horns yields every-other beam sampled array of beams on sky
- Finite area required for receivers (e.g. SuperCam) but with OTF mapping underfilling is not significant issue

Large Format mm/submm Heterodyne Focal Plane Arrays

ARRAY	ANTENNA	FREQ (GHz)	TYPE	NUMBER OF PIXELS	NOM. ANG. RES.
Sequoia	**FCRAO14m LMT 50m**	**80-115**	**HEMT AMP**	**2pol x 16 = 32**	**50" 15"**
HERA	**IRAM 30 m**	**215-272**	**SIS MIXER**	**2pol x 9 = 18**	**10"**
HARPB	**JCMT 15 m**	**330-370**	**SIS MIXER**	**16**	**14"**
SuperCam	**HHT 10 m**	**330-360**	**SIS MIXER**	**64**	**22"**
Champ+	**APEX 12m**	**602-720 790-950**	**MIXER**	**7 7**	**8" 6.5"**

CHARM = CCAT Heterodyne Array for Mapping

- Nominally 64 - 128 pixels covering 650 to 700 GHz
- We should consider 256 pixels as a reasonable target for > 2012
- 4.3” angular resolution @ ^{12}CO J = 6 - 5
- 1 to 4 GHz instantaneous IF bandwidth with flexible digital spectrometer allowing resolution & coverage for galactic and extragalactic astronomy
- Dual polarization is a possible option

Spectrometer for Heterodyne Array

New FPGA signal processing board (D. Hawkins, OVRO)

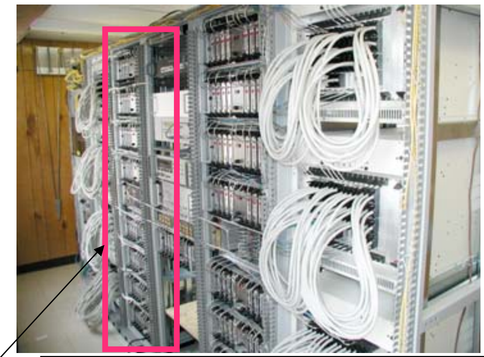
1 GHz bandwidth x 16k lags (~ 100 kHz resolution ⇔ 0.05 km/s)

70W max power

$10K/board today

SZA Correlator –

Next version: rack holds 90 boards



CCAT 64 pixel array spectrometer

Easily fits in 1 rack

Pwr < 4.5 kW

1 GHz BW/pixel

Cost is ~ $10K/pixel (2006)

Some Relevant Numbers for Large Format Heterodyne Camera (Placeholders; 2x SuperCam)

- 1m x 1m x 1m cryostat volume
- 200 kg cryostat weight
- 400 kg electronics weight
- 320 kg compressor weight
- 20 kW electrical power

Conclusion: Heterodyne Systems Can Make Important Contribution to CCAT Science

- Several different “flavors”
  - Facility large-format array
  - Lines of Opportunity special purpose
  - ALMA receiver for joint observations
- Need space, power, and support on Nasmyth plus possibly bent Cassegrain locations
- Spectrometer for array should be close to front end
- Minimal optics complexity, low maintenance
- System cost dropping dramatically due to submm technology and digital processing advances