Studying the Formation and Development of Molecular Clouds: with the CCAT Heterodyne Array Instrument (*CHAI*)

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on behalf of the *CHAI* consortium

How Do We Learn How Molecular Clouds Form and Evolve?

- Surveys of all different types provide basic data using different tracers
- Molecular clouds have structure over a very wide range of scales. Thus, “high resolution” surveys and studies of selected nearby clouds add critical information
- The combination of large-area and high resolution allows Increased spatial dynamic range, which in turn enables detection of new and perhaps critical morphology (e.g. filaments)
- Theoretical modeling has made major progress, and suggests that multiple forces are at work. Galactic-scale modeling also progressing – indicates that stellar feedback is required
- Models must strive to reproduce observed cloud structure at all scales
- Astrochemical observations are not unrelated to questions of cloud evolution and star formation but we are still learning how to use this capability

Is High Resolution Spectroscopy Necessary?

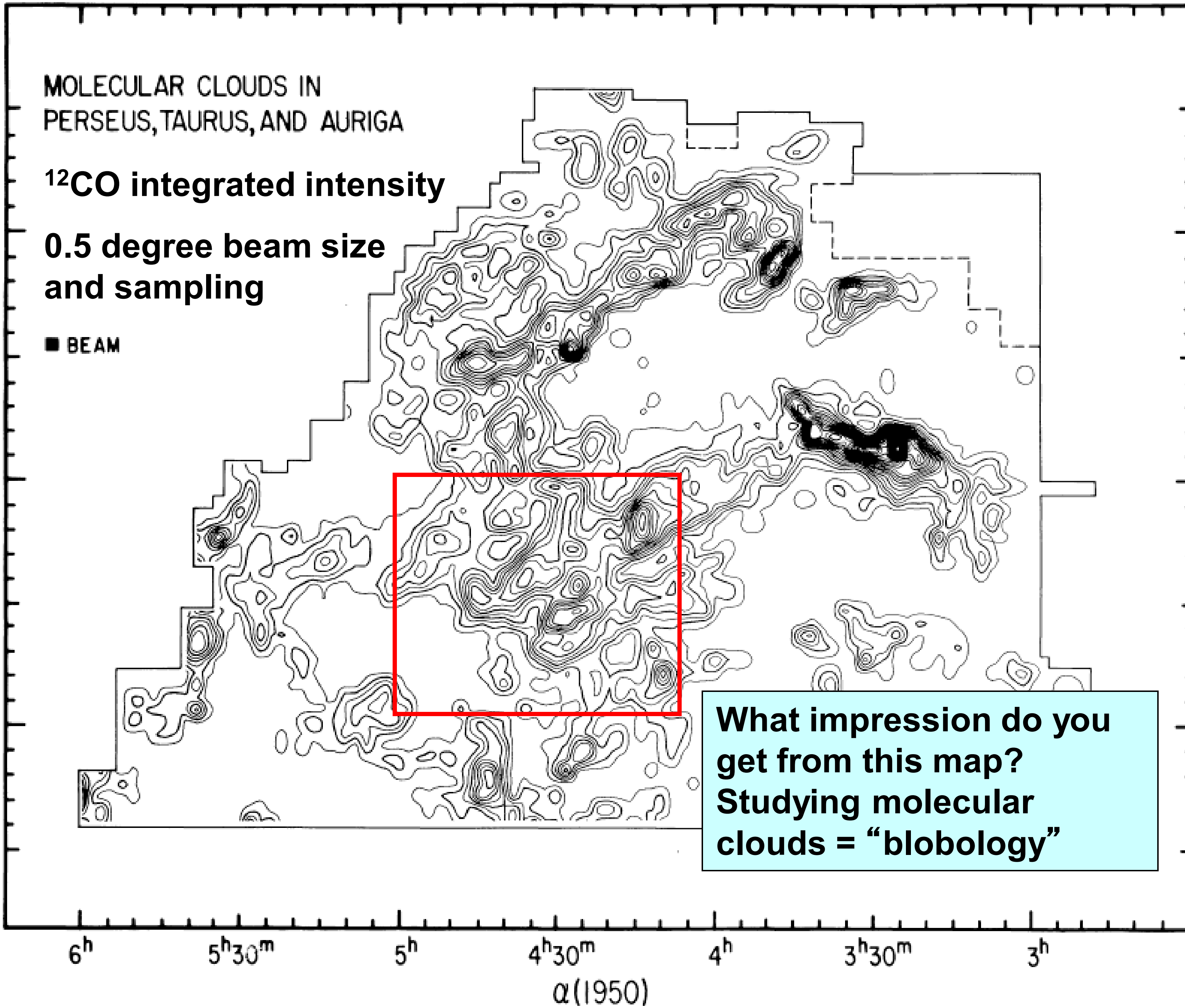
- The complexity of astrochemistry may suggest that we only use relatively invariant tracer, most plausibly dust continuum emission
- However, we may invert that argument to exploit astrochemical selectivity that enhances abundance of certain species in particular environments. Examples might include deuteration in cores, shock tracers, CII as probe of "CO-dark molecular gas"…
- Answering some of the most critical questions demands spectral lines to trace kinematics. Some of the include
  - Cloud virial balance
  - Formation of filaments
  - Accretion of material onto filaments
  - Flows of material within filaments including fragmentation into cores
  - Transition from turbulence to coherence in cloud cores
- All of these occur on scales that are readily probed by CCAT rather than ALMA, as they are typically extended over quite large areas

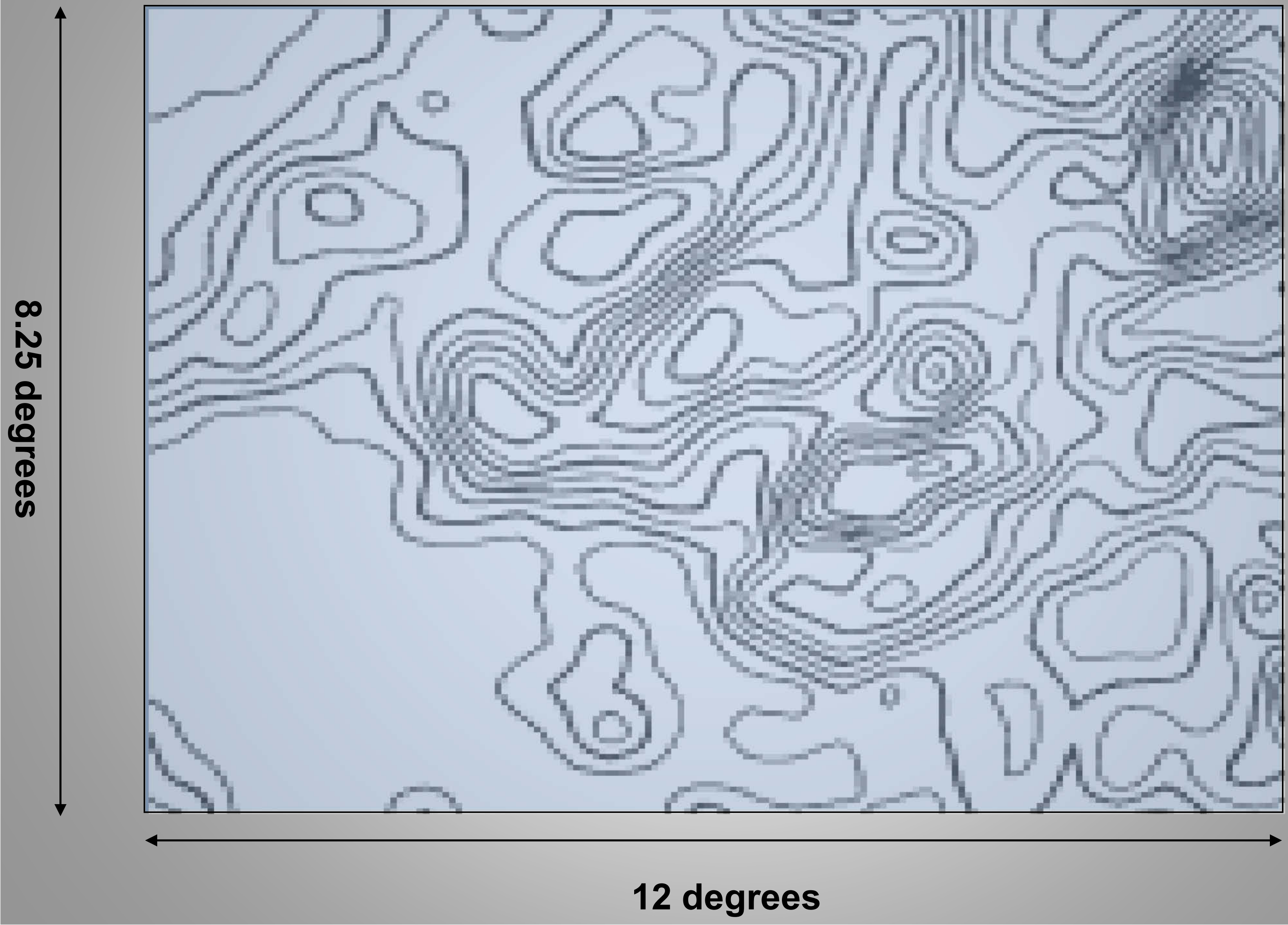
Probing the Evolution and Structure of Molecular Clouds will Require Large-area High-spectral Resolution Imaging

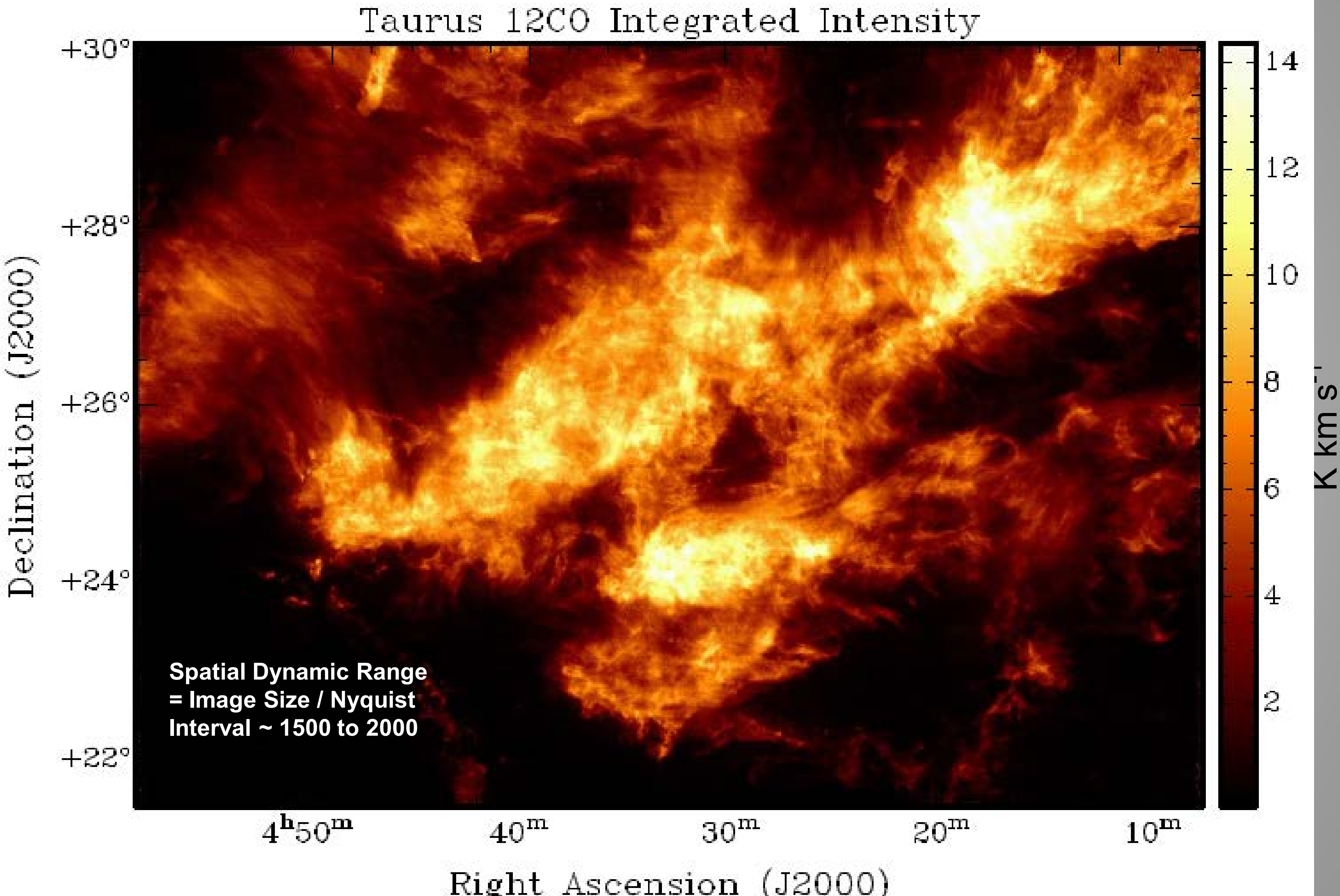
- Surveys will be important.
- What tracers will add the most value?

CCAT is allowing entry into a **new portion of discovery space** defined in terms of sensitivity X area coverage X frequency coverage X angular resolution X spectral resolution

We should be careful not to eliminate prematurely potentially valuable tracers. We need to combine results from simulations of the complex physics and chemistry with the information provided by various available data (ground based, Herschel, SOFIA …)


MOLECULAR CLOUDS IN
PERSEUS, TAURUS, AND AURIGA
12CO integrated intensity
0.5 degree beam size
and sampling
BEAM
45°
40°
35°
30°
25°
20°
15°
6h
5h30m
5h
4h30m
4h
3h30m
3h
α(1950)
What impression do you get from this map?
Studying molecular clouds = "blobology"


8.25 degrees
12 degrees



Taurus 12CO Integrated Intensity
+30°
+28°
+26°
+24°
+22°
Declination (J2000)
4h50m
40m
30m
20m
10m
Right Ascension (J2000)
14
12
10
8
6
4
2
K km s-1
Spatial Dynamic Range
= Image Size / Nyquist
Interval ~ 1500 to 2000

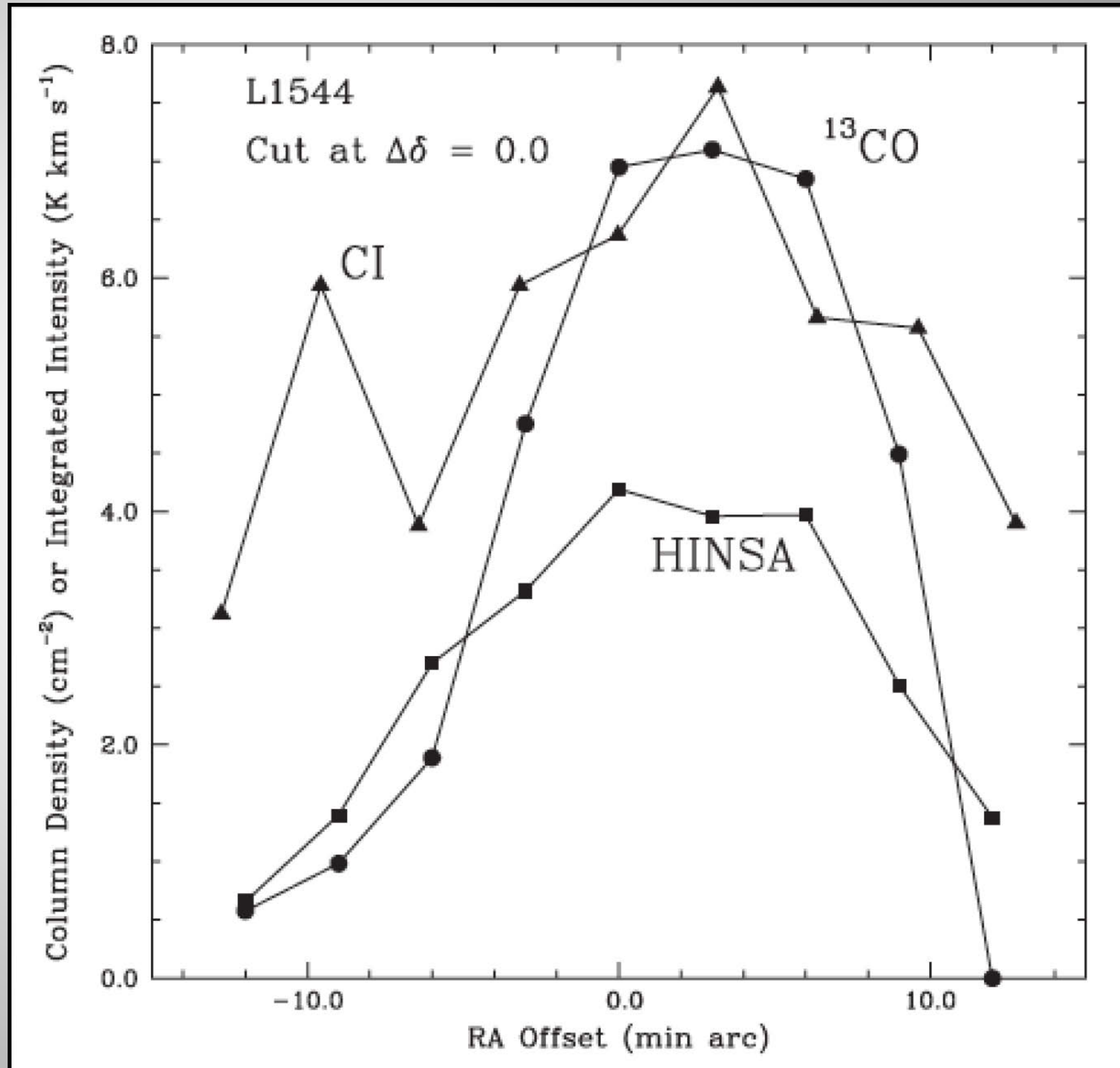
CI – The Cloud Chronometer (?)

CI is rarely observed in dark clouds, but such observations can provide valuable information about cloud structure AND possibly of cloud evolutionary state.

High sensitivity required!

CI observations shown here obtained with SWAS satellite and long integrations (Goldsmith & Li 2005).

CI more spatially extended than ^{13}CO and even than ^{12}CO.



Explaining the "Carbon Skin"

CI is formed by (1) recombination of C^+ [low A_v] and (2) photodissociation of CO [up to A_v ~ few]

For standard ISRF, the 'CI-layer' is located at $A_v \cong 1$

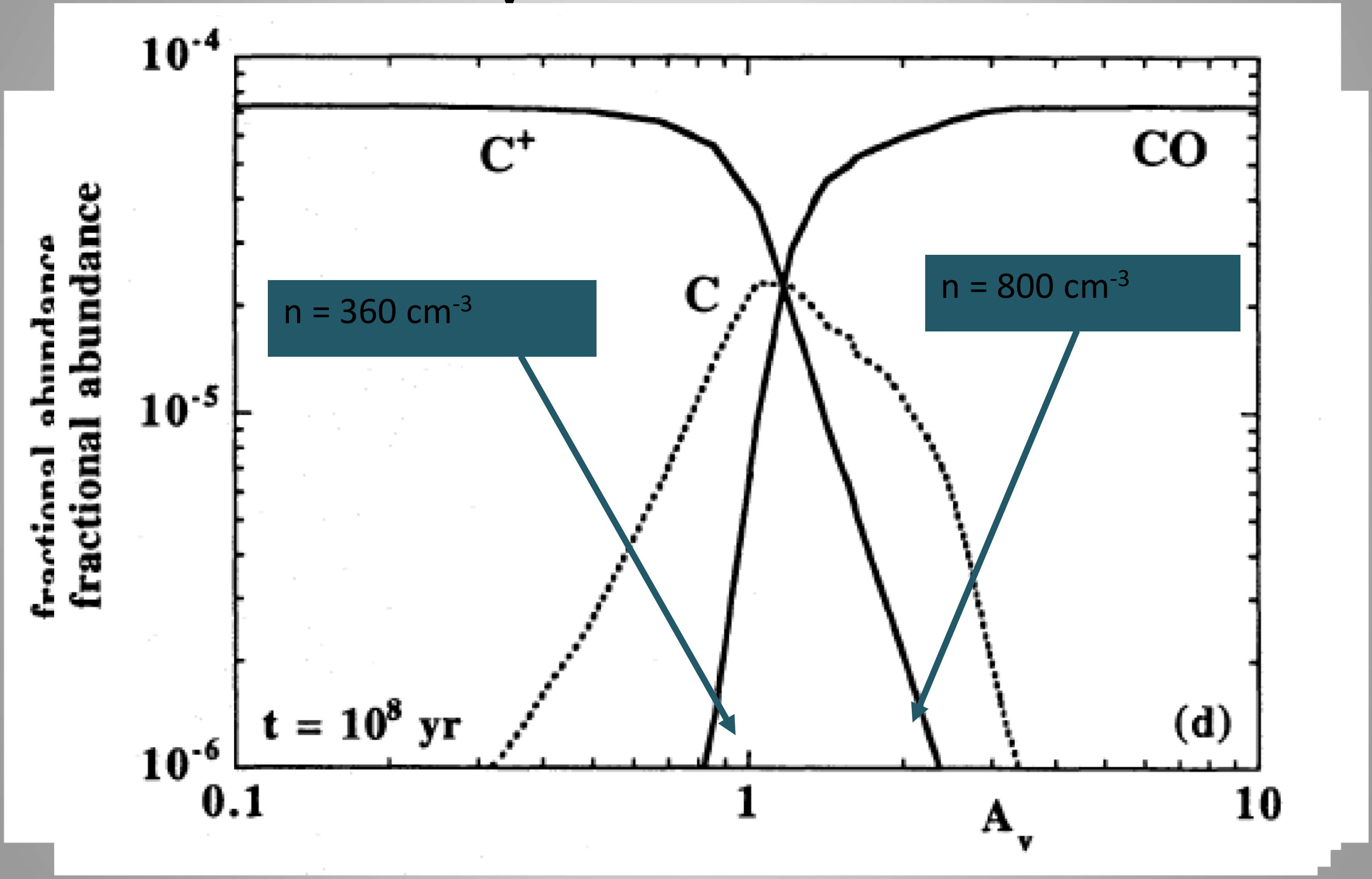
The density in this region is typically not large (~100 cm^{-3}) so that the timescale for the CI abundance to achieve its steady-state value is long.

Time-dependent model by Lee et al. (1996) treated a slab with uniform, time-independent temperature, but density profile

$n(A_v) = 10^2[1 + 9(A_v/A_{v\,max})]^2\ cm^{-3}$ for $0 \leq A_v \leq A_{v\,max} = 10$

External radiation field characterized by X = 1 incident from one side

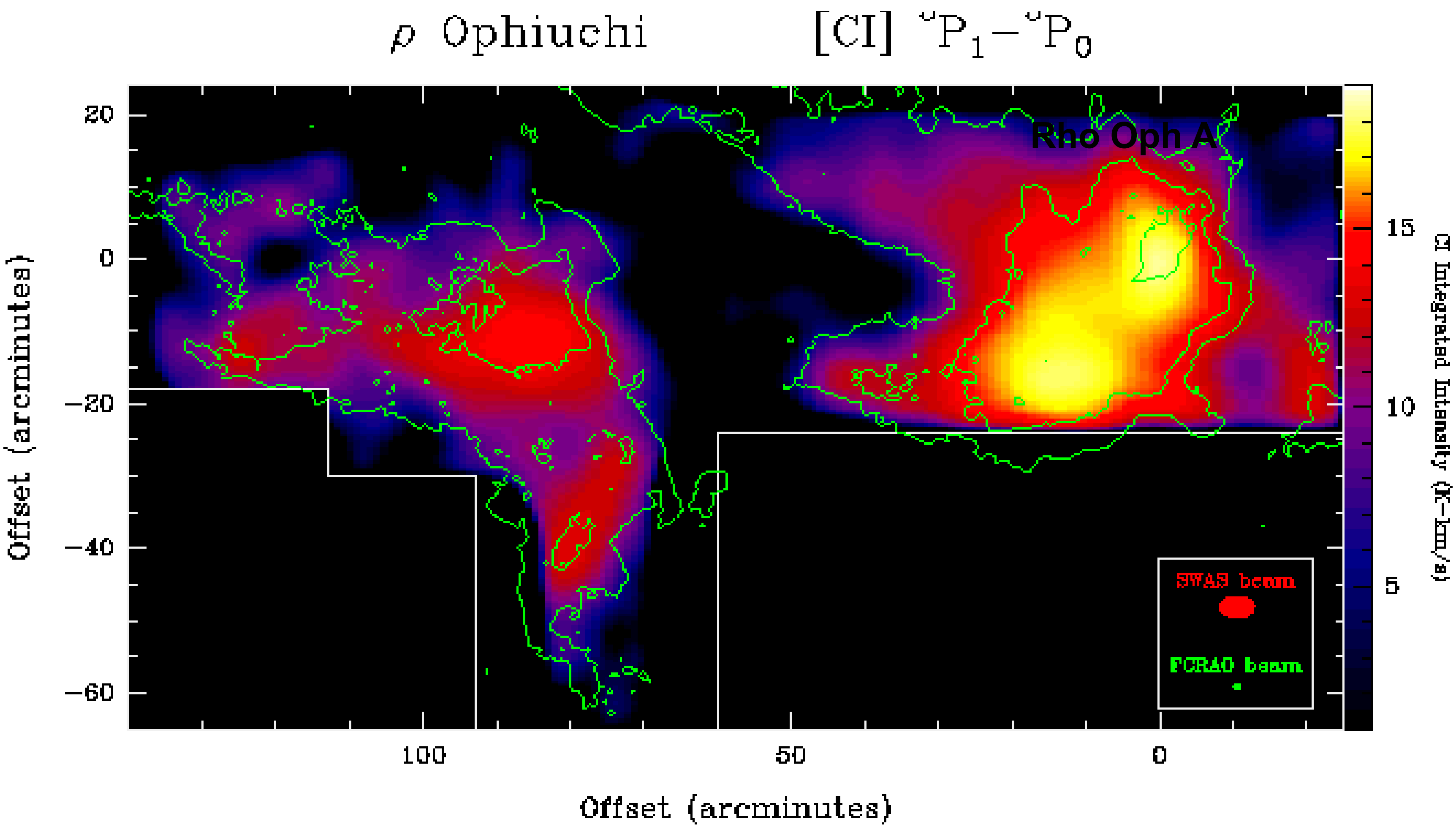
Cloud Composition as Function of A_v and Time



The Carbon Chronometer

- The amplitude (column density) and thickness of the CI layer are sensitive probes of cloud evolution.
- We need good information on the volume density to analyze excitation conditions of CI as well as of CII and CO. Ideally having both CI lines (492 GHz and 809 GHz) will give the most accurate results, but both are challenging from the ground. Only modest angular resolution required (L ~ 1 pc) but very good sensitivity (T_R = 1.6K for 492 GHz and 0.5 K for 809 GHz).
- The CI layer forms part of the **dark molecular gas** that is being probed by CII (Herschel OTKP "GOT-C+"), but it is very much more time-sensitive. The CI layer could thus be an powerful probe of cloud evolutionary state! The critical requirement is a good telescope on the right site.

CI $^3P_1$-$^3P_0$ in Rho Ophiuchi



Potential Cloud Evolution/Structure Tracers for CCAT

- **Medium-J CO** lines, e.g. J = 4-3, J = 6-5, J = 7-6
  - Lower lines possible, but probably not adding too much relative to IRAM, SMT, LMT
  - Some higher lines and isotopologues can be done (limited by atmosphere)
- **Both** CI fine structure lines (492 and 809 GHz)
- **Selected probes** – hydrides, deuterated hydrides, molecular ions (e.g. NH_2 at 460 GHz or H_2Cl^+ at 490 GHz)

WHAT IMAGING CAN WE DO?

$\Delta\Theta_{fwhm}$ = 6” at 492 GHz and 4” at 820 GHz

Time Requirement for Large-scale Survey Carried Out With On-the-Fly (OTF) Mapping

Assume we have a heterodyne array

T_s = average system temperature (SSB including atmosphere)

δf = channel width $\delta f(\mathrm{MHz}) = \delta v(\mathrm{km/s})/\lambda(\mathrm{mm})$

ΔT = rms per beam in reconstructed survey map (antenna temp.)

N_{pix} = # of pixels in the array

t_{int} = integration time per pointing of array

t_{surv} = time to carry out the survey

ε = OTF mapping efficiency (includes time for calibration, acceleration, slewing, reference position observations)

Ω_{surv} = solid angle of the survey

Ω_b = solid angle of the antenna beam = $1.13\theta_{fwhm}^2$

For single pointing we have usual radiometer equation

$\Delta T = T_{sys}/[\delta f\ t_{int}]^{0.5}$

Assume we carry out a large ($\Omega_{surv} >> \Omega_b$) survey with proper (Nyquist) sampling, but reconstruct the final image to angular resolution equal to Θ_{fwhm}

$$\Omega_{surv}/\Omega_b = N_{pix}\ t_{surv}\ \delta f\ (\Delta T/T_{sys})^2\ \varepsilon$$

It does not matter how your array pixels are distributed as long as you use them all in collecting the data

$$t_{surv} = (\Omega_{surv}/\Omega_b)(T_{sys}/\Delta T)^2/(\varepsilon\ \delta f\ N_{pix})$$

Some reasonable values for CCAT to image a **Galactic** source

$T_{sys} = 500$ K

$\delta f = 1$ MHz

$\varepsilon = 0.5$

$\Delta T = 0.1$ K (certainly arbitrary but plausible)

$$t_{surv} = (50/N_{pix})(\Omega_{surv}/\Omega_b)$$

(Galactic) $t_{surv} = (50/N_{pix})\ \Omega_{surv}/\Omega_b$

As an example, choose f = 809 GHz, λ = 0.371mm

Θ_{fwhm} = 3.67" = 0.061'

Ω_b = 0.0042'^{2}

For $\Omega_{surv} = 1^{o2} = 3600'^2$, $\Omega_{surv}/\Omega_b = 8.6\text{x}10^5$

$N_{pix}\ t_{surv} = 4.32\text{x}10^7$ s

Time vs. Pixel Number for 1^{o2} Galactic Survey	
N_{pix}	**T_{surv} (s)**
1	$4.32\text{x}10^7$
32	$1.4\text{x}10^6$
128	$3.4\text{x}10^5$ (94 hr)
512	$8.5\text{x}10^4$ (24 hr)

Nearby Galaxies are Important Targets of CCAT with Heterodyne Array: Example - NGC 6946 (D = 3 Mpc)

(A difficult challenge because you cannot observe it from Chile)

140 CCAT beams at 690 GHz

$t_{surv} = (\Omega_{surv}/\Omega_b)(T_{sys}/\Delta T)^2/(\varepsilon\, \delta f\, N_{pix})$

4.3 km/s ⇔ 10 MHz

Ts = 500 K

$\Delta T = 0.01$ K

$\Omega_{surv} = 100'^2$

$\Delta\Theta = 4.3'' = 0.072'$ $\Omega_b = 5.8\text{x}10^{-3}\ '^2$

$t_{surv} = 500\ (\Omega_{surv}/\Omega_b) = 8.5\text{x}10^6/N_{pix}$

Time vs. Pixel Number for Extragalactic Image	
N_{pix}	T_{surv} (s)
1	$8.5\text{x}10^6$
32	$2.7\text{x}10^5$
128	$6.6\text{x}10^4$ (18 hr)
512	$1.7\text{x}10^4$ (4.6 hr)

Heterodyne Survey Synopsis

A 128 pixel heterodyne array with 500 K SSB system noise temperature would allow

1 sq.degree Galactic source image in 94 hr

50 sq. degree Galactic plane survey in 4700 hr

1 sq. degree extragalactic image in 18 hr

Survey of 50 nearby galaxies in 900 hr

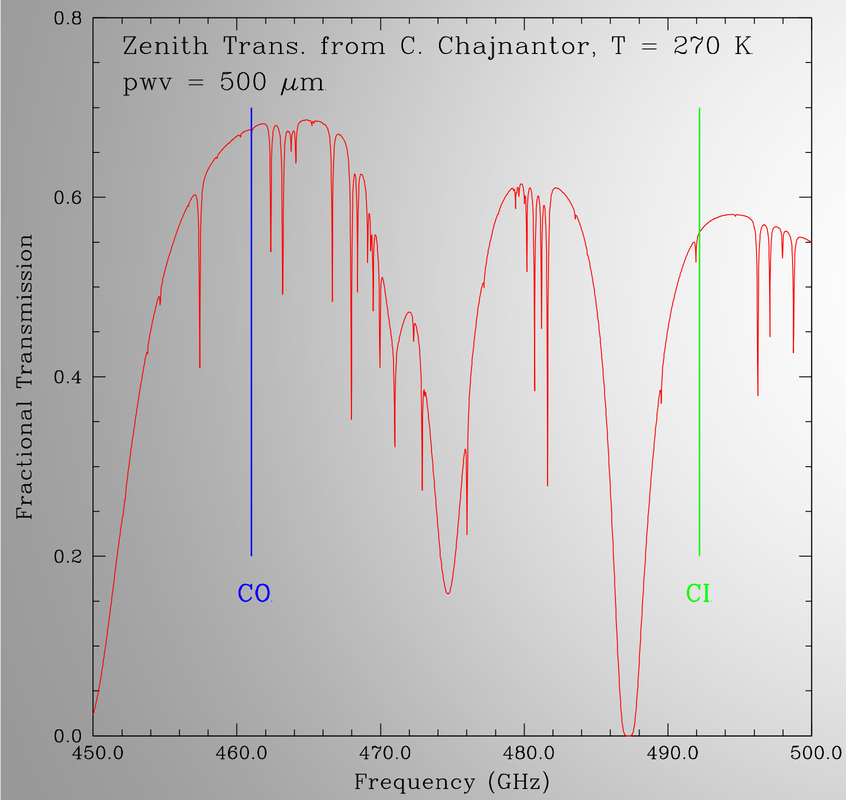
Pick your tracer and source and go for it!

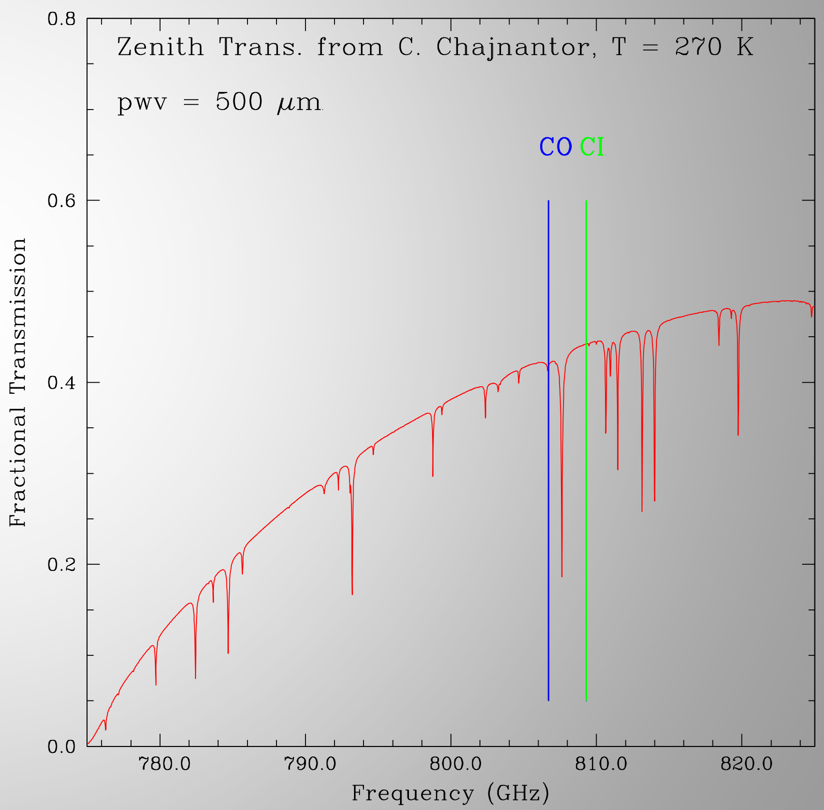
Candidate Spectral Lines of CO and [CI] for CCAT

Frequencies of Transitions of CO and Isotopologues for CCAT at ≤ 1 THz (GHz)			
Transition	**CO**	**^{13}CO**	**$C^{18}O$**
4 – 3	461.0	440.8	439.1
5 – 4	576.3	550.9	548.8
6 – 5	691.5	666.1	658.6
7 – 6	806.7	771.2	766.3
8 – 7	921.8	881.3	877.9
9 – 8	1036.9	991.3	987.6

Frequencies of [CI] Transitions (GHz) (Fractional Strength)				
Transition	**[CI]**	**[^{13}CI] F=3/2–1/2**	**[^{13}CI] F=5/2 –3/2**	**[^{13}CI] F=3/2 – 3/2**
$^3P_1 - {}^3P_0$	492.162 3/2-1/2 and 1/2-1/2 separated by only ~4 MHz Klein+ 1998			
$^3P_2 - {}^3P_1$	809.342	809.126 (0.333)	809.494 (0.600)	809.121 (0.067)

Atmospheric Transmission for Two Key CHAI Bands





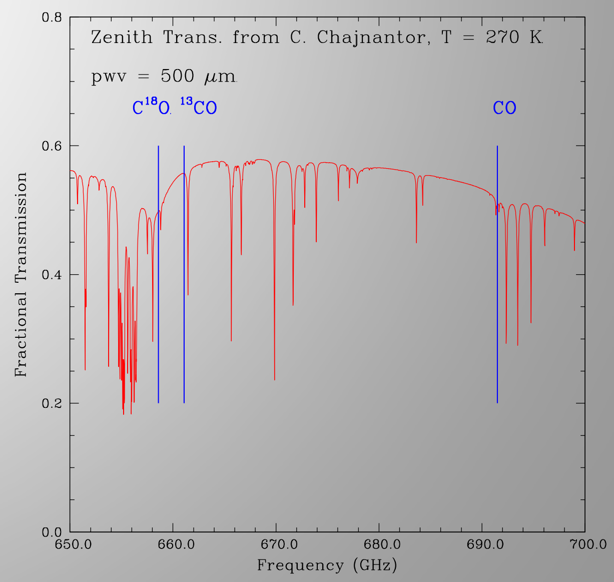
CHAI Baseline Conceptual Design

- **Cover 490 GHz and 810 GHz CI lines using two separate receiver arrays which can operate simultaneously (609 µ and 370 µm)**
- **The HDO 1_{10}-1_{01} line at 509 GHz** (of great interest for solar system/comet work) is covered by the low frequency mixer bandwidth of the **goal** design, and likely of the baseline design
- **$^{13}CH^{+}$ at 835 GHz** is covered by the goal specification or, if not reached, with an additional LO (the mixers are sufficiently wide-band).

EXTENSIONS/UPGRADES

Coverage in the 800 to 880 GHz window to include the upper half, in particular **^{13}CO** 8-7 at 881 GHz.

The third atmospheric window (660 GHz) can be covered by a future upgrade (LO and mixer **array**) with a design very similar to the present frequency bands.

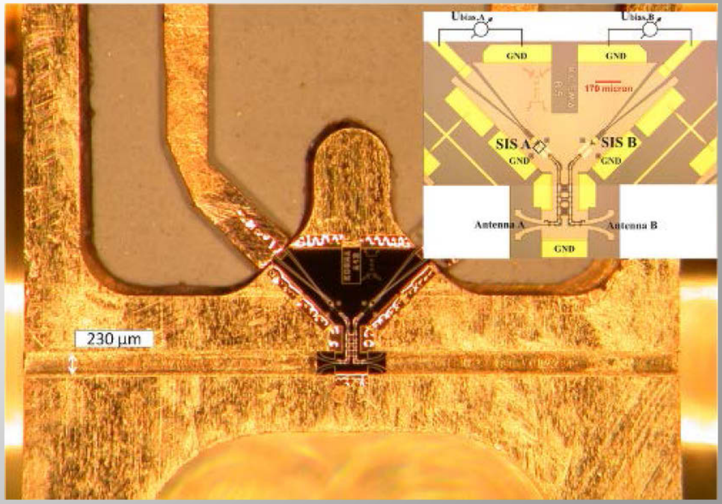


CHAI Mixers: Technical Approach

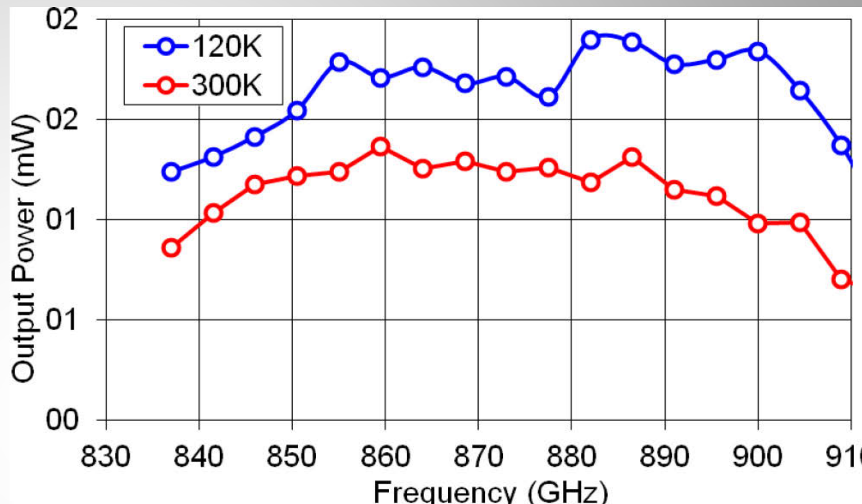
- Use well-proven SIS mixers which have very good reproducibility and reliability. Used for example, in Herschel HIFI with the exception of Band 6.
- Use frequency-multiplied LO source for wide tunability and spectral purity (again with Herschel HIFI heritage).
- Developments at JPL now allow pumping 100 element array throughout CHAI range.
- SIS mixers have advantage of being relatively insensitive to LO power variation (compared to HEB mixers) and can have wide IF bandwidths.

  (U. Graaf, K. Jacobs, N. Honingh KOSMA + J. Kawamura JPL + J. Kooi, Caltech)

Developments will focus on
Packaging multiple mixers, IF, and LO distribution
Improving IF match (avoid isolators)
Maximizing tuning bandwidth
Evaluating use of balanced mixers (reduce LO power requirement and ease LO injection system complexity

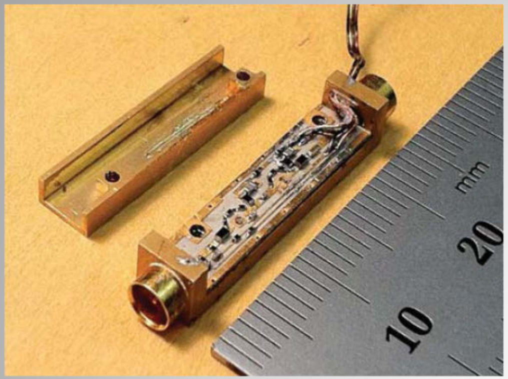


JPL Frequency-Multiplied Local Oscillator Sources



(Left) A JPL fabricated 840-900 GHz tripler chip installed between two waveguides (output waveguide on left; input waveguide on right). (Right) The plot shows measured output power at room temperature and at 120K from a x2x3 LO chain. Waveguide power combining is utilized to increase output power. More than 1 mW of power is thus readily obtainable at both CHAI bands (I. Mehdi, J. Pearson, JPL)

IF Amplifiers



Miniaturized packaging of cryogenic SiGe LNA developed at Caltech. This is an experimental two-stage amplifier packaged to fit within a 5mm footprint with GPO push-on connectors.

An important task is to reduce power consumption and optimize input match, while maintaining noise temperature of few K. (S. Weinreb, Caltech)

Feedhorns

High efficiency beams with reasonable packing efficiency over moderate bandwidths
Scalar feedhorns are possible, but relatively expensive
We are investigating tapered smooth-walled horns which can be directly machined at low cost, and which offer performance comparable to that of scalar horns.
Want every-other beam sampling on the sky
(G. Cortes, Cornell Univ.)

CHAI "Backend" Spectrometer System

Digital signal processing developments make it possible to exploit the output of hundreds of CHAI pixels

Current baseline design (which may well evolve) – use already-developed boards each with 8 Xilinx FPGAs. Each board handles 4 pixels x 4 GHz (1500 km/s @ CI 810 GHz)

Power consumption with today's FPGAs will be 90W/pixel or ~20 kW total. This will be a factor of 2 to 4 times less by the time CHAI hardware is procured.

Current plan based on work done by DRAO (Canada) and will be implemented by Canadian team members.

CHAI Software

Critical observing mode will be "on the fly" mapping to image large regions.
Deeper integrations achieved by multiple repeats
Major advantage is that each direction in sky is observed by multiple array pixels
(J. Stutzki, V. Ossenkopf KOSMA; J. Carpenter, Caltech)

CHAI Offers Major New Astronomy Capability

High resolution velocity-resolved spectral line images of the two CI fine structure transitions and mid-J CO lines in Milky Way and external galaxies

Probe of formation and evolution of molecular clouds, which may well be the rate-limiting step in star formation

Many other spectral lines available for astrochemical and comet and solar system studies

Very modest technical risk with extremely good synergy among consortium members

CHAI Consortium Members
- KOSMA
- Caltech/JPL
- Cornell
- Canada