ALMA and CCAT

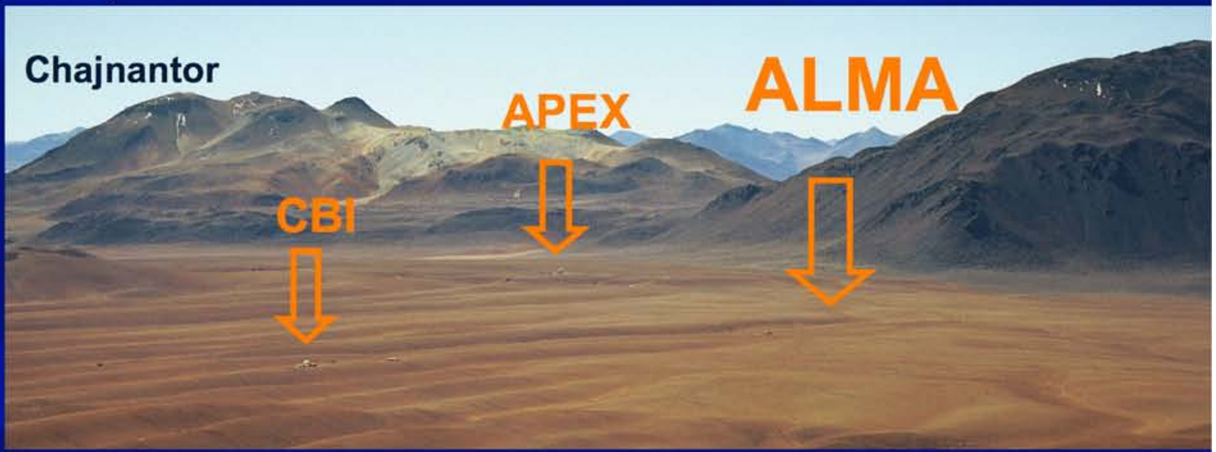
Crystal Brogan

(NRAO/North American ALMA Science Center)

Spectroscopy with CCAT , Boulder, CO May 13, 2008

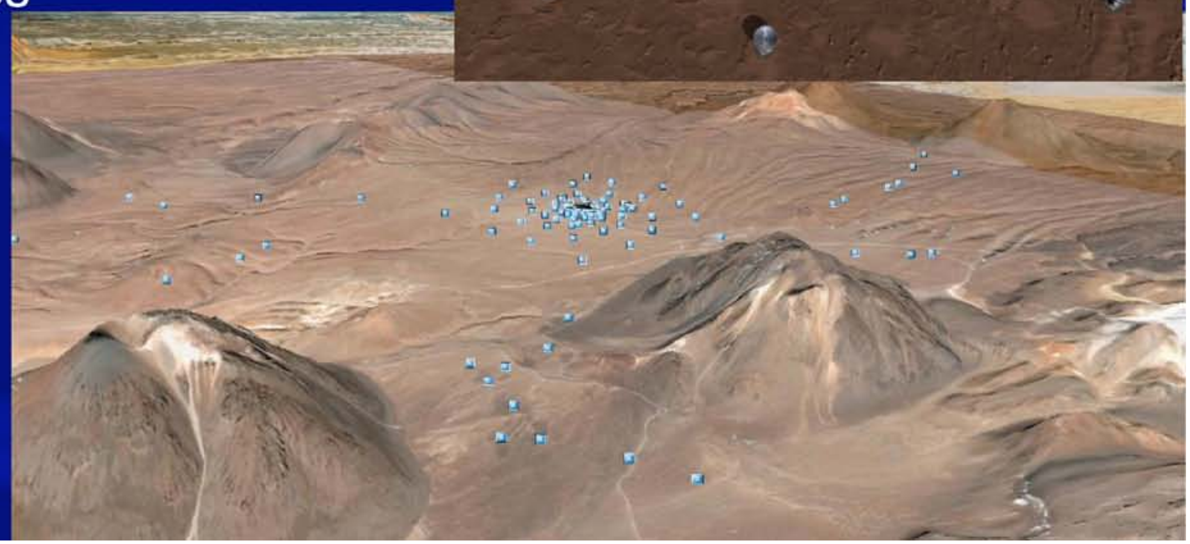
What is ALMA?

- A global partnership to deliver a transformational millimeter/submillimeter instrument
  - North America (US, Canada)
  - Europe (ESO)
  - East Asia (Japan,Taiwan)
- 5000m (16,500 Ft) site in Chilean Atacama desert
- Main Array: 50 x 12m antennas (up to 64 antennas)
  - + 4 x 12m (total power)
  - + ACA: compact array of 12 x 7m antennas
- Total cost ~1.3 Billion ($US)



ALMA

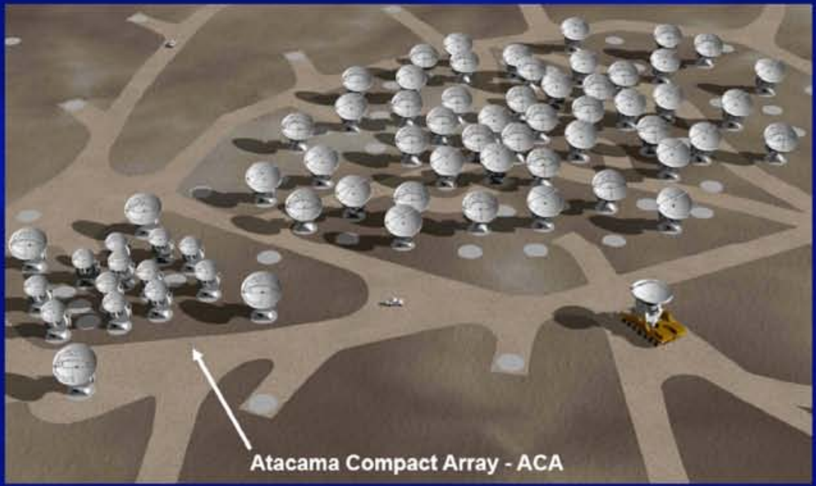
- Baselines up to 15 km (0.015" at 300 GHz) in "zoom lens" configurations
- Sensitive, precision imaging between 30 to 950 GHz (10 mm to 350 μm)
- Receivers: low-noise, wide-band (8 GHz)
- Flexible correlator with high spectral resolution at wide bandwidth
- Full polarization capabilities
- A resource for ALL astronomers including pipeline products and regional science centers



Existing and future mm/sub-mm arrays

Telescope	altitude (feet)	diam. (m)	No. dishes	A (m^2)	ν_{max} (GHz)
NMA	2,000	10	6	470	250
CARMA	7,300	3.5/6/10	23	800	250
IRAM PdBI	8,000	15	6	1060	250
SMA	13,600	6	8	230	690
eSMA	13,600	6/10/15	10	490	690
ALMA	16,400	12	50	5700	950
ACA	16,400	7	12	460	950
CCAT	18,000	25	1	490	1500

ALMA will have 10-100 times more sensitive and 10-100 times better angular resolution compared to current mm/submm telescopes



Receivers/Front Ends

ALMA Band	Frequency Range	Receiver noise temp: T_{Rx} over 80% of the RF band	Receiver noise temp: T_{Rx} at any RF frequency	Mixing scheme	Receiver technology
1	31.3 – 45 GHz	17 K	28 K	USB	HEMT
2	67 – 90 GHz	30 K	50 K	LSB	HEMT
3	84 – 116 GHz	37 K	62 K	2SB	SIS
4	125 – 163 GHz	51 K	85 K	2SB	SIS
5	163 - 211 GHz	65 K	108 K	2SB	SIS
6	211 – 275 GHz	83 K	138 K	2SB	SIS
7	275 – 373 GHz	147 K	221 K	2SB	SIS
8	385 – 500 GHz	98 K	147 K	2SB	SIS
9	602 – 720 GHz	175 K	263 K	DSB	SIS
10	787 – 950 GHz	230 K	345 K	DSB	SIS

Dual, linear polarization channels:
- Increased sensitivity
- Measurement of 4 Stokes parameters

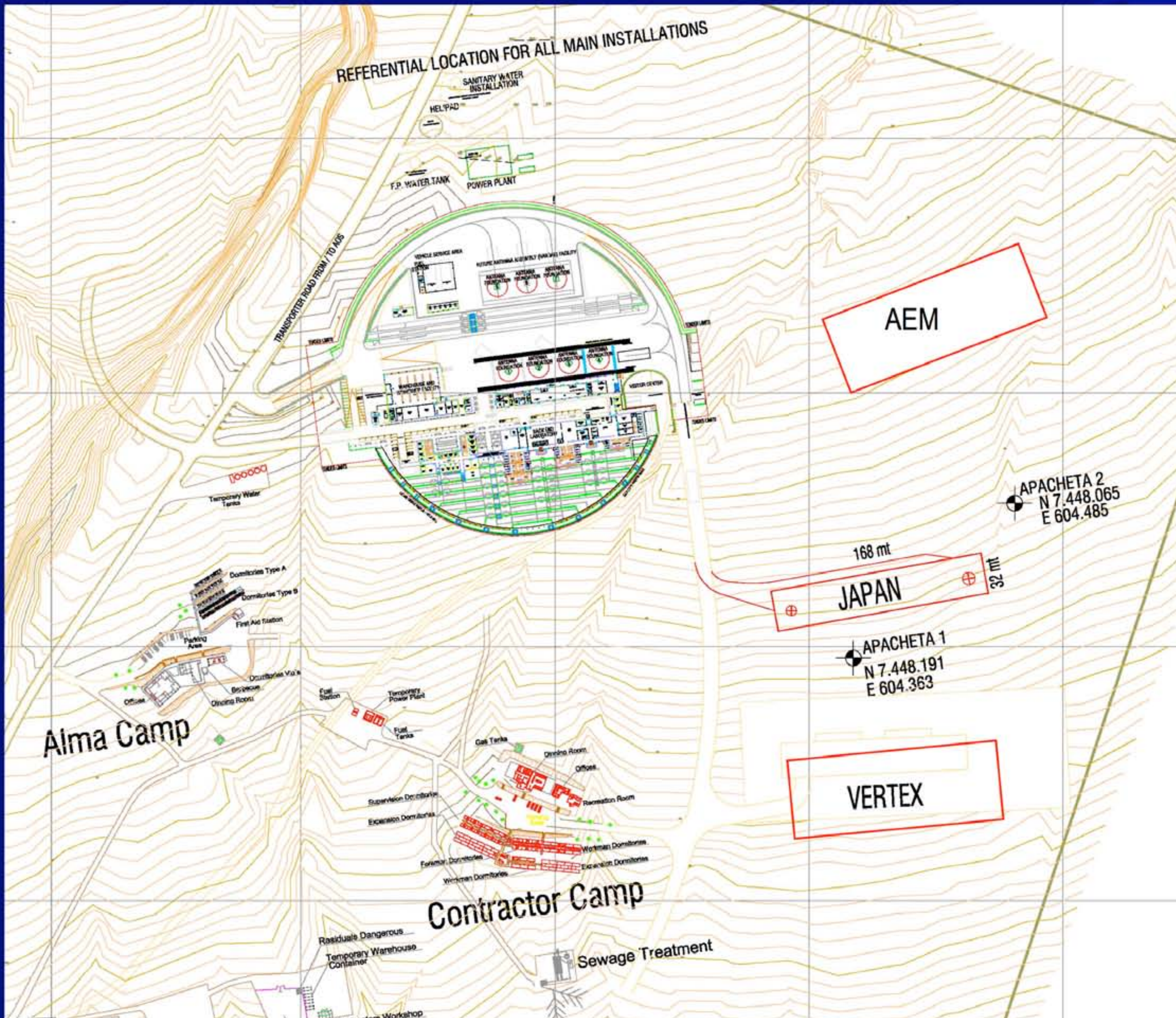
183 GHz water vapour radiometer:
- Used for atmospheric path length correction

AOS (High Site) Completed

Houses the ALMA and ACA correlators

ACA correlator being installed at AOS

OSF (mid-level) Construction Completed



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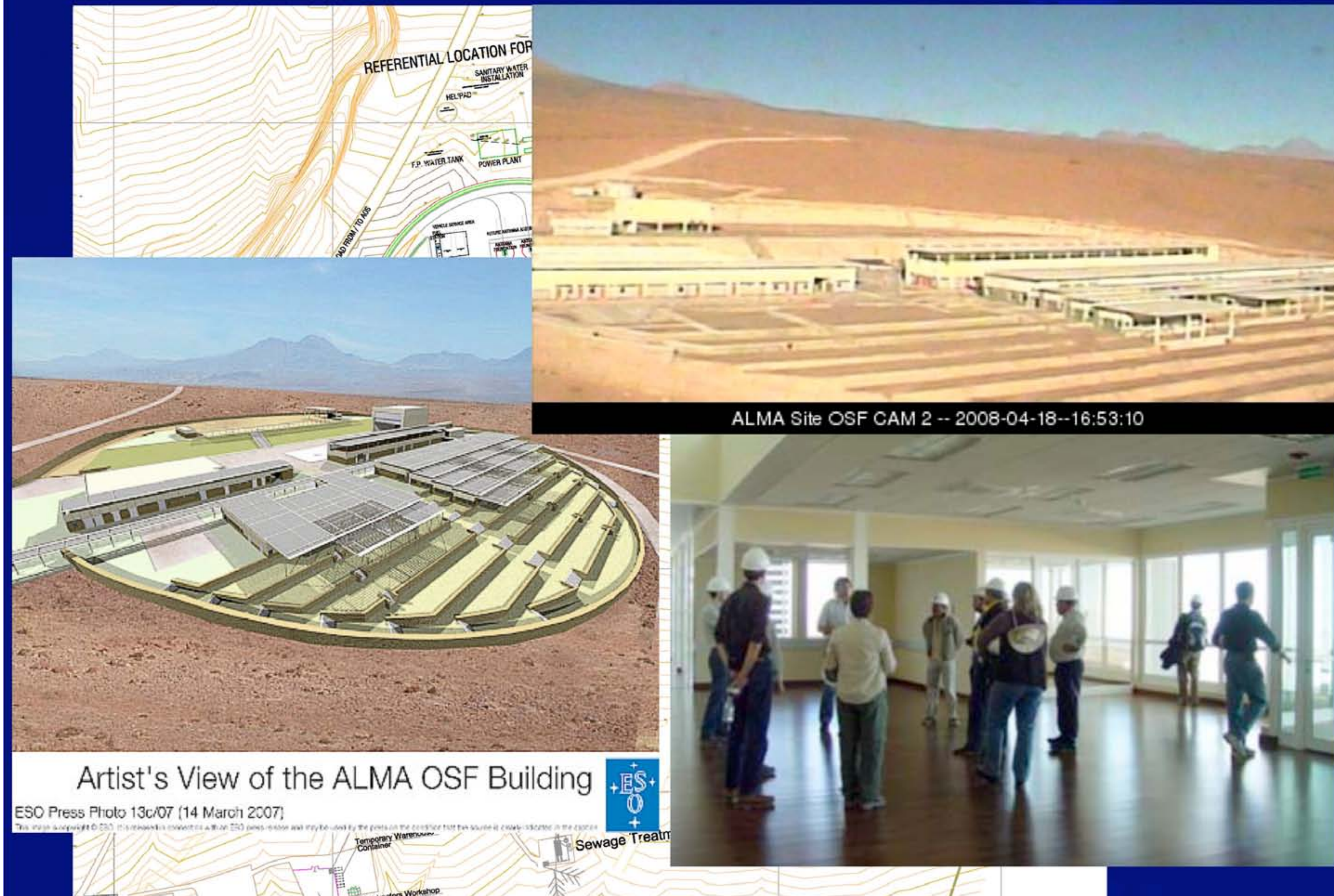
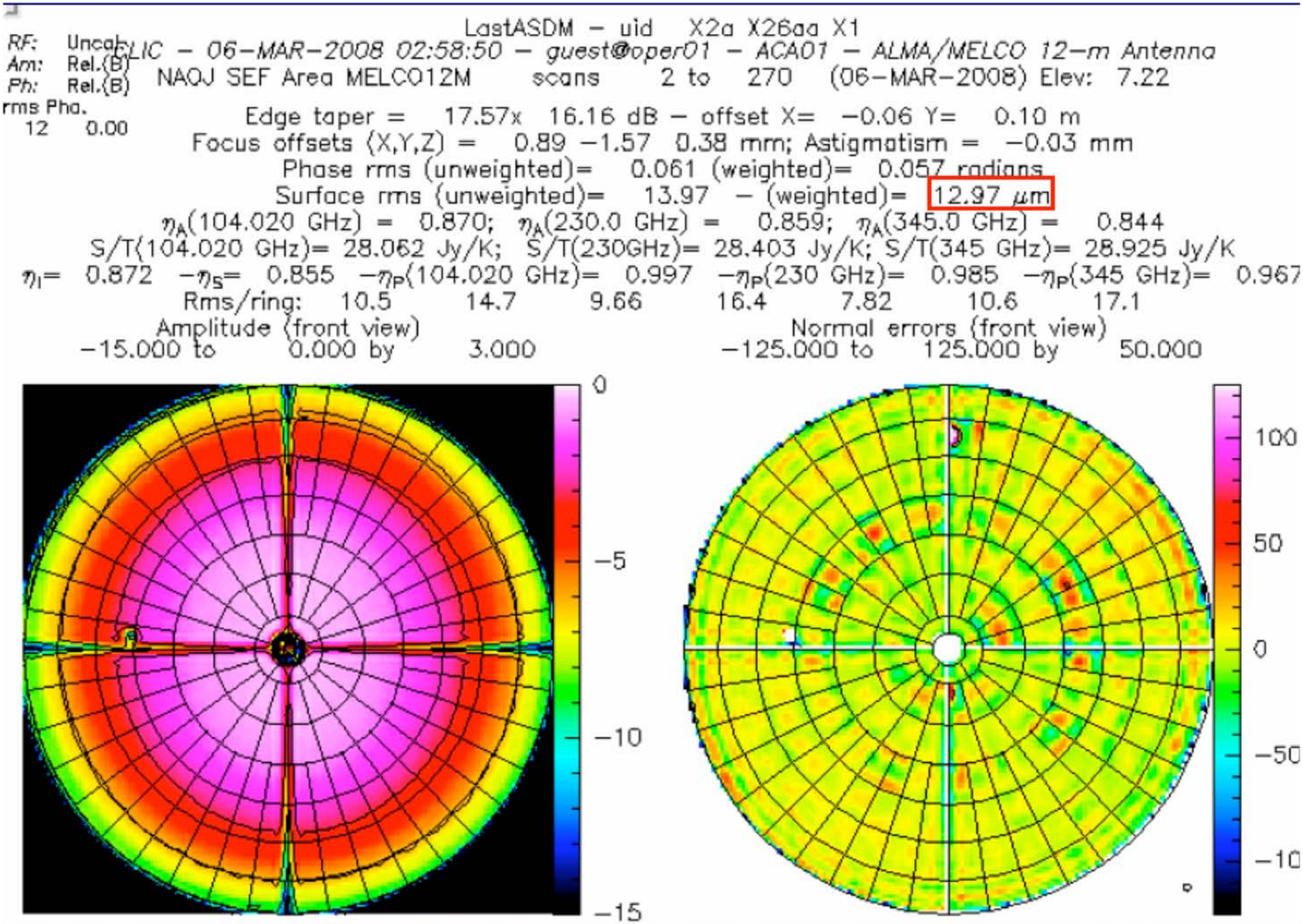


Hardware arriving in Chile

1st quadrant of ALMA correlator

- Surfaces better than 15 μm!
- Pointing accuracy 2” absolute, 0.6” offset
- Fast switching (1.5 deg in 1.5 sec)
- Currently 4 Vertex and all 4 Melco 12m (ACA)


LastASDM - uid X2a X26aa X1
RF: Uncal.
Am: Rel.(B)
Ph: Rel.(B)
CLIC - 06-MAR-2008 02:58:50 - guest@oper01 - ACA01 - ALMA/MELCO 12-m Antenna
NAOJ SEF Area MELCO12M scans 2 to 270 (06-MAR-2008) Elev: 7.22
rms Pha.
12 0.00
Edge taper = 17.57x 16.16 dB - offset X= -0.06 Y= 0.10 m
Focus offsets (X,Y,Z) = 0.89 -1.57 0.38 mm; Astigmatism = -0.03 mm
Phase rms (unweighted)= 0.061 (weighted)= 0.057 radians
Surface rms (unweighted)= 13.97 - (weighted)= 12.97 μm
ηA(104.020 GHz) = 0.870; ηA(230.0 GHz) = 0.859; ηA(345.0 GHz) = 0.844
S/T(104.020 GHz)= 28.062 Jy/K; S/T(230GHz)= 28.403 Jy/K; S/T(345 GHz)= 28.925 Jy/K
ηI= 0.872 -ηS= 0.855 -ηP(104.020 GHz)= 0.997 -ηP(230 GHz)= 0.985 -ηP(345 GHz)= 0.967
Rms/ring: 10.5 14.7 9.66 16.4 7.82 10.6 17.1
Amplitude (front view)
-15.000 to 0.000 by 3.000
Normal errors (front view)
-125.000 to 125.000 by 50.000
0
-5
-10
-15
100
50
0
-50
-10

Current Projected Timeline

Mid 2008	Testing at ATF continues
Fall 2008	Commissioning Begins at OSF
Mid 2009	Commissioning Begins with 3-element array
Mid 2010	Call for Early Science Proposals
	* 24+ antennas, 2+ bands, continuum & spectral line, 1km baselines
Early 2011	Start Early Science
	* Off line data reduction
Mid 2012	Pipeline images for standard modes
End 2012	Baseline ALMA Construction Complete

Highest Level-1 Science Drivers

Bilateral Agreement Annex B:

- 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), 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 detect spectral line emission from CO or CII in a normal galaxy like the Milky Way at a redshift of z = 3, in less than 24 hours of observation.

- 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.

These goals drive the technical specifications of ALMA.

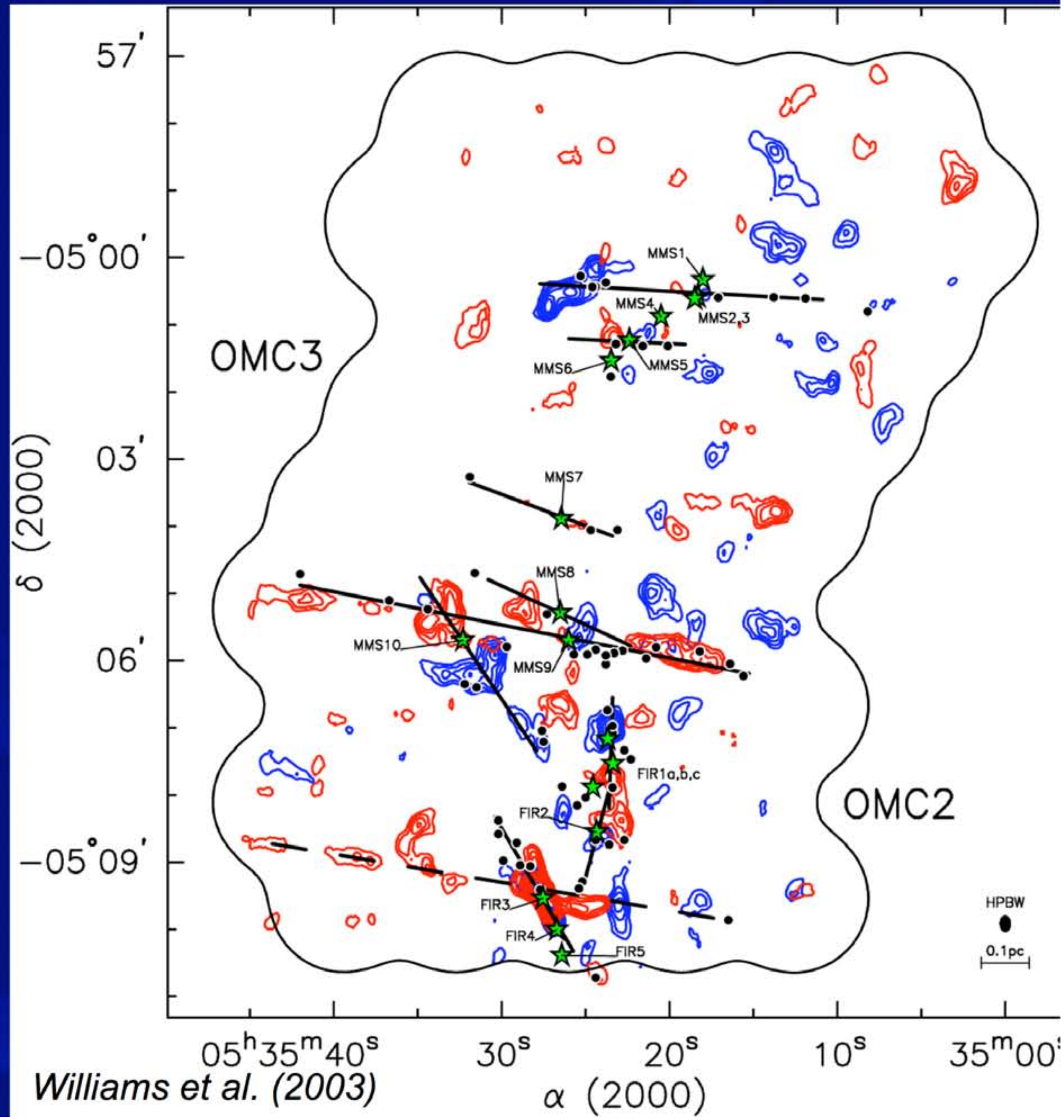
Galactic Star Formation

BIMA 46 pointing mosaic covering 10' x 15'

CO(1-0) at ~ 3mm

~10" resolution

O ALMA 0.85mm PB

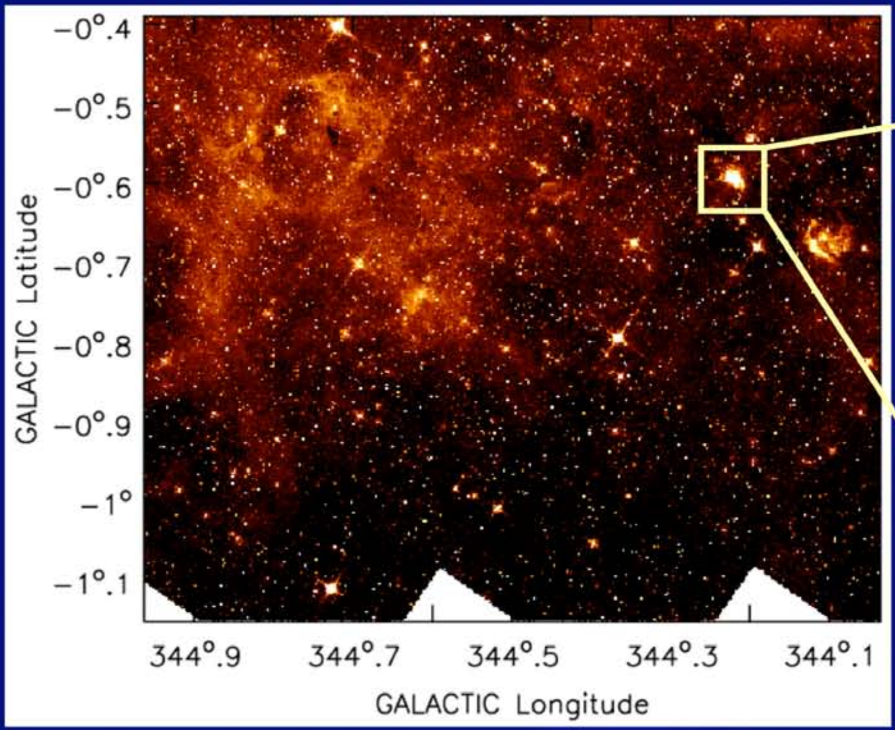


Williams et al. (2003)

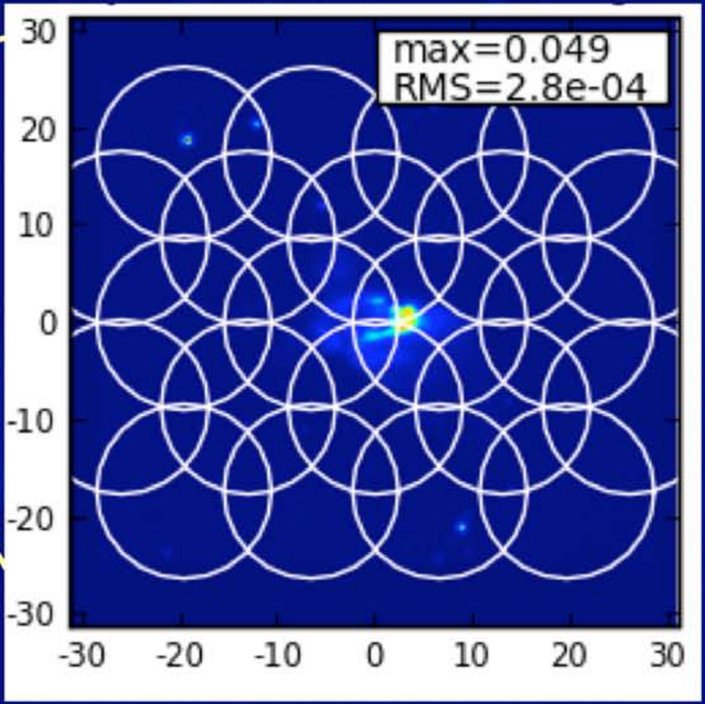
Challenges for mosaicing

- ❖ Image sources larger than the primary beam (PB)
  - at 1mm a 12m dish has PB~21"
    - ⇨ Mosaic, on-the-fly mapping
- ❖ Image sources with structure larger than the largest angular scale
  - Shortest baseline =15m, LAS ~14" at 1mm
    - ⇨ Add total power from single dish
- ❖ Accurate continuum images in presence of copious line emission
    - ⇨ Spectral line mode all the time
- ❖ Sensitive linearly polarized feeds
  - Many quasars are linearly polarized
    - ⇨ Full polarization calibration always
- ❖ Single dish sensitivity often limited by 1/f noise.

CASA Simulation of ALMA Observation



Spitzer GLIMPSE 5.8 μm image



- 50 x 12m antennas in the compact configuration: beam ~1"
- 0.85 mm 38 pointing mosaic
- observing time +/- 1 hrs from transit

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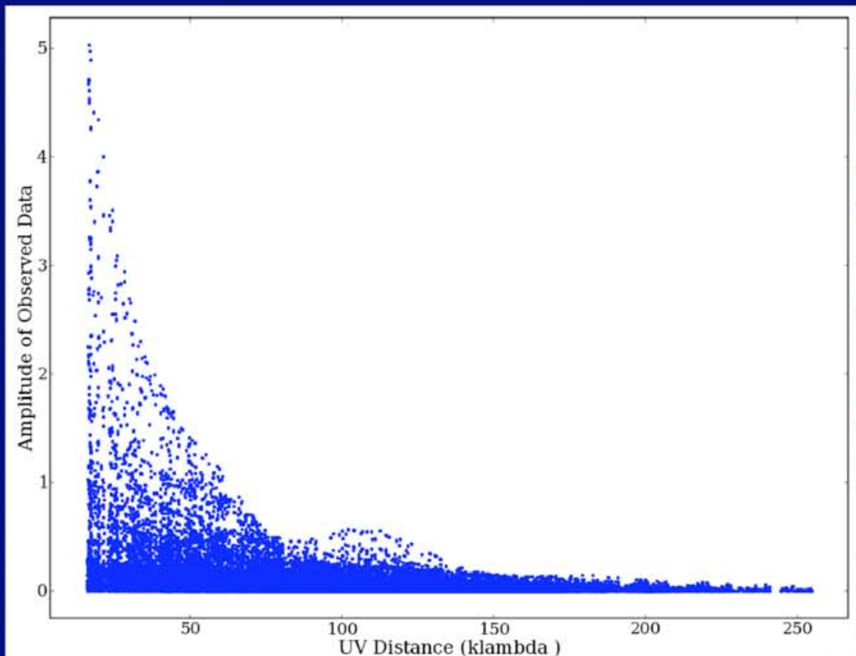

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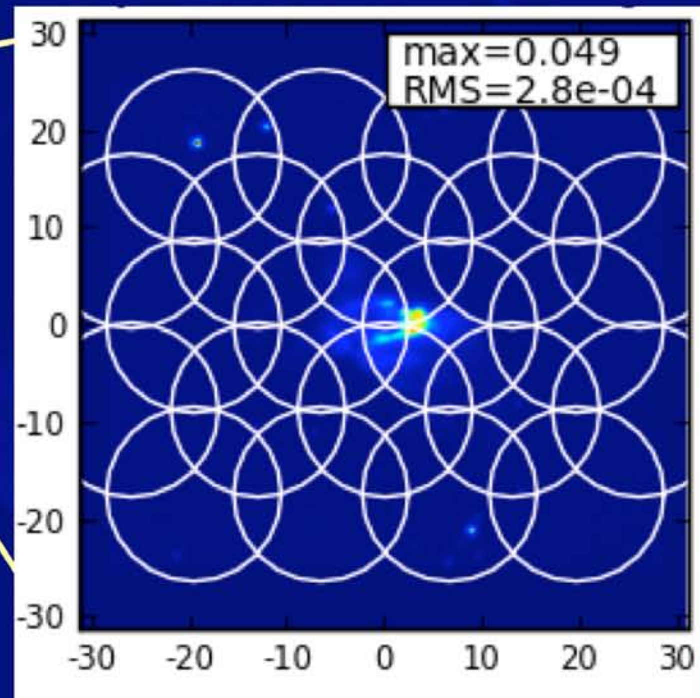

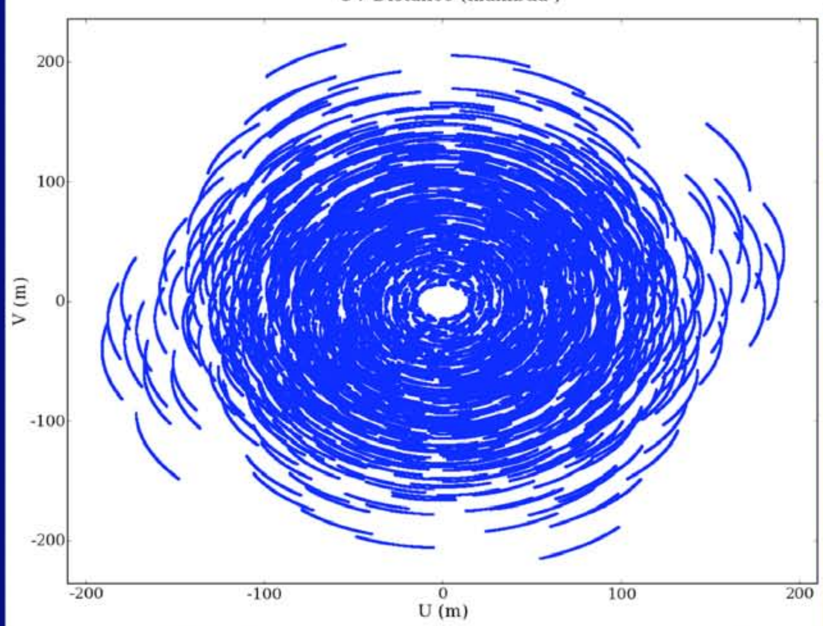

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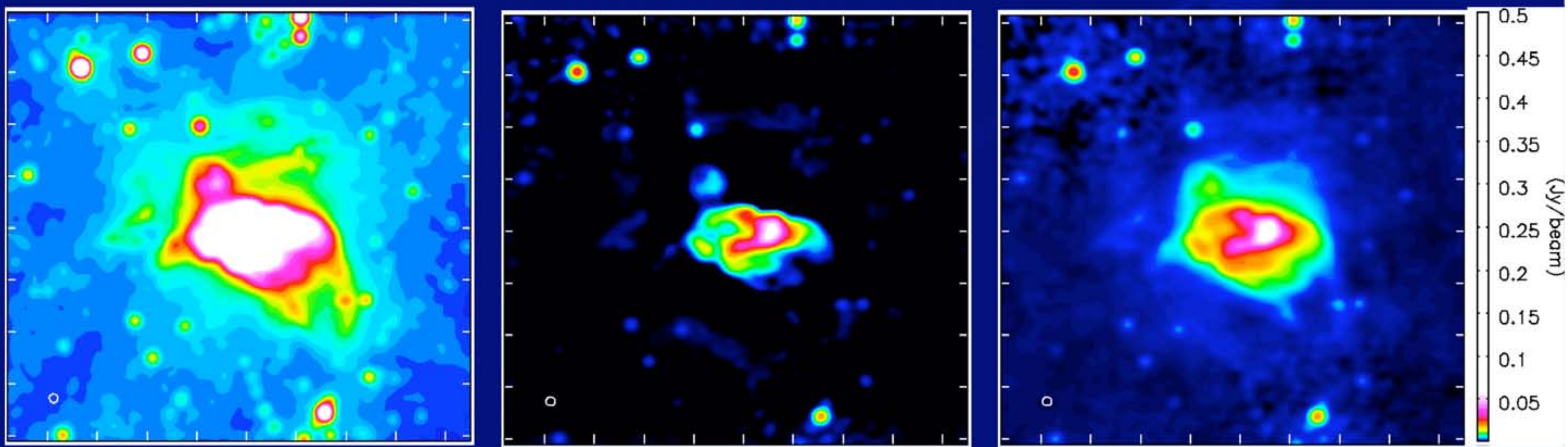
CASA Simulation Results



Model

ALMA

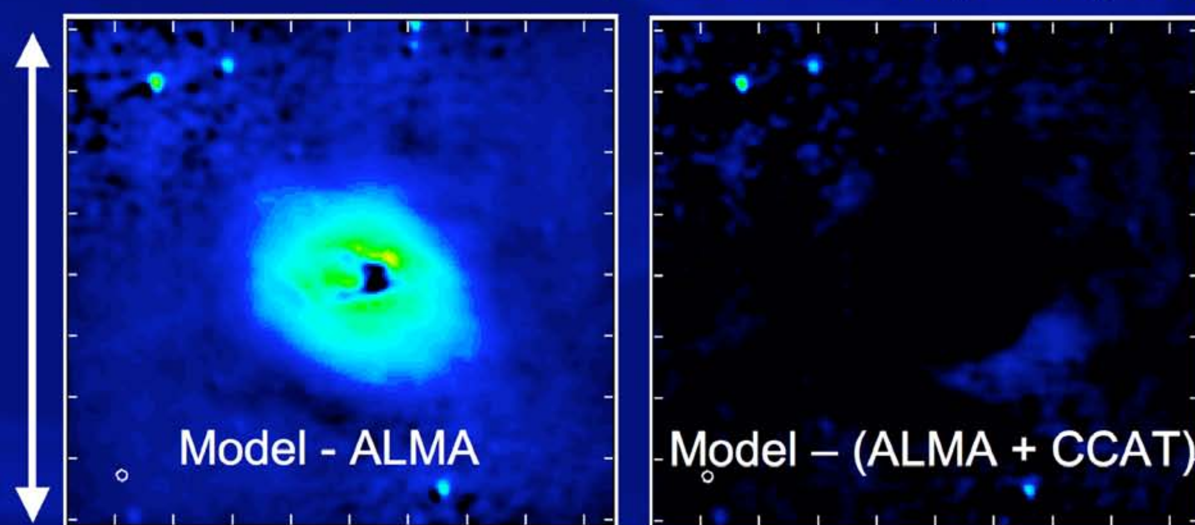
ALMA + CCAT

(This can probably be better with true joint deconvolution, coming soon)

Mosaic was cleaned deeply with interactive clean boxing ⇨

this really is the best you can hope to do without total power…

48”



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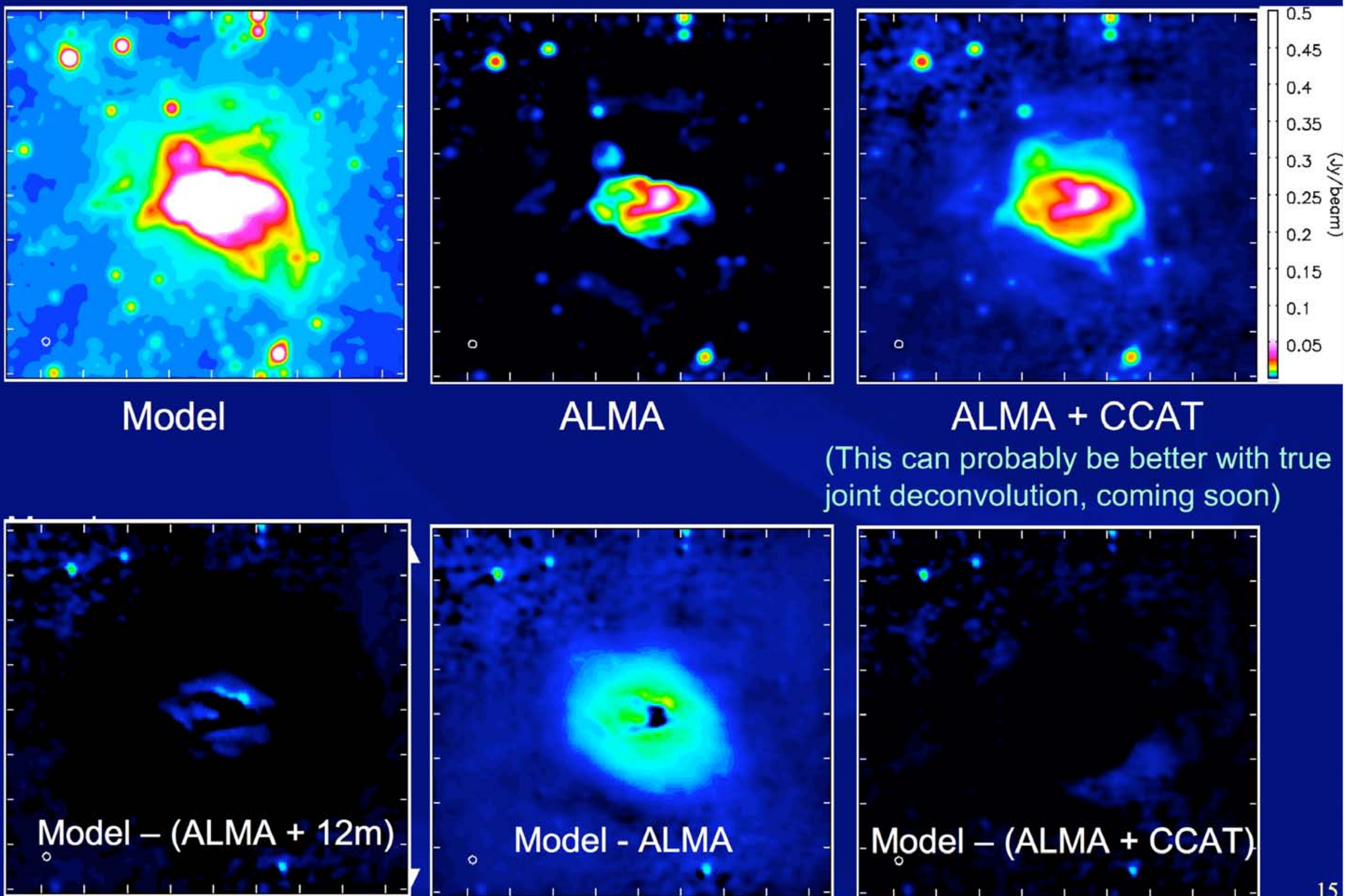


Total Power Considerations

- Getting Single Dish (SD) zero-spacing tricky because it requires
  - Large degree of overlap in order to calibrate with interferometric data
  - Excellent pointing accuracy which is more difficult with increasing dish size
  - On-the-fly mapping requires rapid telescope movement
  - SD calibration – stable, accurate, large throws or alternative sky subtraction scheme
  - SD sensitivity much less than interferometer
- ALMA Specs set for operation below 350 GHz
  - How well can excellent images be achieved at near THz frequencies?
  - Could CCAT total power data be essential at these frequencies?

Minimum CCAT Mapping Speed

ALMA collecting area Factor ~ 11.4 larger

⇨ Equivalent to a 85 m dish

ALMA primary beam area factor of ~4.3 larger

Thus, CCAT needs at least 49 heterodyne pixels

⇨ Easy, even with current technology

- ALMA will be heavily oversubscribed, not clear time for mapping large areas will ever be given
- With exception of confusion limited source counts, really large areas really do not NEED to be mapped at ALMA resolution

  ⇨ Surveys of large areas at higher frequencies clear CCAT niche

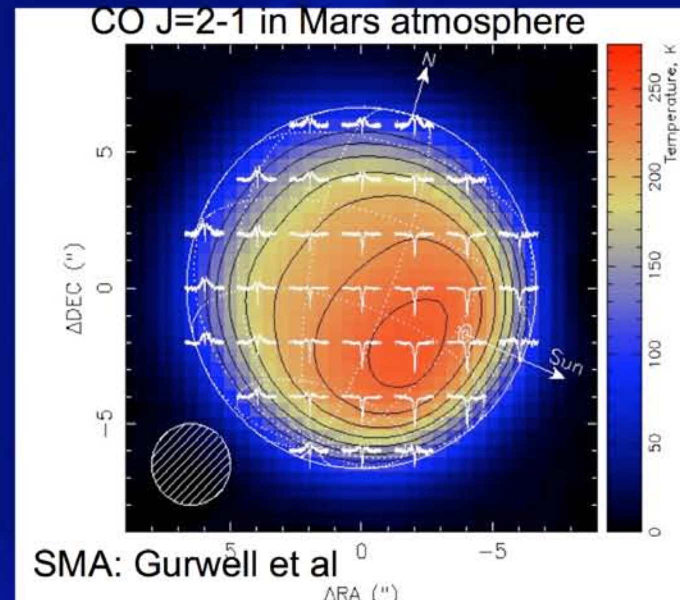
  ⇨ Really large arrays needed to fill this niche uniquely and take full advantage of CCAT's tremendous >10' field of view

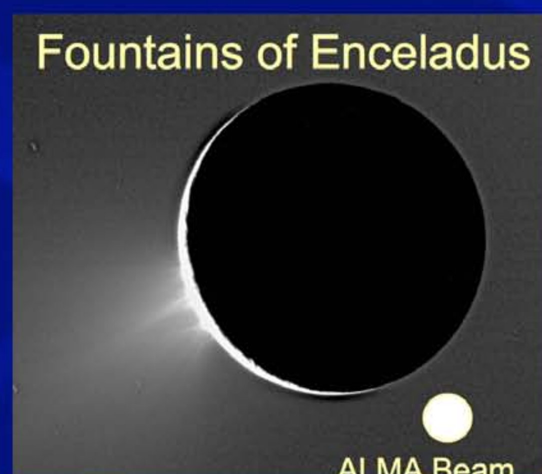
Key Heterodyne CCAT / ALMA Science

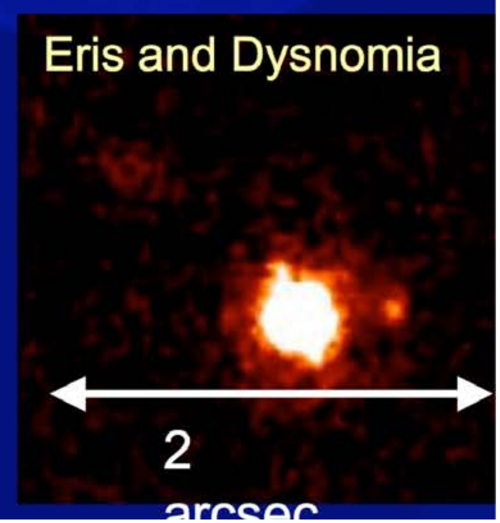
- Needs large survey's to gain understanding of statistical properties, also provides candidates for high spatial resolution ALMA follow-up
  - Heterodyne imaging of large areas can provide for serendipitous discoveries (i.e. more than just observing what you know about)
- Needs high spatial dynamic range at high resolution (total power for ALMA)
  - I believe need for this has been significantly underestimated
  - Deep surveys with CCAT could solve this problem for free while pursuing important science goals
- Needs long observing times that may never be feasible with ALMA because of oversubscription
  - Especially true at higher frequencies
  - "High risk" experiements

Exploration of the Solar System

- 'Weather' on Venus, Mars, Jovian planets
- Composition of Comets
- Volcanism on Io
- Search for Molecules from the "Fountains of Enceladus"
- Minor planet 'Eris' with its moon 'Dysnomia' easily resolved, Eris could be imaged.





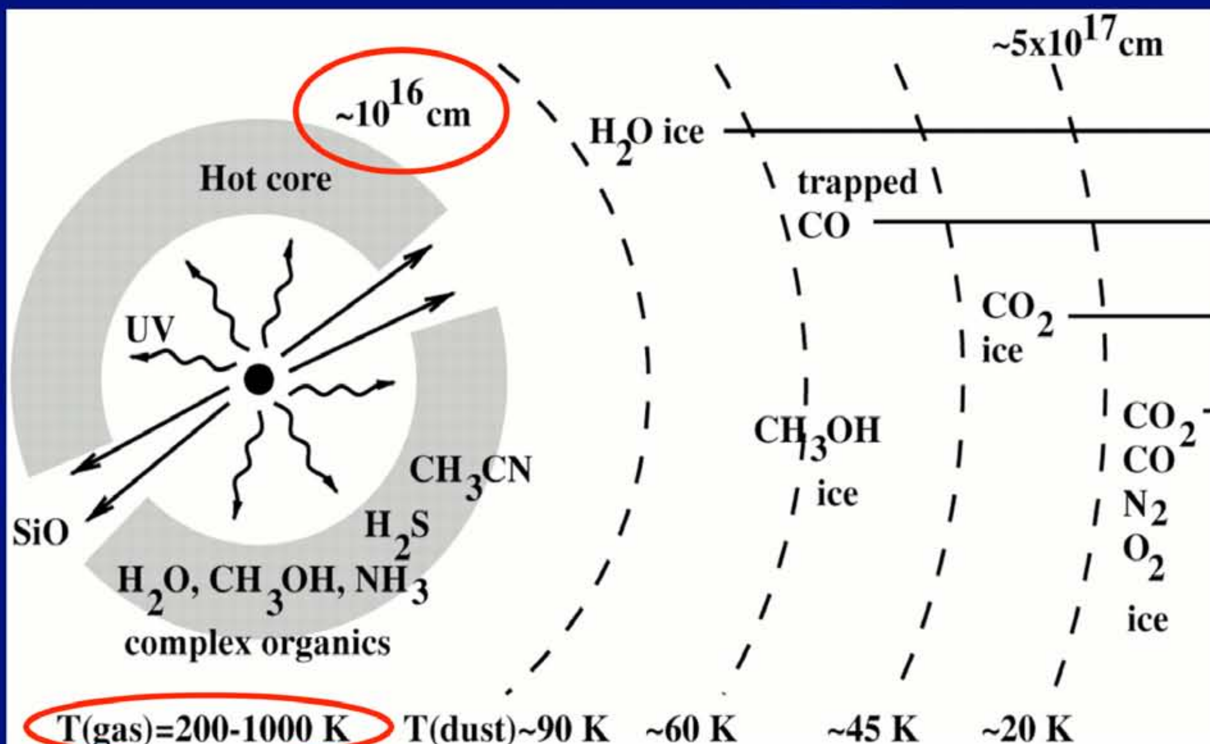


How Do Massive Stars Form?

Although massive stars dominate our view of galaxies through heating, turbulence, and ionization, we do not understand how they form even in our own Galaxy

The "Hot Cores" that form around massive protostars are excellent probes of the earliest stages

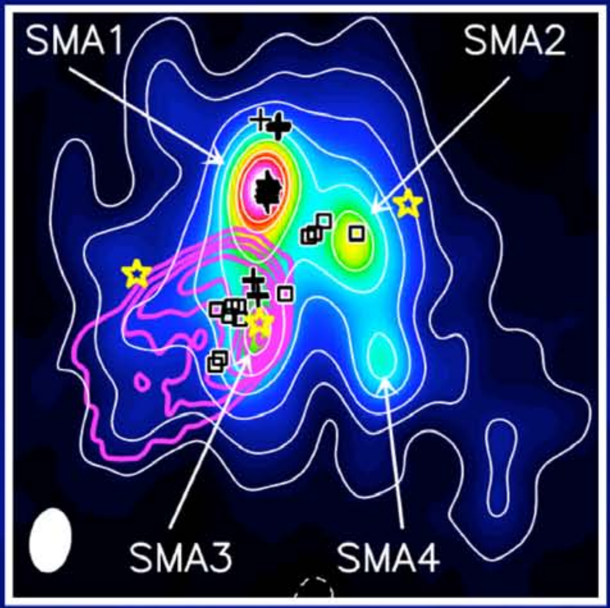
Van Dishoeck & Blake (1998)



2" = 10^{16} cm (2,000 AU) at 1kpc

- High temperatures combined with newly liberated atoms and molecules drive copious organic chemistry
- Can only be observed at high angular resolution (beam dilution)

SMA 1.3 mm Spectra of Massive Protostars in NGC6334I



Brogan, Hunter et al. in prep

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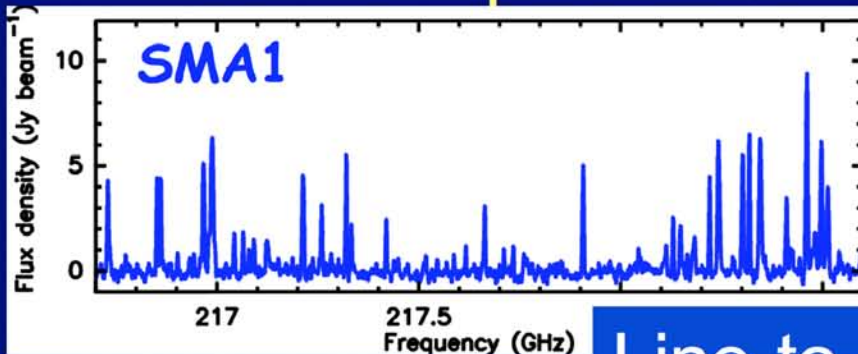
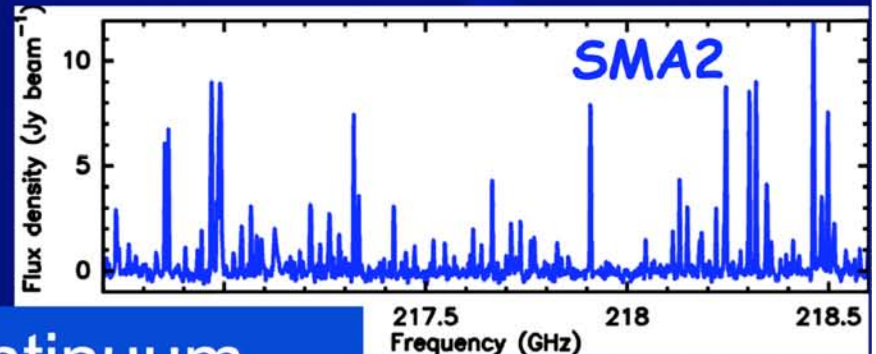
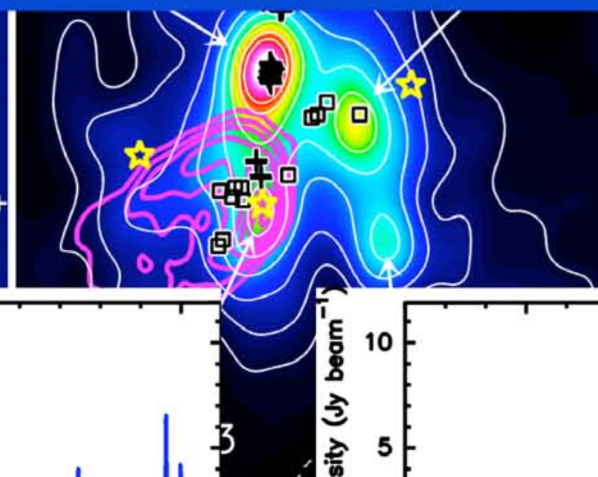


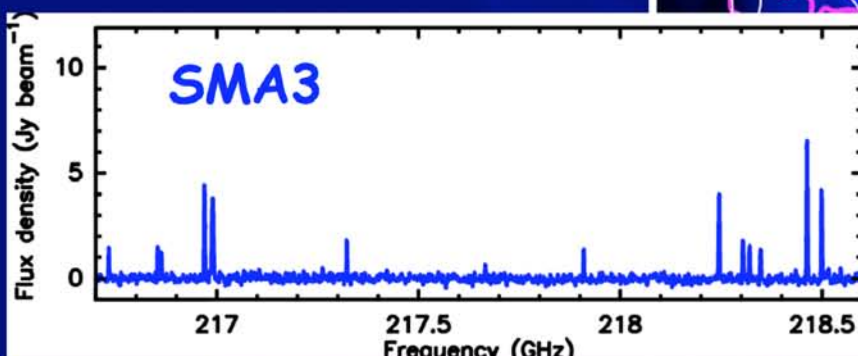


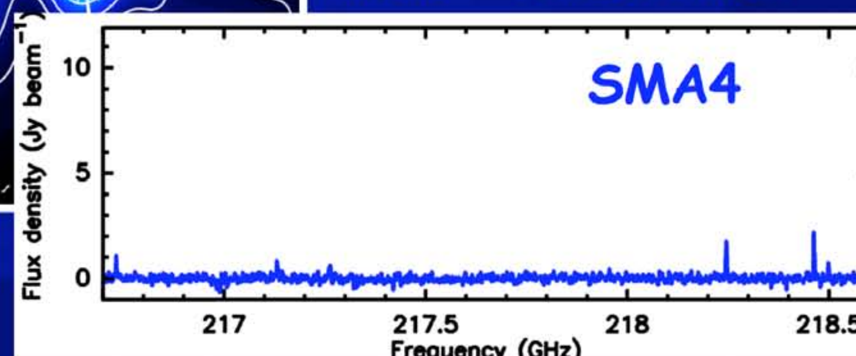
Line-to-continuum ratio 40%!!

CO, ^{13}CO, $C^{17}O$, $C^{18}O$, ^{34}CS, SO, SO_2, $^{34}SO_2$, H_2S, NS, SiO, H_2CO, CH_3OH, $^{13}CH_3OH$, $H^{13}CO^+$



CN, HC_3N, HC_5N, CH_3CN, C_2H_5CN, NH_2CH, CH_3OCH_3, CH_3OCHO + many more + unidentified





ALMA will improve resolution and spectral line sensitivity by more than a factor of 25!

Brogan, Hunter et al. in prep

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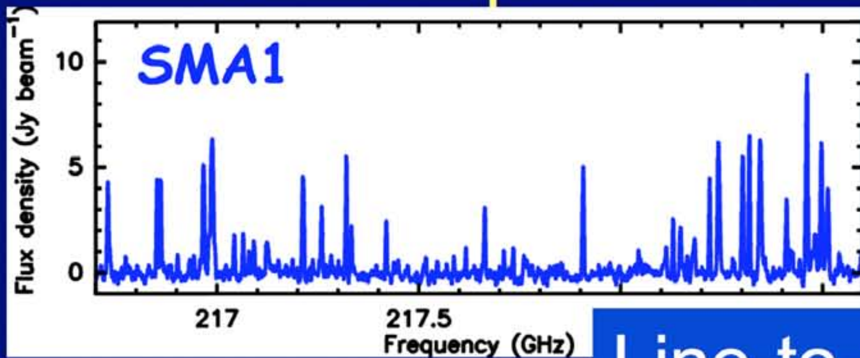

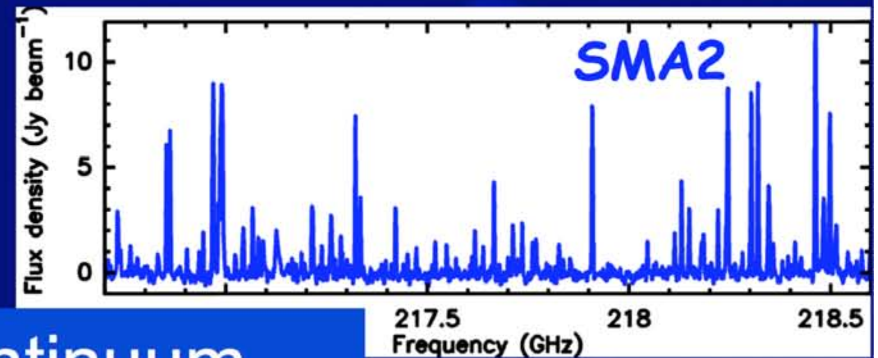

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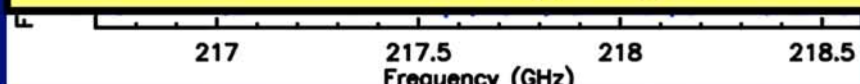
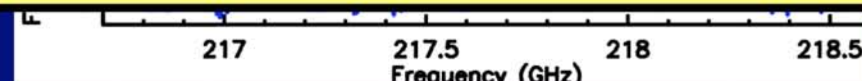
CN, HC_3N, HC_5N, CH_3CN, C_2H_5CN, NH_2CH, CH_3OCH_3, CH_3OCHO + many more + unidentified

Very little of the Southern Galactic plane has been mapped with sub-arcminute resolution in the mm/submm though it is replete with massive star forming regions





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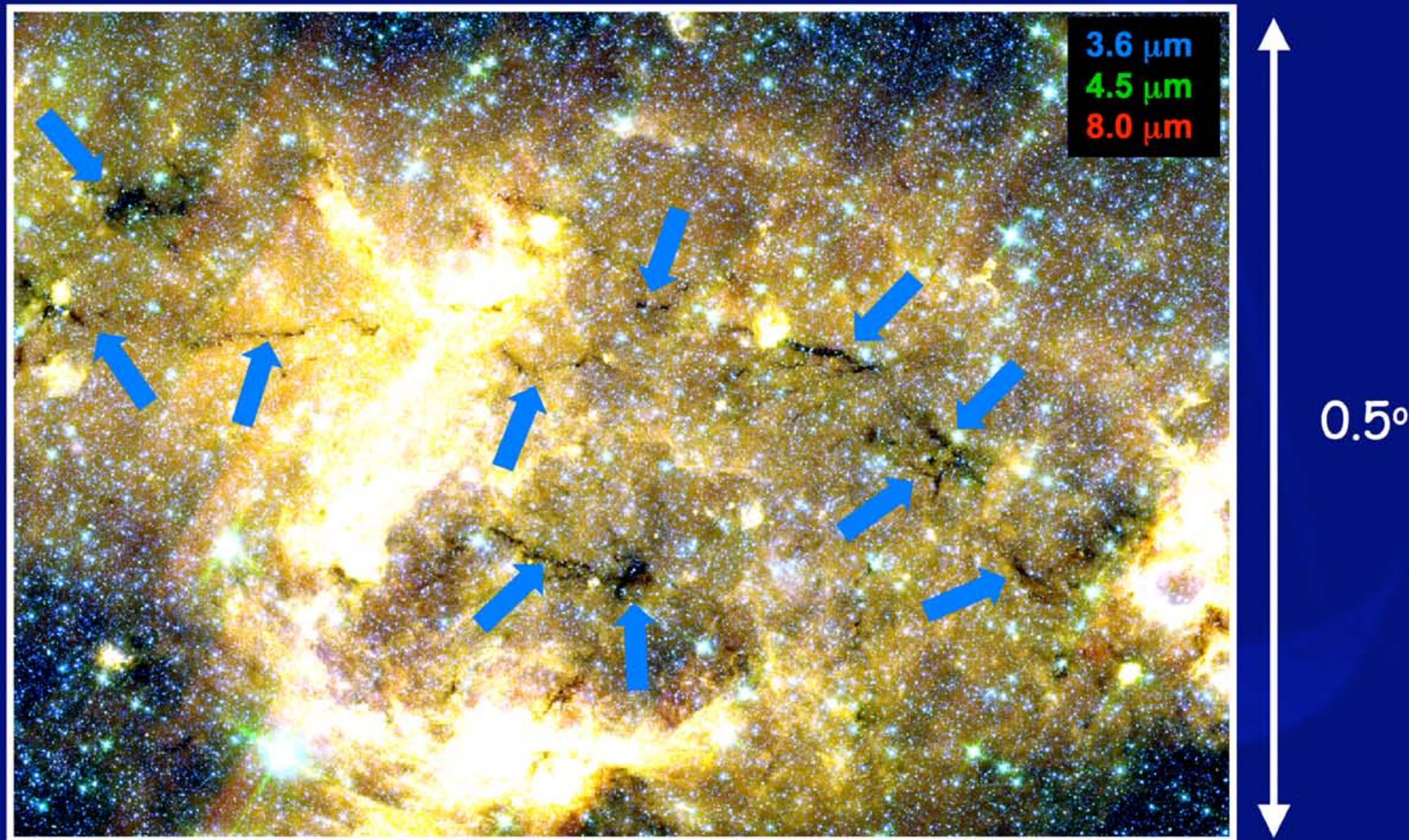
A GLIMPSE of Infrared Dark Clouds (IRDCs)

Egan et al. (1998); Carey et al. (2000); Smith et al. (2006); Rathborne et al. (2006); Pillai et al. (2006) and many others



- Extinction features seen in silhouette against the Galactic IR background
- Often very filamentary and relatively nearby
- 1,000s seen in the Spitzer GLIMPSE survey (and previous surveys like MSX)

⇨ Thought to harbor the earliest observable phases of massive star formation

A GLIMPSE of Infrared Dark Clouds (IRDCs)

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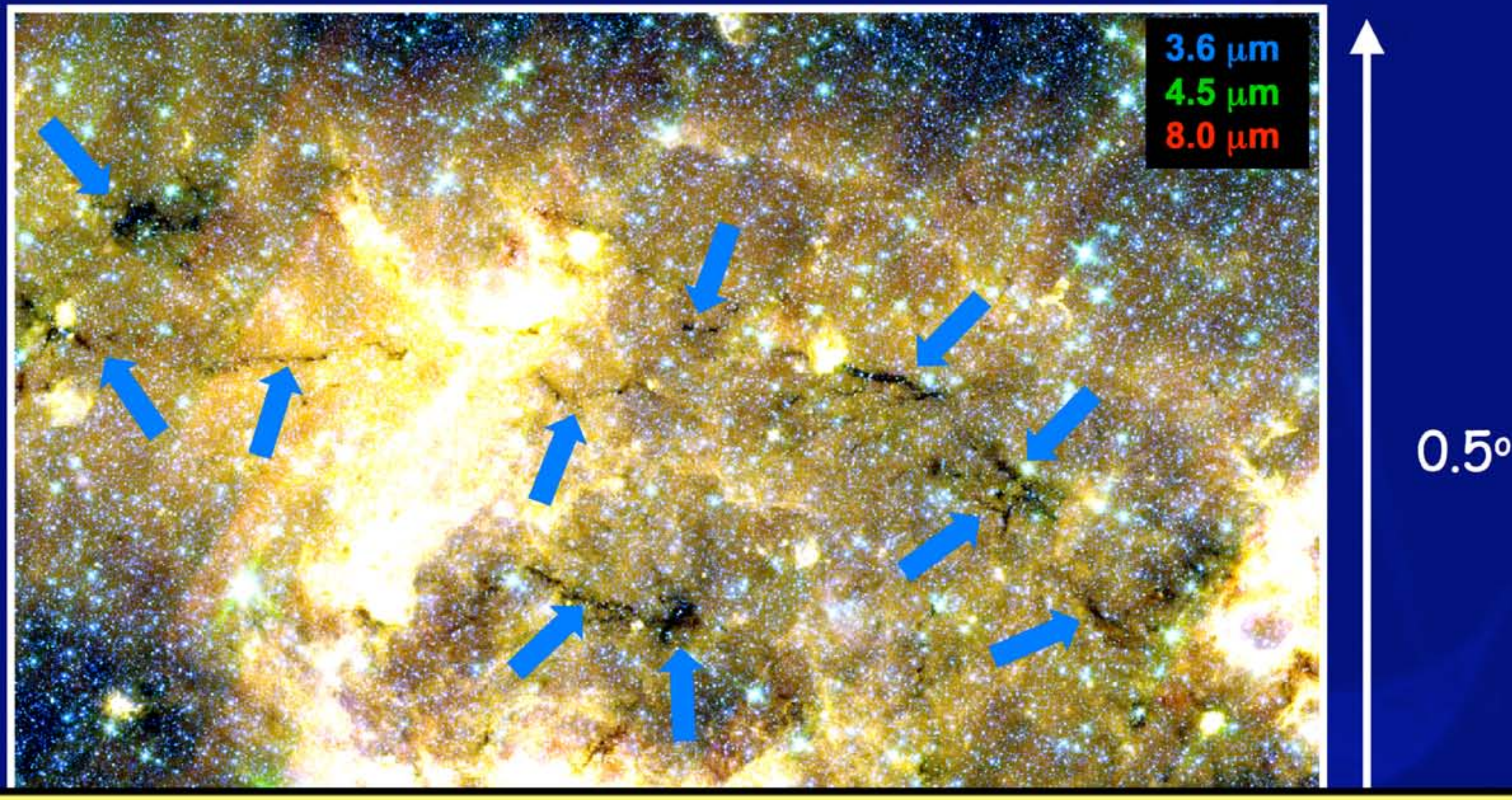

Large scale mapping of the "Galactic Star Forming Web" while simultaneously defining Galactic disk kinematics

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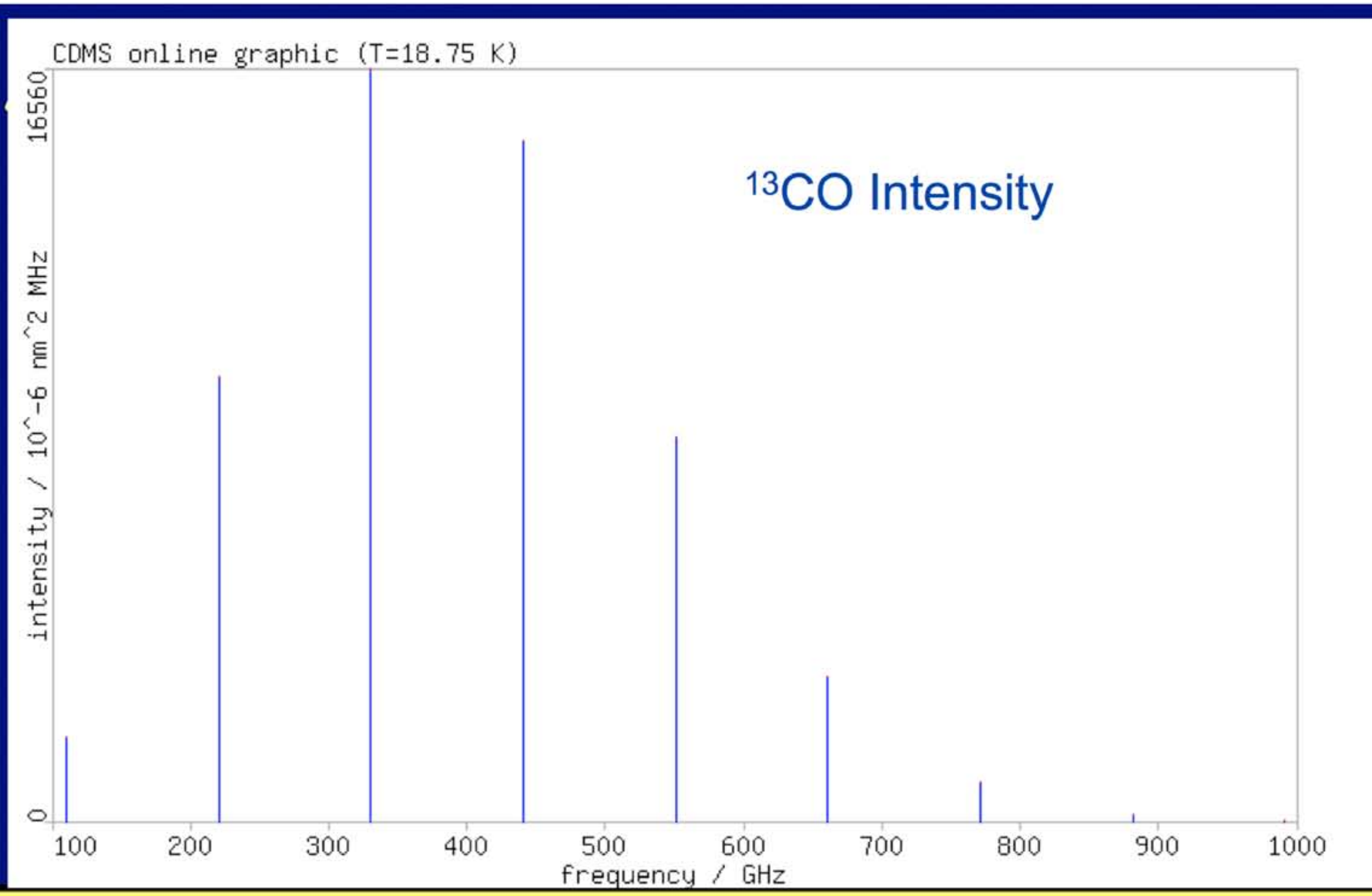

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.5°

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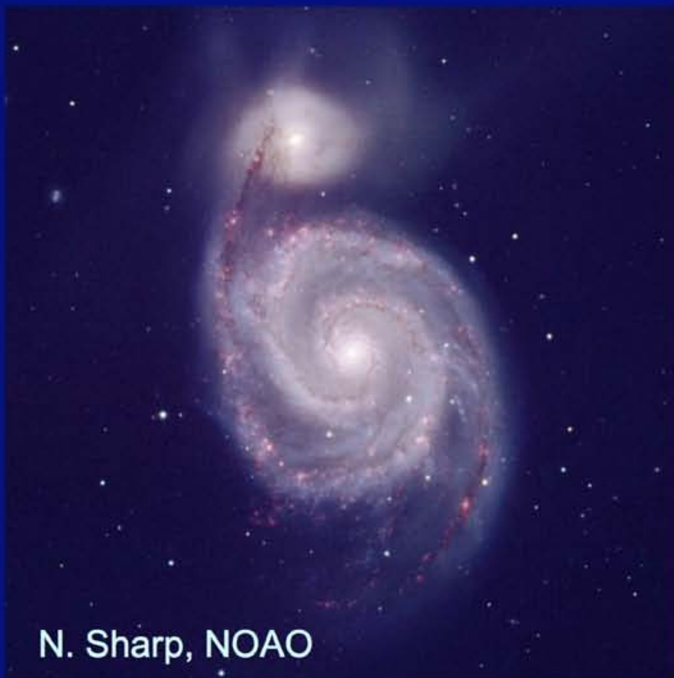
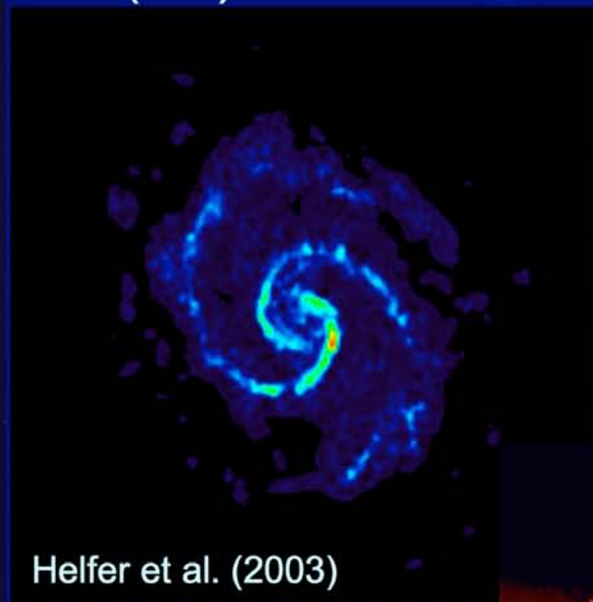
Galaxy Structure and Evolution



N. Sharp, NOAO

CO(1-0)   BIMA-SONG



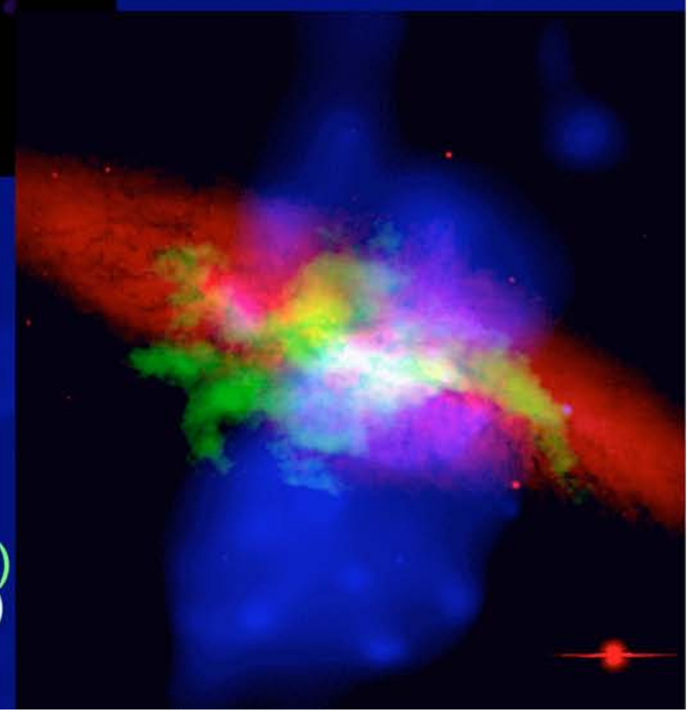
Helfer et al. (2003)

ALMA goal:

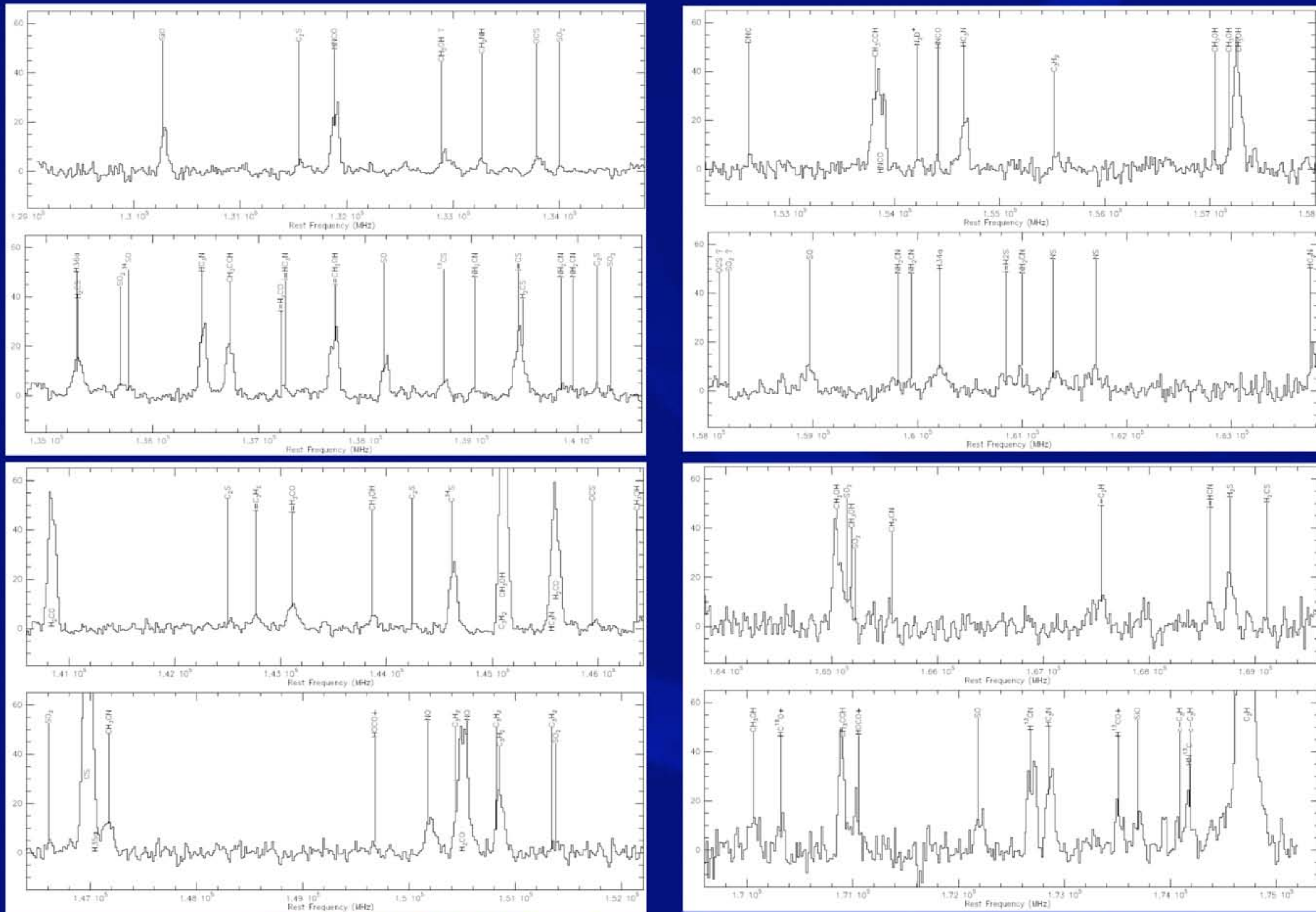
Ability to trace chemical composition of galaxies to z=3 in less than 24 hours

Total power AND high resolution is essential for imaging large nearby galaxies

M82 starburst
Red: optical emission
Blue: x-ray emission
Green: OVRO $^{12}CO(J=1-0)$
(Walter, Weiss, Scoville 2003)



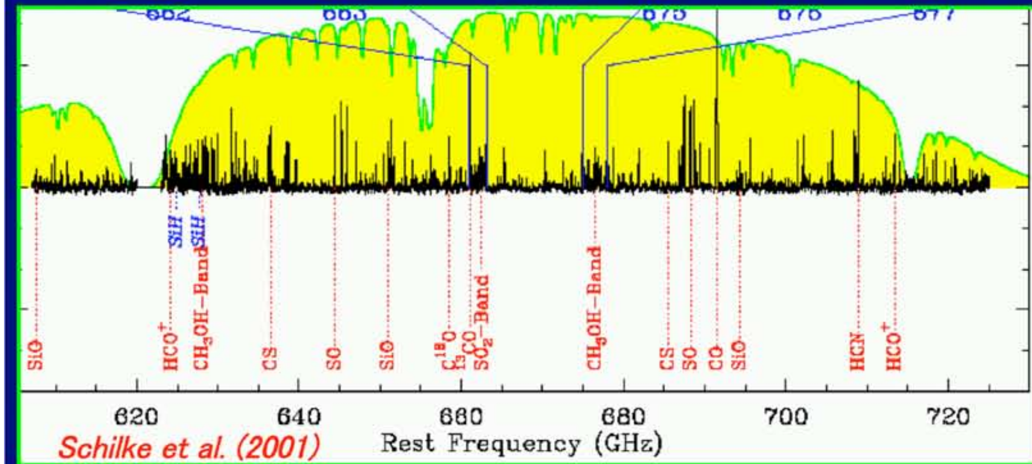
Extragalactic Line Forest in Starburst NGC 253 (d = 2.5 Mpc)



Martin et al. (2006)

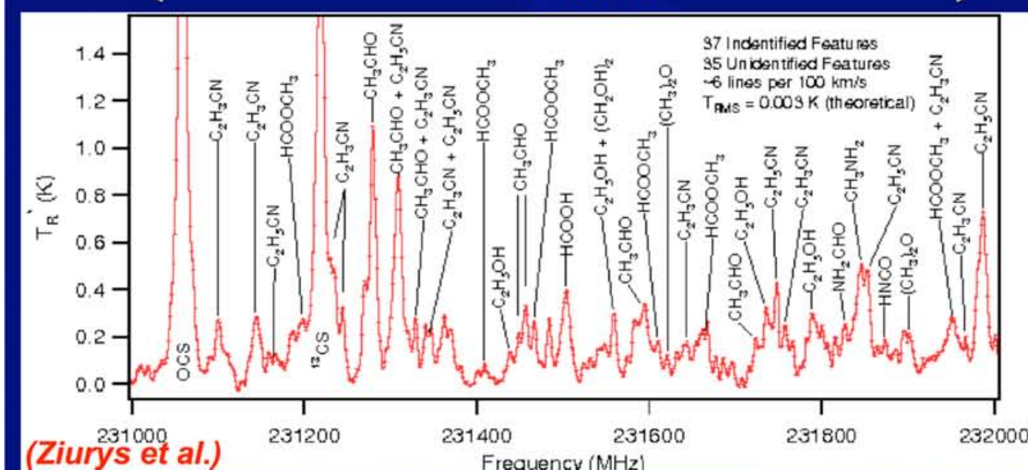
IRAM 30m 2mm Survey Bandwidth ~400 MHz

Spectral Line catalogs and tools needed to deal with tremendous spectral complexity

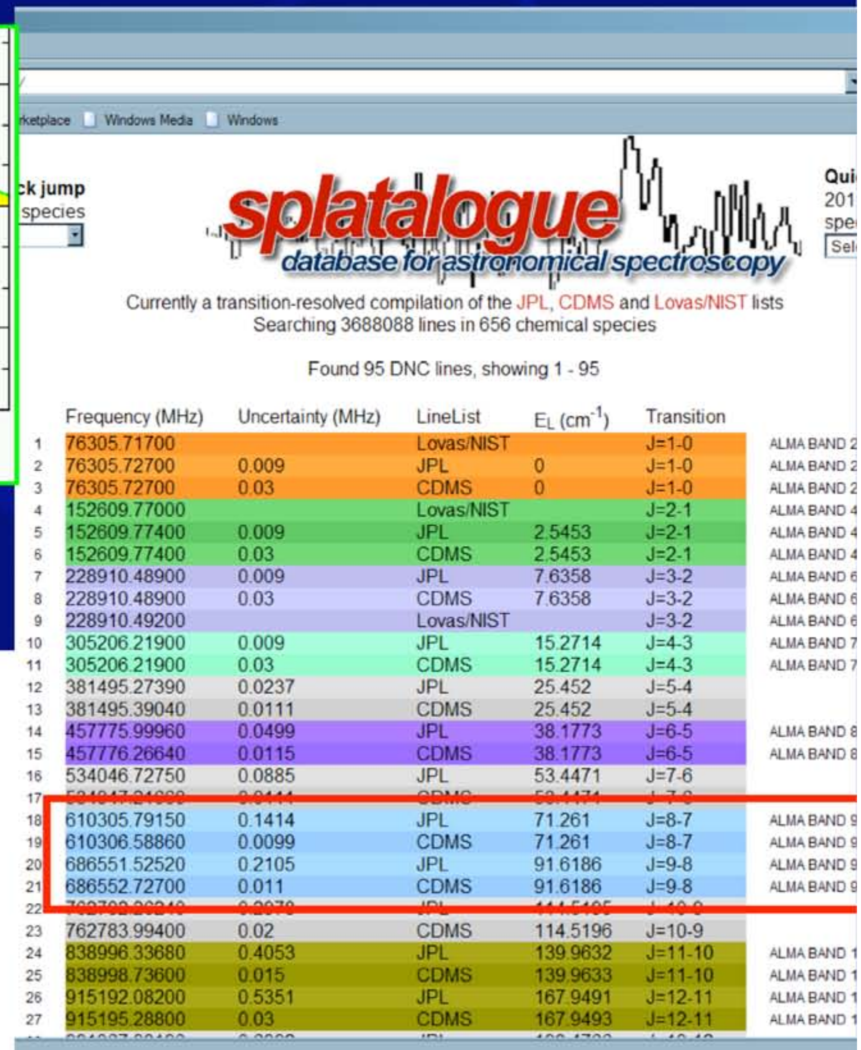


Lines visible in Band 9 (CSO)

1 GHz



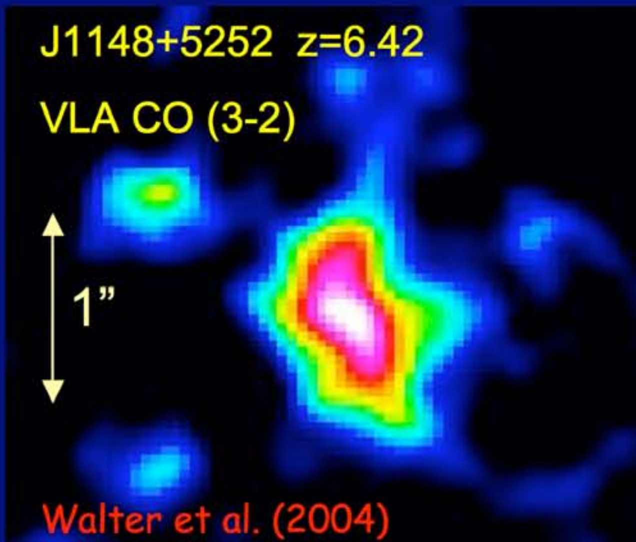
SgrB2(N) spectrum using Band 6 mixer at the SMT



	Frequency (MHz)	Uncertainty (MHz)	LineList	E_L (cm^{-1})	Transition	
1	76305.71700		Lovas/NIST		J=1-0	ALMA BAND 2
2	76305.72700	0.009	JPL	0	J=1-0	ALMA BAND 2
3	76305.72700	0.03	CDMS	0	J=1-0	ALMA BAND 2
4	152609.77000		Lovas/NIST		J=2-1	ALMA BAND 4
5	152609.77400	0.009	JPL	2.5453	J=2-1	ALMA BAND 4
6	152609.77400	0.03	CDMS	2.5453	J=2-1	ALMA BAND 4
7	228910.48900	0.009	JPL	7.6358	J=3-2	ALMA BAND 6
8	228910.48900	0.03	CDMS	7.6358	J=3-2	ALMA BAND 6
9	228910.49200		Lovas/NIST		J=3-2	ALMA BAND 6
10	305206.21900	0.009	JPL	15.2714	J=4-3	ALMA BAND 7
11	305206.21900	0.03	CDMS	15.2714	J=4-3	ALMA BAND 7
12	381495.27390	0.0237	JPL	25.452	J=5-4	
13	381495.39040	0.0111	CDMS	25.452	J=5-4	
14	457775.99960	0.0499	JPL	38.1773	J=6-5	ALMA BAND 8
15	457776.26640	0.0115	CDMS	38.1773	J=6-5	ALMA BAND 8
16	534046.72750	0.0885	JPL	53.4471	J=7-6	
17	[illegible]	[illegible]	CDMS	[illegible]	[illegible]	
18	610305.79150	0.1414	JPL	71.261	J=8-7	ALMA BAND 9
19	610306.58860	0.0099	CDMS	71.261	J=8-7	ALMA BAND 9
20	686551.52520	0.2105	JPL	91.6186	J=9-8	ALMA BAND 9
21	686552.72700	0.011	CDMS	91.6186	J=9-8	ALMA BAND 9
22	[illegible]	[illegible]	JPL	[illegible]	[illegible]	
23	762783.99400	0.02	CDMS	114.5196	J=10-9	
24	838996.33680	0.4053	JPL	139.9632	J=11-10	ALMA BAND 1
25	838998.73600	0.015	CDMS	139.9633	J=11-10	ALMA BAND 1
26	915192.08200	0.5351	JPL	167.9491	J=12-11	ALMA BAND 1
27	915195.28800	0.03	CDMS	167.9493	J=12-11	ALMA BAND 1

Unified spectral line database (to be used in observing tool)

ALMA: study of 'first light' during cosmic reionization

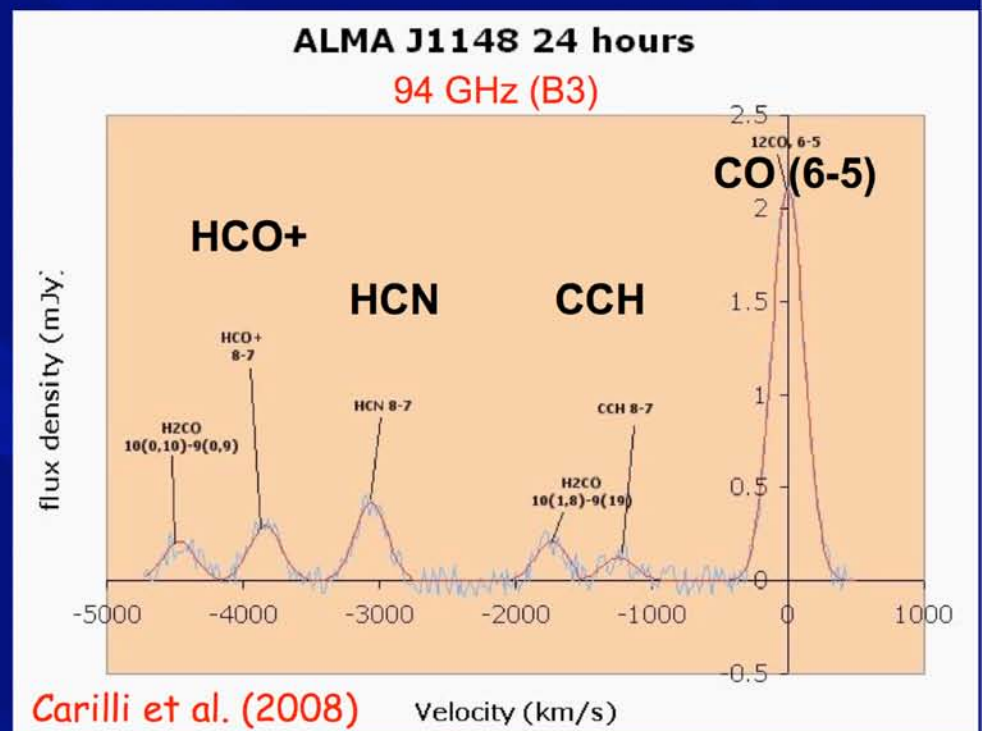


Current State-of-art: Tens of hours to detect rare, systems (FIR ~1×10^{13} $L_\odot$)

Search for mm/submm fine-structure lines from the intergalactic medium could also yield very interesting results – not clear how strong the signal might be

Spectral simulation of J1148+5251

- Detect dust emission in **1sec** (5σ)
- Detect multiple lines => detailed astrochemistry
- Image dust and gas at sub-kpc resolution – gas dynamics!
- Detect continuum of 'normal' galaxies in ~1hr



ALMA and CCAT Complementarities

- Overlap in Frequency
  - ALMA 350 - 10000 microns
  - CCAT 350 - 1400 micron requirement; 200-2500 micron goal

- Surface accuracy -- the CCAT requirement/goal (12.5/9.5 μm) exceeds the ALMA parameters (25/15 μm) by about 2x.

- Overlap in beamsize -- similar when $\nu_{ALMA} > 2x\ \nu_{CCAT}$
  - CCAT will be able to observe at high frequencies more often because of superior site

- Overlap in sky coverage -- nearby site
  - Southern sky virtually unexplored territory

- Comparable sensitivity
  - CCAT continuum can use large arrays
  - CCAT continuum can employ wider bandwidths
  - Need to have high heterodyne mapping speed
  - Mapping/calibration/reduction scheme that does not remove extended structure

ALMA News

European ALMA News (www.eso.org),
ALMA/NA Biweekly Calendar (www.cv.nrao.edu/~awootten/mmaimcal/ALMACalendars.html)

ALMA
ATACAMA LARGE MILLIMETER ARRAY

www.alma.info

The Atacama Large Millimeter Array (ALMA) is an international astronomy facility. ALMA is a partnership between Europe, North America and Japan, in cooperation with the Republic of Chile. ALMA is funded in North America by the U.S. National Science Foundation (NSF) in cooperation with the National Research Council of Canada (NRC), in Europe by the European Southern Observatory (ESO) and Spain. ALMA construction and operations are led on behalf of North America by the National Radio Astronomy Observatory (NRAO), which is managed by Associated Universities, Inc. (AUI), on behalf of Europe by ESO, and on behalf of Japan by the National Astronomical Observatory of Japan.

ALMA Median Sensitivity

(1 minute; 75% Quartile opacities λ>1mm, 25% λ <1mm)

Frequency (GHz)	Continuum (mJy)	Line 1 km s^{-1} (mJy)	Line 25 km s^{-1} (mJy)
35	0.02	5.1	1.03
110	0.027	4.4	0.89
140	0.039	5.1	1.01
230	0.071	7.2	1.44
345	0.12	10	1.99
675	0.85	51	10.2
950	1.26	66	13.3