ALMA

Synergies with the Square Kilometre Array
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Overview

- **What is ALMA?**
- **Main performance numbers**
  - Sensitivity
  - Resolution
  - Spatial scales
  - Spectral-line modes
- **Synergy between ALMA and SKA**
  - Science
  - Wavelengths, resolutions, surveys and follow-up
  - Examples

What is ALMA?

Atacama Large Millimetre/Submillimetre Array

- Aperture synthesis array optimised for millimetre and sub-millimetre wavelengths.
- High, dry site, Chajnantor Plateau, Chile
- North America (NRAO) + Europe (ESO) + Japan (NAOJ) + Chile
- EU/NA: 50 dishes with 12m diameter. Baselines from ~15m to 14km.
- ALMA Compact Array (ACA) provided by Japan
  - 12 7m dishes in compact configurations
  - 4 12m dishes primarily for total-power

What is ALMA (2)?

- Low-noise, wide-band receivers.
- Digital correlator giving wide range of spectral resolutions.
- Software (dynamic scheduling, imaging, pipelines)
- Will eventually provide sensitive, precision imaging between 30 and 950 GHz in 10 bands
  - 350 GHz continuum sensitivity: about 1 mJy in <u>one</u> second
  - Angular resolution will reach ~0.05 arcsec at 100 GHz
- Resolution / arcsec ≈ 0.2 (λ/mm) / (D/km)
- Primary beam / arcsec ≈ 17 (λ/mm)

Highest-level science goals

- Image spectral line emission from CO or C+ in a galaxy with similar mass to the Milky Way at a redshift of z = 3, in less than 24 hours of observation.
- Image the gas kinematics in a solar-mass protostellar/ protoplanetary disk at a distance of 150 pc. Study the physical, chemical, and magnetic field structure of the disk and detect the tidal gaps created by planets undergoing formation.
- Provide precise images at a resolution of 0.1 arcsec.

Key performance numbers

- Baseline range 15m – 14.5 km + ACA + single dish
- Resolution/ arcsec ≈ 0.2(λ/mm)/(max baseline/km)

  0.04 arcsec at 100 GHz, 14.5 km baseline

  0.005 arcsec at 900 GHz, 14.5 km baseline
- Wide bandwidth (8 GHz/polarization), low noise temperatures, good site and antennas, … → excellent continuum sensitivity
- Full polarization

Key antenna specifications

- 12m diameter
- 25 μm rms surface accuracy (goal 20 μm); measure using tower and interferometric holography
- 2 arcsec rms absolute pointing; 0.6 arcsec rms offset
- Tracking speed for on-the-fly mapping 1 deg/s
- Fast switching required between target and calibrator (1.5^{o} in 1.5s)
- Three prototypes (Vertex/RSI, EIE/Alcatel, Mitsubishi) tested at VLA site; all meet specification as far as can be tested at lower altitude.

Sampling of large spatial scales

1 Mpc corresponds to ~125 arcsec at $z = 1$

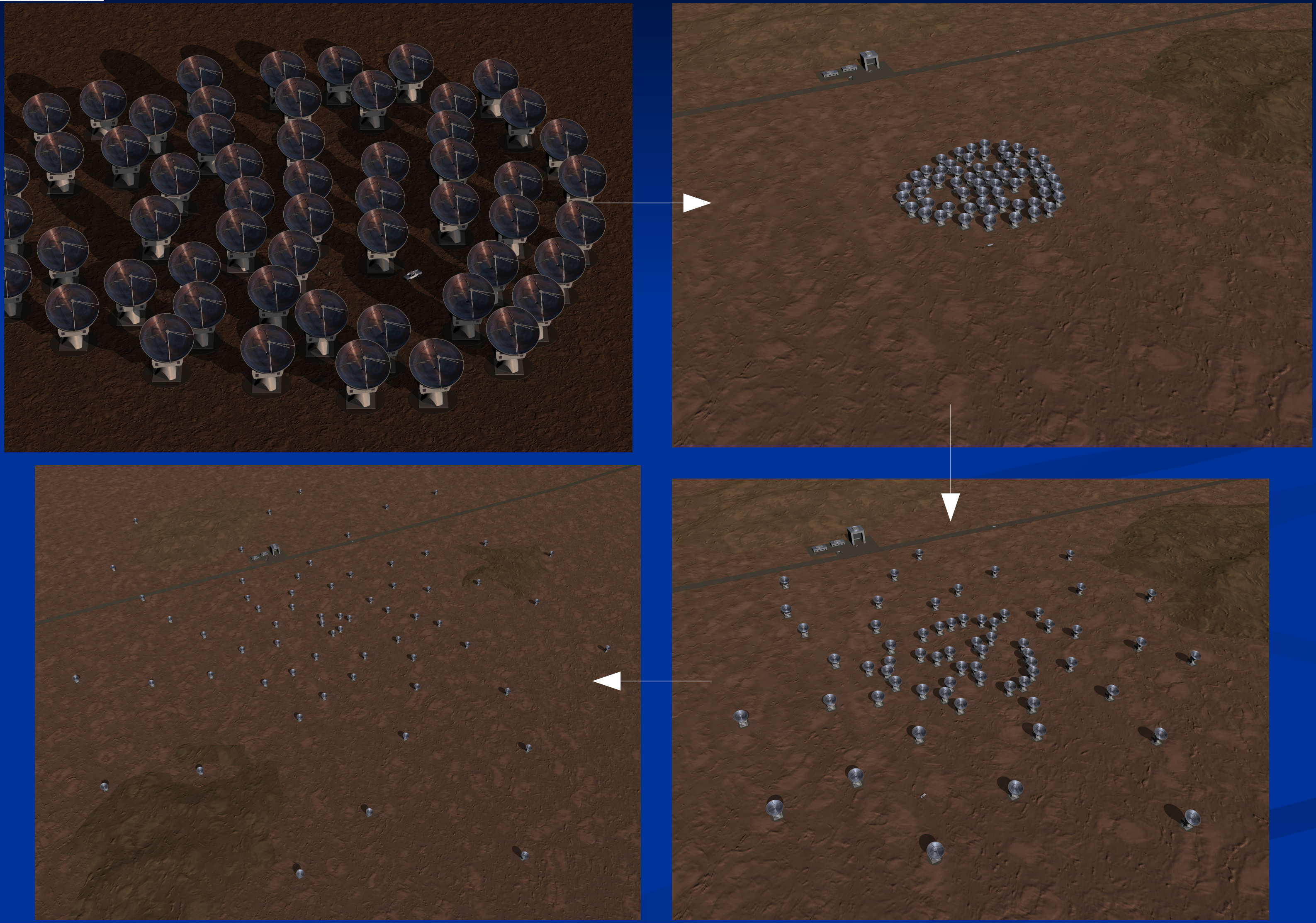
ν	Primary beam λ/D		Minimum λ/D		Resolution
GHz	arcsec		arcsec		arcsec
	12m	7m	Compact	ACA	Compact
35	170	291	116	199	10
110	56	99	37	64	3.1
230	27	46	18	31	1.5
345	18	31	12	21	1.0

Also combine with 12m (single-dish) observations

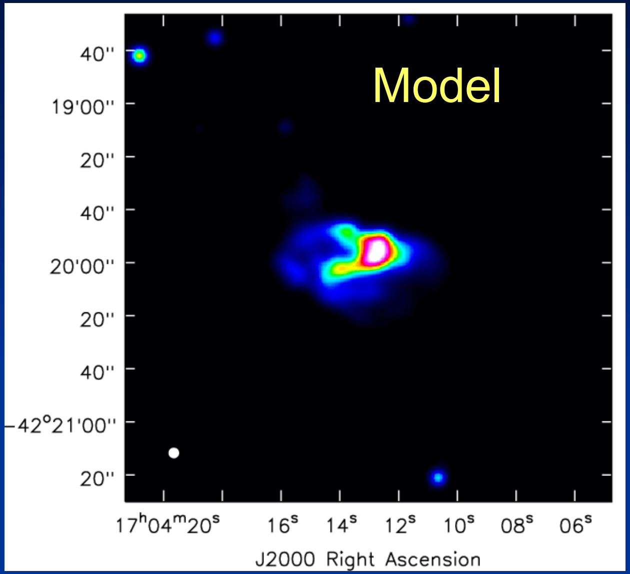
Mosaics and wide-field imaging

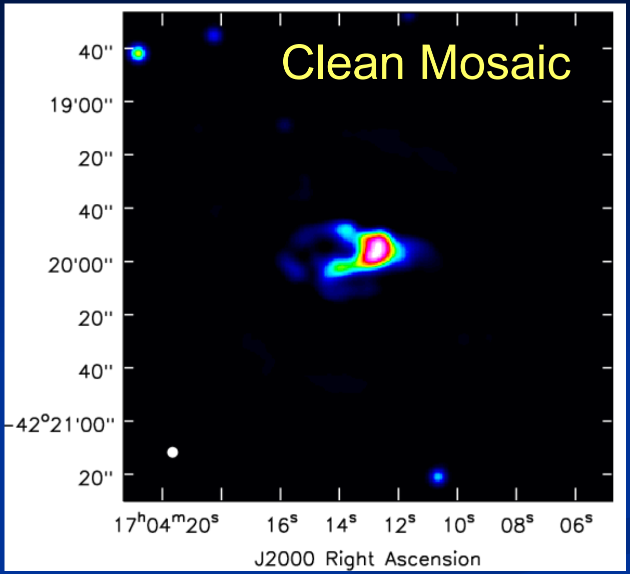
- Basic problem of extremely small fields, limited by primary beam and short spacing coverage
- Combination of a mosaic of pointings with the main array and single-dish data can be used to sample a larger range of spatial scales.
- Pointing errors severely limit the image fidelity unless scales around 10m uv distance are properly sampled.
- ACA 7m antennas fill in short-spacing coverage
- Four 12m antennas used to supply total power data (beam- switching using nutator + on-the-fly mapping)

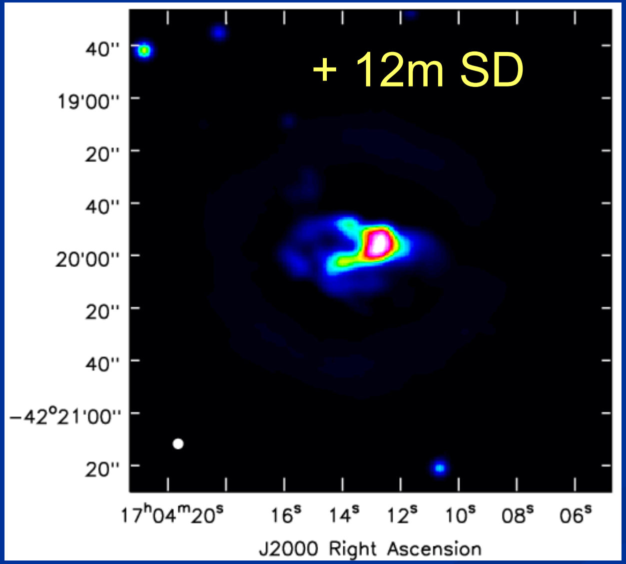
Continuous reconfiguration

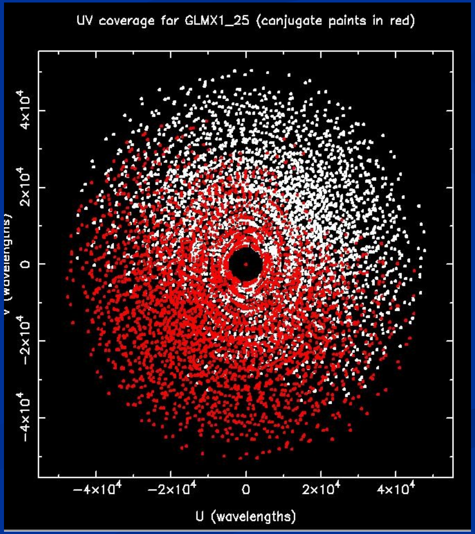


Imaging: 50 antennas + SD



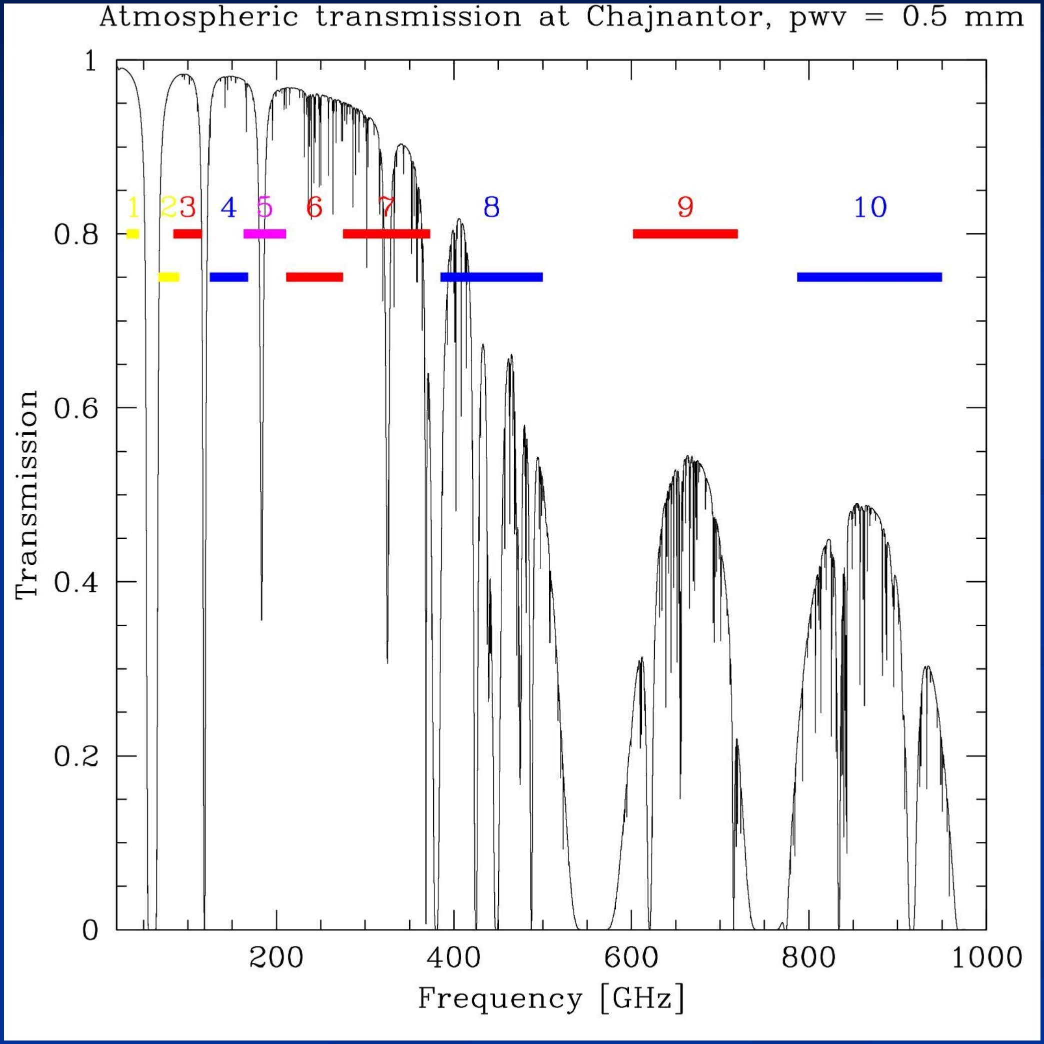






uv coverage
(3 mins)

Transparent site allows full spectral coverage



ALMA Bands

1 31.3 – 45 GHz
2 67 - 90 GHz
3 84 - 116 GHz NRAO
4 125 – 163 GHz
5 163 – 211 GHz
6 211 – 275 GHz HIA
7 275 – 373 GHz IRAM
8 385 – 500 GHz
9 602 – 702 GHz SRON
10 787 – 950 GHz

Under construction (NA/Europe)
Under construction (Japan)
Development study (Japan)
EU FP6 (8 antennas)
Not yet funded

Sensitivity in 1 minute

ν	ΔS	ΔT_B
GHz	mJy	K
35	0.019	0.0003
110	0.033	0.0004
345	0.14	0.0018
409	0.31	0.0040
675	3.8	0.049
	0.46	0.0059
850	5.9	0.080
	1.1	0.014

RMS for 2 polarizations, each with 8GHz bandwidth; elevation of 50°. Brightness temperatures are for a maximum baseline of 200m; 50 antennas

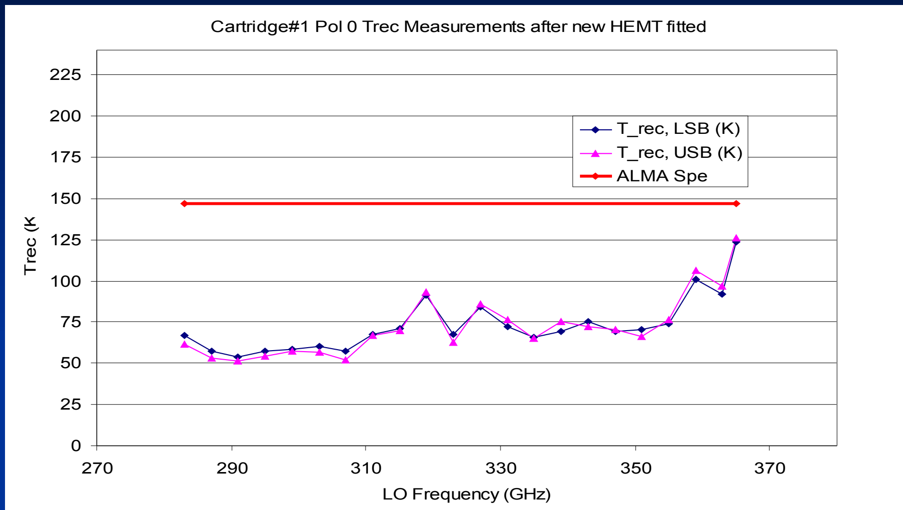
Median PWV = 1.5mm
Best 5% PWV = 0.35mm
ALMA Memo 276

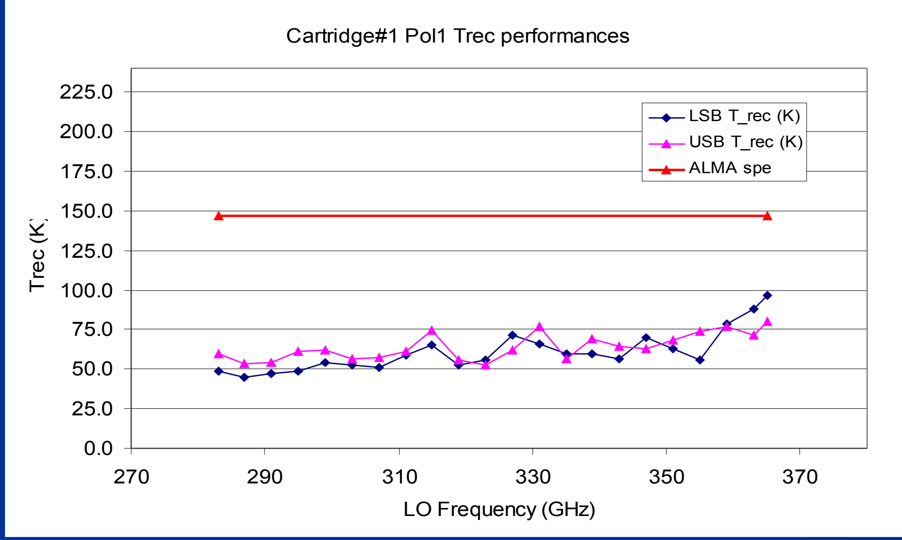
Some receivers will exceed specification

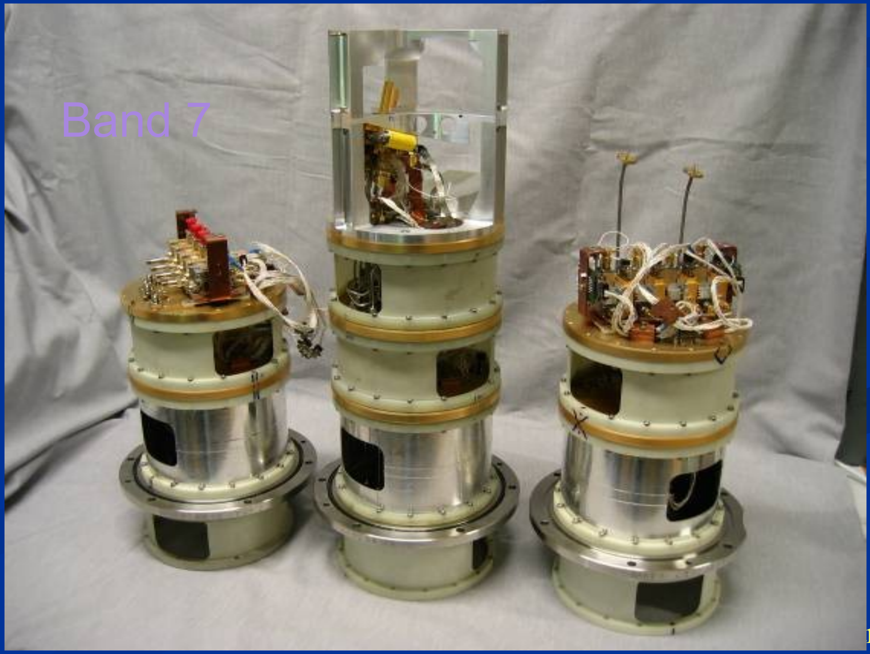
Sensitivity calculator available at

http://www.eso.org/projects/alma/science/bin/sensitivity.html

Band 7 noise performance







Spectral modes

- Channel bandwidth 31.25 MHz – 2 GHz (4 channels)
- Maximum 4096 x (4/N) x (2/P) spectral points/channel, where N = 1, 2 or 4 is the number of channels and P=2 for full polarization; 1 for parallel hands only.
- Maximum spectral resolution 3.8 kHz.
- Tunable FIR filter bank to subdivide bandwidth into 32 (possibly overlapping) sub-channels
- Flexible combinations of centre frequency and resolution

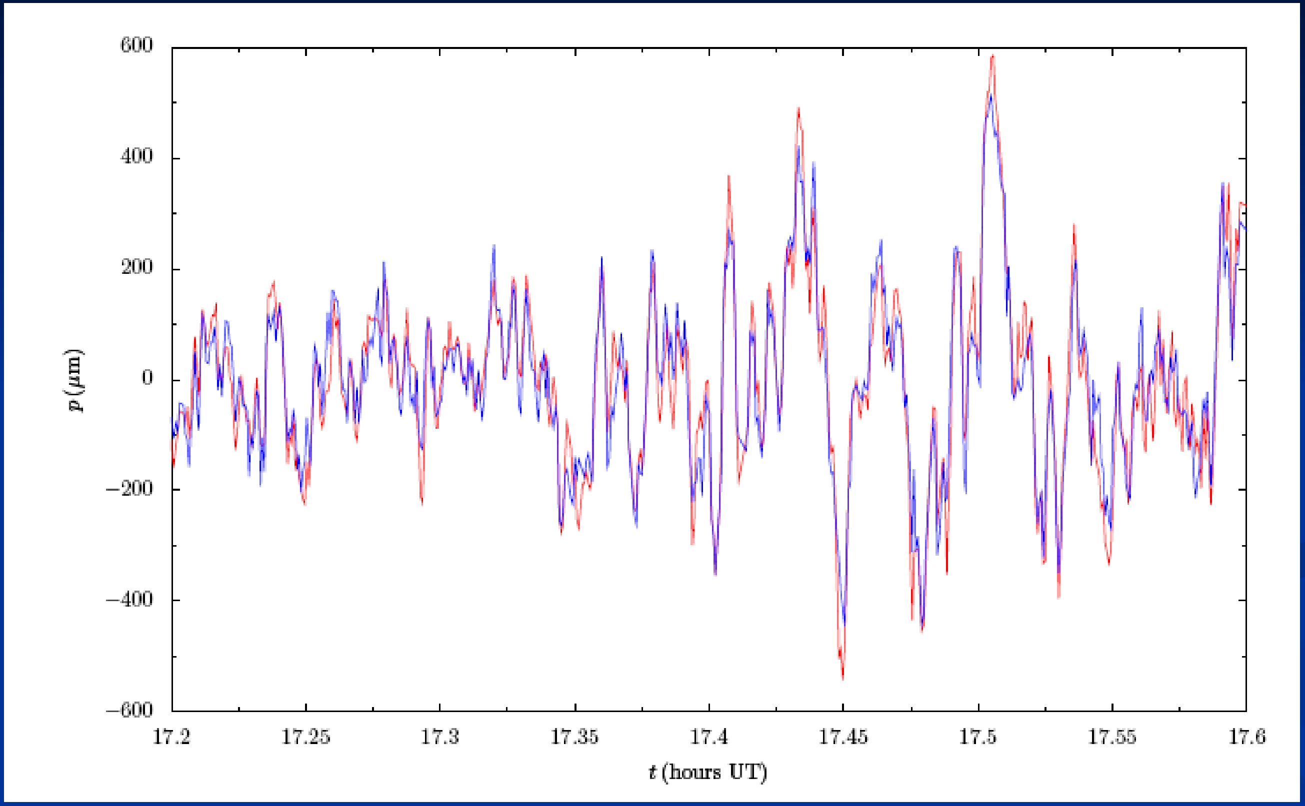
ALMA software

- Control of the ALMA system: antennas, front and back-end electronics, correlator
- Image and quick-look pipelines operating in near real time
- Dynamic scheduling according to scientific priority and atmospheric conditions
- Archiving of raw, calibrated and associated data
- Off-line data processing package is CASA
- Observing tool (Phase 1/2)

Phase calibration

- **Requirements**
  - Reduce atmospheric and electronic phase fluctuations to as low a level as possible
  - Required by imaging and flux scale (decorrelation)
- **Techniques**
  - Fast switching (interleave with observations of a nearby calibrator, perhaps at a lower frequency). 20 – 300s cycle times. Requires calibrator within ~2^{o}.
  - Water-vapour radiometry (measure emission from 183 GHz atmospheric line; deduce phase fluctuations on 1s timescales).
  - Self-calibration

WVR correction in action



SMA observations at 230GHz compared with WVR predictions

Early Science

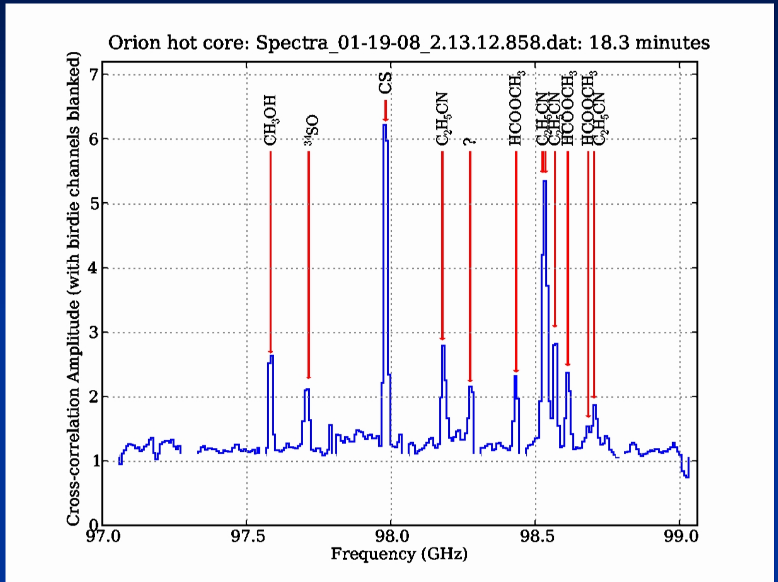
- At least 16 antennas fully commissioned (more in process of integration)
- Receiver bands 3, 4, 6, 7, 8, 9
- Interferometry in single field or pointed mosaic mode
- Significant range of spectral modes, including Tunable filter bank
- Circular and linear polarization (not mosaic)
- Single-dish mosaic (position and beam-switch) and OTF.
- 2 subarrays operational
- Formal proposal call

Project Status

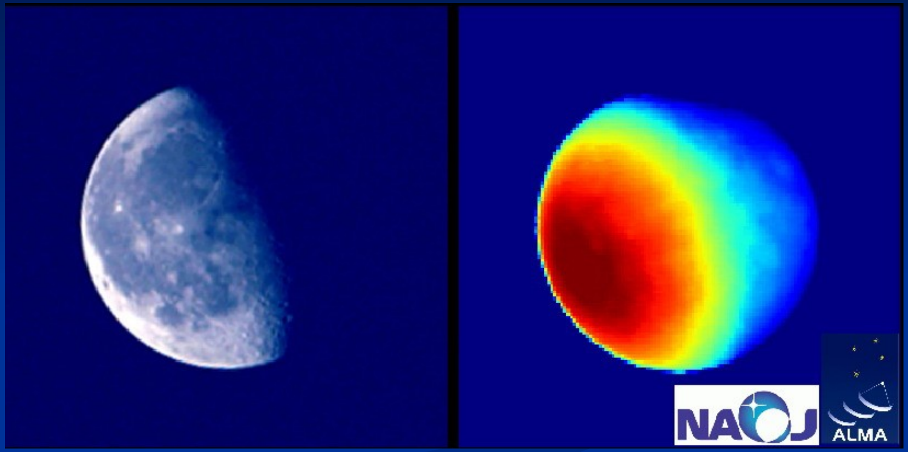
- 7 antennas under test at OSF in Chile
- First front-end assembly at OSF
- Assembly, integration and verification starting
- Prototype interferometer operational in Socorro
- First interferometry at high site 2009
- Commissioning and science verification 2009-10
- "Early Science" (open call) late 2010/early 2011
- Full operations 2013

Antennas and transporters

Early test results



Spectrum of the Orion Hot Core obtained with the prototype interferometer at the VLA site



The Moon, observed at 2mm with an ALMA 12m antenna in Chile

Prototype interferometer

Not without problems

ALMA and SKA

- ALMA is not (usually) a survey instrument, because of the limited field of view in a single observation. More likely to be used for detailed follow-up.
- Complementary frequency ranges (SKA 70MHz – 25GHz?; ALMA 30 – 950GHz)
- Similar maximum resolution (5mas for ALMA at 950GHz); ALMA has difficulty sampling large spatial scales.
- Different emission processes

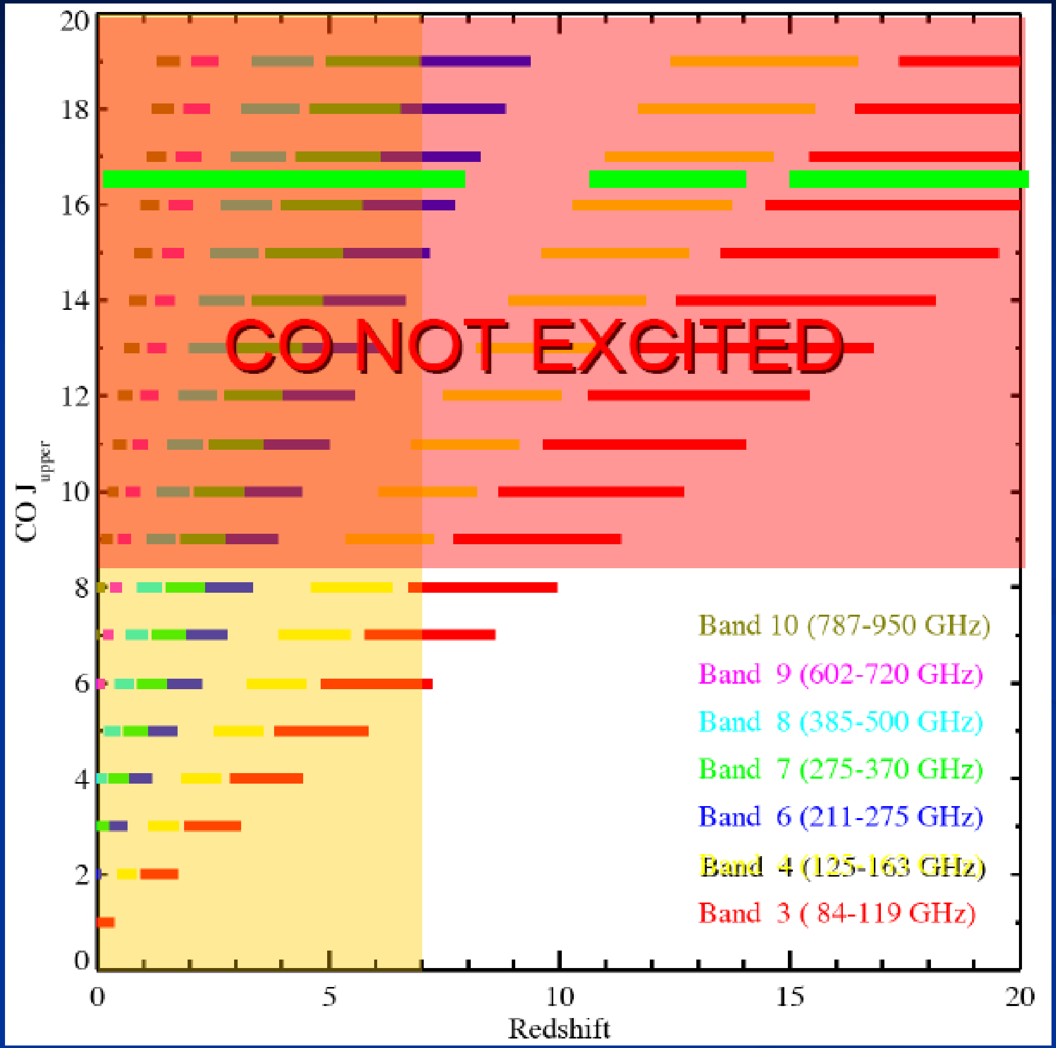
Physical processes: ALMA

- Galaxy, star and planet formation are the key science drivers
- Aside from non-thermal emission, most of what ALMA will see comes from elements heavier than H and He (except recombination lines, LiH). Therefore probe stellar products.
- Temperatures are < stellar surface – the "Cool Universe"
- Continuum: thermal emission from dust (scattered emission polarized)
- Lines: molecular rotational transitions (redshifted atomic)
- Heating via stellar UV, cosmic rays, hard photons from AGN – hence the link to star and galaxy formation
- Non-thermal mechanisms include synchrotron (lower frequencies) and Compton scattering (Sunyayev-Zeldovich).

Physical processes: SKA

- Synchrotron radiation from relativistic electrons (polarized)
- Coherent emission processes (polarized)
- Free-free emission from ionized gas
- HI
- Maser lines: OH, H_20, NH_3, SiO
- Highly redshifted molecular lines
- Recombination lines

ALMA as a redshift machine

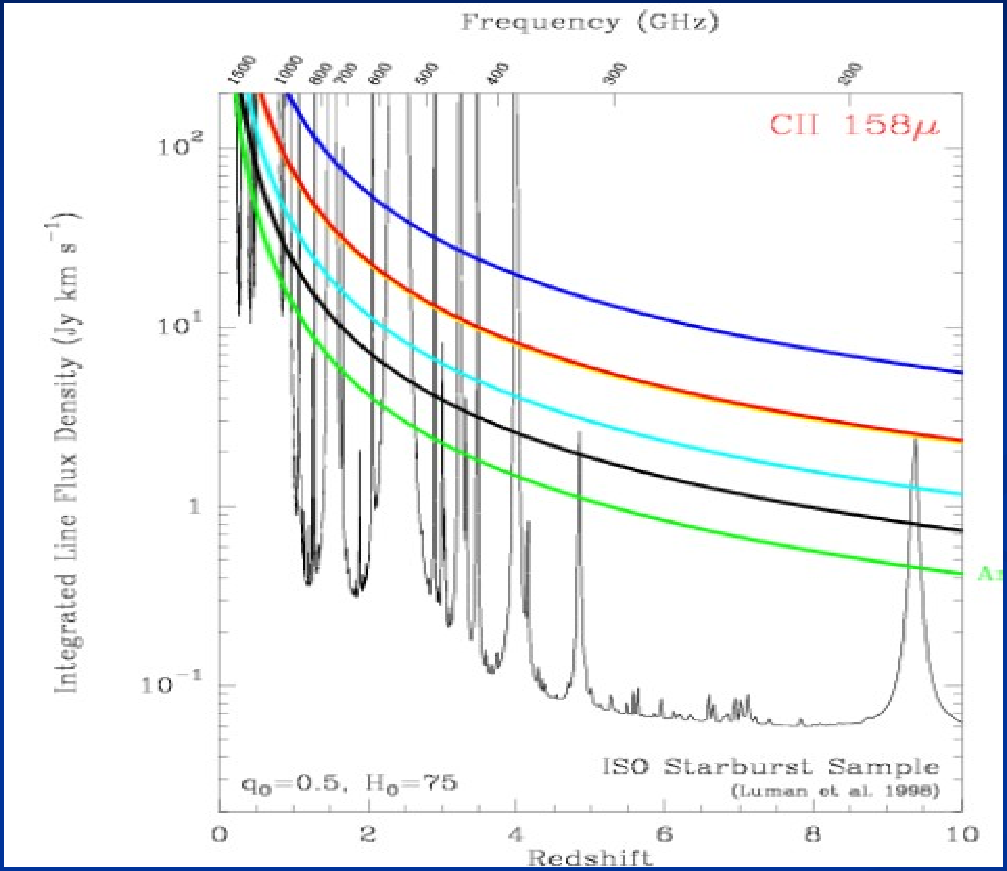


CII – line of choice for EoR studies

CO transitions for $z < 7$

F Walter, Madrid Meeting 2006

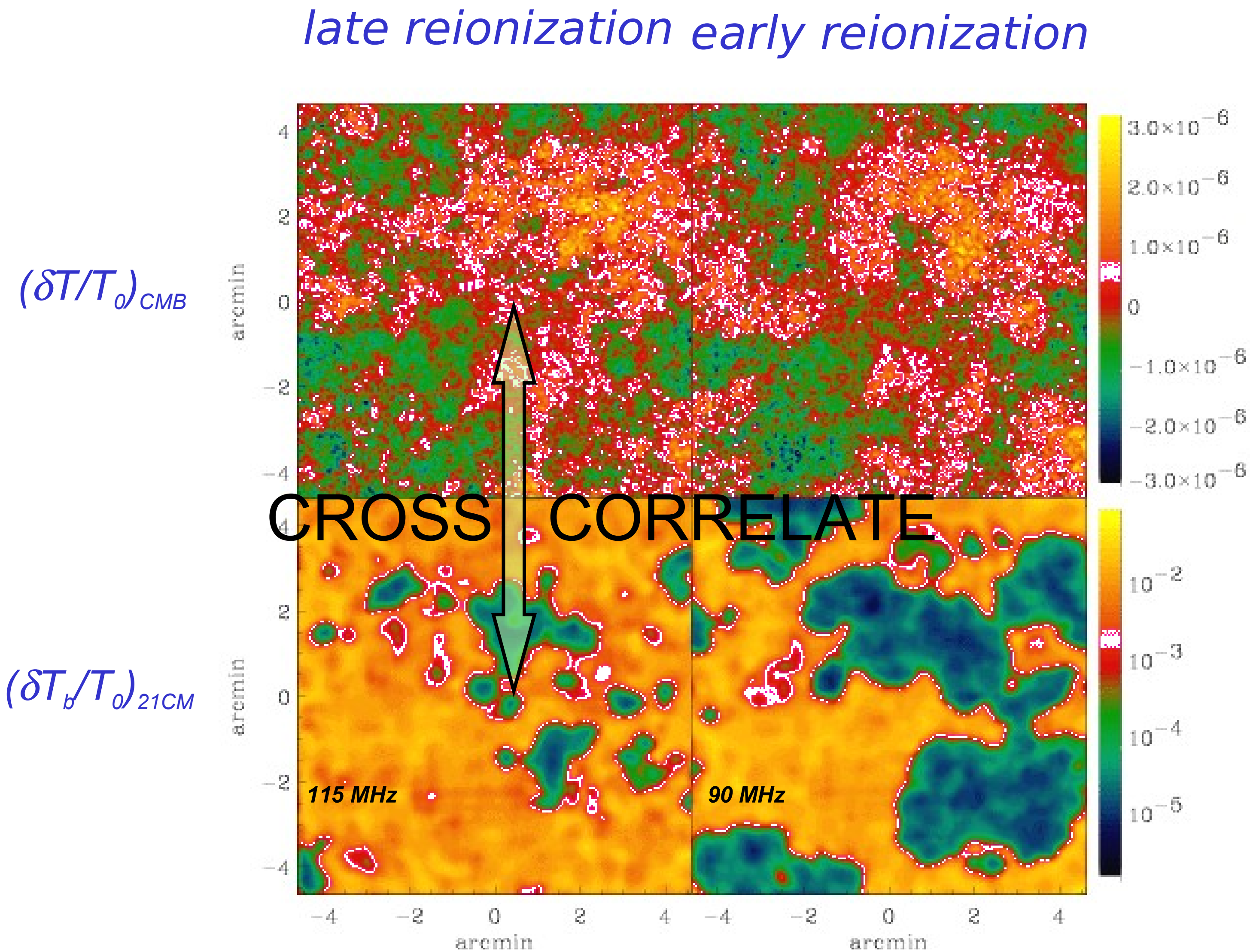
CII line at high redshift



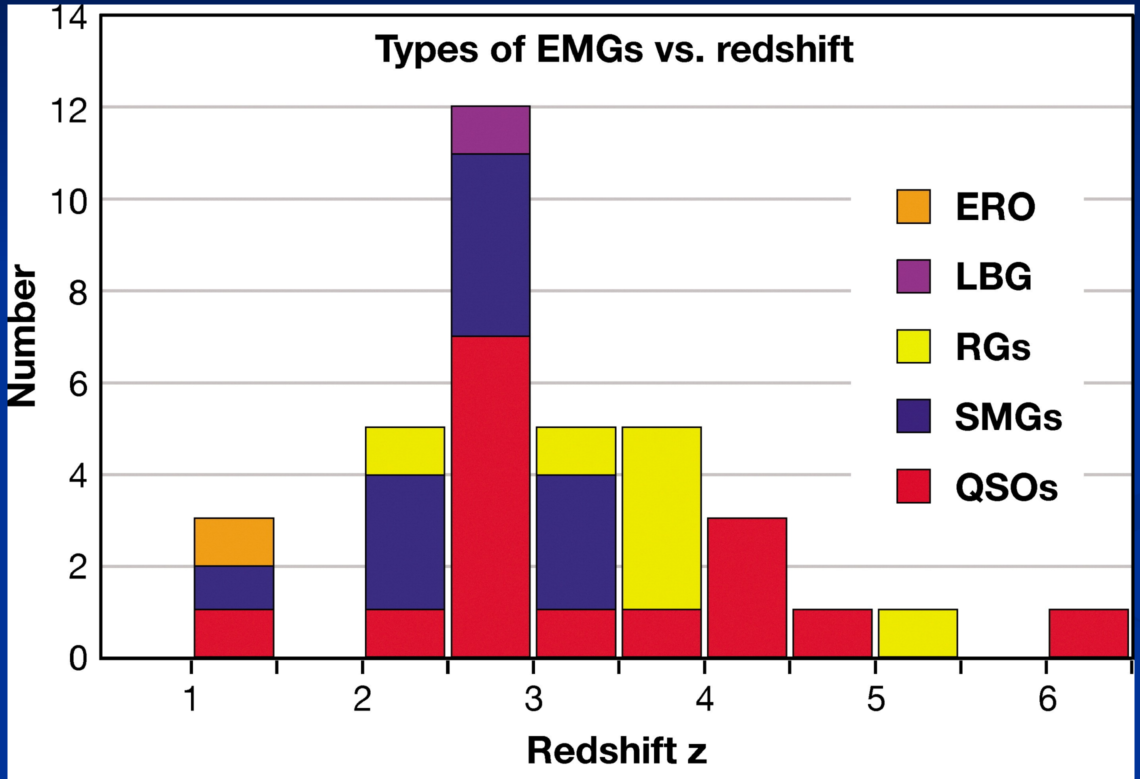
Observed flux density from CII for ultra-luminous IR galaxies compared with the ALMA sensitivity in 2 hours integration.

HINTS FROM COUPLED 21CM/CMB OBSERVATIONS

Salvaterra, Ciardi, AF & Baccigalupi 2005



Sub-mm galaxies

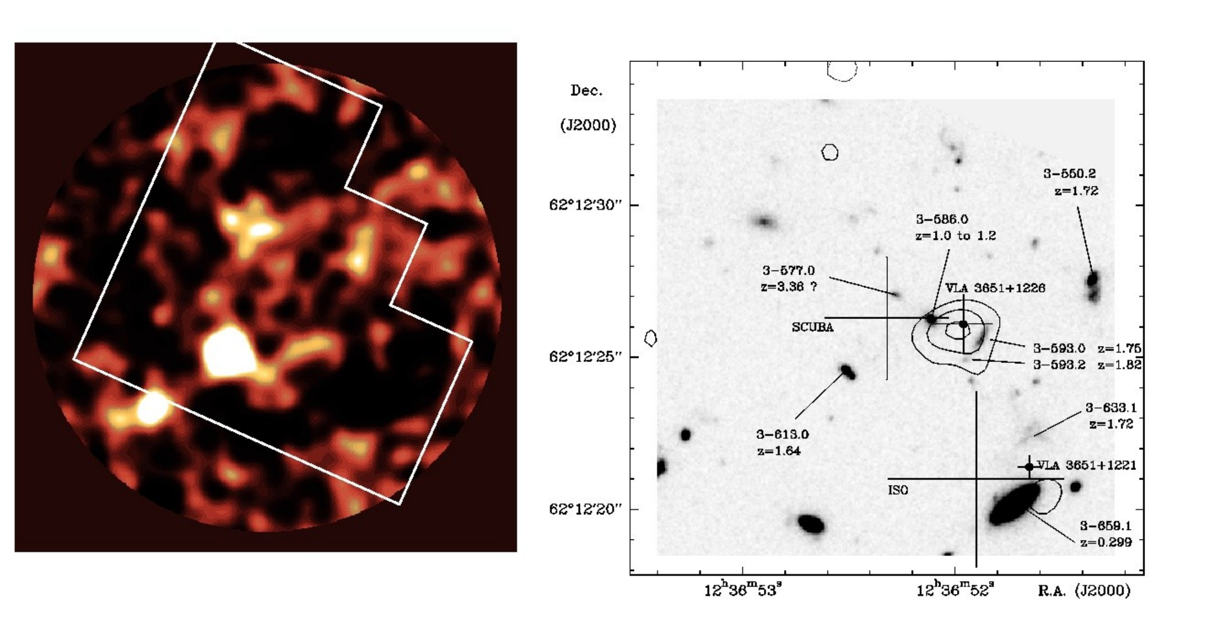


Solomon, PM and Vanden Bout, PA . 2005
Annu. Rev. Astron. Astrophys. 43: 677–725

Currently see only the most luminous and unusual examples (lensed, QSO), but we already know that large masses of molecular gas are assembled by z = 6.5.

Dust and molecular line emission should be observable by ALMA at significantly higher redshifts

Sub-mm galaxy surveys



SCUBA HDF

Optical, cm and mm sources in HDF

Bolometer surveys are usually confusion-limited

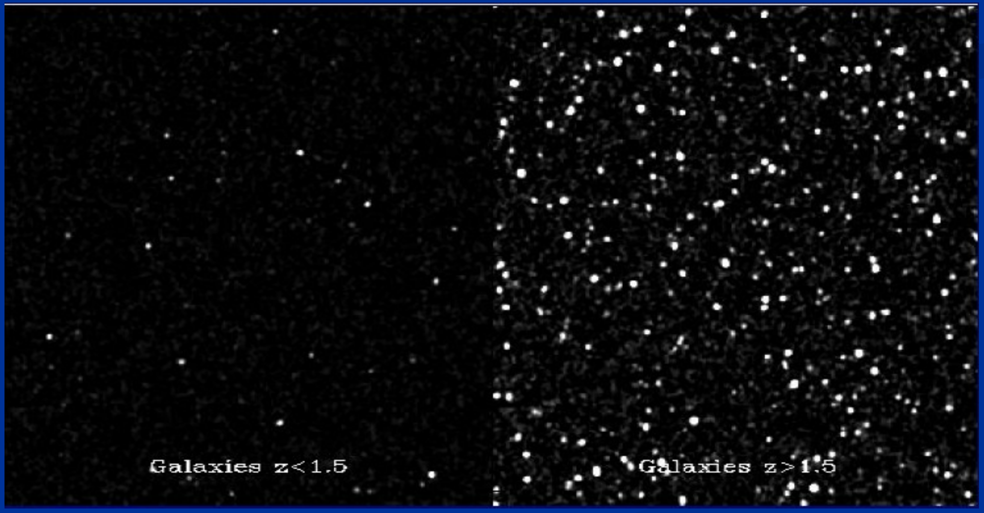
Need ALMA to follow up new surveys (SCUBA2, LABOCA) and to make its own deep surveys over small areas

Example surveys with ALMA

- Broadband continuum survey; 4 x 4 arcmin^2 at 290 GHz); 130 pointings; 30 min each; rms 20μJy, 100 – 300 sources
- Continuum, 4 x 4 arcmin^2 at 90 GHz, 16 pointings; 4 hr each; rms 1.5 μJy
- Line, 50 kms^{-1} spectral resolution, 4 centre frequencies, 4 mJy km s^{-1} for 300 km s^{-1} line, 1 CO line for z > 2, 2 for z > 6
- Then repeat at 200 GHz (6 days)

Redshift distributions

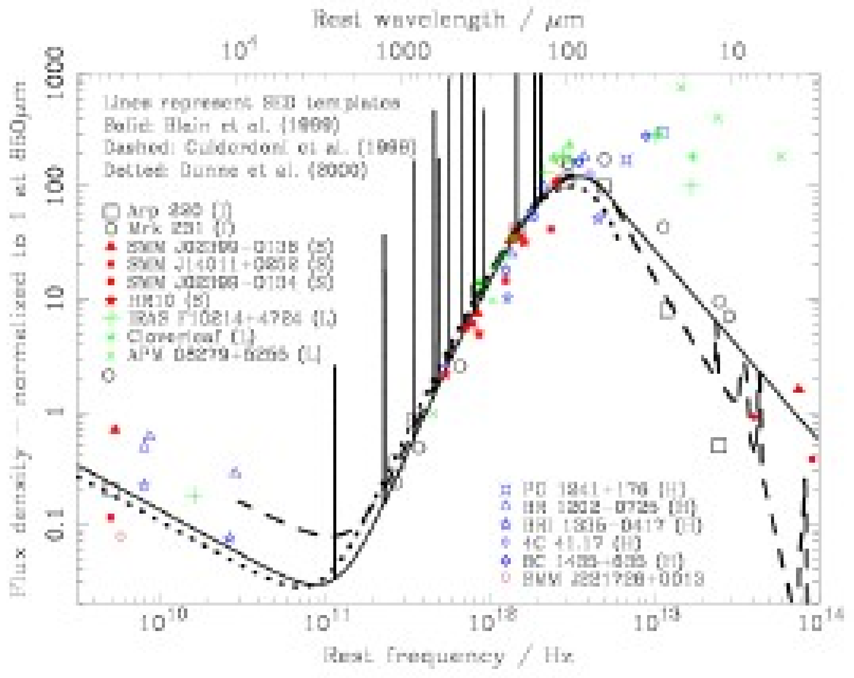
HDF optical

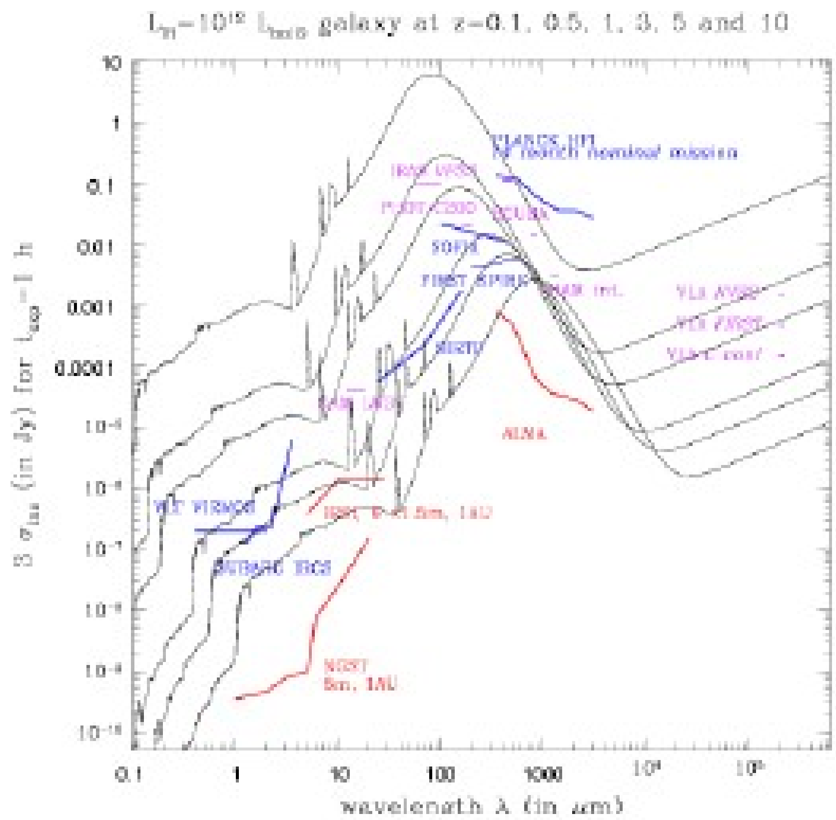


ALMA simulation

$z < 1.5$ $z > 1.5$

The sub-mm conspiracy





Spectral energy distribution of a dusty galaxy

The effect of redshift on the SED: dusty galaxies are easily detected at high z

Spectrum of a normal galaxy

z=2 in this example

$L(CO)_{1-0}$

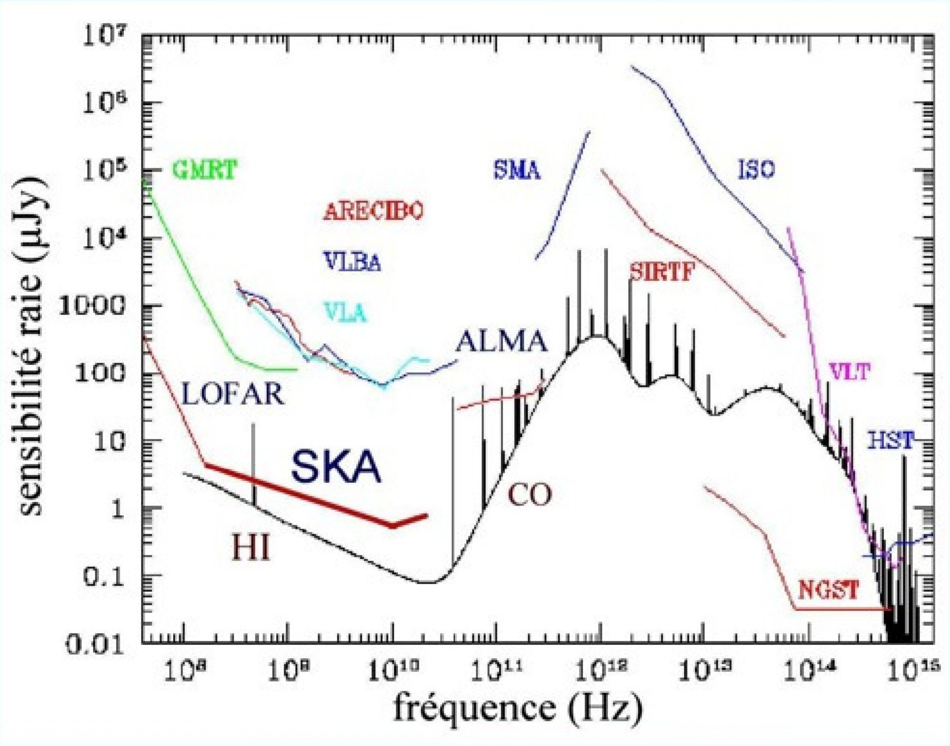
$\sim 5\times10^{8}\,\mathrm{Kkms^{-1}pc^{2}}$

$\sim L(CO)_{2-1}$

$S_{CO_{2-1}} \sim 0.1\,\mathrm{mJy}$

ALMA detects in CO

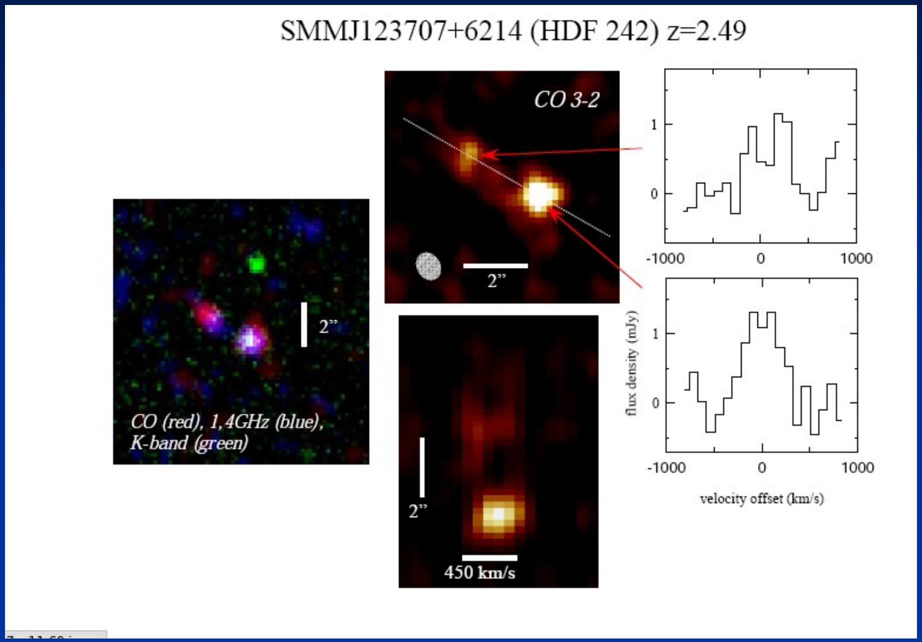
SKA in HI

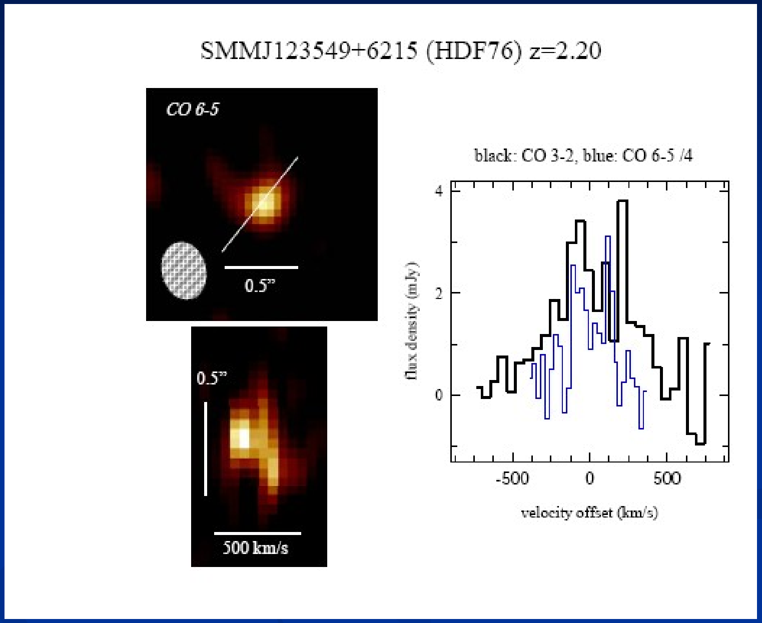


Detection of spectral lines of a 'standard' spiral galaxy at $z = 2$

5σ in 1hour

CO in z ≈ 2 sub-mm galaxies



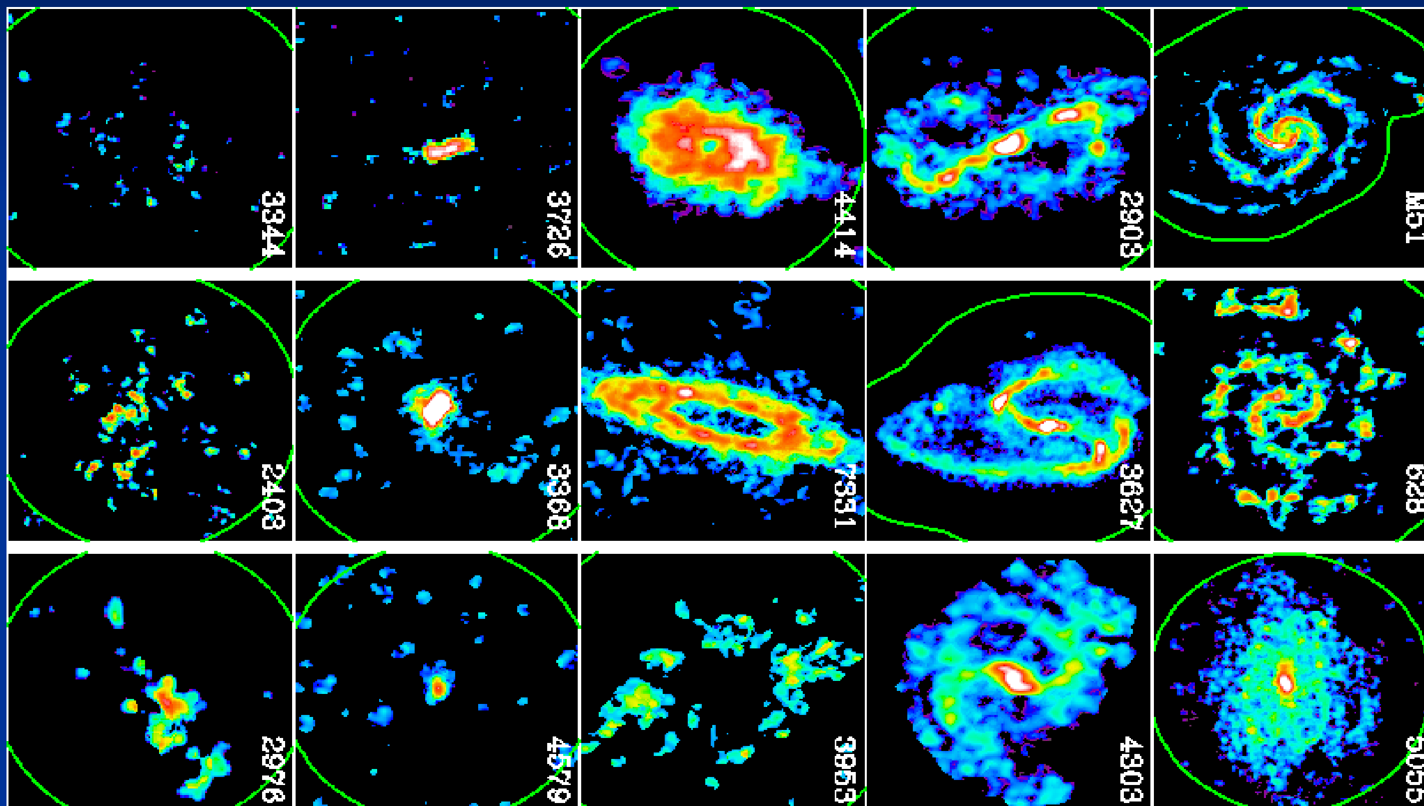


Current observations can resolve only the brightest sub-mm galaxies. These seem to be short-lived examples of maximal star formation in ongoing mergers.

Velocity fields disc-like or irregular.

Compare with molecular gas in nearby disc galaxies

RANDOM PEAKS RINGS BARS SPIRALS

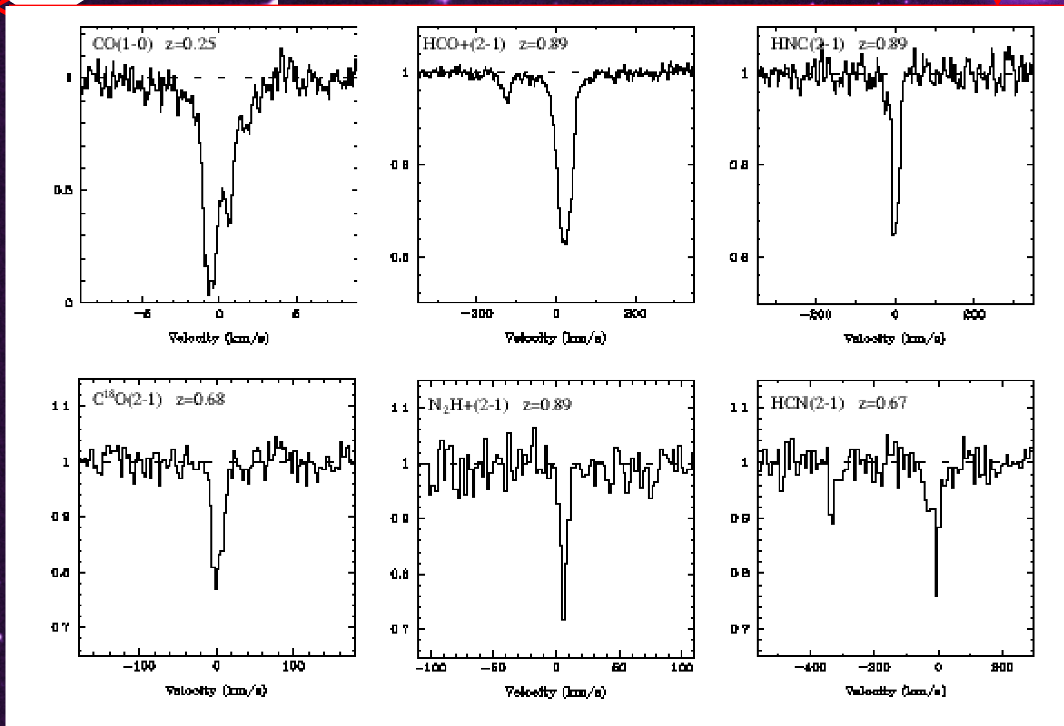


BIMA SONG

~2-6 kpc

Molecular absorption lines

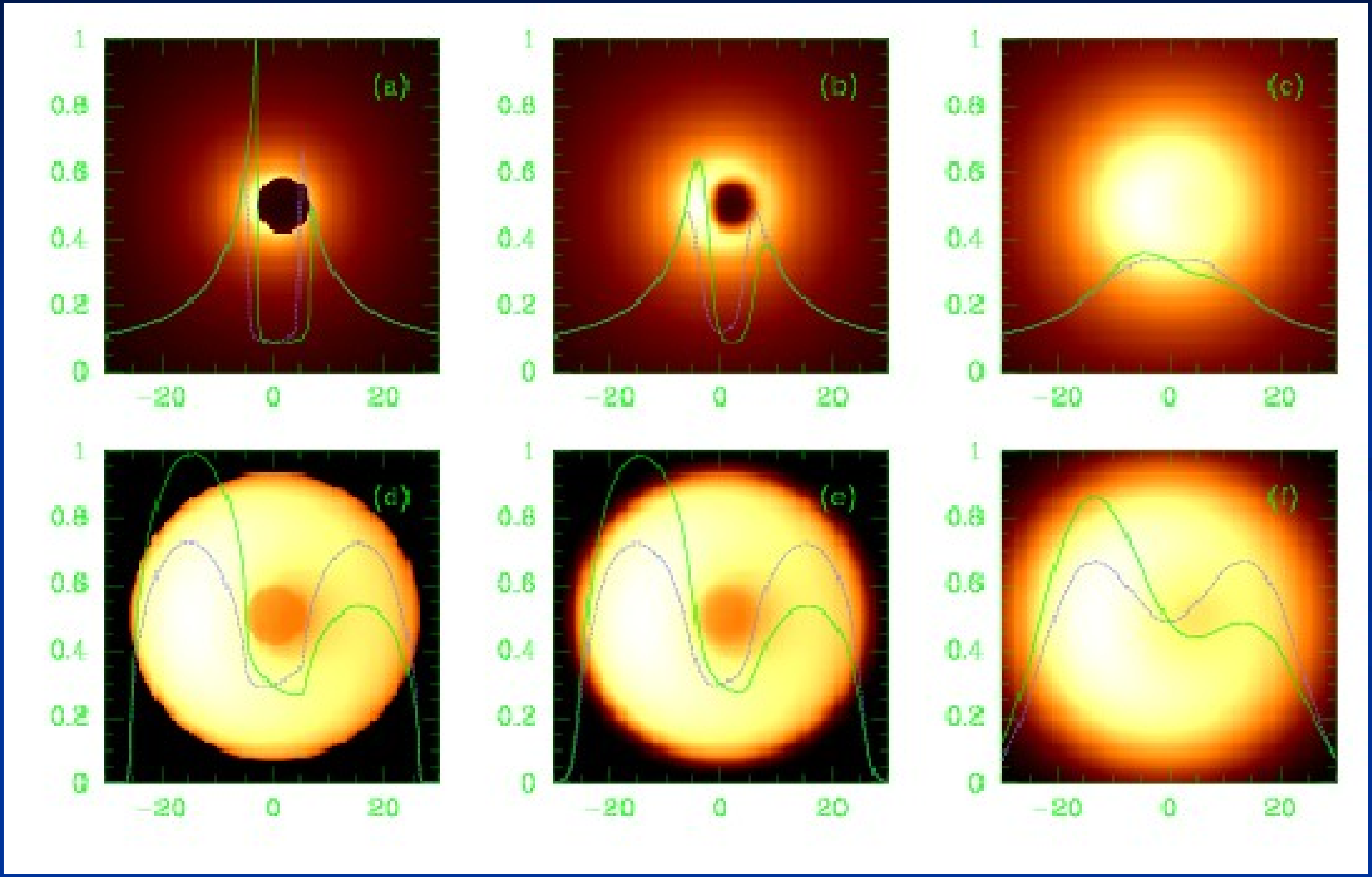
Molecular absorption lines are weak, but essential to probe the ISM in high-redshift galaxies in detail



Strong-field Gravity

- SKA will observe pulsar - black hole binaries, allowing precise tests of strong-field general relativity and measurement of black hole spin
- Observations of the timing of a large number of pulsars with SKA should allow the detection of gravitational waves
- ALMA (as the key element of a sensitive mm-wave VLBI network) will image the event horizon around the nearest supermassive black holes (Sgr A* and M87).

VLBI observations of Sgr A*



Kerr (spinning) black hole

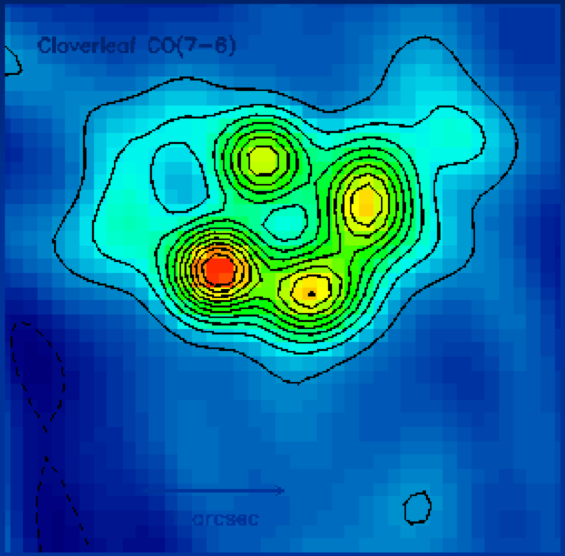
Schwarzschild (non-rotating) black hole

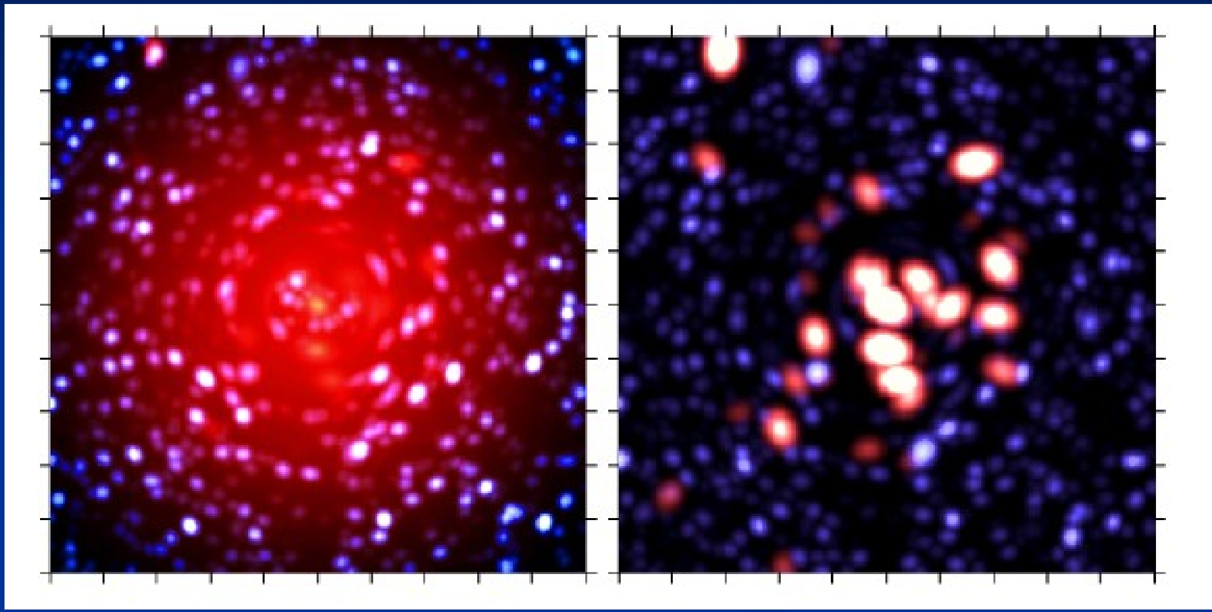
GR ray tracing

0.6mm VLBI

1.3mm VLBI

Gravitational lensing with ALMA



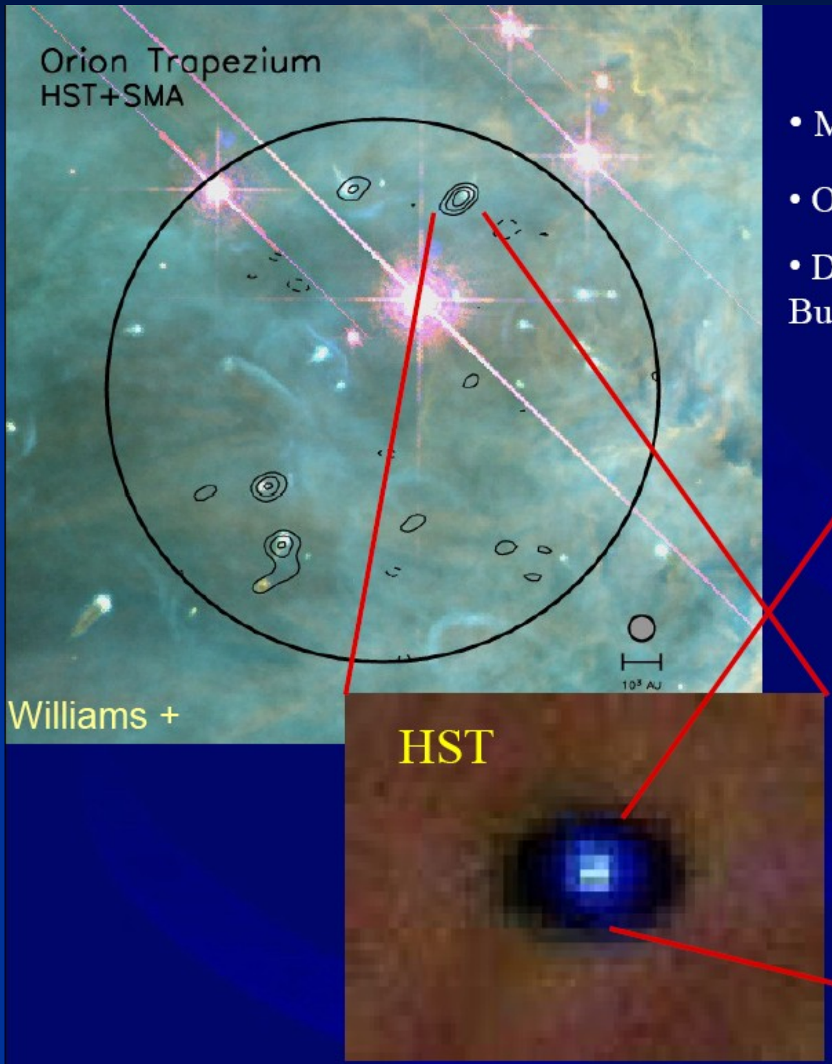


Cloverleaf quasar observed with Plateau de Bure interferometer

Simulated ALMA image of cluster lensing

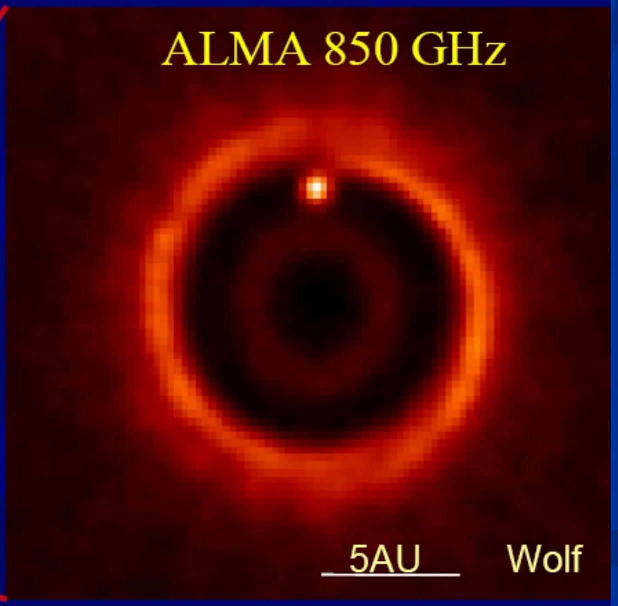
Optical R band

Protoplanetary discs with ALMA

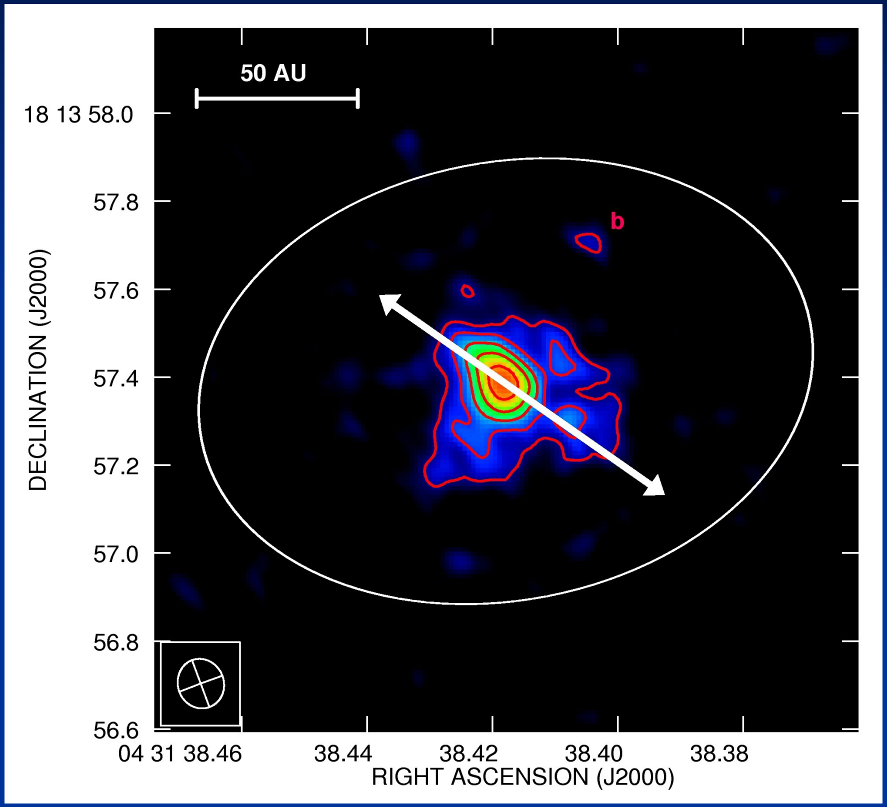


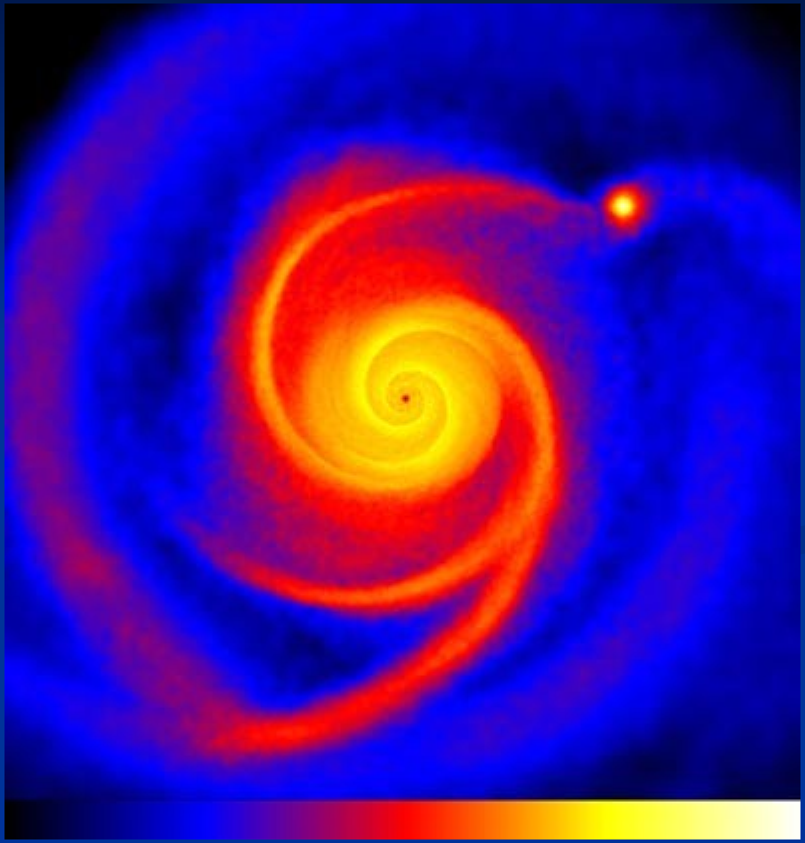
Birth of planets

- $M_{planet} / M_{star} = 1.0\ M_{Jup} / .5\ M_{sun}$
- Orbital radius: 5AU at 50pc distance
- Disk mass = circumstellar disk around the Butterfly Star in Taurus



Protoplanetary discs with SKA





VLA + Pie Town 43GHz Simulation
HL Tau b: a very young planet? (Greaves, Richards et al. 2008)

ALMA or SKA?

- Both arrays can resolve protoplanetary discs around the nearest stars
- Expect to detect gaps caused by Jupiter-mass planets
- May also be able to see heated dust associated with forming giant planets
- Which frequency to use depends on the distribution of grain sizes: we know that debris discs radiate at 1mm; we also know that HL Tau b is clearly visible at 1cm.

Try both and see

Summary

- ALMA is coming shortly. It will give a huge improvement in sensitivity, resolution and frequency coverage over existing instruments.
- ALMA and SKA are complementary.
- We need to ensure that this complementarity can be exploited: SKA must allow high resolution and high frequencies.