Science with ALMA

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thanks to all ALMA colleagues

ALMA
EUROPEAN ARC
ALMA Regional Centre || UK

e-MERLIN
IVOA
EUROPEAN NETWORK
RadioNet

MANCHESTER 1824
UNIVERSITY OF OXFORD
UNIVERSITY OF CAMBRIDGE
UK Astronomy Technology Centre
Rutherford Appleton Laboratory
Science & Technology Facilities Council

What is ALMA?

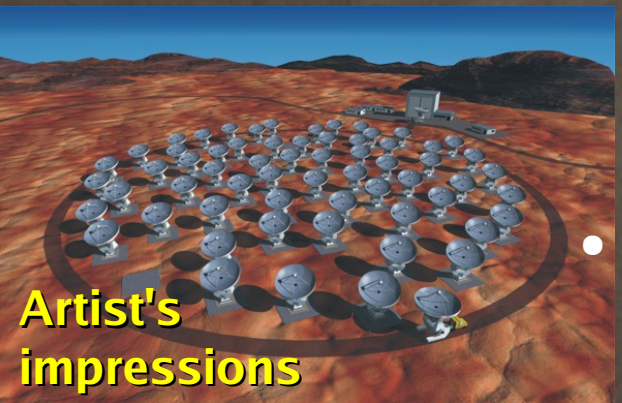
- Atacama Large Millimeter/sub-mm Array
  - Chile, ESO, North America, Japan, Taiwan consortium
- The most ambitious ground-based telescope to date
- 50 12-m antennas for main array
  - Made by US and European consortia
- 12 7-m antennas for compact array
- 4 12-m total power
  - Japanese consortium
- Flexible correlator
  - Up to 8 GHz instantaneous bandwidth (full polarisation)
  - < 0.1 km s^{-1} spectral resolution

Where is ALMA?

- Chajnantor plateau, Atacama Desert, Chile
  - 5000 m altitude
    - Highest workplace apart from Everest Post Office!
  - Driest place on Earth (apart from Antarctica)
  - Precipitable water vapour (PWV) ≥0.1 mm
- Near APEX, ASTE, etc.

Flexible reconfiguration

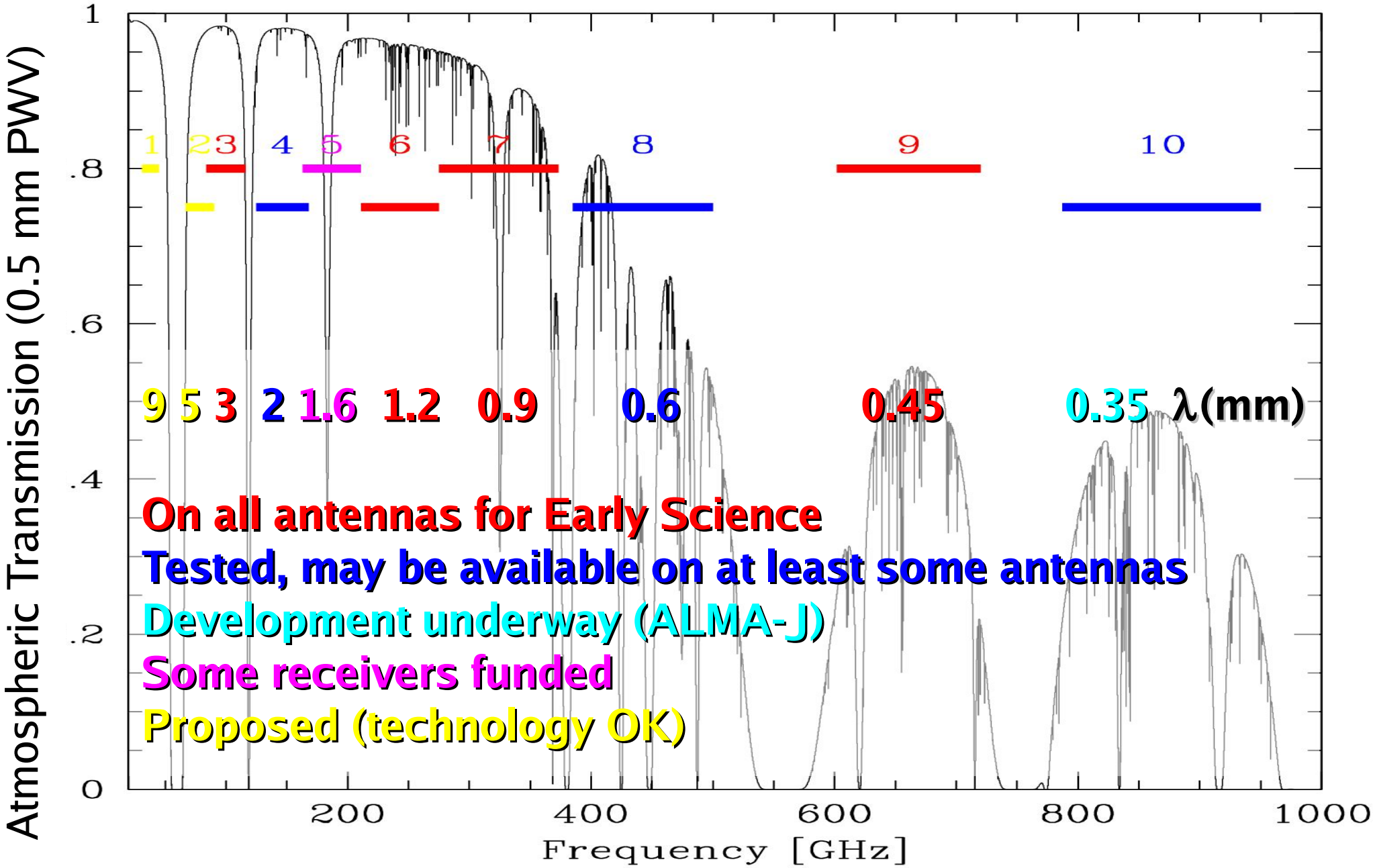
- 25m to ~15 km baselines in full operation
  - Resolution/arcsec: 0.2 (λ/mm) / (max baseline/km)
  - 0.8 –6 arcsec @ λ0.4 - 3 mm, 0.1-km baseline
  - 0.005 - 0.04 arcsec @ λ0.4 –3 mm, 15-km baseline
- FoV/asec: 12-m dish 17(λ/mm); 7-m 29(λ/mm)
  - 7 –50 arcsec @ λ0.4 - 3 mm, 12-m dishes
    - Mosaicing, single dish fill-in



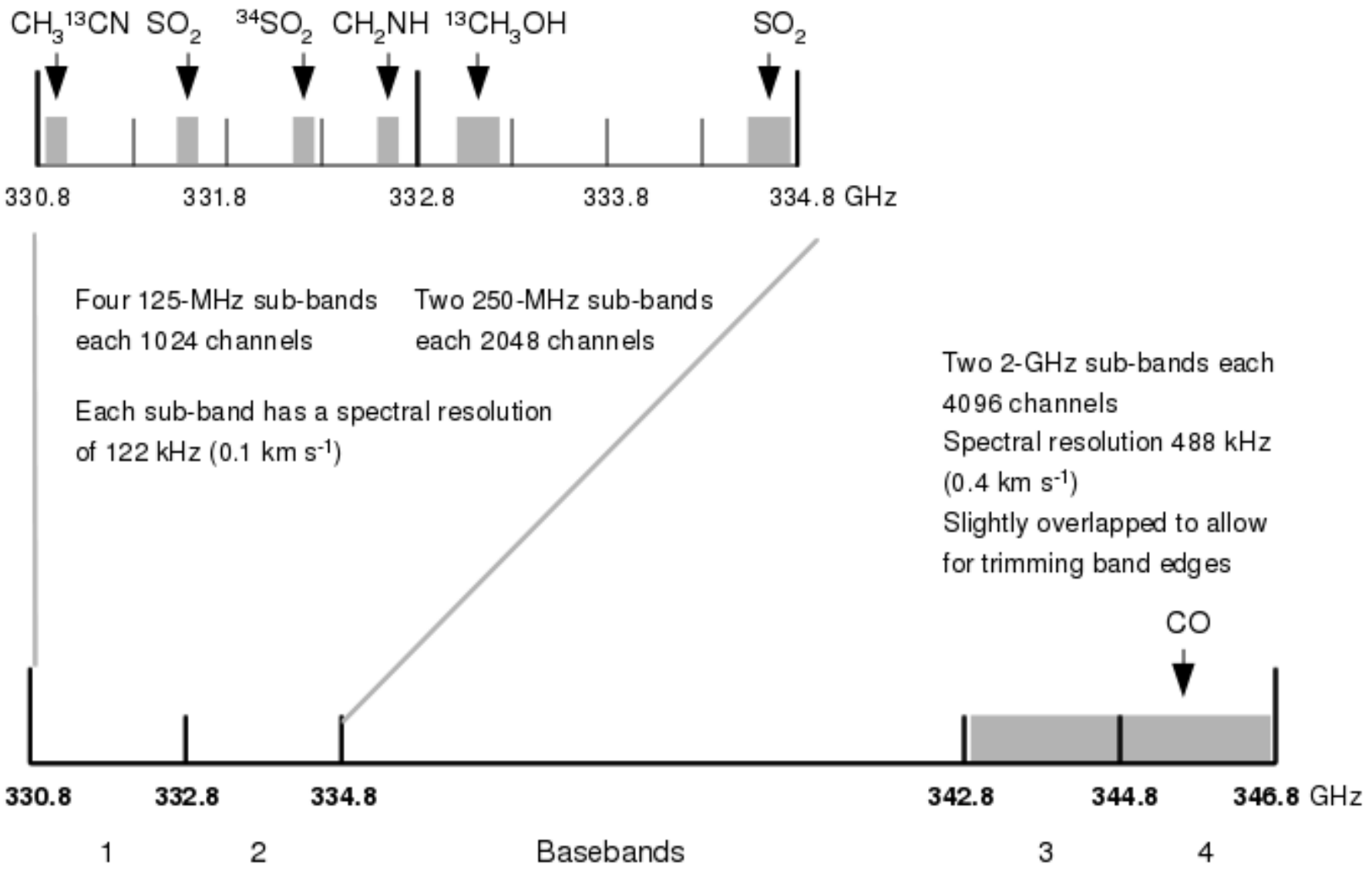
Artist's impressions

- Closest pads 15-m separation
  - Nearly filled aperture at asec resolution

ALMA Receiver Bands



Frequency flexibility



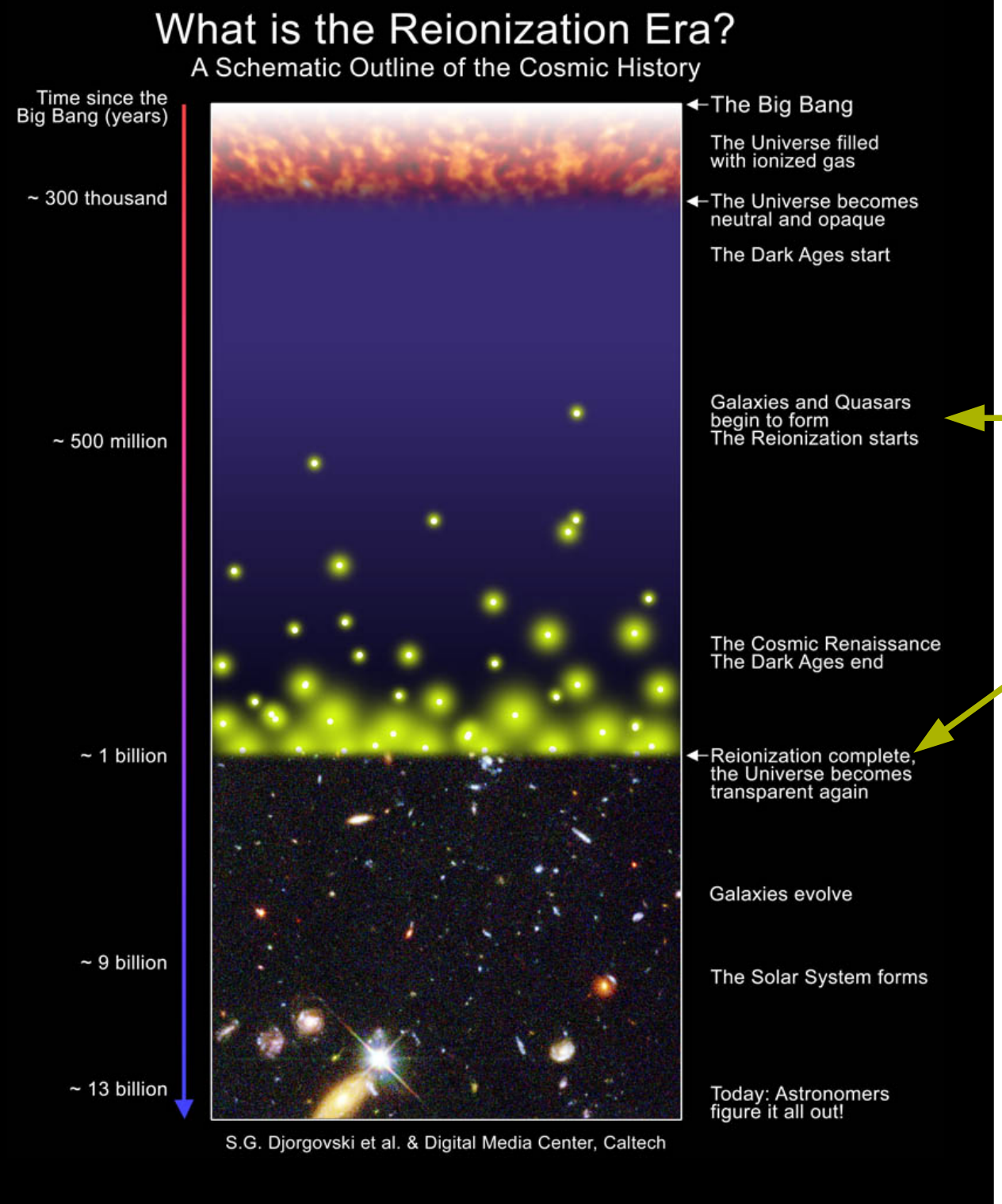
Surface brightness sensitivity

60 sec, full array (10 min Early Science)					Compact		Most Extended	
Band	Frequency	Primary Beam (FOV; ")	Largest Scale (")	Continuum Sensitivity (mJy)	Angular Resolution (")	ΔT_{line} (K)	Angular Resolution (")	ΔT_{line} (K)
Band 1	*31.3 - 45 GHz*			8 GHz		1 km s^{-1}		1 km s^{-1}
Band 2	*67 -90 GHz*							
Band 3	*84 - 116 GHz*	*56*	*37*	*0.05*	*3.18*	*0.07*	*0.038*	*482*
Band 4	*125 - 163 GHz*	*48*	*32*	*0.06*	*2.5*	*0.071*	*0.03*	*495*
Band 5	*163 - 211 GHz*	*35*	*23*					
Band 6	*211 - 275 GHz*	*27*	*18*	*0.10*	*1.52*	*0.104*	*0.018*	*709*
Band 7	*275 - 373 GHz*	*18*	*12*	*0.20*	*1.01*	*0.167*	*0.012*	*1128*
Band 8	*385 - 500 GHz*	*12*	*9*	*0.40*	*0.86*	*0.234*	*0.01*	*1569*
Band 9	*602 - 720 GHz*	*9*	*6*	*0.69*	*0.52*	*0.641*	*0.006*	*4305*
Band 10	*787 - 950 GHz*	*7*	*5*	*1.1*	*0.38*	*0.940*	*0.005*	

To be developed in the future. Available for early science.

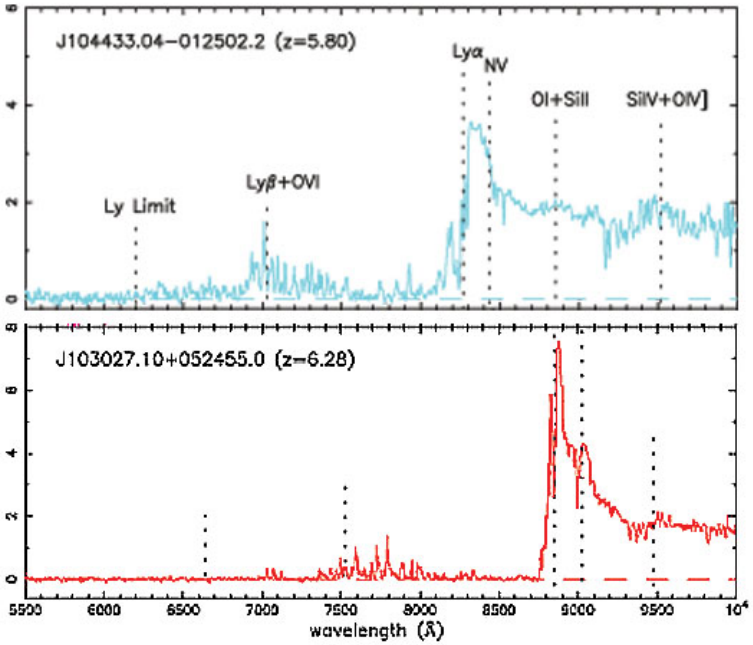
Why ALMA?

- The Cool Universe
  - Sensitive to temperatures << stellar surfaces
  - Galaxy, star and planet formation
- Detect spectral line emission from CO or C+ in a normal galaxy like the Milky-Way at *z*~3 in <24 hr
- Image the gas kinematics of protoplanetary discs/ protostars in the nearest star-forming clouds
  - Physics, chemistry, magnetic field structures
  - Tidal gaps due to planet formation
- Precise imaging at 0.1 arcsec resolution



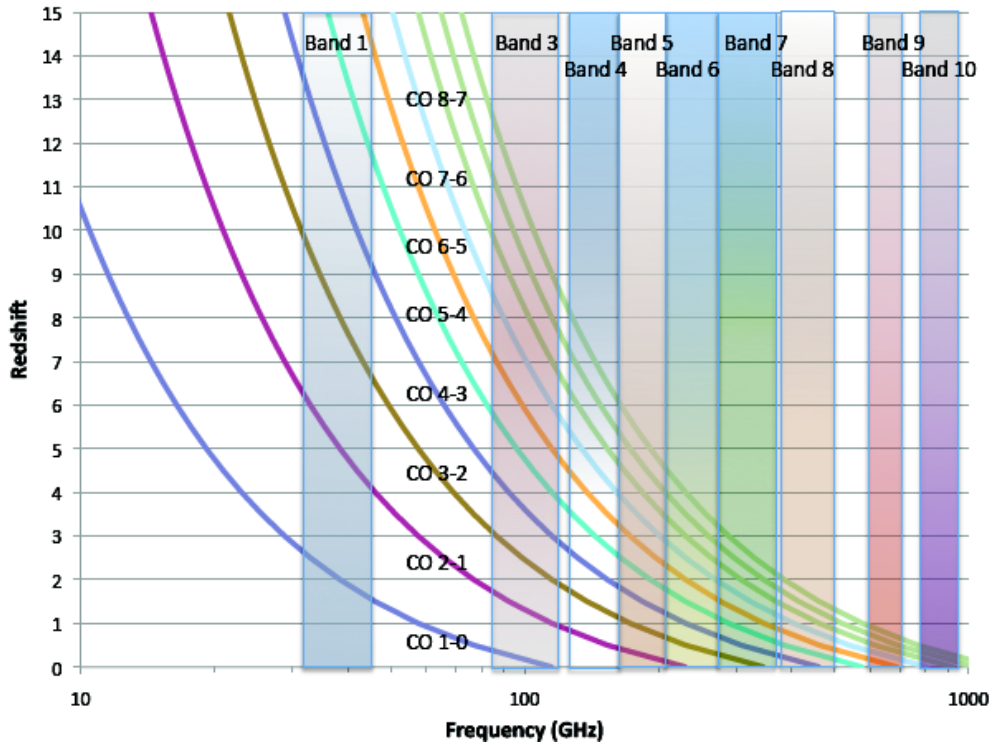
The end of reionisation

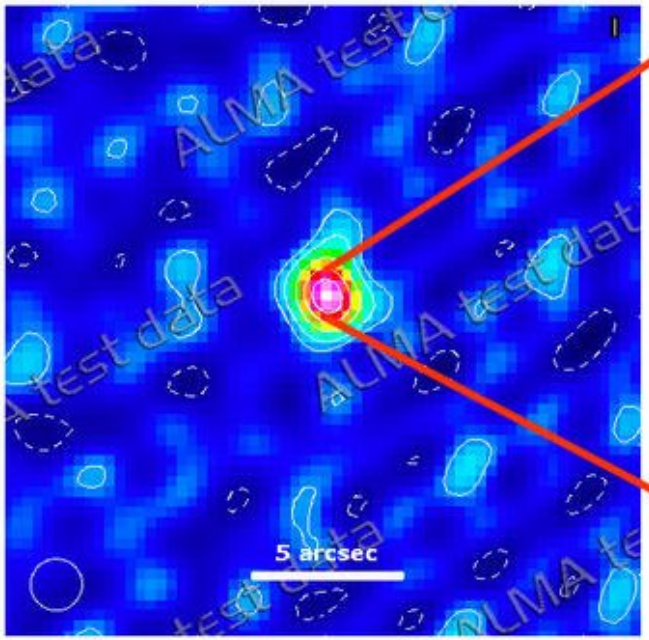
- High electron scattering τ to CMB (WMAP)
  - EOR start z~20?
- Shart rise in neutral IGM z~6 (SDSS)
  - EOR end z~6?

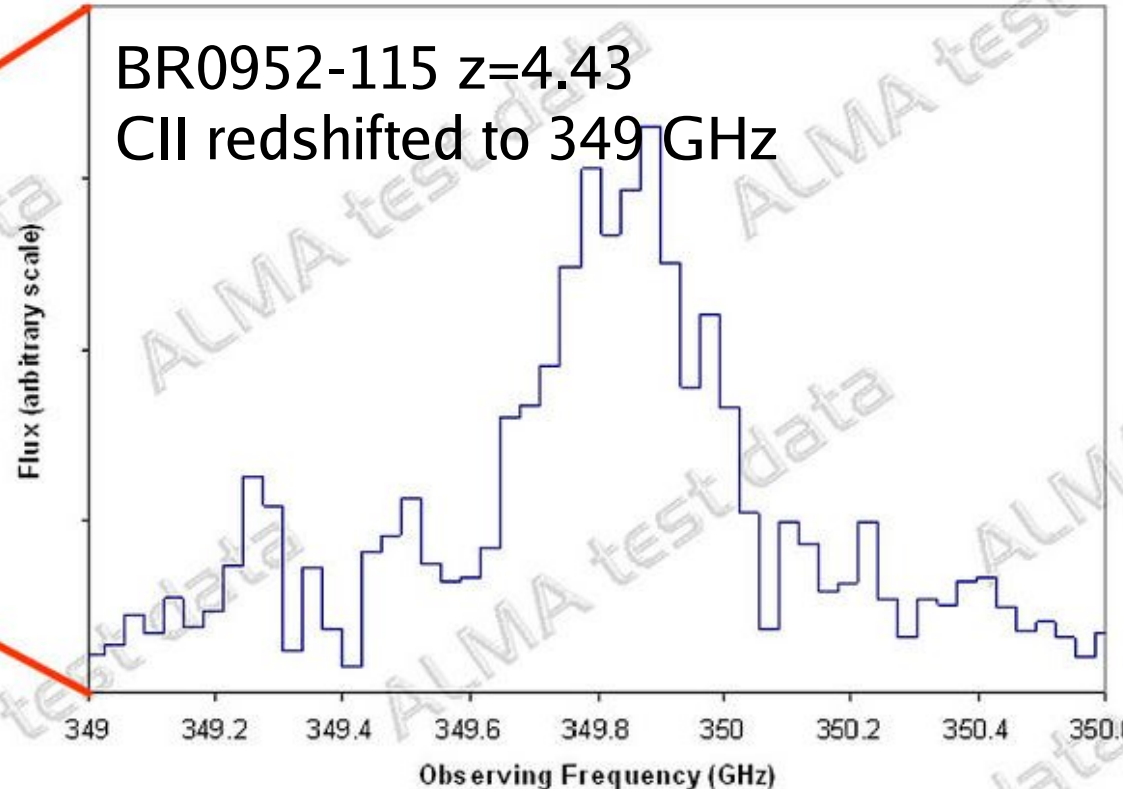


The first galaxies

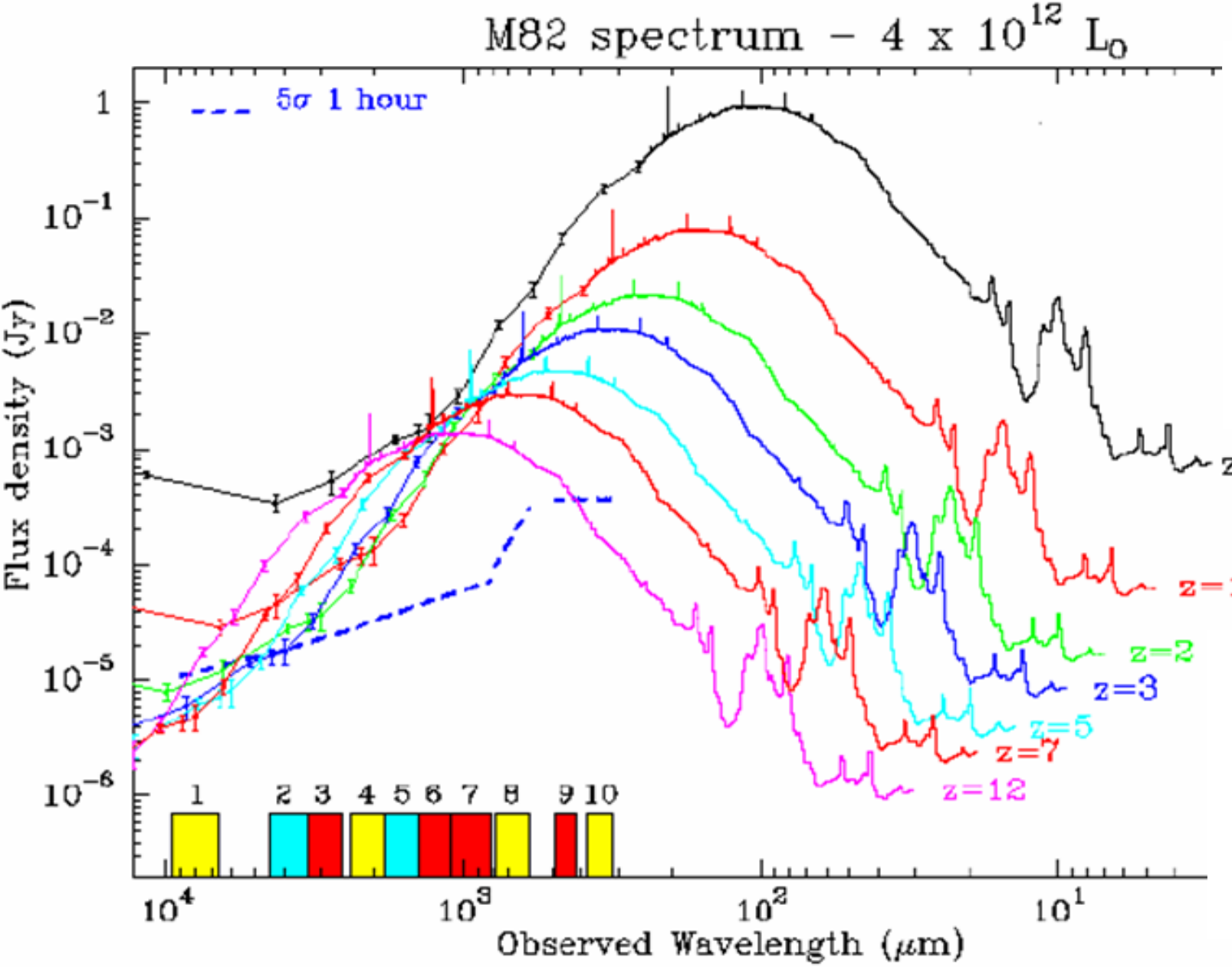
- CO lines at all redshifts
- CII – EOR studies
  - Main Milky Way coolant
  - λ rest 0.158 mm
- Early ALMA detection







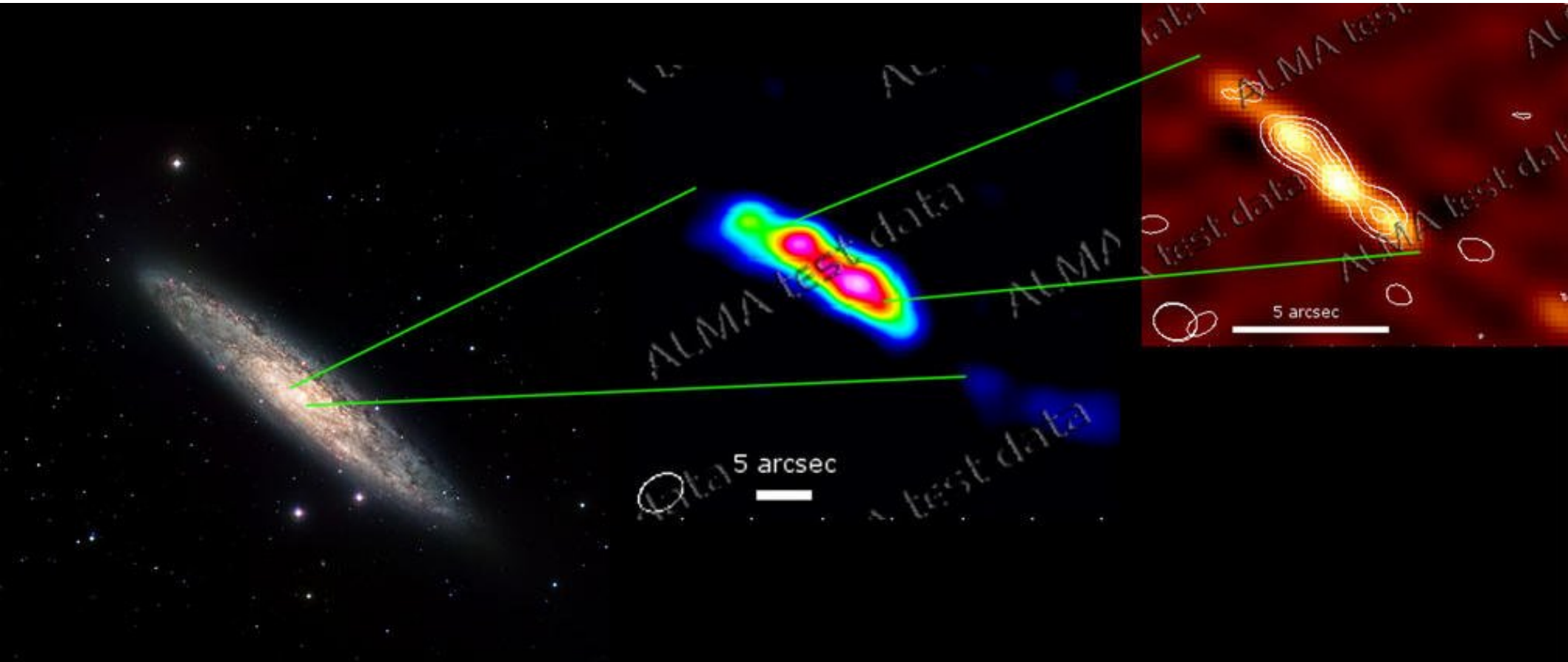
The sub-mm conspiracy



- Dust peak shifted into more sensitive ALMA bands from $z = 0.1$ to $z = 12$
- Detect dusty starbursts anywhere in the universe!

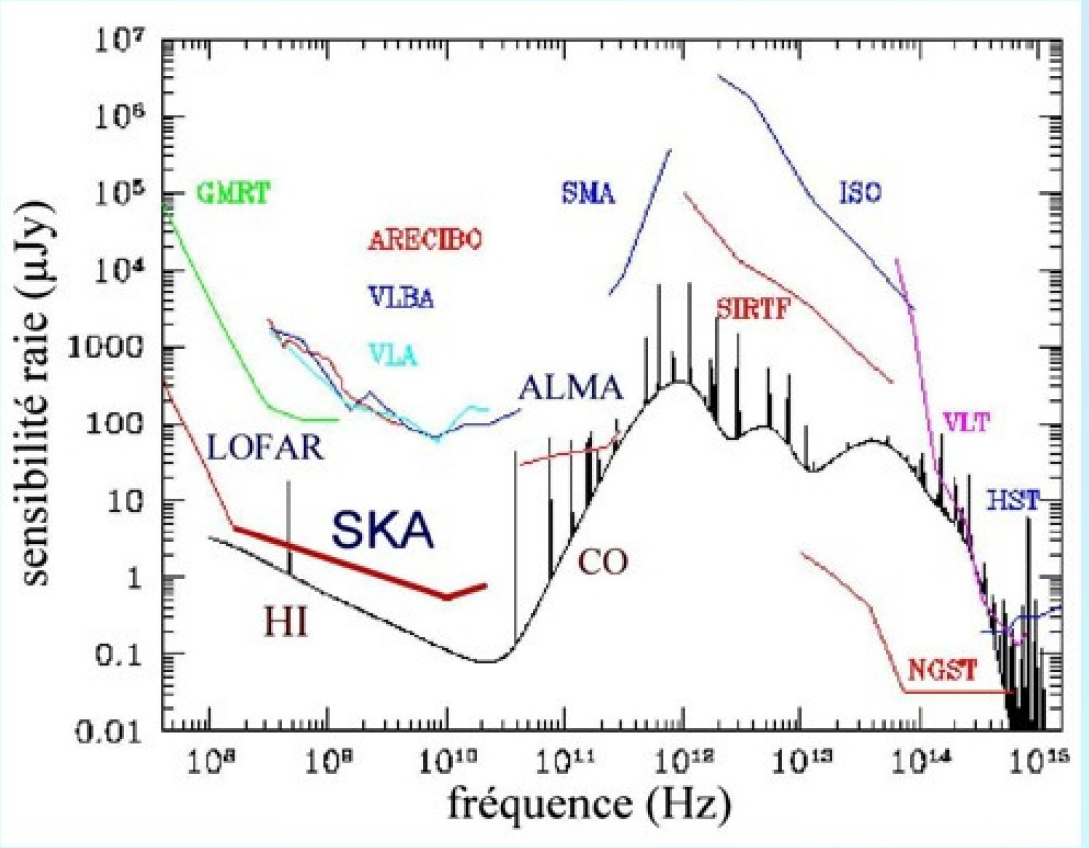
Southern starburst NGC 253

- Few hrs ALMA commissioning data, 4-6 antennas
  - Dust and CO
    - Well-resolved J=3-2 at 345 GHz and J=6-5 at 690 GHz



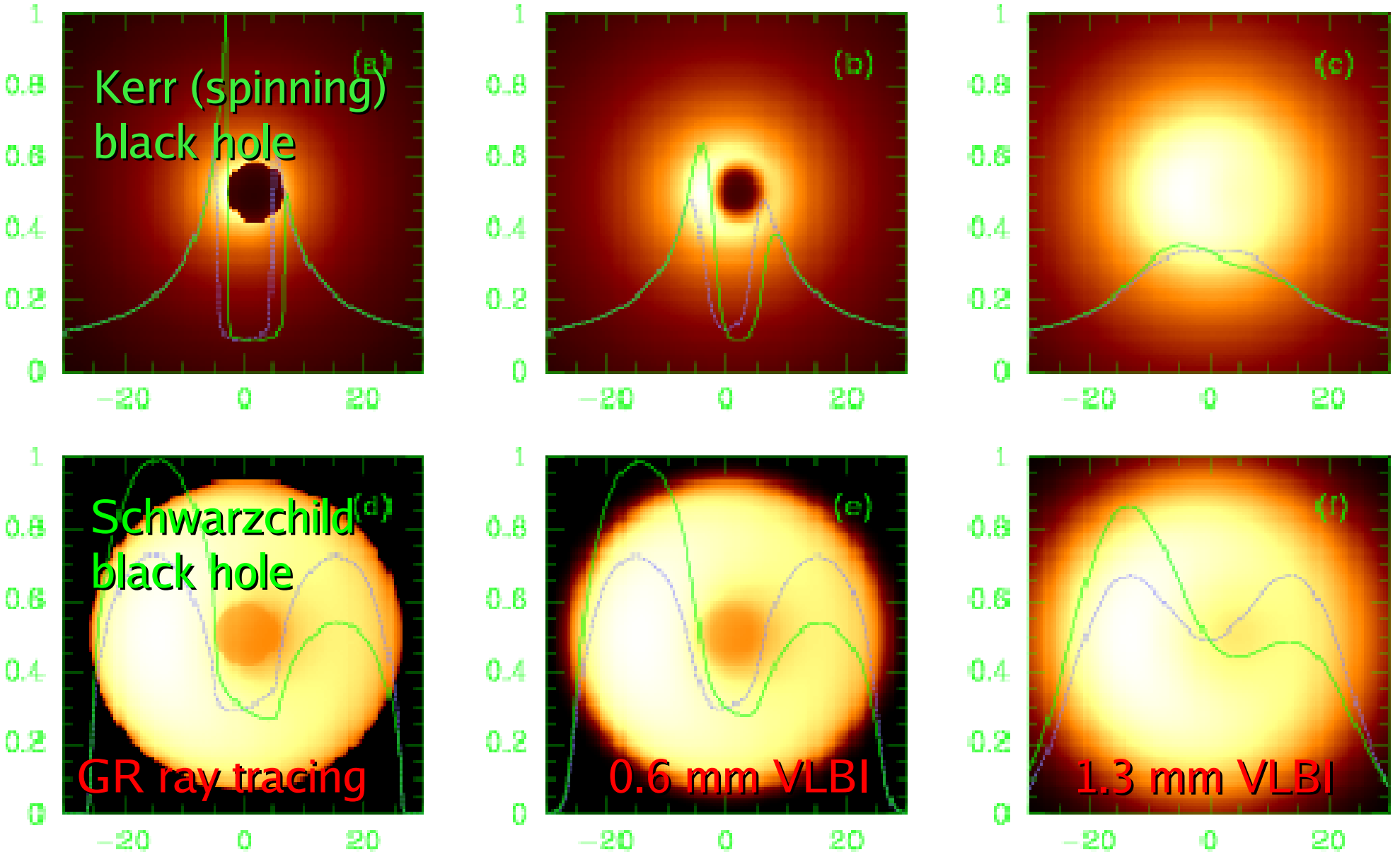
'Normal' galaxies

- 'Standard' spiral
  - $z = 2$
  - CO detection 5σ in 1 hour
  - Imaging in full track (12-24 hr)

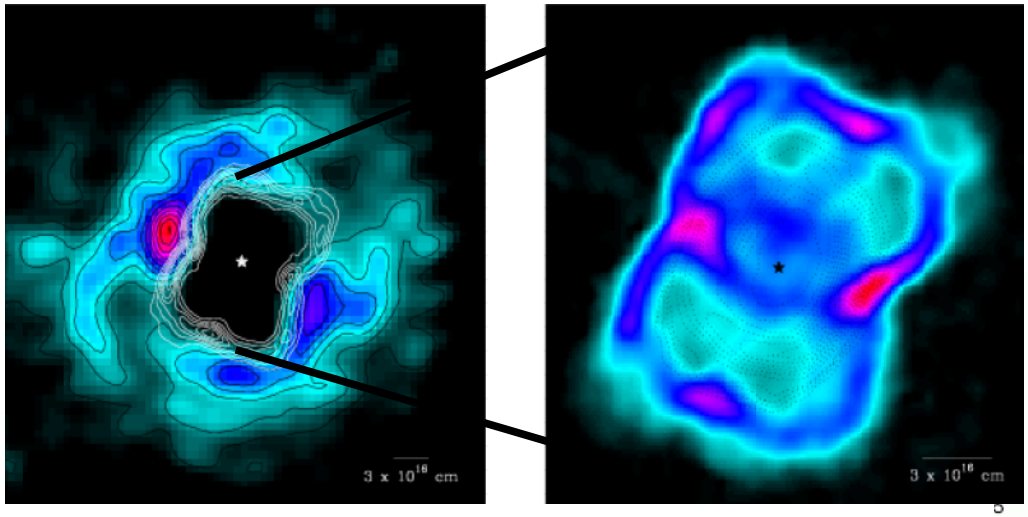


- L(CO J=1-0 or 2-1) ~ 5×10^8 K km s^{-1} pc^2
  - *S*(CO J=2-1) ~ 0.1 mJy
- ALMA will image CO in SKA HI-detected galaxies

VLBI testing GR: Sgr A* (or M87)

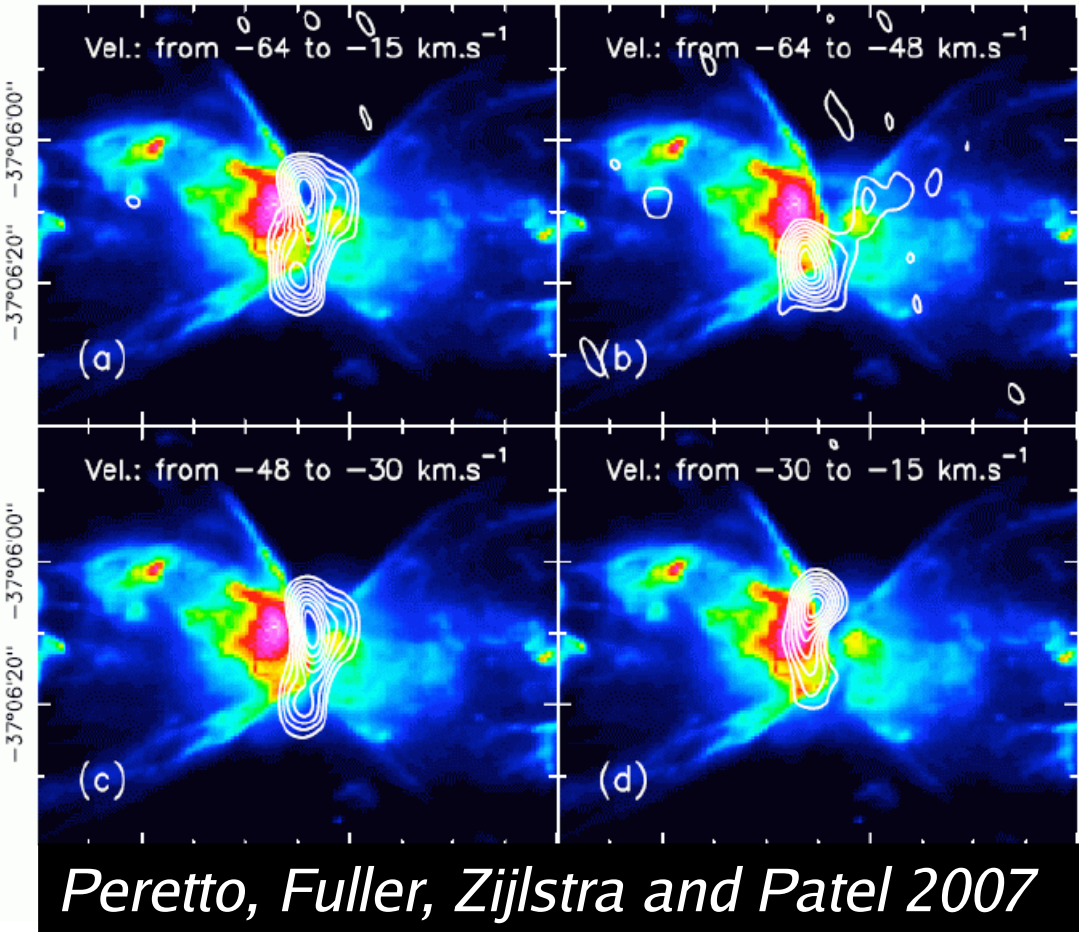


How are PNe collimated?



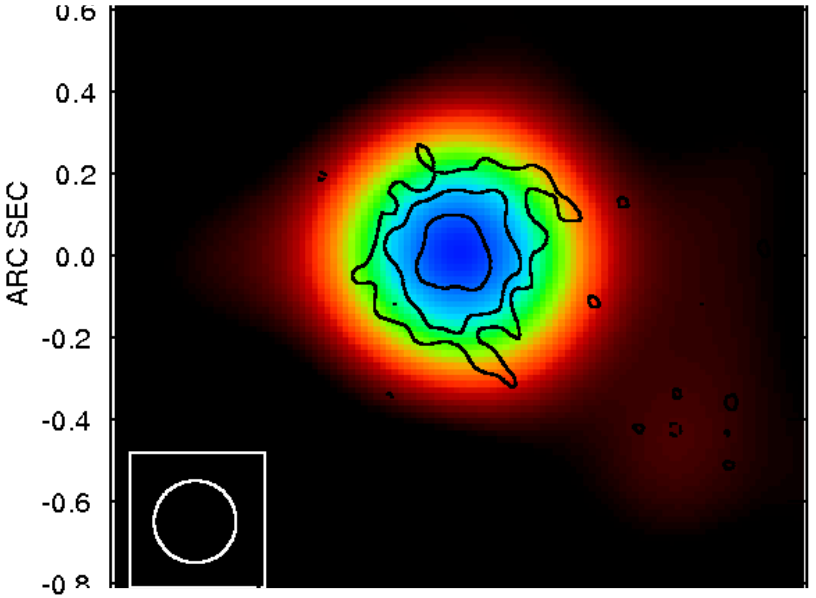
- NGC 7027 hidden bicone
  - Cool AGB CO surrounds H_2 (NIR, white contours) tracing wind collision PDR
  - Zoom shows offset rings

- SMA reveals molecular torus in NGC 6302



Peretto, Fuller, Zijlstra and Patel 2007

Resolving evolved star mass loss

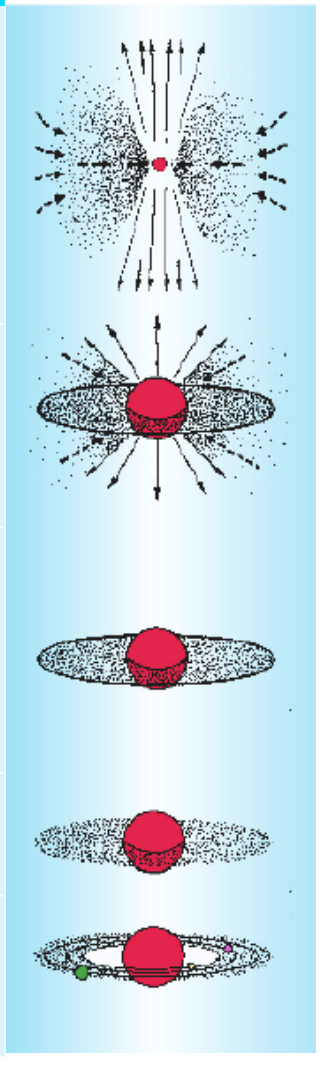


- α Ori MERLIN+VLA
  - So far, only well-resolved star apart from Sun
  - 10+ AGB/RSG accessible to ALMA, EVLA, e-MERLIN

- Pulsations levitate cool layers
- Radiation pressure on dust drives wind
- Winds are clumpy
  - Convection cell scales?
  - Starspots/ magnetic effects?
- Observe ~monthly at increasing wavelength
  - Image successively higher layers
    - Coordinated peturbations imply pulsation dominates
    - Irregularities imply convection
- Are clumps chemically distinct?

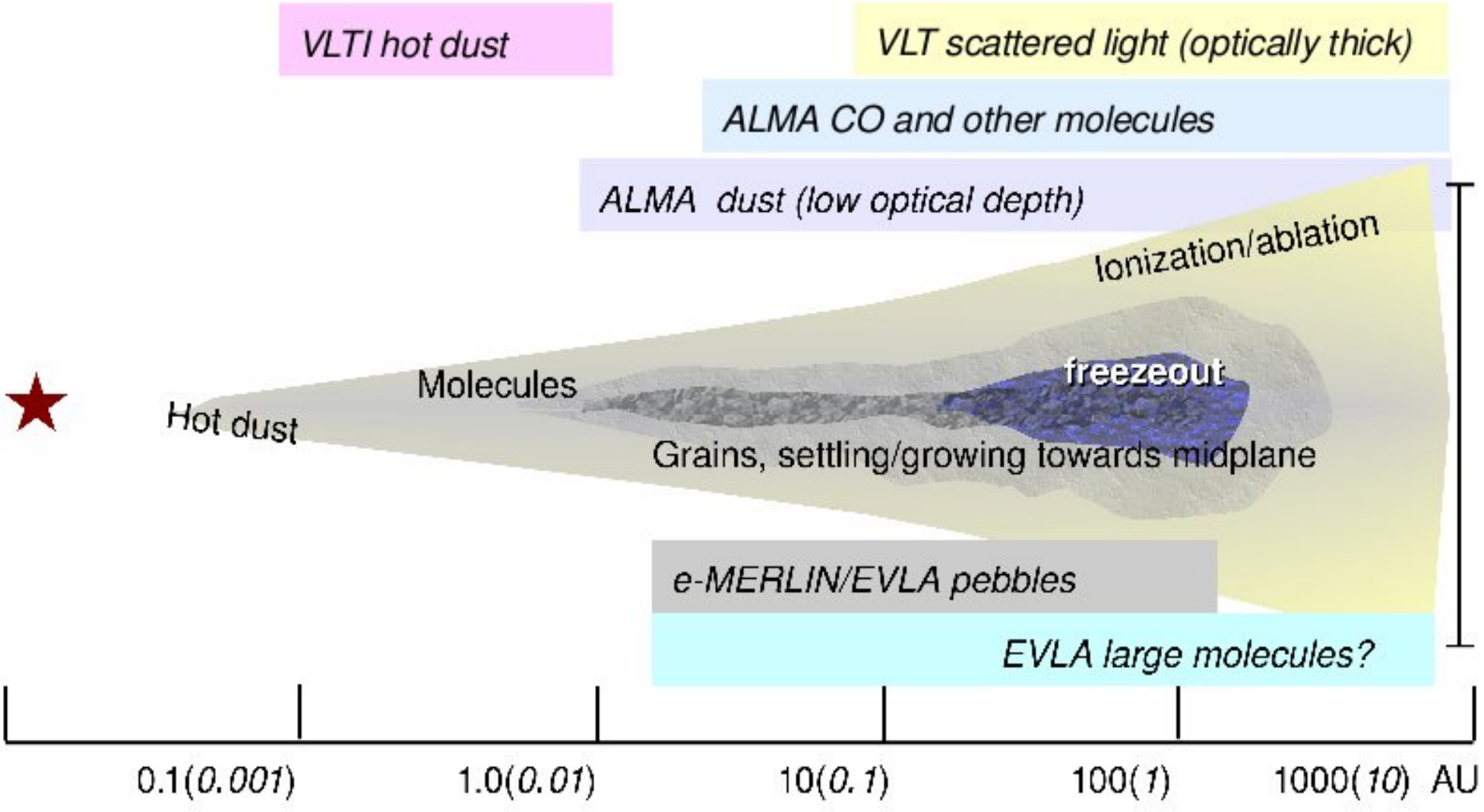
Protostellar evolution

Class	Age yr	Env/ disc mass $M_\odot$	Stage
0	10^4	>0.5	accretion
I	10^5	<0.1	late accretion
II	10^6	~0.01	optically thick disc
III	10^7	<0.003	thin disc
		planetary	system



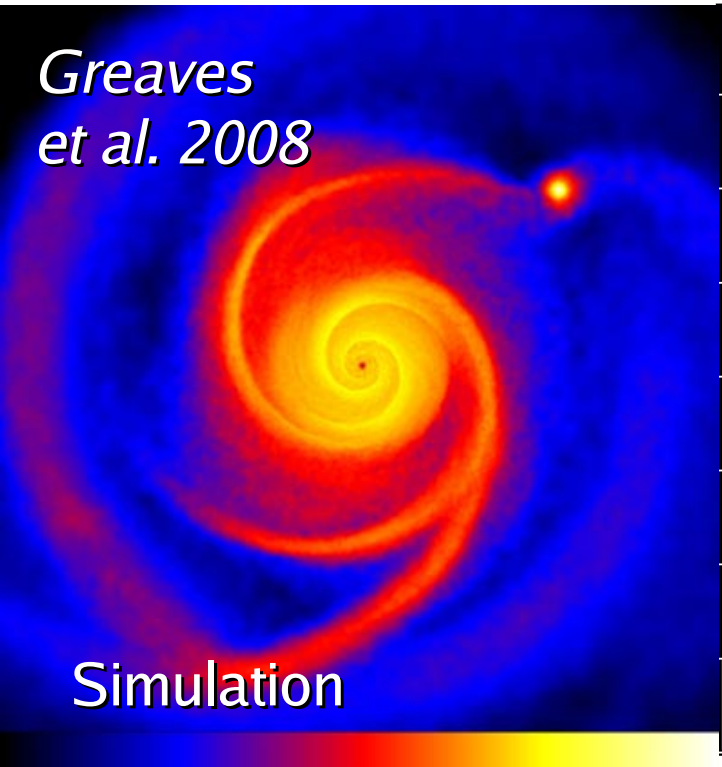
- ALMA, e-MERLIN will image:
  - Sub-stellar clumps
    - low end of IMF
    - magnetic fields
      - Kramer, Vlemmings
  - Direct accretion rate measurement
    - disentangle infall, outflow, rotation
  - Image 0.05 $M_\odot$ disc dust rapidly at 4 kpc
    - Nearby thin discs, gas
  - Protoplanetary discs

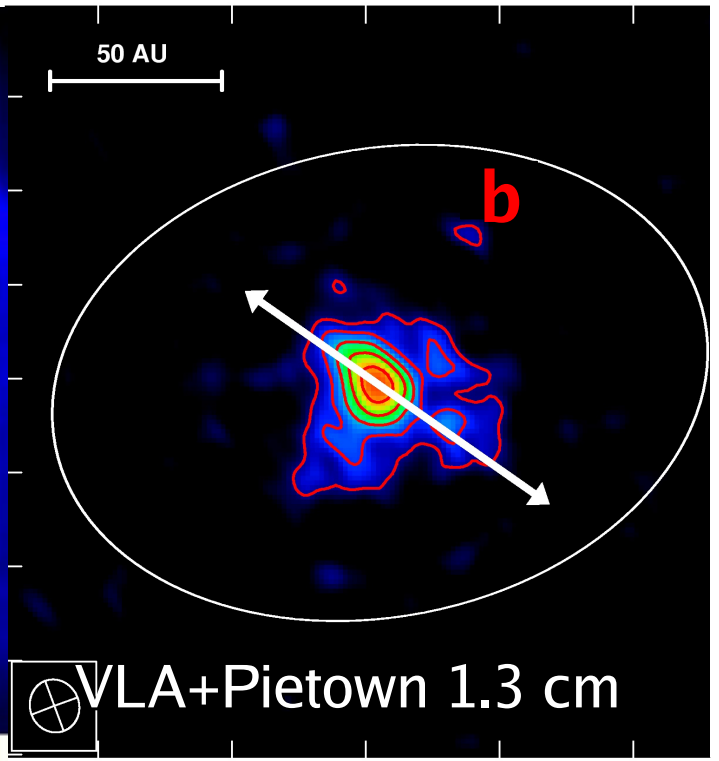
Differentiation in protoplanetary discs

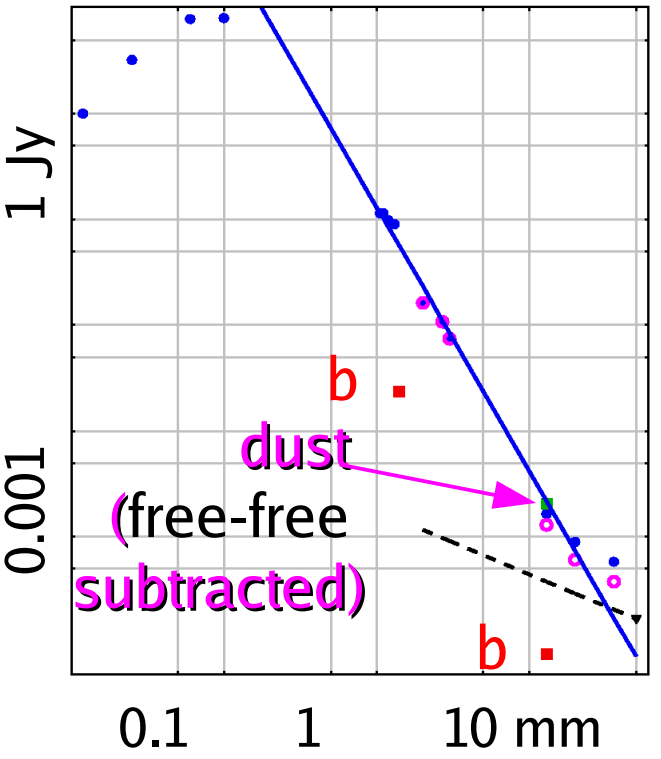


From dust to planets

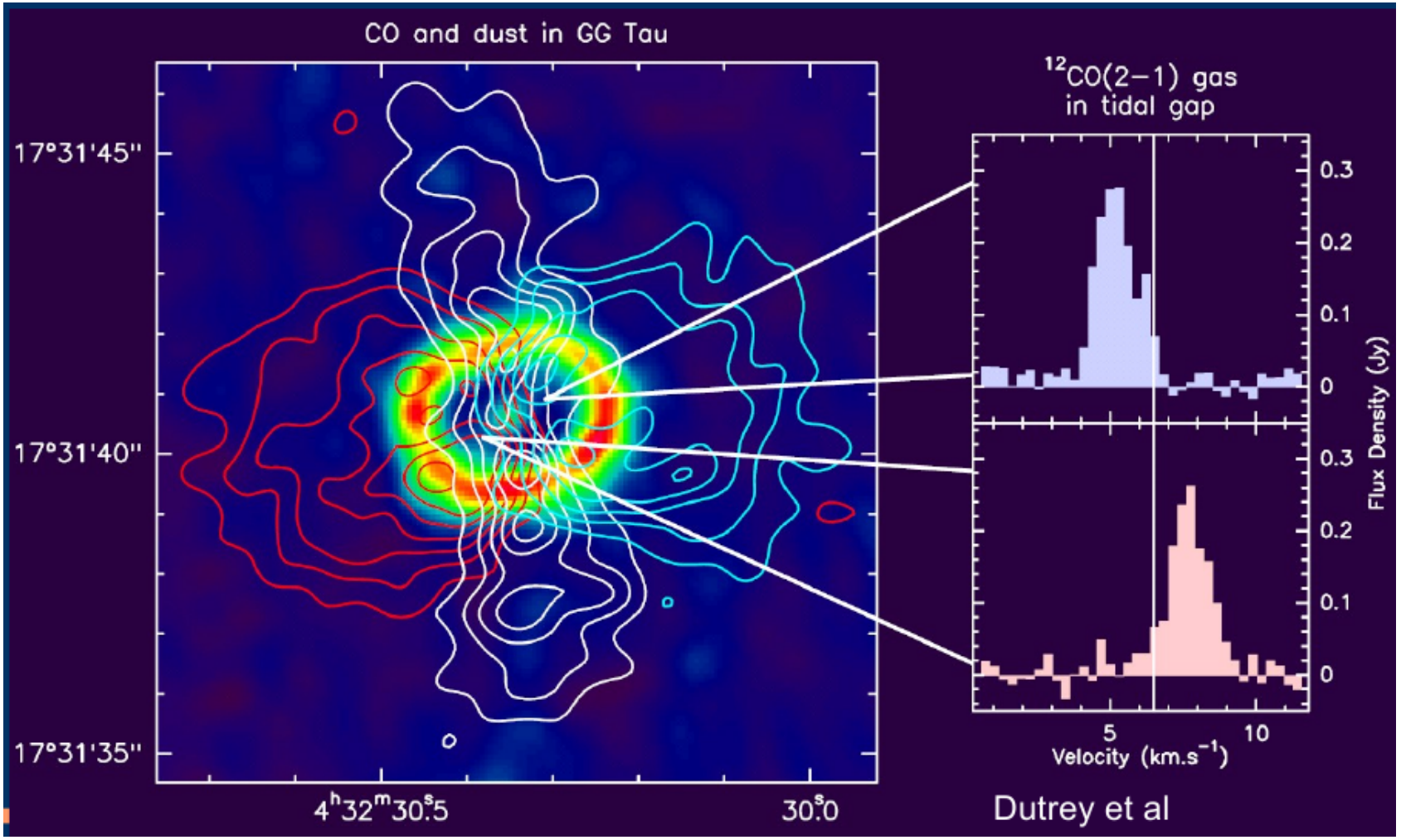
- HL Tau 1/3$M_\odot$ Class I protostar, 100 AU dusty disc
- cm-wave hint of 14 $M_\oplus$ pebbles coalescing into planet **b**
  - mm-cm data disentagle free-free, dust composition
    - Spectral index ~2.5 suggests grain sizes up to at least 3 λ
  - e-MERLIN PEBBLES legacy project (Greaves)







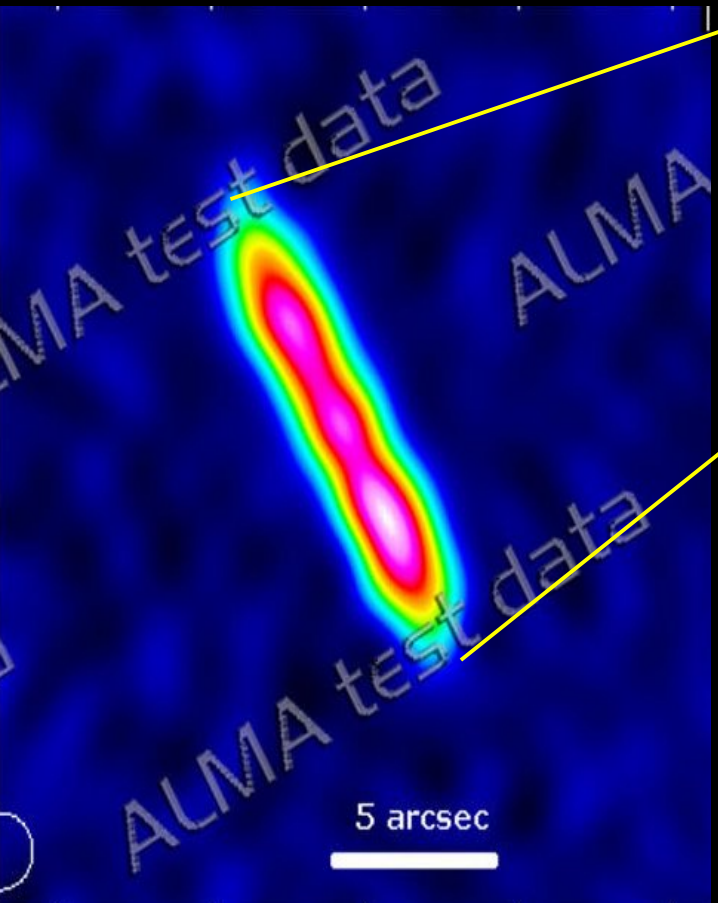
Gas in depleted discs



- CO and dust around GG Tau
  - Inset spectra show CO in tidal gap
  - ALMA will image much larger sample

Debris discs

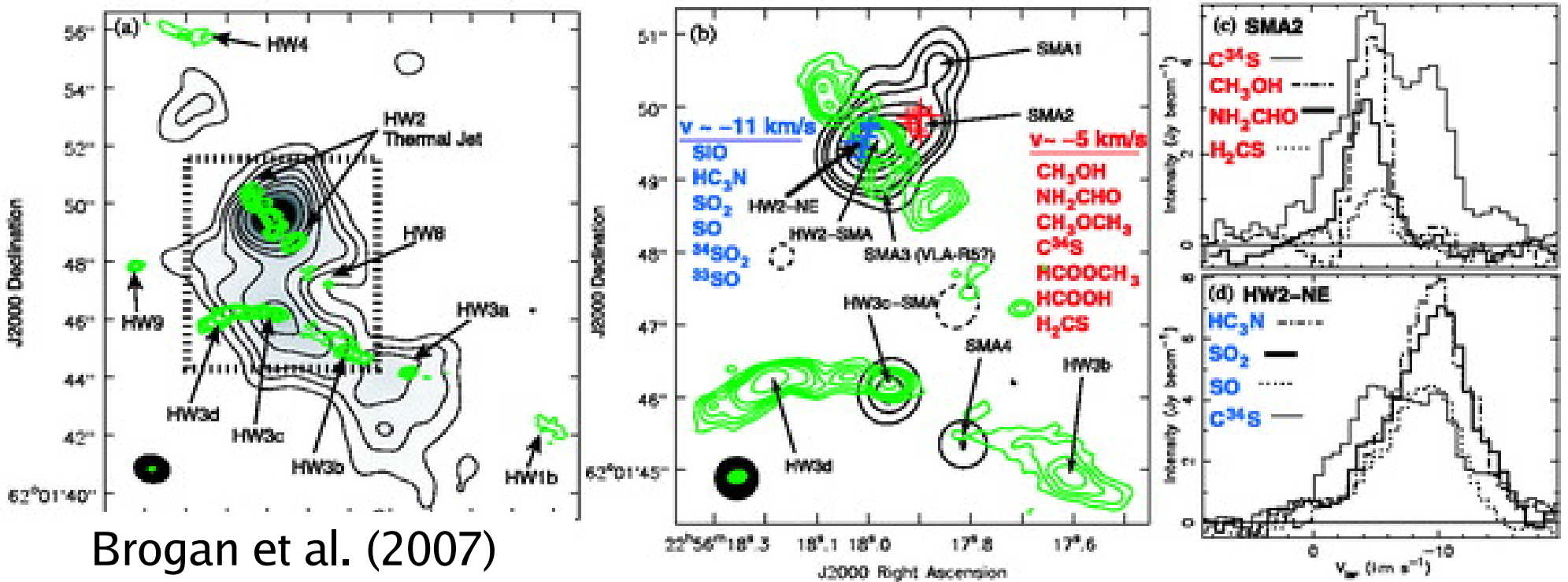
- ALMA test data zooming in on *Herschel* dust
- Full ALMA will image residual gas
  - CO J2-1 ~3h per 10^{-3} $M_\oplus$ in CO at 100 pc
    - Current detections limited by beam dilution
    - <few $M_\oplus$ at T>300 K *Carmona+08*
    - IR CO T Tauri's 0.1 kg m^{-2} (*Najita+'03*)
    - Is gas depletion due to
      - Photoevaporation?
      - Accreted on to star?
      - Wind-blown? (*Zagorovsky+ '10*)
    - Is gas collisionally generated?



β Pic

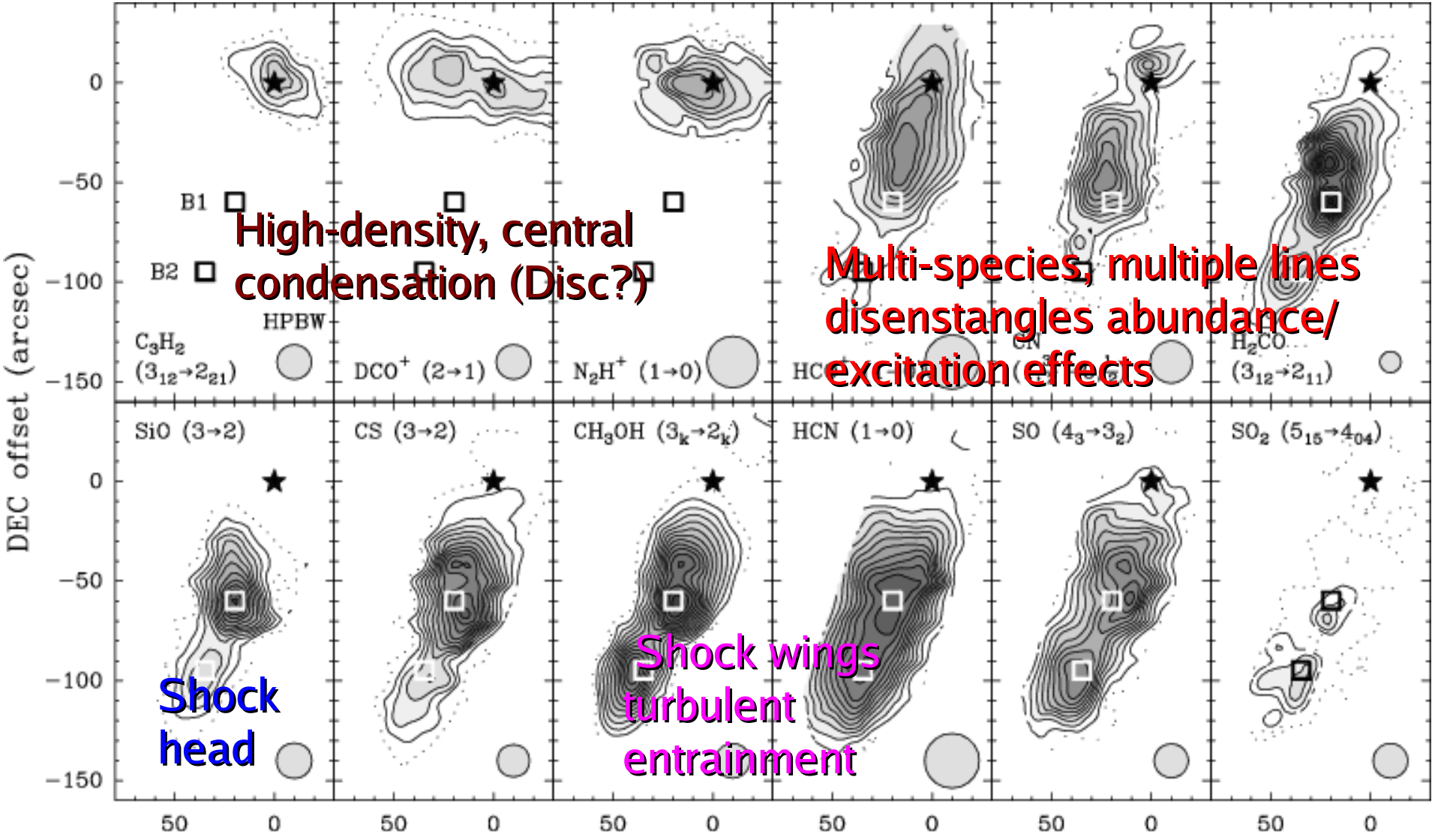
Chemistry reveals CepA E double

- YSO with barely-resolved wind and disc?
  - Contours SMA 875 μm, VLA 3cm, resolution ~ 750 AU
  - Spectra show two groups of different lines
- Multiple protostars at different evolutionary stages?



Brogan et al. (2007)

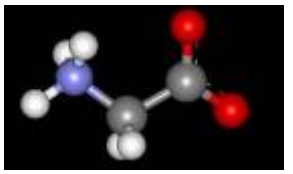
Chemically active protostellar jet



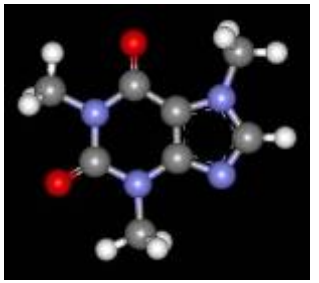
- L1157 Class 0 protostellar jet (*Bachiller+ 2001*)

Chemistry of life

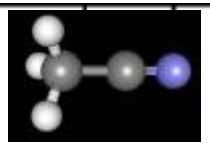
Biologically interesting molecules



Glycine?



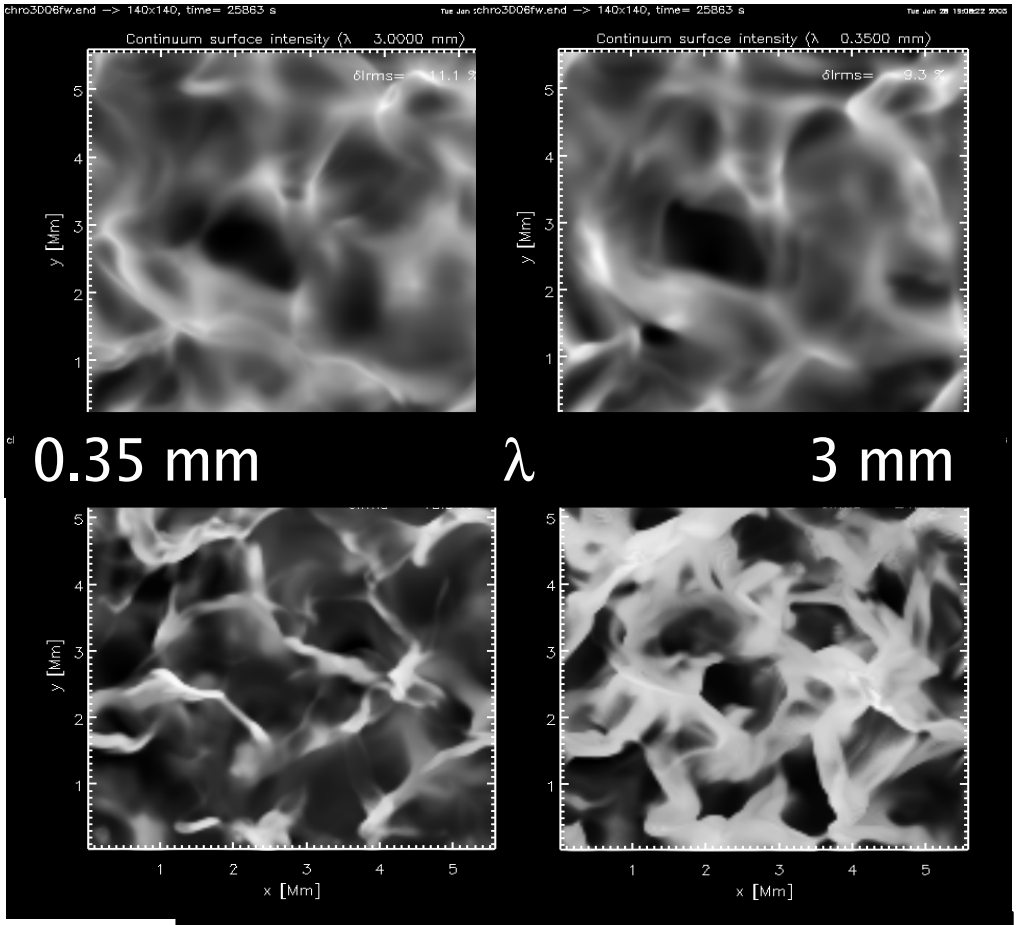
Caffeine?



Methyl Cyanide

Solar System observations

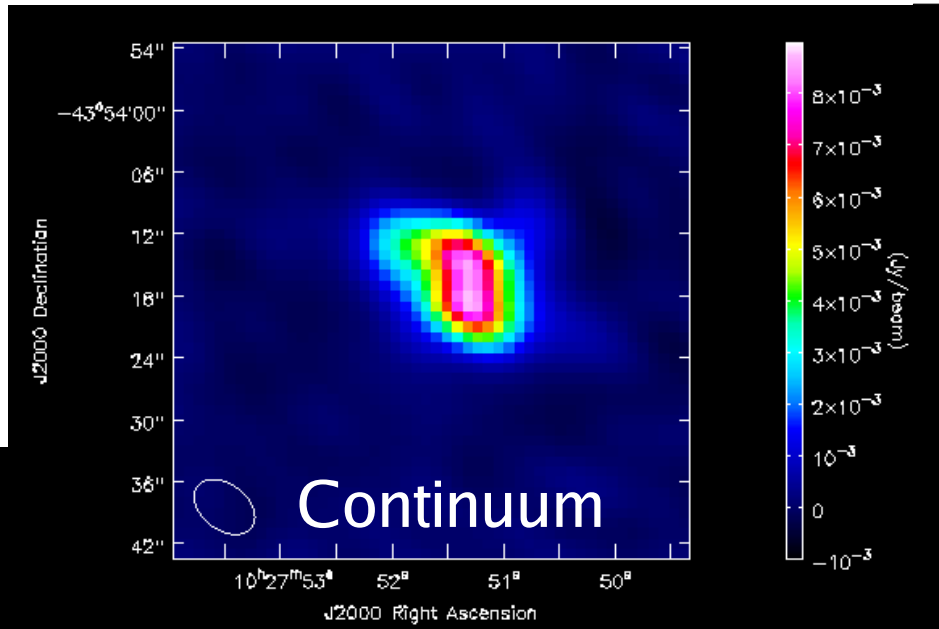
- Planetary atmospheres
- Asteroid tracking
- Solar filters
  - Structure of quiet solar atmosphere
  - Coronal holes
  - Solar active regions
  - Active and quiescent filaments
  - Energetic phenomena
    - Filament eruptions, flares etc.

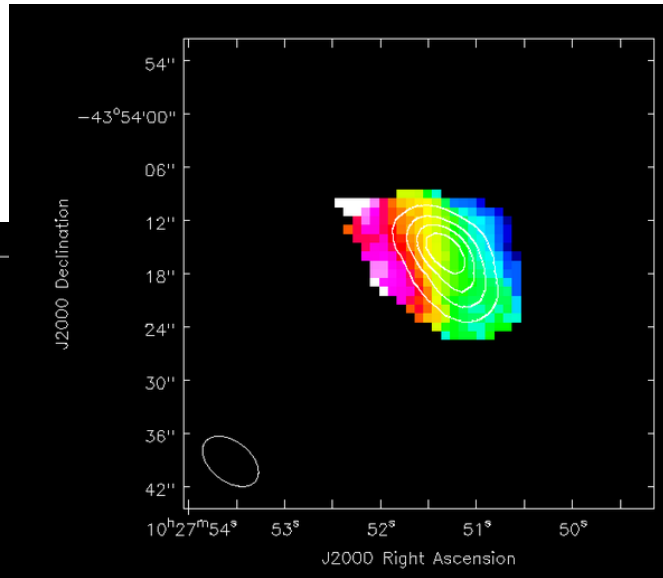


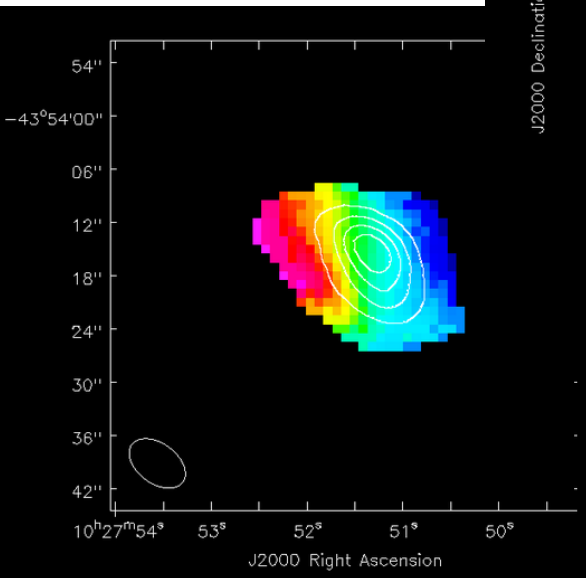
Steffen et al. ALMA models of Solar chromosphere: non-grey (above) and grey-body (below)

Recent science verification I

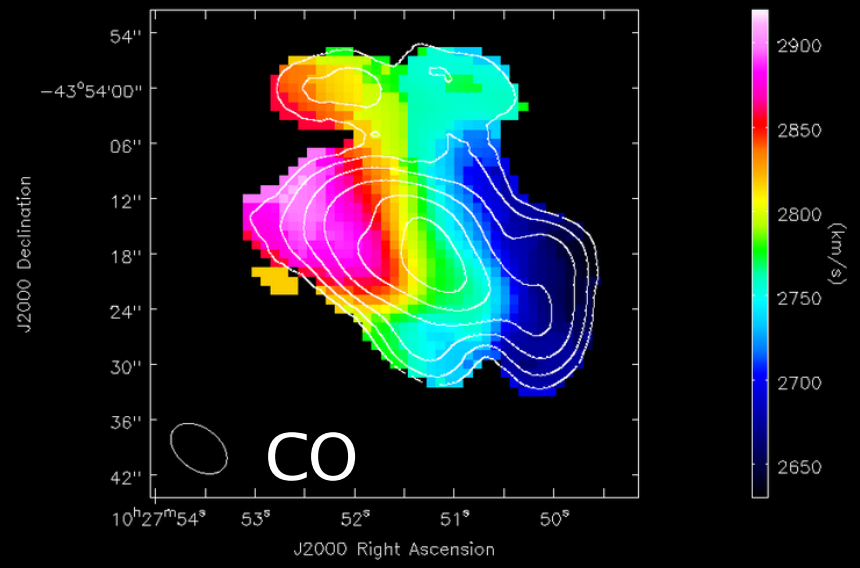
- Nearby galaxy NGC 3256
  - CO J1-0 115 GHz etc.
  - 9 Antennas, 4x1.875 GHz
  - 38 km/s spec resolution





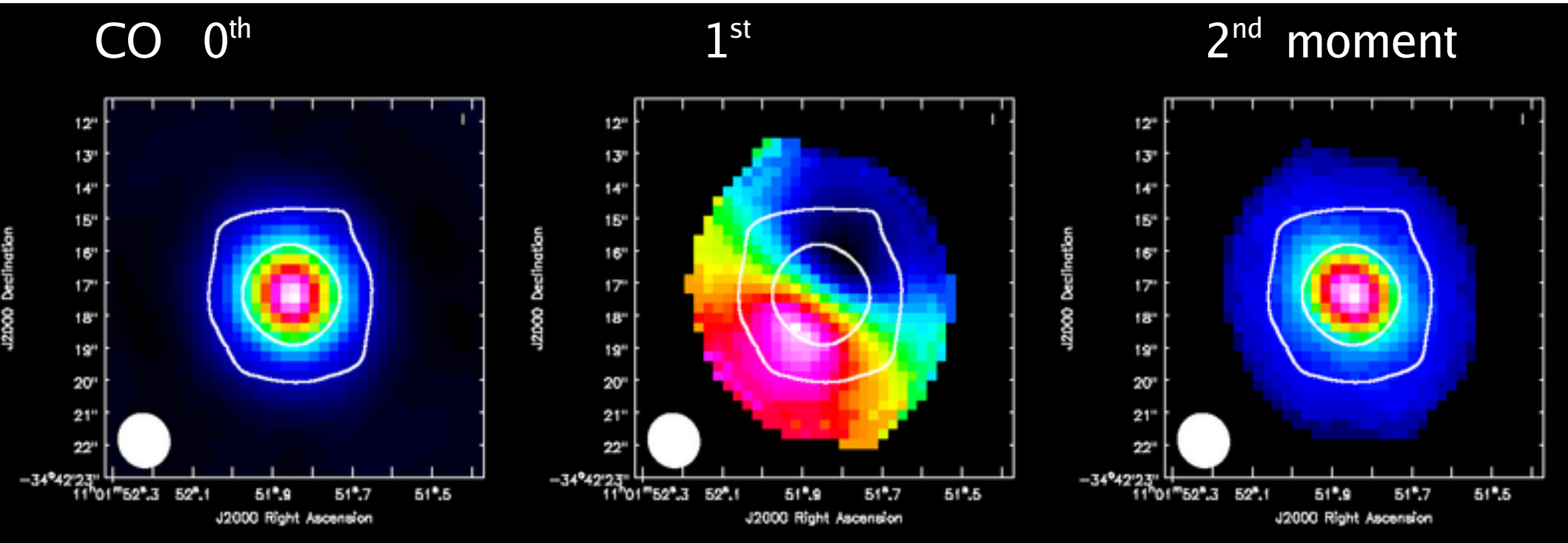


CN lines

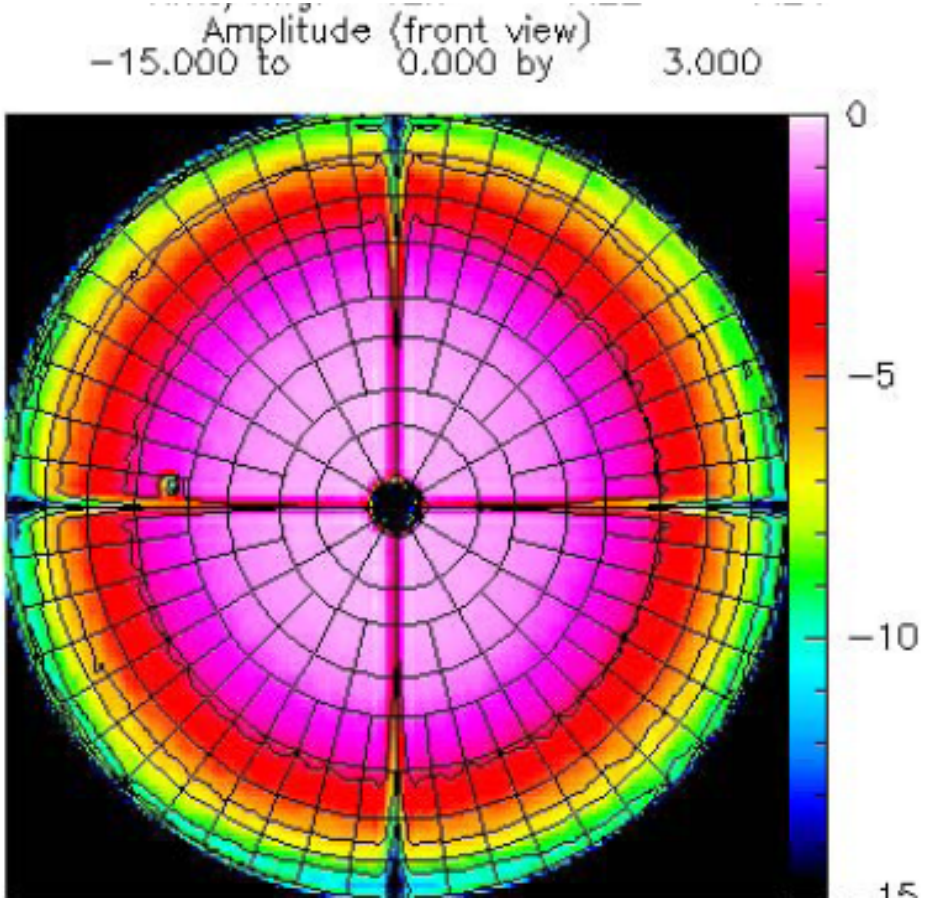


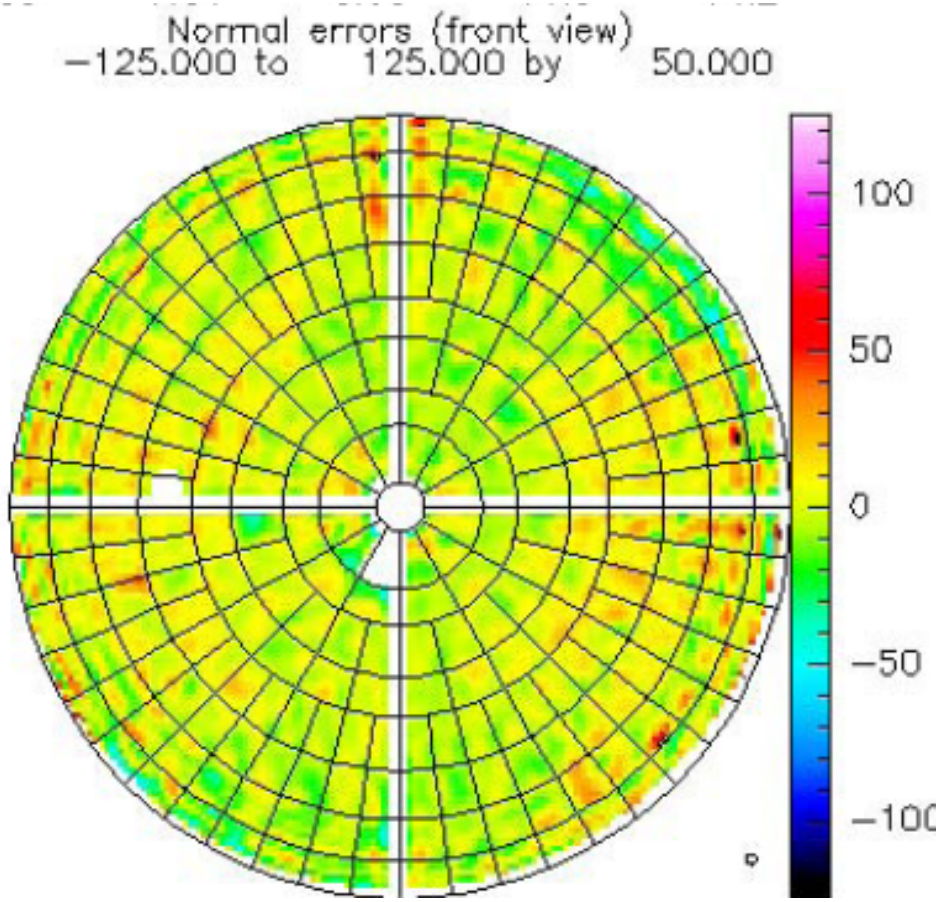
Science verification II

- YSO TW Hya
  - CO J3-2 345 GHz, HCO^+
  - 4.5 hr, 8 antennas
  - 0.45 km/s spec resolution
- Data and scripts available
  - ALMA portal
  - Data Science Verification
  - CASA guides



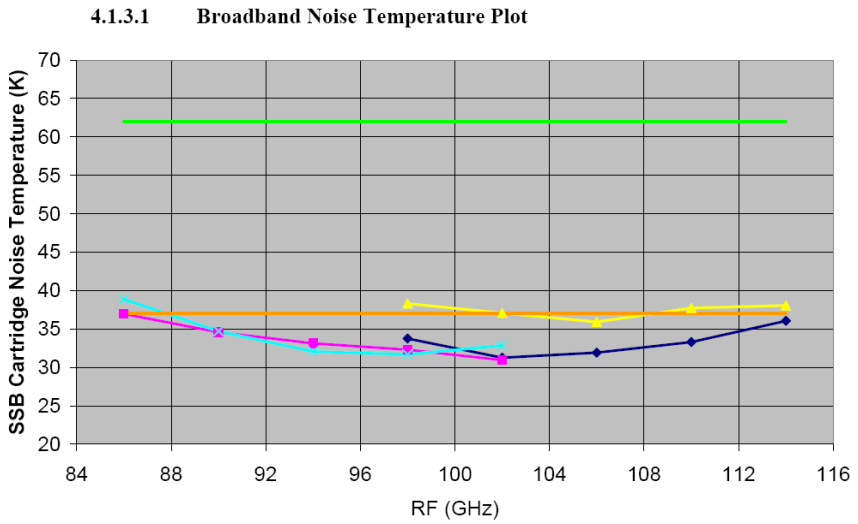
ALMA surface up to spec

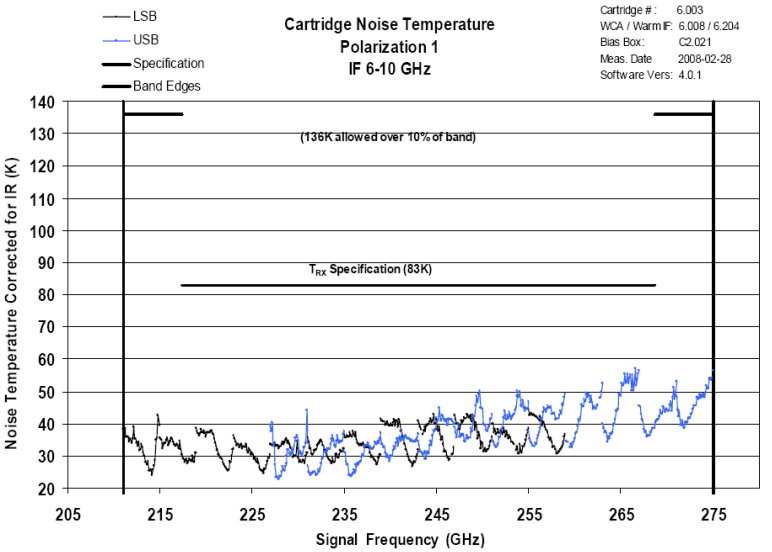


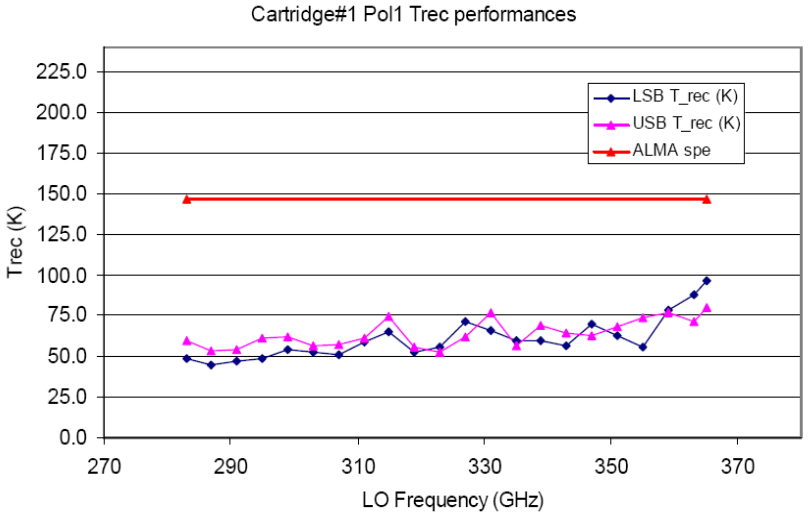


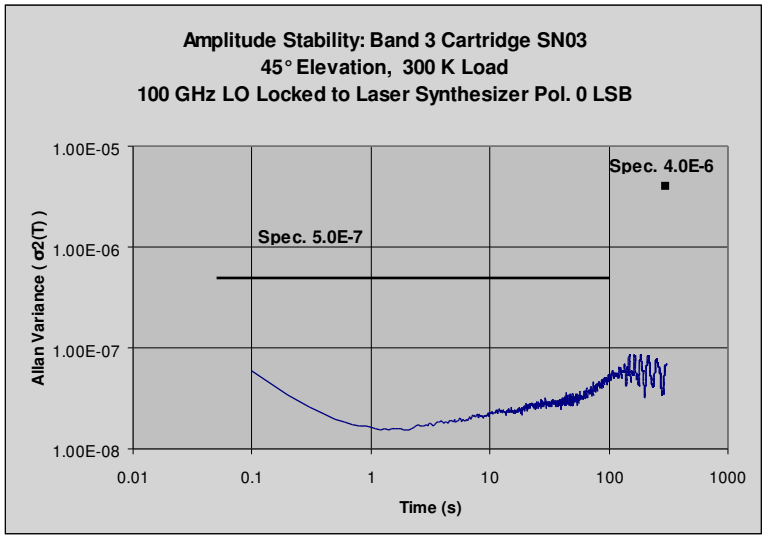
Primary reflector rms 9.8 μm

Receivers better than spec





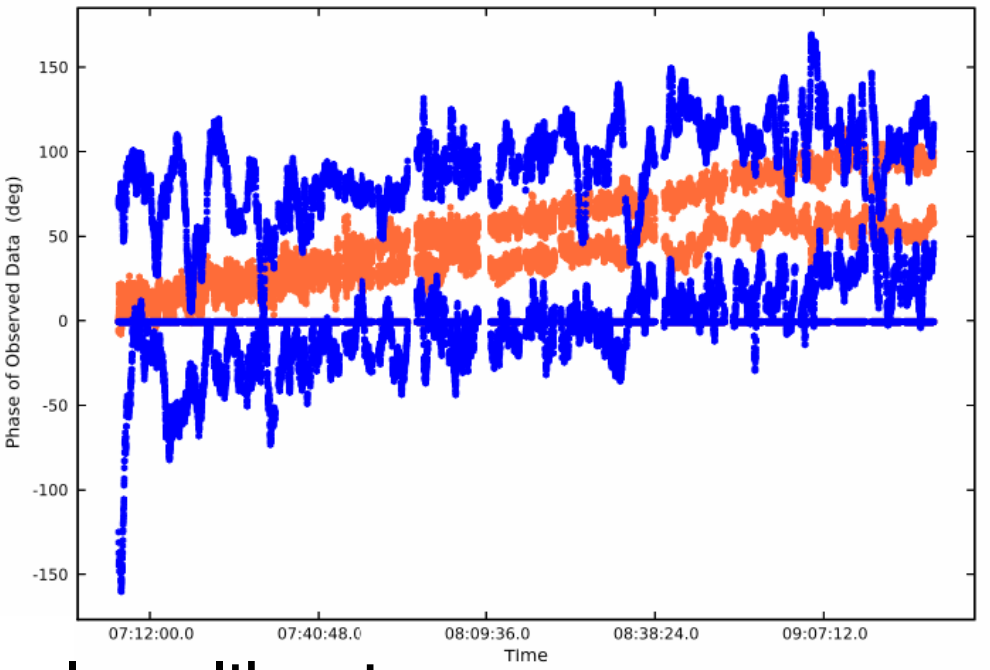




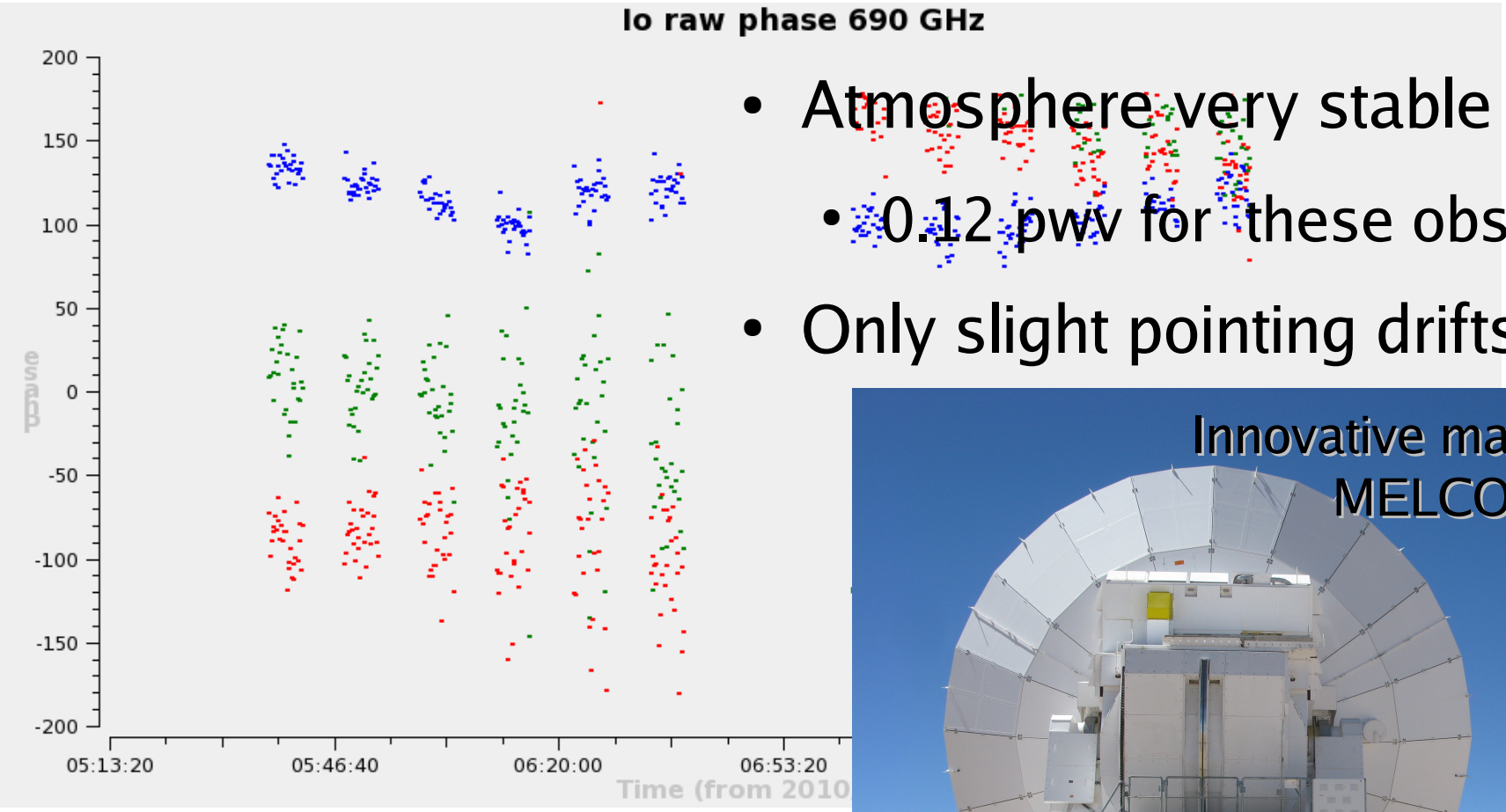
Tropospheric calibration working

- Water Vapour Radiometry
  - Measure 183-GHz atmospheric line every s
    - Calculate path length fluctuations and correct
- T_{sys} measurements: rapid amplitude calibration
- Astrophysical calibration
  - Large moons etc. for flux scale calibration
  - Quasars/compact sources for bandpass calibration
  - Phase-referencing
    - Go to bright source within few degrees every 20–300 s

WVR phase correction in CASA– Blue raw (2 baselines) Orange Corrected



Rapid, accurate tracking



- Atmosphere very stable at λ 450 μm
  - 0.12 pwv for these observations!
- Only slight pointing drifts in hrs

- Observing at higher pwv
  - Fast switching
    - 20:2 sec cycle target: ref source

Weather not always up to spec

This is more usual!

July –15 antennas at AOS

Mostly Vertex, couple Melco

European 12-m, ACA 7-m OSF comissioning

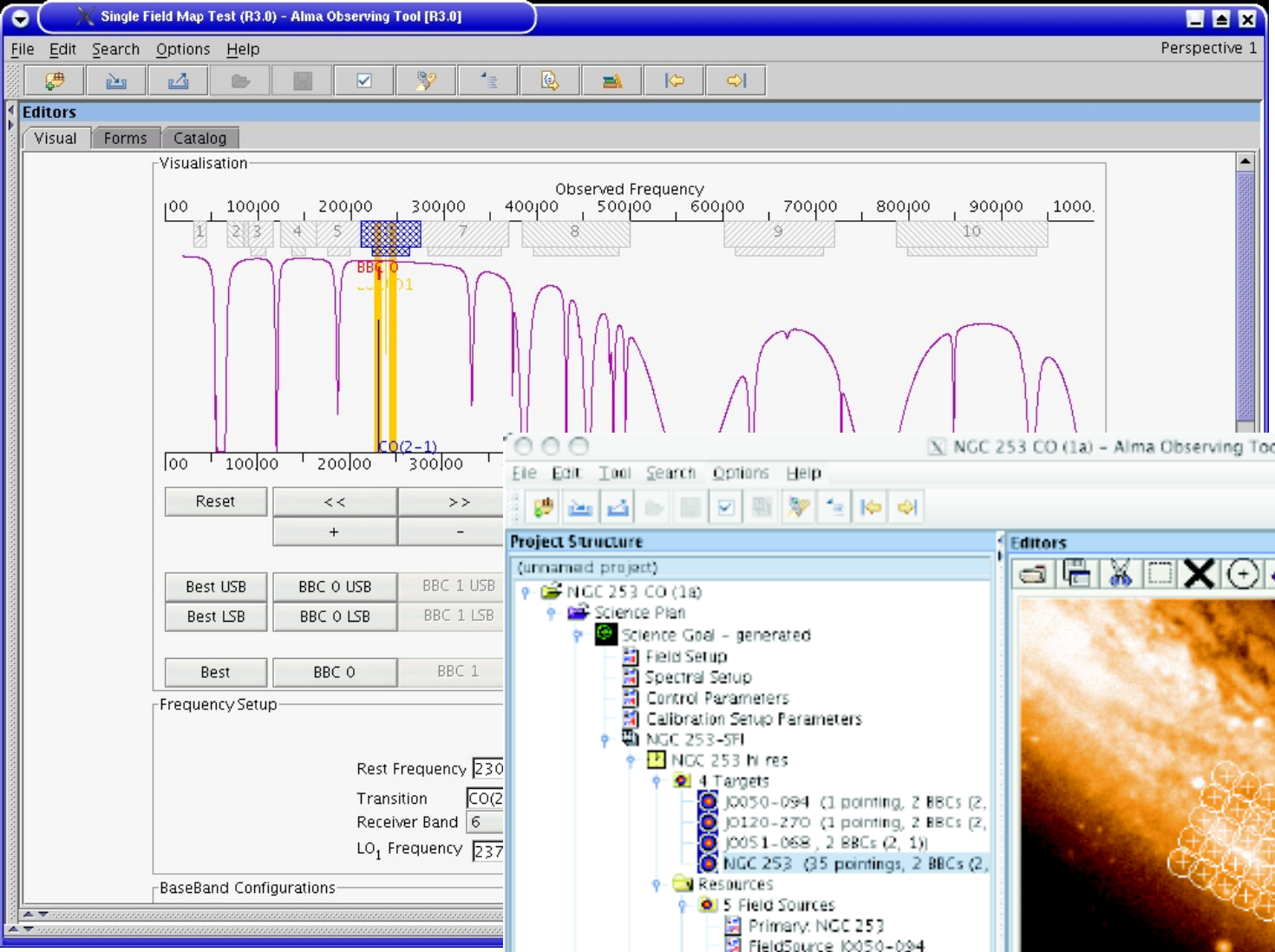
Observation support

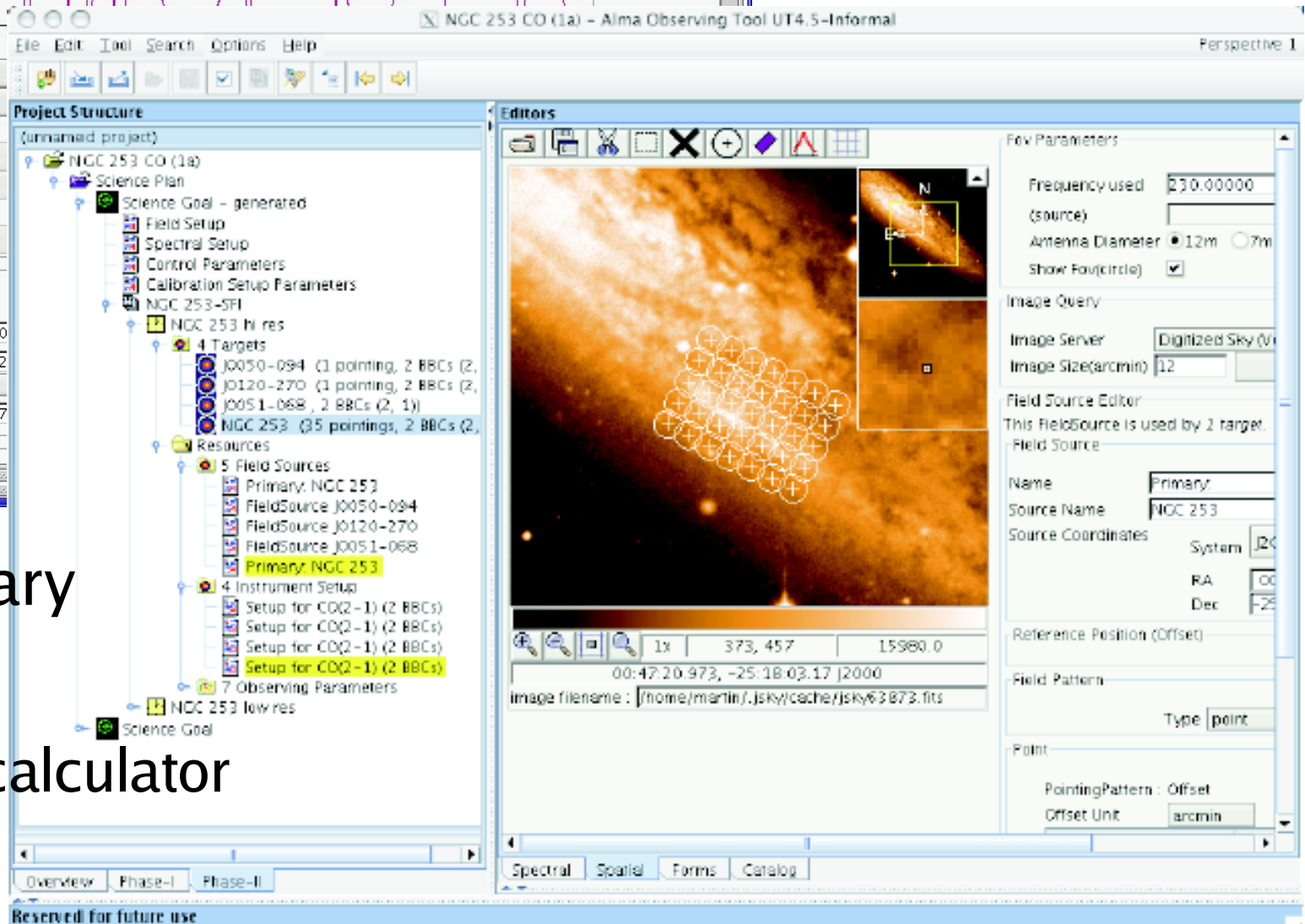
- Face-to-face at ARCs
- Observing Tool (OT)
  - Phase 1: Proposal preparation
    - Line lists, allowed configurations etc.
  - Phase 2: Scheduling blocks
    - (mostly) self-contained target-calibration groups
  - Flexible scheduling to make best use of conditions
- Observing Support Tool (OST)
  - Simulations (also available in CASA)
- CASA –reduce (almost) any radio interferometry data

ALMA Regional Centres

- European ARC coordinated from ESO
  - Commissioning, testing, development, etc.
- Nodes provide face-to-face support
  - All stages of planning/ reducing Early Science
- Additional RadioNet support
  - Meeting sponsorship
  - Contribution to CASA development
- Also NA, EA ARCs

Observing Tool



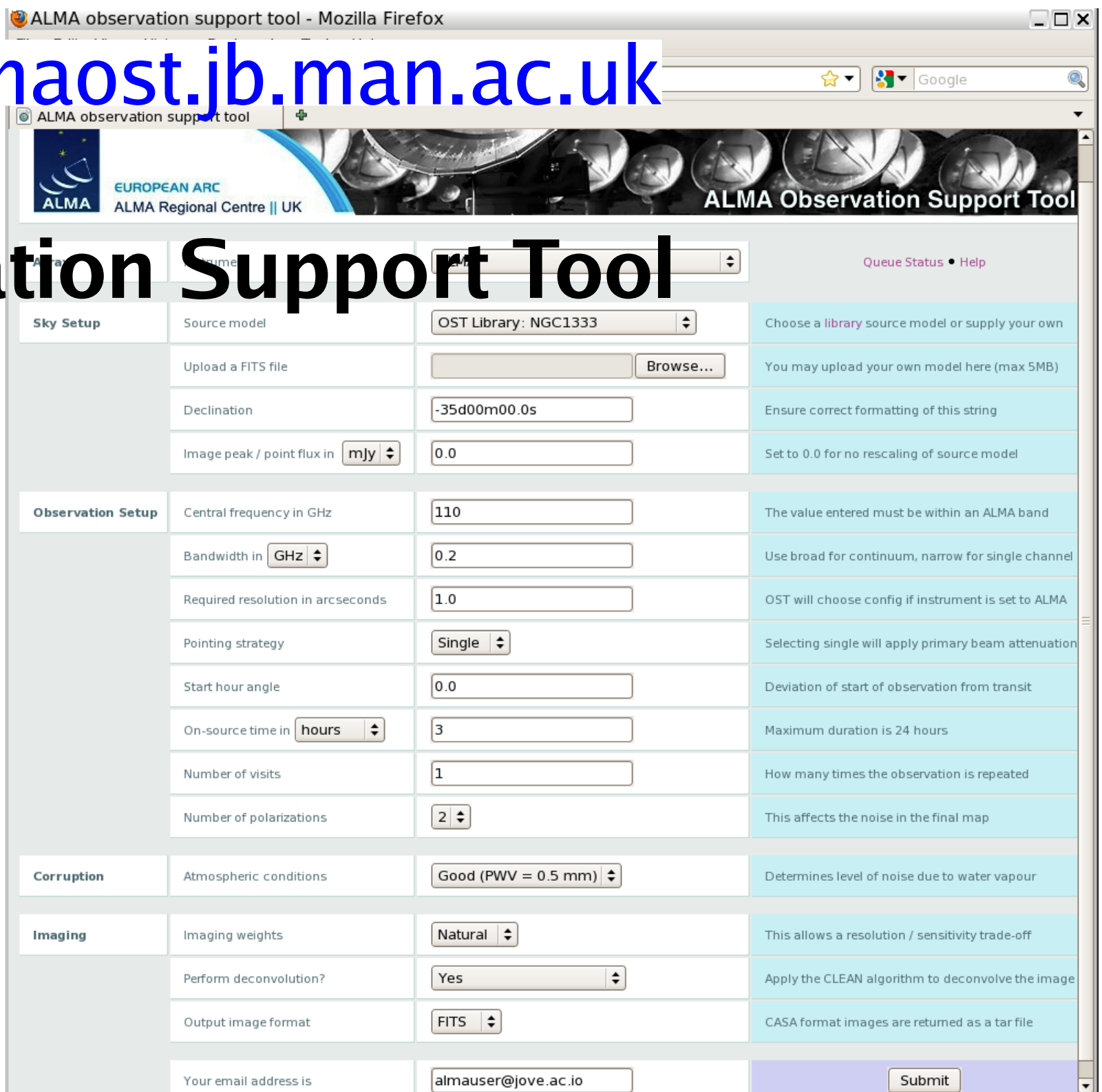


- Template library
- Built-in tools
  - Sensitivity calculator
  - Line list

http://almaost.jb.man.ac.uk

Observation Support Tool

- Oxford/Manc.
- Web interface to ALMA simulations
- Image library or upload FITS
- Select conditions
- Notify results by email



OST results

ALMA observation support tool - Mozilla Firefox

File Edit View History Bookmarks Tools Help

http://almaost.jb.man.ac.uk/

ALMA observation support tool

EUROPEAN ARC
ALMA Regional Centre || UK

ALMA Observation Support

Array	Instrument	ALMA	Queue Status • Help
Sky Setup	Source model	OST Library: NGC1333	Choose a library source model or supply y
	Upload a FITS file	Browse...	You may upload your own model here (ma
	Declination	-35d00m00.0s	Ensure correct formatting of this string
	Image peak / point flux in mJy	0.0	Set to 0.0 for no rescaling of source mode
Observation Setup	Central frequency in GHz	110	The value entered must be within an ALMA
	Bandwidth in GHz	0.2	Use broad for continuum, narrow for singl
	Required resolution in arcseconds	1.0	OST will choose config if instrument is set
	Pointing strategy	Single	Selecting single will apply primary beam a
	Start hour angle	0.0	Deviation of start of observation from tran
	On-source time in hours	3	Maximum duration is 24 hours
	Number of visits	1	How many times the observation is repeat
	Number of polarizations	2	This affects the noise in the final map
Corruption	Atmospheric conditions	Good (PWV = 0.5 mm)	Determines level of noise due to water vap
Imaging	Imaging weights	Natural	This allows a resolution / sensitivity trade-
	Perform deconvolution?	Yes	Apply the CLEAN algorithm to deconvolve
	Output image format	FITS	CASA format images are returned as a tar
	Your email address is	almauser@jove.ac.io	Submit

ALMA OST - Job ID: 20110331154554 - Mozilla Firefox

File Edit View History Bookmarks Tools Help

ALMA OST - Job ID: 2011033115...

EUROPEAN ARC
ALMA Regional Centre || UK

ALMA Observation Support Tool

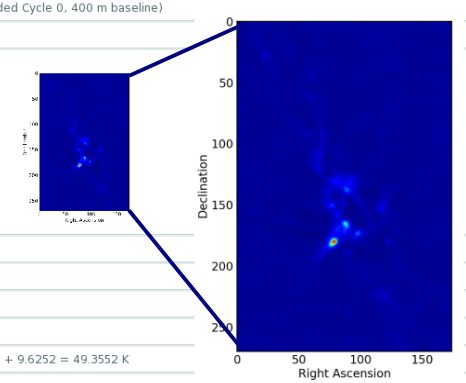
Job ID: 20110331154554 / Submitted by: adam.avison@manchester.ac.uk

Overview

Click thumbnails to view full-size images. Left: linear colour scale, right: with histogram equalization.

Array configuration	Early Science ALMA (Extended Cycle 0, 400 m baseline)
Source model	NGC 1333 at 8 kpc
Maximum elevation	77.88 degrees
Central frequency	110 GHz = Band 3
Bandwidth	0.02 GHz
Track length	5 hours × 1.0 visits
System temperature	Tsys = Trec + Tsky = 37.0 + 9.6252 = 49.3552 K
PWV	0.5 mm
Theoretical RMS noise	0.000113171570311 Jy (in naturally-weighted map)
Restoring beam (resolution)	Major axis = 1.179 arcsec, minor axis = 1.148 arcsec, PA = 69.325 deg

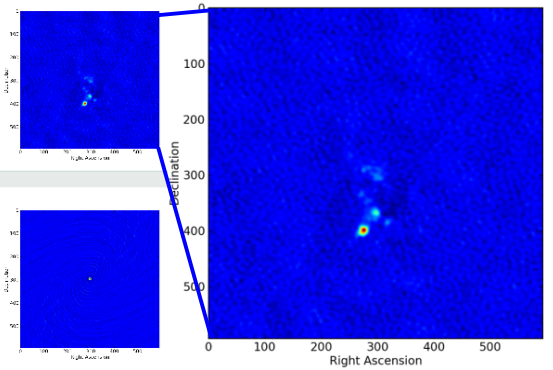
Input model



Data products

Your simulated image
Download FITS file

Output

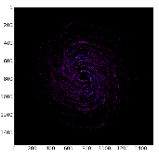


Dirty Beam
(Point Spread Function)

Beam

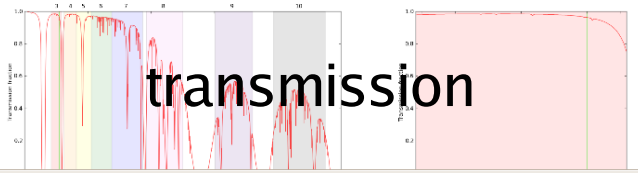
Coverage in the *uv*-plane

uv coverage



Atmospheric transmission for all bands (left) and the selected band (right)

transmission



Timetable

- ALMA Cycle 0 received 919 proposals by 30 June
  - 40% SF/ISM, 47% extragalactic, 13% stars/Solar system
    - Review feedback to PIs September 2011
- ALMA Cycle 1 call for proposals May/June 2012
  - Register/more info at www.almascience.org or via ARCs
- 50+12+4 antennas, 9? bands, 15 km baselines~2013
  - Further enhancements: VLBI, bands 30 GHz - 1 THz
- ALMA workshops www.eso.org/sci/facilities/alma/meetings/
- Other RadioNet-supported events www.radionet-eu.org
  - European Radio Interferometry School
    - Rimini 5-9 September

ALMA Early Capabilities

- 16 antennas (1/3 sensitivity of full 50-element array)
  - Up to 50 pointings for mosaicing
- Baselines from 36-400 m in extended configuration
- 18-125 m in compact configuration

Band	**9**	**7**	**6**	**3**
λ (mm)	0.45	0.85	1.1	3
Res. (asec)	0.23-0.75	0.46-1.1	0.55-1.8	1.5-4.9
Vel. res. (km/s)	0.014-*0.23*	0.03-*0.44*	0.04-*0.6*	0.1-*1.7*

- Up to 4 sub-bands in same spectral config
  - 4 x 2 GHz in 128 chans dual pol (Time Domain Mode)
  - sub-bandwidths 0.125–*2* GHz in 4096 chans (FreqDM)
    - minus edge effects
- 500-700 hr total available Oct 2011 – Jun 2012