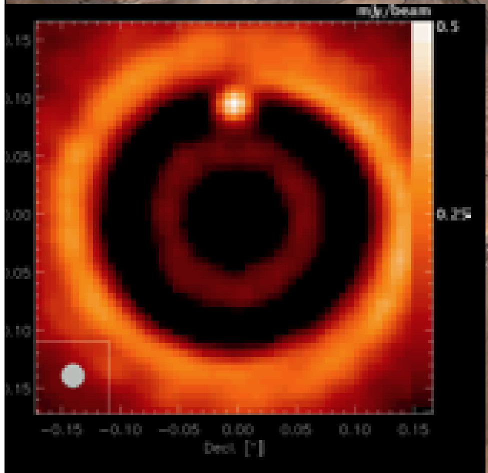
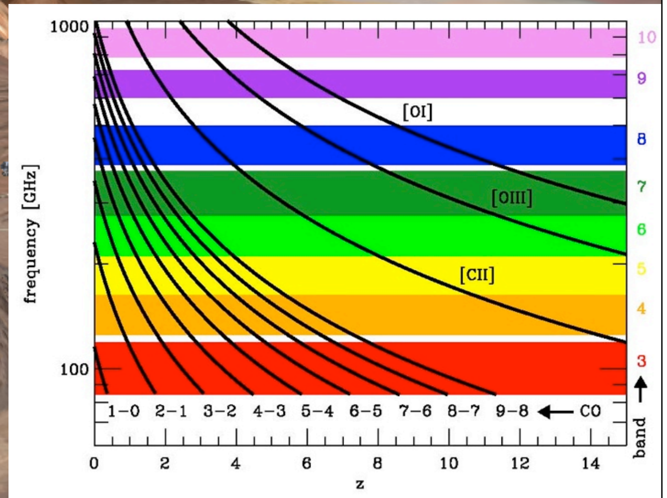
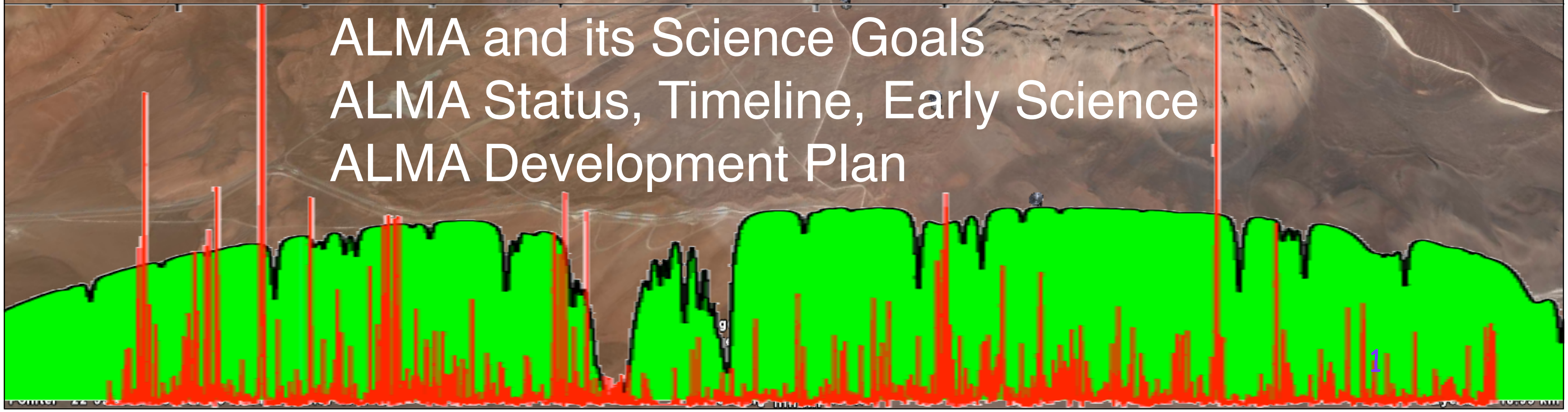
Introduction to ALMA

Leonardo Testi
ESO

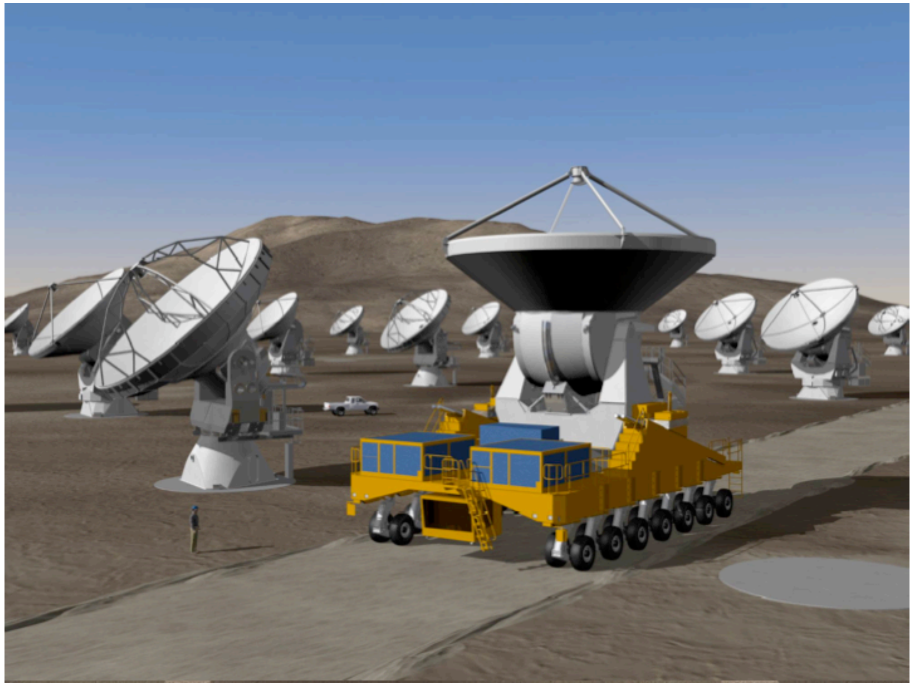




ALMA and its Science Goals
ALMA Status, Timeline, Early Science
ALMA Development Plan



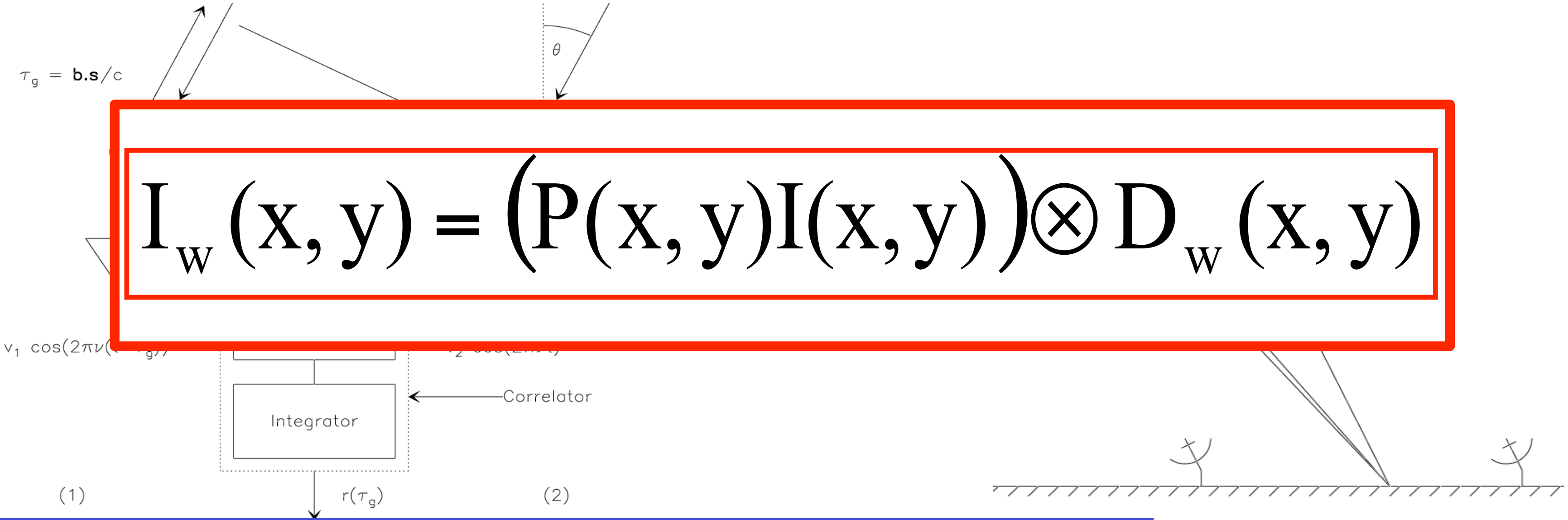
Atacama Large Millimeter Array



- At least 50x12m Antennas
- Frequency range 30-1000 GHz (0.3-10mm)
- 16km max baseline (<10mas)
- ALMA Compact Array (4x12m and 12x7m)

1. **Detect and map CO and [C II] in a Milky Way galaxy at z=3 in less than 24 hours of observation**
2. **Map dust emission and gas kinematics in protoplanetary disks**
3. **Provide high fidelity imaging in the (sub)millimeter at 0.1 arcsec resolution**

Interferometry in 1 slide



$$I_W(x,y) = \left(P(x,y)I(x,y)\right) \otimes D_W(x,y)$$

$$r(t) = \langle v_1 \cos(2\pi\nu(t-\tau_g(t)))v_2\cos(2\pi\nu t)\rangle = v_1 v_2 \cos(2\pi\nu\tau_g(t))$$

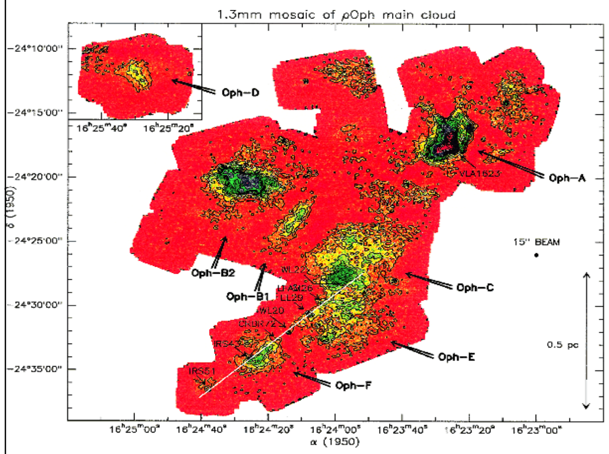
$$r(t) = d\nu \int_{Sorgente} P(\vartheta,\varphi)I(\vartheta,\varphi)\cos(2\pi\nu\, \vec{b}\bullet\vec{s}/c)\, d\Omega$$

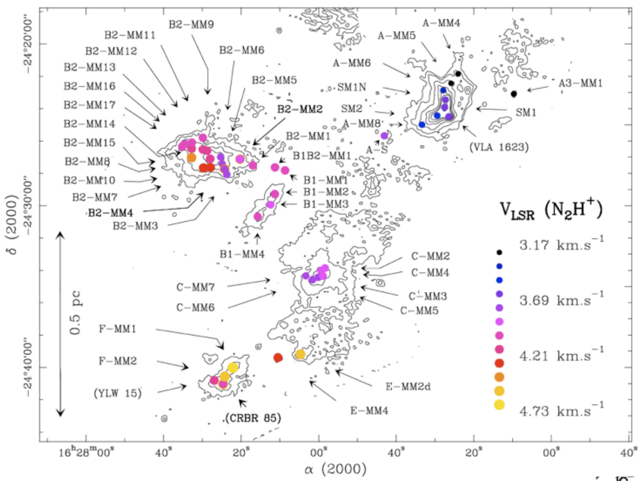
$$V = |V| e^{i\Phi_V} = \int_{Sorgente} P(\vec{\sigma})I(\vec{\sigma})\exp(-2i\pi\nu\, \vec{b}\bullet\vec{\sigma}/c)\, d\Omega$$

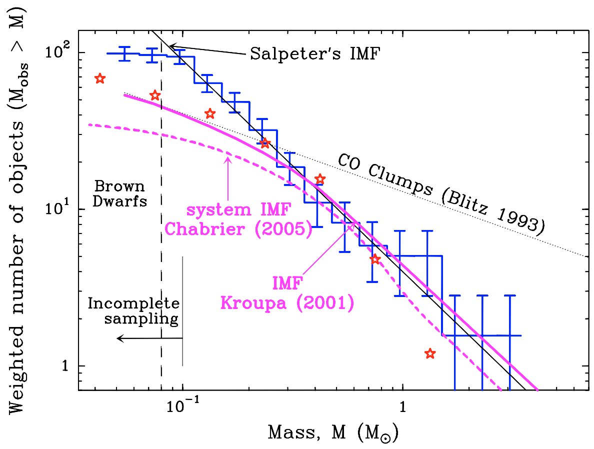
$$V(u,v) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} P(x,y)I(x,y)\exp(-2i\pi(ux+vy))\,dxdy$$

$$I_W(x,y) = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} S(u,v)W(u,v)V(u,v)\exp(-2i\pi(ux+vy))\,dudv$$

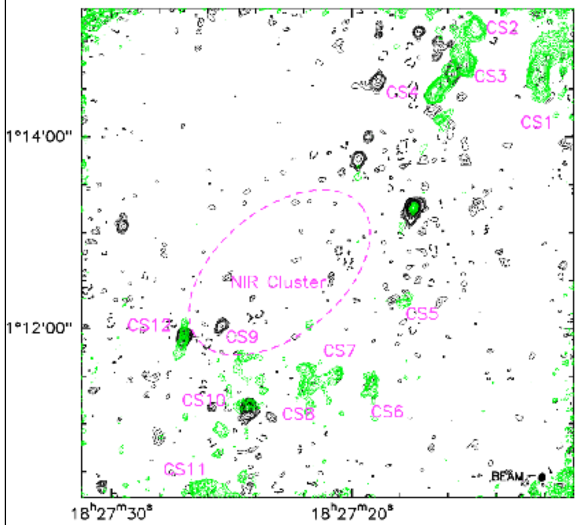
The origin of the stellar IMF

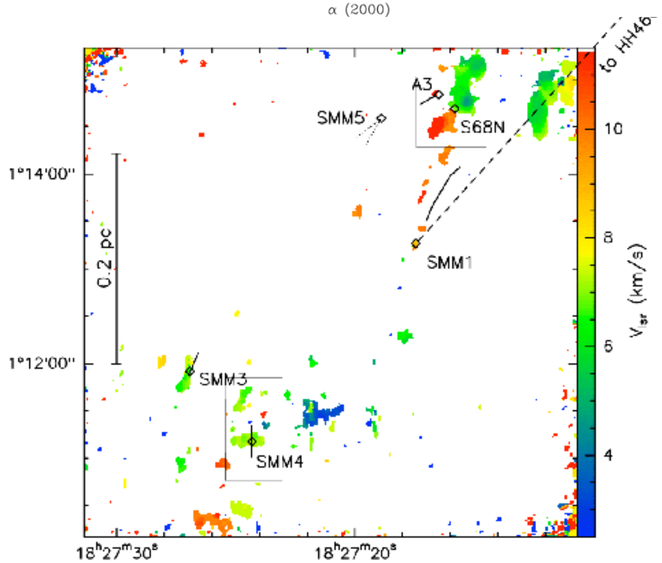


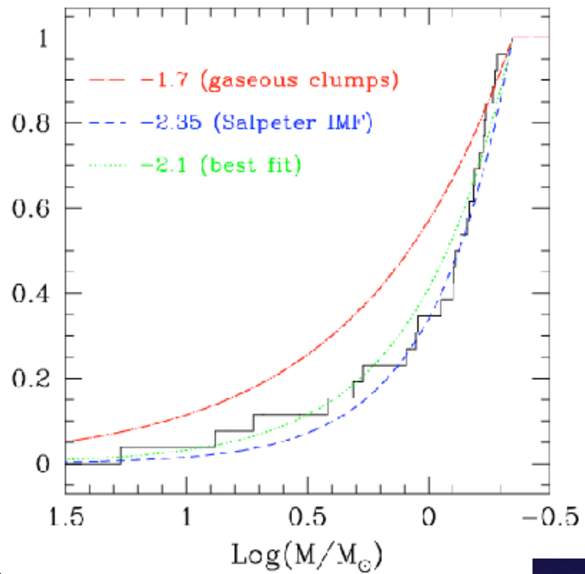




(Motte et al. 1998; André et al. 2007)



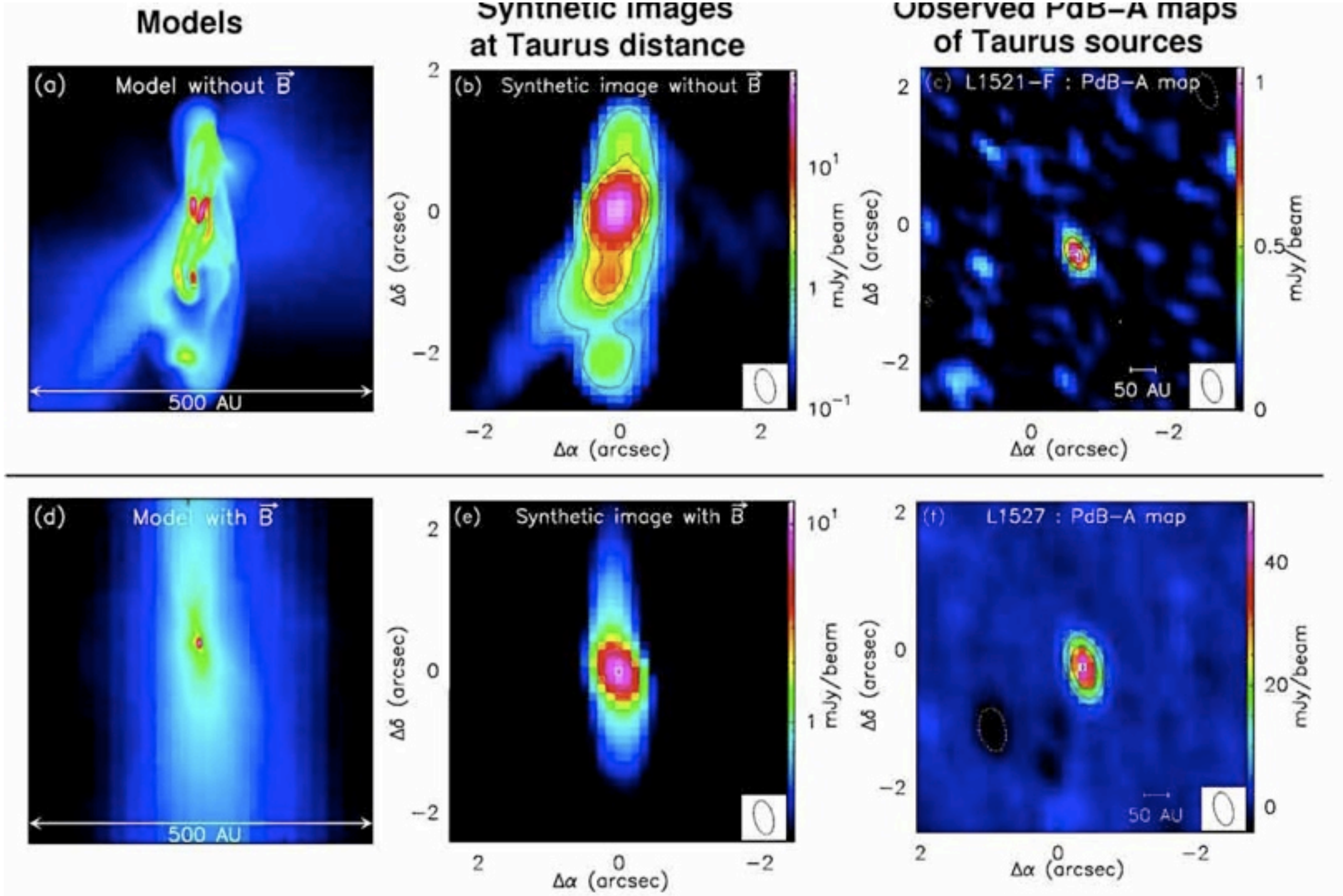




(Testi & Sargent 1998; Testi et al. 2000)

- Physical conditions in individual cores
- Other environments (molecular ring, FOG, ...MC)

Structure of protostars

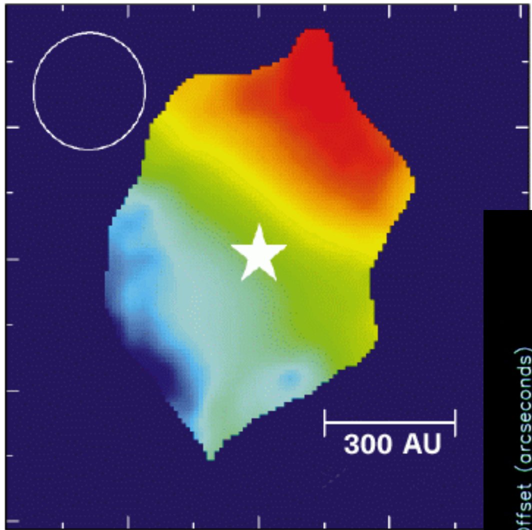


(Maury et al. 2010)

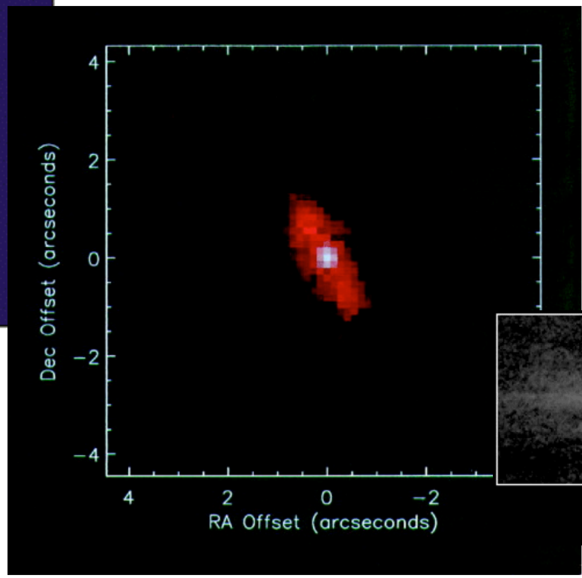
- Multiplicity, disk vs pseudodisk, role of B

Disk Evolution

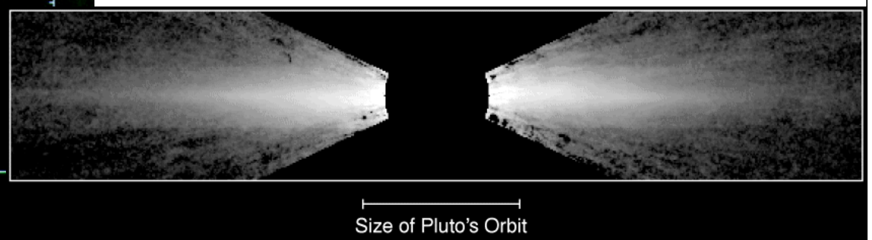
- There is evidence that disk evolution and planet formation systems may occur on timescales of a few million years



MWC 480
Young gaseous disk – 6 Myrs
CO(2-1): Mannings et al 1997

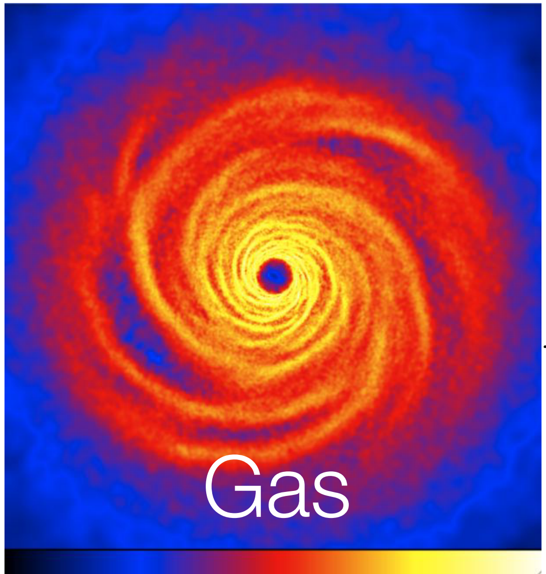


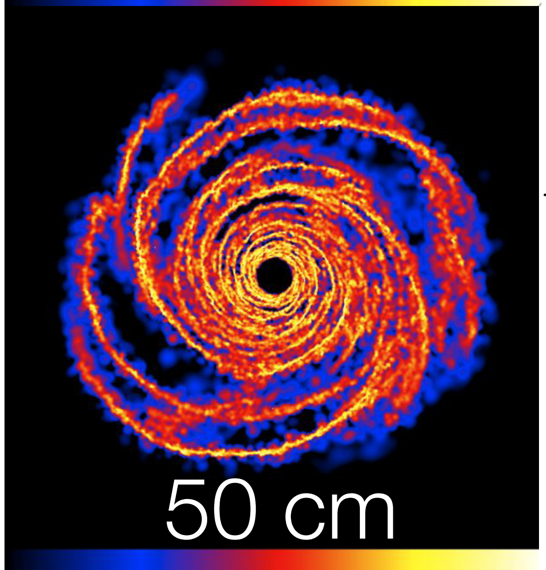
HR 4796 A
Evacuated inner disk – 15Myr
MID-IR: Koerner et al. 1998

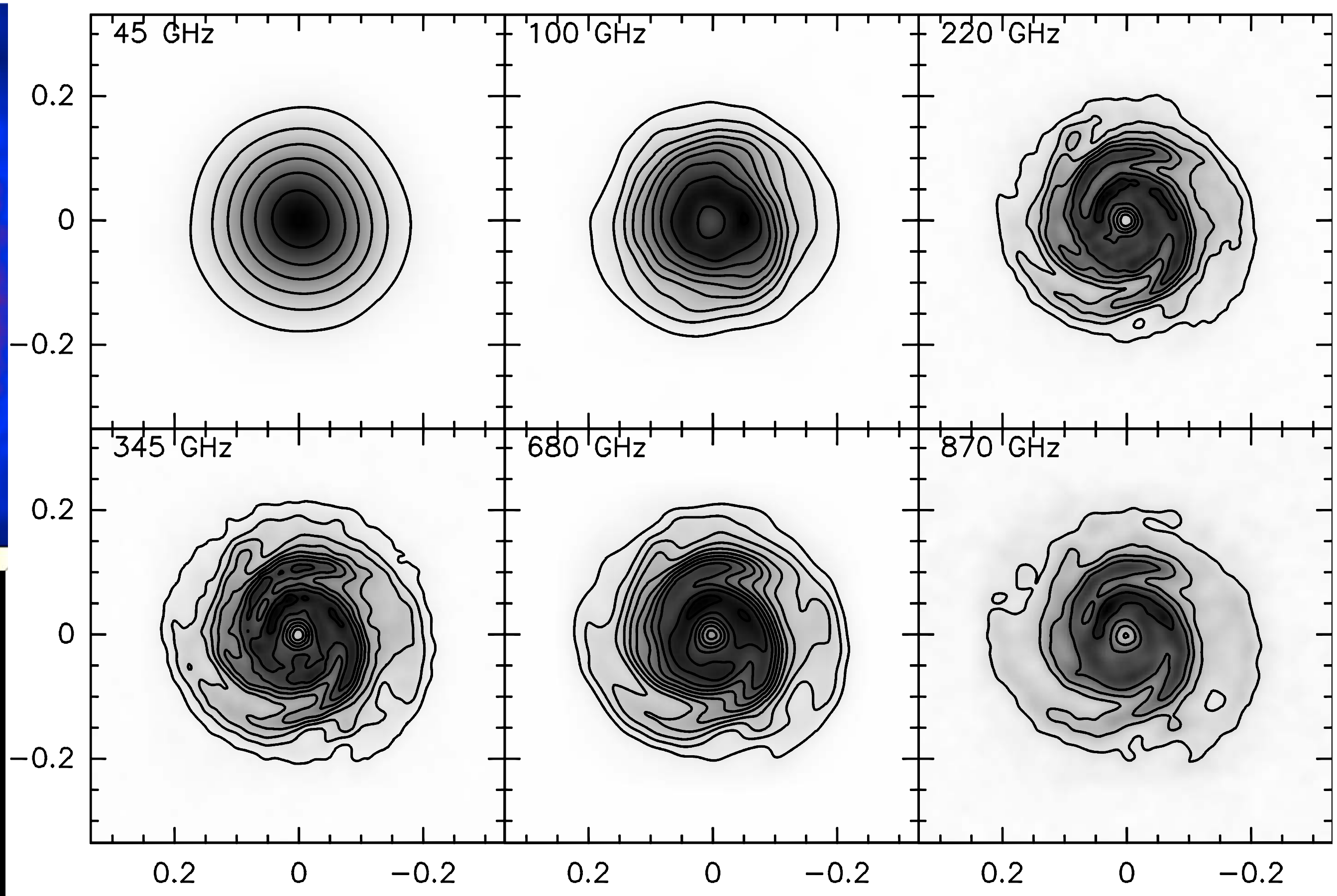


ß Pic
Debris disk – 100 Myrs
Scattered light: Burrows et al. 1995

Gas density maxima and grain trapping

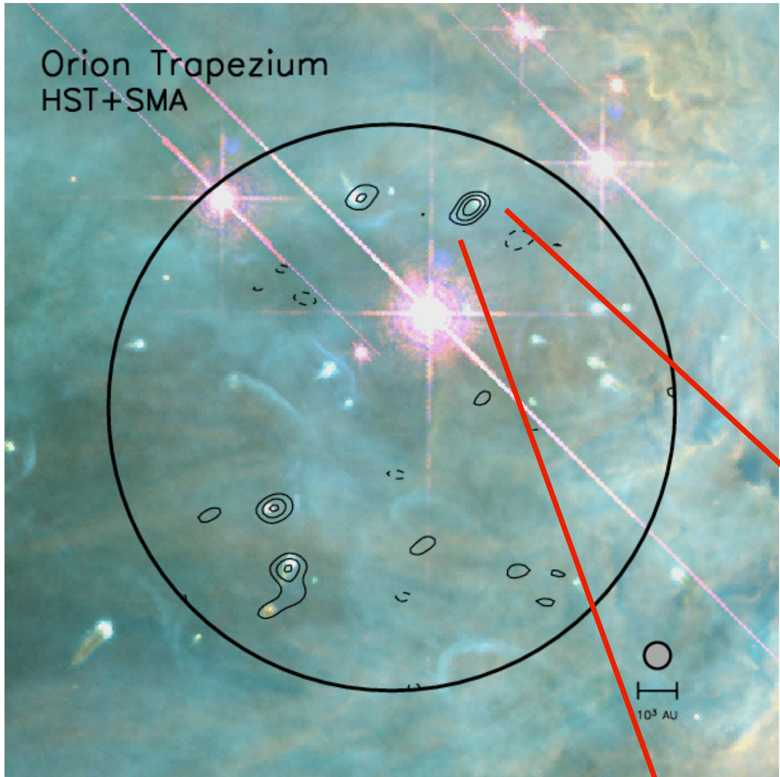






- Resolving disk structures with ALMA (simul from Cossins, Lodato & Testi 2010)

Birth of Planets

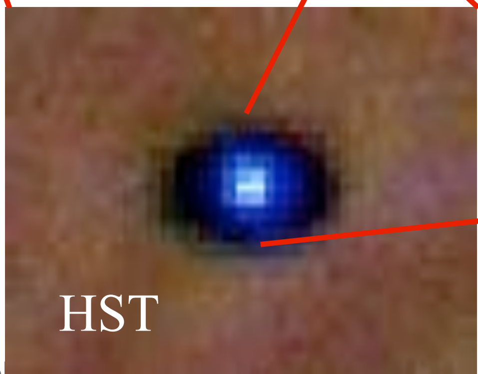


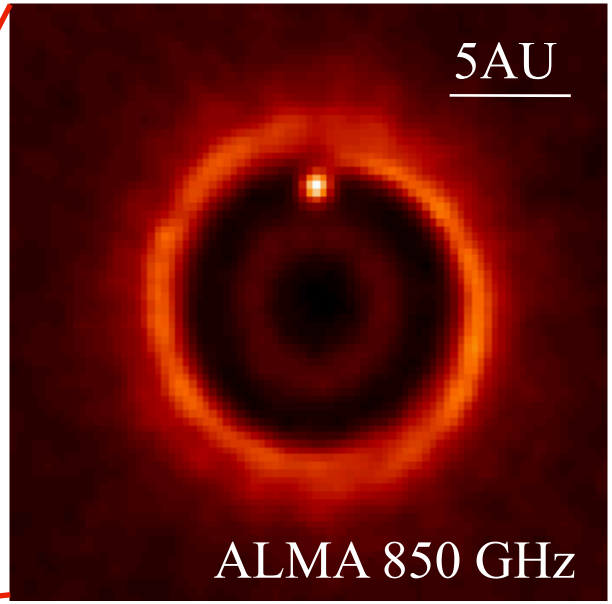
$M_{planet} = M_{Jup}$

$M_{star} \;\; = 0.5\ M_{sun}$

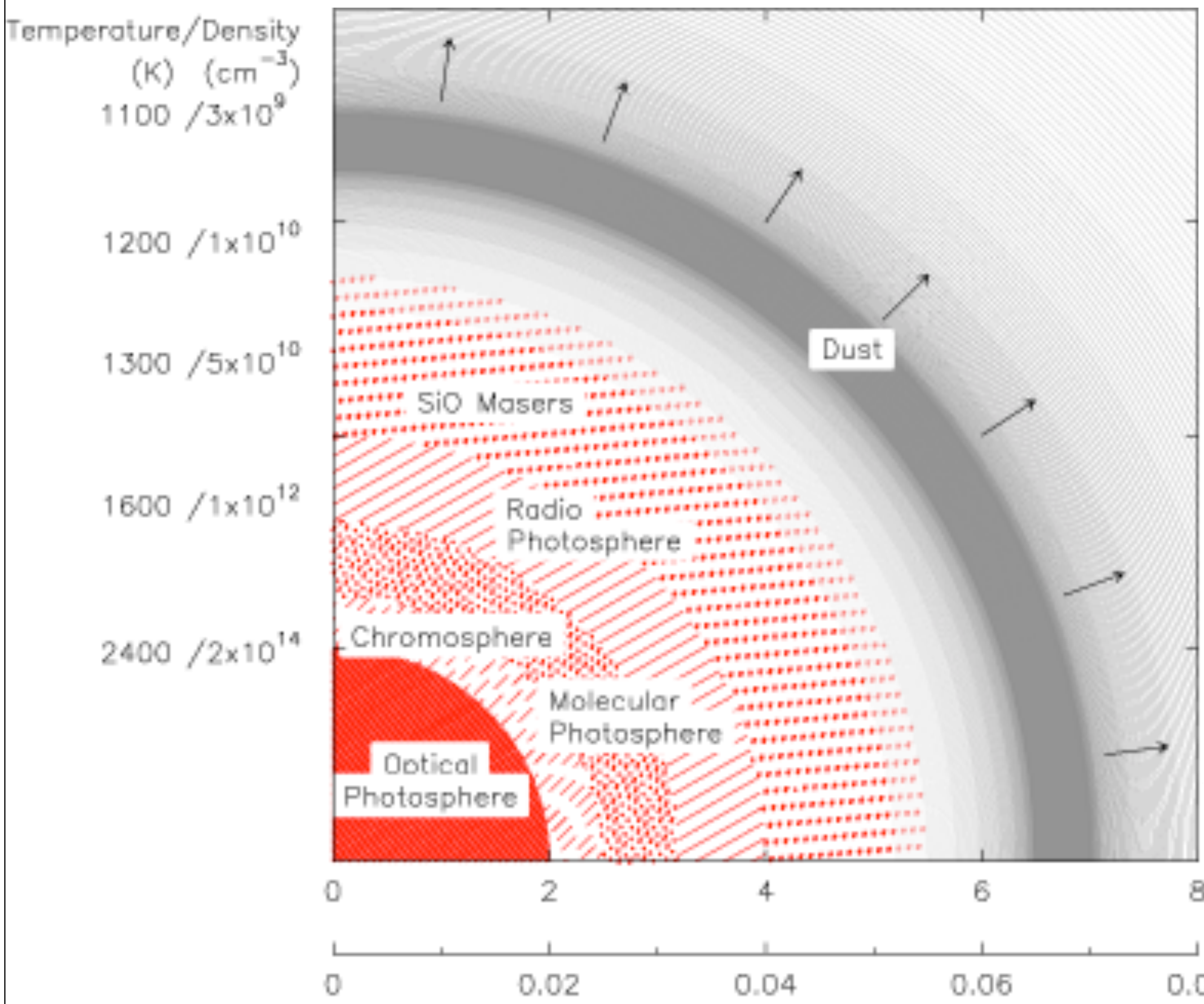
Orbiting at 5AU

Distance 50pc

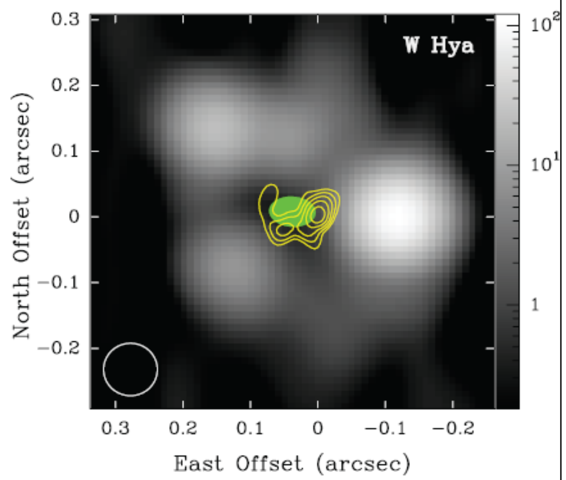




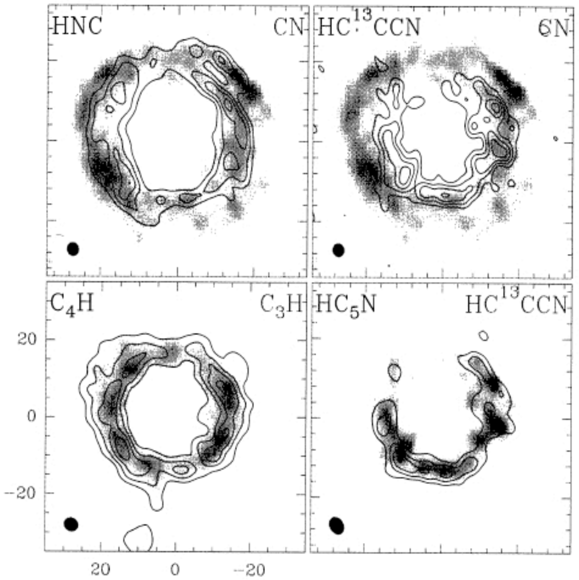
AGB Stars



Temperature/Density
(K) (cm^{-3})
1100 /3x10^{9}
1200 /1x10^{10}
1300 /5x10^{10}
1600 /1x10^{12}
2400 /2x10^{14}
Dust
SiO Masers
Radio Photosphere
Chromosphere
Molecular Photosphere
Optical Photosphere
0 2 4 6 8 Radius (AU)
0 0.02 0.04 0.06 0.08 Radius (arcsec)
(at D=100 pc)



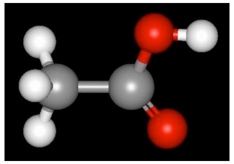
W Hya
North Offset (arcsec)
East Offset (arcsec)



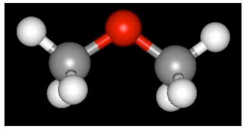
HNC
CN
HC^{13}CCN
6N
C$_4$H
C$_3$H
HC$_5$N
HC^{13}CCN

Complex Organic Molecules

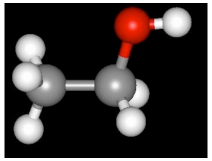
Detected



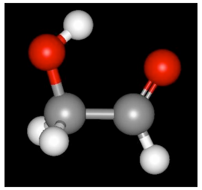
Acetic acid



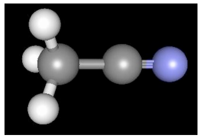
Di-methyl ether



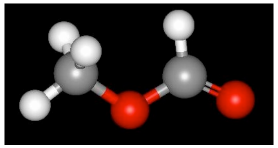
Ethanol



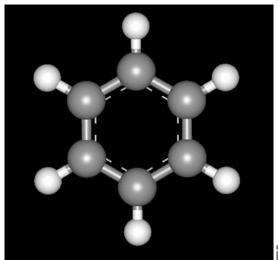
Sugar



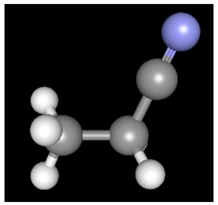
Methyl cyanide



Methyl formate

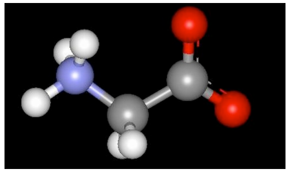


Benzene

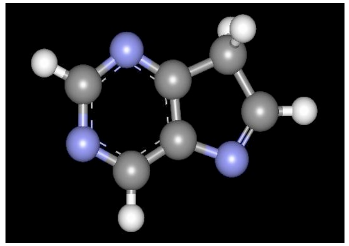


Ethyl cyanide

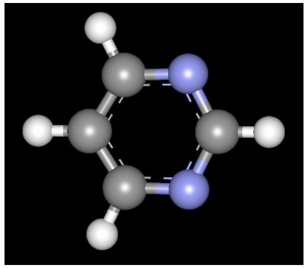
Not (yet) detected



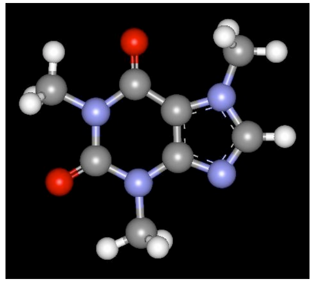
Glycine



Purine



Pyrimidine



Caffeine

How far does chemical complexity go?
Can we find pre-biotic molecules in Disks?

Based on Ehrenfreund 200

History of Galaxies

HST

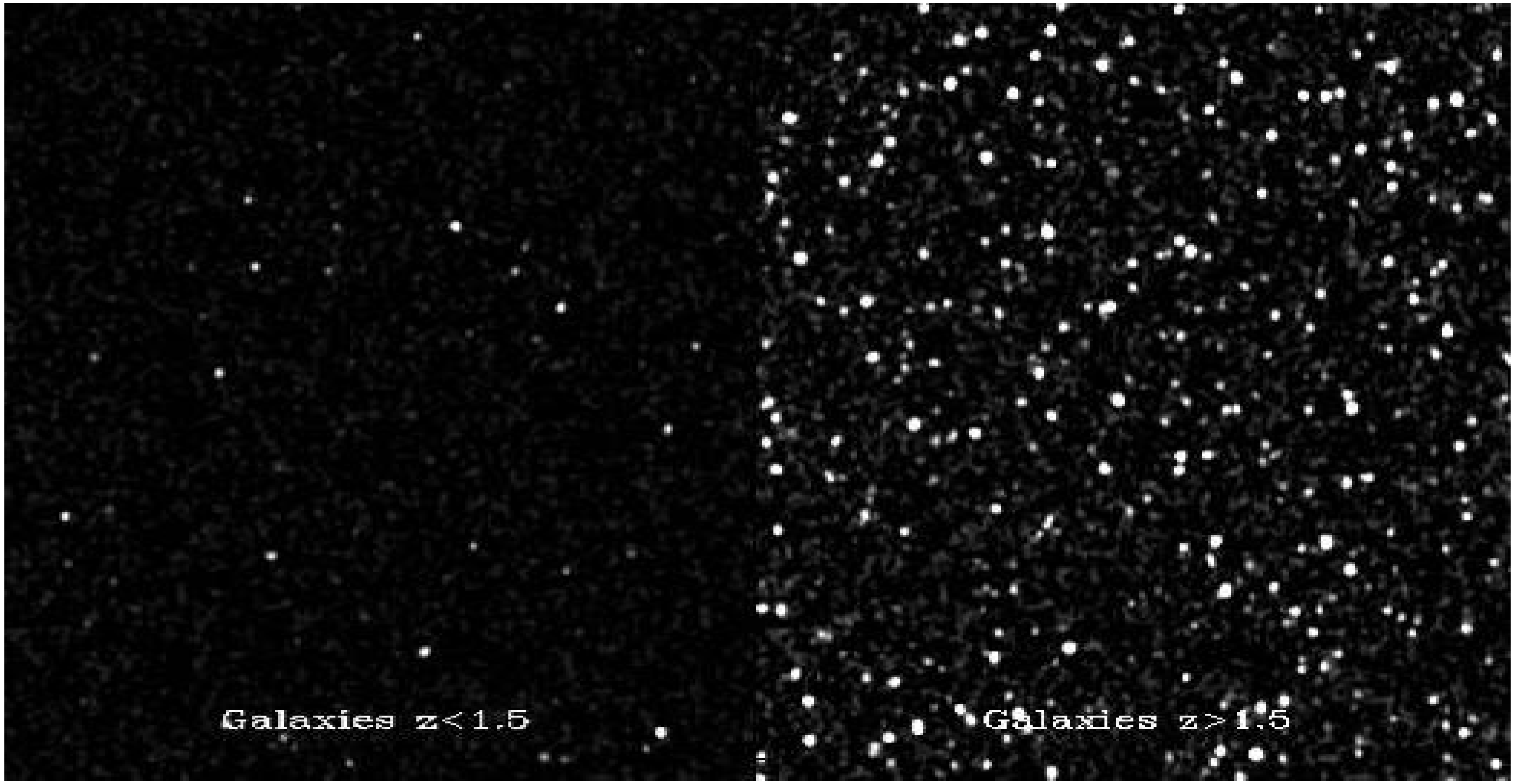
(12 days of integration)

z<1.5

z>1.5

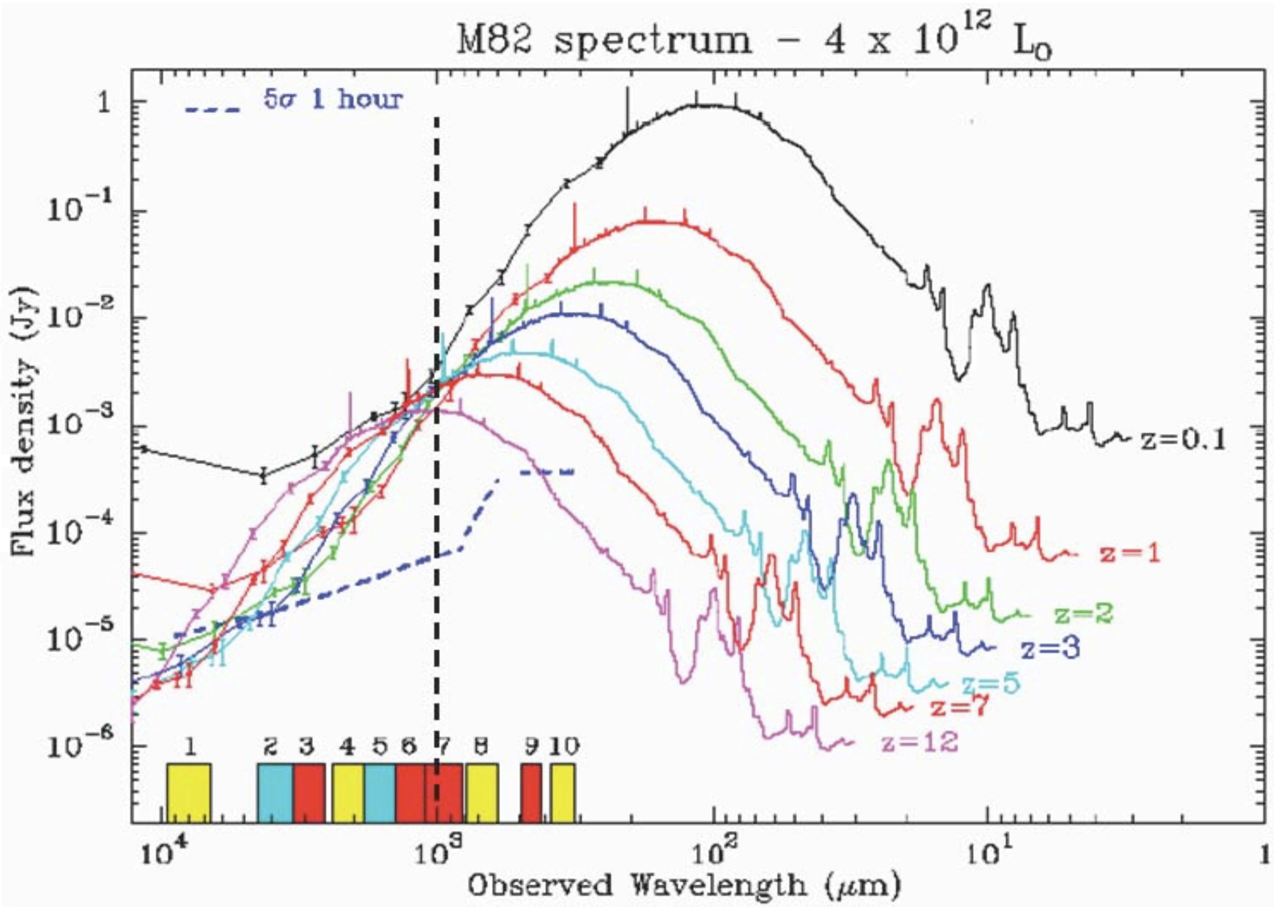
History of Galaxies

ALMA



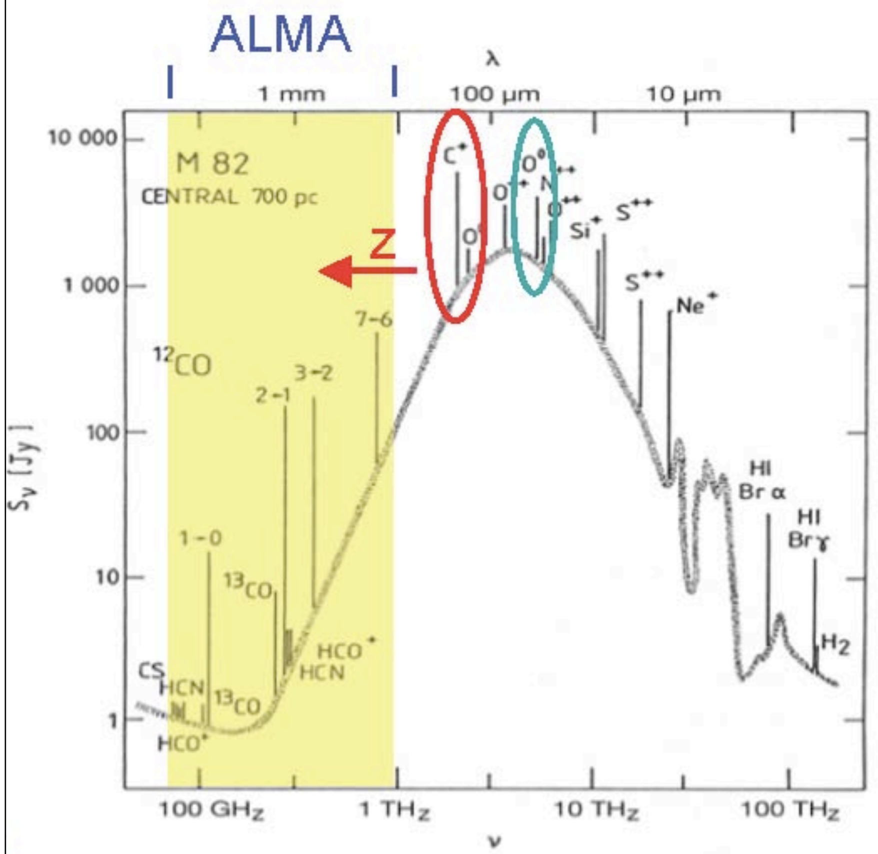
- ALMA will resolve the far infrared background seen by DIRBE and FIRAS

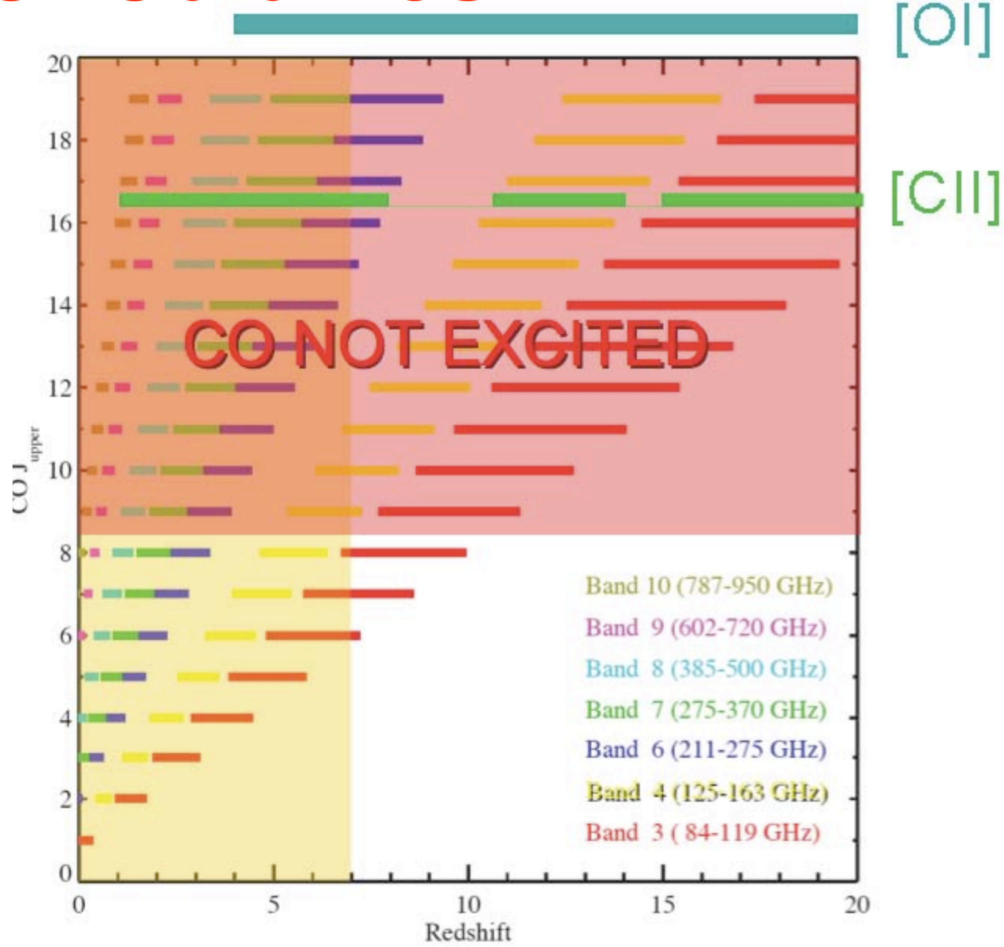
History of Galaxies



- In the (sub-)millimeter the inverse K-correction compensates for the distance as z increases

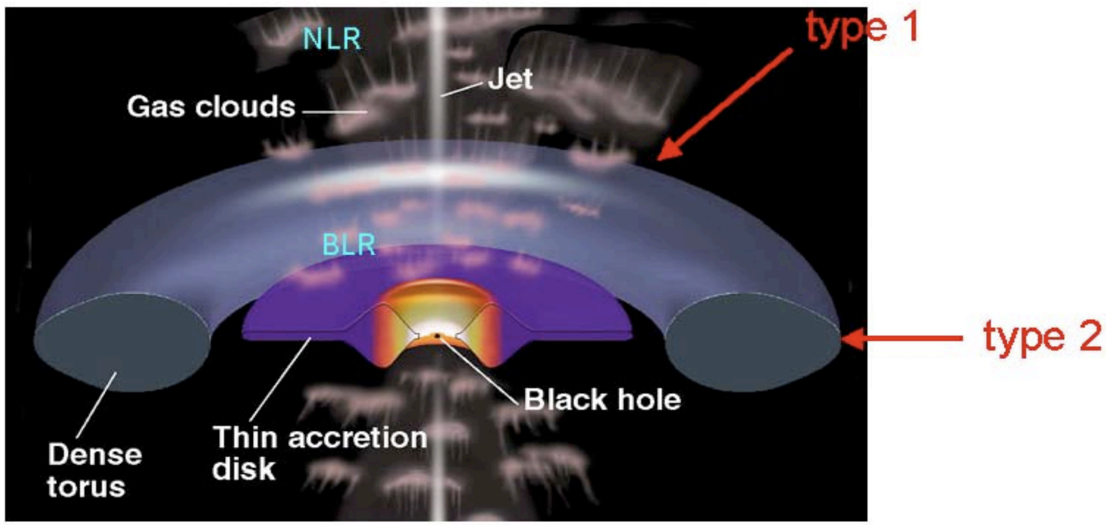
History of Galaxies

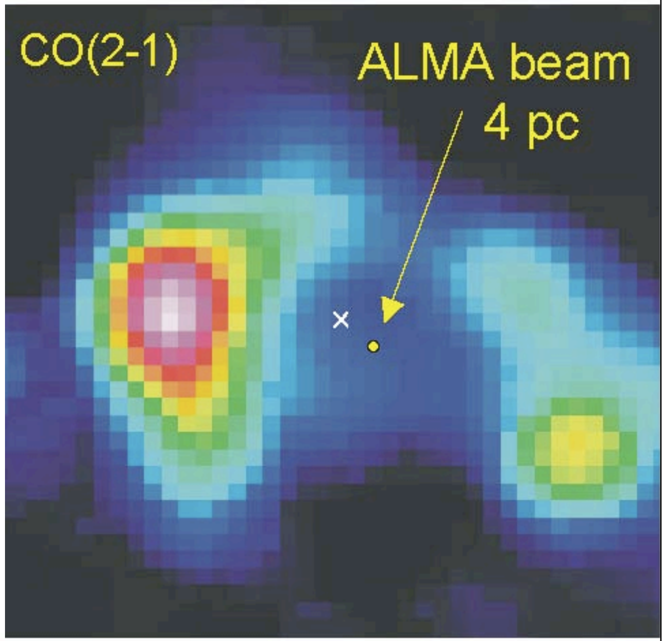




- Measuring redshift (and more) using CO, [CII] or [OI]

The Engine of nearby AGNs





Several (competing) models:

Geometry		Dynamics		Structure	
large ~100 pc	small ~1 pc	rotation	rotation and outflow	cont./diff. medium	clumpy medium
(observed)	(ALMA)		(ALMA)		(ALMA)

- ALMA will resolve the molecular gas structure and dynamics around nearby AGNs

ALMA Science

- ✦ Star Formation, Proto-planets in nearby disks
- ✦ Astrochemistry
- ✦ Interstellar medium (Galaxy, Local Group)
- ✦ High-redshift deep fields

- ✦ *+130 projects in first 3yrs – DRSP 2.0*
  - ➢ http://www.eso.org/sci/facilities/alma/science/drsp/

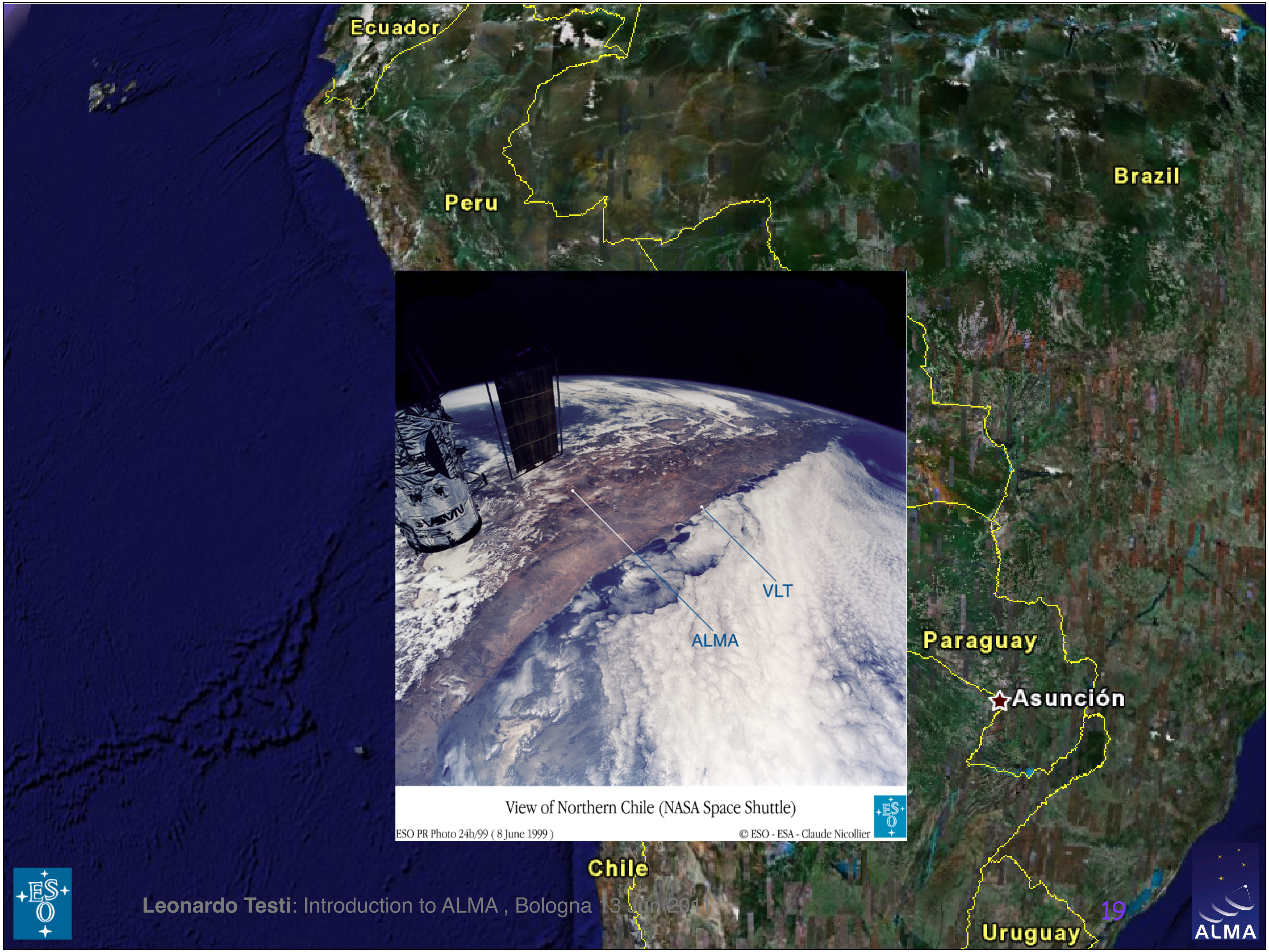
- ✦ **ALMA Science is for everyone**
  - High resolution/sensitivity 3D instrument at mm-wl
  - 100% service observing with full dynamic scheduling
  - Complete e2e data flow system
  - Science quality images (cubes) delivered to the users
  - Raw, calibrations, pipeline processed data and recipes in archive
  - Friendly and widespread User Support through ARCs

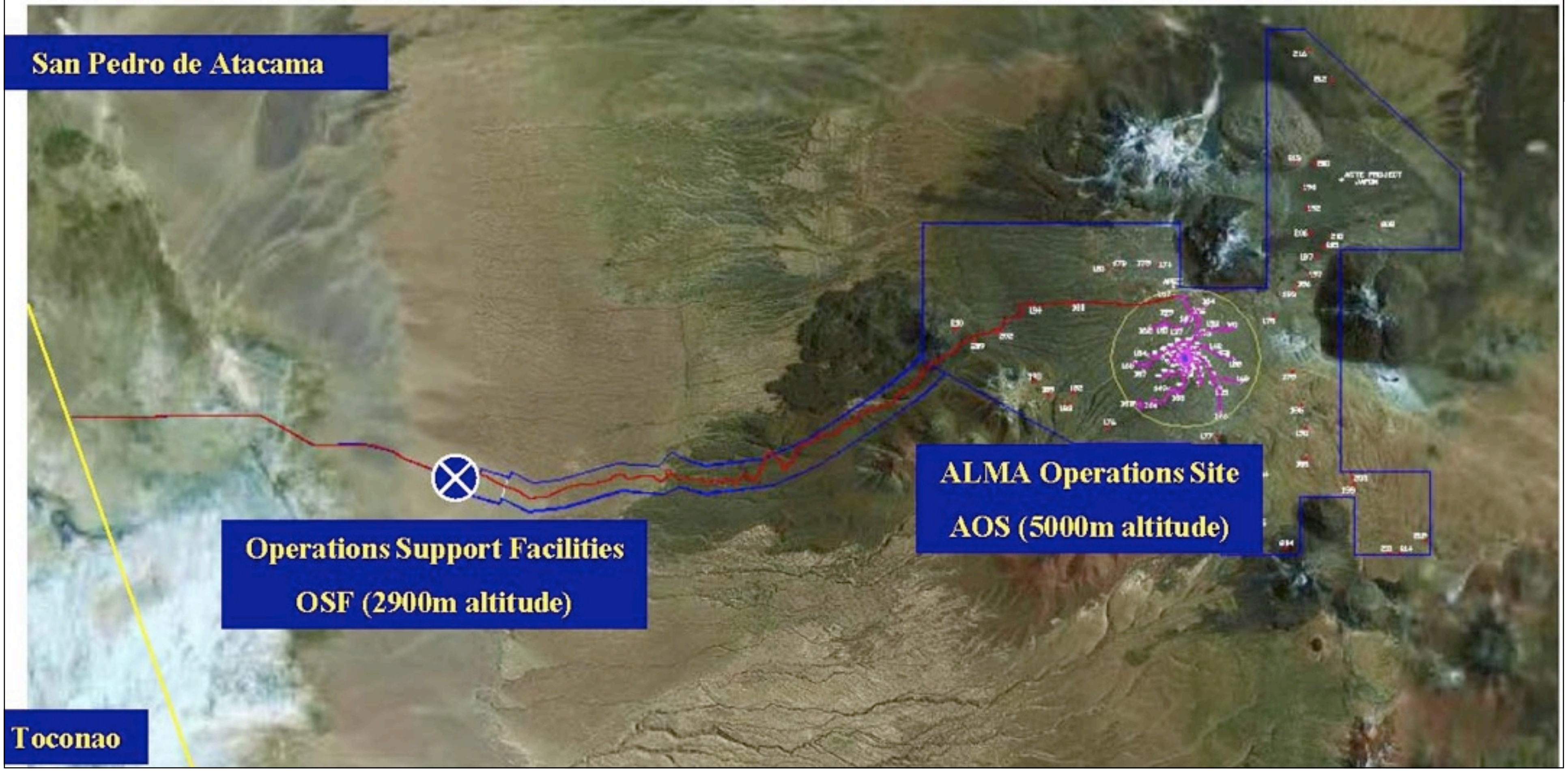
ALMA Science Requirements

- ✦ High Fidelity Imaging.
- ✦ Precise Imaging at 0.1” Resolution.
- ✦ Routine sub-mJy Continuum Sensitivity.
- ✦ Routine mK Spectral Sensitivity.
- ✦ Wideband Frequency Coverage.
- ✦ Wide Field Imaging Mosaicing.
- ✦ Submillimeter Receiver System.
- ✦ Full Polarization Capability.
- ✦ System Flexibility.

Technical Specifications

- 54 12-m antennas, 12 7-m antennas, at 5000 m site
- Surface accuracy ±25 μm, 0.6” reference pointing in 9m/s wind, 2” absolute pointing all-sky.
- Array configurations between 150m to ~16km.
- 10 bands in 31-950 GHz + 183 GHz WVR.
- 8 GHz BW, dual polarization.
- Flux sens. 0.2 mJy in 1 min at 345 GHz (median cond.).
- Interferometry, mosaicing & total-power observing.
- Correlator: 4096 channels/IF (multi-IF), full Stokes.
- Data rate: 6MB/s average; peak 60-150 MB/s.
- All data archived (raw + images), pipeline processing.


Ecuador
Peru
Brazil
VLT
ALMA
View of Northern Chile (NASA Space Shuttle)
ESO PR Photo 24b/99 (8 June 1999)
© ESO - ESA - Claude Nicollier
Paraguay
Asunción
Chile
Uruguay


San Pedro de Atacama
ALMA Operations Site
AOS (5000m altitude)
Operations Support Facilities
OSF (2900m altitude)
Toconao

mm Interferometers (u,v) coverage

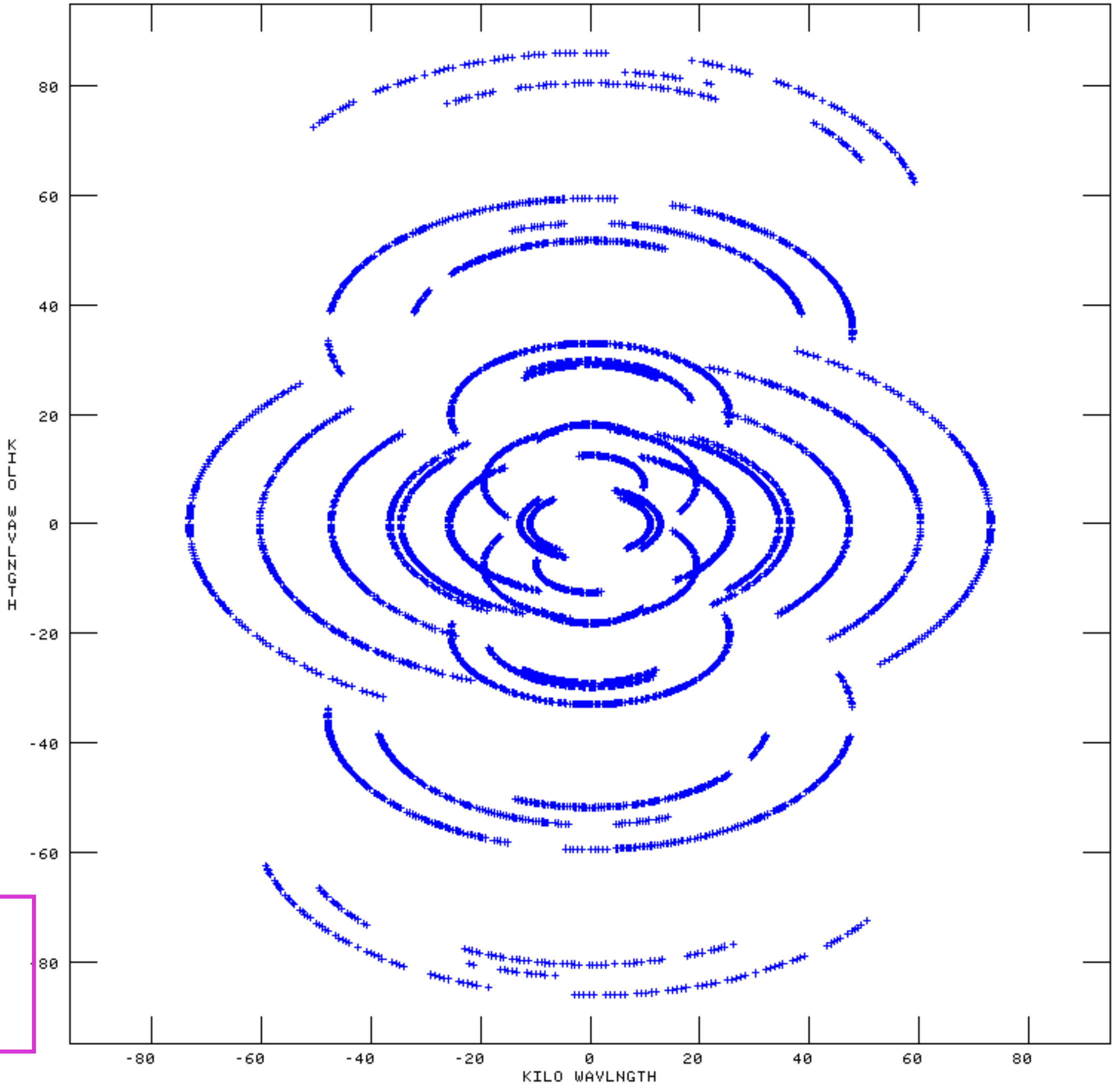
OVRO mm Array,
6 Antennas

L-configuration
single integration

L-Configuration few
hrs of observations

Final coverage: a
few hrs in both the L
and H configurations

<u>N.B.</u> (u,v) coverage
is not uniform

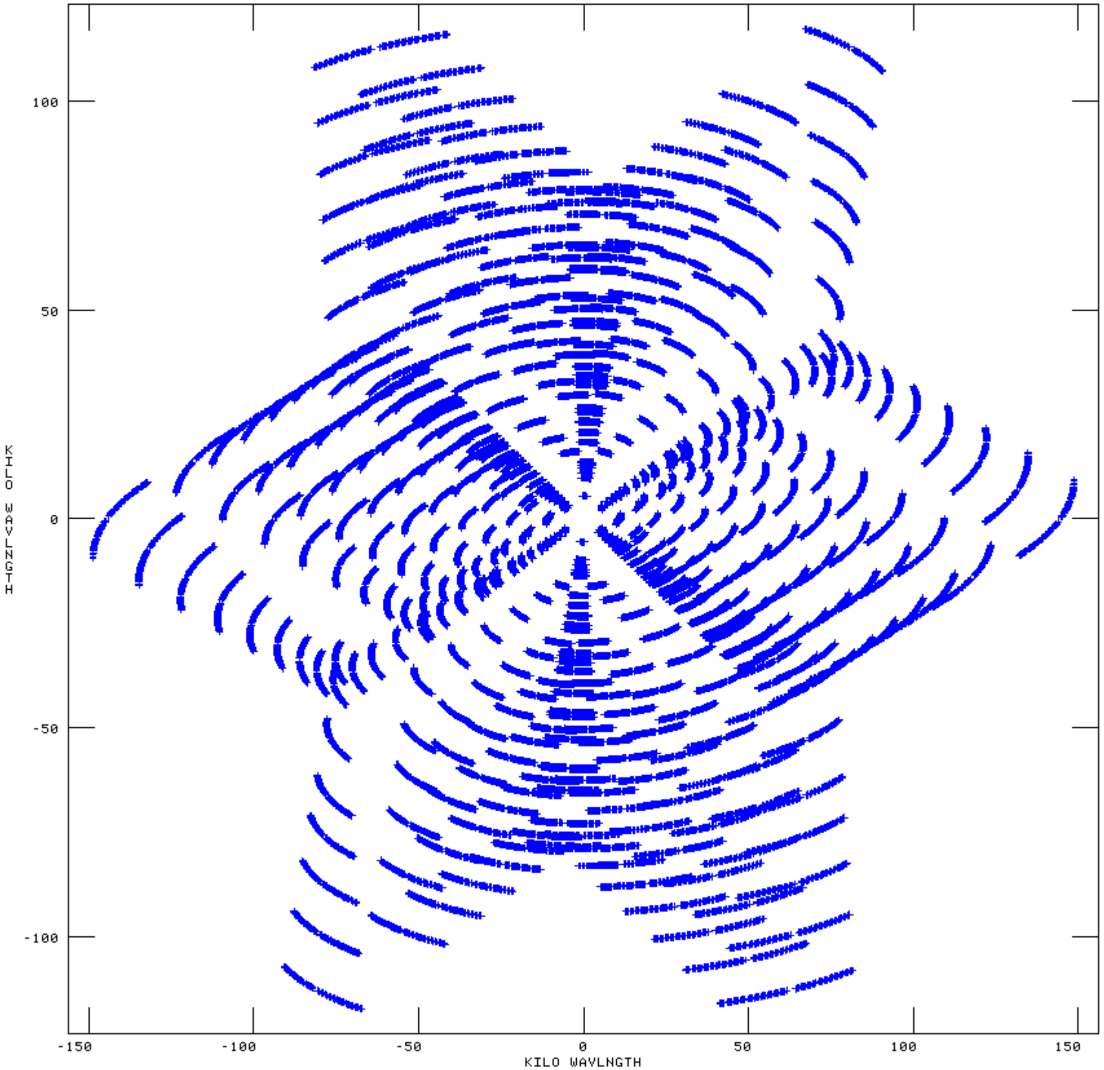


mm Interferometers (u,v) coverage

Very Large Array,
27 Antennas,
1.5h of observing time!

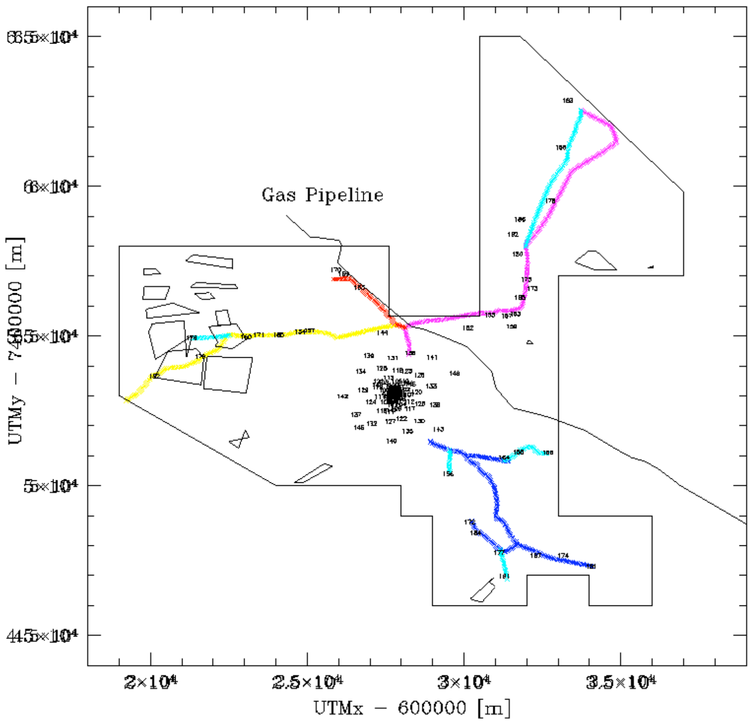
N.B. (u,v) coverage is still not uniform.

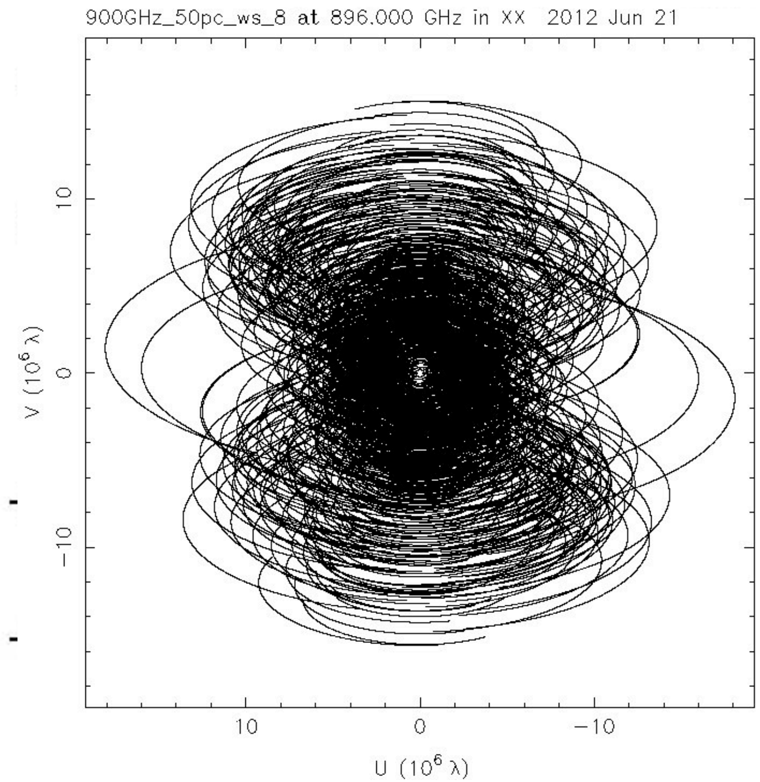
Critical parameters:
- Long baselines
- Short baselines
- Number of (u,v) points
- (u,v) coverage distribution



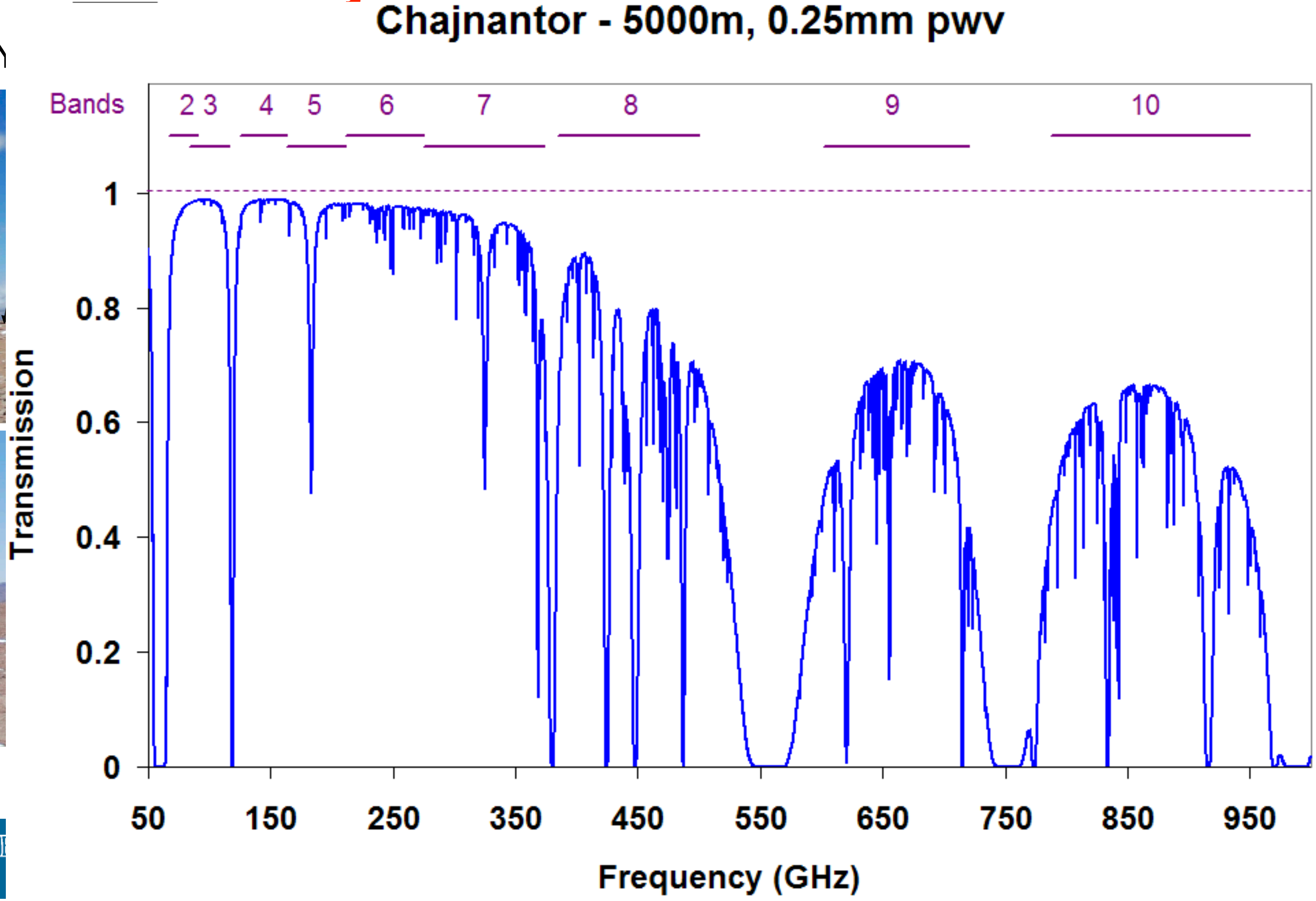
mm Interferometers (u,v) coverage

- Current mm interferometers offer typically ~10^4 visibility measurements in several hours, the VLA delivers ~10^5 visibilities per hour
- ALMA will improve by almost two orders of magnitude





Chajnantor Plateau - 5000m



ALMA Receivers

ALMA Band	Frequency Range	Receiver noise temperature		Mixing scheme	Receiver technology
		T_{Rx} over 80% of the RF band	T_{Rx} at any RF frequency		
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 – 169 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	DSB	SIS
9	602 – 720 GHz	175 K	263 K	DSB	SIS
10	787 – 950 GHz	230 K	345 K	DSB	SIS

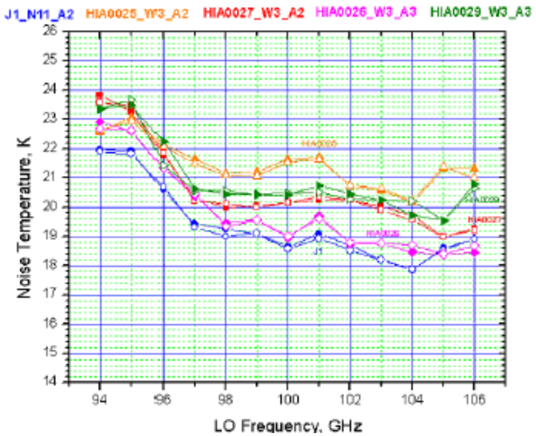
* - between 370 – 373 GHz T_{rx} is less then 300 K

- Dual, linear polarization channels:
  - Increased sensitivity
  - Measurement of 4 Stokes parameters
- 183 GHz water vapour radiometer:
  - Used for atmospheric path length correction

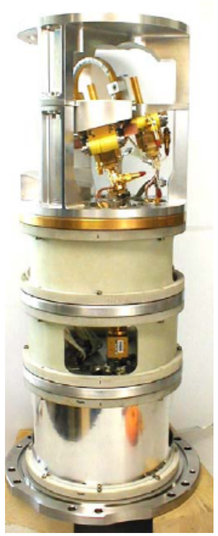
★ Japanese contribution all telescopes plus ACA

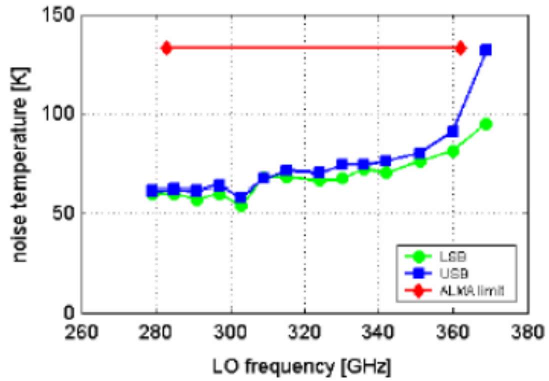
★ EC funded 6 receivers ALMA-Herschel sinergy

ALMA Receivers

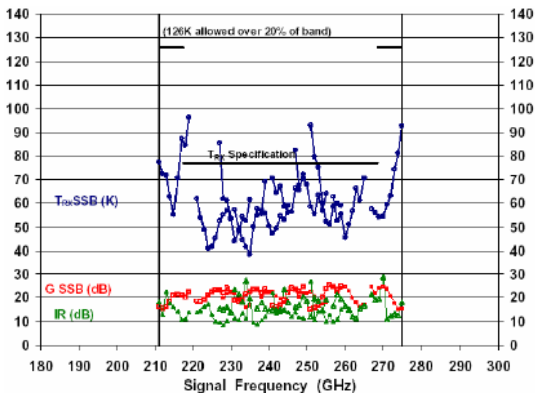


Band 3 ("3mm")

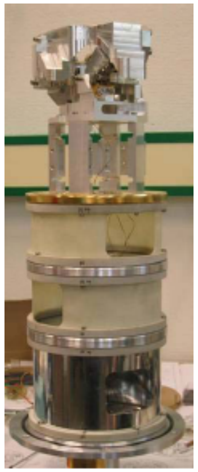


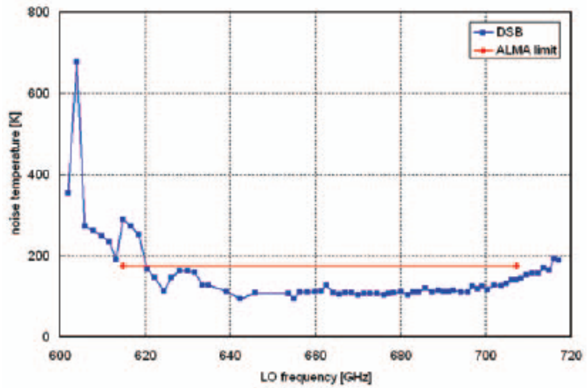


Band 7 ("850μm")



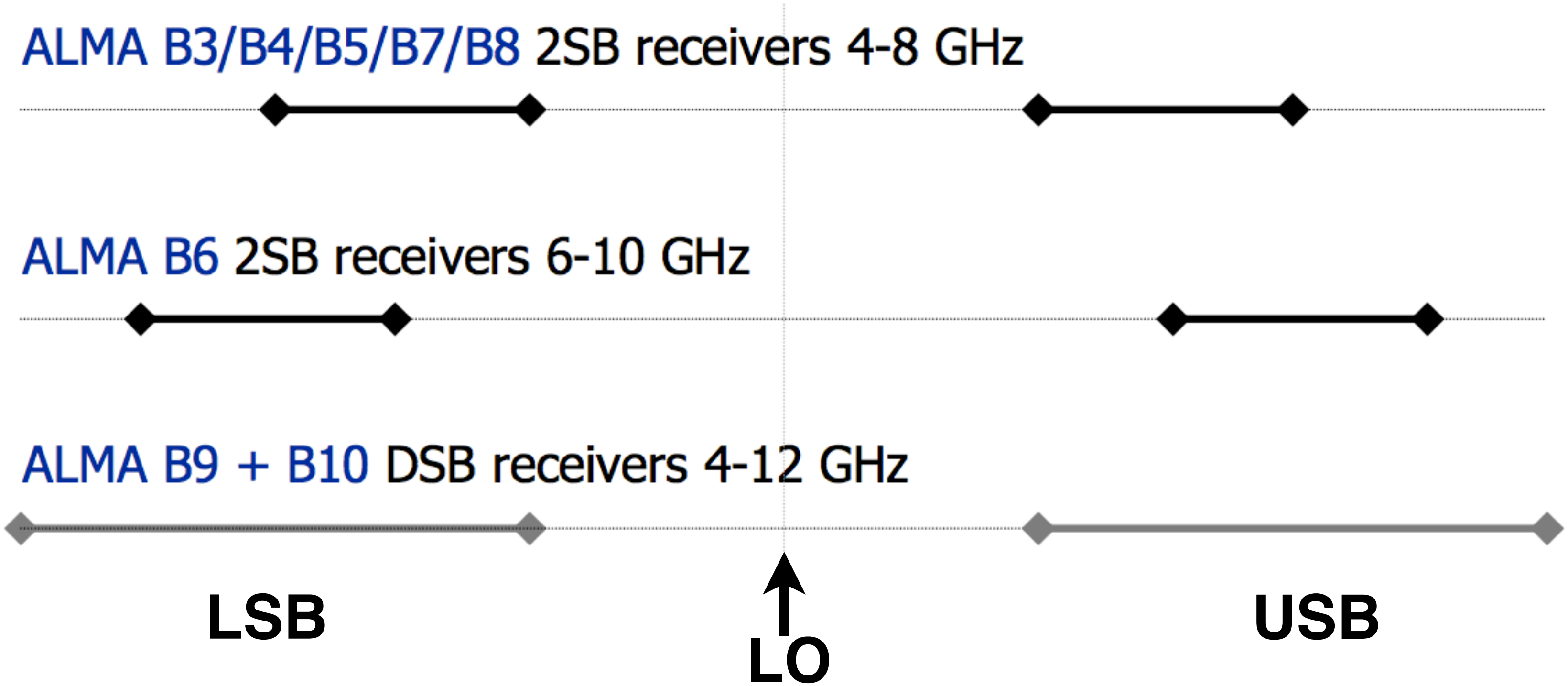
Band 6 ("1mm")





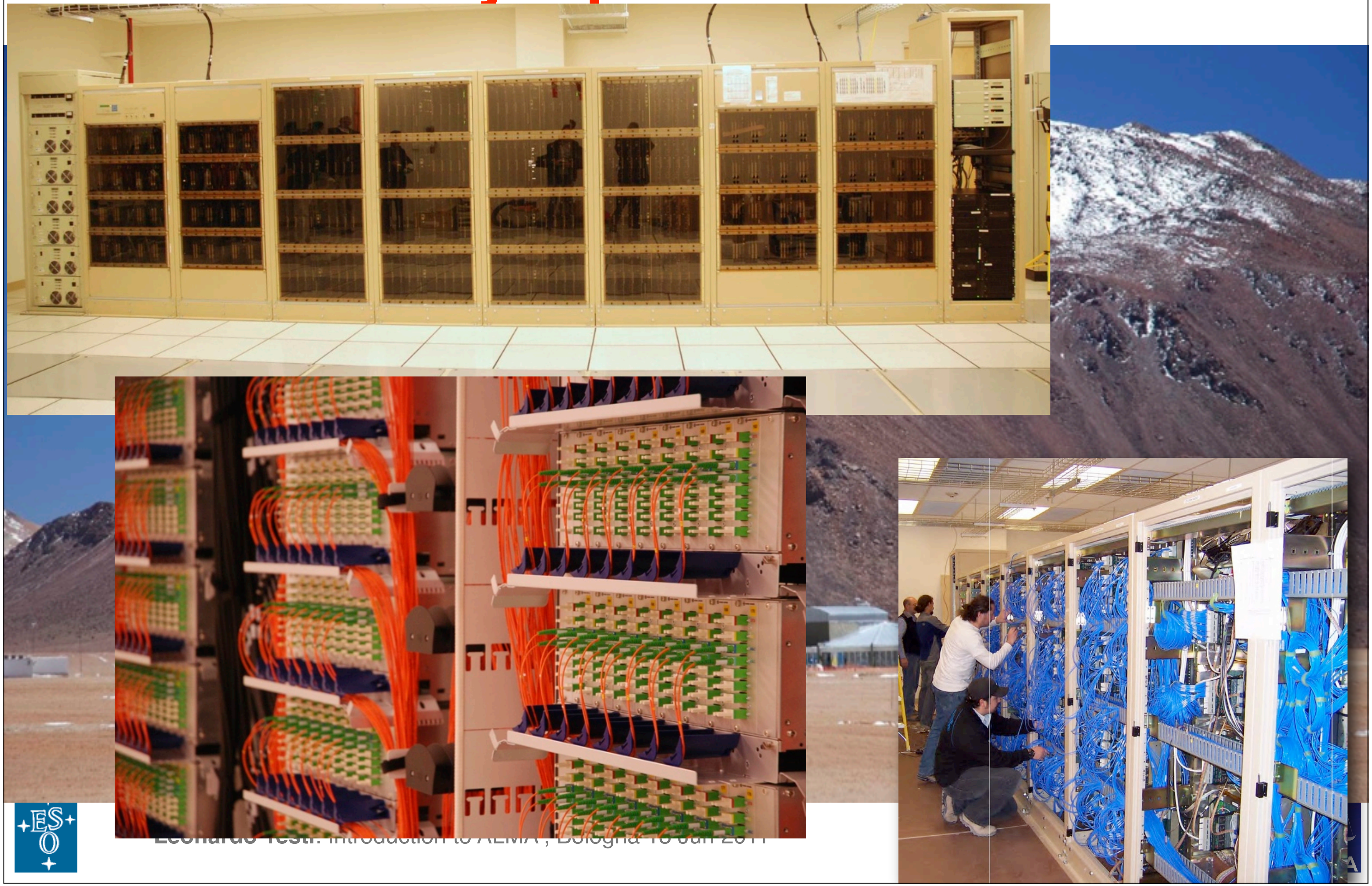
Band 9 ("450μm")

ALMA Receivers



- Lower frequencies ALMA receivers are 2SB receivers (the two sidebands are measured independently)
- The higher frequency receivers are DSB receivers

Array Operations Site



Example of FDM & TDM Modes

for all 4 polarization products with 2 BBs per Quadrant

- ***Not supported for Early Science*** in Table below:

Double Nyquist and 4-bit correlation (despite higher sensitiviy)

Mode #	Number of sub-channel filters	Total Bandwidth	Number of Spectral Points	Spectral Resolution	Velocity resolution at 230 GHz	Correlation	Sample Factor
13	32	2 GHz	2048	976 kHz	1.28 km/s	2-bit x 2-bit	Nyquist
14	16	1 GHz	2048	488 kHz	0.64 km/s	2-bit x 2-bit	Nyquist
32	16	1 GHz	1024	976 kHz	1.28 km/s	2-bit x 2-bit	Twice Nyquist
15	8	500 MHz	2048	244 kHz	0.32 km/s	2-bit x 2-bit	Nyquist
33	8	500 MHz	1024	488 kHz	0.64 km/s	2-bit x 2-bit	Twice Nyquist
16	4	250 MHz	2048	122 kHz	0.16 km/s	2-bit x 2-bit	Nyquist
34	4	250 MHz	1024	244 kHz	0.32 km/s	2-bit x 2-bit	Twice Nyquist
17	2	125 MHz	2048	61 kHz	0.08 km/s	2-bit x 2-bit	Nyquist
35	2	125 MHz	1024	122 kHz	0.16 km/s	2-bit x 2-bit	Twice Nyquist
51	2	125 MHz	512	244 kHz	0.32 km/s	4-bit x 4-bit	Nyquist
18	1	62.5 MHz	2048	30 kHz	0.04 km/s	2-bit x 2-bit	Nyquist
36	1	62.5 MHz	1024	61 kHz	0.08 km/s	2-bit x 2-bit	Twice Nyquist
52	1	62.5 MHz	512	122 kHz	0.16 km/s	4-bit x 4-bit	Nyquist
66	1	62.5 MHz	256	244 kHz	0.32 km/s	4-bit x 4-bit	Twice Nyquist
37	1	31.25 MHz	2048	15 kHz	0.02 km/s	2-bit x 2-bit	Twice Nyquist
67	1	31.25 MHz	512	61 kHz	0.08 km/s	4-bit x 4-bit	Twice Nyquist
70	Time Division Mode	2 GHz	64	31.25 MHz	40.8 km/s	2-bit x 2-bit	Nyquist

Multi resolution modes

Table 8 Multi-resolution mode possibilities

Corr Mode Number	BW	BITS	NYQUIST	POLZ	Full	1/2	1/4	1/8	1/16	1/32
	Mode Identifier				Spectral Channel Resolution for each polarization data set as a function of the fraction of correlator resources assigned in Multi-resolution Mode (Total #spectral channels per polarization data set in parenthesis)					
2	1GHz	2x2	1N	1BB	122 KHz (8192)	244 KHz (4096)	na	na	na	na
3	500MHz	2x2	1N	1BB	61 KHz (8192)	122 KHz (4096)	244 KHz (2048)	na	na	na
4	250MHz	2x2	1N	1BB	30.5 KHz (8192)	61 KHz (4096)	122 KHz (2048)	244 KHz (1024)	na	na
5	125MHz	2x2	1N	1BB	15.3 KHz (8192)	30.5 KHz (4096)	61 KHz (2048)	122 KHz (1024)	244 KHz (512)	na
6	62.5MHz	2x2	1N	1BB	7.63 KHz (8192)	15.3 KHz (4096)	30.5 KHz (2048)	61 KHz (1024)	122 KHz (512)	244 KHz (256)
9	500MHz	2x2	1N	2BB	122 KHz (4096)	244 KHz (2048)	na	na	na	na
10	250MHz	2x2	1N	2BB	61 KHz (4096)	122 KHz (2048)	244 KHz (1024)	na	na	na
11	125MHz	2x2	1N	2BB	30.5 KHz (4096)	61 KHz (2048)	122 KHz (1024)	244 KHz (512)	na	na
12	62.5MHz	2x2	1N	2BB	15.3 KHz (4096)	30.5 KHz (2048)	61 KHz (1024)	122 KHz (512)	244 KHz (256)	na
16	250MHz	2x2	1N	2BB-P	122 KHz (2048)	244 KHz (1024)	na	na	na	na
17	125MHz	2x2	1N	2BB-P	61 KHz (2048)	122 KHz (1024)	244 KHz (512)	na	na	na
18	62.5MHz	2x2	1N	2BB-P	30.5 KHz (2048)	61 KHz (1024)	122 KHz (512)	244 KHz (256)	na	na
25	31.25MHz	2x2	2N	1BB	3.82 KHz (8192)	7.63 KHz (4096)	15.3 KHz (2048)	30.5 KHz (1024)	61 KHz (512)	122 KHz (256)
31	31.25MHz	2x2	2N	2BB	7.63 KHz (4096)	15.3 KHz (2048)	30.5 KHz (1024)	61 KHz (512)	122 KHz (256)	na
37	31.25MHz	2x2	2N	2BB-P	15.3 KHz (2048)	30.5 KHz (1024)	61 KHz (512)	122 KHz (256)	na	na

« *The ALMA Correlators* » A. Baudry, ALMA Newsletter, Jan. 2011, No 7

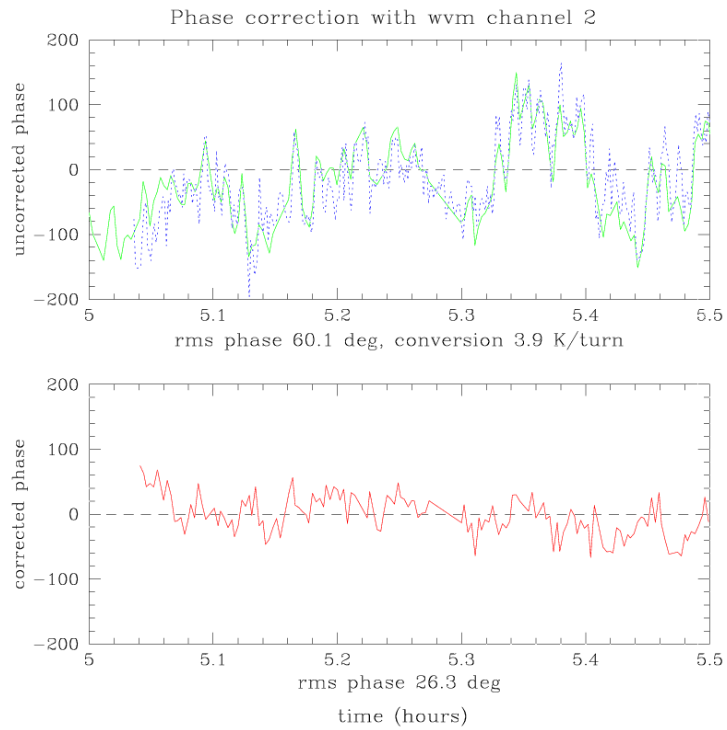
http://www.almaobservatory.org/en/outreach/newsletter/252-newsletter-no-7

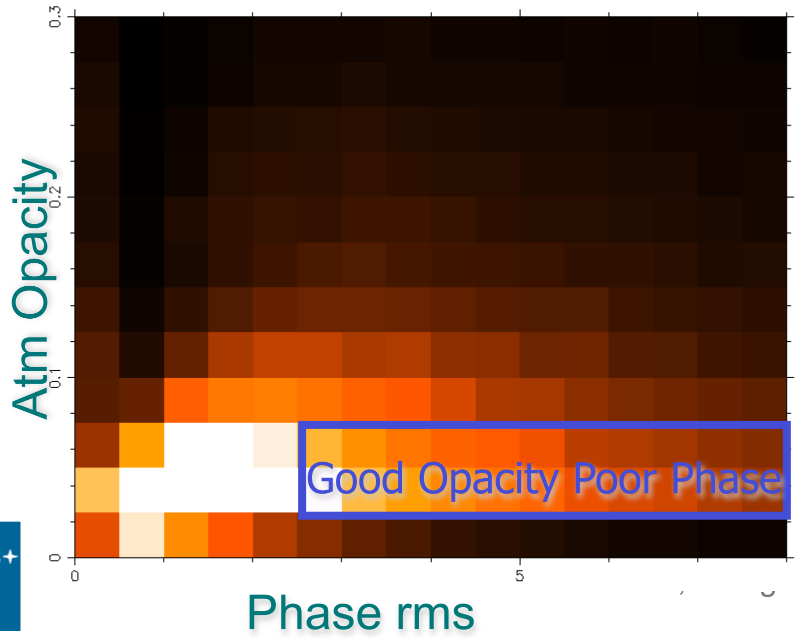
Operations Support Facility - 2900m

ALMA Construction Status

✦ Water Vapour Radiometers

- All ALMA antennas will be equipped with water vapour radiometers observing the 183GHz atmospheric water line.



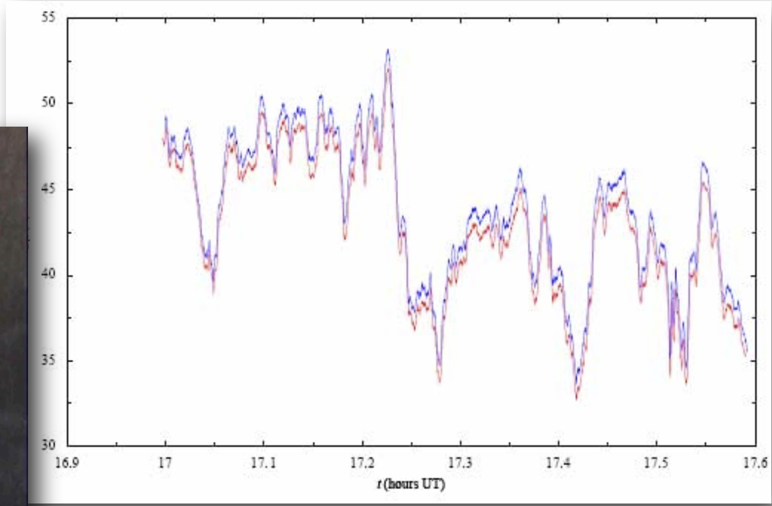


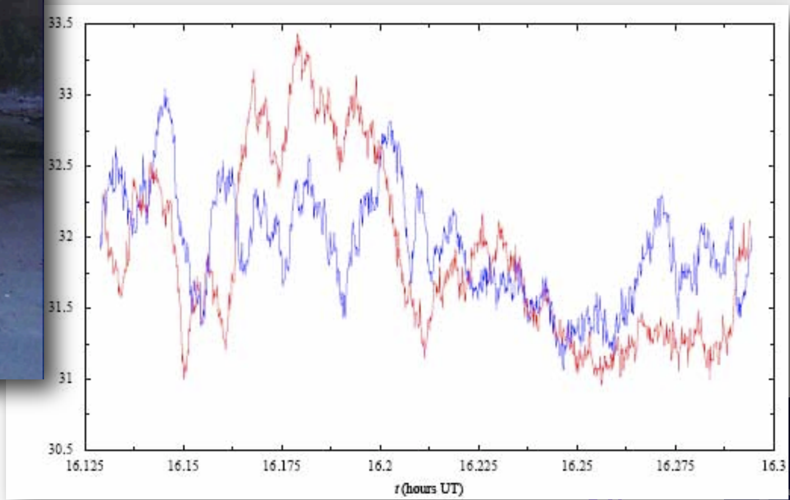
WVRs track phase on 1s timescales along the same path (within 3-10 arcmin) as the astronomical signal from the source (complementary to fastswitching: ≥10s and few degs)

-Improve Sensitivity and Fidelity
-Allow to increase switch time

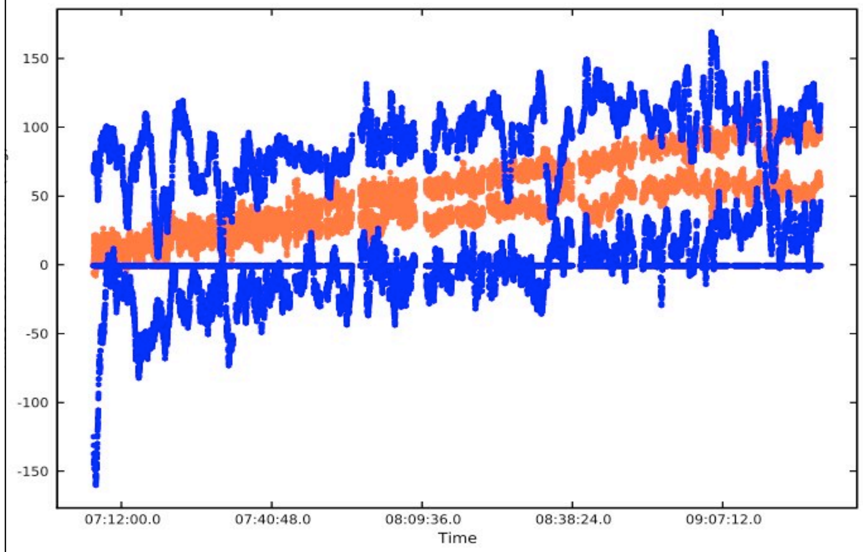
WVR progress

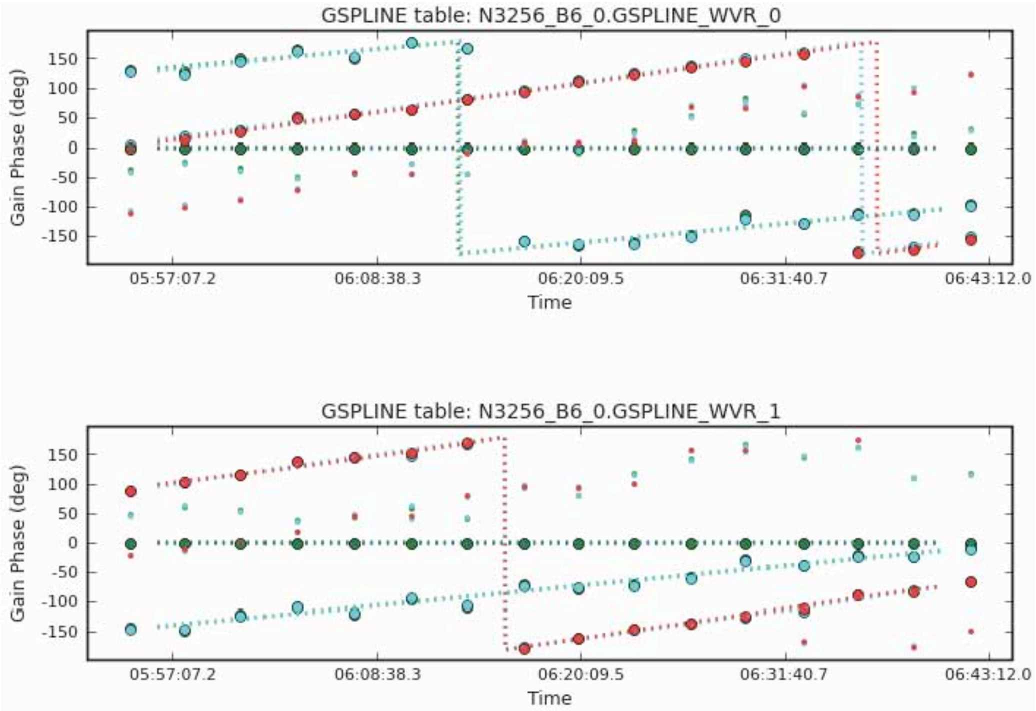
- Successful testing at Onsala, OSF and AOS
- Correction very promising





WVR Phase correction



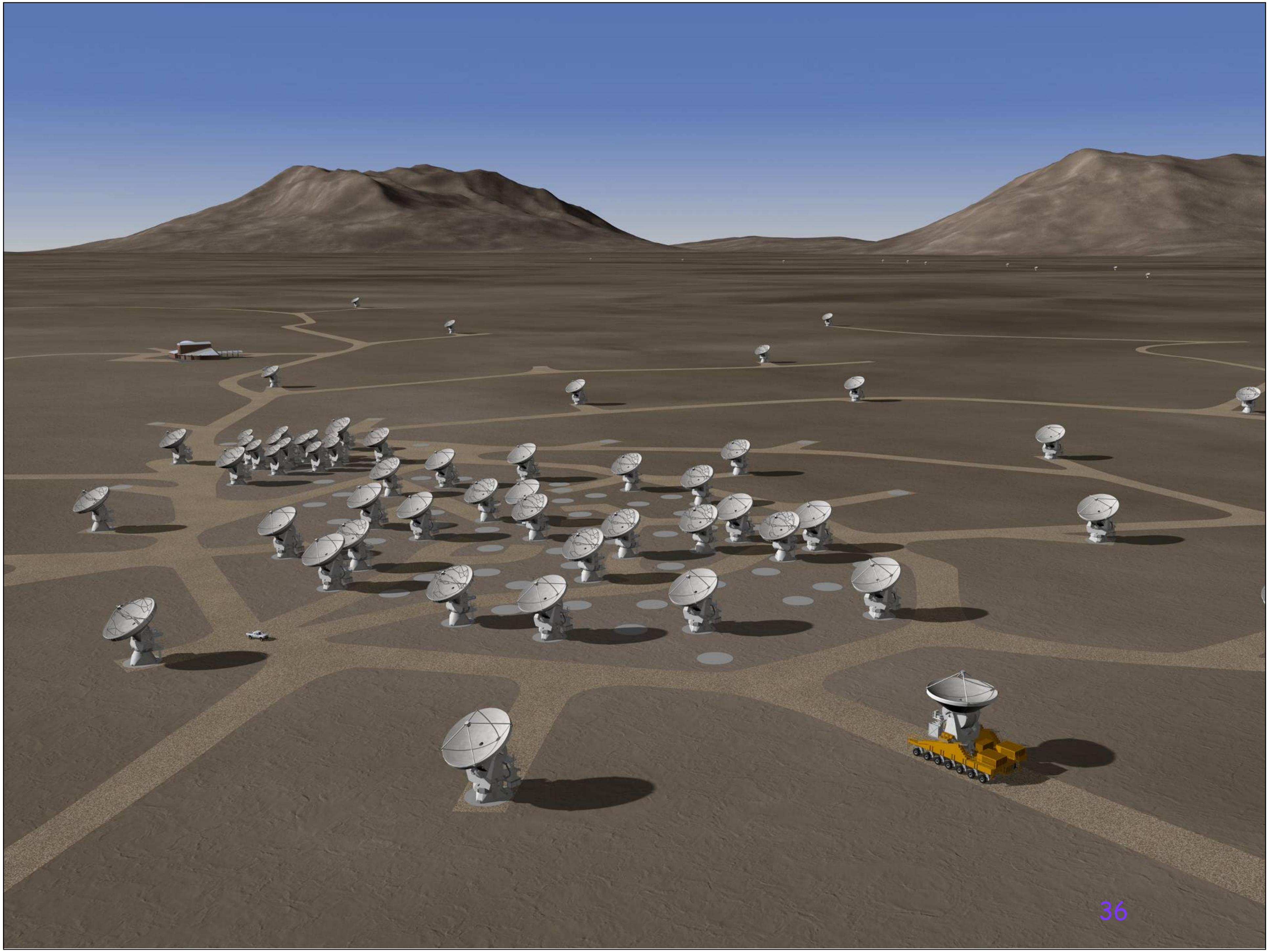


Blue: uncorrected interferometer phase

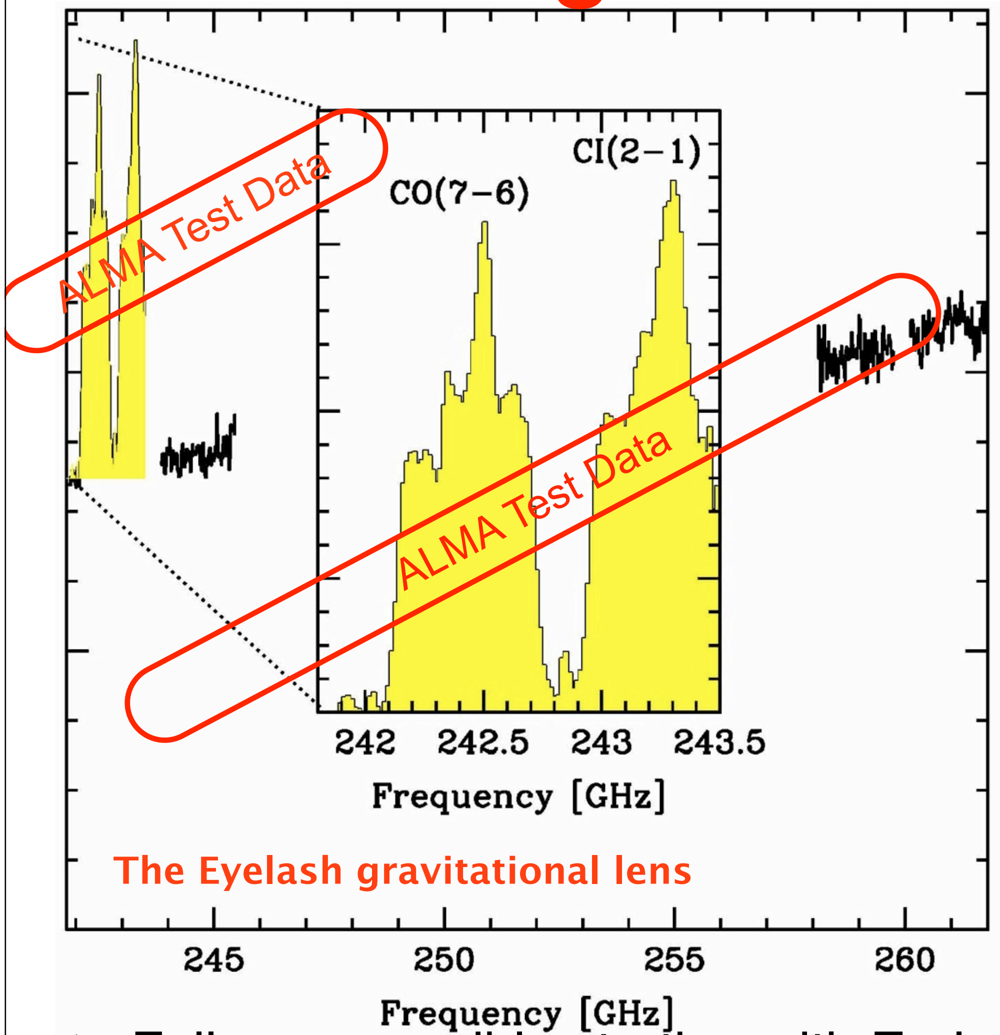
Orange: phase after correction using water-vapour radiometers

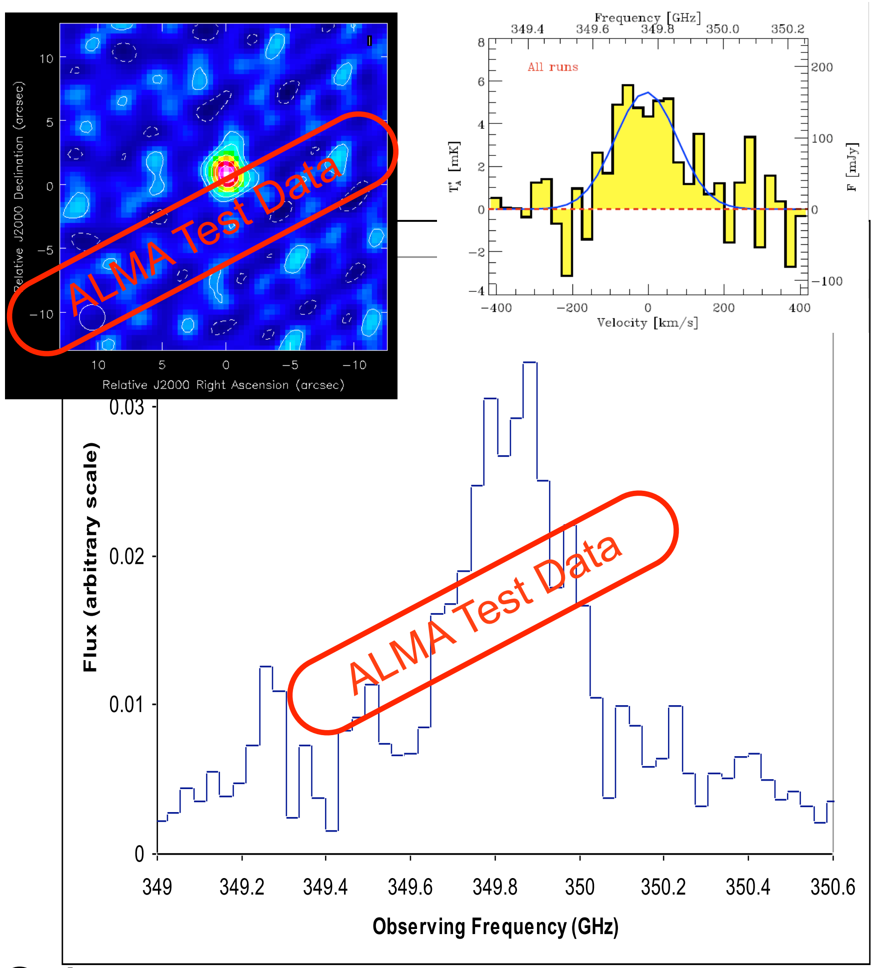
Full calibration test in CASA

Small dots: raw measurements
Large circles: WVR corrected



Extragalactic high-z Surveys



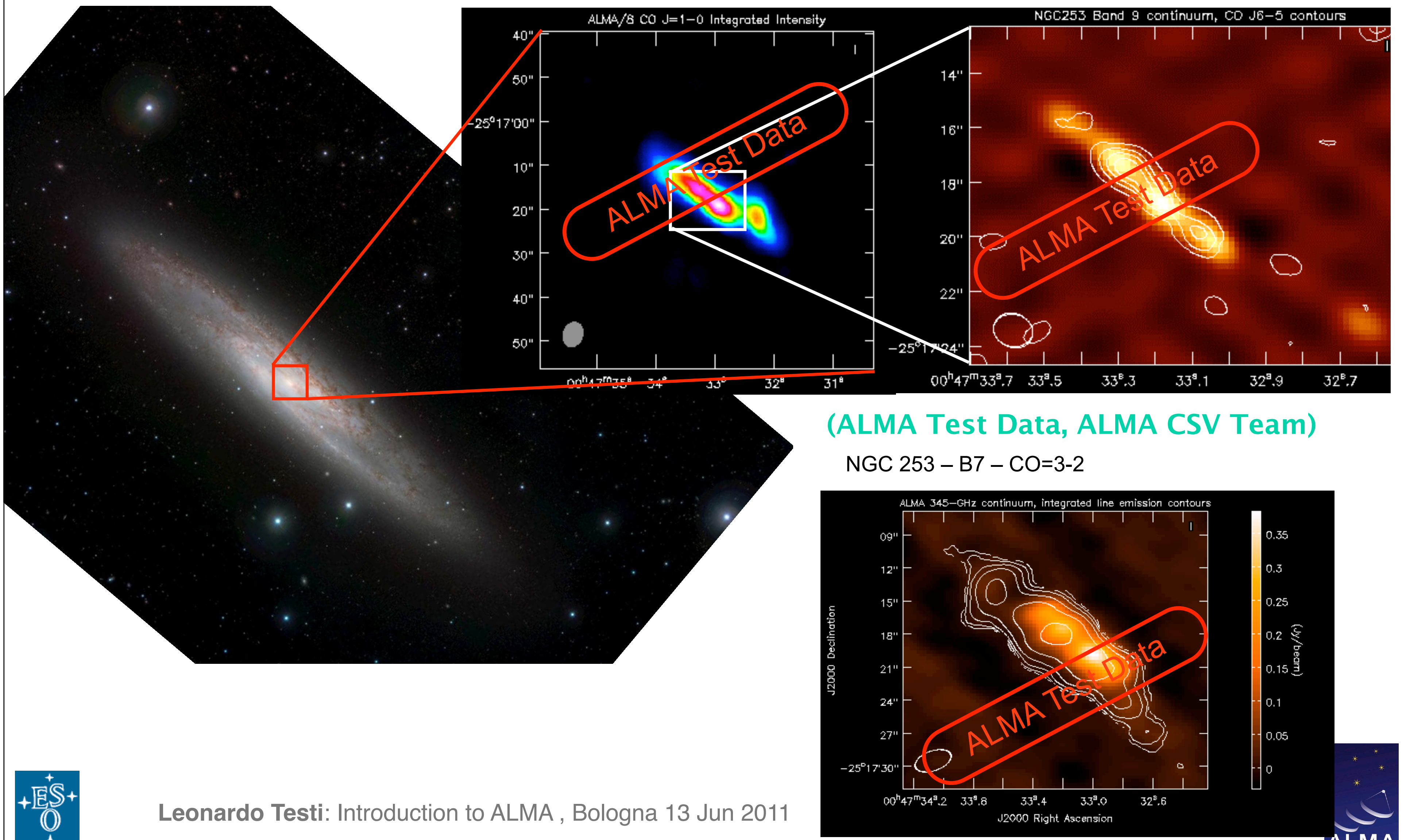


[CII] in BRI 0952 at z=4.4

(ALMA Test Data, ALMA CSV Team)

- ✦ Followup possible starting with Early Science
- ✦ Including spectroscopy (CO, CI, CII)

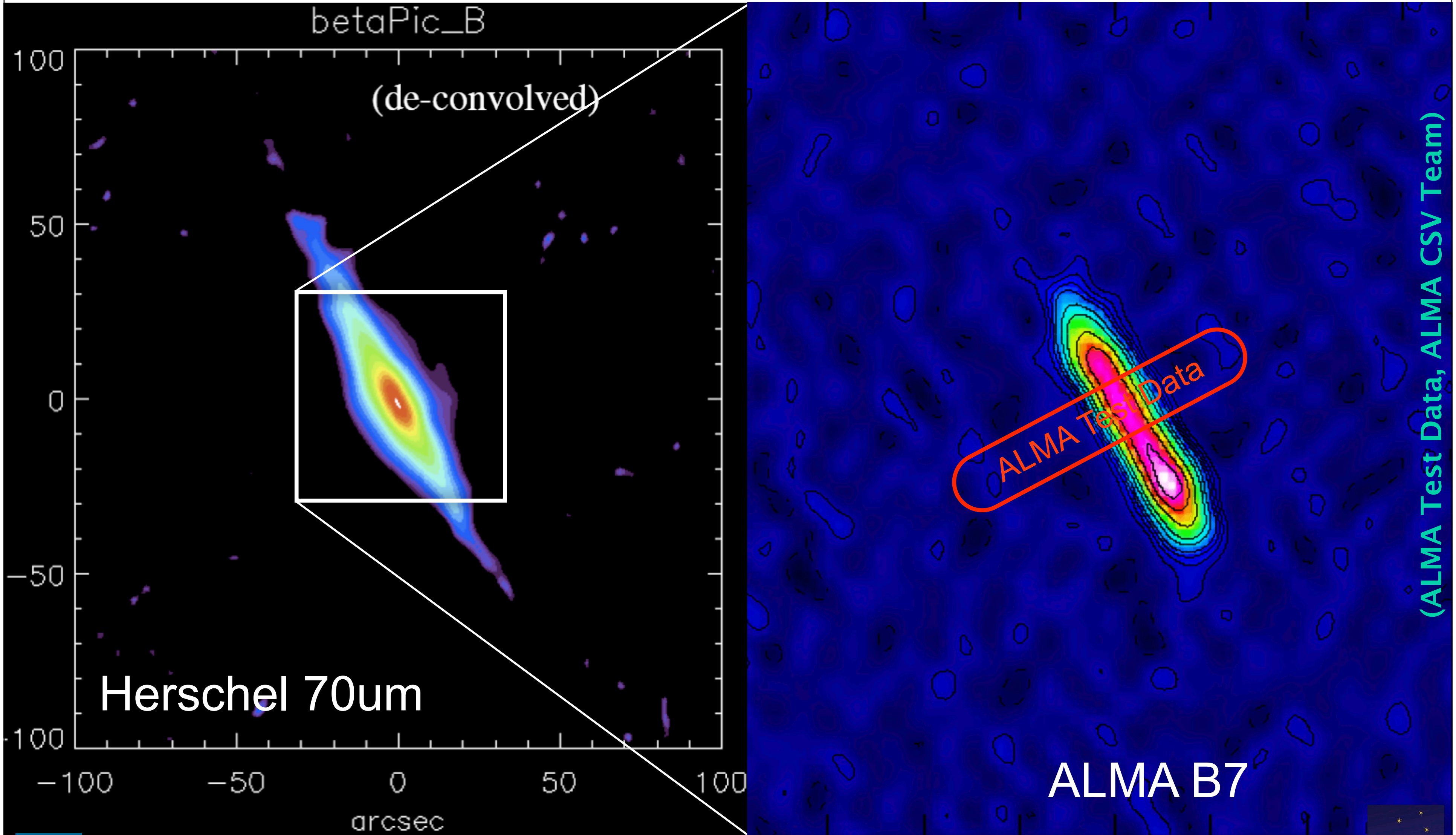
ALMA Test Data on NGC253



(ALMA Test Data, ALMA CSV Team)

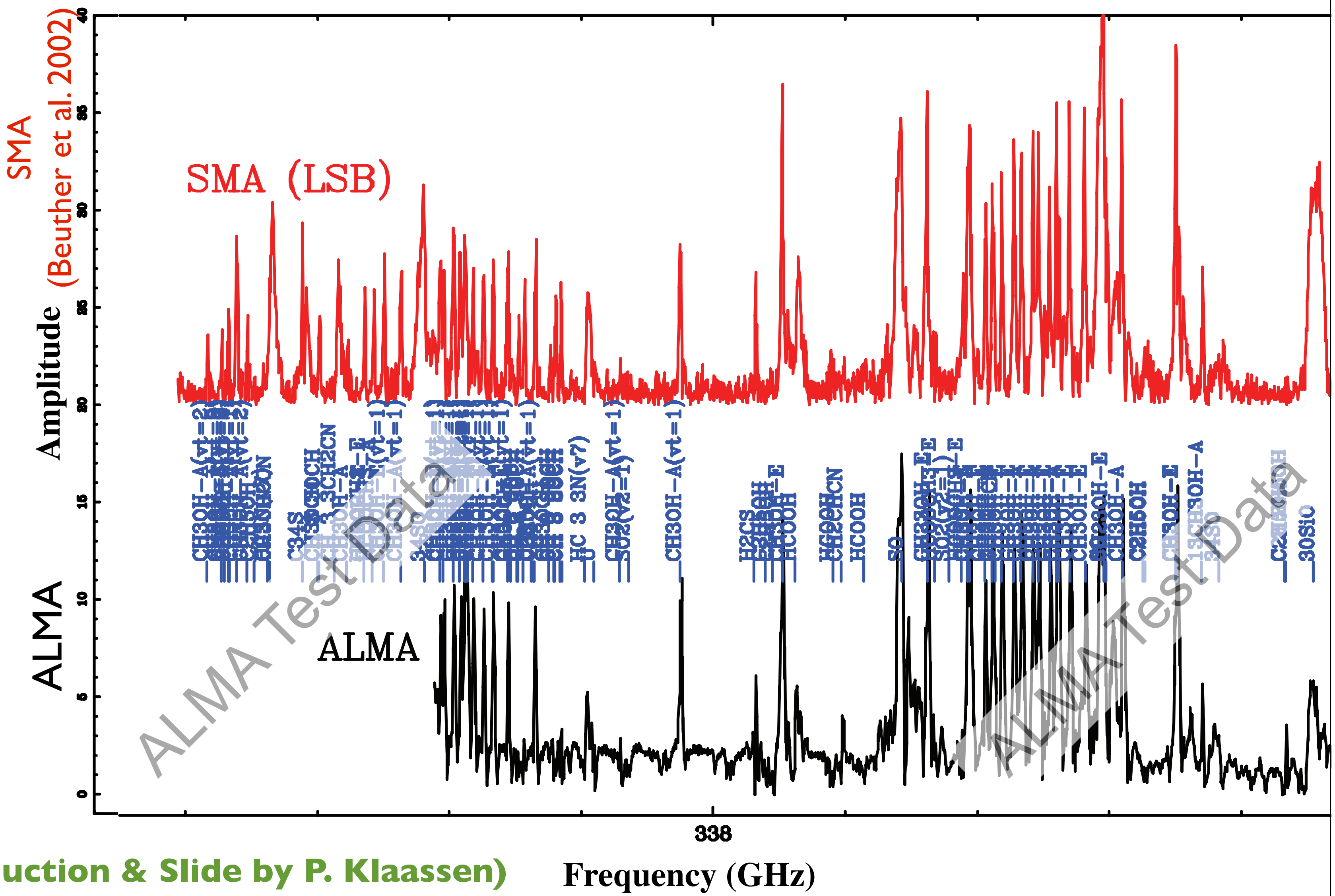
NGC 253 – B7 – CO=3-2

Disk evolution



Line Identifications:
Schilke et al. 1997

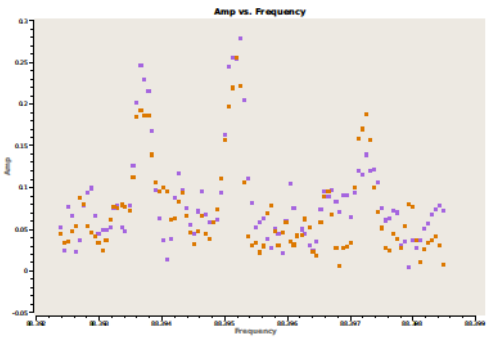
Orion Spectral Sweep

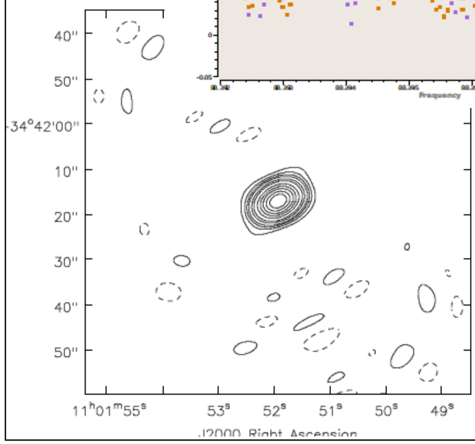


(Data reduction & Slide by P. Klaassen)

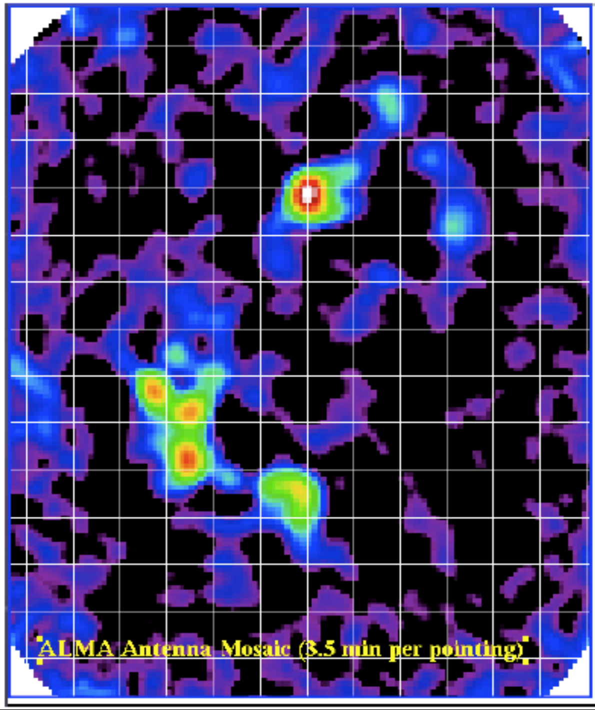
Science Verification

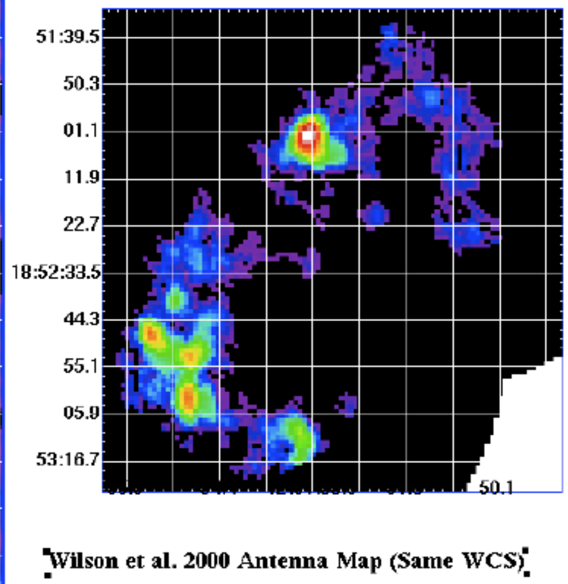
- TW Hya – protoplanetary disc
- NGC3256 – Nearby luminous galaxy
- Antennae – Merger mosaic
- BRI1202-0725 – High-Z CII
- HD 107146 – debris disc





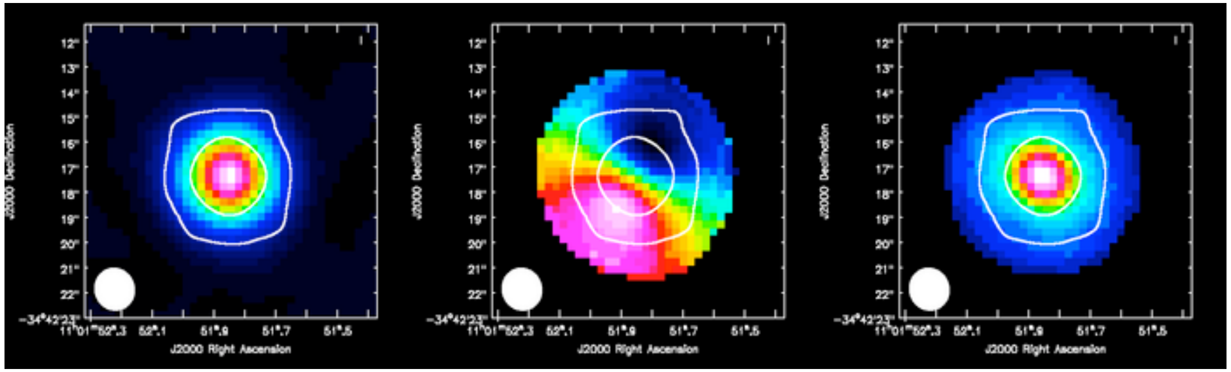
IMAGES:



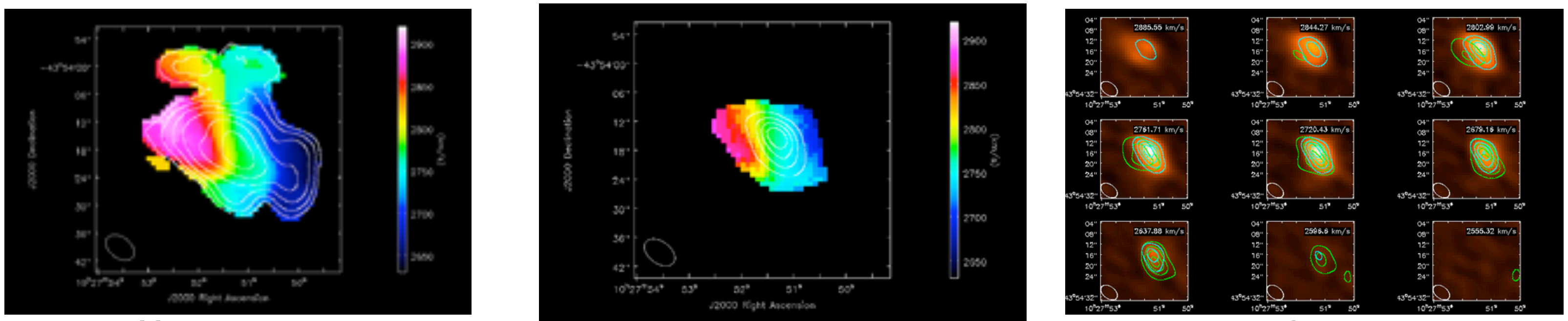


Science Verification

- TW Hya – protoplanetary disc
  - http://casaguides.nrao.edu/index.php?title=TWHydraBand7



- NGC3256 – Nearby luminous galaxy
  - http://casaguides.nrao.edu/index.php?title=NGC3256Band3

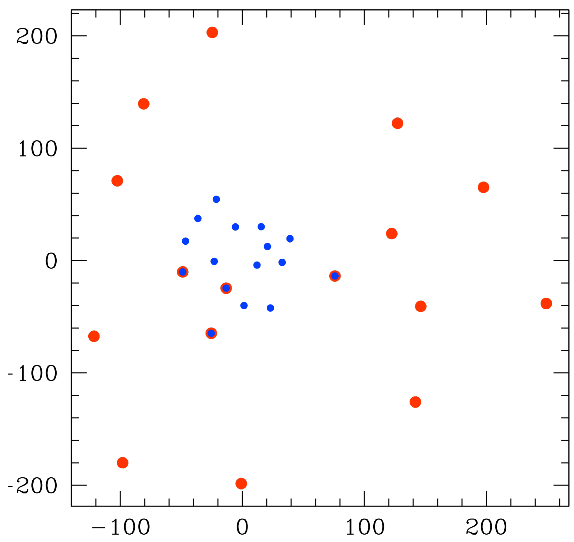


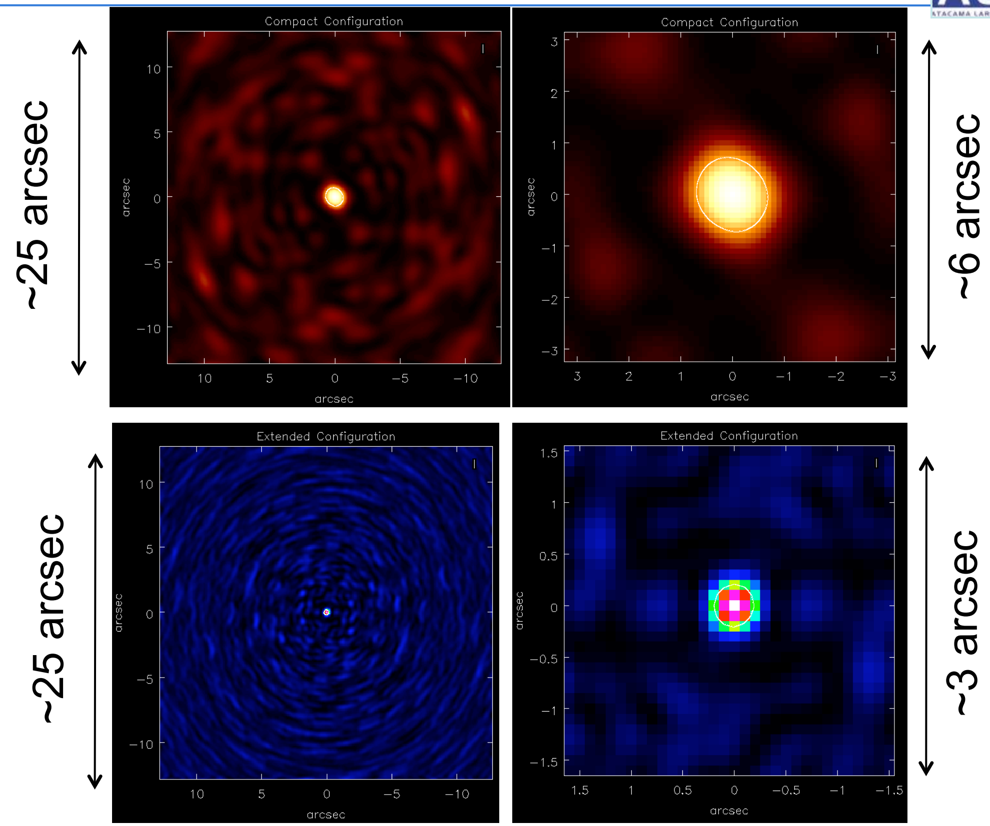
- http://almascience.eso.org/alma-data/science-verification

ALMA Early Science

- When?
  - Deadline 30 June 2011
  - Observations Fall 2011
- What?
  - 16 antennas
  - Configurations from compact (125m) to moderately extended (400m)
  - single field interferometry plus pointed mosaics with up to 50 pointings
  - Bands 3, 6, 7 and 9 (3mm, 1mm, 0.85mm, 0.45mm)
  - Several single spectral resolution modes
  - 1 or 2 polarizations, <u>no full polarization</u>
  - Amplitude calibration: 5% B3, 10% B6 and B7, 20% B9
  - At most 30% of the available time for the first call (period Oct11-Jun12)
  - No Solar observations

ES-Cycle 0 Configs

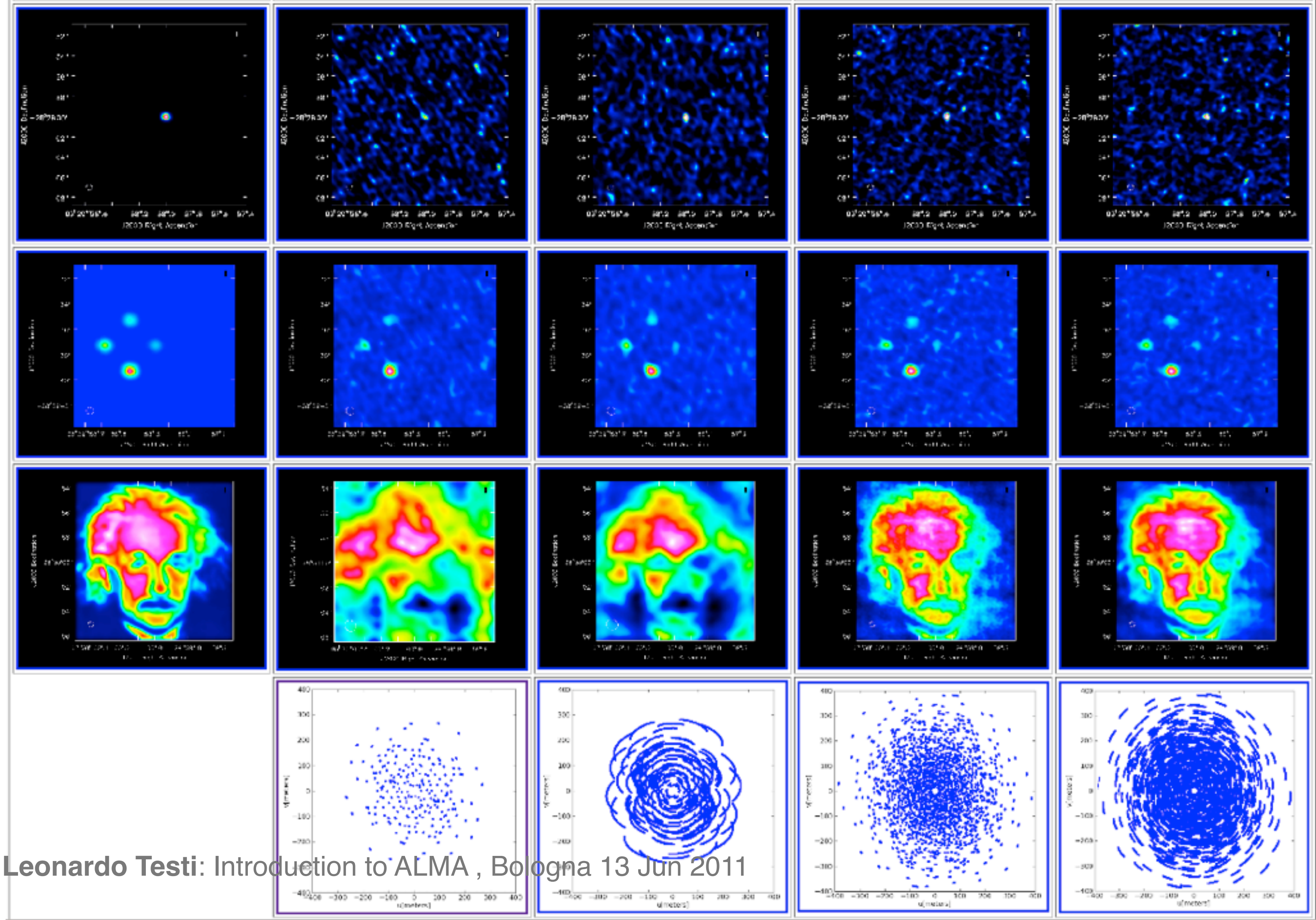




- Compact up to ~130m; short bl ~20m
- Extended up to ~400m; short bl ~35m

Image Fidelity - Early Science

Convolved source models	Early Science		Full Science	
	10 minutes (0.47 mJy rms)	4 hours (0.091 mJy rms)	10 minutes (0.14 mJy rms)	1 hour (0.057 mJy rms)



Spectral modes for Cycle 0

FDM modes		Resolution (kHz)→						
Band-width ↓	MHz	12	25	50	100	200	400	800
	7200							**2**
	3600						**2**	
	1800					**2**		
	900				**2**			
	450			**2**				
	225	**1**	**2**					

TDM modes		Resolution (MHz) →
Band-width	MHz	30
	7200	**2**

The number in each cell shows the number of polarization products provided: 1 – single pol, 2 – both polarizations.

General description of modes and performance in
« The ALMA Correlators » A. Baudry, ALMA Newsletter, Jan. 2011, No 7
http://www.almaobservatory.org/en/outreach/newsletter/252-newsletter-no-7

ALMA Early Science

- Limitations to be kept in mind:
  - Limited number of antennas:
    - limited sensitivity as compared to full ALMA
    - imaging requires Earth rotation synthesis
  - Limited angular resolution
  - No multi resolution available
  - Limited time available for science observations
  - ALMA capabilities ramping up FAST
  - ALMA ES capabilities and constraints are best suited for limited scope projects (as opposed to large scale surveys)
  - Typical project for ES should be few hrs (4-10) and deliver result!

ALMA beyond ALMA

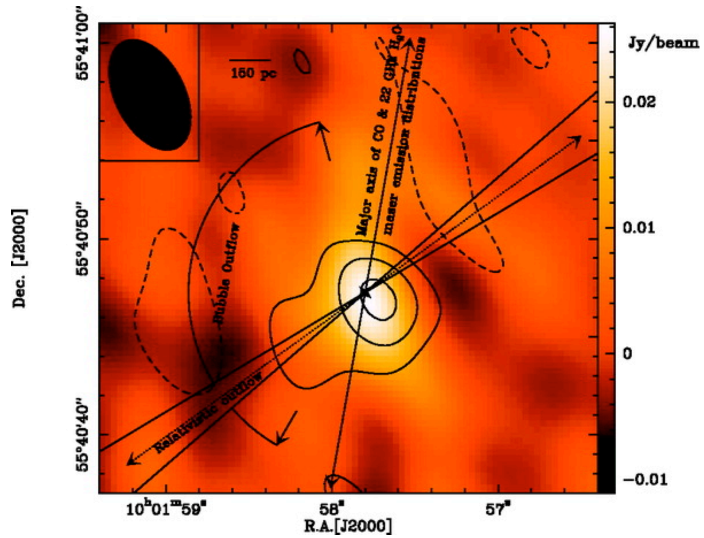
- ALMA will allow transformational science thanks to the sensitivity, angular resolution, spectral coverage and image fidelity, but...

- The baseline ALMA project will only achieve a fraction of the full potential of the site and instrument

- Incomplete Receiver Complement
- Limited Wide Field Capabilities
- Limited Correlator and Data Rate Capabilities
- Extended baselines (30-50km), VLBI (200-10000km)
- Advanced Calibration, Software, Science Tools....

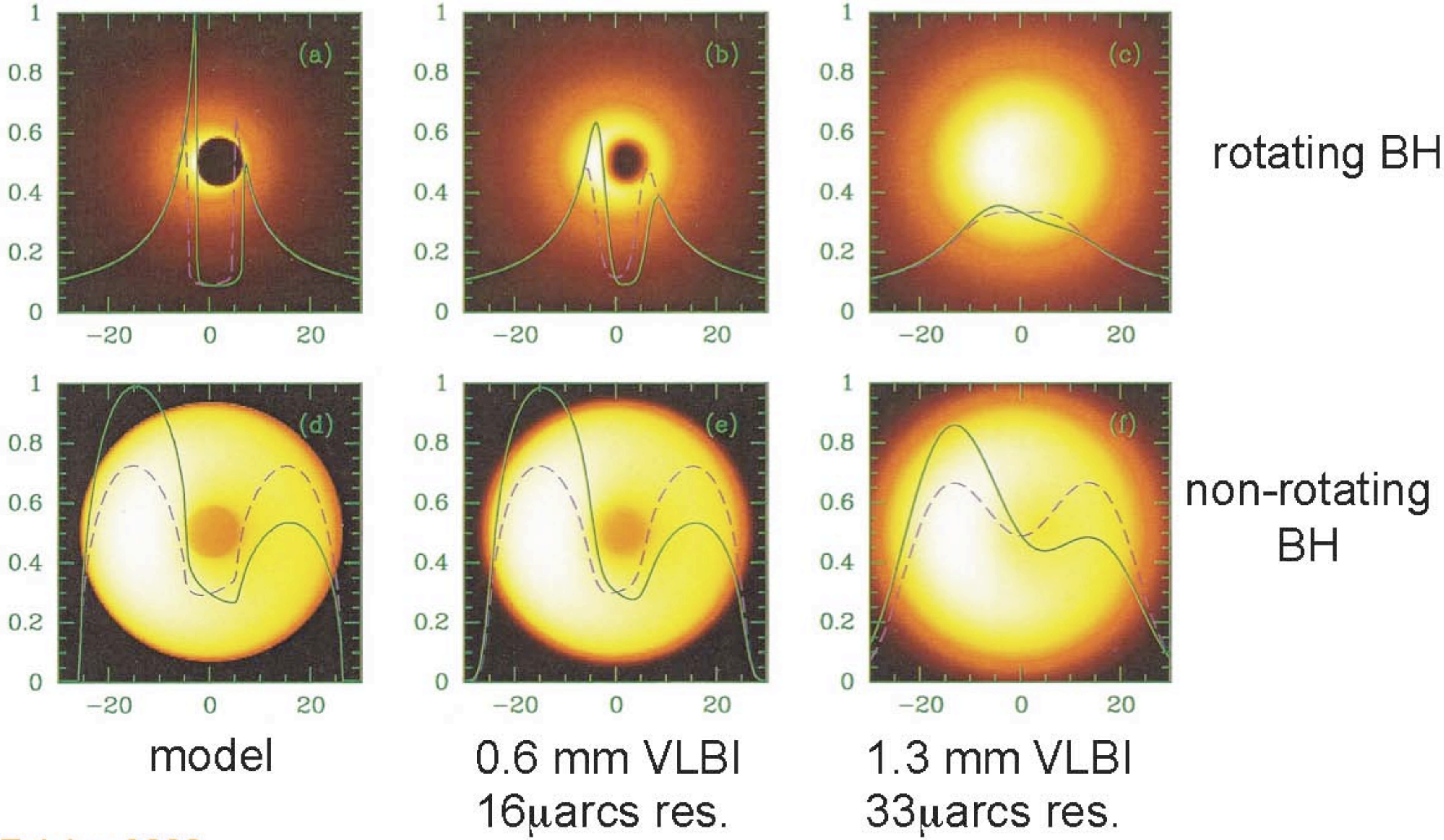
Examples of Scientific Limitations

- Limited Band 5 Complement
  - Eu FP6 6 B5: just a glimpse at B5
  - Water in the Universe
  - [CII] in the range 8 < z < 11
- No Band 1 & 2
  - High-z low excitation CO
  - Sunyaev-Zeld'ovich effect
  - Dust Evolution in Protoplanetary Disks
  - Deuterated molecules, low excitation conditions
- Limited correlator/bandwidth/datarate capabilities
  - Line surveys, chemistry studies very time consuming
- Continuum Wide Field Mapping Efficiency
  - SZ and Molecular Clouds applications very time consuming
  - Instantaneous wide field of view for solar physics



183 GHz H2O maser in NGC3079
(SMA, Humphreys et al 2005)

Galactic Center Black Hole



Falcke+2000

- ALMA + mmVLBI

The ALMA Development Program

- ALMA development budget is proposed to ramp up starting in 2013 to reach ~12M$/yr from ~2015

- ALMA Upgrade Studies in Europe:
  - Preparations for ALMA B5 Full Production
  - Upgrade Options for ALMA B9
  - Phasing up ALMA for mm-VLBI
  - Design and components for ALMA B2
  - Scientific opportunities for supra-THz interferometry with ALMA
  - Options for upgrading the instantaneous bandpass

- Science Case, Technical Readiness, Cost, Timeline
  - Getting ready to implement the upgrades from 2013-2015

Summary

- ALMA is here!
  - Call for Early Science Proposals with capabilities well beyond current instruments - Deadline 30 June 2011

- ALMA ES is just the beginning!
  - Cycle 1 - Deadline Q1 2012 - will already be a huge step in sensitivity and other capabilities (resolution, observing modes, etc.)
  - Full Science Operations - End of Construction in a couple of years

- ALMA is a long lifetime observatory with a healty Development Plan