Interferometry Phrase Book

Tourist Guide to Interferometry Jargon

Optical/IR speak	Radio speak
Optical path difference (OPD)	Delay, lag
Differential piston	Delay residual
Beam combiner	Correlator
Strehl ratio	Antenna gain
Background level	System temperature
Fringe tracking	Phase referencing
Telescope	Antenna
Detector	Feed
Point spread function (PSF)	Dirty (or CLEAN) beam
Magnitudes	log (flux density)
Obscure band designations	Confusing band designations

Cotton

Radio Techniques and ALMA

Liz Humphreys

ESO ALMA Regional Centre

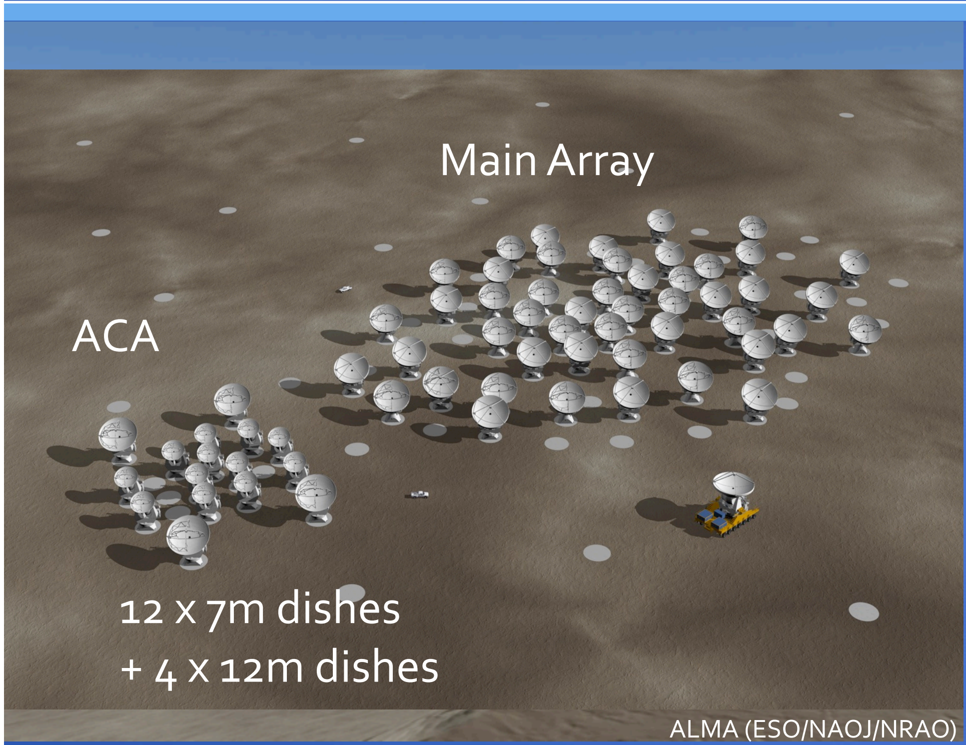
Thanks to many people for providing material, especially Leonardo Testi, Robert Laing and Stuartt Corder

ALMA

EUROPEAN ARC

ALMA Regional Centre

Atacama Large Millimetre/ Submillimetre Array



- Array of 50 dishes with 12 m diameter + ALMA Compact Array (ACA)
- Frequency range 30 – 950 GHz
- (1cm – 0.3 mm)
- High dry site, Chajnantor Plateau (5000m)
- Baselines up to 14 km
- Maximum resolution ~0.01 arcsec
- Continuum & high spectral resolution imaging (R=30,000,000)
- 8 GHz Bandwidth
- Full Polarization

- Detect and map CO and [CII] in a Milky Way galaxy at z=3 in less than 24 hours of observation
- Map dust emission and gas kinematics in protoplanetary disks
- Provide high fidelity imaging in the (sub)millimetre at 0.1 arcsec resolution

ALMA

- International collaboration between
  - Europe (ESO)
  - North America (US, Canada)
  - East Asia (Japan, Taiwan)
- Early Science Operations – 2011
  - 1st call for proposals around the end of this year
  - Andreani Talk
- Full Science Operations – 2012/13

Outline

- Radio Astronomy & Interferometry
- ALMA Techniques
- The Need for ALMA
  - ALMA Science
- ALMA Status Report
- ALMA in Practice
  - Navigating ALMA Software (Paola Andreani)
  - Calibration & Imaging Submillimetre Data (Pam Klaassen)

Radio Astronomy

- Diffraction-limited resolution ~ λ/D

  Radio telescope ~ 1 arcmin

  (D=100m;λ= 3 cm)

  Optical telescope ~ 20 mas

  (D=5m; λ= 500nm)

- Paradox: highest angular resolution achieved in radio

- Radio interferometry is relatively easy technologically
  - Many antennas, long baselines possible
- At cm wavelengths: about 95% of radio astronomy is interferometry

Connected Element Radio Interferometers

(Interferometer Maximum Resolution ~ λ/B, where B is the maximum baseline length)

Expanded Very Large Array (EVLA)

- 27 x 25m antennas
- Maximum baseline: 36 km (0.04 arcsec)
- Number of baselines=N(N-1)/2: 351
- First fringes: 1976

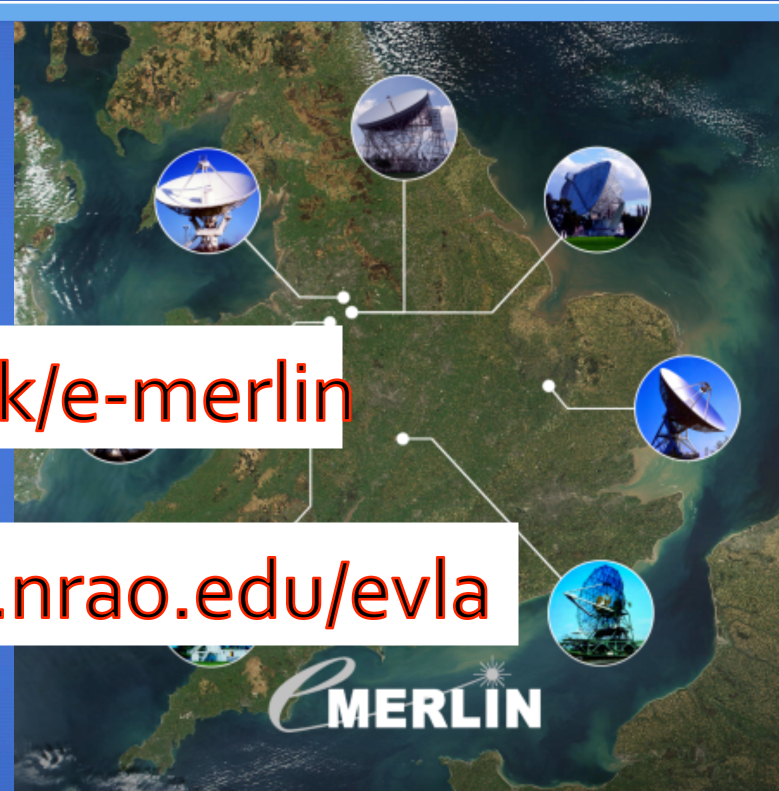
- 7 antennas
- Maximum baseline: 217 km (0.01arcsec)
- Number of baselines: 21
- First fringes: 1980s (as MTRLI)

Connected Element Radio Interferometers

(Interferometer Maximum Resolution ~ λ/B, where B is the maximum baseline length)

http://www.merlin.ac.uk/e-merlin

http://www.aoc.nrao.edu/evla



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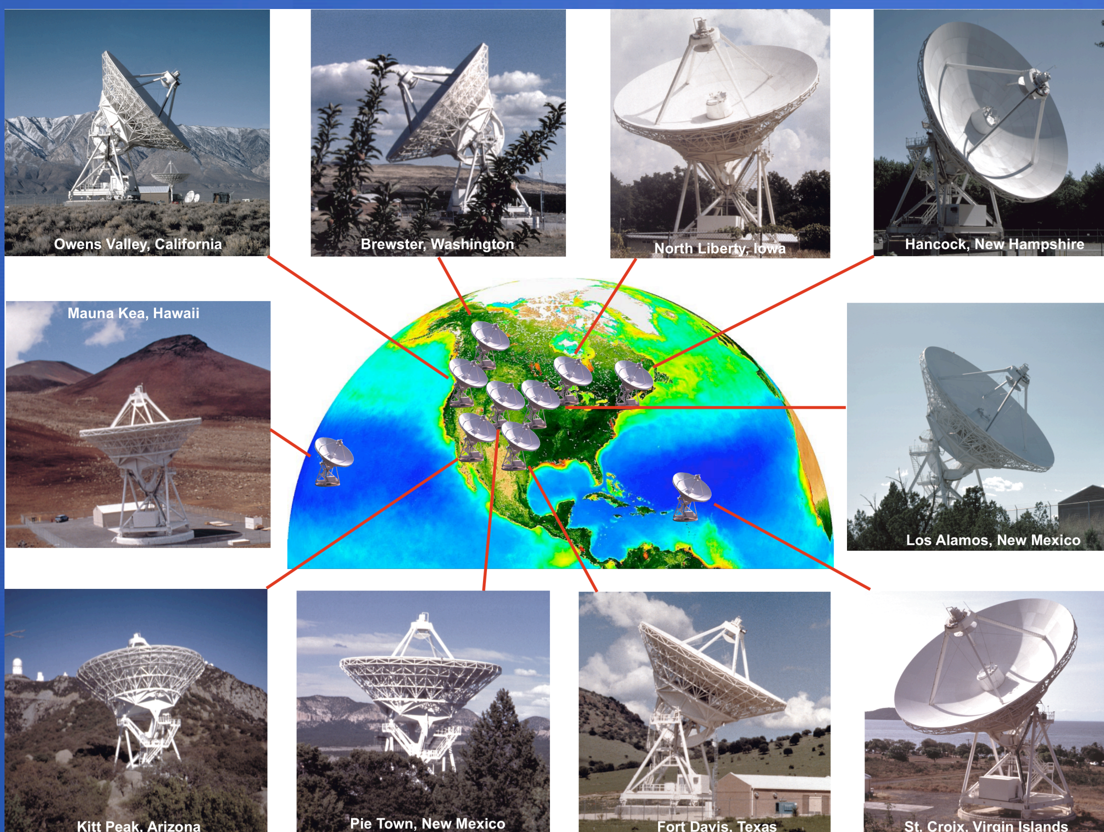
Very Long Baseline Interferometry (VLBI)

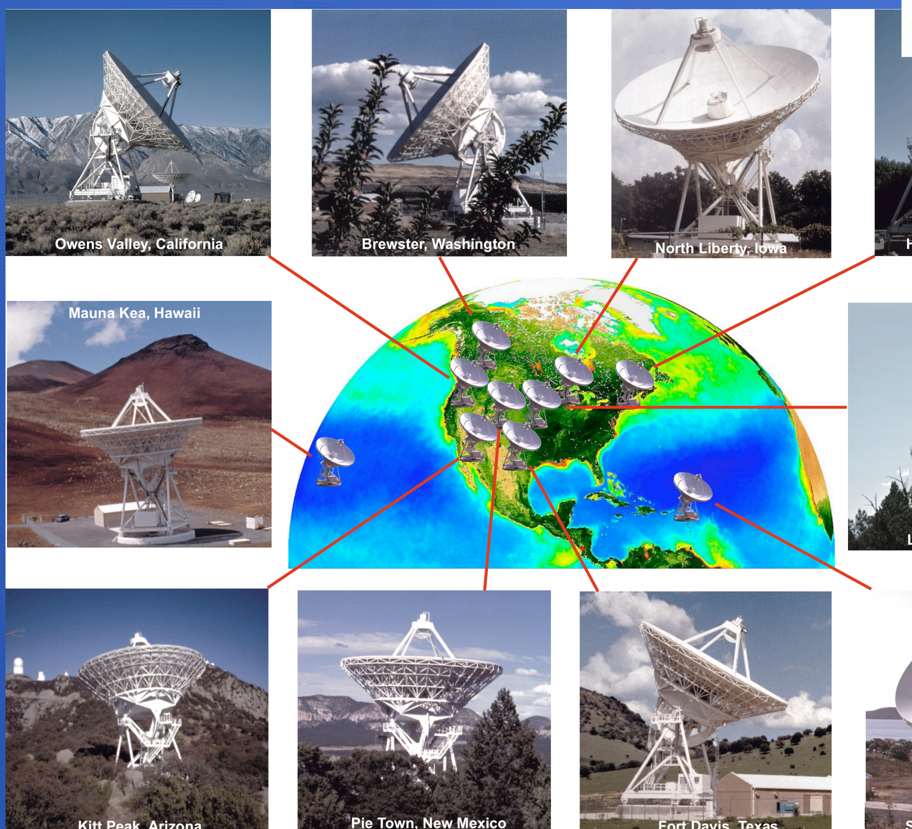


Very Long Baseline Array (VLBA)

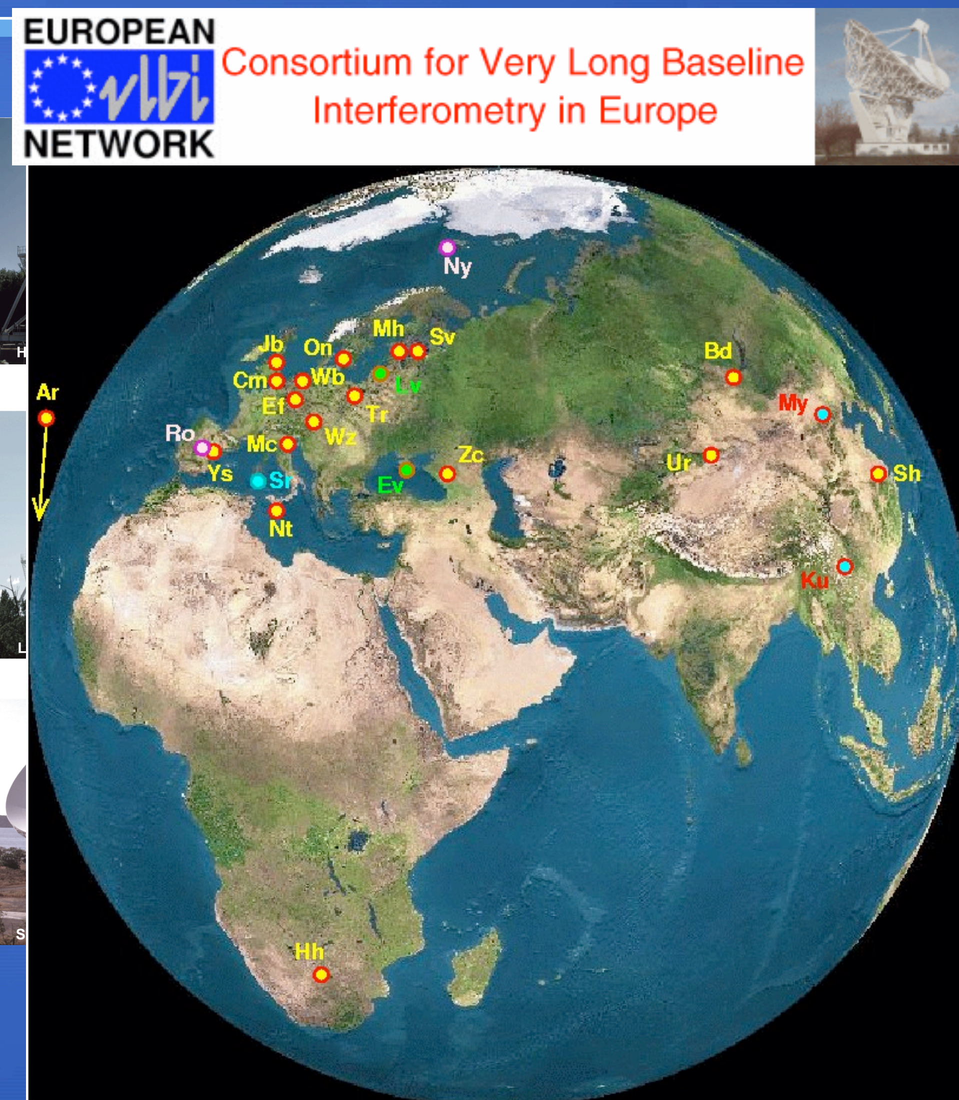
- 10 x 25m antennas
- Maximum baseline: >8000 km
- Maximum resolution ~ 0.3 mas
- Number of baselines=45
- First fringes: 1993

Data is recorded at each telescope separately, and correlated later

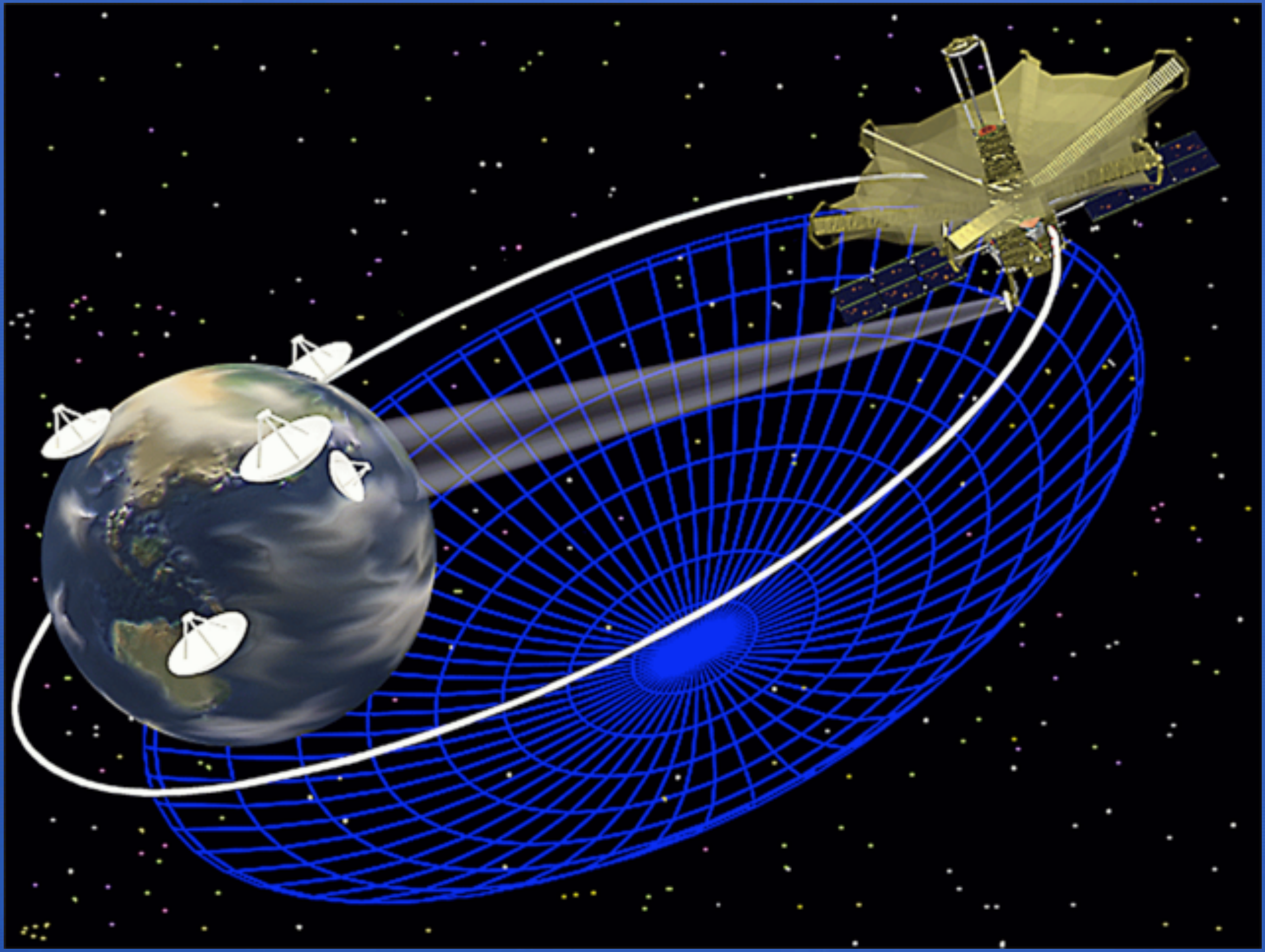
Very Long Baseline Interferometry (VLBI)



Global VLBI



Space VLBI

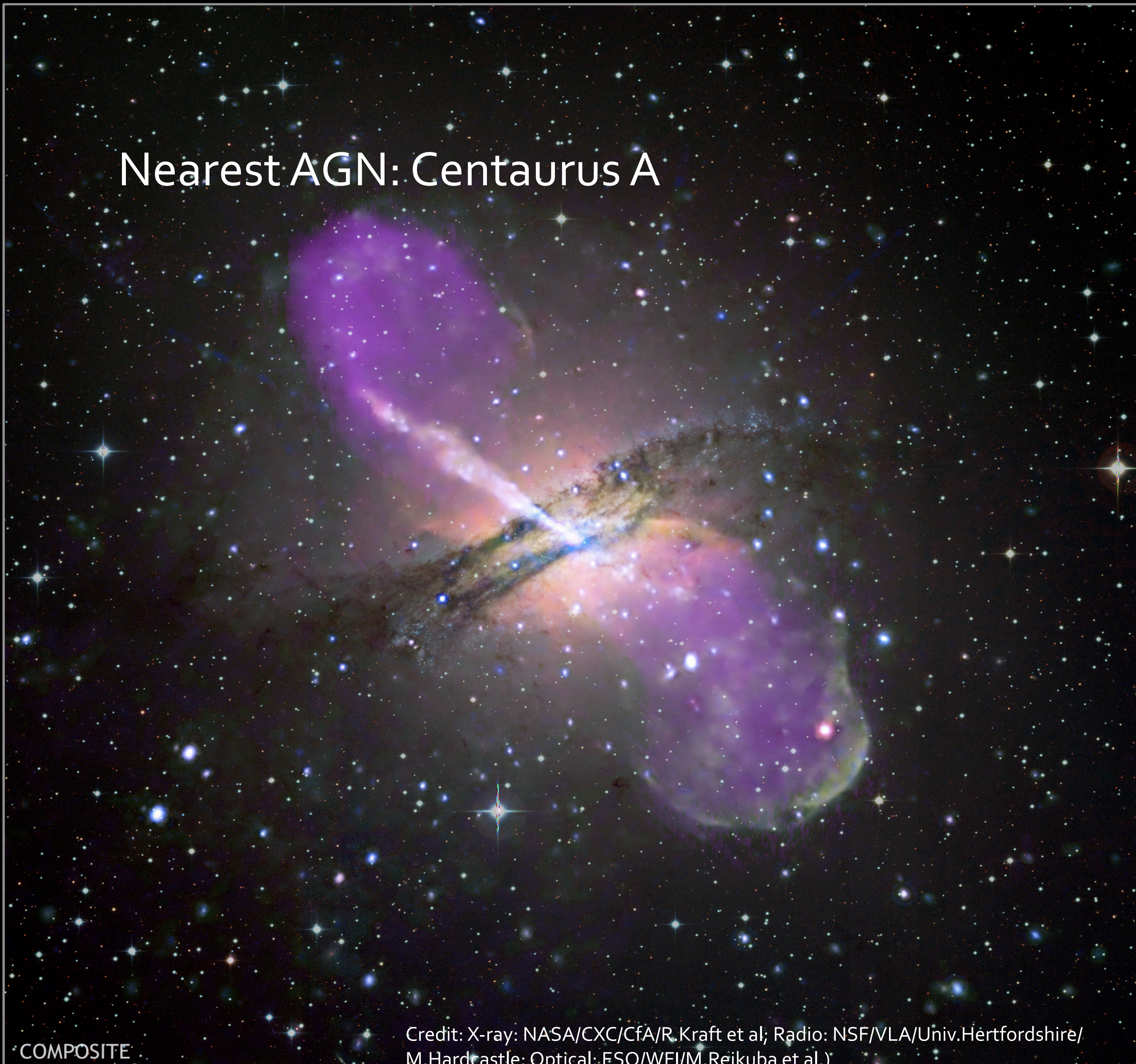


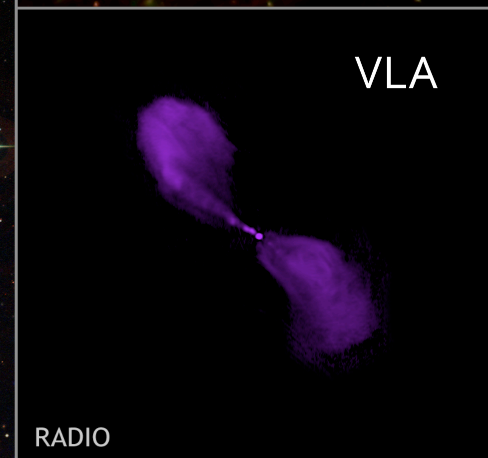
Space VLBI
1997-2004
HALCA

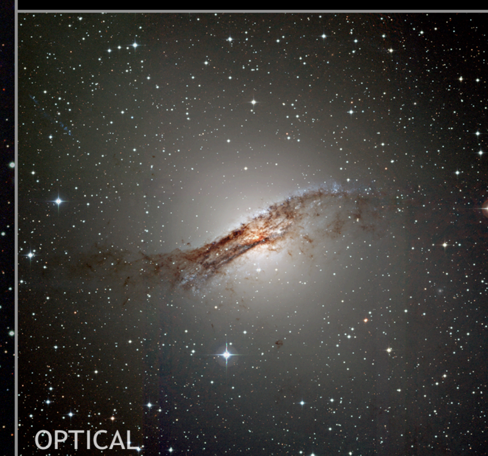
New program currently under development

Maximum angular Resolution
~ 40 microarcseconds

Nearest AGN: Centaurus A





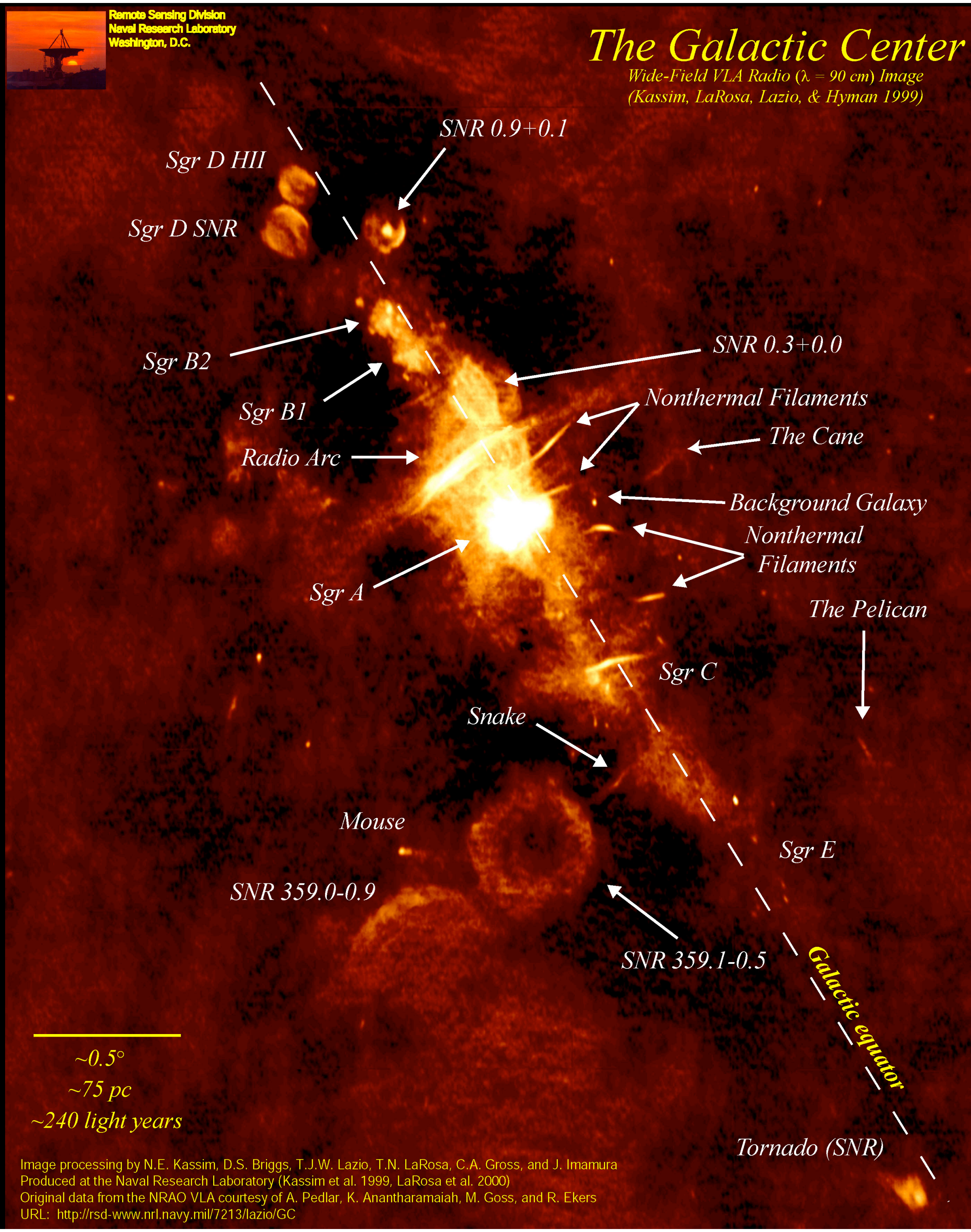


Credit: X-ray: NASA/CXC/CfA/R.Kraft et al; Radio: NSF/VLA/Univ.Hertfordshire/ M.Hardcastle; Optical: ESO/WFI/M.Rejkuba et al.)

3C 321

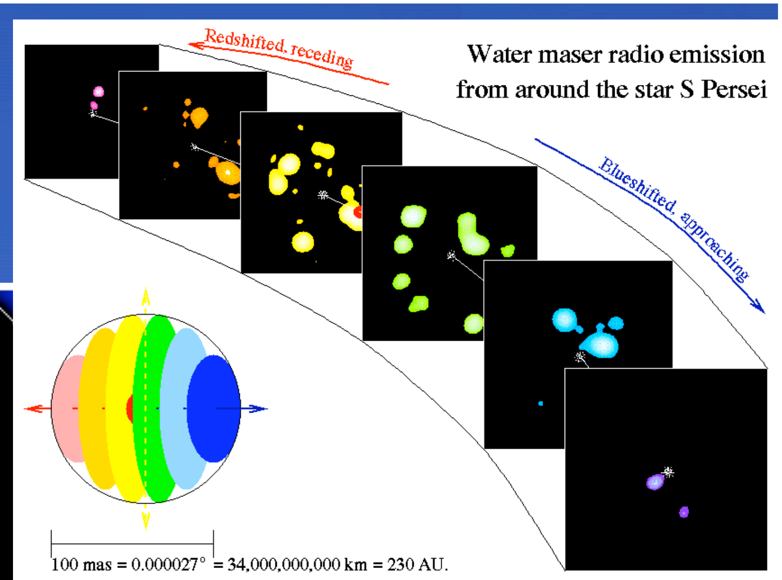
Powerful jet from supermassive black hole is blasting a nearby galaxy

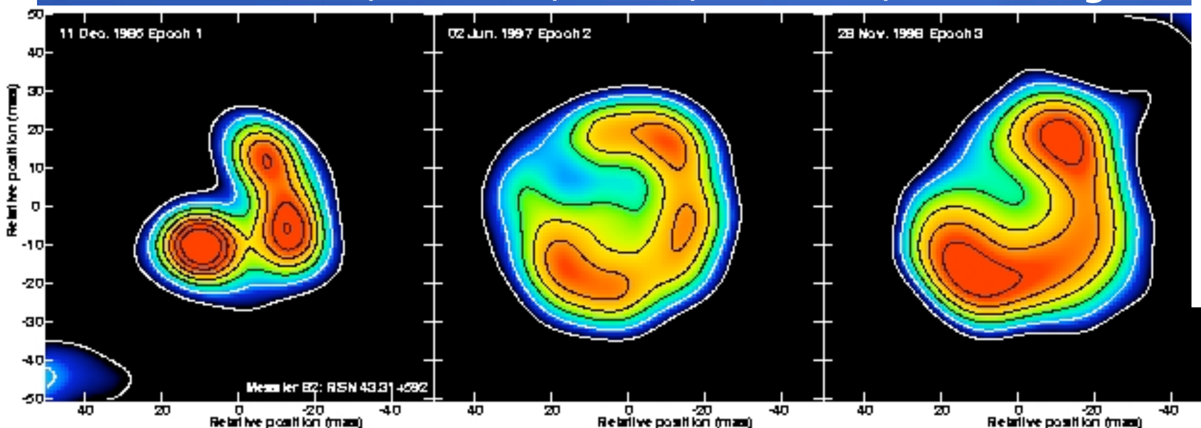
(Credit: X-ray: NASA/CXC/CfA/D.Evans et al.; Optical/UV: NASA/STScI; Radio: NSF/VLA/CfA/D.Evans et al., STFC/JBO/MERLIN)

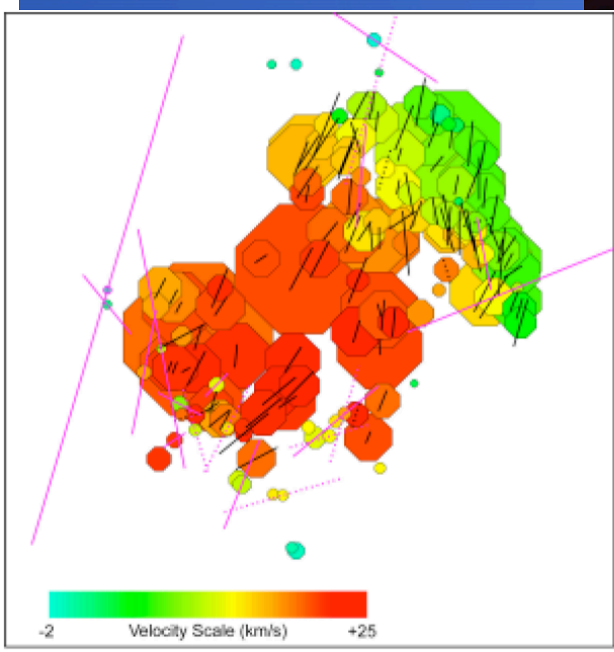

Remote Sensing Division
Naval Research Laboratory
Washington, D.C.
The Galactic Center
Wide-Field VLA Radio (λ = 90 cm) Image
(Kassim, LaRosa, Lazio, & Hyman 1999)
SNR 0.9+0.1
Sgr D HII
Sgr D SNR
Sgr B2
SNR 0.3+0.0
Sgr B1
Nonthermal Filaments
The Cane
Radio Arc
Background Galaxy
Nonthermal
Filaments
Sgr A
The Pelican
Sgr C
Snake
Mouse
Sgr E
SNR 359.0-0.9
SNR 359.1-0.5
Galactic equator
~0.5°
~75 pc
~240 light years
Tornado (SNR)
Image processing by N.E. Kassim, D.S. Briggs, T.J.W. Lazio, T.N. LaRosa, C.A. Gross, and J. Imamura
Produced at the Naval Research Laboratory (Kassim et al. 1999, LaRosa et al. 2000)
Original data from the NRAO VLA courtesy of A. Pedlar, K. Anantharamaiah, M. Goss, and R. Ekers
URL: http://rsd-www.nrl.navy.mil/7213/lazio/GC

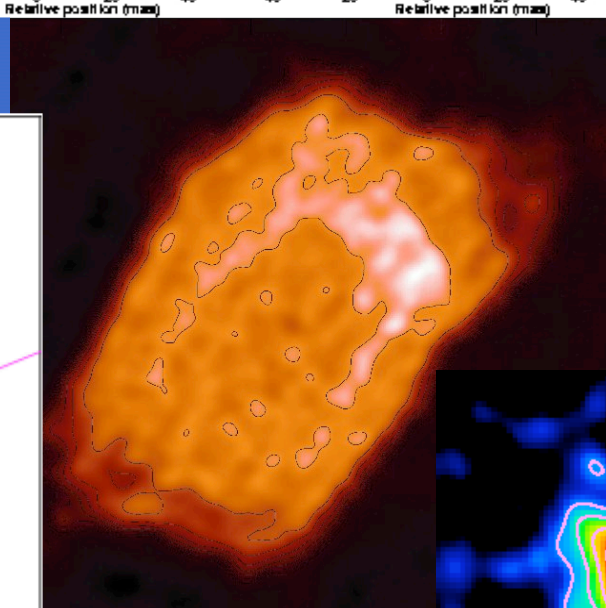
Stellar Evolution

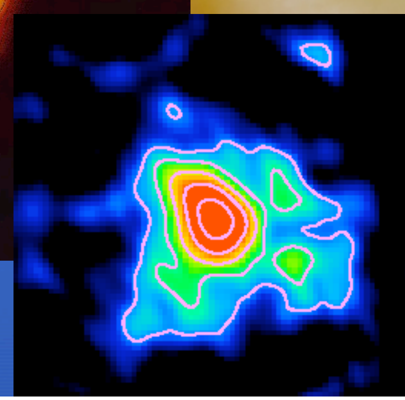
Credits: Bains, Beswick, Etoka, Richards, Vlemmings

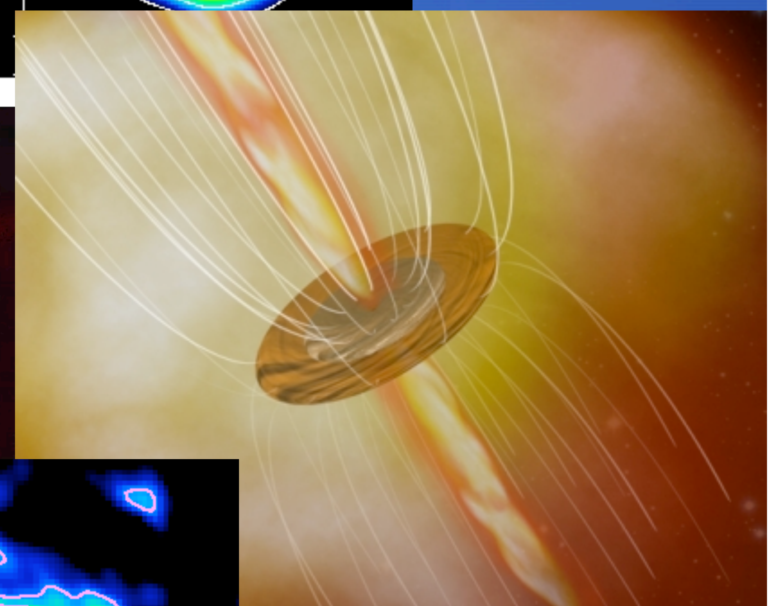






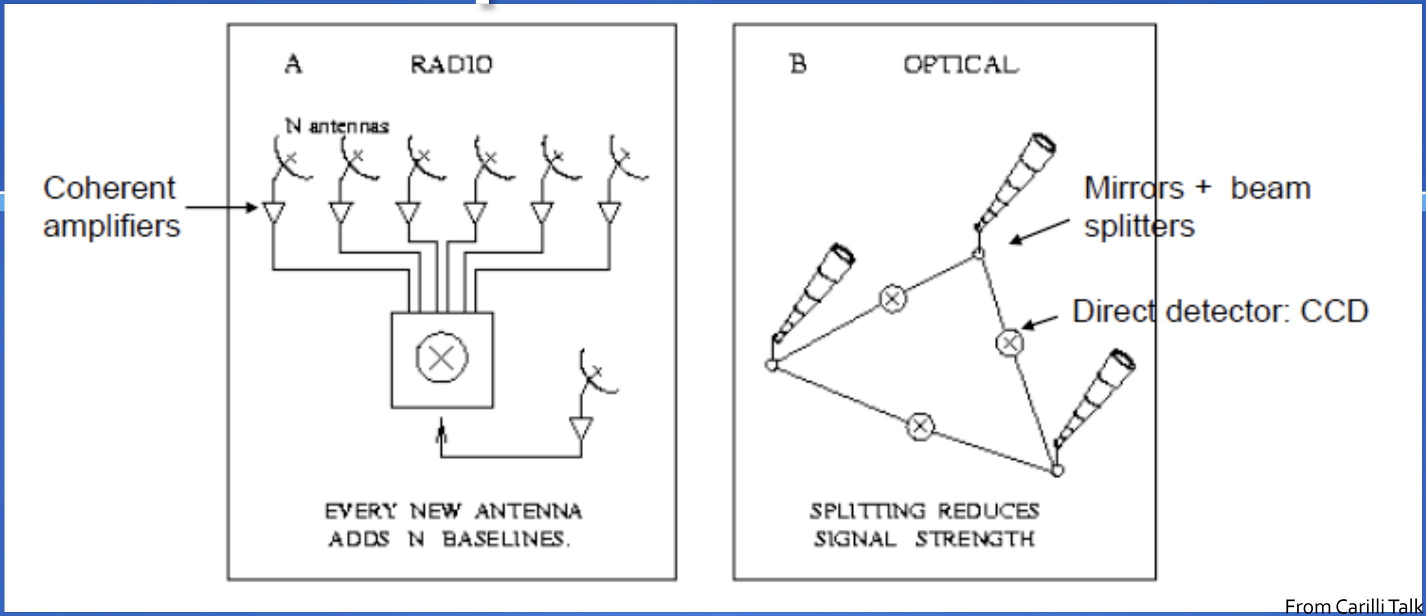






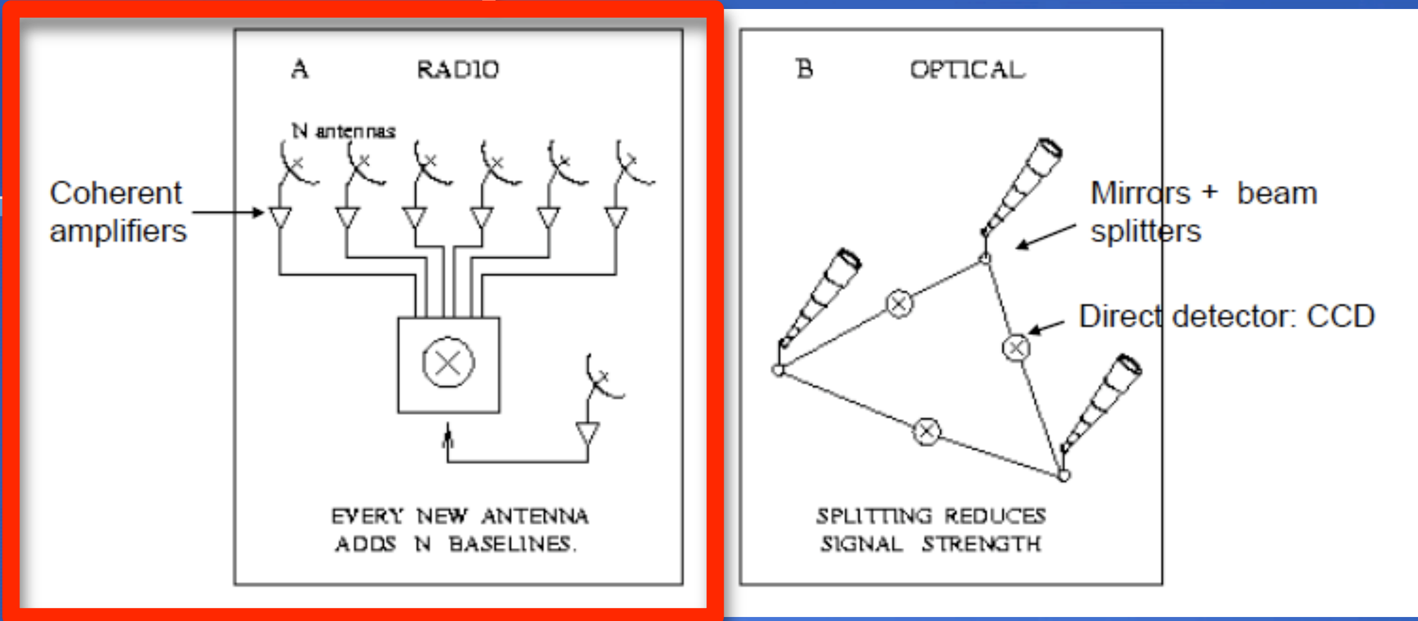
ALMA & Radio/Submm Techniques

Radio vs. Optical Interferometry



- There is a cost of phase sensitive detection (knowledge of photon phase costs knowledge of energy)
  - Radio photons numerous, photon statistics measured
  - Optical photons are sparse & quantum effects matter
- "Quantum Noise" added:
  - Tsys=11 K @ 230 GHz, Tsys=43 K @ 900 GHz
  - Tsys=30,000K in the optical! (Tsys is the power equivalent noise T)

Radio vs. Optical Interferometry

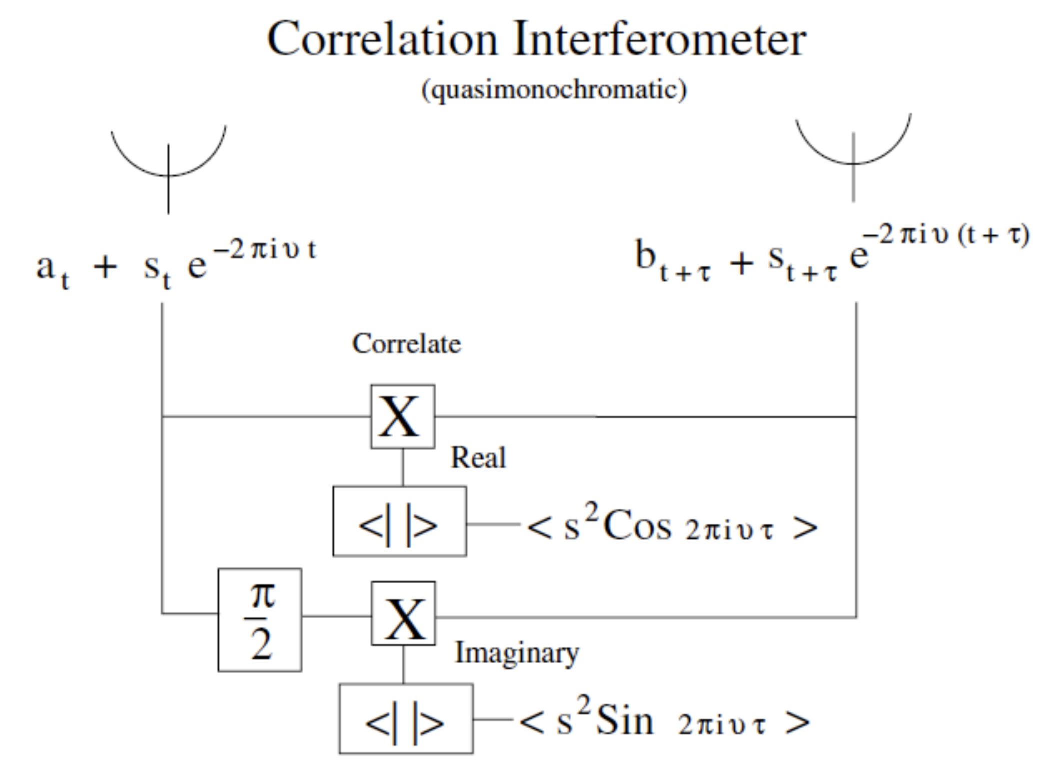


Most radio/submm interferometers use phase-sensitive detection

- **Huge benefits – can add new antennas without signal-to-noise cost**
  - **More collecting area → better sensitivity (ALMA 5700 m²)**
  - **More baselines – better (u,v) coverage and imaging, can go to higher angular resolution – 1225 ALMA baselines**

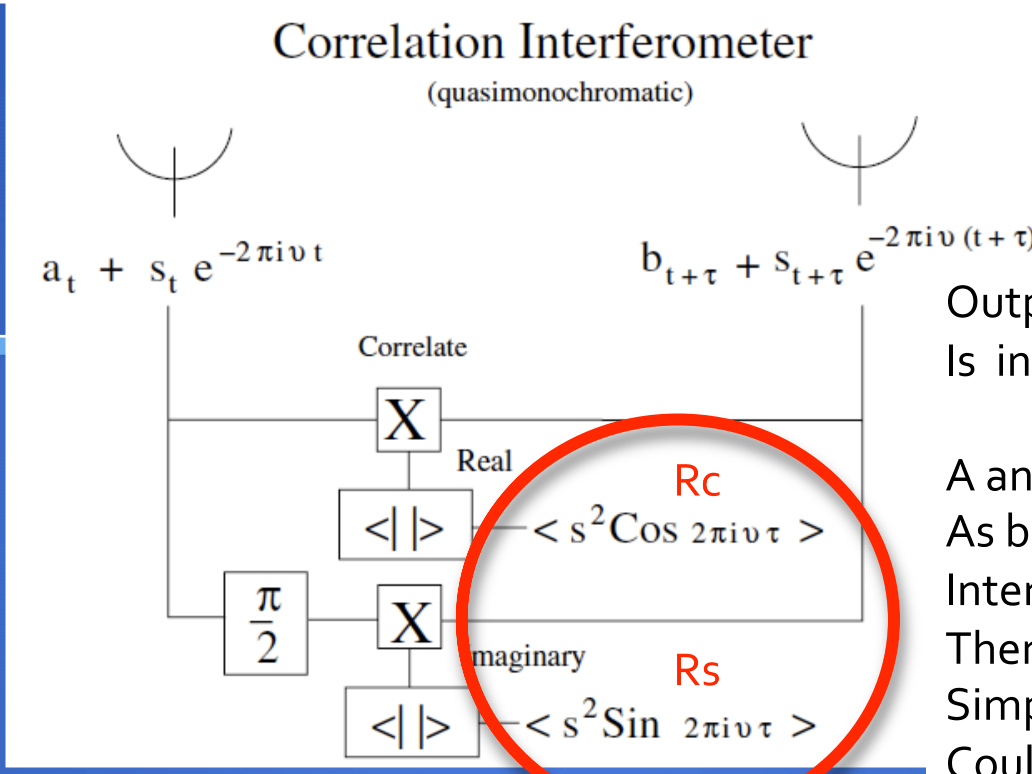
Heterodyne Interferometer (Multiplying)

- Heterodyne=electromagnetic field is sampled before interference is formed
- Sampling procedure= each radio/submm telescope focuses radiation and converts the wave amplitude to a voltage, whose (time-averaged) square represents the power received
- Once the field has been sampled, resultant signal can be replicated as needed
- In a multiplying interferometer, signals from pairs of antennas (each baseline) are multiplied & time-averaged



Cotton (2004)

- **Electric field received by each element of the interferometer**
  - **an independent part (a and b)**
  - **common part due to the unresolved source being observed S_t**
- **Common part of the signal**
  - **phase that rotates at the frequency of the radiation**
  - **phase lag at the more remote telescope of $-2\pi\upsilon\tau$**
  - **τ is the additional time it takes a wavefront passing the first telescope to reach the second – the geometric delay**



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Humphrey

Output of the correlator
Is independent of a and b

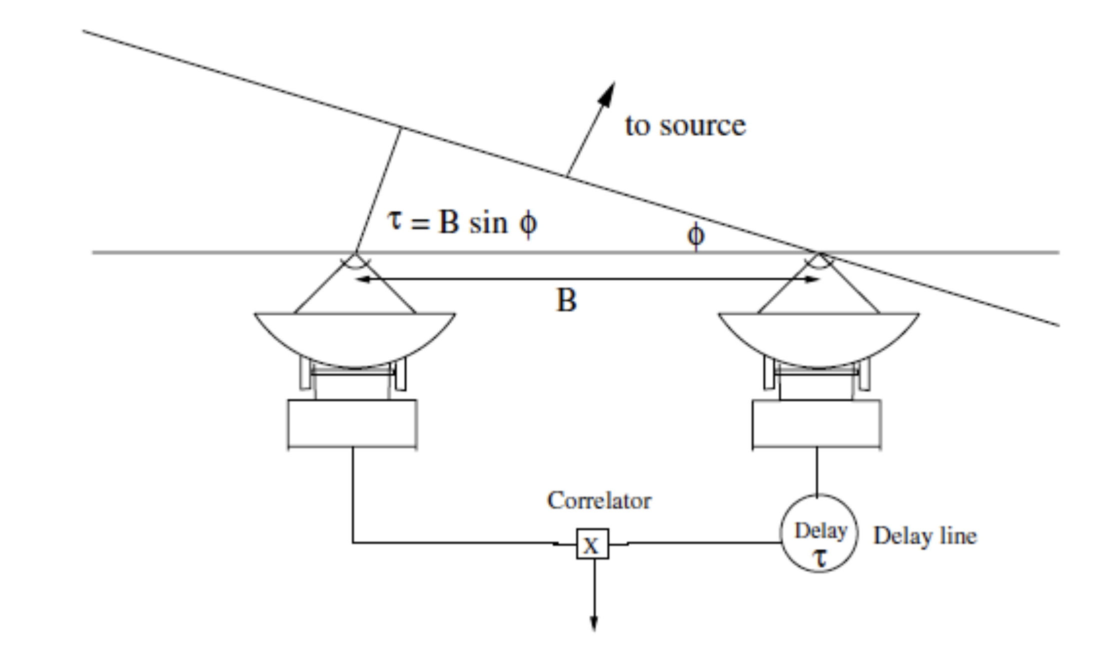
A and b can be considered
As backgrounds we are not
Interested in. Removing
Them is a significant
Simplification (they
Could be large/time-varying)

Define complex visibility
V=Rc – iRs and write it as
$V=Ae^{-i\Phi}$

Visibility amplitude
$A=(Rc+Rs)^{1/2}$

Visibility phase
$\Phi=\tan^{-1}(Rs/Rc)$

Correlation Interferometer with Delay Compensation



Cotton (2004)

Visibility Amplitude: "how much" of a certain frequency component

Visibility Phase: tells you where it is

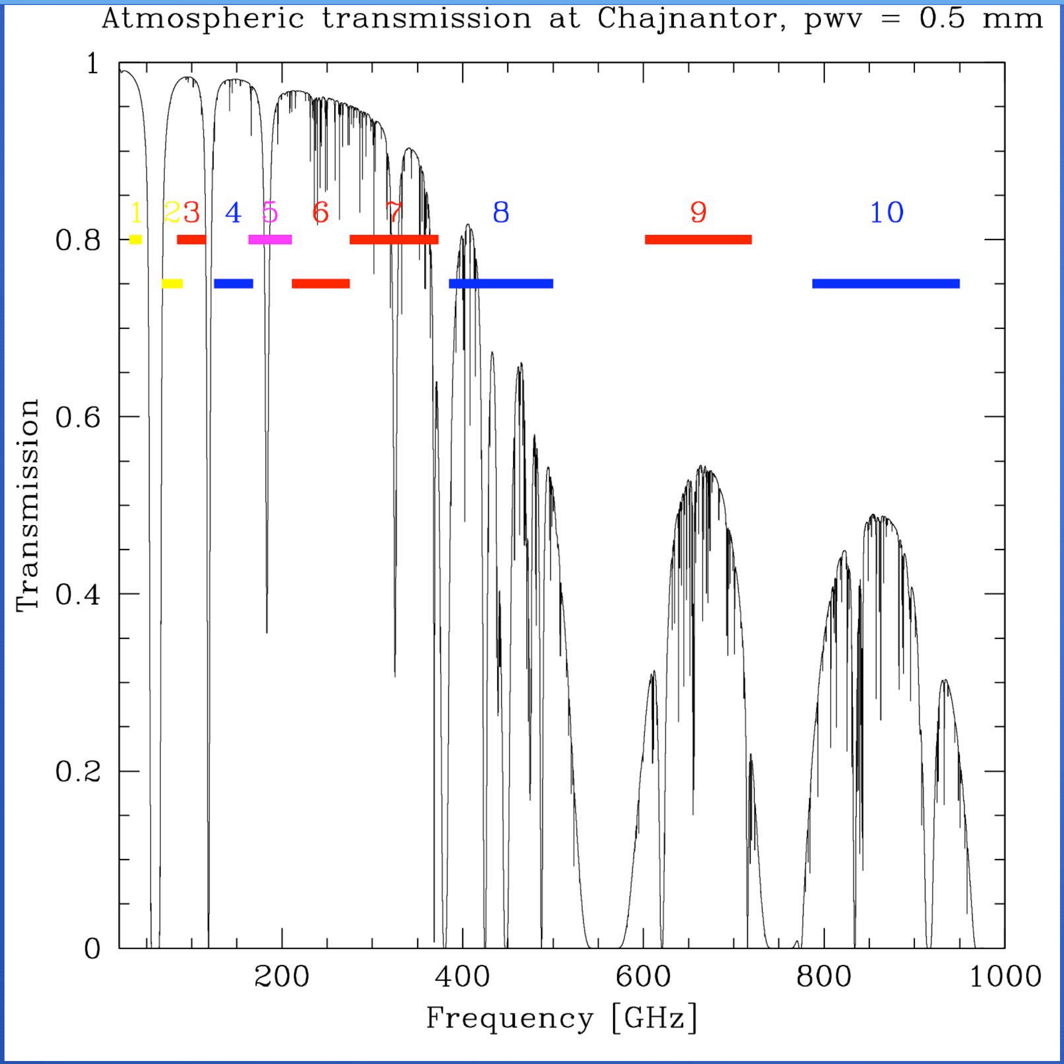
Correlator Output

ALMA Main Array Correlator; Quadrant 1

- Basic observables are the complex visibilities:
  - Amplitude and phase as a function of baseline, time and frequency
- Correlator measures the cross-correlation of the digitized signal, not the original
  - Wide range of spectral resolutions

ALMA Compact Array Correlator

Atmospheric Opacity



- Mainly due to the troposphere
  - Lowest level of atmosphere
  - H < 10 km
- Atmosphere is noisy, often the dominant contribution to Tsys
- Rapidly varying and a function, of airmass, calibrate often

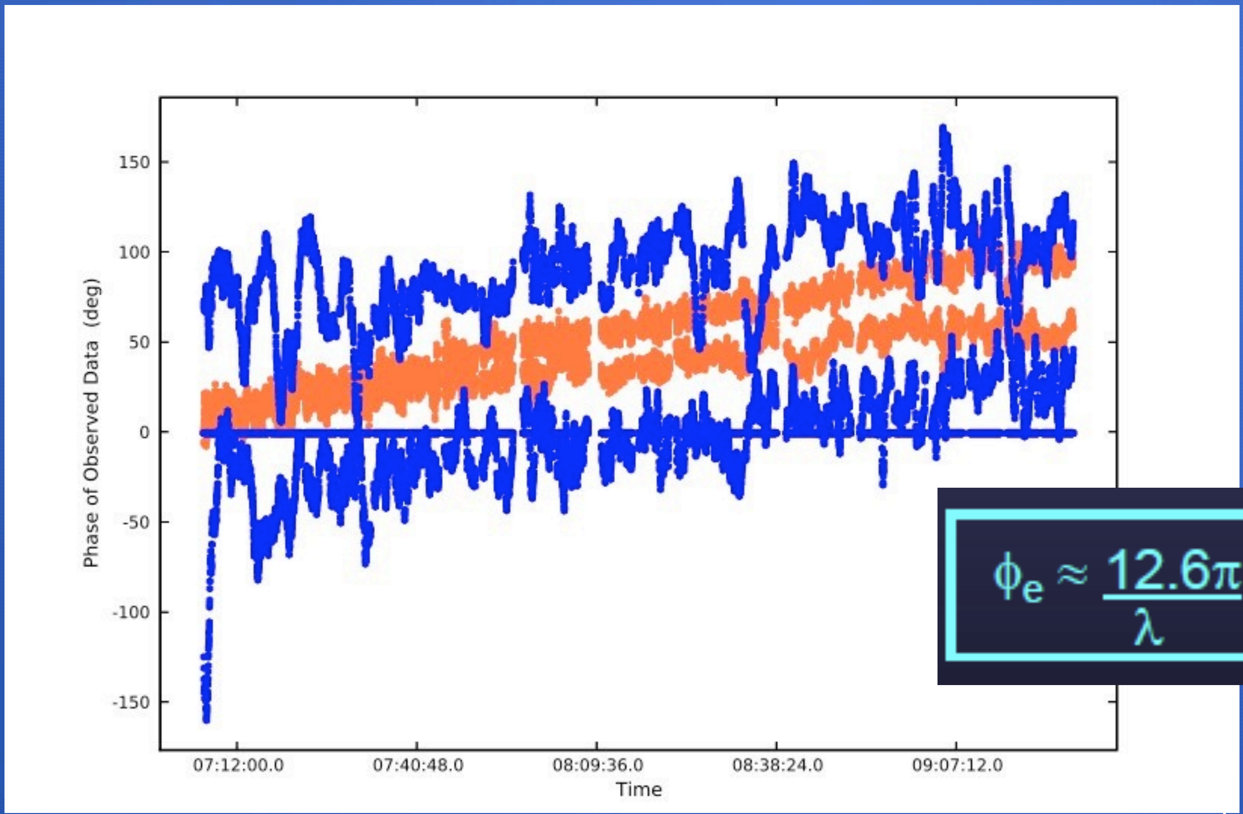
Calibration & Imaging

Klaassen Talk

- <u>Phase calibration strategies</u>
  - Fast switching (interleave with observations of a nearby calibrator, perhaps at a lower frequency). 20 – 300s cycle times. Requires calibrator within ~2°.
  - Water-vapour radiometry (measure emission from 183 GHz atmospheric line; deduce phase fluctuations on 1s timescales).
  - Self-calibration
- Absolute Gain Calibration (Setting the Flux Density Scale)
  - Not quasars (used in radio), no non-time-variable ones
  - Planets/moons can be used in some cases
  - Asteroids may be used

Water Vapour Radiometers

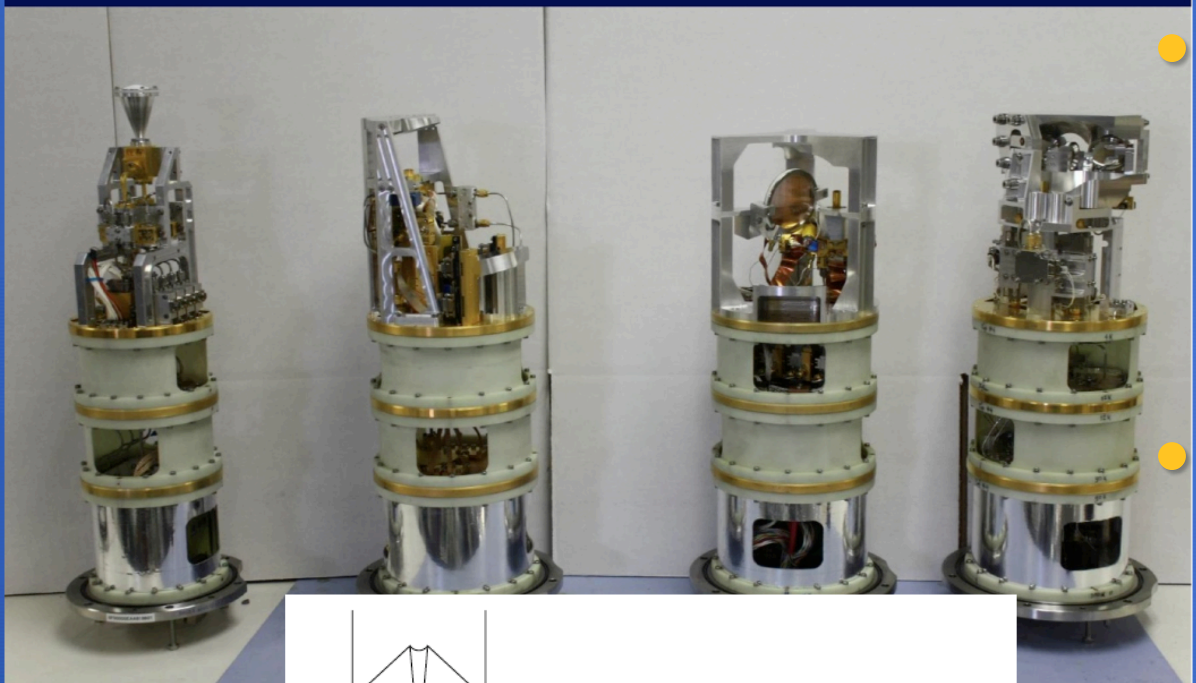
- Deliver atmospheric path-length corrections during observations due to variations in water vapour column
- Derive changes in water vapour column and convert to the frequency-dependent corrections

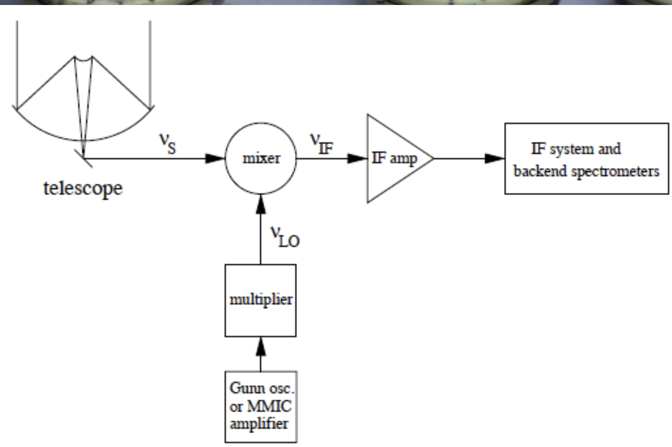


$$\phi_e \approx \frac{12.6\pi}{\lambda} \times w \quad \text{for } T_{atm} = 270\text{ K}$$

Submillimetre Heterodyne Receiver System

Bands 3 (84-116 GHz), 6 (211-275 GHz), 7 (275-373 GHz), and 9 (602-720 GHz) SIS "cartridges"





Zmuidzinas (1998)

- Heterodyne usually means a frequency (down)conversion takes place. Signal is mixed with a reference tone, the local oscillator
- Converts signal to a frequency that is easier to manipulate and allows large amplification
- ALMA receivers are low noise, wide band. Cryogenically cooled to 4 K

ALMA Receivers

ALMA Band	Frequency Range	Receiver noise temperature		Mixing scheme	Receiver technology	Supplier
		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	Not assigned ***
2	67 – 90 GHz	30 K	50 K	LSB	HEMT	Not assigned
3	84 – 116 GHz	37 K (40K)	62 K (50K)	2SB	SIS	HIA
4	125 – 169 GHz	51 K (45K)	85 K (~55K)	2SB	SIS	NAOJ
5	163 - 211 GHz**	65 K	108 K	2SB	SIS	OSO
6	211 – 275 GHz	83 K (40K)	138 K (60K)	2SB	SIS	NRAO
7	275 – 373 GHz*	147 K (75K)	221 K (100K)	2SB	SIS	IRAM
8	385 – 500 GHz	196 K (160K)	294 K (~270K)	2SB	SIS	NAOJ
9	602 – 720 GHz	175 K (120K)	263 K (150K)	DSB	SIS	NOVA
10	787 – 950 GHz	230 K	345 K	DSB	SIS	NAOJ ?

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

** - Limited to 6 units, funded by the EC under FP6

*** - Under consideration by U. Chile

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

Some Unit Definitions

I_ν (or B_ν) = Surface Brightness : erg/s/cm^2/Hz/sr

(= intensity)

S_ν = Flux density : erg/s/cm^2/Hz $\int I_\nu \Delta\Omega$

S = Flux : erg/s/cm^2 $\int I_\nu \Delta\Omega\Delta\nu$

P = Power received : erg/s $\int I_\nu \Delta\Omega\Delta\nu\Delta \mathrm{A}_{\mathrm{tel}}$

E = Energy : erg $\int I_\nu \Delta\Omega\Delta\nu\Delta \mathrm{A}_{\mathrm{tel}}\Delta t$

ALMA Sensitivity

ALMA Sensitivity Calculator (Andreani Talk)

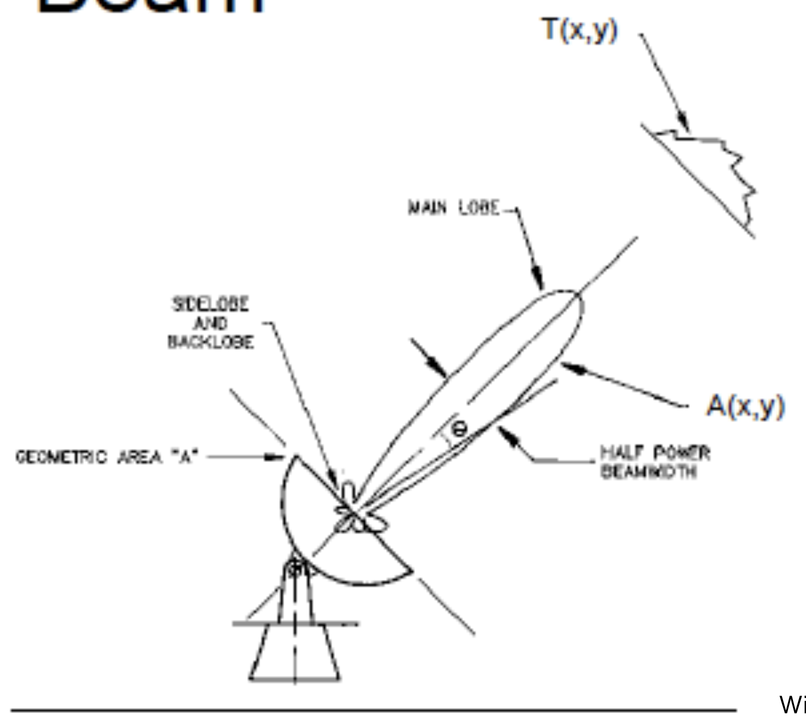
ALMA in a nutshell

Band	frequency range (GHz)	wavelength range (mm)	angular resolution b_{max}=200m ... 18km (arcsec)	line sensitivity (mJy)	continuum sensitivity (mJy)	primary beam (arcsec)	largest scale (arcsec)
3	84-116	2.6-3.6	3.0 ... 0.034	8.9	0.060	56	37
4	125-169	1.8-2.4	2.1 ... 0.023	9.1	0.070	48	32
5	163-211	1.4-1.8	1.6 ... 0.018	150	1.3	35	23
6	211-275	1.1-1.4	1.3 ... 0.014	13	0.14	27	18
7	275-373	0.8-1.1	1.0 ... 0.011	21	0.25	18	12
8	385-500	0.6-0.8	0.7 ... 0.008	63	0.86	12	9
9	602-720	0.4-0.5	0.5 ... 0.005	80	1.3	9	6

Field of View

Primary Beam

- A telescope does not have uniform response across the entire sky
  - main lobe approximately Gaussian, fwhm ~1.2λ/D (where D is ant diameter) = "primary beam"
  - limited field of view
  - sidelobes, error beam (sometimes important)



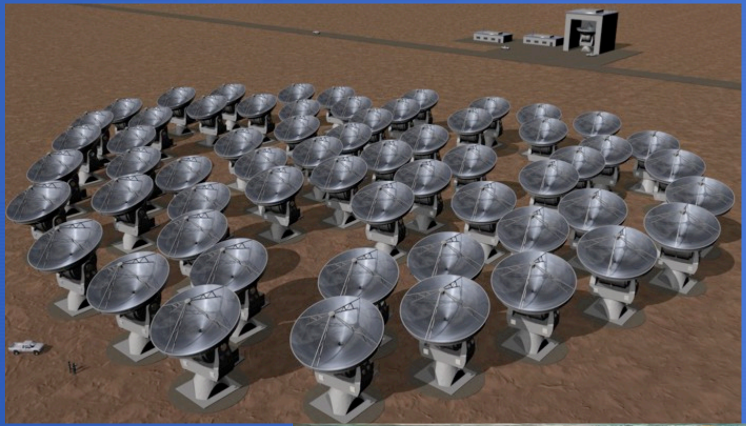
Wilner

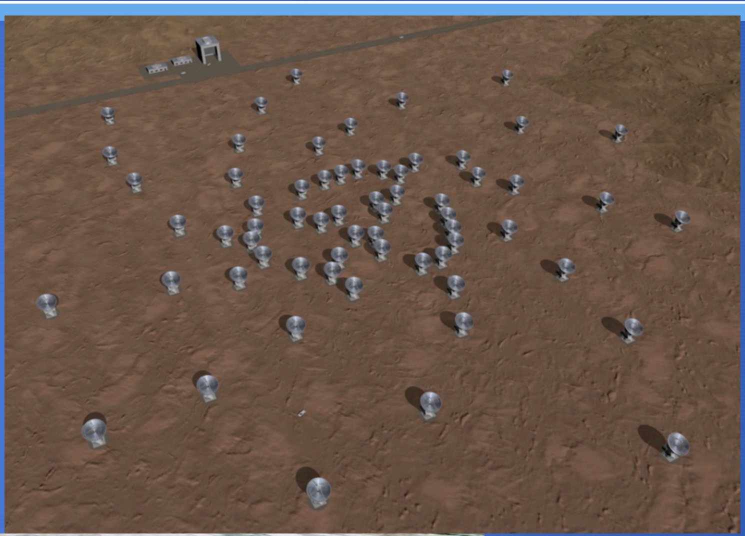
ALMA Antennas

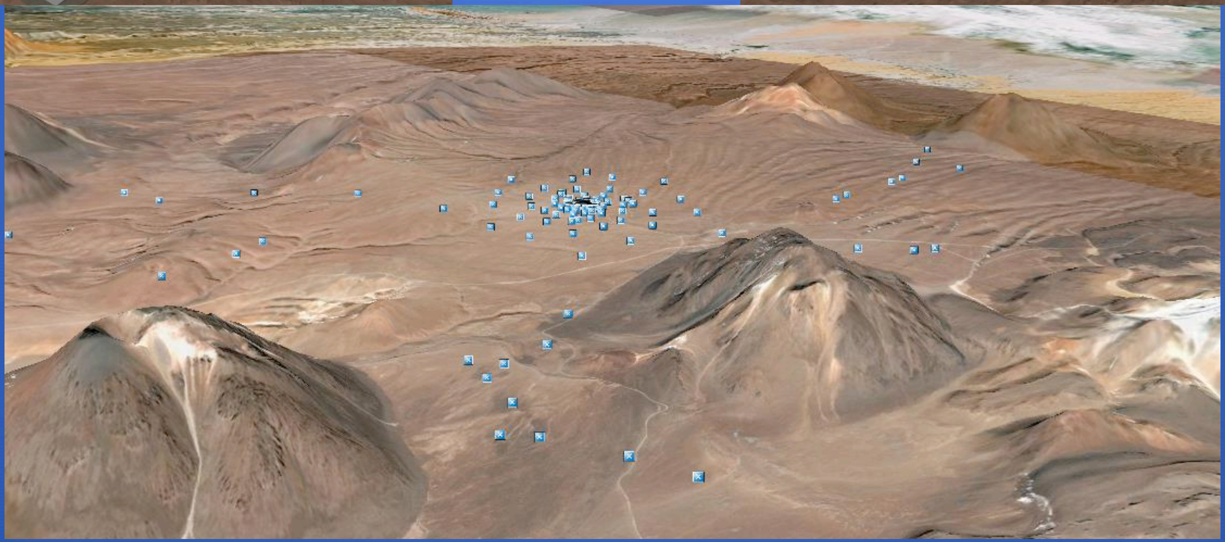
- Alt-azimuth mounted Cassegrain dual reflector systems of 12 metre diameter with a reflector surface and pointing accuracy suitable for observing at 0.3 mm
- Performance requirements:
  - 2″ absolute pointing over the whole sky
  - 0.6″ offset pointing
  - 25 µm rms overall surface accuracy
  - Ability to fast switch (to a calibrator) over a 2 degree range in 1.5 seconds
- Fully-exposed antennas at 5000 m altitude

Angular Resolution

Baselines up to ~14 km





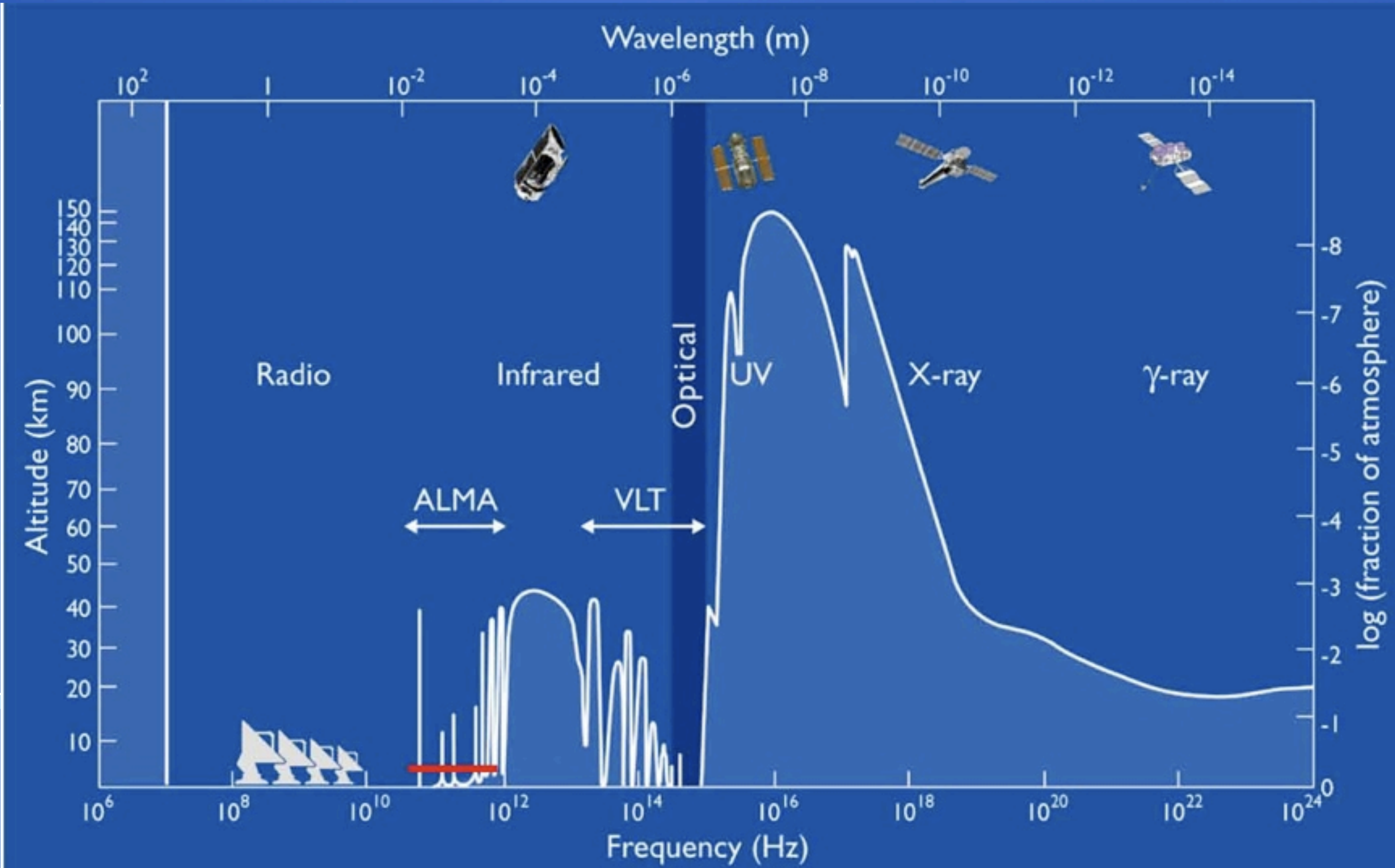


ALMA (ESO/NAOJ/NRAO)

Reconfigure the Array Using Otto and Lore

ALMA (ESO/NAOJ/NRAO)

The Need for ALMA


Wavelength (m)
10^2
1
10^-2
10^-4
10^-6
10^-8
10^-10
10^-12
10^-14
Altitude (km)
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
Radio
Infrared
Optical
UV
X-ray
γ-ray
ALMA
VLT
log (fraction of atmosphere)
-8
-7
-6
-5
-4
-3
-2
-1
0
10^6
10^8
10^10
10^12
10^14
10^16
10^18
10^20
10^22
10^24
Frequency (Hz)

The Need for ALMA

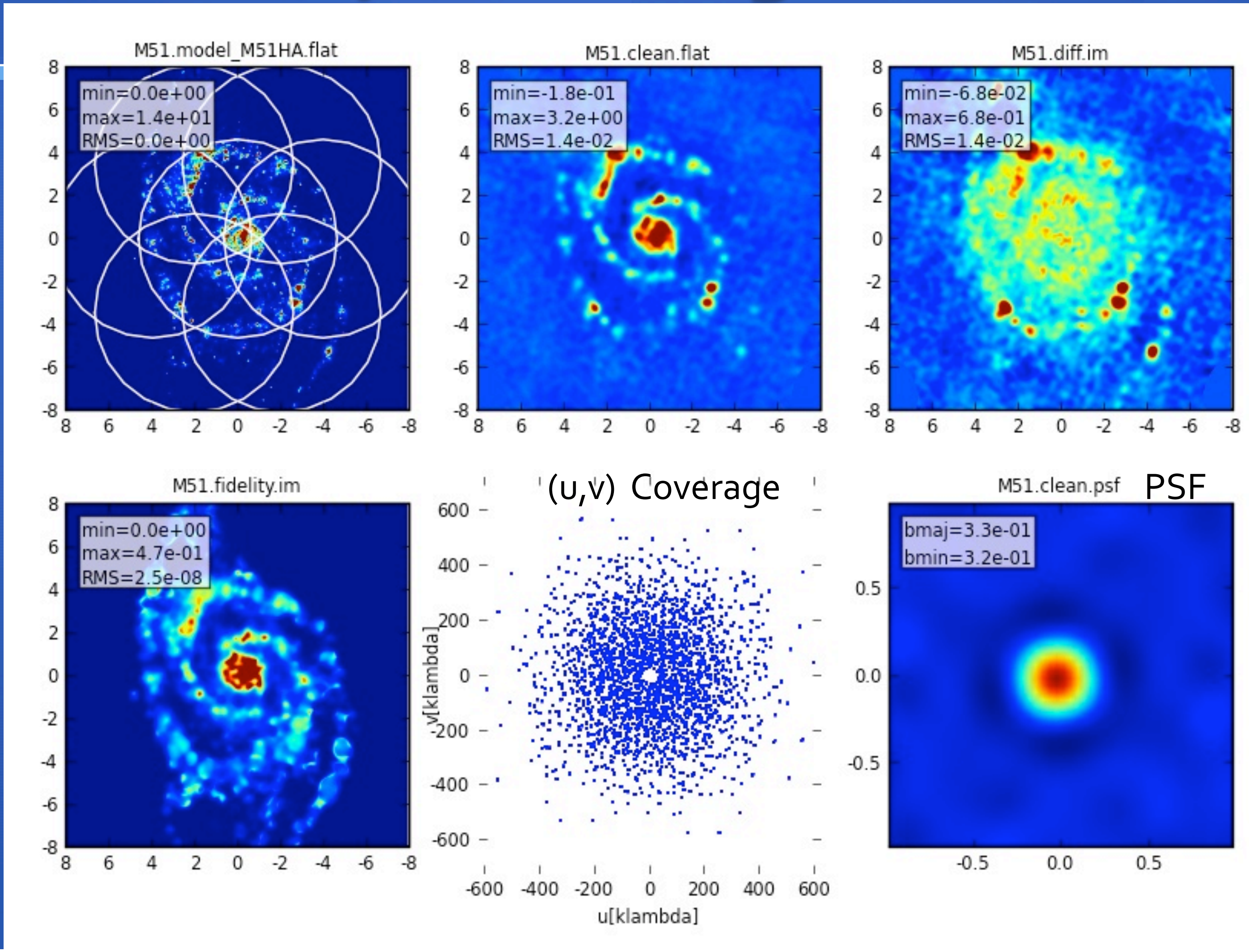
- Why the push for high sensitivity and angular resolution at submillimetre wavelengths?
- Everything is harder than in the radio:
  - Atmospheric Opacity
  - Absolute Gain Calibration
  - Tracking Atmospheric Phase Variations
  - Antenna and instrument constraints
- Unique science at mm & submm wavelengths
- At the moment, only ~50% of mm/submm astronomy is interferometry – this will change with ALMA

Some current Mm/Submm Arrays

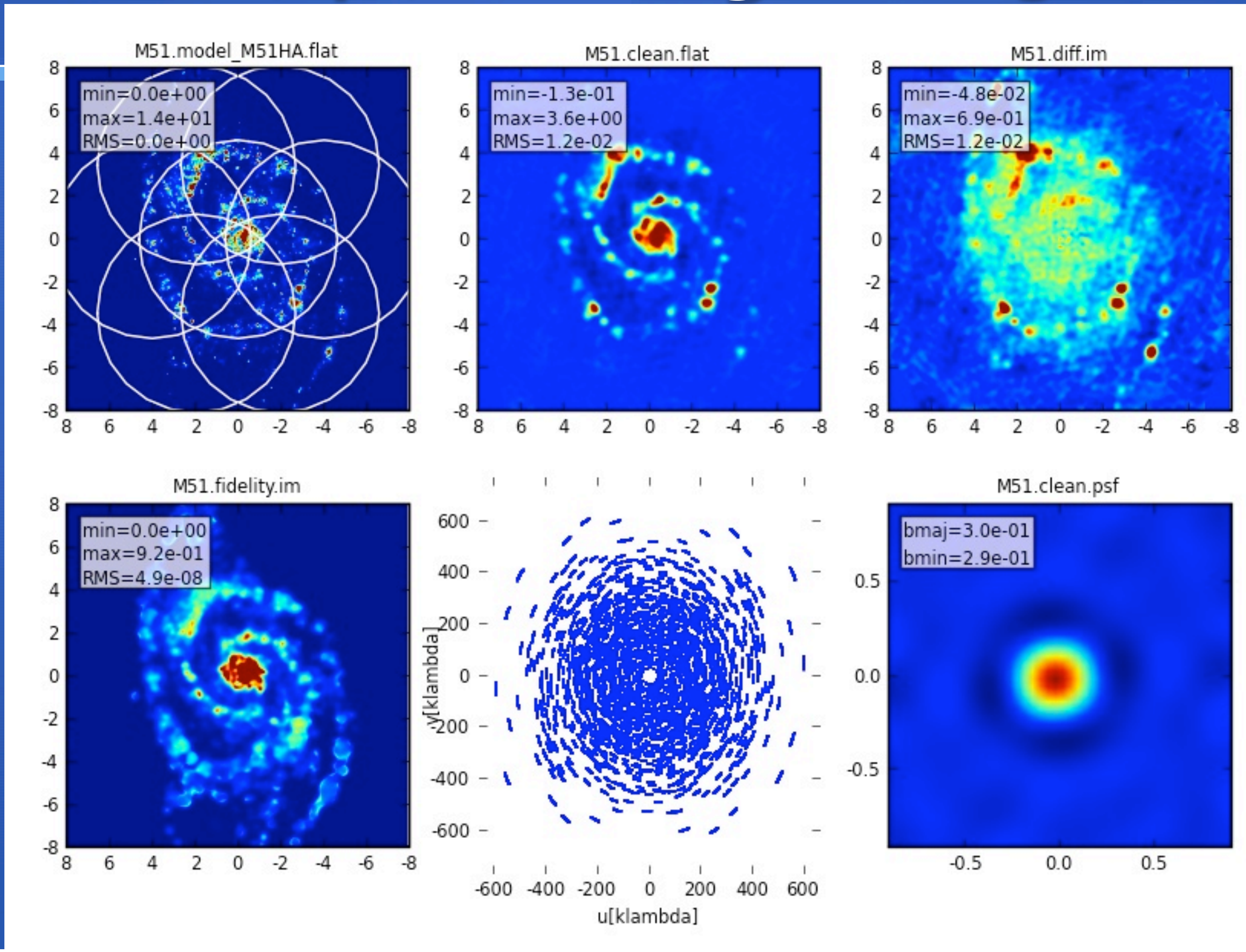
ALMA will be 10 – 100 times more sensitive and have 10 – 100 times better angular resolution compared with current millimetre interferometers

Current mm interferometers deliver ~10^4 visibilities in a few hours, the VLA delivers 10^5 per hour, ALMA will improve on this by 2 orders of magnitude!

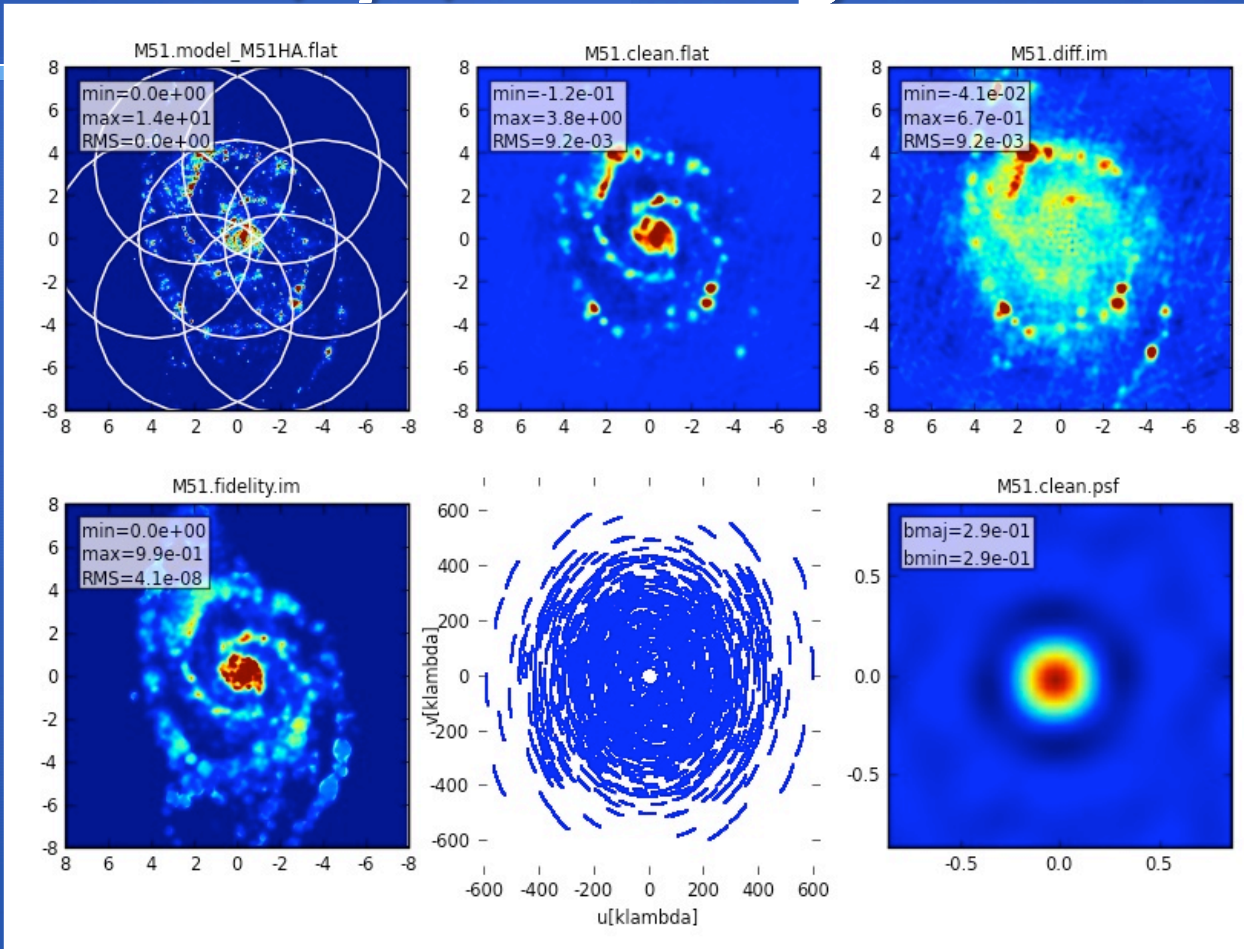
ALMA (u,v) Coverage t=2 min



ALMA (u,v) Coverage   t=30 min



ALMA (u,v) Coverage t=1 hr



ALMA (u,v) Coverage t=5 hr

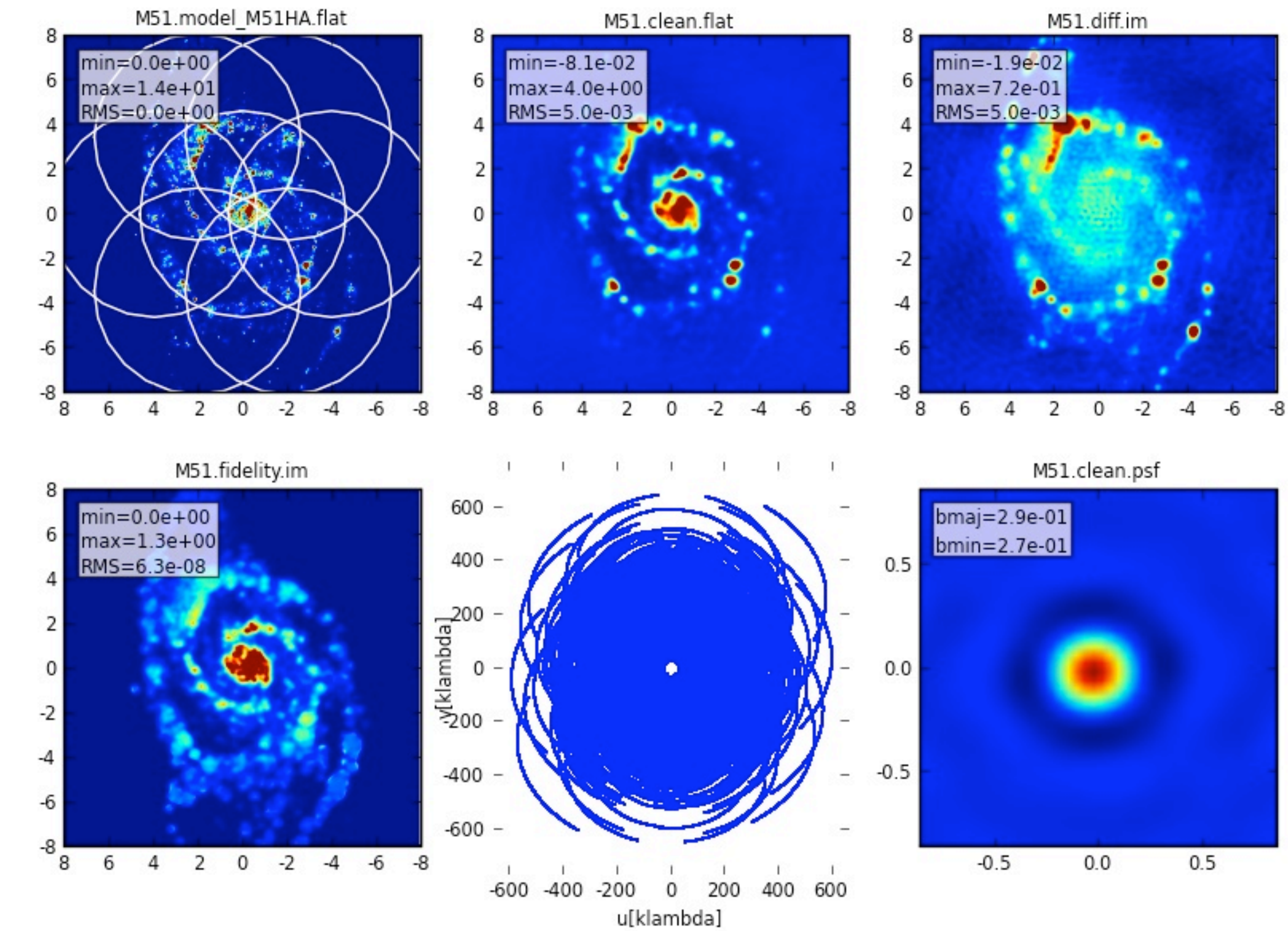
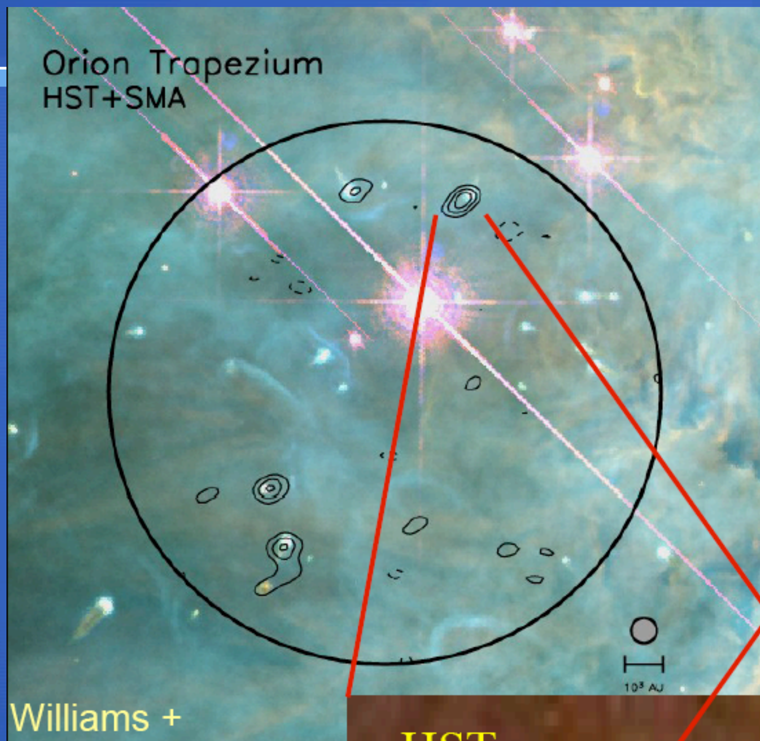
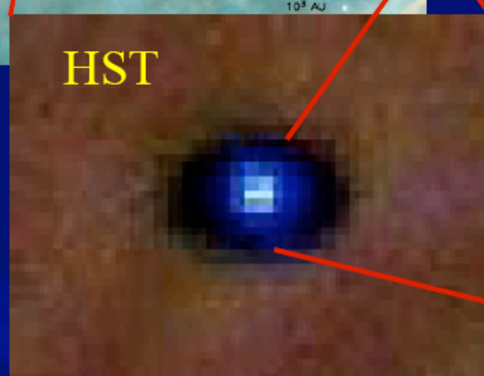


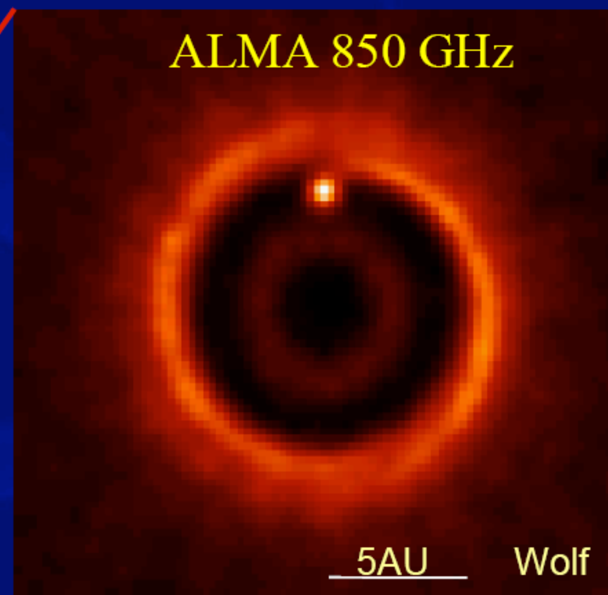
Image the Birth of Planets!



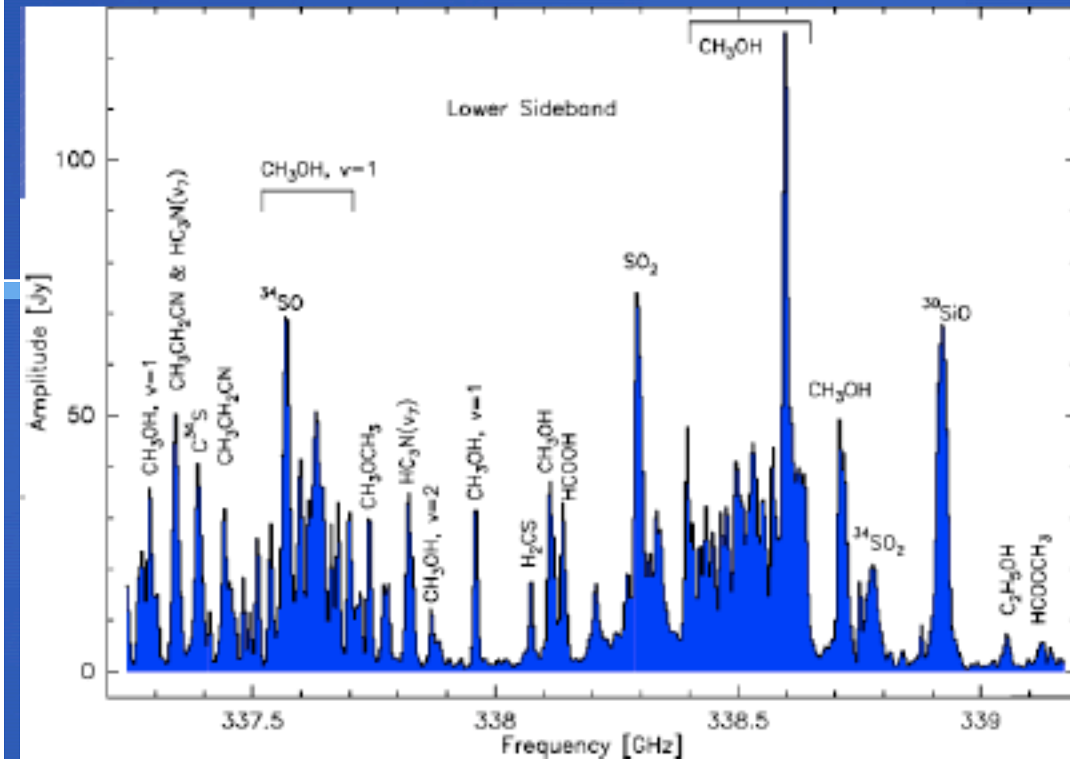


Birth of planets

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

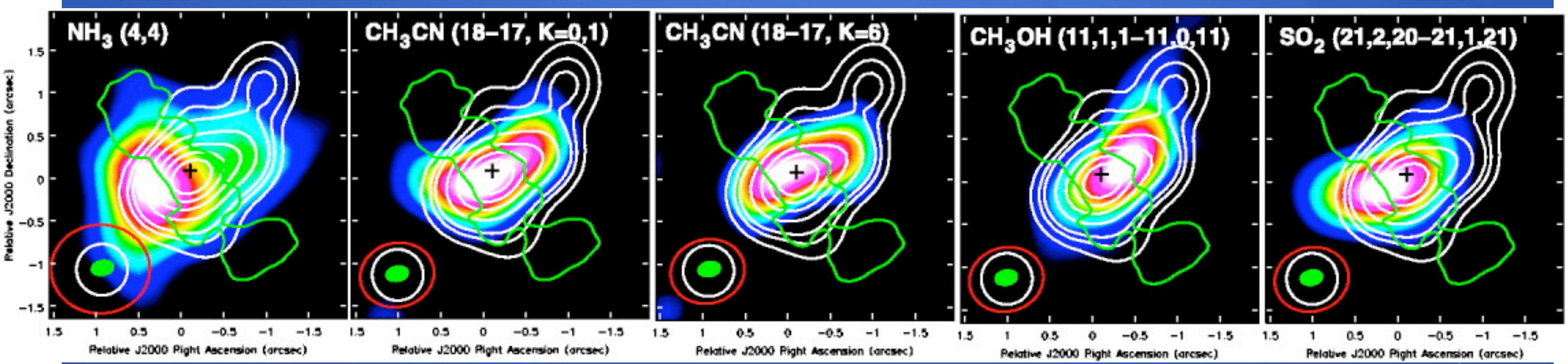


Beuther



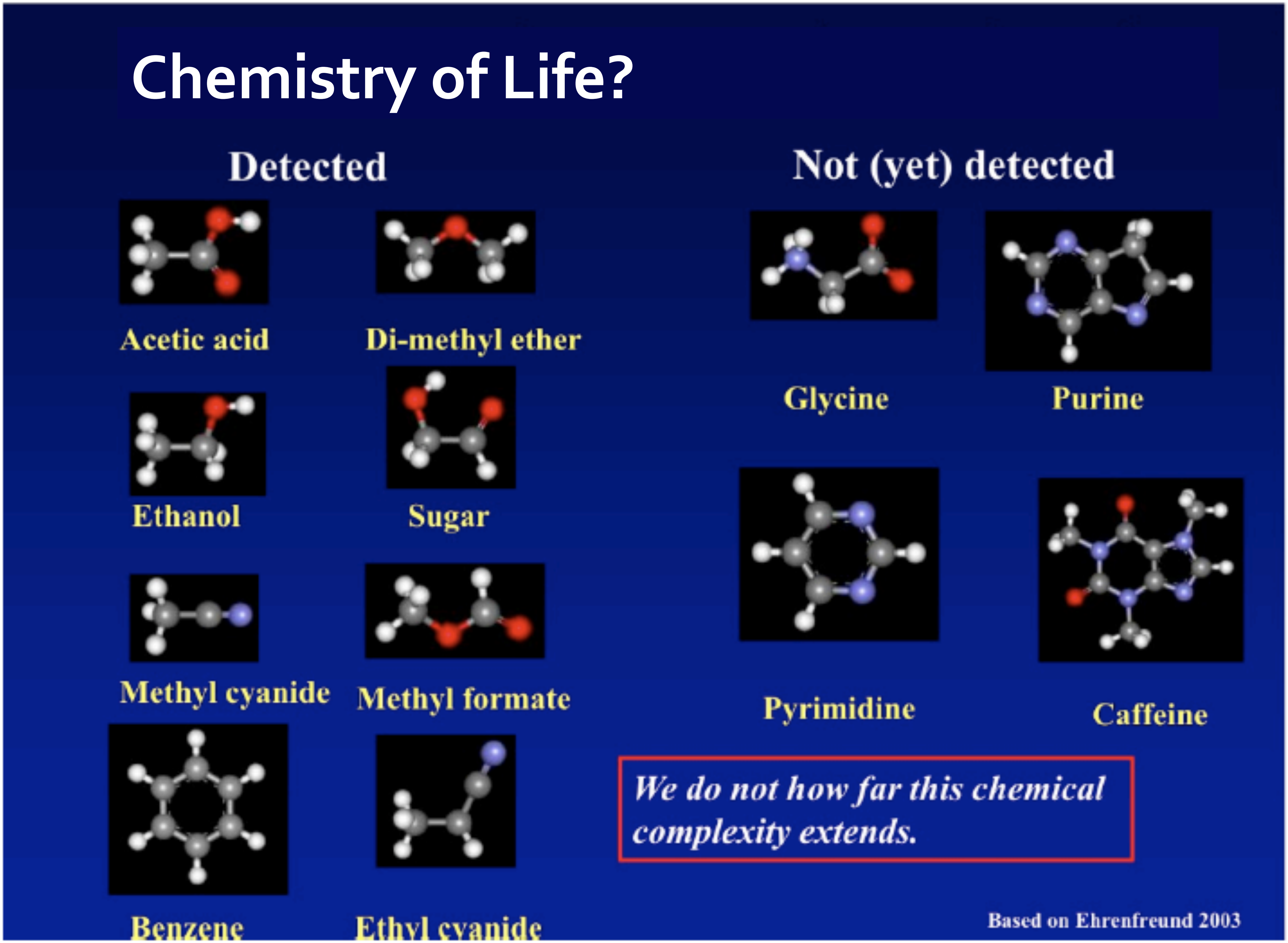
Astrochemistry

Imaging the Submm Line Forest

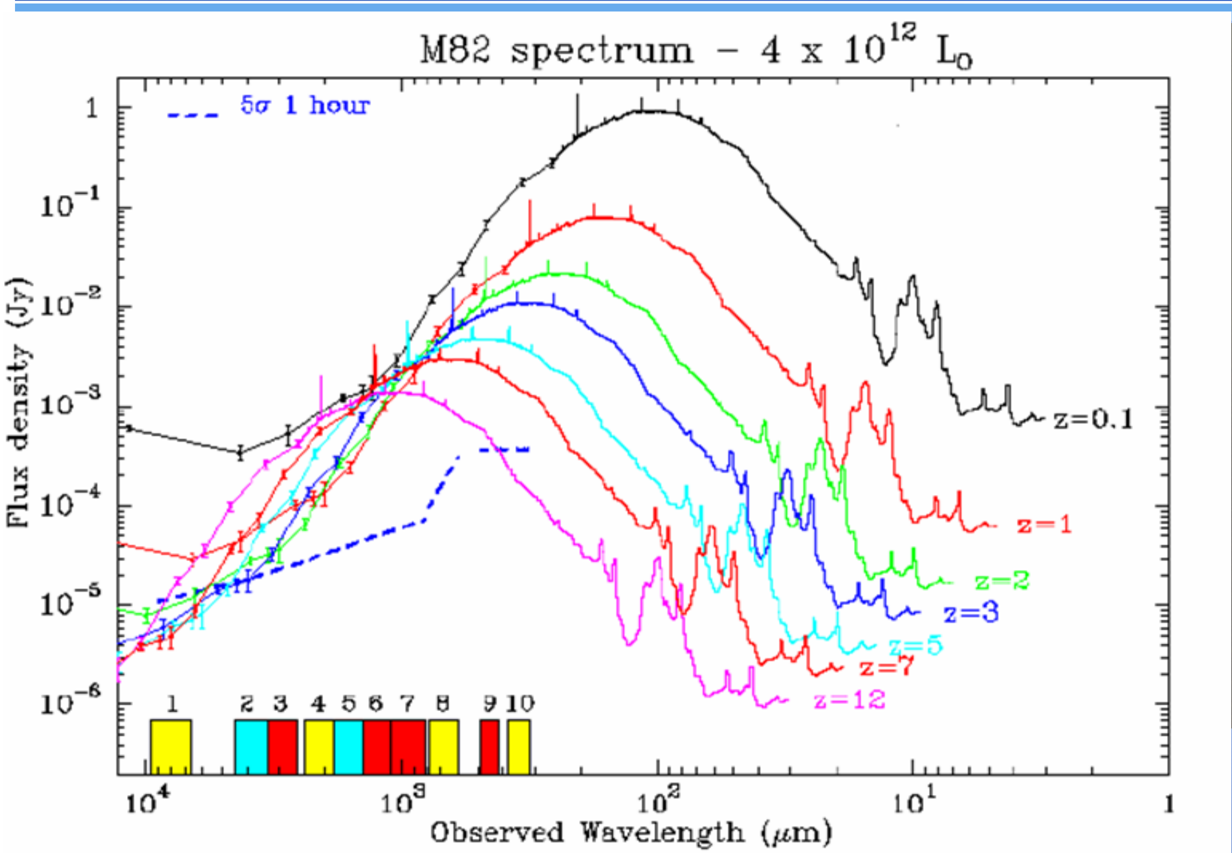


Brogan et al. (2007)

ALMA will have 8 GHz bandwidth


Chemistry of Life?
Detected
Acetic acid
Di-methyl ether
Ethanol
Sugar
Methyl cyanide
Methyl formate
Benzene
Ethyl cyanide
Not (yet) detected
Glycine
Purine
Pyrimidine
Caffeine
We do not how far this chemical complexity extends.
Based on Ehrenfreund 2003

Galaxies at high z!



Spectral energy distribution
of the nearby starburst galaxy M82

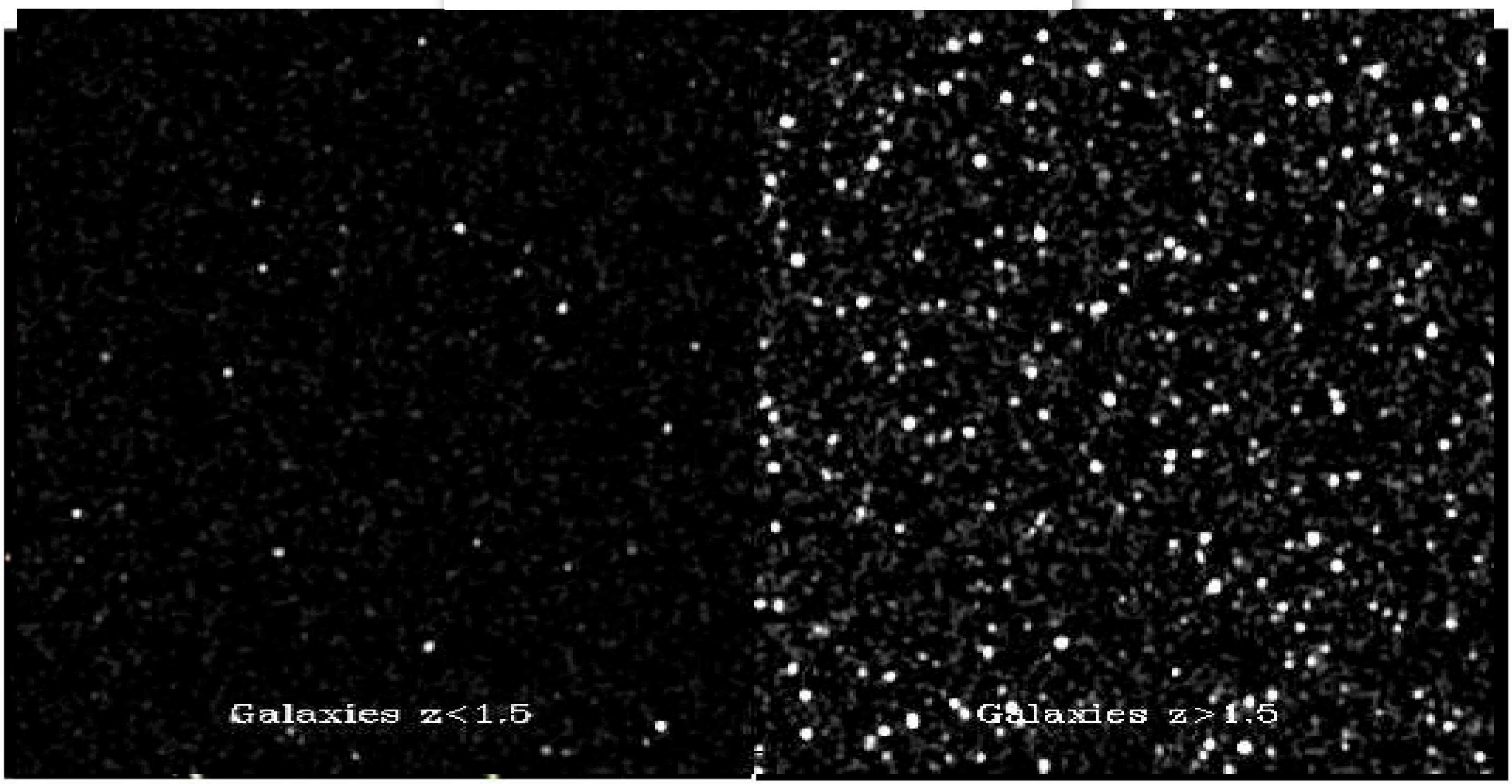
The effect of redshift on the SED: dusty galaxies are easily detected at high z

Slide courtesy Robert Laing

Hubble Deep Field

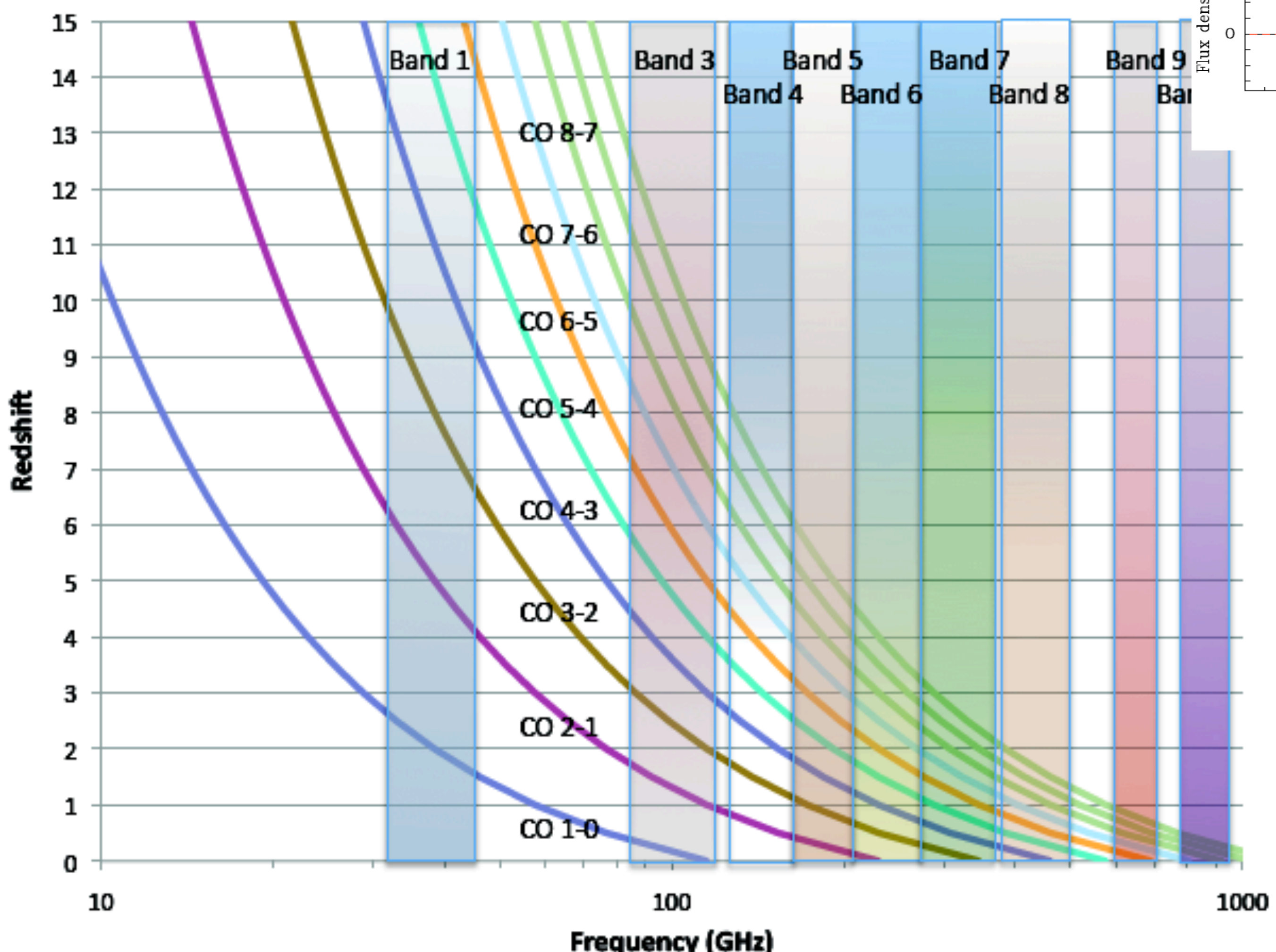
(12 days of integration)

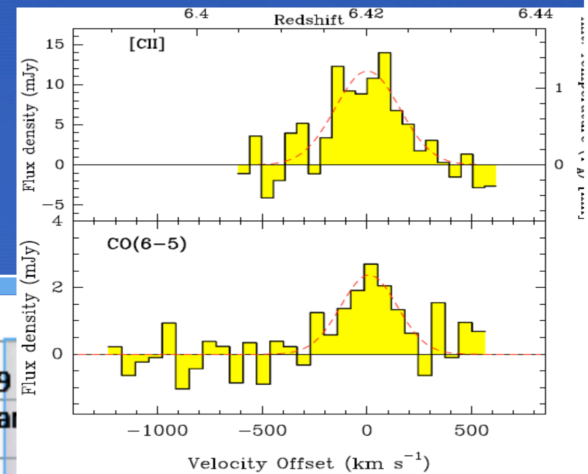
Simulated ALMA Deep Field



z<1.5 Wootten and Gallimore z>1.5

Redshifted Spectral Lines

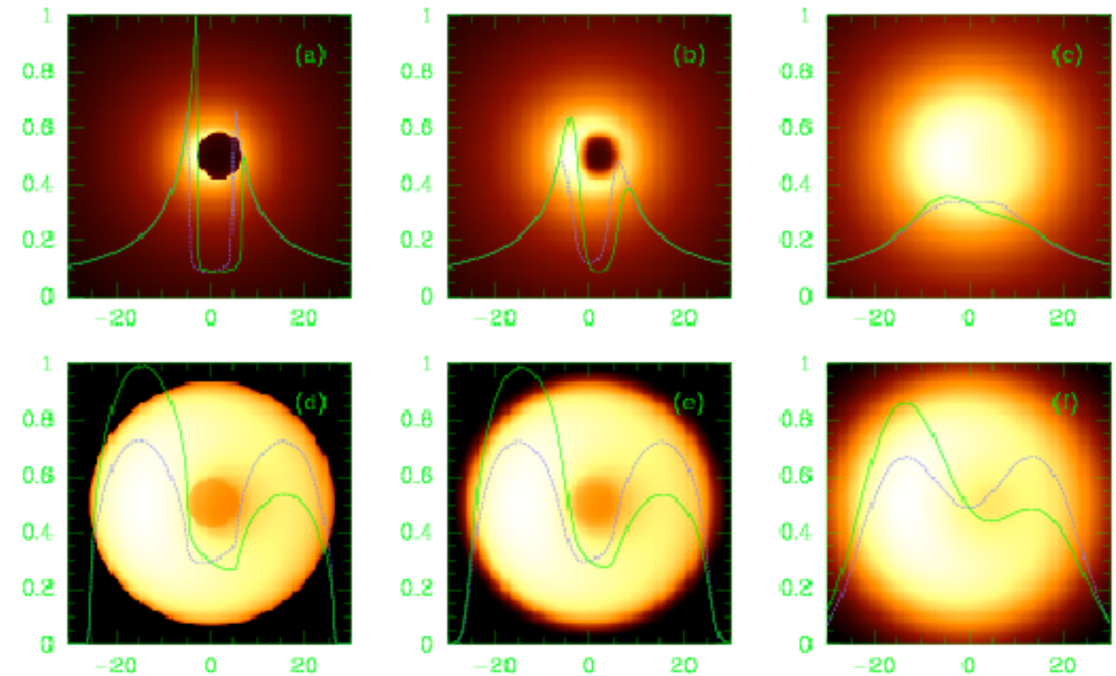




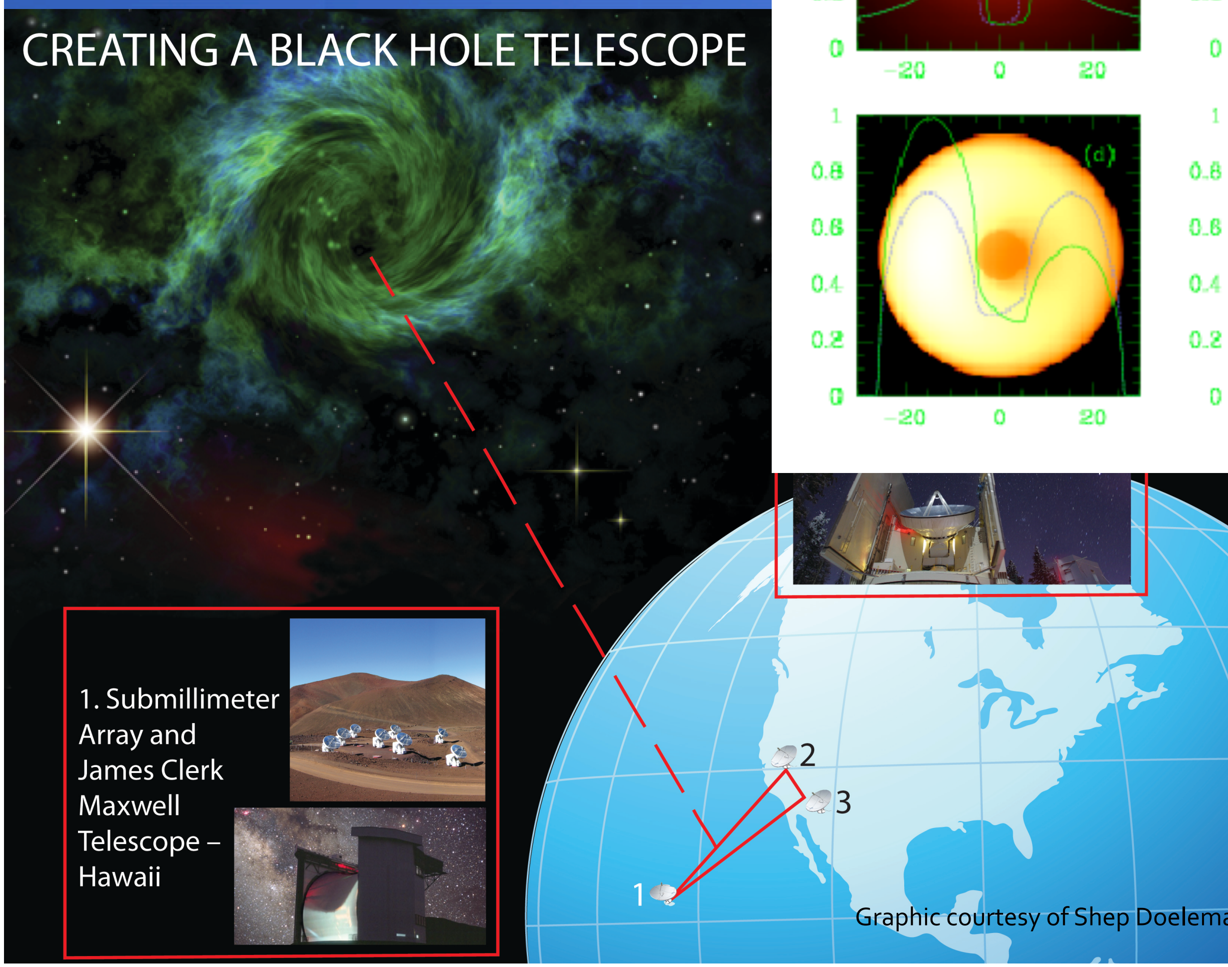
Maiolino et al. (2009)

CII – Main coolant in the Milky Way
Line of choice for EoR studies
Quasar, z = 6.4

ALMA in VLBI: Black Hole Telescope



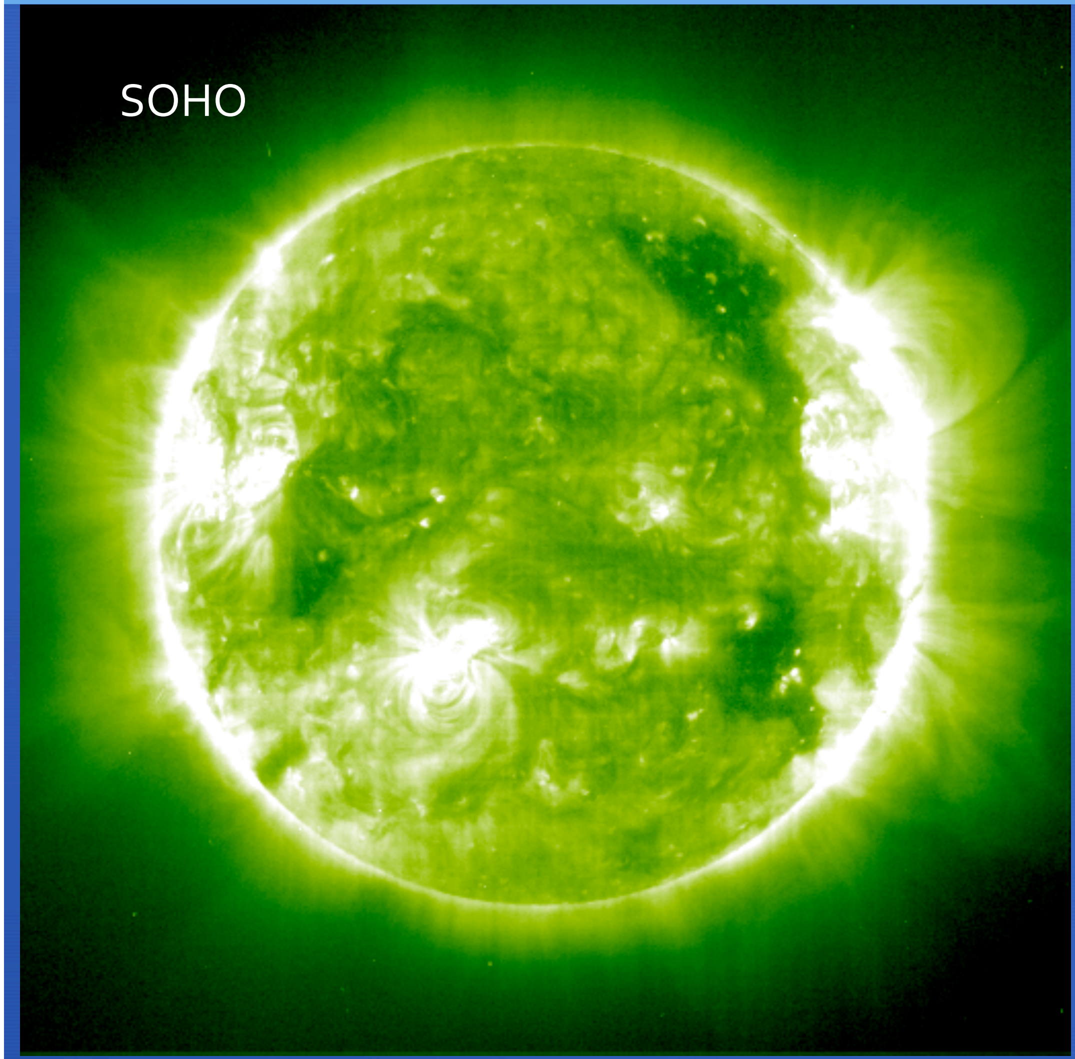
Falcke et al.



Graphic courtesy of Shep Doeleman

First “Direct” Detection of a Supermassive Black Hole?

The Sun



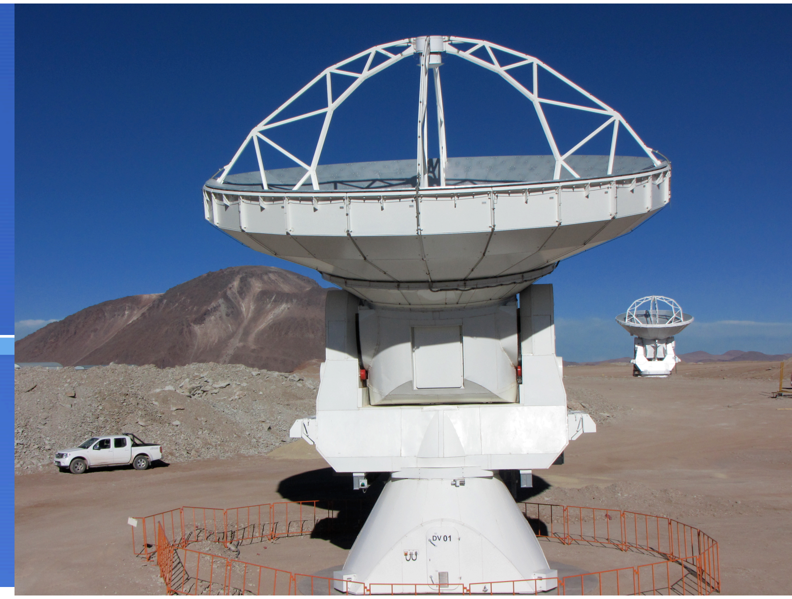
- The structure of the quiet solar atmosphere
- Coronal holes (where vast solar winds originate because of diverging magnetic fields)
- Solar active regions
- Active and quiescent filaments
- Energetic phenomena like filament eruptions and flares.

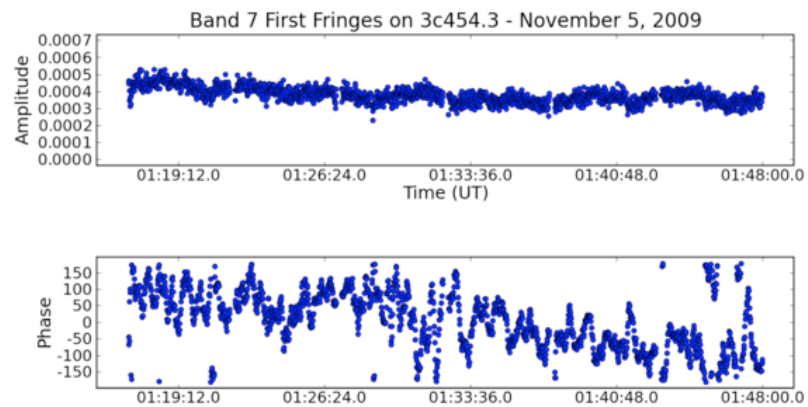
ALMA Current Status

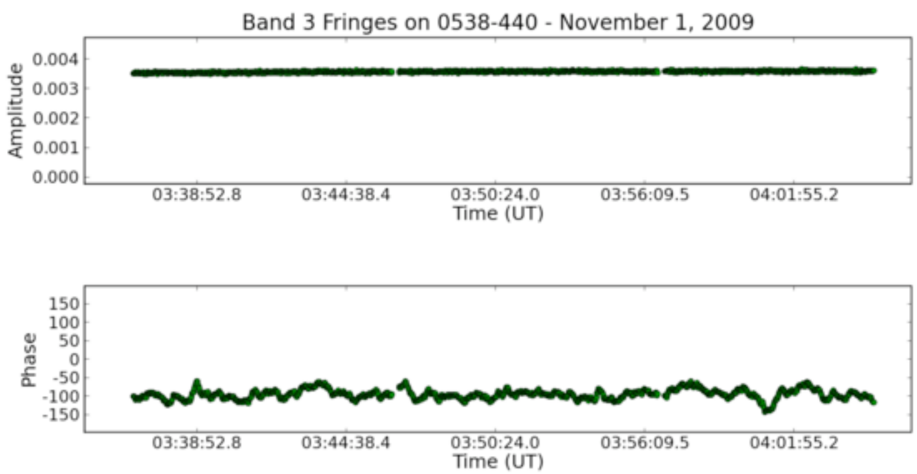
Recent ALMA Milestones

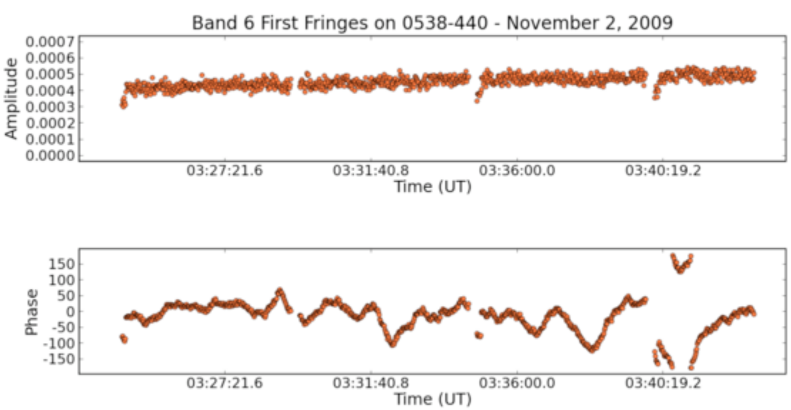
- ALMA First Fringes
- ALMA Closure Phase
- ALMA started official Commissioning and Science Verification activities in January 2010

ALMA First Fringes

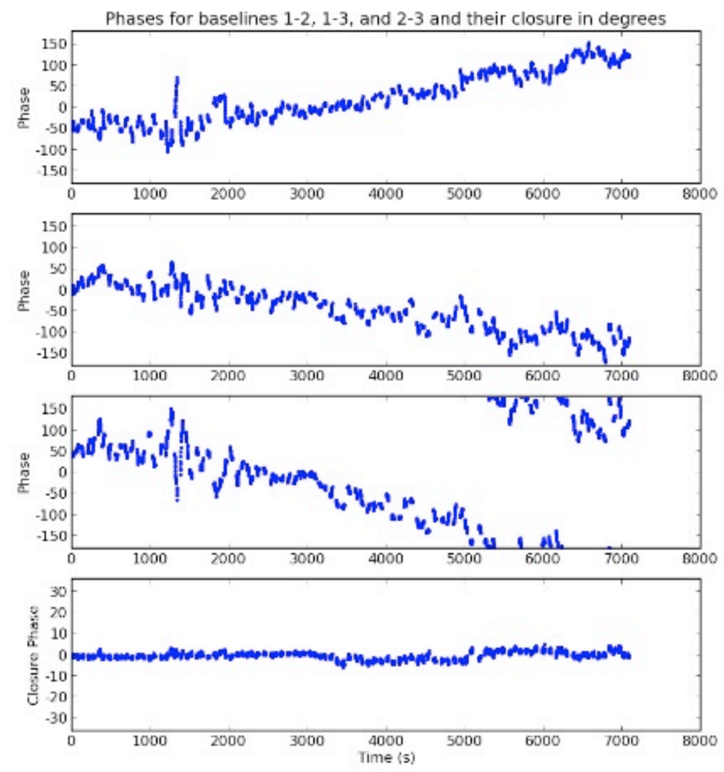




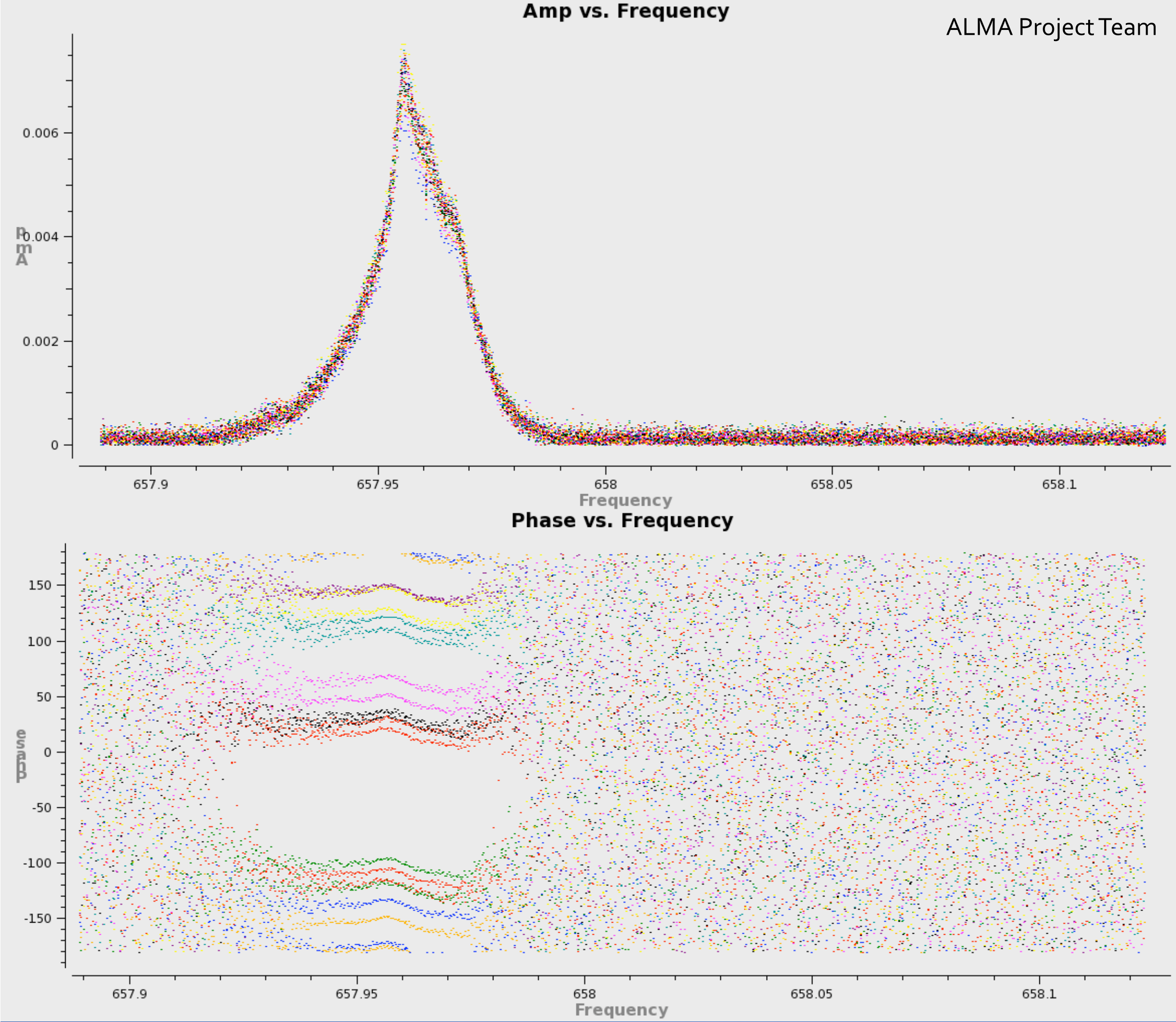




ALMA Closure Phase



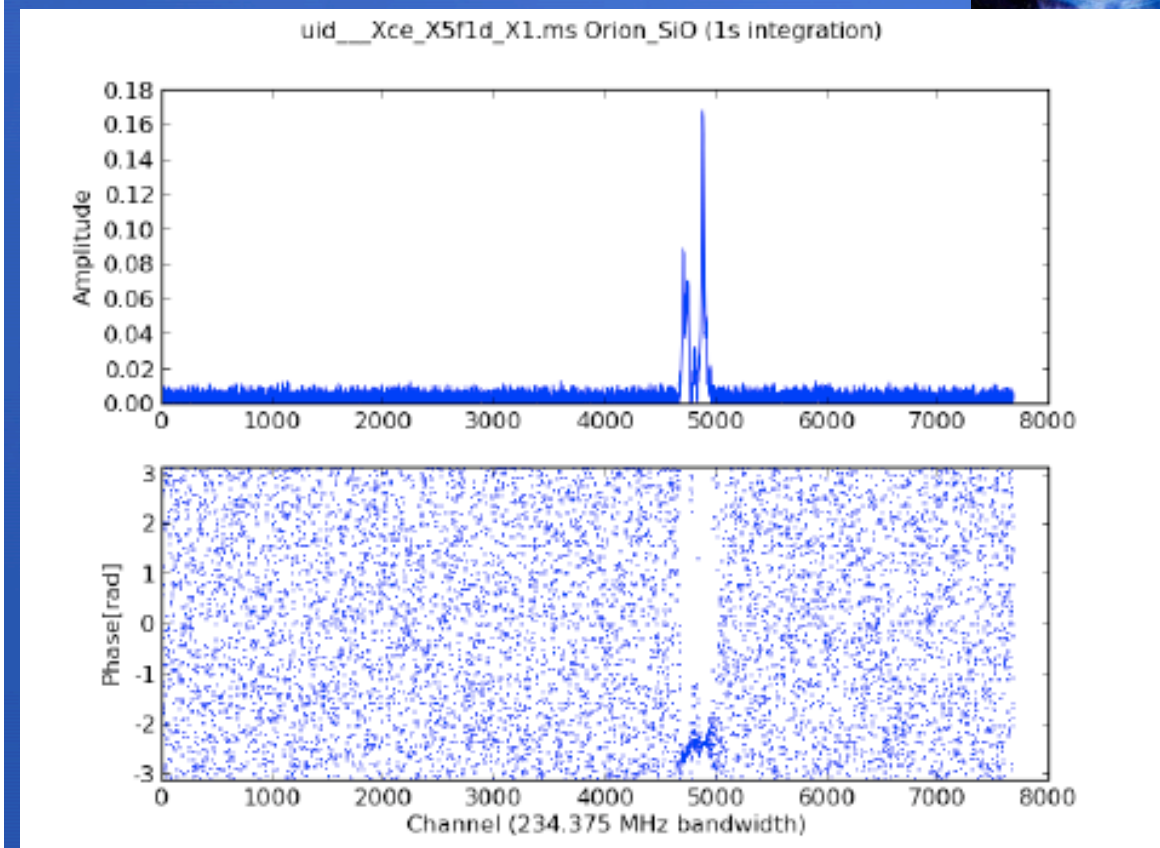
VY CMa

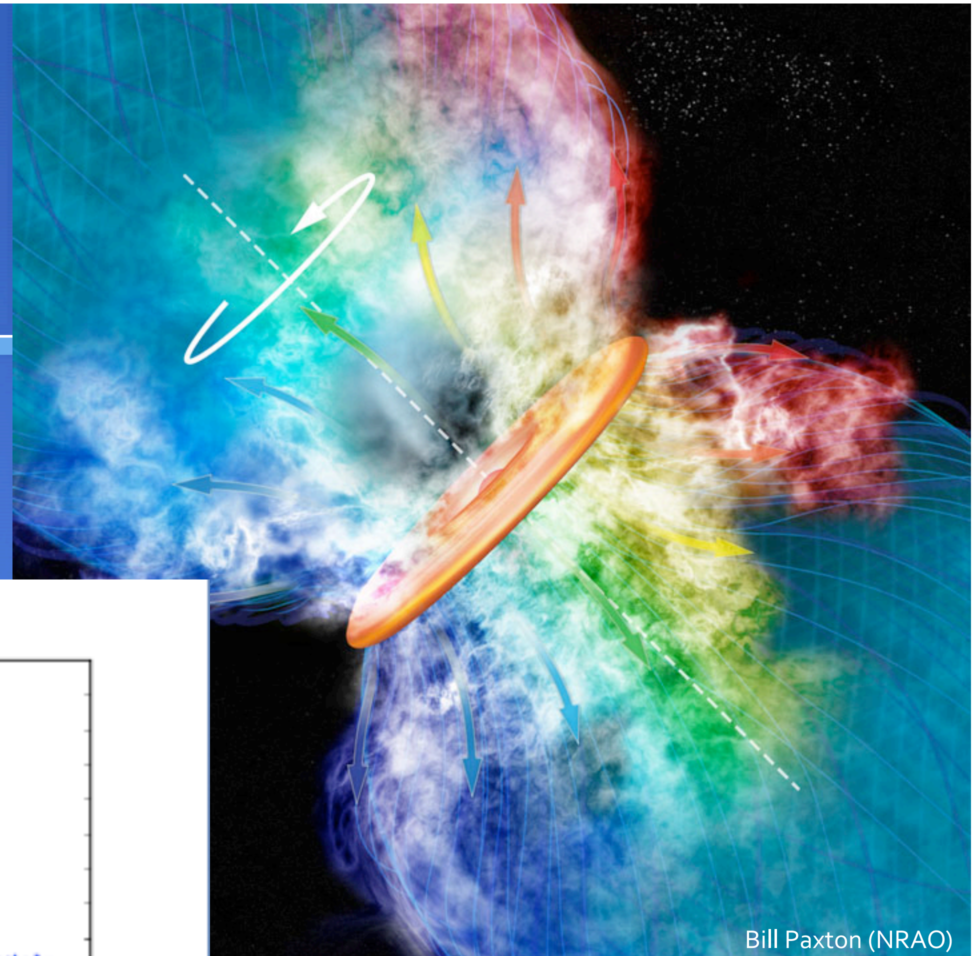


658 GHz VY CMa Water Maser Cross-correlation spectrum

Orion BN/KL

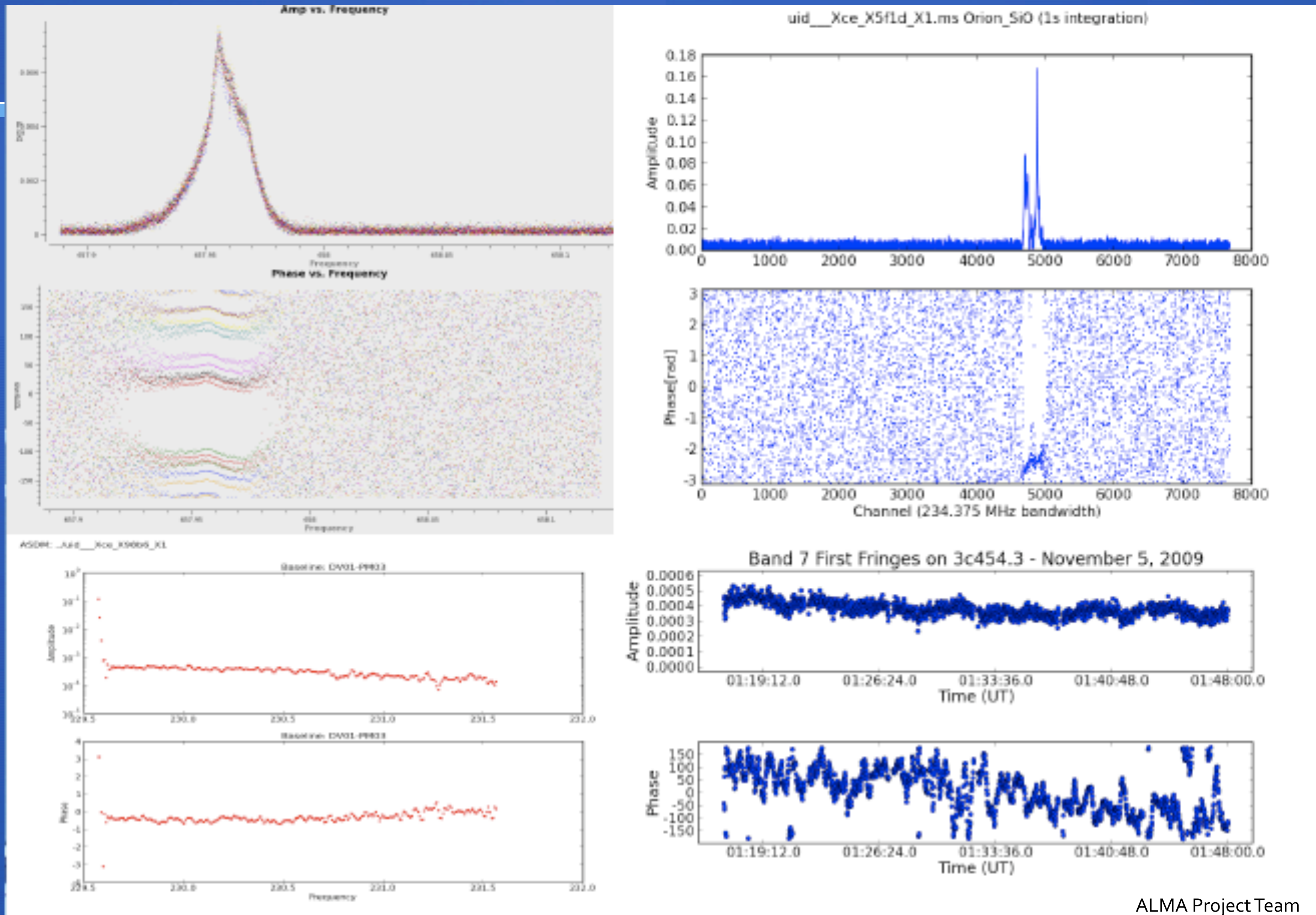
Tracing High Mass Star Formation





86 GHz
SiO Maser
Orion

Fringes At the Four Existing Bands



ALMA Project Team

ALMA in Practice

This Afternoon!

Summary

- ALMA will transform knowledge of many areas of astrophysics
- ALMA is intended for use by non-specialists as well as specialists
  - Idea & Science Goal Driven
  - If you use ALMA, you will receive calibrated data and images back
- There are ALMA Regional Centres in Europe, East Asia and North America that will provide user support, including face-to-face support
- The first Call for Proposals for ALMA Early Science will be soon – around the end of this year!