Radio Interferometry and ALMA

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ESO

PLAN

- Basics of radio astronomy, especially interferometry
- ALMA technical details
- ALMA Science

Some Definitions

$kT_{\mathbf{A}}\ \Delta\nu = 1/2\ S\ A\ \Delta\nu$

$\Sigma\ I\ \Delta\Omega = S = 2kT_B\ \Delta\Omega/\lambda^2$

$T_{\mathbf{B}} = T_{\mathbf{s}}\ e^{-\tau} + T_{\mathbf{atm}}(1\text{-}e^{-\tau})$

Usually: $T_{\mathbf{A}}=0.6T_{\mathbf{B}}$ (approximately!)

A few basics:

Wavelength and frequency: $\lambda \propto \nu$ -1

blackbody temperature λmax(mm) ~ 3/T(K)

Angular resolution: θ ('')=0.2 λ(mm)/baseline(km)

(For ALMA at λ=1 mm, baseline 4 km, same as HST)

Flux Density and Temperature in the Rayleigh-Jeans limit:

$$S(\mathrm{mJy})=73.6\ T(\mathrm{K})\ \theta^2\ ('')/\ \lambda^2(\mathrm{mm})$$

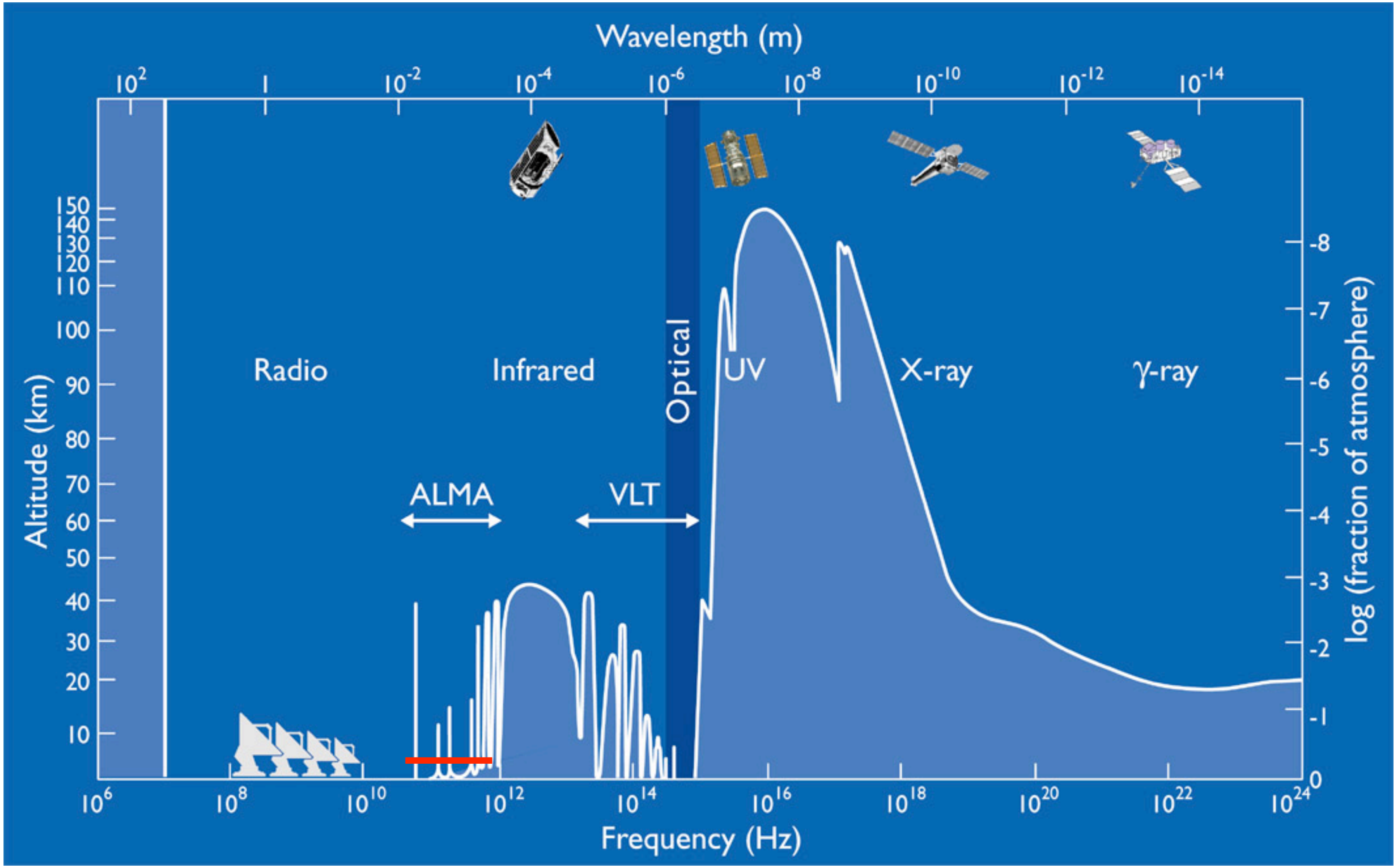
Minimum theoretical noise for heterodyne receivers:

$$T_{rx}=h\nu/k=5.5(\nu\ /115\ \mathrm{GHz})$$

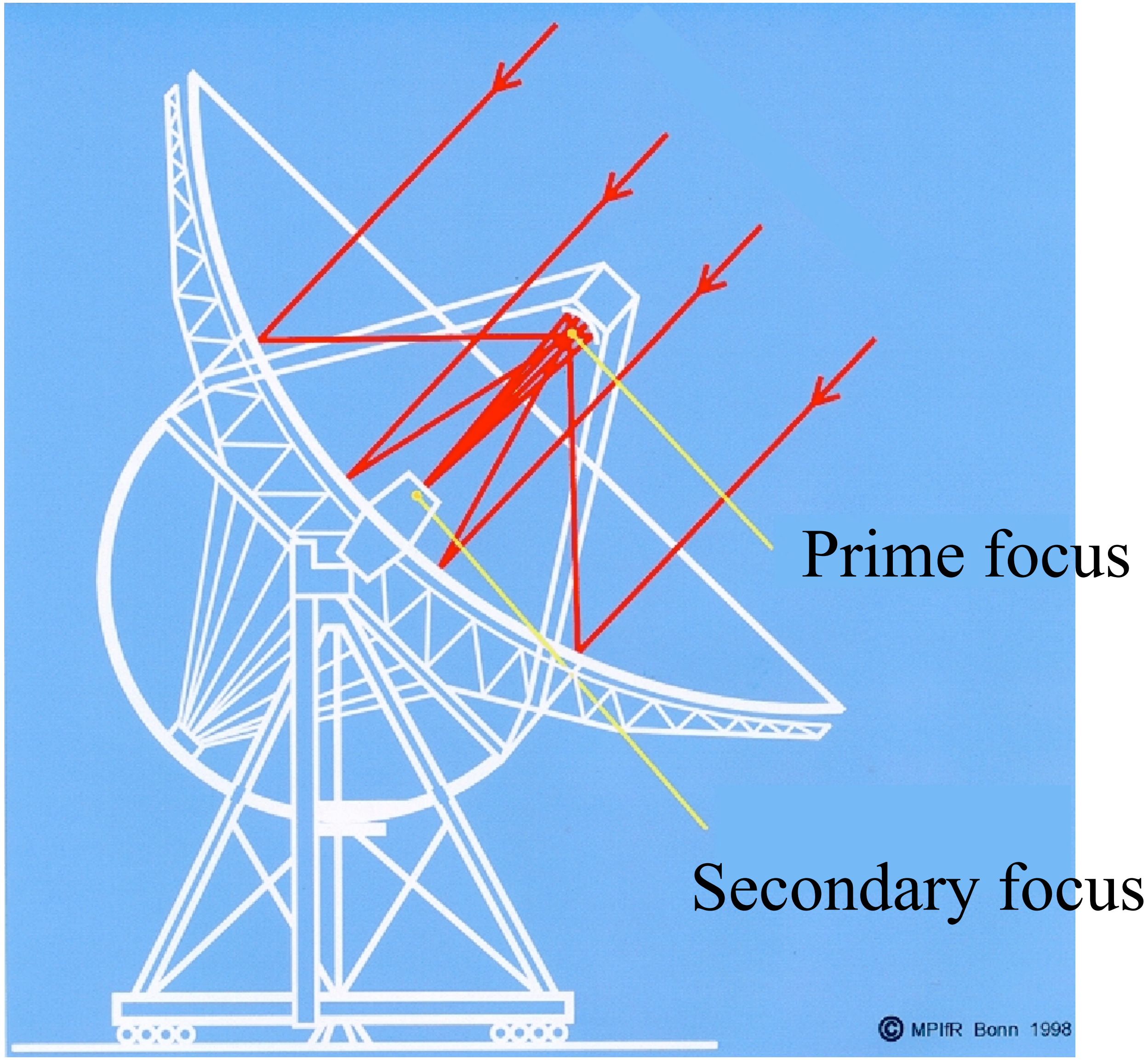
Sensitivity calculator:

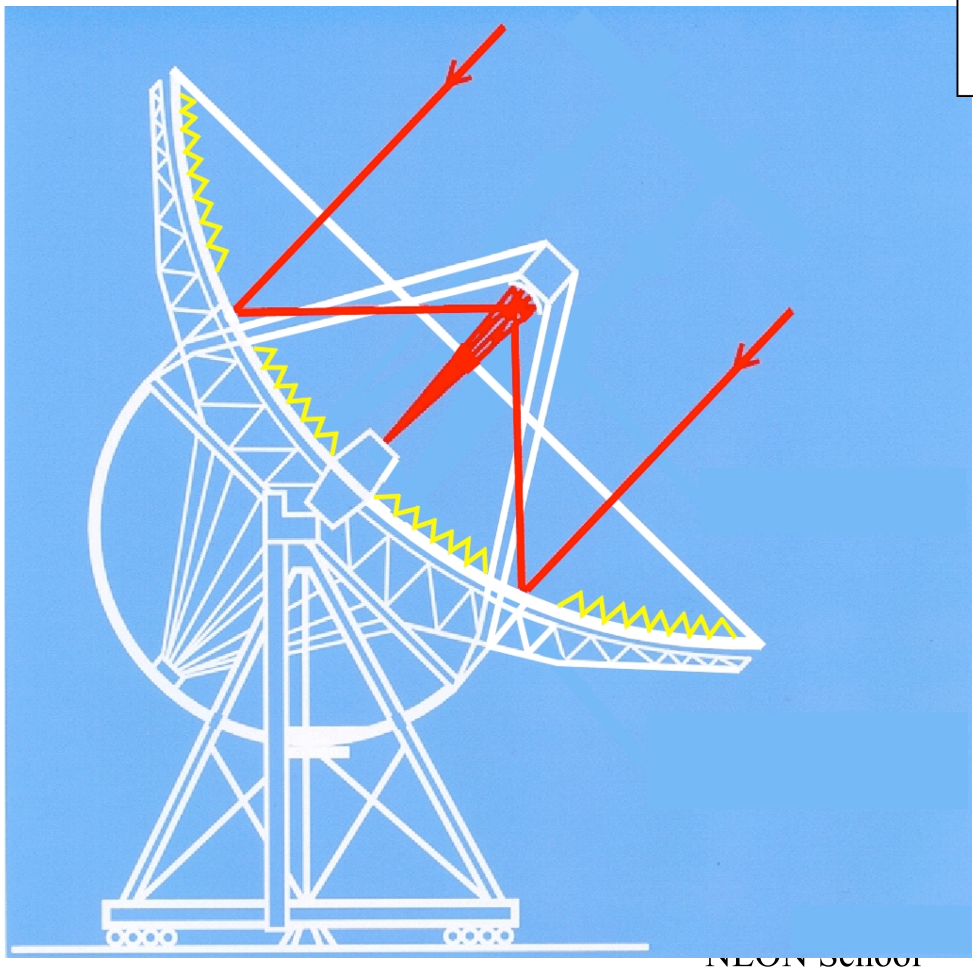
http://www.eso.org/projects/alma/science/bin/sensitivity.html

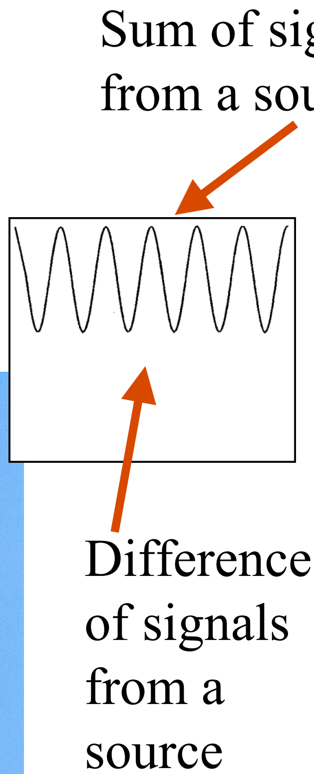
Opacity of the Atmosphere



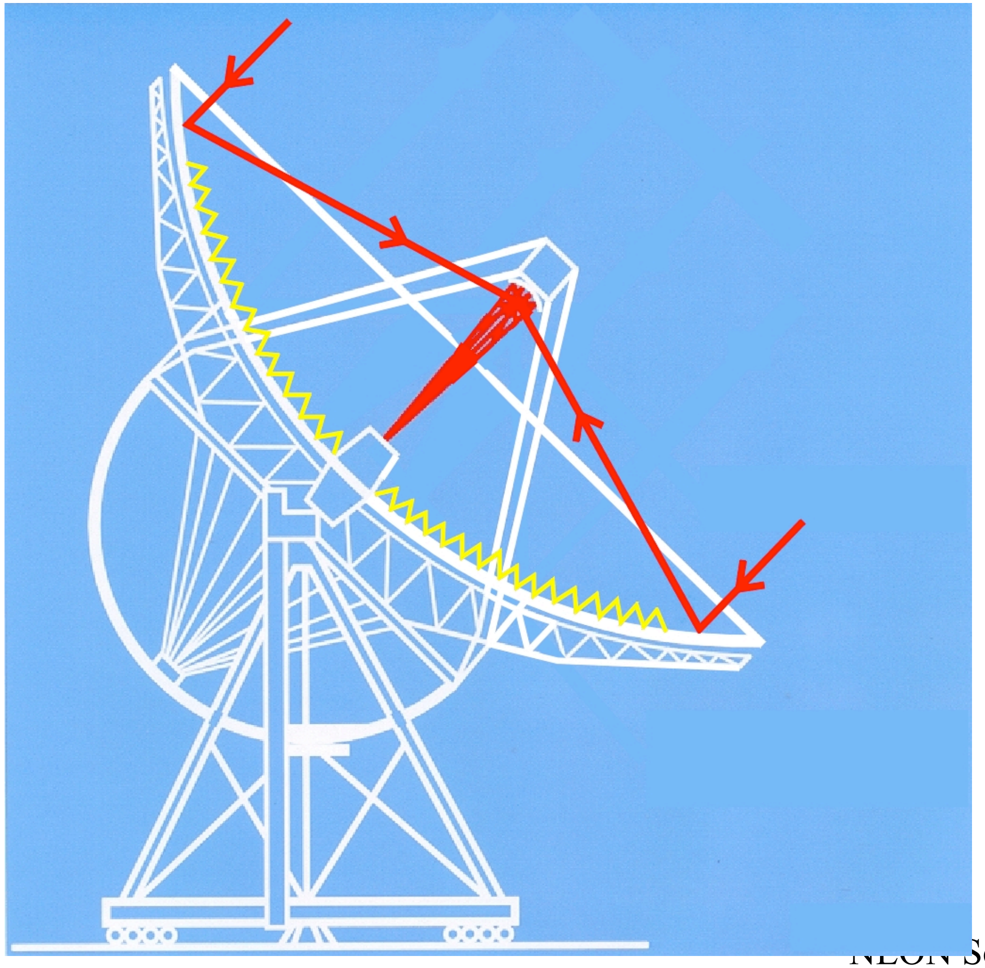
A parabolic radio telescope



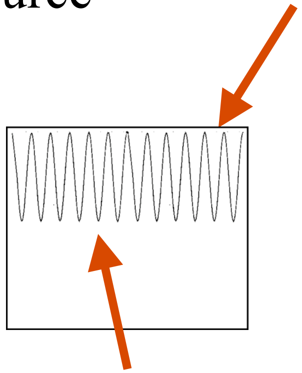




Cover up parts of the dish. The response is the square of signals from specific structural components of the source



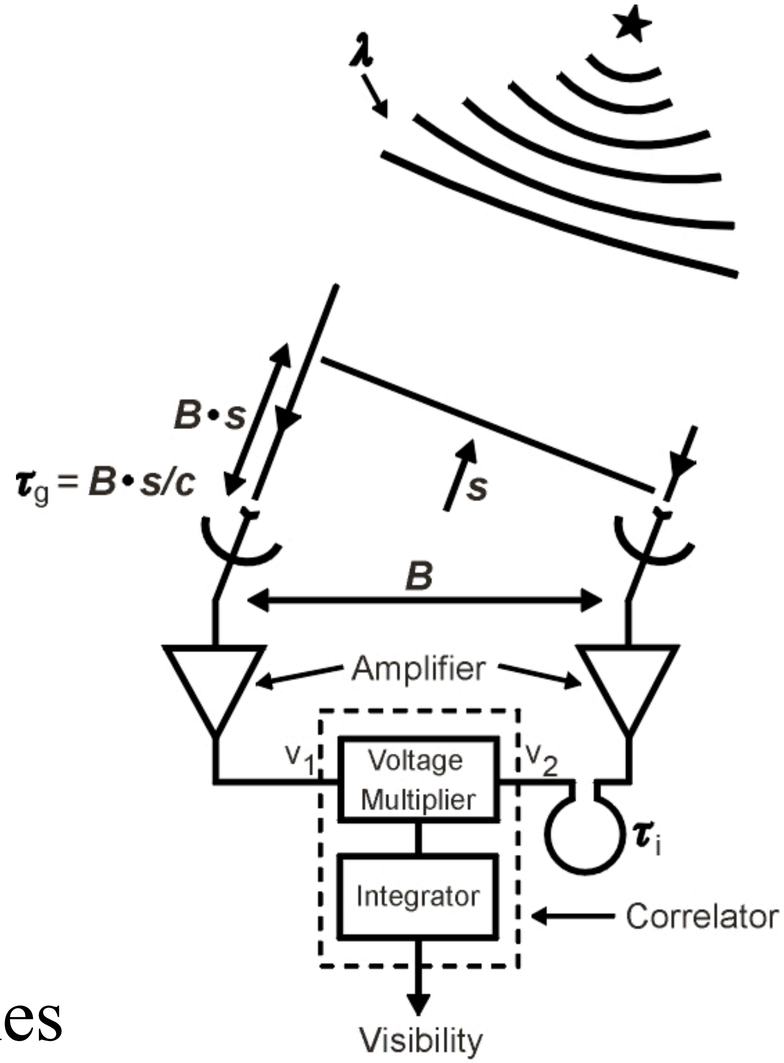
Sum of signals from a source



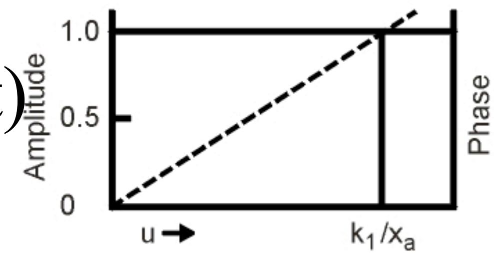
Difference of signals from a source

The parts of the dish where power is received are wider apart, so one is sensitive to smaller structures

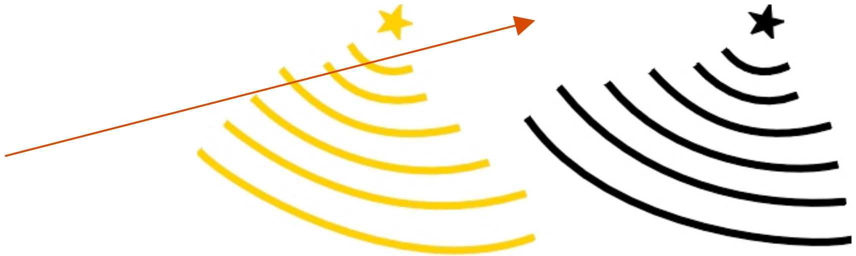
$u = 2\pi[x]/\lambda$

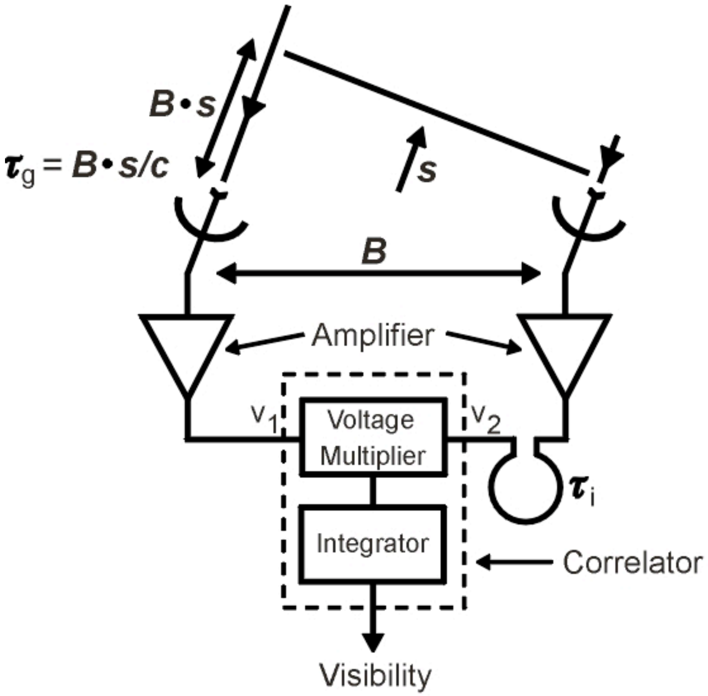


The phase reaches
A value of 2π when
x_a (the angular offset)
is $2\lambda/B_p$

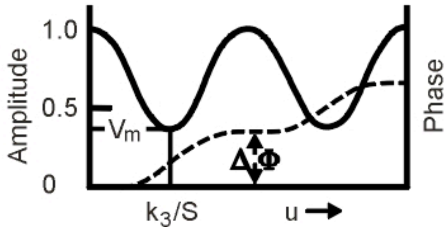


Source separation is ‘S’



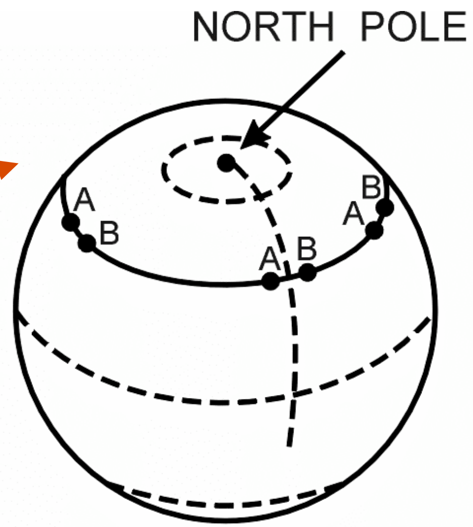


S is λ/B_p

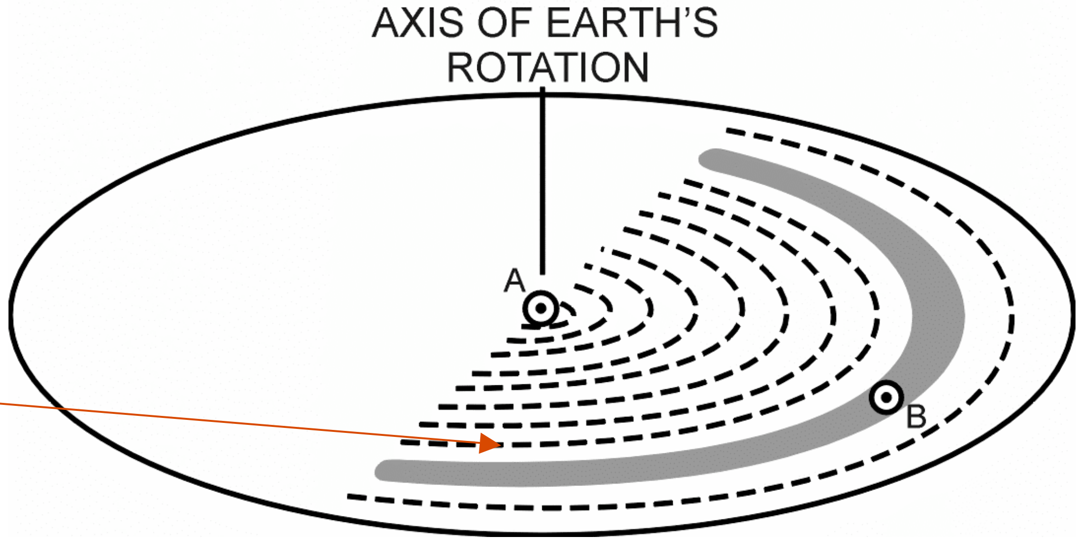


Earth Rotation Aperture Synthesis

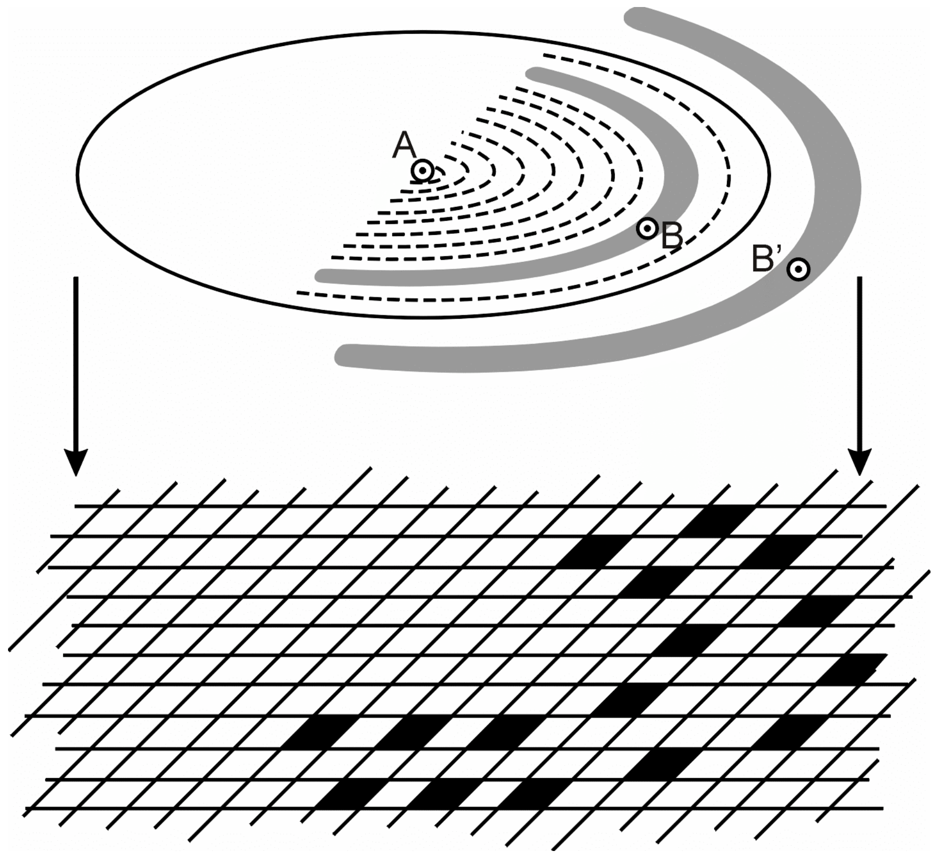
Above: 2 antennas on the earth's surface have a different orientation as a function of time.



Below: the ordering of correlated data in (u,v) plane.

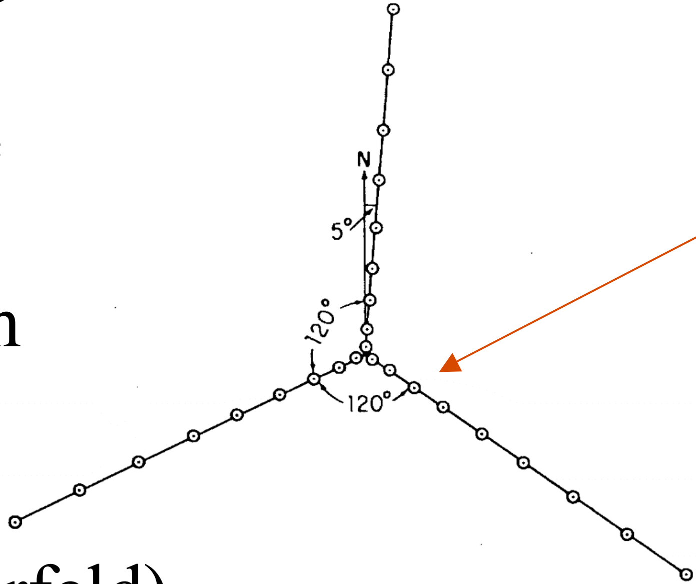


Gridding and sampling in (u,v) plane



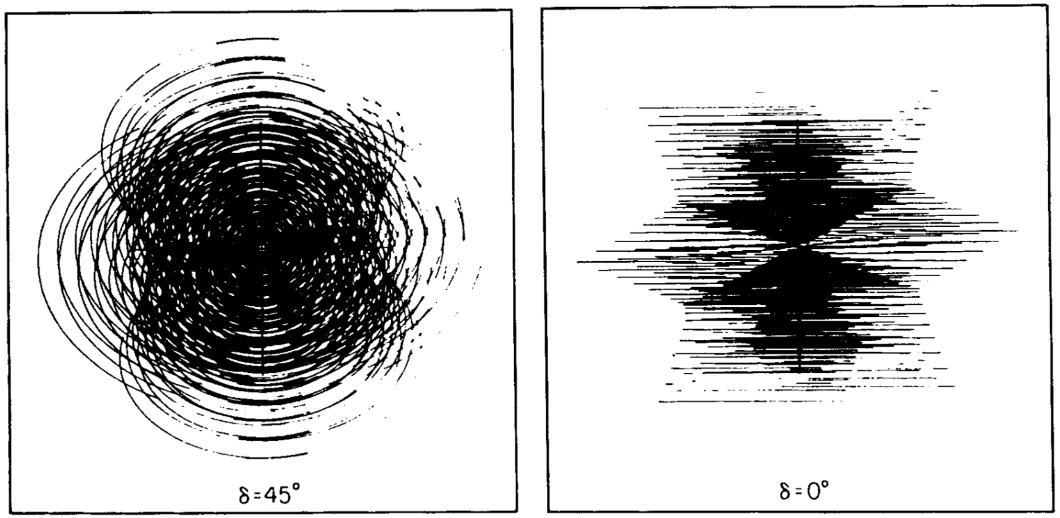
To obtain an image
of the source,
fill the (u,v) plane
with data points,
Fourier Transform
this array of data

(Kirchoff-Sommerfeld)



Arrangement of
The VLA antennas

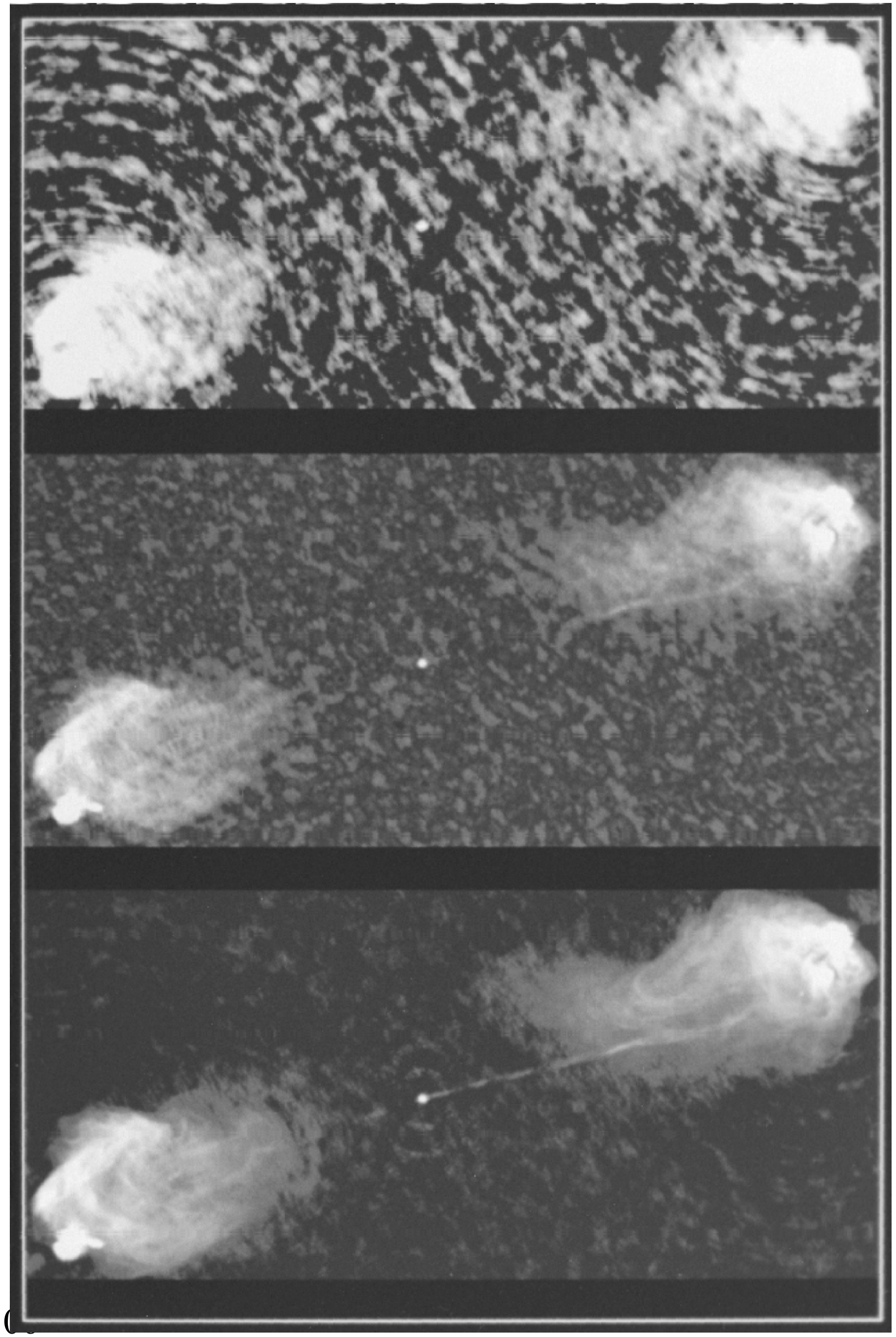
e



Data as taken

Data with MEM

with MEM and Self-Calibration



The radio galaxy Cygnus A as measured with all configurations of the VLA

Inner part of the compact configuration of the Very Large Array

The minimum spacing of the antennas determines the 'largest size of structure that can be measured'. Need a single dish measurement to obtain the total Flux Density

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

From W. D. Cotton (in 'The Role of VLBI in Astrophysics, Astrometry, And Geodesy, ed Mantovani & Kus, Kluwer 2004)

A Next Generation Millimeter Telescope

A major step in astronomy → a mm/submm equivalent of VLT, HST, NGST, EVLA

- **Capable of seeing star-forming galaxies across the Universe**
- **Capable of seeing star-forming regions across the Galaxy**

These Objectives Require:

- **An angular resolution of 0.1” at 3 mm**
- **A collecting area of >6,000 sq m**
- **An array of antennas**
- **A site which is high, dry, large, flat - a high Andean plateau is ideal**

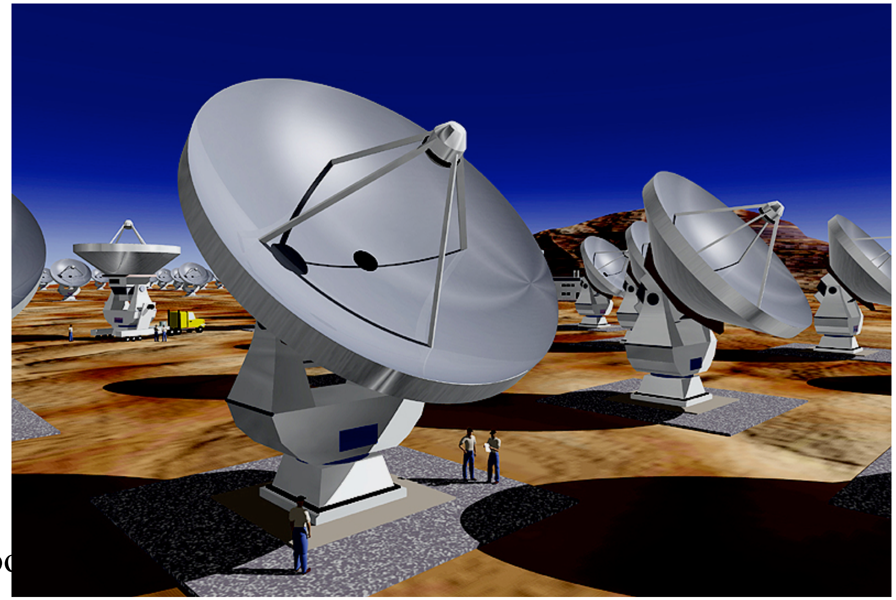
Construction Partners

- ESO for Europe & Spain
- NRAO/AUI for North America
- NINS for Japan (and Taiwan)
- Chile as host country

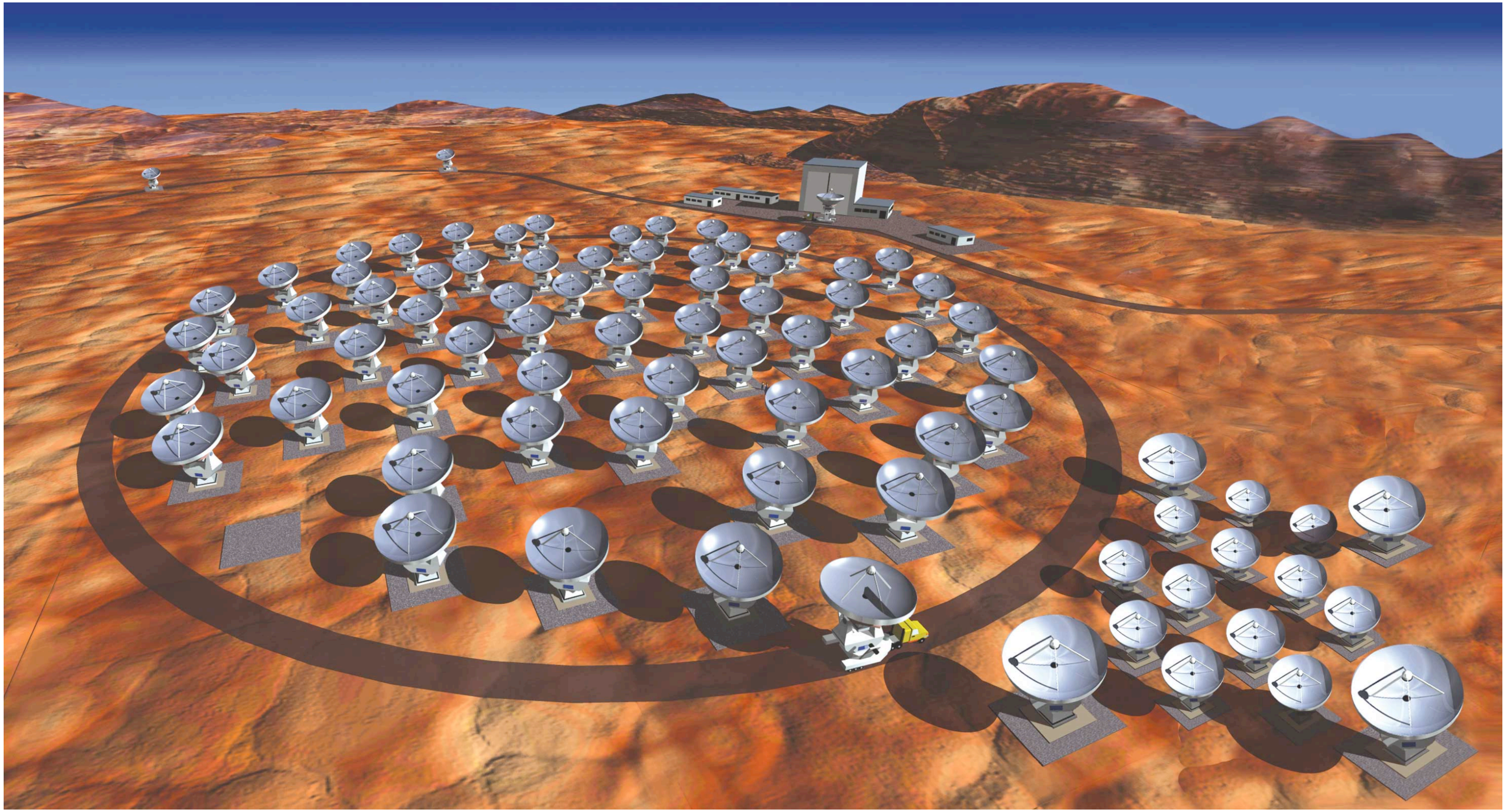
ALMA: The Atacama Large Millimeter Array

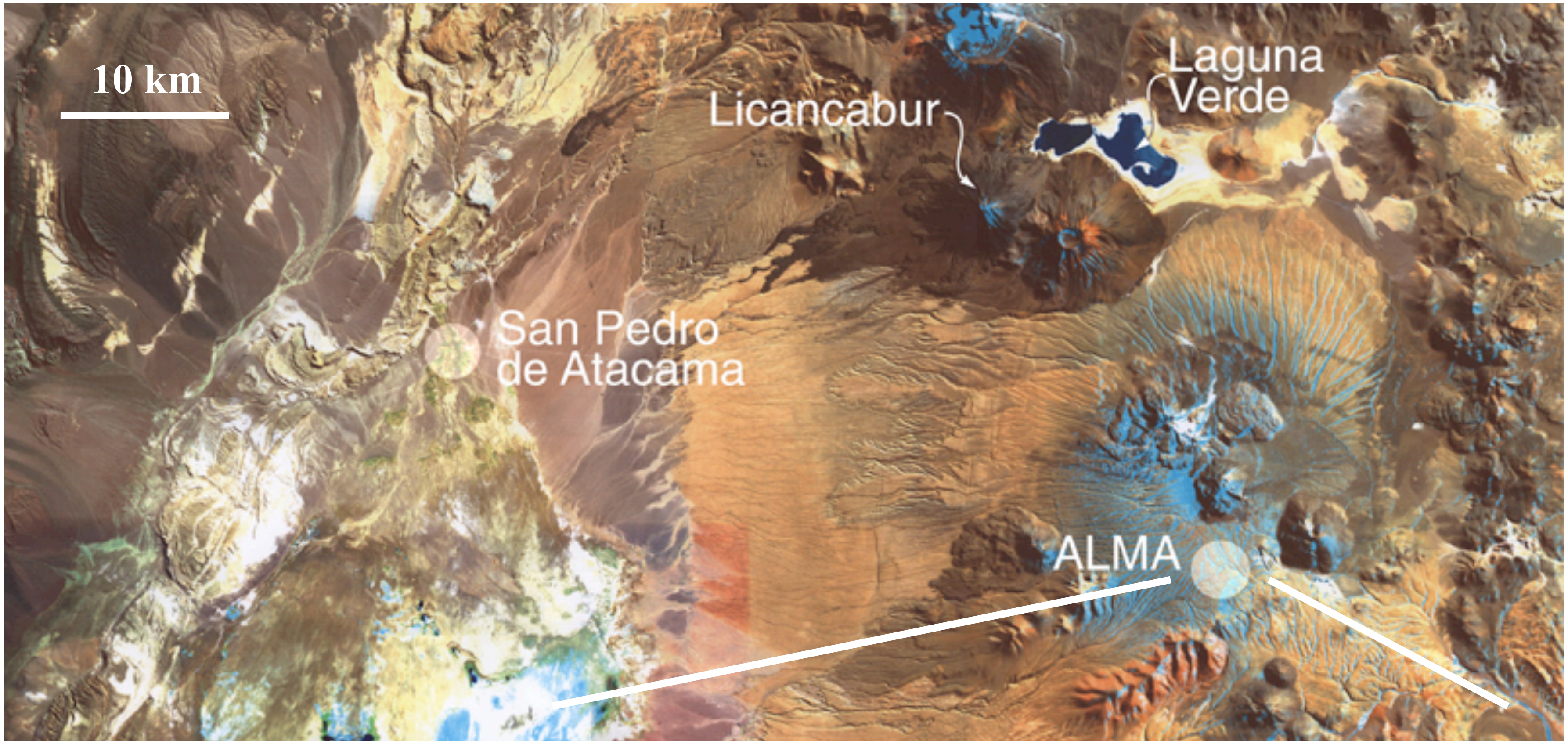
- A mm/submm equivalent of VLT, JWST
- 50 to 64 x 12-meter antennas, surface < 25 μm rms
- Zoom array: 150m → 14.5 kilometers
- Receivers covering wavelengths 0.3 - 10 mm
- Located at Chajnantor (Chile), altitude 5000 m
- Europe and North America sharing the construction cost and operations costs of the bilateral array
- Japan has joined!
- Now a truly global project!

http://www.eso.org/projects/alma/



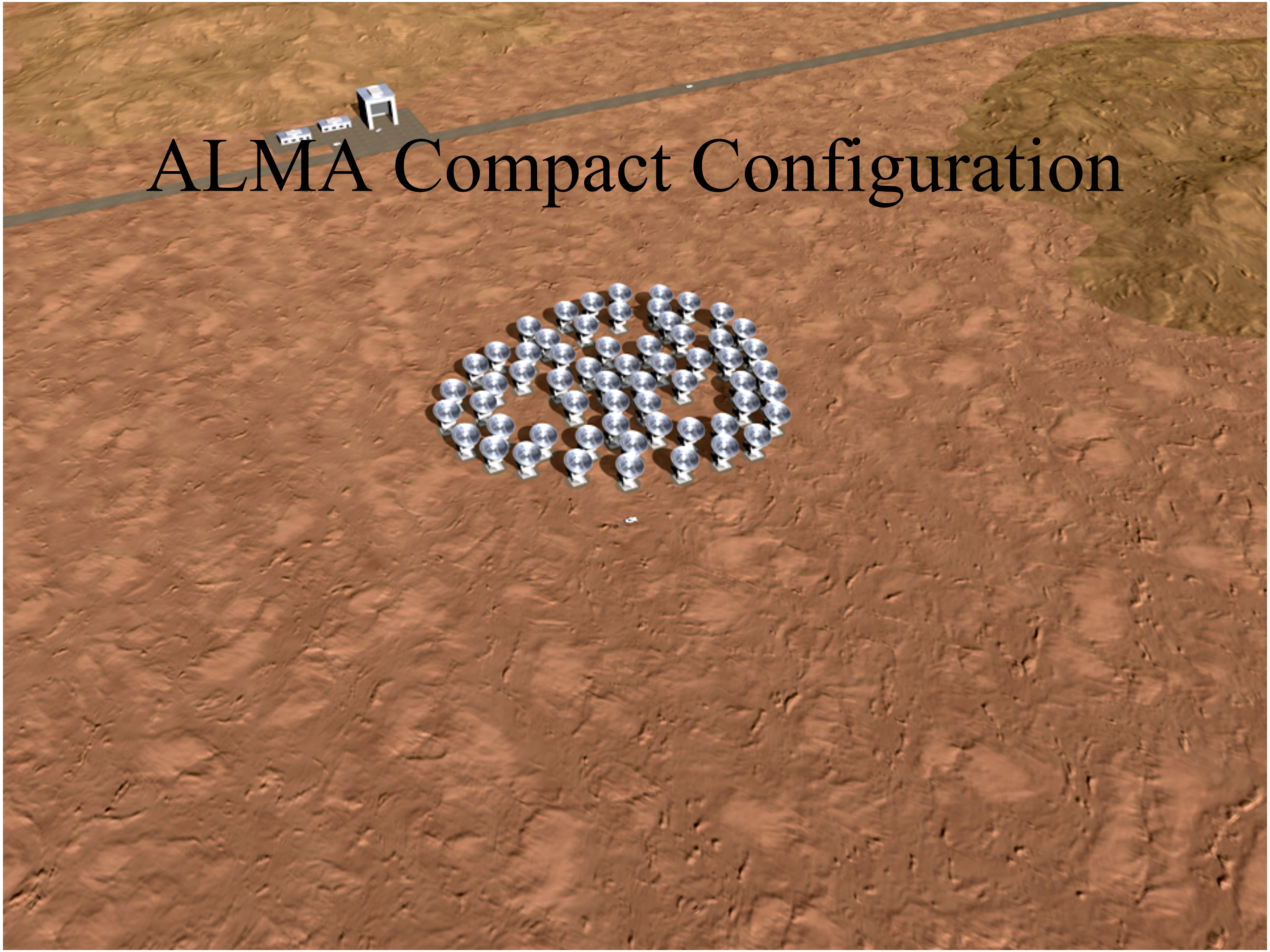
ALMA + ACA



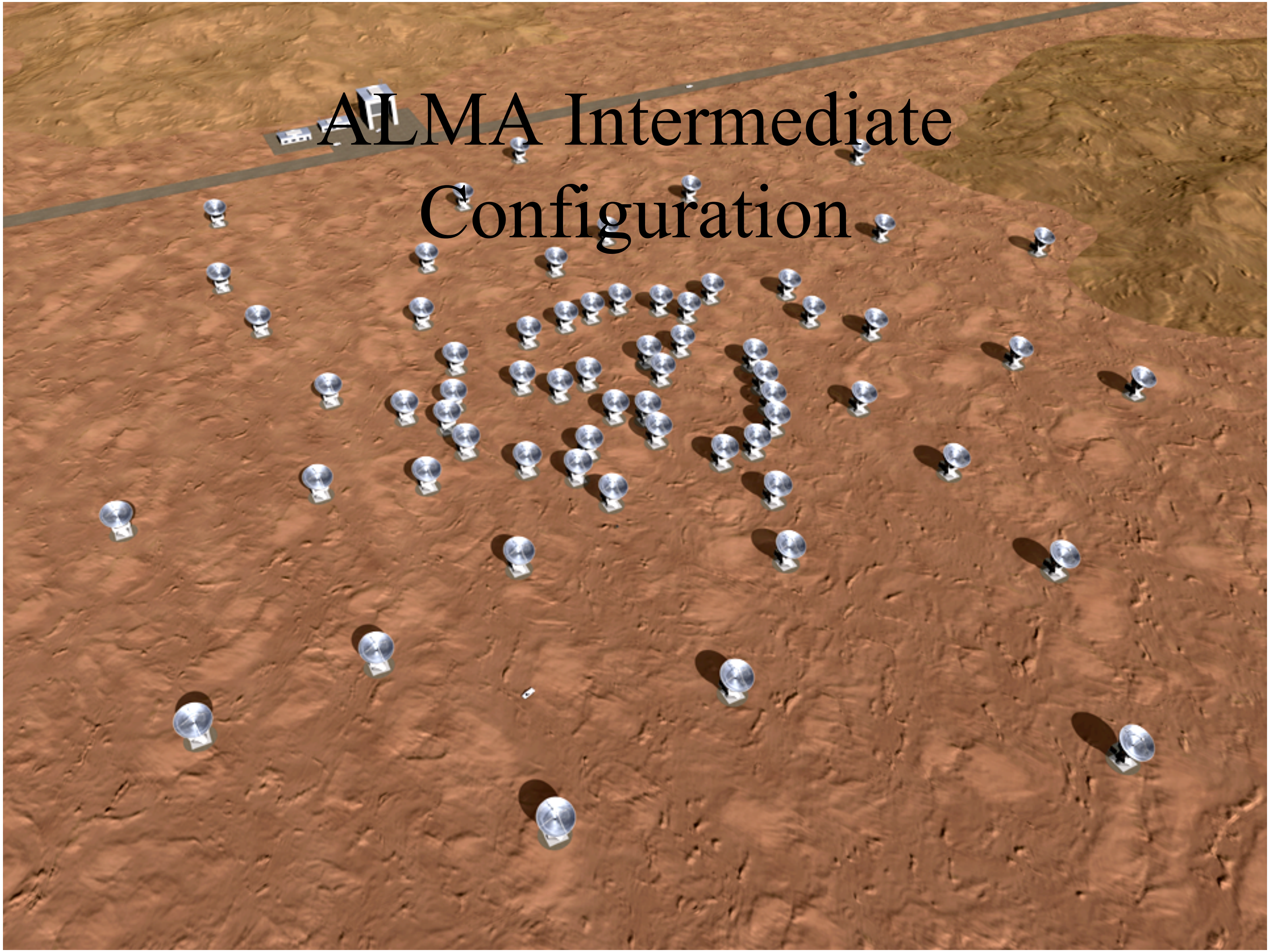

10 km
Laguna
Verde
Licancabur
San Pedro
de Atacama
ALMA


The ALMA site:
Chajnantor, Chile
Altitude 5000m

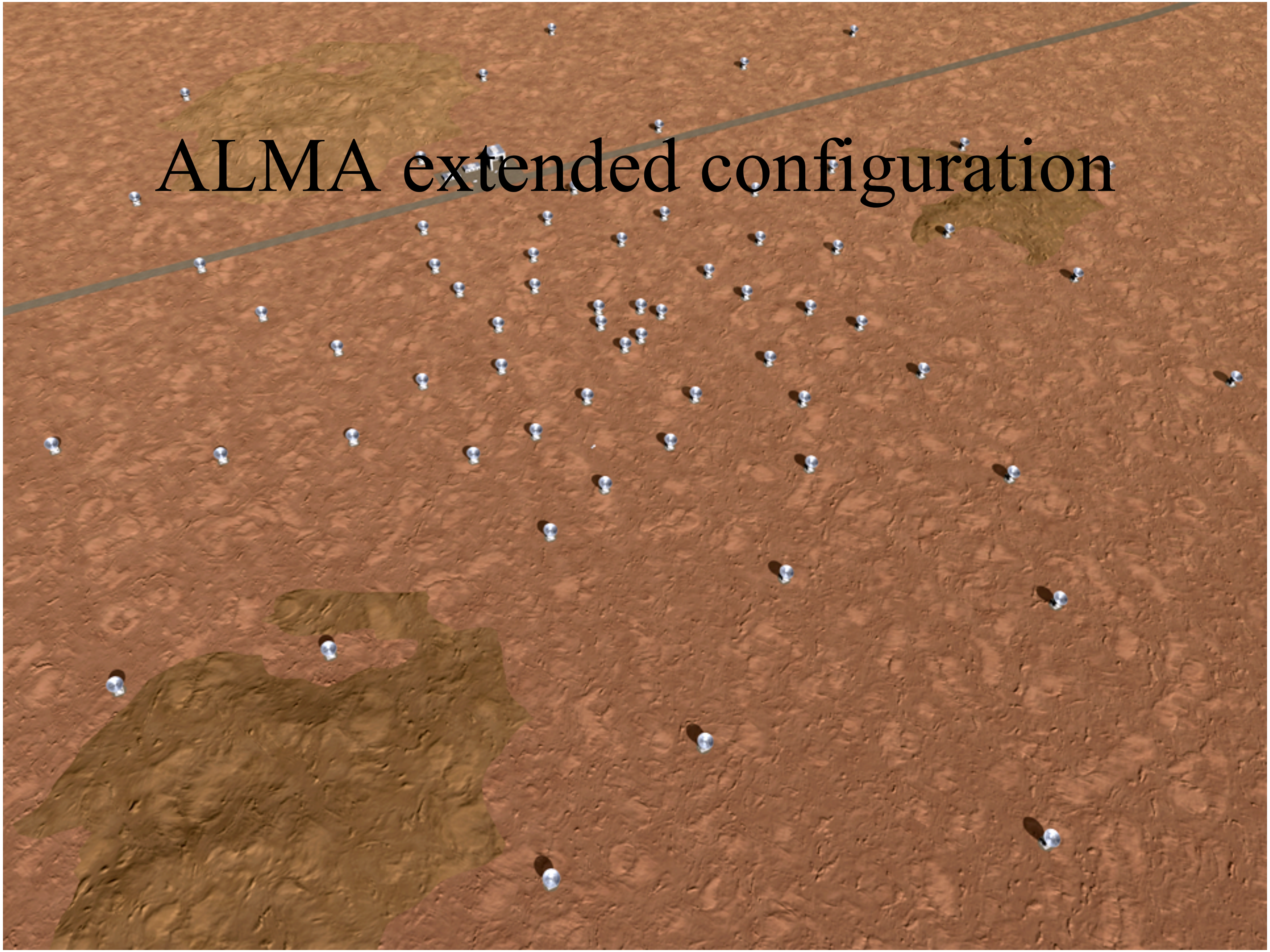
ALMA Compact Configuration



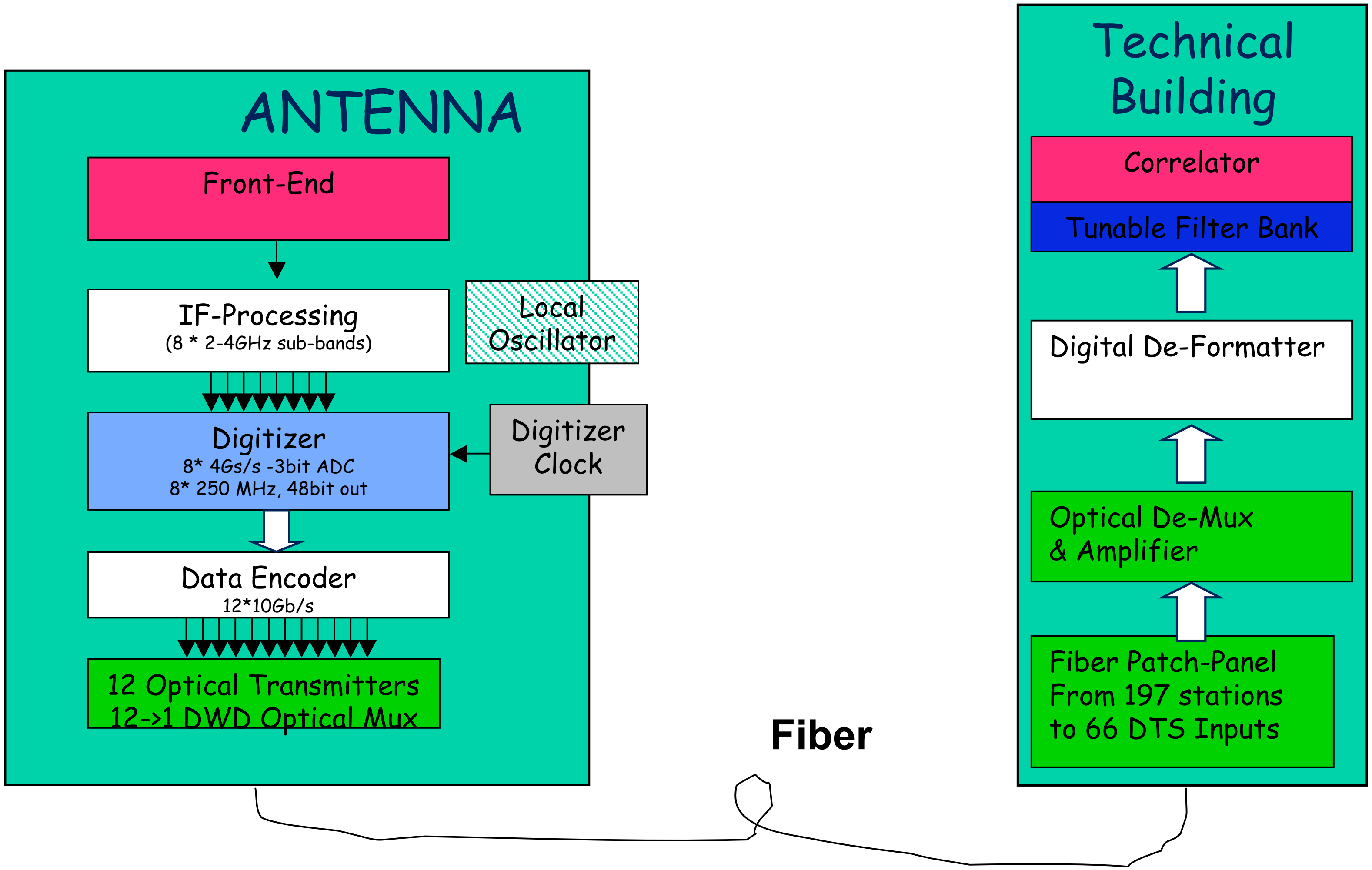
ALMA Intermediate Configuration



ALMA extended configuration

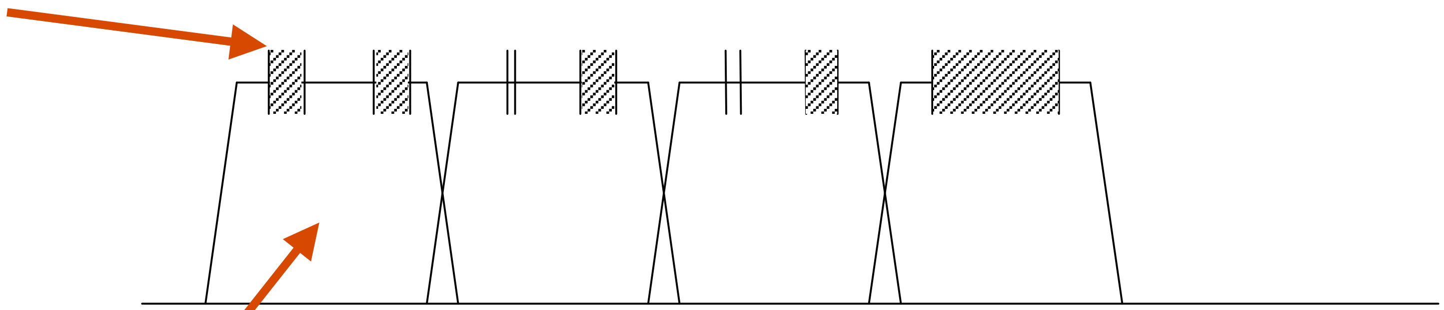


Back End & Correlator



Correlator Set Up: Four IF Bands of 2 GHz Each Can be Analyzed by 32 Filters, 16 in Each Polarization

Region analyzed by a single spectrometer



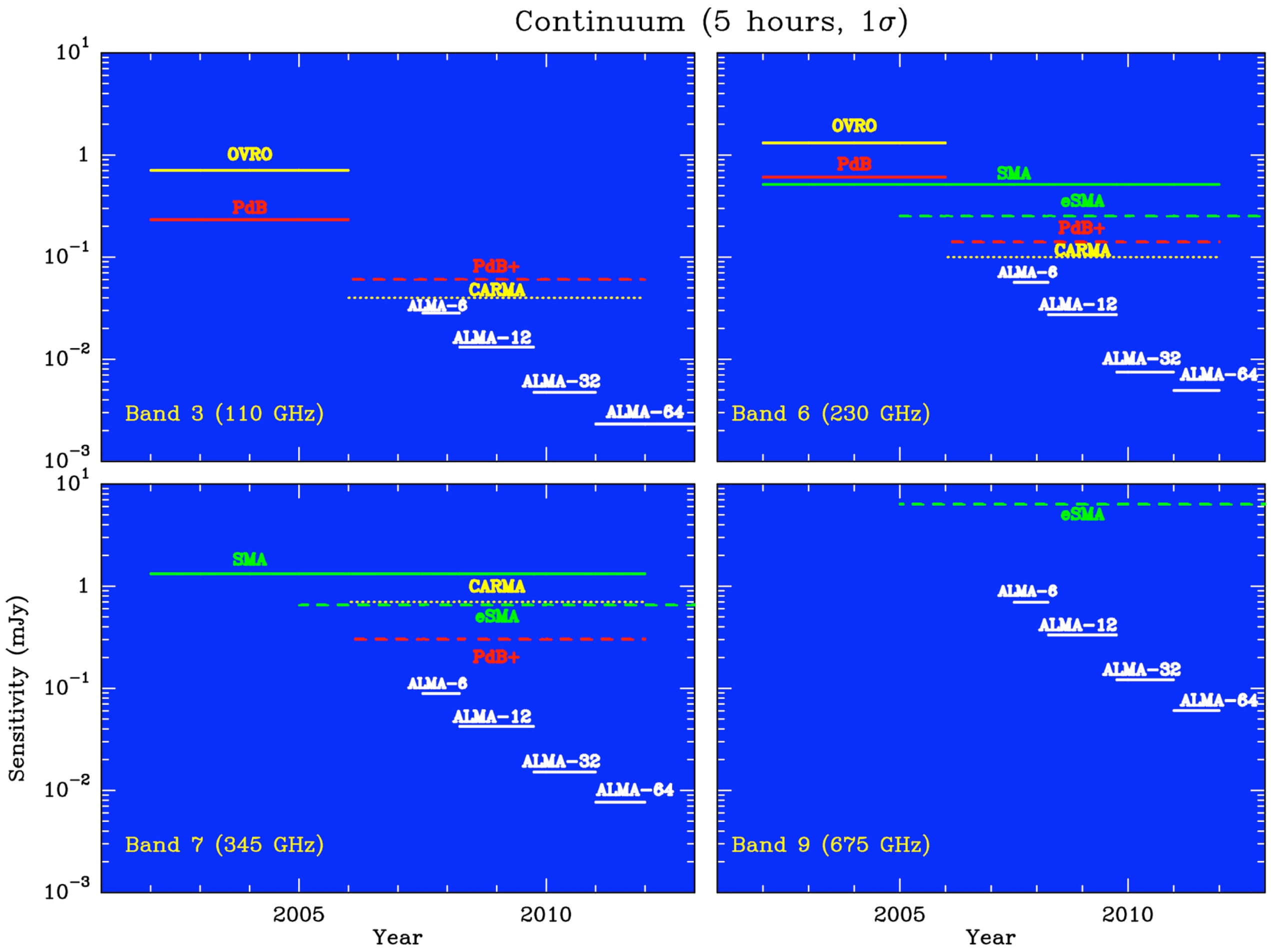
2 GHz wide IF

(we show ½ of the filters)

Spectrometer is a recycling correlator:

# of channels x total bandwidth=(128)x(2 GHz)

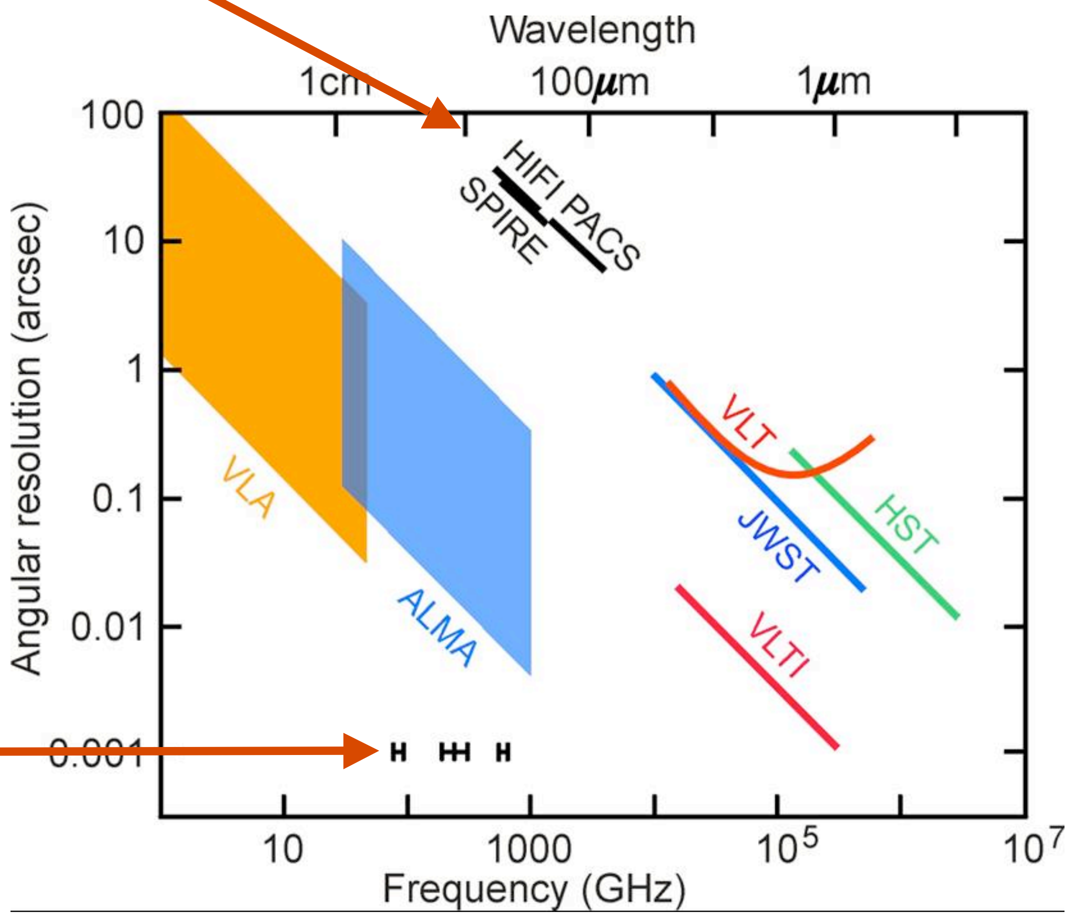
Sensitivity of ALMA



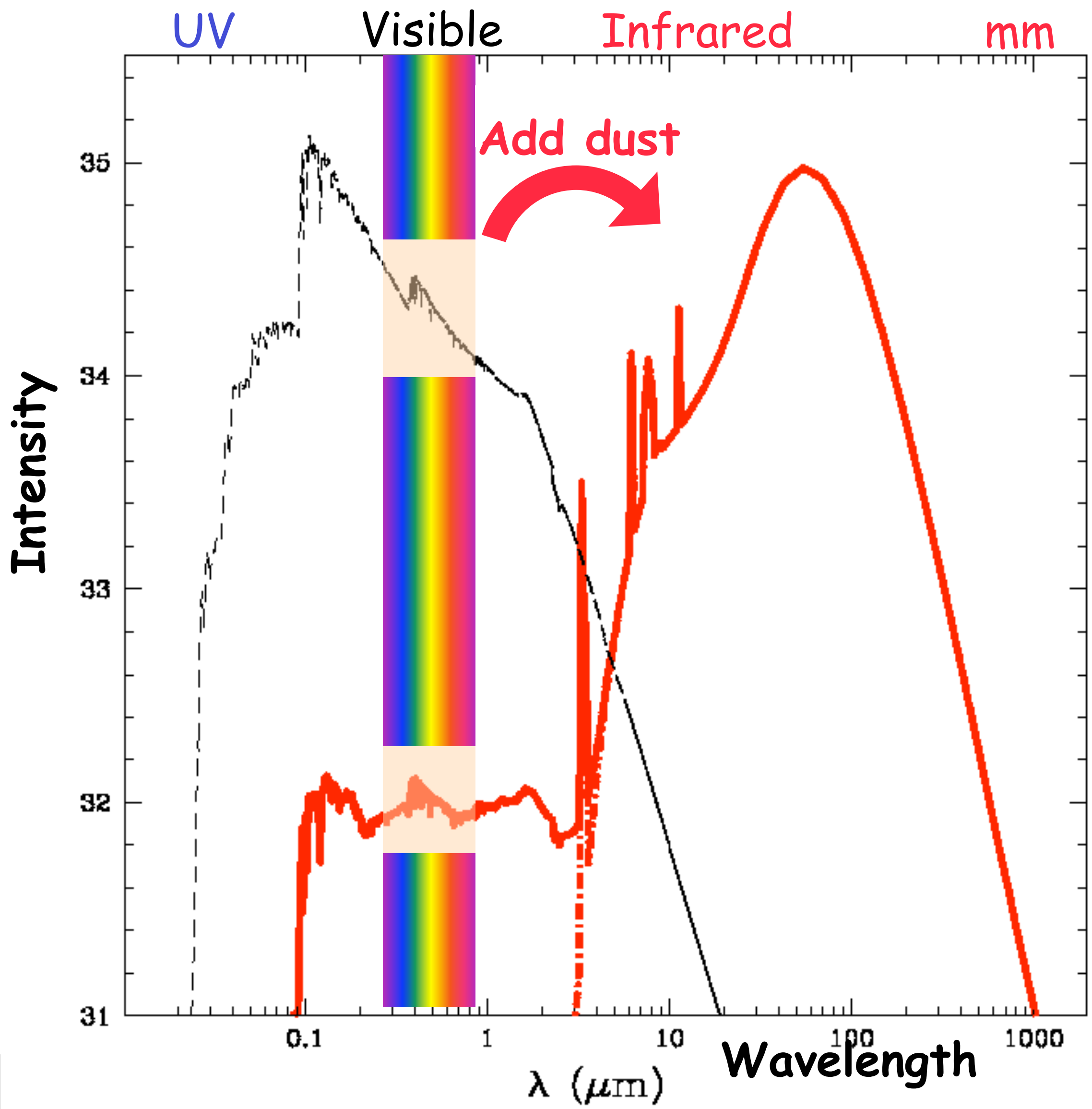
Summary of Requirements

Frequency	30 to 950 GHz (initially 84-720 GHz)
Bandwidth	8 GHz, fully tunable
Spectral resolution	31.5 kHz (0.01 km/s) at 100 GHz
Angular resolution	1.4 to 0.015" at 300 GHz
Dynamic range	10000:1 (spectral); 50000:1 (imaging)
Flux sensitivity	0.2 mJy in 1 min at 345 GHz (median conditions)
Bilateral Antenna Complement	50 to 64 antennas of 12-m diameter
ACA	12 x 7-m & 4 x 12-m diameter antennas
Polarization	All cross products simultaneously

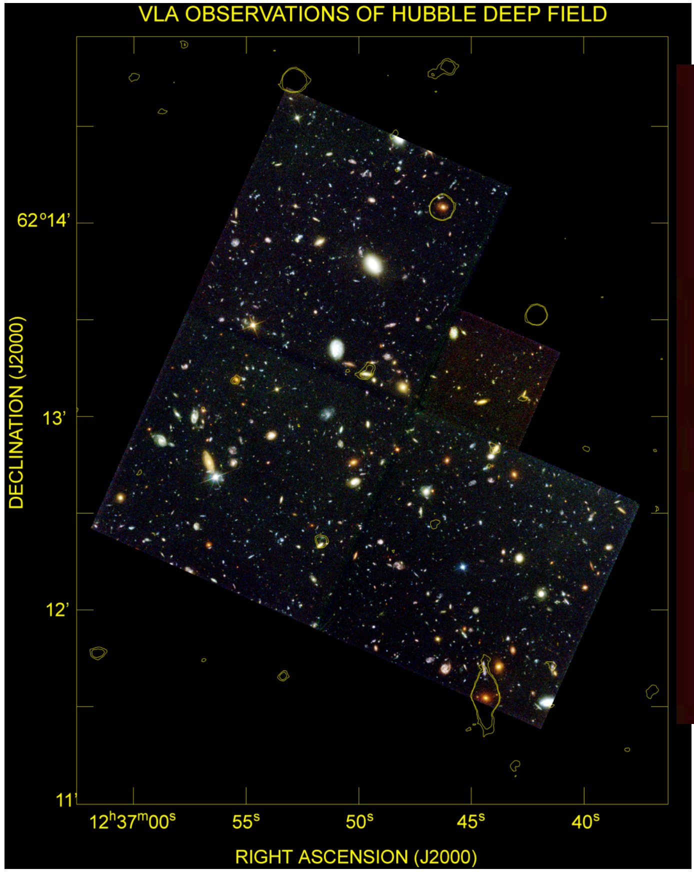
The ALMA FOV is 25” at 1 mm

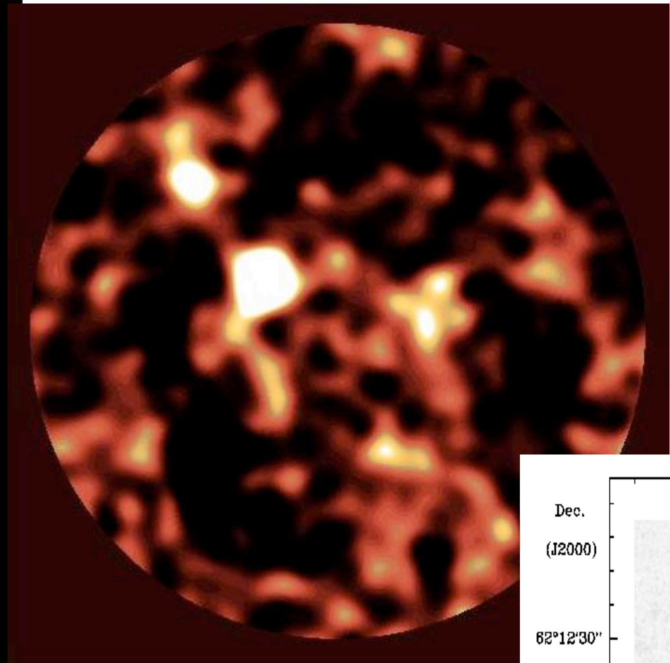


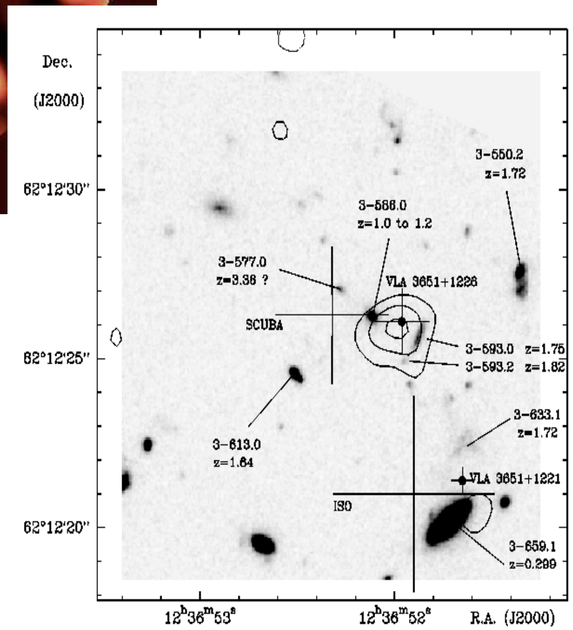
ALMA Receiver Bands (now completely filled!)


UV
Visible
Infrared
mm
Add dust
Intensity
35
34
33
32
31
0.1
1
10
100
1000
λ (μm)
Wavelength

Hubble Deep Field

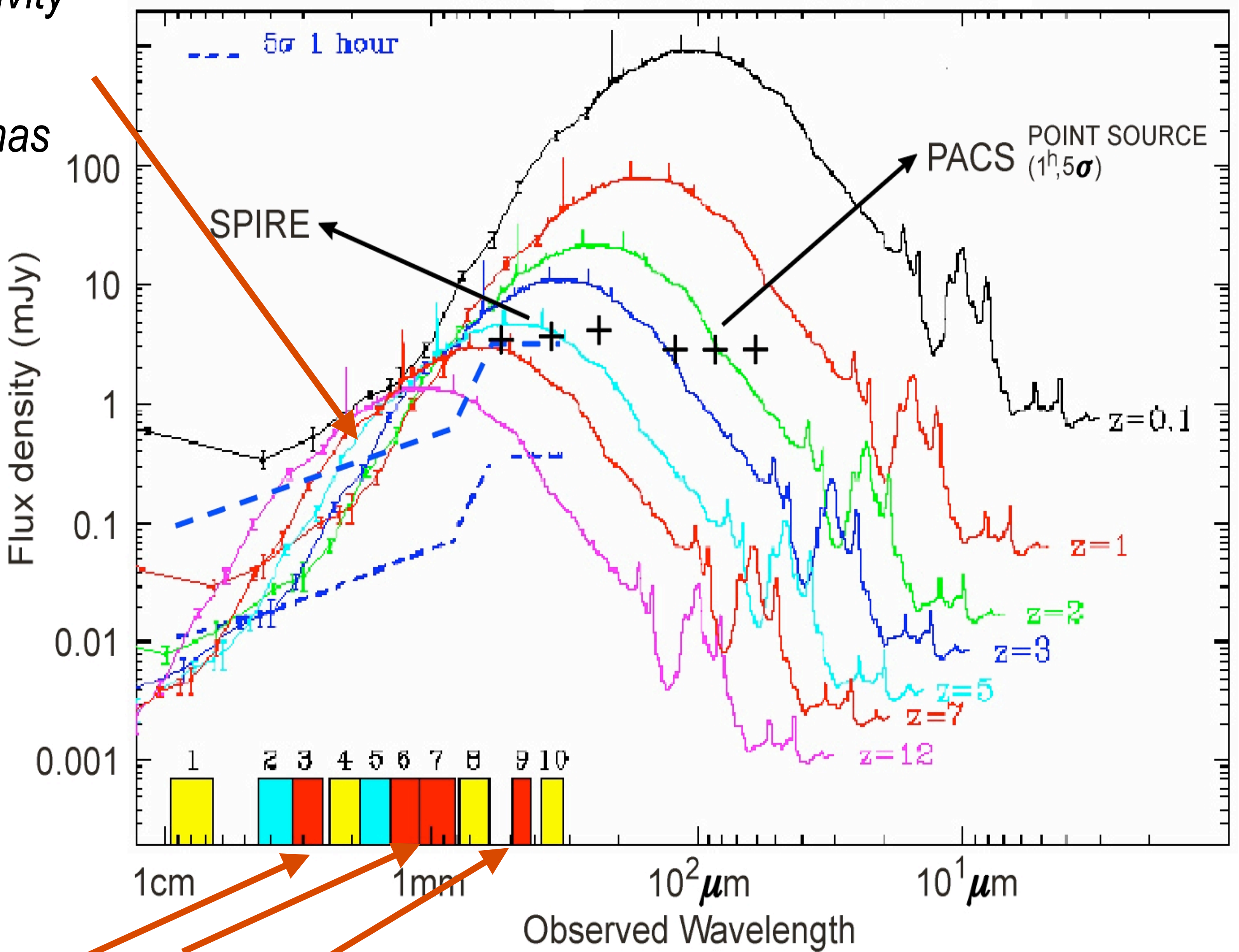






Owing to the redshifts, galaxies which are redshifted *into* ALMA's view *vanish* from view optically. ALMA shows us the distant Universe *preferentially*.

Sensitivity with 6 antennas



Bands 3, 6, 7 and 9 are bilateral, 4, 8, 10 are from Japan

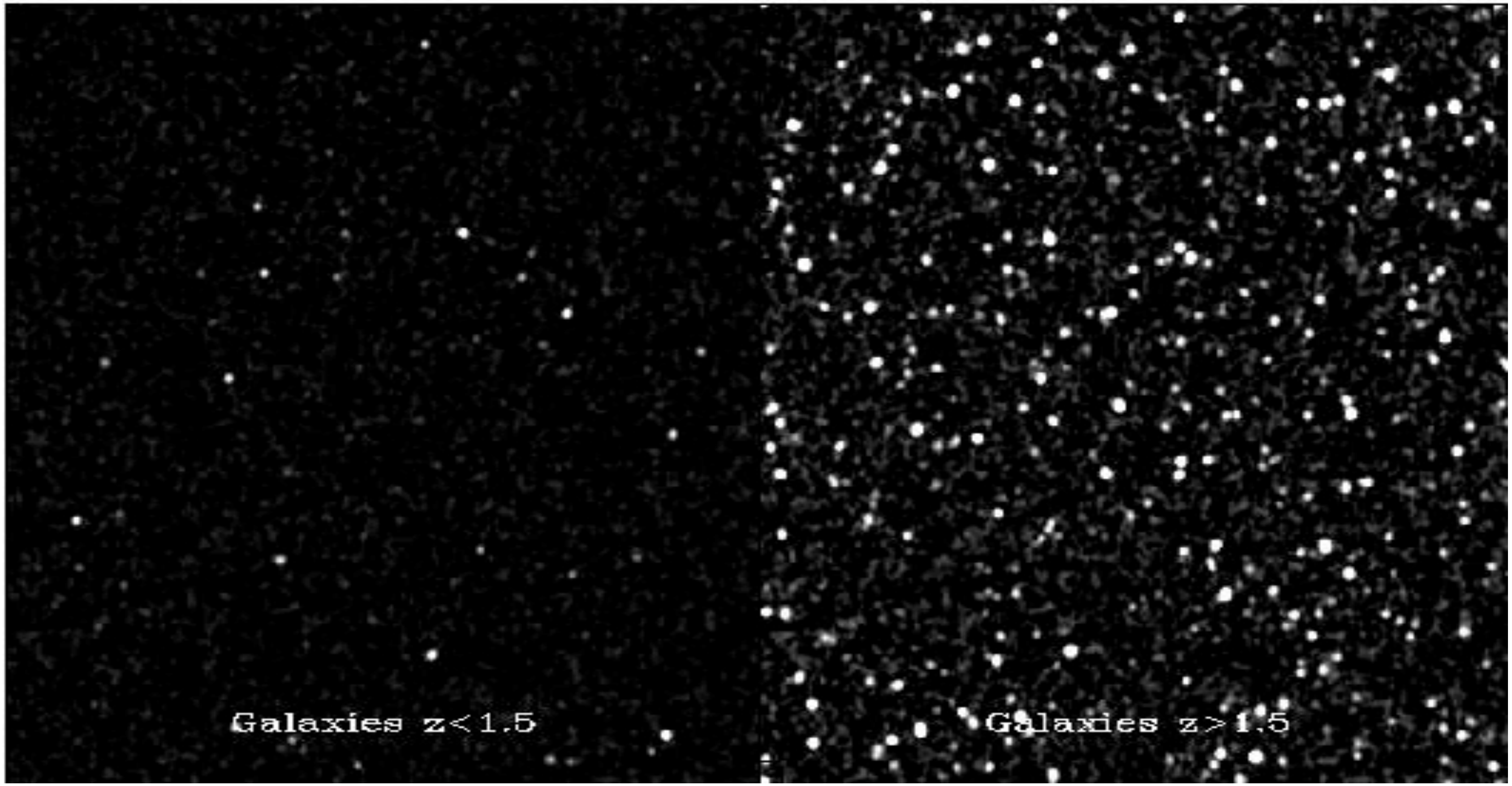
Hubble Deep Field

Rich in Nearby Galaxies, Poor in Distant Galaxies

Nearby galaxies in HDF

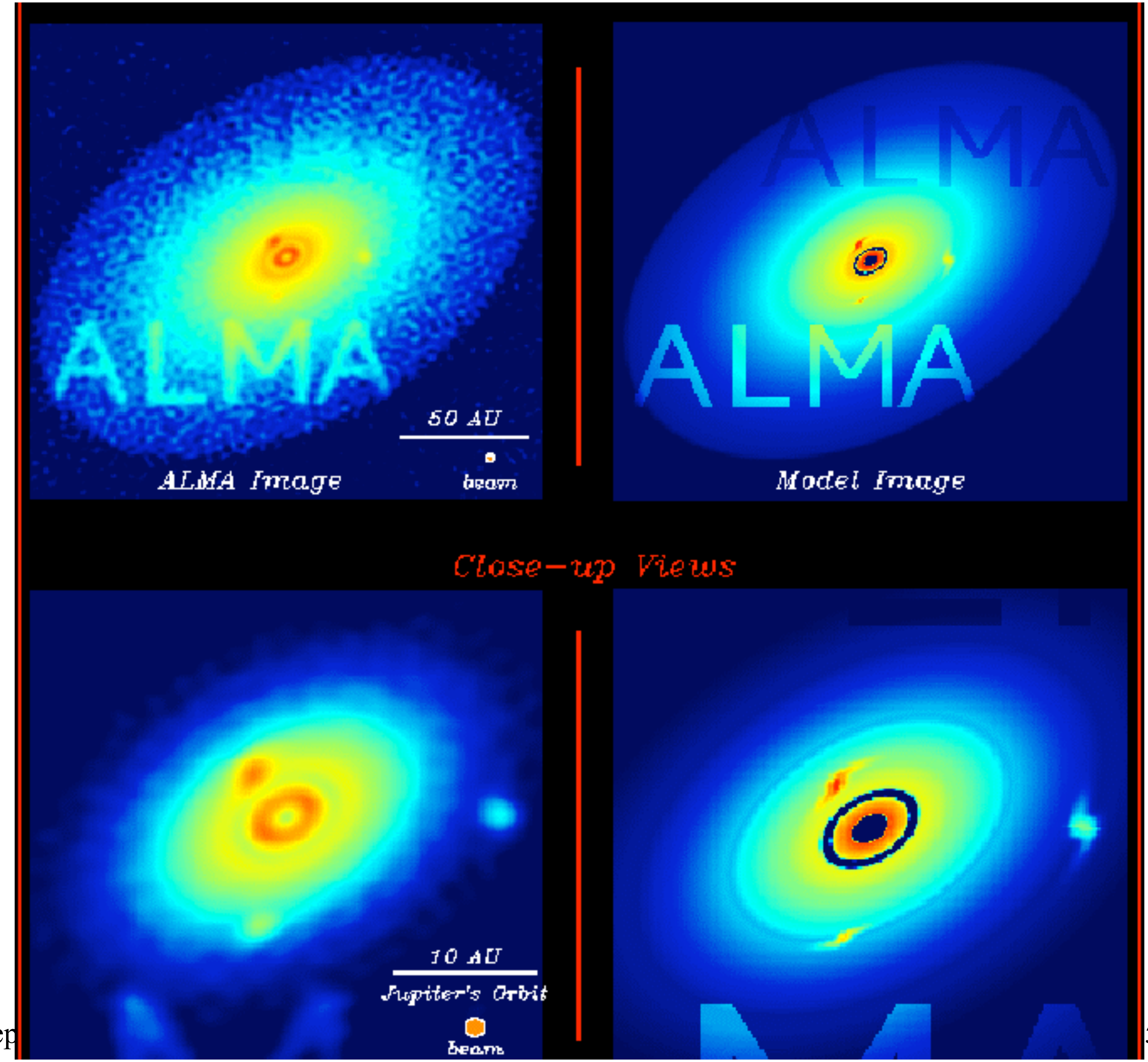
Distant galaxies in HDF

ALMA Deep Field
Poor in Nearby Galaxies, Rich in Distant Galaxies



Nearby galaxies in ALMA Deep Field

Distant galaxies in ALMA Deep Field

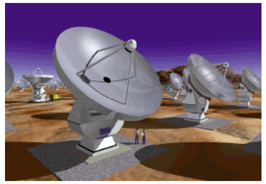


Simulations:
L. Mundy

$M_{planet} / M_{star} = 0.5 M_{Jup} / 1.0\ M_{sun}$

Orbital radius: 5 AU

Disk mass as in the circumstellar disk as around the Butterfly Star in Taurus



Maximum baseline: 10km,

t_{int}=8h,

30deg phase noise

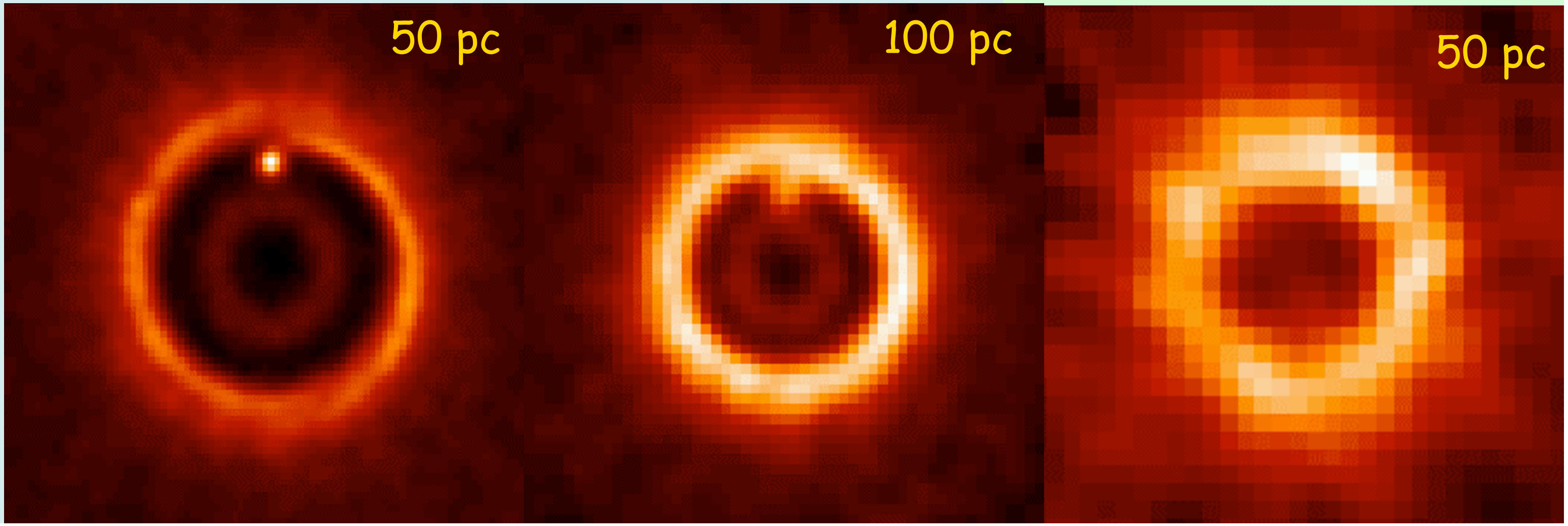
pointing error 0.6"

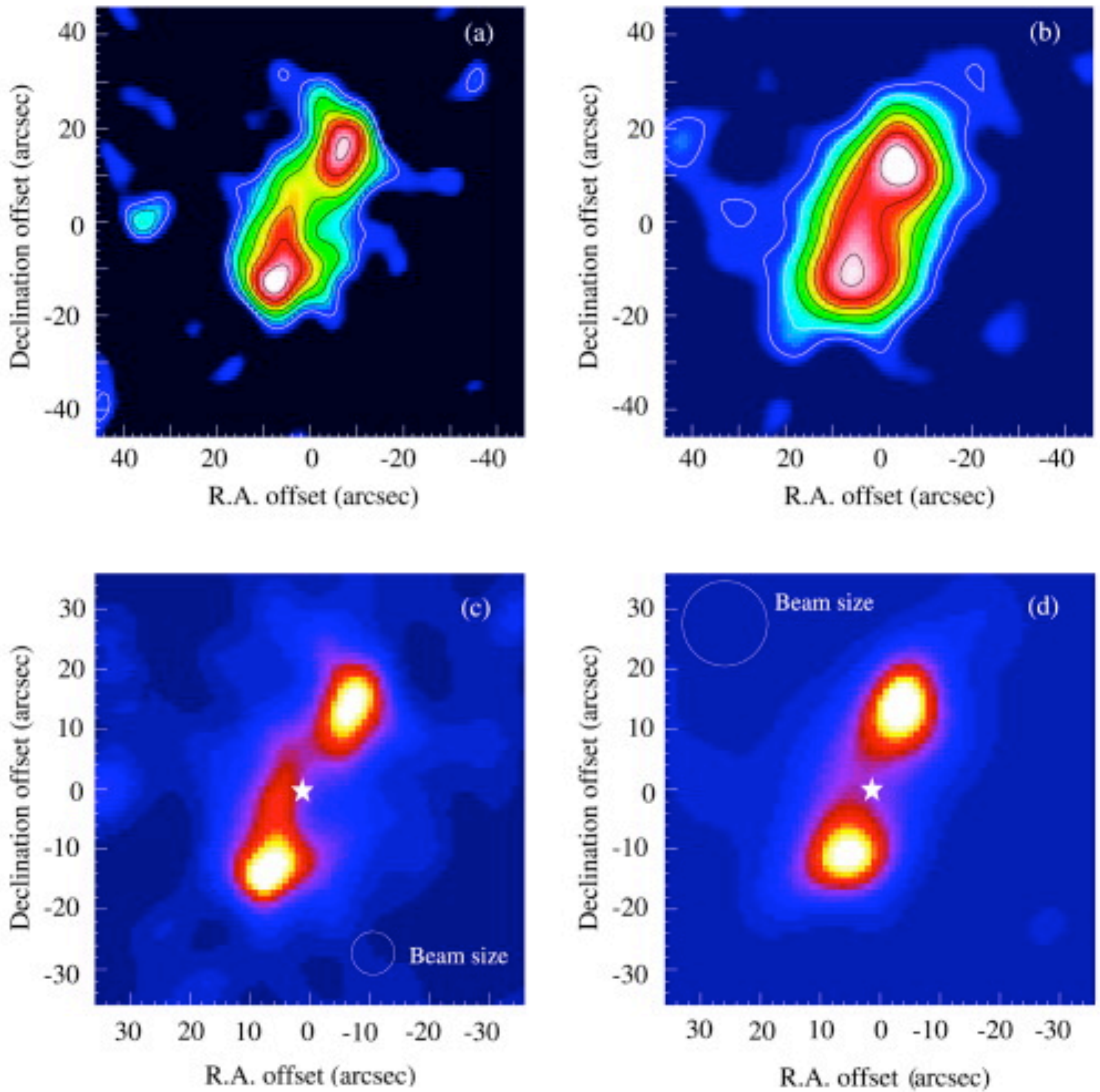
Tsys = 1200K (333μm) / 220K (870μm)

S. Wolf (2005)

λ = 333μm

λ = 870μm

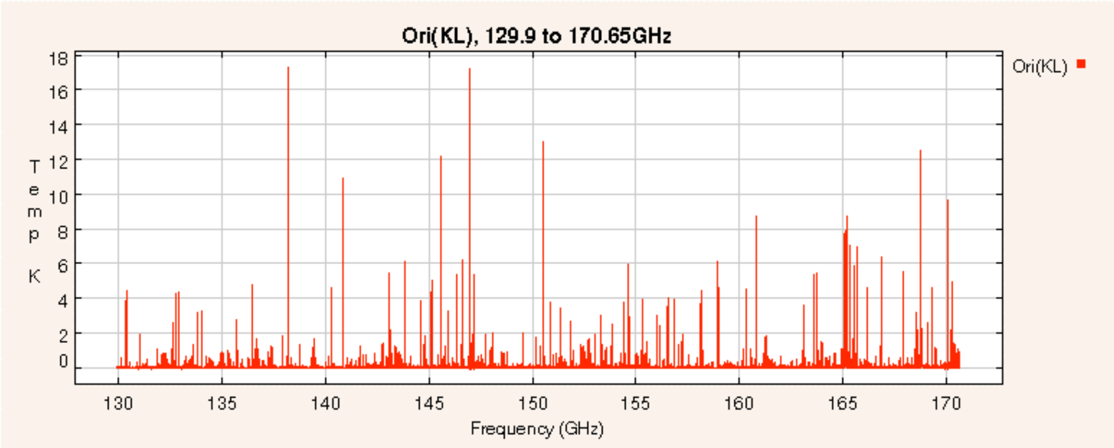


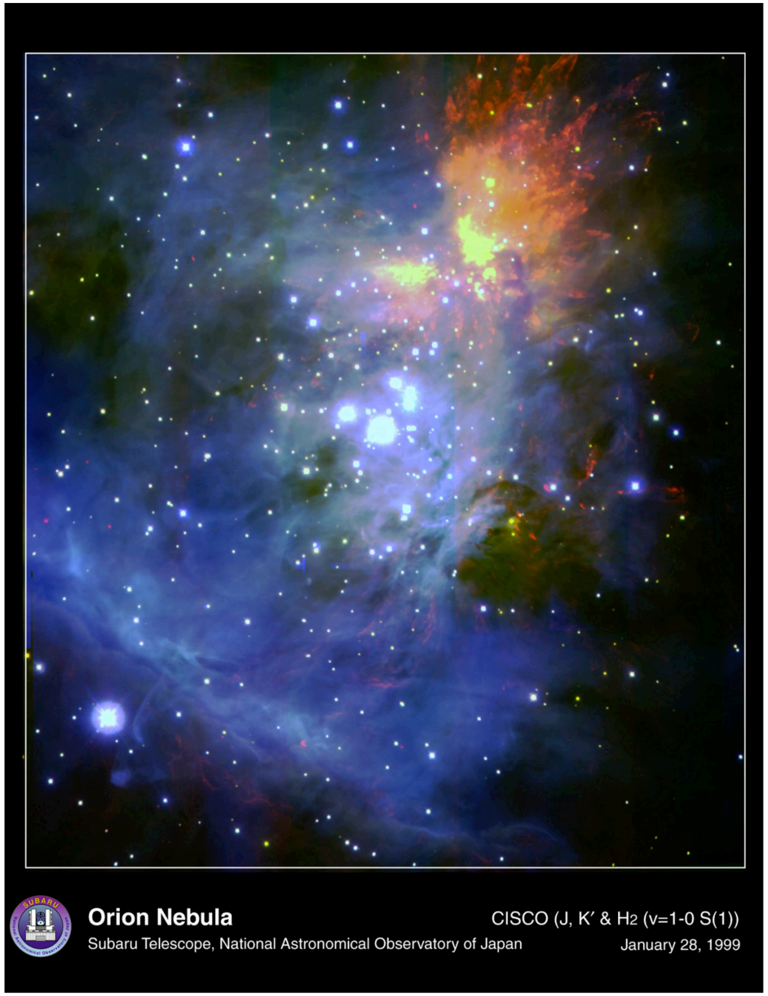


450/850 micrometer images of Fomalhaut. The contours are 13 and 2 mJy/beam. Below are deconvolved images (data from JCMT and SCUBA)

Contributors to the Millimeter Spectrum

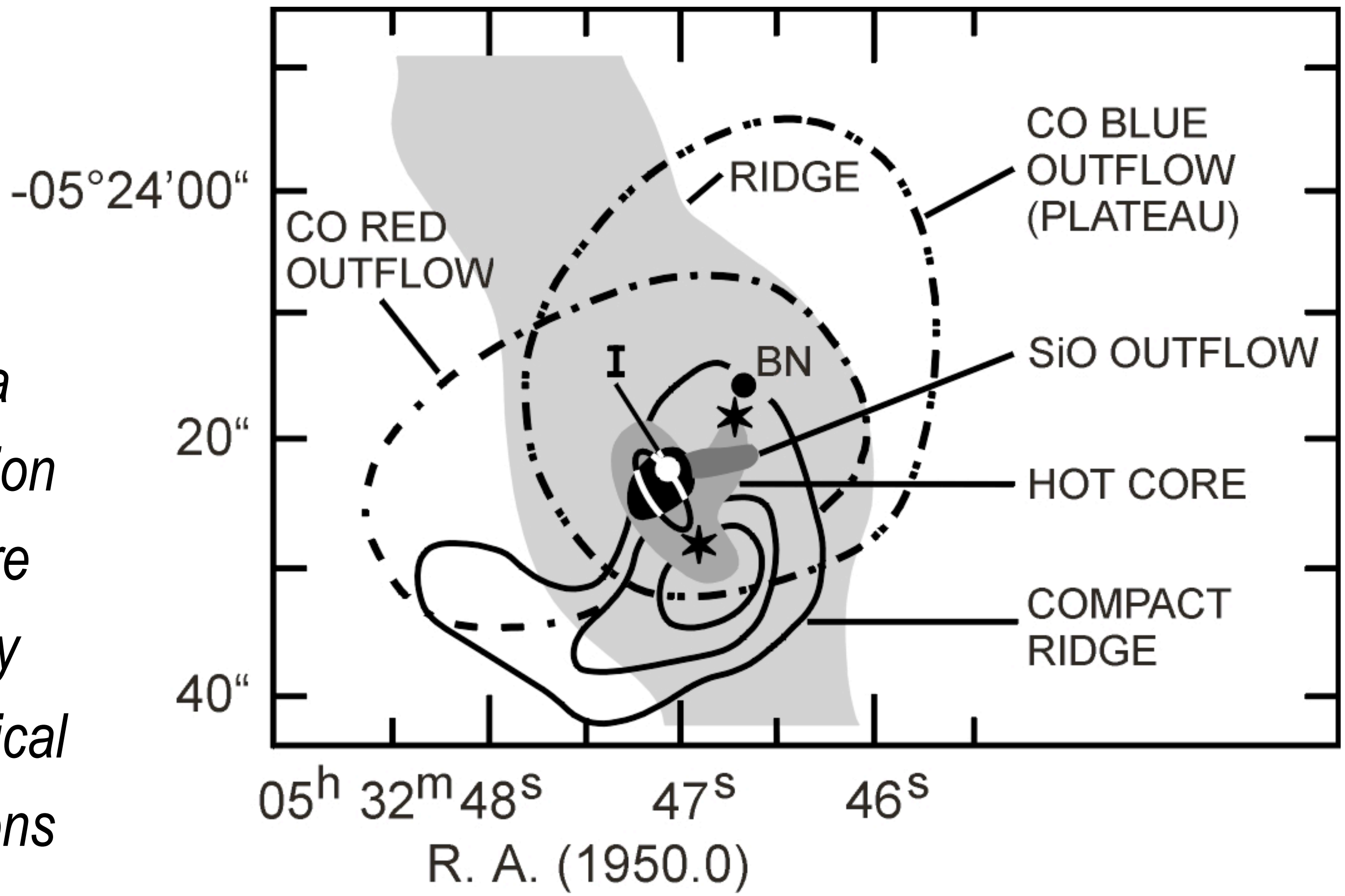
Spectrum courtesy B. Turner (NRAO)





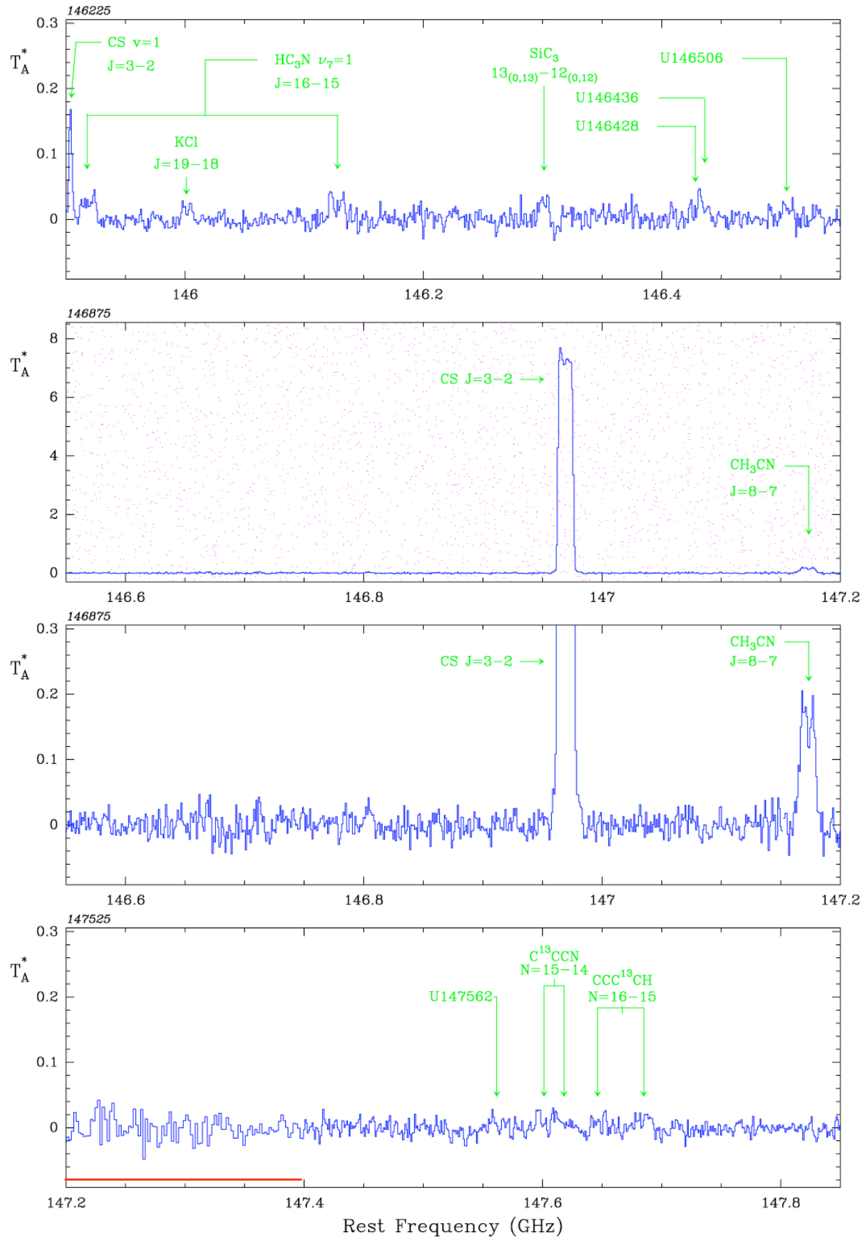
- In addition to dominating the spectrum of the distant Universe, millimeter/submillimeter spectral components dominate the spectrum of planets, young stars, many distant galaxies.
- Cool objects tend to be extended, hence ALMA's mandate to image with high sensitivity, recovering all of an object's emitted flux at the frequency of interest.
- Most of the observed transitions of the 125 known interstellar molecules lie in the mm/submm spectral region—here some 17,000 lines are seen in a small portion of the spectrum at 2mm.
- However, molecules in the Earth's atmosphere inhibit our study of many of these molecules. Furthermore, the long wavelength requires large aperture for high resolution, unachievable from space. To explore the submillimeter spectrum, a telescope should be placed at Earth's highest dryest site.

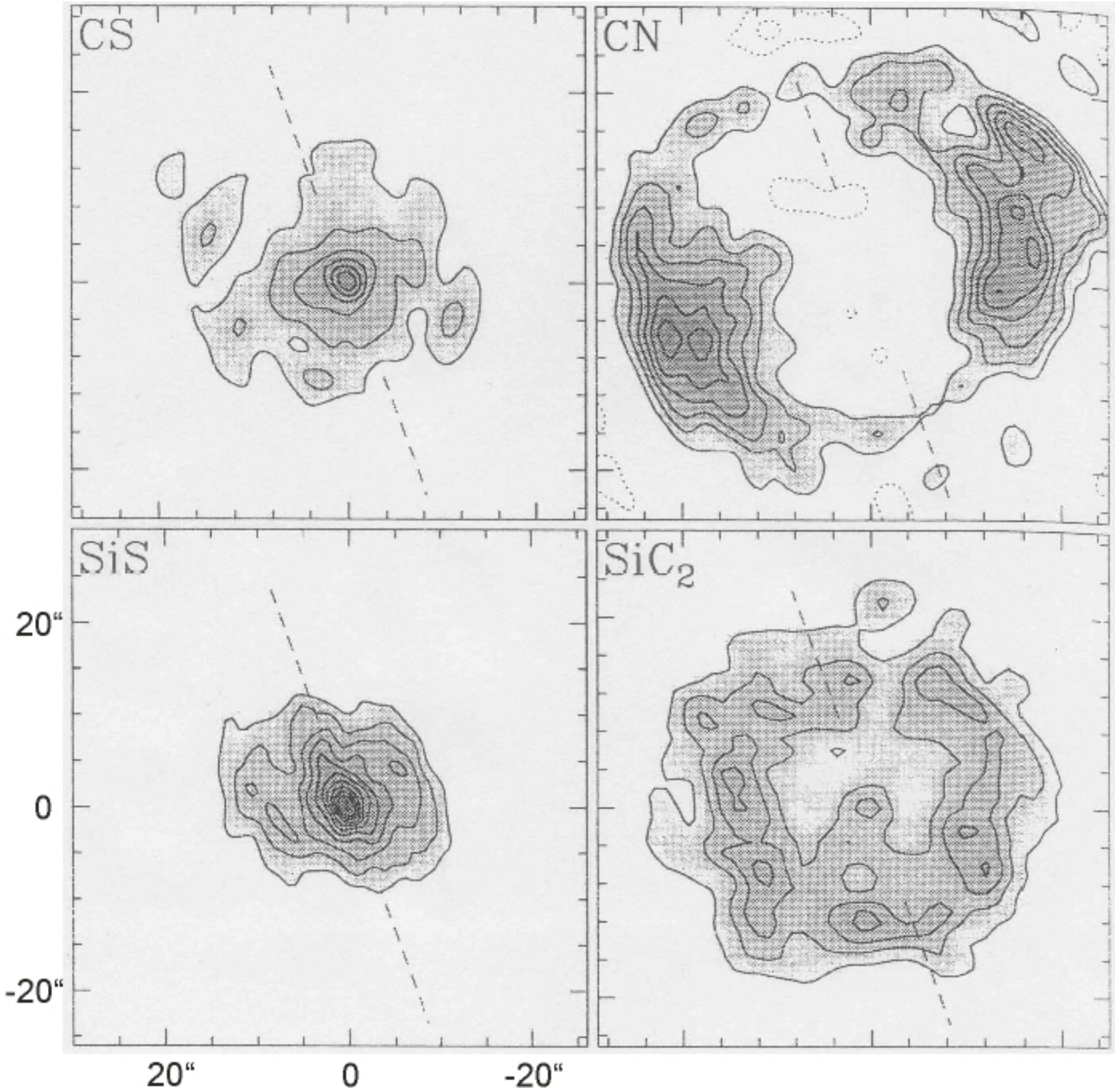
Orion KL: The Classical Hot Core Source



Within a 20" region there are a variety of physical conditions

Sample spectra from IRC+10216 (R Leo), a nearby carbon star





Images of some molecules in IRC10216, a nearby carbon star

Solar System Objects

- Herschel can easily measure outer planets, and moons of these planets, as well as Trans Neptune Objects
  - Highly accurate photometry
  - Water on the giant planets and comets
  - Follow up would be HDO, to determine D/H ratio
- ALMA and Herschel might be used to measure a common source at a common wavelength to set up a system of amplitude calibrators
  - ALMA provides high resolution image, but also records the total flux density