Radio Interferometry and ALMA

T. L. Wilson

ESO

PLAN

- Basics of radio astronomy, especially interferometry
- ALMA technical details
- ALMA Science
  - More details in Interferometry Schools such as the one at IRAM Grenoble at end October

Some Facts

Rayleigh-Jeans:
(hν << kT)

$$I = \frac{2kT}{\lambda^2} = \frac{2kT_{MB}}{\lambda^2}$$

$$S_\nu = \int I_\nu d\Omega = \frac{2kT_{MB}}{\lambda^2} \cdot \Delta\Omega$$

In Janskys,
i.e.
10^{-26} Wm^{-2} Hz^{-1}

$$S_\nu = 2.65 \frac{T_{MB} \cdot \left[\theta_0(')\right]^2}{\left[\lambda(cm)\right]^2} = 2.65 \frac{T_{MB} \cdot \theta_0{}^2(')}{\lambda^2{}_{cm}}$$

Input power is about 10^{-17} watts

And, of course, $\theta = \lambda/D$

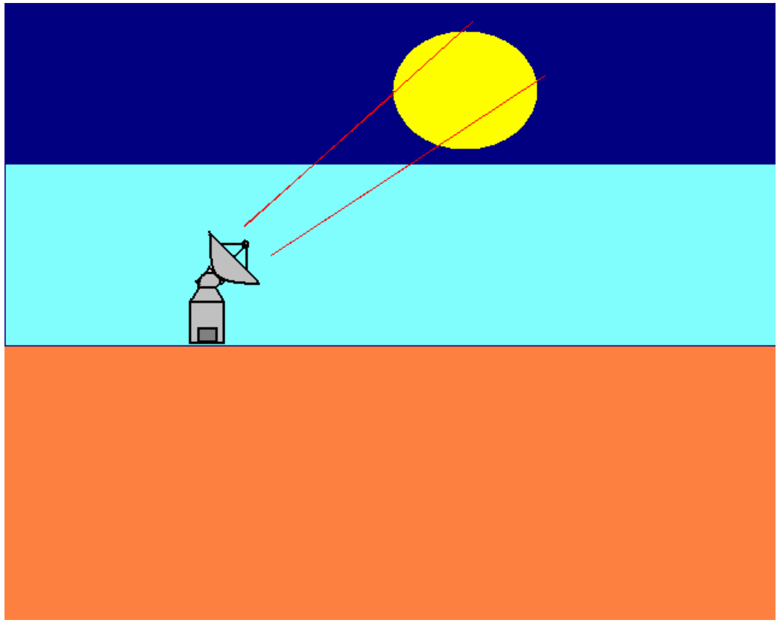
More Definitions

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

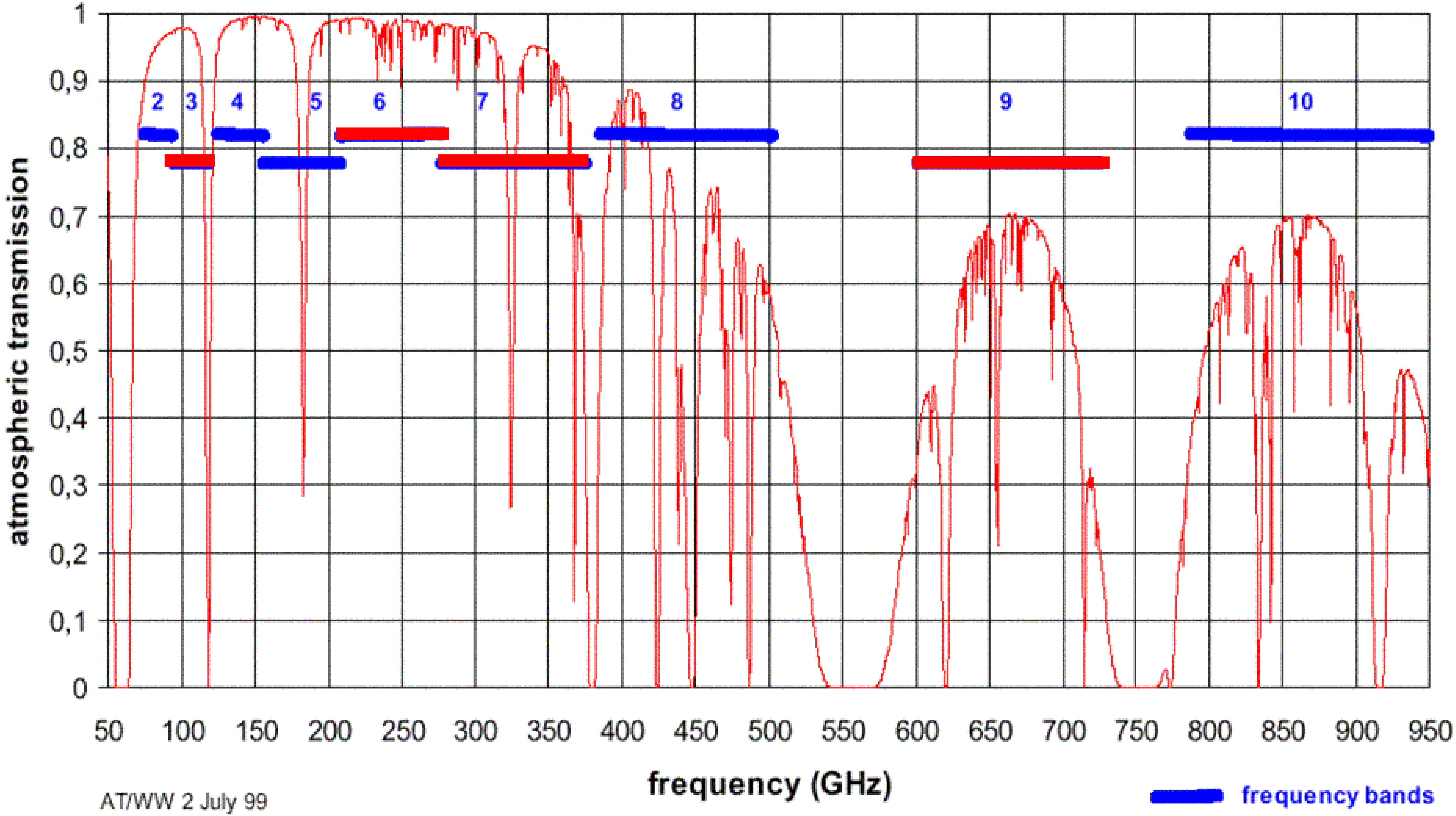
$$T_{\mathbf{sys}} = (T_{\mathbf{rx}} + T_{\mathbf{atm}}(1-e^{-\tau}))\, e^{\tau}$$

[a good T_{rx} *at 3 mm is 40K]*

1 magnitude=4db
$(I=10^{0.1[db]})$



Atmospheric transmission at Chajnantor, pwv = 0.5 mm



AT/WW 2 July 99

Noise in a Receiver

$$\Delta T_{RMS} = \frac{T_{SYS}}{\sqrt{\Delta \nu \cdot \tau}}$$

Receiver itself,
atmosphere,
ground
and source

time

Analyzing bandwidth (for lines, need 3 resolution elements on the line above the ½ power point)

Temperatures from thermal hot and cold load measurements using the receiver.

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:

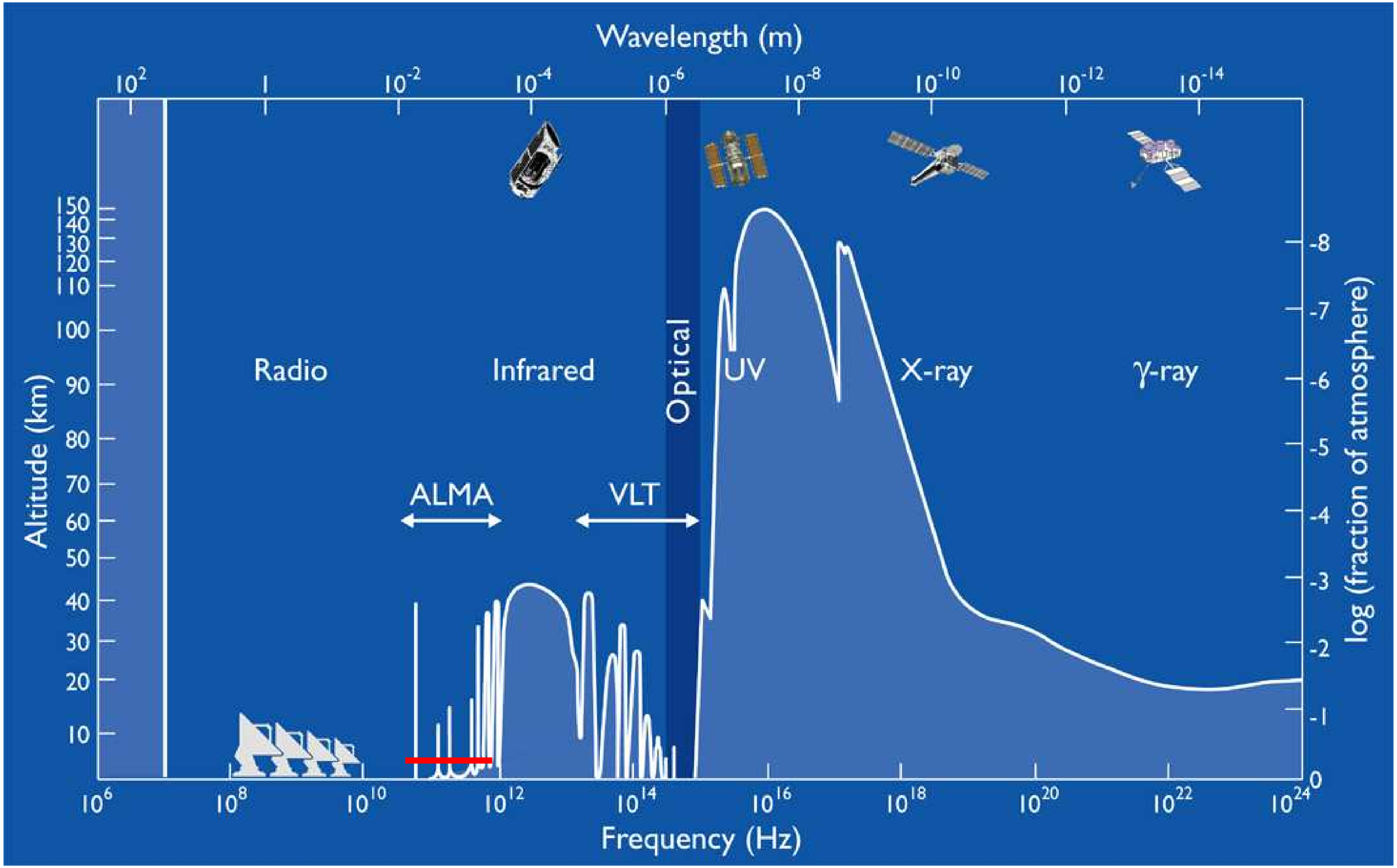
$$S(\mathrm{mJy})=73.6\ T(\mathrm{K})\ \ \theta^2\ ('')/\ \lambda^2(\mathrm{mm})$$

Minimum theoretical noise for heterodyne receivers:

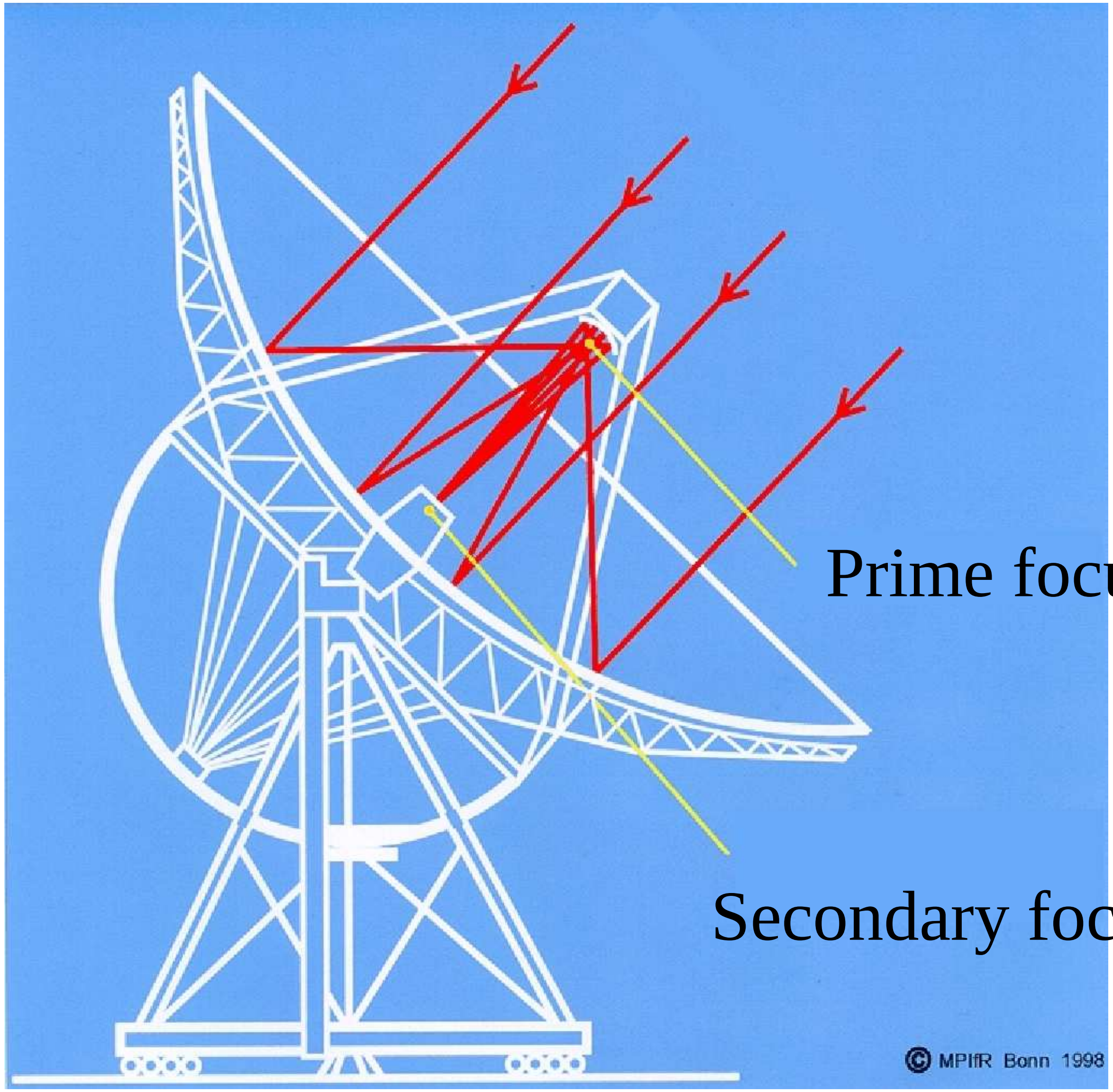
$$T_{rx}=h\nu/k=5.5(\nu\ /115\ \mathrm{GHz})$$

Sensitivity calculator:
http://www.eso.org/sci/facilities/alma/observing/tools/etc/index.html

Opacity of the Atmosphere

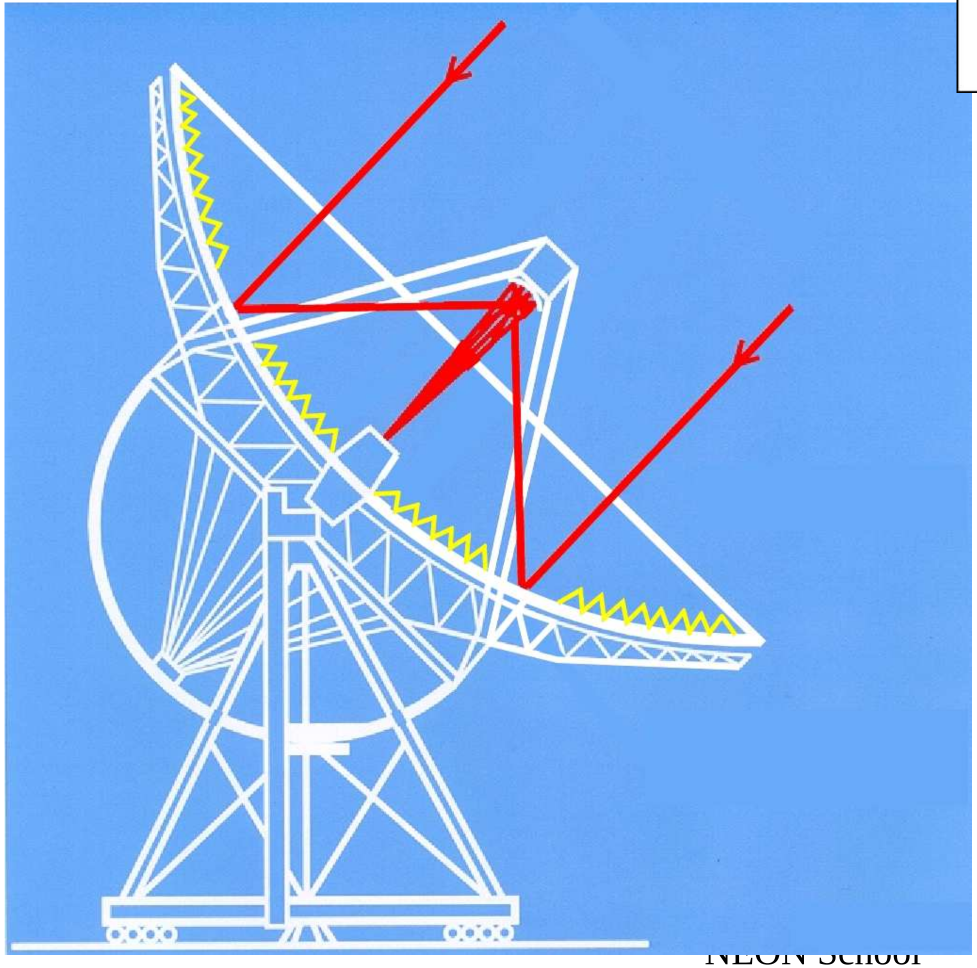


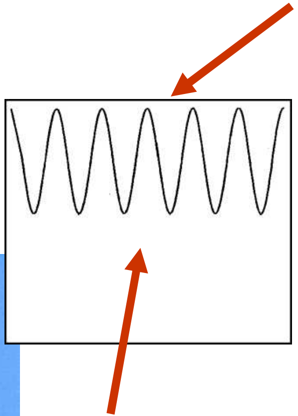
A parabolic radio telescope



Prime focus

Secondary focus

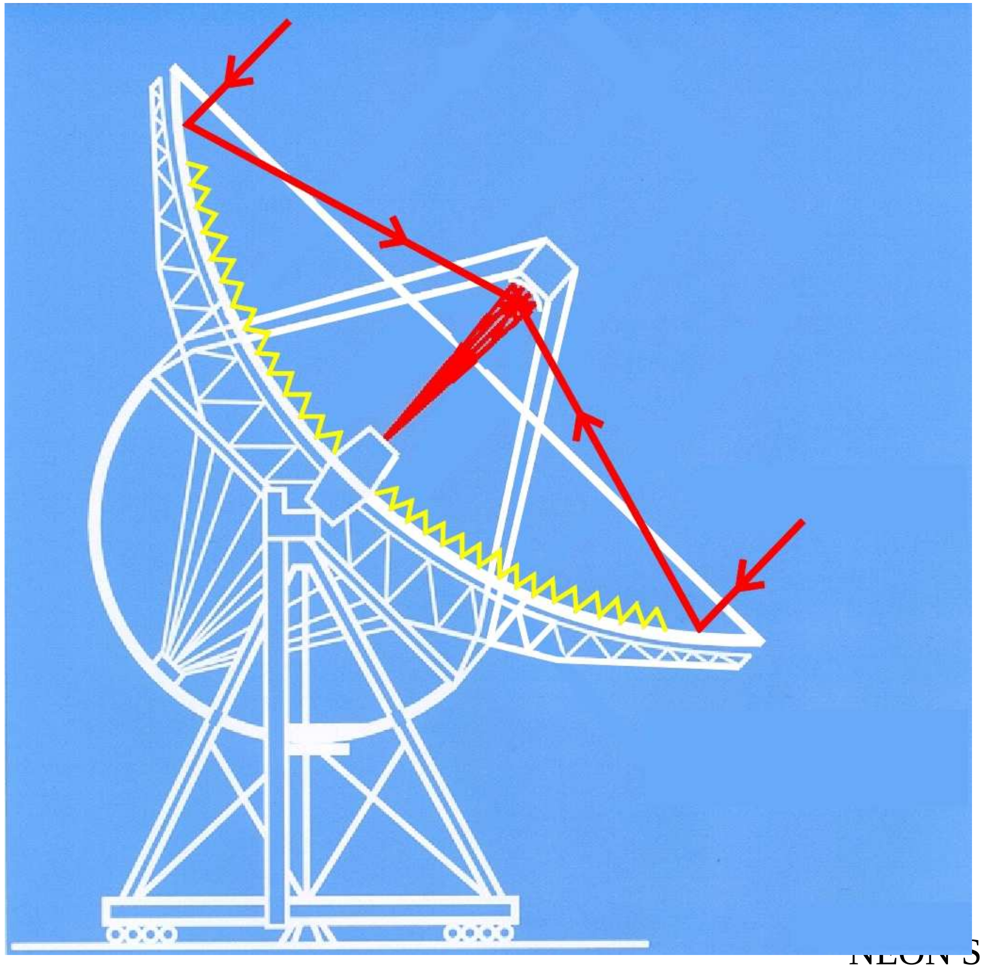


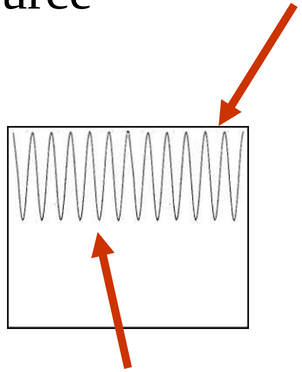


Sum of signals from a source

Difference of signals from a source

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



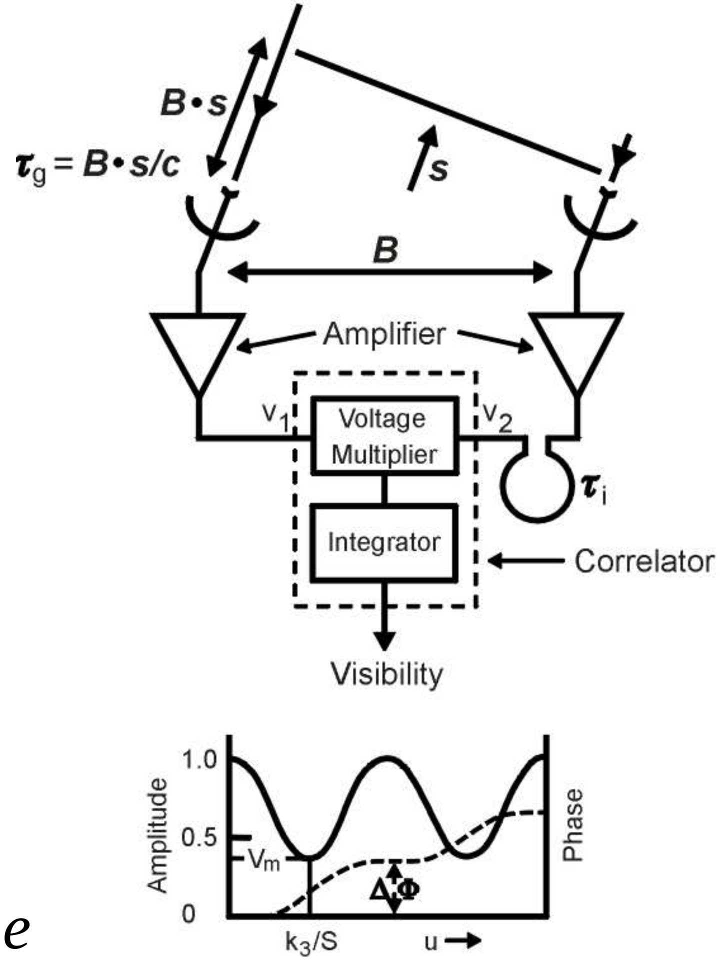


Sum of signals from a source

Difference of signals from a source

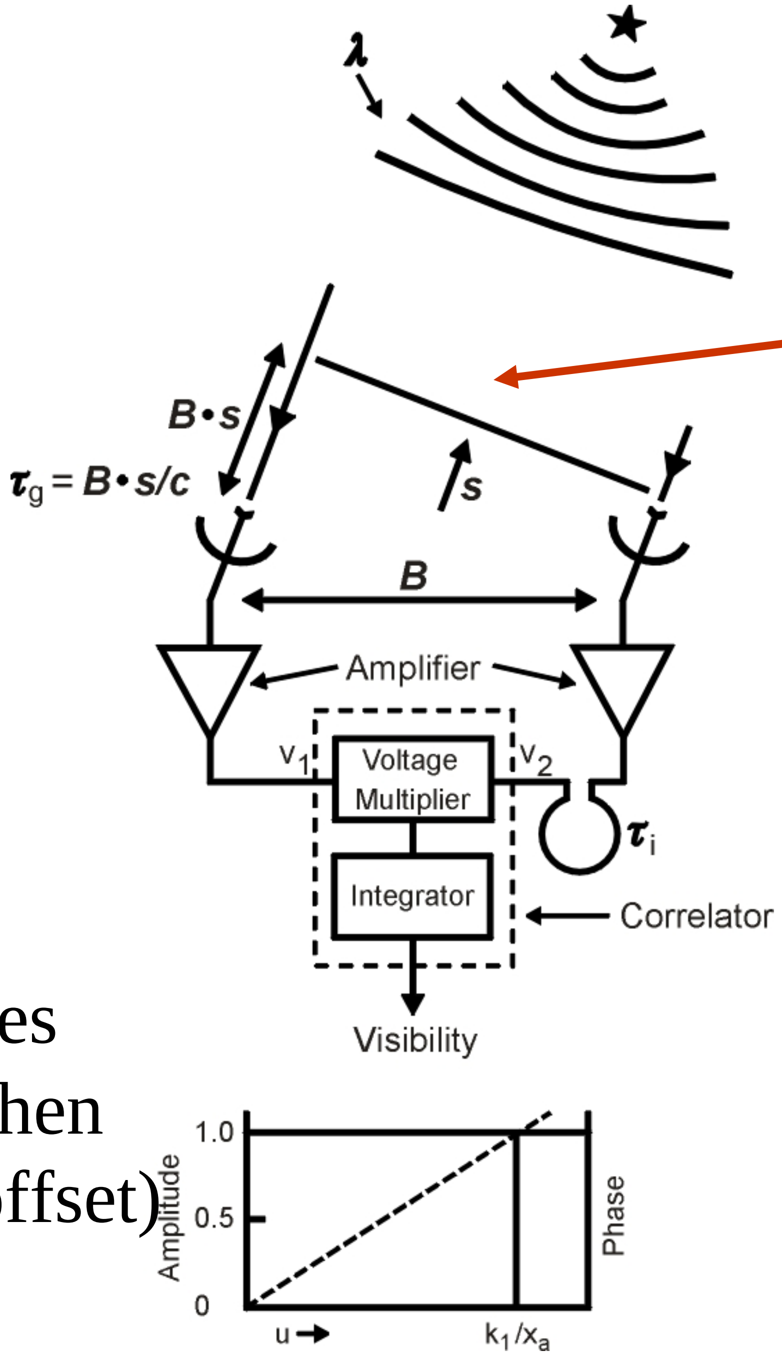
The parts of the dish where power is received are wider apart, so one is sensitive to smaller structures

Source separation is 'S'



S is λ/B_p

projected baseline

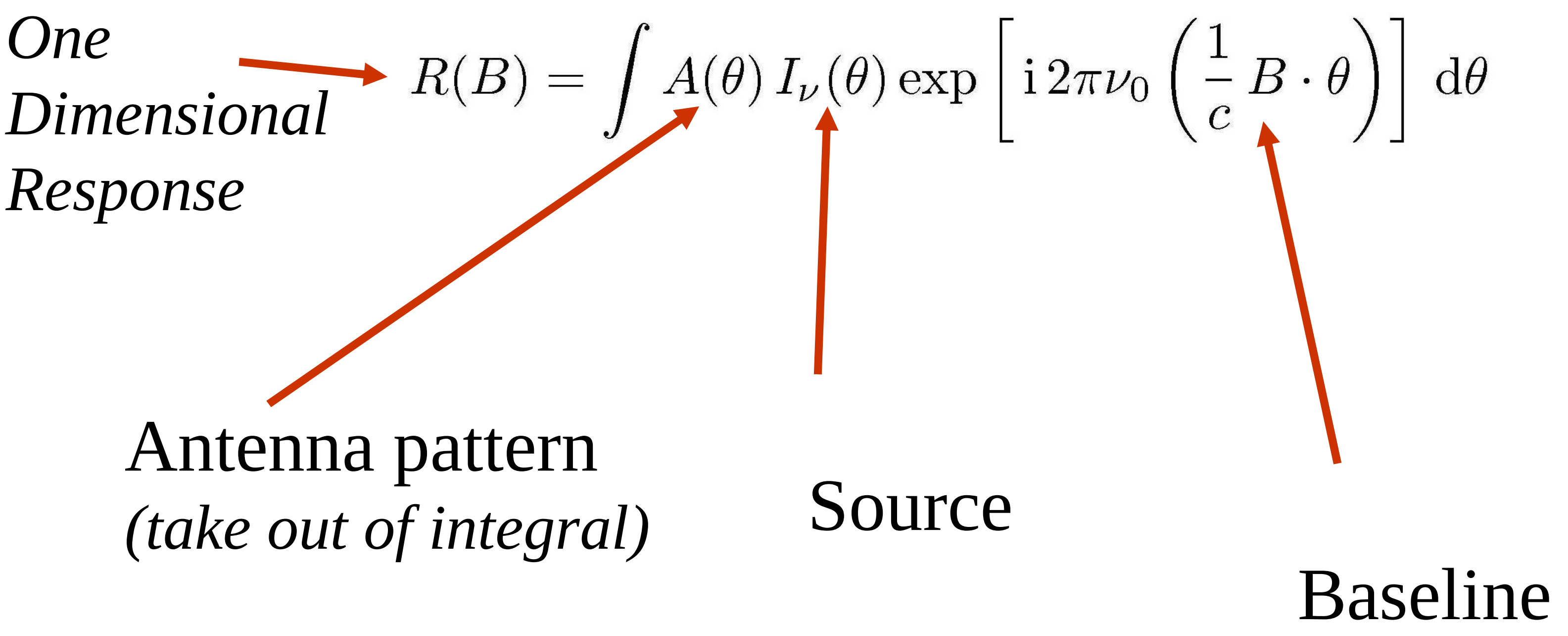


Bp is the projected baseline

$u = 2\pi[x]/\lambda$
$= 1/\theta$

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

B/λ is *u*



One Dimensional Response

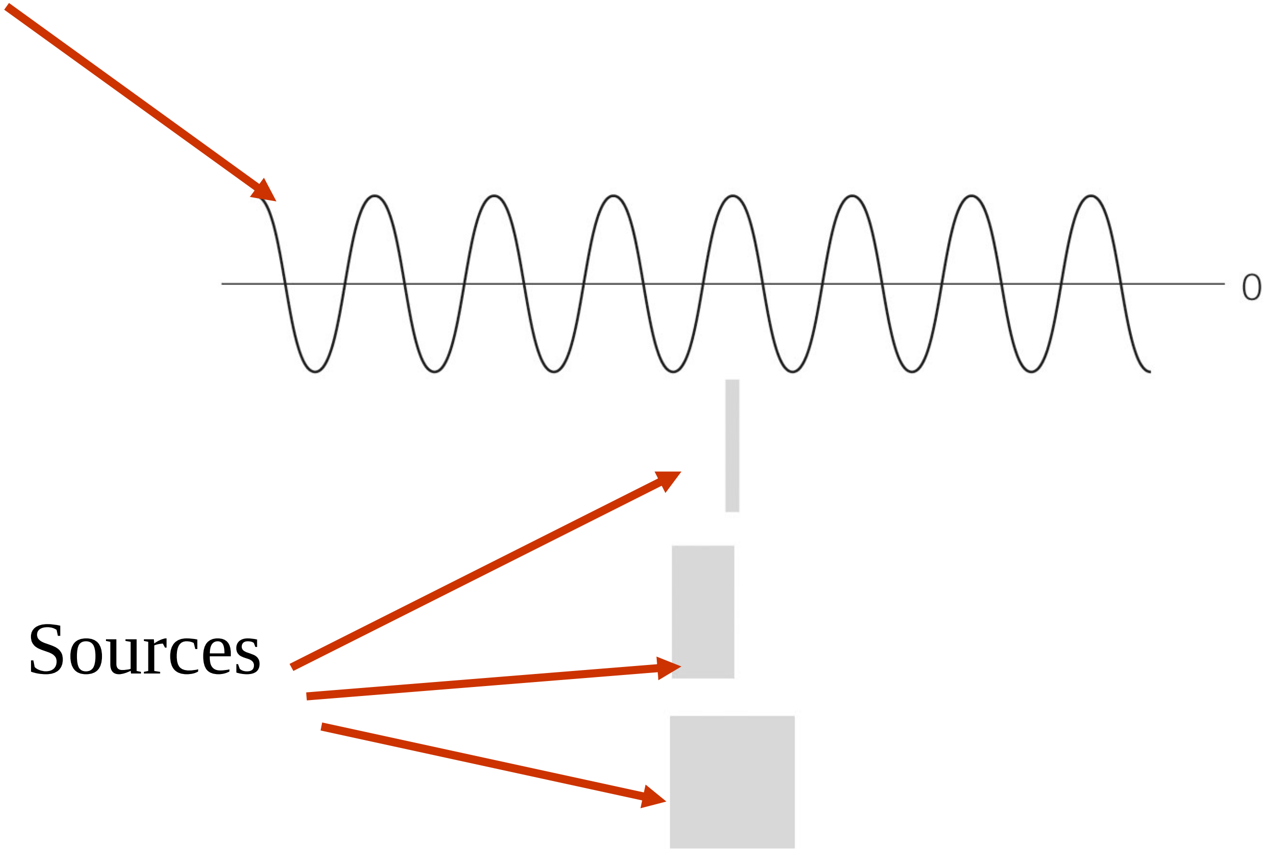
$$R(B) = \int A(\theta)\, I_\nu(\theta) \exp\left[\mathrm{i}\, 2\pi\nu_0 \left(\frac{1}{c}\, B \cdot \theta\right)\right] \mathrm{d}\theta$$

Antenna pattern
(take out of integral)

Source

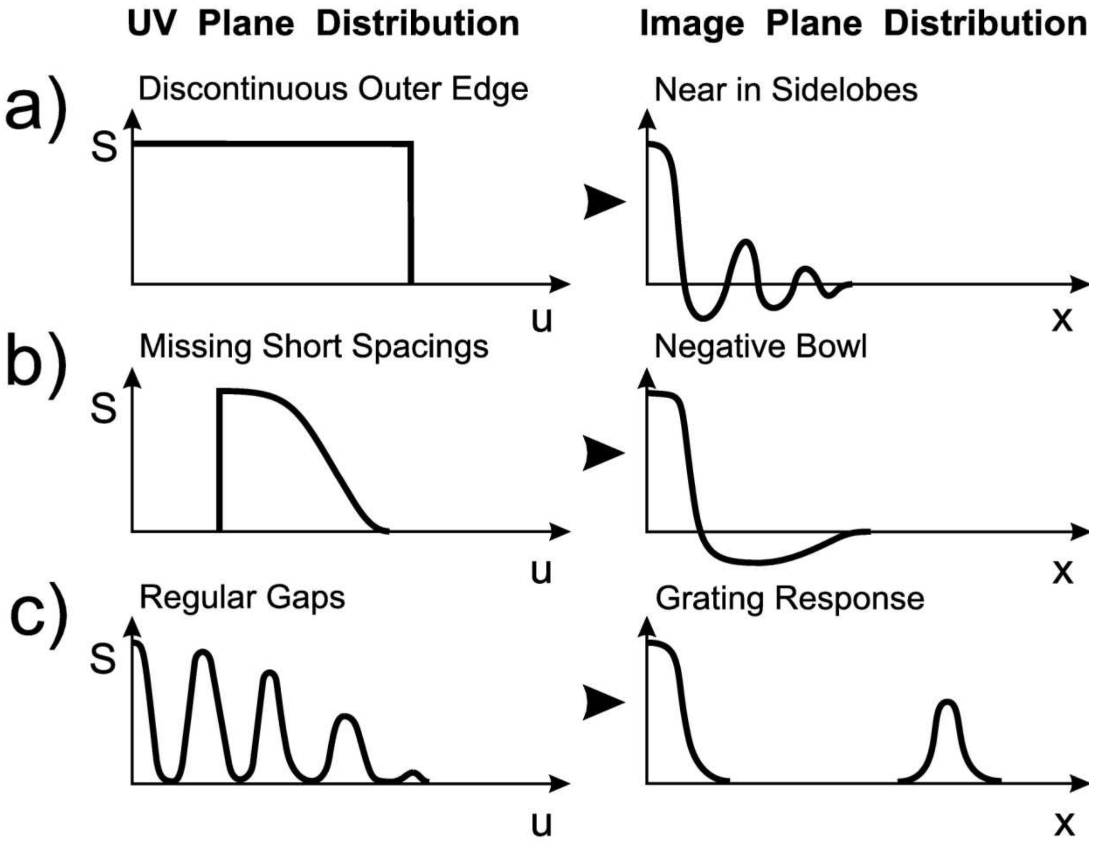
Baseline

interferometer response



Sources

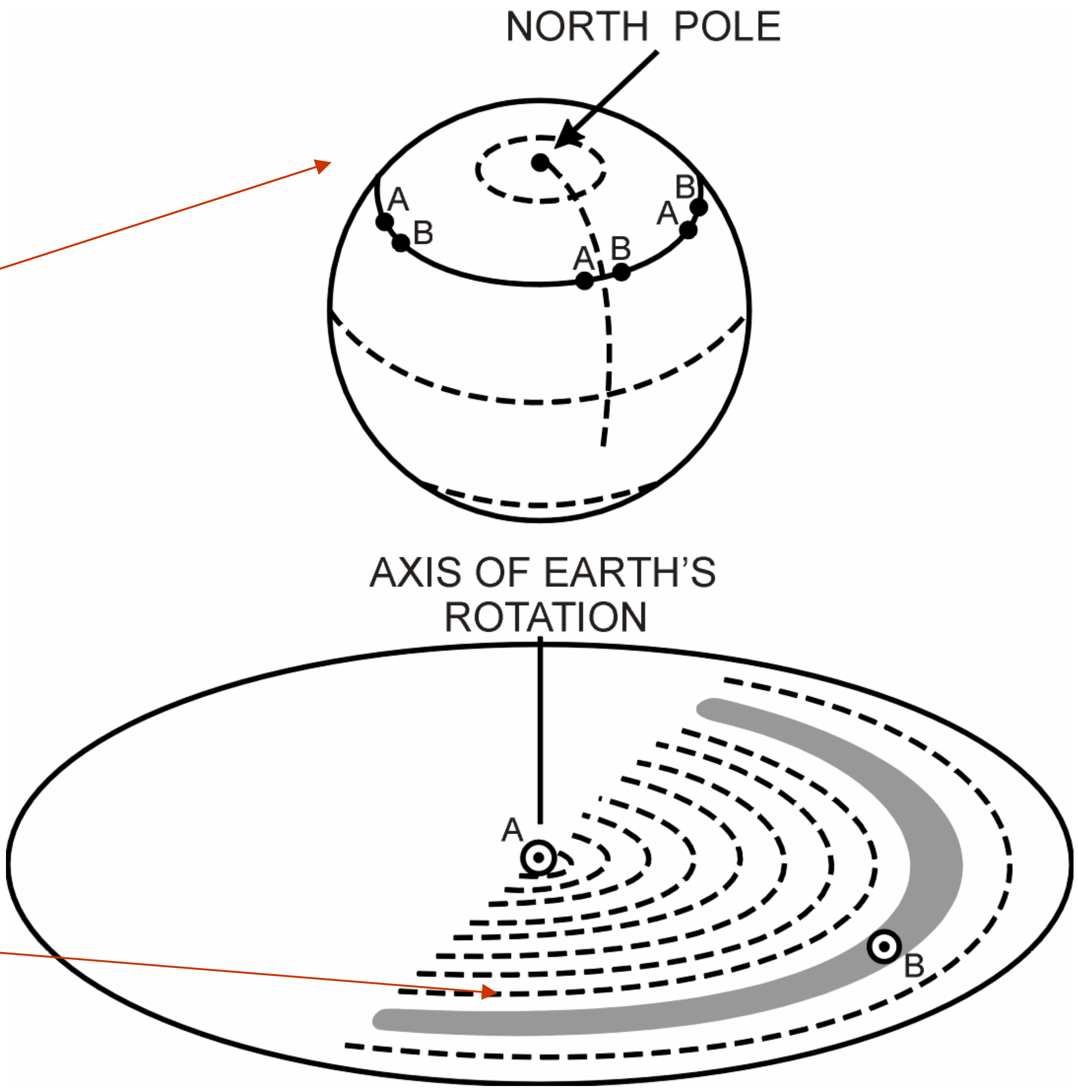
(u,v) and Image plane Distributions



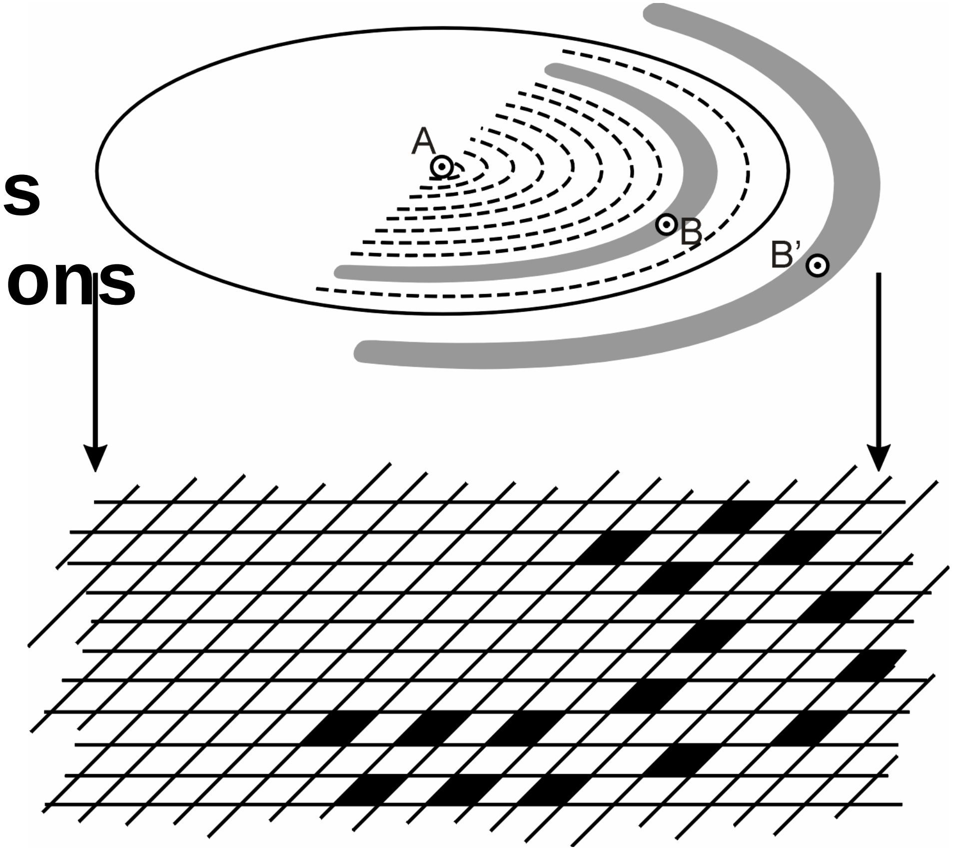
Earth Rotation Aperture Synthesis

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.



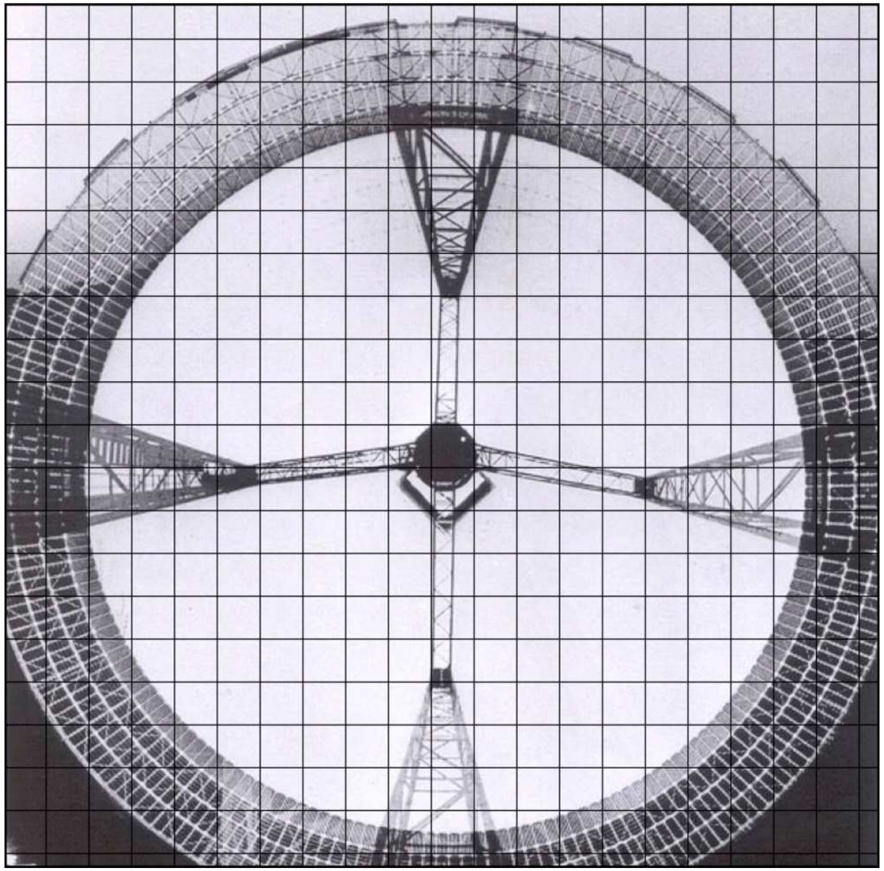
Gridding and sampling in (*u*,*v*) plane



Note the gaps between regions with data

Another Approach to Aperture Synthesis

Question is "How to make images from the (u,v) data?"

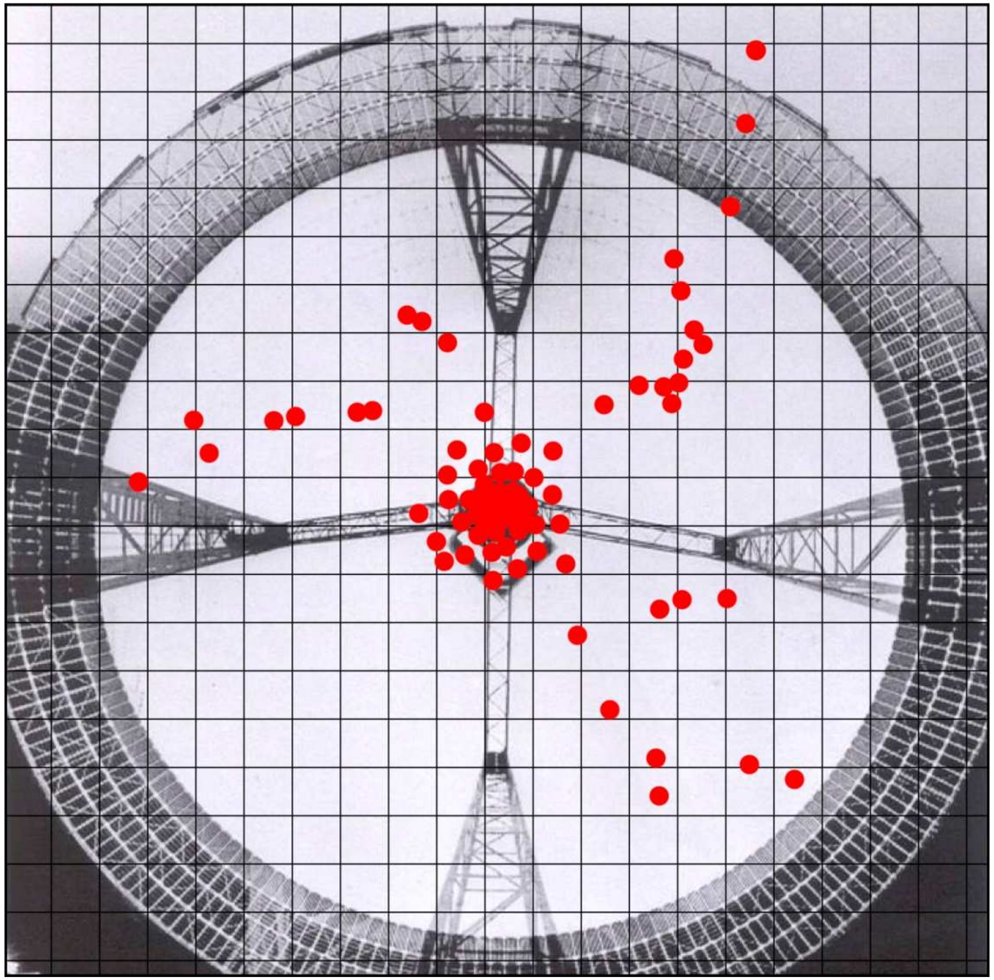


Could imagine that we sample the Electric field (in both amplitude & phase) over the entire aperture. But don't have to!

<u>Just measure the correlations Between points.</u>

The Dots Show Locations of Non-redundant Array

As an instrument tracks a source the dots move along circles



$$\Delta S_\nu = \frac{2\,M\,k\,T'_{\rm sys}}{A_{\rm e}\sqrt{2\,N\,t\,\Delta\nu}}$$

M about 1

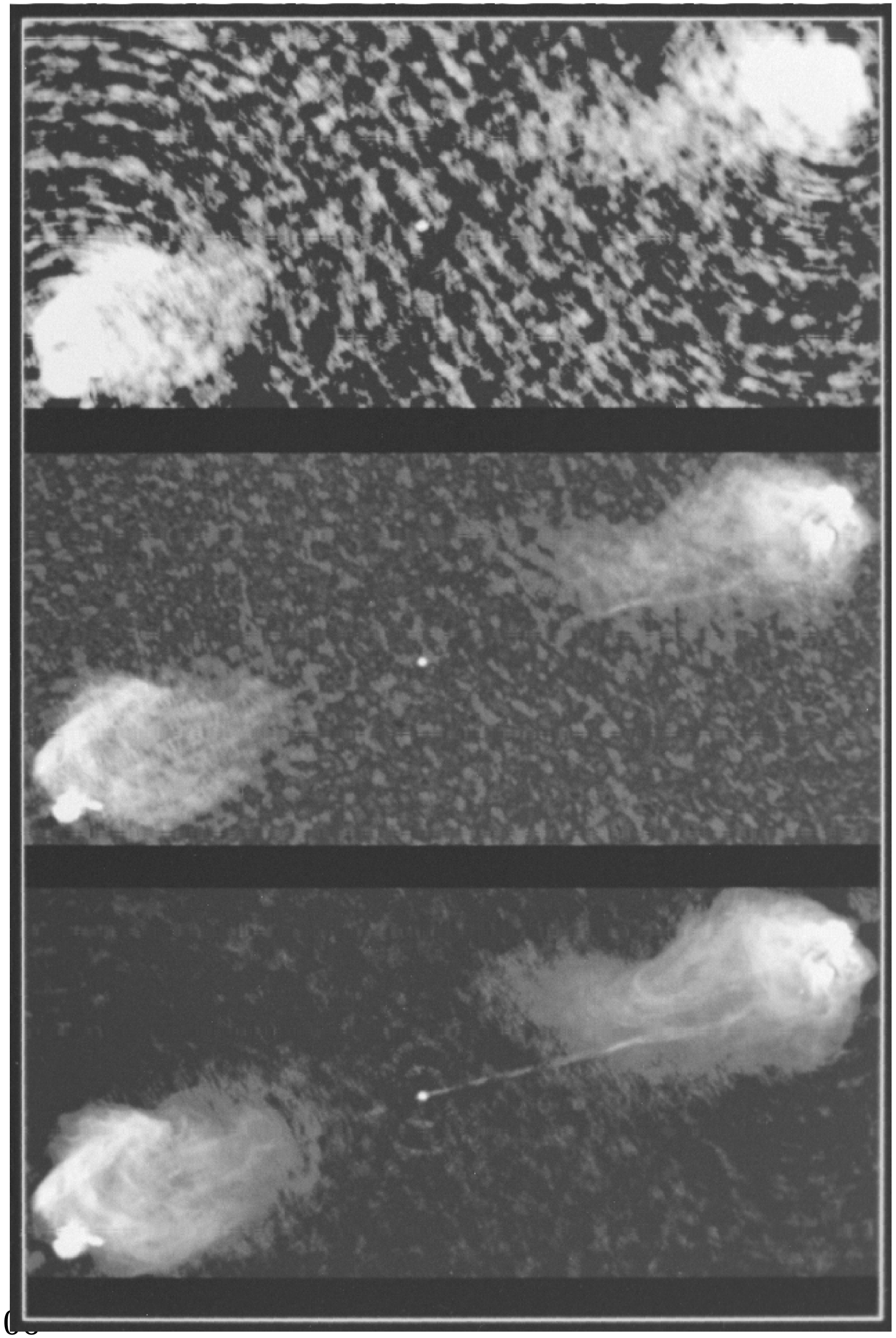
(Difference is R-J)

$$\Delta T_{\rm b} = \frac{2\,M\,k\,\lambda^2\,T'_{\rm sys}}{A_{\rm e}\Omega_{\rm b}\sqrt{2\,N\,t\,\Delta\nu}}$$

$T'_{\rm sys}$ is outside atmosphere

$N = ½n(n-1)$, where n is # of antennas

A_e *is effective collecting area of an antenna*



Data
as
taken

Data
with
MEM

with
MEM
and
Self-
Calibration

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

A Next Generation Millimeter Telescope

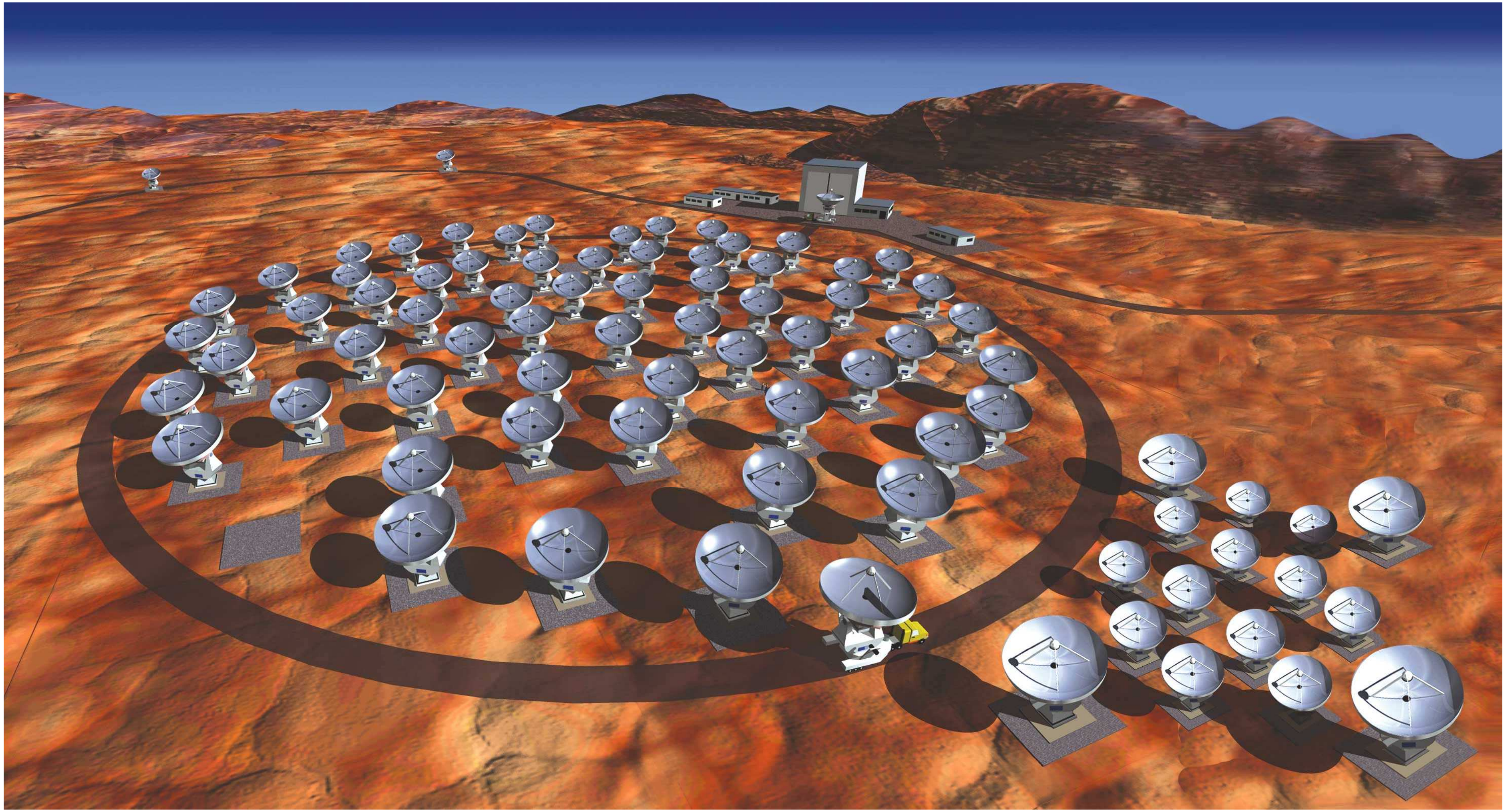
A major step in astronomy → a mm/submm equivalent of VLT, HST, NGST, EVLA

- **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**

ALMA + ACA



Construction Partners

- ESO for European Member States
- NRAO/AUI for North America
  - Includes Canada
- NINS/NAOJ for Japan (and Taiwan)
  - This is East Asia
- Chile as host country

ALMA: The Atacama Large Millimeter Array

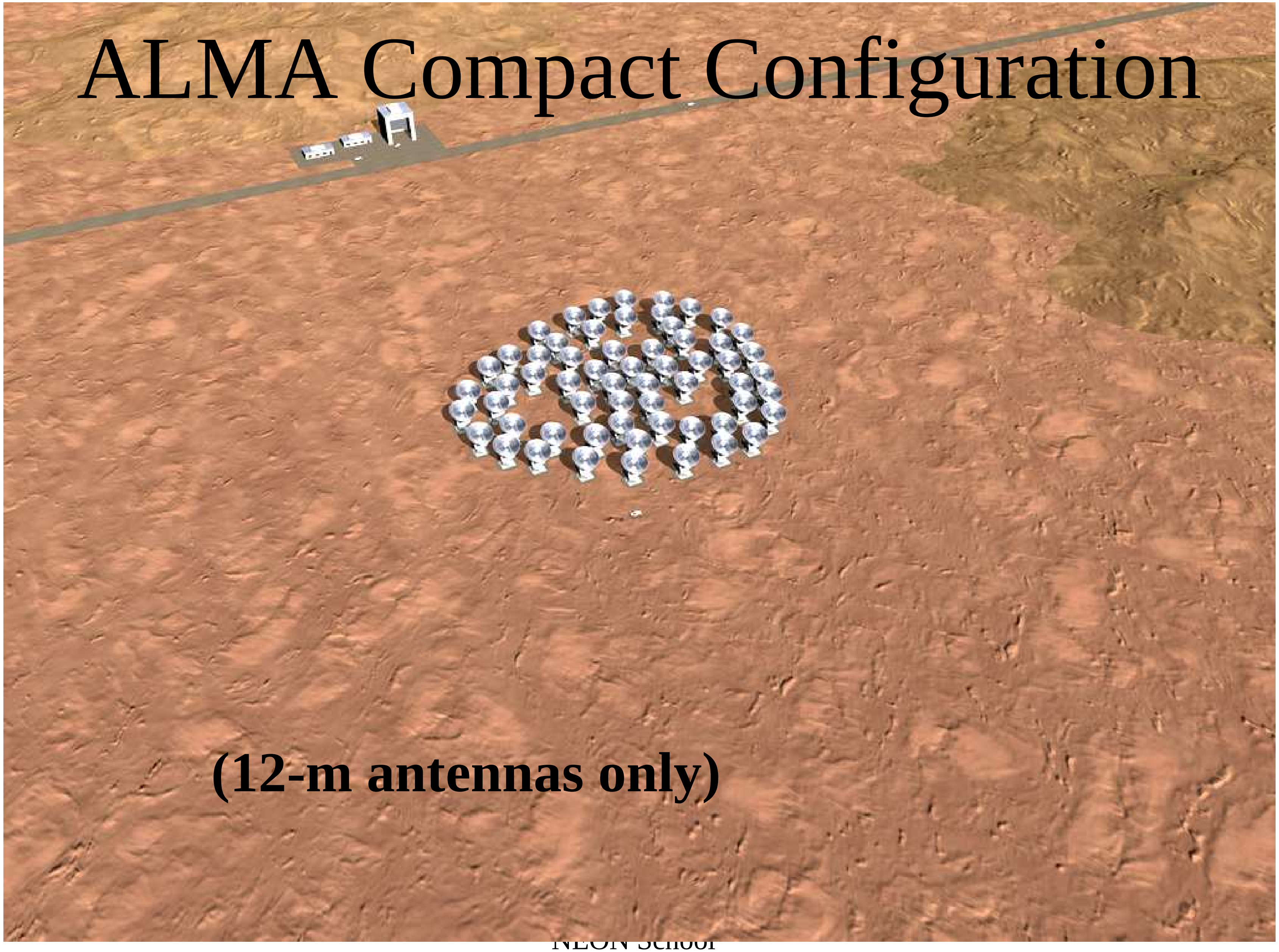
- A mm/submm equivalent of VLT, JWST
- 54 to 68 x 12-meter antennas, surface < 25 µm rms, and twelve 7-meter antennas
- Zoom array: 150m → 14.5 kilometers
- Receivers covering wavelengths 0.3 - 10 mm
- Located at Chajnantor (Chile), altitude 5000 m
- Europe, North America and East Asia sharing the construction cost and operations co
- Now a truly global project!

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


Lore
SCHEUERLE
SCHEUERLE

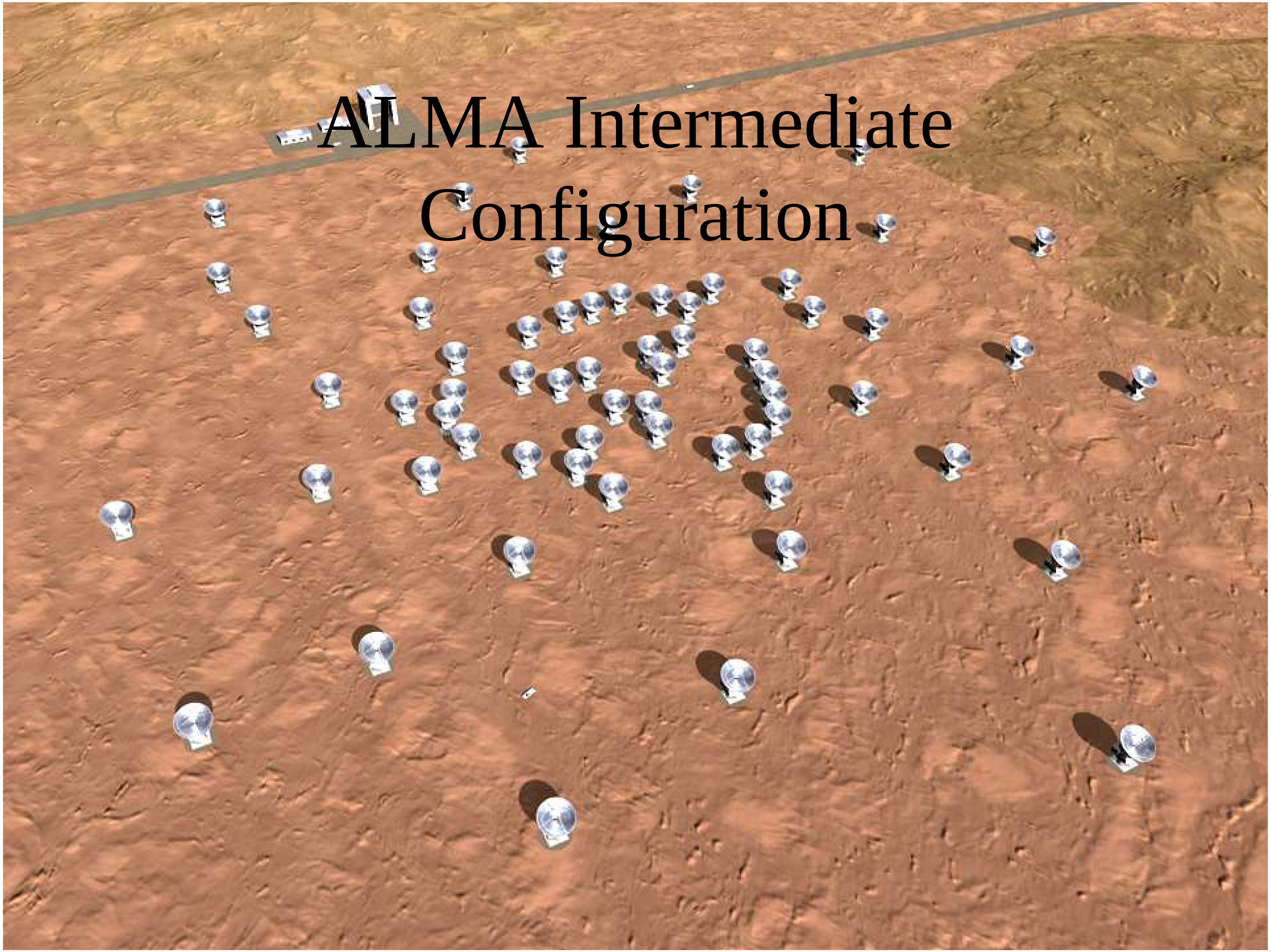
The ALMA site: Chajnantor, Chile Altitude 5000m

ALMA Compact Configuration

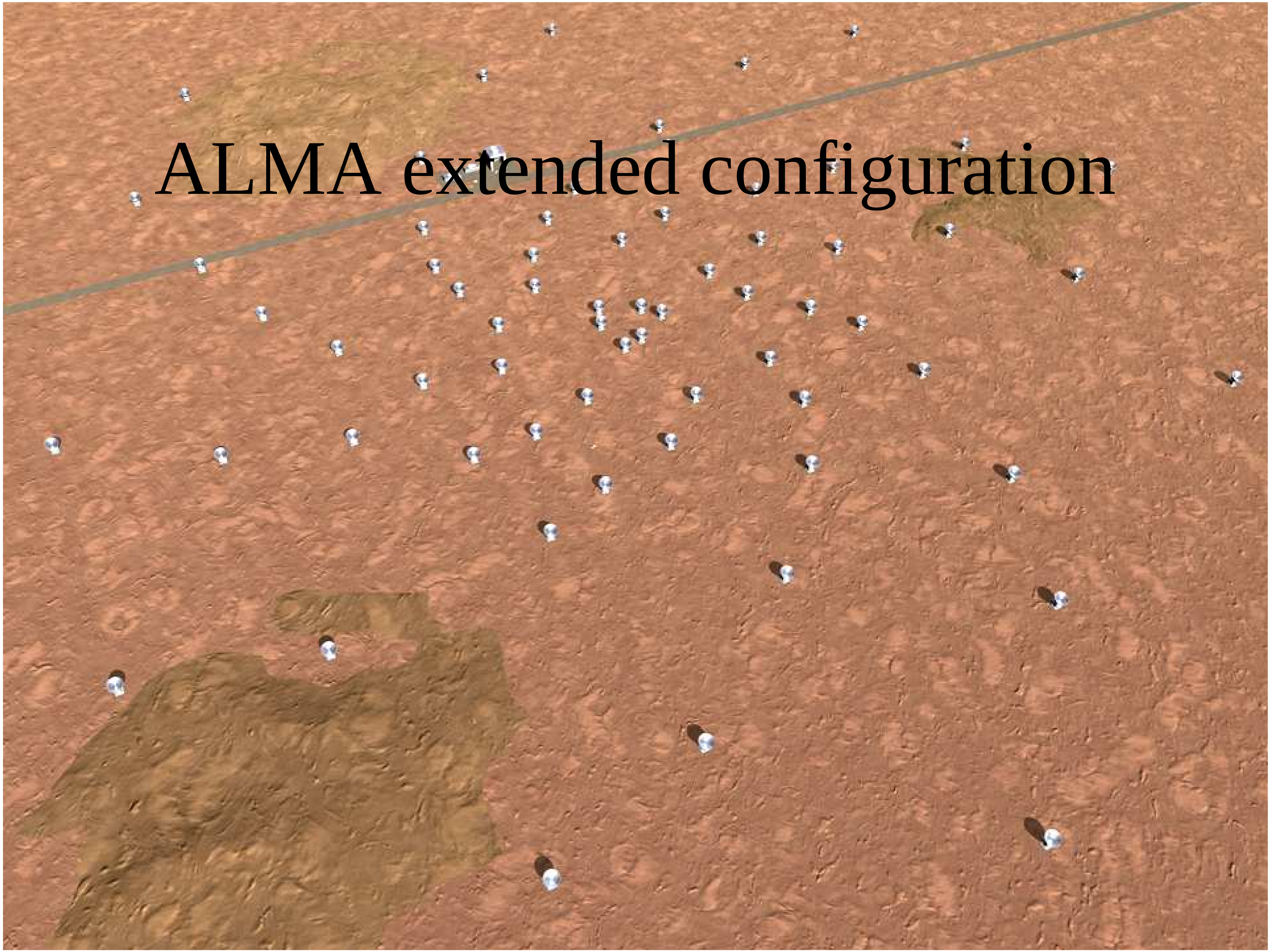


(12-m antennas only)

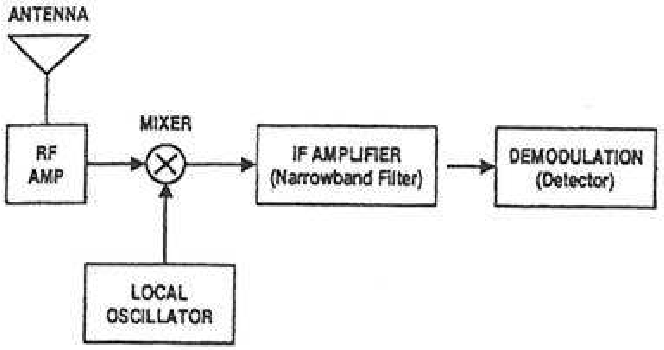
ALMA Intermediate Configuration

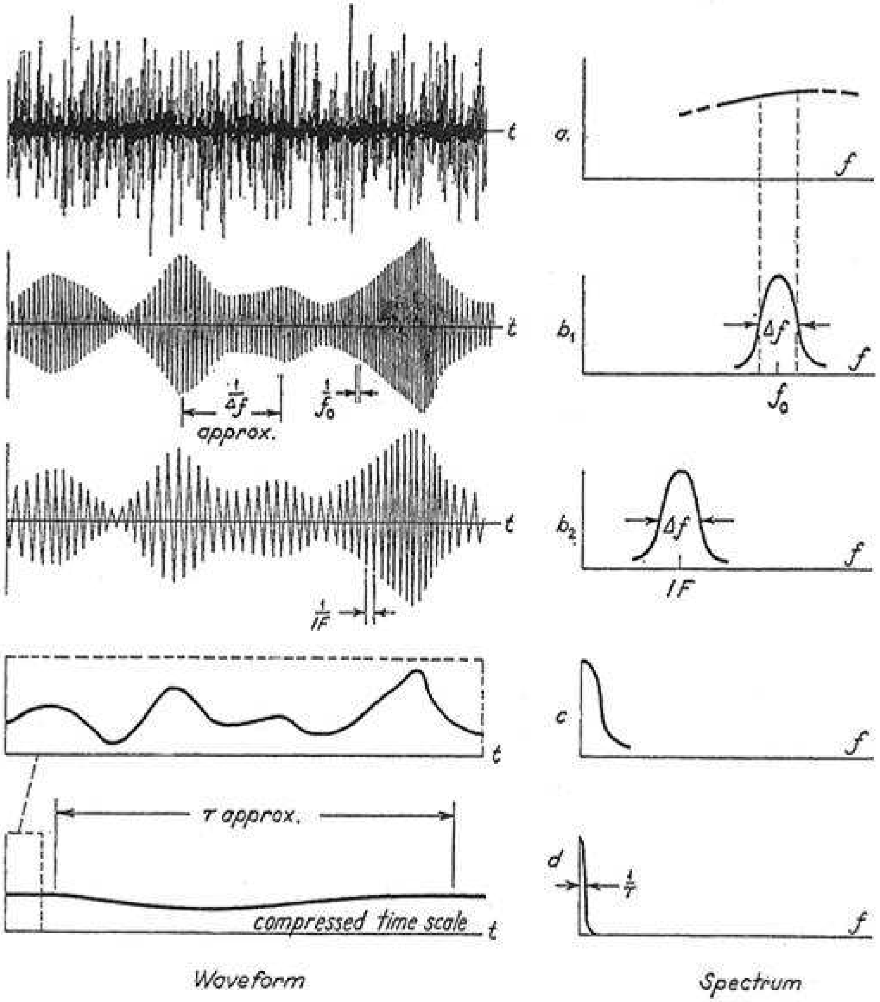


ALMA extended configuration

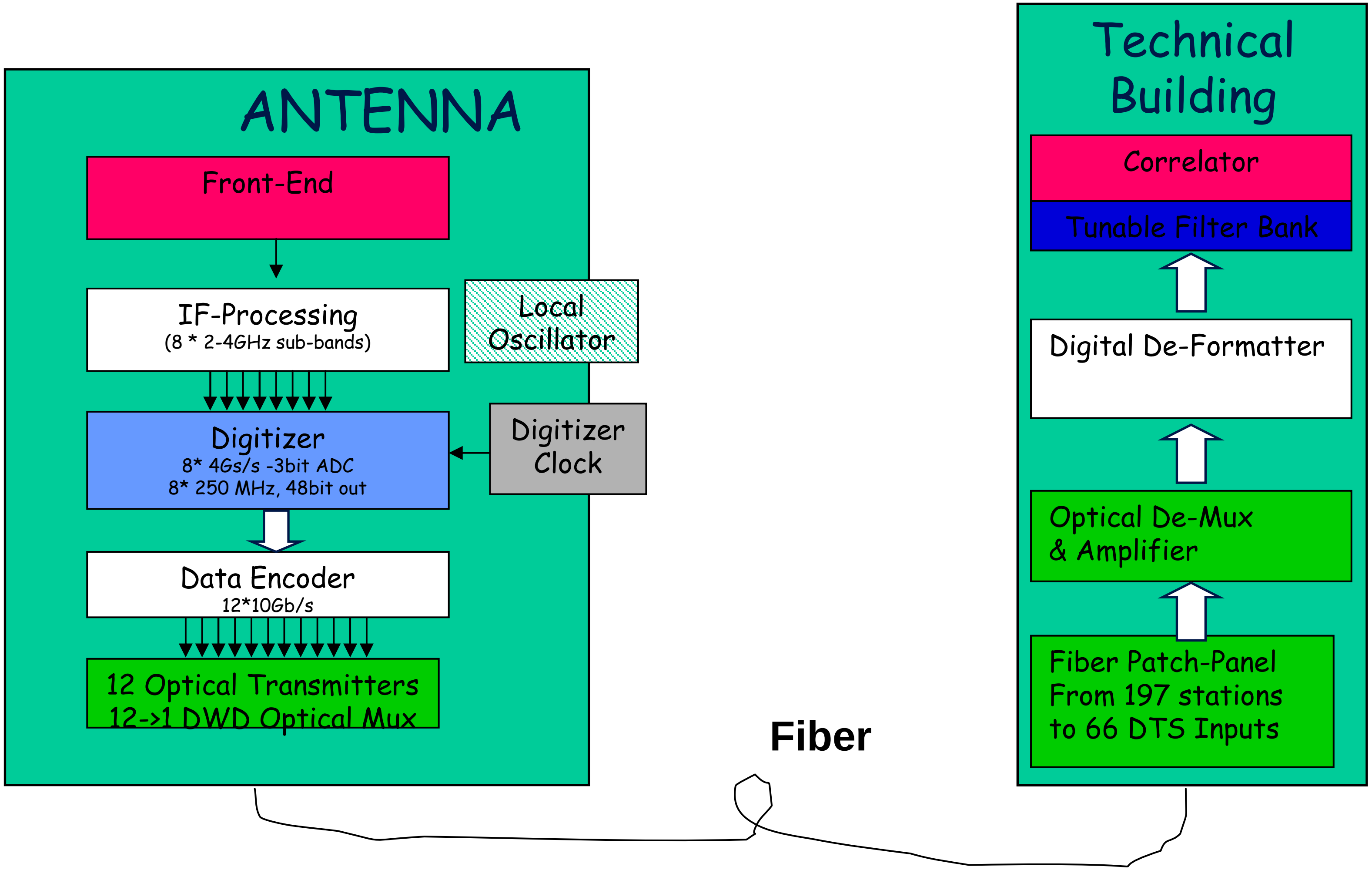


Analog Receiver Block Diagram





Back End & Correlator



ANTENNA

Front-End

IF-Processing
(8 * 2-4GHz sub-bands)

Local Oscillator

Digitizer
8* 4Gs/s -3bit ADC
8* 250 MHz, 48bit out

Digitizer Clock

Data Encoder
12*10Gb/s

12 Optical Transmitters
12->1 DWD Optical Mux

Fiber

Technical Building

Correlator

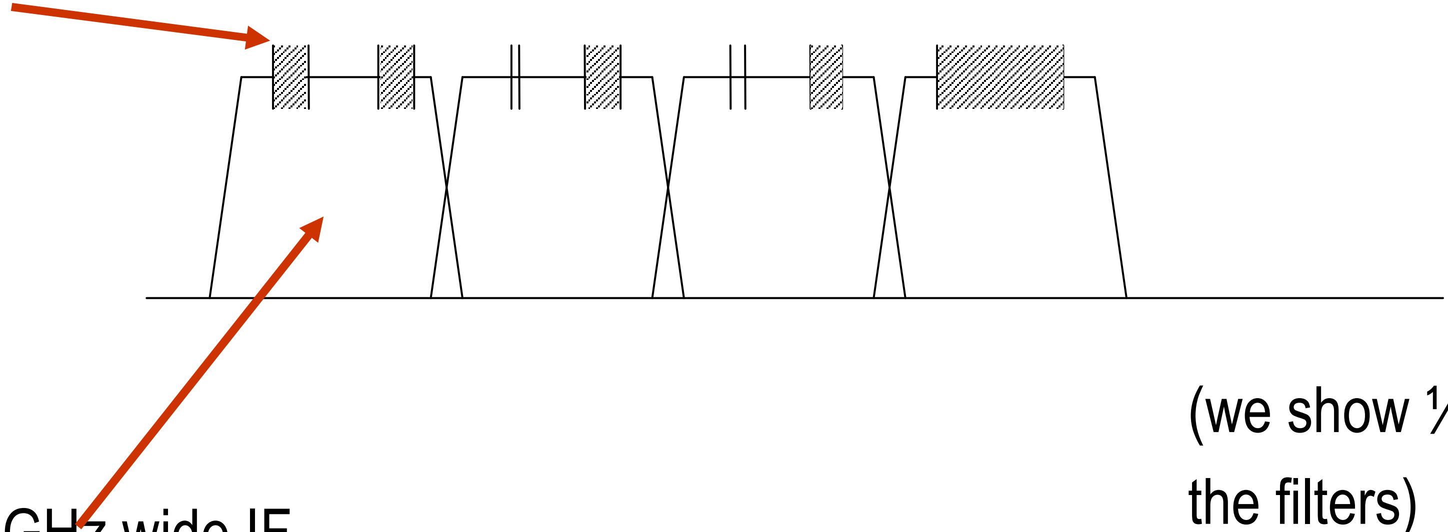
Tunable Filter Bank

Digital De-Formatter

Optical De-Mux
& Amplifier

Fiber Patch-Panel
From 197 stations
to 66 DTS Inputs

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

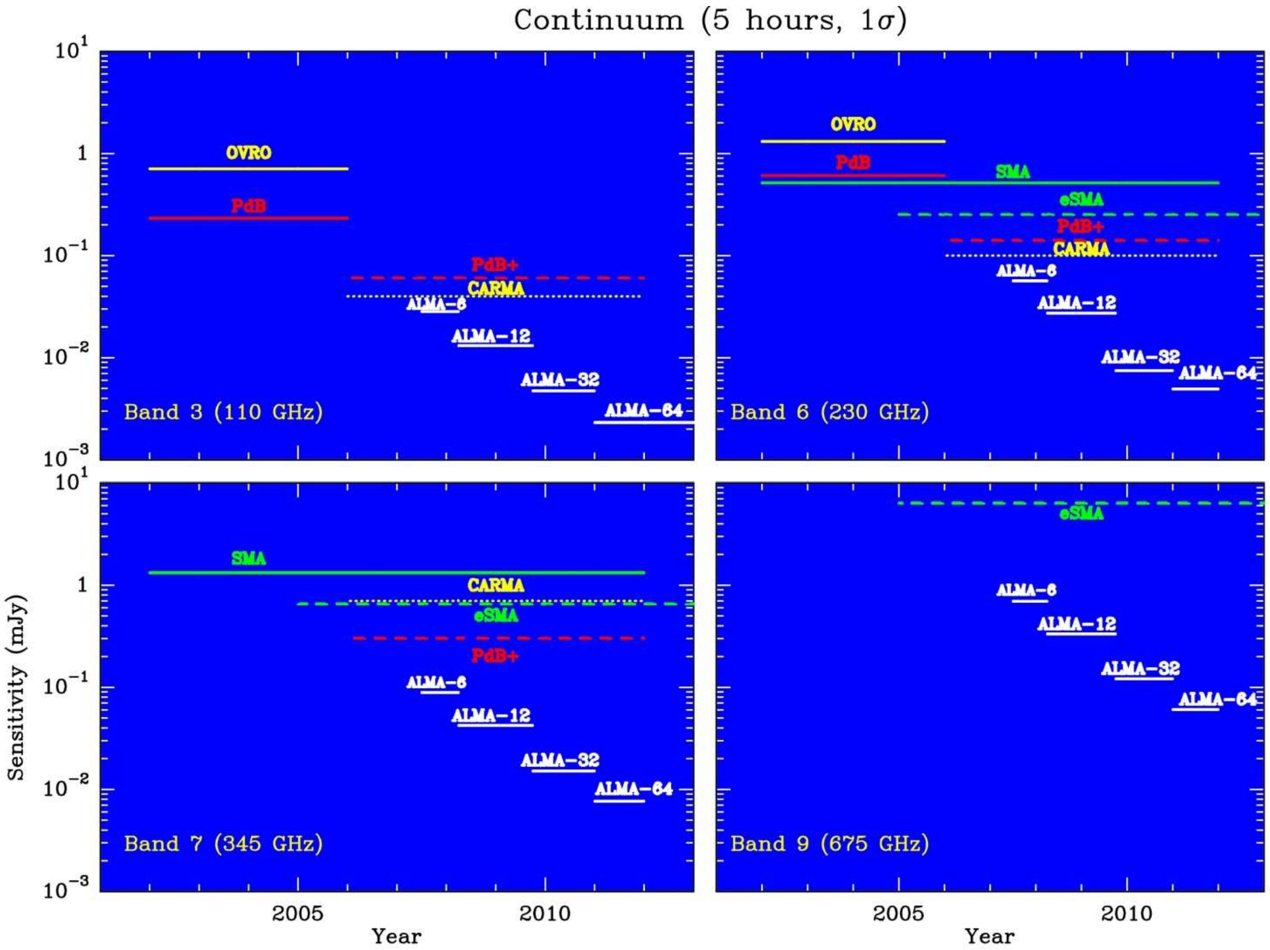
2 GHz wide IF

(we show ½ of the filters)

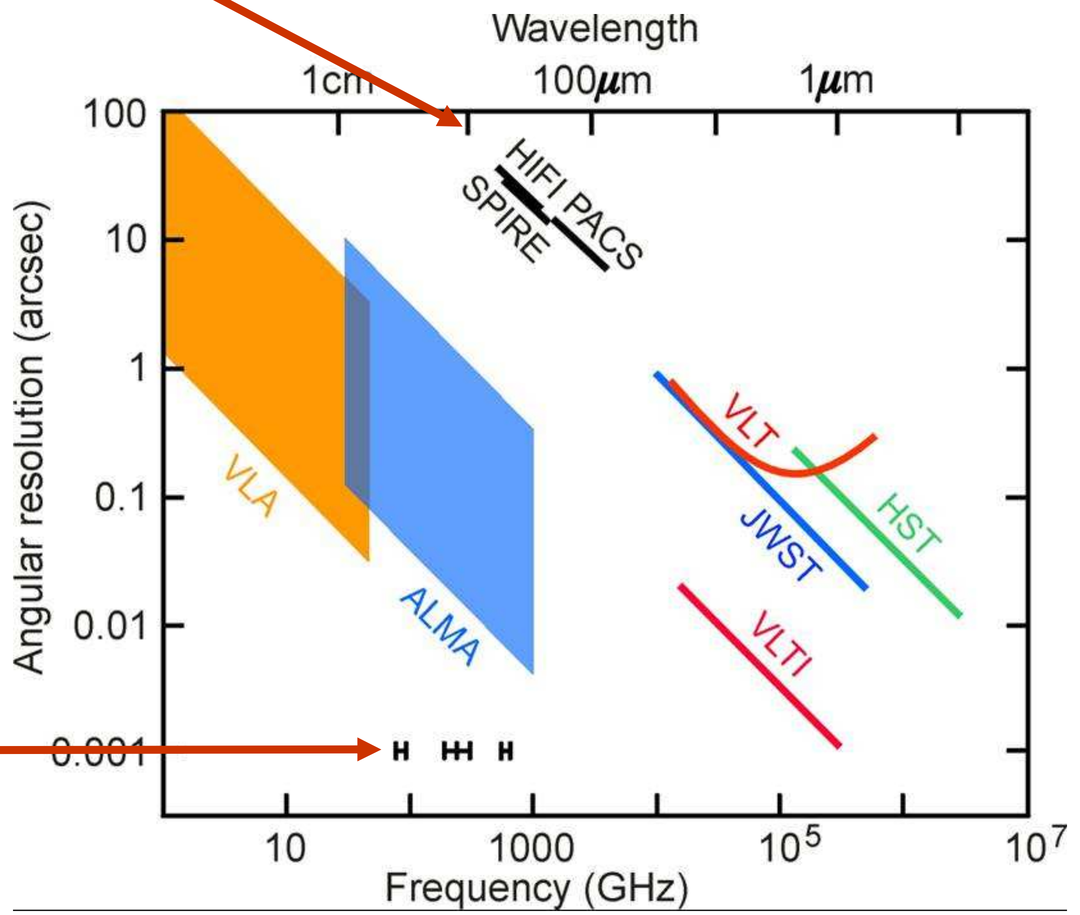
Spectrometer is a recycling correlator:

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

Sensitivity of ALMA

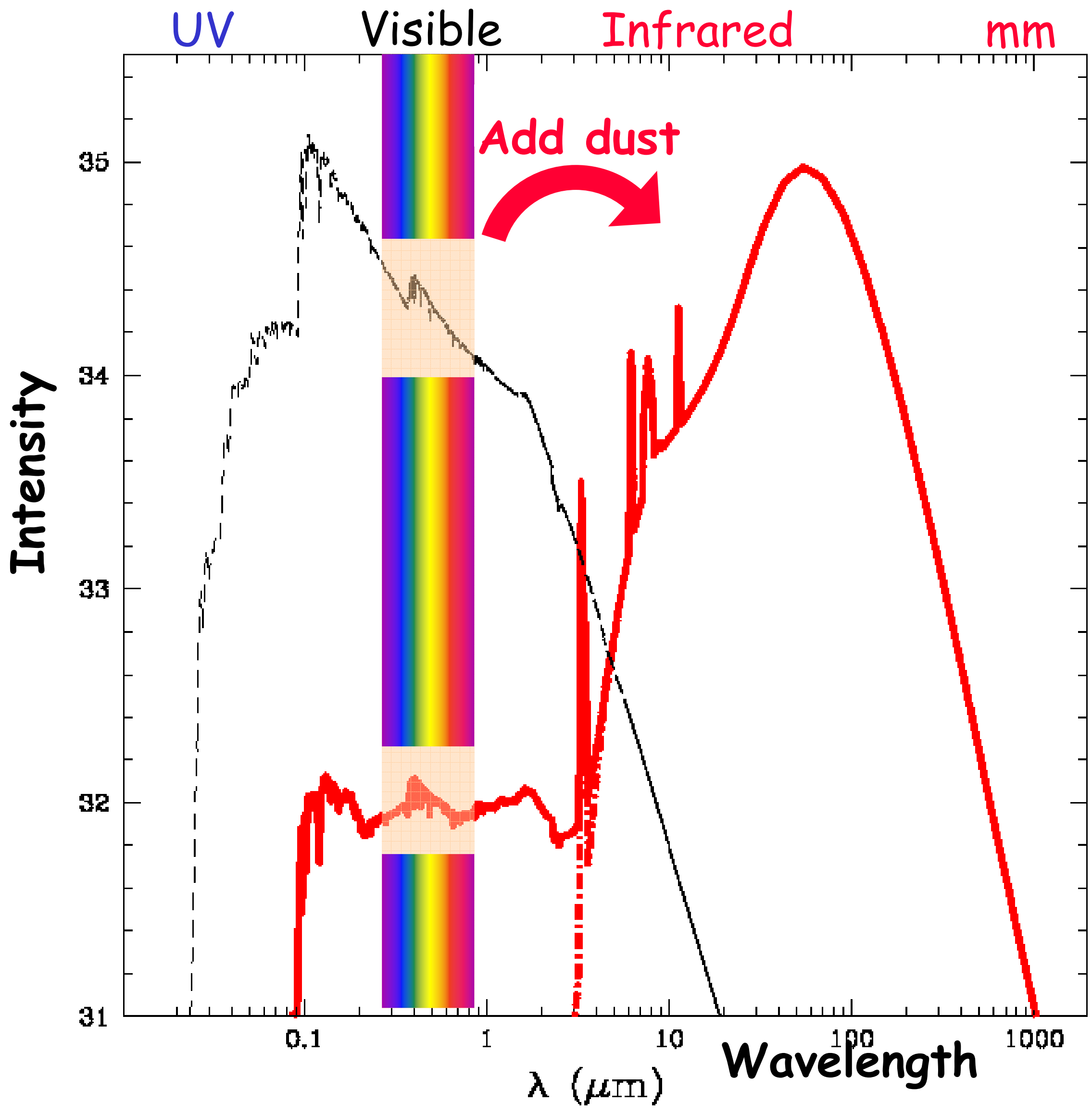


The ALMA FOV is 25” at 1 mm

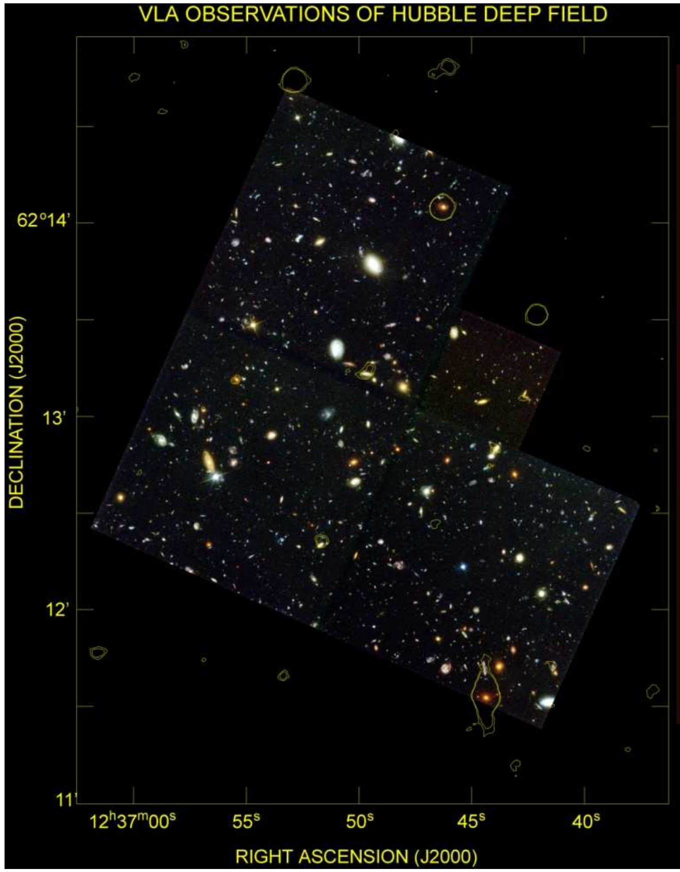


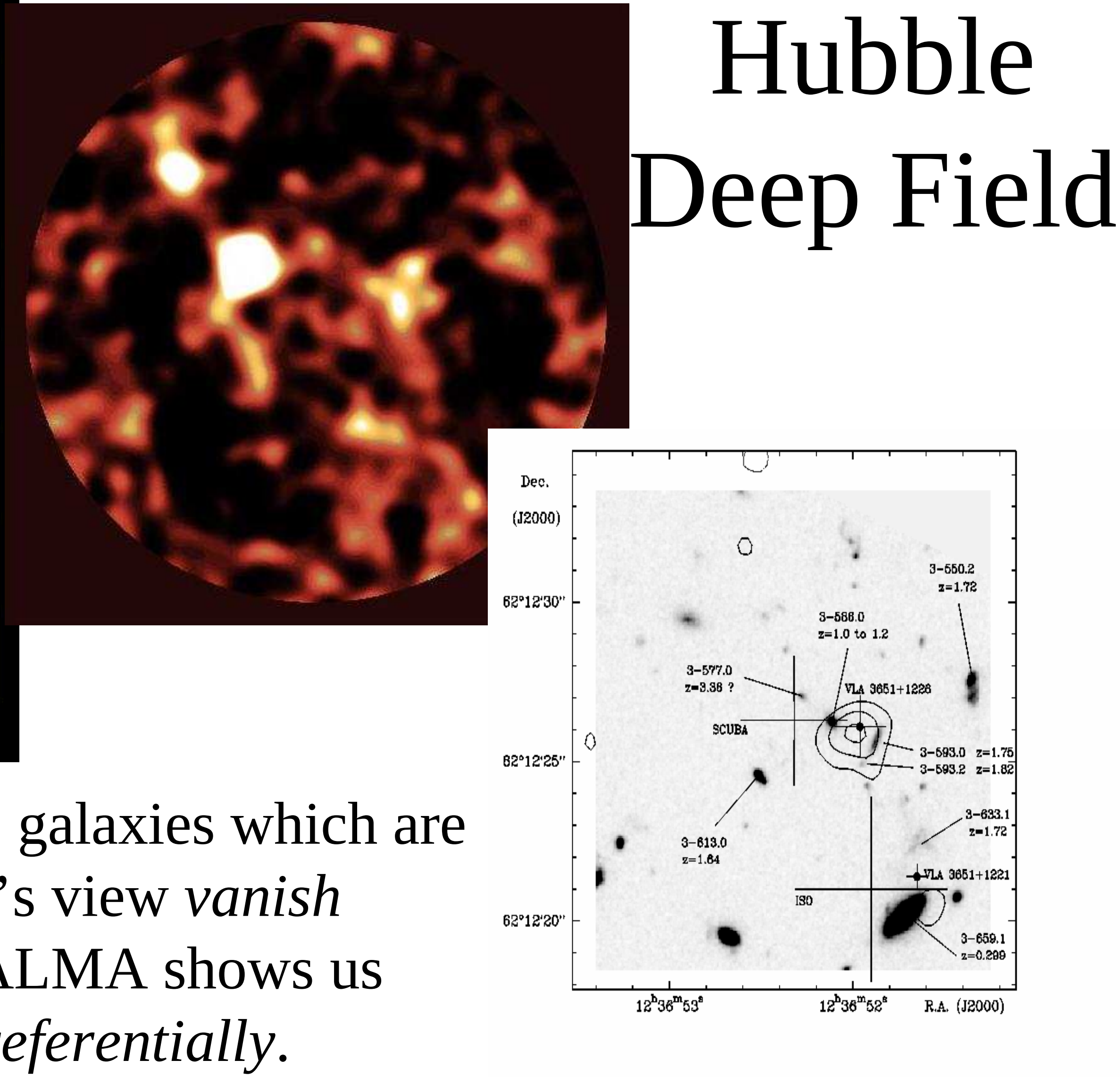
Higher is Worse!

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

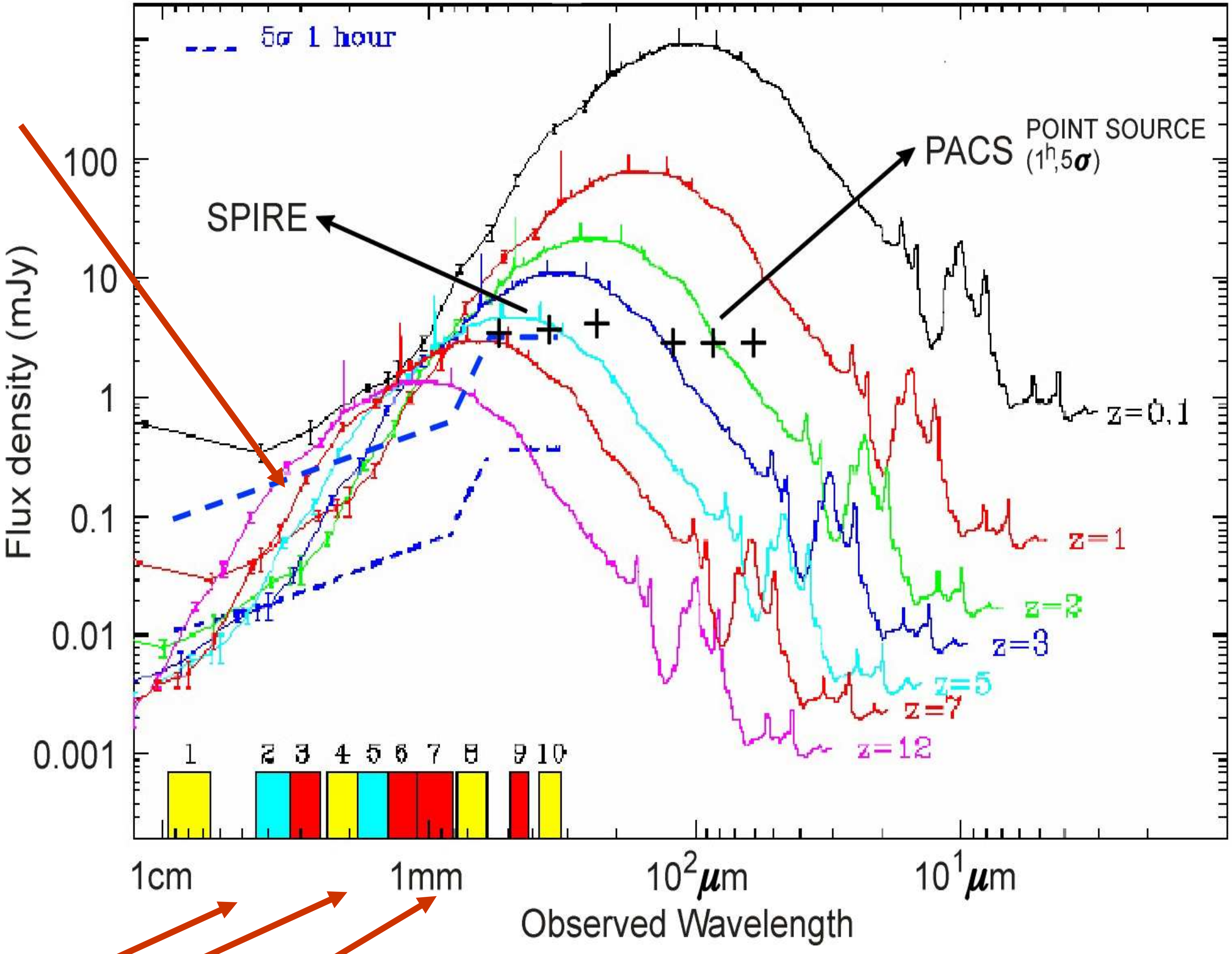
Hubble Deep Field





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

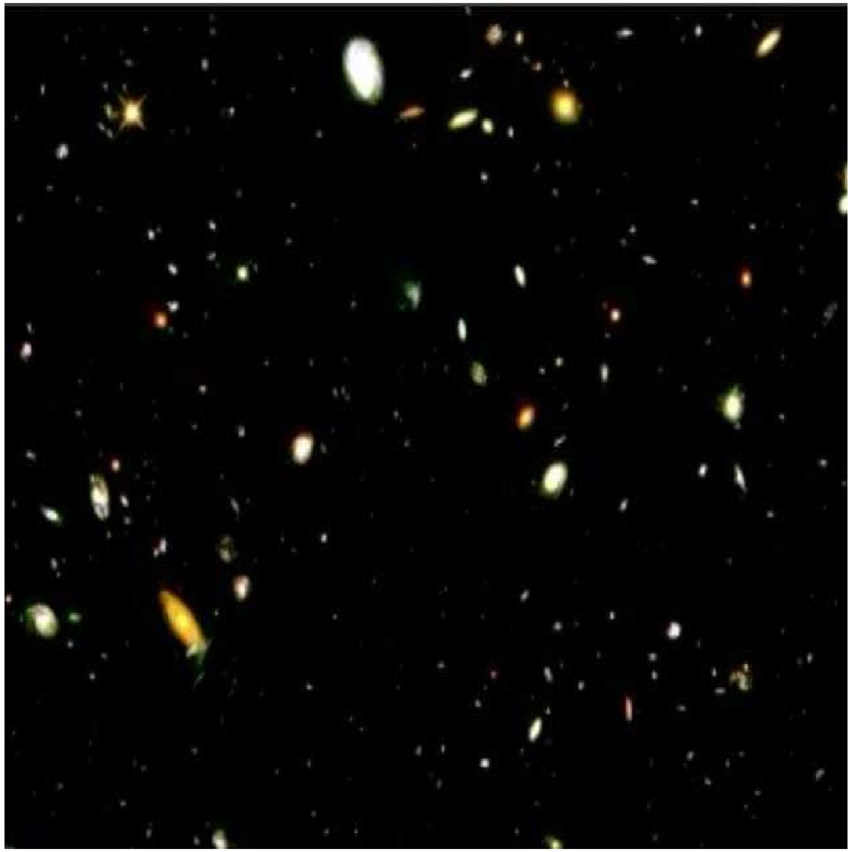
Sensitivity with 6 antennas



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

Hubble Deep Field

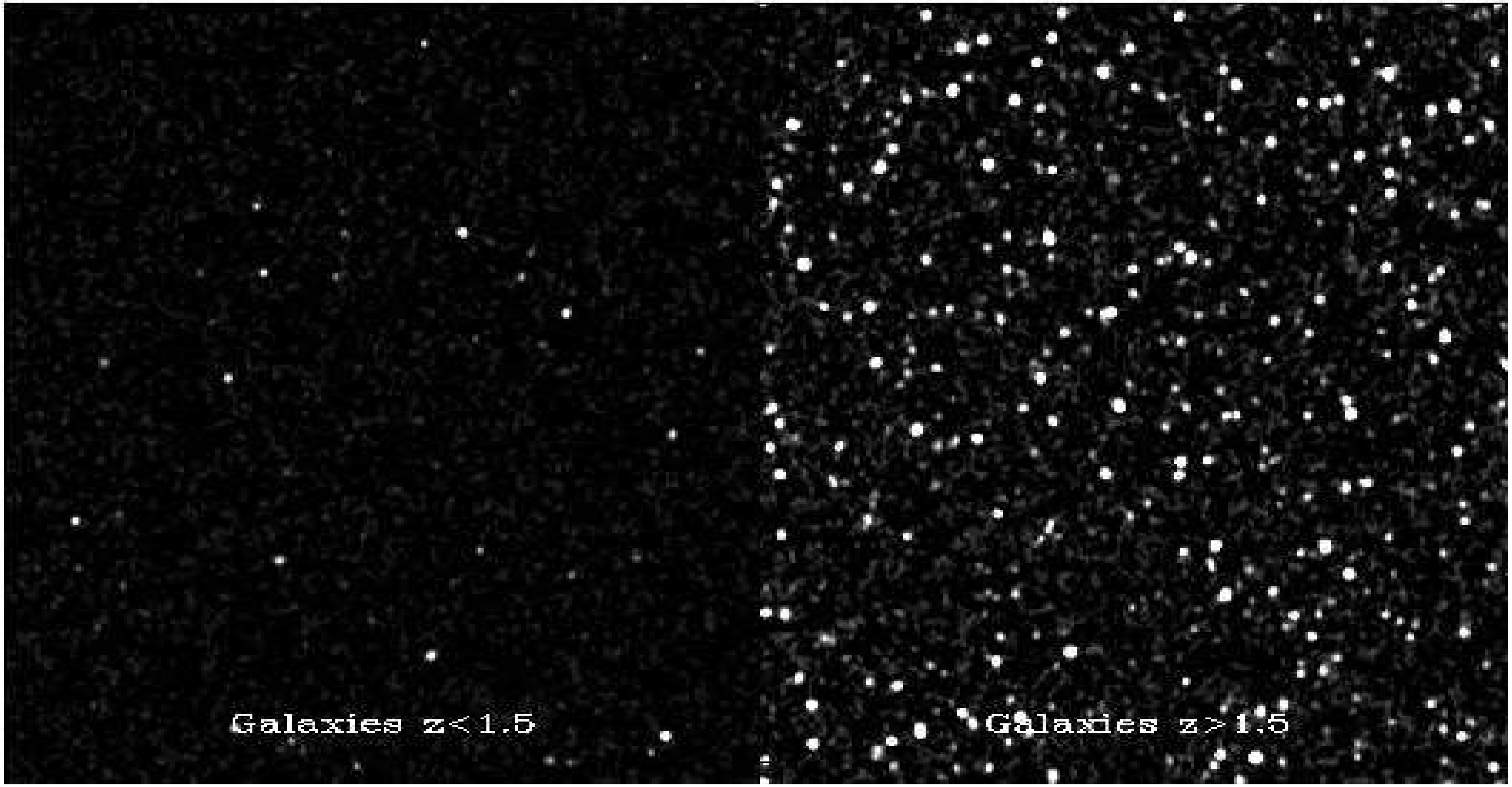
Rich in Nearby Galaxies, Poor in Distant Galaxies



Nearby galaxies in HDF

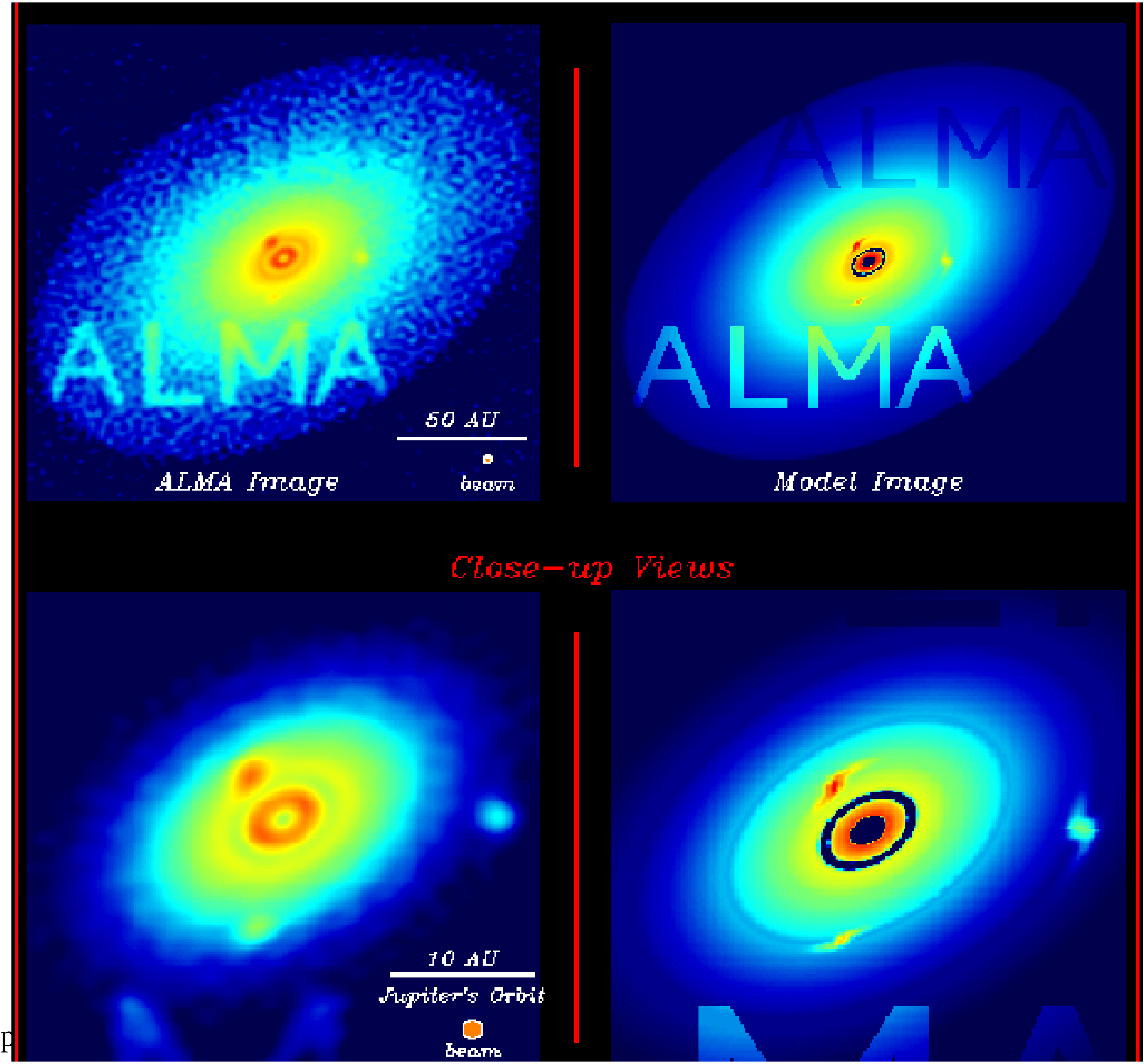
Distant galaxies in HDF

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



Nearby galaxies in ALMA Deep Field

Distant galaxies in ALMA Deep Field

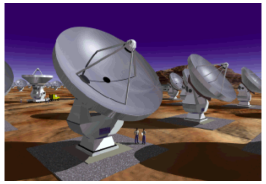


Simulations:
L. Mundy

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

Orbital radius: 5 AU

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



Maximum baseline: 10km,

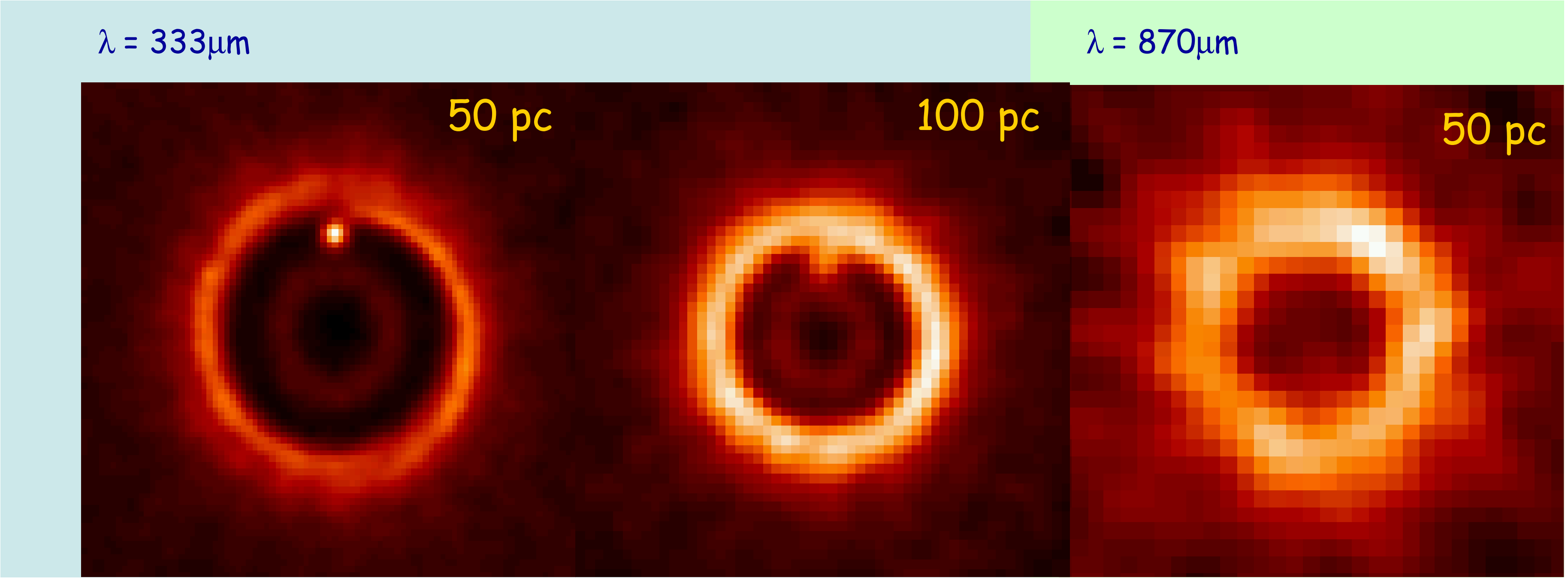
t_{int}=8h,

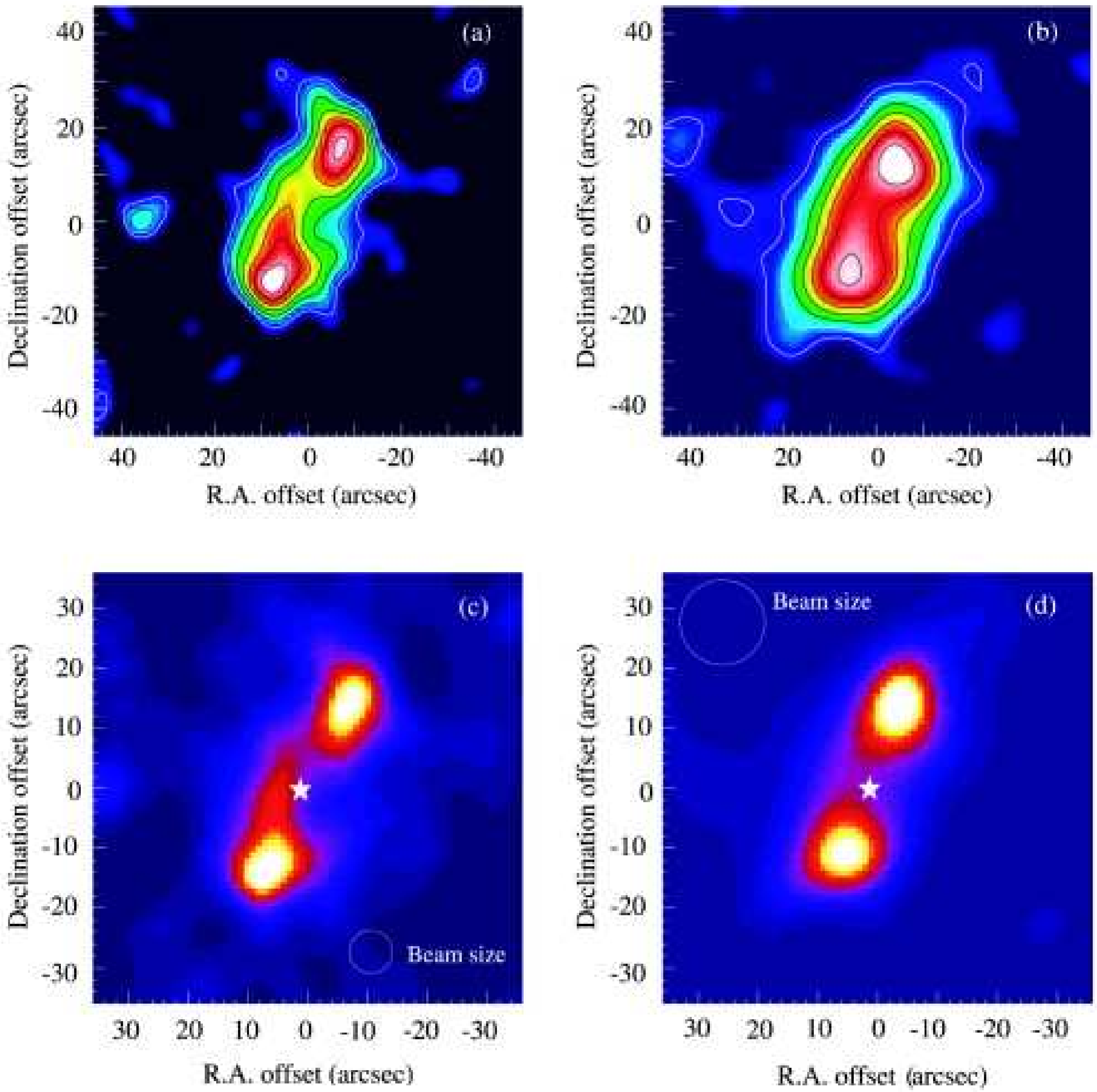
30deg phase noise

pointing error 0.6"

Tsys = 1200K (333µm) / 220K (870µm)

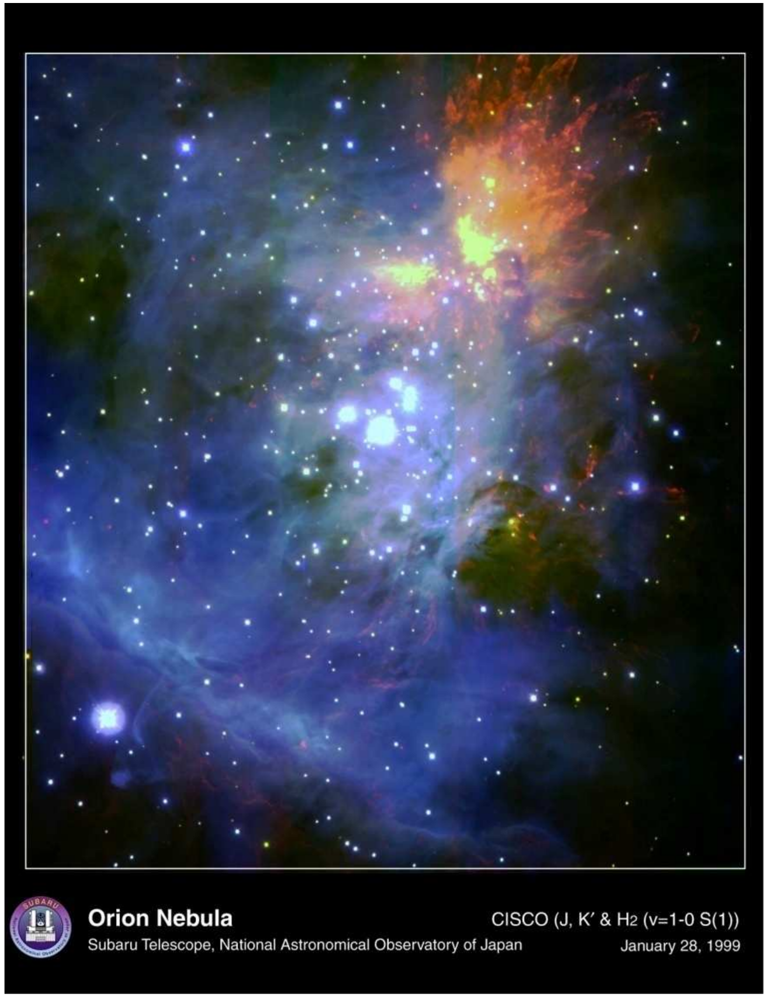
S. Wolf (2005)



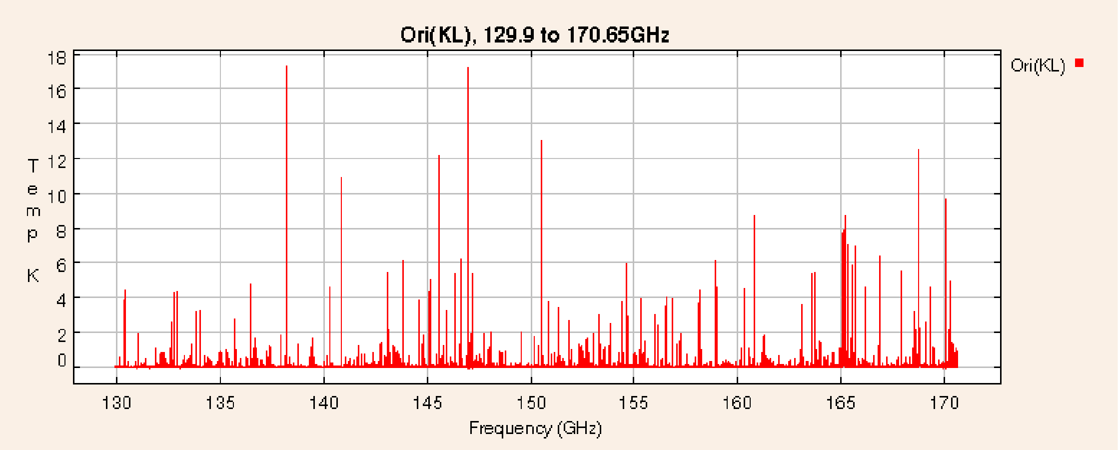


450/850 micrometer images of Fomalhaut. The contours are 13 and 2 mJy/beam. Below are deconvolved images (data from JCMT and SCUBA)

Contributors to the Millimeter Spectrum



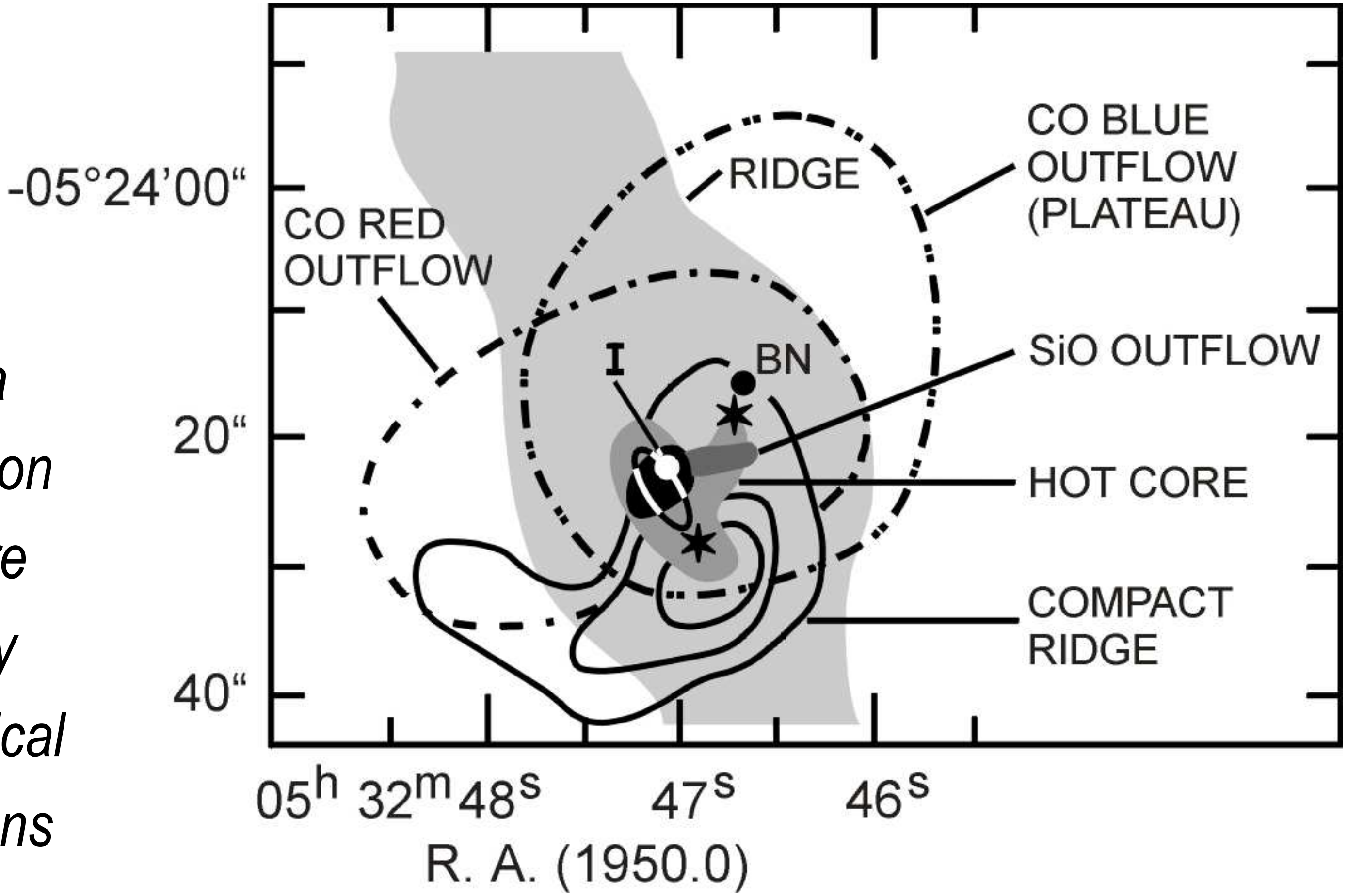
Spectrum courtesy B. Turner (NRAO)



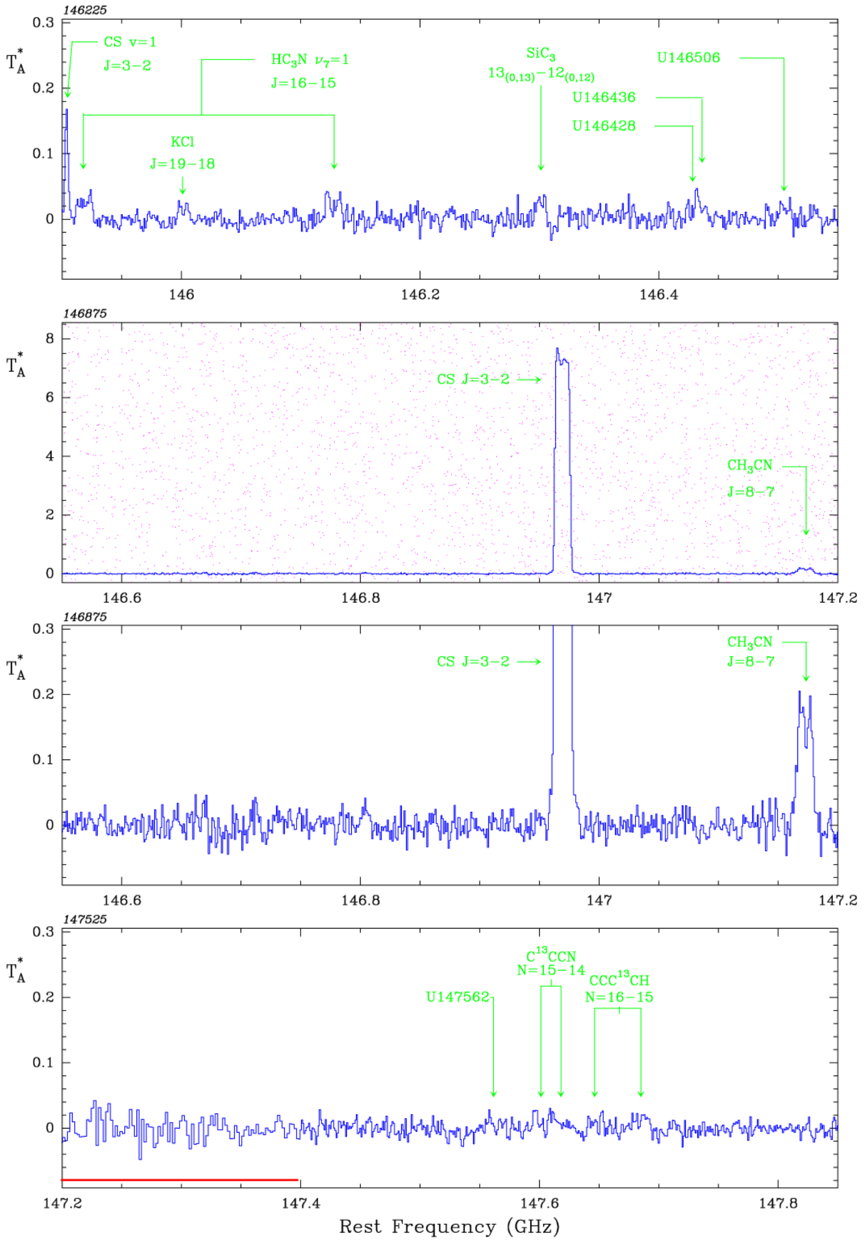
- In addition to dominating the spectrum of the distant Universe, millimeter/submillimeter spectral components dominate the spectrum of planets, young stars, many distant galaxies.
- Cool objects tend to be extended, hence ALMA's mandate to image with high sensitivity, recovering all of an object's emitted 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.

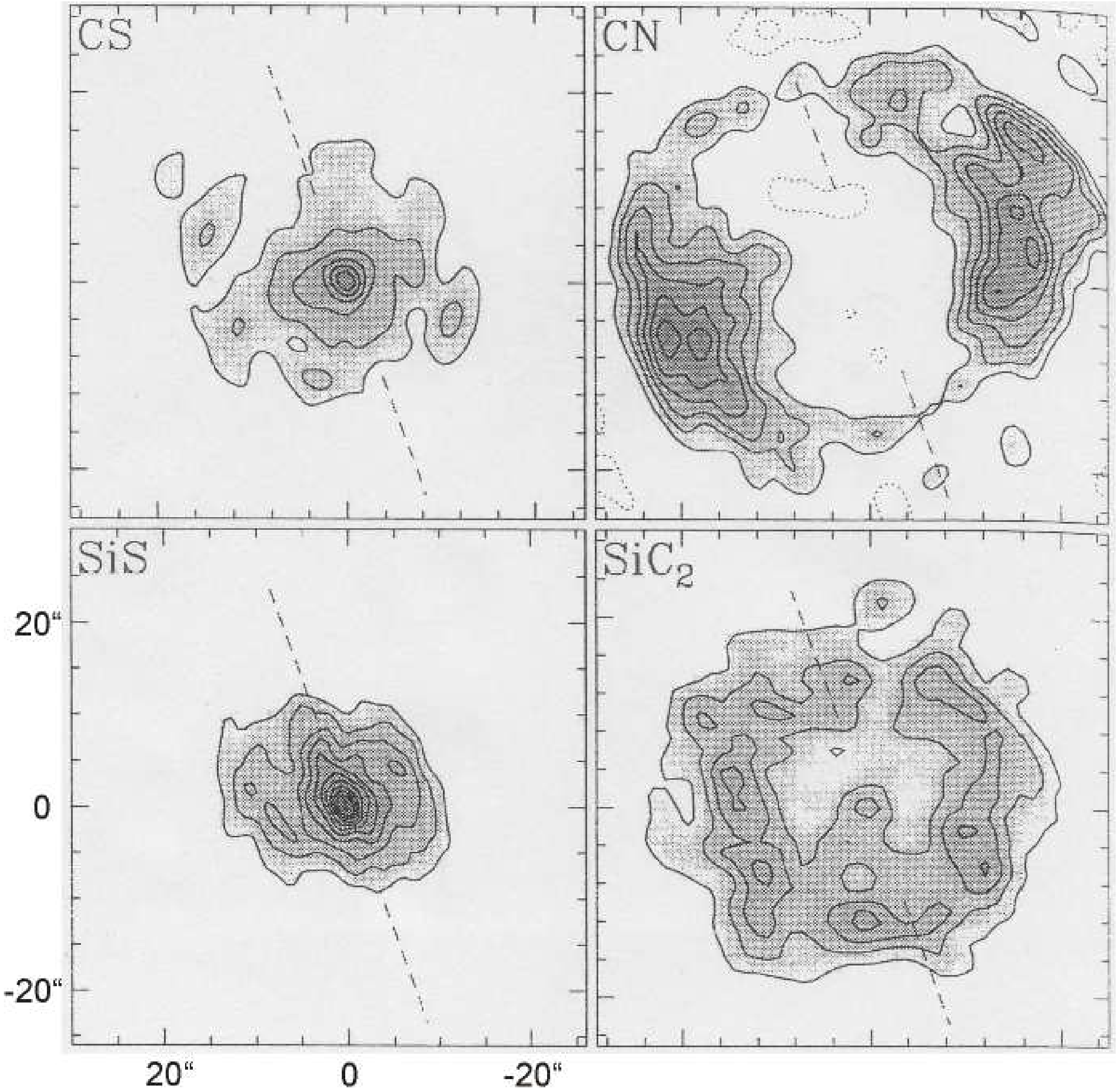
Orion KL: The Classical Hot Core Source

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