the ALMA project

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- A) Optical vs Millimeter Astronomy
- B) Why ALMA ?
- C) What is ALMA, the Atacama Large Millimetre Array
- D) Science with ALMA

A) Optical vs Millimeter astronomy

Item	Radio mm	Optical
λ ν	0.3mm to 1cm 30 to 900 GHz	0.4 to 30 μm 10 to 600 THz
Targets	Cold medium (10-100 K) Molecular clouds Extended structures	Hot medium (a few 1000 K) Stars Point sources

mm astronomy is adapted to the study of the **Cold Universe**. But most of the sky is dark and cold...

Optical vs mm

Item	Radio mm	Optical
λ ν	0.3 mm to 1 cm 30 to 900 GHz	0.4 to 30 μm 10 to 600 THz
	Telescope	
Structure	Open air	In dome
Thermal control	Passive structure	Semi-active control
Wind exposure	Direct	Protection by dome
Observing time	day & night	at night only
Pointing method	Blind pointing	Guide stars
Size for $0.1''$ res.	km $\Rightarrow$ interferometer	4-m, filled aperture
	Atmosphere	
Transparency	Clear means dry	Clear sky means little diffusion
Cloud impact	limited, liquid water	catastrophic
Seeing due to	water vapor fluctuations	temperature fluctuations
Seeing magnitude	0.2 - $2.0''$	0.2 - $2.0''$
Seeing timescale	10 sec - 30 min	0.01 - 0.1 sec
Adaptive optics	blind technique	on guide star

A bit of Jargon

Item	Radio mm	Optical
λ ν	0.3 mm to 1 cm 30 to 900 GHz	0.4 to 30 μm 10 to 600 THz
Resolution	(of array) Synthesized beam (of single telescope) Primary beam	Point Spread Function Airy disk
Field of view	(of single telescope) not used (of array) Primary beam of one telescope	Field
Intensity Units	Jansky (flux density) $1 \text{ Jy} = 10^{-26}$ W.m^{-2}.Hz^{-1} or Kelvin (brightness) (linear scales)	Magnitudes (arbitrary) (log scale)
Detector performance	Noise temperature	Quantum efficiency

mm Interferometry

- Large monolithic telescope cannot be build at mm wavelengths (a 100-m telescope would have only 7″ resolution at 3 mm).
- Instead, arrays of smaller dishes (6 to 15-m) are combined into **interferometers.**
- Heterodyne receivers convert the original signal into lower frequency signals (this preserves the `phase, frequency & amplitude` of the original radio wave, like in your Frequency Modulation radio).
- These low frequency signals are ultimately digitized by high speed Analog/Digital converters (`sampler`).
- The digital outputs from several antennas are multiplied into a digital `correlator`.
- The whole process is equivalent to measuring the `visibility` of the interference pattern between the antennas.
- To produce an image, the visibilities must be measured for all possible separations between the antennas (distance and orientation), to `synthesize` the equivalent of a large antenna (of diameter equal to the longest baseline)
- Earth rotation allows to derive the visibilities on many projected baselines.
- The images are derived from the `visibilities` by Fourier transform, followed by deconvolution techniques.

Interferometry Comparison

Item	Radio mm	Optical
Seeing, origin Fried Parameter r_o (size of the coherence cell) Coherence Time t_o Atm.correction	W(H_2O) $\gg$ antenna Single-speckle 1 min to days T_{sys} variations radiometric phase correction	ΔT_{atm} $\leq$ telescope Multi-speckle 10-100 $m$seconds photometry monitoring adaptive optics
Noise sources	background limited thermal (gaussian dist.) Atmosphere (+receiver)	photon limited $\leq 1\mu$m detector $1 - 2\mu$m thermal(atm) $\geq 2.5\mu$m
Detection Spectral Resolution	Indirect: multiplying $\frac{\Delta\nu}{\nu} = 10^{-3} - 10^{-7}$	direct: adding $\frac{\Delta\lambda}{\lambda} = 10^{-1} - 10^{-3}$
Measurements	complex visibility V complex correlator: r_i,r_r	fringe contrast ($\mid V \mid$) $V_{12}^{raw} = \frac{I_{max}-I_{min}}{I_{max}+I_{min}}$
Imaging Algorithms	$\mid V \mid$ & Φ_V all standard imaging	$\mid V \mid$ + phase retrieval by closure relations + amplitude model fitting in the UV plane

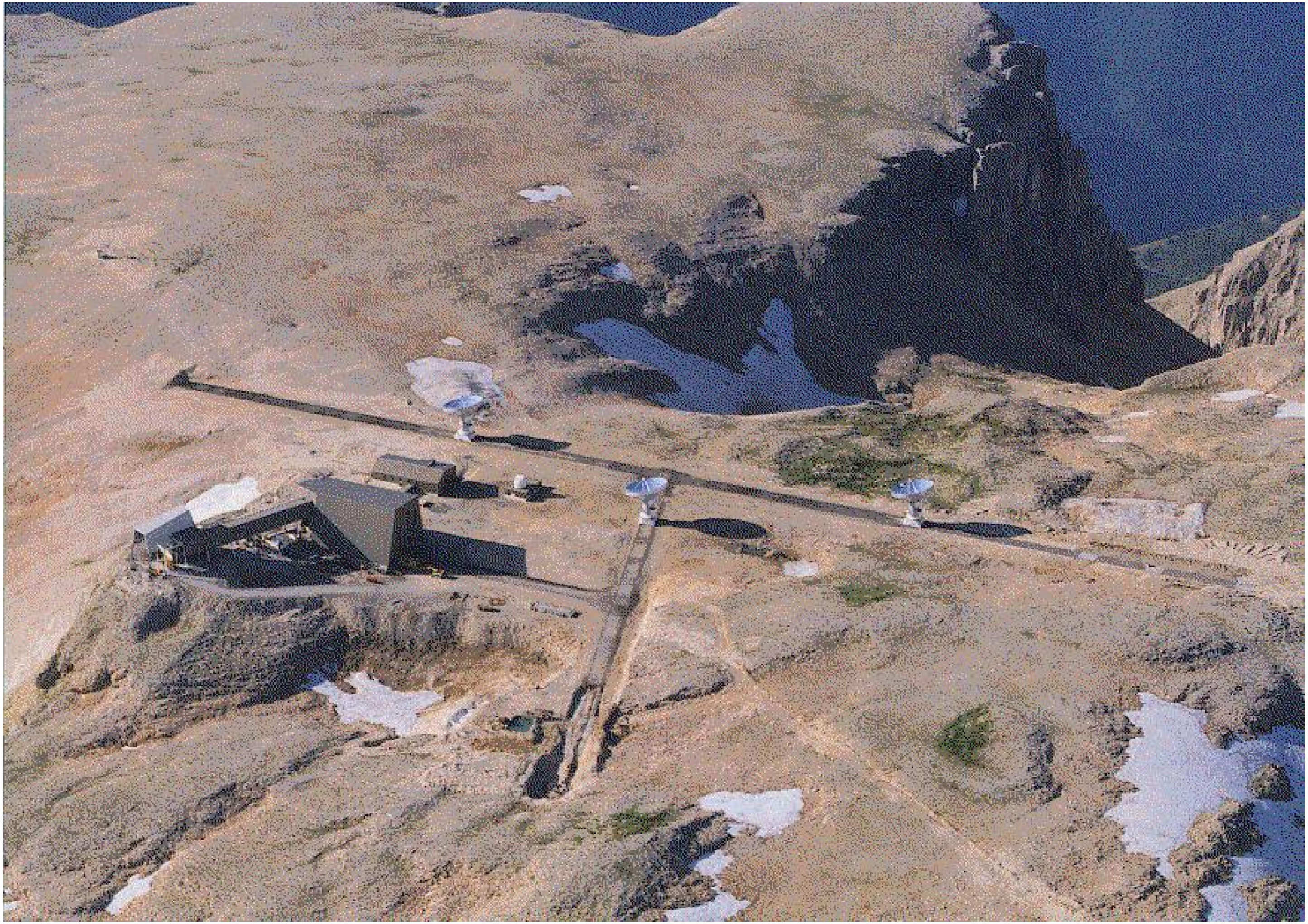
What is ALMA ?

ALMA is the radio equivalent of
an 8-meter class optical telescope

and we will have only one in the world (sigh...)

- Current mm radio-telescopes (single dish) are just somewhat better than Galileo lenses...
- Current mm arrays are comparable with the mid 20$^{\mathrm{th}}$ century typical optical telescope (1-m class).
- Yet, only 4 are into operations now: BIMA, OVRO, NRO and IRAM.
  - **USA BIMA: Berkeley-Illinois-Maryland Array**
  - **USA OVRO: Owens Valley Radio Observatory**
  - **Japan NRO: Nobeyama Radio Observatory (+ Rainbow interferometer)**
  - **EUROPE (IRAM: France/Germany/Spain): Plateau de Bure Interferometer (PdBI)**

IRAM array (oct. 1999, courtesy S.Muller). Plateau de Bure (french Alps, 2550m). Area $= 880\text{m}^2$ (5Ant.). Best Resol. $= 0.5''$ at $\delta \simeq 30^o$. Dual Frequency receivers 85-115 GHz (3mm) & 208-248 GHz (1.3mm).



IRAM array (june 1997, copyright IRAM). The E-W track is doing an angle of $\sim 15^o$ with the west. Baselines are: N-S = 232m, E-W=408m.

B) Why ALMA ?

- **Strong limitations from current arrays (PdBI, OVRO, NRO, BIMA)**
  - In sensitivity (PdBI, the most sensitive)
  - In angular Resolution (baselines of 2 km for BIMA, $\sim$ 500 m elsewhere)
  - In frequency Coverage (SMA will likely open the sub-mm window)
  - In imaging Capability (limited to 5-6 or 9 antennas, in cm VLA has 27 antennas)

- **GOALS: get a factor 5 in resolution = a factor 25 in sensitivity (at 1.3mm)**
  - Continuum: 1 hour integration time $\longrightarrow$ 6 μ Jy/beam or a factor 100 compared to PdBI...
  - Spectral lines: 10 hours integration time $\longrightarrow$ 1.1 m Jy/beam or a factor 30 compared to PdBI...

- **In the mm/sub-mm windows, the atmosphere dominates the noise**

Need for a LARGE COLLECTING AREA $\longrightarrow$ ALMA !

B) ALMA: genesis

- **USA:** a small array (2000 m^2), to produce large field imaging: the MilliMeter Array (MMA), with opening windows towards sub-mm λ.
- **Europe:** a large array (10000 m^2), purely working at mm λ, to produce high angular resolution maps: the Large Southern Array (LSA)
- **Finally:** a combination to get a large array (7000 m^2 done with 64 antennas of 12m diameter) covering all frequencies from 70 GHz to 900 GHz, with baselines up to 10 km.
- **Likely in Collaboration with Japan (initial projet LMSA, 50 antennas of 10-m).**

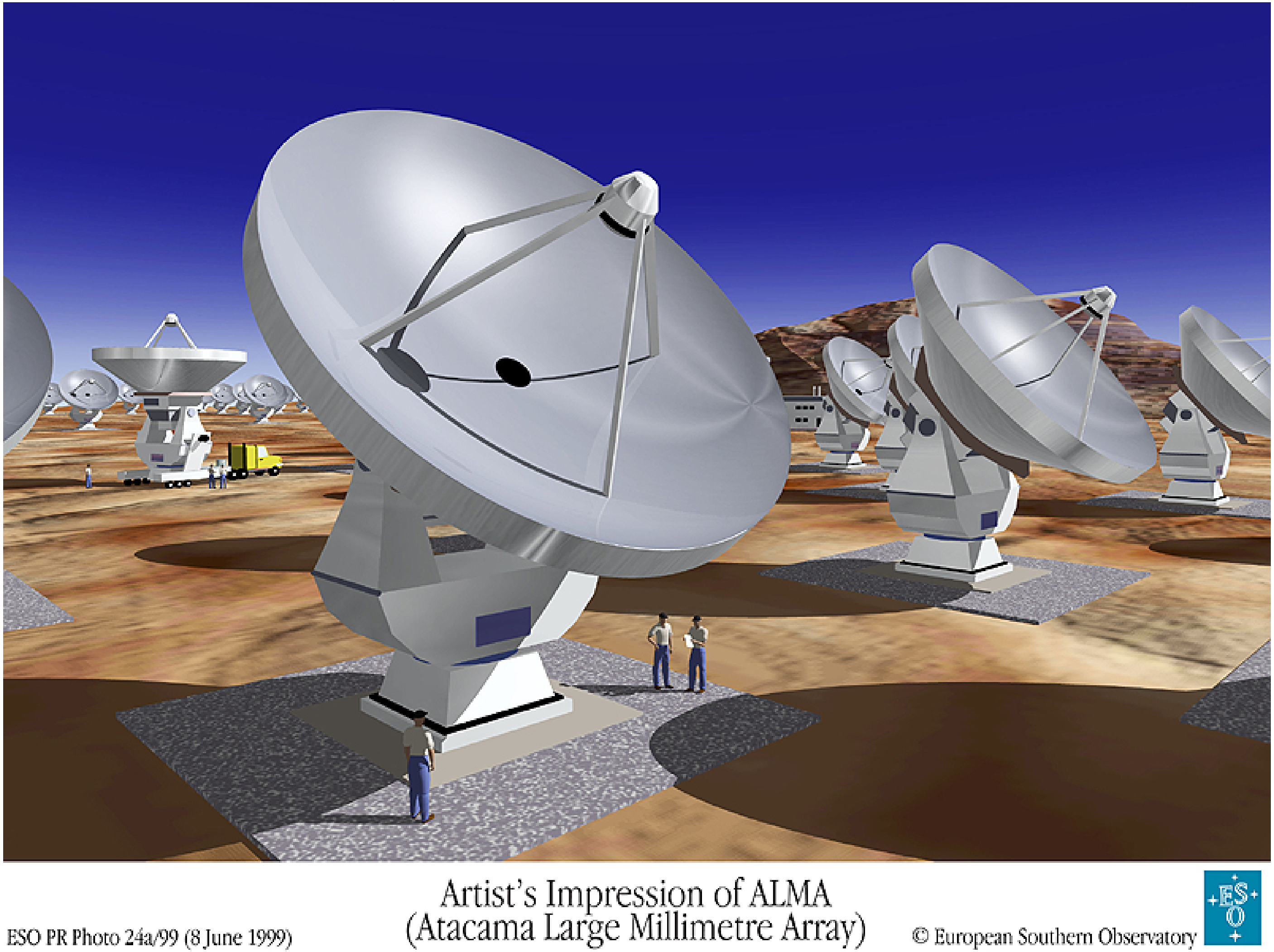
A) ALMA: the Site

Panoramic View of the Proposed Site for ALMA at Chajnantor

ESO PR Photo 24e/99 (8 June 1999)

© European Southern Observatory

A) ALMA: the Instrument

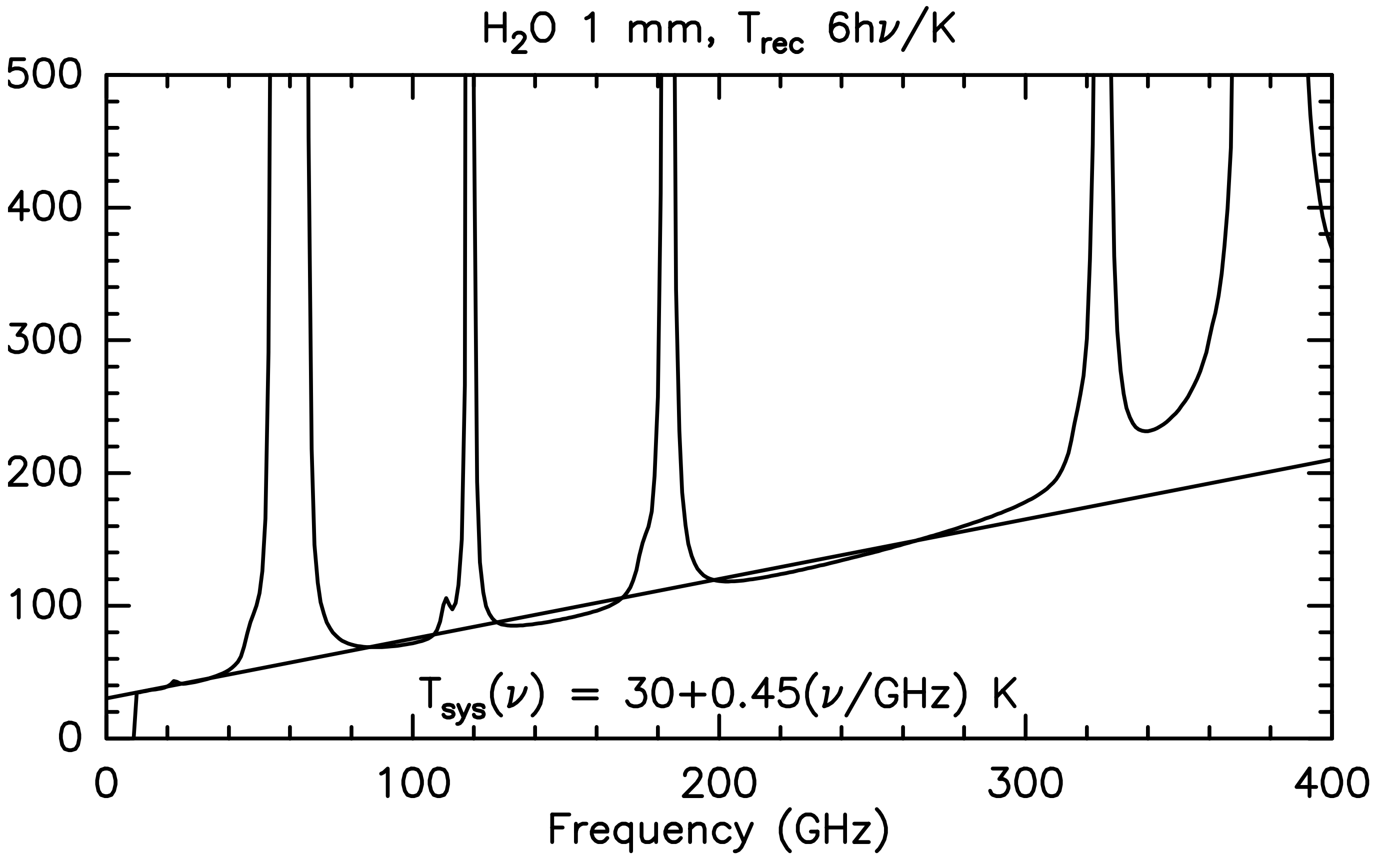


B) ALMA: comparison with current arrays

- Intantaneous UV coverage: 2016 simultaneous baselines. No longer requires to wait for the Earth rotation to get images (at least in the 2 more compact configurations).
- Large spatial dynamic: i.e. images with lots of pixels. The images will have at least 128 x 128 px (for compact array) up to 8192 x 8192 px and more...
- Large field imaging capability (mosaicing): thanks to the total power measurement (well, we would prefer the ALMA Compact Array, but we still can convince Japan to join)
- High fidelity imaging: some images will have a high signal-to-noise ratio (but not all...)
- Multi-frequency receivers: initially 4 bands: 86-116 GHz (# 3) 210-275 GHz (# 6), 275-370 GHz (# 7) and 590-720 GHz (# 9). At the end, frequency ranges from 30 GHz to 900 GHz in 10 bands (# 1 to # 10).
- User friendly instrument: at least for simple imaging... (but not at the beginning for on-the-fly mosaicing at 650 GHz...)
- Large band-width (8 GHz even 2×8 GHz): a revolution to study giant planets atmospheres.
- Very high angular resolution angular: up to $0.01''$ ...
- Polarization

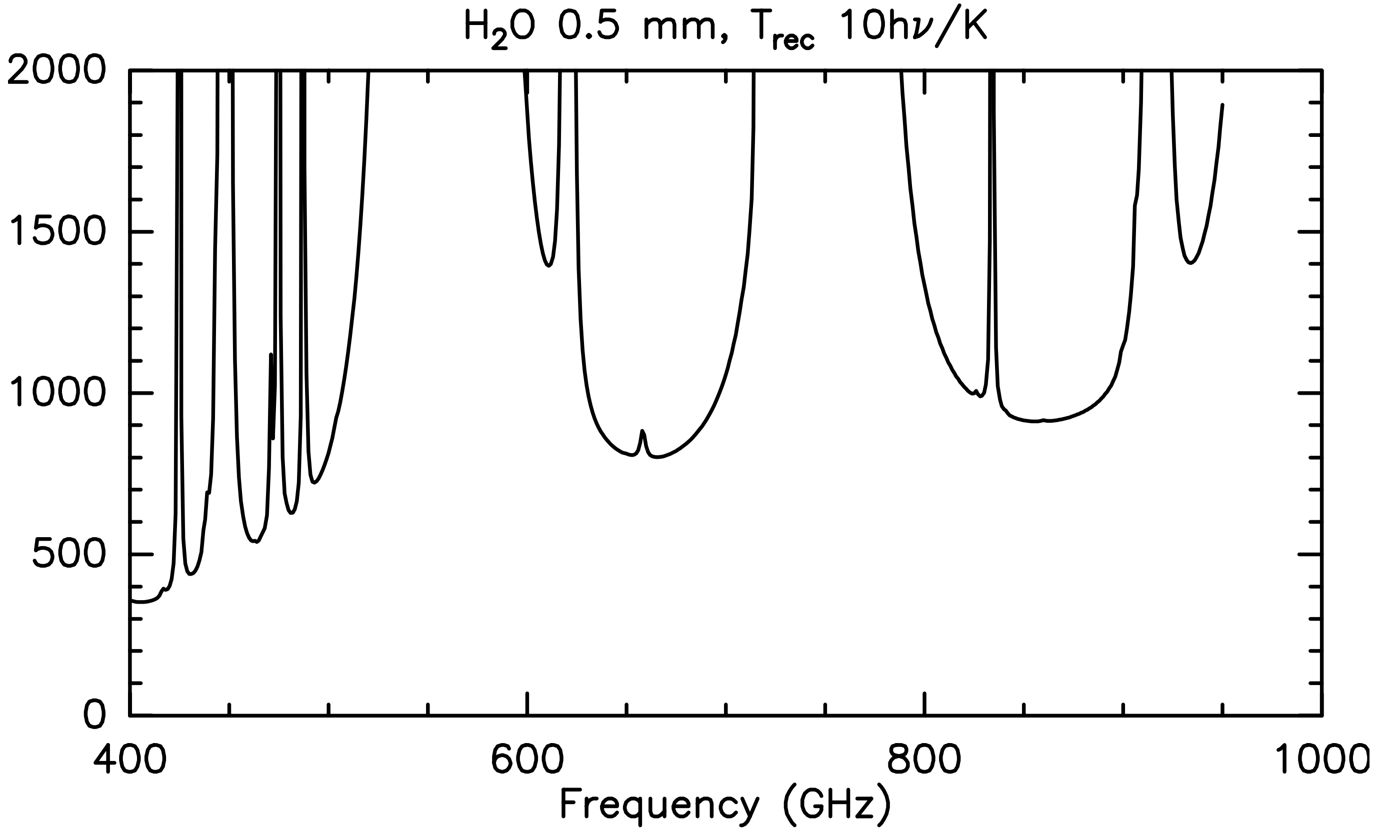
B) ALMA: Sensitivity - *i*

- Empirical law in the mm (75 % of the time is dedicated to observations)



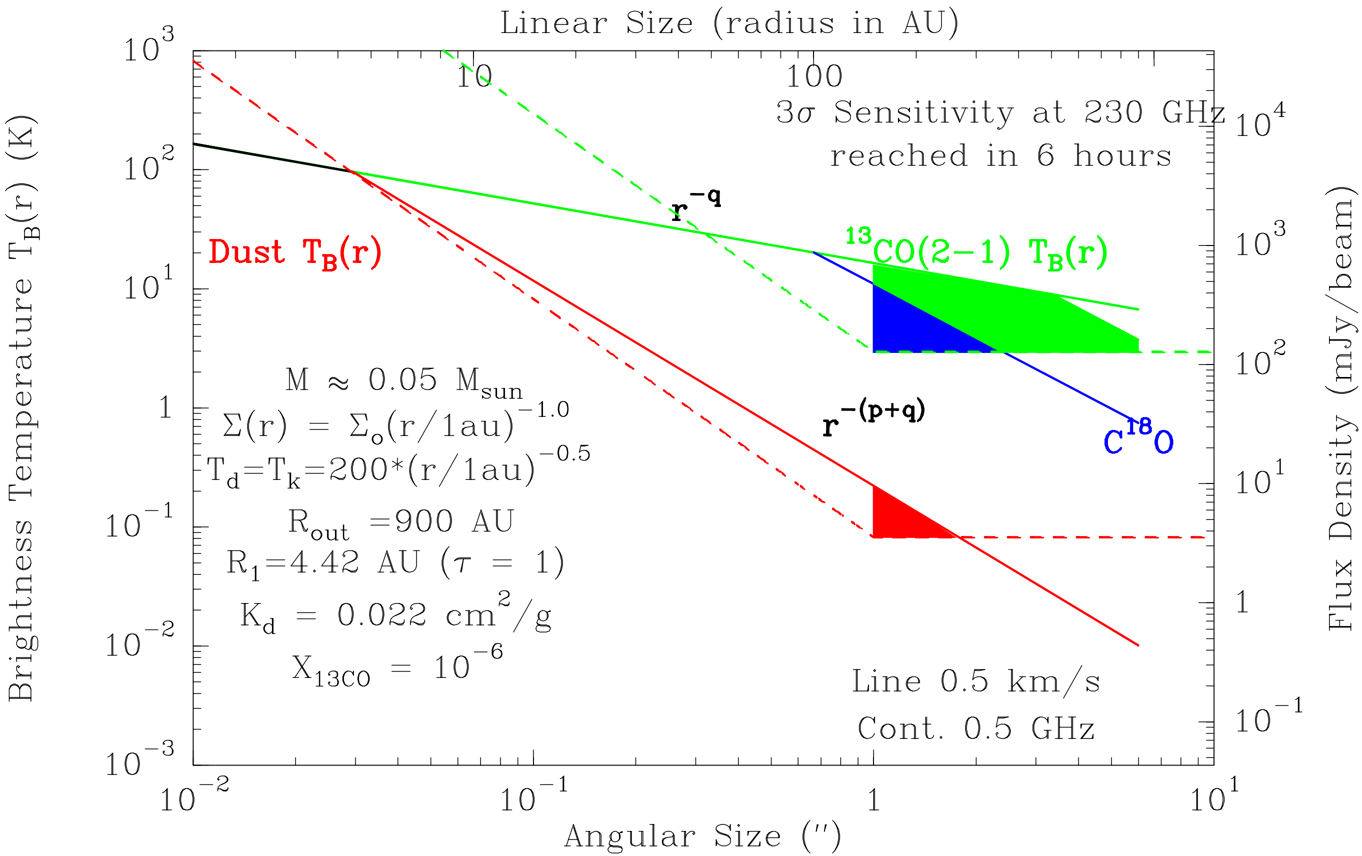
B) ALMA: Sensitivity - *ii*

- Empirical law in the sub-mm (25 % of the time is dedicated to observations)



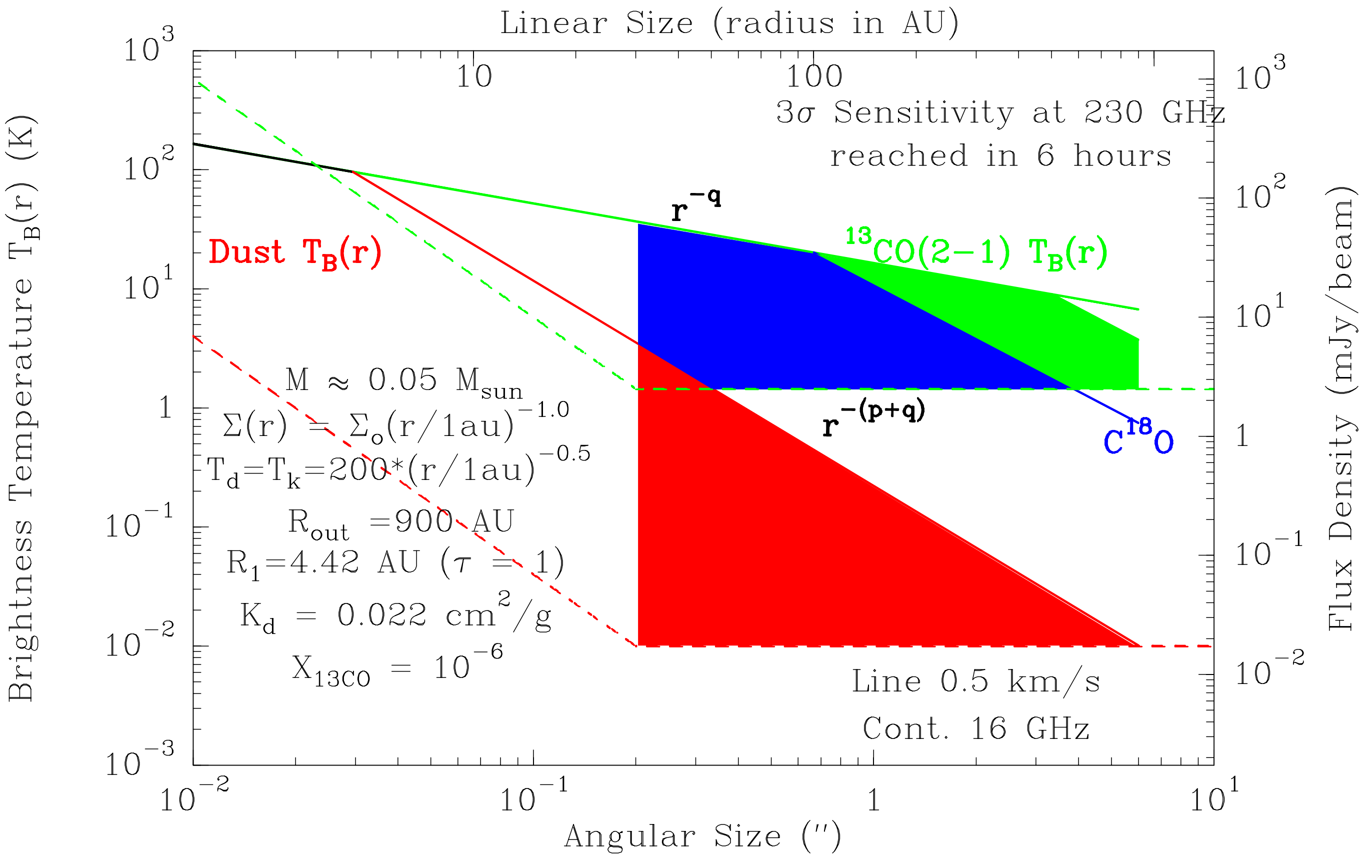
B) Sensitivity curves for protoplanetary disks -

- Current situation at PdBI:

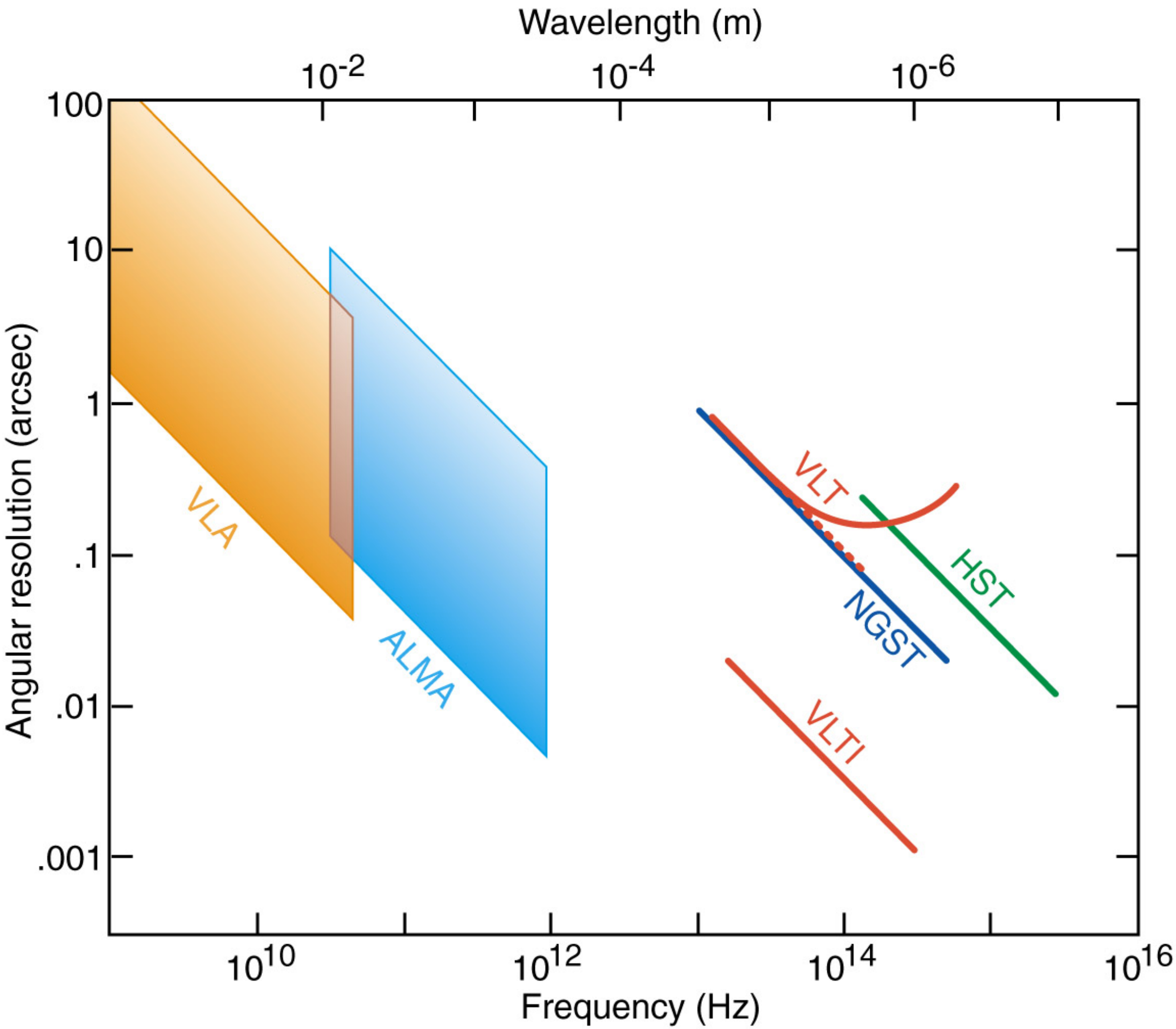


B) Sensitivity curves for protoplanetary disks -

- Future situation with ALMA



B) Resolution compared to other instruments



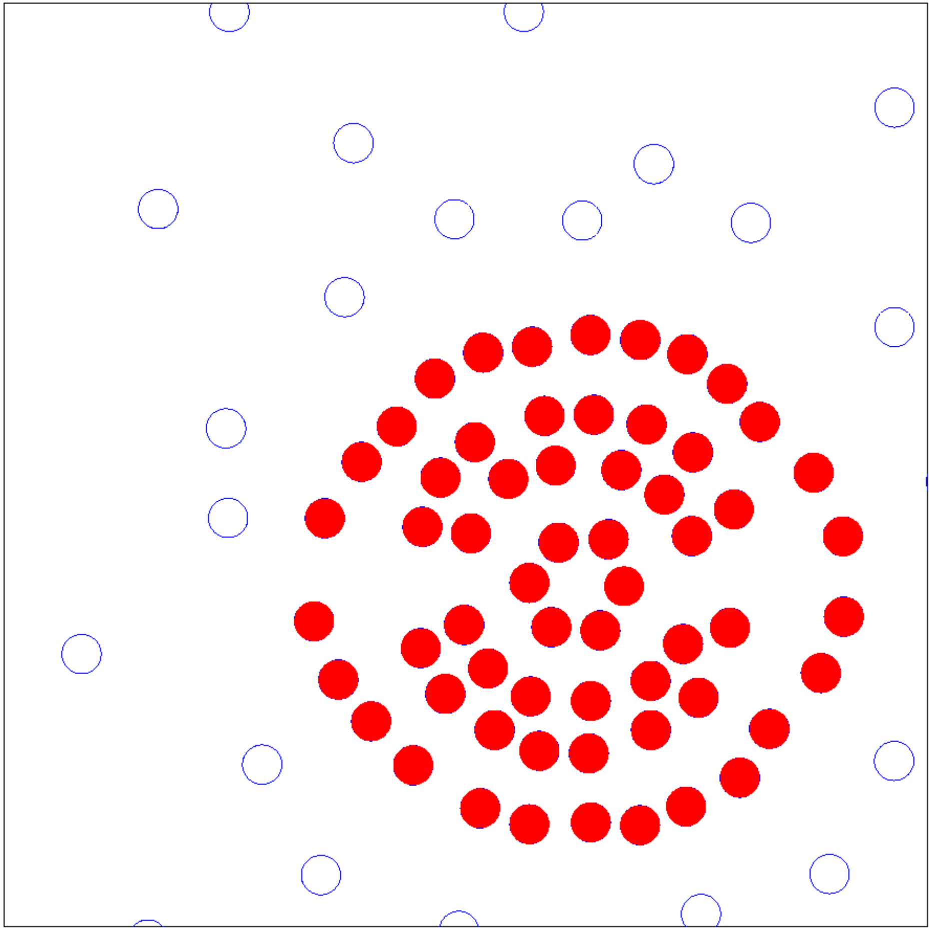
C) What is ALMA ? (1)

- **Atacama Large Millimeter/submillimeter Array**
- 64 antennas of 12-m diameter
  - May-be also $7 - 15$ antennas of $6 - 8$-m to measure the short spacings (the so-called ALMA Compact Array or ACA)
  - High surface accuracy (20 μm rms)
  - High pointing accuracy (0.6$''$ rms)
  - Low antenna noise (good antenna efficiency)
  - **fast repointing** 2 degrees in less than 2 seconds, to freeze the atmosphere to correct for atmospheric phases
- High fidelity imaging:
  - precision calibration (1–3 %)
  - Active compensation of the atmospheric phase (Water Vapor Radiometer)
  - optimized array design
- Baselines: from a compact array of 150-m in diameter to a high angular resolution configuration of 14 km.
- Site of very high altitude (5000 m)

C) What is ALMA ? (2)

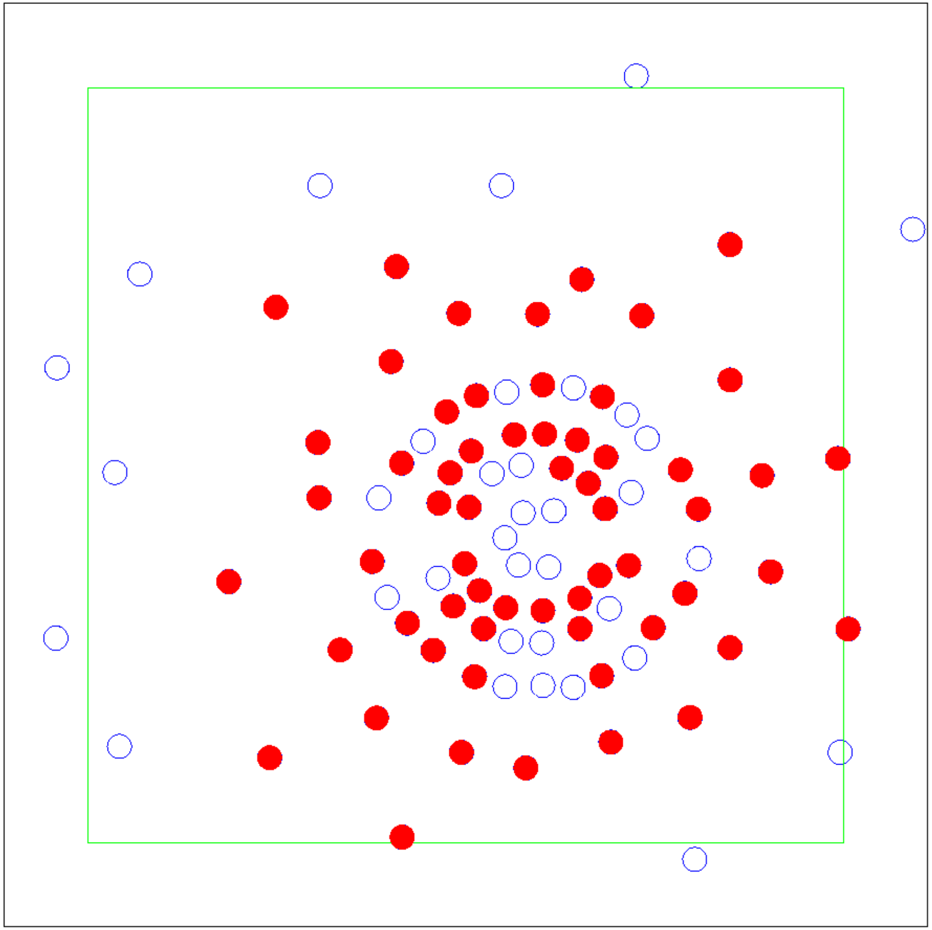
- Multi-frequency receivers
  - Initially 4 bands: 86-116 GHz (# 3) 210-275 GHz (# 6), 275-370 GHz (# 7) and 590-720 GHz (# 9)
  - At the end, frequency ranges from 30 GHz to 900 GHz in 10 bands (# 1 à # 10)
- but not simultaneously: each frequency band points in a different direction
- Dual polarization
- 8 GHz band-widths for each polarization of each receiver ($\Delta\nu = 16$ GHz)
- Digital sampling in 4 bands of 2 GHz each (clock speed at 4 GHz)
- Specialized modes
  - VLBI
  - sub-arrays: e.g. for simultaneous multi-frequency of time variable phenomena
- Mosaicing as a routine observing mode

(possible) ALMA configurations



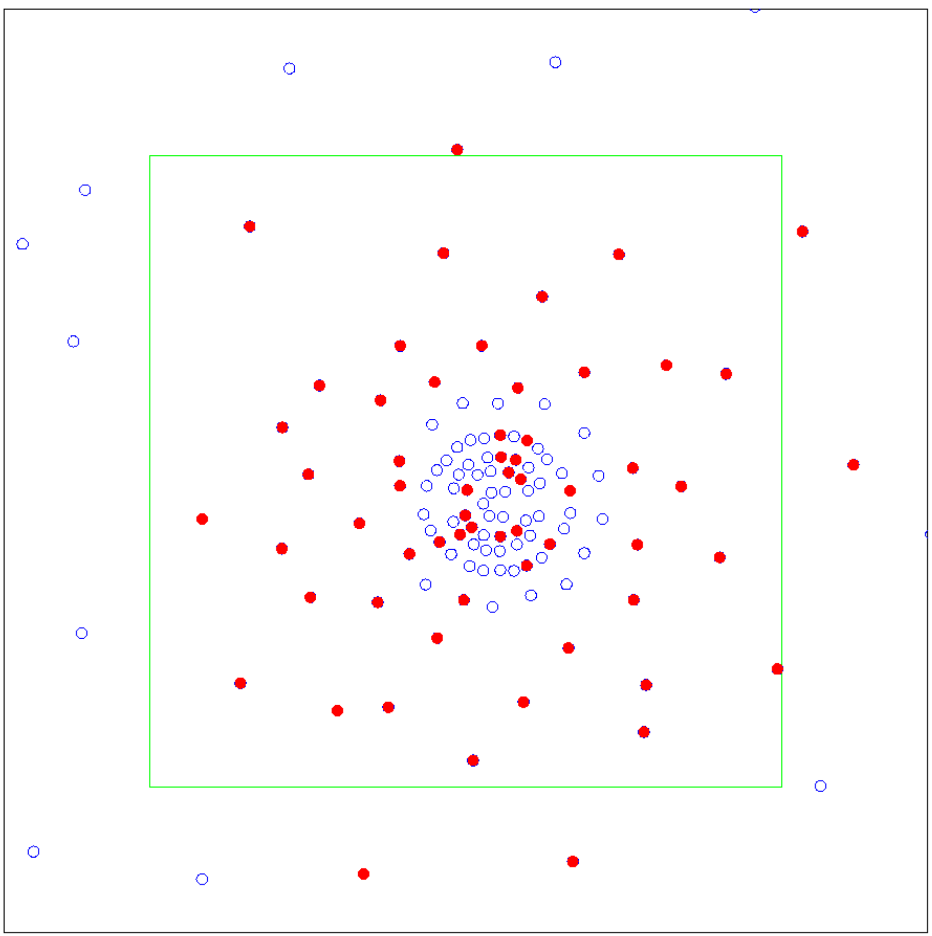
from
a very
compact
(< 200 m)

(possible) ALMA configurations



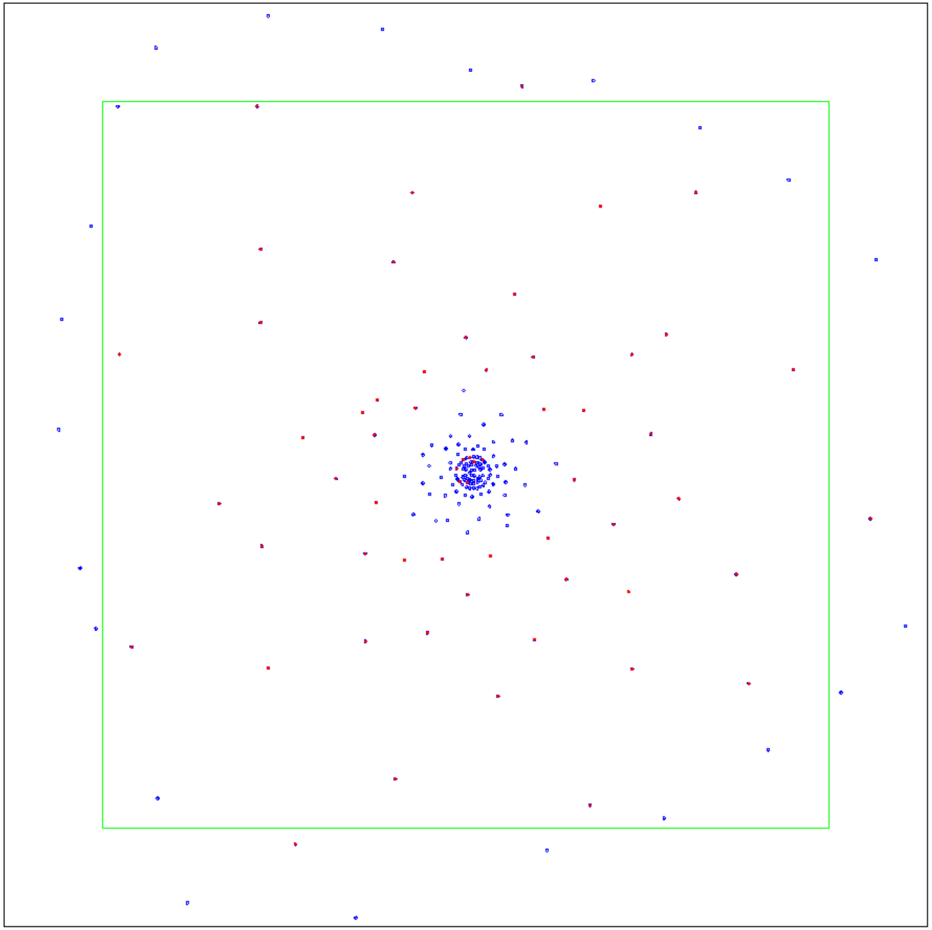
to
larger

(possible) ALMA configurations



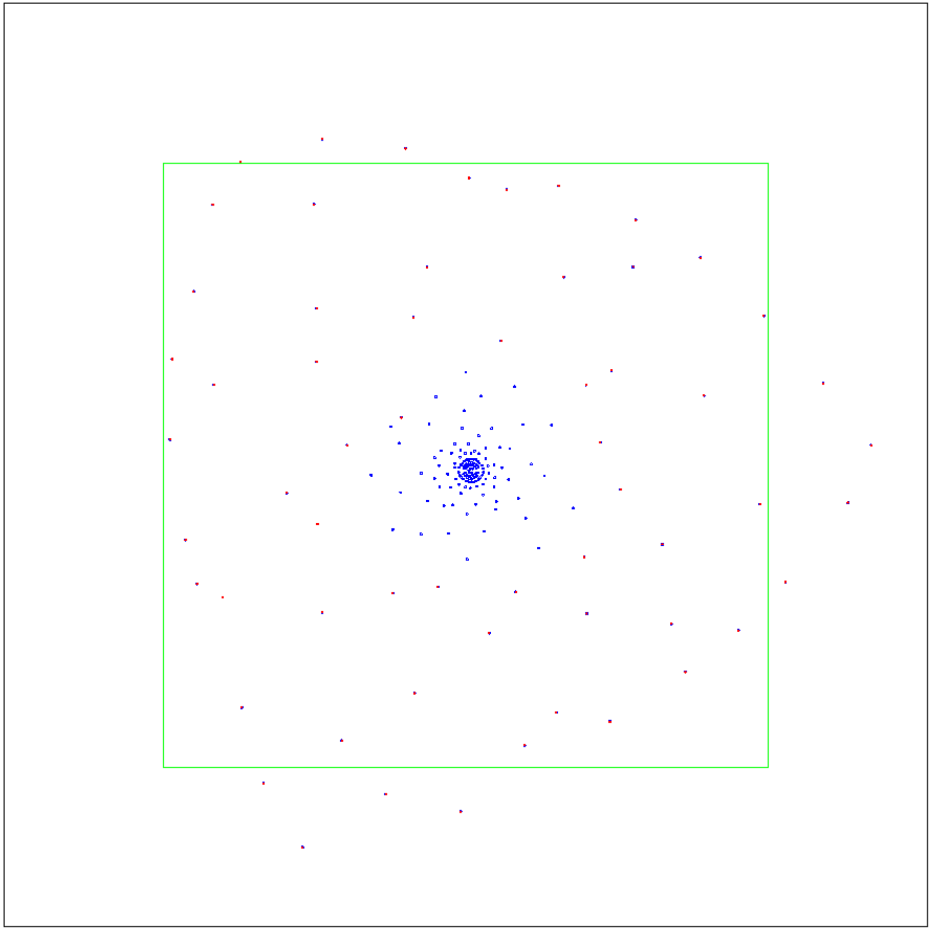
and larger

(possible) ALMA configurations



up to
several km
baselines

(possible) ALMA configurations



almost continuously

C) A unique sensitivity

- Side band separation receivers: to reject the noise from the image band.
- Large band-width (8 GHz): to optimize the continuum sensitivity, in particular will allow a very fast calibration.
- Dual polarization: for a better sensitivity but also to measure polarization in astronomical sources (almost never done yet)
- Antennas of high quality: to reduce the ground noise, and to maximize the coupling to the source. Will also allow high frequency observations.
- Pointing of high accuracy: to allow mosaicing, even at high frequencies.
- The best site: to minimize the atmospheric phase noise and system temperature (therefore to maximize the integration time).
- Active atmospheric phase correction: required even on the best terrestrial site...

Technical Challenges

- Observe Day & Night: no maintenance period ...
- 4 K cryogenic coolers, working 24 hrs a day, 365 days a year
- Ultra high speed digital electronics: 4 GHz clock rate. High performance A/D converters (stability)
- Low cost, zero maintenance, 12-m parabolic antennas, with blind pointing accuracy better than $1''$ under windy conditions, with accurate surface even under solar illumination
- Antennas must be transportable: move 100 tons antennas of 20μm precision over 14 km...
- Fiber connections for the local oscillator signal requires extremely high precision.
- 5000-m elevation site
- Medium sized series (64 antennas, 64 cryostats, 1300 receivers, 1300 high speed A/D converter, 2016 baselines)
- Require smart cost / reliability compromise
- Large collaborations (neither ESO, nor NRAO are/were used to, Japan even less...)

C) ALMA versus the VLT

- ALMA has many telescopes (64) but a unique combined focus, with a unique "focal plane" equipment
- VLT has few telescopes (4) but each with different focal plane instrumentation
- VLT has "wide" field imaging capabilities, with photometric cameras and multi-object spectroscopy.
- ALMA has "small" (less than 1 arcmin) field of view, but with integral field spectroscopy in this field, with high spectral resolution (fraction of km/s).
- ALMA makes up its wide field capability by mosaicing adjacent fields.
- VLT has many observing modes (one per focal plane instrument at least)
- ALMA has basically one observing mode (well, actually two)
- VLT produces images
- ALMA produces visibilities. It relies on software to convert that to images...

D) ALMA: scientific goals

- **ALMA is not a specialized telescope,**
- **but very well suited to some domains**
  - High-Z universe
  - Structure and evolution of galaxies
  - Stellar formation and evolution
  - Planetary system formation
  - Interstellar chemistry (from galaxies to protoplanetary disks)
  - Solar system
- **One should even observe the Sun...**(if antenna surface allows...)

Observing with ALMA

- Only one ALMA in the world:
  - only internal competition
  - in general, no double-check possible
  - may require different strategy to get the best science out of it
  - Large scale surveys may need dedicated scheduling policy
  - ALMA scheduling may resemble satellite operation
- ALMA will make use of flexible scheduling. Observers won't perform their own project, but be delivered the "final product"
- ALMA "final product" will in general be **images**. However, *image analysis* requires to understand the interferometric image properties.
- ALMA will offer a variable choice of angular resolution: science objectives should dictate which is the best (compromise resolution/sensitivity)