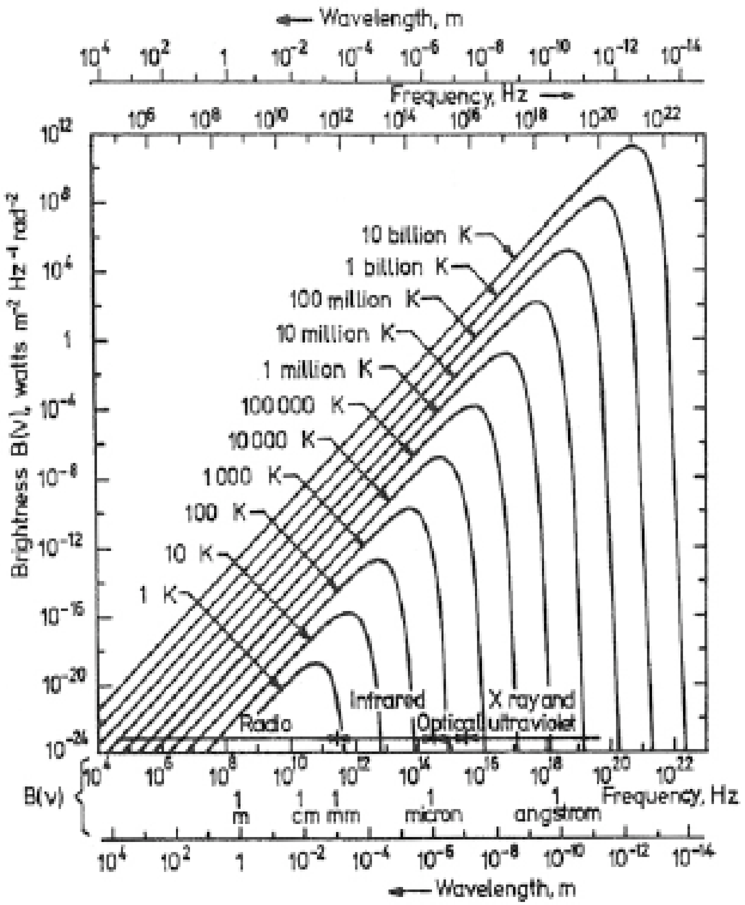
Millimeter observations

- Interest to observe at mm wavelengths
- Instrument basics
- Observing techniques
- Current millimeter facilities
- ALMA
- Science with ALMA

Interest to observe at mm wavelengths

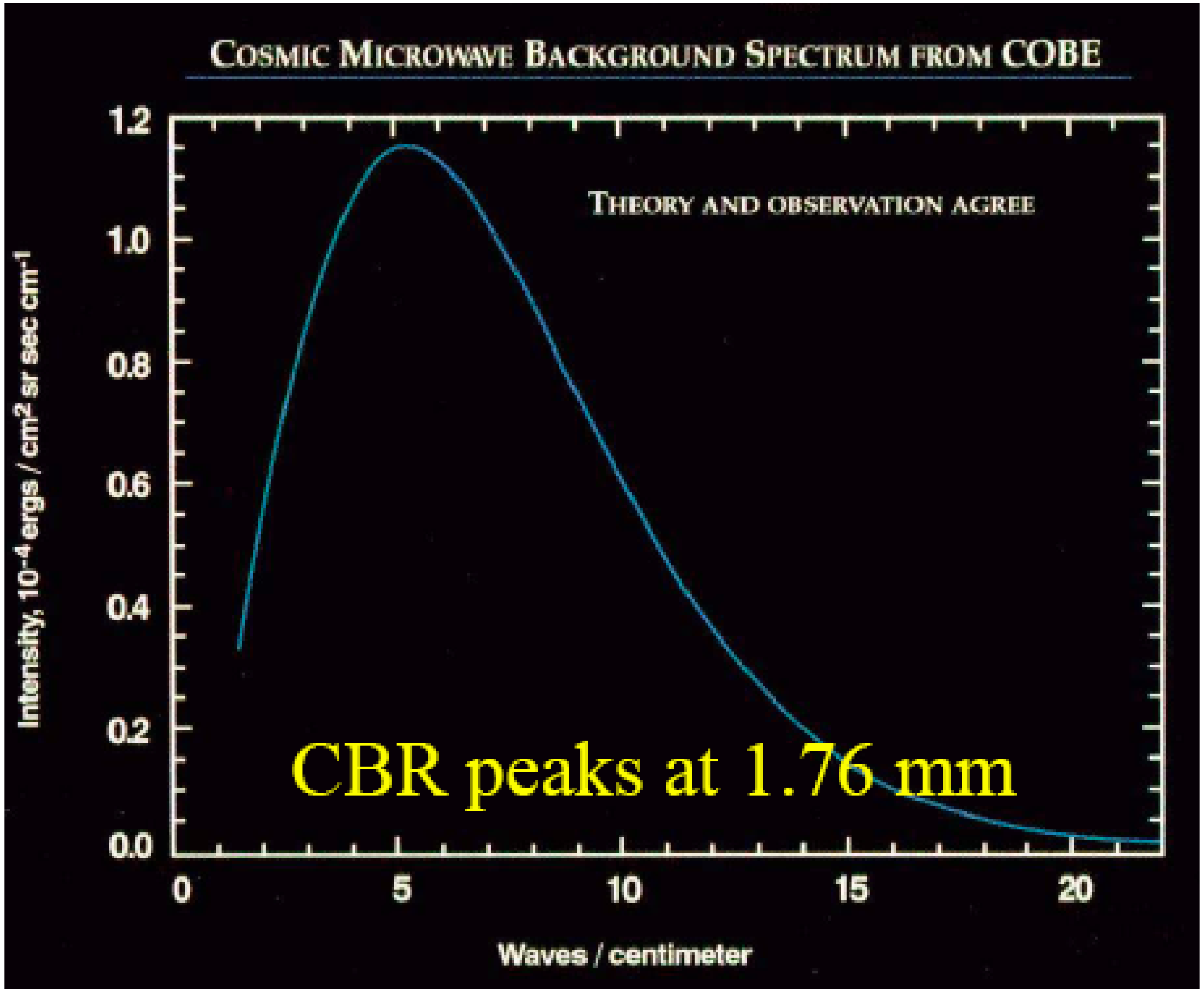
visible	millimeter
Star: 3000-100'000 K Ionized gas: 10'000K	Cold matter: 3-70 K Dust and molecules



- Peak of black body emission:
  λ = hc/3kT = 0.48/T cm
  → T = 3 K, λ = 1 mm
  T = 10 K, λ = 0.3 mm
- Peak of dust emission:
  λ = hc/(3+β)kT = 0.3/T [cm]
- Typical energies involved in molecular transitions
- SED of galaxies
- SZ effect

Examples (1)

Black body emission:
cosmic microwave
background radiation



Examples (2)

Diffuse cloud properties:

$n = 10\text{-}10^3\ cm^{-3}$
$T = 20\text{-}100\ K$
$A_V < 1$

Dark cloud properties:

$n = 10^3\text{-}10^6\ cm^{-3}$
$T = 8\text{-}15\ K$
$A_V > 1$

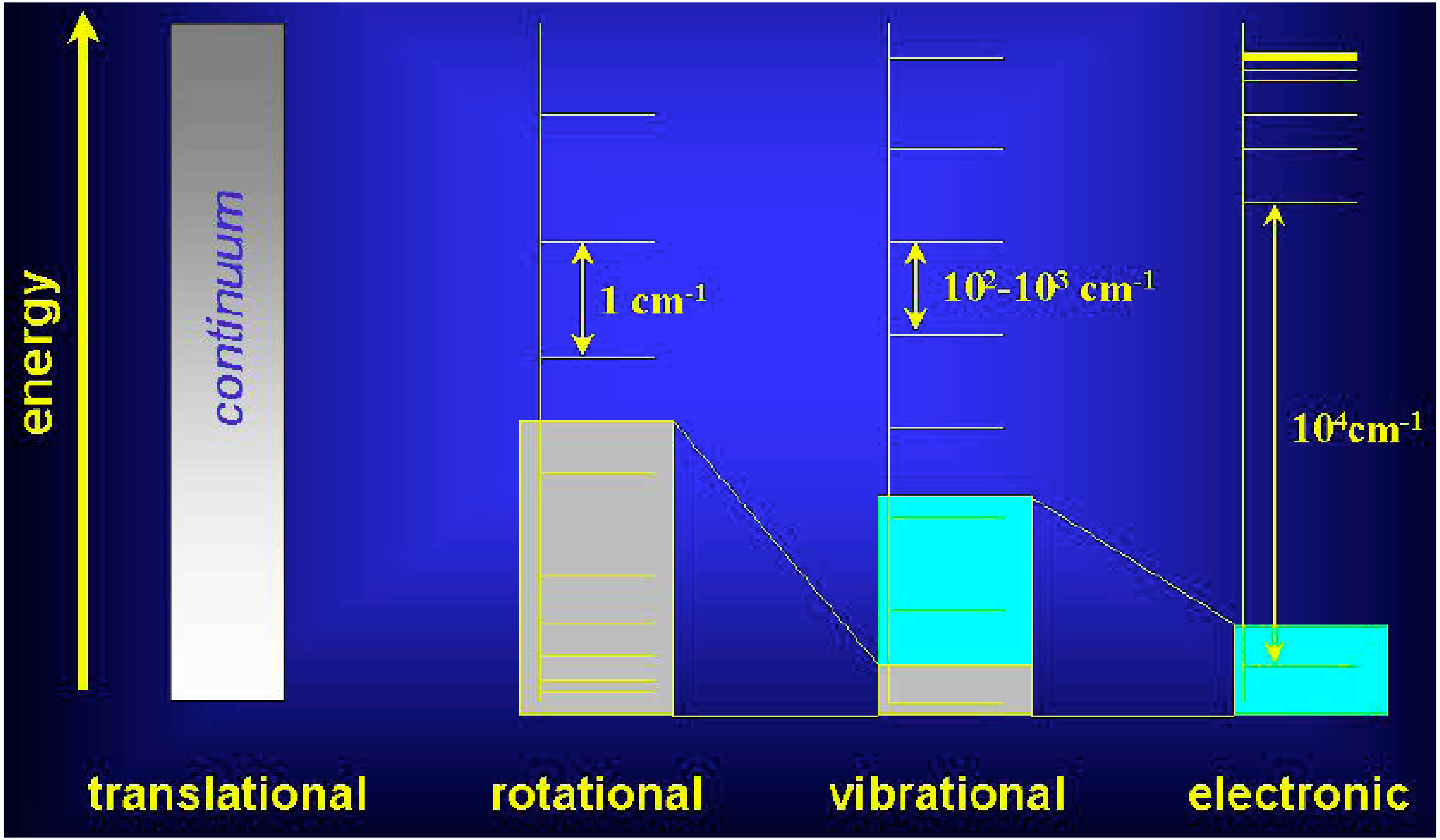
↓

peak of dust emission at 0.3 mm

Examples (3)

Typical energies involved in molecular transitions:

molecular low-energy rotational transitions lie at mm wavelengths



Examples (3)

Presently, more than 140 molecular species have been detected in the ISM:

Hydrogen Compounds

H_2	HD	H_3^+	H_2D^+		

Hydrogen and Carbon Compounds

CH	CH^+	C_2	CH_2	C_2H	*C_3
CH_3	C_2H_2	C_3H(lin)	c-C_3H	*CH_4	C_4
c-C_3H_2	H_2CCC(lin)	C_4H	*C_5	*C_2H_4	C_5H
H_2C_4(lin)	*HC_4H	CH_3C_2H	C_6H	*HC_6H	H_2C_6
*C_7H	CH_3C_4H	C_8H	*C_6H_6		

Hydrogen, Carbon (possibly) and Oxygen Compounds

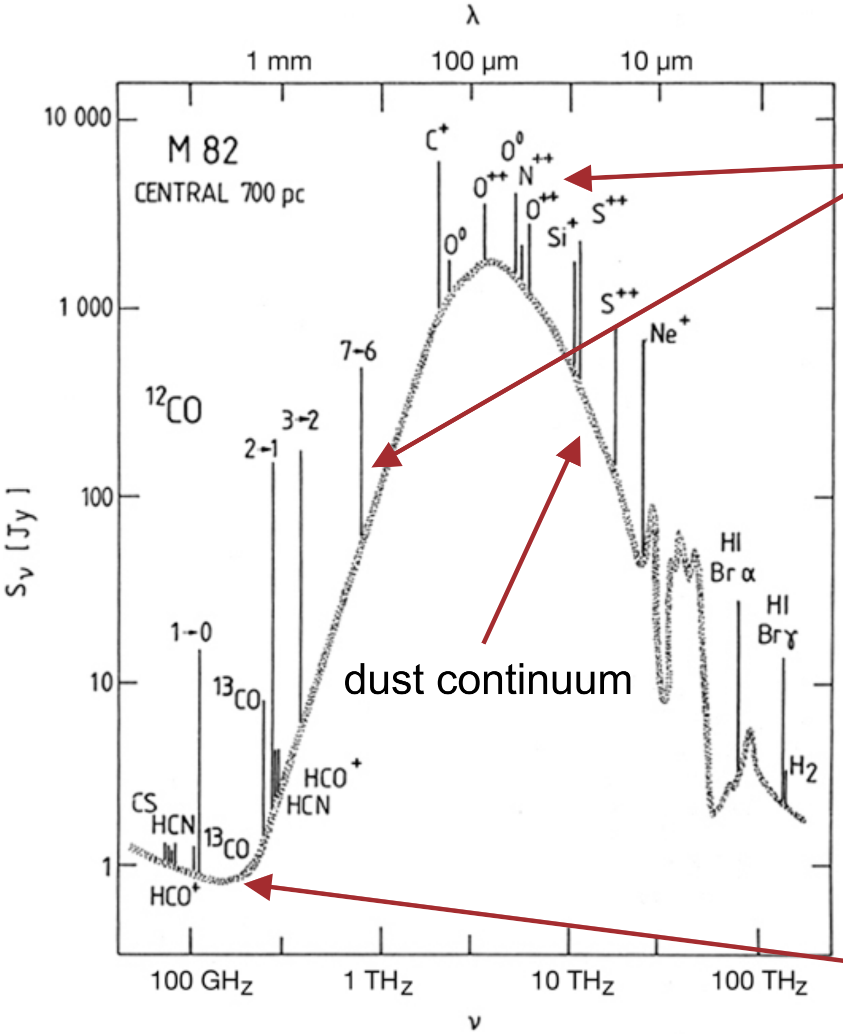
OH	CO	CO^+	H_2O	HCO	HCO^+
HOC^+	C_2O	CO_2	H_3O^+	$HOCO^+$	H_2CO
C_3O	CH_2CO	HCOOH	H_2COH^+	CH_3OH	CH_2CHO
CH_2CHOH	CH_2CHCHO	HC_2CHO	C_5O	CH_3CHO	c-C_2H_4O
CH_3OCHO	CH_2OHCHO	CH_3COOH	CH_3OCH_3	CH_3CH_2OH	CH_3CH_2CHO
$(CH_3)_2CO$	$HOCH_2CH_2OH$	$C_2H_5OCH_3$	$(CH_2OH)_2CO$	CH_3CONH_2	

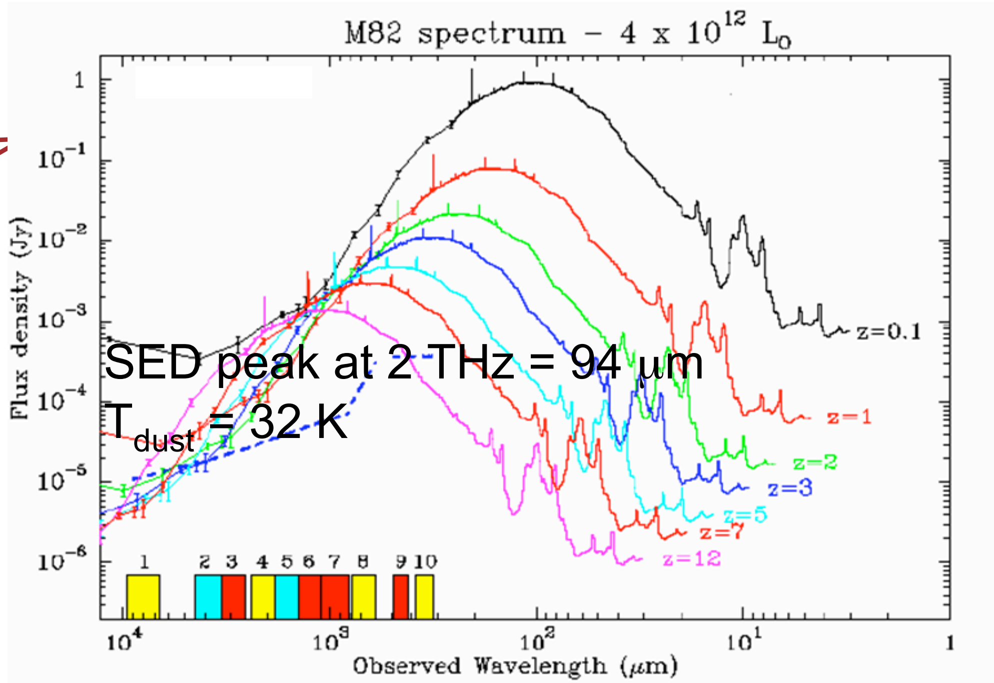
Hydrogen, Carbon (possibly) and Nitrogen Compounds

NH	CN	N_2	NH_2	HCN	HNC
N_2H^+	NH_3	$HCNH^+$	H_2CN	HCCN	C_3N
CH_2CN	CH_2NH	HC_2CN	HC_2NC	NH_2CN	C_3NH
CH_3CN	CH_3NC	HC_3NH^+	*HC_4N	C_5N	CH_3NH_2
CH_2CHCN	HC_5N	CH_3C_3N	CH_3CH_2CN	HC_7N	CH_3C_5N?
HC_9N	$HC_{11}N$				

Examples (4)

M82 in the radio, mm, sub-mm and FIR





SED peak at 2 THz = 94 μm

T_{dust} = 32 K

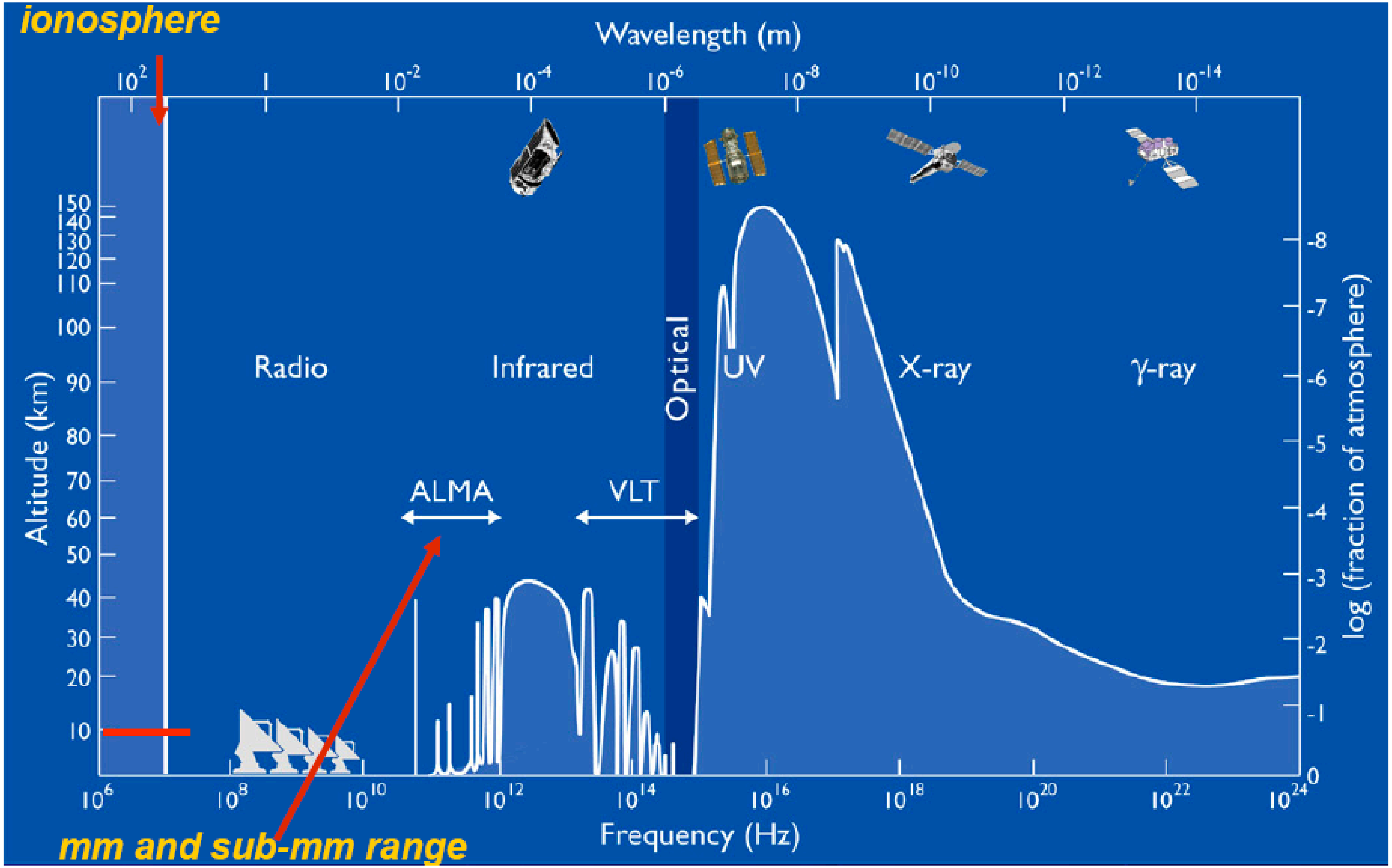
bremstrahlung+synchrotron continuum

Inverse K-correction:

As galaxies get redshifted, their dimming due to distance is offset by the brighter part of the spectrum being redshifted:

galaxies remain at similar brightness up to high z

mm domain in the electromagnetic spectrum

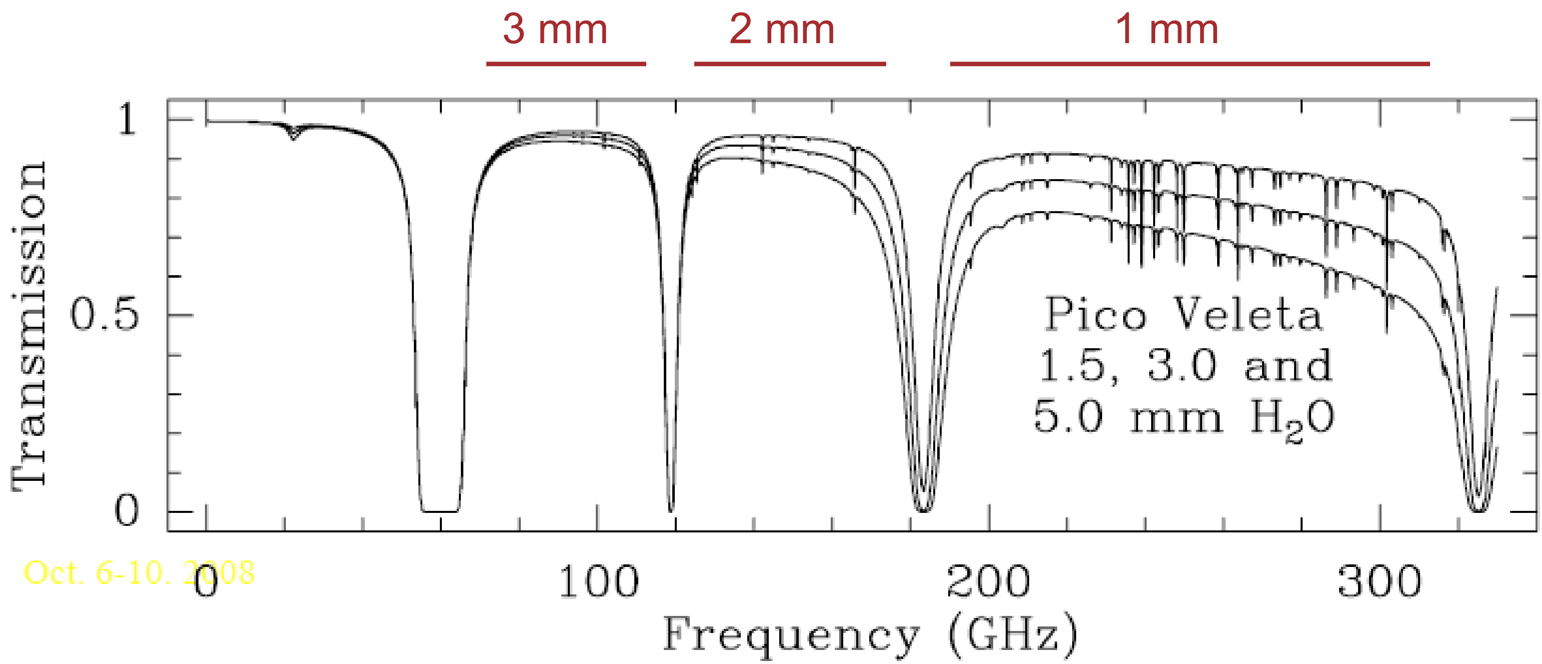


0.3-10 mm ⇆ 30-950 GHz

mm domain in the electromagnetic spectrum

Extremely sensitive to the quantity of water vapor in the atmosphere:

illustration of the atmospheric transmission at the most common atmospheric windows exploited by the current instruments



even worse at higher frequencies…

Site constraint:

high altitude to reduce the atmospheric water vapor absorption

Instrument basics

mm studies fully benefit from the advantages of radio astronomy:

1) high SENSITIVITY with large collecting areas

2) high ANGULAR RESOLUTION with large physical dimensions (~0.2” at 1 mm)

→ achieved with interferometry

3) high SPECTRAL RESOLUTION with heterodyne techniques (~ 10 m/s)

Instrument basics: SENSITIVITY

The spectral energy distribution of the radiation of a black body is given by the Planck law:

$$B_\nu(T) = \frac{2h\nu^3}{c^2}\frac{1}{e^{h\nu/kT}-1}$$

$h\nu \ll kT$ → Rayleigh-Jeans law

$$B_{\rm RJ}(\nu,T) = \frac{2\nu^2}{c^2}kT$$

The total flux density of a source integrated over the total solid angle is:

$$S_\nu = \int B_{\rm RJ}(\nu,T)d\Omega \quad \longrightarrow \quad S_\nu = \frac{2\,k\,\nu^2}{c^2}T_{\rm b}\,\Delta\Omega$$

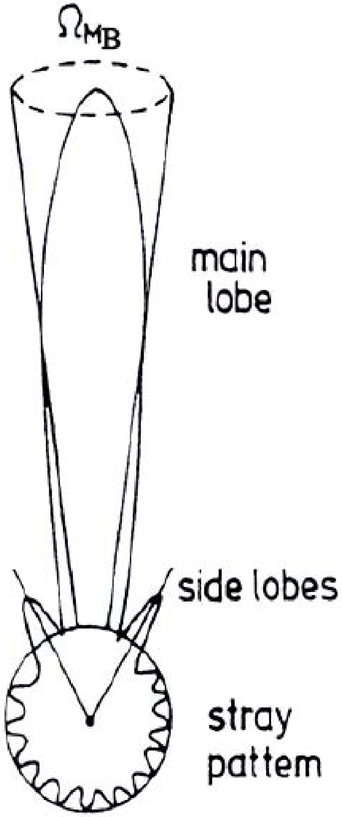
For a Gaussian source:

$$\left[\frac{S_\nu}{\rm Jy}\right] = 0.0736\,T_{\rm b}\left[\frac{\theta}{\rm arc\,seconds}\right]^2\left[\frac{\lambda}{\rm mm}\right]^{-2}$$

with S_ν in 10^{-26} W m^{-2} Hz^{-1} = 1 Jy
θ = source size
$T_{\rm b}$ = brightness temperature in K

Instrument basics: SENSITIVITY

The brightness temperature, T_b, of the source is not what we measure:



1) Antenna quality:

The quality of an antenna depends on how the power pattern is concentrated in the main beam. A part of the received power comes from side lobes

→ main beam efficiency η_{mb} = main beam / antenna beam = Ω_{mb}/Ω_A

2) Atmospheric effects:

The signal received from a source has to be corrected from earth's atmospheric effects

→ forward efficiency η_F

3) Antenna effective area:

Let a plane wave be intercepted by an antenna. A certain amount of power is extracted by the antenna from this wave

→ aperture efficiency η_A = effective aperture / geometric aperture = A_{eff}/A

Instrument basics: SENSITIVITY

This leads to a jungle of temperature quantities in use:

Physical quantities:

S_ν = flux density

T_b = brightness temperature

Antenna dependent quantities:

T_{mb} = main beam brightness temperature

T_A = antenna temperature through the atmosphere

T_A' = antenna temperature outside the atmosphere

T_A^* = corrected antenna temperature or forward beam brightness temperature

Relations between these temperatures:

$$T'_A = \eta_{mb} T_{mb}$$

$$T^*_A = \frac{T'_A}{\eta_F}$$

measured

$$T^*_A = \frac{\eta_{mb}}{\eta_F} T_{mb}$$

$$\Longrightarrow \quad S_\nu = \frac{2k}{A_{eff}} T'_A \quad \Longrightarrow$$

$$S_\nu / T'_A = \frac{2k}{A} \frac{1}{\eta_A}$$

$$S_\nu / T^*_A = \frac{2k}{A} \frac{\eta_F}{\eta_A}$$

$$S_\nu / T_{mb} = \frac{2k}{A} \frac{\eta_{mb}}{\eta_A}$$

To remember:

$$S_\nu = 3520 \frac{T'_A[\mathrm{K}]}{\eta_\mathrm{A}[\mathrm{D/m}]^2}$$

- for a source that fills the main lobe: $T_b = T_{mb}$
- for a source < Ω_{mb} : correction for beam dilution

$$T_b = T_{mb} \frac{(\theta_s^2 + \theta_b^2)}{\theta_s^2}$$

- for a source > Ω_{mb} : more complex analysis

Instrument basics: SENSITIVITY

Examples …

NGC7027 (a PNe) has S_ν = 5.4 Jy at 1.3 cm. What is the T_{MB} (main beam brightness temperature) if the 100-m FWHP beam size is 43”?

Use

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

$$5.4 = 2.65 \frac{T_{MB} \cdot \left(\frac{43}{60}\right)^2}{(1.3)^2}$$

$$T_{MB} = 6.7K$$

(Problem: Repeat for the 30-m, with beam 27’’, wavelength 3.5 mm, flux density 4.7 Jy)

Venus, at closest approach has a size of 62”. If we measure an antenna temperature, T_A, of 4.2 K with an 8.7’ beam, and a beam efficiency of η_B = 0.5, what is the surface temperature of Venus?

$$T_A = 4.2K = \eta_B \cdot T_{MB} = 0.5 \cdot T_{MB} \qquad so \quad T_{MB} = 8.6K$$

$$T_S \cdot \theta_S^2 = T_{MB} \cdot \left(\theta_B^2 + \theta_S^2\right)$$

$$T_S = 8.6 \cdot \left(\frac{(8.7)^2 + \left(\frac{62}{60}\right)^2}{\left(\frac{62}{60}\right)^2} \right) = 660K$$

Instrument basics: SENSITIVITY

In practice the rms is given by:

SINGLE DISH:

$$\frac{\sigma}{T_{\rm sys}} = \frac{1}{\sqrt{\Delta\nu\,\tau}}$$

(σ in K)

with T_{sys} = noise temperature of the entire system that includes noise from receiver, atmosphere, ground and source; $\Delta\nu$ = bandwidth; τ = time integration

INTERFEROMETER:

$$\sigma = \frac{2k}{A\eta_{\rm A}\eta_{\rm Q}\eta_{\rm P}} \cdot \frac{T_{\rm SYS}}{\sqrt{N(N-1)\,B\,T}}$$

(σ in K)

with A = antenna aperture; η_X = different efficiencies; N = number of antennas; B = bandwidth; T = time integration

⇨ The more antennas we have, the higher sensitivity we reach

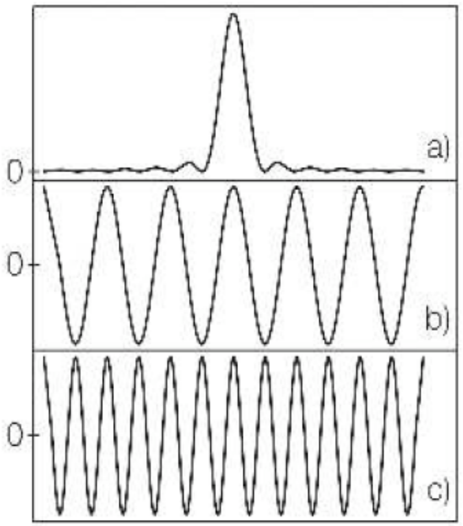
Instrument basics: ANGULAR RESOLUTION

From diffraction theory:

The angular resolution is

$$\theta = k\frac{\lambda}{D}$$

with $k \sim 1$; θ in arcsec; 206 λ in mm;
D = diameter of the instrument in m



Still valid when coherently combining the output of several reflectors of diameter $d \ll D$ separated by a distance D.

Power patterns for different antenna configurations:
a) uniformly illuminated single dish aperture ➝ main beam
b) 2 elements-interferometer with a spacing D ➝ fringes
c) same as b), but with a spacing 2D ➝ the fringe width is halved

⇨ The larger baselines we have, the higher angular resolution we reach

Instrument basics: CALIBRATION

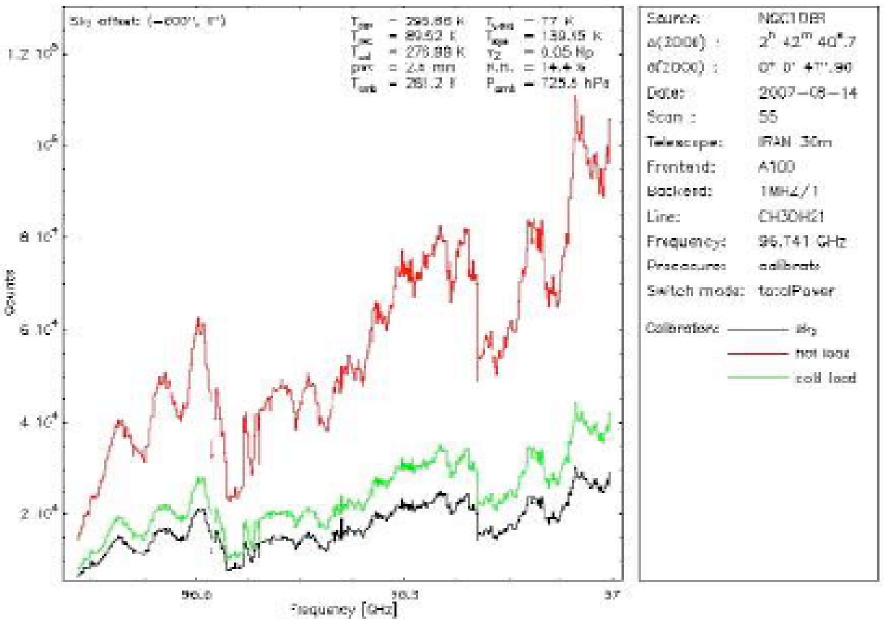
Calibration is mandatory at mm wavelengths due to:

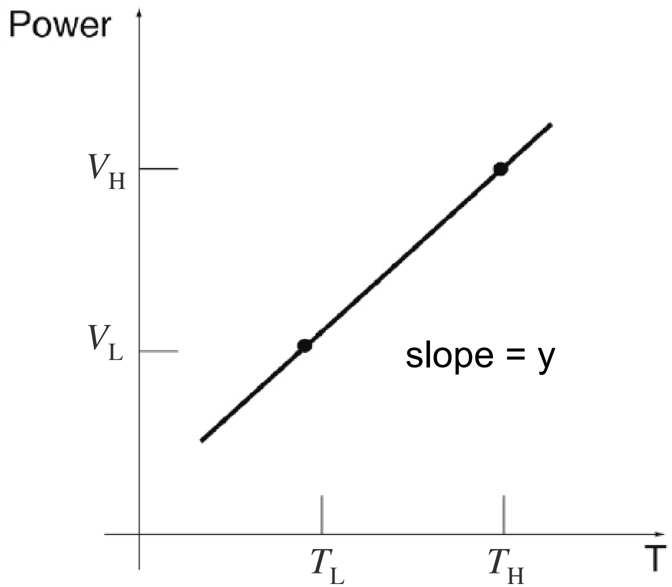
- the atmospheric effects
- the instrumental noise

A few numbers: T_A ≤ 1 K
T_{sky} ~ 30 K (at 3 mm)
T_{rx} ~ 100 K

At the IRAM 30m telescope:

a cold (liquid nitrogen) and hot load (ambient temperature) is used





This directly constrains the receiver noise:

$$T_{rx} = \frac{T_H - T_L\, y}{y - 1}$$

Instrument basics: CALIBRATION

Chopper wheel method:

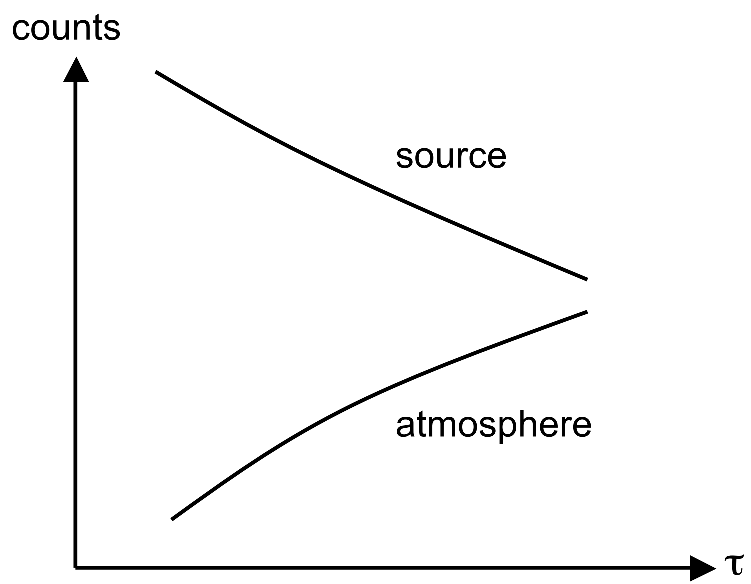
$$V_{amb} = G\,(T_{amb} + T_{rx})$$
$$V_{sky} = G\,(T_{sky} + T_{rx})$$
$$V_{ON} = G\,(T_{sky} + T_{rx} + T_A)$$
$$V_{OFF} = G\,(T_{sky} + T_{rx})$$

(*)

$$\Delta V_{cal} = V_{amb} - V_{sky} = G\,(T_{amb} - T_{sky}) =$$
$$= G\,(T_{amb} - T_{amb}(1 - e^{-\tau_\nu})) = G\,T_{amb}\,e^{-\tau_\nu}$$

$$\Delta V_{sig} = V_{ON} - V_{OFF} = G\,T_A = G\,T_A^*\,e^{-\tau_\nu}$$

(τ_ν = atmospheric absorption at the frequency of interest)



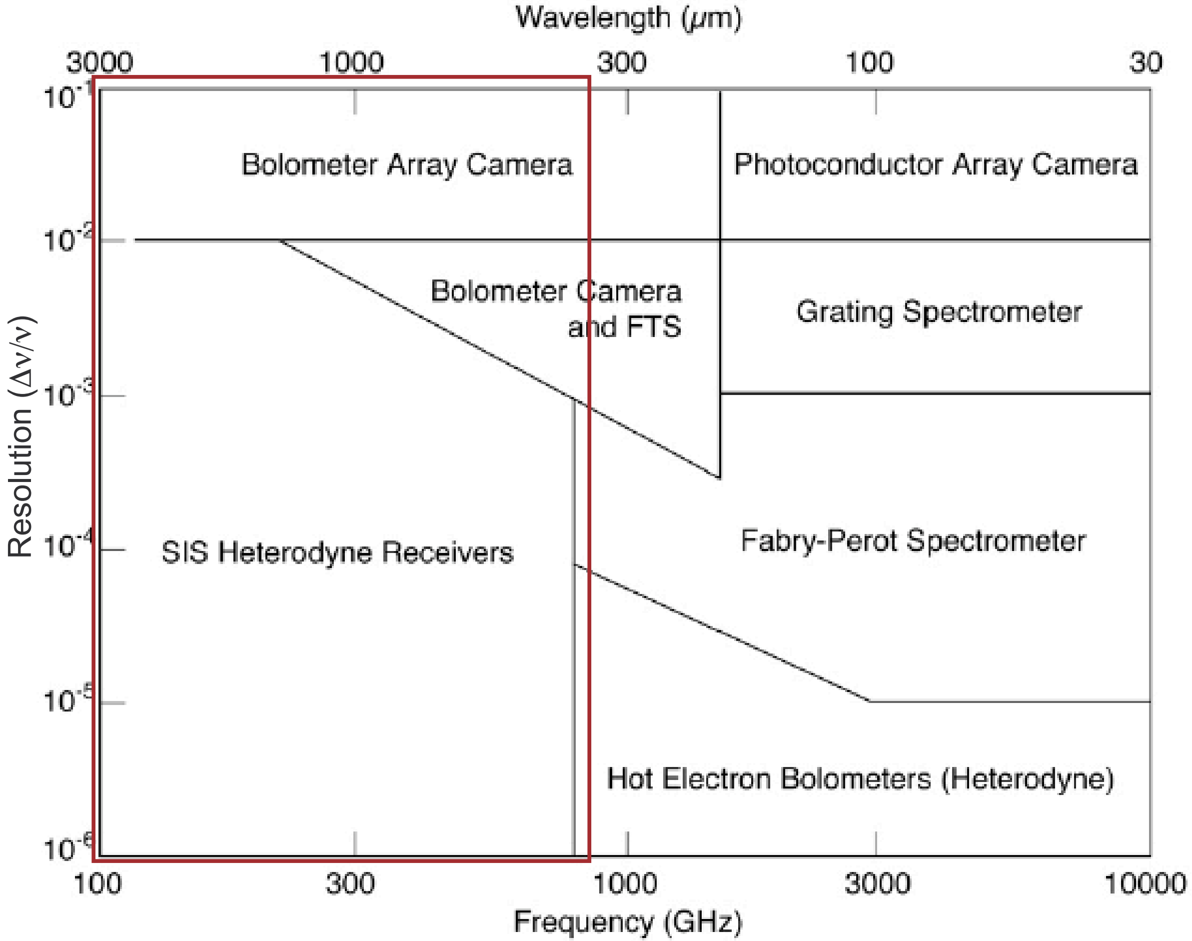
As a result, the measured antenna temperature is:

$$T_A^* = \frac{\Delta V_{sig}}{\Delta V_{cal}} T_{amb}$$

(*) Nyquist theorem which relates voltage to temperature

Observing techniques

Receivers in use at FIR and mm wavelengths:

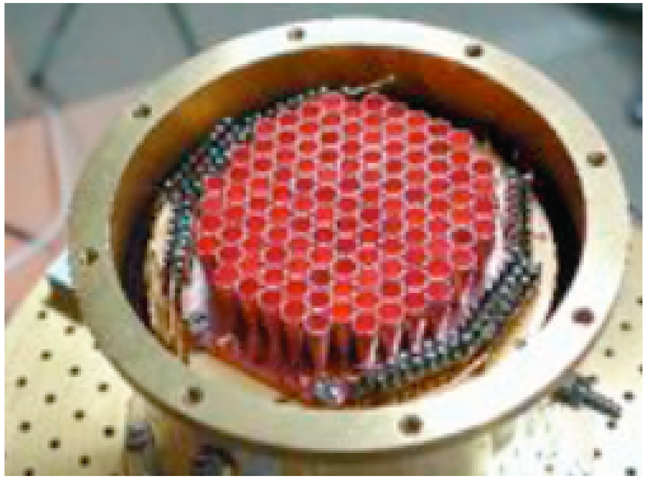


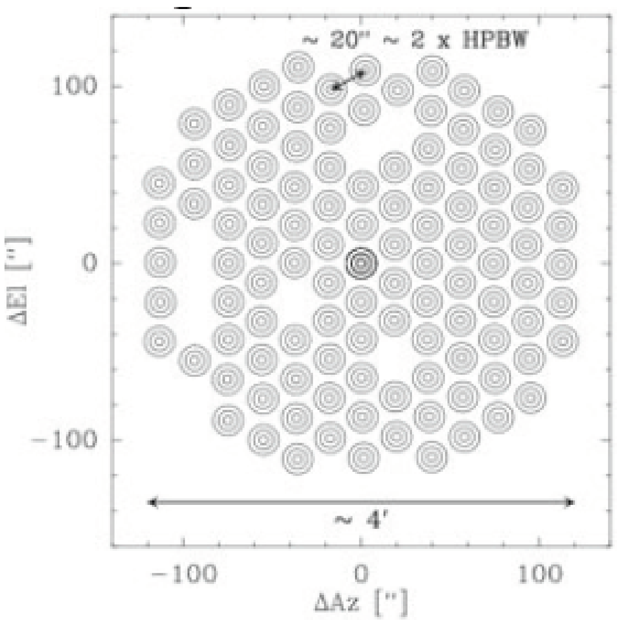
<u>Bolometers</u>:
used for imaging

<u>Heterodyne receivers</u>:
used for spectroscopy

Observing techniques: Bolometers

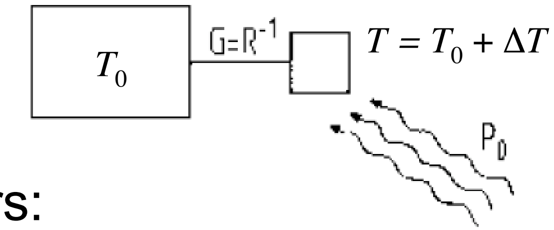
MAMBO-2: 117 pixels





Wide-field imagers:

Principle: when a radiation is absorbedby the bolometer material, T varies;
this ΔT change is a measure of the intensity of the incident radiation

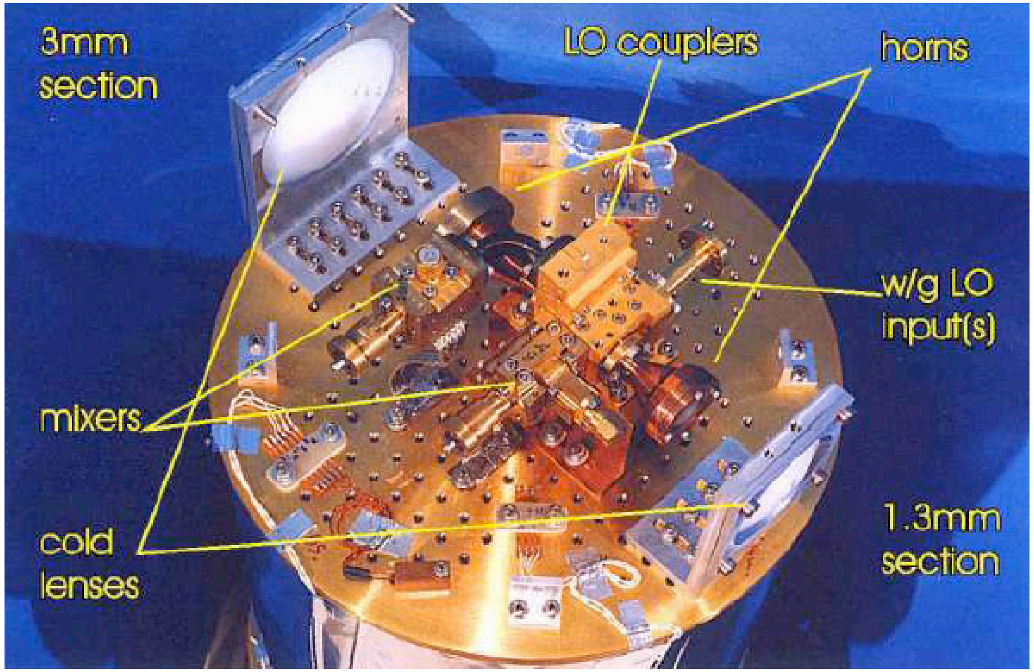


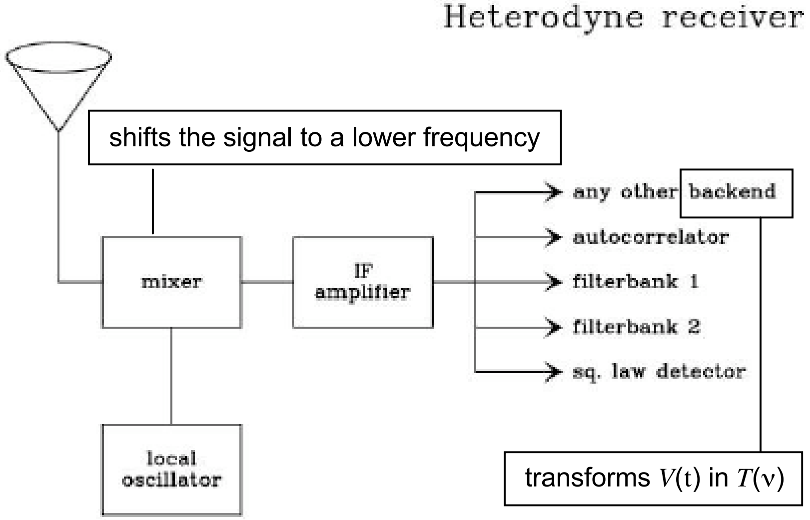
Current Bolometers:

Instrument	Wavelength (µm)	Field of view (arcmin^2)	Beam (arcsec)
Herschel-SPIRE	**250**	**4 x 8**	**17.5**
ArTéMiS / 12m APEX	200 350 450	1.8 x 1.8 3.2 x 3.2 4.1 x 4.1	4.2 7.3 9.4
SCUBA-2	450	8 x 8	7.5
SHARC-2	350	0.9 x 2.5	8.5
LABOCA	870	11.4’	18.2
MAMBO-2	1200	4’	11

Bandwidth:
$\Delta\nu \sim 100$ GHz

Observing techniques: Heterodyne receivers





Single pixel multi-channel spectrometers:

<u>resolution</u>: 10 m/s (3 kHz) – 3 km/s (1 MHz)

<u>bandwidth</u>: 10 MHz – 500 MHz

New heterodyne receivers:

e.g., HERA on the IRAM 30m: 9 pixel array

VOCABULARY:

scans = exposures

sub-scans = short exposures (usually 30 s) making up a scan

channels = pixels along the "dispersion"

Observing techniques: Strategies

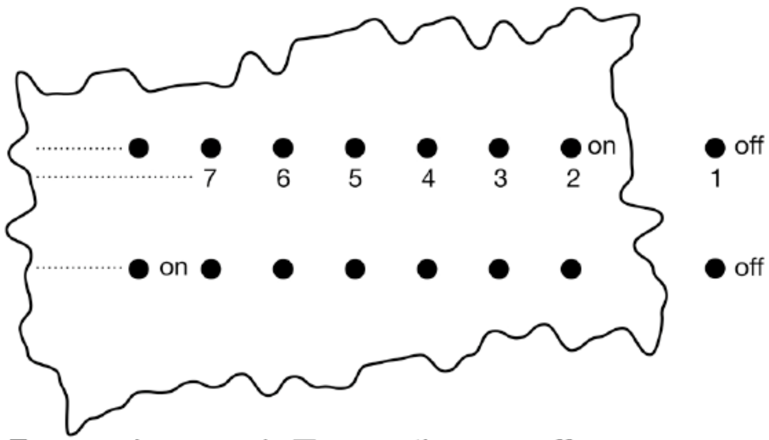
To get read off the atmospheric effects:

• Position switching

• Beam switching

(tilting of the secondary mirror - Wobbling;
Wobbler through 30−120'')

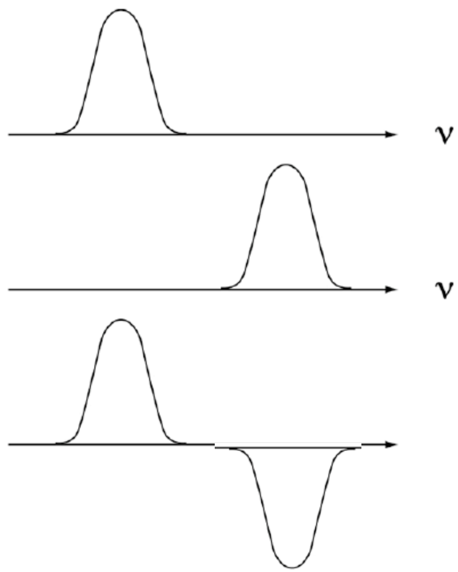
• On-the-fly mapping



For n on's, spend $\sqrt{n}$ more time on off source

• Frequency switching

(solely for narrow spectral line observations)



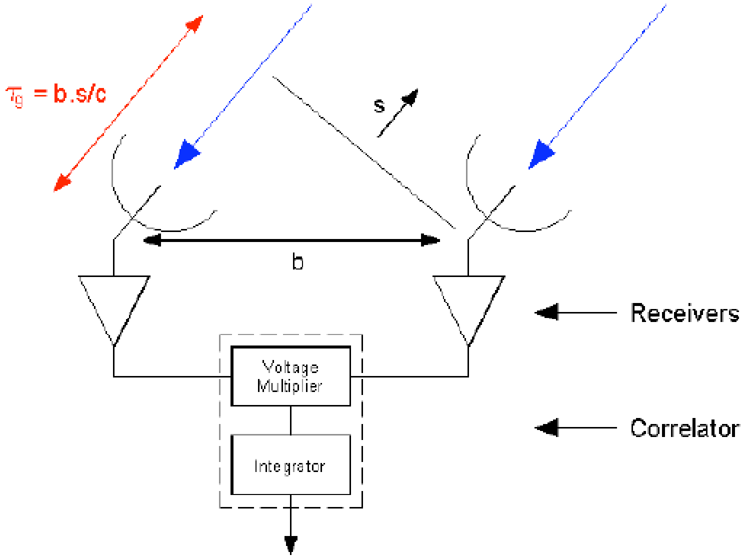
Observing techniques: Strategies

In addition, we need to do focus and pointing of the antenna:

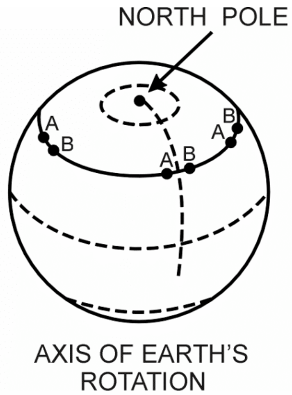
- must be fairly intense sources with known fluxes and positions
- must be small sources compared to the antenna beam
- often used: planets, strong mm emitters, quasars

Do a focus every 4-6 hours
Do a pointing every 2-3 hours

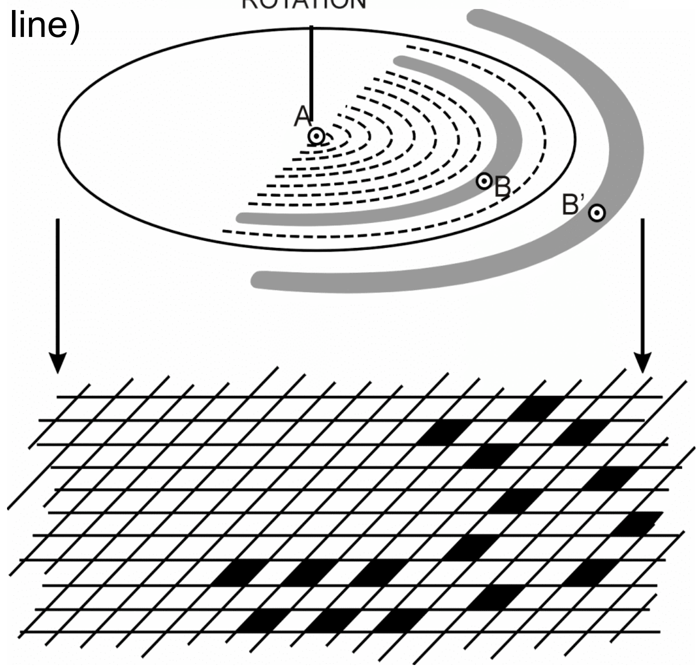
Observing techniques: Interferometry



(u,v) is the 2 antennas vector baseline projected on the plane perpendicular to the source



(u,v) describe an ellipse in the (u,v) plane (for δ = 0 deg, a line)



Gridding and sampling in (u,v) plane

(u,v) plane ⇆ image plane

Fourier transforms

Geometrical delay τ_g between antennas

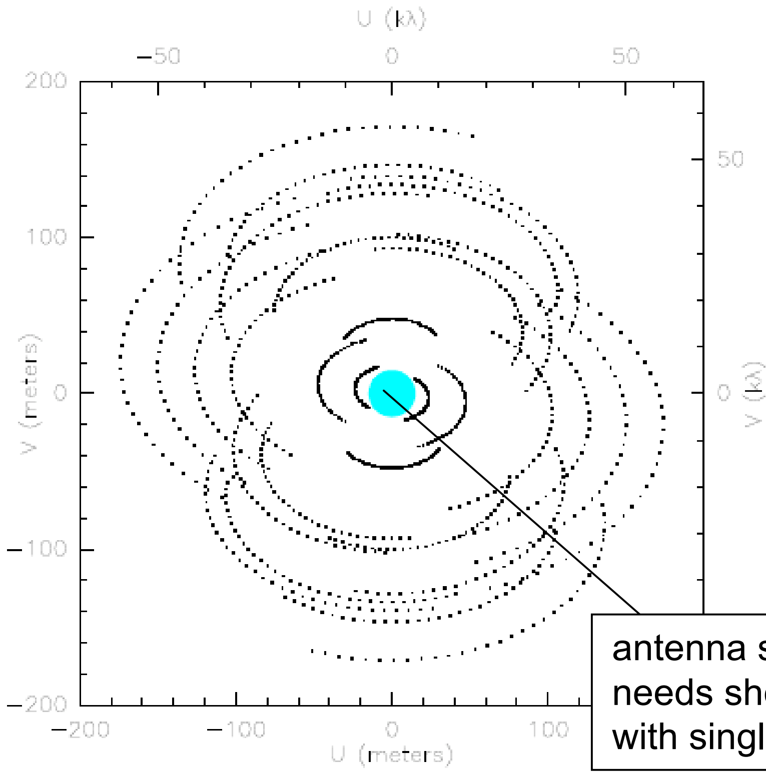
→ τ_g varies slowly with time due to the Earth rotation and produces fringes

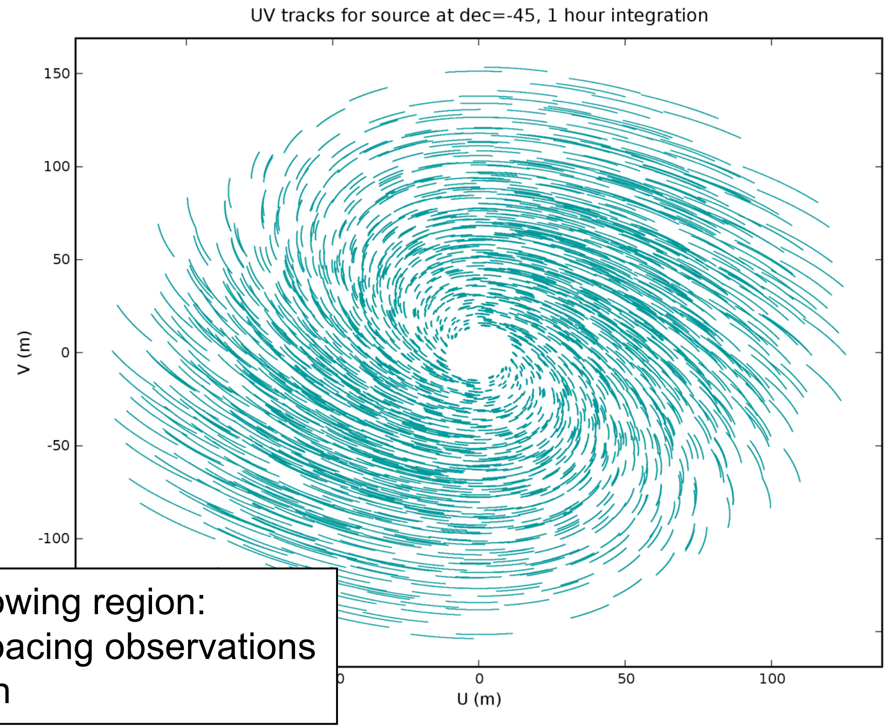
→ As τ_g varies, we sample different source structures

→ The distances between antennas must be arranged to cover the (u,v) plane as quickly as possible

Observing techniques: Interferometry

The more antennas we have, the more the efficiently the (u,v) plane will be filled and the more precise the image reconstruction will be !





antenna shadowing region:
needs short-spacing observations
with single dish

6 antennas (PdBI)

50 antennas (ALMA)

Observing techniques: Interferometry

A brief guide to the 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

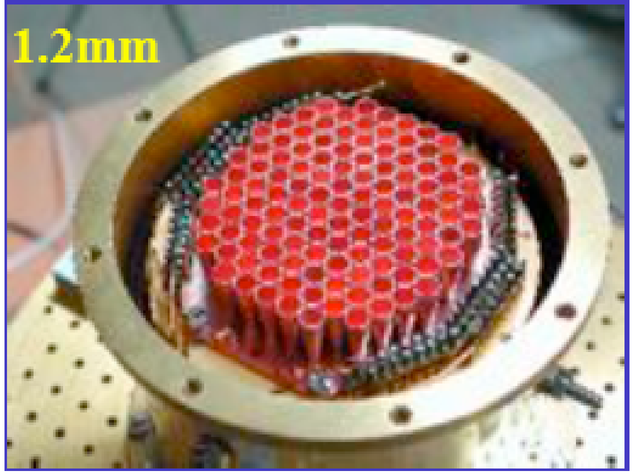
Current millimeter facilities: Single Dish

IRAM 30m telescope (Pico Veleta, Spain), altitude 2900m, surface accuracy 50 μm

APEX 12m telescope (Chajnantor, Chile), altitude 5100m, surface accuracy 17 μm

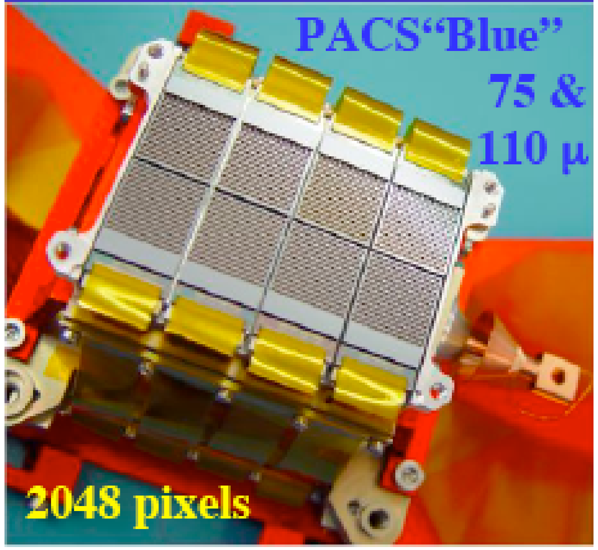
Current millimeter facilities: Bolometers

MAMBO @ IRAM 30m (117 elements)

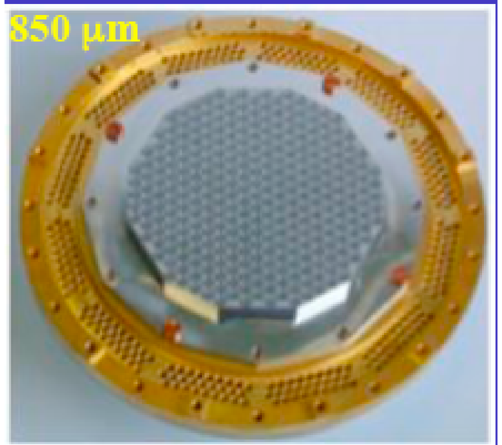


SCUBA-2 @ JCMT

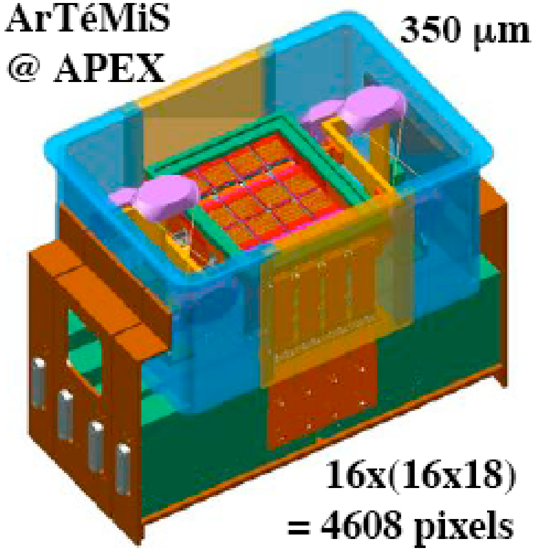
PACS on HERSCHEL



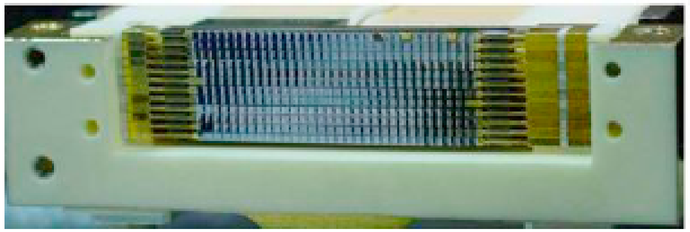
LABOCA @ APEX (295 elements)



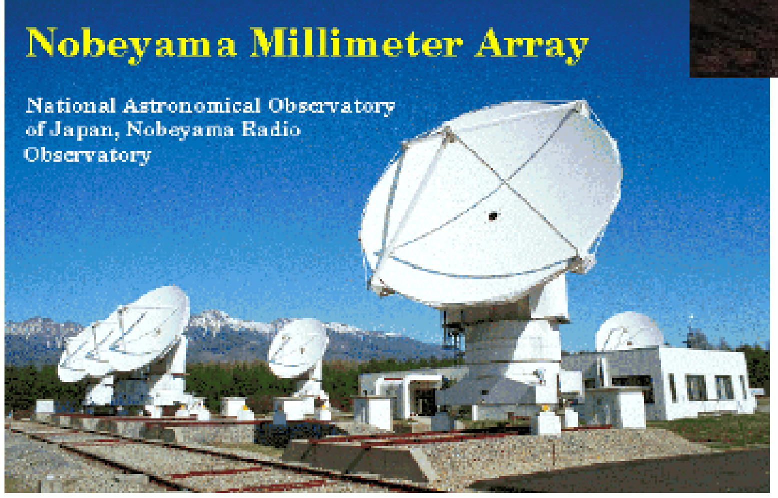
ArTéMiS @ APEX

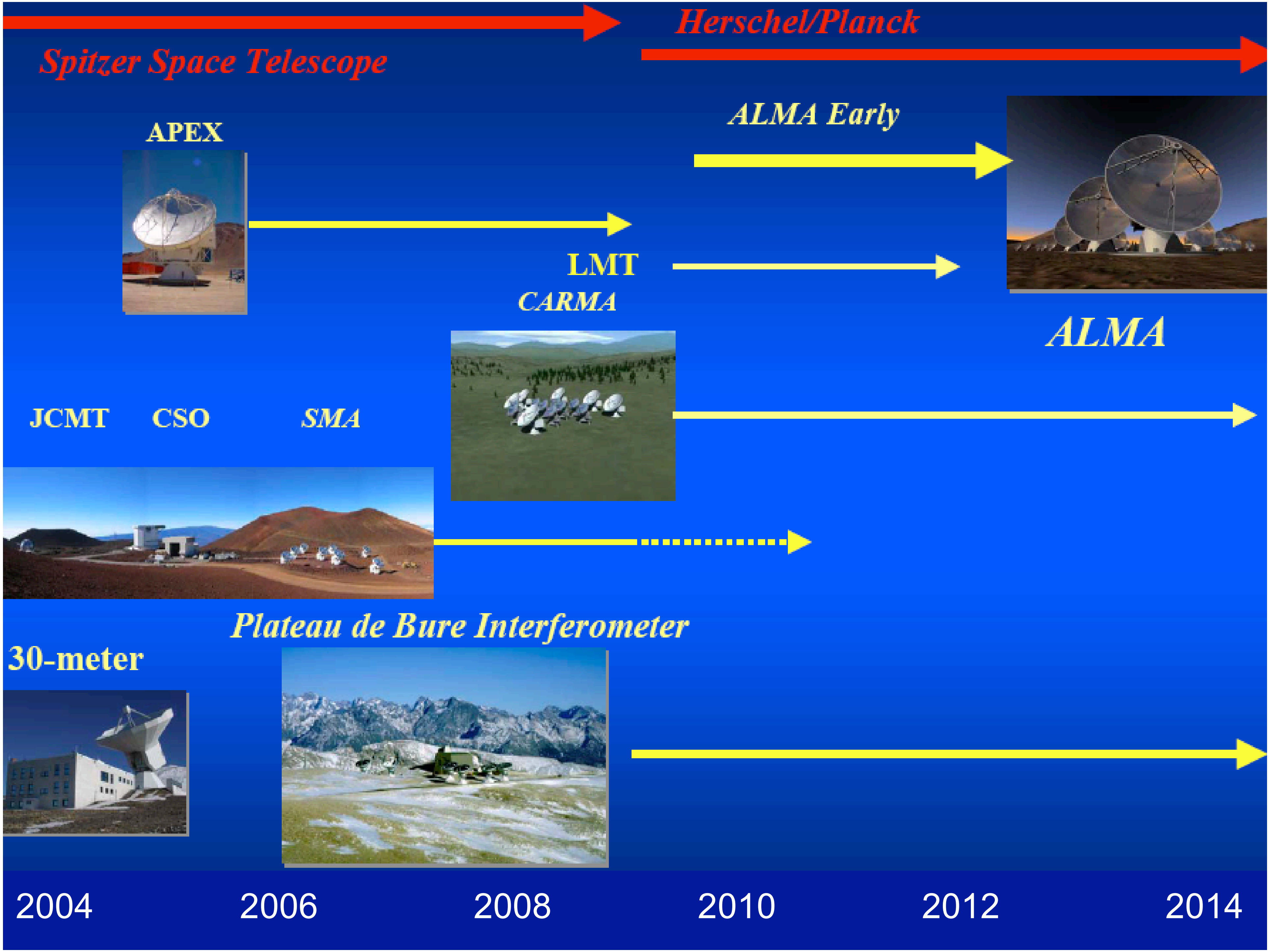


SHARC-2 @ CSO (384 elements @ 350 µm)



Current millimeter facilities: Interferometers





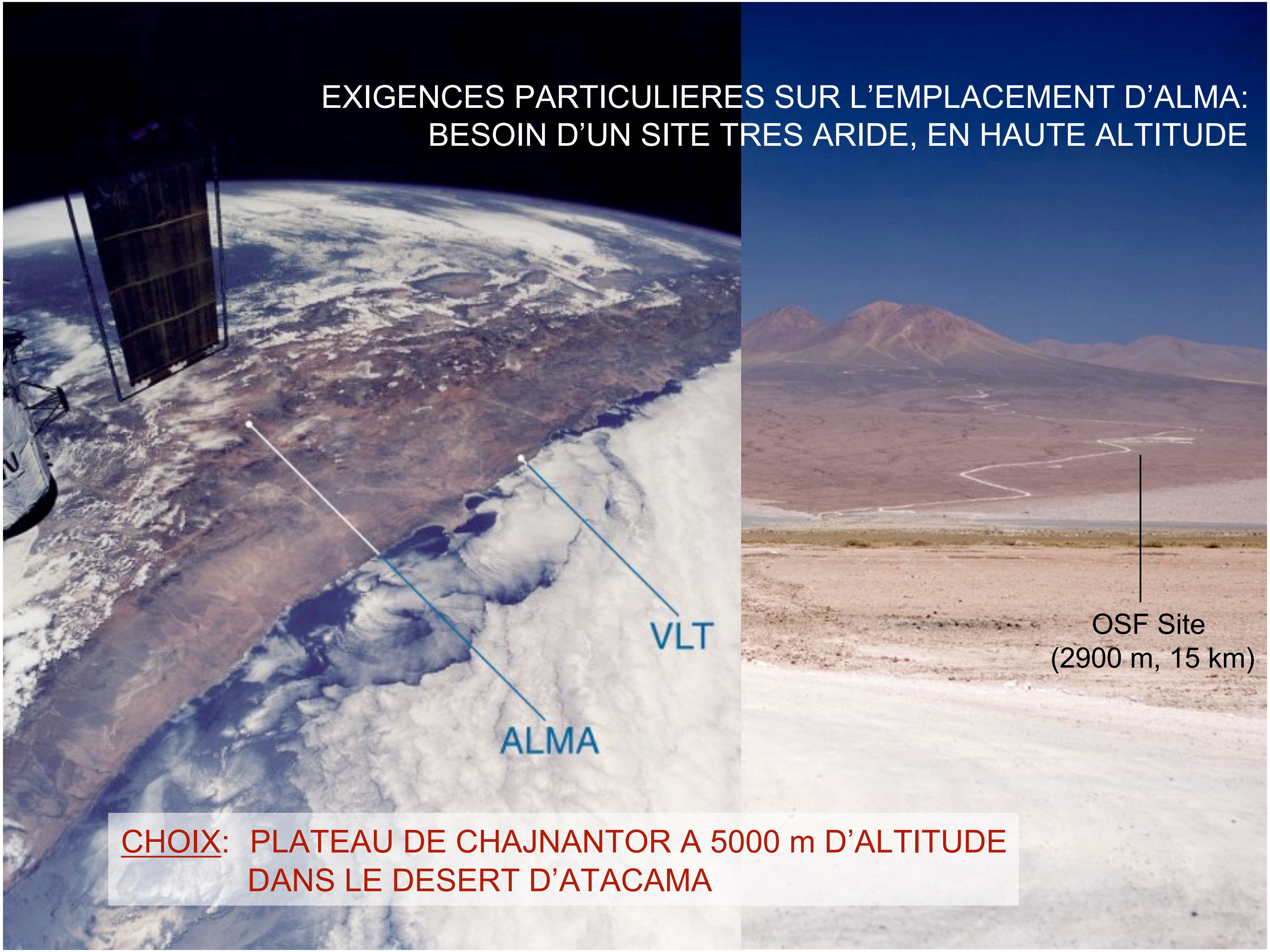
Herschel/Planck
Spitzer Space Telescope
ALMA Early
APEX
LMT
CARMA
ALMA
JCMT
CSO
SMA
Plateau de Bure Interferometer
30-meter
2004
2006
2008
2010
2012
2014

50 ANTENNES DANS LE DESERT

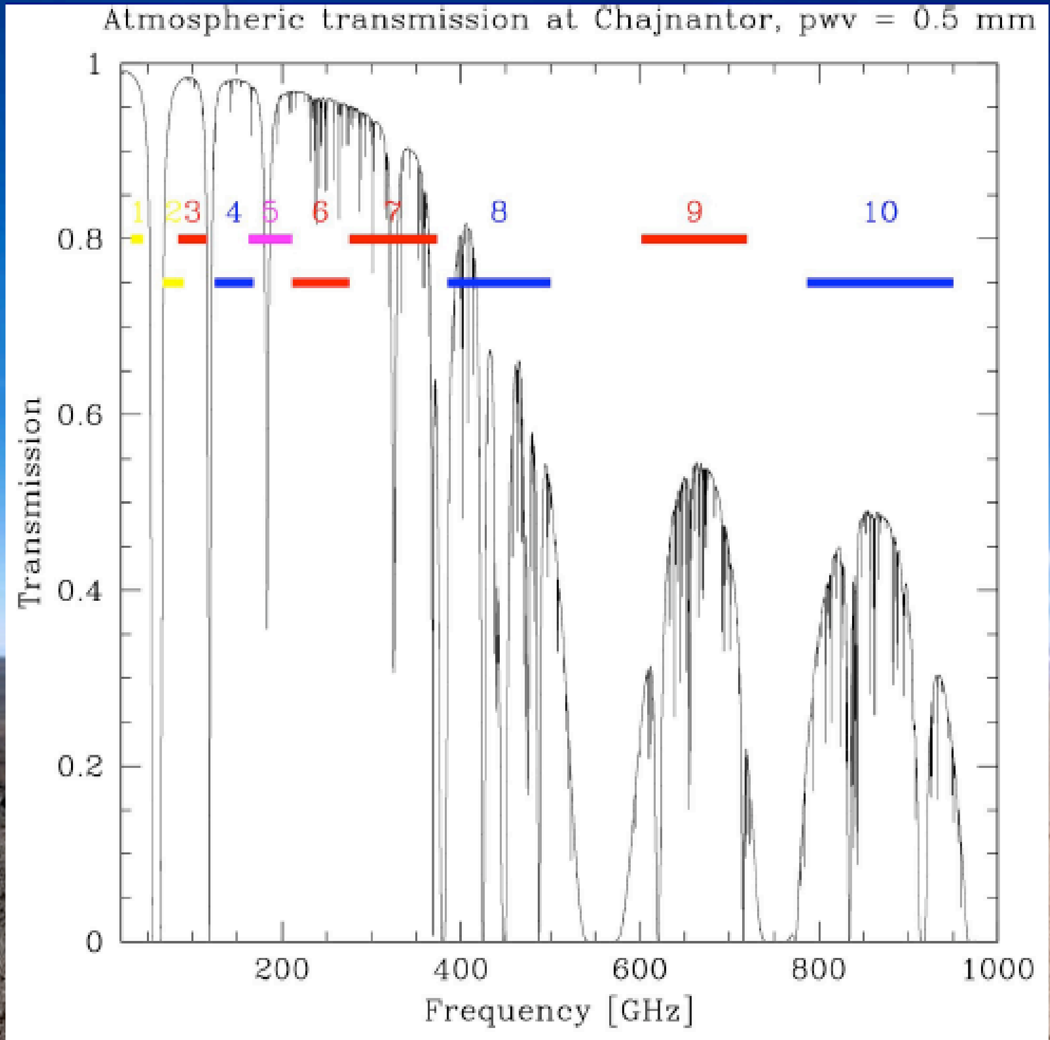
ALMA - ATACAMA LARGE MILLIMETER ARRAY

UN PROJET INTERNATIONAL REGROUPANT L'EUROPE,
L'AMERIQUE DU NORD (USA, CANADA), LE JAPON ET LE CHILI

EXIGENCES PARTICULIERES SUR L’EMPLACEMENT D’ALMA:
BESOIN D’UN SITE TRES ARIDE, EN HAUTE ALTITUDE



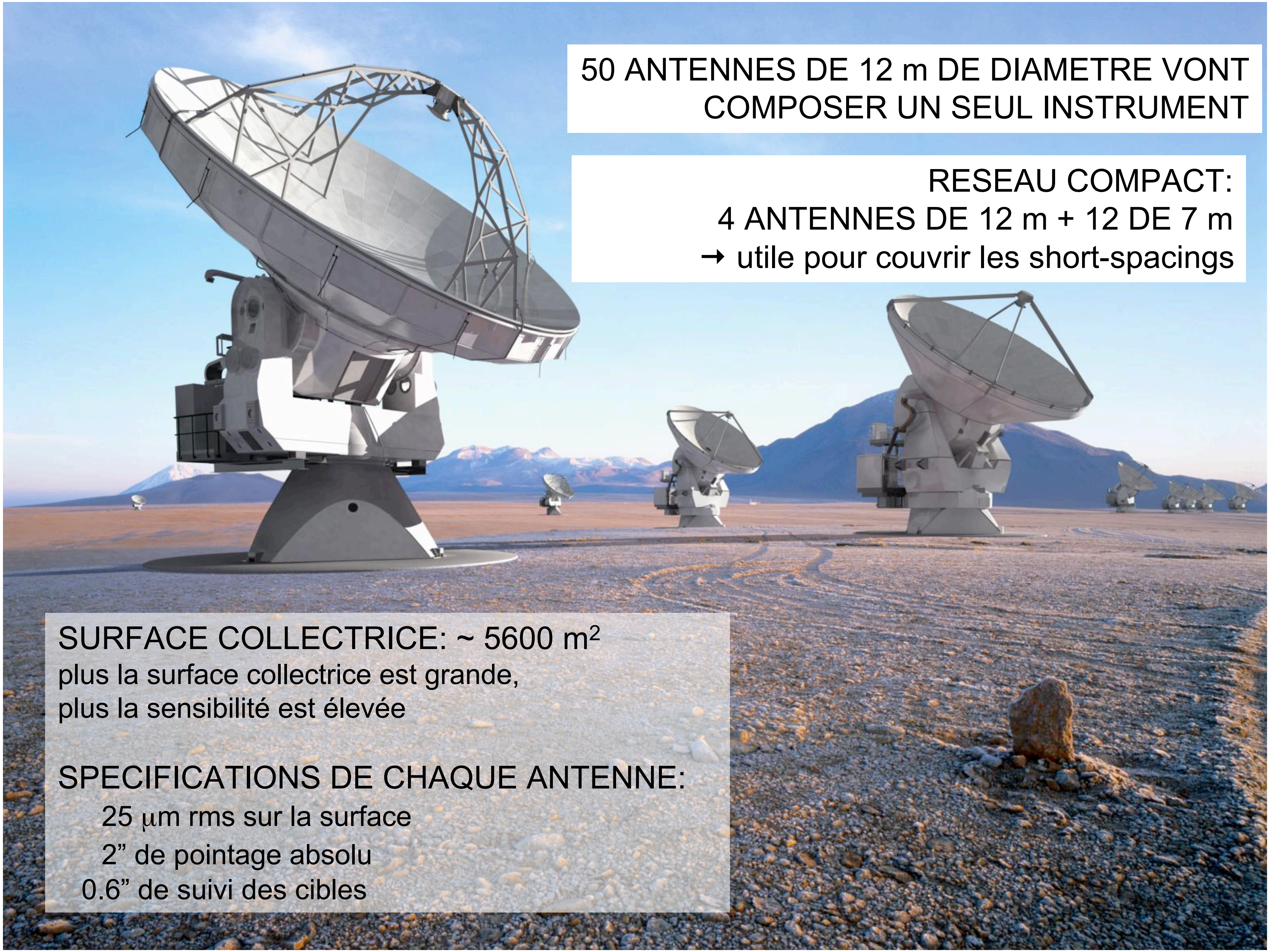
CHOIX: PLATEAU DE CHAJNANTOR A 5000 m D’ALTITUDE
DANS LE DESERT D’ATACAMA



1	31.3 – 45 GHz	
2	67 - 90 GHz	
3	84 - 116 GHz	HIA
4	125 – 163 GHz	Japan
5	163 – 211 GHz	OSO
6	211 – 275 GHz	NRAO
7	275 – 373 GHz	IRAM
8	385 – 500 GHz	Japan
9	602 – 702 GHz	SRON
10	787 – 950 GHz	Japan

10 BANDES DE FREQUENCE
ENTRE 30 ET 950 GHz

SEULES 6 BANDES SONT
ACTUELLEMENT FINANCEES:
3, 4, 6, 7, 8, 9


50 ANTENNES DE 12 m DE DIAMETRE VONT COMPOSER UN SEUL INSTRUMENT
RESEAU COMPACT:
4 ANTENNES DE 12 m + 12 DE 7 m
→ utile pour couvrir les short-spacings
SURFACE COLLECTRICE: ~ 5600 m^2
plus la surface collectrice est grande,
plus la sensibilité est élevée
SPECIFICATIONS DE CHAQUE ANTENNE:
25 μm rms sur la surface
2” de pointage absolu
0.6” de suivi des cibles

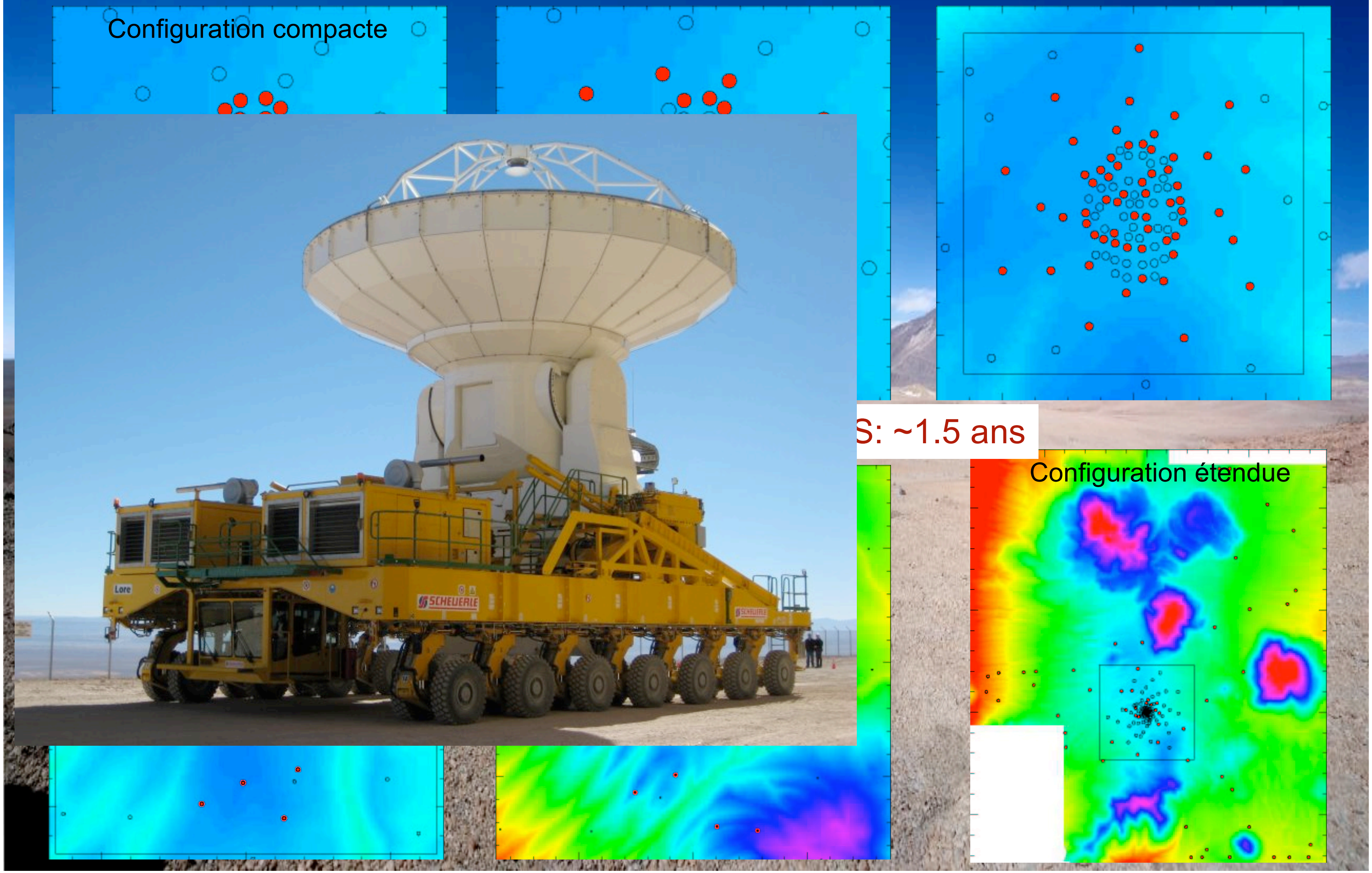
ANTENNES: 3 PROTOTYPES

JAPON	MITSUBISHI	4 x 12 m + 12 x 7 m
AMERIQUE DU NORD	VERTEX	25 x 12 m (→ 32)
EUROPE	ALCATEL	25 x 12 m (→ 32)

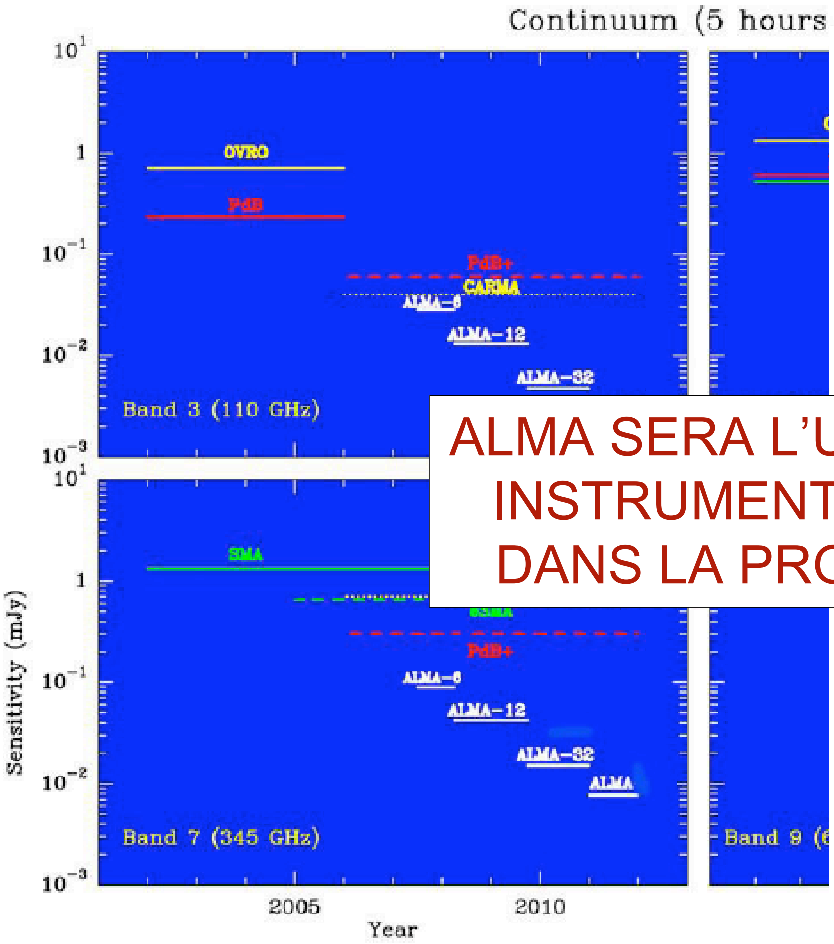
ALMA TEST FACILITY (SOCORRO, USA)

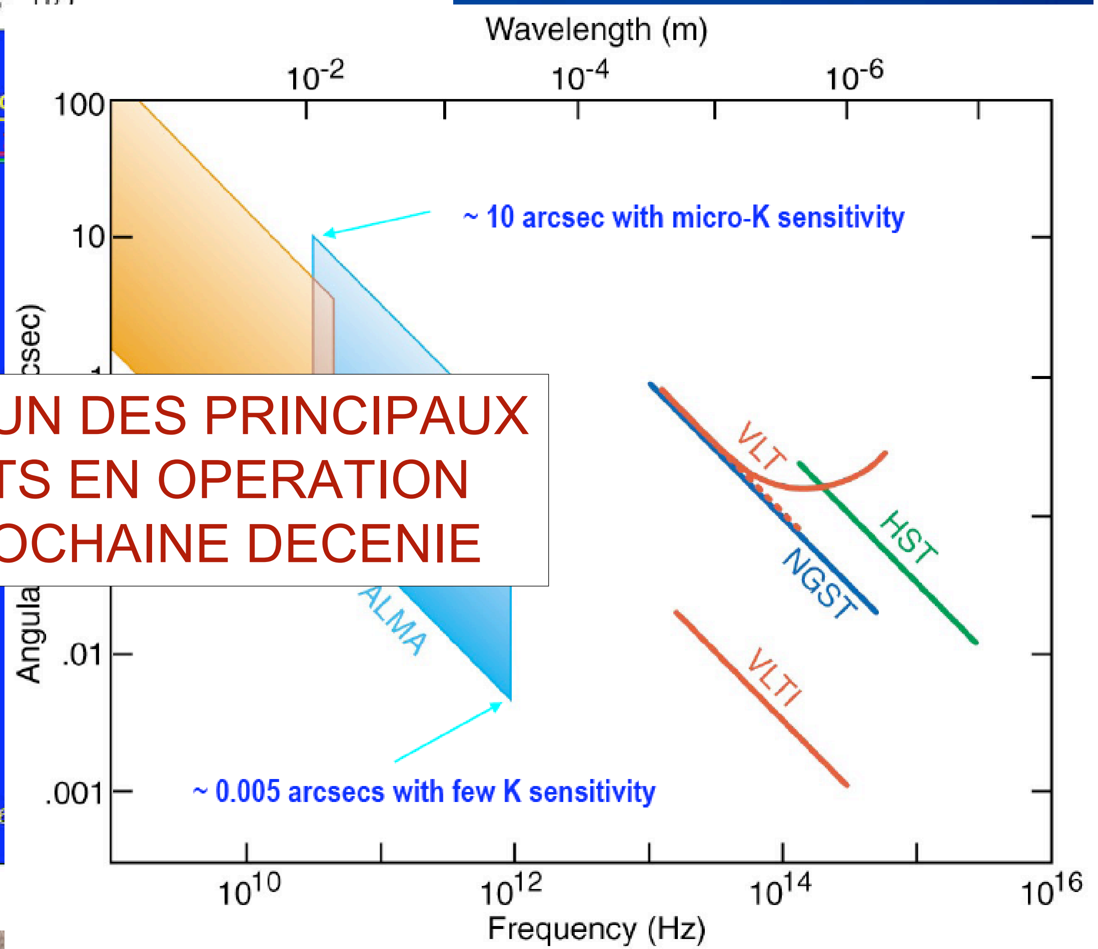
LIGNES DE BASE DE L'INTERFEROMETRE: ENTRE 15 m et 16 km

plus les lignes de base sont grandes, plus la résolution angulaire est élevée



SENSIBILITE ET RESOLUTION ANGULAIRE 10-100 MEILLEURES QUE LES TELESCOPES (MILLIMETRIQUES) ACTUELS





ALMA SERA L'UN DES PRINCIPAUX INSTRUMENTS EN OPERATION DANS LA PROCHAINE DECENIE

<u>ATTENTES</u>:

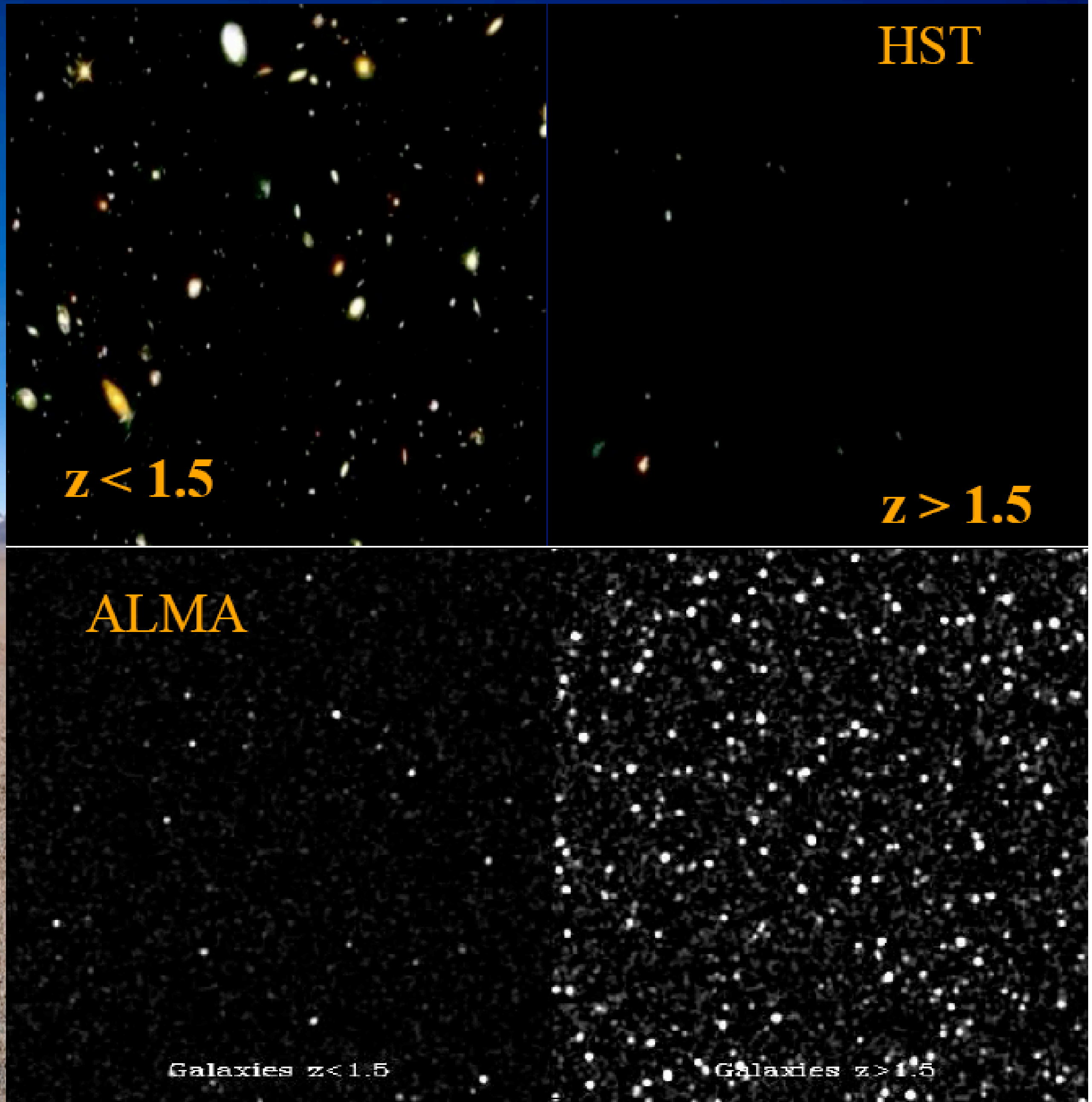
SENSIBILITE (continu):
0.02 mJy (1σ) en 5 h à 345 GHz

RESOLUTION ANGULAIRE:
40 mas à 100 GHz
5 mas à 900 GHz

OBJECTIFS SCIENTIFIQUES MAJEURS D'ALMA

1) DECOUVRIR DES GALAXIES A z > 10

origine et formation des galaxies, premières étoiles, premiers métaux



HST DEEP FIELD: détection de nombreuses galaxies à z < 1.5

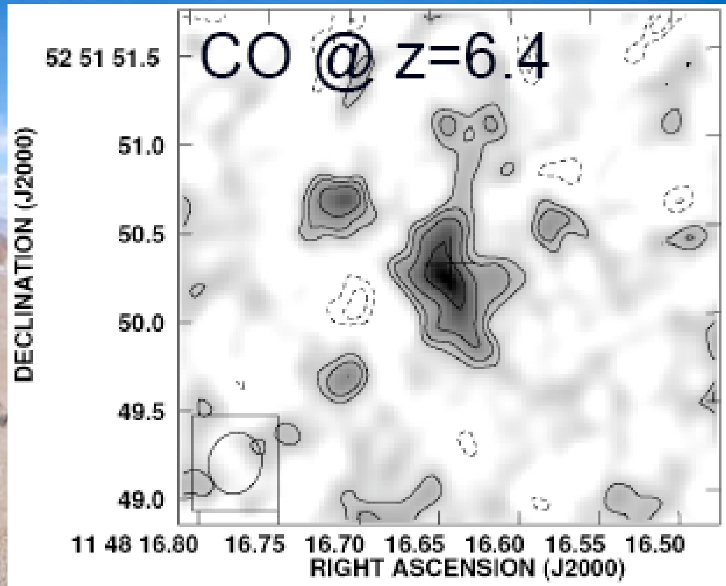
ALMA DEEP FIELD: pauvre en galaxies à bas redshift et riche en galaxies à z > 1.5

WILL ALMA BE REALLY ABLE TO DETECT MOLECULAR LINE EMISSION AT VERY HIGH z ?

ALMA will not be a survey machine: small FOV ~ 1’

MOLECULAR LINES USEFUL FOR WHAT ?

M_{gas}	fuel for SF, evolutionary state
morphology	sizes, mergers vs disks
M_{dyn}	masses, hierarchical models



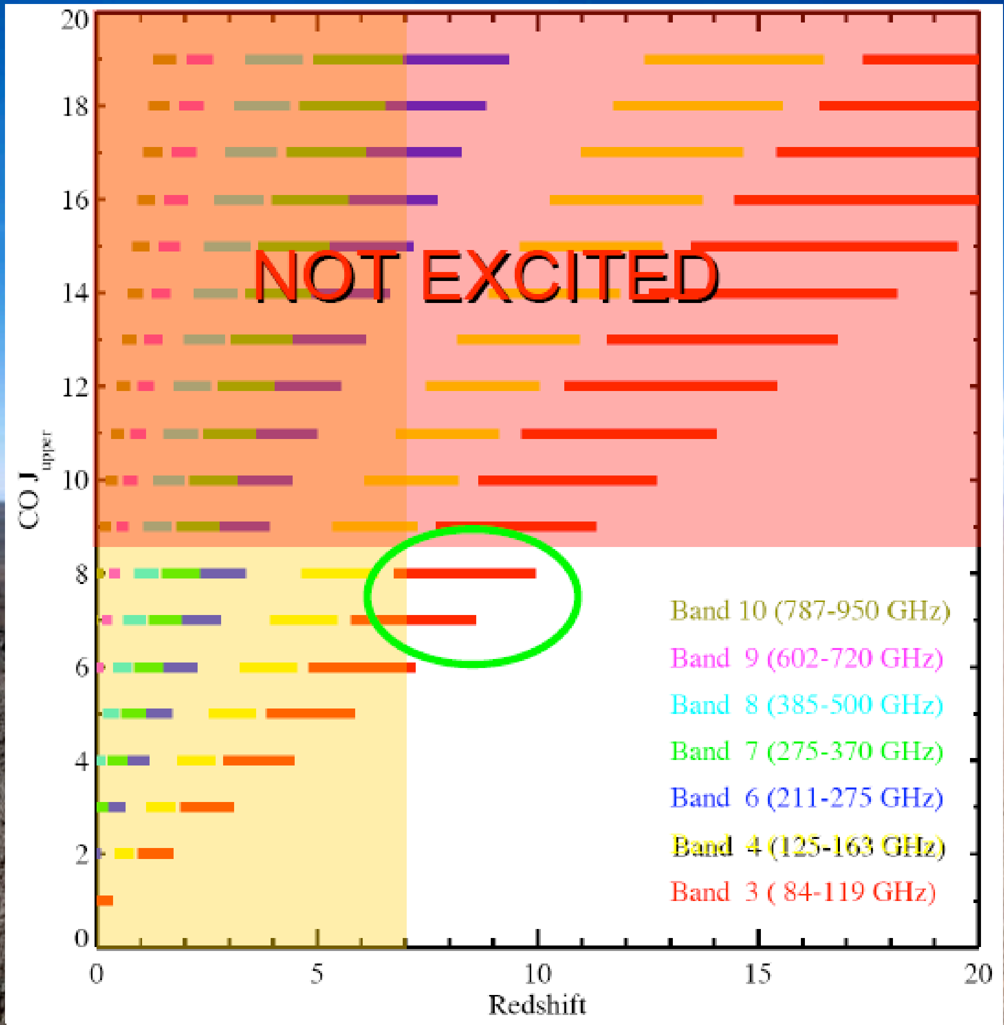
LINE OF CHOICE SO FAR AT HIGH z: CO

WHY ?

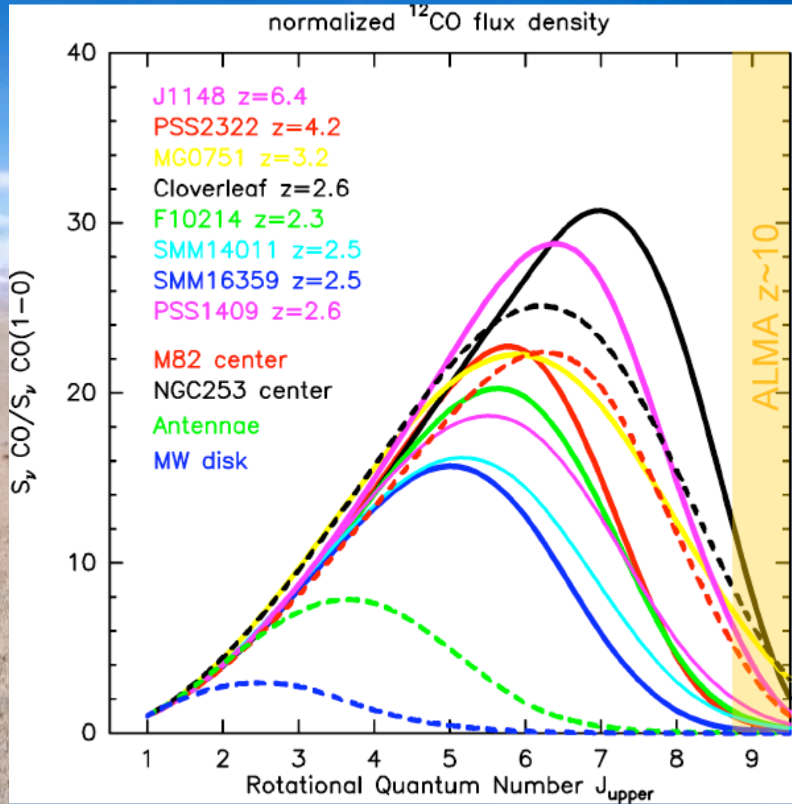
Not because it is the best tracer …

… but because it is the easier to observe

z > 8 SOURCES: ALMA CO DISCOVERY SPACE



CO line SEDs



For z~10, need to observe CO J>8
→ is the gas actually excited ?

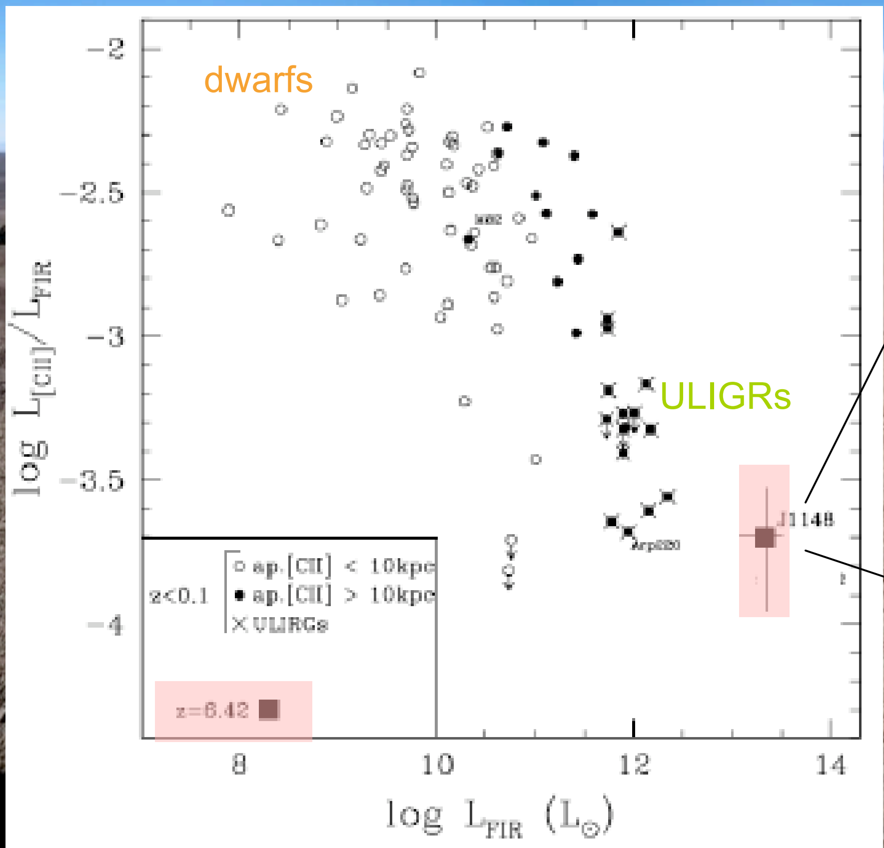
Bad news for z~10 ALMA obs !

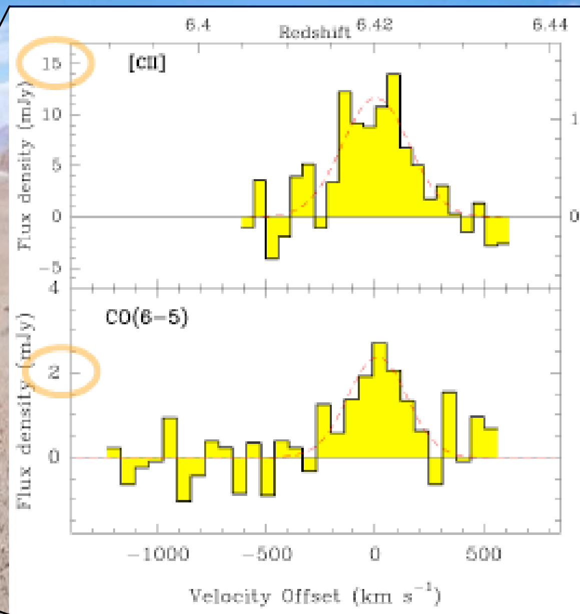
[CII] TO THE RESCUE

[CII] is the major cooling line of the ISM

$^2P_{3/2}$-$^2P_{1/2}$ fine-structure line; PDR / SF tracer; ν = 1900 GHz (158 μm)

[CII] carries high fraction of L_{FIR}:

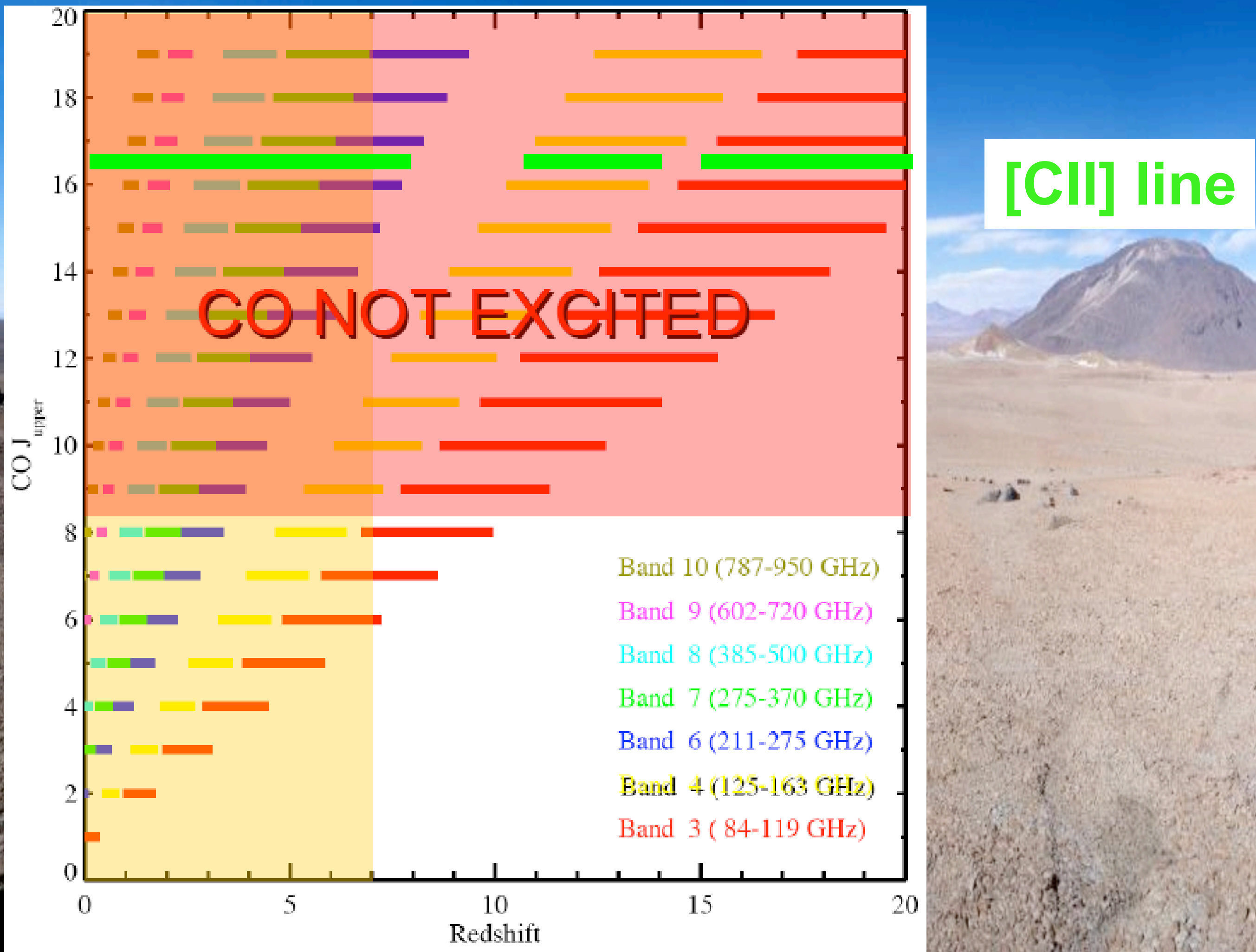




Detection of [CII] at z=6.42
in J1148+5251:
6 x brighter than the strongest CO

[CII] TO THE RESCUE

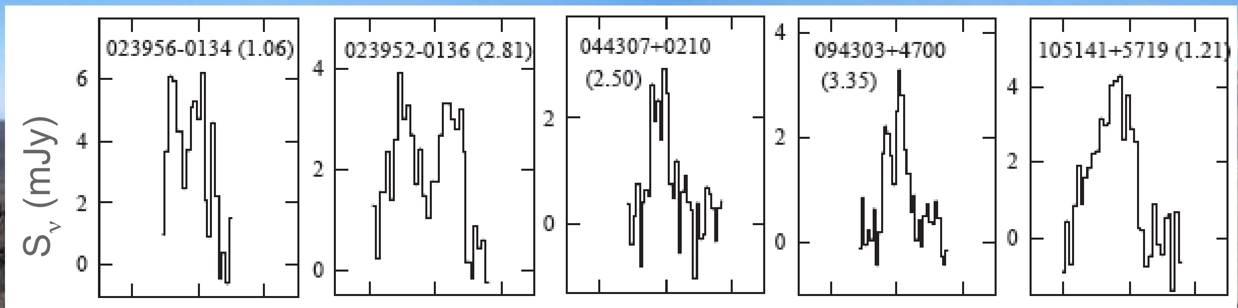
[CII] is the major cooling line of the ISM



OBJECTIFS SCIENTIFIQUES MAJEURS D'ALMA

2) DETECTER L'EMISSION CO ET CII DES GALAXIES DE TYPE VOIE LACTEE A z = 3 (< 24 h)

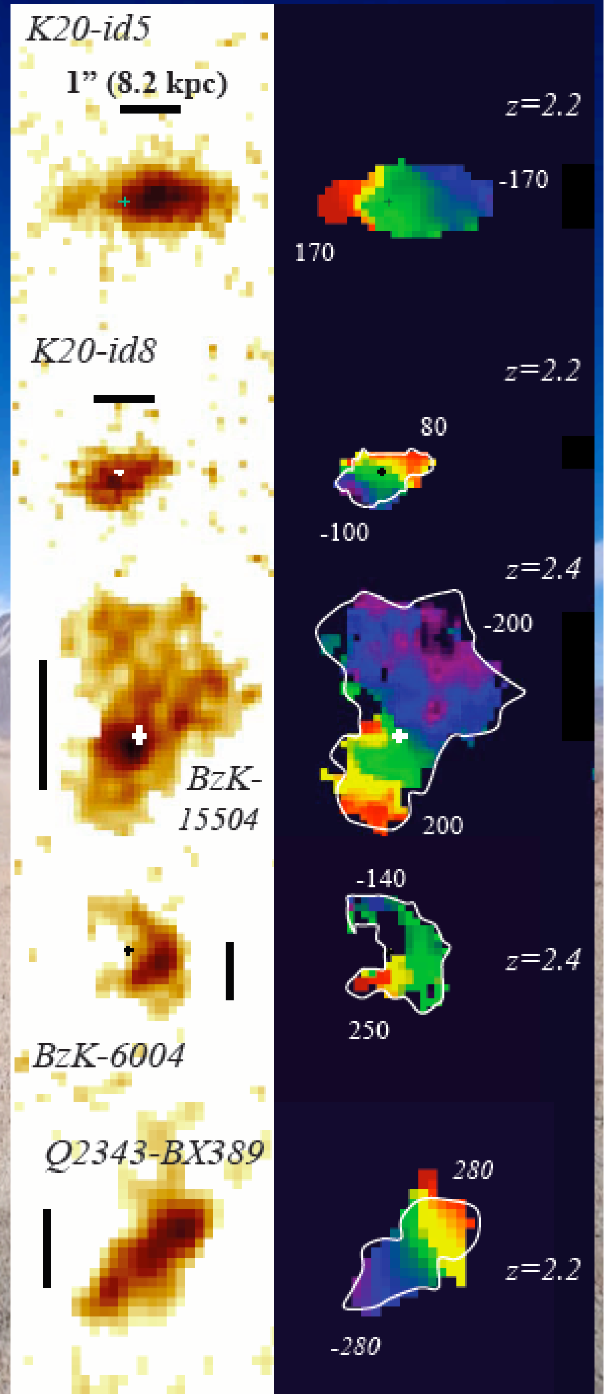
masse du gaz moléculaire, cinématique,
évolution des galaxies, histoire de la formation stellaire



Seuls les AGNs, starbursts et objets gravitationnellement amplifiés sont détectés à haut redshfit

LES GALAXIES NORMALES SONT 20 - 100 FOIS PLUS FAIBLES

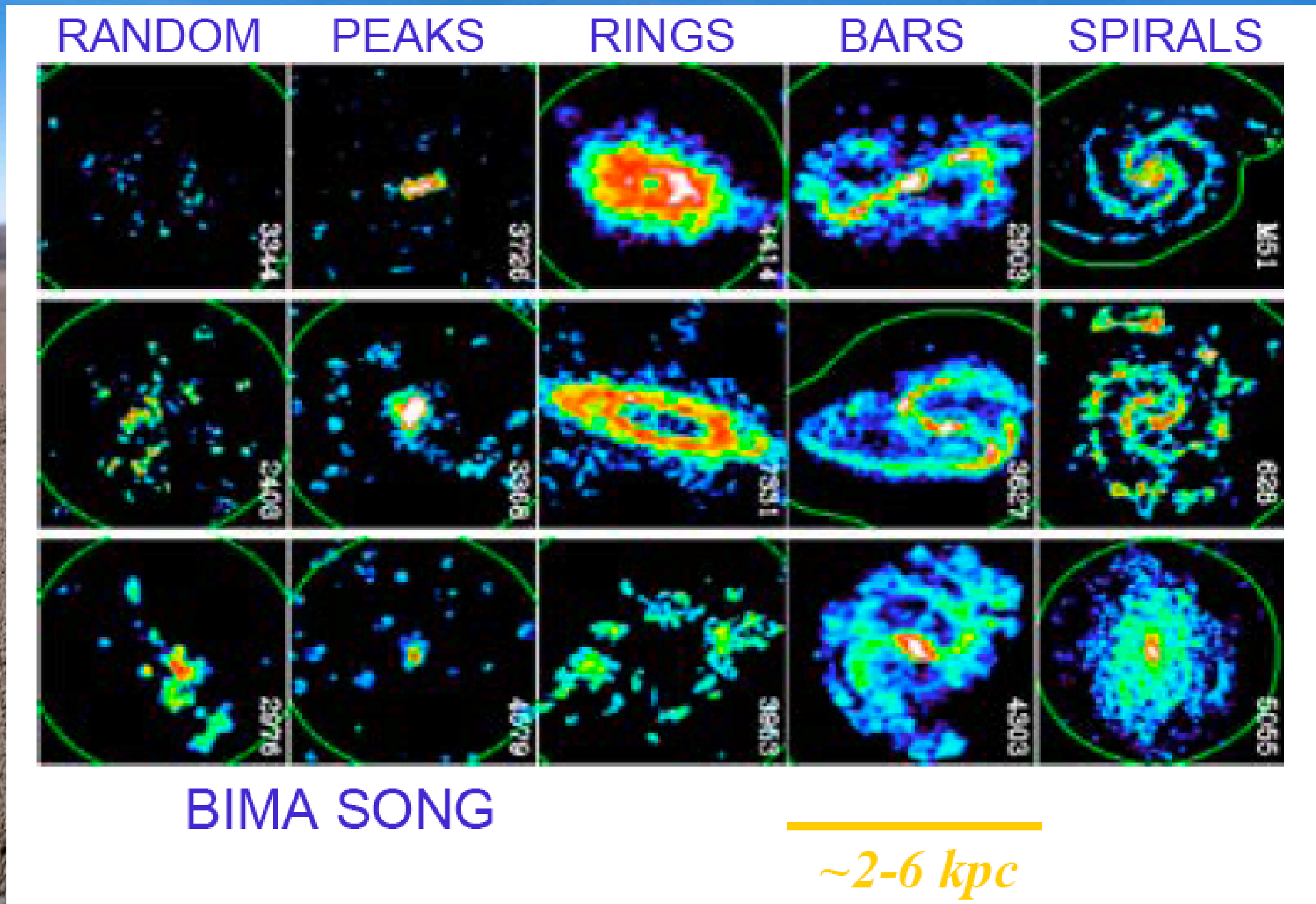
→ signal d'une Voie Lactée à z = 3: 0.01 mJy



OBJECTIFS SCIENTIFIQUES MAJEURS D'ALMA

3) MILIEU INTERSTELLAIRE DES GALAXIES PROCHES

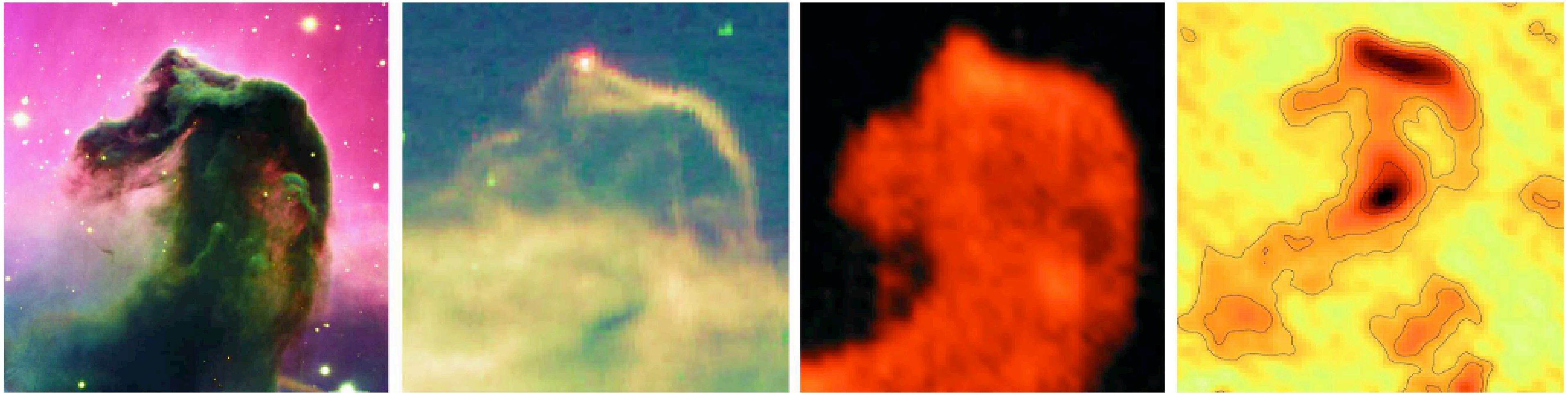
rôle des poussières froides et du gaz moléculaire dans l'histoire de la formation stellaire, conditions physiques, structures galactiques



OBJECTIFS SCIENTIFIQUES MAJEURS D'ALMA

4) FORMATION STELLAIRE

effondrement du nuage moléculaire, formation des proto-étoiles, cinématique des disques proto-stellaires, distribution des masses



→ λ

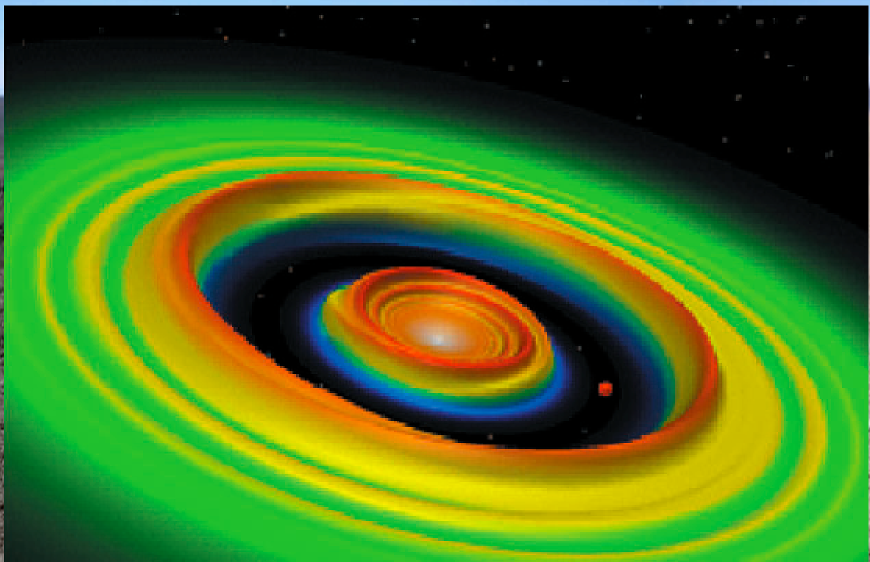
Optique	Infrarouge	Radio	Sub-millimétrique
Les étoiles se forment à l'intérieur des nuages moléculaires qui sont opaques dans l'optique	Dans l'infrarouge, les fines couches de poussières chaudes autour du nuage deviennent visibles	Dans le radio, les poussières et le gaz moléculaire sont visibles et apportent des infos sur la structure interne, la densité et la cinématique	Les nuages moléculaires deviennent transparents aux λ d'ALMA et les disques proto-stellaires sont visibles

OBJECTIFS SCIENTIFIQUES MAJEURS D'ALMA

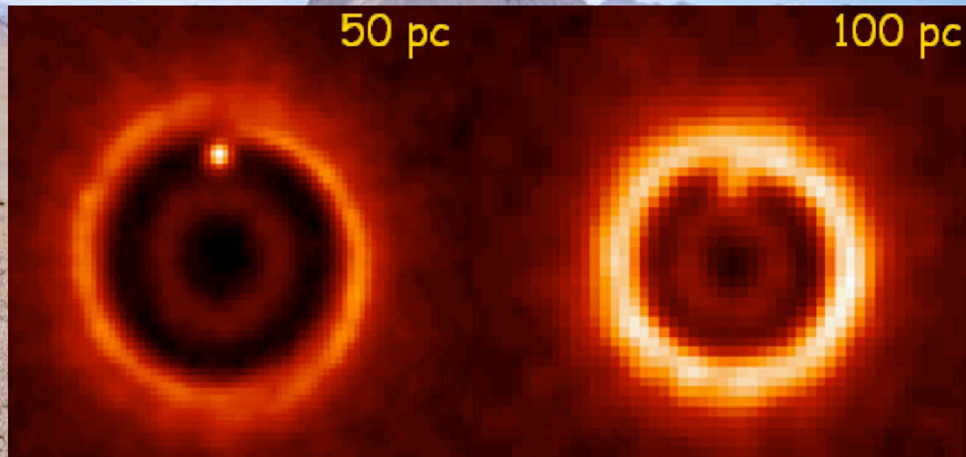
5) FORMATION DES PLANETES

cinématique des disques proto-planétaires, structure physique et chimique du disque

RESOLUTION ANGULAIRE AVEC ALMA: qqs UA → des distances de 150 pc
(distance des nuages de formation stellaire dans le Serpentaire ou la Couronne Australe)



Simulations hydrodynamiques d'une planète géante ($1\ M_J$) dans un disque proto-planétaire;
un sillon est formé dans le disque par la matière chassée par la proto-planète



De tels sillons seront résolus avec ALMA

Simulations des observations ALMA à 672 GHz d'un disque à 50 et 100 pc avec une proto-planète de $1\ M_J$ orbitant à 5 UA autour d'une étoile de $0.5\ M_\odot$

ALMA TIMELINE

1999 PREMIER ACCORD ENTRE L'EUROPE ET L'AMERIQUE DU NORD

2003 ACCORD FINAL ENTRE L'EUROPE ET L'AMERIQUE DU NORD

2003 DEBUT DES TESTS DES 3 PROTOTYPES D'ANTENNE A NEW MEXICO

2005 DEBUT DES TRAVAUX A CHAJNANTOR

2005 DERNIERS TESTS DES 3 PROTOTYPES D'ANTENNE

2006 ACCORD SIGNE ENTRE L'EUROPE, L'AMERIQUE DU NORD ET LE JAPON

2007 PREMIERES FRANGES AVEC 2 ANTENNES A NEW MEXICO

2007 PREMIERES ANTENNES AU CHILI

2008 INTERFEROMETRIE AVEC 2 ANTENNES

2009 INTEGRATION DES ANTENNES ET TESTS (1 antenne par mois)

2010 EARLY SCIENCE (début des demandes de temps)

2012 RESEAU COMPLET DES 50 ANTENNES OPERATIONNEL