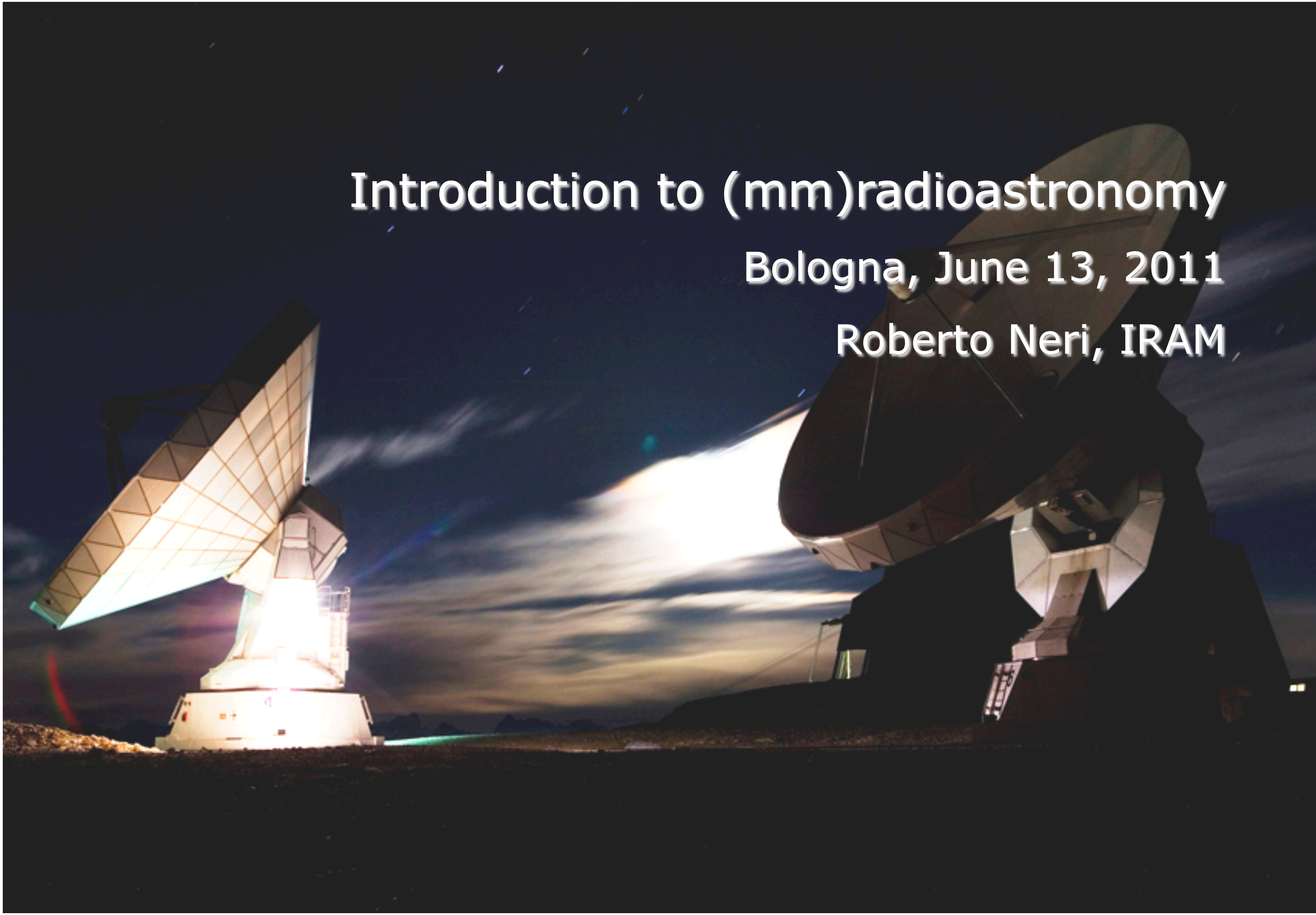


Introduction to (mm)radioastronomy

Bologna, June 13, 2011

Roberto Neri, IRAM

Summary

- historical overview
- from free-space to science
- a few words on calibration

or a couple of things you might want to know!

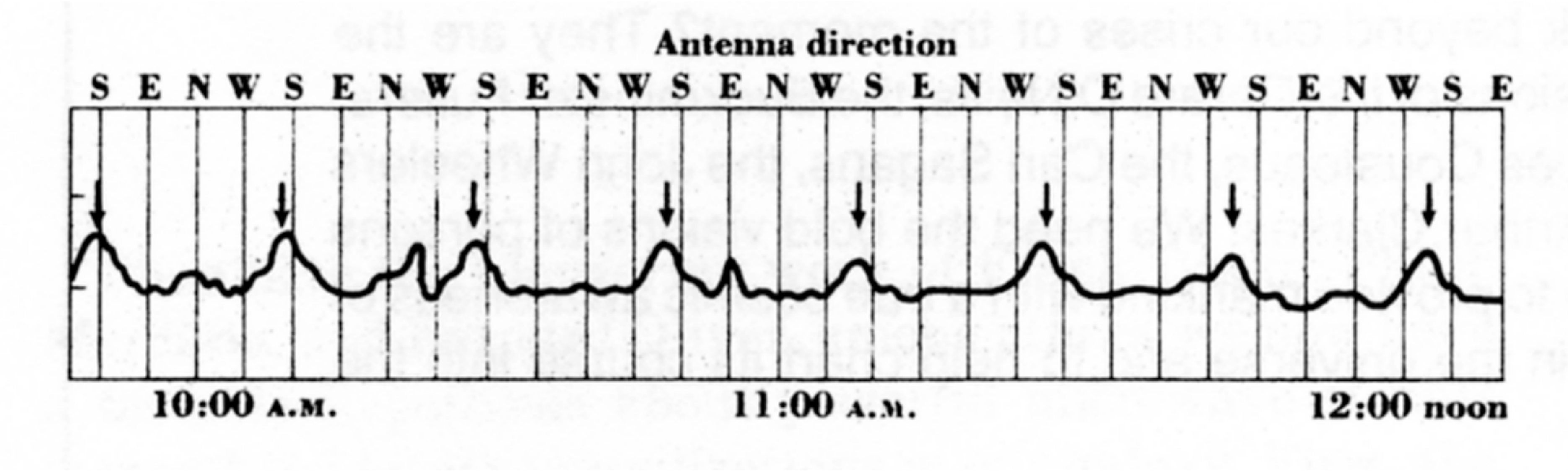
Historical Overview

- H.Hertz (1888)
  - Hertz oscillator : first radio wave transmitter
  - existence of electromagnetic waves
  - confirms Maxwell's theory

- G.Marconi (1901)
  - first transatlantic radio communication @ 820 KHz

- K.Jansky (1932)
  - azimuth rotating antenna @20.5 MHz
  - discovery of cosmic radio emission (GC)
  - 1 Jy = 10^{-26} W.m^{-2}.Hz^{-1}

Historical Overview



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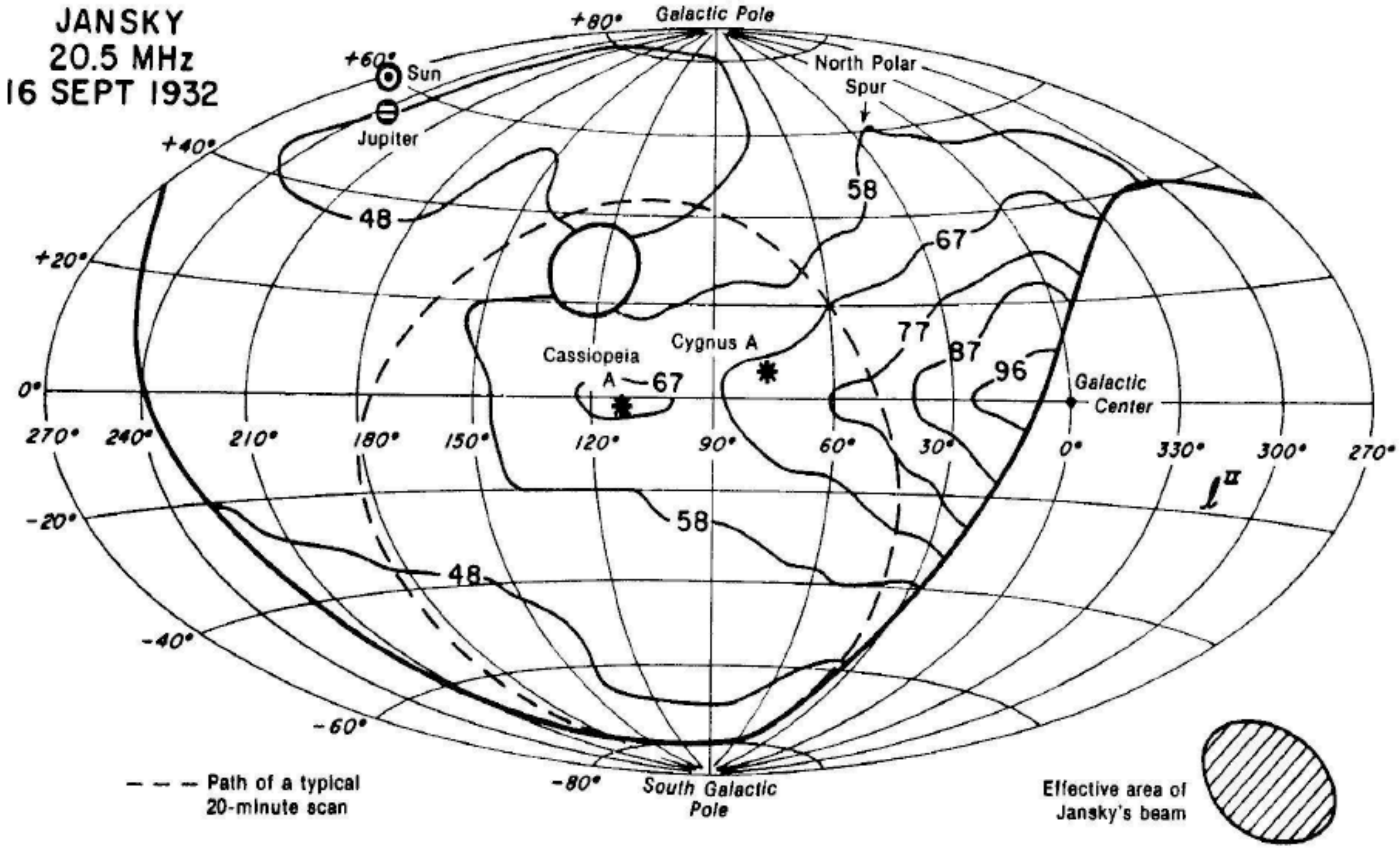
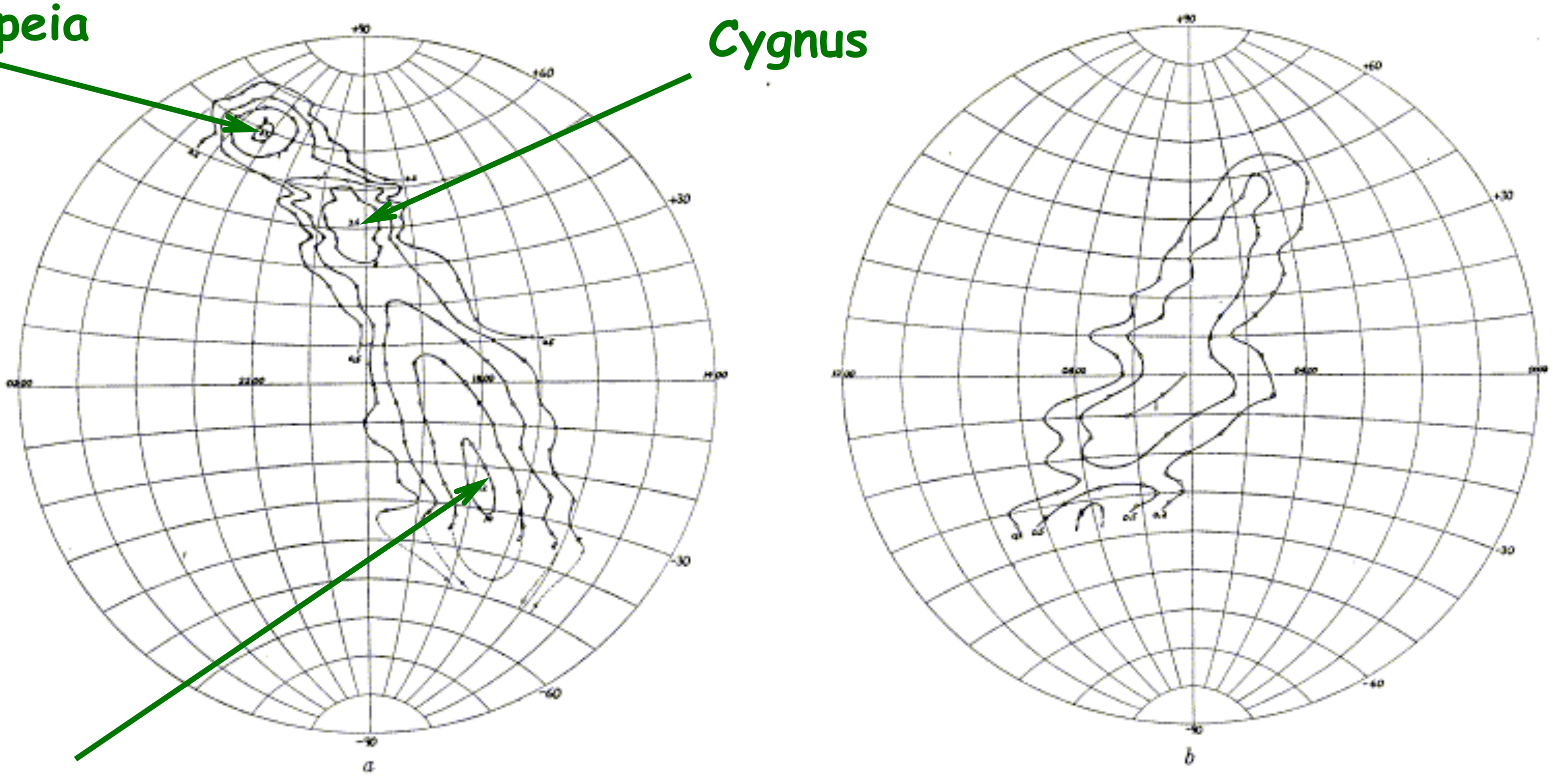


Historical Overview

- G.Reber (1938)
  - first parabolic radio dish @ 160 MHz (=1.8 m)
  - confirms Jansky's discovery
  - first synchrotron survey

Historical Overview

- G.Reber (1944, ApJ, 100, 279)



Cassiopeia

Cygnus

Sagittarius

FIG. 4.—Constant intensity lines in terms of 10^{-22} watt/sq. cm./cir. deg./M.C. band

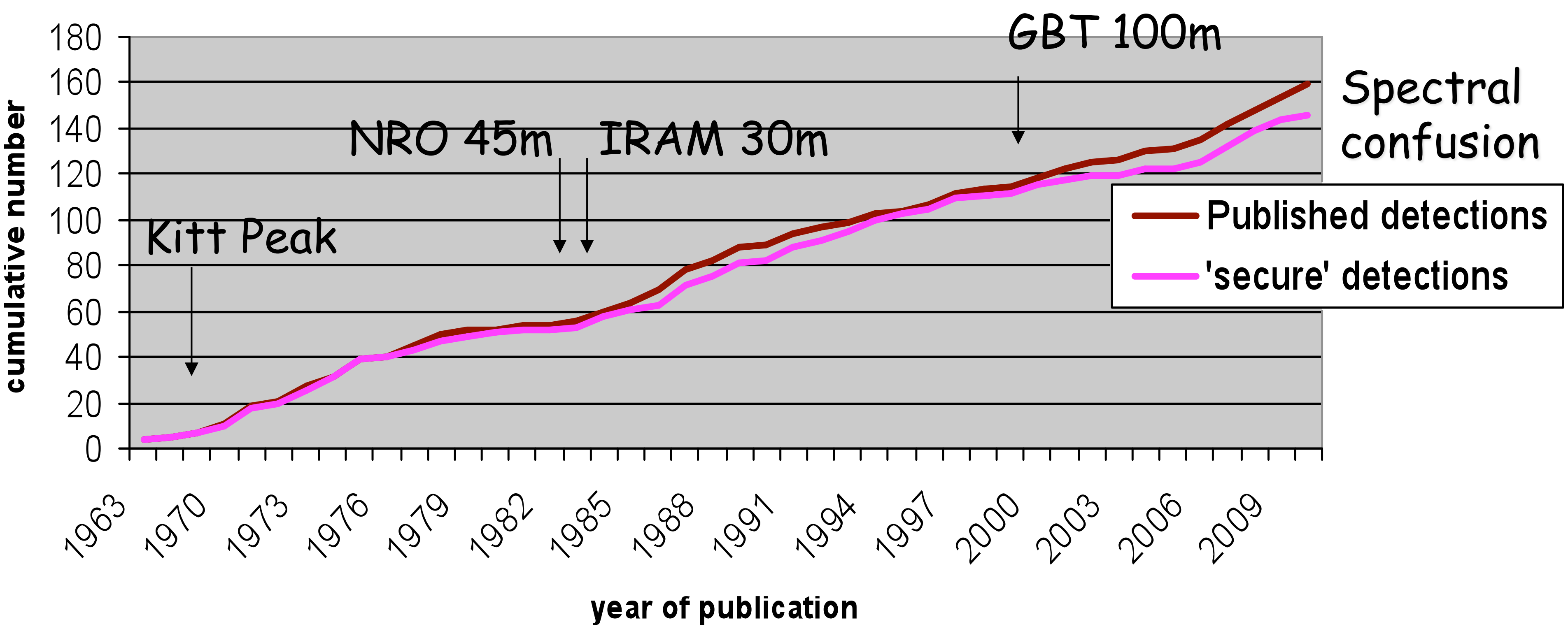
Historical Overview

- G.Reber (1944, ApJ, 100, 279)
  - first parabolic radio dish @ 160 MHz (=1.8 m)
  - confirms Jansky's discovery
  - first synchrotron survey - no detection @ 900 and 3300 MHz
- A.Penzias and R.Wilson (1965, ApJ, 142, 419)
  - discovery of the CMB @ 41 GHz

Historical Overview

- H I @ 21 cm : Ewen & Purcell 1951 ; Oort & Muller 1951
- OH @18 cm: Weinreb et al. 1963
- 1st polyatomic molecule in 1968: NH_3 (Cheung et al.)
- H_2O @ 1 cm (22 GHz) : Cheung et al. 1969
- start of UV astronomy: H_2 in 1970
- 1970: CO
- many more molecules, more and more complex (e.g. C_2H_5COOH) and more and more long (13 atoms ?)

Historical Overview : detected molecules



Guélin, priv.comm.

Historical Overview : some (sub)mm-Telescopes

- 1964: Haystack 37-m tel. (up to to λ=10/6mm)
- 1965: Green Bank 140ft telescope (λ>6mm)
- 1969: Kitt Peak 36'/12m telescope (λ>2/1mm)
- 1970: Effelsberg 100m telescope (λ>3mm)
- 1982: Nobeyama 45m telescope (λ>2mm)
- 1984: IRAM 30m telescope (λ>0.8mm)
- 1988: CSO 10.4m telescope (λ>0.3mm)
- 1990: Plateau de Bure Interferometer (λ>0.8mm)
- 2000: GBT 105m telescope (λ>3mm)
- 2004: APEX (λ>0.3mm)
- 2012: ALMA (λ>0.1mm)

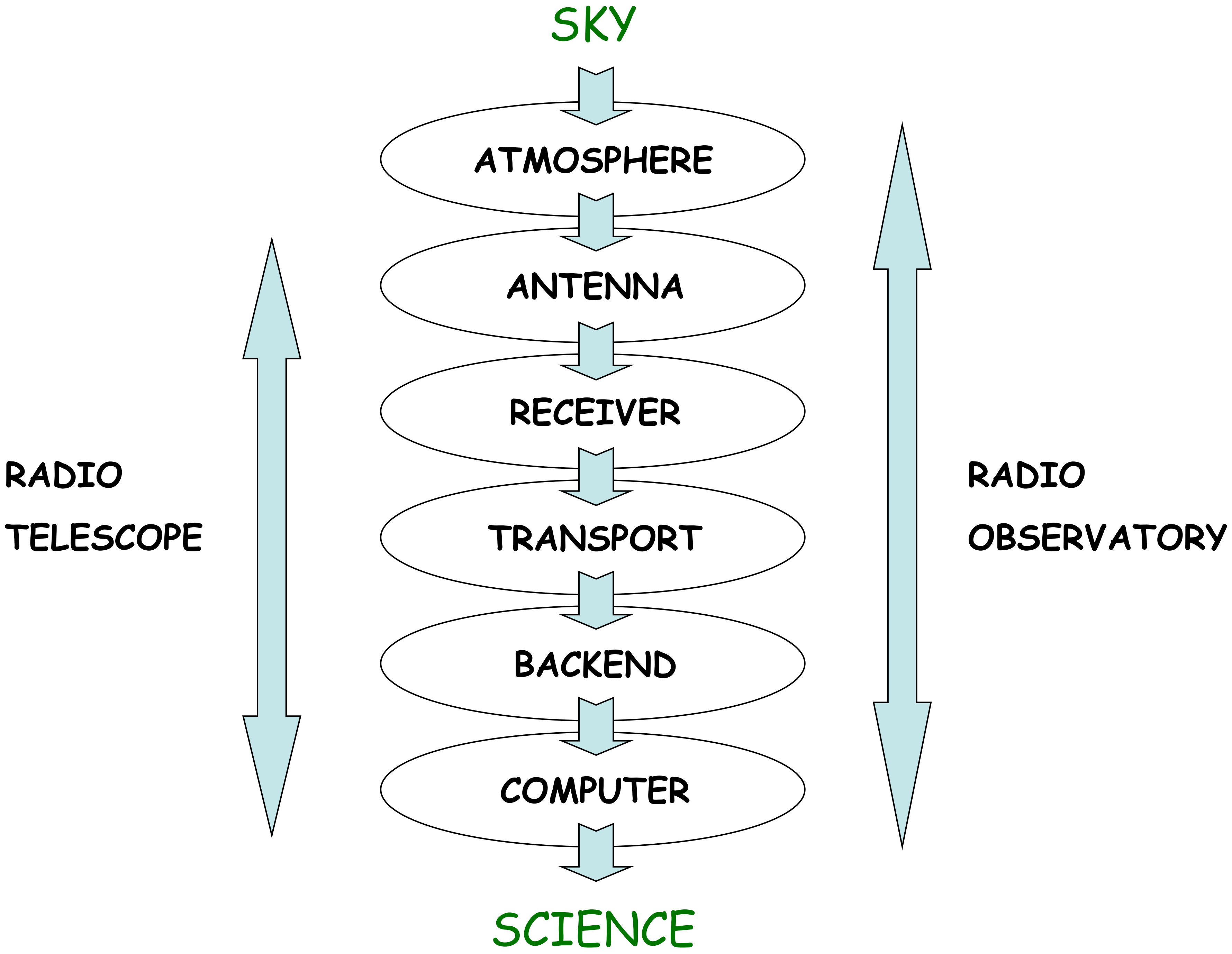
IRAM Science

Science Drivers 2005 >	Allocated Time	Keyword
Galaxies @ high-z : LBG, SMM, ERO, RG	30%	"CSF history"
Nearby Galaxies : Spirals, (U)LIRGs	30%	"dynamics + structure"
YSO : Prestellar Clouds → T-Tauri Stars	30%	"SF + evolution"
Evolved Stars	5%	"mass loss"
Chemistry, Solar System, …	5%	

VLBI	10 days	

mm-astronomy …

- ⇨ … not anymore in a proof-of-concept stage
- ⇨ … belongs to mainstream science



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ATMOSPHERE

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RECEIVER

TRANSPORT

BACKEND

COMPUTER

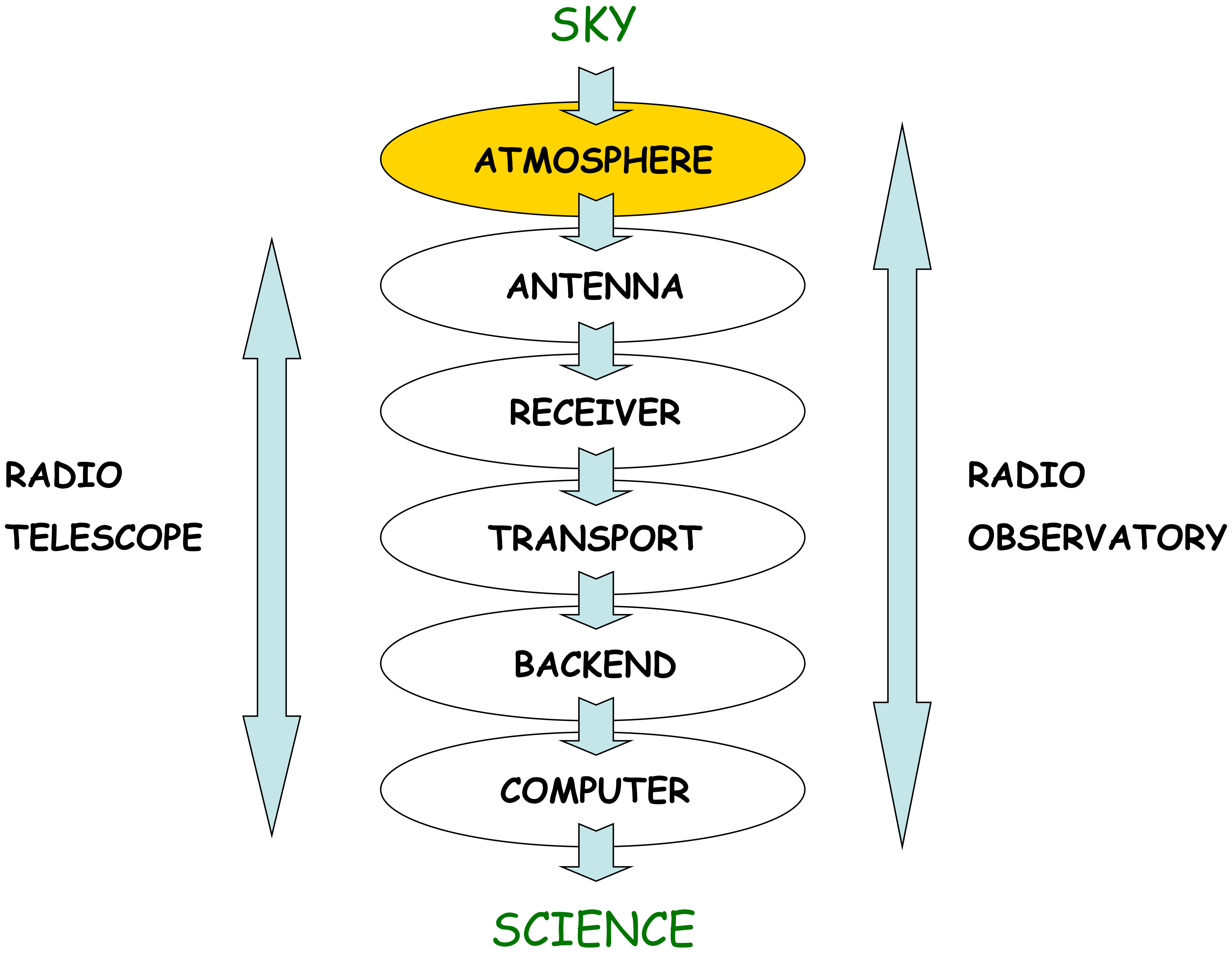
SCIENCE

RADIO

TELESCOPE

RADIO

OBSERVATORY



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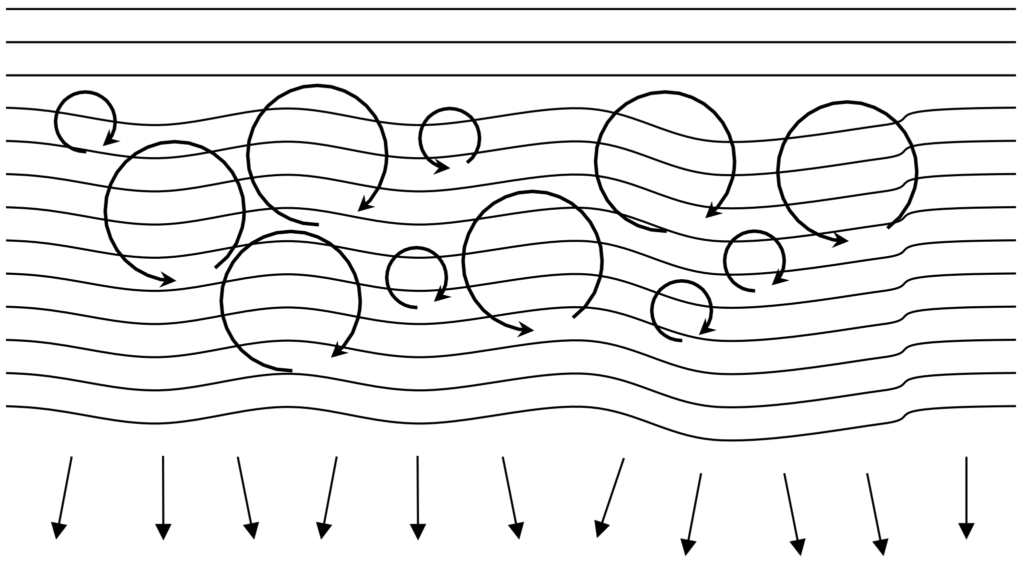
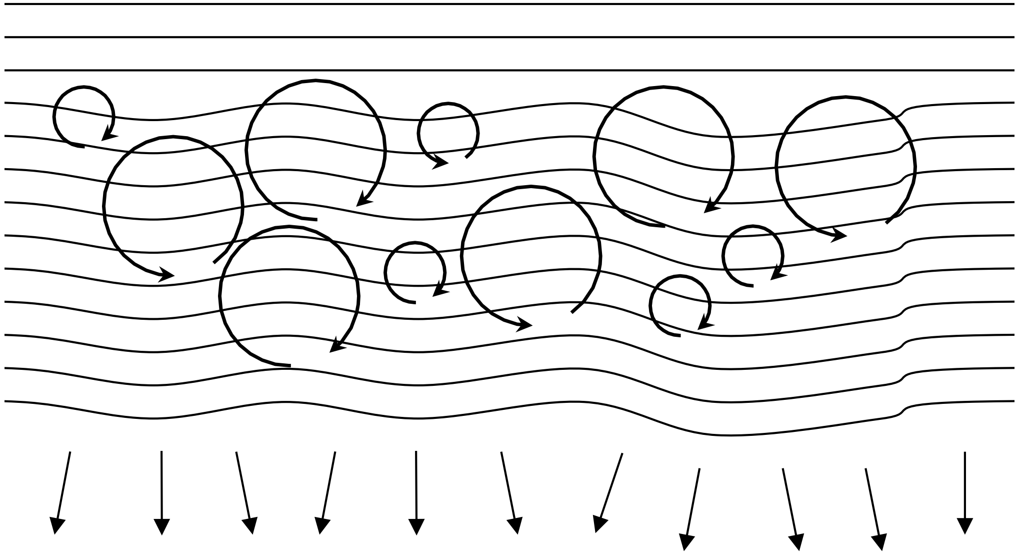
Atmosphere

- has a refractive index : $n' = n - i\kappa$
    - κ = absorbs/emits electromagnetic radiation = extinction
    - n = path delay = seeing
- water vapor poorly mixes with dry air > eddies
- eddies = atmosphere is turbulent > fluctuating path delay
- time varying deformation of wavefront > phase fluctuations



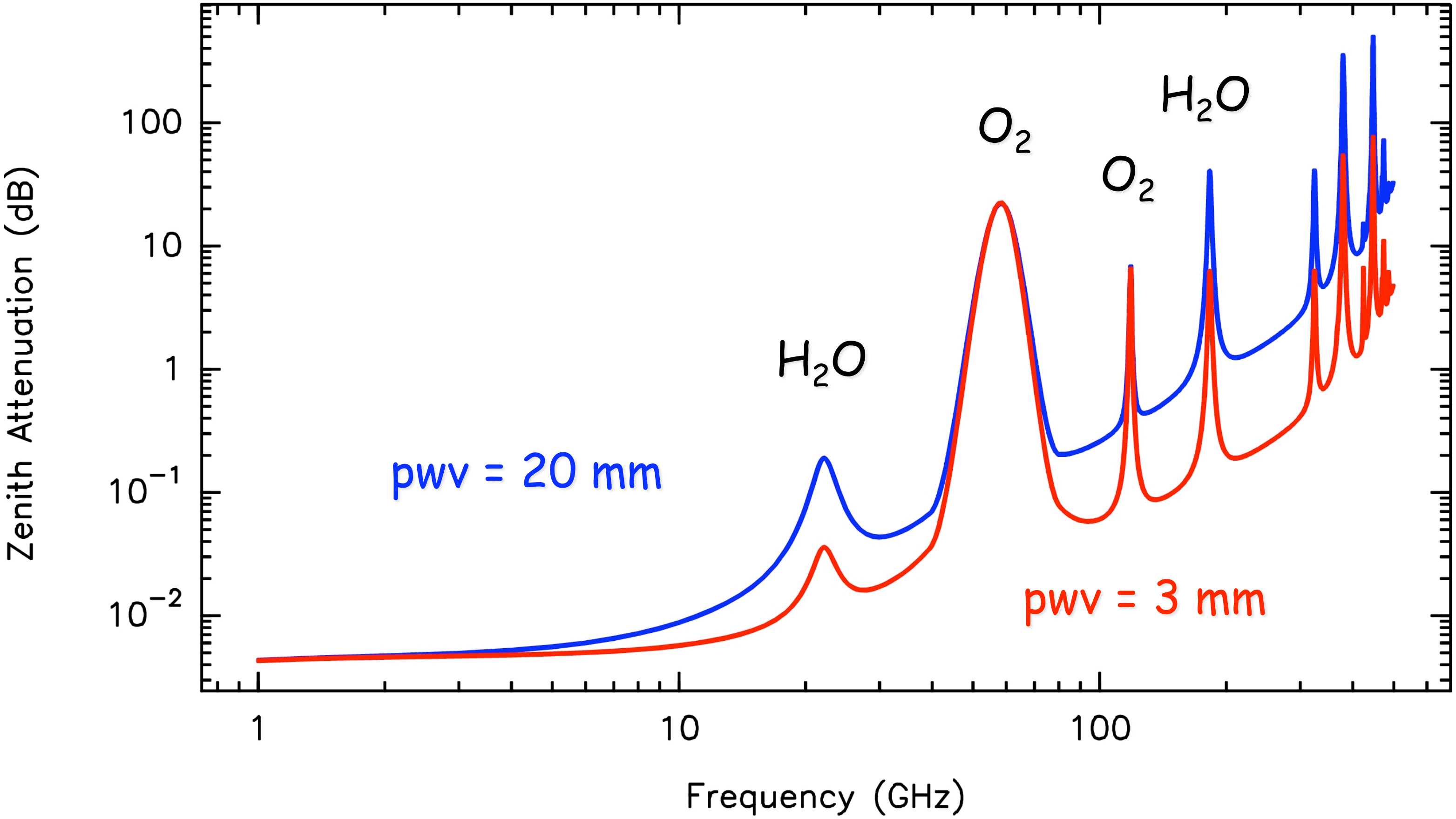
Atmosphere

- extinction = degradation of source amplitude
- phase noise = degradation of spatial resolution
  - SD: anomalous refraction
  - Interferometers: phase decorrelation



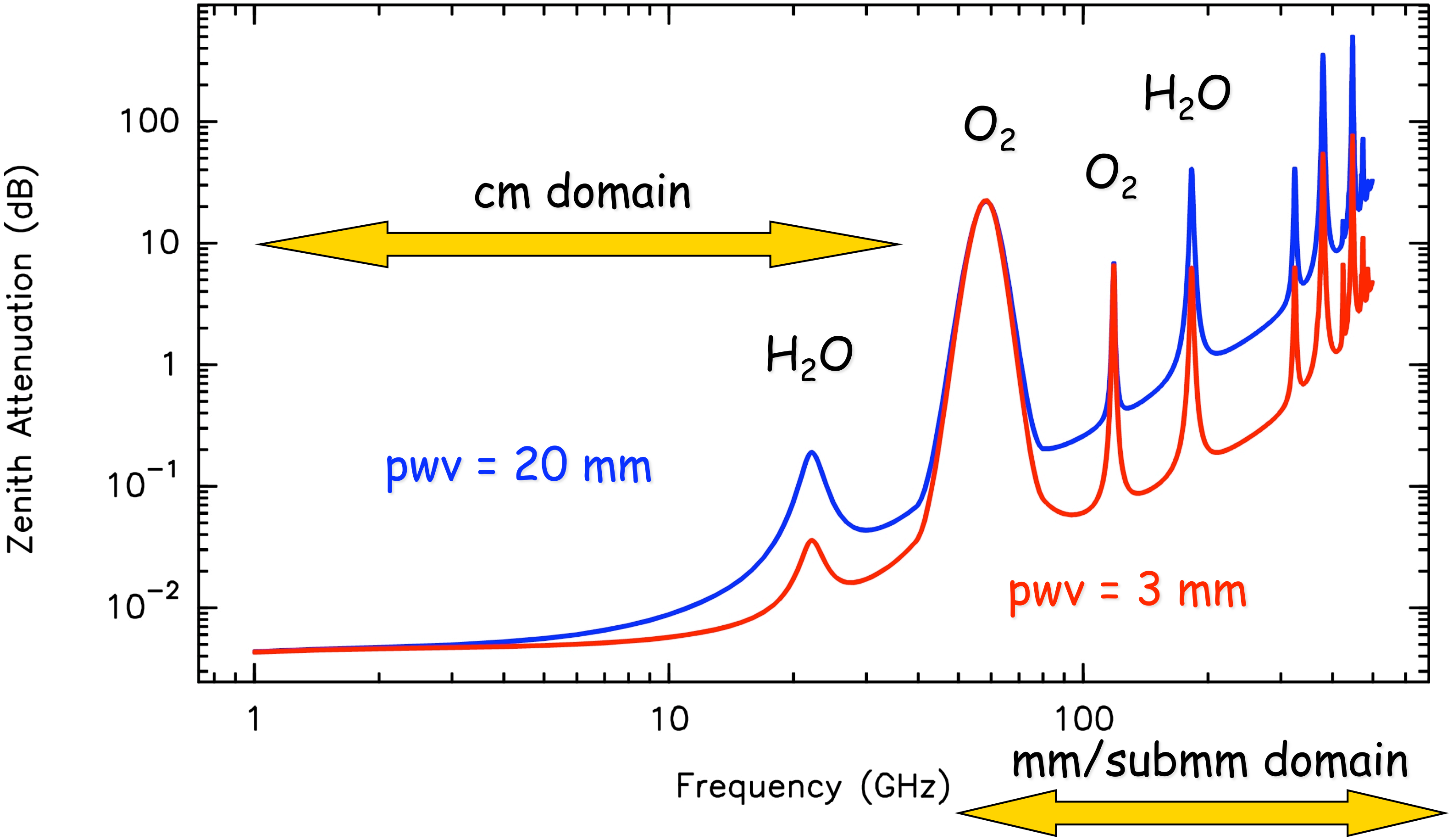
Atmosphere

Chernicharo & Pardo (ATM)



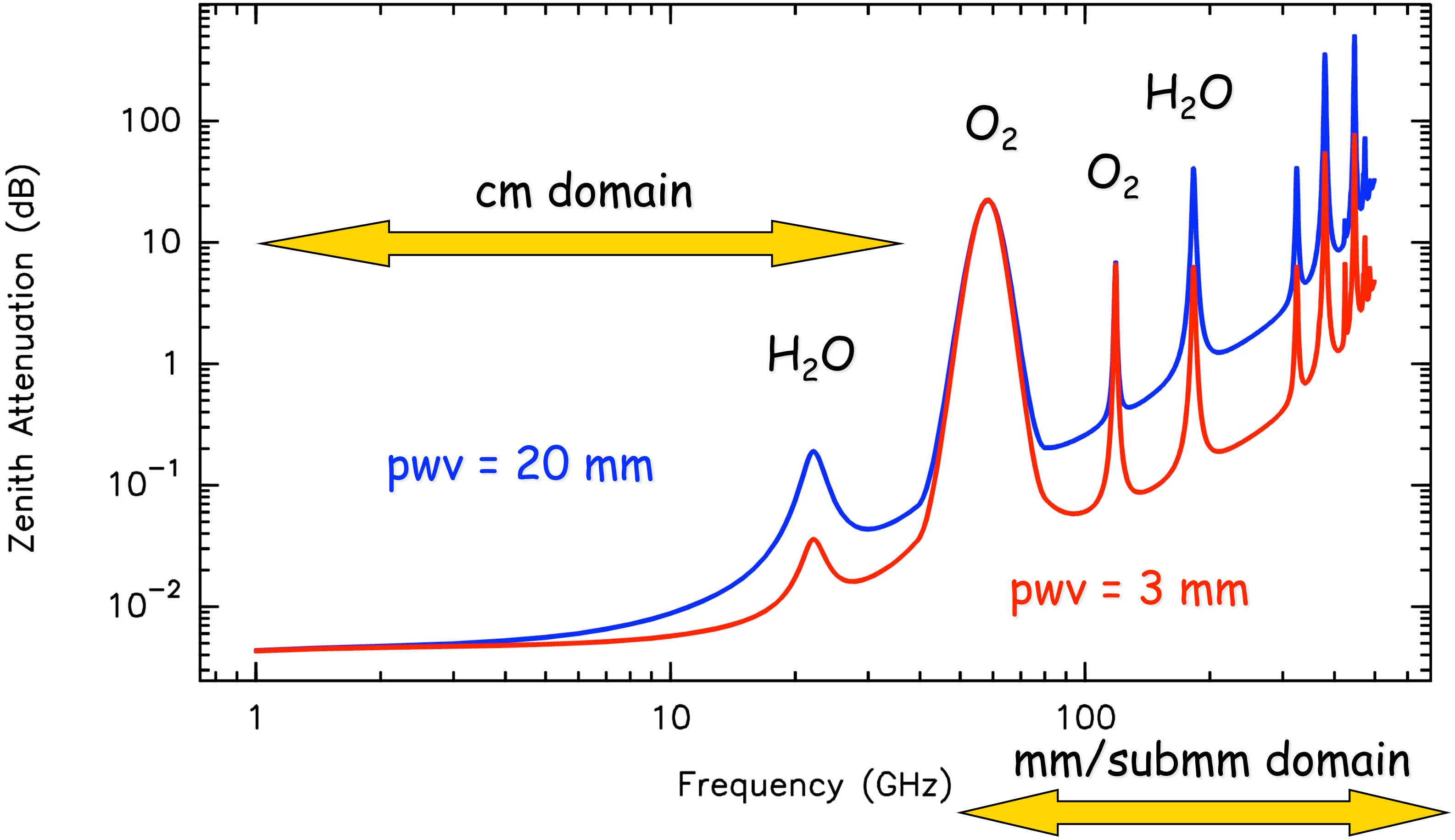
- main contributors to the atmospheric refraction: H_2O, O_2, O_3
- scale heights: H_2O = 2 km, O_2 = 8 km, O_3 = 20 km

Atmosphere



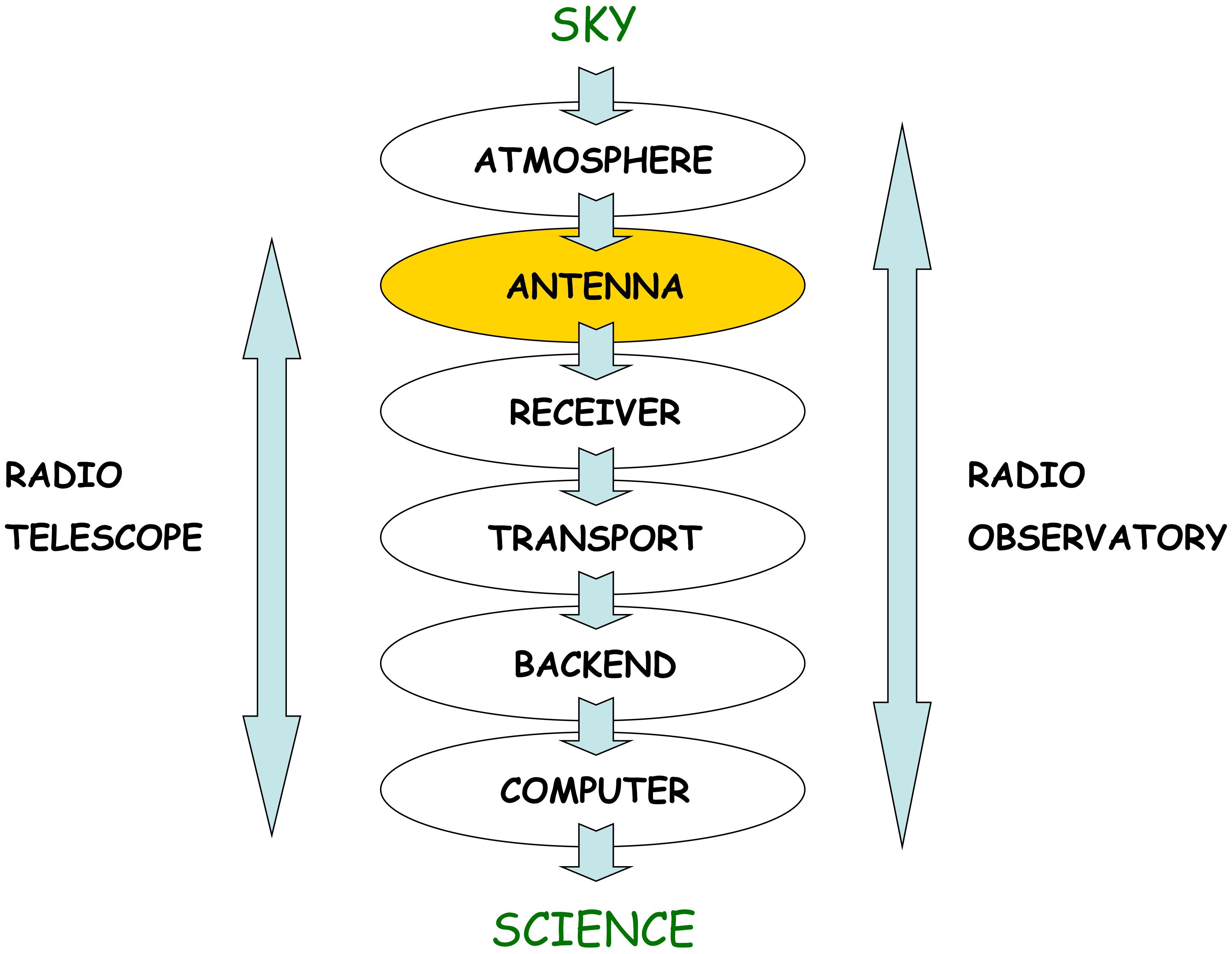
Zenith Attenuation (dB)
100
10
1
10^{-1}
10^{-2}
1
10
100
Frequency (GHz)
cm domain
mm/submm domain
H_2O
O_2
O_2
H_2O
pwv = 20 mm
pwv = 3 mm

Atmosphere



⇨ impacts on the observatory's altitude

Telescope	Altitude	Frequencies
EFFELSBERG 100m	320	<90 GHz
SRT 64m	700	<120 GHz
SMA 8	4030	<700 GHz
ALMA 50	5000	<1000 GHz



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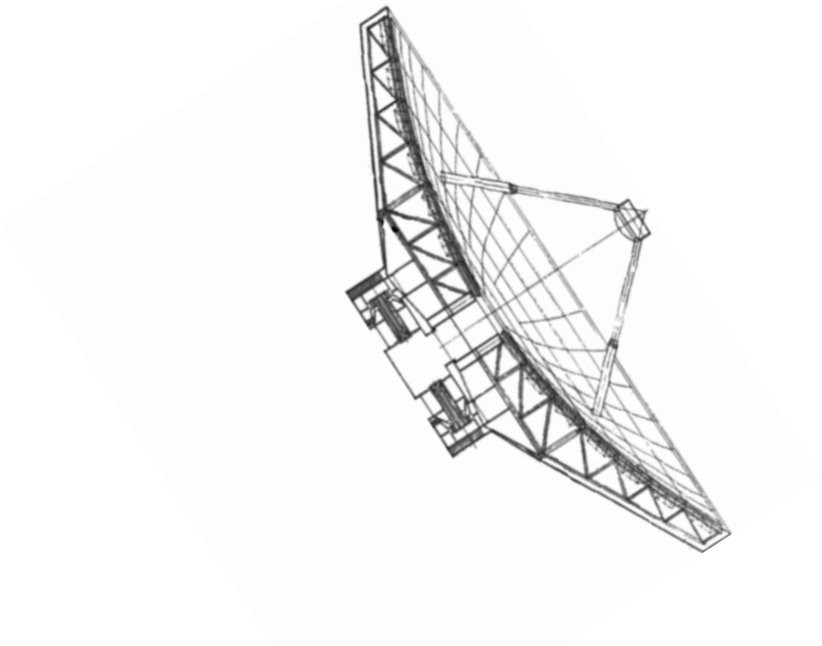
Telescopes

- prime-focus (Effelsberg)
- Cassegrain (GBT)
- Gregorian (SRT)
- Nasmyth (IRAM 30m)

Array, Single-Dish



D = diameter

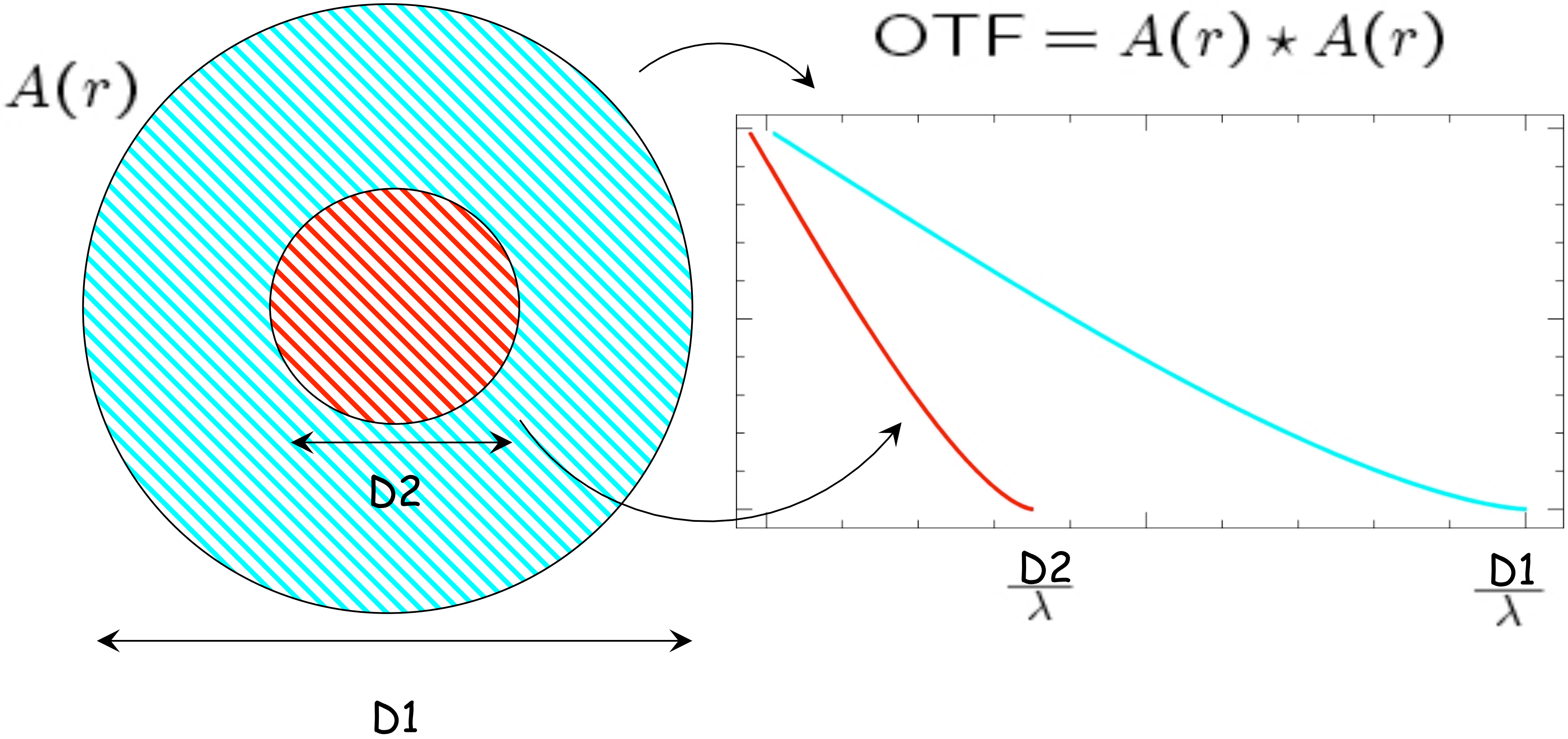
F = focal length

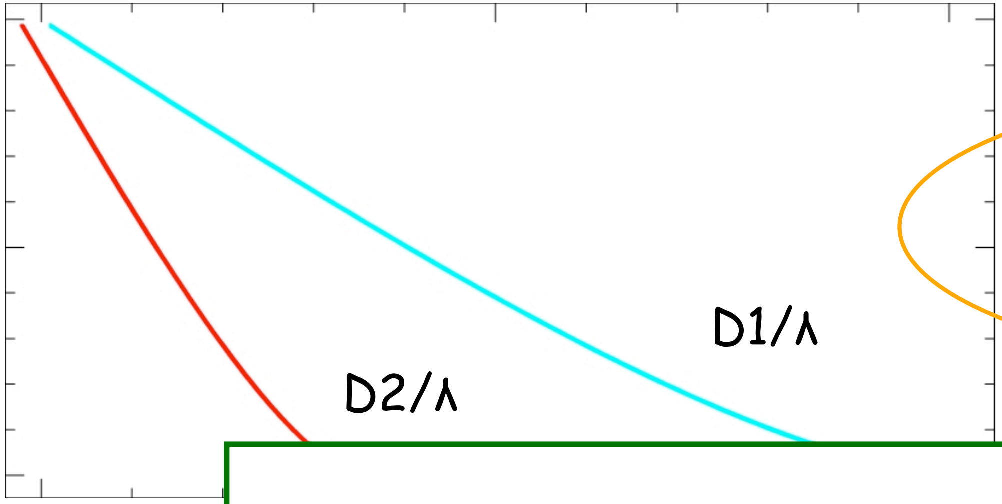
M = magnification

η_A = aperture efficiency

The perfect Single-Dish

samples all spatial frequencies up to D/λ – the lower frequencies are favored

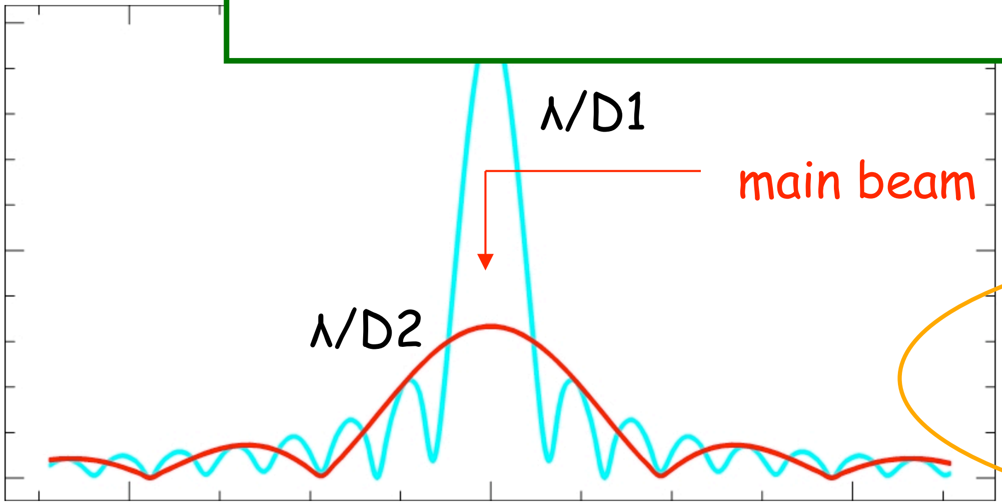




weighting function

$$\mathrm{OTF} = A(r) \star A(r)$$

main beam = primary beam = FOV

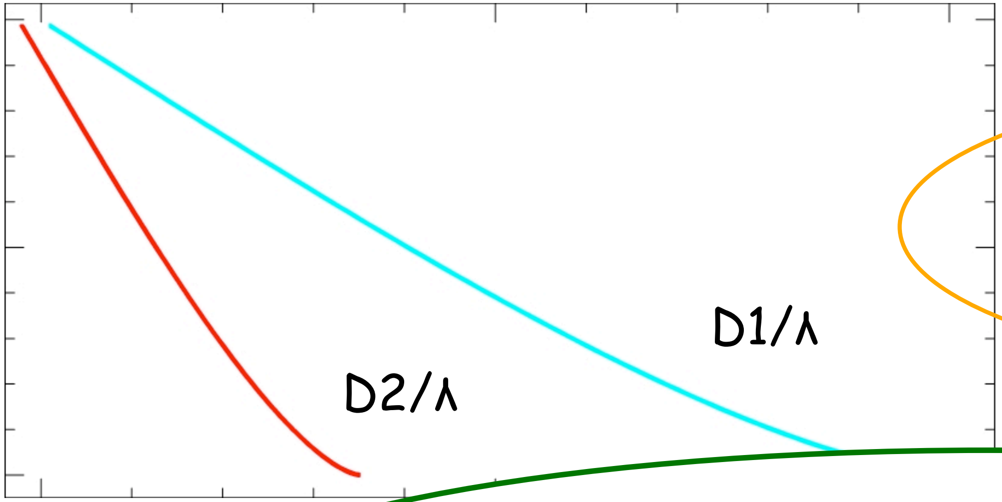


Spatial resolution

$$\mathrm{PSF} = FFT(\mathrm{OTF})$$

$$= |FFT(A(r))|^2$$

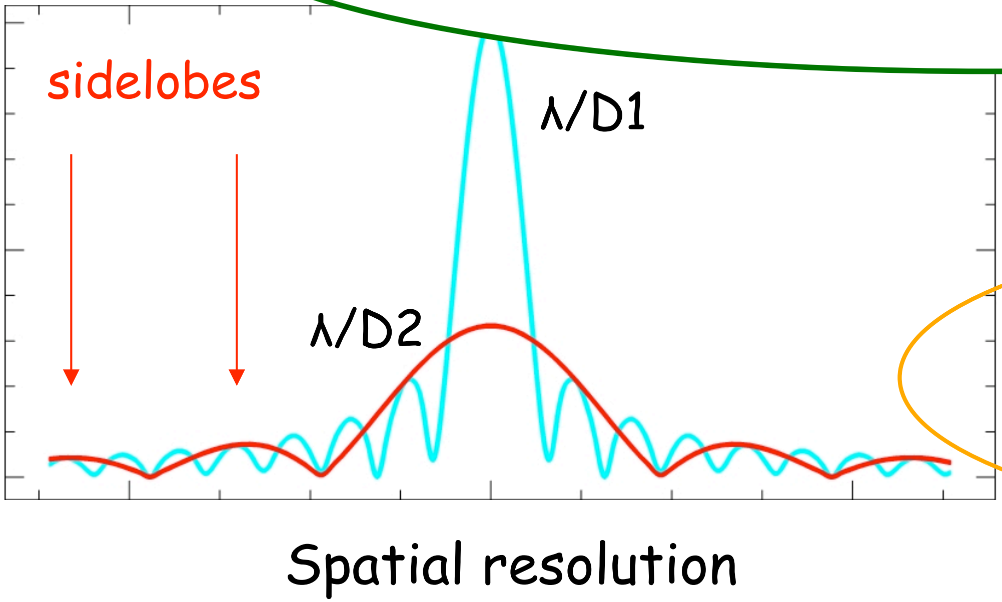
primary beam



weighting function

$$\mathrm{OTF} = A(r) \star A(r)$$

finite surface = secondary lobes



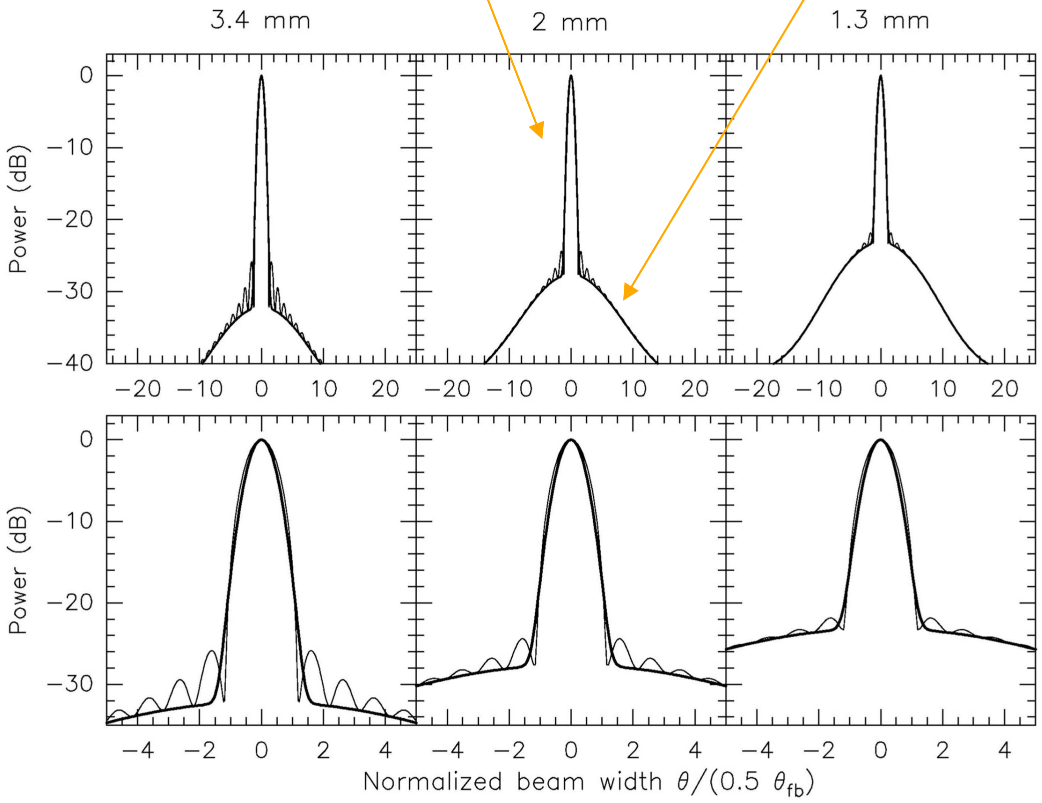
$$\mathrm{PSF} = FFT(\mathrm{OTF})$$

$$= |FFT(A(r))|^2$$

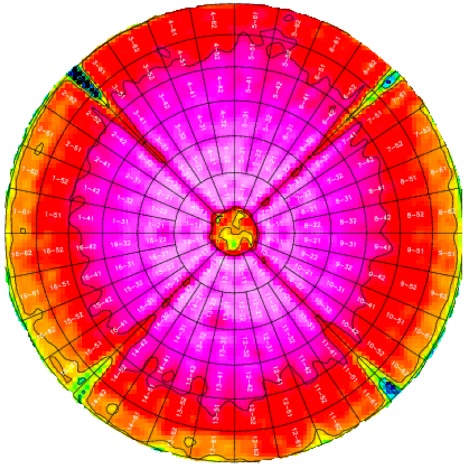
primary beam

From a perfect to a real single-dish

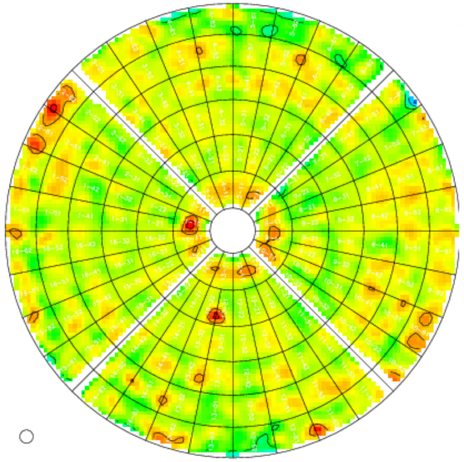
- optical alignment is never perfect
- surface irregularities introduce error lobes
- illumination is tapered (-10 ... -15dB)
- real beam = main beam + error lobes + sidelobes



Power Pattern



Antenna surface



From a perfect to a real single-dish

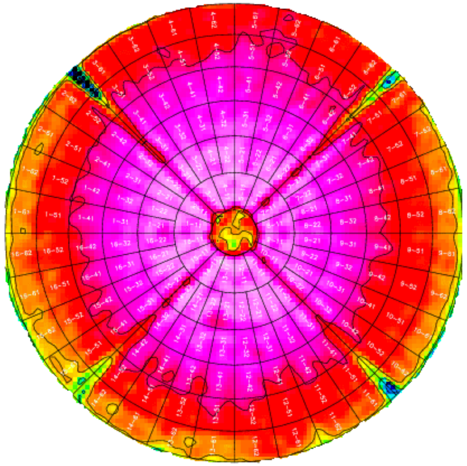
- optical alignment is never perfect
- surface irregularities introduce error lobes

- illumination is tapered (-10 ... -15dB)
- real beam = main beam + error lobes

- main beam (FWHM) $= 1.16\,\lambda/D$ [rad] -13dB
  $= 2.4\,10^5\,\lambda/D$ ["]

- main beam solid angle $= 1.13\,\theta_{\rm mb}^2$ [sterrad]

Power Pattern



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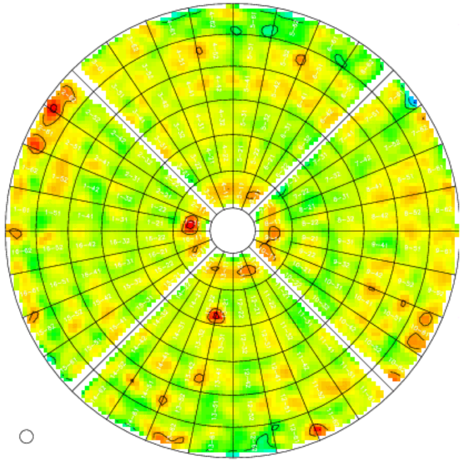
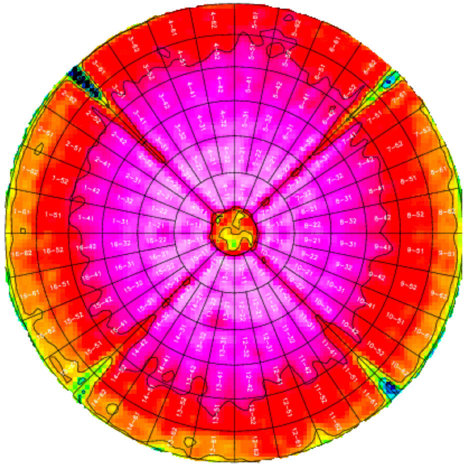


From a perfect to a real single-dish

Power Pattern



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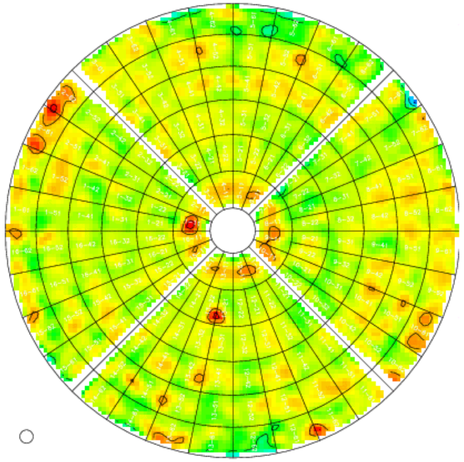

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- main beam solid angle $= 1.13\,\theta_{\mathrm{mb}}^2$ [sterrad]

- aperture efficiency

$$\eta_A = \eta_{\text{Blocage}} \cdot \eta_{\text{Spillover}} \cdot \eta_{\text{Receiver}} \cdot \eta_{\text{Ruze}}$$

$=$ 0.7 (ALMA B7) ... 0.8 (ALMA B3)

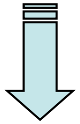
Single-Dish limitations

1. angular resolution : ~1/D

Need to

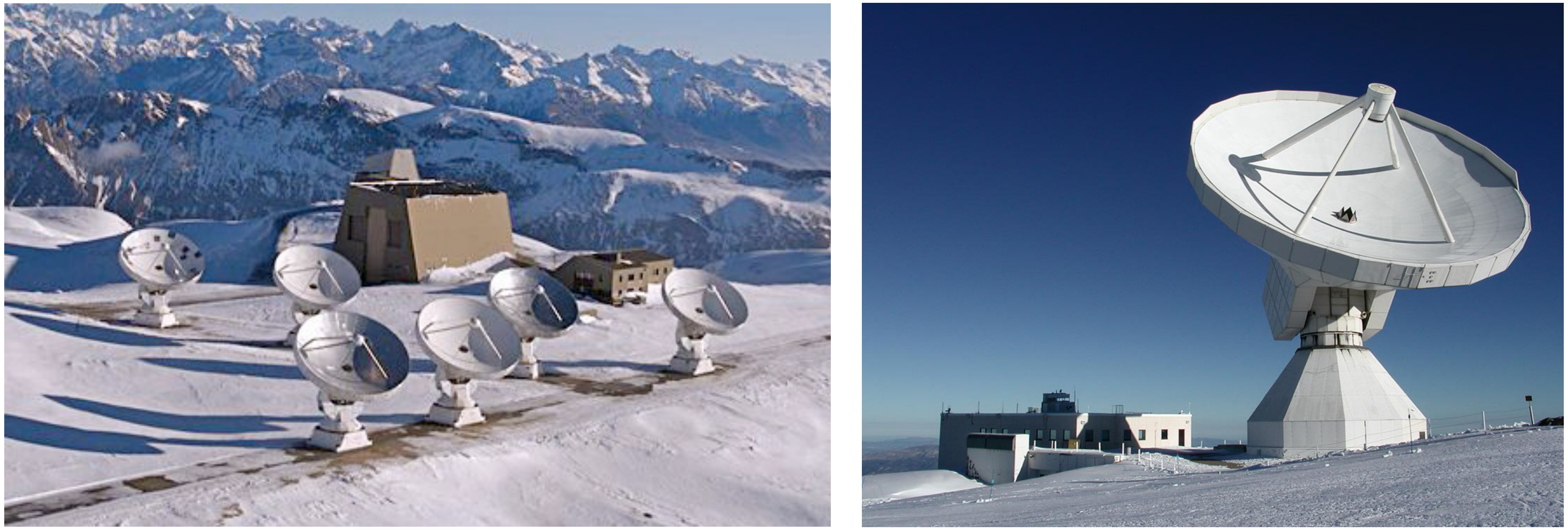
1. increase diameter
2. increase the pointing accuracy
3. keep a high surface quality

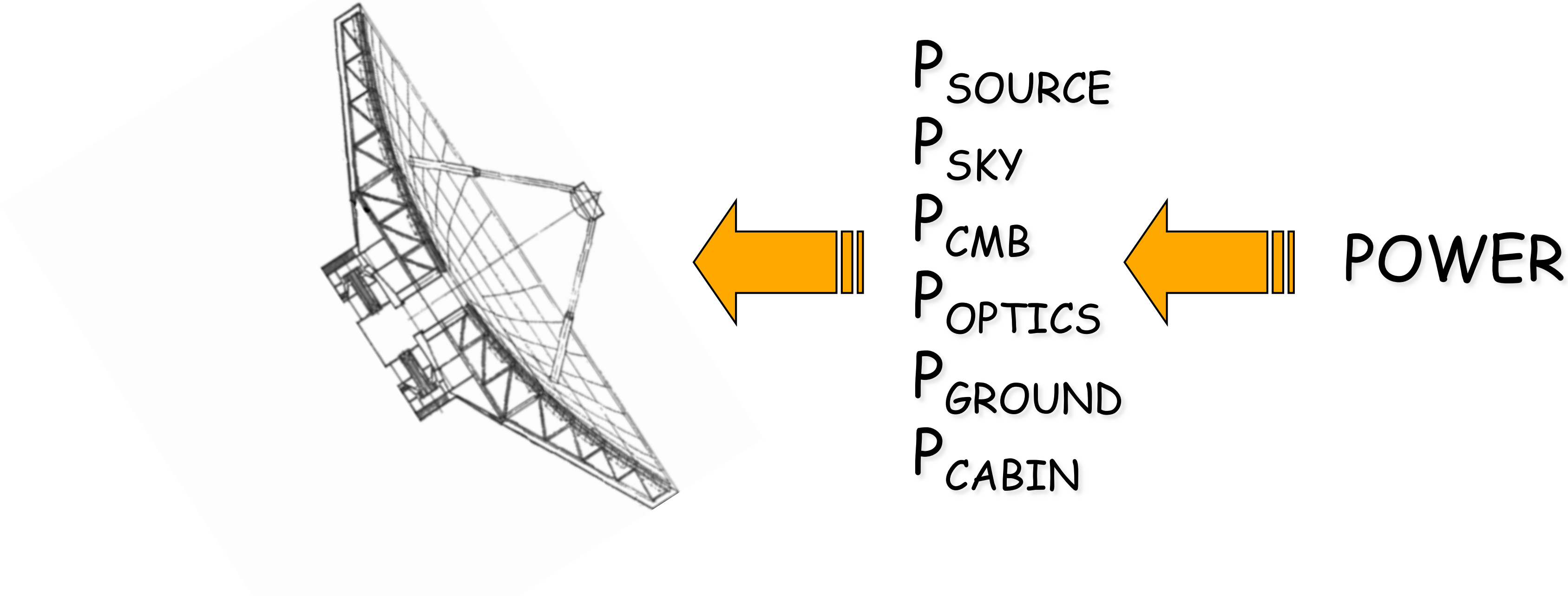
Single-Dish	Angular resolution @ 1mm
CSO 10m	24"
IRAM 30m	9"
LMT 50m	6"



TOMORROW: the power of interferometers

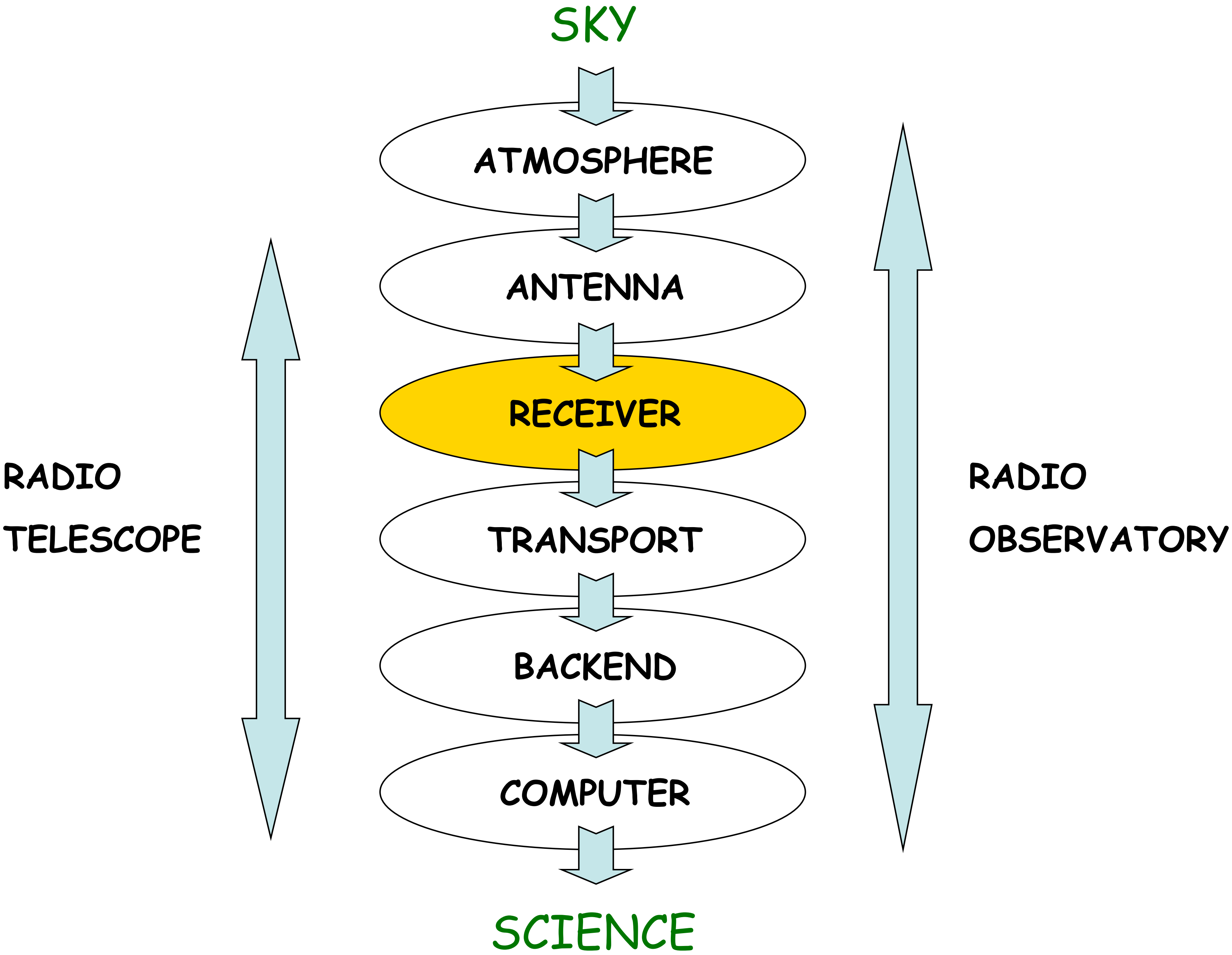
Array = Single-Dish





P_{SOURCE}
P_{SKY}
P_{CMB}
P_{OPTICS}
P_{GROUND}
P_{CABIN}

POWER



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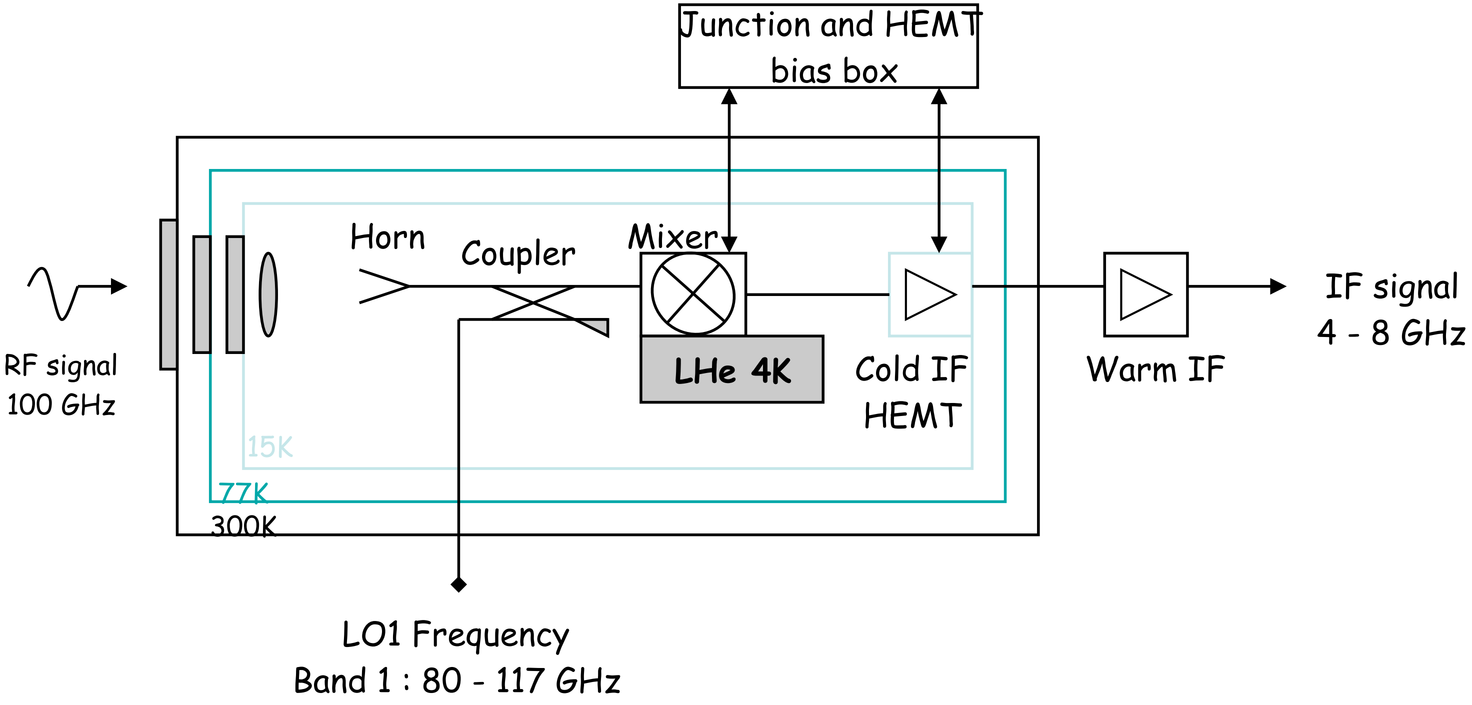
Receiver system

- is an efficient mixer-based photon converter
- performs a heterodyne down-conversion
- amplifies incoming signal with minimum extra noise



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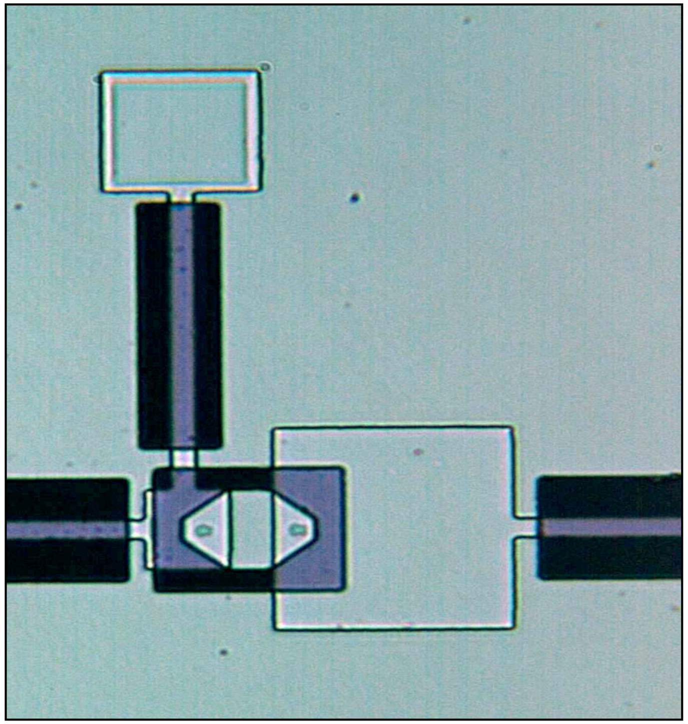

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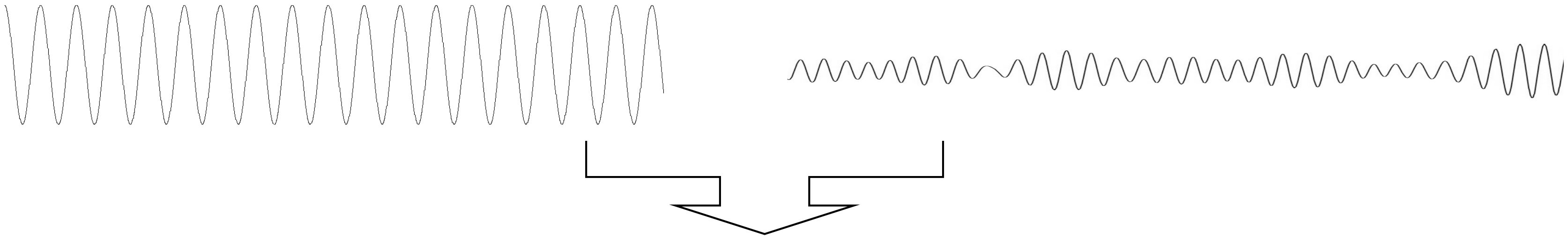

$$(\cos\omega_{\rm L}t + \epsilon\cos\omega_{\rm RF}t)^2 \quad \Longrightarrow \quad \epsilon\ \cos\omega_{\rm L}t\ \cos\omega_{\rm RF}t = \frac{1}{2}\epsilon\cos(\omega_{\rm L} - \omega_{\rm RF})t$$

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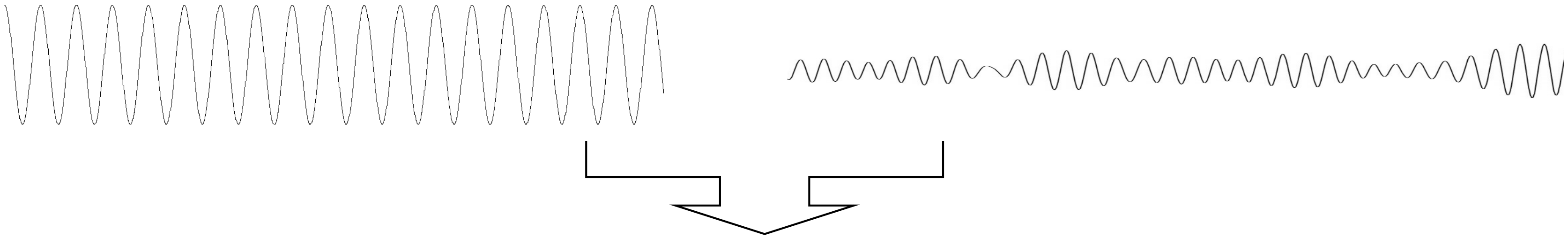

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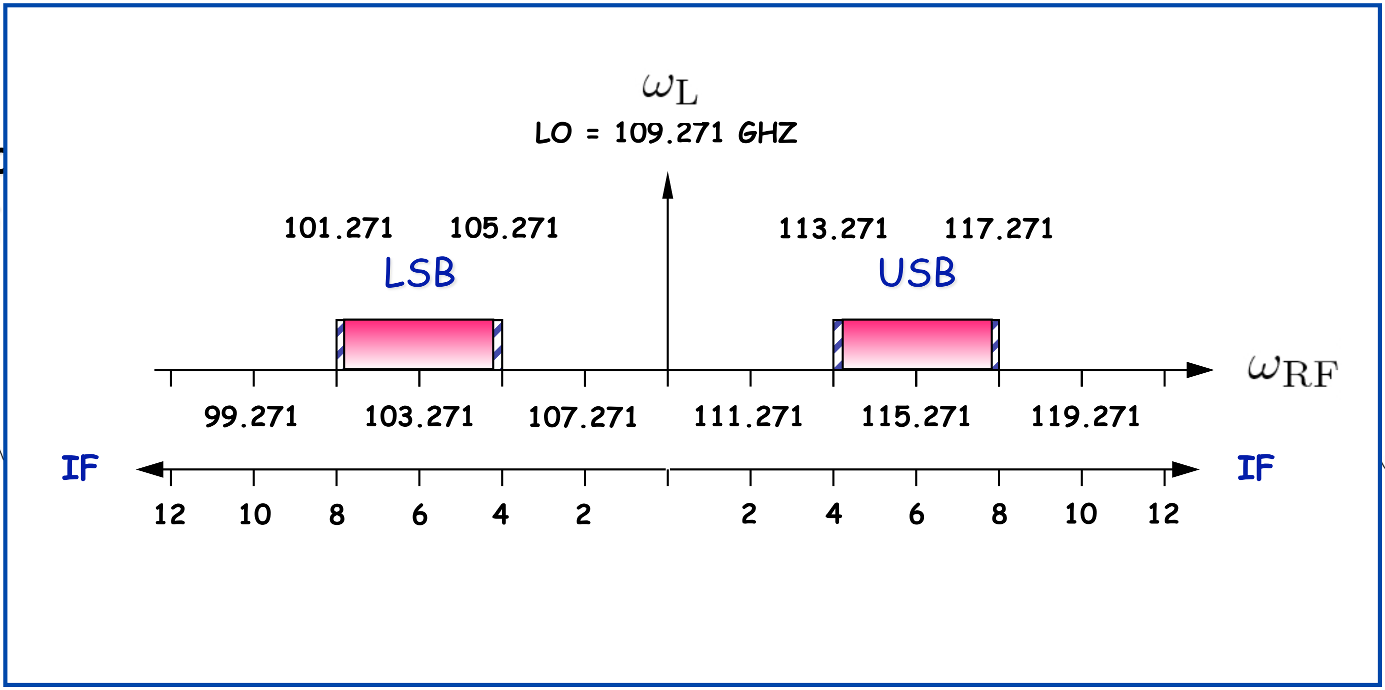
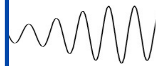
Receiver system

- is an
- perfo
- ampli





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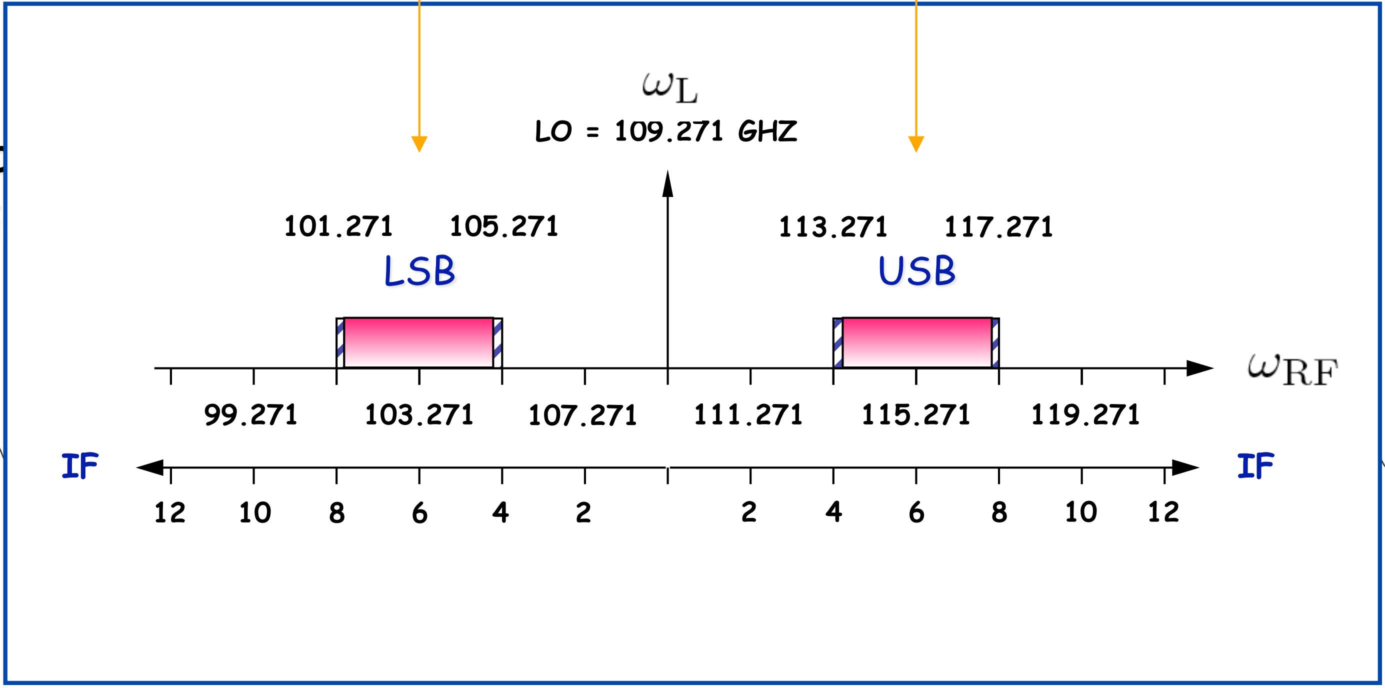
- is (ideally) a (lossless) bandpass filter
- output voltage is proportional to its input (noise) power

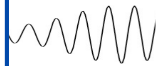
Receiver system

Sidebands

Image / Signal

- is an
- perfo
- ampli





$$(\cos\omega_{\rm L}t + \epsilon\cos\omega_{\rm RF}t)^2 \Longrightarrow \epsilon\ \cos\omega_{\rm L}t\ \cos\omega_{\rm RF}t = \frac{1}{2}\epsilon\cos(\omega_{\rm L}-\omega_{\rm RF})t$$

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Receiver system

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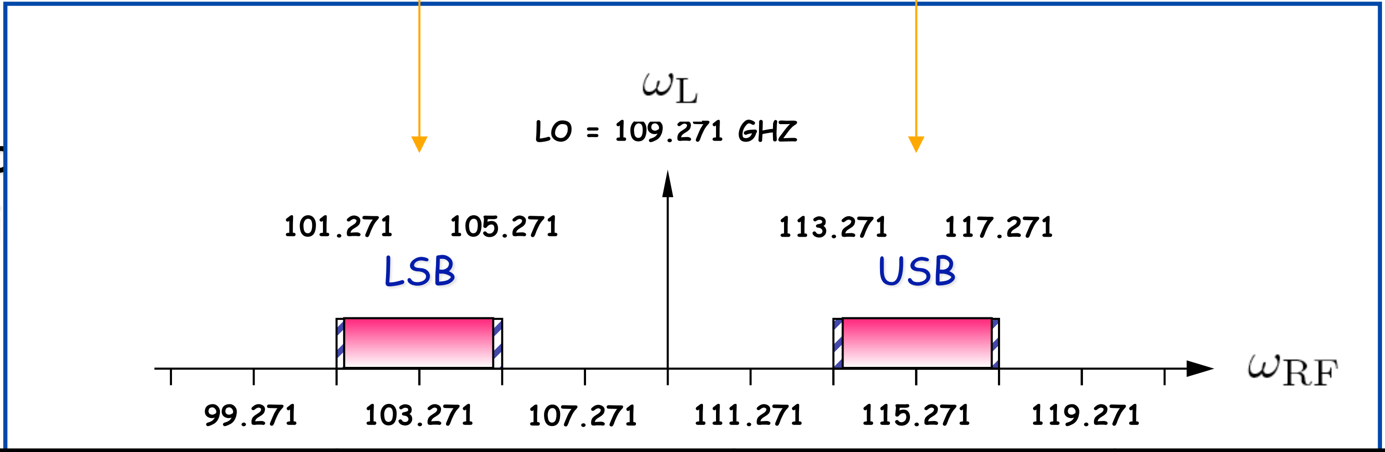


	SSB	DSB	2SB
Noise	<2	1	<2
Single-Dish	Yes	No	Yes
Interferometer	Yes	Yes	Yes

$)t$

- output voltage is proportional to its input (noise) power

PdBI Receiver Capabilities

Item	Value	Notes
RF bands		
	19 – 26	Atmospheric phase correction
1 = ALMA Band 3	80 – 117	SSB
2 = ALMA Band 4	129 – 174	SSB
3 = ALMA Band 6	200 – 269	SSB
4 = ALMA Band 7	277 – 371	2SB
RF response	SSB	LSB or USB Image Gain >-10dB
IF band	4 – 8 GHz	
Polarization	Dual linear	Circular also possible
Observing mode	Single frequency Dual polarization	Second band in standby Potential for Dual freq, Dual pol

Multibeam receiver systems

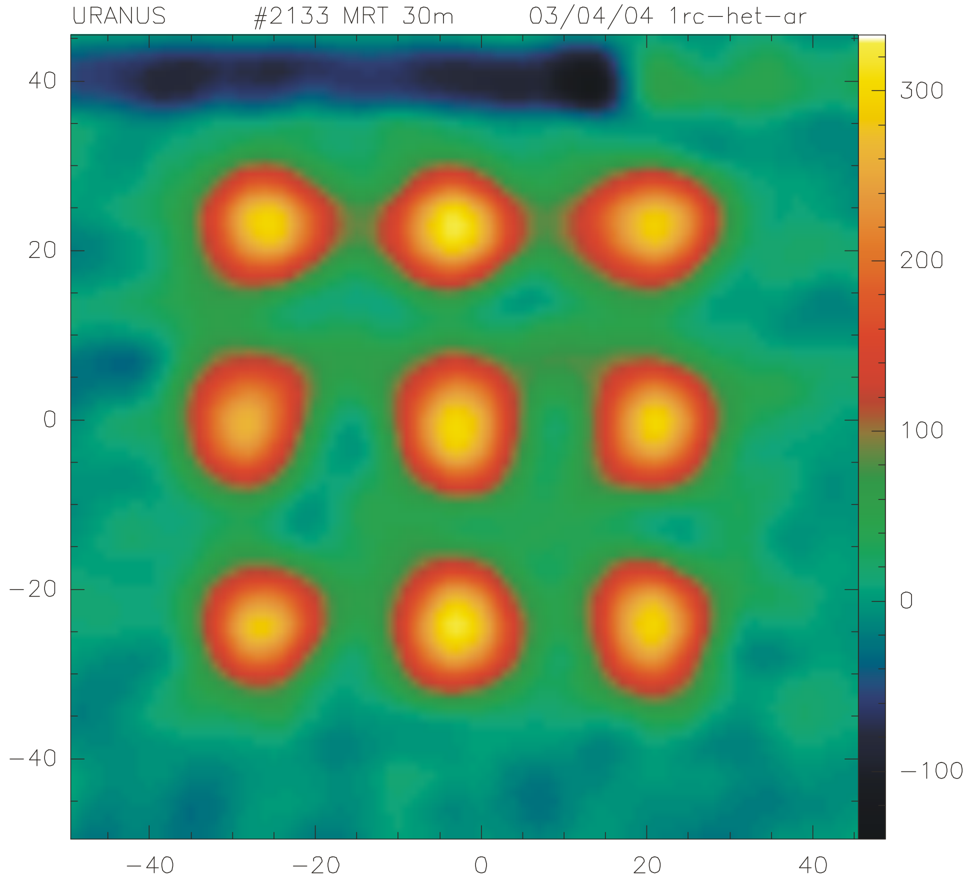
After very first attempts in the early 90's a second generation of multibeam instruments have successfully been commissioned since 2000:

BEARS	3mm at Nobeyama 45m (25 beams)
SEQUOIA	3mm at FCRAO 14m (LMT) (32 beams)
CHAMP(+)	0.7/0.45mm at CSO/APEX (16/14 beams)
HERA	1.3mm at IRAM 30m (18 beams)
HARP	0.8mm at JCMT (16 beams)

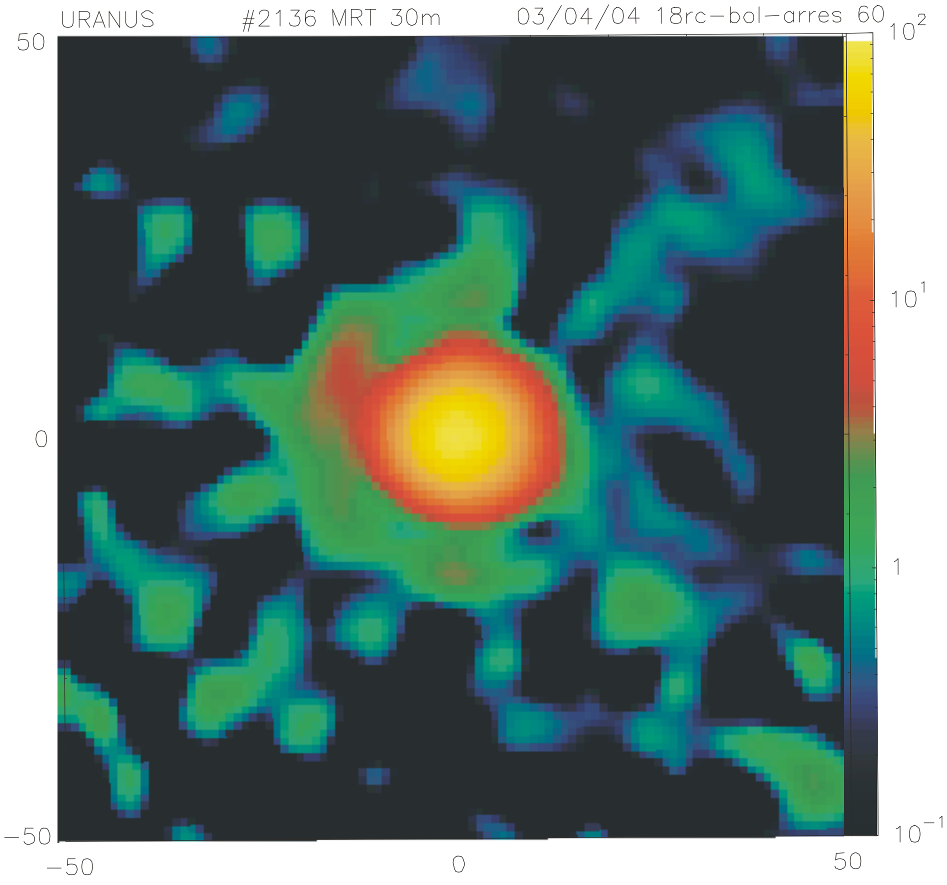
These instruments are largely based on assembled single pixel technology.

HERA Pol 2

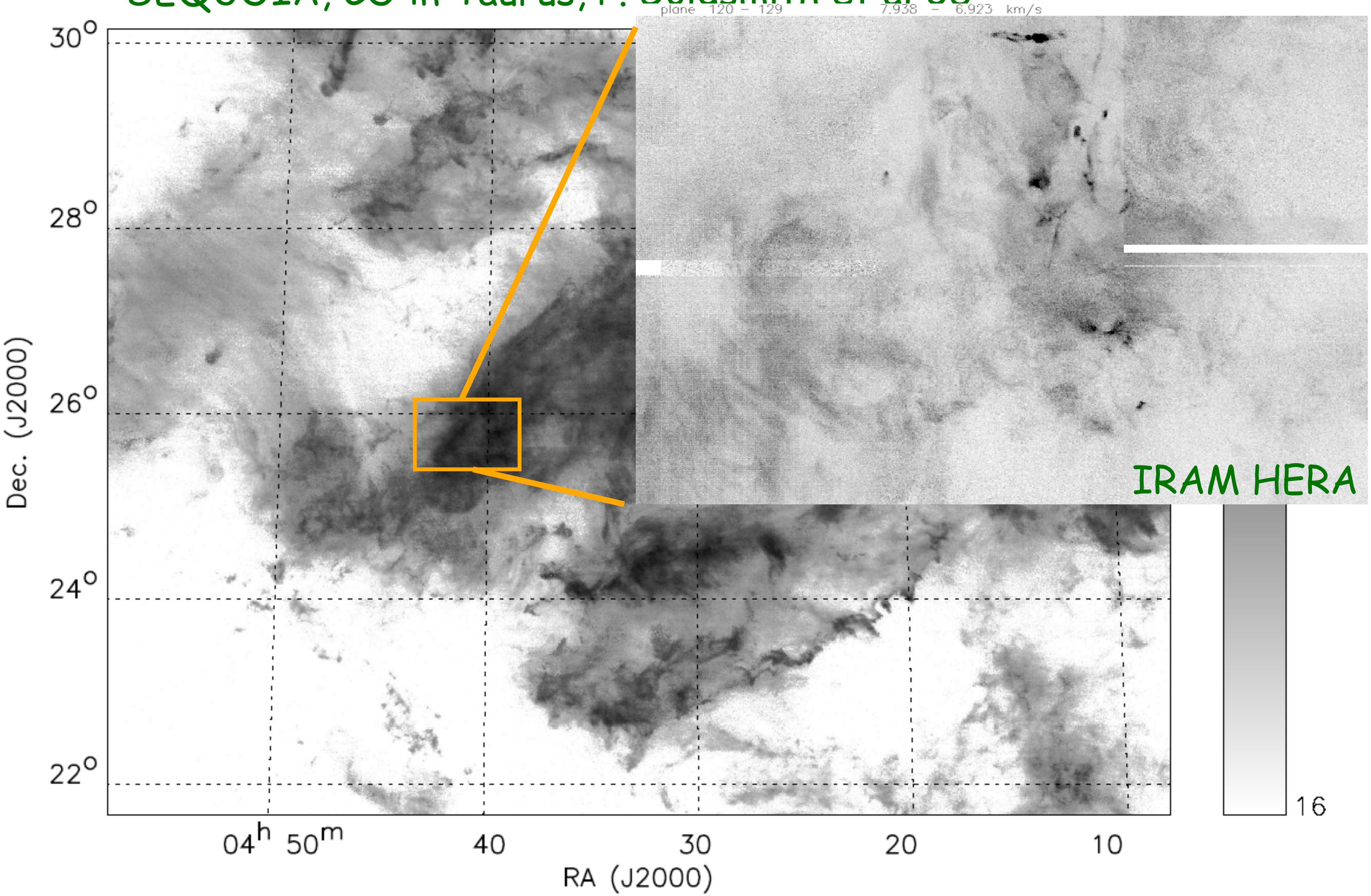
230 GHz Continuum on URANUS



Error beams come up at the 3% or -17dB level (cons with moon scans).



SEQUOIA, CO in Taurus, P. Goldsmith et al 08



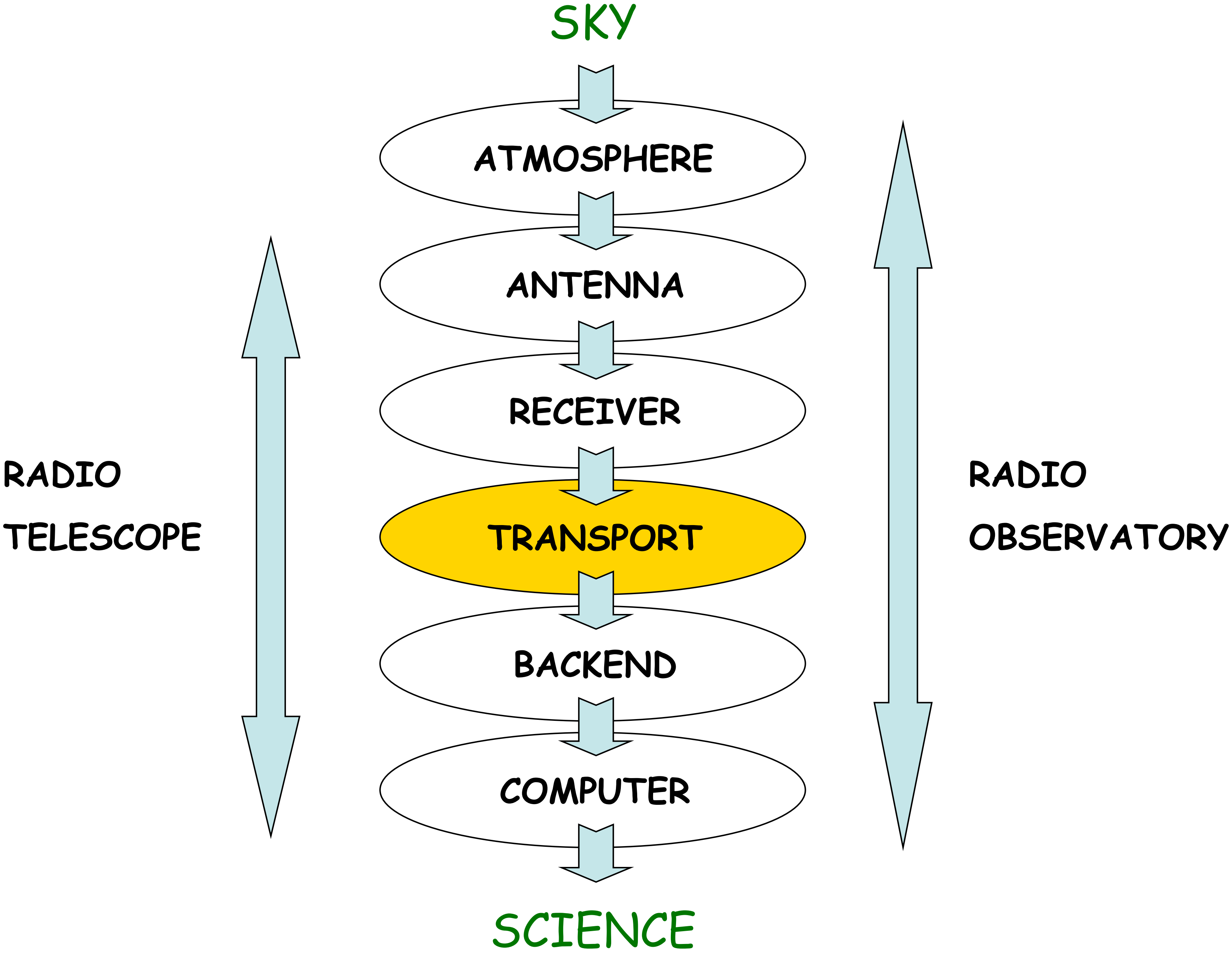
Next generation multibeam receiver systems @ IRAM

- Sensitivity x 2 + pixel x 5 + IF BW x 4 (8)
  = receiver with 50-100 high performance pixels

(> to 20 times faster mapping)

- That's about the difference between TMC-1 and TMC.
- Will allow to study the role of galactic low column density CO
- Is about the step required to map samples of nearby galaxies in ^{13}CO and HCN, HCO+.
- For adventurers this will also be the threshold where large high-z fields become interesting, provided there is enough bandwidth per pixel.

- To make this come true we need new and more integrated technology !



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RECEIVER

TRANSPORT

BACKEND

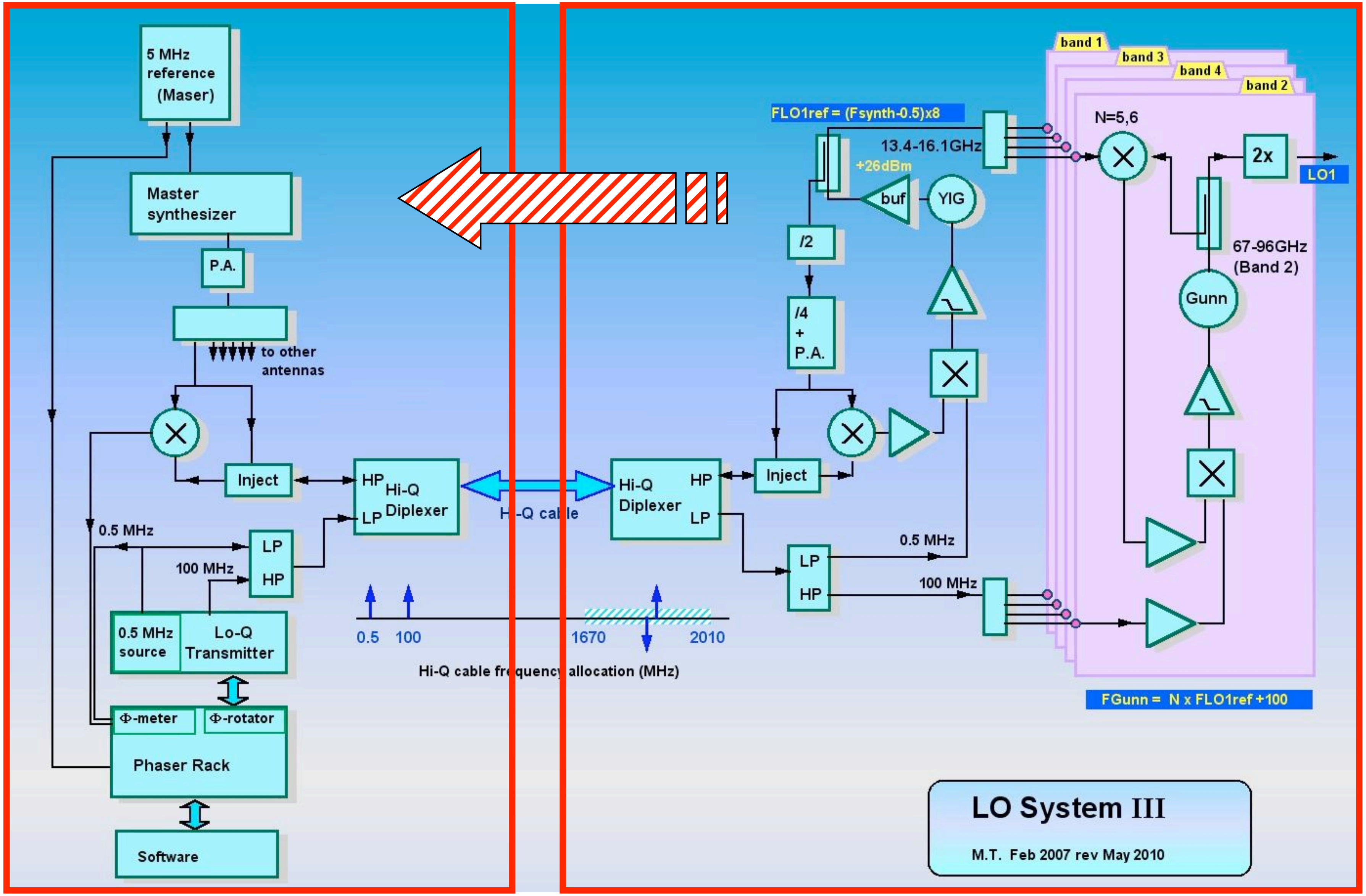
COMPUTER

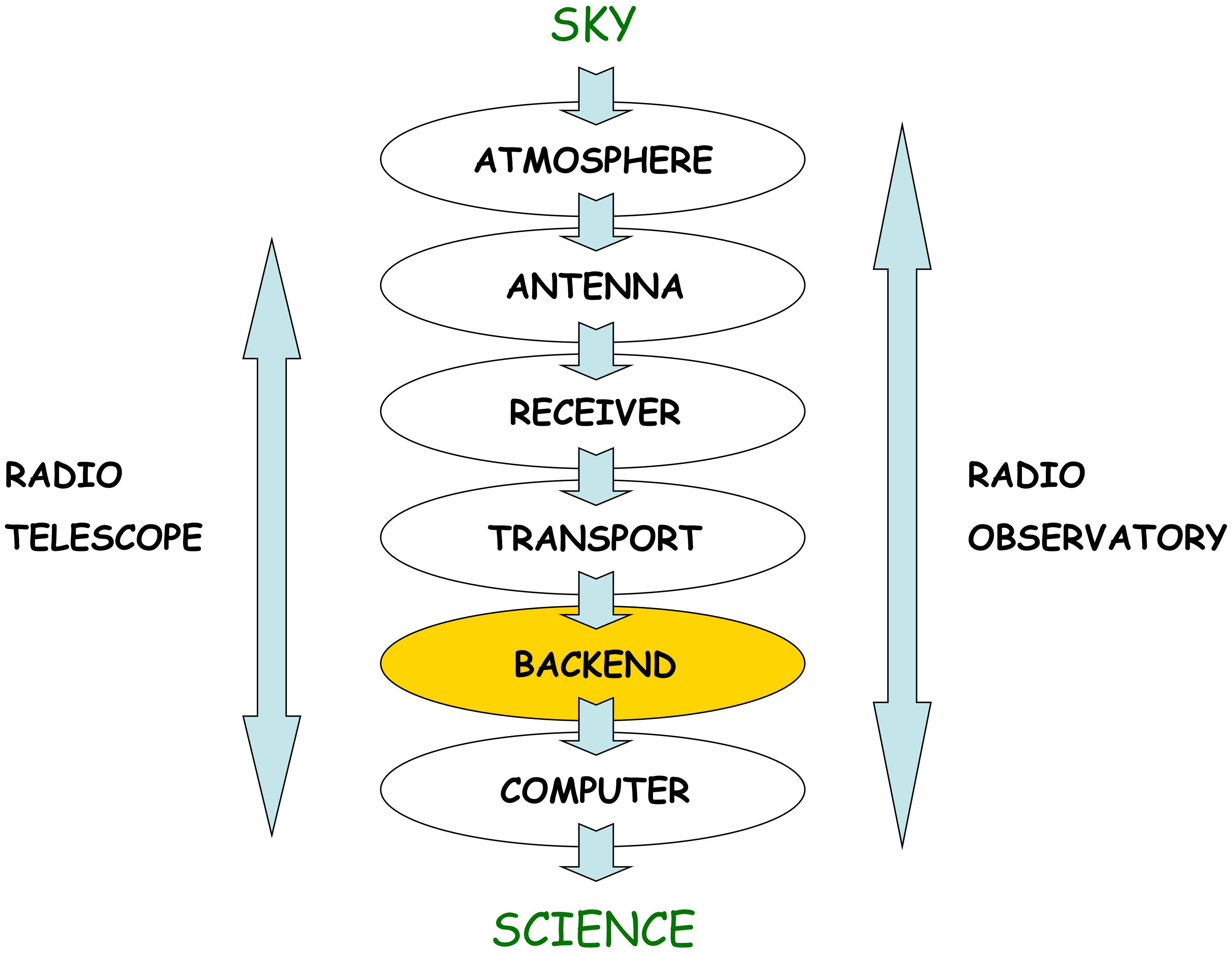
SCIENCE

RADIO TELESCOPE

RADIO OBSERVATORY

Transport from the antenna





SKY

ATMOSPHERE

ANTENNA

RECEIVER

TRANSPORT

BACKEND

COMPUTER

SCIENCE

RADIO

TELESCOPE

RADIO

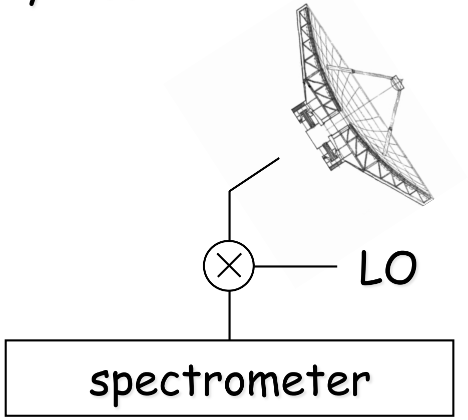
OBSERVATORY

Backend

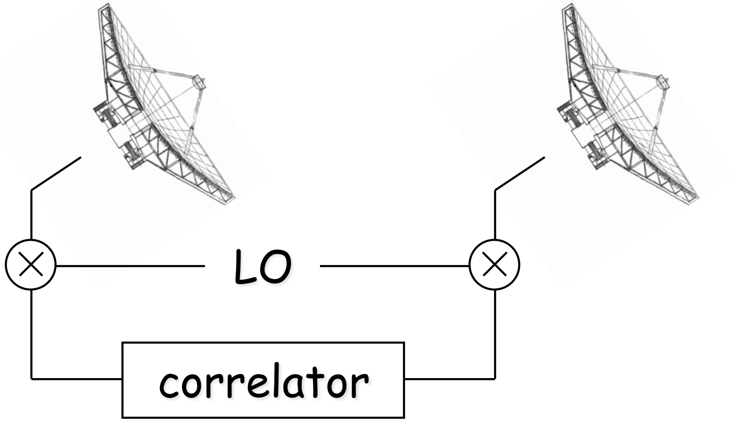
SINGLE-DISH

ARRAY

- very different backend architectures



amplitude



amplitude + phase

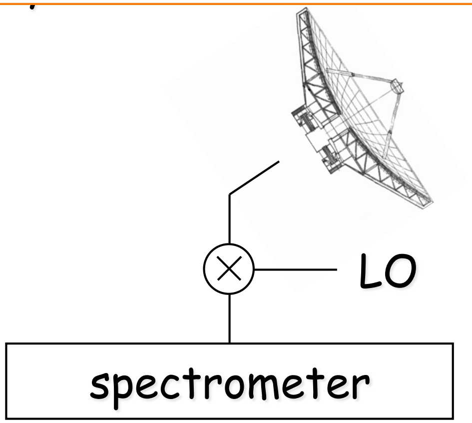
Backend

SINGLE-DISH

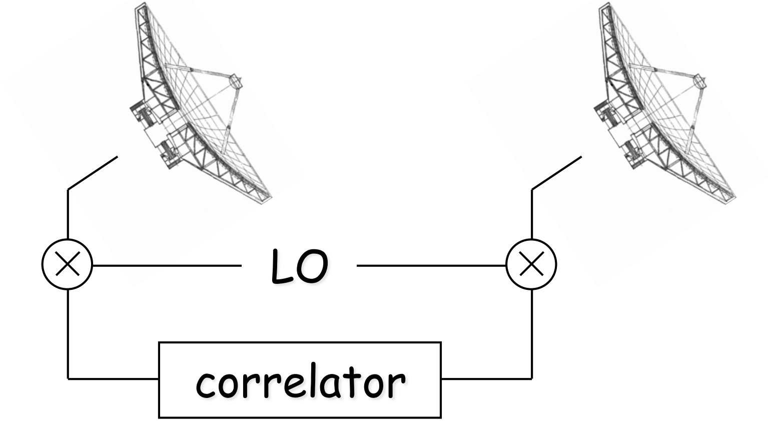
ARRAY

Spectral resolution much better than in the optical !

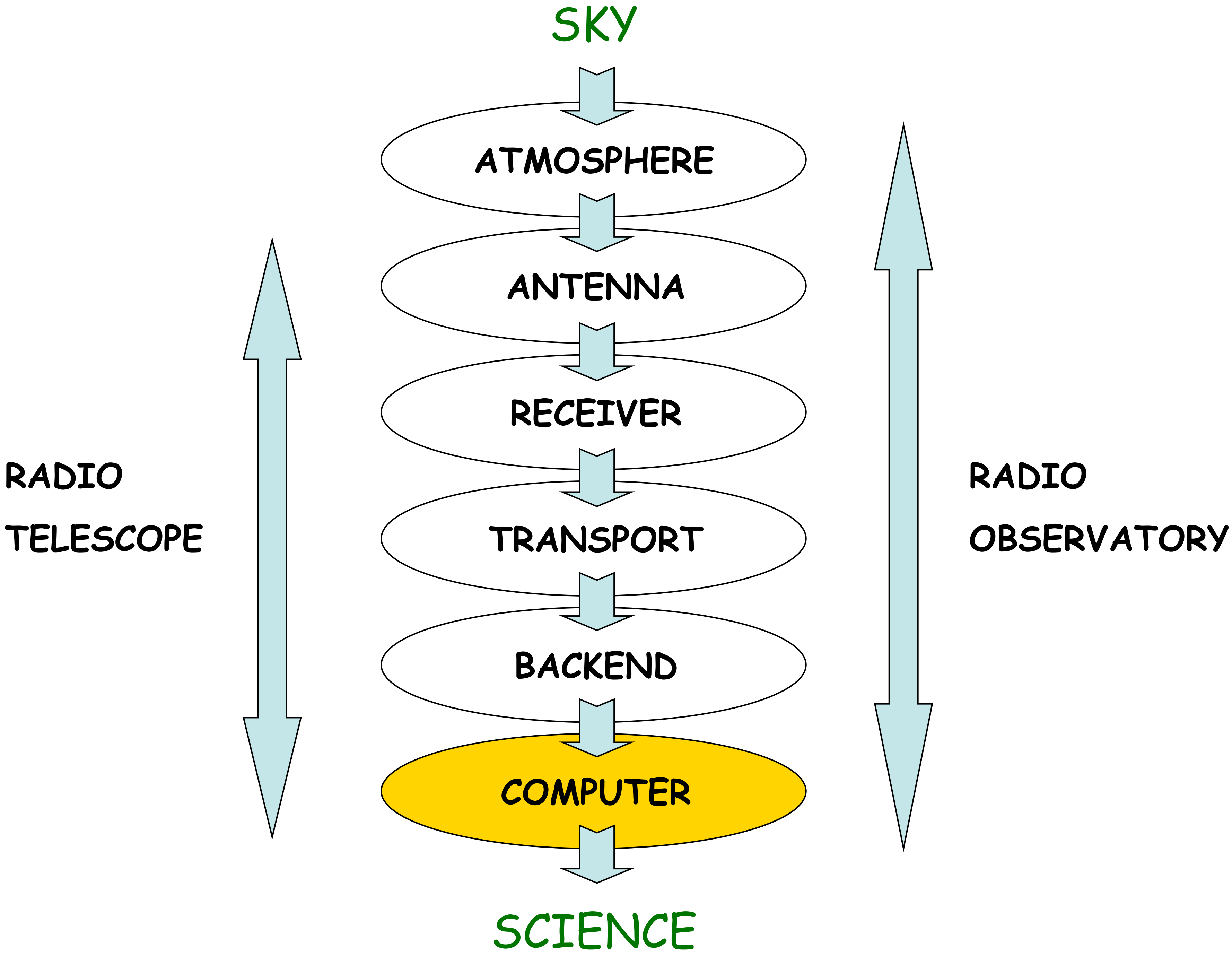
10 KHz (10 m/s @ 300 GHz)



amplitude



amplitude + phase



SKY

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OBSERVATORY

Computer

- a signal averaging or integrating device that smoothes out the rapidly fluctuating detector output
- control of the instruments, telescope
- calibration
- science output

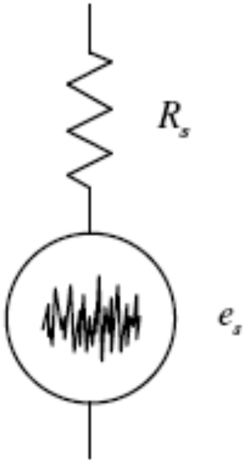
Calibration : definition of temperatures

- antenna temperature
- system temperature
- brightness temperature
- etc.

Calibration : antenna system temperature

The output power of a …

… resistor :



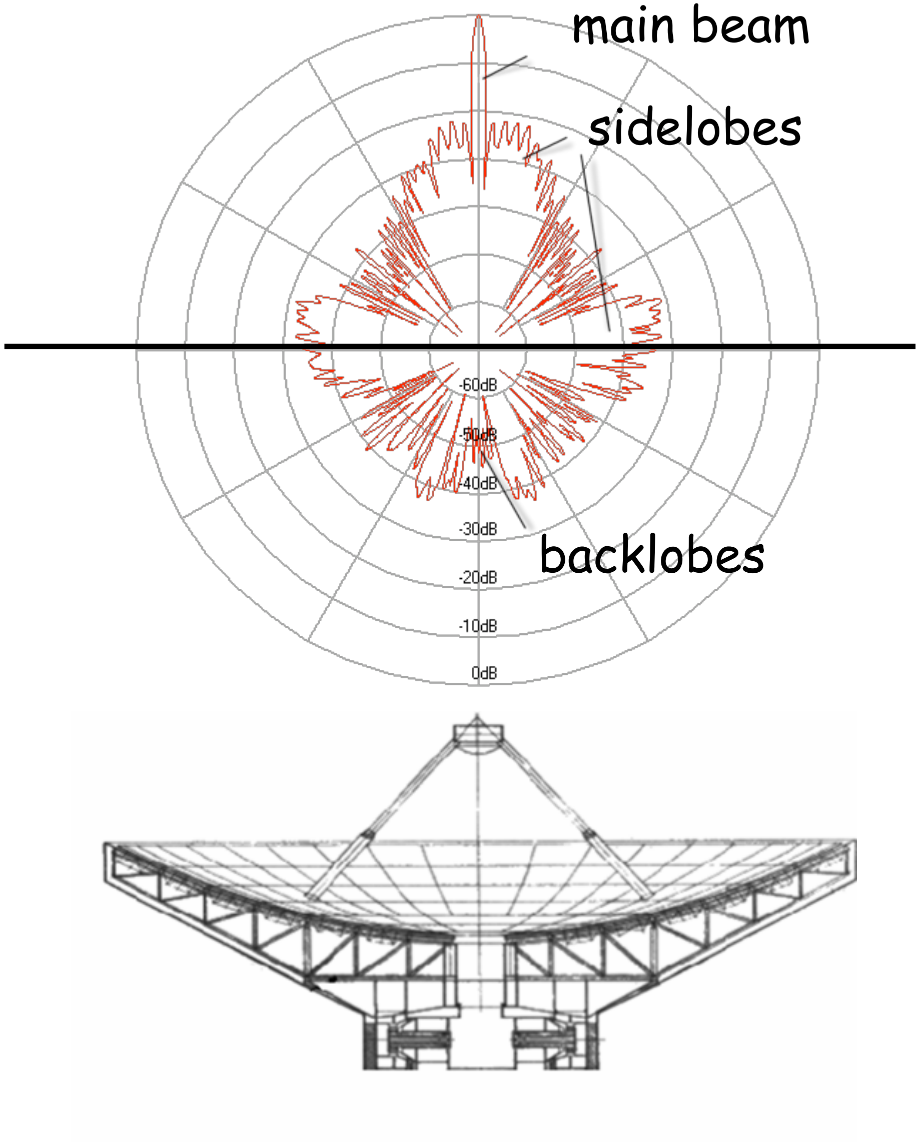
$$P_N = kT\Delta\nu$$

… receiving System :

$$P_N = \underbrace{kT_{ant}}\Delta\nu$$

antenna system (noise) temperature

Calibration : back to definitions

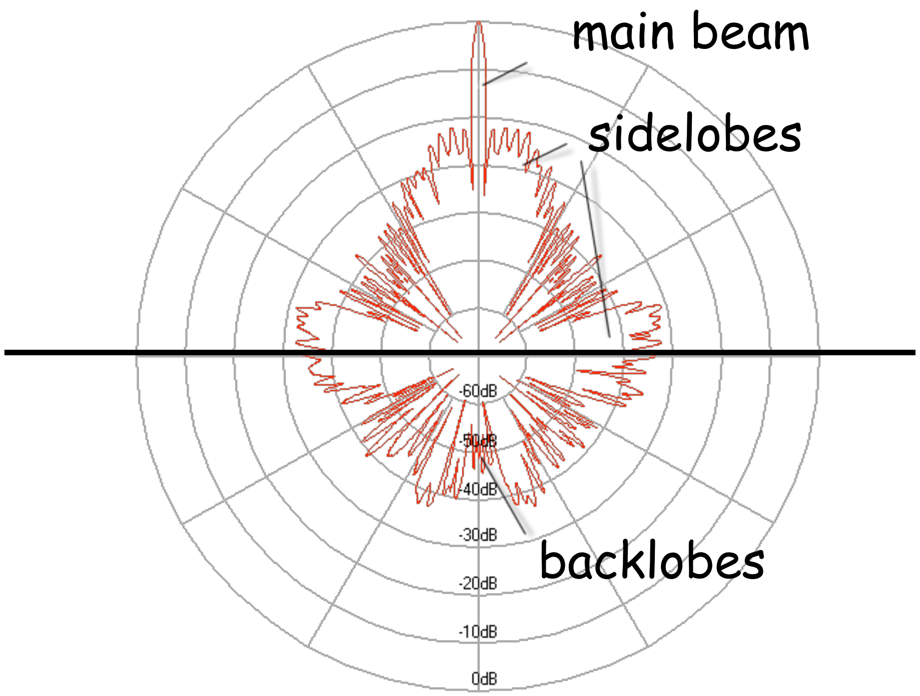


$$B_{\mathrm{eff}} = P_{\mathrm{mb}} / P_{4\pi}$$

$$F_{\mathrm{eff}} = P_{2\pi} / P_{4\pi}$$

$$(1 - F_{\mathrm{eff}})$$

Calibration : back to definitions



$$B_{\rm eff} = P_{\rm mb}/P_{4\pi}$$

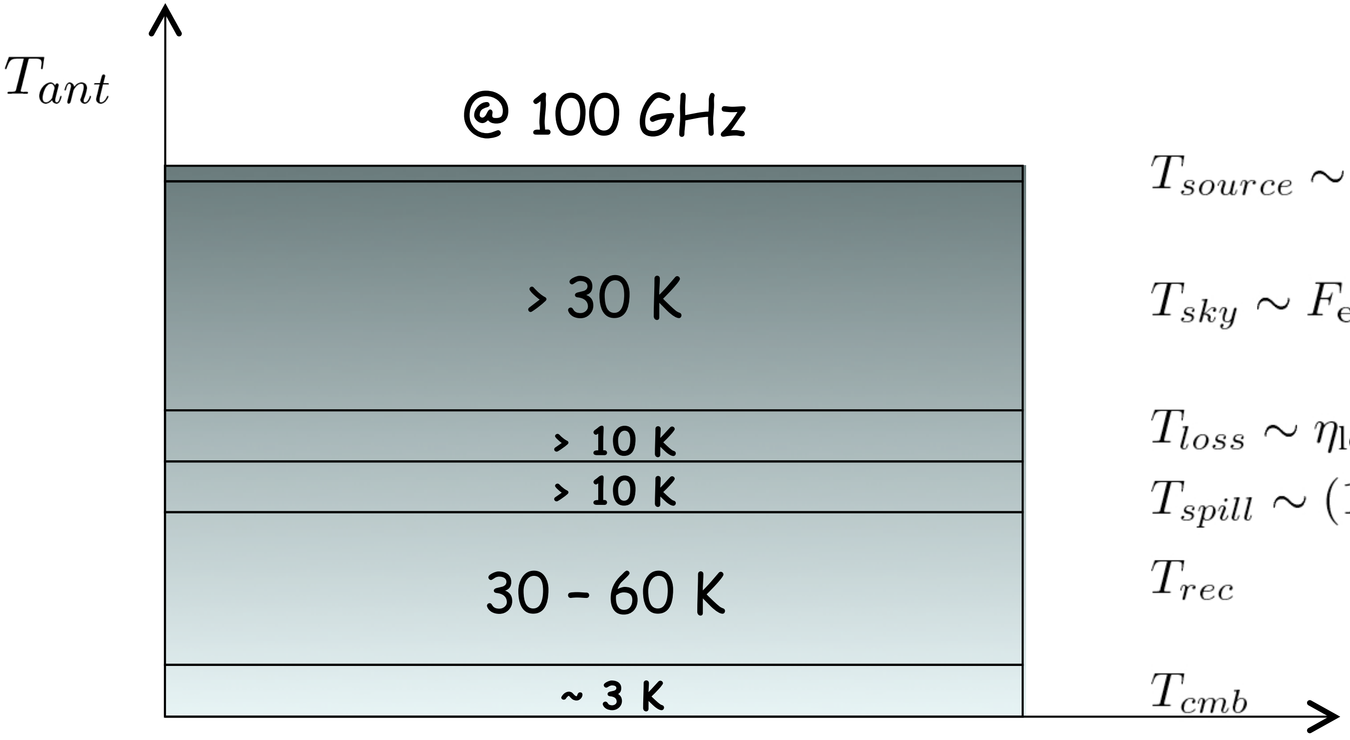
$$F_{\rm eff} = P_{2\pi}/P_{4\pi}$$

$$(1 - F_{\rm eff})$$

- a bit more complicated

$$F_{\rm eff} = F_{\rm sky} + F_{\rm spill} + F_{\rm optics} + \ldots$$

Calibration : antenna system temperature



Beam to source coupling factor

$T_{source} \sim B_{source} T_{\rm B}$

$T_{sky} \sim F_{\rm eff}(1 - e^{-\tau_{\rm atm}})T_{\rm atm}$

$T_{loss} \sim \eta_{\rm loss} T_{\rm cab}$

$T_{spill} \sim (1 - \eta_{\rm loss} - F_{\rm eff})T_{\rm ground}$

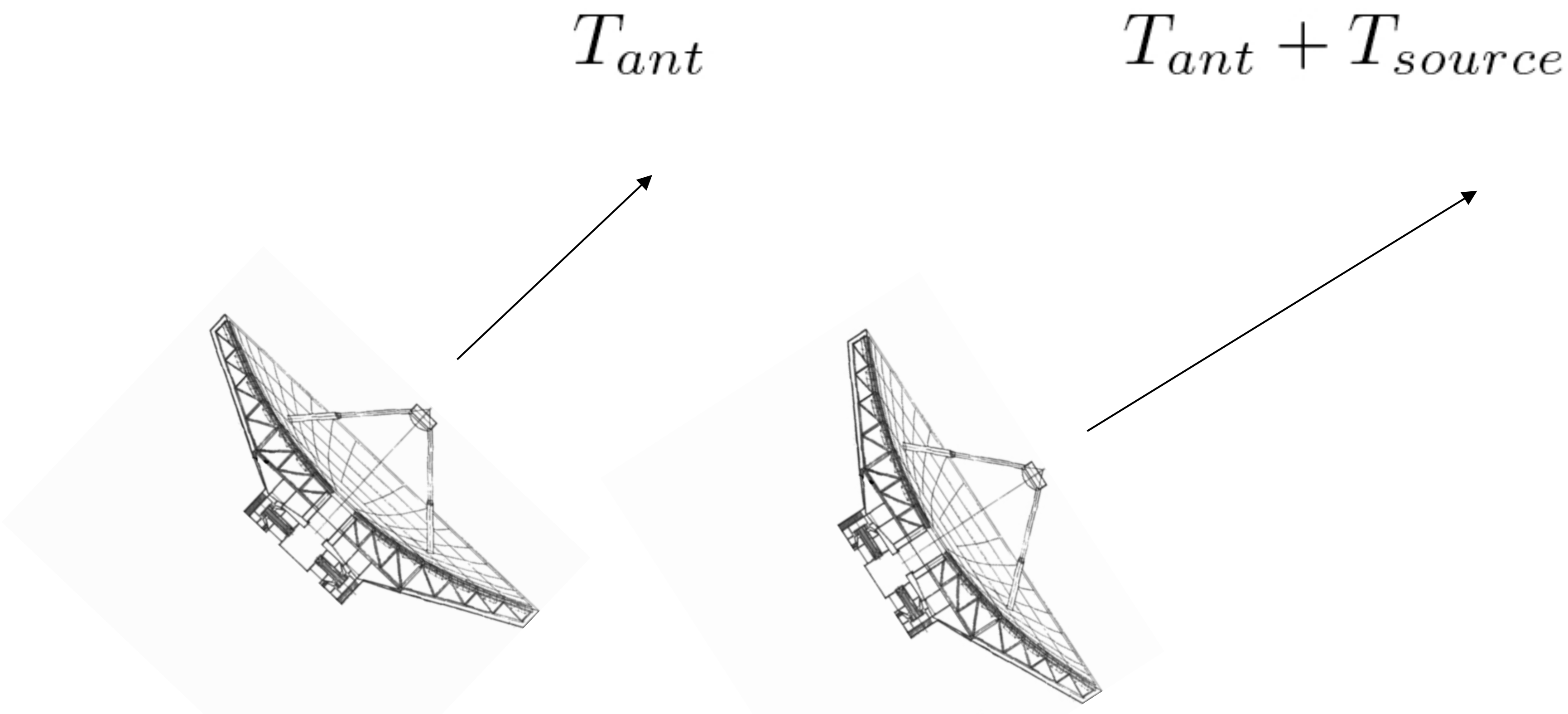
T_{rec}

T_{cmb}

$$\boxed{T_{ant} = T_{cmb} + T_{sky} + T_{spill} + T_{loss} + T_{rec}}$$

antenna system temperature is the temperature of the equivalent blackbody observed by the antenna

Single-Dish (only!)



$$T_{ant}$$

$$T_{ant} + T_{source}$$

The difference in the two outputs gives the contribution from the source alone

Calibration : system and antenna temperature

We refer the system temperature

noise power →

$$\boxed{T_{sys} = \frac{e^{\tau_{atm}}}{F_{\mathrm{eff}}} T_{ant}}$$

and the antenna temperature

astronomical signal →

$$\boxed{T_A^\star = \frac{e^{\tau_{atm}}}{F_{\mathrm{eff}}} T_{source}}$$

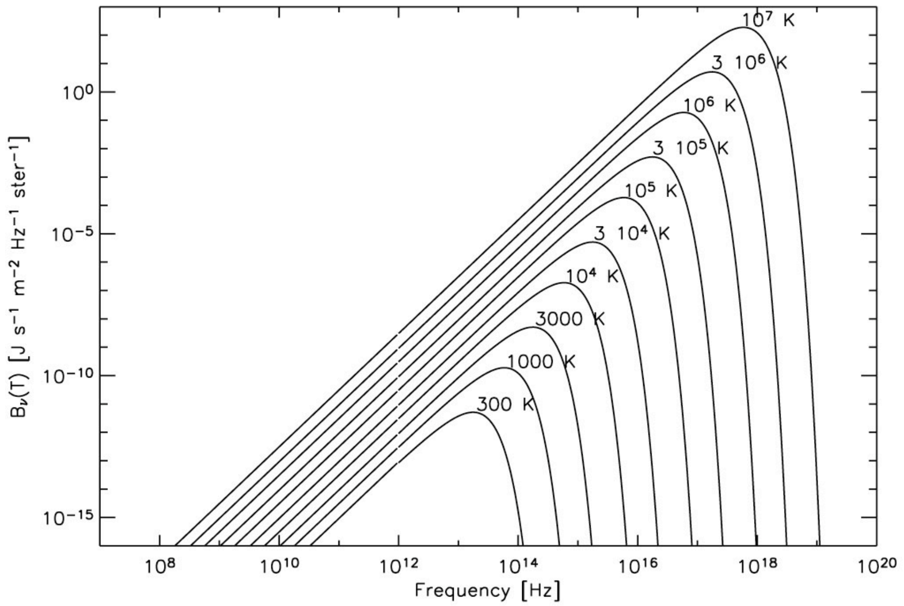
to an ideal antenna located outside the atmosphere.

Calibration : brightness temperature and RJ-approximation

- ➢ black-body radiation at temperature T

Brightness Temperature

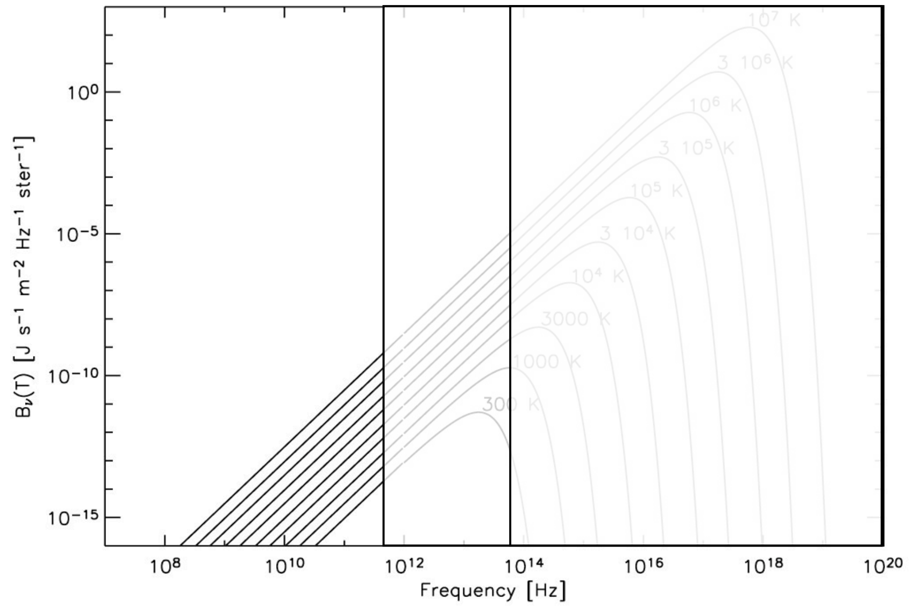
Brightness



$$B_\nu(T) = 2h\nu^3 c^{-2}(e^{h\nu/kT} - 1)^{-1} \qquad [\mathrm{J\,s^{-1}\,m^{-2}\,Hz^{-1}\,sr^{-1}}]$$

Calibration : brightness temperature and RJ-approximation

- black-body radiation at temperature T
- Rayleigh-Jeans approximation $h\nu << kT$



Brightness Temperature

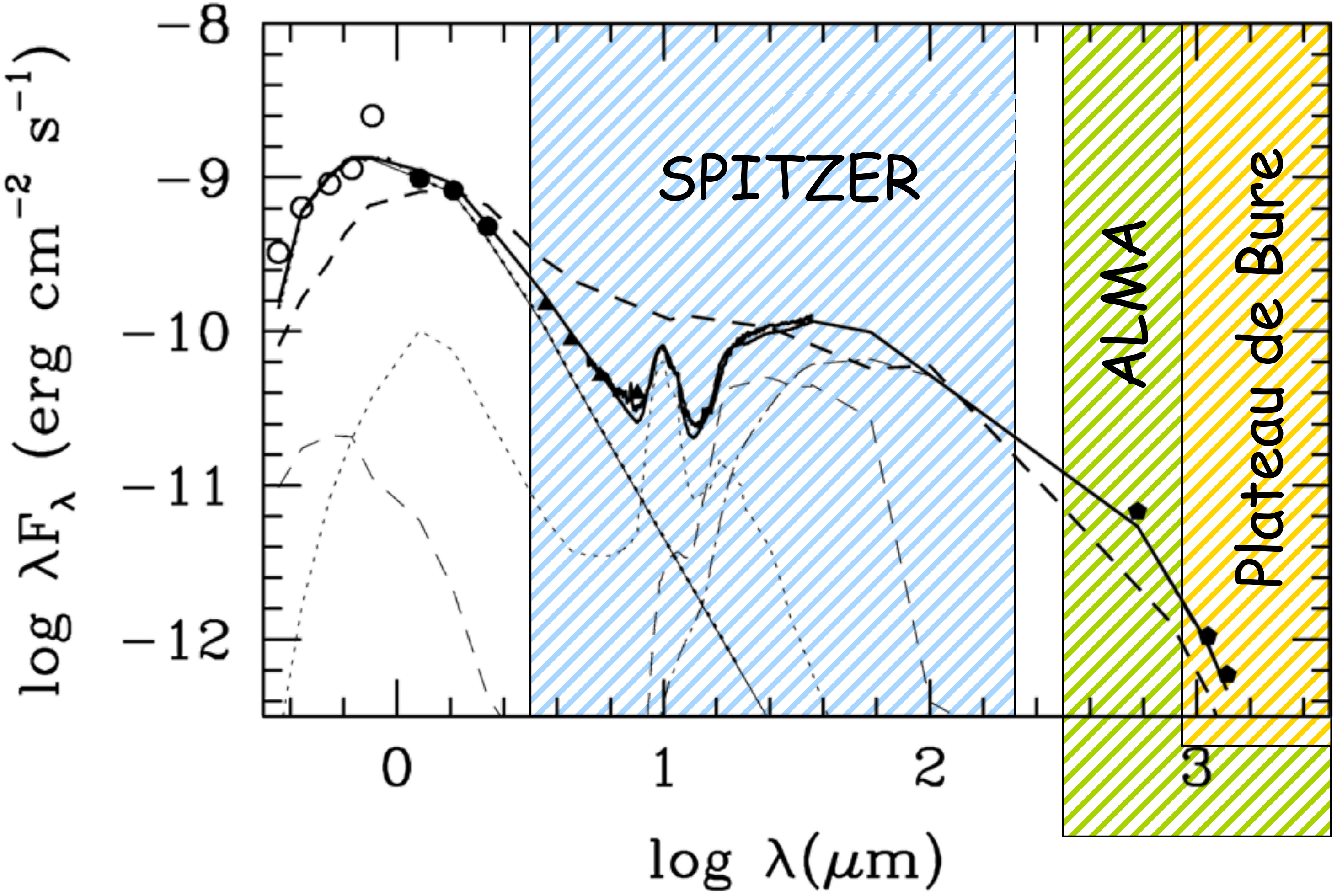
Brightness

$$B_\nu(T) = 2h\nu^3 c^{-2}(e^{h\nu/kT} - 1)^{-1} \qquad [\mathrm{J\,s^{-1}\,m^{-2}\,Hz^{-1}\,sr^{-1}}]$$

$$B_\nu(T) = 2k\lambda^{-2}\,T \qquad [\mathrm{W\,m^{-2}Hz^{-1}}]$$

Calibration : black-body radiation ?

GM Aur (Calvet et al. 2005, Hughes et al. 2009)



Calibration : back to definitions

- source brightness and brightness temperature

$$I_\nu(\Omega) = B_\nu(T_\mathrm{B}, \Omega) \qquad [\mathrm{W\,m^{-2}\,Hz^{-1}\,sr^{-1}}]$$

- source brightness and radiation temperature

$$I_\nu(\Omega) = 2k/\lambda^2\, T_\mathrm{R}(\Omega) \qquad [\mathrm{W\,m^{-2}\,Hz^{-1}\,sr^{-1}}]$$

- flux density and source brightness

$$S_\nu = \int B_\nu(T, \Omega)\, d\Omega \qquad \boxed{[\mathrm{W\,m^{-2}\,Hz^{-1}}] \equiv [10^{26}\ \mathrm{Jy}]}$$

Calibration : system and antenna temperature

We refer the system temperature

noise power →

$$\boxed{T_{sys} = \frac{e^{\tau_{atm}}}{F_{\mathrm{eff}}} T_{ant}}$$

and the antenna and brightness temperature

astronomical signal →

$$\boxed{\begin{aligned} T_A^\star &= \frac{e^{\tau_{atm}}}{F_{\mathrm{eff}}} T_{source} \\ T_{\mathrm{mb}} &= \frac{e^{\tau_{atm}}}{B_{\mathrm{eff}}} T_{source} \end{aligned}}$$

to an ideal antenna located outside the atmosphere.

Which coupling coefficient: main beam, antenna or else?

INTERFEROMETERS ⇨

$$\begin{aligned} T_B &= T_A^\star \\ &= \frac{e^{\tau_{atm}}}{F_{\mathrm{eff}}} T_{source} \end{aligned}$$

- source size = main beam size

$$\begin{aligned} T_B &= T_{\mathrm{mb}} \\ &= \frac{e^{\tau_{atm}}}{B_{\mathrm{eff}}} T_{source} \end{aligned}$$

- known source size

$$T_B = \frac{e^{\tau_{atm}}}{B_{source}} T_{source}$$

INTERFEROMETERS REQUIRE A SECONDARY CALIBRATION

Equations for antenna and brightness temperature

	Equivalent resistor	Equivalent Black-Body
point source:	$S = \frac{2k}{\eta_A A} T_A^\star$	$S = \frac{2k}{\lambda^2} T_{\rm mb} \theta_b$
gaussians:	$S = \frac{2k}{\eta_A A} T_A^\star \frac{\theta_r^2}{\theta_{\rm mb}^2}$	$S = \frac{2k}{\lambda^2} T_{\rm mb}\, 1.13\, \theta_r^2$

Calibration : from Kelvin to Jansky

Flux density

$$\begin{aligned} S_\nu &= \int B_\nu(T_\mathrm{B}, \Omega) d\Omega \\ &= \frac{2k}{\eta_A A} B_\mathrm{eff} T_\mathrm{mb} \end{aligned}$$

and where

$$\frac{S_\nu}{T_\mathrm{mb}} = \frac{2k}{\eta_A A} B_\mathrm{eff} \qquad [\mathrm{Jy/K}]$$

Calibration : sensitivity

- apply the radiometer equation :

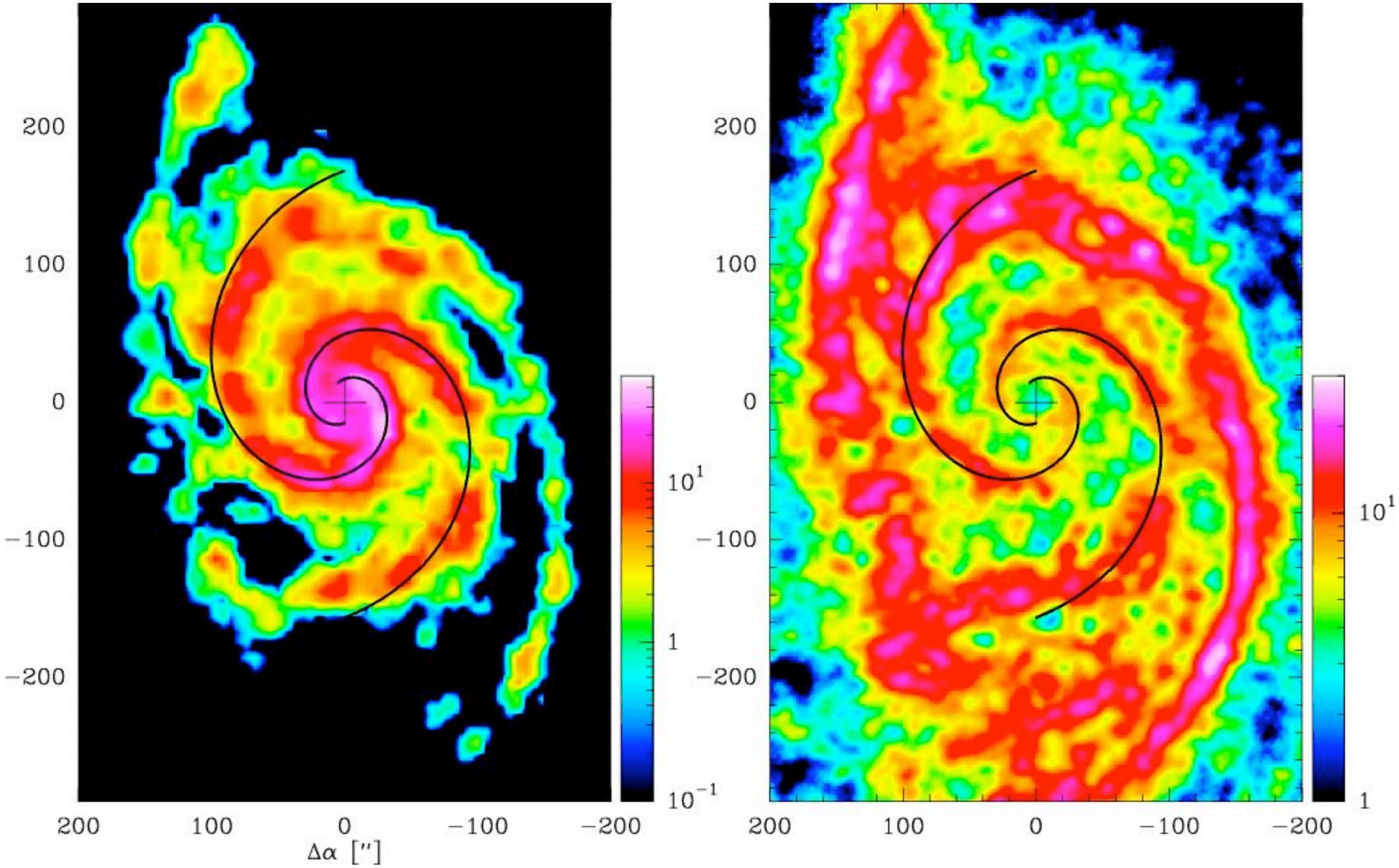
$$\sigma(T_{\mathrm{sys}}) = \frac{\kappa T_{\mathrm{sys}}}{\sqrt{\Delta\nu \Delta t}}$$

κ : observing mode specific coefficient

$\Delta\nu$: bandwidth, spectral resolution

Δt : integration time

A complete CO(2-1) Map of M51 with HERA



Schuster et al. (2008); Hitschfeld et al. (2009)