Millimetre Interferometry

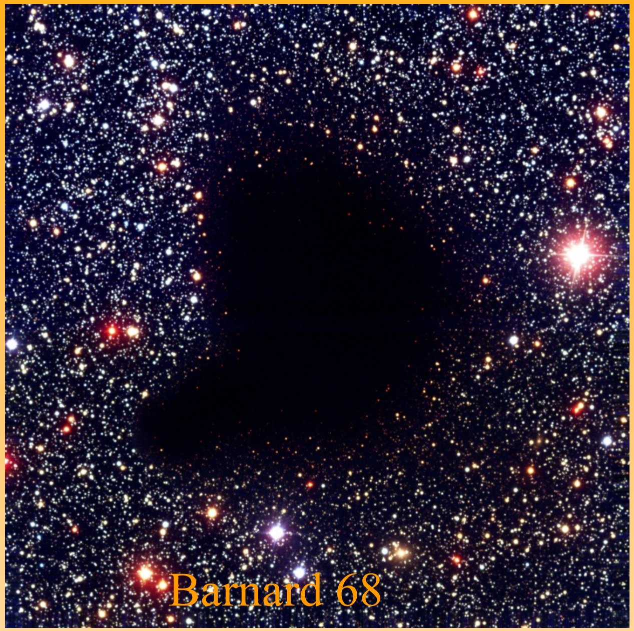
ERIS 2013

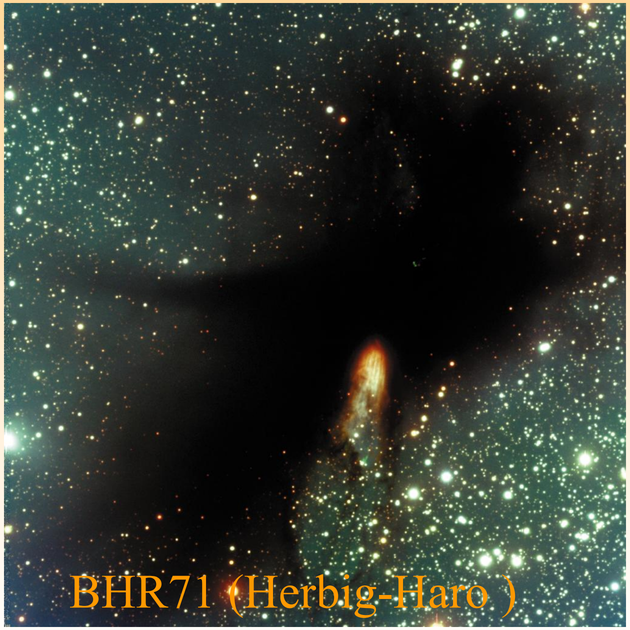
Dwingeloo, The Netherlands, 9-13 September 2013

Michael Bremer, IRAM Grenoble

- Dark clouds in space and their molecules
- Building millimetre antennas
- What changes for the observer for cm ⟶ mm
- Calibration
- Atmospheric water vapour
- Flux
- NOEMA

Motivation: Dark Clouds in Space

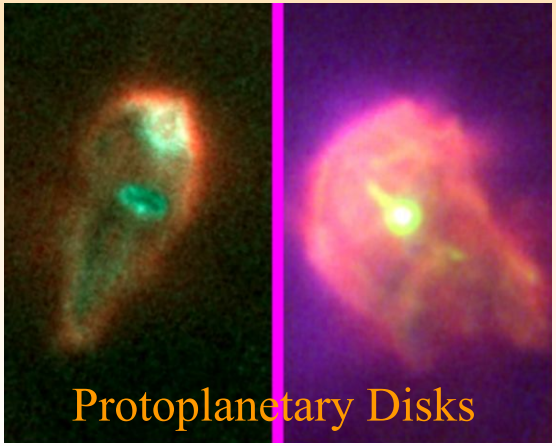




Motivation: more Dark Clouds in Space


Butterfly Nebula


Large-angle night sky (the Milky Way)


Protoplanetary Disks


Sombrero Galaxy

Dark clouds are of interest because:

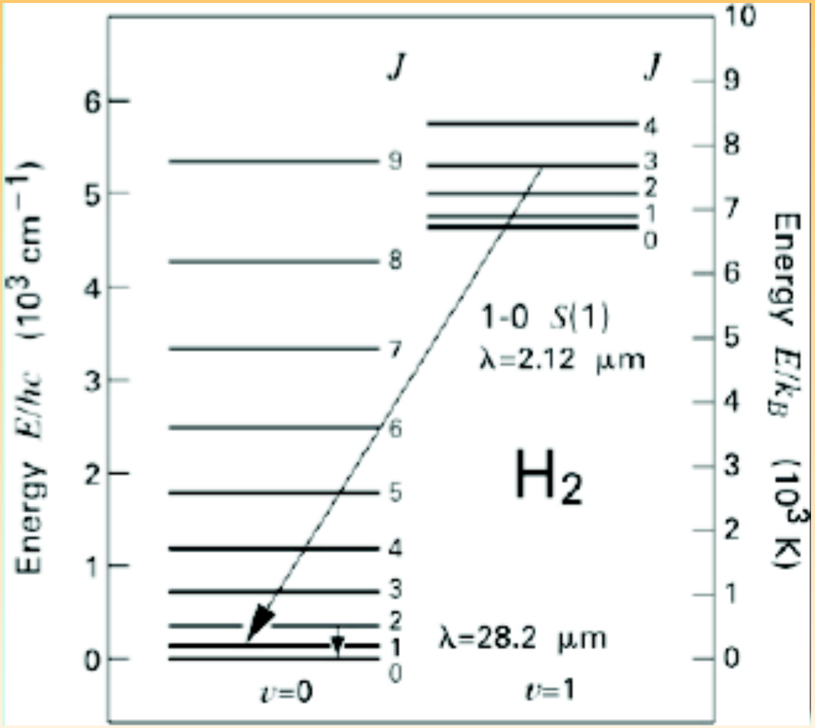
- The formation of stars takes place in dark clouds,
- the late Red Giant phases of the life of a "medium mass" star involve heavy mass loss by stellar winds that hide the star in a cold, dusty cocoon,
- Many galaxies show large-scale structures of dark clouds in their morphology.

This part of the stellar and galactic life cycle is completely inaccessible for optical astronomy!

Dynamics? Masses? Composition? Chemistry? ...

The first obvious approach: look for molecular Hydrogen

- H_2 is a symmetric molecule.
- Unfortunately it has a very low angular momentum, which requires a lot of energy to excite:
  $E_{rot} = \hbar^2/(2\Theta)\ J\cdot(J+1)$
- Consequence: H_2 has transitions from the IR to the UV, but its emission traces only hot or shocked gas.
- In cold, dark clouds H_2 may be abundant, but it does not emit!



We need another molecule …

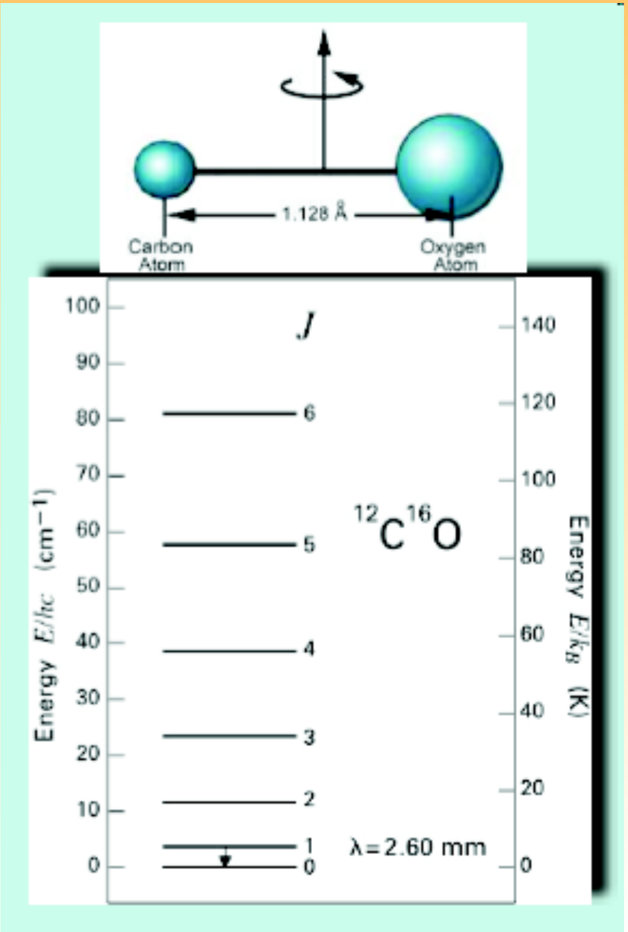
Next choice: Carbon monoxide (CO)

- Asymmetric molecule, easy to excite even in cold clouds.
- UV radiation above 11.09 eV required to break it up
- Most abundant molecule after H_2, ~ 10^{-4}
- CO can self-shield in dark clouds (see e.g. Visser et al, A&A 503, 323)
- Line frequencies for dominant isotopes:

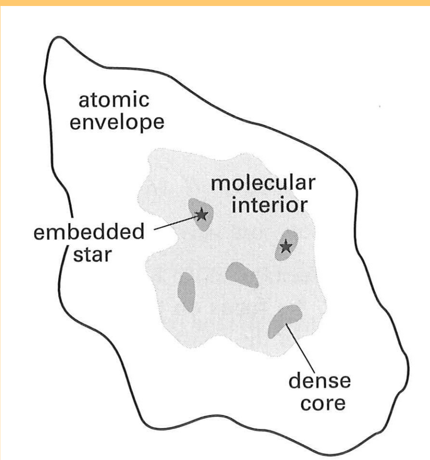
  see http://spec.jpl.nasa.gov/ftp/pub/catalog/catform.html

  or http://physics.nist.gov/cgi-bin/micro/table5/start.pl

	$^{12}C\ ^{16}O$	$^{13}C\ ^{16}O$	$^{12}C\ ^{18}O$
(1-0)	115.271 GHz	110.201 GHz	109.782 GHz
(2-1)	230.538 GHz	220.399 GHz	219.560 GHz
(3-2)	345.796 GHz	330.588 GHz	329.331 GHz
(4-3)	461.041 GHz	440.765 GHz	439.089 GHz
…	…	…	…

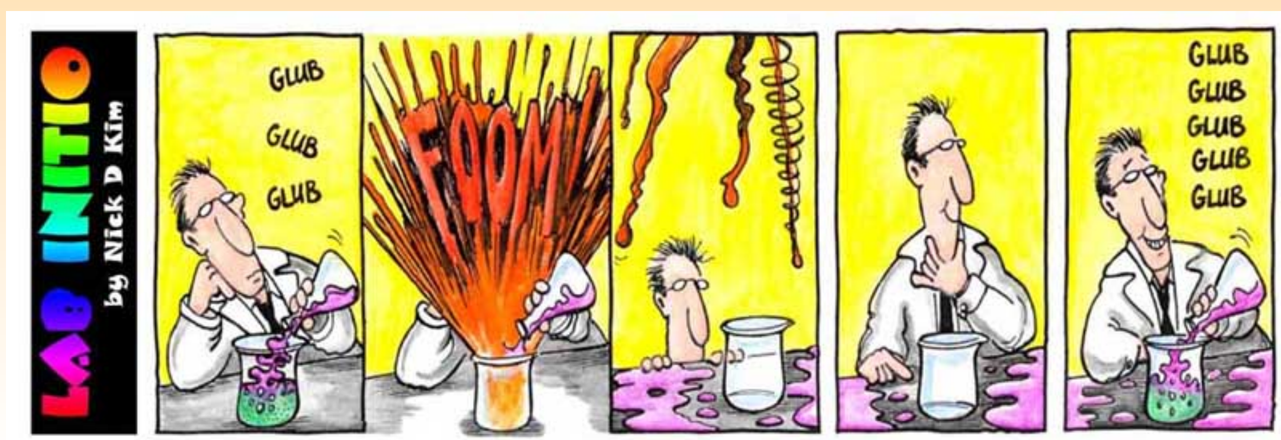


Chemistry in dark clouds



dark + cold ≠ slow + inactive + boring!

- supersonic turbulence, magnetic fields
- photochemistry based on the interstellar radiation filed in outer layers, cosmic rays on the inside
- catalytic reactions on dust grains
- freeze-out of components on dust grains
- very reactive molecules, sometimes faster than expected under terrestrial conditions



Reaction networks for Carbon-rich molecules

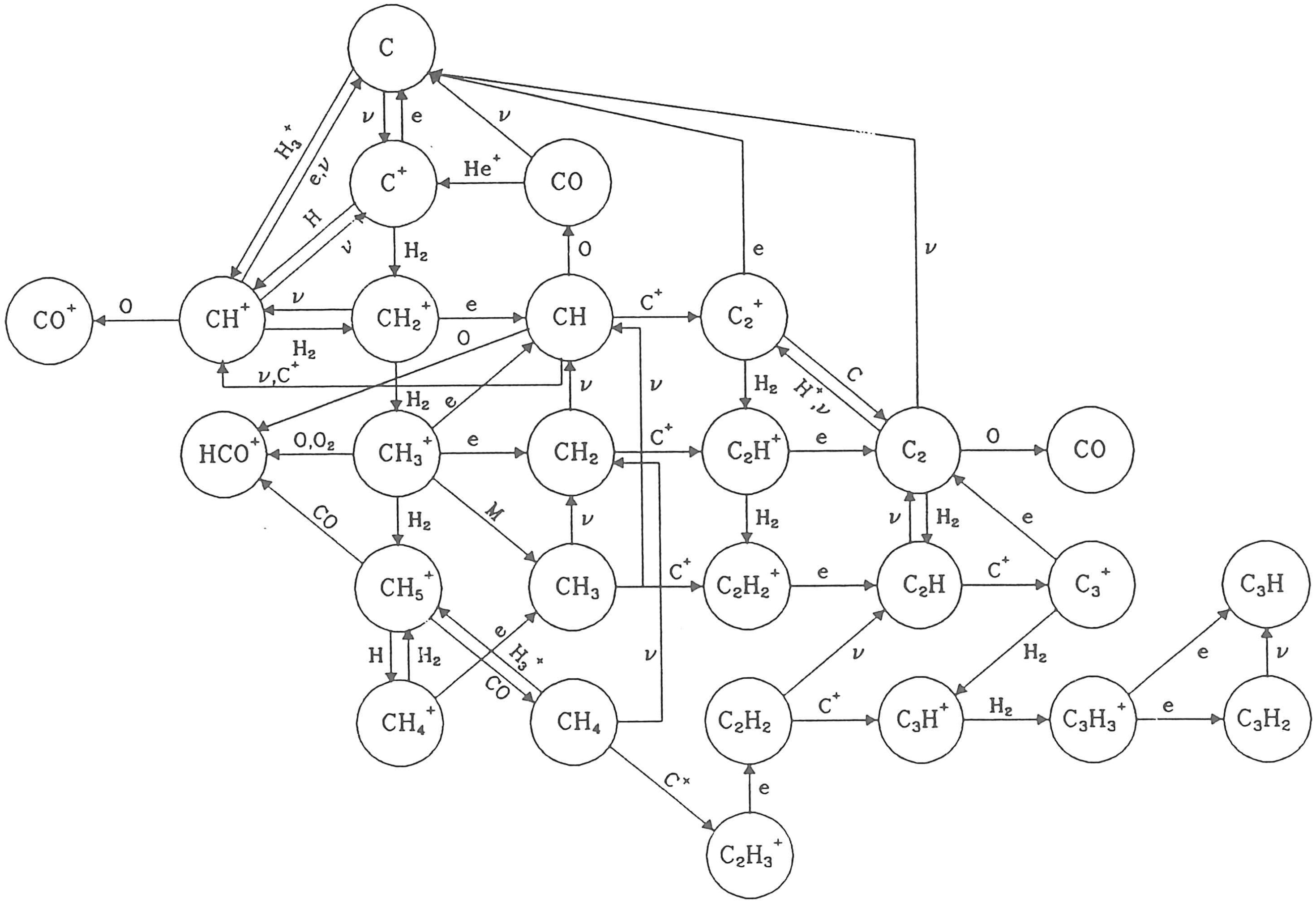


Figure 6. *The most important chemical reactions involving carbon–bearing molecules. M stands for metal.*

From van Dishoeck, 1988

Reaction networks for Oxygen-rich molecules

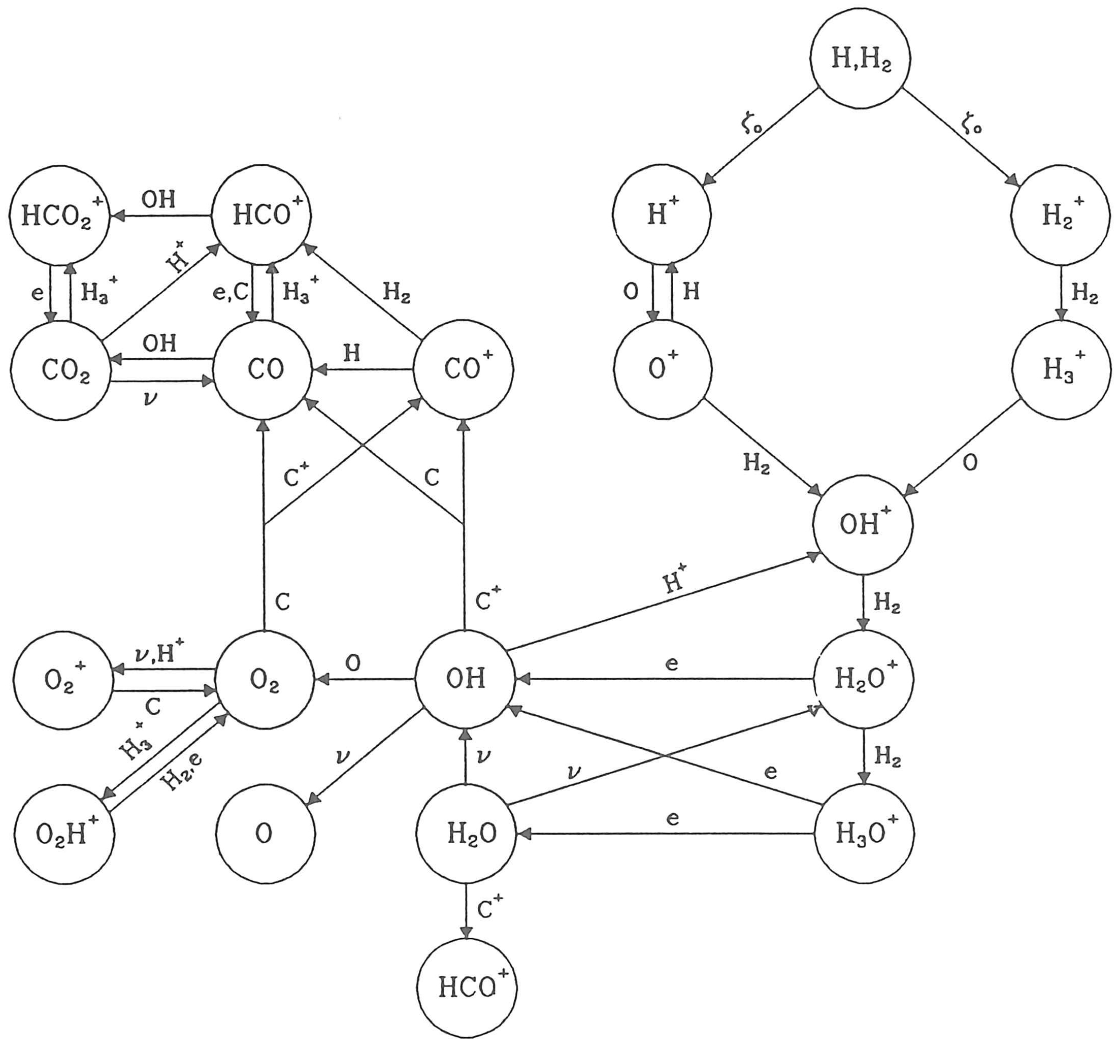


Figure 7. *As Figure 6, but for oxygen–bearing molecules.*

From van Dishoeck, 1988

Reaction networks for Nitrogen-bearing molecules

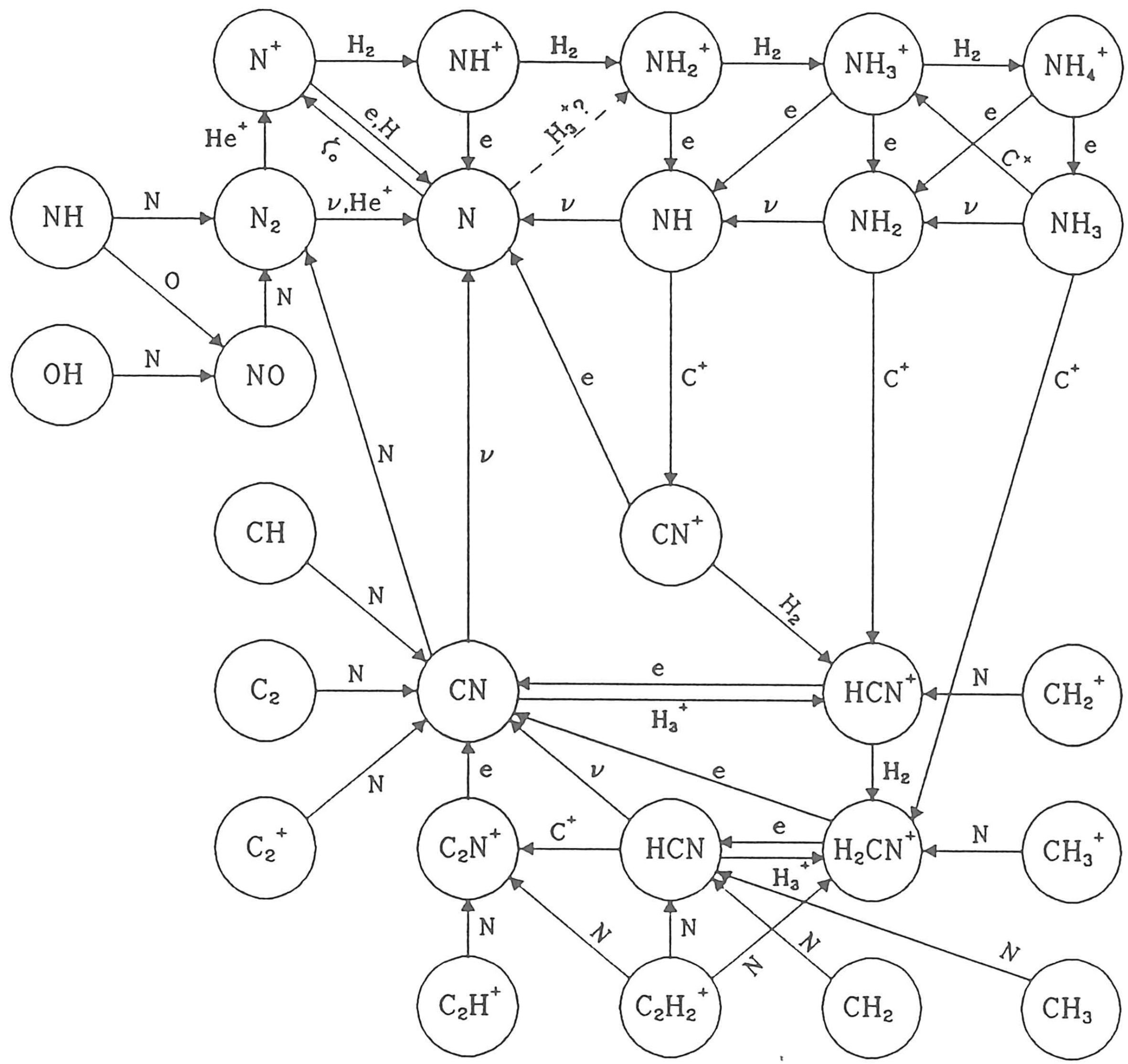


Figure 8. *As Figure 6, but for nitrogen–bearing molecules.*

From van Dishoeck, 1988

Some useful molecules

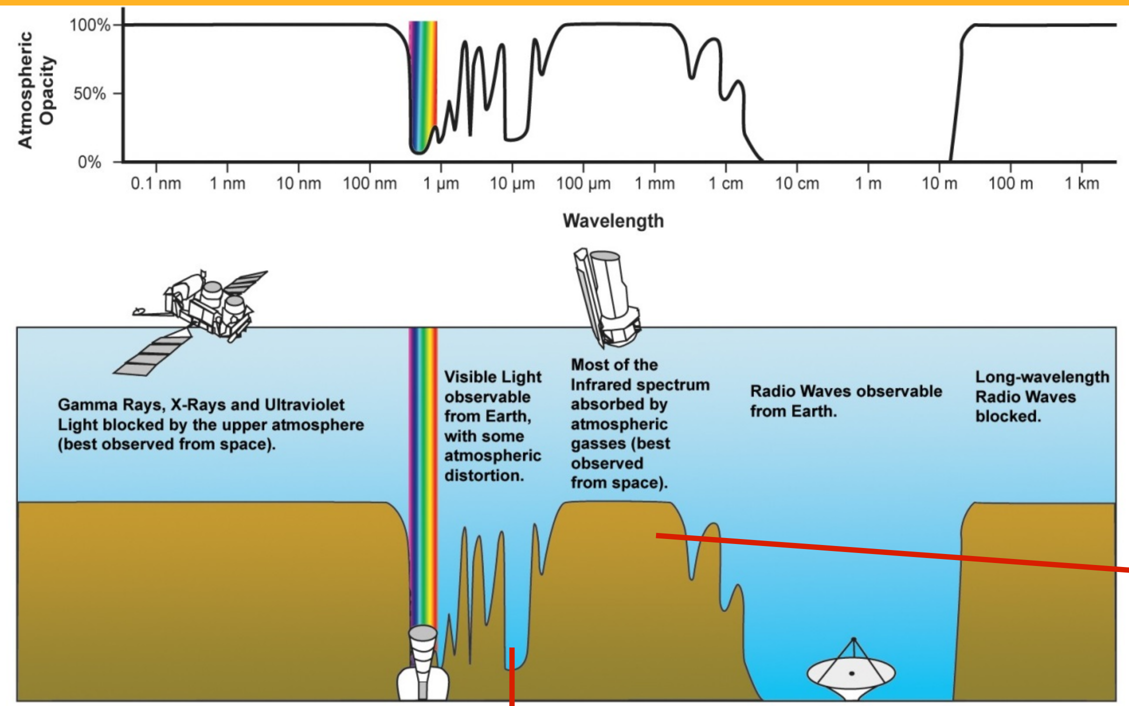
molecule	abundance[a]	transition	type	λ	$T^b_\circ$ (K)	A_{ul} (s^{-1})	n^c_{crit} (cm^{-3})	comments
H_2	1	$1 \rightarrow 0$ S(1)	vibrational	2.1 μm	6600	8.5×10^{-7}	7.8×10^{7}	shock tracer
CO	8×10^{-5}	$J= 1 \rightarrow 0$	rotational	2.6 mm	5.5	7.5×10^{-8}	3.0×10^{3}	low density probe
OH	3×10^{-7}	$^2\Pi_{3/2}$;J=3/2	Λ-doubling	18 cm	0.08	7.2×10^{-11}	1.4×10^{0}	magnetic field probe
NH_3	2×10^{-8}	(J,K)=(1,1)	inversion	1.3 cm	1.1	1.7×10^{-7}	1.9×10^{4}	temperature probe
H_2CO	2×10^{-8}	$2_{12} \rightarrow 1_{11}$	rotational	2.1 mm	6.9	5.3×10^{-5}	1.3×10^{6}	high density probe
CS	1×10^{-8}	$J= 2 \rightarrow 1$	rotational	3.1 mm	4.6	1.7×10^{-5}	4.2×10^{5}	high density probe
HCO^+	8×10^{-9}	$J= 1 \rightarrow 0$	rotational	3.4 mm	4.3	5.5×10^{-5}	1.5×10^{5}	tracer of ionization
H_2O		$6_{16} \rightarrow 5_{23}$	rotational	1.3 cm	1.1	1.9×10^{-9}	1.4×10^{3}	maser
//	$<7\times10^{-8}$	$1_{10} \rightarrow 1_{11}$	rotational	527 μm	27.3	3.5×10^{-3}	1.7×10^{7}	warm gas probe

[a] number density of main isotope relative to hydrogen, as measured in the dense core TMC–1
[b] equivalent temperature of the transition energy; $T_\circ \equiv \Delta E_{ul}/k_B$
[c] evaluated at T=10 K, except for H_2 (T=2000 K) and H_2O at 527 μm (T=20 K)

From: Stahler & Palla, "The Formation of Stars"

The importance of CO was the main driver to build instruments for frequencies beyond 100 GHz !

The atmospheric transmission windows



Main absorbers between the optical and radio transmission windows:

- H_2O
- CO_2

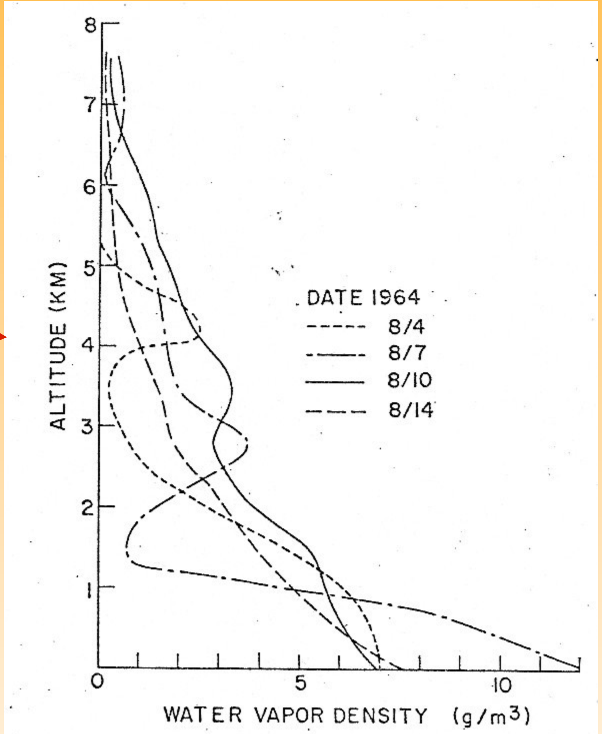
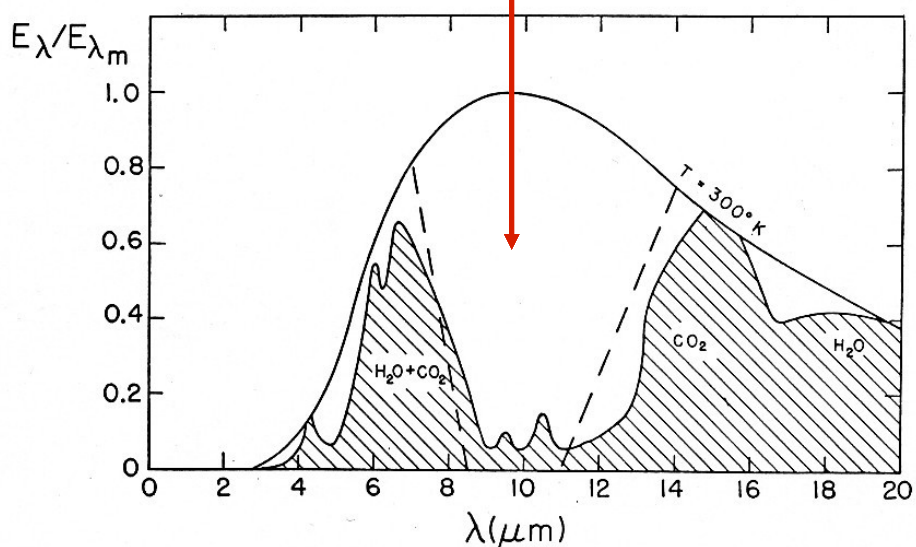


Fig. 3. Atmospheric water vapor profiles measured by radiosondes.



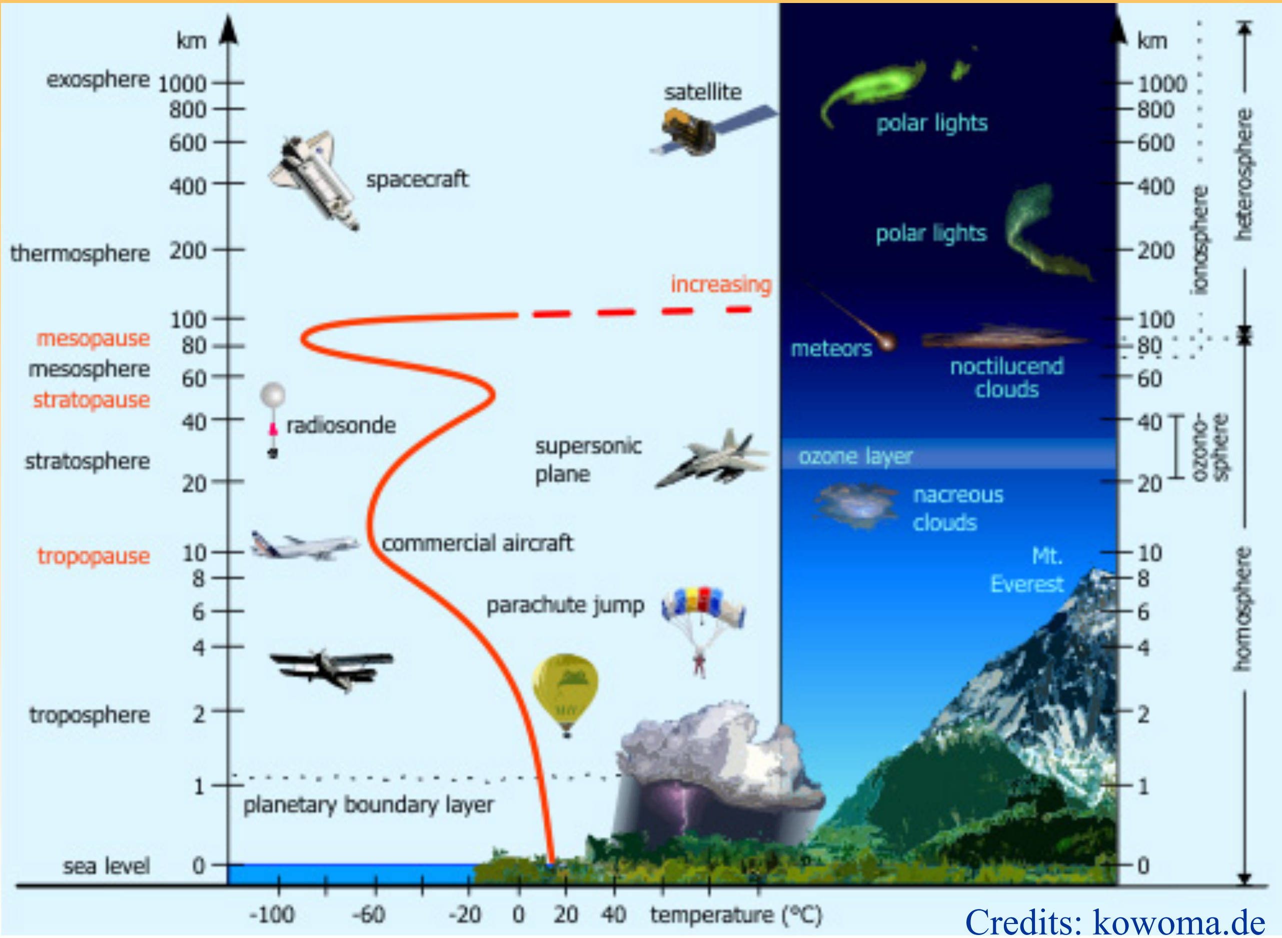
From: Staelin, 1966 (method: radiosondes)

From: Irbarne & Cho, Atmospheric Physics

Do we need to go to Space?

Dry air: scale height 8.4 km
Water vapour: scale height 2.0 km

You can (nearly) walk into Space for mm radio astronomy!
A desert can do for the 3mm band. **Favourite:** High altitude desert.

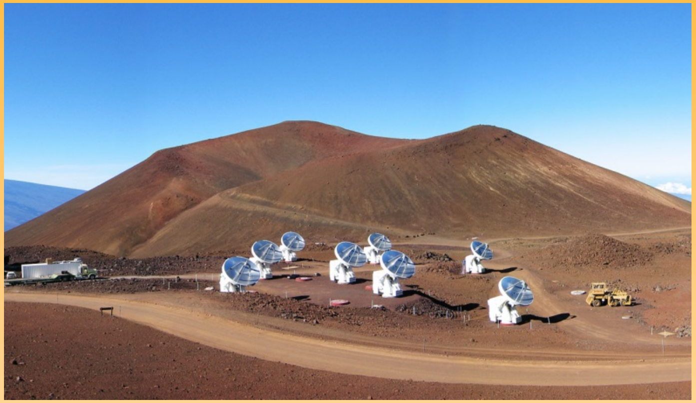


Credits: kowoma.de

Getting rid of water vapour by going high and/or dry

ALMA: 5000m

SMA: 4100m



PdBI: 2550m

CARMA: 2440m

ATCA: 208m

What properties must a mm telescope have?

Table 1.2 Electromagnetic Reflector Diameter and Surface Precision.

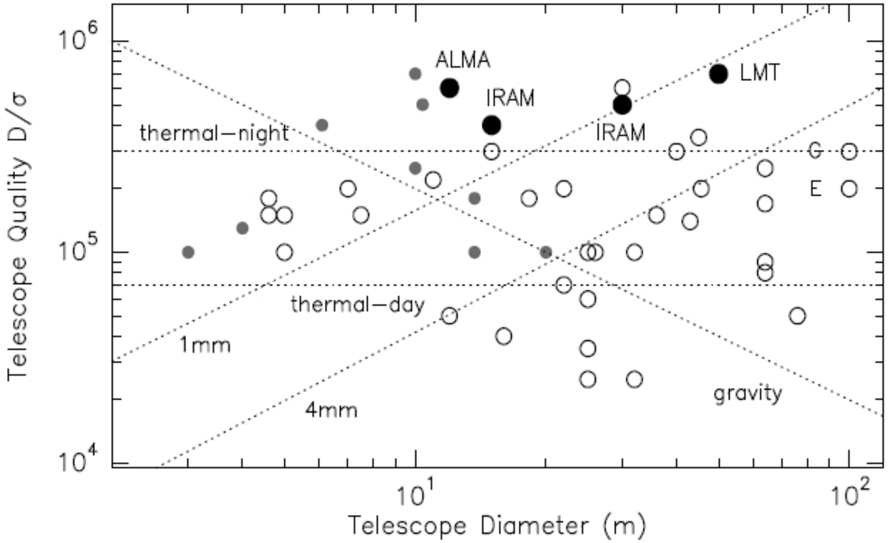
Telescope (Country) [a]	Reflector Diameter [m]	Wavelength (λ)/ Frequency (ν) [b] [mm]/[GHz]	Electromagnetic Diameter $\mathscr{D} = D/\lambda$ [$\mathscr{D}$/1000]	Reflector Quality $Q = D/\sigma$ [b] [Q/1000]
Radio Telescope				
Arecibo (USA)	300	60 / 5	5	200
Effelsberg (Germany)	100	10 / 30	10	150
Nobeyama (Japan)	45	3 / 100	15	400
IRAM (Spain)	30	1.3 / 230	23	460
IRAM (France)	15	1.3 / 230	11	300
JCMT (Hawaii)	15	0.65 /460	23	750
CSO (Hawaii)	10	0.37 /800	27	500
Optical Telescope				
Palomar (USA)	5	$5\times10^{-4}/5\times10^{15}$	10 000	100 000
KECK (USA)	10	$5\times10^{-4}/5\times10^{15}$	20 000	200 000
ELT [c]	$\sim$50	$5\times10^{-4}/5\times10^{15}$	100 000	1 000 000

[a] see list of Acronyms of observatory sites;
[b] approximately shortest wavelength of observation, estimated precision σ;
[c] next generation extremely large optical telescope (see http://www.eso.org).

Radio telescopes and their optics: Gaussian optics formalism required.

Unwanted wavefront deformation must be $< \lambda / 10$ (i.e. surface + pointing + focus +…)

How to build a millimetre antenna



Von Hoerner–diagram. Telescope quality D/σ (D = reflector diameter, σ = surface precision, rms value) and natural limits of gravity and thermal effects, for mm – wavelength (•) and cm–wavelength telescopes (○). The lines labelled 1 mm and 4 mm show the relation $\lambda_{min} = 16\,\sigma$. For the limiting relations see von Hoerner [1967 a, 1977 a] and Baars [2007]. G = GBT telescope, E = Effelsberg telescope.

Problem:

- must be precise enough for your highest frequency,
- with a large collecting area,
- in a place where you have encouraging weather statistics,
- and stay within budget.

Homological Design:

Manage grav. deformations: Tilted main reflector changes its focus but stays a paraboloid !

Millimetre Telescopes vs. the Real World

Forces acting on a Telescope (and Enclosure).

Influence/ Force	Time Variability	Components	Loss of Observing Time
Gravity	quasi–static	gravity	negligible
Temperature	slow 1/4 – 3 h	air, wind, sun, sky, ground & internal heat source	some
Wind & Gusts	fast, 1/10 – 10 s	ambient air	important
Atmosphere	fast	temperature, H_2O vapour, clouds, precipitation	(dominant)

Temperature variations and telescope geometry

Two approaches to get the desired millimetre telescope performance:

- choose a material with compatible constant of thermal expansion
- control the reflector temperature (insulation, climatisation, radome, astrodome)

$$6\,[\mathrm{mm}](D/100[\mathrm{m}])(\Delta T/^{\circ}\mathrm{C}) \lesssim \lambda_{\mathrm{min}}$$

$$\Delta T \lesssim \lambda_{\mathrm{min}}[\mathrm{mm}]/(6D/100[\mathrm{m}]) \quad (\mathrm{steel})$$

Von Hoerner (1967, 1975)

Reflector Diameter D	100 m	30 m	20 m	15 m	12 m	12 m
Material	steel	steel	aluminium	CFRP–steel	steel	CFRP
CTE [μm/m/K]	12	12	22	5 [a]	12	3
Example	Effelsberg	IRAM	Onsala	IRAM		ALMA
λ_{min} [mm]/ν_{min} [GHz]	30/10	1/300	3/100	1/300	0.375/800	0.375/800
ΔT [$^{\circ}$C] $\lesssim$	5	0.5	1.25	2.5	0.5	2

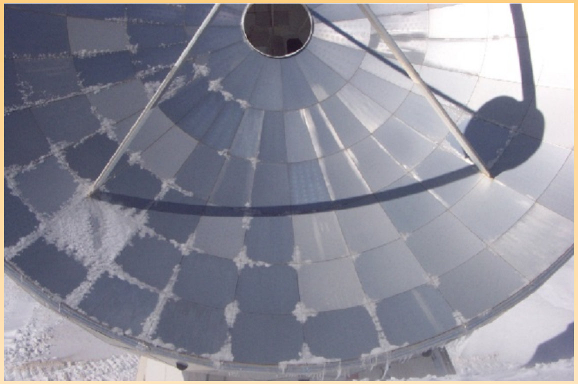
[a] estimated value for a combination of CFRP and steel.

Wind and Ice

At high altitude, one has to expect wind and large temperature fluctuations, and often snow and ice.

- MM Telescopes are mostly of Cassegrain or Gregorian design, with filled reflector surfaces (no wire mesh). Wind force: $F_w = \frac{1}{2} \rho V^2 A c_w$

  Free-standing telescopes are more sensitive to high wind speeds but protective radomes absorb strongly at mm and sub-mm wavelengths



- Reflectors may need de-icing (heated surfaces). Pre-emptive heating to avoid ice attachment, getting rid of ice after formation is not easy.

Table 4.4 Thermal Properties of Water, Frost, Snow and Ice.

Precipitation	Density ρ [kg/m^3]	Heat Capacity $\mathscr{C}$ [J/kg/K]	Volume Heat Capacity $\rho\mathscr{C}$ [MJ/m^3/K]	Heat Conductivity k [W/m/K]
Water	1 000	4 200	4.20	0.6
Ice	920	2 000	1.84	2.25
Snow	400	2 000	0.80	0.5
Frost	~ 100 – 200	~ 600	~ 0.1	~ 0.05 – 0.2

Receiver technology and backends

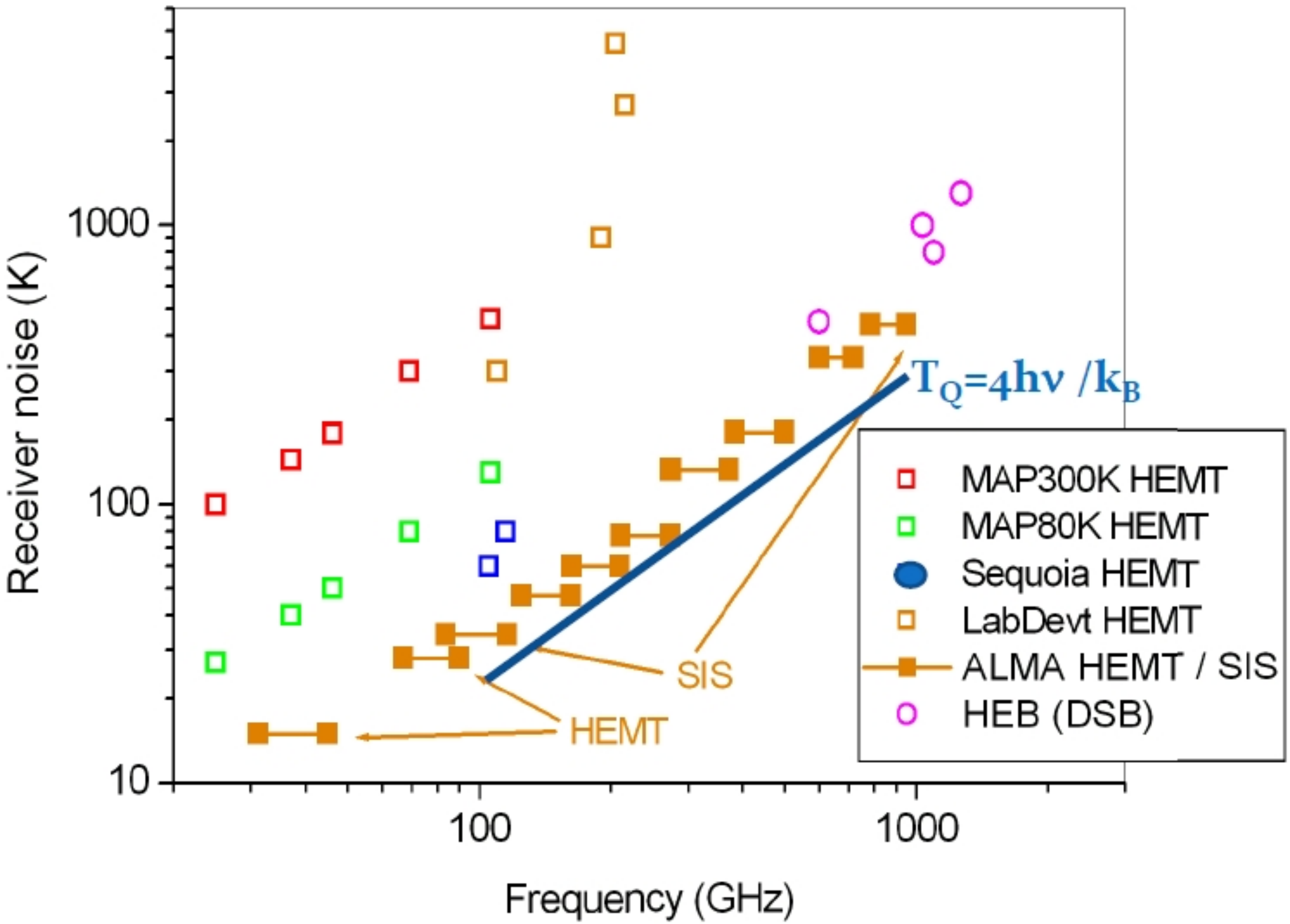
Problem: take a part of the spectrum at high frequencies and convert it to low frequencies where conventional electronics work.

In the cm range: first amplify, then down convert in frequency
In the mm range: first down convert in frequency, then amplify.

- **HEMT amplifiers: Direct amplification, ~15 K cooling sufficient**
  Today up to 115 GHz on telescopes; beyond 200 GHz in the lab
  Instantaneous b/w ~ 30%
- **SIS Mixers: 4 K cooling necessary**
  Heterodyne mixing
  up to 700 GHz (Niobium); > 1THz (NbTiN)
  Instantaneous b/w 2 x 8 GHz
- **HEB mixers: typically 4 K cooling**
  Heterodyne mixing
  Several THz
  Instantaneous b/w ~ 4 GHz

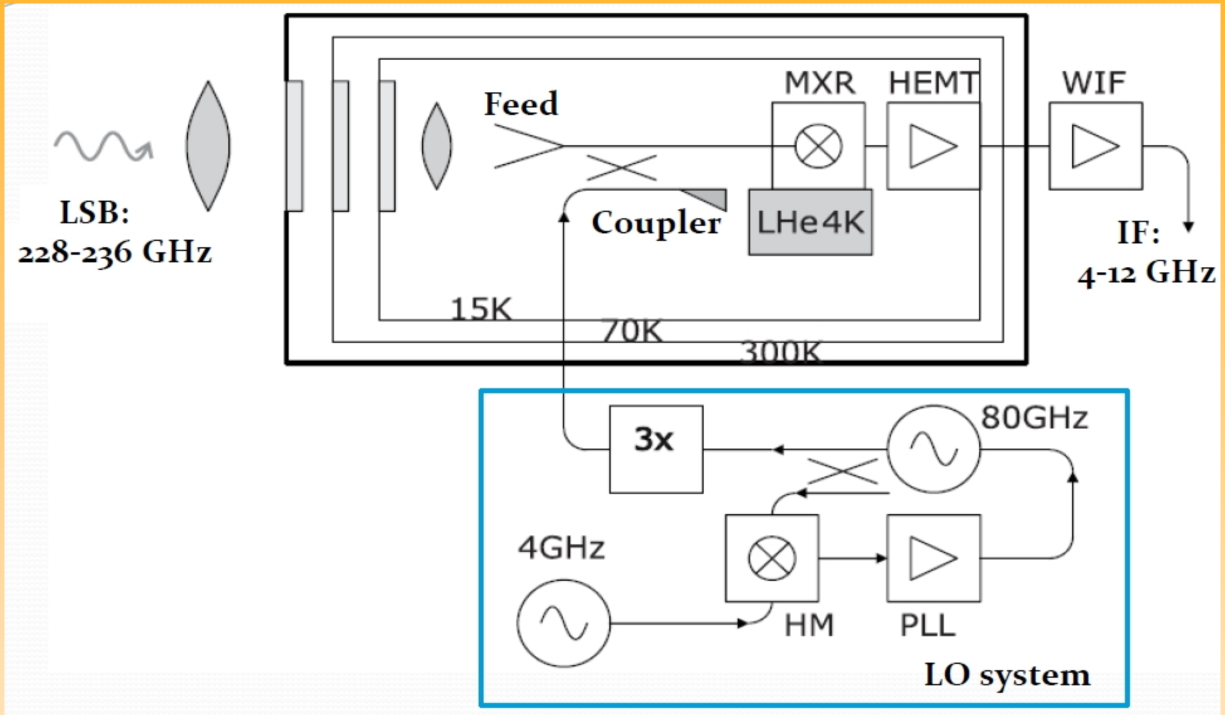
(**HEMT**=High Electron Mobility Transistor; **SIS**=Supraconductor-Isolator-Supraconductor, **HEB**=Hot Electron Bolometers)

Overview of HEMT, SIS and HEB performance



Courtesy A. Navarrini, IRAM

Schematic view of a cooled receiver

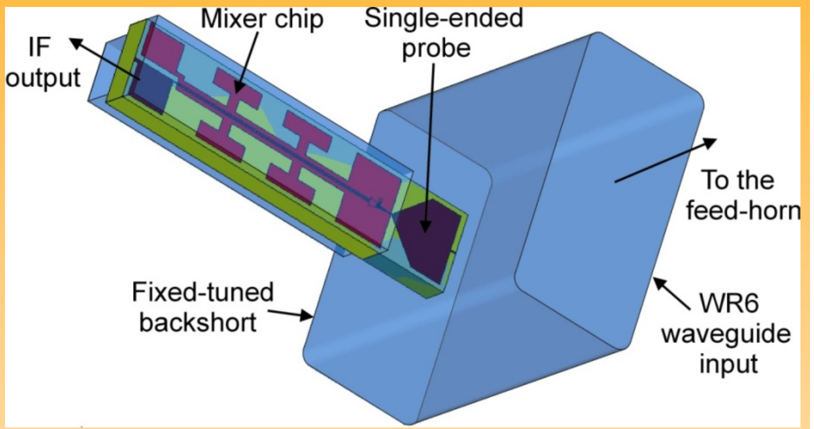


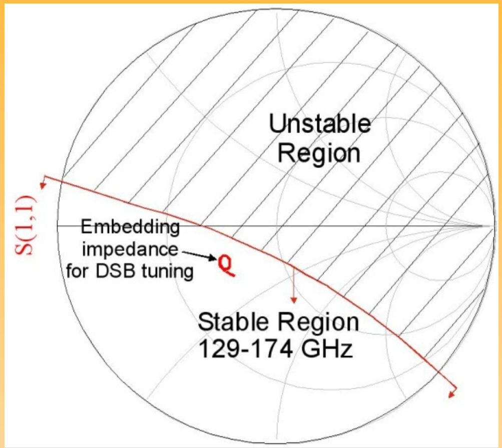
SIS receivers are currently the dominant technology in mm interferometers above 100 GHz.

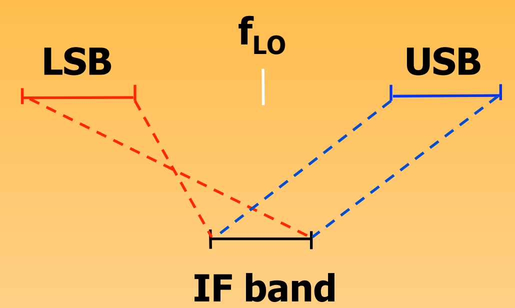
There are three sub-types:

SIS mixer types: DSB, SSB and 2SB

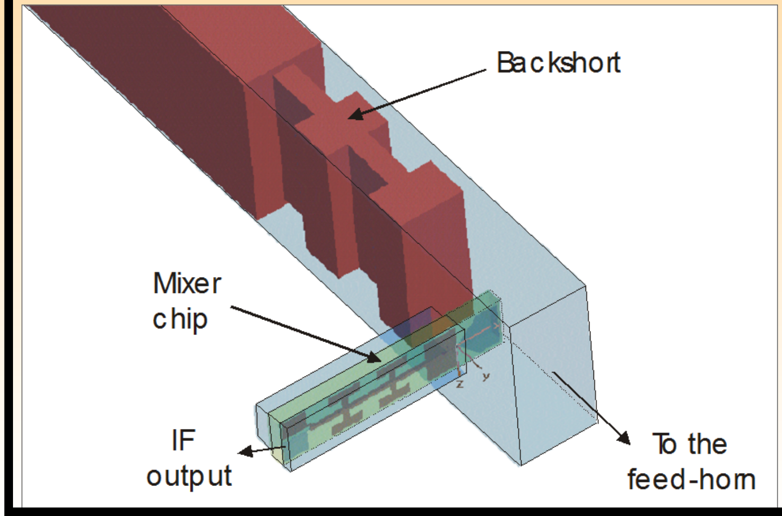
Double Side Band (DSB): Both the USB and the LSB are downconverted and superimposed on each other at the IF:

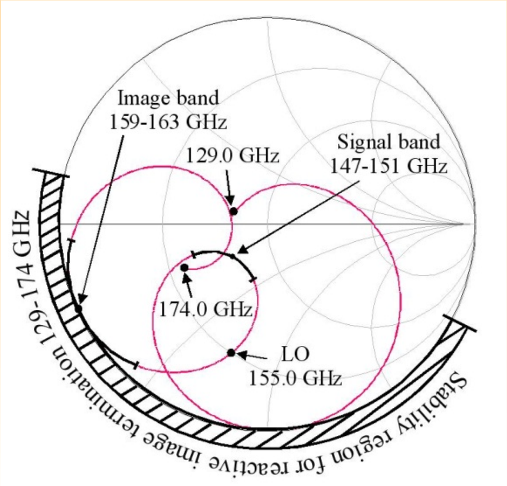




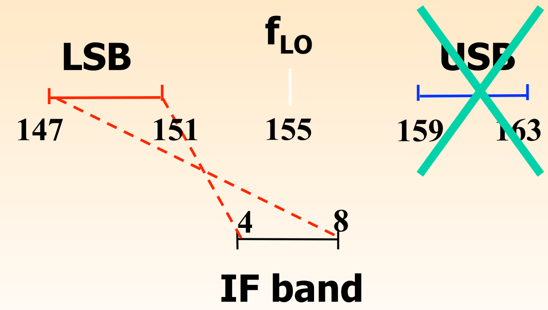


Single Side Band (SSB): Either the USB or the LSB is downconverted to IF, i.e. one sideband is rejected. Sideband rejection achieved (at Iram) by mechanically tunable backshort:





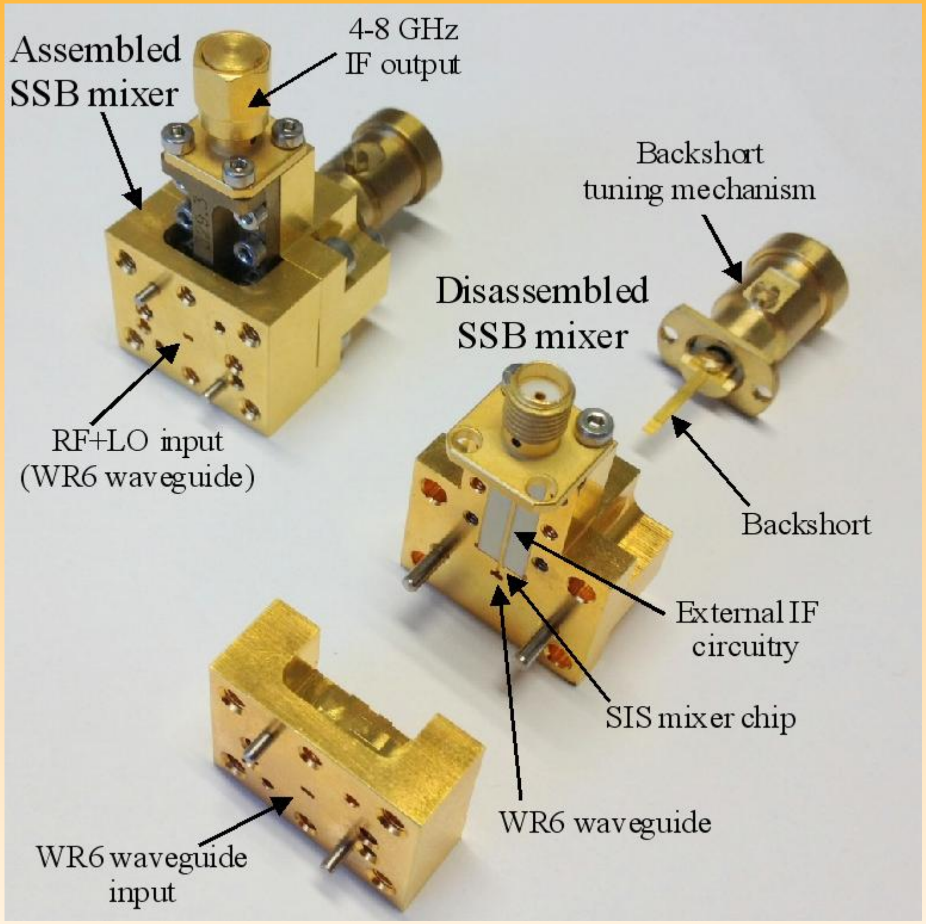
Example of LSB tuning
(USB is rejected)

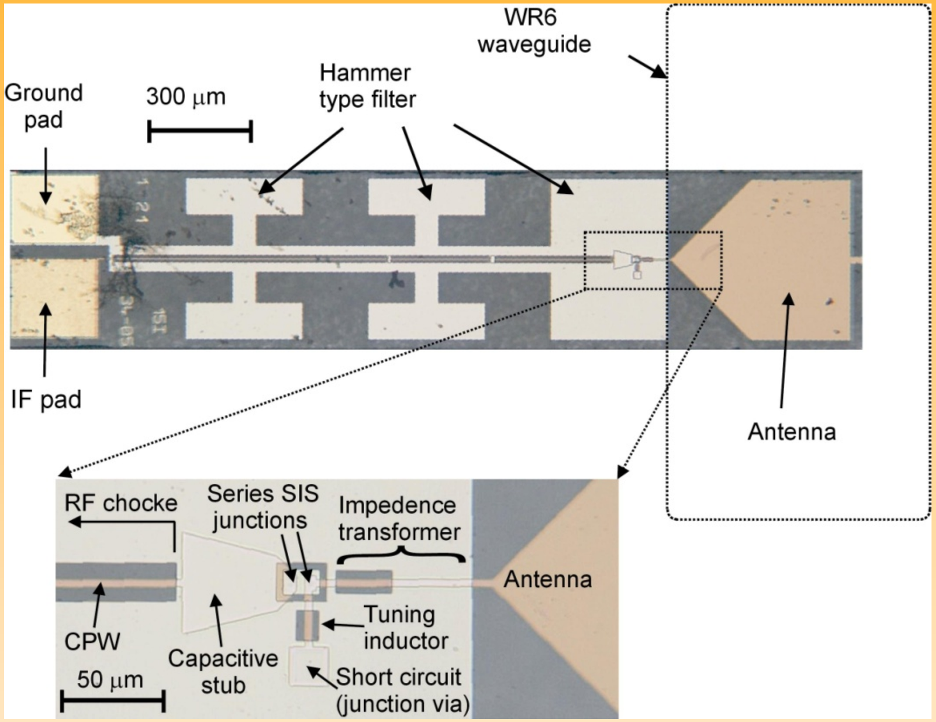


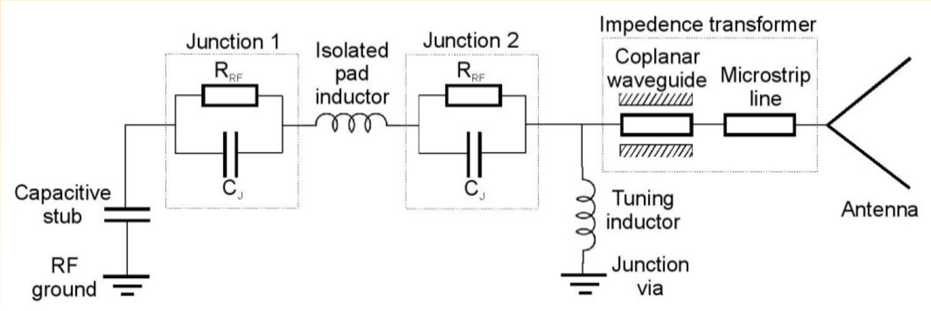
Courtesy A. Navarrini, IRAM

SSB SIS mixer currently installed in EMIR and PdBI Band 2 receivers

RF band: 129-174 GHz (2 mm band);
IF Band: 4-8 GHz



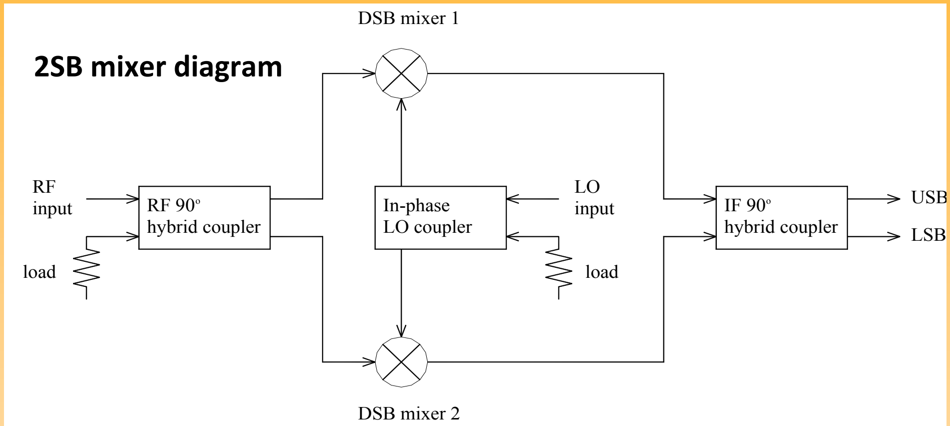


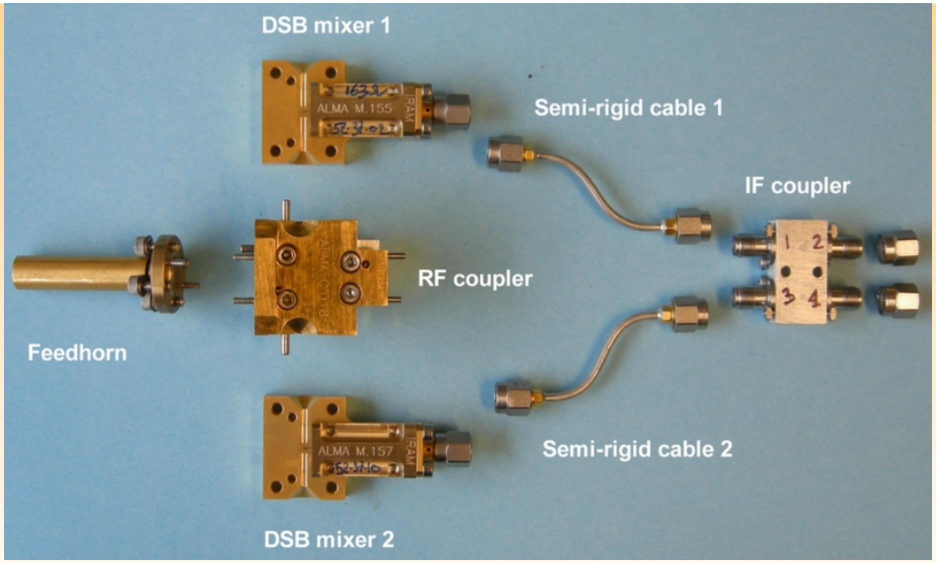


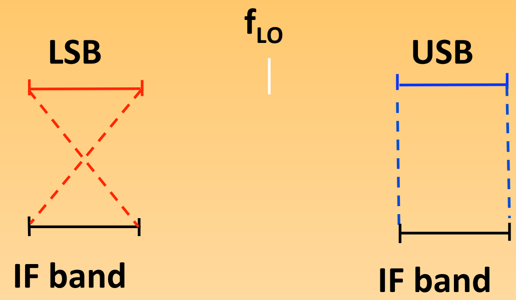
Courtesy A. Navarrini, IRAM

SIS mixer types: DSB, SSB and 2SB

Sideband Separating mixer (2SB): Both sidebands (USB and LSB) downconverted and separated to independent outputs







SIS mixers currently installed on IRAM receivers are SSB and 2SB (no DSB).

Courtesy A. Navarrini, IRAM

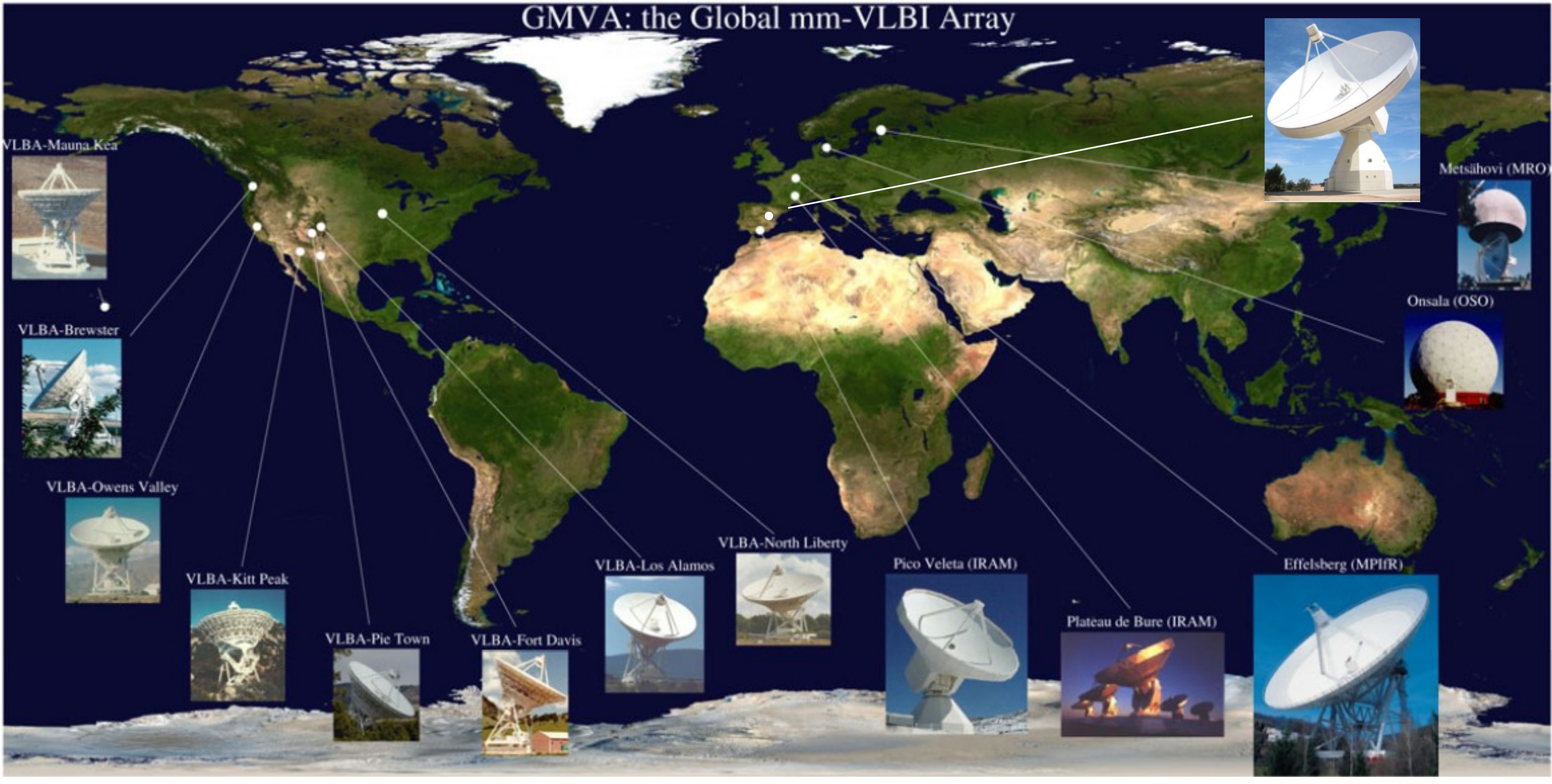
Connecting millimetre antennas into an interferometer

Same as for cm instruments, but with scaled-up performance.

- **LO system:** The frequency for the heterodyne detection must either be generated from a common frequency source (connected element array) or be re-generated from first principles at each antenna (e.g. VLBI).
- **Correlators:** must be high-speed machines in the Tera to Peta operations/sec range that can be extensively re-configured for the placement of bands and spectral resolution
- **Computer systems:** required to control antennas, frontends, backends and to record the data

Special case: 3mm VLBI (GMVA)

- Detection must be achieved within the atmospheric coherence time.
  The higher the frequency, the shorter the time. Needs high instantaneous bandwidth.
- Frequency standards on each antenna must have excellent short-term phase noise, which is dominated by a quartz phase-locked to an active hydrogen maser.



Intermediate conclusion:

Fig. 1-5. Grote Reber's meridian-transit radio telescope. Many modern radio telescopes bear a striking resemblance to this early instrument.

Building your own millimeter interferometer (trying to follow the steps of Grote Reber) takes a lot of time.

It is typically easier to submit proposals to existing facilities:

ALMA: http://almascience.eso.org/

SMA: http://www.cfa.harvard.edu/sma/

IRAM: http://www.iram-institute.org/

CARMA: http://www.mmarray.org/

ATCA: http://www.narrabri.atnf.csiro.au/

What changes for the observer between cm and mm waves?

With increasing frequency:

- No external human interference in the data
- Non-thermal sources become weaker
  but thermal sources are not strong yet,
- atm. water vapour and clouds become more absorbent, therefore:
    - stronger weather dependency of observations
    - Tsys of low elevation observations becomes a lot worse
      (choose your sources carefully, don't skim the horizon!)
- polarization in astronomical objects becomes weaker
- the time variability of quasars increases (flux and polarisation)

Calibration steps (several we know already)

Opacity correction: observe (every 20 minutes or more often) hot load, cold load, sky and determine T_{sys}, T_{rec} and receiver gain

- RF calibration on a strong quasar
- Phase calibration on point-like quasars
- Real-time phase correction (more on this in a moment)
- Flux calibration (more on this in a moment)
- Amplitude calibration

For the IRAM Plateau de Bure, we use the **GILDAS package**.
Easy to install and use, graphical user interface, ASTRO software to plan your observations, CLIC software for interferometric data reduction, MAPPING to map, clean and analyse your data cubes…

Calibration steps (several we know already)

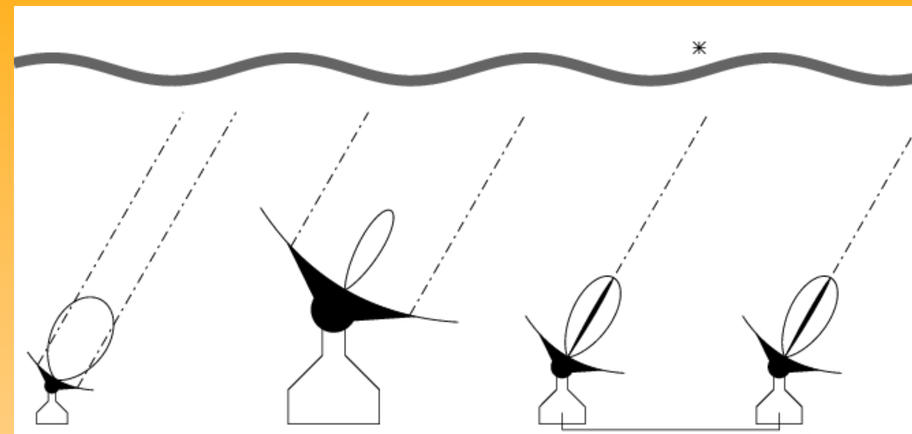
Opacity correction: observe (every 20 minutes or more often) hot load, cold load, sky and determine T_{sys}, T_{rec} and receiver gain

• RF calibration on a strong quasar
• Phase calibration on point-like quasars
• Real-time phase correction (more on this in a moment)
• Flux calibration (more on this in a moment)
• Amplitude calibration

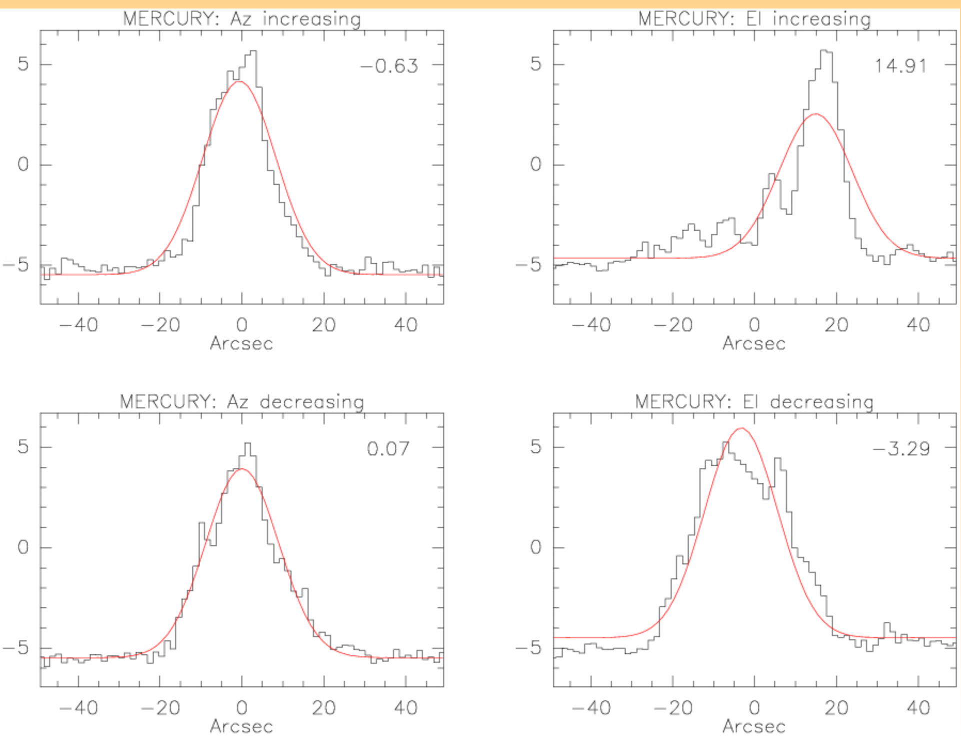
For the IRAM Plateau de Bure, we use the GILDAS package.
Going really into details here would take too much time. If you are interested:
IRAM organizes an interferometry school every two years, past lectures are available on-line under the "science users - events" section of http://www.iram-institute.org .

Real-time phase correction of water vapour

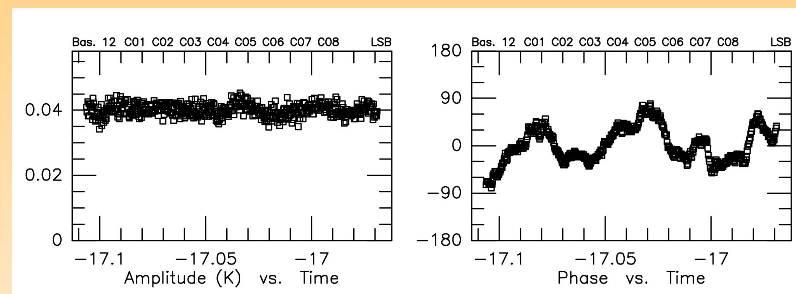
Ionospheric plasma phase noise scales down with 1/ν, and can be neglected above 80 GHz



30m pointing under anomalous refraction



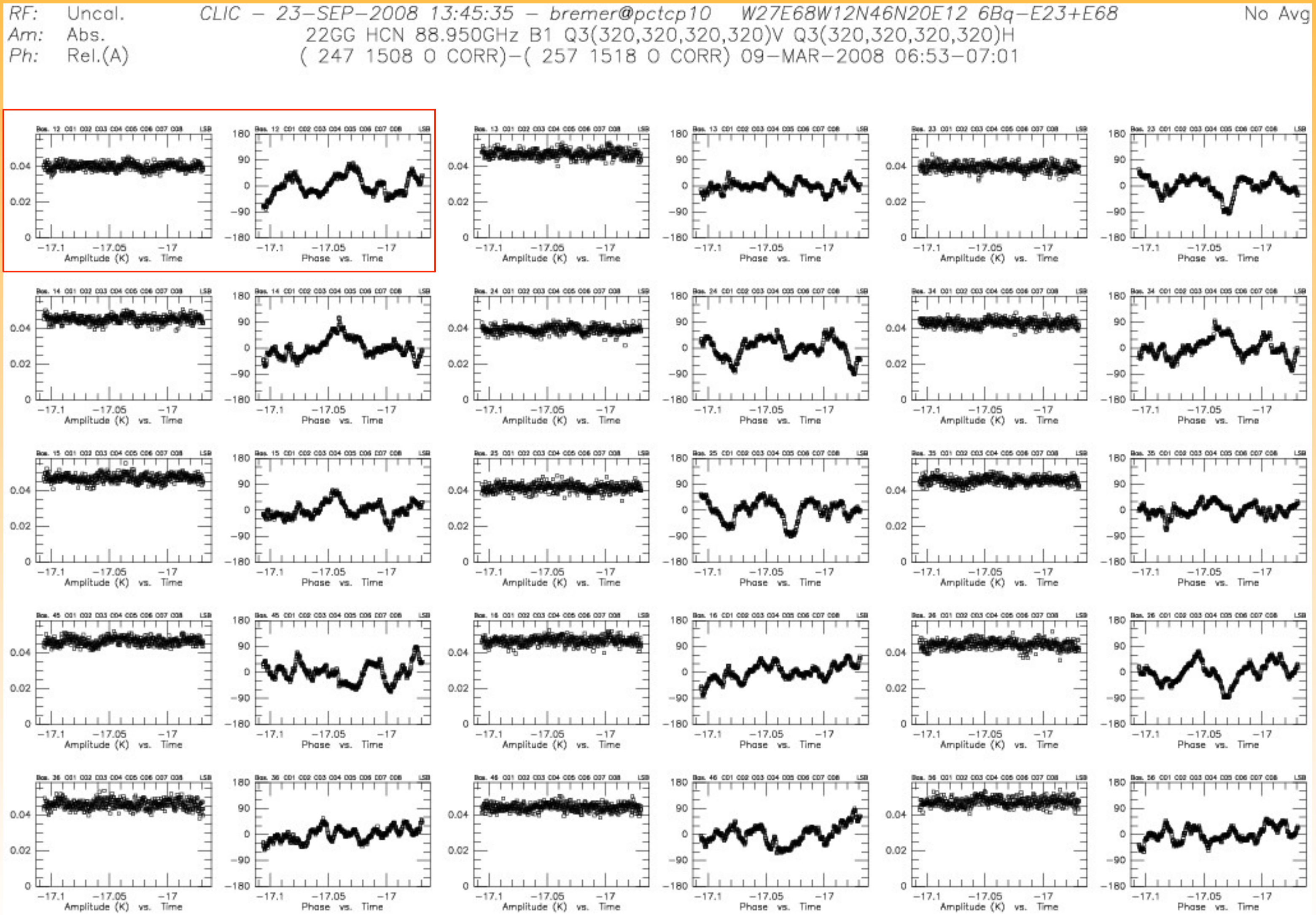
PdBI observation with phase noise



We will look at the PdBI phase noise in more detail …

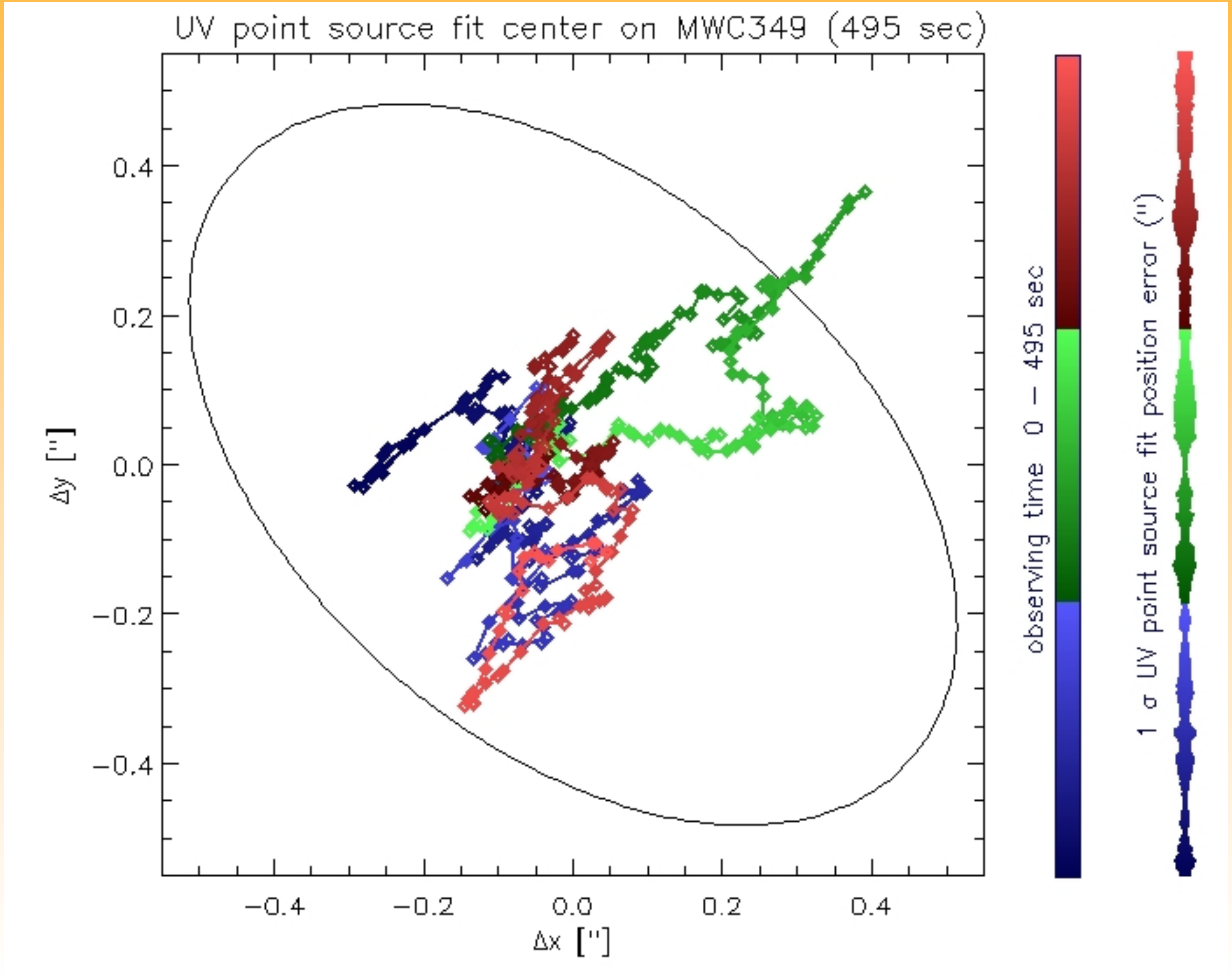
Amplitudes and phases on a point source

6-antenna observation (15 baselines) in extended configuration, ~ 8 minutes



Tropospheric phase noise

Three impacts on observations: a) the point source appears to move,



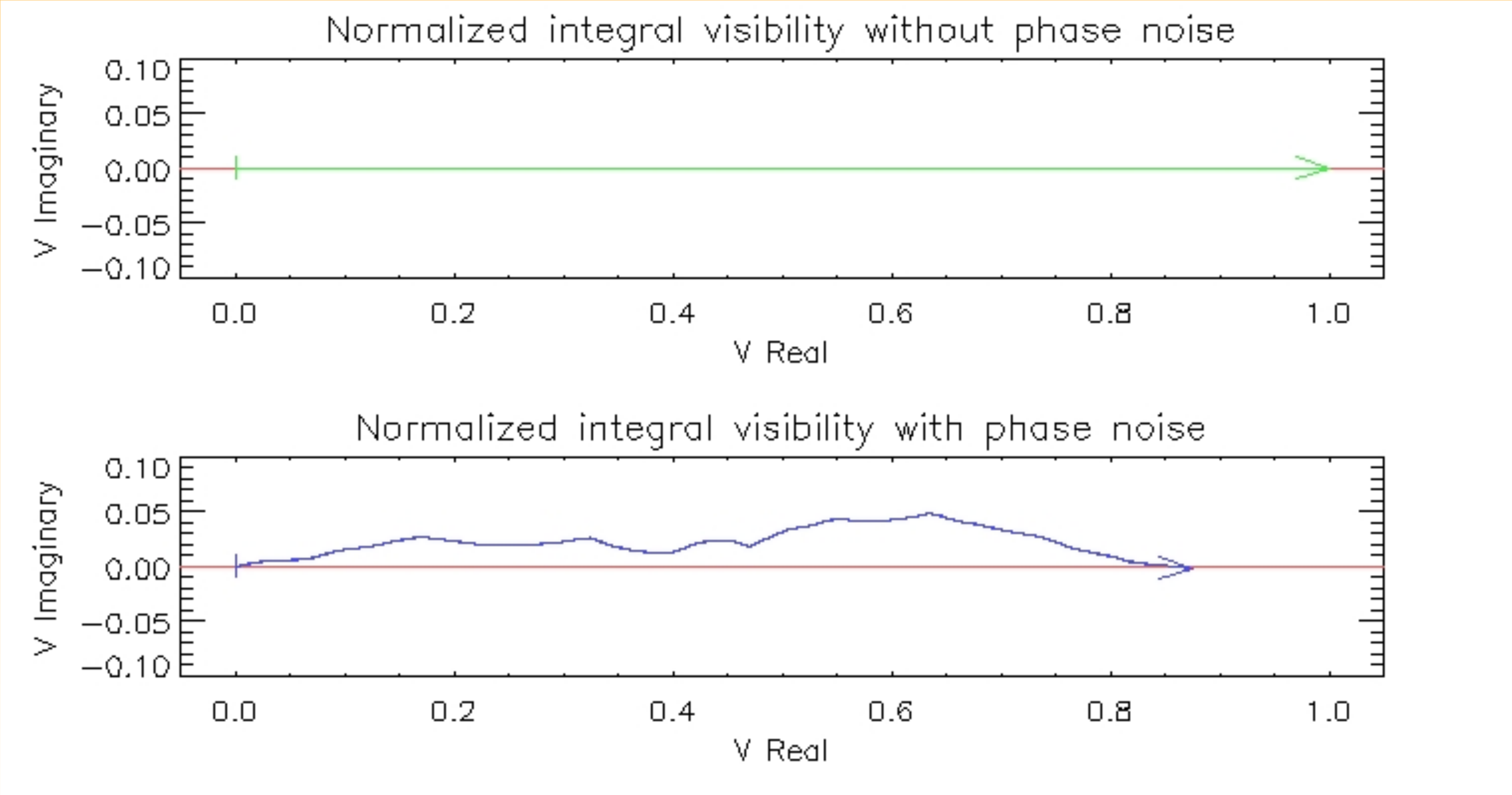
Tropospheric phase noise

b) we loose integrated flux because visibility vectors partly cancel out. Formula:

$$V_{OBS}=V_{IDEAL} \cdot \exp(-\varphi^2/2)$$ with phase noise φ in radian.

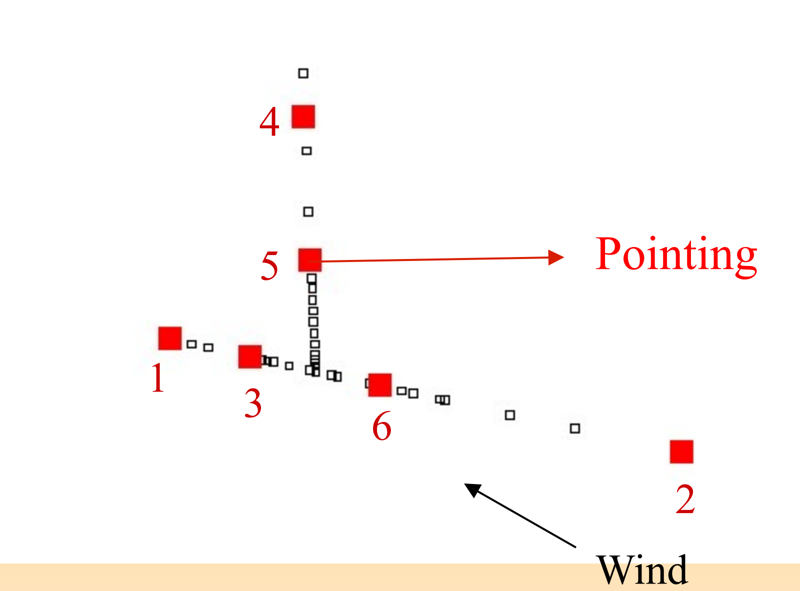
Observations were at 89 GHz and average phase noise 30º: 12.5% loss.

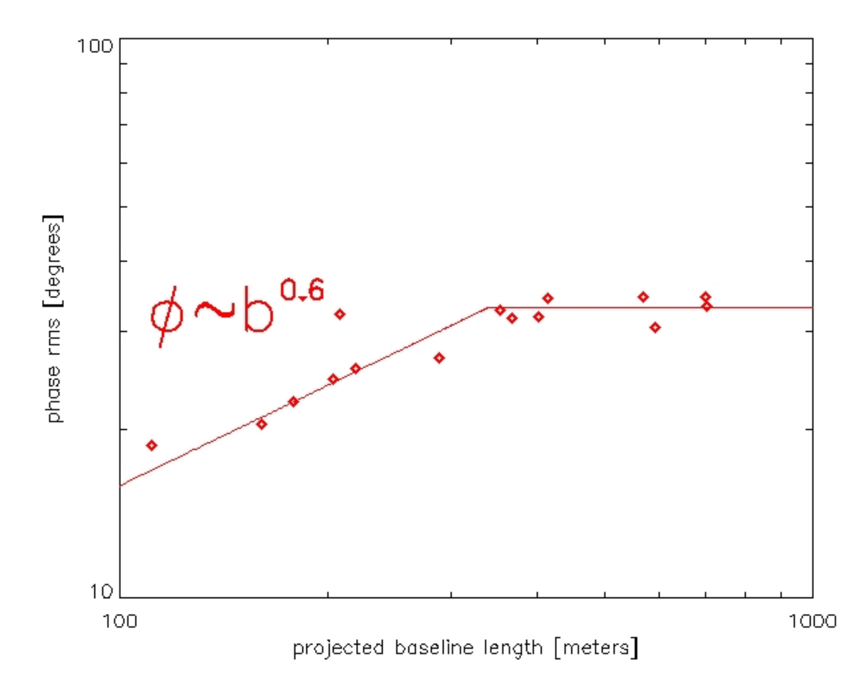
If we would have used a frequency 2 or 3 times higher: 42% or 71% loss …



Tropospheric phase noise

c) and we loose more signal on the longest baselines, which provide the finest details of our maps.





Configuration:W27-E68-W12-N46-N20-E12

Wind speed : 9 m/s from Azimuth -59°
Pointing : Azimuth=-91°, Elevation=67.3°
Frequency : 88.950 GHz

- *Atmospheric phase noise is worst on the longest baselines.*
- *The power-law break is weather dependent, and can be at several km.*

The physics behind the scenes

What we experience in the radio range differs from optical seeing.

Table 1: Expected image patterns for different scales of moist air turbulence.

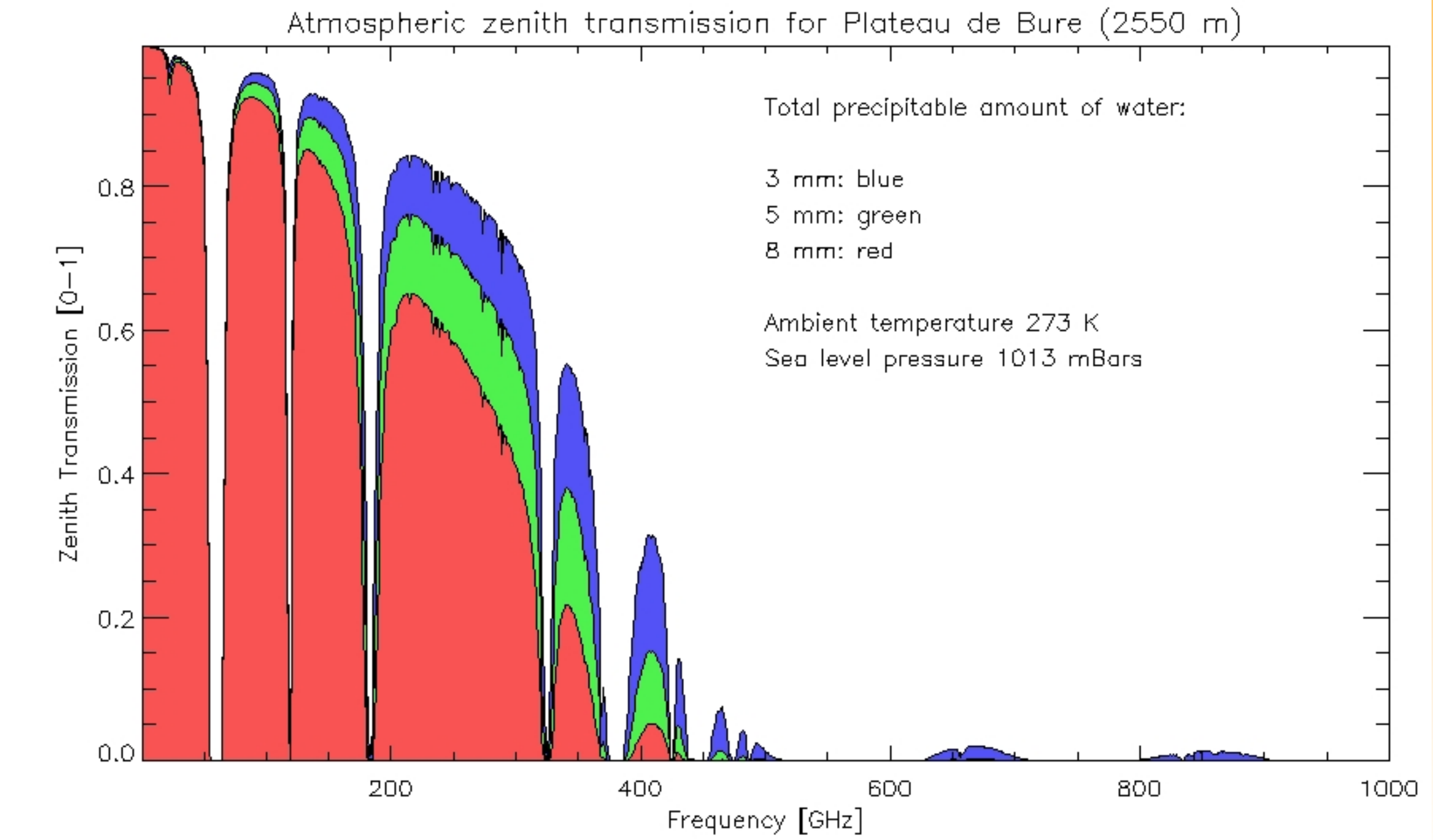
Scale of turbulence:	FINE SCALE (diffractive regime, $a \ll D$)		INTERMEDIATE $a \le D$	LARGE SCALE (refractive regime, $a > D$)
Phase variation over scale a:	$\Delta\phi < 1$ radian	$\Delta\phi > 2.6$ radians	$\Delta\phi > 2.5$ radians	
	VLBI		***Optical***	***30M, PDBI***
Short integration result	IMAGES superimposed on "error" beam	BLUR ("seeing disk")	SPECKLES	IMAGE MOTION (= Anomalous Refraction)
Remark	Images can still be formed. Some of the power is scattered to large angles (λ/a).	The diffraction limited beam disappears into the "error" pattern.	$(D/r_o)^2$ images	
Long integration result	same as snapshot result.	same as snapshot result.	BLUR (beam size convolved with seeing disk)	BLUR (In long integrations, the radio seeing disk is the smoothed envelope of the image motion.)
Point source image size: snapshot:	$\frac{\lambda}{D}$	$\frac{\lambda}{a}$	$\frac{\lambda}{D}$	$\frac{\lambda}{D}$
Long integration:	same	same	$\left(\frac{\lambda^2}{{r_o}^2} + \frac{\lambda^2}{D^2}\right)^{1/2}$	$\left(1.4\frac{\lambda^2}{{r_o}^2} + \frac{\lambda^2}{D^2}\right)^{1/2}$

Symbols: a = scale size of moist air packet; D = size of antenna, or interferometer baseline; r_o = diameter of atmospheric coherence region; at radius $r_o/2$, wavefront phase error $\Delta\phi = 2.6$ radians.

From: Downes and Altenhoff (1989), Anomalous Refraction at Radio Wavelengths, Proc. of the URSI/IAU Symposium on Radioastronomical Seeing, Beijing 15-19 May 1989

Monitoring wet path delay: where to look

- Δ radio path ~ Δ quantity of water vapor along the line of sight
- water vapor emits in the radio range, we can measure Δ T(sky).
  - clear sky: Δ path ~ Δ vapor ~ Δ T(vapor) = Δ T(sky) *(easy)*
  - cloudy sky: Δ path ~ Δ vapor
    Δ T(sky) = Δ T(vapor) + Δ T(cloud) *(tricky)*



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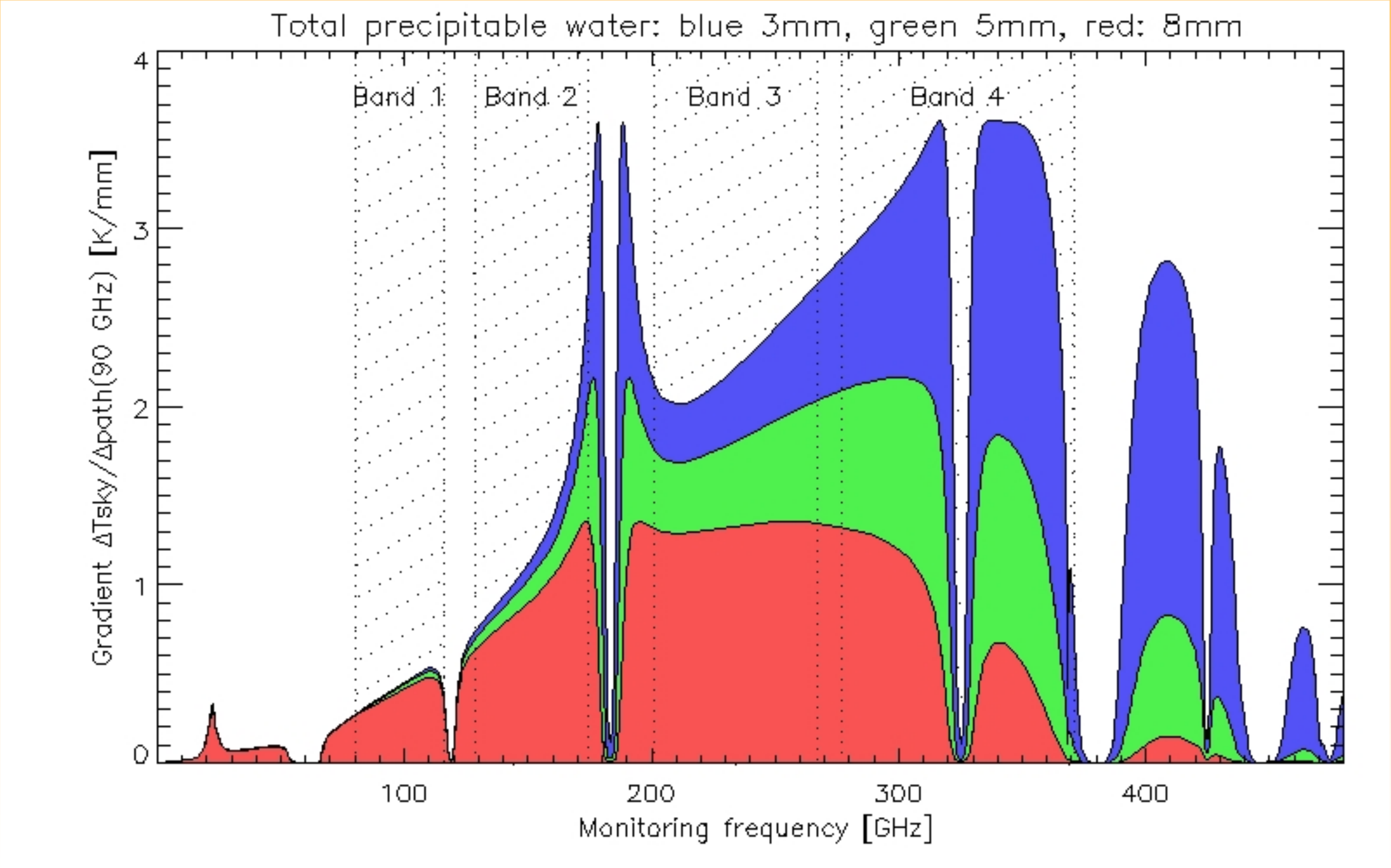


PdBI 22 GHz radiometers

- Cloud opacity is ~ υ^2 for wavelength » droplet size.
- All exponential terms at 22 GHz can be linearized for realistic observing conditions at 82 GHz.
- $T_{wvr} = F_{eff} \cdot (T_{vap} + T_{cloud}) + (1 - F_{eff}) \cdot T_{amb} + T_{rec}$

Then the combination of 3 channels

$$T_{triple} = (T_1 - T_2 \cdot \upsilon_1^2/\upsilon_2^2) - (T_2 - T_3 \cdot \upsilon_2^2/\upsilon_3^2)$$

removes cloud emission and constant temperature offsets if

$$\upsilon_1^2/\upsilon_2^2 = \upsilon_2^2/\upsilon_3^2$$

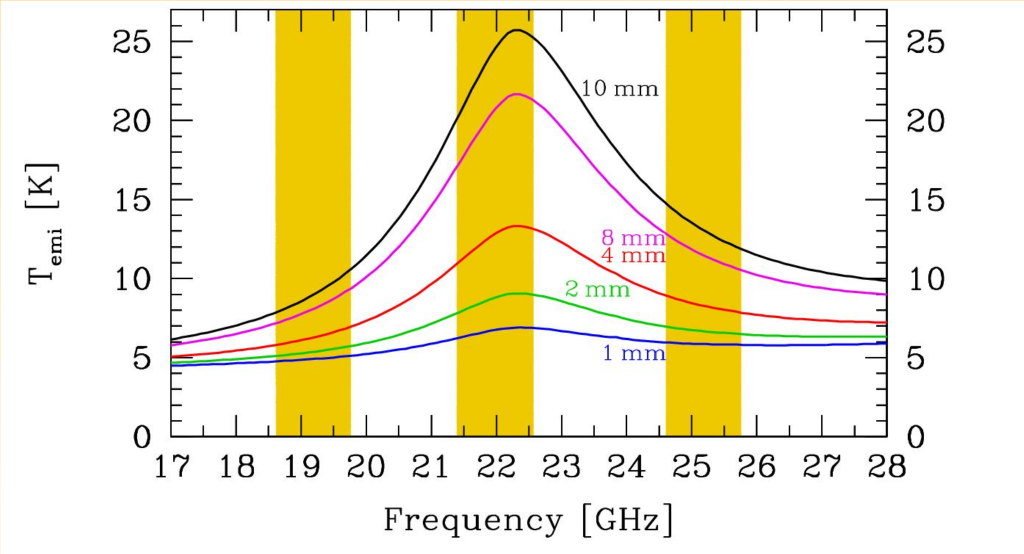
PdBI 22 GHz radiometer

Choice of frequencies for the Plateau de Bure Radiometers:

Three channels of 1 GHz bandwidth each:

υ_1=19.175 GHz , υ_2=21.971 GHz , υ_3 = 25.175 GHz

Selected by fixed filters on the 8 GHz bandpass of a single receiver.



It was not possible to stay on ITU protected frequency bands

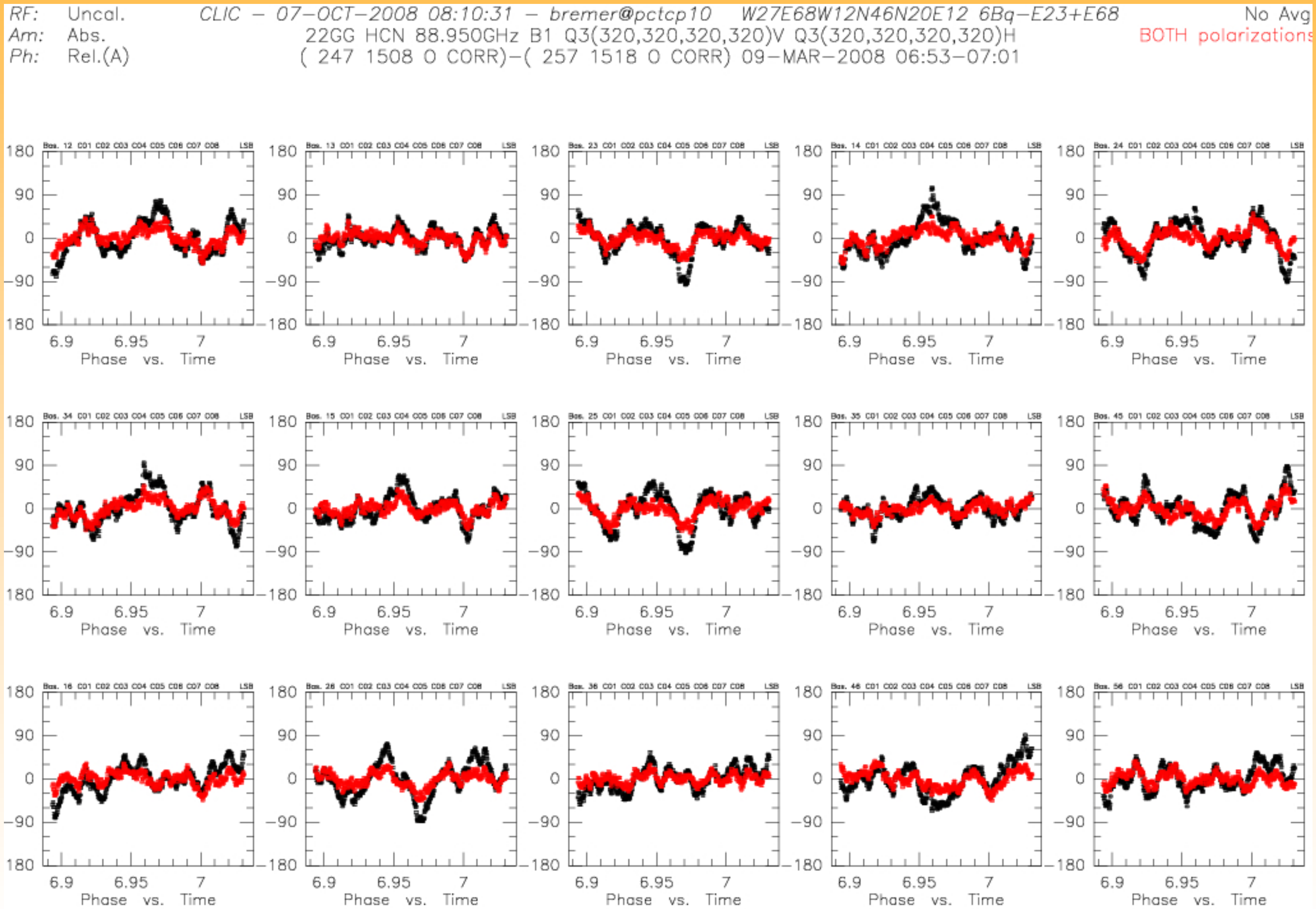
to reach the required sensitivity.

Calibration hardware: a waveguide-mounted noise diode

and an ambient load table.

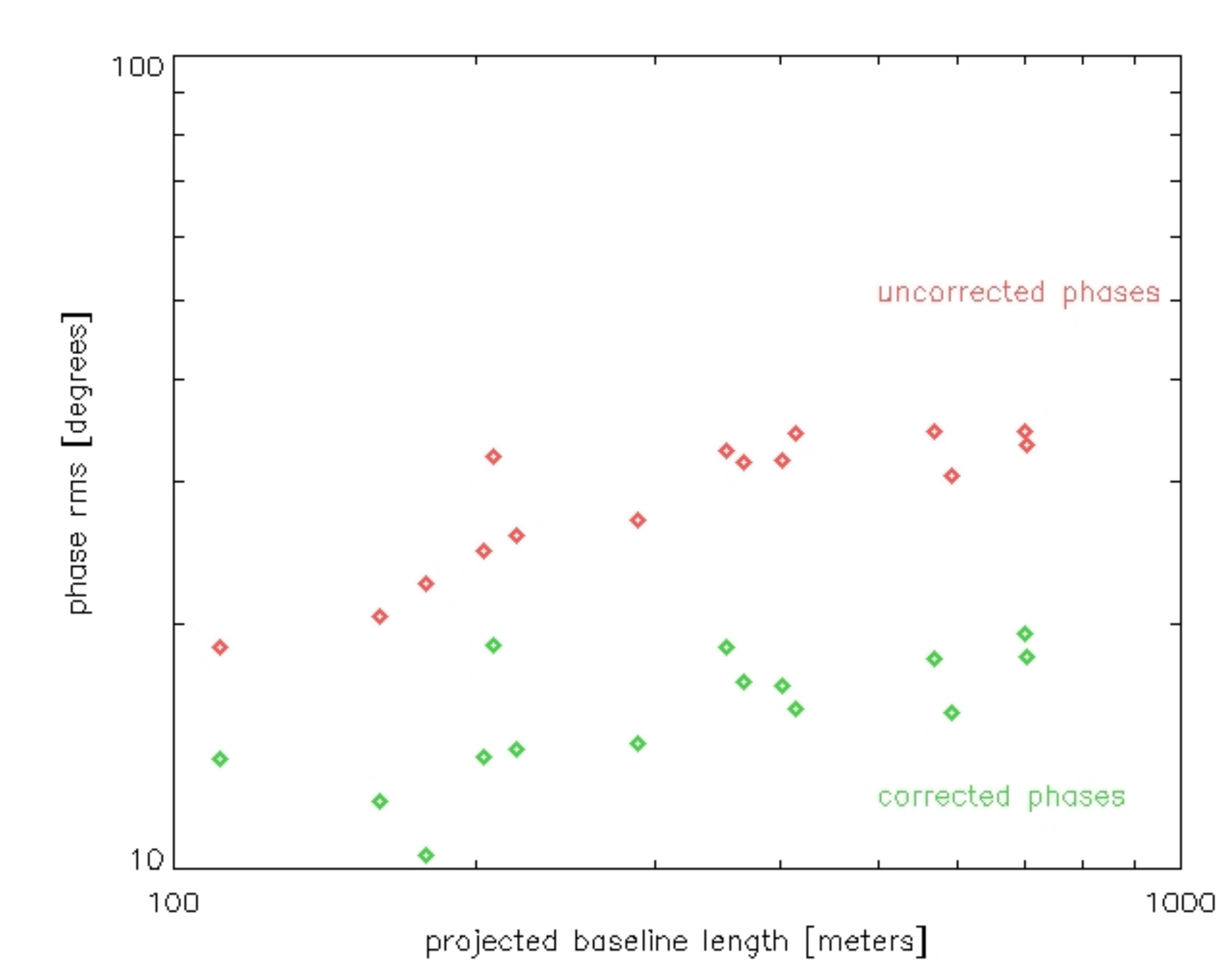
22 GHz radiometer – practical implementation

Our example on MWC349 from the beginning:



22 GHz radiometer – practical implementation

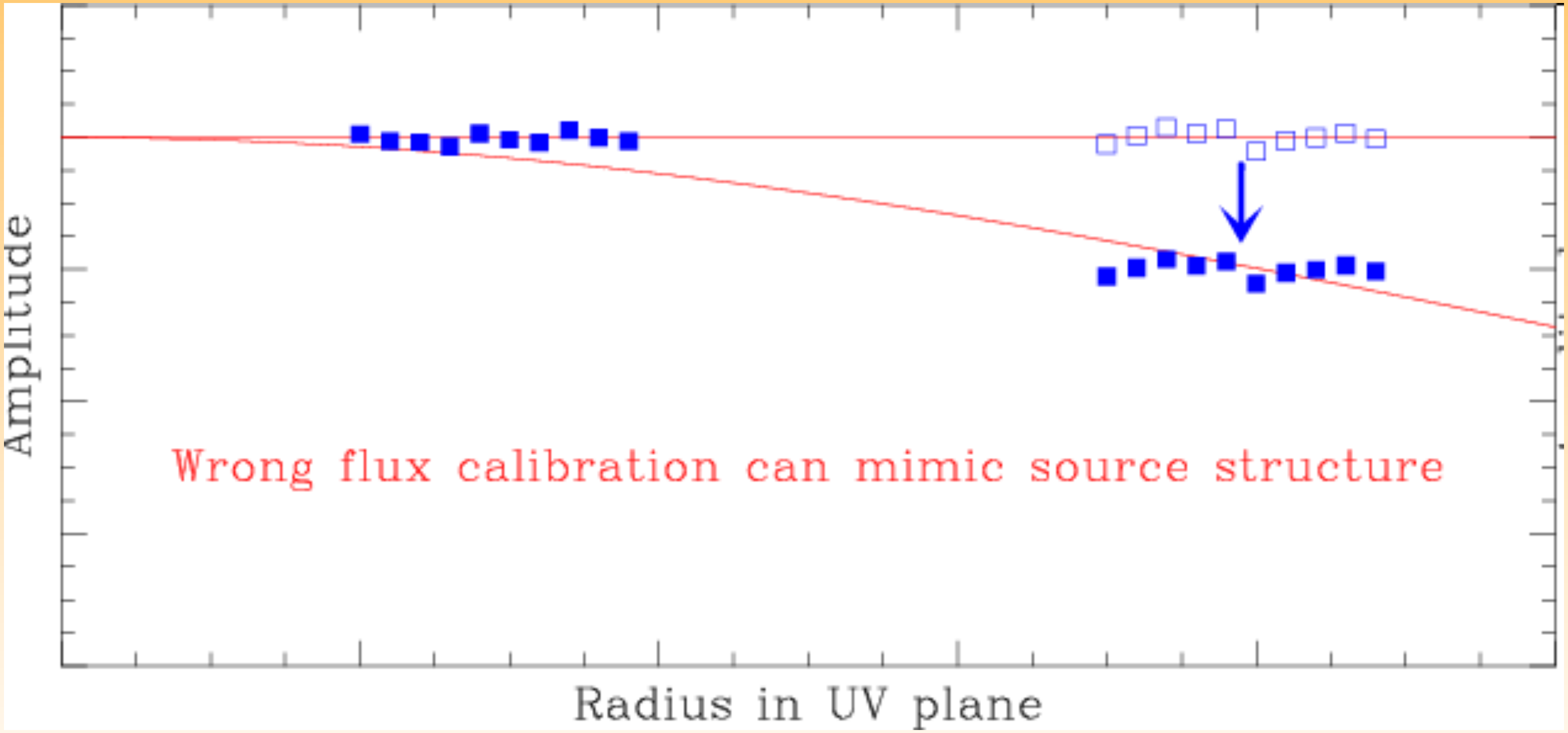
The corresponding phase noise vs. projected baseline plot:



Primary flux calibration

Required:

(a) for correct global flux scale and
(b) to combine observations of different epochs and configurations



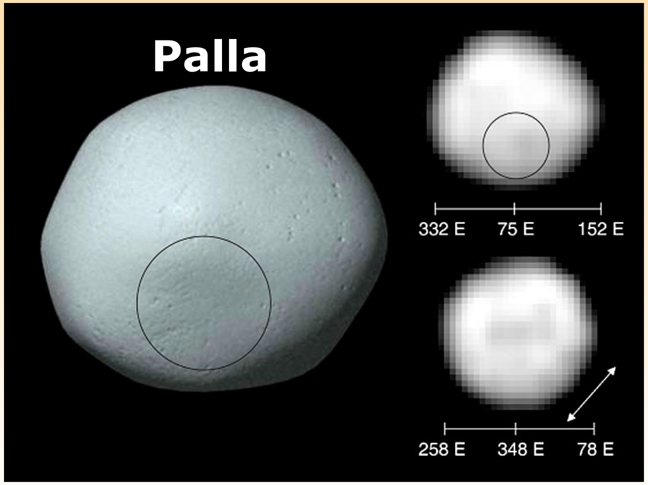
Sometimes used but problematic:

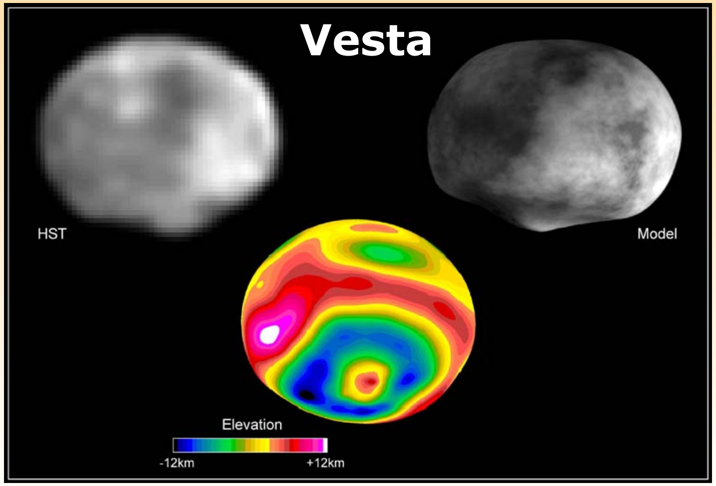
Antenna Efficiencies: decorrelation is neglected

Planets: already resolved at 3mm, spectral absorption lines (e.g. Mars, Jupiter, Saturn), slowly time variable, not always visible.

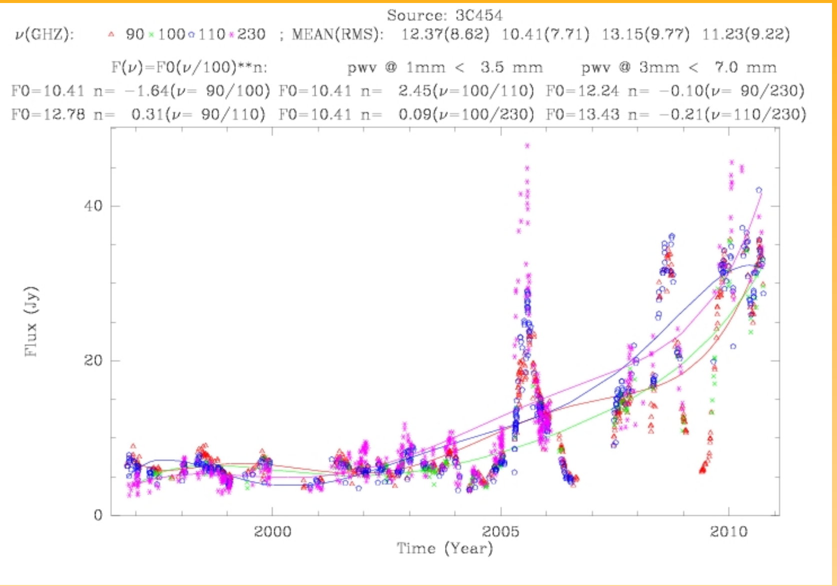
Moons of outer planets: often too close to the parent planet (we need at least 3 primary beams distance), flux models less known

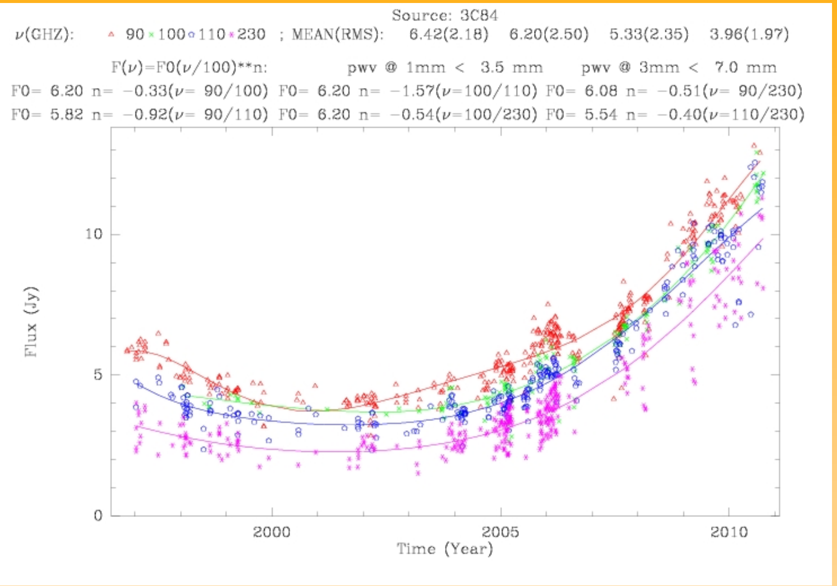
Minor Planets: fluxes can vary within a day, models not well known

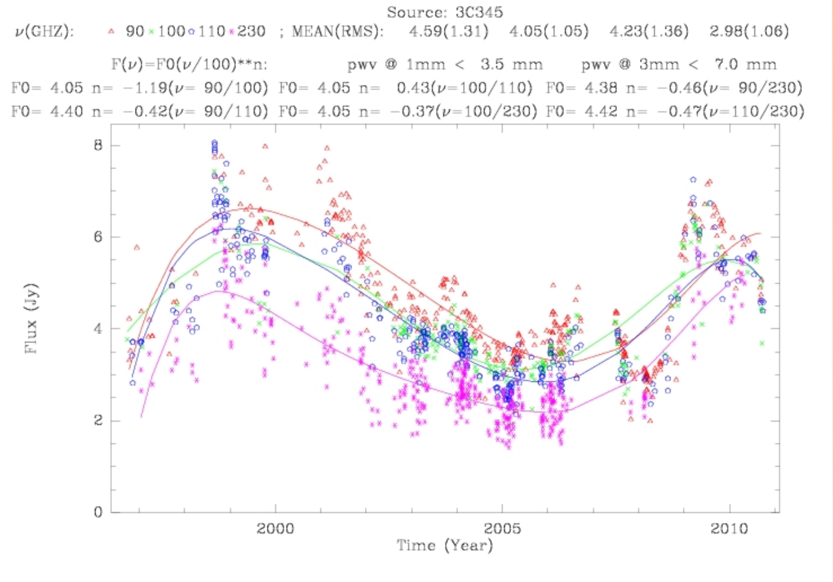


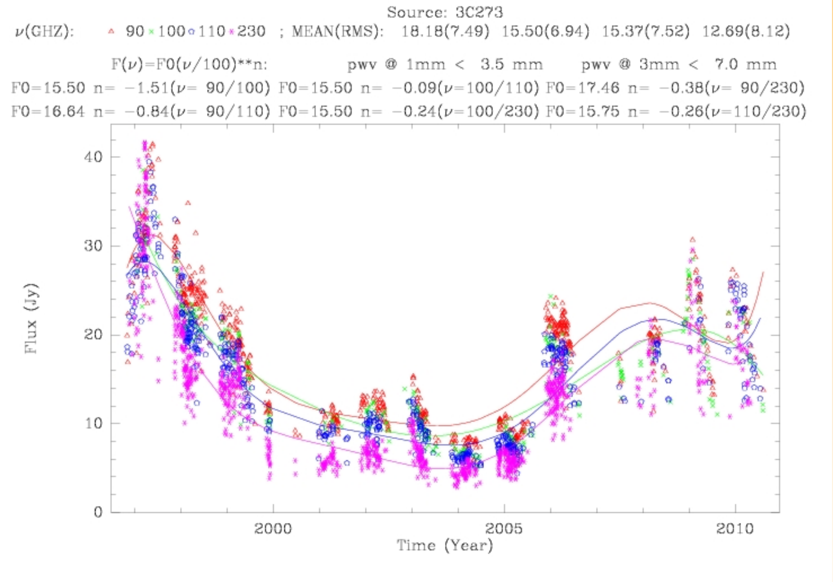


Time variability of quasars



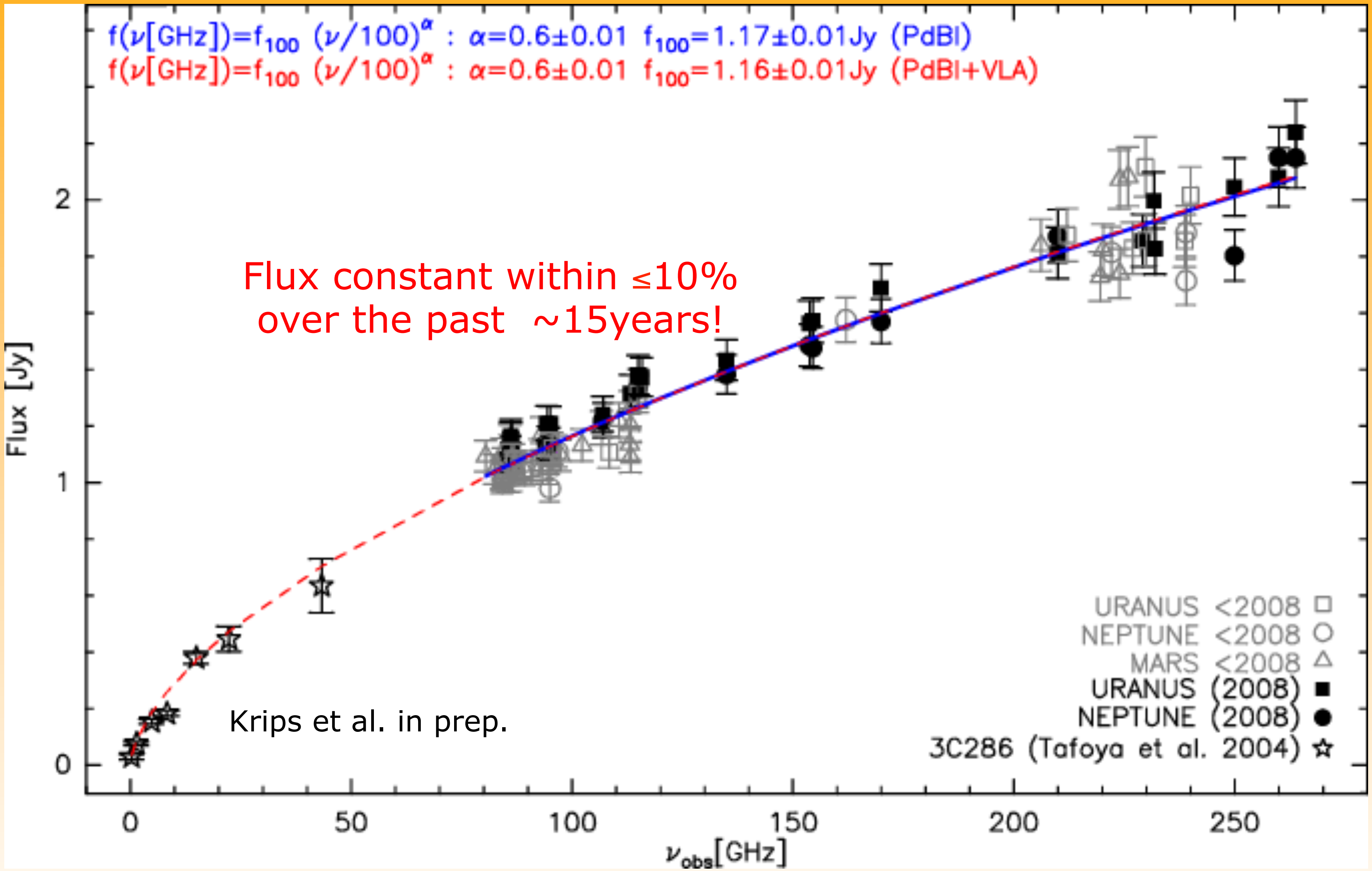






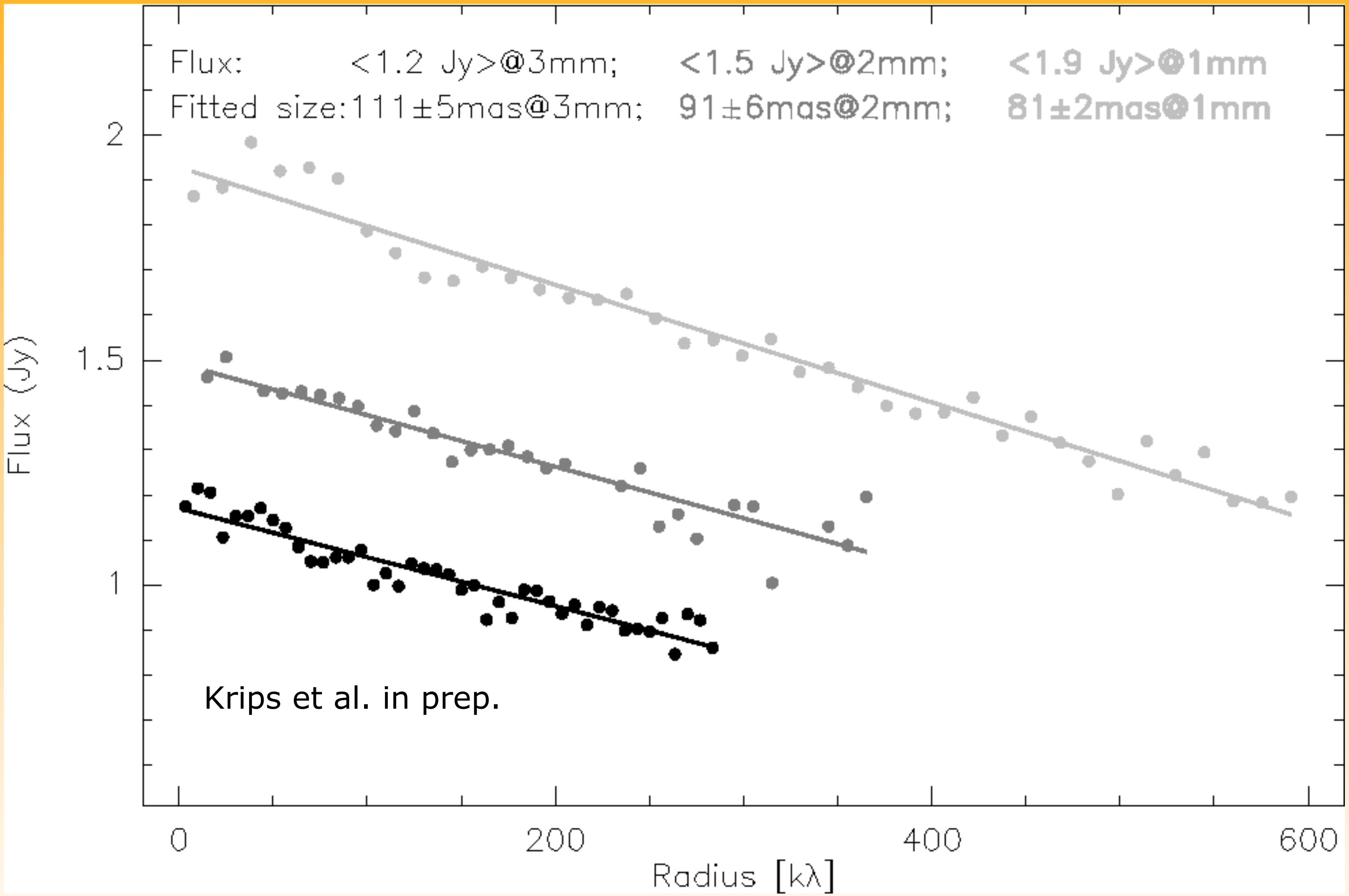
Courtesy M. Krips (IRAM)

Best solution so far (PdBI): Radio star MWC349



Courtesy M. Krips (IRAM)

MWC349 is resolved but not complicated

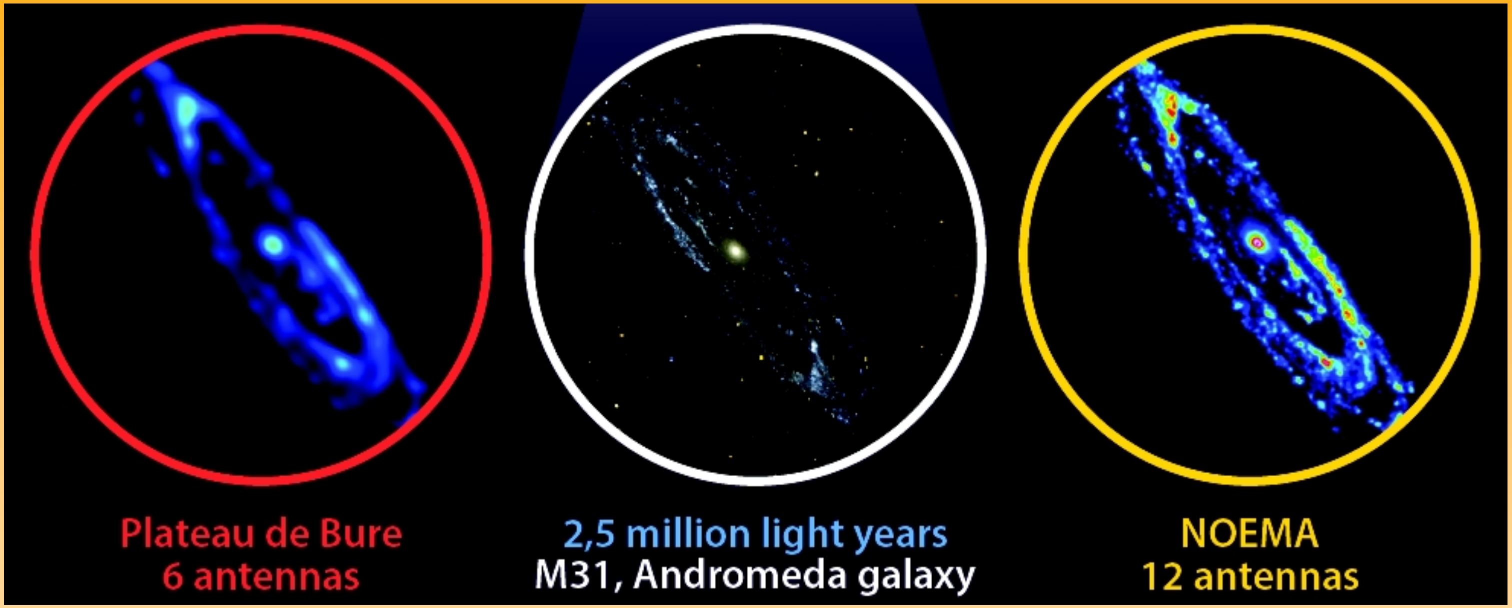


Courtesy M. Krips (IRAM)

A short glance into the future

The Northern extended mm Array (NOEMA) Project

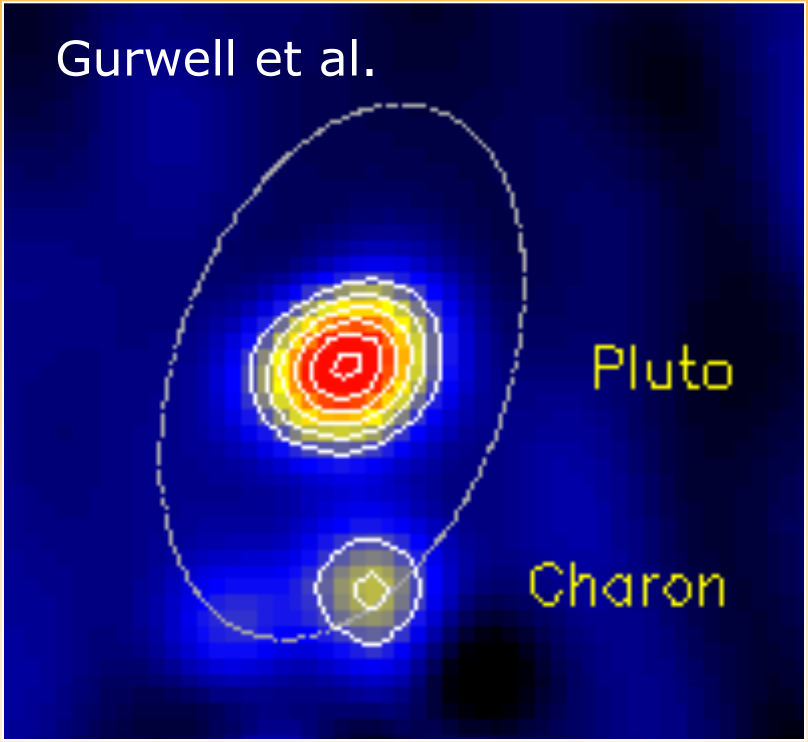
The Northern extended mm Array (NOEMA) Project

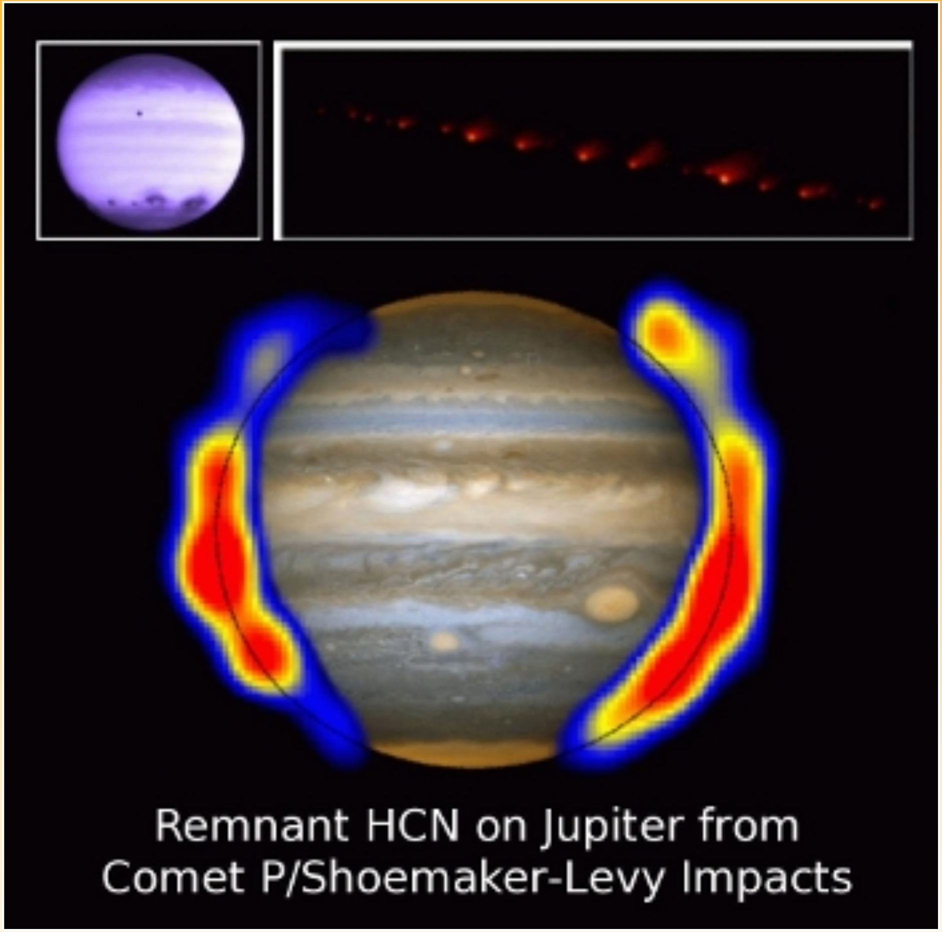


	Plateau de Bure 2012	NOEMA 2016	NOEMA 2018
Number of antennas	6	10	12
Track length	1200 m	1200 m	2000 m
Collecting surface	1 060 m^2	1 766 m^2	2 120 m^2
Best angular resolution	0.2 arc seconds	0.2 arc seconds	0.1 arc seconds
Bandwidth	120 GHz	1 440 GHz	2 112 GHz
Number of baselines	15	45	66

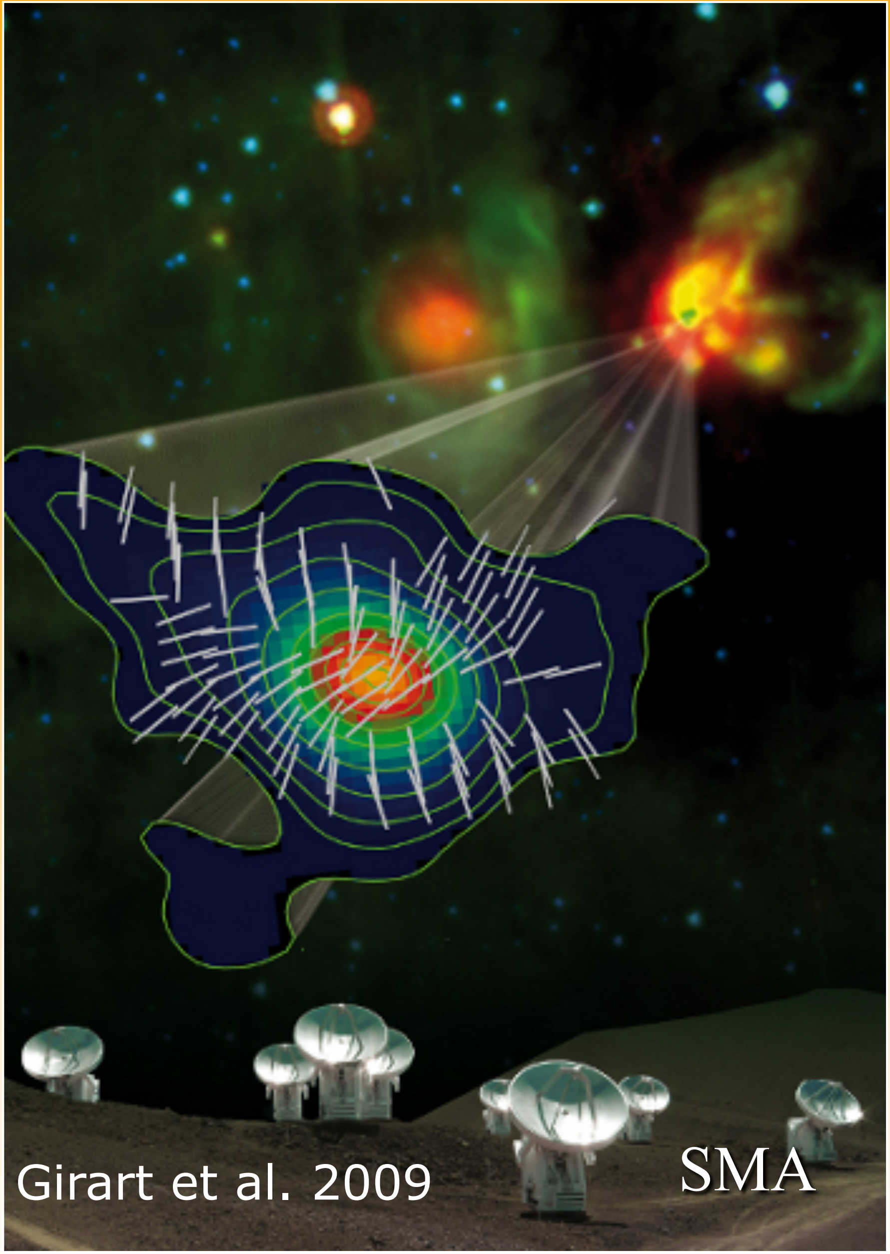
Some more scientific highlights if you are not too hungry yet …

Planetary science





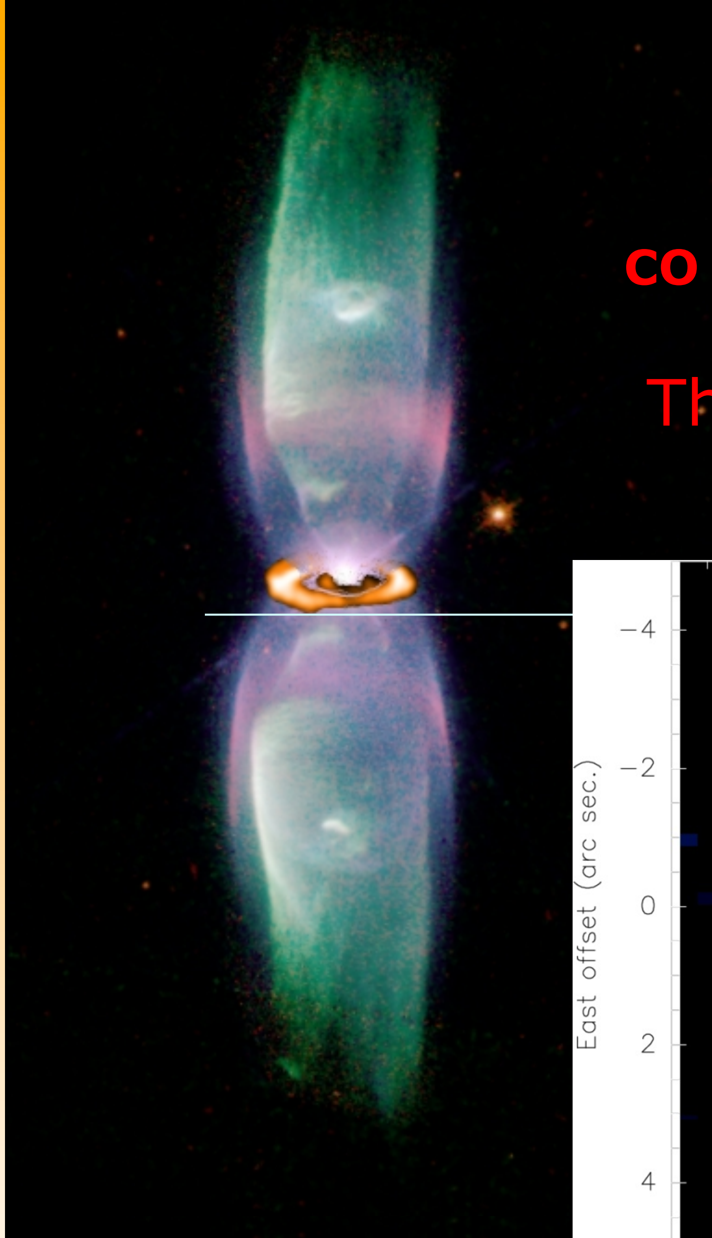
Map polaristion

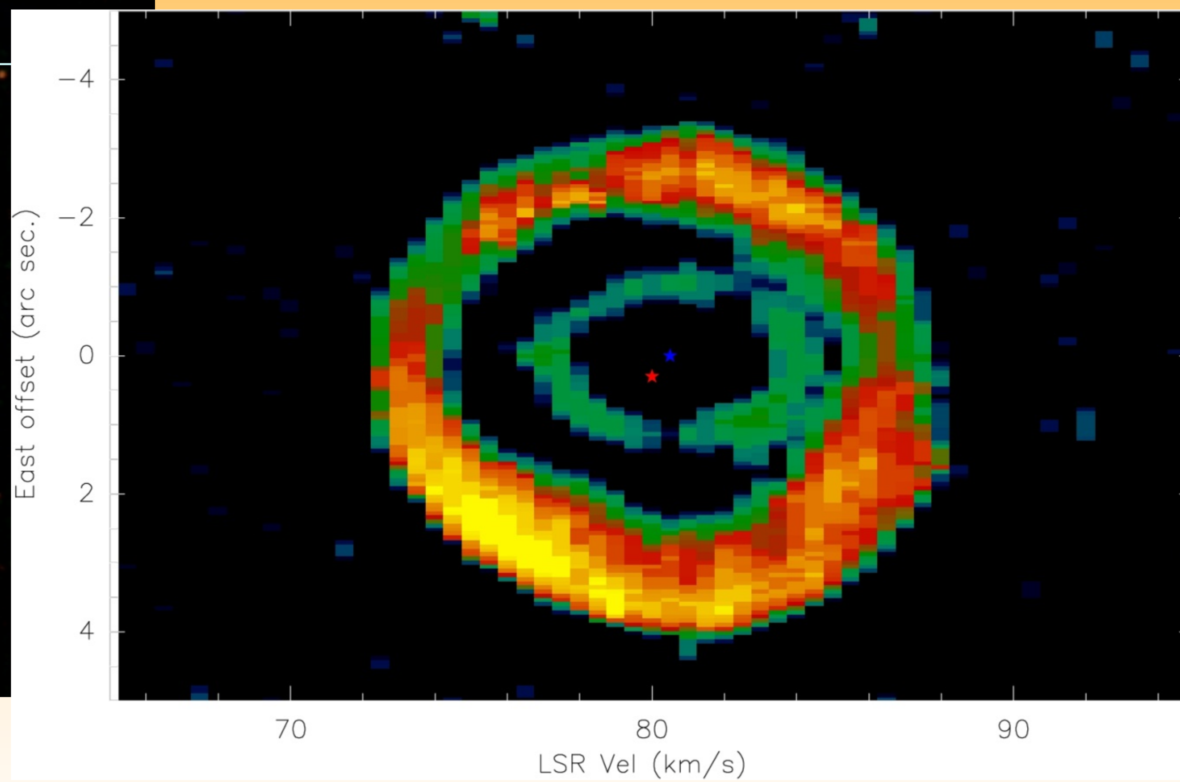


M 2-9

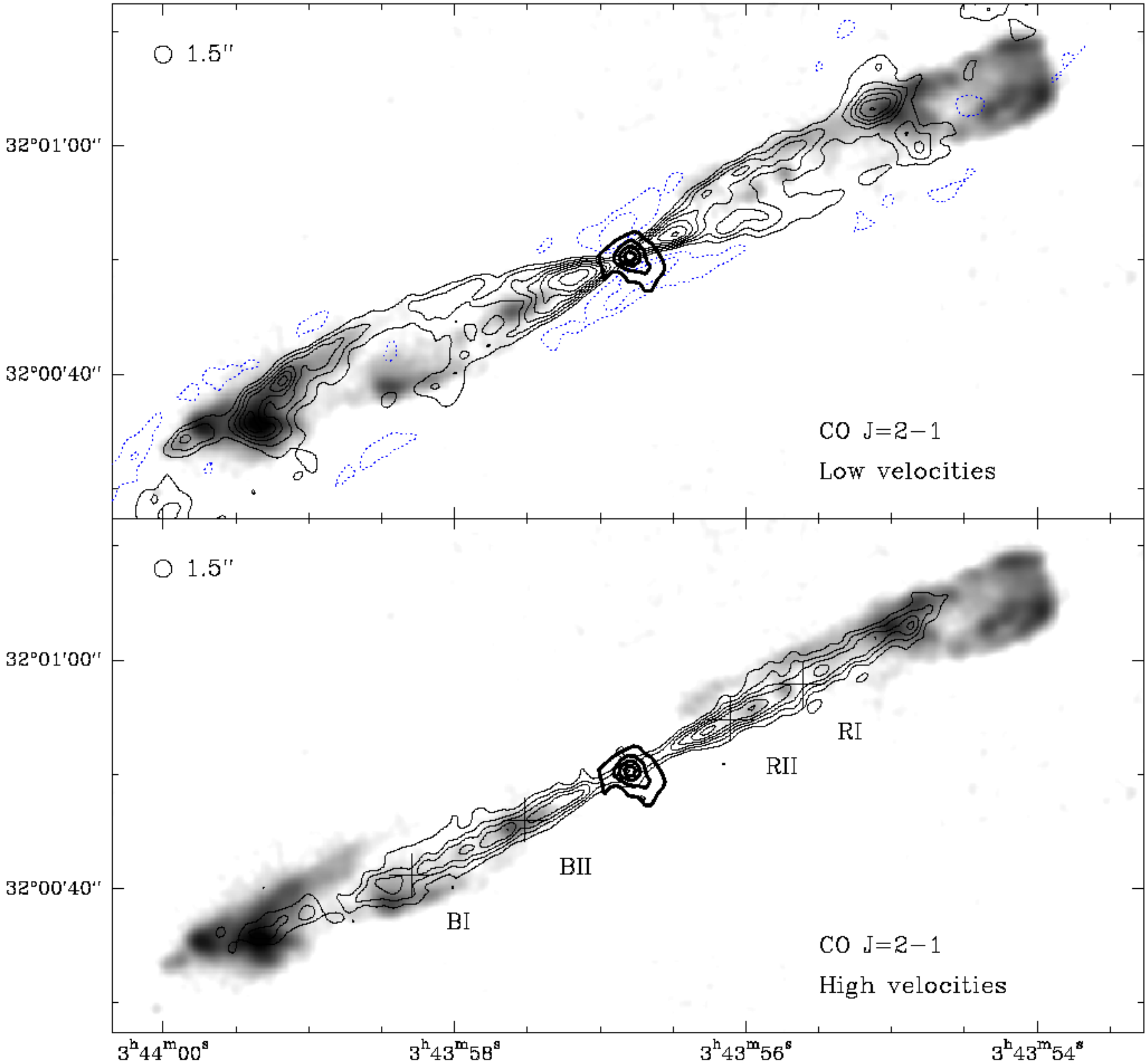
CO *J*=2-1….

The tight waist of the Butterfly nebula

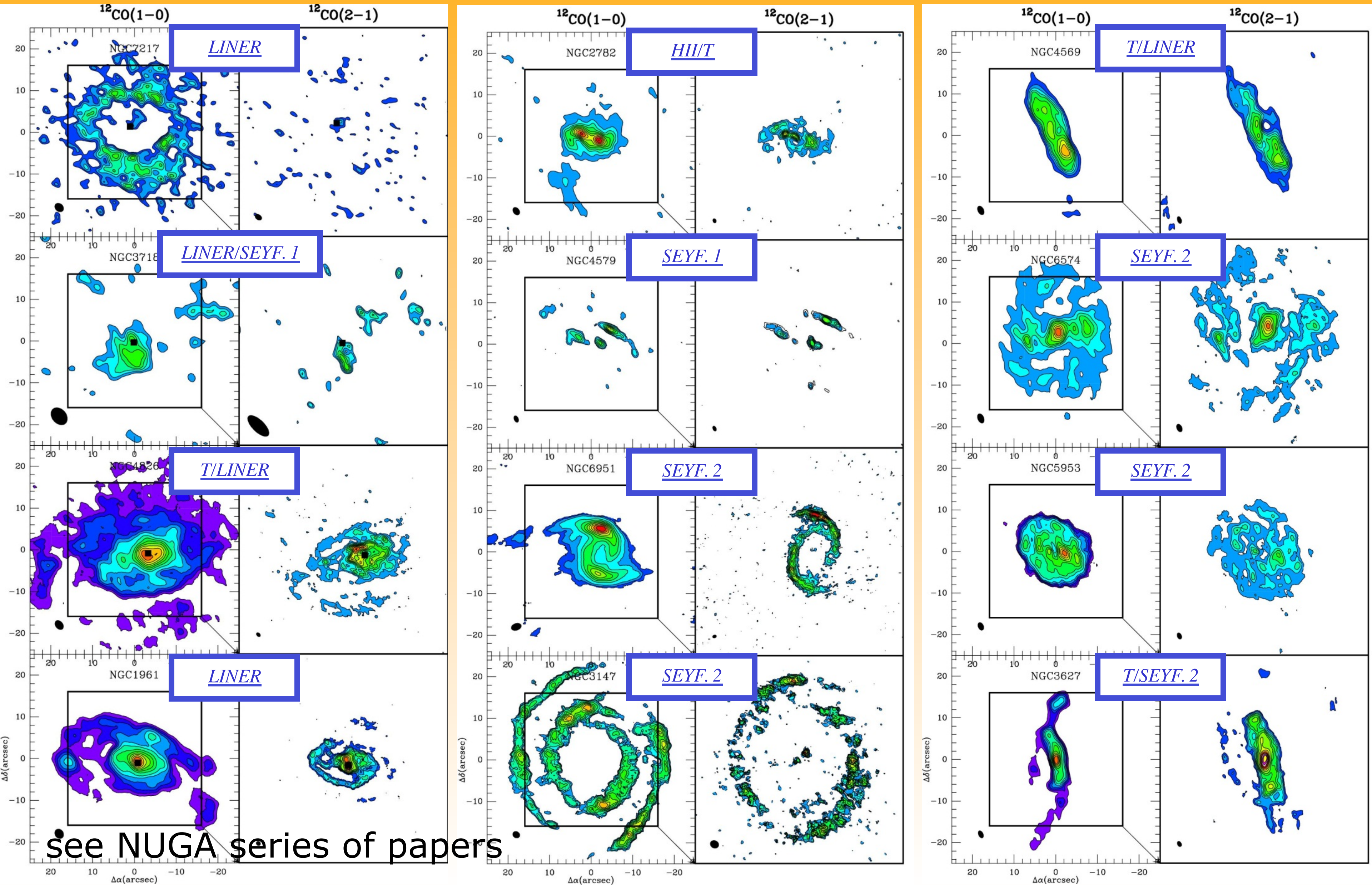




Castro-Carrizo et al.


○ 1.5″
32°01′00″
32°00′40″
CO J=2−1
Low velocities
○ 1.5″
32°01′00″
32°00′40″
RI
RII
BII
BI
CO J=2−1
High velocities
3h44m00s
3h43m58s
3h43m56s
3h43m54s

Study accretion mechanisms onto AGN



see NUGA series of papers

Massive dense cores (MDRs)

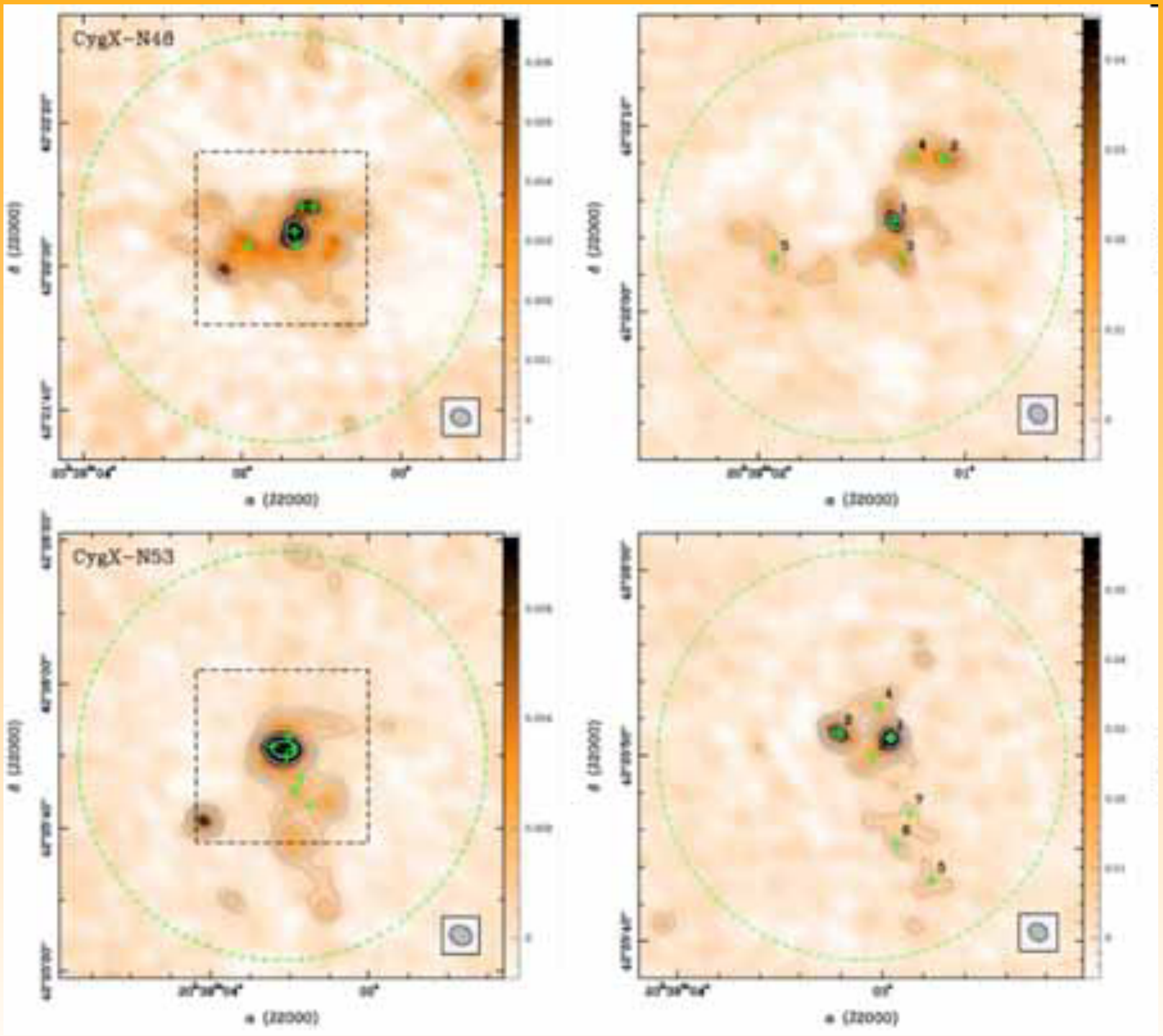
CygX-N48 (top) and

CygX-N53 (bottom)

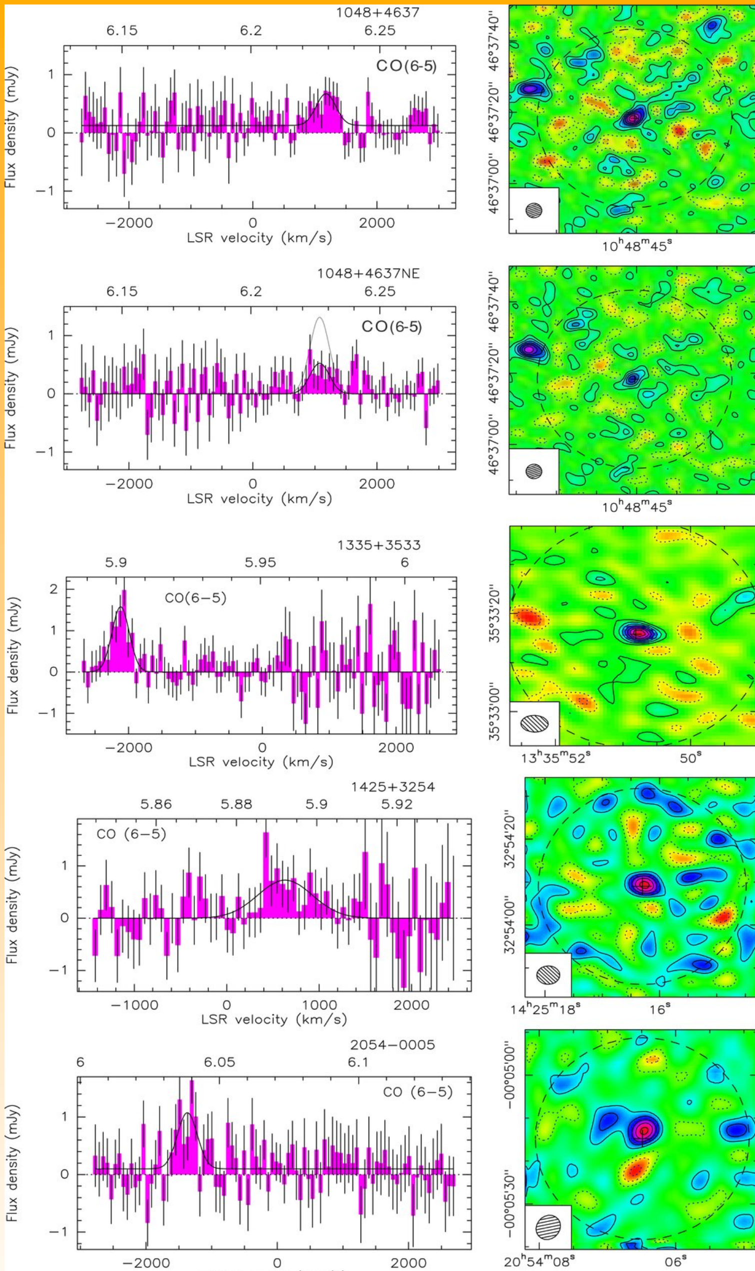
At 3.5mm (left) with one or two main cores in the central regions

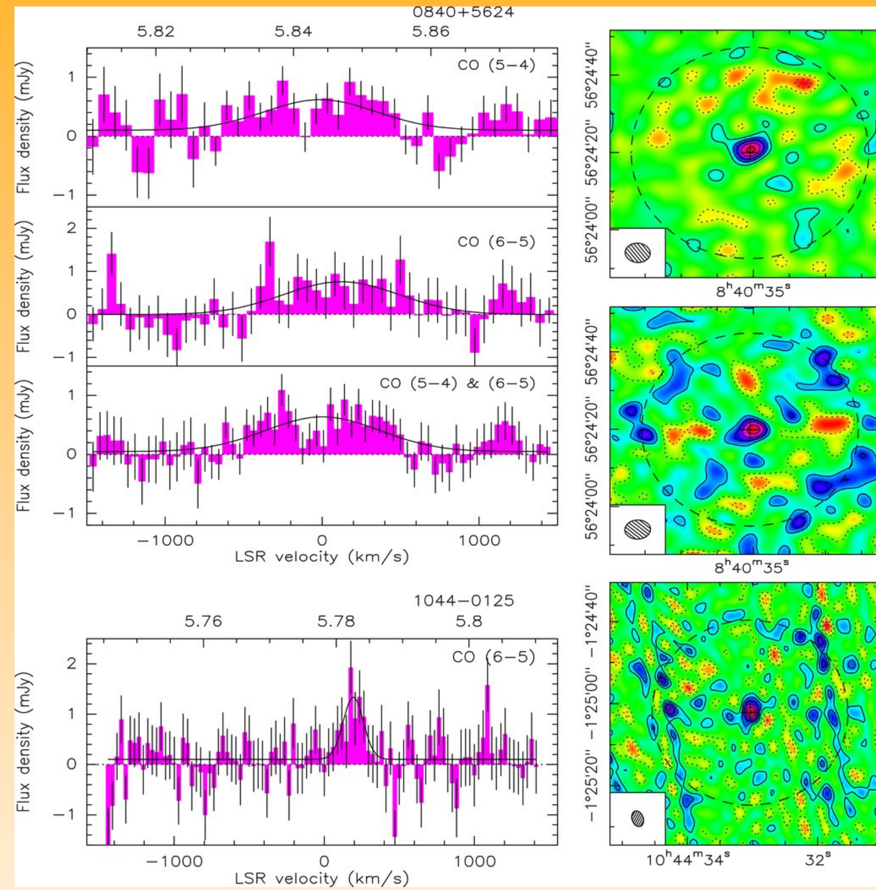
that divide into smaller fragments at 1.3mm (right).

From Bontemps et al. 2010, A&A 524, 18



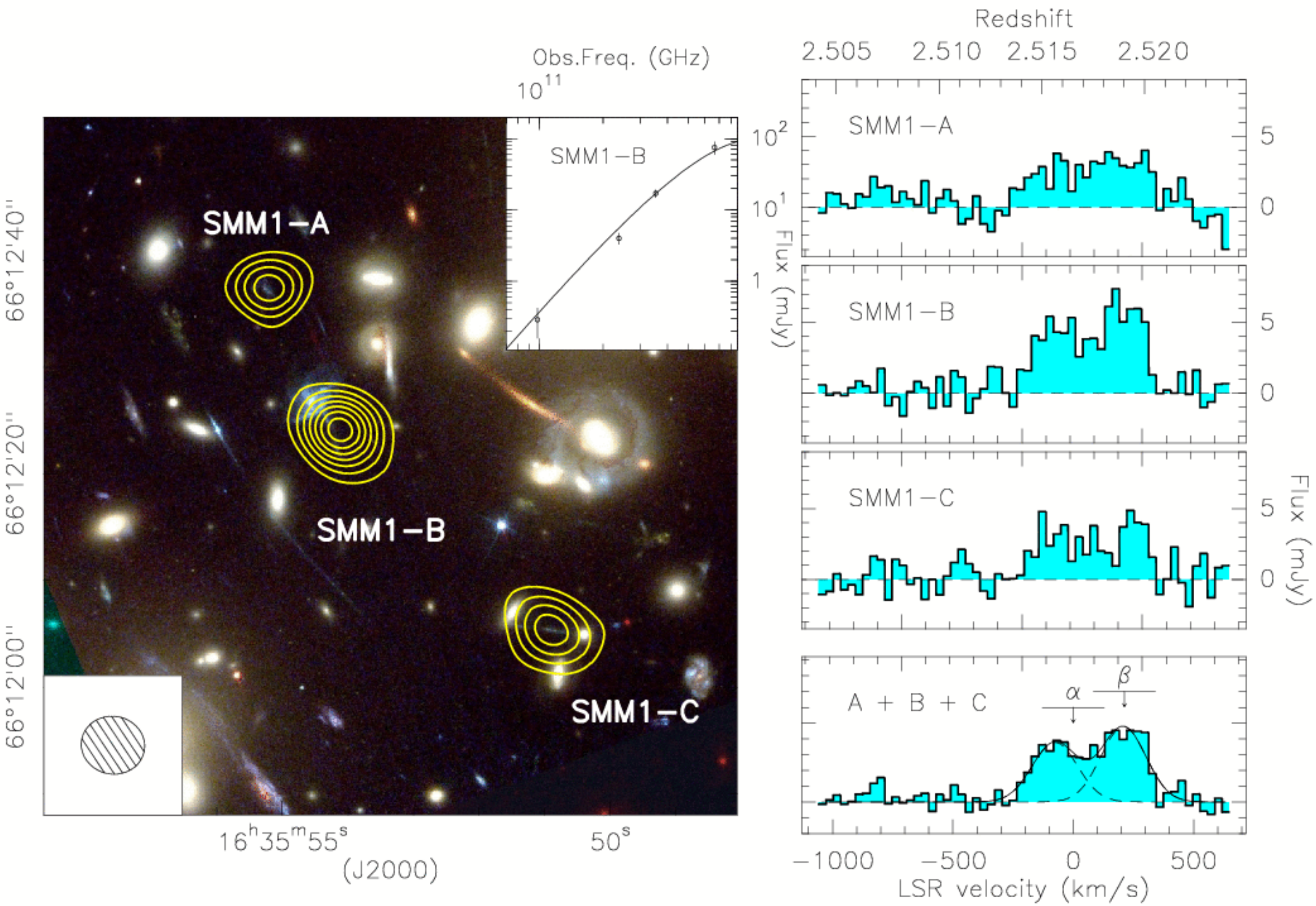
z = 6 QSOs





Wang et al. 2010

Gravitationally lensed sources……



Kneib et al. 2005

The End.

Thank you!