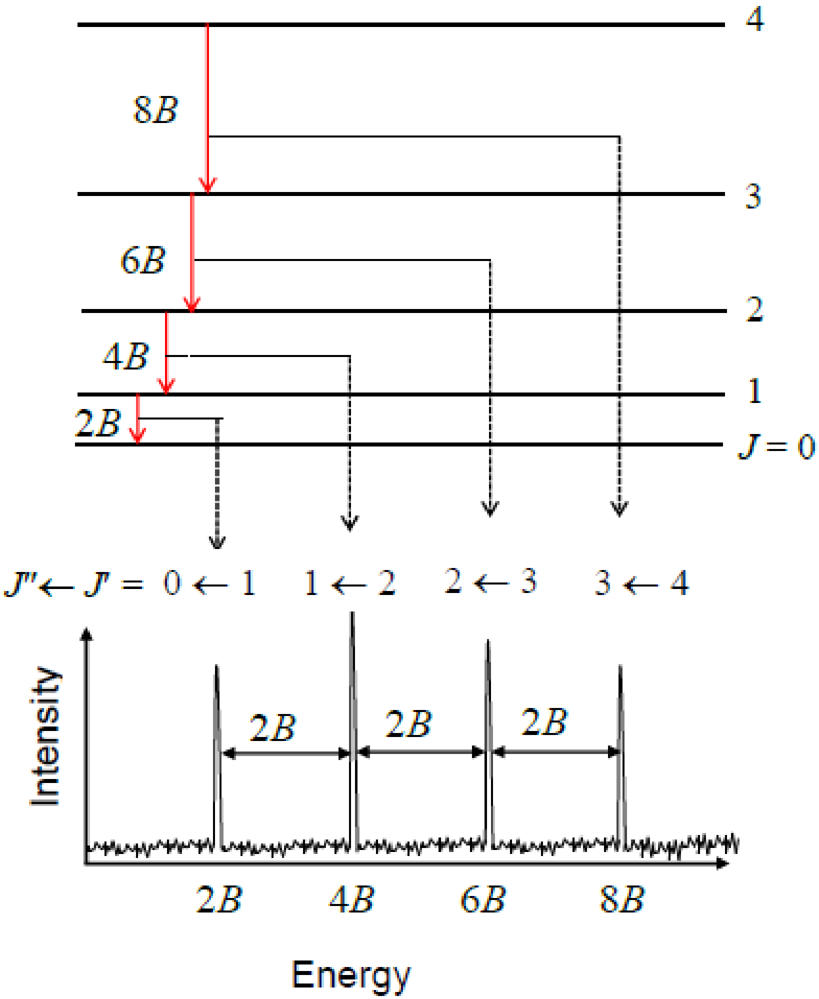
mm/sub-mm interferometry

Vincent Pietu
IRAM

Material from Melanie Krips, Michael Bremer, Frederic Gueth

Motivation

Rotation lines



- Quantification of angular momentum. Example for a linear molecule: rotational ladder.
- H2 difficult to excite, does not emit in cold environments.
- Second most abundant molecule is CO.

THE ASTROPHYSICAL JOURNAL, **161**:L43–L44, July 1970

CARBON MONOXIDE IN THE ORION NEBULA

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Crawford Hill Laboratory, Murray Hill, New Jersey

Received 1970 June 5

ABSTRACT

We have found intense 2.6-mm line radiation from nine galactic sources which we attribute to carbon monoxide.

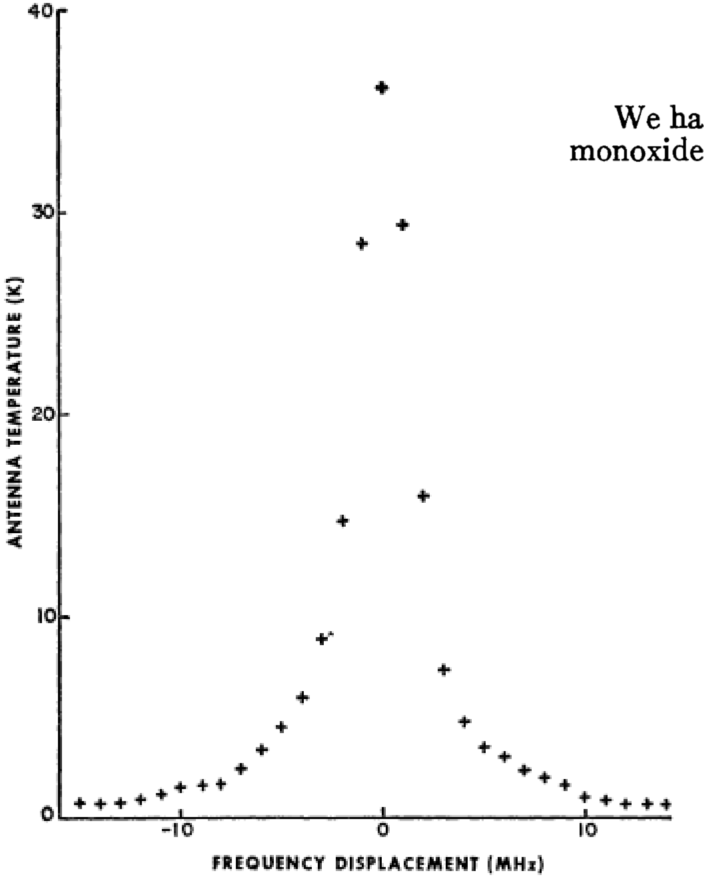


FIG. 1

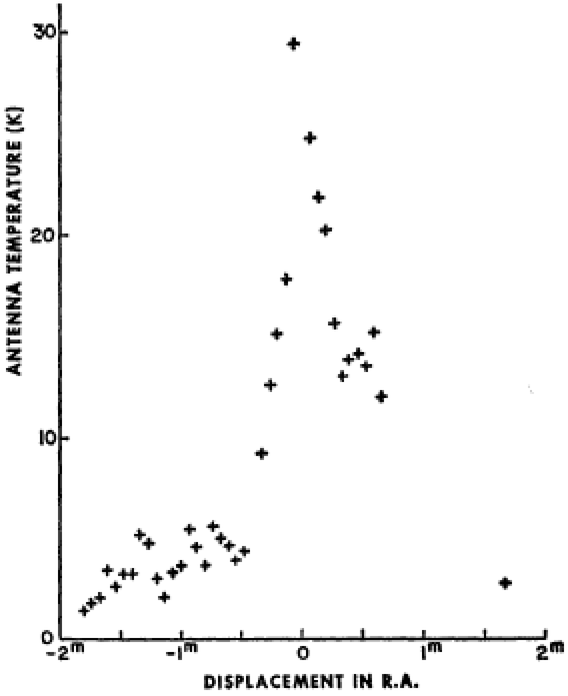
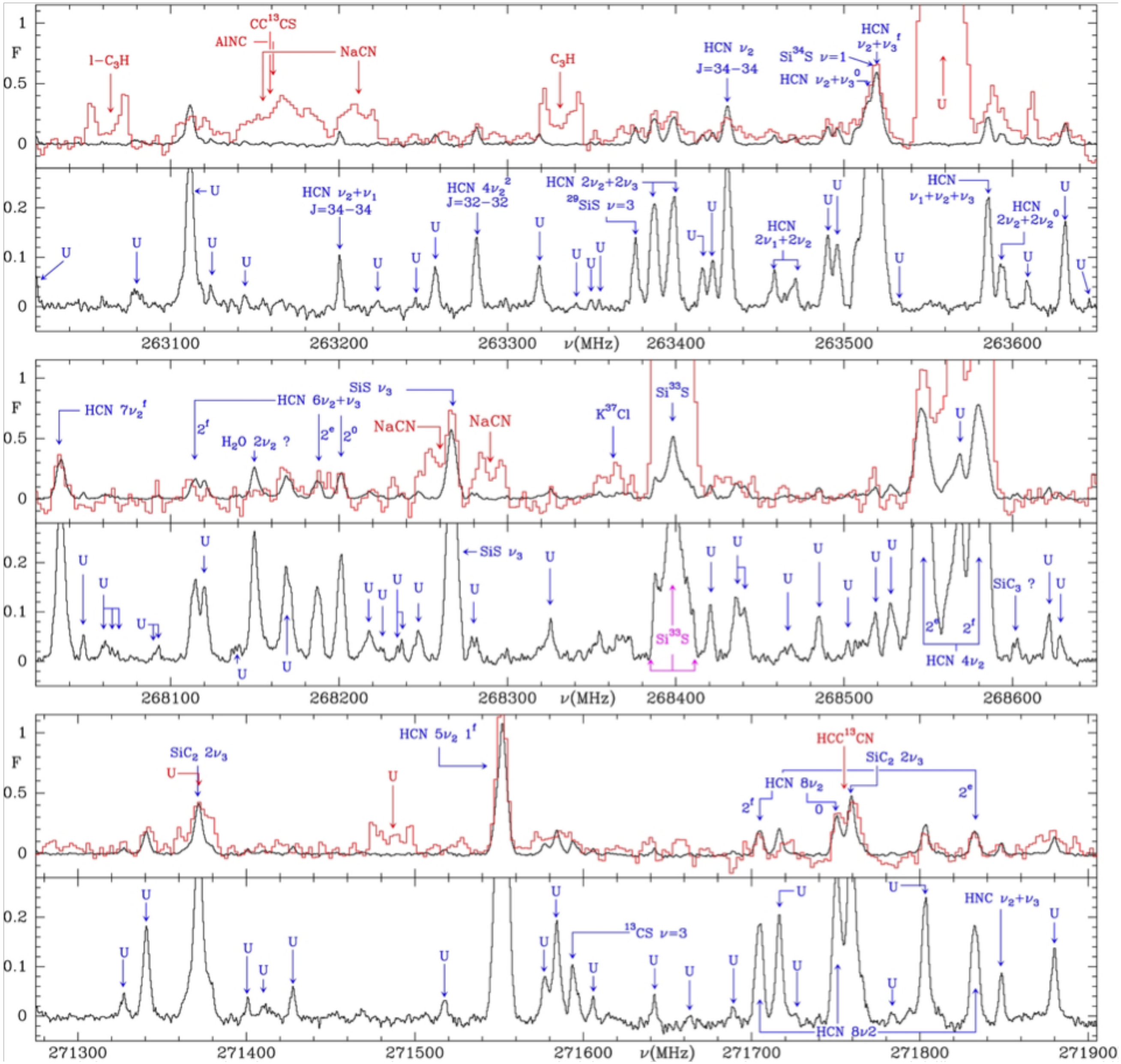


FIG. 2

FIG. 1.—Spectrum of CO radiation in the Orion Nebula made with the NRAO forty-channel line receiver. The center frequency is 115, 267.2 MHz.

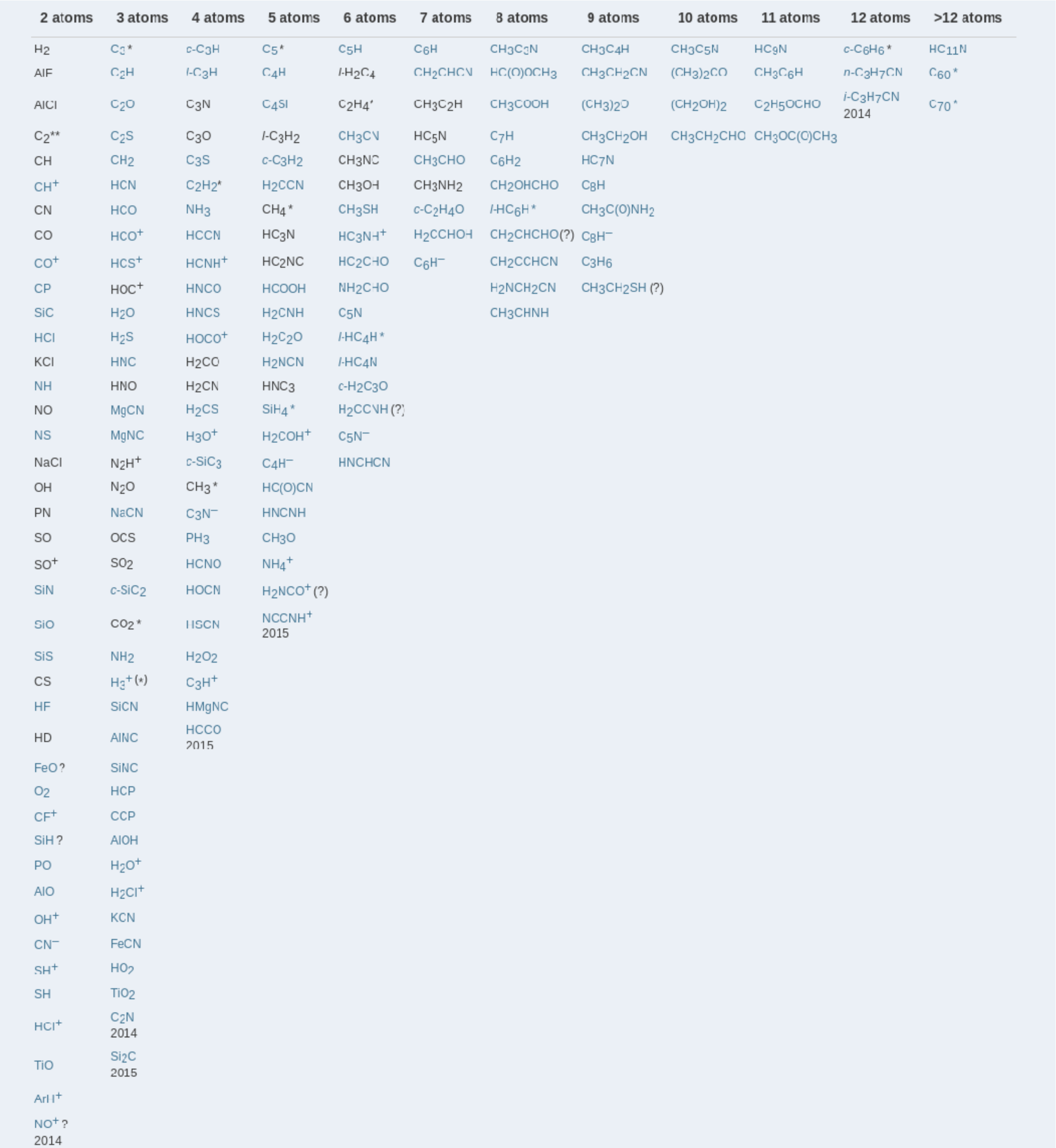
FIG. 2.—Distribution in right ascension of the peak antenna temperature of CO radiation at a declination of −5°24′21″.

Rotation lines



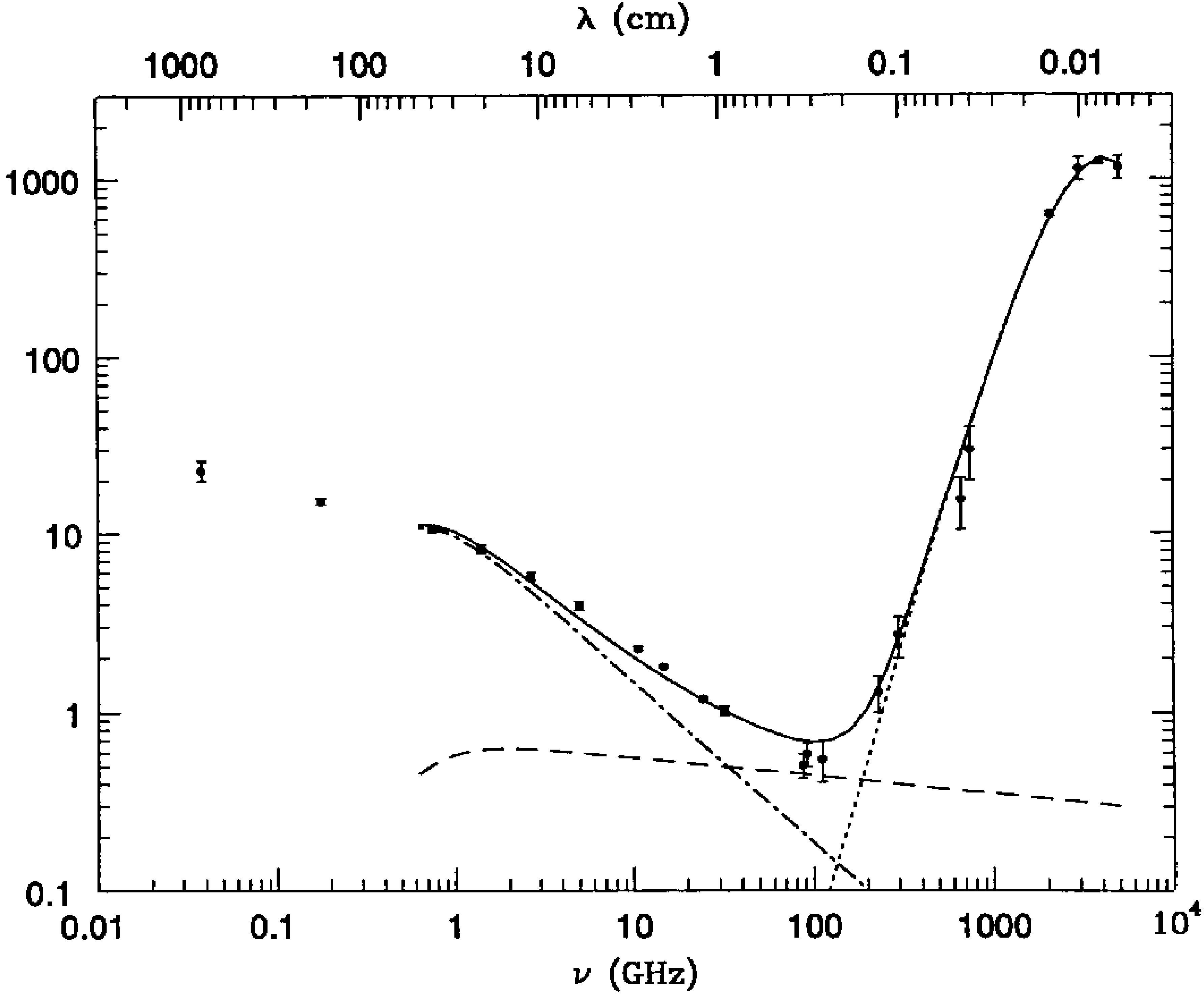
IRC+10216

- Mm spectrum full of molecular lines.
- Already many are unidentified (U)
- Interferometer helps beating the spectral confusion by resolving out emission from different regions.



2 atoms	3 atoms	4 atoms	5 atoms	6 atoms	7 atoms	8 atoms	9 atoms	10 atoms	11 atoms	12 atoms	>12 atoms
H_2	$C_3{}^*$	c-C_3H	$C_5{}^*$	C_5H	C_6H	CH_3C_3N	CH_3C_4H	CH_3C_5N	HC_9N	c-$C_6H_6{}^*$	$HC_{11}N$
AlF	C_2H	l-C_3H	C_4H	l-H_2C_4	CH_2CHCN	$HC(O)OCH_3$	CH_3CH_2CN	$(CH_3)_2CO$	CH_3C_6H	n-C_3H_7CN	$C_{60}{}^*$
AlCl	C_2O	C_3N	C_4Si	$C_2H_4{}^*$	CH_3C_2H	CH_3COOH	$(CH_3)_2O$	$(CH_2OH)_2$	C_2H_5OCHO	i-C_3H_7CN 2014	$C_{70}{}^*$
$C_2{}^{**}$	C_2S	C_3O	l-C_3H_2	CH_3CN	HC_5N	C_7H	CH_3CH_2OH	CH_3CH_2CHO	$CH_3OC(O)CH_3$		
CH	CH_2	C_3S	c-C_3H_2	CH_3NC	CH_3CHO	C_6H_2	HC_7N				
CH^+	HCN	$C_2H_2{}^*$	H_2CCN	CH_3OH	CH_3NH_2	CH_2OHCHO	C_8H				
CN	HCO	NH_3	$CH_4{}^*$	CH_3SH	c-C_2H_4O	l-$HC_6H{}^*$	$CH_3C(O)NH_2$				
CO	HCO^+	HCCN	HC_3N	HC_3NH^+	H_2CCHOH	CH_2CHCHO(?)	C_8H^-				
CO^+	HCS^+	$HCNH^+$	HC_2NC	HC_2CHO	C_6H^-	CH_2CCHCN	C_3H_6				
CP	HOC^+	HNCO	HCOOH	NH_2CHO		H_2NCH_2CN	CH_3CH_2SH (?)				
SiC	H_2O	HNCS	H_2CNH	C_5N		CH_3CHNH					
HCl	H_2S	$HOCO^+$	H_2C_2O	l-$HC_4H{}^*$							
KCl	HNC	H_2CO	H_2NCN	l-HC_4N							
NH	HNO	H_2CN	HNC_3	c-H_2C_3O							
NO	MgCN	H_2CS	$SiH_4{}^*$	H_2CCNH (?)							
NS	MgNC	H_3O^+	H_2COH^+	C_5N^-							
NaCl	N_2H^+	c-SiC_3	C_4H^-	HNCHCN							
OH	N_2O	$CH_3{}^*$	HC(O)CN								
PN	NaCN	C_3N^-	HNCNH								
SO	OCS	PH_3	CH_3O								
SO^+	SO_2	HCNO	$NH_4{}^+$								
SiN	c-SiC_2	HOCN	H_2NCO^+ (?)								
SiO	$CO_2{}^*$	HSCN	$NCCNH^+$ 2015								
SiS	NH_2	H_2O_2									
CS	$H_3{}^+\ (*)$	C_3H^+									
HF	SiCN	HMgNC									
HD	AlNC	HCCO 2015									
FeO ?	SiNC										
O_2	HCP										
CF^+	CCP										
SiH ?	AlOH										
PO	H_2O^+										
AlO	H_2Cl^+										
OH^+	KCN										
CN^-	FeCN										
SH^+	HO_2										
SH	TiO_2										
HCl^+	C_2N 2014										
TiO	Si_2C 2015										
ArH^+											
NO^+ ? 2014											

http://www.astro.uni-koeln.de/cdms/molecules


λ (cm)
1000
100
10
1
0.1
0.01
1000
100
10
1
0.1
S (Jy)
0.01
0.1
1
10
100
1000
10^4
ν (GHz)

Why do we need sensitivity

- For studying faint objects:
  - “normal” galaxies at cosmological distances
  - “faint” protoplanetary disks
- For detecting faint lines
  - Aminoacids for example

- But also because we want high angular resolution. Brightness sensitivity goes as $1/\theta^2$.

Sensitivity

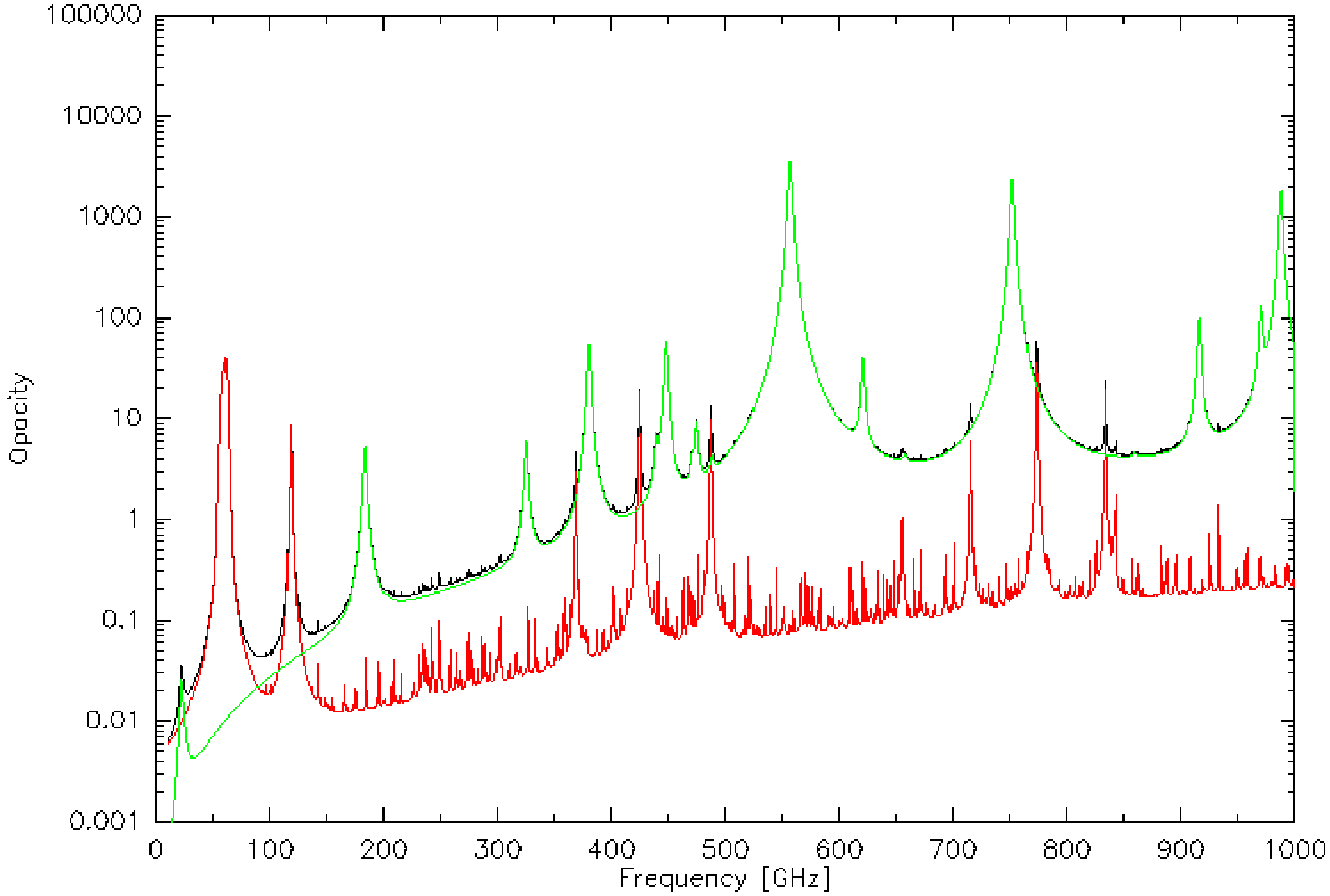
Sensitivity

$$\delta S_\nu = \frac{JT_{sys}}{\eta\sqrt{n.(n-1)\Delta\nu\Delta t}}$$

- Lowering Tsys.
- Improving antenna efficiency
  - Larger antennas
  - Better antenna surfaces
- More antennas
- Larger bandwith

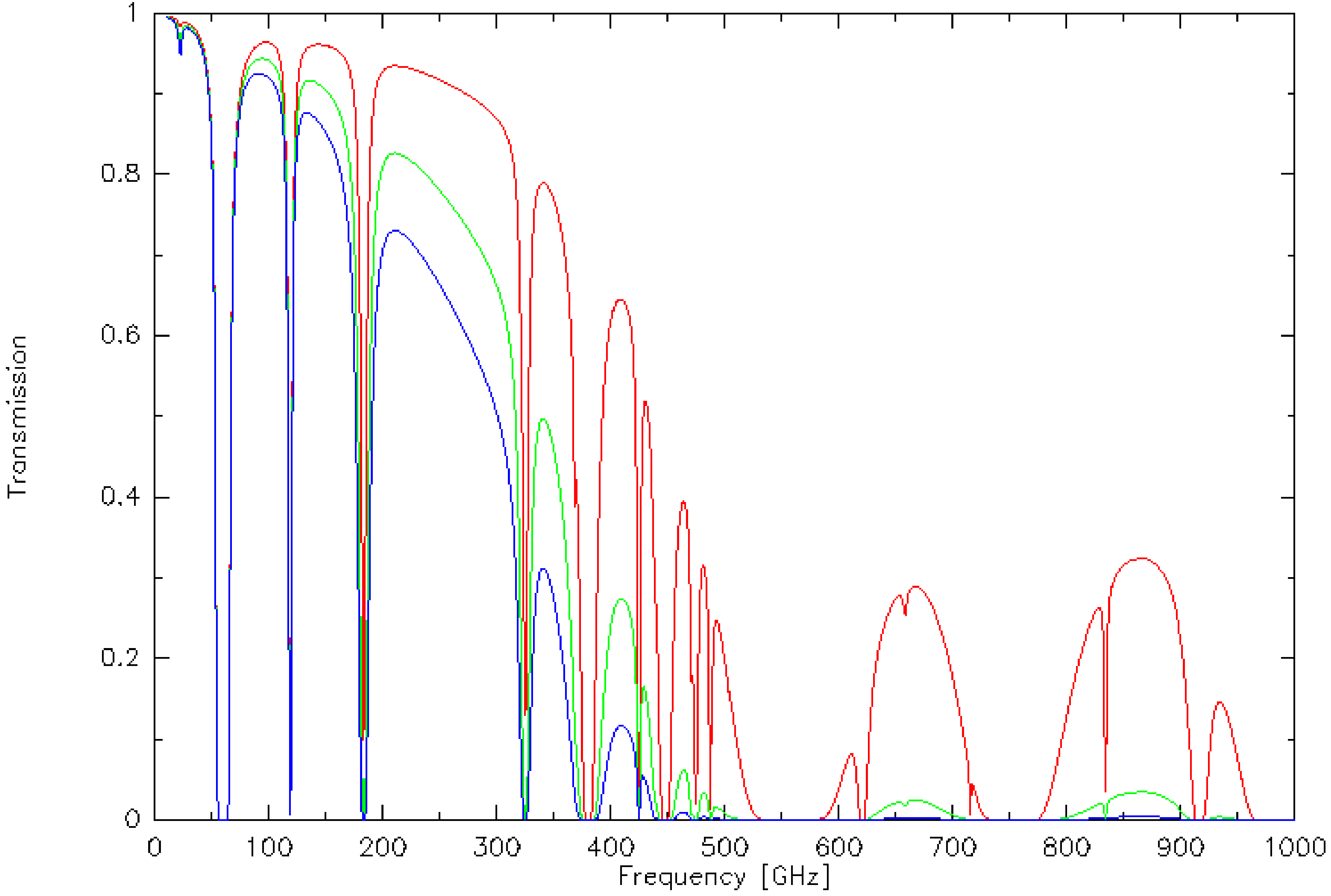
Atmosphere

- Atmospheric lines: mainly H2O, O2, O3 in the mm/sub-mm range



Atmospheric model ATM (Pardo et al.)

Atmospheric “windows”



Radiative transfer

Radiative transfer equation

$$\begin{aligned} I_\nu(l) &= I_\nu(0)\exp\left[-\int_0^l \kappa_\nu(l')\mathrm{d}l'\right] + \int_0^l \epsilon_\nu(l')\exp\left[-\int_l^{l'} \kappa_\nu(s)\mathrm{d}l'\right]\mathrm{d}l \\ I_\nu(\tau_\nu) &= I_\nu(0)\exp(-\tau_\nu) + \int_0^{\tau_\nu} S_\nu(\tau')\exp[-(\tau_\nu - \tau'_\nu)]\mathrm{d}\tau'_\nu \end{aligned}$$

Or:

$$I_\nu = I_{bg}\exp(-\tau) + (1 - \exp(-\tau))S_\nu$$

Temperatures

Planck function: $B_\nu(T) = \frac{2\mathrm{h}\nu^3}{c^2}\frac{1}{e^{-\frac{\mathrm{h}\nu}{\mathrm{k}T}} - 1}$

Rayleigh-Jeans $I_\nu = T\frac{2\mathrm{k}\nu^2}{c^2}$

Brigthness temperature: $T_b = I_\nu \times \frac{c^2}{2\mathrm{k}\nu^2}$

Optically thick emission: $T_b = T_k$

Optically thin emission $T_b = \tau.T_k$

System temperature

$$\begin{aligned} T_{ant} &= T_{bg} \\ &+ T_{sky} \sim \eta_f (1 - \exp(-\tau_{atm}) T_{atm} \\ &+ T_{spill} \sim (1 - \eta_f - \eta_{loss}) T_{ground} \\ &+ T_{loss} \sim \eta_{loss} T_{cabin} \\ &+ T_{rec} \end{aligned}$$

- At mm wavelength, we are dominated by the atmosphere.
- 35K < Trec < 100 K
- Taking into account receiver rejection and refering to a perfect antenna outside atmosphere, one gets:

$$T_{sys} = (1+g) \frac{\exp(\tau_{atm})}{\eta_f} T_{ant}$$

- Opacity correction allows to have sources on a scale proportional to their intensities (no more elevation dependant)

Solution: get rid of water vapor

- Atmospheric scale height:
  - Dry air: 8.4 km
  - Water vapor: 2 km

- Solution: go to a dry high altitude site:
  - ALMA: Chajnantor (5000 m)
  - SMA: Mauna Kea (4000 m)
  - NOEMA: (2500 m)

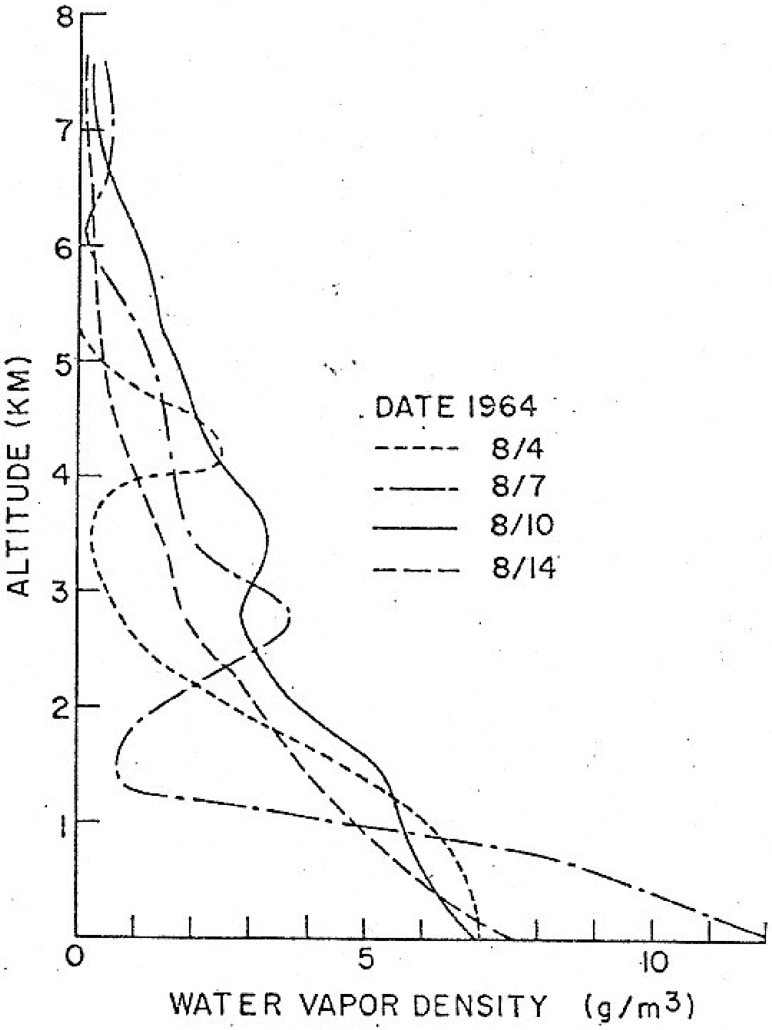


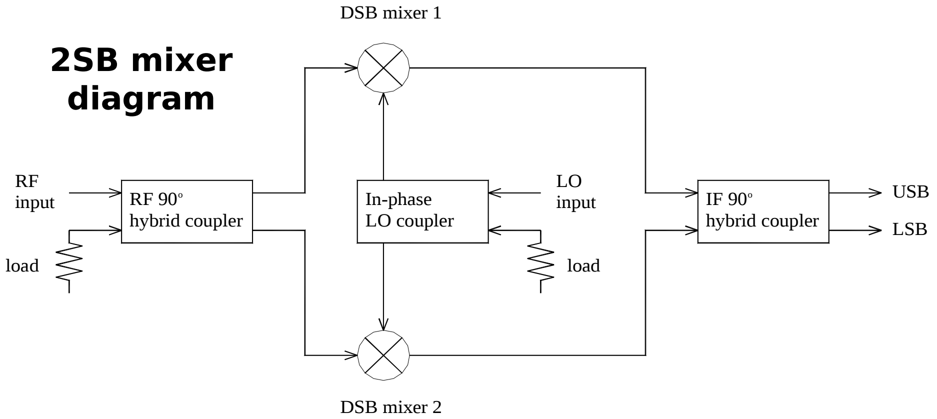
Fig. 3. Atmospheric water vapor profiles measured by radiosondes.

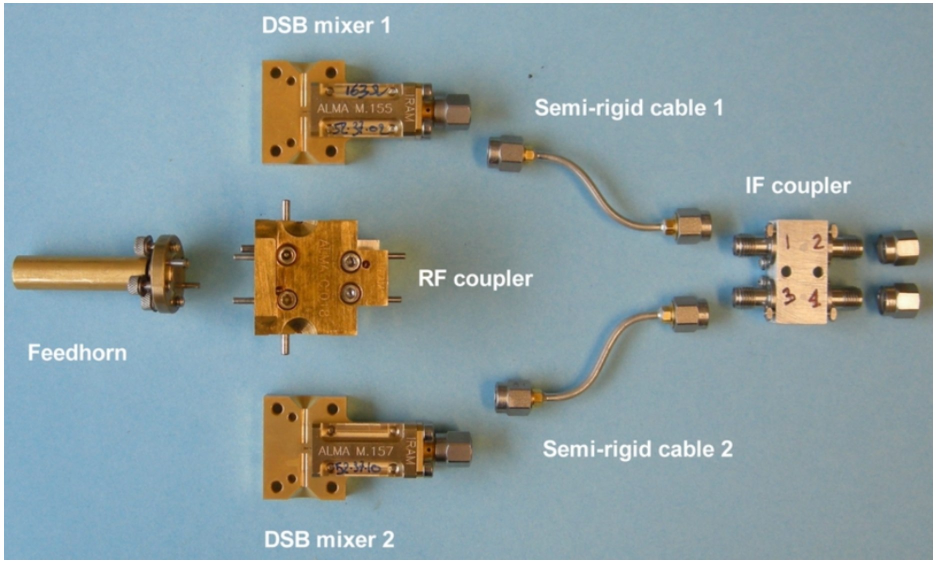
Receiver

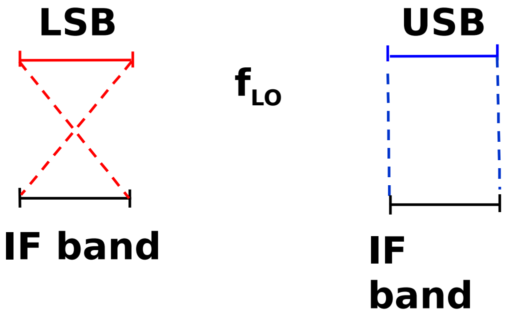
- High frequencies are not suited for a direct processing: needs a (frequency) down-conversion
  - Cm: amplify then down-convert
  - Mm: down-convert then amplify
- Technologies:
  - SIS mixers: needs a 4 K cooling, 2 times 8 GHz bandwidth
  - HEMT: direct amplification, 15 K sufficient. Bw up to 30%
  - HEB: 4 K cooling, up to Thz frequencies, 4 GHz bandwidth

Sideband

2SB mixer diagram



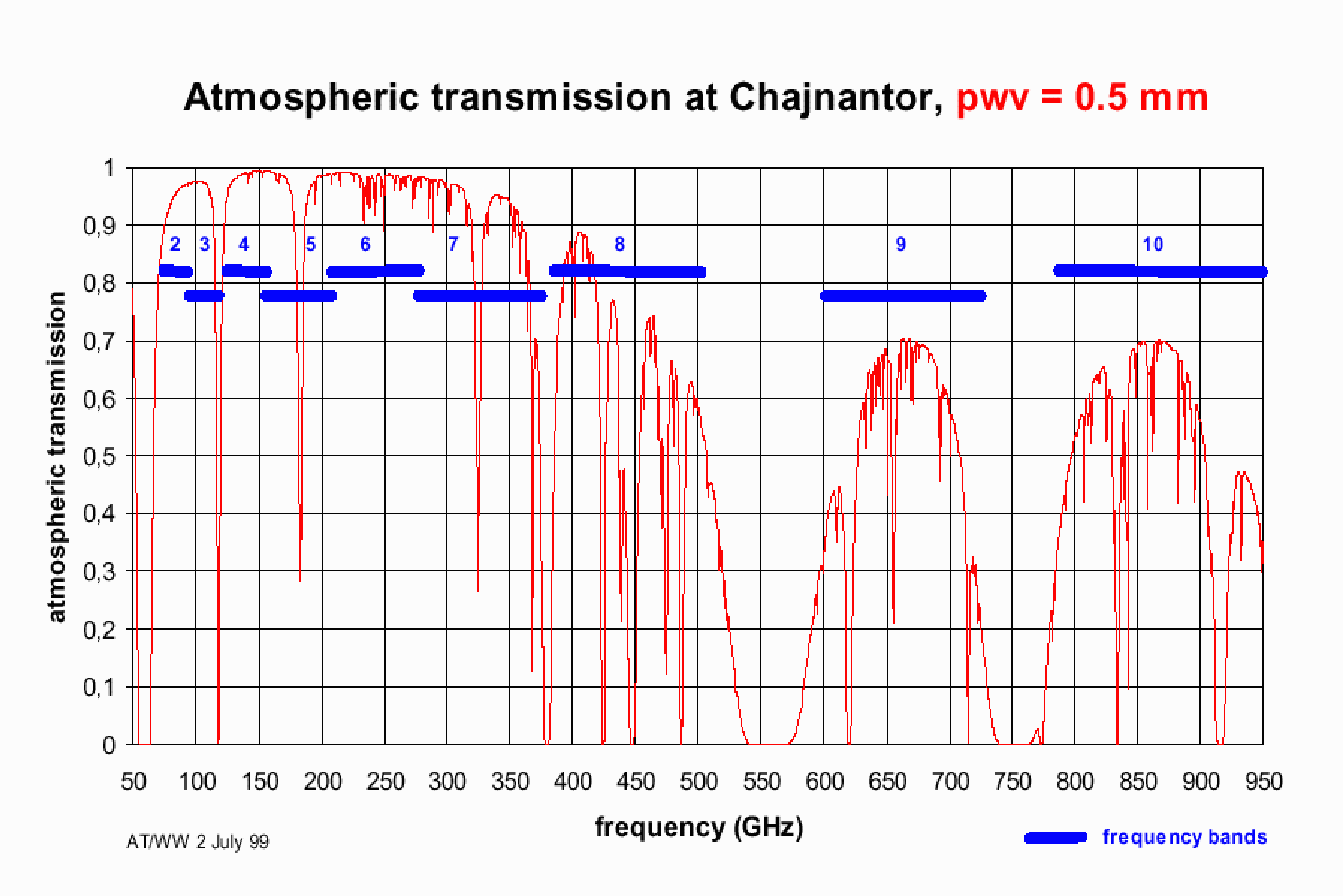




- DSB: both sidebands superimposed after downconversion
- SSB: one sideband is suppressed
- 2SB: sidebands are separated

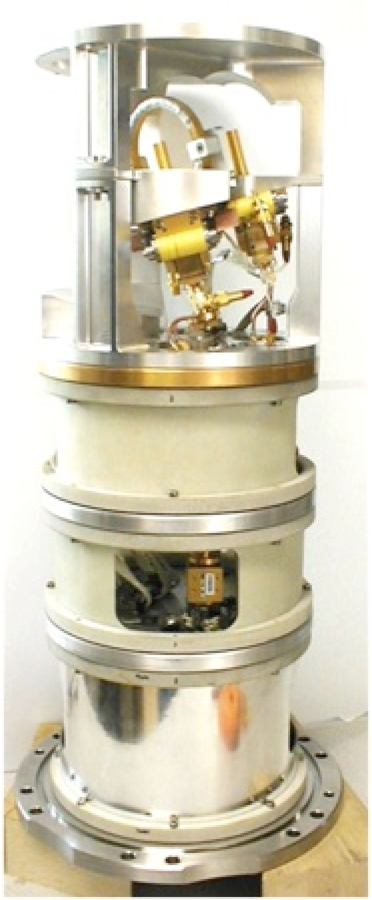
- SSB have typically factor 2 lower system temperatures.
- In interferometry, phase control allows separation (walsh switching)/suppression (LO offseting) of signal from image sideband

ALMA receivers



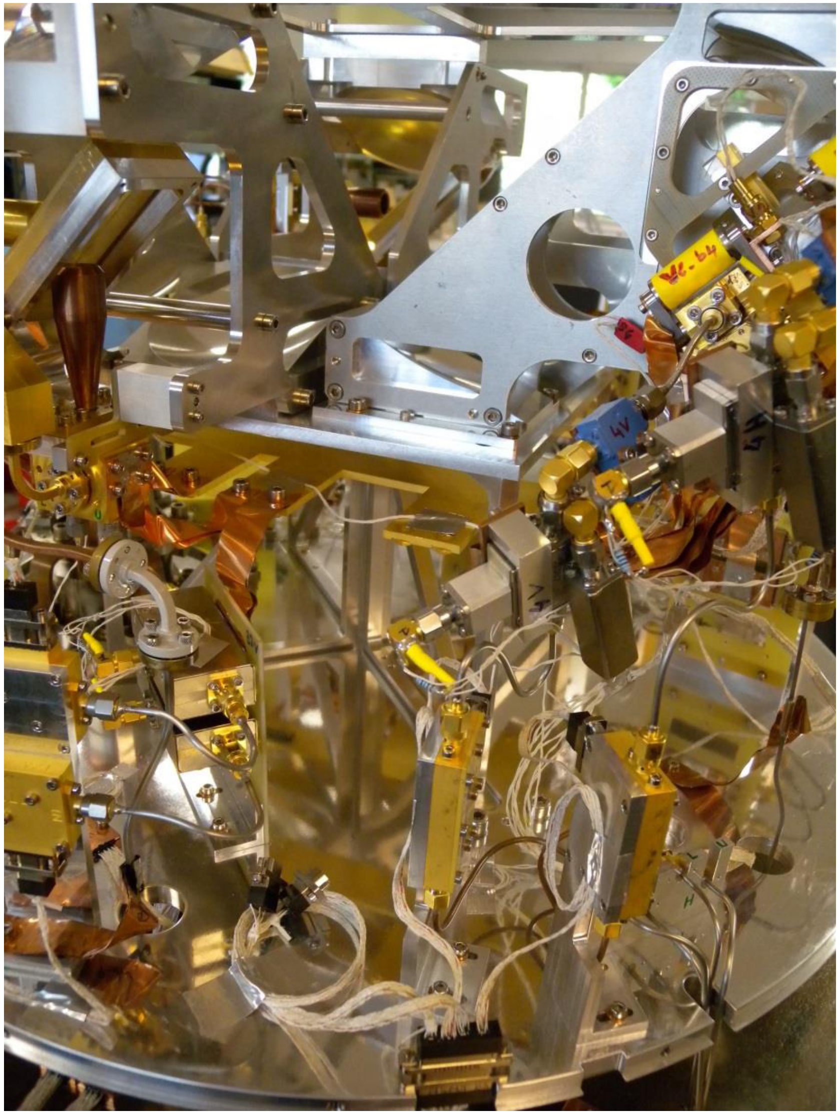
ALMA Receivers

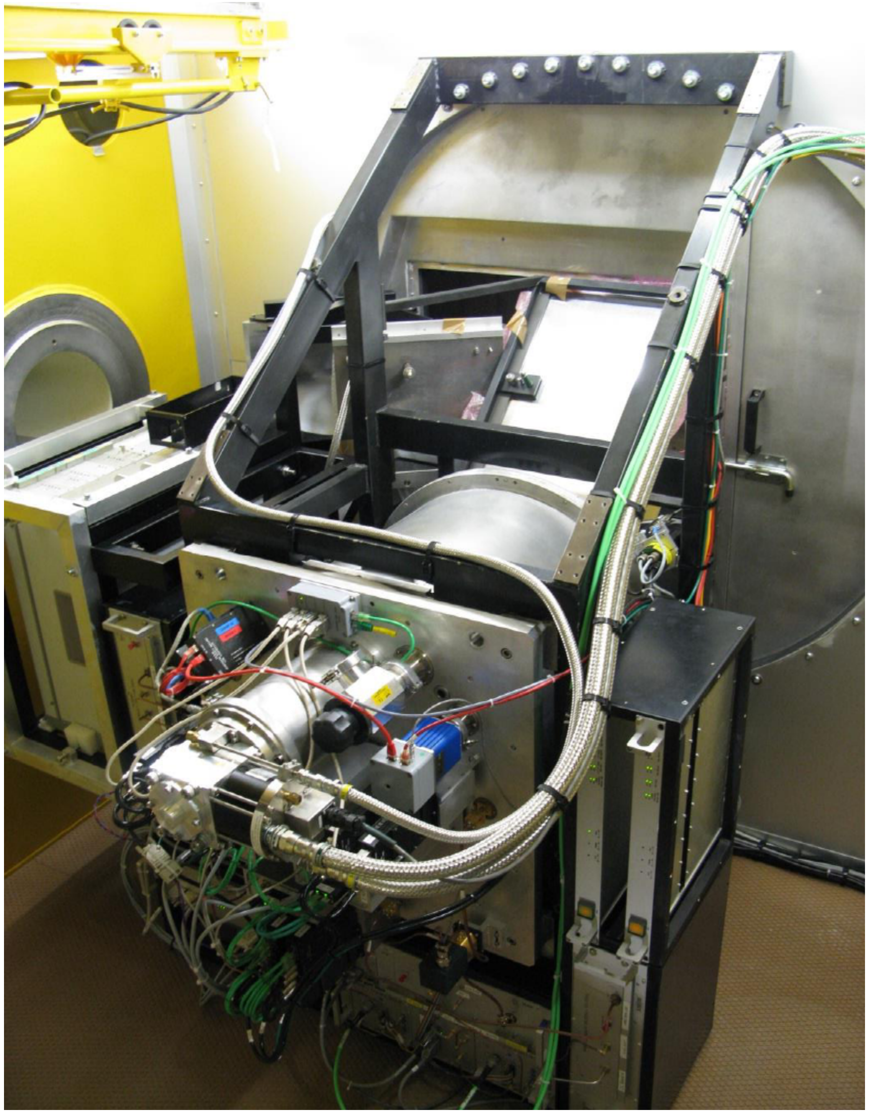
- Receiver Bands currently installed on all antennas:
  - Band 3: 3 mm (84-116 GHz)
  - Band 6: 1 mm (211-275 GHz)
  - Band 7: 850 µm (275-370 GHz)
  - Band 9: 450 µm (602-720 GHz)
  - Band 4: 2 mm (125-163 GHz)
  - Band 8: 650 µm (385-500 GHz)
  - Band 10: 350 µm band (787-950 GHz)



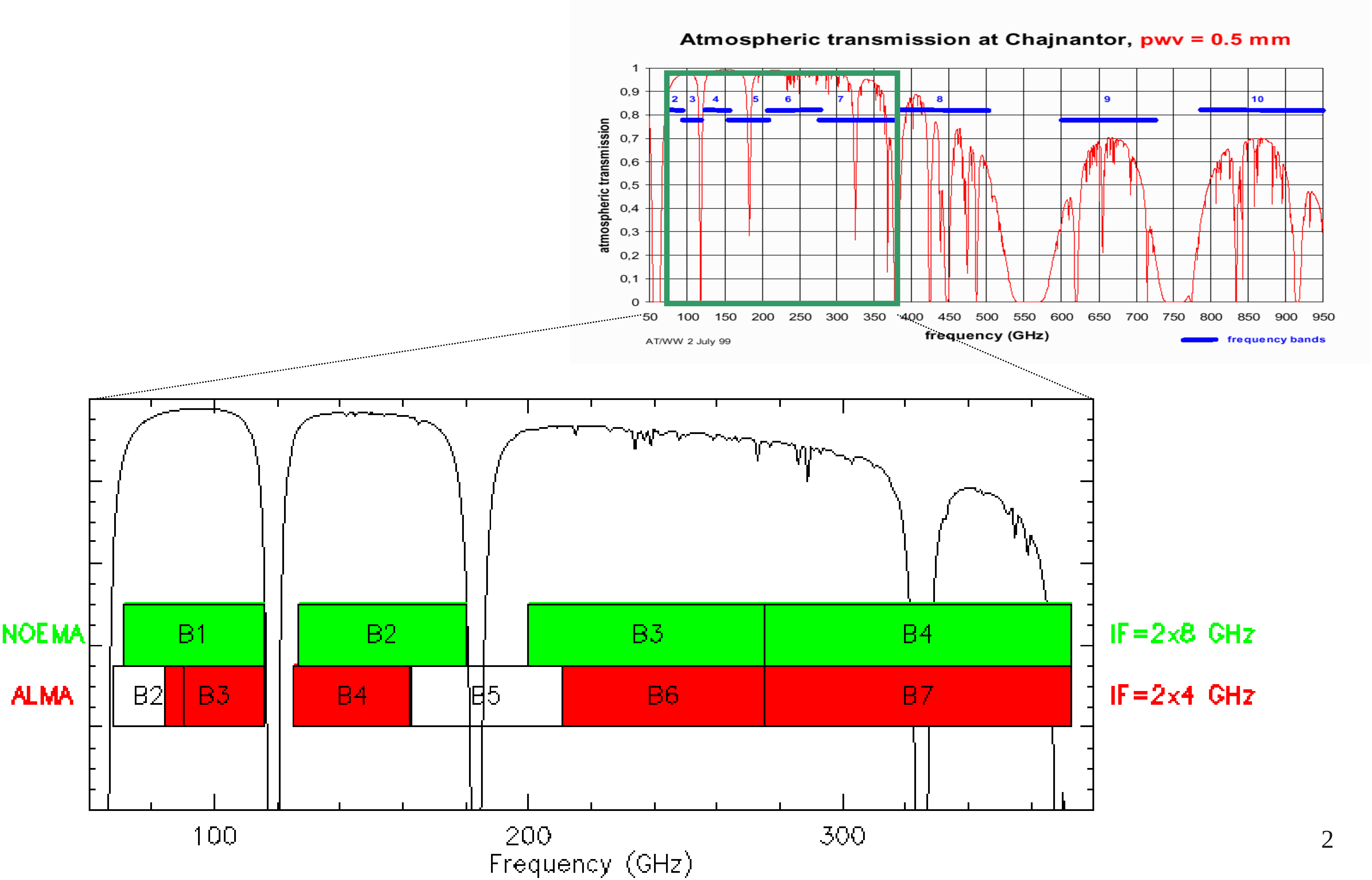
- All receivers **8 GHz bandwidth x 2 polar**.

NOEMA Receivers





NOEMA receivers



Sensitivity

$$\delta S_\nu = \frac{JT_{sys}}{\eta\sqrt{n.(n-1)\Delta\nu\Delta t}}$$

- Lowering Tsys.
- Improving antenna efficiency
  - Larger antennas
  - Better antenna surfaces
- More antennas
- Larger bandwith

Antenna efficiency

- Antenna efficiency (Jy/K) is the reverse of

$$J = \frac{2\mathrm{k}}{A_{eff}} = \frac{2\mathrm{k}}{\eta_A A}$$

- Solution: larger antenna
- But this is:
  - Difficult
  - Costly
  - Reduce the field of view

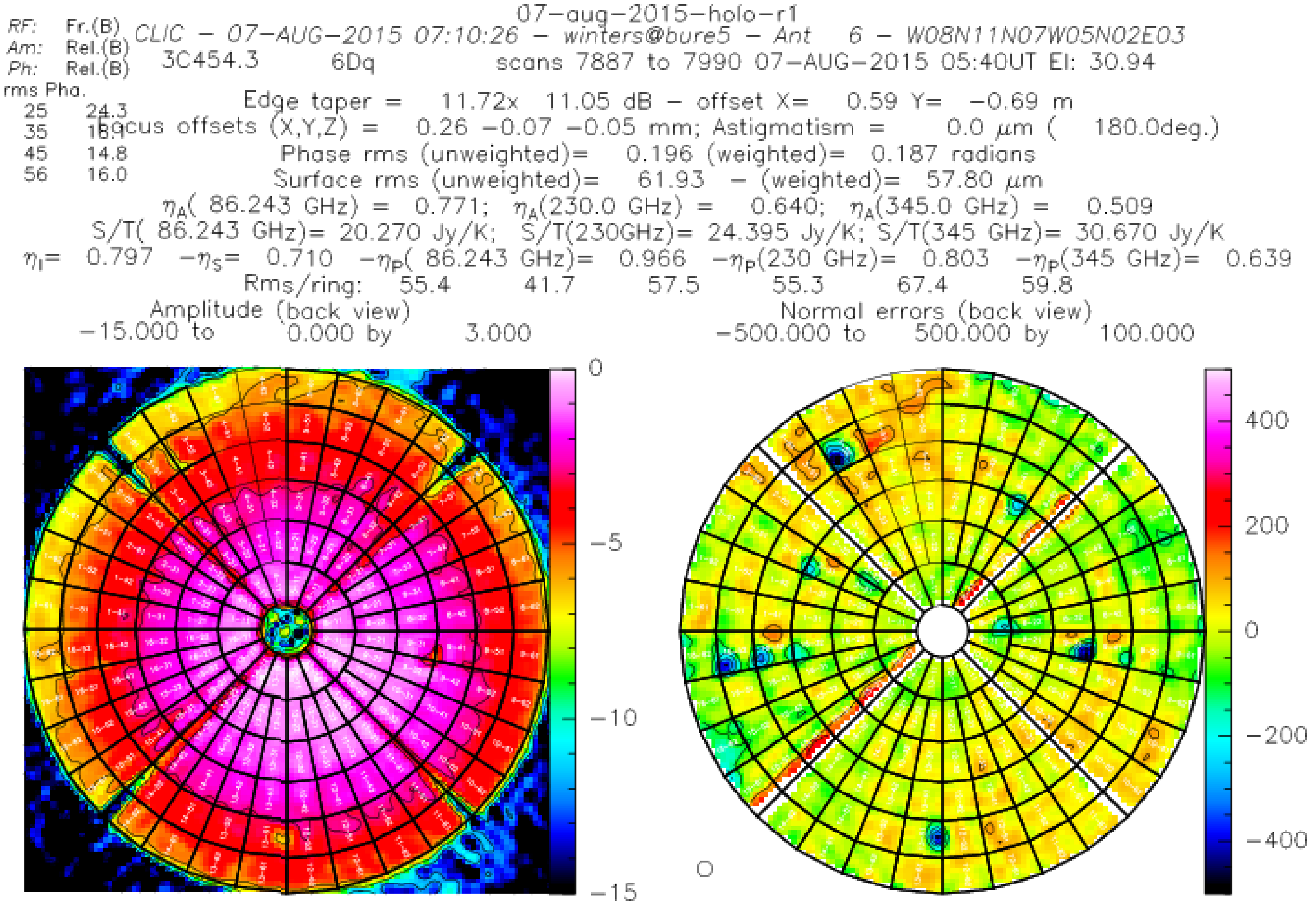
Aperture efficiency

- Ruze formula relates surface errors r.m.s. and aperture efficiency

$$\eta_a = \eta_0 \exp(-(4\pi\sigma/\lambda)^2)$$

- With $\sigma = \lambda/16$ one gets 50% efficiency.
- ALMA, 350 microns, needs 25 micron surface rms.
- NOEMA, 850 microns, needs 50 micron surface rms.
- Actual numbers are slightly better.
- Antenna panels position adjusted using holographic measurements.

Astro holography



07–aug–2015–holo–r1

RF: Fr.(B)
Am: Rel.(B)
Ph: Rel.(B)

CLIC – 07–AUG–2015 07:10:26 – winters@bure5 – Ant 6 – W08N11N07W05N02E03

3C454.3 6Dq scans 7887 to 7990 07–AUG–2015 05:40UT El: 30.94

rms Pha.

25	24.3
35	18.9
45	14.8
56	16.0

Edge taper = 11.72x 11.05 dB – offset X= 0.59 Y= –0.69 m

Focus offsets (X,Y,Z) = 0.26 –0.07 –0.05 mm; Astigmatism = 0.0 μm (180.0deg.)

Phase rms (unweighted)= 0.196 (weighted)= 0.187 radians

Surface rms (unweighted)= 61.93 – (weighted)= 57.80 μm

η_A(86.243 GHz) = 0.771; η_A(230.0 GHz) = 0.640; η_A(345.0 GHz) = 0.509

S/T(86.243 GHz)= 20.270 Jy/K; S/T(230GHz)= 24.395 Jy/K; S/T(345 GHz)= 30.670 Jy/K

η_I= 0.797 –η_S= 0.710 –η_P(86.243 GHz)= 0.966 –η_P(230 GHz)= 0.803 –η_P(345 GHz)= 0.639

Rms/ring: 55.4 41.7 57.5 55.3 67.4 59.8

Amplitude (back view)
–15.000 to 0.000 by 3.000

Normal errors (back view)
–500.000 to 500.000 by 100.000

Sensitivity

$$\delta S_\nu = \frac{J T_{sys}}{\eta \sqrt{n.(n-1)\Delta\nu\Delta t}}$$

- Lowering Tsys.
- Improving antenna efficiency
  - Larger antennas
  - Better antenna surfaces
- More antennas
- Larger bandwith

Large bandwidth

- Large bandwidth allows to gain sensitivity for continuum data
- But lines have limited (by physics) linewidth
  - However one can get through simultaneous observations of many lines at once (e.g. Spectral surveys). Share a common calibration.
  - One gets a larger discovery space for redshift search
  - Or for detecting new molecules
- This produces huge datasets (100's of GB).

- Integration time cannot go beyond reasonnable values
  - After observing 1 day, one needs to observe 100 days to gain a factor of 10, 10 000 days to gain another of 10. This is almost 30 years of observing time

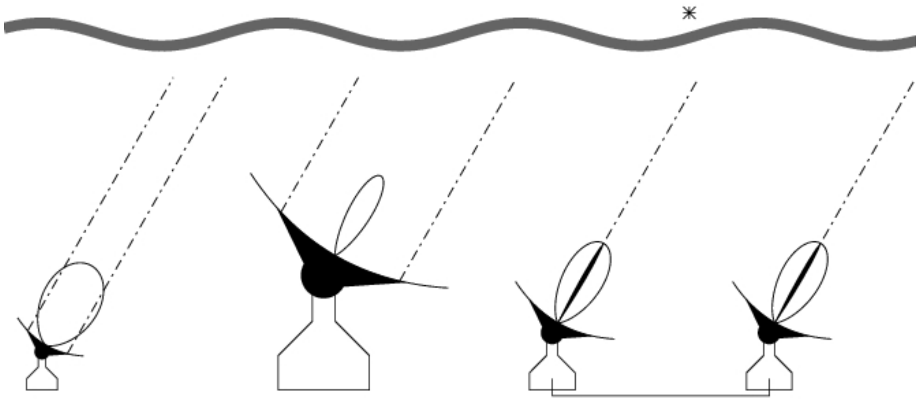
(some) Specificities of mm/sub-mm interferometry

Tropospheric phase noise

- Water vapor along the line of sight adds a phase:

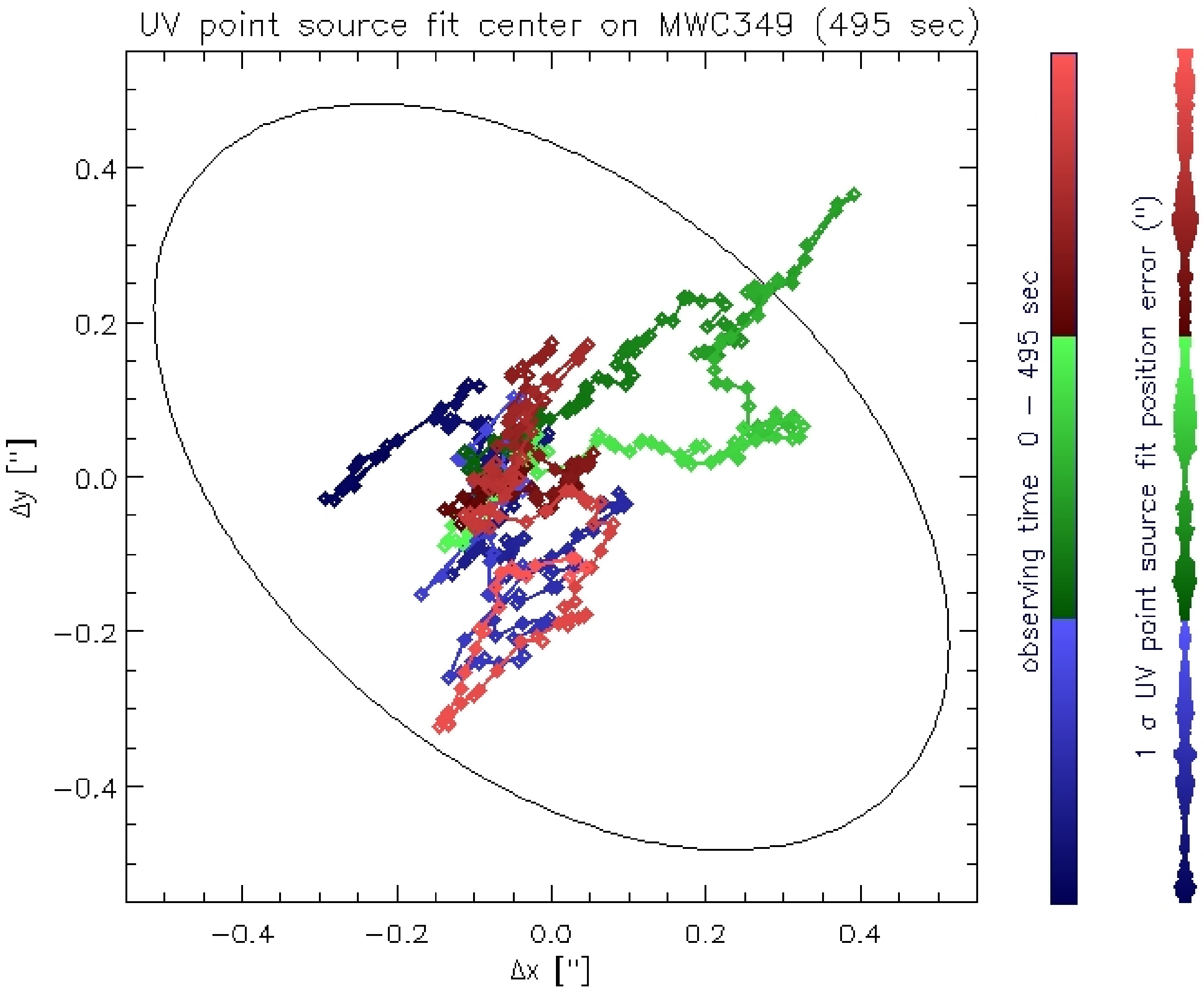
$$\phi \simeq \frac{12.6\pi}{\lambda} \times w$$

- And the air does not mix well



Tropospheric phase noise

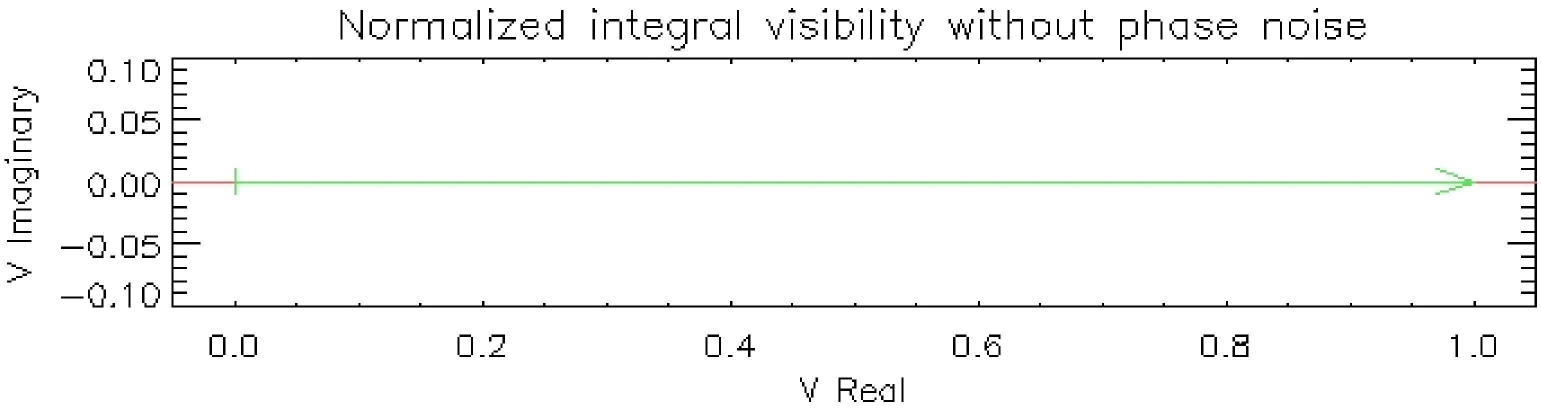
- Point source appears to move

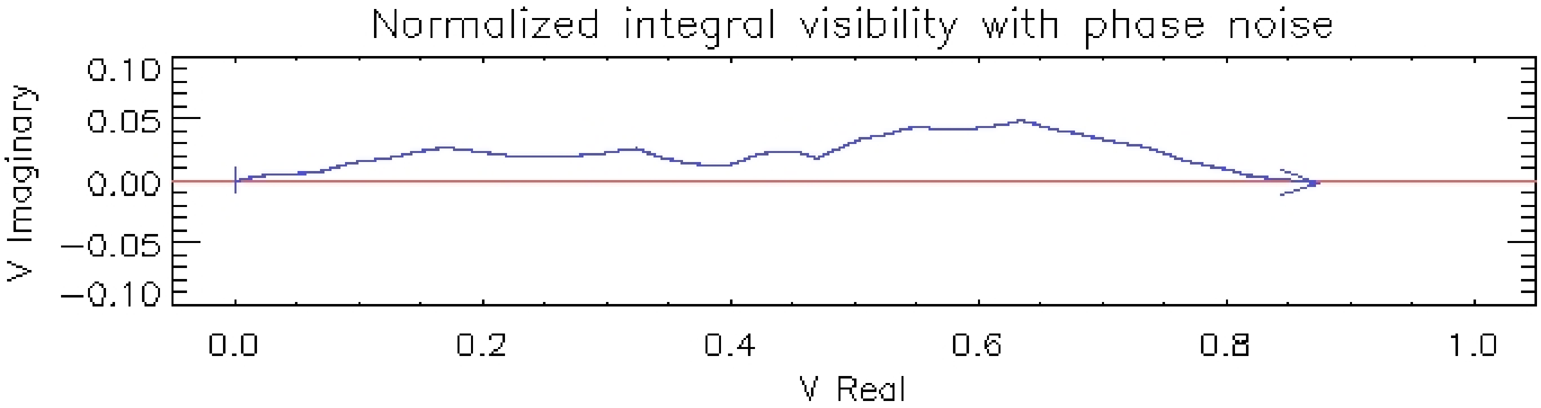


Tropospheric phase noise

- We lose integrated flux due to phase jitter

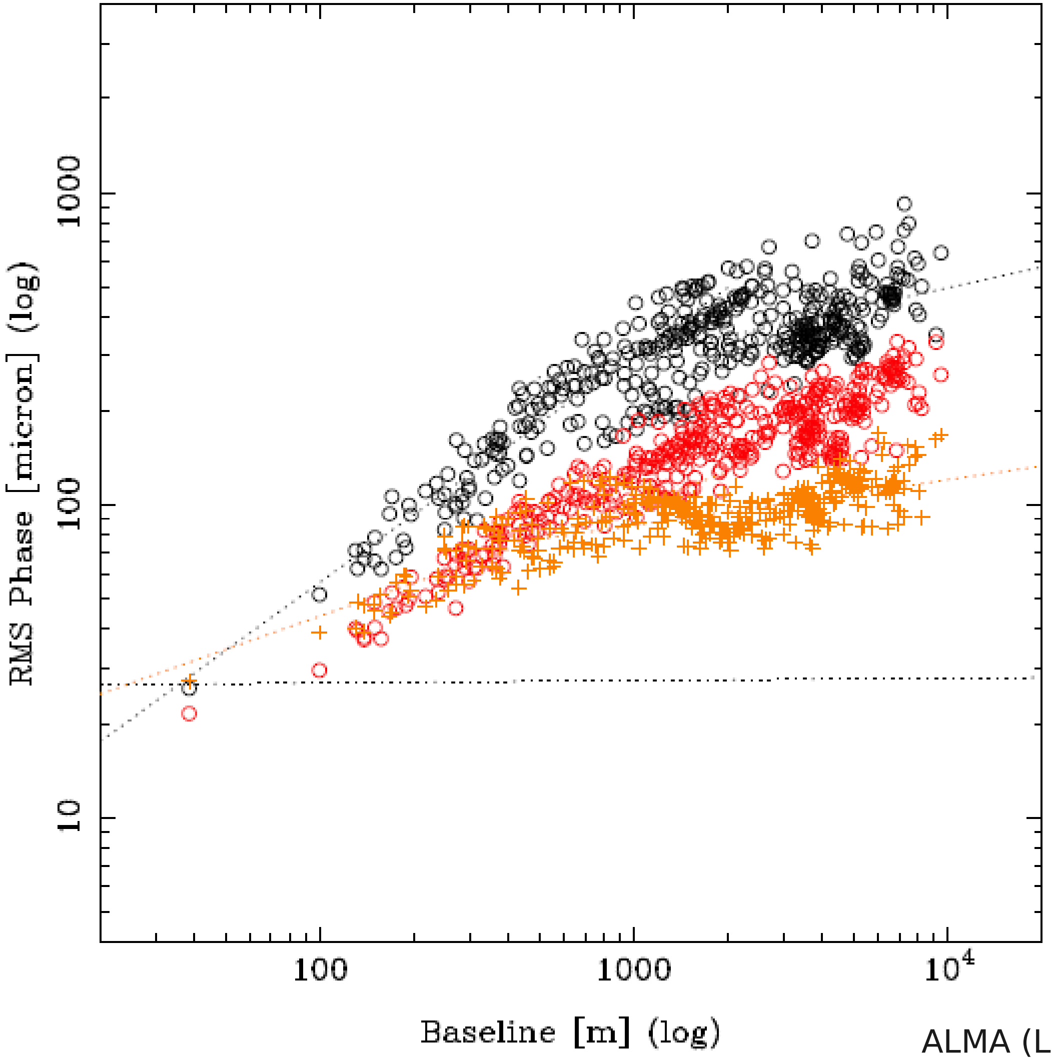
$$V_{obs} = V_{ideal}\exp(-\phi^2/2)$$

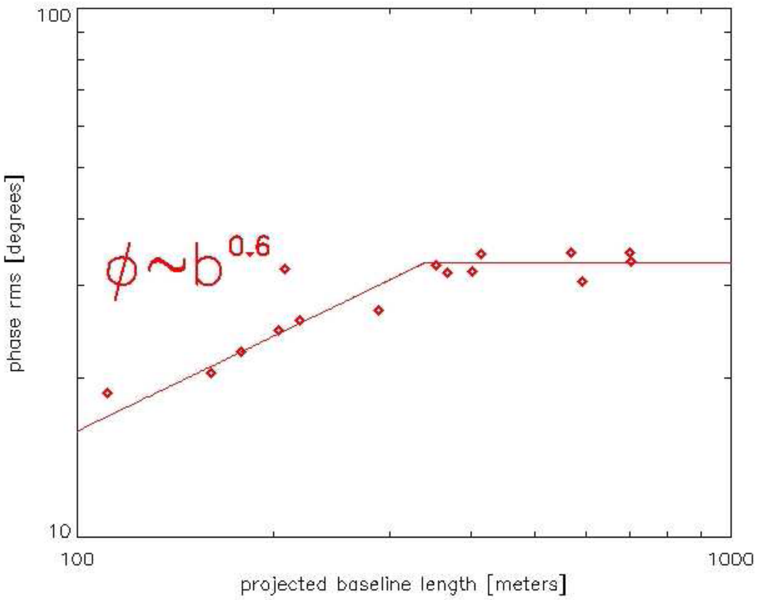

Normalized integral visibility without phase noise


Normalized integral visibility with phase noise

Structure function of the atmosphere

Following Kolmogorov theory, phase rms increases up to an outer scale



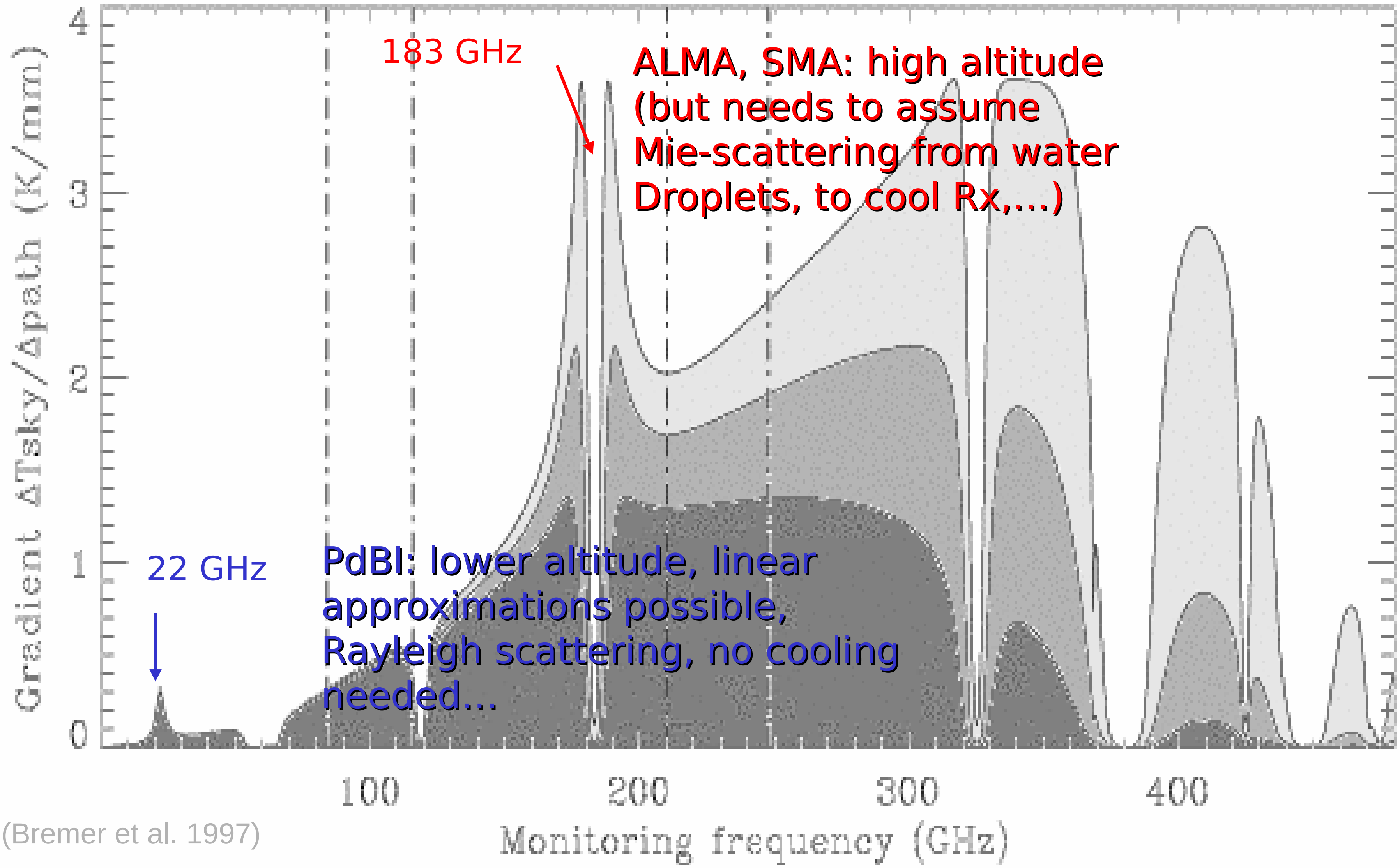


PdBI (Bremer 2010)

ALMA (LBC)

Radiometers

(Un)fortunately, water vapor has emission lines.



ALMA, SMA: high altitude (but needs to assume Mie-scattering from water Droplets, to cool Rx,...)

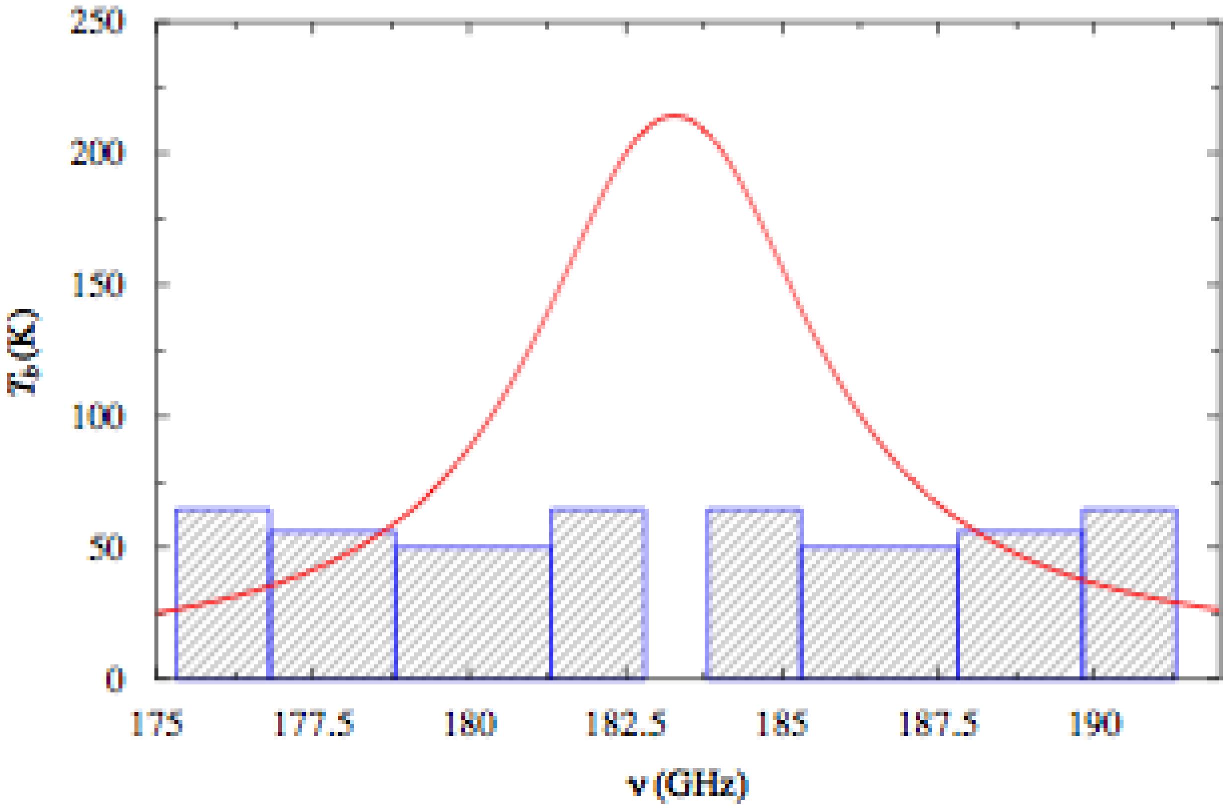
PdBI: lower altitude, linear approximations possible, Rayleigh scattering, no cooling needed...

(Bremer et al. 1997)

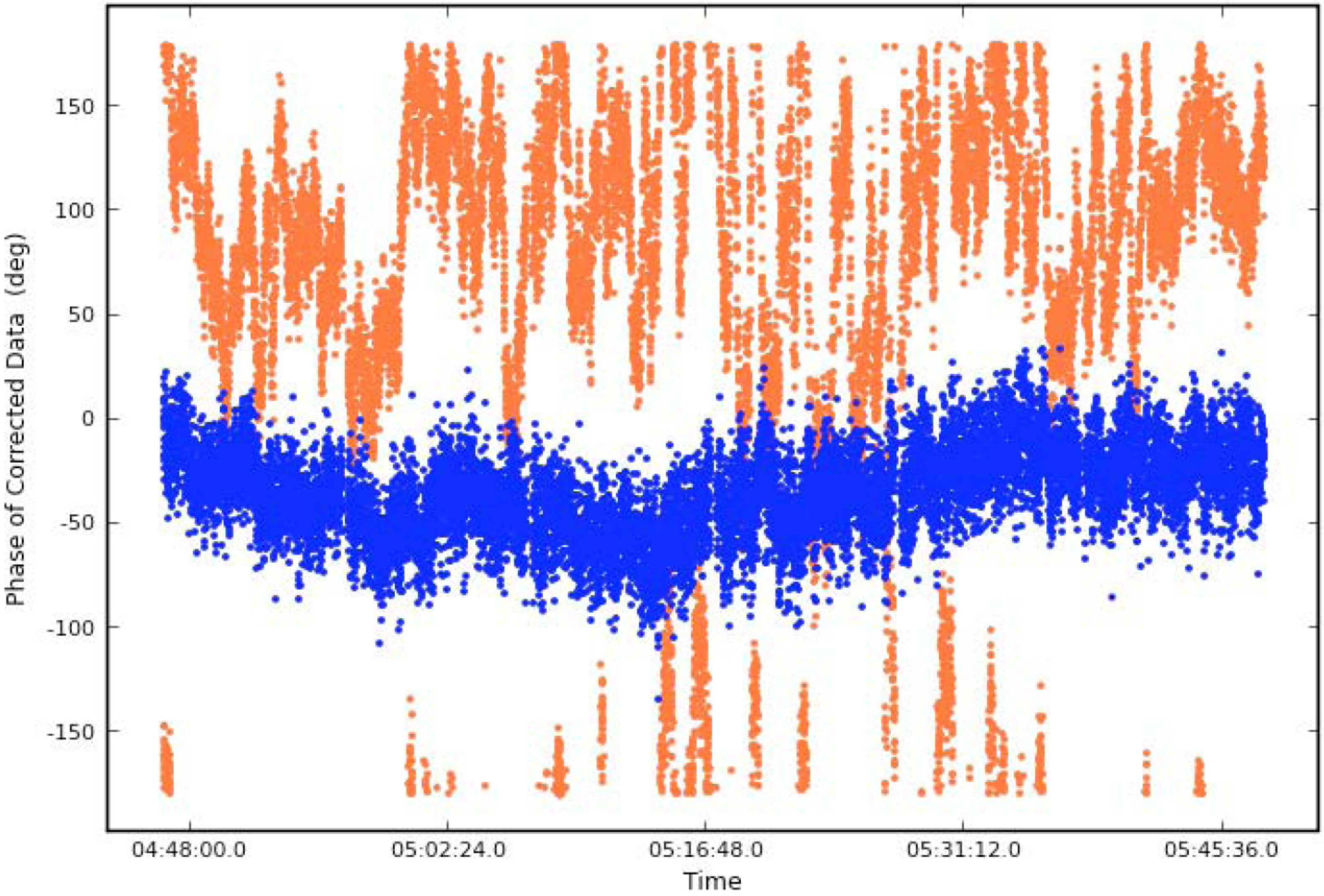
ALMA radiometers

The 183 GHz Water Vapour Line

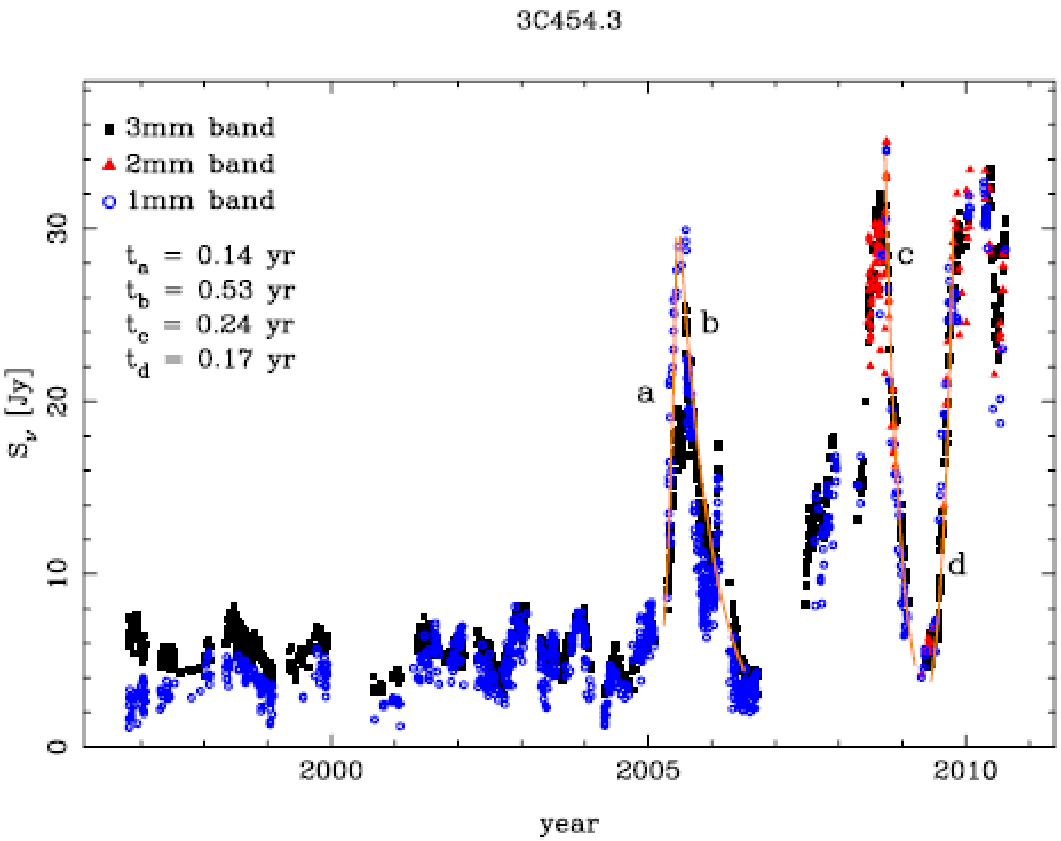
Blue rectangles are the production WVR filters



Applying radiometric correction

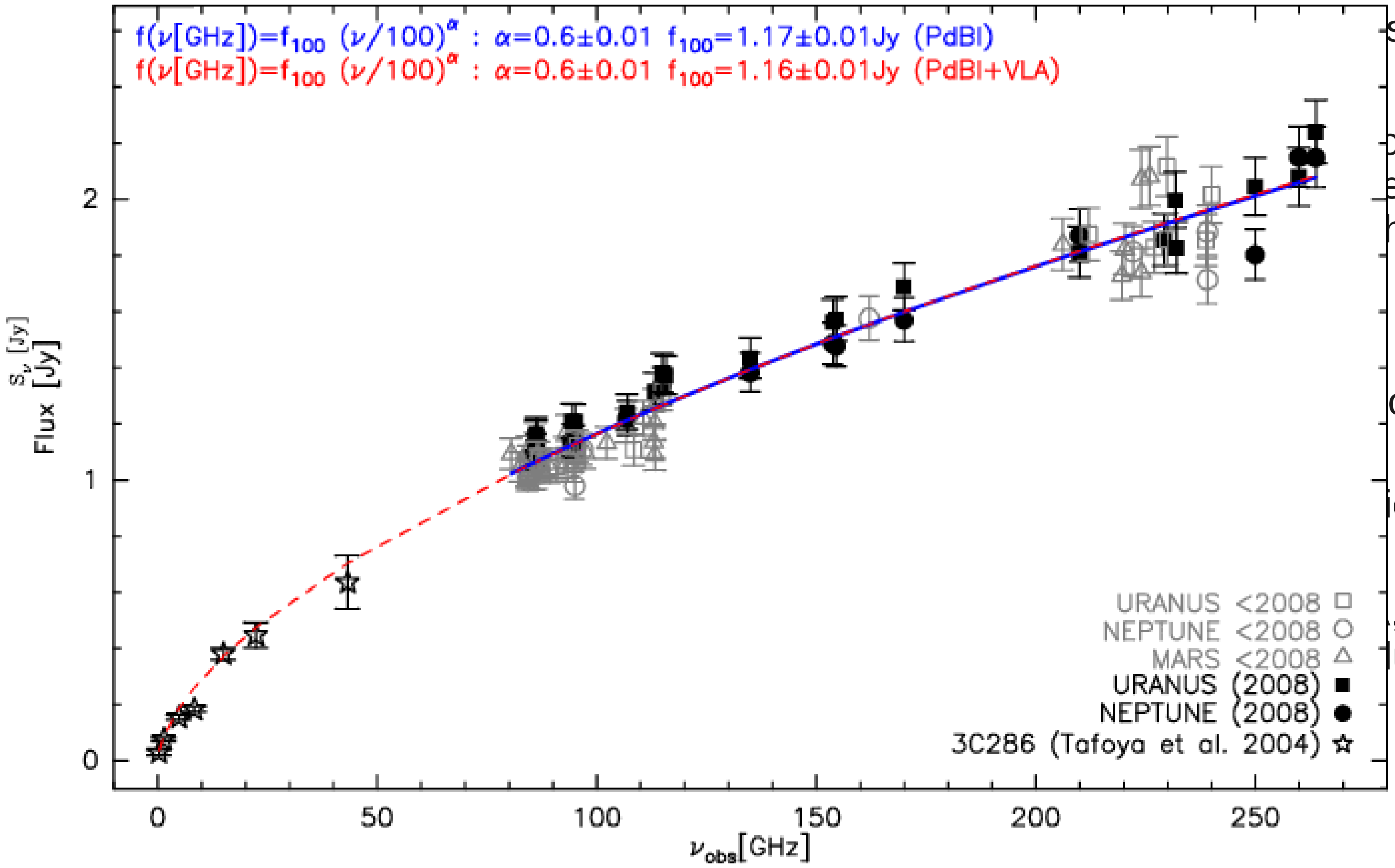


Quasars are variable



- Use primary calibrators to set the flux scale
  - Planets, but can be resolved out depending on frequency and configuration. Can have absorption line.
  - Satellites
    - Take care that it is not too close from planet
  - Solar system small bodies, but need a good model.
  - Radio-stars. At NOEMA, MWC349 is used as a flux reference

Quasars are variable



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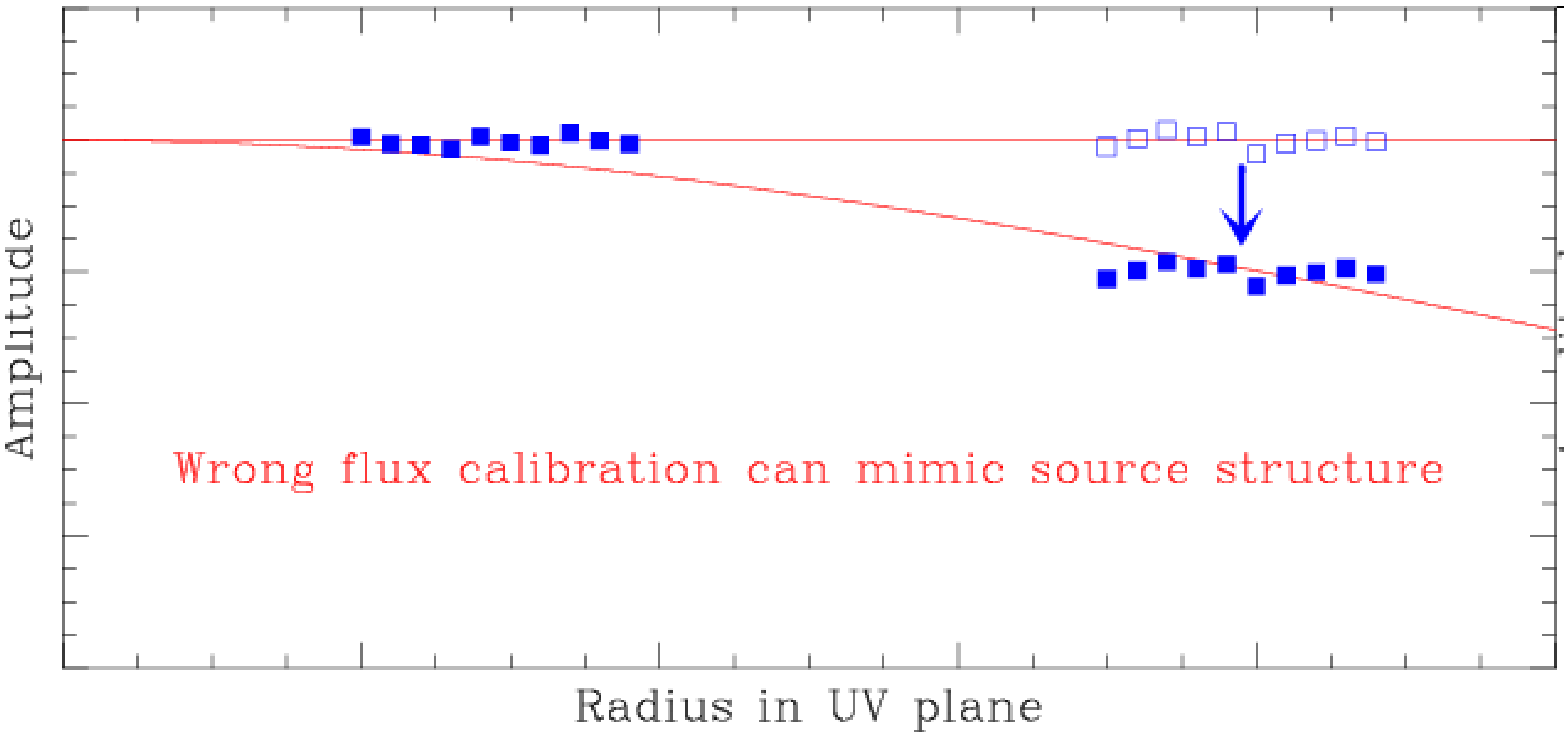
Why flux scale matters

- Direct error on temperature or surface density.
- When observing with multi configurations:



mm-submm observatories

1964: Haystack 37-m tel. (up to to $\lambda=10/6$mm)
1965: Green Bank 140ft telescope ($\lambda>6$mm)
1969: Kitt Peak 36'/12m telescope ($\lambda>2/1$mm)
1970: Effelsberg 100m telescope ($\lambda>3$mm)

- 1979: Berkley interferometer (-> BIMA)
- 1982: OVRO

1982: Nobeyama 45m telescope ($\lambda>2$mm)
1984: IRAM 30m telescope ($\lambda>0.8$mm)

- 1985: Nobeyama interferometer

1988: CSO 10.4m telescope ($\lambda>0.3$mm)

- 1990: Plateau de Bure Interferometer ($\lambda>0.8$mm)

2000: GBT 105m telescope ($\lambda>3$mm)

- 2003: SMA

2004: APEX ($\lambda>0.3$mm)

- 2011: ALMA ($\lambda>0.1$mm), ES

Mm/sub-mm interferometers

Mm/sub-mm interferometers

ALMA

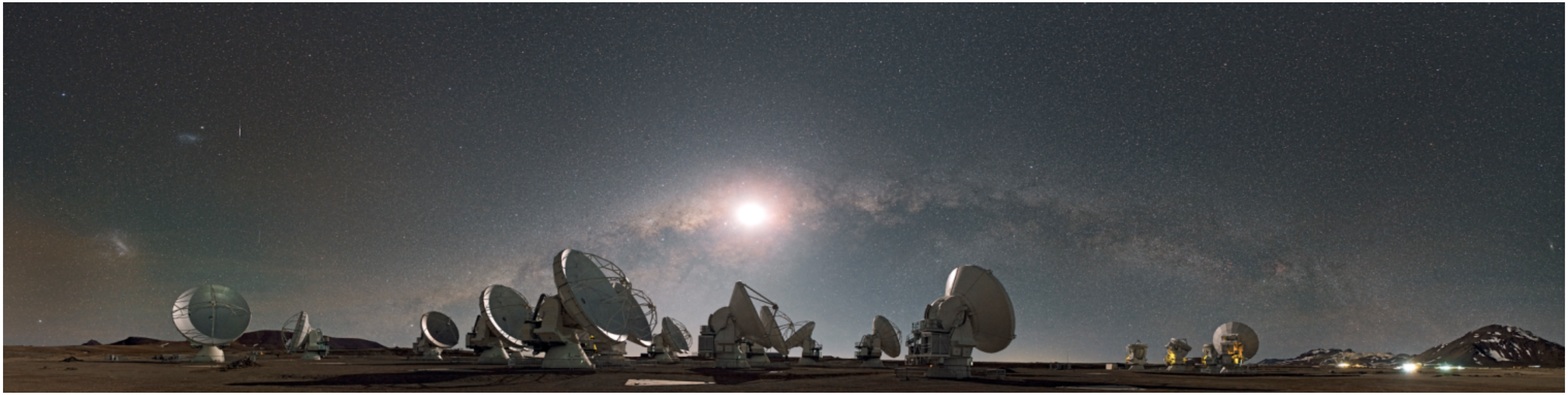
Atacama Large Millimeter/Submillimeter Array

Europe (**ESO**)

North America (USA, Canada, Taiwan)

Eastern Asia (Japan, Taiwan, South Korea)

Chile



ALMA

Atacama Large Millimeter/Submillimeter Array

Europe (**ESO**)

North America (USA, Canada, Taiwan)

Eastern Asia (Japan, Taiwan, South Korea)

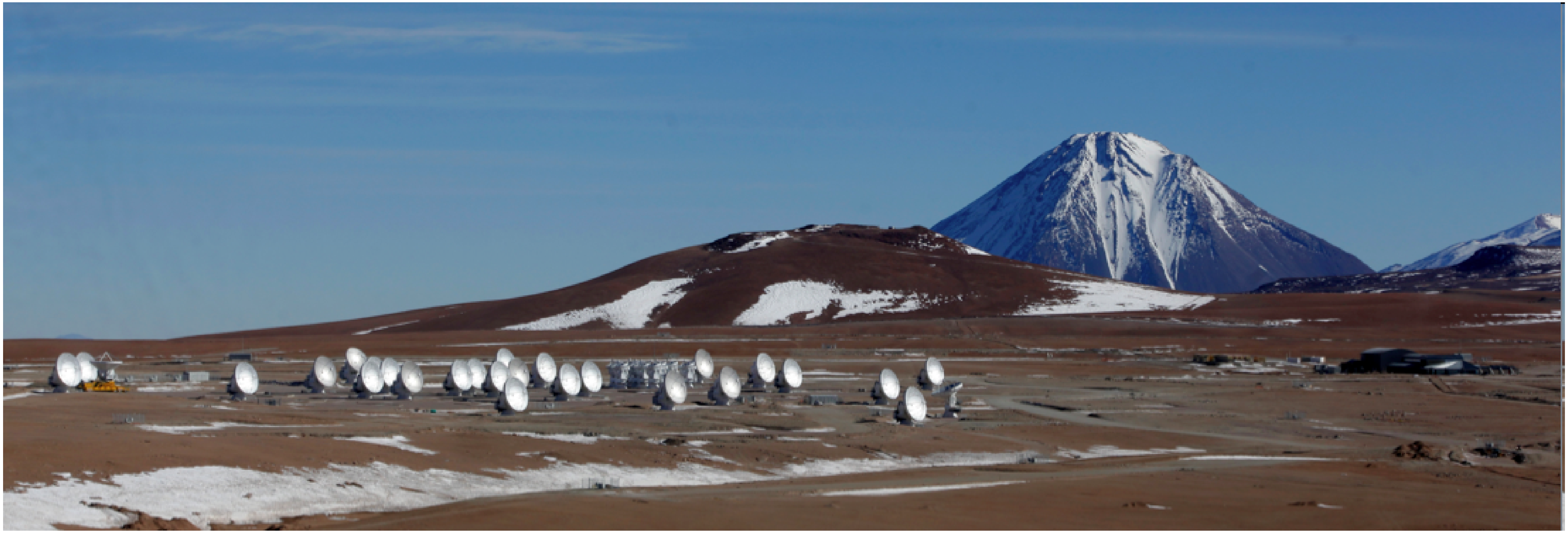
Chile

- Main array: 50 x 12 m antennas
- ALMA Compact Array (ACA): 4 x 12m + 12 x 7m
- Frequency range: 30—900 GHz (0.3—10 mm)
- 16 km max. baseline

ALMA antennas

NA and EA antennas

EU antenna + transporter



ALMA Compact Array

Morita-array

- 12 7-m antennas to observe the short spacings
- Not (yet) offered in stand-alone mode

Single-dish antennas

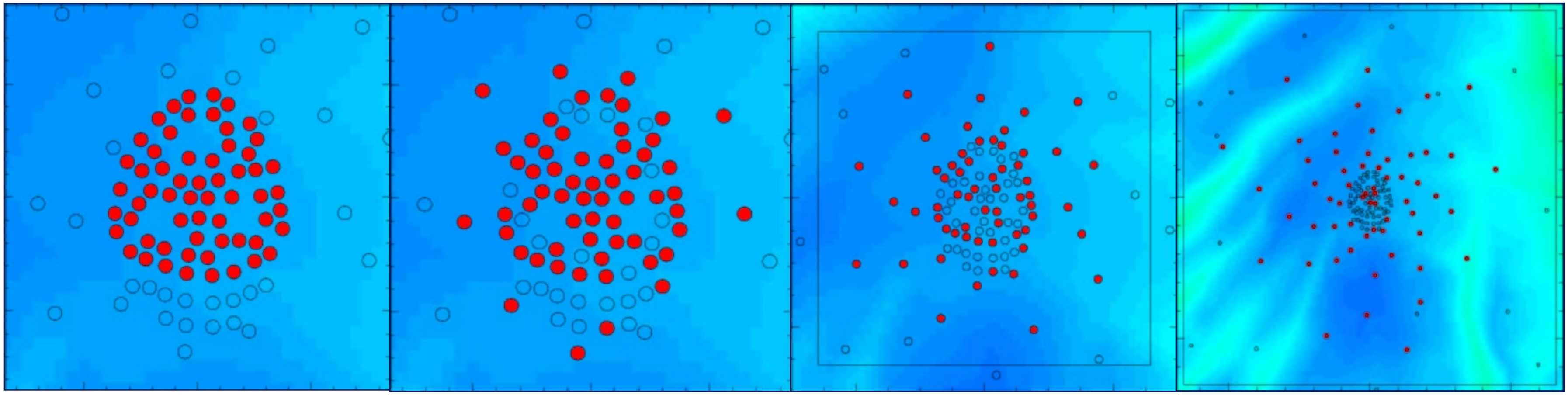
- 4 12-m antennas used in single-dish mode to observe the zero-spacings

Imaging

50 antennas, 1225 baselines (**Goal = 45 antennas used**)

Angular resolution λ/B down to 40 mas (100 GHz), 5 mas (900 GHz)

28 (TBC) different antenna configurations, from compact to ~16 km



Short spacings: ACA observations + 4 single-dish antennas

Caution: not all projects can have ACA data!

ALMA imaging simulator in GILDAS and CASA

ALMA Early Science

Best effort basis

Cycle 0: deadline mid 2011 ; observations in 2012

Cycle 1: deadline mid 2012 ; observations in 2013-2014-2015

Cycle 2: deadline end of 2013: observations in 2014-2015

Cycle 3: deadline spring 2015

1582 proposals

Pressure factor ~ **5—10**

ALMA capabilities deployment

Now distinguish between standard and non-standard modes

- ACA & SD, polarimetry, long baselines

Mm/sub-mm interferometers

Mm/sub-mm interferometers

NOEMA

Northern Extended Millimeter Array

Extension of the IRAM Plateau de Bure interferometer

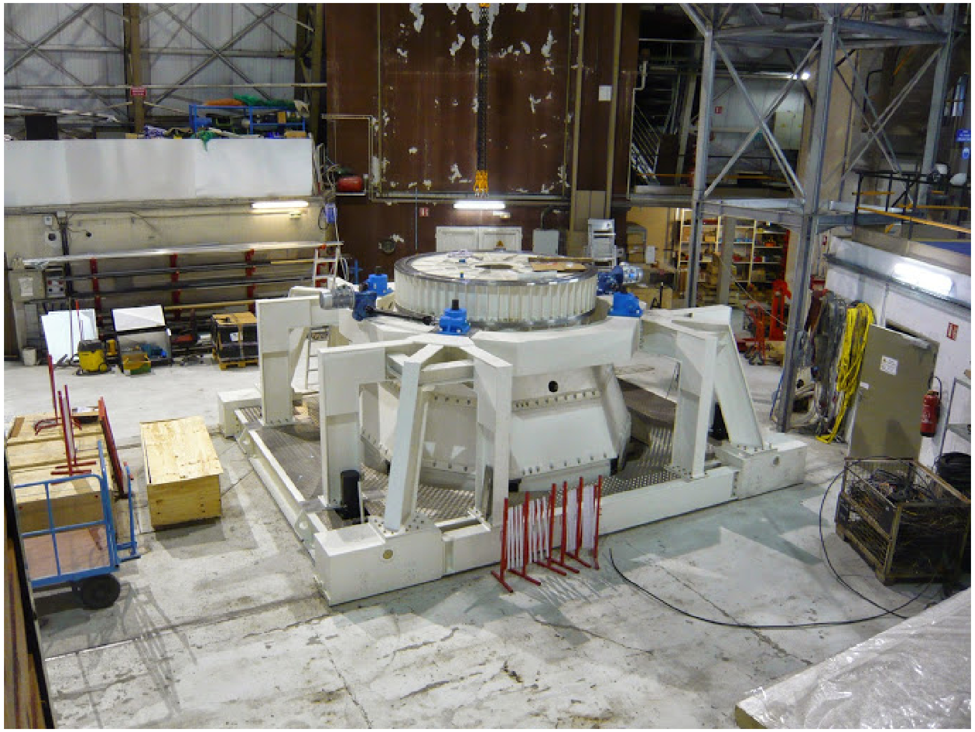
- Double the number of 15 m antennas from 6 to 12
- New receivers: increase of IF bandwidth from 8 GHz to 32 GHz
- New correlator (FPGA technology)
- Extension of the baselines from 0.8 to 1.6 km

NOEMA

NOEMA Phase I (2017)
4 new antennas (7-8-9-10)
10 new receivers
12-antennas correlator

NOEMA Phase II (2019)
2 new antennas (11-12)
Baseline extension (1.6 km)
Band 4 (0.8 mm / 345 GHz)

Antenna 7 inauguration 22 Sept. 2014



January 2015

Antenna 8

28 May 2015

NOEMA factsheet

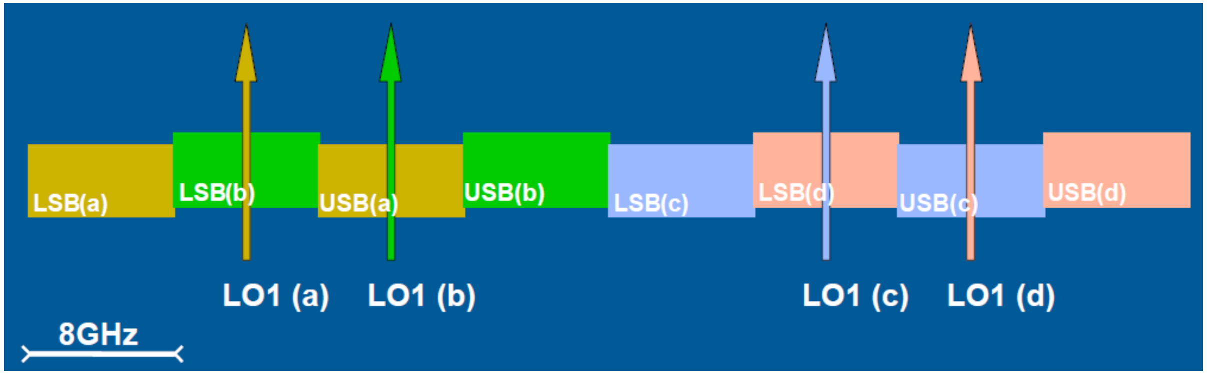
	Collecting area	
	Interferometry	Short spacings
ALMA/ACA	5655 m^2	914m^2
NOEMA/30m	2121 m^2	707m^2

	Bandwidth per polarization
PdBI	4 GHz
ALMA	2 x 4 GHz
NOEMA/30m	2 x 8 GHz

- Line observations: NOEMA rms < 3 ALMA rms
- Continuum observations: NOEMA rms < 2 ALMA rms

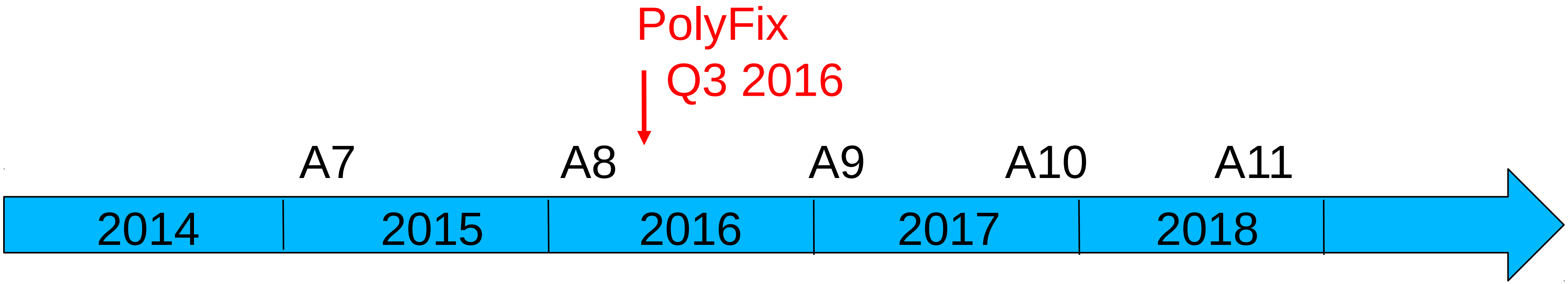
NOEMA features

- Correlator provides full continuum **and** (up to) 128 spec. windows
- Frequency plan + correlator mode optimized for **frequency surveys**



- **Dual-band observations** (with 2nd correlator) funded by the MPG

Timeline NOEMA



PolyFix
Q3 2016

A7
A8
A9
A10
A11

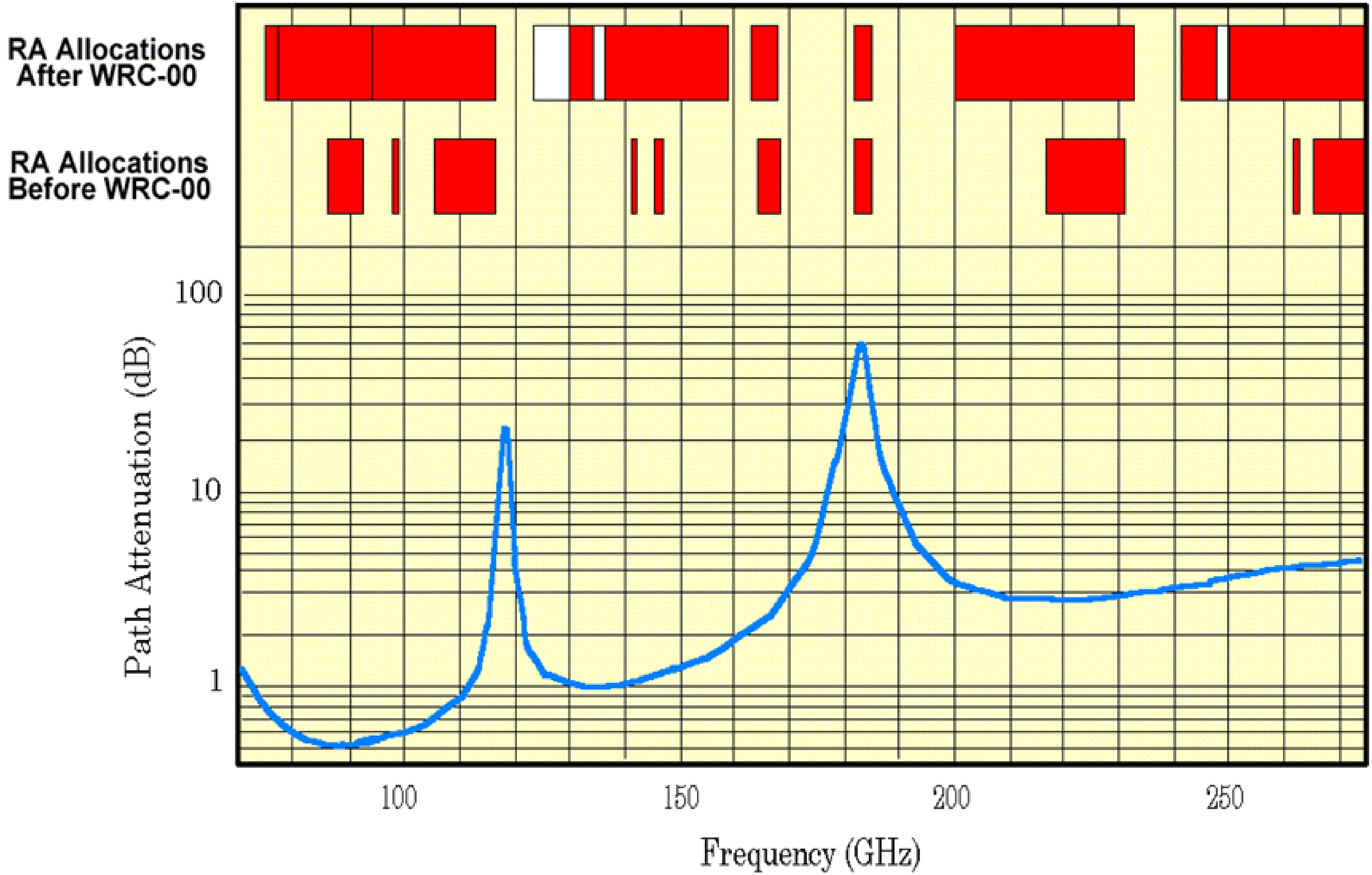
2014
2015
2016
2017
2018

- A8: Q1 2016
- A9: Q1 2017
- A10: Q4 2017
- A11: Q3 2018
- A12: Q2 2019

Radio allocation summary

- **< 30 GHz:**
    - 1.3% primary exclusive for passive frequency use
    - 1.2% primary shared allocations
    - 0.5% secondary allocations
- **30 - 275 GHz:**
    - 16.8% primary exclusive for passive frequency use
    - 38.3% primary shared allocations
    - 5.1% secondary allocations
- **> 275 GHz:**
    - No allocation yet

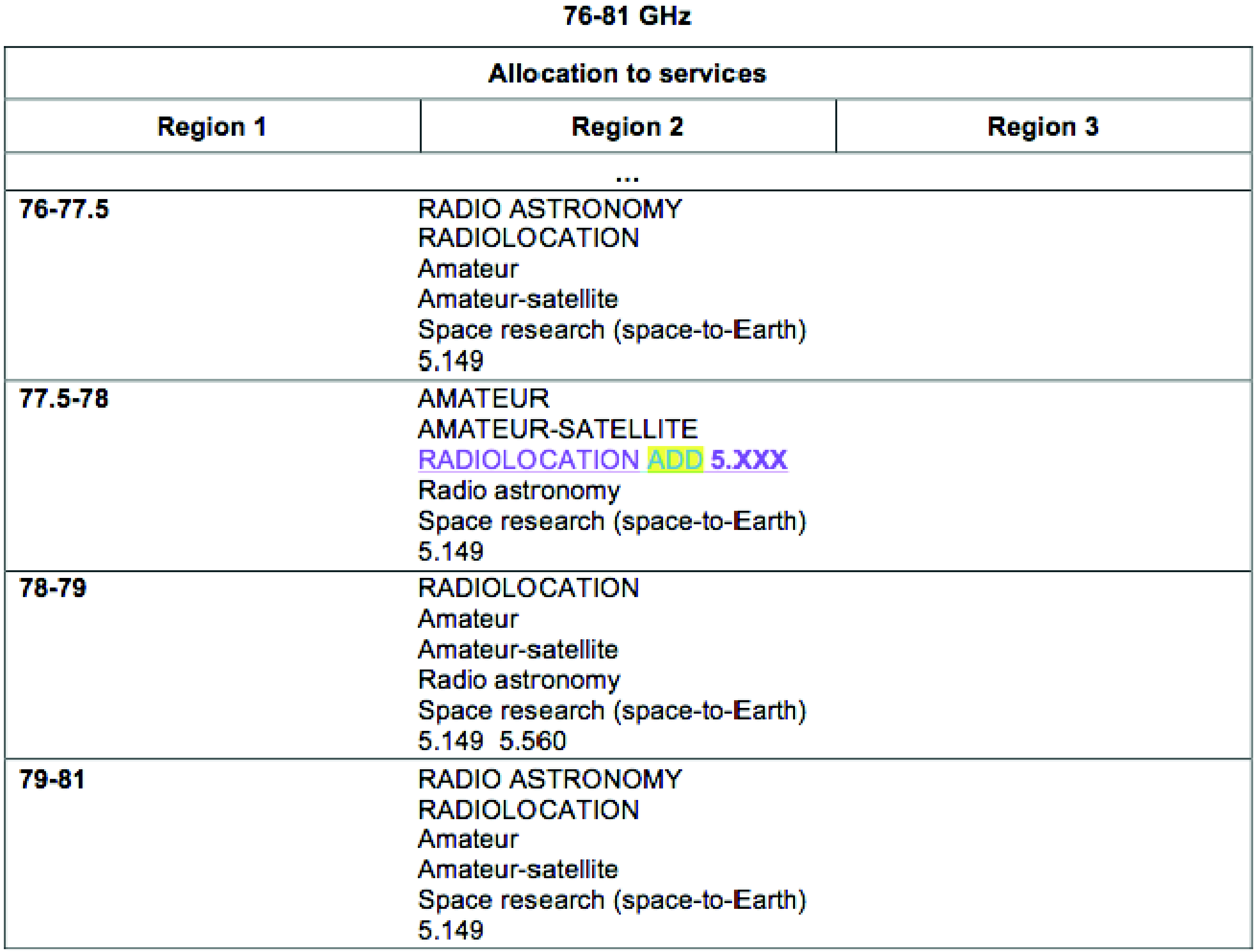
Tzioumis, IUCAF Spectrum management SS 2010.



Tzioumis, IUCAF Spectrum management SS 2010.

WRC 15

- Agenda item 1.18
  - To consider a primary allocation to the radiolocation service for automotive applications in the 77.5-78 GHz frequency band in accordance with Resolution 654 (WRC12)

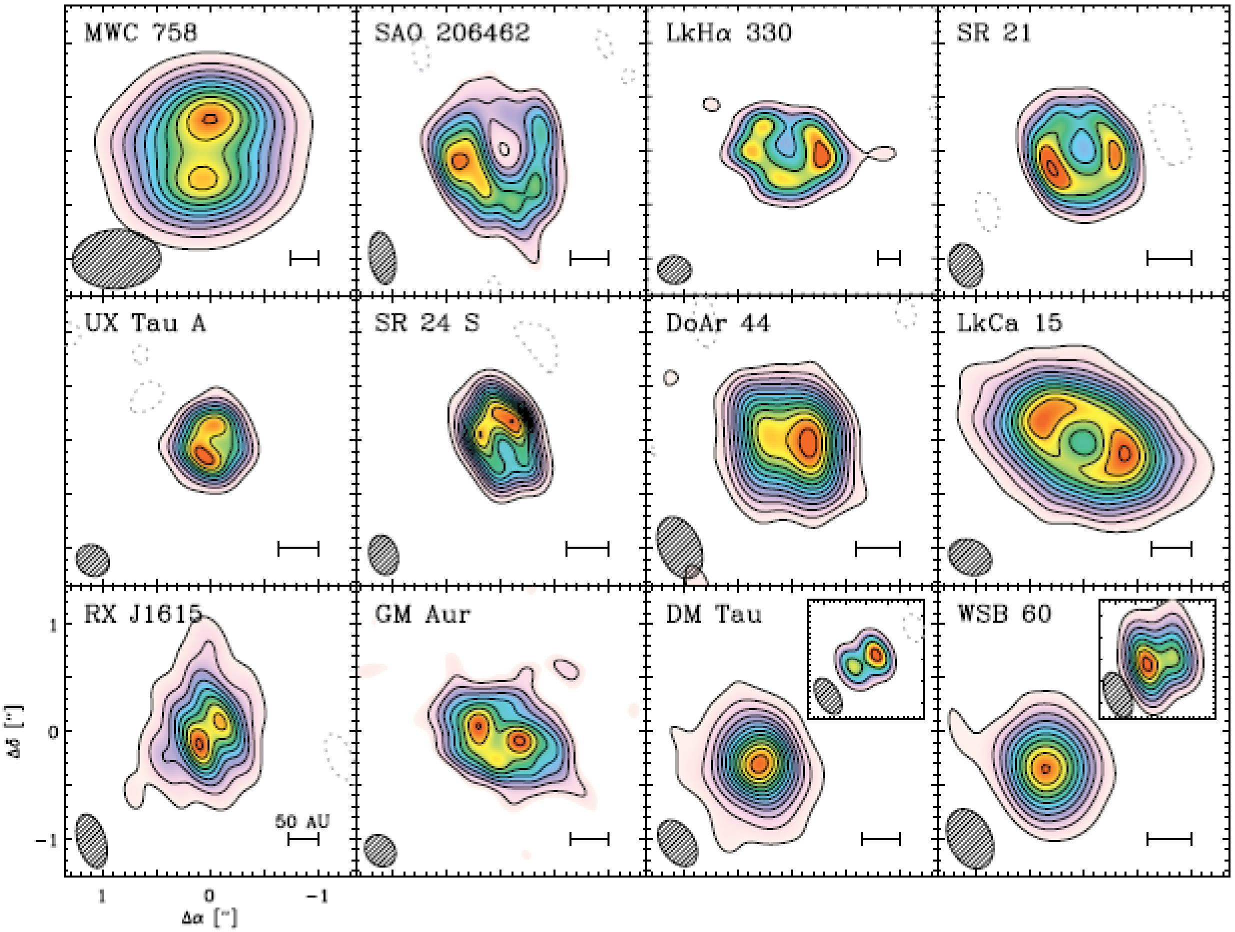


76-81 GHz

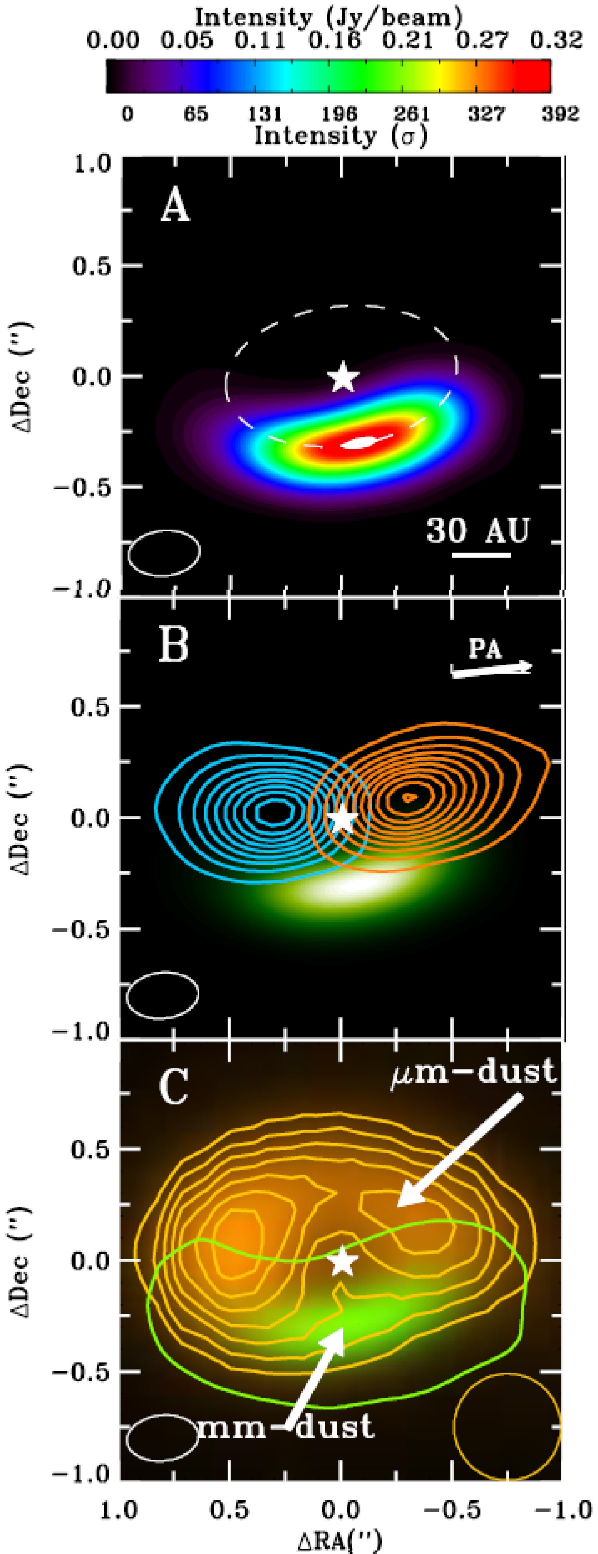
Allocation to services		
Region 1	**Region 2**	**Region 3**
...		
76-77.5	RADIO ASTRONOMY RADIOLOCATION Amateur Amateur-satellite Space research (space-to-Earth) 5.149	
77.5-78	AMATEUR AMATEUR-SATELLITE RADIOLOCATION ADD **5.XXX** Radio astronomy Space research (space-to-Earth) 5.149	
78-79	RADIOLOCATION Amateur Amateur-satellite Radio astronomy Space research (space-to-Earth) 5.149 5.560	
79-81	RADIO ASTRONOMY RADIOLOCATION Amateur Amateur-satellite Space research (space-to-Earth) 5.149	

Observations of inner cavities in protoplanetary disks

- SMA observations of large cavities within protoplanetary disks. Possibly linked to planetary formation



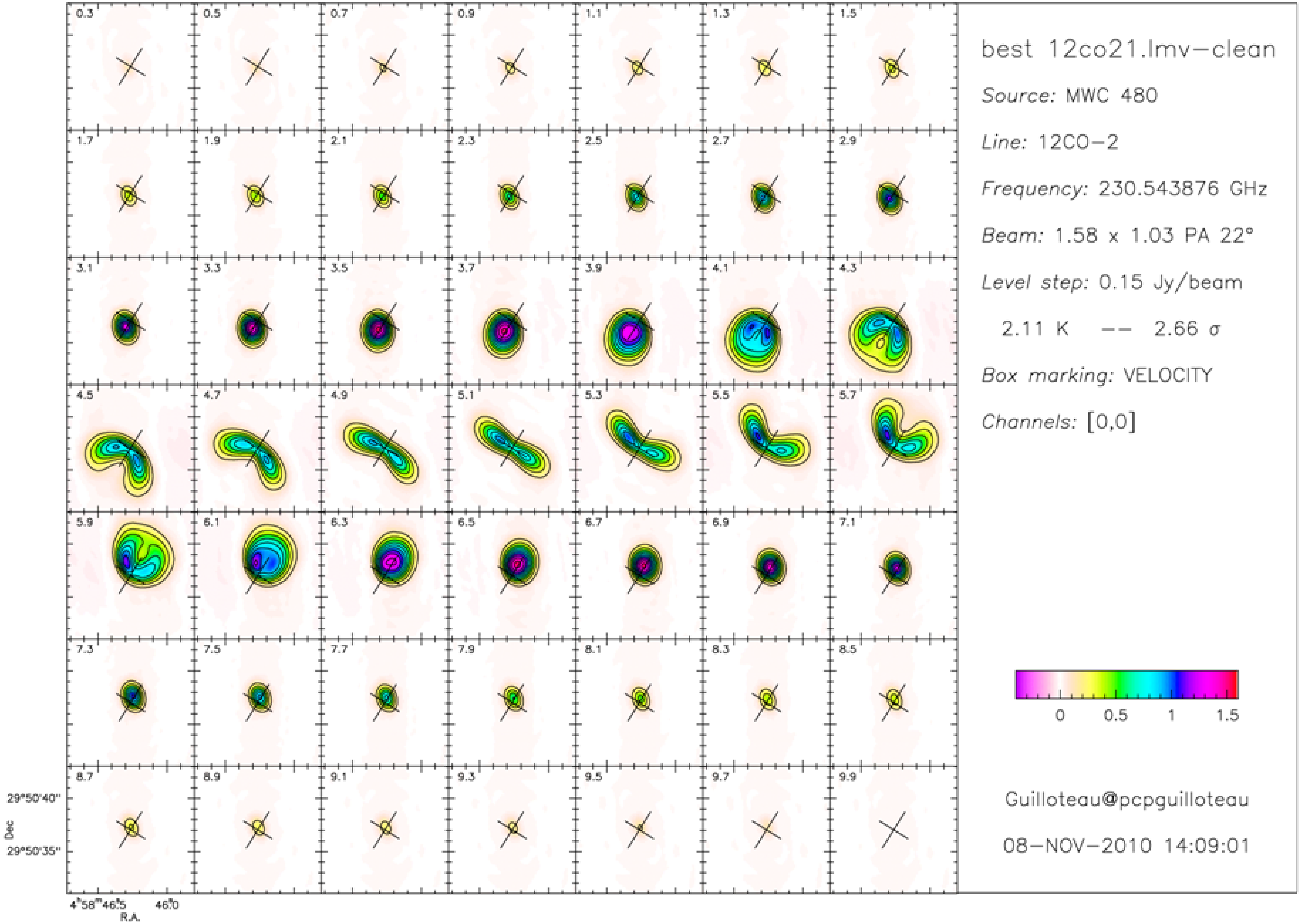
Andrews et al. 2011



A dust trap ?

- ALMA B9 observations of IRS48 (Herbig Ae star).
- Asymetry of the dust continuum
- Possibly tracing dust trapping in a local pressure extremum

Van der Marel et al 2013, Science


best 12co21.lmv−clean
Source: MWC 480
Line: 12CO−2
Frequency: 230.543876 GHz
Beam: 1.58 x 1.03 PA 22°
Level step: 0.15 Jy/beam
2.11 K -- 2.66 σ
Box marking: VELOCITY
Channels: [0,0]
0
0.5
1
1.5
Guilloteau@pcpguilloteau
08−NOV−2010 14:09:01
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0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
2.1
2.3
2.5
2.7
2.9
3.1
3.3
3.5
3.7
3.9
4.1
4.3
4.5
4.7
4.9
5.1
5.3
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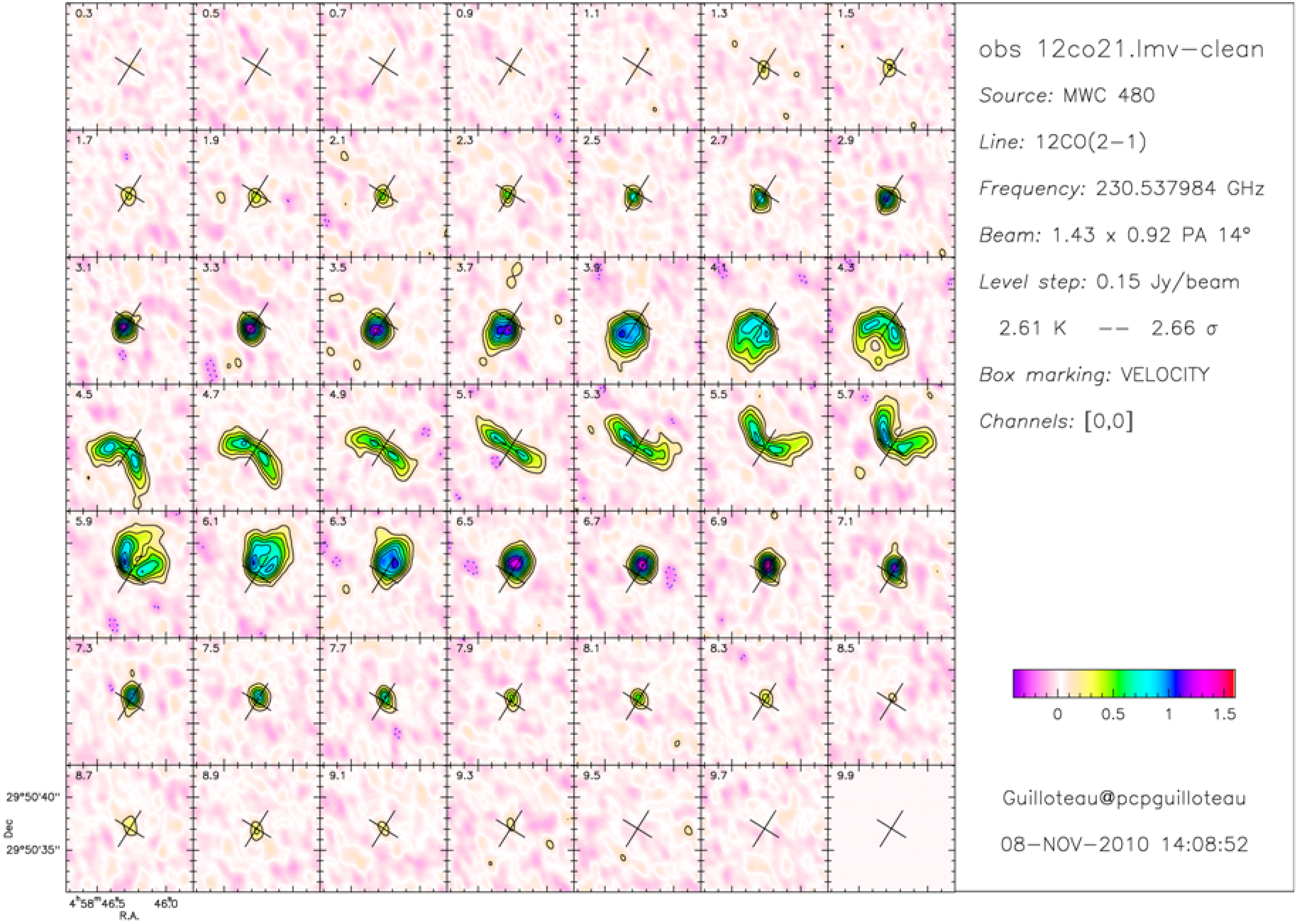
5.7
5.9
6.1
6.3
6.5
6.7
6.9
7.1
7.3
7.5
7.7
7.9
8.1
8.3
8.5
8.7
8.9
9.1
9.3
9.5
9.7
9.9
29°50'40''
Dec
29°50'35''
4h58m46.s5
46.s0
R.A.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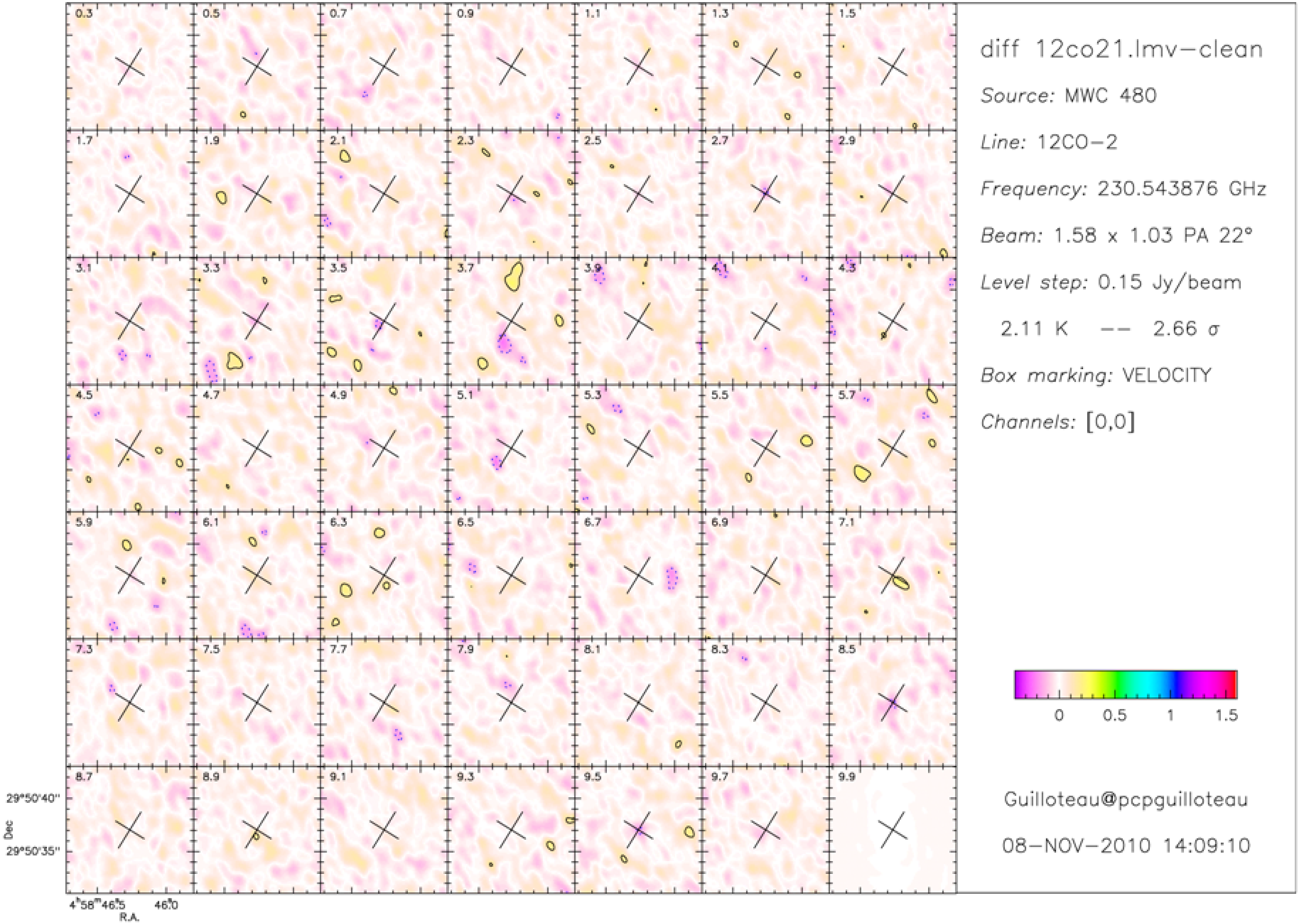
9.3
9.5
9.7
9.9
29°50'40''
Dec
29°50'35''
4h58m46s.5
46s.0
R.A.
obs 12co21.lmv−clean
Source: MWC 480
Line: 12CO(2−1)
Frequency: 230.537984 GHz
Beam: 1.43 x 0.92 PA 14°
Level step: 0.15 Jy/beam
2.61 K −− 2.66 σ
Box marking: VELOCITY
Channels: [0,0]
0
0.5
1
1.5
Guilloteau@pcpguilloteau
08−NOV−2010 14:08:52


diff 12co21.lmv−clean
Source: MWC 480
Line: 12CO−2
Frequency: 230.543876 GHz
Beam: 1.58 x 1.03 PA 22°
Level step: 0.15 Jy/beam
2.11 K −− 2.66 σ
Box marking: VELOCITY
Channels: [0,0]
0
0.5
1
1.5
Guilloteau@pcpguilloteau
08−NOV−2010 14:09:10
29°50'40''
Dec
29°50'35''
4h58m46.5
46.0
R.A.
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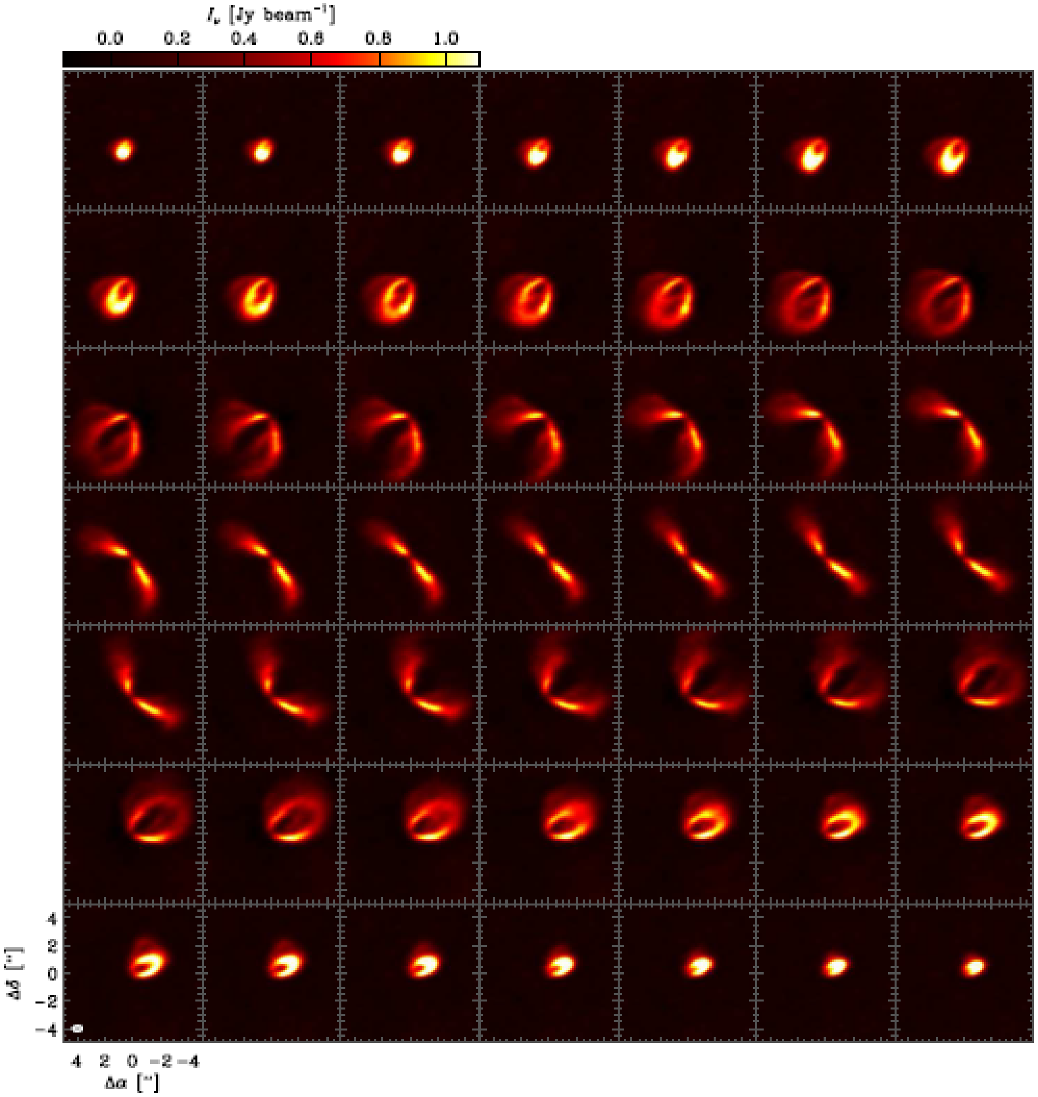
9.9

Molecular content



ALMA Science verification CO observations of HD163296, a Herbig Ae star.

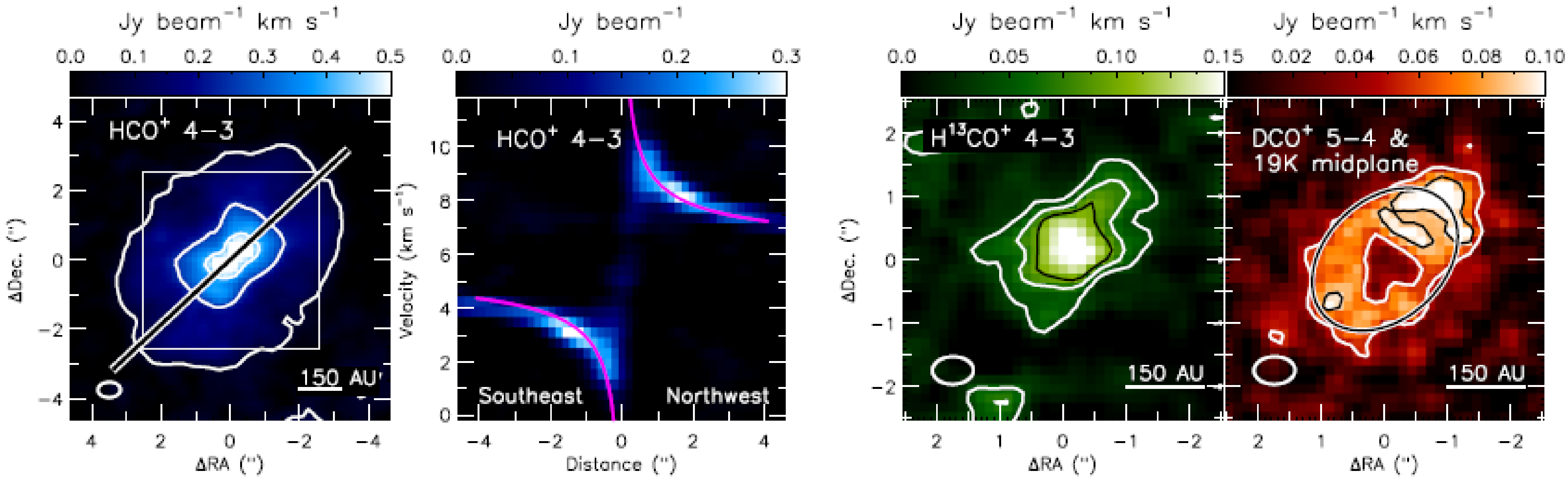
Better resolution

One sees not one, but two disks.

Evidence for CO freeze-out onto grains ?

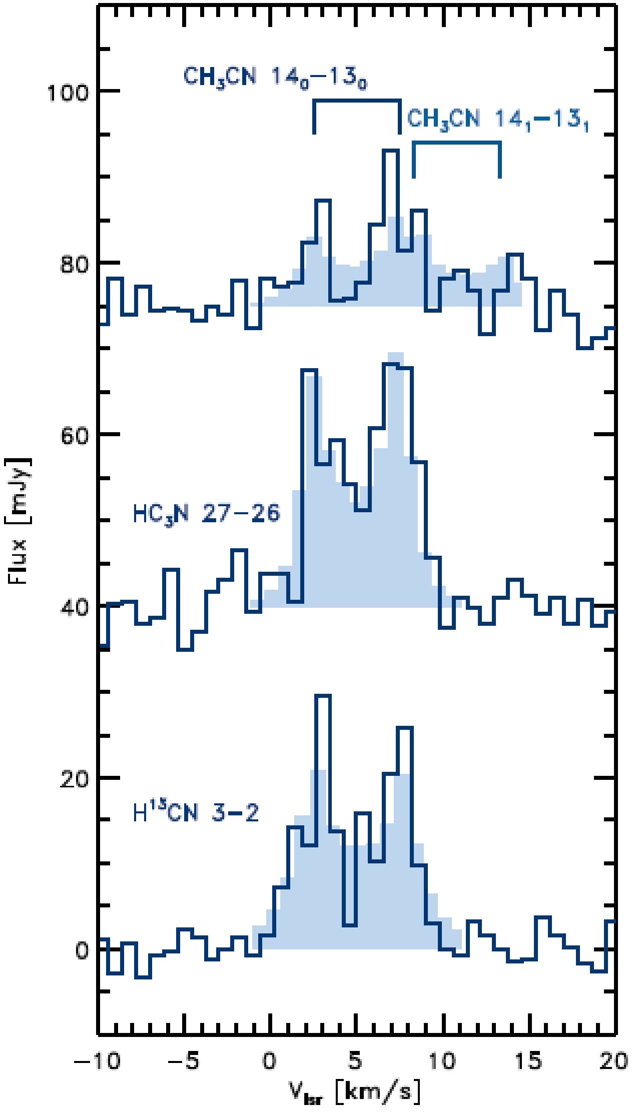
CO snowline

- Snowline corresponds to the region below which water condensates
- Found using ^{13}CO(2-1) by *Qi et al 2011*.
- DCO$^+$ confined in a ring where temperature 19< T < 21 K. (no H$_2$D$^+$ if hotter, no CO if colder).

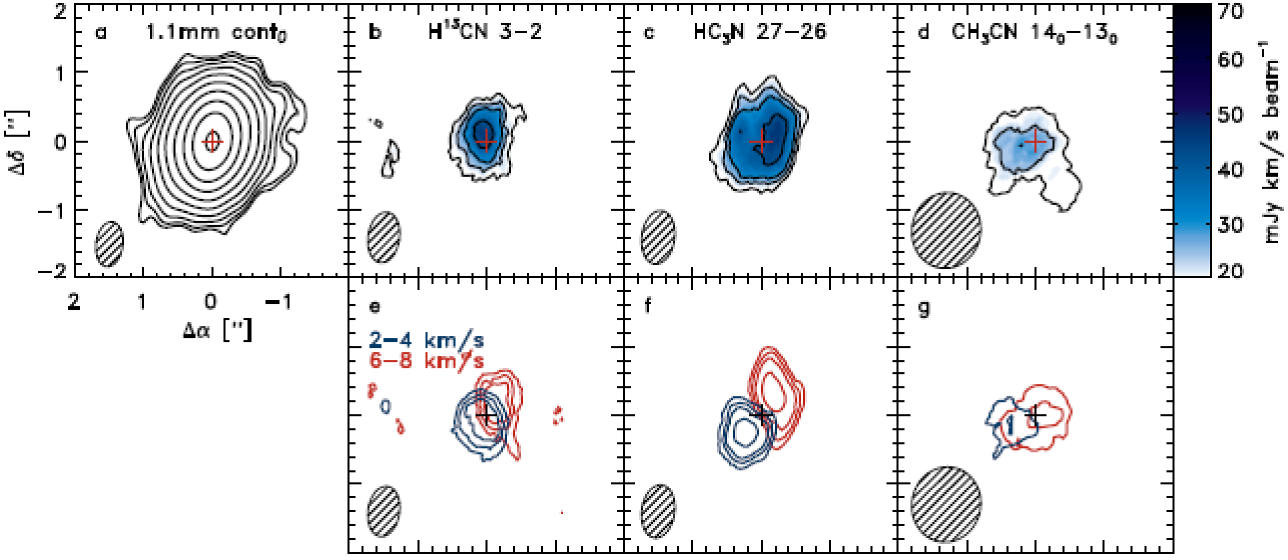


HD163296: *Matthews et al. 2013*

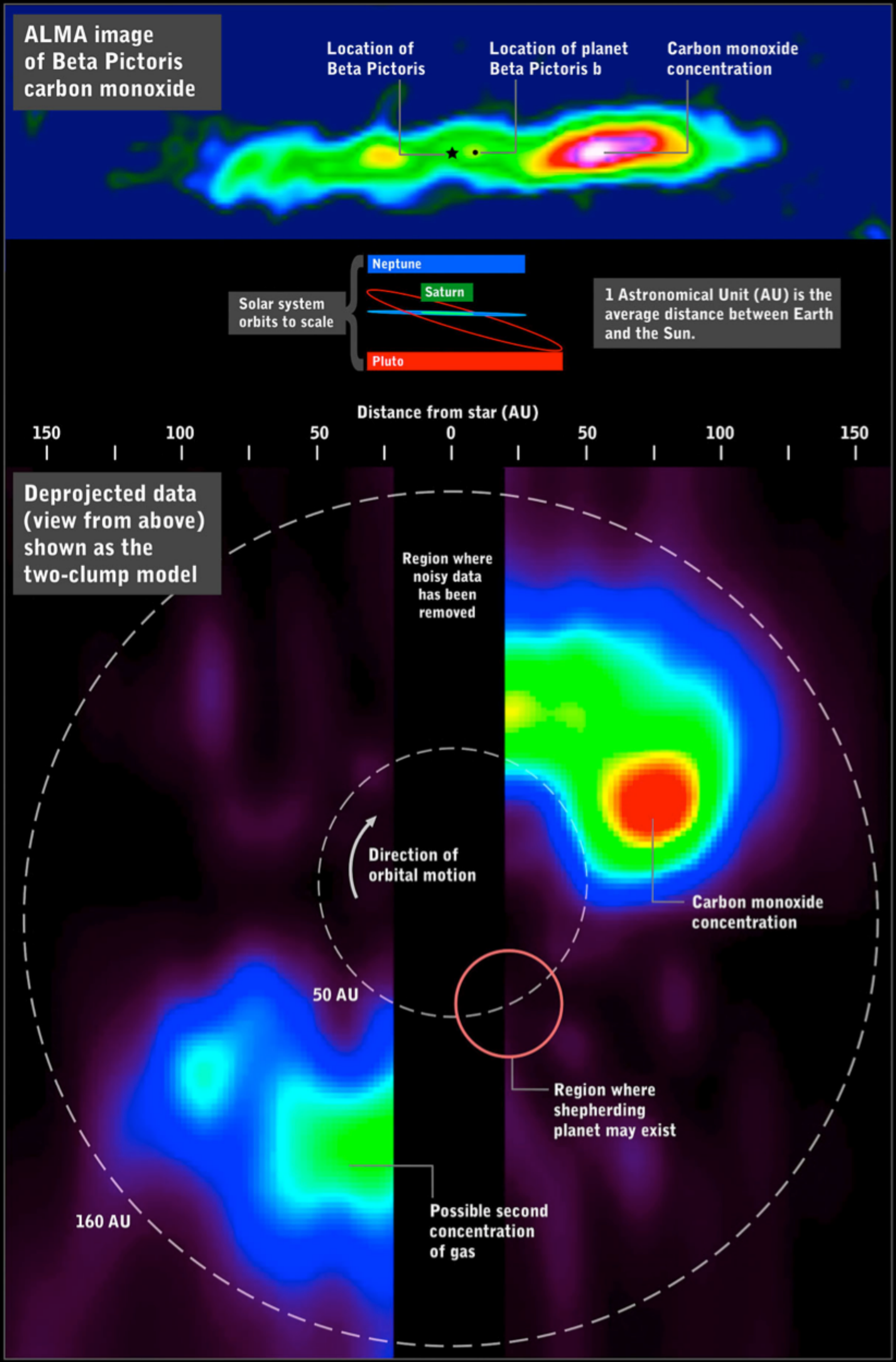
New molecules in disks

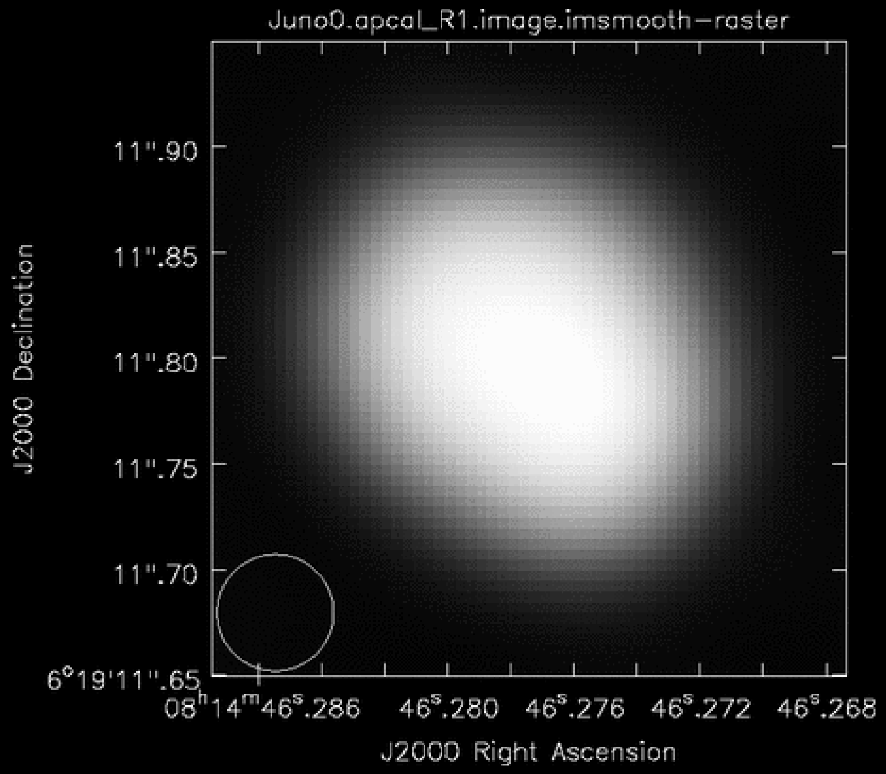


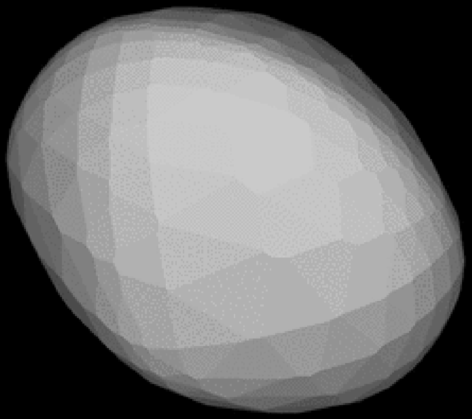
- ALMA observation of MWC480
- Detection of CH_3CN

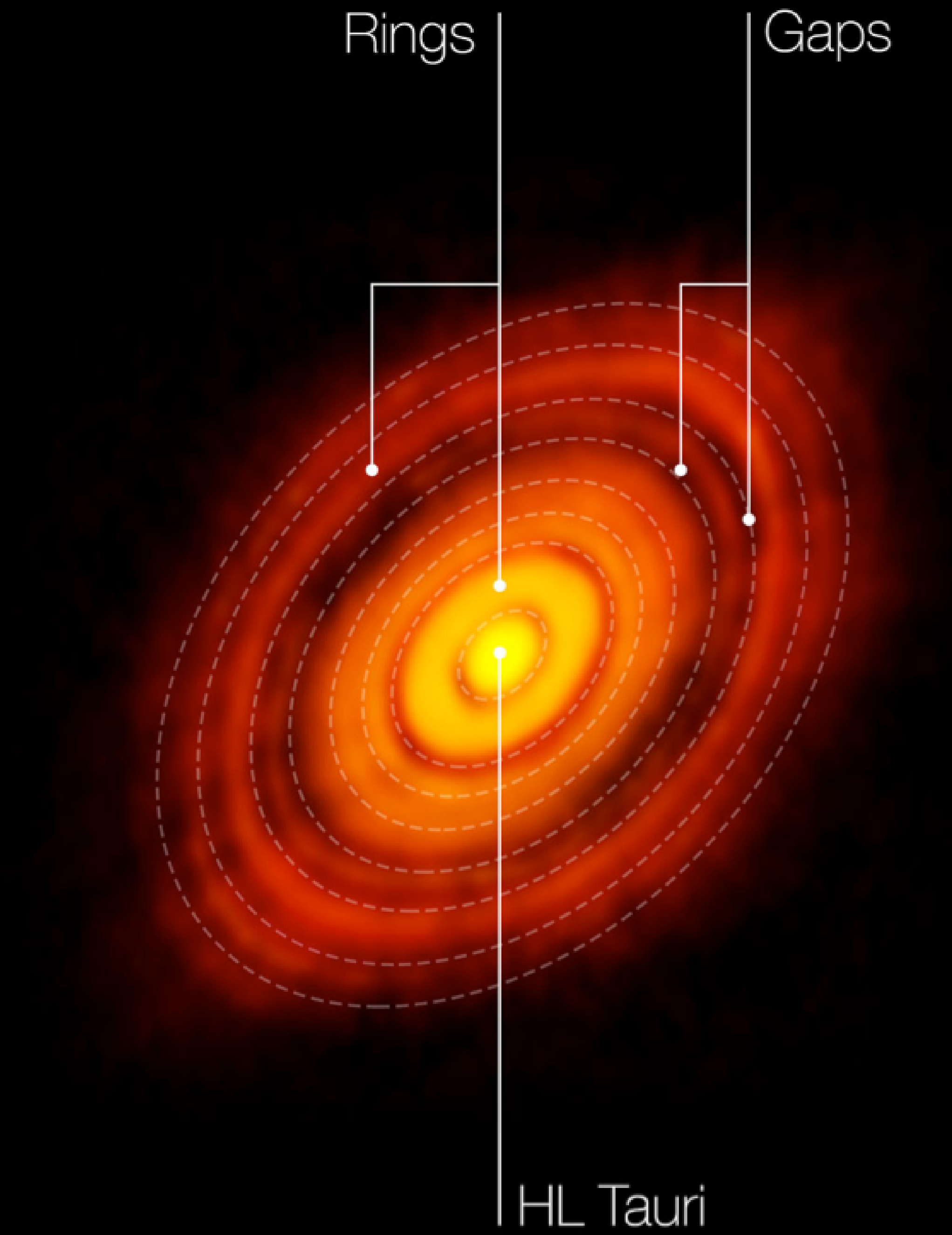


Oberg et al. 2015, Nature


ALMA image of Beta Pictoris carbon monoxide
Location of Beta Pictoris
Location of planet Beta Pictoris b
Carbon monoxide concentration
Solar system orbits to scale
Neptune
Saturn
Pluto
1 Astronomical Unit (AU) is the average distance between Earth and the Sun.
Distance from star (AU)
150
100
50
0
50
100
150
Deprojected data (view from above) shown as the two-clump model
Region where noisy data has been removed
Direction of orbital motion
Carbon monoxide concentration
50 AU
Region where shepherding planet may exist
160 AU
Possible second concentration of gas


Juno0.apcal_R1.image.imsmooth-raster
J2000 Declination
11".90
11".85
11".80
11".75
11".70
6°19'11".65
08h14m46s.286
46s.280
46s.276
46s.272
46s.268
J2000 Right Ascension




Rings
Gaps
HL Tauri

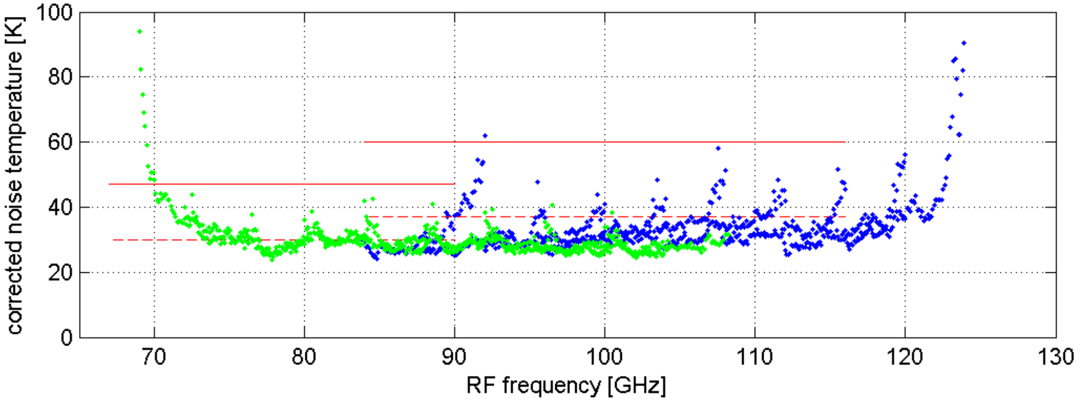
Summary

- Mm/sub-mm interferometry is similar in many aspects with lower frequency interferometry
  - You can use all the generic background of this school
- Smaller field of view, demanding on antenna performances.
  - To increase mapping speed, use focal arrays ?
- Needs cryo-cooled receivers
- Some specificies:
  - Atmosphere:
    - Absorbing incident radiation and emitting (noise)
    - Corrupting the astronomical phases
    - But one can use radiometers
- Not so much RFI so far, but this may (will ?) change

NOEMA receivers

- Receivers are 2 polar x 2 sidebands x 8 GHz = 32 GHz/ant.

NOEMA receivers		
Band 1	3 mm	72-116 GHz
Band 2	2 mm	127-179 GHz
Band 3	1.3 mm	200-276 GHz
Band 4	0.8 mm	275-373 GHz



NOEMA Band 1 72-120 GHz

NOEMA correlator: PolyFix

- New generation correlator based on FPGAs
- Simultaneous continuum and line capabilities
- Up to 150000 spectral channels

Mode 1 : continuum + lines	complete 16 GHz coverage in each polarization with 2 MHz channels
	AND
	128 windows of 64 MHz (= 8 GHz coverage) with 62.5 kHz channels, each window tunable individually in steps of 64 MHz*
Mode 2 : survey mode	complete 16 GHz coverage in each polarization with 250 kHz channels
Mode 3 : continuum + high-resolution lines	same as mode 1, but with 64/32/16** windows of 64 MHz with 32/15/8 kHz channels

** Number of windows may eventually be lower

NOEMA - summary

- NOEMA optimized for millimeter domain + intermediate angular resolution (compared to 30m/ALMA)

- Post-ALMA technology
  - 2x8GHz 2SB receivers
  - FPGA-based correlator

- NOEMA vs ALMA: complementarity + unique features
  - Northern hemisphere
  - Optimized for mm/surveys/spectral surveys
  - Easier access for French community

- Long term: equip antennas with multi-beams?