Observing in the (sub-)mm windows

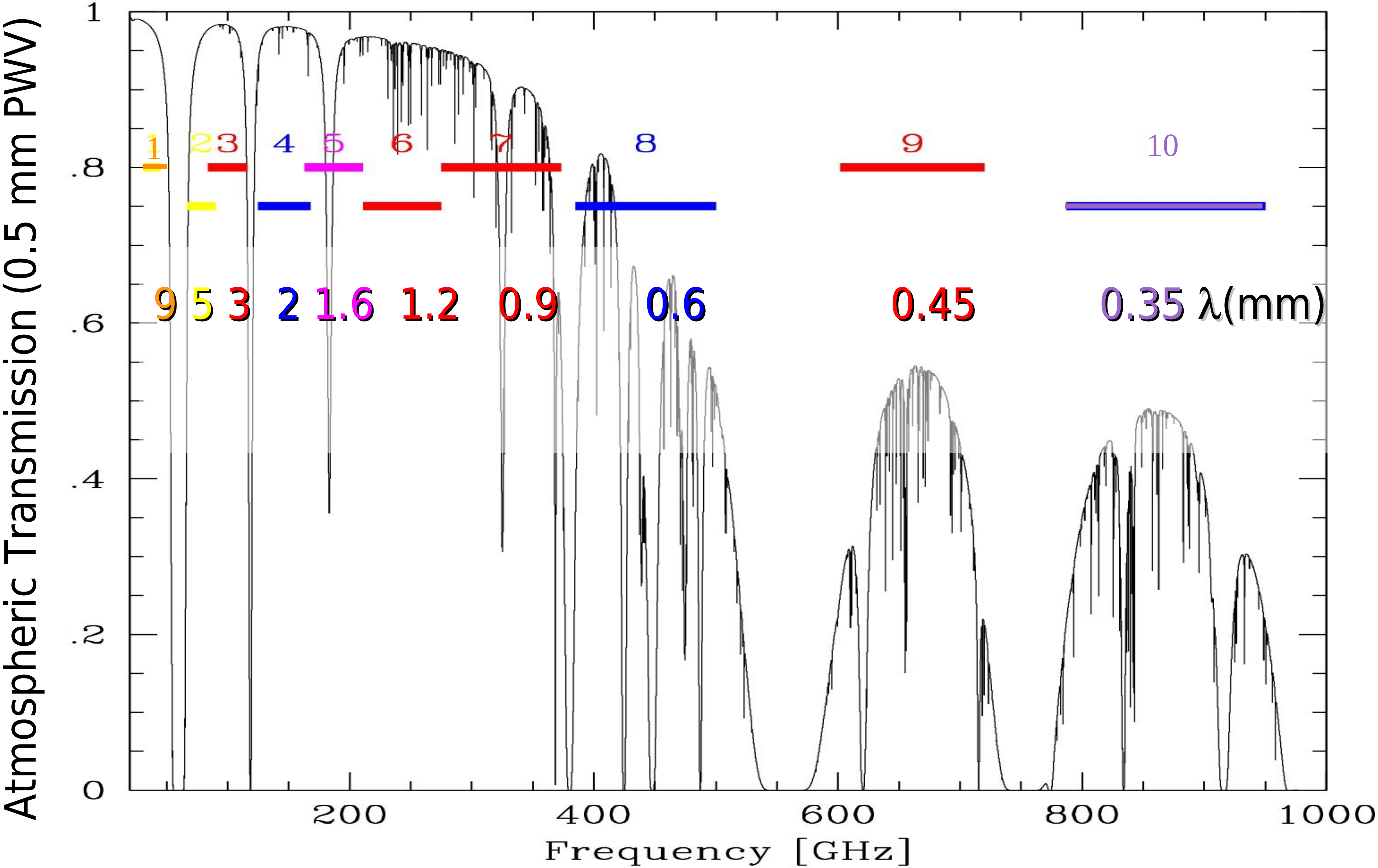
Anita Richards
UK ALMA Regional Centre
Jodrell Bank Centre for Astrophysics University of Manchester
thanks to Robert Laing, Melanie Krips, Crystal Brogan et al.

ALMA
EUROPEAN ARC
ALMA Regional Centre || UK

eMERLIN
EUROPEAN VLBI NETWORK
IVOA
RadioNet

MANCHESTER 1824 The University of Manchester
UNIVERSITY OF OXFORD
UNIVERSITY OF CAMBRIDGE
UK Astronomy Technology Centre
Rutherford Appleton Laboratory
Science & Technology Facilities Council

(sub-)mm windows & ALMA bands



International radio arrays

Operating at >65 GHz

Space VLBI (Russia/Japan/ Global)

WSRT (NL)

e-MERLIN (UK)

LOFAR (NL/W.Europe)

EVN /GMVA ~86 GHz

VERA (Jap)

IRAM/ NOEMA ~370 GHz (F)

VLBA 86 GHz (USA)
SMA 700 GHz
CARMA 270 GHz

KVASAR

KVN 129 GHz Korea

VLA(USA/Mexico)

GMRT (India)

And more being developed all the time!

ALMA ~950 GHz (ESO/N.America /E.Asia/Chile)

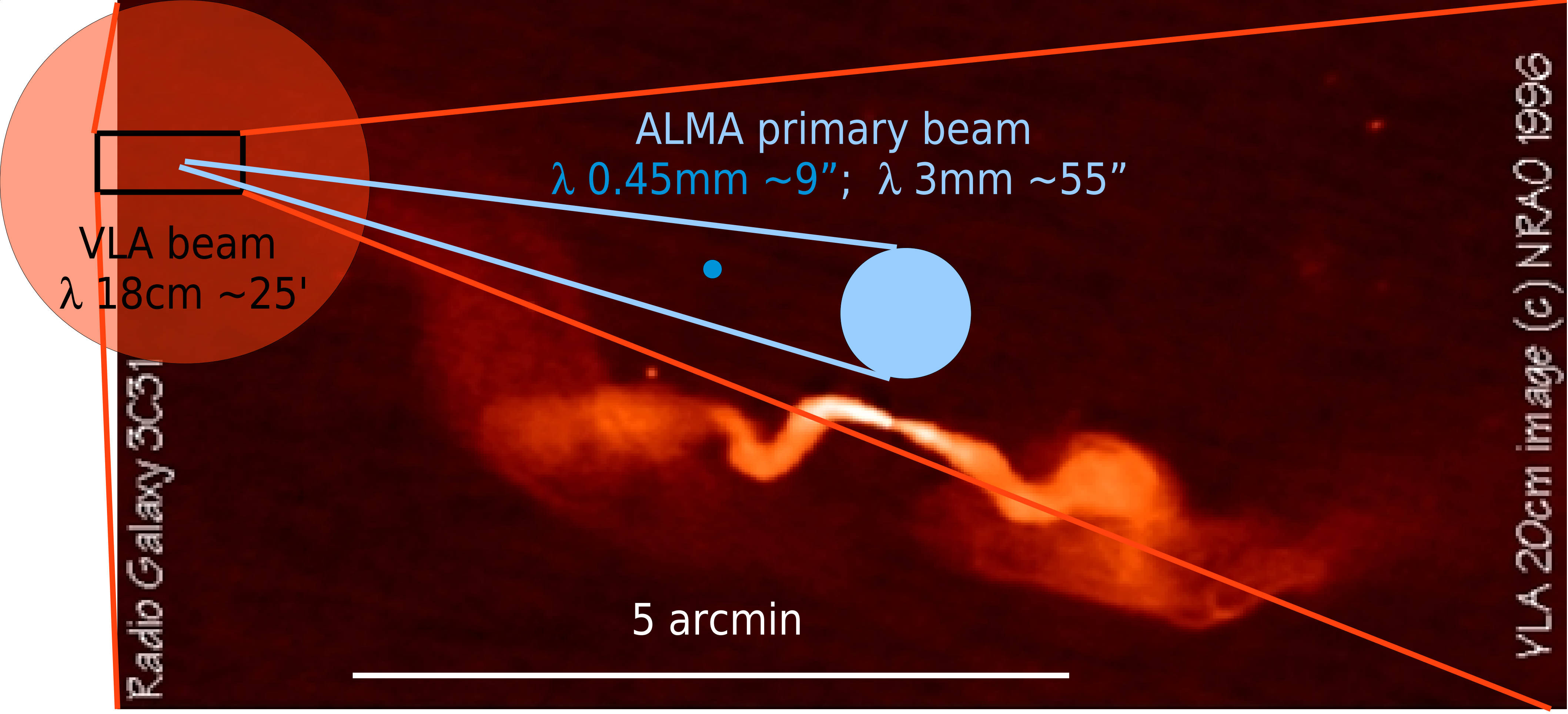
ATCA ~86 GHz
LBA (Aus)

SKA and pathfinders (S.Africa/Aus/Global; project office UK)

Global Very Long Baseline Interferometry

High-frequency considerations

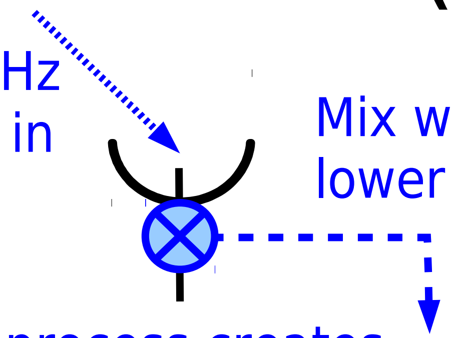
- Same principles as any radio interferometry
  - Technology differences e.g. 2 sidebands, polarization
- You are *unlikely* to be bothered by:
  - Ionosphere ($\delta delay_{ionosphere} \propto \lambda^2$)
  - Confusion ($\Theta_{PrimaryBeam} \sim \lambda/B$ ~ 55" @ 3mm, 12-m dish)
    - Most bright extragal. sources have $\alpha<0$ where $S \propto \nu^{\alpha}$
- You *will* suffer from:
  - Small field of view ($\Theta_{PrimaryBeam}$ ~9" @ 0.45 mm)
    - Calibration sources few, extended &/or variable
    - ALMA pointing must be good to 2 arcsec rms
  - Tropospheric refraction ($\delta\phi_{troposphere} \propto 1/\lambda$)
    - phase affected, amps if signal decorrelates
  - Tropospheric absorption and emission
    - amplitudes affected



- Small field of view ($\Theta_{PrimaryBeam}$ ~9” @ 0.45 mm)
  - Calibration sources few, extended &/or variable
- Tropospheric refraction ($\delta delay_{troposphere} \propto 1/\lambda$)
  - phase affected, amps if signal decorrelates
- Tropospheric absorption and emission
  - amplitudes affected

(sub-) mm signal transport

100s GHz
radio ν in

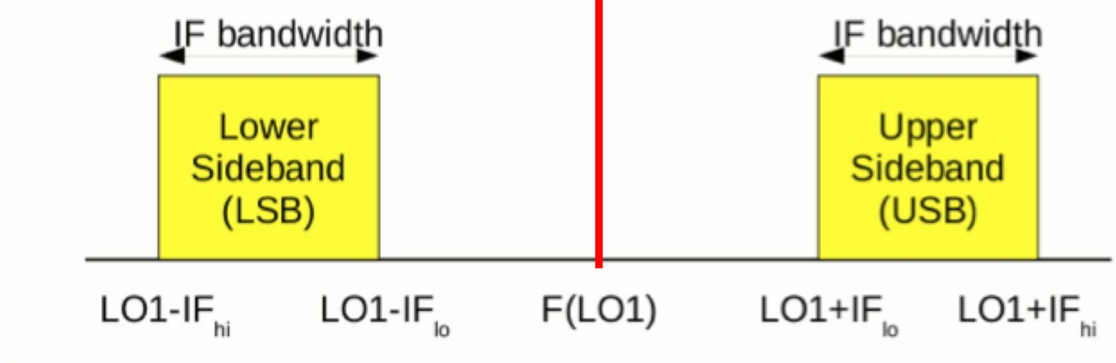


Mix with Local Oscillator signal: downconvert to lower ν optimised for low-noise amplifiers etc.

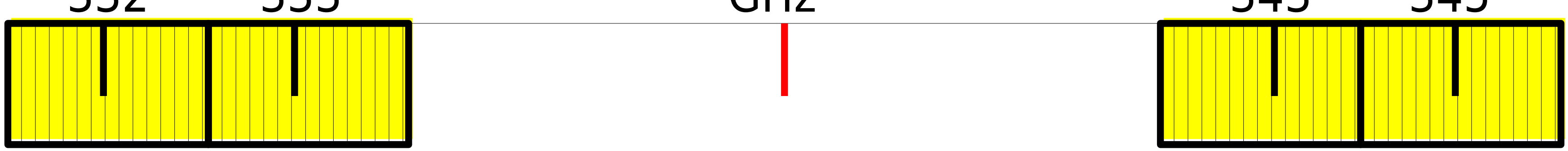
Mixing process creates two sidebands, initially superimposed.

After mixing, freqs near F(LO1) are close to DC, cannot be used

Sidebands can be separated electronically at ≲600 GHz. At higher ν, you can have separate basebands in either sideband; 'image' signal suppressed by rotating phase; noise remains.



Sideband spacing fixed, e.g. centres separated by 12 GHz in ALMA Band 7
Sideband width fixed e.g. 4 GHz



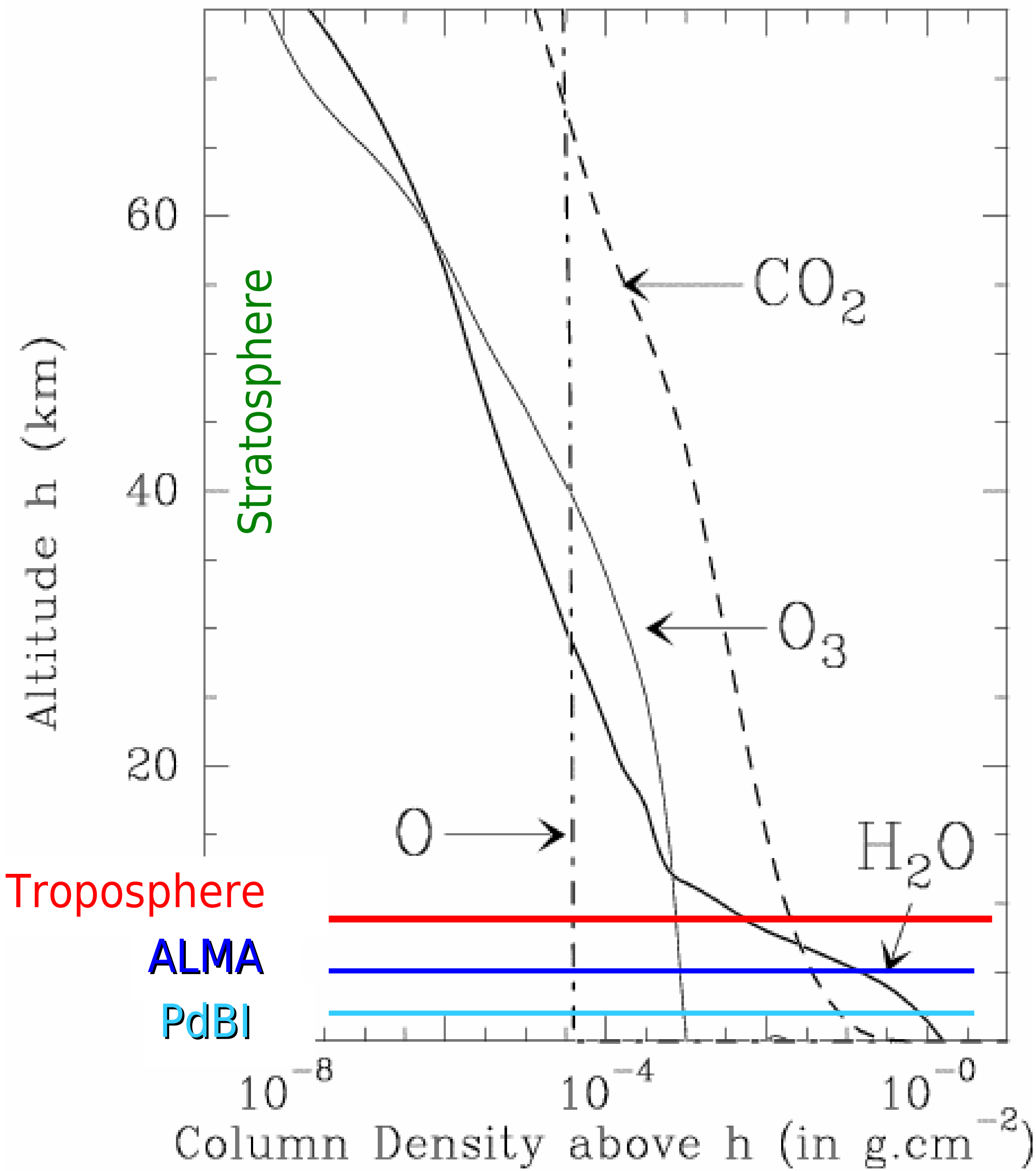
Baseband Baseband

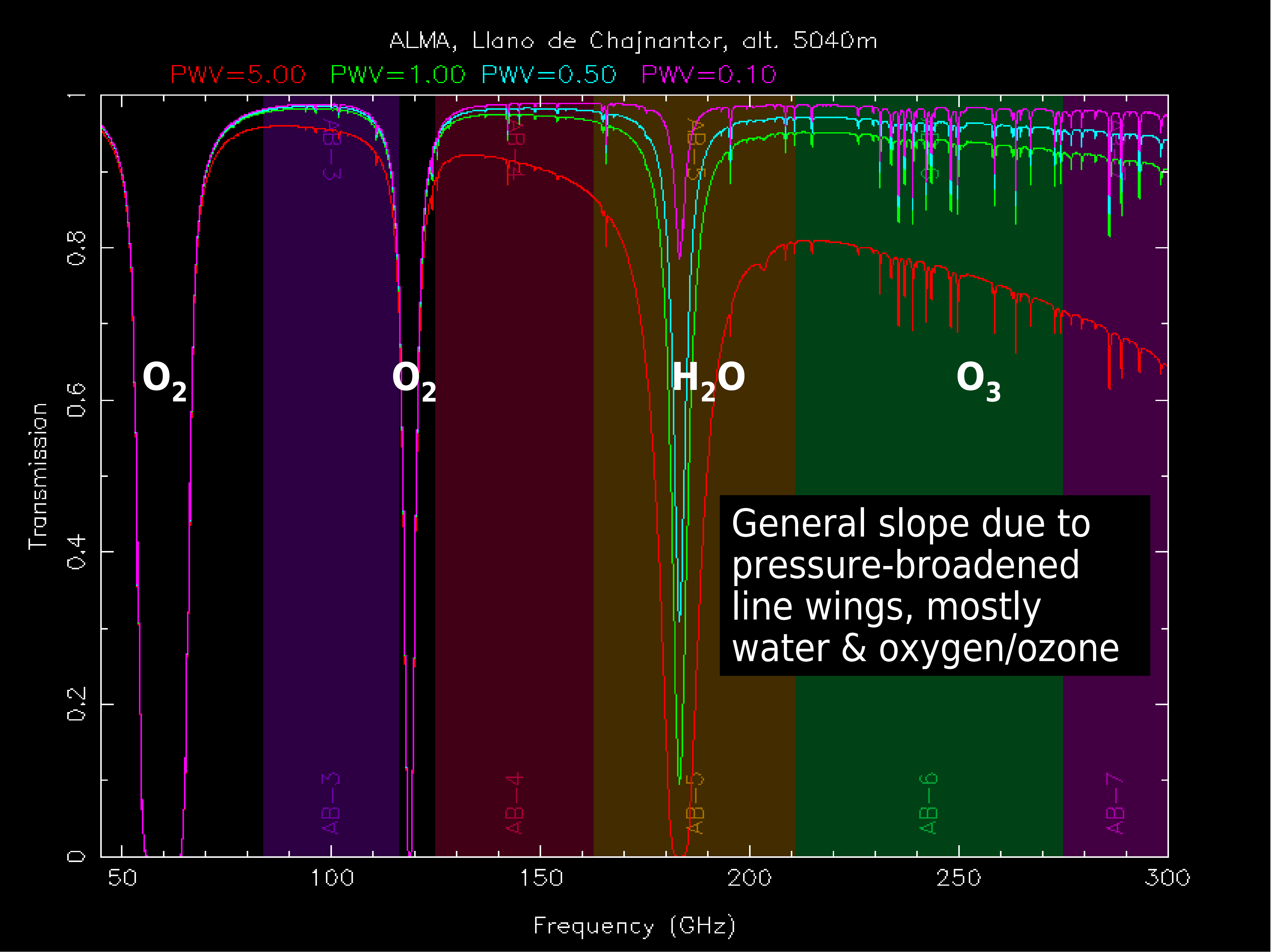
Each ALMA B7 sideband has 2 basebands (BB)
Each BB may contain 1, 2, 4... spectral windows (spw)
Each spw can contain many channels

Atmosphere

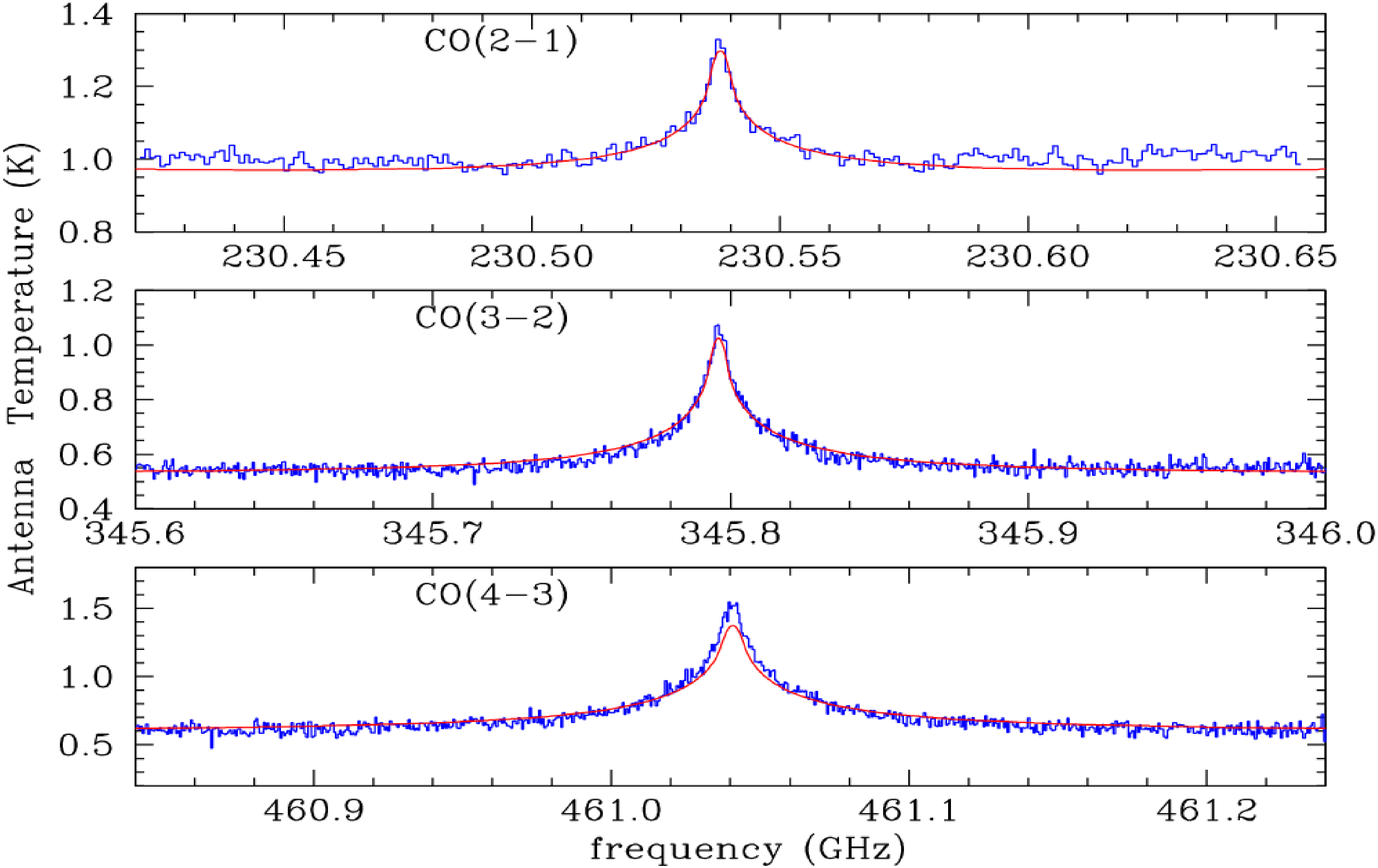
- 'Dry' component:
  - Worst O_2, O_3
- 'Wet' component:
  - H_2O vapour/clouds
  - Highly turbulent layer
    - Measure PWV = precipitable water vapour
- Atmospheric depth increases at lower elevation
  - Larger zenith distances *z*

Column density as function of altitude




ALMA, Llano de Chajnantor, alt. 5040m
PWV=5.00 PWV=1.00 PWV=0.50 PWV=0.10
Transmission
Frequency (GHz)
0
0.2
0.4
0.6
0.8
1
50
100
150
200
250
300
AB-3
AB-4
AB-5
AB-6
AB-7
O_2
O_2
H_2O
O_3
General slope due to pressure-broadened line wings, mostly water & oxygen/ozone

Calibration sources have lines too



Neptune *Marten et al. 2005*

Refractive phase error

- Electro-magnetic wave propagates distance d through medium with refractive index n

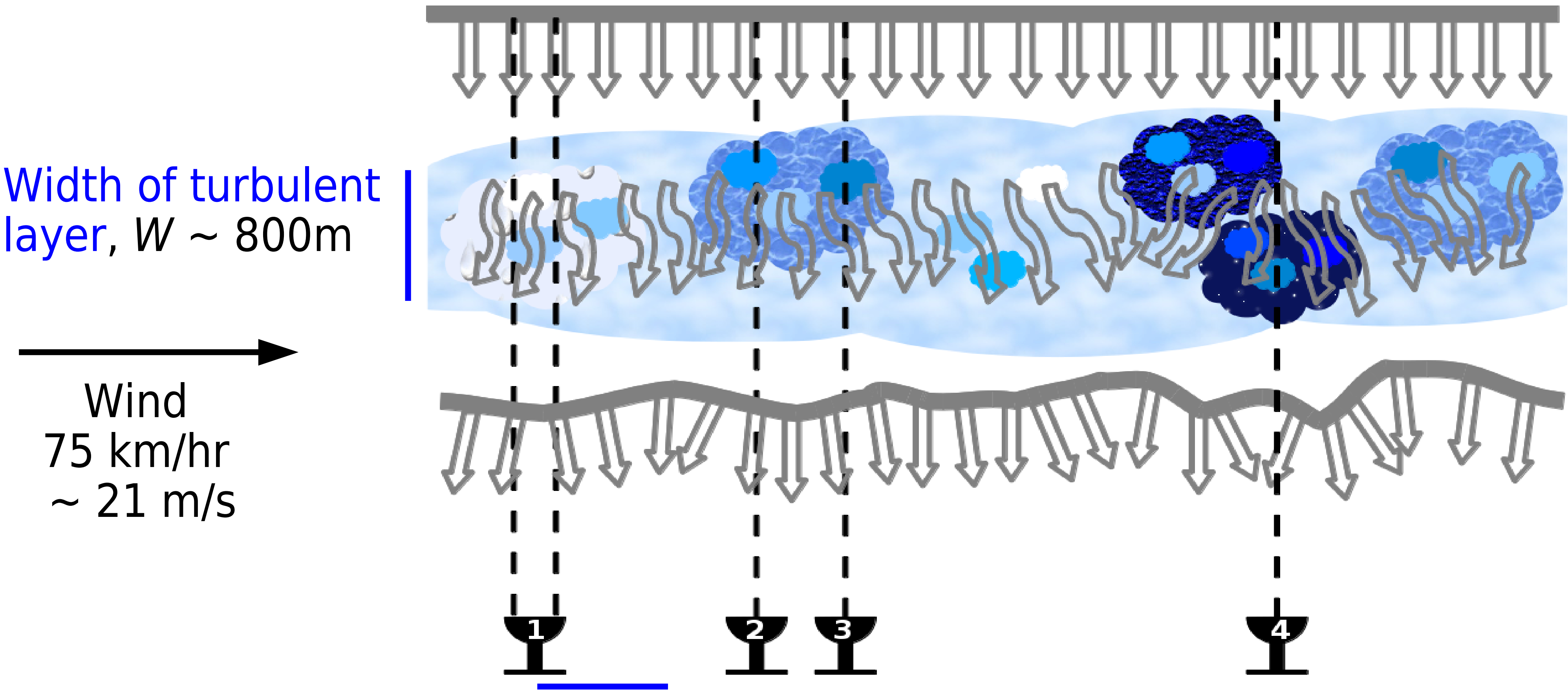
  $(1+n_{H2O}) \propto$ PWV / $d\ T_{atm}$
  - where PWV=precipitable water vapour column at atmospheric temperature T_{atm}
    - Refractive index mostly constant >100 GHz
- Total phase error $\Phi_e \propto (2\pi/\lambda)\ (1+n_{H2O})d$

  $\propto (2\pi/\lambda)$ PWV/ T_{atm}
- Average, *total* PWV and dry component effect on delay and pointing corrected on-line for ALMA
  - 1 mm PWV ~ 7 mm extra path ~ 0.023 ns delay
  - Snell's Law: $\sin(i_{n1})/\sin(i_{n2}) = n1\ /\ n2$

    Refraction angle $\delta\theta \sim \delta n \tan(i)$

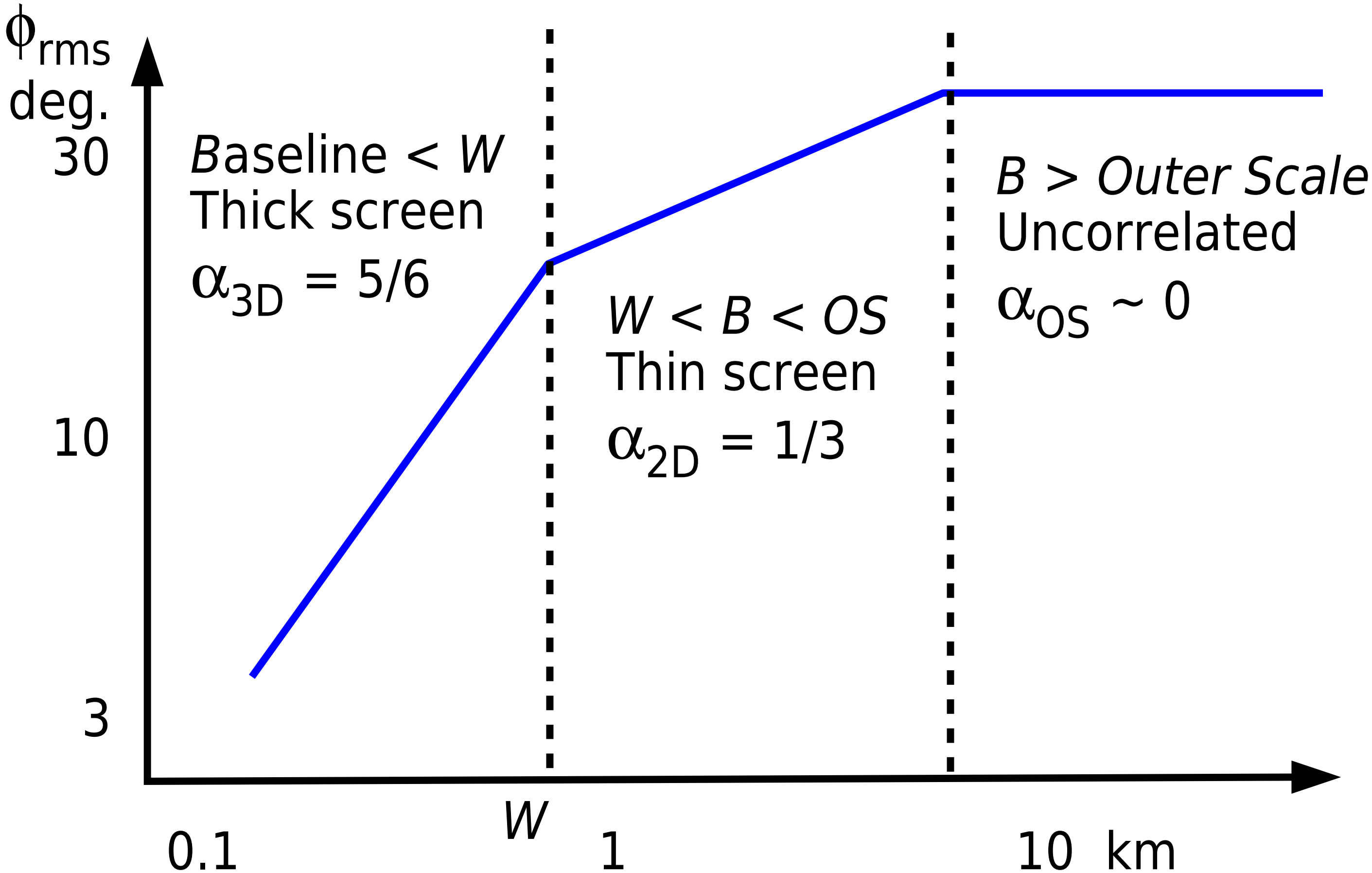
    $\delta\theta$ < arcmin for ALMA

Troposphere variability scales



- Isoplanatic patch > sky area above single mm antenna
- Antennas 1, 2, 3 see slightly different disturbances
- Sky above antenna 4 very different, varies independently

Kolmogorov turbulence



Kolmogorov prediction (*Coulman*'*90*)

$$\varphi_{rms} = \frac{K}{\lambda} B^{\alpha}$$

where K~100 at ALMA for λ in mm and α depends on the length of baseline B compared with W, the thickness of the turbulent layer

- Baseline 2-3 < W
  - Phase noise ϕ_{rms} increases as $B^{5/6}$
- Baselines 1-2, 1-3 > W but < OS: $\phi_{rms} \propto B^{1/3}$
- Baselines 4-* in outer scale regime: ϕ_{rms} levels off

Variation in atmospheric refraction

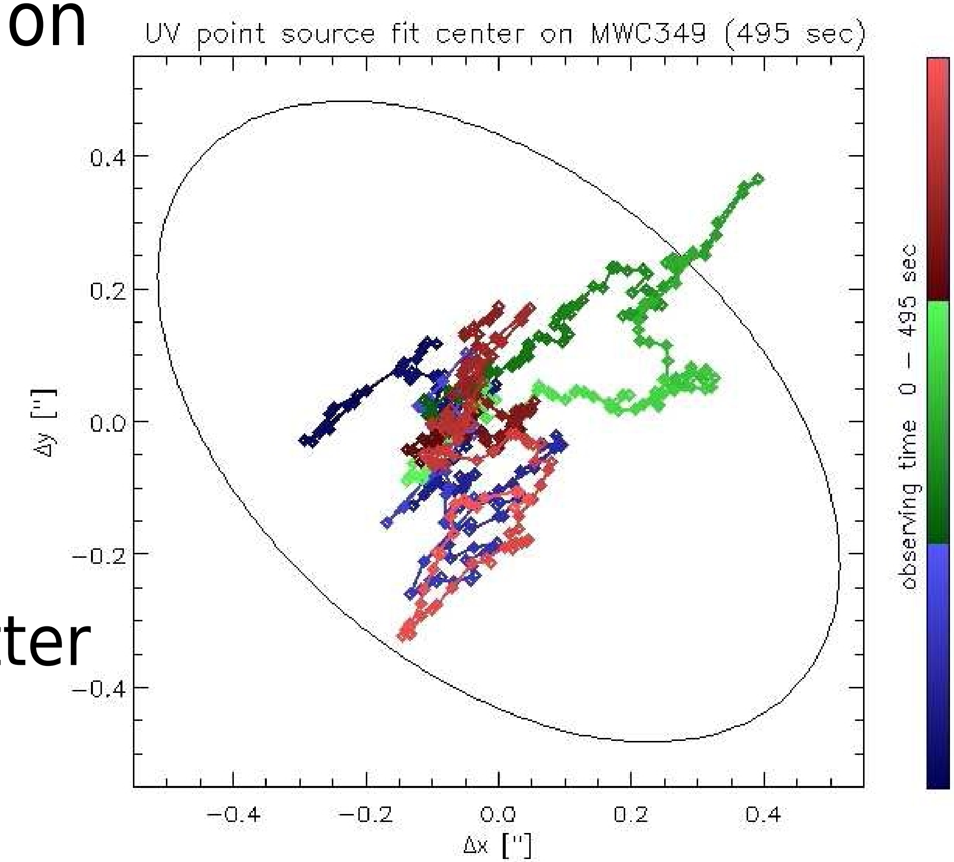
- Phase fluctuations shorter than integration time cause irreversible decorrelation
  - Visibility $V = V_o e^{i\phi}$

    $$\langle V \rangle = V_o \langle e^{i\varphi} \rangle = V_o e^{-(\varphi_{rms}^2)/2}$$

    ϕ_{rms} in radians
    Lose 5% amplitude for 5^o ϕ_{rms}
- Fluctuations on time-scales of few sec: raw data position jitter

$$d\theta = \frac{10^6 \lambda}{\left(1.2 \frac{\lambda}{180/\pi \ K}\right)^{(1/\alpha)}} \quad \text{rad}$$

$d\theta$ ~ 300 mas for λ 1mm, K 100, α 5/6



Position per integration fit to PdBI *uv* data (courtesy *Krips*)

Absorption and emission

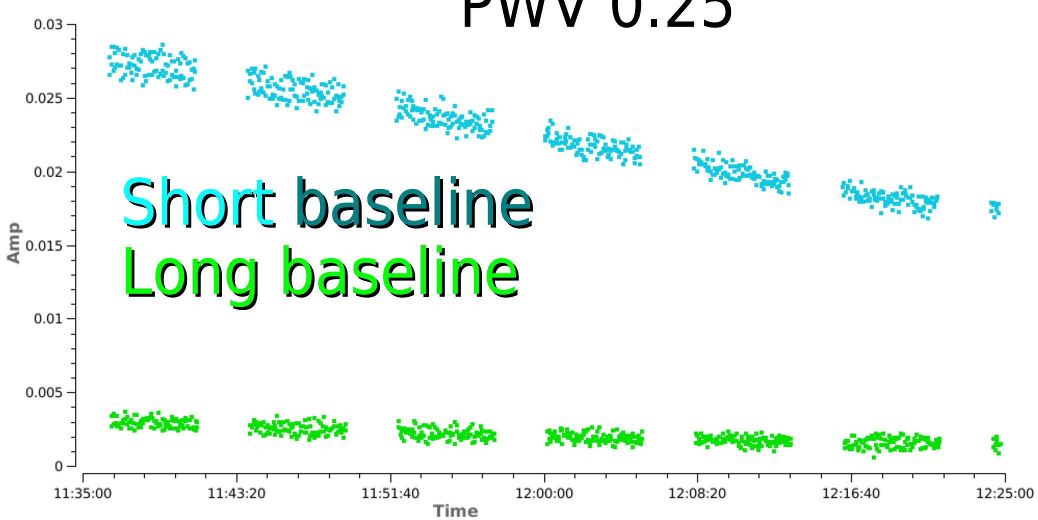
- The atmosphere both absorbs the astrophysical signal, and adds noise

$$T_{received} = T_{source} e^{\tau_{atm}/\cos z} + T_{atm} \left(1 - e^{\tau_{atm}/\cos z}\right)$$

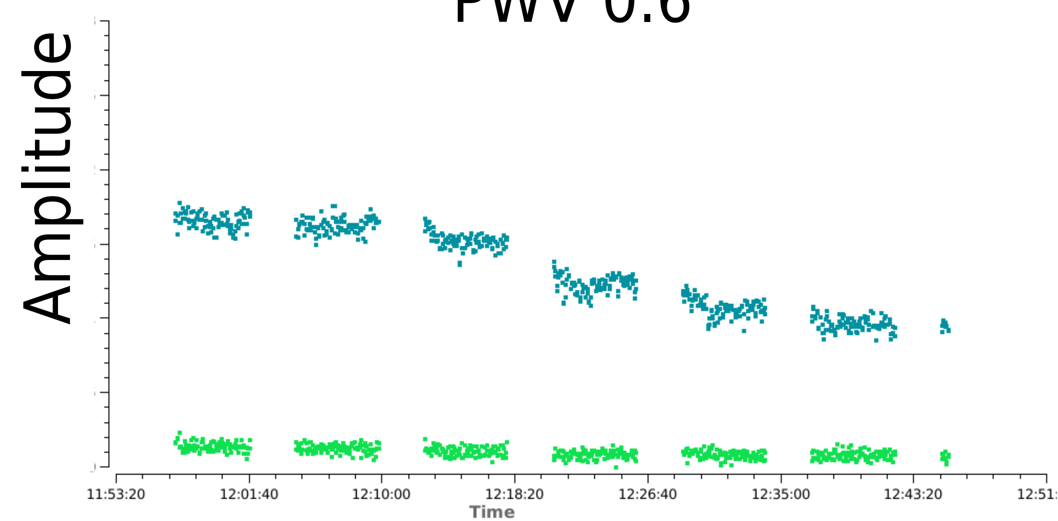
where the source would provide temperature T if measured above the atmosphere and z is the zenith distance

- Same source, same baselines
  - Raw amplitudes significantly lower at higher PWV

PWV 0.25



PWV 0.6

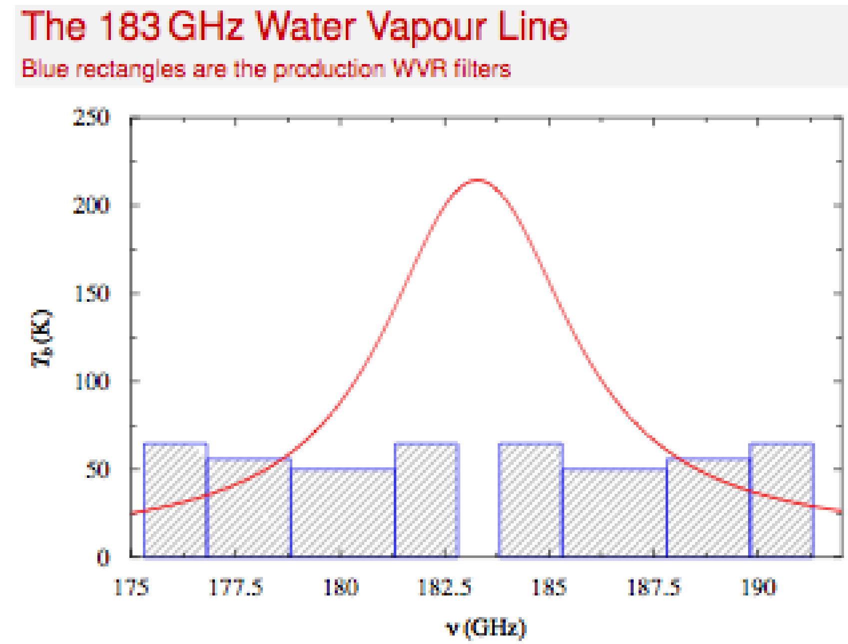


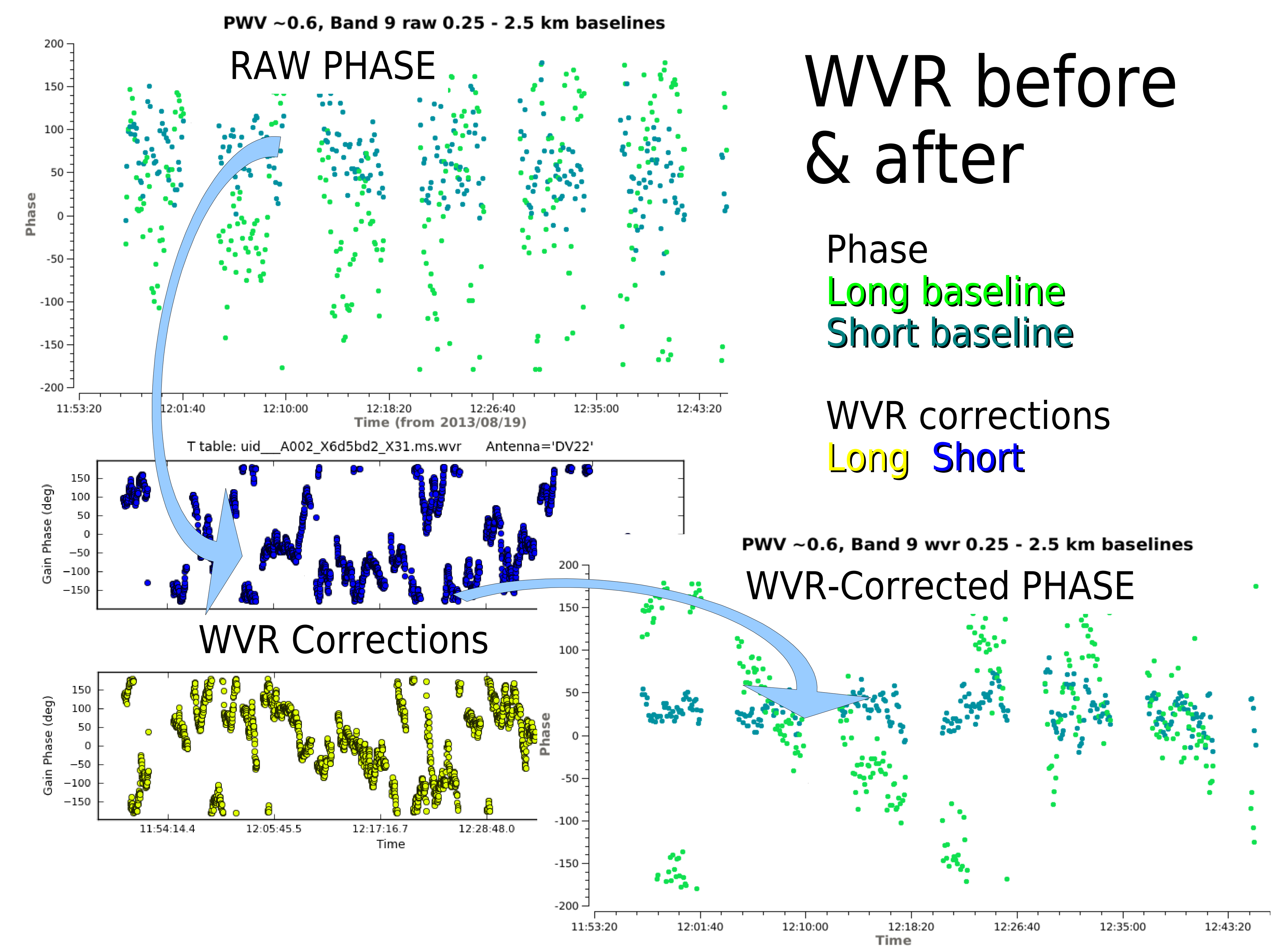
Water Vapour Radiometry

- Each ALMA 12-m has water vapour radiometer
- ~1-sec integrations
  - Close to 183-GHz line
- Recorded in dedicated spw
- n_{H2O} ~constant at ν>100 GHz
  - Except near strong H_2O lines
- ALMA scales phase correction per band

$$\Phi_e \propto (2\pi/\lambda)\ \mathrm{PWV}$$

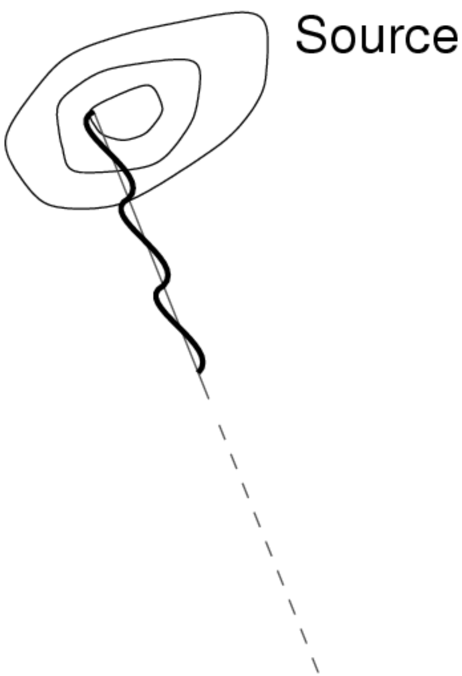
  - Apply during data processing (at present)
- PdBI measures PWV at 22 GHz, corrects amplitudes

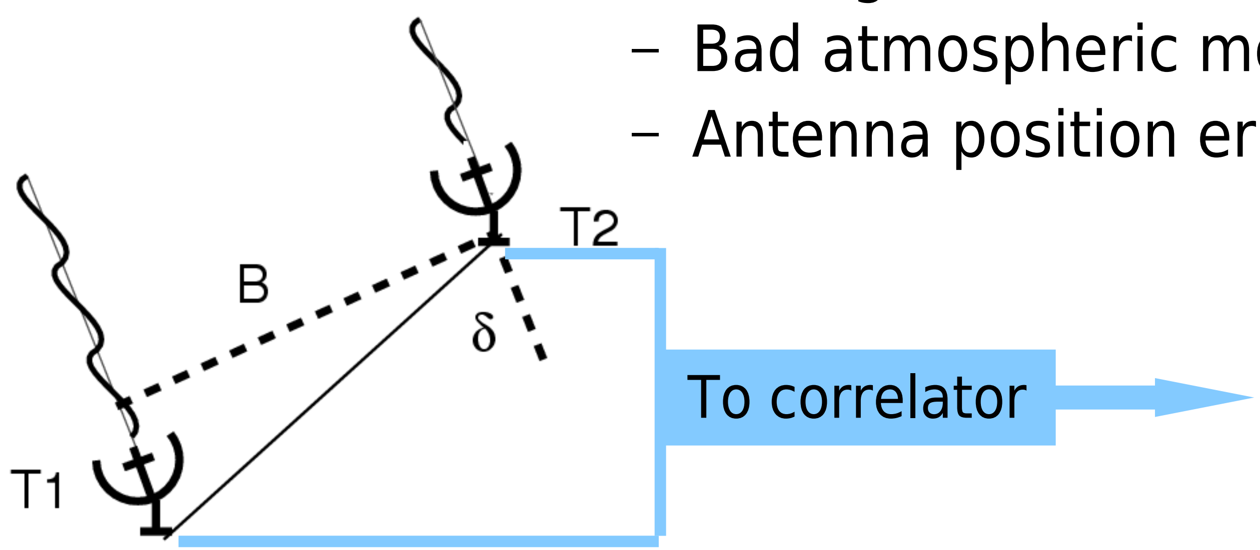



WVR before & after
Phase
Long baseline
Short baseline
WVR corrections
Long Short
PWV ~0.6, Band 9 raw 0.25 - 2.5 km baselines
RAW PHASE
Phase
Time (from 2013/08/19)
T table: uid___A002_X6d5bd2_X31.ms.wvr Antenna='DV22'
Gain Phase (deg)
WVR Corrections
11:54:14.4
12:05:45.5
12:17:16.7
12:28:48.0
Time
PWV ~0.6, Band 9 wvr 0.25 - 2.5 km baselines
WVR-Corrected PHASE
11:53:20
12:01:40
12:10:00
12:18:20
12:26:40
12:35:00
12:43:20

Timing and antenna position errors

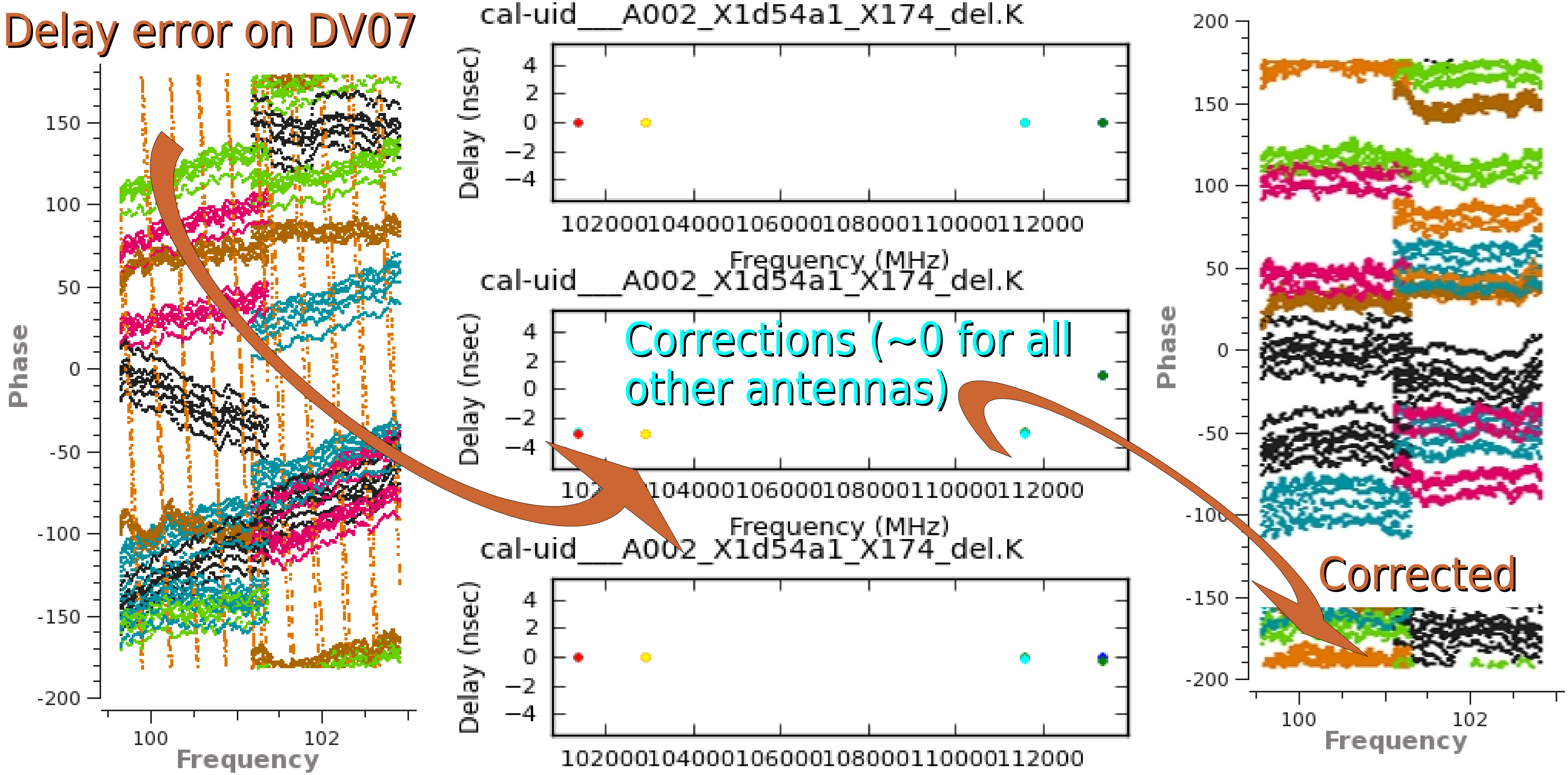
- Signals from off-centre source reach telescopes T1, T2 slightly out of phase
  - Geometric delay δ needs to be removed and travel-time from T1 and T2 to correlator equalised to preserve astrophysical phase
    - Delays added per-antenna before correlation
  - 1 ns delay error = $1/10^9$ = 1 GHz freq error
- Causes of delay error include:
  - Timing error in correlator
  - Bad atmospheric model
  - Antenna position error





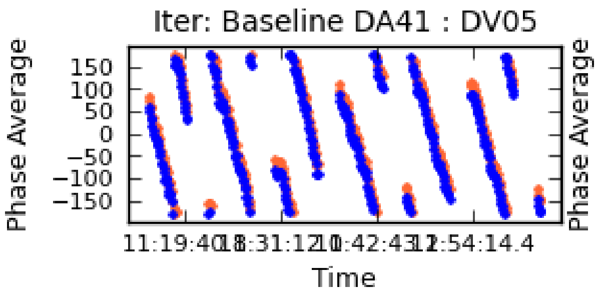
Delay error

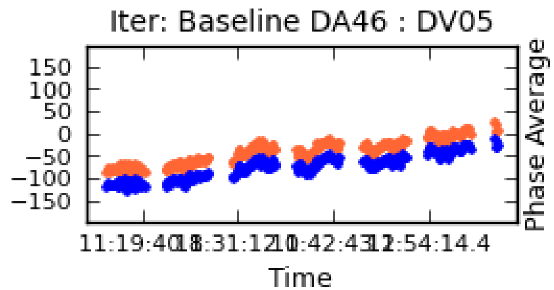
- Phase across 2 GHz undergoes 6 full turns on one antenna
  - Delay error $6/2\times10^{9} = 3$ ns

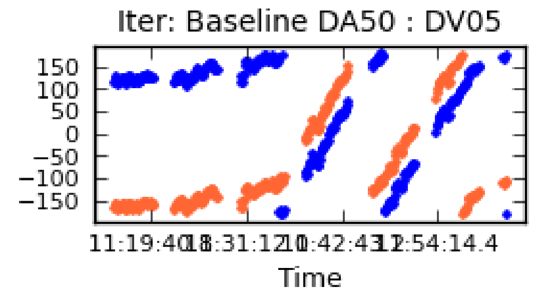


Two x 2-GHz spw. Each baseline is shown in a different colour

Antenna positions

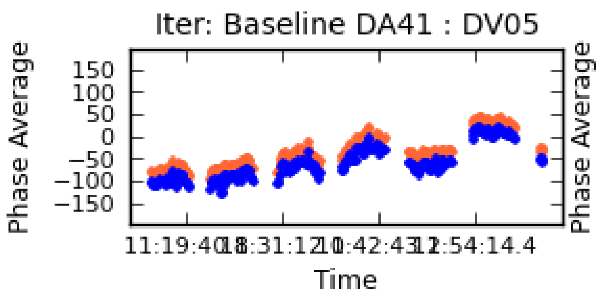


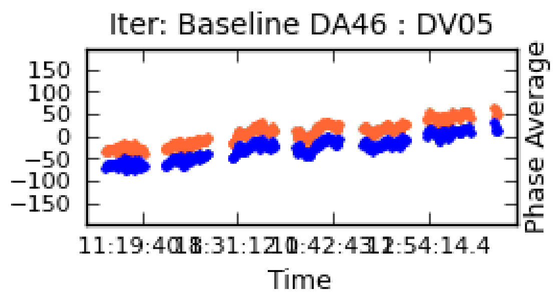


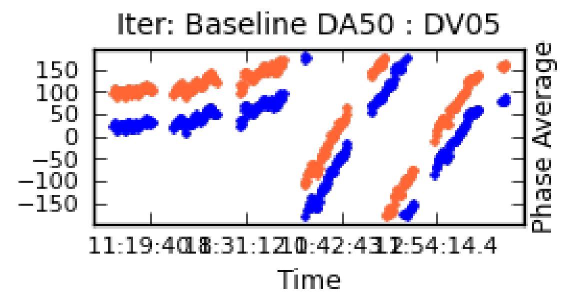


DA41 position error

DA50 ????





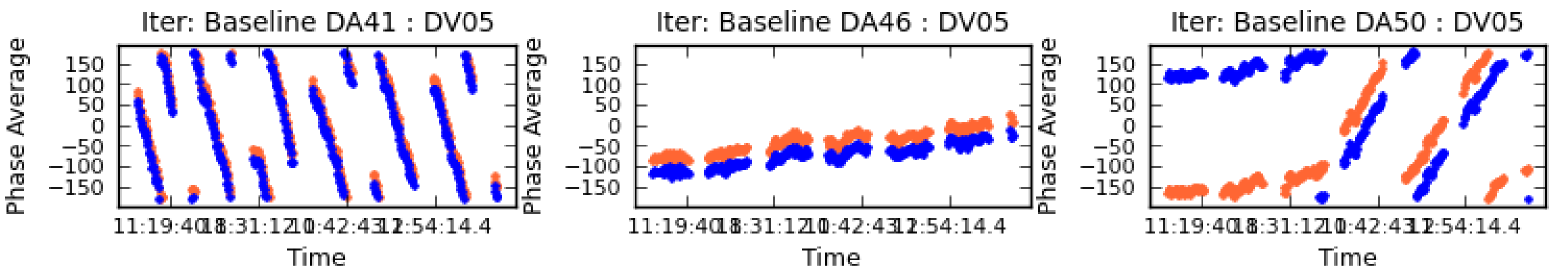


DA41 position corrected during data processing

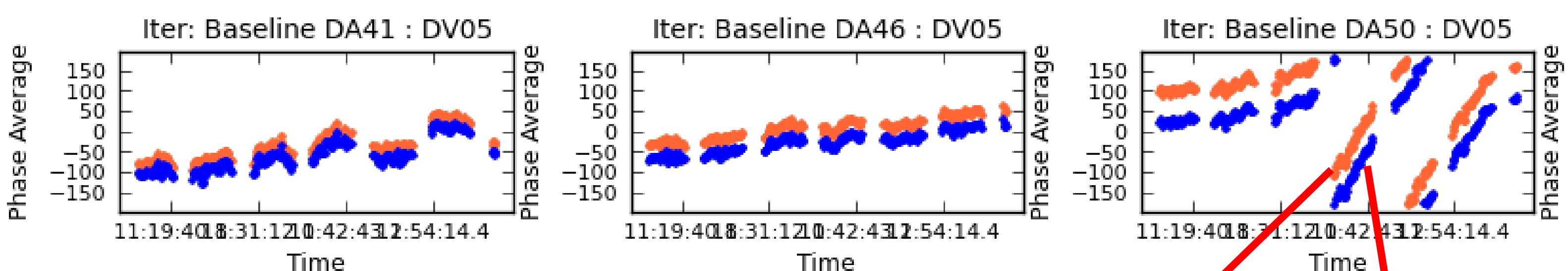
DA50 ????

- Antenna positions measured after every move
  - May need updating
  - DA41 ~10 cm position error ~ 0.33 ns delay error
  - Also causes time-dependent phase error
    - Incorrect model for updating geometric delay

Timing and antenna position errors



DA41 position error



DA41 position corrected

DA50 ????

Noise: recap and expand

- Noise σ_{sys} is given by $\sigma_{sys} = \frac{T_{sys}}{\eta_A A_{eff} \sqrt{N(N-1)/2 \ \ \Delta\nu \ \ \Delta t N_{pol}}}$

  antenna area A_{eff}, efficiency η_A

  N antennas, frequency span $\Delta\nu$, time span Δt, N_{pol} Rx pols

- System temperature T_{sys}

  $$T_{sys}(DSB) = \frac{1+g_{SB}}{\eta_A e^{-\tau_{atm}}}\left[T_{Rx} + \eta_A T_{sky} + (1-\eta_A) T_{amb}\right]$$

  contributions from Receiver, sky and 'ambient' e.g. hardware, ground temperature

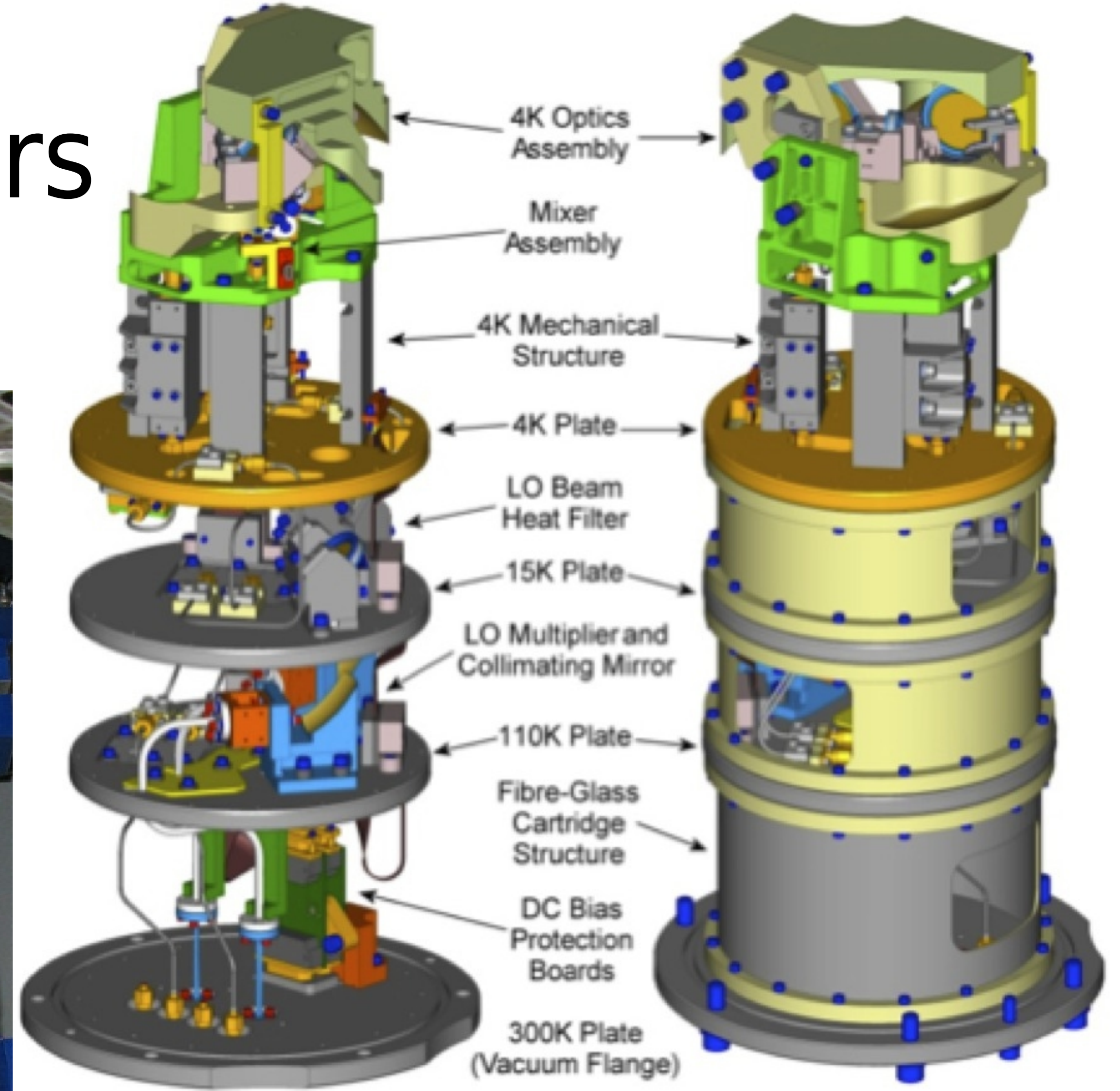
  - g_{SB} factor if there is an unwanted if sideband.

  g_{SB} =0 v. 1 in single/dual v. double sideband systems

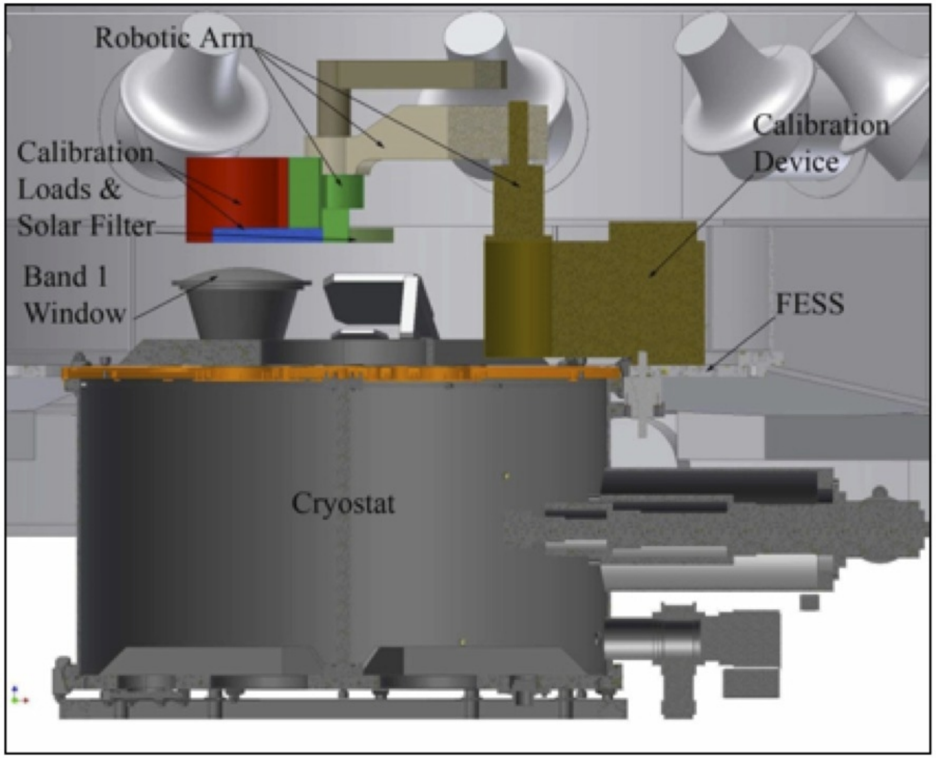
- Noise increases exponentially with opacity and zenith angle $T_{received} = T_{source} e^{\tau_{atm}/\cos z} + T_{atm}\left(1 - e^{\tau_{atm}/\cos z}\right)$

Receiver
cabin

Cooled Receivers

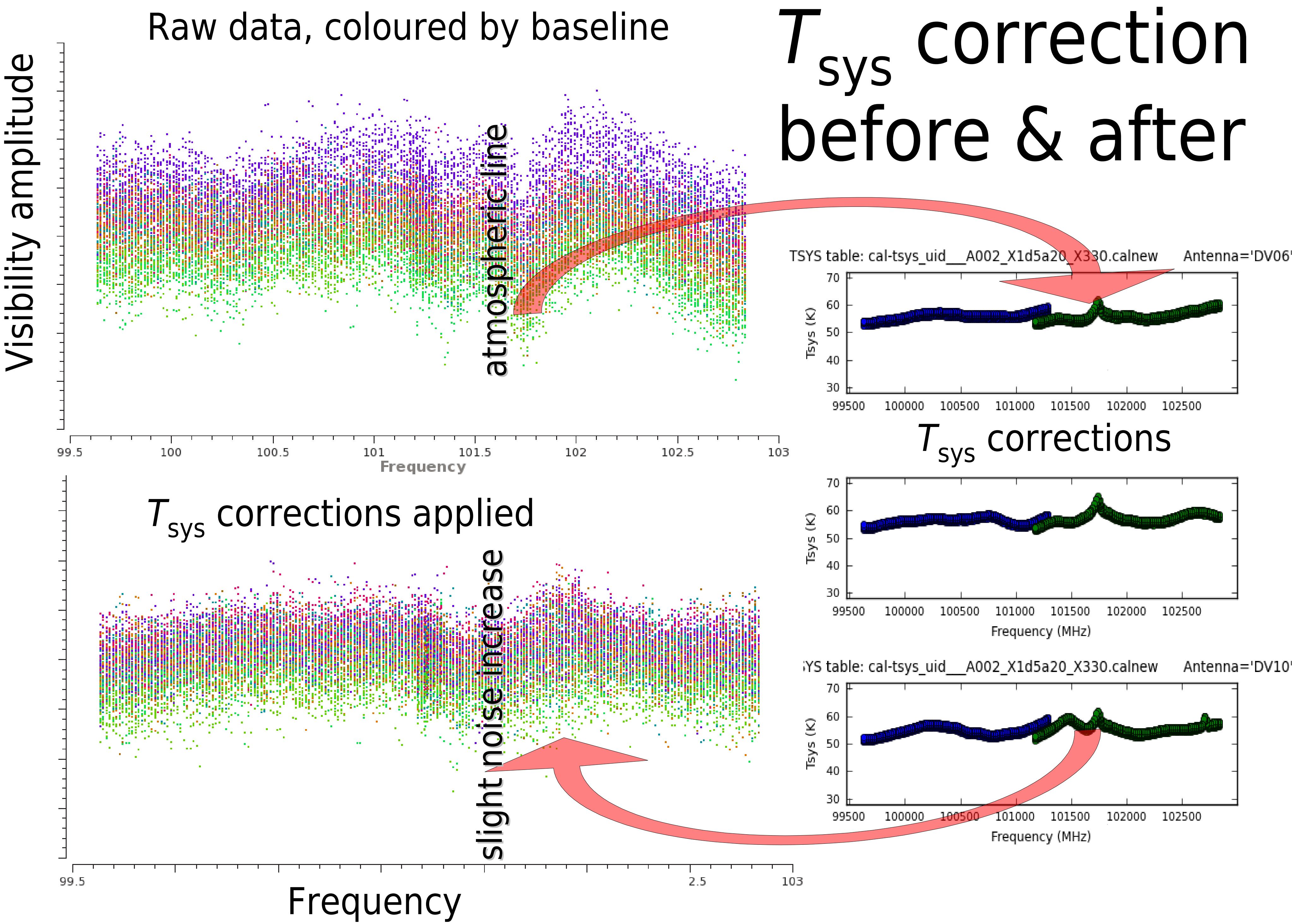


Measuring noise

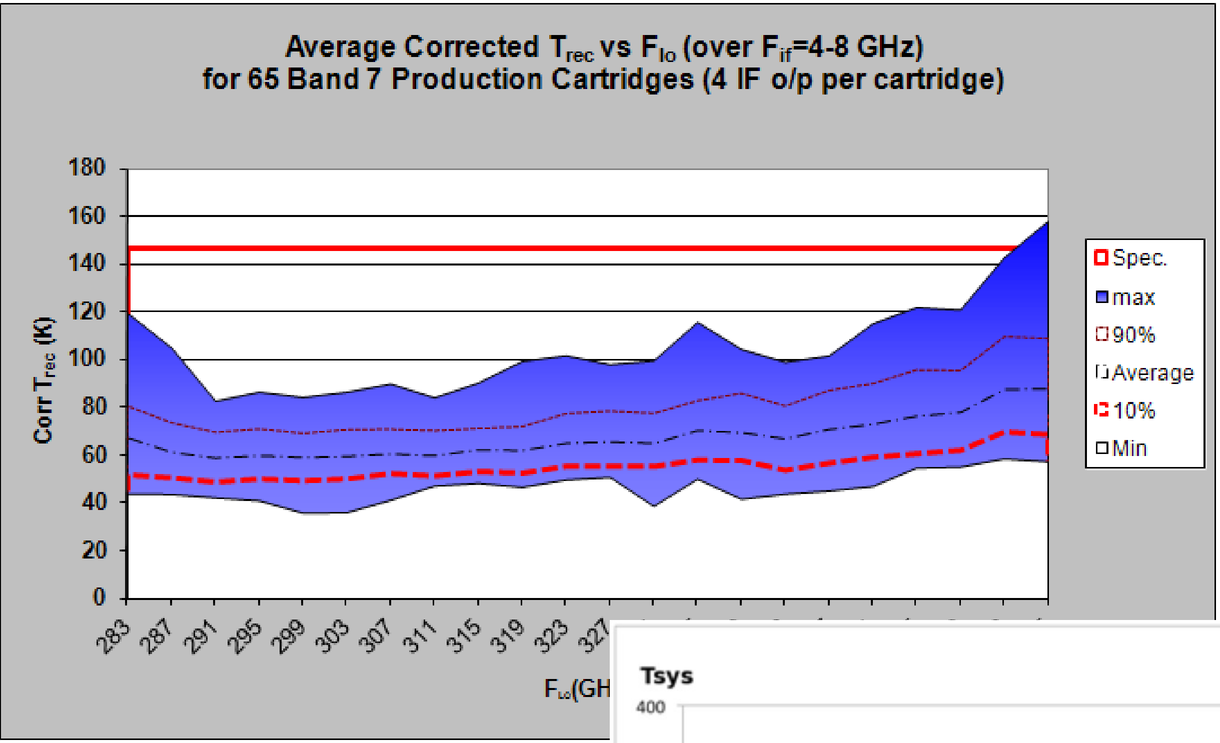


- ALMA uses cold/hot loads at ~293 K, ~353 K
  - Swing in and out of beam and measure voltage V

    $V_L = \alpha V_{cold} + (1-\alpha) V_{hot}$
    - Weight α is a function of the factors contributing to T_{sys} chosen so $V_L \sim V_{sky}$, minimising opacity dependence at weighted temperature T_{cal}
  - This leads to $T_{sys} = T_{cal} V_{sky}/(V_L - V_{sky})$
- T_{sys} correction means a consistent amplitude scale
  - At different elevations
  - Under different weather conditions
- Allowing transfer of calibration e.g. from a bandpass calibrator in a different direction at different elevation
  - Or combination of data taken at different times


T_{sys} correction before & after
Raw data, coloured by baseline
Visibility amplitude
atmospheric line
Frequency
99.5
100
100.5
101
101.5
102
102.5
103
TSYS table: cal-tsys_uid___A002_X1d5a20_X330.calnew Antenna='DV06'
Tsys (K)
70
60
50
40
30
99500
100000
100500
101000
101500
102000
102500
T_{sys} corrections
Frequency (MHz)
T_{sys} corrections applied
slight noise increase
TSYS table: cal-tsys_uid___A002_X1d5a20_X330.calnew Antenna='DV10'
2.5

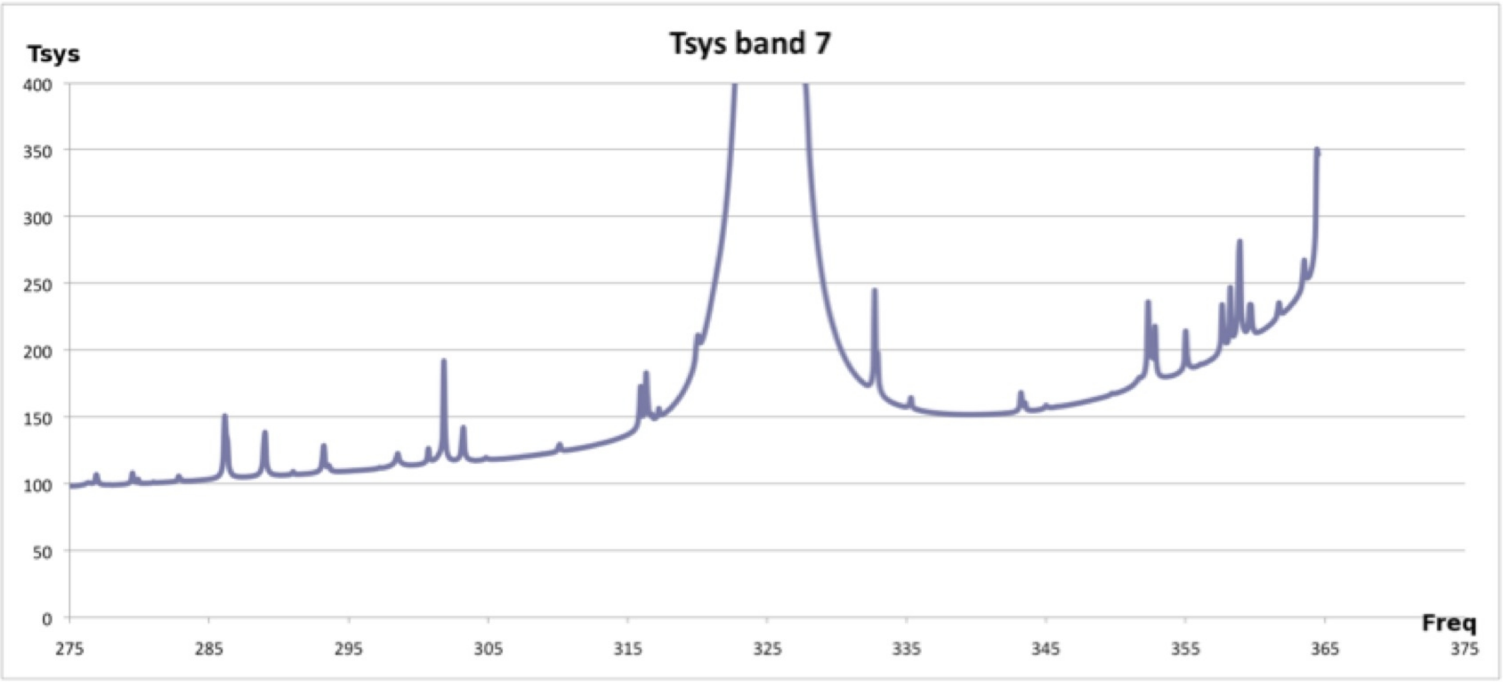
Receiver temperatures



ALMA Band 7

Average T_{Rx} 60 – 80 K

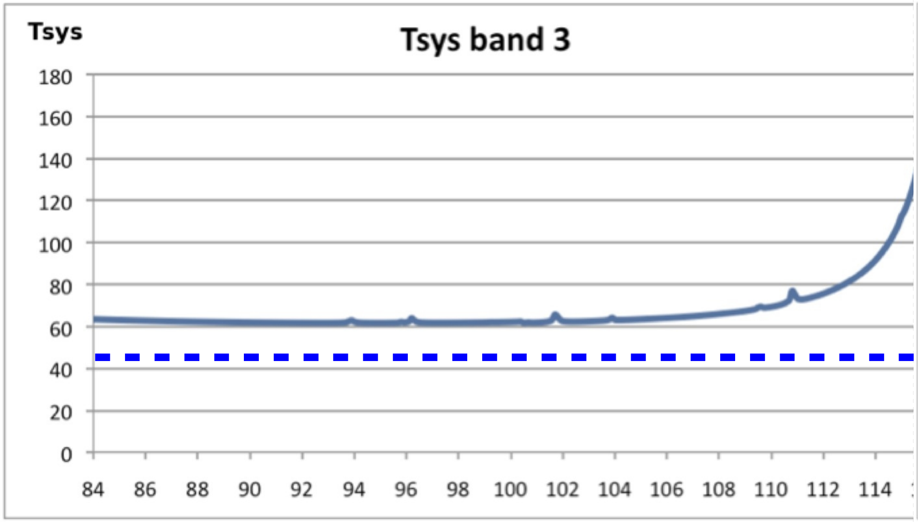
Much better than spec!

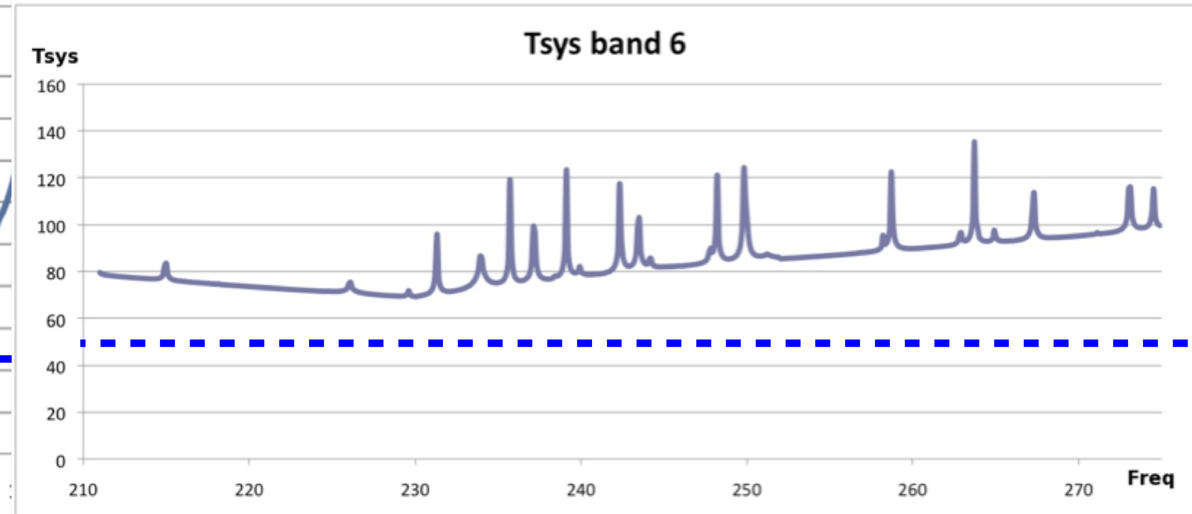


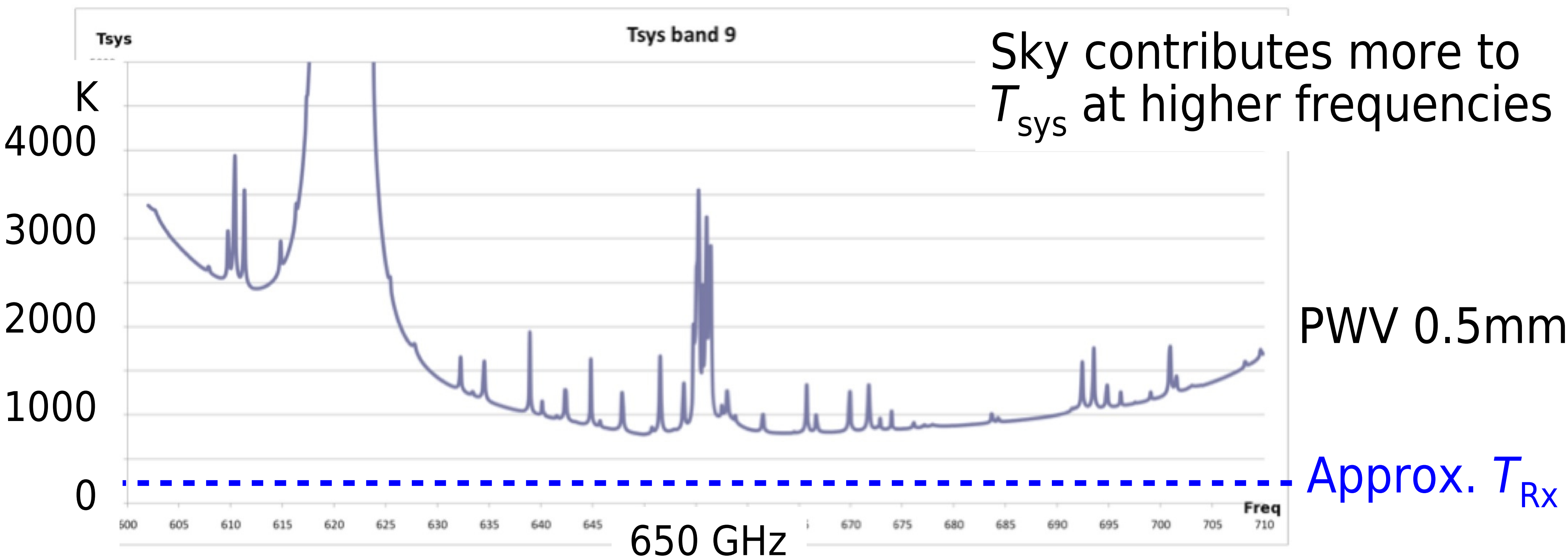
Actual T_{sys} >100 K

Sky contributes +>50% (1 mm PWV)

Receiver temperatures





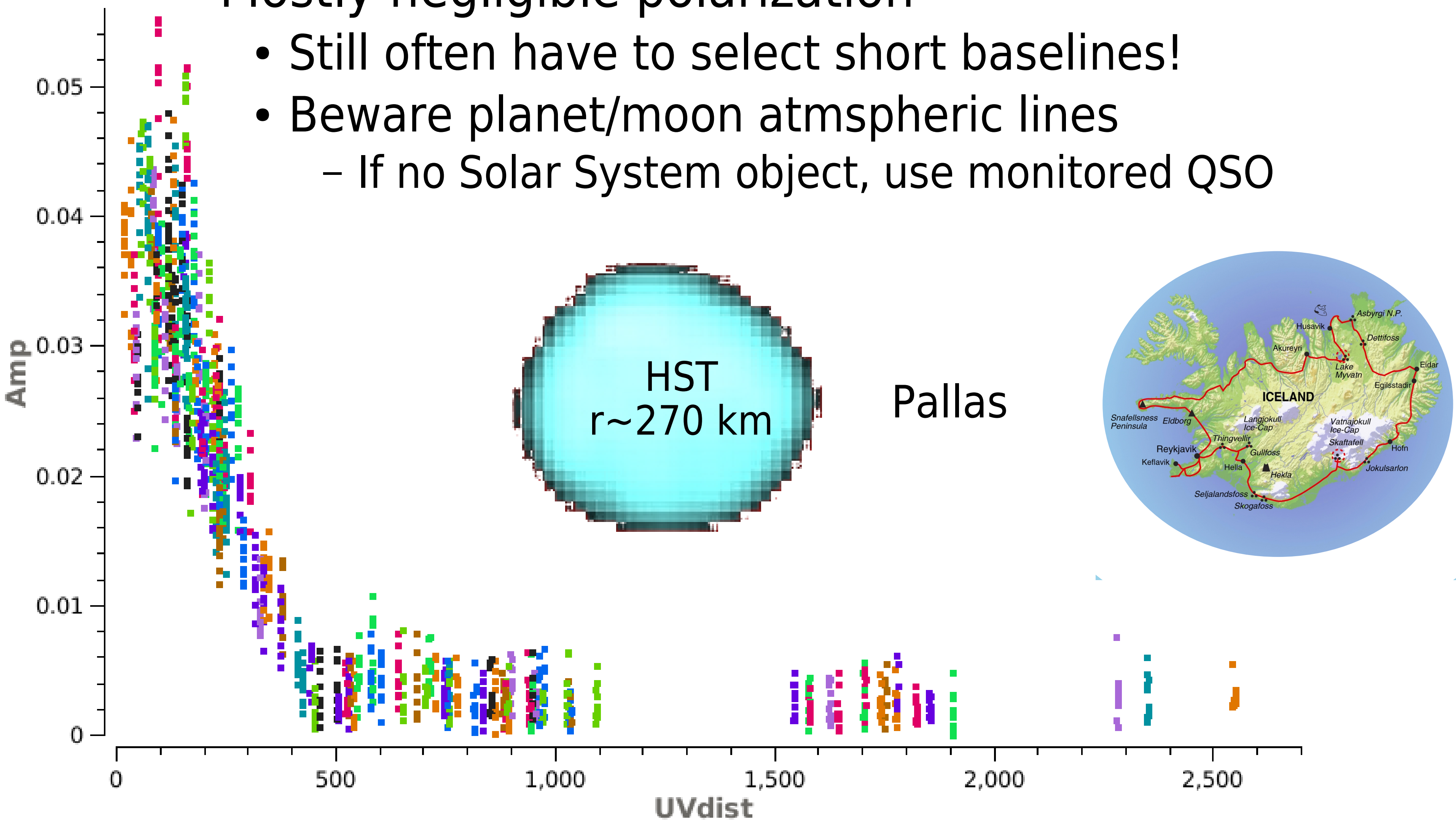


Calibration sources

- Most bright extragal. sources have $\alpha<0$ ($S \propto \nu^{\alpha}$)
  - i.e. they get fainter at high frequencies
    - Compact, bright sources are very variable
  - Can use bright stars, maybe even stable lines
    - Sky density low
  - ALMA monitors ~100 QSO
    - *Select calibration sources at time of observation*
      - Cone-search for phase-reference if needed
- Phase-referencing option for ALMA
  - WVR allows 5-10 min cycles, 5^{o}-20^{o} separation
    - OK so far, on baselines up to a few km…
  - Use lower-ν band where calibrators brighter
    - Analytic scaling of corrections to higher ν (as for PWV)
    - Observe a bright source at both ν to calibrate instrumental offset
  - Fast switching possible, ~30 s cycles

Calibration sources: flux density

- Primary flux calibration uses planets, moons, asteroids
  - Models and ephemerides available
  - Mostly negligible polarization
    - Still often have to select short baselines!
    - Beware planet/moon atmspheric lines
      - If no Solar System object, use monitored QSO

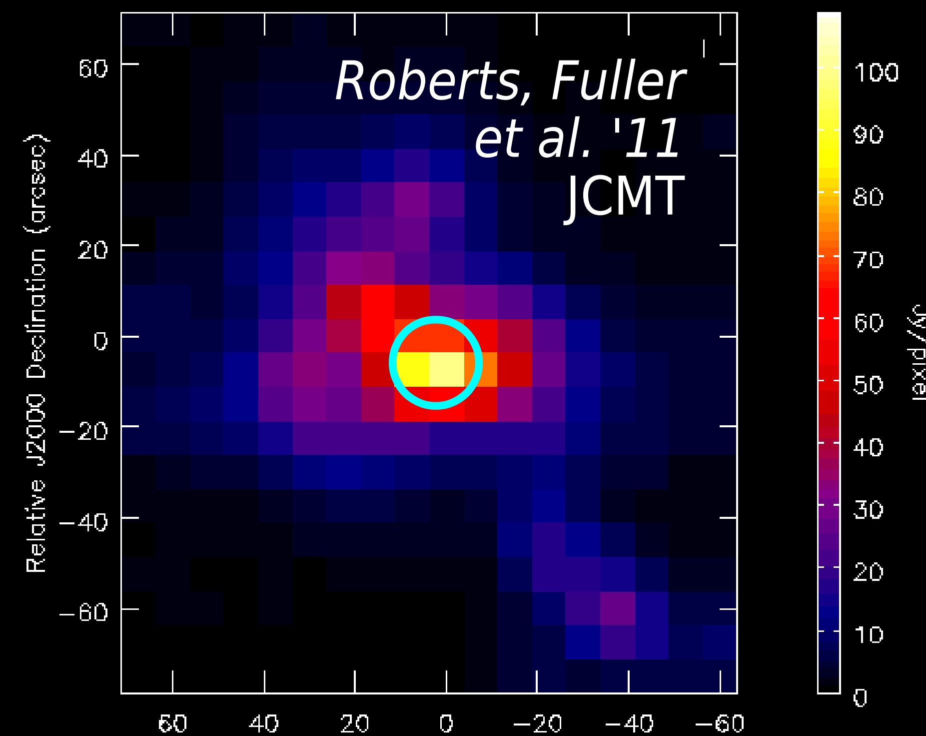


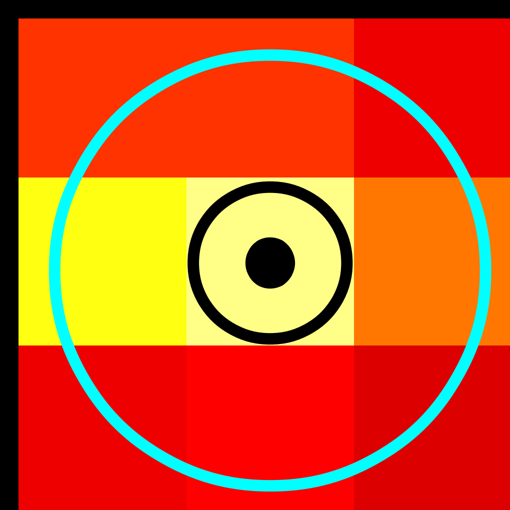
I've got a single dish image
What will ALMA see?

- Brightness temperature $T_b = S_{source}\ 10^{-26}\ \lambda^2 / 2k_B\ \Omega$
  - Ω emitting area (sr), λ (m), S (Jy $= 10^{-26}$ W m^{-2} Hz^{-1})
    - Resolved?
      - Use S per measured Ω
    - Unresolved measurement over large area?
      - Estimate actual Ω
        - Will ALMA recover all the flux?
  - Use S per best estimate of Ω to find T_b
  - Predict ALMA flux density $S = T_b\ 2k_B\ \theta_b^2 / 10^{-26}\ \lambda^2$
    - Substitute $\Omega = \theta_b^2$ (ALMA synthesised beam)
  - Use **Sensitivity Calculator**
    - Need $>5\sigma_{rms}$ on peak and $3\sigma_{rms}$ on extended details

Structure scales

- JCMT mosaic: W49 (11 kpc)
  - Peak 100 Jy/ 7''.5 pixel
  - 354 GHz = λ 0.85 mm
- **ALMA field of view**
  - 1.2 x λ / 12 ≈ **18''**
    - 12-m dish primary beam
- Most compact configuration
- ALMA synthesized beam •
  - λ /longest baseline (150 m)
    - 0.00085/150 ≈ 1''.5
- Largest spatial scale ○
  - λ / shortest baseline (18 m)
    - 0.00085/18 ≈ 6''

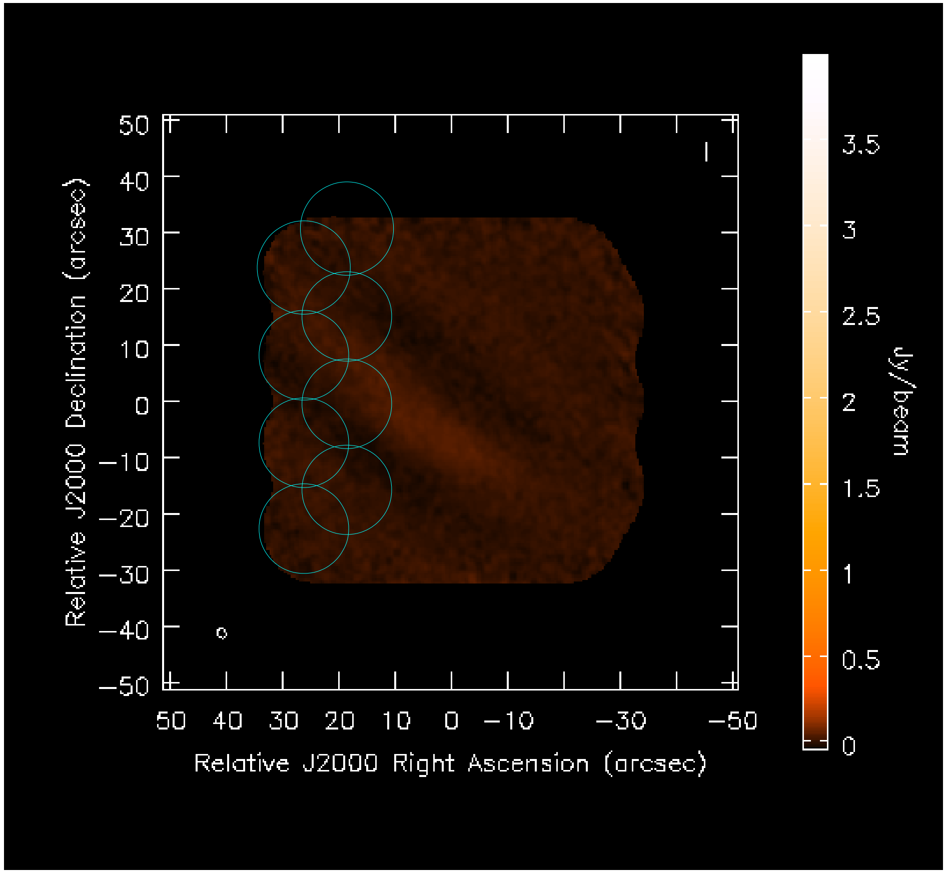




ALMA's view on same pixel scale

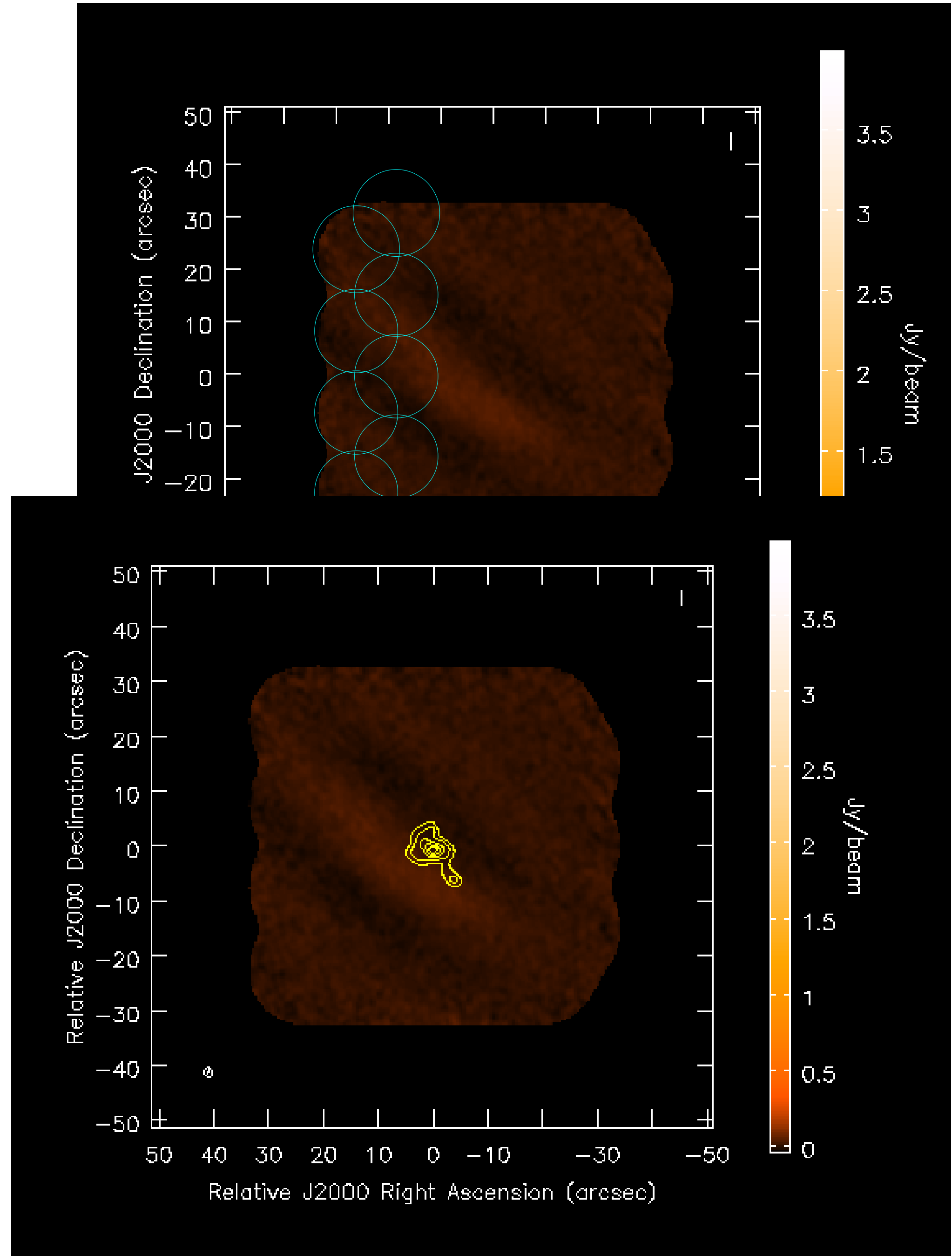
ALMA observations at 11 kpc

- JCMT 150'', peak 100 Jy
  - ~32 ALMA mosaic pointings
- ALMA compact config
  - Synthesised beam 1''.5
    - Expect peak 100 $(1.5/7.5)^2$ = 4 Jy/beam?
  - Largest angular scale 6''
    - Smaller than input pixel!
- Flux which is *smooth* on JCMT scales is ~invisible!



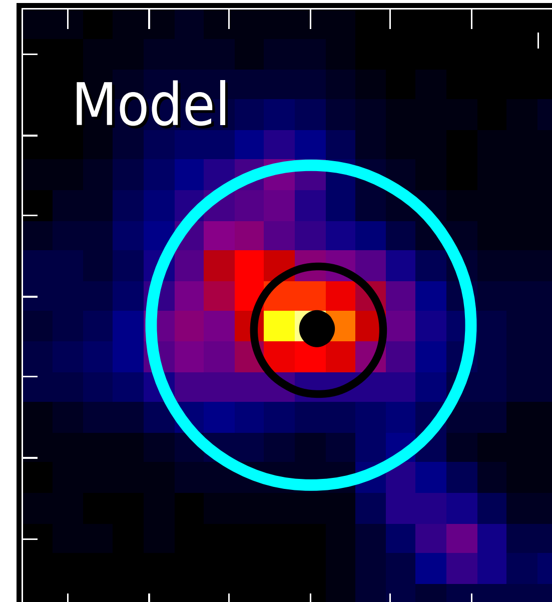
ALMA observations at 11 kpc

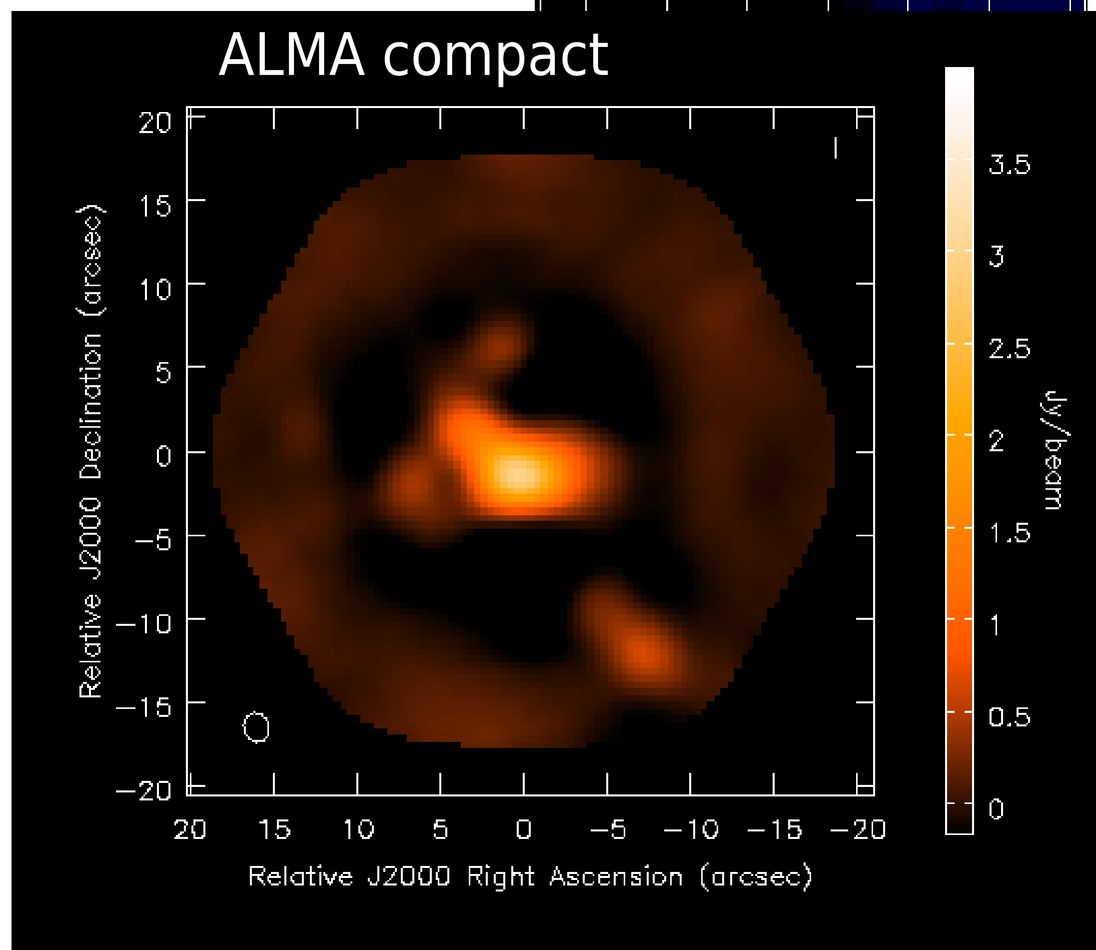
- JCMT 150'', peak 100 Jy
  - ~32 ALMA mosaic pointings
- ALMA compact config
  - Synthesised beam 1''.5
    - Expect peak 100 $(1.5/7.5)^2$ = 4 Jy/beam?
  - Largest angular scale 6''
    - Smaller than input pixel!
- Flux which is *smooth* on JCMT scales is ~invisible!
  - But ...
- **Small-scale details could appear**
- (Could add ACA/single dish to avoid missing scales problem)



d=55 kpc

- JCMT object now 30''
  - Pixel p = 7''.5x 11/d = 1''.5
  - = ALMA compact θ_{bc} =1''.5
  - ALMA maximum flux density
    - $100(11/d)^2 \times (\theta_{bc}/p)^2$
      $= (11/55)^2 \times (1.5/1.5)^2$
      ~ 4 Jy/beam?
  - Actual peak is ~ 4 Jy/beam
    - Some larger scale flux still missing
  - Only 7 mosaic pointings needed

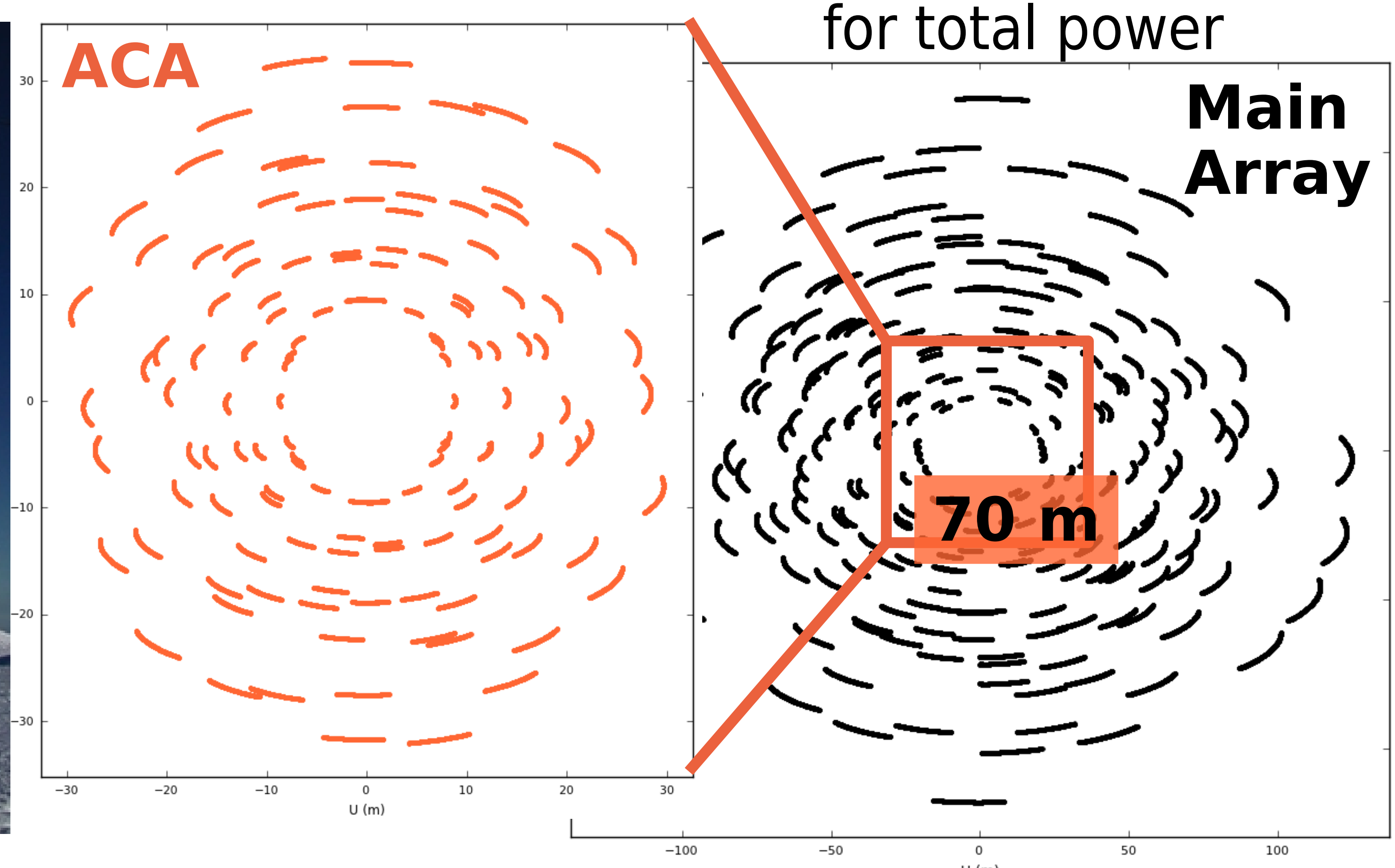




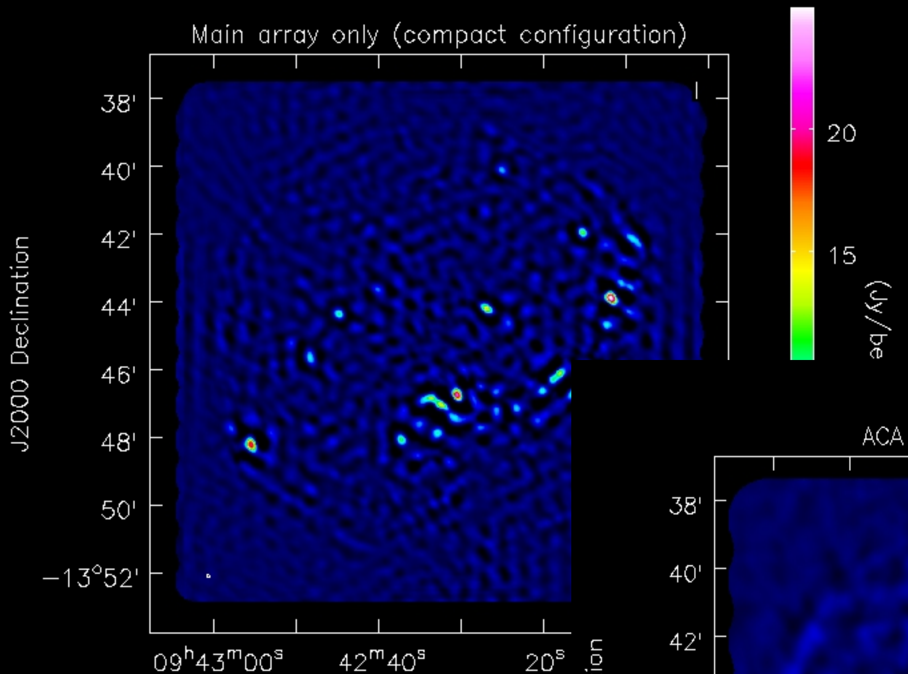
Visibility plane coverage

- IRAM PdB /NOEMA
  - six / twelve 15m
  - Scales≳15” resolved out at λ≳3mm
- Add IRAM 30-m single dish for larger scales

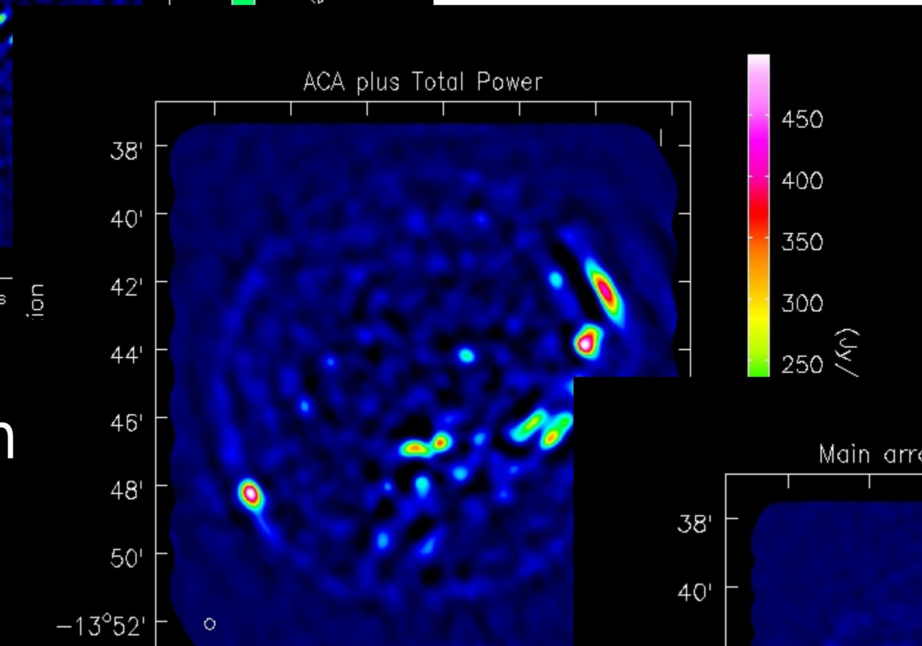
- ALMA main array:
  - fifty 12-m antennas
- ALMA Compact Array:
  - twelve 7-m antennas
  - four 12-m antennas for total power



Combining arrays
(solar simulation)

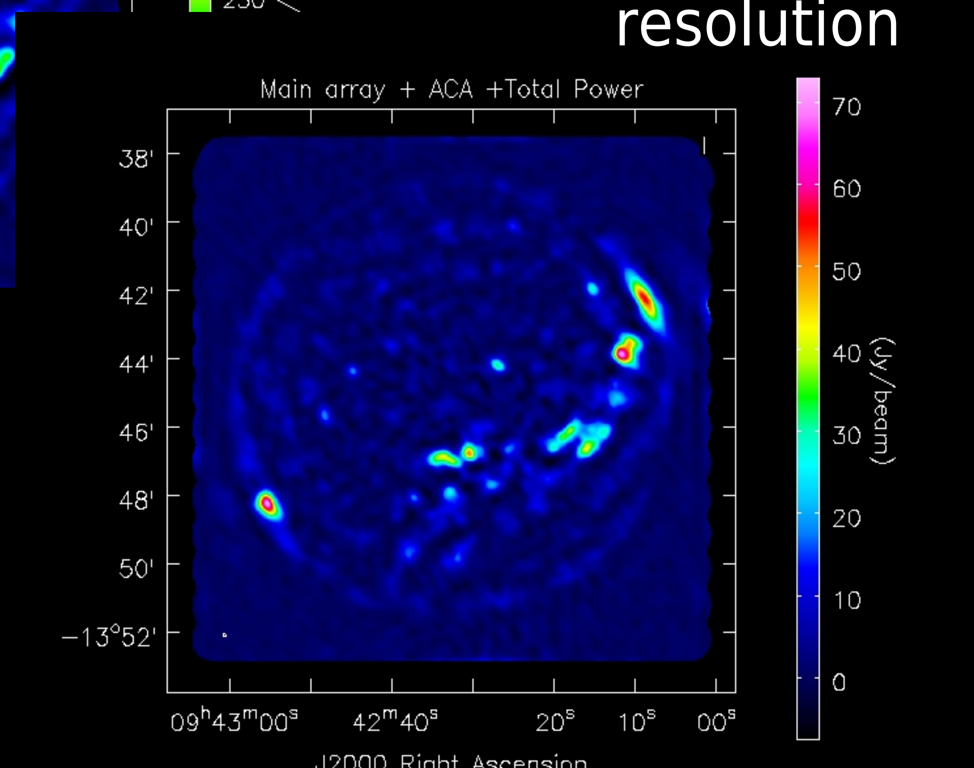


Main array only:
extended emission
resolved out



ACA plus
single dish
~18 arcsec
resolution

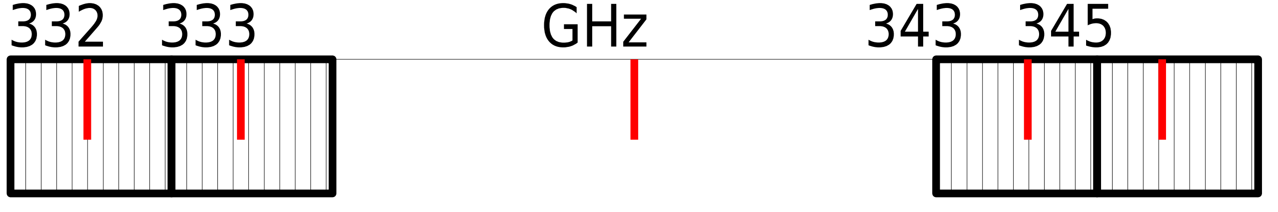
Main array + ACA
+ single dish
~6 arcsec
resolution



Peak Jy/beam ∝
resolution^2
SD 1500 Jy/bm
+ ACA 500 Jy/bm
+ main array 75Jy/bm

ALMA correlator configurations

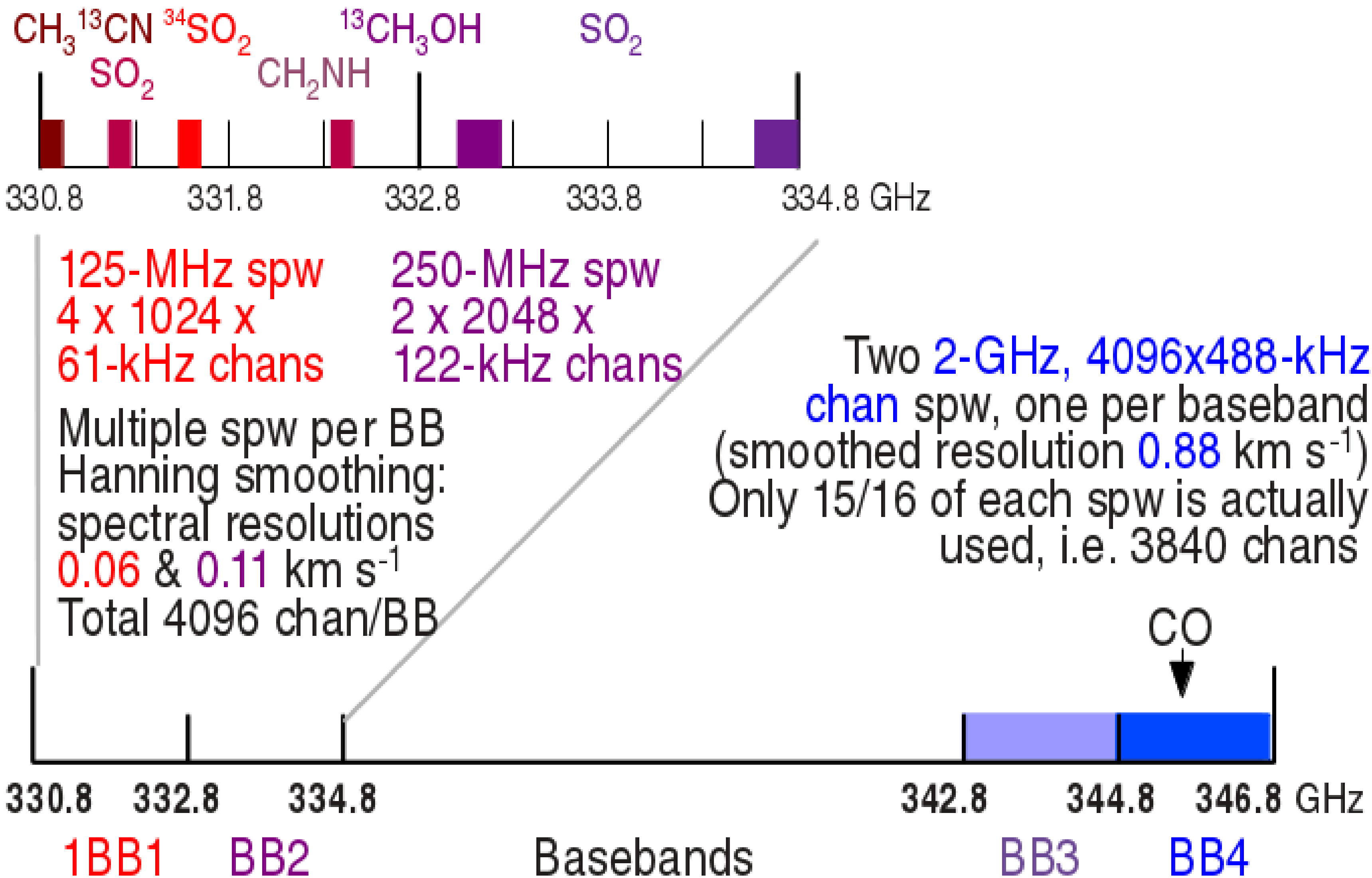
- Four spectral windows (spw), max. width 2 GHz
  - 128 chans per spw (dual pol) TDM
    - Allows shorter integrations
  - 4096 chans per spw (~0.5 km/s at 300 GHz) FDM
    - Useful max. 1.875 GHz (so 3840 channels usable)
- Narrower spectral windows for higher resolution
  - Factors of two down to 62.5 MHz (15.25 kHz chans)
  - Higher spectral resolution in single pol.
- Two sidebands, spacing depends on band
  - e.g. B7, B3 sideband centres separated by 12 GHz
    - Two spw in each sideband, centre spacing 2 GHz



- **See documentation and OT for full details**

Frequency flexibility

ALMA correlator (dual polarization example)



ALMA sensitivity with 50 antennas

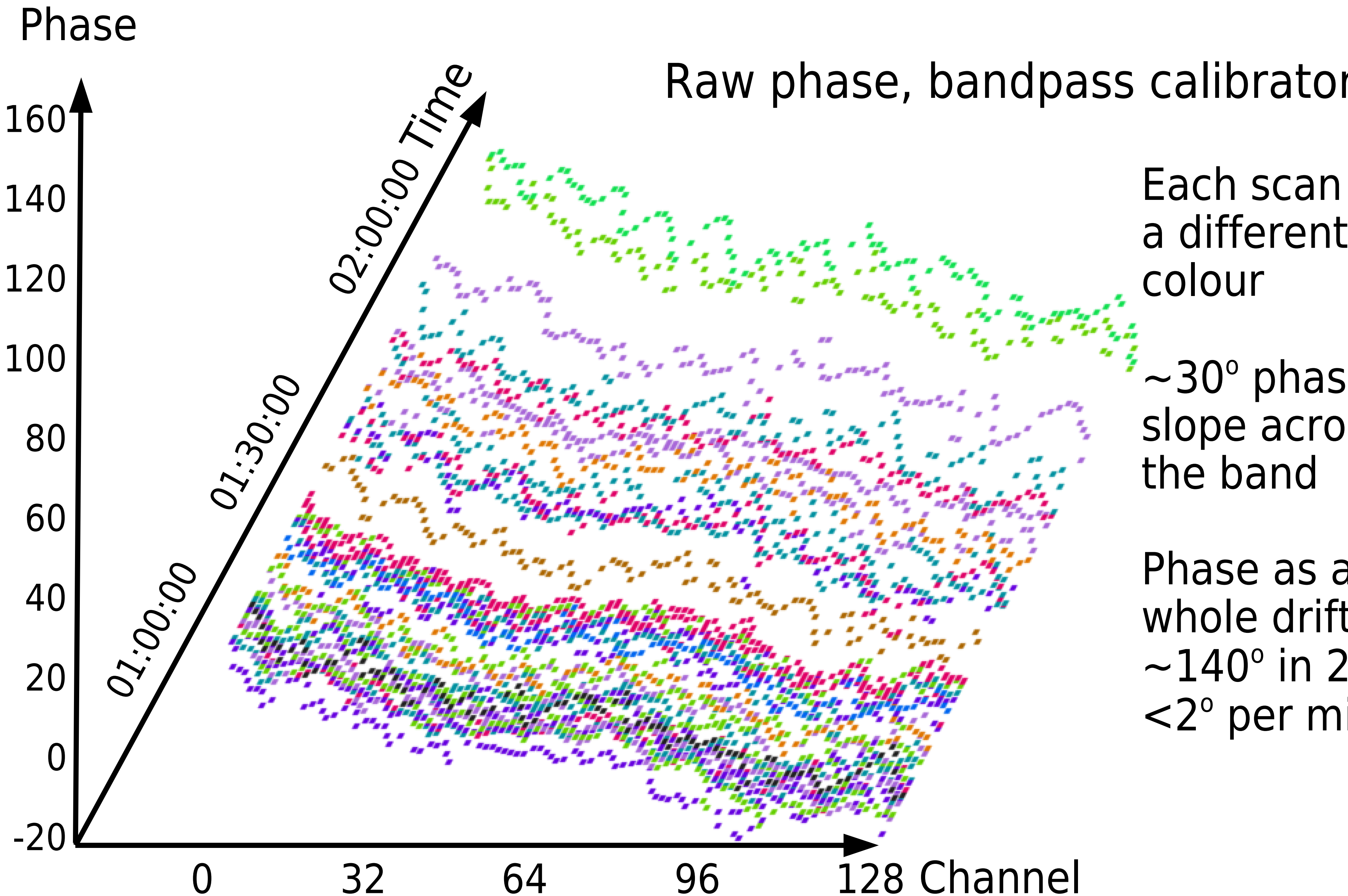
Band	ν *GHz*	λ *mm*	PB (field of view) *arcsec*	Continuum sensitivity *mJy/bm*	Resol'n *arcsec*	Line sensitivity *mJy/bm*
3	84 - 116	3	72 - 52	0.07	0.5 - 4	12
4	125-163	2.1	49 - 37	0.06	0.4 - 3	10
6	211-275	1.2	29 - 22	0.09	0.2 - 1.5	12
7	275-373	0.9	22 - 16	0.15	0.15 - 1.1	17
8	385-500	0.7	16 - 12	0.45	0.11 - 0.9	47
9	602-720	0.45	10 – 8.5	1.4	0.07 - 0.6	104

- Use sensitivity calculator for fewer antennas in Cycle 2
  - and, generally, for most recent values
- $1\sigma_{rms}$ noise, 1 min on-target, reasonable conditions
  - Continuum b/w 7.5 GHz
  - Line width 0.5 km/s, close to CO line/good transmission
- Highest resolution given for 1.5-2 km baselines

Phase referencing

- Observe phase-ref source close to target
  - Point-like or with a good model
  - Close enough to see same atmosphere
    - 1 – few degrees (isoplanatic patch)
  - Bright enough to get good SNR much quicker than the atmosphere changes, τ
    - τ 10 min/30 s short/long *B* & low/high ν
  - Nod on suitable timescale e.g. 5:1 min
    - Derive time-dependent corrections to make phase-ref data match model
    - Apply same corrections to target
  - May correct amplitudes similarly
- Self-calibration works on similar principle

Phase errors in 3D



Each scan in a different colour

~30° phase slope across the band

Phase as a whole drifts ~140° in 2 hr <2° per min

Calibration strategy

- Usually start with bandpass calibration
  - Instrumental artefacts, shallow atmospheric lines...
    - May need to perform time-dependent ϕ calibration first
- Need Signal to Noise Ratio $\sigma_{ant}/S_{calsource} > 3$
  - per calibration interval per antenna

$$\sigma_{ant}(\delta t, \delta\nu) \approx \sigma_{array}\sqrt{\frac{N(N-1)/2}{N-3}}$$

    - σ_{array} is noise in all-baseline data per time-averaging interval per frequency interval used for calibration
  - Have to average in time and/or frequency
    - Bandpass first or time-dependent cal. first?
      - *Do not average over interval where phase change $d\phi > \pi/4$*
    - *Keep polarizations separate if possible in early calibration*

This example: $d\phi < \pi/4$ over inner 50% band

- Bandpass calibrator – bright as possible

  1. Average inner 50% band, perform time-dependent phase (maybe & amp.) calibration (G1) with solint required for SNR

  - If atmospheric lines, chose channel intervals to avoid

  2. Apply calibration (G1), average all times for freq. dependent phase and amplitude calibration, i.e. bandpass calibration (B1).

  – Smooth every e.g. 20 channels if necessary for SNR

  - G1 *is not used any more*

- Phase-reference – fairly bright source

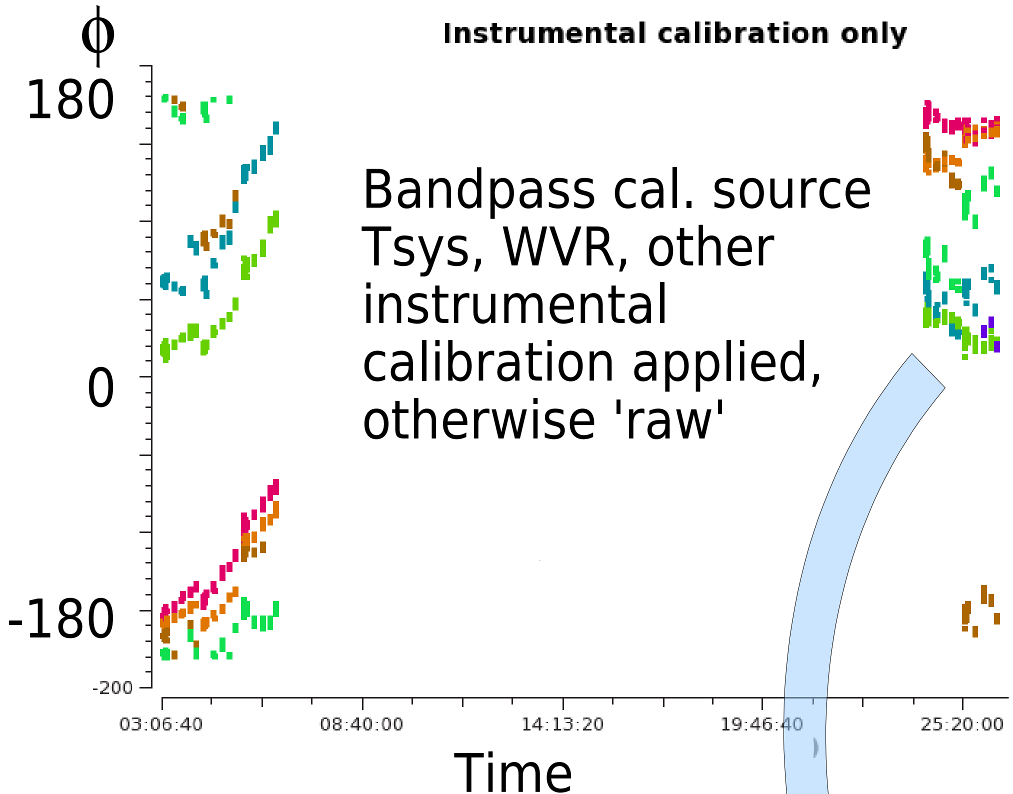
  3. Apply B1 and perform time-dependent phase calibration (G2) averaging all channels, shortest *dt* for enough SNR

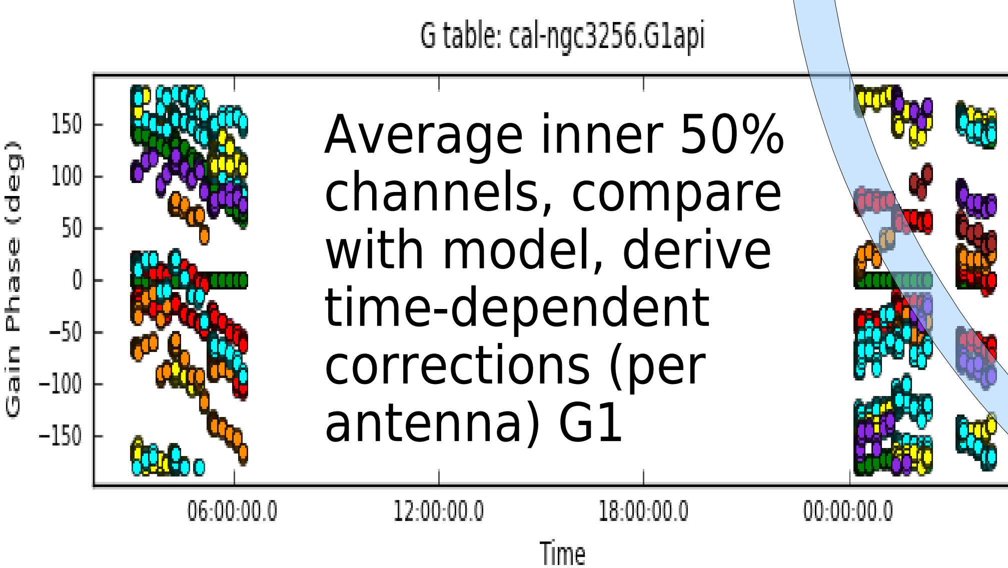
  - Apply B1 for all calibration hereafter, to all sources

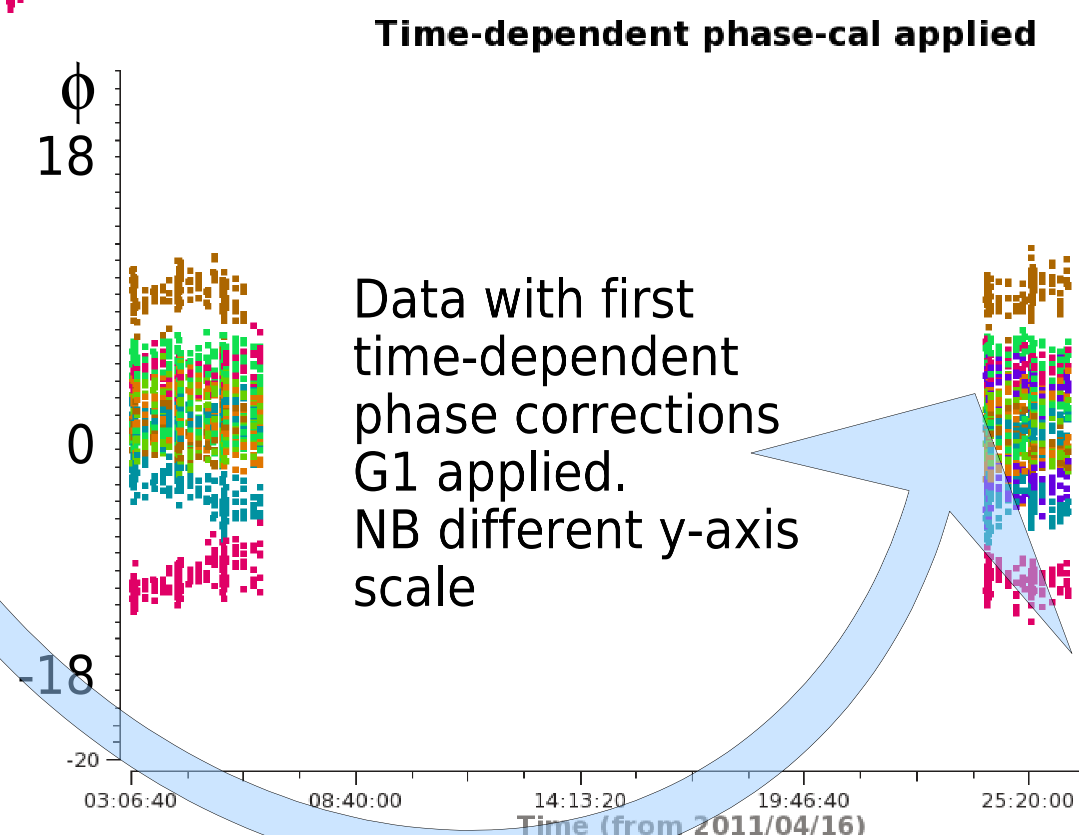
  4. Apply B1 and G2 and perform time-dependent amp. cal.

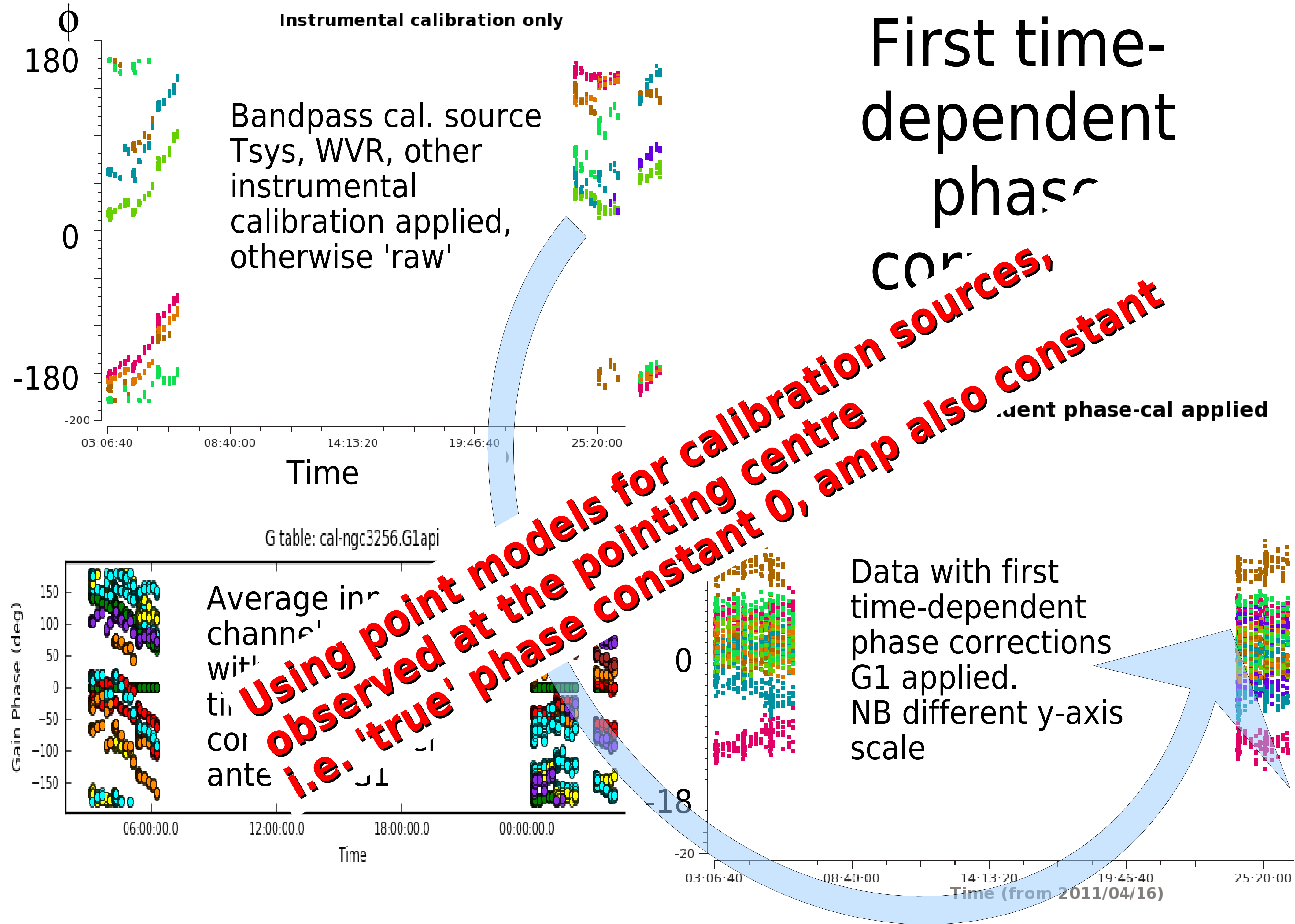
  - Amp calibration needs higher SNR than phase-only; for bright sources you can do it all in step 3.

First time-dependent phase correction

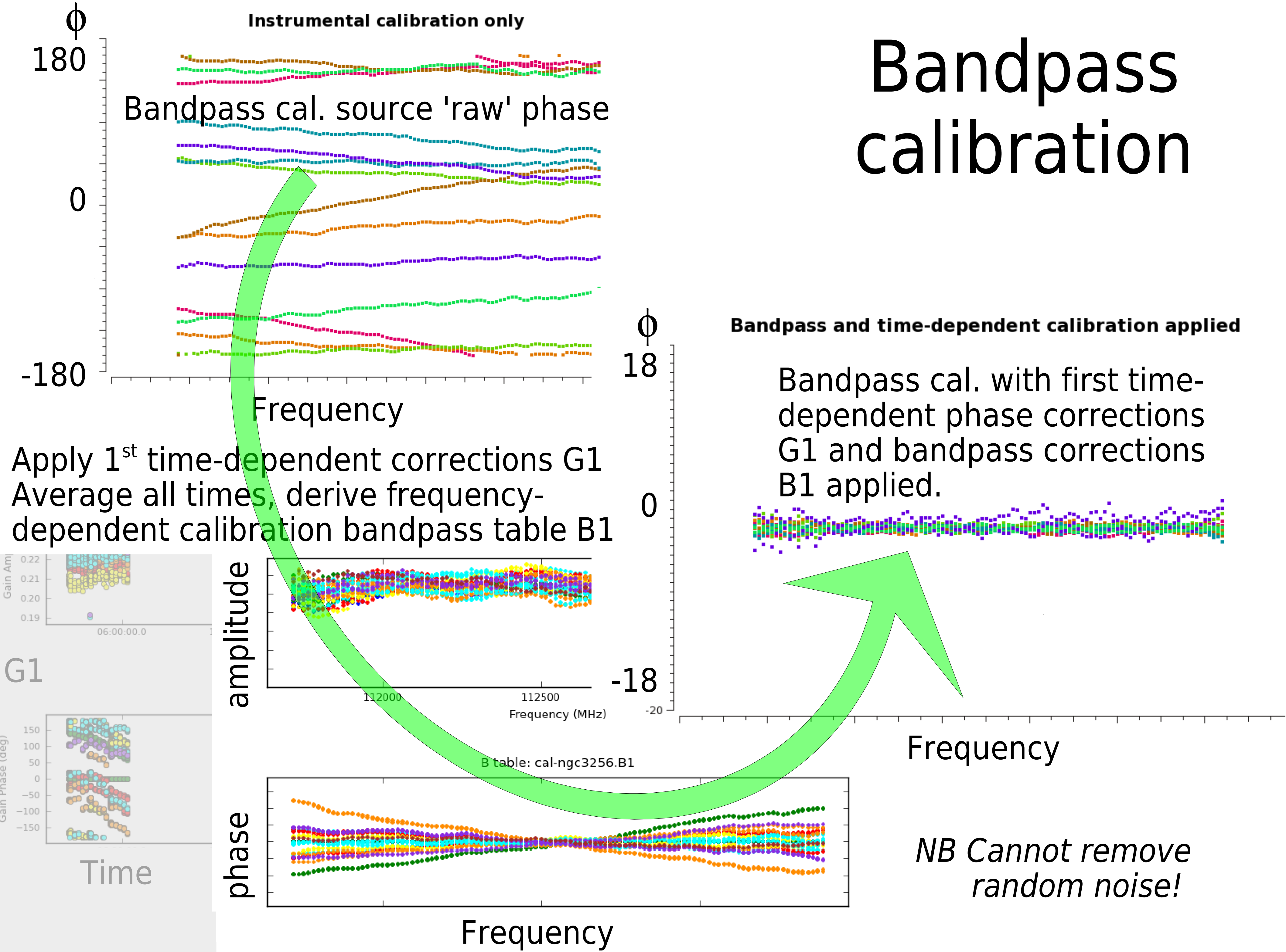




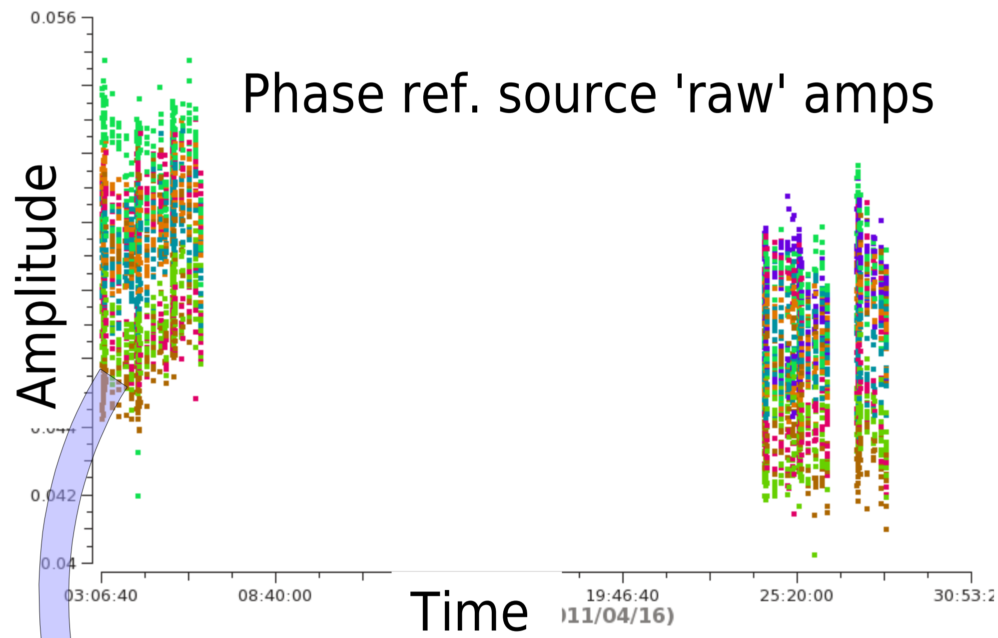


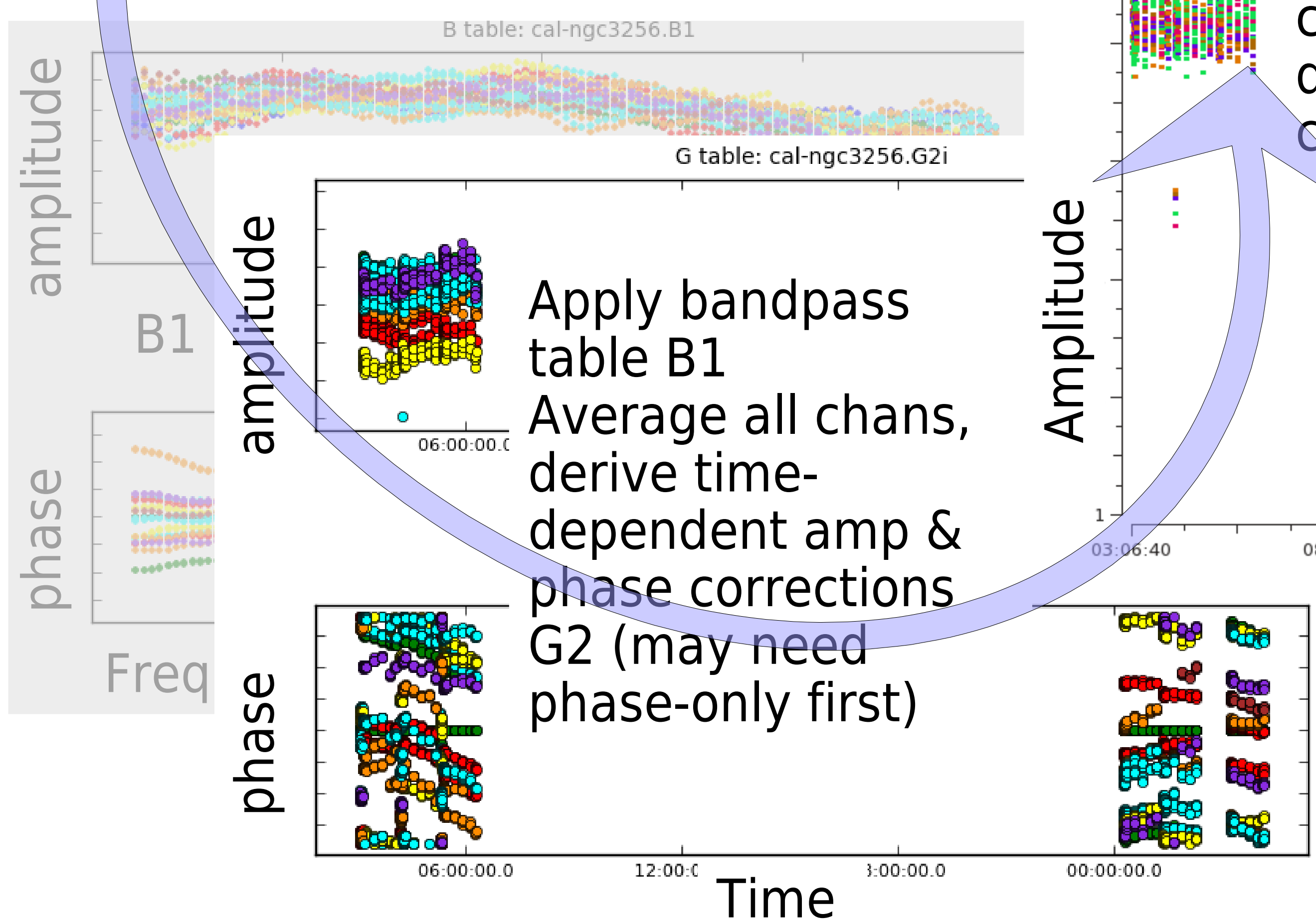

First time-dependent phas… cor…
Instrumental calibration only
ϕ
180
0
-180
-200
03:06:40
08:40:00
14:13:20
19:46:40
25:20:00
Time
Bandpass cal. source Tsys, WVR, other instrumental calibration applied, otherwise 'raw'
Using point models for calibration sources, observed at the pointing centre
i.e. 'true' phase constant 0, amp also constant
…dent phase-cal applied
G table: cal-ngc3256.G1api
Gain Phase (deg)
150
100
50
0
-50
-100
-150
06:00:00.0
12:00:00.0
18:00:00.0
00:00:00.0
Time
Average in… channel… wit… ti… co… ante… G1
Data with first time-dependent phase corrections G1 applied.
NB different y-axis scale
0
-18
-20
03:06:40
08:40:00
14:13:20
19:46:40
25:20:00
Time (from 2011/04/16)

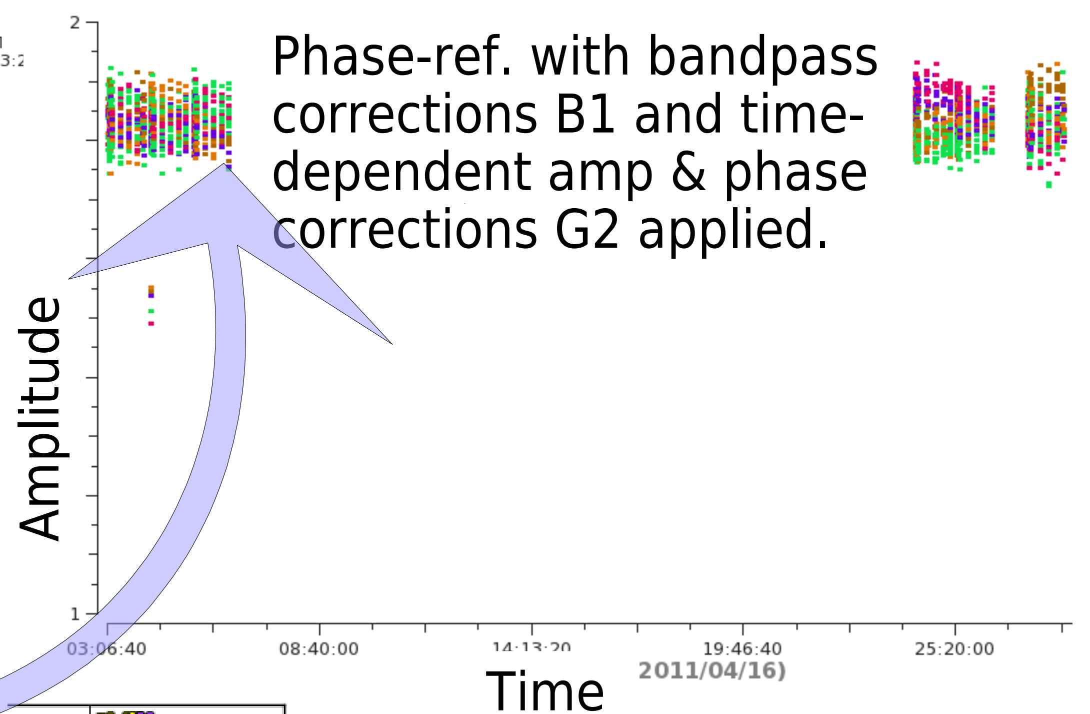
Bandpass calibration



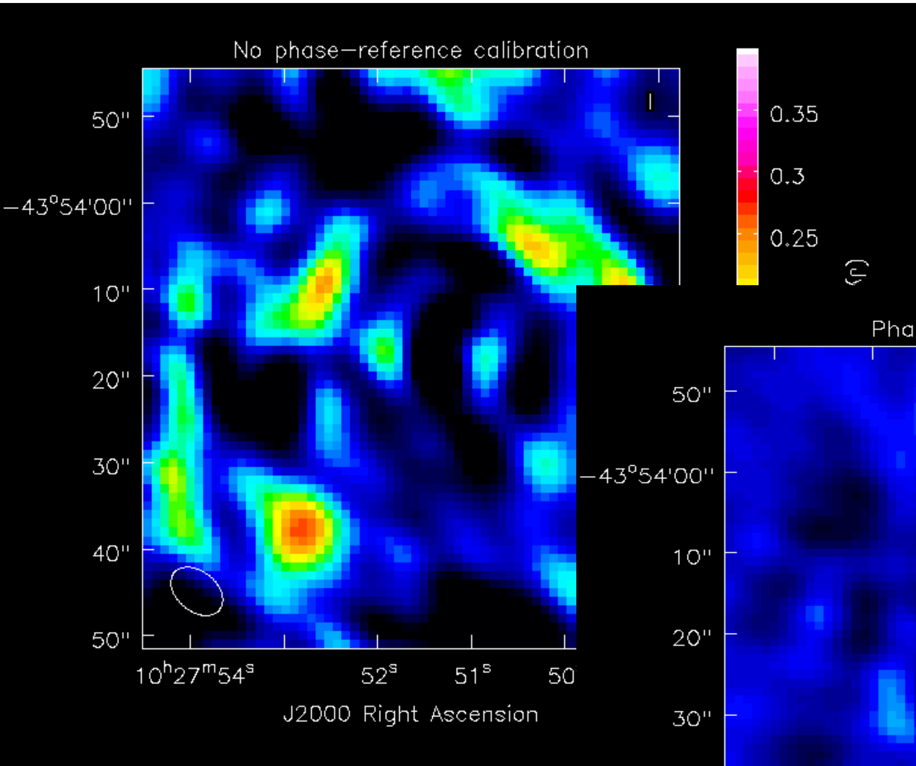
Phase-ref amp & phase calibration



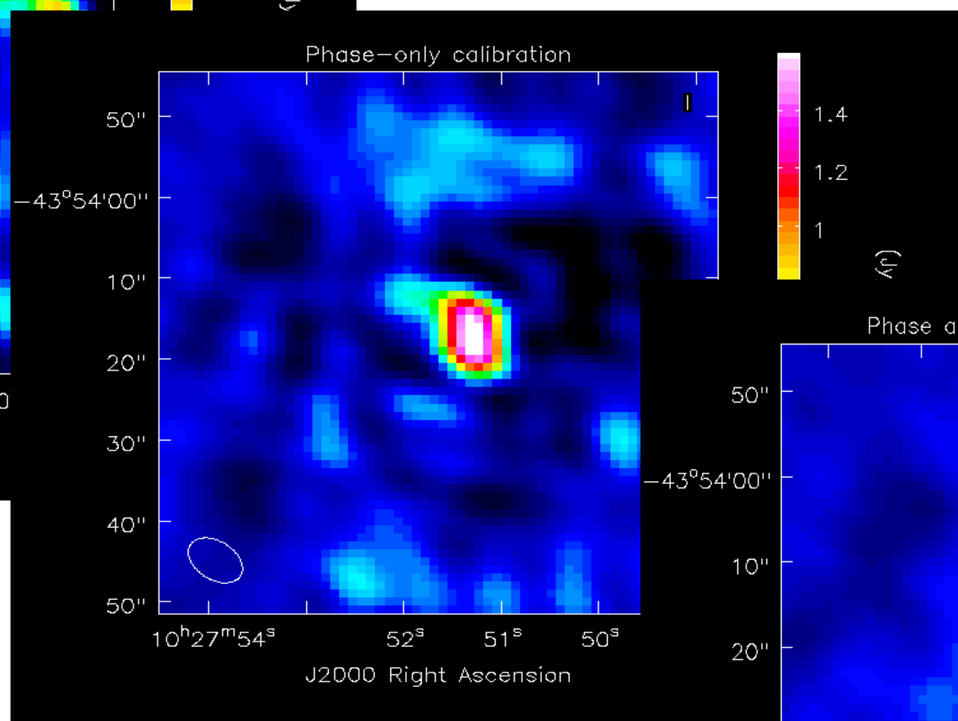




Effects on imaging

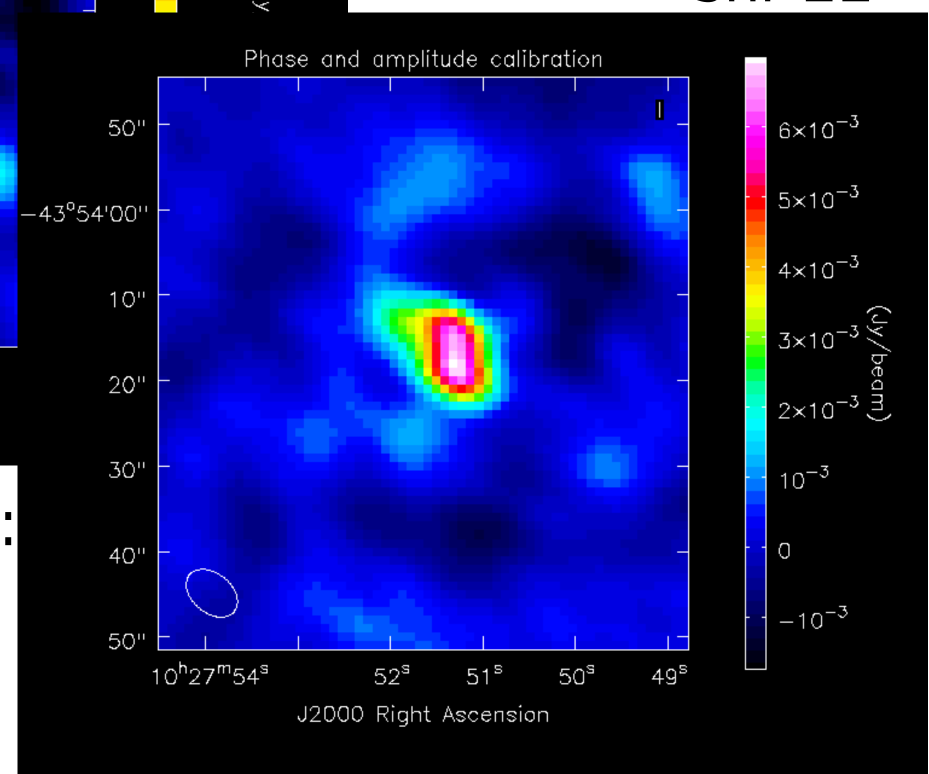


No astrophysical calibration:
no source seen

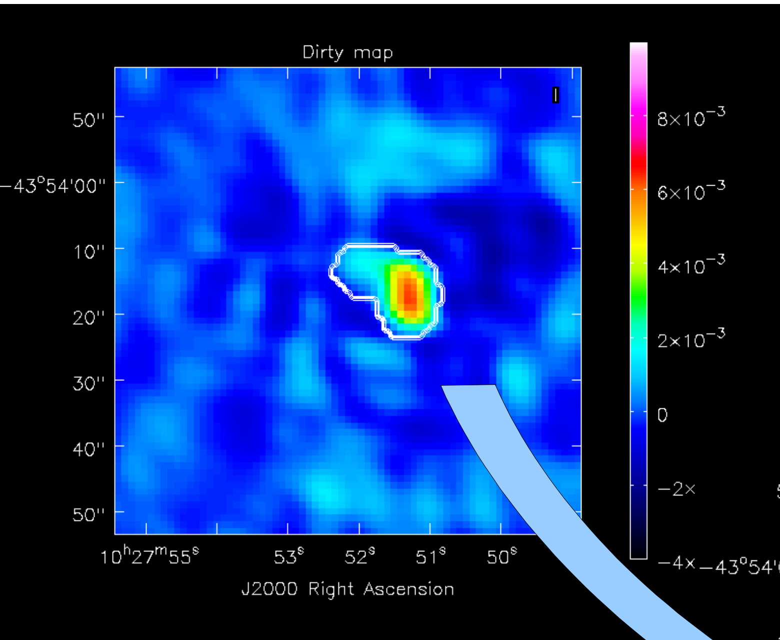


Phase-only solutions:
source seen, snr 15
flux scale arbitrary

Amplitude and
phase solutions:
image improved,
snr 22

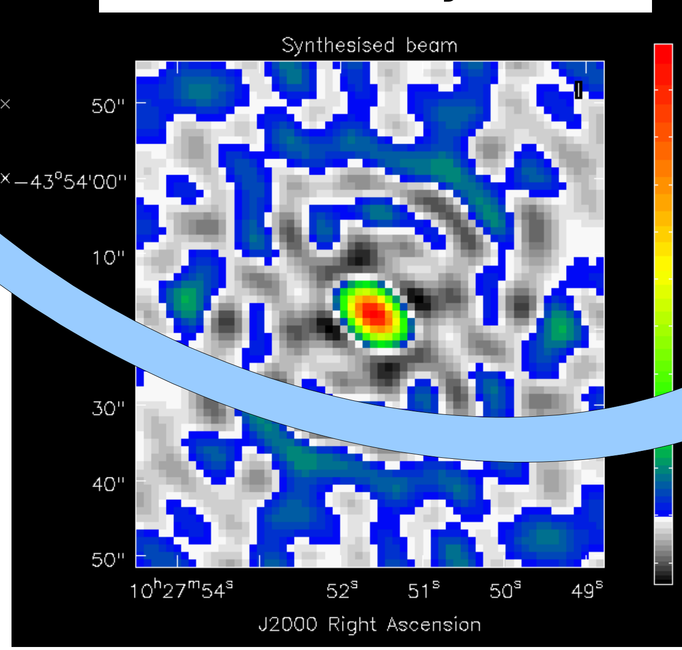


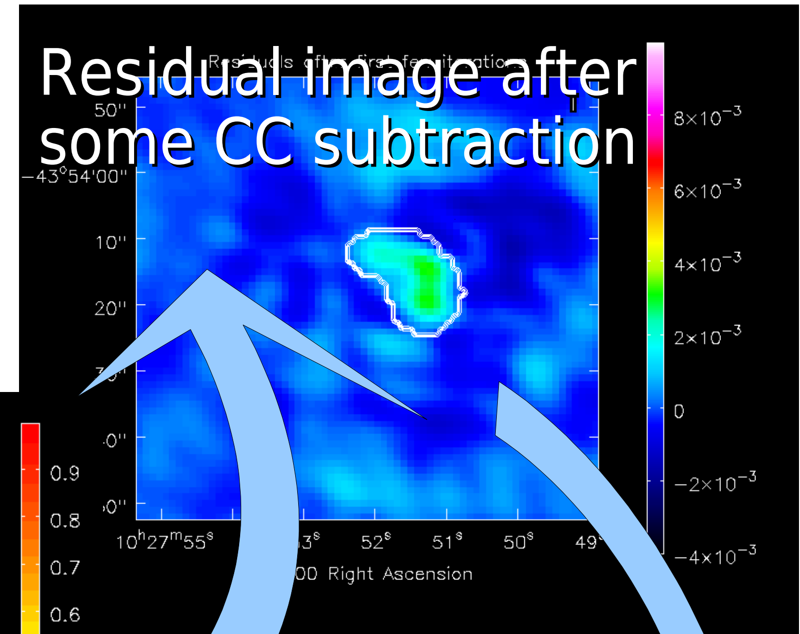
Fourier transform and clean

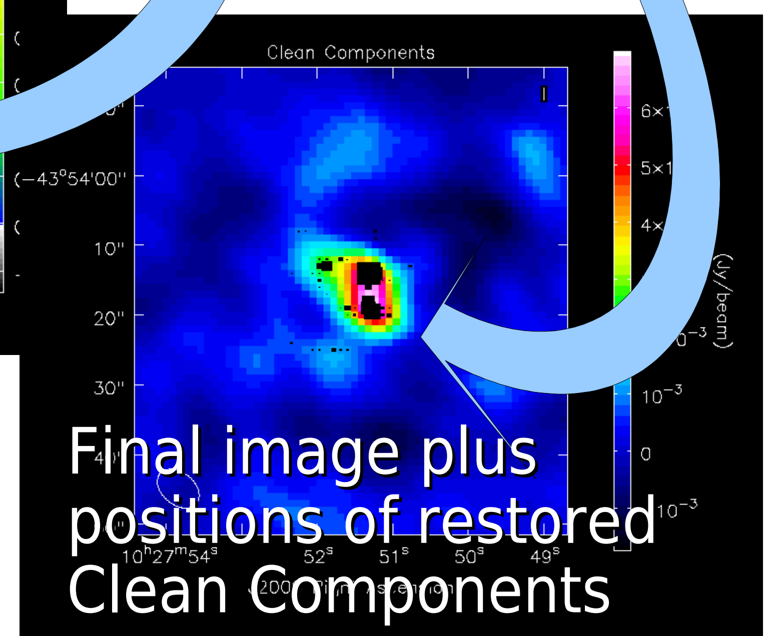


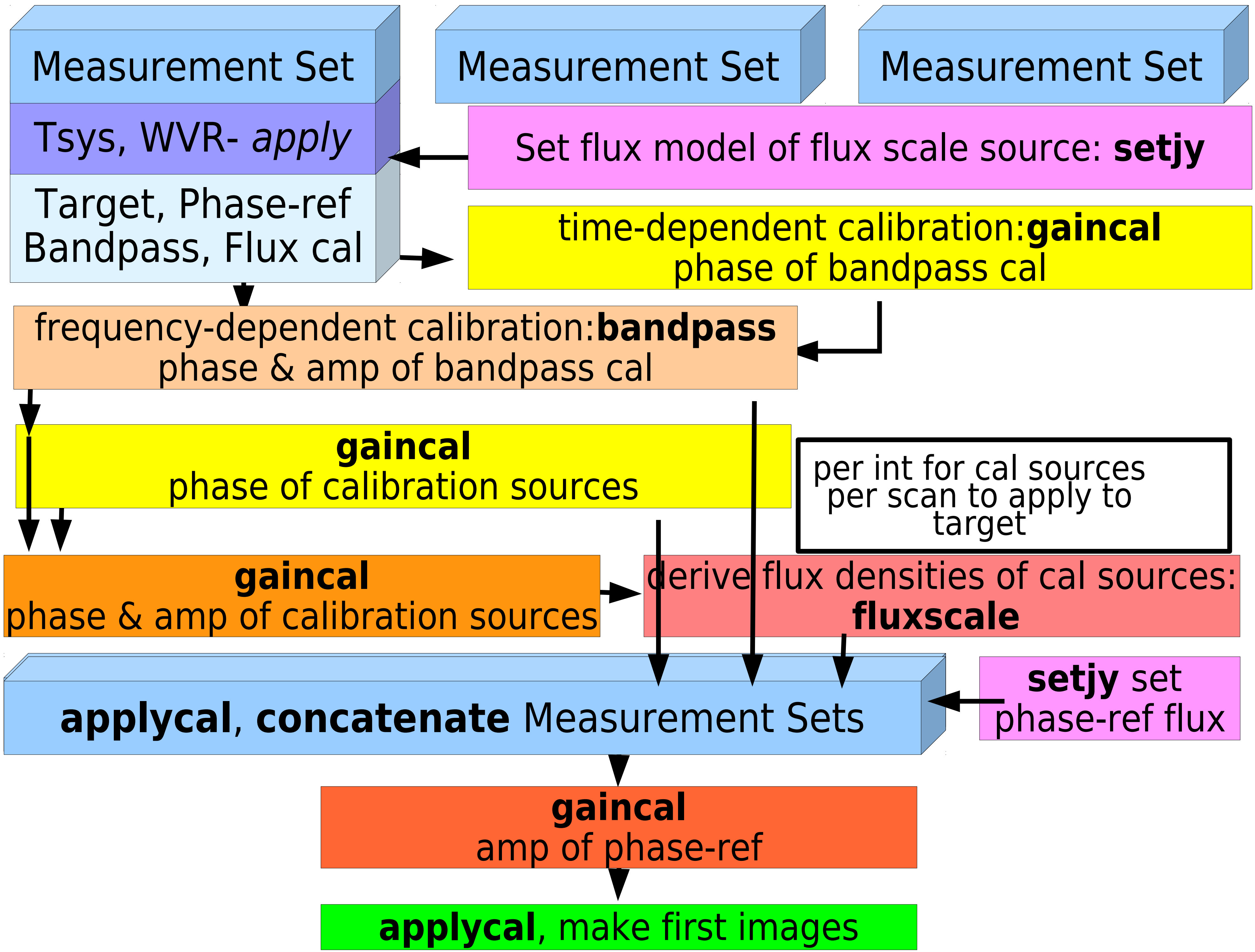
FT calibrated
visibilities to give
Dirty Map
Mask emission likely
to be 'real'

Deconvolve
Dirty Beam
iteratively



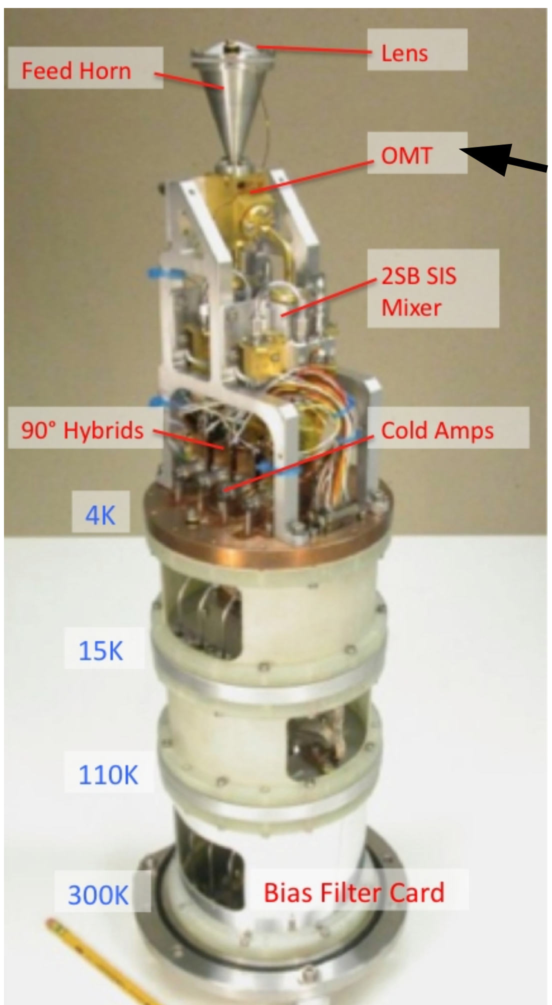





Measurement Set
Measurement Set
Measurement Set
Tsys, WVR- *apply*
Target, Phase-ref
Bandpass, Flux cal
Set flux model of flux scale source: **setjy**
time-dependent calibration:**gaincal**
phase of bandpass cal
frequency-dependent calibration:**bandpass**
phase & amp of bandpass cal
gaincal
phase of calibration sources
per int for cal sources
per scan to apply to
target
gaincal
phase & amp of calibration sources
derive flux densities of cal sources:
fluxscale
applycal, **concatenate** Measurement Sets
setjy set
phase-ref flux
gaincal
amp of phase-ref
applycal, make first images

Polarization

Different methods used to separate polarizations at higher frequencies

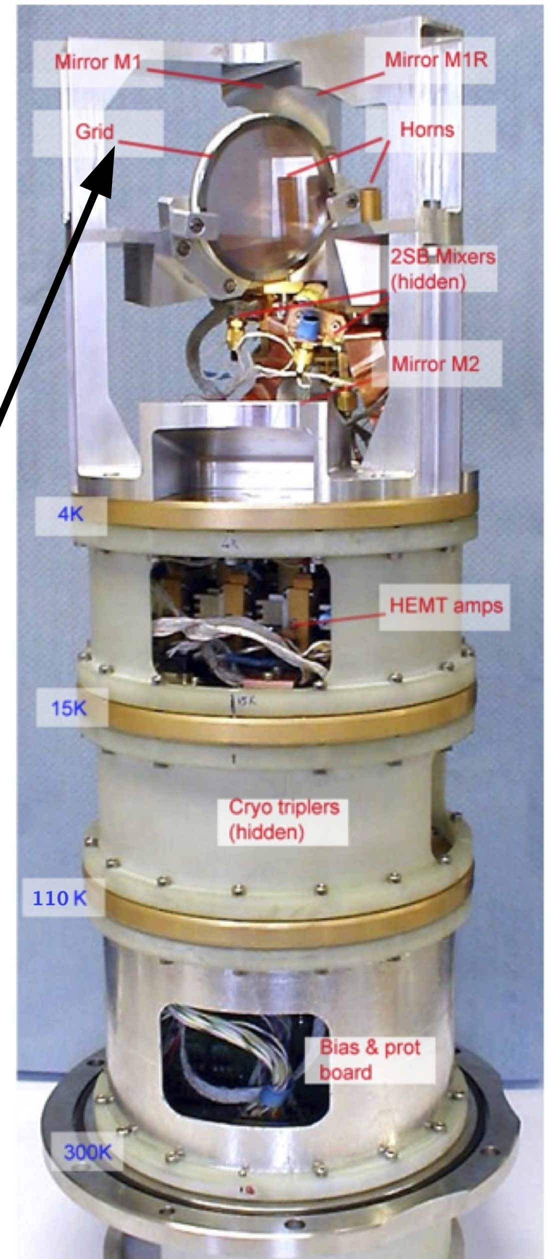


ALMA Band 3 (λ~3mm) uses Ortho Mode Transducer

Band 9 (λ~0.45mm) uses wire grid

Produces two linearly polarised signals X and Y

Correlator output XX or (XX, YY) or (XX, YY, XY, YX)



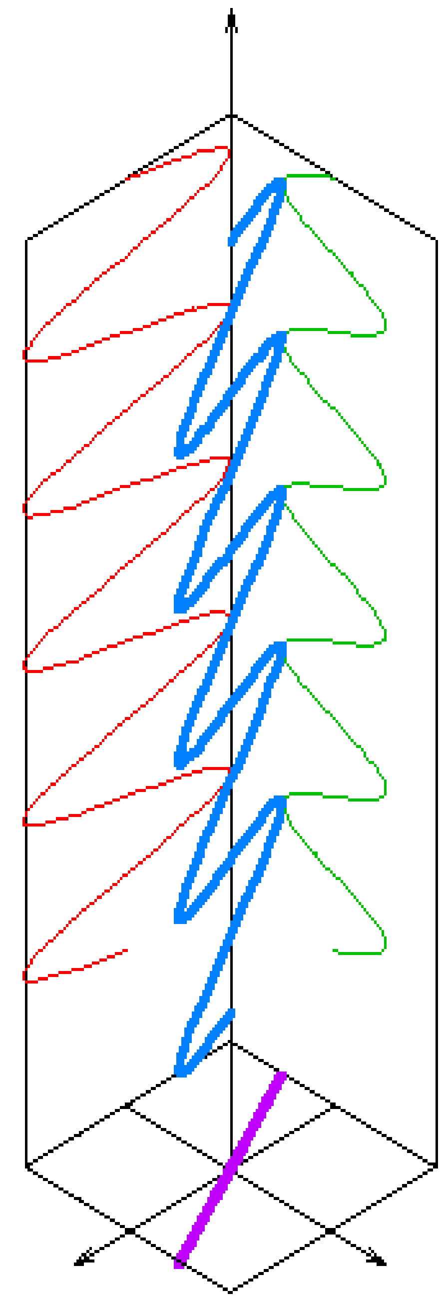


Diagram thanks to Wikipaedia

ALMA polarization

- XX only may be used to double spectral resolution
  - Assume linear pol. of thermal lines negligible
- XX + YY (parallel hands) give total intensity
  - QSO used for calibration may be 10% polarized
    - Care needed in setting amplitude scale
- Must also have XY, YX (cross hands) to calibrate either or both of linear and circular polarization

$$V_{XX} = I + Q$$
$$V_{XY} = U + iV$$
$$V_{XY} = U - iV$$
$$V_{YY} = I - Q$$

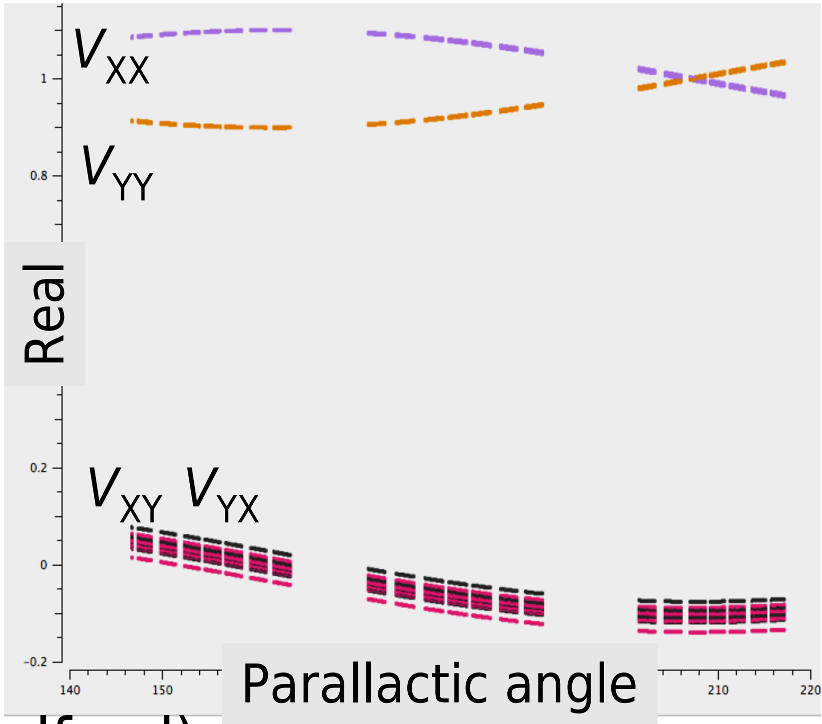
$$I = (V_{XX} + V_{YY})/2$$
$$Q = (V_{XX} - V_{YY})/2$$
$$U = (V_{XY} + V_{YX})/2$$
$$V = (V_{XY} - V_{YX})/2i$$
$$\chi = 0.5 \text{ atan}(U/Q)$$

- Stokes parameters
  - I total intensity; Q, U linear, V circular polarization

ALMA polarization calibration

- Calibration source has unknown linear polarization
  - Gain solutions decomposed into *X* and *Y* per antenna

    $g_x' = g_x(1+Q/I)^{0.5}$ $g_y' = g_y(1 - Q/I)^{0.5}$
- Leakage between *X* and *Y* feeds ('*D*'-terms)
- Feeds rotate on sky as alt-az antenna tracks source
  - Parallactic angle rotates
  - Q_{obs} time-dependent
- 3+ scans, >3hr HA coverage
  - Solve for leakage and source polarization
- Known feed orientation
  - Directly correct pol. angle
- For high pol. purity correct 2nd order terms
  - Need source model (external or self-cal)

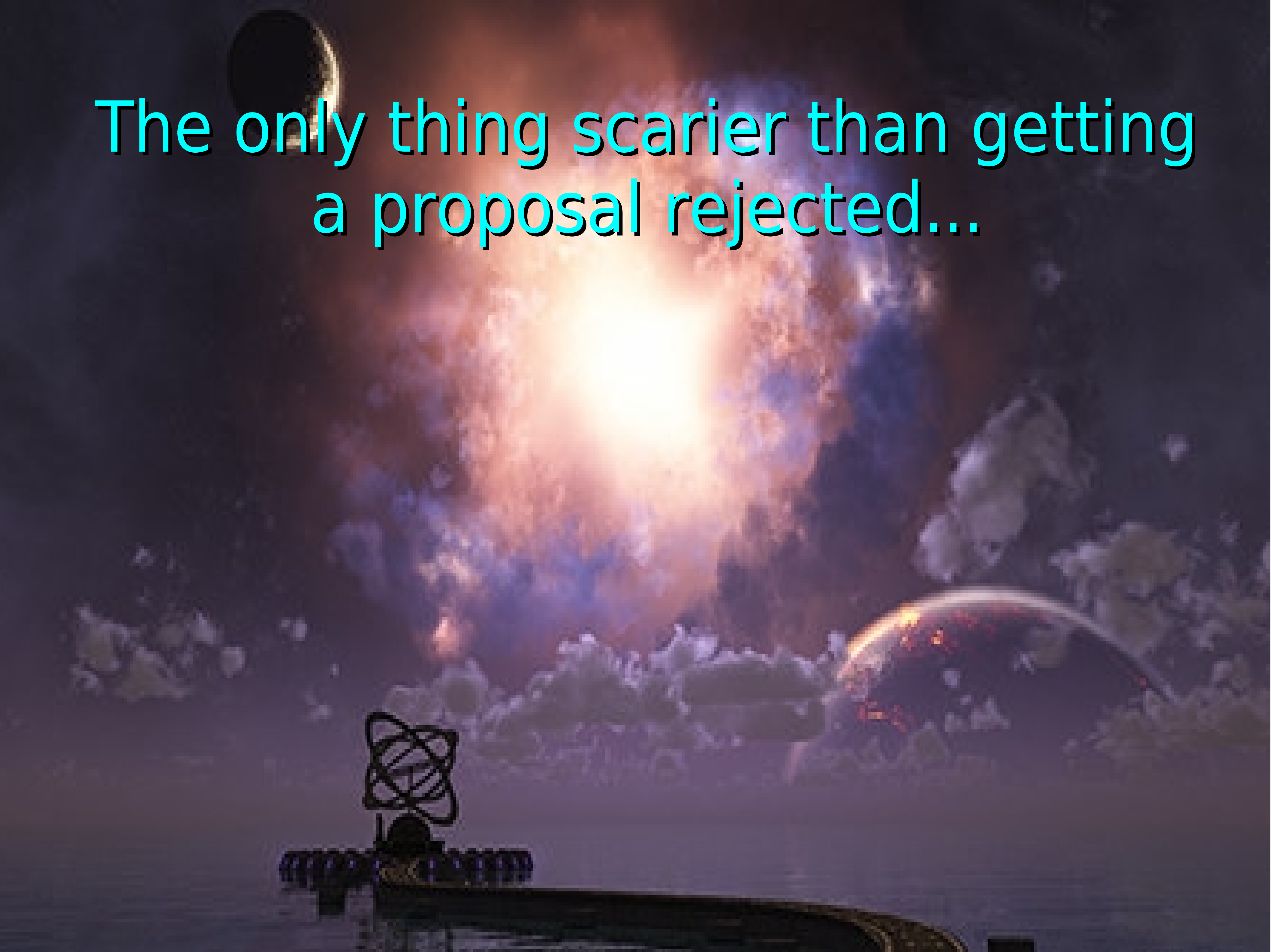


Observing support

- www.almascience.org
  - Observing Support Tool for quick simulations
  - Splatalogue for line frequencies etc.
  - Sensitivity Calculator
  - Observing Tool for preparing proposals, observations
  - Archive including public-domain data
  - On-line Helpdesk
  - ALMA Regional Centre Nodes face-to-face support
    - Community days, schools
    - RadioNet MARCuS support to visit nodes for data red^{n}
- http://www.iram.fr/IRAMFR/
  - IRAM Interferometry & single dish schools
    - Biennial, alternate – next mm-dedicated ERIS 2014
  - RadioNet TNA support for observations

(sub-)mm Interferometry Summary

- Atmospheric refraction/absorption dominates quality
  - Cold dry sites OK ≲370 GHz, exceptional sites ≲1 THz
  - Troposphere affects phase & amp on ≳1s timescales
    - Instrumental calibration (WVR, T_{sys}) etc.
  - Sub-mJy sensitivity at sub-arcsec resolution
    - Extended sources need multiple arrays/SD fill in
    - Large fields need mosaicing
- Normally observe two separate sidebands
  - May have 'mirror' or noise
- Need models for resolved/variable calibrator sources
  - They may have lines, as well as your target!
- CASA for ALMA data reduction, later stages of any data
  - 'Native' package, e.g. GILDAS for some instrument-specific data formats/early corrections


The only thing scarier than getting
a proposal rejected...

is getting it when the data comes!