What is this radio interferometry stuff?

Anita Richards
UK ARC
with thanks to ALMA colleagues

What are you letting yourself in for?

EUROPEAN ARC
ALMA Regional Centre || UK

ALMA data will be science-ready, right?

- Pipelined, quality-controlled image cubes will be delivered in full operations
  - With expert/ARC help in Early Science

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- Change resolution? Self-calibration? Combine data?
  - Apply calibration provided, continue in CASA (or your favourite package)

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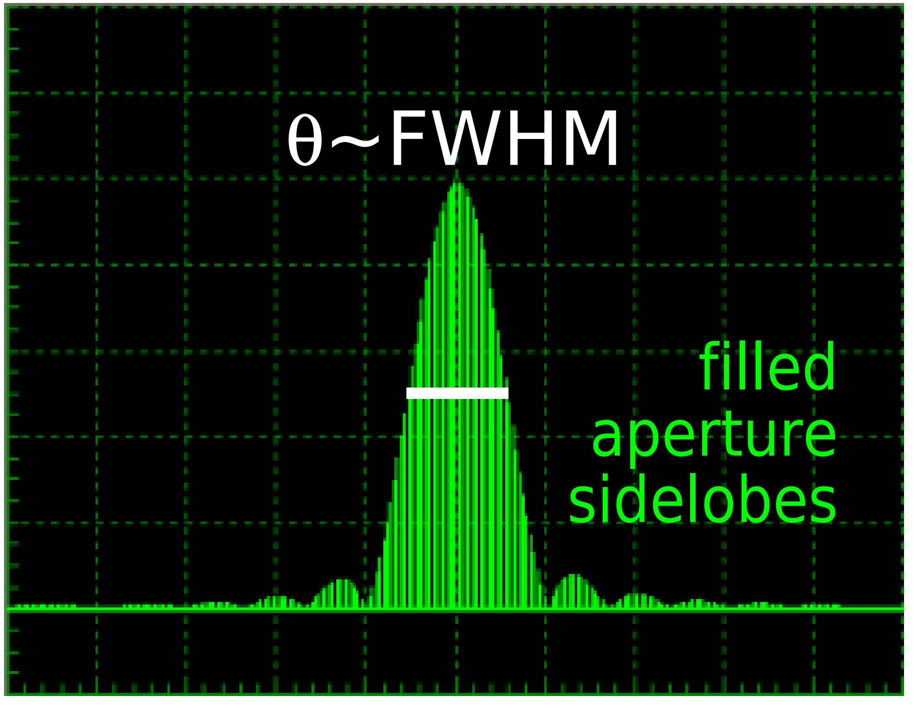
- Early science or challenging observations
  - Full/partial data reduction (recipes and pipeline scripts provided, ARC assistance).

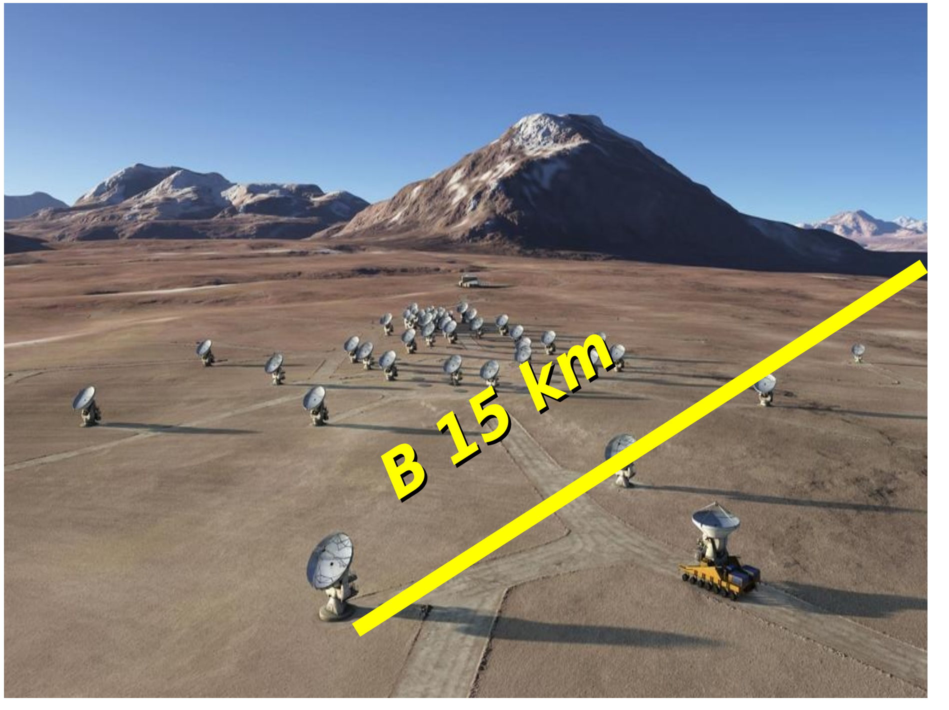
Getting the best out of ALMA

- High spectral resolution (up to ~10^8)
  - Channels linearly spaced in frequency
- High angular resolution (≥ 0''.005 full ops)
  - Relatively small FoV
  - 'missing spacings' in extended configurations
- Instrumental corrections
- Atmospheric refraction and absorption
  - Correct refractive (phase) errors
    - Reference source within few deg
      - Also provides astrometry
  - Correct time-dependent amplitude fluctuations
    - Best sensitivity to short λ in good weather
- Sensitivity: $\sigma_{rms} \propto T_{sys} \div [(N(N\text{-}1)/2)\ \mathrm{d}\nu\ \Delta t]^{\mathbf{0.5}}$
  - *N*umber antennas (ALMA's huge collecting area!)
  - dν freq. per image, Δ*t* total time on source

Interferometry resolution

- One antenna: maximum resolution $\theta \sim \lambda / D$
  - D 12m, λ 1 mm (ν 300 GHz) gives $\theta \sim 17$ arcsec





- Many antennas: maximum resolution $\theta \sim \lambda / B$
  - B 15 km at λ 1 mm gives $\theta \sim 0.014$ arcsec
  - Sensitivity helped if noise decorrelates
    - but sparse coverage gives worse sidelobes

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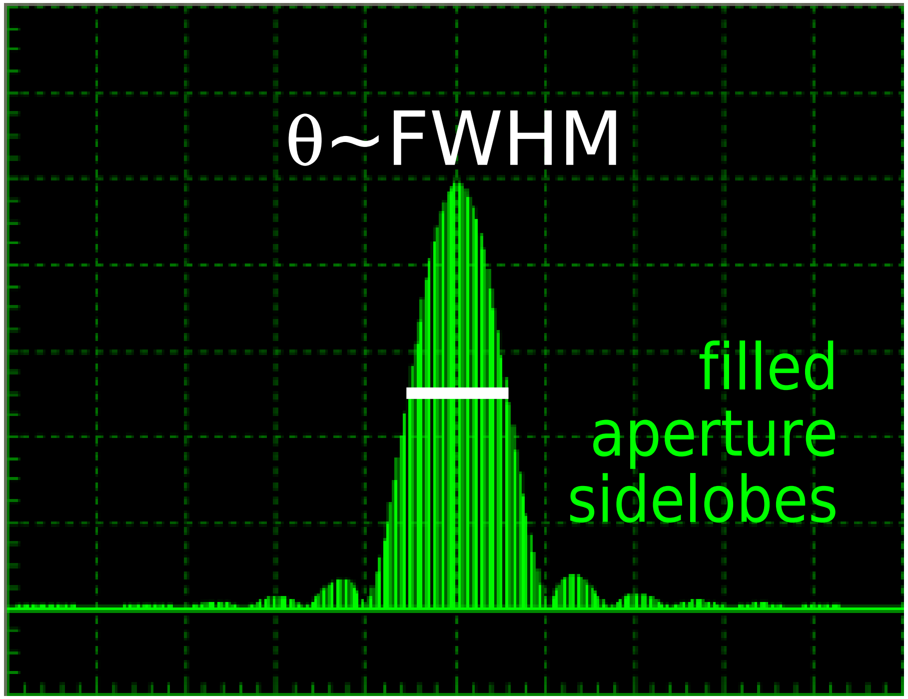

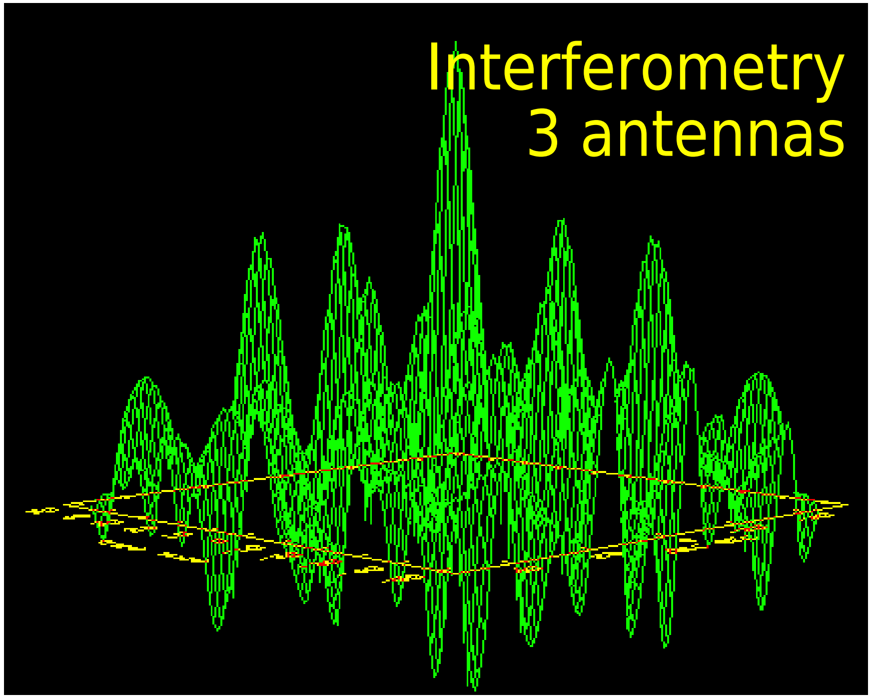

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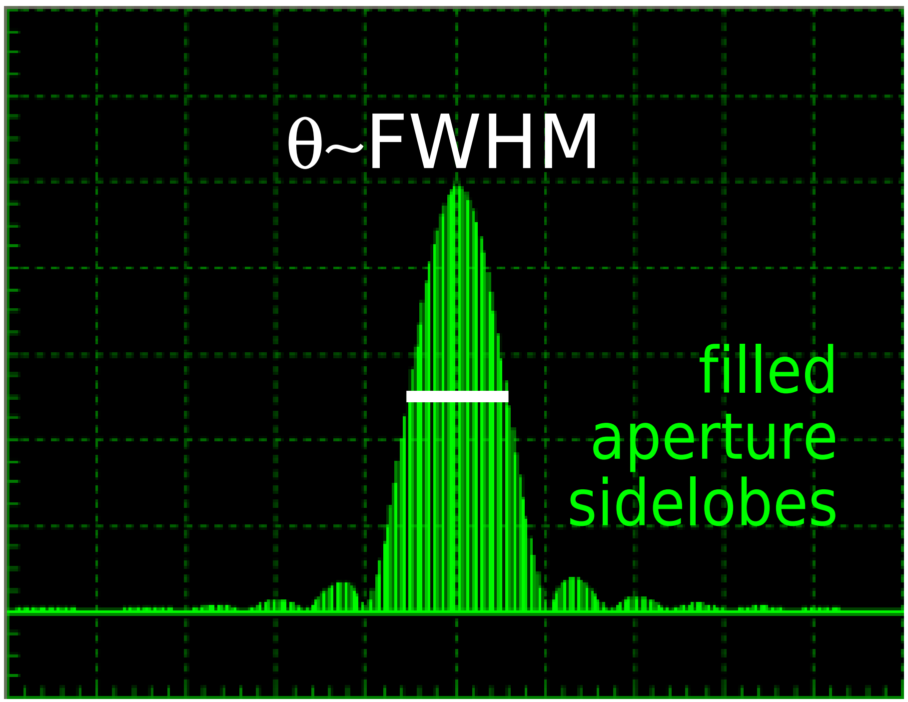
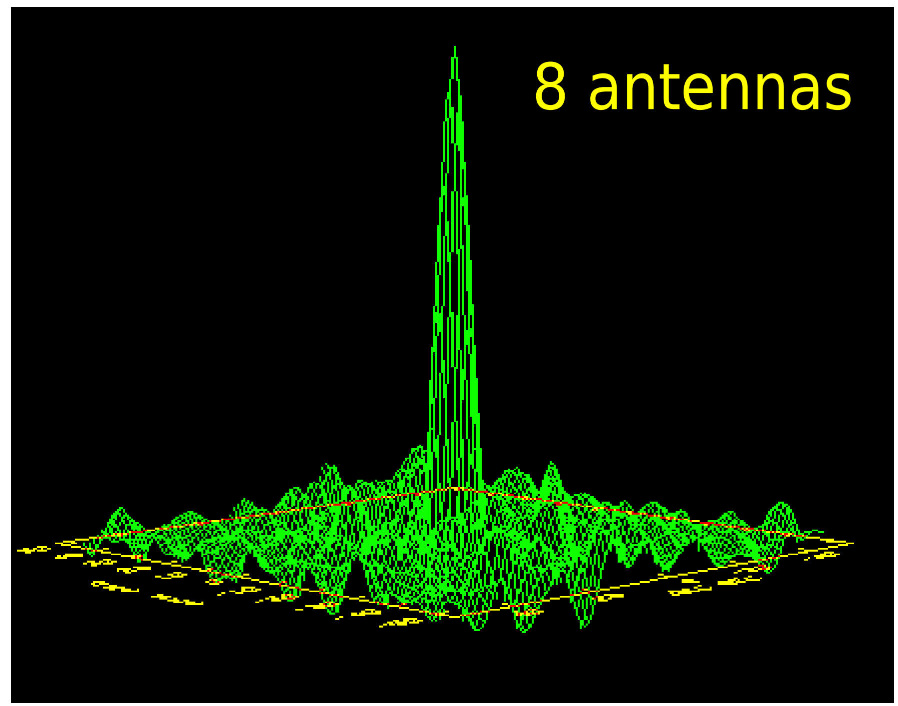
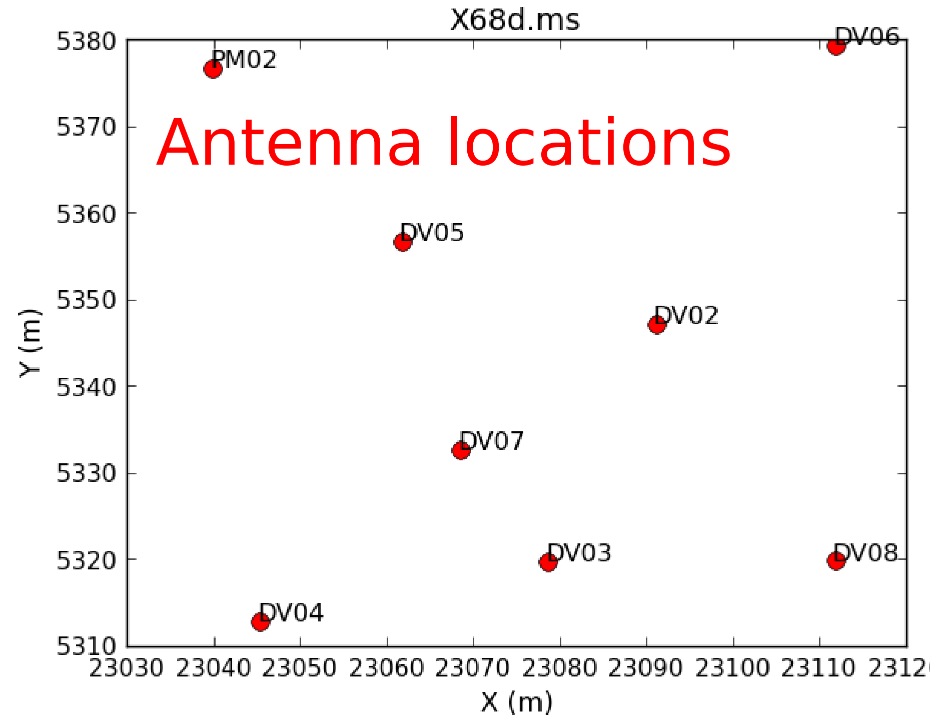


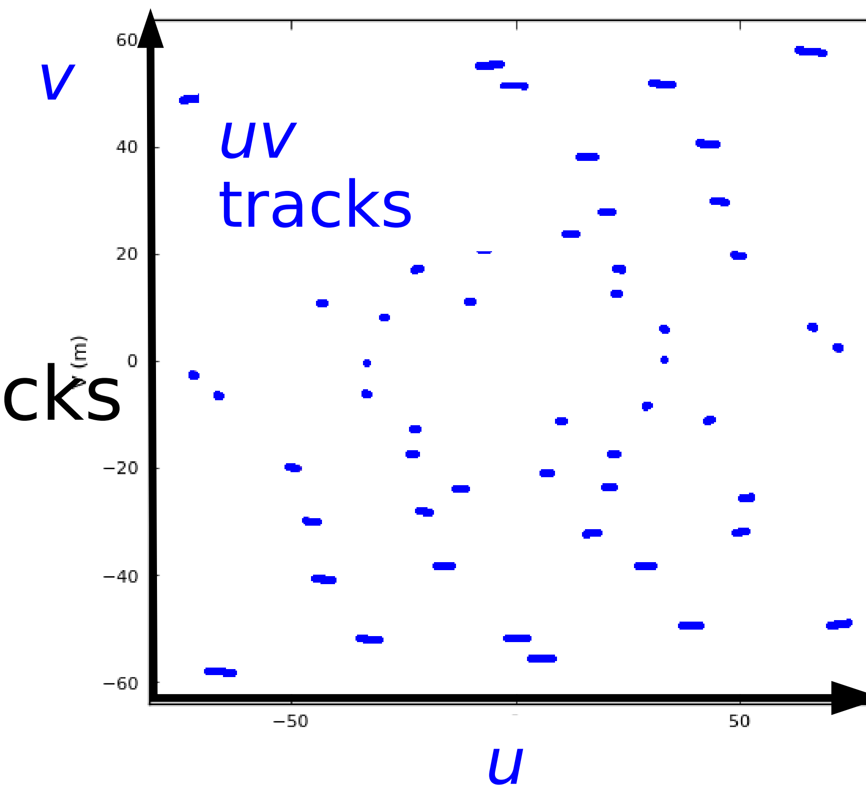


- Many antennas: maximum resolution $\theta \sim \lambda / B$
  - B 15 km at λ 1 mm gives $\theta \sim 0.014$ arcsec
  - Sensitivity helped if noise decorrelates
    - Better with more antennas/longer track

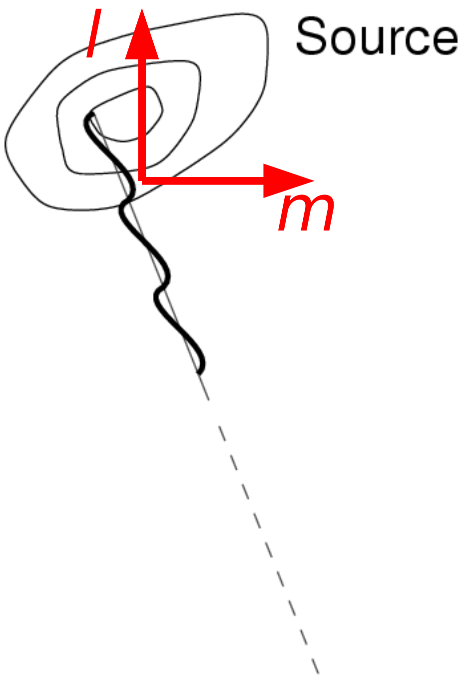
Interferometry



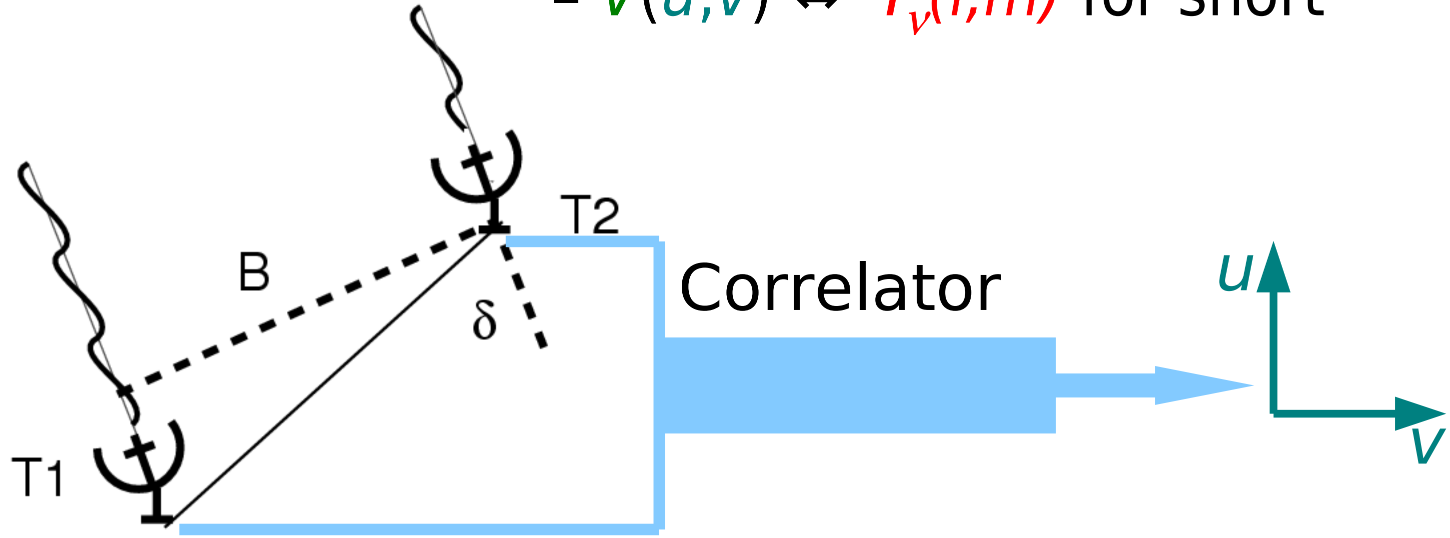
- Earth rotation aperture synthesis
- Vectors between pairs of baselines sweep out *uv* tracks
  - Record combined signals every few sec
  - Few antennas/short runs means lots of gaps



From interferometry to images

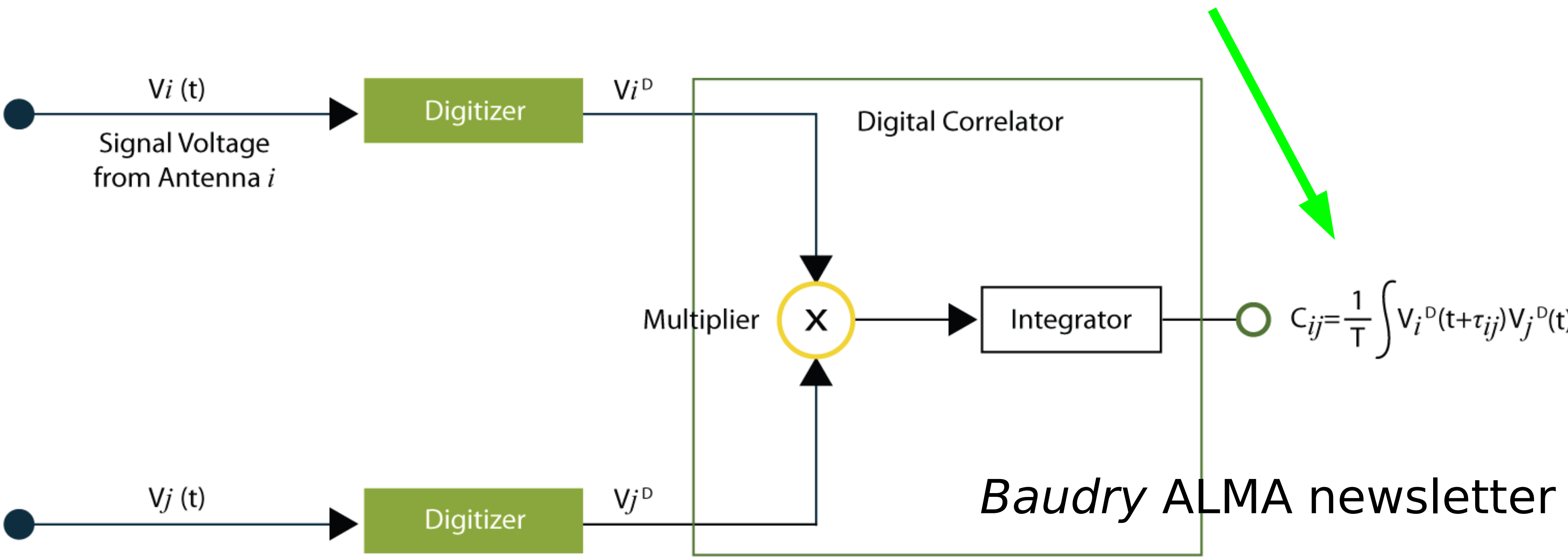


- Signals from different parts of source reach different telescopes at different times/phases
  - Fourier transform of complex visibility amplitude and phase gives sky brightness distribution
  - $\sum V_\nu(u_\nu,v_\nu)\, e^{[2\pi i(u\nu l + v\nu m)]}\, du dv = I_\nu(l,m)$
    - $V(u,v) \Leftrightarrow I_\nu(l,m)$ for short



Correlation

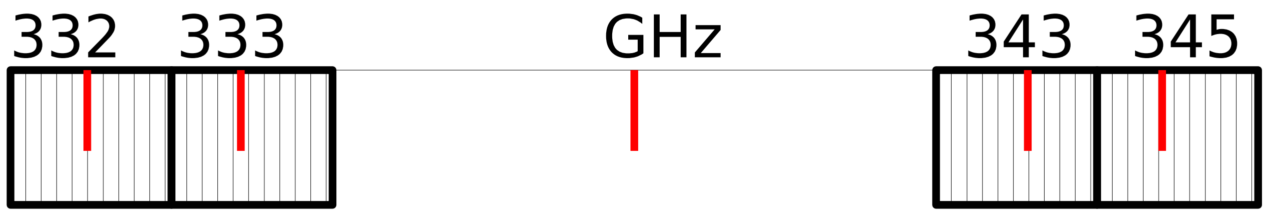
- Digitise and combine signals in correlator
  - Create spectral channels by adding ~μsec time lags
  - Make parallel (and cross) polarizations
    - FT into frequency domain
      - Output averaging determines integration time
- Produces complex visibility data
  - **Time series of amps & phases per baseline per pol.**



Baudry ALMA newsletter 7

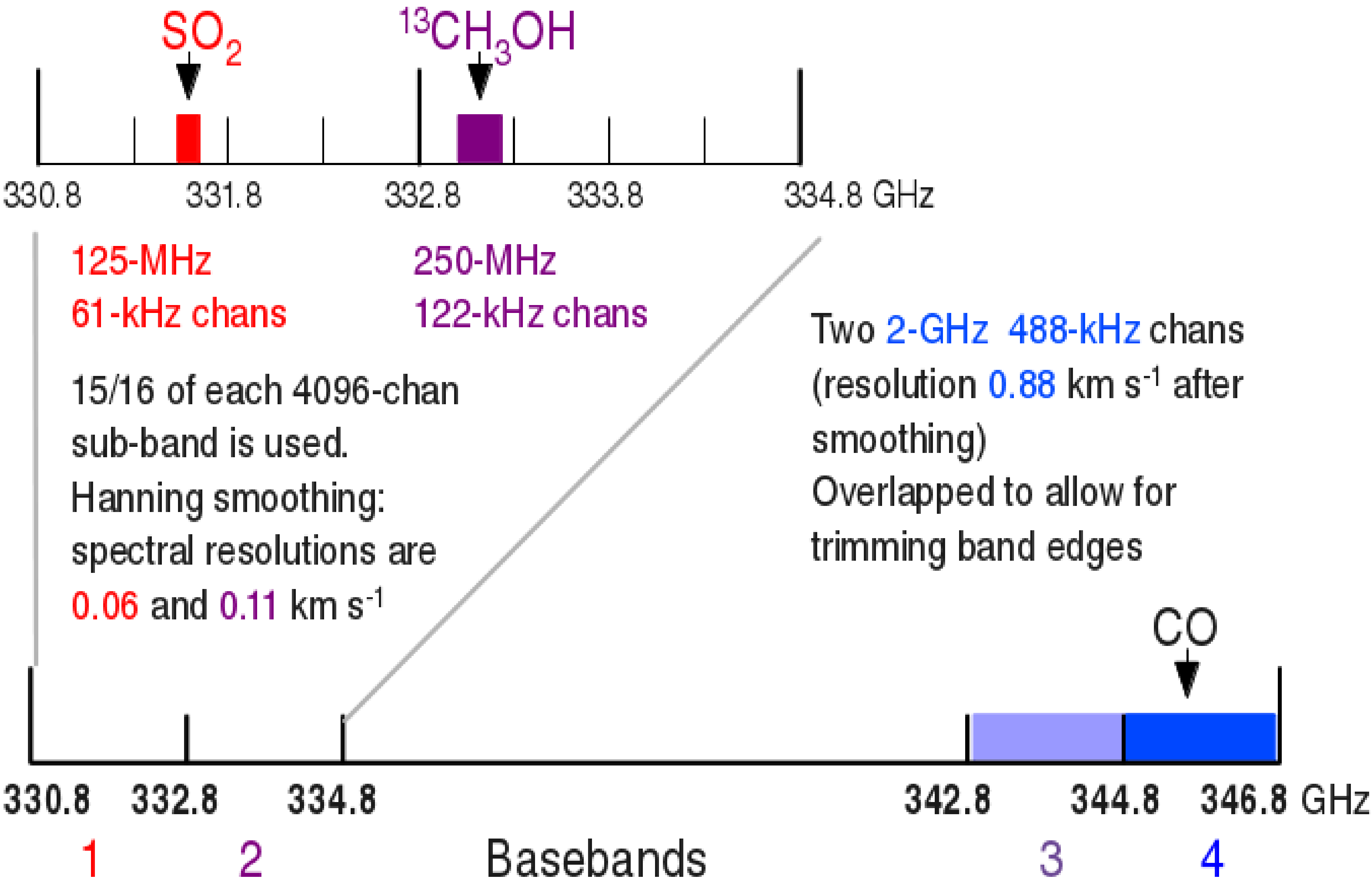
Correlator configurations

- Four spectral windows (spw), max. width 2 GHz
  - 128 chans per spw (dual pol) TDM
  - 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**

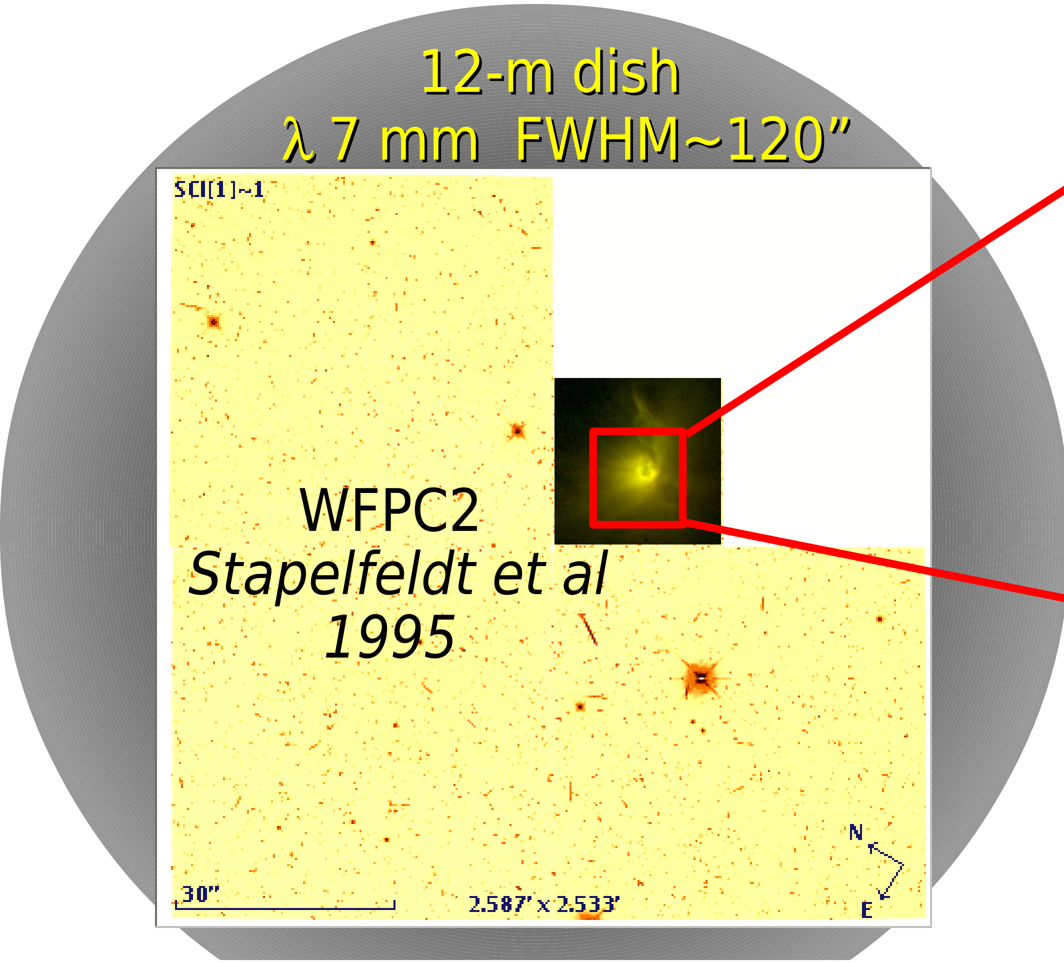
Frequency flexibility (Cycle 1)

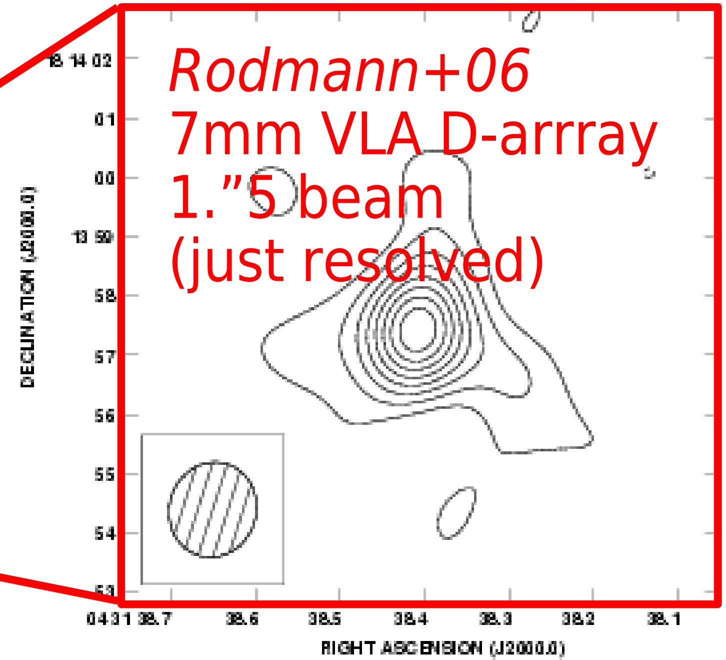


Brightness temperature

- 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

HL Tau on large scales





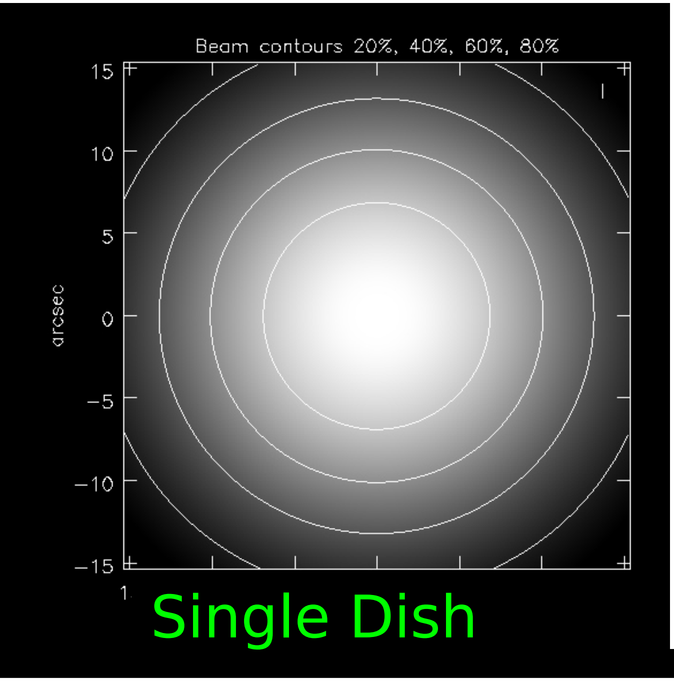
- Total 5 mJy in 0.57 asec^2
- T_b~10 K average in 0.57 asec^2

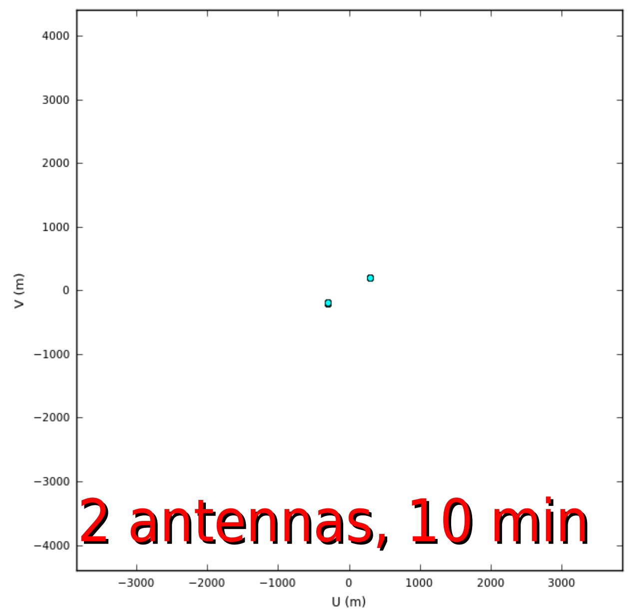
- $T_b = [(S/\mathrm{Jy})10^{26}\,(\lambda/\mathrm{m})^2\,] \div [2\,k_B\,\Omega/\mathrm{Sr}]$
  - Use *smaller* of (actual size) or (beam size) as area Ω
    - *Smooth* 5mJy in whole 120” would be ~1μJy/1.”5 beam

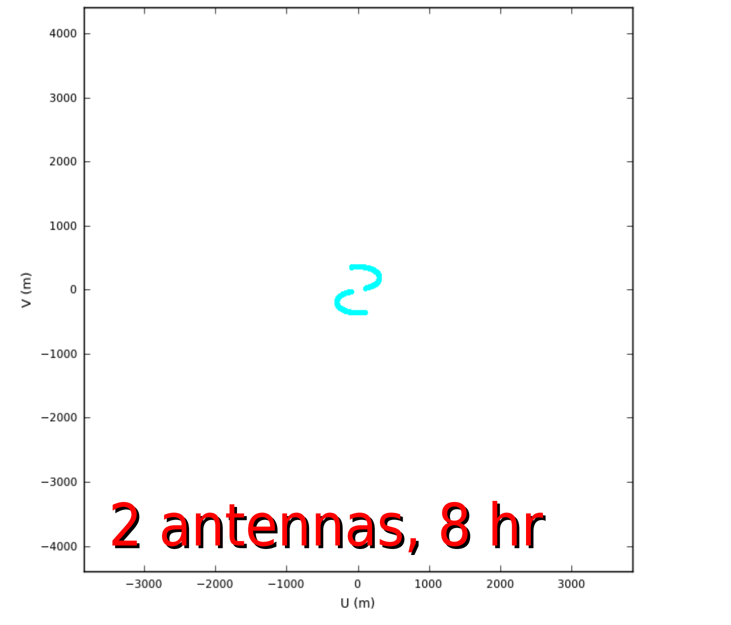
High-resolution brightness of HL Tau

- D-array lowest contour 0.3 mJy in 1500-mas beam
  - Fit Gaussian peak~3 mJy in ~200-mas diameter region
    - ≡ 0.18 mJy in 50-mas beam
- A-array lowest contour 0.15 mJy in 50-mas beam
  - Missing smooth, extended bright flux: missing spacings
  - Missing weak flux: small beam ⇒ higher T_b threshold

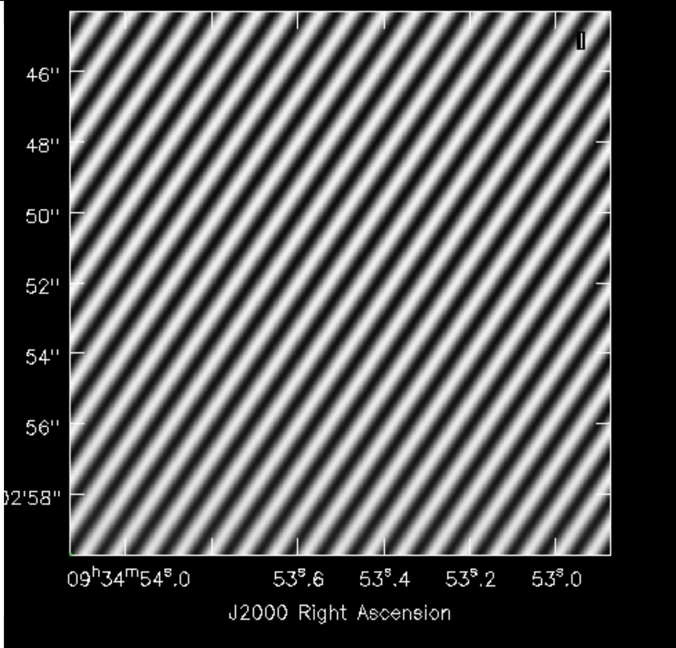
Visibility coverage and imaging

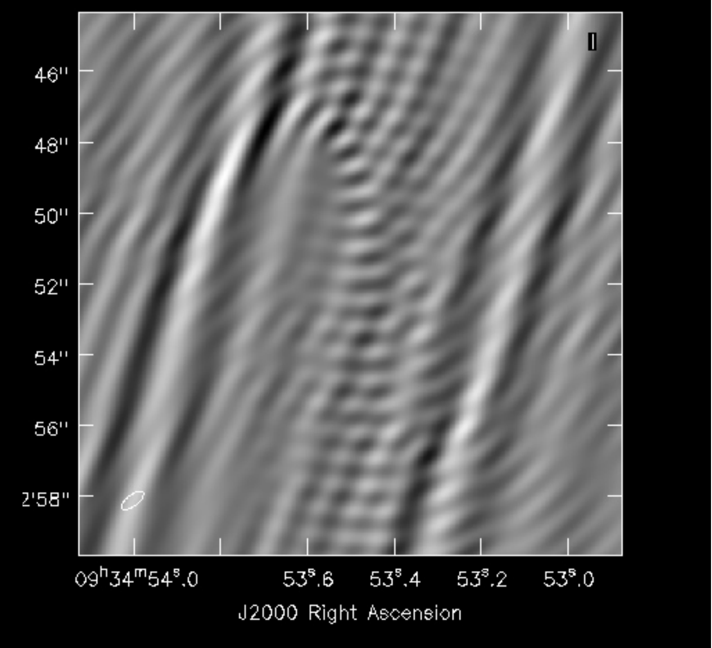




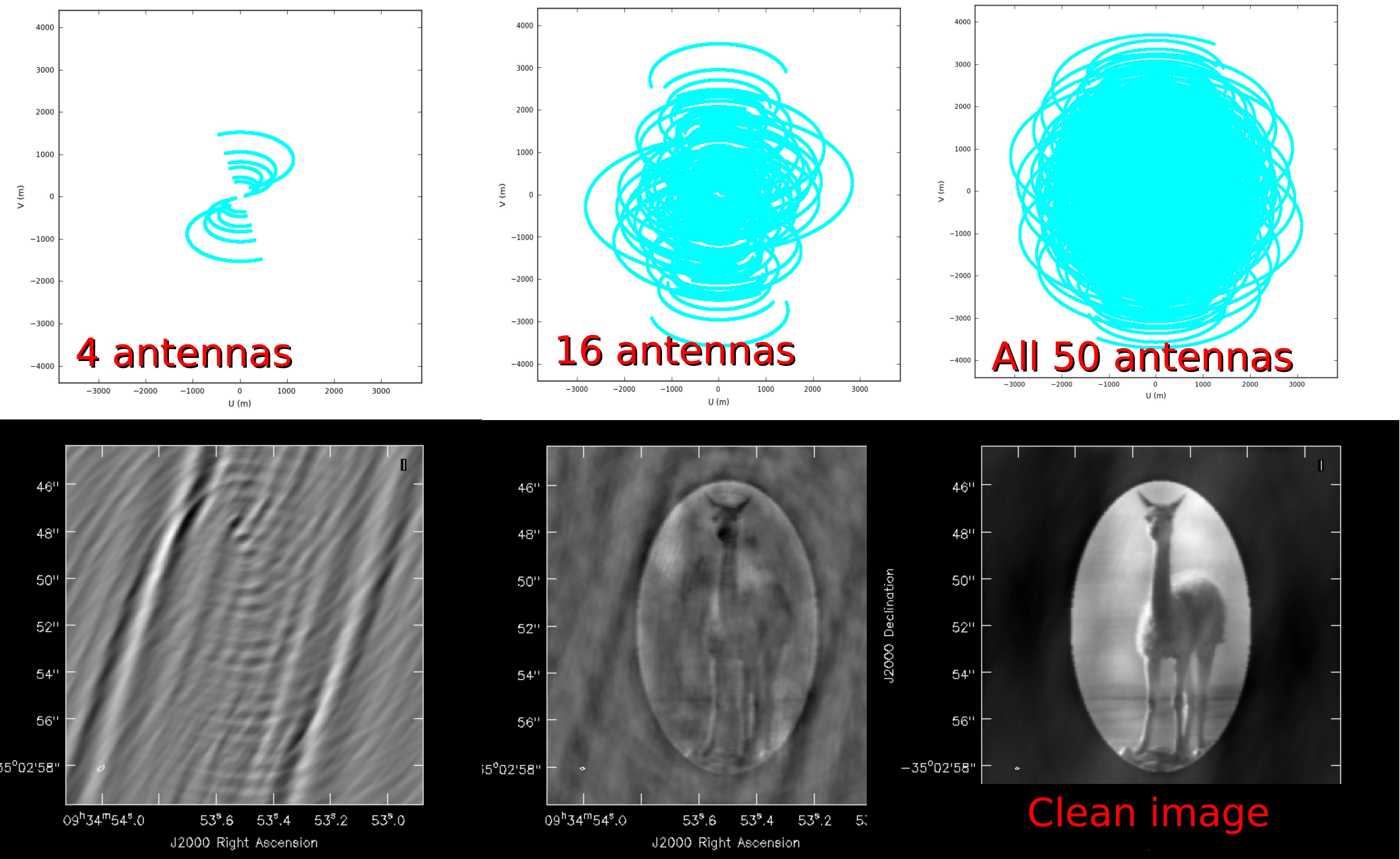


- Single dish just gives flux measurement
- FT of two short samples is stripes
- Long track on single baseline only point sources

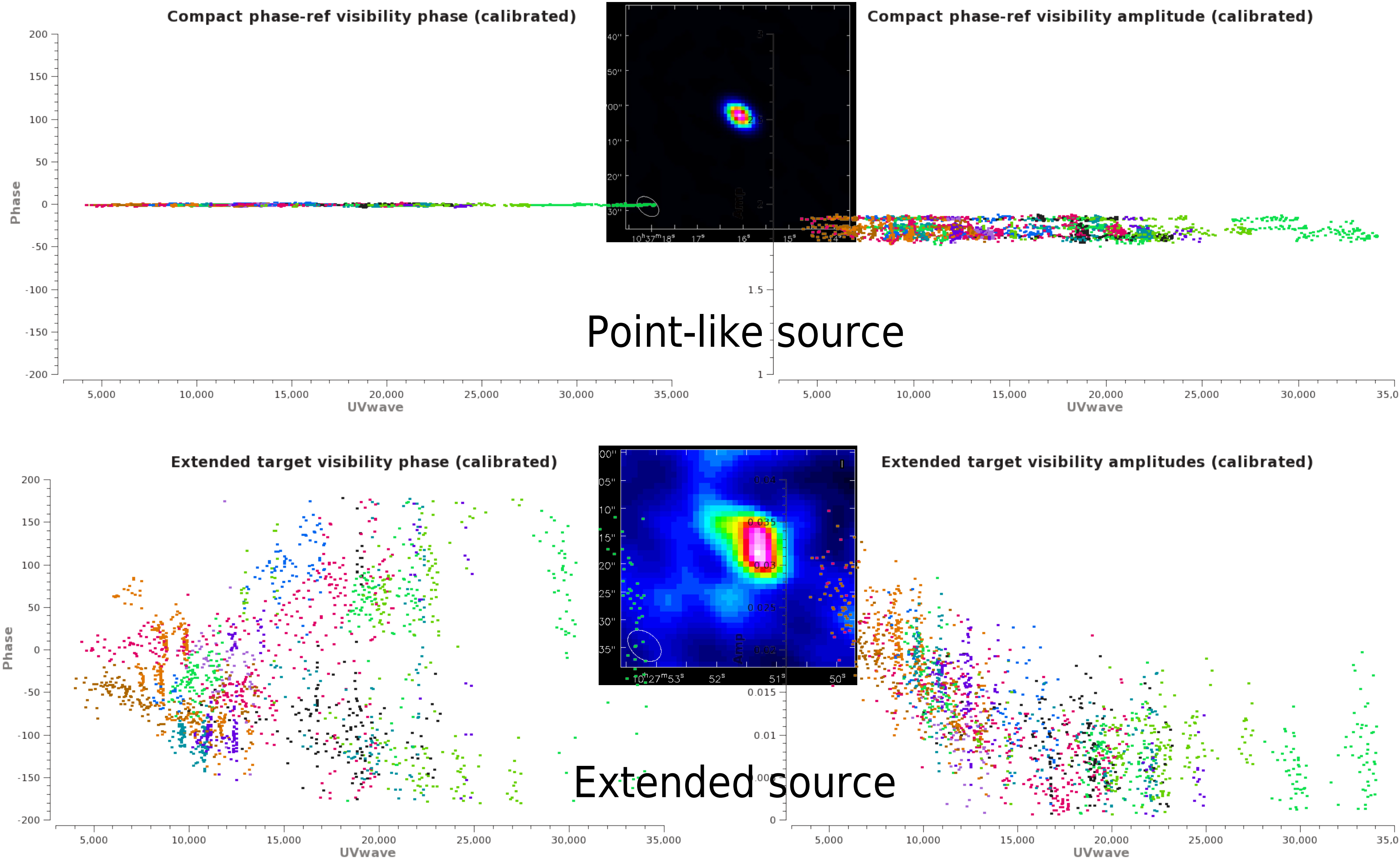




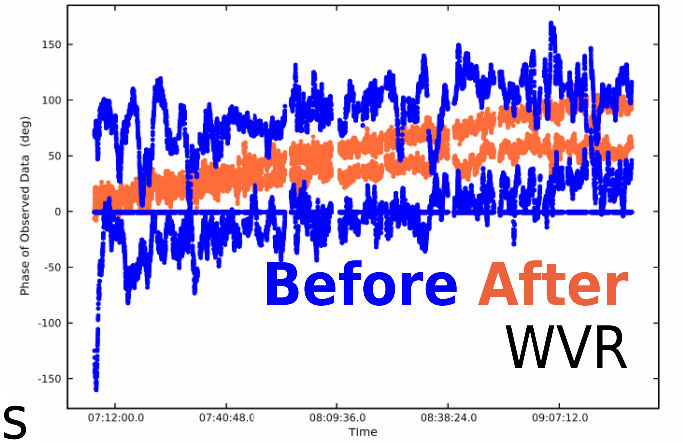
Adding more antennas....



Visibility phase and amplitude

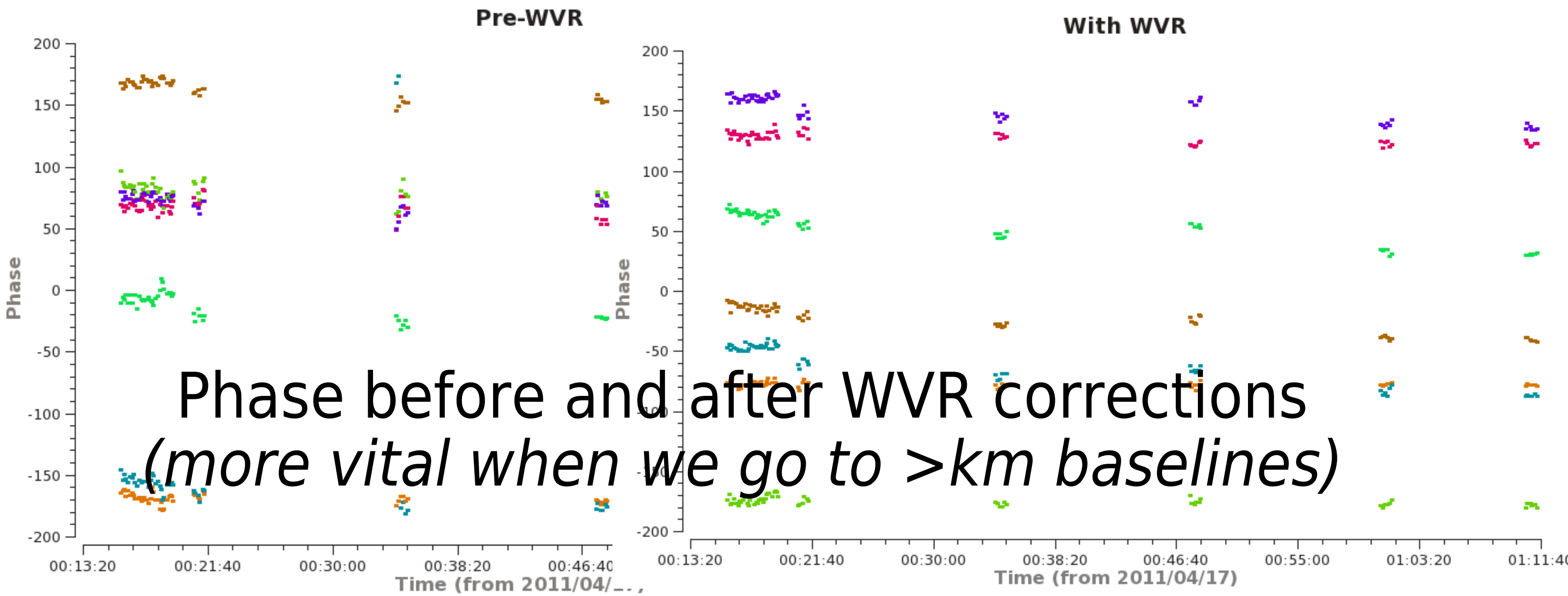


ALMA calibration



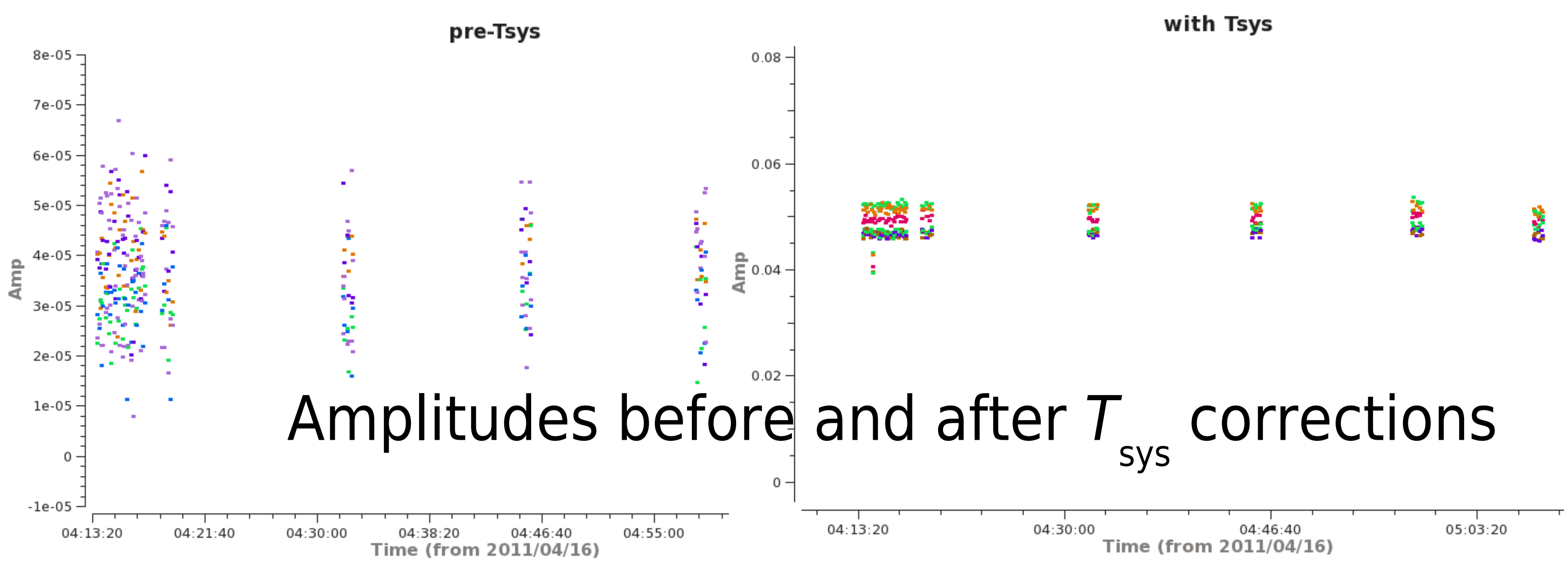
- Water vapour in the troposphere
  - Delay to incoming wavefronts
    - Water Vapour Radiometry (WVR)
    - Measure 183-GHz atmospheric line
      - Derive path length corrections every s
  - Amplitude absorption
    - System temperature (T_{sys}) measurements every few min
- Residual delay and bandpass errors
  - Phase & amplitude corrections as a function of ν
  - Derive from bright astrophysical source
    - Good signal to noise in a single channel
- Planets, large moons, asteroids to set flux scales
- Phase-referencing for remaining time-dependent errors

Time-dependent instrumental corr.



Phase before and after WVR corrections

(more vital when we go to >km baselines)

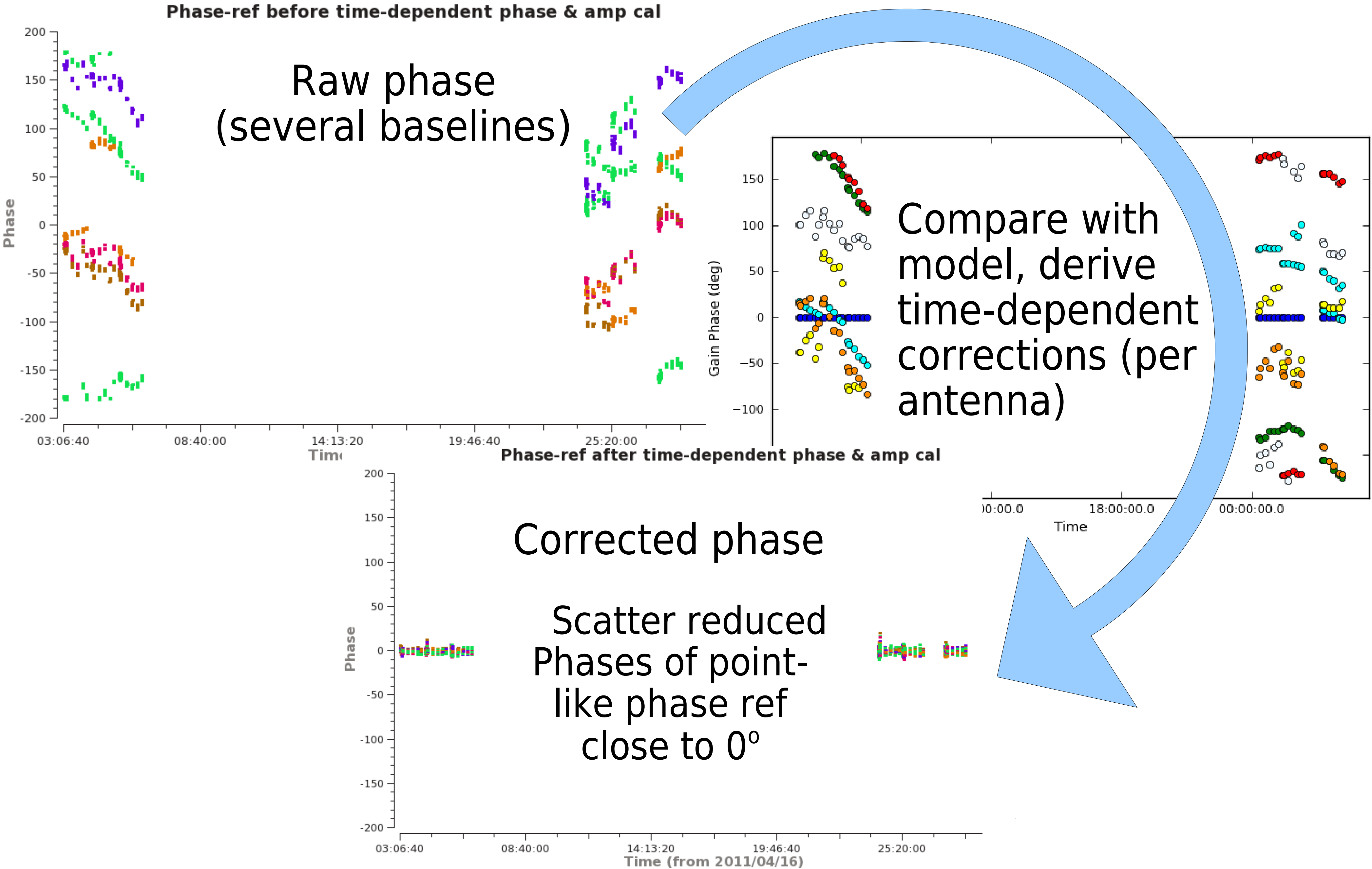


Amplitudes before and after T_{sys} corrections

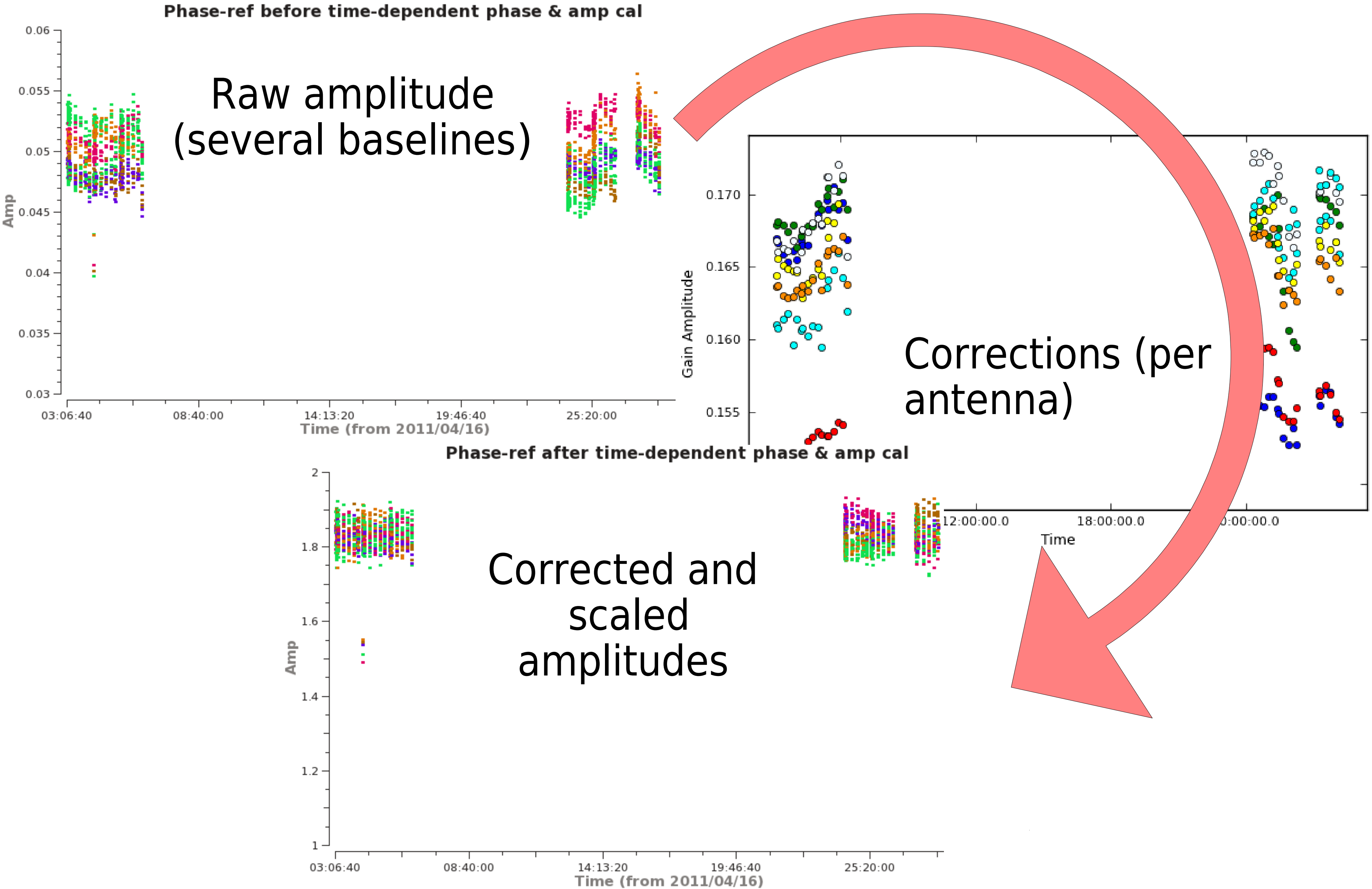
Phase referencing

- 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

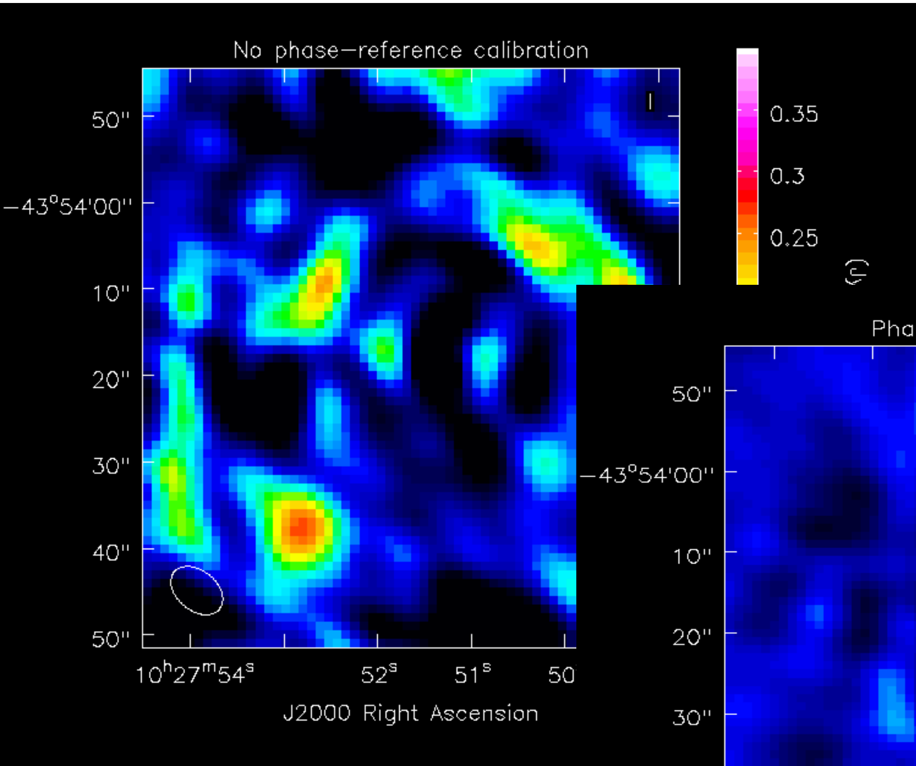
Reference phase corrections



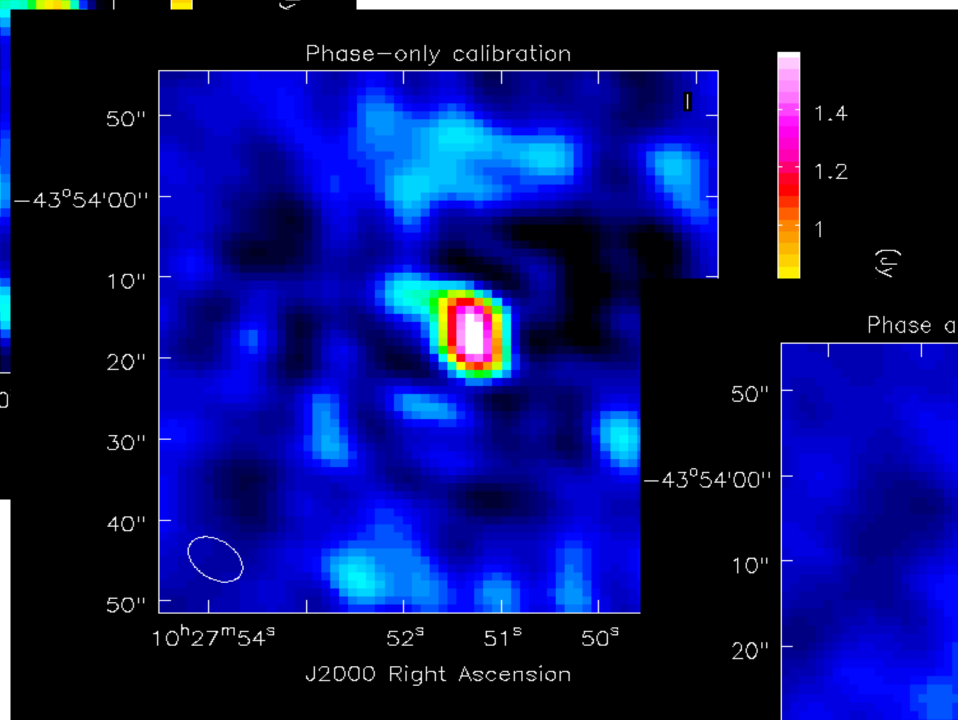
Amplitude corrections



Effects on imaging

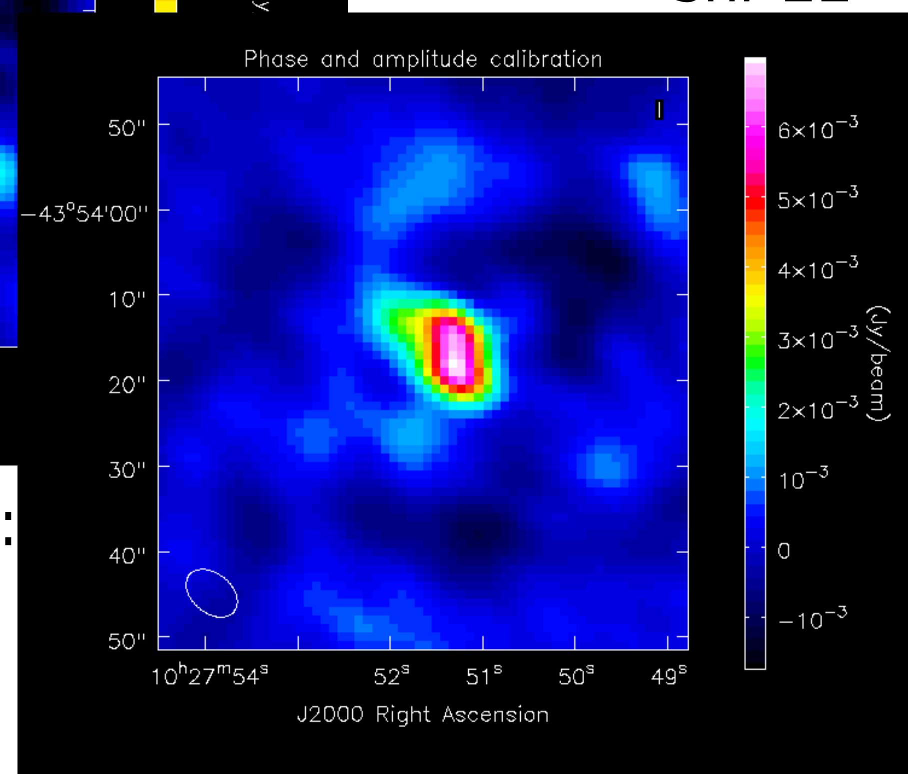


No astrophysical calibration:
no source seen

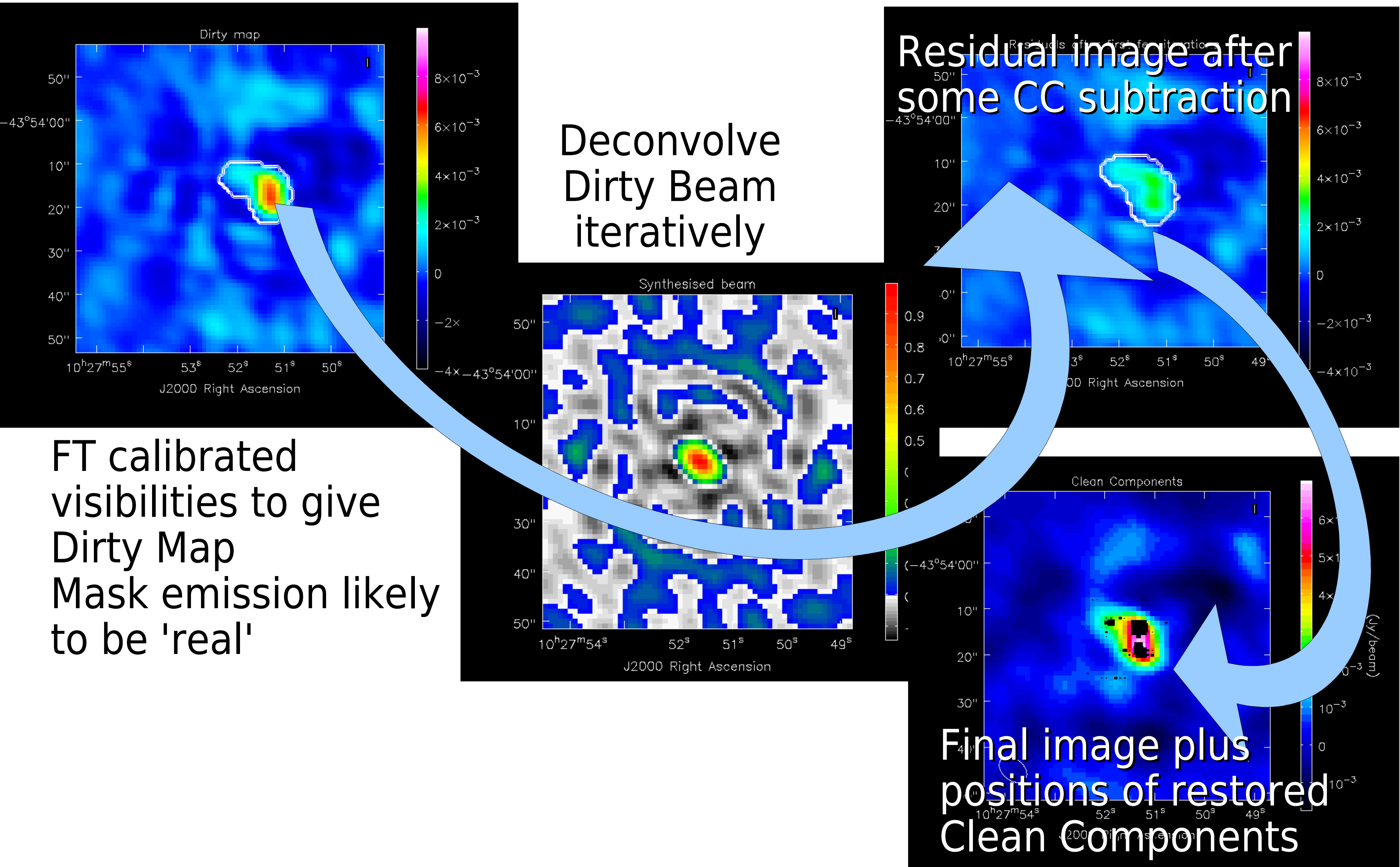


Phase-only solutions:
source seen, snr 15
but no flux scale

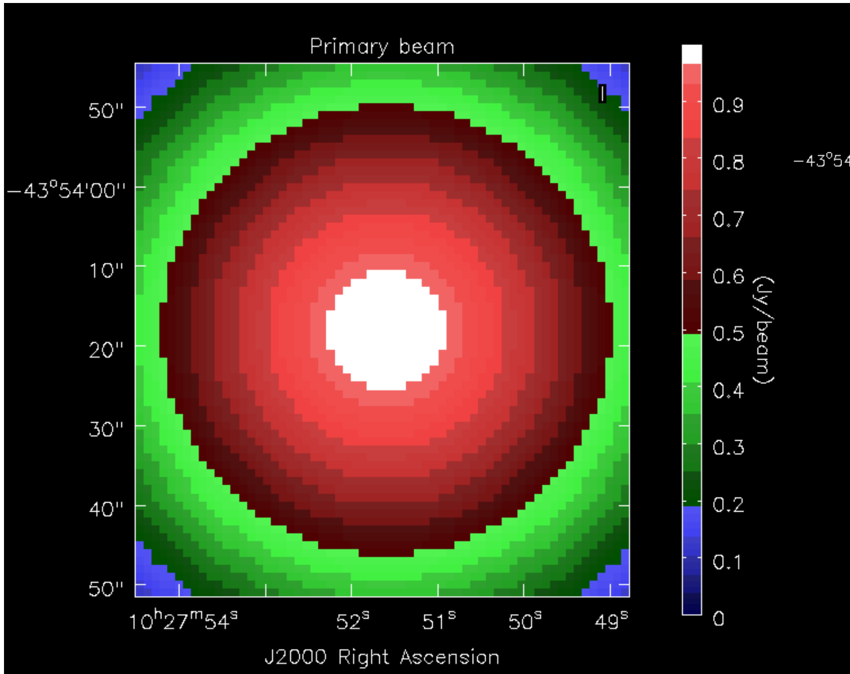
Amplitude and
phase solutions:
source seen,
snr 22



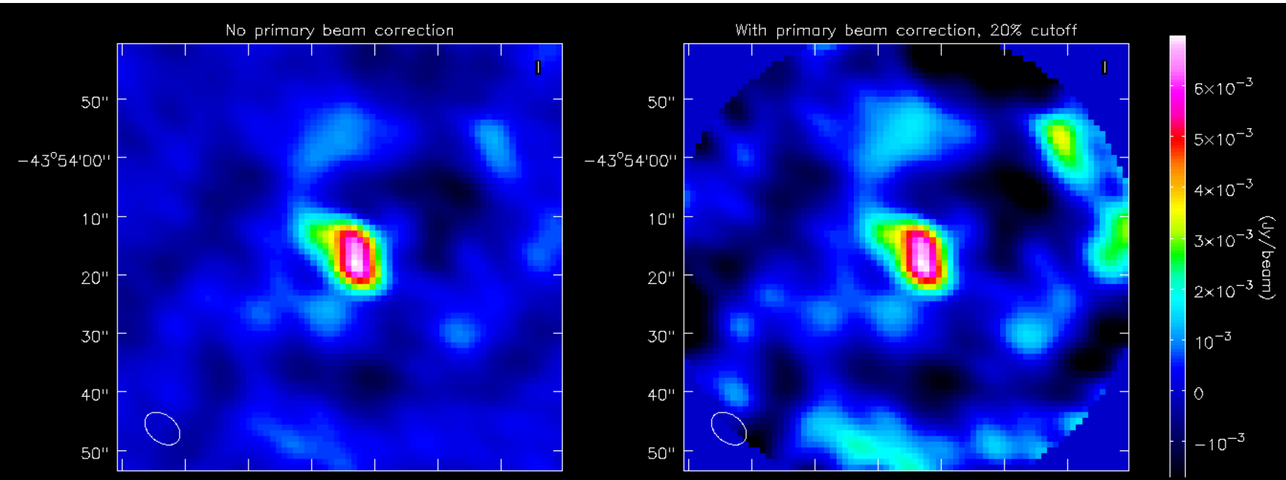
Fourier transform and clean



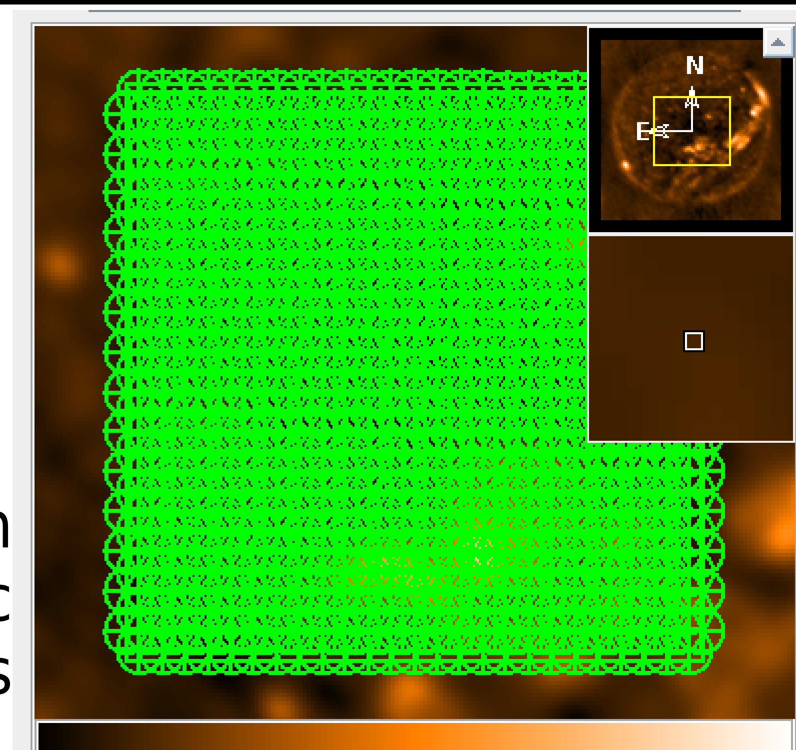
ALMA Field of View



100-GHz Primary beam
~60'' (half sensitivity)

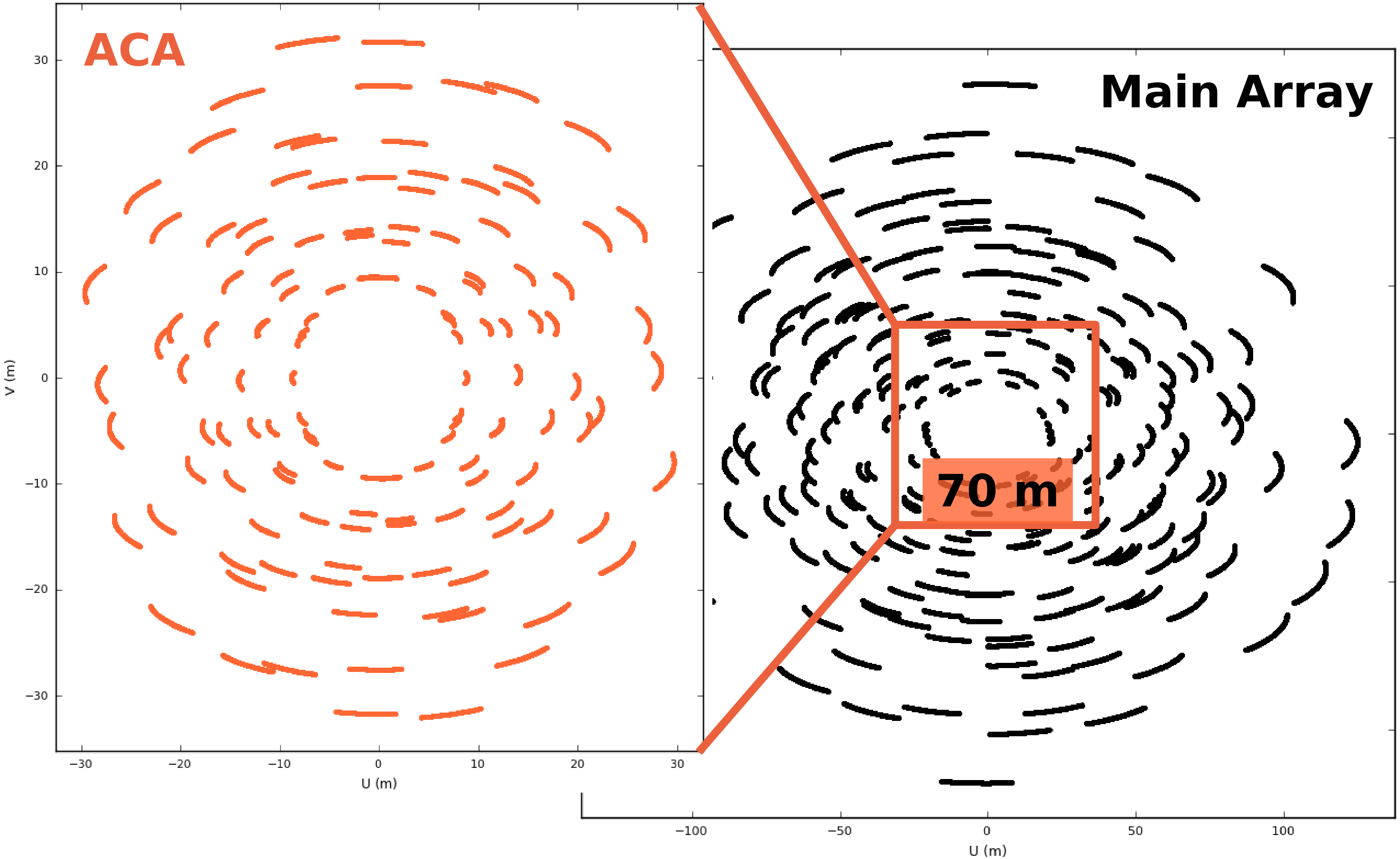


Without With PB correction

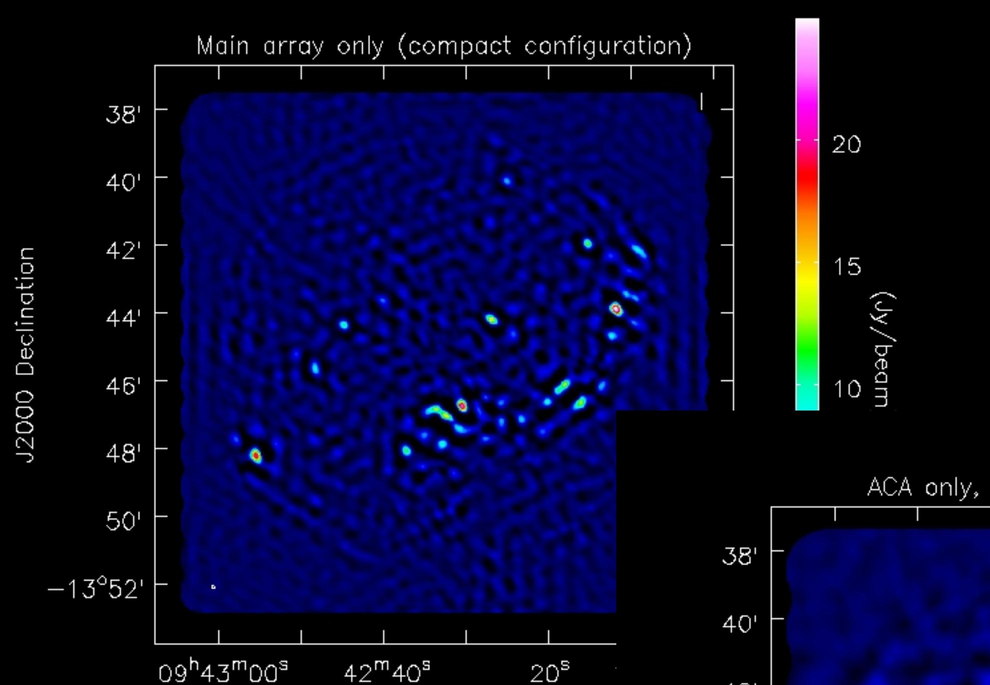


Whole Sun ~7000 12-m
100-GHz mosaic
pointings

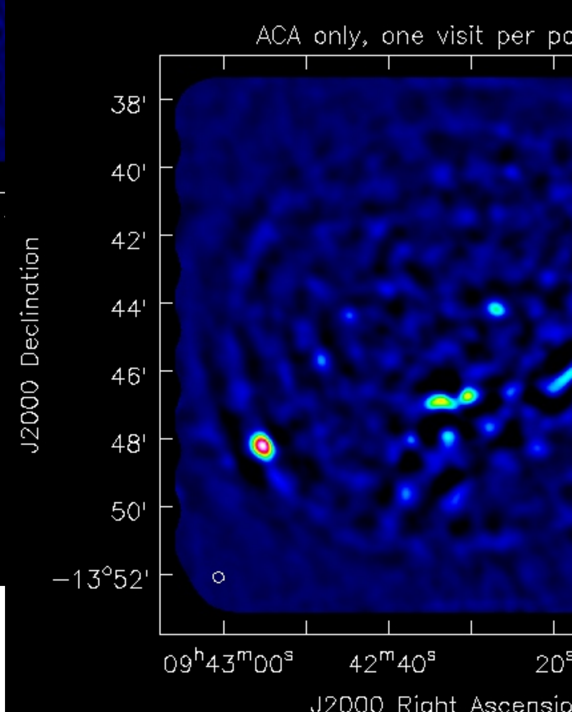
Visibility coverage



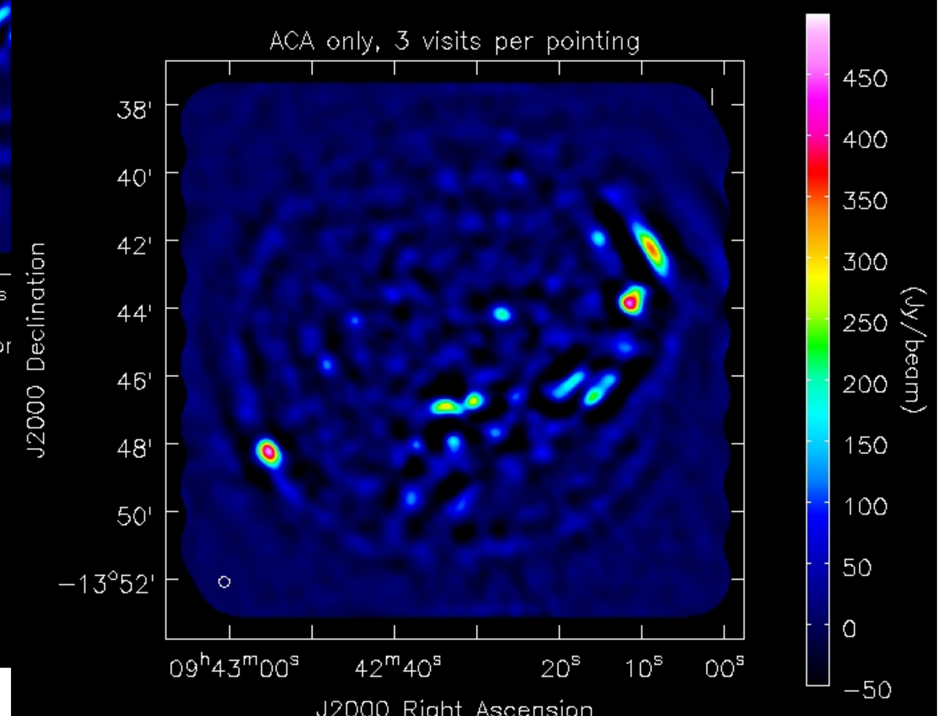
Incomplete *uv* coverage of Sun



Main array only



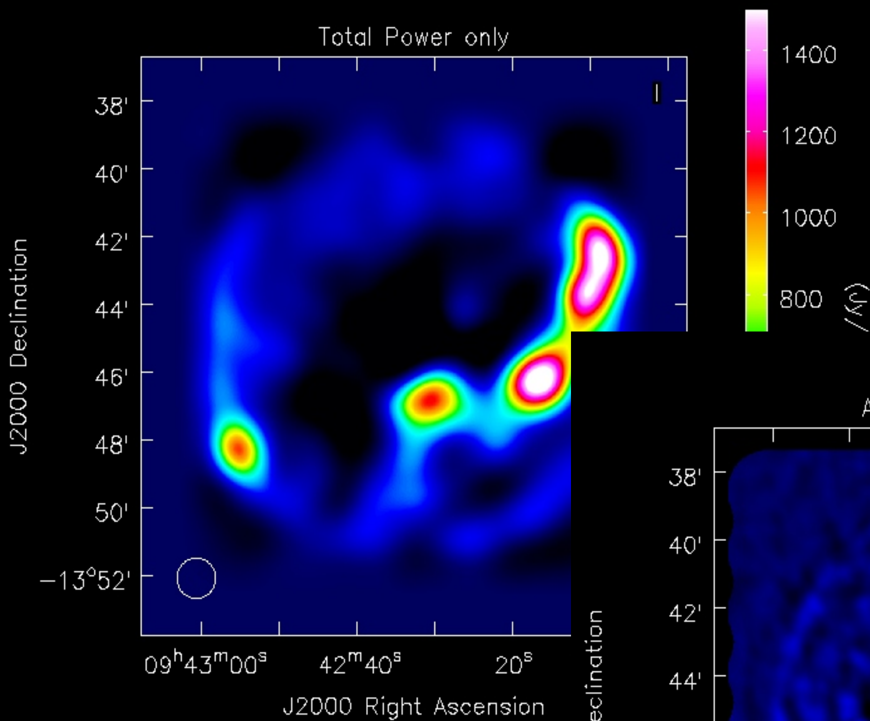
ACA only, one visit per pointing



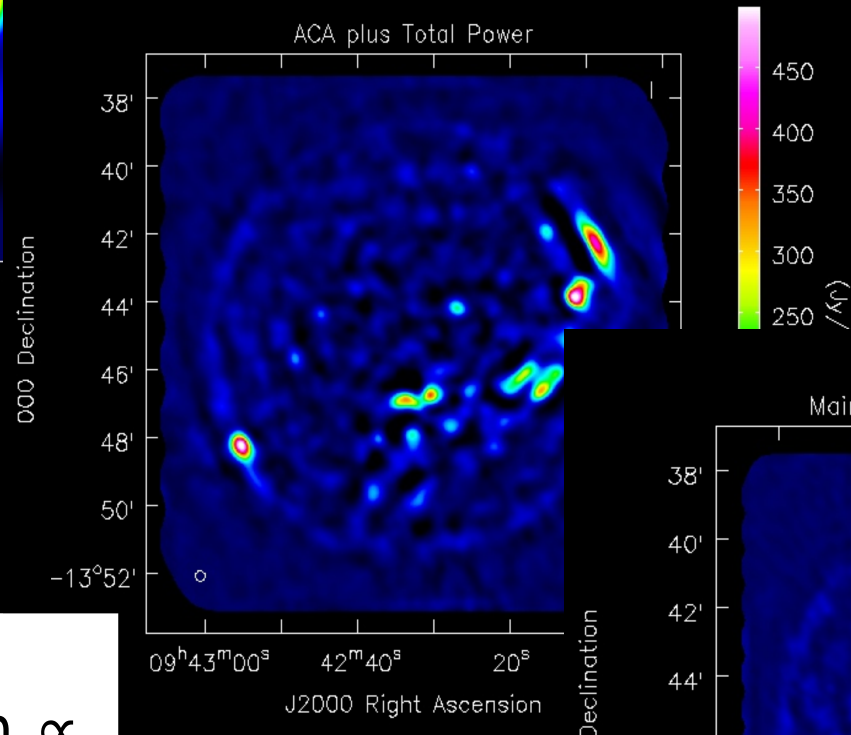
ACA only, 3 visits per pointing

(ALMA simulations based on VLA image from Czech ARC node)

Combining arrays

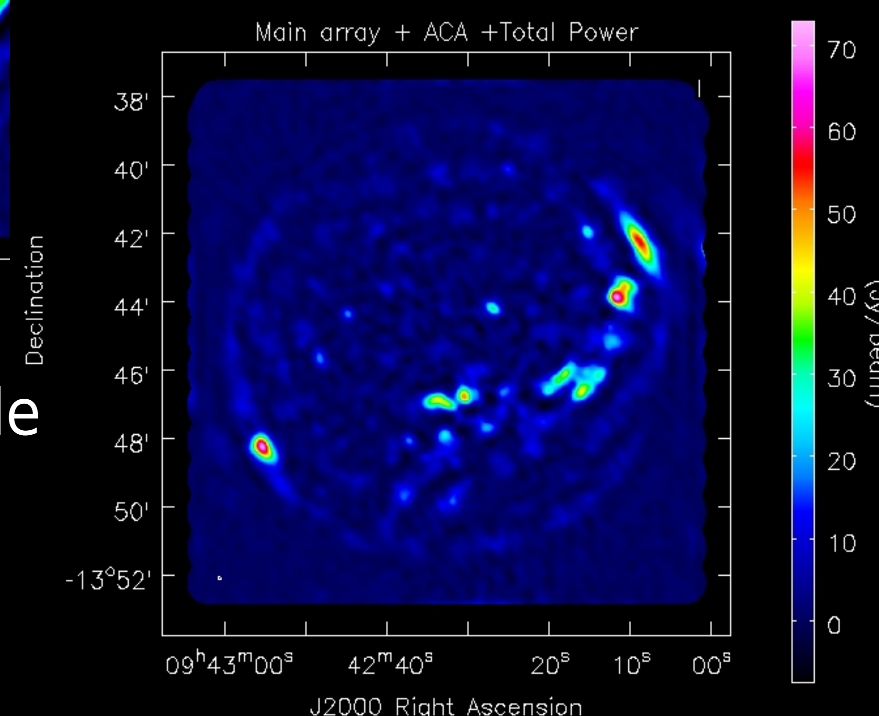


12-m single dish
arcmin resolution



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

CASA uses Measurement Equation

$$\underline{V}_{ij} = \mathbf{M}_{ij}\mathbf{B}_{ij}\mathbf{G}_{ij}\mathbf{D}_{ij}\int \mathbf{E}_{ij}\mathbf{P}_{ij}\mathbf{T}_{ij}\mathbf{F}_{ij} S \underline{I}_{\nu}(l,m) e^{-i2\pi(u_{ij}l+v_{ij}m)} dl\,dm + \underline{A}_{ij}$$

Vectors

Starting point

$\underline{V}$ isibility = *f(u,v)*

$\underline{I}$ mage — The goal

$\underline{A}$ dditive baseline error

Scalars

Methods

S mapping $\underline{I}$ to observer pol.

l,m image plane coords

u,v Fourier plane coords

i,j telescope pair

Jones Matrices

Hazards

Multiplicative baseline error

Bandpass response

Generalised electronic gain

Dterm (pol. leakage)

E (antenna voltage pattern)

Parallactic angle

Tropospheric effects

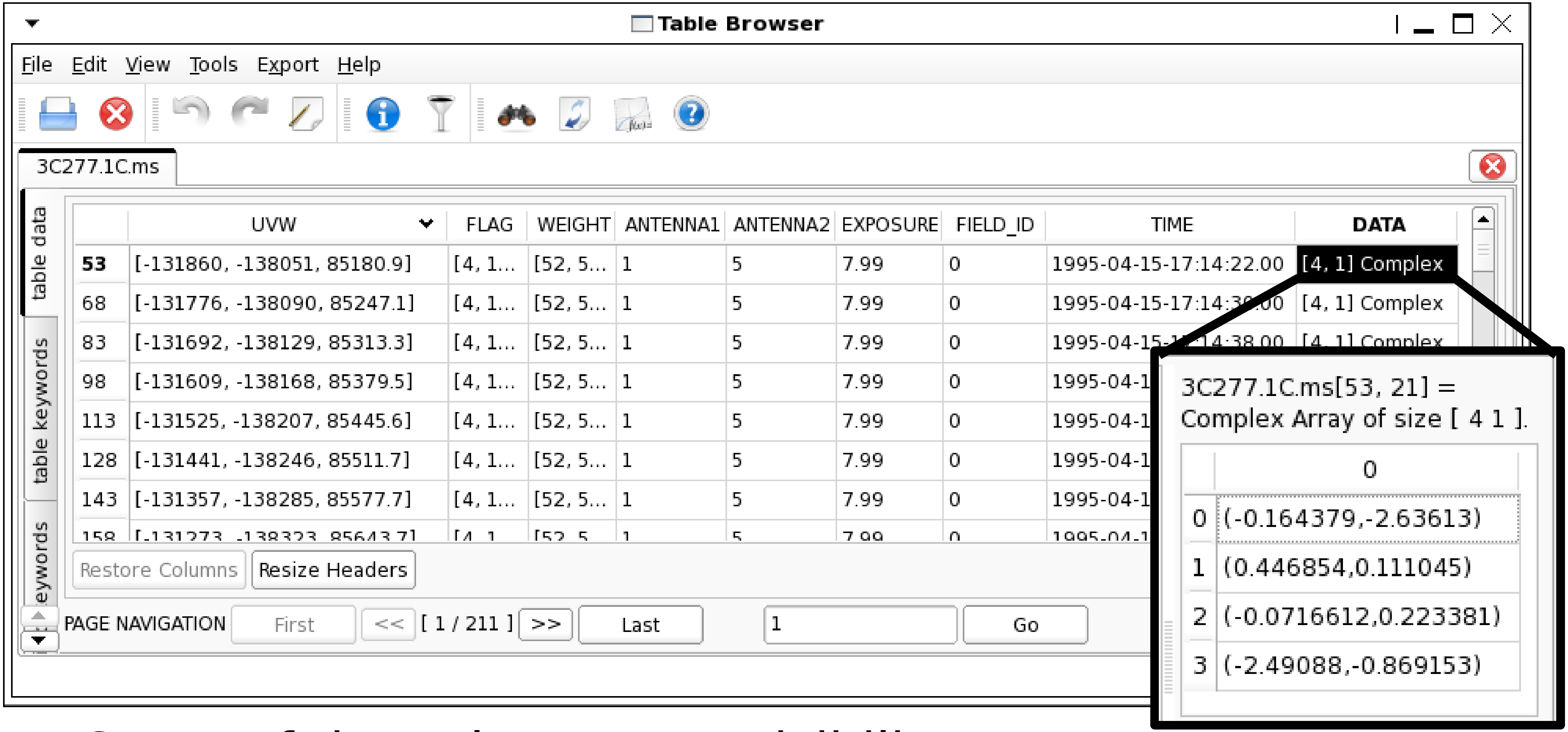
Faraday rotation

Visibility data: Measurement Set format

MAIN	**Model, e.g.:**	**Corrected data**	**Flags**
Original visibility data	*FT of image made from MS* *FT of supplied model image* *FT of point flux density*	*Copy of visibilities with calibration tables applied* (Used in imaging not calibration)	(Edits are stored here first; backup tables can be made and used to modify)

- Unix-like directory structure with binary data and ascii metadata files arranged in subdirectories
- Additional tables in MS or free-standing:
  - *Admin*: Antenna, Source etc.
  - *Processing*: calibration, flags, etc.
- ~interconvertible with FITS; similar image format

Measurement Set MAIN table



- Some of the columns per visibility measurement
  - Correlated amp & phase per baseline per integration
- **Data**: Complex value per spectral channel for each polarization (XX YY XY YX)

Time jargon

Total integration time = 456357 seconds
Observed from 15-Apr-1995/17:13:58.0 to 20-Apr-1995/
(UTC)

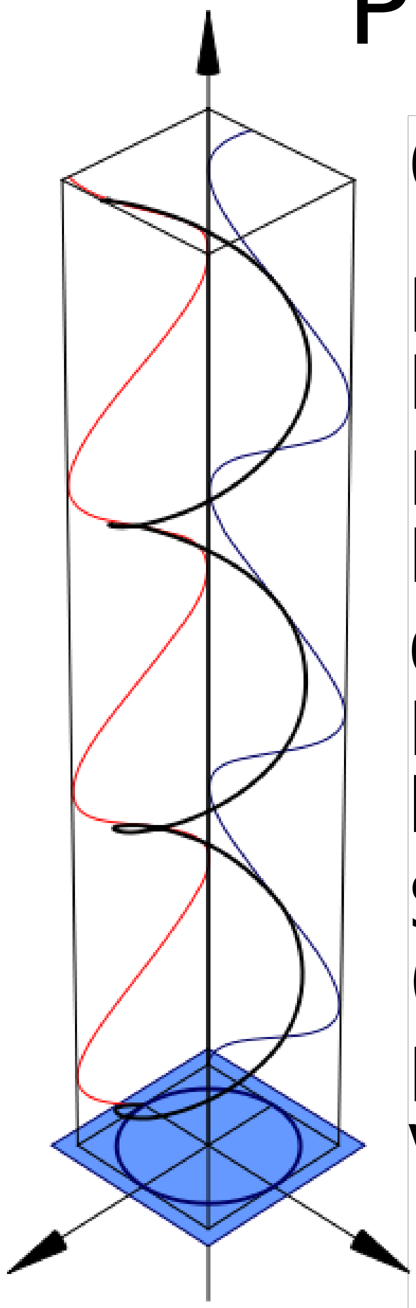
Timerange (UTC)	Scan	FldId	FieldName	nVis	Int(s)
17:13:58.0 - 17:28:38.0	1	0	3C286	1665	7.99
17:29:38.0 - 18:29:30.0	2	1	OQ208	6750	7.99
.....					
17:07:38.0 - 17:09:54.0	8	10	1300+580	270	7.99
17:10:37.0 - 17:17:49.0	9	11	3C277.1	825	7.99
17:18:36.0 - 17:19:56.0	10	10	1300+580	165	7.99
17:20:35.0 - 17:27:55.0	11	11	3C277.1	840	7.99
17:28:42.0 - 17:29:54.0	12	10	1300+580	150	7.99

- Time on all sources
- Span of observations (might be gaps)
- Flux scale/polarisation calibration scans

- Alternate phase-ref/target scans
- Single integration time

- Estimate hour angle coverage
- An integration is the shortest averaging time in correlated data
- A scan is usually the time between source changes
  - The phase-ref/target cycle should be less than the atmospheric coherence time (after WVR correction)

Polarization jargon



CIRCULAR

Left-hand
LHC, L, LL

Right-hand
RHC, R, RR

Cross hands
LR RL make linear

Stokes V =
(RR-LL)/2

Fractional
V/I, |V|/I, %

LINEAR

Stokes Q =
(RL + LR)/2

Stokes U =
(RL - LR)/2i

Polarized intensity
$P = \sqrt{(Q^2+U^2+V^2)}$

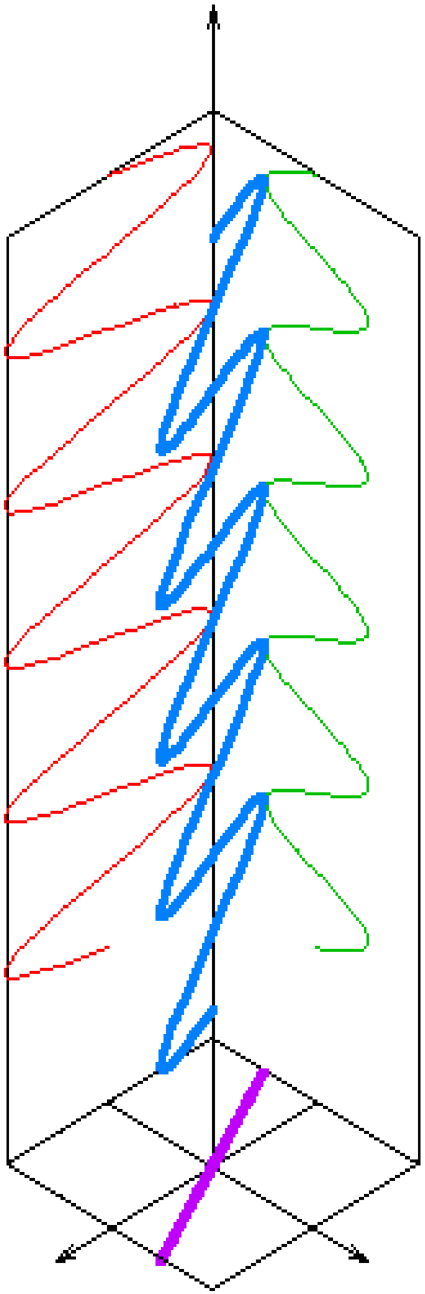
Polarization angle
$\chi = ½ \text{ atan}(U/Q)$

Linear feeds ALMA

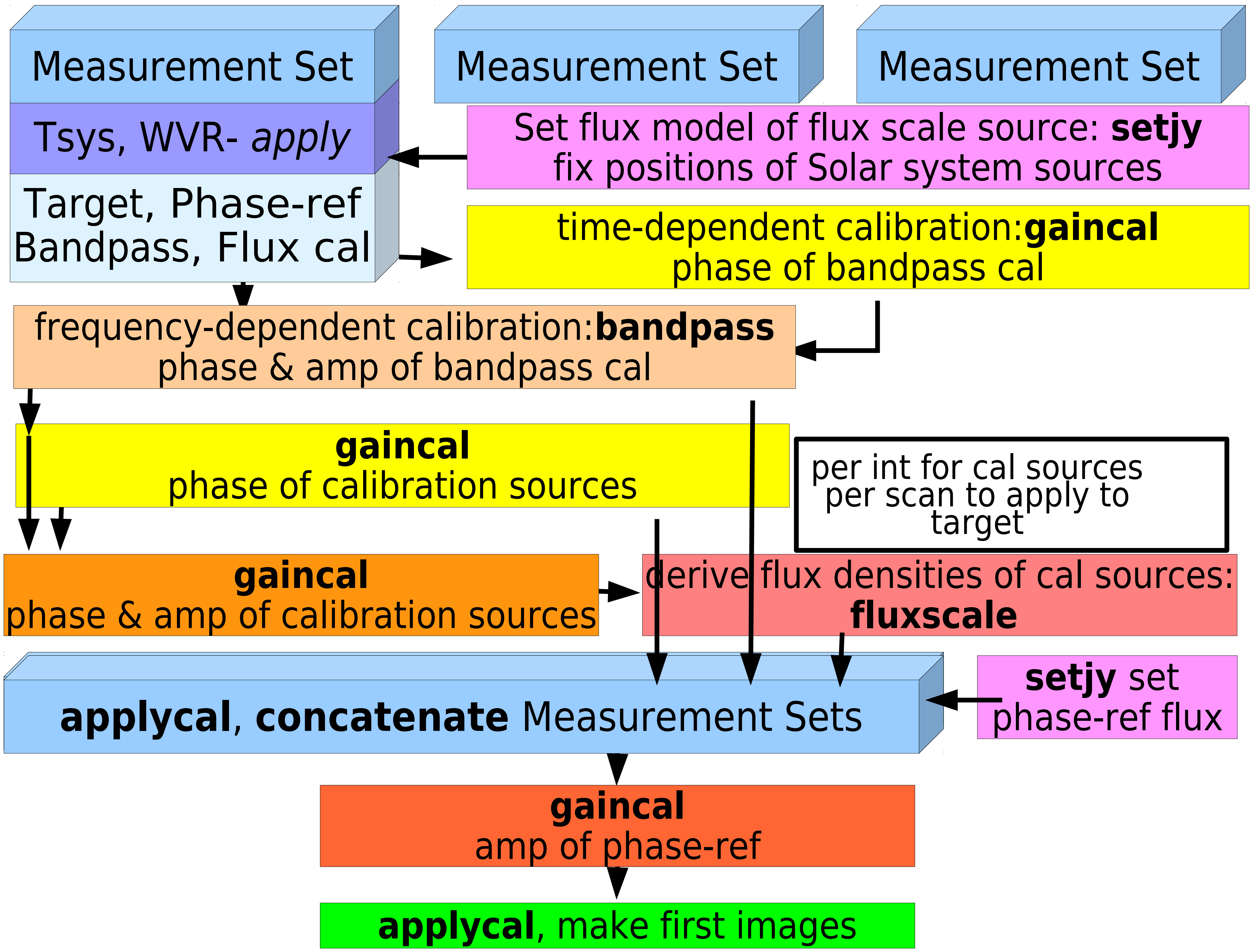
X, XX, Y, YY

Cross hands

XY YX



Diagrams thanks to Wikipaedia



Measurement Set
Measurement Set
Measurement Set
Tsys, WVR- apply
Target, Phase-ref
Bandpass, Flux cal
Set flux model of flux scale source: setjy
fix positions of Solar system sources
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

Proposal writing

- OT steers you towards suitable configurations
  - Multiple source/ν changes inefficient, deprecated
    - Stretching the system is more likely to go wrong!
- Strong science case, unique to ALMA
  - Evidence for ability to interpret results e.g. modelling
- Check precise positions (small field of view)
  - Proper motions for Galactic objects
  - Sensitivity, resolution, field of view
    - Allow at least $5\sigma_{rms}$ for detection experiments
      - Noise very elevation-dependent (Sensitivity Calculator)
      - ~10% of time suitable for Band 9 (450 μm)
- Accurate freq/vel, correct reference frame/convention
  - Spectral set-ups may cover many lines
    - Give observing frequency of most important lines
      - Helps Quality Assurance process

What ALMA data do you get?

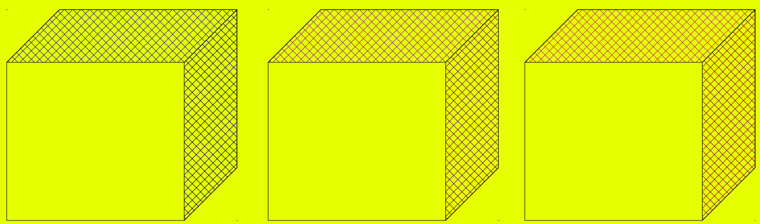
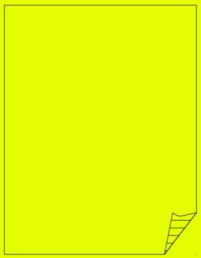


Image cubes for principal science target channels

Information and processing summary

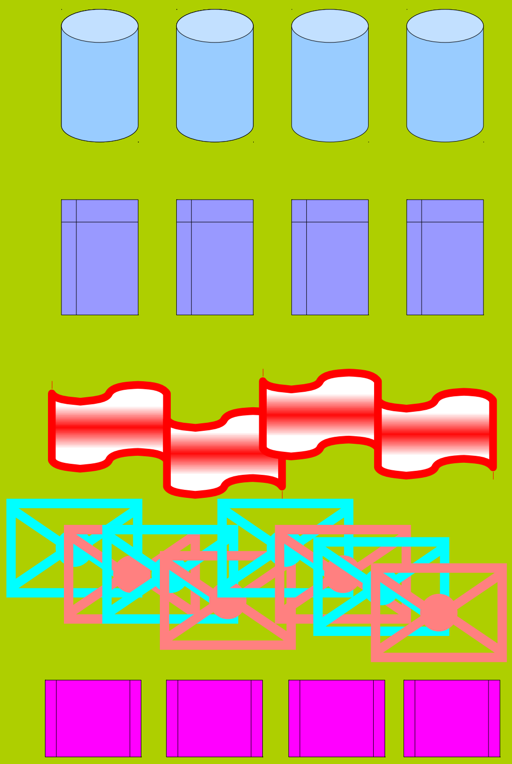


Data processing scripts

Science products + info always delivered to PI

+ Visibility data sufficient to re-do processing in CASA subject to what was available when observations were taken.

All products available from Archive



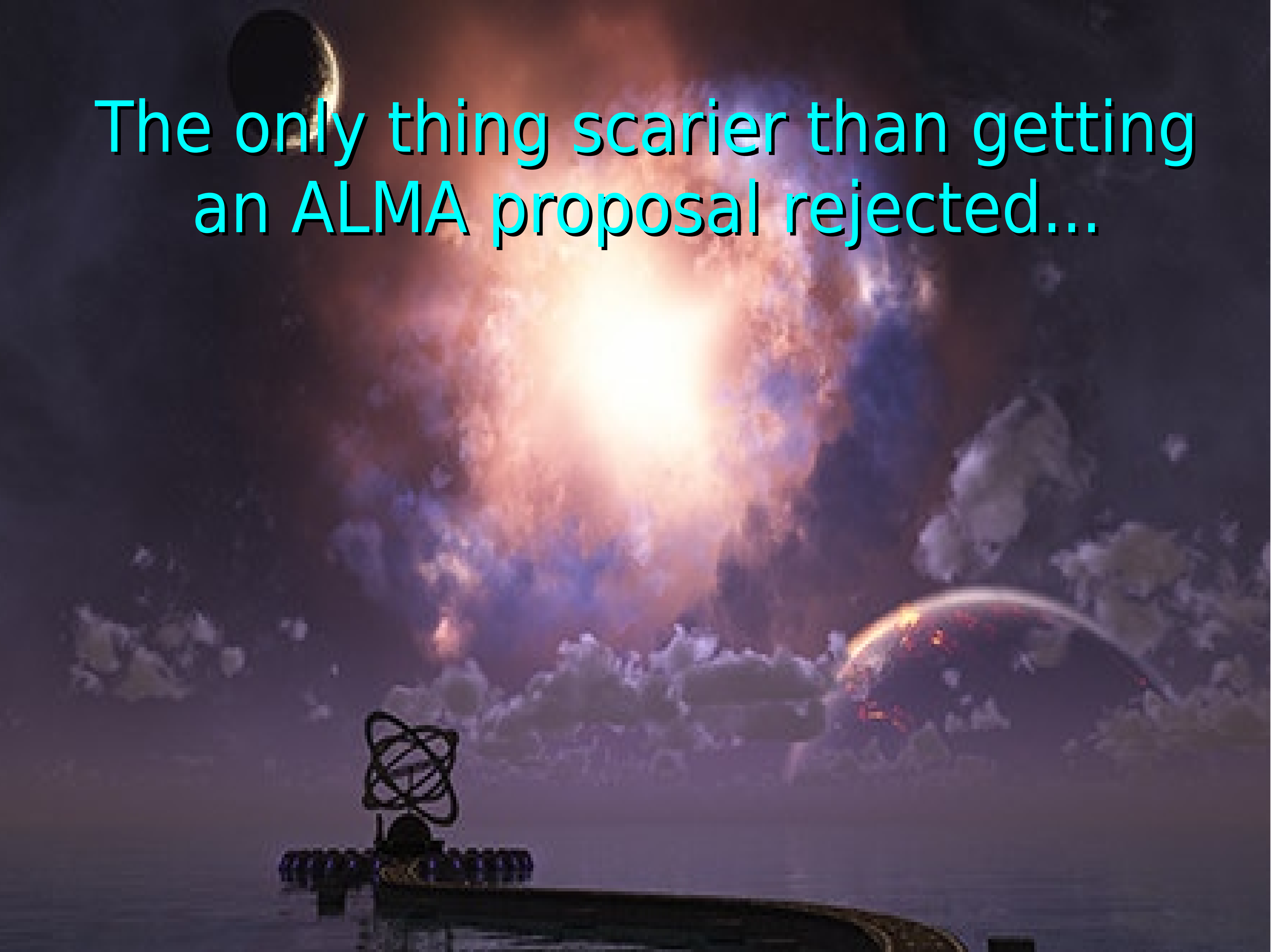
Any or all of ASDM (one per SB)

Part-calibrated MS

Flag tables

Calibration tables

Calibrated MS


The only thing scarier than getting an ALMA proposal rejected...

is if you do get the data!