What is this radio interferometry business anyway?

What are you letting yourself in for?

EUROPEAN ARC
ALMA Regional Centre || UK

What is useful to know

- Basics of interferometry
- Calibration
- Imaging principles
- What provides detectable sources?
  - ALMA spatial coverage
  - Spectral details: see OT session
- Simulations for ALMA

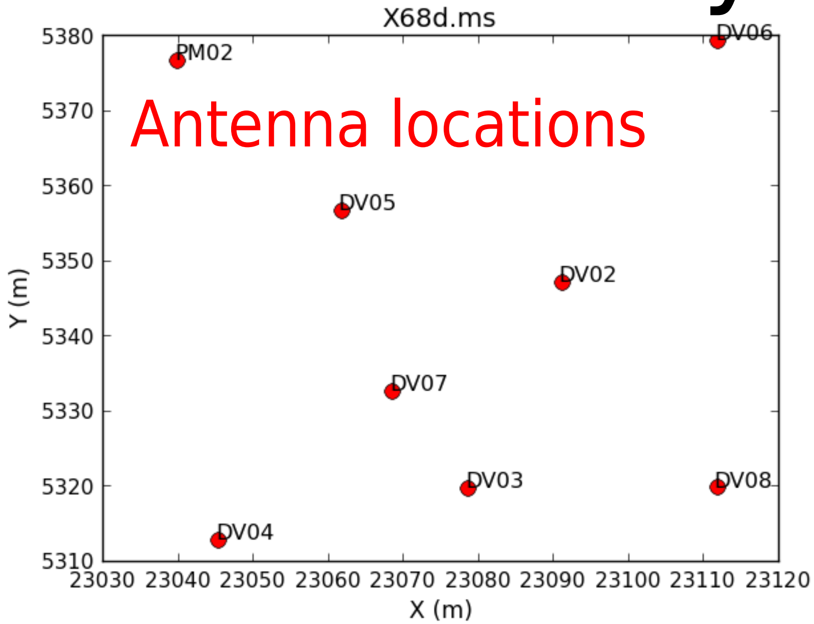
What is useful to know

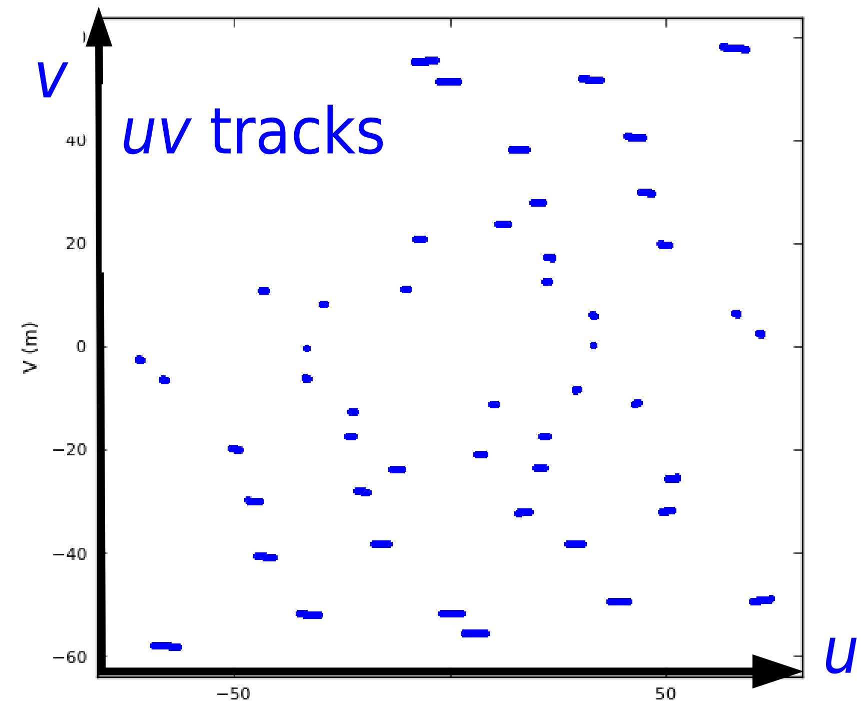
- Basics of interferometry
- Calibration
- Imaging principles
- What provides detectable sources?
  - ALMA spatial coverage
  - Spectral details: see OT session
- Simulations for ALMA

sim•u•late (ˈsɪm yəˌleɪt)
to intend to deceive; make a pretence of; feign:
e.g. to simulate illness:

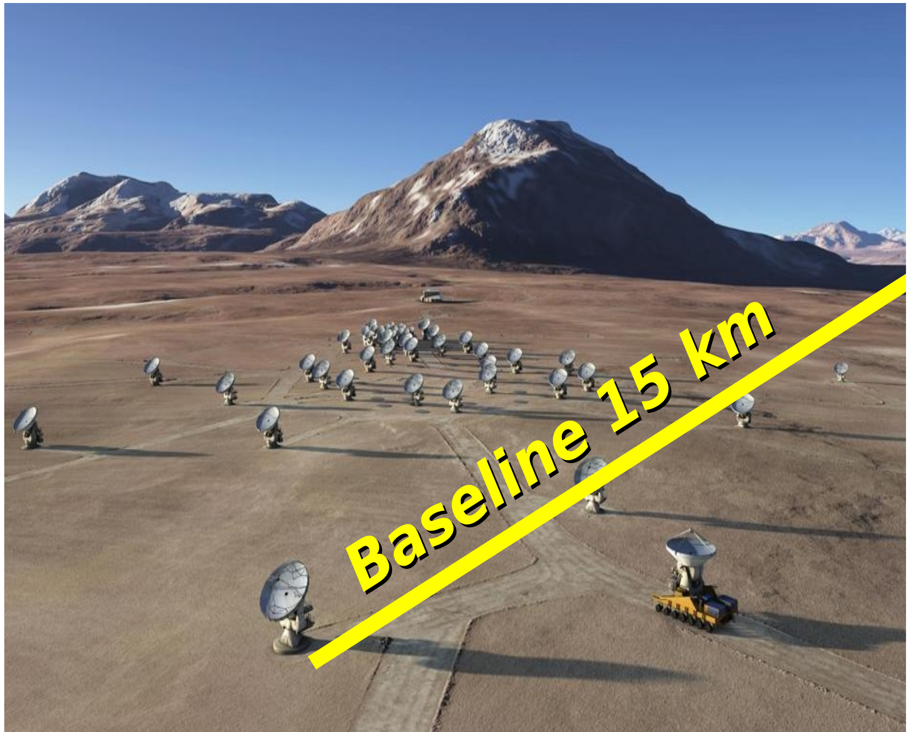
Friquet …. under the pretext of having a swollen face which he had managed to simulate by introducing a handful of cherry kernels into one side of his mouth, and had procured a whole holiday from Bazin.
Twenty years after (Alexandre Dumas)

Interferometry

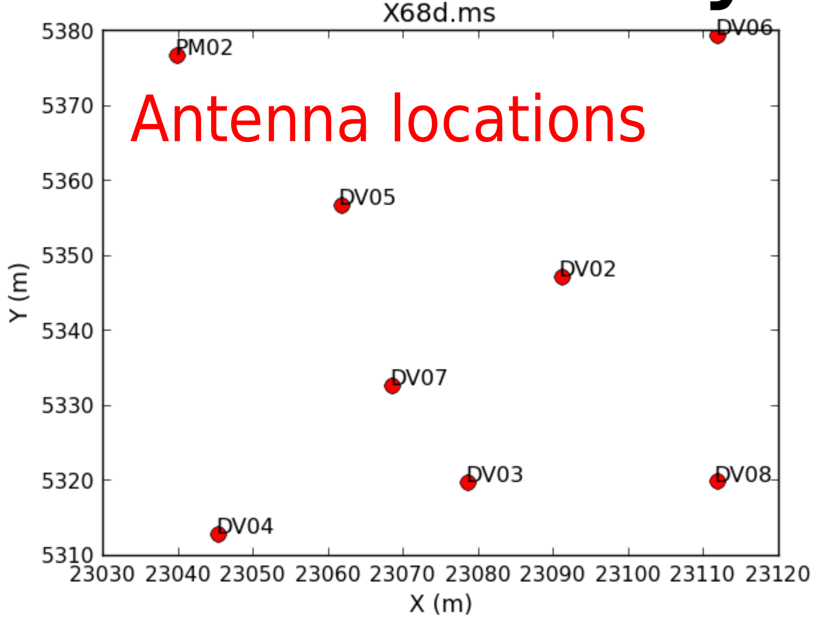


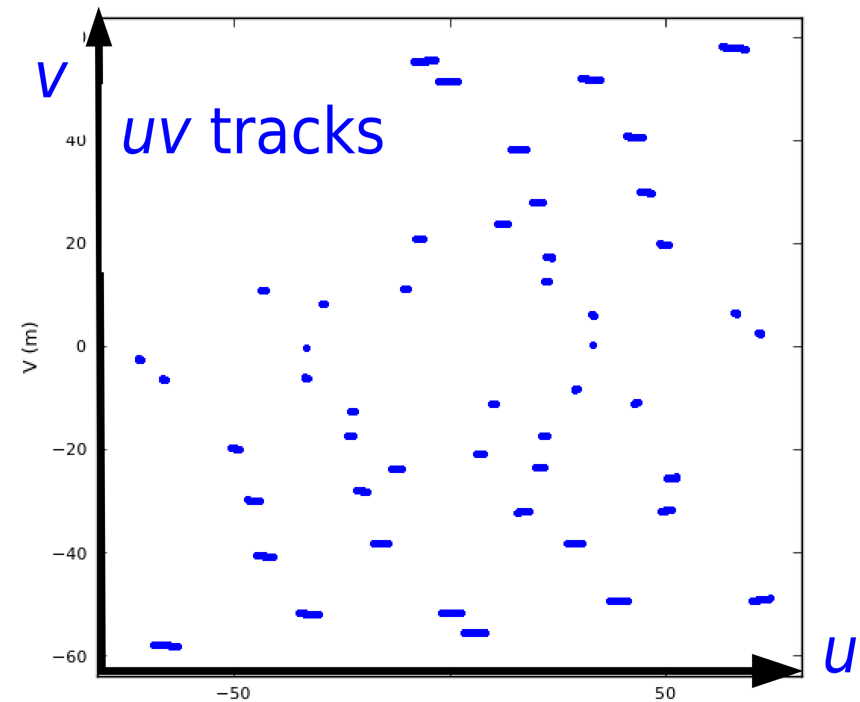


- Earth rotation aperture synthesis
- Vectors between pairs of baselines sweep out *uv* tracks
  - Record combined signals per sec
- Maximum resolution (synthesised beam) $\theta \sim \lambda / B_{max}$
  - *B* 15 km, λ 1 mm = θ~14 mas
- Field of view $\lambda / D_{antenna}$ ~20''
  - Equivalent to single dish resolution

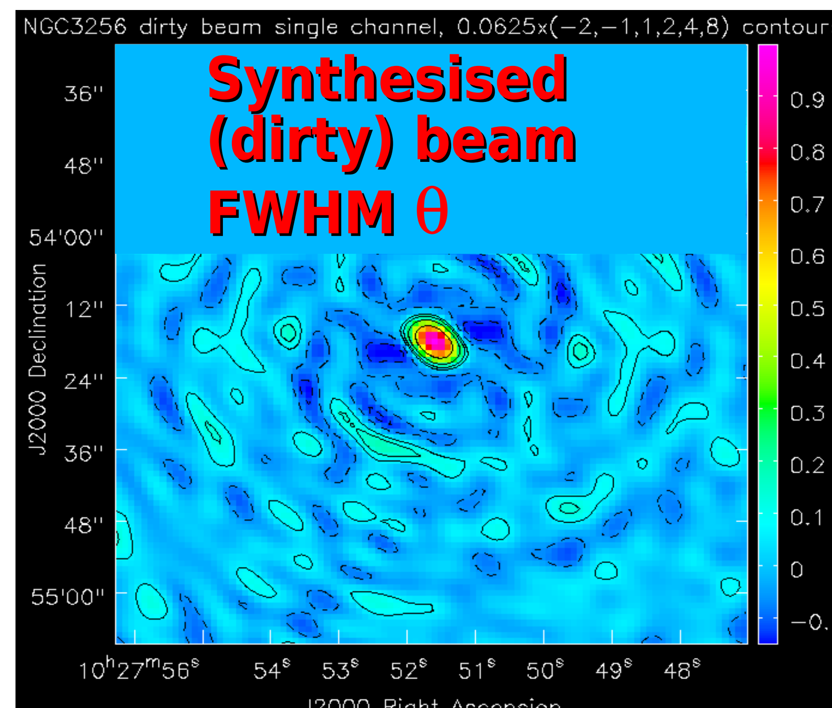


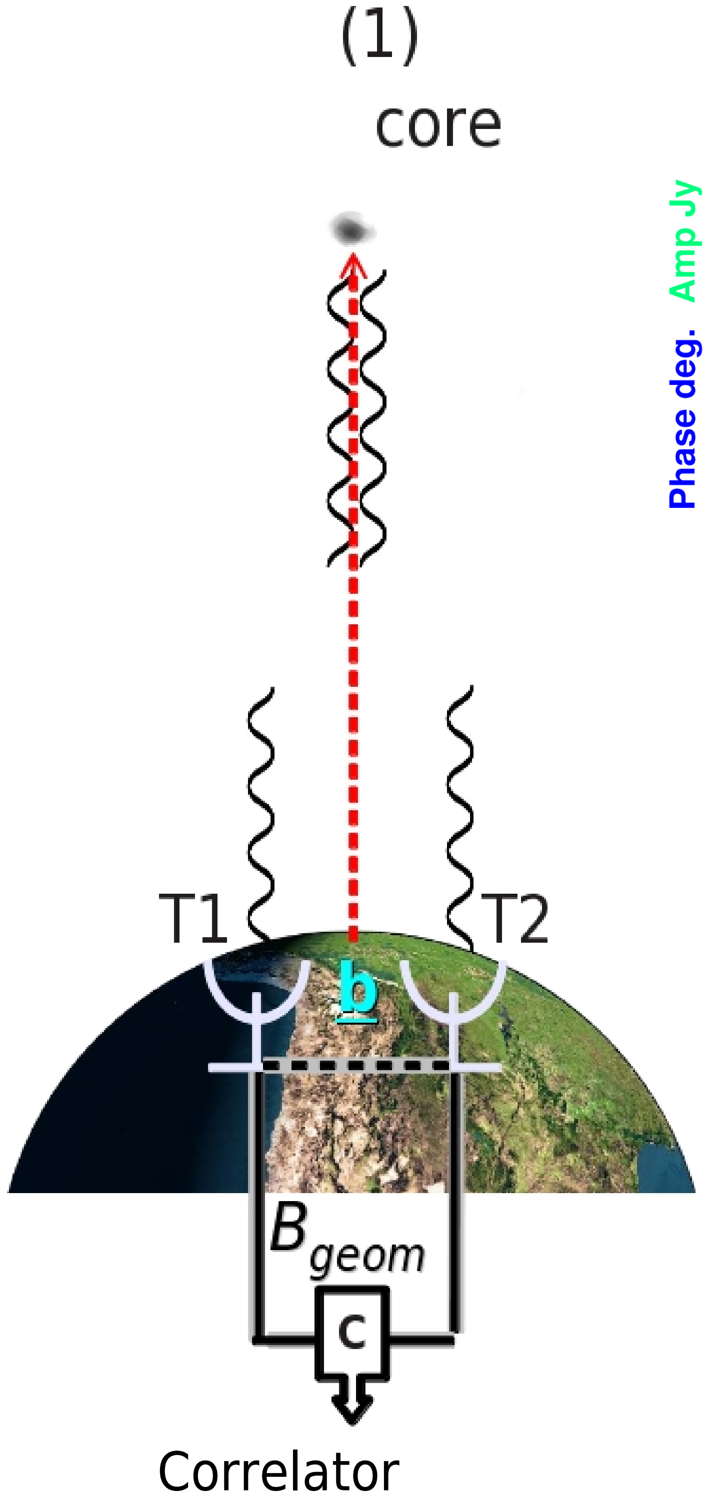
Interferometry



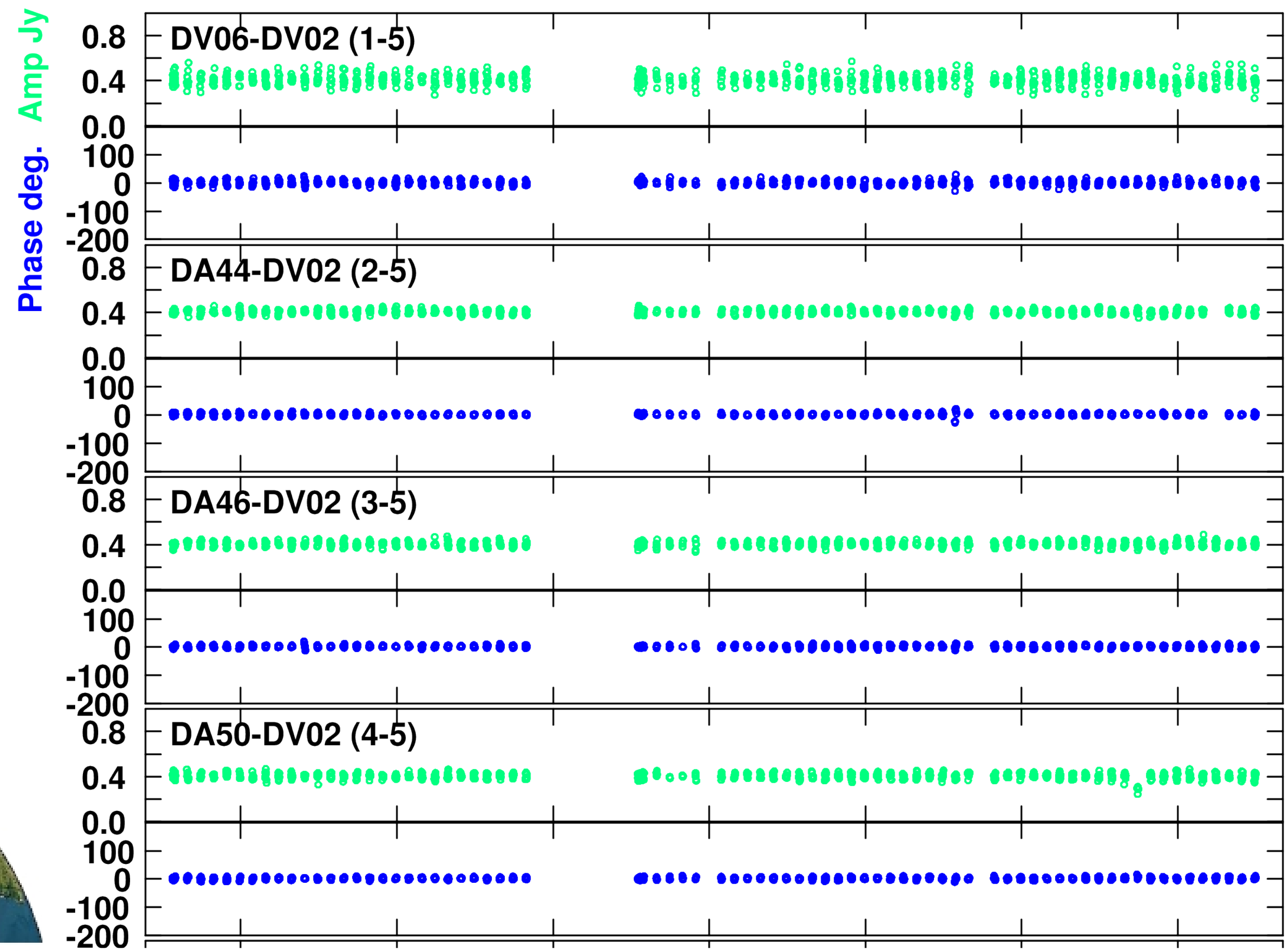


- Earth rotation aperture synthesis
  - Fourier transform ⇔ Dirty Beam
- Sensitivity helped as noise decorrelates *but*
  - Sparse coverage gives sidelobes
- Max. angular scale imageable
  - $\sim 0.6\ \lambda/\boldsymbol{B}_{\mathbf{min}}$ ~8'' (λ 1 mm)
    - no ACA, compact 12-m config

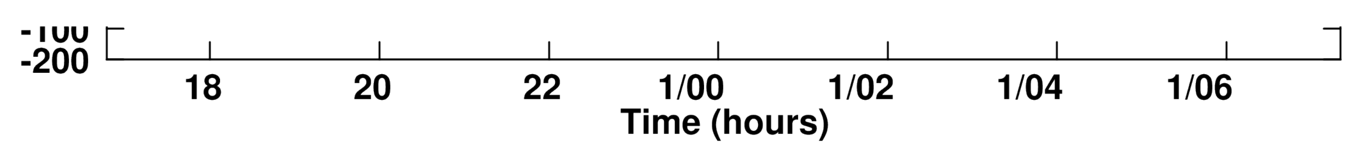




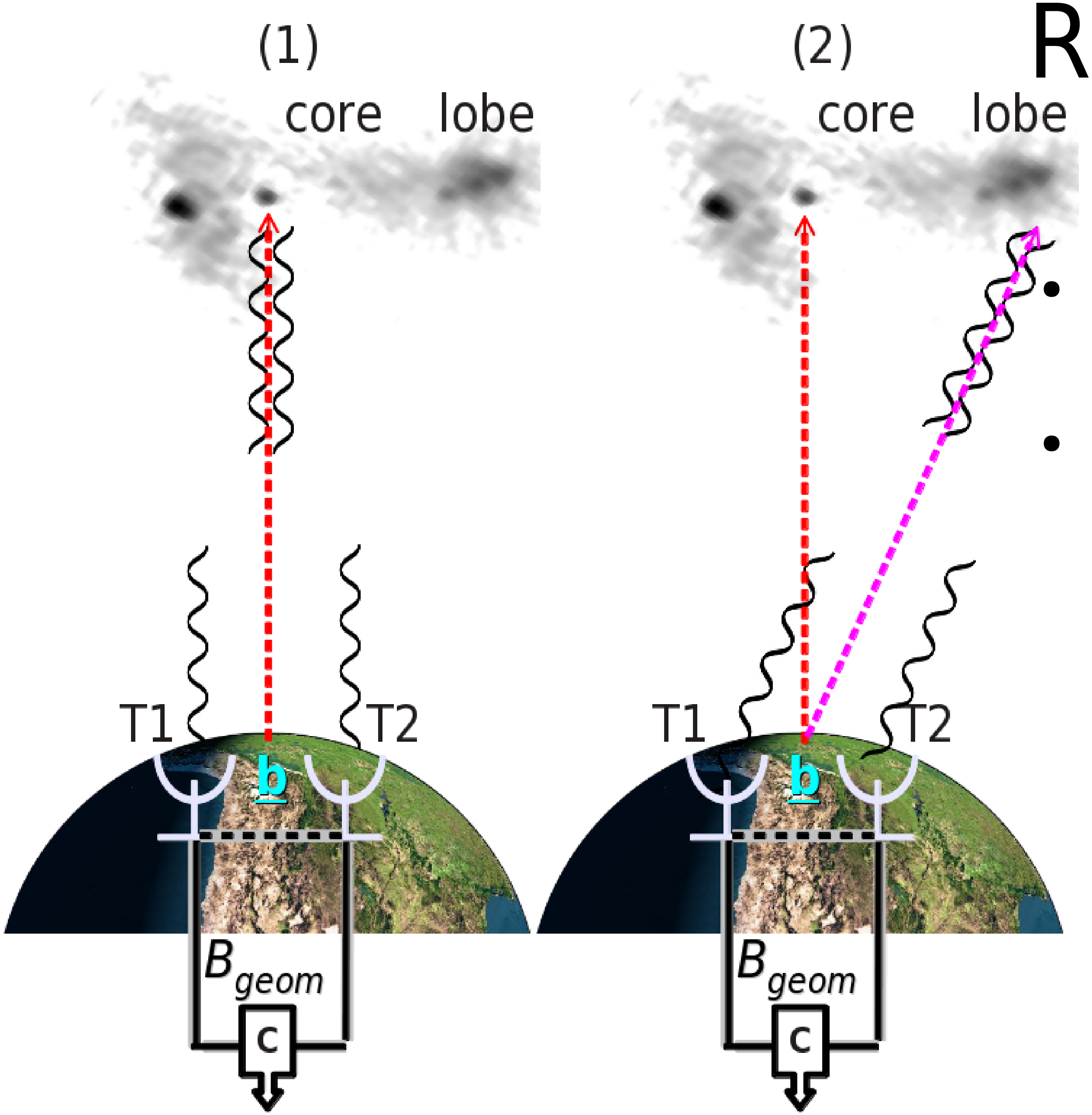
Point source overhead



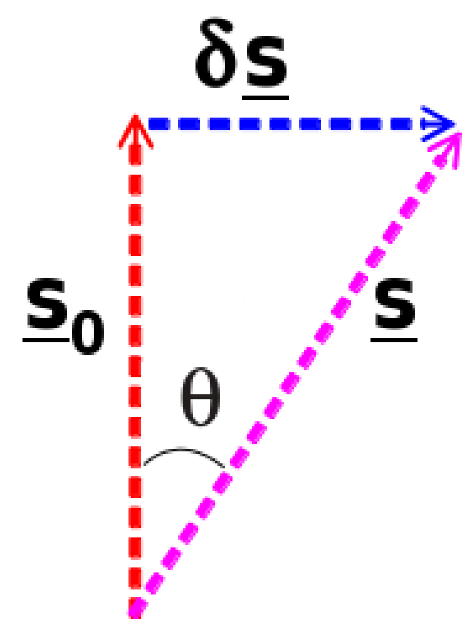
- Signals in phase, interfere constructively
  - Combined phase ϕ 0°, amp constant



Resolved source overhead

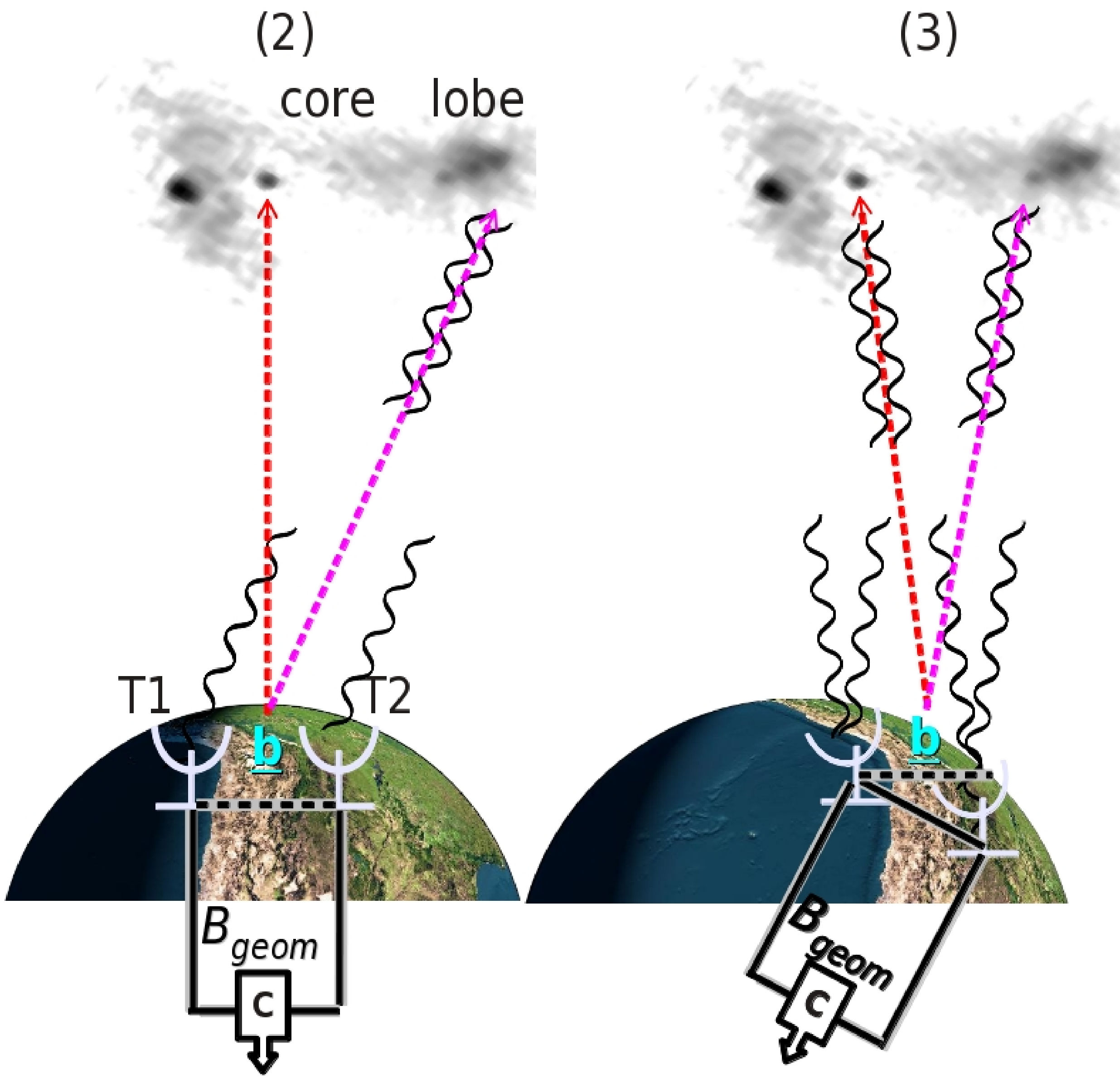


- Signals from overhead vector $\mathbf{s_0}$
- Signals from lobe
  - Angular offset vector $\delta\mathbf{s}$
  - Path length $\mathbf{s} = \delta\mathbf{s} \cdot \mathbf{s_0}$

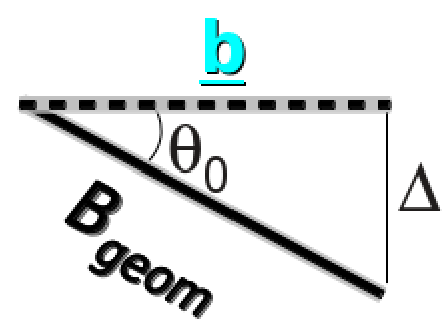


- Combined ϕ depends on $\delta\mathbf{s}$
- Complex visibility amplitude is sinusoidal function of ϕ

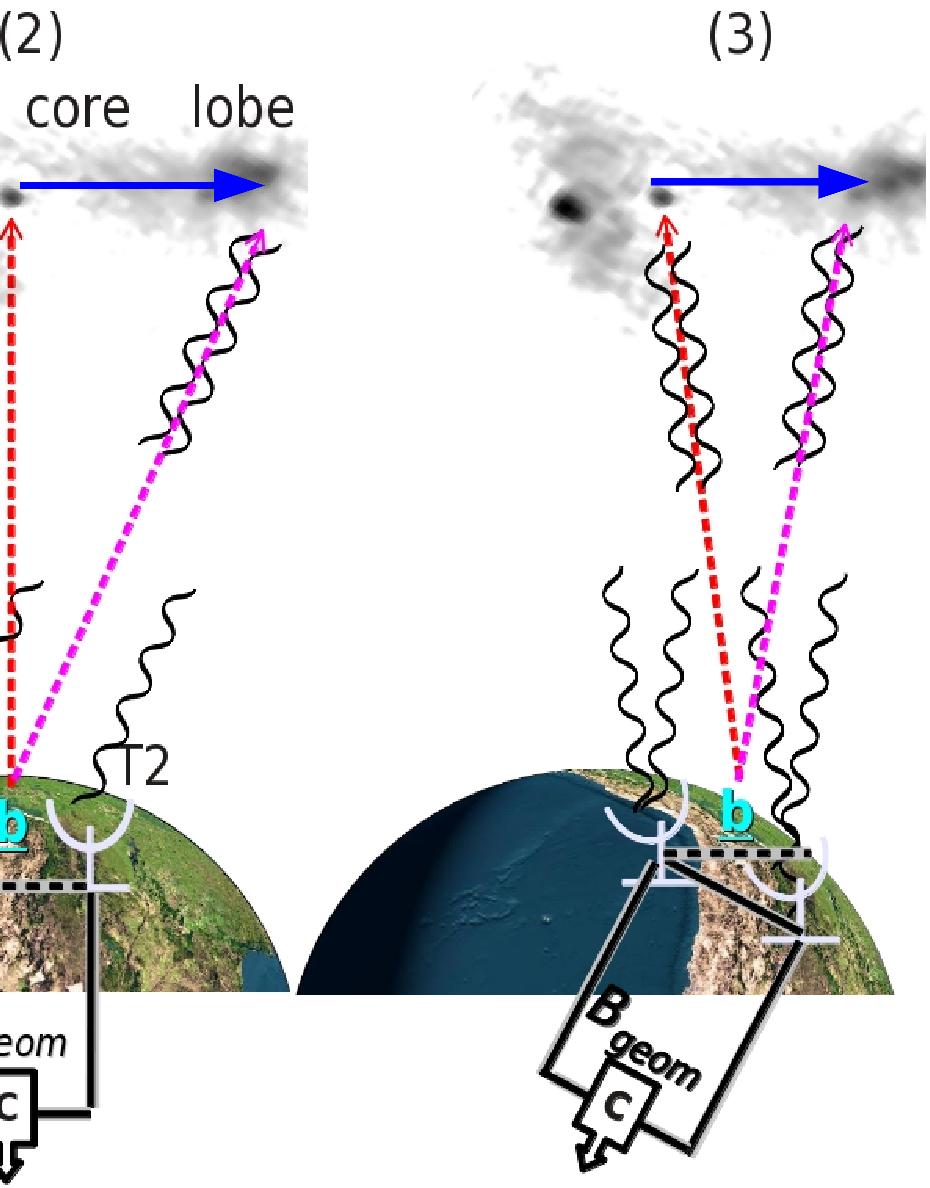
Earth rotation aperture synthesis

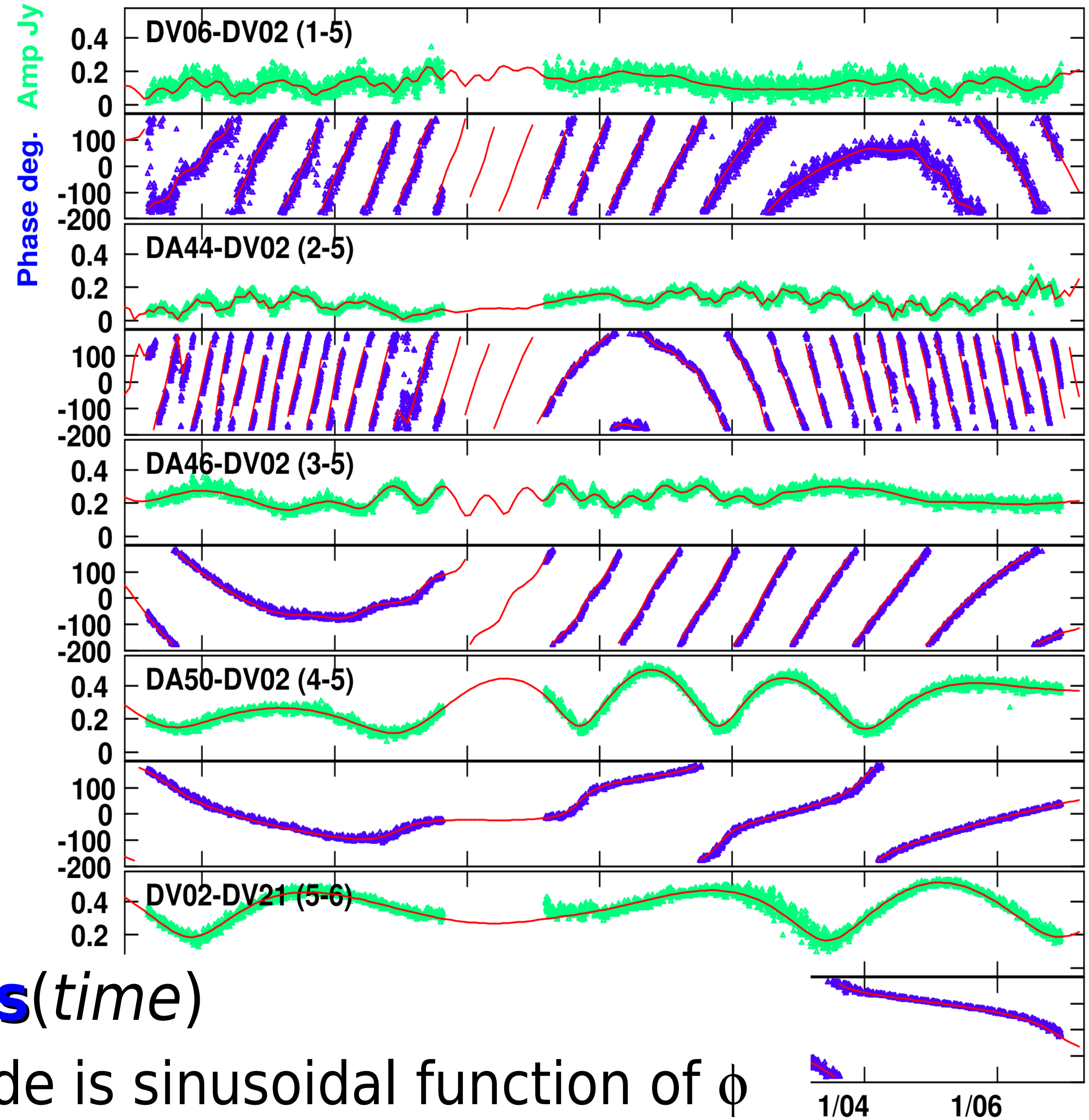


- Telescopes separated by baseline B_{geom}
- Earth rotates
  - Projected separation $b = B_{\text{geom}} \cos \theta_0$
- Samples different scales of source
- Additional geometric delay path Δ
  - Remove in correlator



Earth rotation aperture synthesis

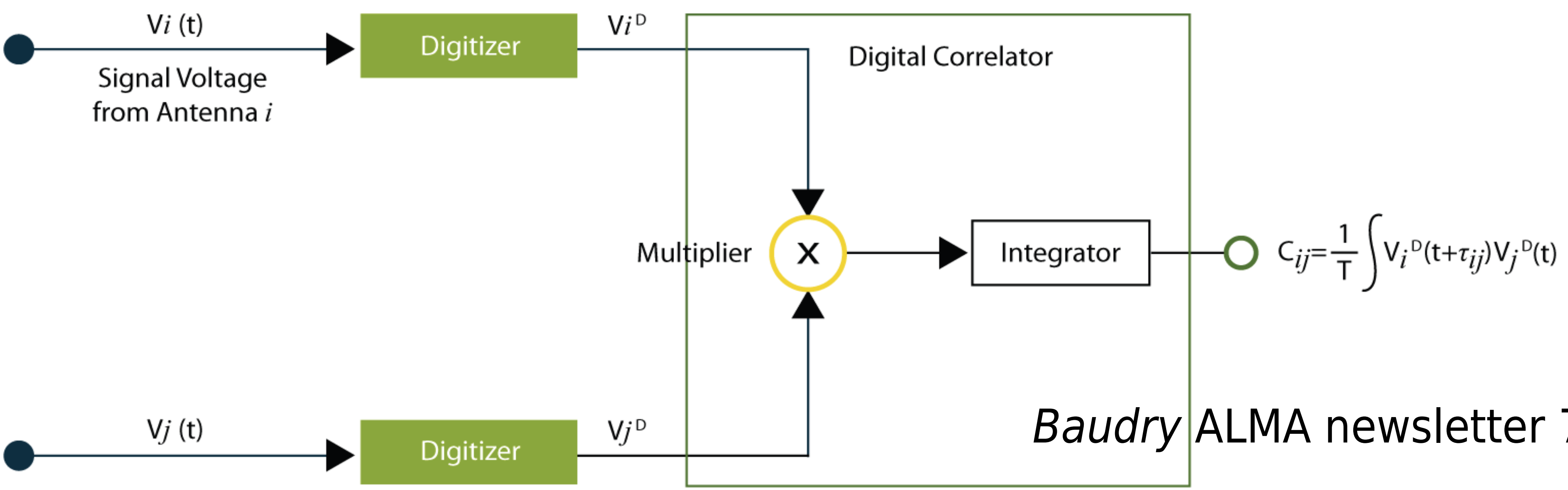




- Combined ϕ depends on $\delta \mathbf{s}(time)$
- Complex visibility amplitude is sinusoidal function of ϕ

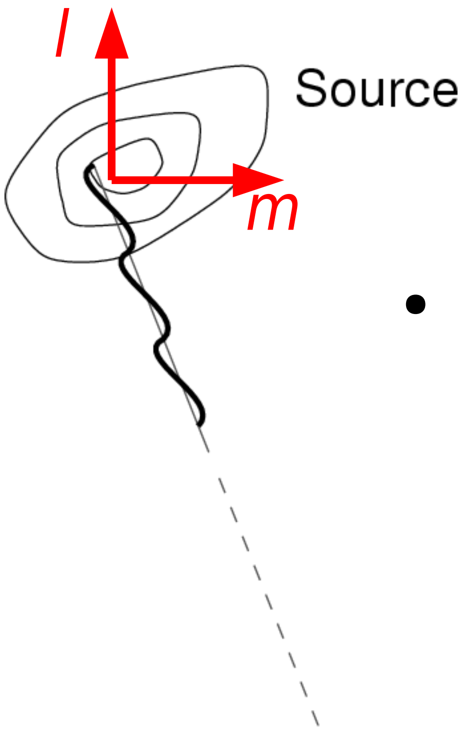
Correlation

- Digitise and combine signals in correlator
  - Create spectral channels by adding ~msec time lags
  - Make parallel (and cross) polarizations
    - (another) FT into frequency domain
      - Output averaging determines integration time
- Produces complex visibility data
  - Time series of amplitudes & phases per baseline
    - per polarization, per spectral channel



Baudry ALMA newsletter 7

From interferometry to images



- Fourier transform of complex visibility amplitude and phase gives sky brightness

  $$\sum V_\nu(u_\nu,v_\nu)\, e^{[2\pi i(u\nu l\, +\, v\nu m)]}\, du\,dv = I_\nu(l,m)$$

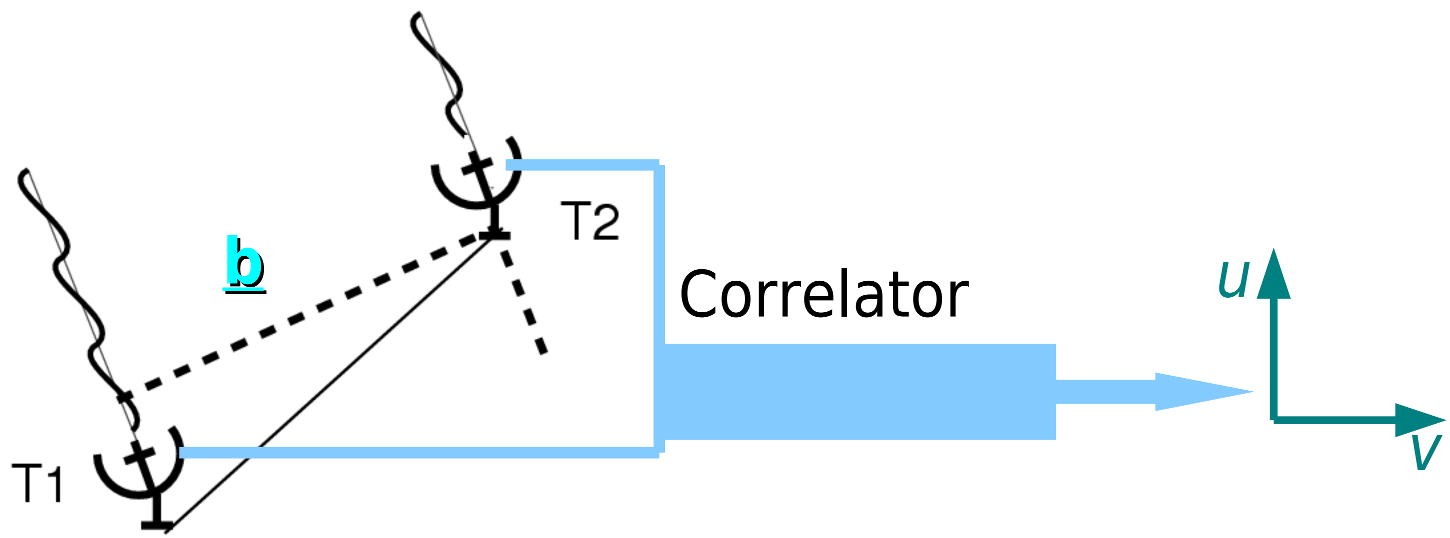
  – or $V(u,v) \Leftrightarrow I_\nu(l,m)$ for short

- Sensitivity:

  $$\sigma_{rms} \propto \frac{T_{sys}}{\sqrt{N(N-1)/2\ \ \delta\nu\ \ \Delta t}}$$

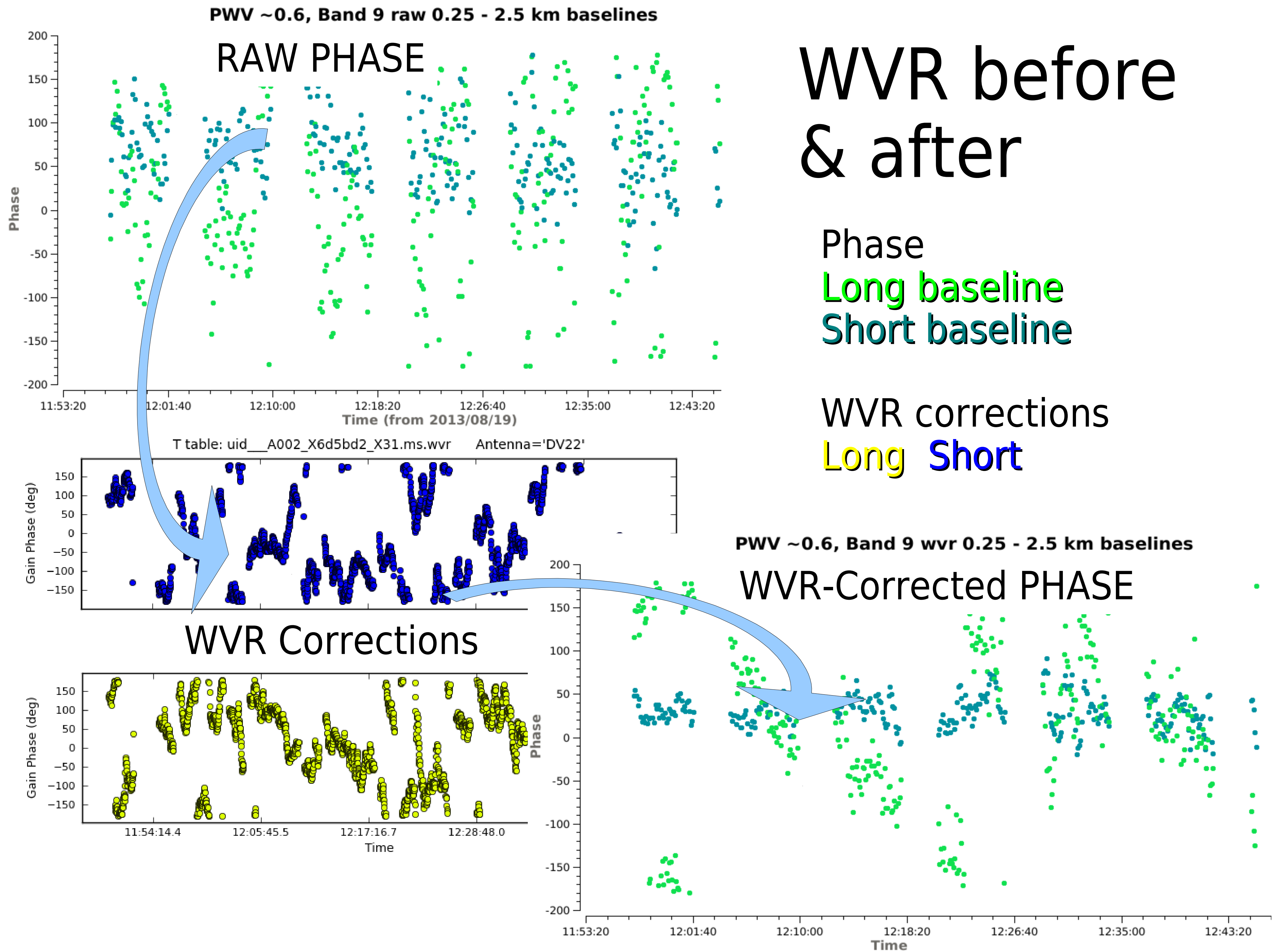
  – Number antennas (ALMA's huge collecting area!)

  – $d\nu$ freq. width per image, Δt total time on source

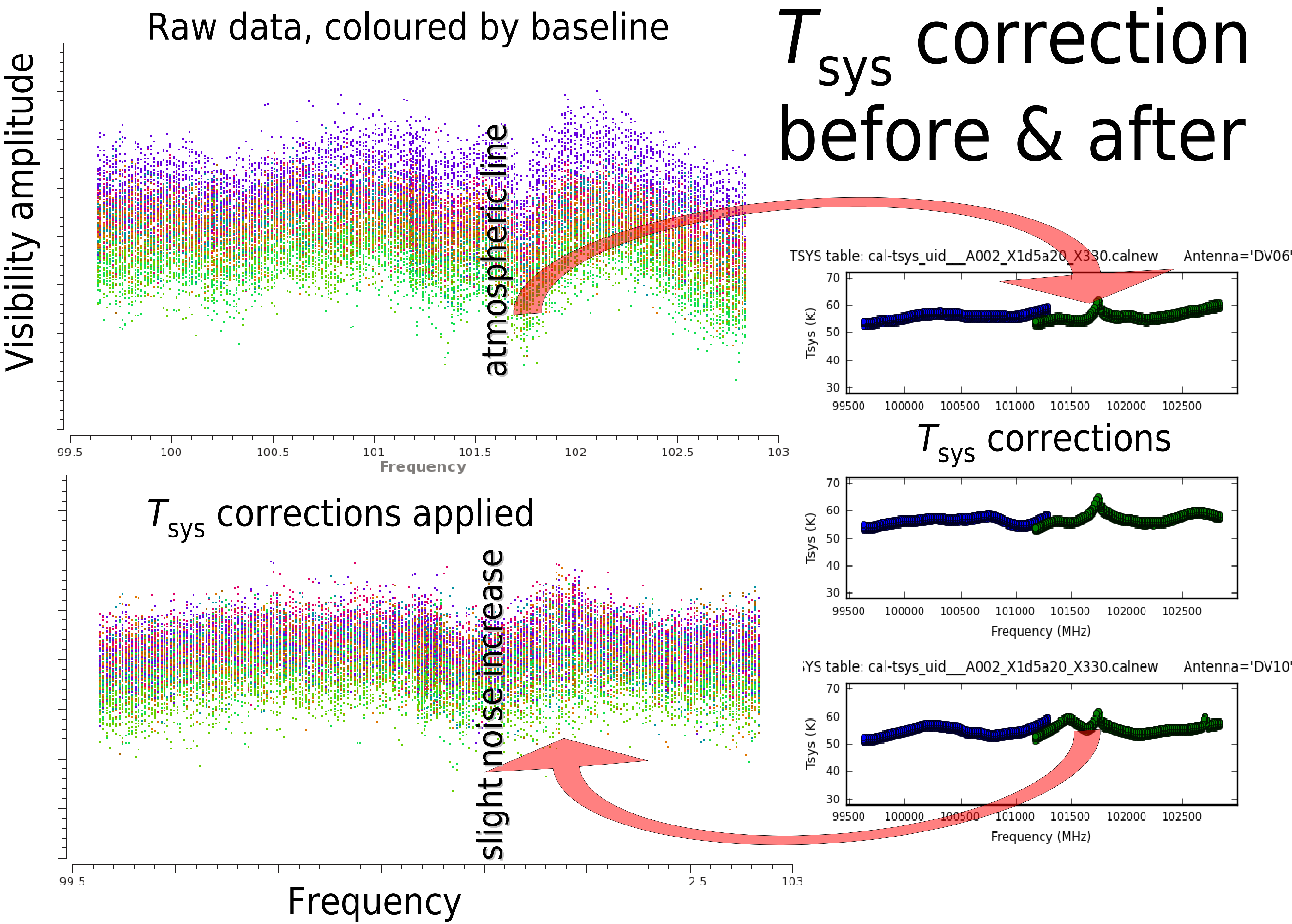


ALMA instrumental calibration

- Pointing corrections before correlation
- Water vapour in the troposphere
  - Refraction: delay to phase of incoming wavefronts
    - Water Vapour Radiometry (WVR)
    - Measure 183-GHz atmospheric line
      - Derive path length corrections at observing ν every second
  - Amplitude absorption amd emission
    - System temperature measurements every few min (T_{sys})
- 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 corrects time-dependent errors



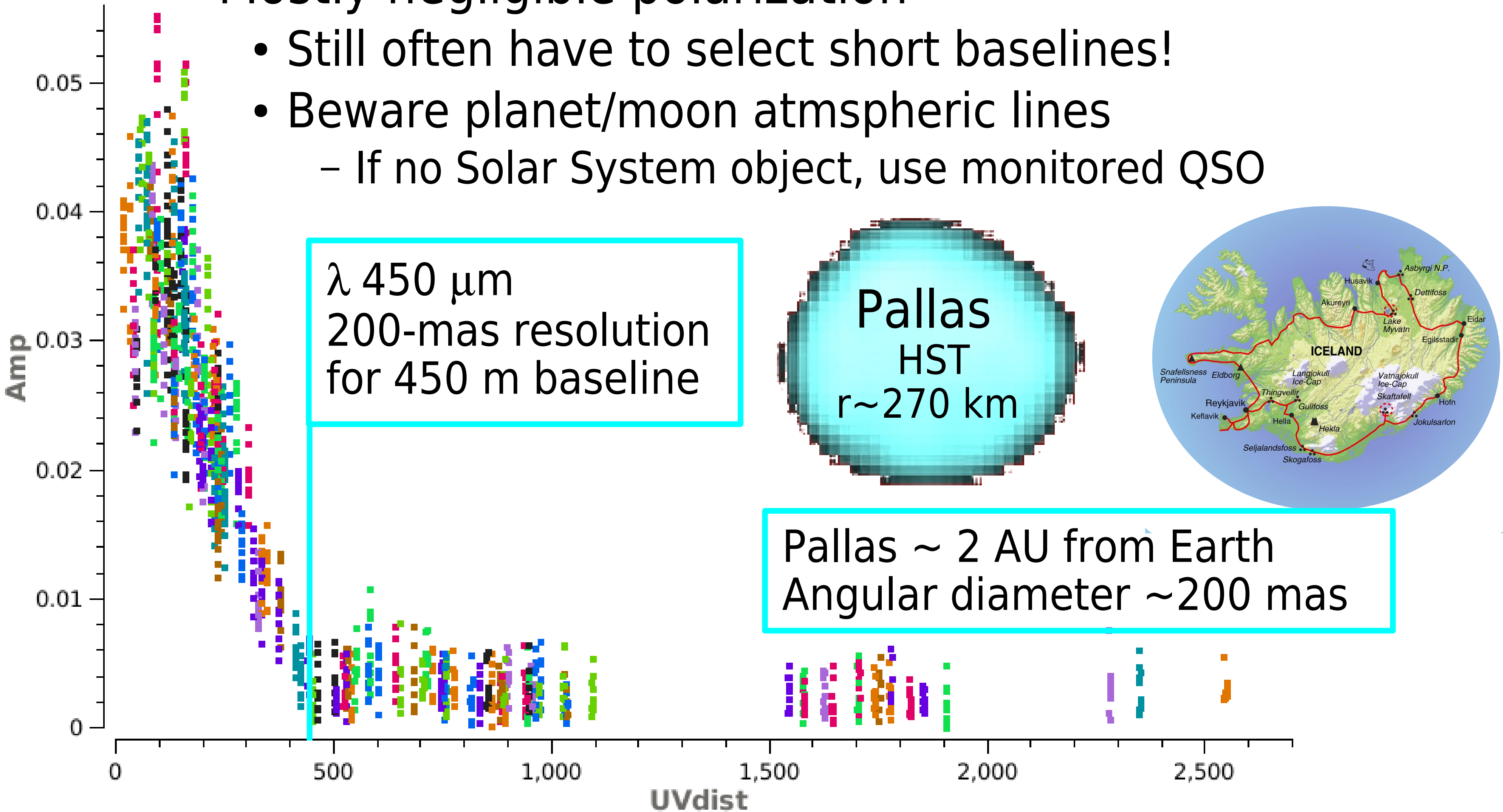
WVR before & after
Phase
Long baseline
Short baseline
WVR corrections
Long Short
PWV ~0.6, Band 9 raw 0.25 - 2.5 km baselines
RAW PHASE
Phase
Time (from 2013/08/19)
T table: uid___A002_X6d5bd2_X31.ms.wvr Antenna='DV22'
Gain Phase (deg)
WVR Corrections
Time
PWV ~0.6, Band 9 wvr 0.25 - 2.5 km baselines
WVR-Corrected PHASE
Phase
Time



T_{sys} correction before & after
Raw data, coloured by baseline
Visibility amplitude
atmospheric line
99.5
100
100.5
101
101.5
102
102.5
103
Frequency
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
'YS table: cal-tsys_uid___A002_X1d5a20_X330.calnew Antenna='DV10'
99.5
2.5
103
Frequency

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



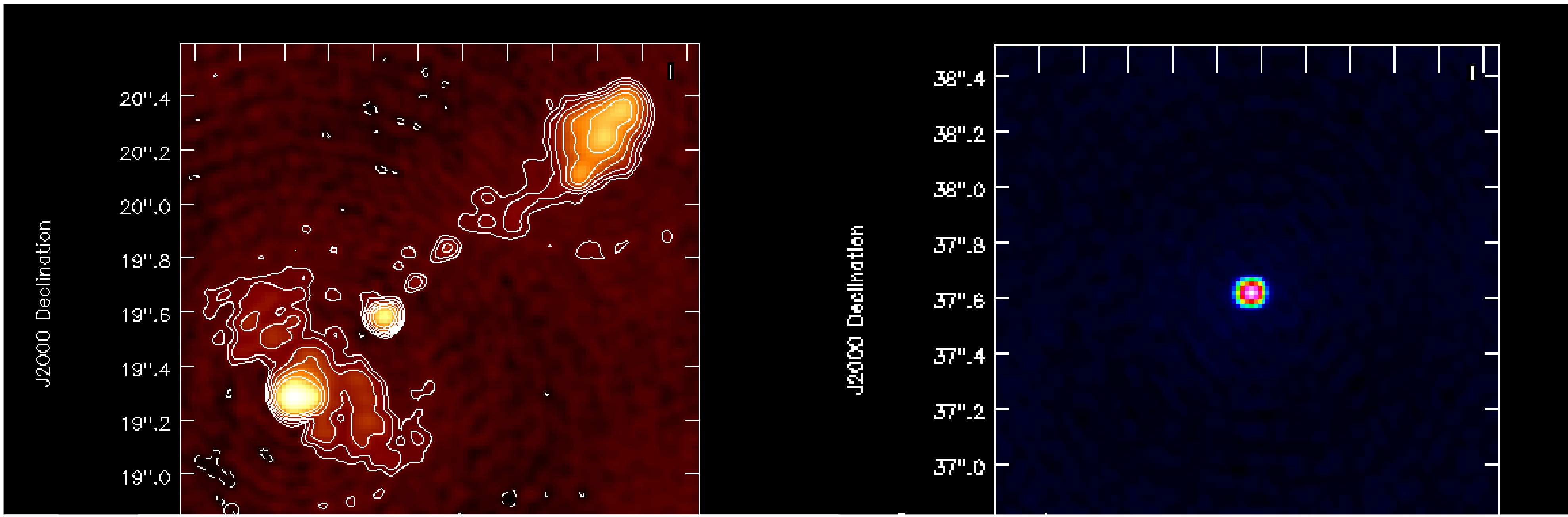
λ 450 μm
200-mas resolution
for 450 m baseline

Pallas ~ 2 AU from Earth
Angular diameter ~200 mas

Phase referencing

- Observe phase-ref source close to target
  - Point-like or with a good model
  - Close enough to see same atmosphere
    - Few - 10 degrees (isoplanatic patch)
  - Bright enough to get good SNR quicker than atmospheric timescale τ
    - (after WVR applied)
    - 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

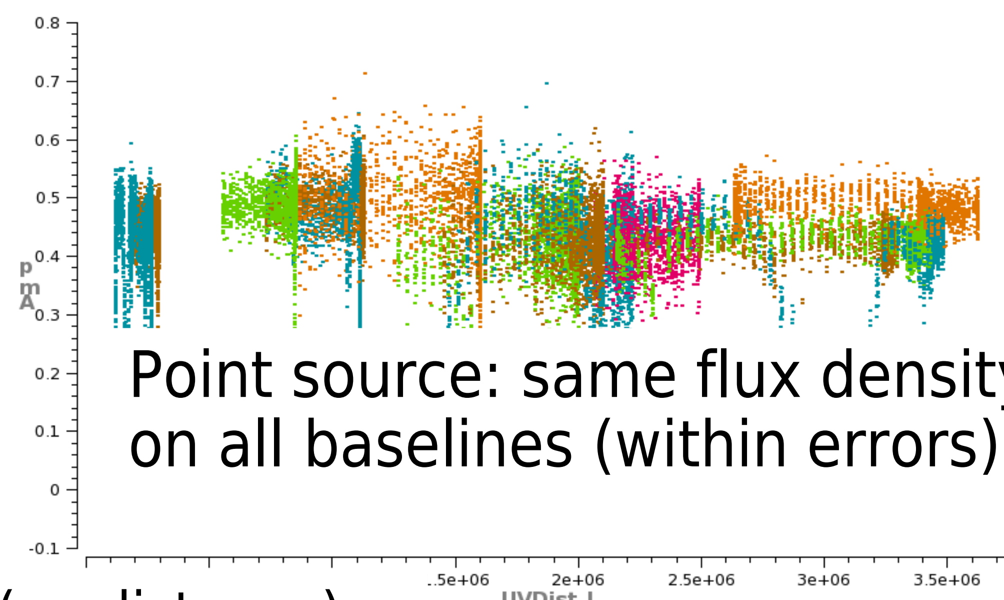
Source structure in *uv* plane



Extended source: more flux on short baselines

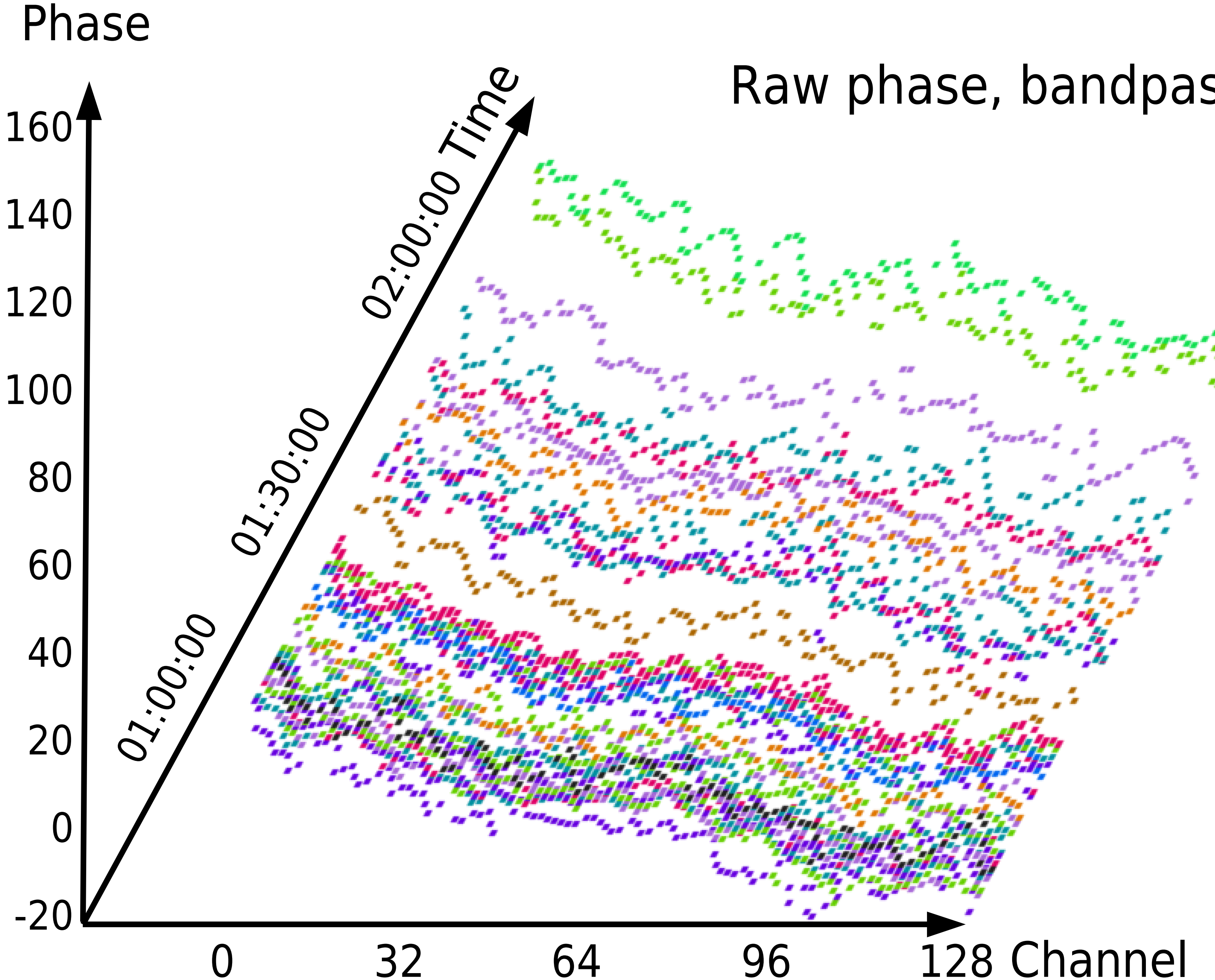
Visibility amplitudes

Baseline length in wavelengths (*uv* distance)



Point source: same flux density on all baselines (within errors)

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

- 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*
- Usually start with bandpass calibration
  - Instrumental artefacts, shallow atmospheric lines...
    - May need to perform time-dependent ϕ calibration first

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

- Bandpass calibrator – bright as possible

1. Average inner 50% band, perform time-dependent phase & 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

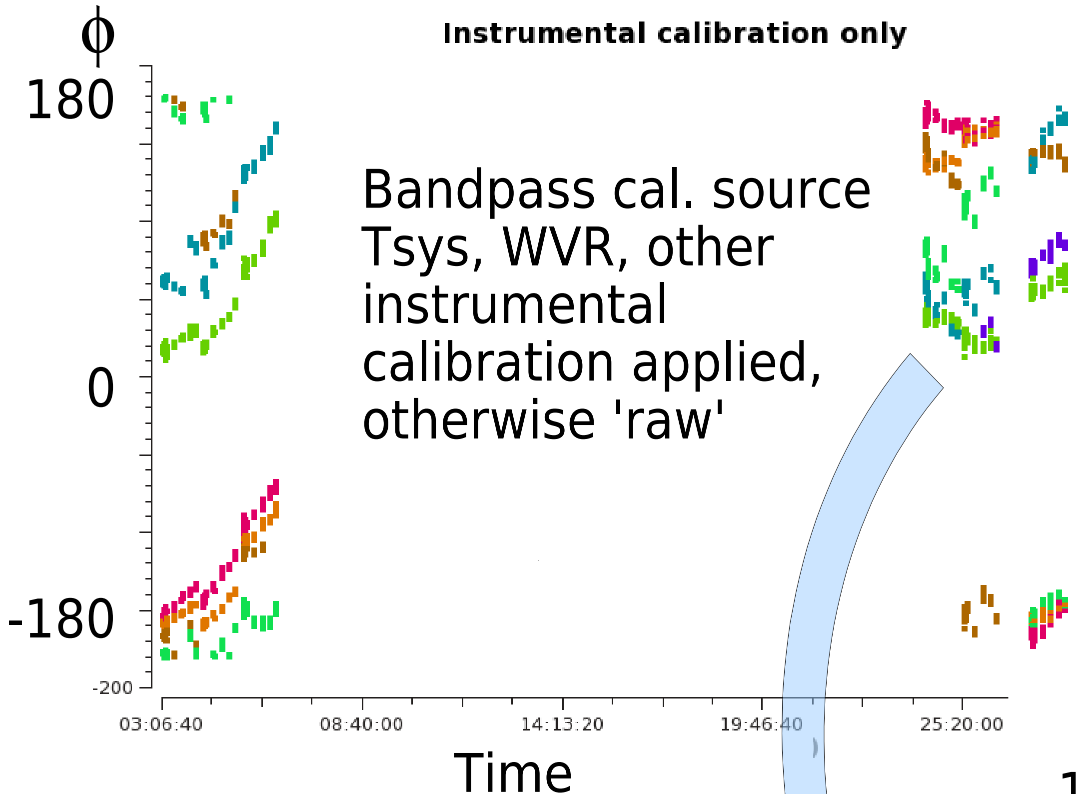
3. Apply B1 and perform time-dependent phase calibration (G2) averaging all channels, shortest *dt* for enough SNR

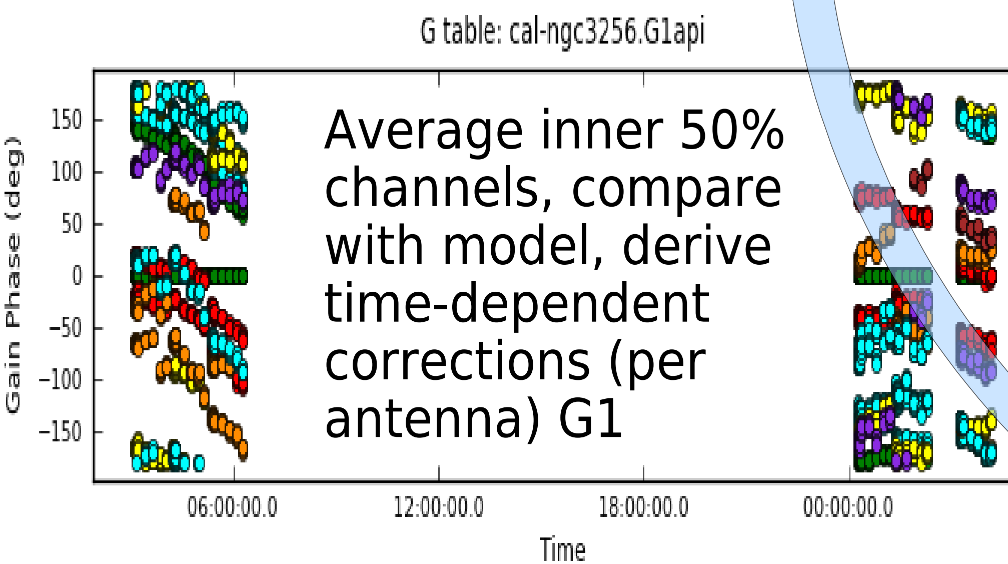
  - Apply B1 for all calibration hereafter, to all sources

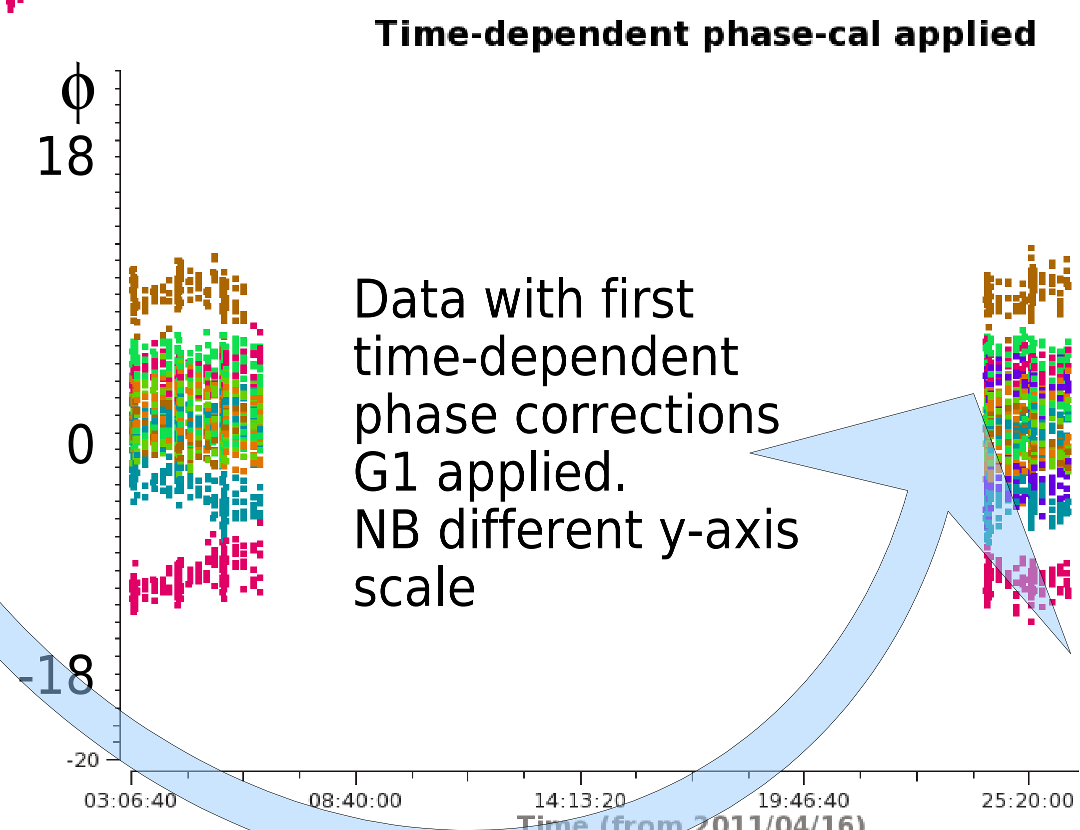
4. Apply B1 and G2 and perform time-dependent amp. cal.

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

First time-dependent phase correction

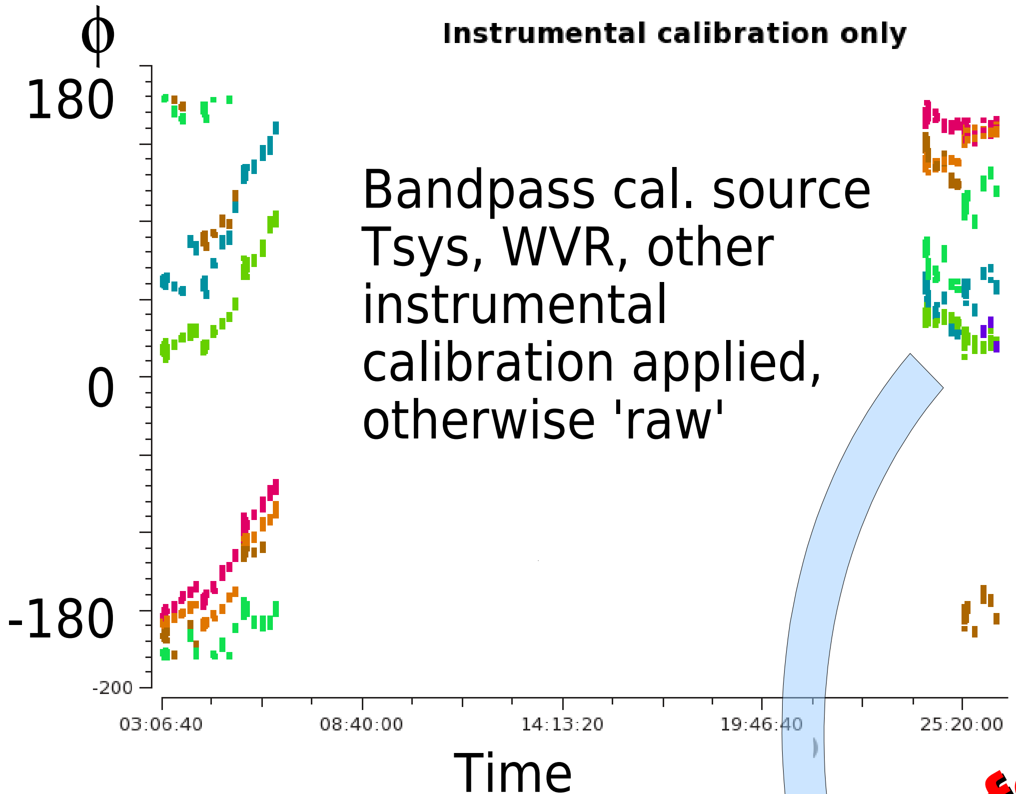


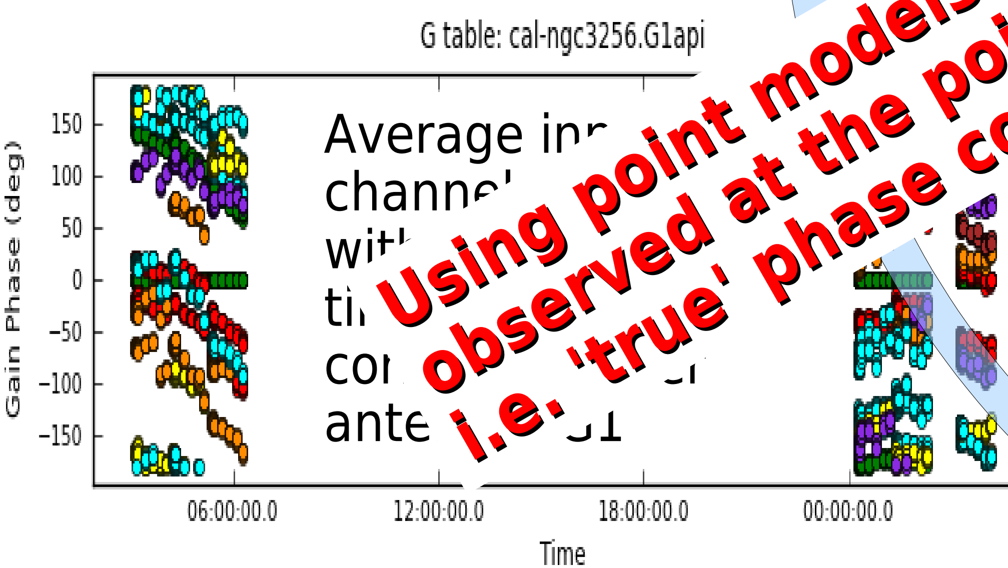


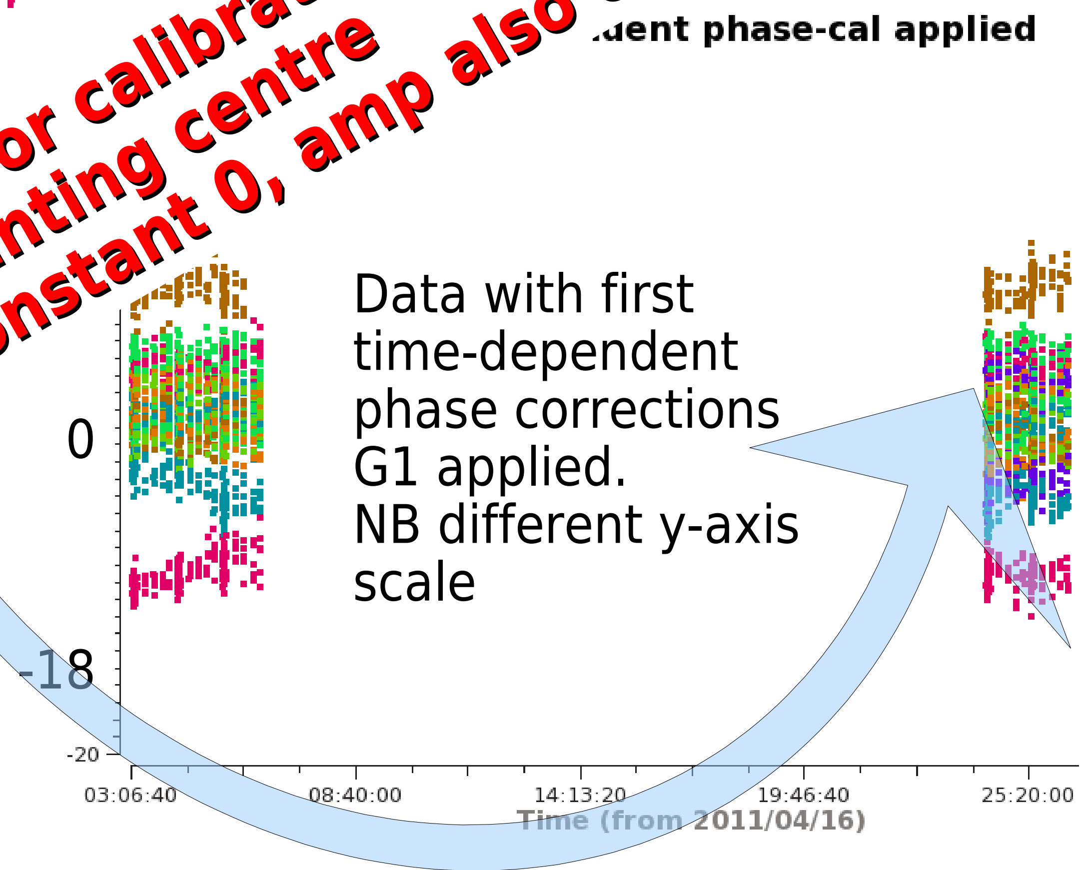


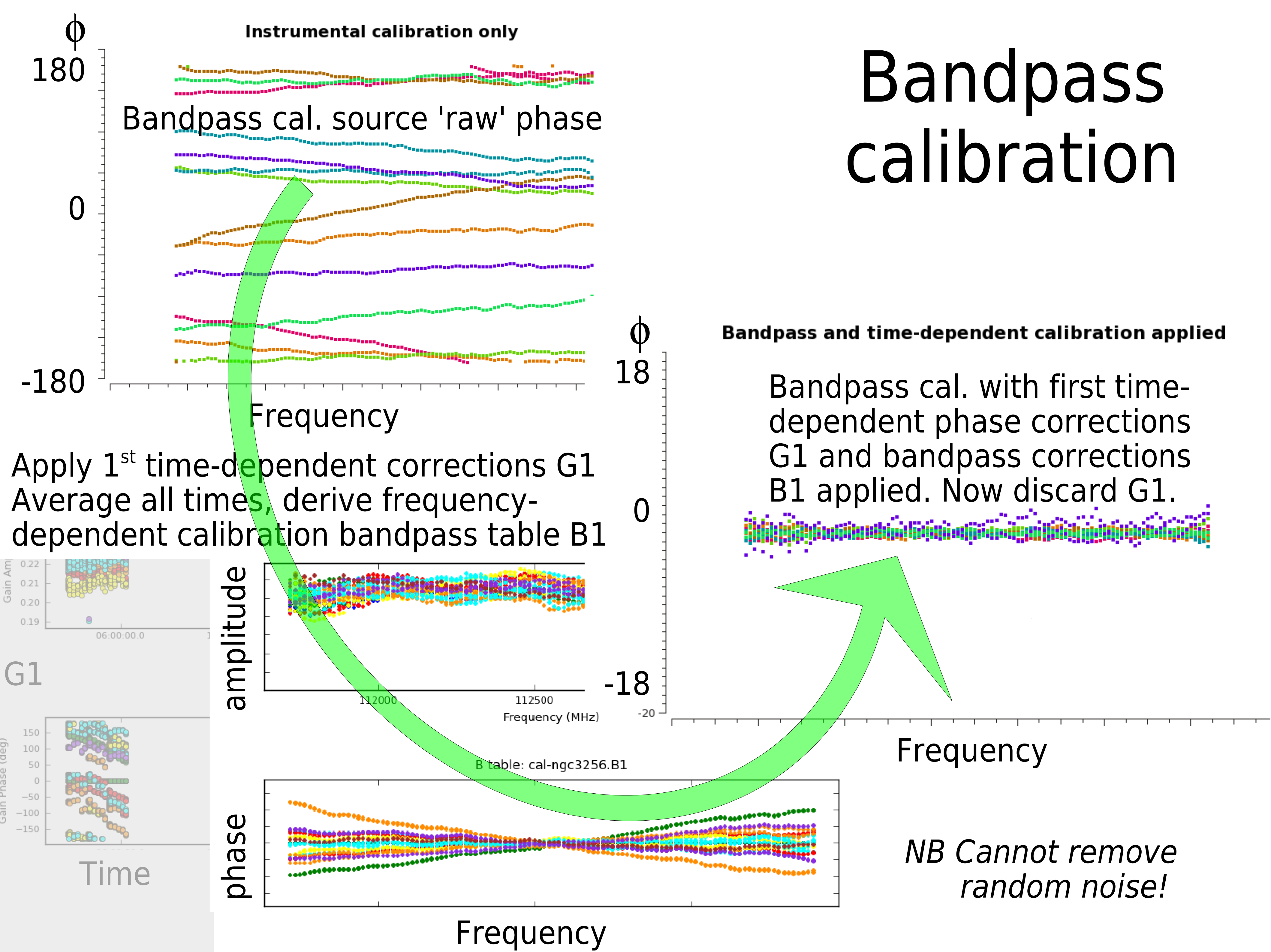
First time-dependent phas cor

Using point models for calibration sources, observed at the pointing centre i.e. 'true' phase constant 0, amp also constant

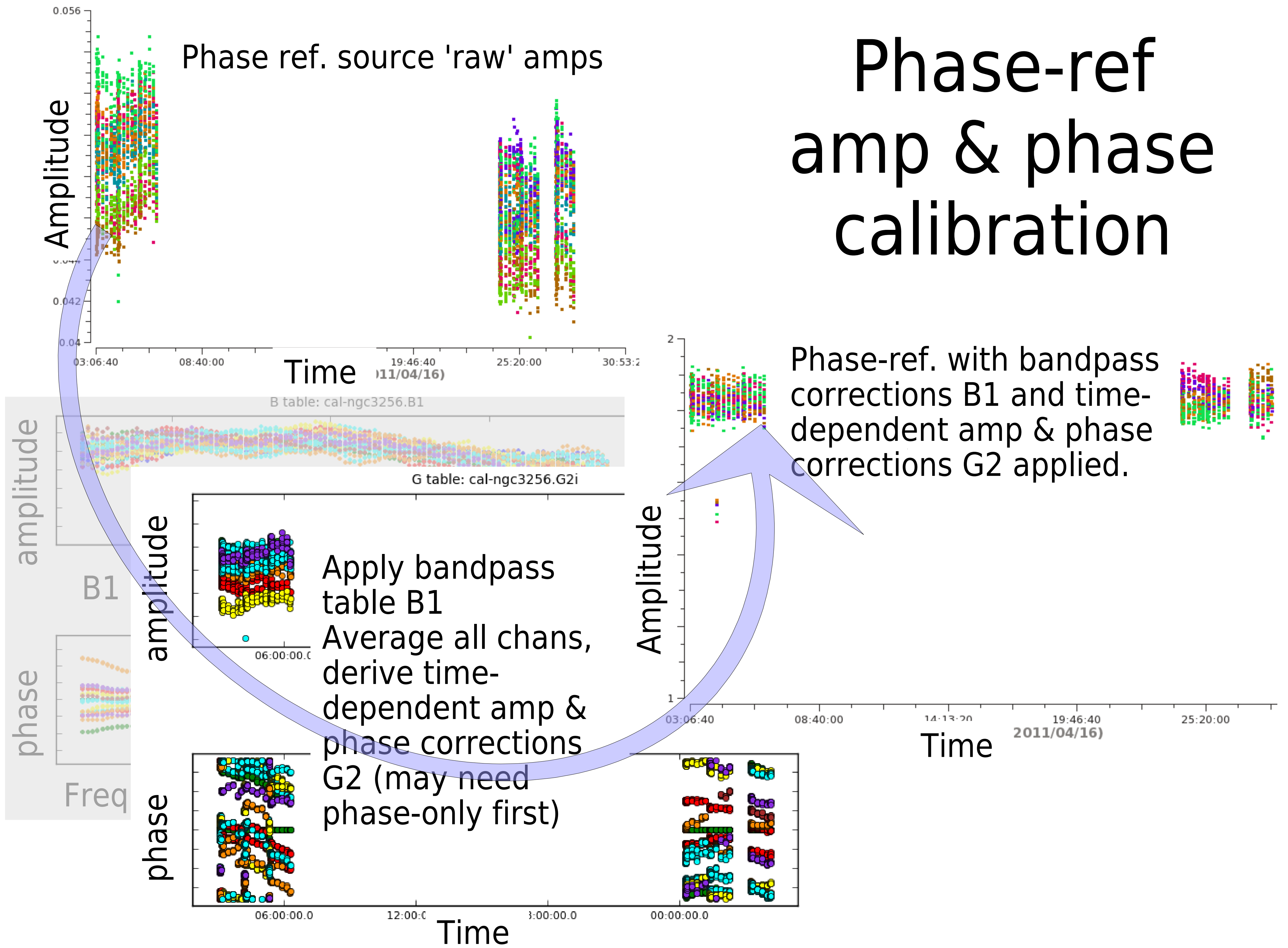




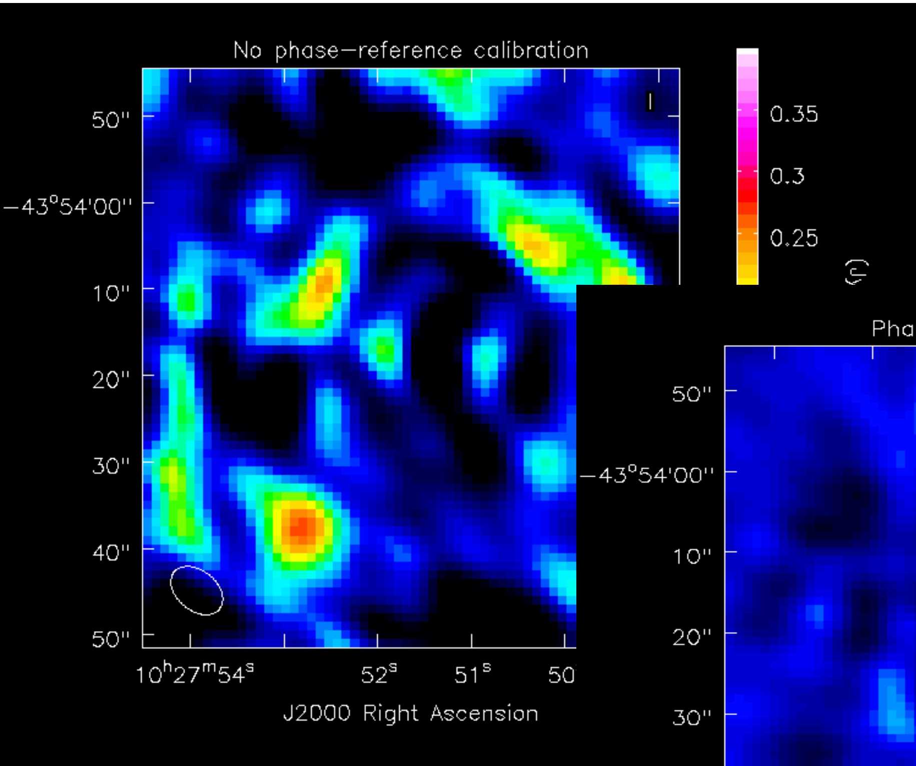



Bandpass calibration
ϕ
Instrumental calibration only
180
0
-180
Bandpass cal. source 'raw' phase
Frequency
Apply 1st time-dependent corrections G1
Average all times, derive frequency-dependent calibration bandpass table B1
0.22
0.21
0.20
0.19
06:00:00.0
G1
150
100
50
0
−50
−100
−150
Time
amplitude
112000
112500
Frequency (MHz)
B table: cal-ngc3256.B1
phase
Frequency
ϕ
Bandpass and time-dependent calibration applied
18
0
-18
-20
Bandpass cal. with first time-dependent phase corrections G1 and bandpass corrections B1 applied. Now discard G1.
Frequency
NB Cannot remove random noise!

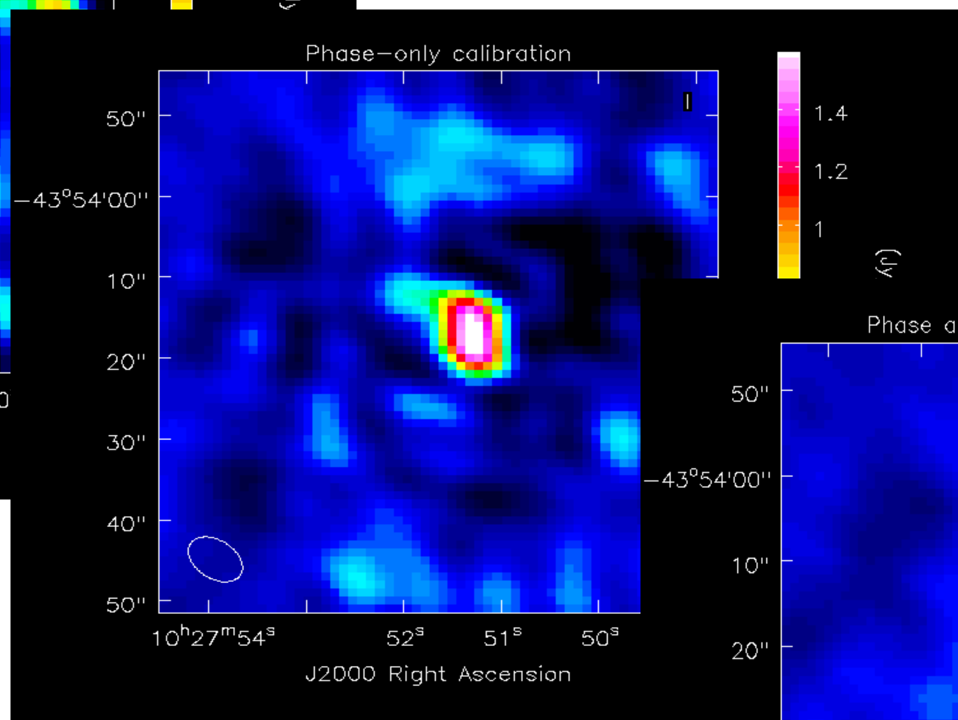
Phase-ref amp & phase calibration



Effects on imaging

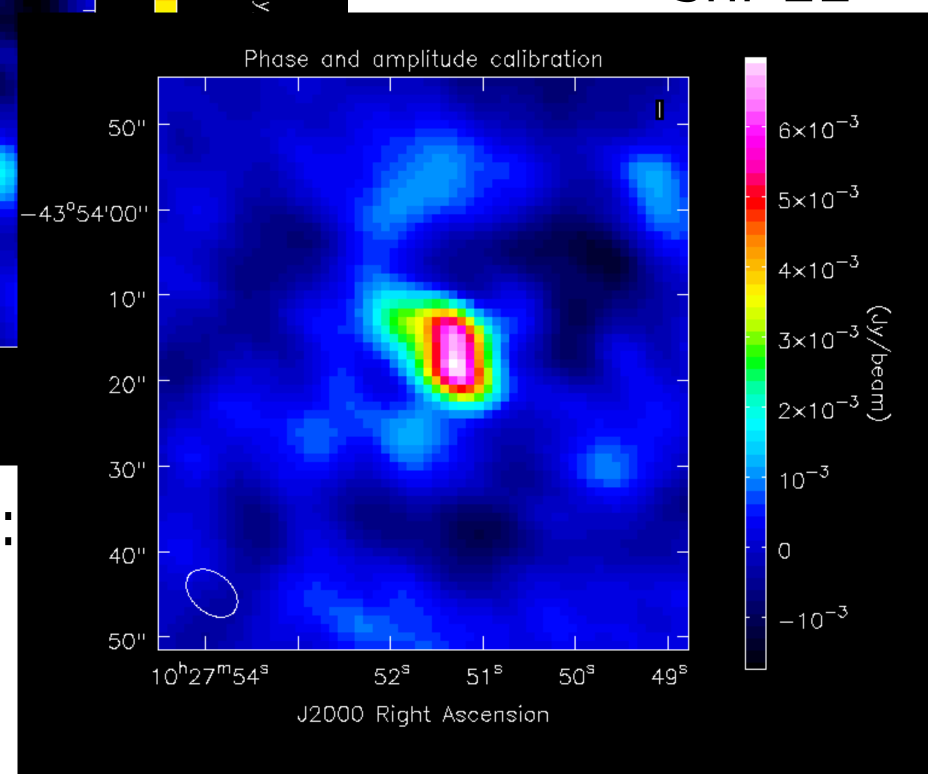


No astrophysical calibration:
no source seen



Phase-only solutions:
source seen, snr 15

Amplitude and
phase solutions:
source seen,
snr 22



CASA calibration: Measurement Equation

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

Vectors

Starting point

V isibility = *f(u,v)*

Goal

I mage

A dditive baseline error

Scalars

Methods

S (mapping I to observer polarization)

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

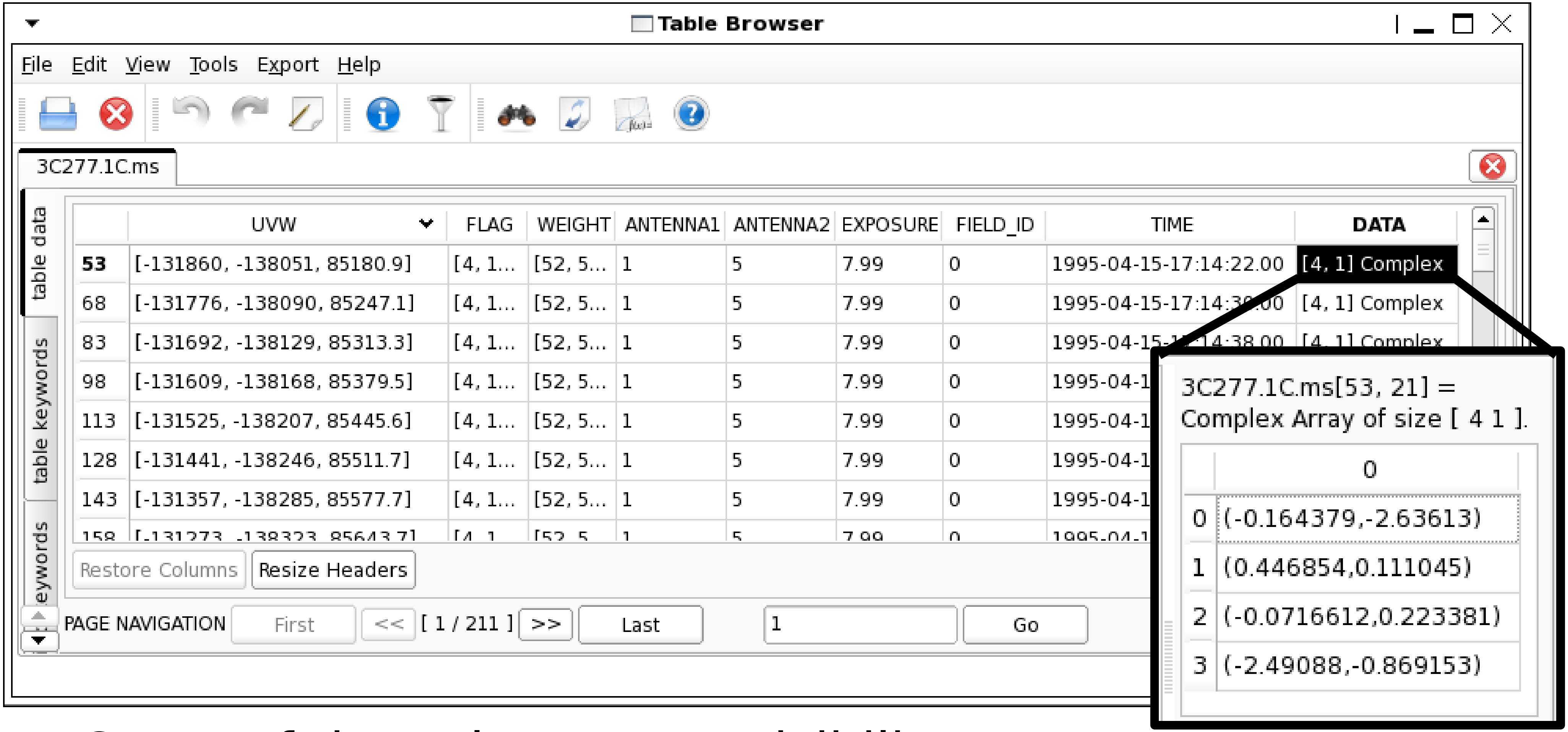
Faraday rotation

Visibility data: Measurement Set format

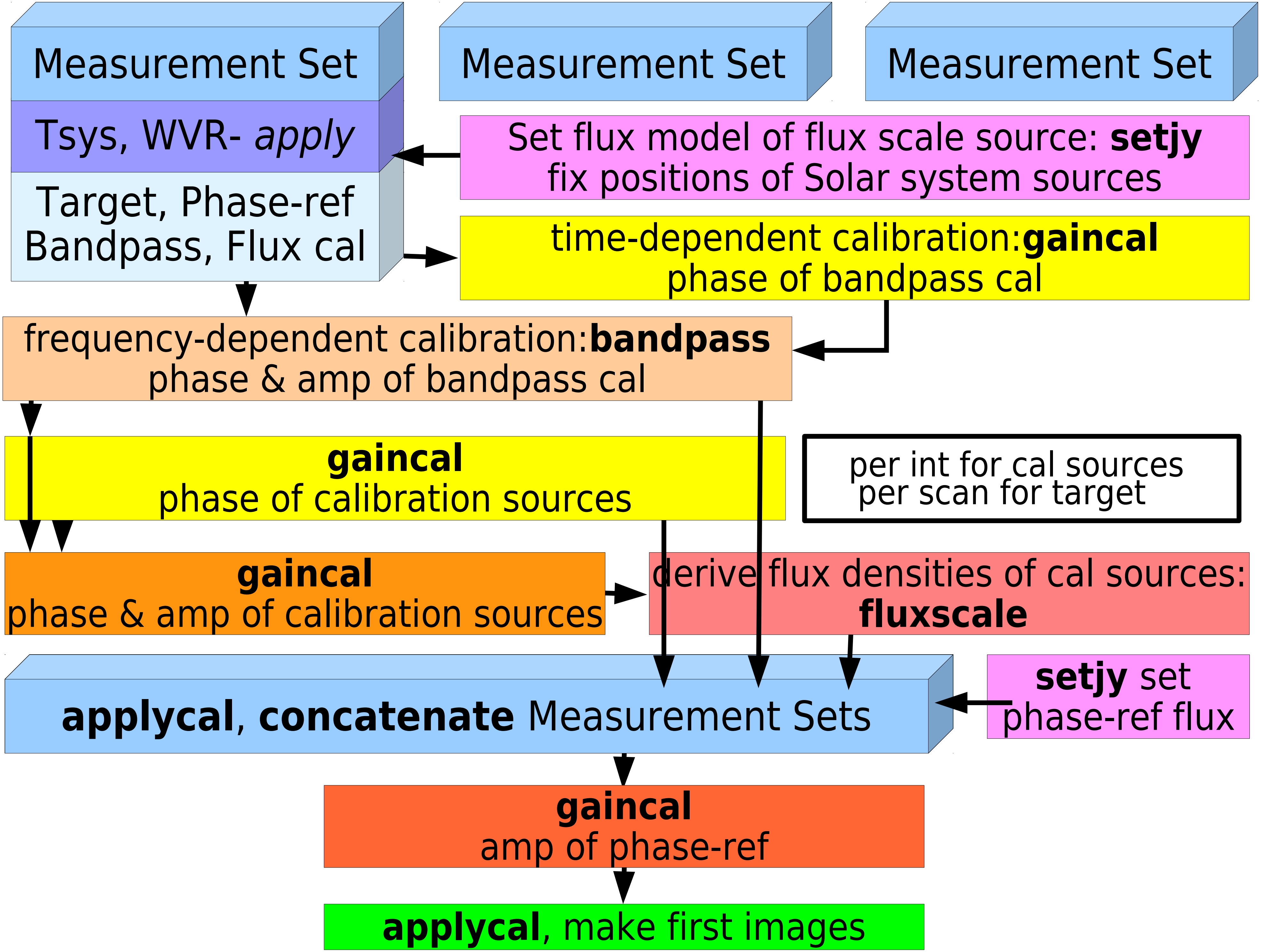
MAIN	**Model, e.g.:**	**Corrected data**	**Flags**
Original visibility data	*FT of image made from MS* *FT of supplied model image* *FT of point flux density*	*Copy of visibilities with calibration tables applied* (Used in imaging not calibration)	(Edits are stored here first; backup tables can be made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

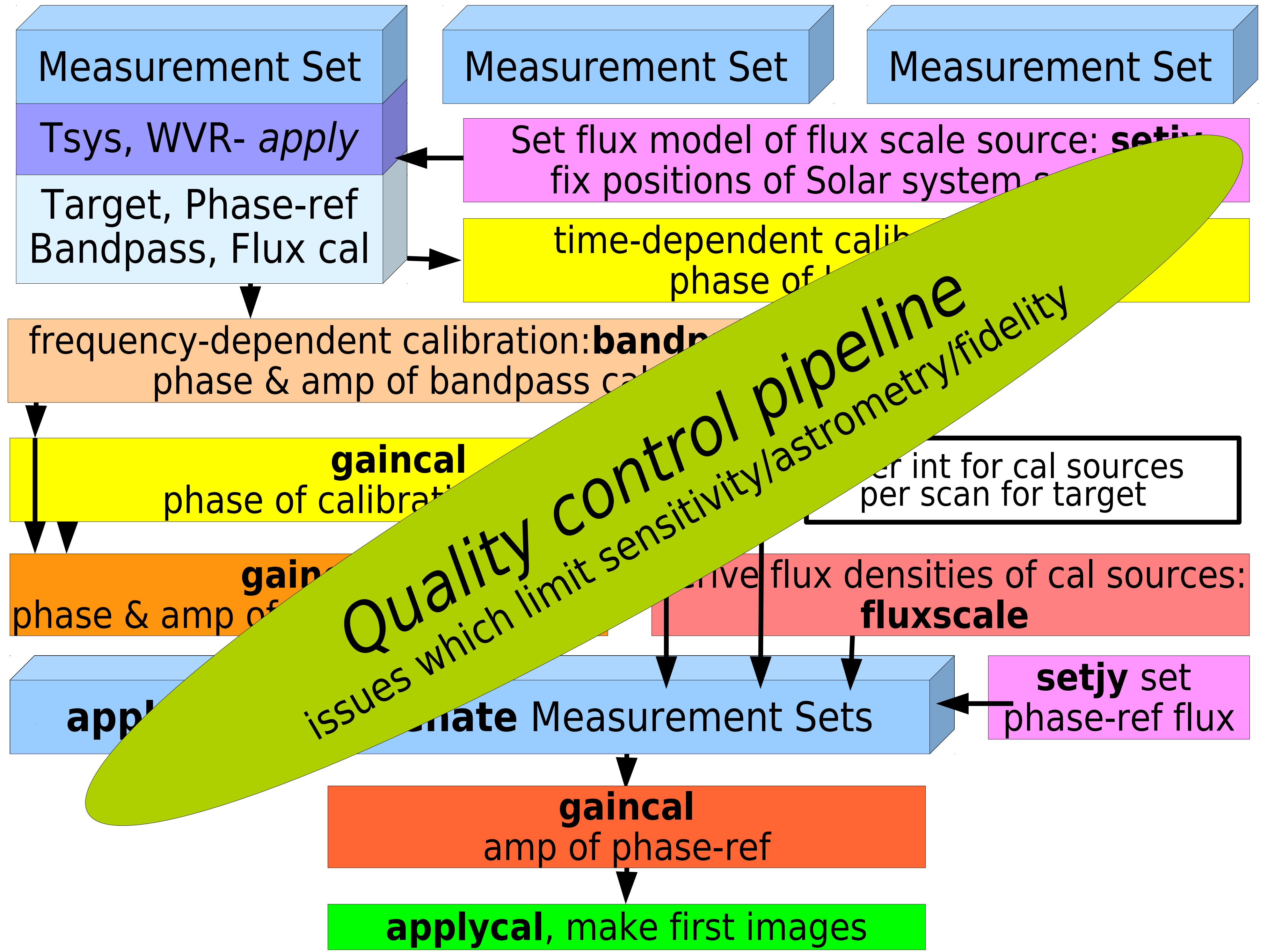
- Unix-like directory structure with binary data and ascii metadata files arranged in subdirectories
- Additional tables in MS and free-standing:
  - *Admin*: Antenna, Source etc.
  - *Processing*: calibration, flags, etc.
- ~interconvertible with FITS; similar image format

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)


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 for 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


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 s
time-dependent calib
phase of
frequency-dependent calibration:bandp
phase & amp of bandpass ca
gaincal
phase of calibrat
er int for cal sources
per scan for target
gain
phase & amp of
rive flux densities of cal sources:
fluxscale
appl
nate Measurement Sets
setjy set
phase-ref flux
gaincal
amp of phase-ref
applycal, make first images
Quality control pipeline
issues which limit sensitivity/astrometry/fidelity

Time jargon

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

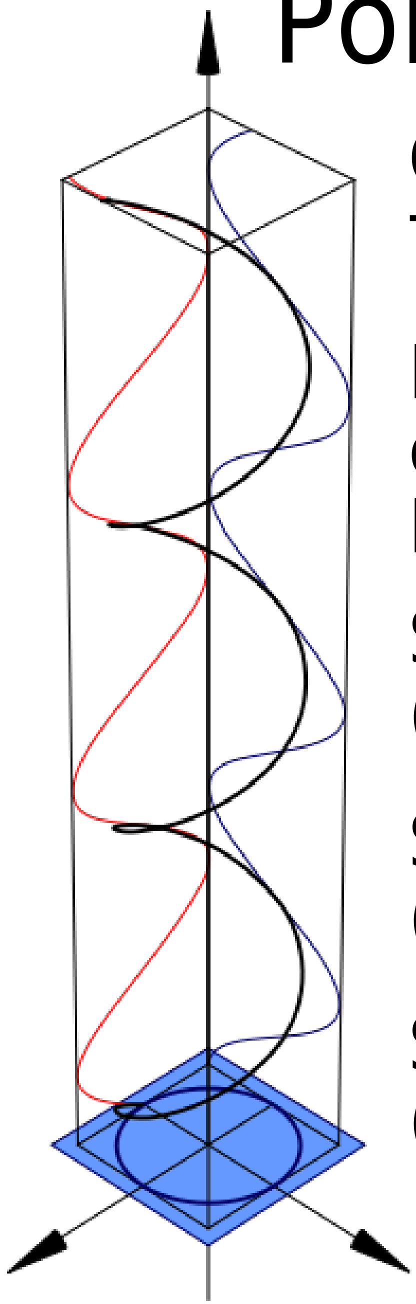
Timerange (UTC)	Scan	FldId	FieldName	nVis	Int(s)
17:13:58.0 - 17:28:38.0	1	0	3C286	1665	7.99
17:29:38.0 - 18:29:30.0	2	1	OQ208	6750	7.99
.....					
17:07:38.0 - 17:09:54.0	8	10	1300+580	270	7.99
17:10:37.0 - 17:17:49.0	9	11	3C277.1	825	7.99
17:18:36.0 - 17:19:56.0	10	10	1300+580	165	7.99
17:20:35.0 -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

Polarization jargon: Rx feeds



CIRCULAR feeds

Left/Right/cross correlations LL RR LR RL

Stokes V = (RR-LL)/2

Stokes Q = (RL + LR)/2

Stokes U = (RL – LR)/2*i*

ALMA LINEAR feeds

Correlations XX, YY, XY, YX

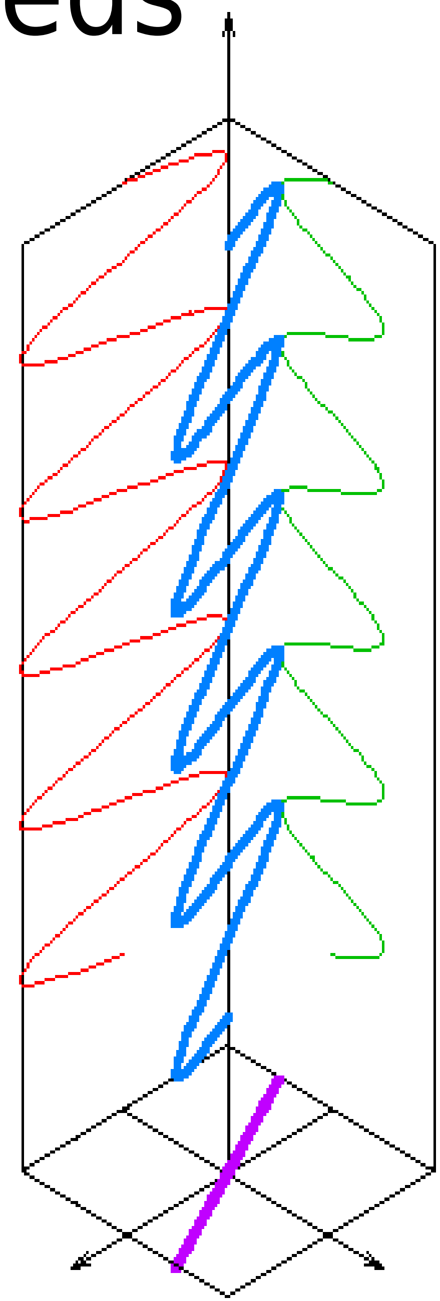
Stokes Q = (XX – YY)/2

Stokes U = (XY – YX)/2

Stokes V = (XY – YX)/2*i*

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

Polarization angle χ = ½ atan2(U/Q)

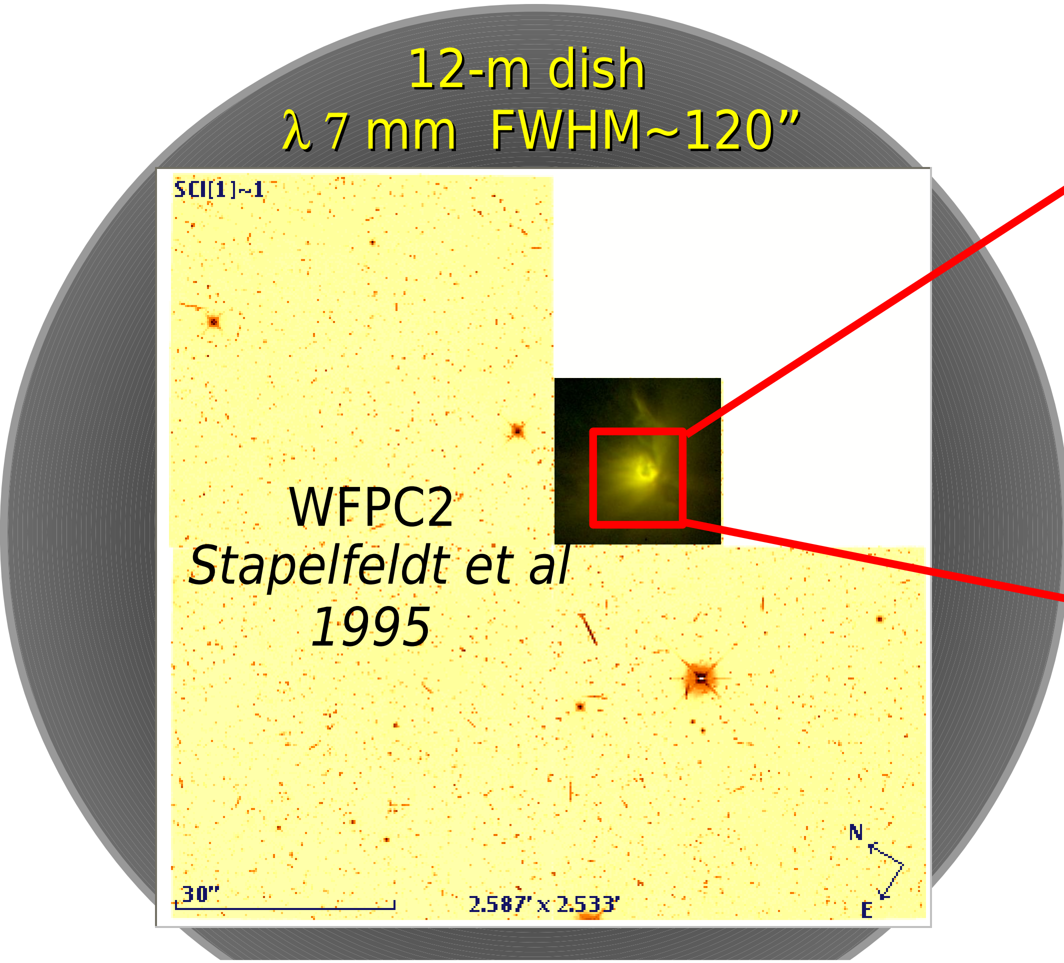


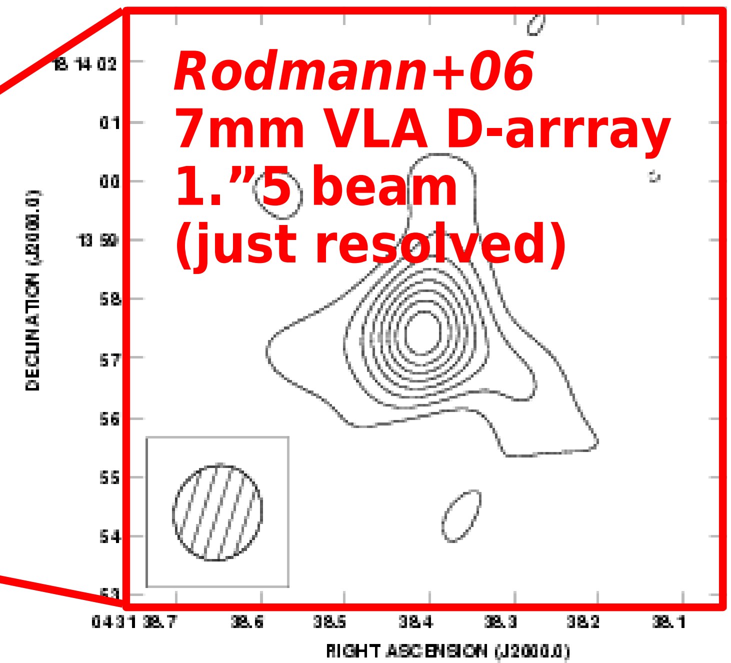
Diagrams thanks to Wikipaedia

Brightness temperature

- Brightness temperature $T_b = S_{source}\ 10^{-26}\ \lambda^2 / 2k_B\ \Omega$
  - S (Jy) in single dish beam area Ω_{SD} (sr) at λ(m)
    - Resoved by SD? $\Omega = \Omega_{SD}$
    - Unresolved? Ω = estimated true (smaller) source size
- Predict ALMA flux density per synthesized beam θ_b
  - $S_{ALMA} = T_b\ 2k_B\ \Omega_{ALMA} / 10^{-26}\ \lambda^2$
    - Now $\Omega_{ALMA} = \theta_b{}^2$
  - Use **Sensitivity Calculator**
    - At least $5\sigma_{rms}$ on peak and $3\sigma_{rms}$ on any extended details
- Check ALMA maximum spatial scale
  - Use **OST** or **CASA** simdata to check imaging fidelity

HL Tau on arcmin-arcsec scales

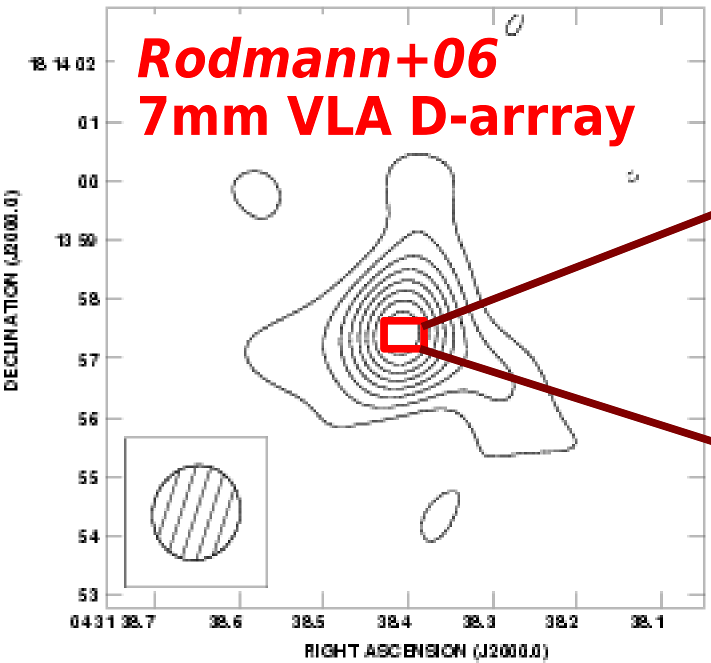




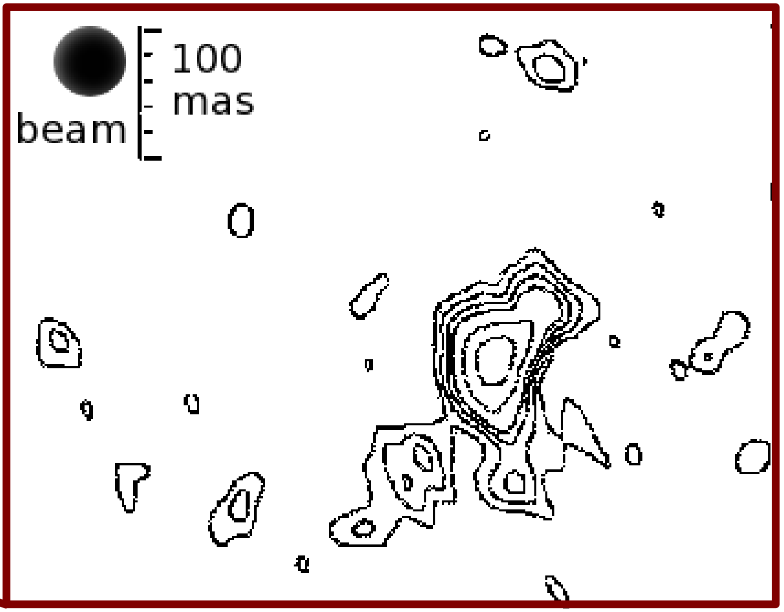
- Total 5 mJy in 0.57 asec^2
- T_b~10 K average in 0.57 asec^2

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

HL Tau on sub-arcsec scales

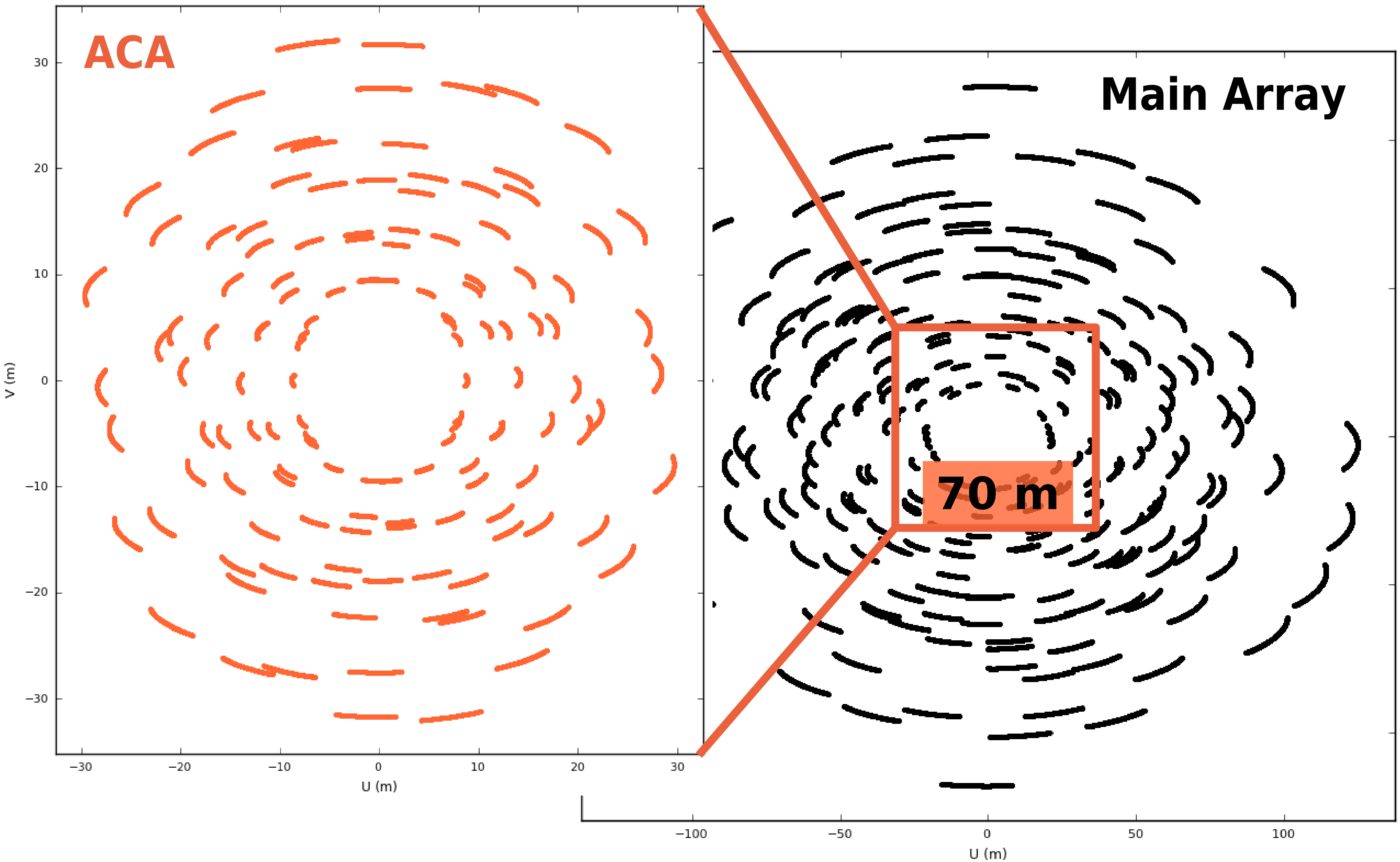


Carrasco-Gonzalez+09
7mm VLA A-arrray
50-mas beam



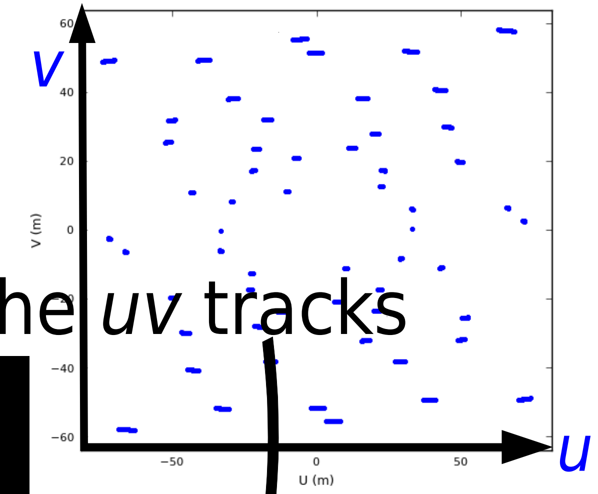
- D-array lowest contour 0.3 mJy in 1500-mas beam
  - Peak~3 mJy in ~200 mas diameter ≡ 0.18 mJy in 50-mas
- A-array lowest contour 0.15 mJy in 50-mas beam
  - Missing *smooth, extended* bright flux: missing spacings
  - Missing *sub-asec* flux: small beam ⇒ higher T_b threshold

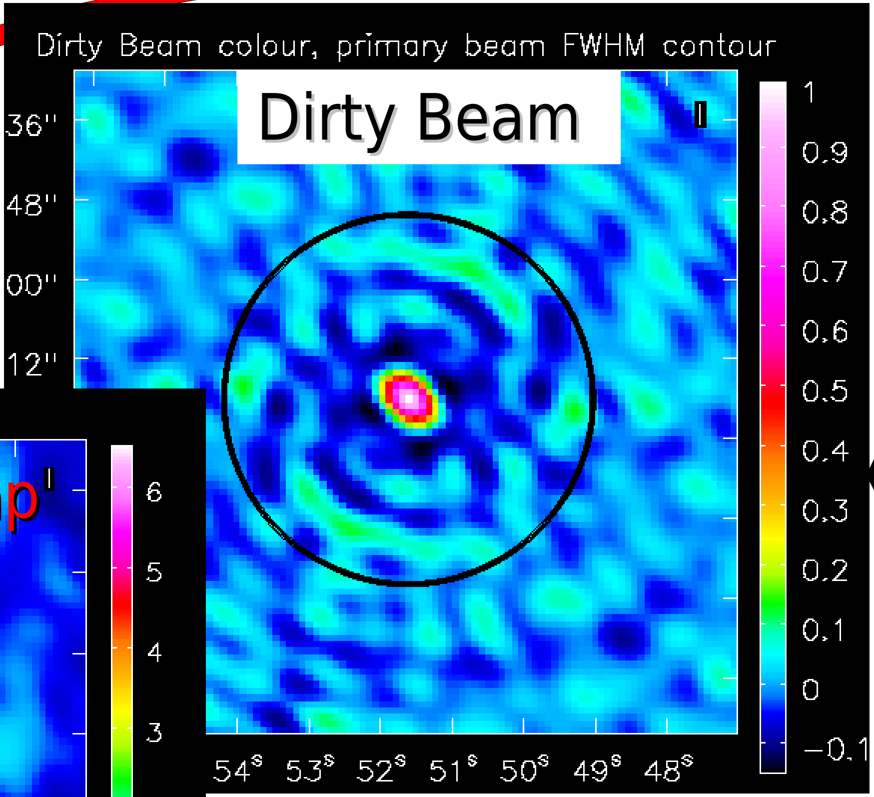
Solution: include ACA (also TP)

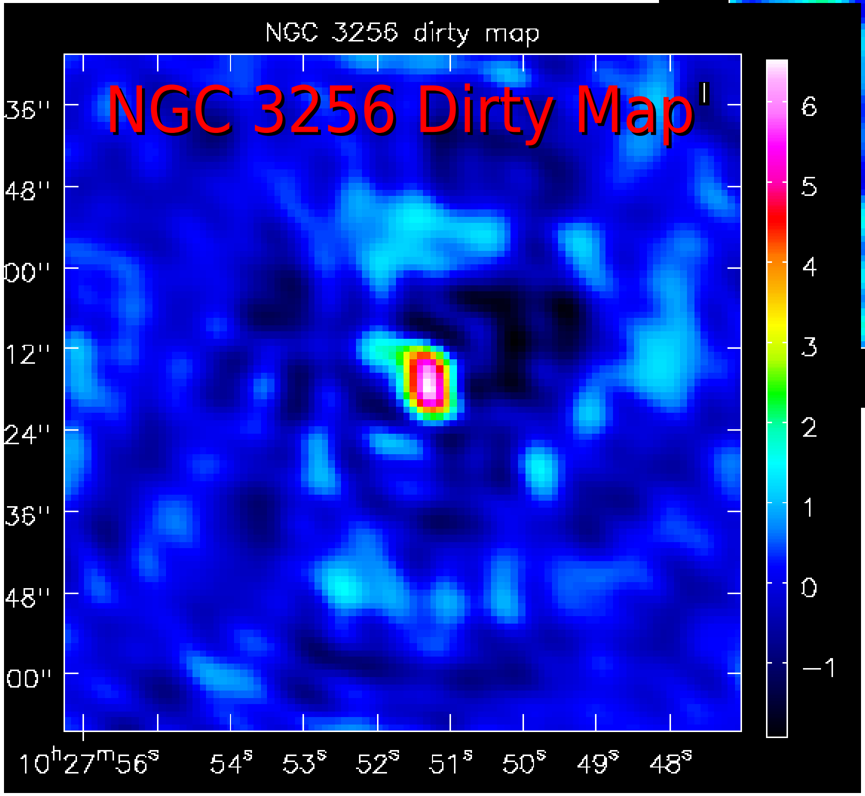


Cleaning

- Fourier transform the visibilities and the *uv* tracks

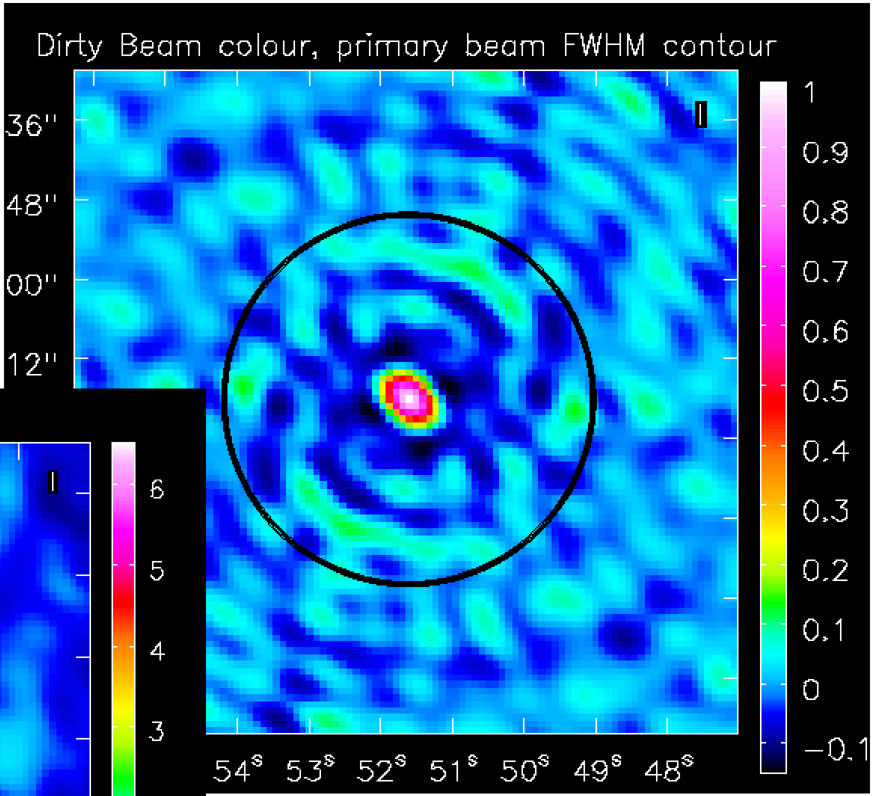


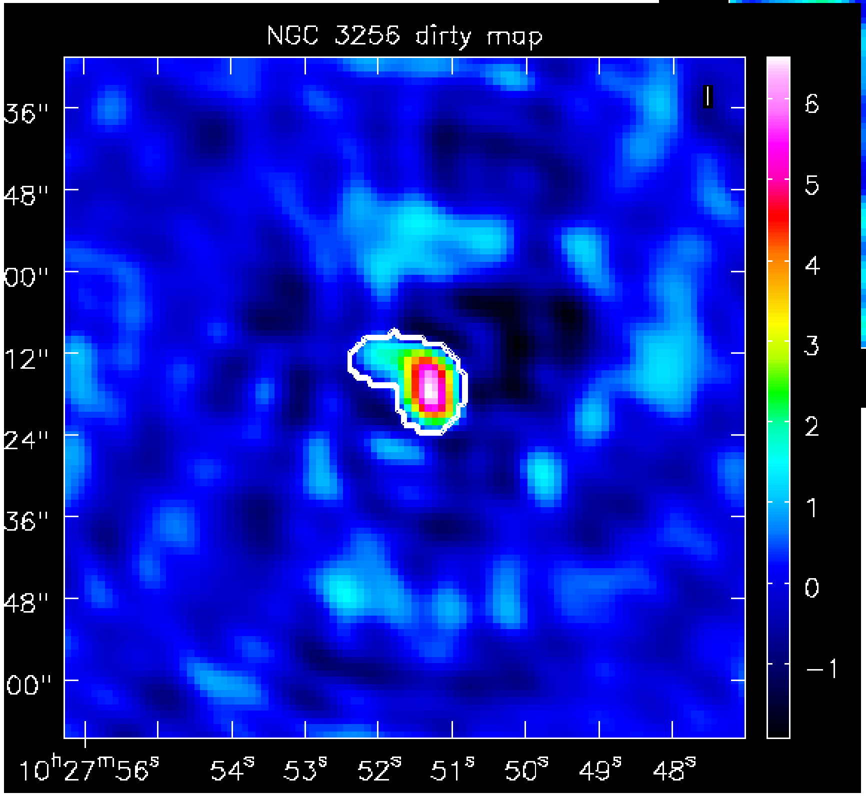




Cleaning

- Fourier transform the visibilities and the *uv* tracks
- Set a mask to include obvious emission

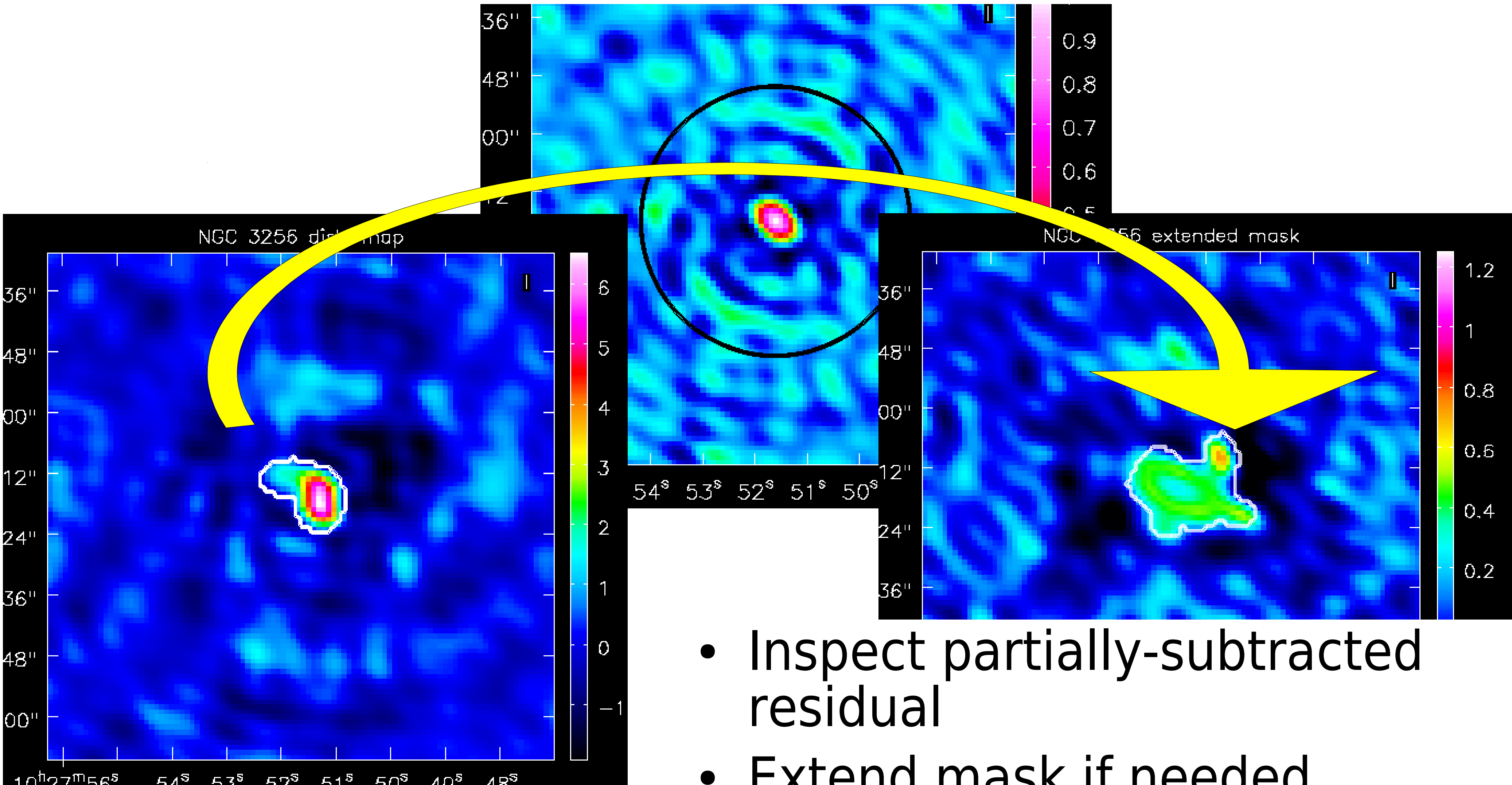




- CLEAN algorithm identifies brightest pixels
- Store e.g. 10% of each peak as Clean Component

Cleaning

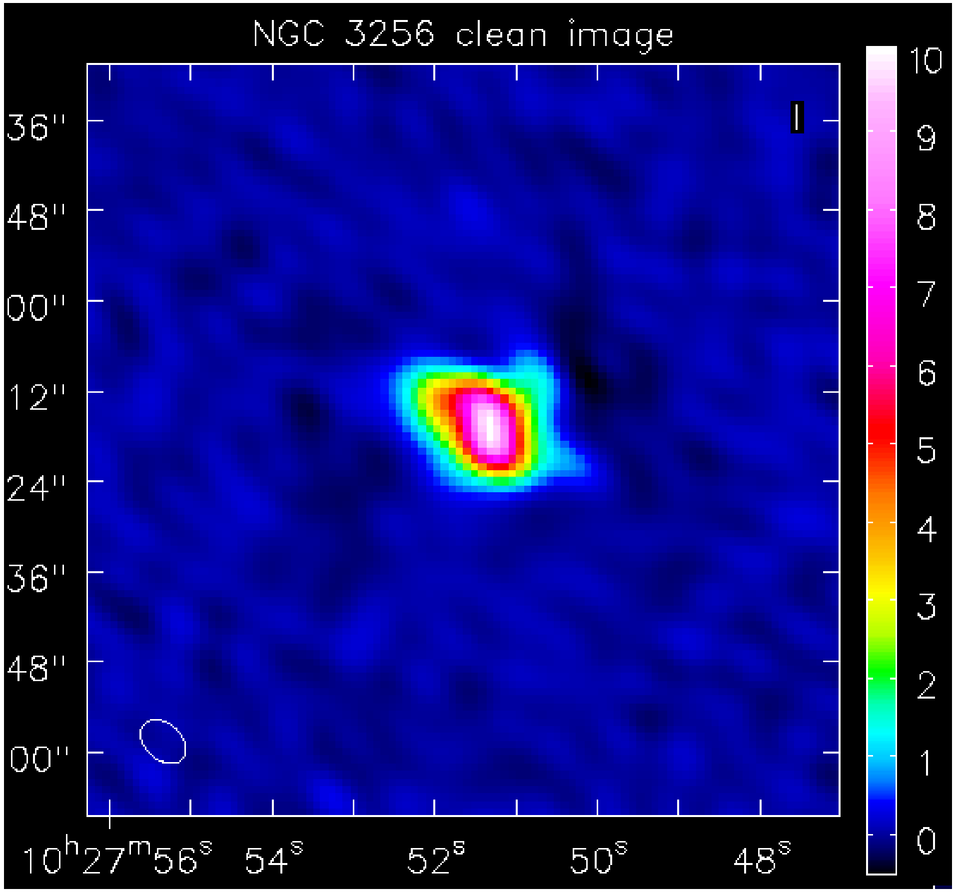
- Iteratively subtract scaled dirty beam at positions of bright pixels



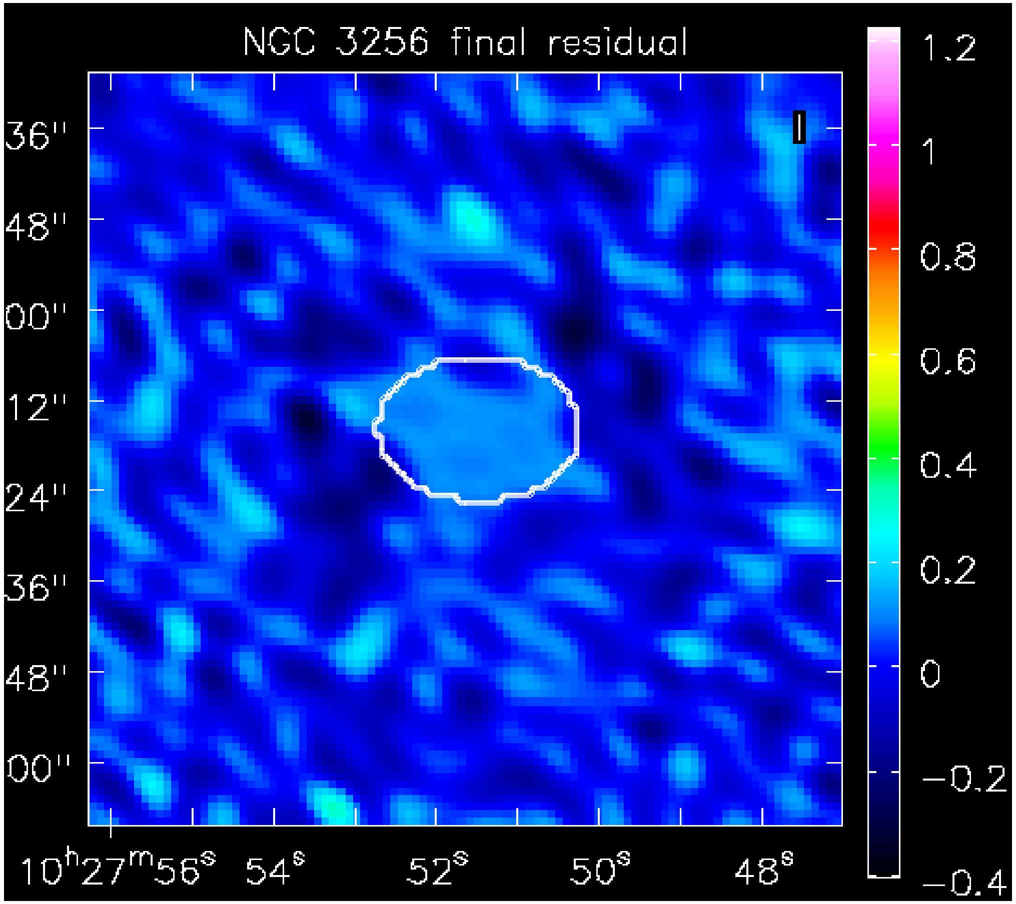
- Inspect partially-subtracted residual
- Extend mask if needed

CLEANed image

- Improved signal-to-noise in final image

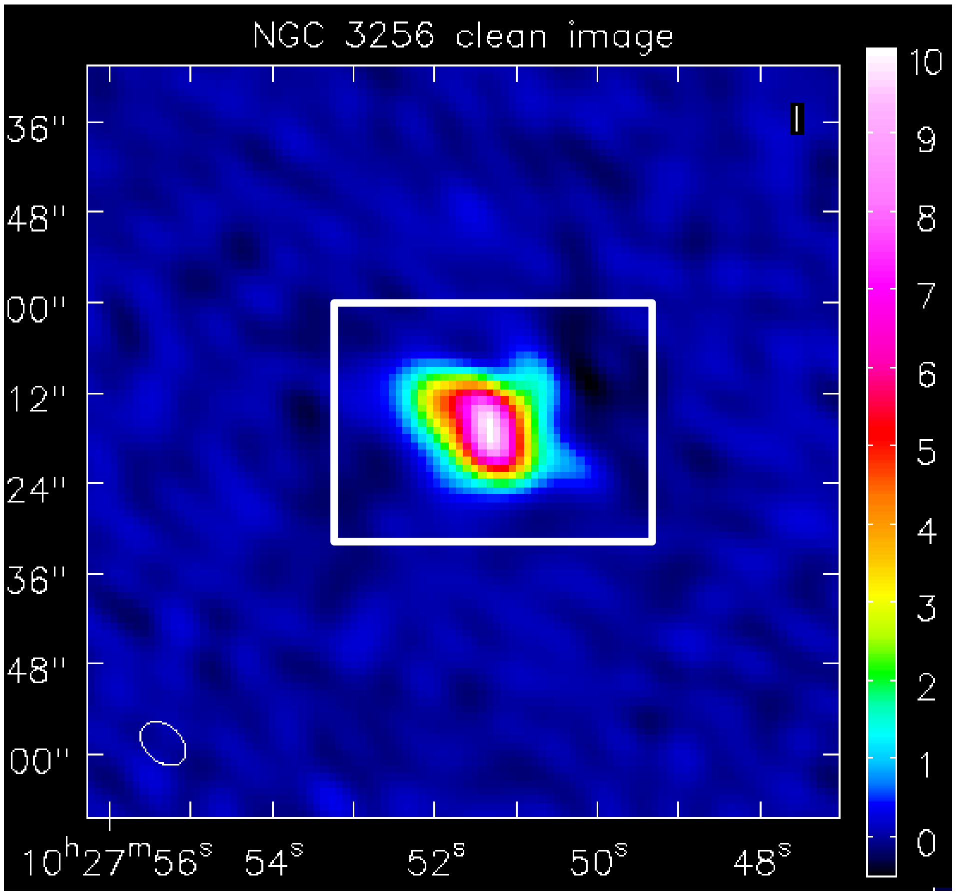


- Residual is just noise
  - Note different flux scale

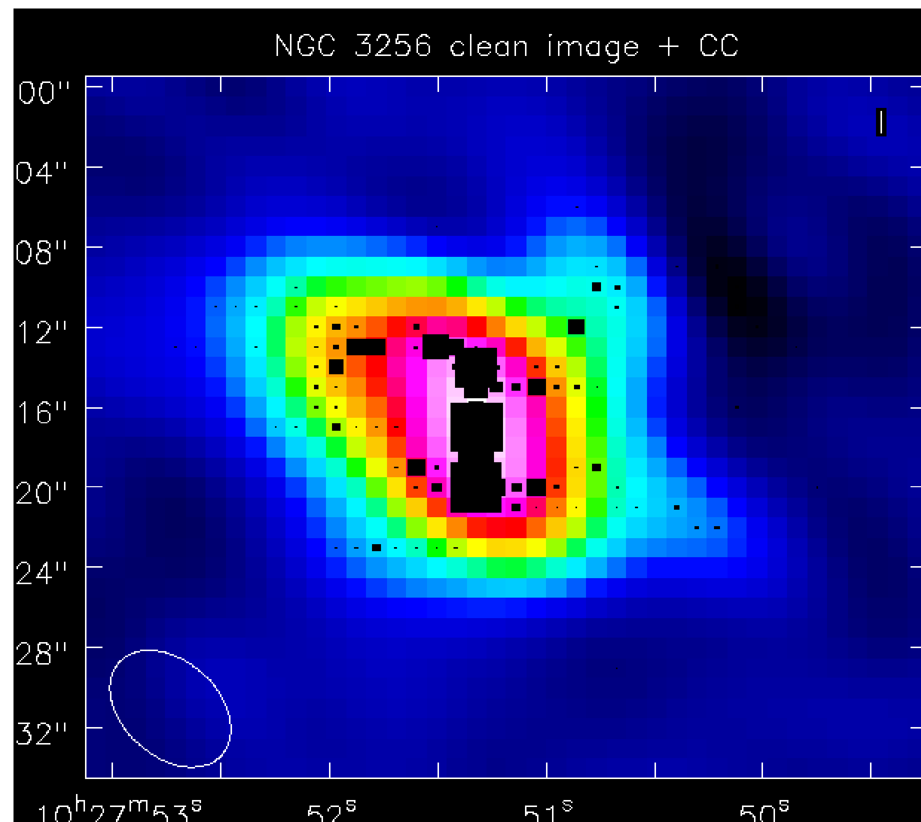


CLEANed image

- Note improved signal-to-noise in image

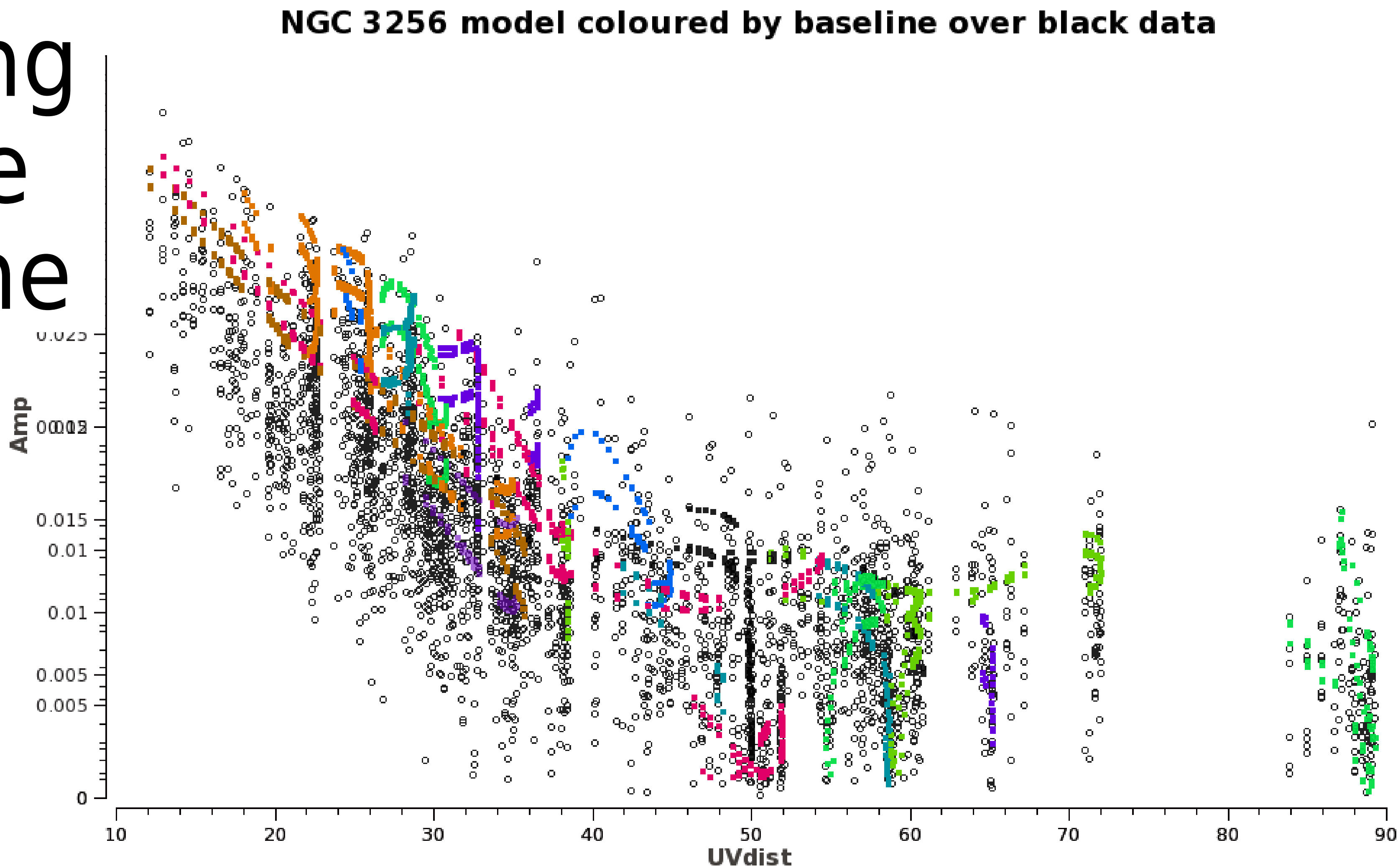


- Final image is combination of residual and Clean Components convolved with restoring beam



- NB if snapshot, extended array, narrow channels….
  - Sparse *uv* coverage can limit dynamic range

Cleaning and the *uv* plane



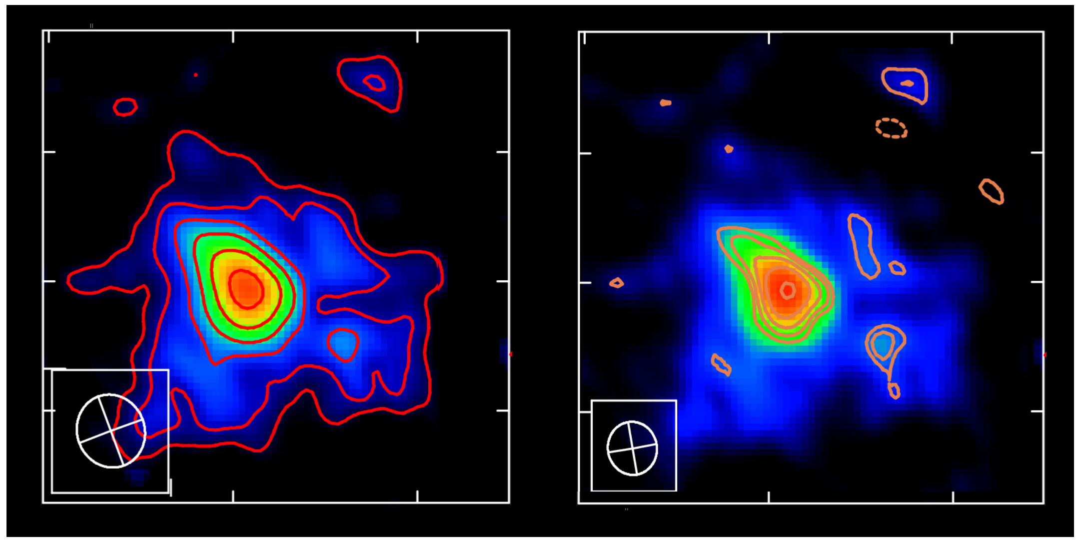
- *uv* model (colour) is FT of Clean Components
  - 'Major Cycles' subtract model from *uv* data and re-make dirty residual image
- Compare model with data to assess quality
  - Use for further rounds of self-calibration

Weighting

- Each visibility has a weight:
  - Intrinsic, for same t_{int}, T_{sys} etc.:
    - ACA baseline has noise $12^2/7^2$ × 12-m baseline
    - Single 12-m TP dish has noise √2 × 12-m baseline
  - Different $N_{samples}$ per averaged integration/channel
  - Variance of calibration solutions
- Weights can be adjusted further during imaging
  - Grid samples in uv plane
    - Natural: Original samples per cell (empty between)
      - Maximum sensitivity to extended structure
    - Uniform: Extrapolate uniformly
      - Finest resolution, worse noise
    - Intermediate (`robust` parameter)
  - Change resolution ≲2x at cost of higher noise

Weighting

- **Natural:**
  - 110-mas resolution, 3σ 51 μJy/bm



- **Uniform:**
  - 80-mas resolution, 3σ 63 μJy/bm

HL Tau *Greaves+'07*

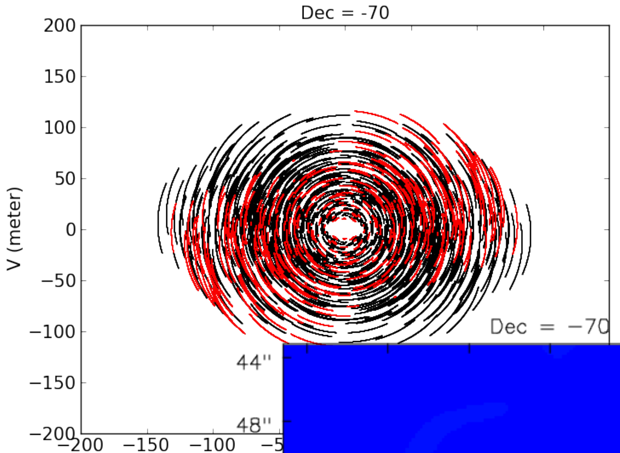
- Weights can be adjusted further during imaging
  - Grid samples in uv plane
    - Natural: Original samples per cell (empty between)
      - Maximum sensitivity to extended structure
    - Uniform: Extrapolate uniformly
      - Finest resolution, worse noise
    - Intermediate (`robust` parameter)
  - Change resolution ≲2x at cost of higher noise

Simulating interferometry data

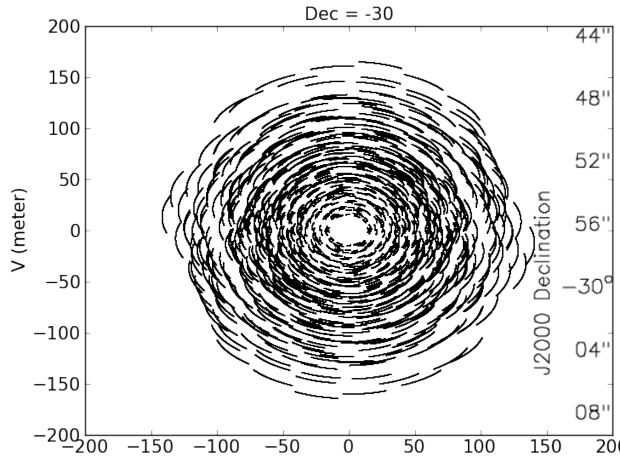
- CASA tasks
  - `simobserve`, `simanalyse`
    - Any array if antenna configs provided
    - Detailed parameters
  - `simalma`
    - Tailored for ALMA
- Observing Support Tool
  - Based on CASA library, results should be same
  - Web interface, limited inputs
    - Less flexible but easier to use
- Why simulate?
  - Effects of interferometer sampling large structures
    - Dynamic range limitations
  - Mosaicing
  - ***But*** check predicted noise with sensitivity calculator

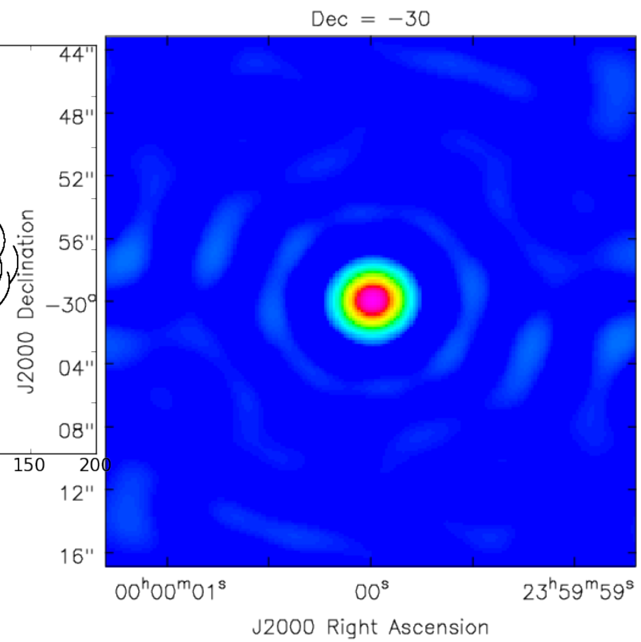
Input for simulations

- See http://almaost.jb.man.ac.uk/help/
  - FITS image
    - Required keywords (script available to check):
      - BUNIT, CDELTn, CROTAn, CDn_n, CTYPEn, NAXIS, NAXISn
  - Declination
    - Very high/low Dec:
      - Elongated synthesised beam
      - Shadowing

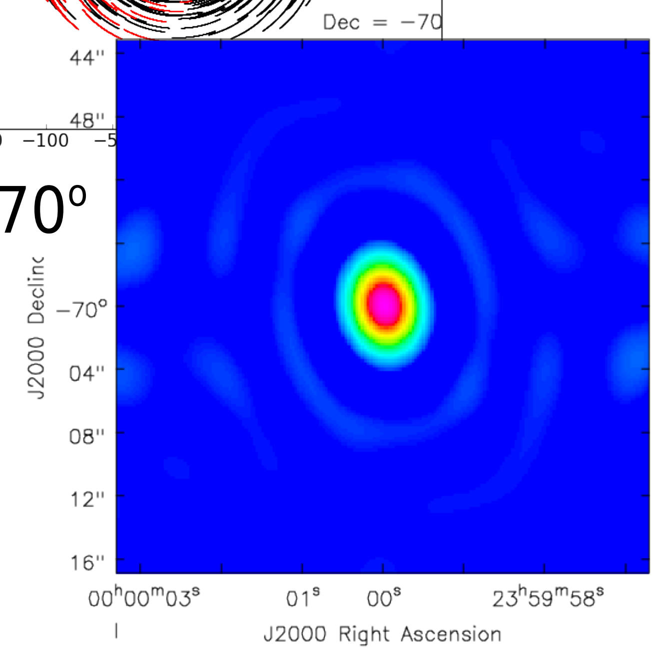


Dec -70°



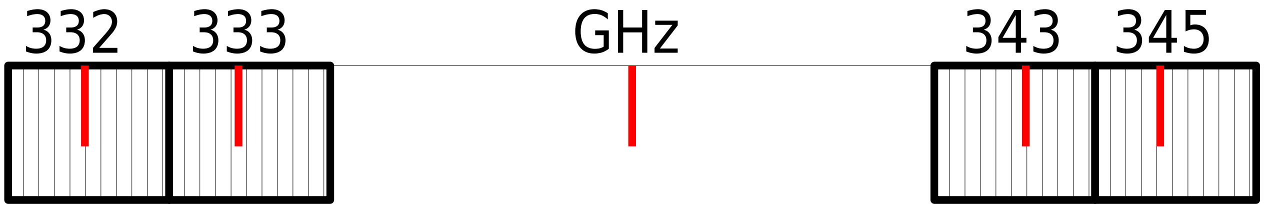


Dec -30°



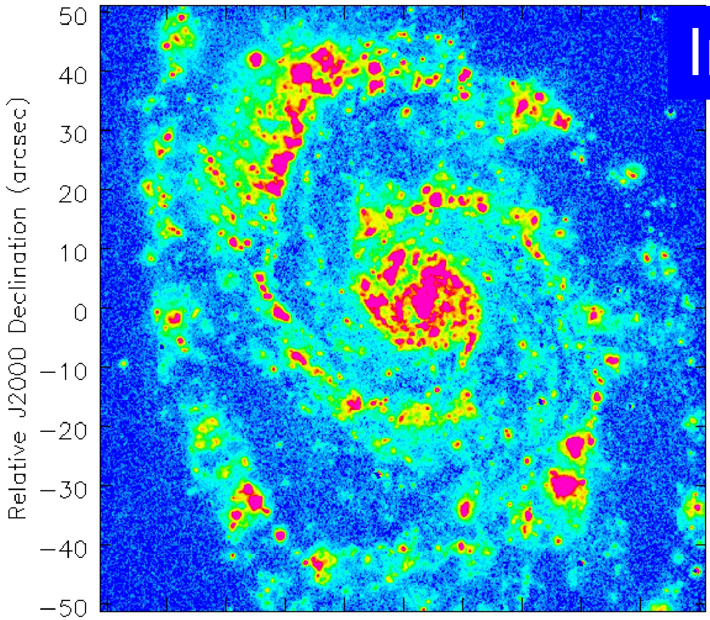
Input for simulations

- Bandwidth, frequency etc.
  - Line: OST handles a single channel only
  - Continuum: OST can adopt optimum place in band
    - NB bands 3,4,6,7,8 full b/w *gap between sidebands*

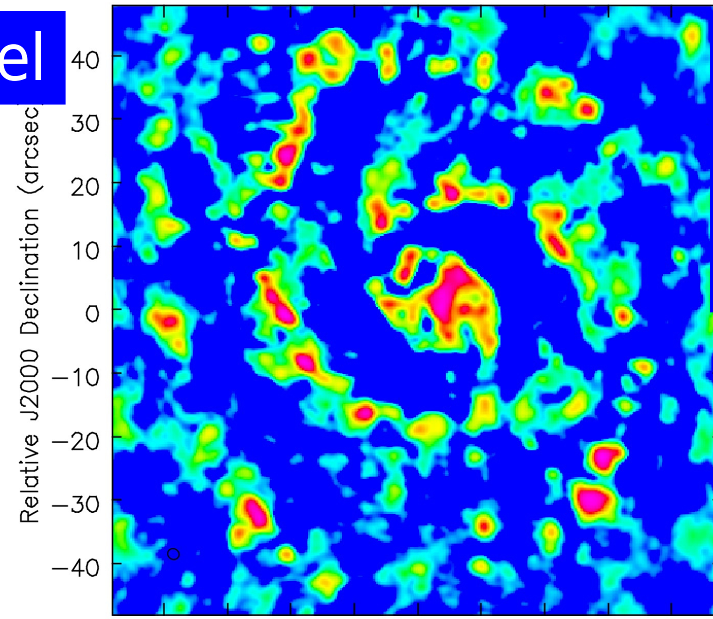


- Automatically mosaics if required by input size
  - Crop large input if you only need a single pointing!
- Resolution: Cycle 2, select array(s) directly
- Peak μ/m/Jy/pixel (to rescale input)
- Time needed to reach sensitivity
- Add noise
  - OST does not simulate phase/amp correction!

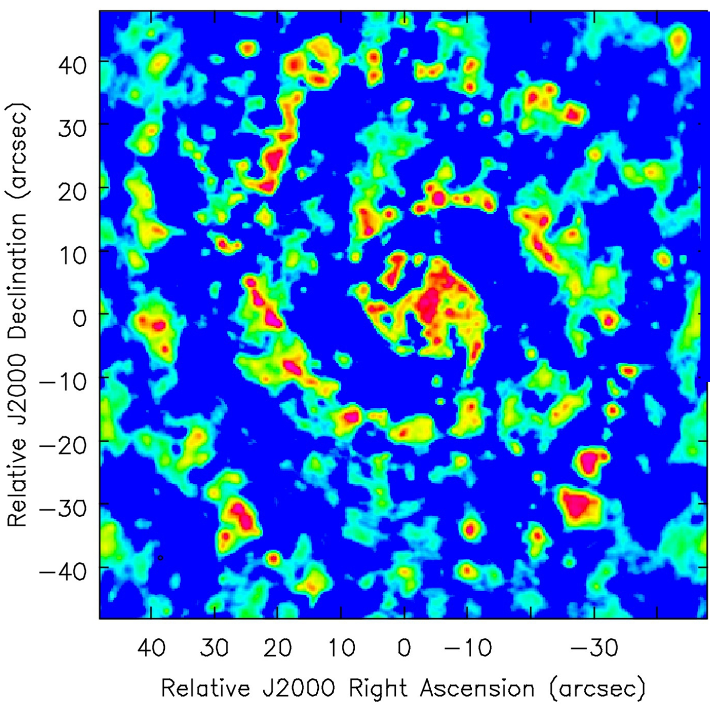
Cycle 2 resolution (scales @100 GHz)



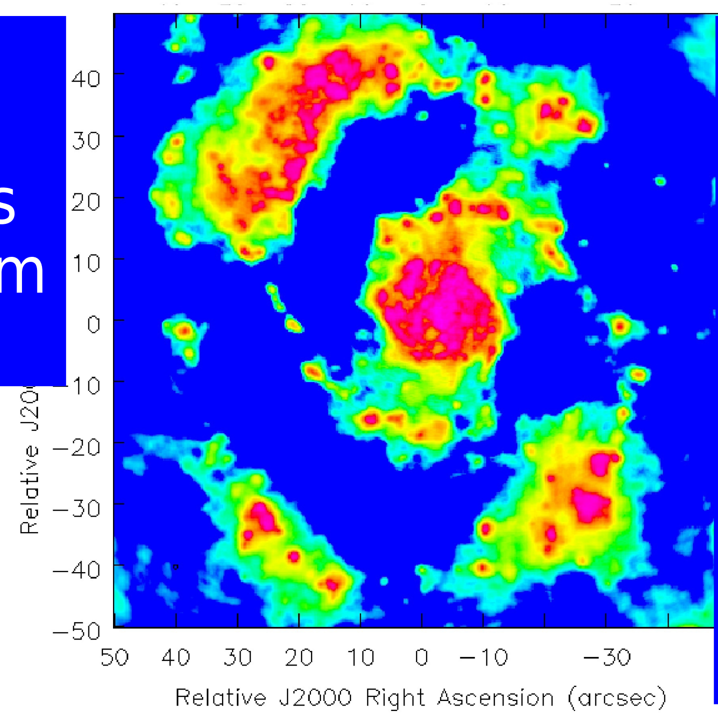
Input model



C34-3
Baselines
21 – 443 m
(1.4-18'')



C34-3 +
C34-7
Baselines
21–1508m
(0.5-18'')

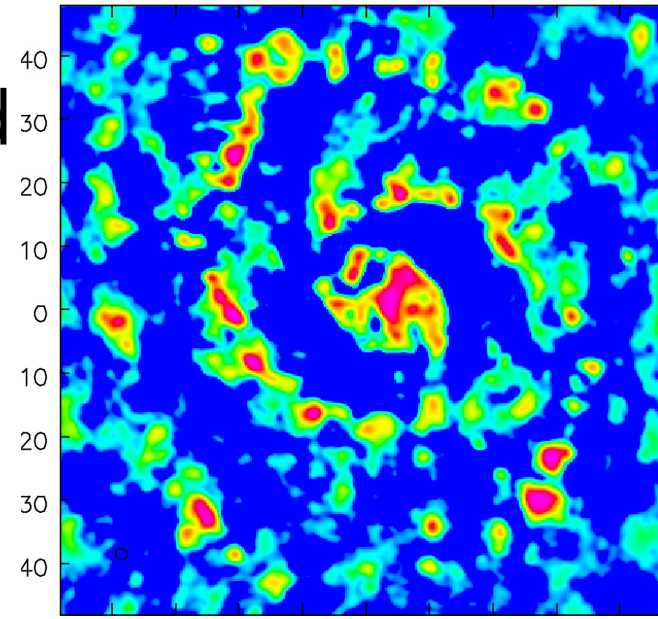


ACA +
C34-3 +
C34-7
Baselines
9–1508m
(0.5-42'')

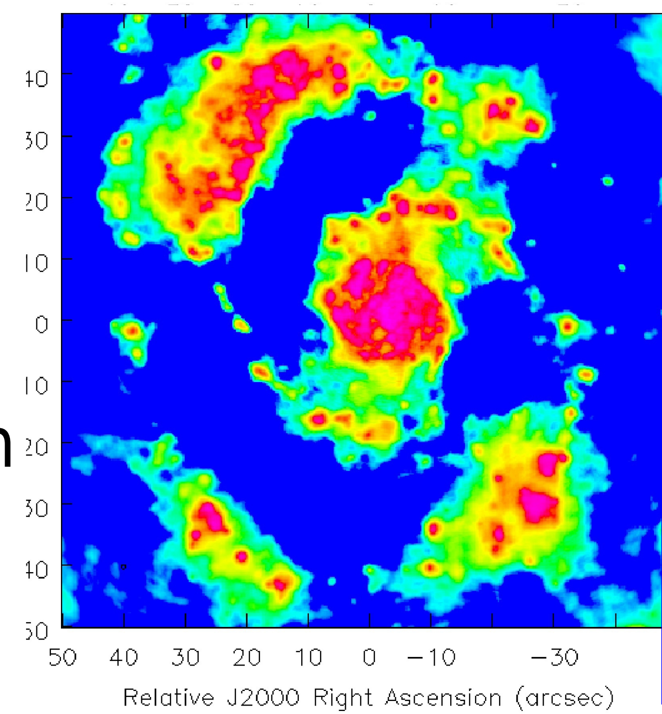
Add TP for
larger
scales

Cycle 2 examples (scales @100 GHz)

- Data for each array supplied separately by OST
  - Adjust weights when combining arrays
  - Further modify resolution by chosing degree of uniform/natural weighting in imaging
- No unique map
  - Vary combinations to emphasize regions of interest
  - Higher resolution can mean higher noise as well as resolving-out extended structure



C34-3
Baselines
21 – 443 m
(1.4-18'')

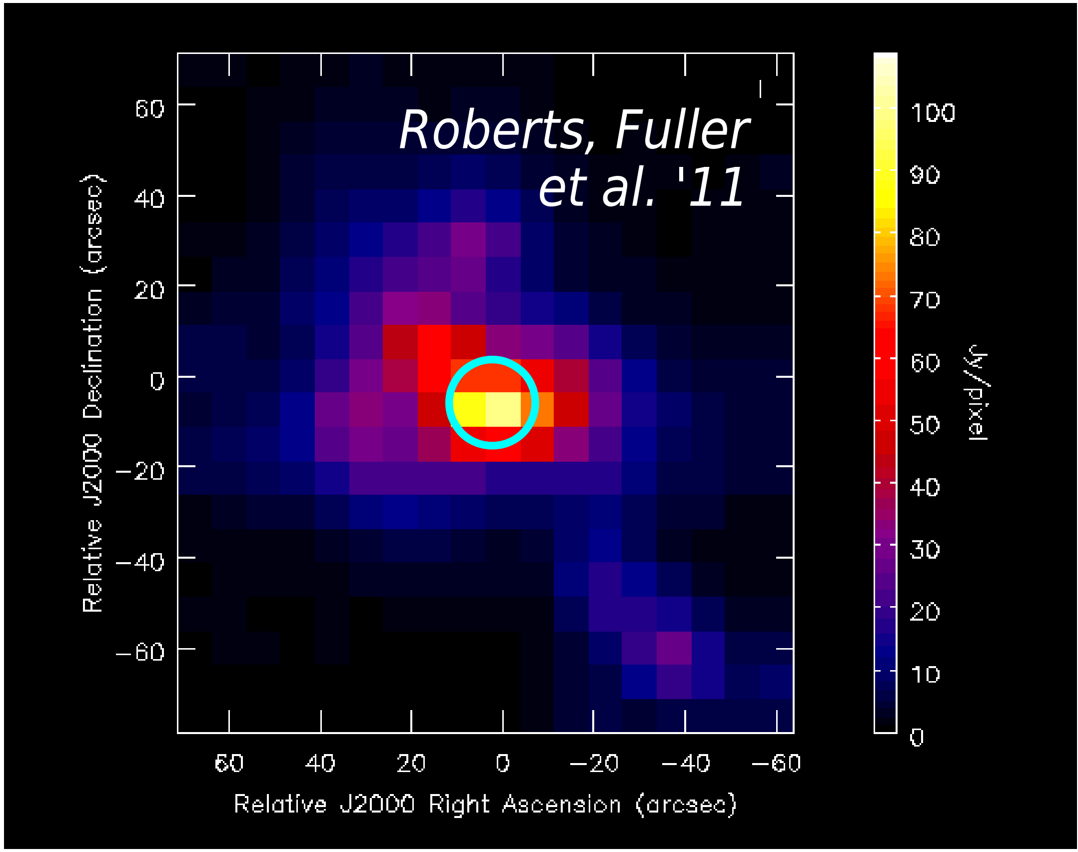


ACA +
C34-3 +
C34-7
Baselines
9–1508m
(0.5-42'')

Add TP for larger scales

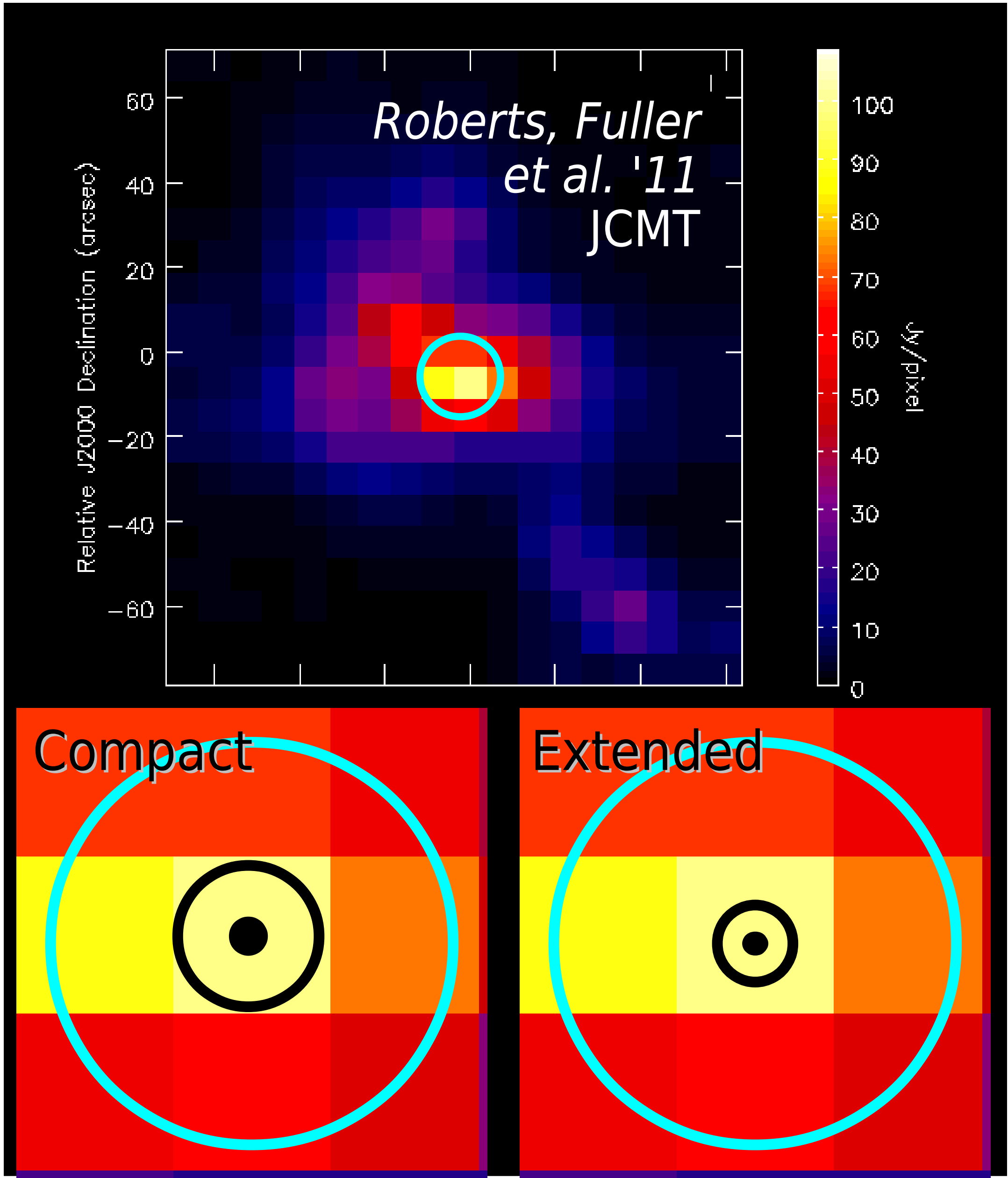
Structure scales

- JCMT single-dish mosaic of source at 11 kpc
  - 7''.5 pixels
  - Field of view 150''
  - Peak 100 Jy/ 7''.5 pixel
  - 354 GHz = λ 0.85 mm



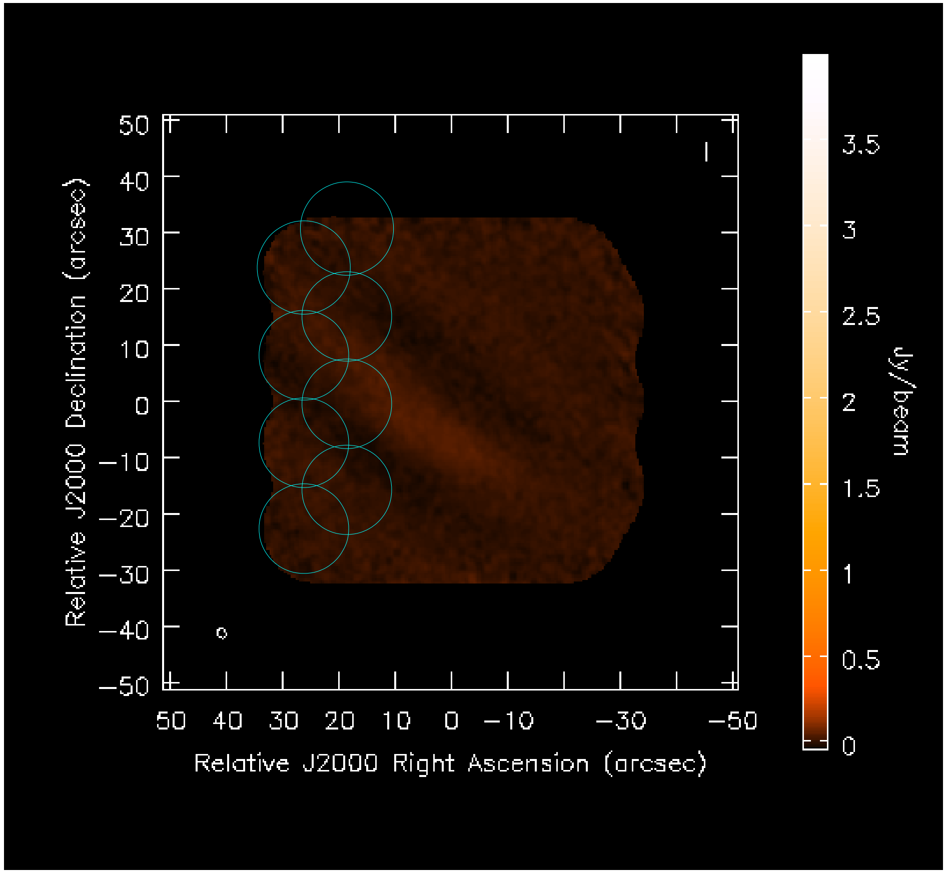
Structure scales

- JCMT source at 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
- ALMA synthesized beam
  - λ / longest baseline ●
    - Compact array: 1''
    - Intermediate: 0''.45
- Largest spatial scale ○
  - λ / shortest baseline
    - Compact array λ/14≈7.6''
    - Intermediate λ/21≈5.2''



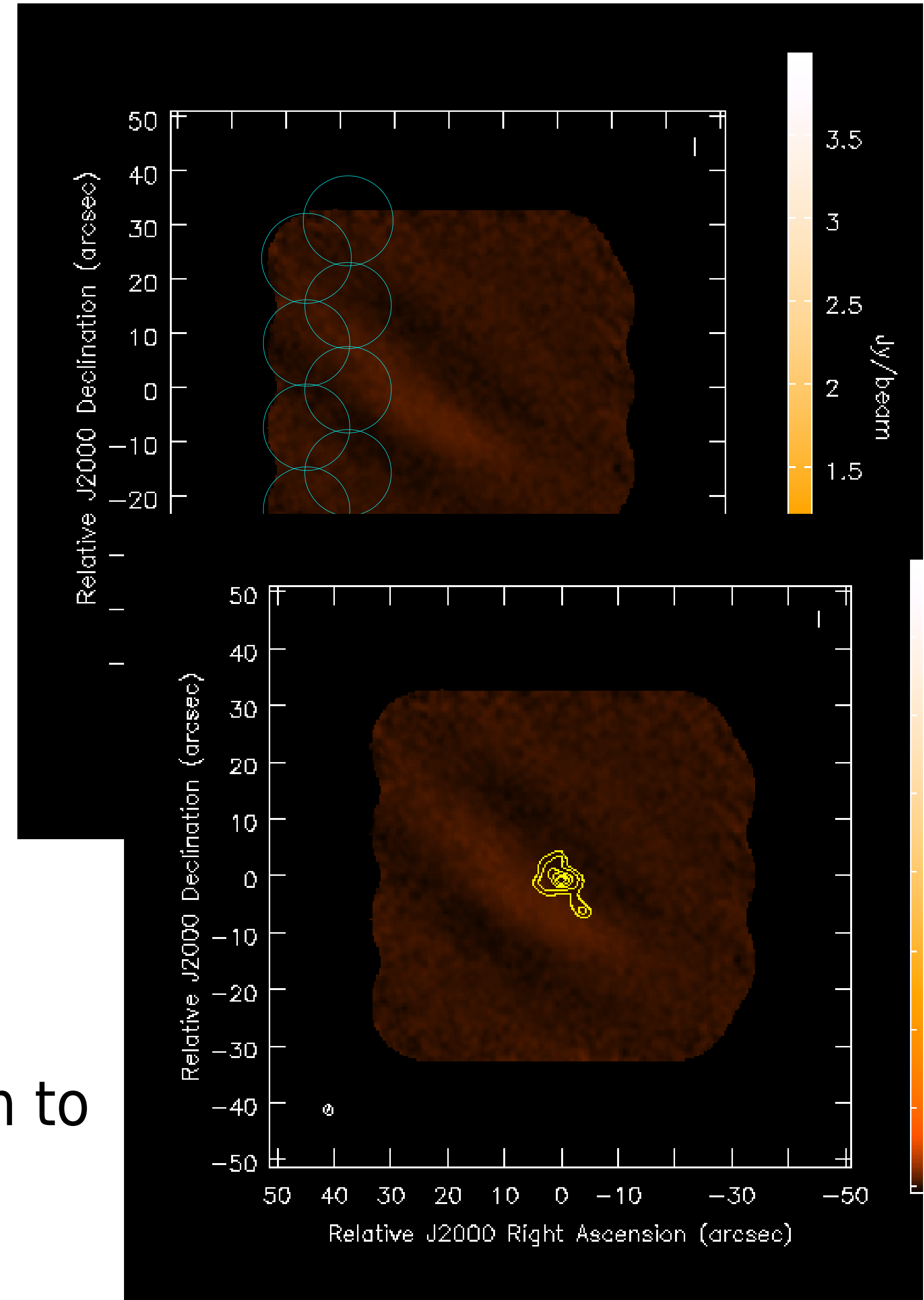
ALMA observations at 11 kpc

- Source original size 150''
  - ALMA mosaic
- Peak S_{JCMT} 100 Jy/pixel
- ALMA compact config
  - Synthesised beam θ_{bc} 1''
    - Expect peak 100 $(1/7.5)^2$ = 1.8 Jy/beam?
  - Largest angular scale 7.6''
    - ~Input pixel!
- Flux which is *smooth* on JCMT scales is ~invisible!
  - Standard ALMA simulation fails



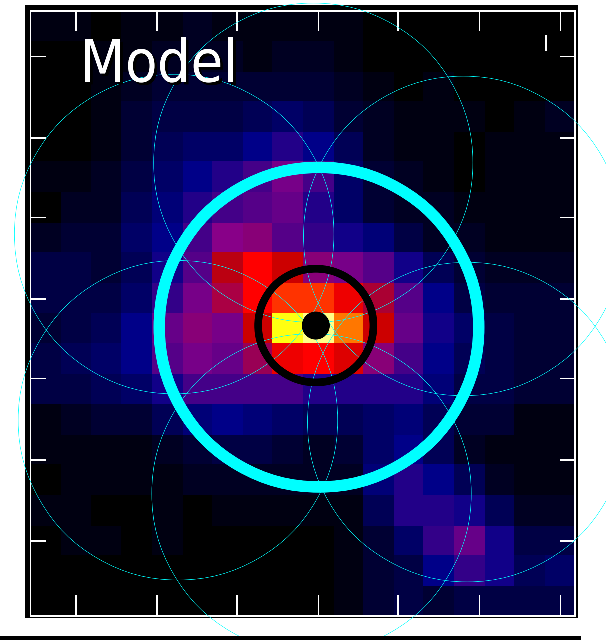
ALMA observations at 11 kpc

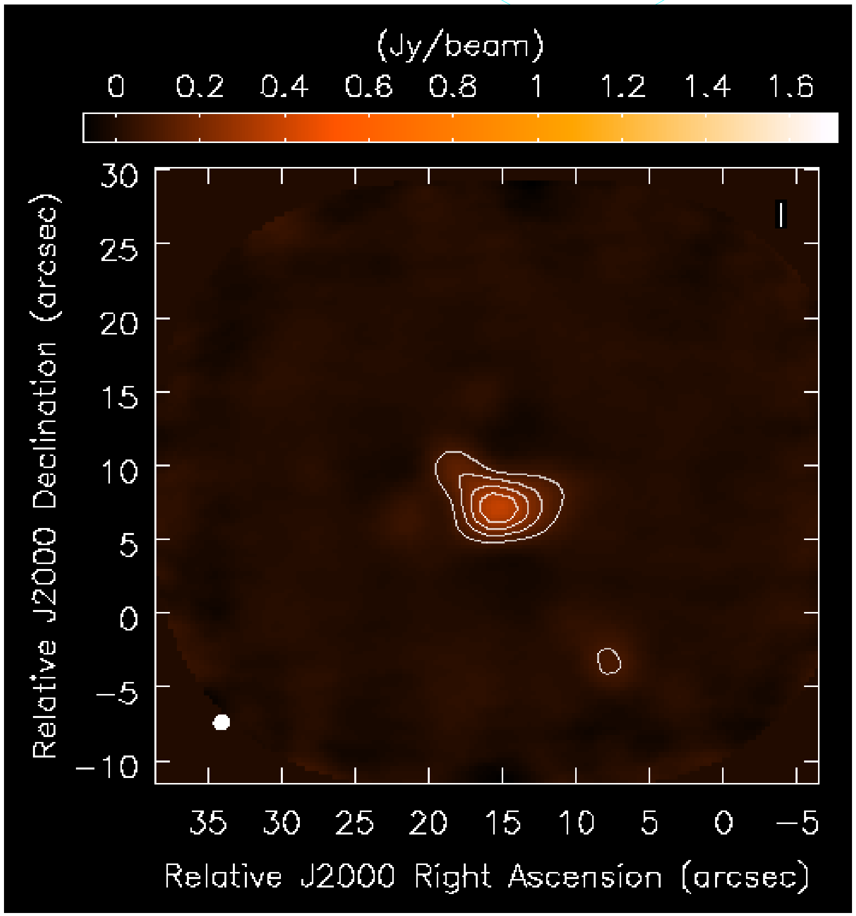
- Source original size 150''
  - ALMA mosaic
- Source original peak 100 Jy ALMA compact config
  - Synthesised beam θ_{bc}1''
    - Expect peak 100 $(1/7.5)^2$ = 1.7 Jy/beam?
  - Largest angular scale 7.6''
    - ~Input pixel!
- Flux which is *smooth* on JCMT scales is ~invisible!
- Small-scale details may appear
  - But only if you have added them to the model!



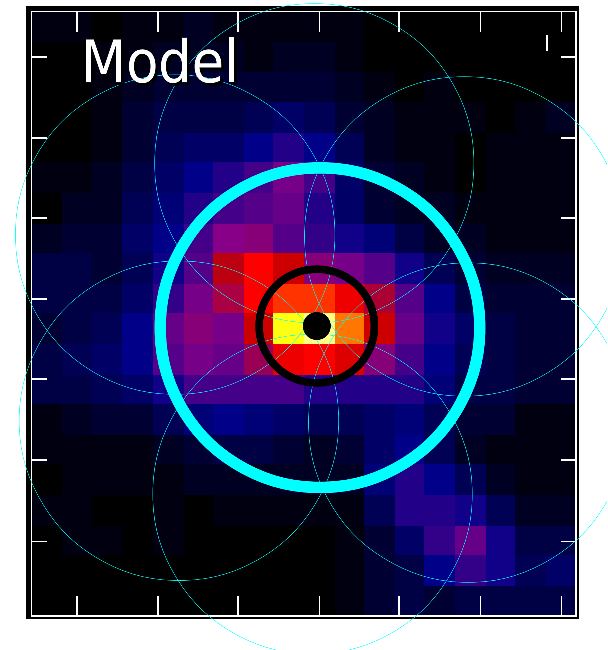
d=55 kpc

- JCMT field 30'', distance d = 55 kpc
  - Pixel p = 7''.5x 11/d = 1''.5
  - S_{JCMT} 100x(11/d)^2 = 4 Jy/pix
- ALMA compact θ_{bc} =1''
  - 7 mosaic pointings
  - S_{ALMA}=S_{JCMT} x (θ_{bc} /p)^2 ~1.8 Jy/bm?
    - Actual peak ~ 0.4 Jy/beam
    - Large scale flux still missing

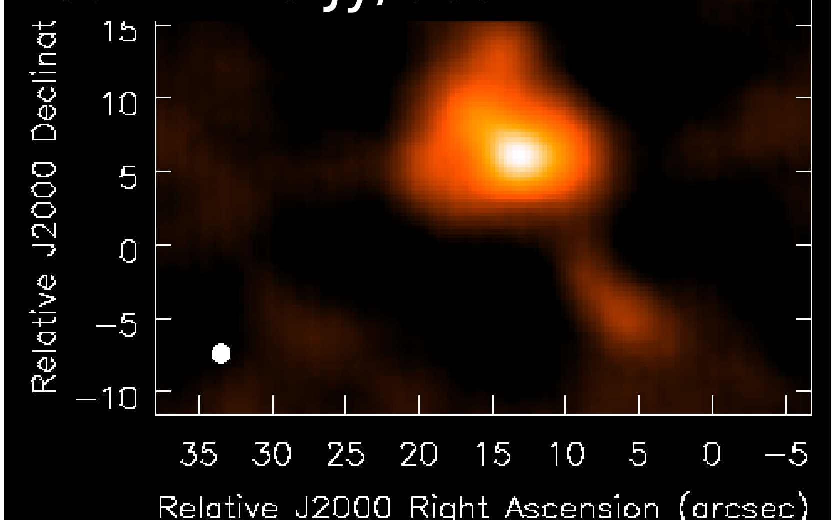


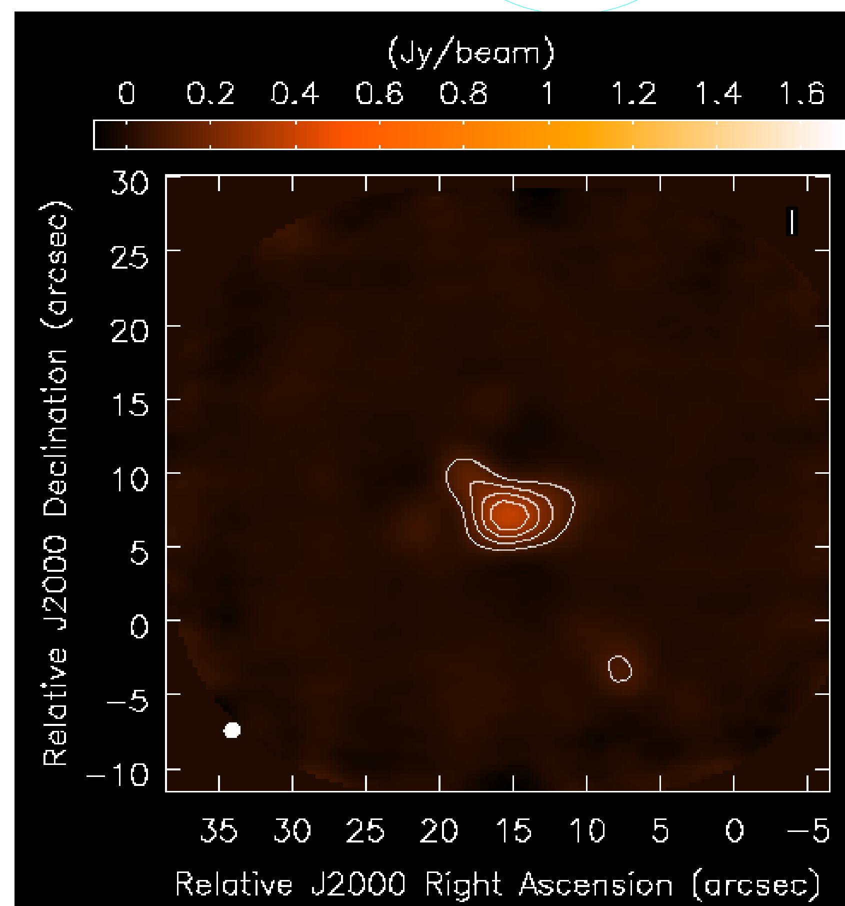


d=55 kpc

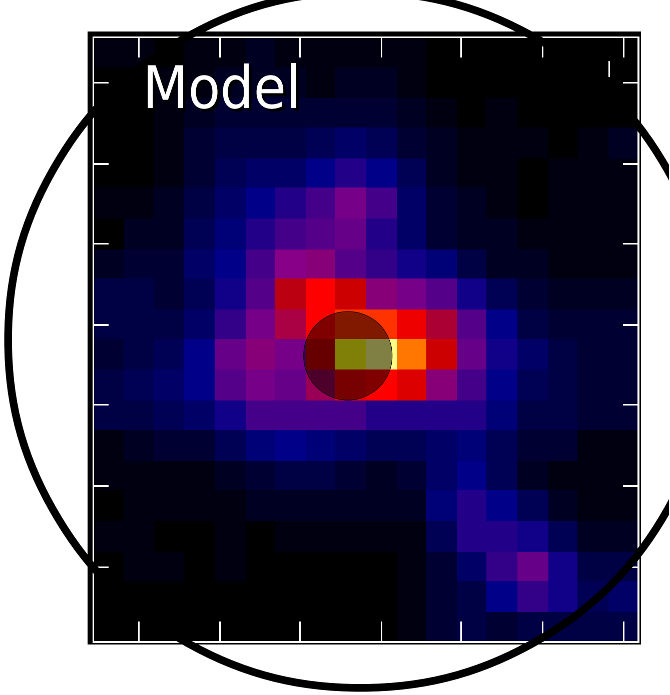


- JCMT field 30'', distance d = 55 kpc
  - Pixel p = 7''.5x 11/d = 1''.5
  - S_{JCMT} 100x$(11/d)^2$ = 4 Jy/pix
- ALMA compact θ_{bc} =1''
  - 7 mosaic pointings
  - S_{ALMA}=S_{JCMT} x $(\theta_{bc}/p)^2$ ~1.8 Jy/bm?
    - Combine with ACA θ_{bcA}= 1''.5
    - Peak ~1.8 Jy/beam

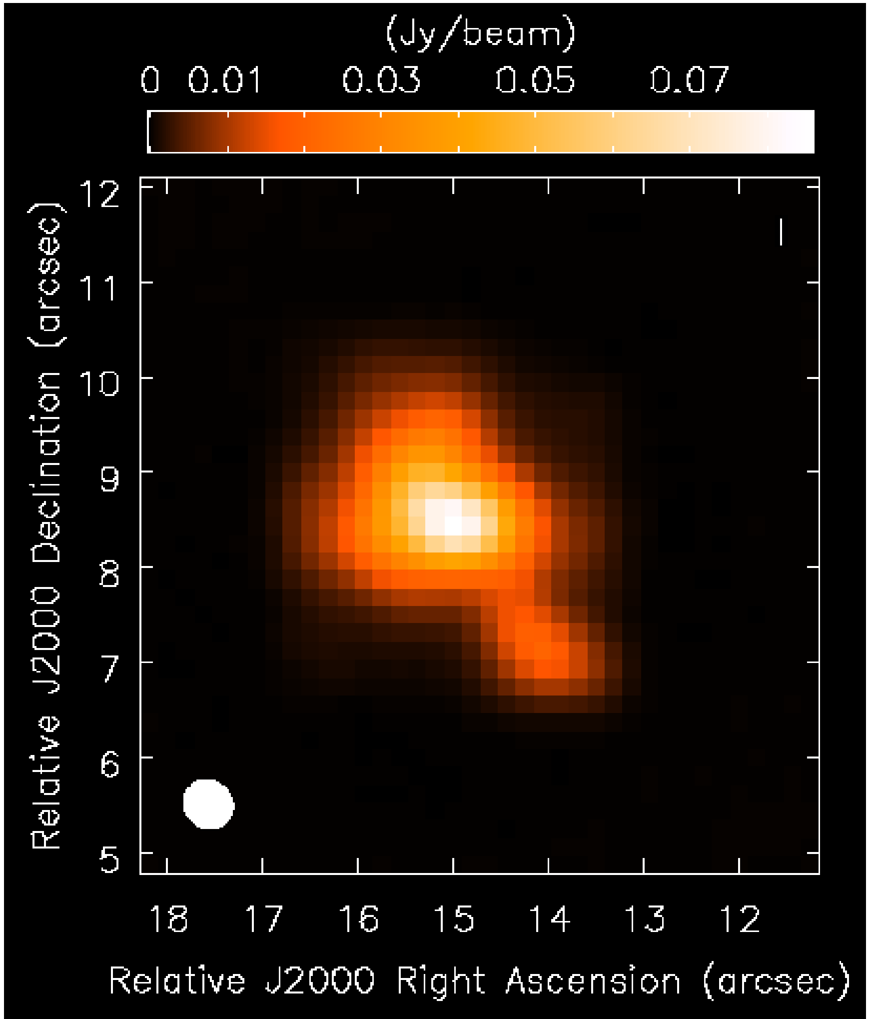




d=440 kpc



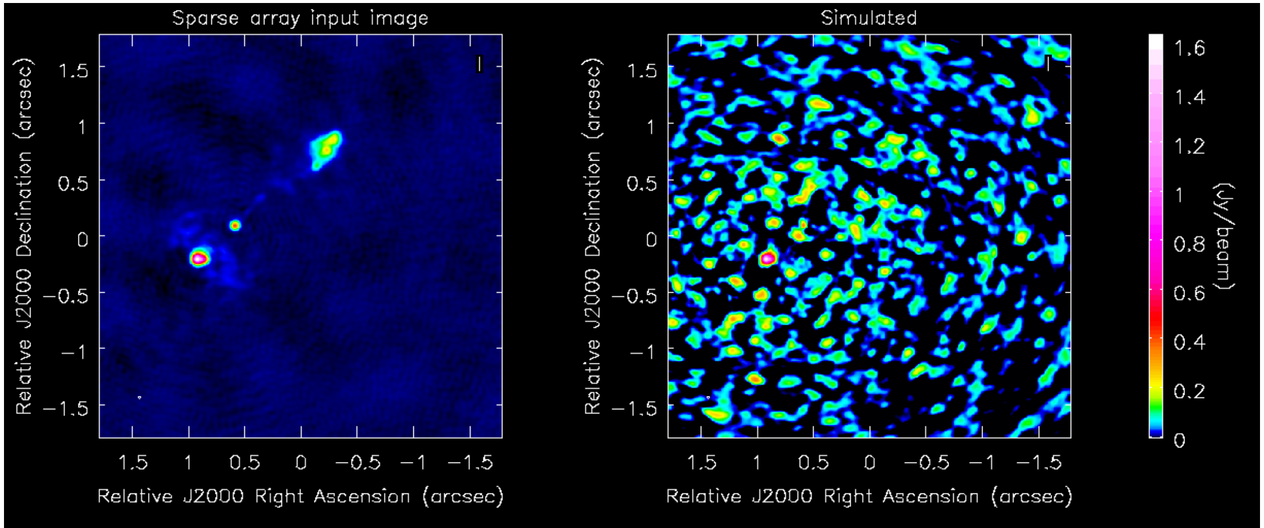
- JCMT field 30'', distance d = 440 kpc
  - Pixel p = 7''.5x 11/d = 0''.1875
  - $Stot_{\mathrm{JCMT}}$ ~ 2.2 Jy



- ALMA intermediate θ_{bi} =0.45''
  - Total model ~ largest angular size 5''.2
    - Well within field of view
- ALMA recovers all 2.2 Jy
- e.g. use Galactic single dish YSO model, for SFR in nearby galaxy seen with ALMA

Noise

- Input is noiseless model?
  - Select PWV appropriate for observing band
- Input has smooth noise σ_{in}?
  - e.g. well-calibrated single-dish/optical etc. image
  - Estimate likely ALMA noise σ_A (sensitivity calculator)
  - Reduce added noise so that $\sigma_{added}^2 + \sigma_{in}^2 \sim \sigma_A^2$
- Input is interferometry image?
  - Beware re-sampling a poorly-sampled image!



In conclusion...

- Decide what you want to observe – science goal!
  - What frequency (and channel width, for lines)?
  - What angular resolution?
  - Largest smooth angular scale within source
    - OT will advise if you need to combine arrays
  - Field of view – will you need a mosaic?
  - What flux density per ALMA synthesised beam?
    - Detection experiments $\geq 5\sigma_{rms}$ noise
      - Sensitivity calculator/OT – roughly reasonable time?
- Find an input FITS model
  - Image at another wavelength, theoretical model...
  - Rescale size, brightness as required
    - Details on similar scales as you hope ALMA will see
  - Read the OST Help and simulate!

What ALMA data do you get?

Always:

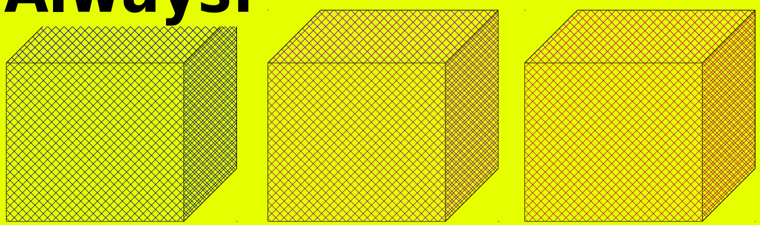
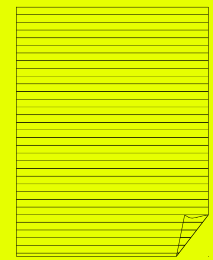


Image cubes for principal science target channels

Information and processing summary



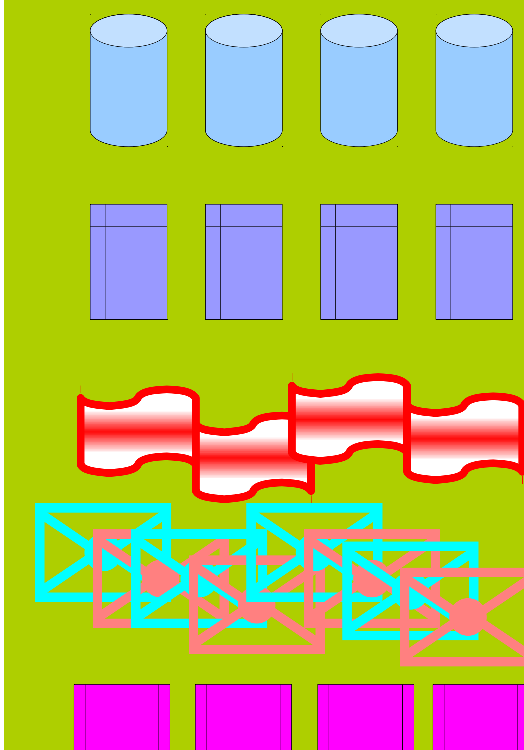
Data processing scripts

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 ASDM & FITS images available from Archive

+ any or all of:



ASDM (one per EB)

Part-calibrated MS

Flag tables

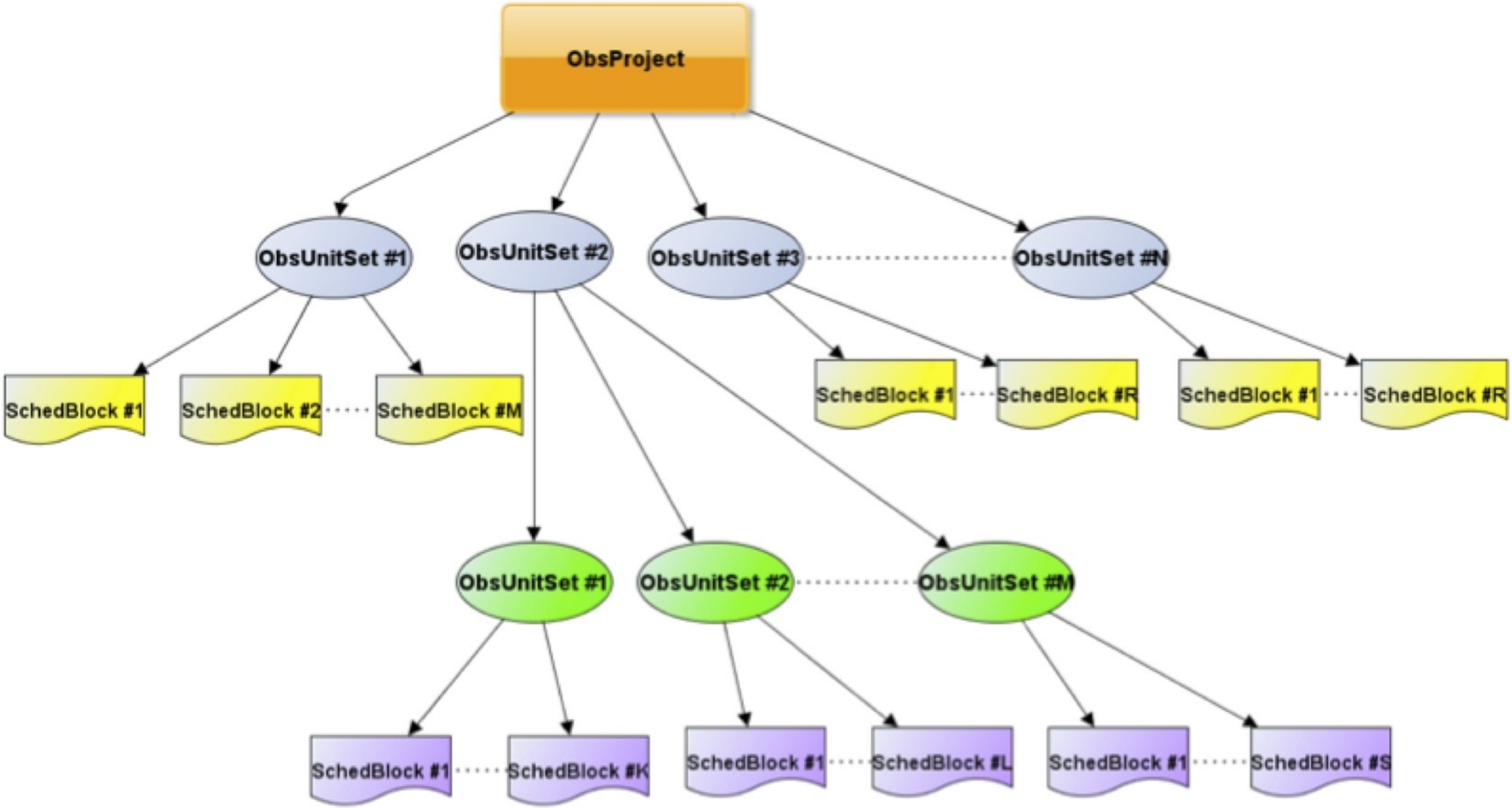
Calibration tables

Calibrated MS

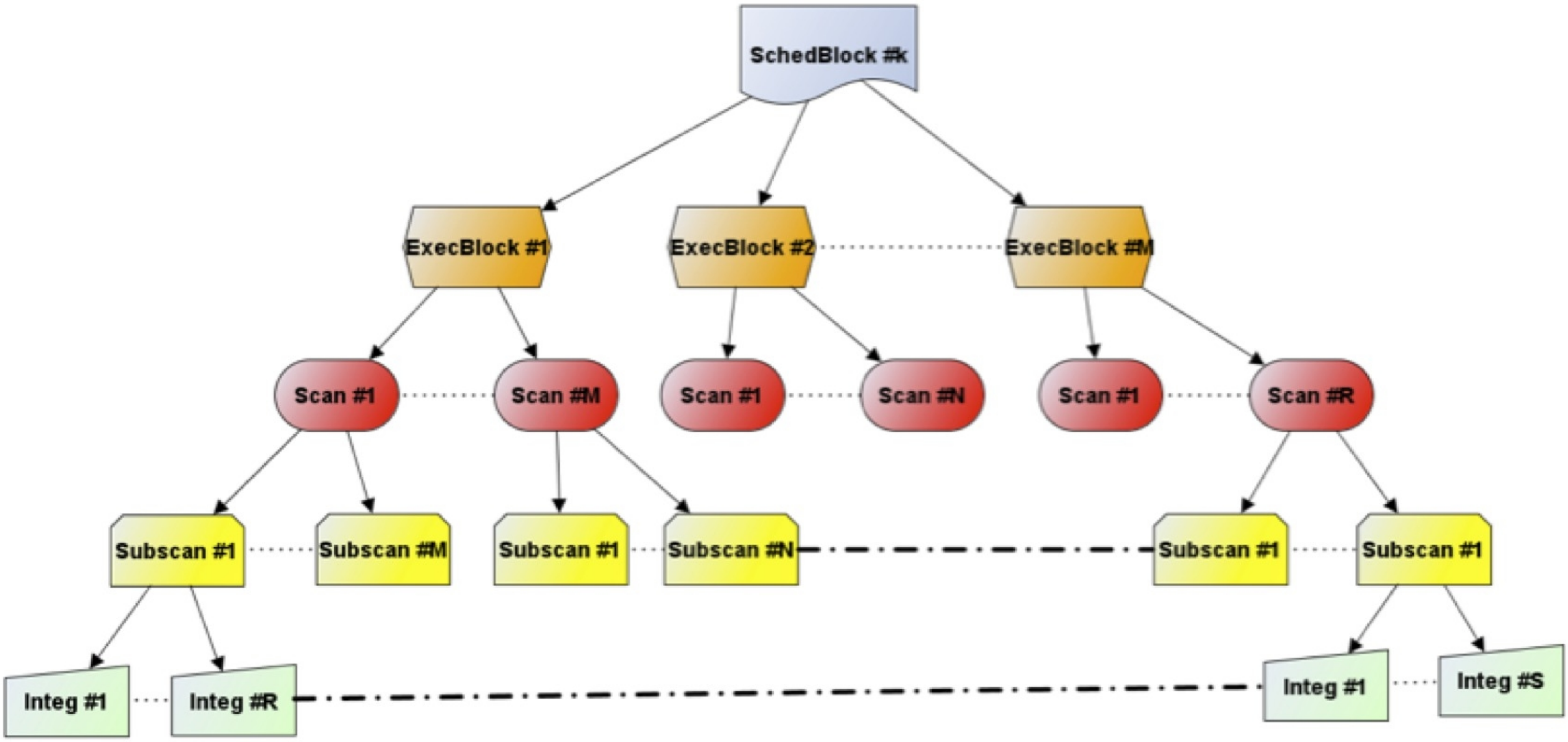
ALMA data conventions

- Scheduling Block: self-contained observation series
  - Short pointing, flux scale, bandpass, (pol.) cal scans
  - ~20-30 mins alternating between target(s)/ph ref(s)
    - Including multiple mosaic pointings
  - Repeat Execution until desired sensitivity is reached
    - All in same spectral and array configuration
    - Each EB produces one ASDM (ALMA Science Data Model) with binary data and lots of metadata
- Initial data processing (calibration, editing) per-EB
  - Convert ASDM to Measurement Set
- Combine EBs for final target imaging
- May also combine different SBs e.g. ACA+main

Data organisation for a project

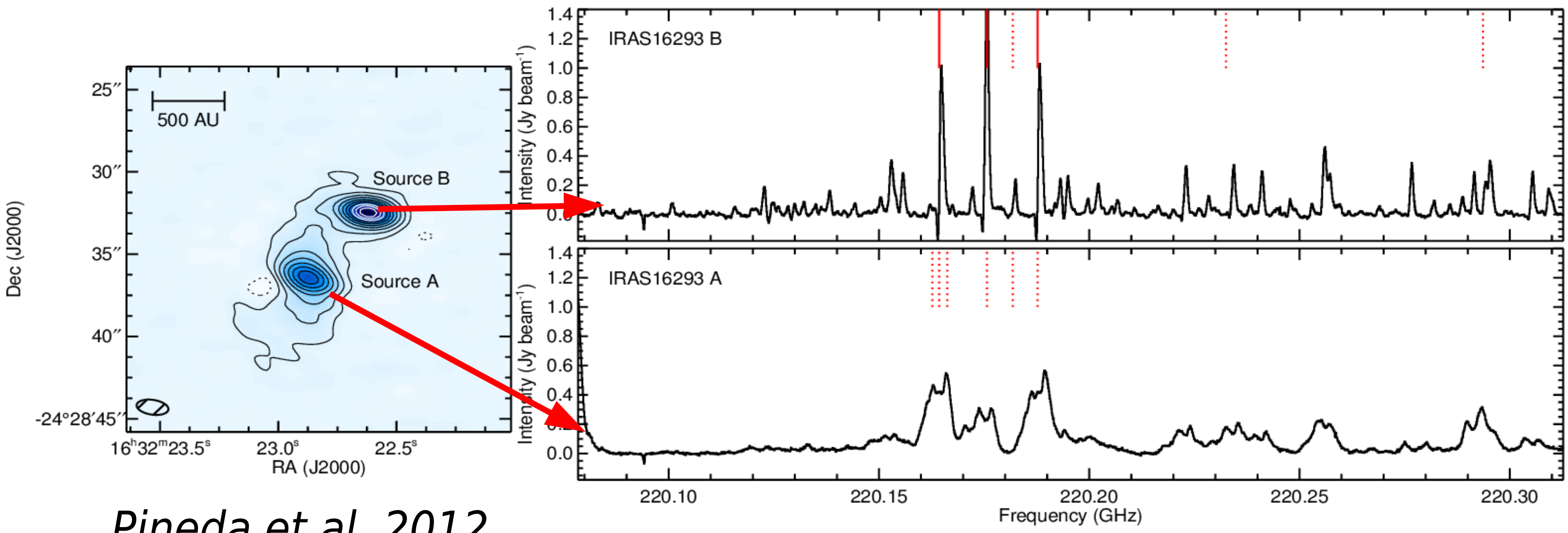


Individual scheduling block



Data reduction summary

- Initial steps common to most data sets
  - Standard procedures usually reliable
- Likely to want to self-calibrate
  - Re-make images at different resolutions etc.



Pineda et al. 2012