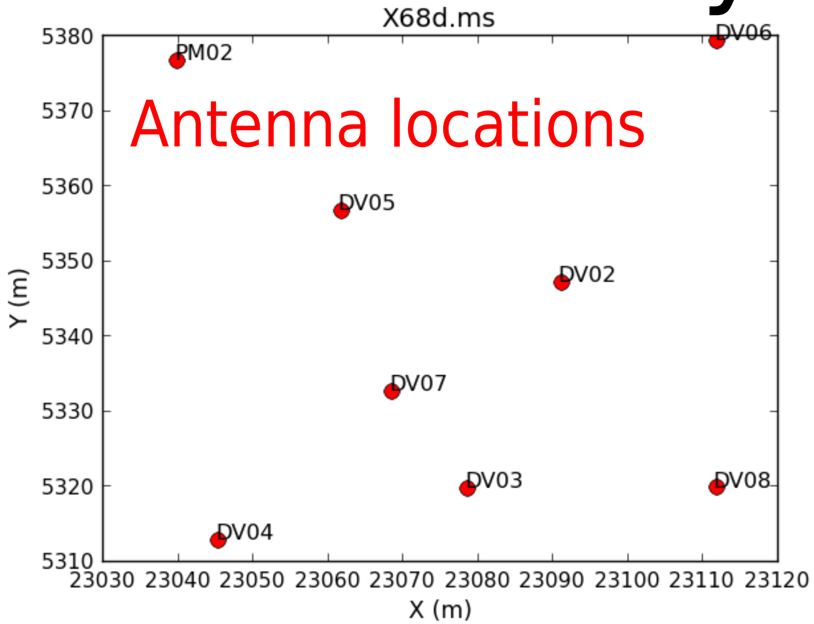
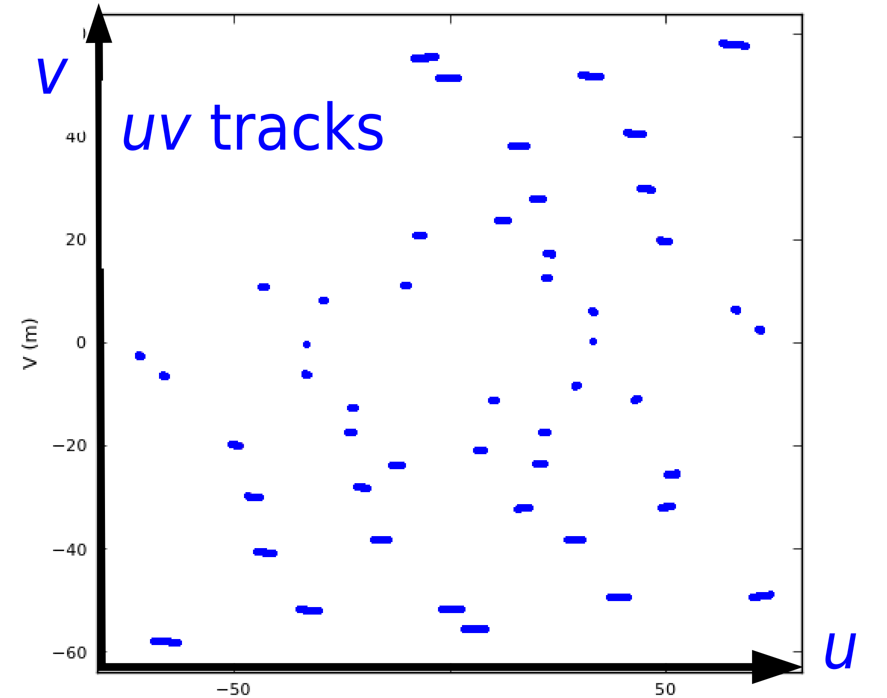
What is this radio interferometry business anyway?

- Basics of interferometry
- Calibration
- Imaging principles
- Detectability
- Using simulations

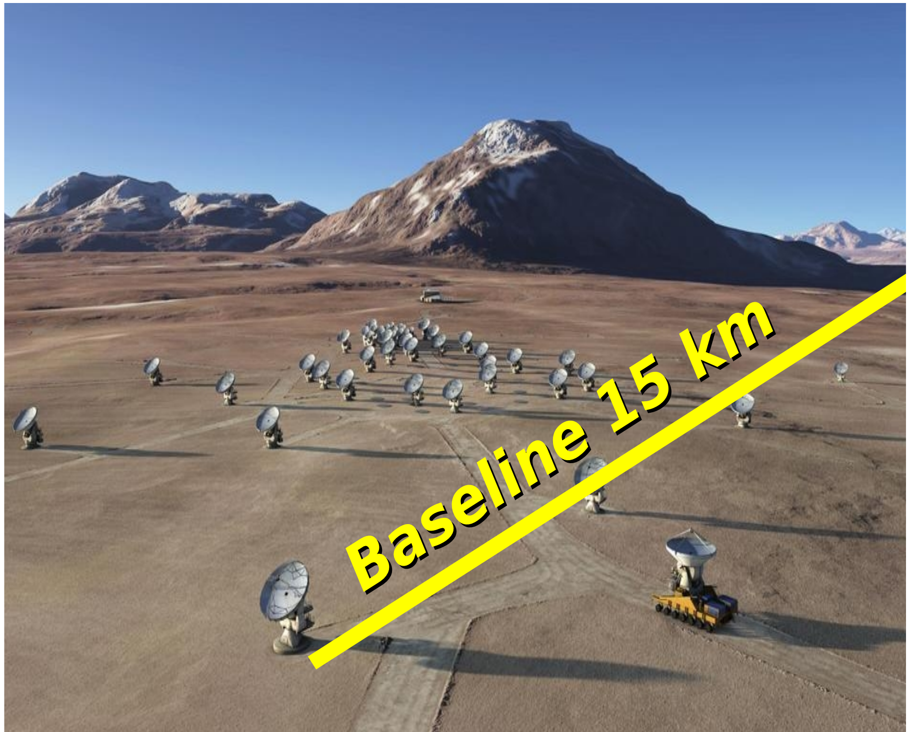
EUROPEAN ARC
ALMA Regional Centre || UK

Interferometry

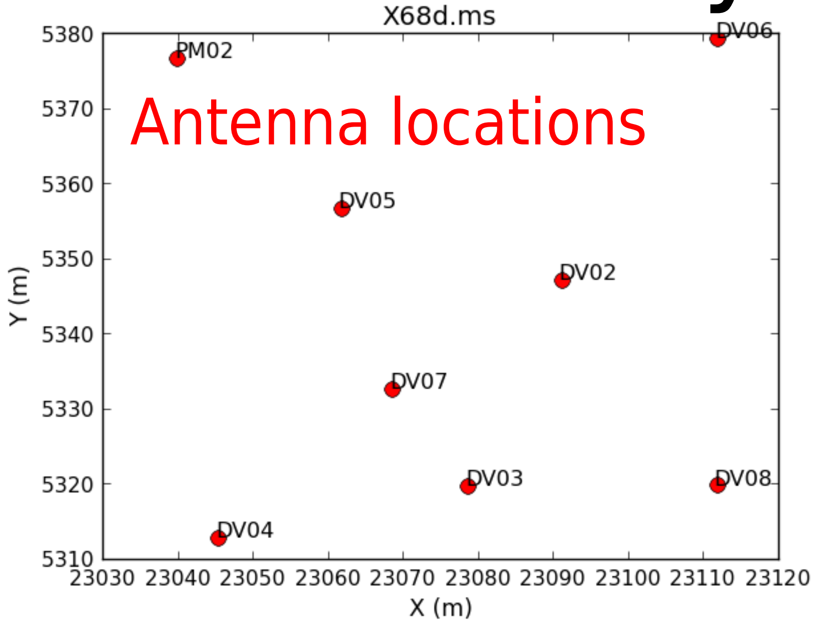


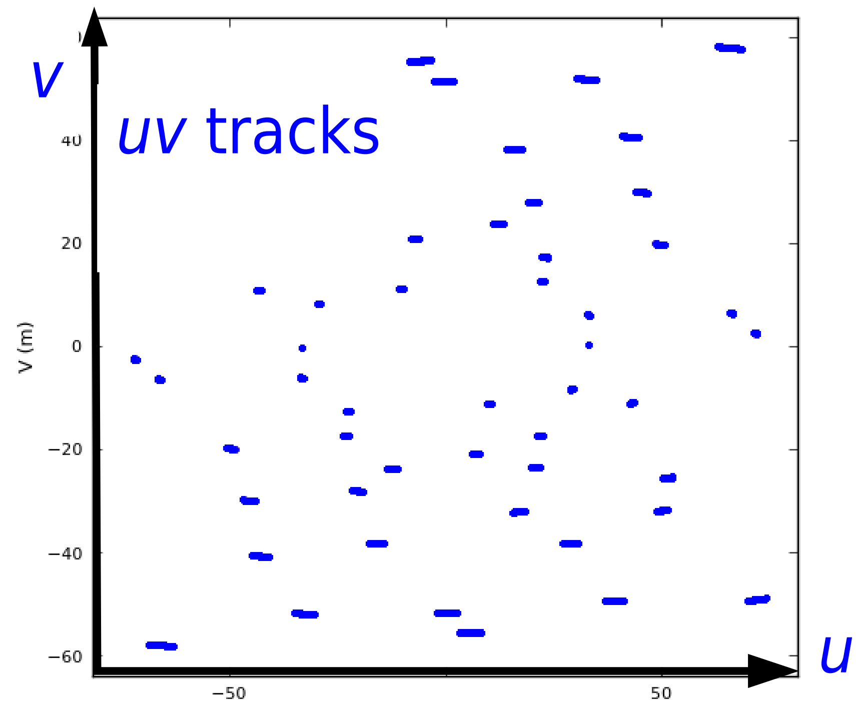


- Earth rotation aperture synthesis
- Vectors between pairs of baselines sweep out *uv* tracks
  - Record combined signals per sec
- Maximum resolution (synthesised beam) $\theta \sim \lambda / B_{max}$
  - *B* 15 km, λ 1 mm = $\theta \sim 14$ mas
- Field of view $\lambda / D_{antenna}$ ~20''
  - Equivalent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

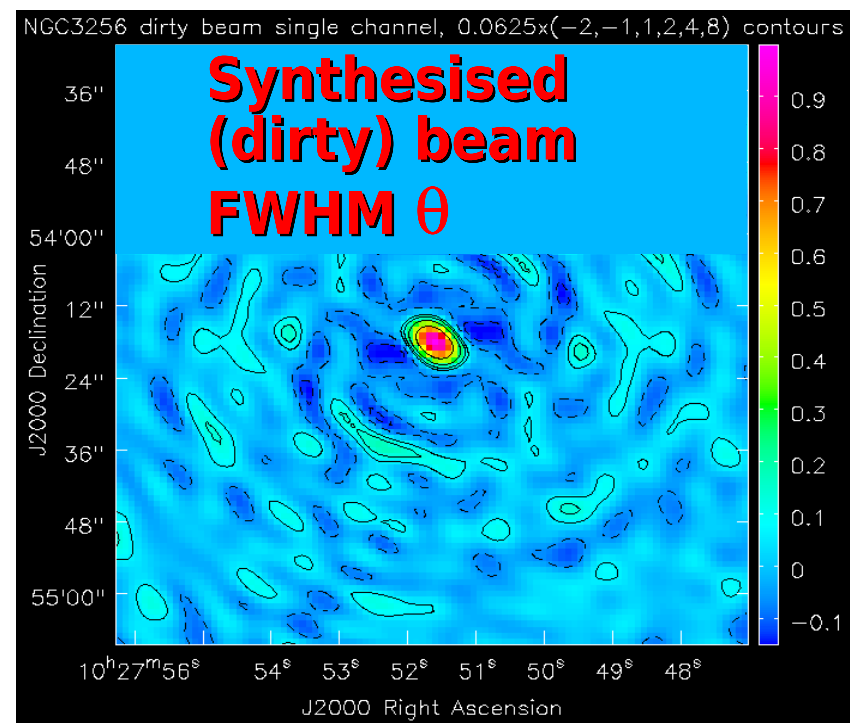


Interferometry

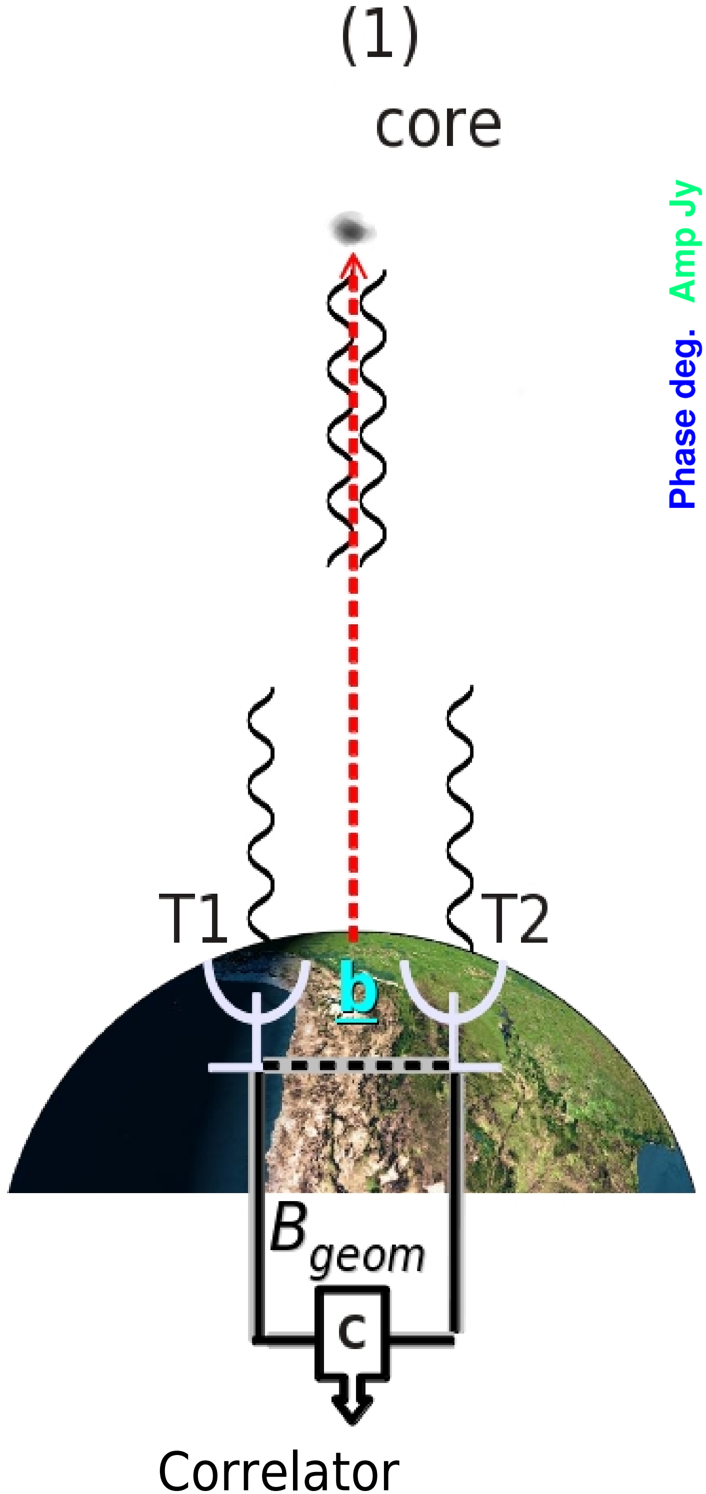


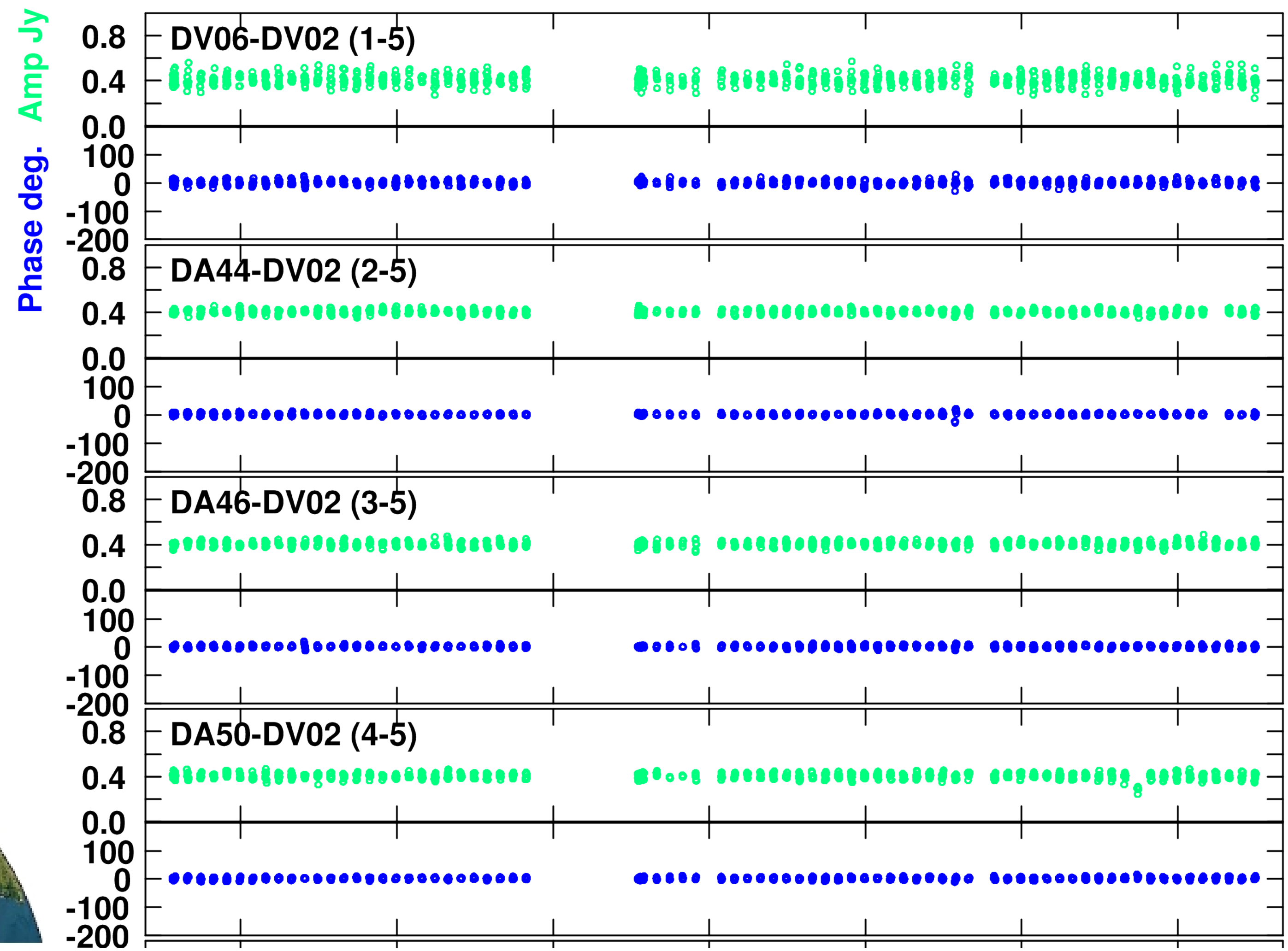


- Earth rotation aperture synthesis
  - Fourier transform ⇔ Dirty Beam
- Sensitivity helped as noise decorrelates *but*
  - Sparse coverage gives sidelobes
- Max. angular scale imageable
  - ~0.6 λ/B_{min} ~8'' (λ 1 mm)
    - no ACA, compact 12-m config

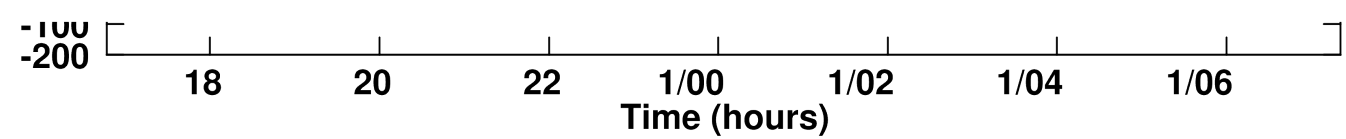


Point source overhead

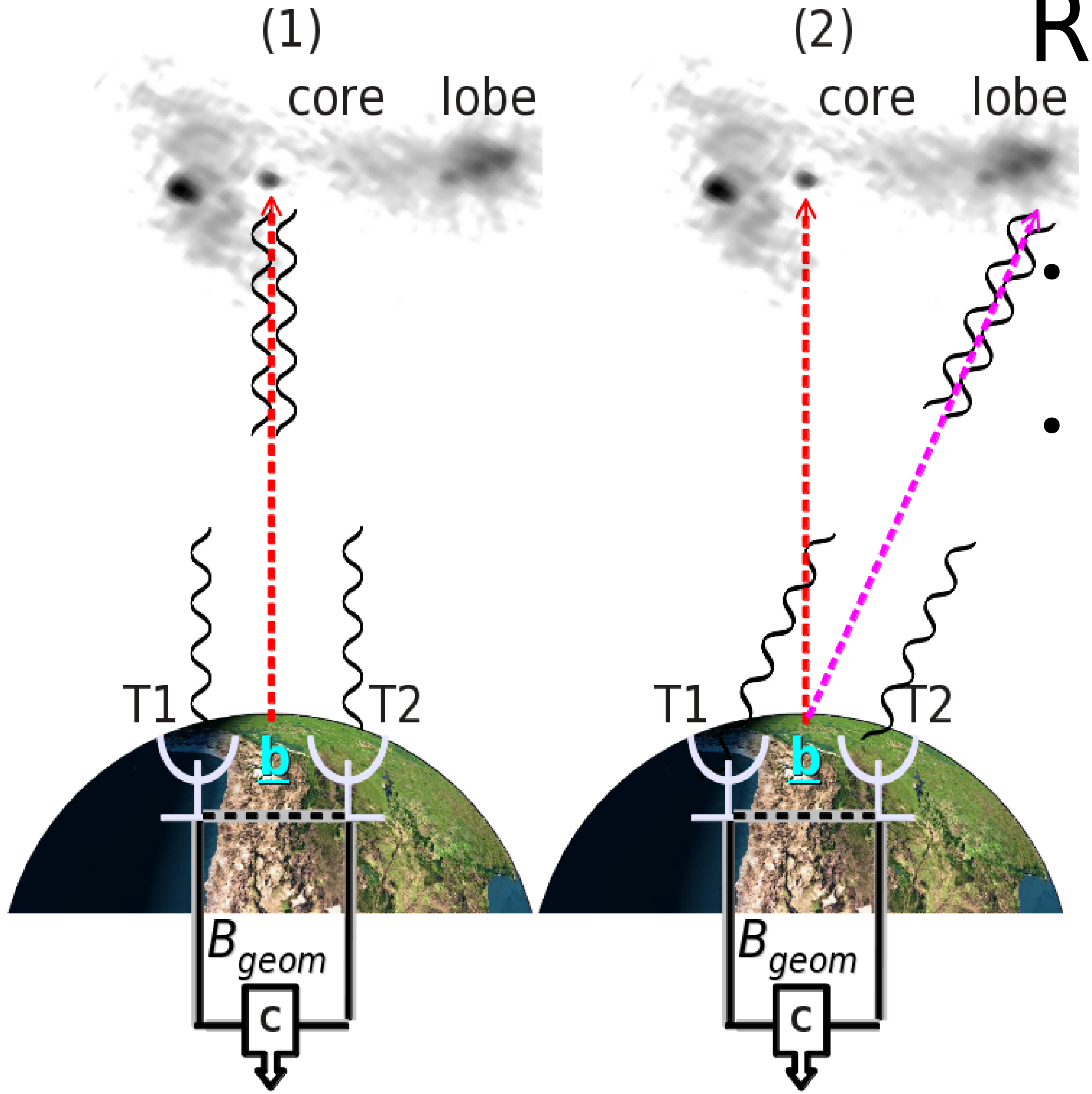




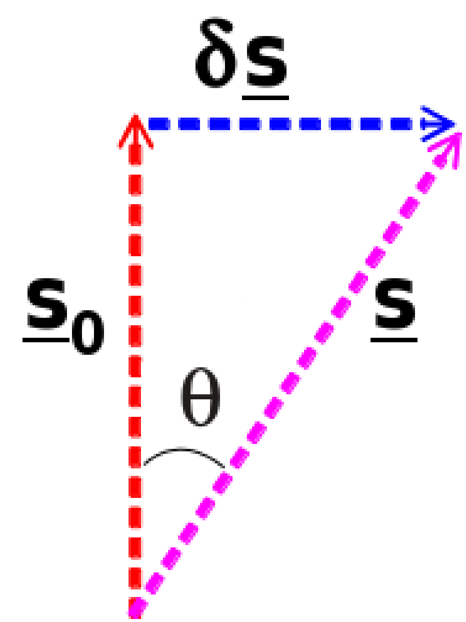
- Signals in phase, interfere constructively
  - Combined phase ϕ 0°, amp constant



Resolved source overhead

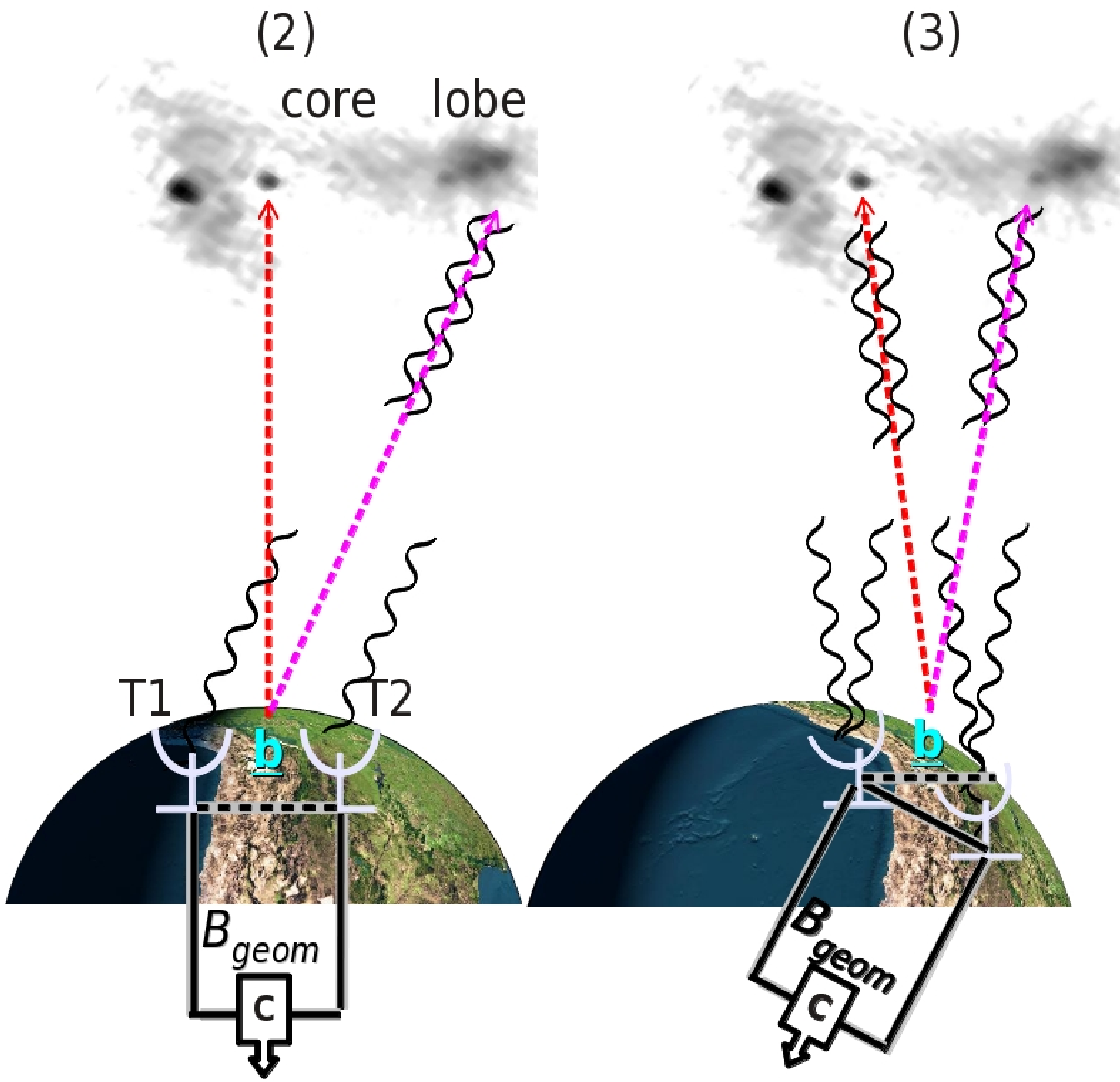


- Signals from overhead vector $\mathbf{s_0}$
- Signals from lobe
  - Angular offset vector $\delta\mathbf{s}$
  - Path length $\mathbf{s} = \delta\mathbf{s} \cdot \mathbf{s_0}$

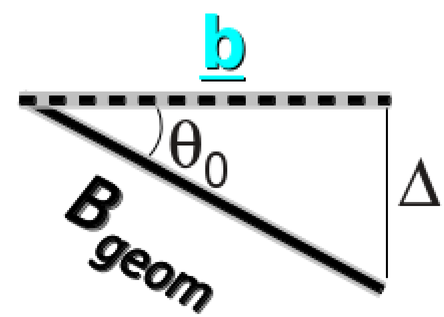


- Combined ϕ depends on $\delta\mathbf{s}$
- Complex visibility amplitude is sinusoidal function of ϕ

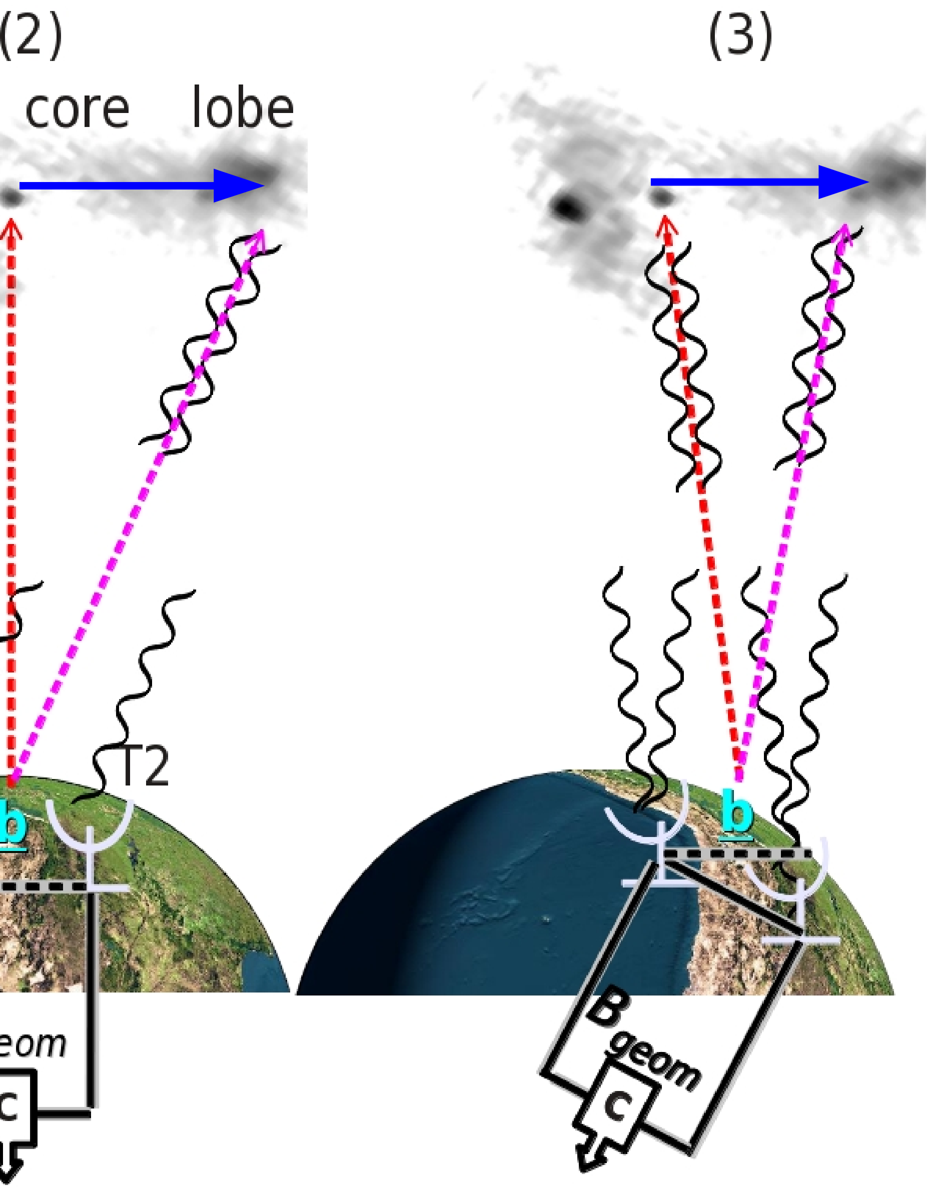
Earth rotation aperture synthesis

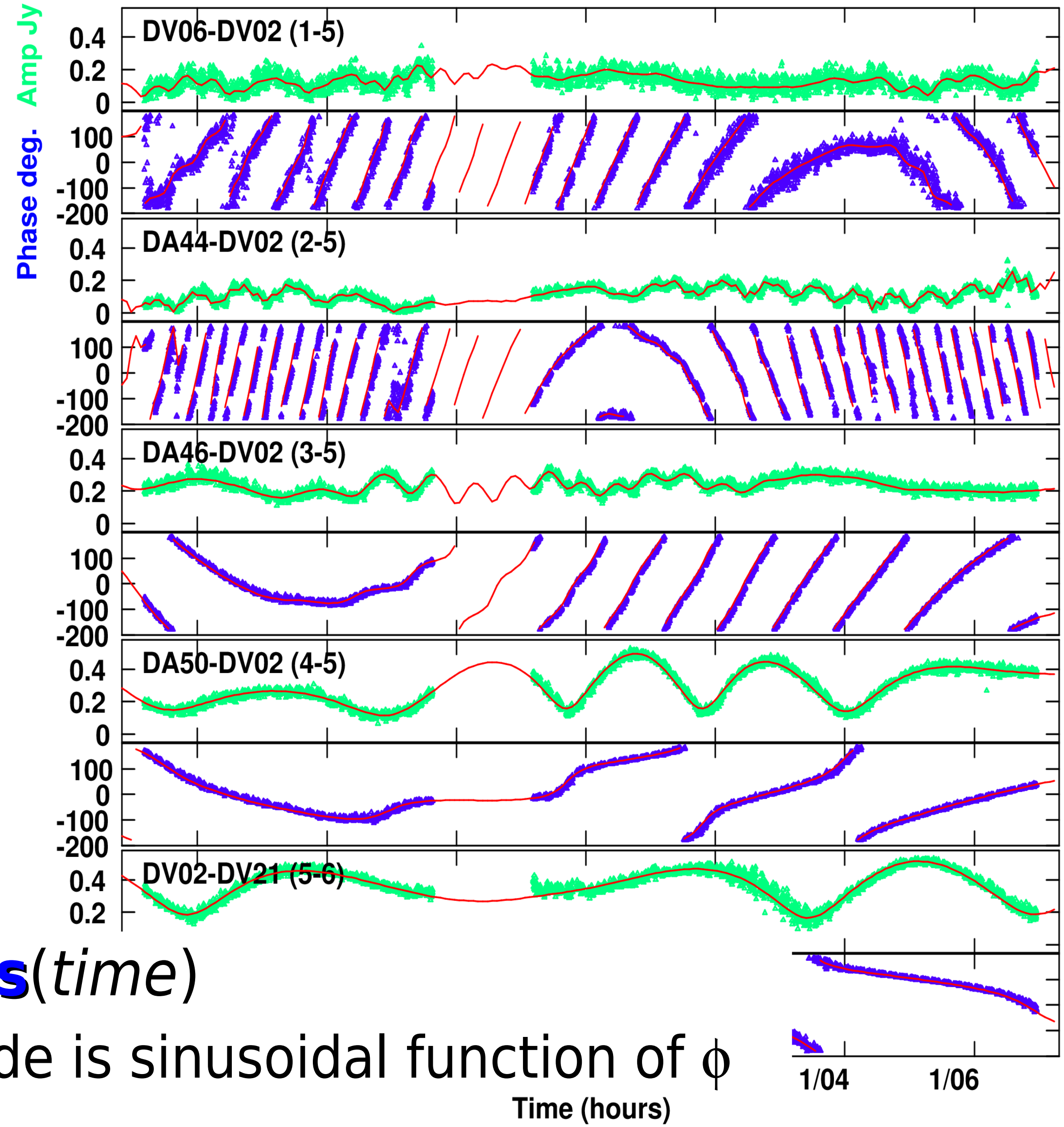


- Telescopes separated by baseline B_{geom}
- Earth rotates
  - Projected separation $b = B_{geom} \cos \theta_0$
- Samples different scales of source
- Additional geometric delay path Δ
  - Remove in correlator



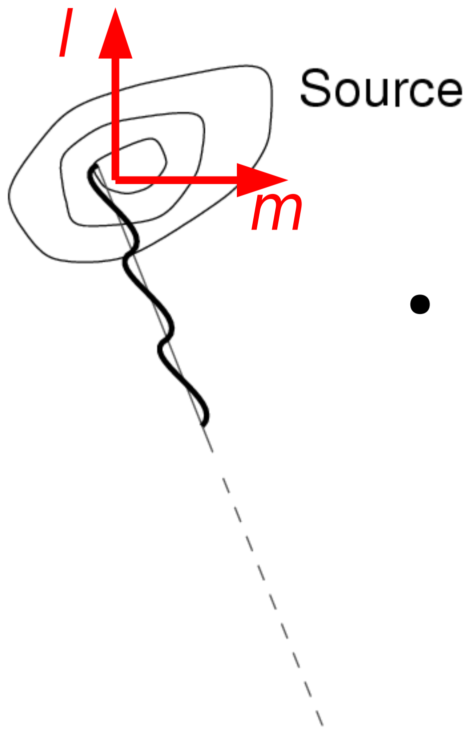
Earth rotation aperture synthesis



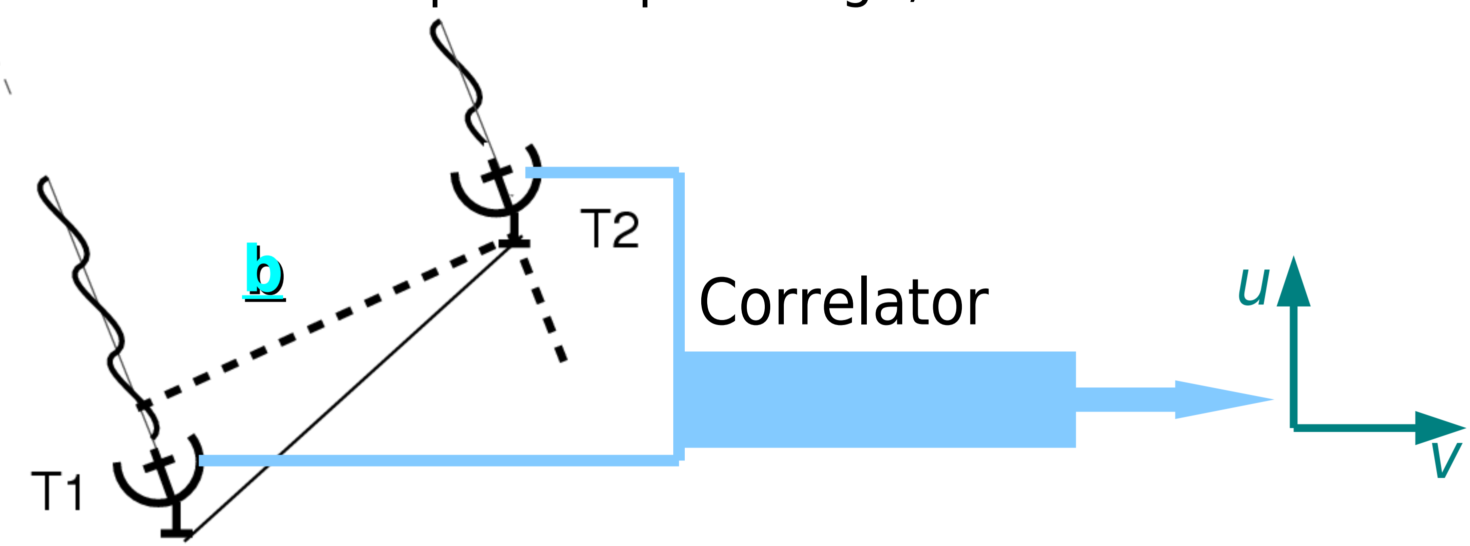


- Combined φ depends on δ**s**(*time*)
- Complex visibility amplitude is sinusoidal function of φ

From interferometry to images

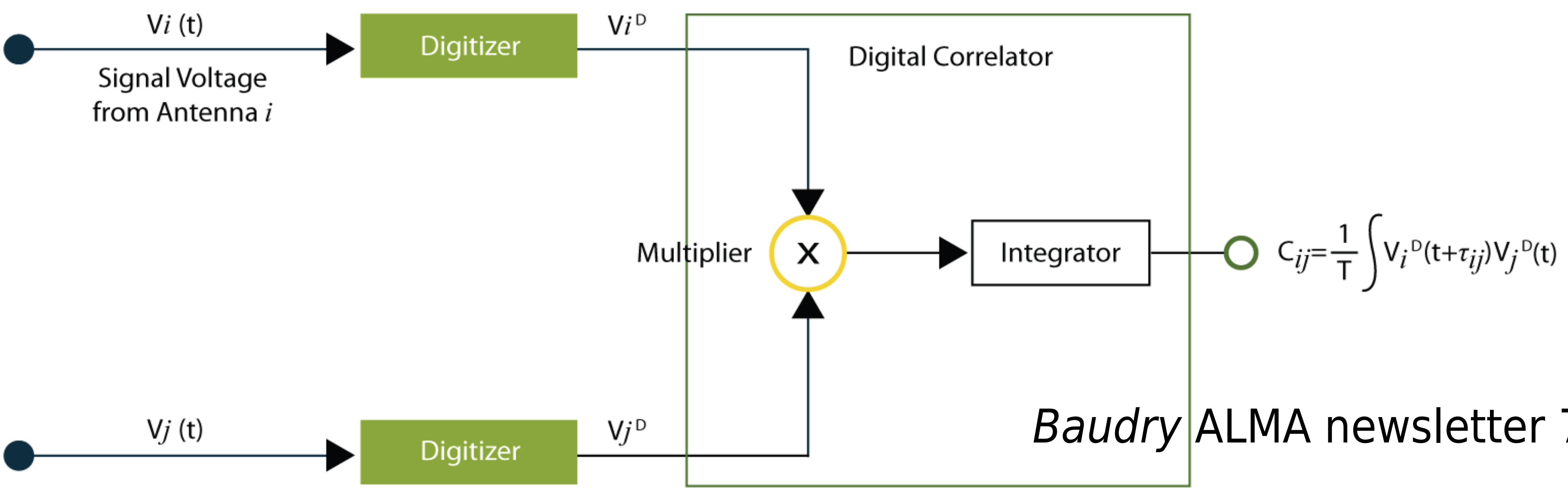


- Fourier transform of complex visibility amplitude and phase gives sky brightness
  $$\sum V_\nu(u_\nu, v_\nu)\, e^{[2\pi i(u\nu l + v\nu m)]}\, du dv = I_\nu(l,m)$$
  – or $V(u,v) \Leftrightarrow I_\nu(l,m)$ for short
- Sensitivity:
  $$\sigma_{rms} \propto \frac{T_{sys}}{\sqrt{N(N-1)/2 \;\; \delta\nu \;\; \Delta t}}$$
  – Number antennas (ALMA's huge collecting area!)
  – $d\nu$ freq. width per image, Δt total time on source



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

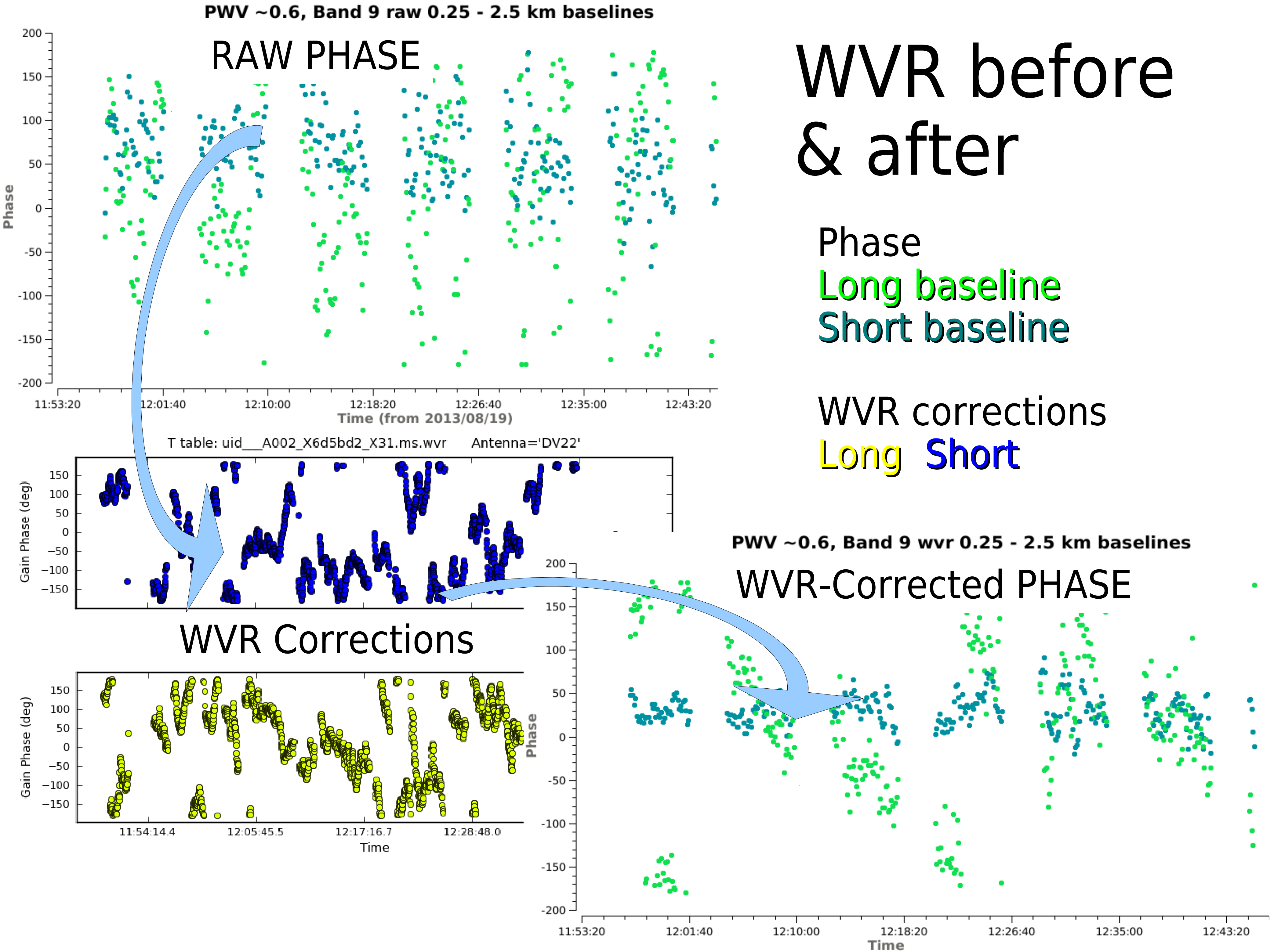
ALMA instrumental calibration

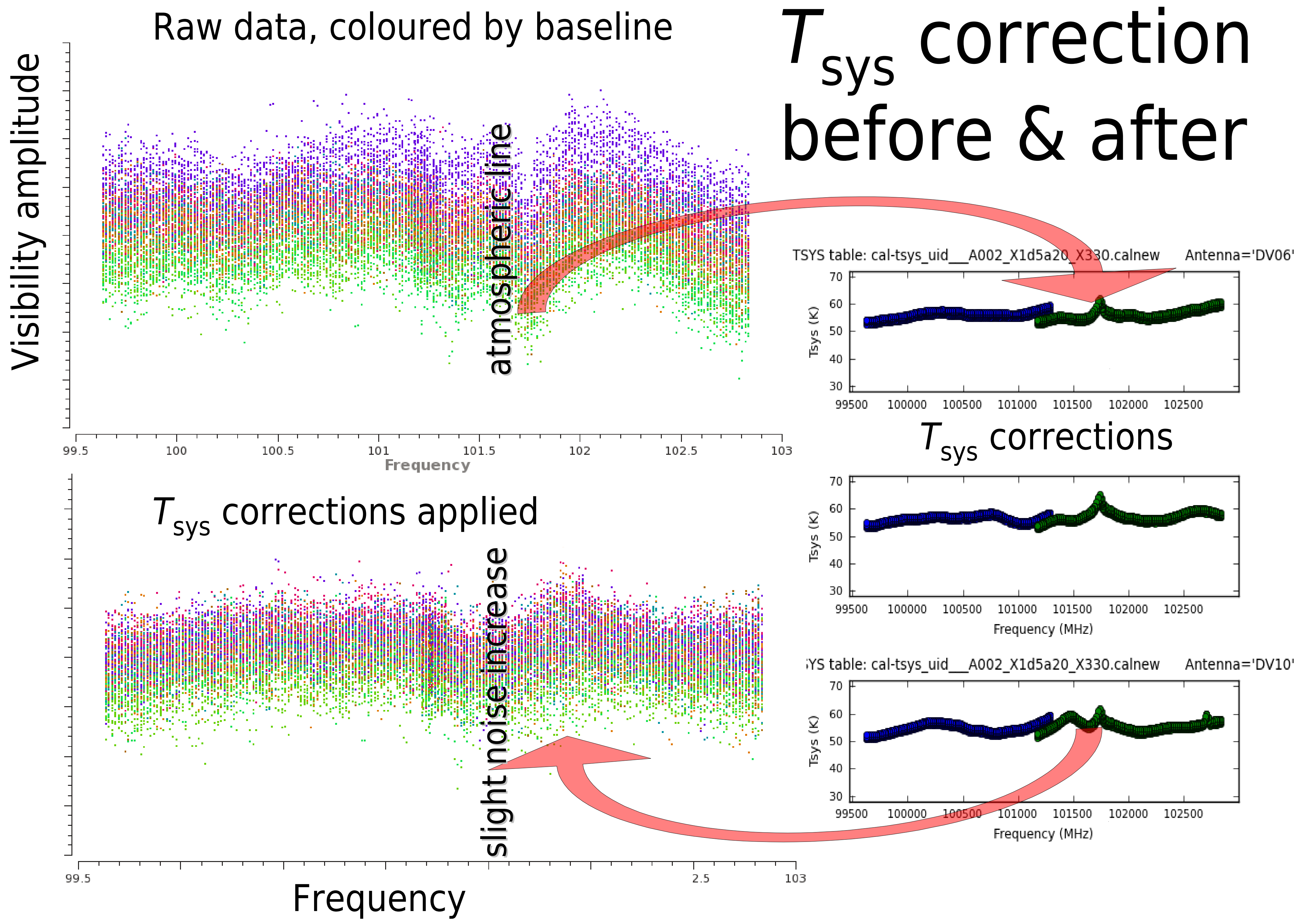
- Pointing corrections before correlation
- Water vapour in the troposphere
  - Refraction: delay to phase of incoming wavefronts
    - Water Vapour Radiometry (WVR)
    - Measure 183-GHz atmospheric line
      - Derive path length corrections at observing ν every second
  - Amplitude absorption amd 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

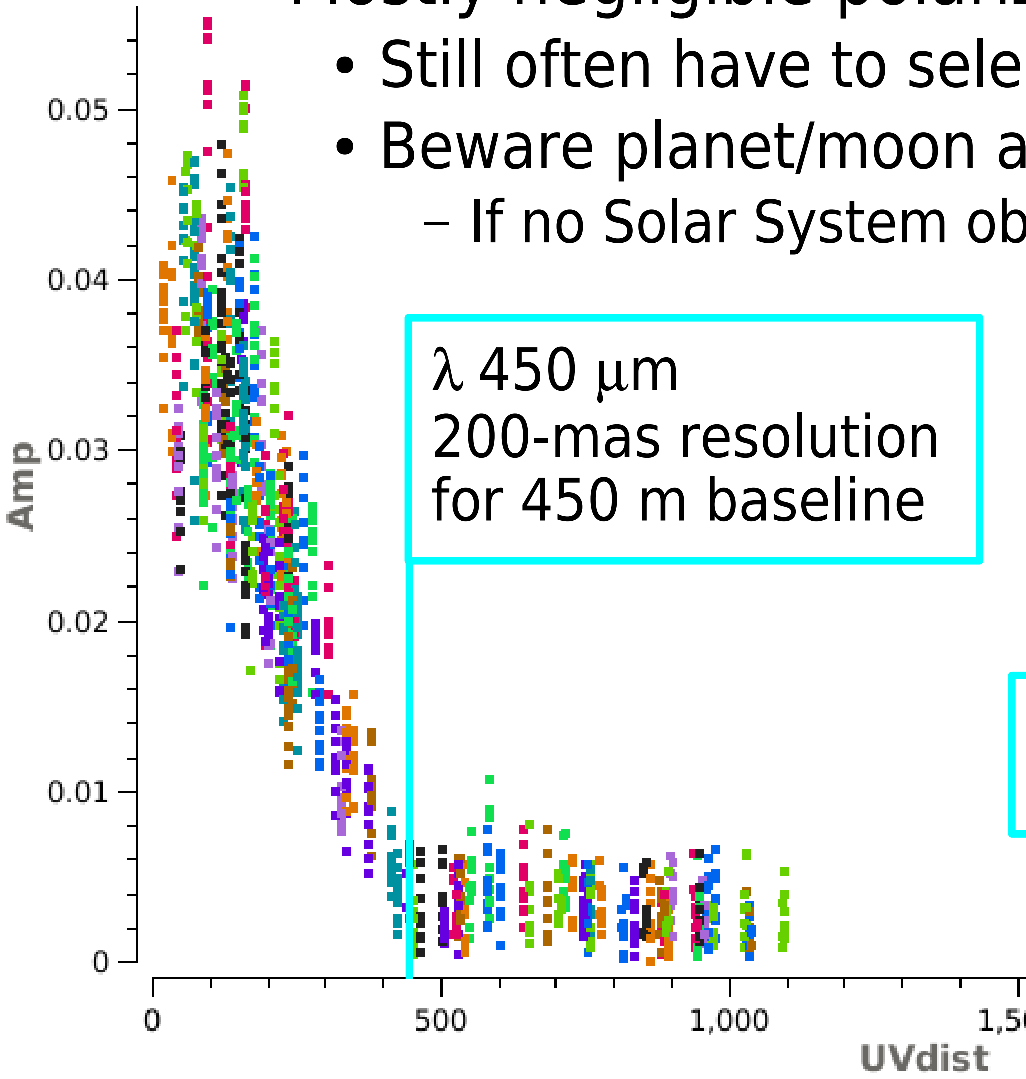




T_{sys} correction before & after
Raw data, coloured by baseline
Visibility amplitude
atmospheric line
99.5
100
100.5
101
101.5
102
102.5
103
Frequency
T_{sys} corrections applied
slight noise increase
99.5
2.5
103
Frequency
TSYS table: cal-tsys_uid___A002_X1d5a20_X330.calnew Antenna='DV06'
Tsys (K)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

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



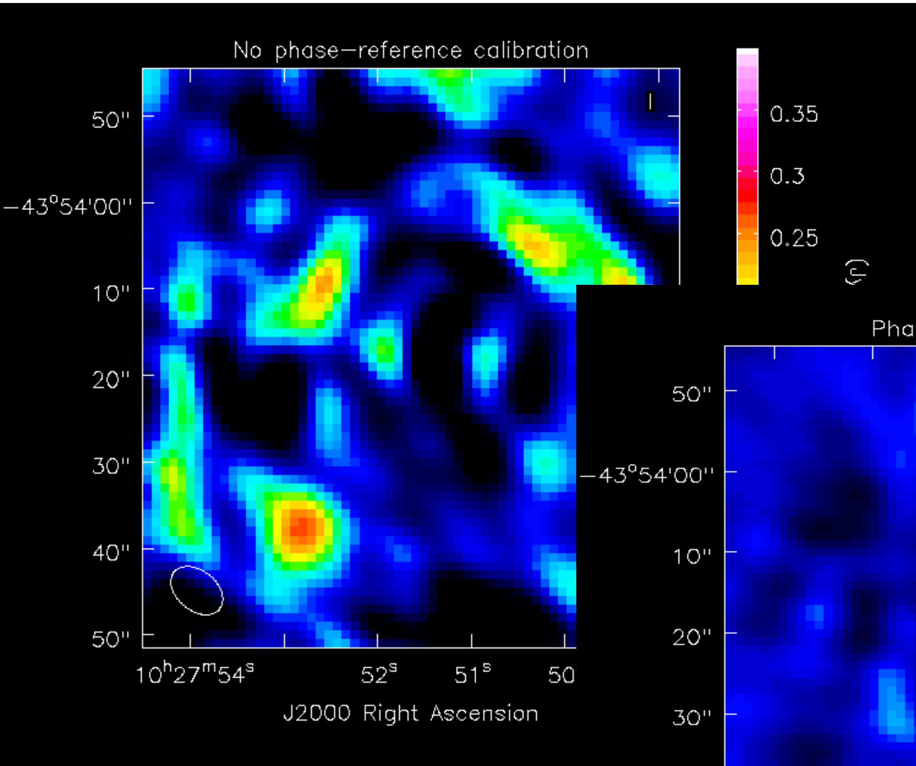
λ 450 μm
200-mas resolution
for 450 m baseline

Pallas ~ 2 AU from Earth
Angular diameter ~200 mas

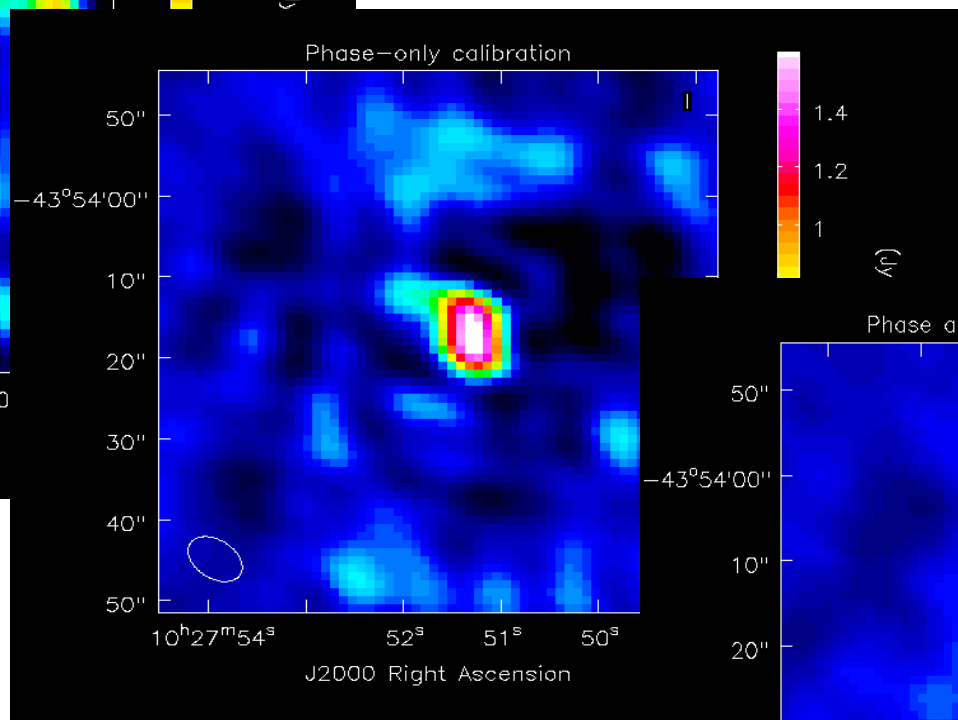
Phase referencing

- Observe phase-ref source close to target
  - Point-like or with a good model
  - Close enough to see same atmosphere
    - d_{sky} few - 15º (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 ϕ & amp correct-ions to make phase-ref data match model
  - Apply same corrections to target
- Accuracy limited by phase-ref S/N, d_{sky}
  - Best target astrometric position
  - Image may be dynamic-range limited

Improvements in imaging

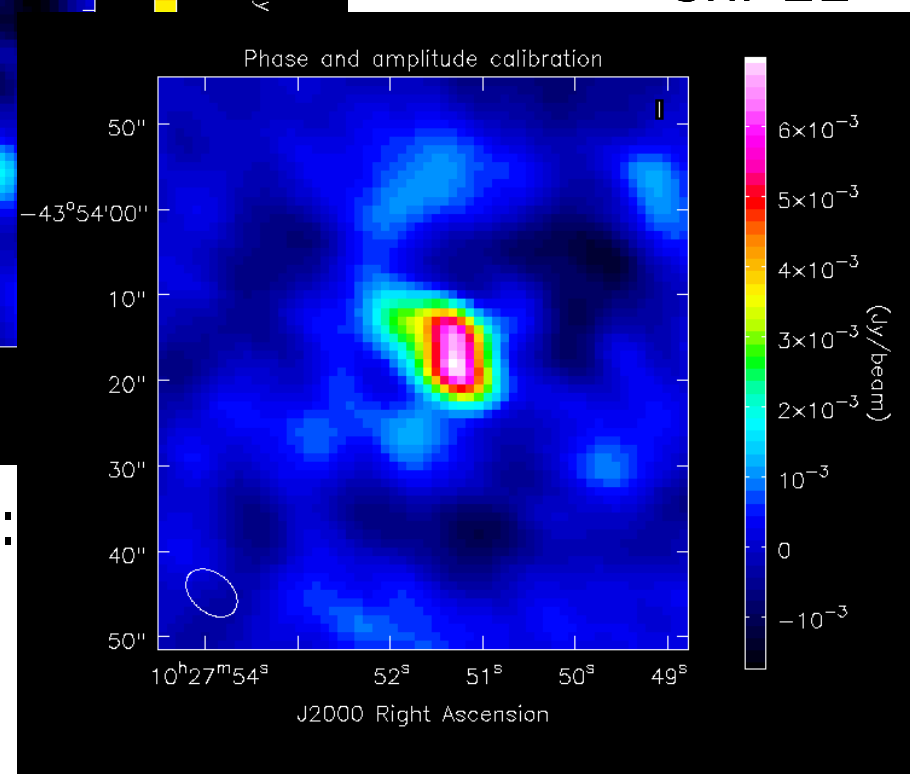


No astrophysical calibration:
no source seen



Phase-only solutions:
source seen, snr 15

Amplitude and
phase solutions:
source seen,
snr 22



Self-calibration

- Apply instrumental, bandpass & phase ref calibration
- Make initial image(s)
  - Does a line peak or continuum have good S/N ratio?
    - S/N(ant) $\sigma_{\text{ant}}/S_{\text{peak}} > 5$ per calibration interval per antenna

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

    - σ_{array} off-source noise in image using $\delta\nu$ freq width
    - per time interval δt, usually ~10 min scan or less
      - **Worth trying self-cal if image S/N >20, noise >predicted**
  - Use model in MS (FT of clean components)
    - Start phase calibration only, then amp if S/N(ant) >> 10
      - Iteratively improve model and calibration
    - Can apply from line to continuum or v.v.

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

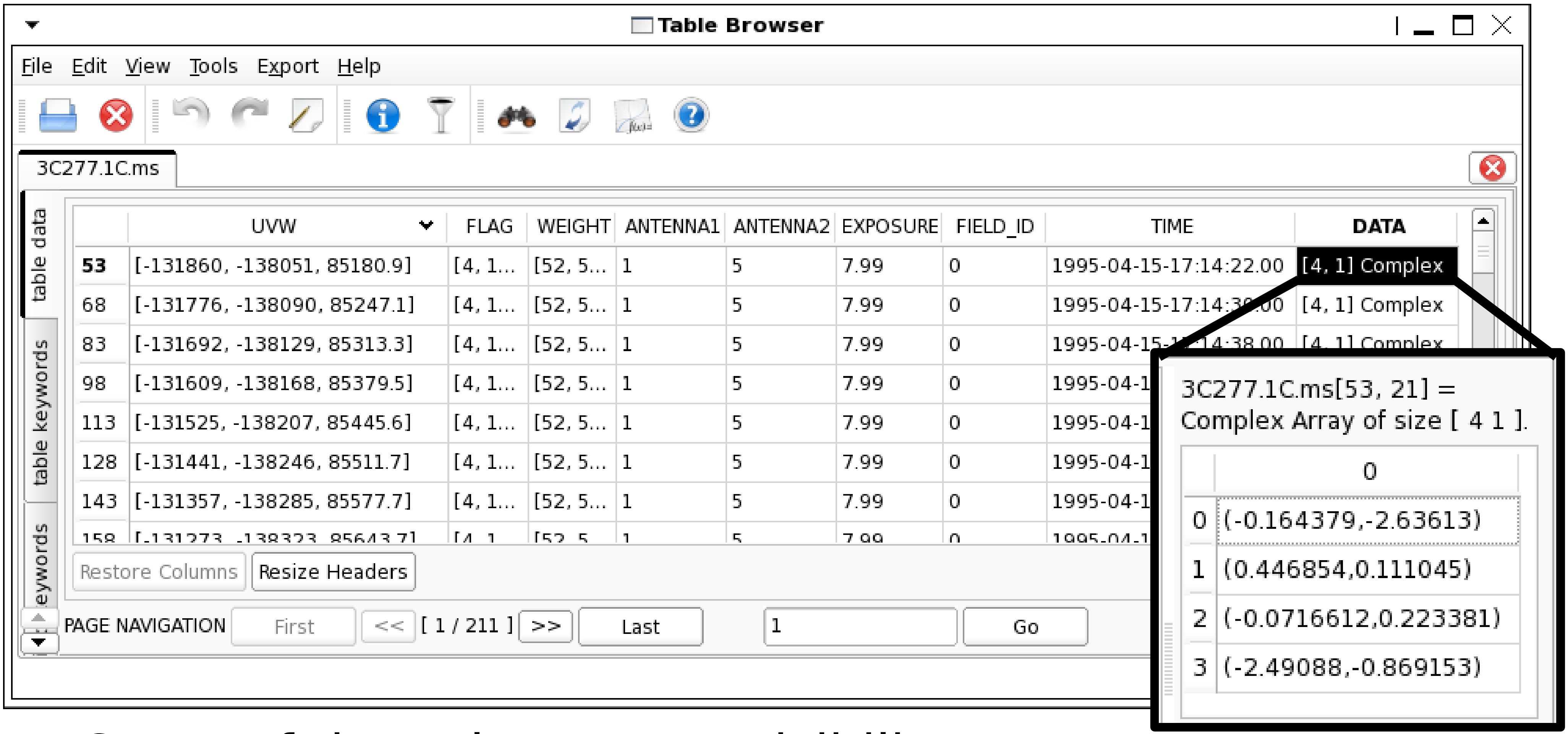
Faraday rotation

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

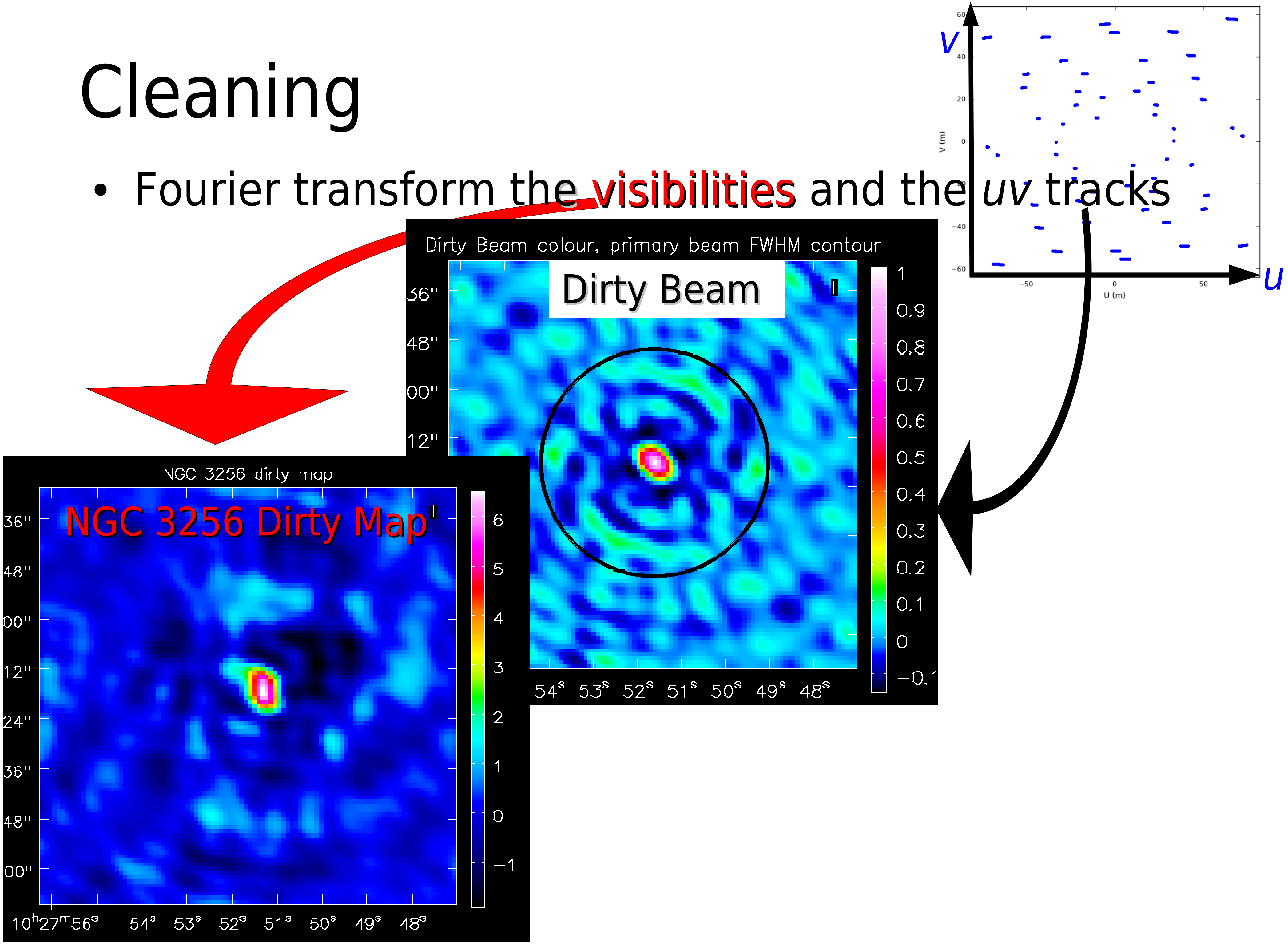
Measurement Set MAIN table



- 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)

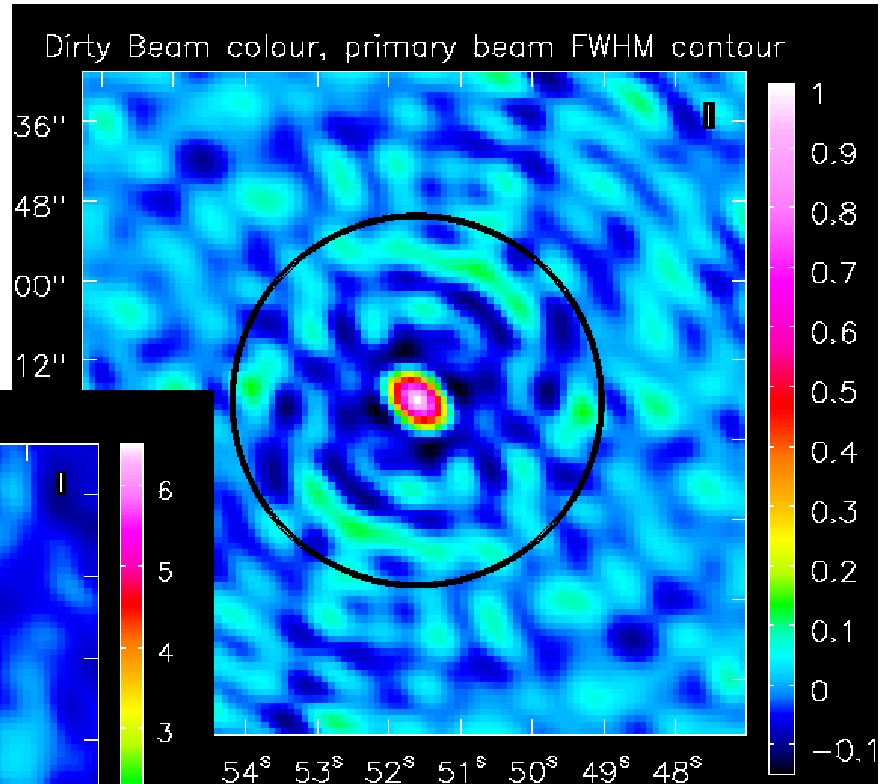
Cleaning

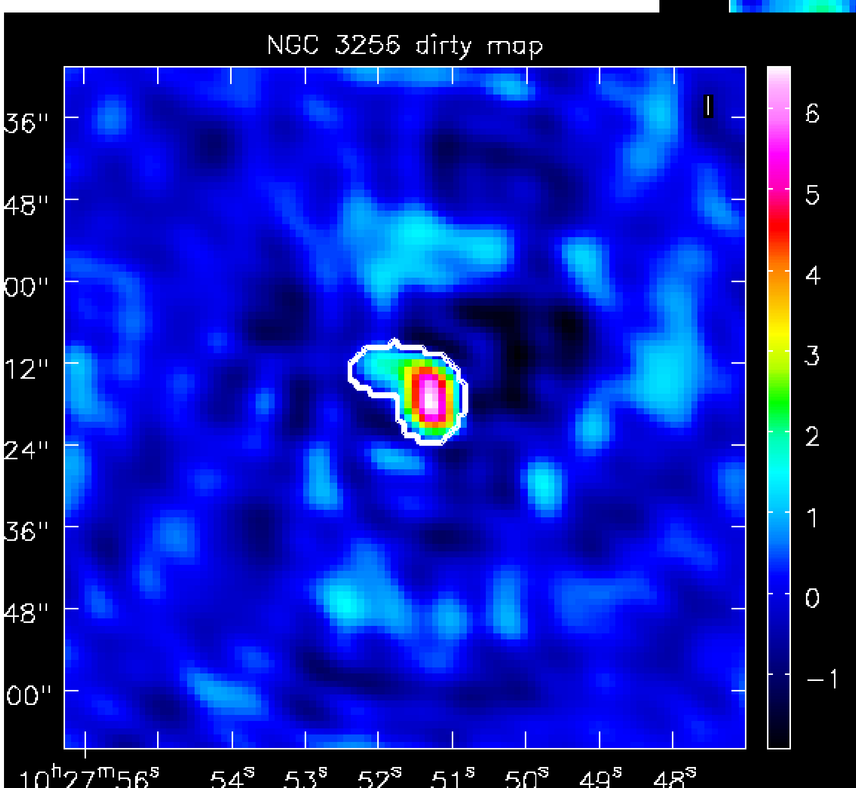
- Fourier transform the visibilities and the *uv* tracks



Cleaning

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

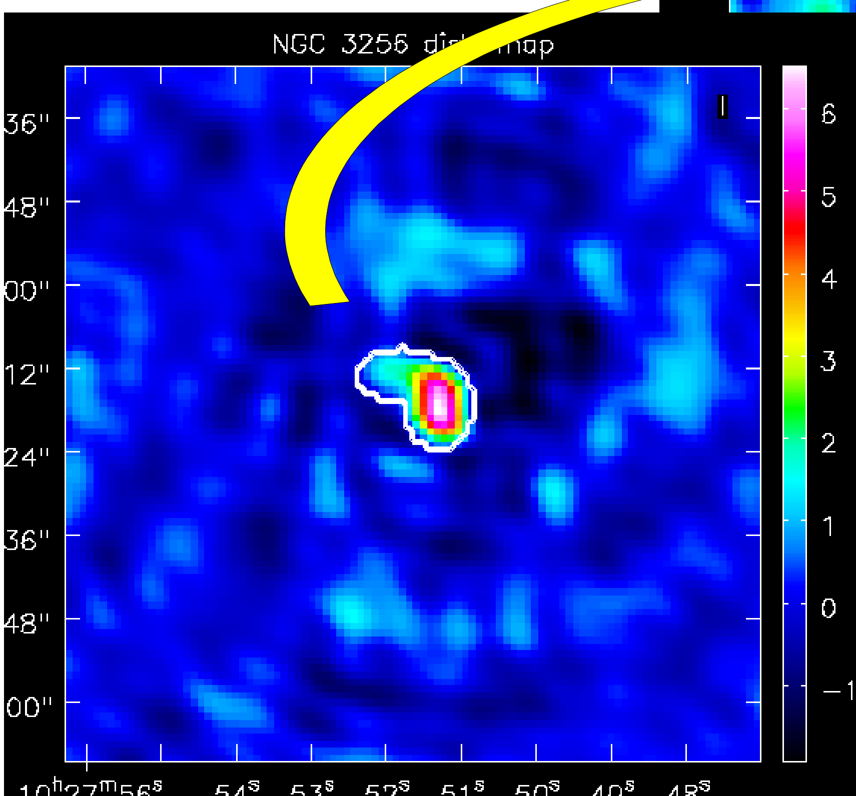


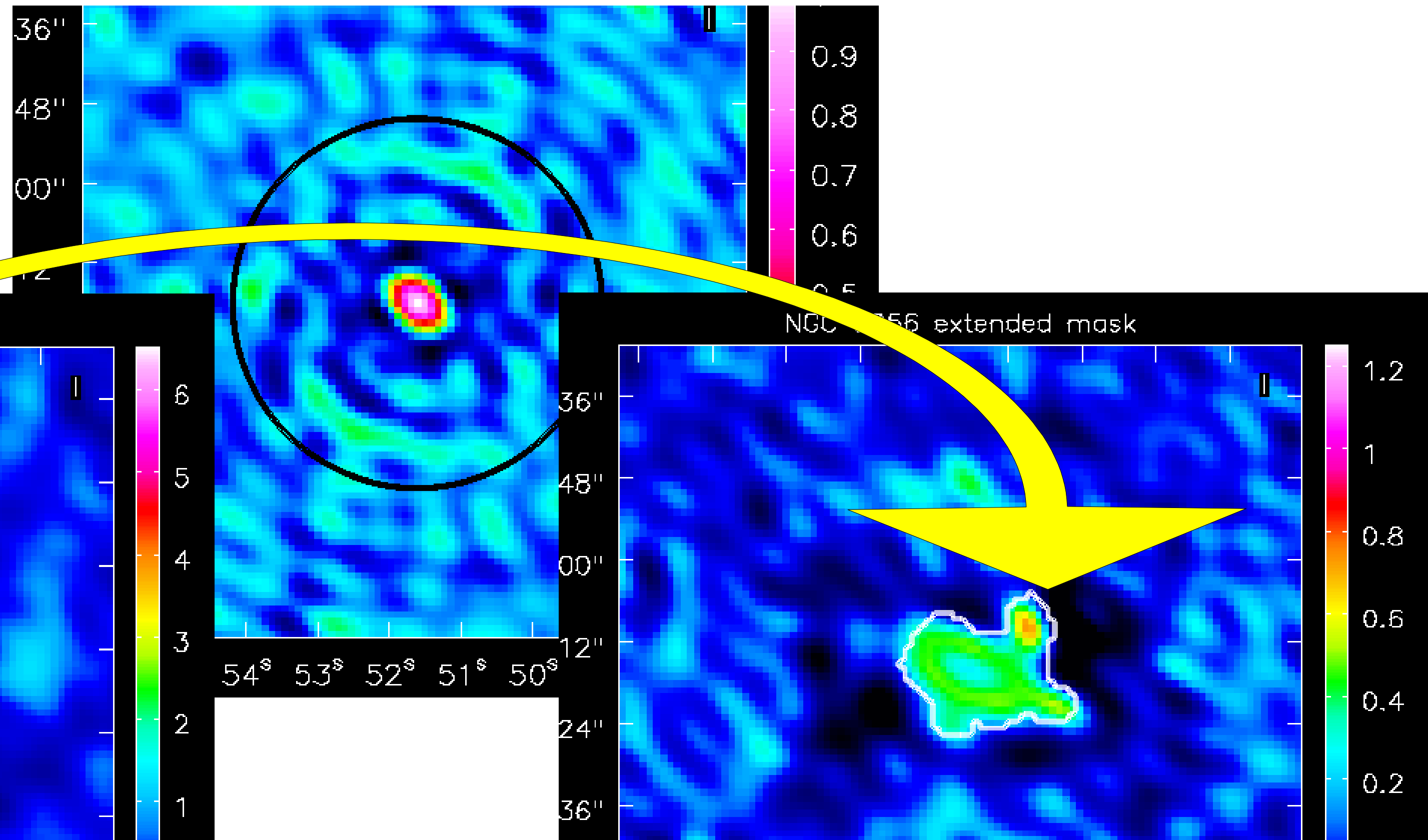


- CLEAN algorithm identifies brightest pixels
- Store e.g. 10% of each peak as Clean Component

Cleaning

- Iteratively subtract scaled dirty beam at positions of bright pixels

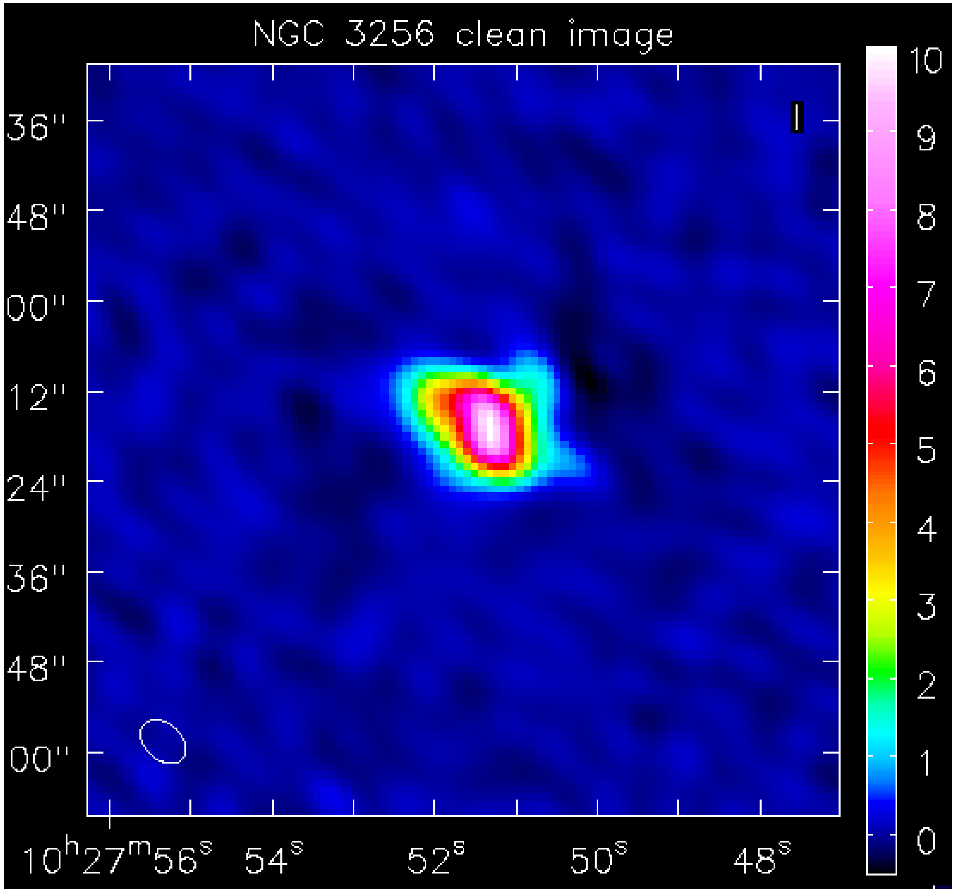




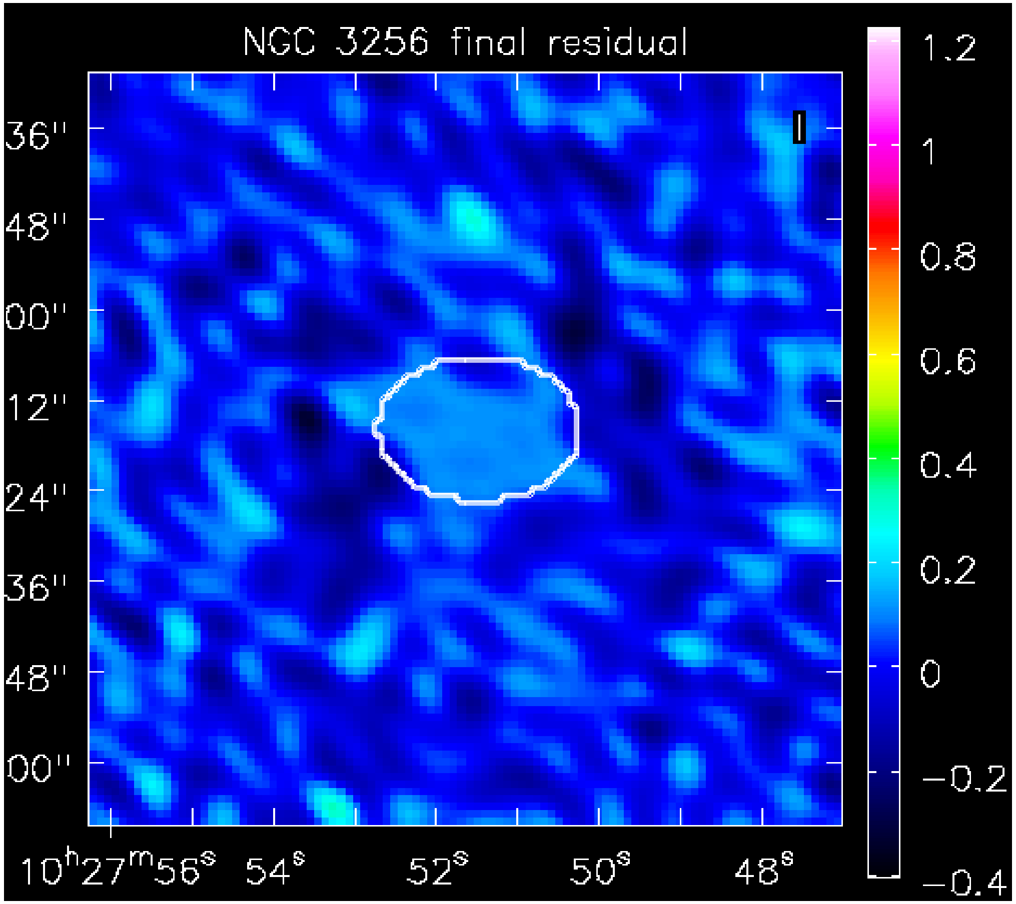
- Inspect partially-subtracted residual
- Extend mask if needed

CLEANed image

- Improved signal-to-noise in final image

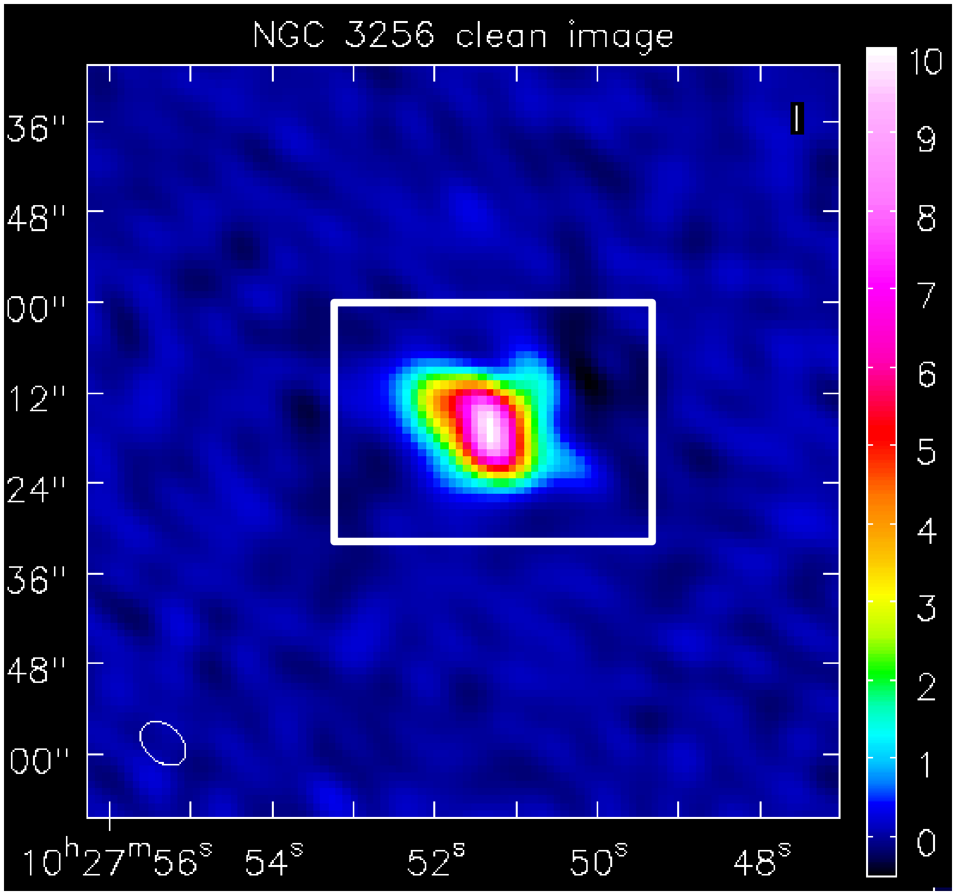


- Residual is just noise
  - Note different flux scale

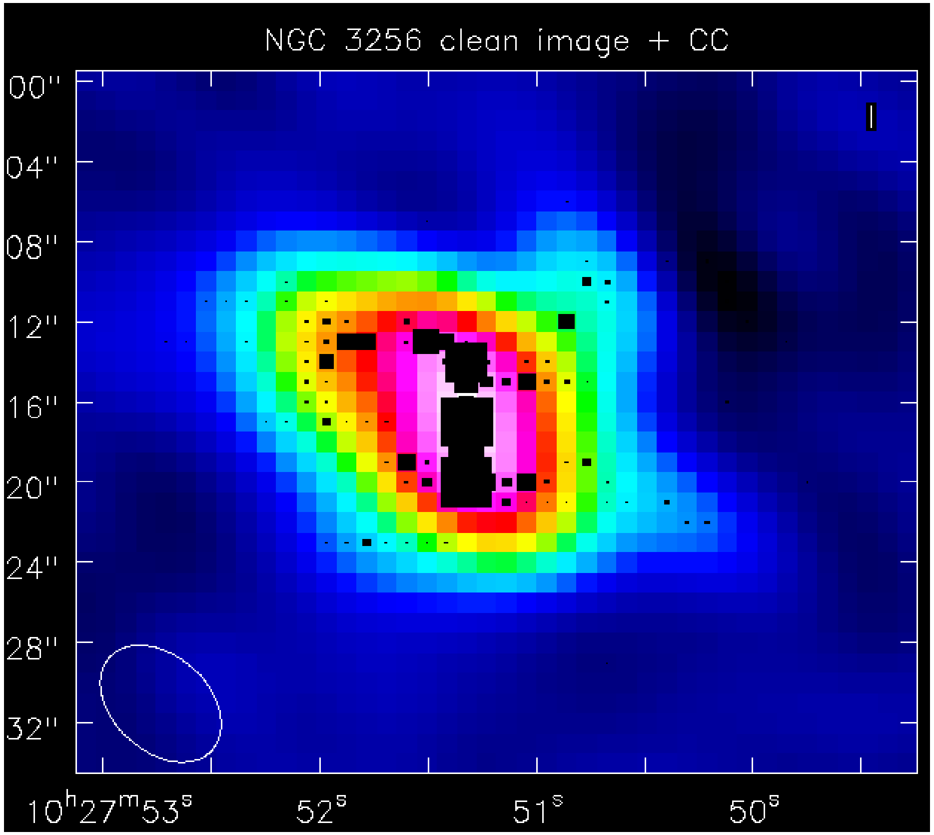


CLEANed image

- Note improved signal-to-noise in image



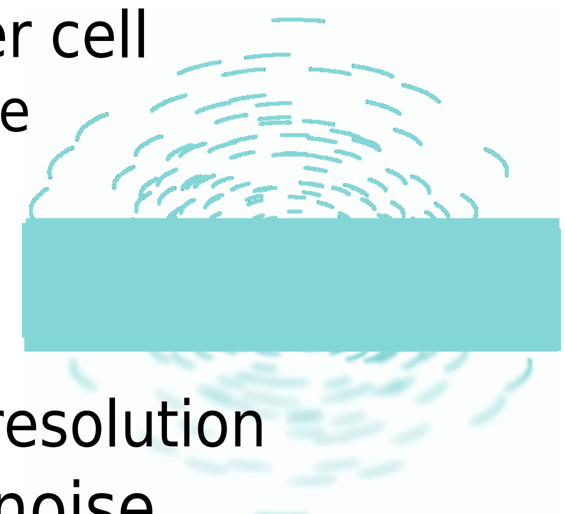
- Final image is combination of residual and Clean Components convolved with restoring beam



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

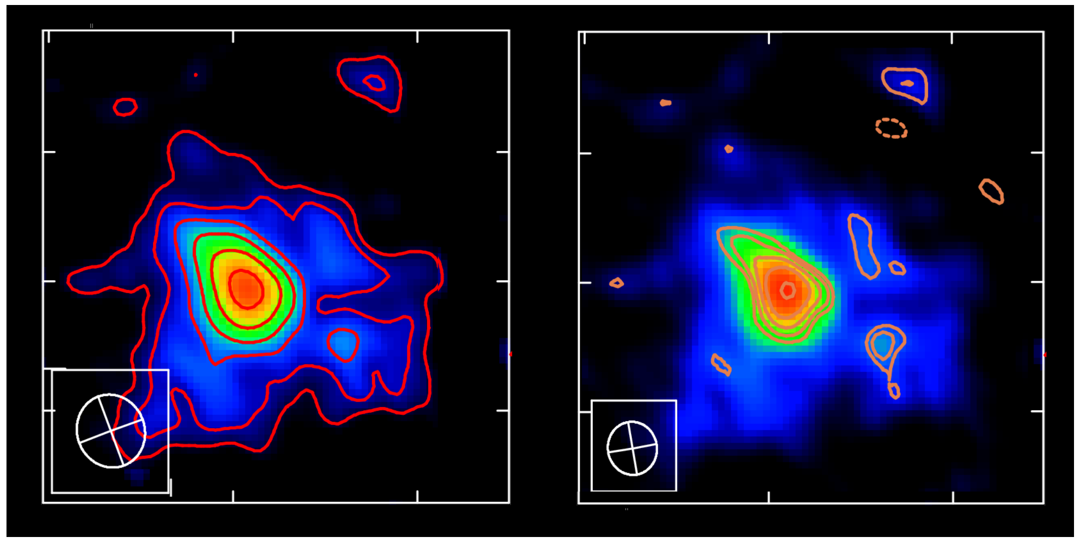
Weighting

- Each visibility has a weight:
  - Intrinsic, for same t_{int}, T_{sys} etc.:
    - ACA baseline has noise $12^2/7^2 \times$ 12-m baseline
    - Single 12-m TP dish has noise $\sqrt{2} \times$ 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: Weighted by number samples per cell
      - Maximum sensitivity to extended structure
    - Uniform: Every cell has same weight
      - Finest resolution, worse noise
    - Intermediate (`robust` parameter)
    - Taper: suppress long baselines, coarsen resolution
  - Change resolution $\lesssim$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*

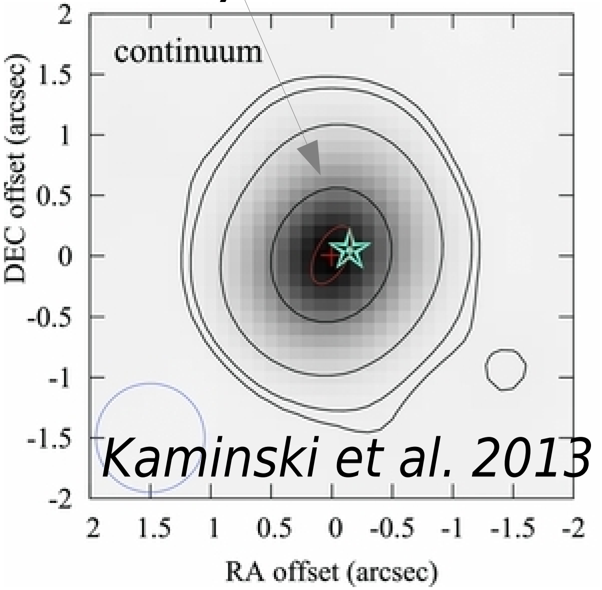
- Weights can be adjusted further during imaging
  - Grid samples in uv plane
    - Natural: Only take account of uv cells with samples
      - Maximum sensitivity to extended structure
    - Uniform: All cells same weighting
      - Finest resolution, worse noise
    - Intermediate (`robust` parameter)
    - Taper: suppress long baselines, coarsen resolution
  - Change resolution ≲2x at cost of higher noise

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

T_b for ALMA: VY CMa continuum

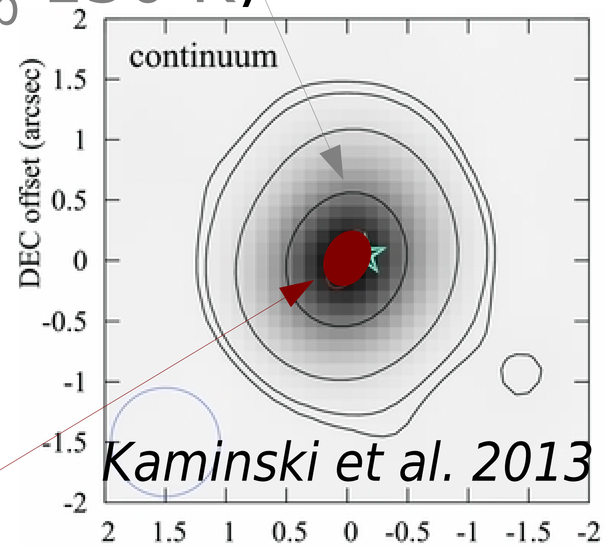
- SMA beam 1''; ALMA beam ~0''.17
- SMA peak 670 mJy/bm (apparent T_b 130 K)
  - If source <0''.17, T_b 4500K, ALMA detects 670 mJy/bm (unresolved)
  - If smooth, ALMA flux density $670x(1/0.17)^2$ ~19 mJy/bm
- How best predict ALMA flux?

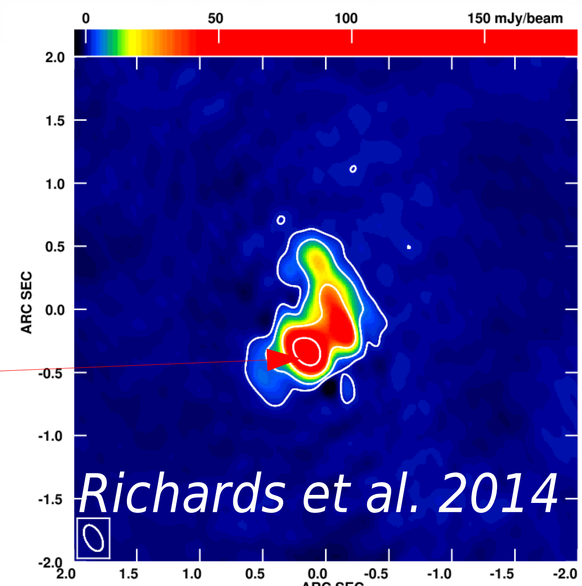


Kaminski et al. 2013

T_b for ALMA: VY CMa continuum

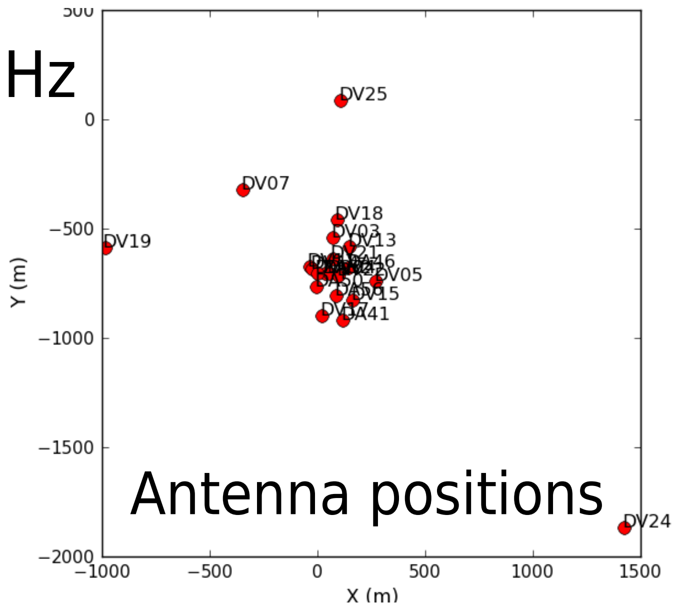
- SMA beam 1''; ALMA beam ~0''.17
- SMA peak 670 mJy/bm (apparent T_b 130 K)
  - If source <0''.17, T_b 4500K, ALMA detects 670 mJy/bm (unresolved)
  - If smooth, ALMA flux density 670x(1/0.17)^2 ~19 mJy/bm
- How best predict ALMA flux?
  - Fit Gaussian ellipse to SMA, deconvolve beam, T_b 980 K
    - Consistent with size/ temperature expected for hot dust
- Actual ALMA peak 190 mJy/bm ~ T_b 1300 K
  - SMA-based prediction OK

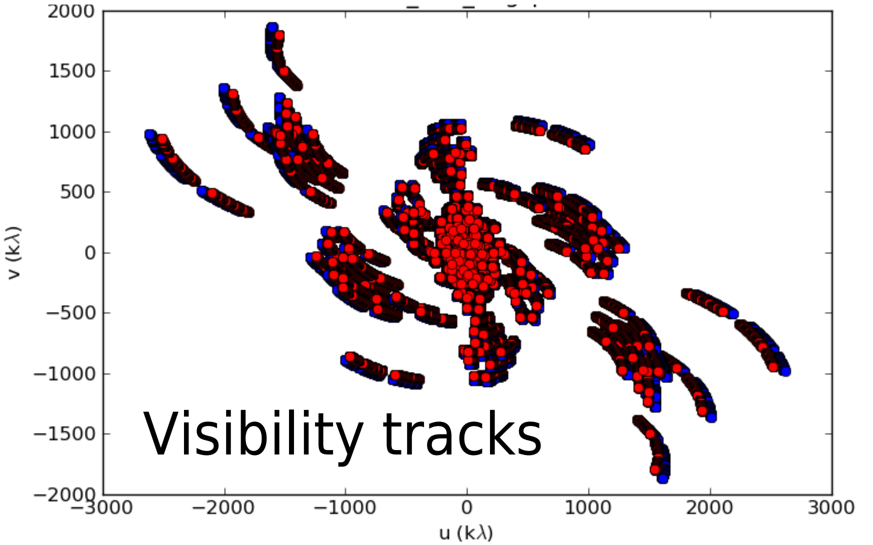




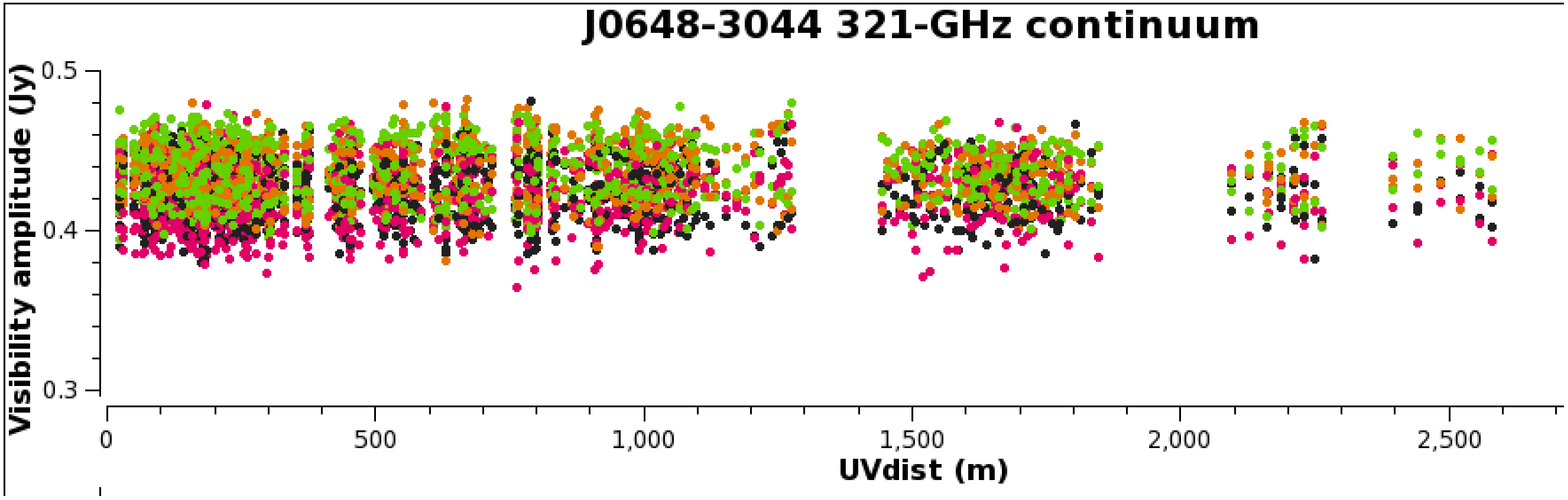
Visibility coverage: VY CMa in SV

- Around 320 GHz
- Up to 2.7 km baselines
- ~1.5 hr on source
- Phase-ref point-like



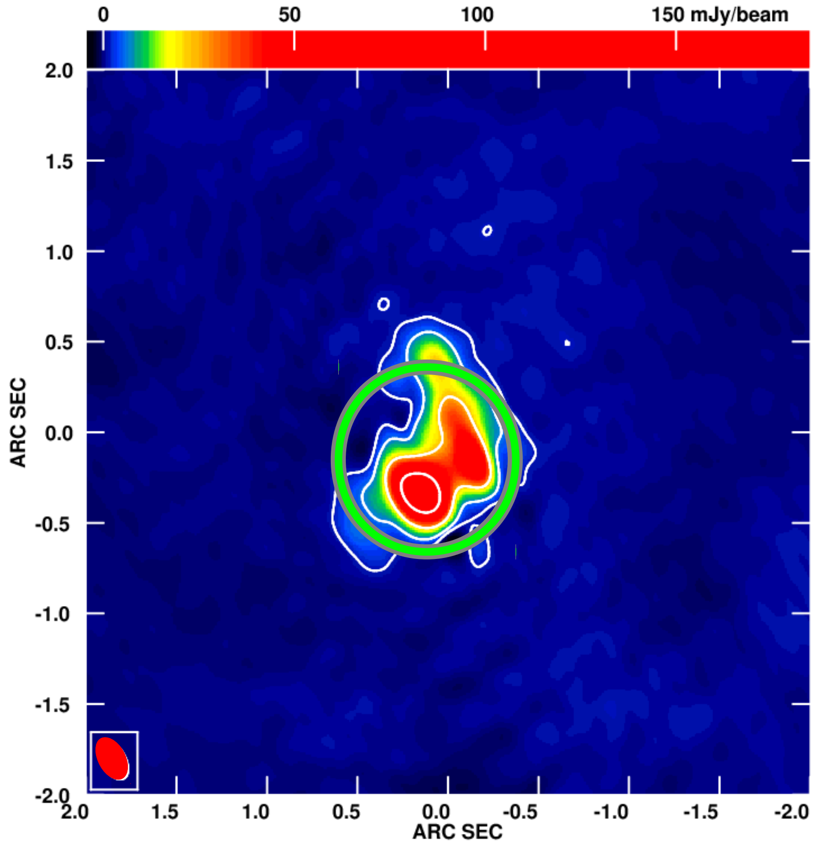


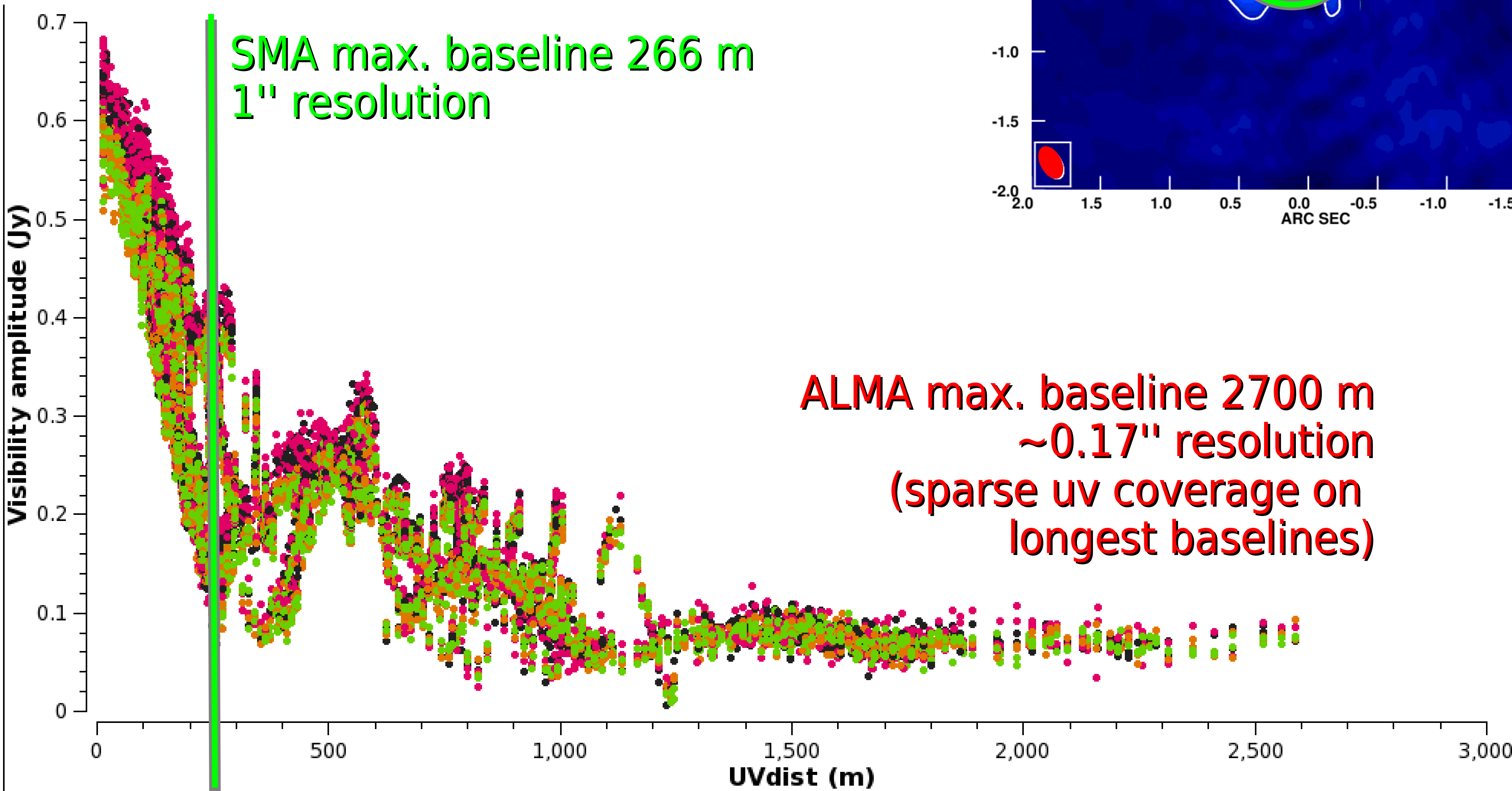
- Same flux density on all baseline lengths



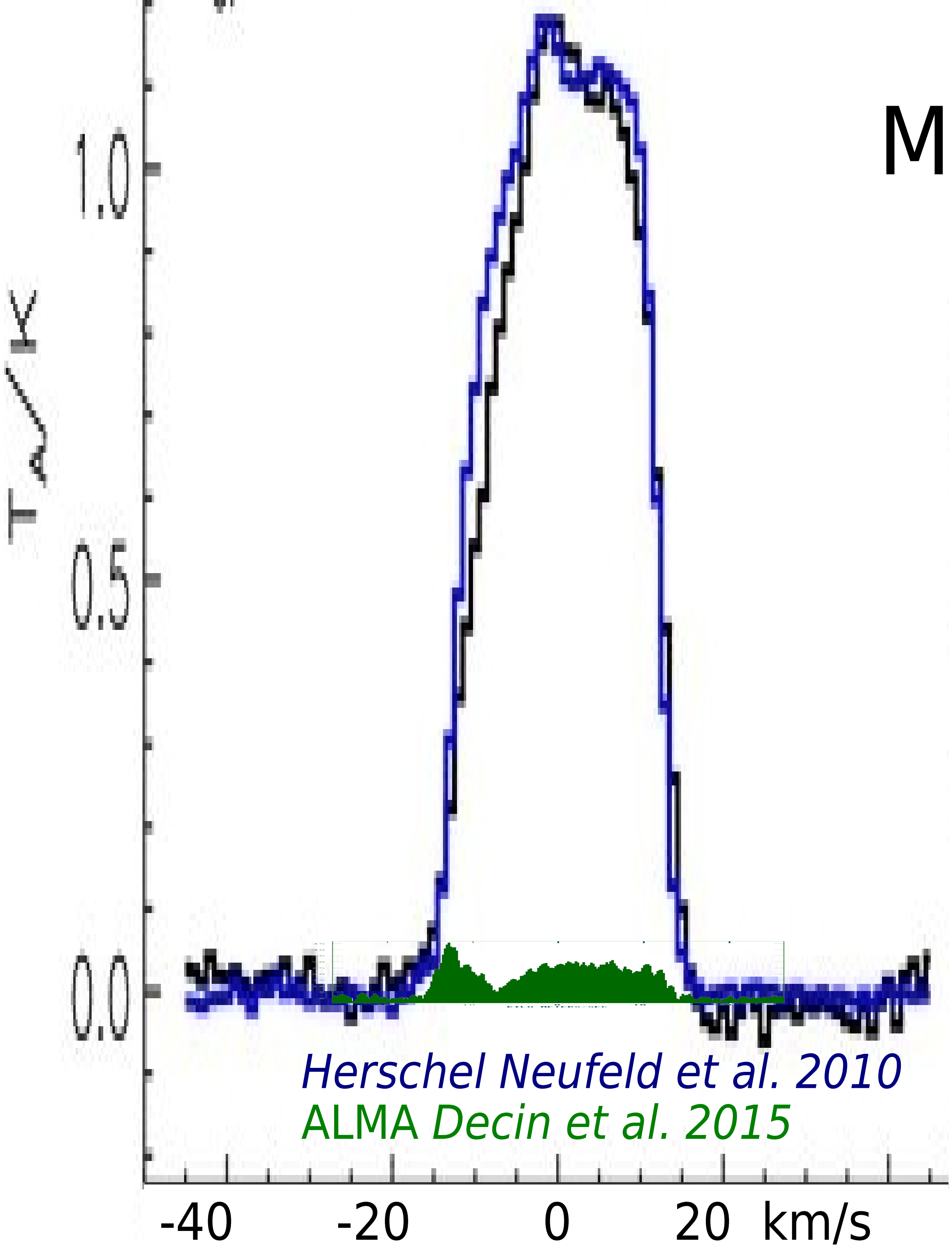
Visibility structure

- VY CMa resolved continuum
- Longest baselines correspond to smallest image structures



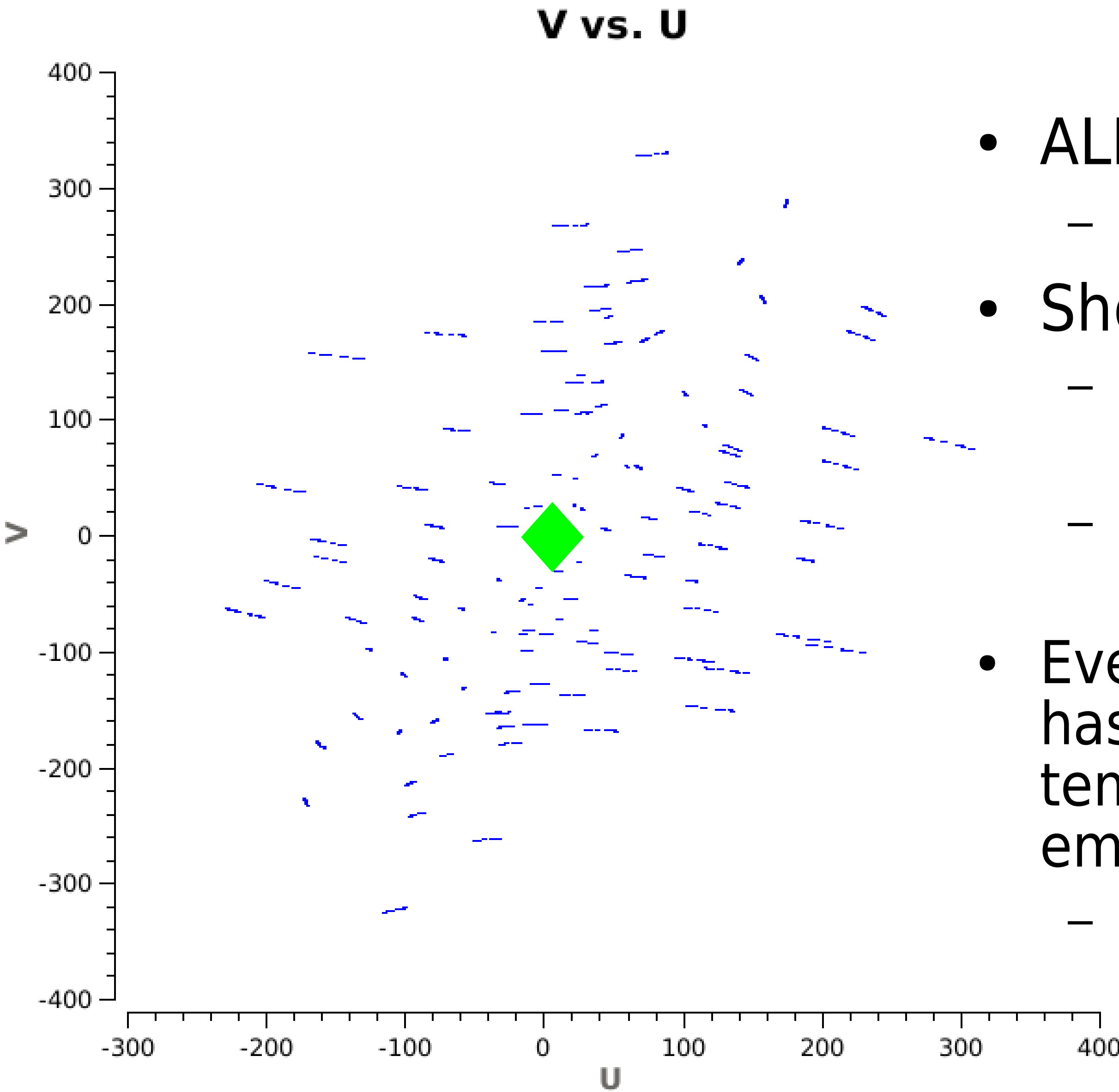


Missing spacings



- CW Leo ^{13}CO J6-5
- *Herschel* 575 Jy peak
- ALMA 21 Jy (scale x 2)
- ALMA detects <5% CO
  - E_U 111 K
  - Similarly for $C^{18}O$
  - Cool, extended,
    - Resolved out
- Detects 50-100% other lines e.g. SiC_2 E_U >500 K
  - Hot gas near star
    - More compact

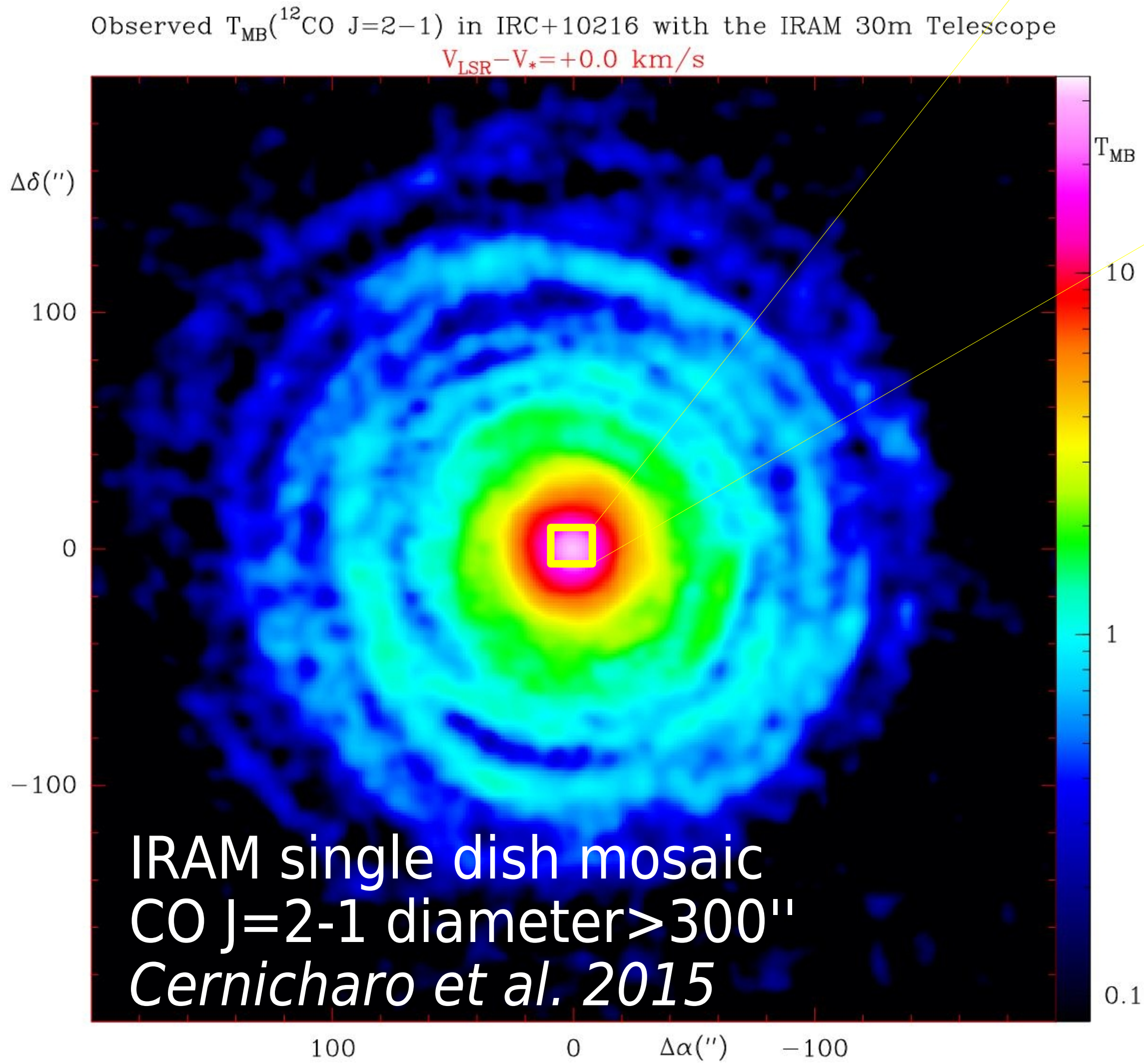
Missing spacings

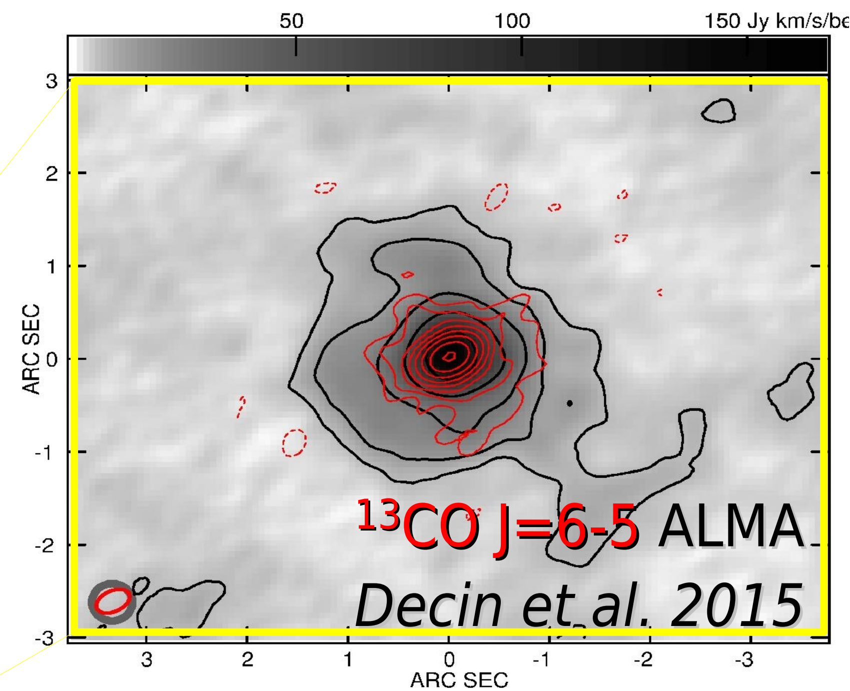


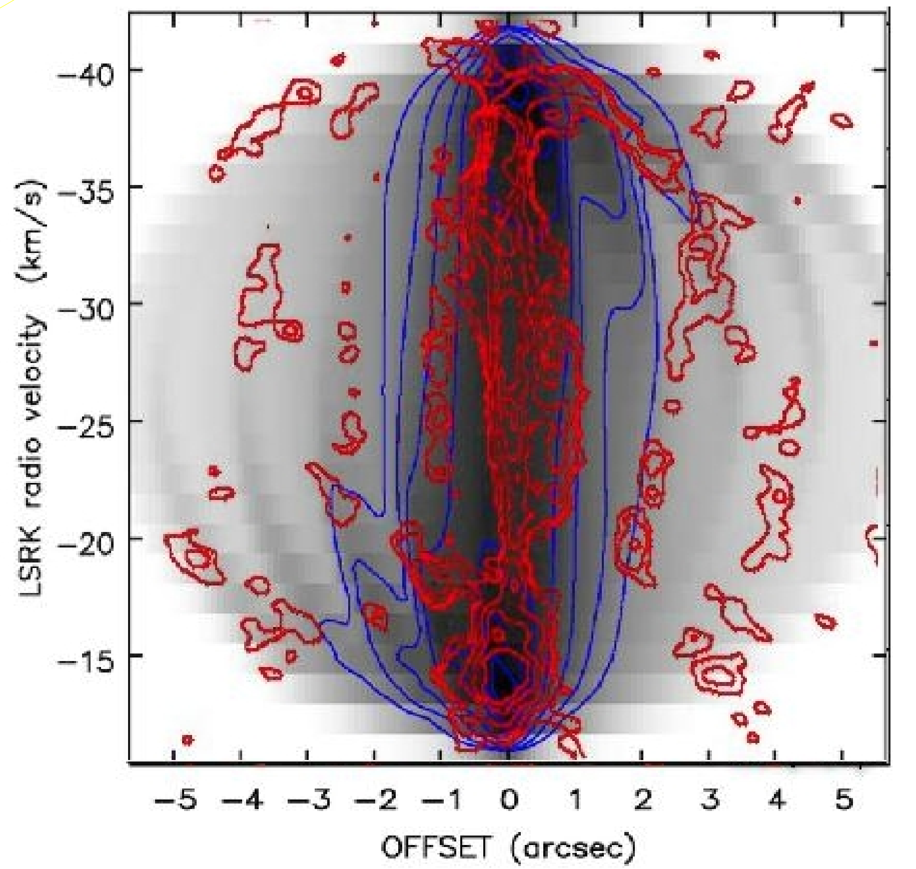
- ALMA longest baseline 340 m
  - λ 0.45 mm, beam ~0''.3
- Shortest spacing 25 m
  - Resolves out emission smooth over 6''
  - Emission on scales 3-6'' produces artefacts
- Even though total CO emission has high enough brightness temperature, the extended emission is invisible to ALMA
  - Unless you add in the ACA!

Effect on imaging

- ALMA only images inner~5''
- Reconstruct spiral from PV

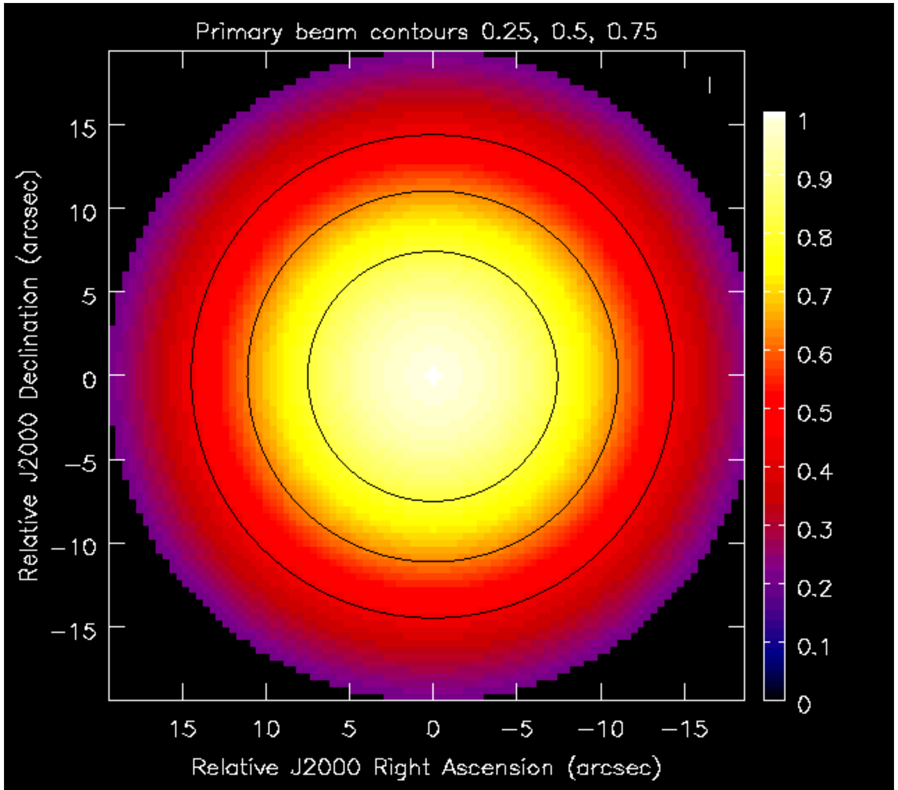


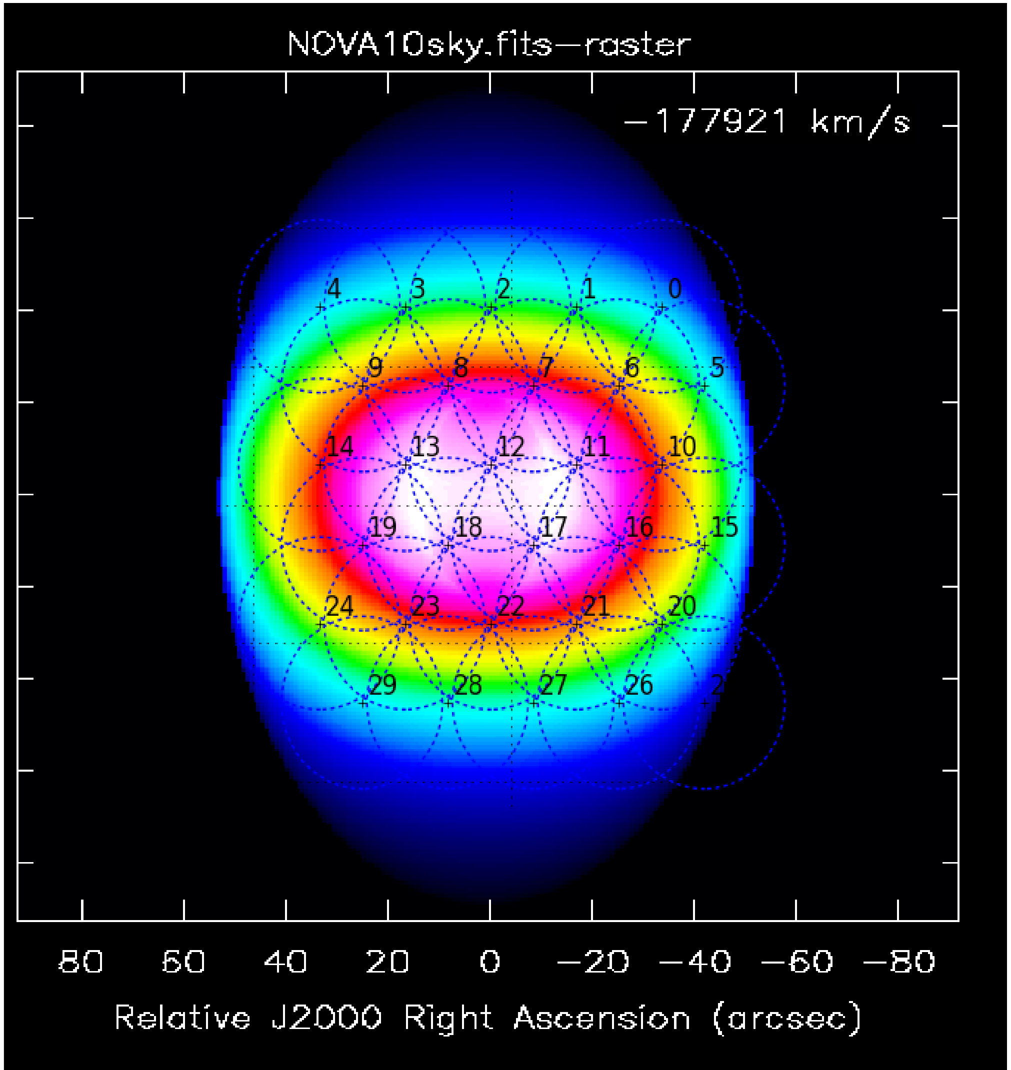




Field of view

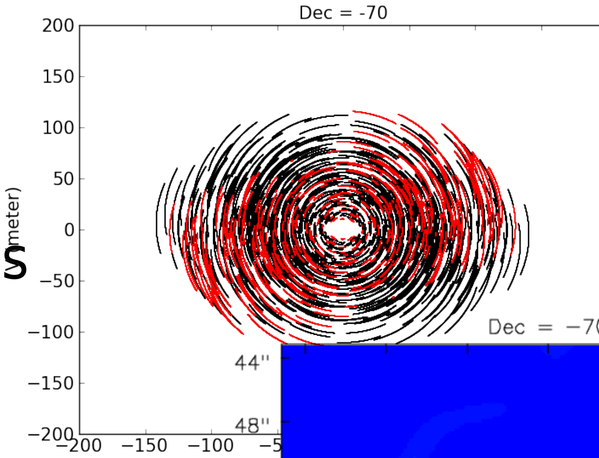
- Primary beam depends on λ/antenna diameter
  - Not hard edge; FWHM is half sensitivity (i.e. 2x noise)
- Mosaic larger targets
  - >10” B9, >1' B3
  - Must image area covering all bright emission



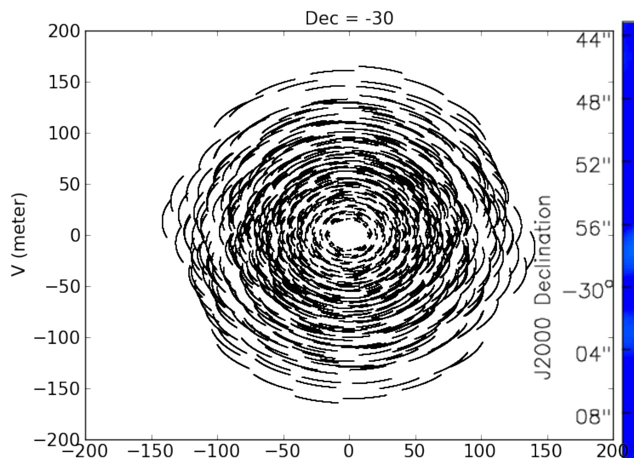


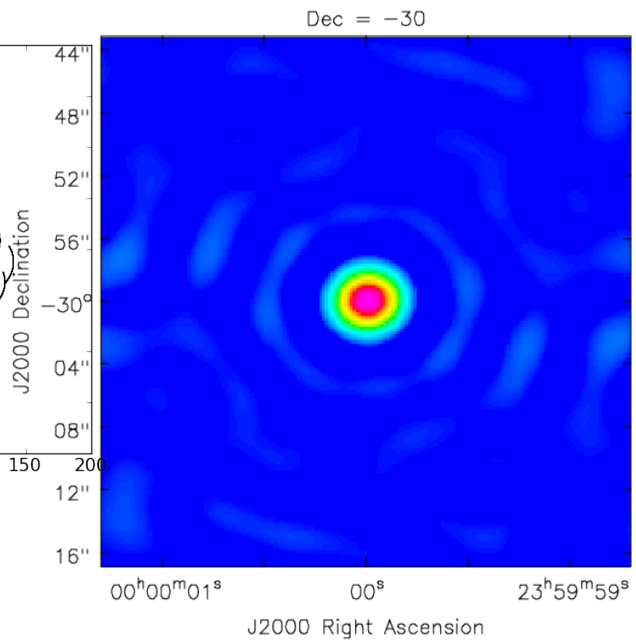
Input for simulations

- 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 in compact configs

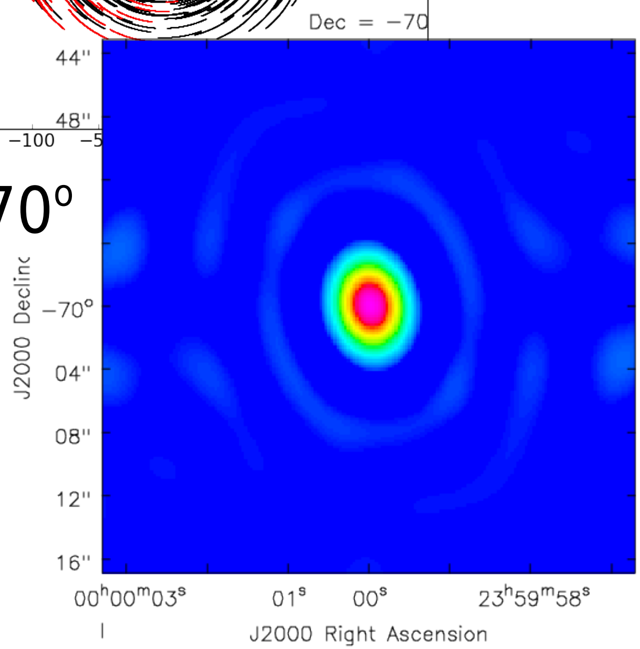


Dec -70°





Dec -30°

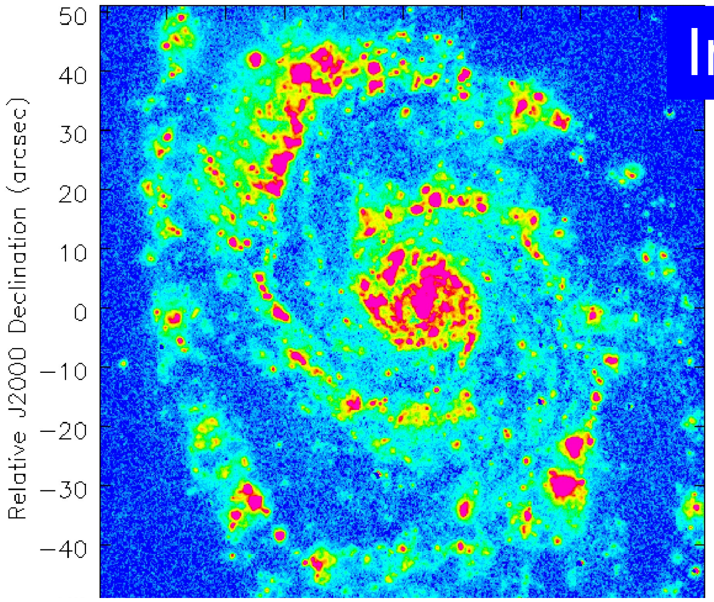


Input for OST simulations

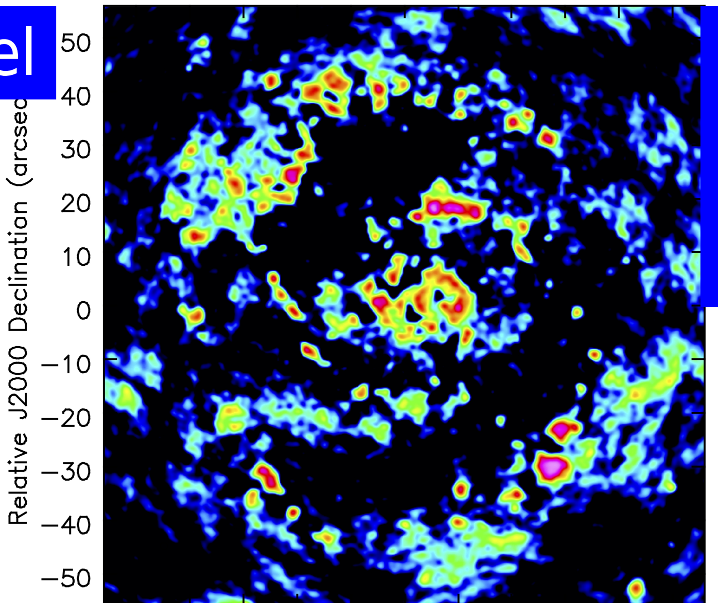
- Bandwidth, frequency etc.
  - Line: small cubes $N_{pix}(x*y)*N_{chan}$ <~2048^2 ('handluggage')
  - Continuum: OST can adopt optimum place in band
    - NB bands 3,4,6,7,8 full b/w *gap between sidebands*

- Automatically mosaics if required by input size
  - Crop large input if you only need a single pointing!
- Resolution: Cycle 3, select array(s) directly
- Peak Jy/pixel (to rescale input)
- Time needed to reach sensitivity
- Add noise
  - OST does not simulate phase/amp correction!

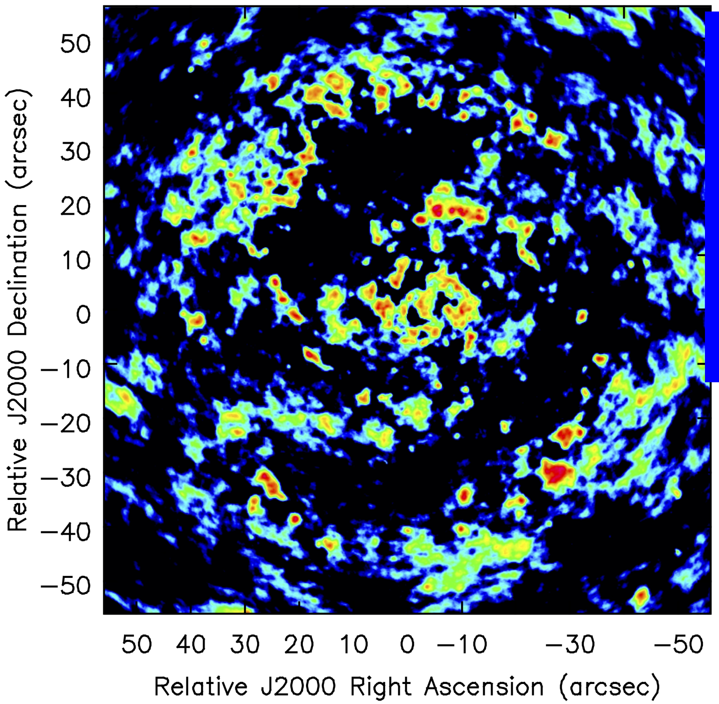
Cycle 3 resolution (scales @100 GHz)



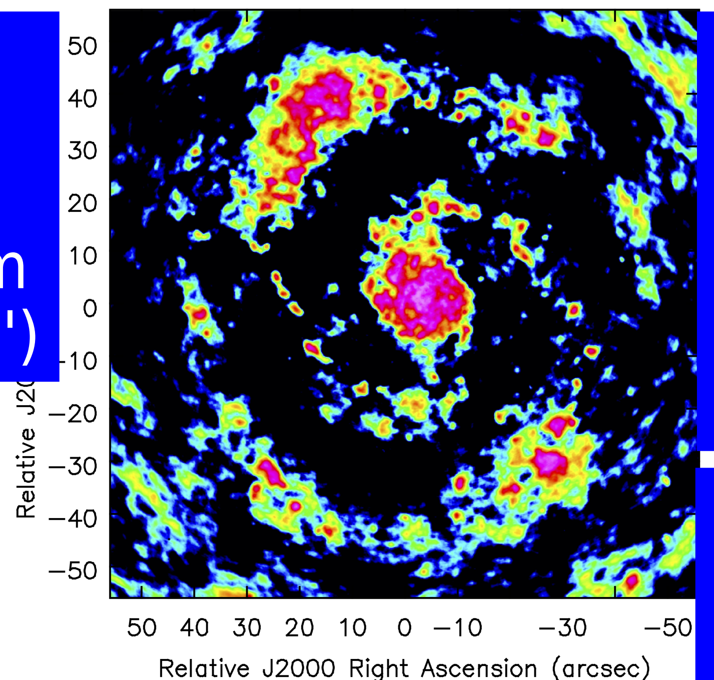
Input model



C36-3
Baselines
15 – 539 m
(1.2-25.2")



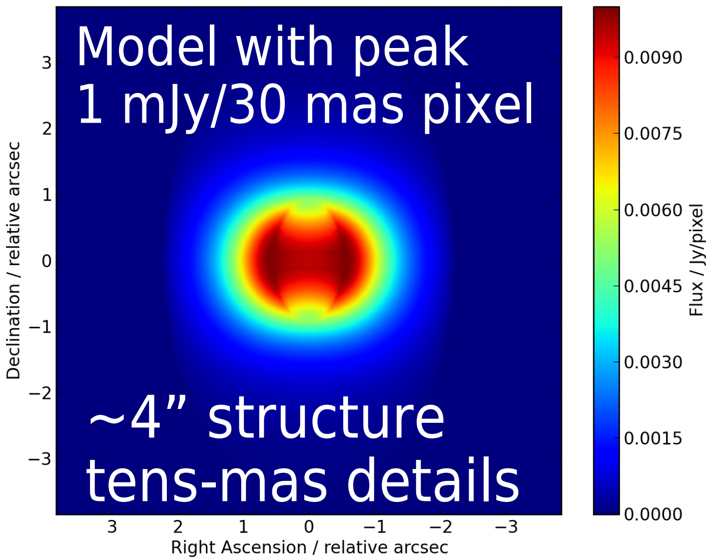
C36-3 +
C36-6
Baselines
15–1396m
(0.3-25.2")

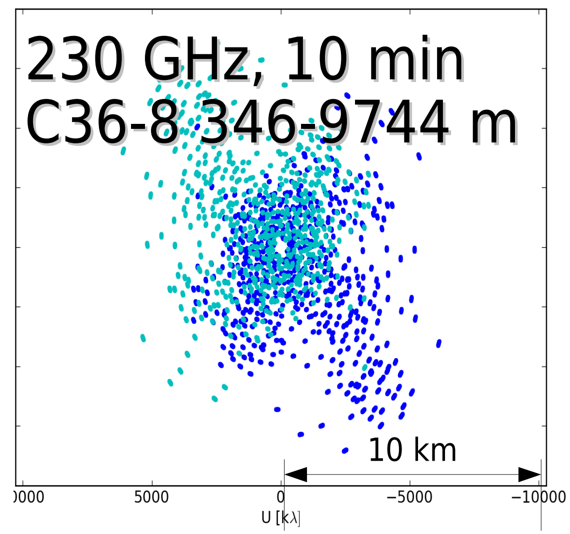


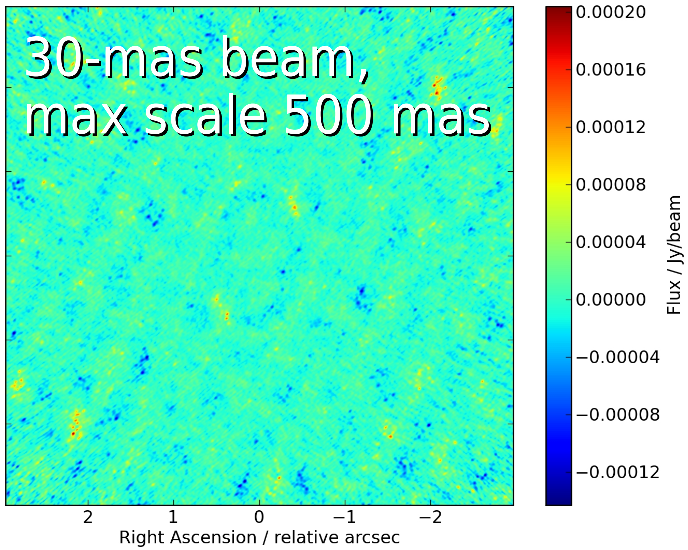
ACA +
C36-3 +
C36-6
Baselines
9–1396m
(0.3-43")

Add TP for
larger
scales

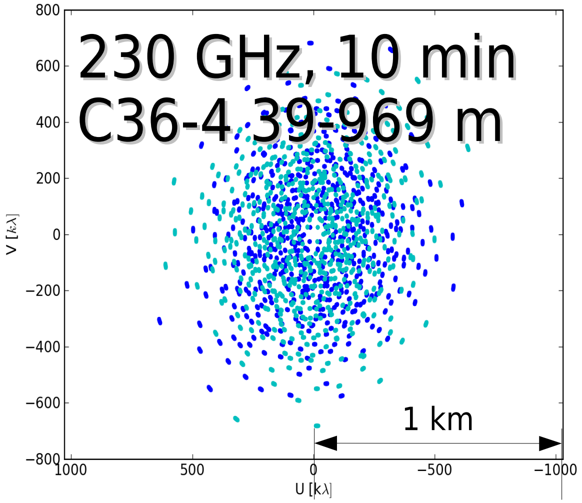
Nova simulation

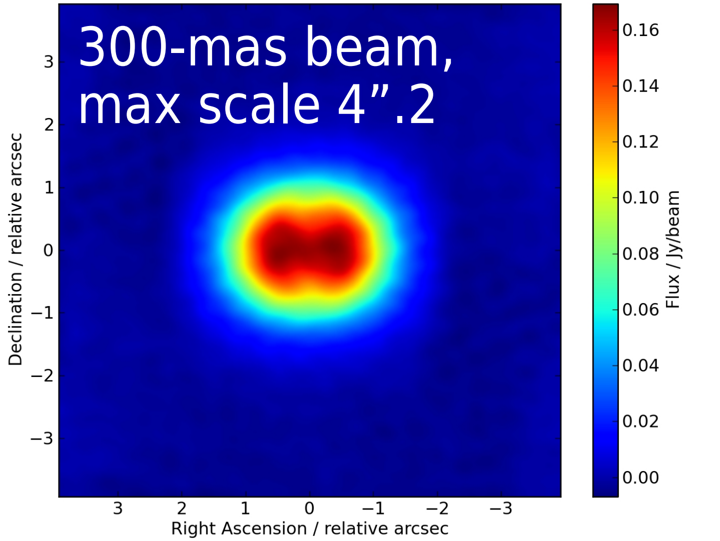






- OST, various array configs
- Resolved-out at 30-mas resolution
  - Despite rms 0.035 mJy/bm
- Lose detail at 300-mas resolution

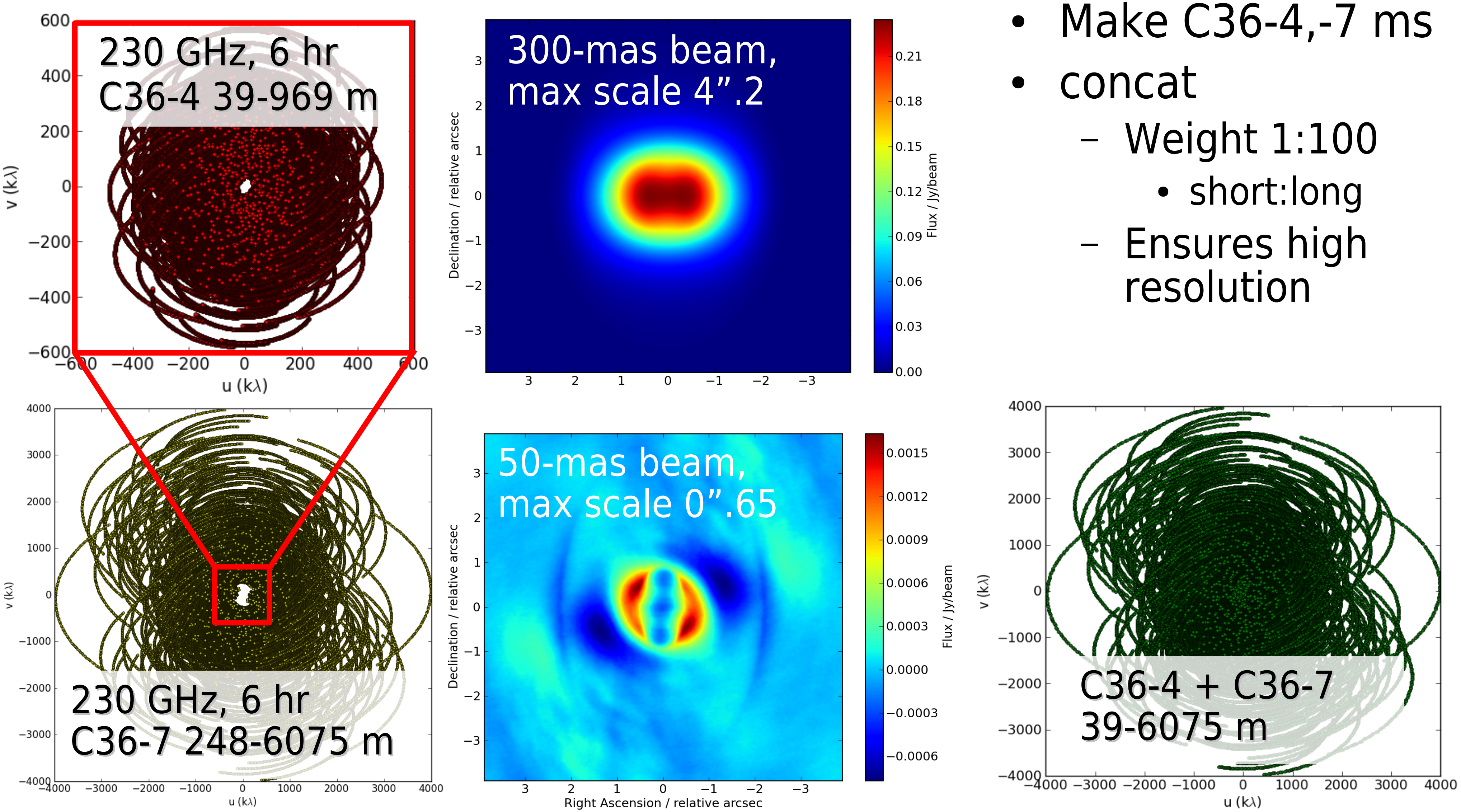




Combining arrays

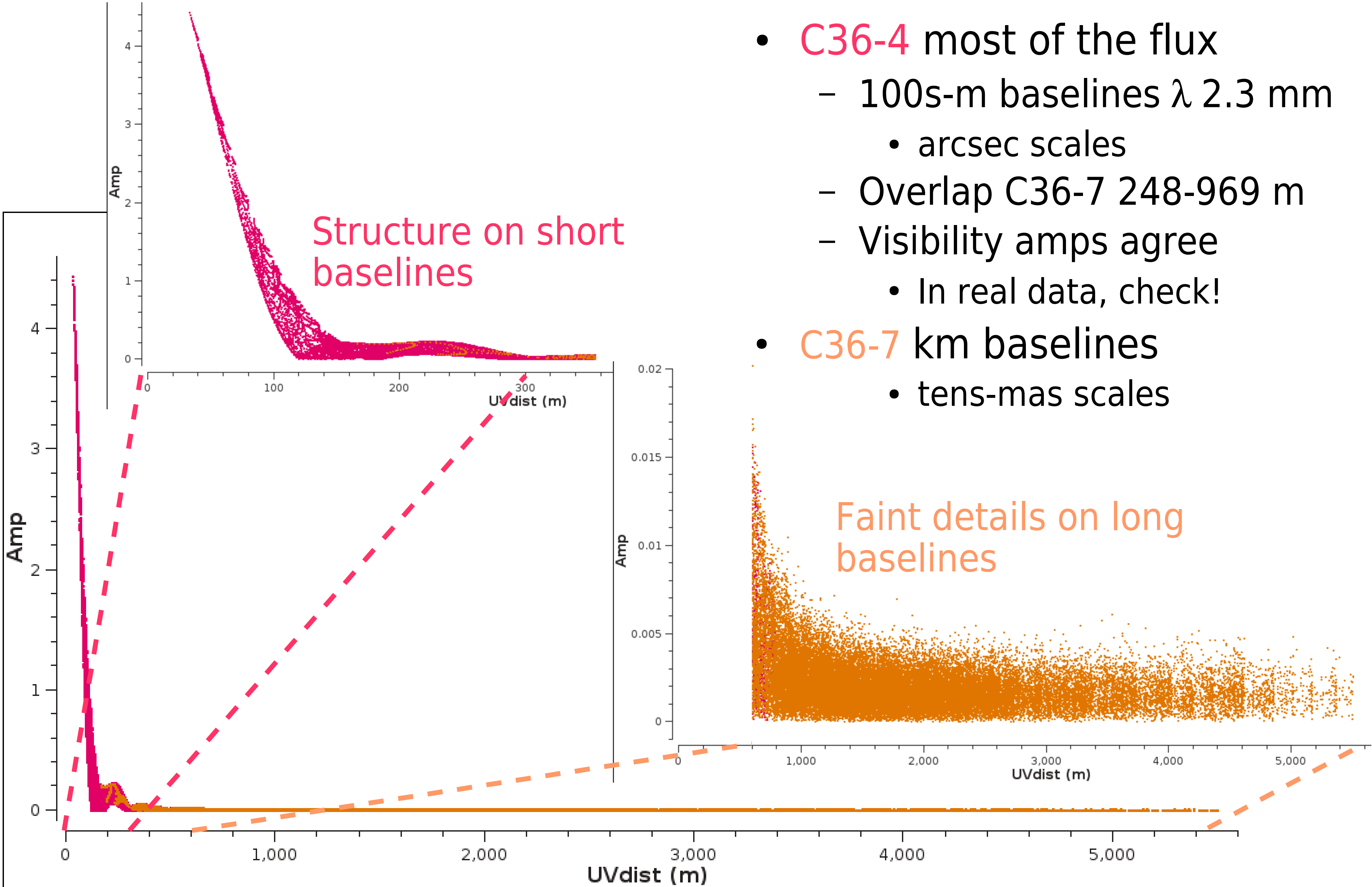
- Separate 300-mas and 70-mas simulatons
- Download *modelsky.fits, *simdata.last

- Edit simobserve inputs
- Make C36-4,-7 ms
- concat
  - Weight 1:100
    - short:long
  - Ensures high resolution



Combined visibilities

- C36-4 most of the flux
  - 100s-m baselines λ 2.3 mm
    - arcsec scales
  - Overlap C36-7 248-969 m
  - Visibility amps agree
    - In real data, check!
- C36-7 km baselines
    - tens-mas scales



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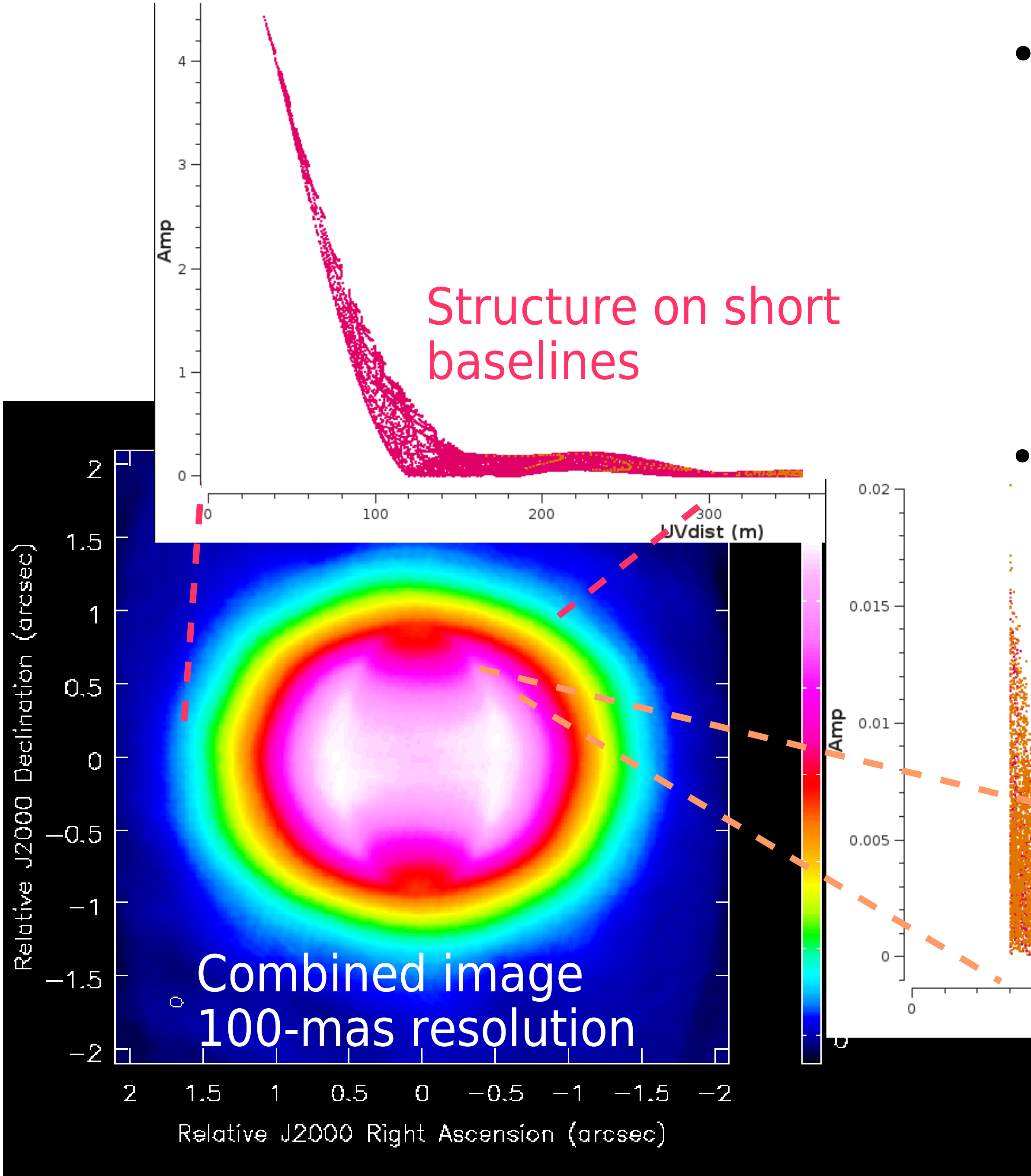
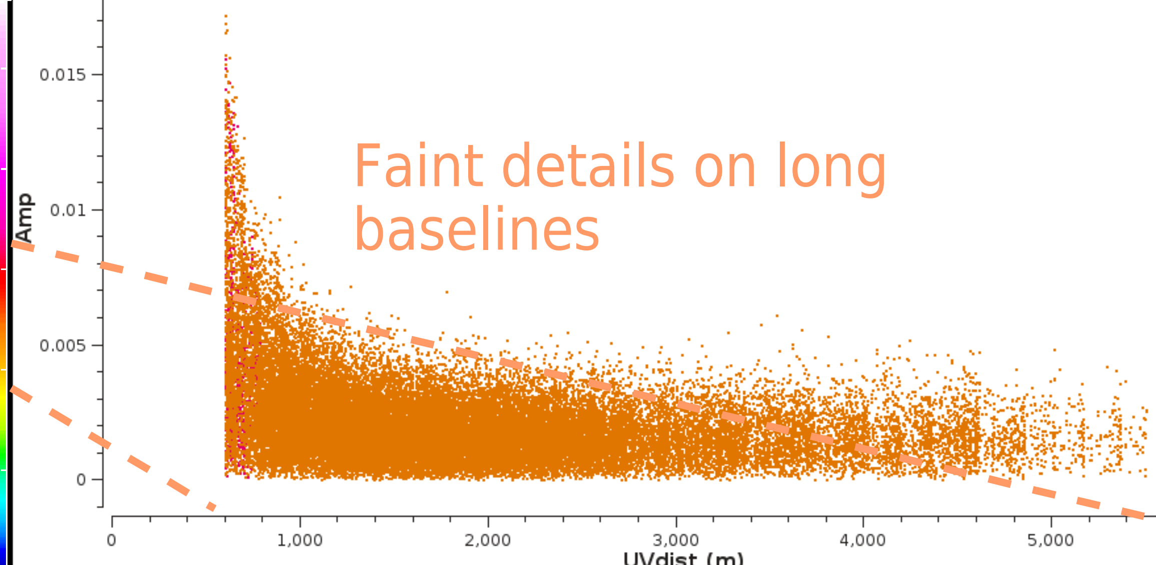
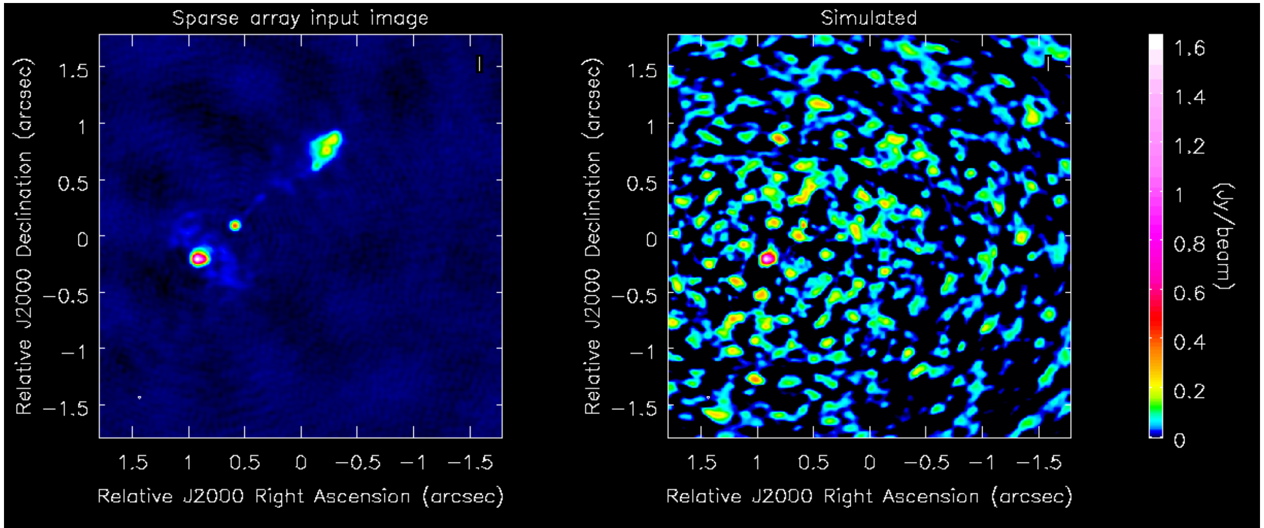




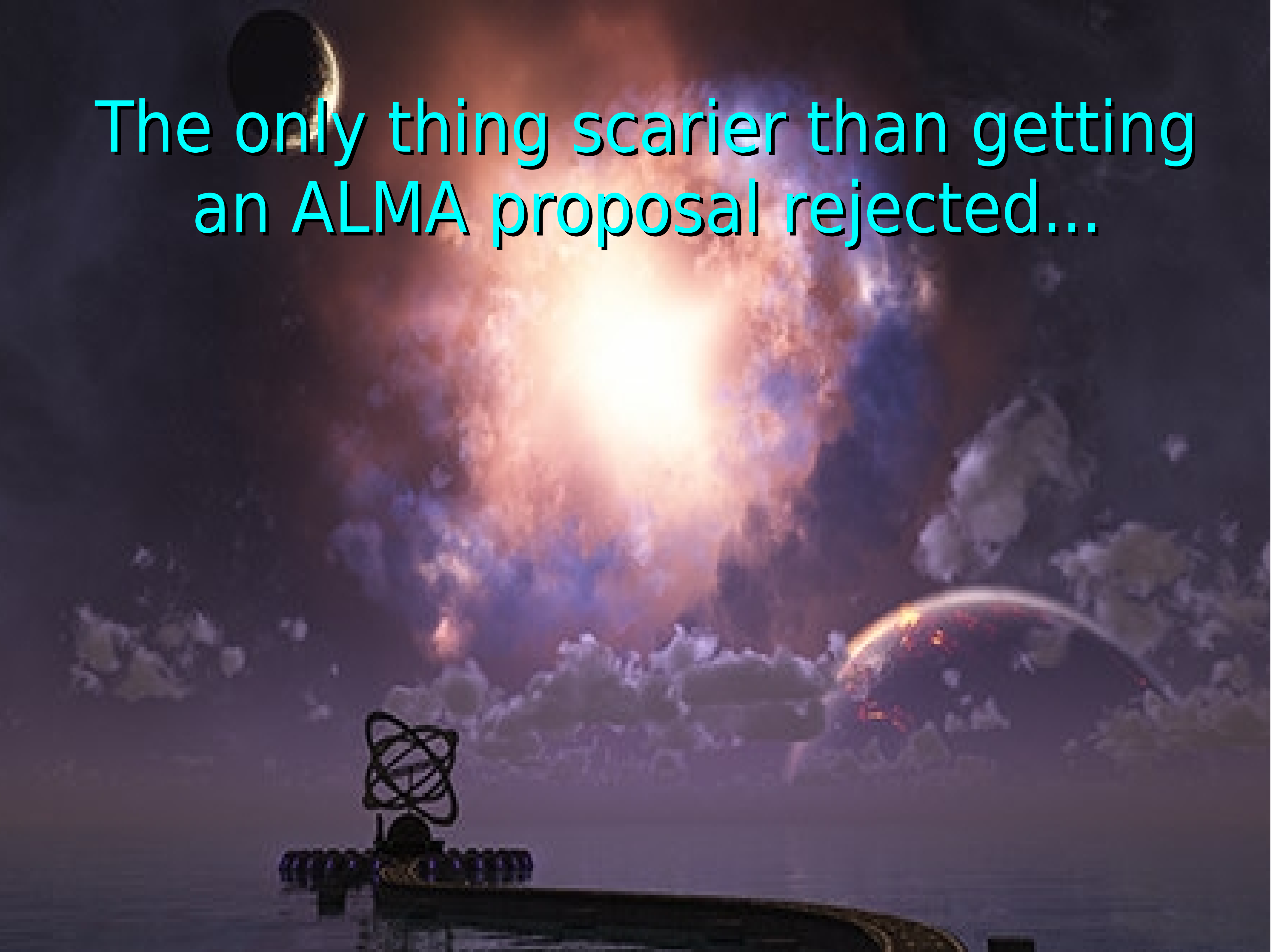
Noise

- 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!



Planning summary

- 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!


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

is if you do get the data!