Widefield Imaging II: Mosaicing

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What is it all about?

- Imaging regions on the sky that are larger than the primary beam
- The primary beam depends on **the individual size of the dish**, not your array configuration
- Re-gain some of the short spacing information
- Is this important? Yes!
- Sky has about 41,253 deg2
- 1 primary beam is:
- EVLA (25m dishes): 20cm: 0.25 deg2, 7mm: 0.0003 deg2
- ALMA (12m dishes): band 3, 3mm: 0.02 deg2, band 9 (650GHz): 0.000005 deg2
- **Solution 1:** go to smaller dishes (e.g. ATA, 6m dishes @20cm: 6.3 deg2) but you will need a lot of dishes to gain sensitivity (ATA plans hundreds)
- **Solution 2:** Mosaicing

Small Dishes: SKA

What is it all about?

- Galactic Center: image: 1deg x 0.2 deg, primary beam @ 1cm: 2.4'

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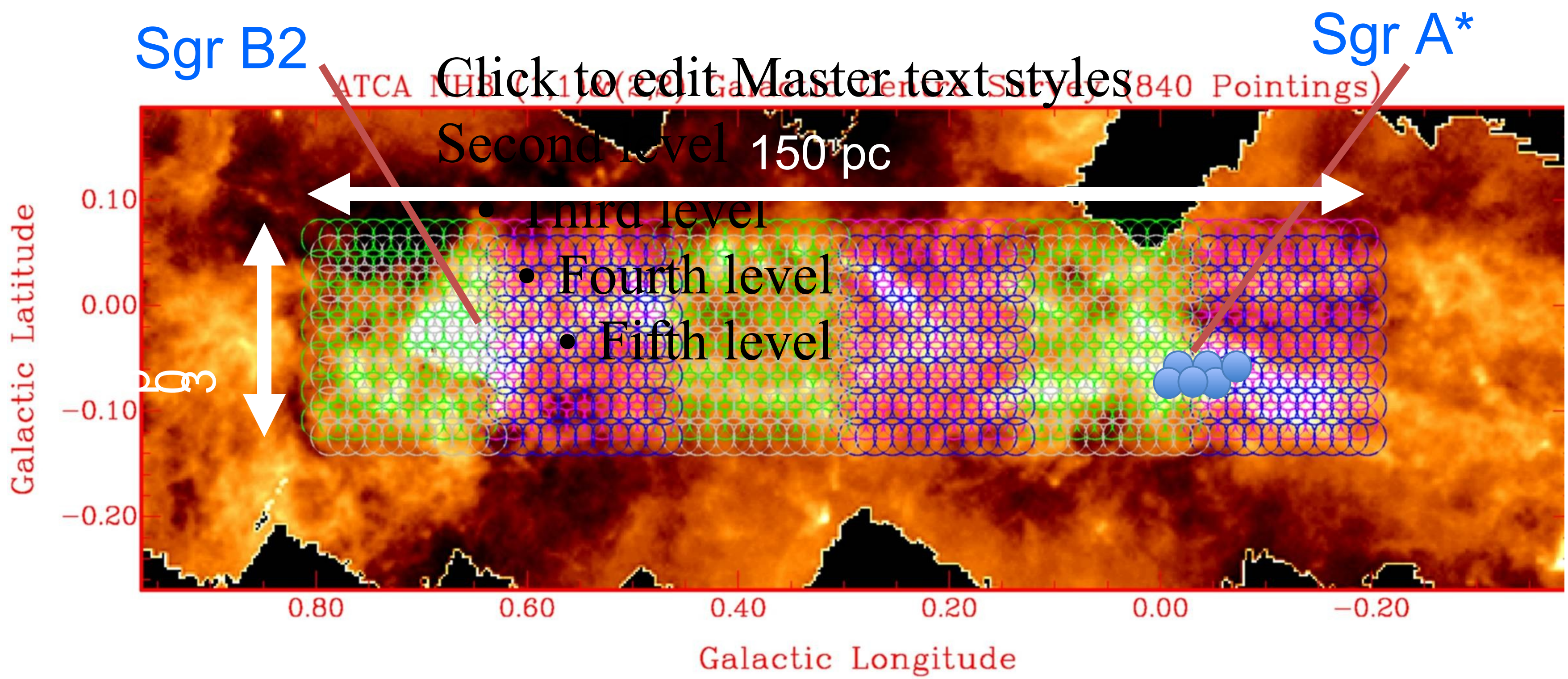
- Second level
  - Third level
    - Fourth level
      - Fifth level



Galactic Center

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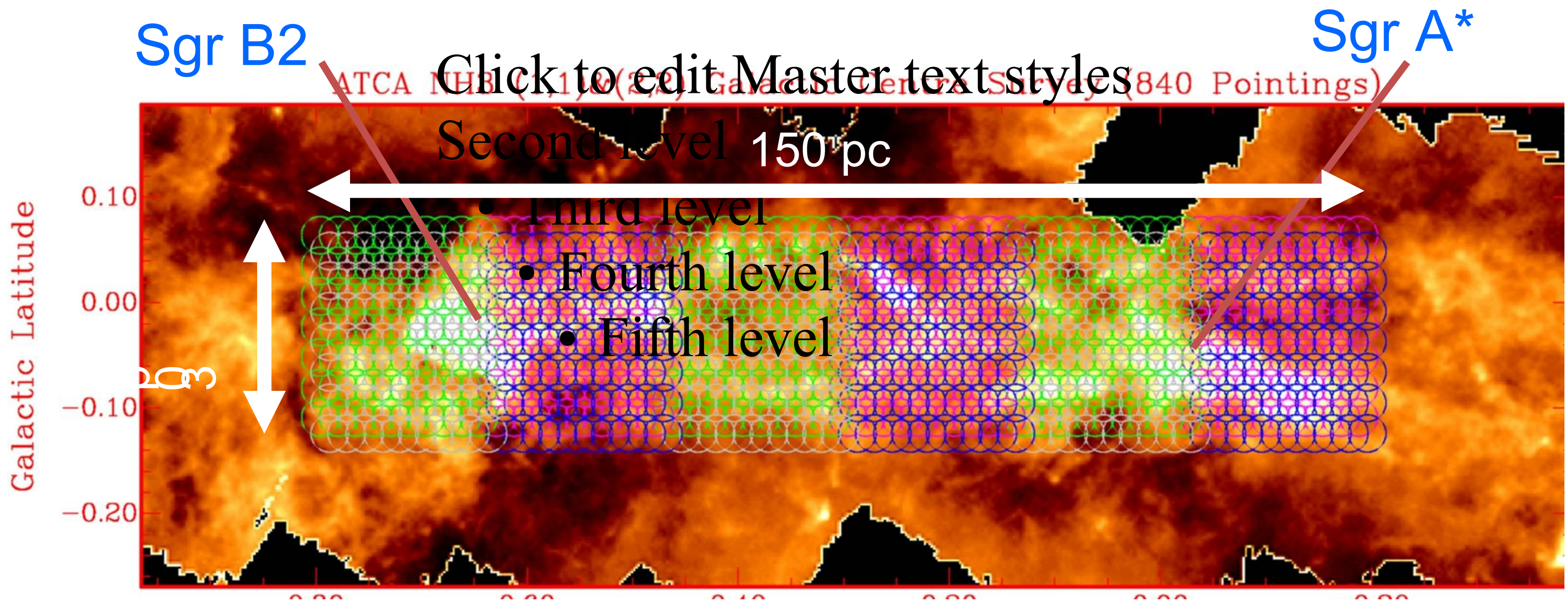
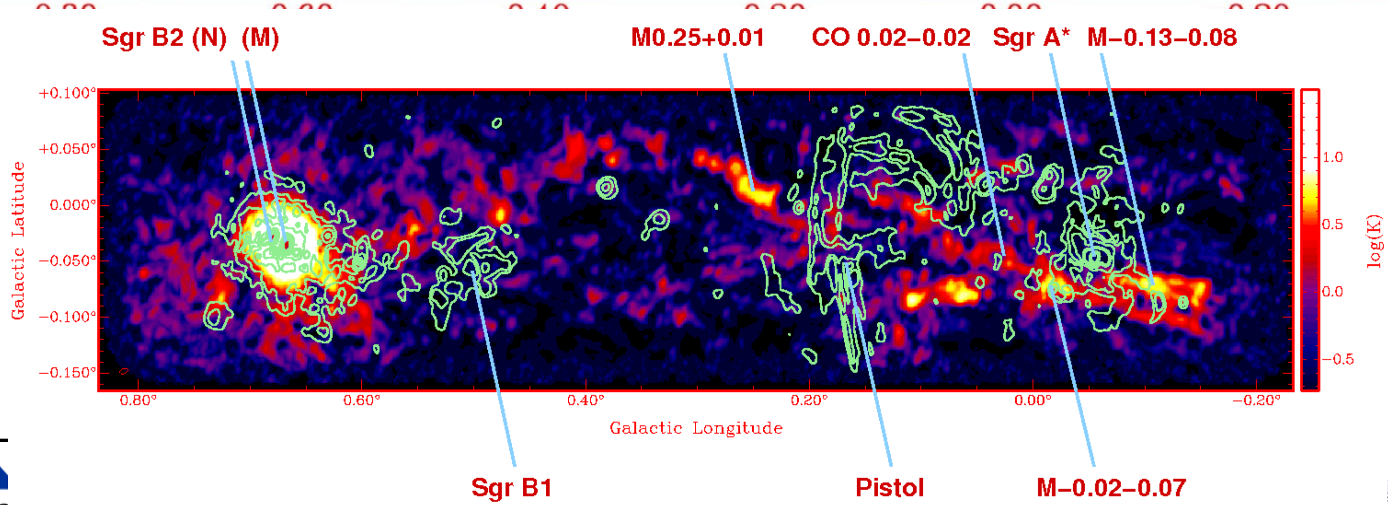
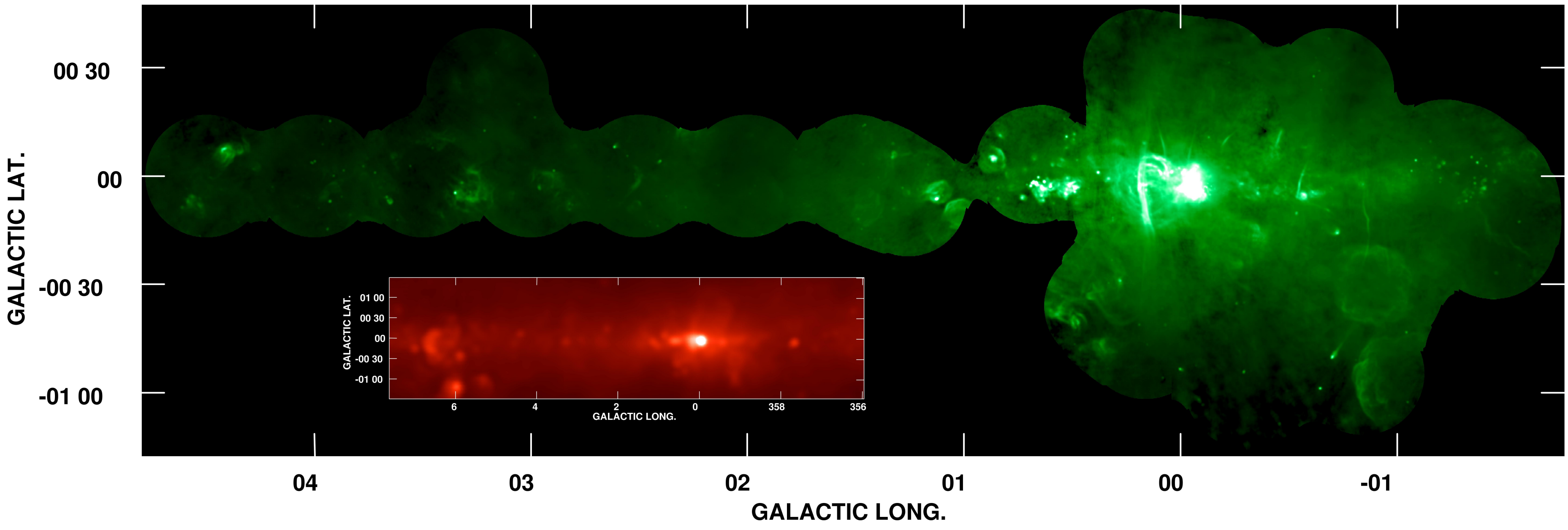




Galactic Center



Yusef-Zadeh et al.

Problems to solve

- Each primary beam has attenuation which needs to be accounted for
- Non-linearity in deconvolution process
- Obtain adequate sky coverage, try to keep Nyquist sampling when needed
- At high frequencies: atmospheric variation on small time scales
- Minimize drive time but maximize well spaced uv-coverage across map
- Gain some of the shorter spacings, maybe add single dish data for zero spacings

The effect of the Primary Beam

PB defined by single antenna (SD). Not by the array.

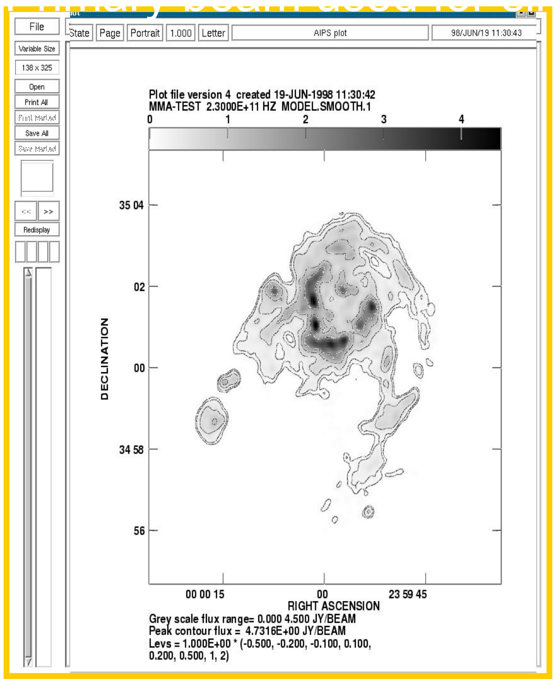
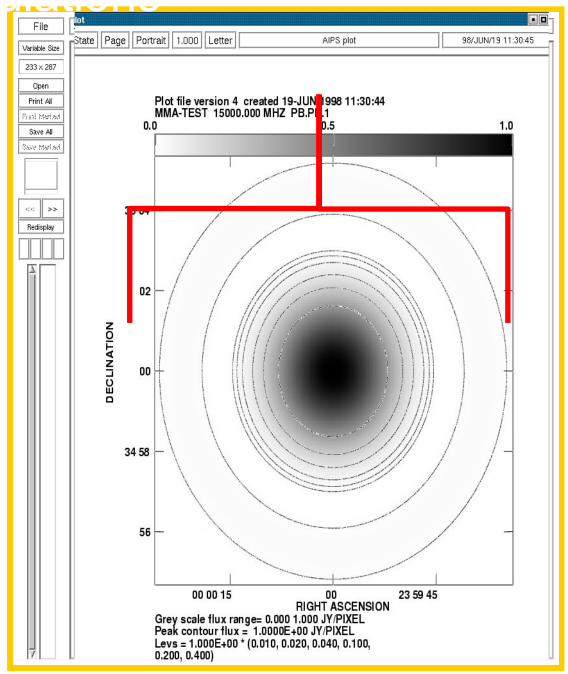
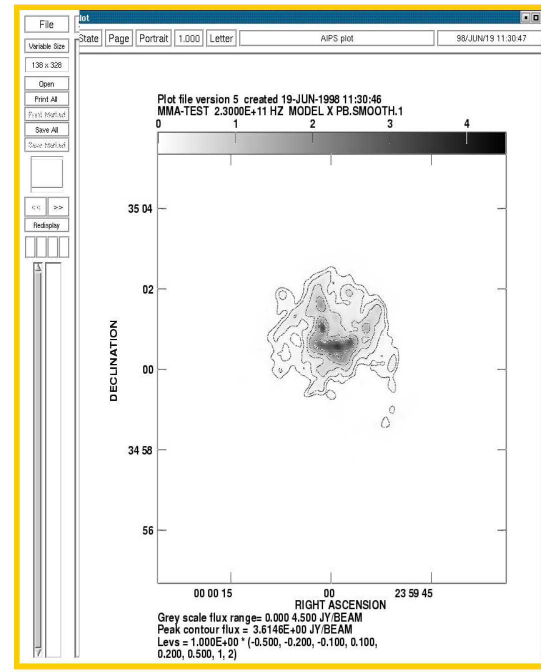


Image larger than PB



PB provides sensitivity pattern on sky



PB applied: sensitive to center only

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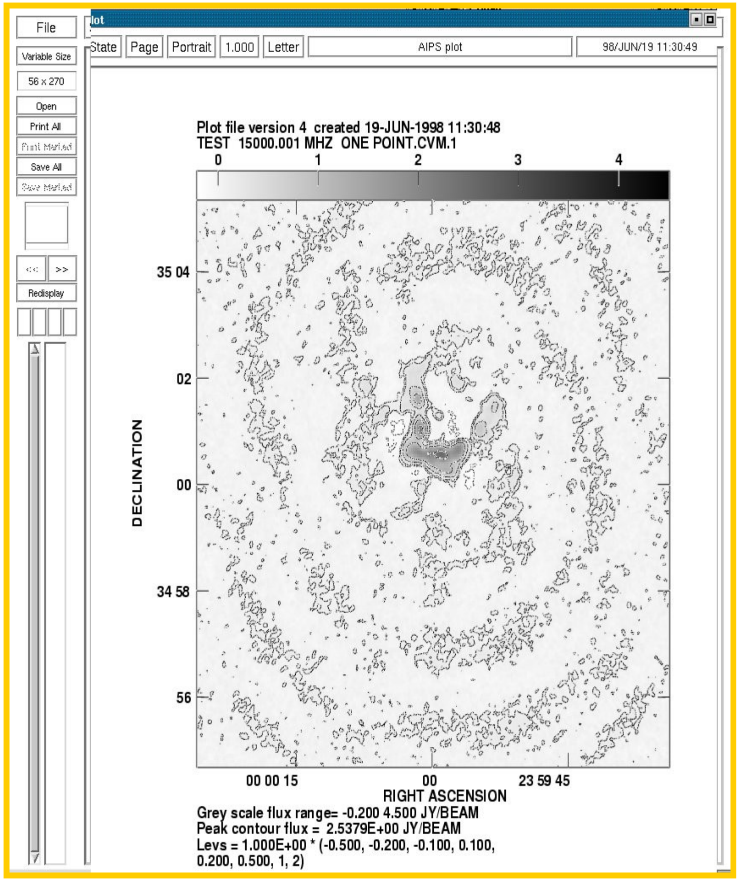
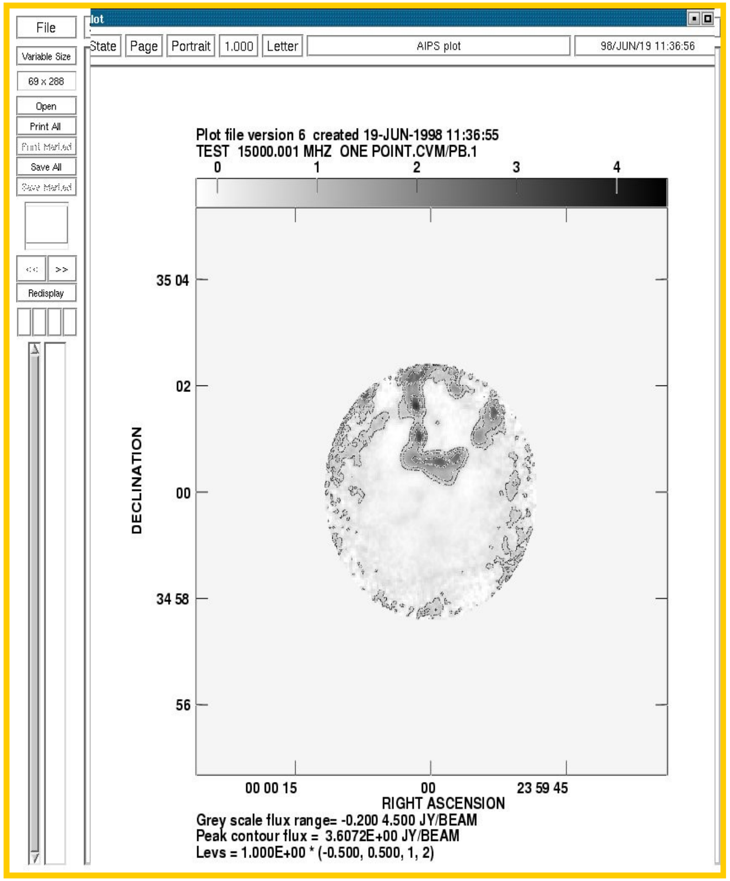
The effect of the Primary Beam



Noise before PB correction



PB correction changes noise characteristics

Stitching the maps together

3 main methods for mosaicing:

1) Linear combination of deconvolved maps
2) Joint deconvolution
3) Regridding of all visibilities before FFT

Mosaicing: Linear Combination of Images

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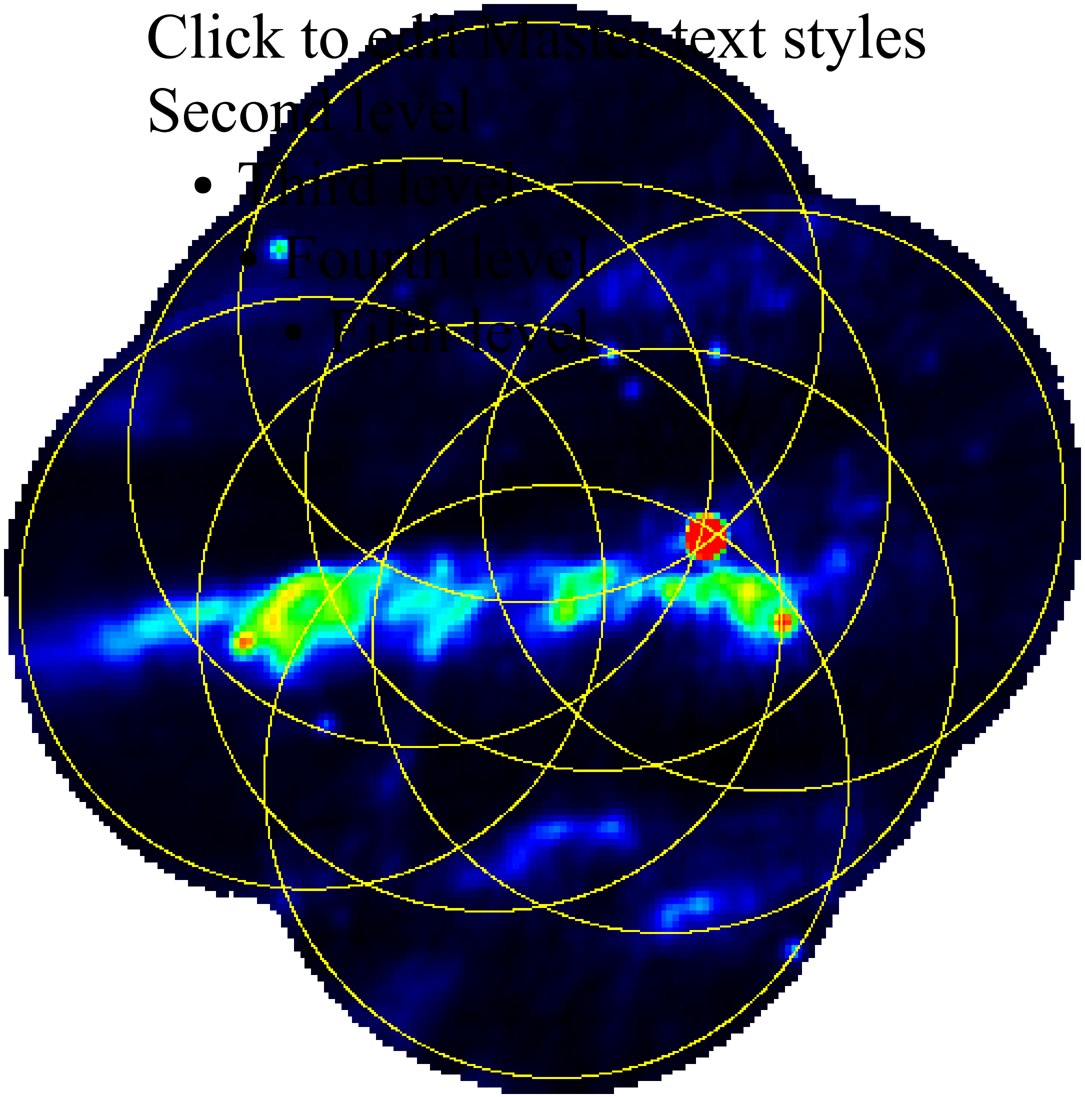
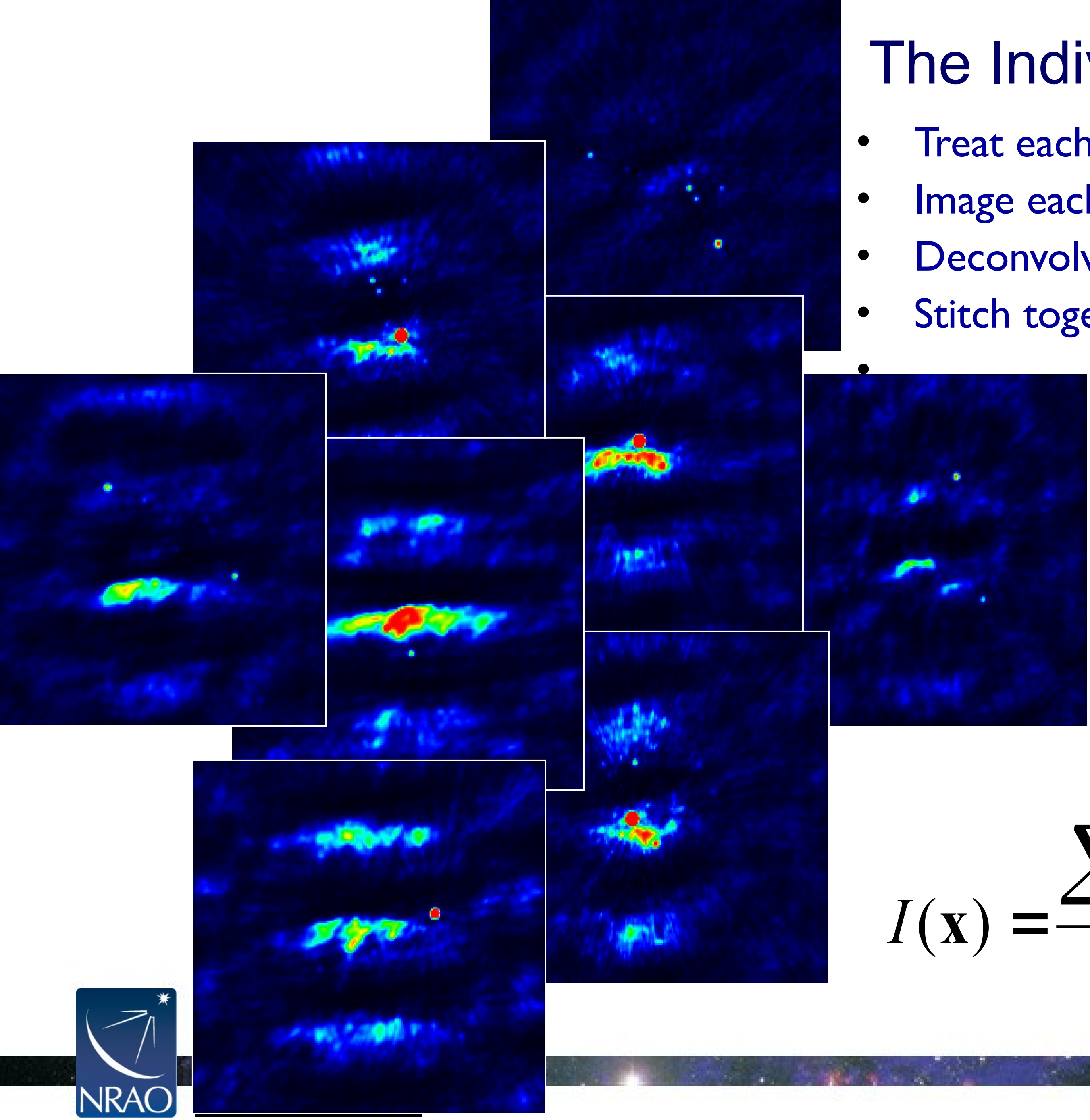
Second level

- Third level
  - Fourth level
    - Fifth level



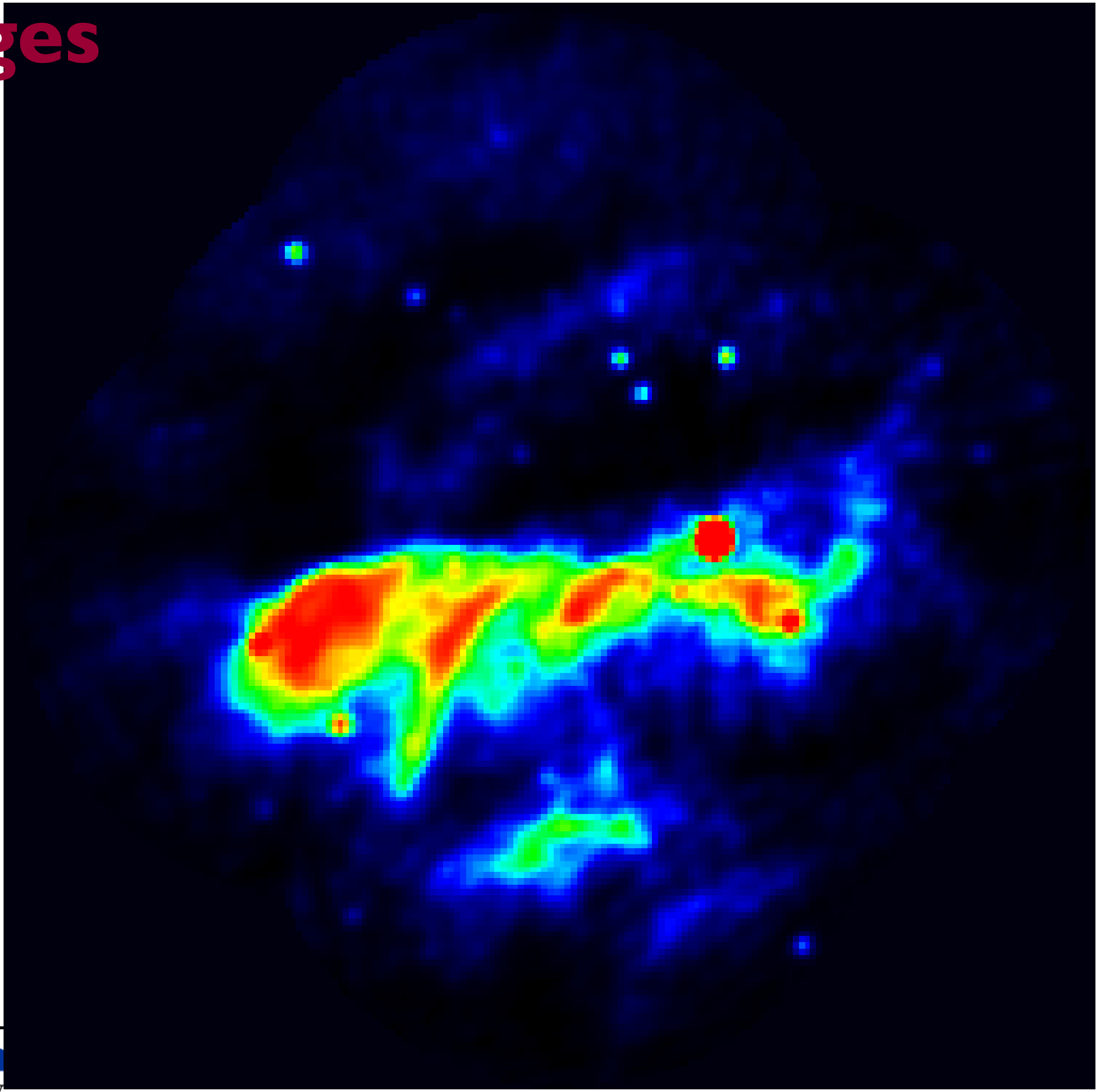
The Individual Approach

- Treat each pointing separately
- Image each pointing
- Deconvolve each pointing
- Stitch together linearly with weights
- for primary beam



$$I(\mathbf{x}) = \frac{\sum_p A(\mathbf{x} - \mathbf{x}_p) I_p(\mathbf{x})}{\sum_p A^2(\mathbf{x} - \mathbf{x}_p)}$$

Mosaicing: Linear Combination of Images



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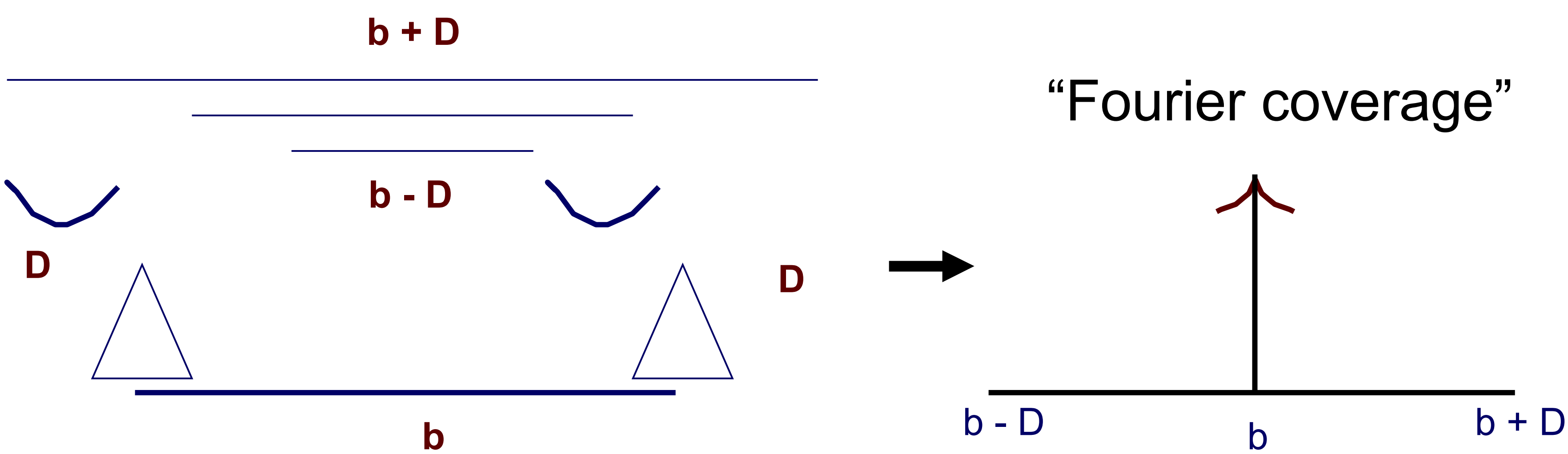
Mosaicing: Linear Combination of Images

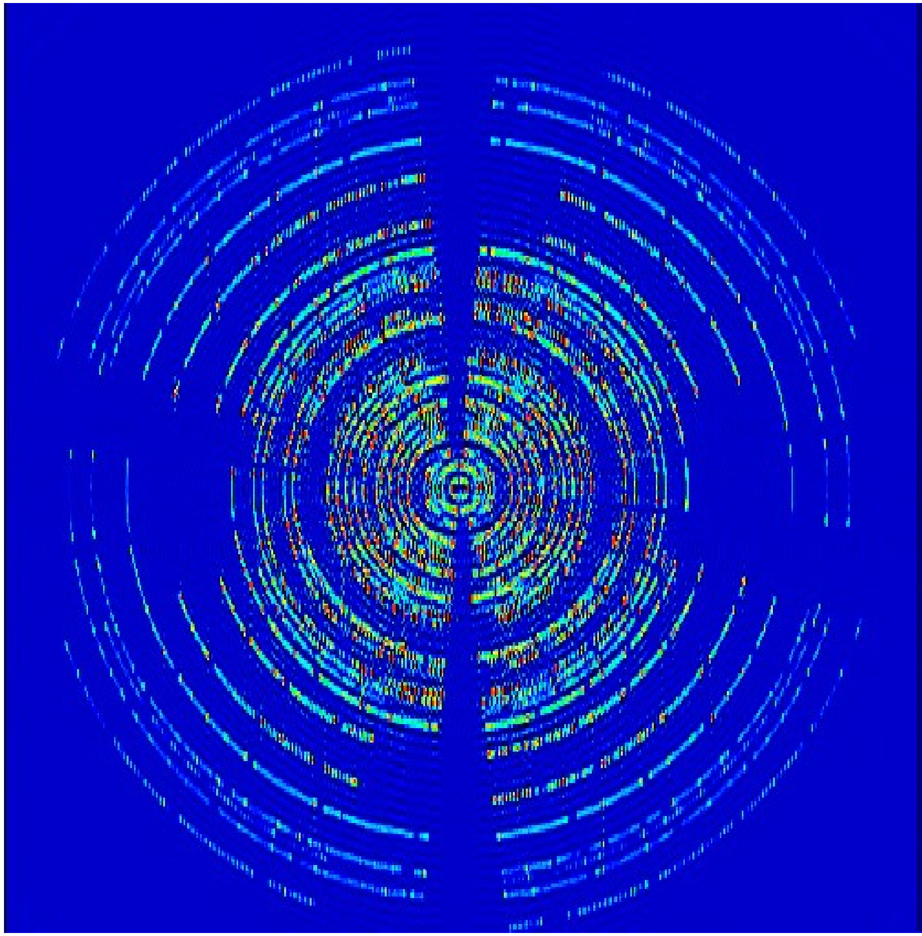
- Most straightforward method to create map
- But deconvolution is **non-linear**
- Artifacts, in particular at edges may creep in
- But still a very good method for high-dynamic range imaging
- One can manipulate every pointing extensively (e.g. solve for off-axis gains, like 'peeling')
- Depends less on exact knowledge of primary beam shape, as it is used typically only to the half power point

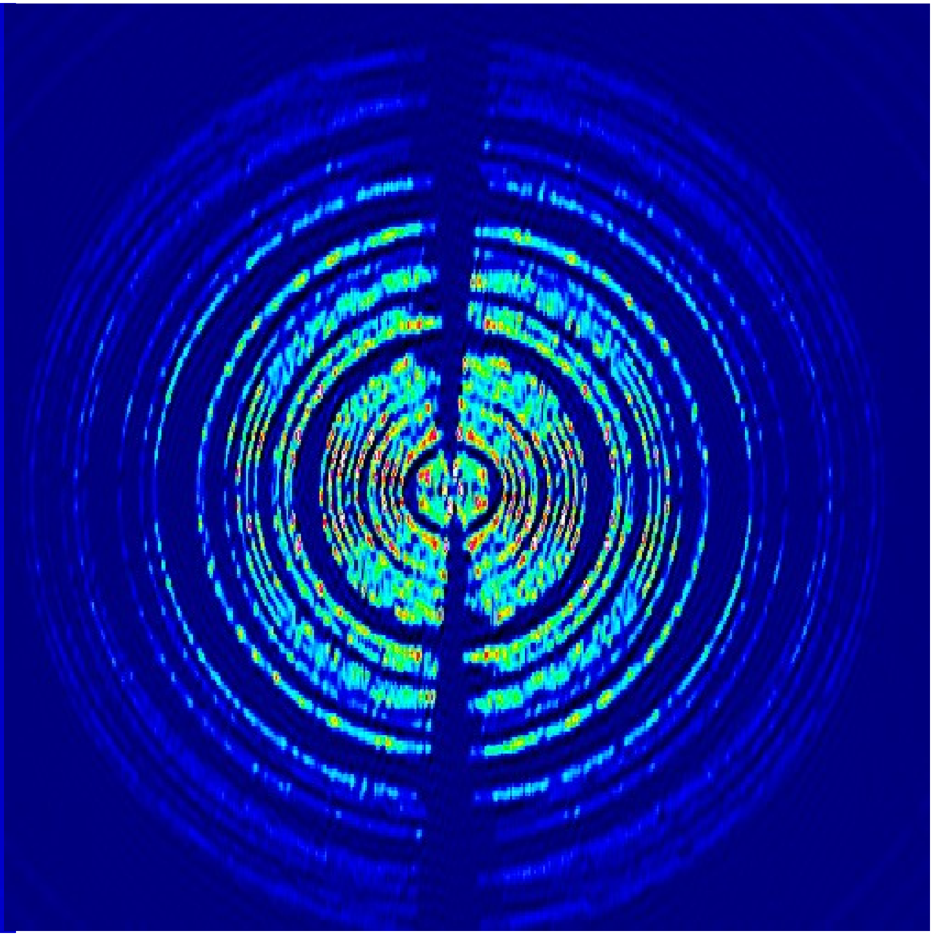
Ekers & Rots Theorem

Extended this formalism to interferometers to show that an interferometer doesn't just measure angular scales $q = l / b$ it actually measures $l / (b - D) < q < l / (b + D)$



Comparison of *u-v* coverage





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Ekers & Rots Theorem

But you can't get all that extra info from a single visibility

Interferometer measures a number per baseline not a range.

Same as with a single dish, you have to scan to get the extra "spacings"

Ekers & Rots showed that you can recover this extra information by scanning the interferometer

The sampling theorem states that we can gather as much information by sampling the sky with a regular, Nyquist spaced grid

Convolution of the FT of the primary beam with your uv plane

The Joint Approach

Form a linear combination of the individual pointings, p on

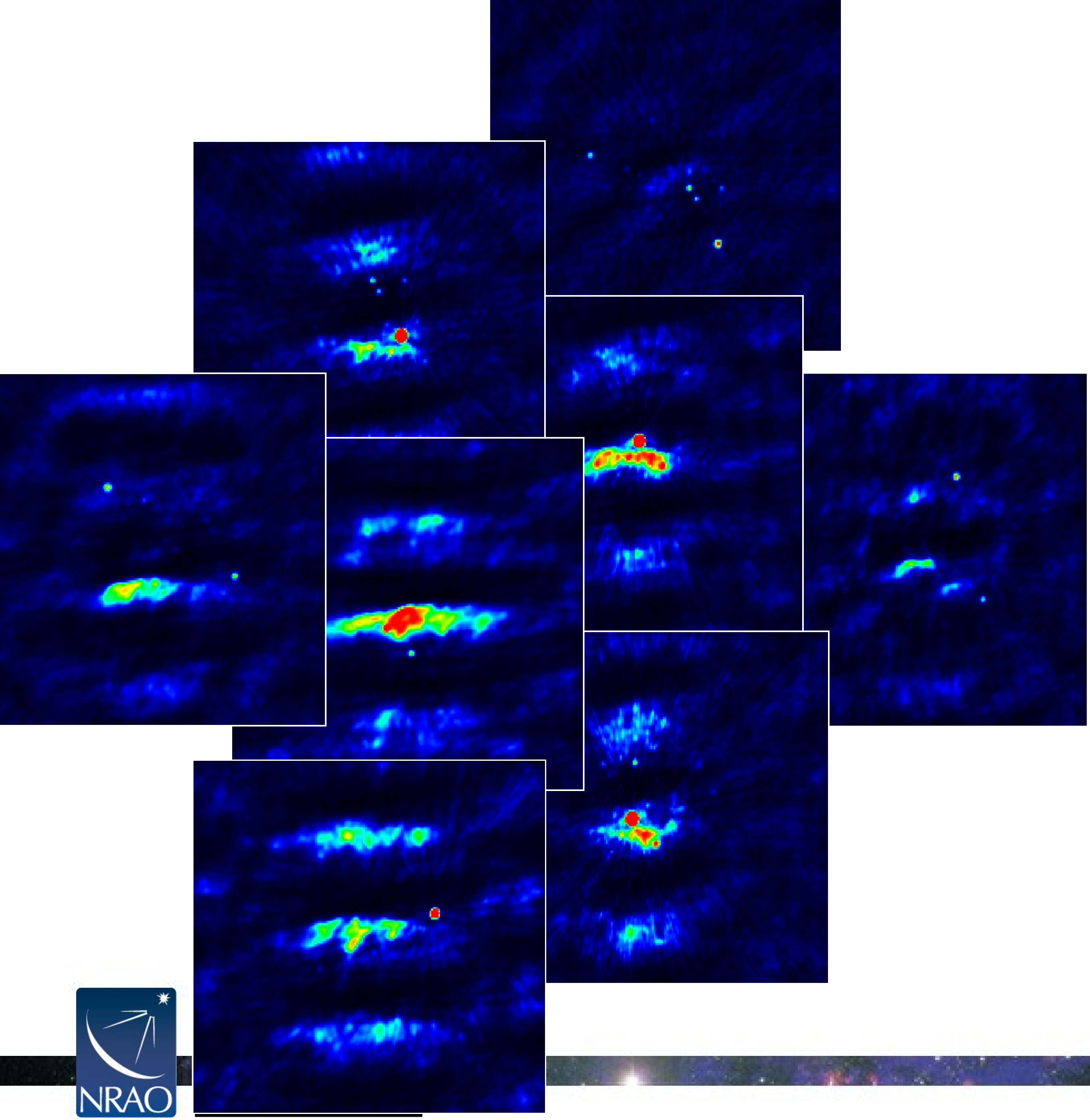
DIRTY IMAGE:

$$I(\mathbf{x}) = W(\mathbf{x}) \frac{\sum_p A(\mathbf{x} - \mathbf{x}_p) I_p(\mathbf{x}) / \sigma_p^2}{\sum_p A^2(\mathbf{x} - \mathbf{x}_p) / \sigma_p^2}$$

Here σp is the noise variance of an individual pointing and A(**x**) is the primary response function of an antenna (primary beam)

W(**x**) is a weighting function that suppresses noise amplification at the edge of mosaic

Sault, Staveley-Smith, Brouw (1996)



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Mosaicing: Joint Approach

Joint dirty beam depends on antenna primary beam, ie weight the dirty beam according to the position within the mosaiced primary beams:

$$B(\mathbf{x};\mathbf{x}_0) = W(\mathbf{x}) \frac{\sum_p A(\mathbf{x}_0 - \mathbf{x}_p) B_p(\mathbf{x} - \mathbf{x}_0) / \sigma_p^2}{\sum_p A^2(\mathbf{x} - \mathbf{x}_p) / \sigma_p^2}$$

Use all *u-v* data from all points simultaneously

Extra info gives a better deconvolution

Provides Ekers & Rots spacings and therefore better beam

Better for extended emission

But: overlapping pointings require knowledge of shape of PB further out than the half power point

Mosaicing Example

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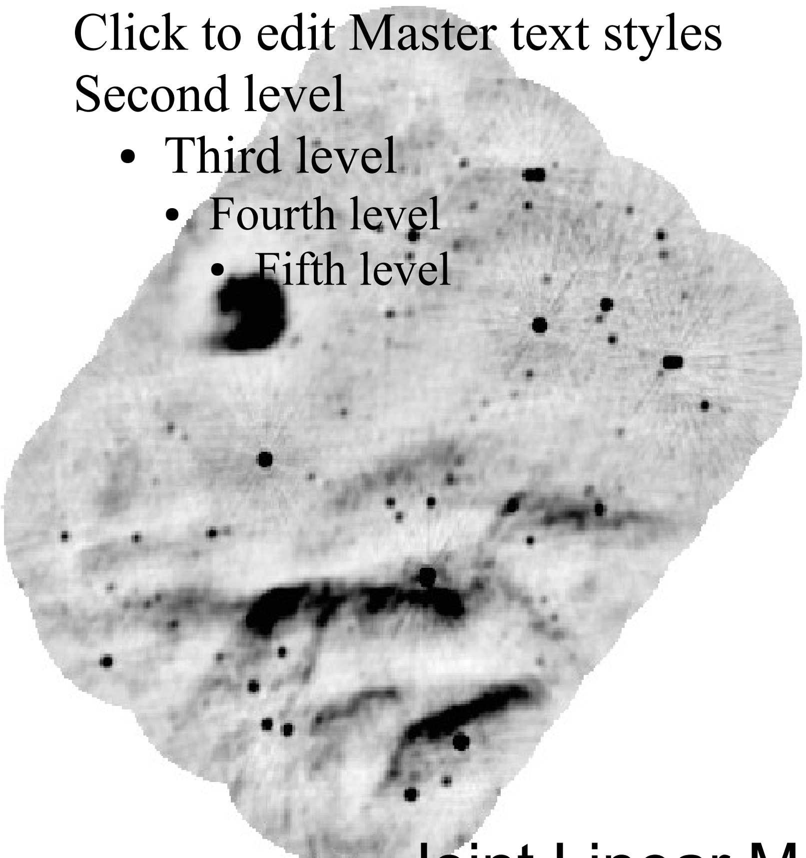
- Third level
  - Fourth level
    - Fifth level



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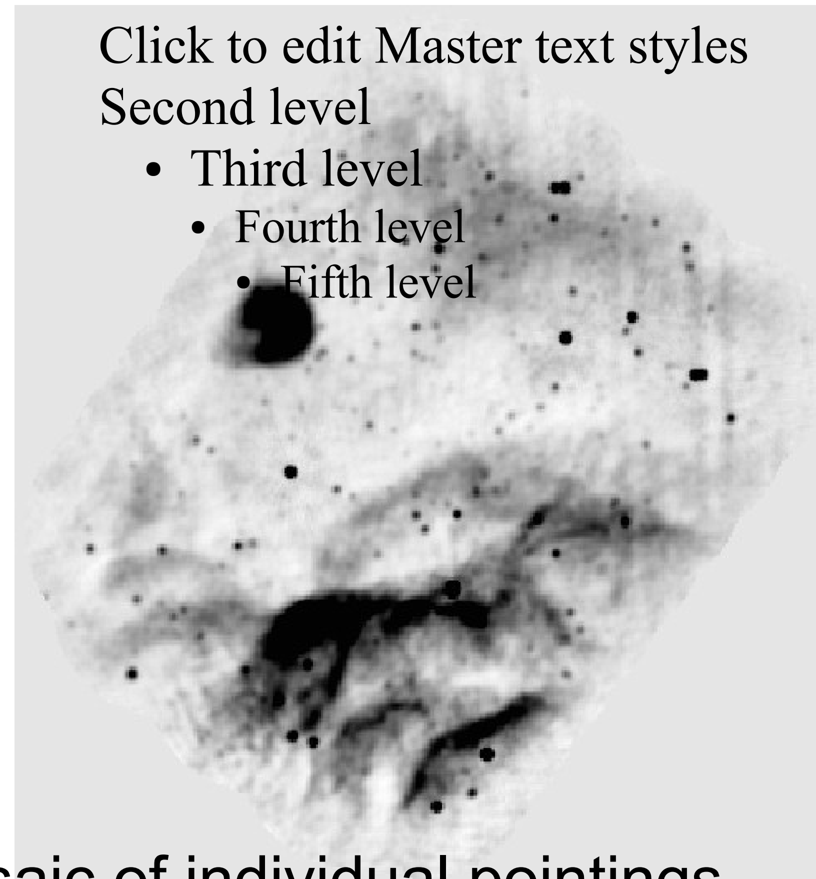


Joint Linear Mosaic of individual pointings

int Imaging and Deconvolution

Mosaicing: Comparison

Individual approach:

Disadvantages:

- Deconvolution non-linear (cleaning bowl)
- Overlap regions noisy (primary beam shape)

Advantage:

- Not susceptible to deconvolution errors due to poor primary model, so good for high-resolution, high-dynamic range images

Joint Approach:

Advantages:

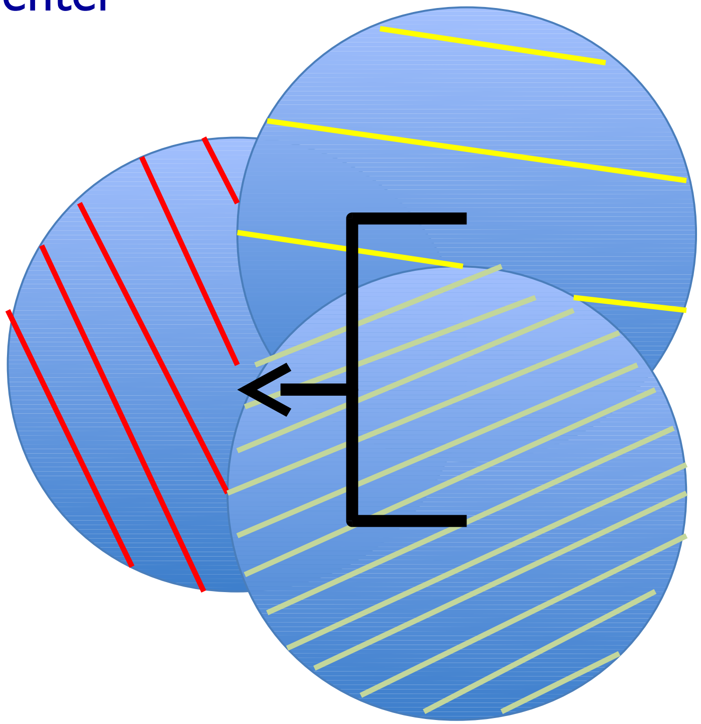
- Uses all u-v info -> better beam
- More large-scale structure

Disadvantage:

- Requires a good model for the primary beam

Widefield Imaging

- What if you have many many points? (e.g. OTFI)
- Take each uv data for each pointing and regrid to a common phase reference center



Then:
Regrid in Fourier domain

Widefield Imaging

- Next Step: Perform weighting for primary beam(s)
- Multiplication in image domain = convolution in FT domain

(+ weighting terms)

- The PBs for each pointing are identical but shifted
- FT of a shift is a phase gradient
- Sum of Phase gradient for each offset pointing * single FT{A} is the weighting for each visibility to correct for primary beams
- Deconvolution with synthesized beam of one of the pointings

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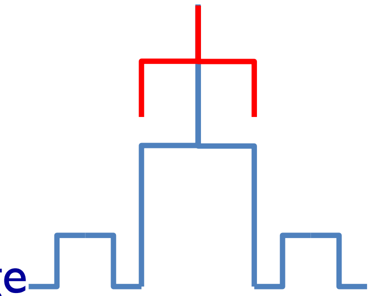
Deconvolution

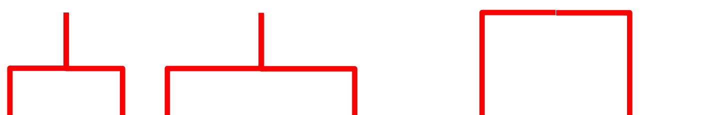
- Mosaics can be lots of point like sources but typically are performed for extended emission
- 3 main deconvolution algorithms

  (Preferably Cotton-Schwab, with small gain;

  FFT of major cycle will reduce sidelobes):
- **CLEAN:** subtract dirty beam (point sources) from dirty image



- **Multiscale clean**: Use a number of kernel sizes for different scales



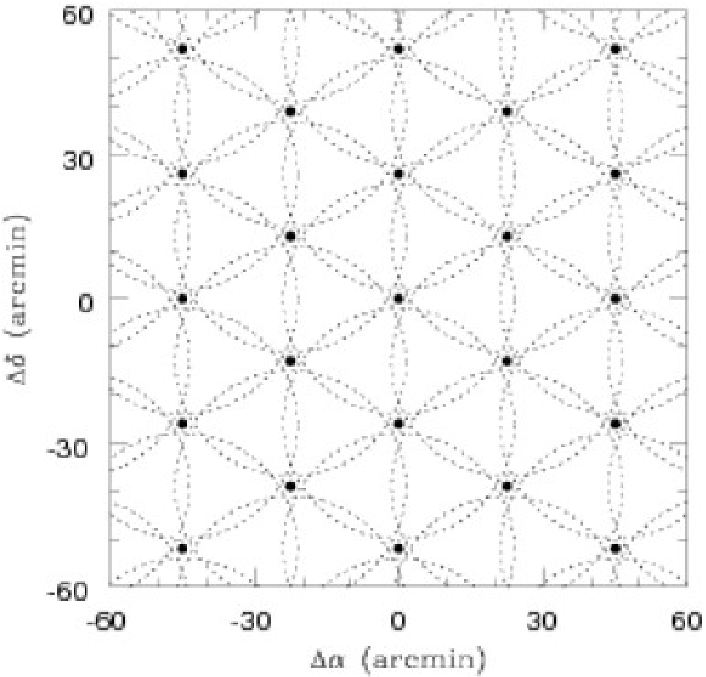
- **Maximum entropy**: iterate on minimizing c2 between

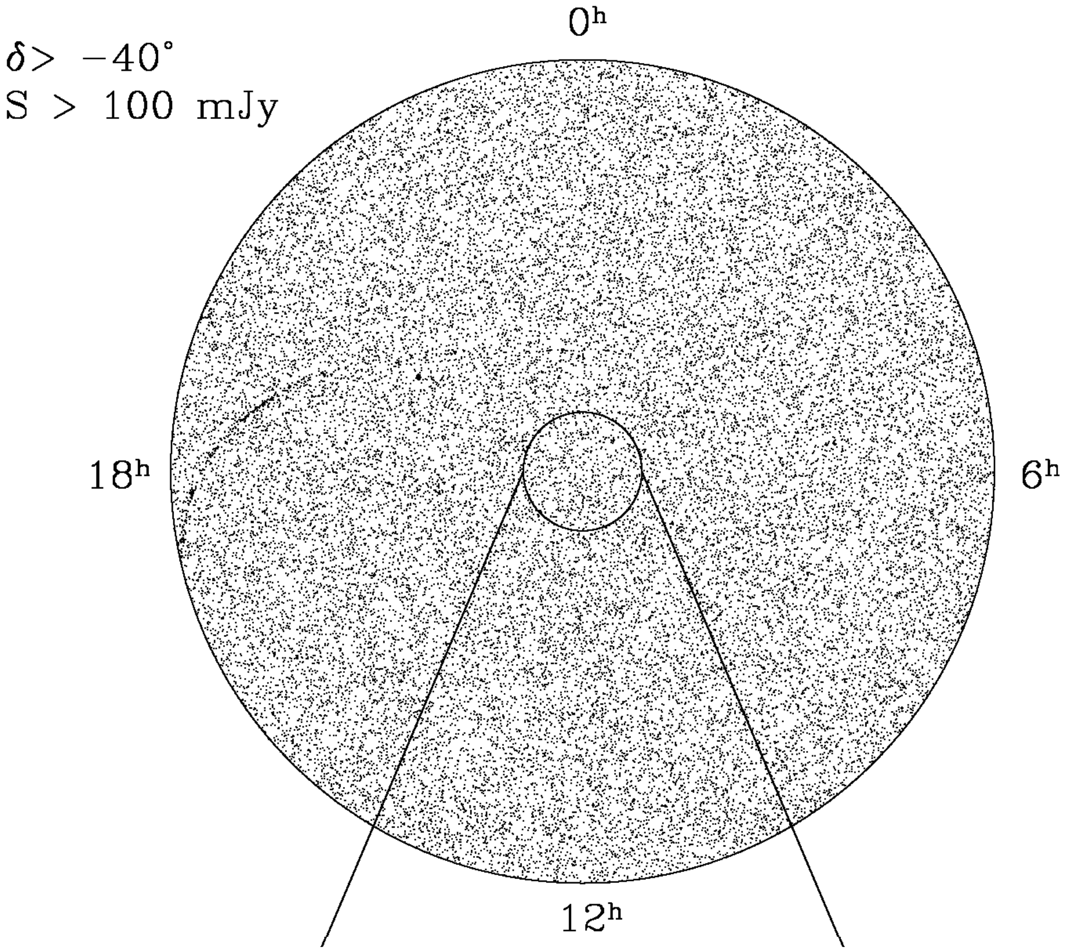
  data and a model

Mosaicing in CASA

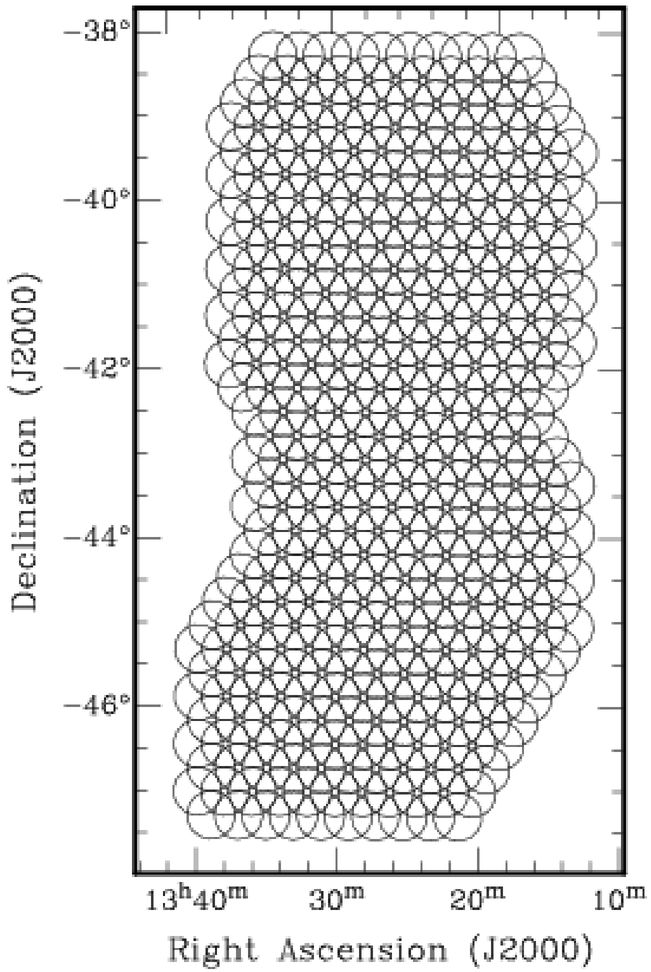
- Don't panic!
- Most of the tricky techniques are performed under the hood for your convenience
- Calibrate as you would do for a single pointing
- Use the **clean** task with your favorite parameters
- In *imagermode* use *'mosaic'*
- Use *ftmachine='ft'* for joint deconvolution, *'mosaic'* for the widefield imaging
- Use *psfmode='clark'* for Cotton-Schwab Algorithm
- Fill in *'multiscale'* parameters (scales) for MS Clean
- Maximum Entropy and linear mosaicing of cleaned images is available from the CASA toolkit at this stage

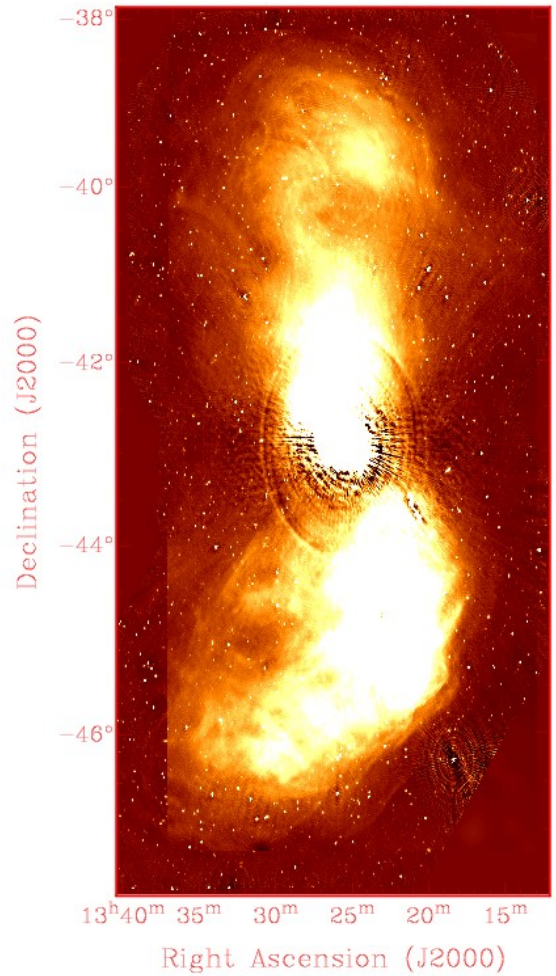
NVSS: 217,446 pointings





Centaurus A 406 pointings





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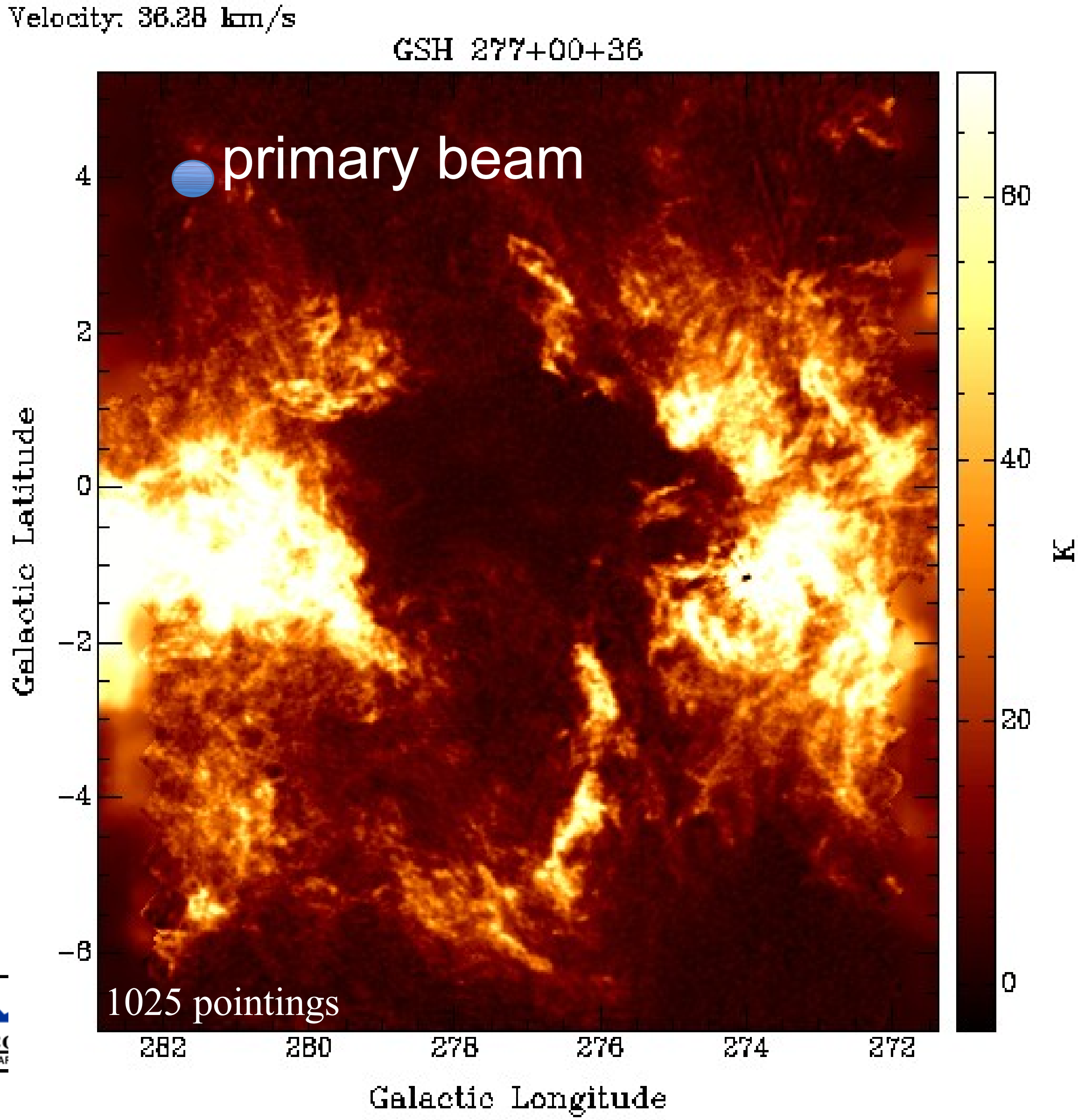
Southern Galactic Plane Survey



Practical Considerations

What grids to use?

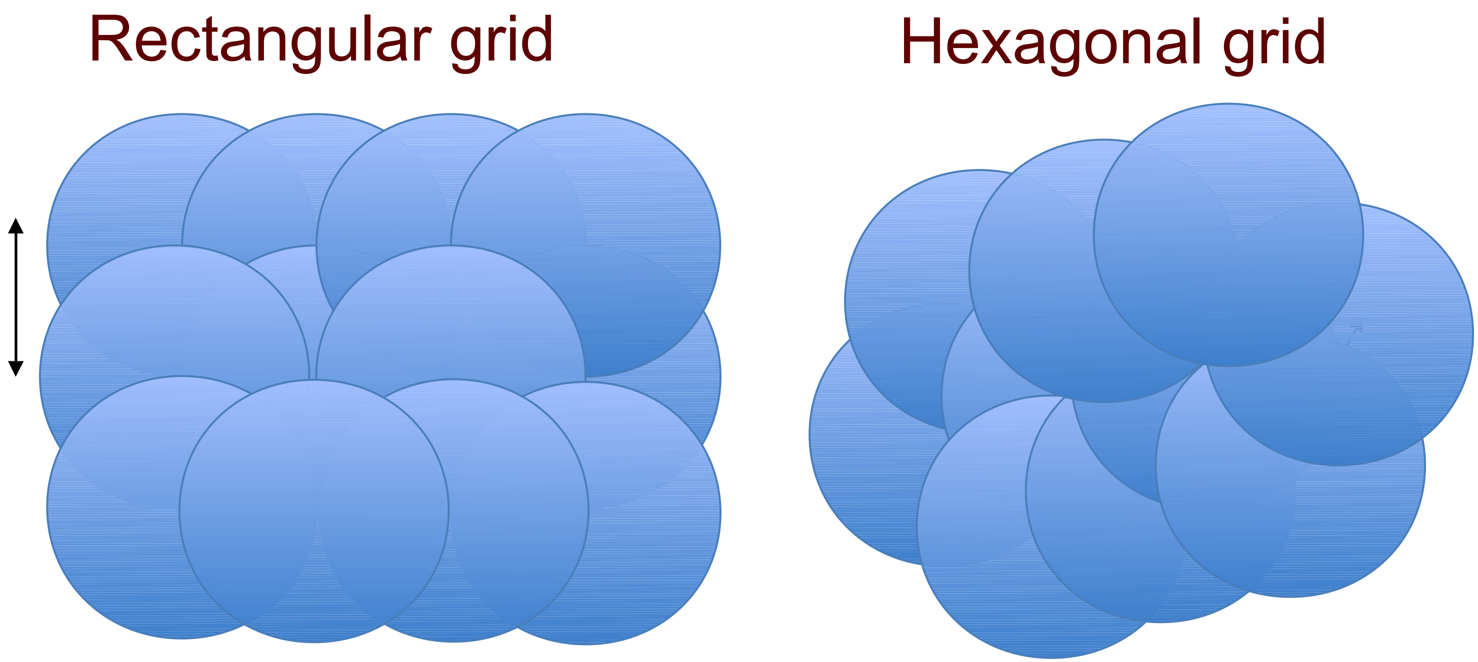
How often to come back to a individual pointing

Slew time of Antennas

Change of atmospheric conditions

Practical Consideration: Choice of Grid

- Different ways to layout the grid on the sky:
- Nyquist sampling:



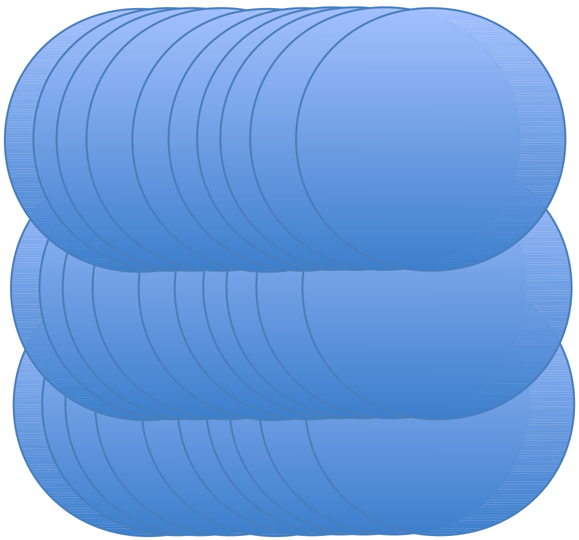
Nyquist for structure information recovery, but some areas only covered by single pointing

Oversampled but every position at least covered twice

Practical Consideration: Choice of Grid

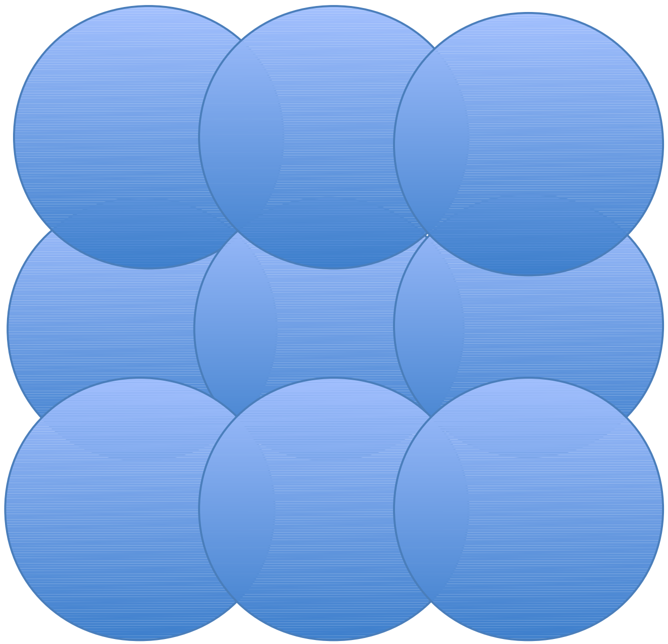
- On-The-Fly Interferometry
- Non-Nyquist sampling

OTF



Scan does not stop
fast dumping of data

Non-Nyquist



Basic Sky coverage

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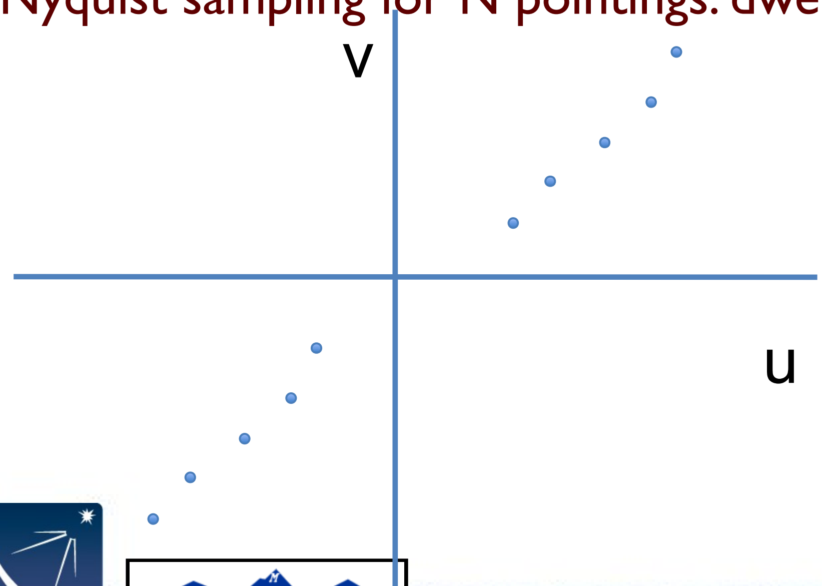
Complete *u-v* sampling

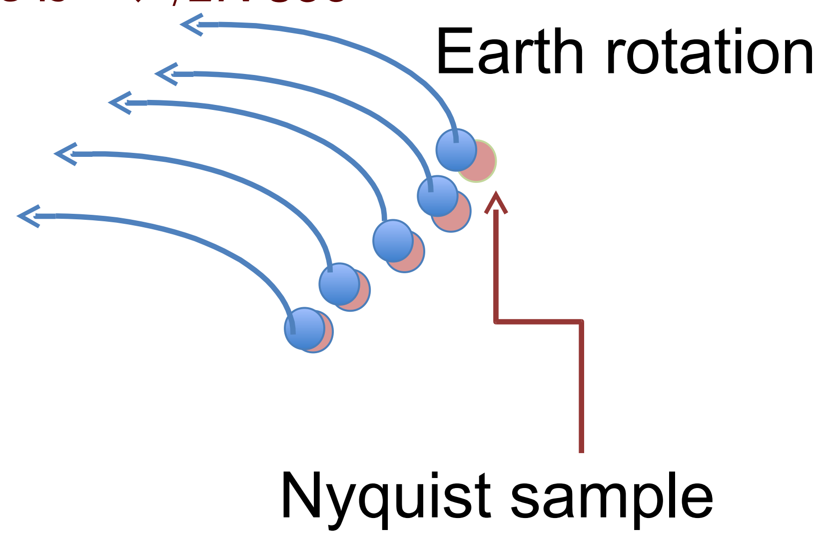
One baseline measures region in *u-v* plane with size 2*D*

Want adjacent samples to be completely independent

At transit, the time between independent points is ⟐ = (86400 / 2□)(2*D* / *L*) sec, where *D* = antenna diameter, *L* = longest baseline

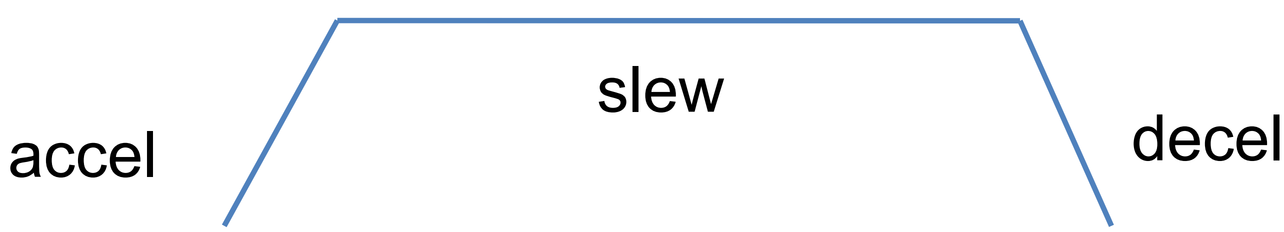
Nyquist sampling for N pointings: dwell time is ⟐ /2*N* sec



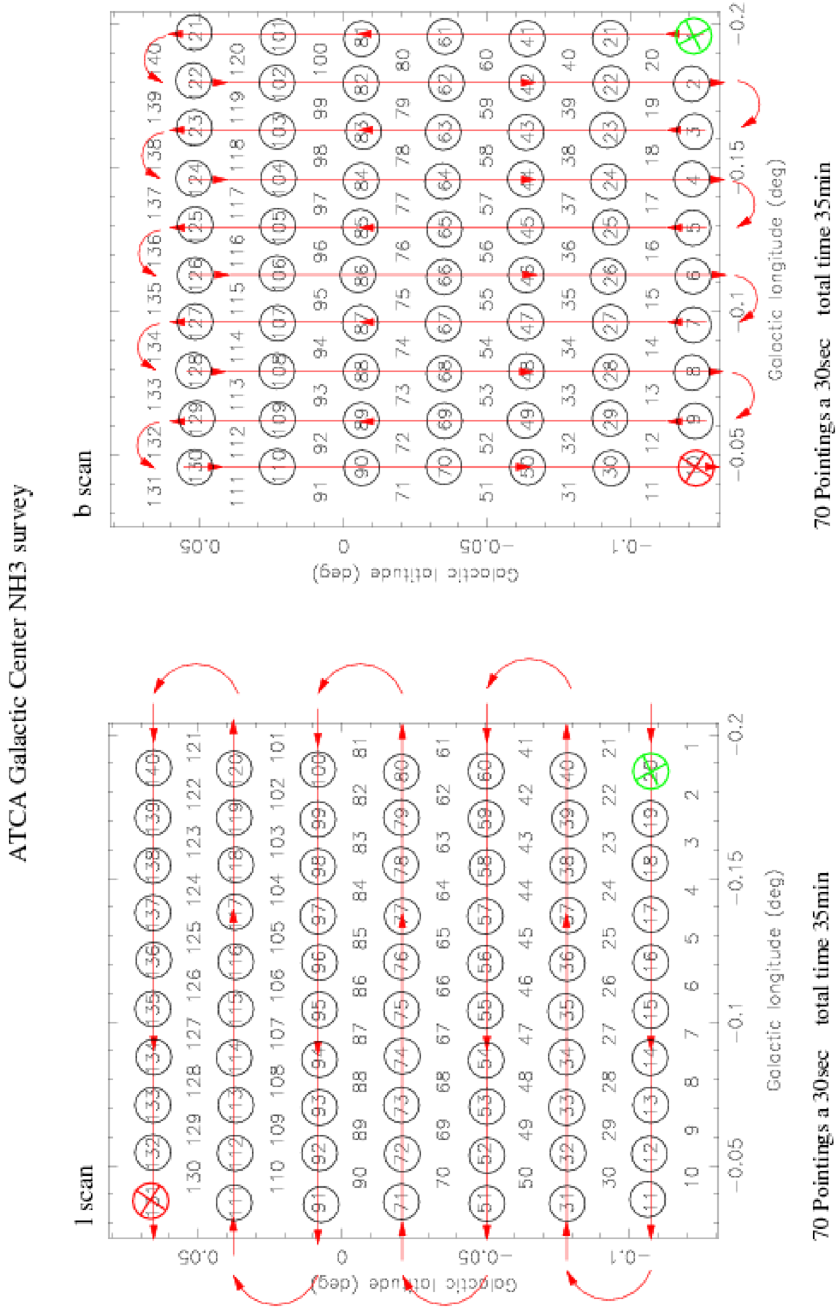


Practical Consideration: Slew Time

- Telescope slew times are calculated by:
- Acceleration
- Constant Slew velocity
- Deceleration
- Settling time
- Some telescopes may have variations in Az and El
- EVLA: acceleration: 0.2 deg s-2, slew rate: 20 deg min-1 in El, 40 in Az
- ALMA: acceleration: 24 deg s-2, slew rate 180 deg min-1 in El, 360 in Az



Practica


ATCA Galactic Center NH3 survey
b scan
l scan
Galactic longitude (deg)
Galactic latitude (deg)
70 Pointings a 30sec total time 35min
70 Pointings a 30sec total time 35min

Practical Consideration: Changing Atmosphere

- The water content of the atmosphere can change on small timescales
- In particular variations in individual cells
- On long baselines this can lead to:
- Variations in opacity
- Larger phase noise

It may be advisable to:

- Slew fast. Try to cover the full mosaic more frequently
- This will make the map more uniform

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Mosaicing Practicalities

Sensitivity concerns

Time per pointing reduced, but adjacent pointings contribute so for a fixed time observation the total noise is

$$\sigma_t \sim \sigma_p \sqrt{n} / 1.4$$

where n is the number of pointings

Mosaicing requires a good model of the primary beam

Pointing errors can significantly impact your mosaic

Pointing errors are **first order in mosaics** (only second order in single pointing obs of sources smaller than primary beam)

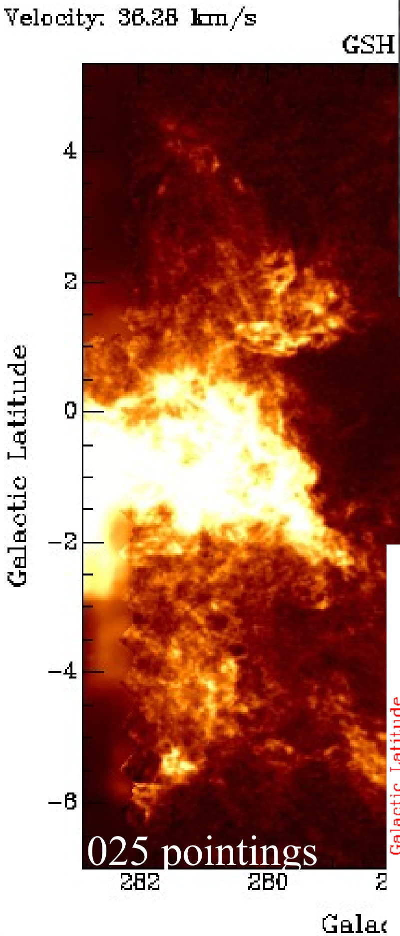
Solution: do reference pointing at higher frequencies

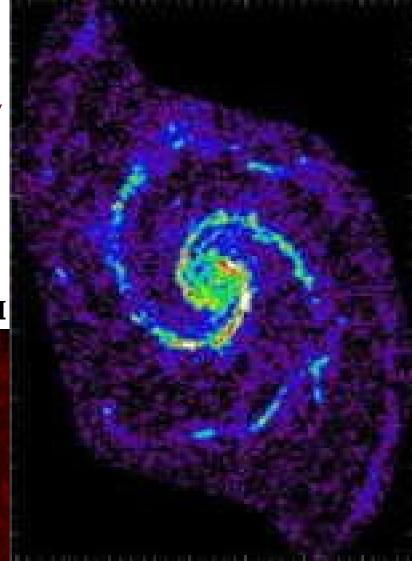
Summary

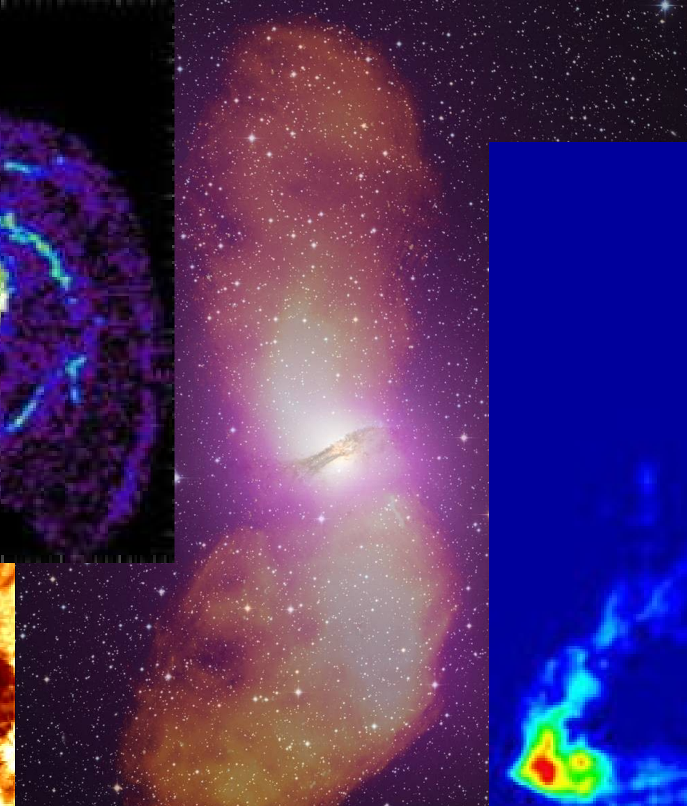
- Mosaicing is a technique to image objects much larger than the primary beam
- Unlocks additional uv spacings added by single dish elements
- Needs a bit of care to setup
- Mosaicing techniques will be used very commonly in the future:
- ALMA will work mostly in mosaic mode: primary beam @ band 3 (3mm) about 1 arcminute, band 9 (600GHz) about 10 arcsec! ☾ **mosaicing becomes more important at smaller wavelengths**
- SKA demonstrators cover large areas at once, but aim for frequent full sky coverage (ASKAP, MWA, MEERKAT, …)

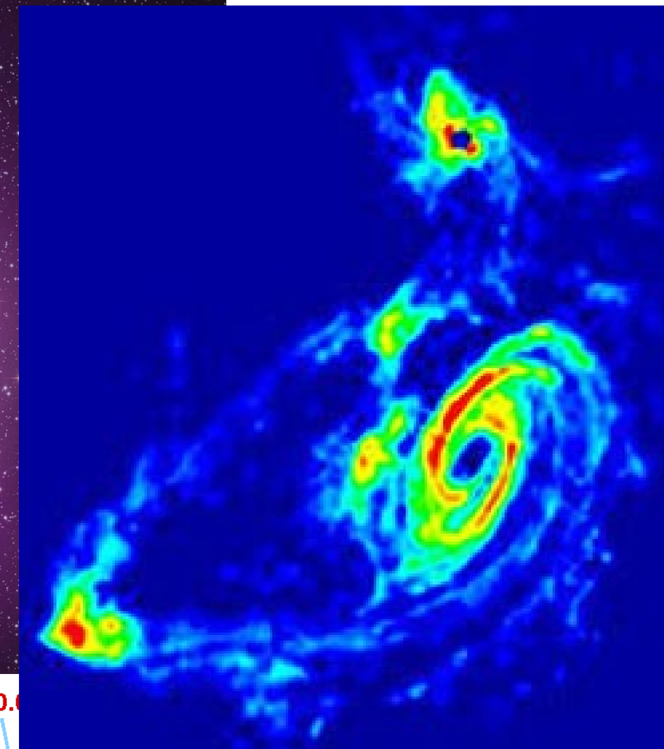
- Fun to reduce and you will obtain beautiful images!

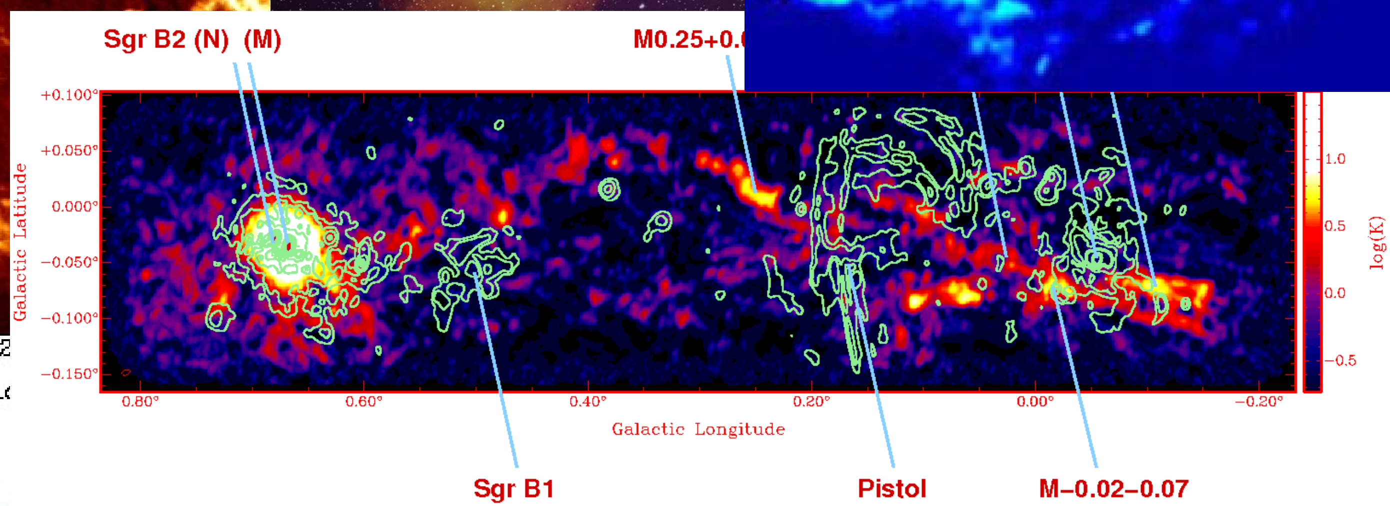
Summary











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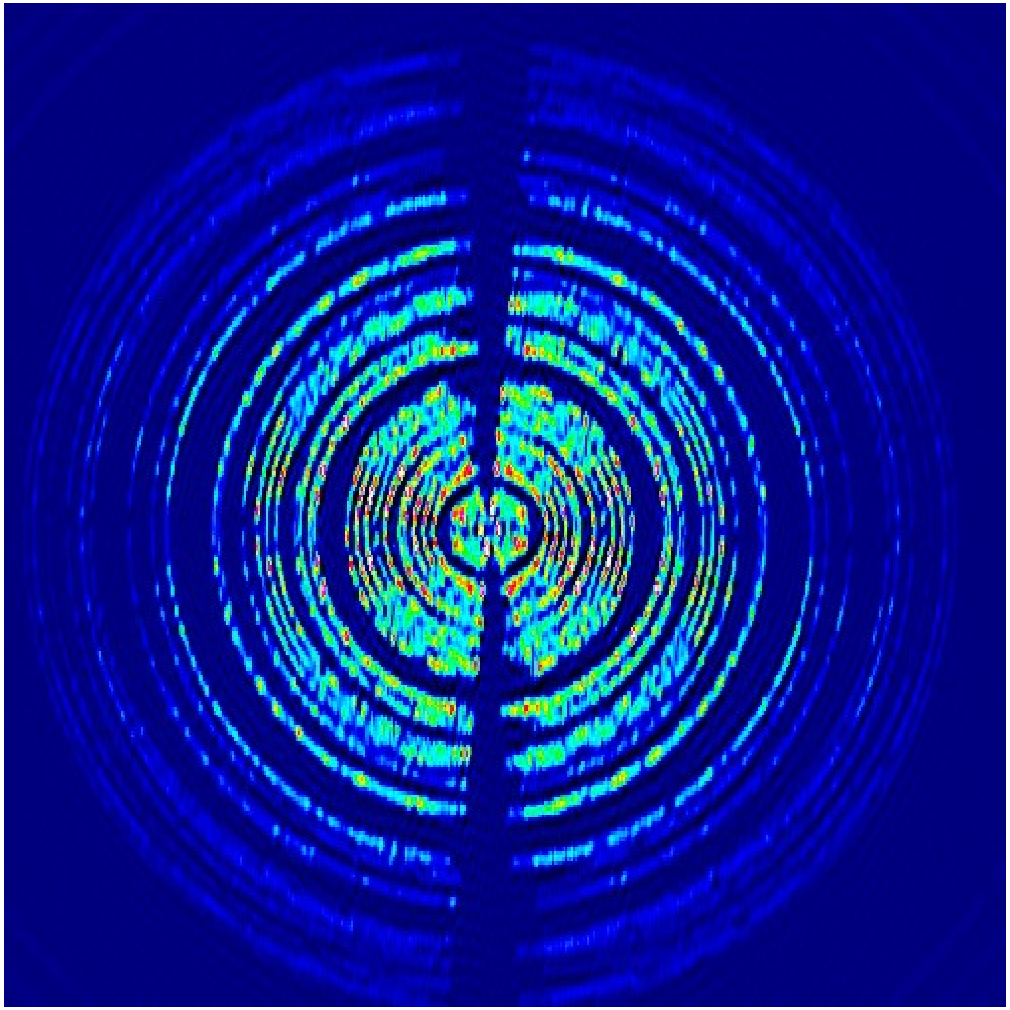
Is that all? No – add in zero spacings

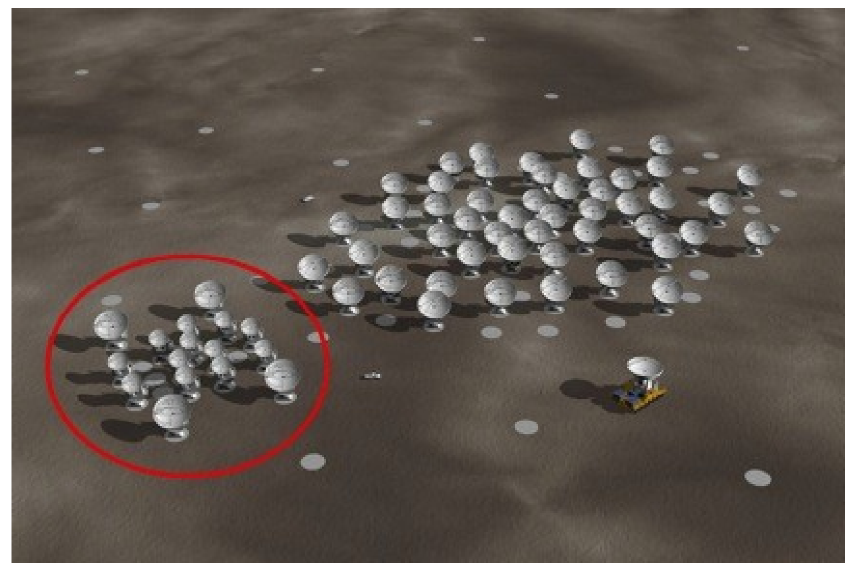



Looks unimportant, but the hole is where the flux of the entire map is defined!!
Zero spacings, can only be recovered by a single dish telescope

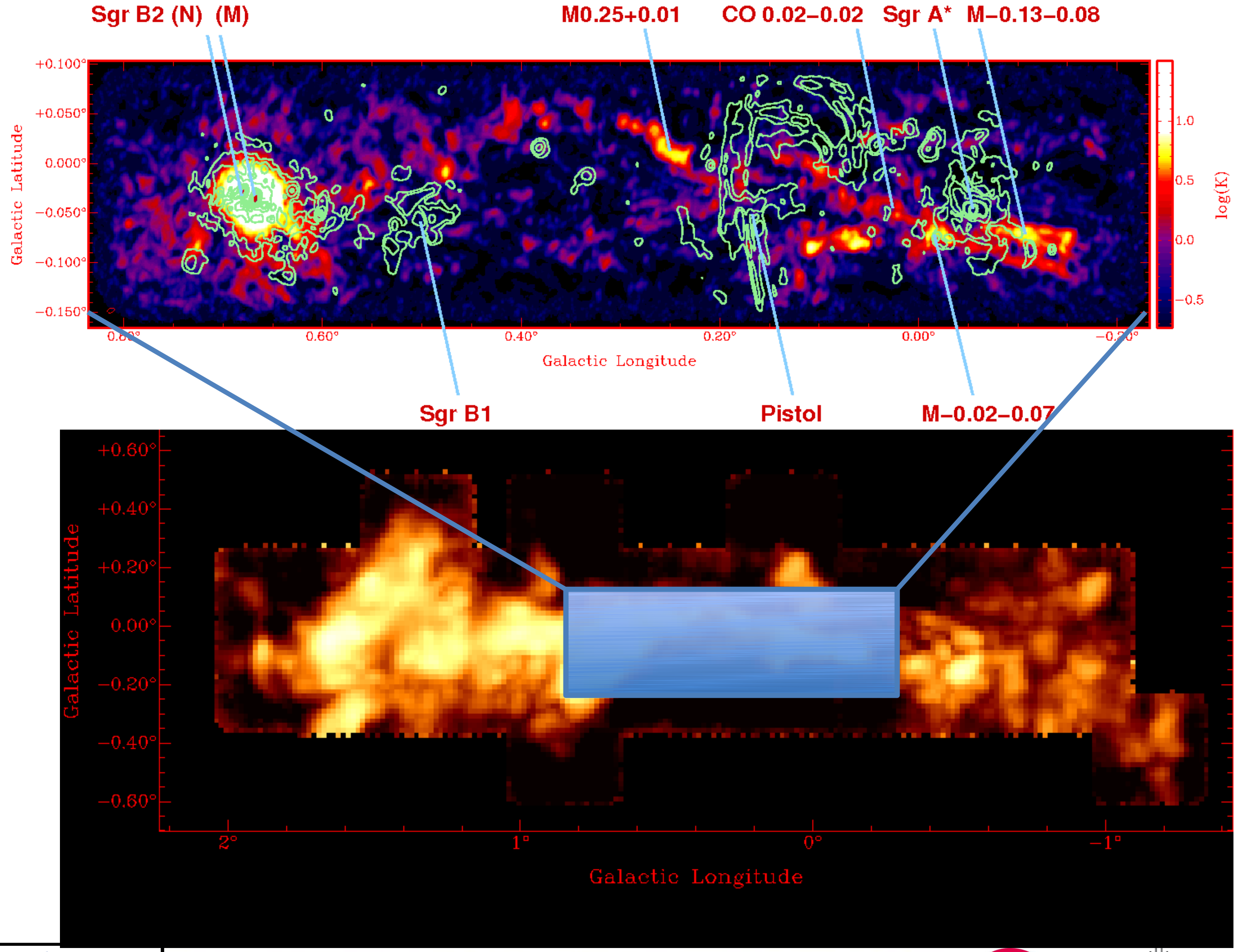
Heterogeneous Arrays

- Mix small and large antennas as a compromise between sensitivity and field of view
- Regain smaller spacings

CARMA=OVRO(10m)+BIMA(6m) ALMA(12m)+ACA(7m)



Zero spacing correction



Zero spacing correction

- Get an interferometric observation!
- Go to a single dish and map the same region, use a SD with a diameter larger than the shortest baseline of your interferometric map
- Aim for same surface brightness sensitivity at shortest BL and SD
- Calibrate, calibrate, calibrate!
- 3 basic methods:

1) FT SD map ☾ combine with UV data of interferometer ☾ FT to image ☾ deconvolve with combined dirty beam
2) Get your interferometric map ☾ deconvolve, it will extrapolate the center ☾ FT back to FT domain ☾ cut out the central info as clean is only an extrapolation ☾ replace by SD FT and ☾ FT back to image
3) Use the SD map as a model for deconvolution with maximum entropy/feather

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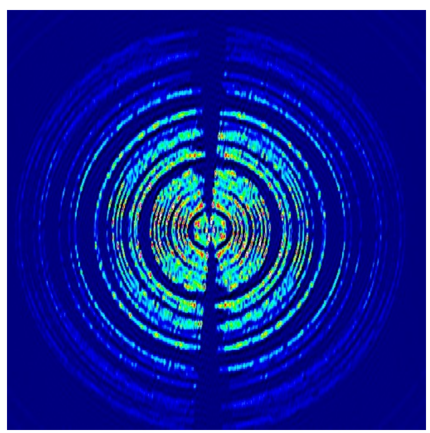
Zero spacing correction

l) FT SD map ☾ combine with UV data of interferometer ☾ FT to image ☾ deconvolve with combined dirty beam

\+ =



\+ weighting

Zero spacing correction

I) Clean you interferometric map ☾ deconvolve, it will extrapolate the center ☾ FT back to FT domain ☾ cut out the central info as clean is only an extrapolation ☾ replace by SD FT and ☾ FT back to image