Single-Dish Mapping Techniques

Alyson Ford (NRAO – Green Bank)

Why make maps?

Why make maps?

- Survey large areas
  - to find new objects
  - to obtain large, unbiased samples

Why make maps?

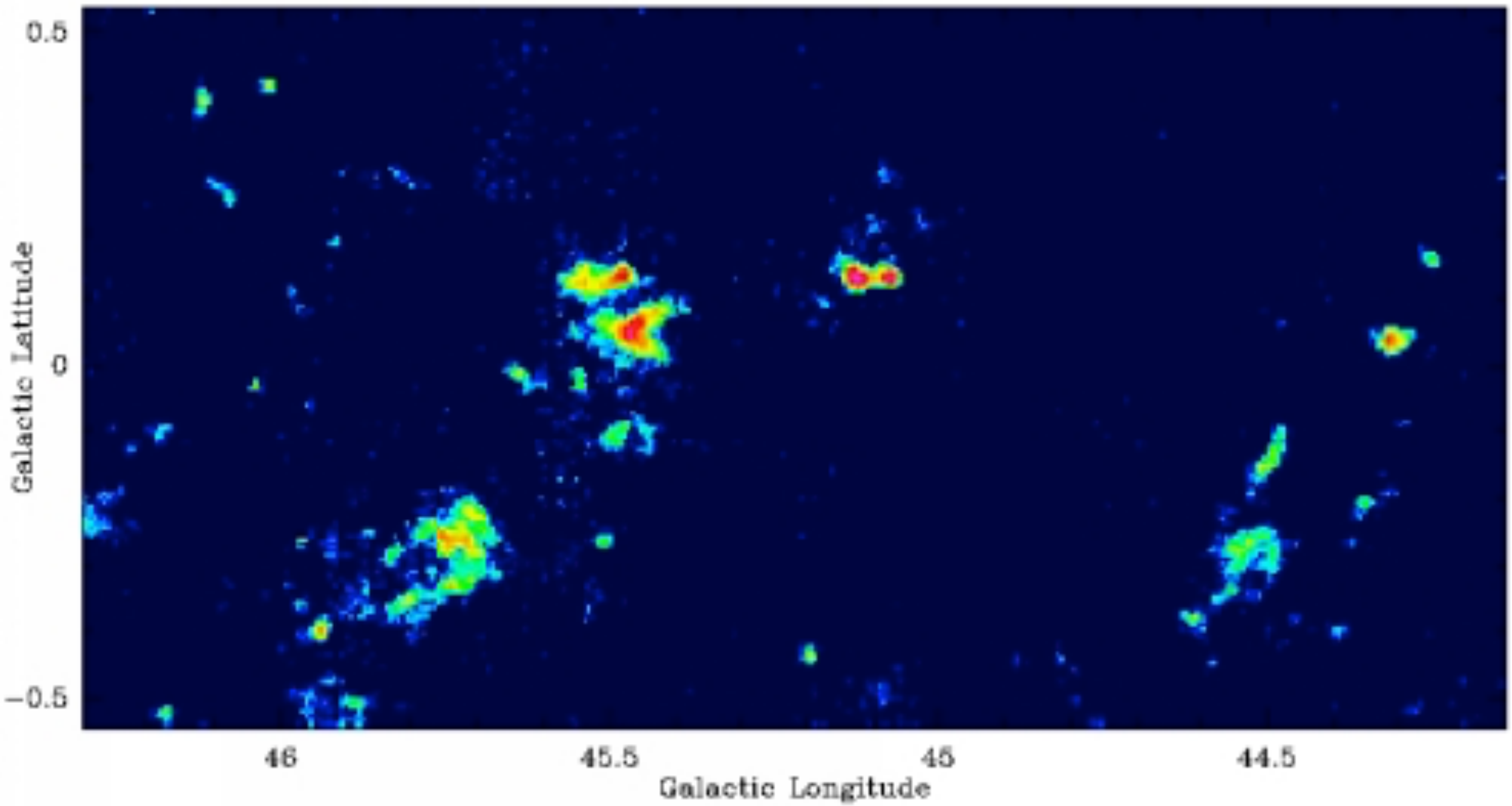
- Survey large areas
  - to find new objects
  - to obtain large, unbiased samples
- Study the structure of extended objects

Why single-dish telescope maps?

- Larger collecting area = better sensitivity
- Find diffuse emission
- Large structures are resolved out by interferometers

- In combination with interferometers, even more improved maps can be made (see A. Kepley's talk)

Maps



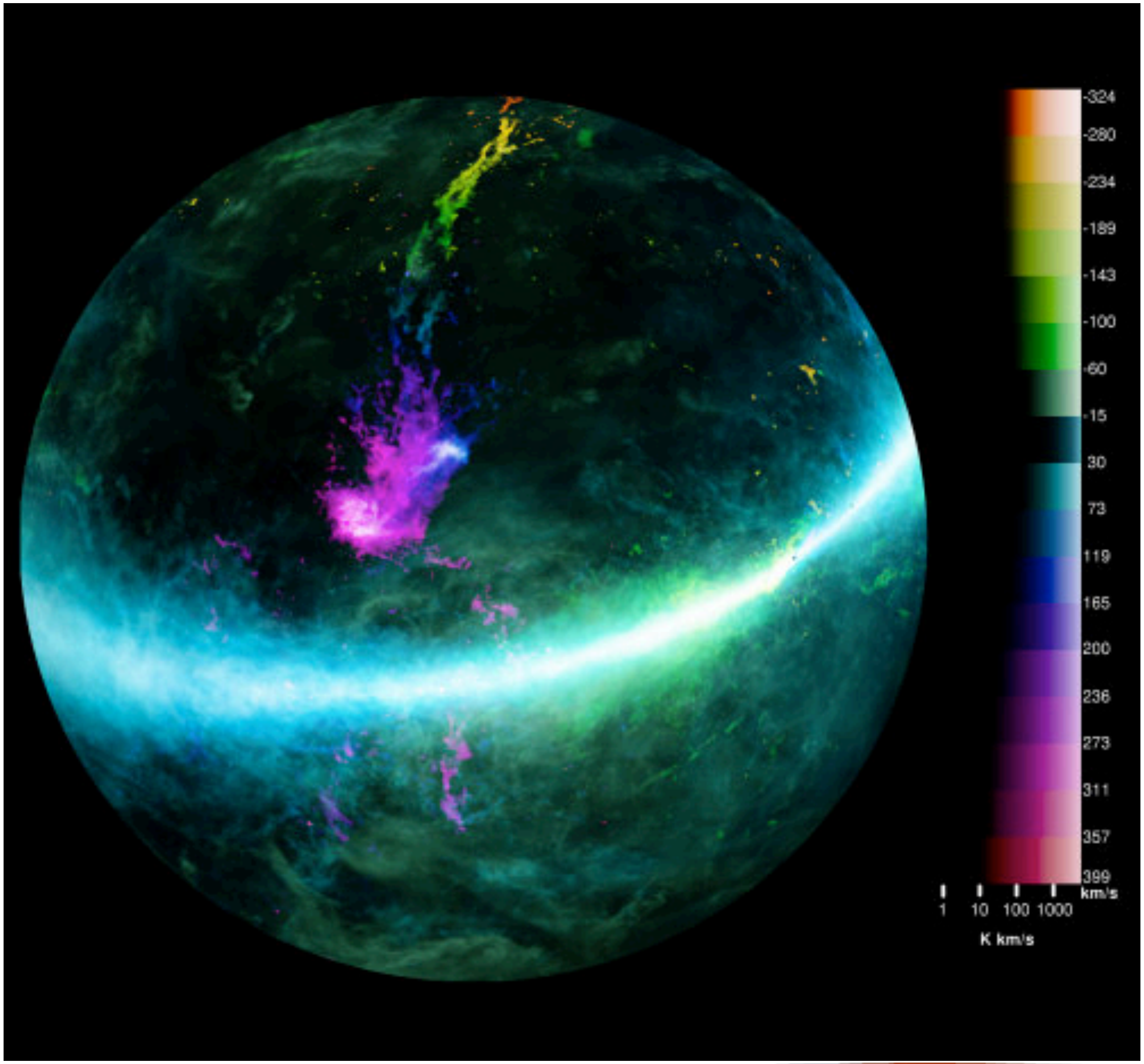
Locating dense star-forming cores in a giant molecular cloud, traced by CS (McQuinn et al. 2002).

Maps

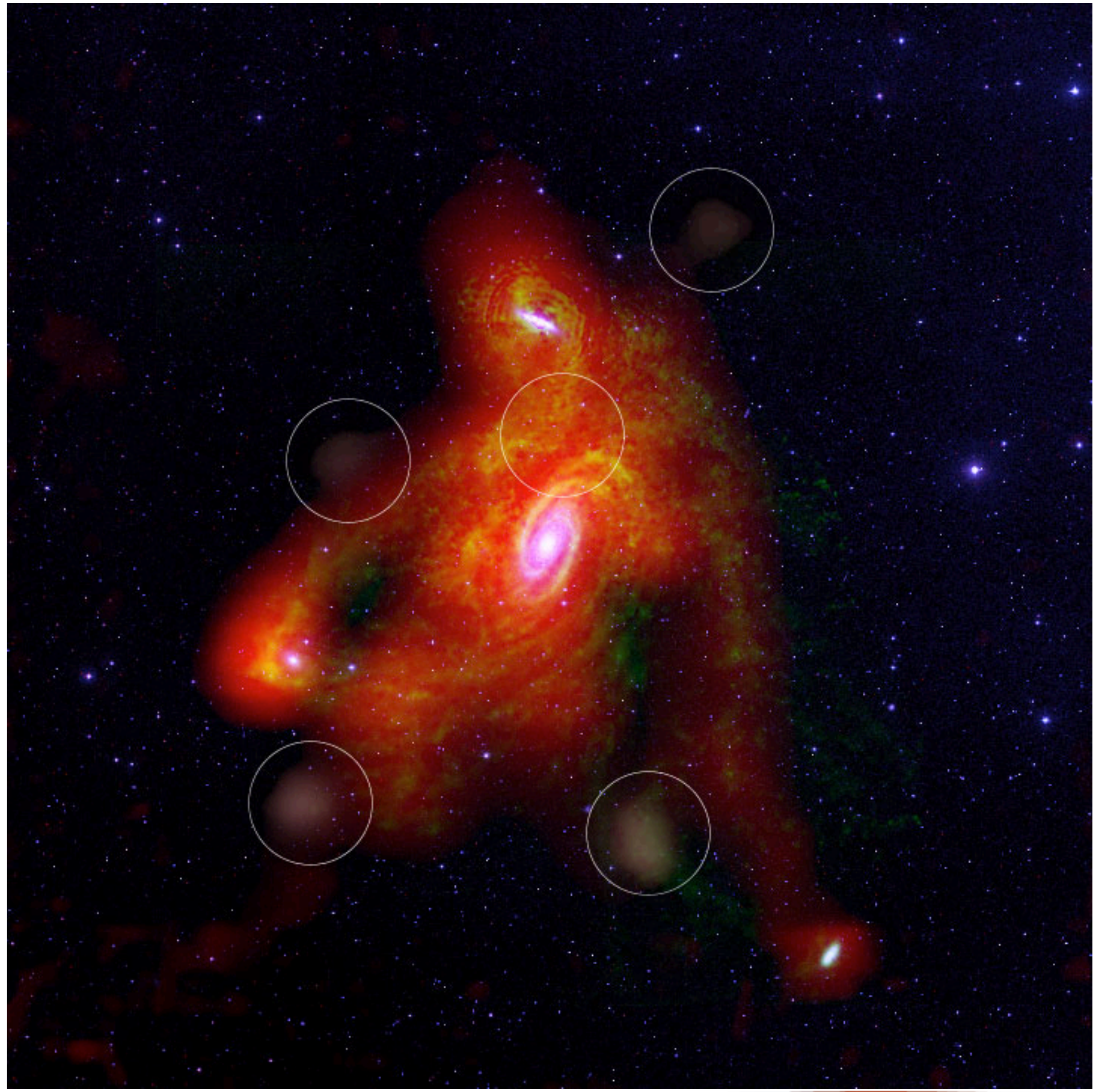
Discovery of pebble-sized particles near the Orion Nebula (Schnee et al. 2014).

Maps

Surveying neutral hydrogen in and around the Milky Way (McClure-Griffiths et al. 2006).

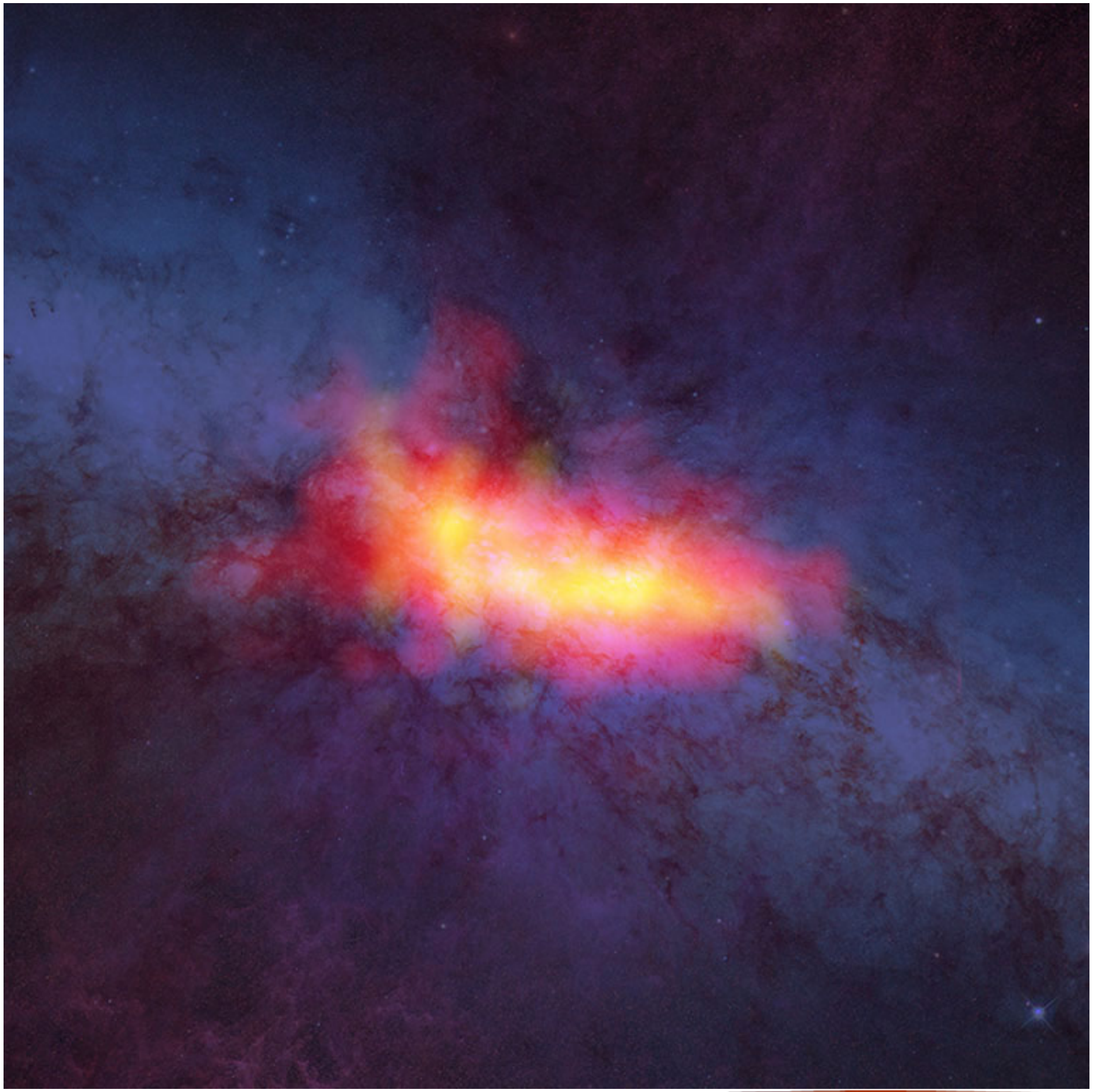


Maps



Revealing galaxy interactions and faint high-velocity clouds within the M81 group (Chynoweth et al. 2008).

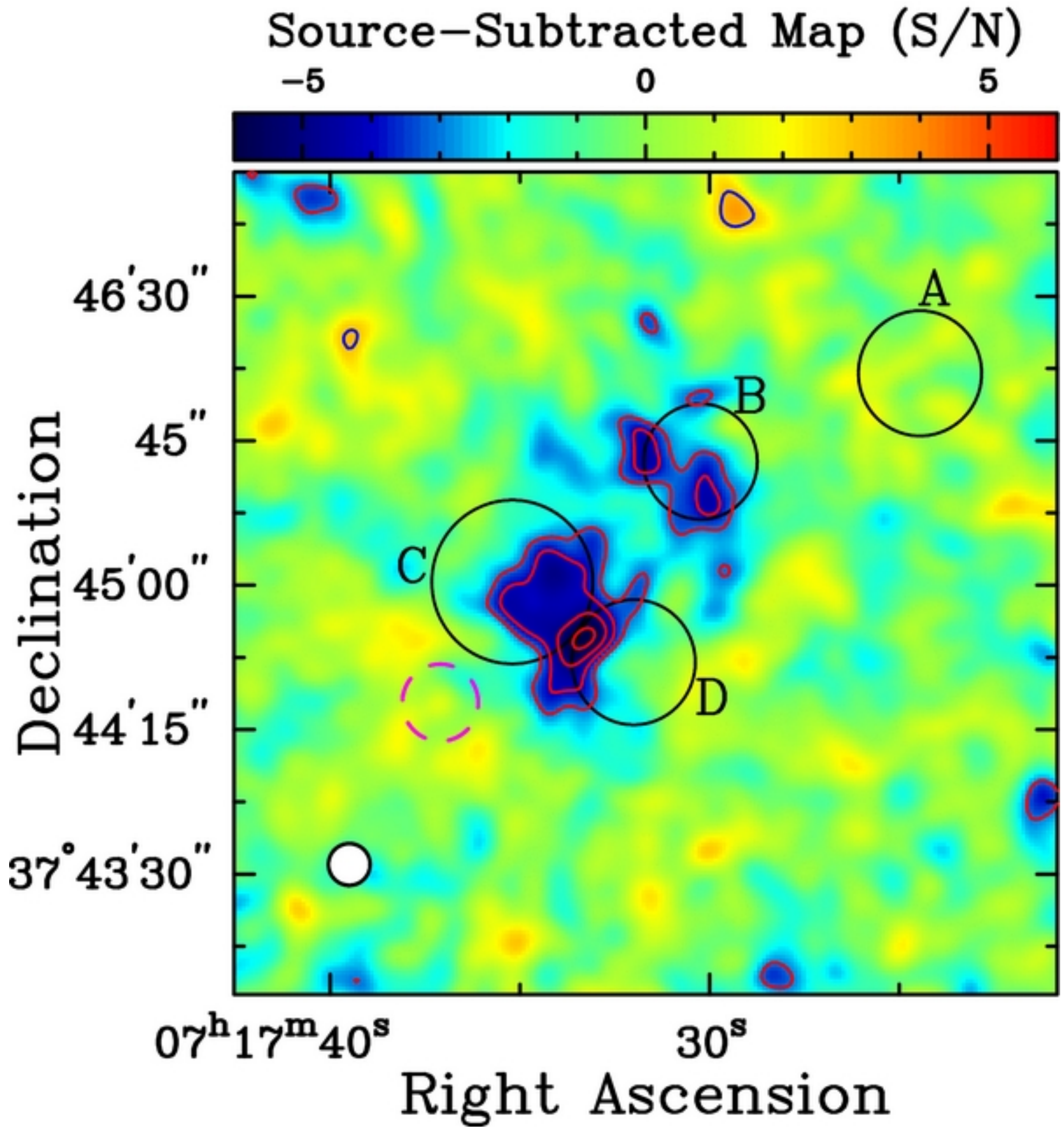
Maps



Quantifying the dense molecular gas in starburst galaxy M82 (Kepley et al. 2014).

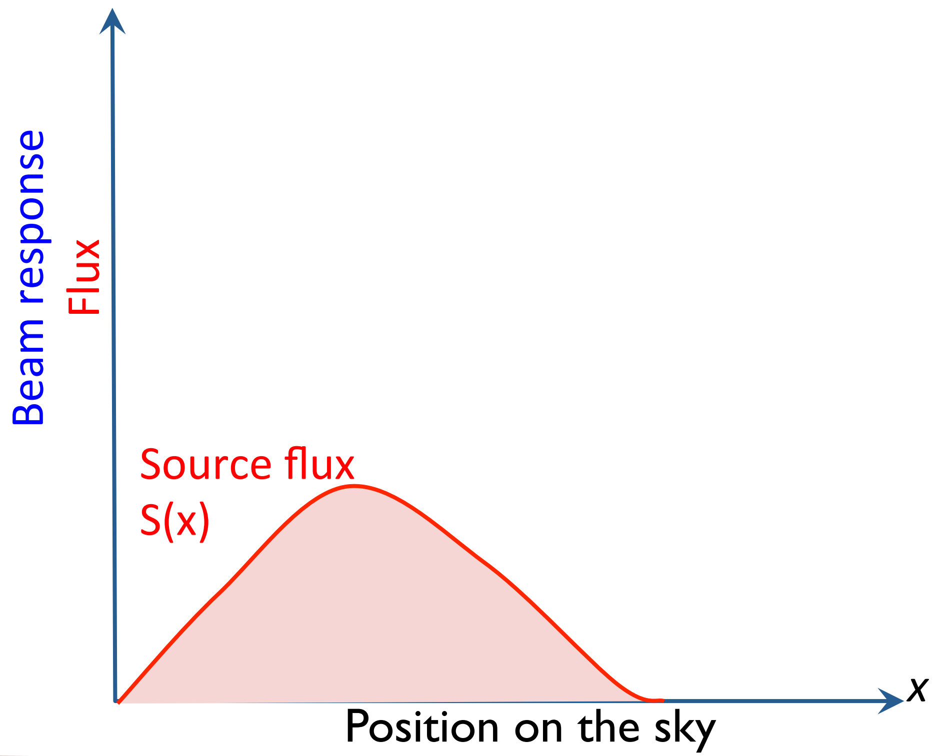
Maps

Showing the Sunyaez-Zeldovich effect through a z=0.55 cluster (Mroczkowski et al. 2012).



Mapping basics

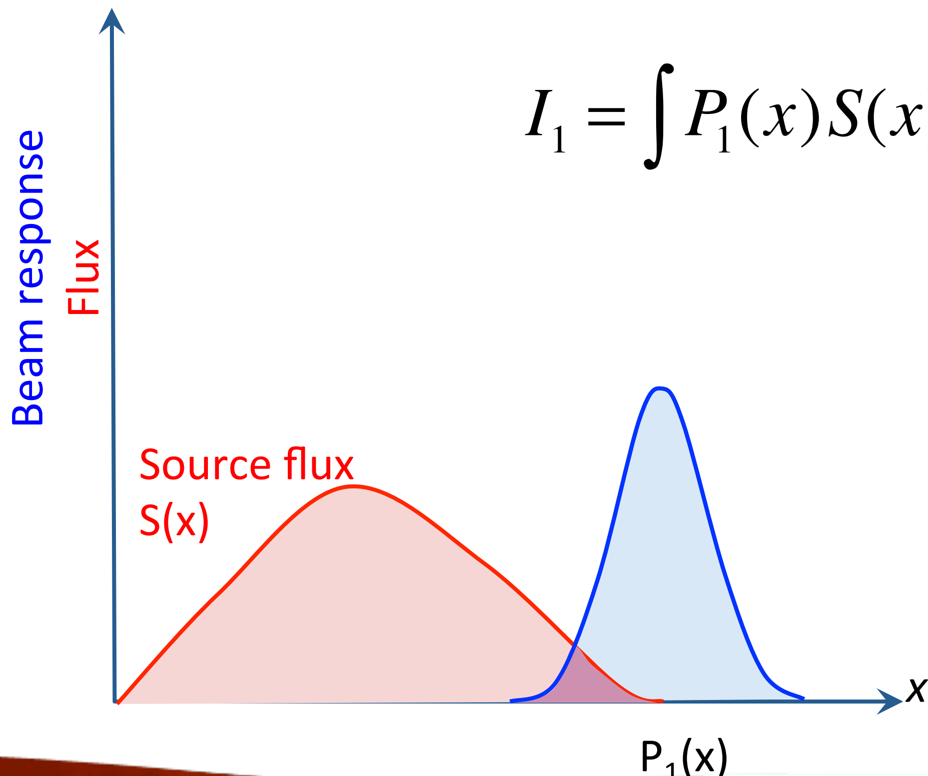
- Make multiple measurements

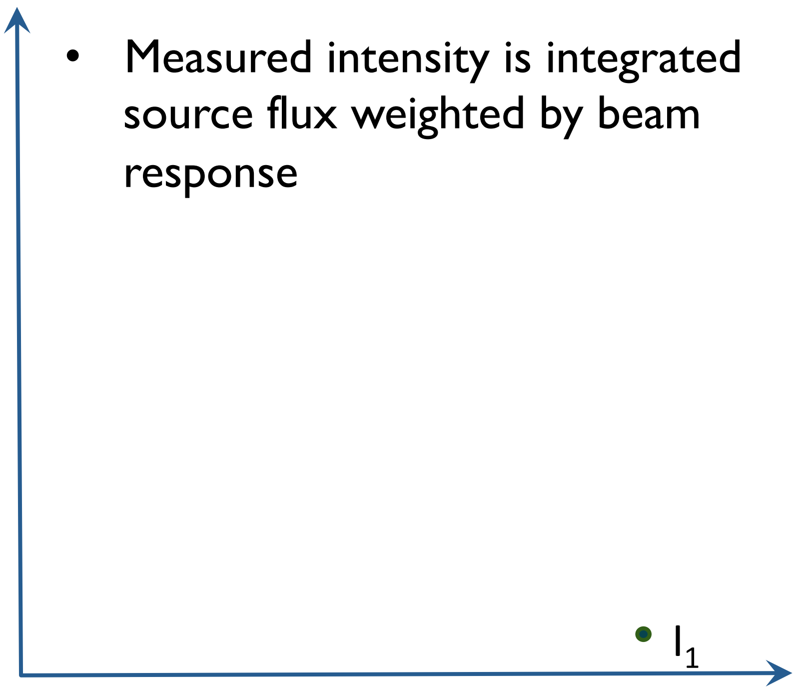


Mapping basics

- Make multiple measurements

$$I_1 = \int P_1(x) S(x) dx$$



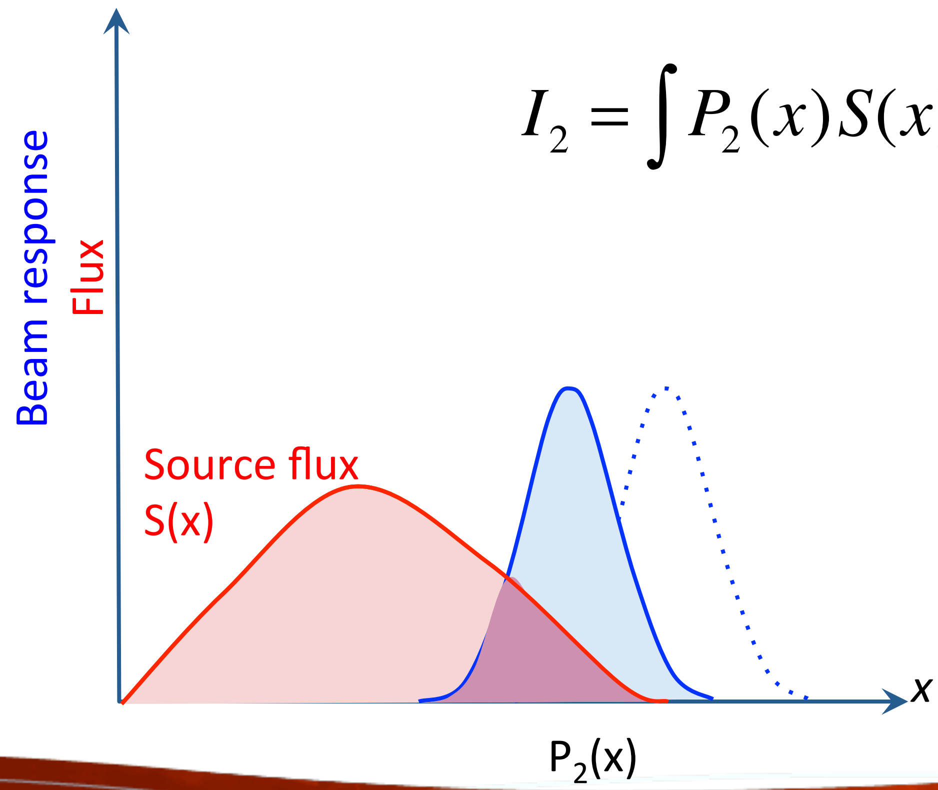


- Measured intensity is integrated source flux weighted by beam response

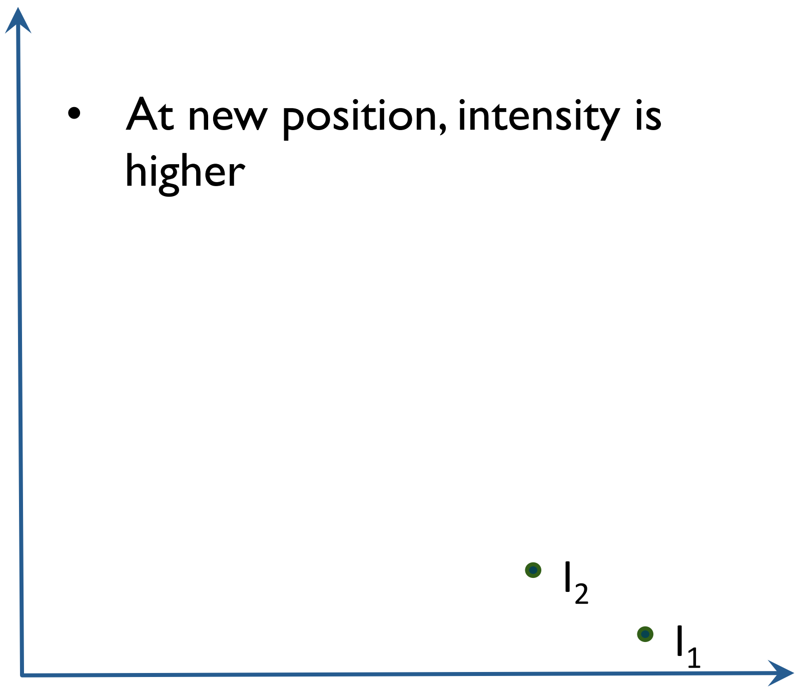
Mapping basics

- Make multiple measurements

$$I_2 = \int P_2(x) S(x) dx$$



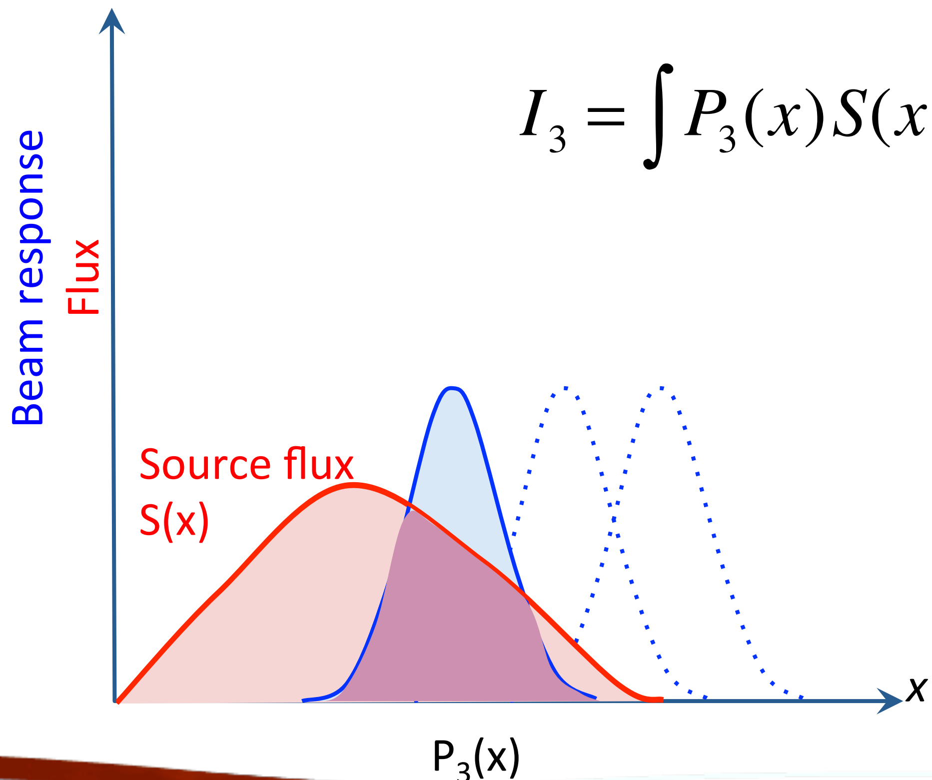
- At new position, intensity is higher



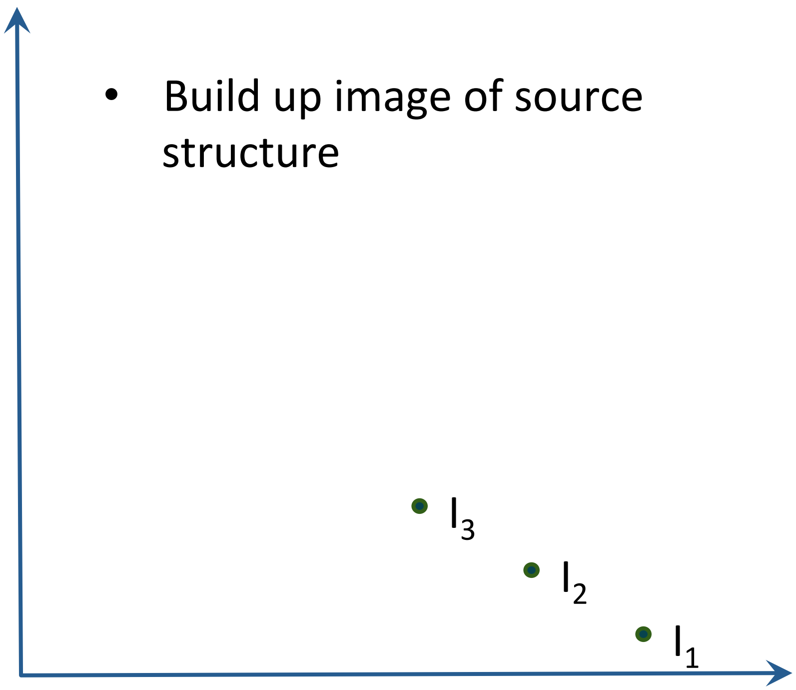
Mapping basics

- Make multiple measurements

$$I_3 = \int P_3(x) S(x)\, dx$$

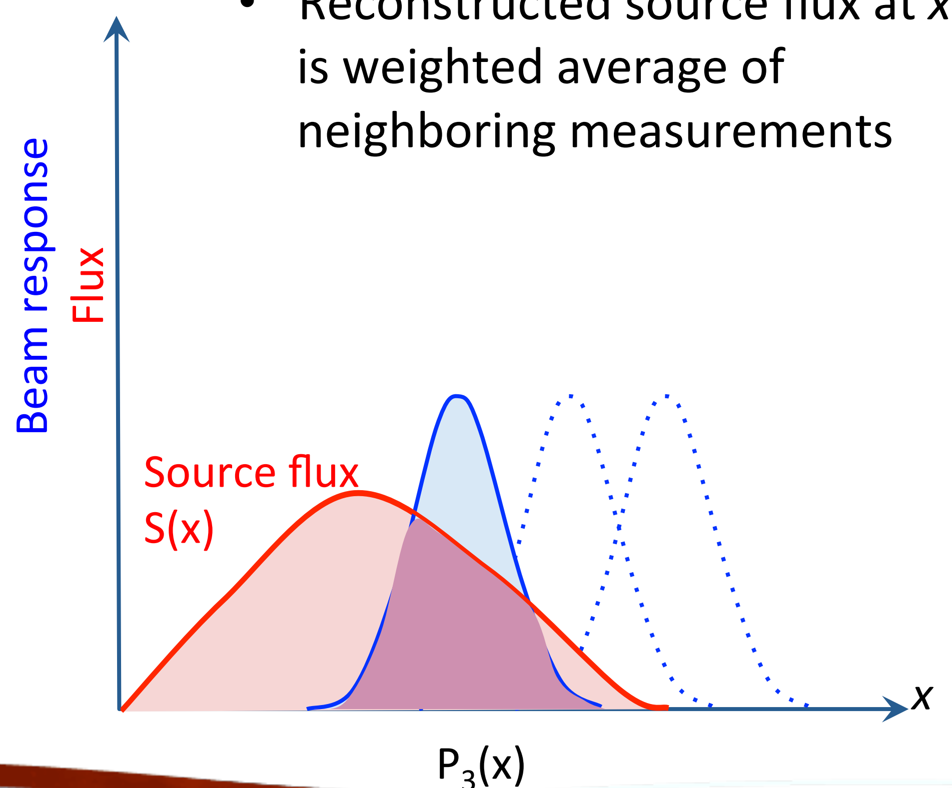


- Build up image of source structure

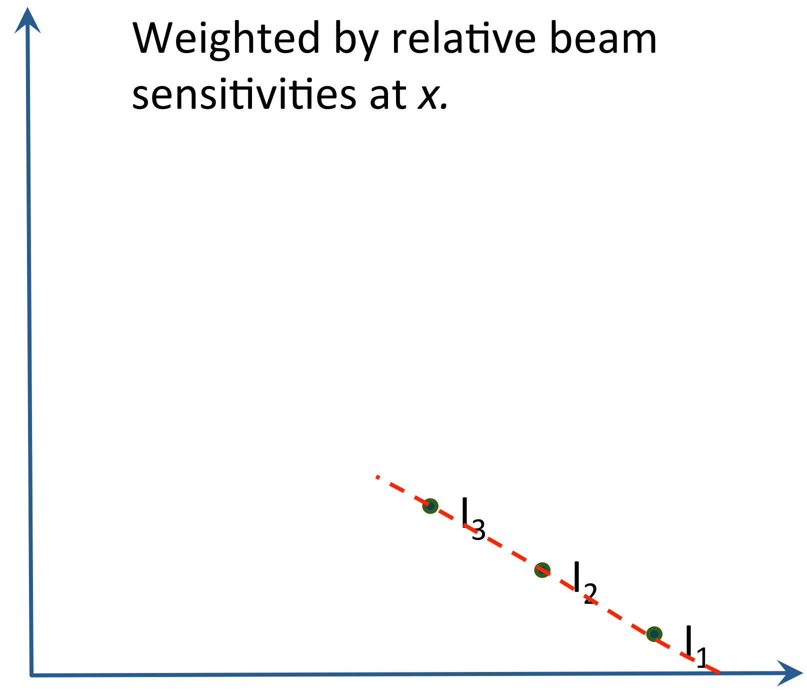


Mapping basics

- Make multiple measurements
  - Reconstructed source flux at *x* is weighted average of neighboring measurements

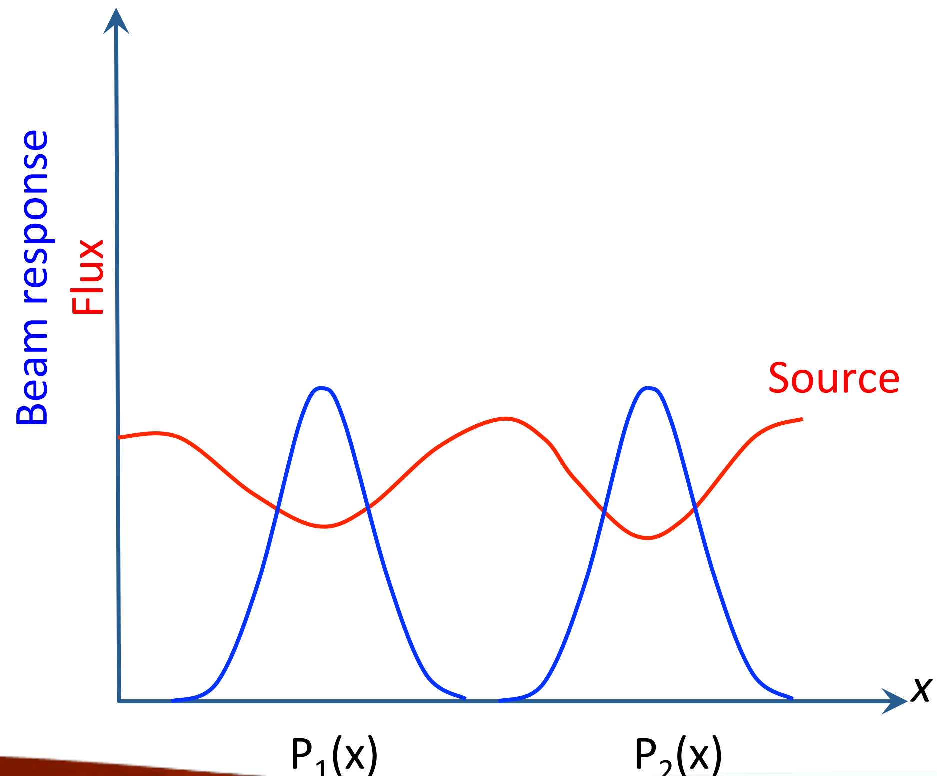


Weighted by relative beam sensitivities at *x.*



Nyquist sampling

- Imagine the beams are farther apart



Nyquist sampling

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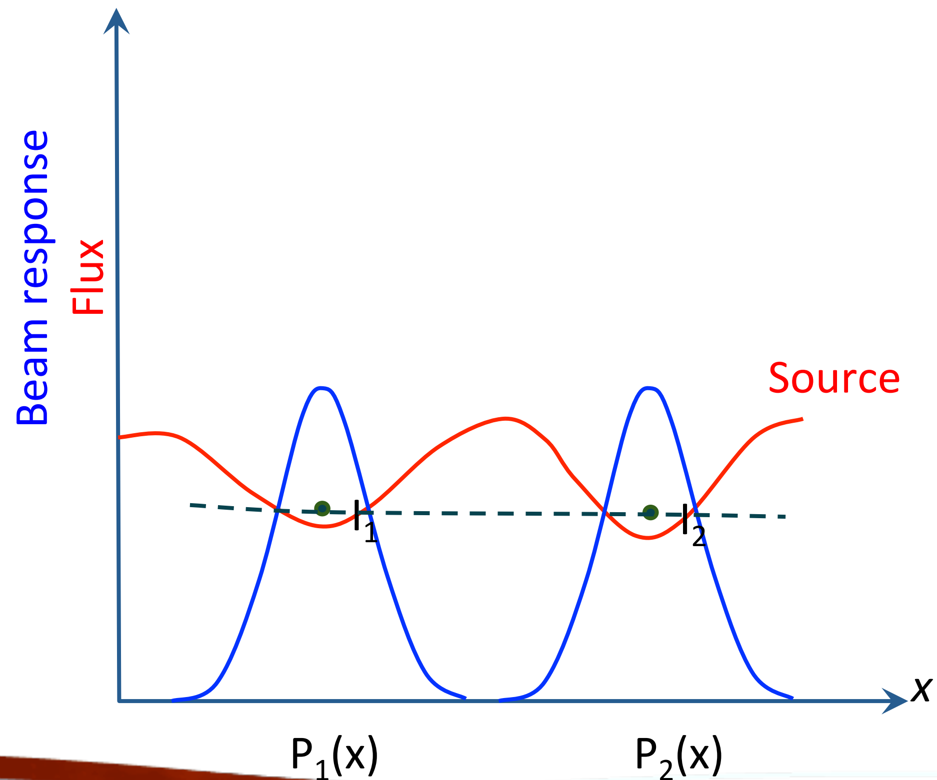
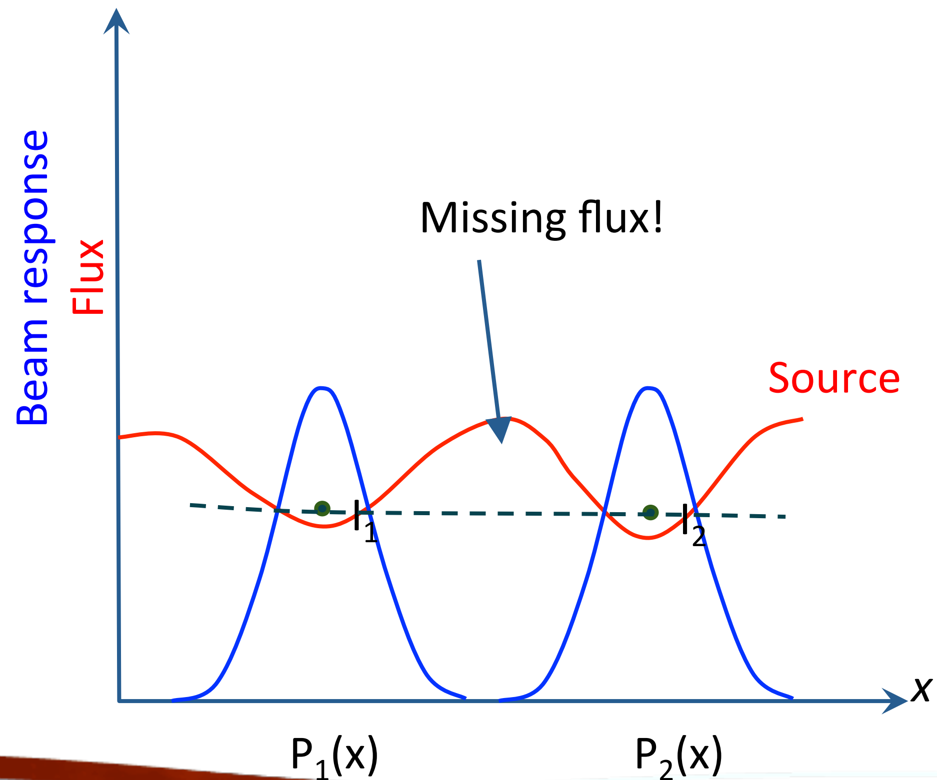


Measured intensity for each of these beams is the same

Nyquist sampling

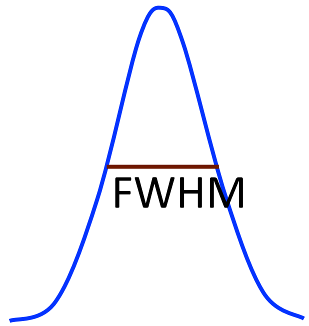
- Imagine the beams are farther apart



Nyquist sampling

Nyquist Theorem (1928):

Fully-sampled observations must be separated spatially by no more than FWHM / 2.



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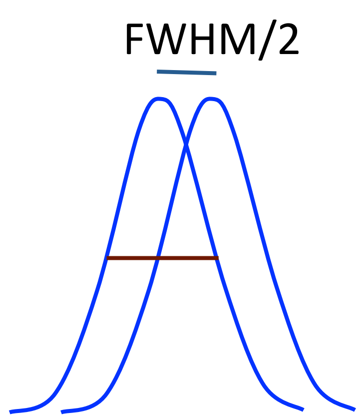
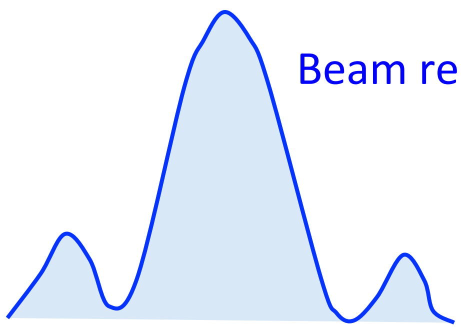
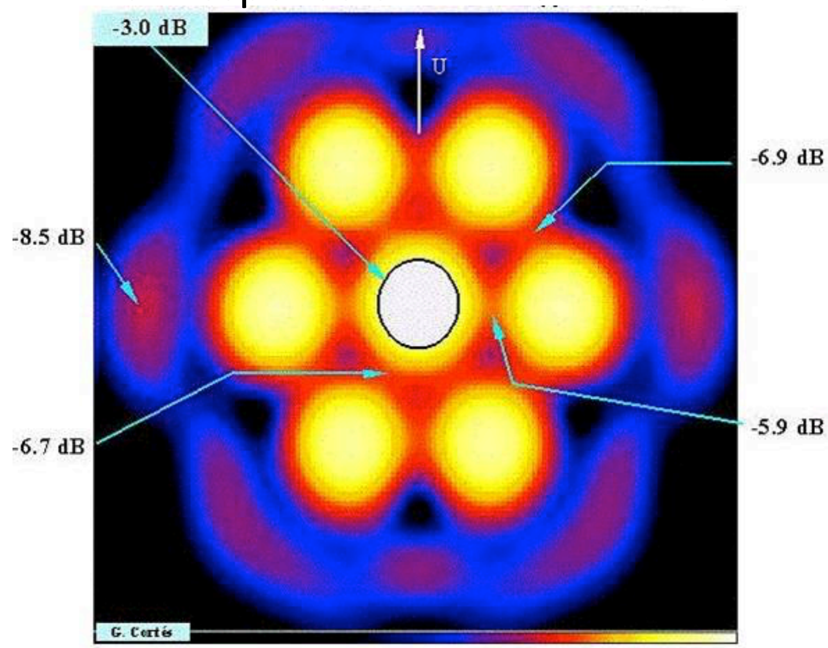


Stray radiation

Real beams have *sidelobes* due to diffraction.



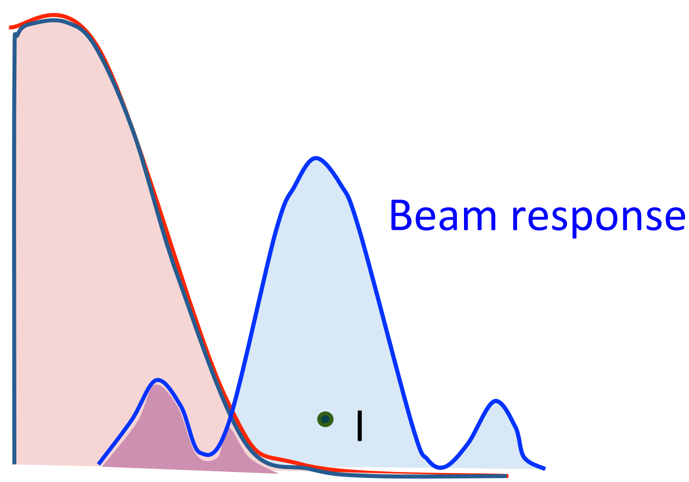
Full response of ALFA on Arecibo

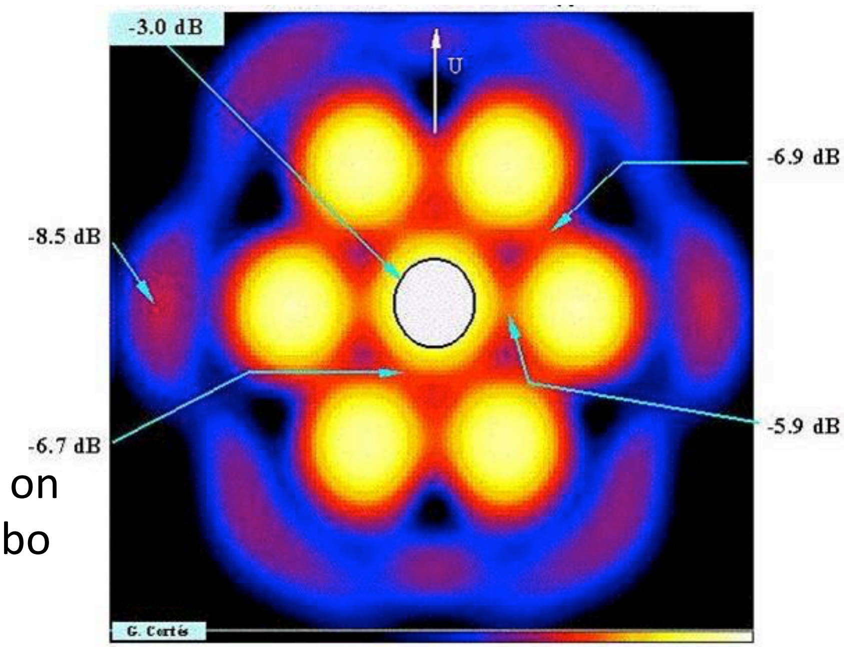


Stray radiation

Real beams have *sidelobes* due to diffraction.

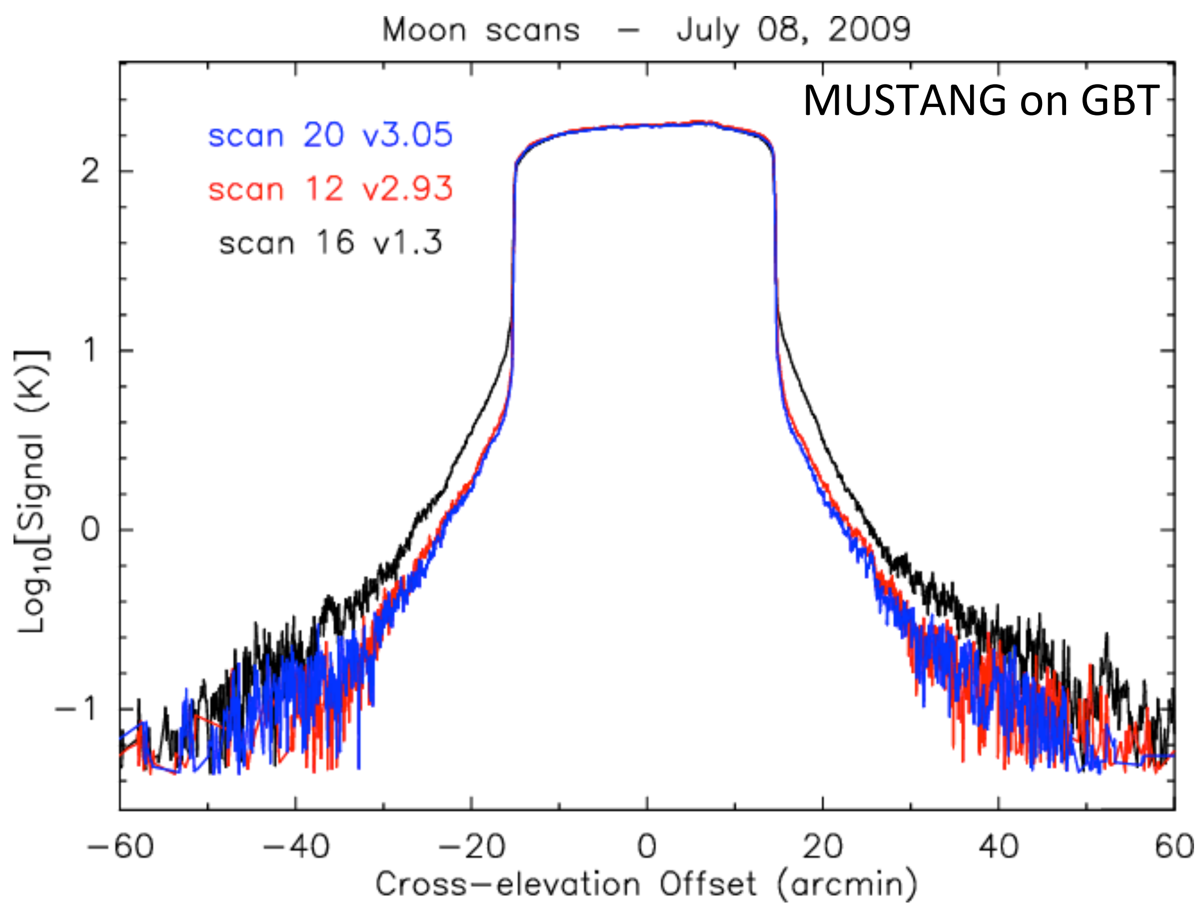
- because of overlap between source and left sidelobe, measured intensity is too high
- Flux from bright regions leaks into surrounding map





ALFA on Arecibo

Stray radiation



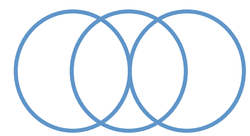
- GBT's clean beam results in great maps!

-20 dB

Mapping Techniques

Pointed maps

- move, integrate, move, integrate, move, integrate...



Mapping Techniques

On-the-fly mapping

- continuously move telescope across sky while taking regular integrations
- often faster than pointed maps

"boustrophedonic" pattern (from Greek "as the ox plows")

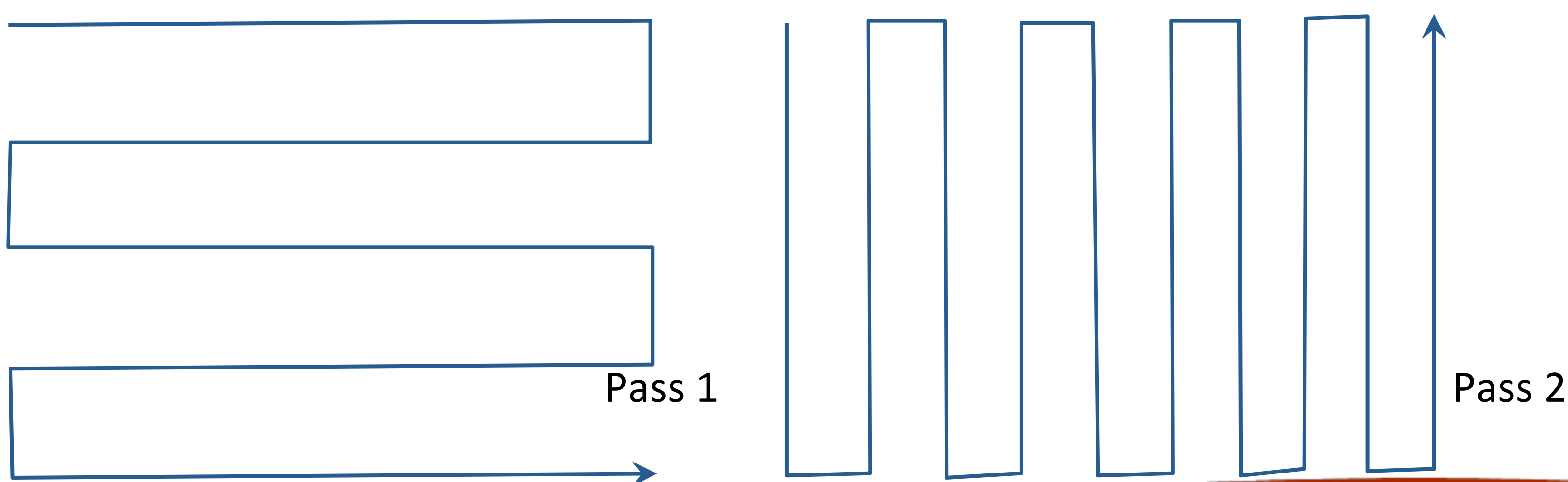
Mapping Techniques

On-the-fly mapping

Adjust spacing to ensure
Nyquist sampling

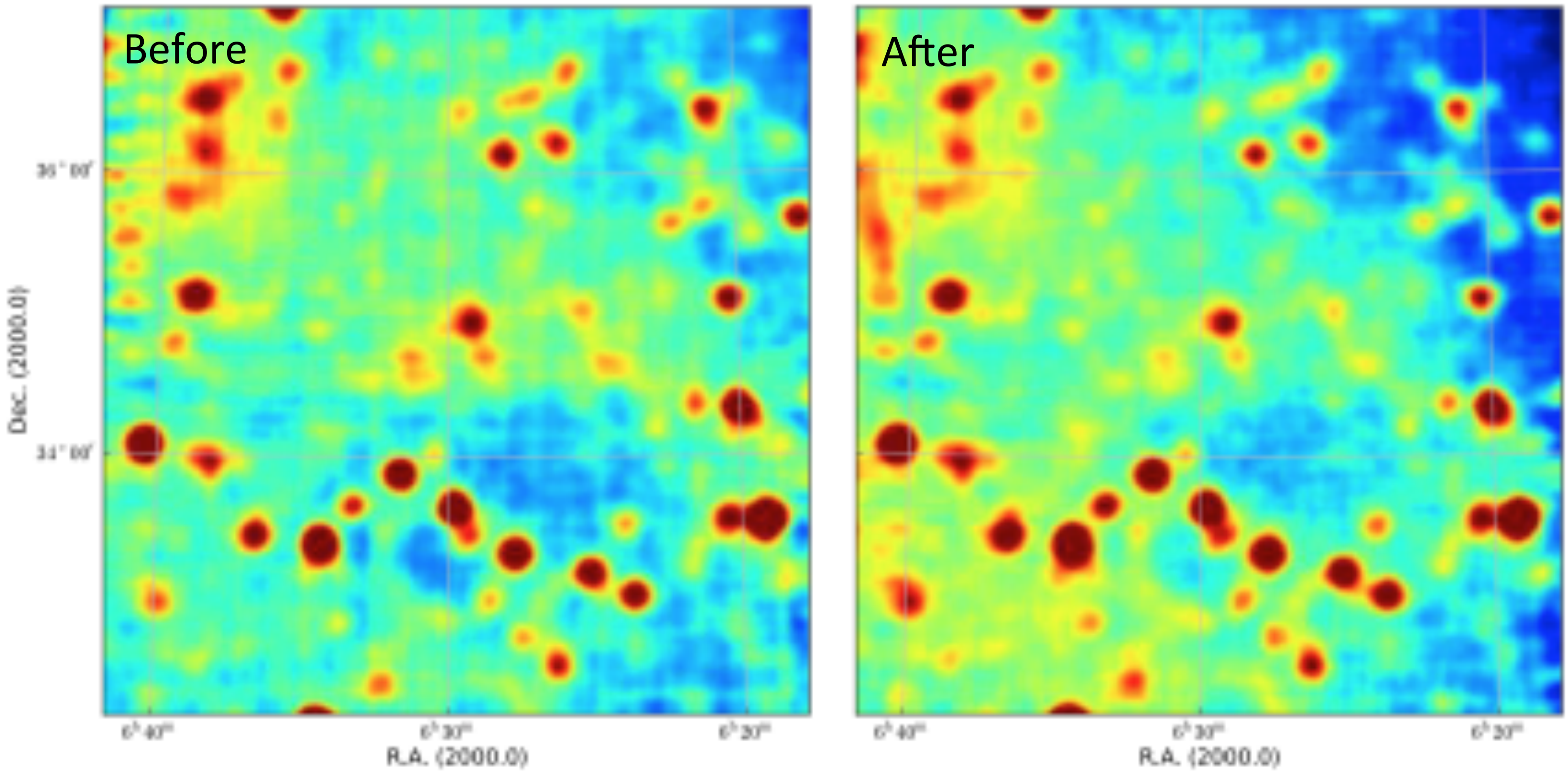
Mapping Techniques

- Atmospheric component to measured flux is correlated along a given scan (observed at same time, similar angle, etc)
- Results in artifacts along scan direction
- "Basketweaving" ameliorates this



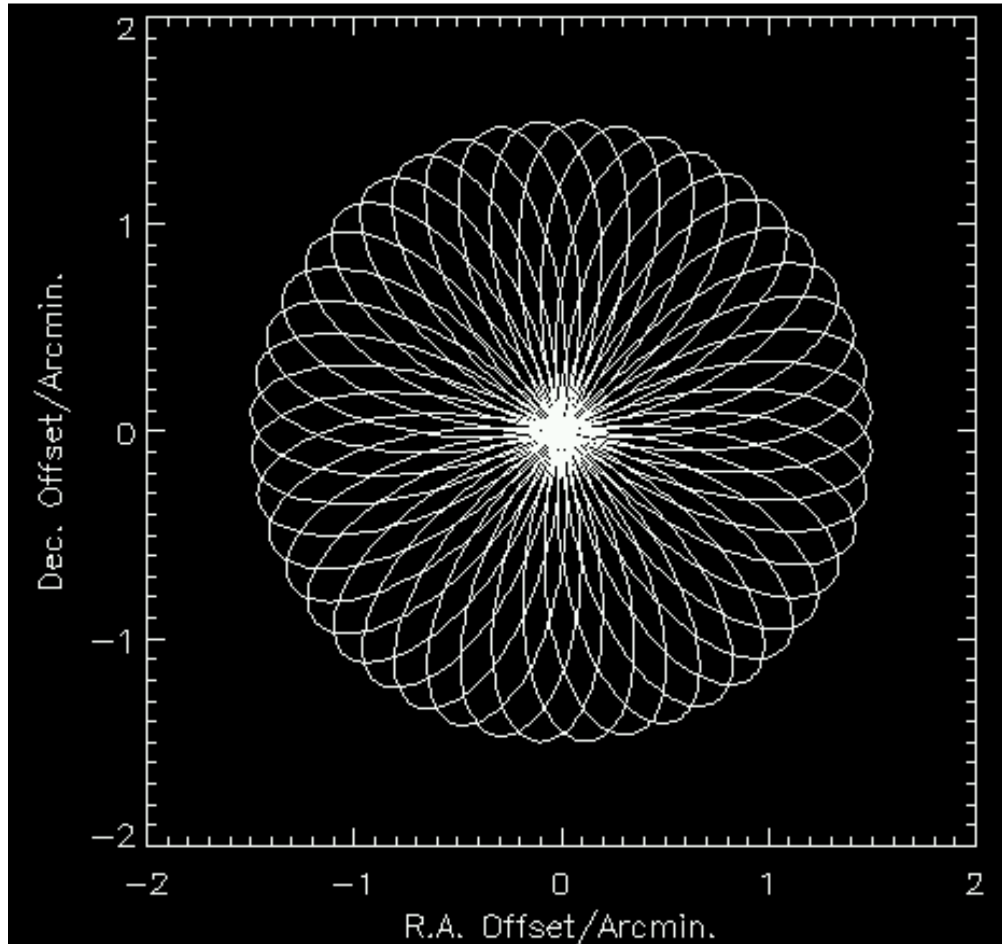
Mapping Techniques

Improvement from basketweaving (Winkel et al. 2012)



Other mapping options

- Daisy pattern: continuous scan
- can reduce overheads
  - especially for small maps with small beams
- Non-uniform coverage
- Trajectory calculation overwhelms benefits for large maps



Reference observations

- Required for bandpass calibration
- Several techniques are available

Reference observation techniques

- OFF position
  - Interrupt map periodically to go to a known nearby emission-free position

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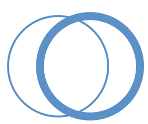

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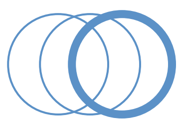

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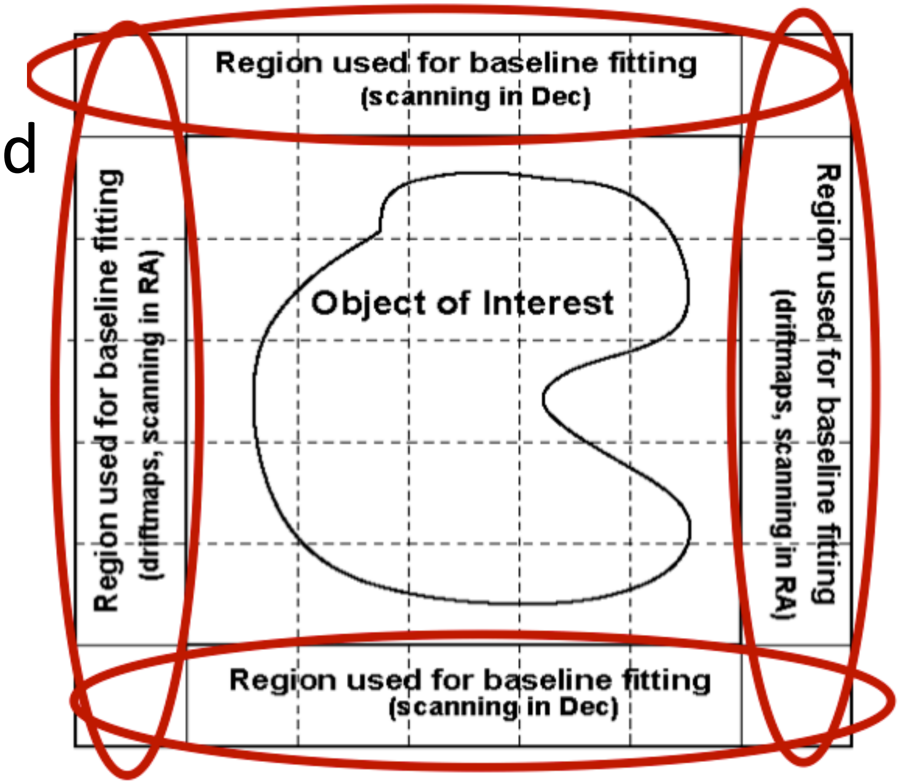
Reference observation techniques

- OFF position
  - Interrupt map periodically to go to a known nearby emission-free position

  - Takes time not on source

Reference observation techniques

- OFF position
- Map edges
  - No extra time required
  - Edges **must** be truly free of emission



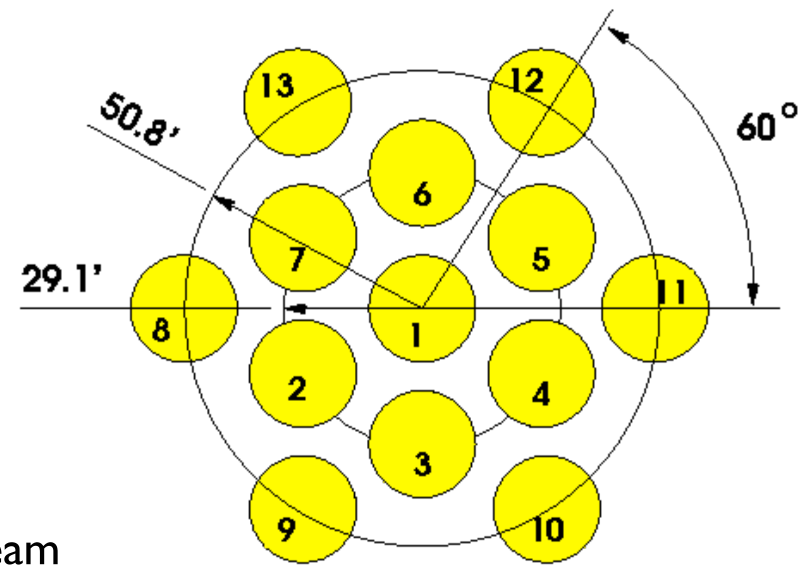
Reference observation techniques

- OFF position
- Map edges
- Frequency switching
  - Only option for very extended emission (e.g. Galactic HI) where there is no good off position

Array receivers

- Multiple beams on the sky at once

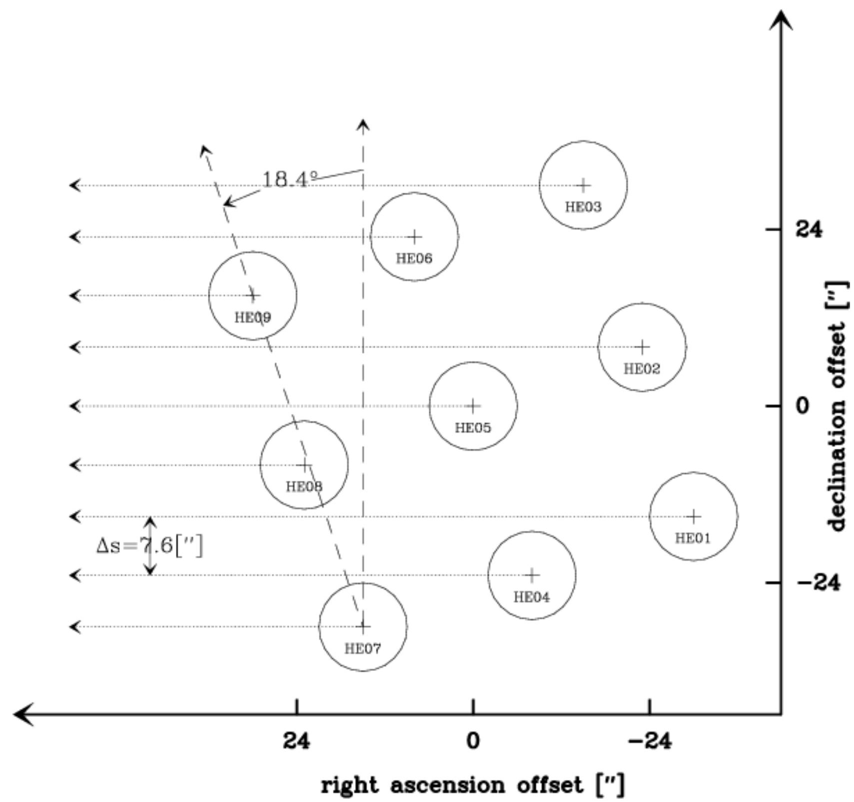
Parkes multibeam



For *N* beams, mapping efficiency is *N*x faster.

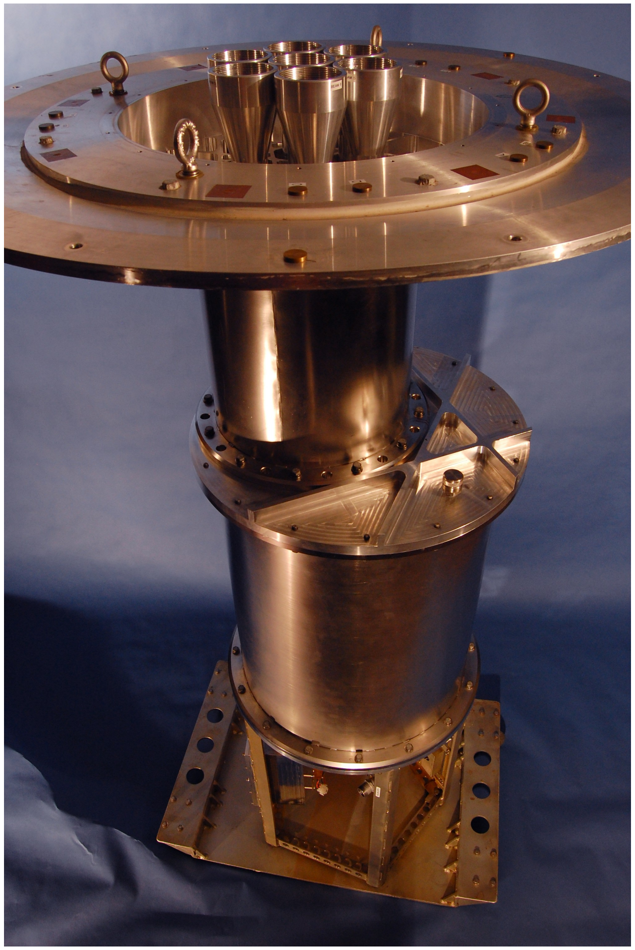
Array receivers

With correct orientation relative to scan direction, can generate a Nyquist-sampled map with the width of array in one scan.

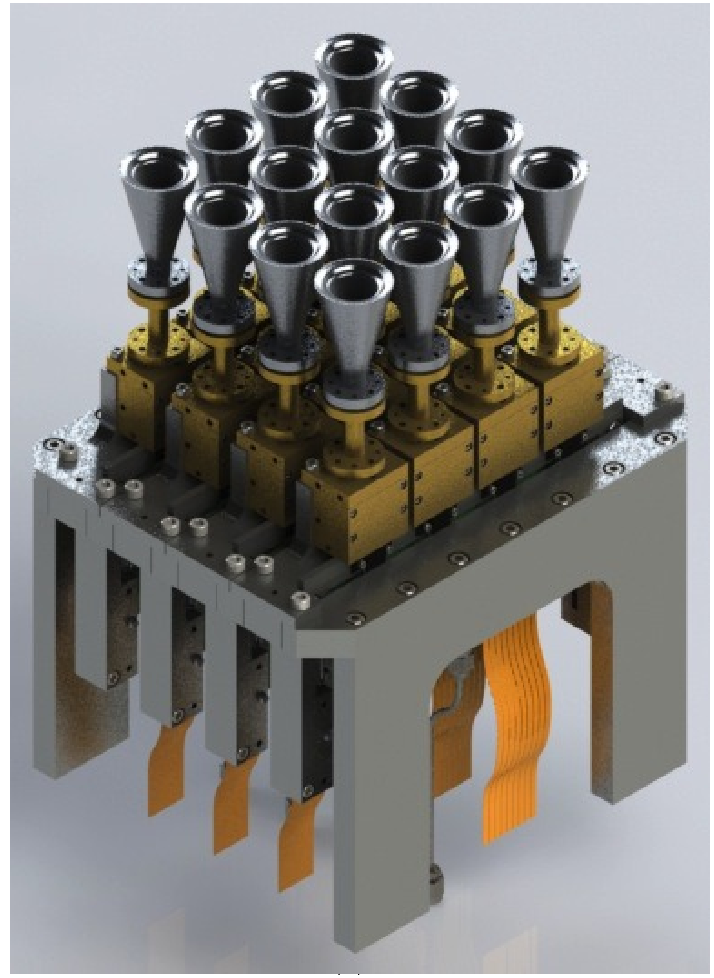


230 GHz array on the IRAM 30m.

Array receivers



KFPA



ARGUS - Sieth et al. 2014

NRAO NSF Associated Universities, Inc.

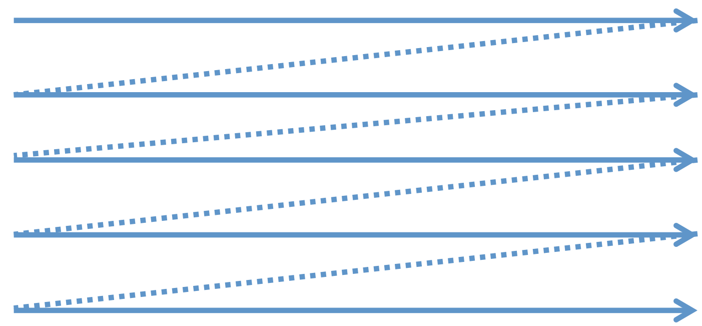
Mapping Overheads

- Reference scans
- Time between scans
  - Slewing to new scan line
  - System takes time to reset (GBT: 25s)
  - Scans should be longer than 1 minute at least to minimize this overhead fraction

Mapping Overheads

- Different mapping patterns can reduce overhead in some cases

Boustrophedonic (bidirectional)



Unidirectional

Optimize mapping by considering…

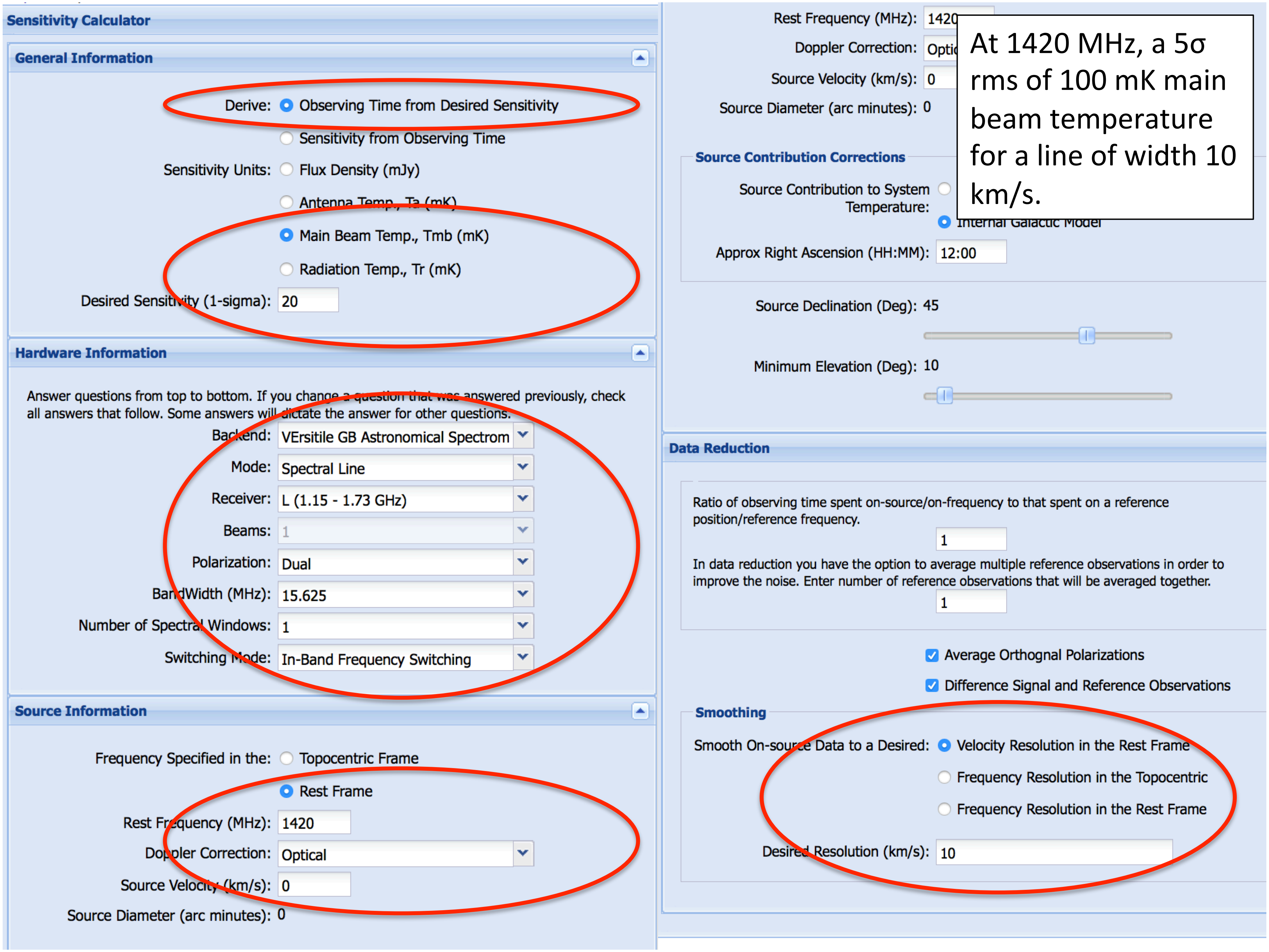
- Maximum scan rate can limit speed of map
  - Maximum telescope slew rate
  - Minimum time per sample set by backend (typically 0.5 – 1.5s), need ~4 samples/beam due to Nyquist theorem and smearing of beam along scan direction
    - for $t_{sample} > 1s$, must spend at least 4s per beam, even if not required for science case
    - often limiting mapping factor at high frequencies (e.g., KFPA) where beam is small

Planning Mapping Observations

- What sensitivity do you need at each point in the map?
  - E.g. "At 1420 MHz, a 5σ rms of 100 mK main beam temperature for a line of width 10 km/s"
  - Determined by your science

Planning Mapping Observations

- What integration time per beam is required to reach that sensitivity?
  - Sensitivity calculator



At 1420 MHz, a 5σ rms of 100 mK main beam temperature for a line of width 10 km/s.

Controls

Update Results | Save to File

Results | Result Grids

Messages

Warning - Minimum elevation is below the suggested minimum of 23.00 degrees.
Warning - Since source is extended, the calculated results are approximations.

Results

Derived Total Observing Time:	22.8 s

Integration time per beam!

Time at Siginal Position or Frequency:	11.40 s
Time at Reference Position or Frequency:	11.40 s
Effective Integration Time:	5.70 s
Obs. Mode Time Mult. Factor:	4
FWHM Beamwidth:	8.68 '
Aperture Efficiency:	0.70
Extended Source Efficiency:	0.82
Confusion Limit:	173.66 Tm (mK)
# Hrs Above Min Elevation:	15.83 hours
Topocentric Frequency:	1420.000 MHz
Min. Topocentric Channel Width:	0.260 kHz
Desired Freq. or Vel. Resolution:	10.000000 MHz or km/s
Typical Air Mass:	1.8
Typical Atmospheric Attenuation:	1.013
Typical System Temperature:	16.8 K
Backend Sampling Efficiency (K1):	1.0000
Backend Channel Weighting (K2):	1.0000

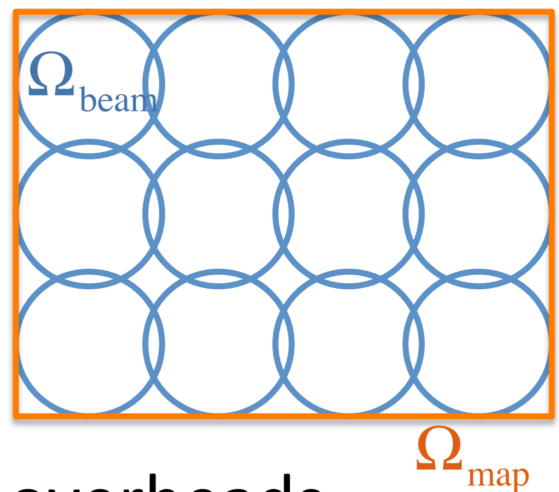
Other Results

Maximum Elevation:	83.4 d
Pulsar Factor (bw / eff_bw * dc / (100.0 - dc)):	1.0000

Planning Mapping Observations

- Once we have integration time per beam, can determine how long the full map will take
  - Simple calculation:

$$t_{\text{map}} = t_{\text{beam}} \frac{\Omega_{\text{map}}}{\Omega_{\text{beam}}}$$



+ OFF scans, slewing time, other overheads

Planning Mapping Observations

- How long will the full map take?

GBT Mapping Calculator

Last Modified: December 31, 2014
Ronald J Maddalena

Calculates the time needed to map,an area including overhead, based on the integration time per beam area (e.g., the results from the Sensitivity Calculator) and the area to be mapped. Provides example ASTRID commands as well as other mapping parameters. Supports the typical mapping commands for on-the-fly (OTF) rectangular maps, OTF Daisy maps, and point rectangular maps.

Backend and Observing Modes

Vegas-16.9MHz; 8k Chans; 8 Bands

Mode:
- (●) Frequency Switching (Line Only)
- ( ) Total Power (Line or Continuum)

Noise Diode:
- (●) On
- ( ) Off

Doppler Tracking (Line Only):
- ( ) On (Hardware)
- (●) Off (Software)

Map Type
- (●) OTF Rectangle
- ( ) OTF Daisy
- ( ) Point Rectangule

Frequency

1420.0 MHz

Integration Time Per Beam

22.8 seconds

Map Size

Either Rectangle Size:
Horizontal 4 Deg
Vertical 4 Deg
Or Map Radius:
5.0 Deg

Row/Column/Petal Oversampling:

1.0

On-The-Fly Oversampling

2.0

Planning Mapping Observations

- How long will the full map take?

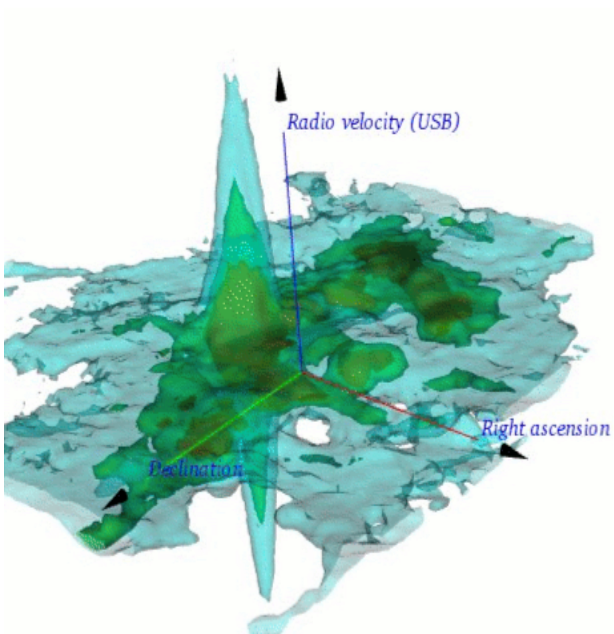
```
============================== General Results ===============================
        Approximate Aperture Efficiency at Rigging Angle = 0.70988
        Wavelength = 21.127 cm
        FWHM = 8.6661 arcmin
        Nyquist Sampling (lambda/(2*DishDiam)) = 3.6314 arcmin
        Map Area (xSize*ySize) = 16 degrees^2
        Beam Area (Omega_MB) = 77.958 arcmin^2
        Number of beams in map = 738.86
============================= RALongMap Results ==============================
        Sample time = 1.9288 sec
        Actual time per beam area = 22.806 sec
        Number of samples per beam area = 11.824
        Time for Map = 4.6807 hrs
        Overhead = 17 min
        -----------
        Total Time = 4.964 hrs
        -----------
        Row Seperation = 3.5821 arcmin
        Number of Rows = 68
        Time per Row = 4.2756 min
        Slew Rate = 0.94135 arcmin/sec
        Number of Accelerations/min = 0.23388
        -----------
        ASTRID directive:
                RALongMap( srcName,
                        Offset("J2000", 4, 0.0, cosv=True),
                        Offset("J2000", 0.0, 4, cosv=True),
                        Offset("J2000", 0.0, 3.5821/60., cosv=True),
                        scanDuration=256.53638 )
        Config Tool entries:
                tint = 1.928845
                swper = 0.48221125
```

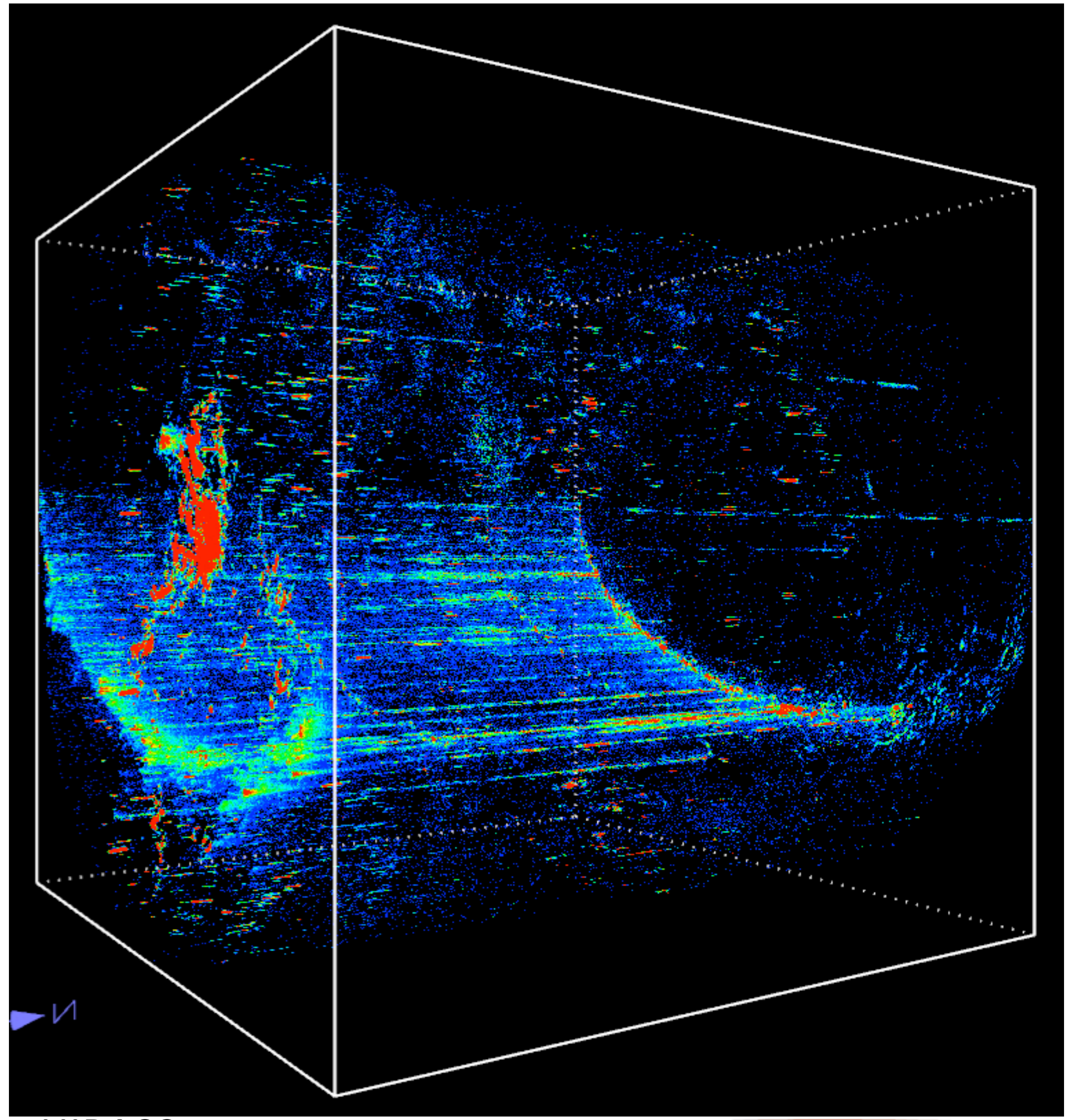
After you have a mapping plan…

- Propose for time on a telescope
- Conduct observations
- Reduce your data (a pipeline exists for GBT mapping data!)

Data cubes

- grid reduced data into 3D data cube
  F(RA, Dec, freq)

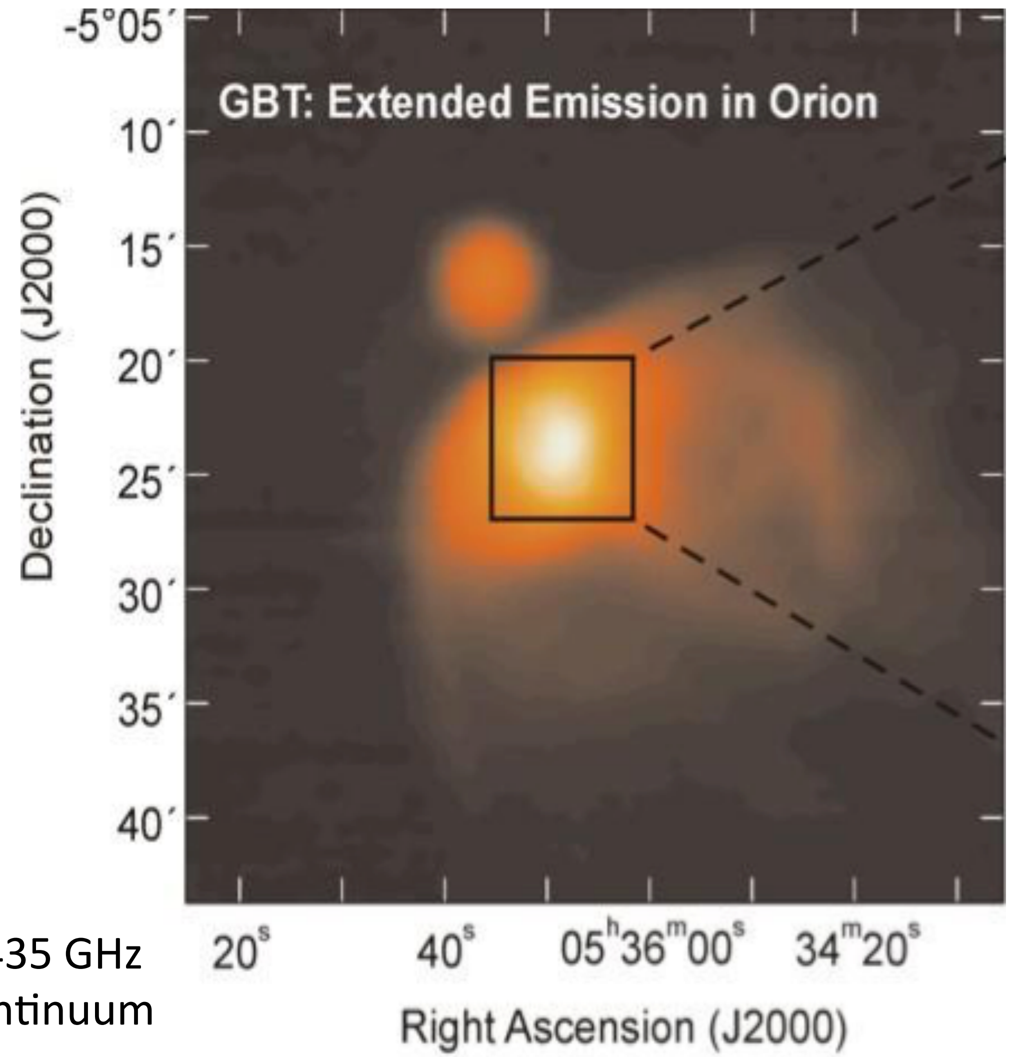




HIPASS

Data cubes

- Continuum data:
  – add up total flux at each sky position to make a 2D image



8.435 GHz continuum

Data cubes

Spectral line data:

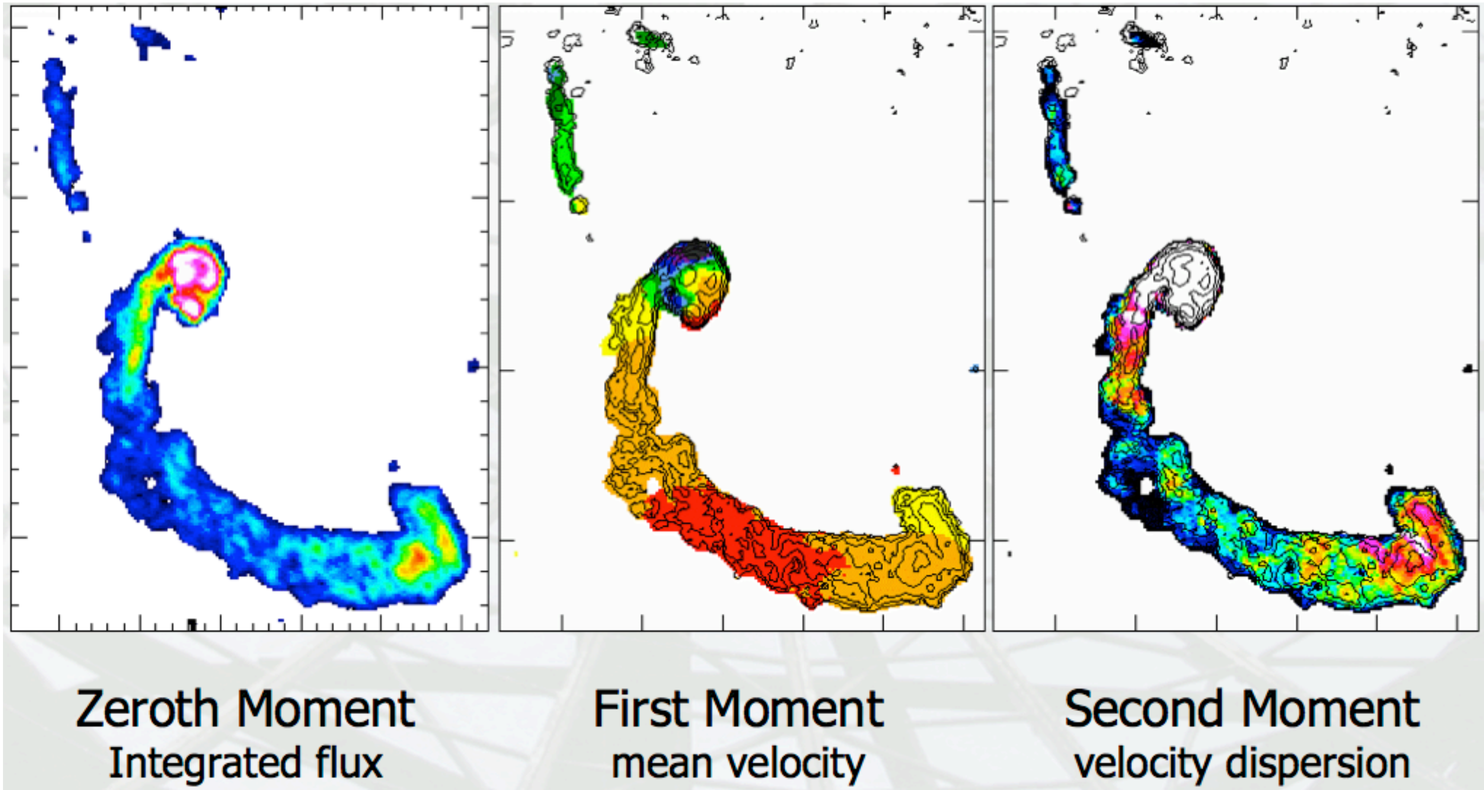
- Often useful to make moment maps for analysis:

$$m_i(\mathrm{RA},\mathrm{Dec}) = \int v^i\, F(\mathrm{RA},\mathrm{Dec},v)\, dv$$

  - 0th moment: integrated flux over velocity
  - 1st moment: velocity weighted by flux - mean velocity of emission
  - 2nd moment: velocity dispersion

Data cubes

…and then these map directly to physics of the object, so you can do science!



ASTRON

Summary

- Maps are required to survey large areas and study extended objects (variety of science topics and frequencies)
- A variety of mapping techniques exist (pointed maps, OTF mapping, daisy scans)
- Arrays allow for more efficient mapping
- Need to consider several items when designing maps: science goals, overheads, equipment limitations, calibrations, sampling
- Many tools exist to aid in making maps for your science!

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