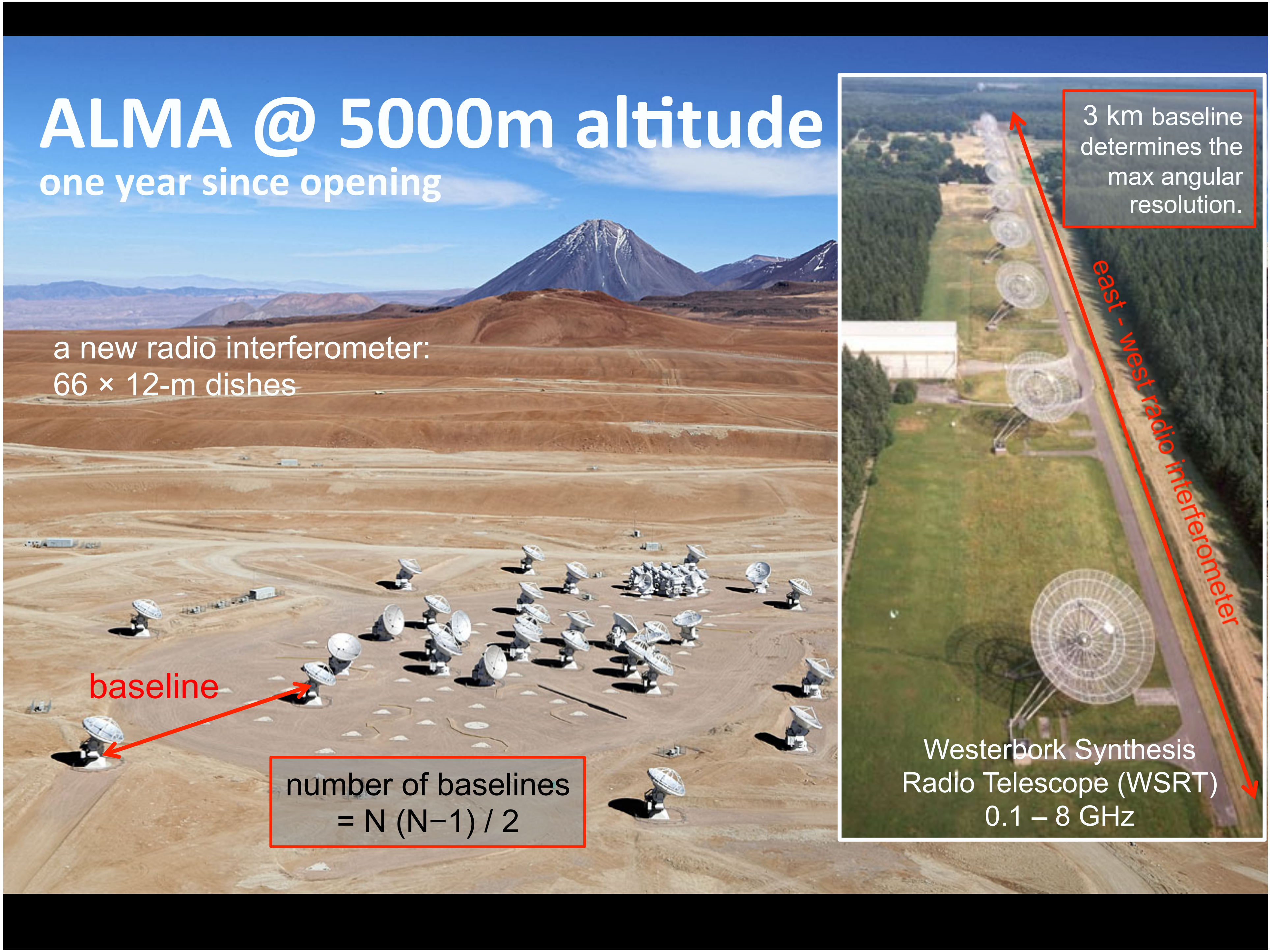
Overview of 3D Radio Techniques

3D2014: Gas and Stars in Galaxies

Bärbel Koribalski, Australia Telescope National Facility

10 March 2014


ALMA @ 5000m altitude
one year since opening
a new radio interferometer:
66 × 12-m dishes
baseline
number of baselines
= N (N−1) / 2
3 km baseline
determines the
max angular
resolution.
east - west radio interferometer
Westerbork Synthesis
Radio Telescope (WSRT)
0.1 – 8 GHz


ALMA @ 5000m altitude
one year since opening
a new radio interferometer:
66 × 12-m dishes
Very Large Array (VLA)
1 – 50 GHz
baseline
number of baselines
= N (N−1) / 2

ALMA @ 5000m altitude

one year since opening

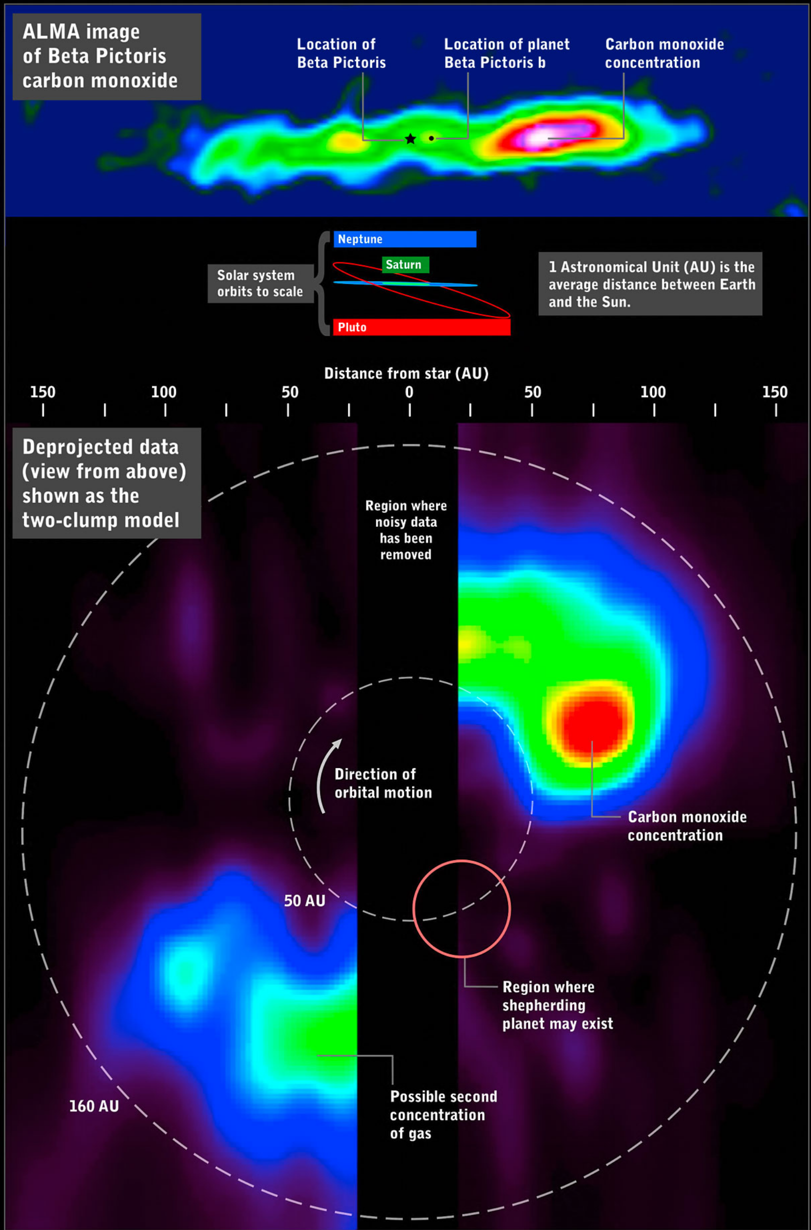
sophisticated antennas for high-frequency (84 – 950 GHz) radio observations

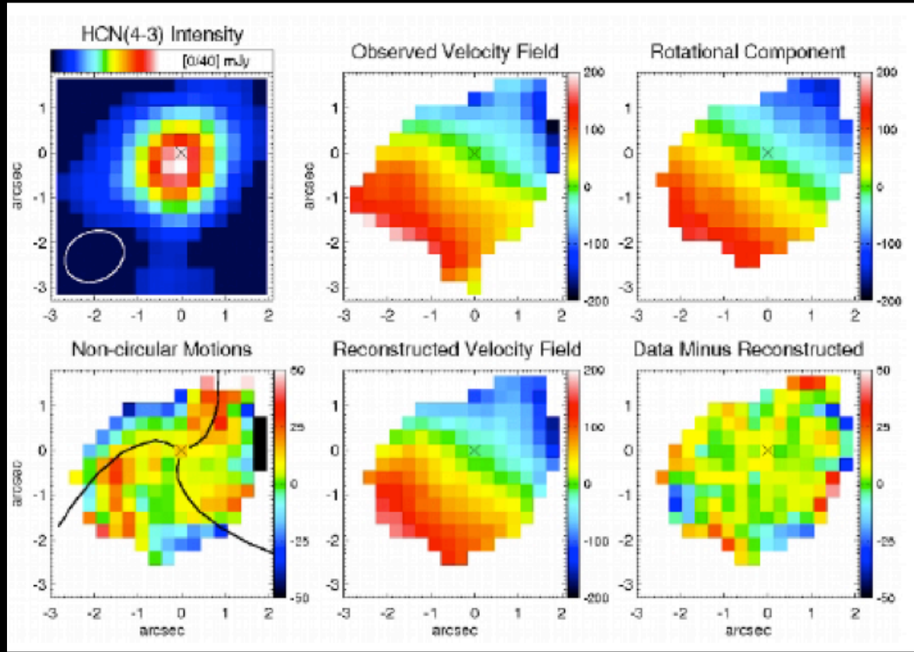
Visibilities (amplitude & phase)

$$\mathcal{V} = N(N-1)/2 \times N_{pol} \times T/\Delta t \times N_{channels}$$

Imaging based on
Earth rotation aperture synthesis

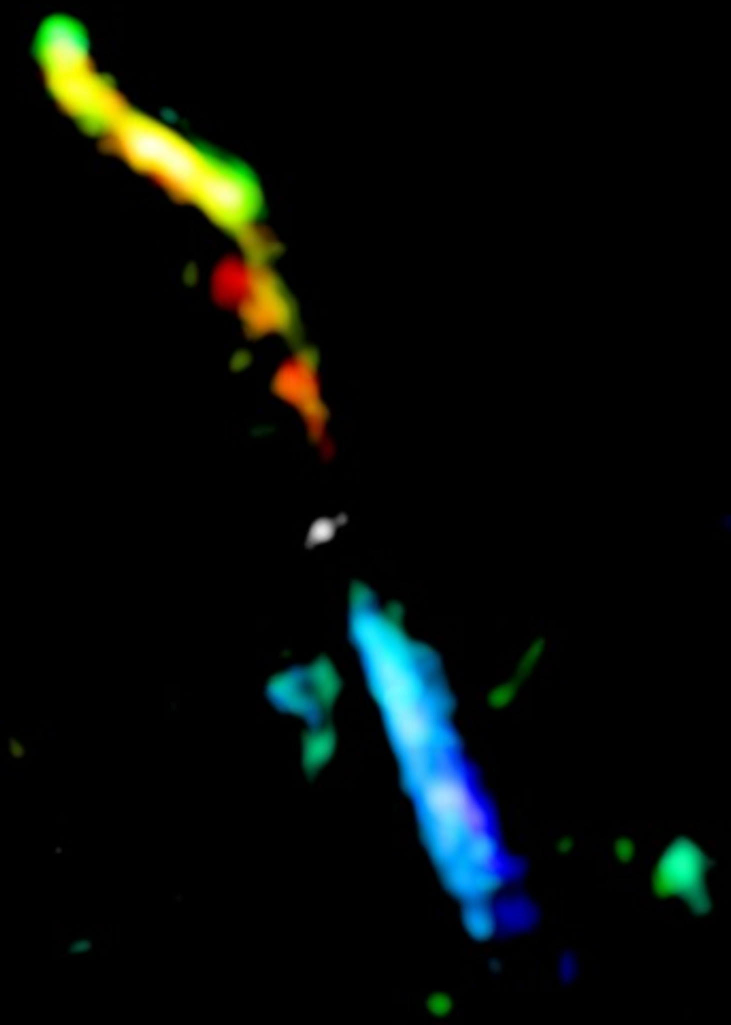
Why use 3D radio techniques ?



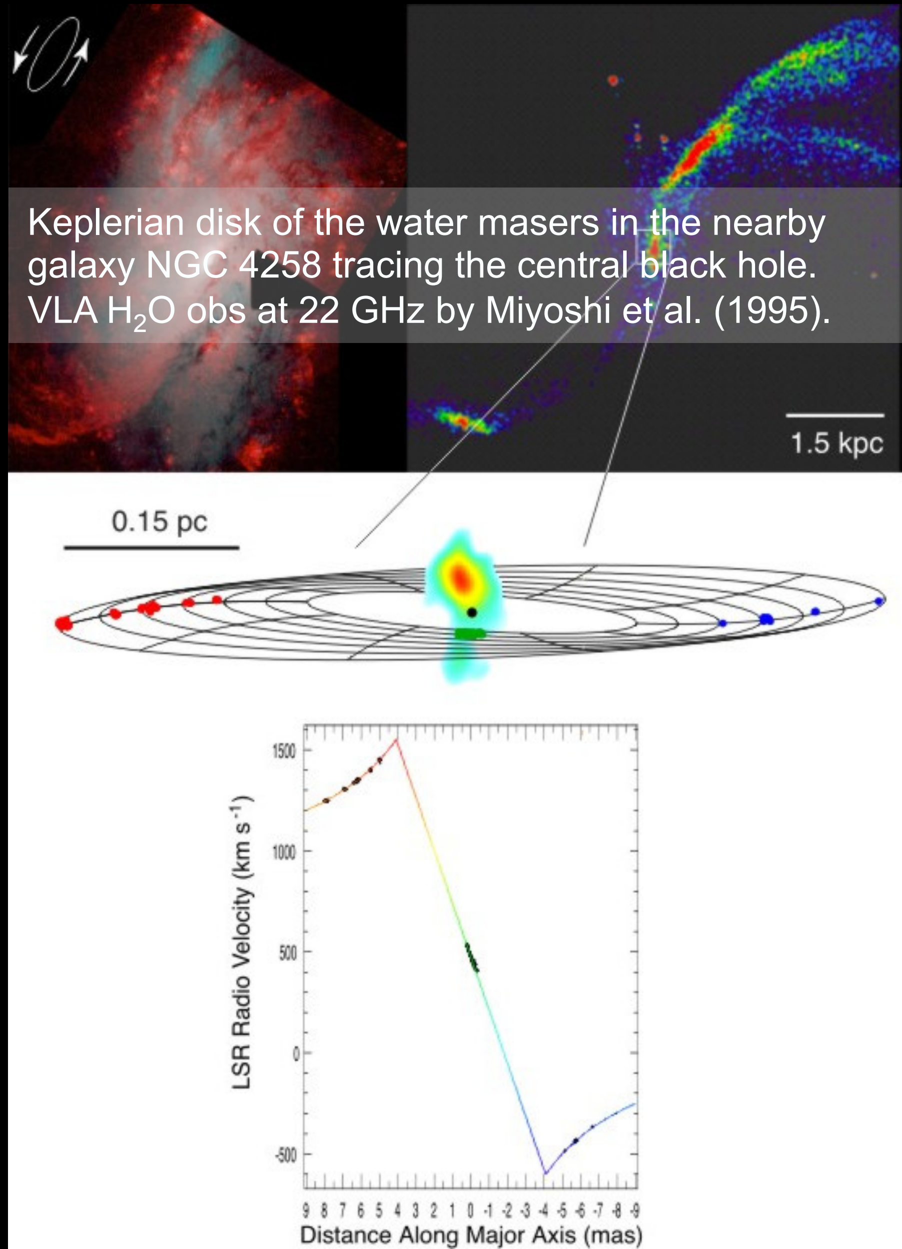


Top: **ALMA** HCN(4-3) moment maps of the inner 200 pc of the nearby Seyfert 1 galaxy NGC 1097 (Fathi et al. 2013).

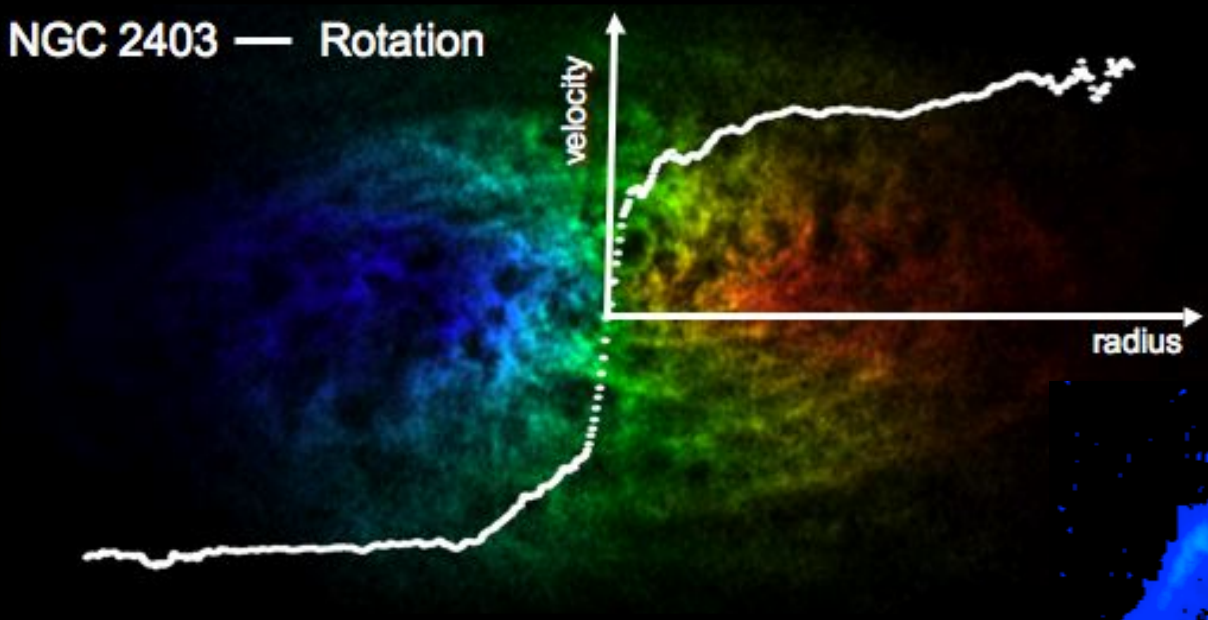
Left: **ALMA** CO maps of the large dusty debris disk around the star Beta Pictoris (Dent et al. 2014).

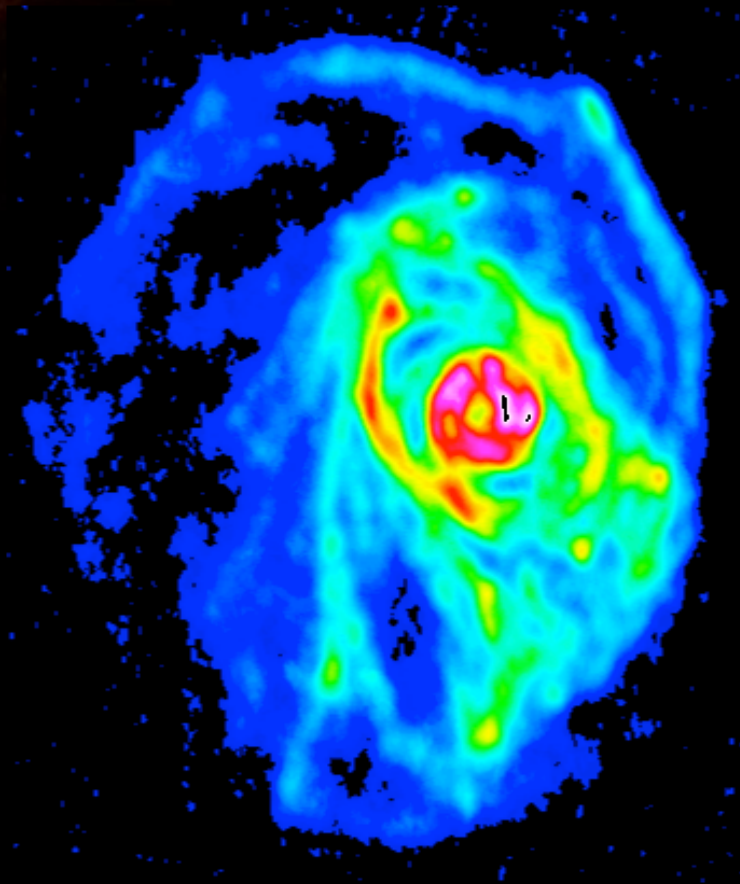


Supersonic jets from the protostar NGC 1333 IRS 4A. VLA SiO obs at 43 GHz (Choi et al. 2007).



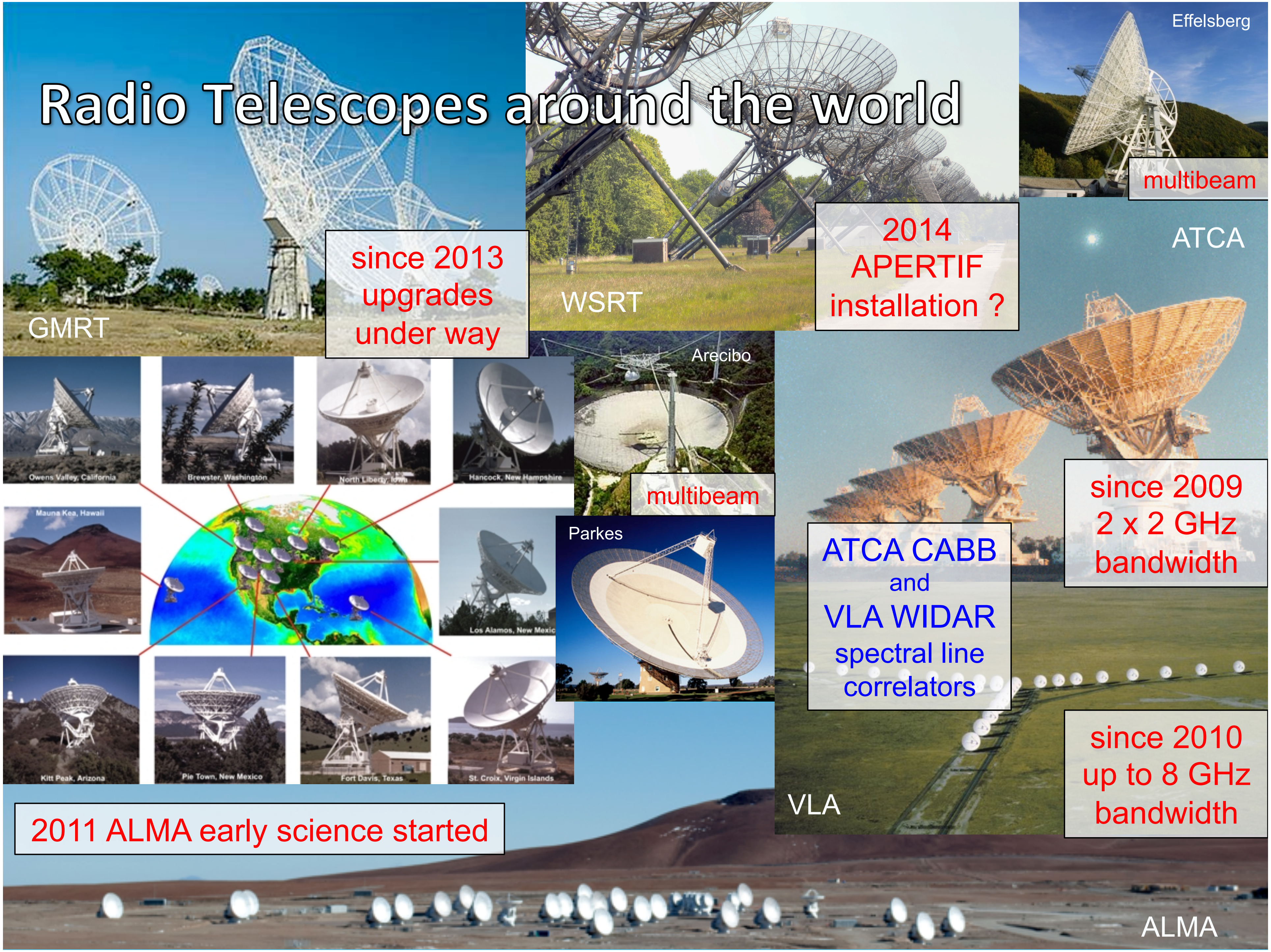
Keplerian disk of the water masers in the nearby galaxy NGC 4258 tracing the central black hole. VLA H_2O obs at 22 GHz by Miyoshi et al. (1995).





Top: High-resolution HI rotation curves of galaxies. VLA HI data by Walter et al. (2009).

Right: Measure the extended HI disks and environment of galaxies with ATCA. Discovery of an HI tidal arm in M83 (Koribalski et al.)



Radio Telescopes around the world
GMRT
since 2013 upgrades under way
WSRT
2014 APERTIF installation ?
Effelsberg
multibeam
ATCA
Arecibo
multibeam
Parkes
ATCA CABB and VLA WIDAR spectral line correlators
since 2009 2 x 2 GHz bandwidth
since 2010 up to 8 GHz bandwidth
VLA
Owens Valley, California
Brewster, Washington
Hancock, New Hampshire
Mauna Kea, Hawaii
Los Alamos, New Mexico
Kitt Peak, Arizona
Pie Town, New Mexico
Fort Davis, Texas
St. Croix, Virgin Islands
2011 ALMA early science started
ALMA


Nobeyama
Molonglo
GBT
IRAM PdB
Lovell
SEST
Nancay
APEX

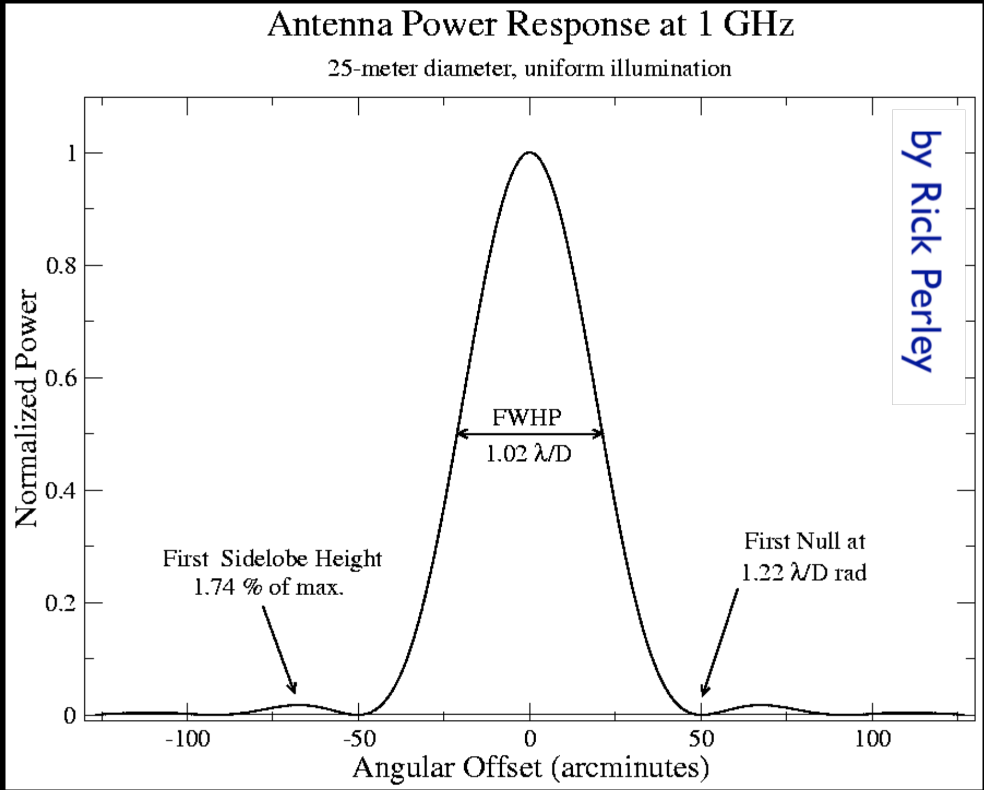
Single dish radio telescopes

Largest single-dish radio telescopes

Singe Dish Beam FWHM

- Arecibo 300 m : ~3' at λ = 21-cm
- Effelsberg 100 m : ~9' "
- Parkes 64 m : ~15' "

64-m Parkes Telescope

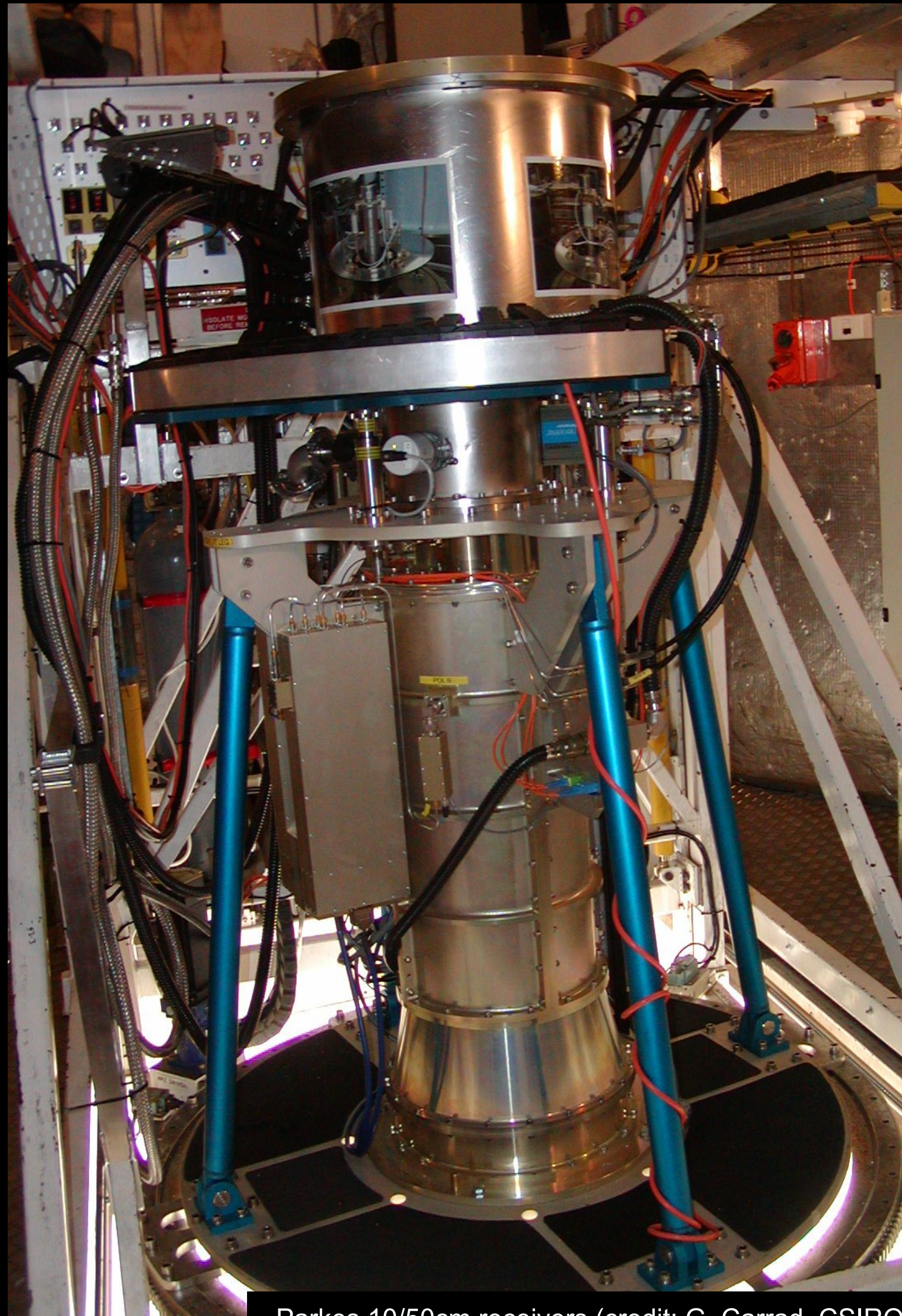


Single dish spectral line observing modes:

1) track source, get spectrum
   - single beam: on - off
   - multibeam: 100% on

2) scan field (ideally basket-weave), get cube

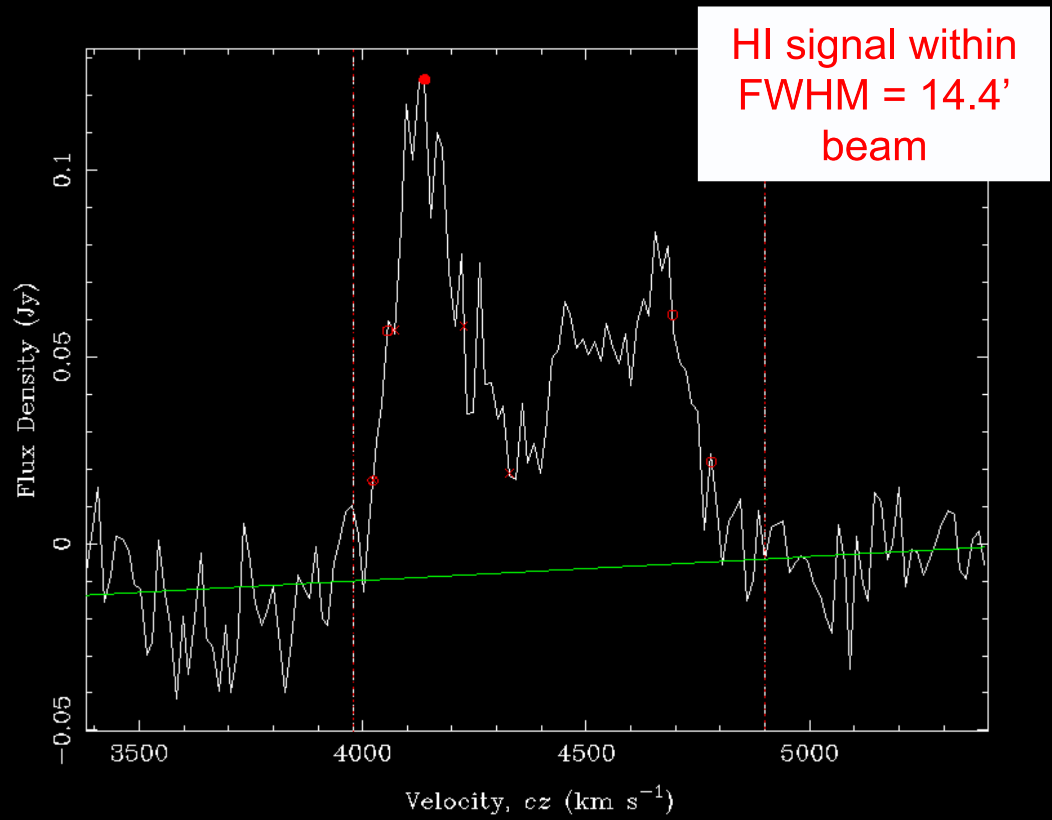
64-m Parkes Telescope



Parkes 10/50cm receivers (credit: G. Carrad, CSIRO)

Single dish spectral line observing modes:

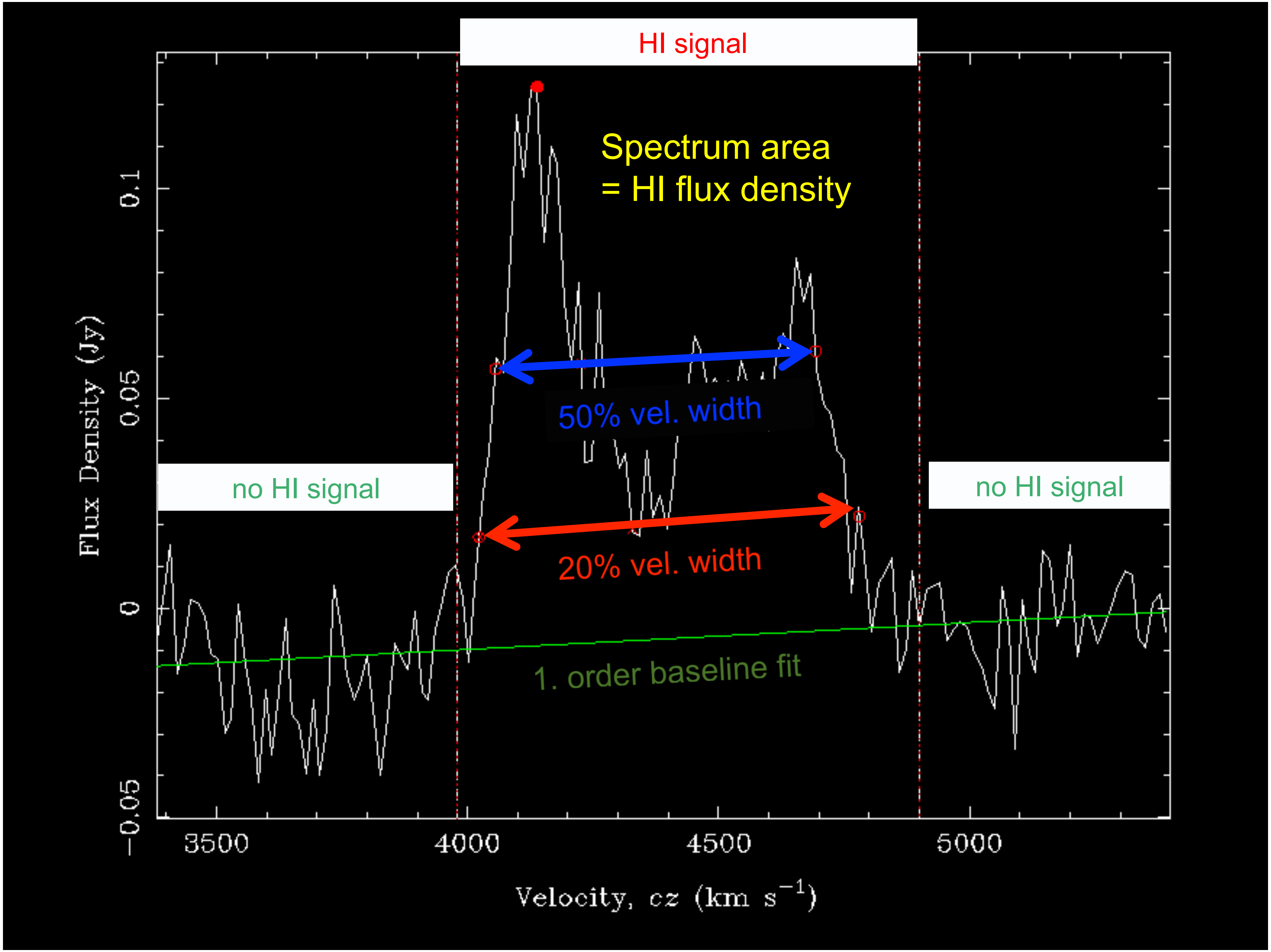
1) track source, get spectrum
   - single beam: on - off
   - multibeam: 100% on
2) scan field (ideally basket-weave), get cube



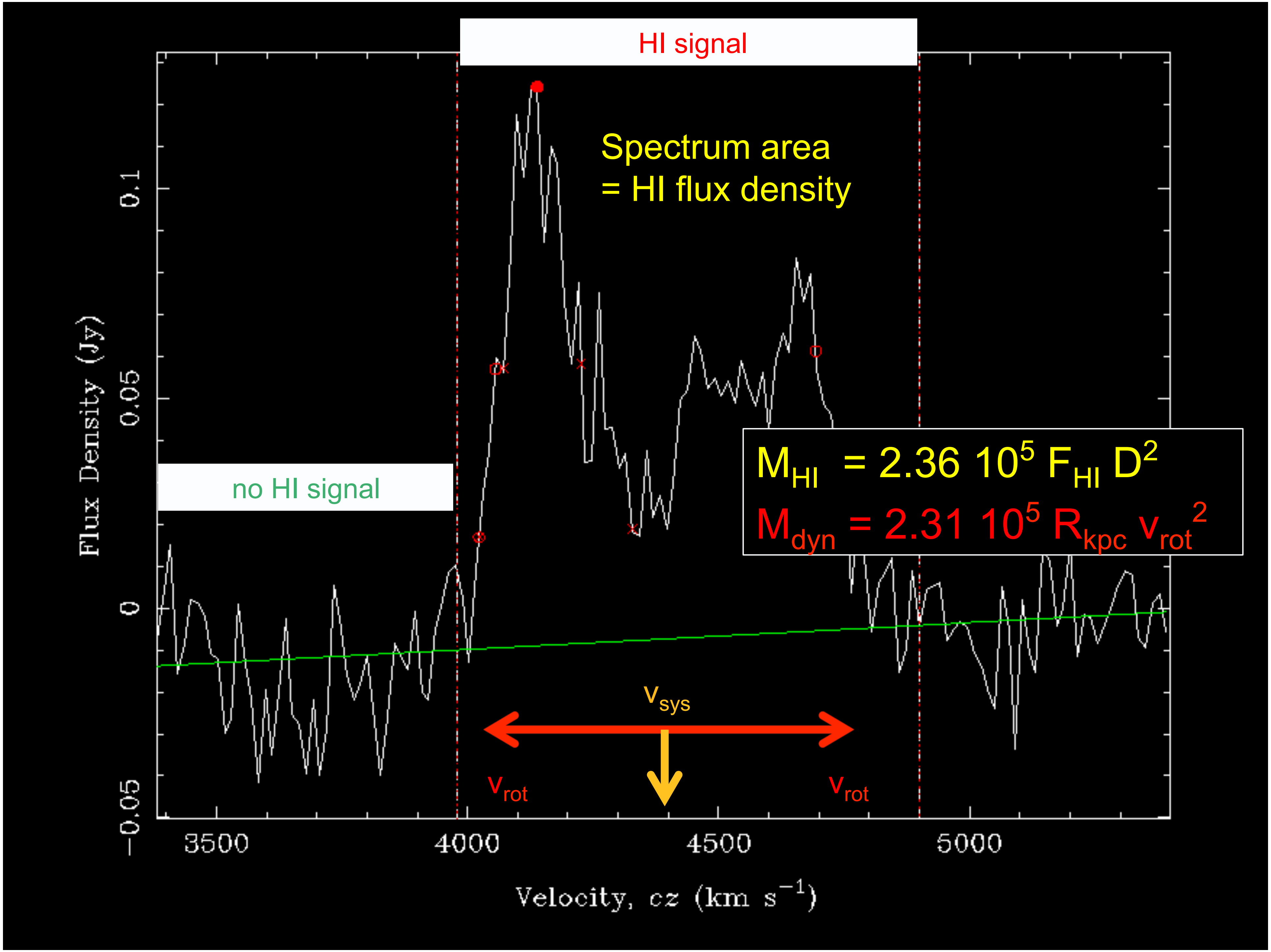
64-m Parkes Telescope

Single dish data archives, download:

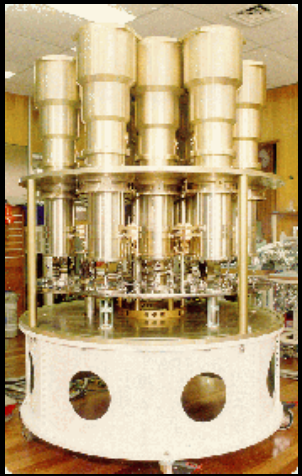
1) original sdfits files
2) original spectra
3) calibrated spectra
4) source catalog



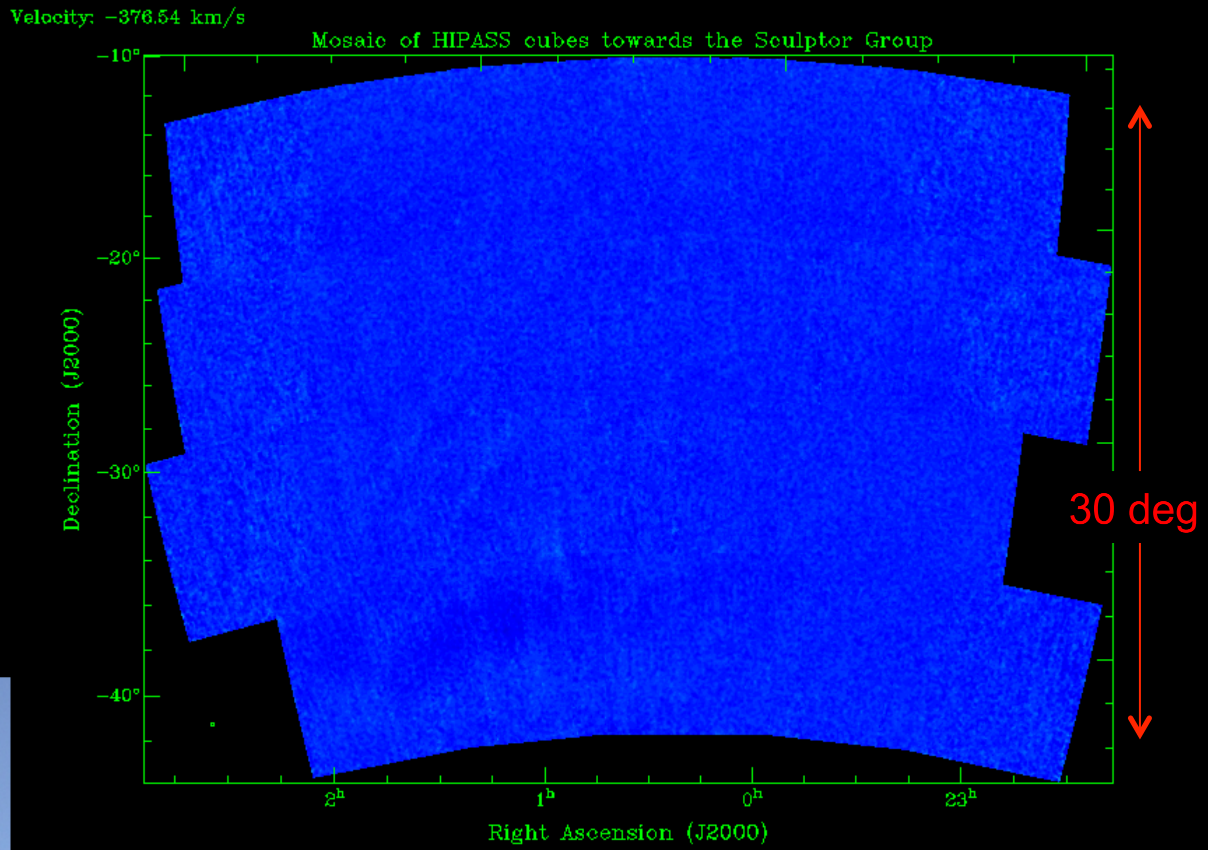
HI signal
Spectrum area
= HI flux density
50% vel. width
20% vel. width
no HI signal
no HI signal
1. order baseline fit
Flux Density (Jy)
0.1
0.05
0
−0.05
3500
4000
4500
5000
Velocity, cz (km s^{-1})



HI signal
Spectrum area
= HI flux density
no HI signal
M_{HI} = 2.36 10^5 F_{HI} D^2
M_{dyn} = 2.31 10^5 R_{kpc} v_{rot}^2
v_{sys}
v_{rot}
v_{rot}
Flux Density (Jy)
Velocity, cz (km s^{-1})
3500
4000
4500
5000
0.1
0.05
0
−0.05



Parkes 13-beam receiver



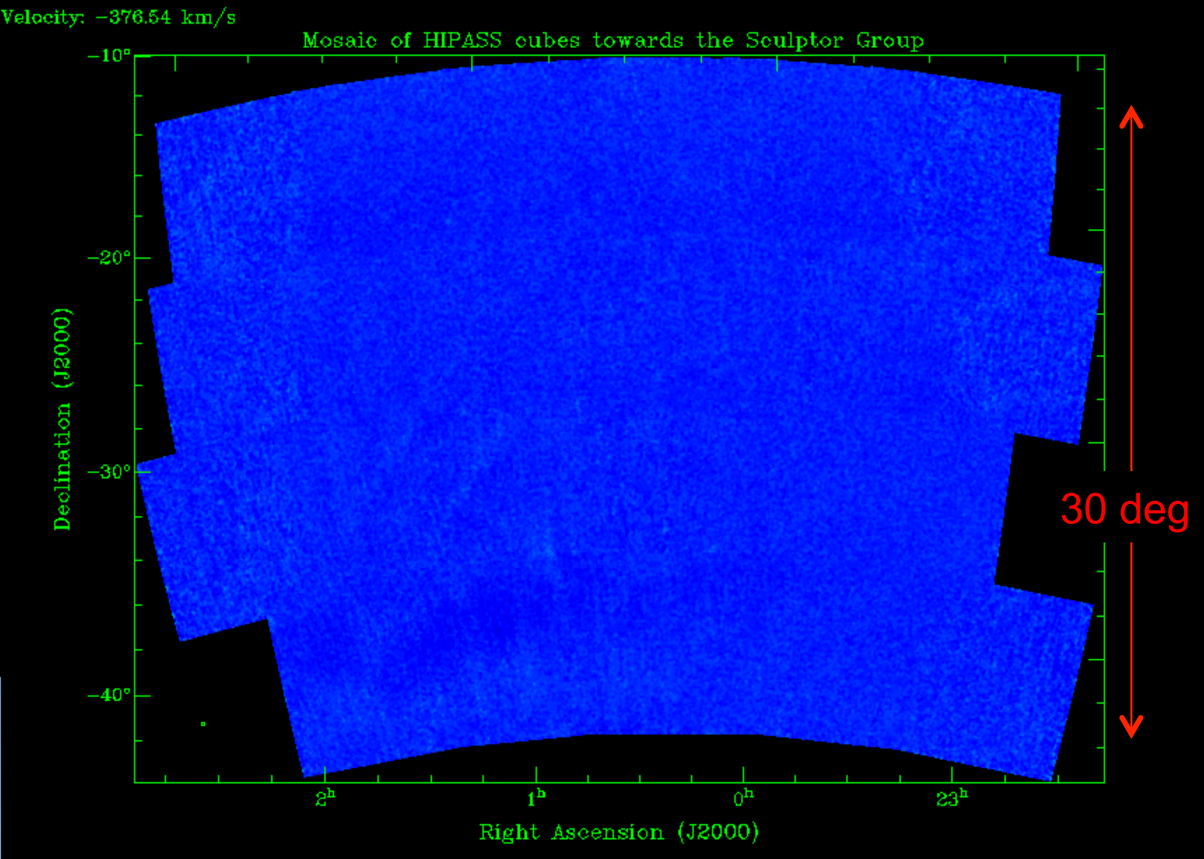
64-m Parkes Telescope

Single dish data archives, download:

1) calibrated spectra and cubes
2) source catalogs

http://www.atnf.csiro.au/research/multibeam/release/

Phased Array Feed



64-m Parkes Telescope

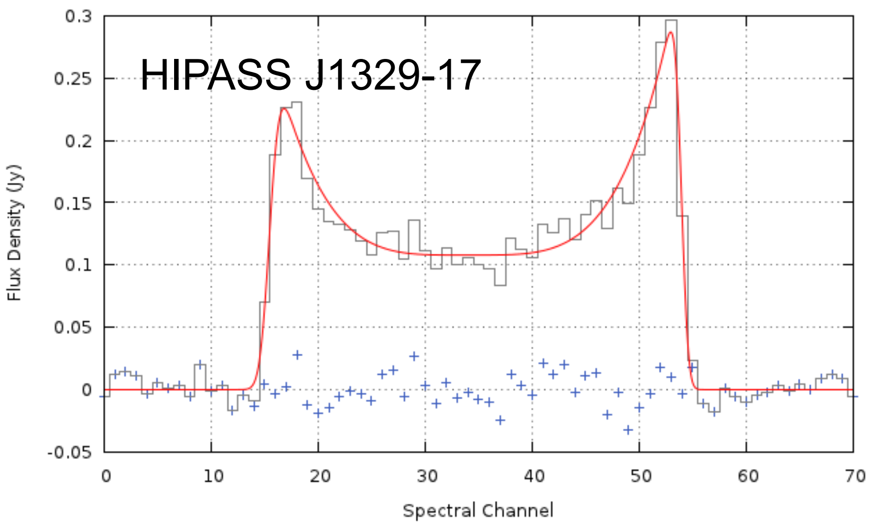
Single dish data archives, download:

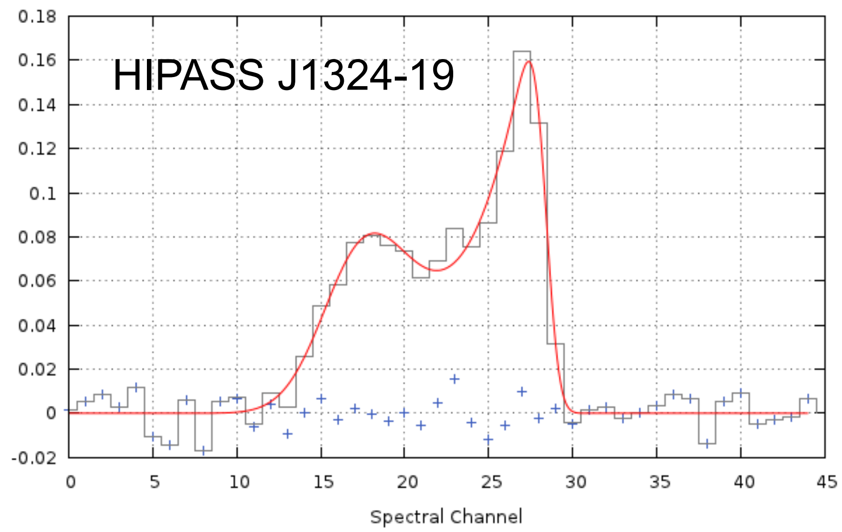
1) calibrated spectra and cubes
2) source catalogs

http://www.atnf.csiro.au/research/multibeam/release/

The Busy Function:

a new analytic function for describing the integrated 21-cm spectral profile of galaxies





Westmeier, T., Jurek, R., Obreschkow, D., Koribalski, B.S., Staveley-Smith, L. 2014, MNRAS 438, 1176

*http://www.atnf.csiro.au/people/Tobias.Westmeier/**tools_software_busyfit.php***

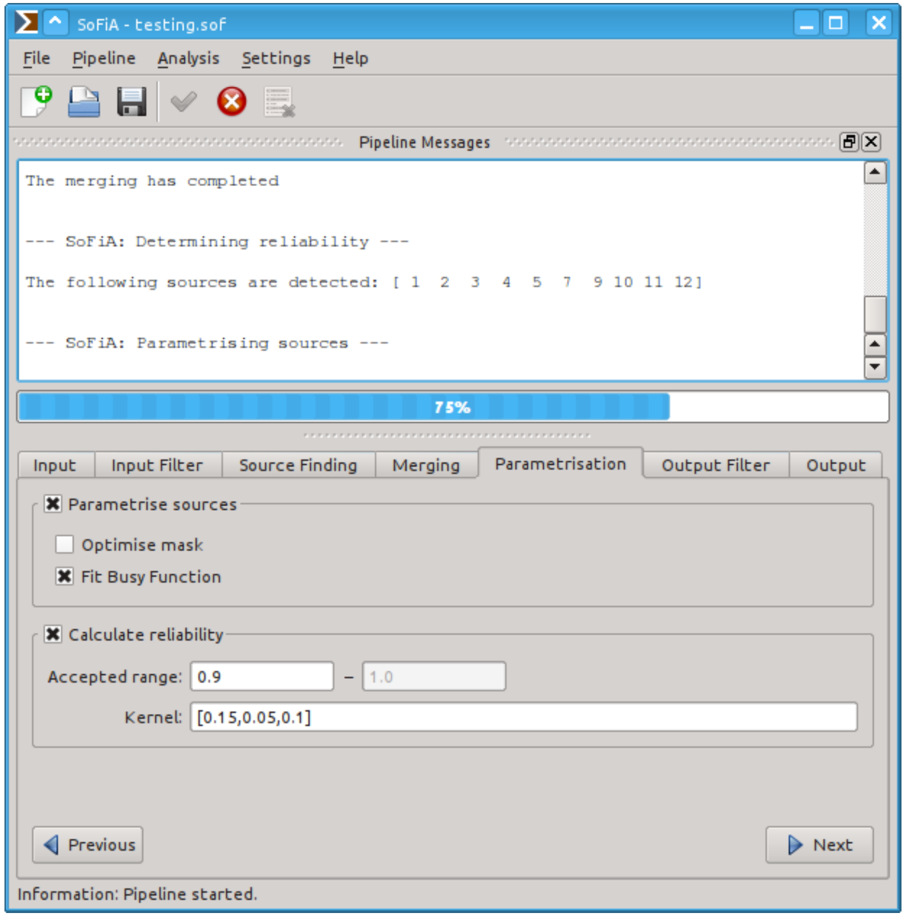
SoFiA - our new Source Finding Application

SoFiA
Source Finding Application

developed by members of the **WALLABY source finding working group (TWG4)**

Tobias Westmeier, **Paolo Serra, Nadine Giese**, Russell Jurek, Lars Flöer, Attila Popping and Benjamin Winkel

* SoFiA Handbook (on-line)

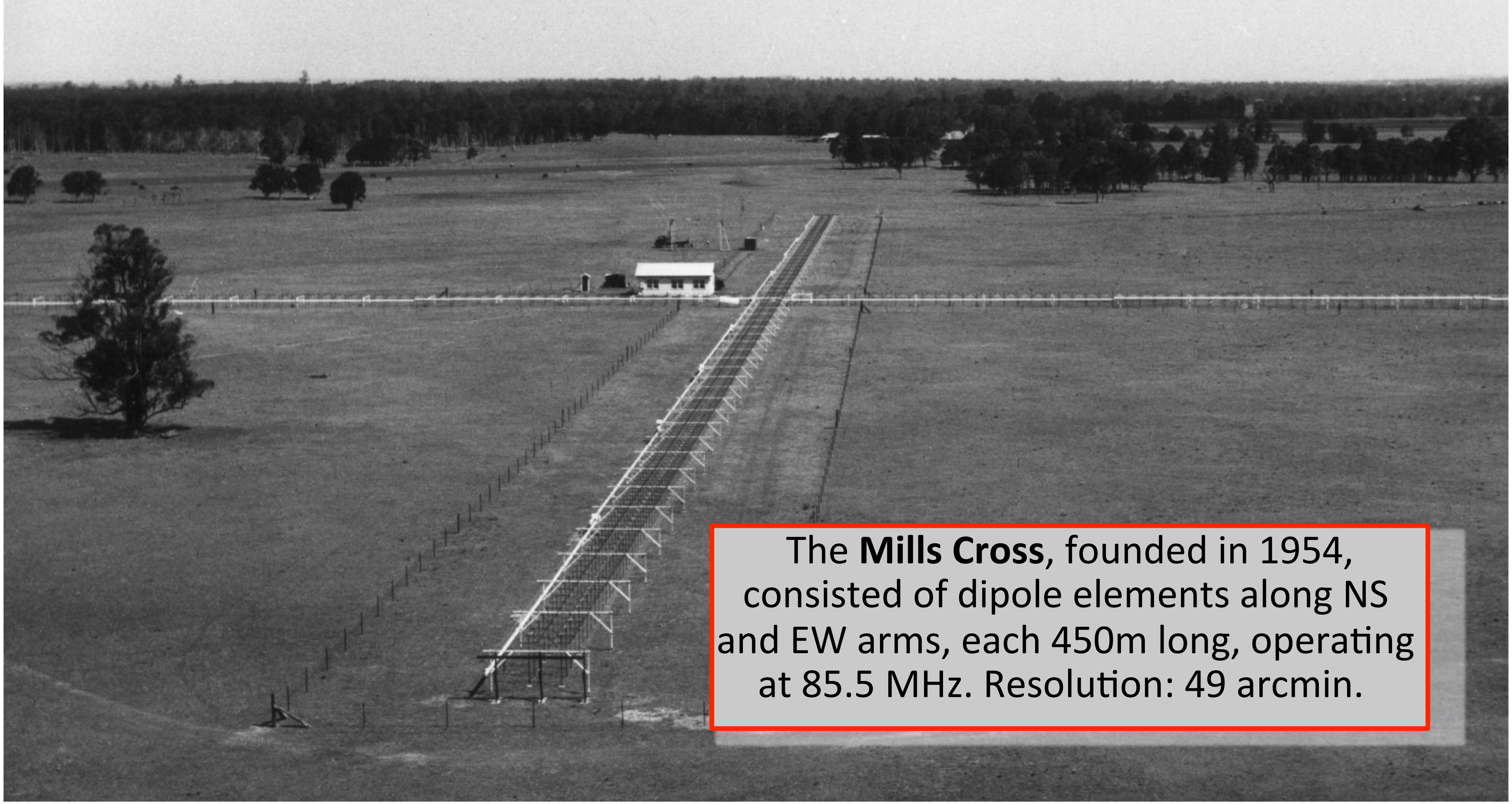


*http://www.atnf.csiro.au/people/Tobias.Westmeier/**tools_software_sofia.php***

CSIRO

Radio interferometers

… some early radio interferometers



The **Mills Cross**, founded in 1954, consisted of dipole elements along NS and EW arms, each 450m long, operating at 85.5 MHz. Resolution: 49 arcmin.

http://www.atnf.csiro.au/news/newsletter/jun02/Flowering_of_Fleurs.htm (by *Wayne Orchiston and Bruce Slee)*

… some early radio interferometers

Centre of the **Chris Cross**, an array of 32 × 5.8m parabolic dishes, operating at 1420 MHz. Resolution: 1.5 arcmin.

Westerbork Synthesis Radio Telescope (WSRT)

1970 – 2020?

14 × 25-m dishes on a 3 km long East-West track

(frequency range: 0.1 – 8 GHz)

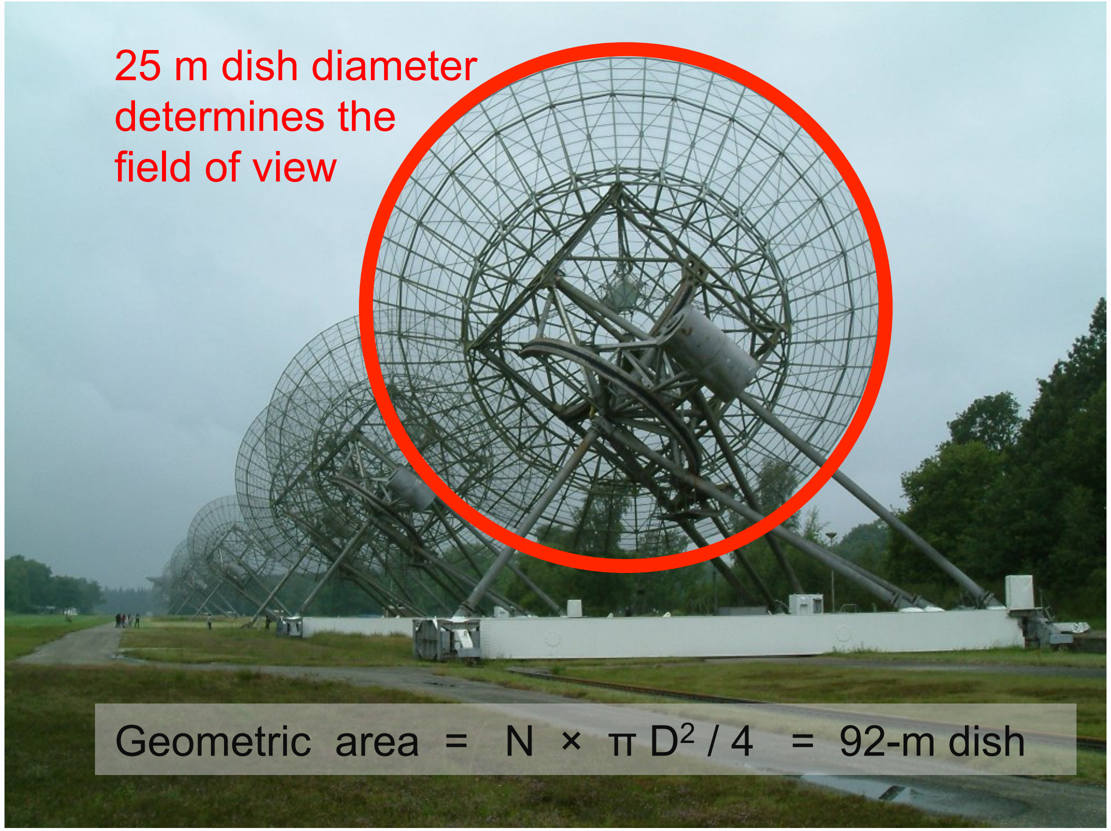


Image credit: ASTRON, The Netherlands.

Australia Telescope Compact Array (ATCA)

6 × 22-m telescopes on a 6-km long East-West track (configurable) since 1988

+ North-South spur (frequency range: 1 – 105 GHz)

Very Large Array (VLA)

27 × 25-m telescopes in a Y-shaped array (configurable: A, B, C, D) with baselines up to 40 km (frequency range: 1 – 50 GHz)

Image credit: NRAO, US.

Giant Meterwave Radio Telescope (GMRT)

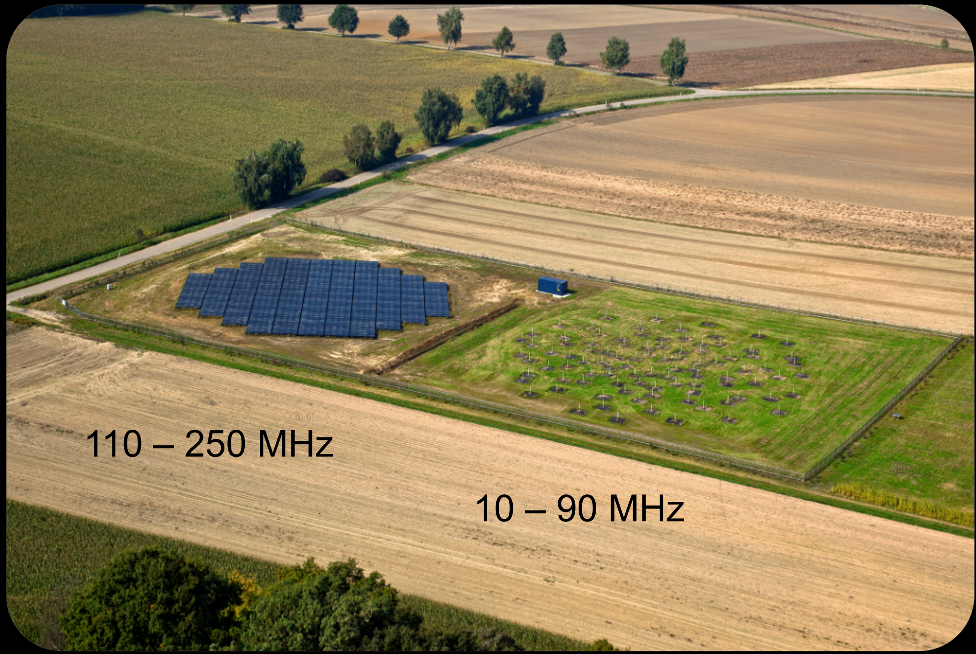
30 × 45-m dishes

(frequency range: 0.05 – 1.5 GHz)

GMRT is a Y-shaped array, operating since 1998.

Image credit: NCRF, India

What’s new ?



LOFAR stations in Europe (left), incl. Garching (above).

www.lofar.org

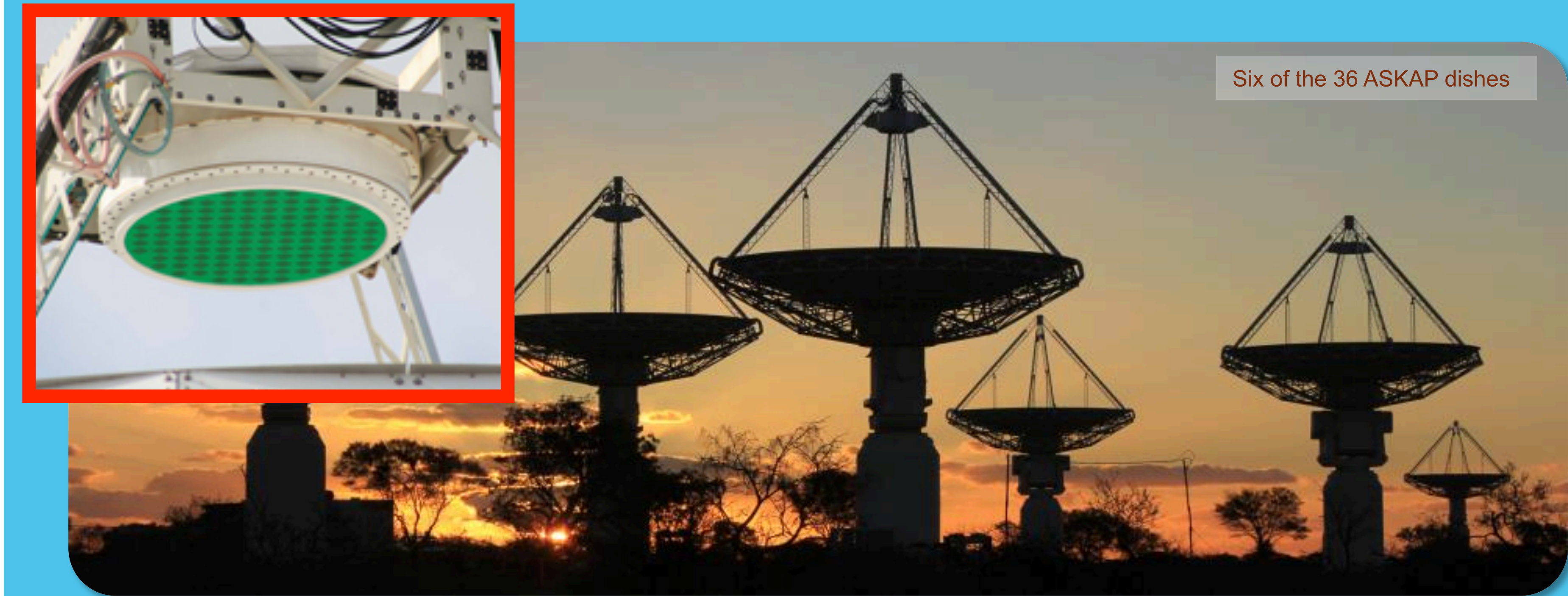
www.mwatelescope.org

KAT-7 : precursor to MeerKAT

ASKAP – the Australian SKA Pathfinder (in BETA commissioning)

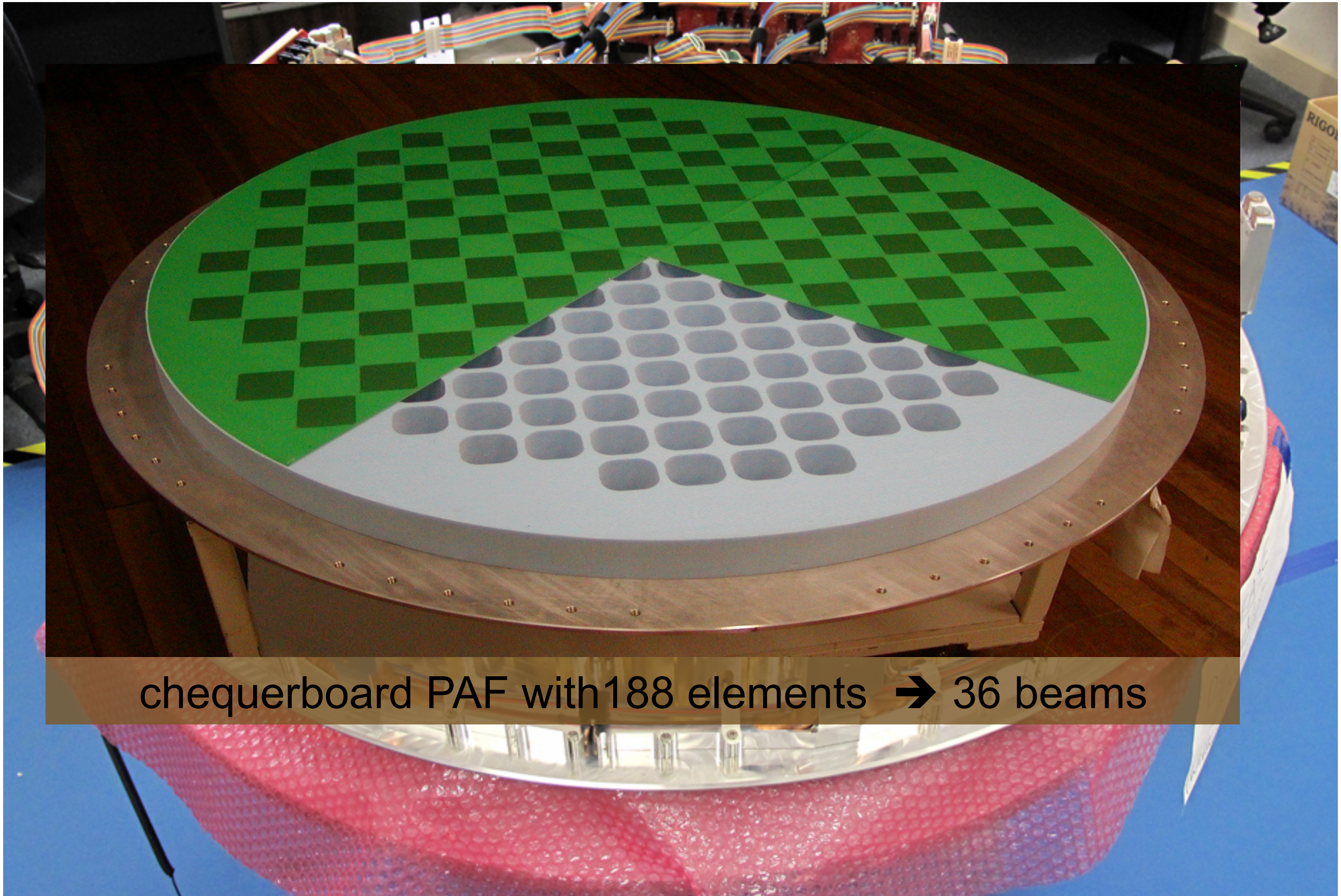
The Atacama Large Millimetre Array

- **ALMA**: 66 ×12-m dishes (5000 m altitude; freq. 84 – 950 GHz, baselines up to 160 km; high-res. imaging of the "cool Universe")
- starting full operation now (official opening on 13 March 2013)
- ALMA's **data rate** is **96 Gbit/s**; raw data **~200 TB /yr** is currently stored and mostly downloaded & processed by the users
- **ALMA correlator** (delivering **17 PetaOPS** - fastest of its kind)
- partnership between Europe, North America & East Asia + Chile

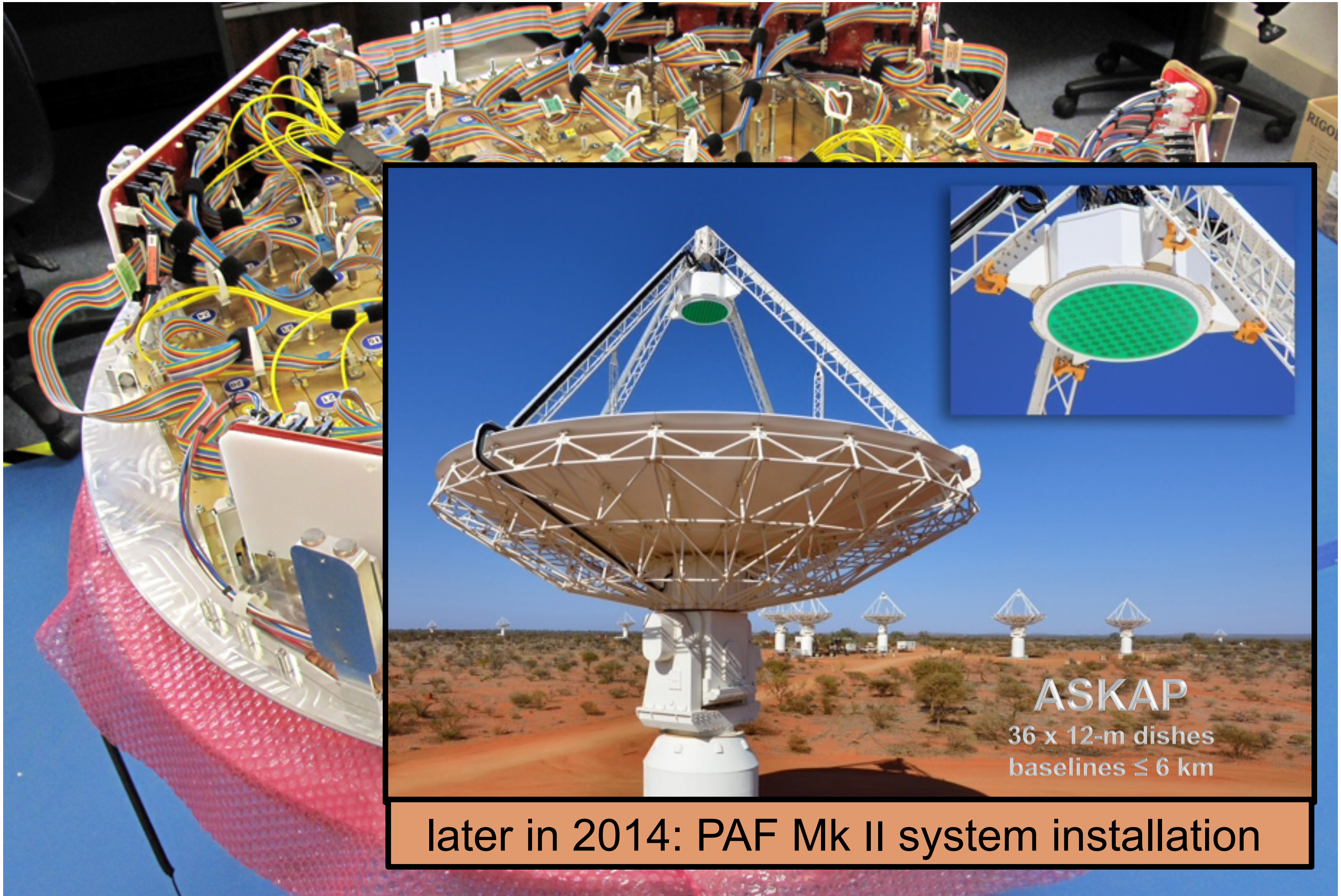


The Australian SKA Pathfinder

- **ASKAP**: 36 ×12-m dishes (freq. 0.7 – 1.8 GHz, baselines up to 6 km; eg., mapping the 21-cm line of neutral atomic hydrogen gas)
- started preliminary commissioning work with 3-6 antennas
- ASKAP's **data rate** is expected to be **72 Tbit/s**; (once fully operational), data output **~500 PB /yr**; raw data will be stored only temporarily; archive data outputs (images/cubes) long term
- **ASKAP correlator** (delivering **340 Tflop/s**)



ASKAP Mk II Phased Array Feed (PAF) assembly



ASKAP Mk II Phased Array Feed (PAF) assembly

uv-coverage

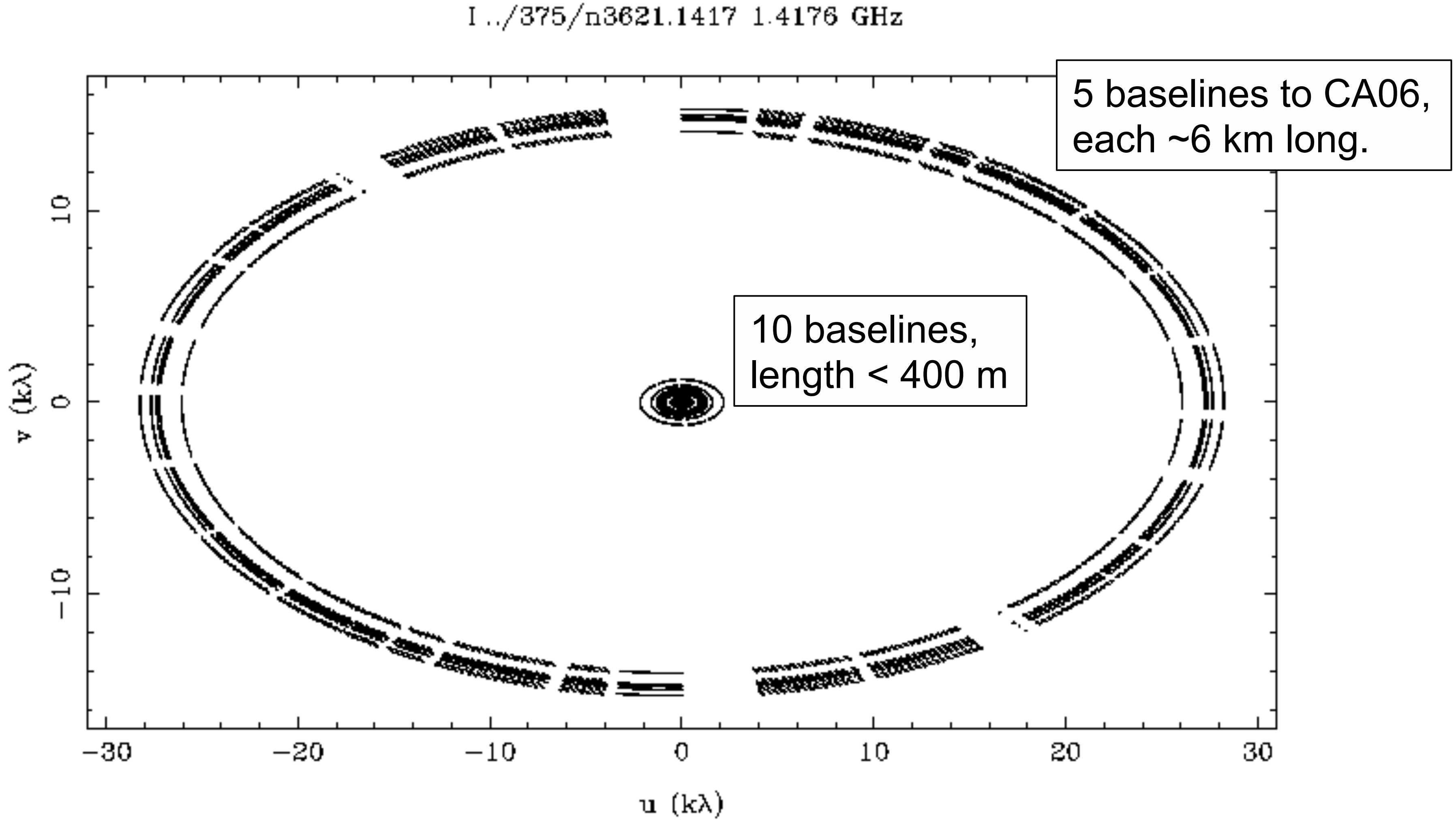
Interferometry uses earth rotation

Full *uv*-coverage achieved in …

- 12 hours for an east-west array (eg WSRT, ATCA)
- 8 hours for a Y-array (eg VLA, GMRT)

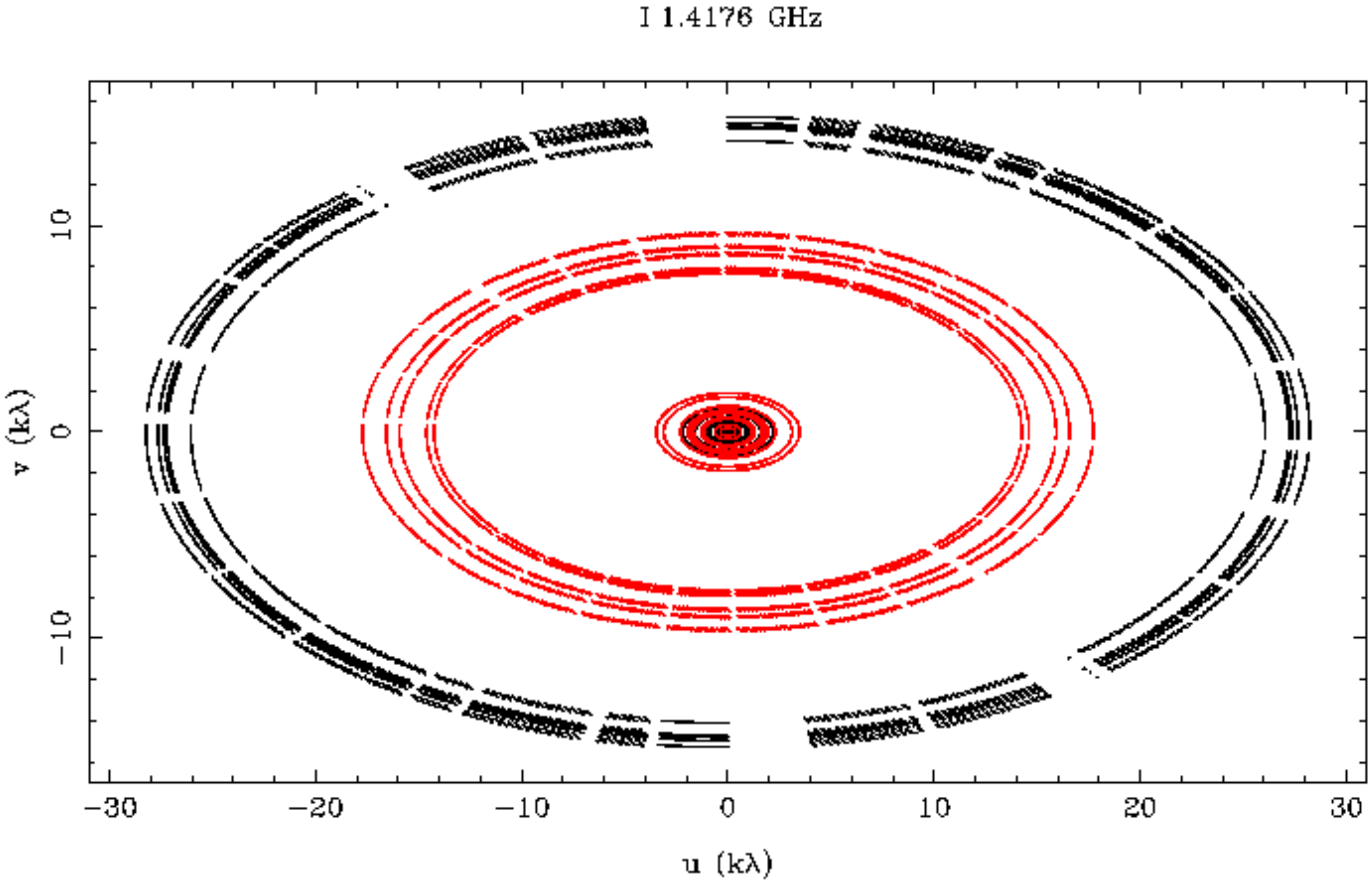
Interferometry & Earth-rotation Aperture Synthesis, eg, see
http://www.cv.nrao.edu/course/astr534/Interferometers1.html

uv-coverage: one configuration (15 baselines)



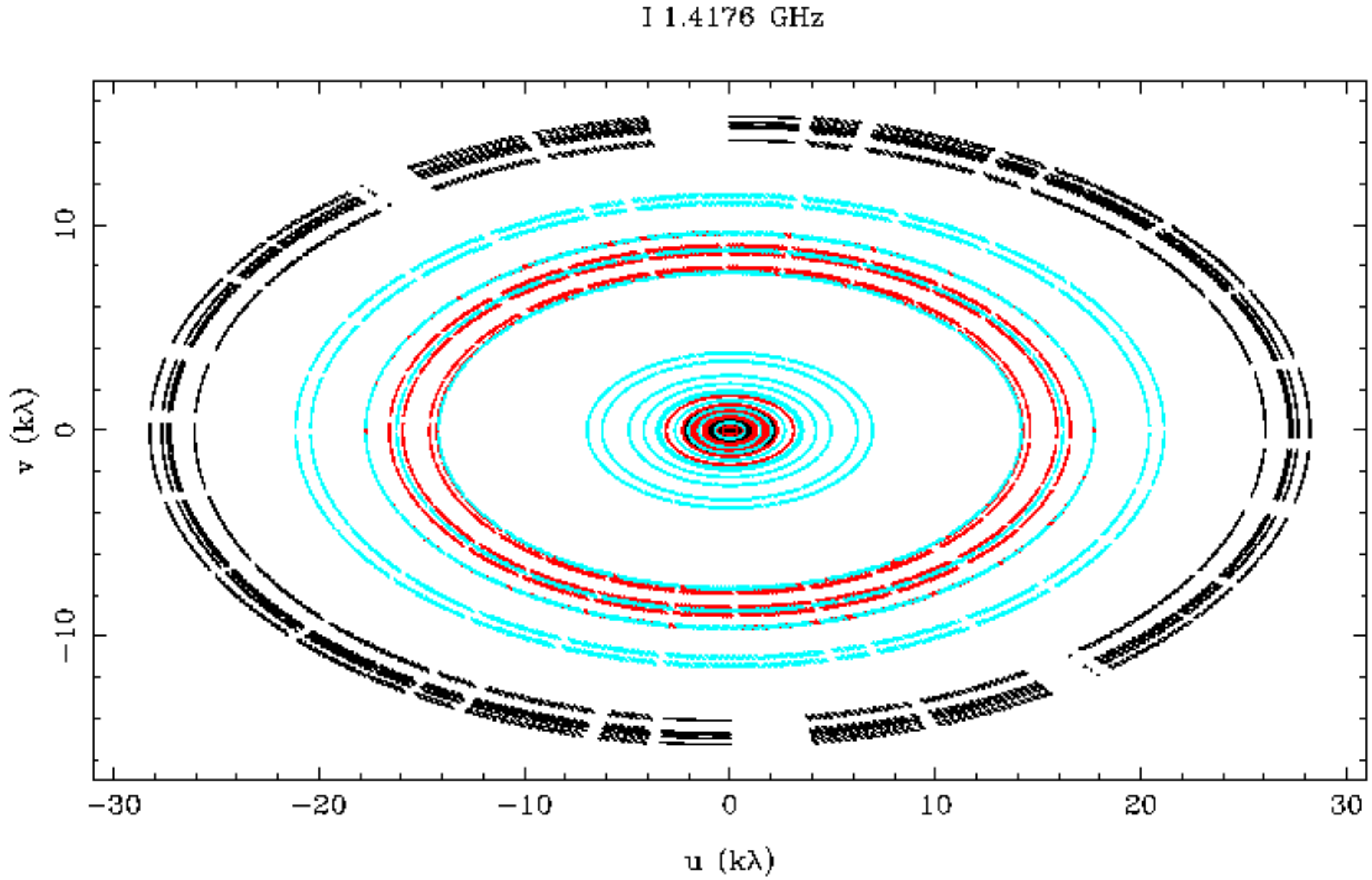
One HI channel at 1.417 GHz, ~12h obs in ATCA 375m array

uv-coverage: two configurations (30 baselines)



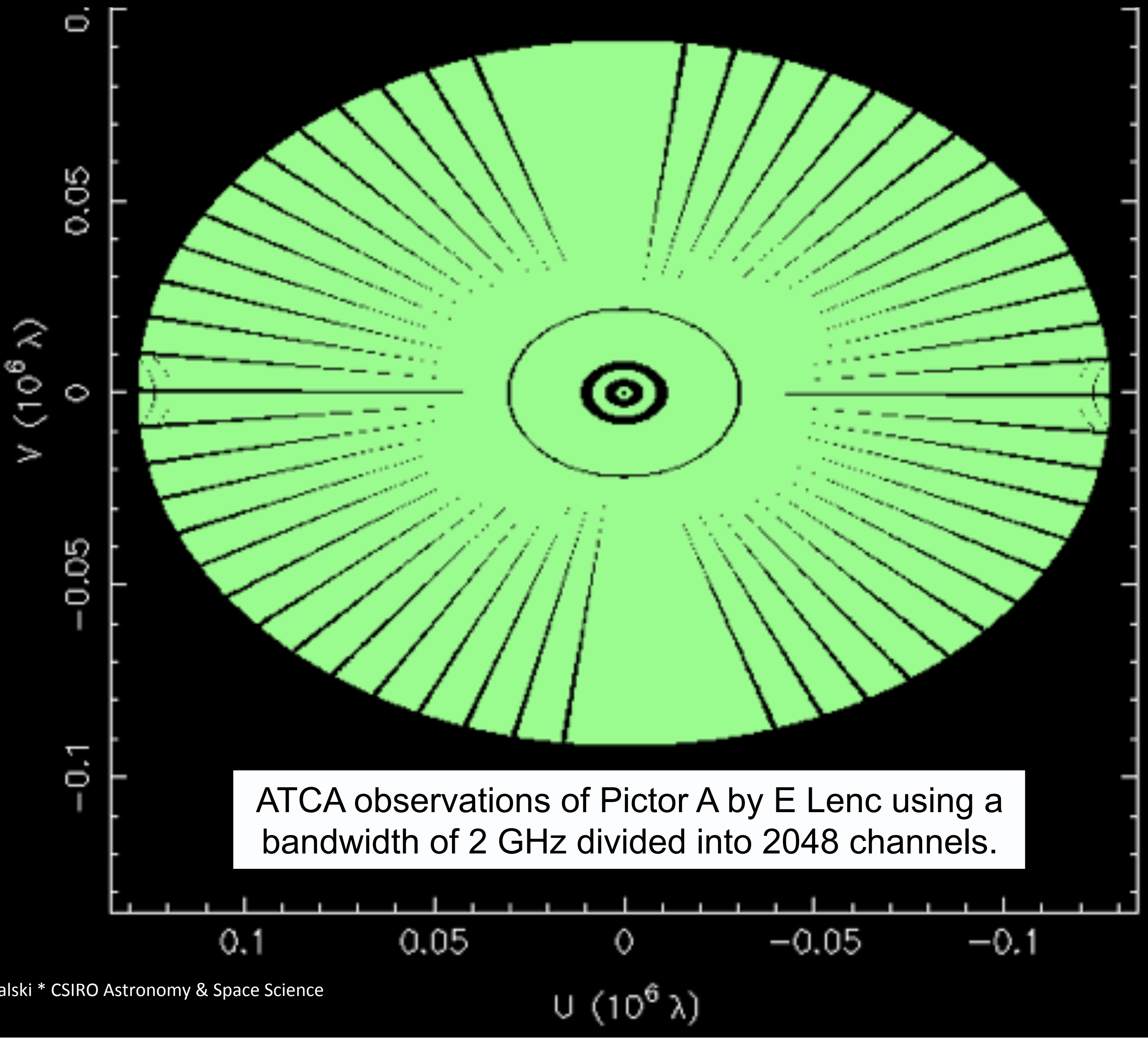
One HI channel at 1.417 GHz, ~24h obs in ATCA 375+750A array

uv-coverage: three configurations (45 baselines)



One HI channel at 1.417 GHz, ~36h obs in ATCA 375+750A+1.5A arrays

uv-coverage: single configuration (15 baselines)

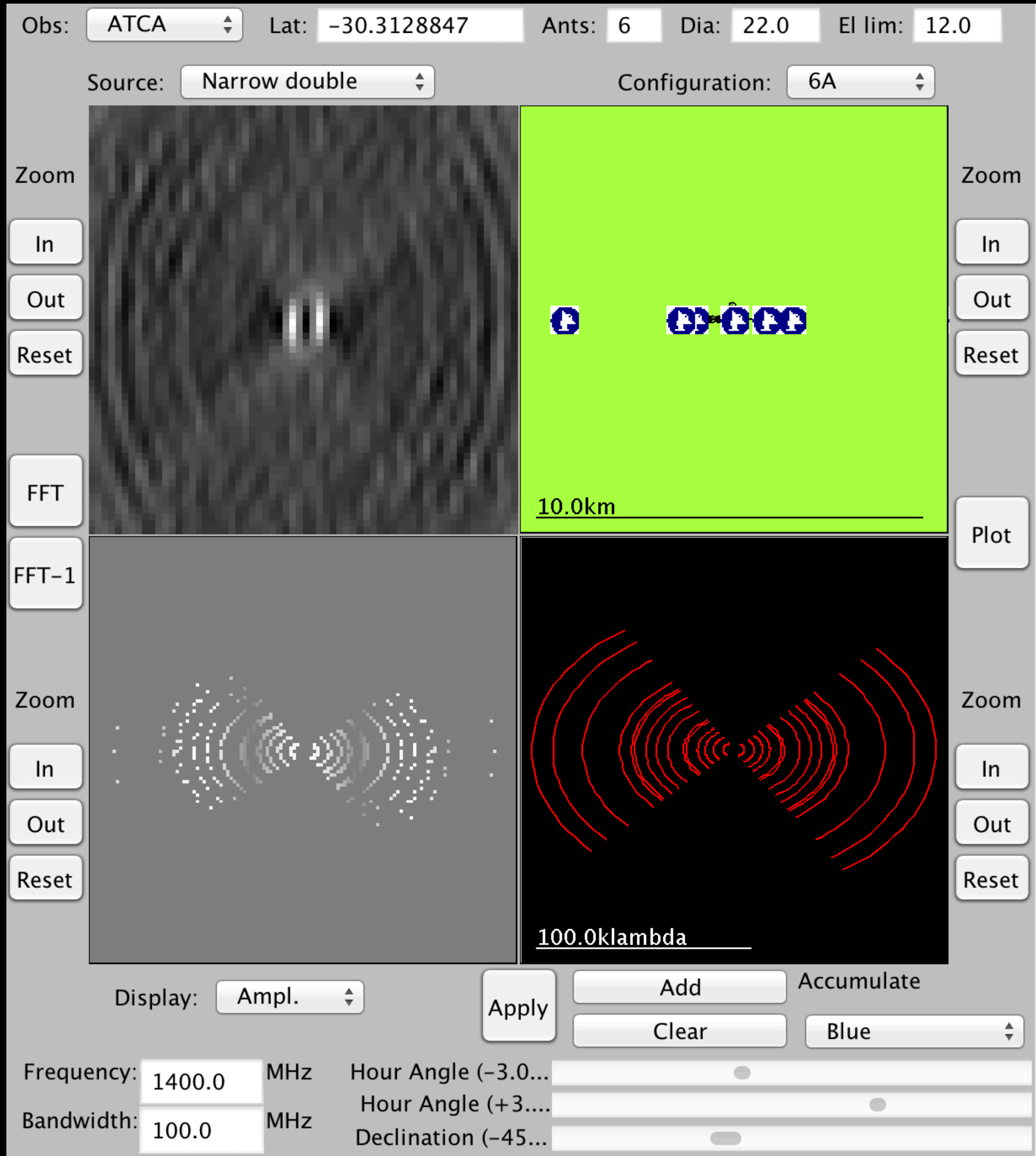


ATCA observations of Pictor A by E Lenc using a bandwidth of 2 GHz divided into 2048 channels.

NOTE:
multi frequency synthesis for continuum mapping

V.R.I.

Virtual
Radio
Interferometer

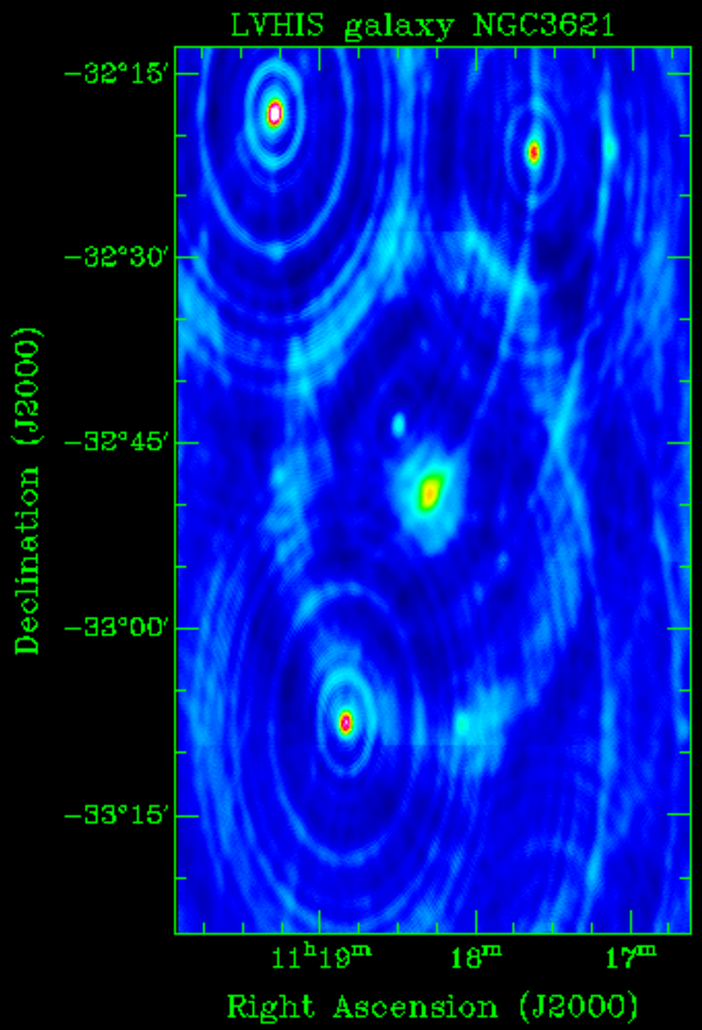


http://www.narrabri.atnf.csiro.au/astronomy/vri.html

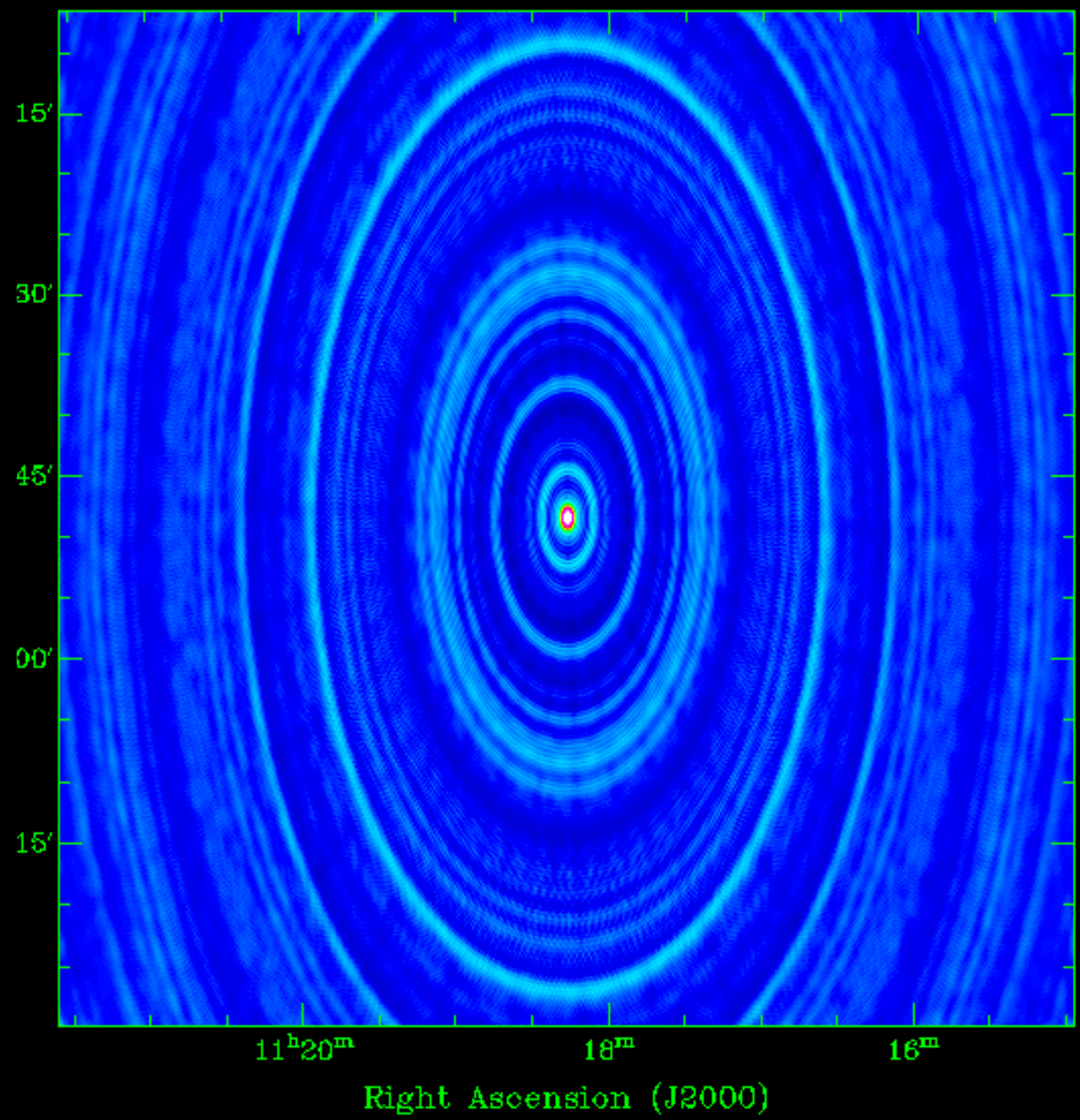
Imaging and cleaning

Example: ATCA 20-cm radio continuum image towards the galaxy NGC 3621

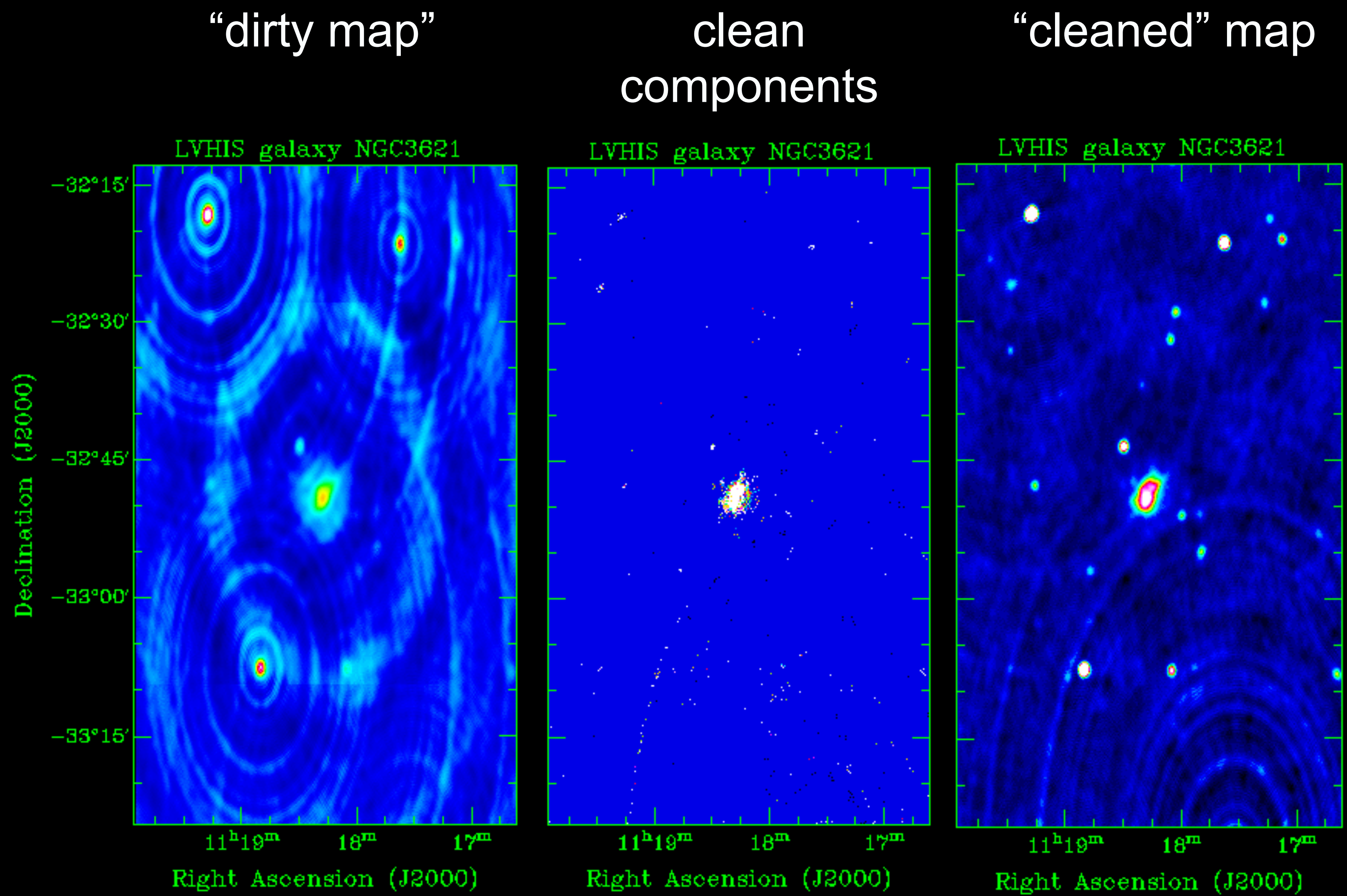
“dirty map”



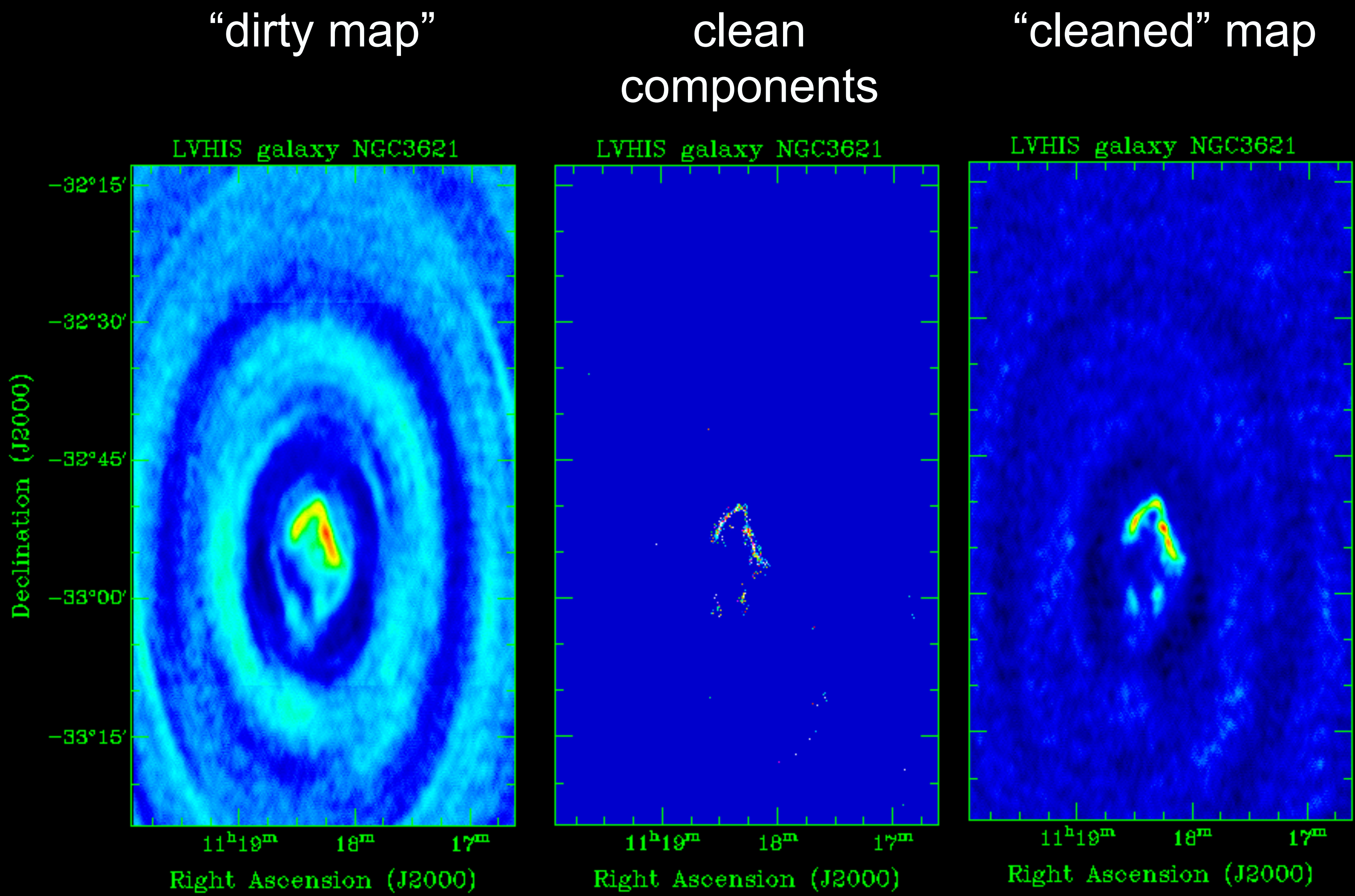
“dirty beam”



Example: ATCA 20-cm radio continuum image towards the galaxy NGC 3621

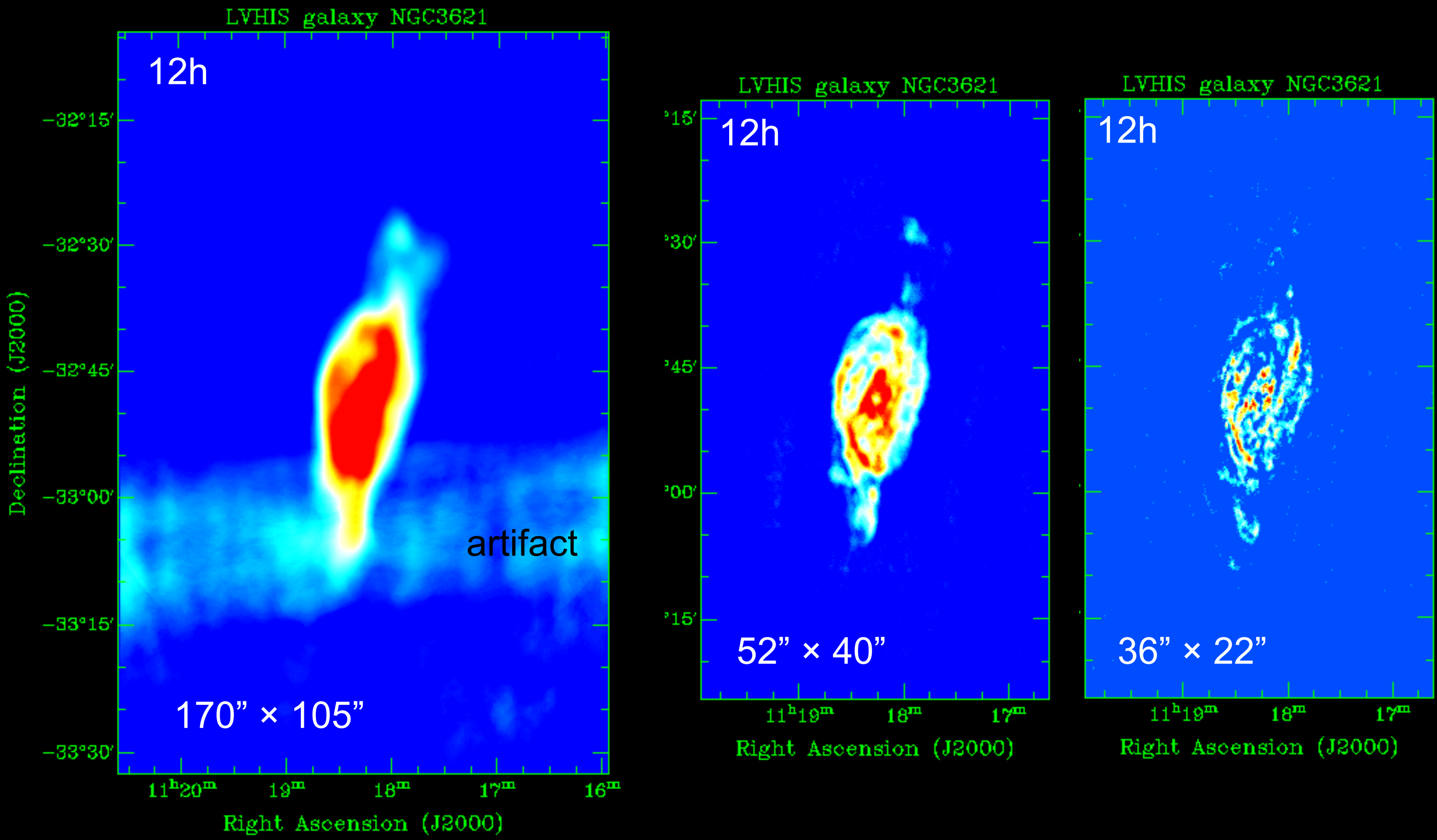


Example: ATCA HI channel map of the galaxy NGC 3621

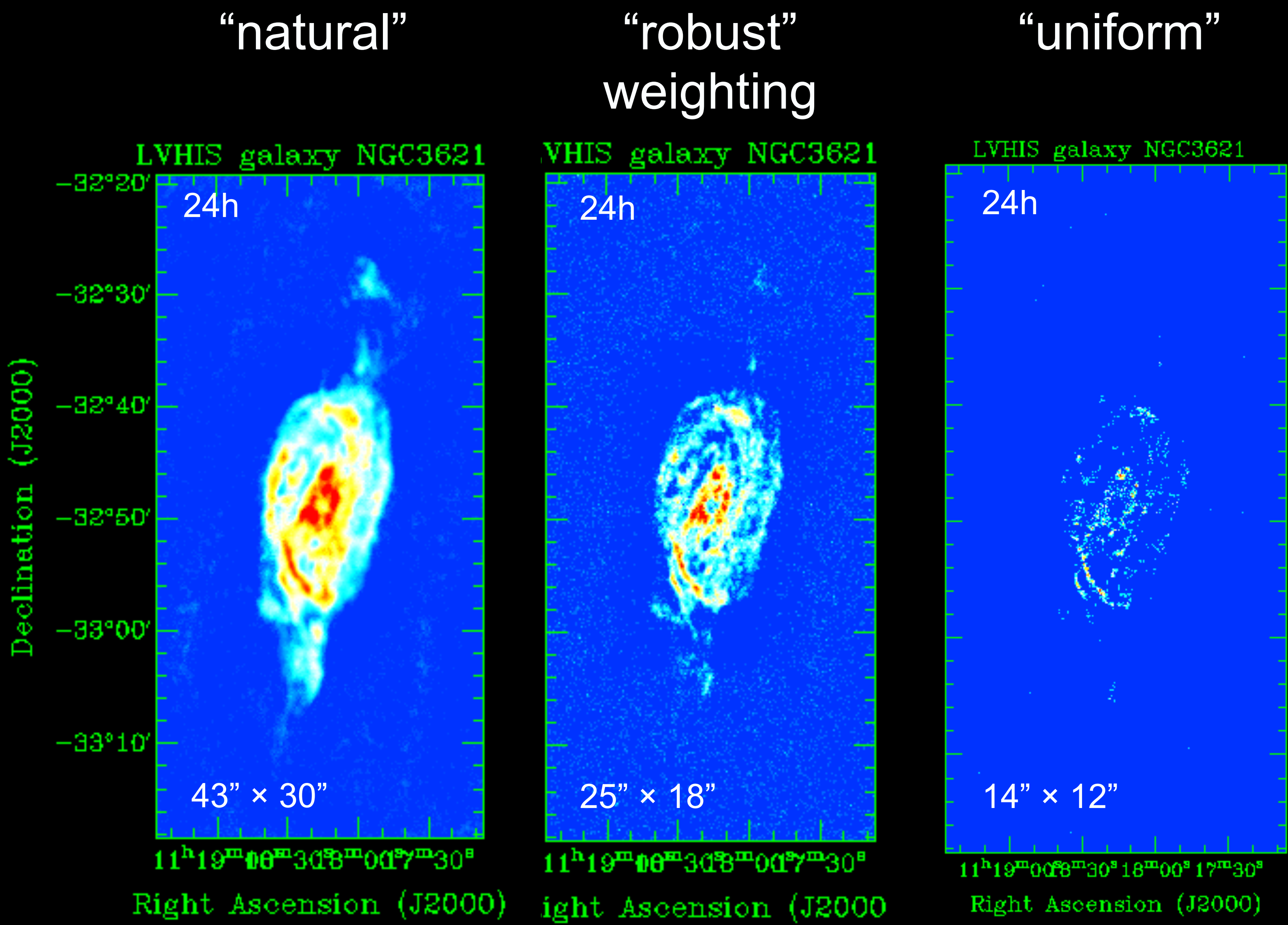


Example: ATCA HI moment maps of the galaxy NGC 3621

baselines < 400 m   < 800 m   < 1500 m



Example: ATCA HI moment maps of the galaxy NGC 3621



Error recognition

EXAMPLE 1

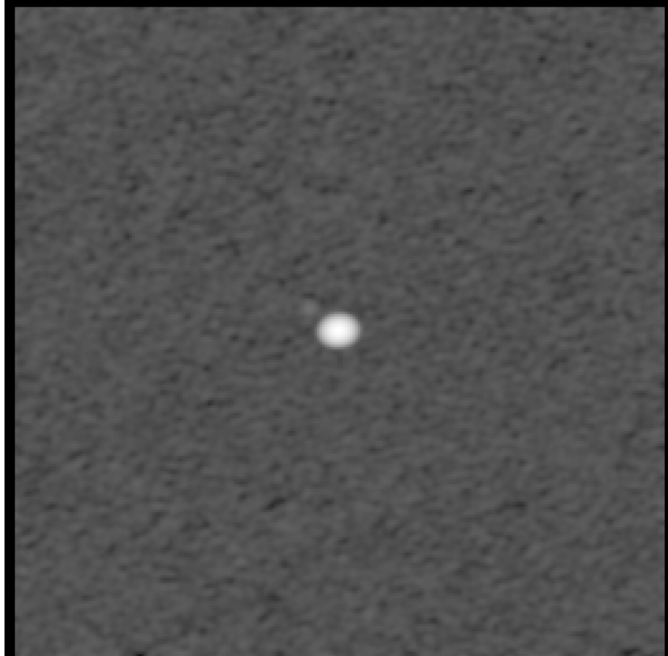
Data bad over a short period of time

Slide by Greg Taylor

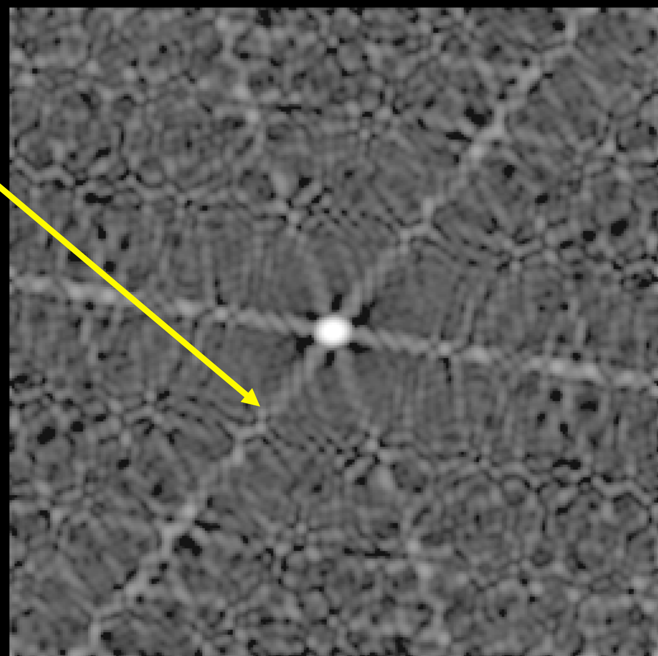
Results for a point source using VLA. 13 x 5min observation over 10 hr.
Images shown after editing, calibration and deconvolution.

no errors:
max 3.24 Jy
rms 0.11 mJy

10% amp error for all antennas for 1 time period
rms 2.0 mJy



6-fold symmetric pattern due to VLA "Y".
Image has properties of dirty beam.



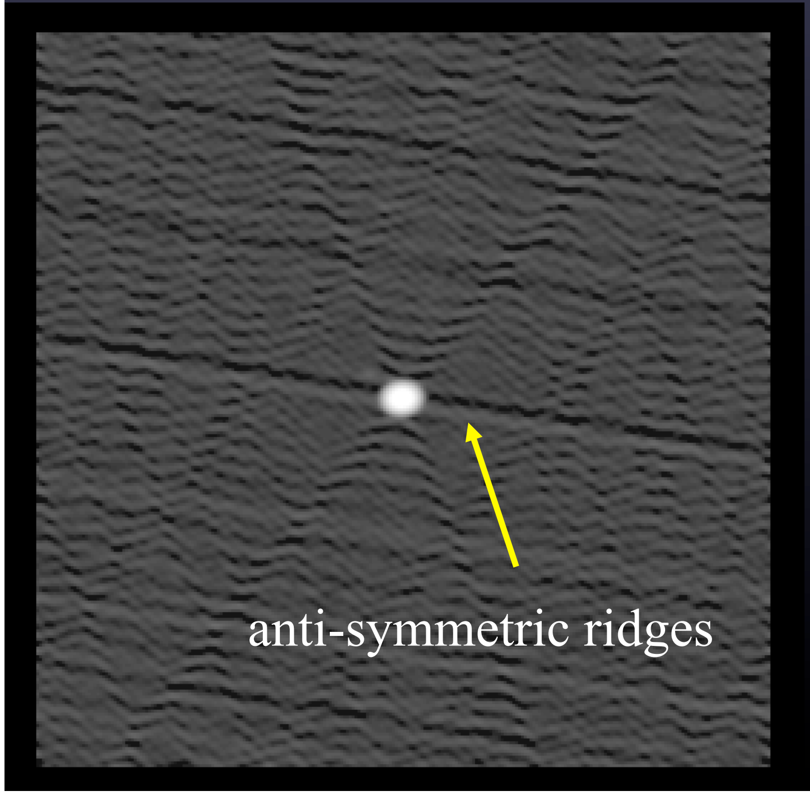
EXAMPLE 2
Short burst of bad data

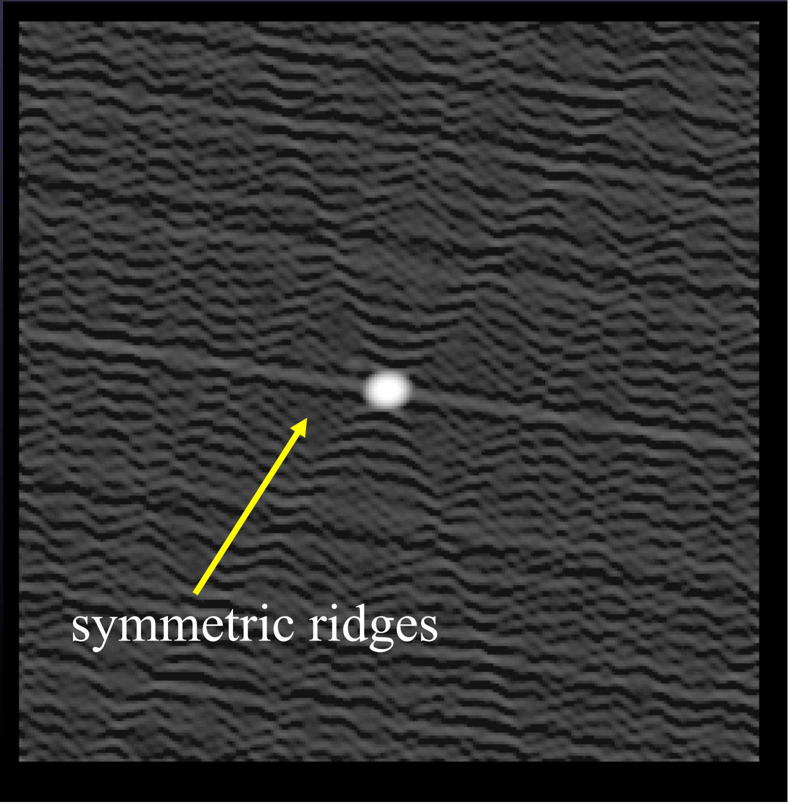
Slide by Greg Taylor

Typical effect from one bad antenna

10 deg phase error for
one antenna at one time
rms 0.49 mJy

20% amplitude error for
one antenna at one time
rms 0.56 mJy (self-cal)





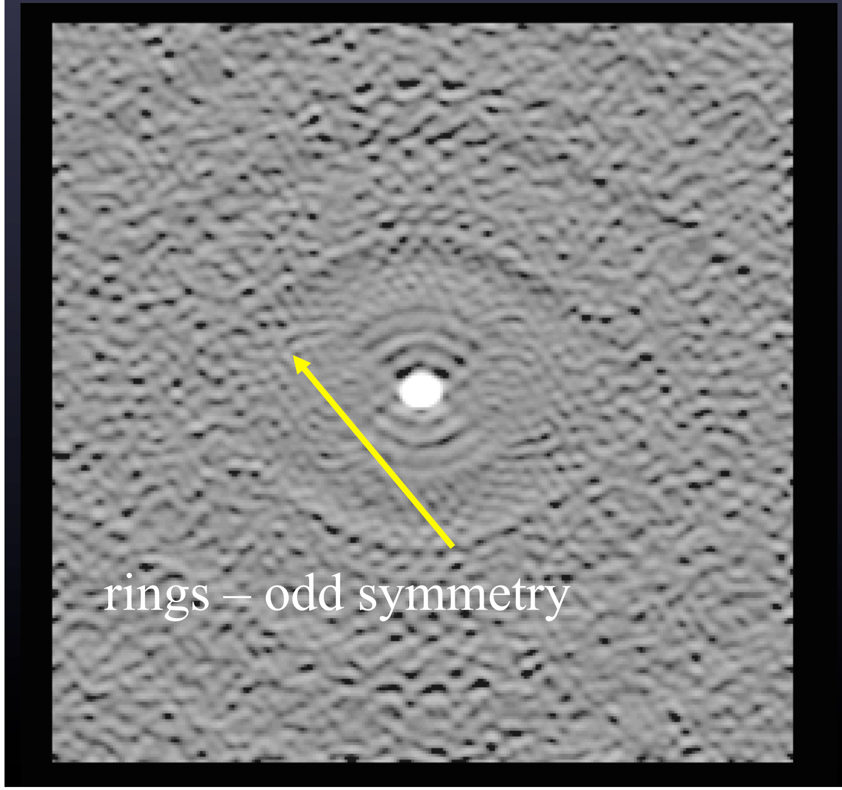
EXAMPLE 3

Slide by Greg Taylor

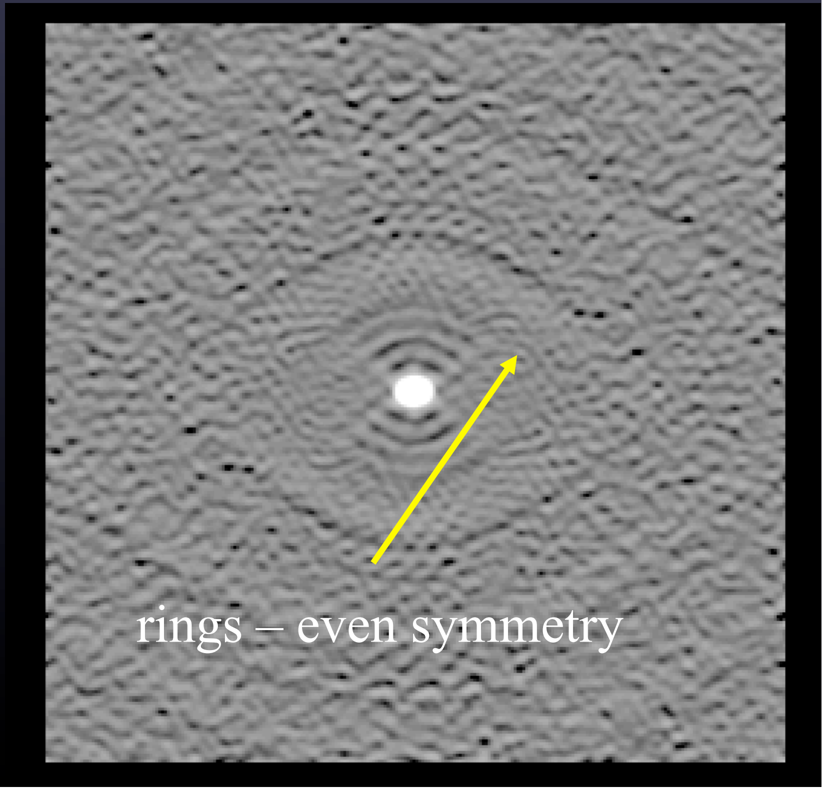
Persistent errors over most of observations

NOTE: 10 deg phase error to 20% amplitude error
cause similar sized artifacts

10 deg phase error for one antenna all times
rms 2.0 mJy



20% amp error for one antenna all times
rms 2.3 mJy



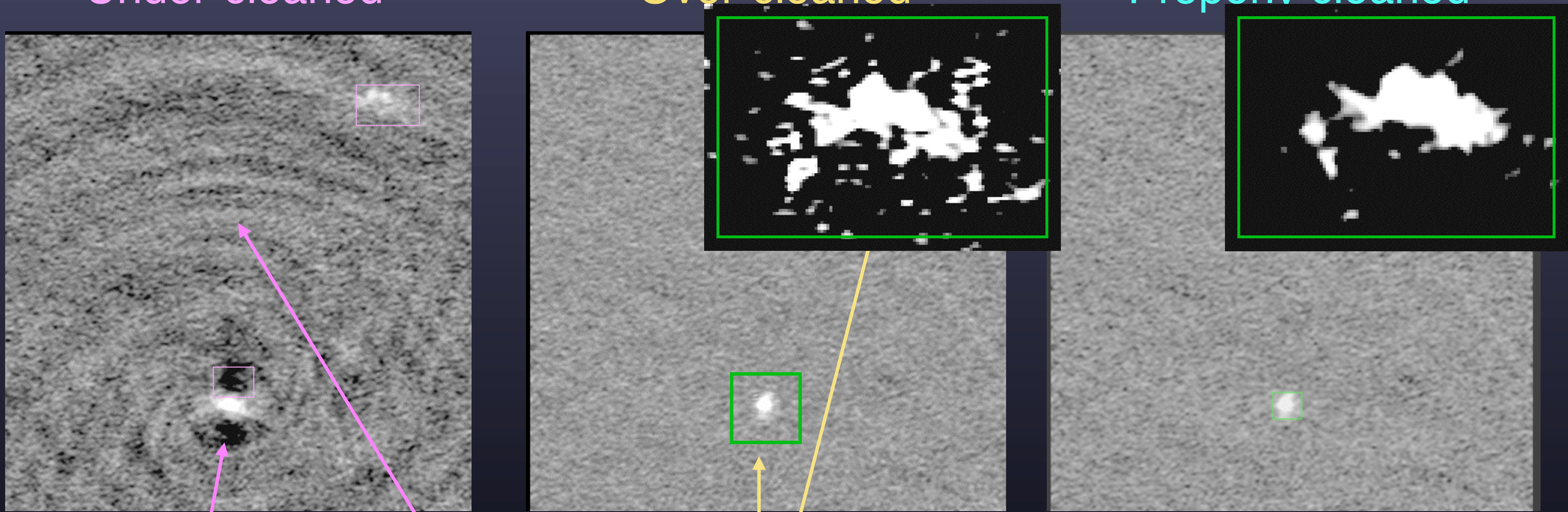
Slide by Greg Taylor

How Deep to Clean?

Under-cleaned

Over-cleaned

Properly cleaned



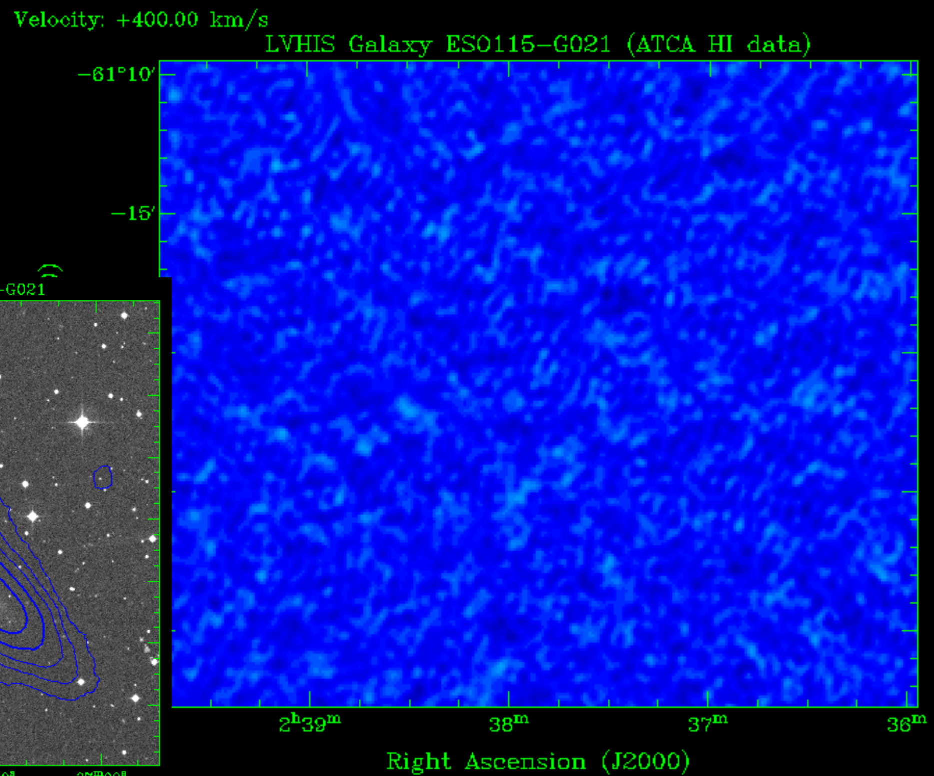
Residual sidelobes dominate the noise

Emission from second source sits atop a negative "bowl"

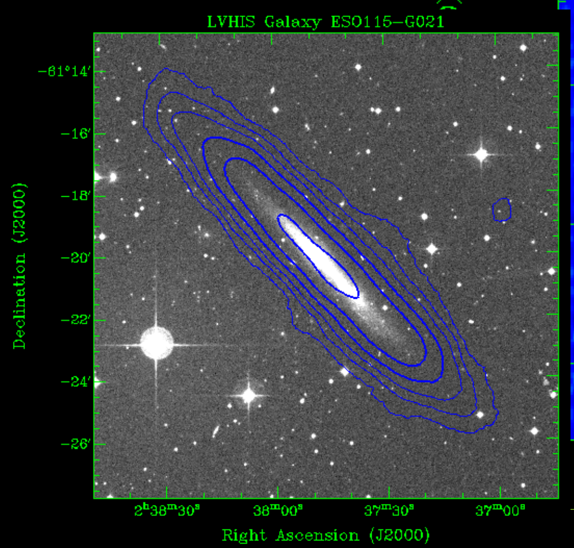
Regions within clean boxes appear "mottled"

Background is thermal noise-dominated; no "bowls" around sources.

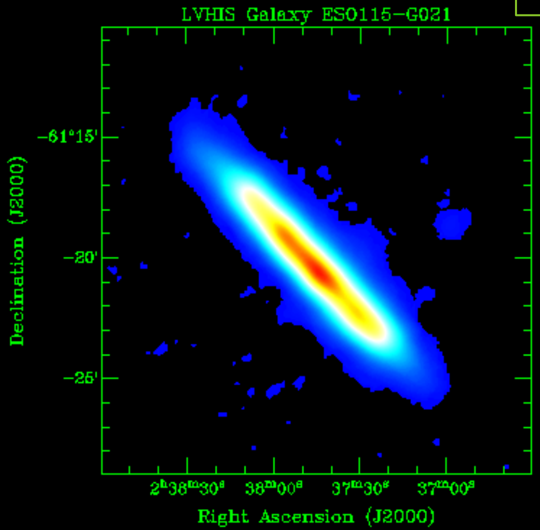
Channel maps and moment maps

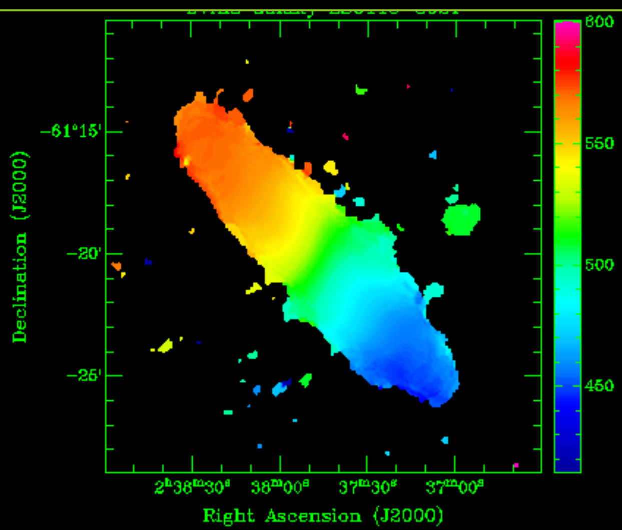


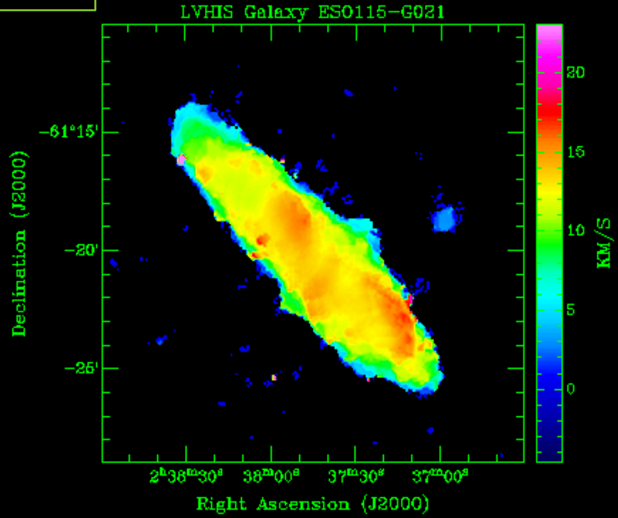
HI channel maps

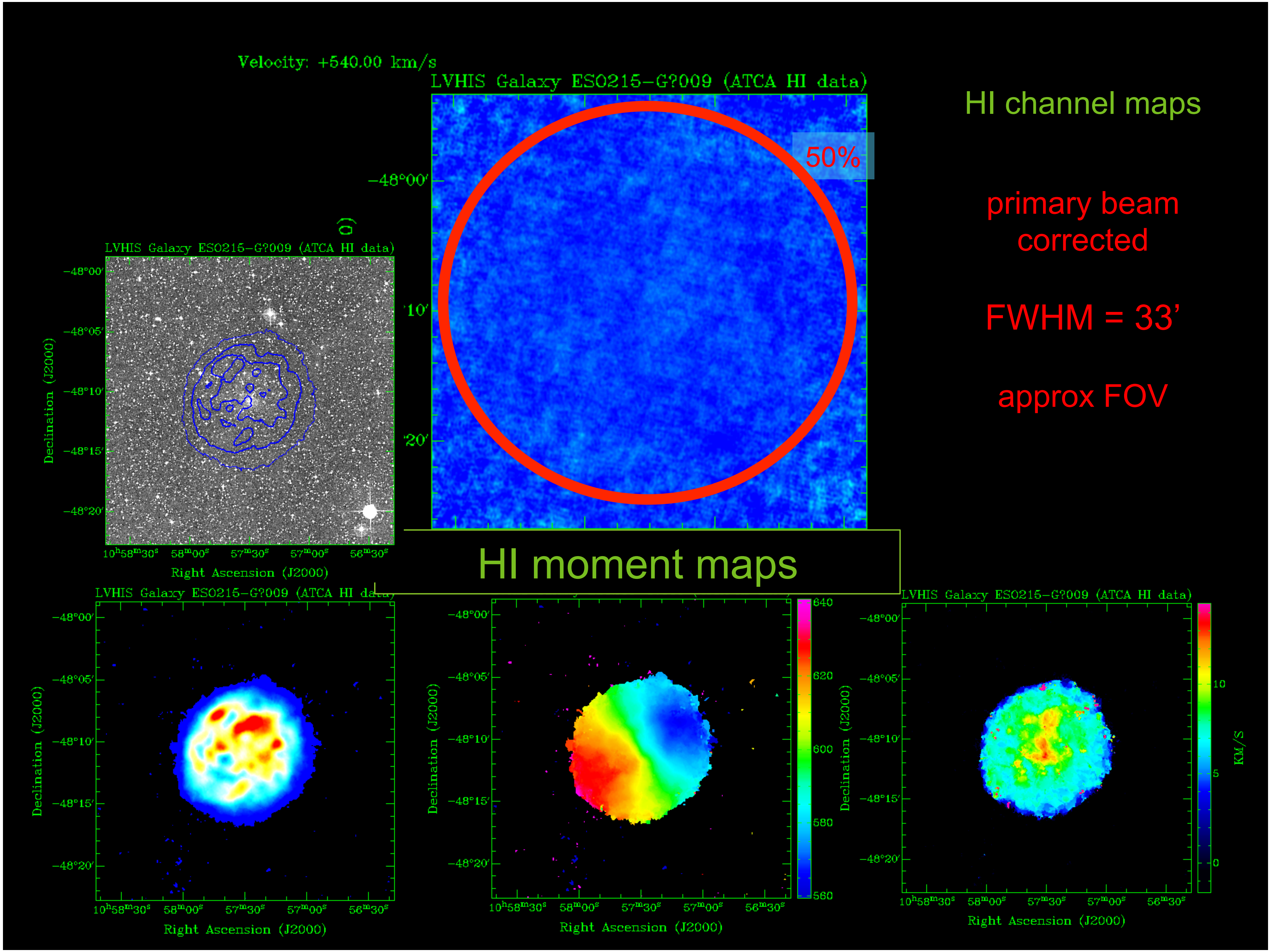


HI moment maps

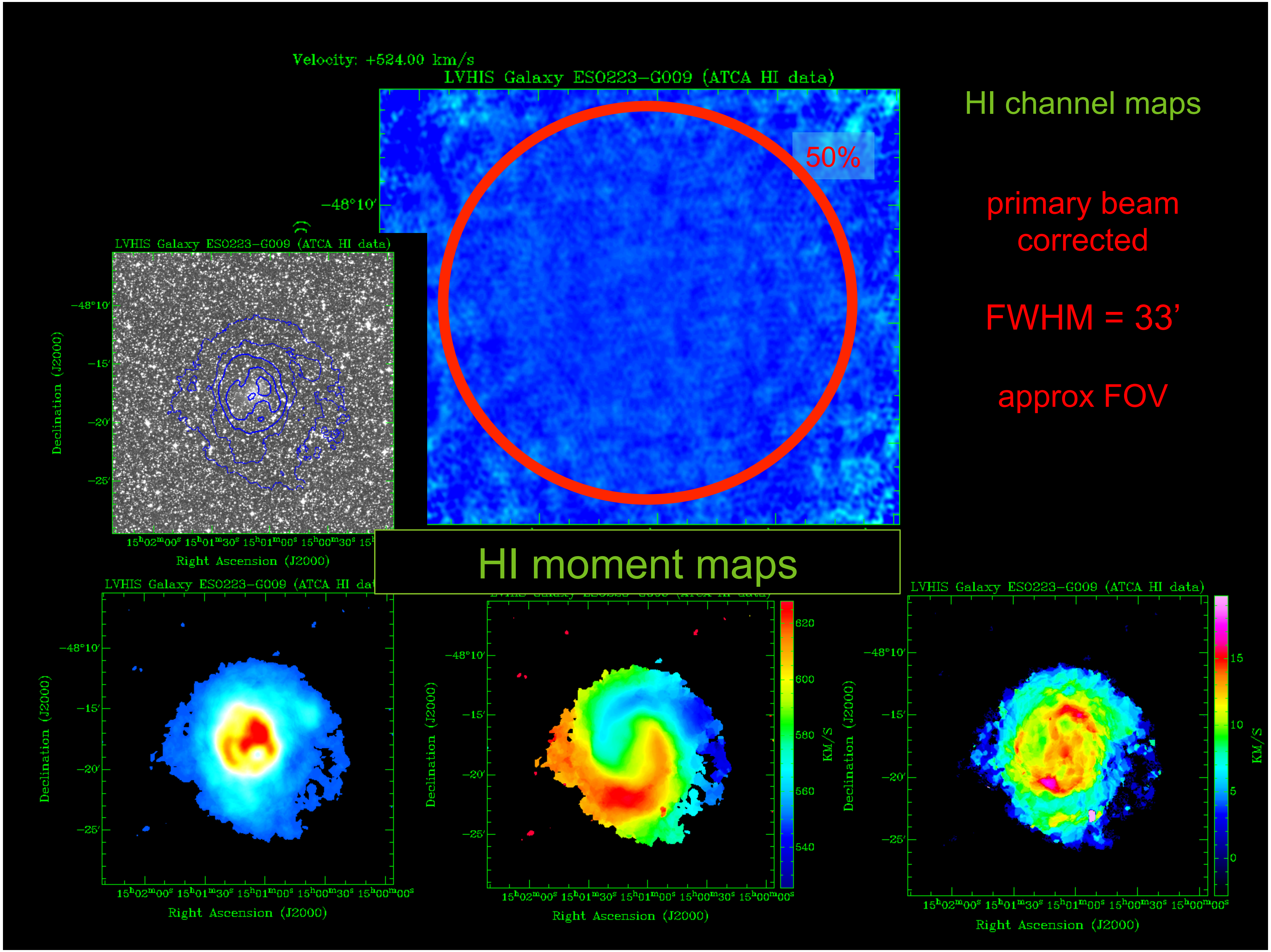








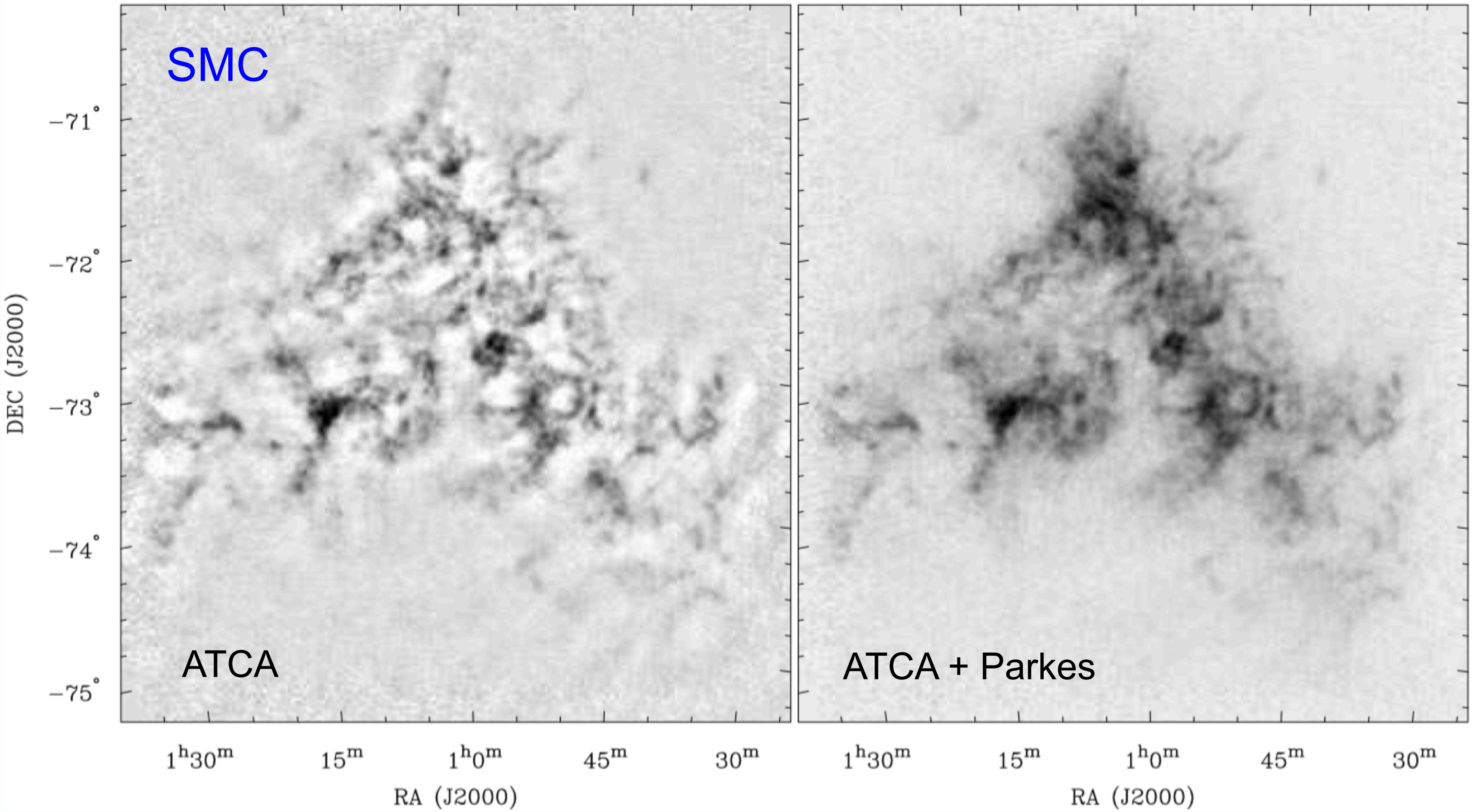
Velocity: +540.00 km/s
LVHIS Galaxy ESO215-G?009 (ATCA HI data)
-48°00'
10'
20'
50%
HI channel maps
primary beam corrected
FWHM = 33'
approx FOV
LVHIS Galaxy ESO215-G?009 (ATCA HI data)
Declination (J2000)
-48°00'
-48°05'
-48°10'
-48°15'
-48°20'
Right Ascension (J2000)
HI moment maps
LVHIS Galaxy ESO215-G?009 (ATCA HI data)
640
620
600
580
560
KM/S
10
5
0



Velocity: +524.00 km/s
LVHIS Galaxy ESO223-G009 (ATCA HI data)
50%
-48°10′
HI channel maps
primary beam corrected
FWHM = 33’
approx FOV
LVHIS Galaxy ESO223-G009 (ATCA HI data)
-48°10′
-15′
-20′
-25′
Declination (J2000)
15h02m00s 15h01m30s 15h01m00s 15h00m30s
Right Ascension (J2000)
HI moment maps
LVHIS Galaxy ESO223-G009 (ATCA HI data)
Declination (J2000)
Right Ascension (J2000)
620
600
580
560
540
KM/S
15
10
5
0
KM/S

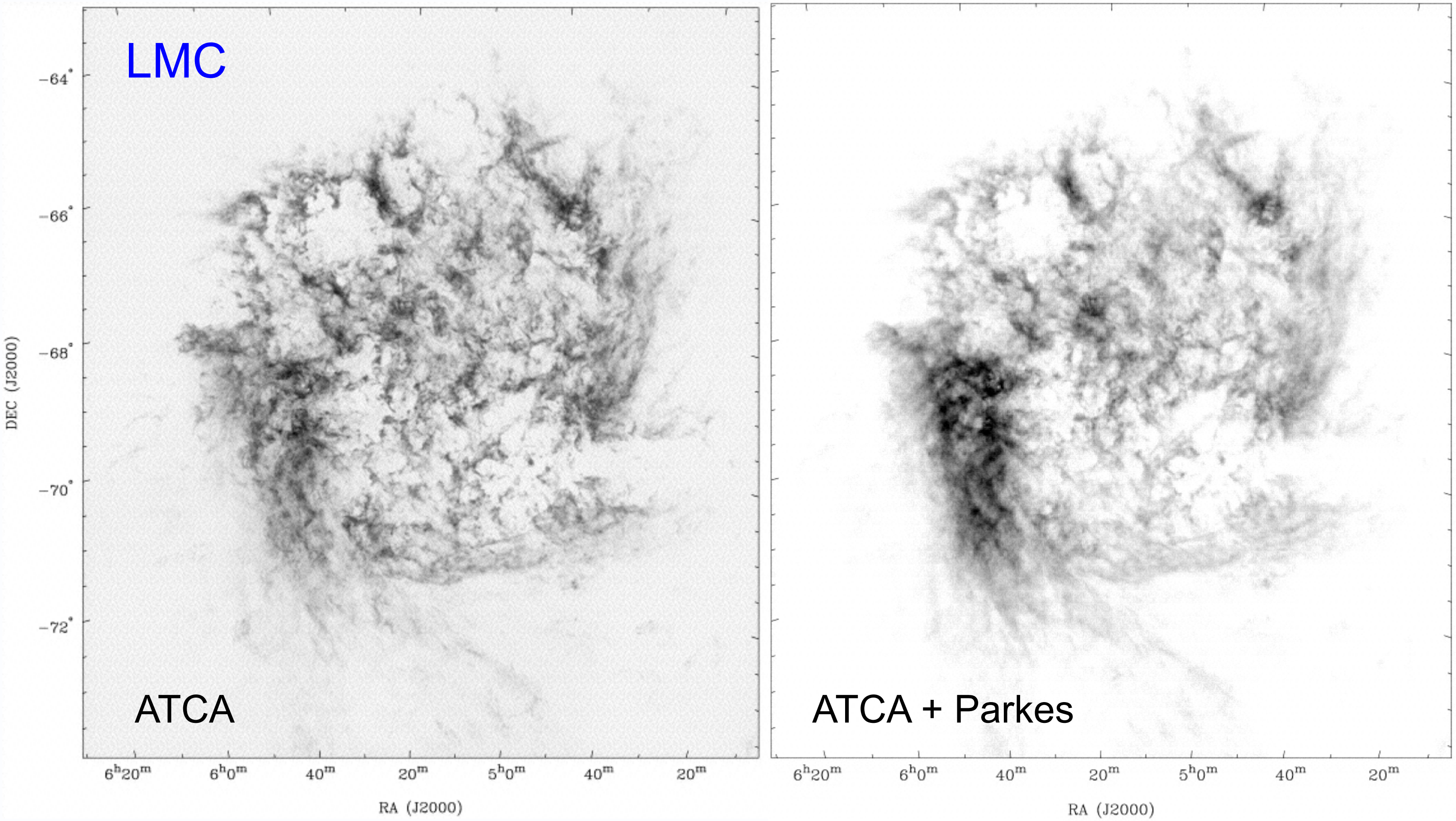
Single dish + interferometer data

Combining single dish and interferometer data



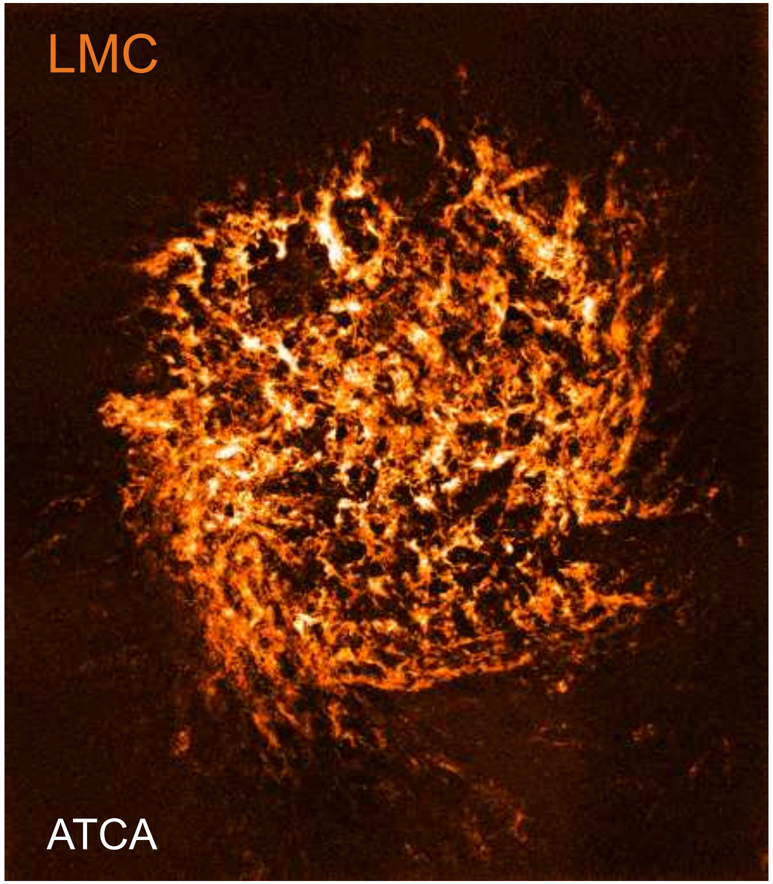
HI mosaic (144 pointings) of the Small Magellanic Cloud by Stanimirovic et al. (1999).

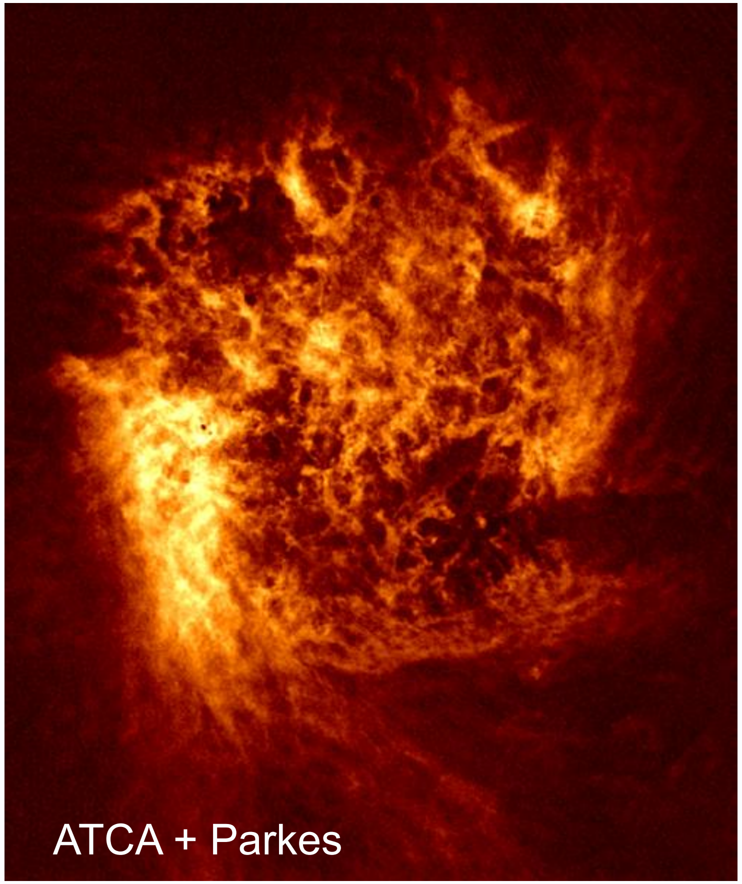
Combining single dish and interferometer data



HI mosaic (1344 pointings) of the Large Magellanic Cloud by Kim et al. (1998, 2003).

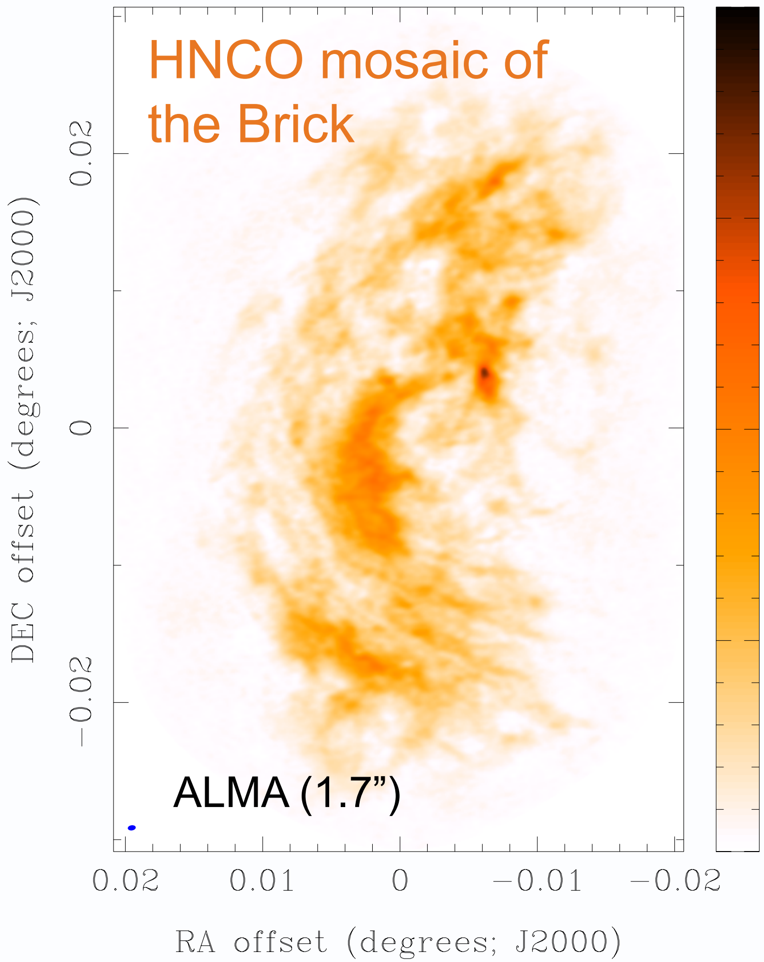
Combining single dish and interferometer data

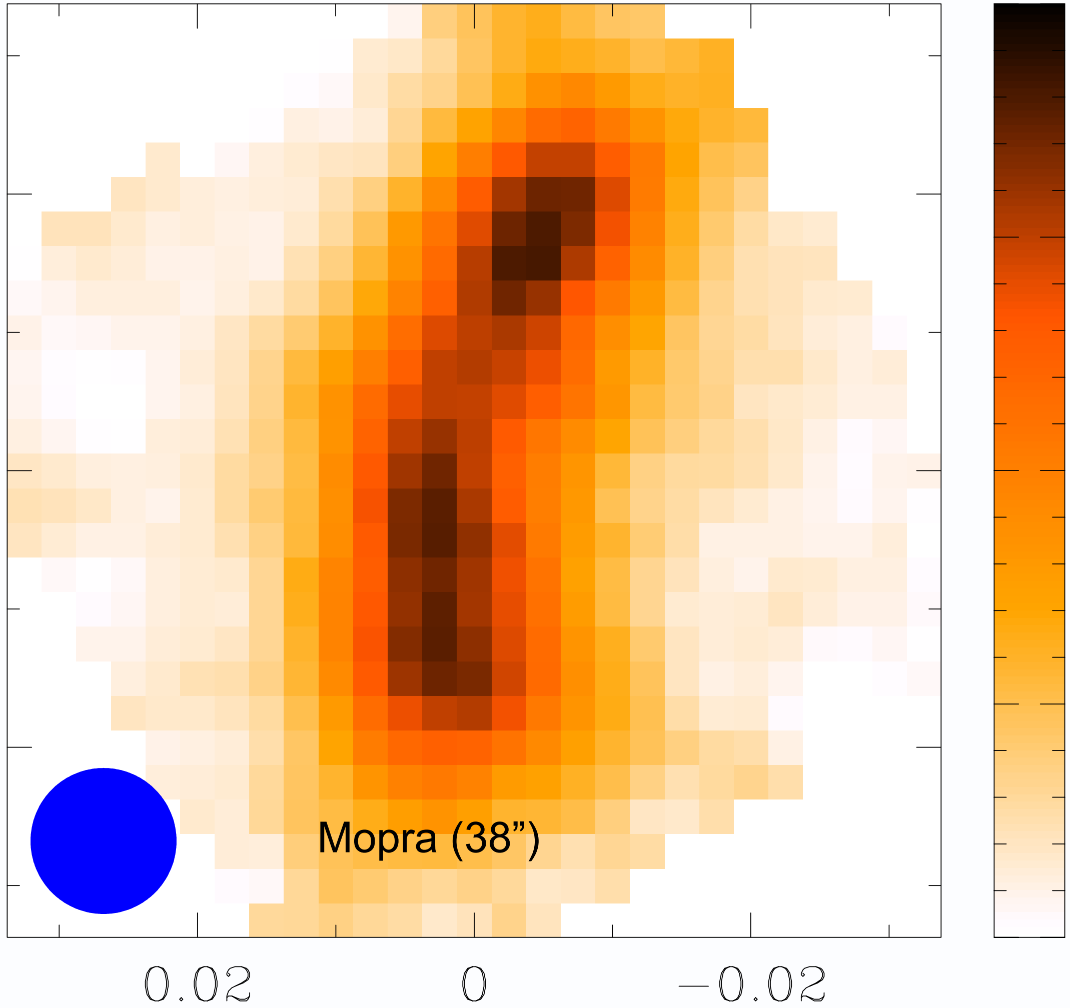




HI mosaic (1344 pointings) of the Large Magellanic Cloud by Kim et al. (1998, 2003).

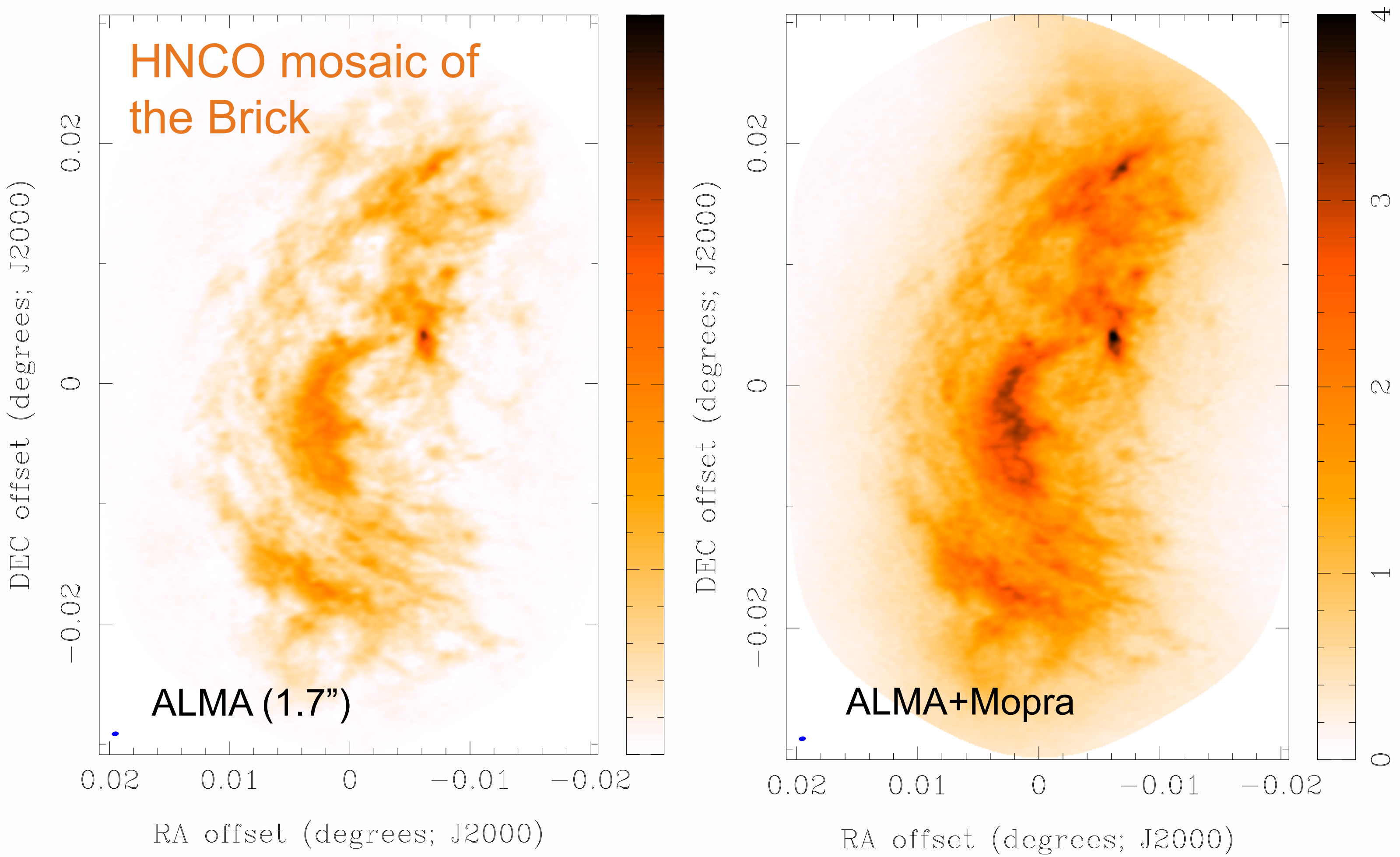
Combining ALMA and Mopra mm-data





Rathborne et al. (2014, in prep). – ALMA 13-point mosaic (5h, 25 antennas); field 3' × 1.5'.

Combining ALMA and Mopra mm-data



Rathborne et al. (2014, in prep). – ALMA 13-point mosaic (5h, 25 antennas); field 3’ × 1.5’.

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Overview of 3D Radio Techniques

Thank you

Dr. Bärbel Koribalski

CSIRO Astronomy and Space Science

Australia Telescope National Facility

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