New software developments in VLBI:

CASA

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Team

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Outline

Why changing to CASA?

What are the advantages of CASA?

CASA pipeline development

An example of a CASA reduction

Conclusions

Maser astrometry (optional)

Reasons for changing AIPS

- AIPS (Greissen+ 2003, and various AIPS memos) developed in the 80s
- Official support for AIPS has been discontinued
- Limited support for batch processing
- Not easily scriptable even despite ParselTongue (Kettenis+ 2016), especially not for the "python generation"

Common Astronomy Software Applications

- Secure development future (ALMA, JVLA)
- python based, well equipped for batch processing
- easy for scripting
- auto logging
- mpi scaling to deal with large data volumes for several tasks (divide jobs over several nodes)
- Well documented: CASA guide online tutorials, CASA cookbook, AIPS-CASA cheat sheet, CASA task reference manual

Getting ready for VLBI

- CASA originally for connected interferometry-> no need to for determining rates and delays (see lectures by Stan/Paco)
- In VLBI phase can change with frequency or time due to:position errors (antenna and source), antenna systematics (LO off sets), atmospheric interference etc.
- CASA **`fringefit`** task (JIVE/BlackHoleCam) solves for phases, delays and rates
- present in CASA since version 5.4: ready for VLBI!

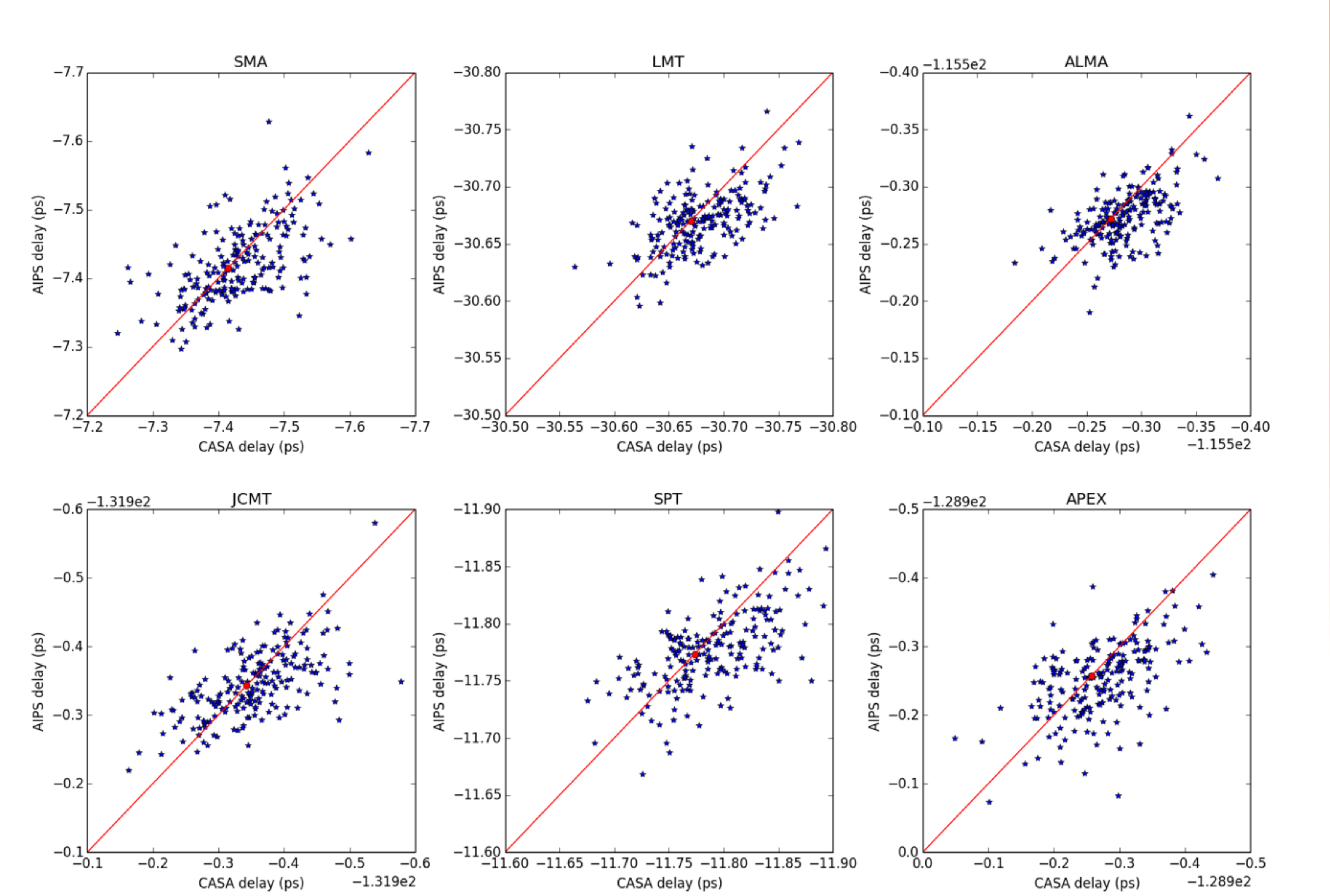
observed phase $$\phi_{t,\nu} \approx \phi_0 + \frac{\partial \phi}{\partial \nu}\Delta\nu + \frac{\partial \phi}{\partial t}\Delta t$$

phase offset — delay — rate

determined by **`fringefit`** *(Schwab-Cotton algorithm)*

Comparisons with AIPS: fringe functionality

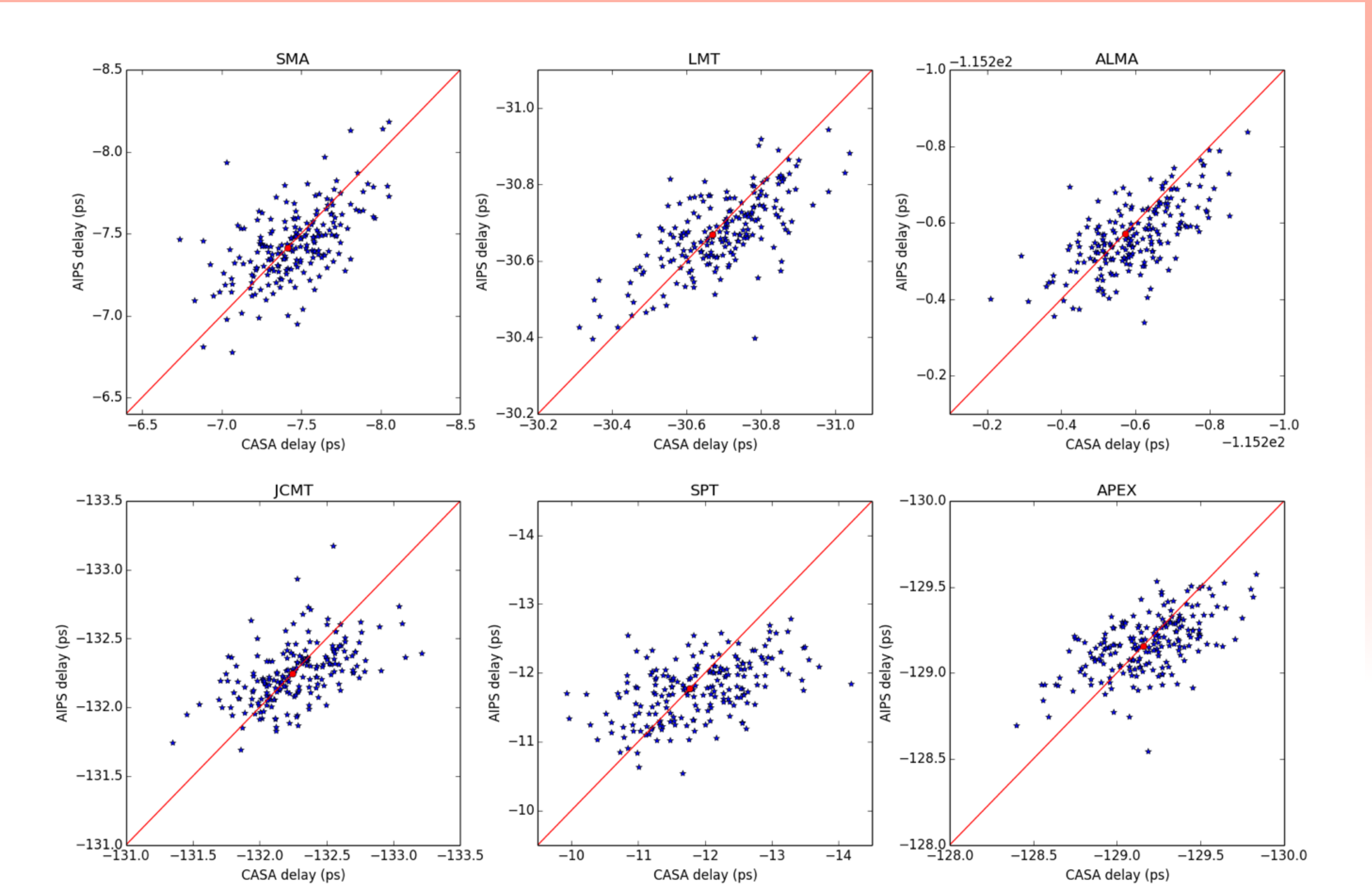
Comparison of **`fringe`** (AIPS)/**`fringefit`** (CASA) for a point source



van Bemmel et al. (2019)

Comparisons with AIPS: fringe functionality

Comparison of **`fringe`** (AIPS)/**`fringefit`** (CASA) for a extended source



van Bemmel et al. (2019)

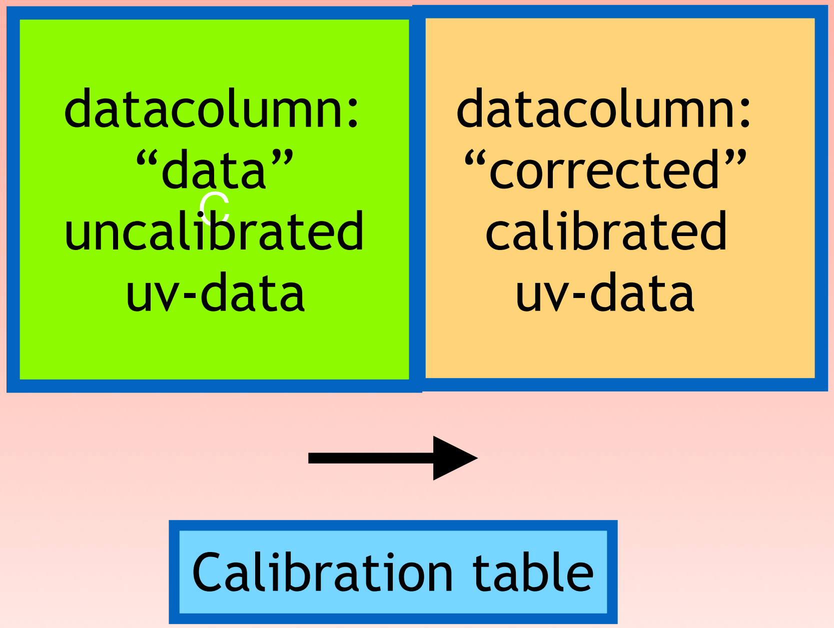
CASA ready for VLBI : ongoing evolution

- more VLBI specific tasks added (aside **`fringefit`**)
- ex. importing through **`importfitsidi`** (exporting by **`exportuvfits`**)
- CASA VLBI tasks still experimental (**user feedback is strongly welcome!**)
- CASA VLBI capabilities improve with every CASA version (as does CASA)

Advantages of CASA: data structure

- clean structure
- the measurement set: “data” and “corrected”
- calibration tables are external, when applied they work on “data” and create “corrected”
- application of calibration tables *on-the-fly* (for example when fringefitting)
- good flagtable management (save/restore)

measurement set:



Apply the calibration table (**`applycal`**)

CASA working structure

more calibration tables

```
CASA <10>: ls
Archive_data/                casa-20180827-181114.log  n14c3.flag
EVN.gc/                      casa-20180827-181725.log  n14c3.gcal/
Online materials/            casa-20180827-182113.log  n14c3.ms/
Scripts/                     casa-20180830-095529.log  n14c3.ms.flagversions/
Tsys_append_data/            casa-20180830-113754.log  n14c3.sbd/
applycal.last                flagdata.last             n14c3.tsys/
bandpass.last                fringefit.last            n14c3.uvflg
casa-20180827-163538.log     gencal.last               n14c3_1_1.IDI1
casa-20180827-163901.log     importfitsidi.last        n14c3_1_1.IDI2
casa-20180827-163917.log     ipython@                  plotcal.last
casa-20180827-164751.log     listobs.last              plotms.last
casa-20180827-165047.log     n14c3-1848.mbd/           testplotms.jpg
casa-20180827-173748.log     n14c3.antab
casa-20180827-174753.log     n14c3.bpass/
```

measurement set

flag versions

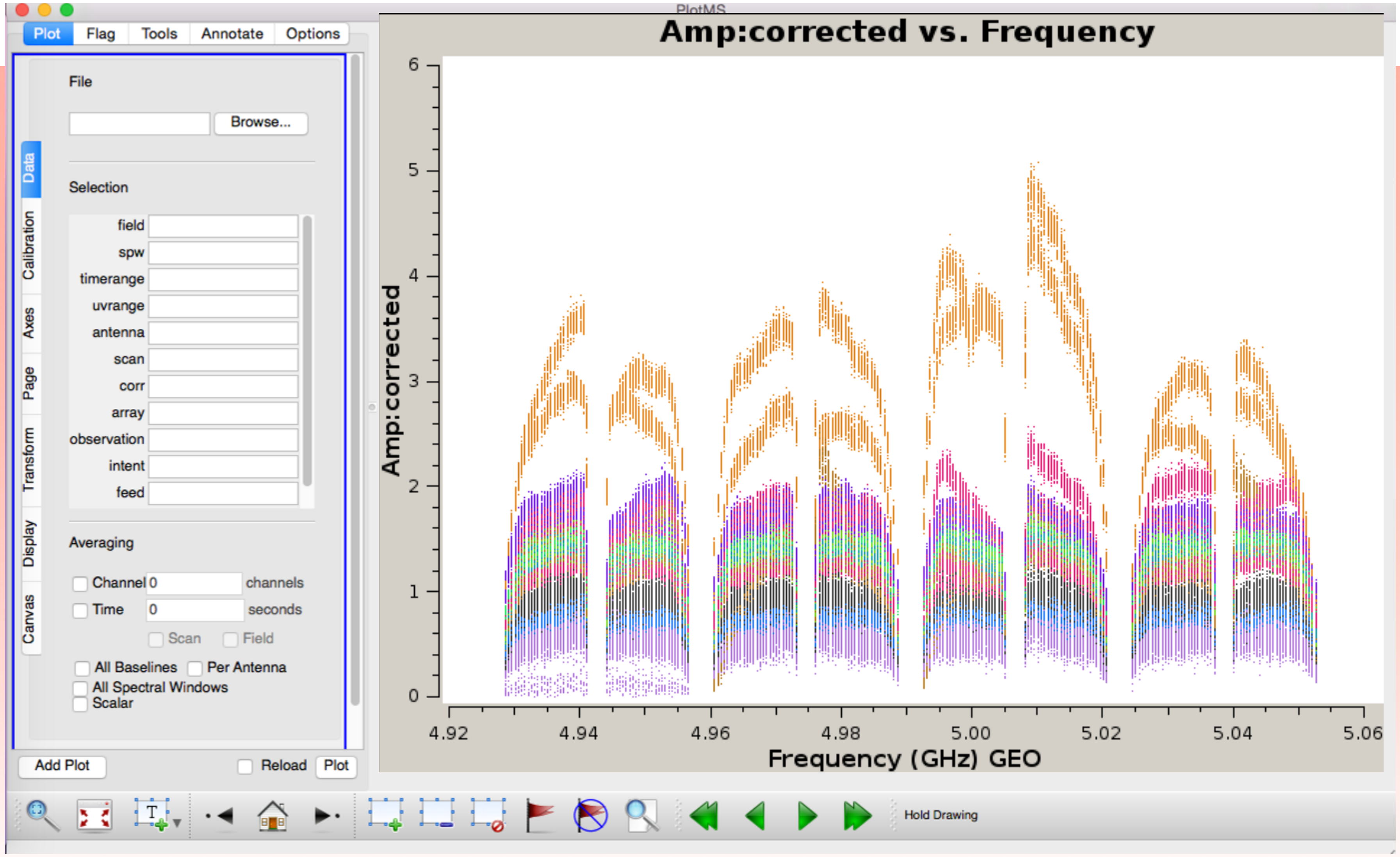
fitsIDI files

Casa logs

calibration tables

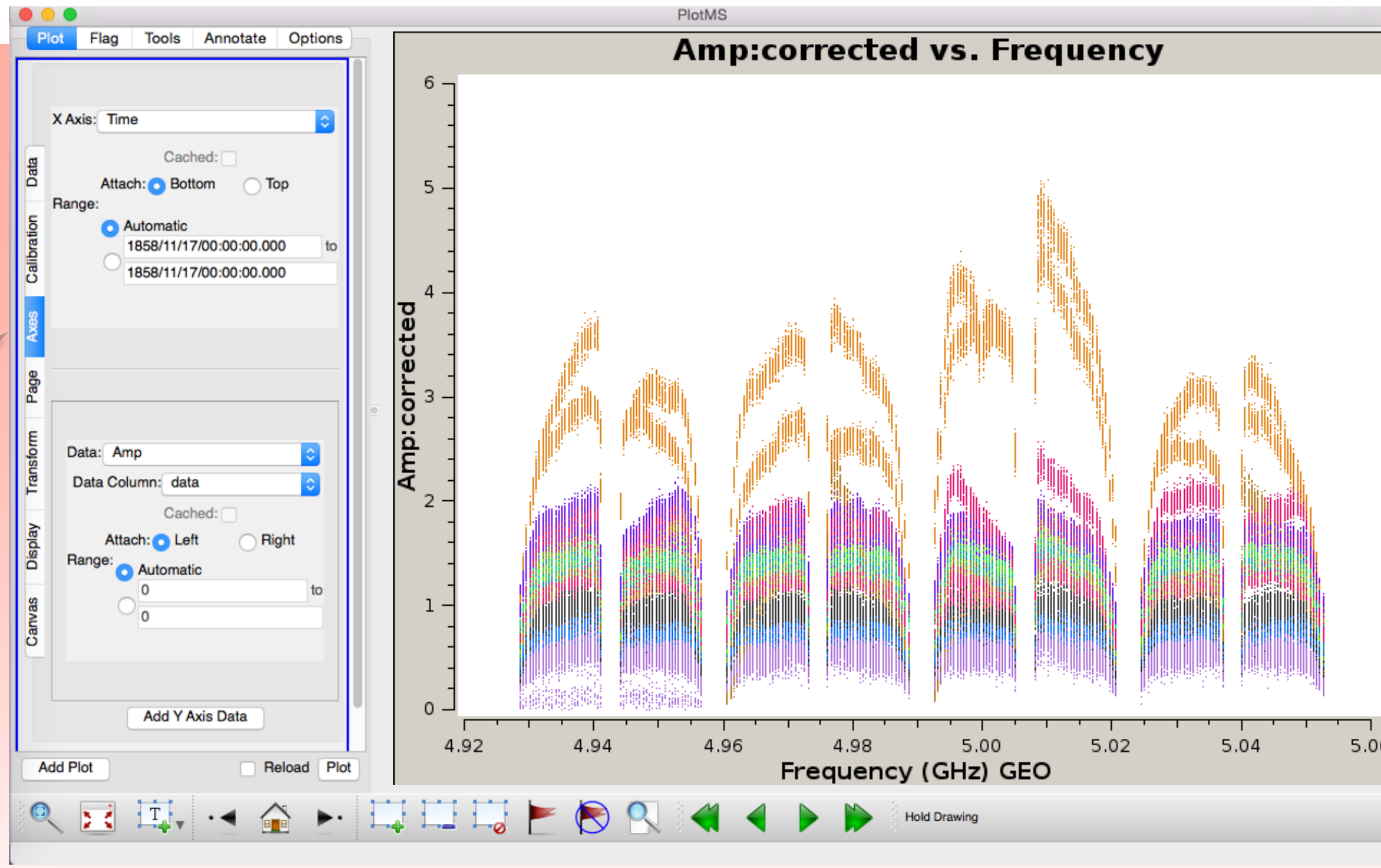
Advantages of CASA: visualisation

Select ms



- the **`plotms`** gui tool (slow, but powerful)
- selecting various axes, coordinate transformation, coloring by type
- inspecting: obtaining the provenance of a uv datapoint
- writing out images

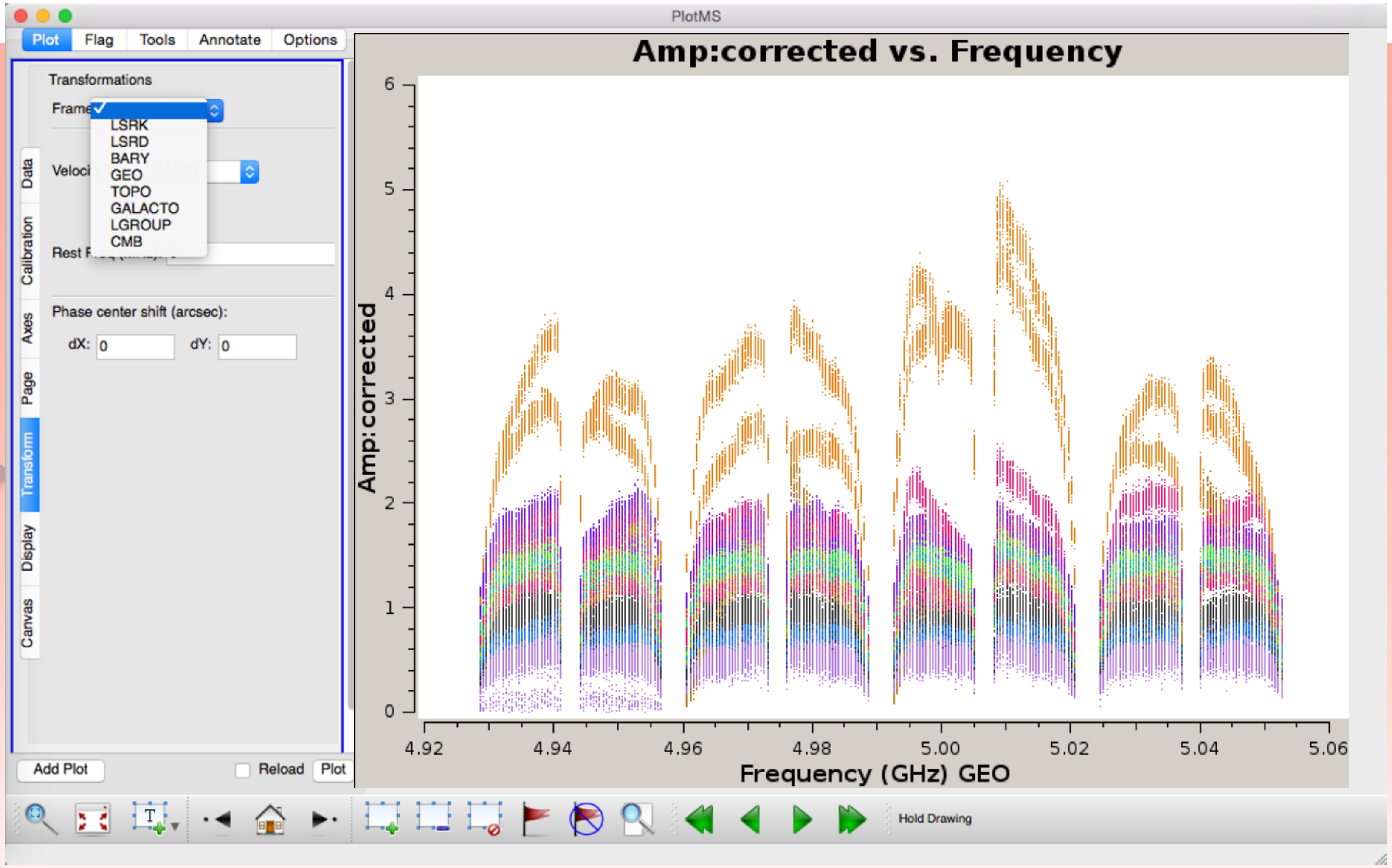
Advantages of CASA: visualisation



Select axes

- the **plotms** gui tool (slow, but powerful)
- selecting various axes, coordinate transformation, coloring by type
- inspecting: obtaining the provenance of a uv datapoint
- writing out images

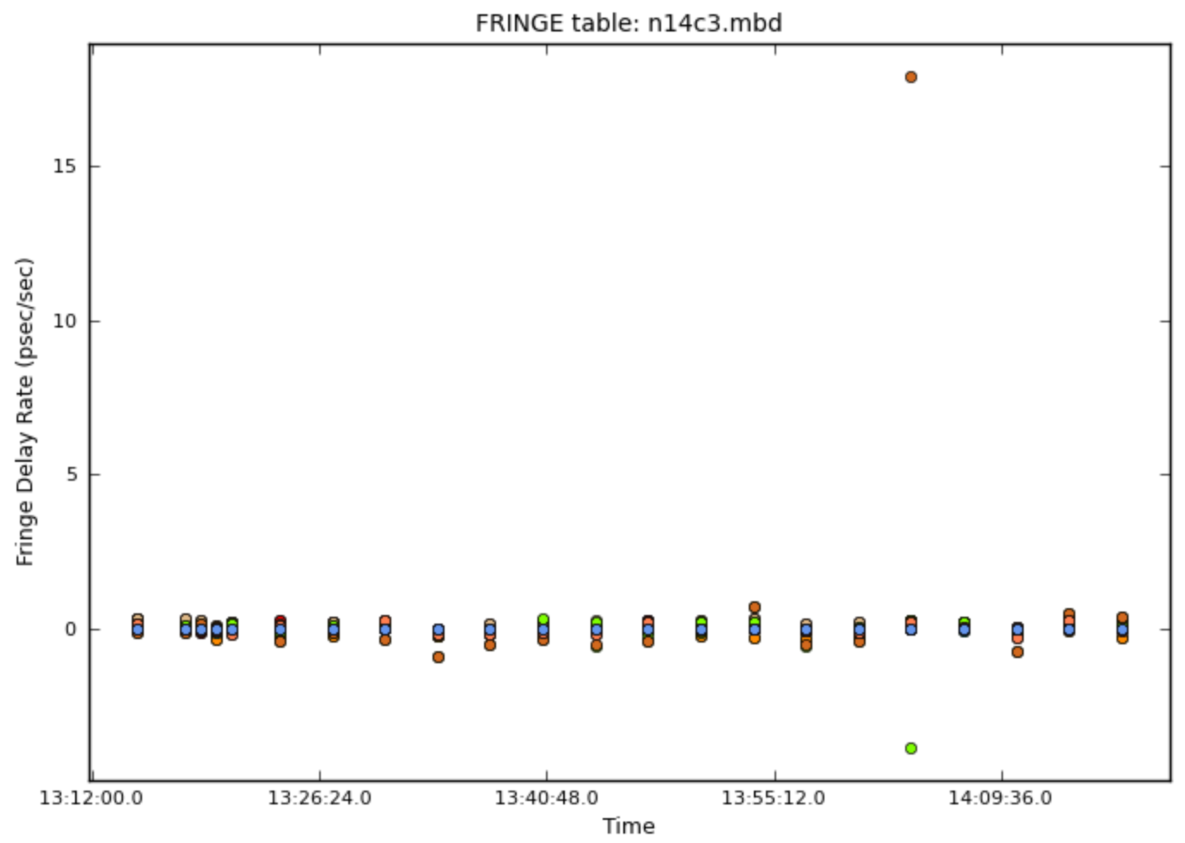
Advantages of CASA: visualisation



Transform Frame

- the **`plotms`** gui tool (slow, but powerful)
- selecting various axes, coordinate transformation, coloring by type
- inspecting: obtaining the provenance of a uv datapoint
- writing out images

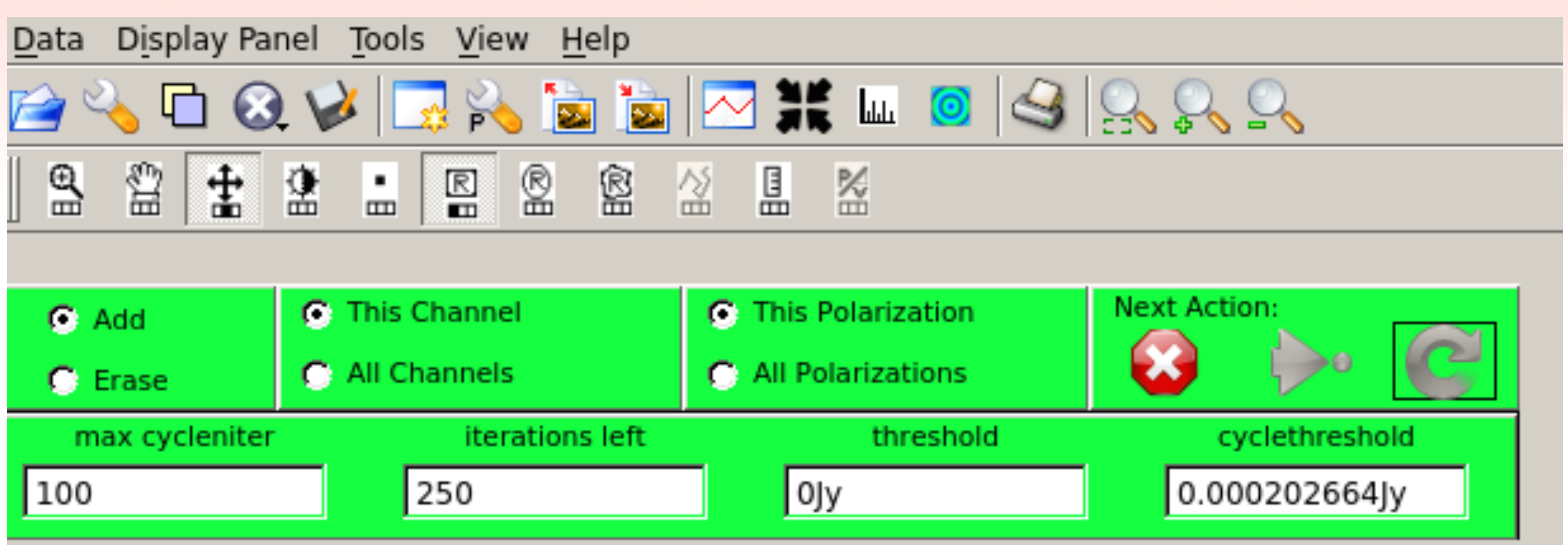
Advantages of CASA: visualisation



- inspecting calibration table with **`plotcal`** (fast)
- coloring by parameter, selecting axes, writing out plots

Advantages of CASA: imaging functionality

- making images of uvdata is **`tclean/clean`** tasks do an inverse fourier transform, fit a model, subtract that and restore the residuals plus the model convolved by the clean beam (see Paco's lecture)
- **`tclean/clean`** can be done interactively
- interactive masking: by hand, automasking, and defined masks (box, circle etc).

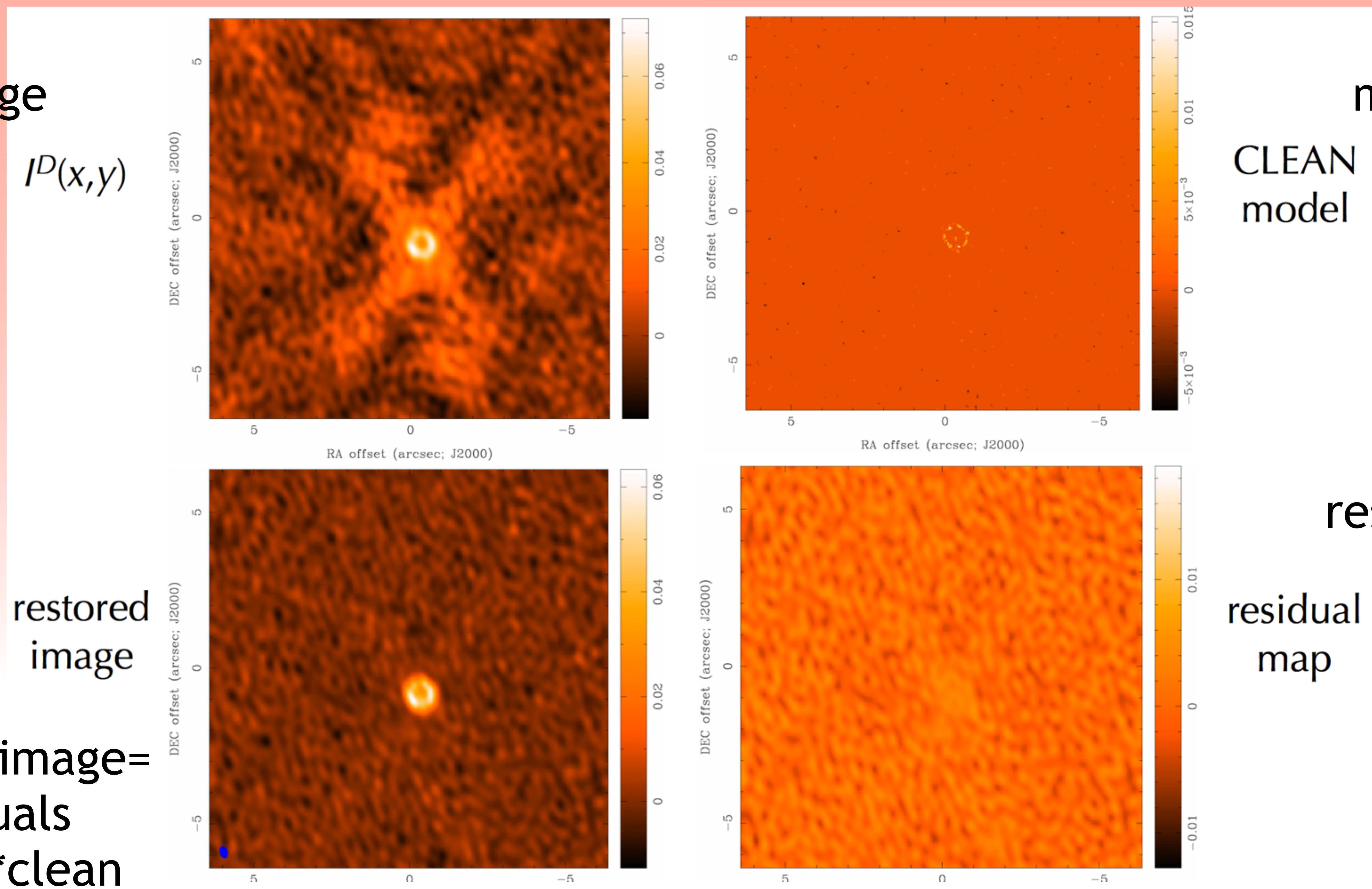


zoom of interactive **`clean/tclean`** gui

How does clean/tclean work?

dirty image

model



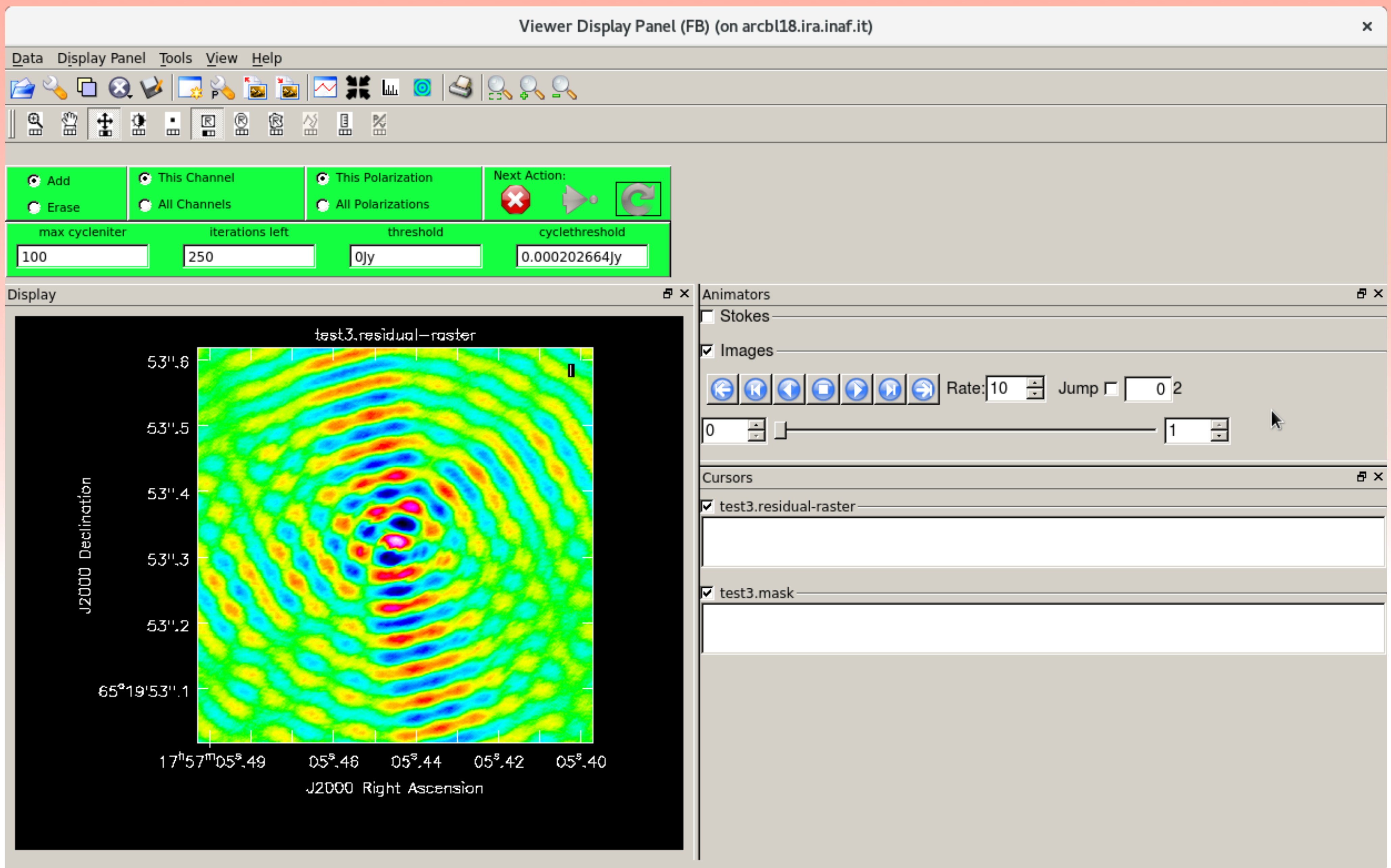
residuals

restored image= residuals +model*clean beam

Di Francesco, NSAAC webinar

CASA: imaging functionality

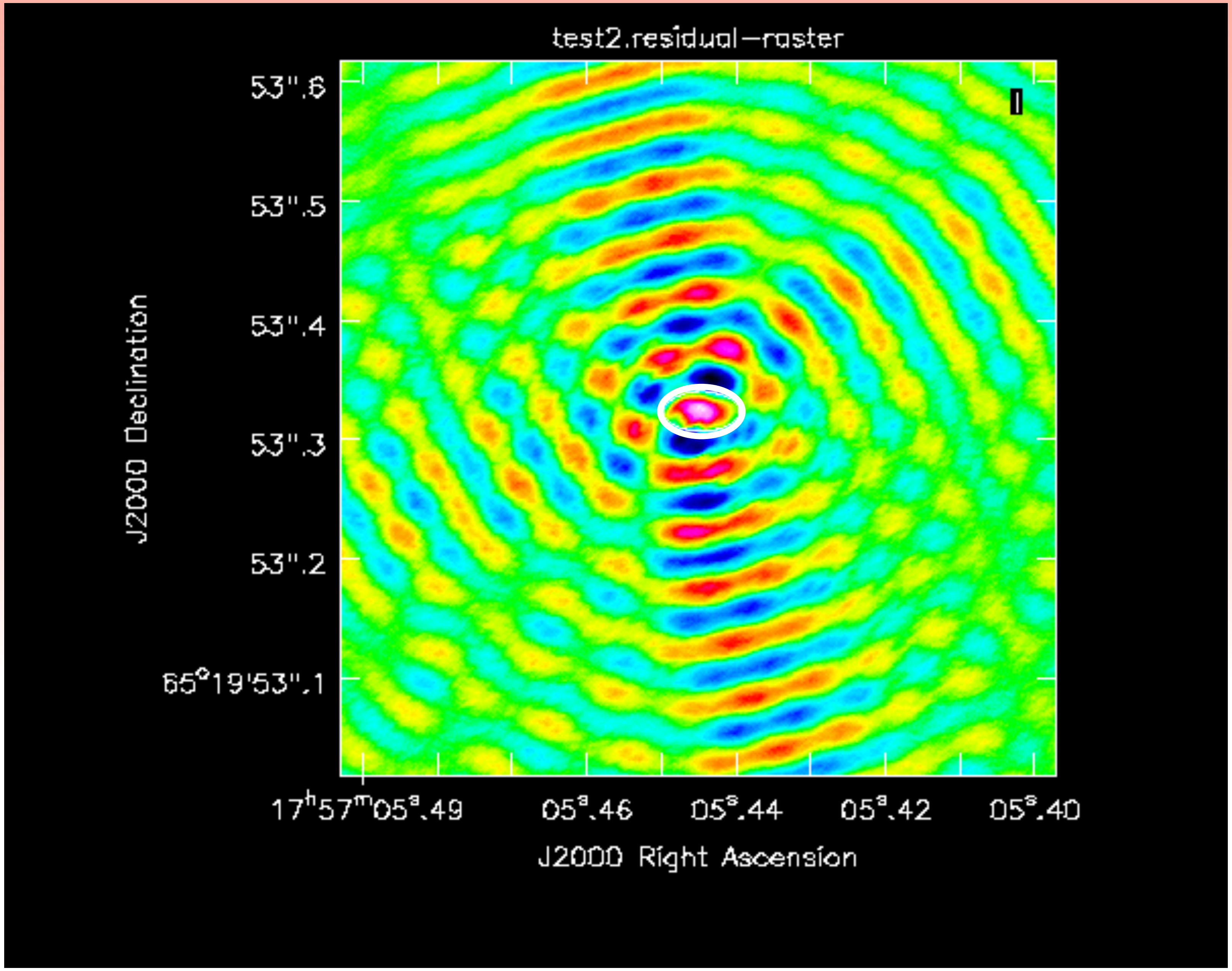
`tclean` dirty image, interactive imaging



High z radio galaxy
EVN 5cm
Liuzzo et al.

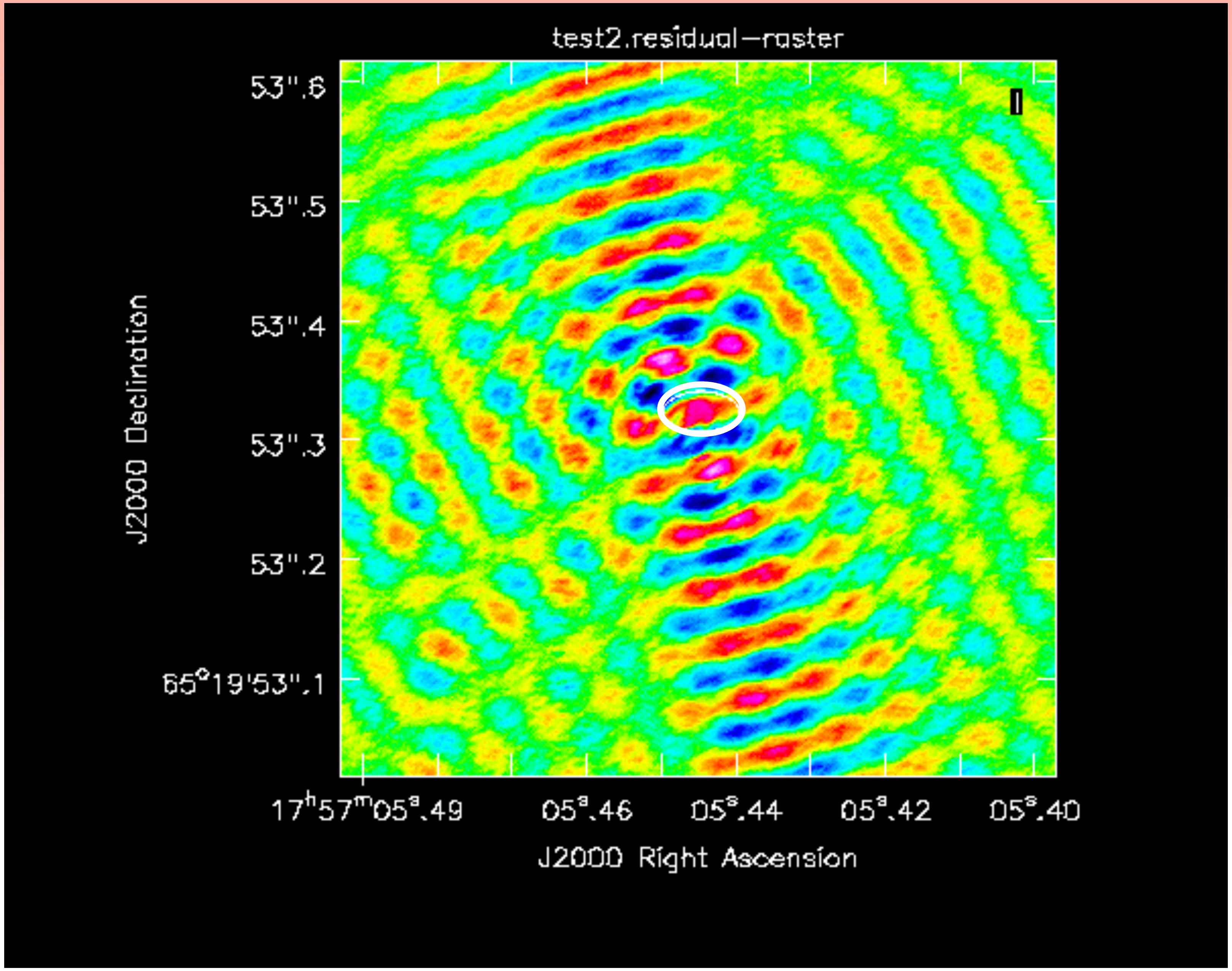
CASA: imaging functionality

`tclean` set cleanbox



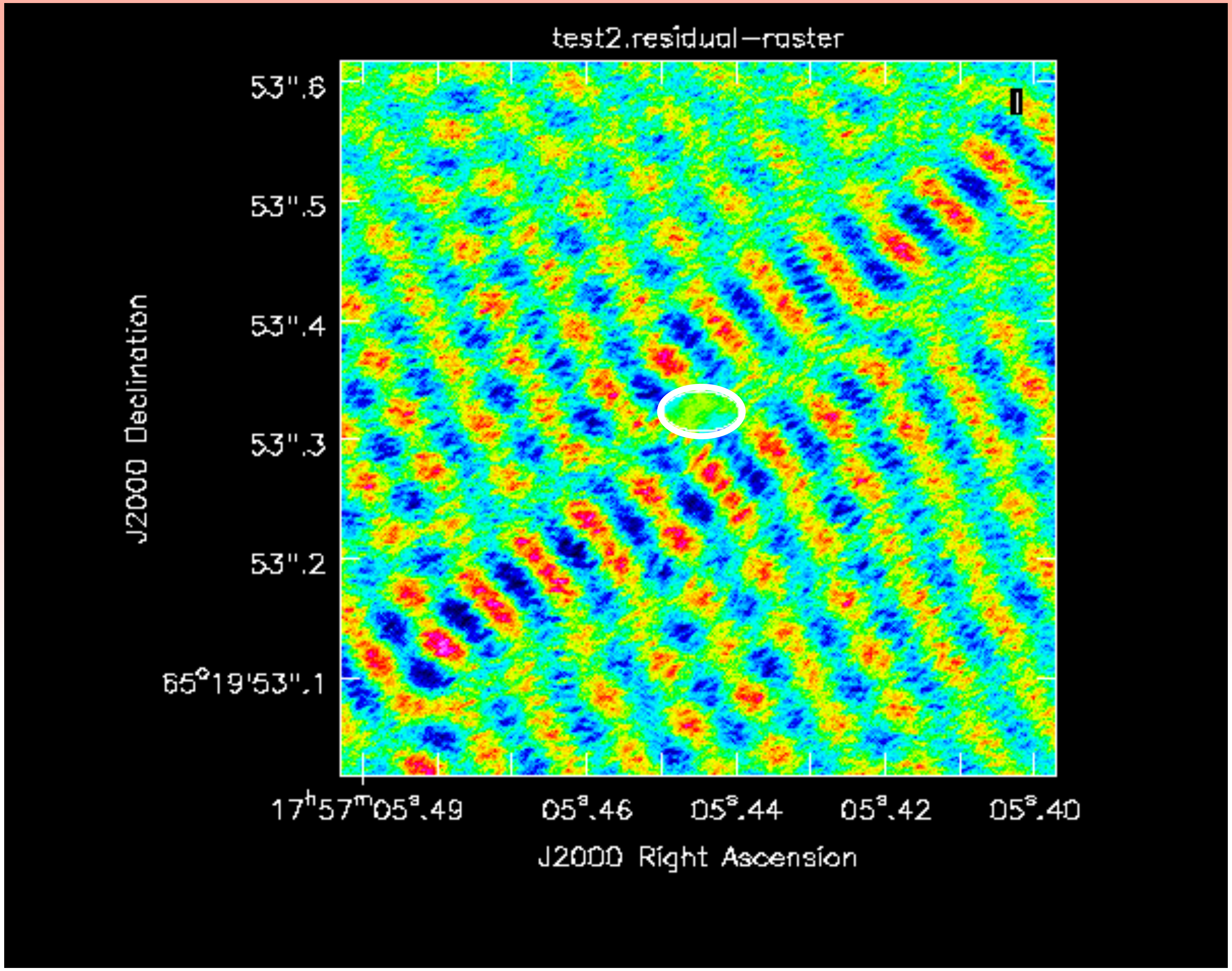
CASA: imaging functionality

`tclean` iterate



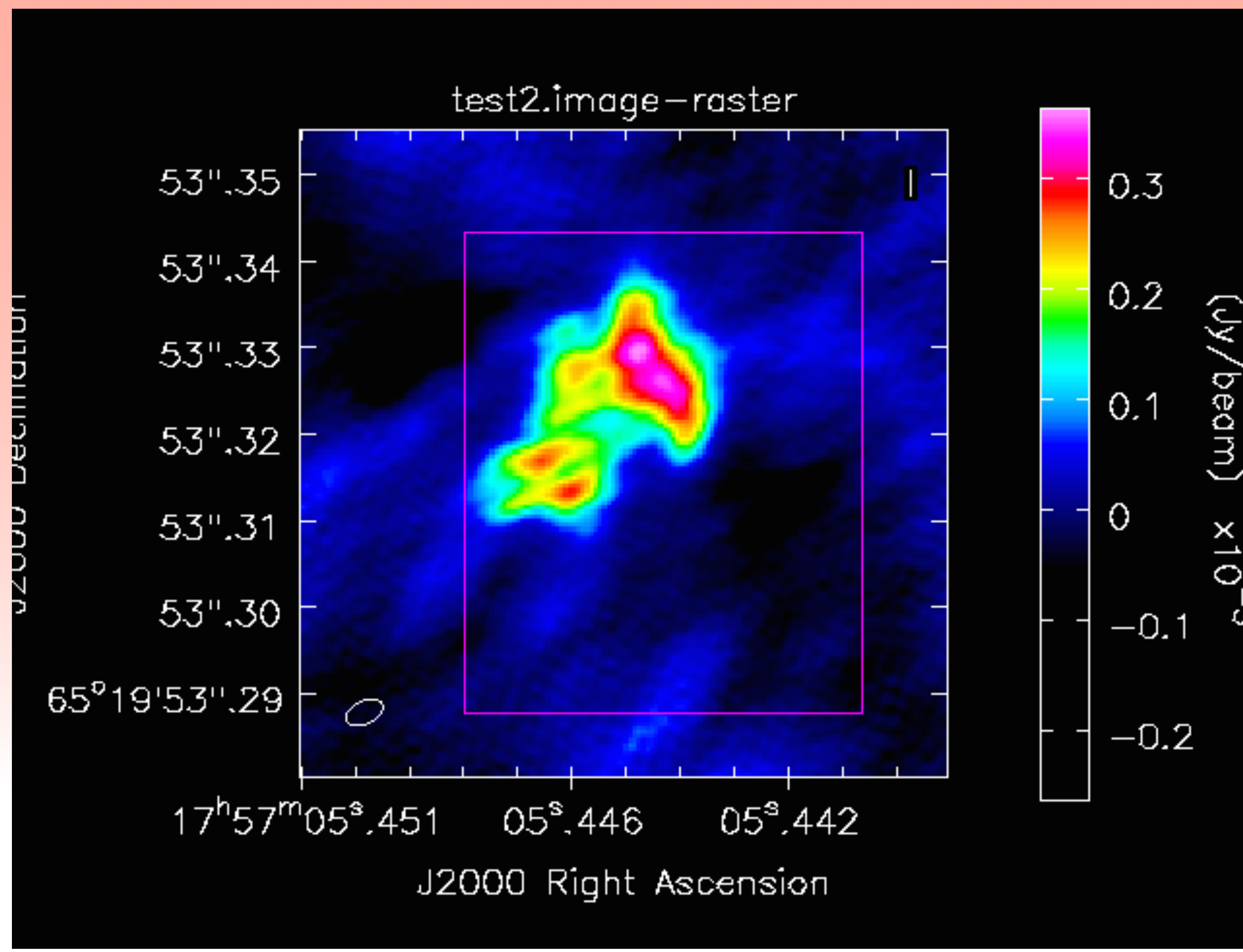
CASA: imaging functionality

`tclean` stop cleaning



CASA: inspecting images

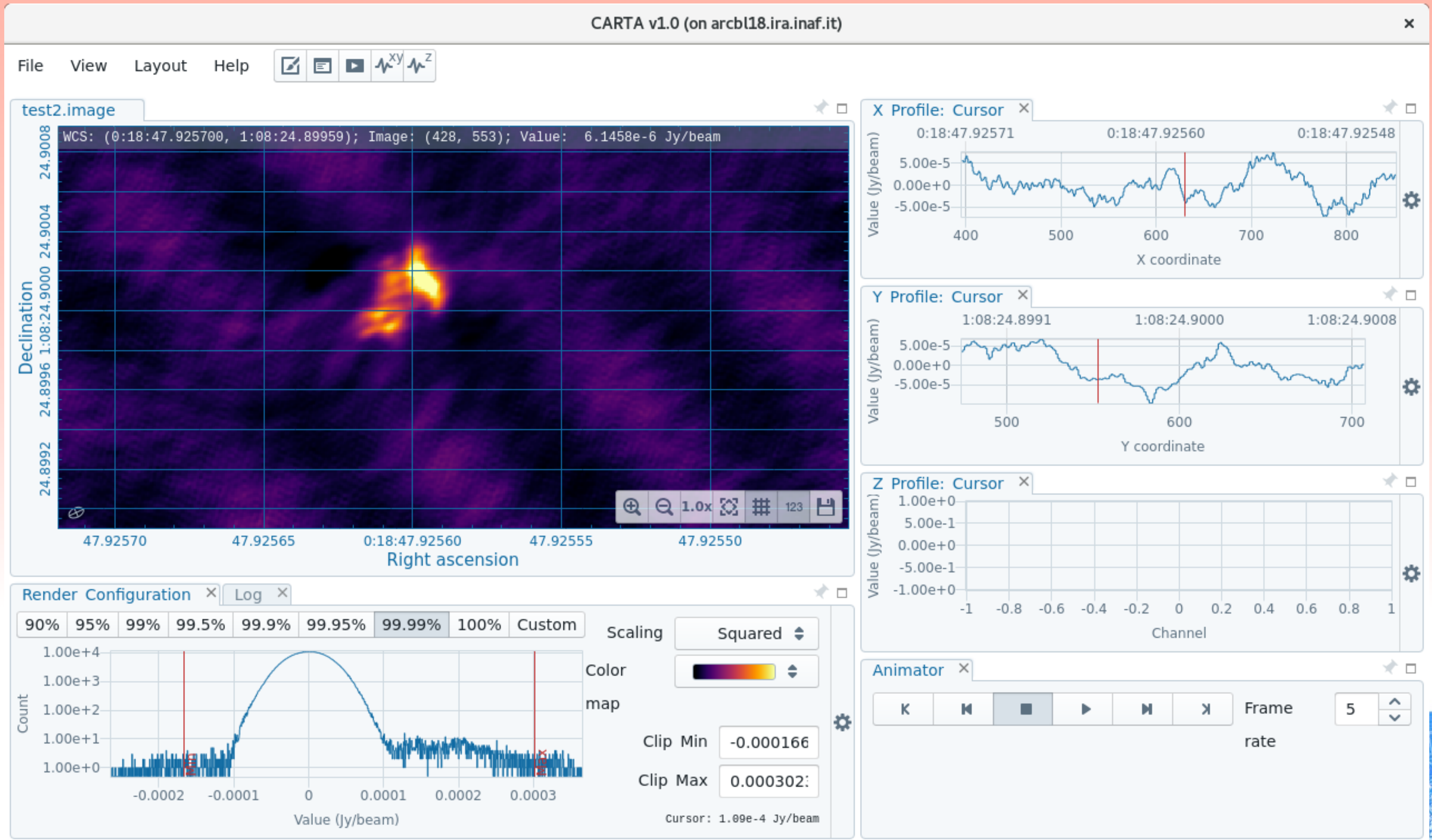
`viewer` to inspect your images and get image statistics



High z radio galaxy
EVN 5cm
Liuzzo et al.

CARTA: inspecting images

CARTA is a software external to casa, made for image inspection



High z radio galaxy
EVN 5cm
Liuzzo et al.

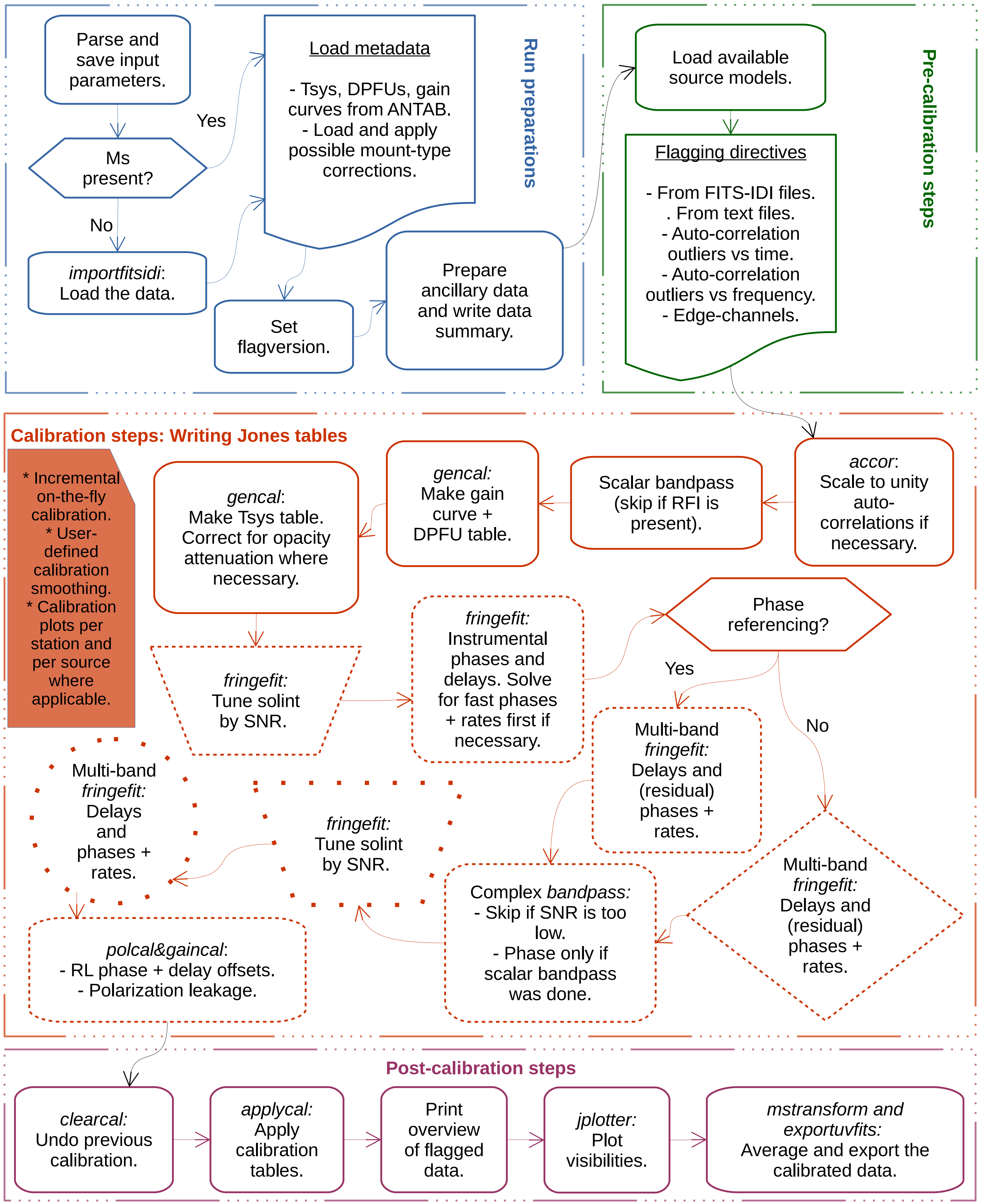
CASA pipeline development

- rPicard: VLBI general, mm-VLBI in particular-> 1/3 EHT pipelines (Janssen et al. 2019)
- e-Merlin pipeline (Moldon)
- EVN pipeline (Marcote, in prep)

rPicard calibration pipeline

- python based, open source, self-tuning parameters
- **built for mm-VLBI, applicable to cm-VLBI for most arrays**
- takes in fits idi/fits, writes out calibrated data (uvfits and ms), cal tables, calibration plots (QA), and logs
- **Optimisation of solution interval used for fringefit based on SNR**
- **can be rerun many times, one can intervene semi-interactively**
- **Imaging and self calibration module (separate from pipeline) can be used interactively**
- science reproducibility!
- Janssen+2019, ArXiv:1902.01749

rPicard - scheme

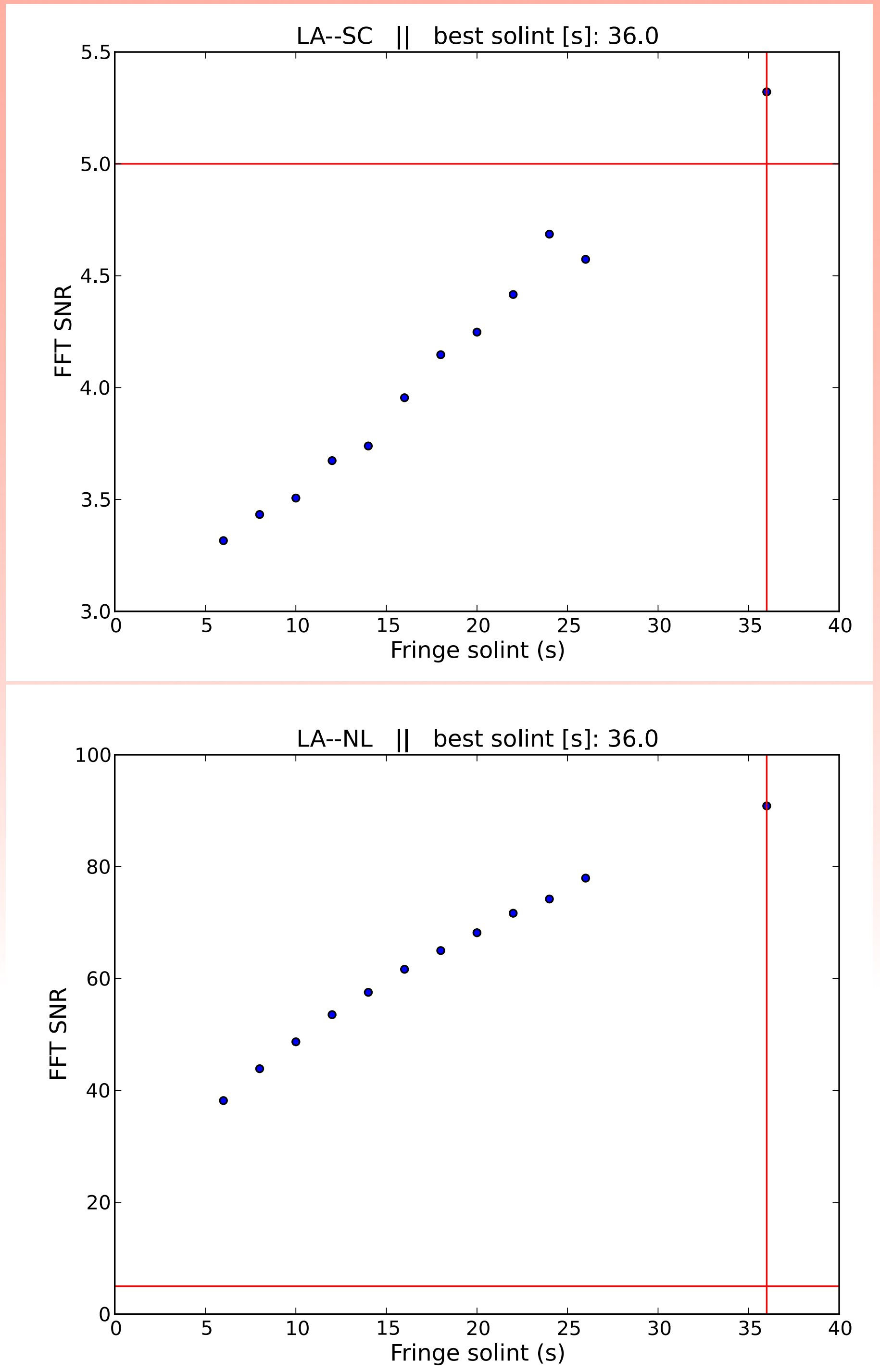


Janssen et al. 2019

- loading data into ms
- flagging autocorrelations and outliers
- calibration (optimal solint search, calibrator and science separate)
- apply all calibration tables, and write to uvfits

rPicard - optimal solint search for fringefit

- you want solution intervals as short as possible to solve for fast-changing atmosphere (frequency dependant)
- however, you want enough SNR to have good fringefit solutions
- optimal solint search is done for each scan *per baseline* for all stations to the reference station using a SNR cutoff of 5
- Then the *largest* solint is used for fringefit (allowing reliable fringe detections on all baselines with source detections)



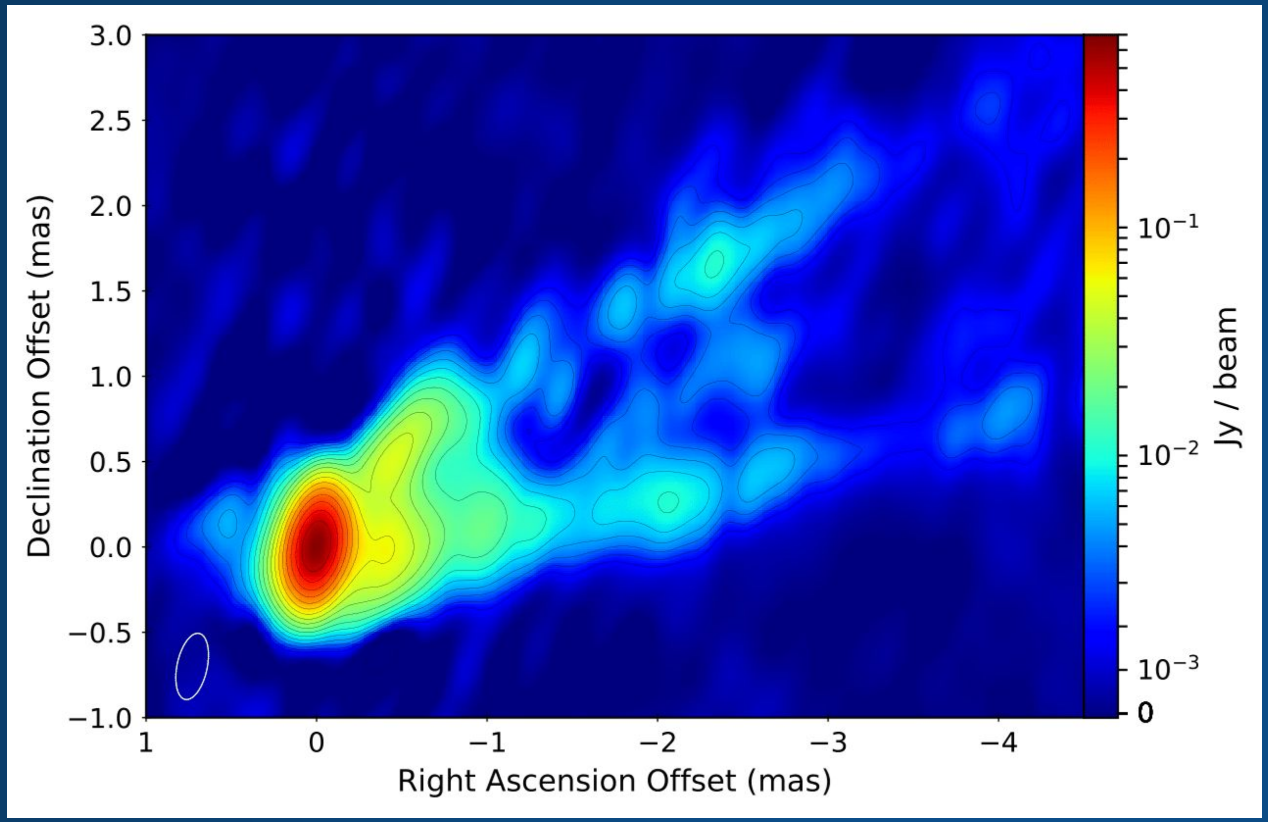
Janssen et al. 2019

rPicard - installation & use

- Download from https://bitbucket.org/M_Janssen/picard
- Follow readme for installation
- contains manual
- setup script prepares a defaut script for a number of arrays
- modify input files (typically only the calibrators and the workdir should be specified)

```
michael@mjpc:~/JeanLuc/Picard$ ./setup.py -p ~/Software/

*** This script will link your CASA installation to the pipeline. ***

Found
 /home/michael/Software/CASA_builds_from_JIVE/casa-feature-CAS-10684-24.el7/bin/casa
 as your CASA executable.
 Checking this CASA version:

      Has mpi:          True
      Has fringefit.py: True
      Has accor.py:     True

 Press Enter and I will use the absolute path to this executable for picard.sh.
 Write anything else (and then press Enter) to abort.
 >

Writing the CASA executable path to a <your_casapath.txt> file, which will be used by picard.sh.


Making picard.sh executable.


Editing the input/mpi_host_file using the determined name of this computer (mjpc)
and 4 cores. Change this setup manually if desired.

I could put some default values for array.inp depending on which array you inted to use.

  0 for VLBAlo (for low frequencies)

  1 for EHT

  2 for VLBAhi (for high frequencies)

  3 for EVN

  4 for GMVA
Press enter without entering anything else to continue without altering your array.inp file.
Else, enter the number corresponding to the array you want to use and press Enter
 >3


The pipeline should be ready to run now.
If there are issues with mpicasa contact M.Janssen@astro.ru.nl
or look at https://casa.nrao.edu/casadocs/@@search?SearchableText=mpi


If you want to be able to run the pipeline from everywhere,
then you should add the following line to your .bashrc folder:
export PATH=$PATH:/home/michael/JeanLuc/Picard/picard/


Remember set some input parameters in the beginning, before running the pipeline.
At least edit input/observation.inp and input/array.inp


Please read documentation/picard_documentation.pdf and follow the Quick Start Guide chapter to get started
michael@mjpc:~/JeanLuc/Picard$ cp -r picard/input/ ../testrun/input
 Checking this CASA version:
```

rPicard interactive imaging/selfcal module

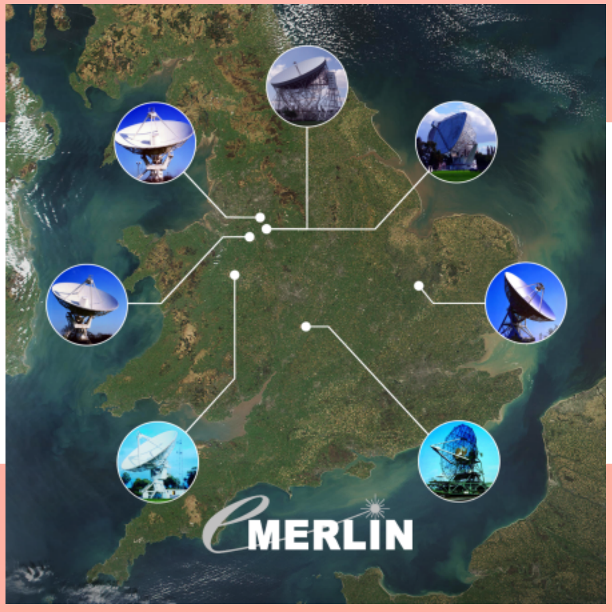


7mm VLBA data of M87 from June 2013.
Project code: BW0106.

- **Calibrated and imaged with CASA-based rPICARD pipeline.**
- **Results agree with Walker et al. (2018):**
  - **Weak counterjet.**
  - **Edge-brightening.**
  - **Large initial opening angle.**
  - **Re-collimation of upper arm.**

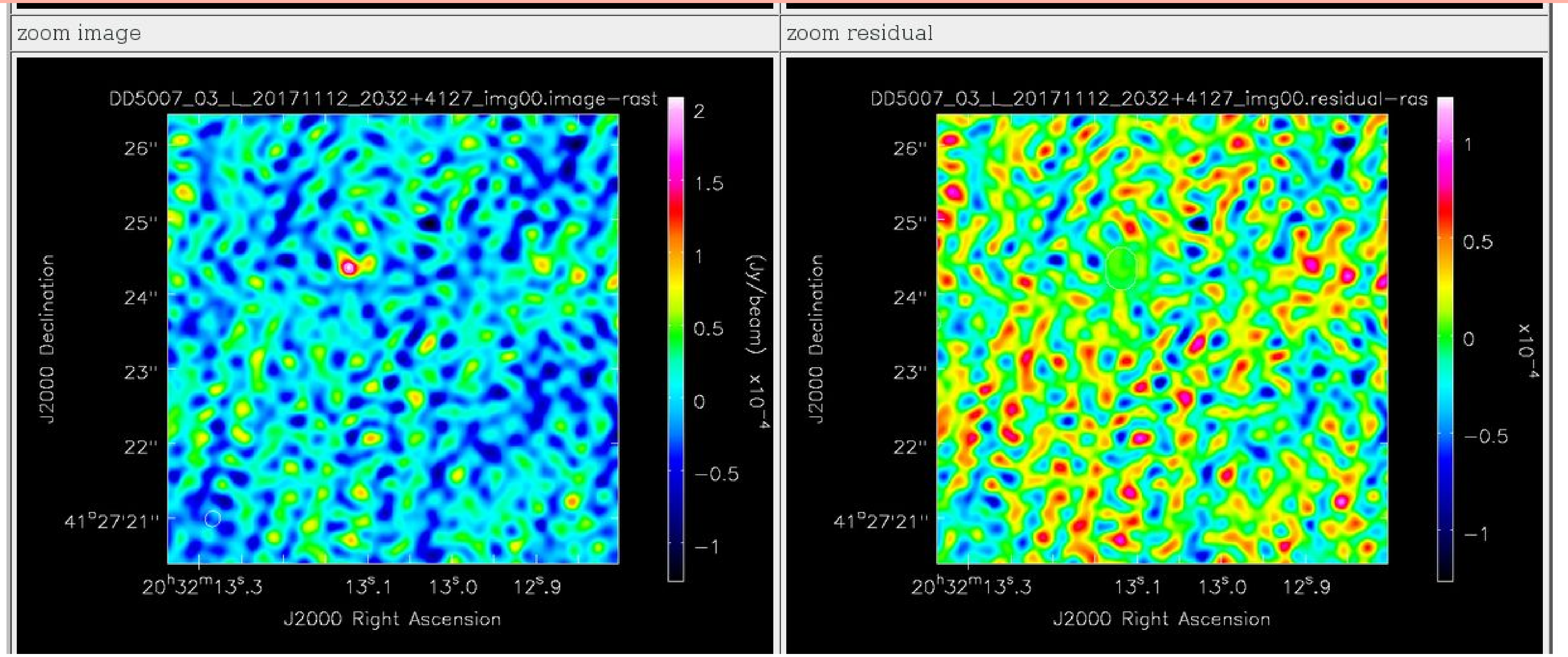
Janssen et al. 2019

e-Merlin pipeline



- takes in idifits data, creates calibrated data, cal tables, QA plots, crude images and summary weblog
- **optimised for e-Merlin only**
- **works automatically on L and C band continuum data**
- K band calibration possible, but not automated
- no self calibration done
- future plans: self cal, polarisation, spectral line, wide-field imaging
- open source: https://github.com/e-merlin/CASA_eMERLIN_pipeline
- (Moldon+ 2018, http://www.e-merlin.ac.uk/tools/eMCP-2.pdf)

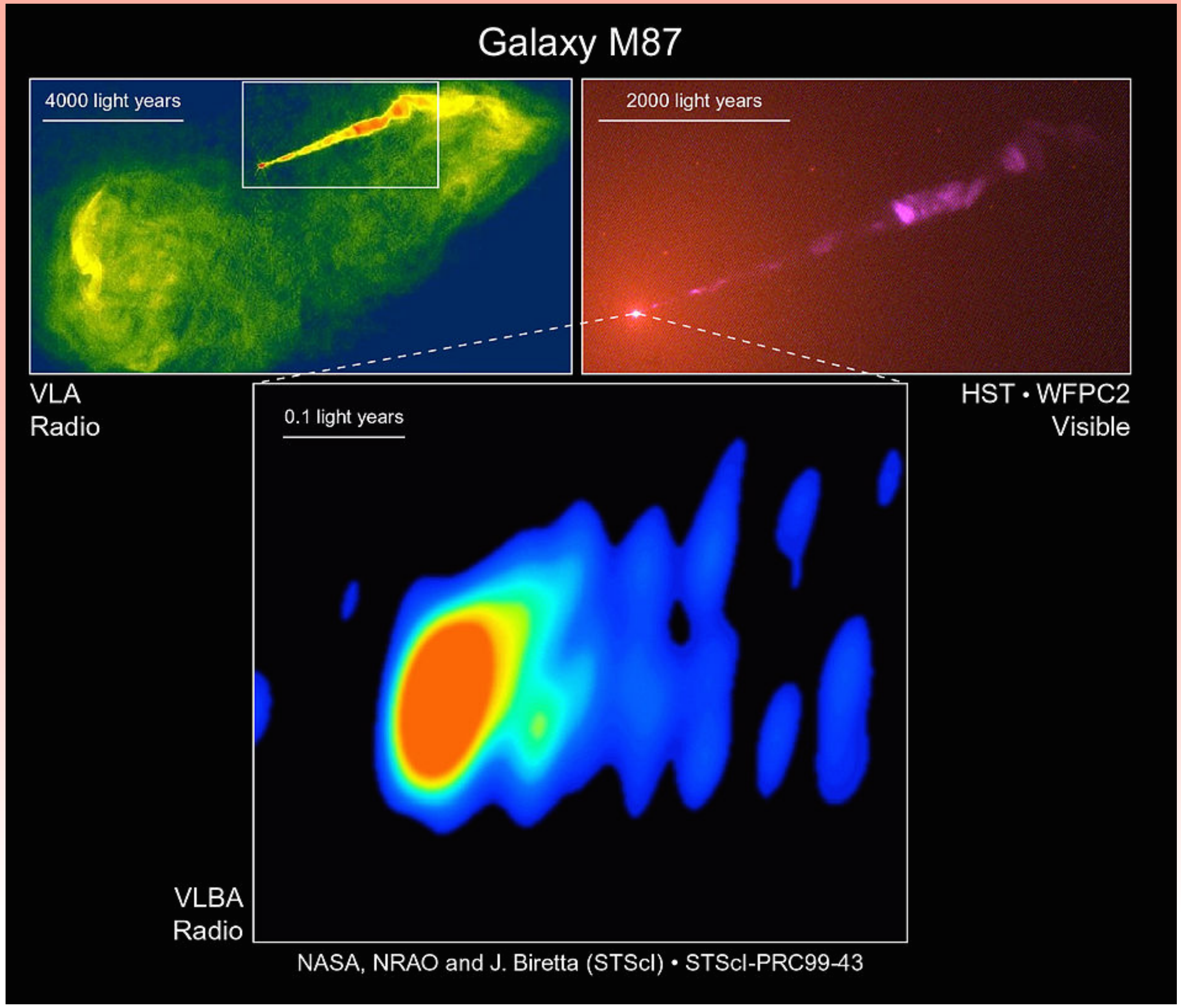
e-Merlin pipeline imaging example



Automated imaging of L-band data, detecting a 100microJansky source

Example of CASA reduction: M87 at 5cm

- EVN 5cm C band dataset from 2013, EG063D, PI: Marcello Giroletti
- angular resolution: 8.5x5.5mas (~1.5ly)
- jet should be visible



Data reduction methods to compare

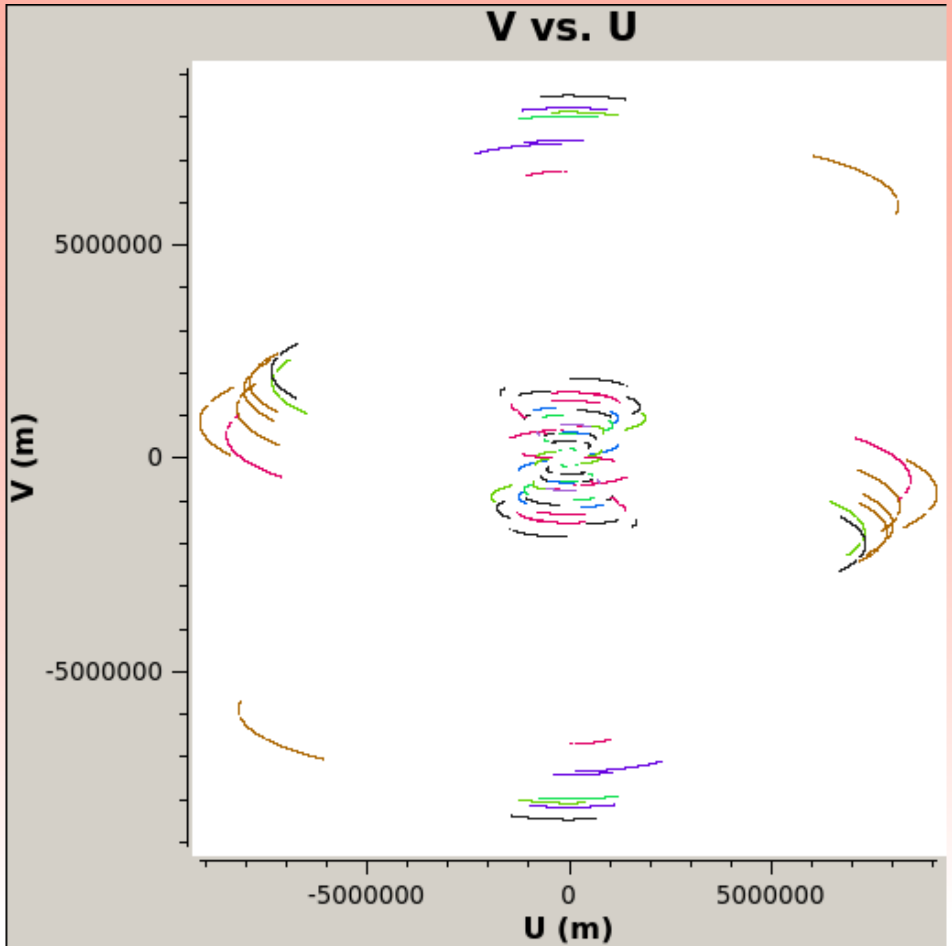
- **manual reduction in CASA** tutorial:
  - http://jive.nl/~small/FringeFitting/n14c3_tutorial.html
  - requires additional auxiliary scripts from https://github.com/jive-vlbi/casa-vlbi
- **rPicard CASA pipeline**
- **AIPS EVN pipeline**

CASA: Apriori calibration

- The flagtables, tsys and gaincurve tables have to be generated with dedicated python scripts outside CASA based on ANTAB and UVFLG tables (downloaded from the archive)
- load data into CASA: **`importfitsidi`**
- create tsys and gaincurve calibration tables with **`gencal`**
- flag and apply apriori cal tables (amplitude calibration)
- use **`flagmanager`** to save various versions of flagtables

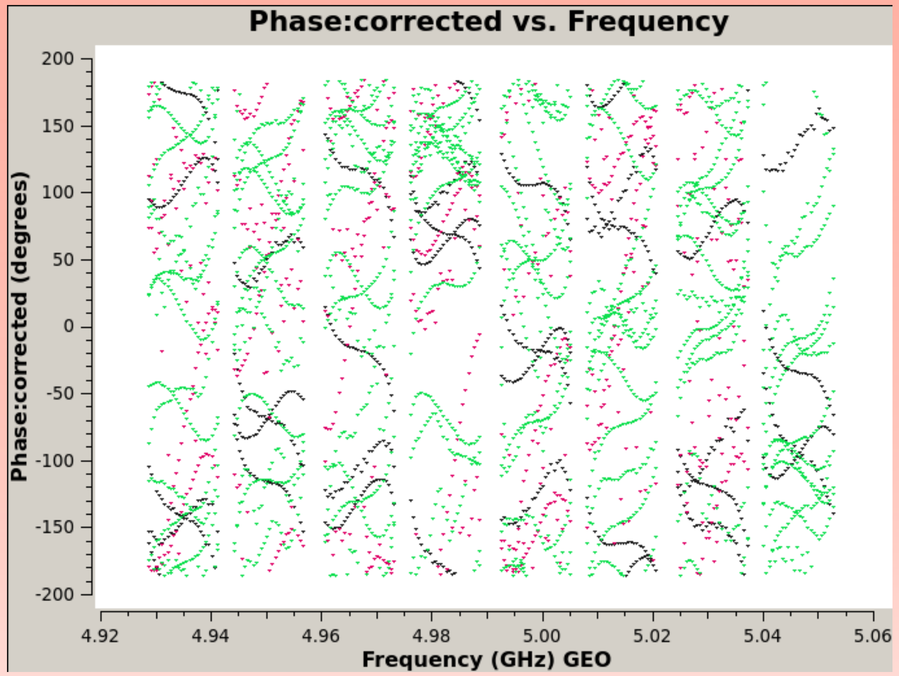
First inspection of data

- flag out autocorrelations, edge channels
- look at uv coverage (color by antenna)
- and amp vs uvdistance of target

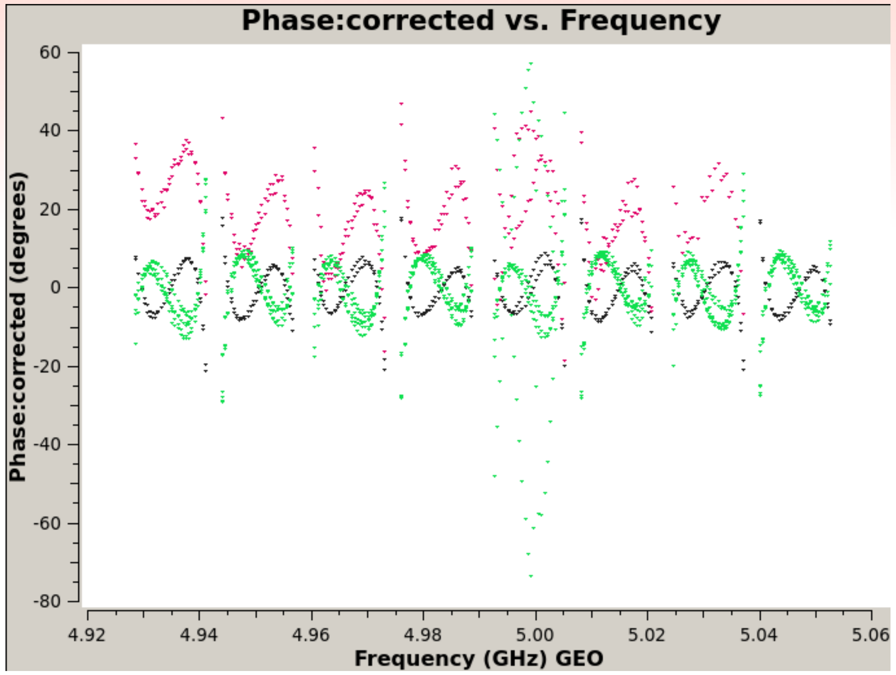


Calibrating the instrumental phases/delays

- **`fringefit`** determine single band delays (per spw/IF) on the fringe finder
- **`applycal`** apply to all sources



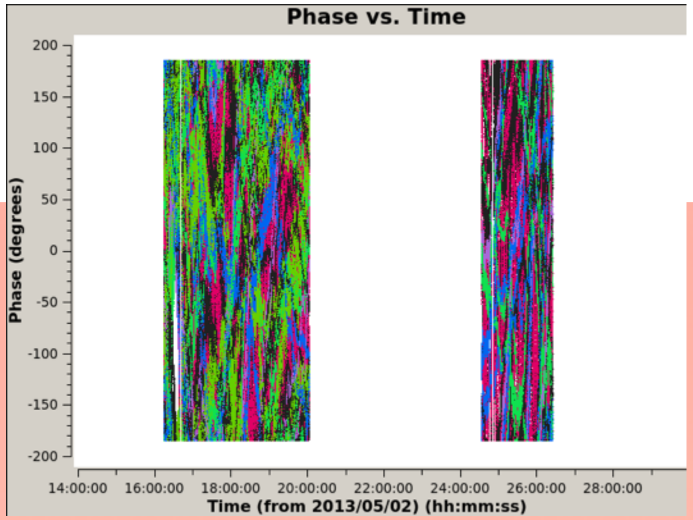
before



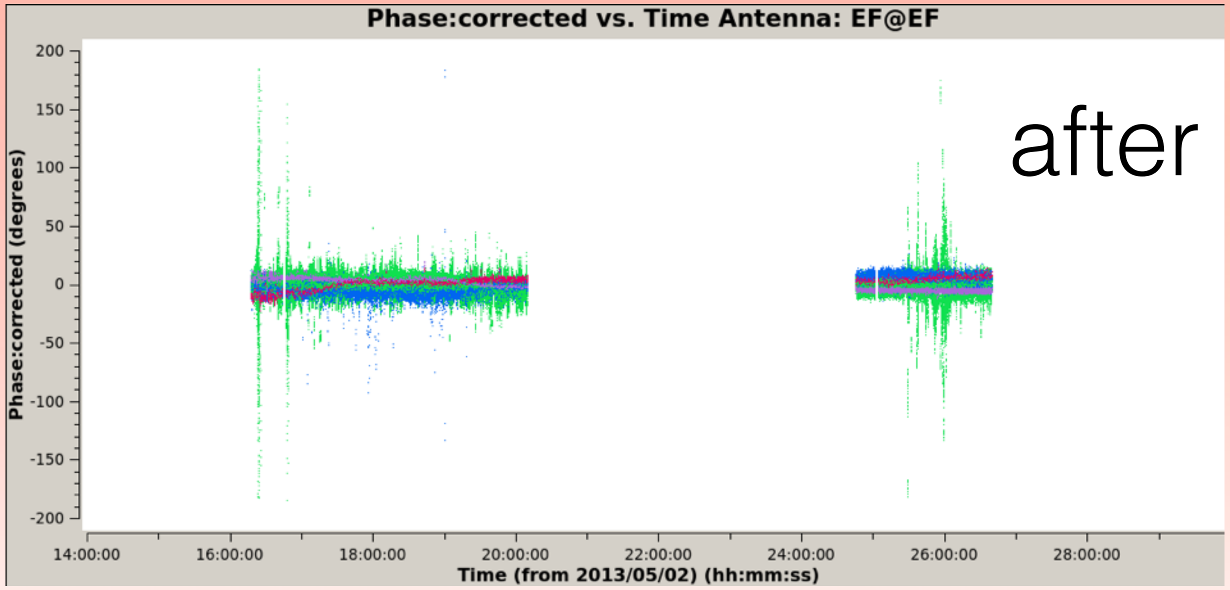
after

Calibrating the atmosphere

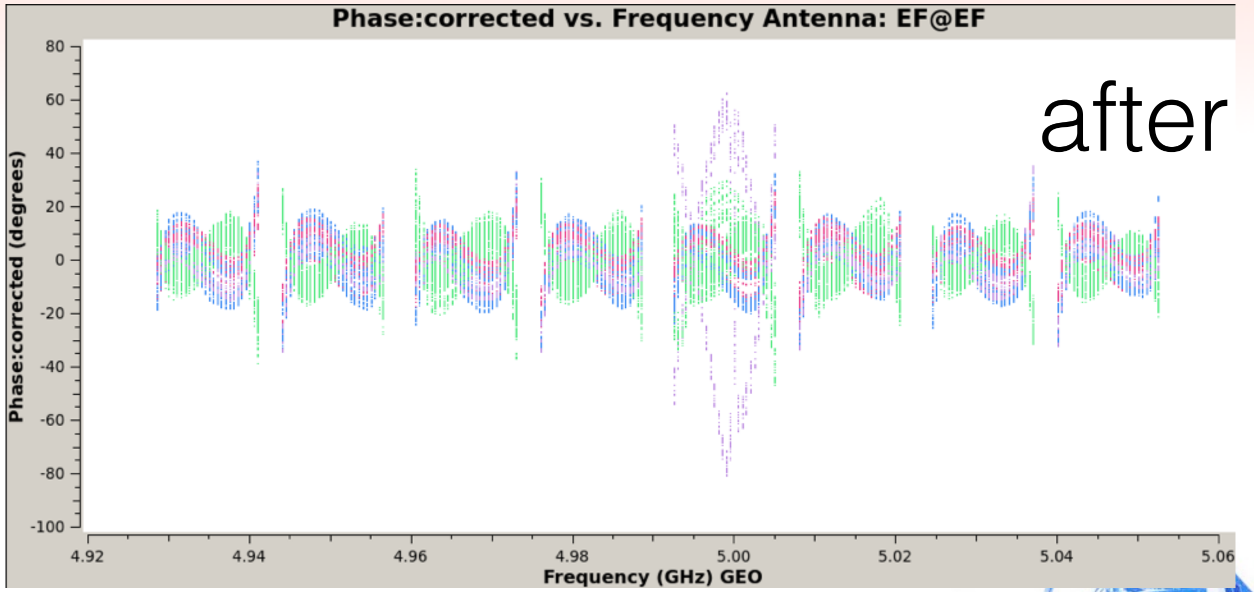
- **`fringefit`** determine multiband delay on target or phase calibrator (combine spw)
- **`applycal`** apply to target (using spwmap)
- identify antennes/times to flag



before



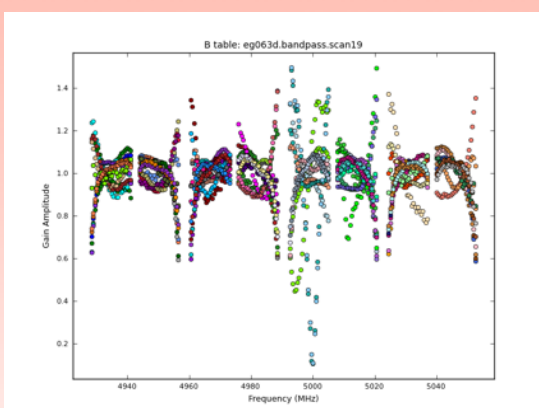
after



after

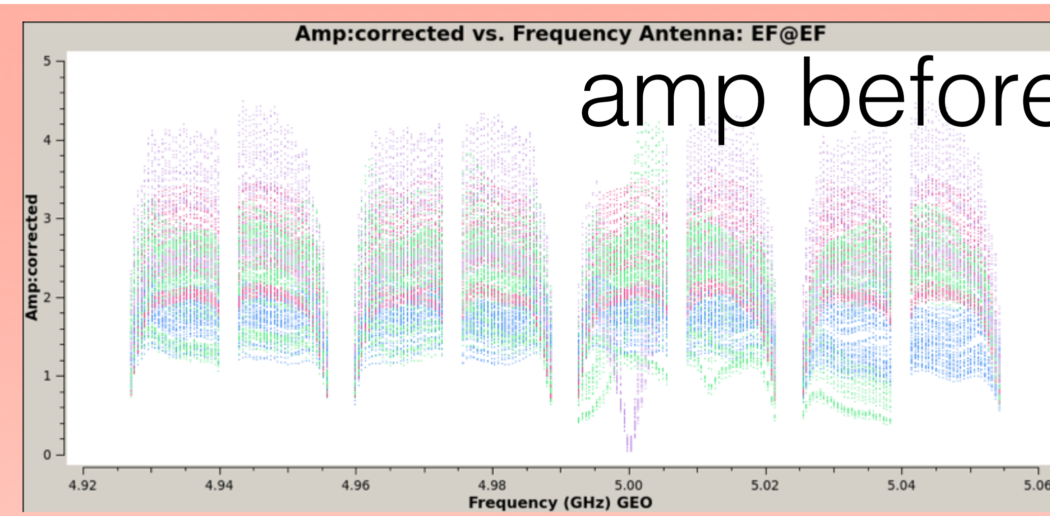
Calibrating the bandpass

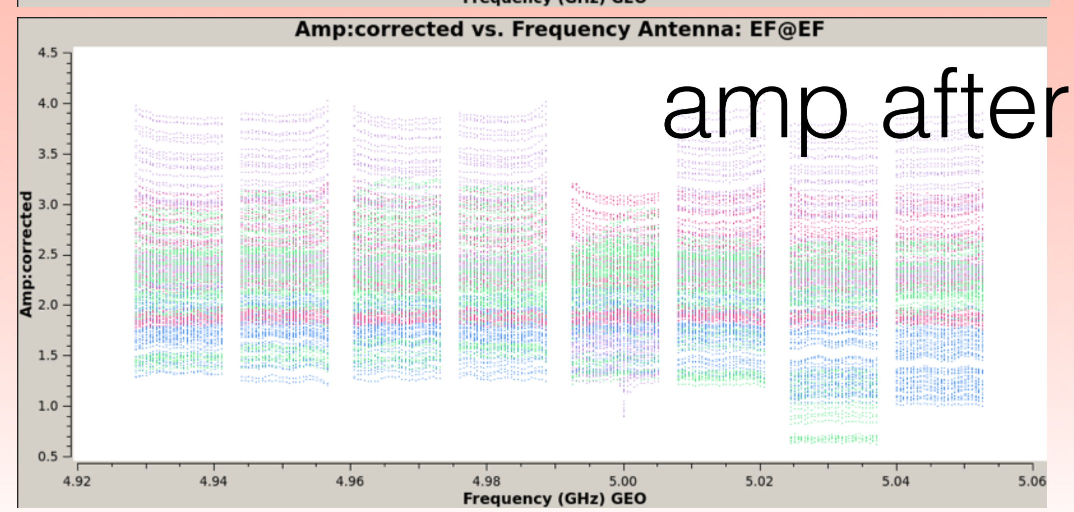
- **`bandpass`** to determine the spectral passband function on a bright target (solves for phases and amplitude)

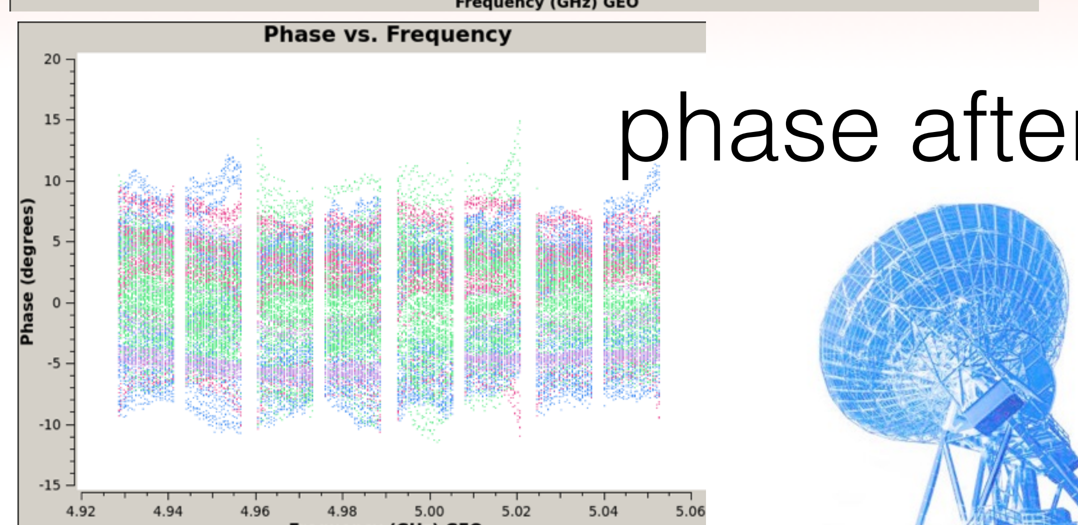


- **`applycal`** apply to target

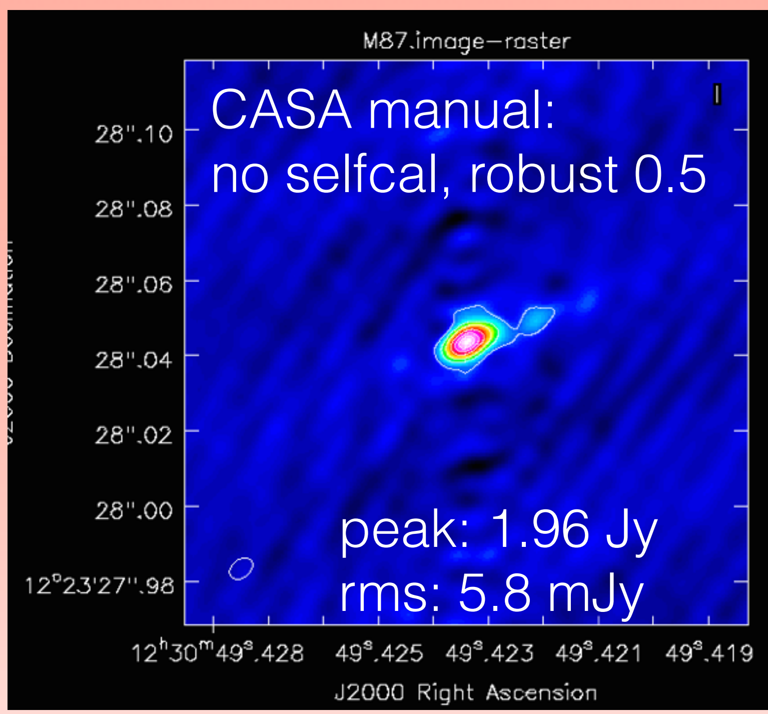
- identify antennes/spw to flag



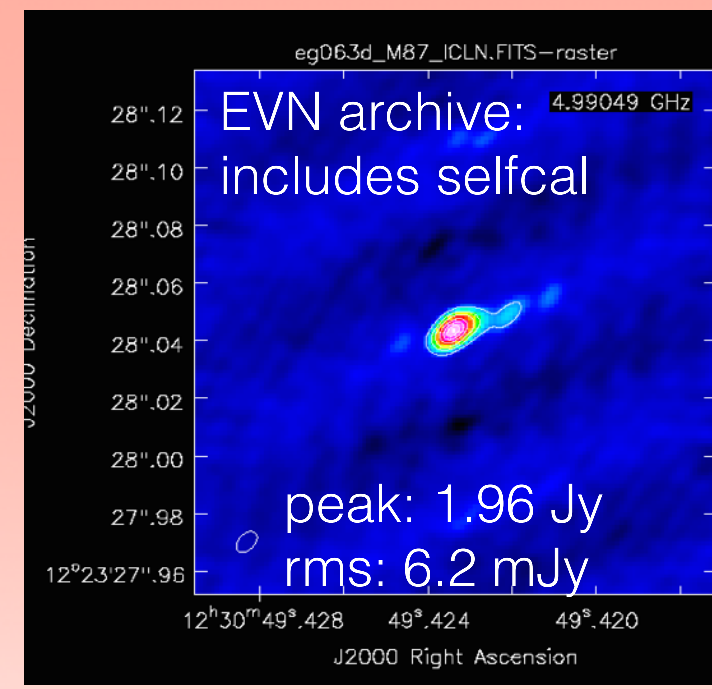


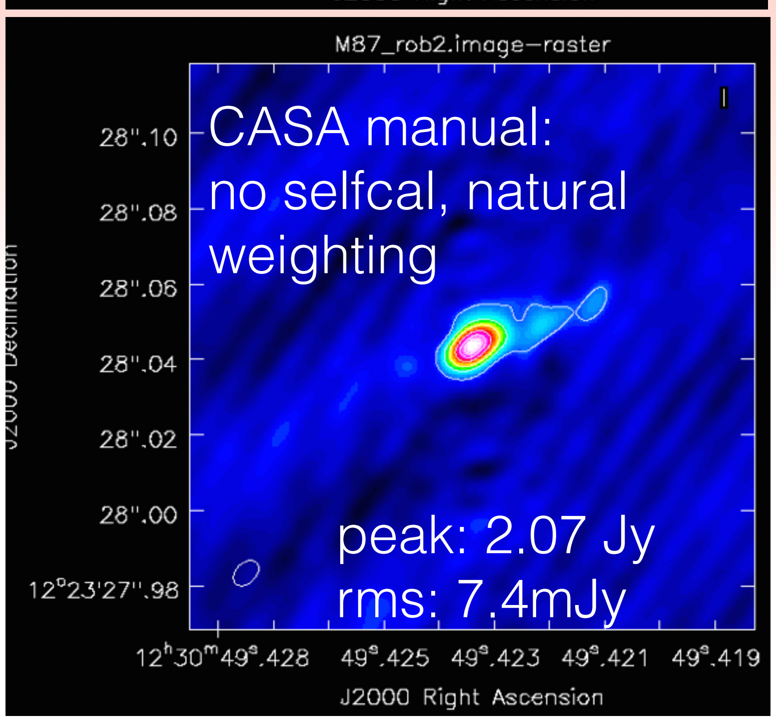


Imaging the calibrated ms

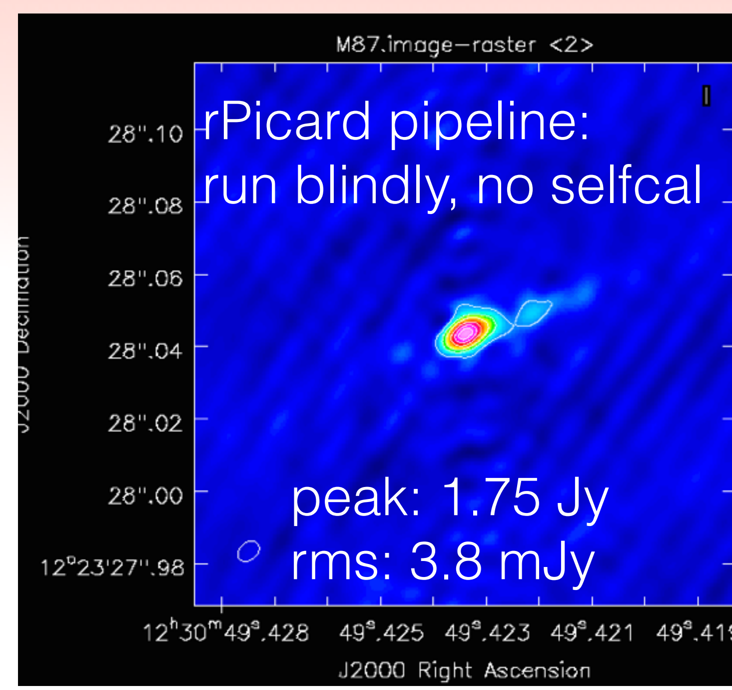


M87 (EG063D, EVN 5cm):
CASA reduction and imaging finds similar structure and flux values as AIPS



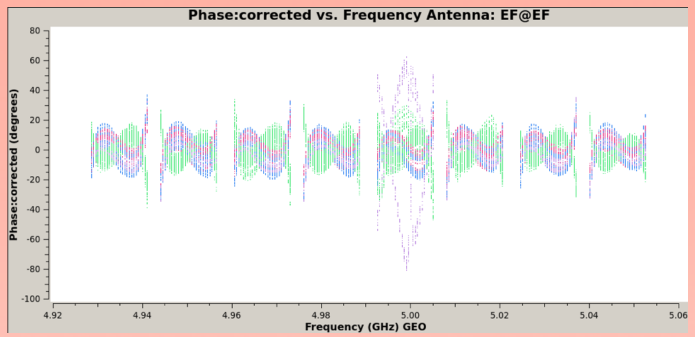


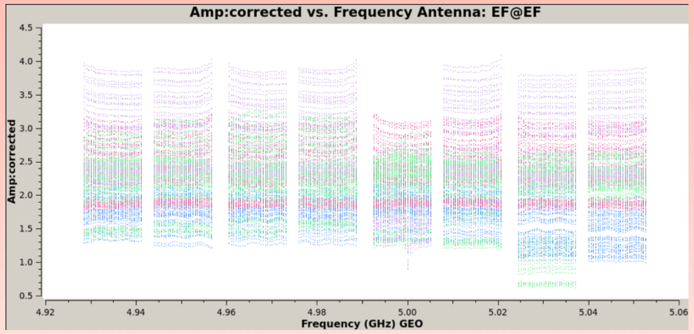
Self calibration would have improved the background of the CASA images

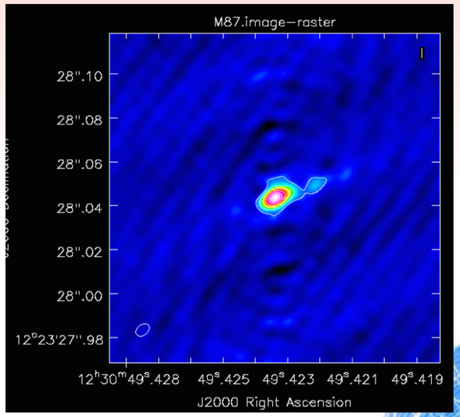


Take home messages

- CASA has become a valid new VLBI reduction software
- It performs equally well as classical reduction software AIPS
- CASA has a cleaner data structure, very powerful visualisation tasks, interactive cleaning
- CASA VLBI is still in the experimental phase, and will improve with every CASA version
- CASA VLBI pipelines available: rPicard for VLBA, EVN , EHT, GMVA data, e-Merlin pipeline

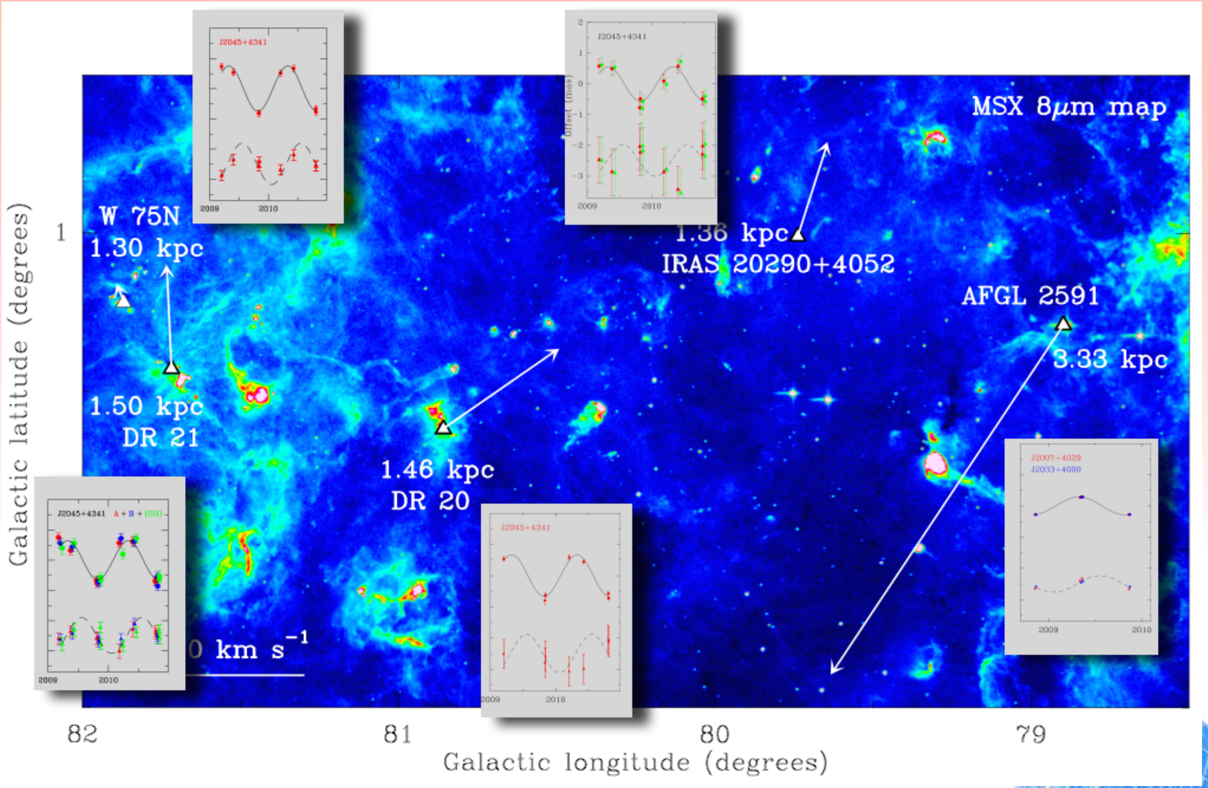






Science with maser astrometry

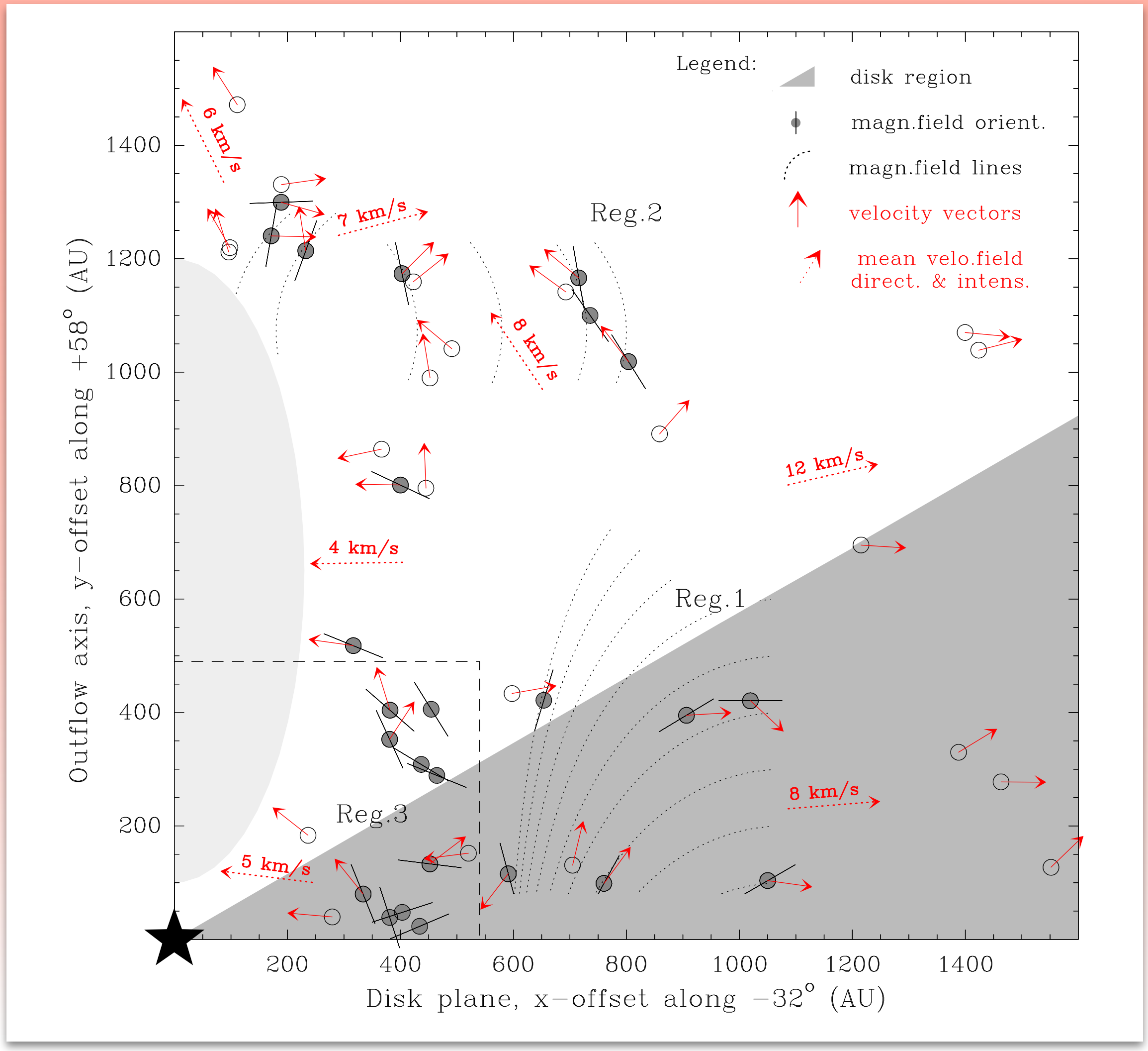
- maser is stimulated spectral line emission originating in environments where a pumping mechanism is available and velocity coherence along LOS
- strong, compact emission, one of most used spectral lines for VLBI - fantastic for astrometry!
- molecules: H2O, CH3OH, SiO, OH
- proper motions and distances
- internal proper motions
- magnetic fields fields



EVN methanol maser astrometry of Cygnus X (Rygl+ 2012)

What is masing?

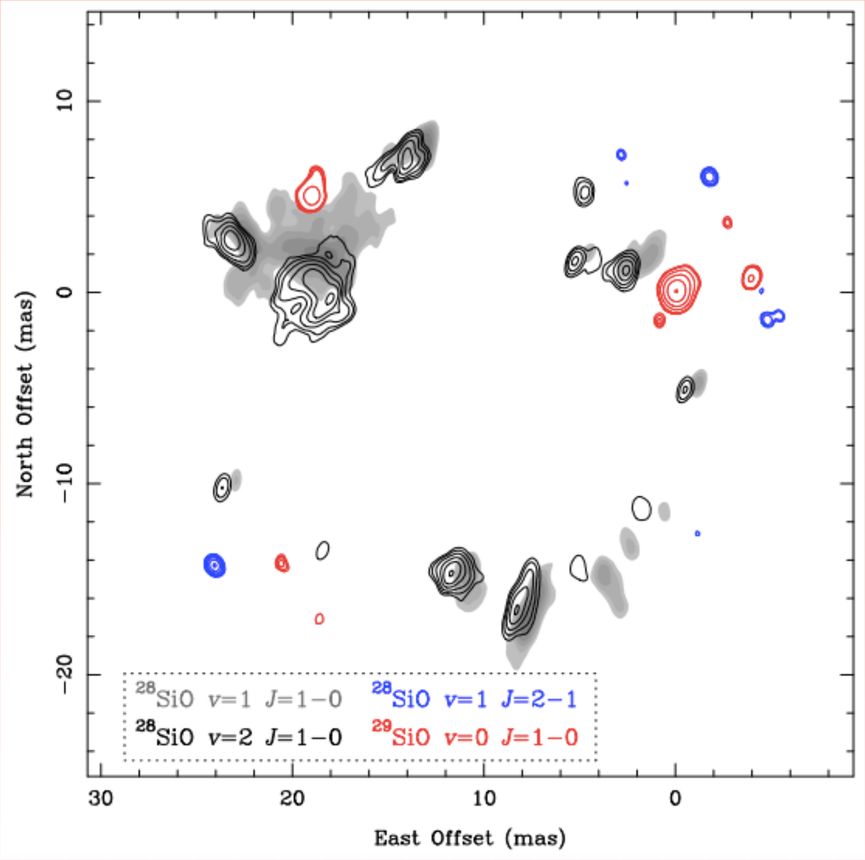
- Gas around high-mass star forming regions (HMSFRs) in outflows, envelopes, disks: maser astrometry reveals the gas dynamics and B field orientation



Gas and B field dynamics in the inner 2000au of high-mass YSO G23.01-00.41 (Sanna+ 2015)

What is masing?

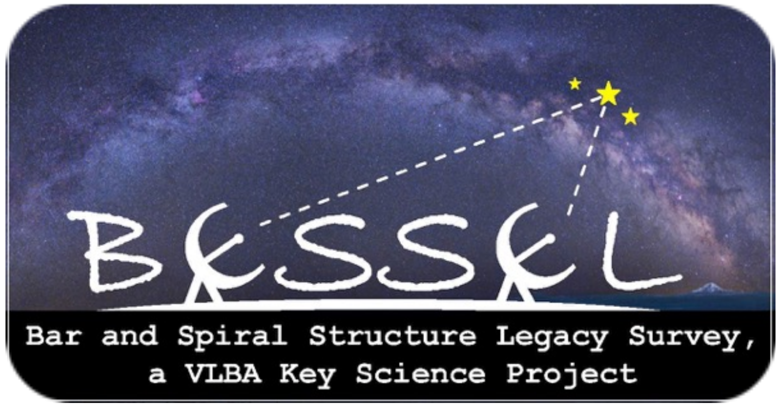
- Gas in envelopes of evolved stars: different maser transitions reveal different pumping processes and can constrain the IR radiation field
- Also B field measures possible



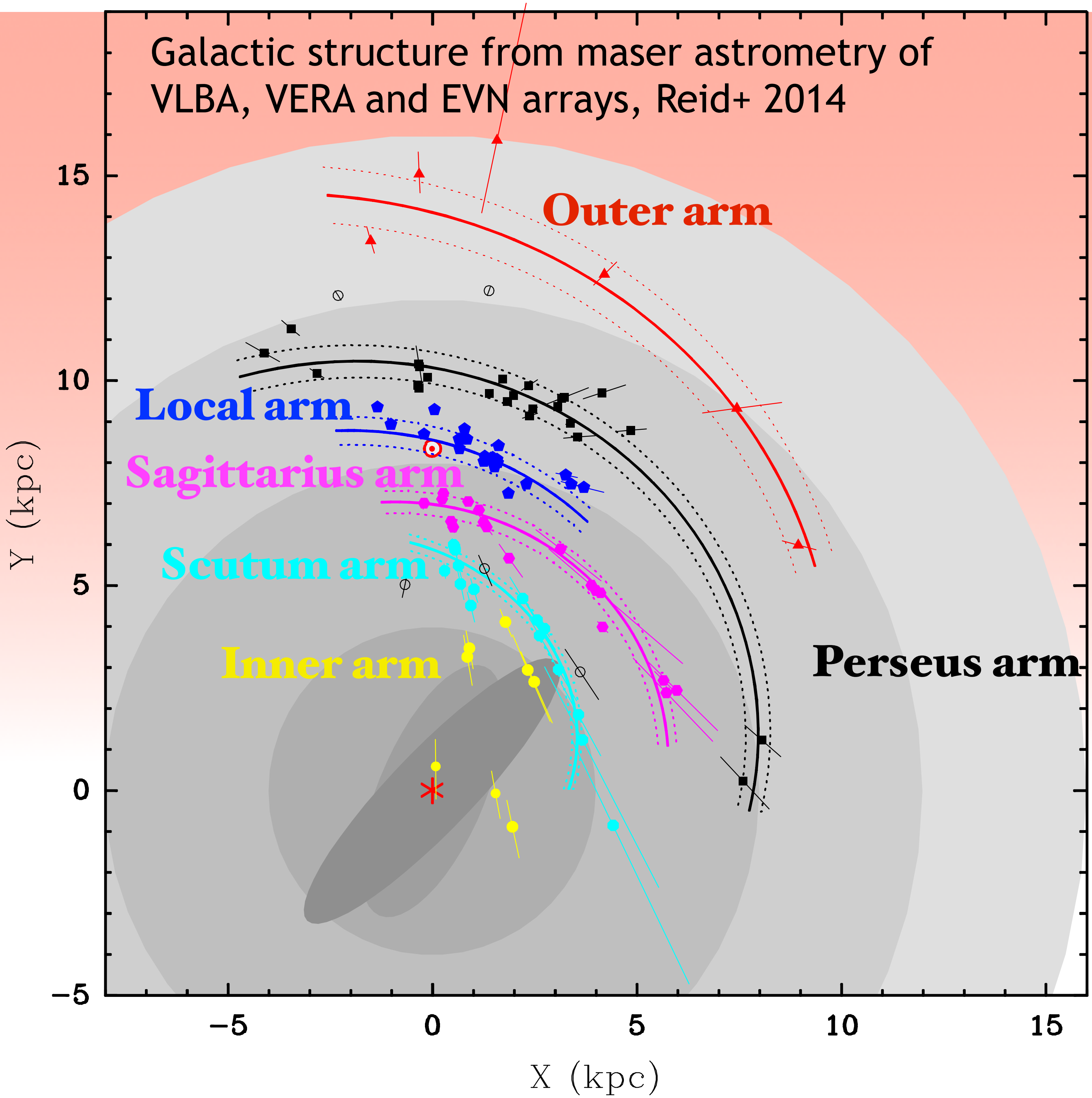
Various SiO maser transitions in the envelope of AGB star IRC+10011 (Soria-Ruiz+ 2014)

Bar and Spiral Structure Legacy (BeSSeL) survey

- Large collaboration led by Mark Reid (CfA)
- Goal: to measure the spiral structure and Galactic parameters of the Milky Way
- Method: VLBA maser parallaxes and proper motions of ~200 HMSFRs using methanol and water masers
- Parallax uncertainties of up 10 microarcsecond allowing 10% uncertainties on 10kpc distance (see Honma&Reid 2014 review)



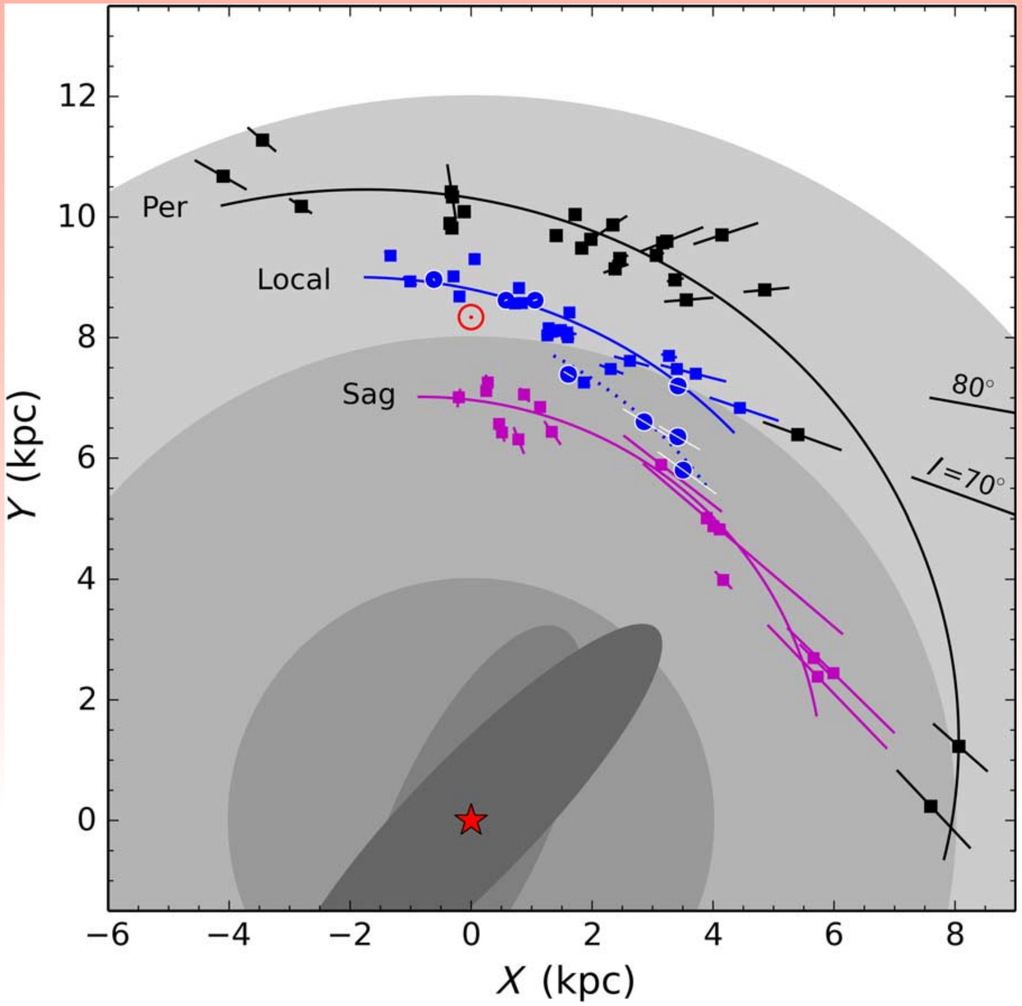
Milky Way parallaxes 2014



- determined pitch angles for the arms
- improved determination of Galactic parameters:
  - ✦ distance to Galactic centre (8.3 kpc) and
  - ✦ Galactic rotation velocity (240 km/s)

New BeSSeL results: Local Arm is not a spur

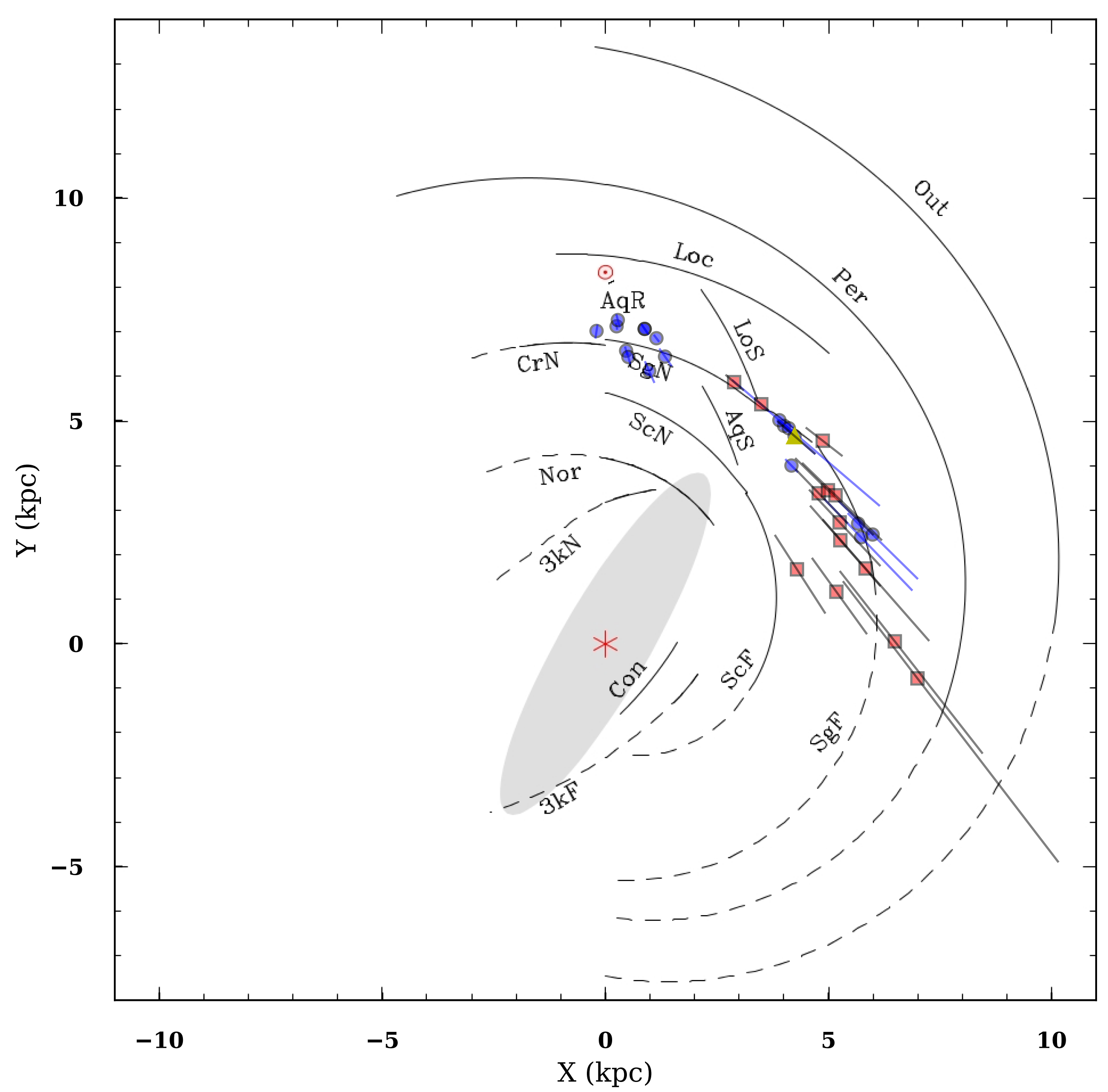
Local Arm structure, Xu+ 2016



- added 8 new HMSFRs
- Local arm (sometimes referred to as spur or Orion spur) has a similar pitch angle and star formation rate as other spiral arms in the Milky way. **No spur!**
- new spur in between Loc/Sgr arm found

New BeSSeL results: Sagittarius Far Arm

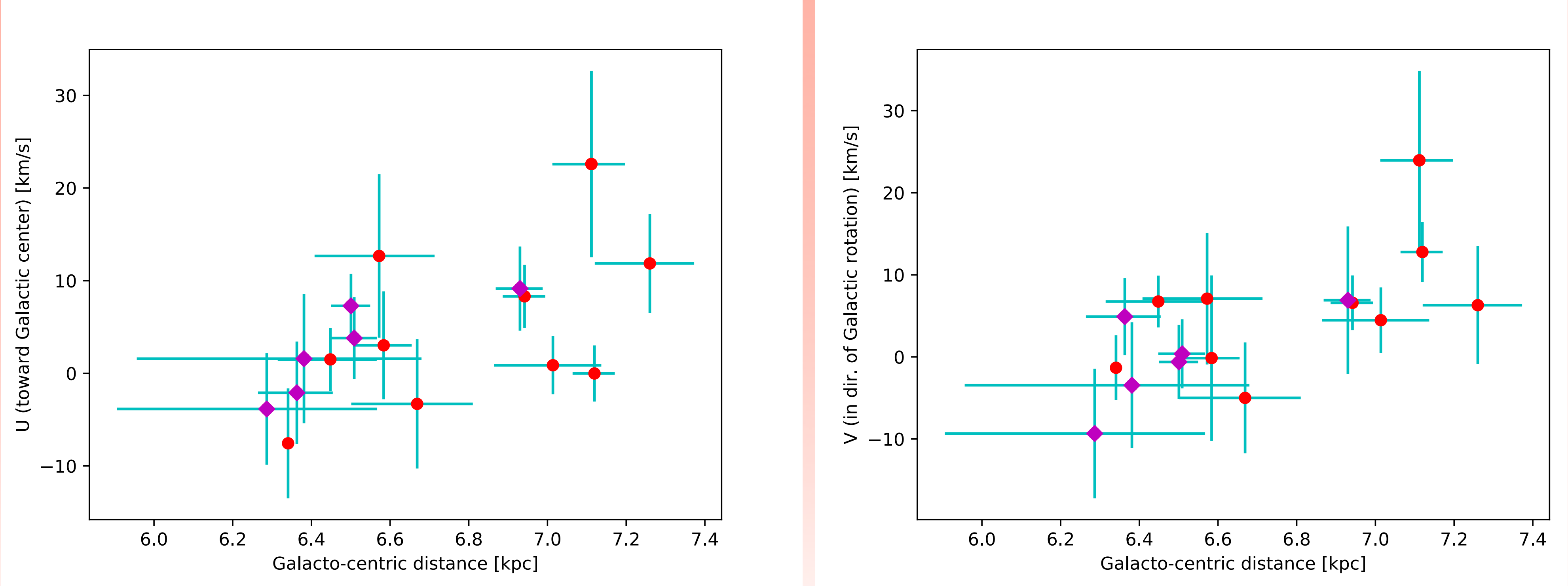
Sgr Far Arm structure, Wu+ 2019



- added 13 new HMSFRs and extended the Sgr arm beyong the tangential point
- distances for famous star-forming regions W51, M17
- Sgr Far appears to be on average 15pc below the IAU defined Galactic plane

New BeSSeL results: Sagittarius Near Arm

Sgr Near Arm kinematics, Rygl+ 2019, EVN Symposium



Across Sgr Near arm we find motions of HMSFRs are correlated with Galacto-centric distance - something which is expected in simulations that study the dynamical influence on spiral arms.

More about masers and astrometry in this meeting

- AVN *and masers* by James Chibueze
- YSO astrometry in continuum by Gisela Ortiz-Leon
- Evolved stars *and masers* by Elizabeth Humpreys
- EAN and Masers by Taehyun Jung
- Megamasers by Jim Braatz