

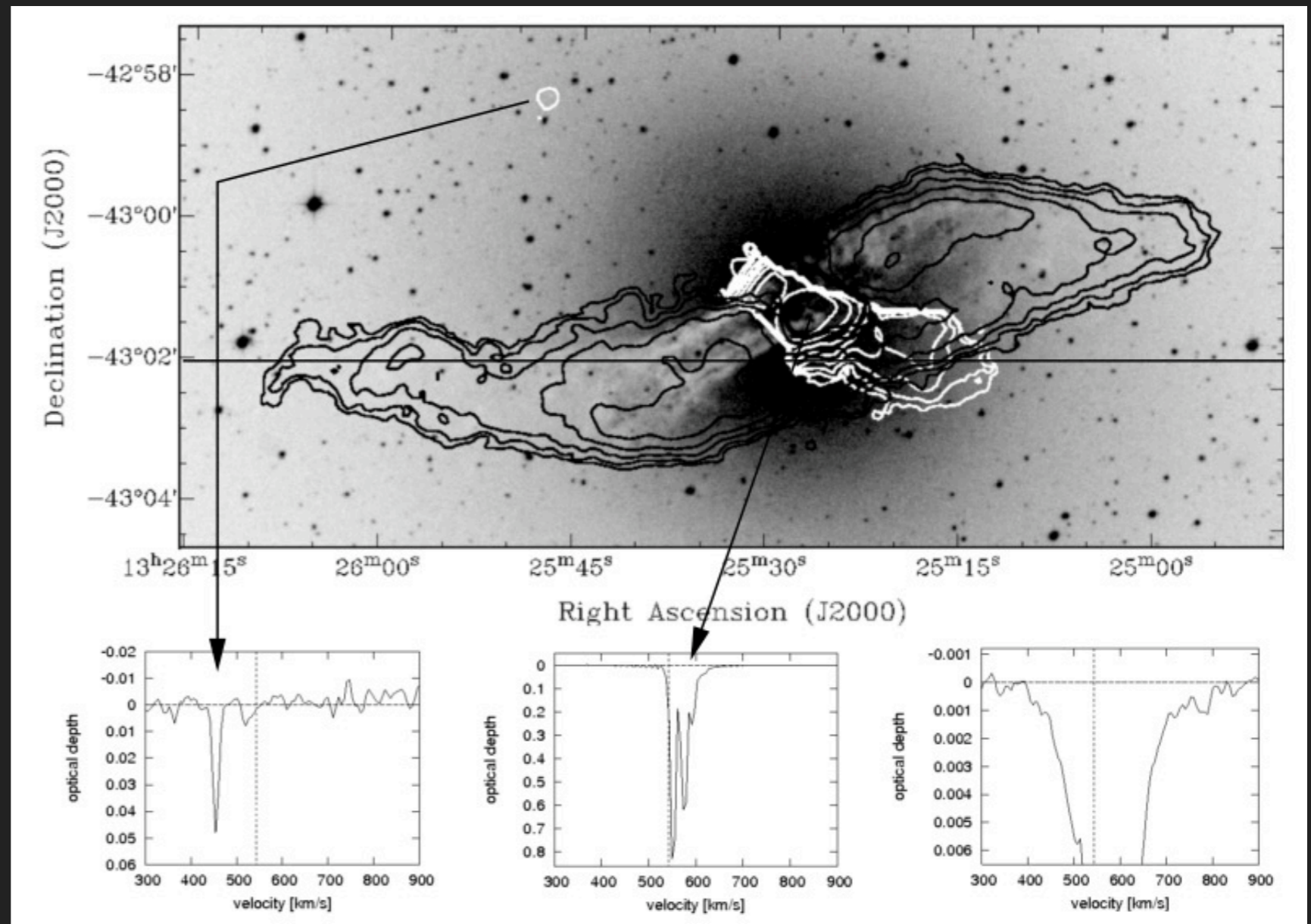
F. Maccagni; R. Morganti; T. Oosterloo; J. Allison,  
Apertif Commissioning Team, MeerKAT Fornax Survey Team

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# SOFTWARE TOOLS FOR HI ABSORPTION SURVEYS

# HI absorption in radio AGN

- ▶ Early-type galaxies are the typical host of a radio-AGN
- ▶ ~ 40% of early-type galaxies have neutral hydrogen HI [ATLAS<sup>3D</sup> · Serra et. al 2012]
  - ▶ HI absorption traces interplay between the radio source and the ISM
- ▶ Narrow lines at systemic velocity
  - ▶ rotating disks
- ▶ Shallow blue shifted wings
  - ▶ outflows pushed by the radio jet
- ▶ Redshifted lines
  - ▶ inflowing gas
- ▶ HI and molecular cold gas components (e.g. CO, H<sub>2</sub>, etc) show similar kinematics

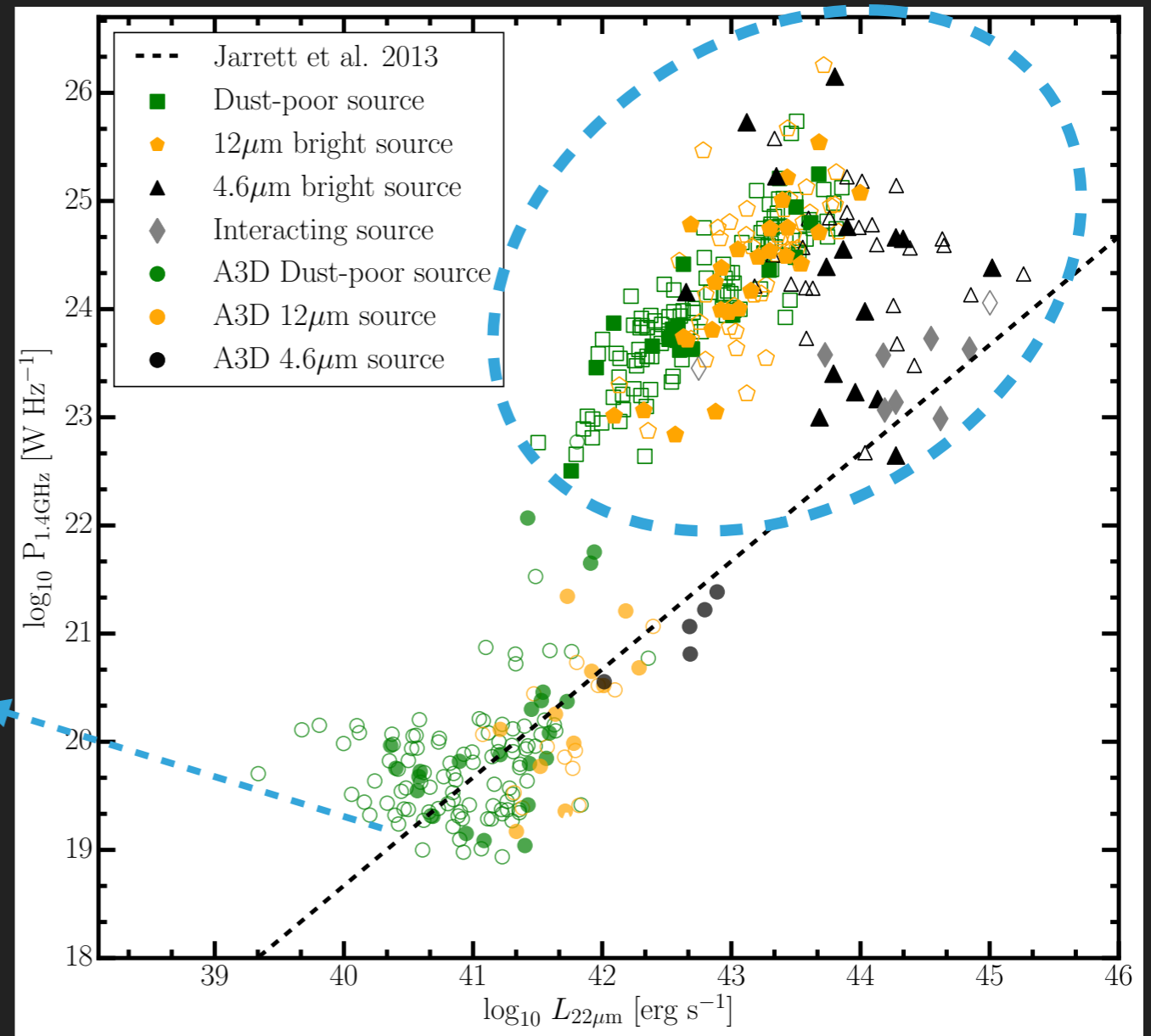


# WHISA: Westerbork HI Survey in Absorption

## 248 radio-galaxies

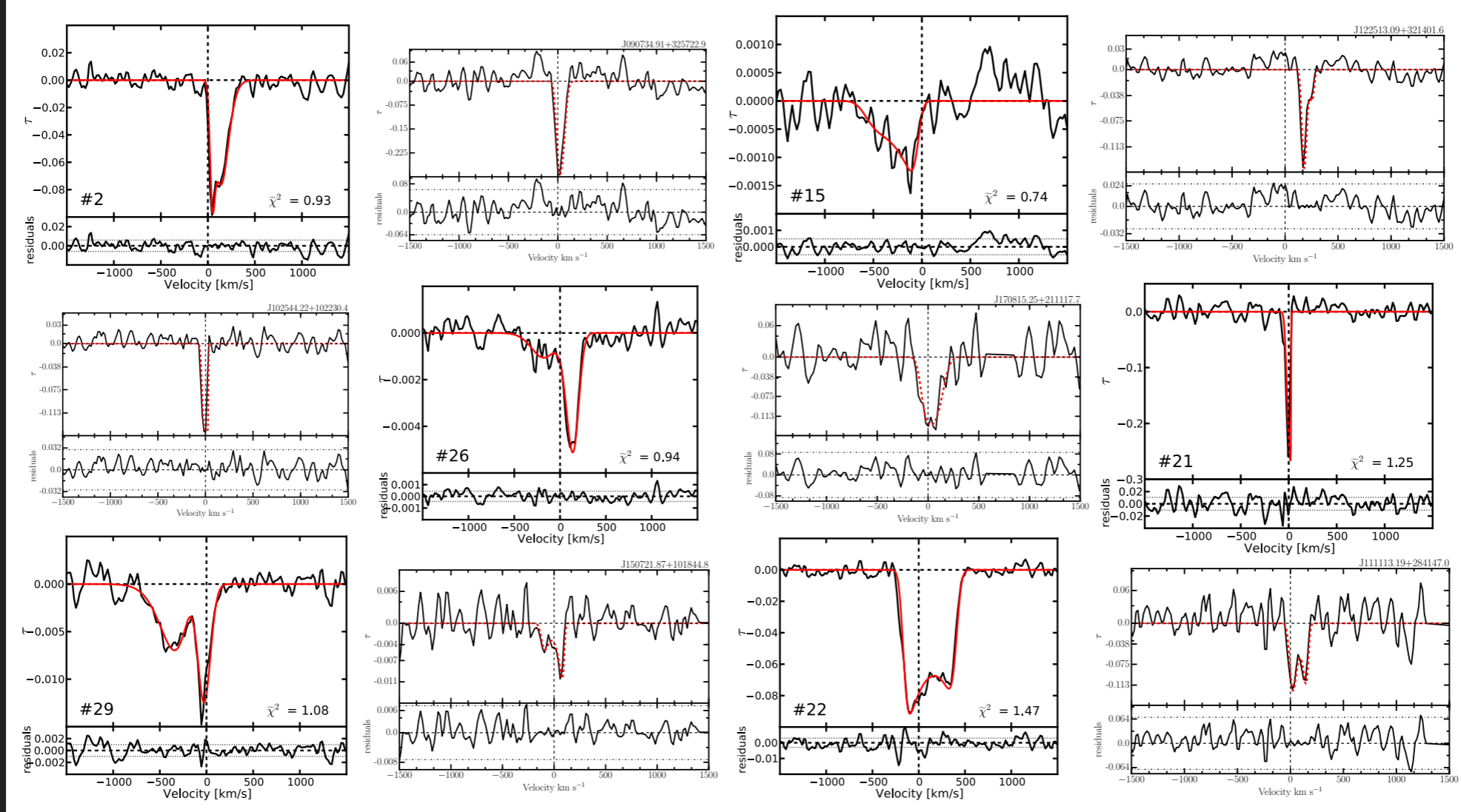
- ▶  $0.02 < z < 0.25$
- ▶ SDSS spectroscopy
- ▶  $S_{\text{Cont}} \geq 30$  mJy
- ▶ Wide range of Radio Powers
- ▶ mostly AGN in early-type galaxies

## Mid-InfraRed [ $22 \mu\text{m}$ ] - Radio Power Relation

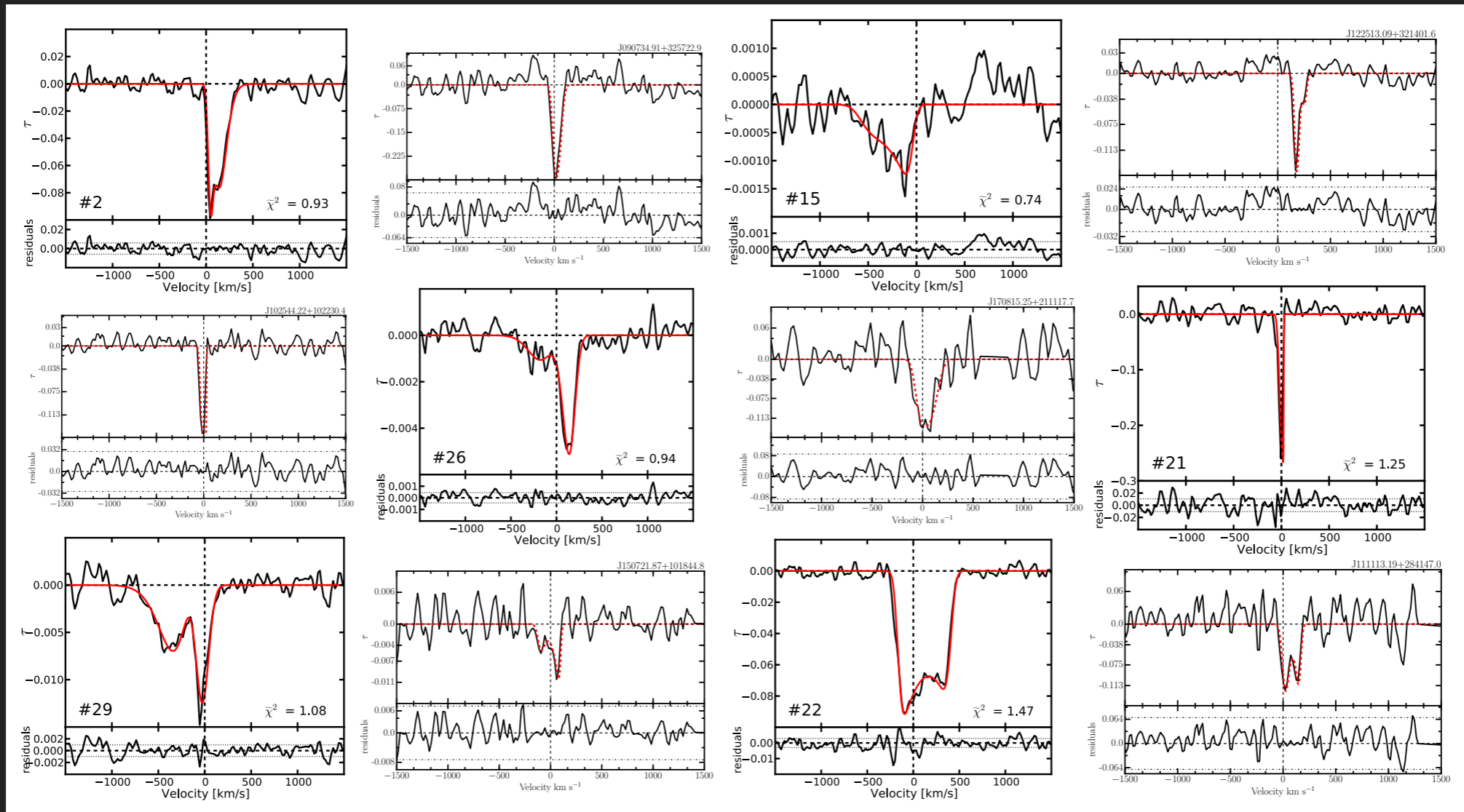


- ▶ 101 sources;  $S_{\text{Cont}} \geq 50$  mJy
  - ▶ Stacking experiment [Geréb et al., 2014]
  - ▶ Analysis of the detections [Geréb, Maccagni, et al., 2015]
- ▶ All 248 sources
  - ▶ Analysis of the full sample [Maccagni et al., 2017]
  - ▶ Stacking analysis of the ATLAS<sup>3D</sup> sample

# WHISA: the Westerbork Survey



# WHISA: Main Results



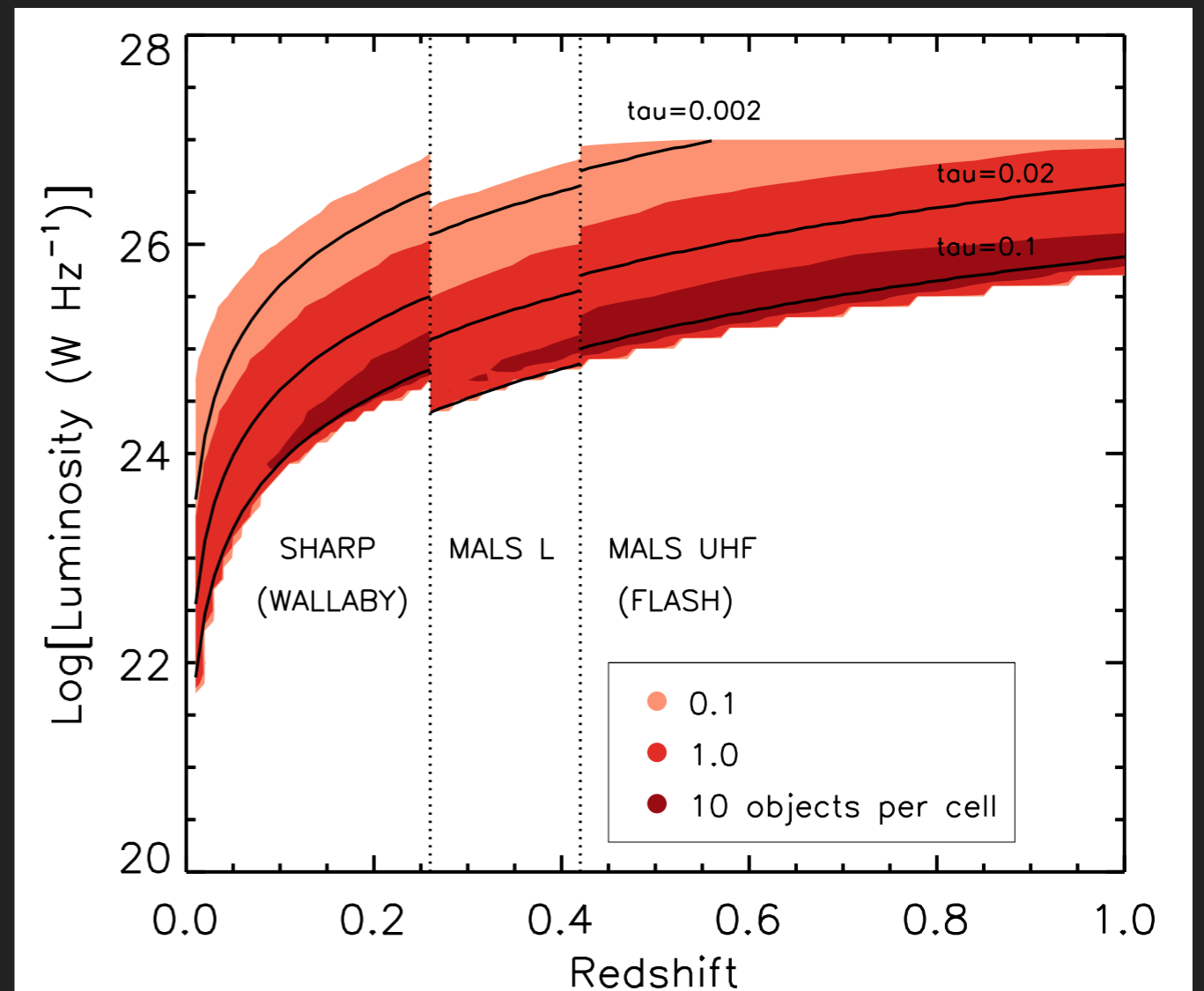
[Maccagni et al., 2017]

- ▶ Detect associated HI absorption against the radio continuum emission
  - ▶ **27% detection rate**
  - ▶ Variety of lines with different shapes, widths and optical depths
    - ▶ Trace the interaction between the radio activity and the interstellar medium, i.e. **Feedback from AGN**
      - ▶ Circumnuclear disks, fast outflows, inflows.

# Upcoming HI Absorption Surveys

- ▶ HI absorption surveys with SKA pathfinders and precursors
  - ▶ SHARP (Raffaella's talk), FLASH (Elaine's talk), MALS (Neeraj's talk)
- ▶ From the continuum source population and WHISA detection rate (27%) we predicted what these surveys will detect for HI absorption

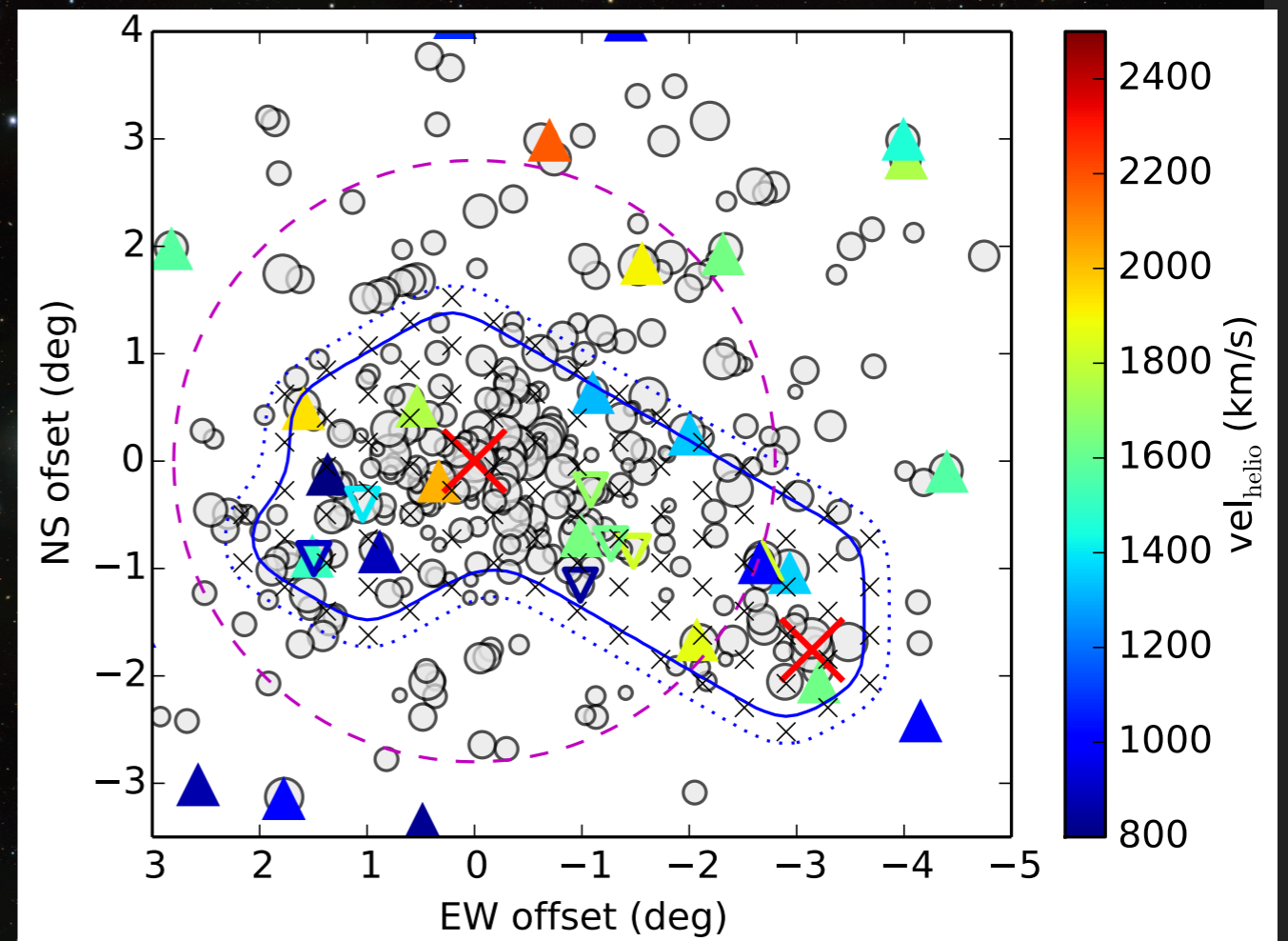
- ▶ The surveys are complementary
- ▶ SHARP will detect HI absorption in low-power radio sources
- ▶ Each pointing will have a hundreds of l.o.s. where to extract spectra (sources > 5 mJy)
  - ▶ Need for automated tools for HI absorption studies.



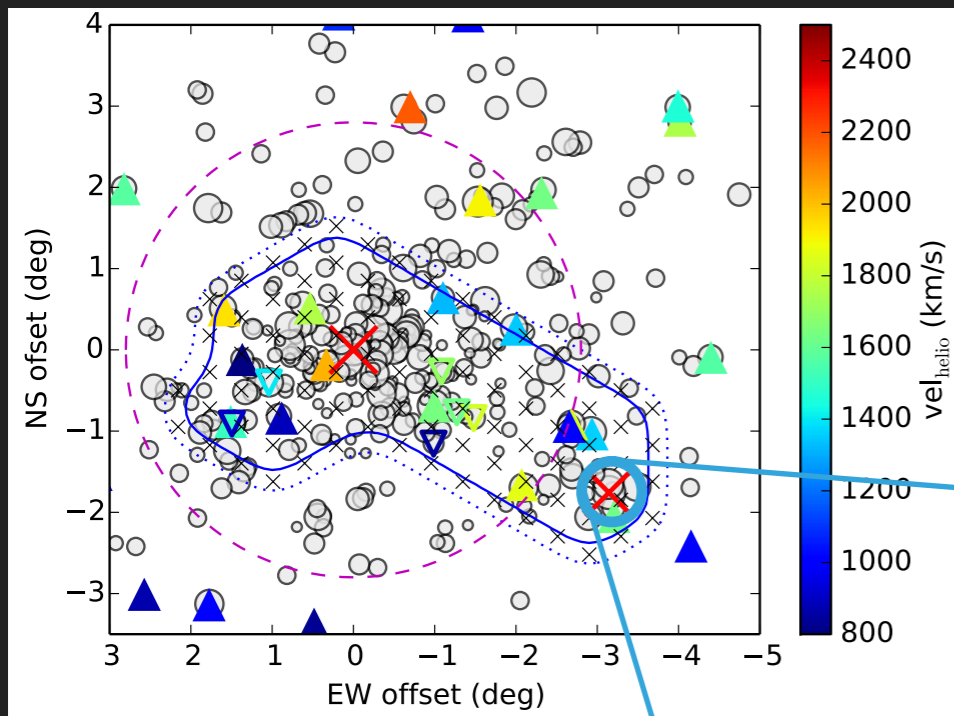
# MeerKAT Fornax Survey

- ▶ **Observe the Fornax Cluster and the group of Fornax A with MeerKAT**
- ▶ PI: Paolo Serra; Collaborators: E. de Blok (ASTRON, Kapteyn, UCT), G. Bryan (Columbia), S. Colafrancesco (Wits), R.-J. Dettmar (Bochum), B. Frank (SARAO), F. Govoni (INAF), G. Józsa (SARAO, Rhodes, Bonn), R. Kraan-Korteweg (UCT), I. Loubser (NWU), F. Maccagni (INAF), M. Murgia (INAF), T. Oosterloo (ASTRON, Kapteyn), R. Peletier (Kapteyn), R. Pizzo (ASTRON), M. Ramatsoku (INAF), P. Serra (INAF), M. Smith (Cardiff), S. Trager (Kapteyn), J. van Gorkom (Columbia), M. Verheijen (Kapteyn).
- ▶ Survey F.O.V: 91 pointings covering 11.8 deg<sup>2</sup>
- ▶ Expected natural r.m.s. noise: 0.1 mJy/beam in a 5 km/s (~25 kHz) channel.

- ▶ Science goals:
  - ▶ Study gas removal and accretion in galaxies.
  - ▶ HI in the ISM and ICM.
    - ▶  $N(\text{HI}) \sim 10^{18} \text{ cm}^{-2}$  at 10 kpc
    - ▶  $N(\text{HI}) \sim 10^{19} \text{ cm}^{-2}$  at 1 kpc
  - ▶ HI mass function
    - ▶ down to  $M(\text{HI}) \sim 5 \times 10^5 M_{\text{sun}}$

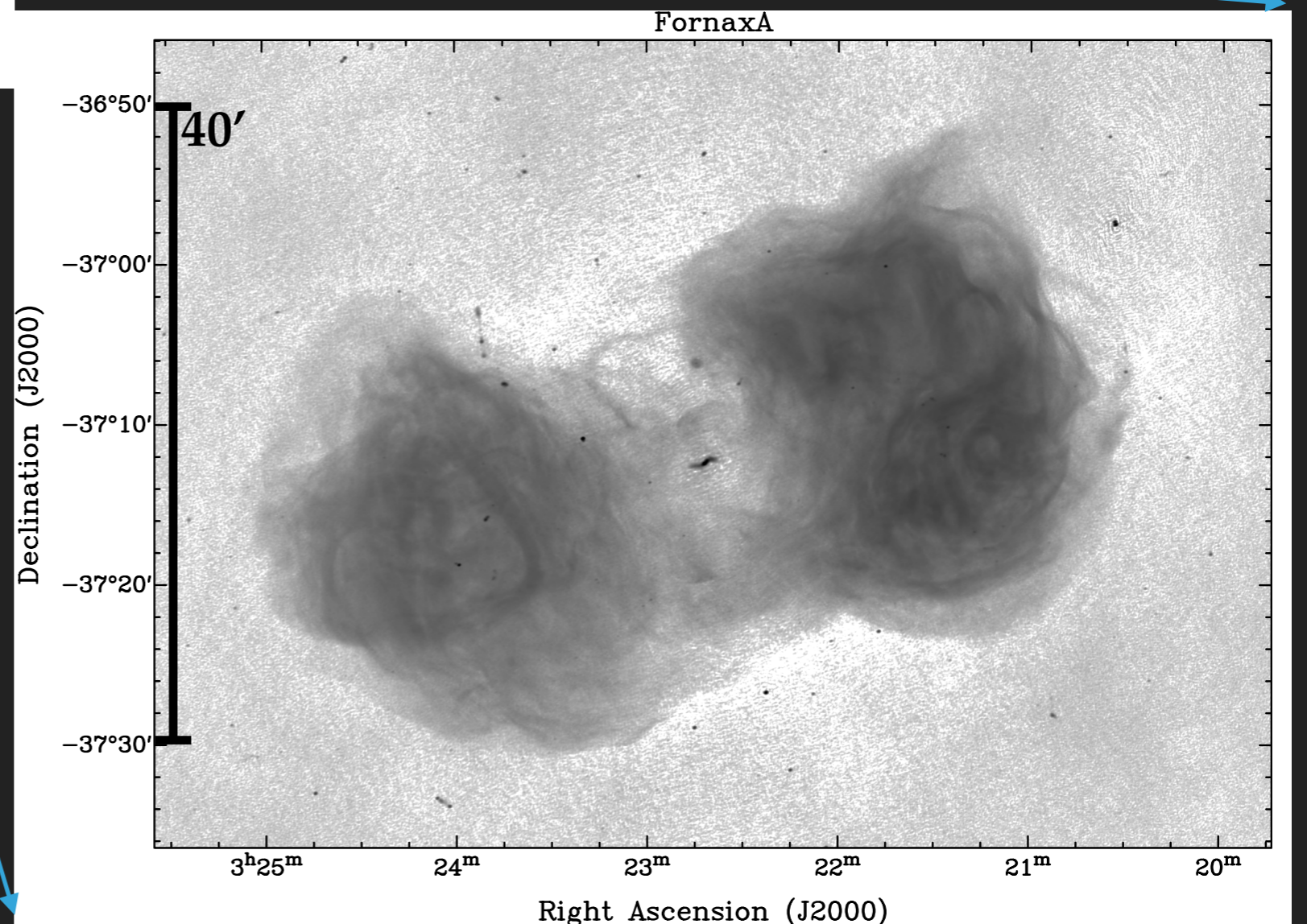


# Expectations for the MeerKAT Fornax Survey



- ▶ Each pointing has  $\sim 100$  l.o.s. ( $S_{1.4\text{GHz}} > 5$  mJy) where to search for HI absorption

- ▶ It's necessary to have tools to automatically identify continuum sources, extract the spectra and look for absorption.
  - ▶ SHARPenner

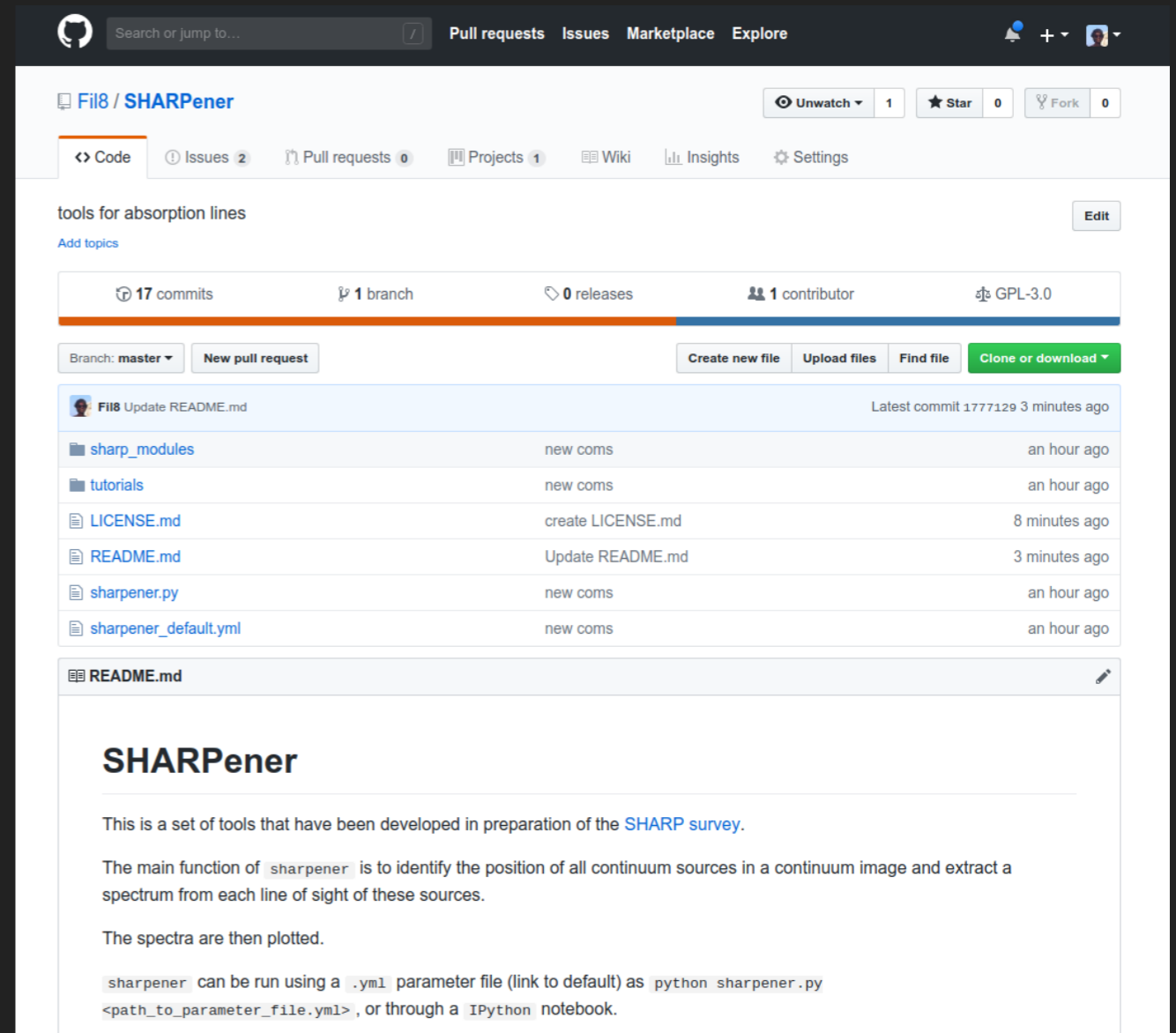


[MeerKAT 40 Antennas]



# SHARPENER: Tools for Absorption Lines

- ▶ All tools are written in Python
- ▶ Identifies continuum sources, extract spectra, finds & characterises lines
- ▶ Packages and options enabled in a parameter file
  - ▶ Run as an automated pipeline
  - ▶ Used on individual spectra
  - ▶ Applications on subsamples
    - ▶ stacking experiments
    - ▶ cross-correlation with LOFAR



GitHub repository page for Fil8 / SHARPEner. The page shows the repository name, navigation tabs (Code, Issues, Pull requests, Projects, Wiki, Insights, Settings), and a commit history table. The commit history table lists files like sharp\_modules, tutorials, LICENSE.md, README.md, sharpener.py, and sharpener\_default.yml with their respective commit times. Below the table is the README.md content, which describes the tools and their usage.

File	Commit Message	Time
sharp_modules	new coms	an hour ago
tutorials	new coms	an hour ago
LICENSE.md	create LICENSE.md	8 minutes ago
README.md	Update README.md	3 minutes ago
sharpener.py	new coms	an hour ago
sharpener_default.yml	new coms	an hour ago

**SHARPEner**

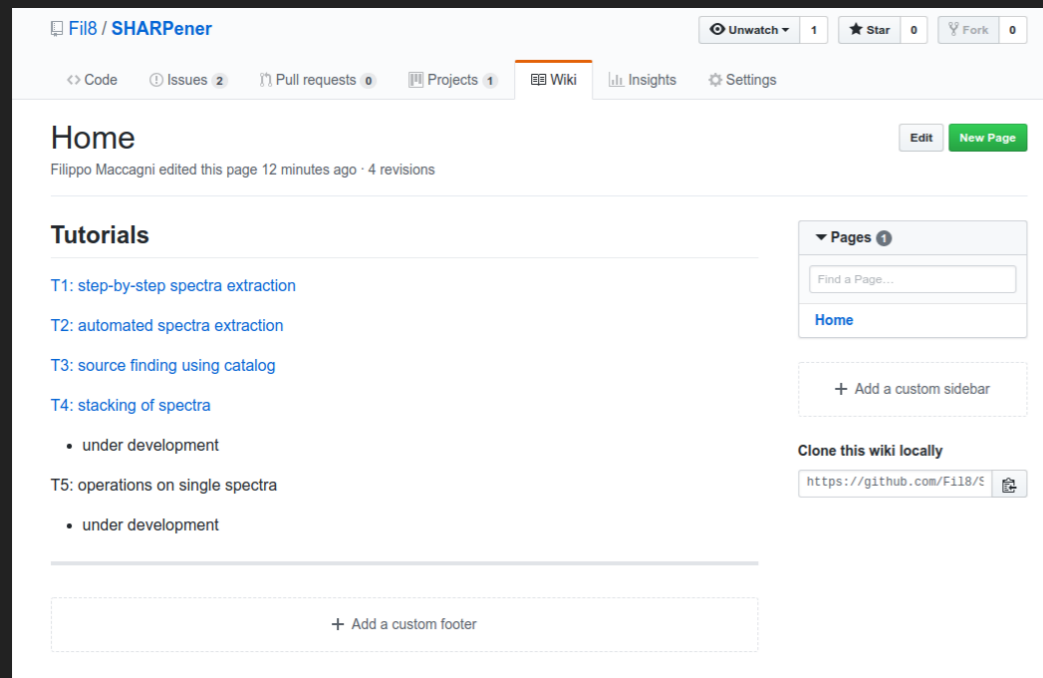
This is a set of tools that have been developed in preparation of the [SHARP survey](#).

The main function of `sharpener` is to identify the position of all continuum sources in a continuum image and extract a spectrum from each line of sight of these sources.

The spectra are then plotted.

`sharpener` can be run using a `.yml` parameter file (link to default) as `python sharpener.py <path_to_parameter_file.yml>`, or through a `IPython` notebook.

[\[https://github.com/Fil8/SHARPEner\]](https://github.com/Fil8/SHARPEner)



GitHub Wiki page for Fil8 / SHARPEner. The page is titled 'Home' and lists several tutorials (T1 to T5) under the 'Tutorials' section. The tutorials include step-by-step spectra extraction, automated spectra extraction, source finding using catalog, stacking of spectra, and operations on single spectra. The page also features a search bar, a 'Clone this wiki locally' button, and a footer area.

**Tutorials**

- T1: [step-by-step spectra extraction](#)
- T2: [automated spectra extraction](#)
- T3: [source finding using catalog](#)
- T4: [stacking of spectra](#)
  - under development
- T5: [operations on single spectra](#)
  - under development

- ▶ Part of Apercal, Apertif pipeline (Raffaella's talk)
- ▶ Easy to install, notebook tutorials for different available tools.

# SHARPENER Automated Pipeline

**SHARP/FLASH/MEERKAT observations**

*cube high spatial resolution*, e.g. output of *Apercal*



**Continuum source finder**

RA & DEC of all sources in the f.o.v. of the cube

Continuum image

Catalog (NVSS, SUMSS)



**Extraction of the spectra @ location continuum sources**



**Identify HI absorption detections:** *non-detections => upper limit to NHI*

FLASHfinder (Elaine, James talks)



**Intervening or associated?**  
**cross-correlation with spectral surveys**



**Characterising absorption**  
**(width, centre, asymmetry**  
**etc. using e.g. busy function)**

**Tools for spectral analysis**

- convert units (velocity, optical depth)
- hanning, convolution, continuum subtraction
- measure noise
- simulate background continuum sources

**stacking**

**comparison with**  
**modelling: MoD\_AbS**

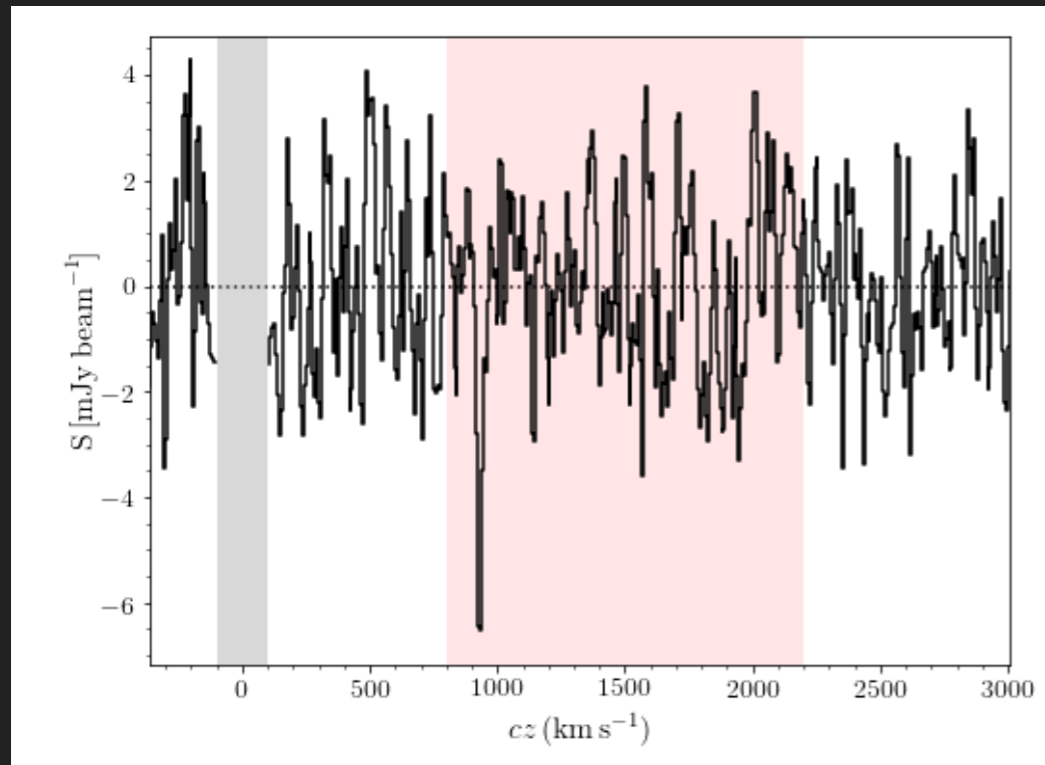
Cross-  
correlation  
with catalogs,  
e.g. LOFAR

Database  
(e.g. CHAD?  
Vanessa's talk)

other ideas?

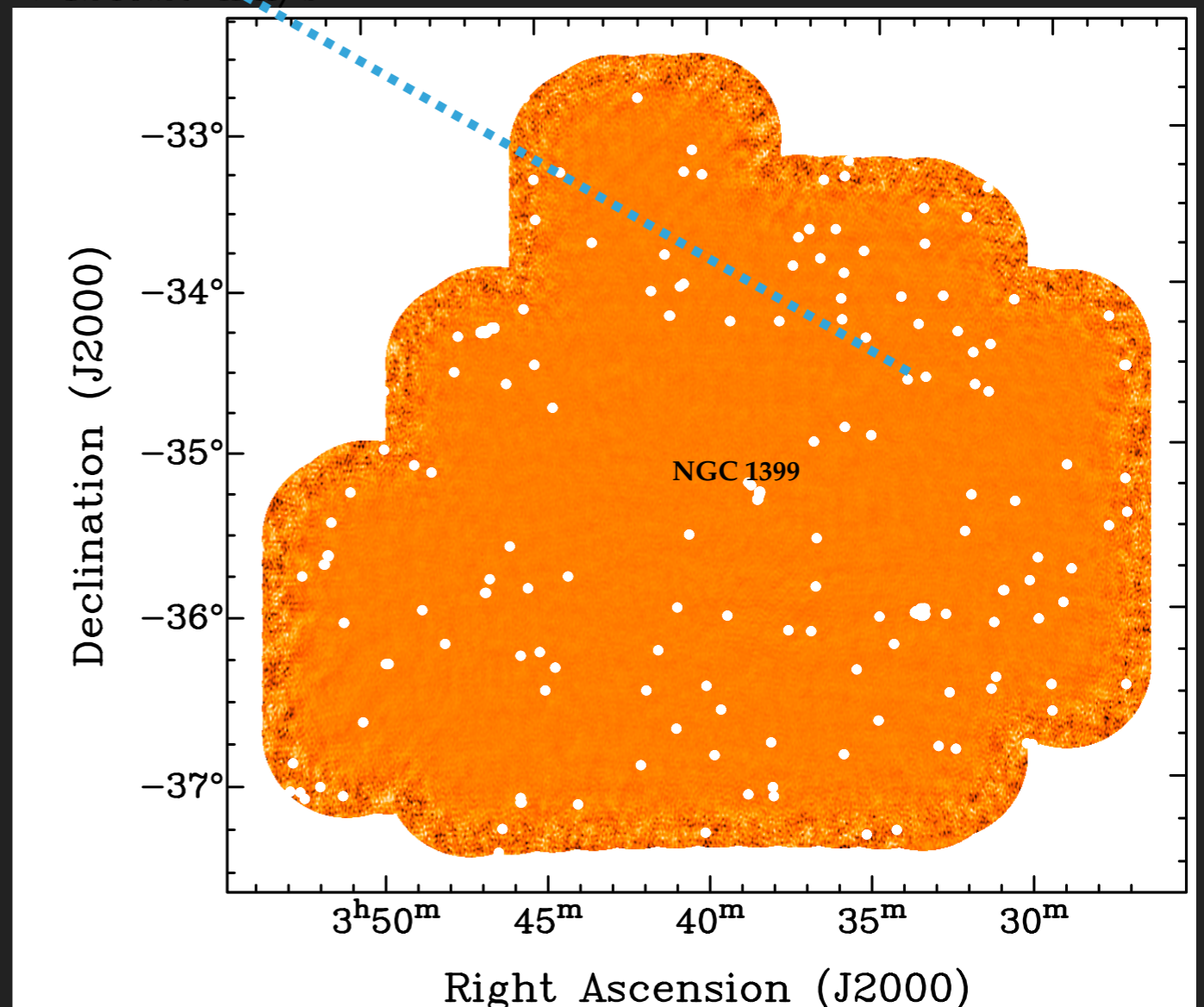


# HI Absorption in the Fornax Cluster

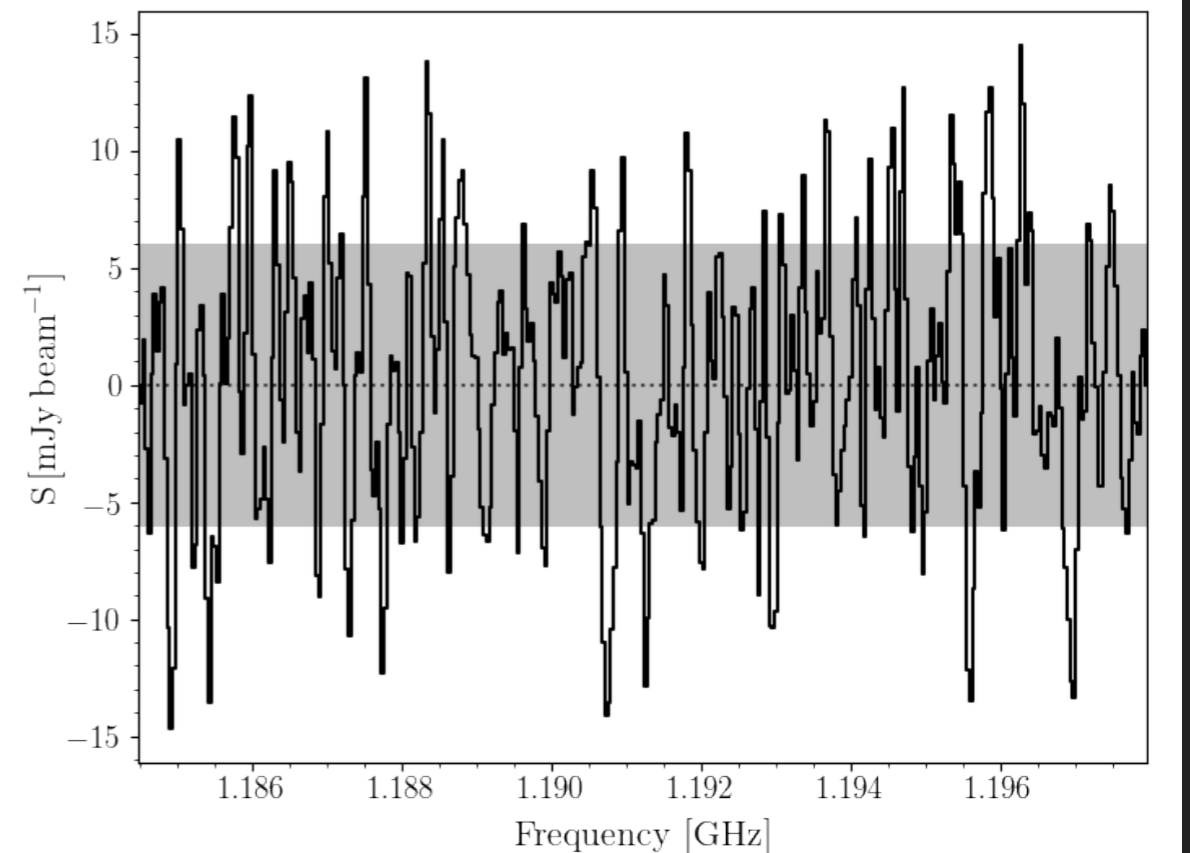
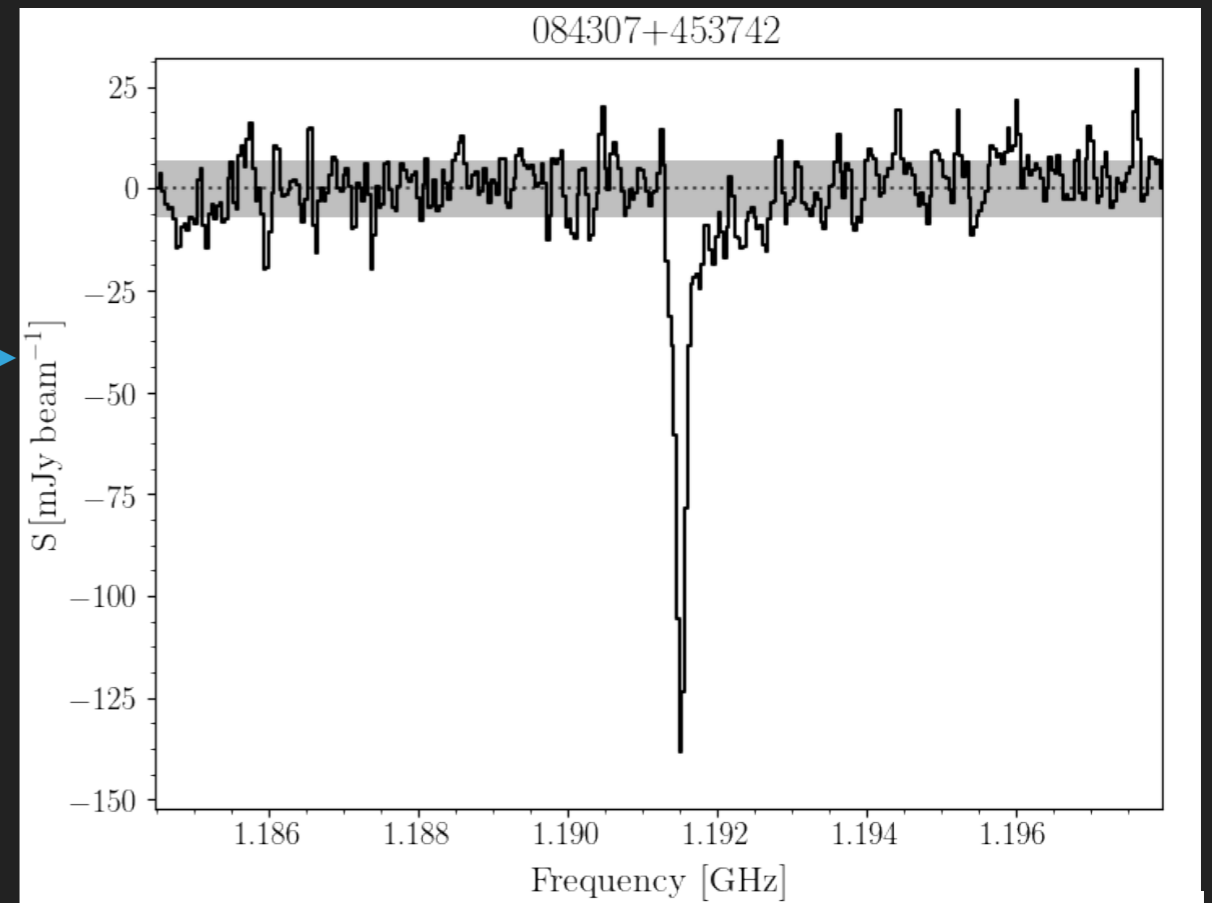
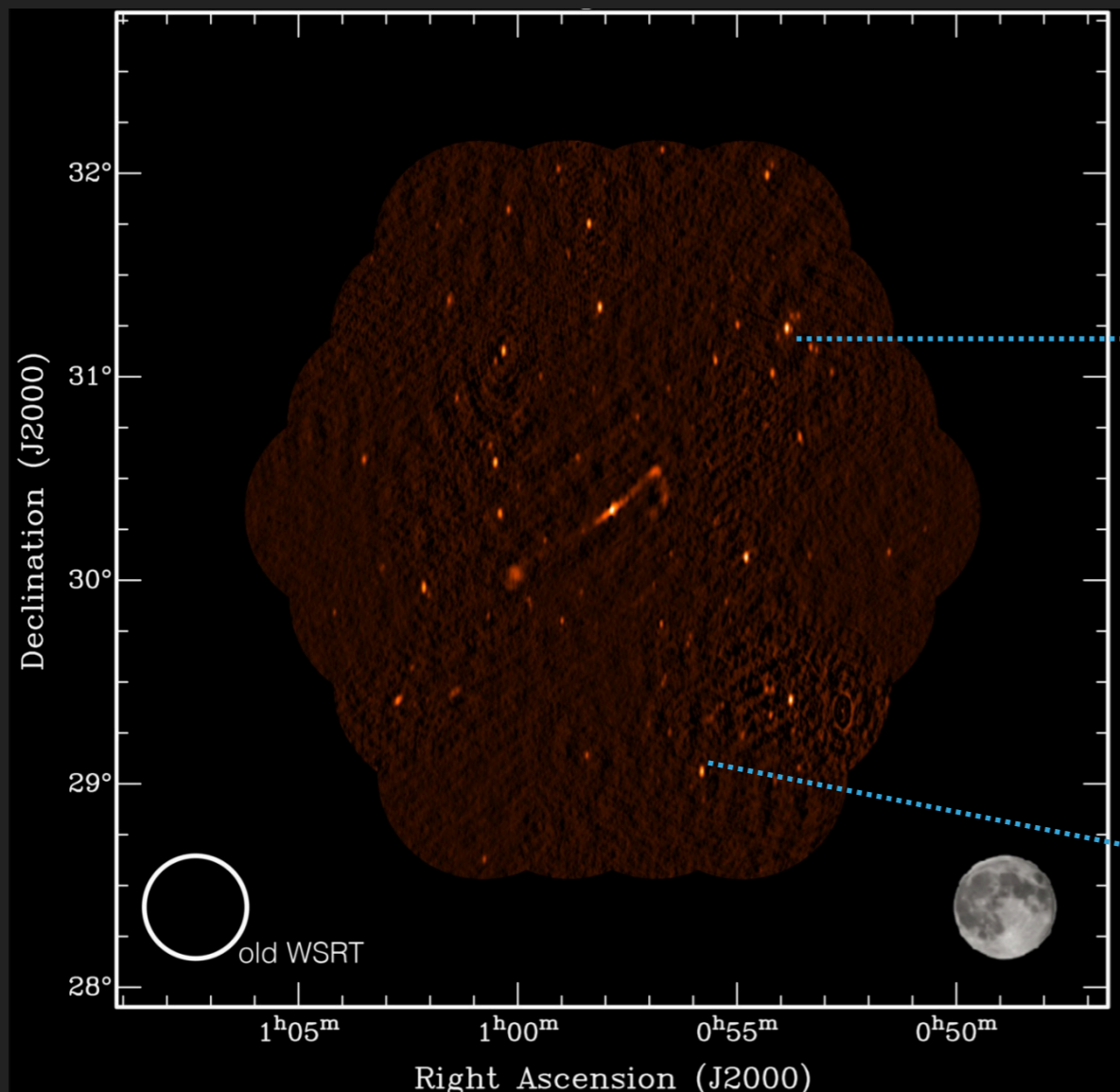


- ▶ Centre of Fornax Cluster observed with ATCA (by Paolo Serra)

- ▶ Operations on extracted spectra
  - ▶ Identify presence of a line
  - ▶ Estimate noise
  - ▶ Mark flagged regions
  - ▶ Mark regions of interests



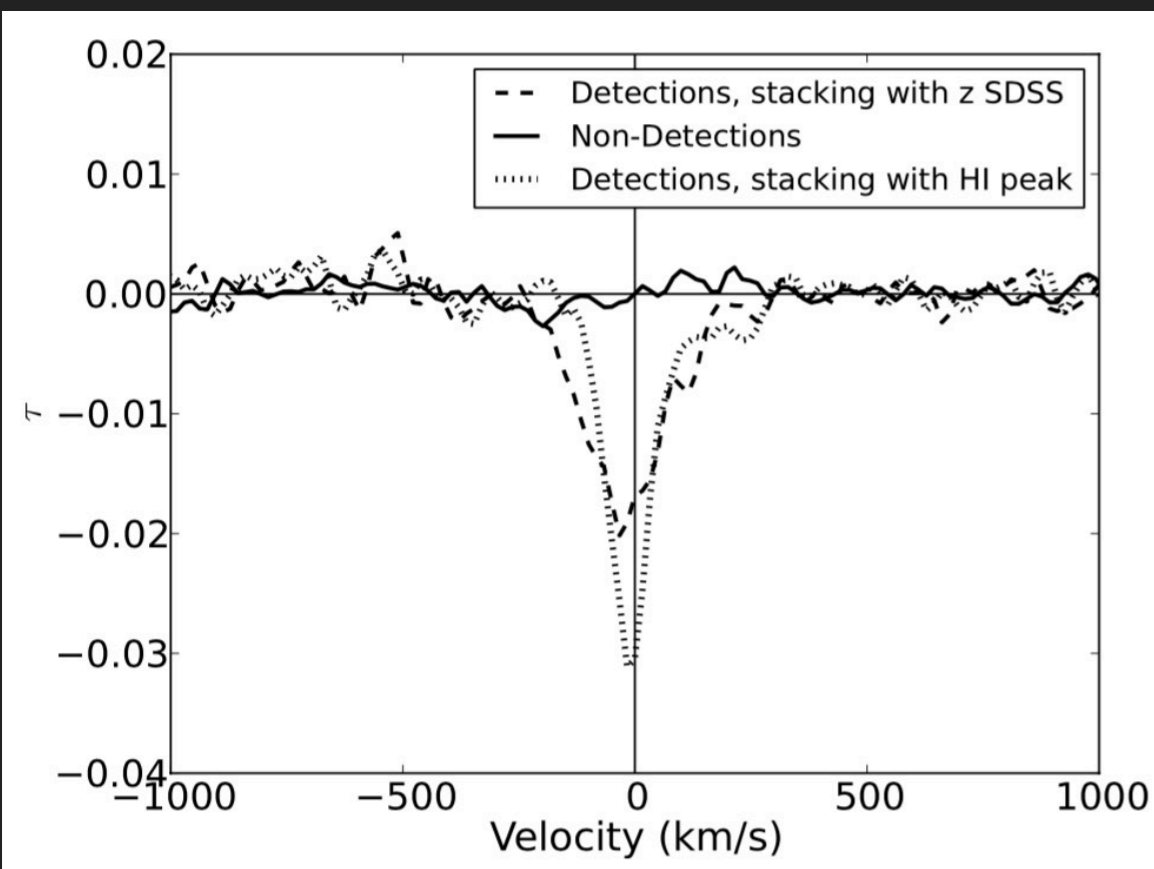
# SHARPENER: Test on ApertiF Fields



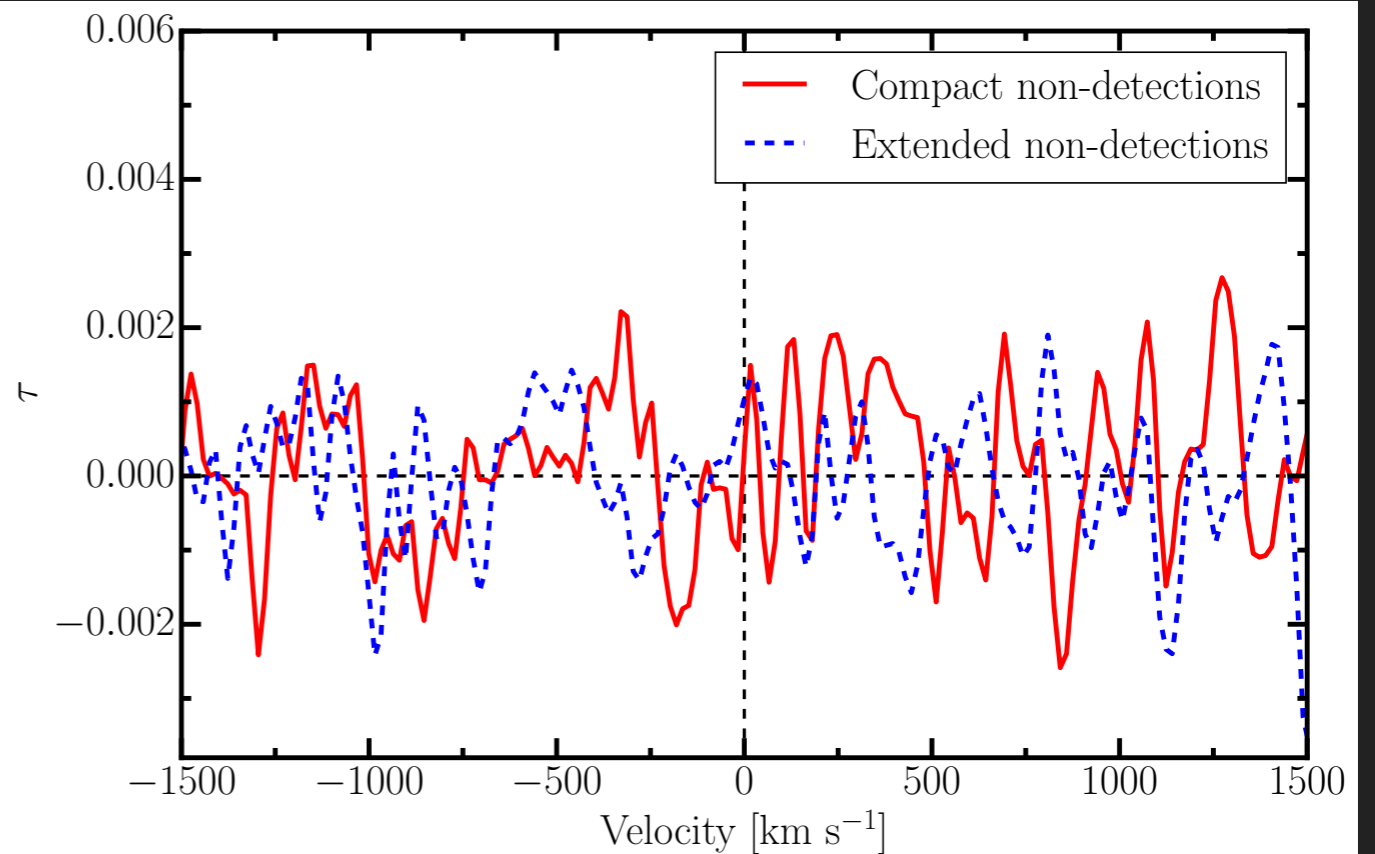
- ▶ **SHARPENER extracts spectra against each line of sight**
  - ▶ **HI absorption lines can be identified**
  - ▶ **Grey shaded region = average noise**

# SHARPENER Stacking Experiments

- ▶ ~70% of extracted spectra are non-detections
- ▶ SHARPENER collects from database the spectra of non-detections and performs **stacking experiments**
  - ▶ Selection of subsamples of sources
    - ▶ Non-detections: stacking according to optical redshift of different subgroups
  - ▶ Detections: stacking also according to peak of HI line
  - ▶ Automated check if the noise of the stacked spectrum decreases as  $1/\sqrt{N_{\text{sources}}}$



[Gereb et al. 2014]

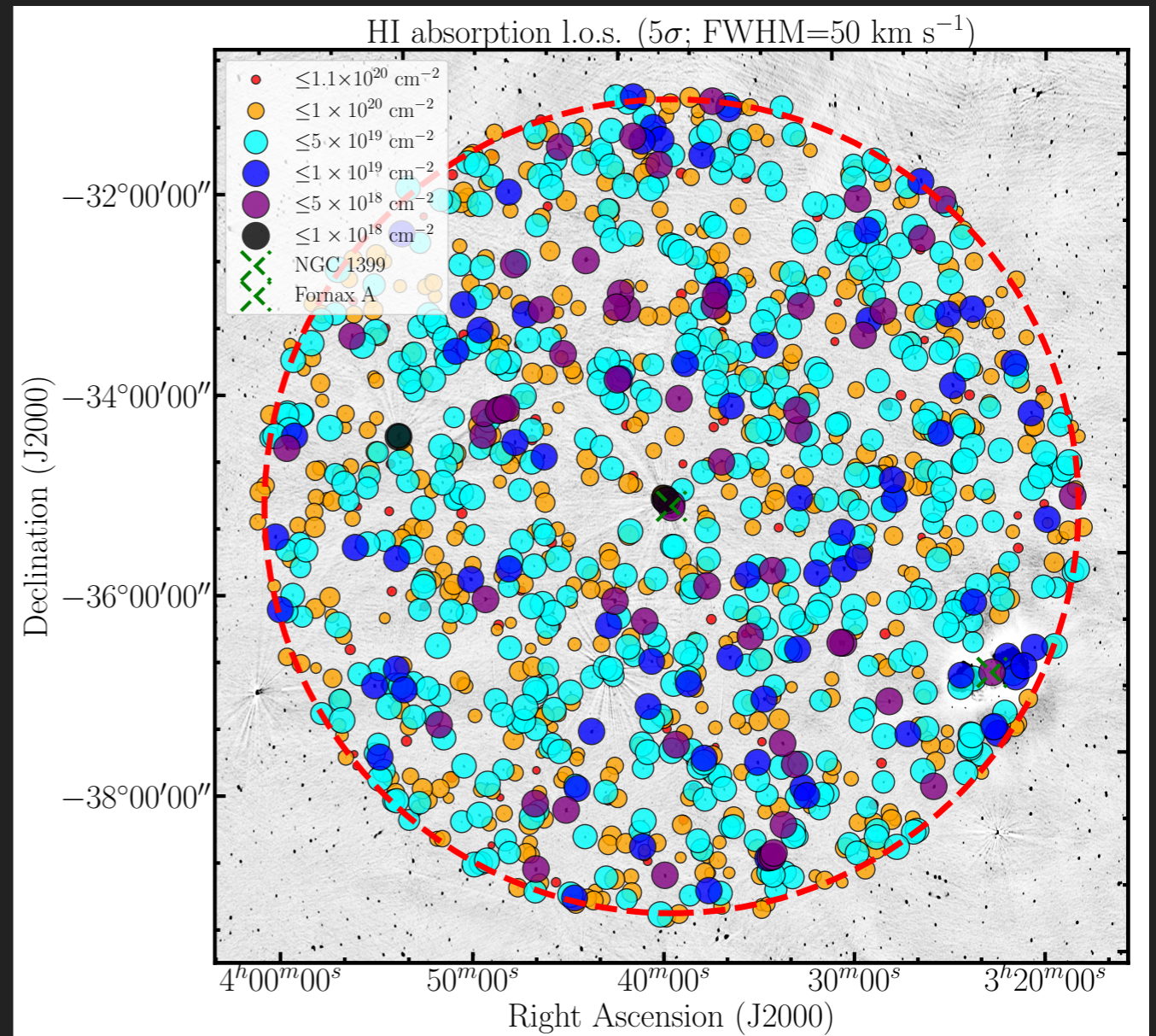


[Maccagni et al. 2017]

# SHARPener and Predictions

- ▶ MeerKAT Fornax Survey: also an f.o.v. for HI absorption studies
- ▶ Use SHARPener to predict the HI absorption detection limits within 4 deg<sup>2</sup> from NGC 1399 (centre of the cluster)
- ▶ NVSS catalog: ~1100 sources above 10 mJy
  - ▶ Given the sensitivity of MFS **we will detect HI absorption (5 sigma detection, FWHM 50 km/s) in ~30% of the following sources:**

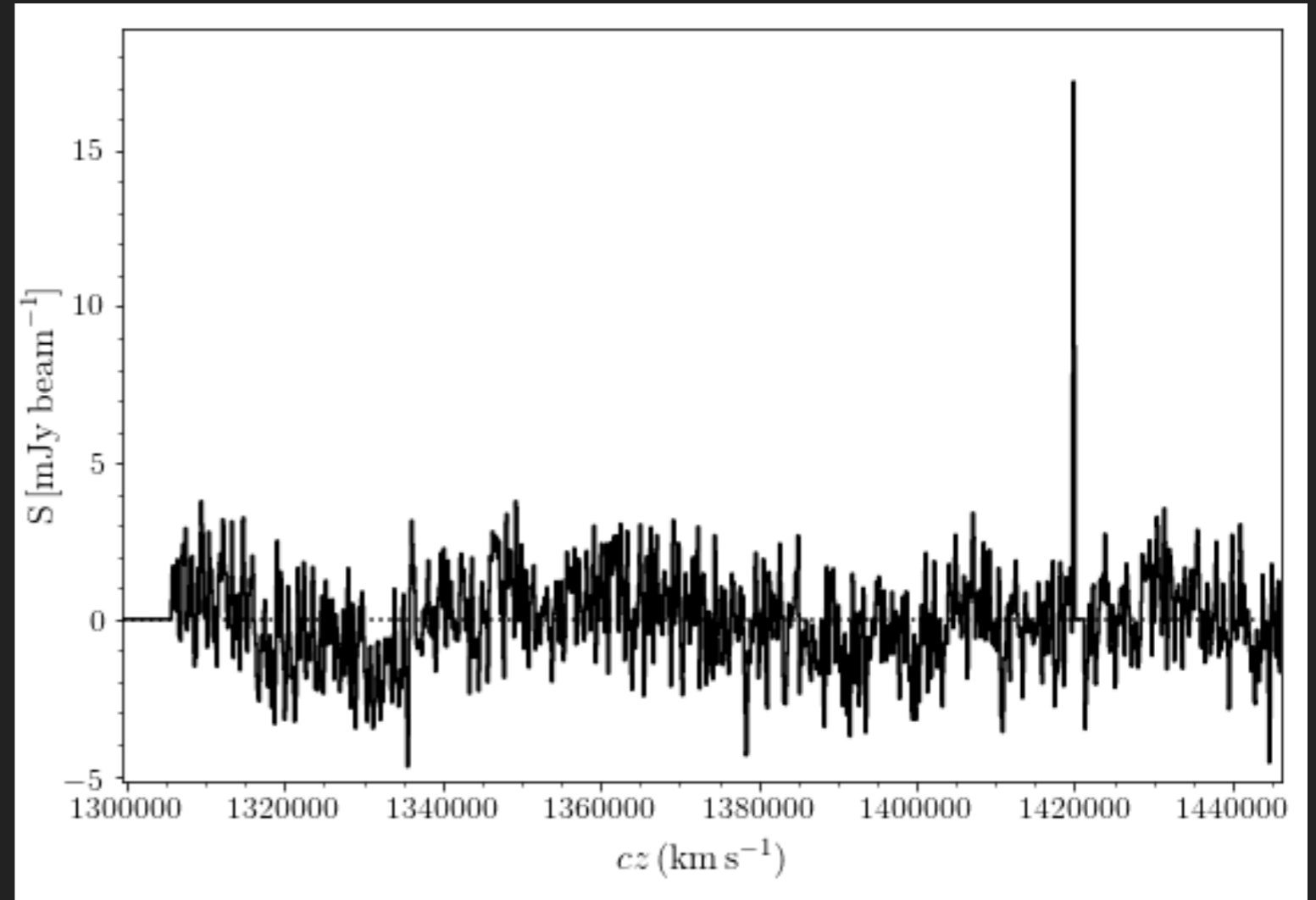
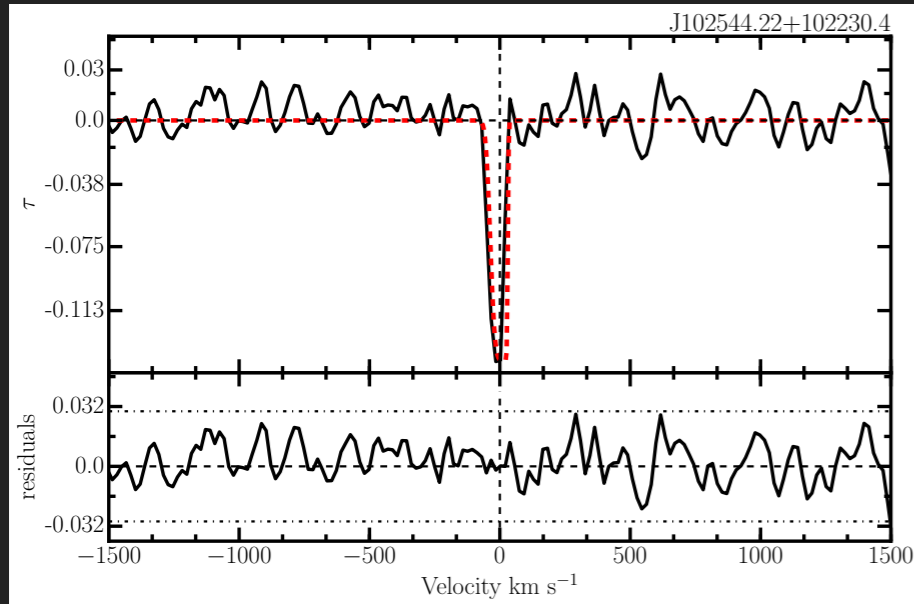
- ▶ ~500 l.o.s.
  - ▶  $N(\text{HI}) \sim 7 \times 10^{19} - 2 \times 10^{20} \text{ cm}^{-2}$
- ▶ ~300 l.o.s.
  - ▶  $N(\text{HI}) \sim 3-7 \times 10^{19} \text{ cm}^{-2}$
- ▶ ~150 l.o.s.
  - ▶  $N(\text{HI}) \sim 1.5-3 \times 10^{19} \text{ cm}^{-2}$
- ▶ ~100 l.o.s.
  - ▶  $N(\text{HI}) \sim 7 \times 10^{18} - 1 \times 10^{19} \text{ cm}^{-2}$
- ▶ ~40 l.o.s.
  - ▶  $N(\text{HI}) \sim 2.3- 7 \times 10^{18} \text{ cm}^{-2}$
- ▶ ~ 3 l.o.s.
  - ▶  $N(\text{HI}) \sim 5 \times 10^{17} - 2 \times 10^{18} \text{ cm}^{-2}$
- ▶ No distinction between intervening and associated HI
- ▶ MFS f.o.v. is smaller



# SHARPENER: Tool for Data Quality

Spectrum that we see after 1st reduction (new instrument, new pipeline)

Spectrum that we would like to see



- ▶ Fast extraction of all spectra in a field
- ▶ Error recognition by the blink of an eye
  - ▶ leftover RFI
  - ▶ errors in the spectra
  - ▶ bad continuum subtraction

# RFinder: RFI at Westerbork

- ▶ Tool to identify RFI affecting an observation and study its:
  - ▶ Frequency dependency
  - ▶ Baseline dependency
- ▶ Used to investigate the RFI present at Westerbork
- ▶ RFinder predicts:
  - ▶ Noise increase per frequency and baseline
  - ▶ Beam shape

GitHub repository page for Fil8 / RFinder. The page displays the repository name, navigation tabs (Code, Issues, Pull requests, Projects, Wiki, Insights, Settings), and a list of files including RFinder\_modules, tutorials, LICENSE.md, README.md, rfinder.py, and rfinder\_default.yml. The README.md file is selected, showing its content.

**RFinder**

This is a set of tools that have been developed in preparation of the [Apertif surveys](#).

The main function of `rfinder` is to identify the presence of RFI in an observation and visualize it according to different parameters.

These are the available functions:

- visualize the presence of RFI per frequency channel and baseline length.
- visualize the percentage flagged visibilities due to RFI per frequency channel.

[\[https://github.com/Fil8/RFinder\]](https://github.com/Fil8/RFinder)

GitHub Wiki page for Fil8 / RFinder. The page shows the 'Home' section with a 'Parameter file' section and 'Tutorials' section. The 'Parameter file' section contains a detailed description of the parameter file used by `rfinder` and its keywords. The 'Tutorials' section lists two tutorials: T1: step-by-step RFI investigation and T2: automated spectra extraction.

**Parameter file**

A detailed description of the parameter file used by `rfinder` and its keywords can be found [here](#).

**Tutorials**

T1: step-by-step RFI investigation

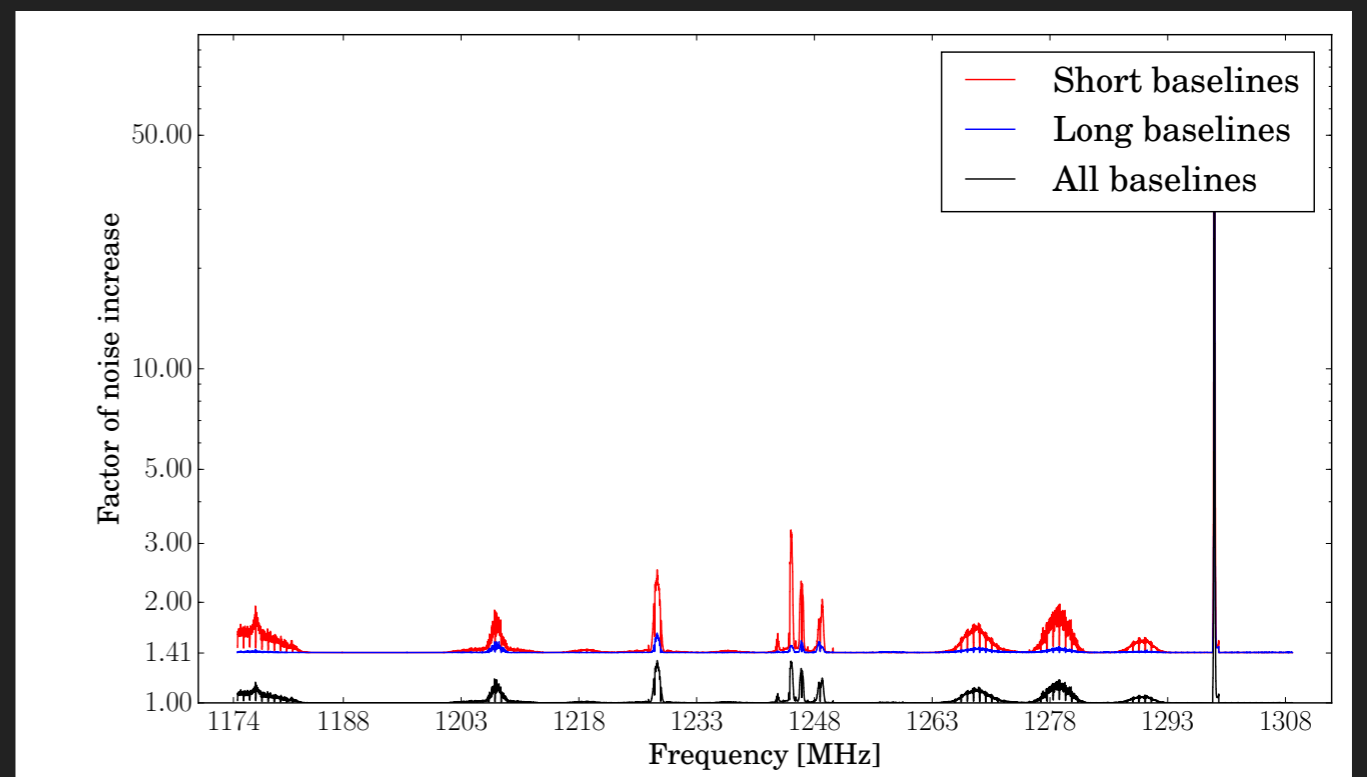
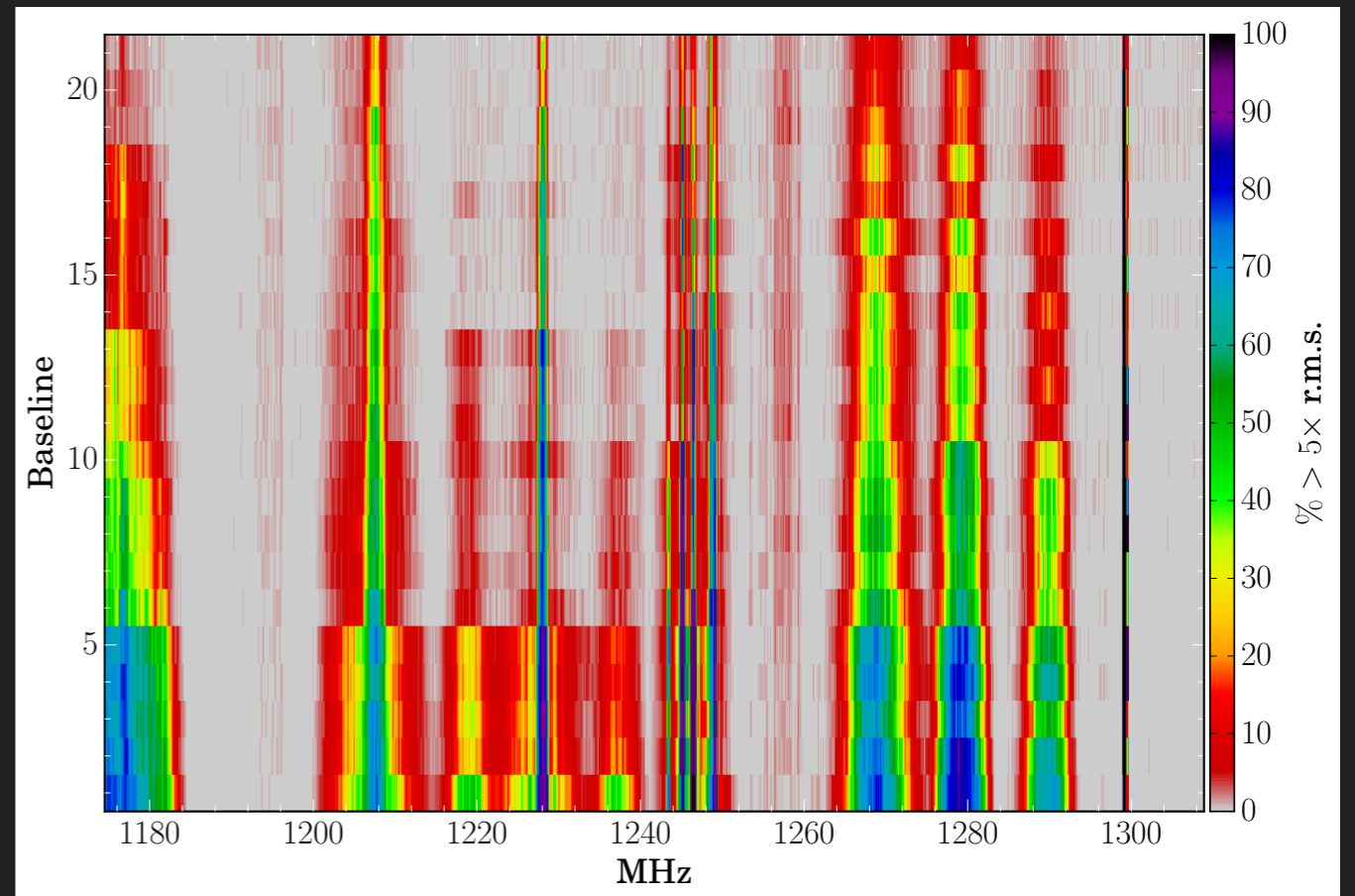
T2: automated spectra extraction

- ▶ Works similarly to SHARPener
  - ▶ Parameter file
  - ▶ Works as a pipeline or with notebook
  - ▶ Tutorials illustrate the different tools



# RFInder: RFI at Westerbork

- ▶ RFInder is used to investigate how RFI will affect Apertif surveys
- ▶ Applications for HI absorption
  - ▶ Long baselines are less affected by RFI
    - ▶ Identify noise increase selecting only short baselines
  - ▶ RFInder indicates the spectral regions where HI line finders must be cautious



# MoD\_AbS: interpreting HI absorption

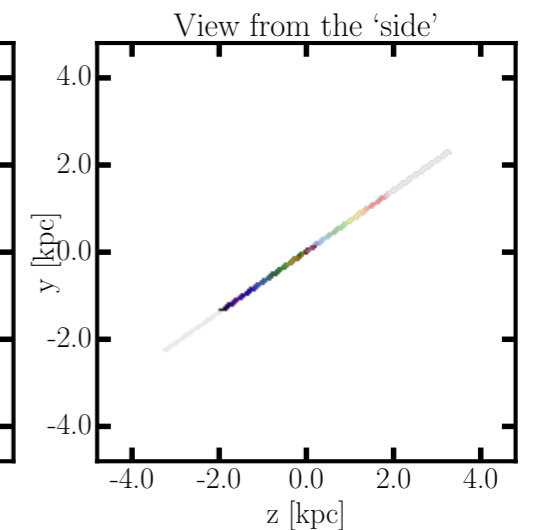
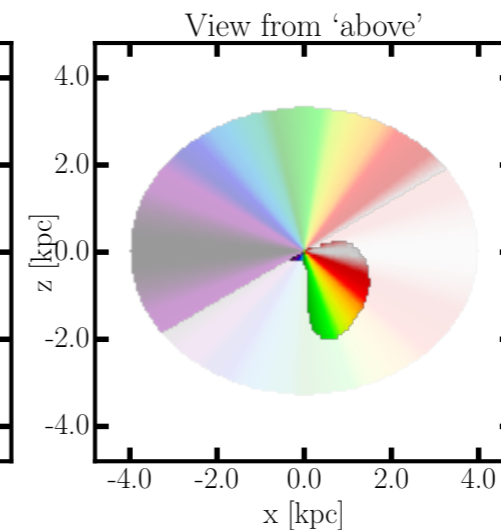
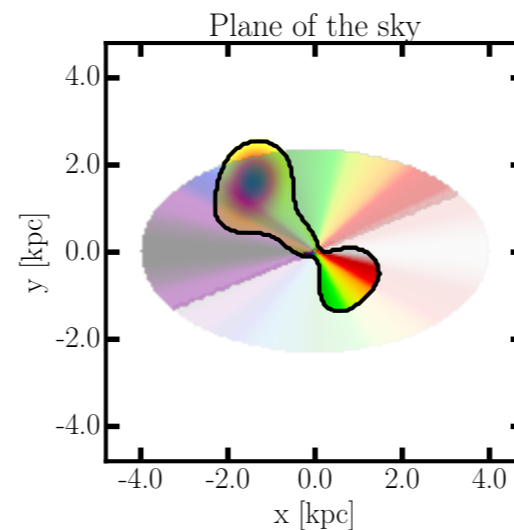
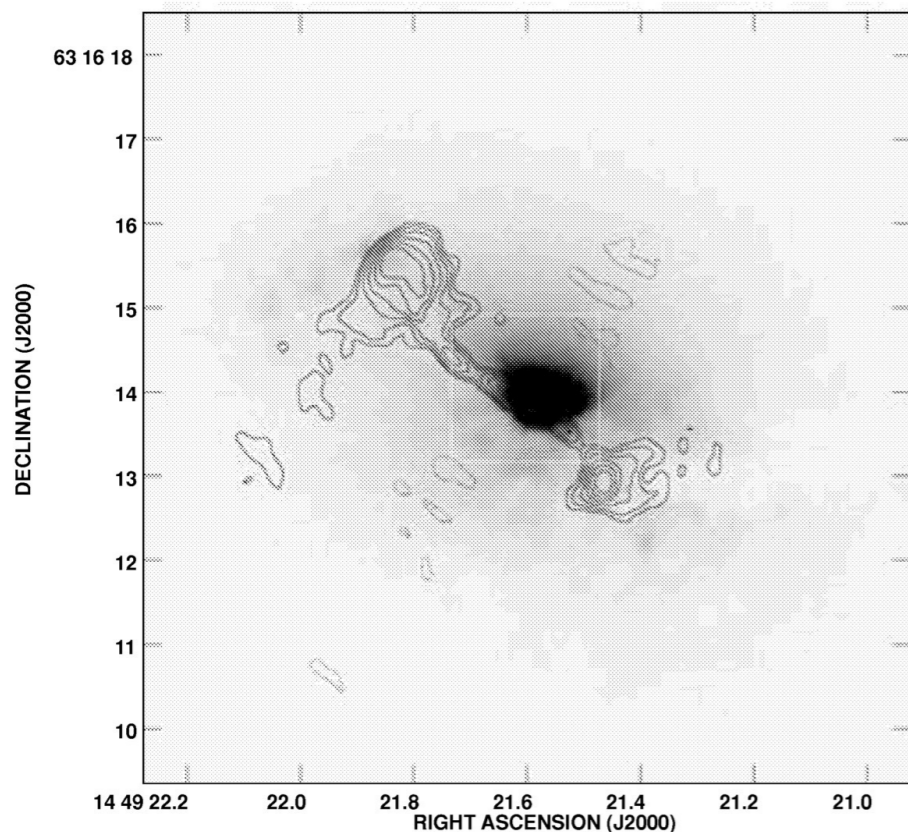
- ▶ What is the overall distribution of the HI traced by the absorption line?
  - ▶ Narrow lines at the systemic velocity usually identify a rotating disk
  - ▶ Can we understand distribution and kinematics of the gas from only the integrated line and the continuum image?
  - ▶ Developed kinematical model, MoD\_AbS
    - ▶ Model the rotating HI disk in front of the radio continuum

3C 305

Observation



Model



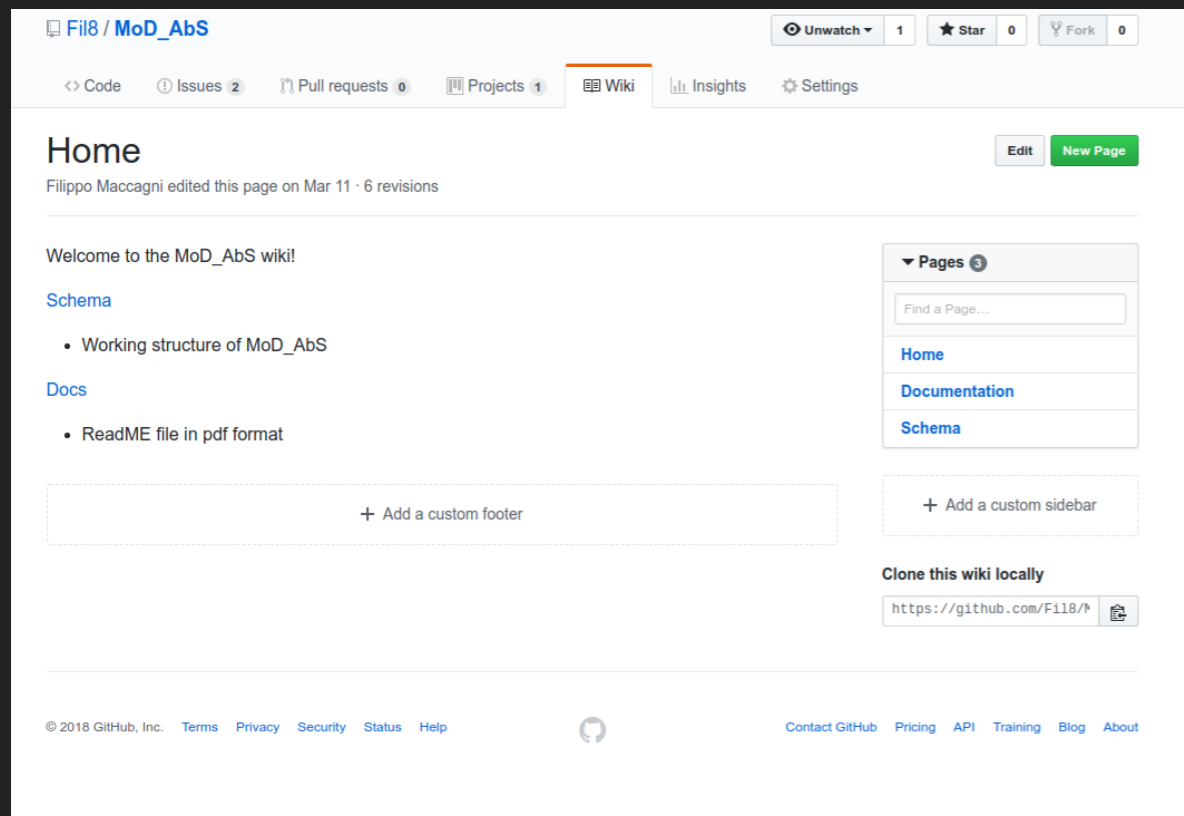
Plane of the sky : x,y

Side view: z,y

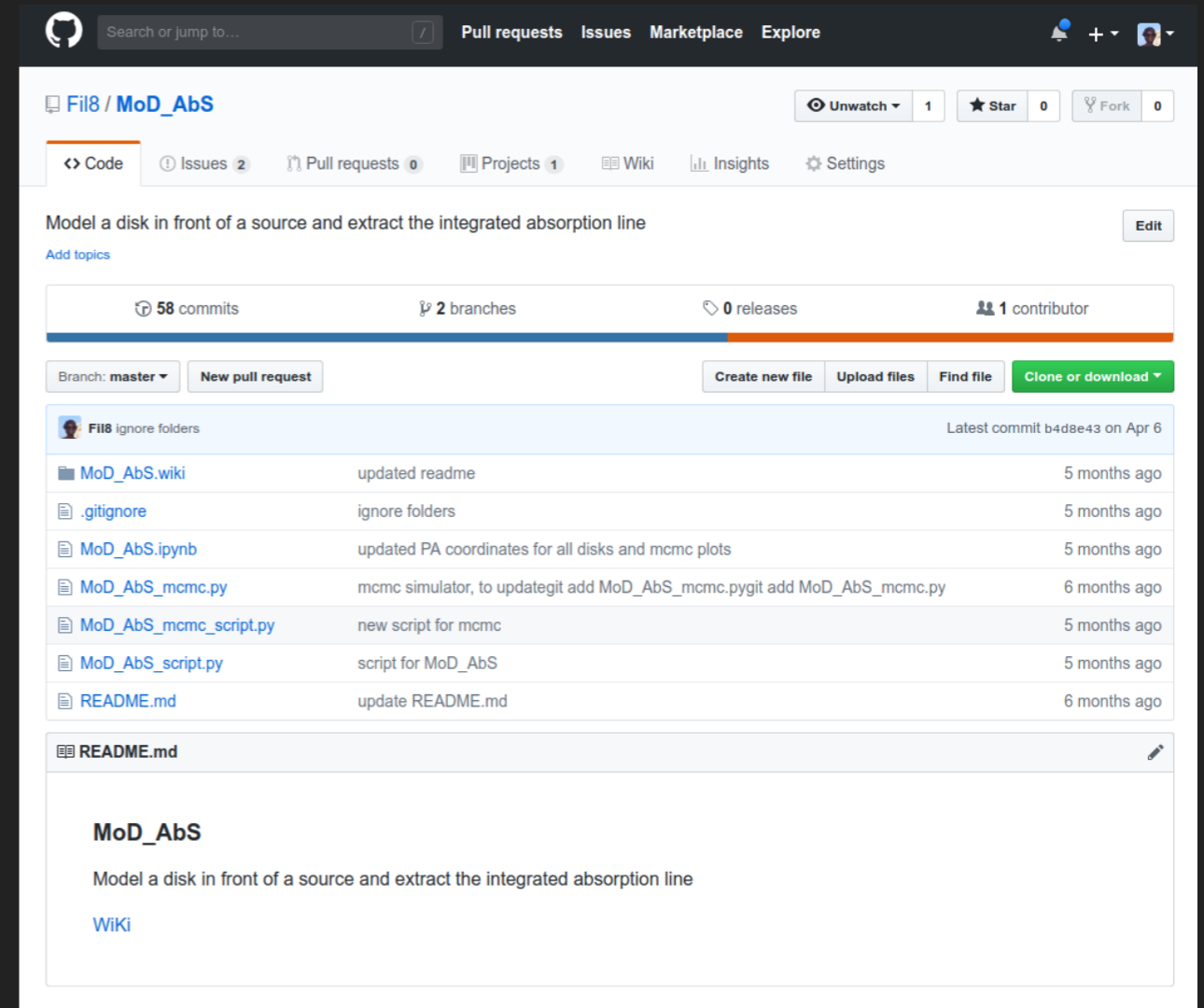
From above: x,z

# MoD\_Abs: Introduction

- ▶ Main features of HI disk specified in parameter file
  - ▶  $R_{\max}$ ,  $R_{\min}$ ,  $i$ , PA
  - ▶  $V_{\text{rot}}$ : flat or rising rotation curve



The screenshot shows the GitHub Wiki page for the MoD\_Abs repository. The page title is "Home" and it was last edited by Filippo Maccagni on March 11. The content includes a welcome message, a "Schema" section with a link to "Working structure of MoD\_Abs", and a "Docs" section with a link to "ReadME file in pdf format". There are also options to "Add a custom footer" and "Add a custom sidebar", and a "Clone this wiki locally" button with the URL <https://github.com/Fil8/>.



The screenshot shows the GitHub repository page for Fil8 / MoD\_Abs. The repository has 58 commits, 2 branches, 0 releases, and 1 contributor. The README.md file is selected, showing the following content:

```
MoD_Abs

Model a disk in front of a source and extract the integrated absorption line

Wiki
```

[\[https://github.com/Fil8/MoD\\_Abs\]](https://github.com/Fil8/MoD_Abs)

- ▶ 2 User Friendly modes
  - ▶ Model complex distribution of HI
  - ▶ MCMC simulation to identify the spectrum that best reproduces an observed line

# MoD\_AbS: a disk around the radio source

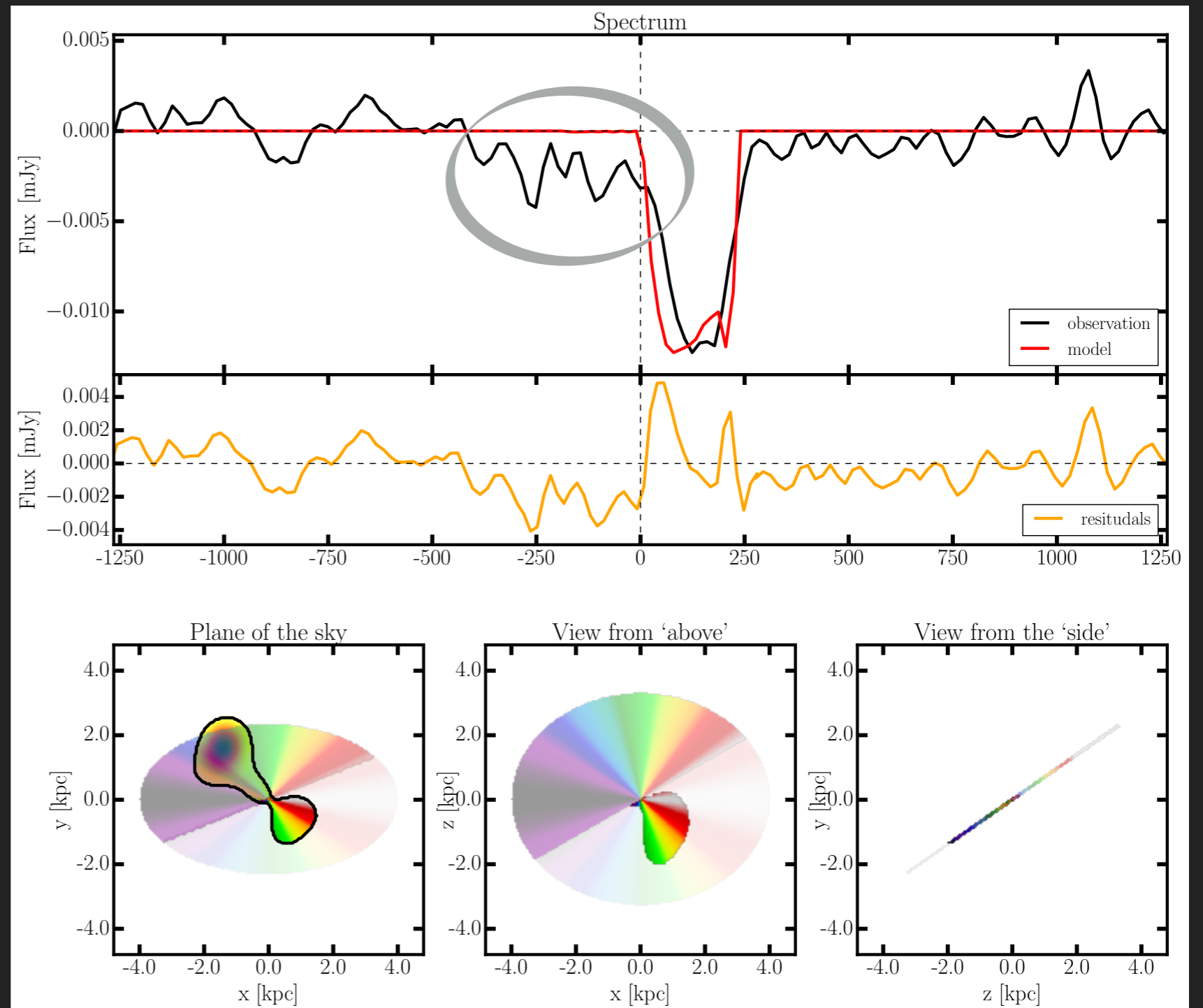
- ▶ Fix parameters of the disk from available information on the galaxy:

- ▶ Optical Image:  $i$ , PA
- ▶ Continuum image
- ▶ Tully Fisher  $\rightarrow V_{\text{flat}}$

- ▶ MoD\_AbS: finds the disk that best fits the line(\*)

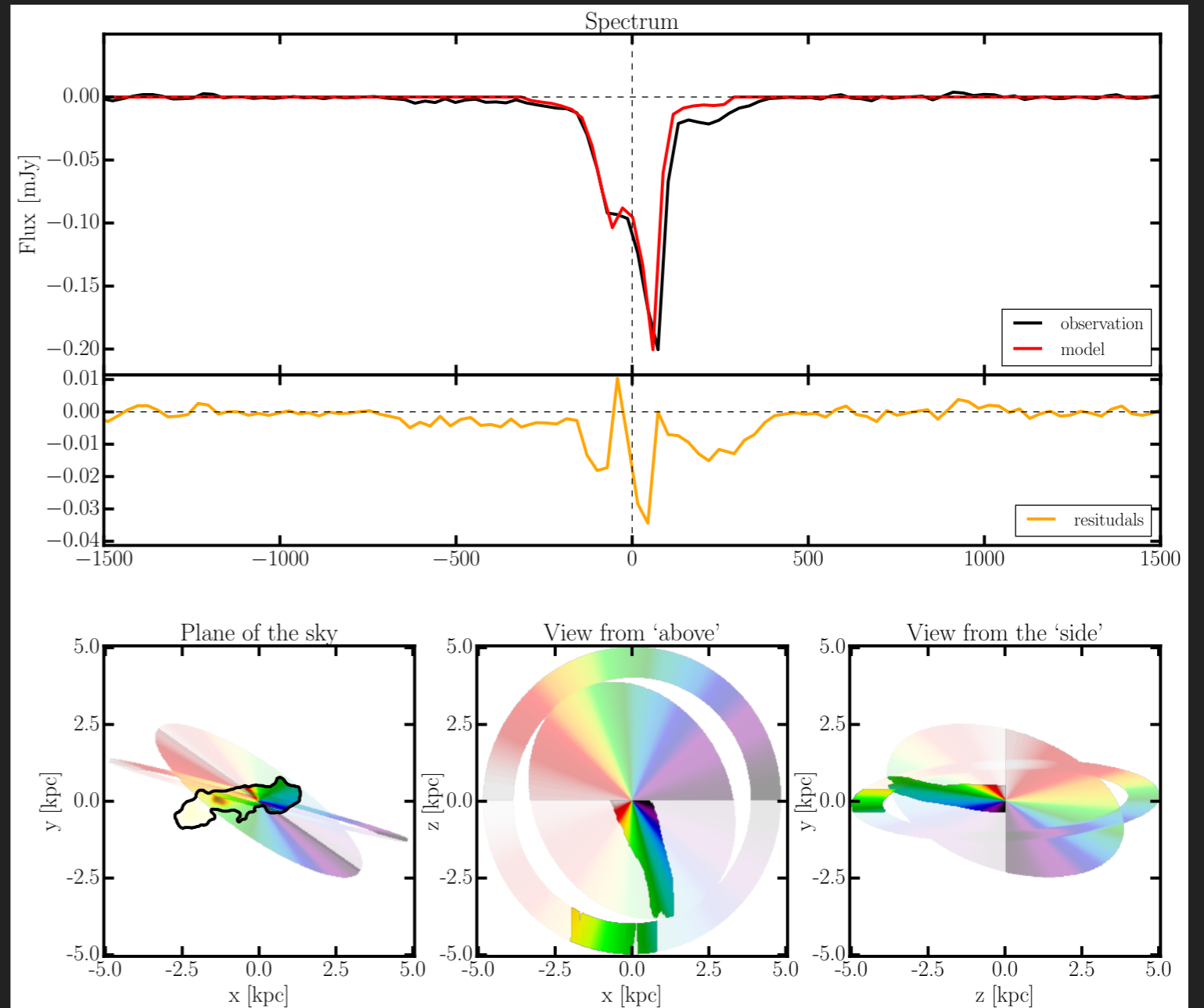
- ▶ 3C305:

- ▶ Bulk of absorption is well reproduced by a rotating disk
- ▶ Blue-shifted wing not reproduced by the model



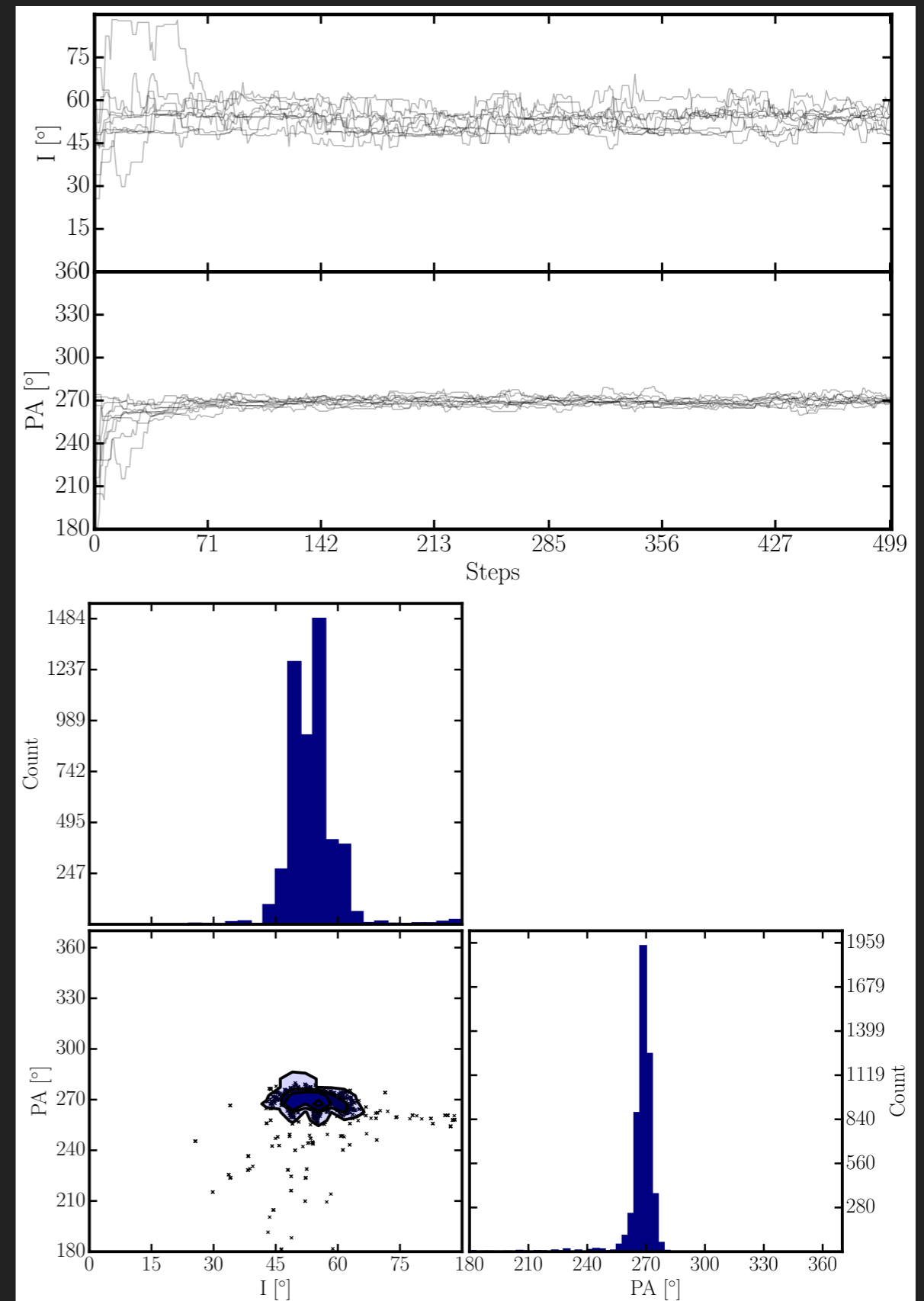
# MoD\_AbS: complex distributions

- ▶ MoD\_AbS can also model a double disk.
  - ▶ 3C293: a double disk best fit the absorption line.
    - ▶ Good to identify what is an outflow (blueshifted wing) and what probably is not (redshifted bump)
  - ▶ Future upgrades:
    - ▶ Model a clumpy distribution of HI



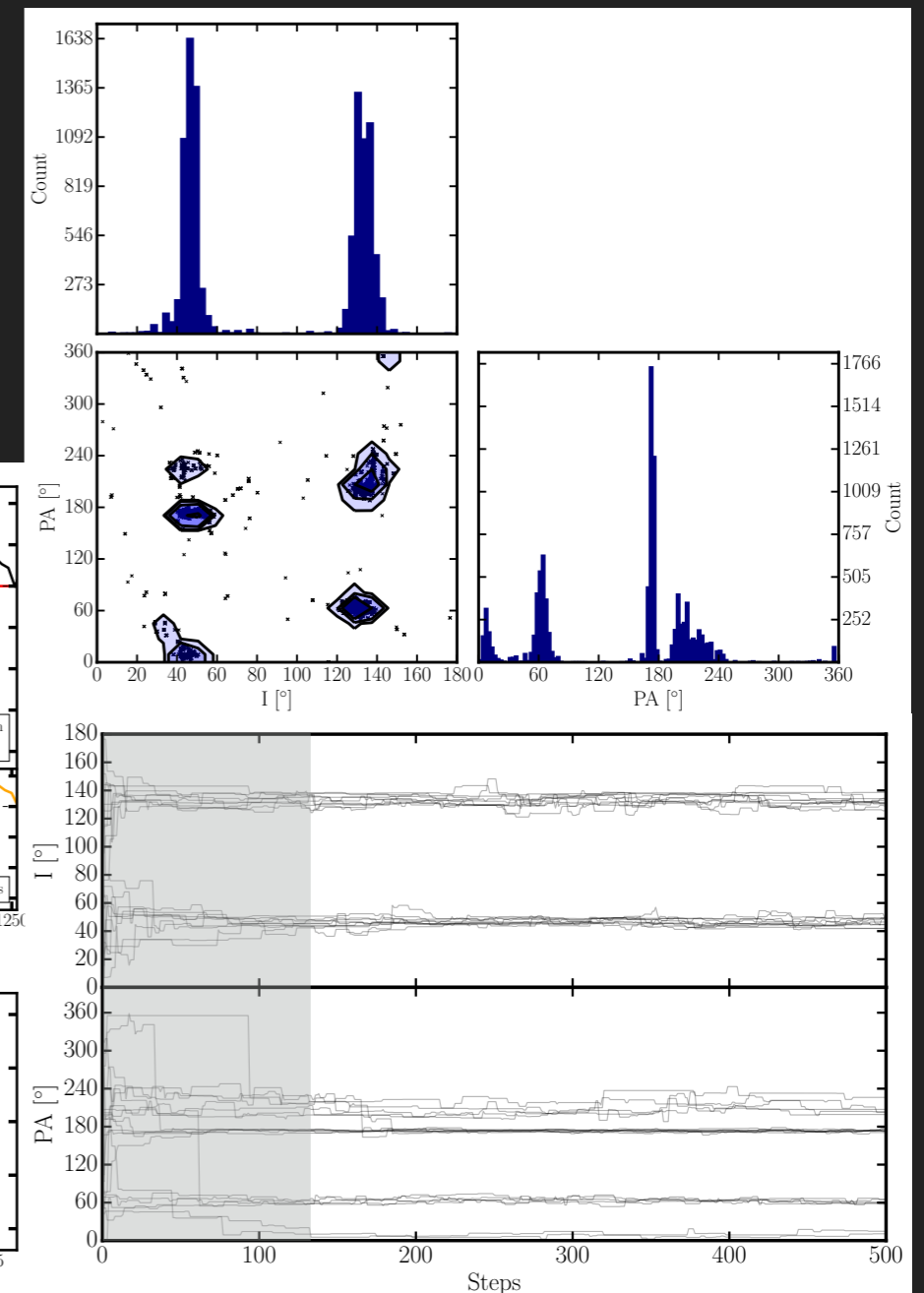
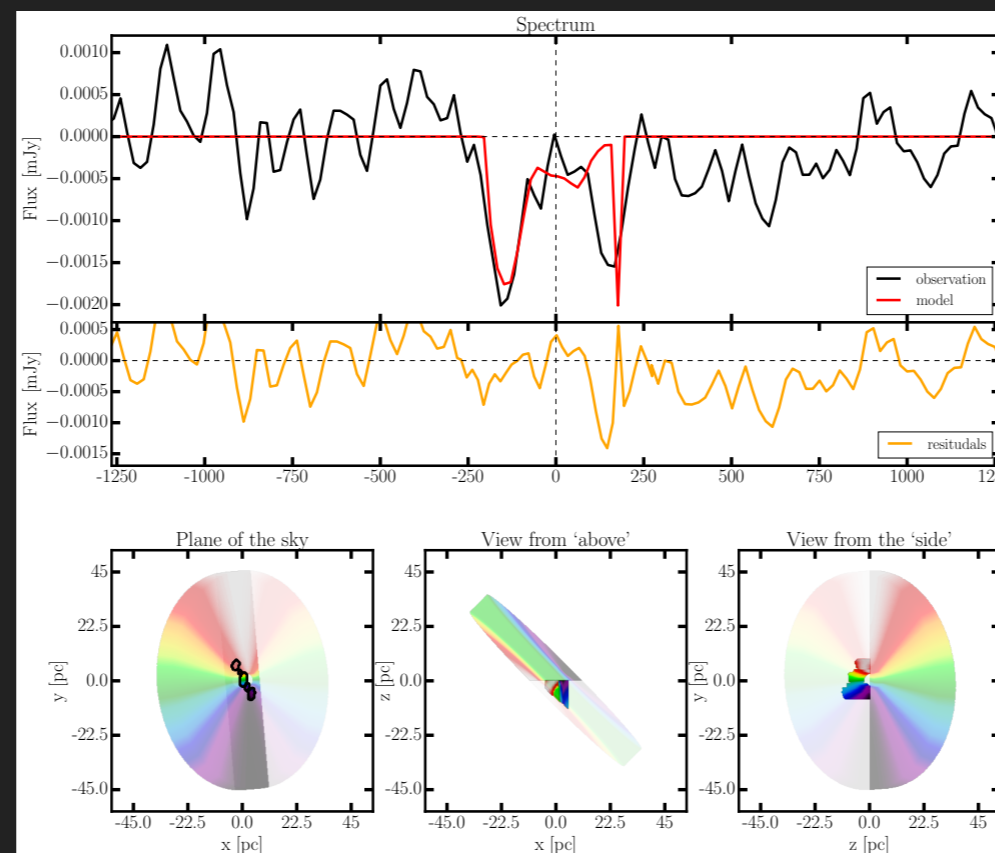
# MoD\_AbS: finding the disk of best fit

- ▶ MCMC simulation
- ▶ investigate parameter space of I & PA
  - ▶ automated algorithm
  - ▶ associate probability distribution function to investigated params
    - ▶ Minimum = params of best fit



# MoD\_AbS: HI disks of compact sources

- ▶ Generate absorption lines for which we have less information
  - ▶ 6 CORALz radio sources detected in HI absorption [Chapter 1]
    - ▶ Compact sources radio  $< 500$  pc
    - ▶ Available continuum image, SDSS optical image
- ▶ MoD\_AbS identifies the combination of  $i$  & PA best reproducing the observed lines
- ▶ Compact sources: likely the HI is in front of all the continuum
  - ▶ inclination of disk determines width of the line



# Summary & Open Issues

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- ▶ Software can always be improved.
- ▶ Open source and GitHub: you can upload your issues/requests. You can also contribute to its development.
- ▶ **SHARPenner** [<https://github.com/Fil8/SHARPenner>]
  - ▶ Automatic extraction of spectra against all radio sources in a field
  - ▶ Useful for both spectral analysis and data quality assessments.
    - ▶ **Connection with line finder, database and other tools (e.g. RFInDer, MoD\_AbS)**
- ▶ **RFInDer** [<https://github.com/Fil8/RFInDer>]
  - ▶ Automatic identification of RFI in a measurement set
    - ▶ Visualization of RFI per frequency, baseline length, time
    - ▶ Estimate of PSF variation due to RFI flagging
    - ▶ **Complete the investigation of RFI at Westerbork - How does this a priori knowledge helps us improve RFI flagging**
- ▶ **MoD\_AbS** [[https://github.com/Fil8/MoD\\_AbS](https://github.com/Fil8/MoD_AbS)]
  - ▶ Automatic identification of RFI in a measurement set
    - ▶ Visualisation of RFI per frequency, baseline length, time
    - ▶ Estimate of PSF variation due to RFI flagging
  - ▶ **Clumpy HI distribution - Study the distribution of line widths for different radio continuum sources.**