Osservatorio
Astronomico
di Cagliari

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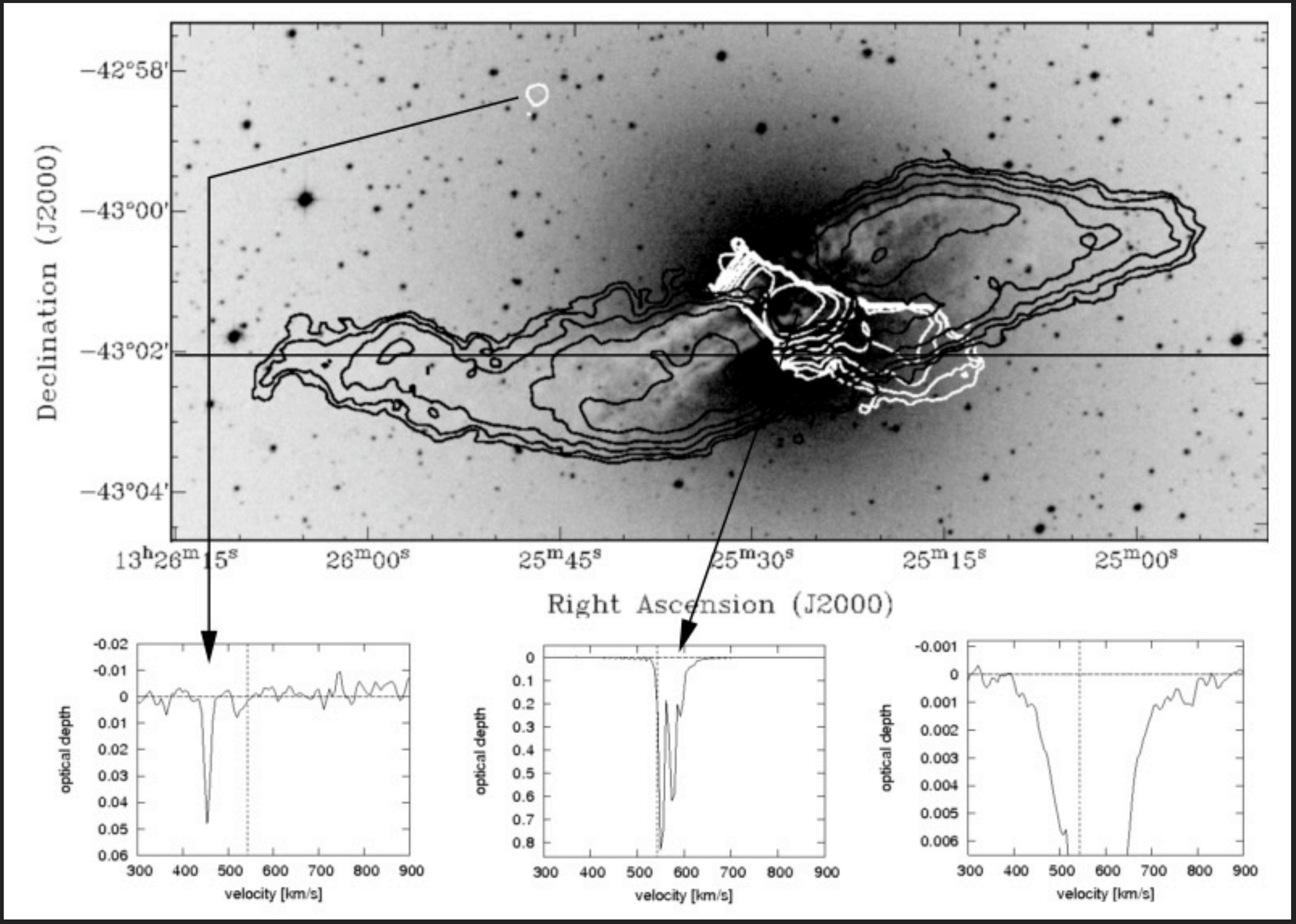
SOFTWARE TOOLS FOR HI ABSORPTION SURVEYS

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^{3D} · 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, H2, etc) show similar kinematics



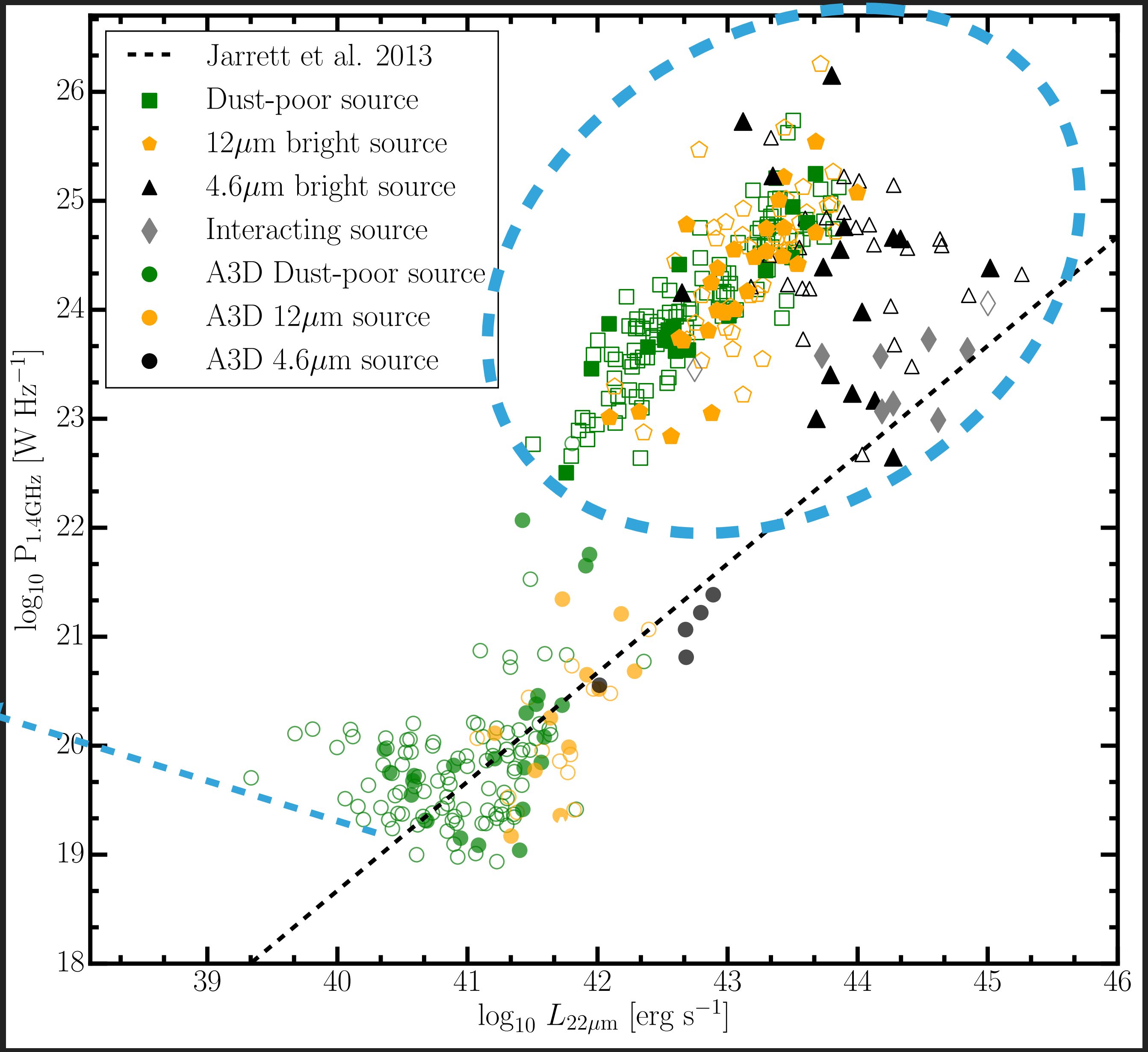
[Centaurus A: Struve et al. 2010]

WHISA: Westerbork HI Survey in Absorption

248 radio-galaxies

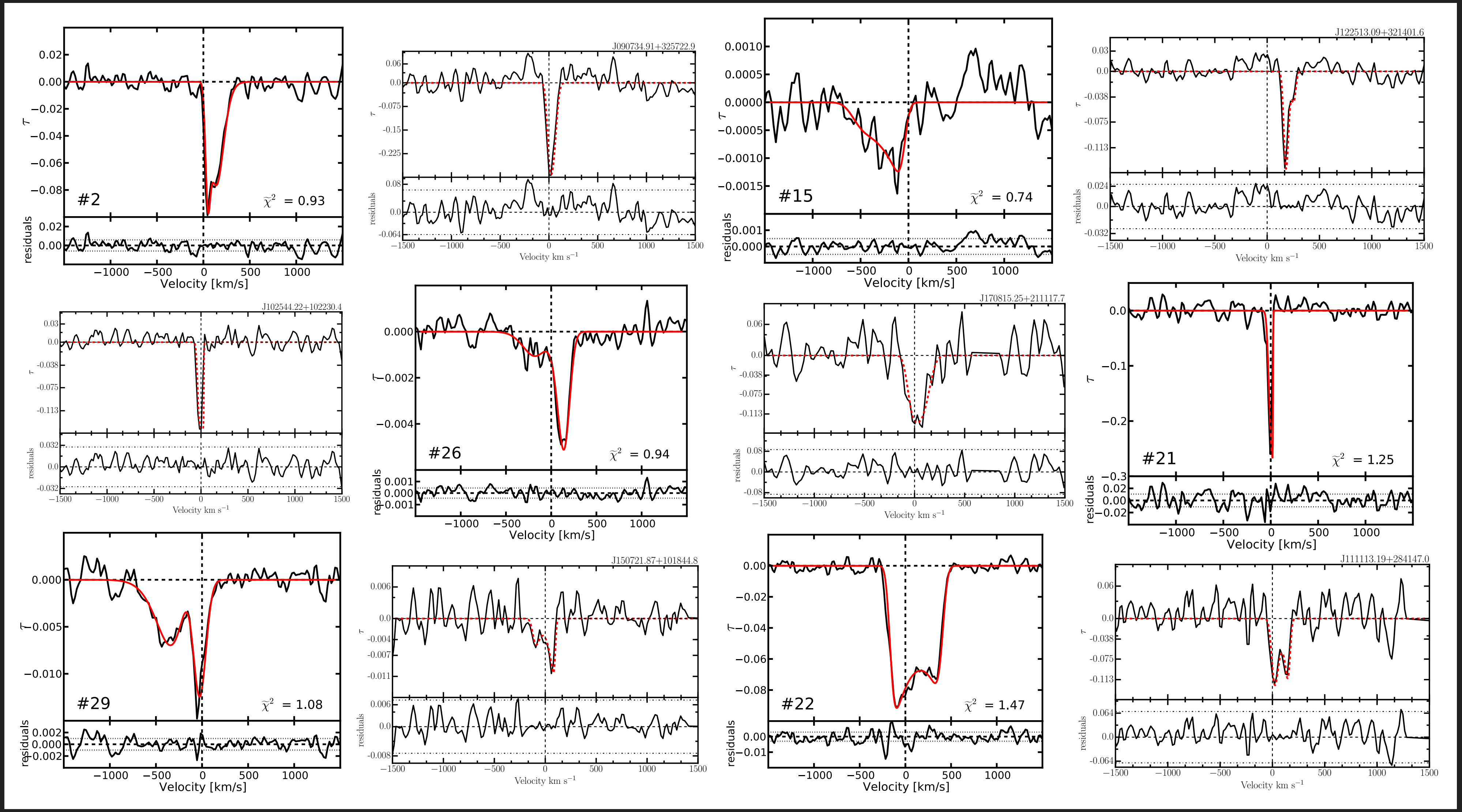
- 0.02 < z < 0.25
- SDSS spectroscopy
- $S_{Cont} \geq 30$ mJy
- Wide range of Radio Powers
- mostly AGN in early-type galaxies

Mid-InfraRed [22 μm] - Radio Power Relation

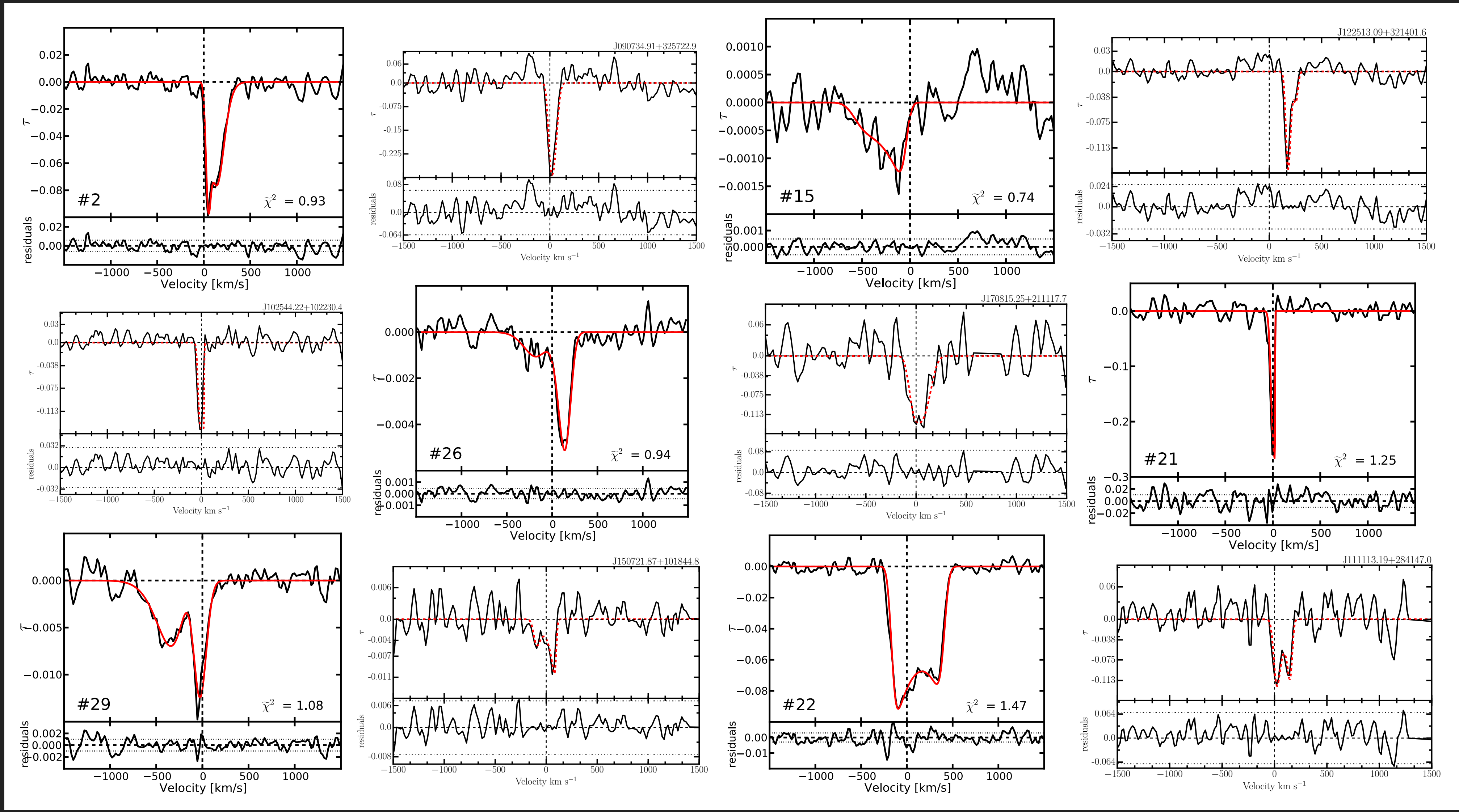


- 101 sources; $S_{Cont} \geq 50$ mJy
  - Stacking experiment [Geréb et al., 2014]
  - Analysis of the detections [Geréb , Maccagni, et al., 2015]
- All 248 sources
  - Analysis of the full sample [Maccagni et al., 2017]
  - Stacking analysis of the ATLAS^{3D} sample

WHISA: the Westerbork Survey



WHISA: Main Results



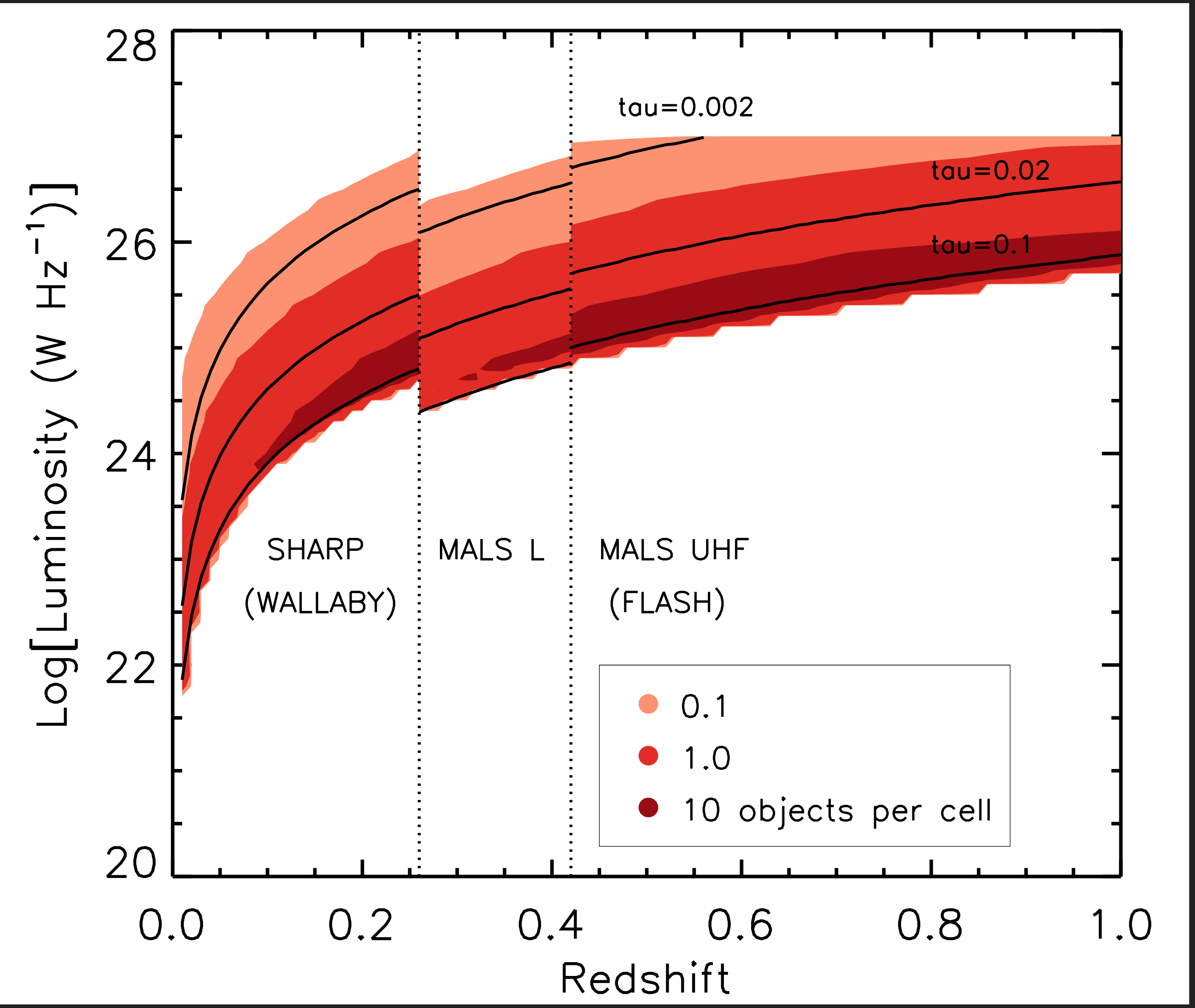
[Maccagni et al., 2017]

- 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.



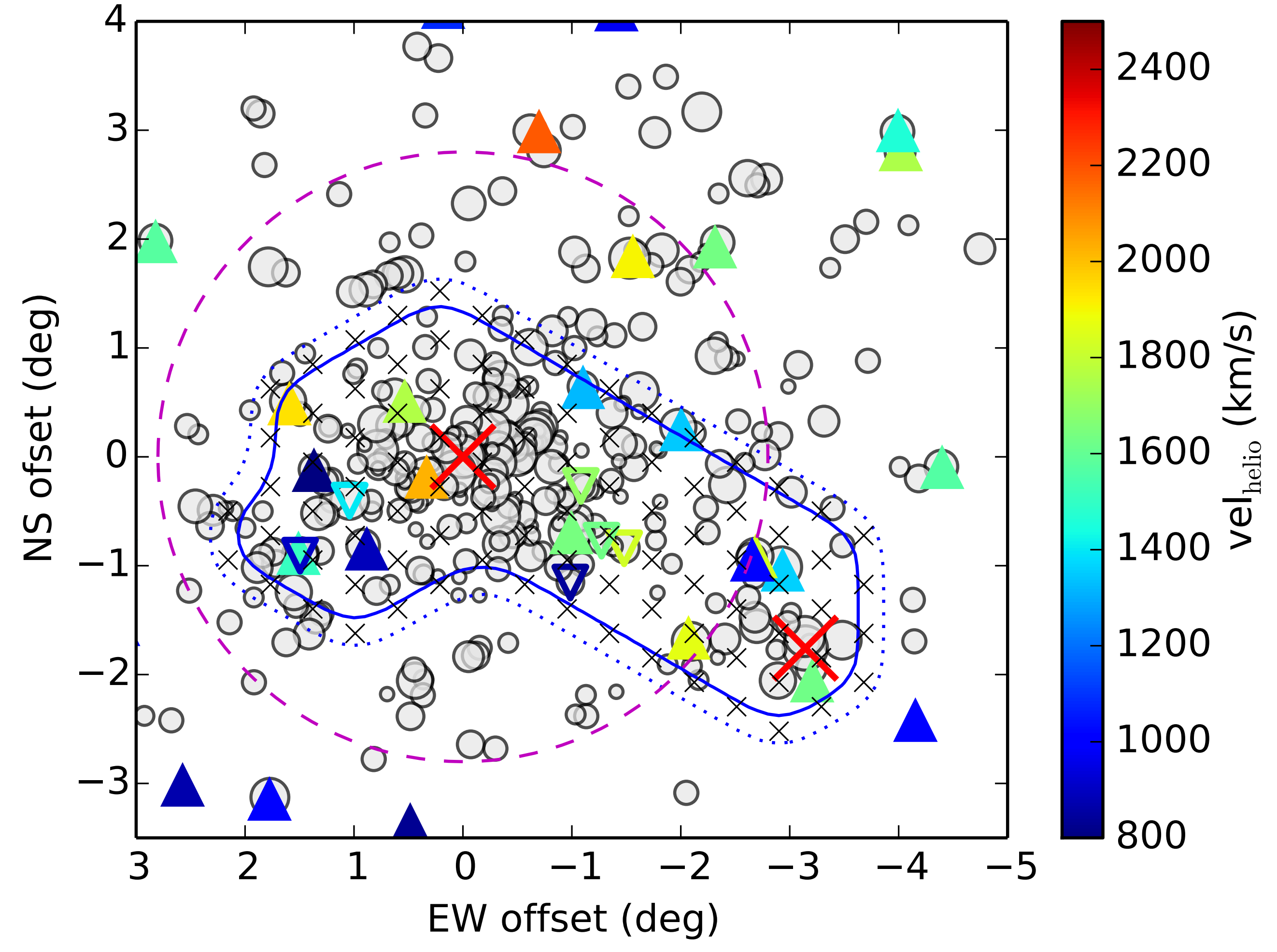
[by N. Maddox; Maccagni et al. 2017]

MeerKAT Fornax Survey

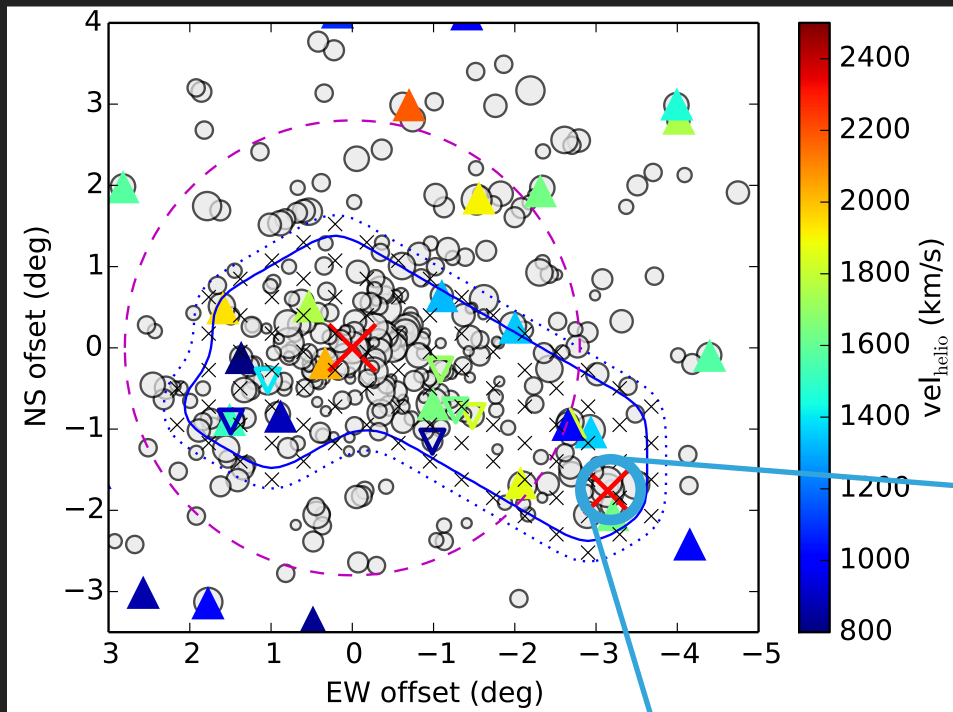
- Observe the Fornax Cluster and the group of Fornax A with MeerKAT
  - PI: Paolo Serra; Collaborators: E. de Blok (ASTRON, Kapteyn, UCT), G. Bryan (Columbia), S. Colafrancesco (Wits), R.-J. Dettmar (Bochum). B. Frank (SARAO), F. Govoni (INAF), G. Józsa (SARAO, Rhodes, Bonn), R. Kraan-Korteweg (UCT), 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^2
- 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(HI)~ 10^{18} cm^{-2} at 10 kpc
    - N(HI) ~10^{19} cm^{-2} at 1 kpc
  - HI mass function
    - down to M(HI) ~ $5x10^5$ M_{sun}

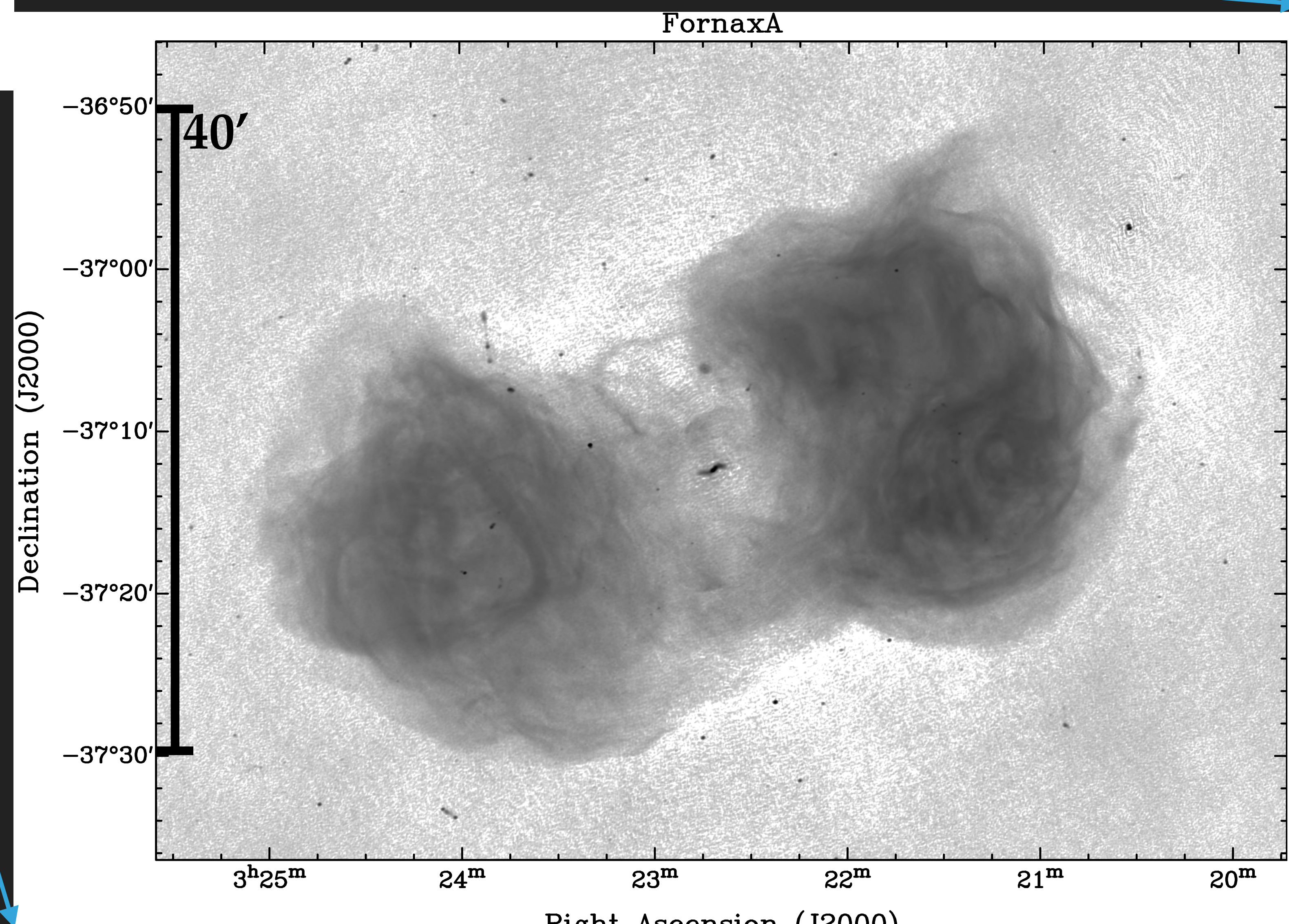


Expectations for the MeerKAT Fornax Survey



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

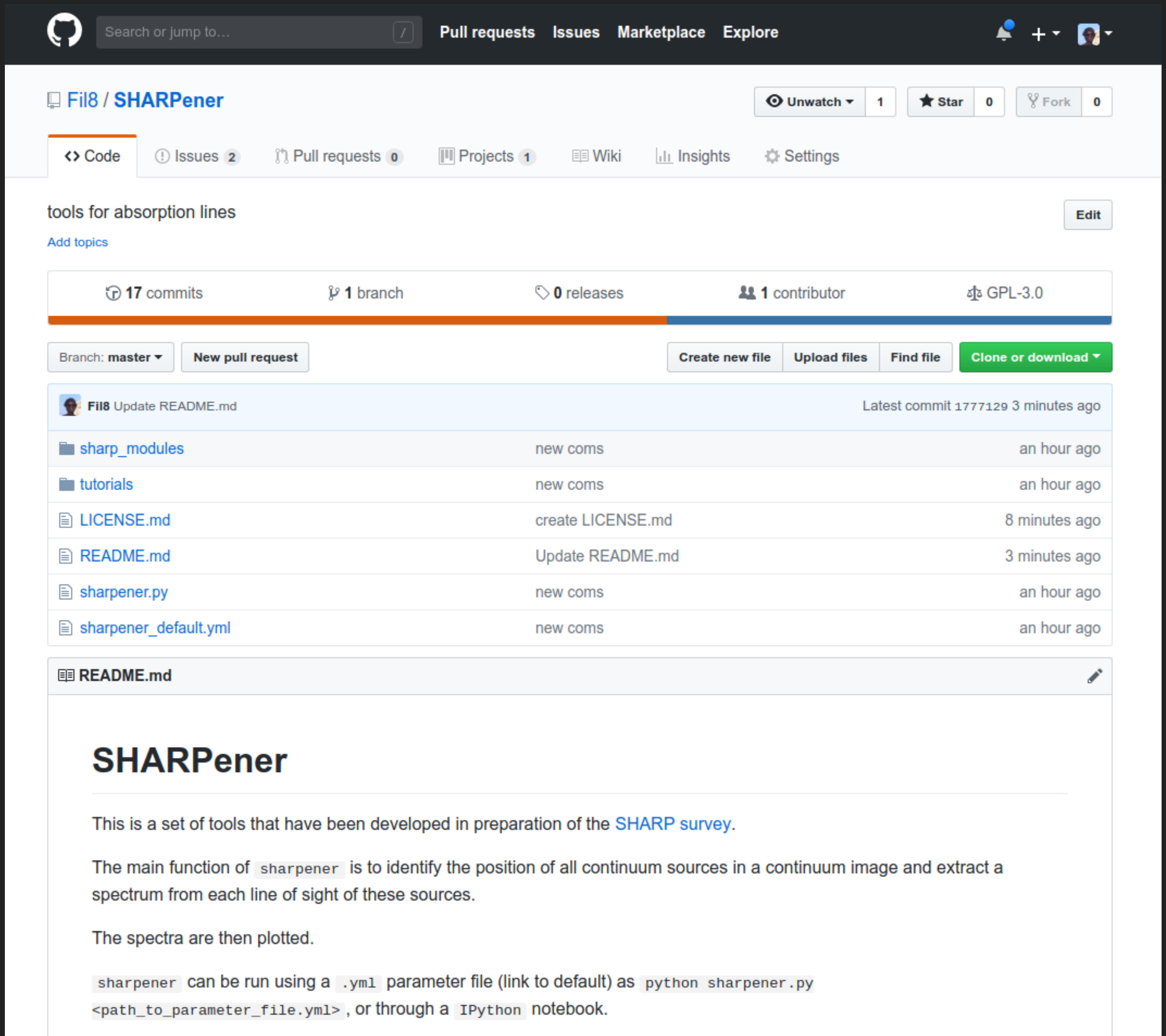
- It's necessary to have tools to automatically identify continuum sources, extract the spectra and look for absorption.
  - SHARPener



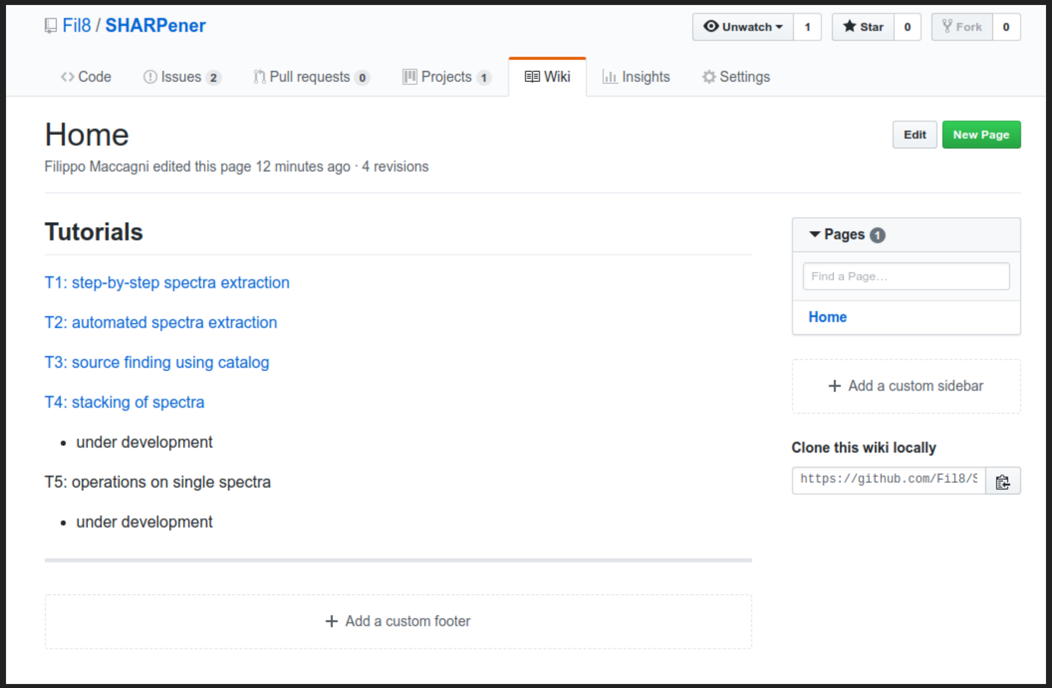
[MeerKAT 40 Antennas]

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



[https://github.com/Fil8/SHARPener]



- 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:

FLASHfinder (Elaine, James talks)

non-detections => upper limit to NHI

detections

Intervening or associated?

cross-correlation with spectral surveys

→

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

↑

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

stacking

Tools for spectral analysis

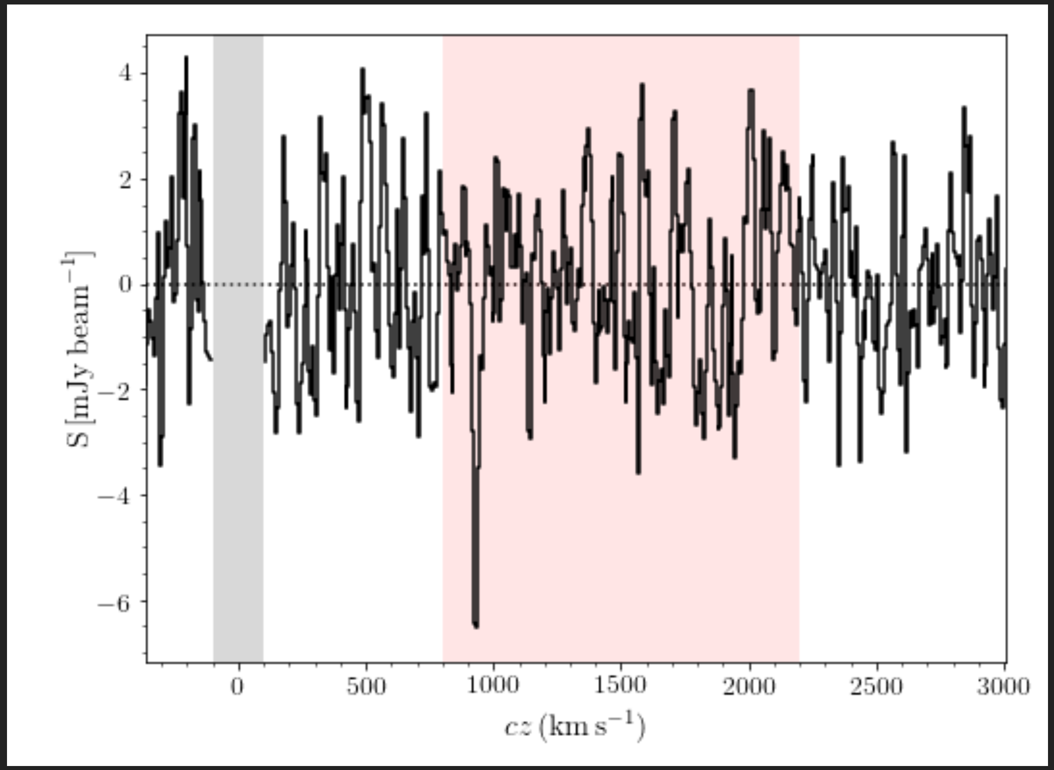
- convert units (velocity, optical depth)
- hanning, convolution, continuum subtraction
- measure noise
- simulate background continuum sources

comparison with modelling: MoD_AbS

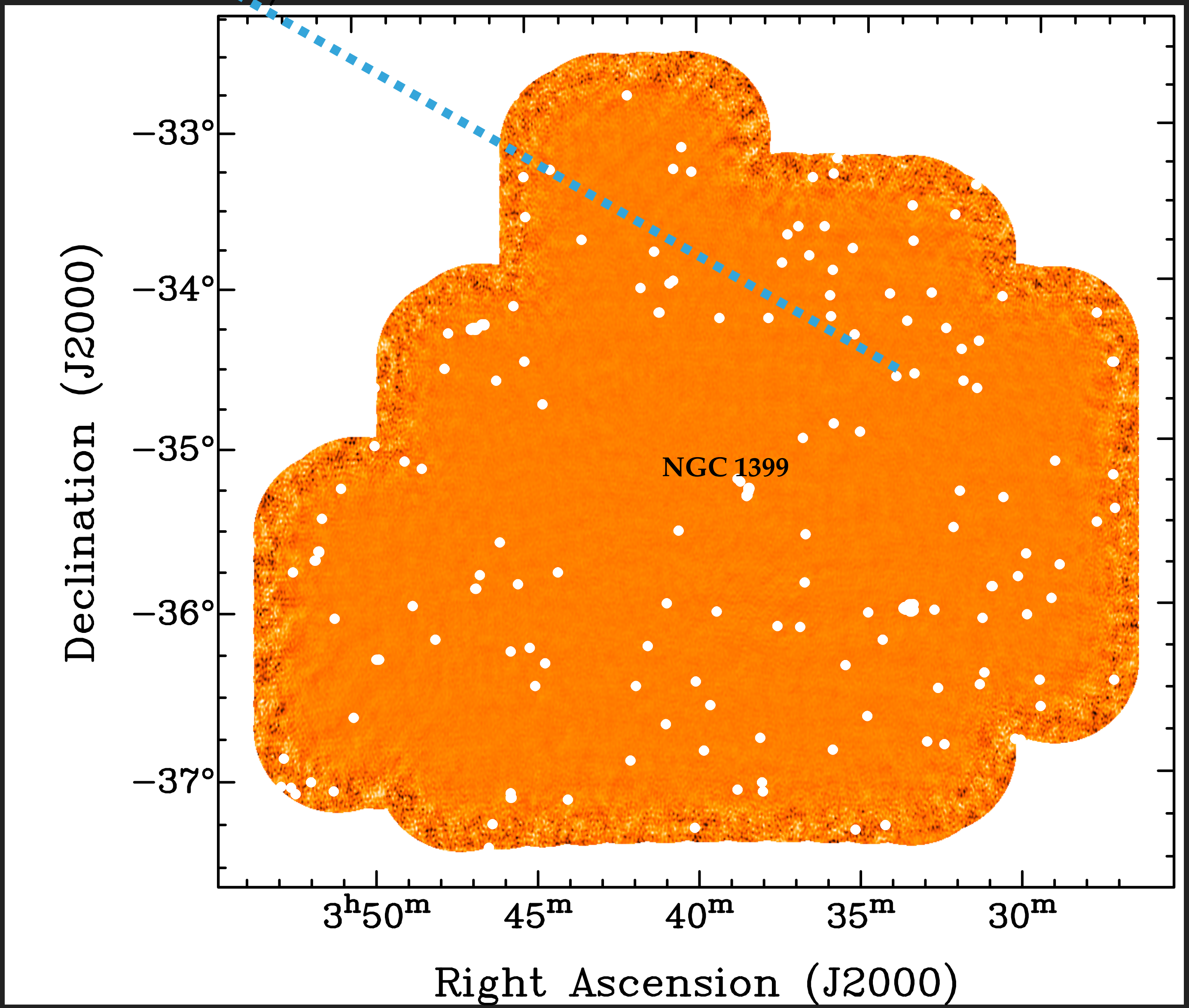
Cross-correlation with catalogs, e.g. LOFAR

other ideas?

HI Absorption in the Fornax Cluster

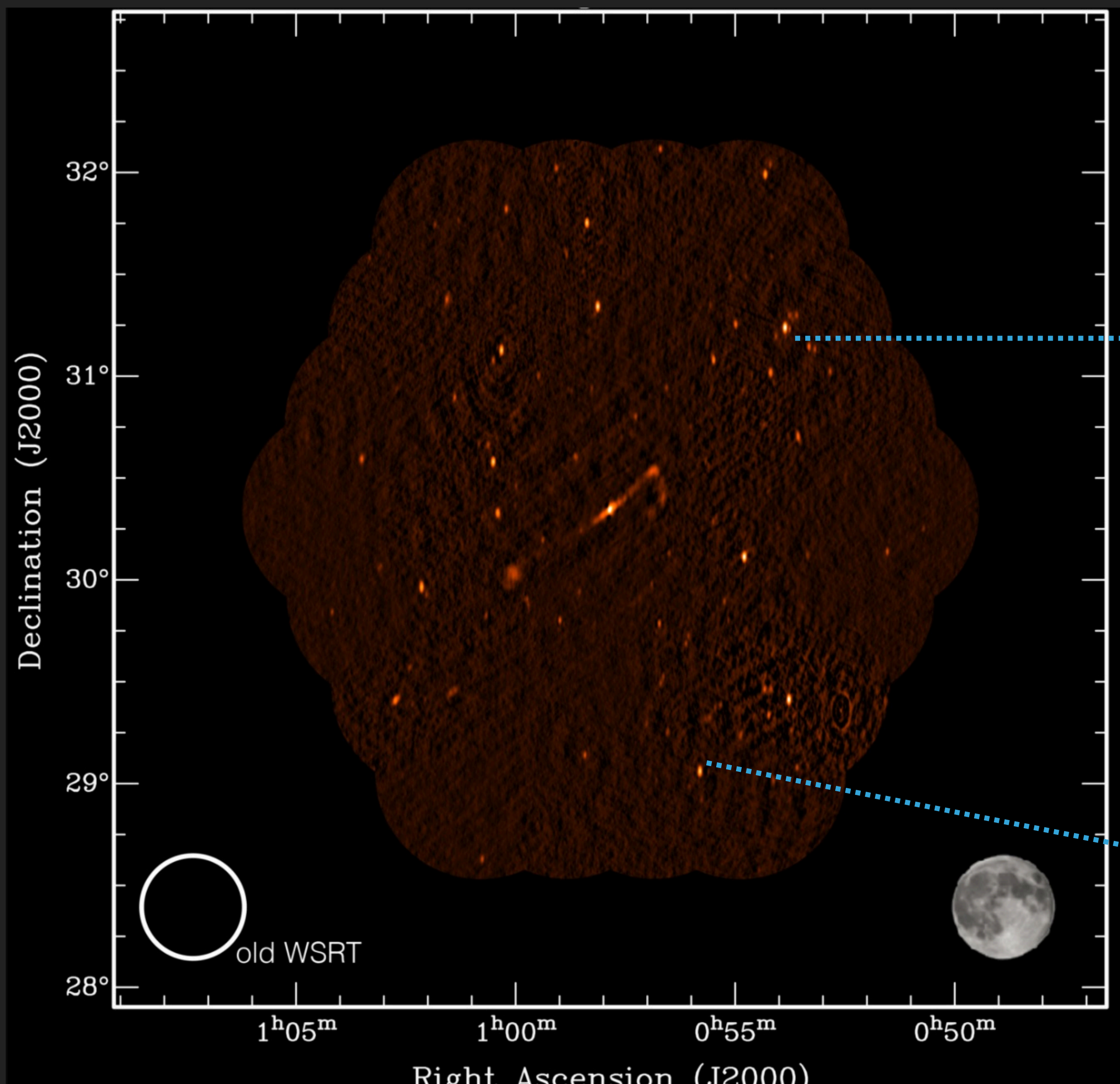


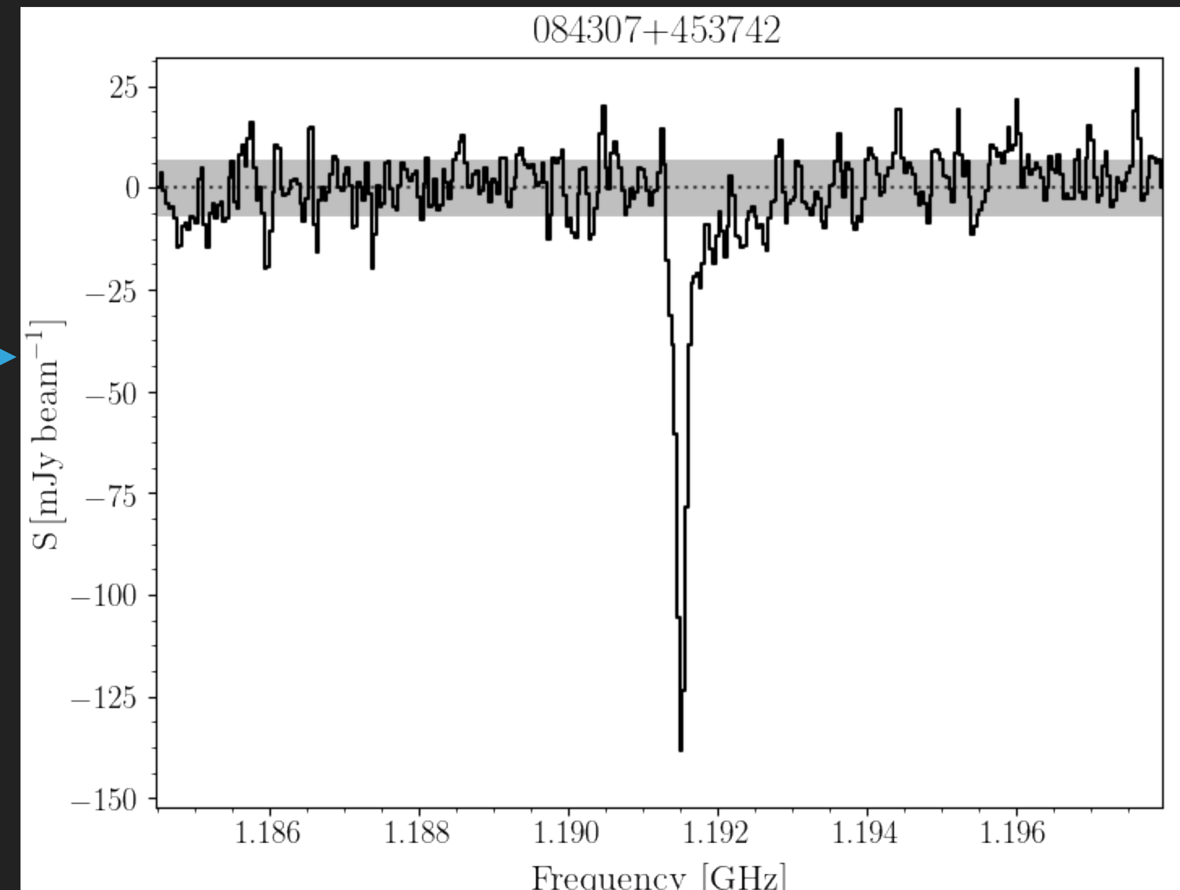
- Centre of Fornax Cluster observed with ATCA (by Paolo Serra)

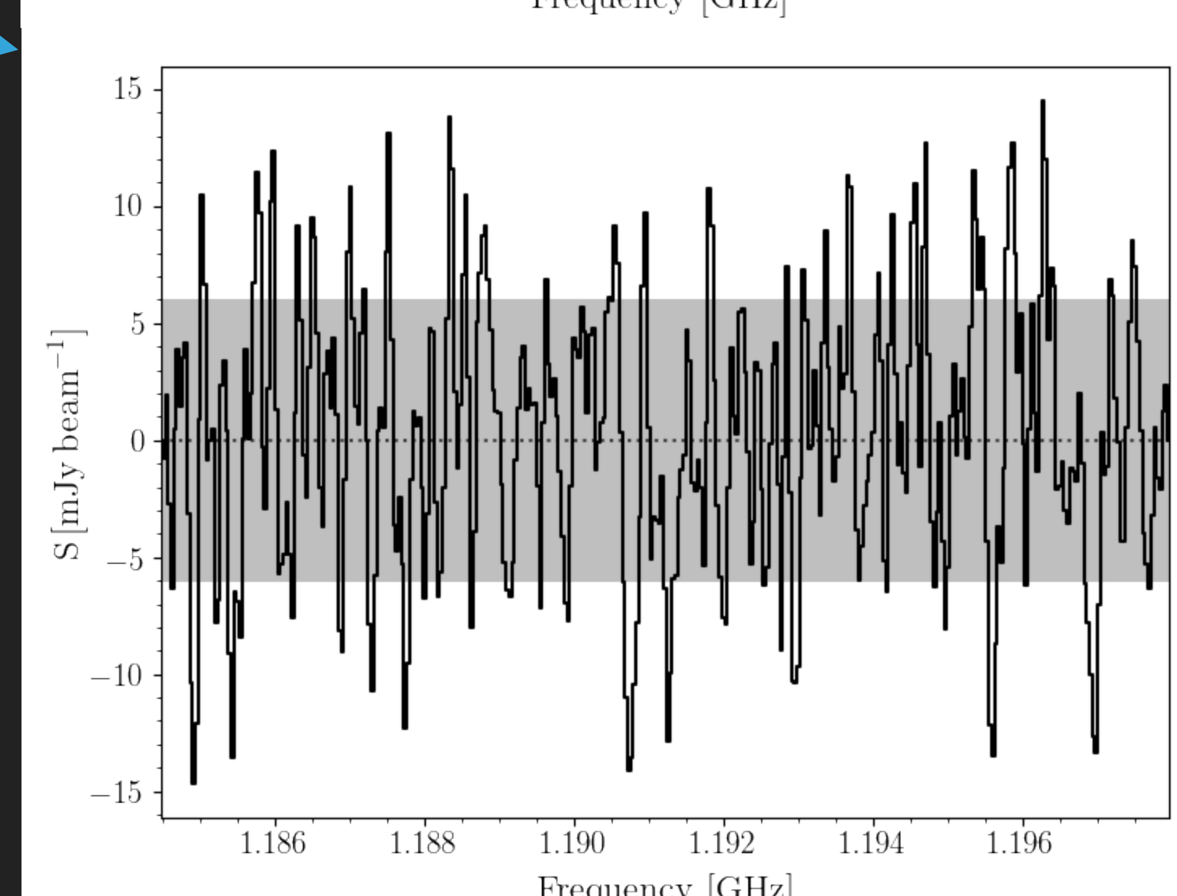


- Operations on extracted spectra
  - Identify presence of a line
  - Estimate noise
  - Mark flagged regions
  - Mark regions of interests

SHARPENER: Test on ApertiF Fields



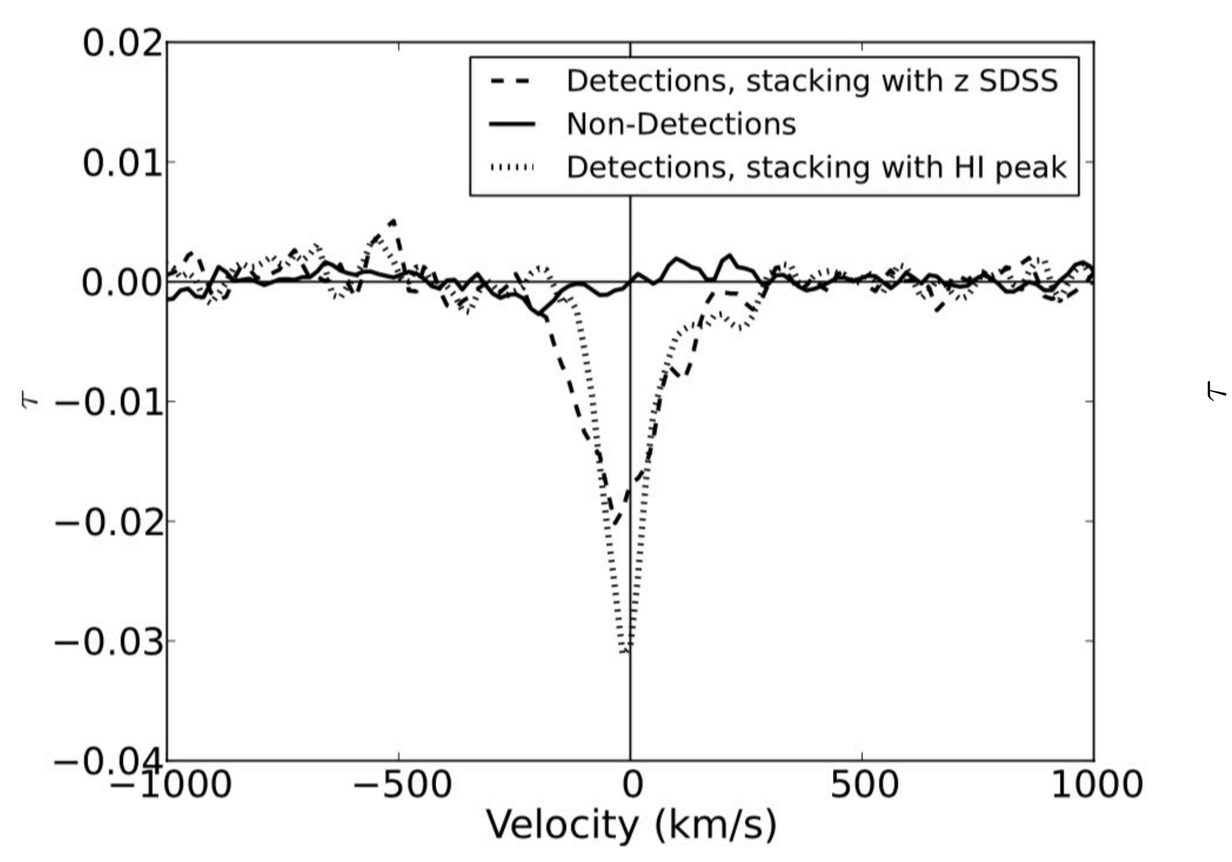




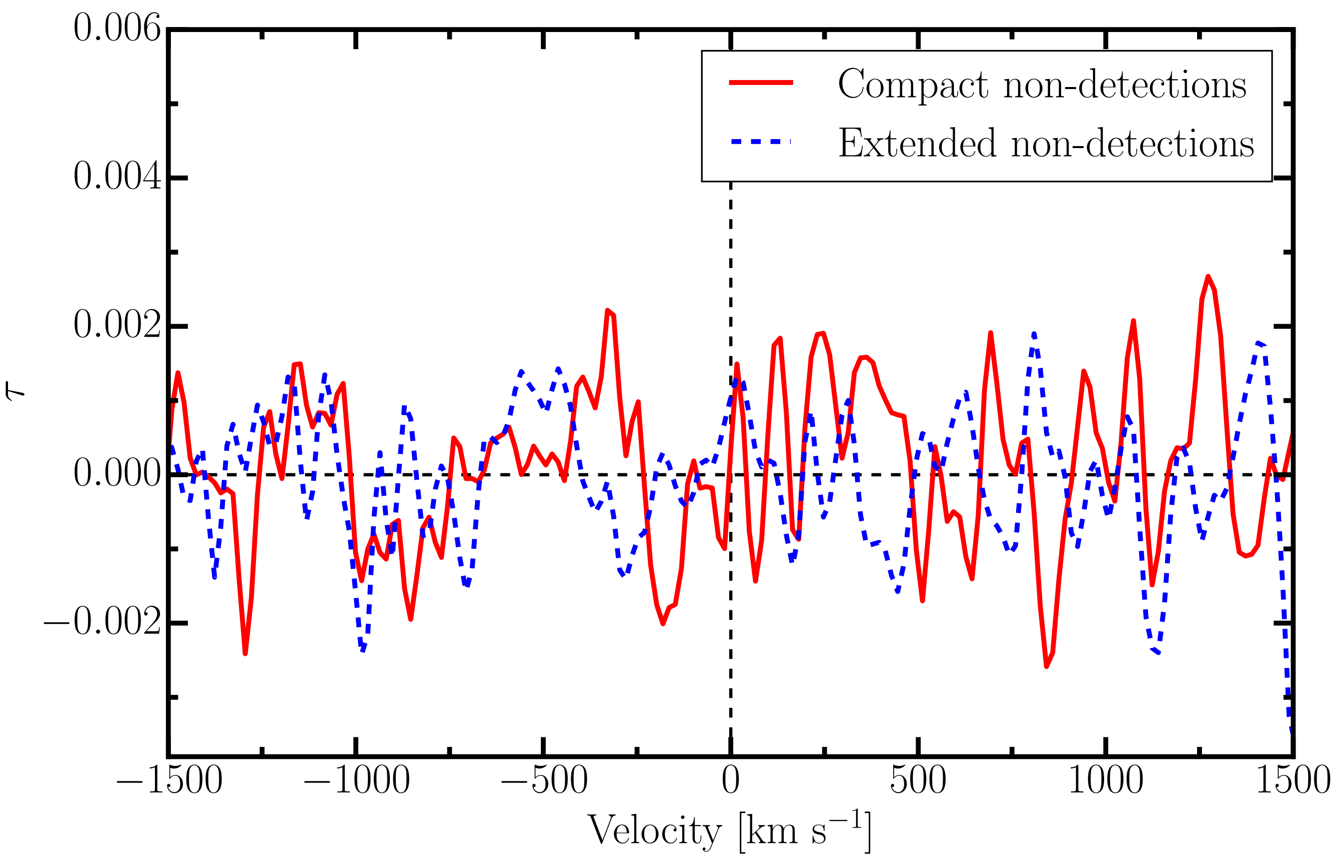
- SHARPENER extracts spectra against each line of sight
  - HI absorption lines can be identified
  - Grey shaded region = average noise

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 $1/\sqrt{N_{sources}}$



[Gereb et al. 2014]

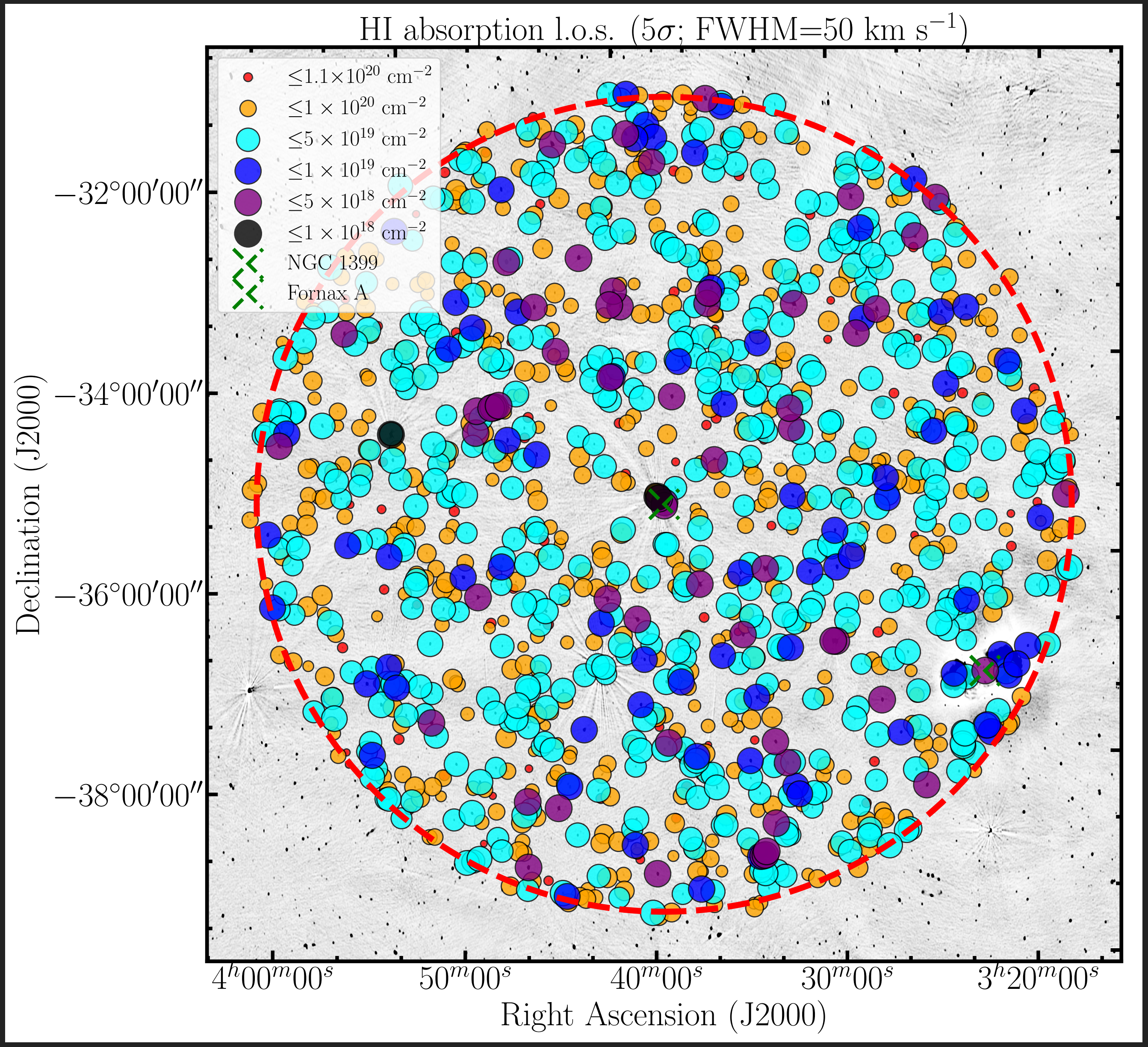


[Maccagni et al. 2017]

SHARPener and Predictions

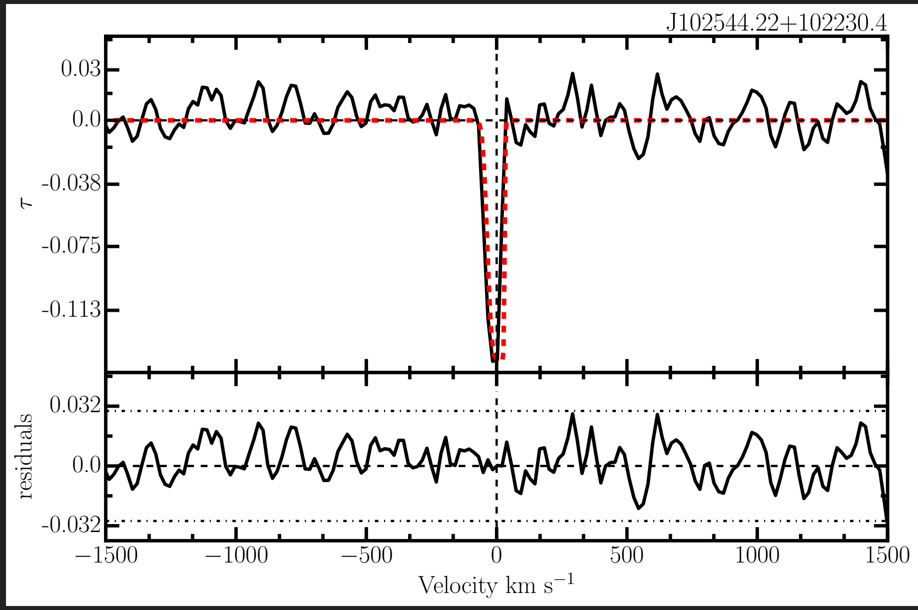
- MeerKAT Fornax Survey: also an f.o.v. for HI absorption studies
- Use SHARPener to predict the HI absorption detection limits within 4 deg^2 from NGC 1399 (centre of the cluster)
- NVSS catalog: ~1100 sources above 10 mJy
  - Given the sensitivity of MFS **we will detect HI absorption (5 sigma detection,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

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

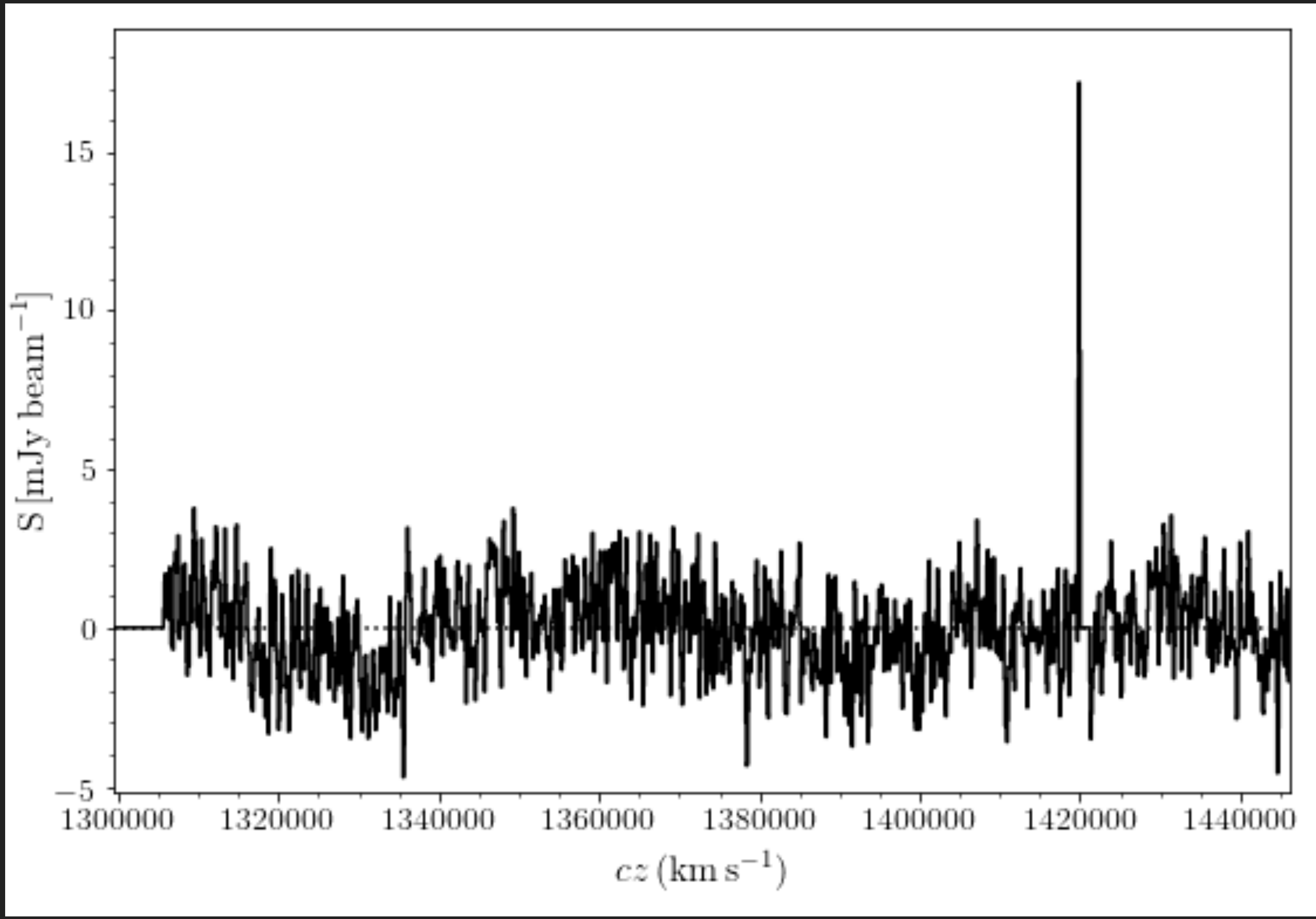


SHARPENER: Tool for Data Quality

Spectrum that we would like to see



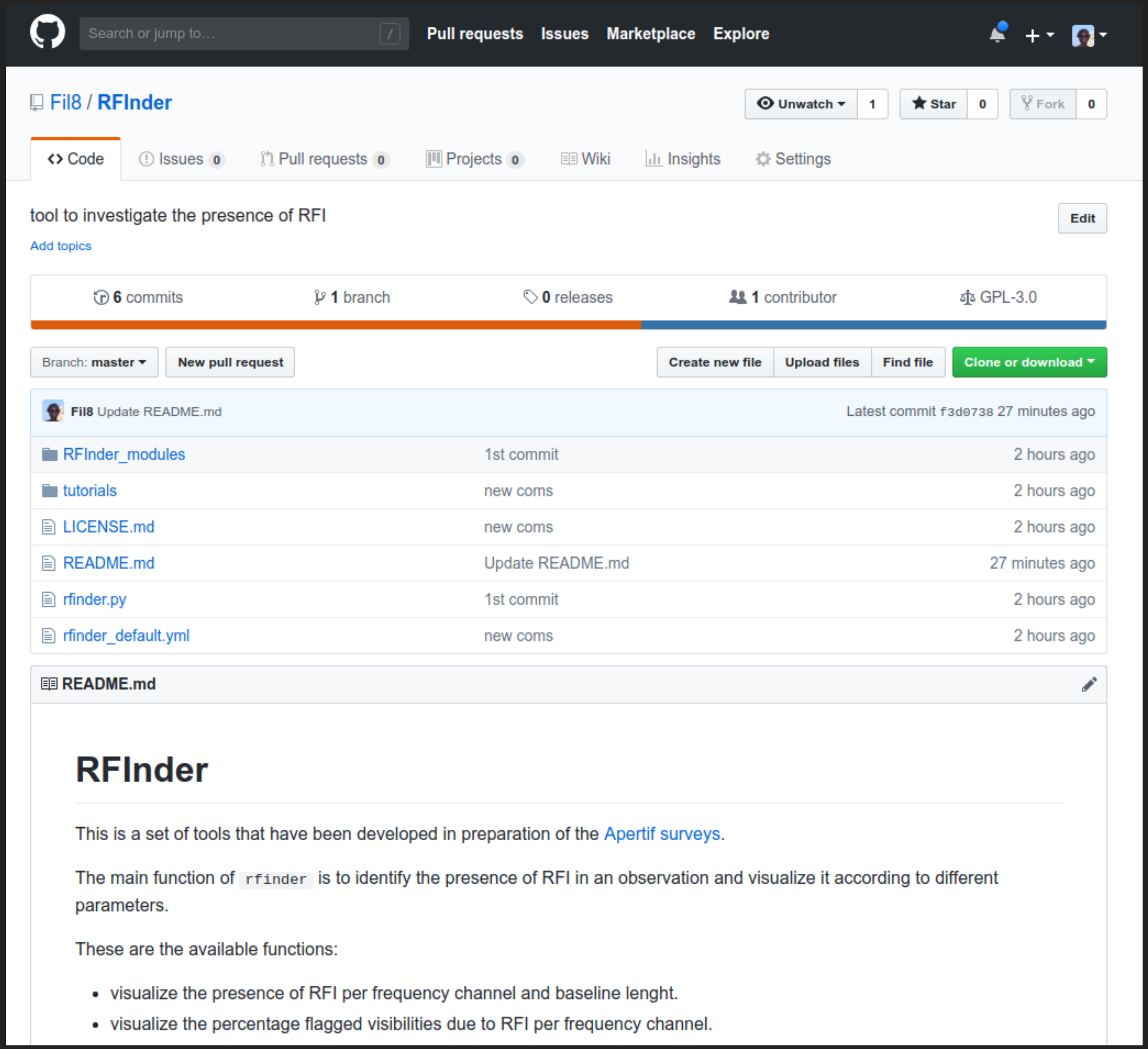
Spectrum that we see after 1st reduction (new instrument, new pipeline)



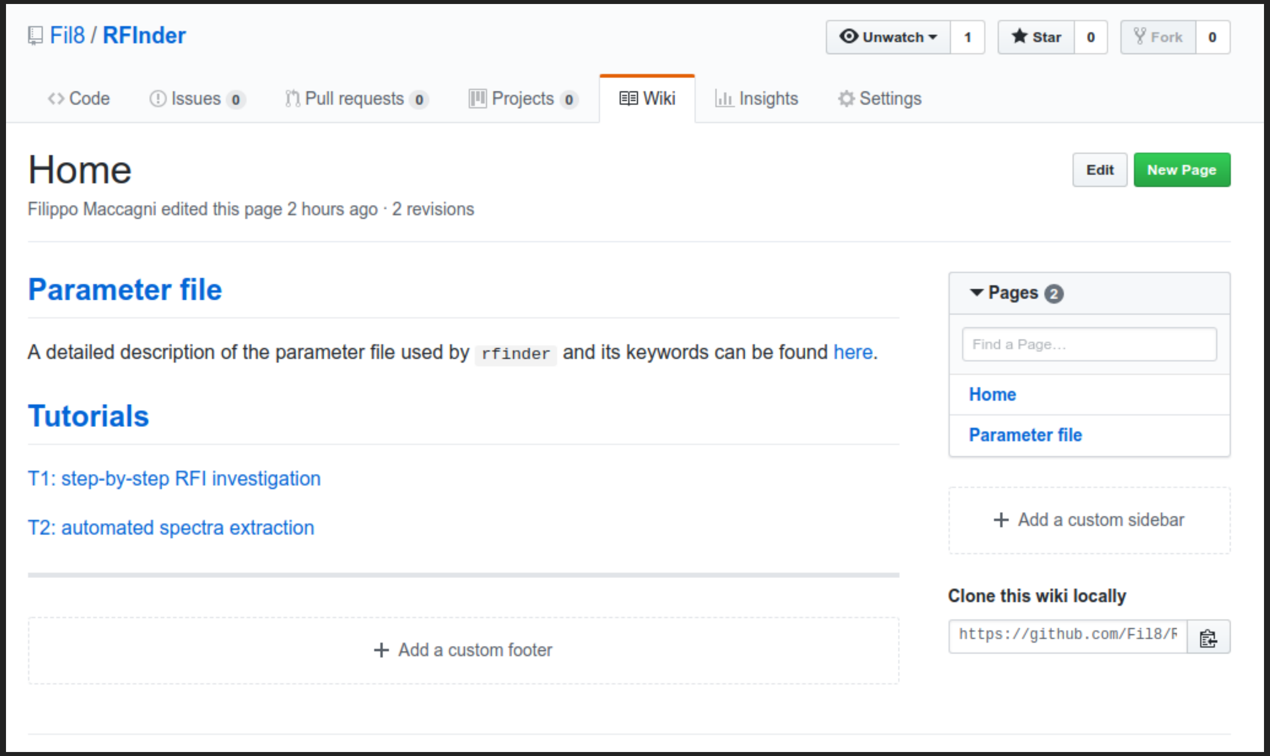
- Fast extraction of all spectra in a field
- Error recognition by the blink of an eye
  - leftover RFI
  - errors in the spectra
  - bad continuum subtraction

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



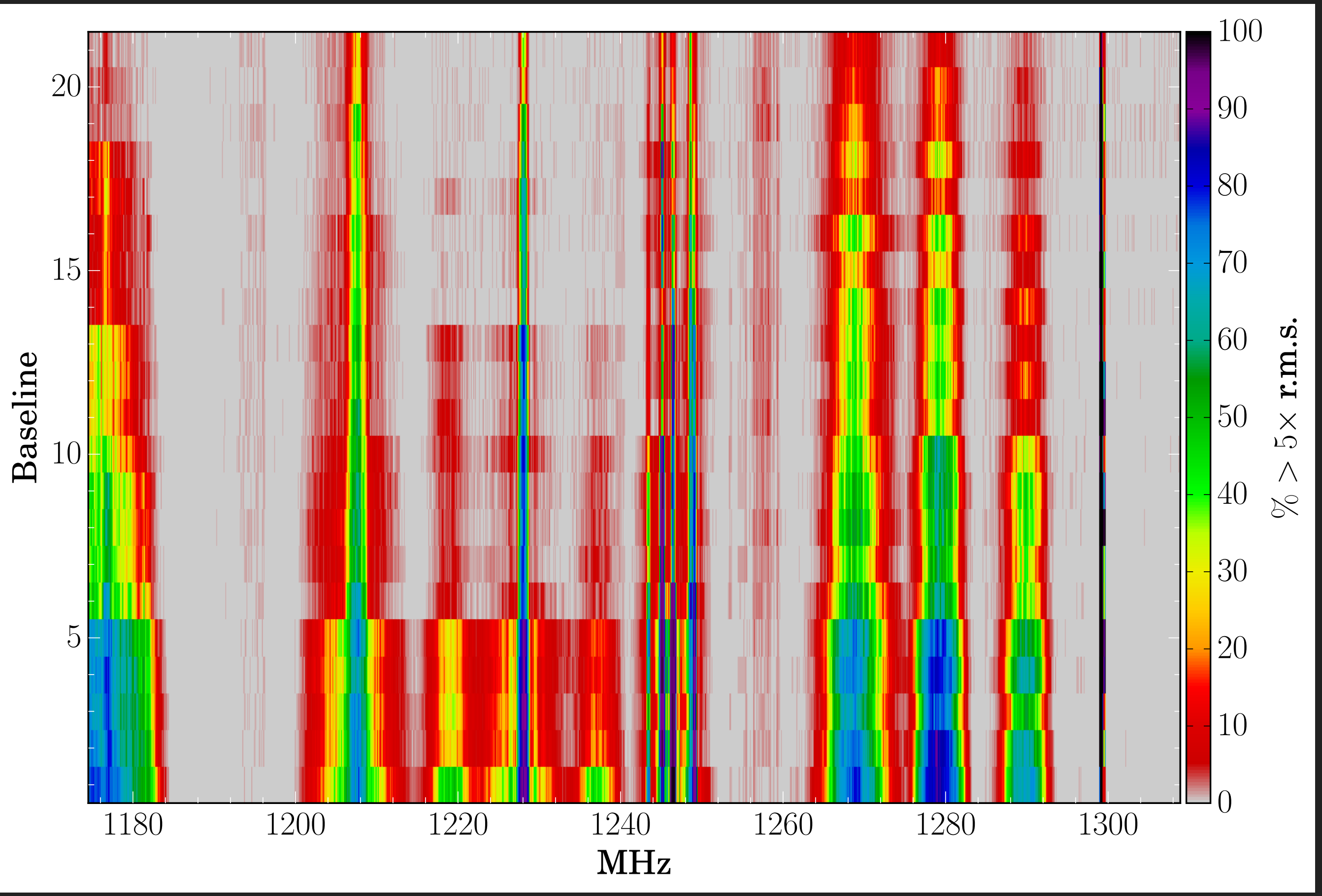
[https://github.com/Fil8/RFInder]

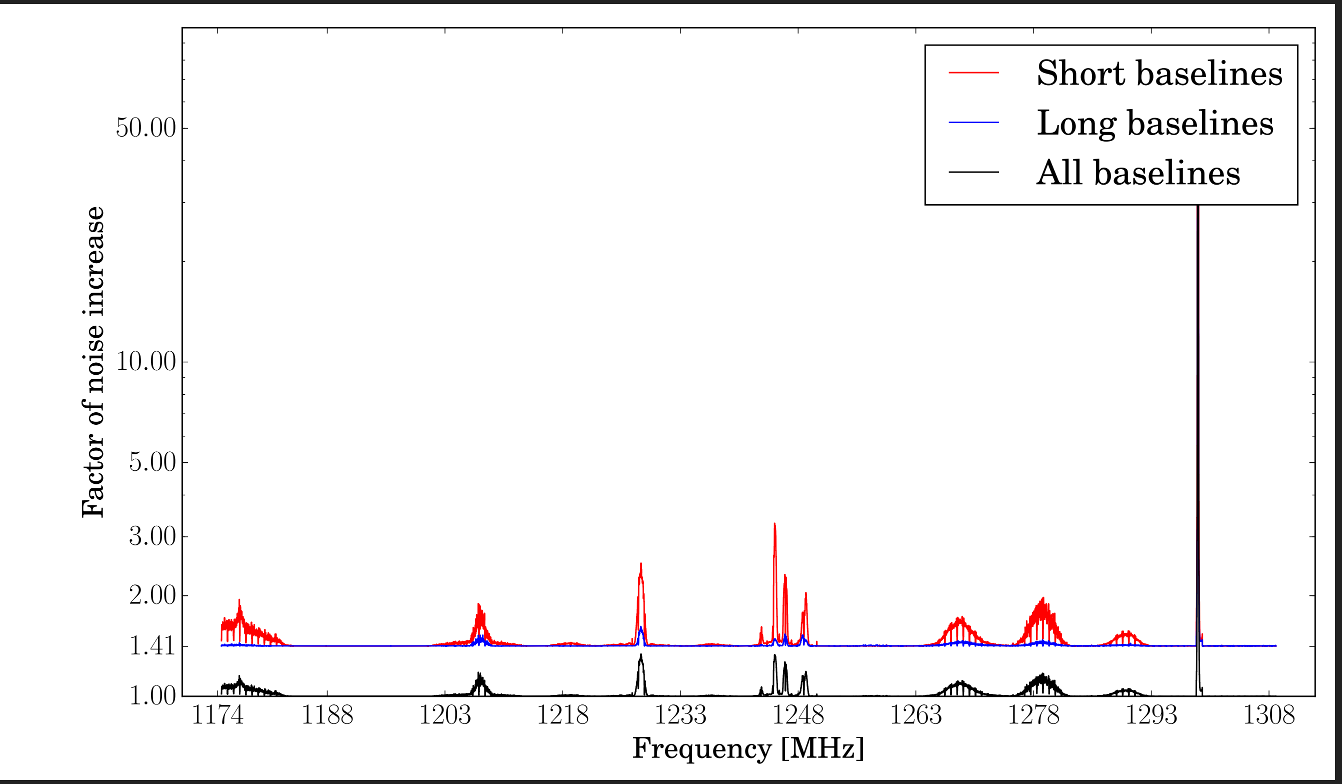


- Works similarly to SHARPener
  - Parameter file
  - Works as a pipeline or with notebook
  - Tutorials illustrate the different tools

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

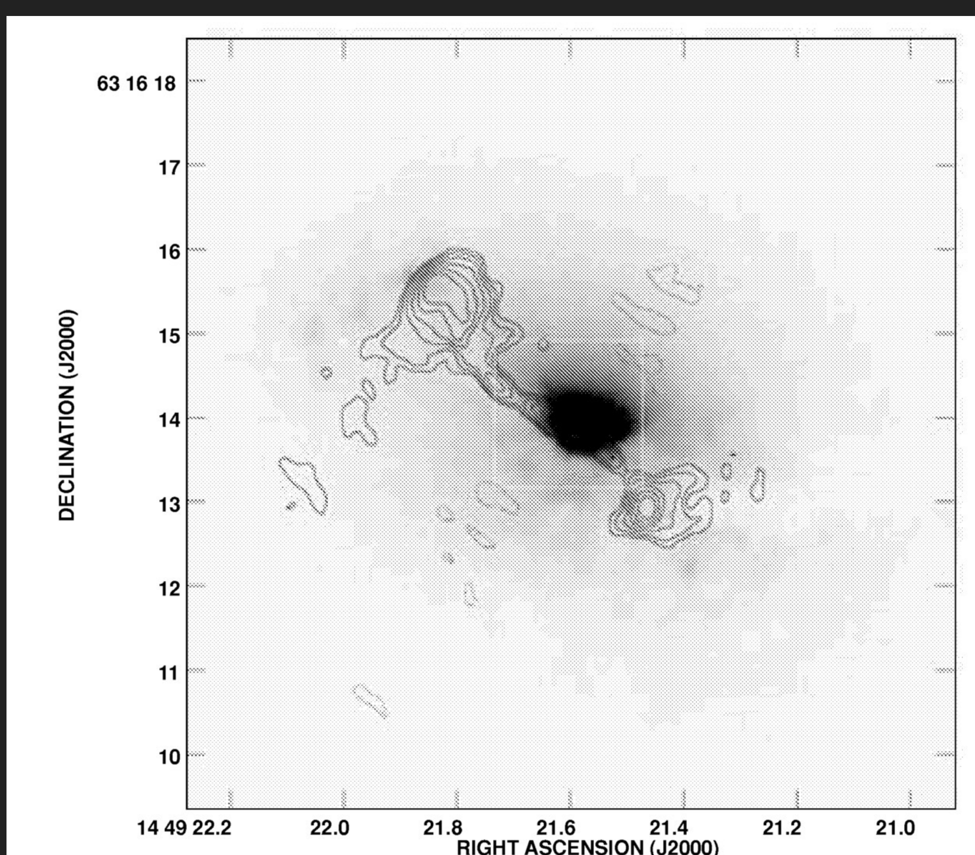


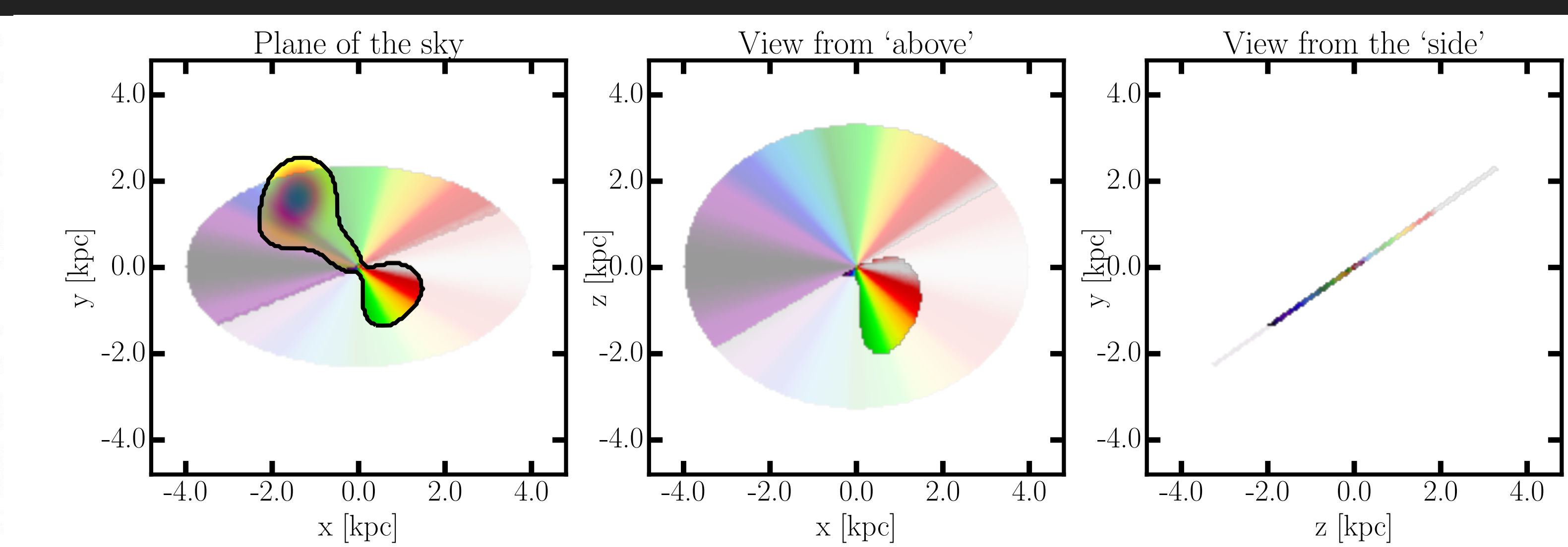


MoD_AbS: interpreting HI absorption

- 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 <u>kinematical model, MoD_AbS</u>
    - Model the rotating HI disk in front of the radio continuum

3C 305 Observation → Model

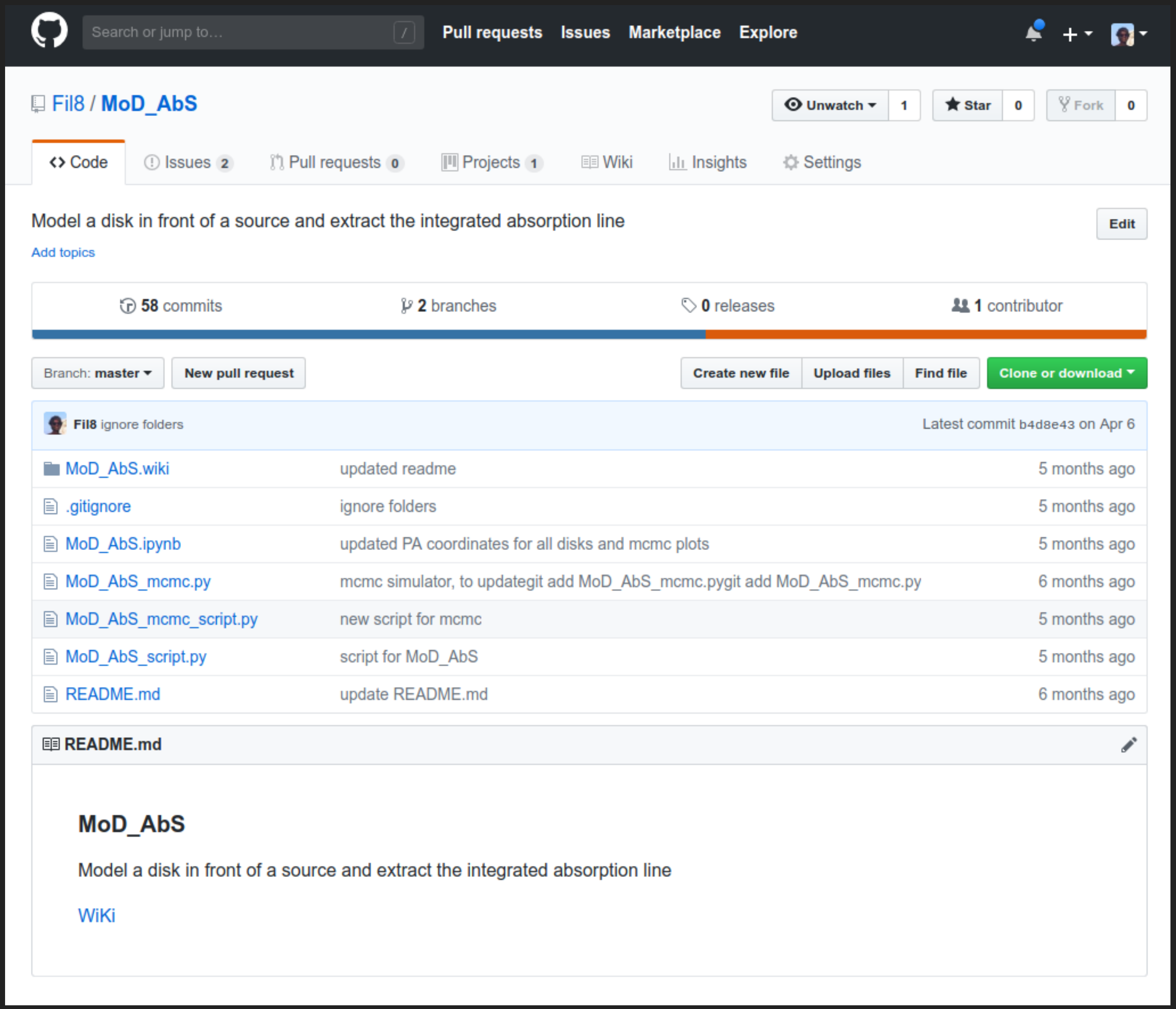




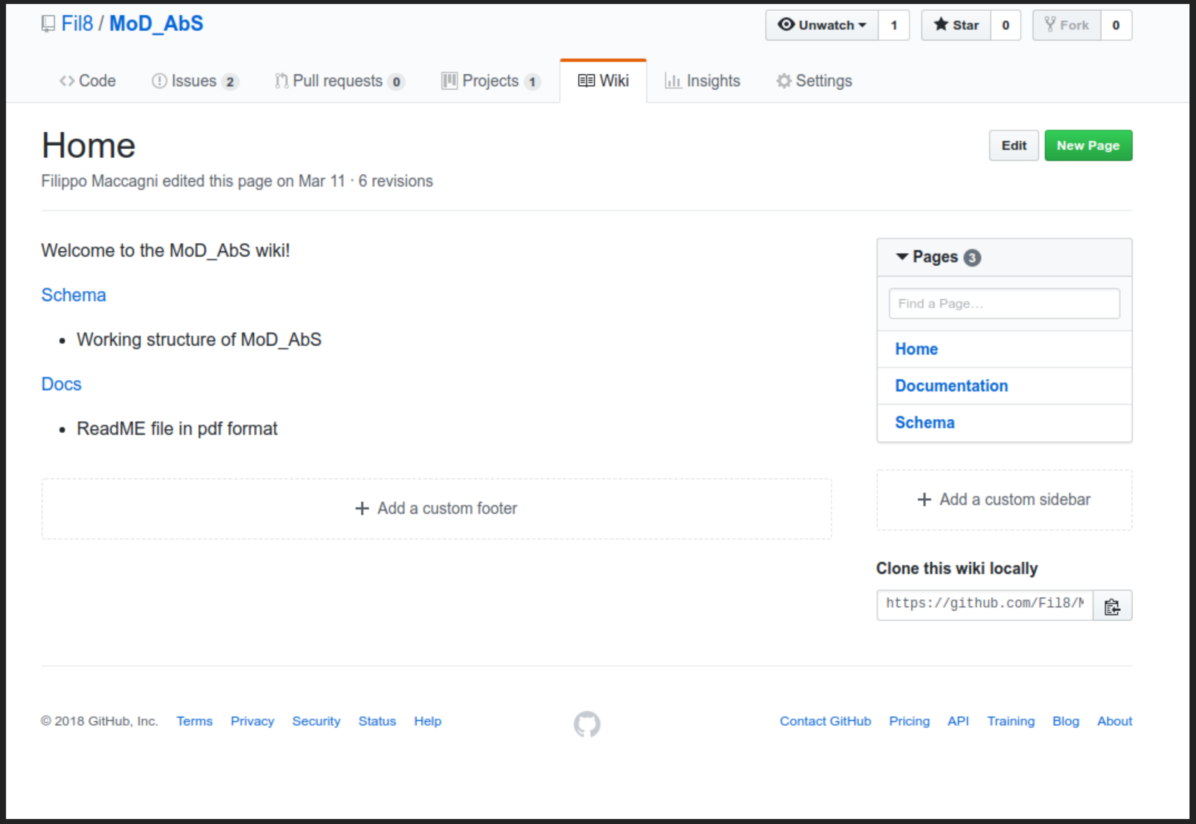
Plane of the sky : x,y Side view: z,y From above: x,z

MoD_Abs: Introduction

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



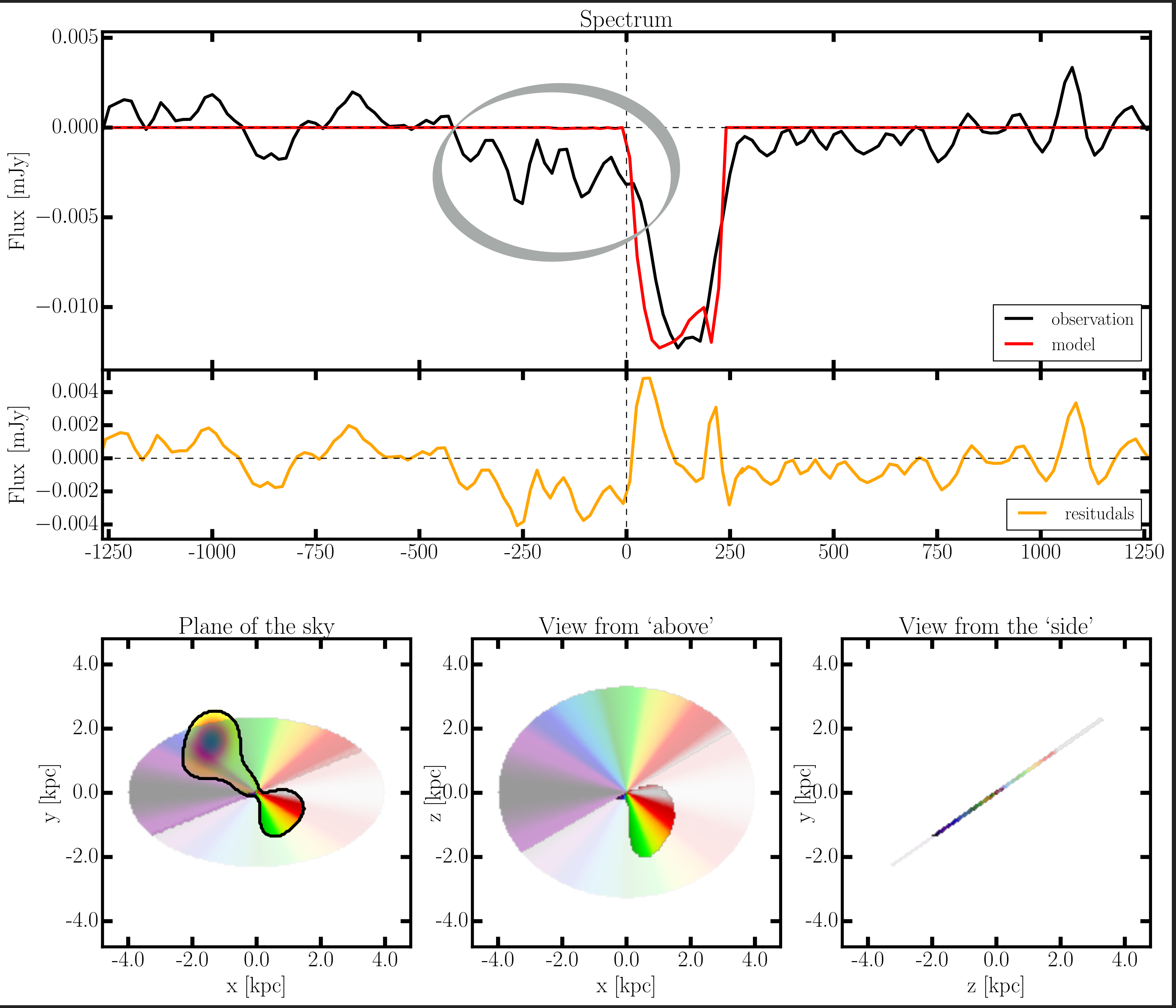
[https://github.com/Fil8/MoD_AbS]



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

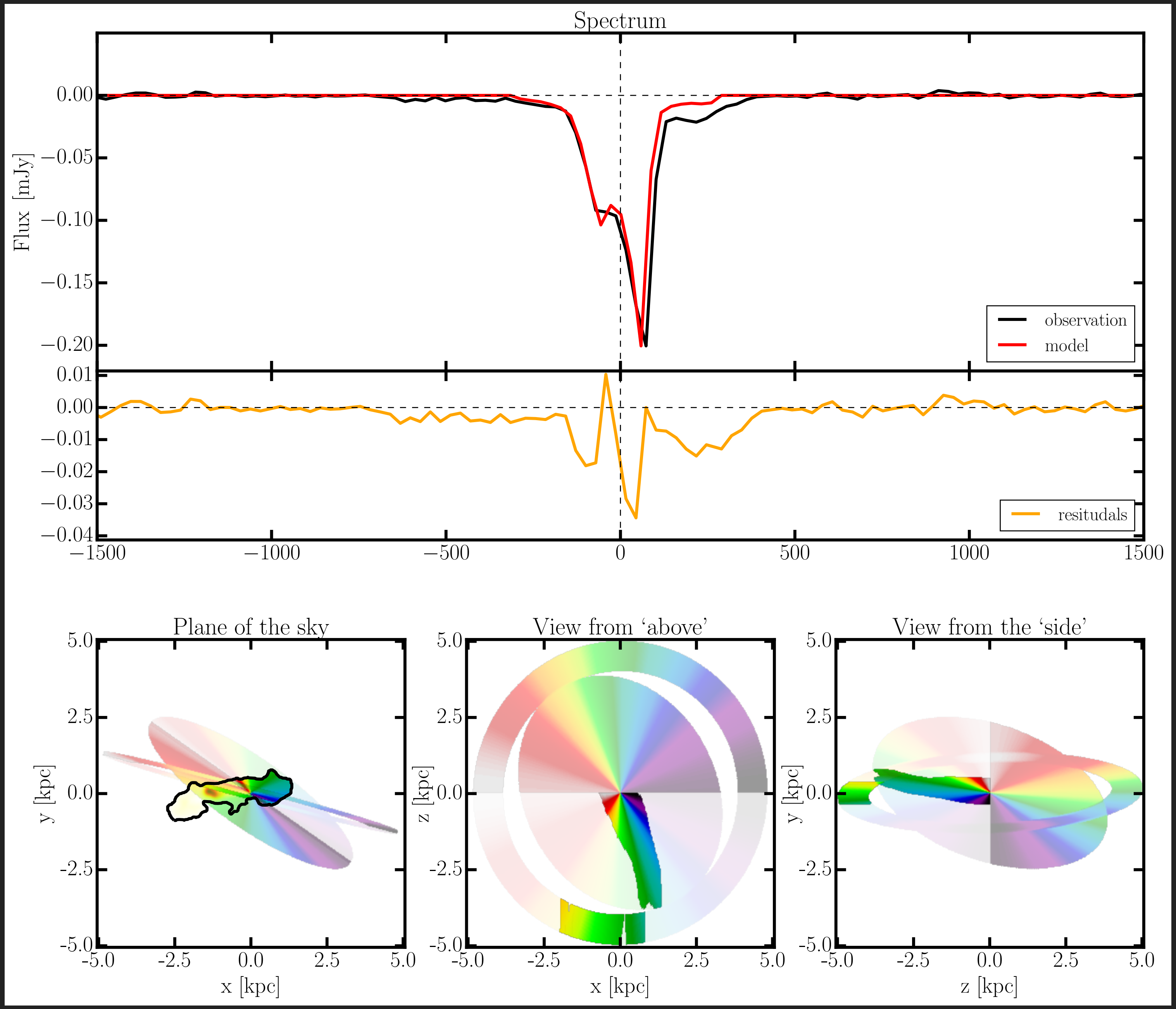
MoD_AbS: a disk around the radio source

- **Fix parameters of the disk from available information on the galaxy:**
  - **Optical Image: i, PA**
  - **Continuum image**
  - **Tully Fisher -> V_{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**



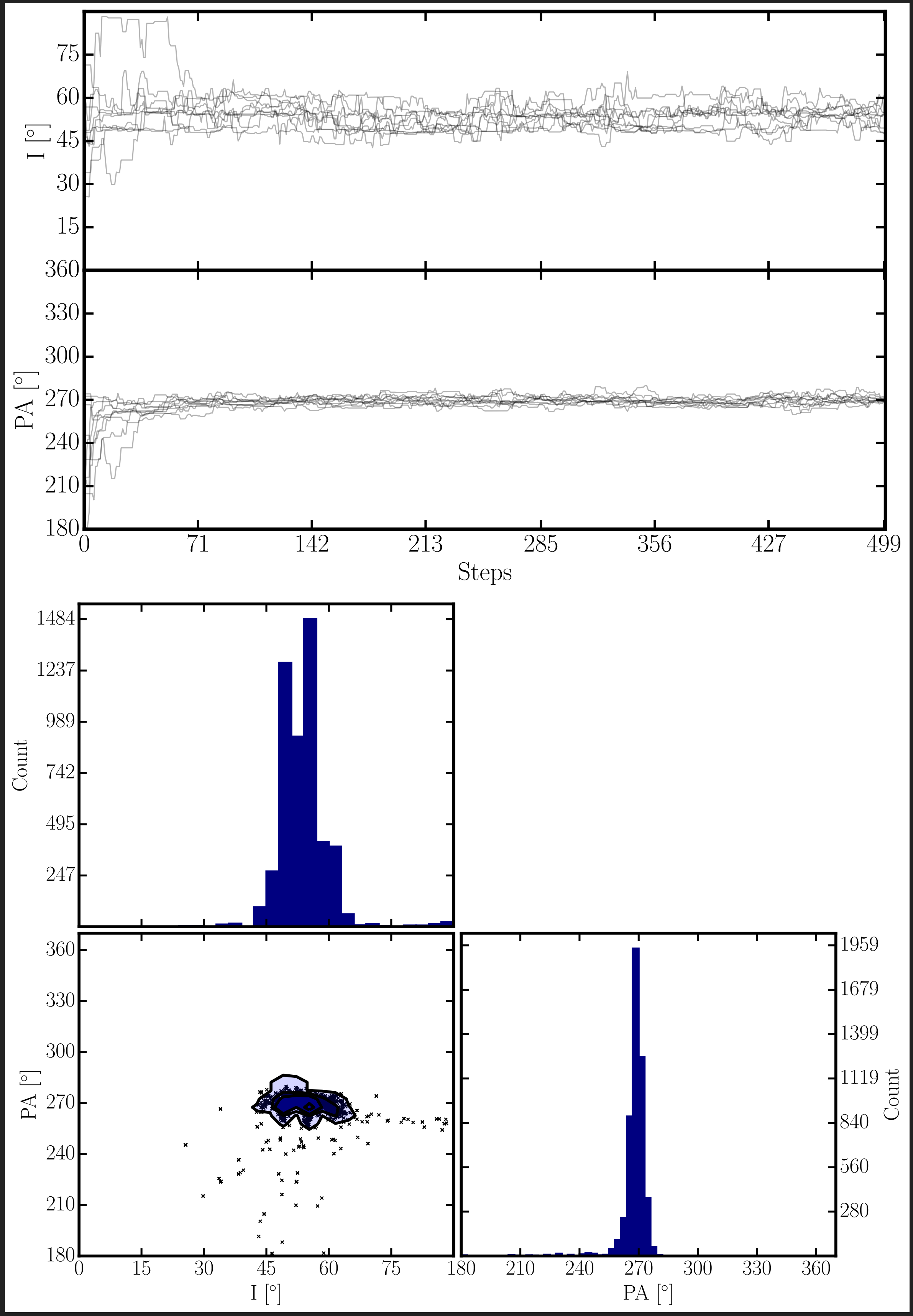
MoD_AbS: complex distributions

- 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



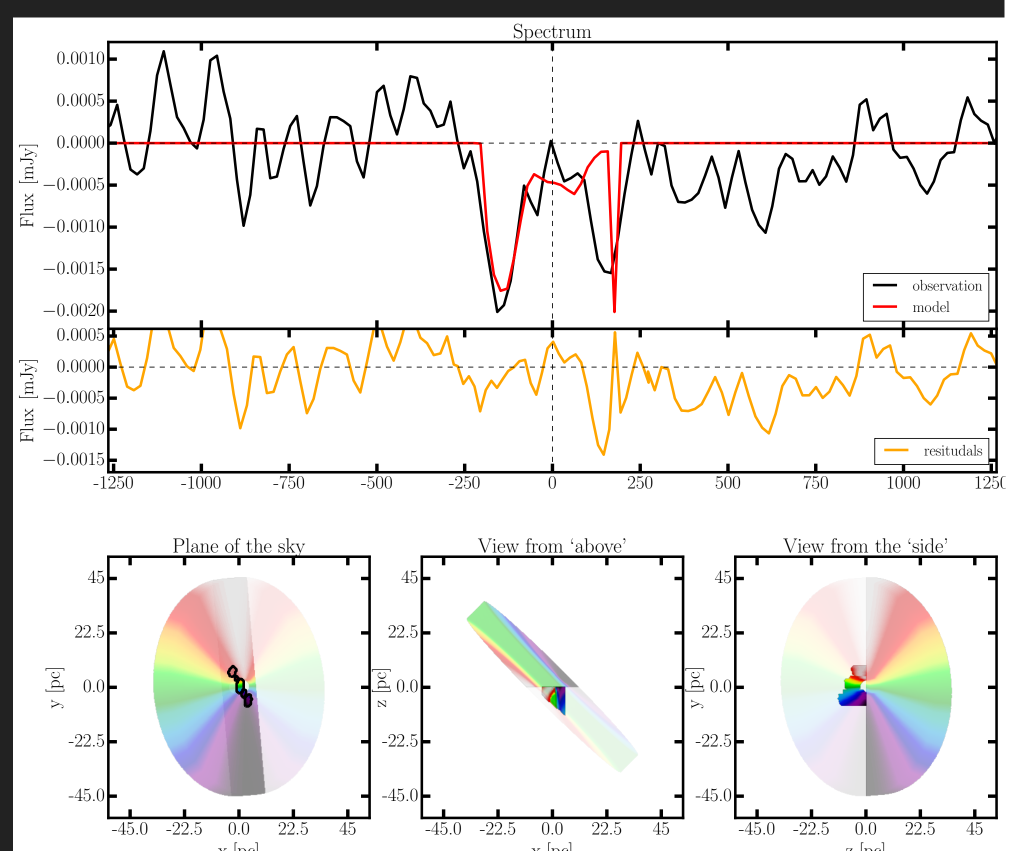
MoD_AbS: finding the disk of best fit

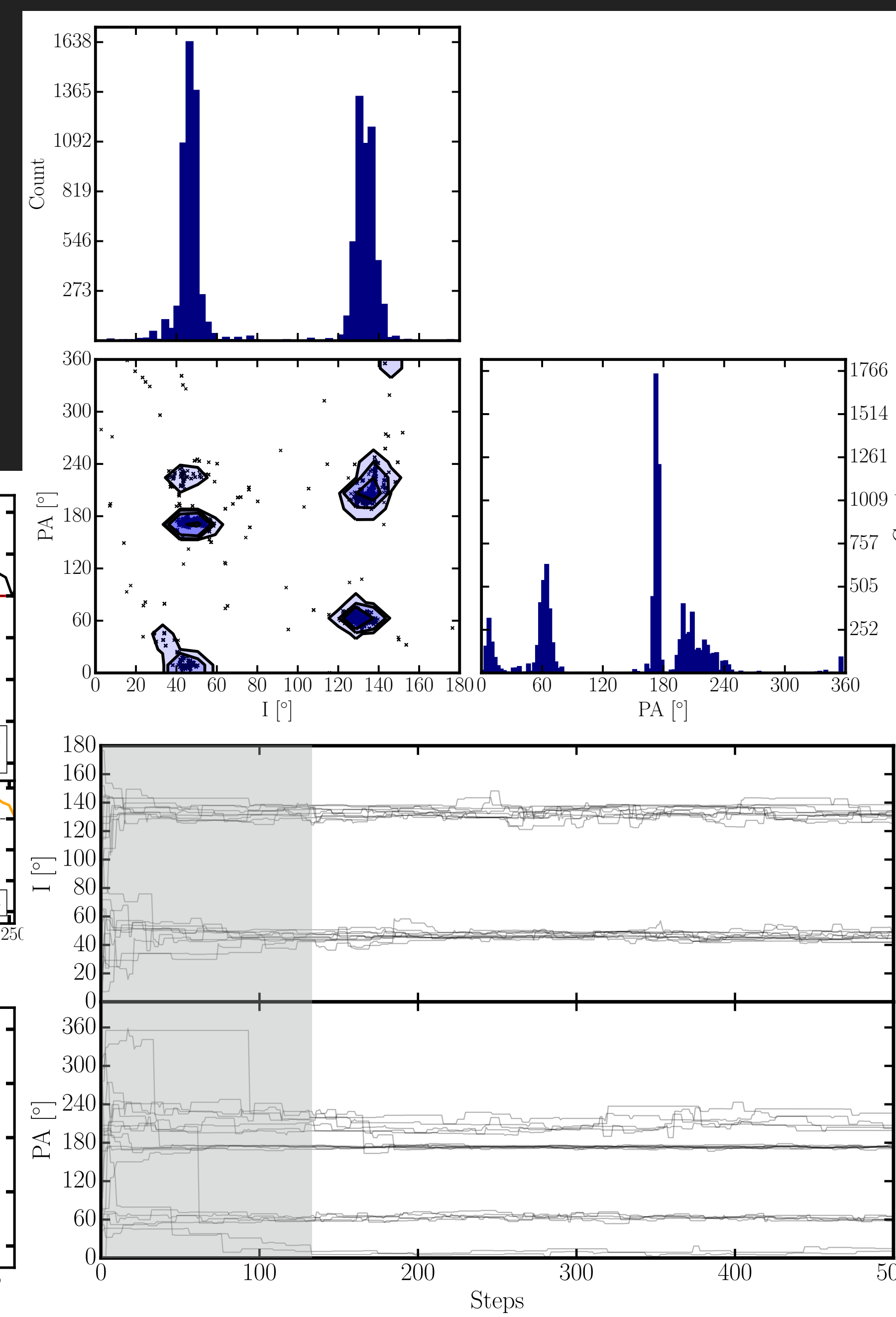
- MCMC simulation
- investigate parameter space of I & PA
  - automated algorithm
  - associate probability distribution function to investigated params
    - Minimum = params of best fit



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

- Software can always be improved.
- Open source and GitHub: you can upload your issues/requests. You can also contribute to its development.

- SHARPener [https://github.com/Fil8/SHARPener]
  - 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 lengh, 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]
  - Automatic identification of RFI in a measurement set
    - Visualisation of RFI per frequency, baseline lengh, time
    - Estimate of PSF variation due to RFI flagging
  - Clumpy HI distribution - Study the distribution of line widths for different radio continuum sources.