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MeerKAT Fornax Survey Team (PI P. Serra) @ INAF/OAC
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Cold Gas in nearby radio galaxies

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Outline

- Goal
  - Study neutral hydrogen (HI) from the micro-scale (r~100 pc) to the macro-scale (>100 kpc)
- Fundamental question
  - Does cold gas contribute in regulating the recursive nuclear activities of galaxies?
- Observations
  - ATCA-HI observations of NGC 3100

    Maccagni, Kleiner, Ruffa, Ragusa, Loni, Serra, Prandoni, Iodice
  - MeerKAT-HI observations of NGC1566 & NGC5643

    Mhongoose, MeerKAT open time
  - MeerKAT, ALMA, MUSE observations of Fornax A

    MeerKAT Fornax Survey — Maccagni et al. 2020, Maccagni et al. 2021
- Bring home message
  - The look of HI in galaxies is changing thanks to the SKA precursors
    - We can <u>for the first time</u> to study extensively the physics of low column density HI (<10^19 cm-2).
    - Multi-wavelength studies of nearby galaxies (<1000 Mpc) are crucial to understand the life-cycle of AGNs

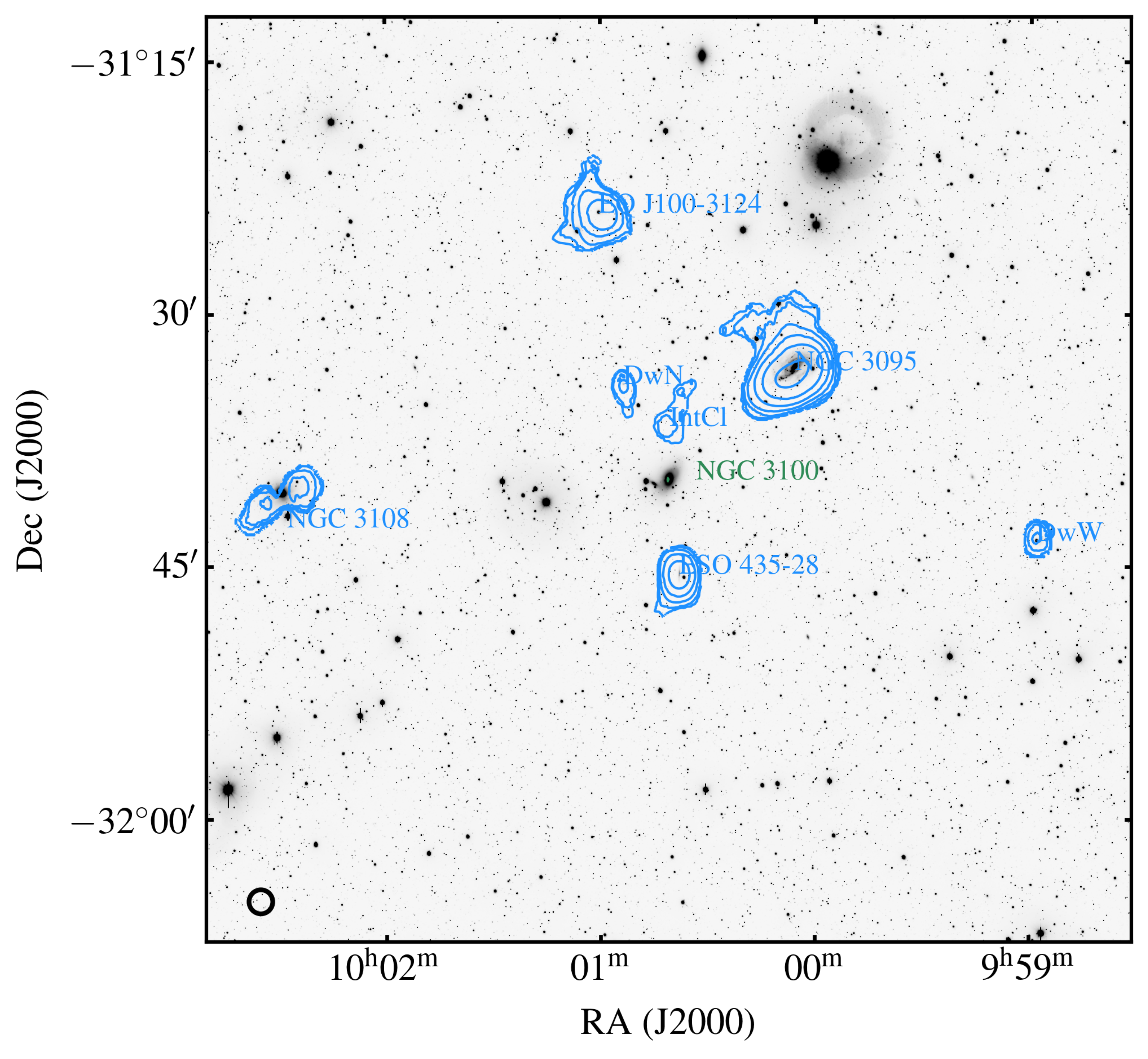
NGC3100

Radio loud ETG
<u>Ilaria's talk</u>

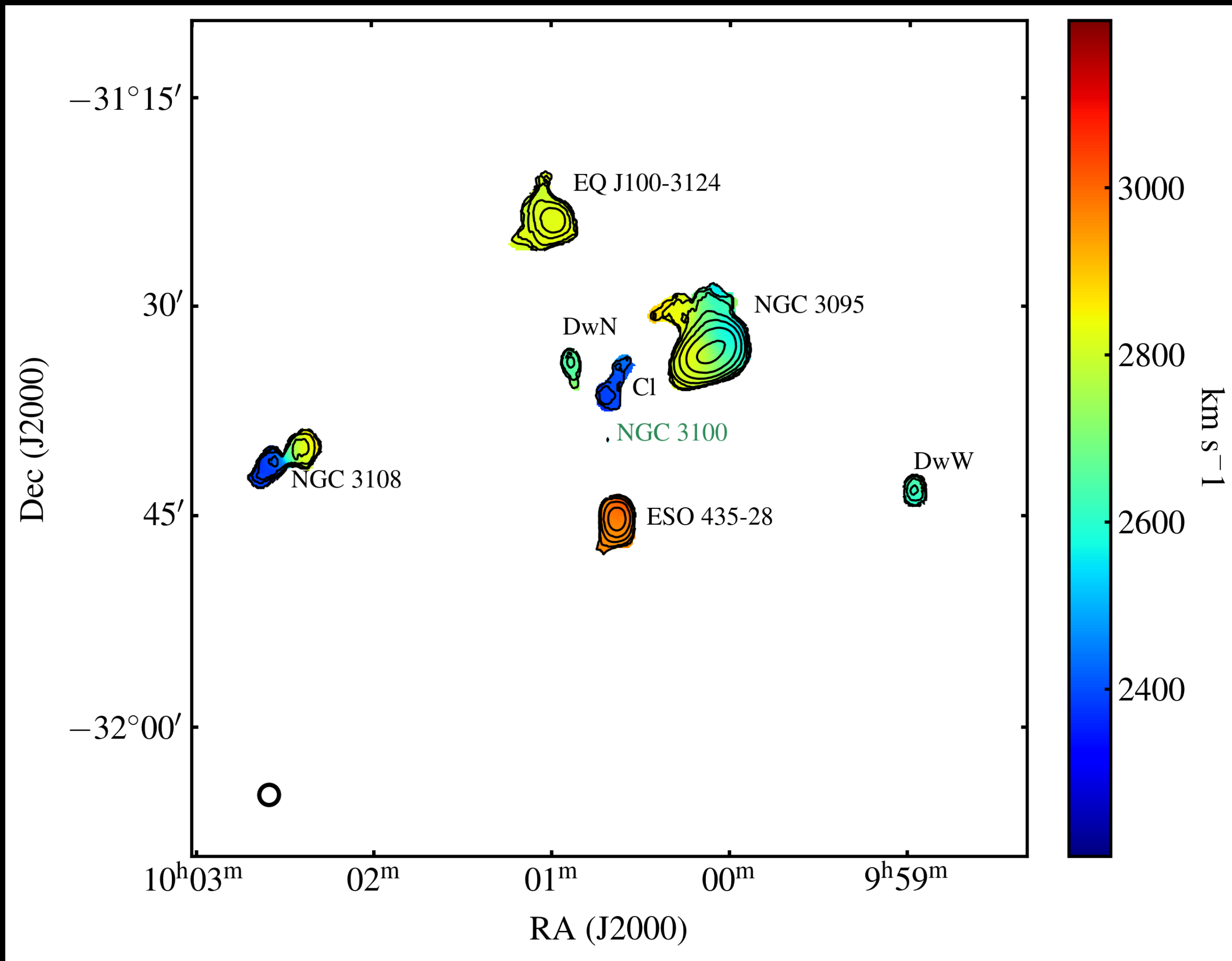
36hrs ATCA HI observations

6 antennas, 6.6 km/s
Datacube noise: 1 mJy/b channel

3σ detection limit cm^{-2} — 90" resolution: ~1 x 10^19 cm^{-2}



NGC3100

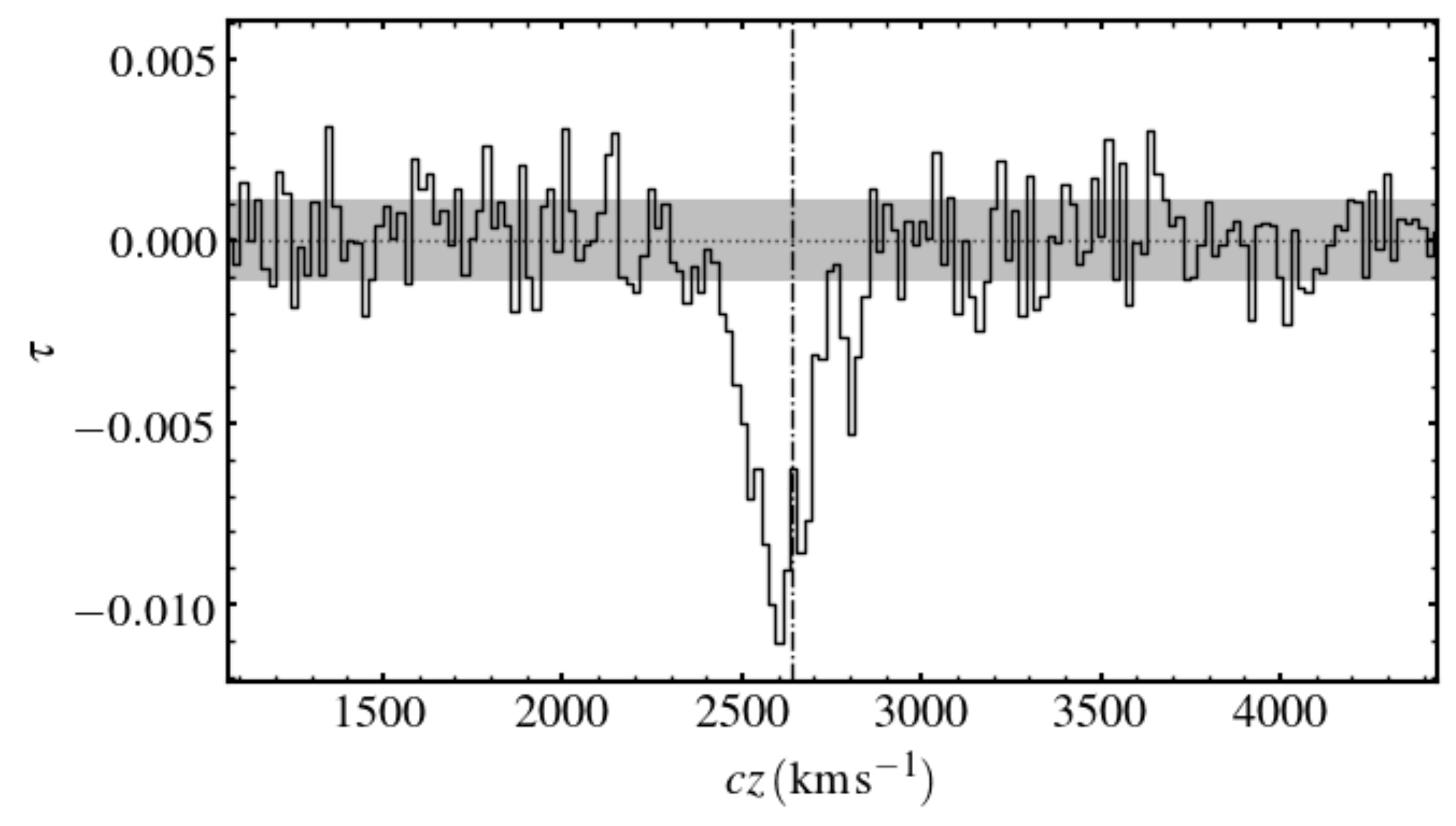


An HI rich group is revealed

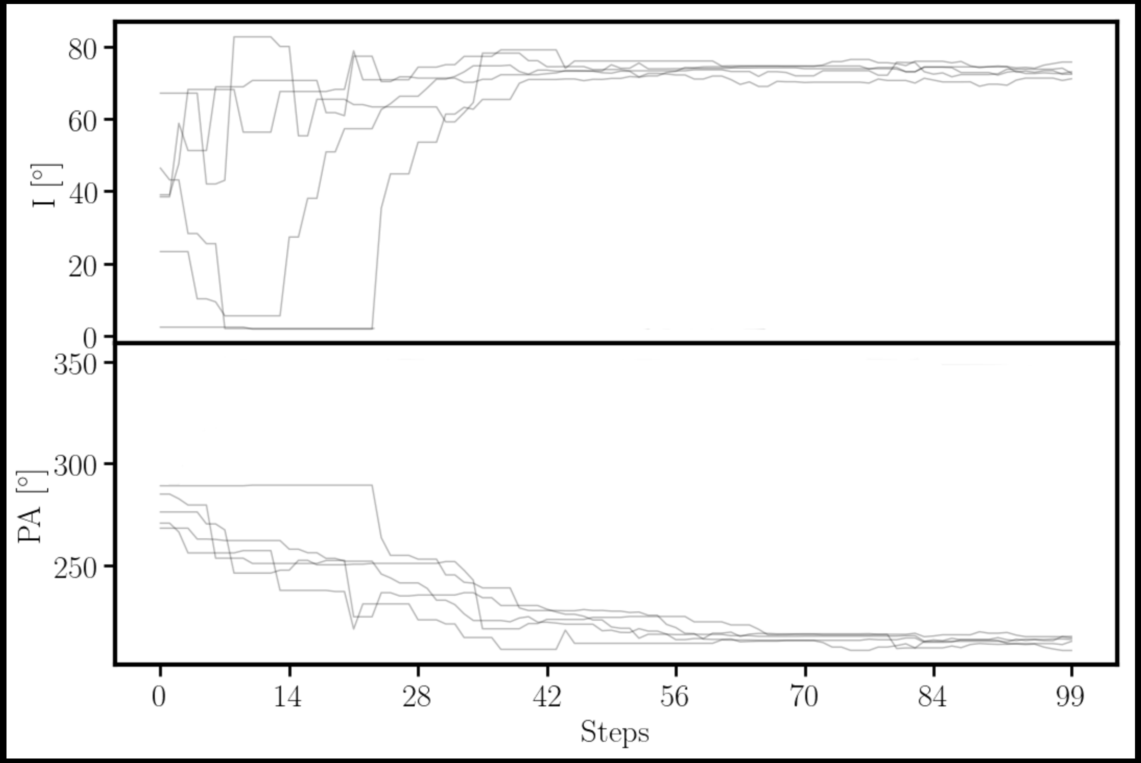
New detections:

- DWN, DWW & Cl
- Asymmetries in J100-324, NGC3095

NGC3100
broad (500km/s) HI absorption

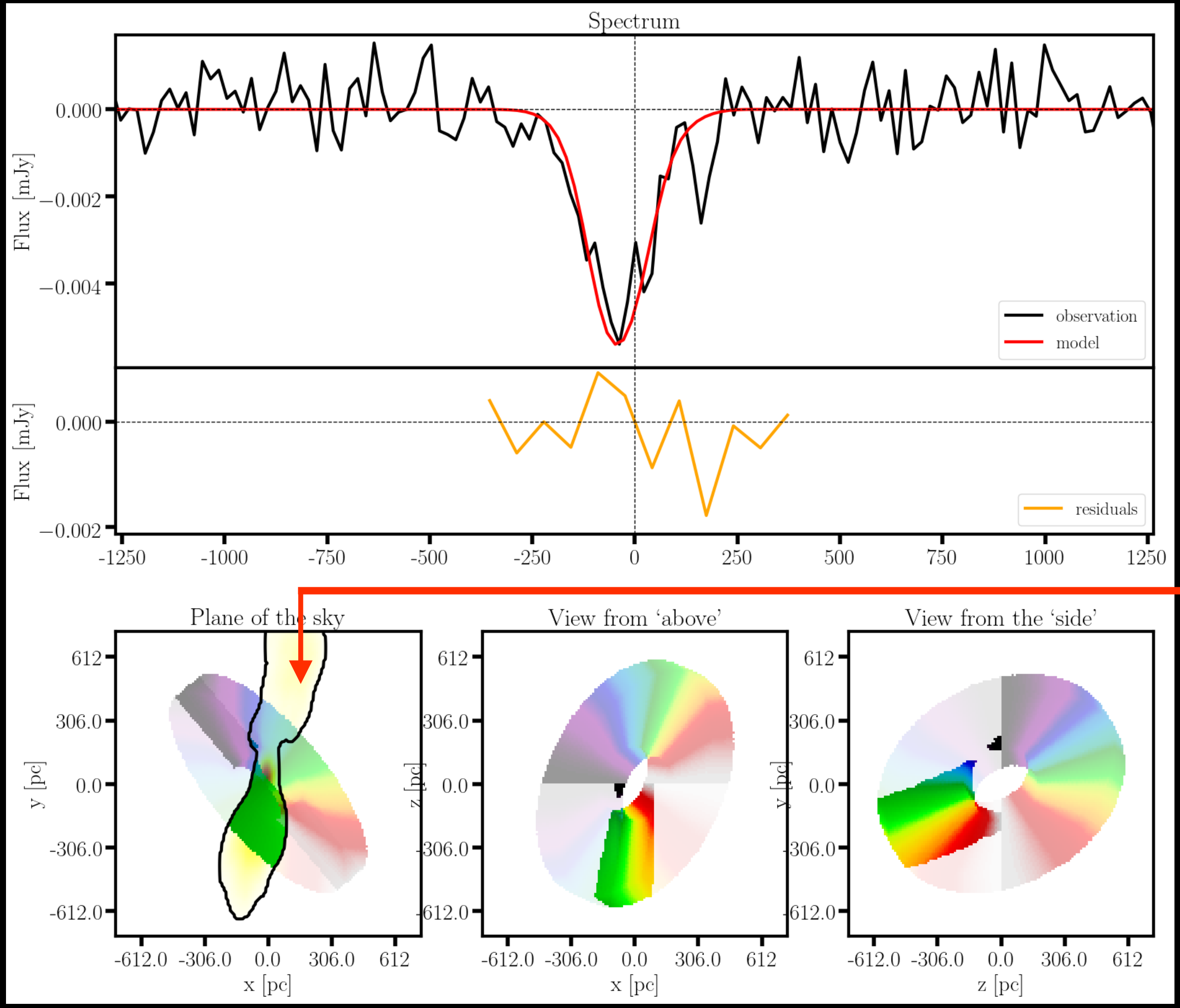


NGC3100: Modelling the Absorption

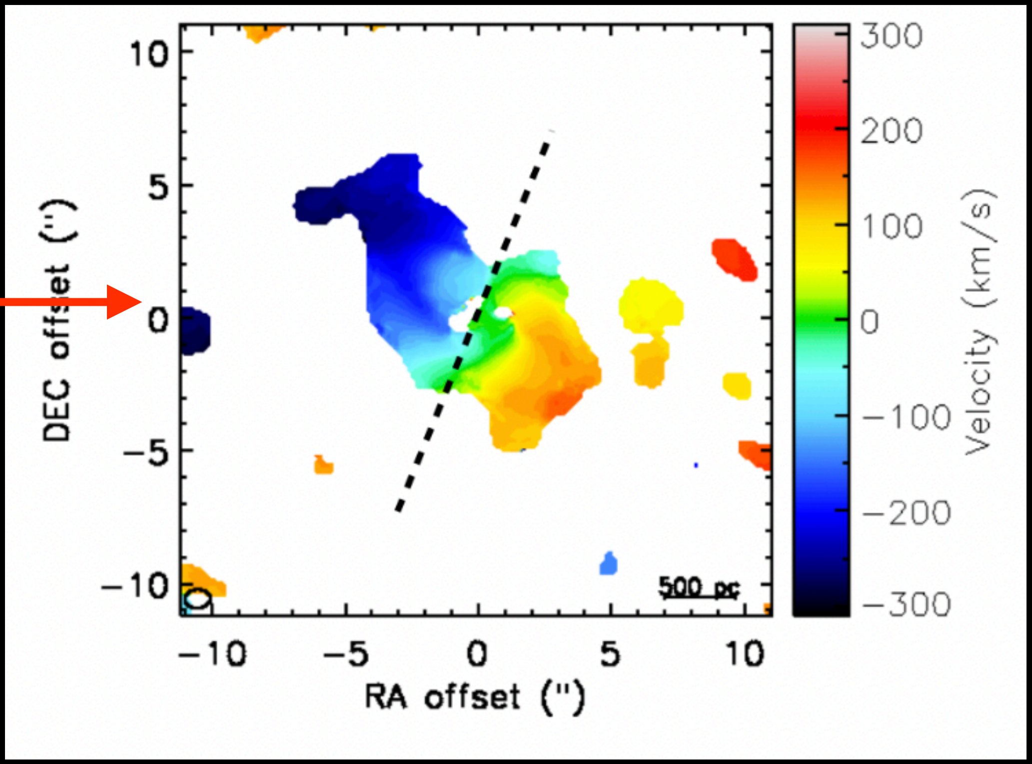


Mod_Abs : geometrical model of a disk in front of radio continuum.

- MCMC fit all possible inclinations and PA of that produce an absorption line



The best match has i & PA equal to the CO disk (Ruffa et al. 2020)



From ATCA to MeerKAT

10 hours observations with MeerKAT of 2 nearby massive Seyfert galaxies

64 antennas, 25 kHz (1 km/s) or 3.2 kHz (1.4 km/s)

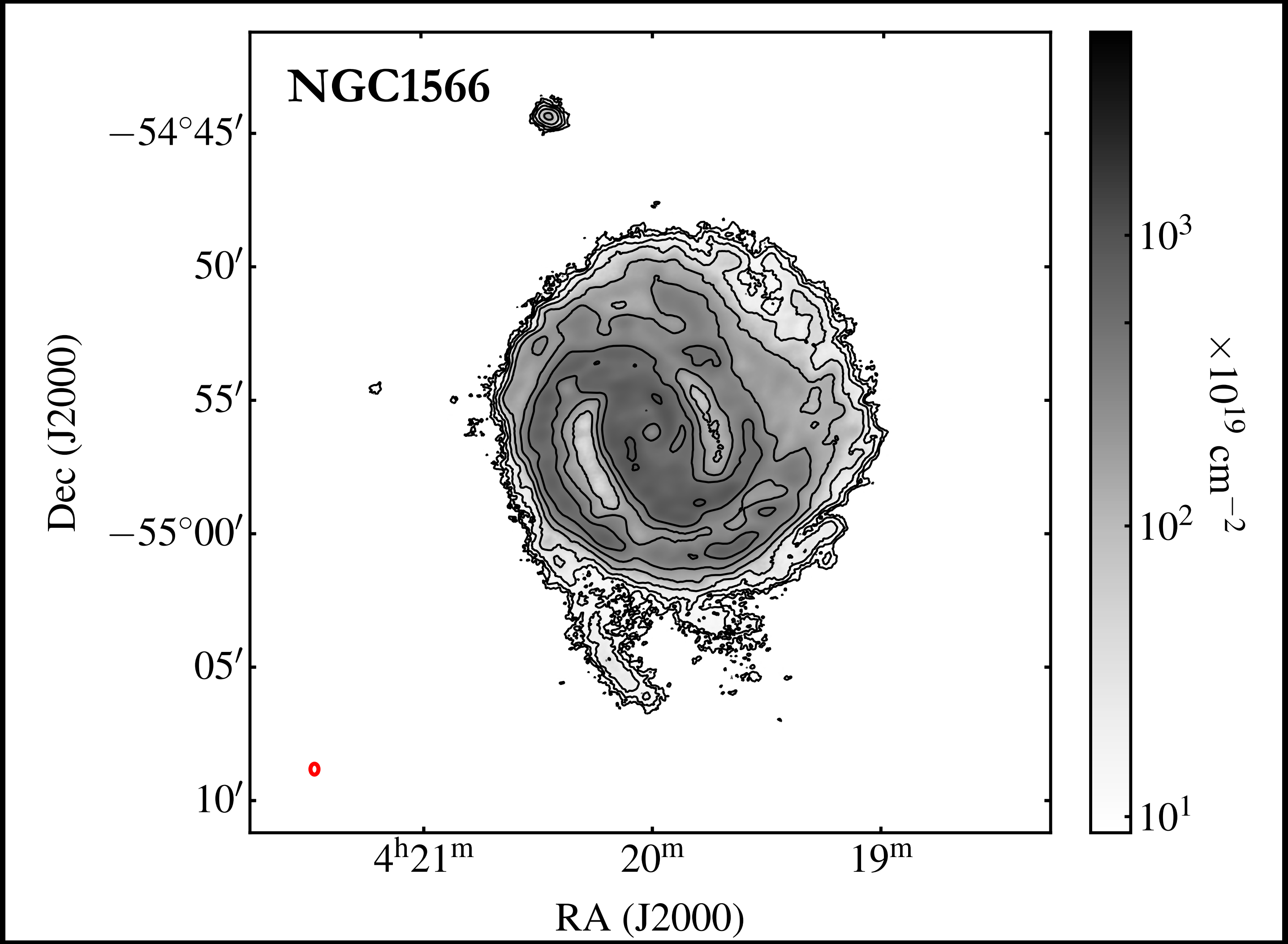
Datacube noise: 0.3 mJy/b channel

3σ detection limit cm^{-2} at 30" resolution over 5 channels: <1 x 10^^{19} cm^{-2}

NGC1566 (Mhongoose, PI de Blok)

Mhongoose: MeerKAT LSP of 30 nearby galaxies of varying masses observed for 60 hours.

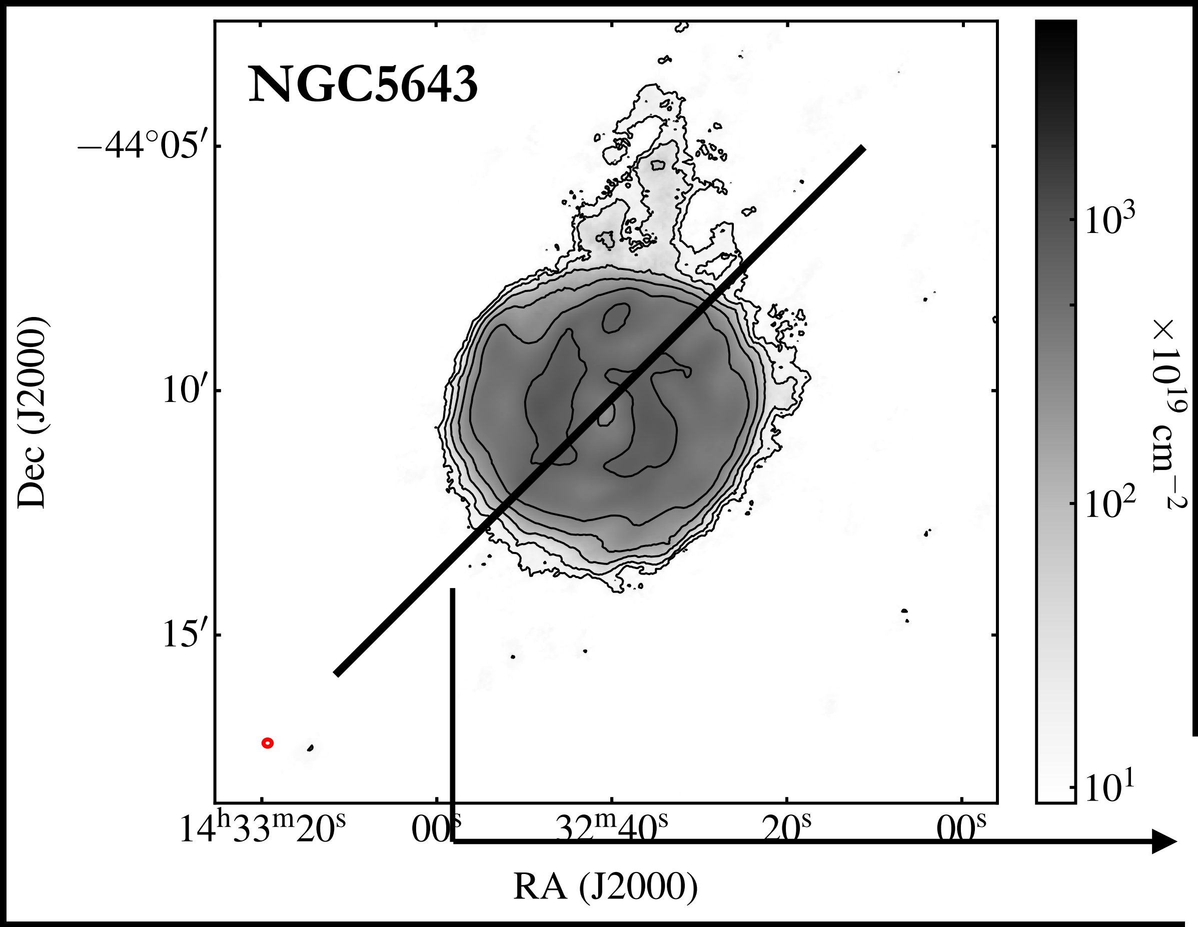
Extra-planar low-column density gas (~10^^{19}) easily detected.



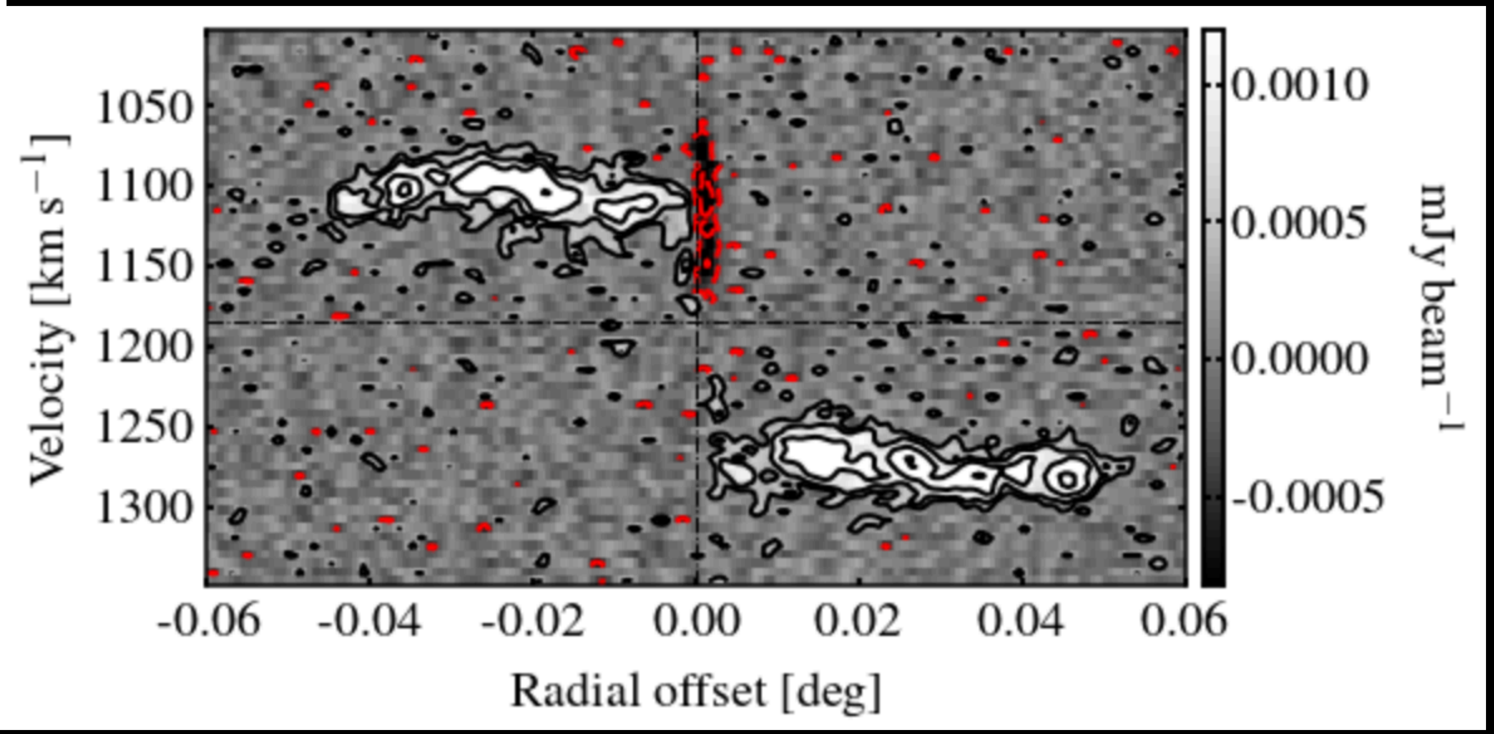
From ATCA to MeerKAT

HI Gas Accretion in Seyferts (PI Maccagni + INAF-OAC-BO-FI + ASTRON + SARAO + Curtin)

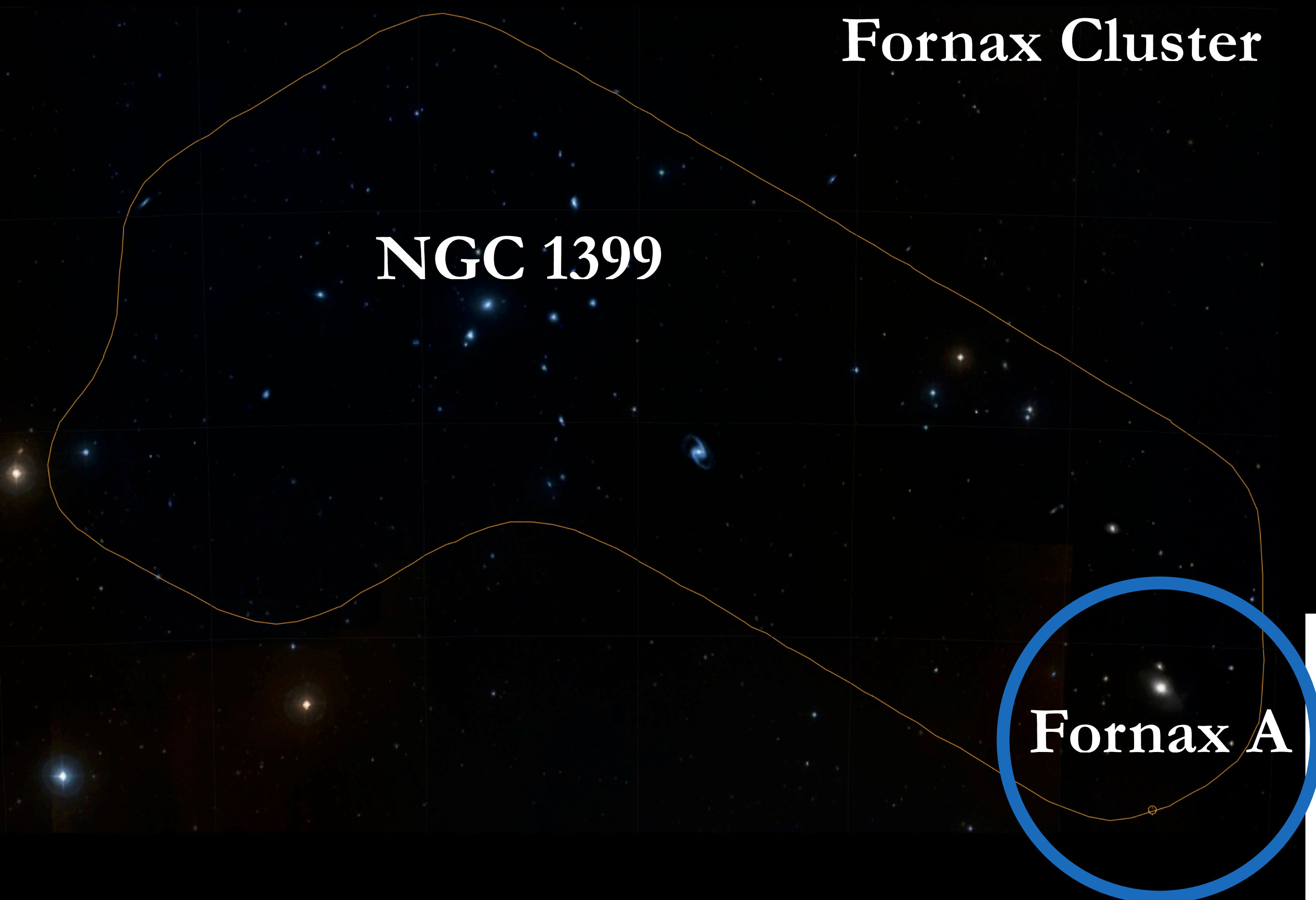
- MeerKAT open time 10 hrs HI observations of 4 Seyfert galaxies
  - N5643, N1433, ESO 428GO14 & CenA



- <10^19 cm-2 HI stream
- HI blue-shifted absorption ($S_{1.4GHz}$=25 mJy)
- Possible outflow (?)

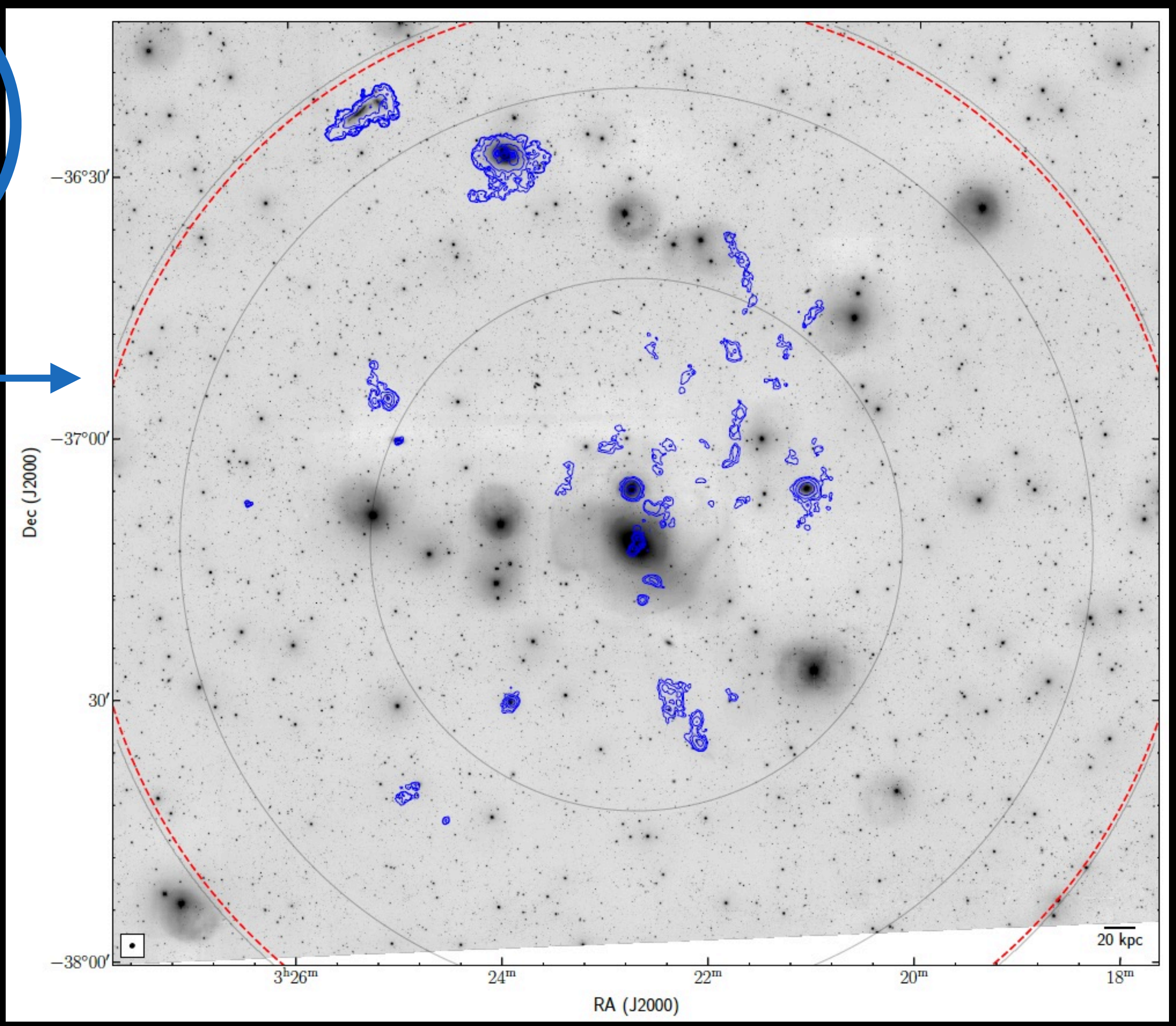


Fornax A



Fornax A (NGC 1316) belongs to a group falling into the Fornax cluster.

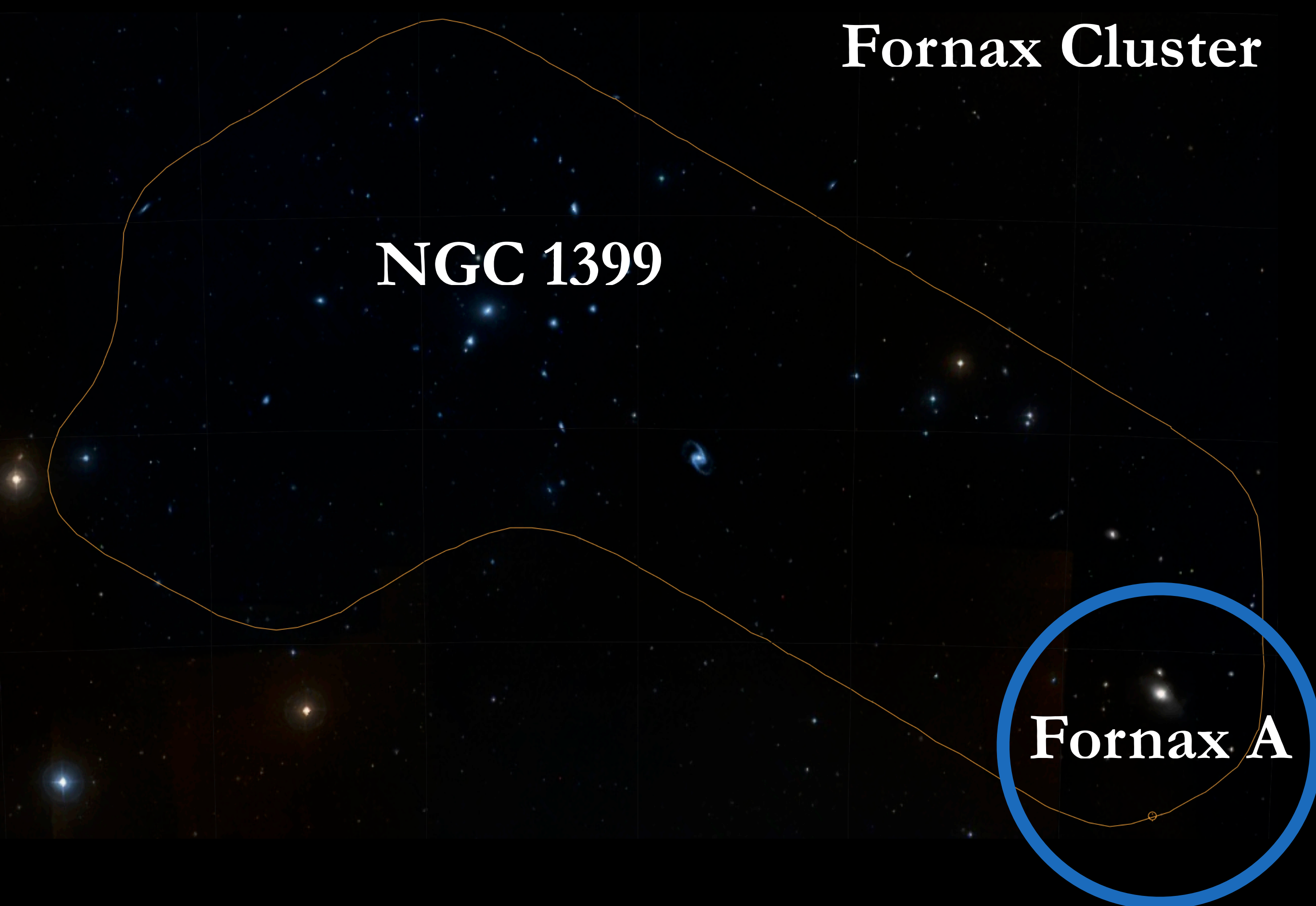
$D_L \sim 20$ Mpc

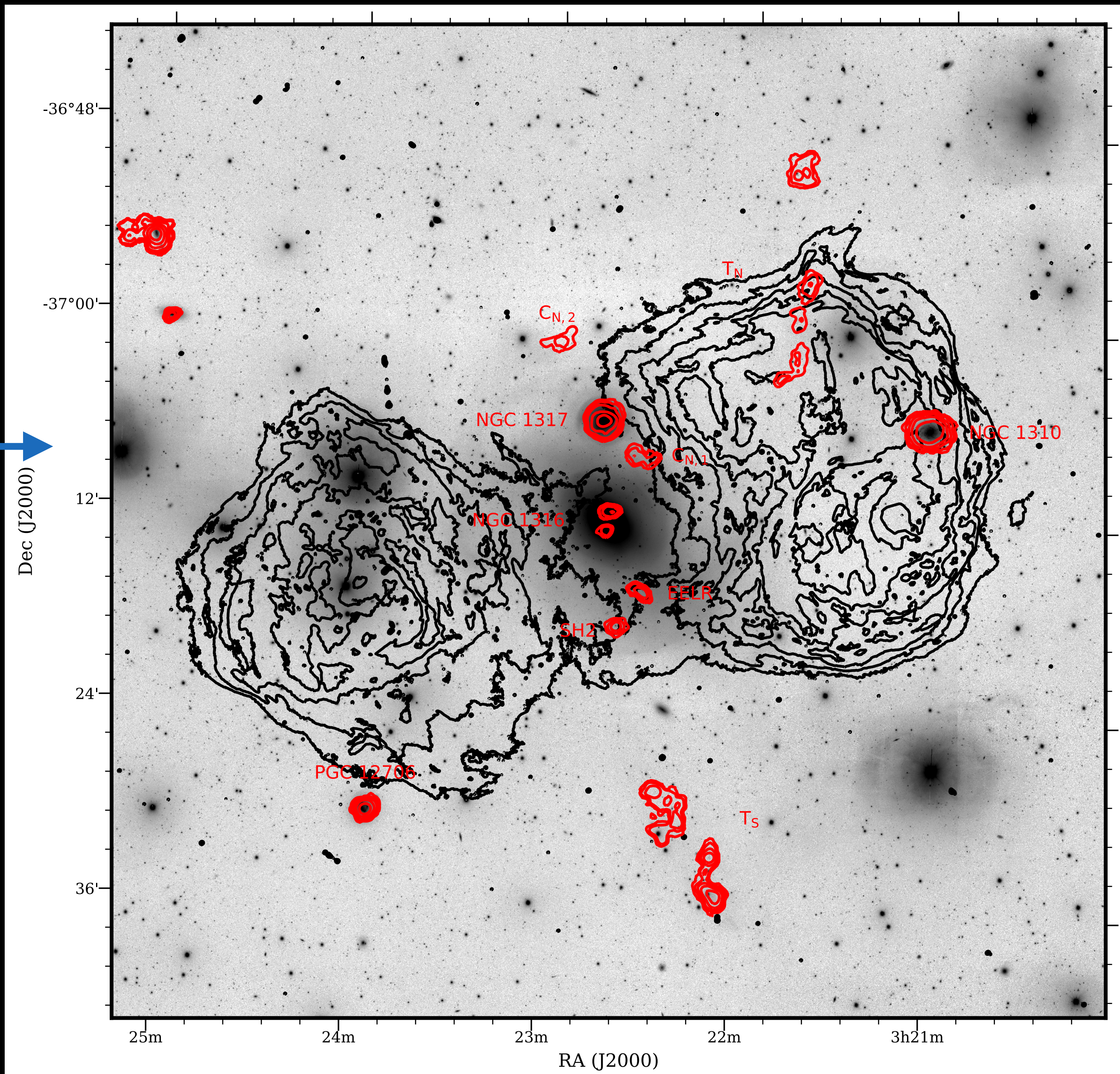


- **MeerKAT 40+60 antennas, ~18 hours**
- **New HI clouds and streams**

  <u>Serra, et al. 2019, Kleiner et al. 2021</u>

Fornax A





3rd near brightest nearby radio galaxy

(S_{tot}(1.4GHz) ~ 130 Jy)

Giant filamentary radio lobes (300 kpc)

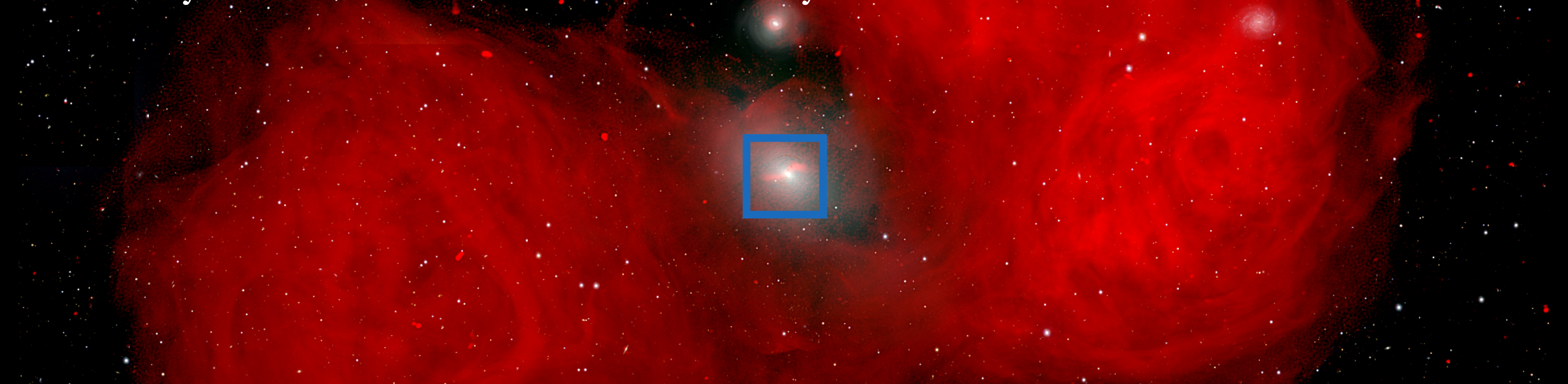
Fornax A — Outline

- The flickering activity of Fornax A [Maccagni et al., 2020]

F. Maccagni, M. Murgia, P. Serra, F. Govoni, K. Morokuma-Matsui, D. Kleiner, D. Molnar, M. Ramatsouku [OAC (INAF)]; MeerKATHI group & MeerKAT commissioning team @ SARAO

Radio continuum observations between 84 MHz and 217 GHz

determine the flux density distribution of the radio lobes and jets and <u>infer the history and timescale of the nuclear activity of Fornax A</u>



- AGN Feeding and Feedback in Fornax A (r<6 kpc) [Maccagni et al. 2021]

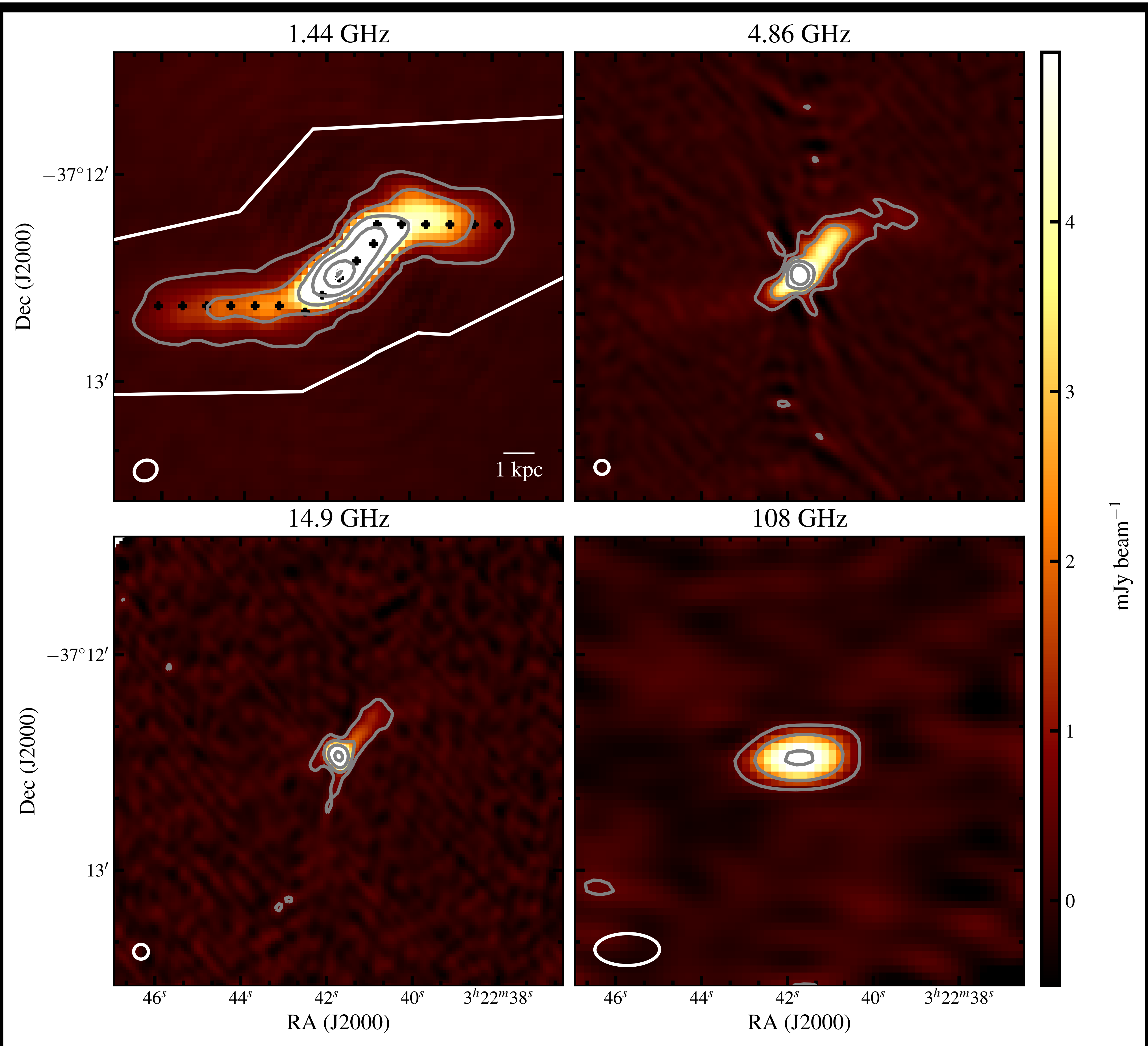
F. Maccagni, P. Serra [OAC-INAF], M. Gaspari [Princeton], T. Oosterloo [Astron], K. Morokuma-Matsui [IOA - Tokyo Uni.], M. Onodera [NAOJ], D. Kleiner [INAF-OAC]

CO (1-0), HI & Ionized gas

<u>what processes sustain the rapid recursive activity of Fornax A</u>

[Maccagni & Kleiner]

The Central Jets



The Flickering Activity of Fornax A

Phase 1:

- 24 Myr ago began the <u>last</u> injection of the lobes
- 12 Myr ago AGN switch-off

Phase 2:

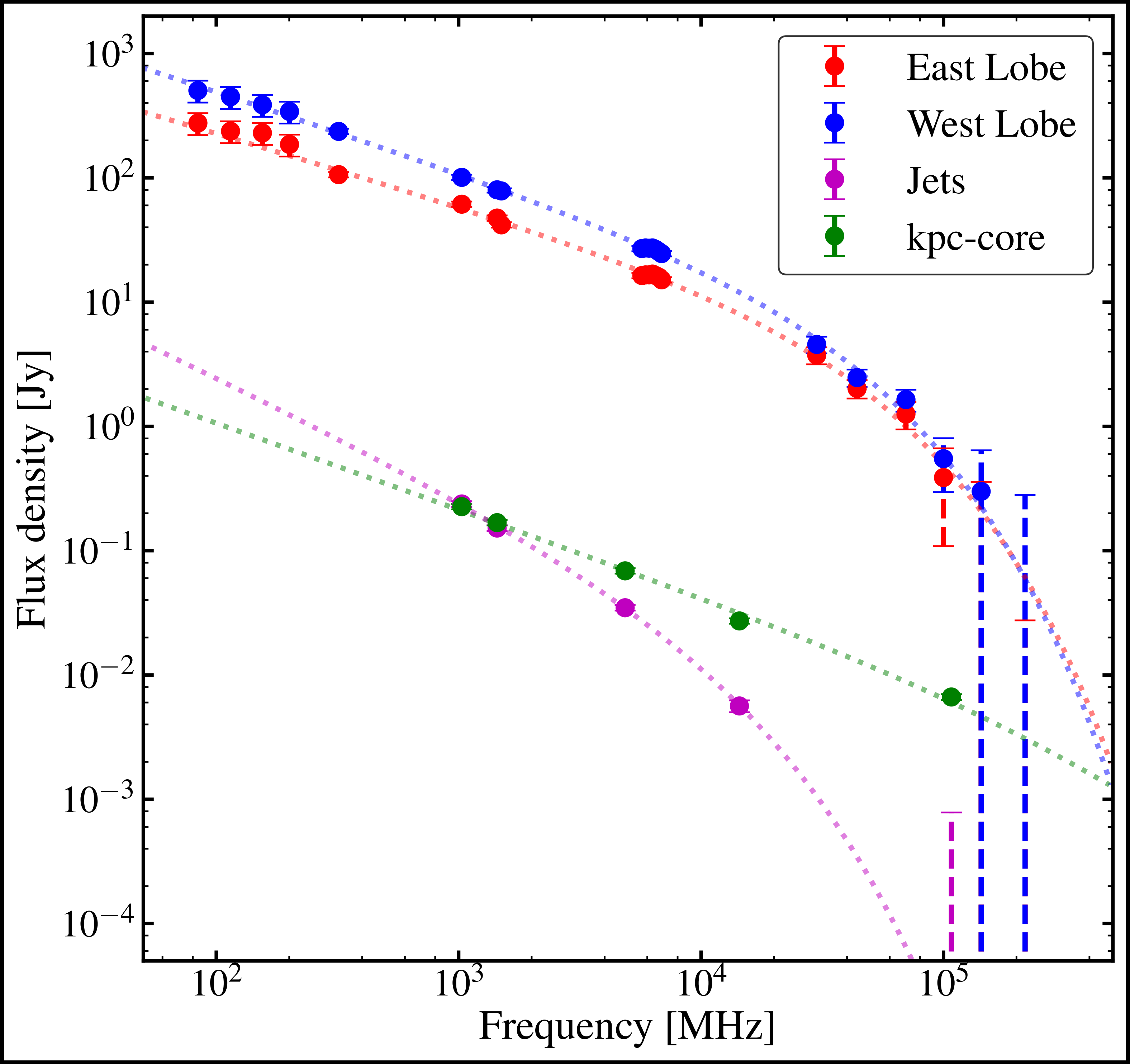
- 3 Myr ago AGN formed the jets
- 1 Myr ago AGN switch-off

Phase 3:

- kpc-core may be active (< 1 Myr)

<u>What regulates the fast duty cycle?</u>

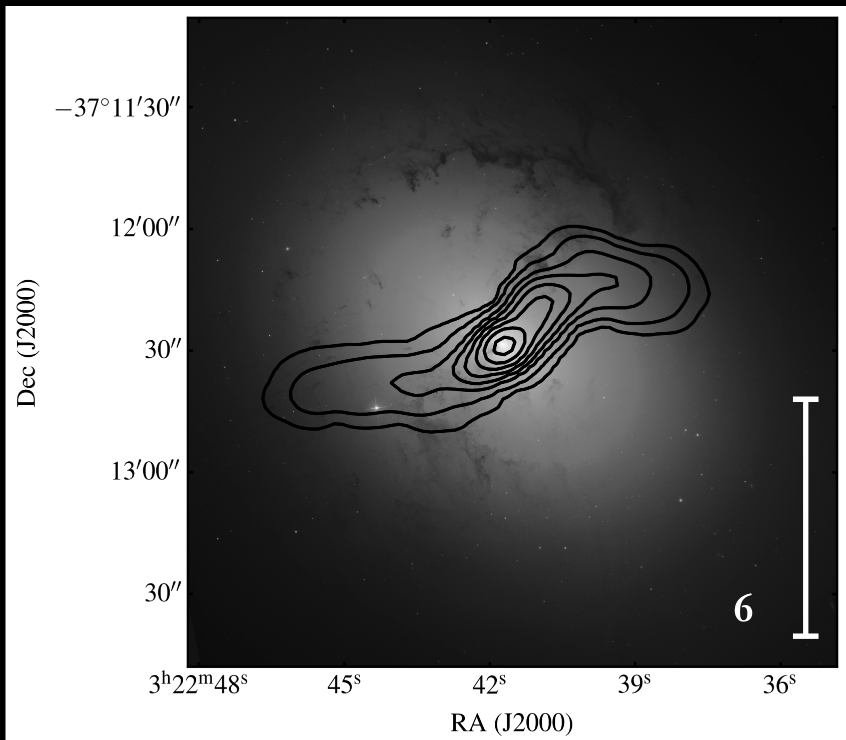
merger 1 Gyr: did not trigger the latest phases of the AGN but brought turbulent gas and filaments



<u>[Maccagni et al., 2020]</u>

Cold Gas Distribution and Kinematics

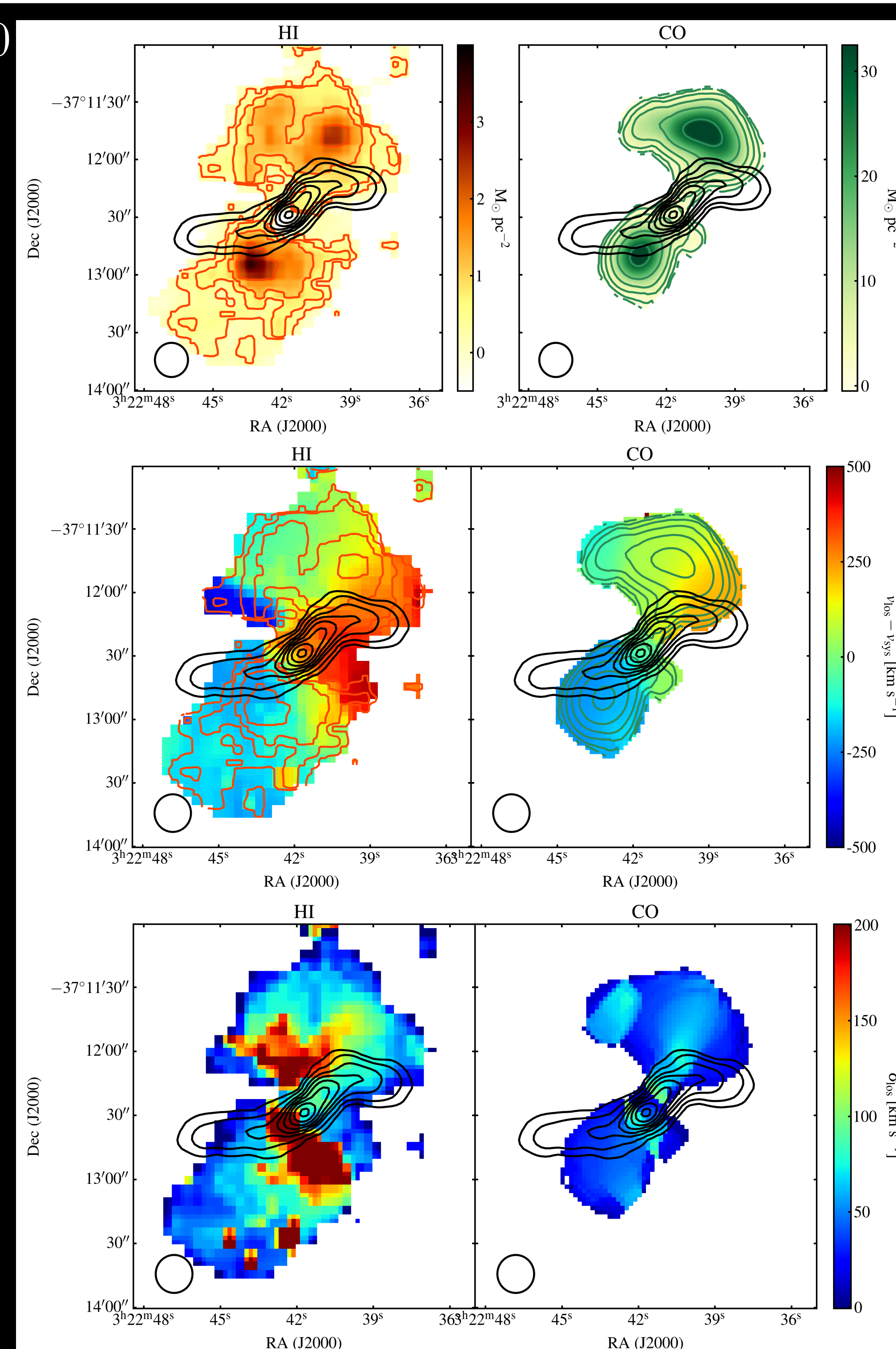
Dust



HI, CO (1-0) — Mom 0

Mom 1

Mom 2



M (HI) = 6.7 x 10^7 M $_\odot$

M (H2) = 5.8 x 10^8 M $_\odot$

Rotation axis of the gas (NW-SE) perpendicular to the stellar body

Several deviations from rotation

Ionised Gas Distribution and Kinematics

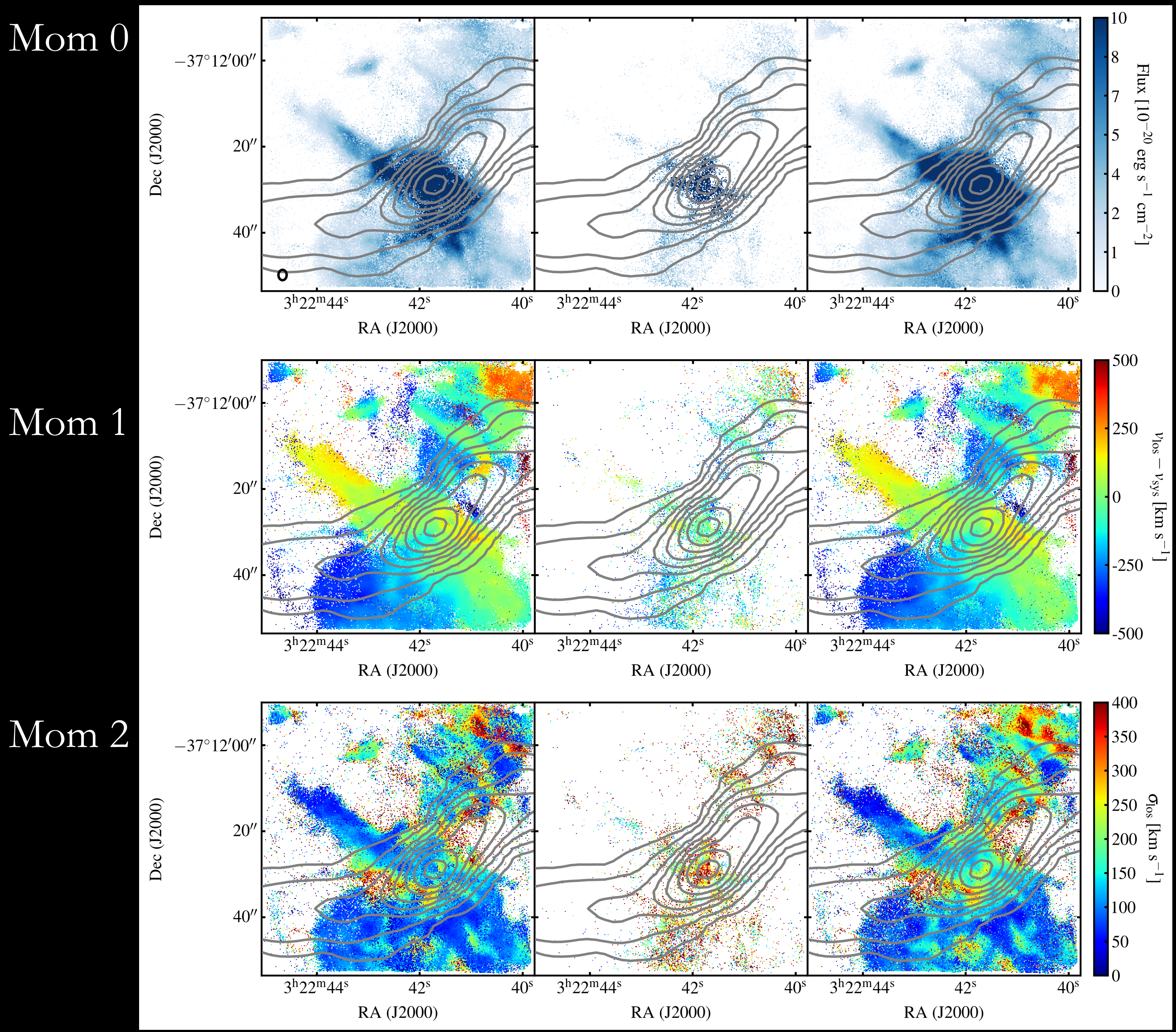
Moment maps from simultaneous multi-component fits of [OIII], Balmer lines, [SII] and [NII] ([OI] is also detected)

Rotation axis (NW-SE) similar to the cold gas

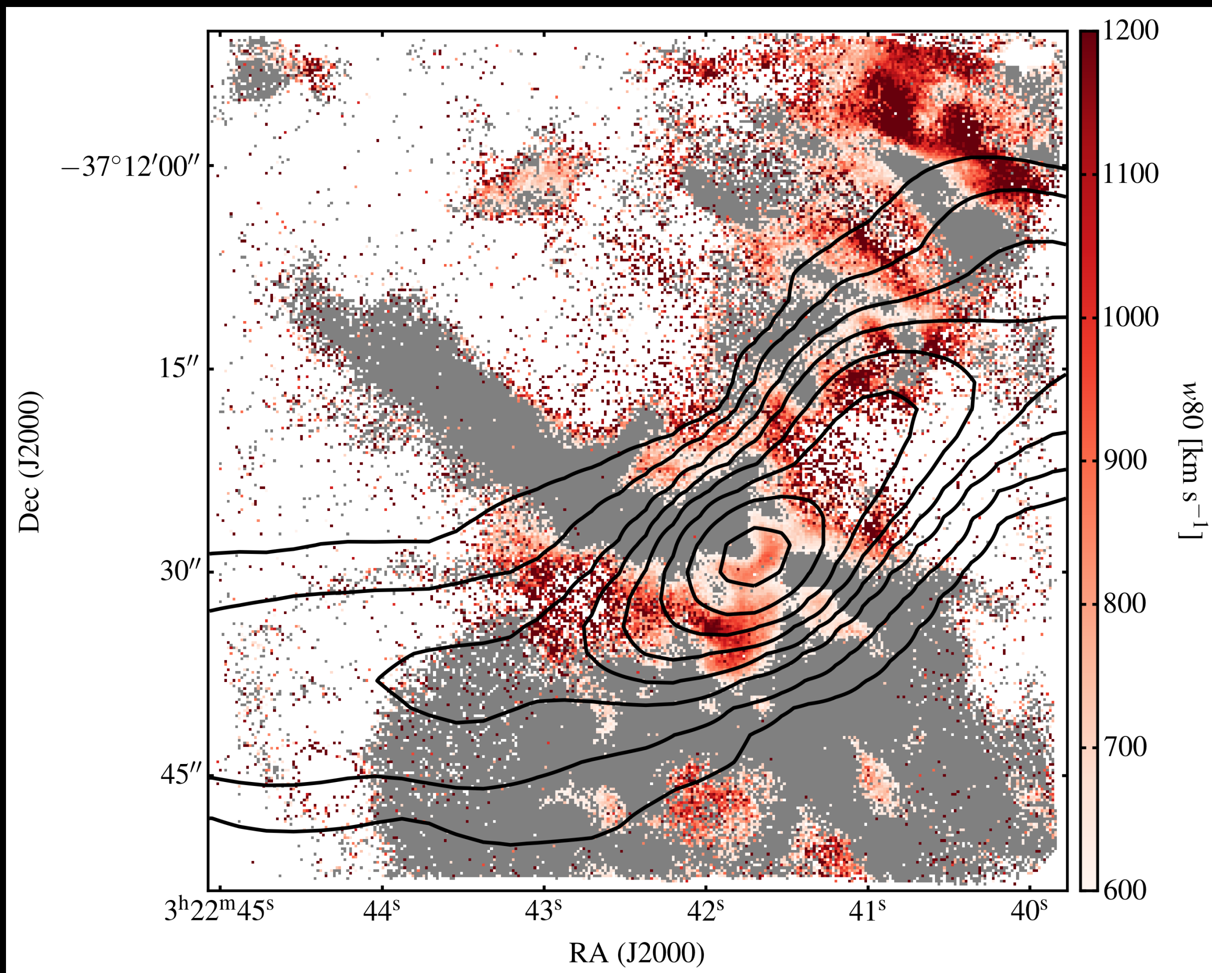
Several deviations:

- EW stripe & filaments
- Clouds in the wake of the radio jets

M (Ion) = 1.6 x 10^6 $M_\odot$



Multi-Phase Outflow in Fornax A

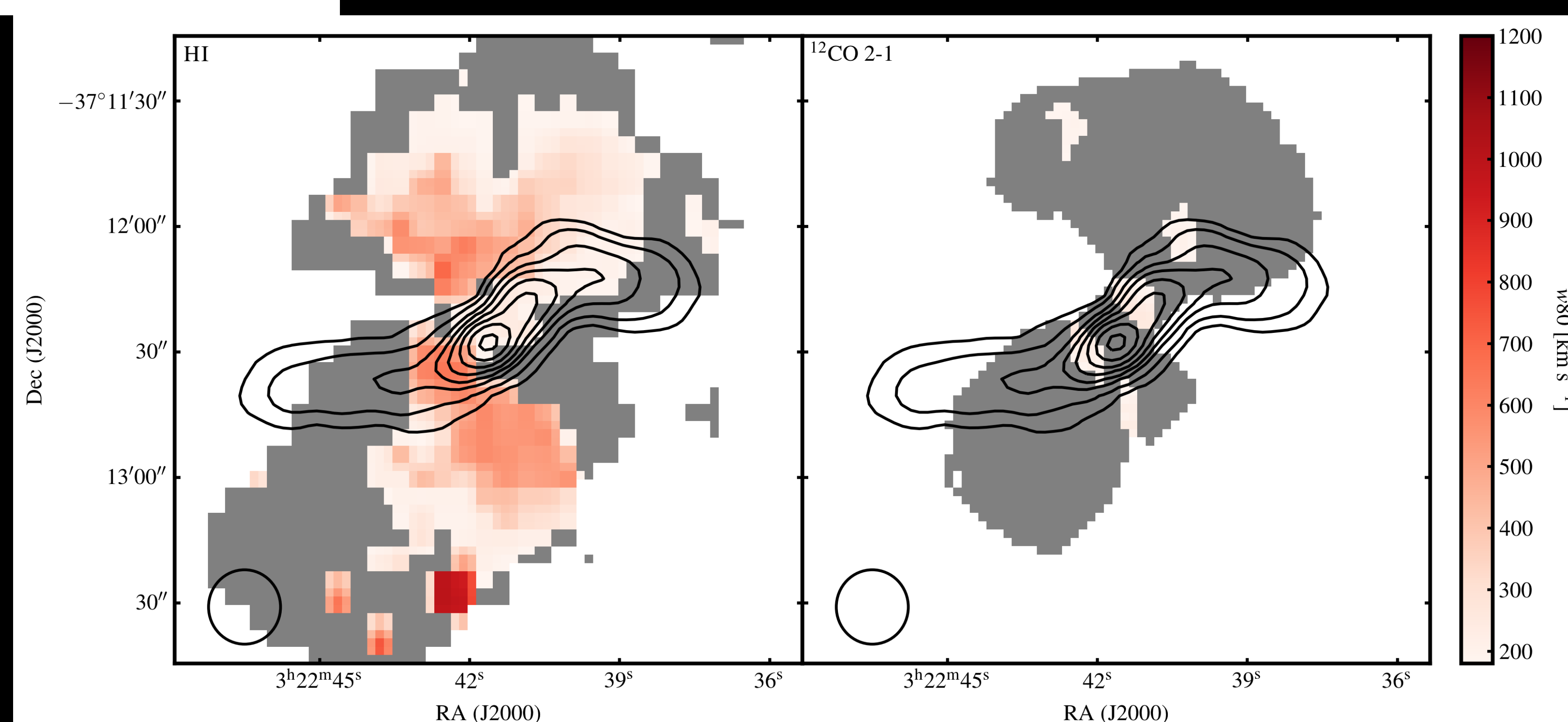


- <u>Ionised gas:</u>
  - w80 > 600 km s^{-1} in the wake of the radio jets
- <u>Cold gas</u>
  - w80 > 600 km s^{-1} in along the jets and in the outer ring

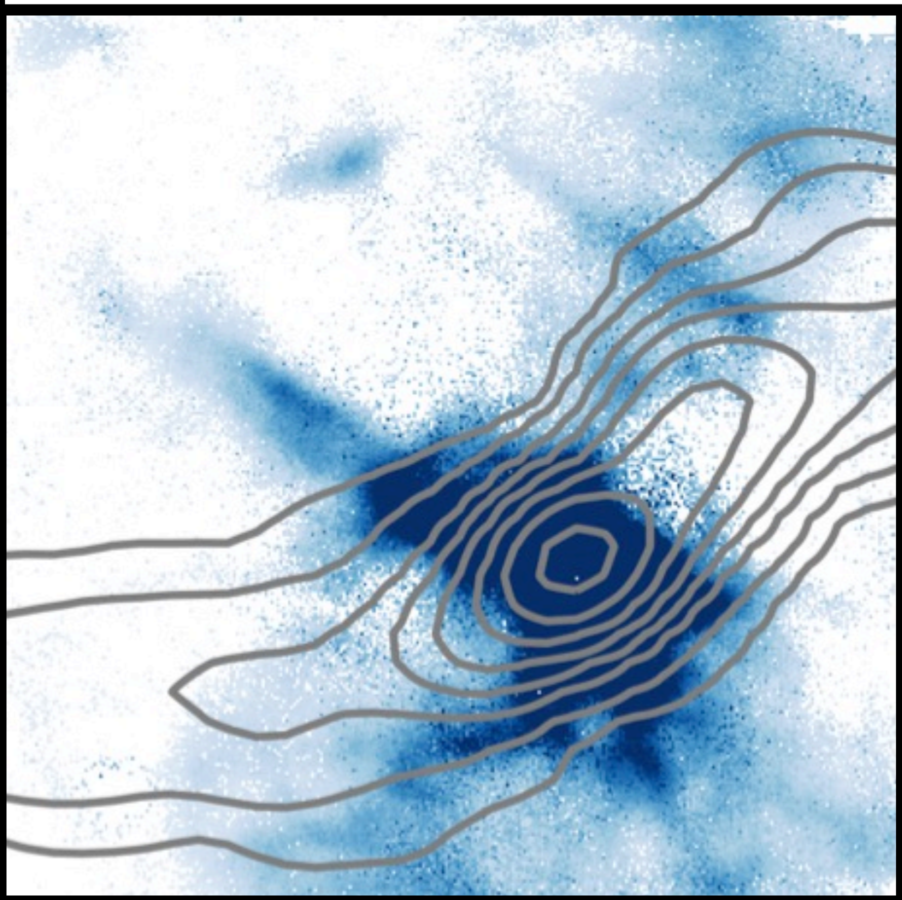
- At its outflow velocity (2000 km s^{-1}) the outer ring would have reached its distance from the centre in ~ 3 Myr

  ==

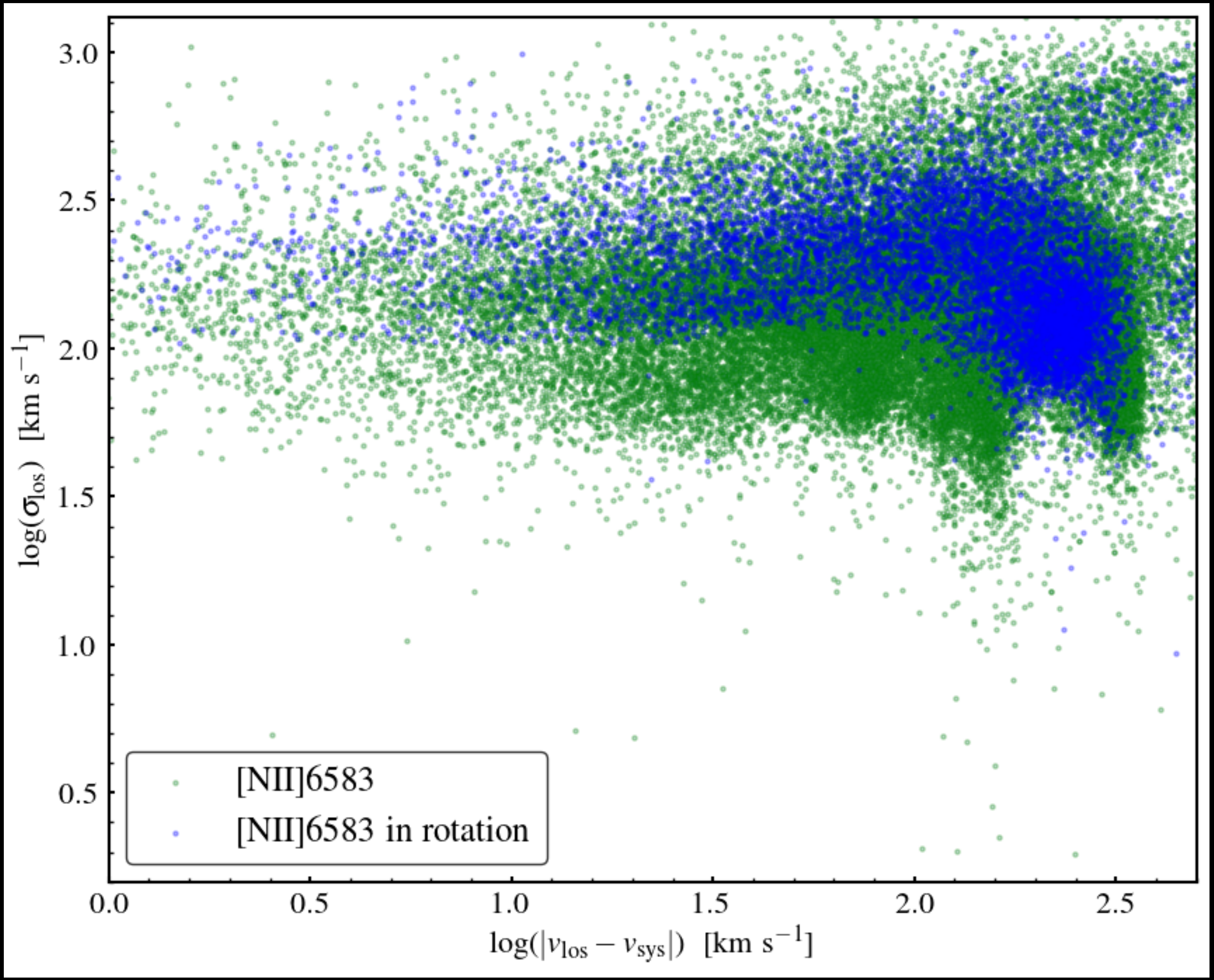
  Age of the radio jets



The Kinematical Plot (K-Plot)

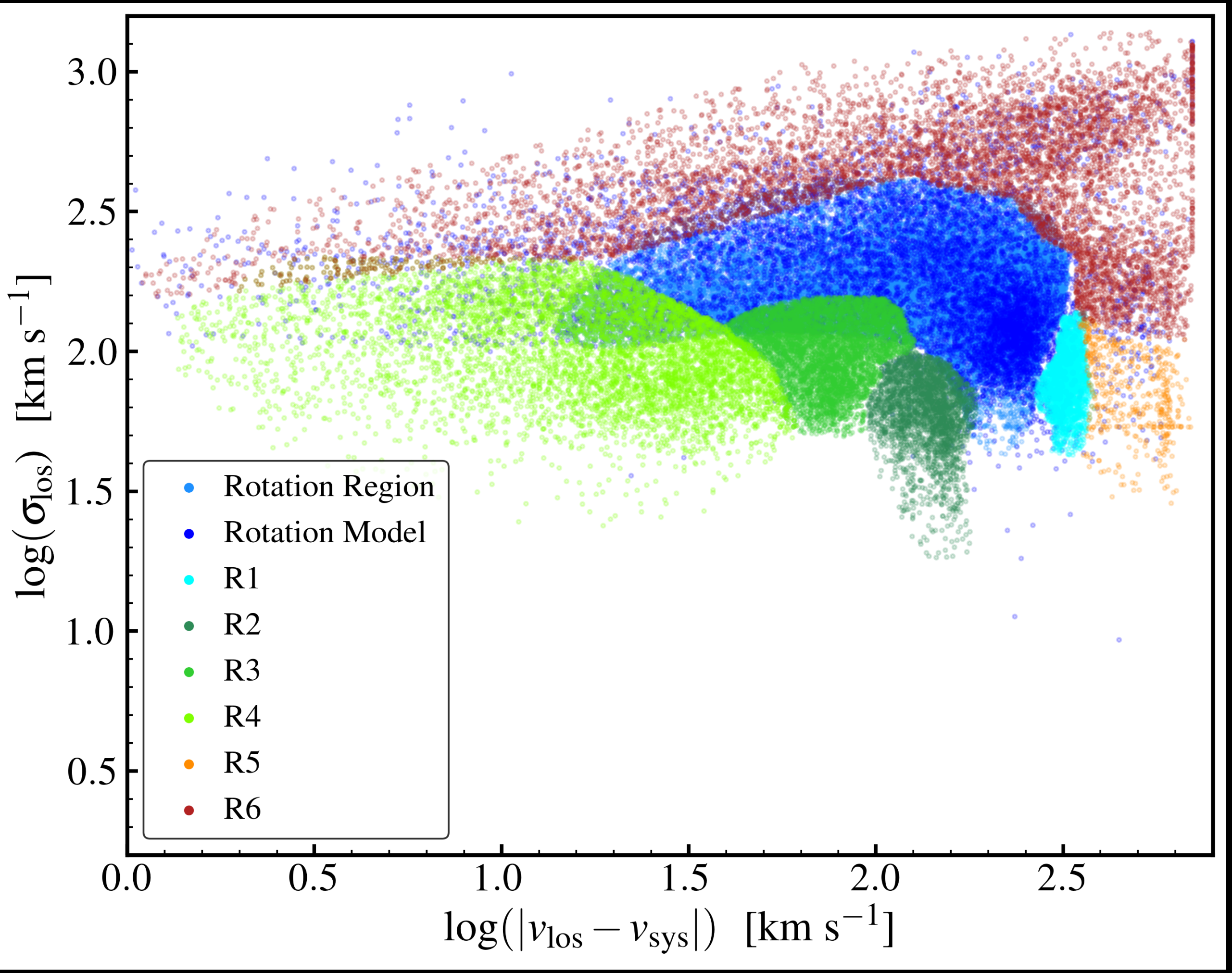


- Kinematical plot of the [NII]6583 line
  - width of the line vs velocity centroid w.r.t. v_{sys}
    - **Gaspari et al. 2018**

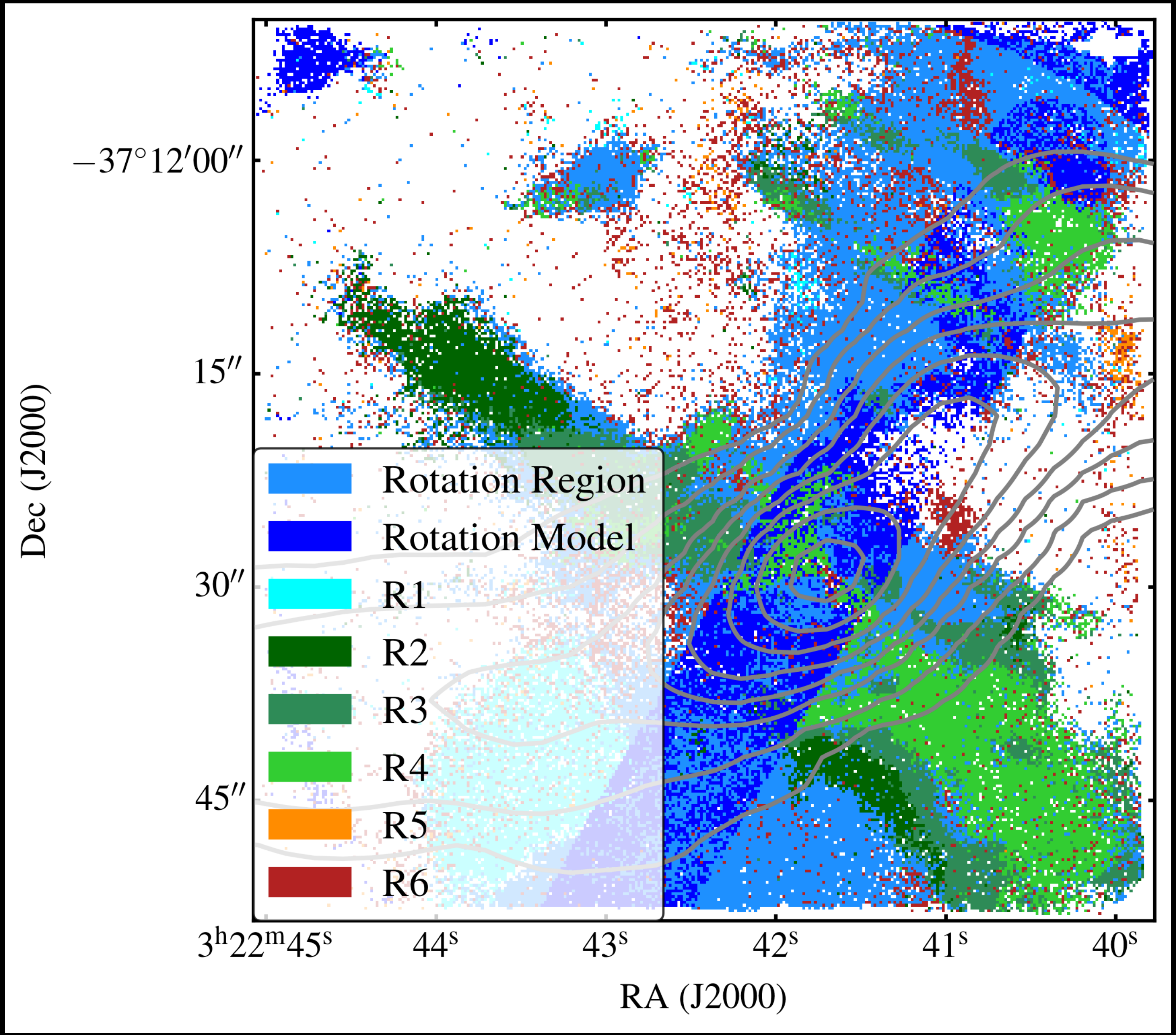


- **Green** all independent l.o.s. in the innermost arcminute
- **Blue** pixels matching with the rotating model

Regions With Similar Kinematics



- **Kinematical plot of the [NII]6583 line**
  - naturally identifies loci with common kinematics

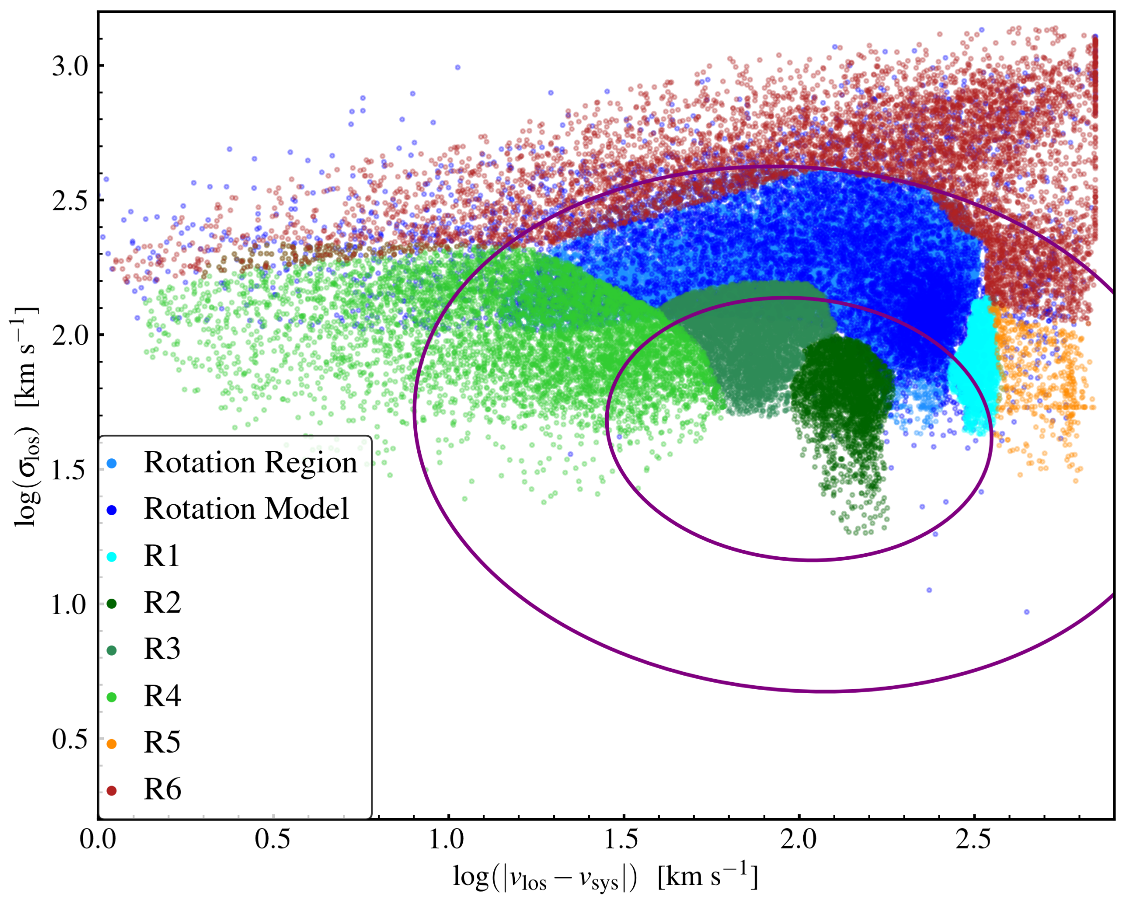


broad line-widhts (R6) -> outflow in the wake of the radio jet

narrow line-widhts -> EW stripe and filament and stripes

K-plot of HI and CO shows same properties

AGN Feeding in Fornax A



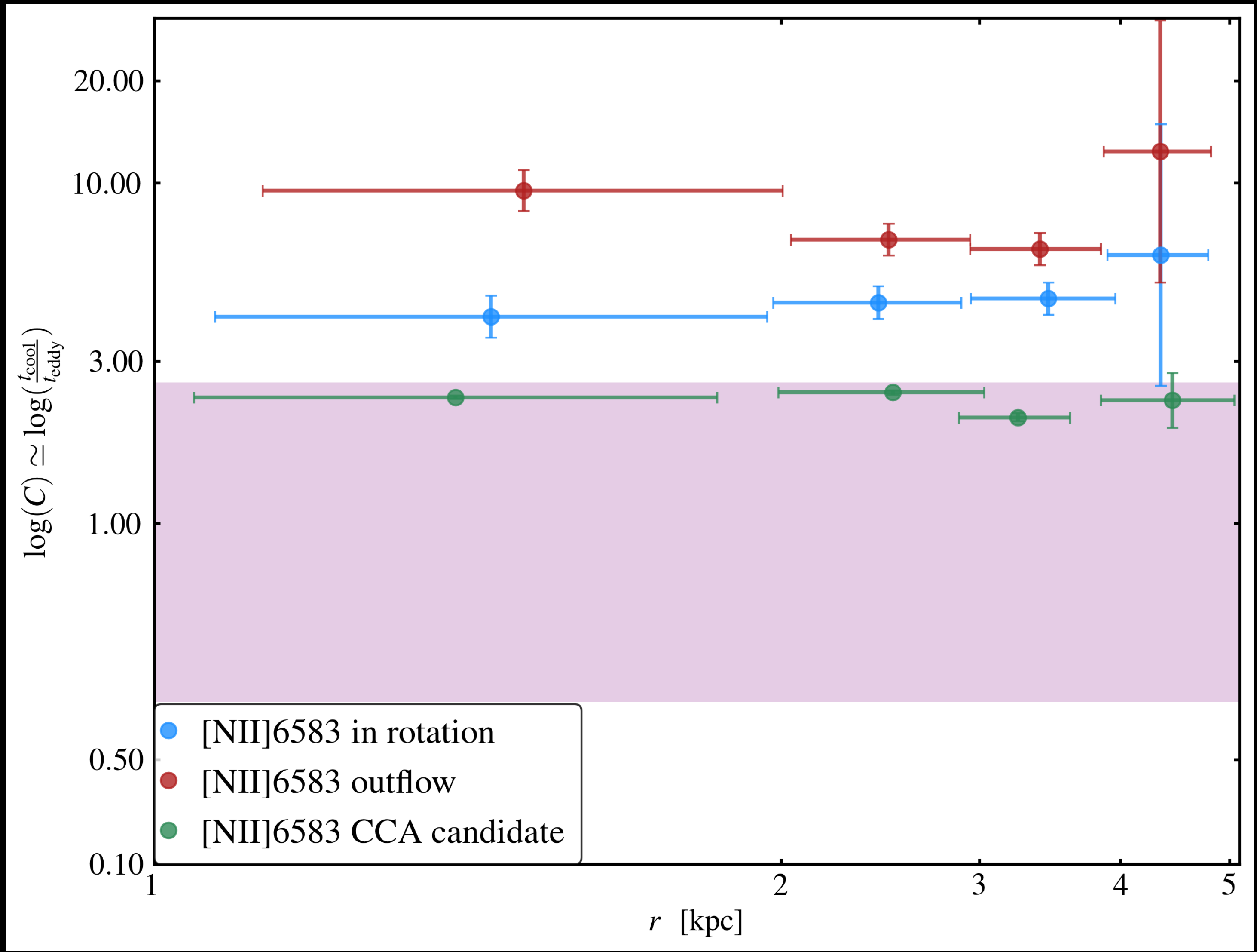
- **Purple ellipsis**
  - expectations of **Cold Chaotic Accretion** simulations (Gaspari+13,18…) for infalling material

The EW stripe and filaments may be feeding the AGN

- **C-Ratio**

cooling time / eddy turnover time

- measures the role of turbulence in causing condensation of the gas
- **EW filaments**
  - turbulence may cause cooling and infall
- **Outflow**
  - very different physical conditions



Conclusions

- The HI component of the circumnuclear disk of NGC3100 is revealed through absorption.
  - The kinematics are similar to the molecular component: rotation+inflow?/outflow?

- Short MeerKAT observations reveal low column density (10^{19} cm^{-2}) extra-planar gas and absorption against low-power radio sources (<30 mJy)

- The nucleus of Fornax A is rapidly flickering [Maccagni et al., A&A, 2020]
- MeerKAT (HI) ALMA (CO 1-0) MUSE (ionised gas) observations of the innermost 6 kpc suggest the gas is distributed in a
  - Multi-phase AGN **feedback** is on-going
    - outflow along the radio jets and in the outer ring
    - radial velocity of outflowing ring consistent with age of the radio jets
  - Multi-phase AGN **feeding** is on-going
    - EW gaseous stripe is condensing and falling onto the AGN
  - Cold chaotic accretion may be self-regulating the flickering activity of Fornax A