

MAGNHIFPIC - MeerKAT AGN HI Feeding and Feedback Investigation close-by

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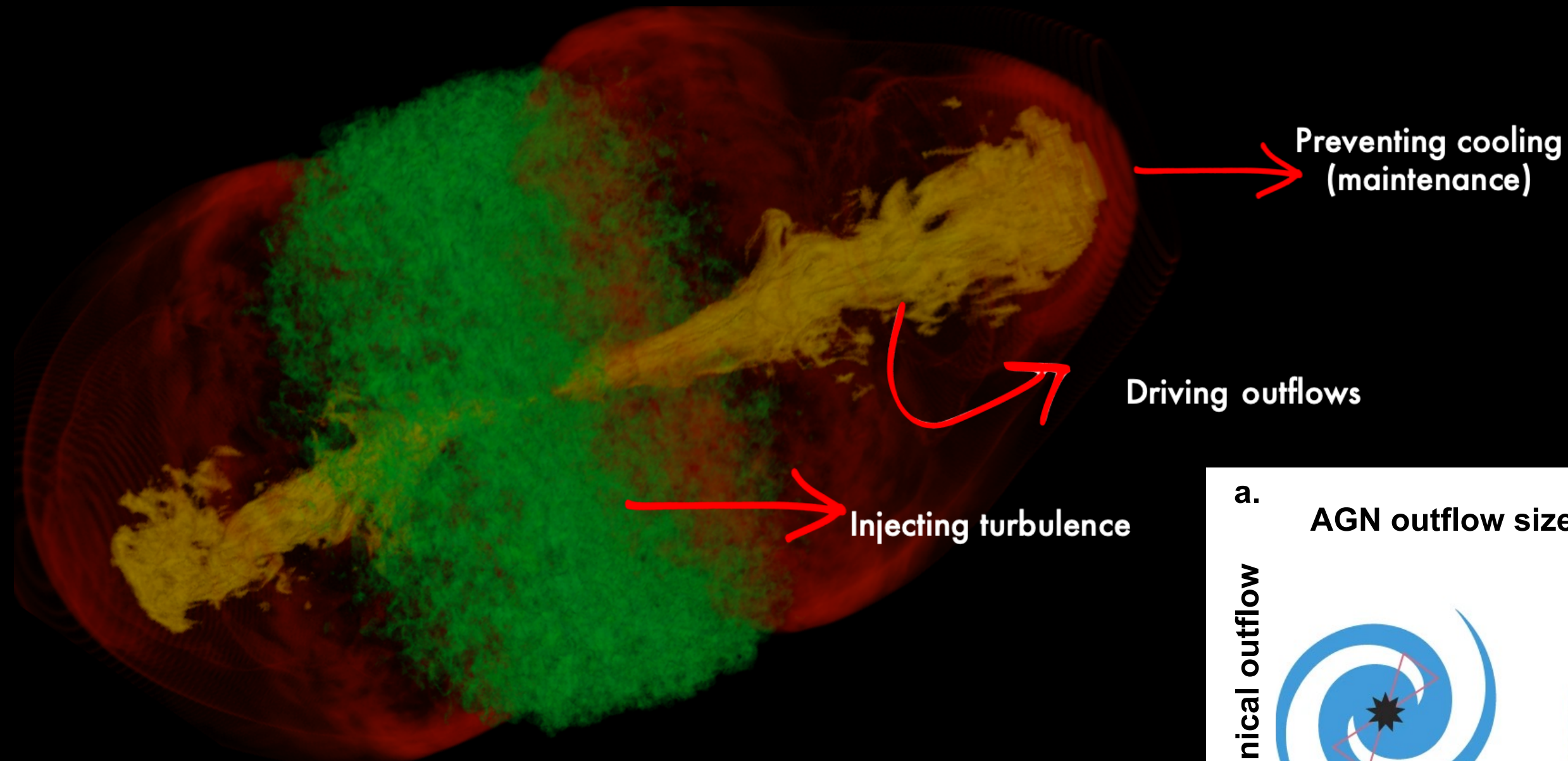


This project has received funding from the European Research Council (ERC) under the European Union's Horizon 2020 research and innovation programme (grant agreement no. No 882793/MeerGas).

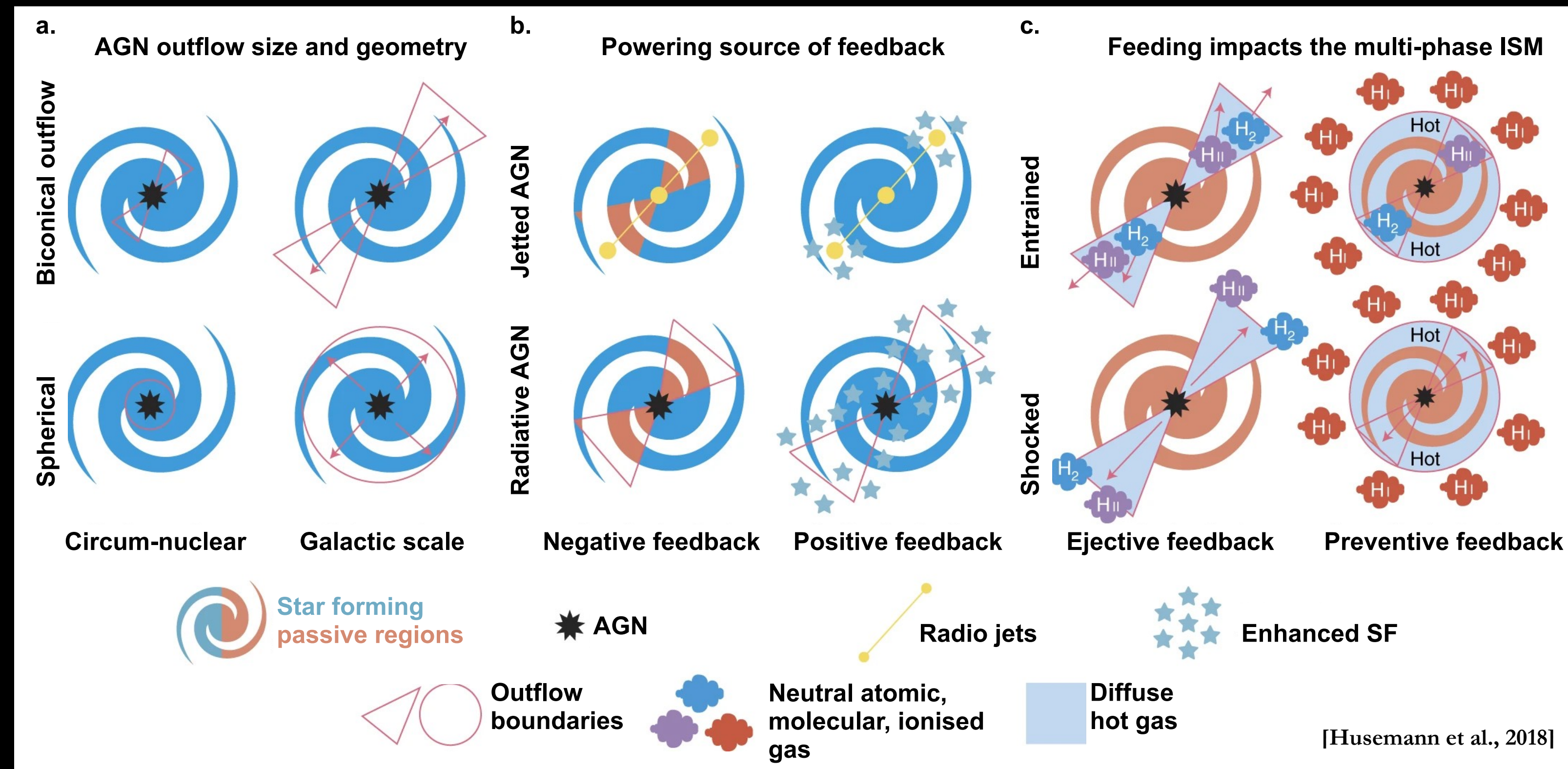


HI deep studies - AGN Feeding and Feedback

Simulation
courtesy of D. Mukherjee



- AGN radiative winds and radio plasma jet/lobes generate (massive) multi-phase outflows
 - Negative and positive feedback
- Cold gas fuels nuclear activity (recursively?): feeding
- How F&F affect SF and the evolution of galaxies?

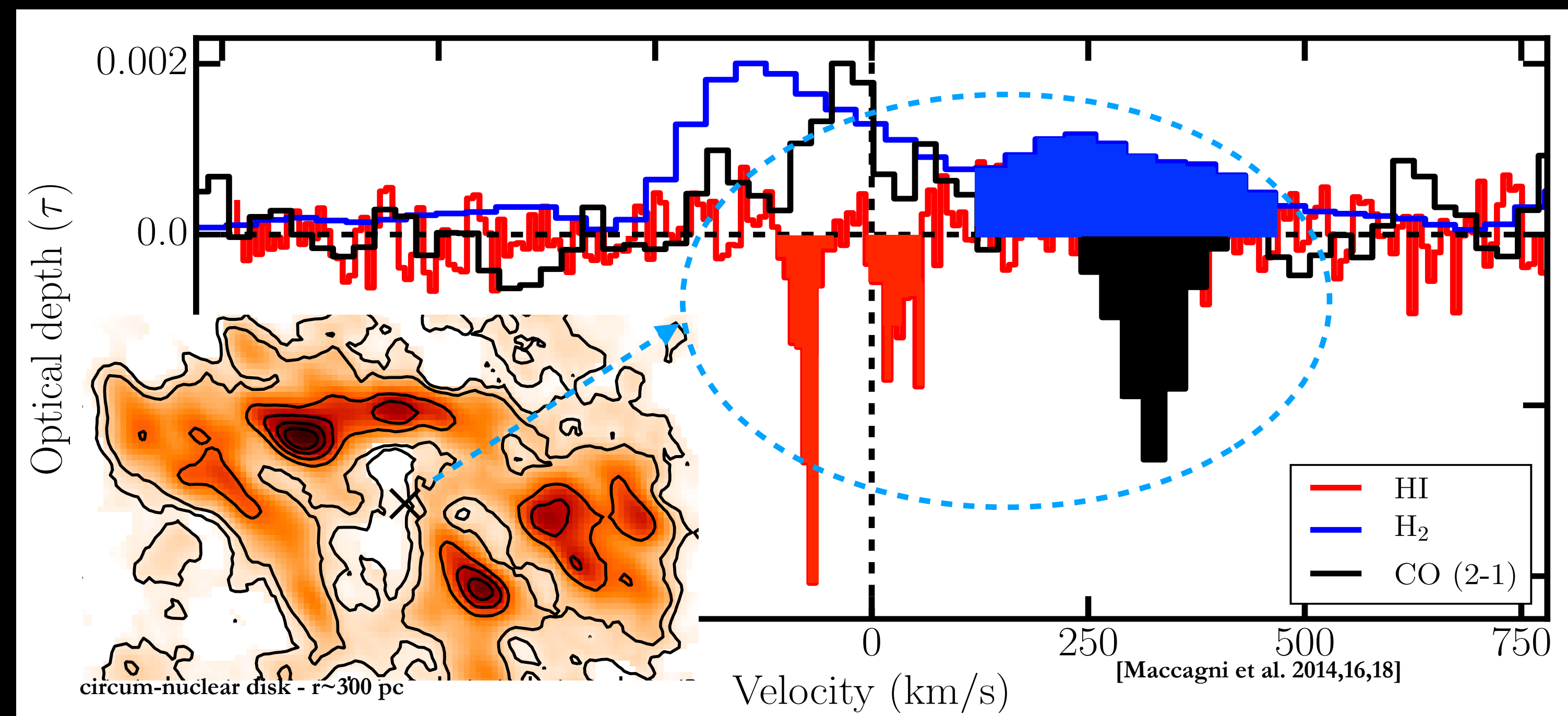


HI deep studies - AGN Feeding and Feedback

- HI traces the neutral atomic phase (i.e. most massive phase) of gas involved in AGN feeding mechanism
- Because of the low-column density of gas involved in F&F so far most HI studies have been limited to absorption

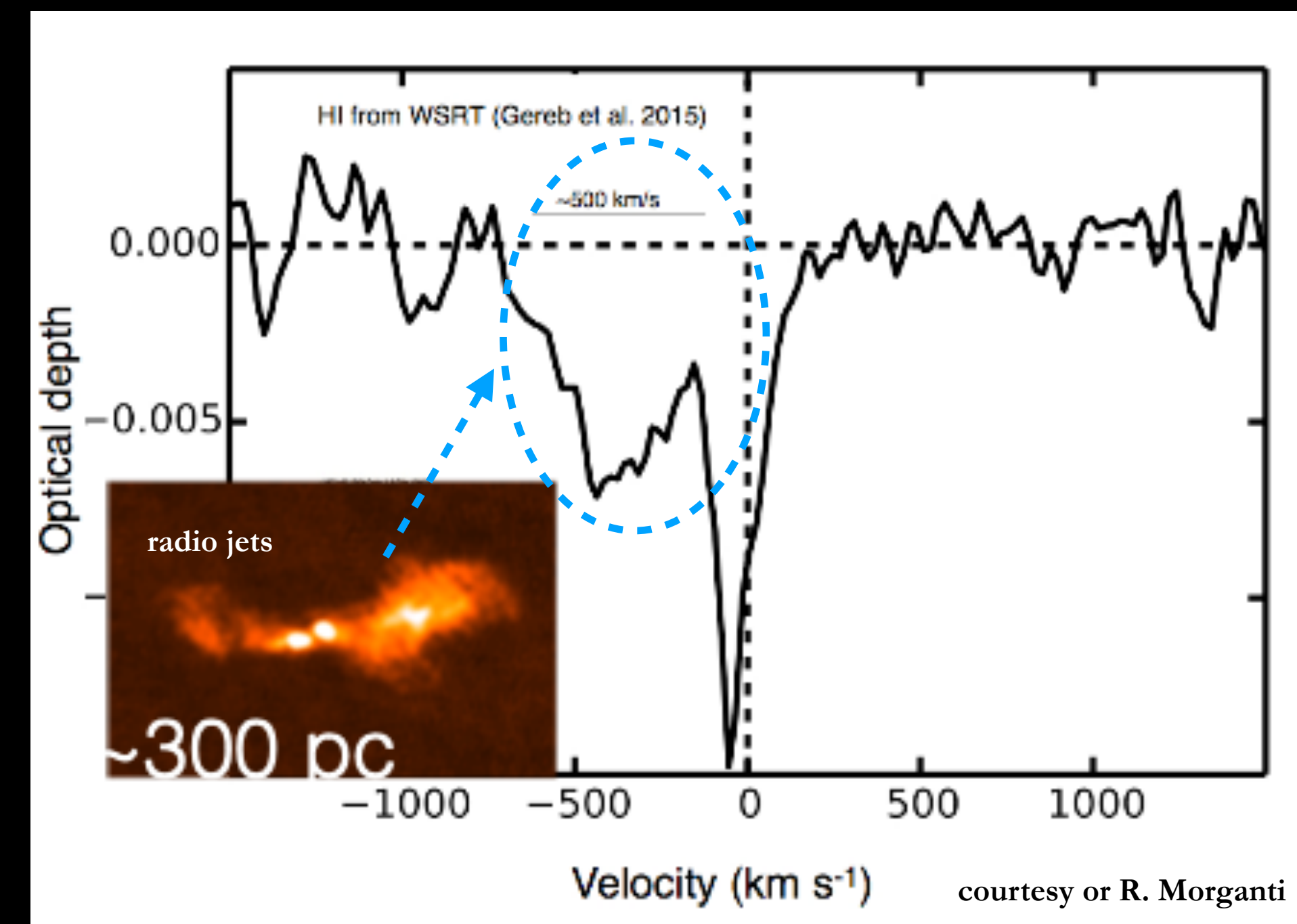
Feeding

HI & CO in-falling clouds on circum-nuclear scale



Feedback

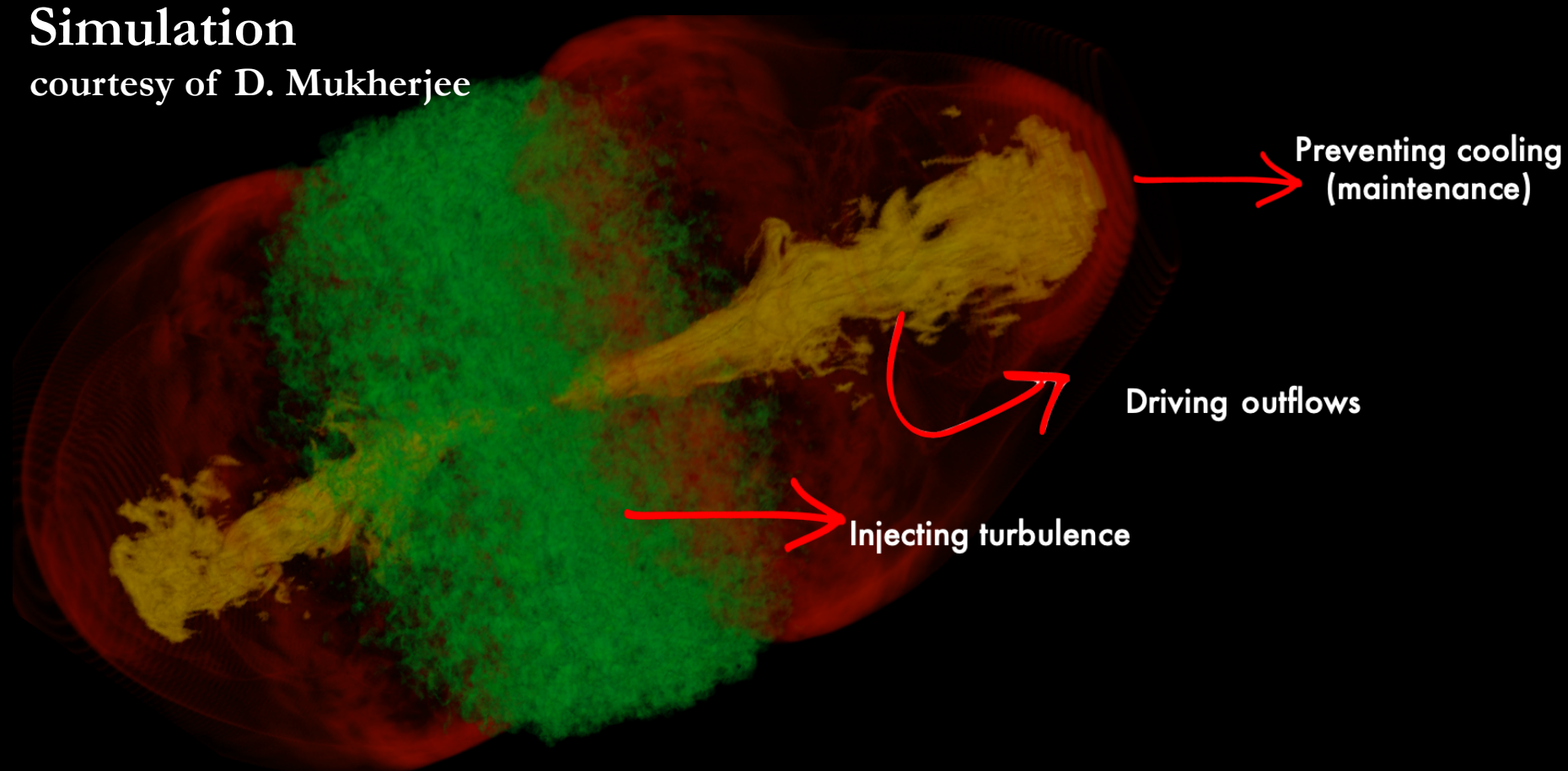
HI outflow on circum-nuclear scale



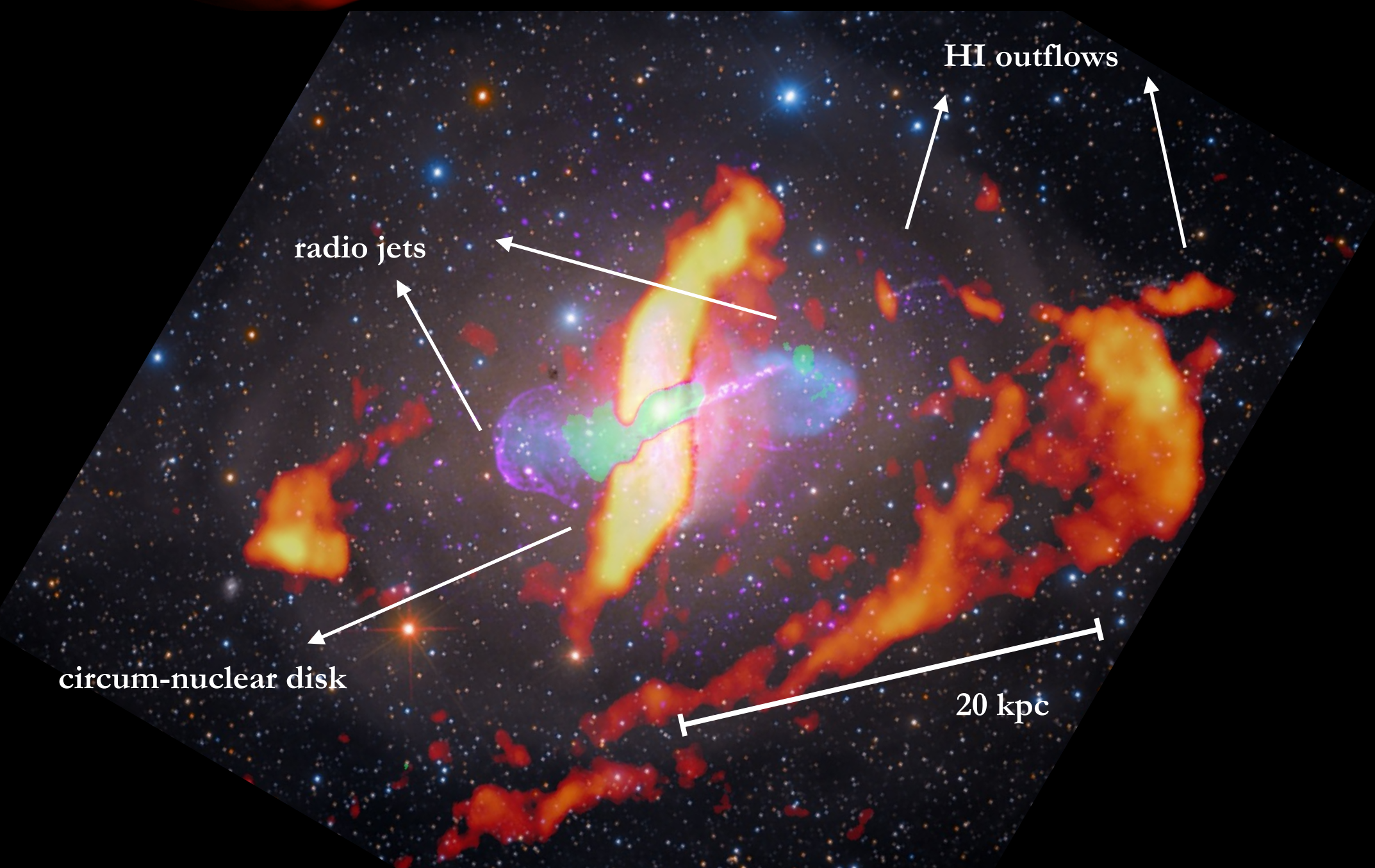
- Can we connect the gas fuelling the AGN with its duty-cycle and the interaction history of the galaxy?
 - need for wide-field sensitive high resolution observations

HI deep studies - AGN Feeding and Feedback

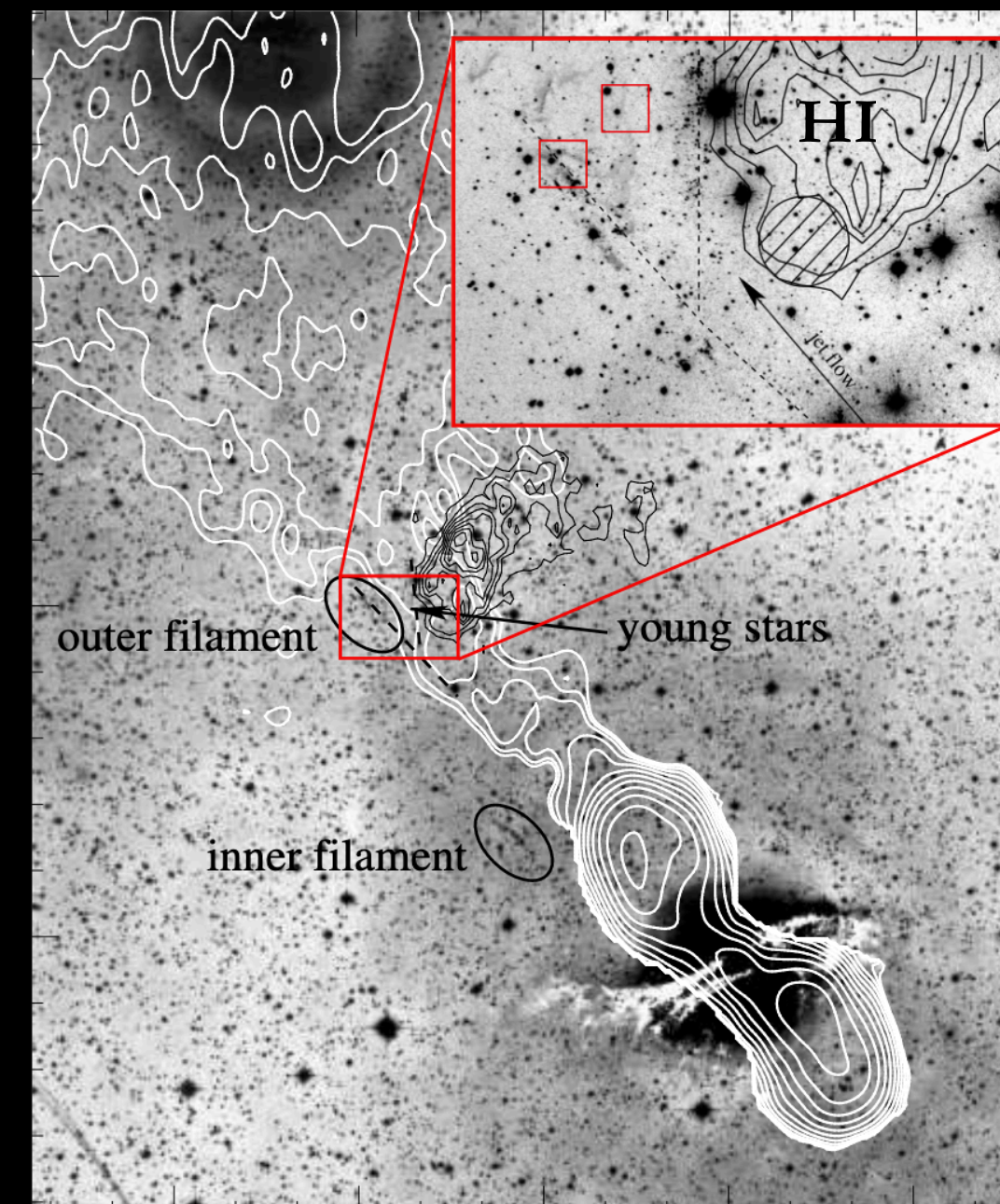
Simulation
courtesy of D. Mukherjee



- AGN-jets eject, displace, shock, and heat the gas from the ISM into the IGM
- Prevent further cooling and quench SF?
- Enhance SF in particular regions at the outskirts of galaxies



Centaurus A [Santoro et al. 2016]



HI

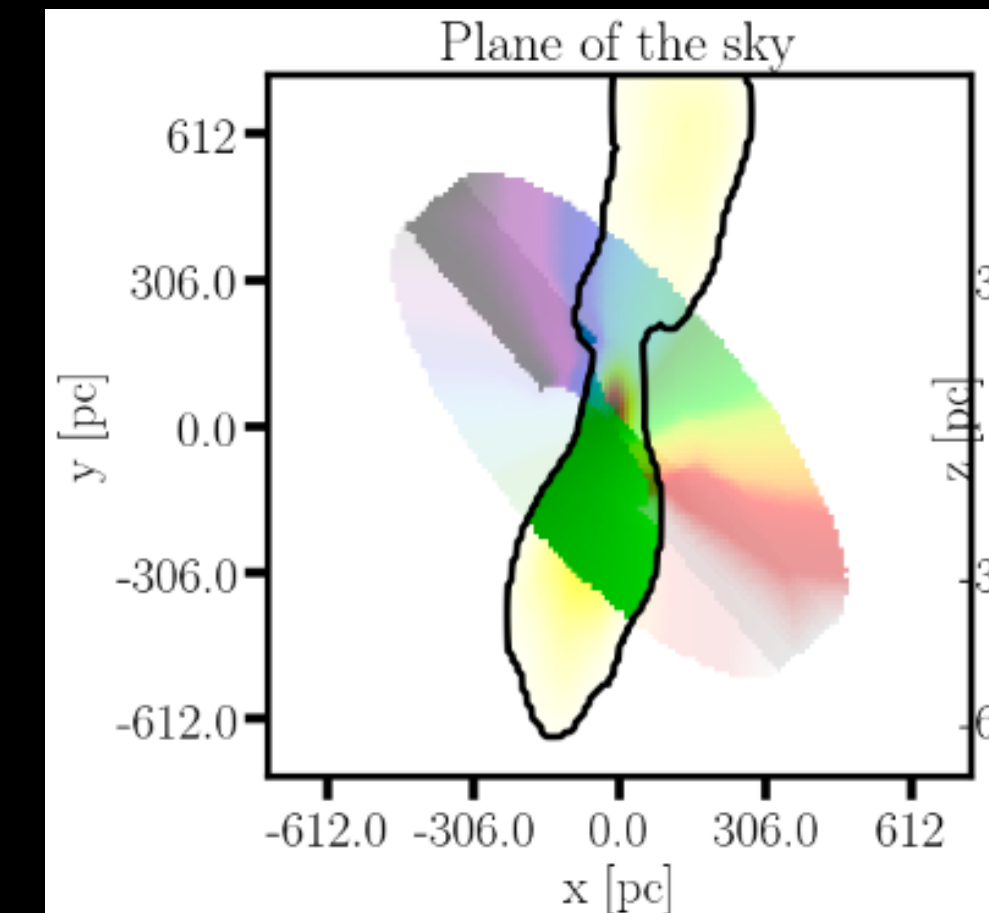
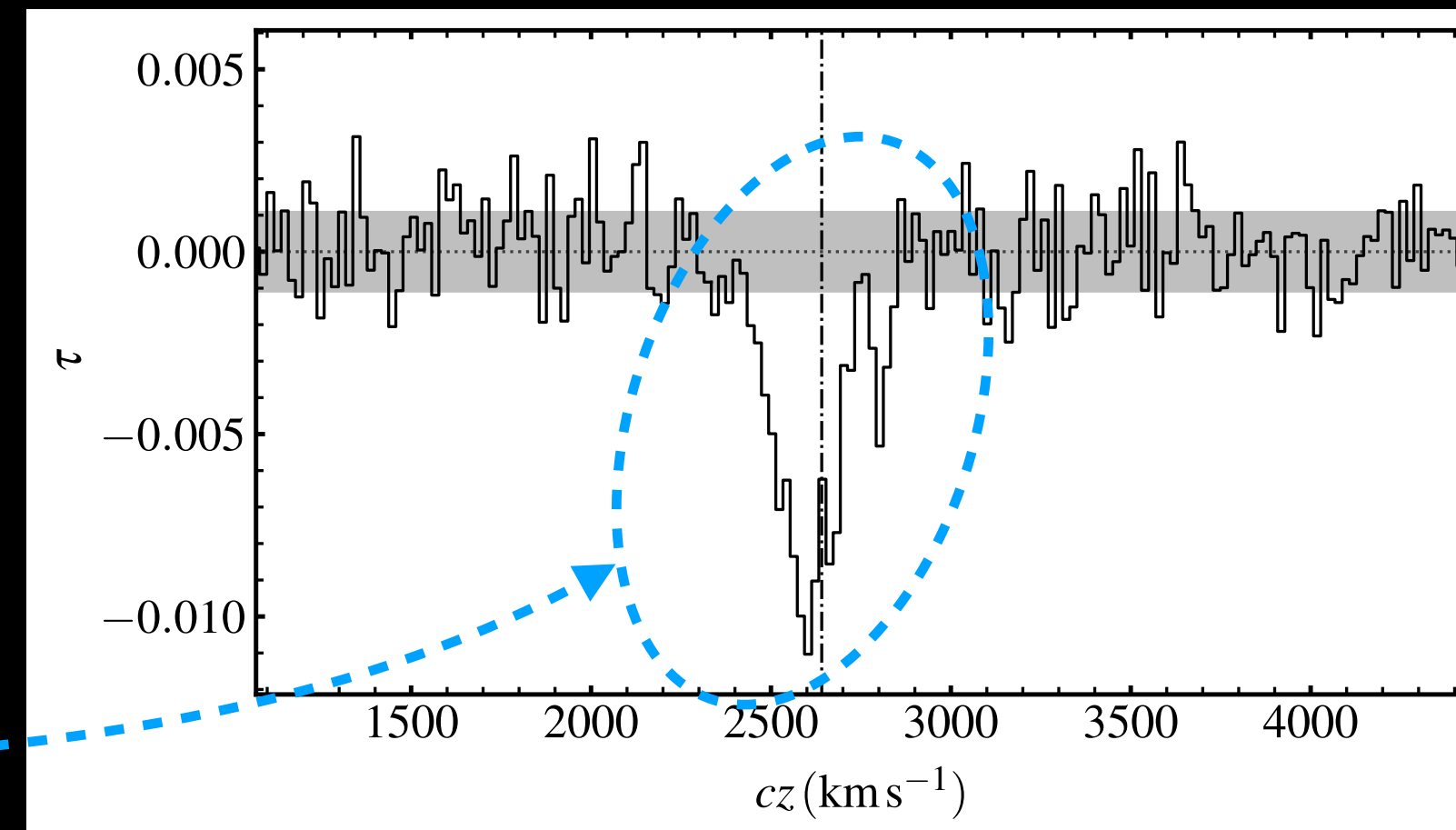
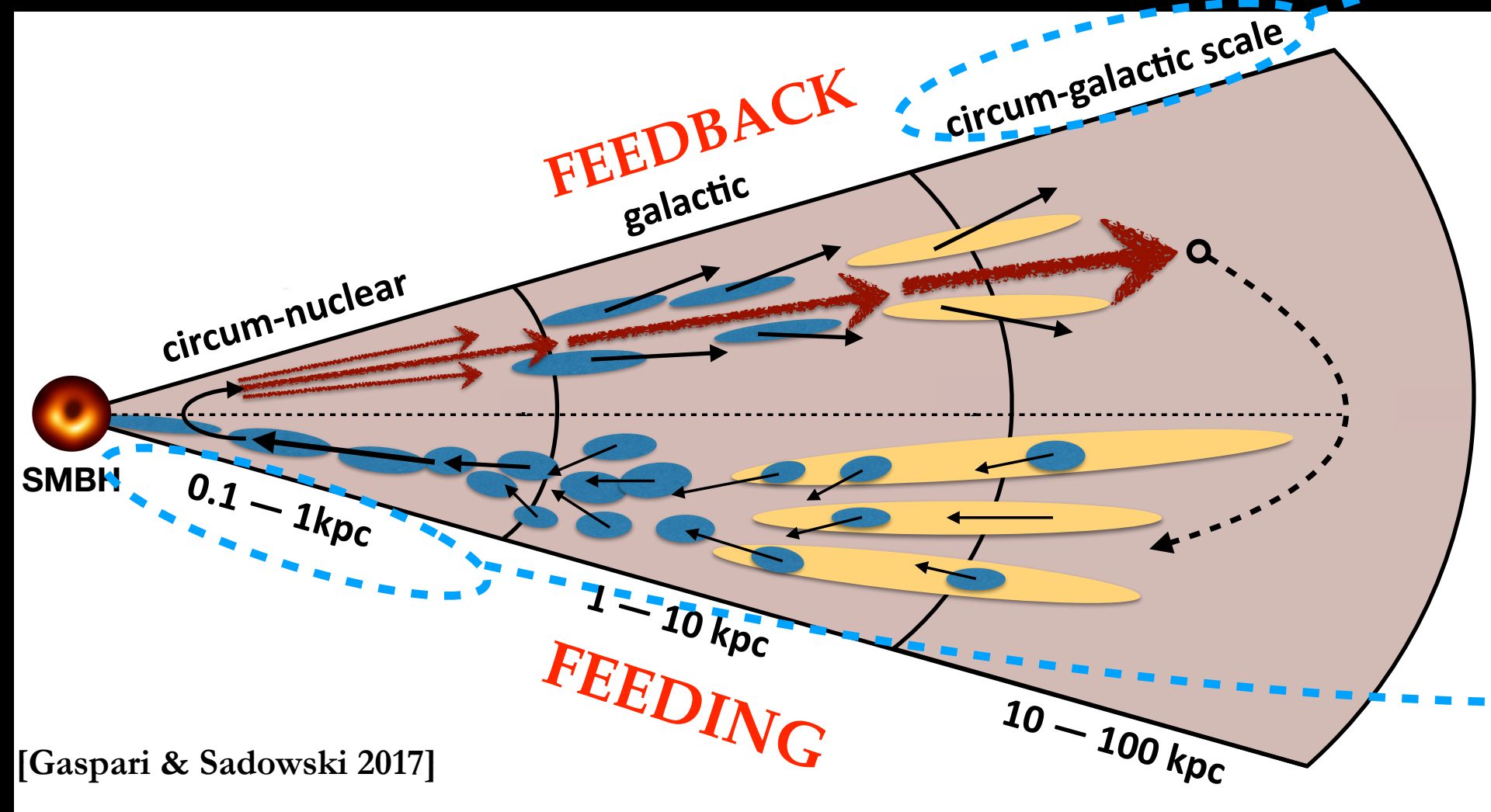
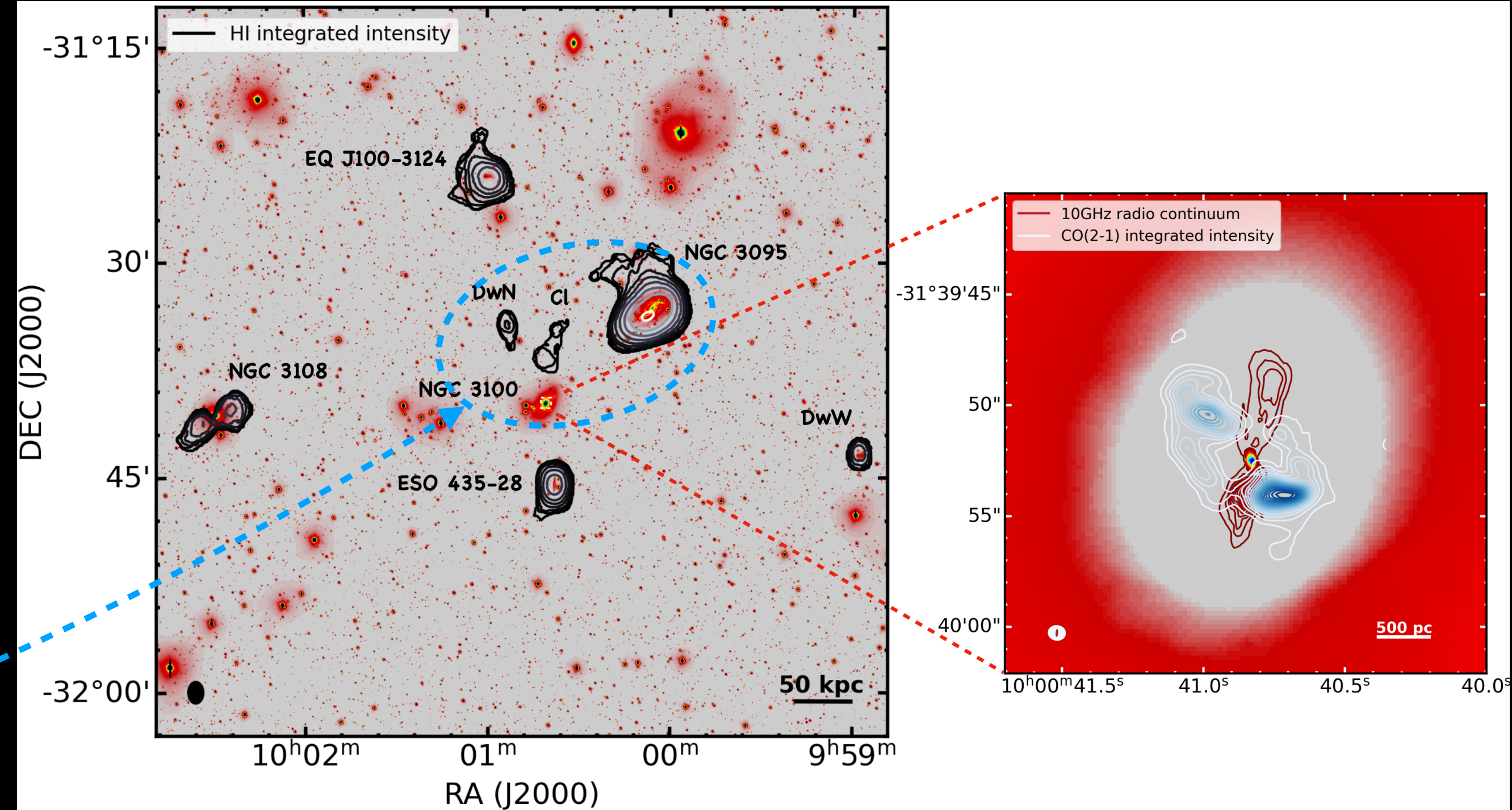


Mikowski object [Croft et al. 2006]

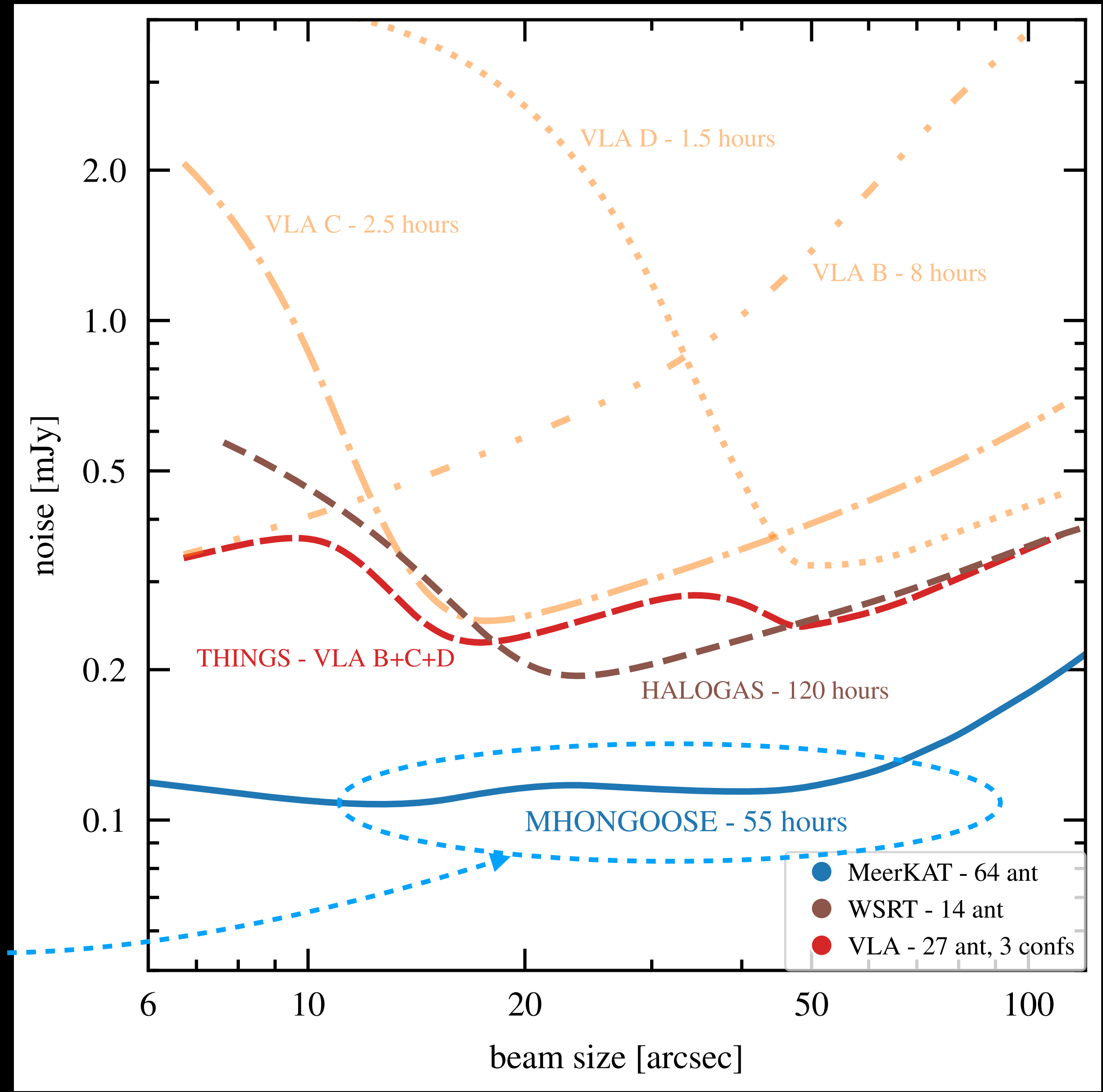
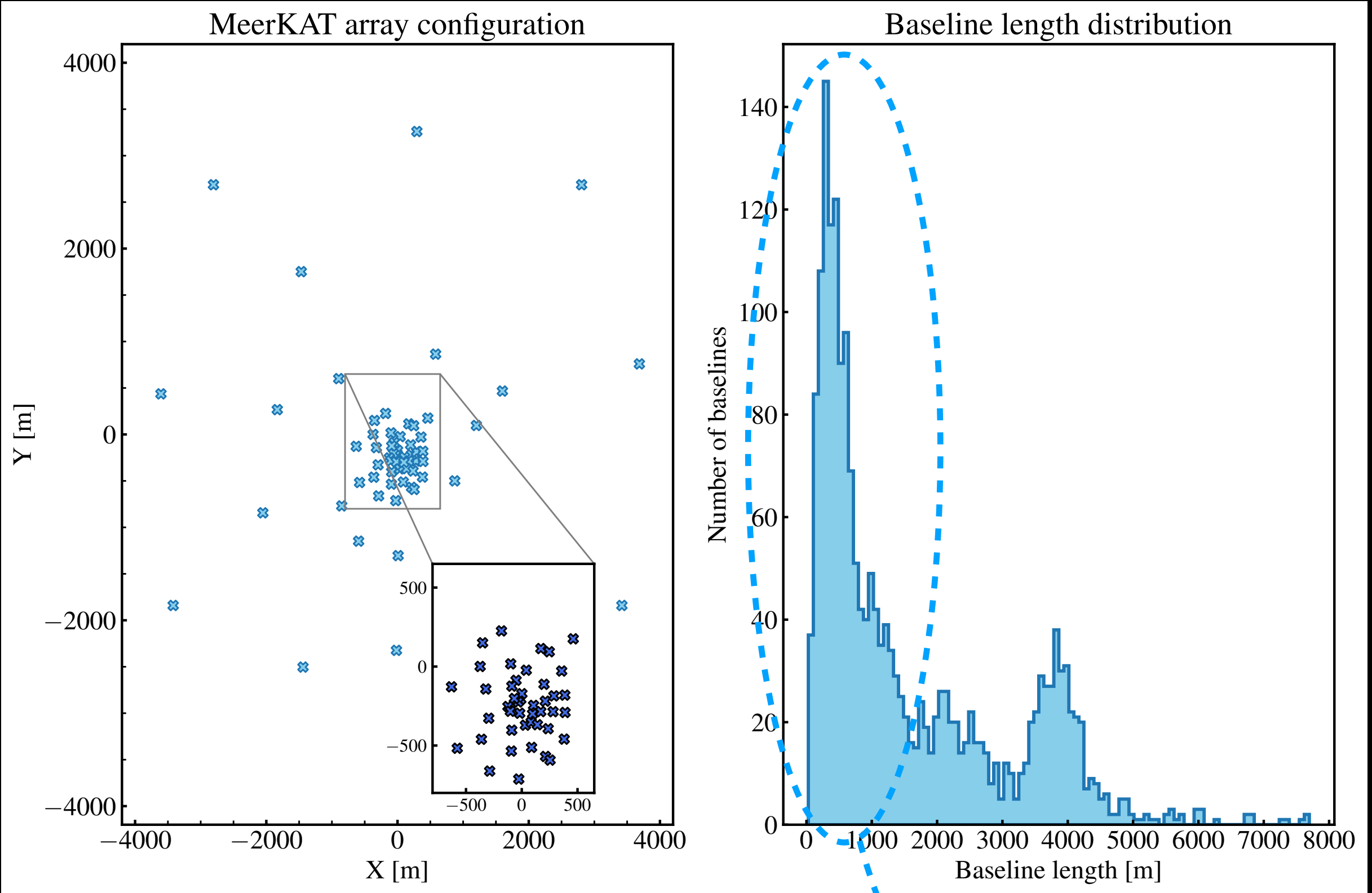
- Studies limited to low resolution or small field of view
 - Very difficult to obtain a full picture of the AGN and its environment

HI in AGN before MeerKAT - NGC3100 with ATCA

- NGC3100 Radio loud nearby ETG [Maccagni et al., submitted]
- 36hrs ATCA + deep photometry VEGAS [Iodice et al. 2019]
- HI from the circum-nuclear to circum-galactic scale
- 3σ N(HI) cm^{-2} @ 90'': $<1 \times 10^{19} \text{cm}^{-2}$
- HI emission \rightarrow interaction history of the group
 - A 'dark' HI cloud falls into the ETG
- HI absorption
 - multi-phase circum-nuclear disk & non-rotating red-shifted gas

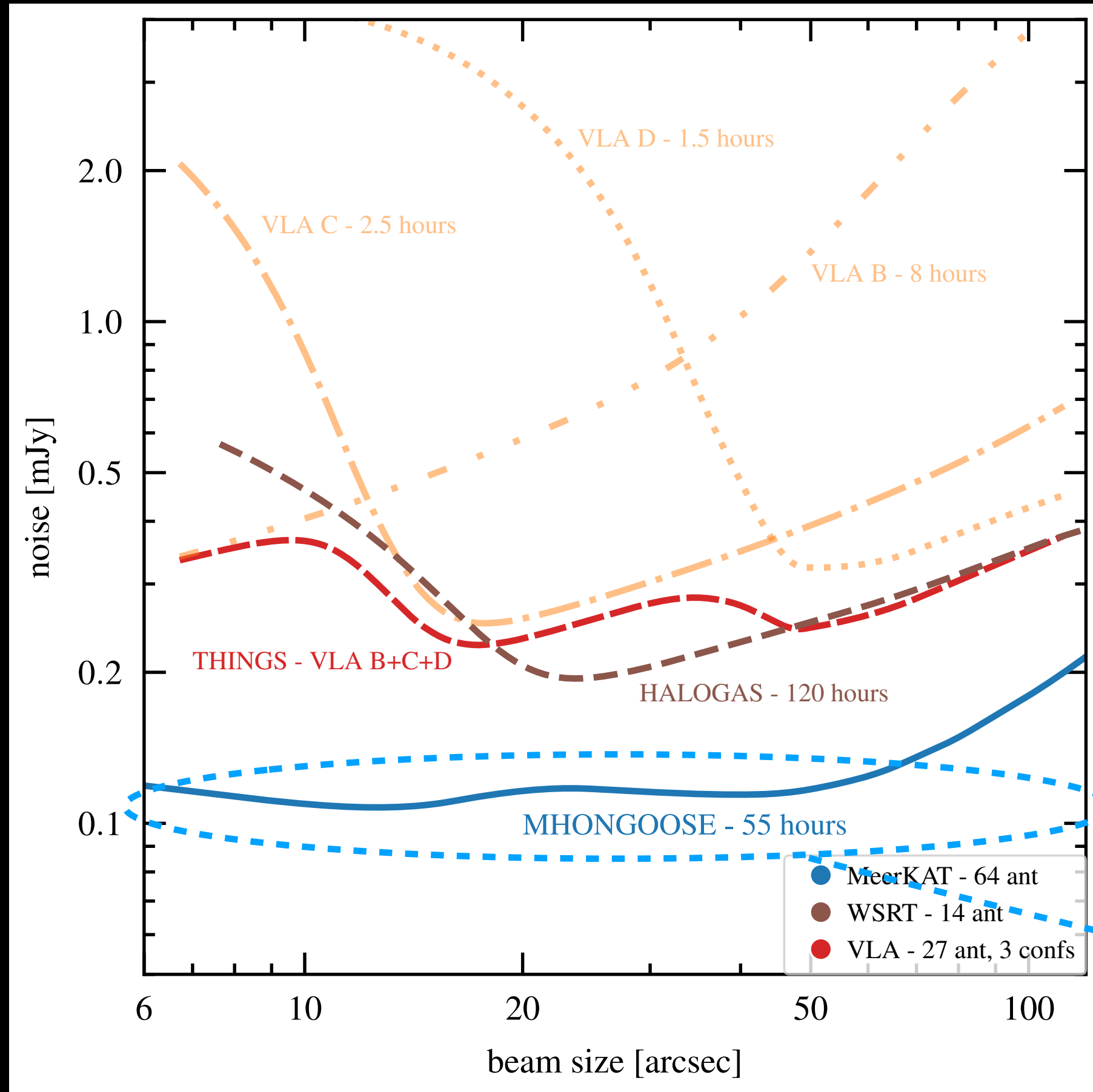


MeerKAT - a dense core of antennas

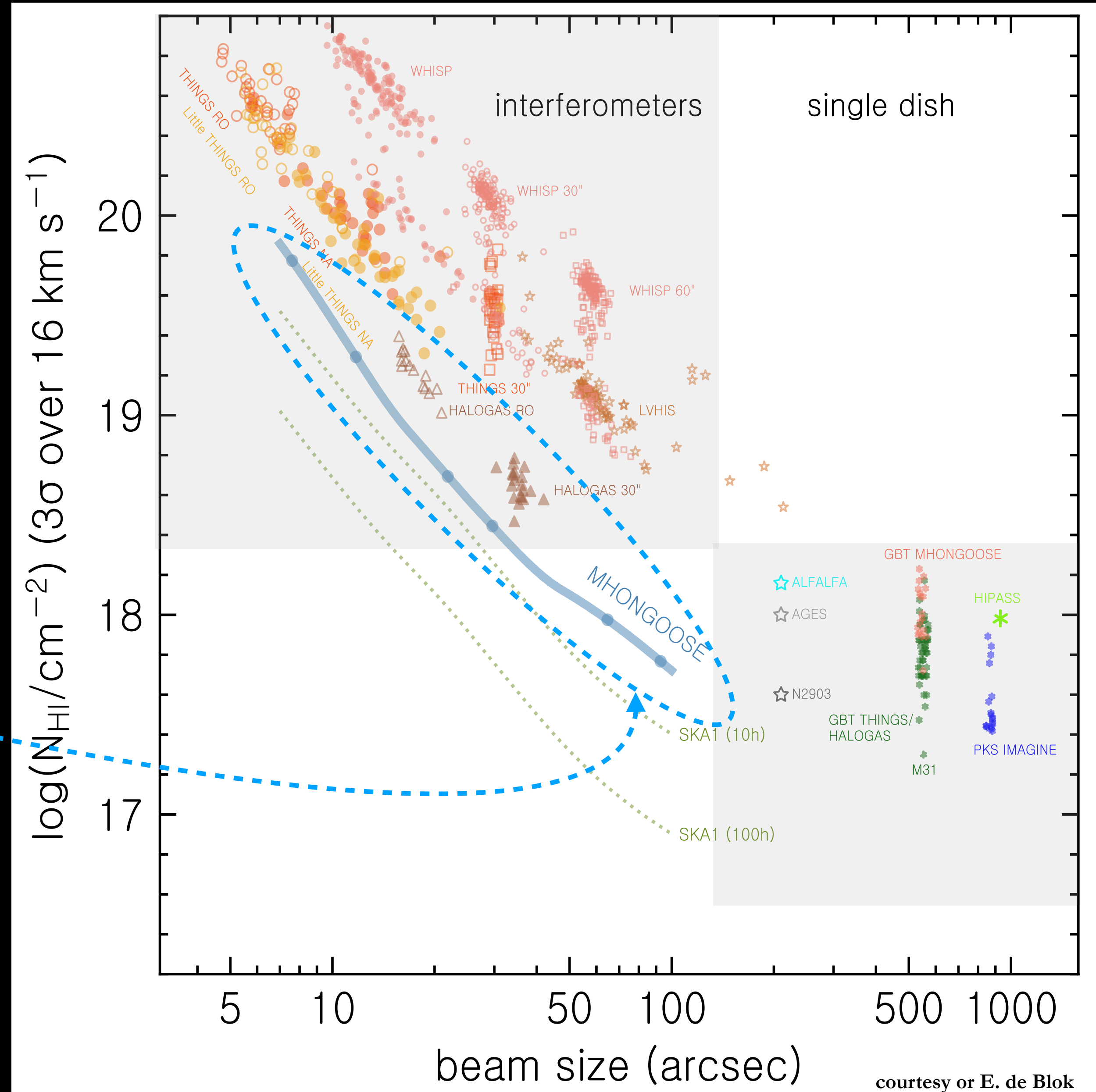


MeerKAT's dense core of antennas guarantees
constant sensitivity over all scales

MeerKAT - constant sensitivity on all scales

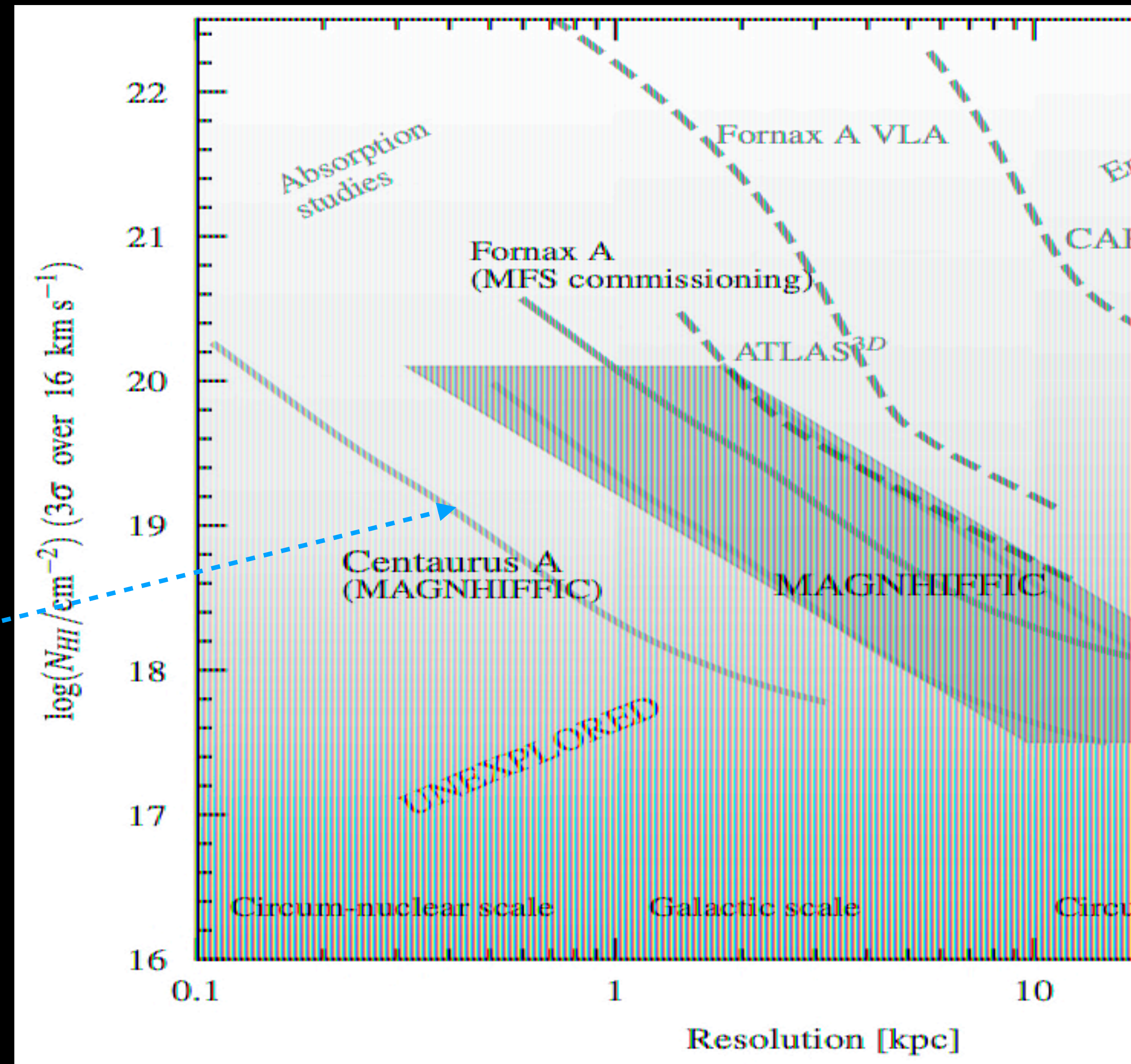


- MeerKAT has constant noise over all scales
- MHONGOOSE detects low column density HI with single dish survey sensitivity, over all scales



MAGNHIFC - sensitivity and resolution

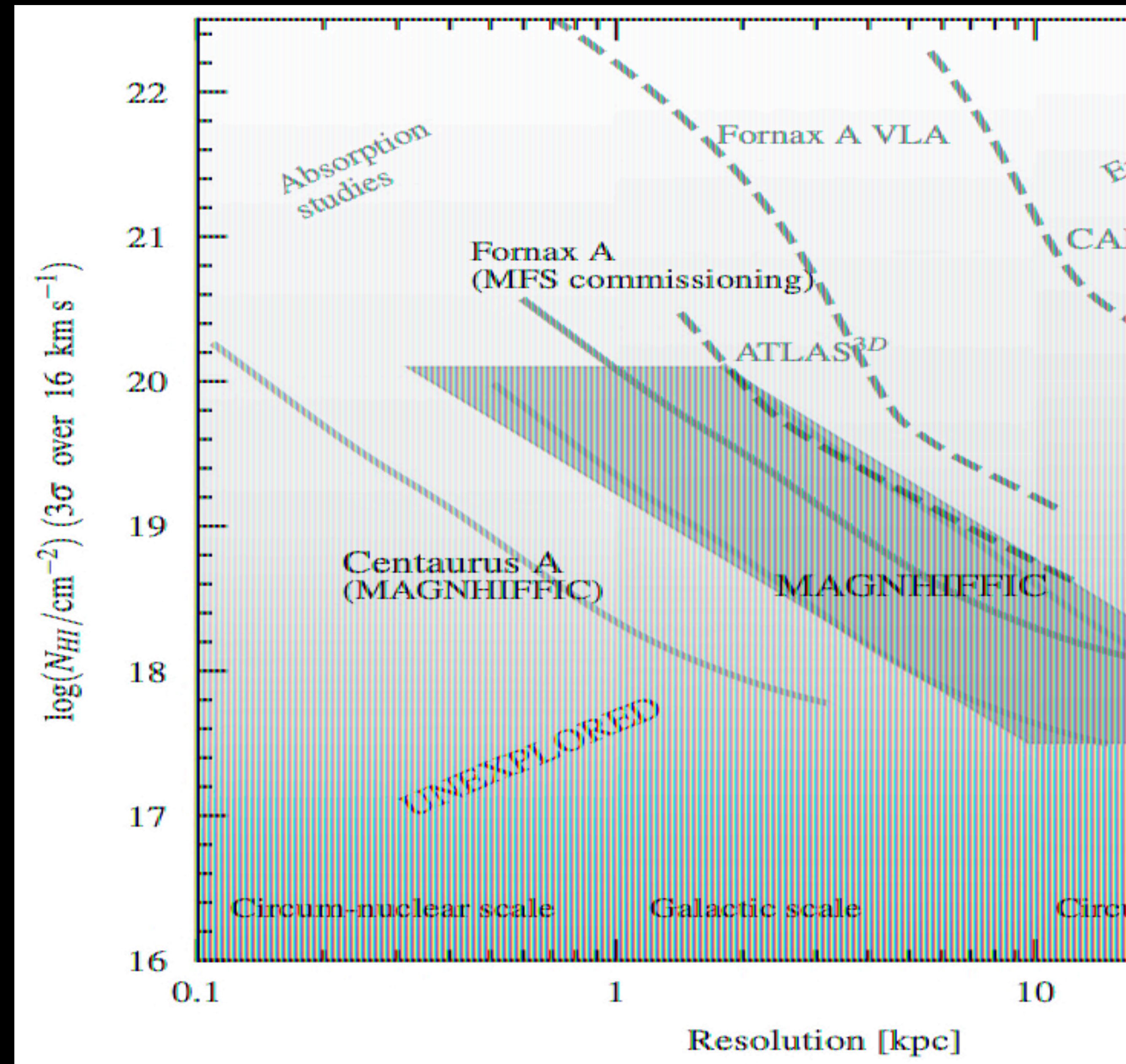
- MeerKAT observations of nearby AGN (≈ 130 Mpc)
- Investigating a new parameter space for AGN feeding & feedback
 - Unexplored column densities on kilo-parsec scales



MAGNHIFFIC - sensitivity and resolution

MAGNHIFFIC

- How does gas regulate the recursive nuclear activities of galaxies?
- Wide field deep HI observations of **22 nearby AGN ($D_L < 130$ Mpc)**
- Study the low column density neutral hydrogen: **$N(\text{HI}) \sim 10^{18-20} \text{ cm}^{-2}$**
- Connect the life cycle of AGN with the physical conditions of the ISM and IGM
- Understand the impact of multi-phase AGN feeding and feedback from the circum-nuclear to the circum-galactic scale



MAGNHIFPIC - the sample

MeerKAT AGN HI Feeding & Feedback Investigation Close-by
 22 nearby AGN (<130 Mpc) with different energetic outputs, ages, hosts and environments

3σ N(HI) at $30'' < 5 \times 10^{18} \text{ cm}^{-2}$

3σ N(HI) at $8'' < 5 \times 10^{19} \text{ cm}^{-2}$

Radiative AGN/Seyferts

- 4 MHONGOOSE
- 3 Fornax Cluster [MFS]
- 3 Open-time 2022 [PI Maccagni]

Jetted AGN

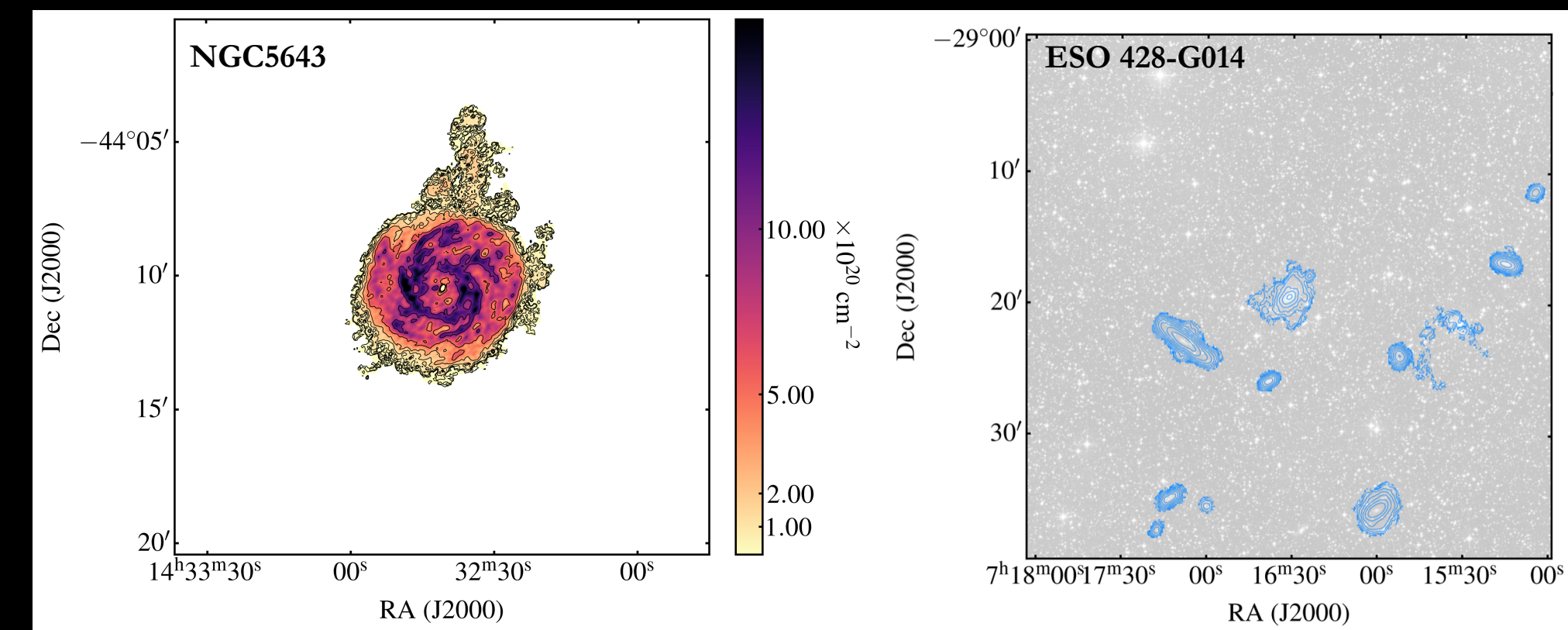
- Complete sample of radio loud AGN observed in CO 9 sources [Ruffa et al. 2020] (Open-time, Maccagni & Prandoni)
- NGC1399 (BCG Fornax)
- **Fornax A** [Maccagni et al. 2020,2021]
- **Centaurus A** [Maccagni & McKinley, in prep.]



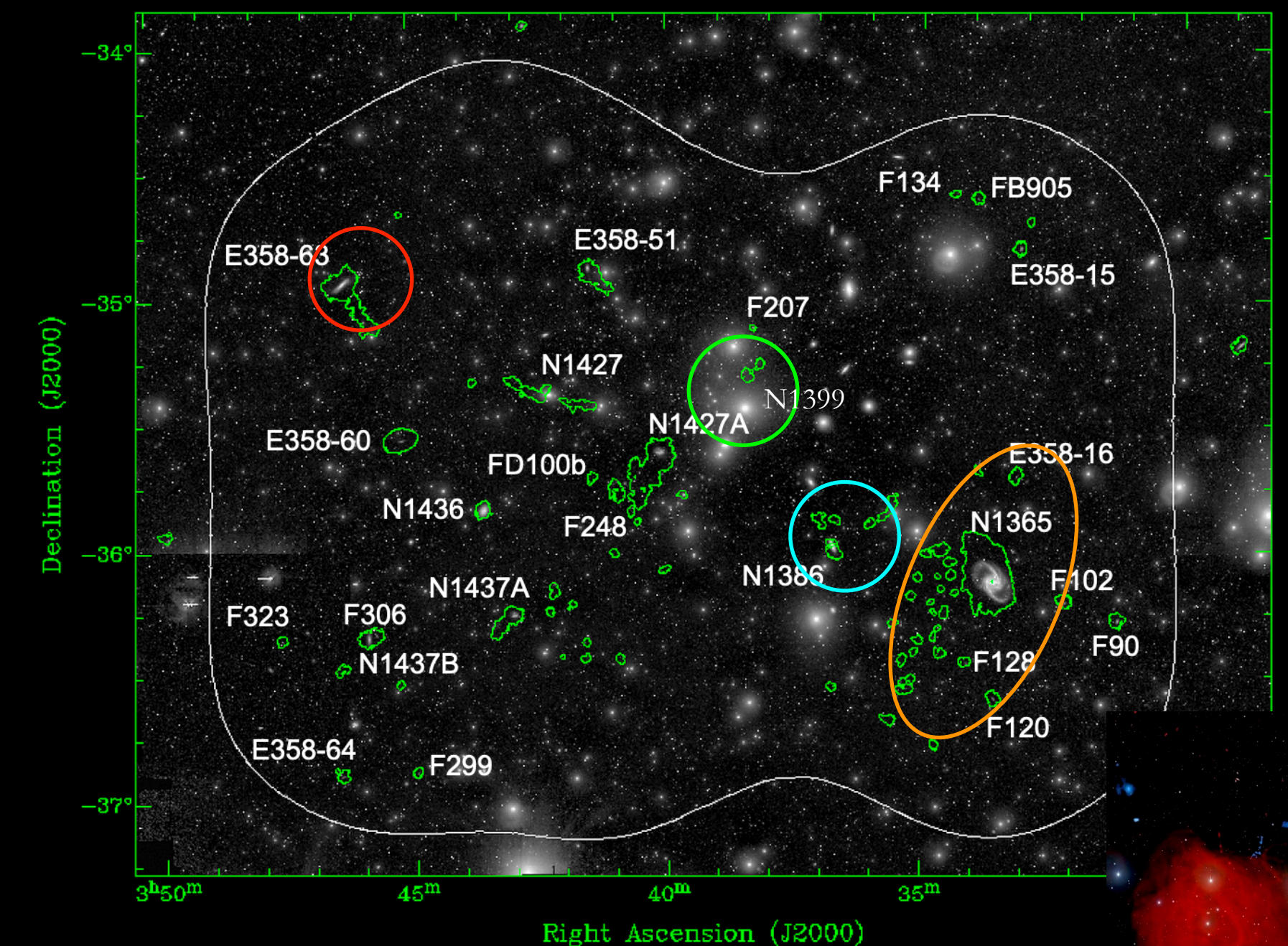
Next Generation MeerKAT LSP? : all (50?) nearby (<100 Mpc)

AGN, 32k narrow band, 25 hours per source?

Nearby Seyfert galaxies



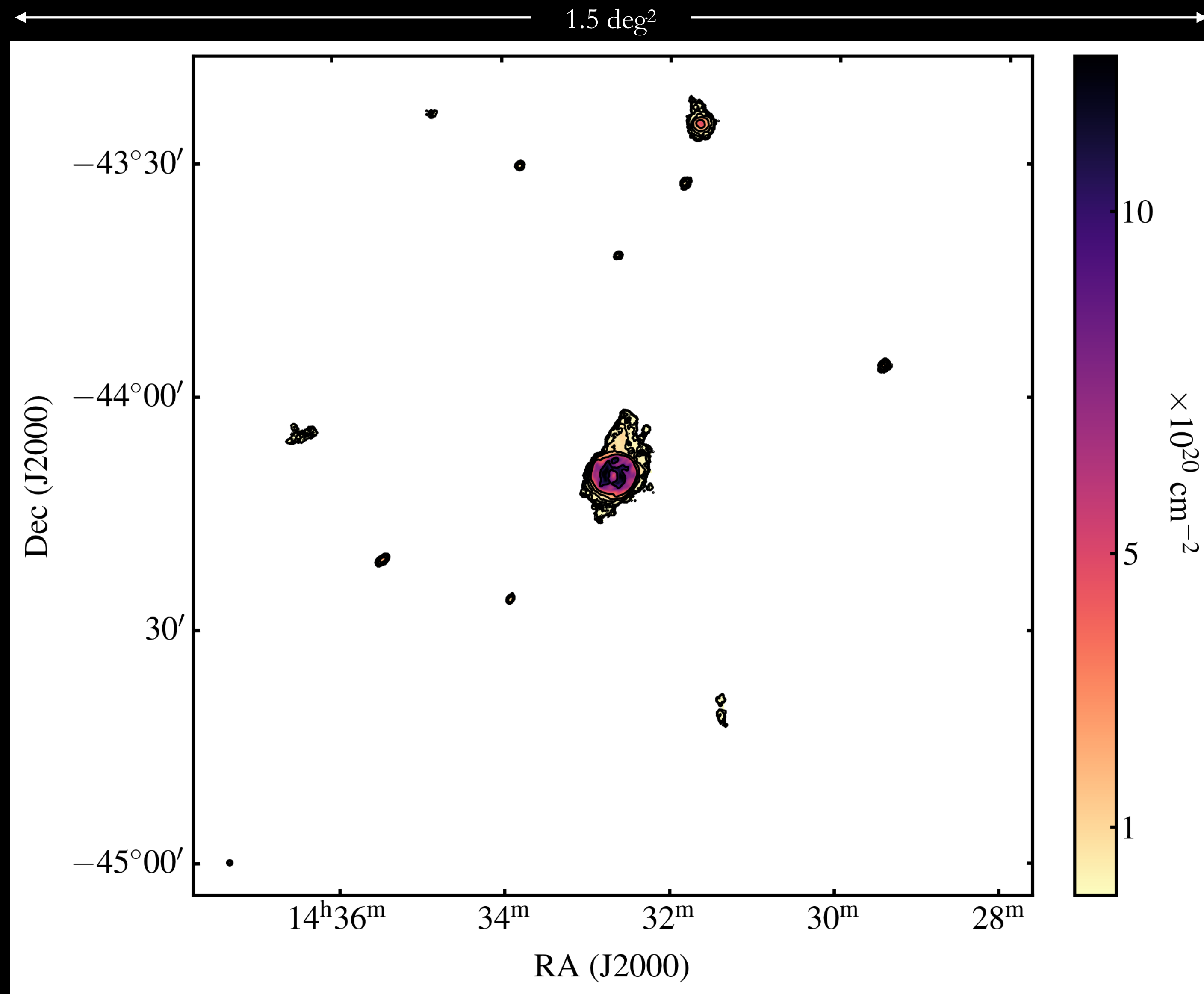
AGN in the Fornax Cluster and Group [MeerKAT Fornax Survey]



<https://magnhiffic.astron.nl/>

MAGNHIFFIC - NGC5643

NGC5643 ($D_L = 20.7$ Mpc) shows an AGN driven outflow in the core [X-ray, MUSE & ALMA observations]

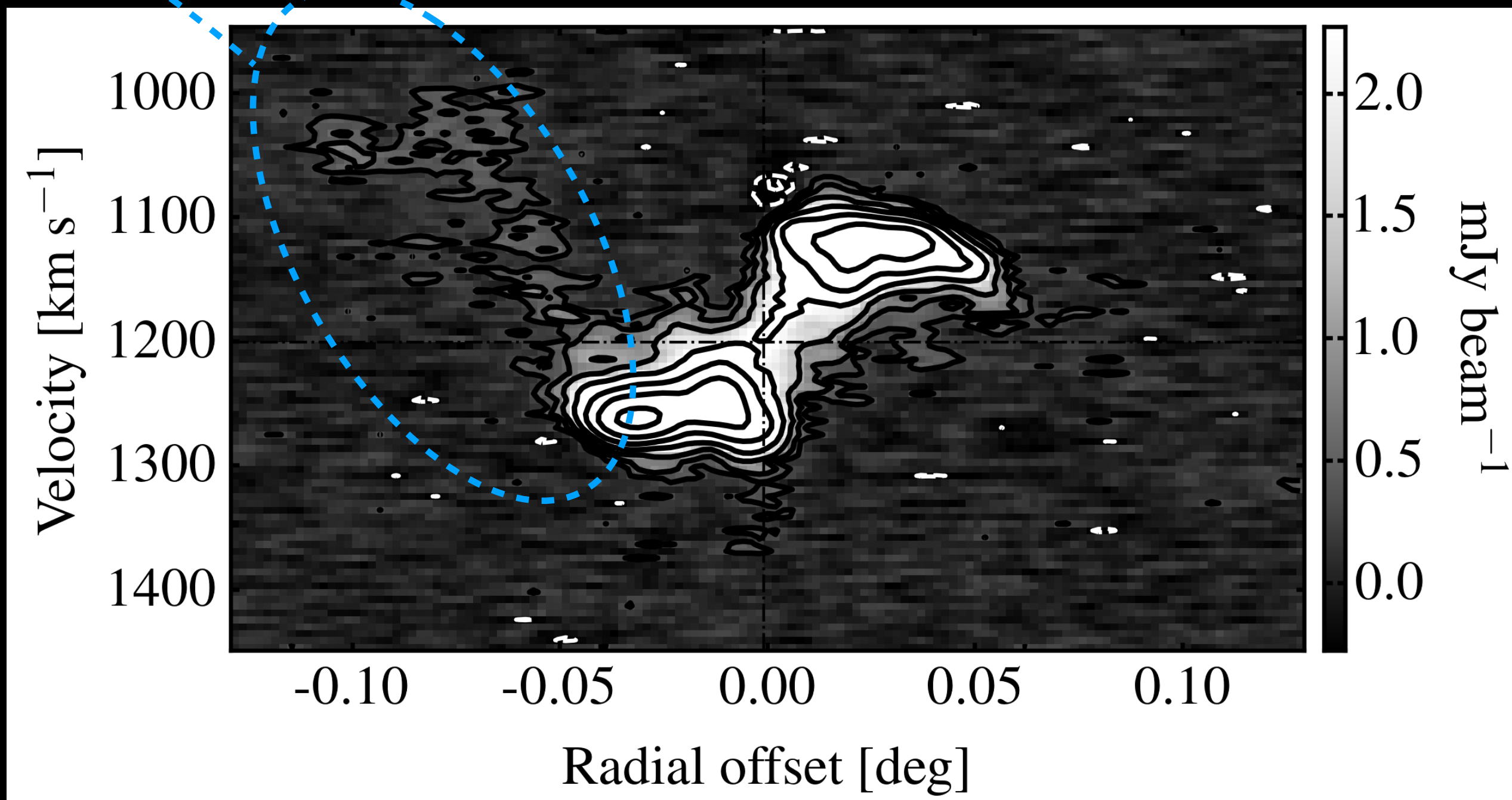
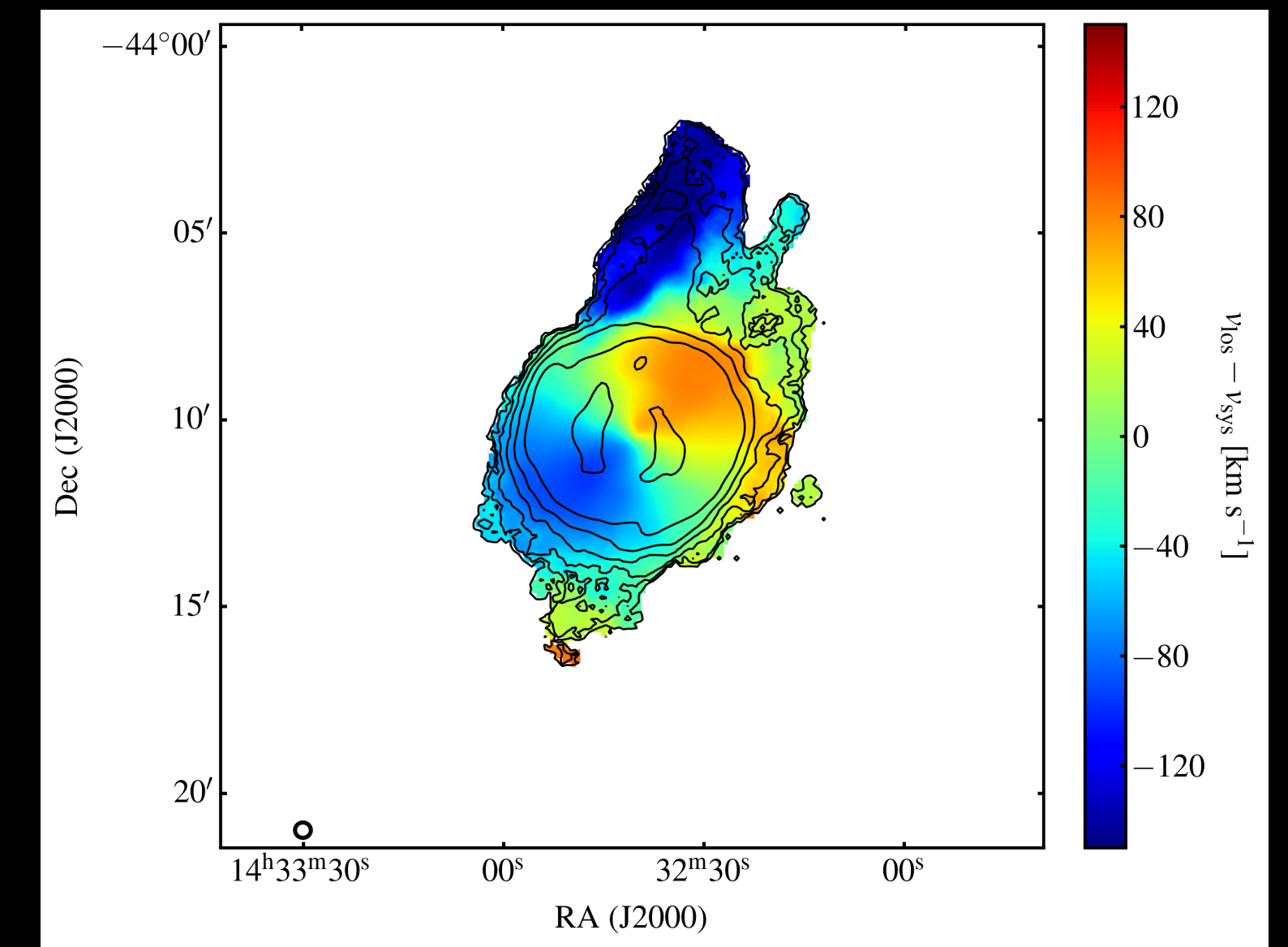
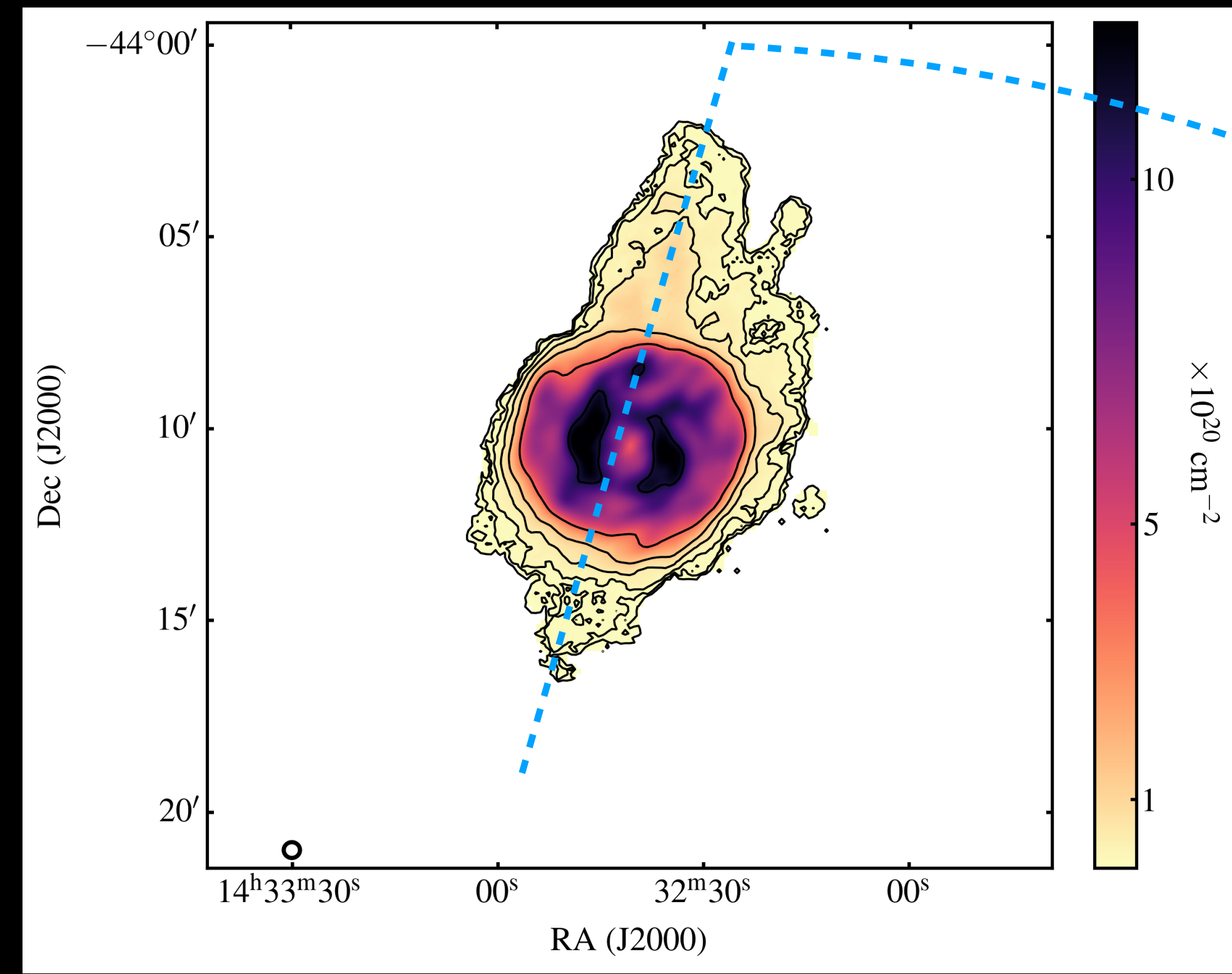


With multi-resolution datacubes MeerKAT (as often) reveals NGC5643 is in a group with several low mass satellites ($5 \times 10^6 M_\odot$) within $\pm 700 \text{ km s}^{-1}$, and much more:

- what is the origin of the northern tail?
- is there an HI outflow?

MAGNHIFFIC - NGC5643

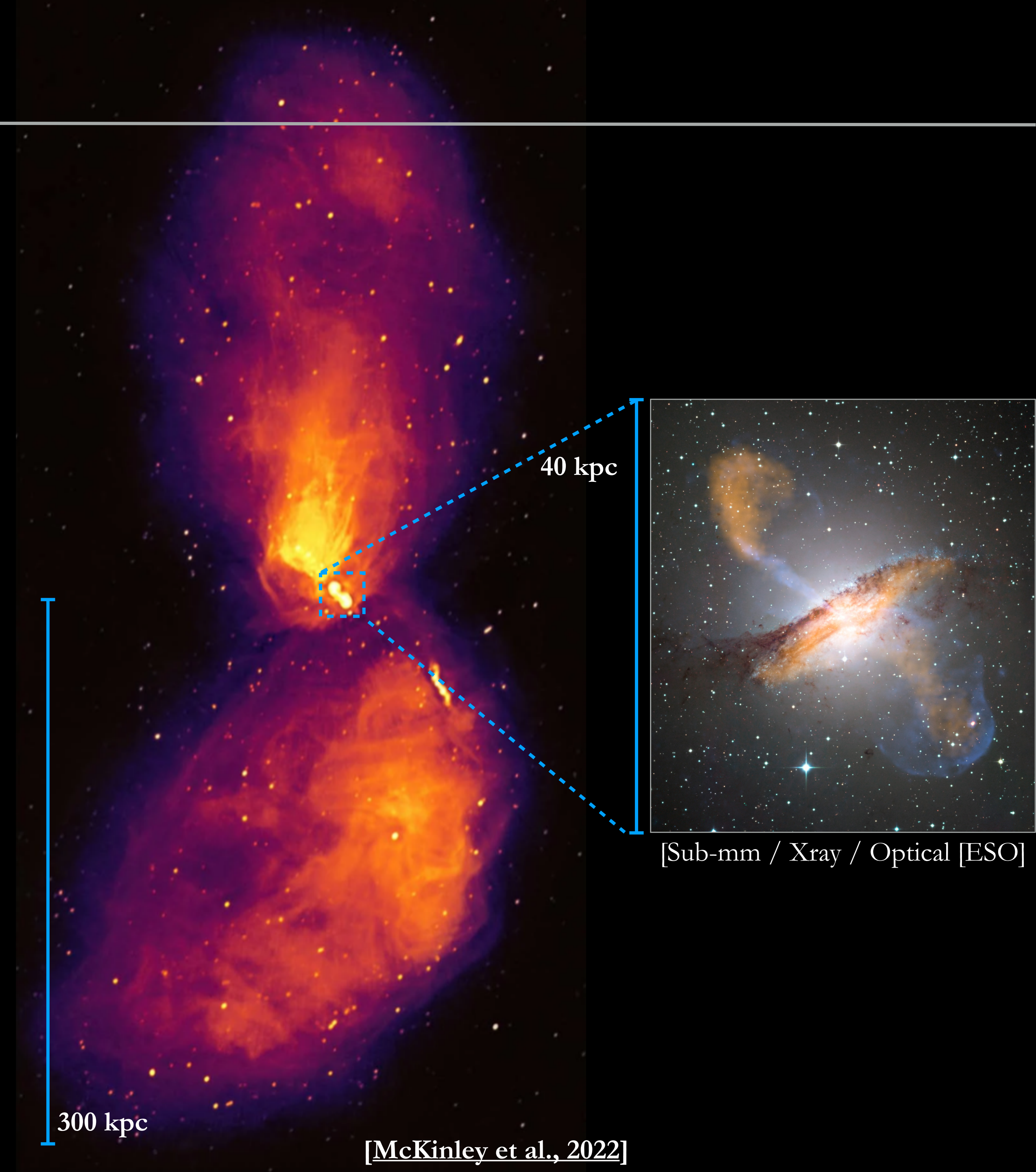
- What is the origin of the northern tail in NGC5643?
- Is gas falling towards the AGN?
- Is NGC5643 undergoing a tidal interaction with a satellite?



-> Answers will be found by Karina Santana @ ASTRON Summer Student program 2023

Centaurus A

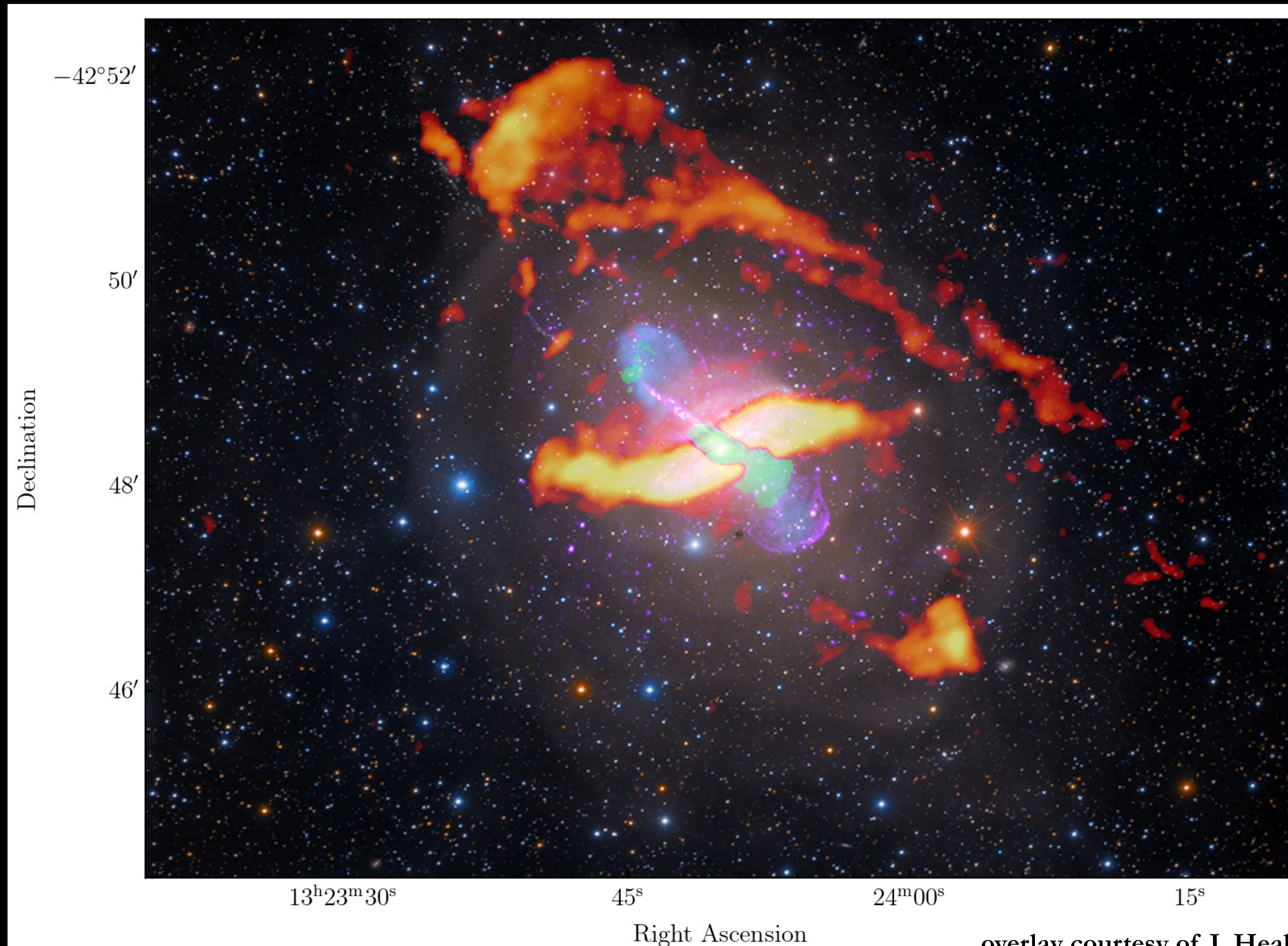
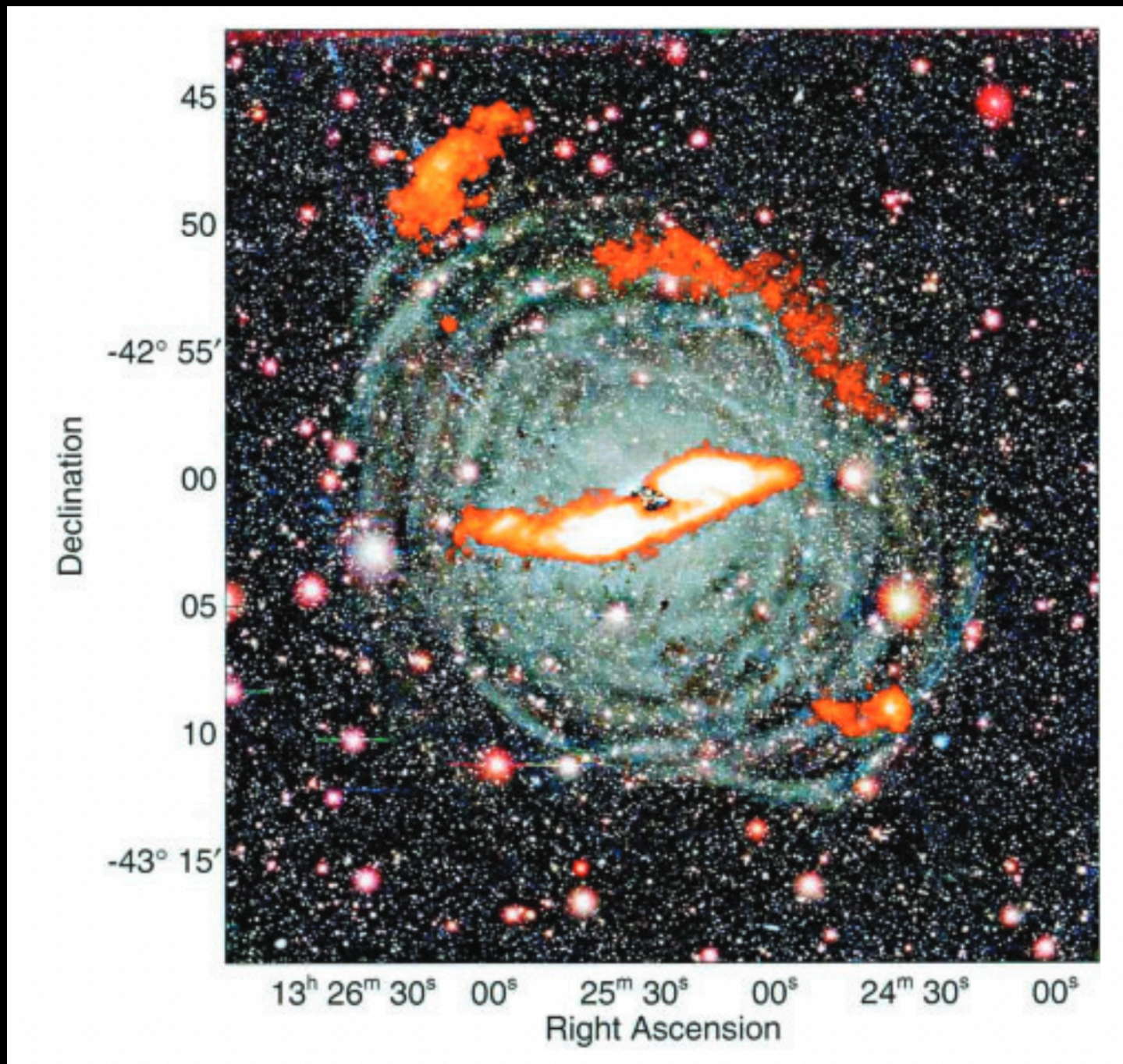
- AGN structures within the stellar body (< 25 kpc)
 - Jets & filament
 - Lobes
 - Bubbles
 - Circumnuclear dusty disk ($r \sim 6$ kpc)
- Regions of AGN-triggered star formation
 - Outer Filament (20 kpc from centre) e.g. [Santoro et al. 2016](#)
 - Inner Filament (7 kpc from centre) e.g. [Crockett et al. 2015](#)



Centaurus A - Neutral Hydrogen

ATCA [Morganti 2010]

MeerKAT [Maccagni, McKinley in prep.]



- Radio continuum

- HI emission

- HI absorption

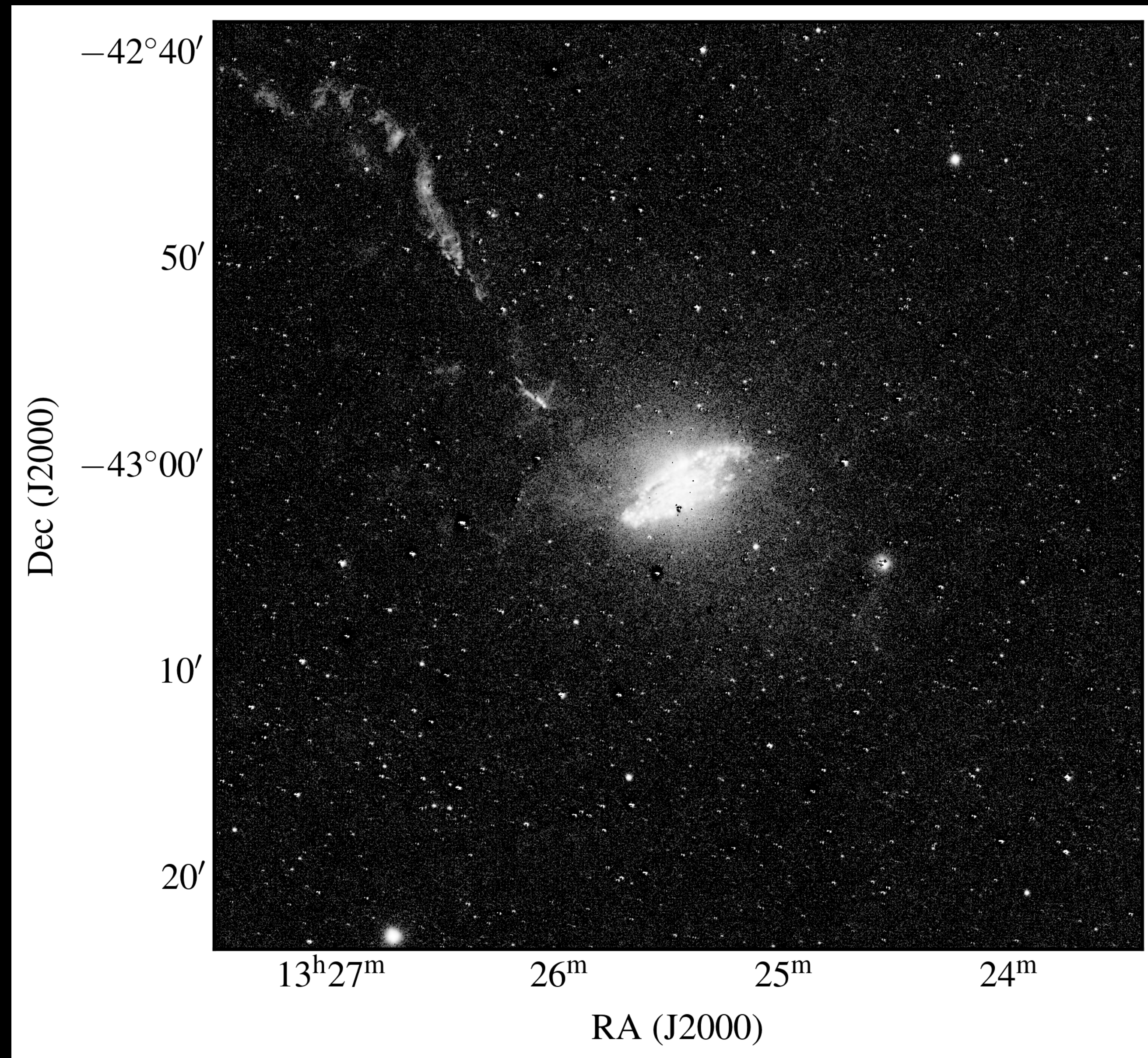
HI clouds along the jets and filaments of ionised gas

Low column density HI $\sim 10^{19} \text{ cm}^{-2}$

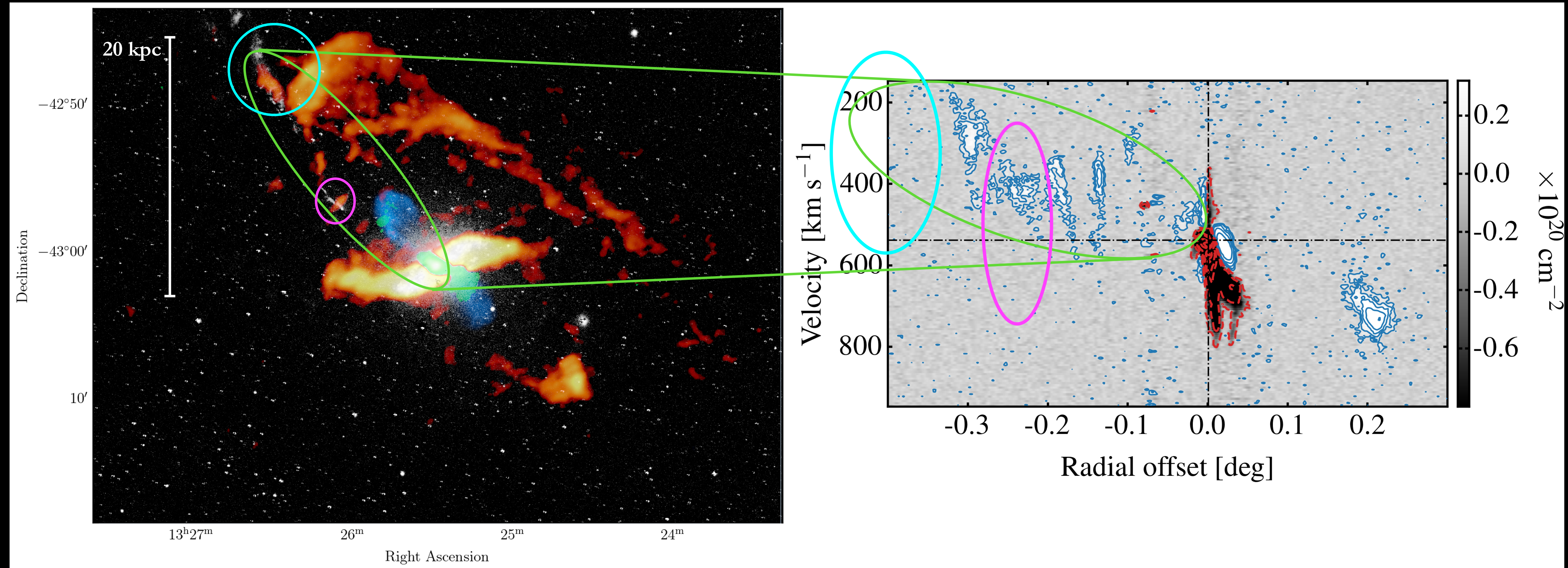
overlay courtesy of J. Healy

Centaurus A - H α filament

- Deep Narrowband H α photometry
- 50 hours Observations + flat fielding and sky subtraction made by **Mathew Ludgate** (astrophotographer)
- Nikon 400mm f2/8 lens + full frame mono camera. FOV = 5.15 x 3.44 deg, resolution 2".



Centaurus A - HI outflowing clouds along the H α filament



- Coherent velocity outflow $\sim 200 \text{ km s}^{-1}$

- AGN jets slowly piercing through the HI disk, ionisation & enhanced SF?

- Regions of AGN-triggered star formation show outflowing HI clouds ($M_{\text{HI-cloud}} \sim 10^6 M_{\odot}$)

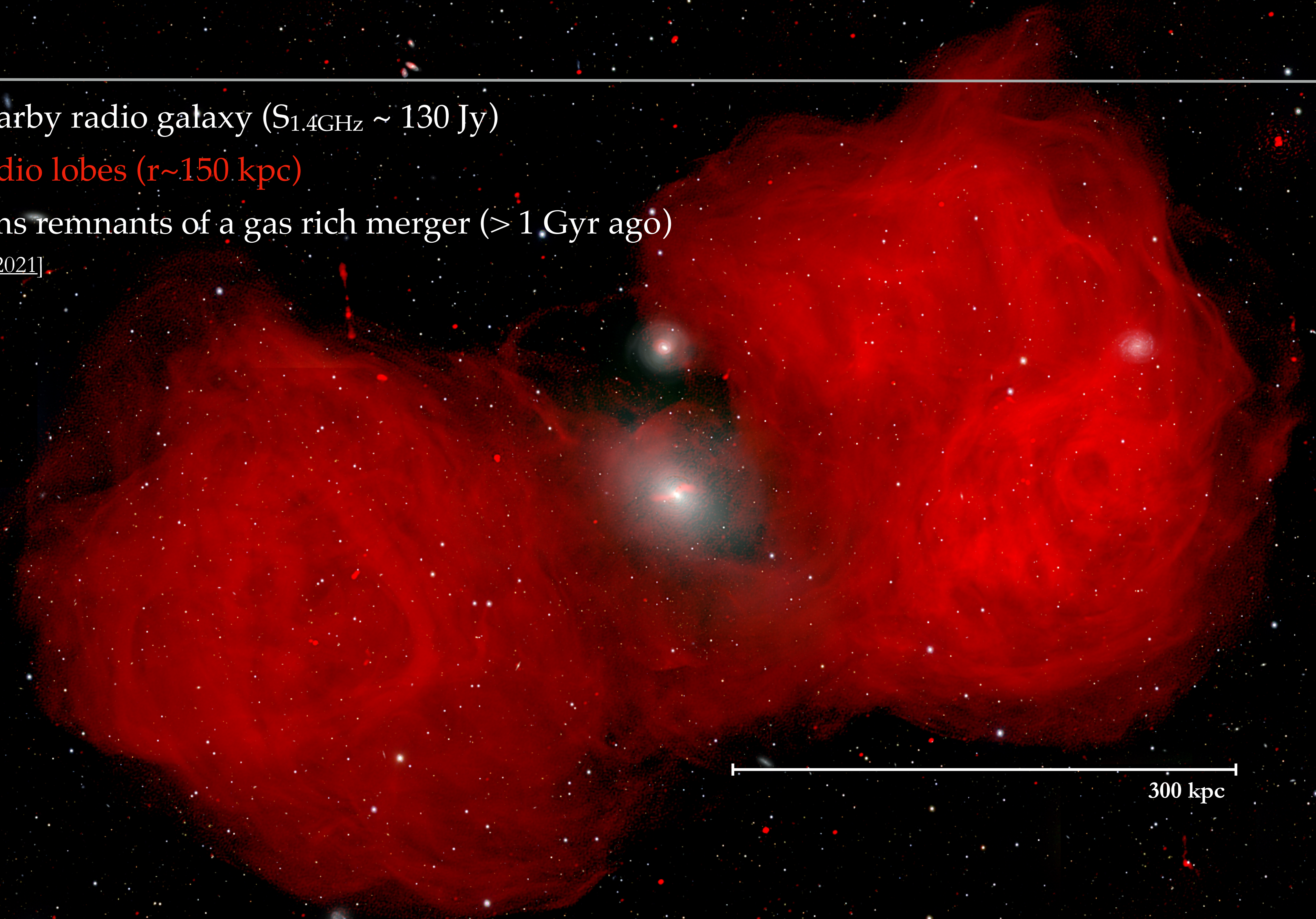
- Outer Filament, HI outflow extends for 2.5 kpc

- Inner Filament, HI \perp to H α filament

Fornax A

- 3rd near brightest nearby radio galaxy ($S_{1.4\text{GHz}} \sim 130 \text{ Jy}$)
- Giant filamentary radio lobes ($r \sim 150 \text{ kpc}$)
- HI clouds and streams remnants of a gas rich merger ($> 1 \text{ Gyr ago}$)

[Serra, et al. 2019, Kleiner et al. 2021]



300 kpc

Fornax A - radio and HI

- How did the radio lobes and inner jets form? in which timescales?
- Is the HI fuelling the nuclear activity of Fornax A?
- Is AGN feedback changing the conditions of the ISM and IGM?

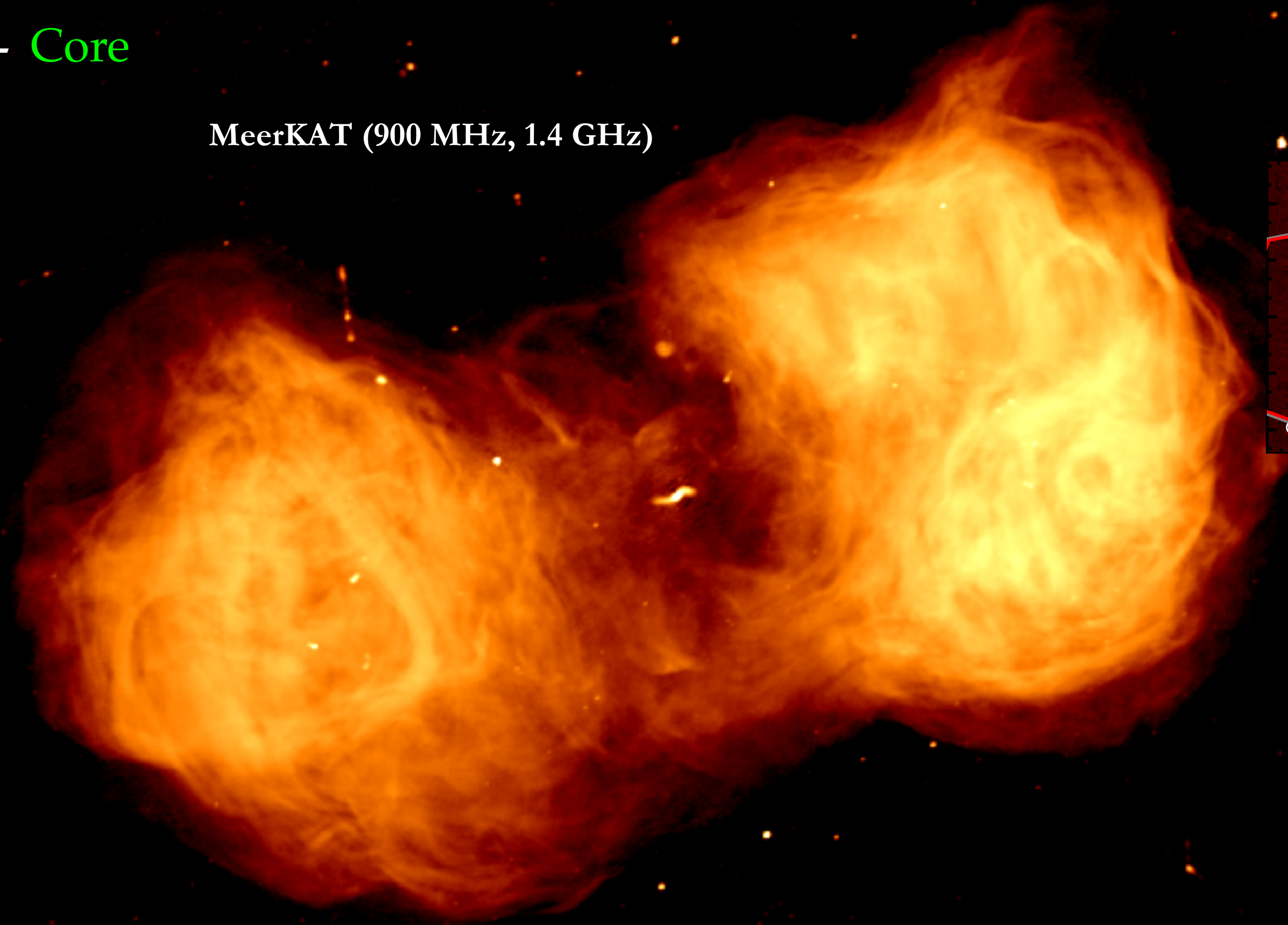


Fornax A - broadband radio continuum

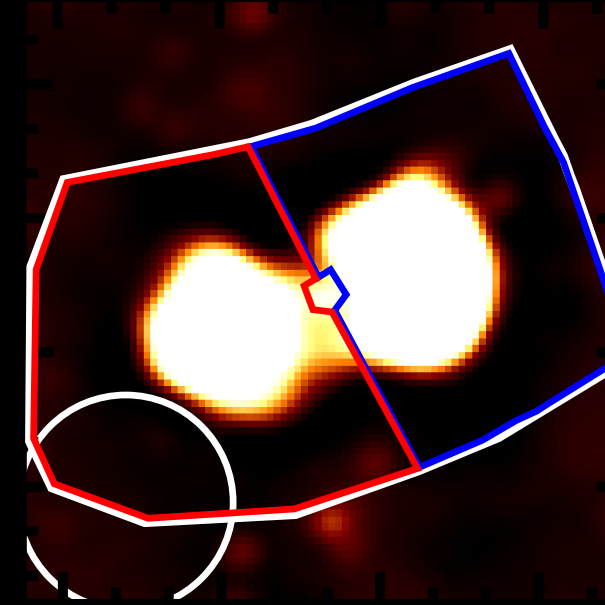
Characterize the duty cycle of the AGN:

Spectral flux density distribution

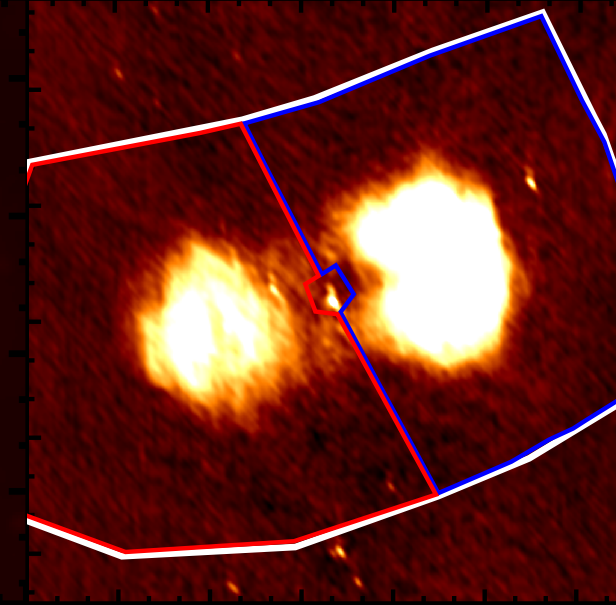
- East & West Lobe
- Inner Jets
- Core



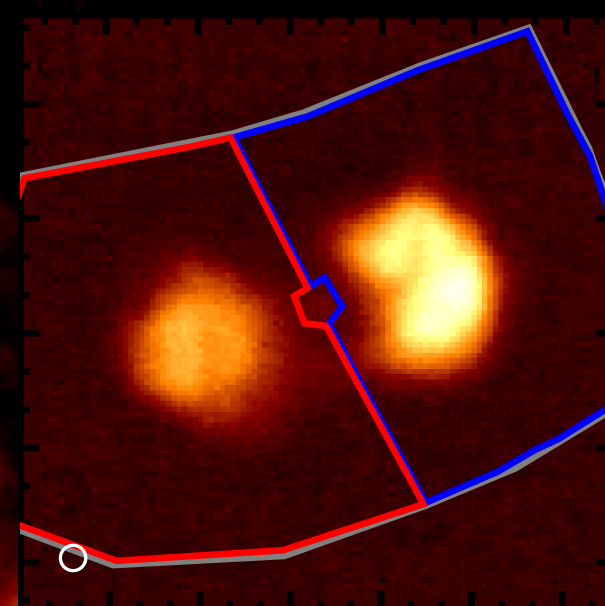
MWA (84 - 200 MHz)



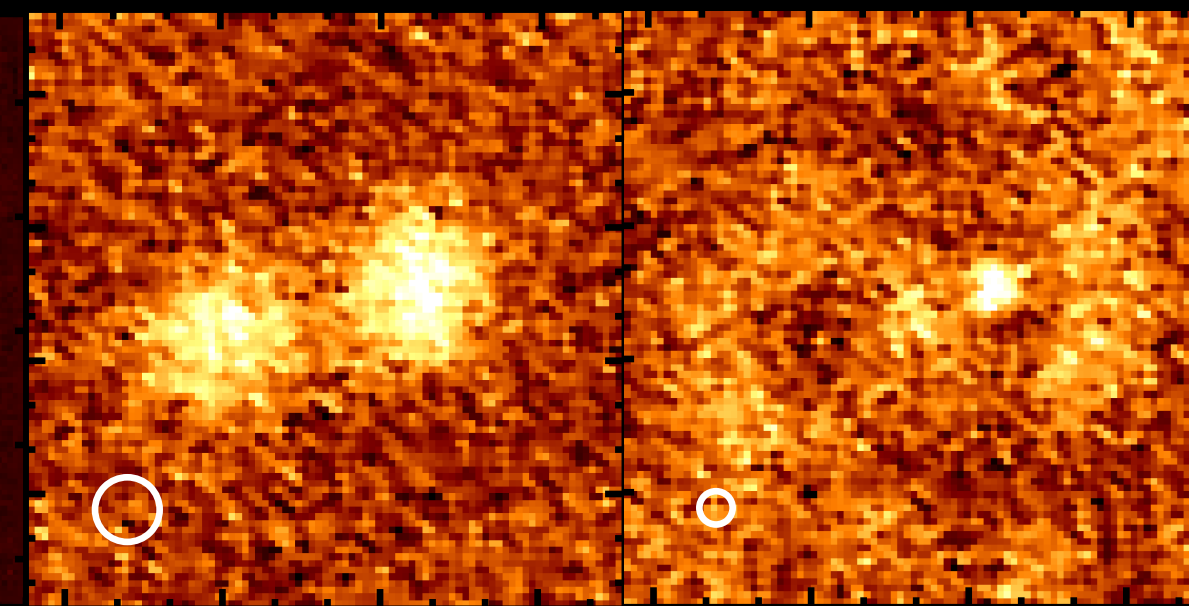
VLA (320 MHz)



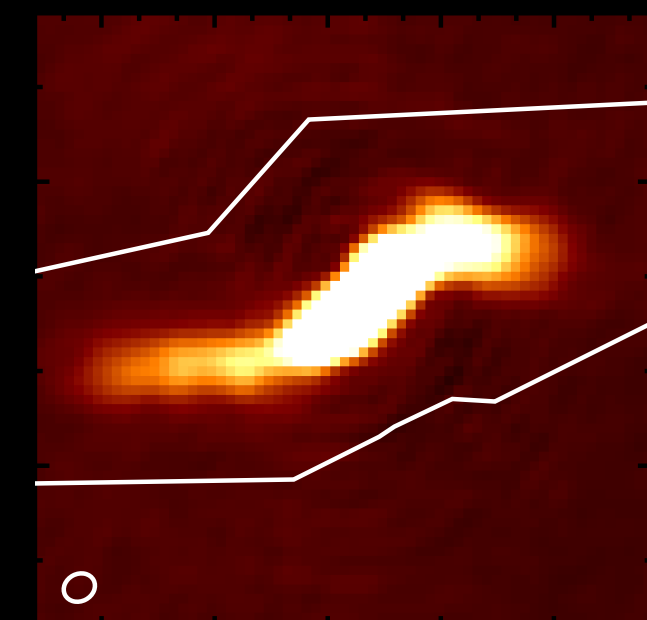
SRT (5.7-6.8 GHz)



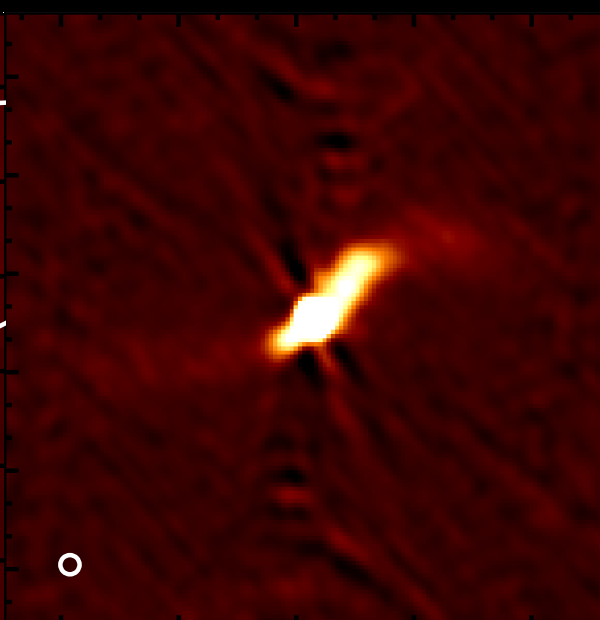
Planck (30 - 217 GHz)



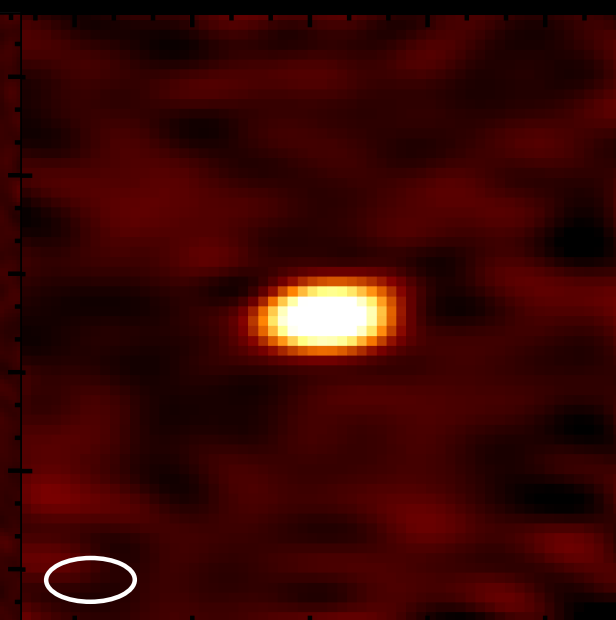
MeerKAT (1.4 GHz)



VLA (4.8 GHz)



ALMA (108 GHz)



Fornax A - AGN flickering activity

- Phase 1 — Lobes

- 24 Myr ago began the last injection of the lobes
- 12 Myr ago AGN switch-off

- Phase 2 — Jets

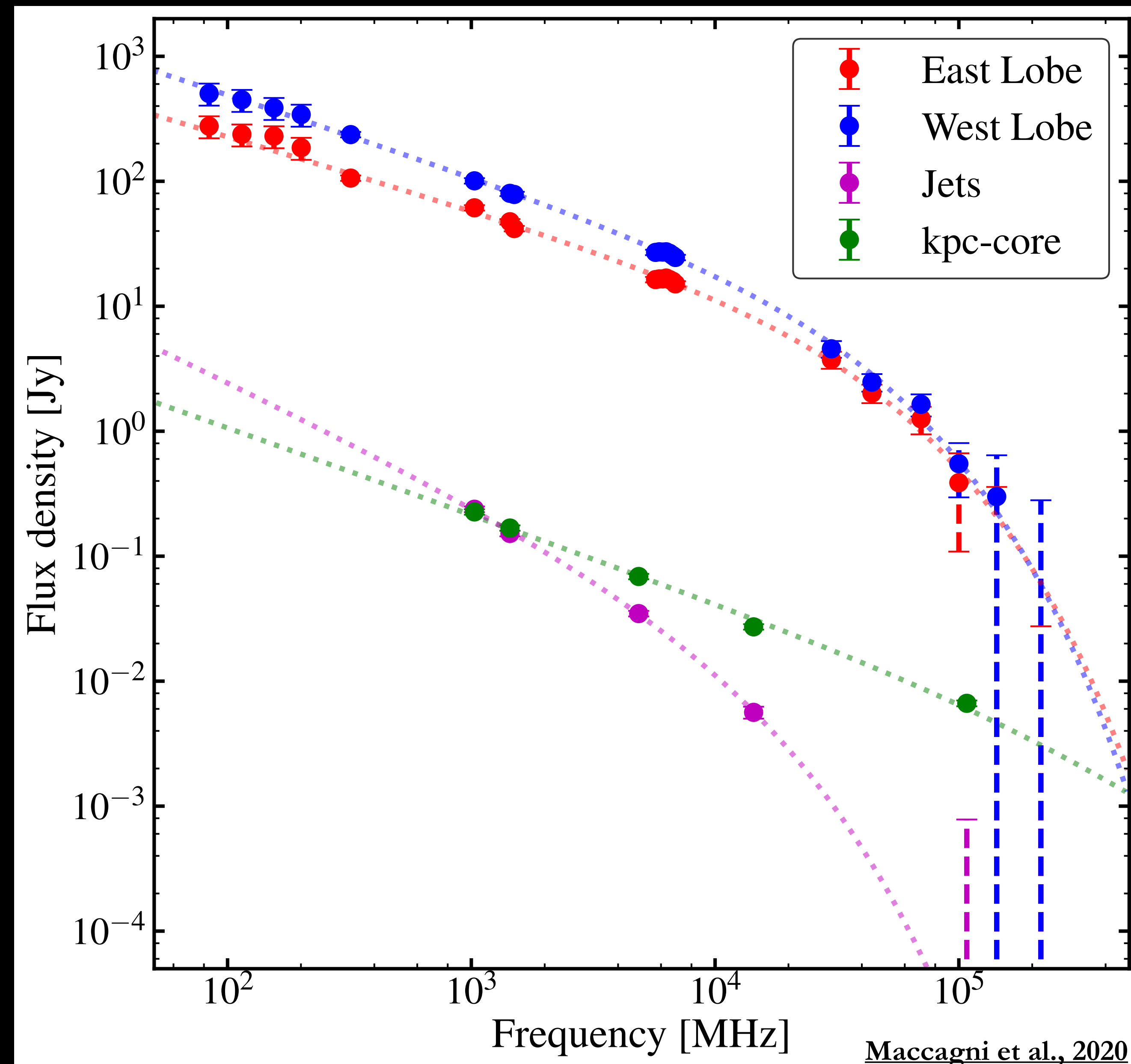
- 3 Myr ago AGN formed the jets
- 1 Myr ago AGN switch-off

- Phase 3 — Core

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

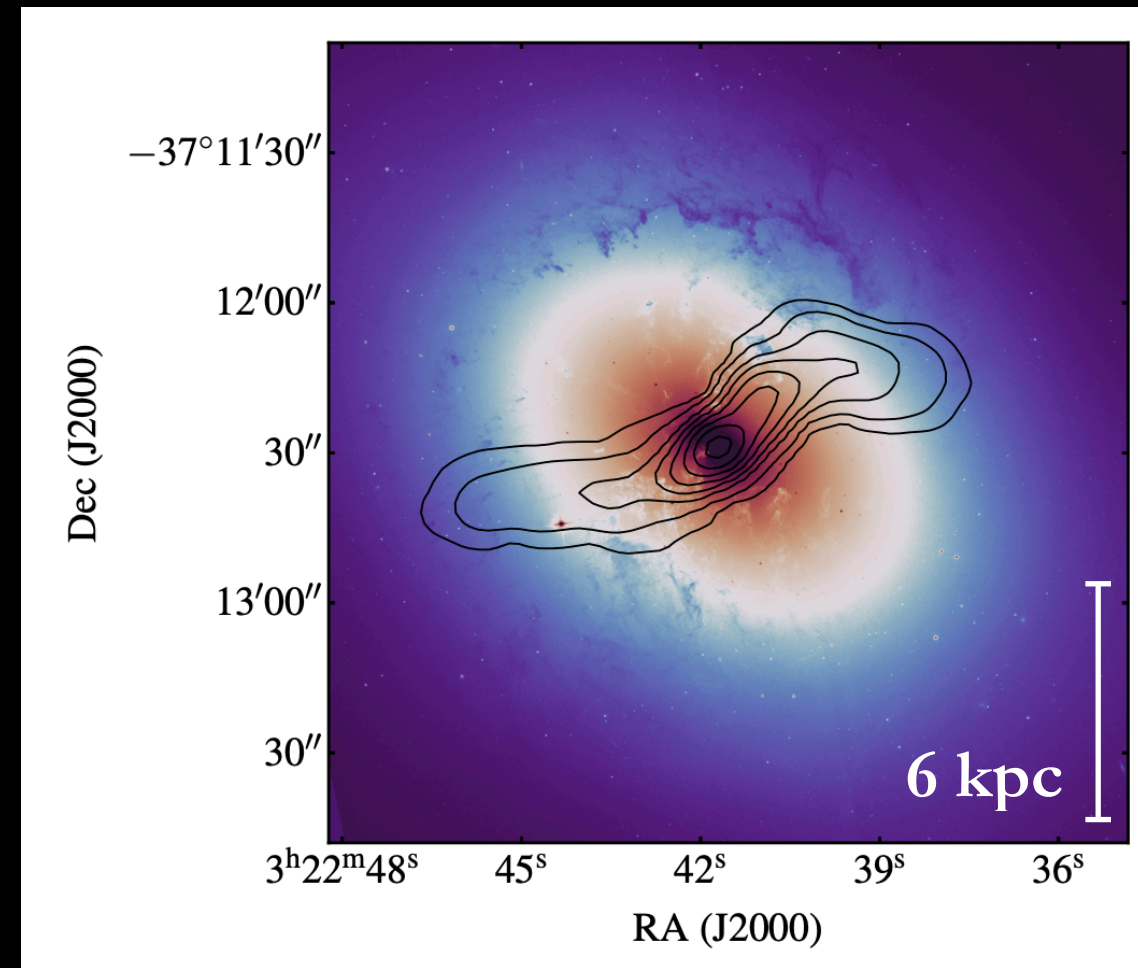
What regulates the fast duty cycle?

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

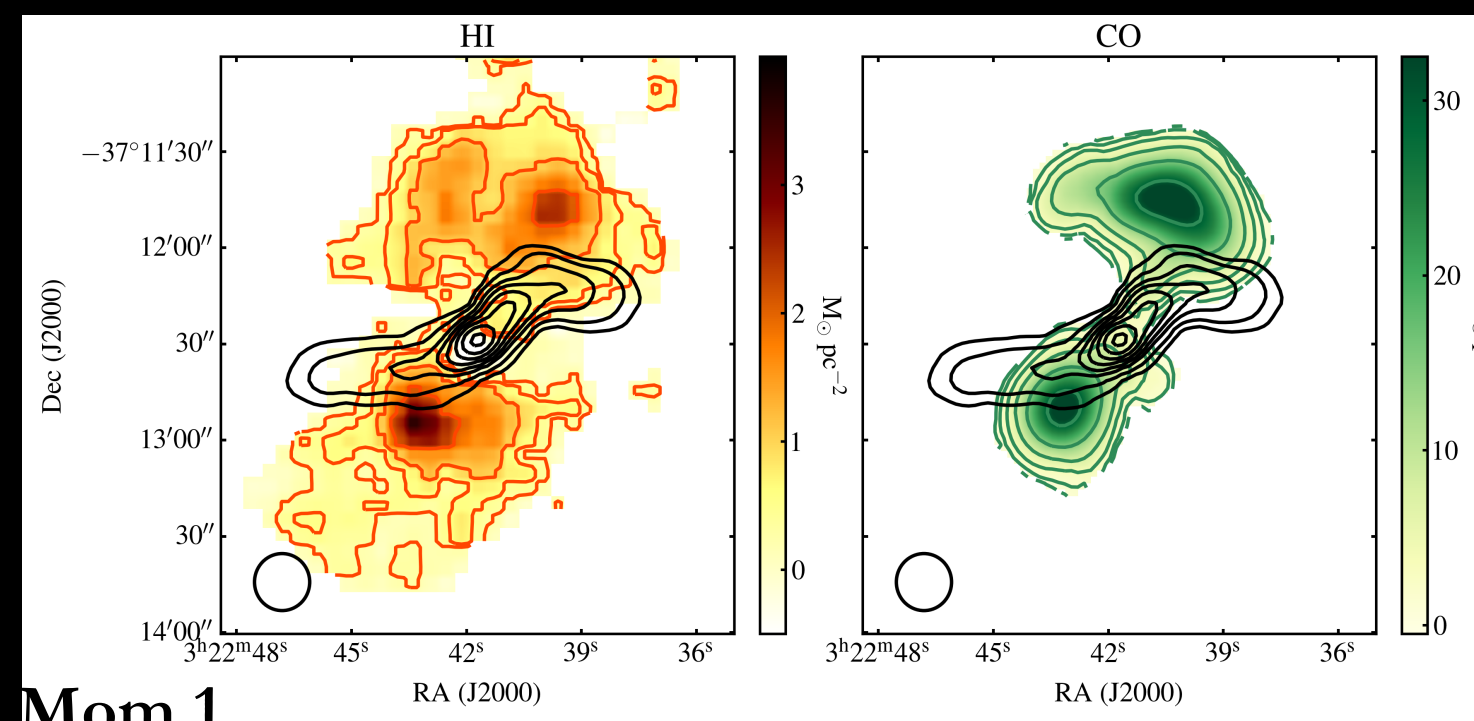


Fornax A - Central cold gas distribution and kinematics

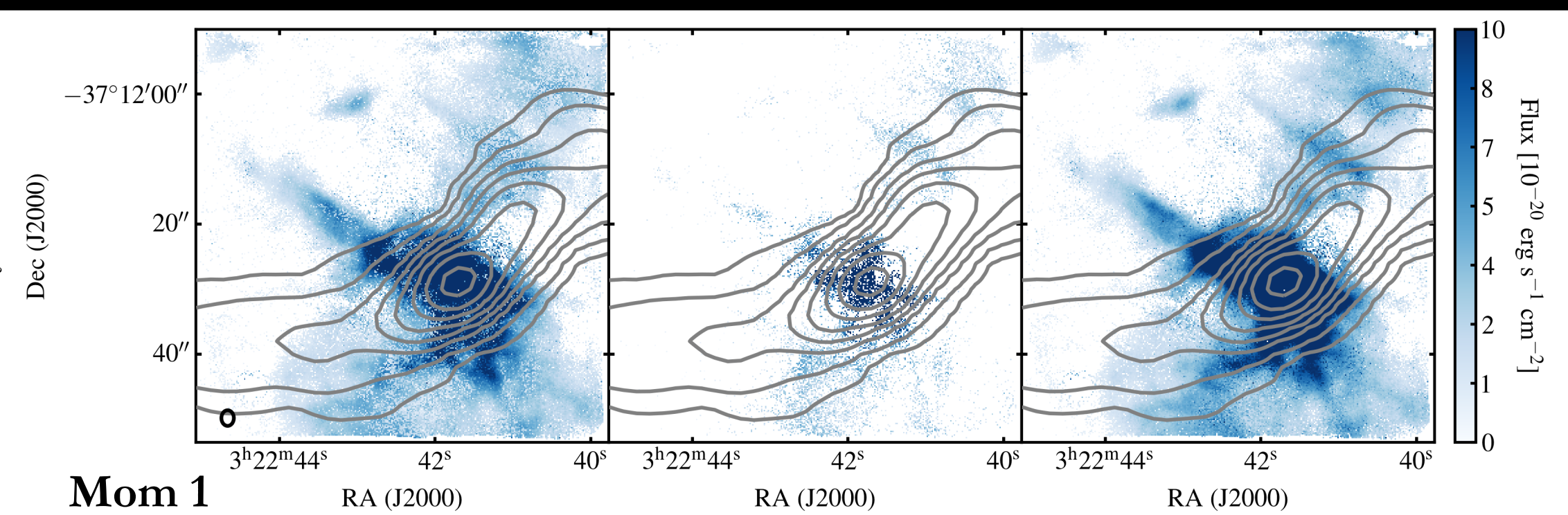
Dust



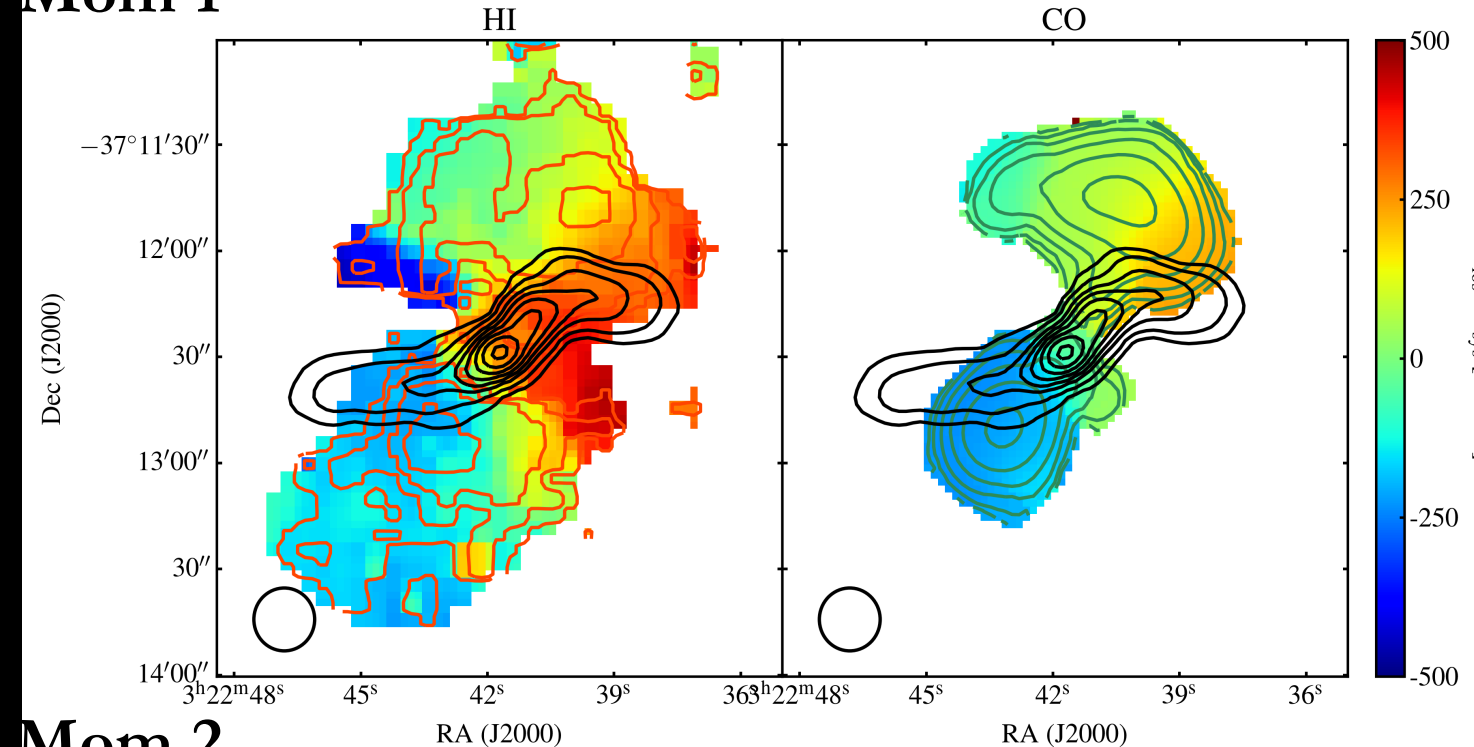
HI, CO (1-0) — Mom 0



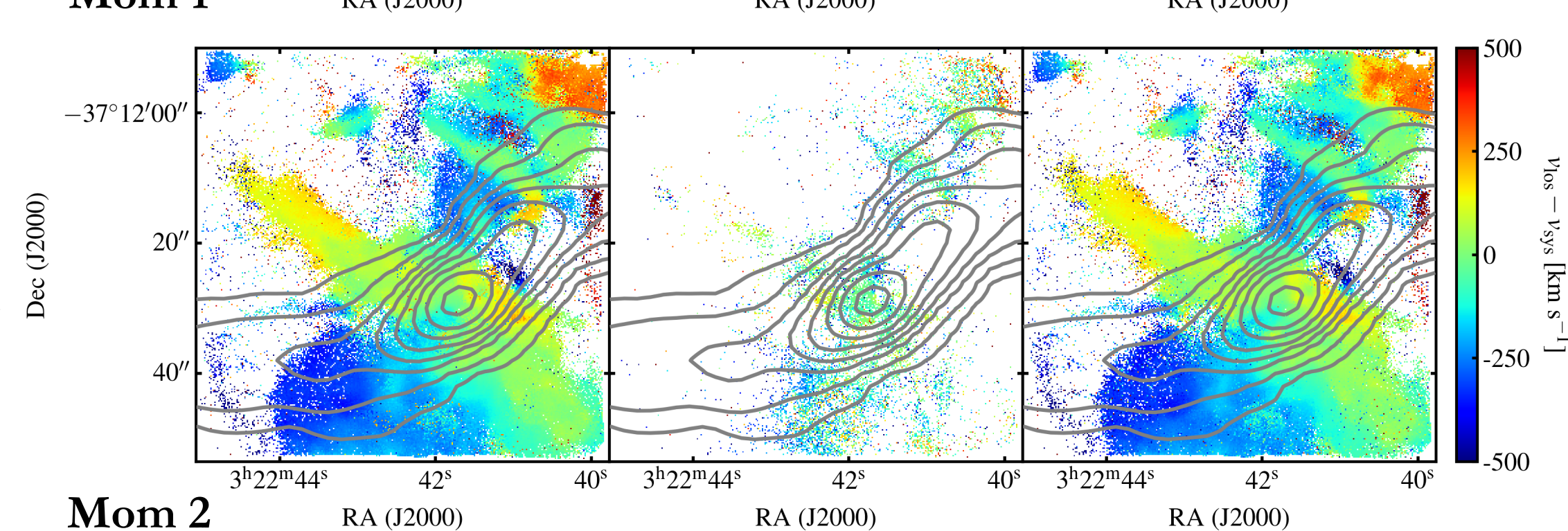
[NII]6583 — Mom 0



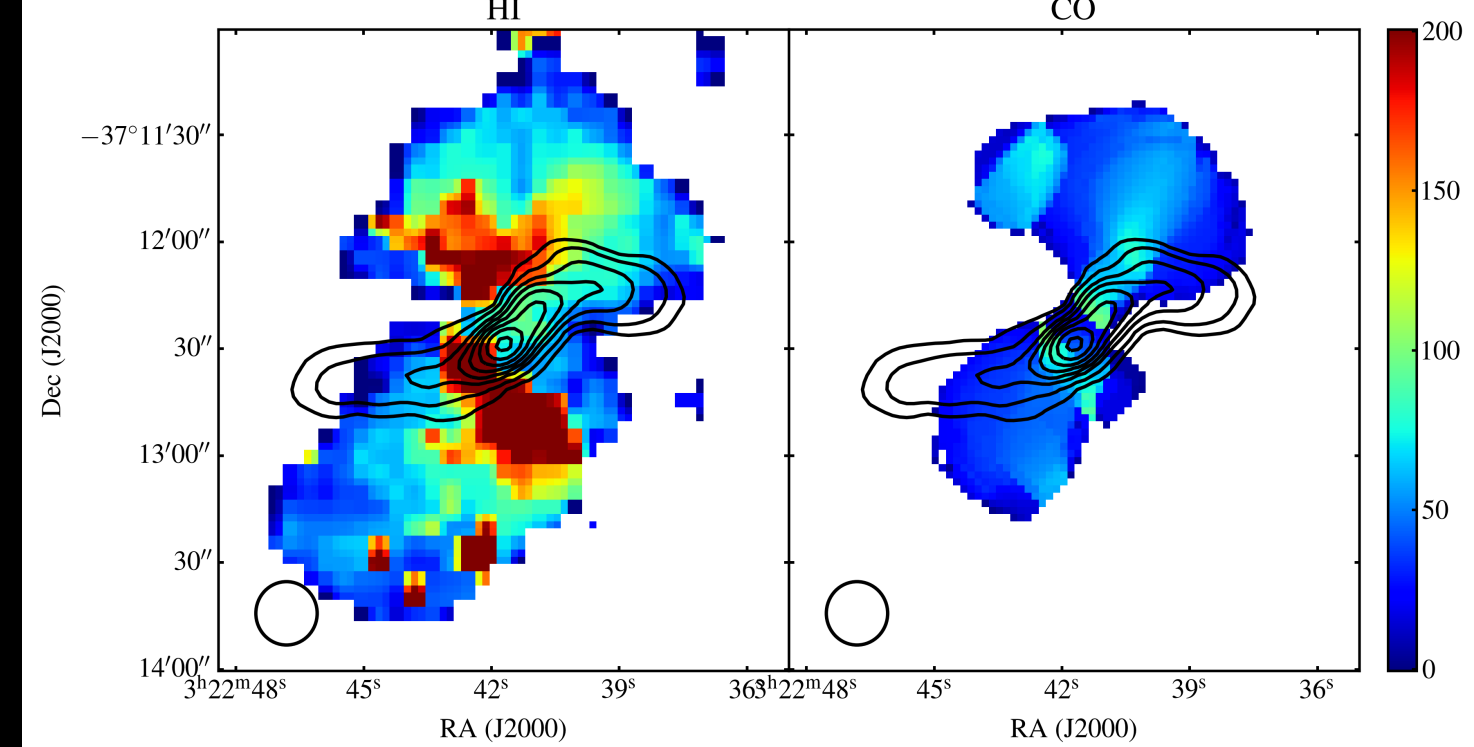
Mom 1



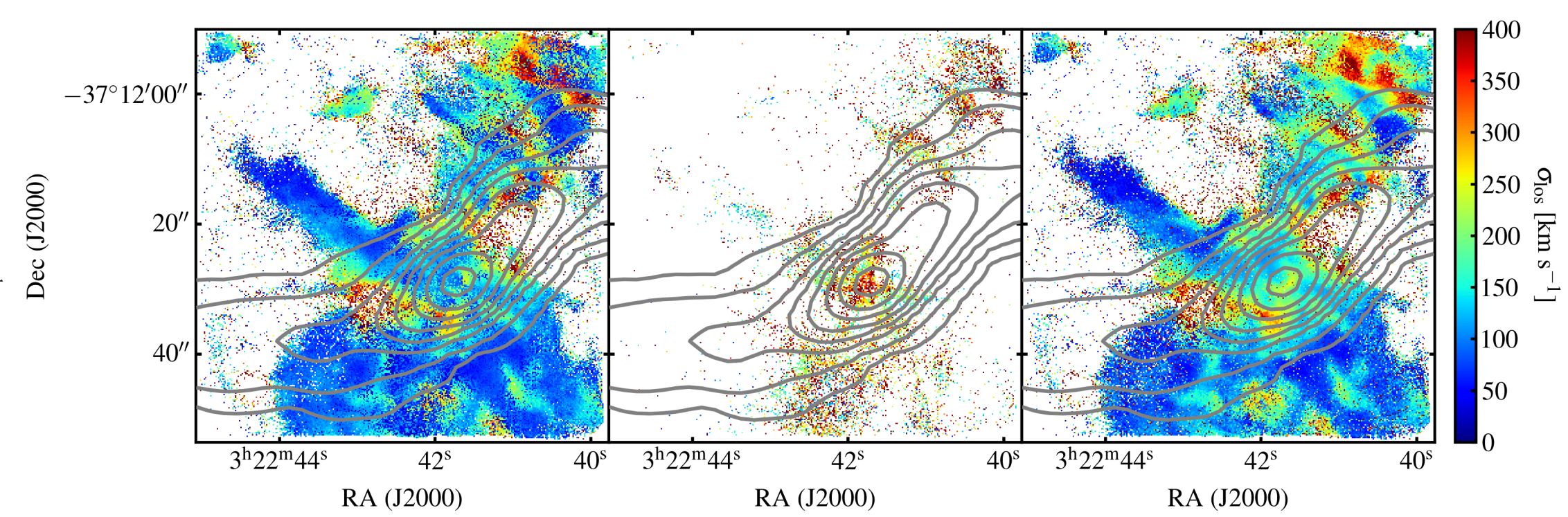
Mom 1



Mom 2



Mom 2

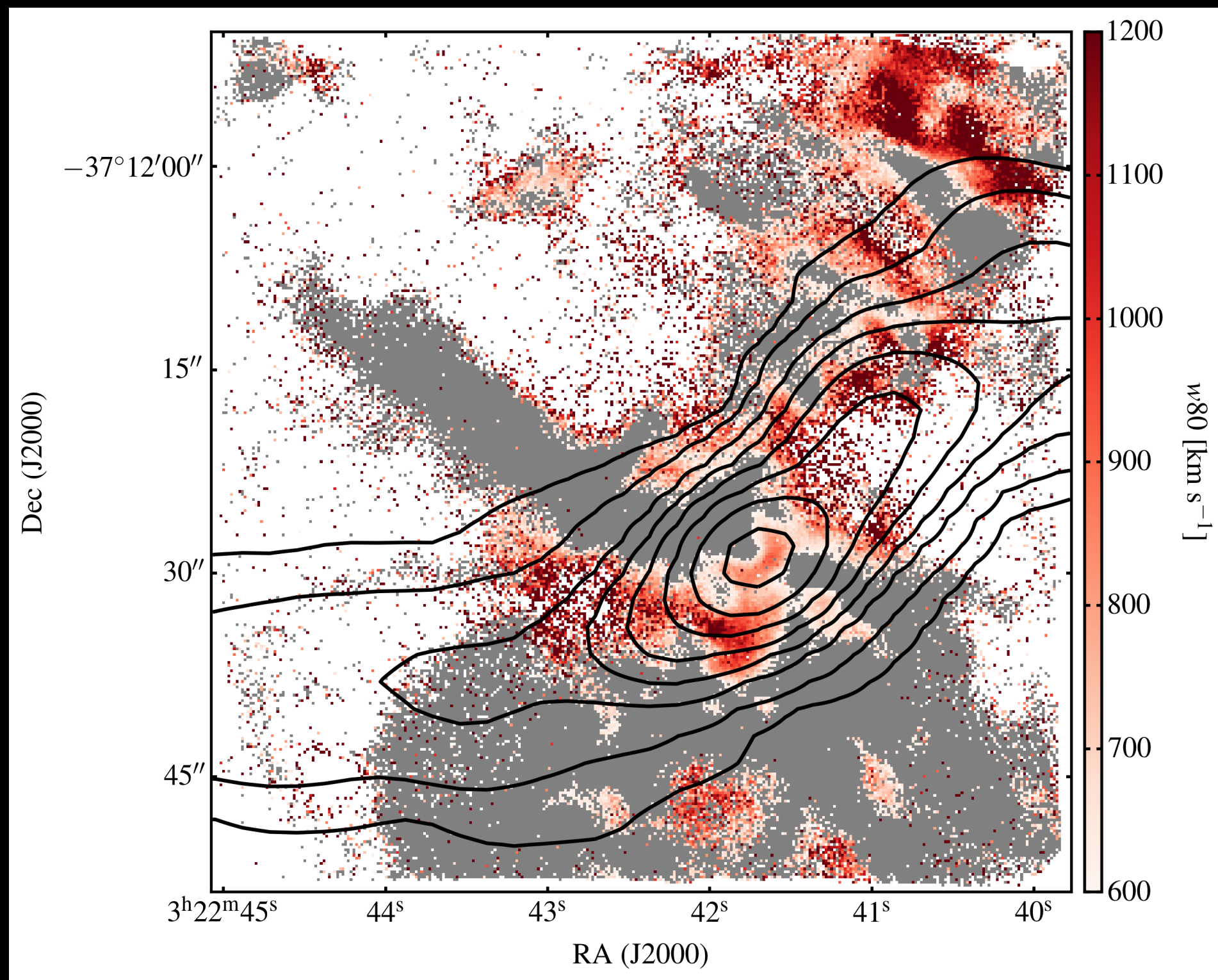


Rotation axis of the gas
(NW-SE) perpendicular
to the stellar body

Several deviations from
rotation

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

Fornax A - galactic multi-phase outflow

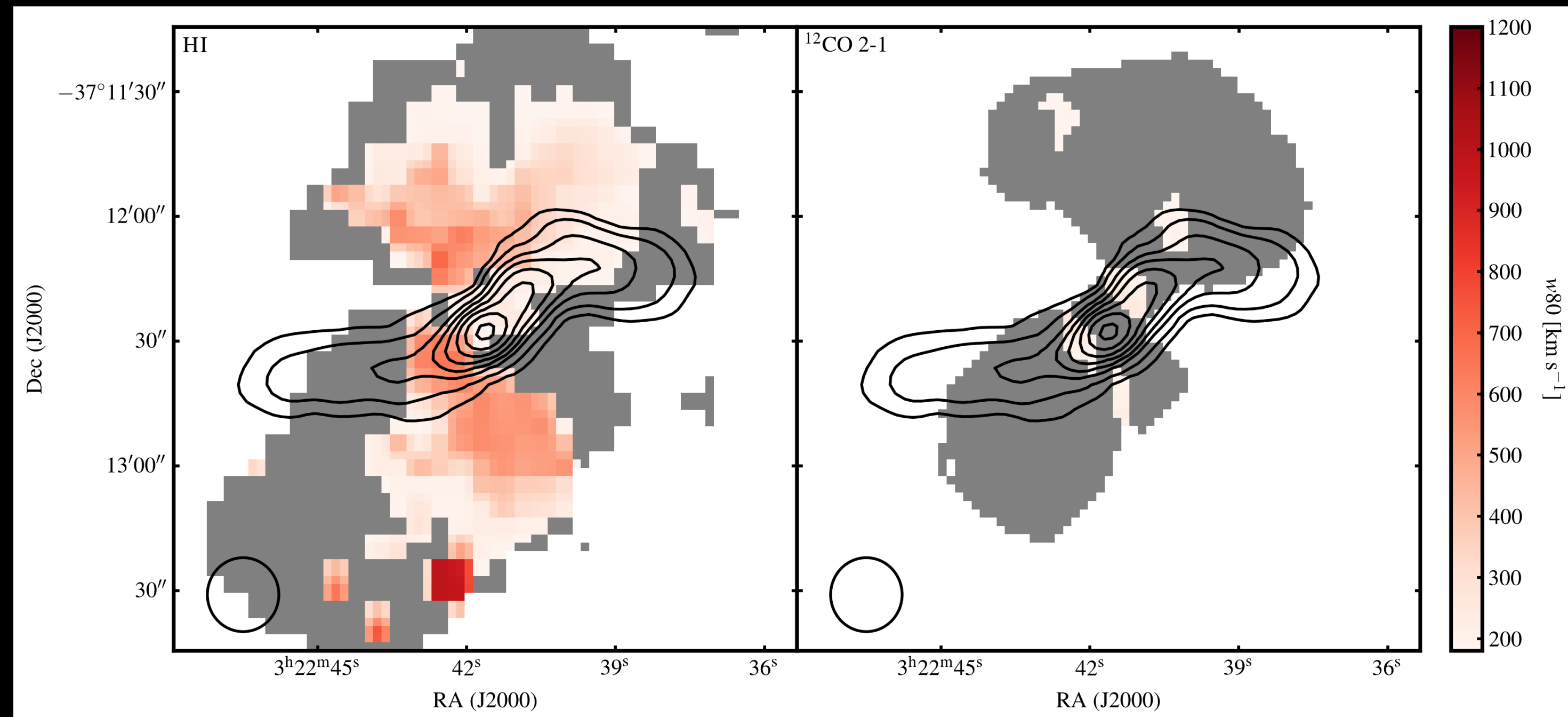


- Ionised gas
 - $w_{80} > 600 \text{ km s}^{-1}$ in the wake of the radio jets
- Cold gas
 - $w_{80} > 600 \text{ km s}^{-1}$ along the jets and in the outer ring

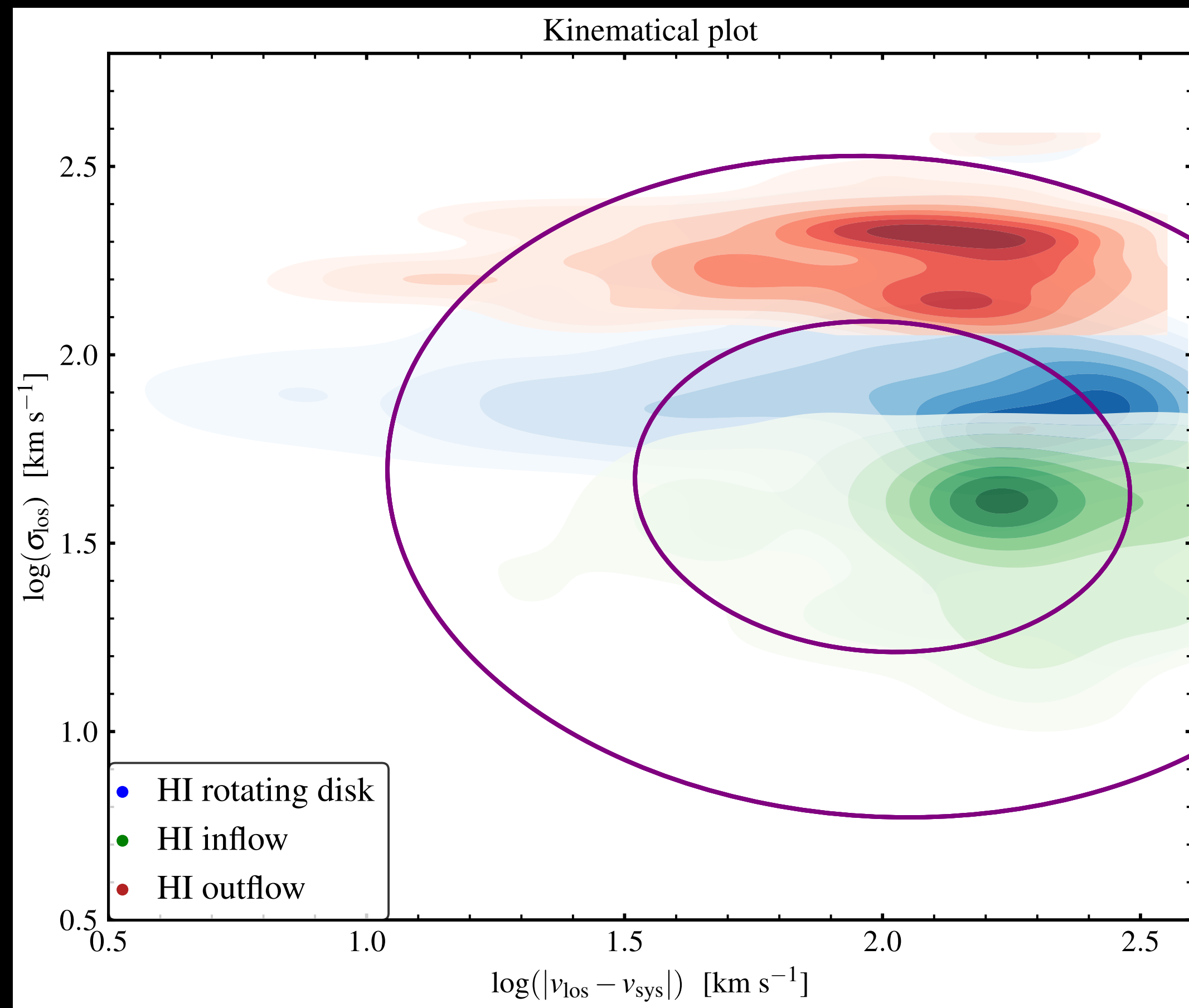
At its outflow velocity (2000 km s^{-1}) the outer ring would have reached its distance from the centre in $\sim 3 \text{ Myr}$

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Age of the radio jets



Fornax A - regions with similar kinematics



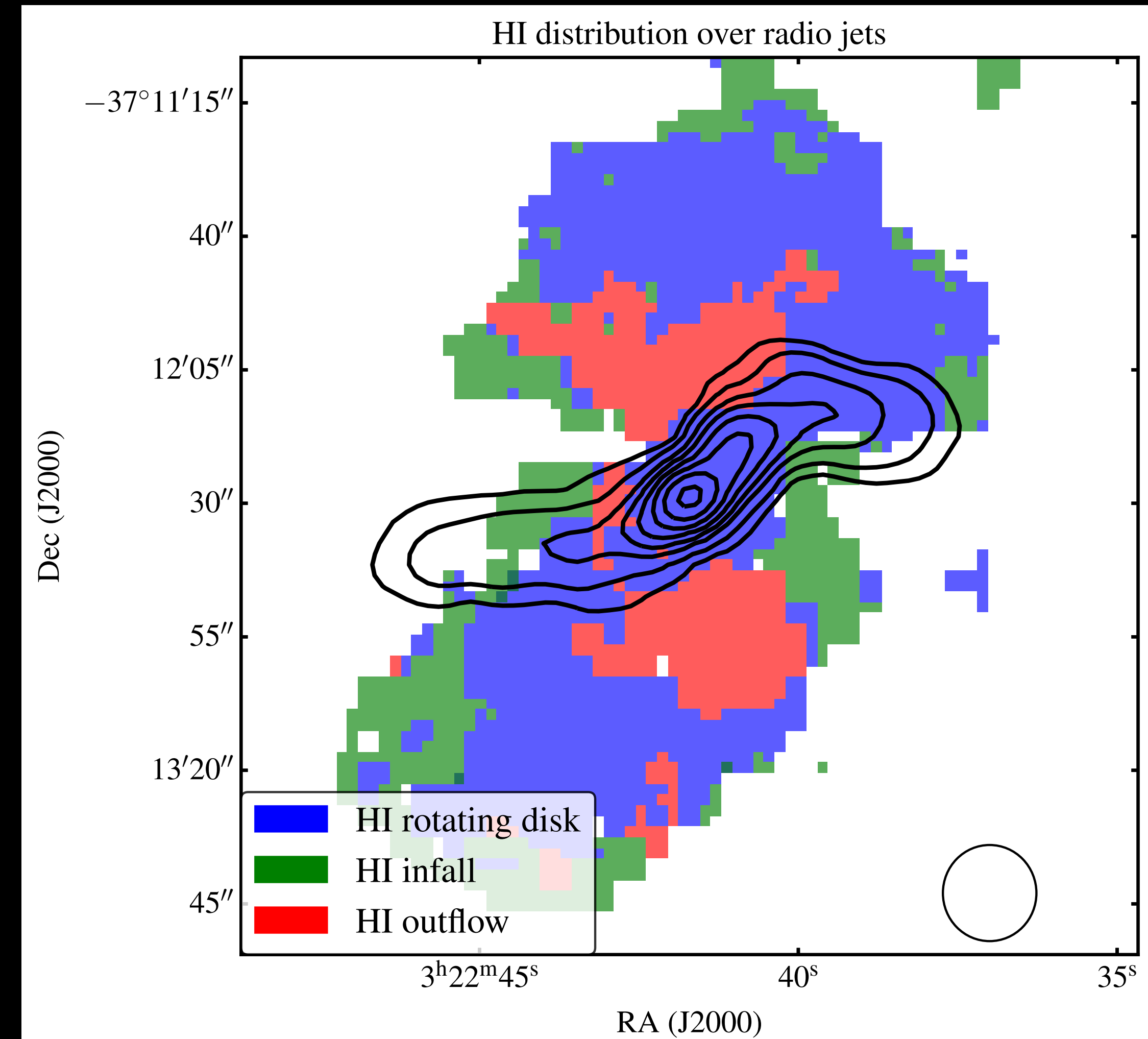
Kinematical plot (k-plot)

naturally identifies loci with similar kinematics

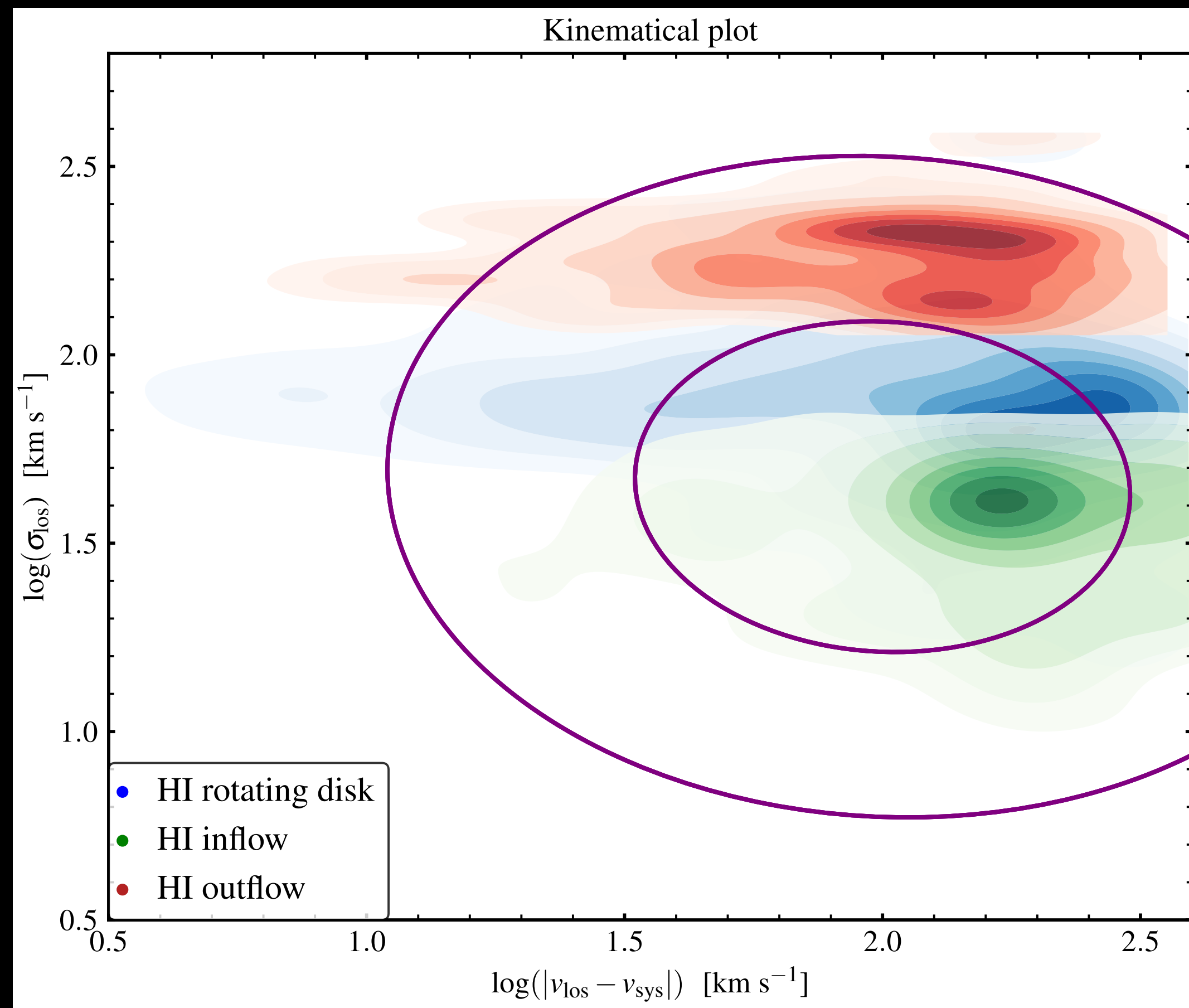
broad line-widths (R6) -> outflow in the wake of the radio jet

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

k-plot of ionised gas and CO show the same properties

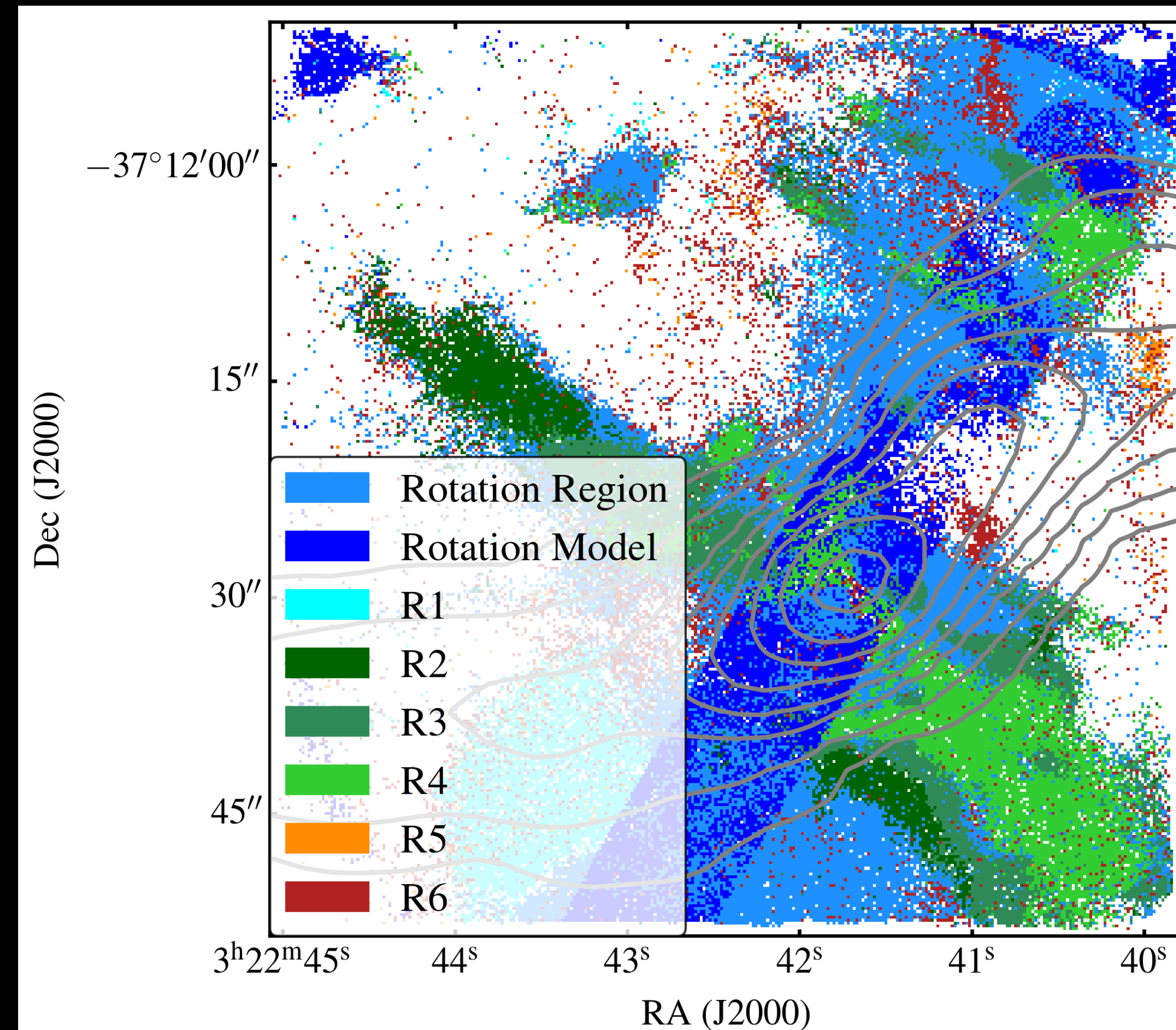


Fornax A - regions with similar kinematics



Kinematical plot (k-plot)

naturally identifies loci with similar kinematics

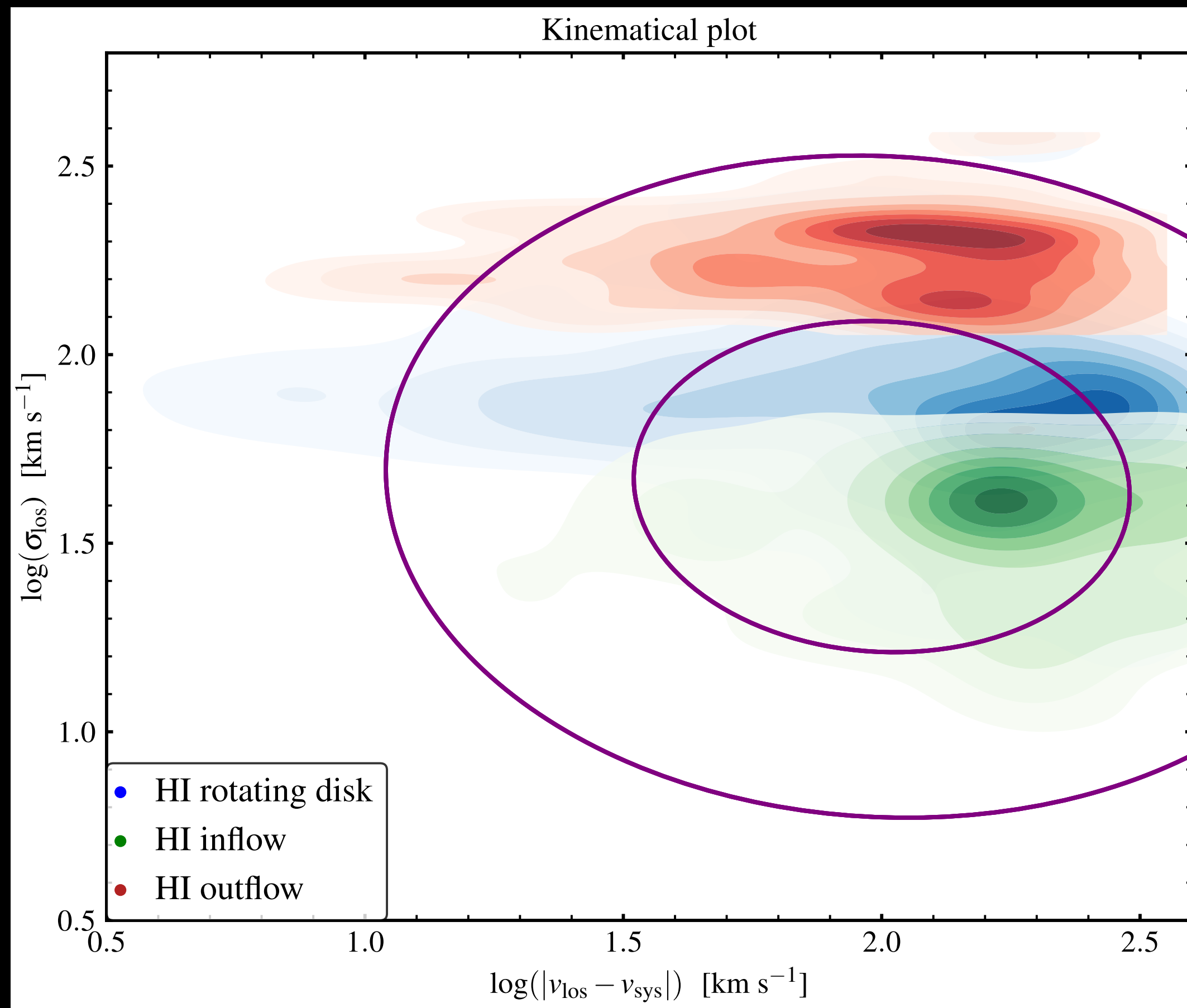


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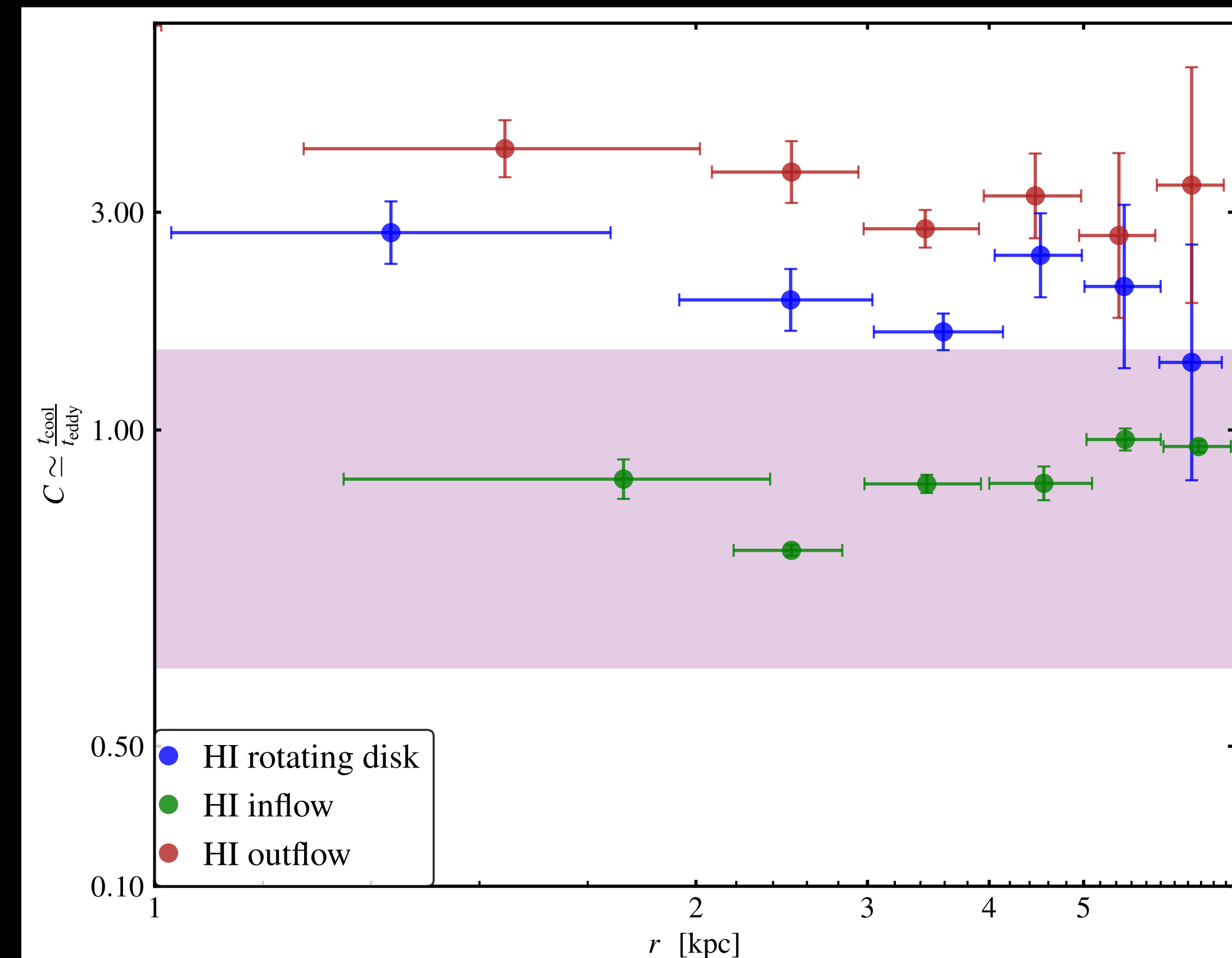
Fornax A - cold gas AGN feeding



- 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

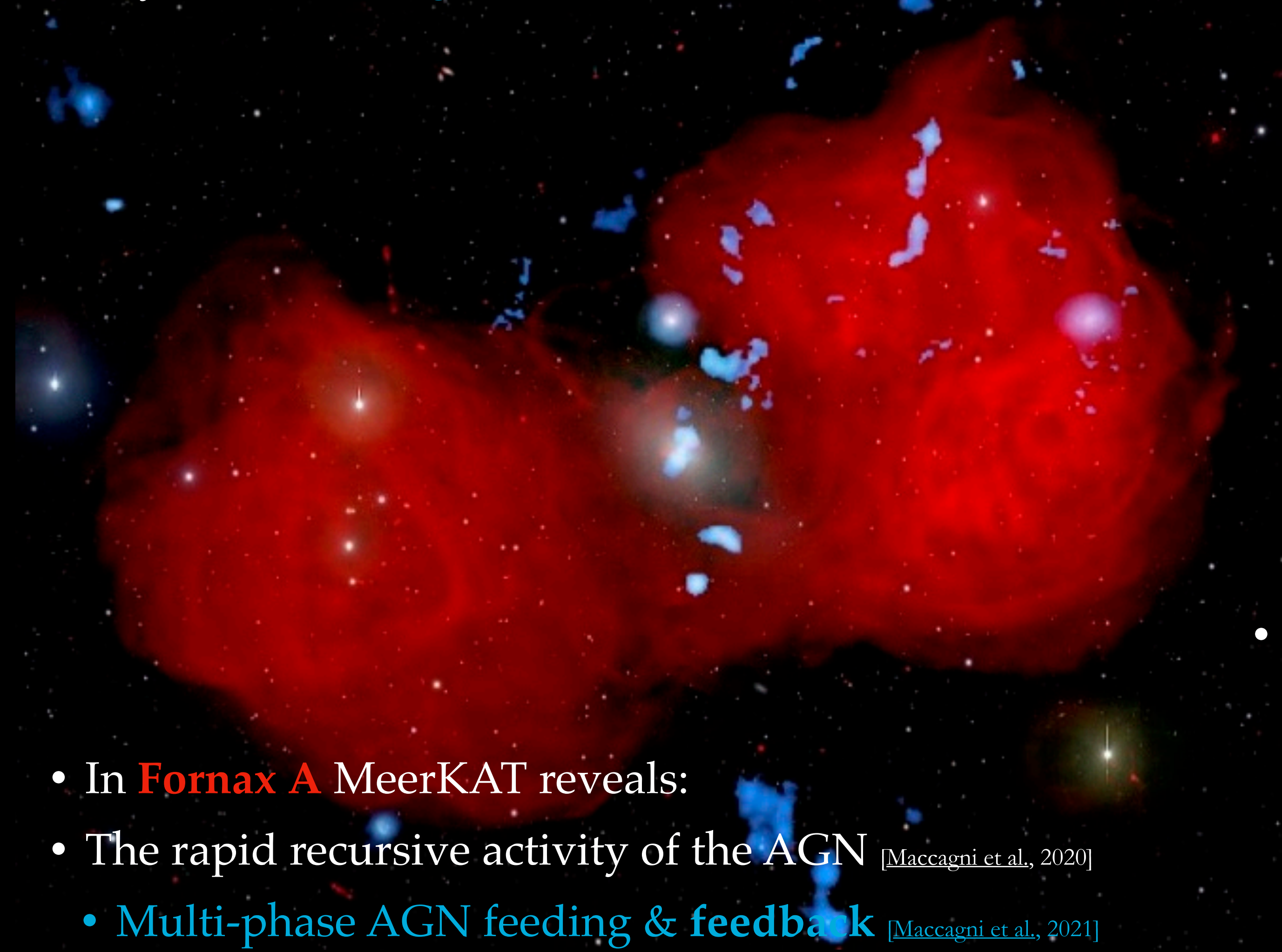
measures the role of turbulence causing condensation of the gas

EW filaments: turbulence may cause cooling and infall

Outflow: very different physical conditions

MAGNHIFFIC - Conclusions

- The future of HI deep studies is on **diffuse and low-column gas**
- **MeerKAT** enables wide-field deep HI surveys (i.e. **MAGNHIFFIC**) to:
study **AGN feeding & feedback from the circumnuclear to the circumgalactic scale**

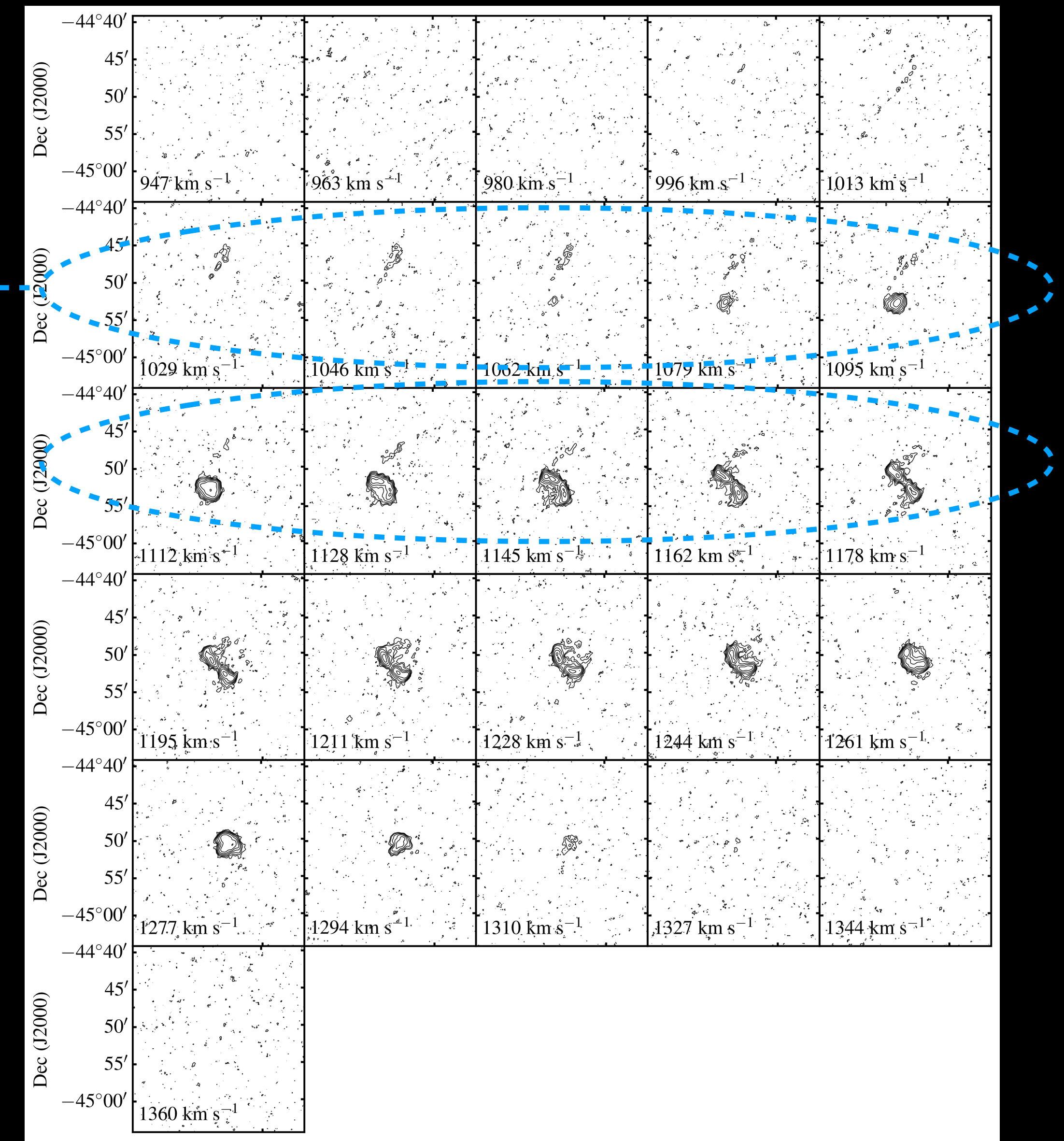
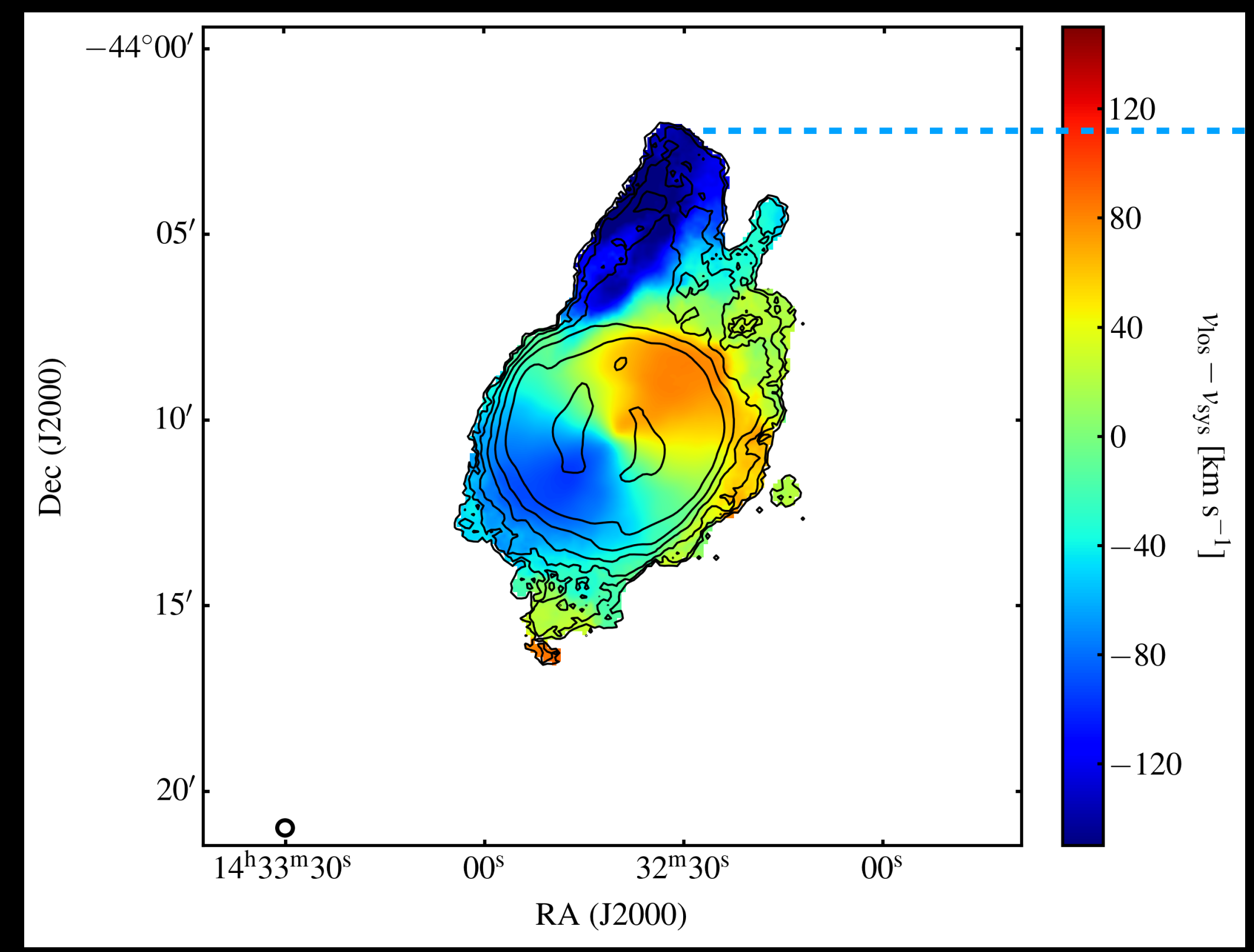


- In **Centaurus A** MeerKAT reveals:
 - A disrupted outer disk of cold gas
 - A turbulent circum-nuclear disk
 - **Coherent multi-phase outflow fuelling SF (positive feedback)** in several regions along an ionised filament

- In **Fornax A** MeerKAT reveals:
 - The rapid recursive activity of the AGN [Maccagni et al., 2020]
 - **Multi-phase AGN feeding & feedback** [Maccagni et al., 2021]

MAGNHIFFIC - NGC5643

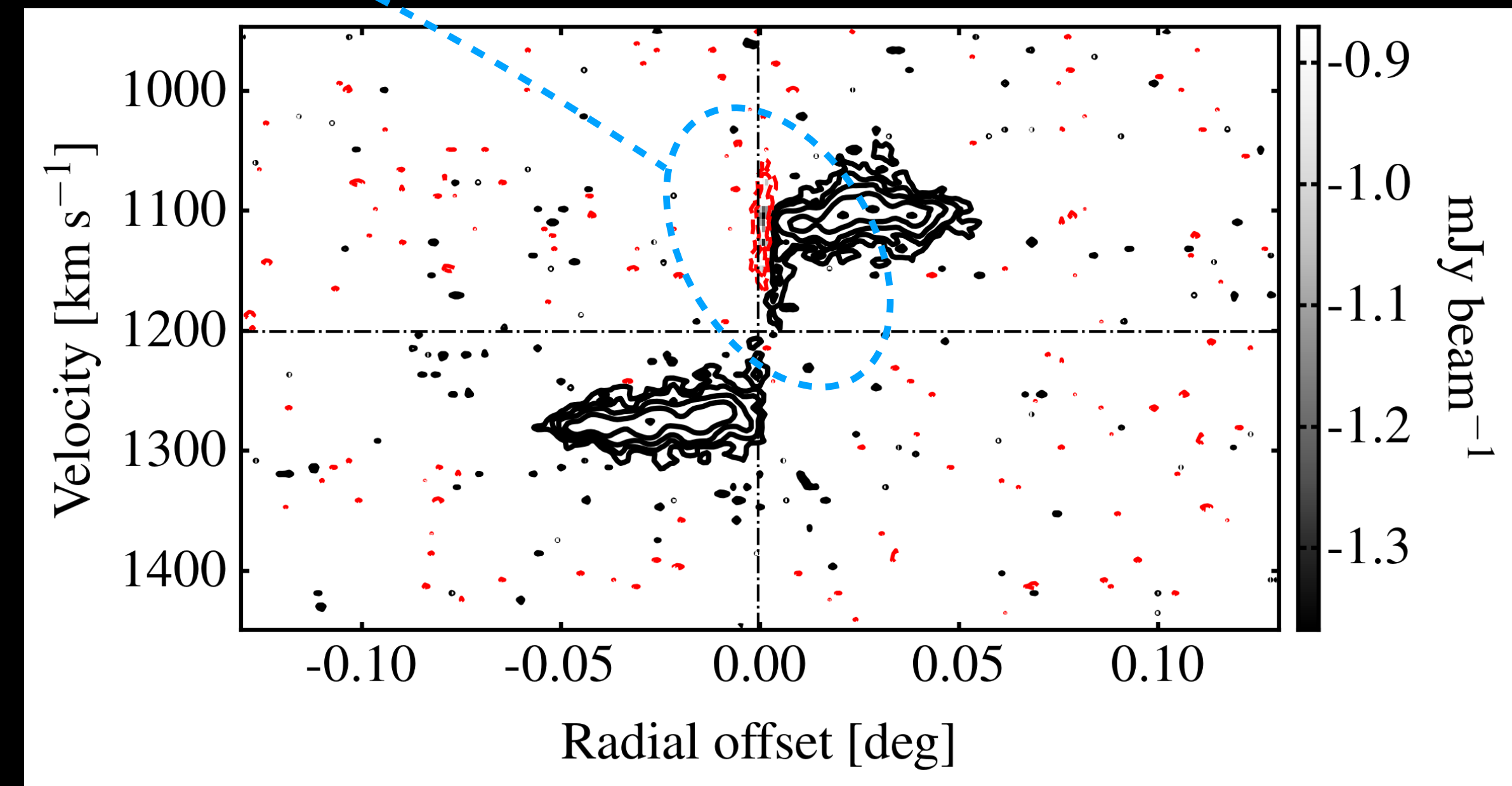
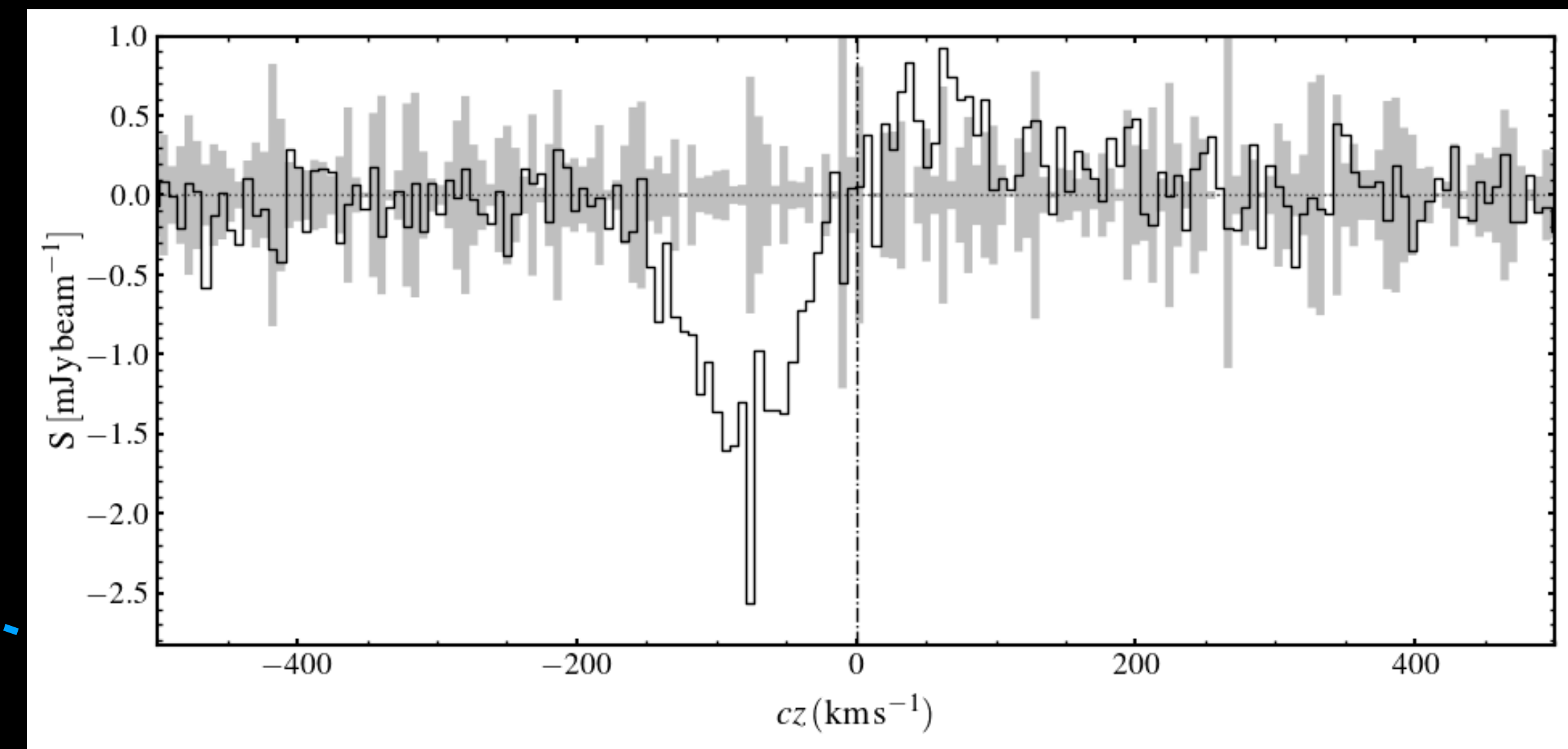
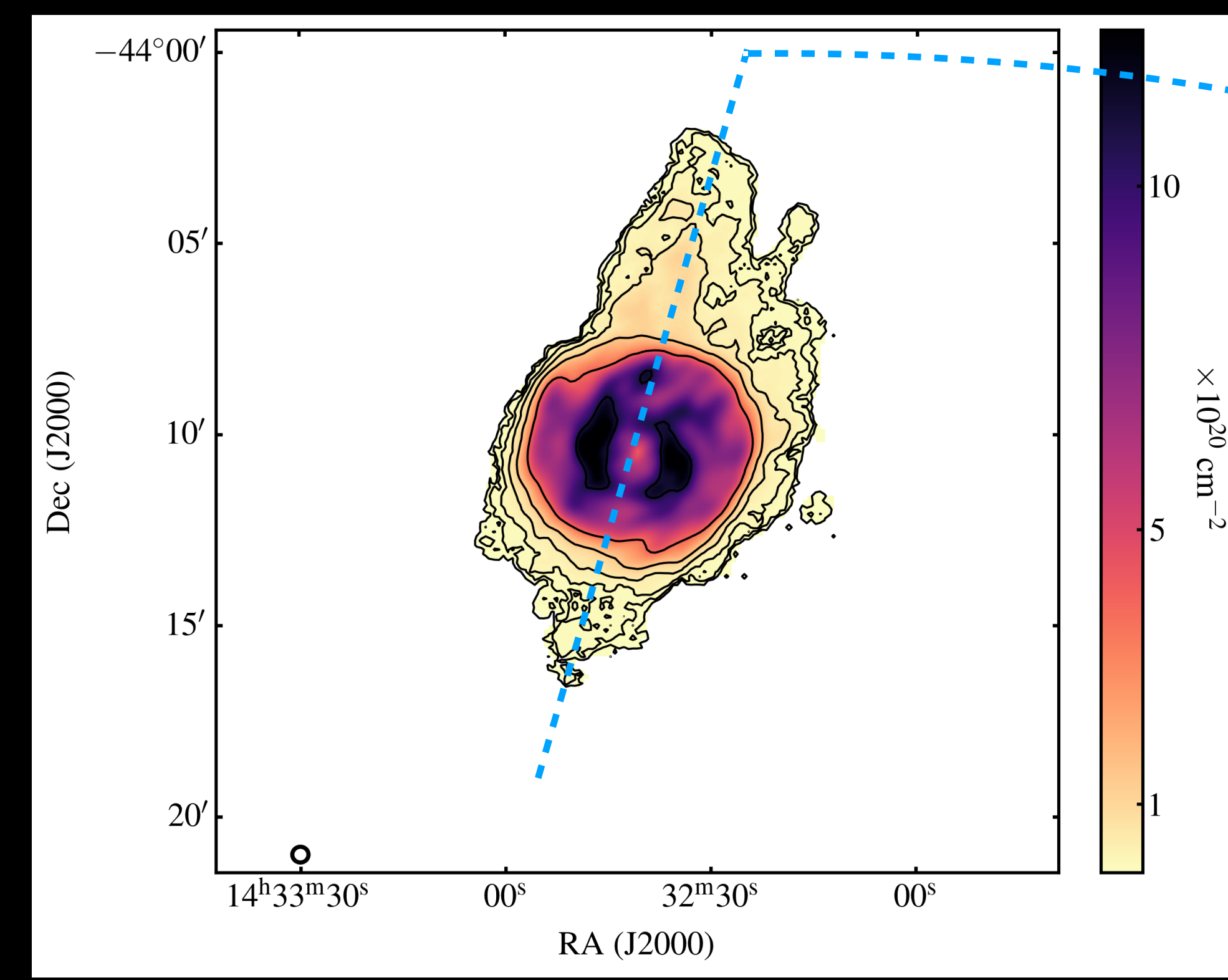
- What is the origin of the northern tail in NGC5643?
- Is gas falling towards the AGN?
- Is NGC5643 undergoing a tidal interaction with a satellite?



-> Answers will be found by Karina Santana @ ASTRON Summer Student program 2023

MAGNHIFFIC - NGC5643

- Is **HI absorption** tracing the neutral atomic counterpart of the ionised and molecular outflow?
- What is the **total mass** of the outflowing gas? **Till where does it extend?**



-> Answers will be found by Karina Santana @ ASTRON Summer Student program 2023