

AGN feeding & feedback

revealed in detail by

MeerKat and the SKA

Filippo Maccagni - INAF Cagliari

Erwin de Blok, Dane Kleiner, Julia Healy, Simone Veronese - **MHONGOOSE** - ASTRON

Paolo Serra, Matteo Murgia, Francesca Loi - **MeerKAT Fornax Survey** - INAF Cagliari

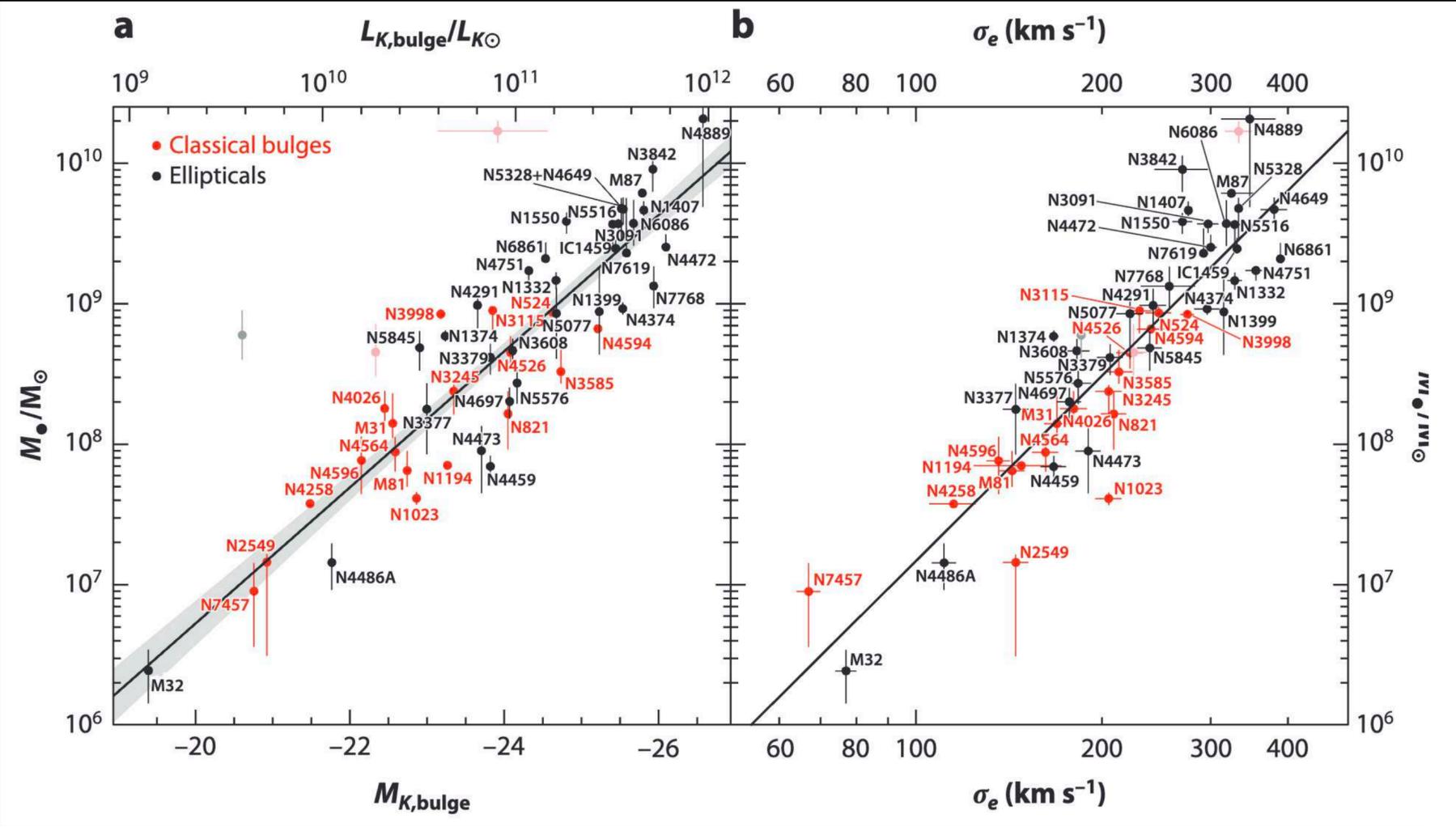
Enrica Iodice, Alessandro Loni, Rossella Ragusa, Marilena Spavone - INAF Napoli

Isabella Prandoni, Ilaria Ruffa - INAF IRA & Arcetri

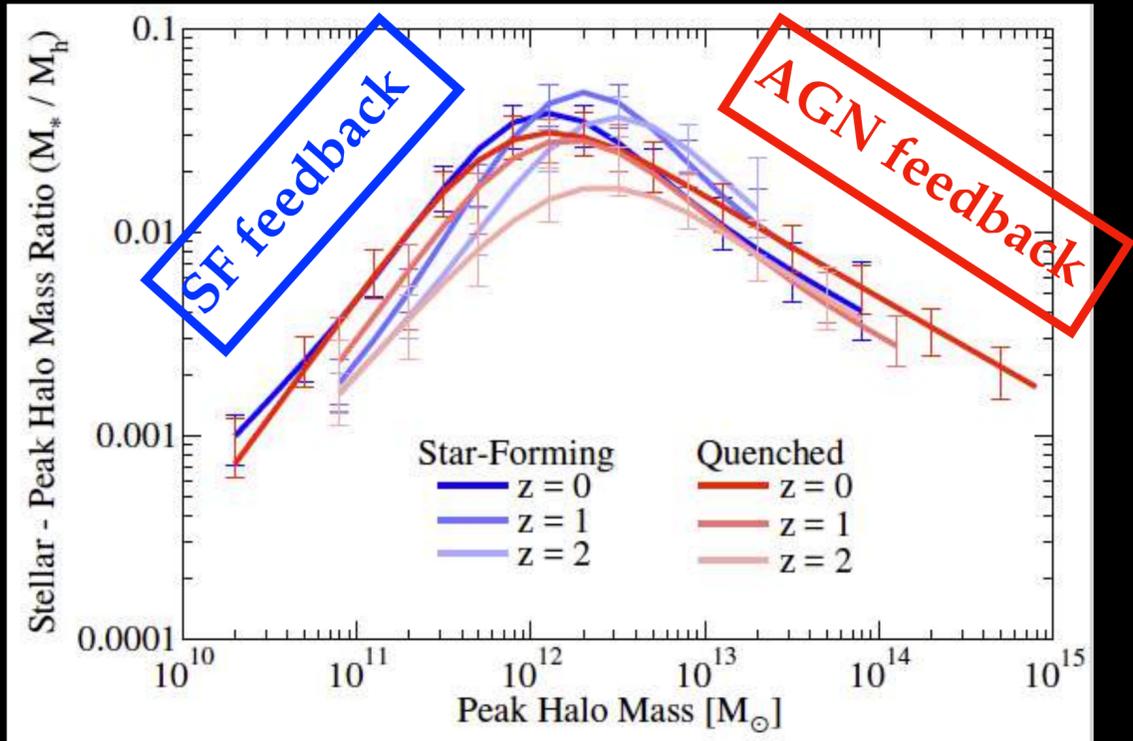
Max Gaspari - UNIMORE

Micro and macro - AGN Feeding and Feedback

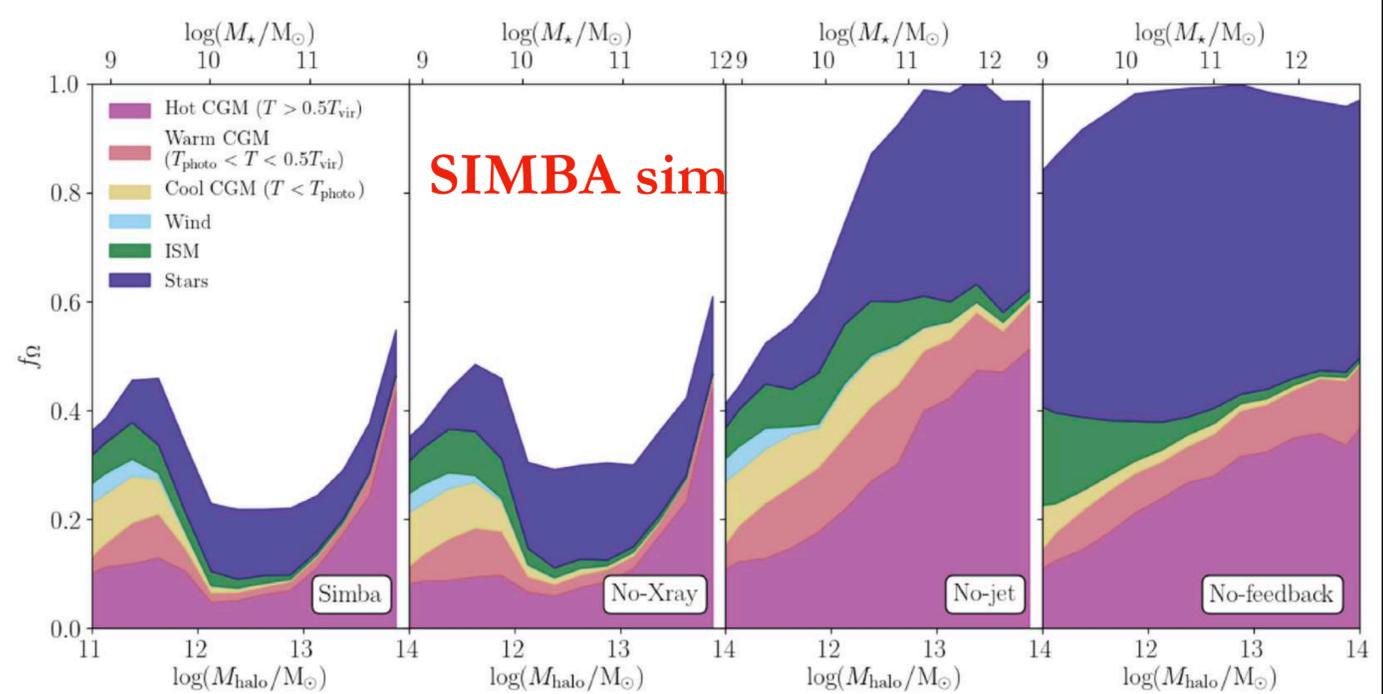
AGN are interesting? why?
 SMBH and host galaxy co-evolution
 AGN feedback and quenching



[Kormendy & Ho 2013]



[Behroozi+19]



[Appleby+21]

Micro and macro - AGN Feeding and Feedback

AGN feeding & feedback is a **MULTI-SCALE** phenomenon in **SPACE** and **TIME**

[Gaspari & Sadowski 2017]

- SPACE

- link the circum-nuclear scale (pc) to the circum-galactic scale (hundreds of kpc)

- TIME

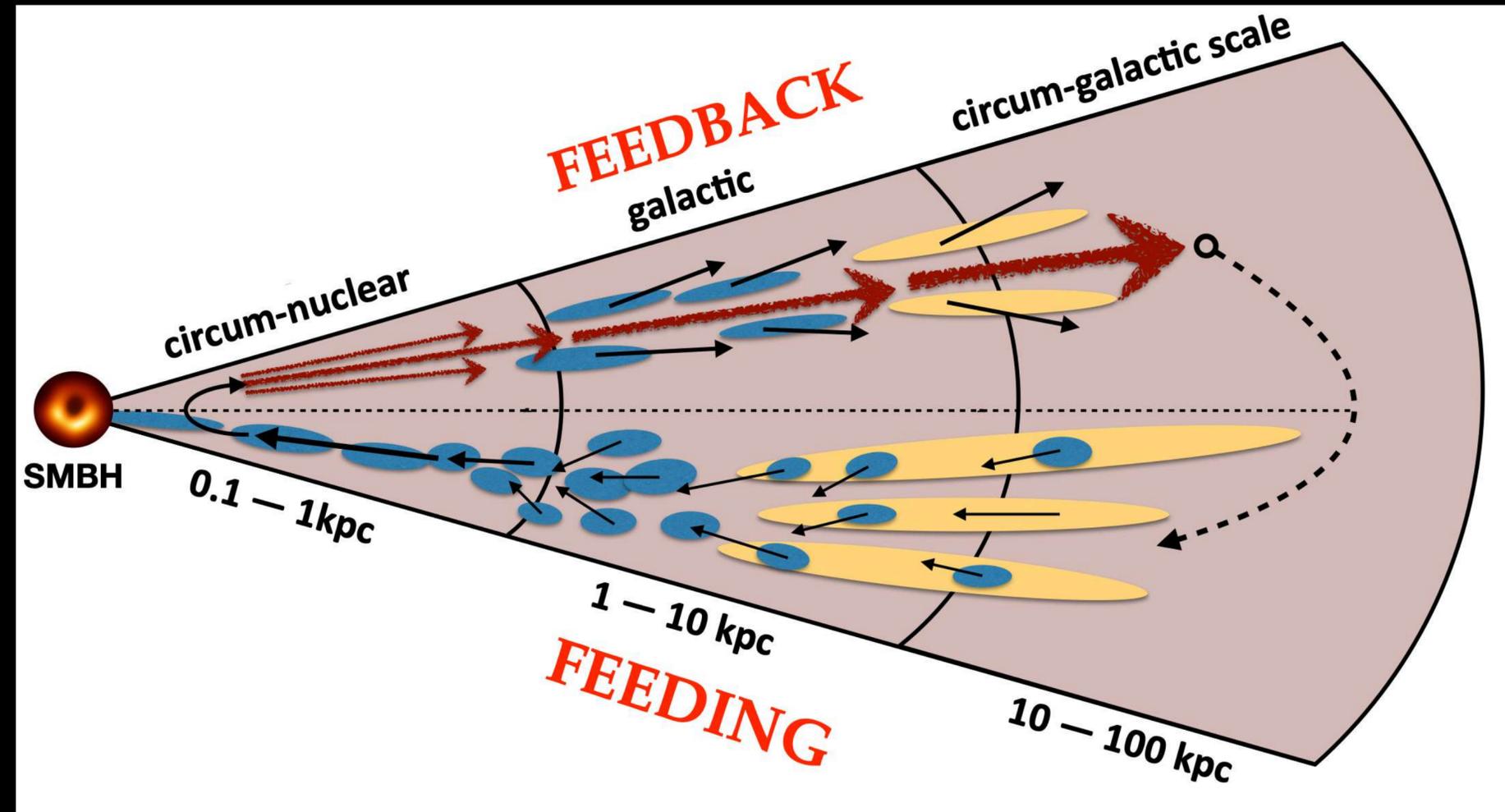
- AGN are rapid & recursive while galaxy evolution is slow and continuous

- radio jets trace the timescales of nuclear activity

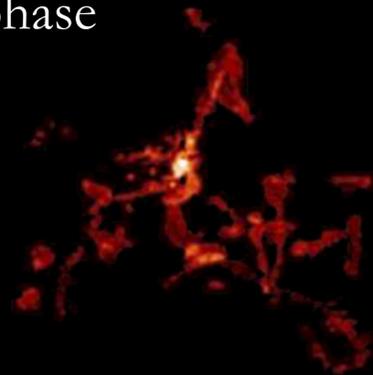
- AGN feeding & feedback is **MULTI-**

PHASE

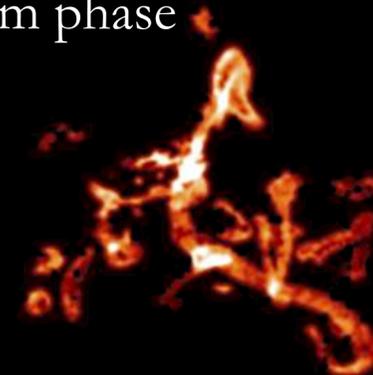
- hot, warm and cold gas co-exist and contribute over all spatial scales



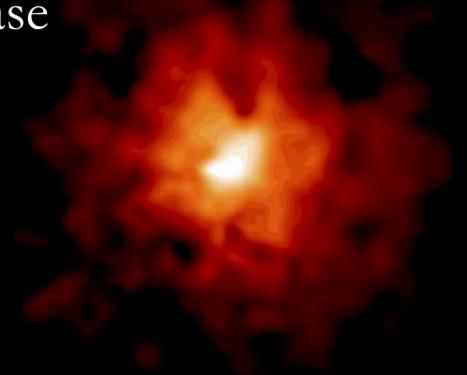
cold phase



warm phase

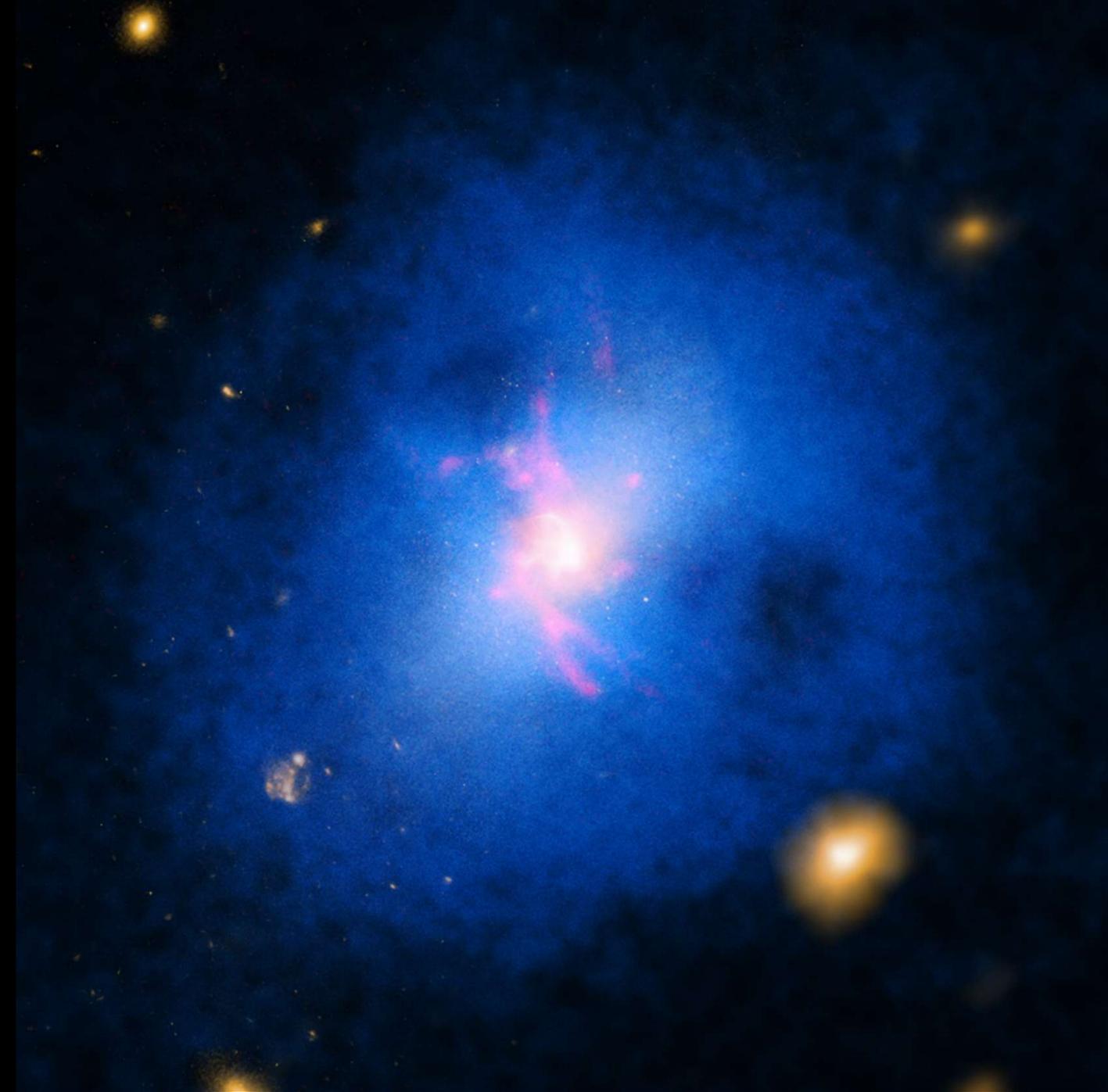


hot phase



From micro to macro - AGN radio jets inflate X-ray cavities

releasing energy, displacing and shocking the ISM and heating the CGM

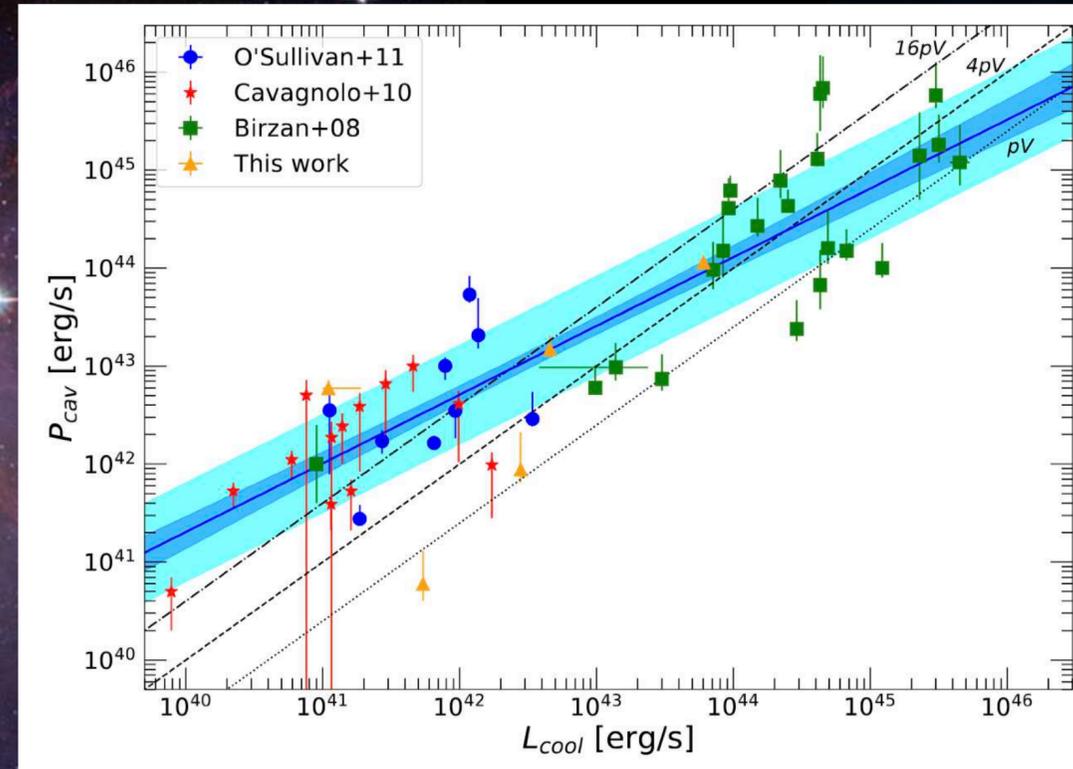


Perseus A, 3C 84, NGC1275

A2597

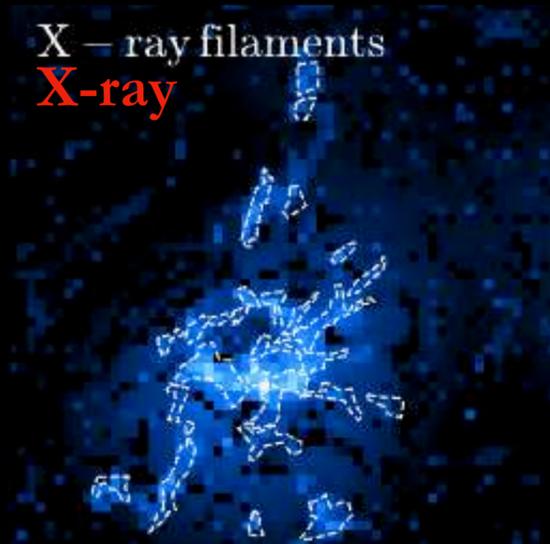
From micro to macro - AGN radio jets inflate X-ray cavities

releasing energy, displacing and shocking the ISM and heating the CGM

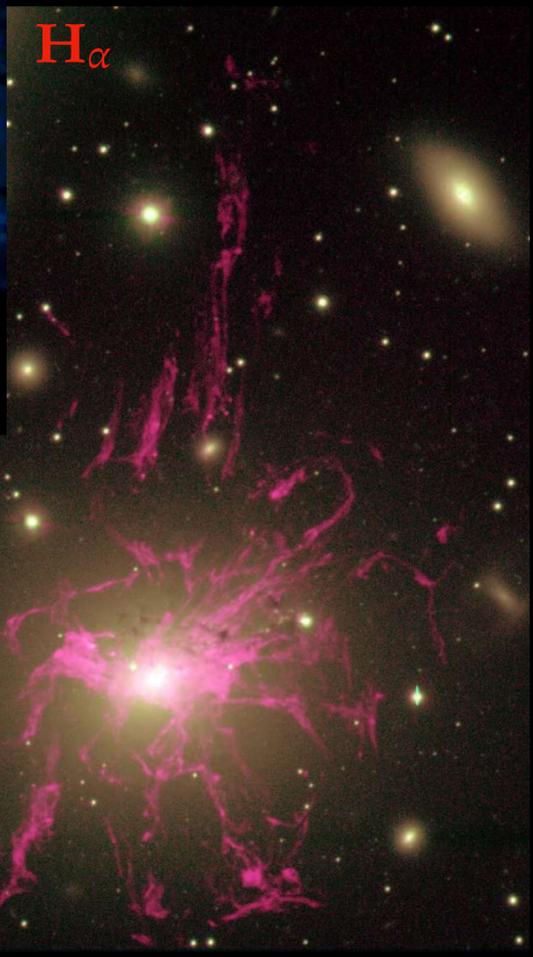


[Eckert+21]

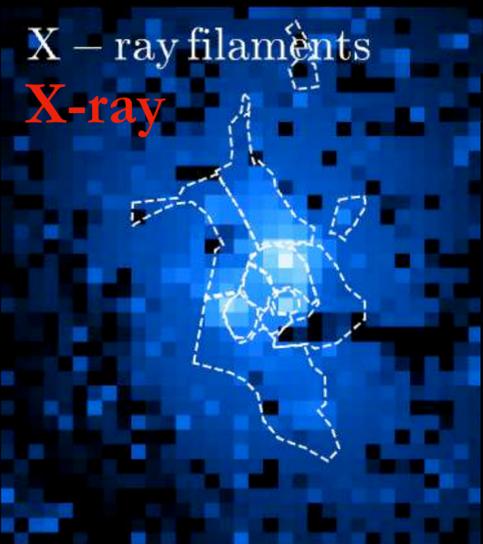
From macro to micro - multi-phase filaments fuel AGN in BCG



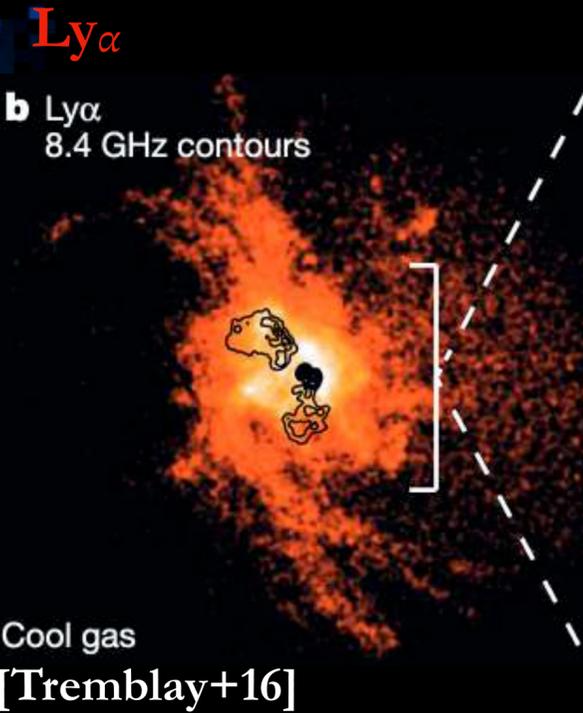
[Olivares+25]



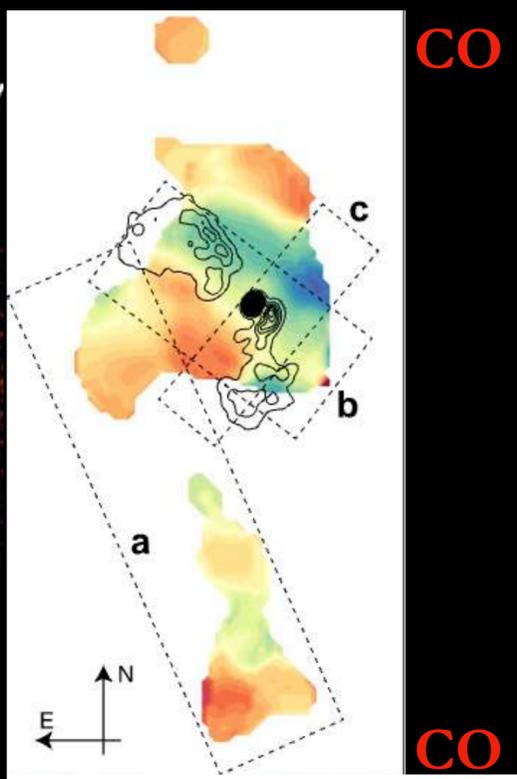
[Conselice+01]



[Olivares+25]

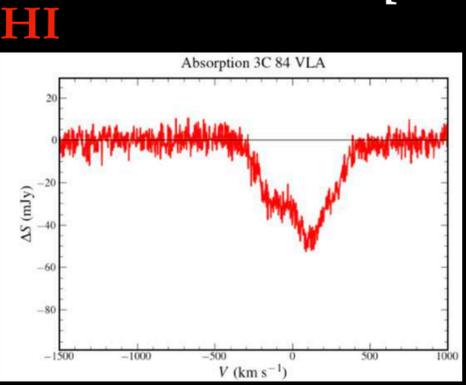


[Tremblay+16]

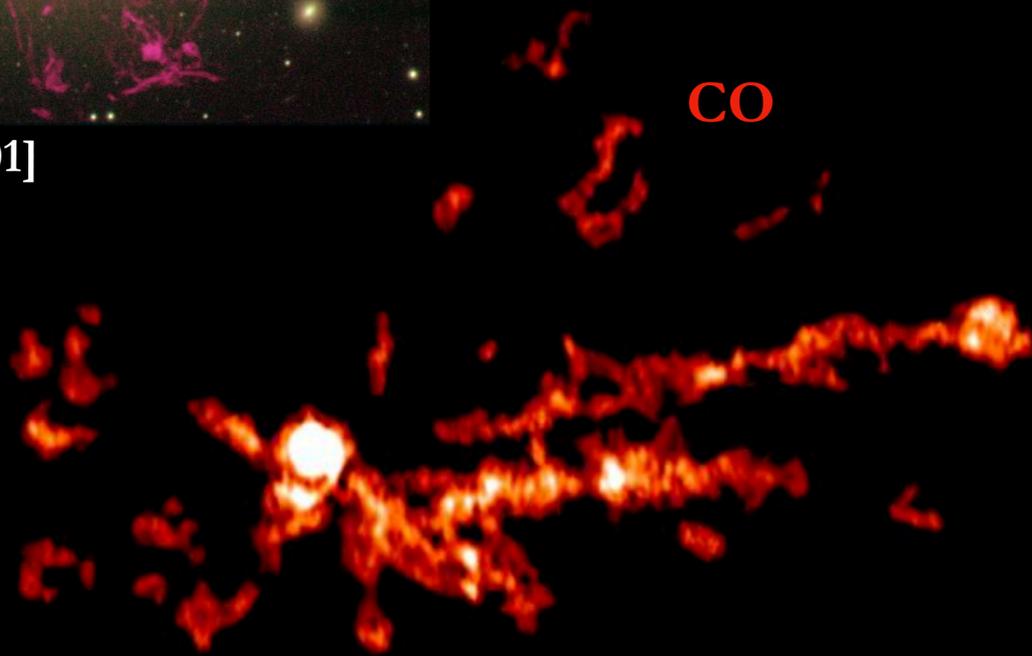


CO

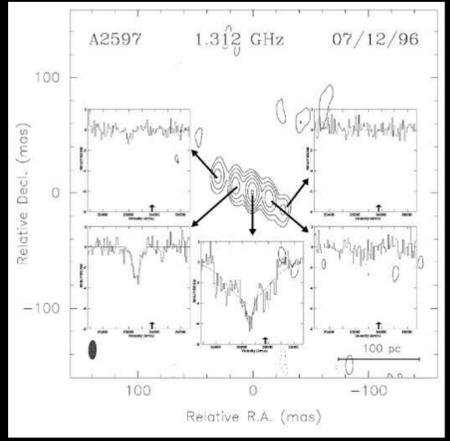
for molecular inflows see also Tamhane+22



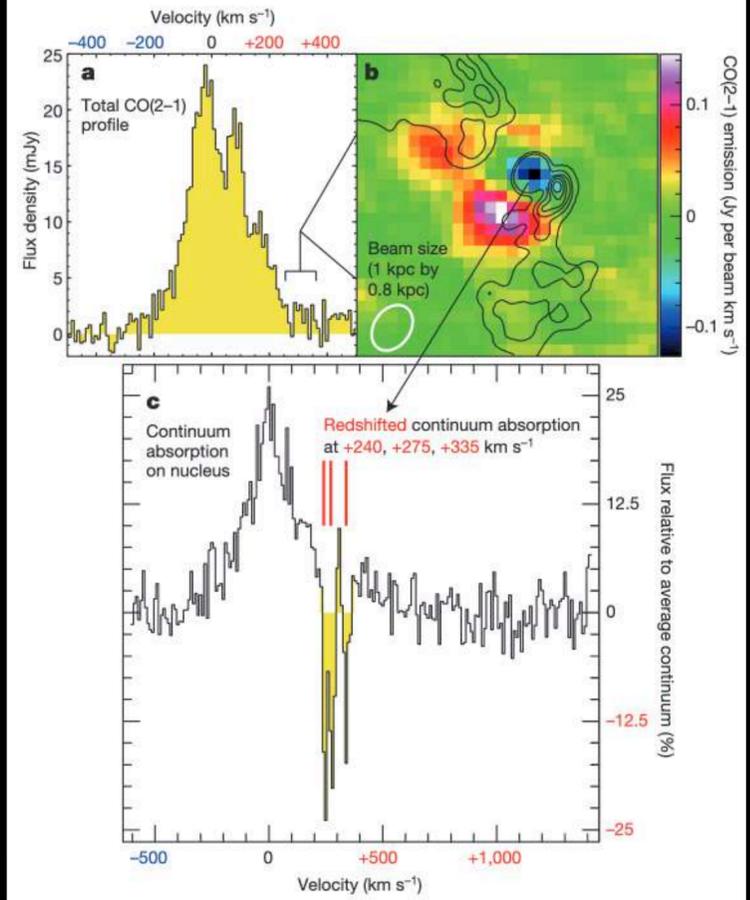
[Jaffe, 90]



[Oosterloo+24]



[Taylor+99]



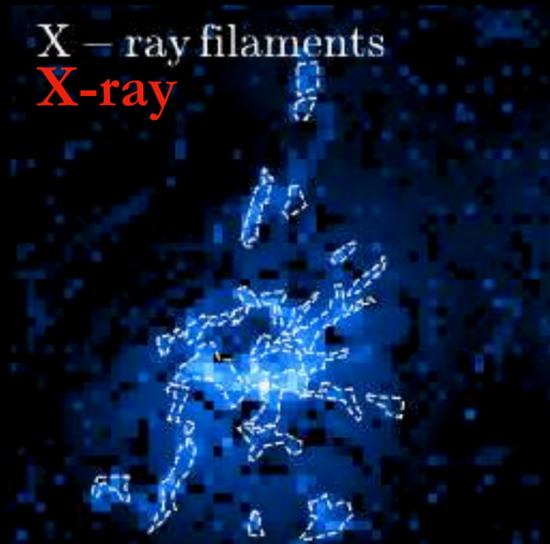
[Tremblay+16,18]

Perseus A, 3C 84, NGC1275

1 kpc

A2597

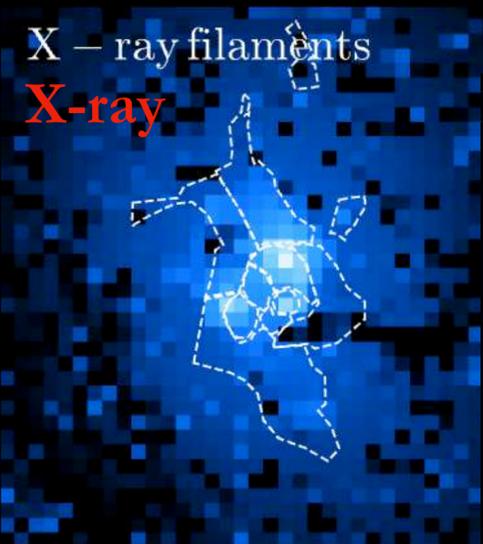
From macro to micro - multi-phase filaments fuel AGN in BCG



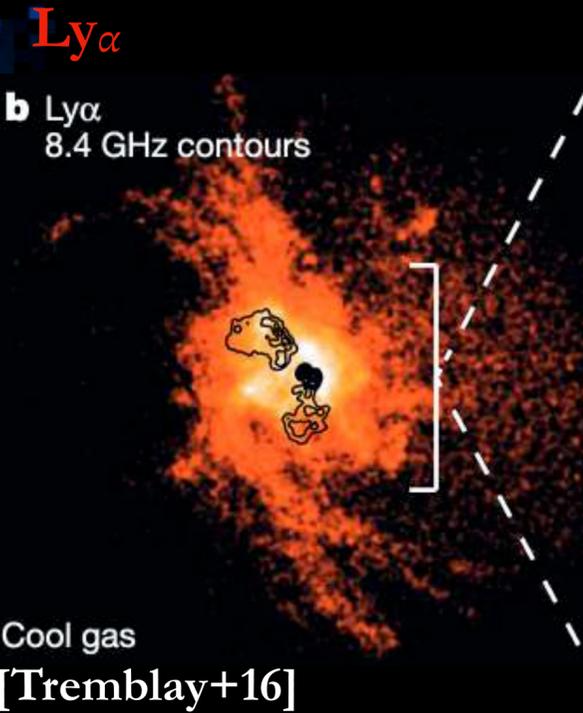
[Olivares+25]



[Conselice+01]

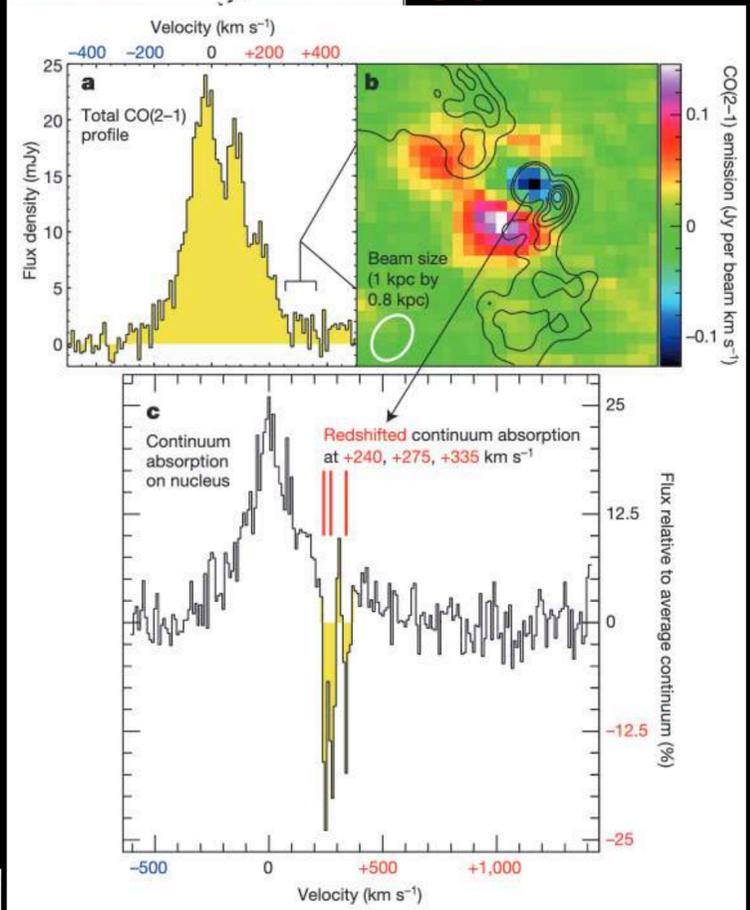
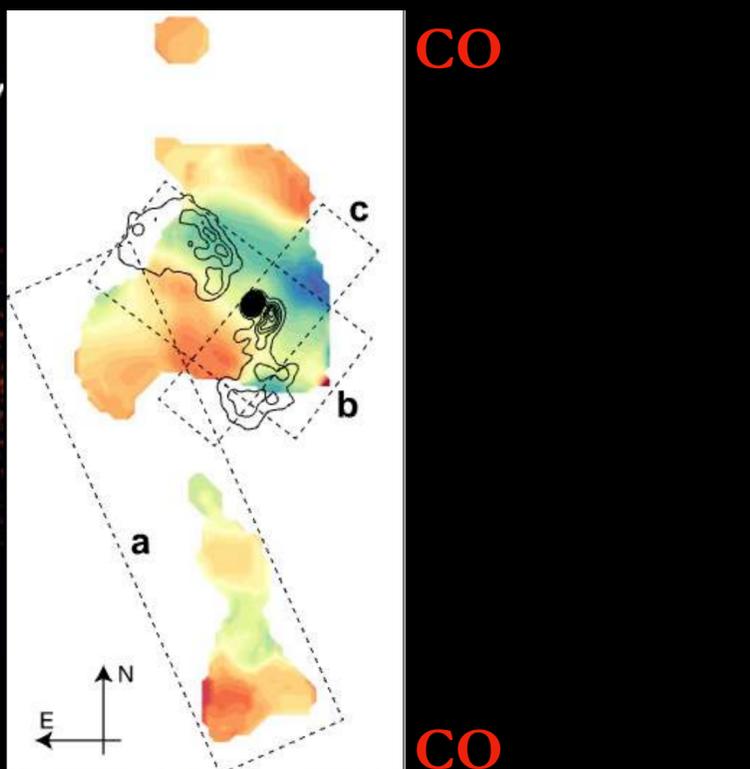


[Olivares+25]



[Tremblay+16]

What causes filamentary COOLING?



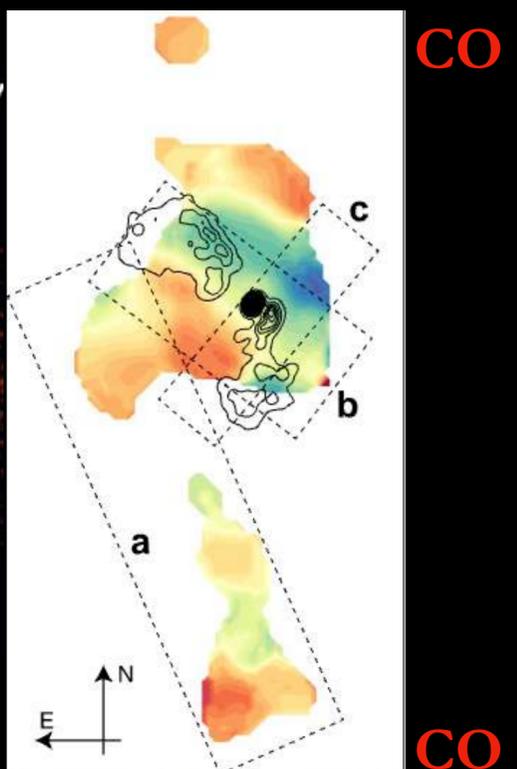
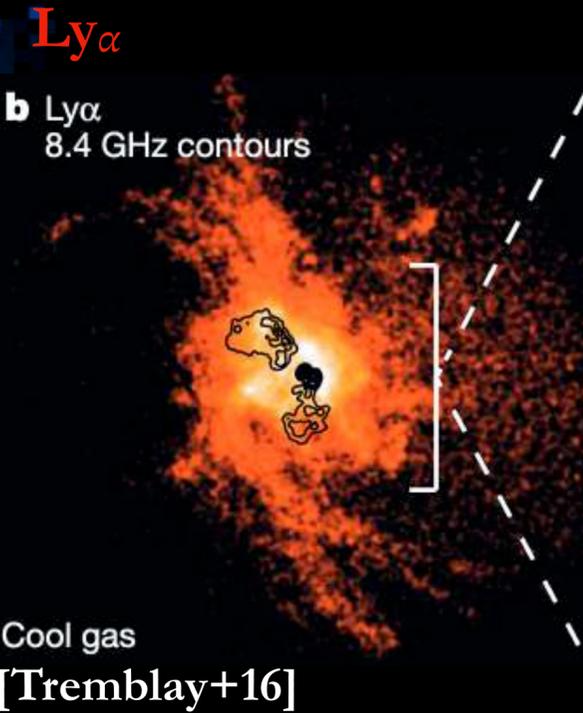
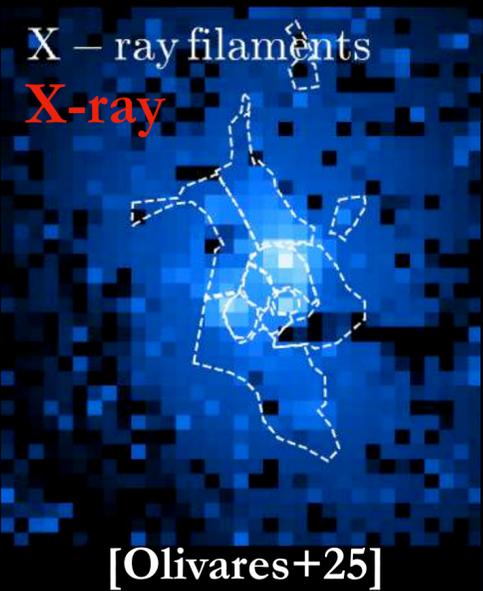
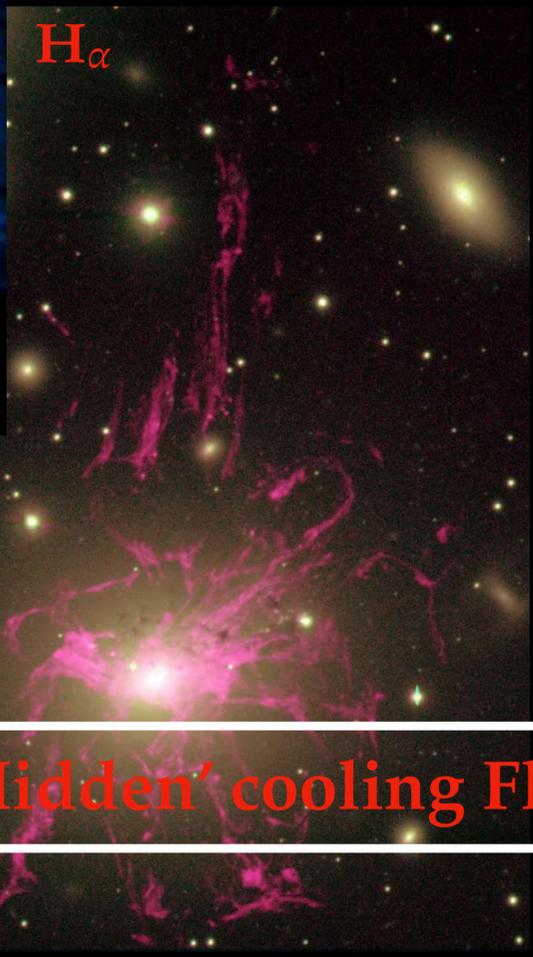
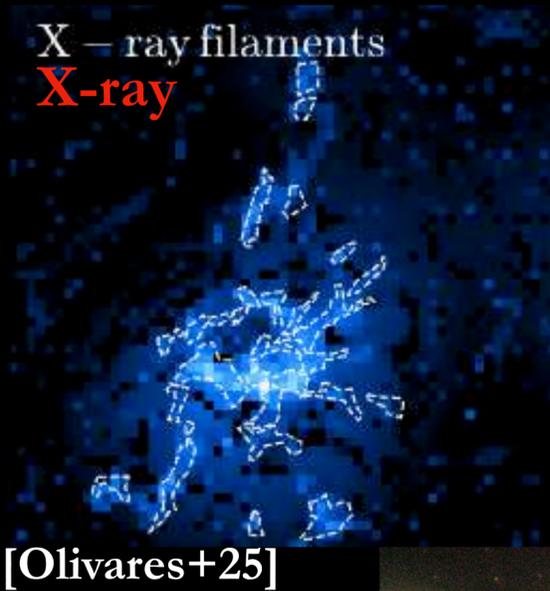
Perseus A, 3C 84, NGC1275

1 kpc [Oosterloo+24]

A2597

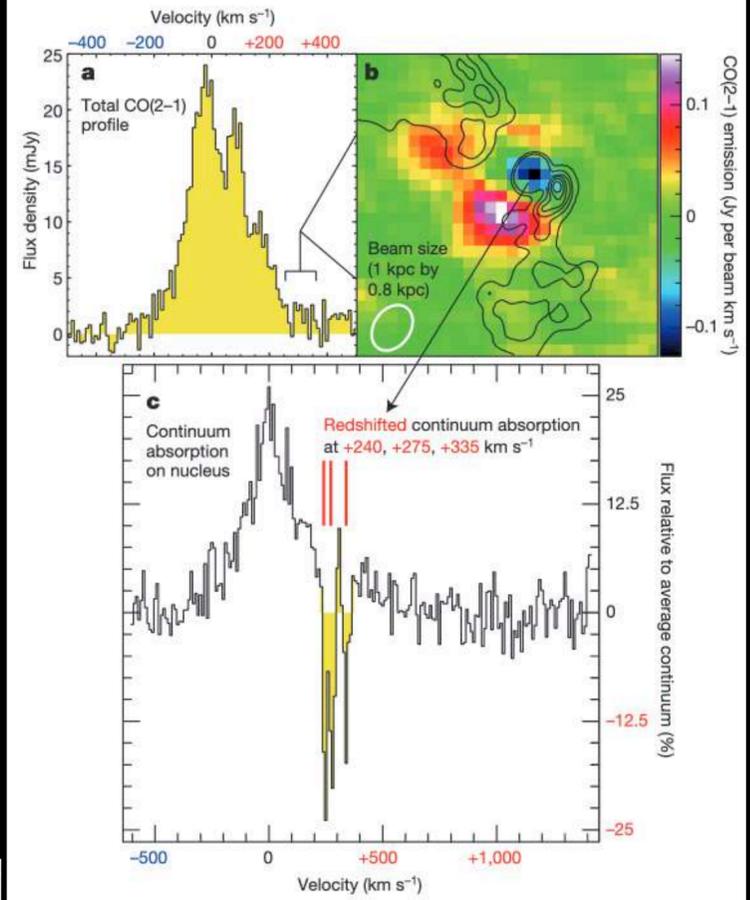
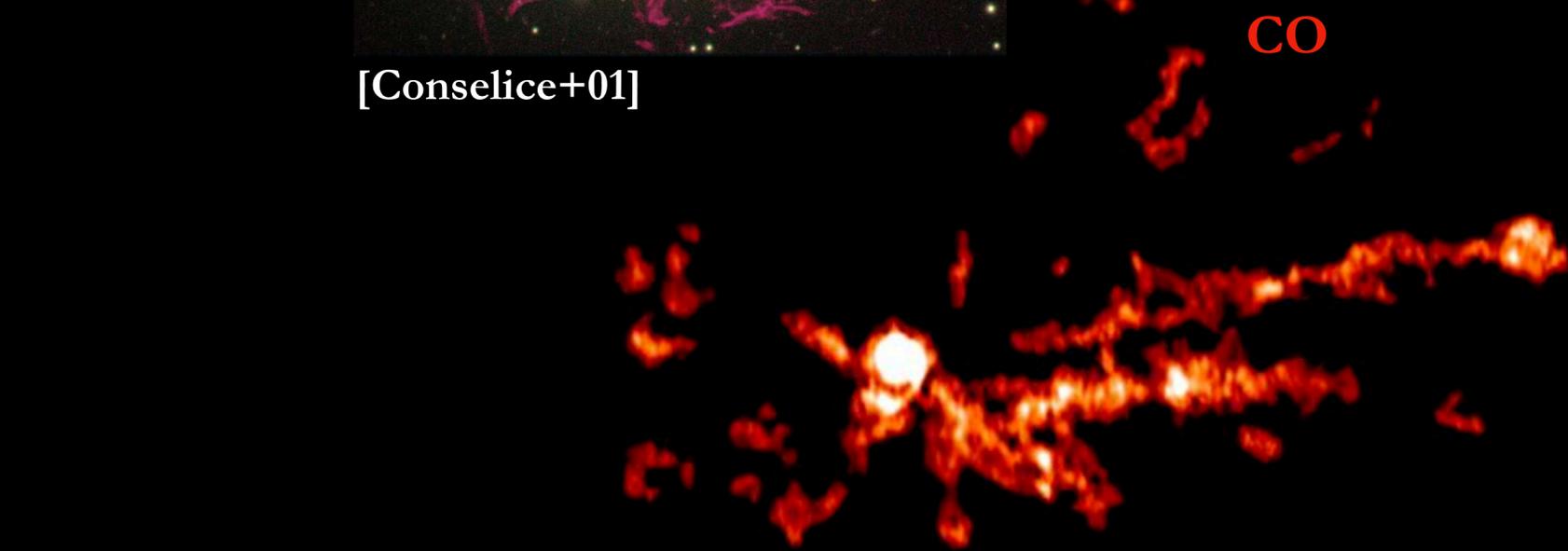
[Tremblay+16,18]

From macro to micro - multi-phase filaments fuel AGN



'Hidden' cooling Flows?

Chaotic Cold Accretion?



Perseus A, 3C 84, NGC1275

1 kpc

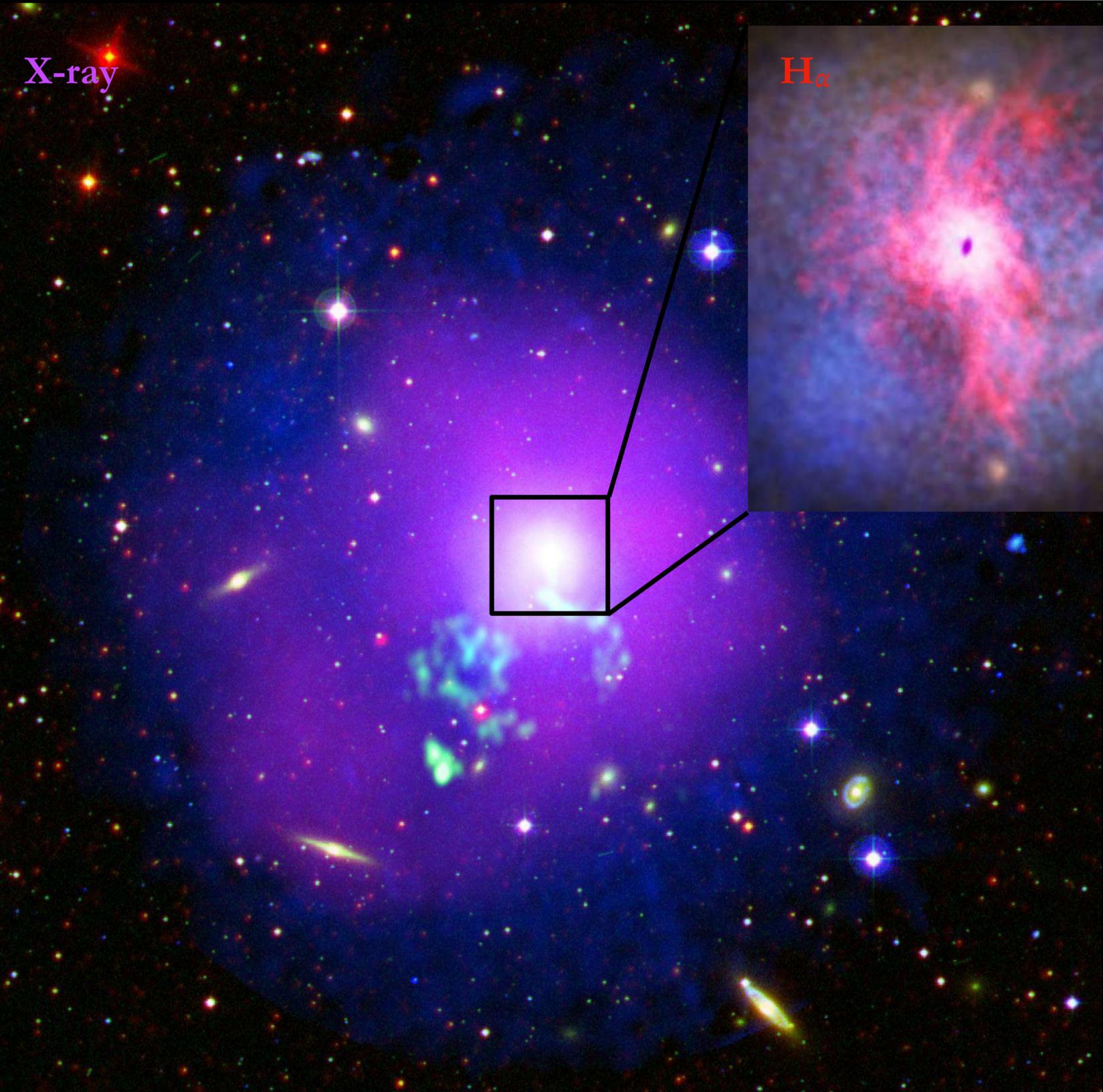
A2597

[Tremblay+16,18]

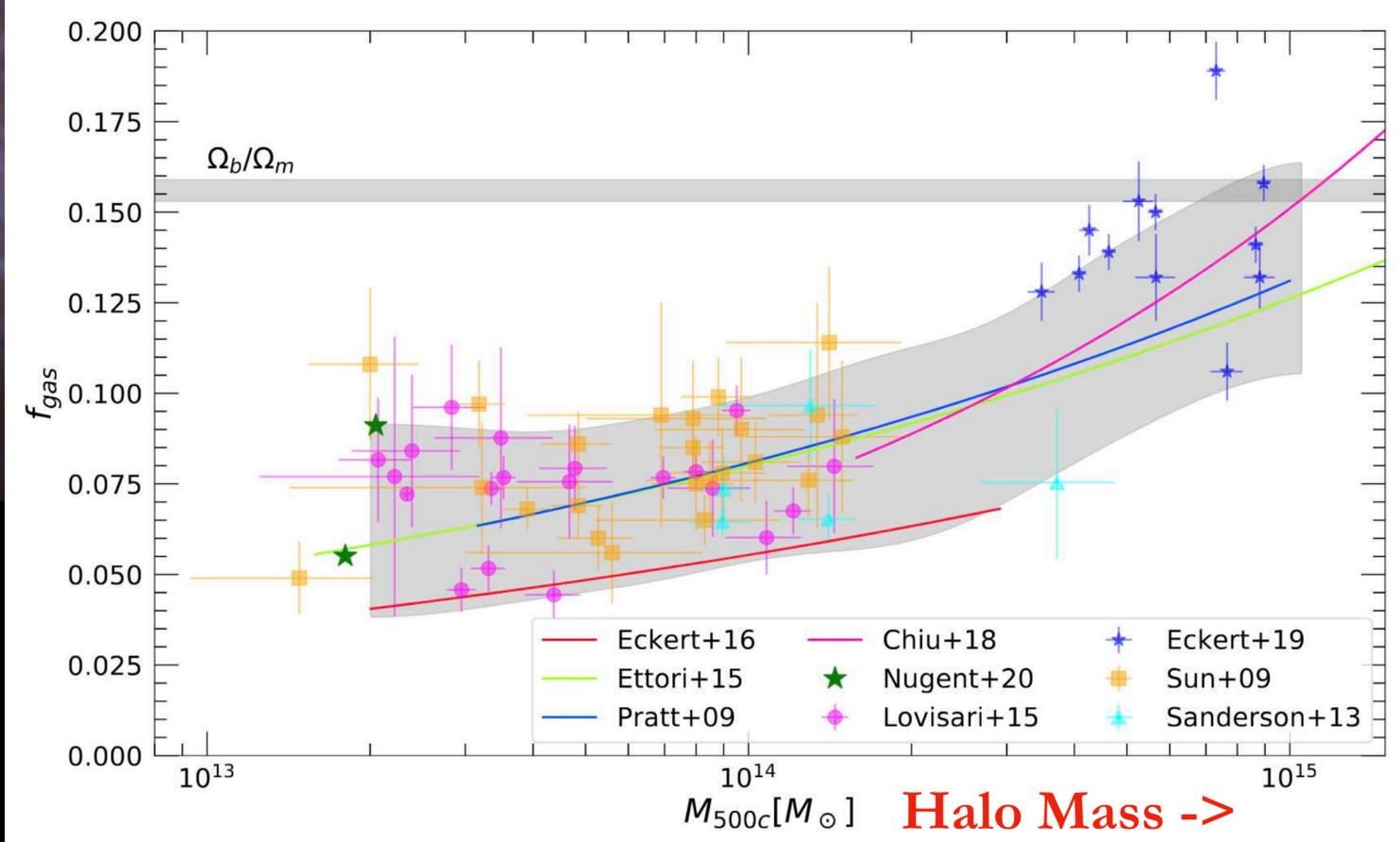
From macro to micro - F&F in galaxy groups

X-ray

H α



Gas Fraction ->



[Eckert+21]

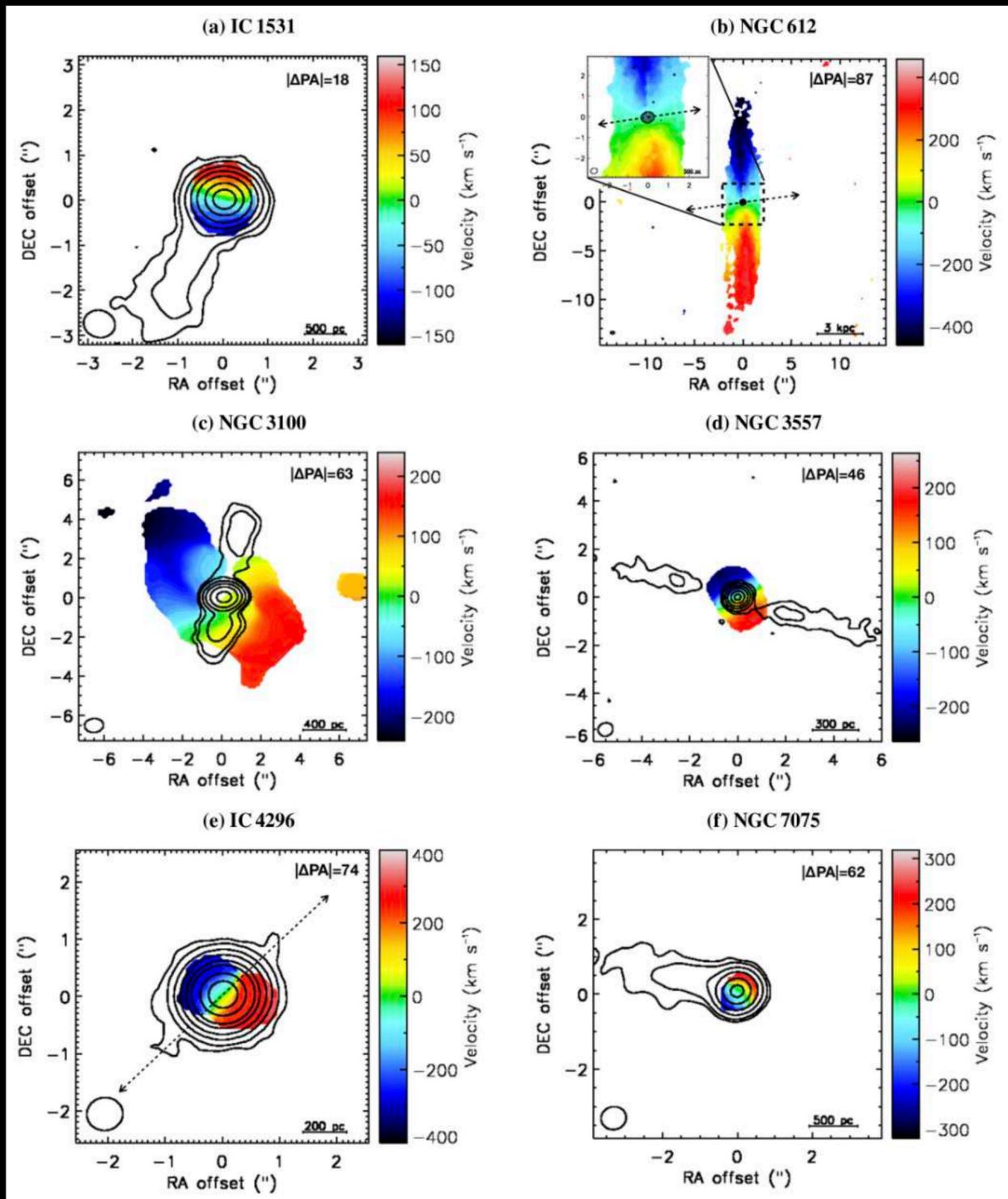
Groups: baryons have been lifted because of efficient AGN feedback .

Clusters: baryons stay within the virial radius.

NGC5044 [O'Sullivan]

From macro to micro - circum-nuclear cold gas in radio AGN

AGN-CGM interaction in smaller and lower-power AGN ($P_{1.4\text{GHz}} < 10^{24}$ W/Hz) in poorer environments (groups, field)



[Ruffa+19]

ALMA revolution:

- Jetted AGN show massive ($10^{7-9} M_{\odot}$) **circum-nuclear disks of molecular gas**

e.g. Garcia-Burillo+14,16,21(Gatos) Ruffa+19, Smith+21, Combes+21 (NUGA)

- On (sub)-kpc scales **cold gas is the most massive outflowing component of jet-ISM interaction**

e.g. Oosterlo+17, Fiore+17, Fluetsch Audibert+19, Murthy+22 (NOEMA),

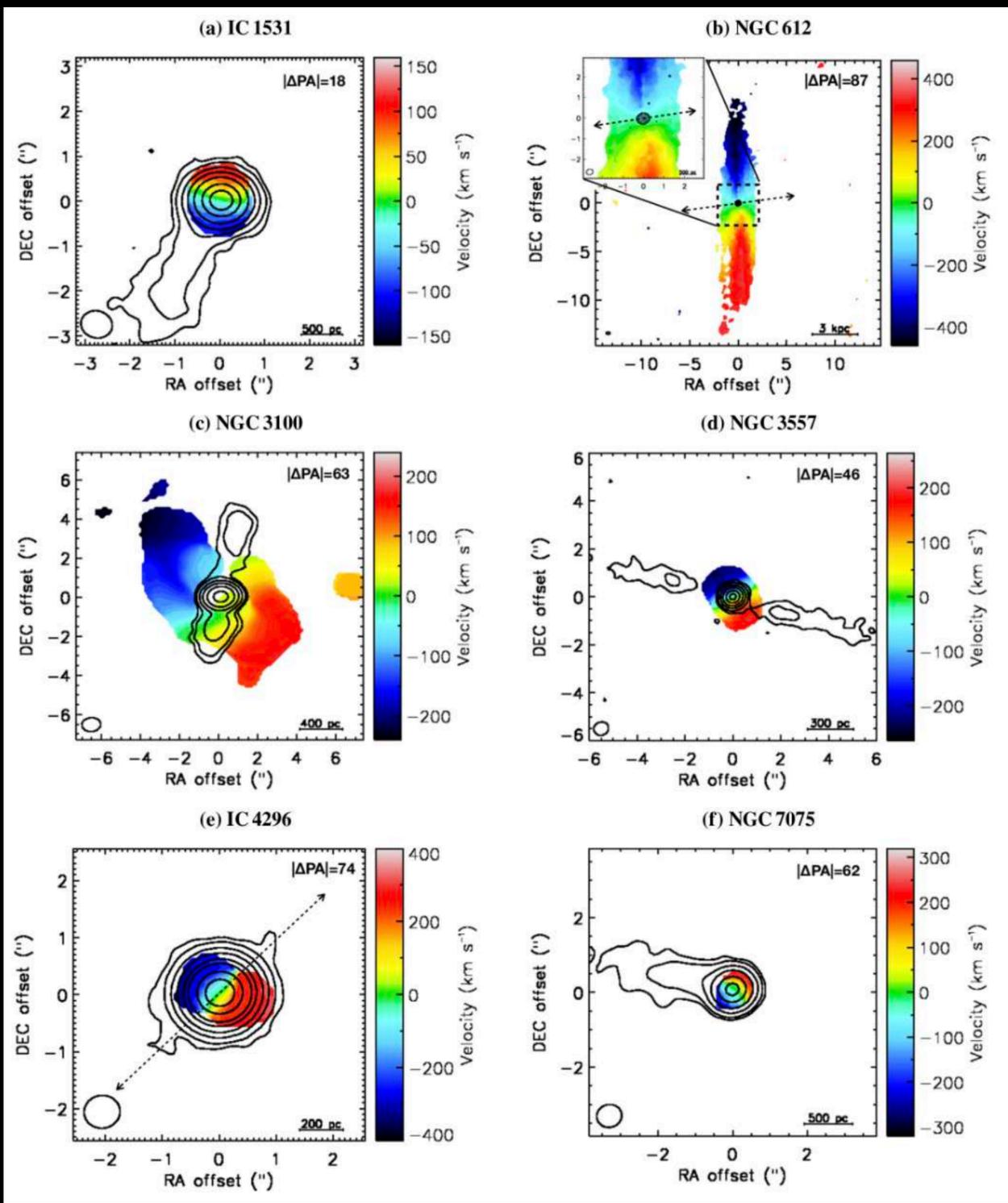
- **Molecular gas disks and outflows at high redshifts**

e.g. Kakkad+17, Talia+18, Herrera-Camus+20, Jones+22, Holden+24



From macro to micro - circum-nuclear cold gas in radio AGN

AGN-CGM interaction in smaller and lower-power AGN ($P_{1.4\text{GHz}} < 10^{24}$ W/Hz) in poorer environments (groups, field)

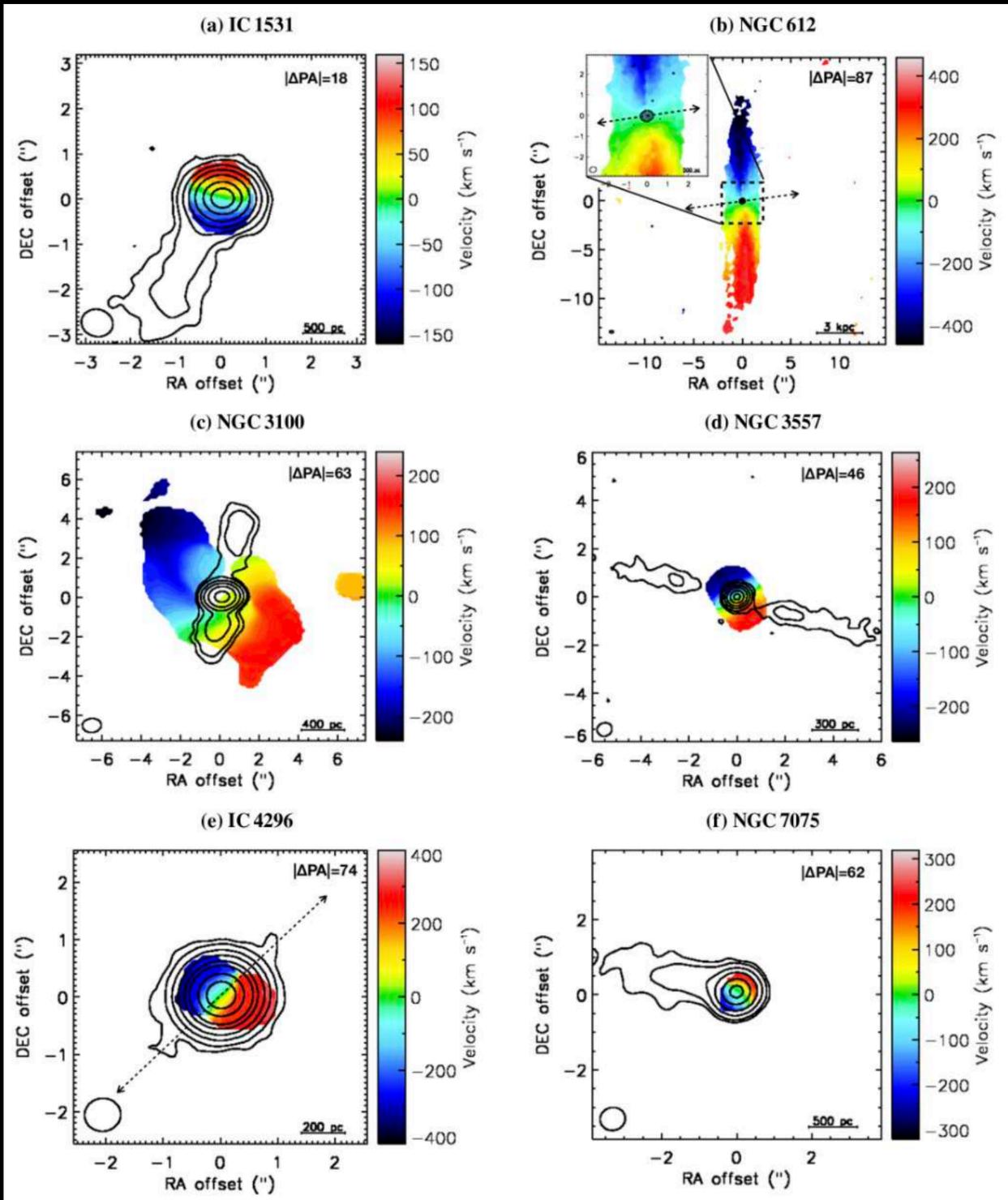


What is the origin of the cold gas?



From macro to micro - circum-nuclear cold gas in radio AGN

AGN-CGM interaction in smaller and lower-power AGN ($P_{1.4\text{GHz}} < 10^{24}$ W/Hz) in poorer environments (groups, field)



ALMA limitation:

- The f.o.v. limits investigation of the cold gas at sub-pc resolution to the innermost kpc



Neutral Hydrogen in AGN - F&F in the micro and macro

Can observations of neutral atomic hydrogen help?

HI traces AGN Feeding & Feedback BUT so far limited to:

absorption studies (MICRO)

low resolution & sensitivity emission studies (MACRO)

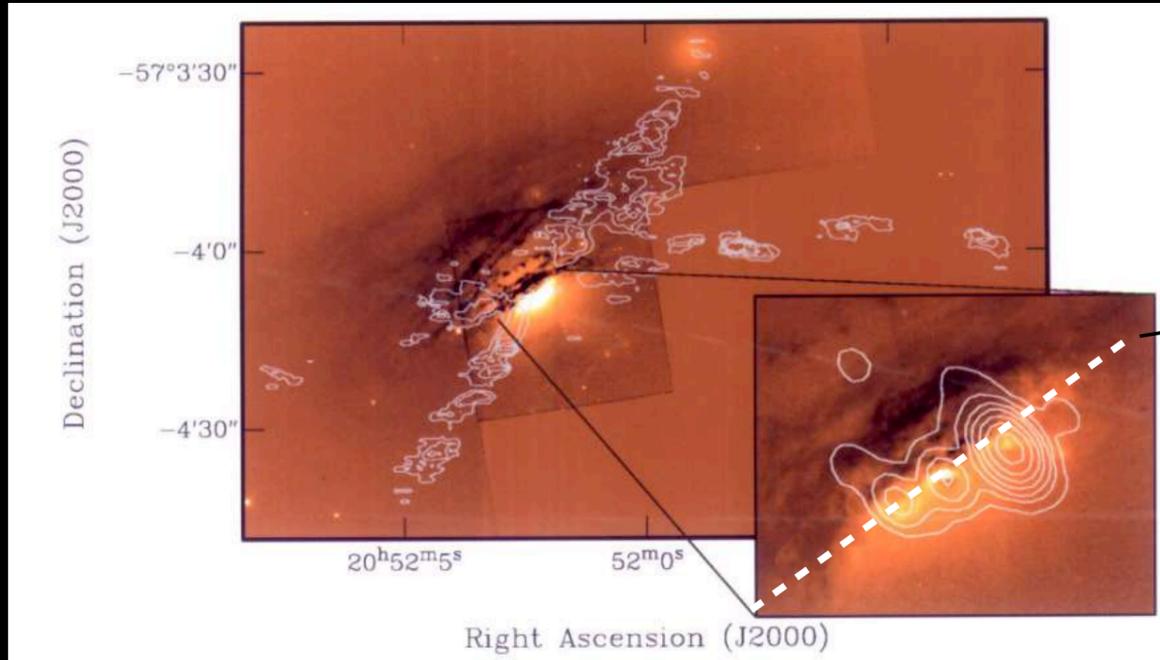
BECAUSE cold gas in F&F has LOW column density:

$< 1 \times 10^{20} \text{ cm}^{-2}$

Neutral Hydrogen in AGN - F&F in the micro and macro

FEEDBACK

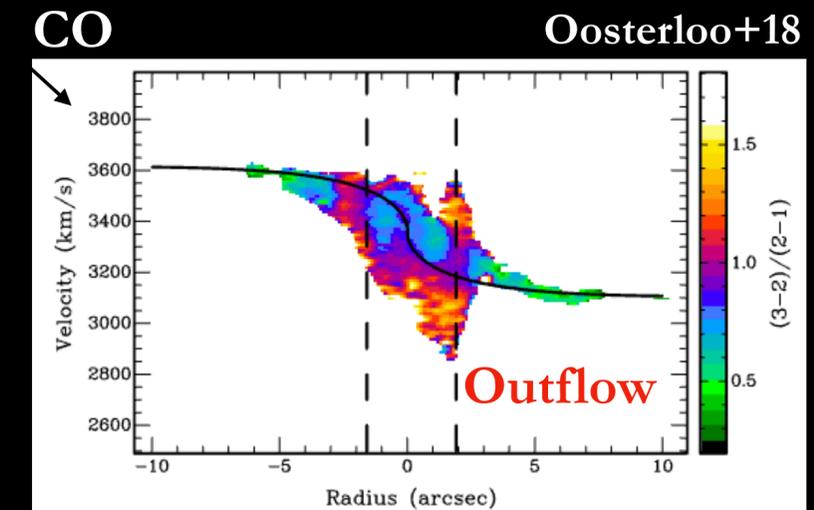
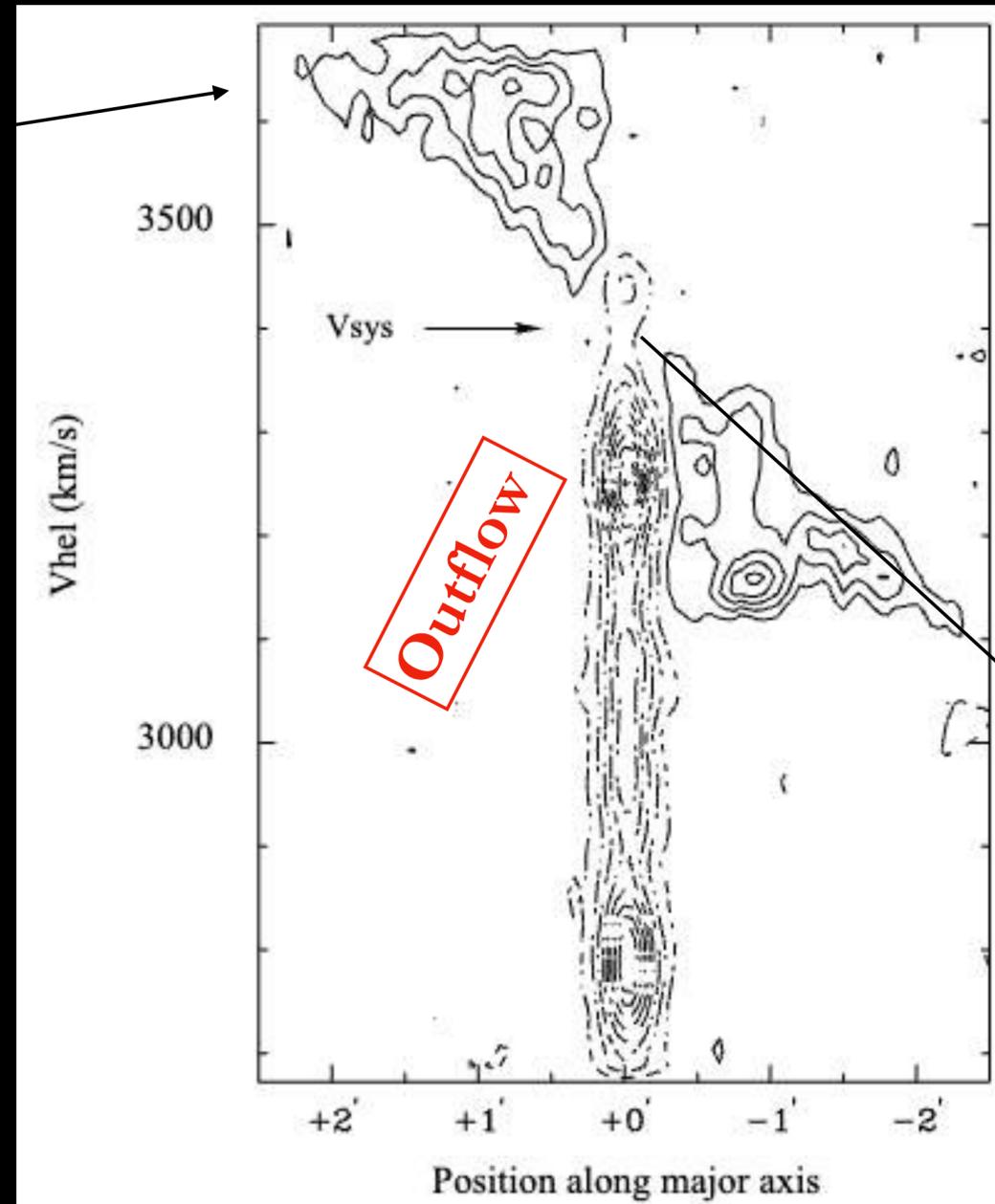
IC5063 - Morganti 1998



Outflows on MICRO scale identified by HI absorption in low radio power AGN (10^{23} W/Hz)

(see also Gallimore+94, Morganti+05, Alatalo+11, Kanekar & Chengalur 08, Mahony+13, Gereb+15)

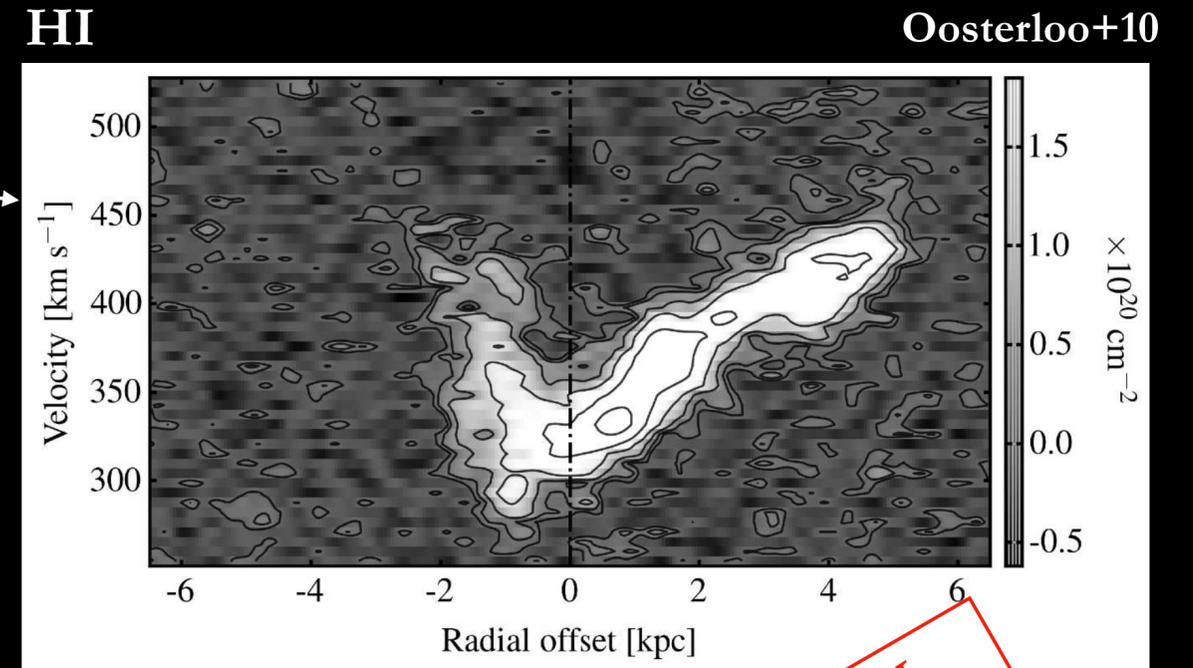
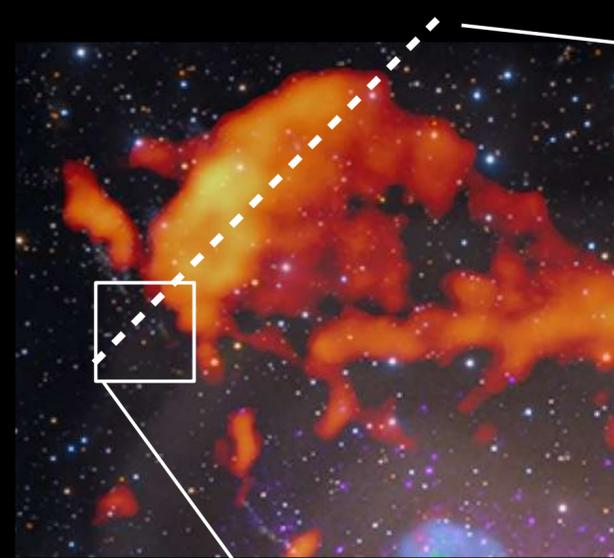
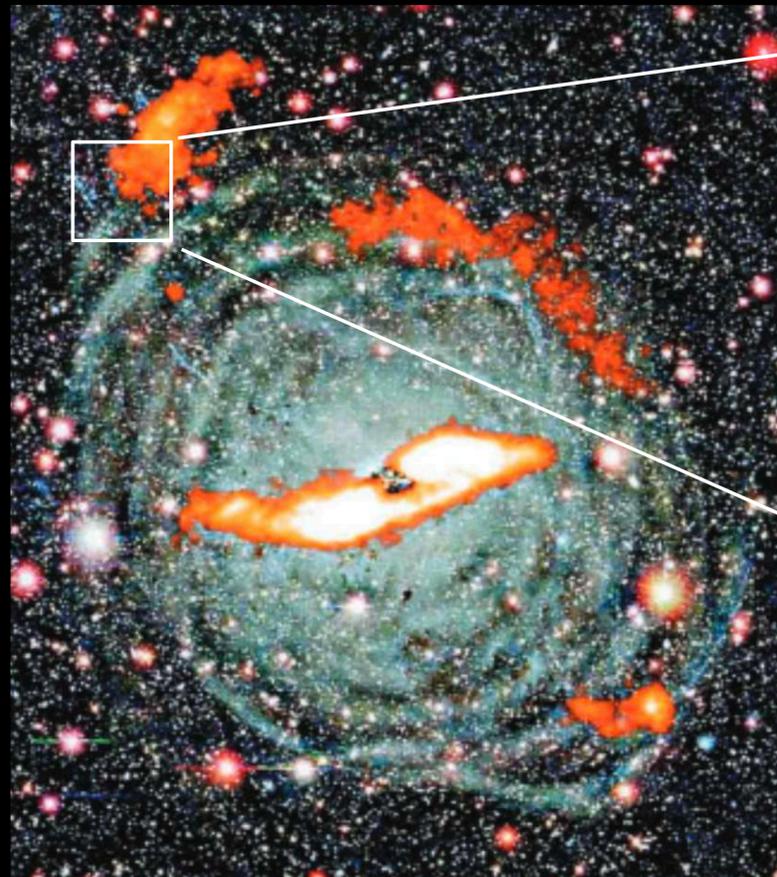
IC5063 - radio jets in a Seyfert AGN carve their way through the galaxy disk



Neutral Hydrogen in AGN - F&F in the micro and macro

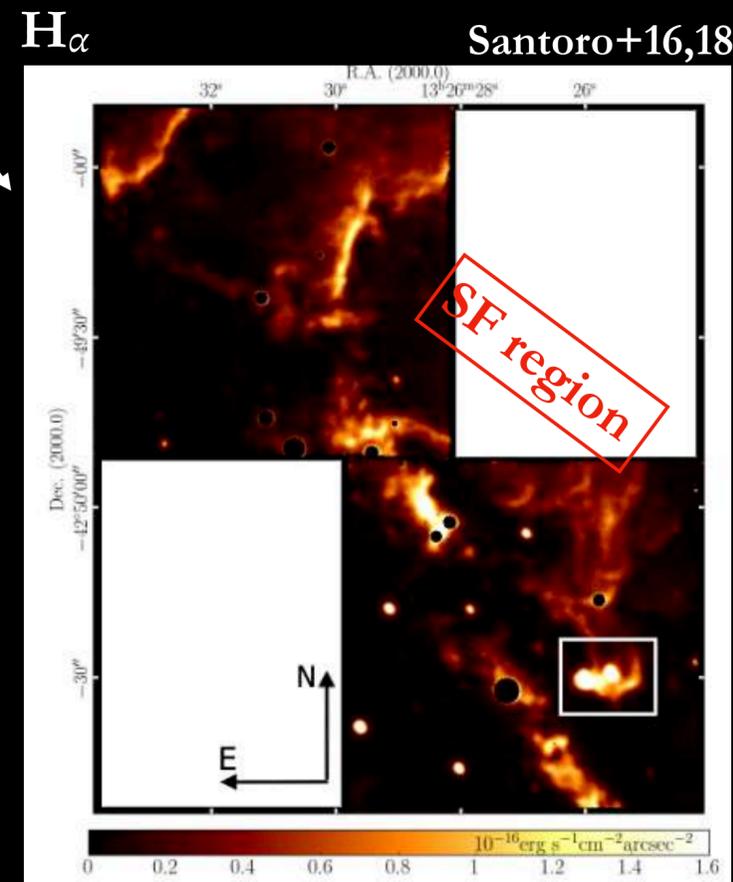
FEEDBACK

Centaurus A - Morganti 2011, Struve+2012



Jet-ISM interaction

Centaurus A - radio jets in a Seyfert AGN carve their way through the galaxy disk impacting its outer edge

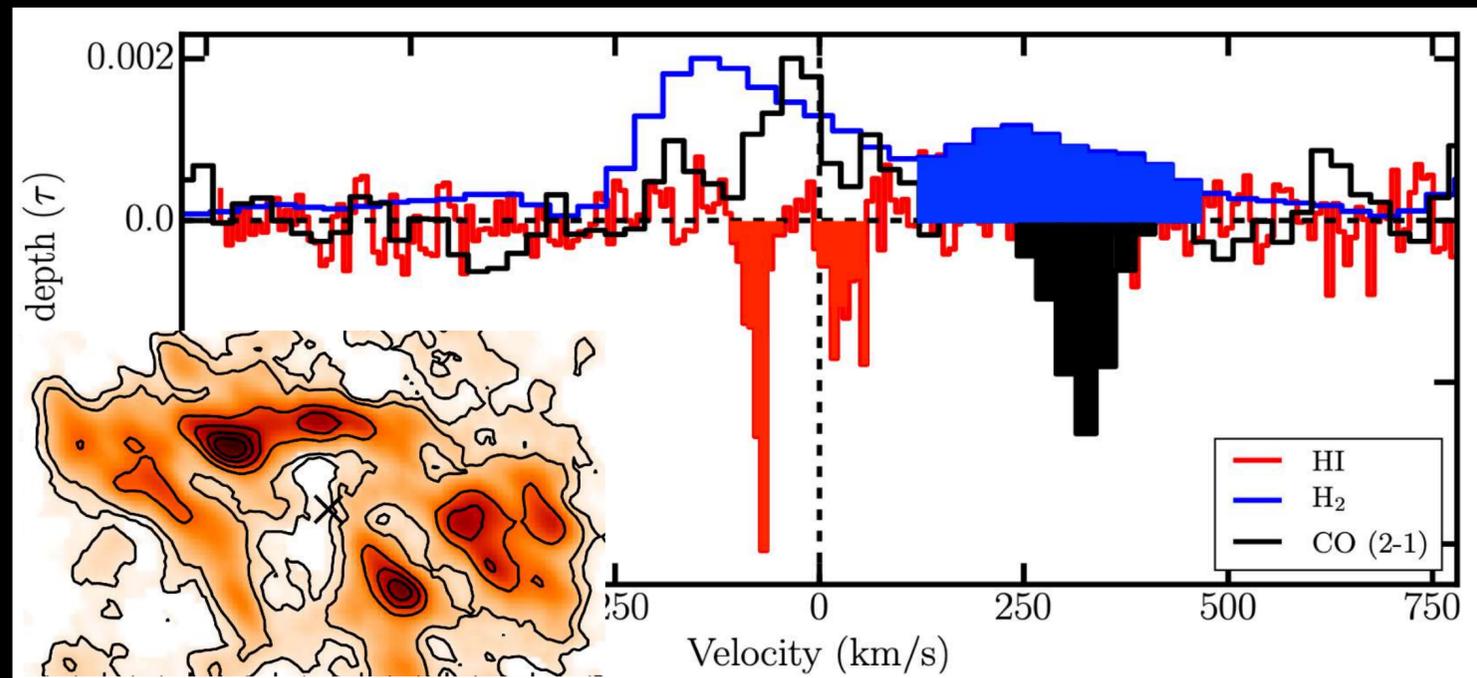


HI outflows on MACRO scales enhance SF

Neutral Hydrogen in AGN - F&F in the micro and macro

FEEDING

HI & CO in-falling clouds from circum-nuclear disk



PKS1718-649, Maccagni+ 14,16,18

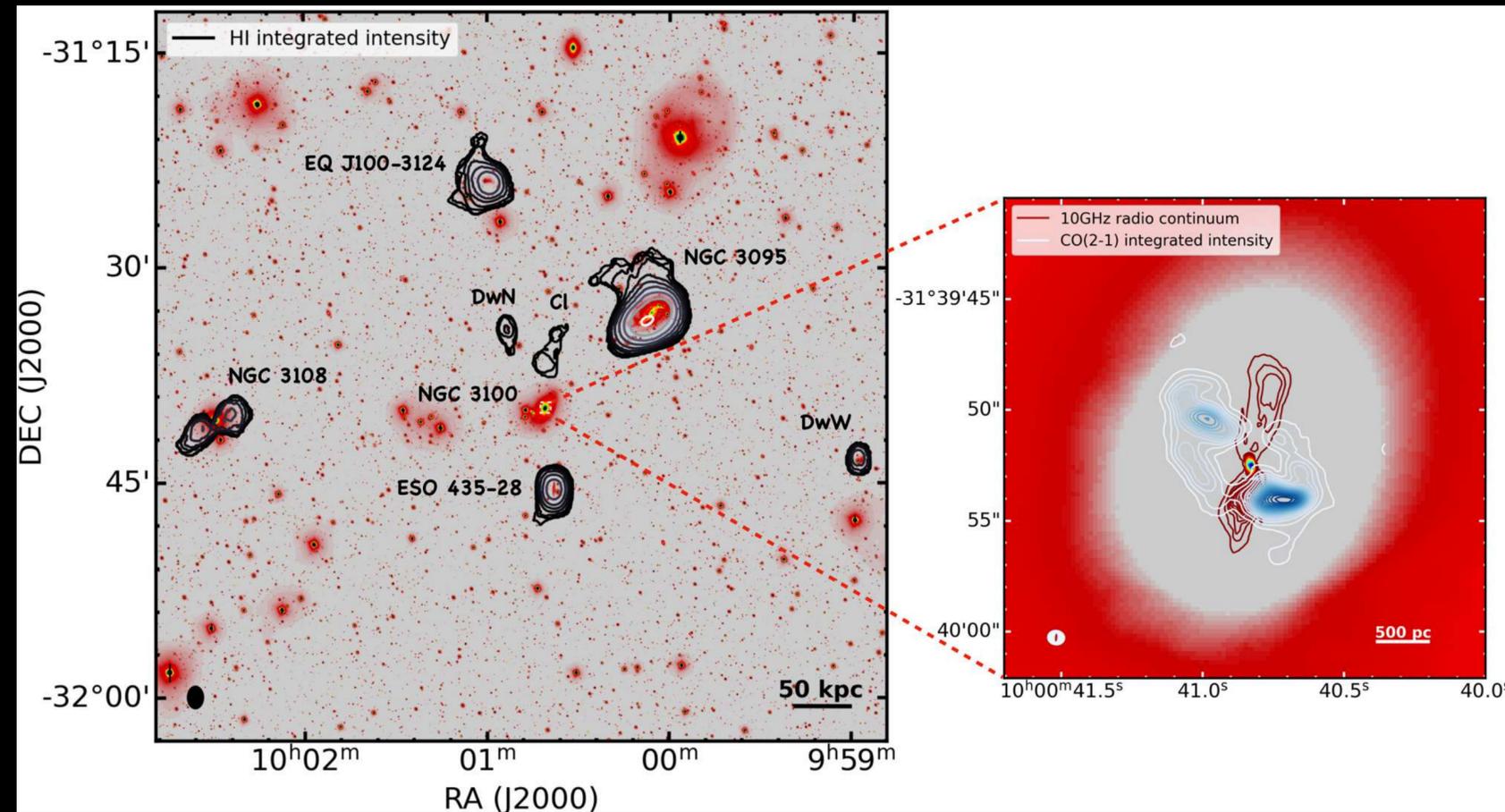
HI inflow on MICRO scale

(see also Gallimore+1999, O'Dea+94 Morganti+09)

HI inflow on MACRO scale

(see also van Gorkom+1989, Taylor+1999)

HI cloud fuelling circum-nuclear disk from the galaxy halo

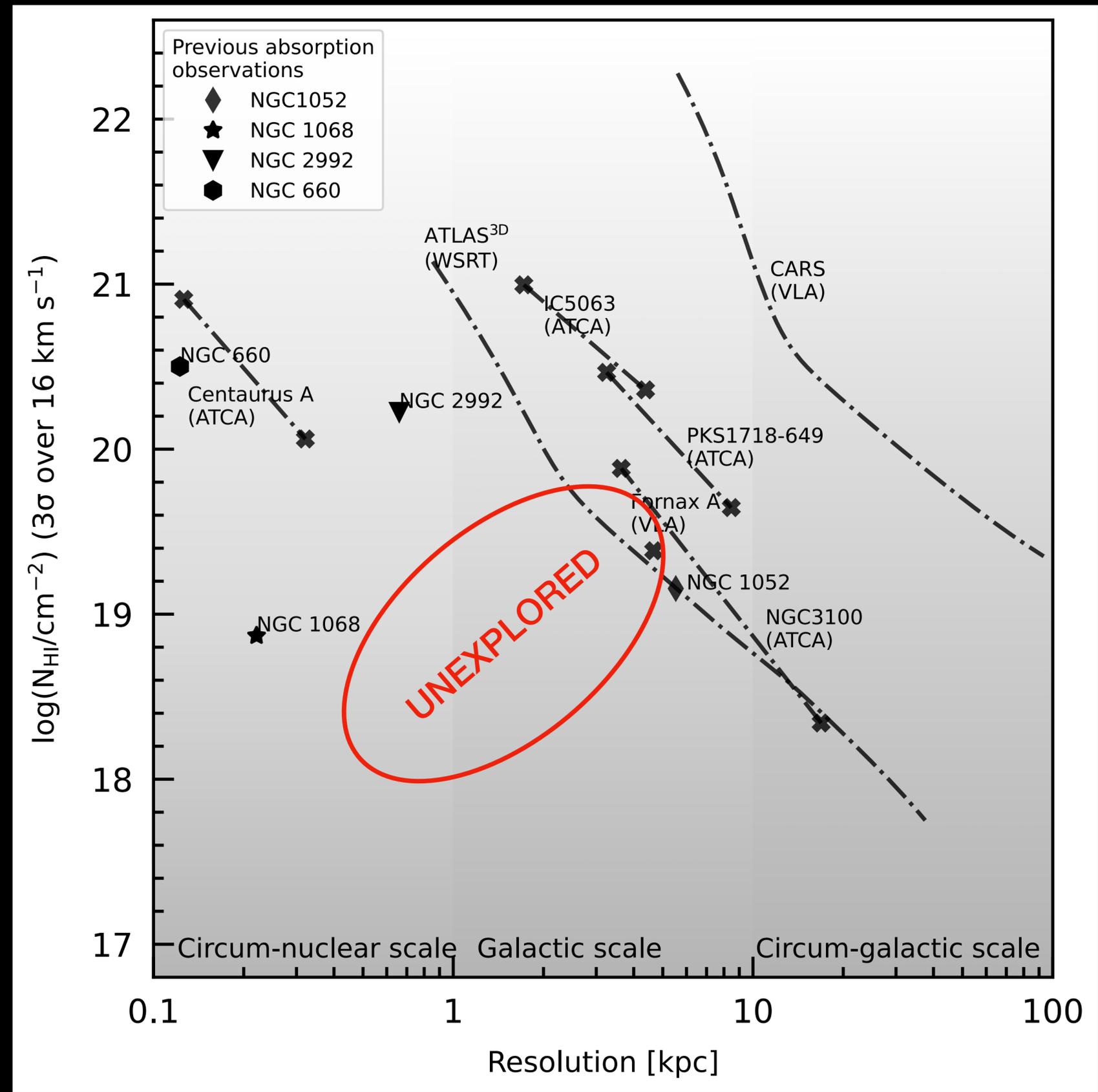


NGC3100, Maccagni+ 23

Past HI studies in AGN

in HI, AGN are
~10 times less
observed than
nearby SF
galaxies

from Morganti+
1998, Struve+ 2012,
Gallimore+ 1999,
Maccagni+2014,2023
(non-exhaustive list)



nevertheless, 1/3 of
ETGs has HI...

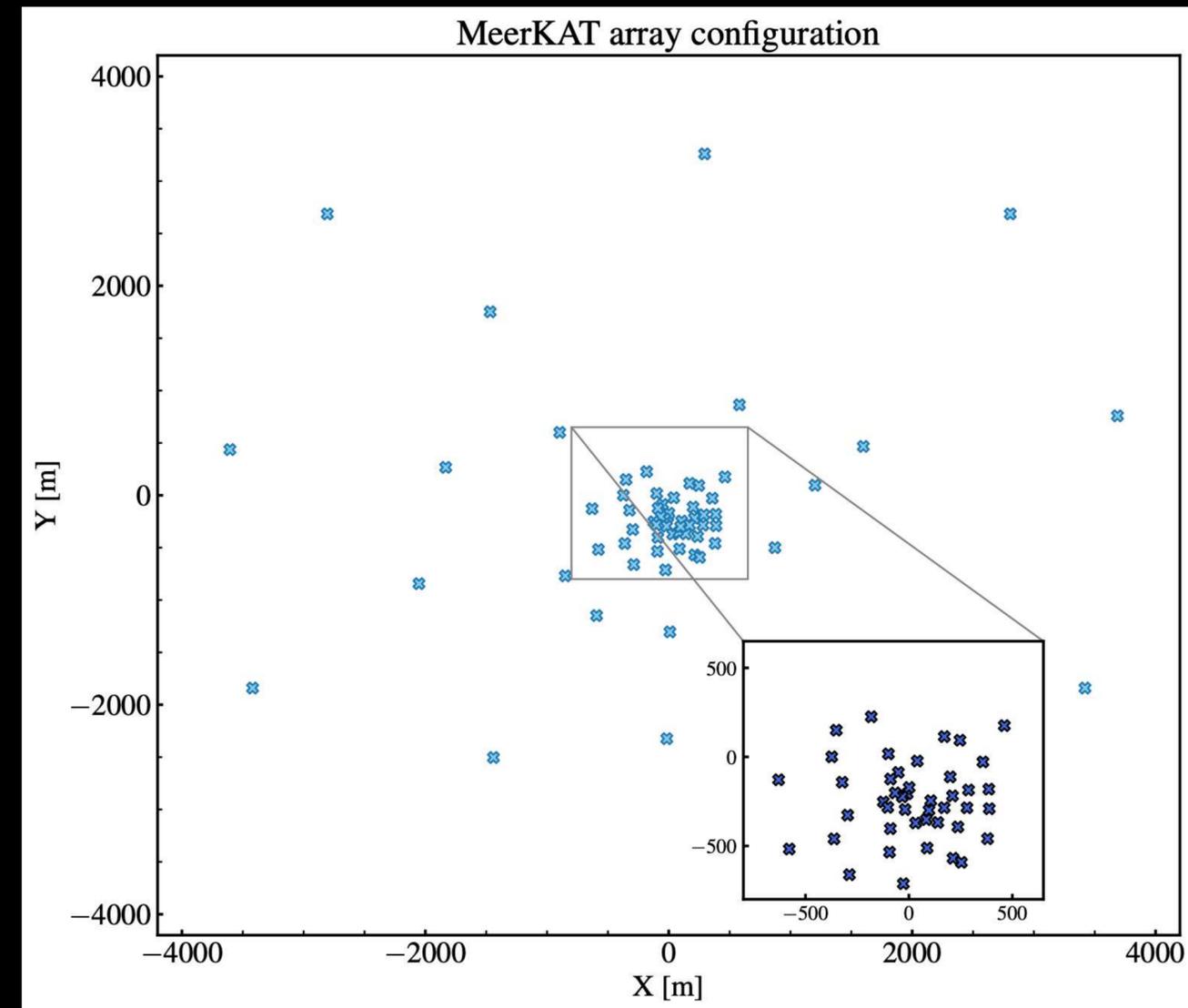
[Serra et al. 2012]

stacking shows
low-column
density HI in ETGs

[Maccagni et al. 2017]

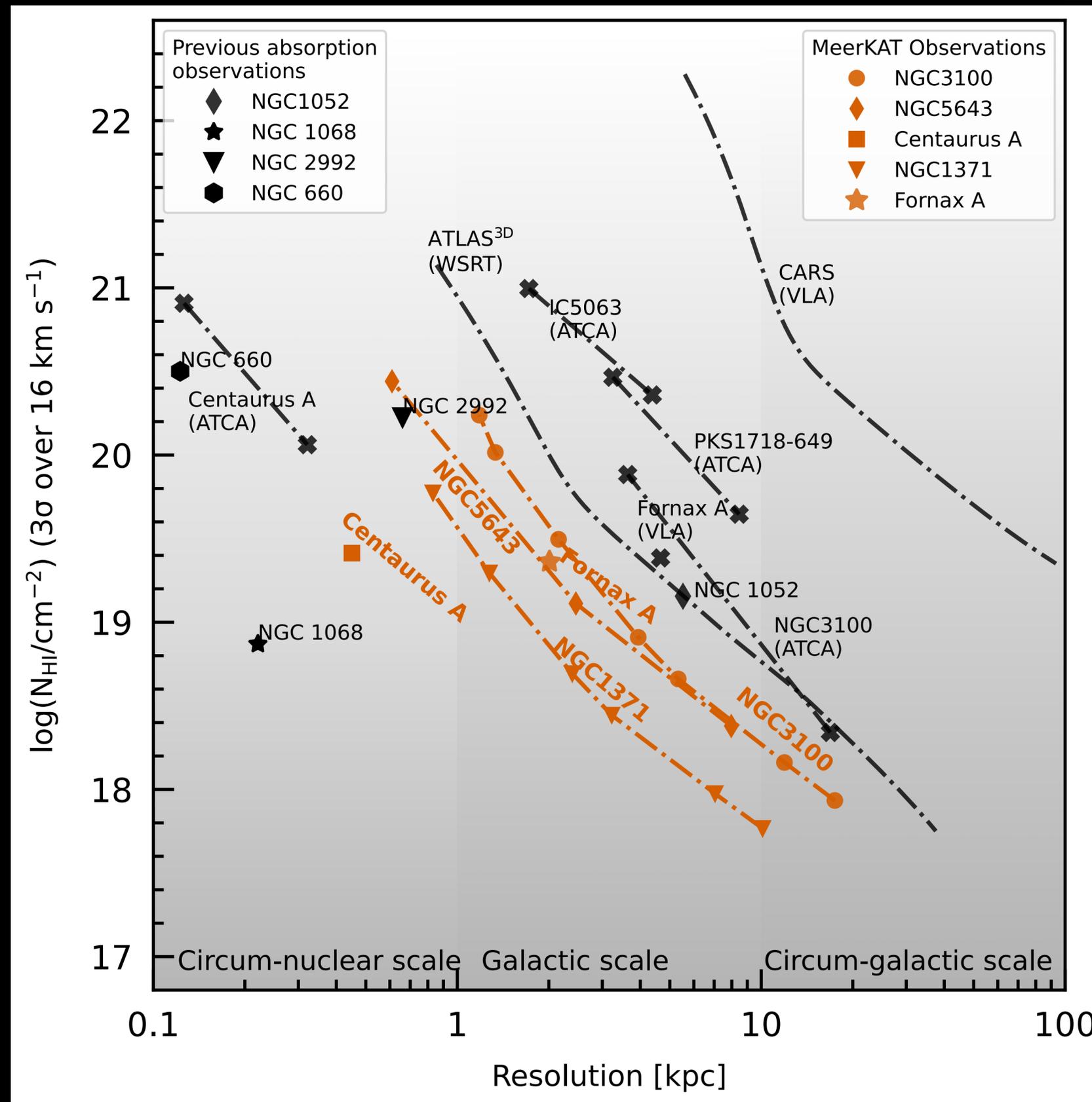
MeerKAT - telescope specs

- **core of SKA-MID** located in the Karoo desert, South Africa
- 64 dishes of 13.5m
- $T_{\text{sys}} = 22\text{K}$
- baselines 29m-8km
- **70% of baselines in a 1 km core**



MAGNHIFPIC - MeerKAT AGN feeding & feedback investigation close-by

Opening a new
parameter space of HI
observations in AGN
 $D < 35$ Mpc



Feeding - HI in and around NGC5643

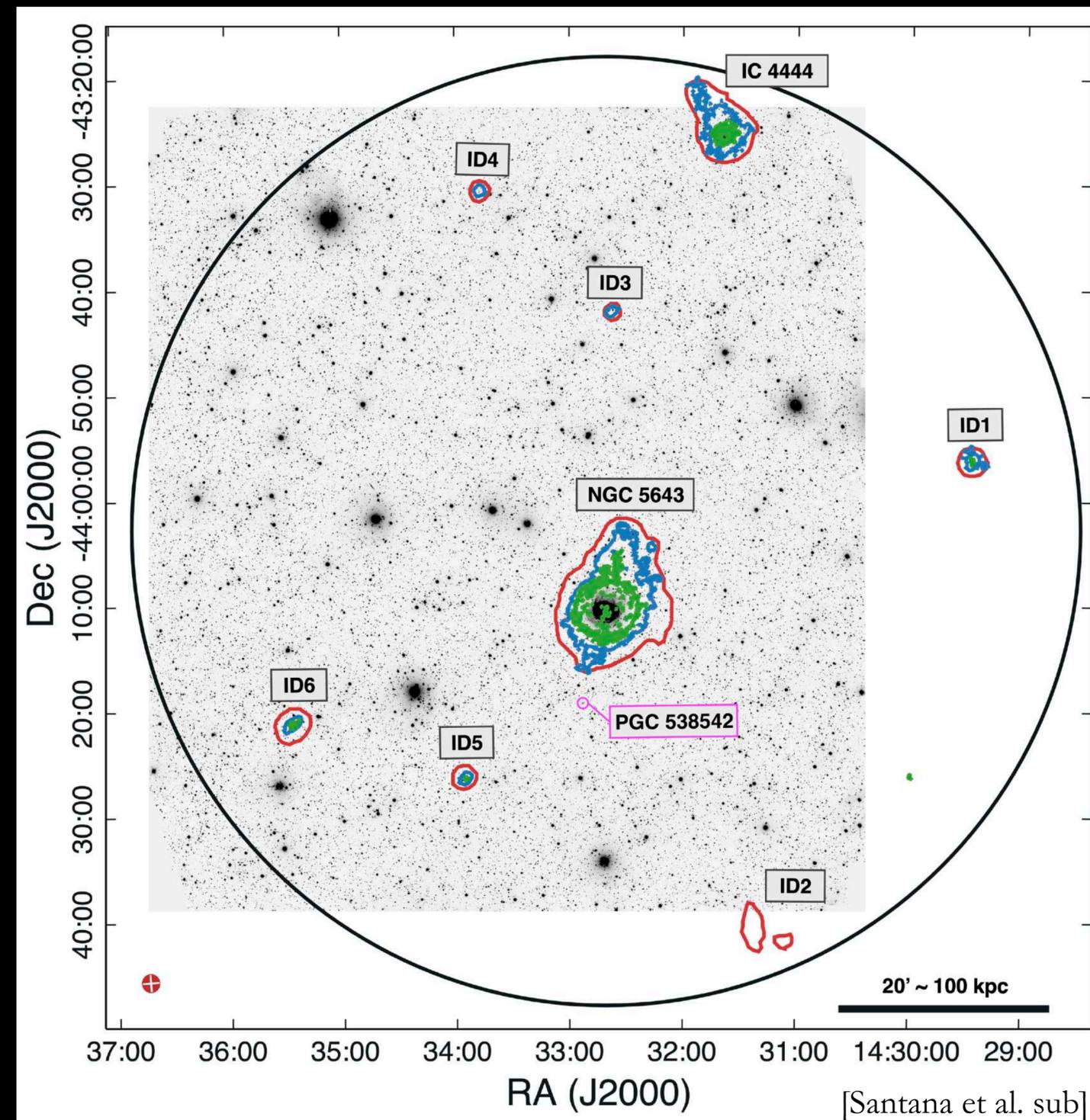


Karina Santana
PhD student (WITS)
Supervisors: R. Deane, F. Maccagni

NGC 5643: Seyfert-2 galaxy with AGN outflow studied in the ionised and molecular phases

MeerKAT observations (12hours)

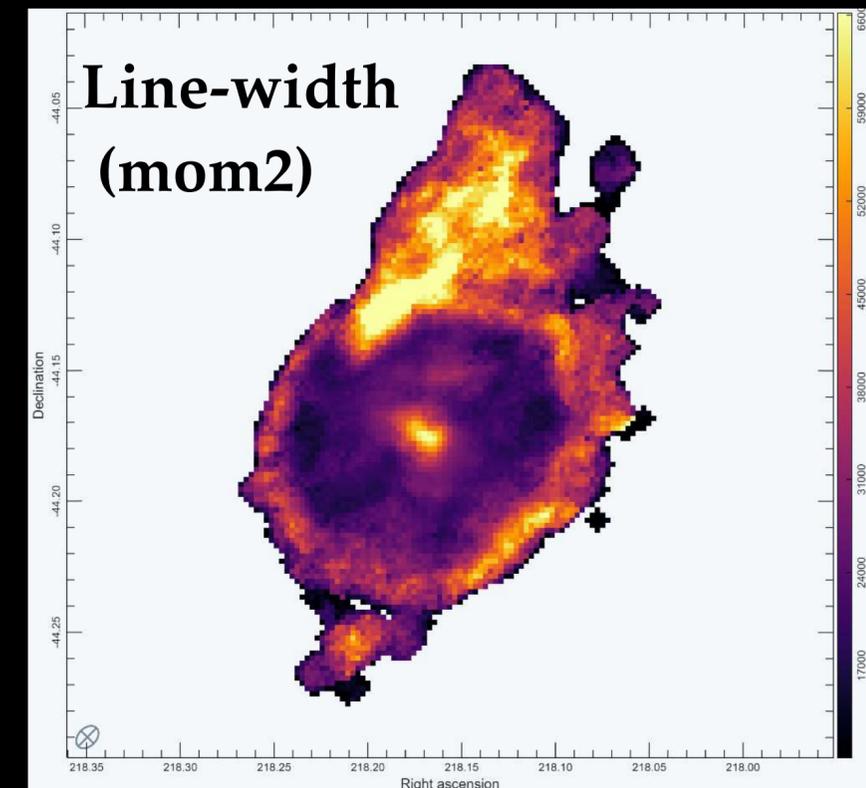
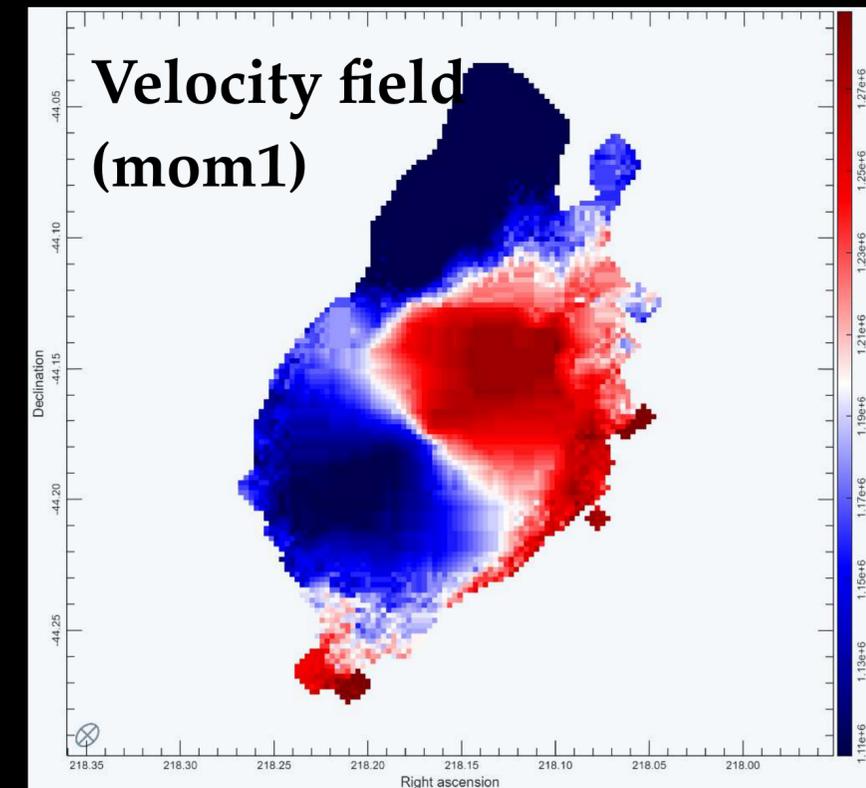
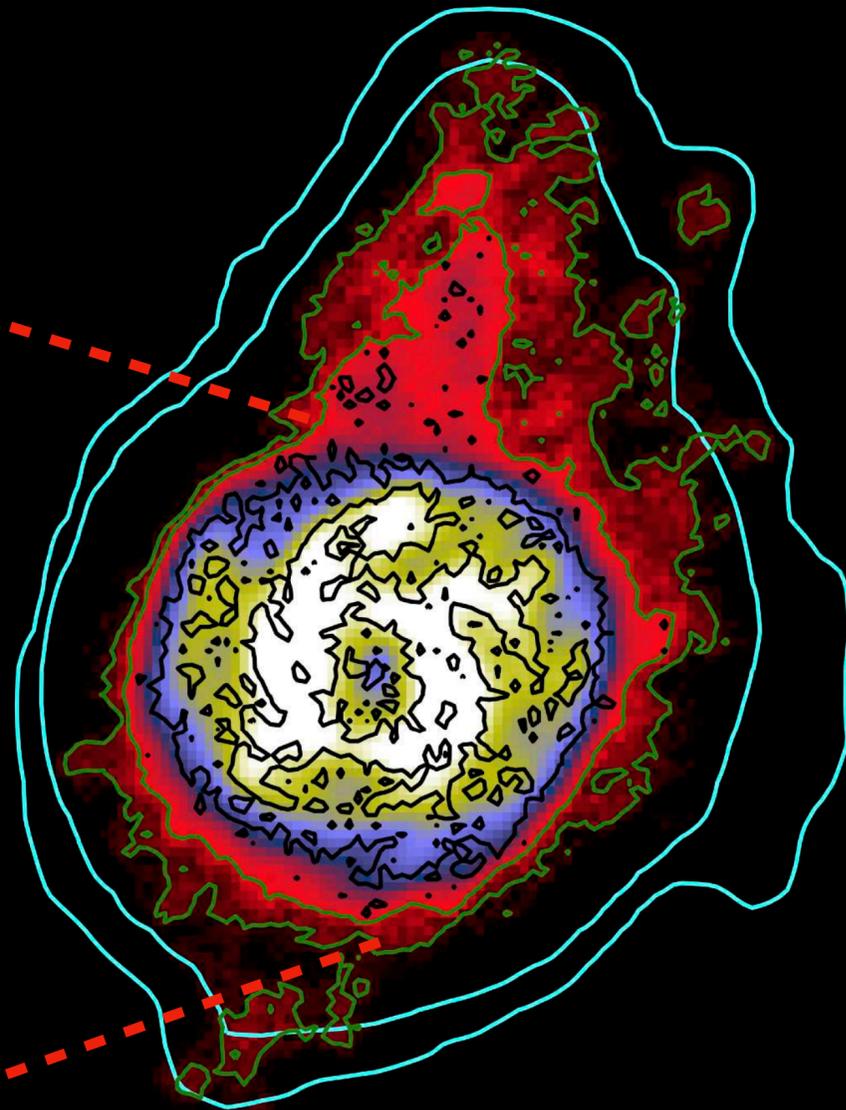
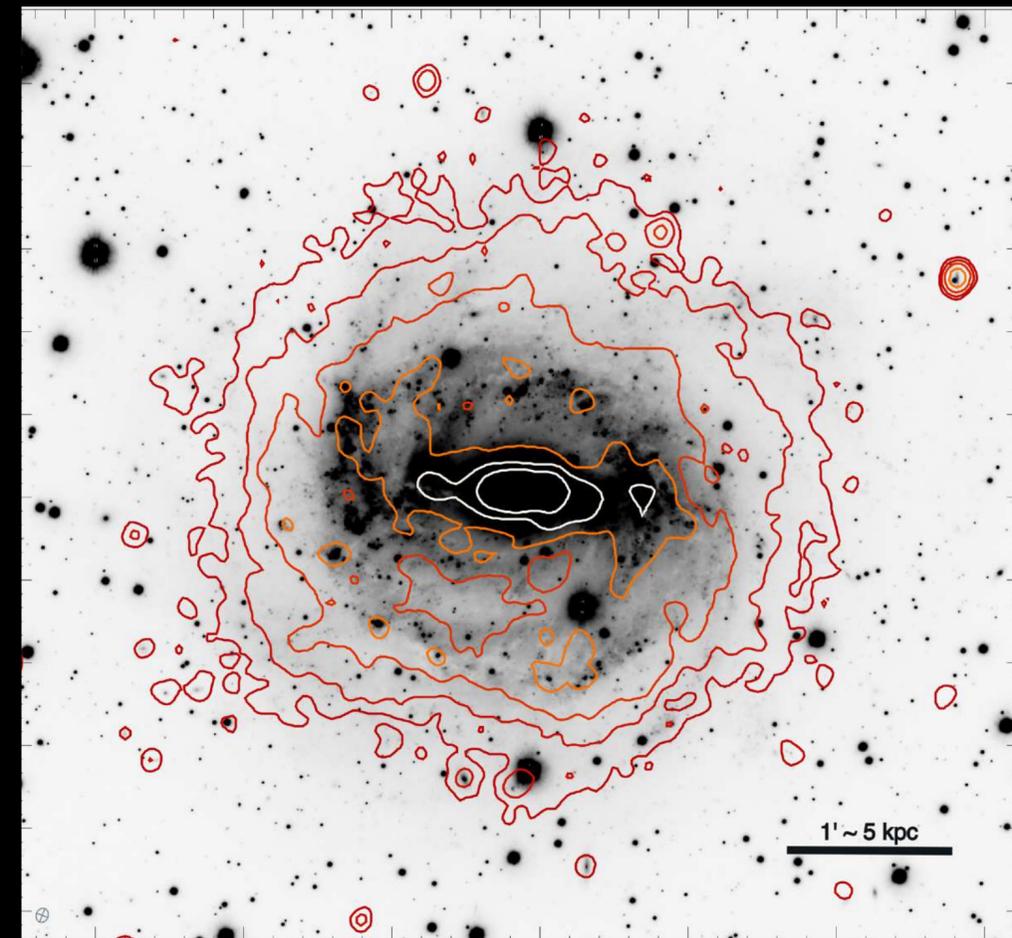
- several satellites between **120 and 300 kpc**
- **HI disk of NGC5643 $\sim 4e9 M_{\odot}$**
- extended asymmetry in the HI disk of NGC 5643 **$\sim 5e7 M_{\odot}$**
- blue-shifted HI absorption in the centre



[Santana et al. sub]

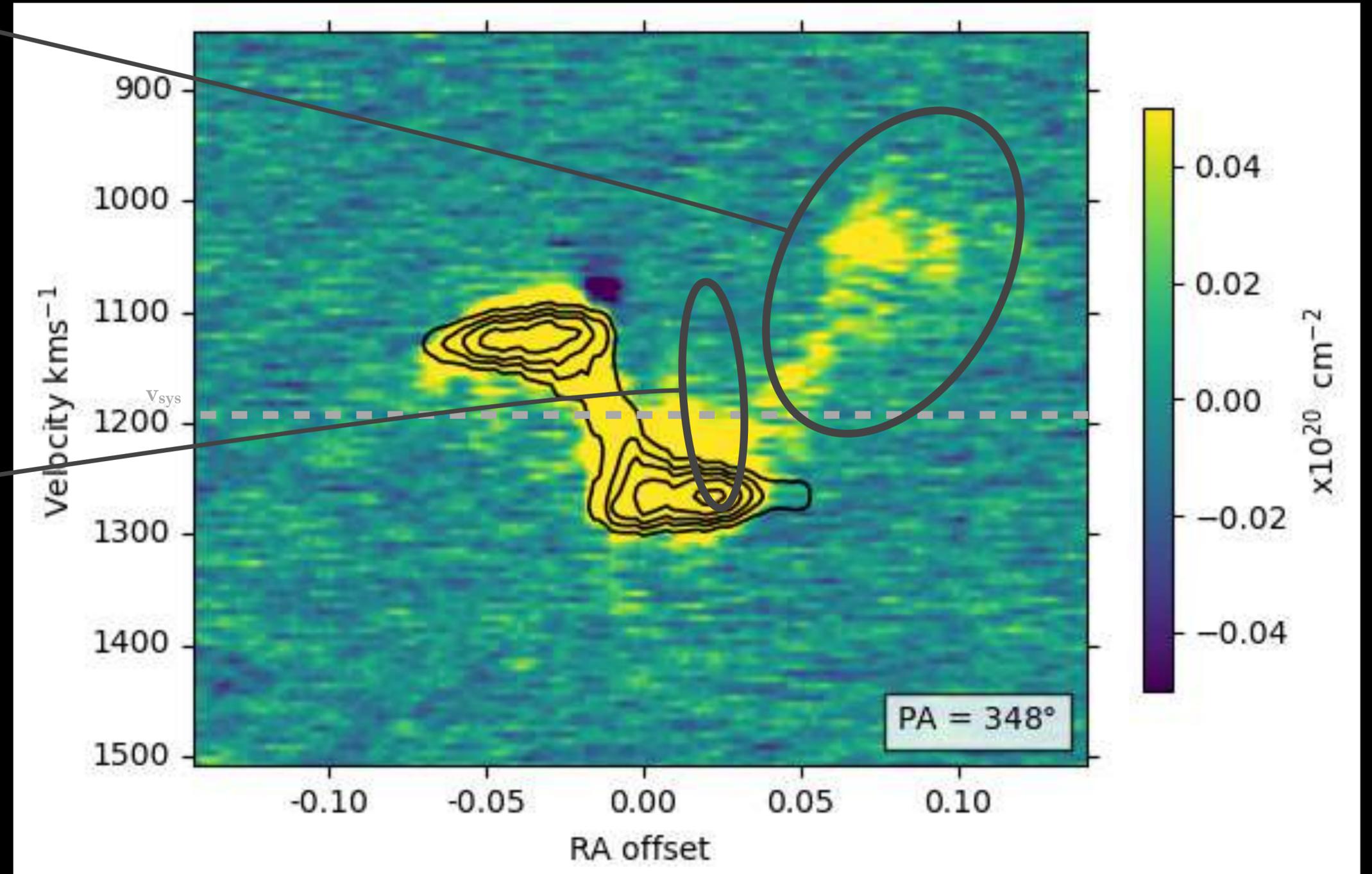
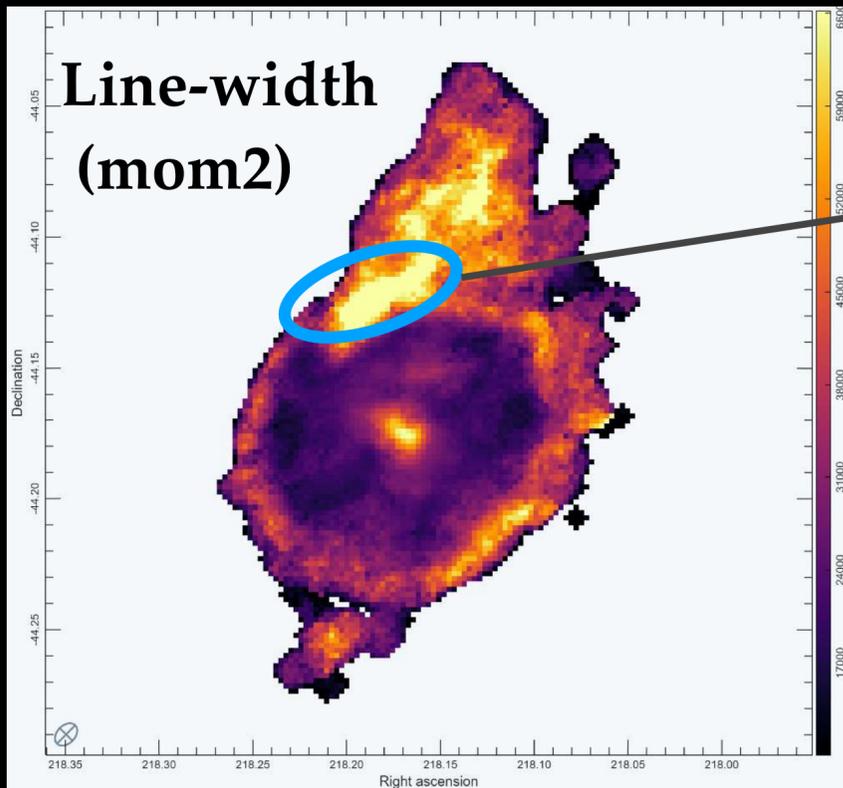
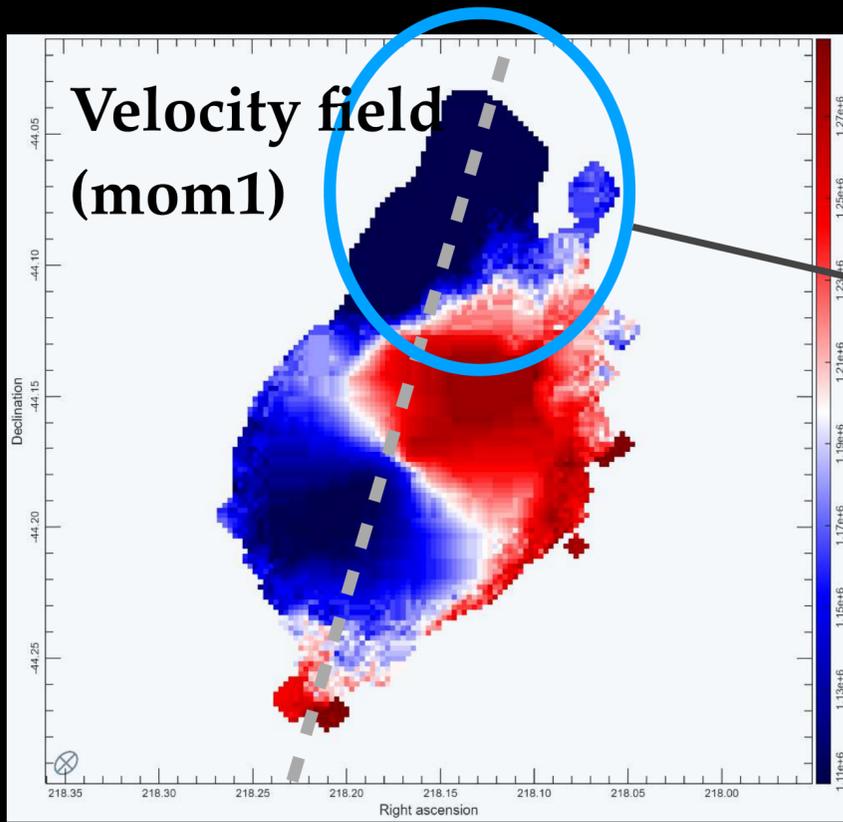
Feeding - HI in and around NGC5643

Radio continuum &
r-band with VST



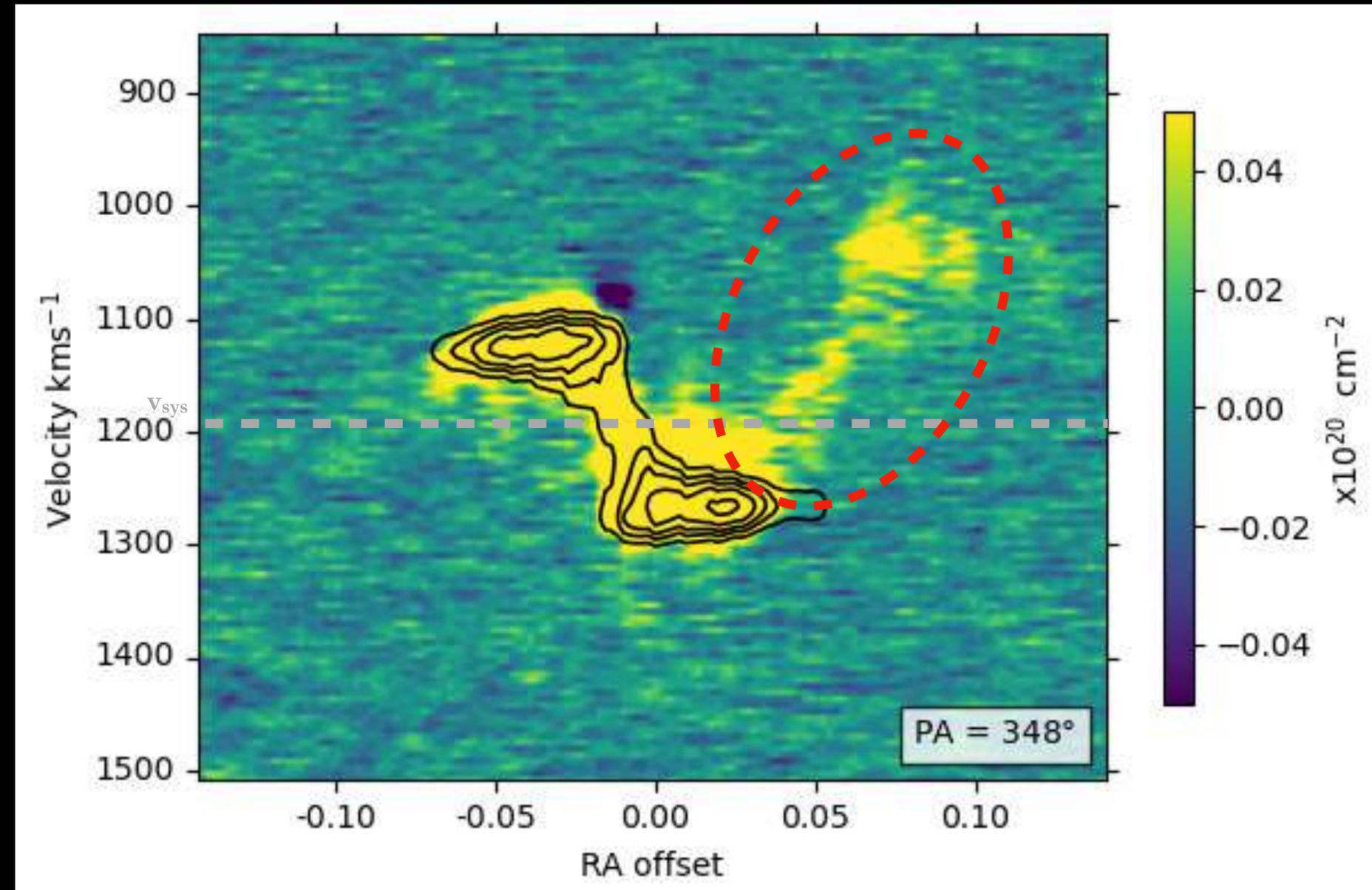
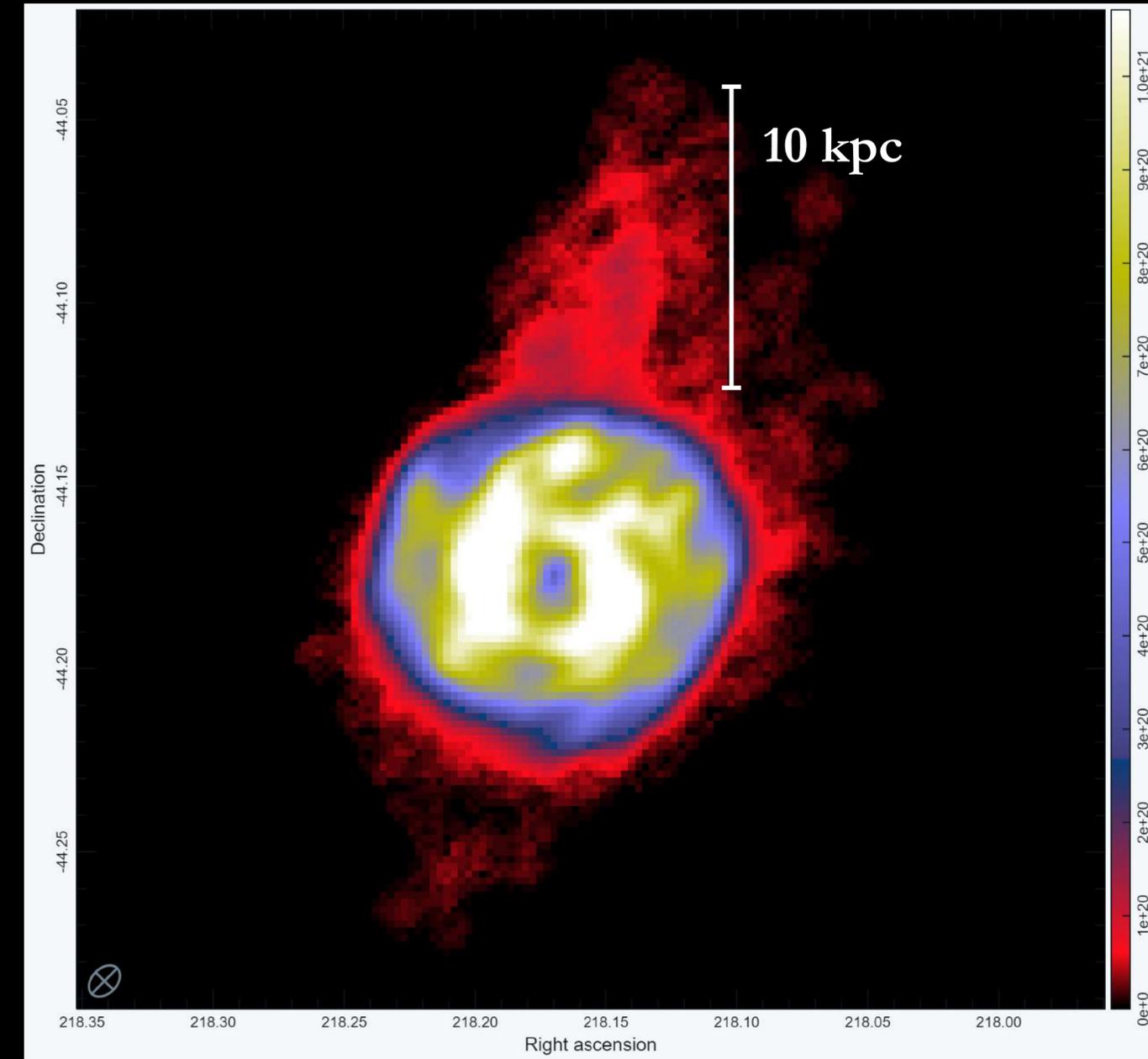
Feeding - HI in and around NGC5643

- Asymmetric tail high dispersion counter-rotating velocities - $\Delta v \sim 300$ km/s
- Several 'beards' across the disk and at its edges



Feeding - Origin of the HI tail

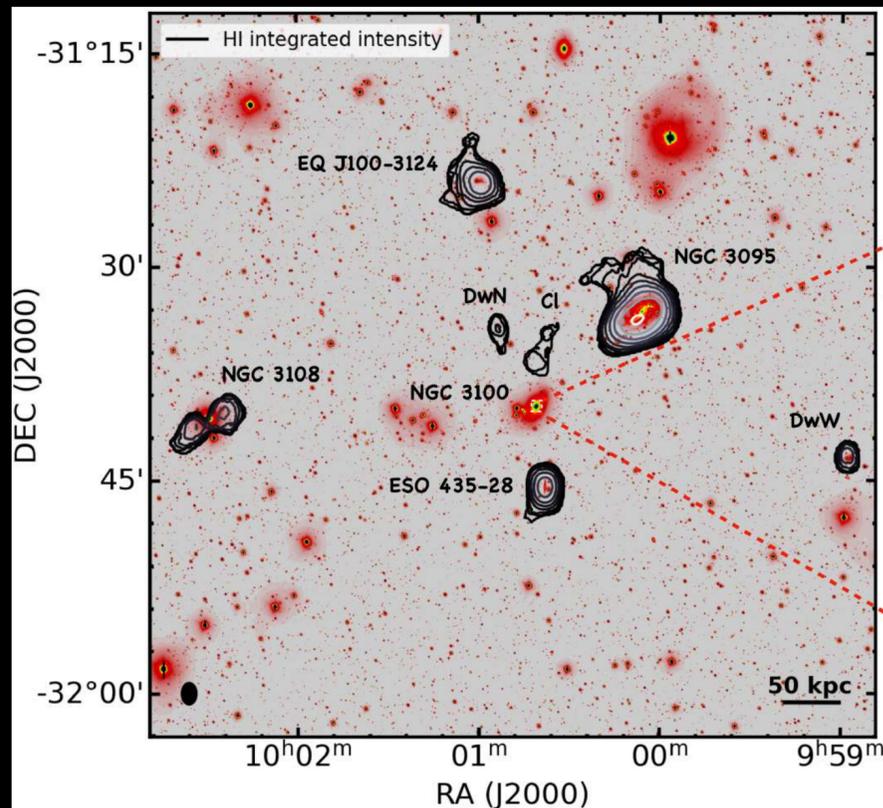
- Tidal interactions? but distance of other sources > 100 kpc
- Ram pressure: excluded by pv-plot
- **Accretion of cold gas from IGM**



Feeding - NGC 3100 with VST & MeerKAT



ATCA 36 hours - 90''

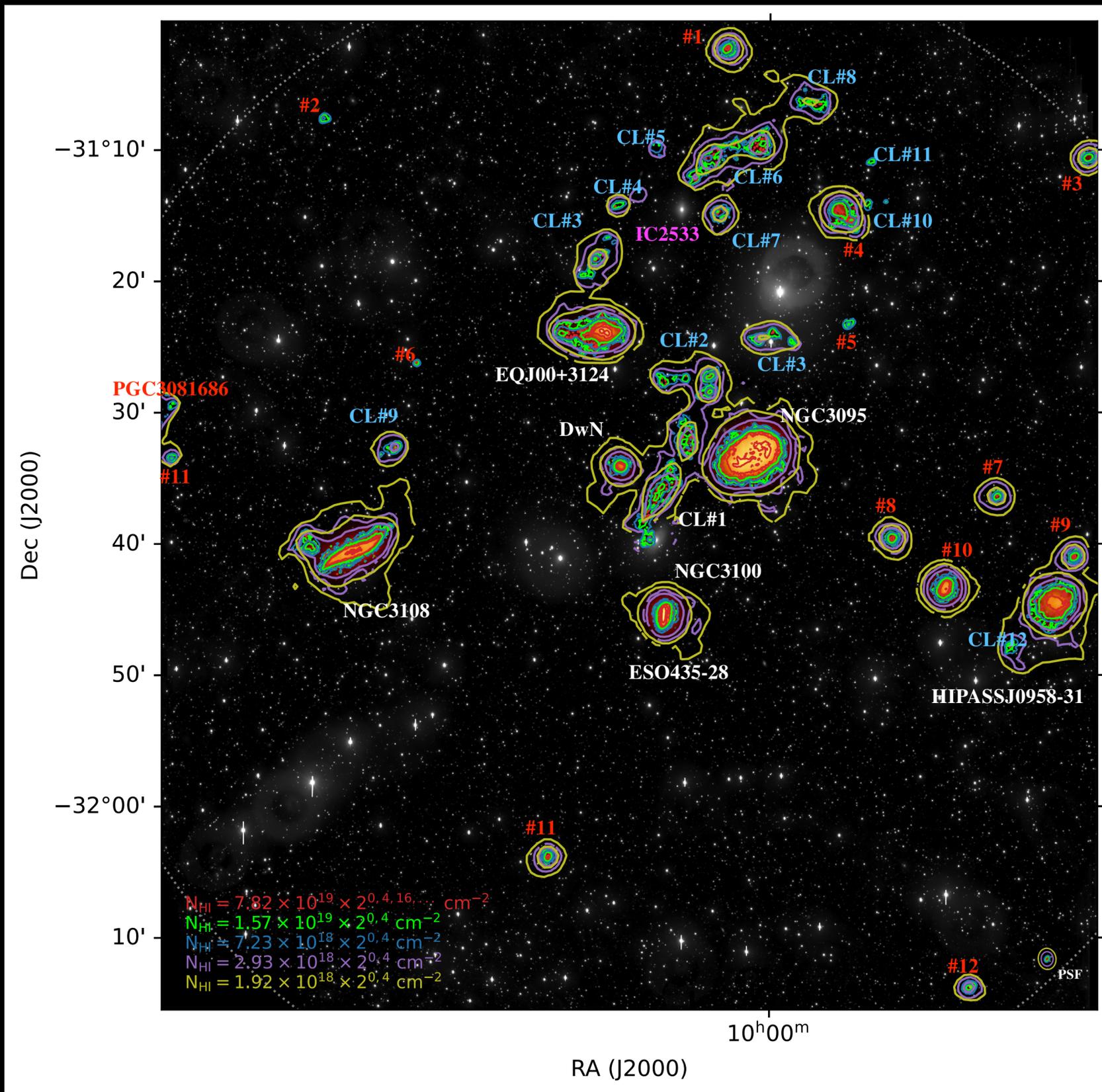


MeerKAT 25 hours:
Resolution: 10'' - 90''

$\Delta v = 1.4 \text{ km s}^{-1}$

VST r-band

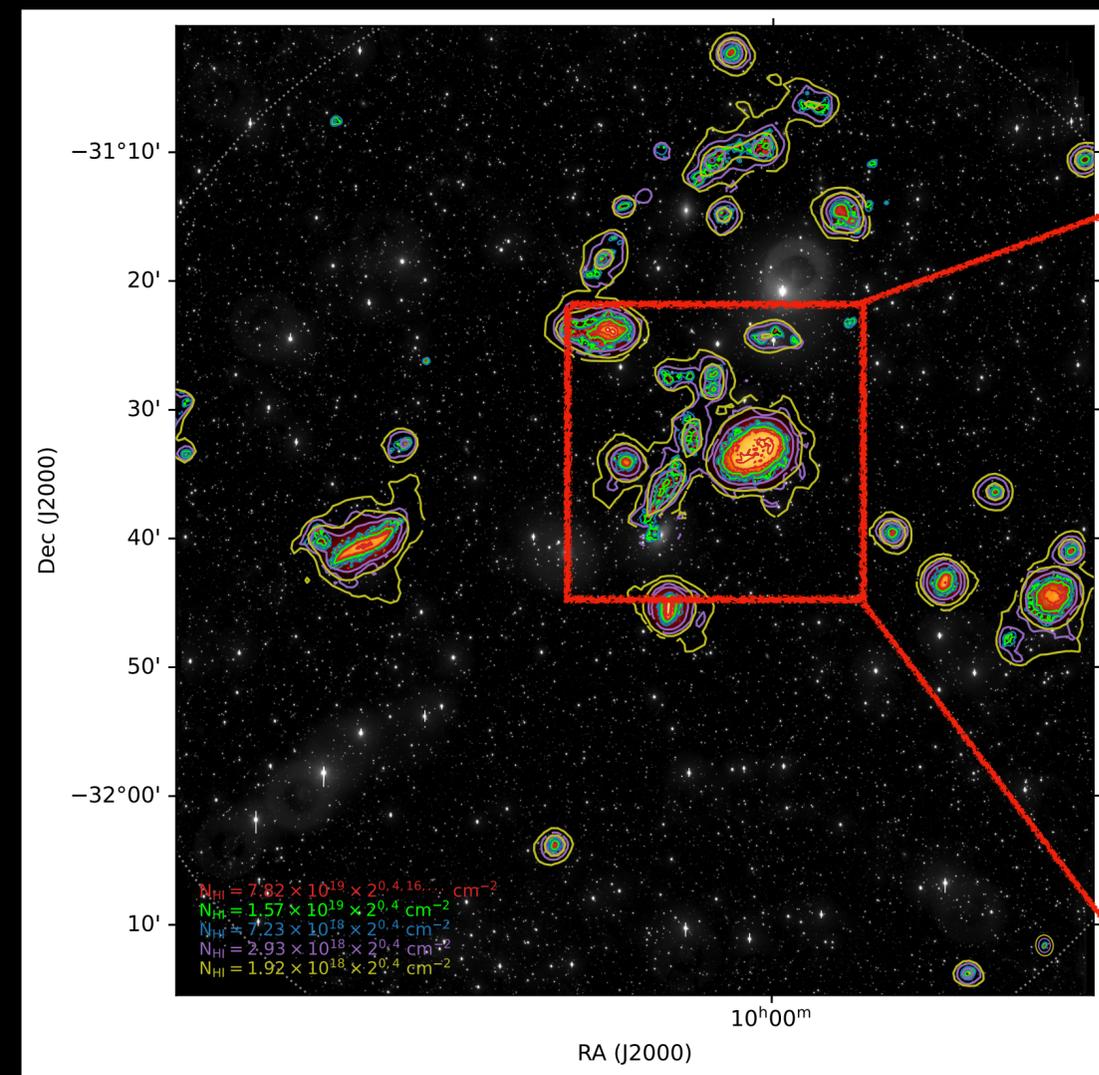
27 mag/arcsec²



NGC3100 is located in an HI rich group (BGG:IC2533)

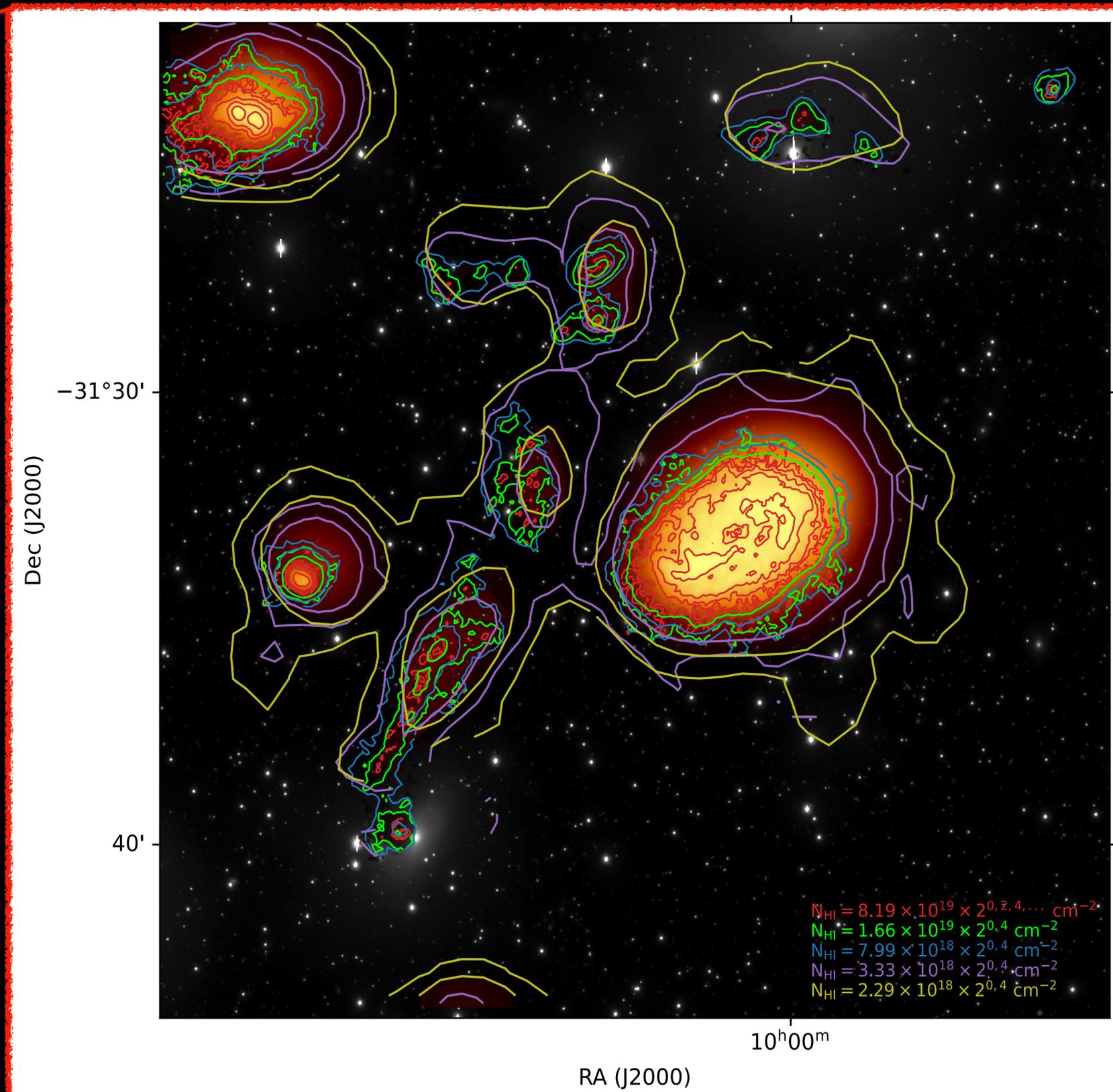
- Previous HI detections
- HI detections associated to galaxies (LSBs, UDGs)
- HI detections without optical counterpart

Feeding - NGC 3100 with VST & MeerKAT

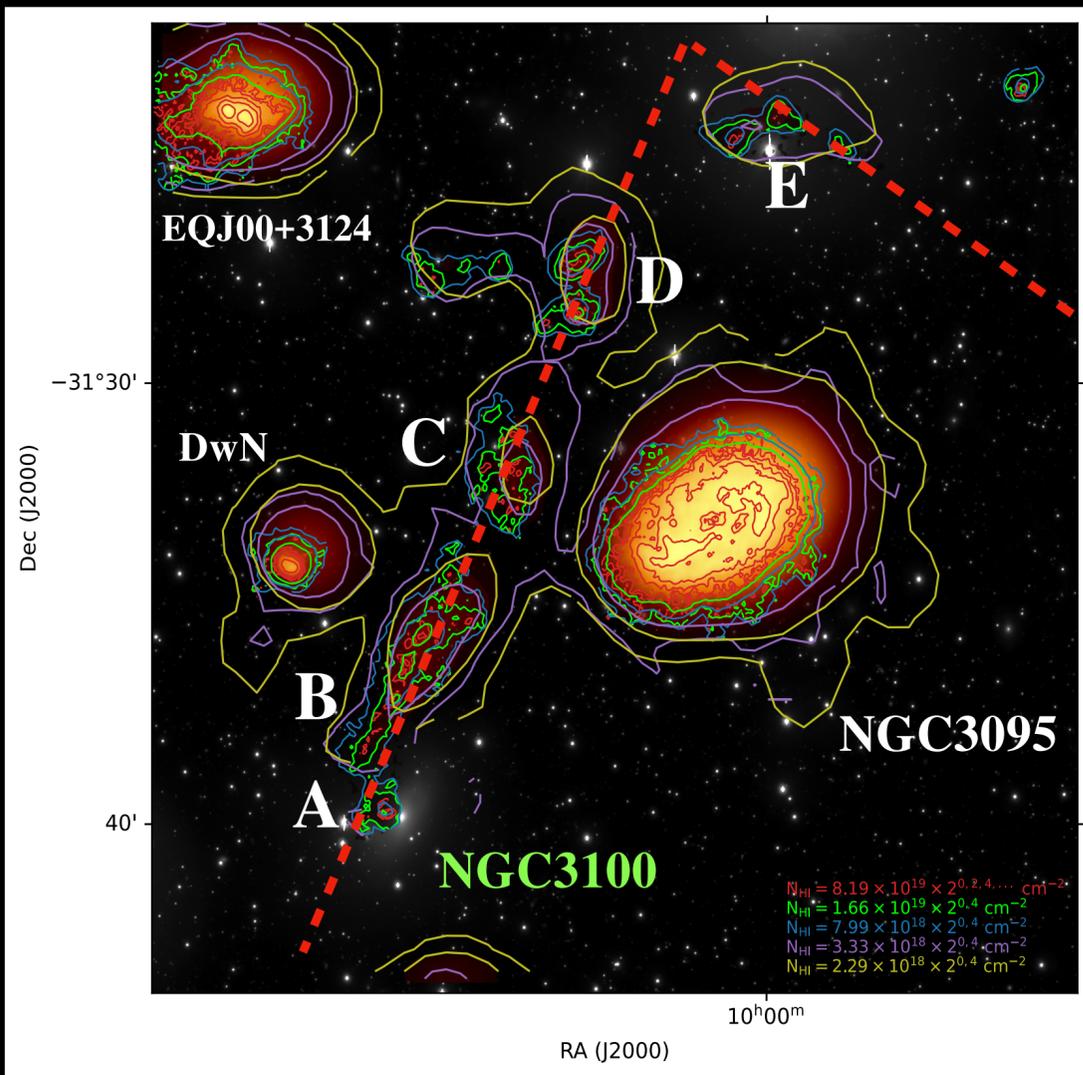


'Dark cloud'

- extends for 90 kpc
- remnant of interaction between surrounding galaxies
- falling onto NGC3100

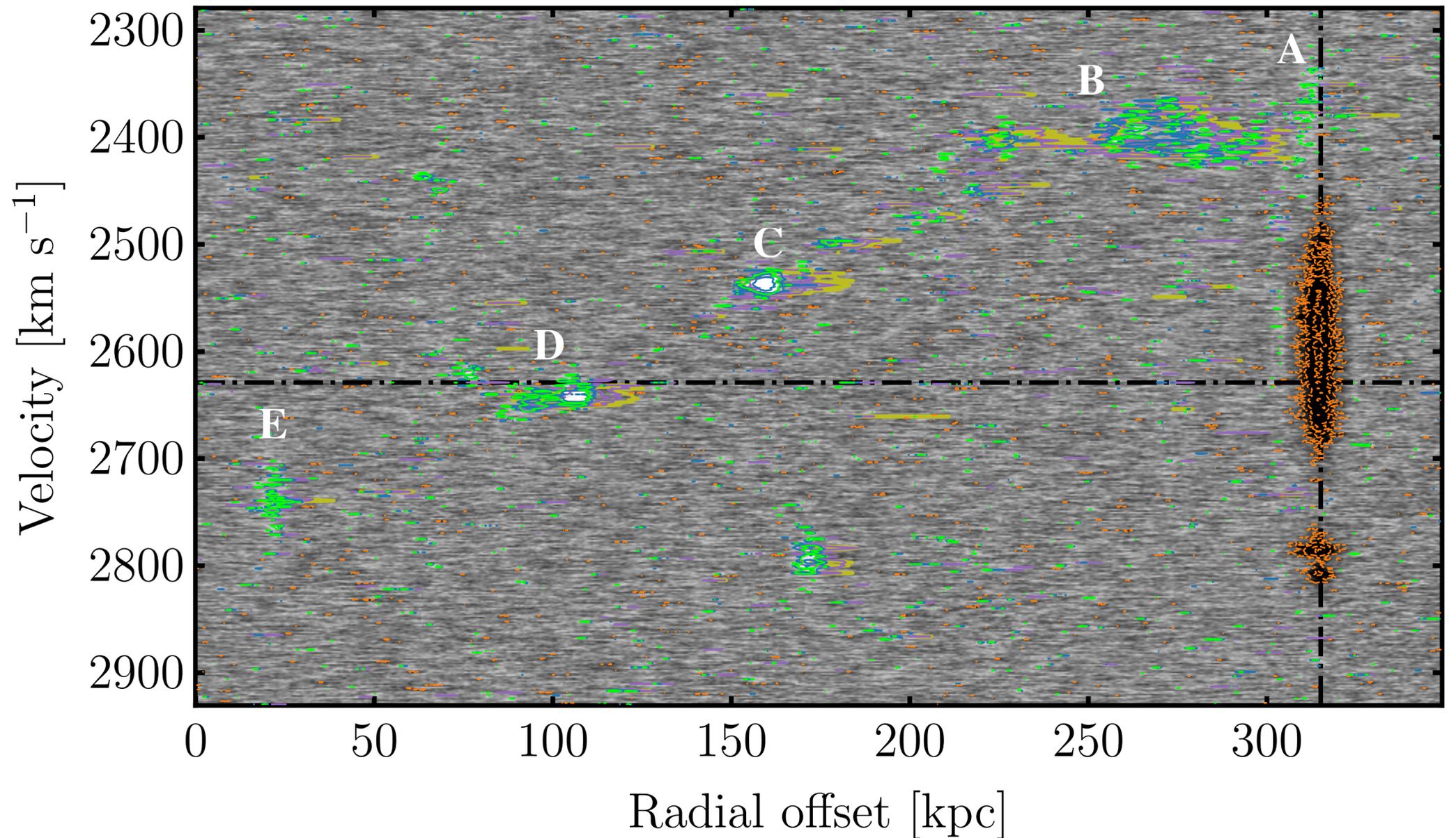


Feeding - NGC 3100 fuelled by 'external' accretion



'Dark cloud'

- connected spatially and kinematically with **HI absorption**



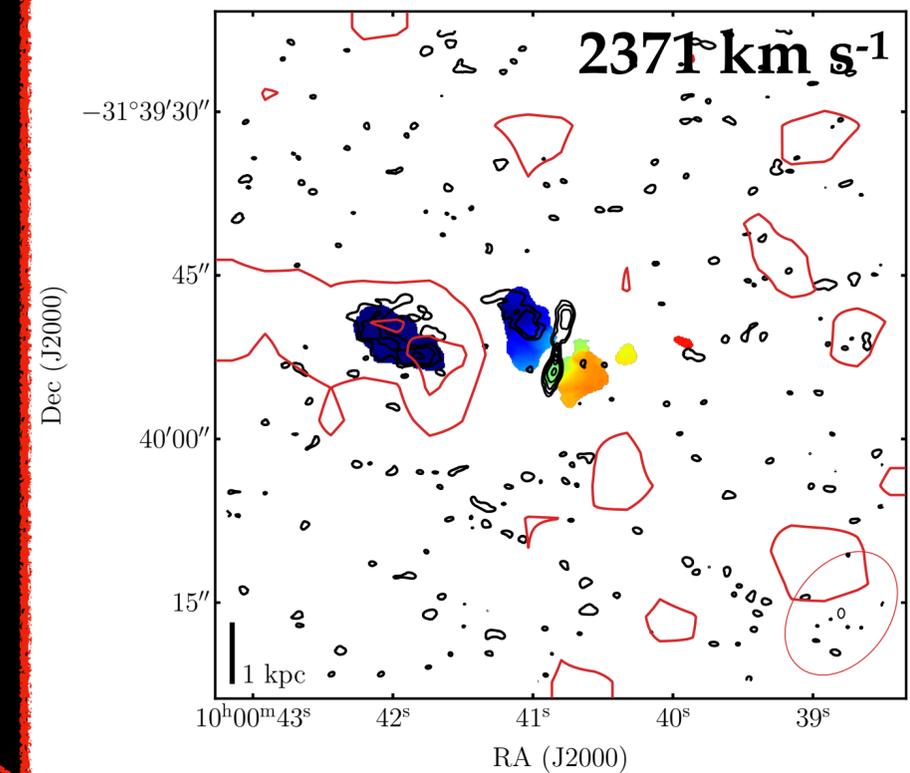
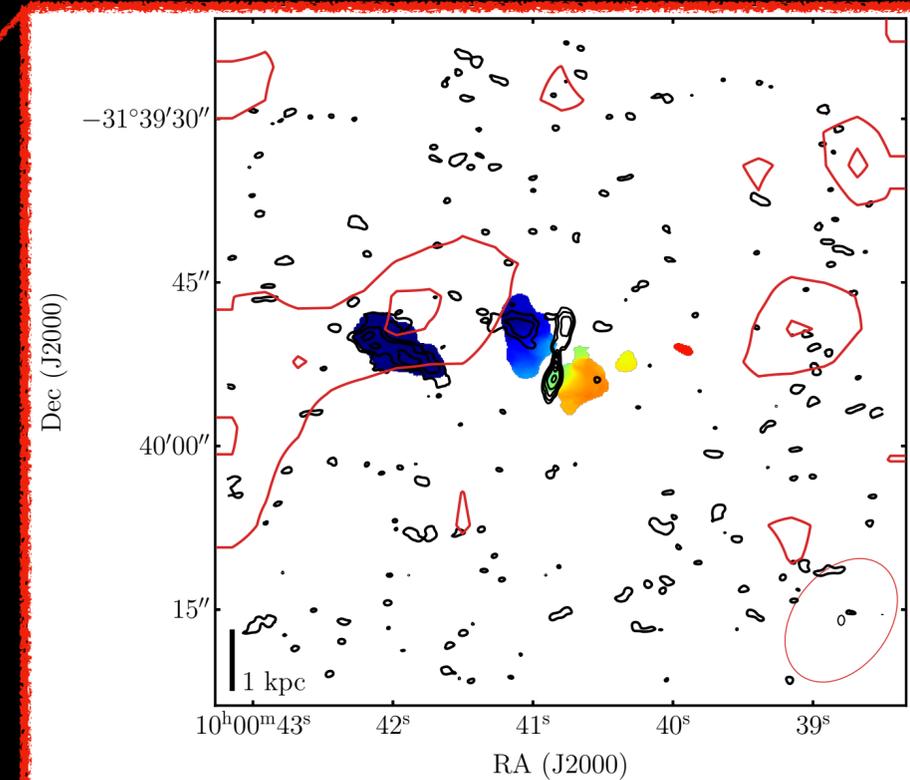
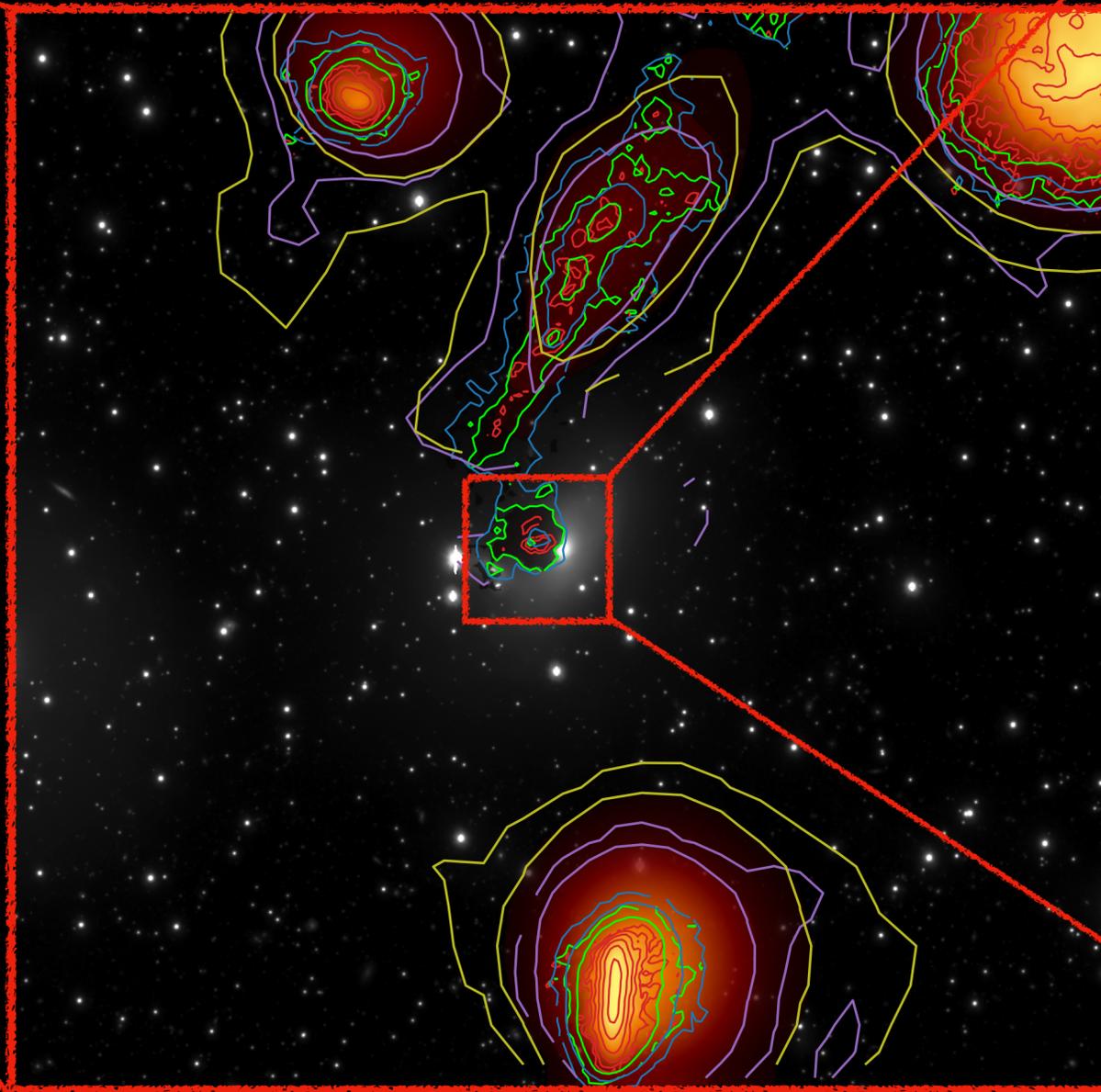
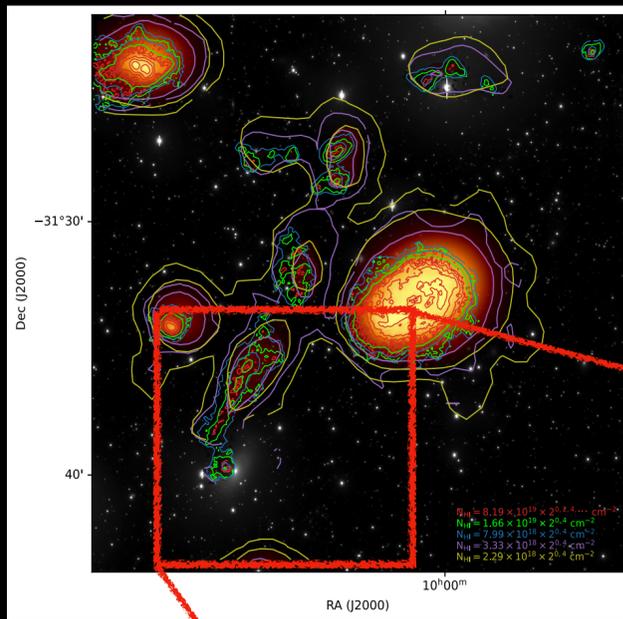
Cold gas accretion from remnant of tidal interaction is directly feeding the circum-nuclear disk

Feeding - HI fuelling the circum-nuclear disk of NGC3100

'Dark cloud'

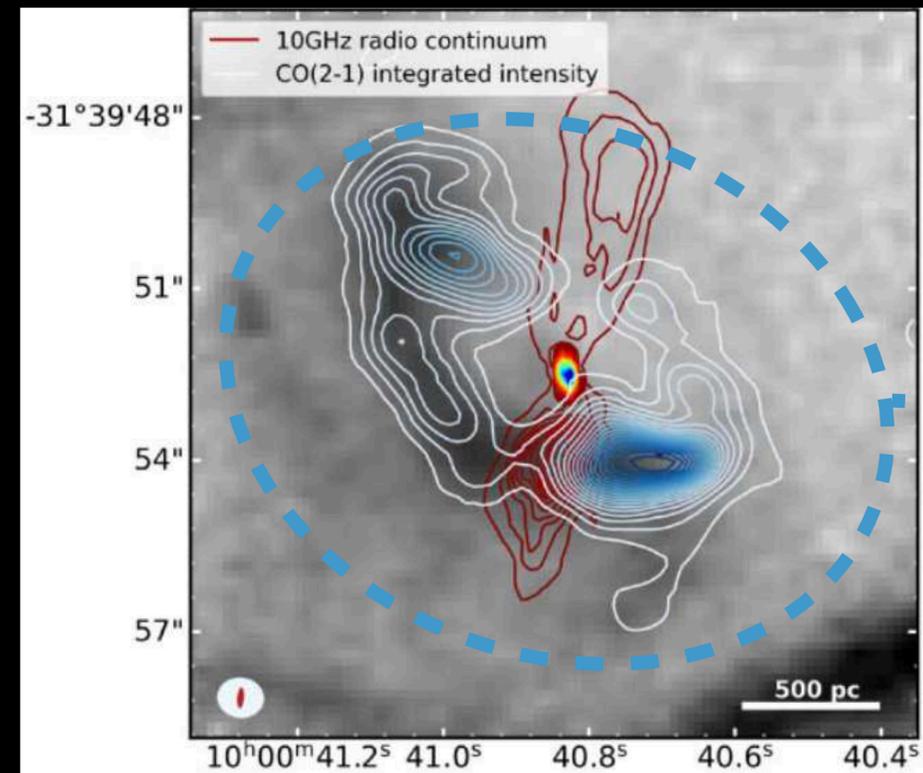
- spatially and kinematically connected with the molecular gas

Channel maps : HI + CO (1-0)

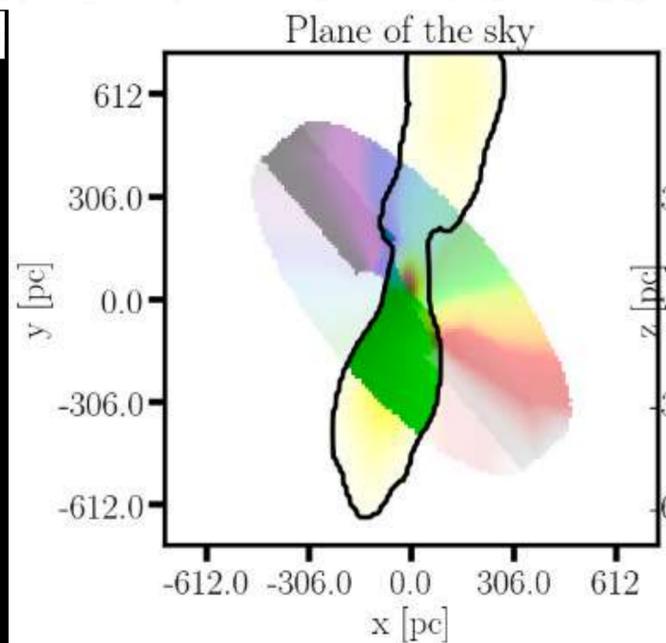


Feeding - Redshifted absorption clouds

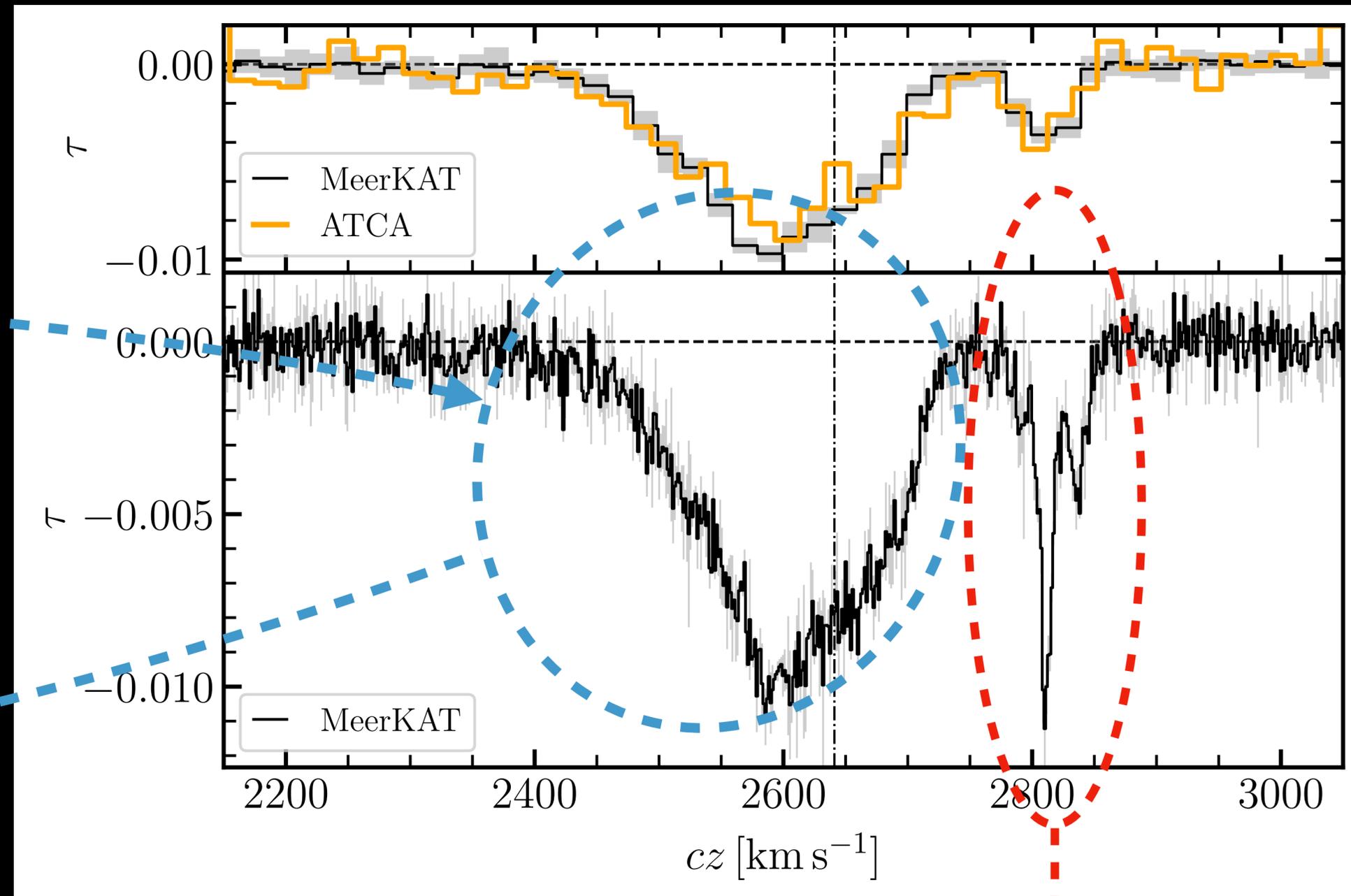
CO circum-nuclear disk



[Ruffa+22]



[Maccagni+23]



- HI:

- atomic counterpart of circum-nuclear disk & redshifted clouds infalling within 200 pc from SMBH

Fornax A

- How did the radio lobes and inner jets form?
- In which timescales?

MeerKAT commissioning observations

Serra et al. 2019 : merger history of Fornax A

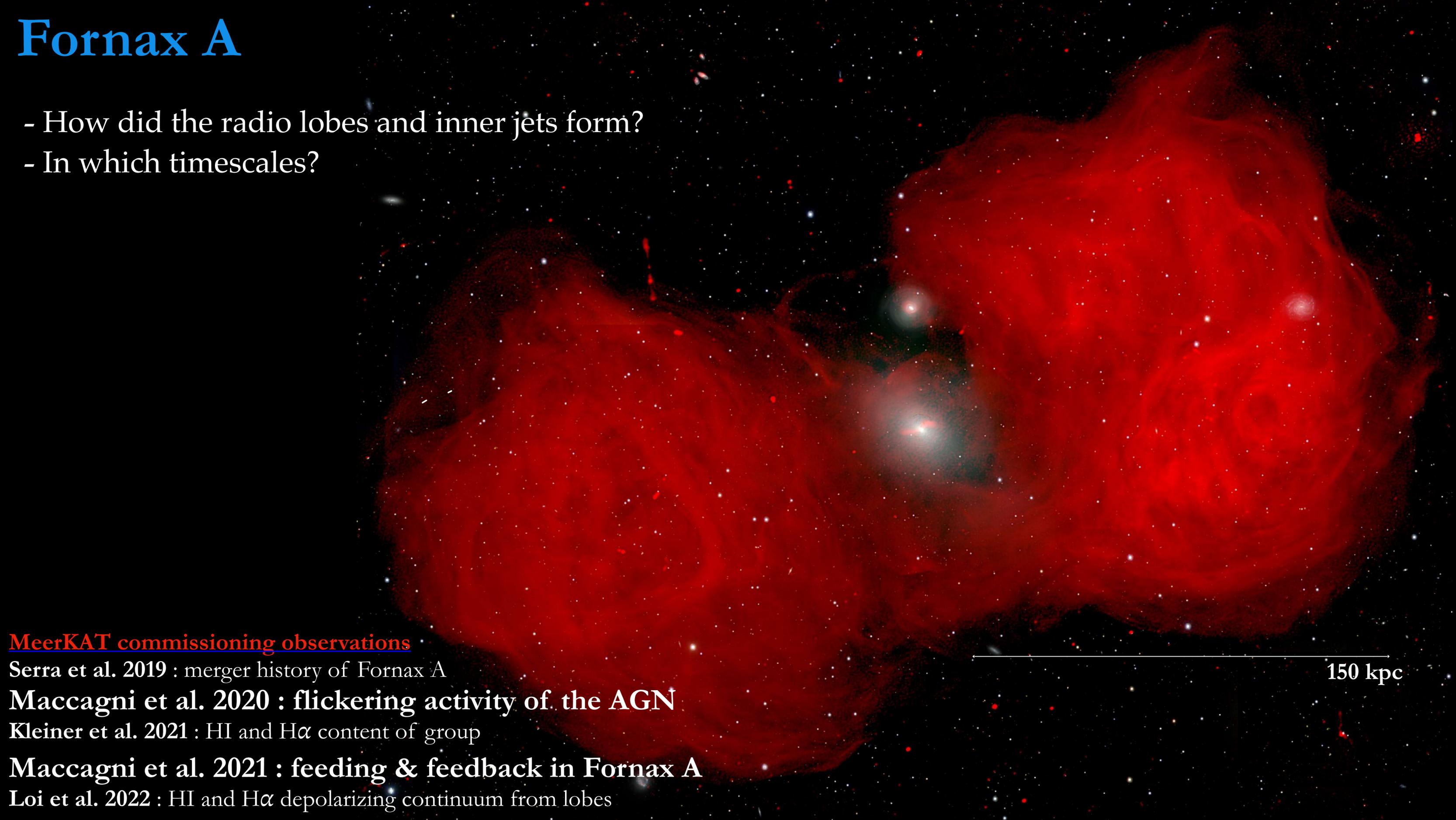
Maccagni et al. 2020 : flickering activity of the AGN

Kleiner et al. 2021 : HI and H α content of group

Maccagni et al. 2021 : feeding & feedback in Fornax A

Loi et al. 2022 : HI and H α depolarizing continuum from lobes

150 kpc



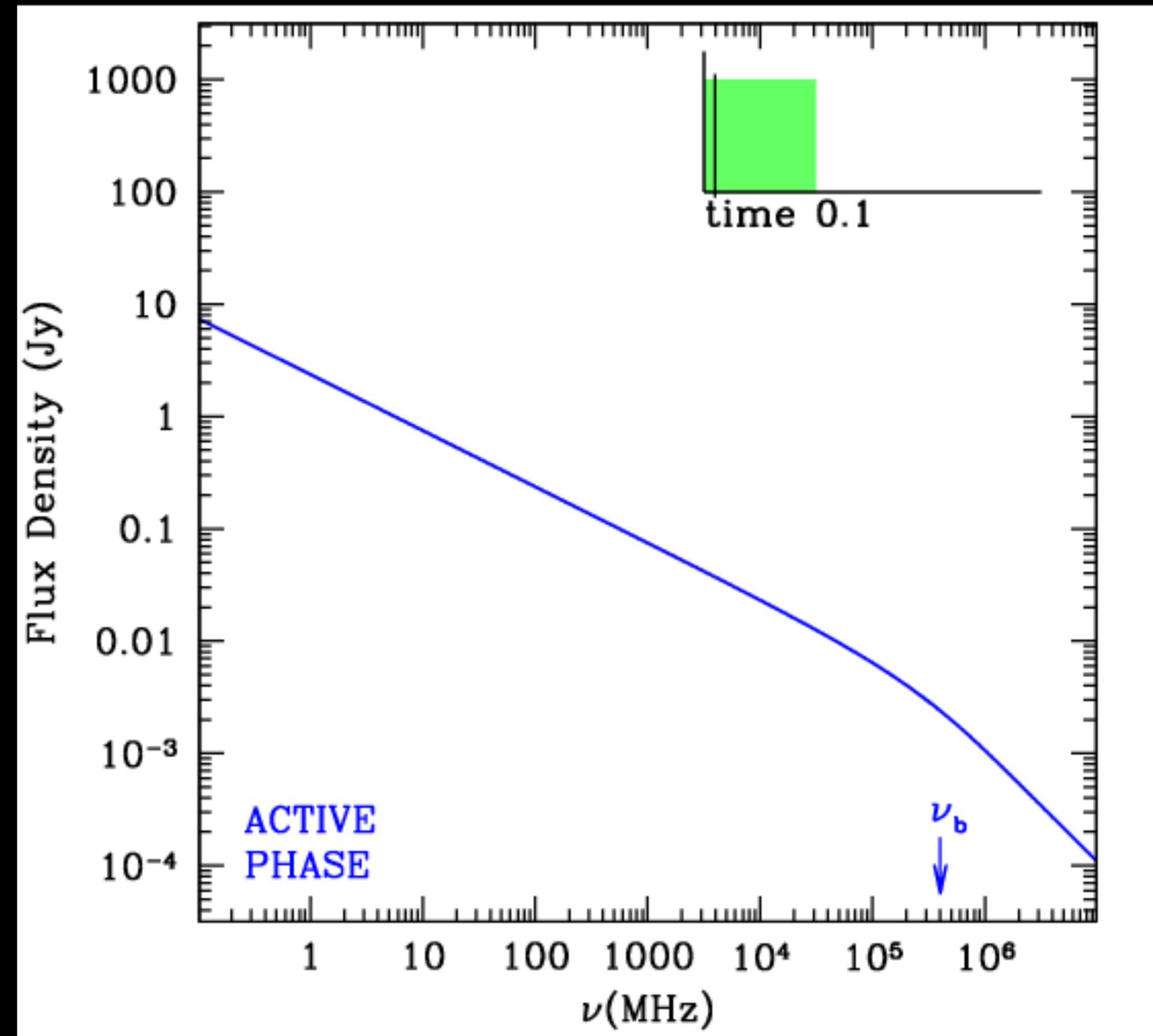
AGN spectral analysis: the timescale of activity

Timescale of Nuclear Activity is inferred from the shape of the flux density distribution

- Synchrotron emission: high energy particles are injected in a medium with constant magnetic field, and then lose energy over time.
- Active phase + turn off

For AGN timescales from spectral index analysis see (for example)

Kardashev 62, Parma+99, Murgia+10, Harwood+13, Kolokythas+15, Brienza+17,23, Shulevski+24



Continuum observations between 84 MHz and 217 GHz

Characterise the duty cycle of the AGN:

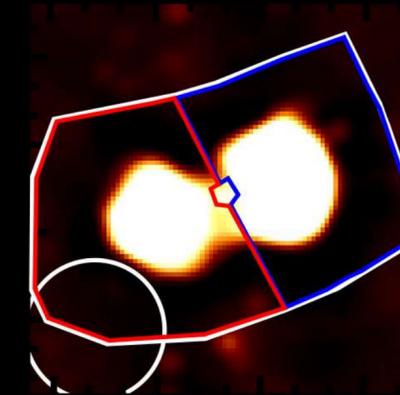
Spectral flux density distribution

- East & West Lobe
- Inner Jets
- Core

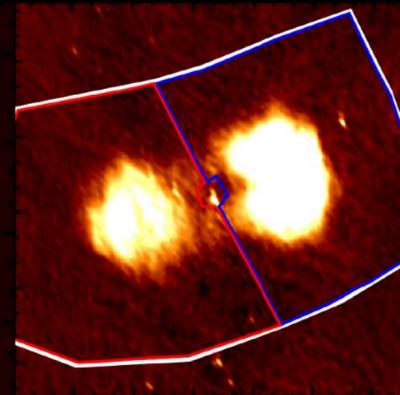


MeerKAT (900 MHz, 1.4 GHz)

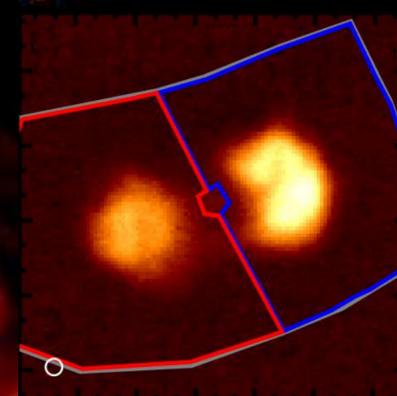
MWA (84 - 200 MHz)



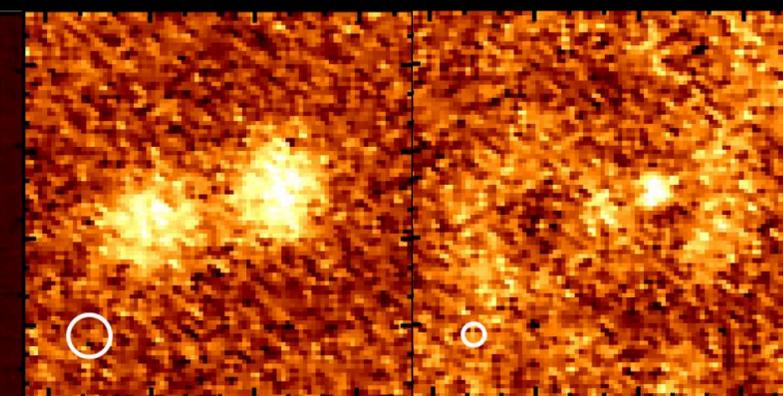
VLA (320 MHz)



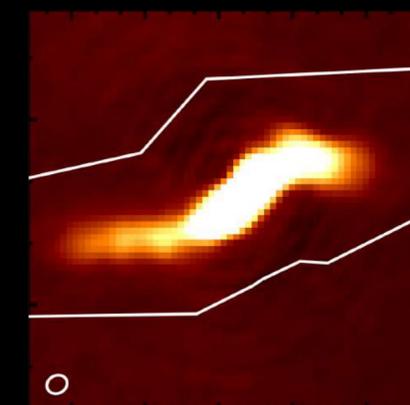
SRT (5.7-6.8 GHz)



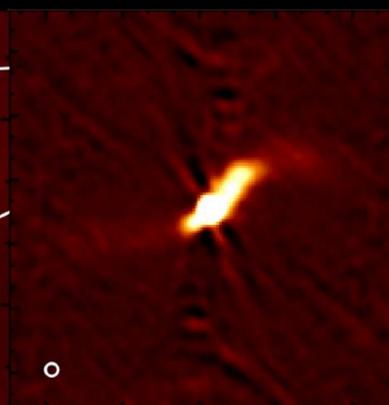
Planck (30 - 217 GHz)



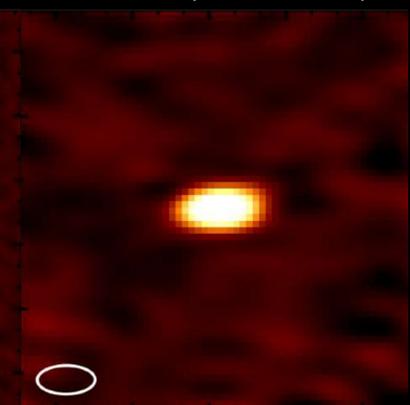
MeerKAT (1.4 GHz)



VLA (4.8 GHz)



ALMA (108 GHz)



The flickering activity of Fornax A

- Phase 1 — Lobes

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

- Phase 2 — Jets

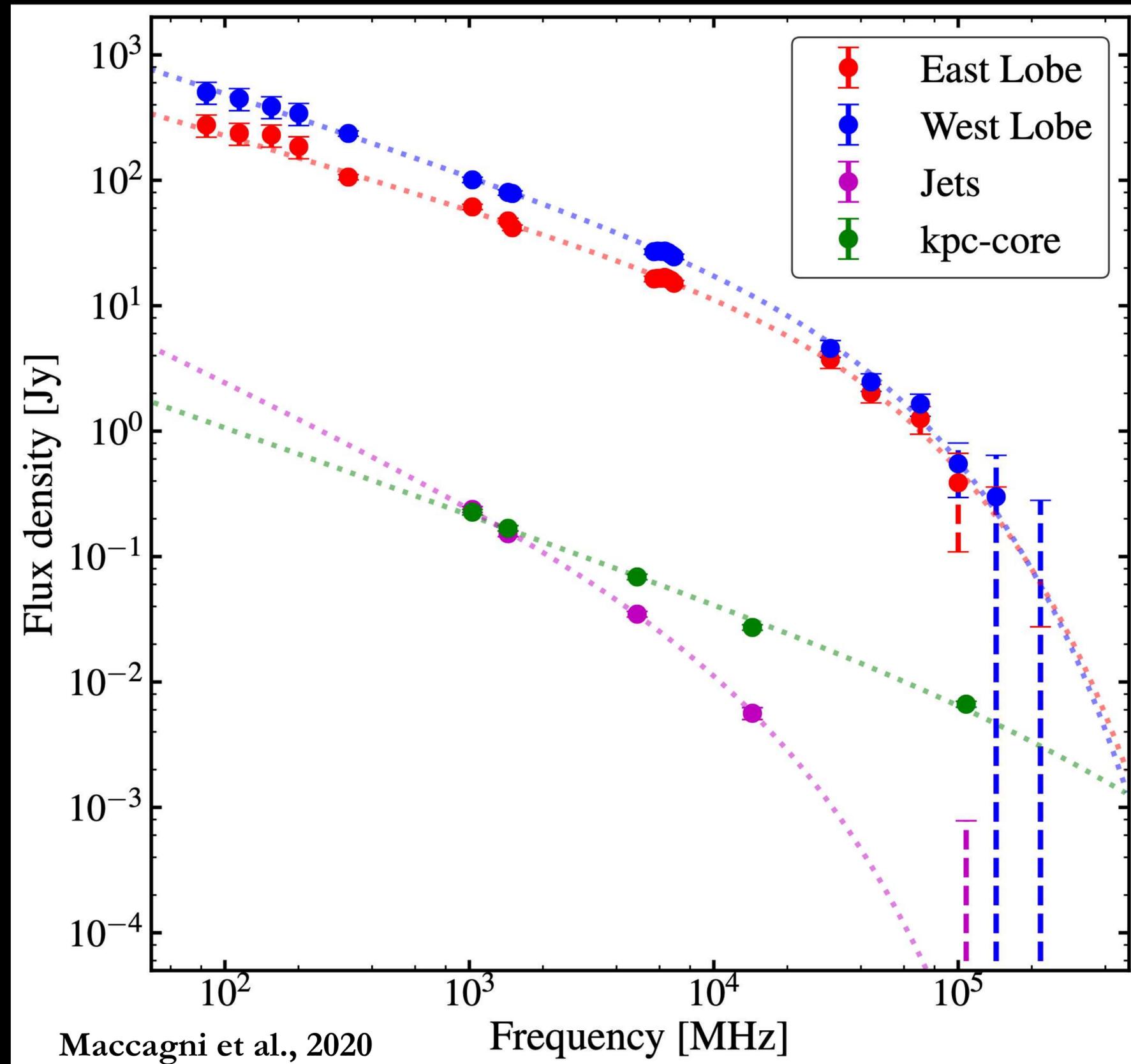
- 3 Myr ago AGN formed the jets
- 1 Myr ago AGN switch-off

- Phase 3 — Core

- kpc-core is active (< 1 Myr) [Paraschos+24]

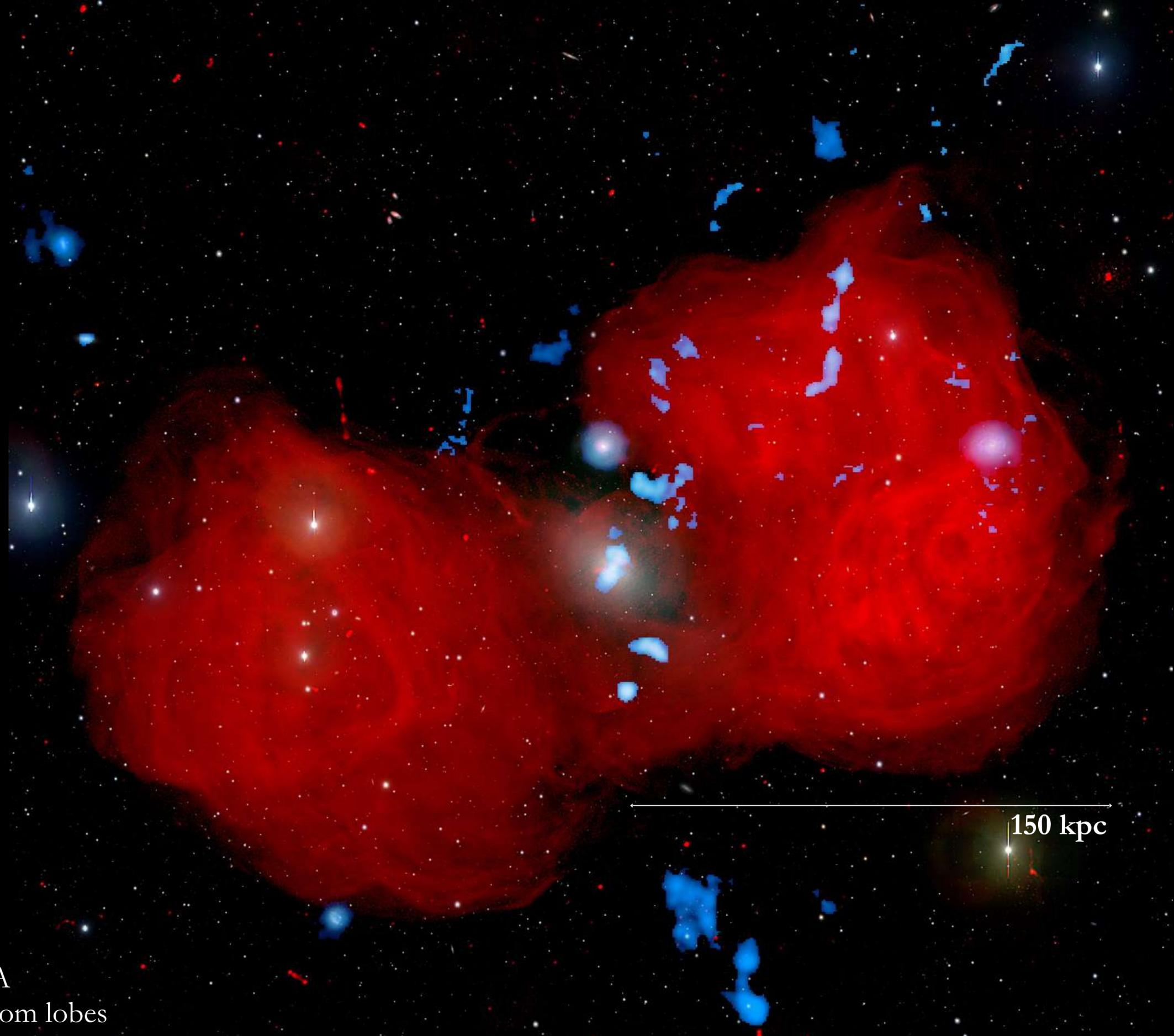
What regulates the fast duty cycle?

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



Fornax A & HI

- What is fuelling and sustaining the rapid duty cycle of the AGN?
- Is AGN feedback changing the conditions of the ISM and IGM?



MeerKAT commissioning observations

Serra et al. 2019 : merger history of Fornax A

Maccagni et al. 2020 : flickering activity of the AGN

Kleiner et al. 2021 : HI and H α content of group

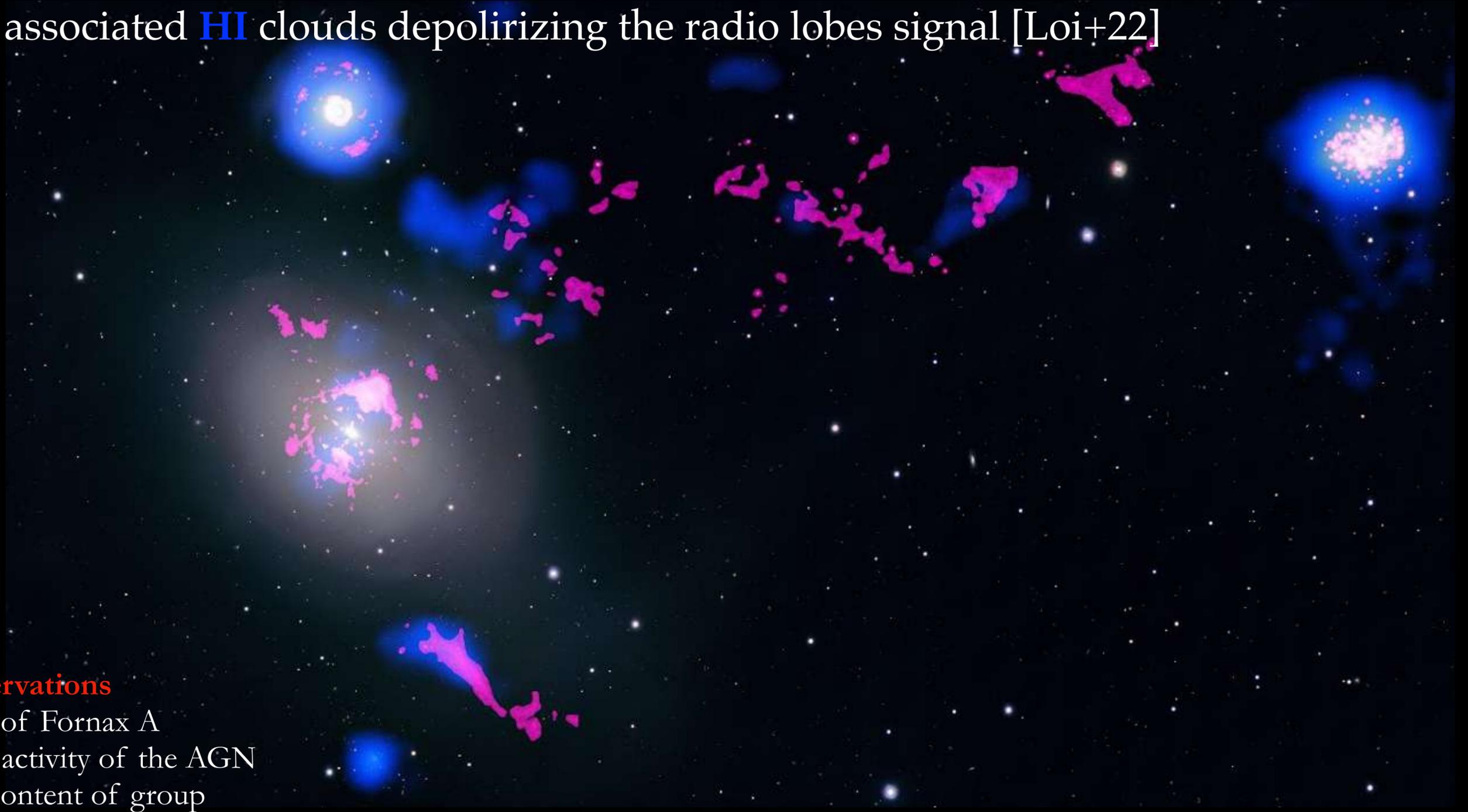
Maccagni et al. 2021 : feeding & feedback in Fornax A

Loi et al. 2022 : HI and H α depolarizing continuum from lobes

Fornax A & HI & H α

-100 kpc extended **H α** filaments embedded in the radio lobes [Kleiner+21]

- some filaments have associated **HI** clouds depolarizing the radio lobes signal [Loi+22]



MeerKAT commissioning observations

Serra et al. 2019 : merger history of Fornax A

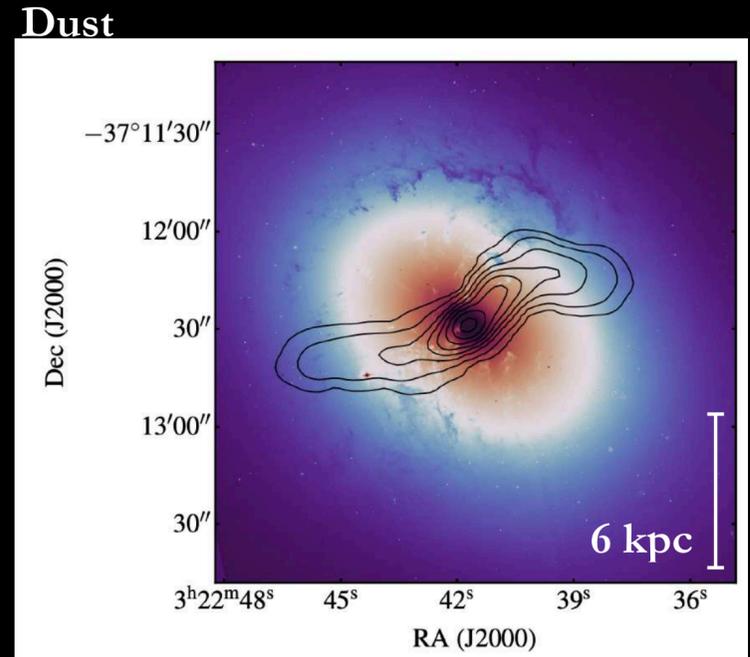
Maccagni et al. 2020 : flickering activity of the AGN

Kleiner et al. 2021 : HI and H α content of group

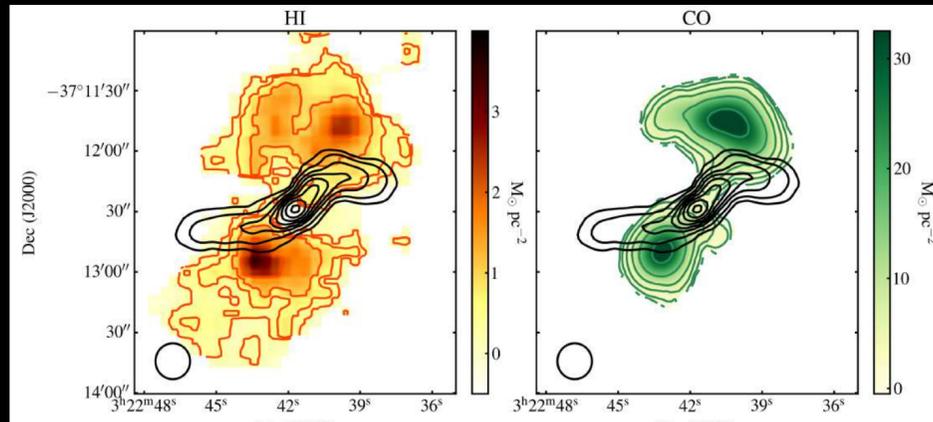
Maccagni et al. 2021 : feeding & feedback in Fornax A

Loi et al. 2022 : HI and H α depolarizing continuum from lobes

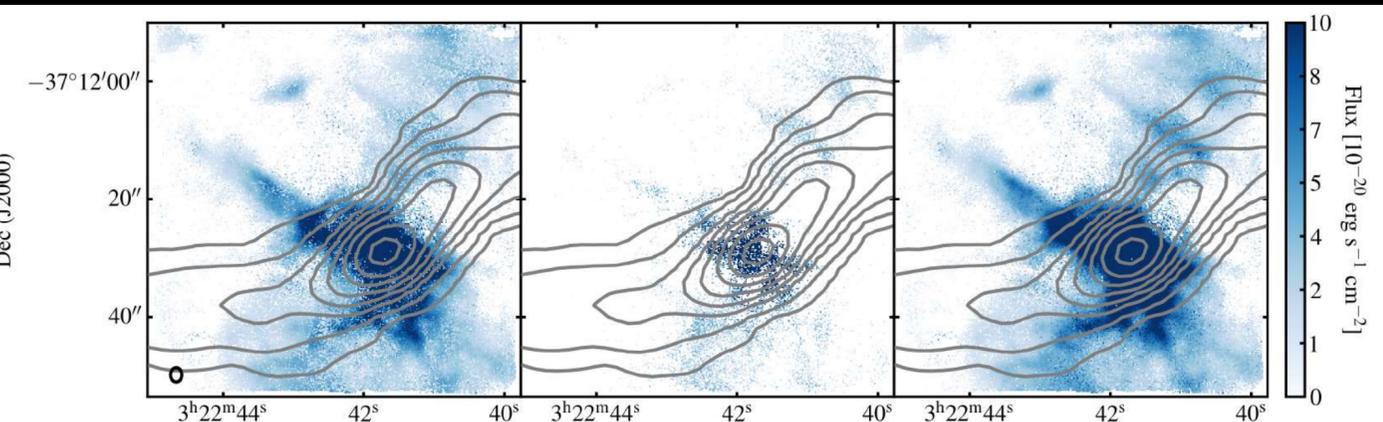
Cold gas distribution and kinematics in the centre



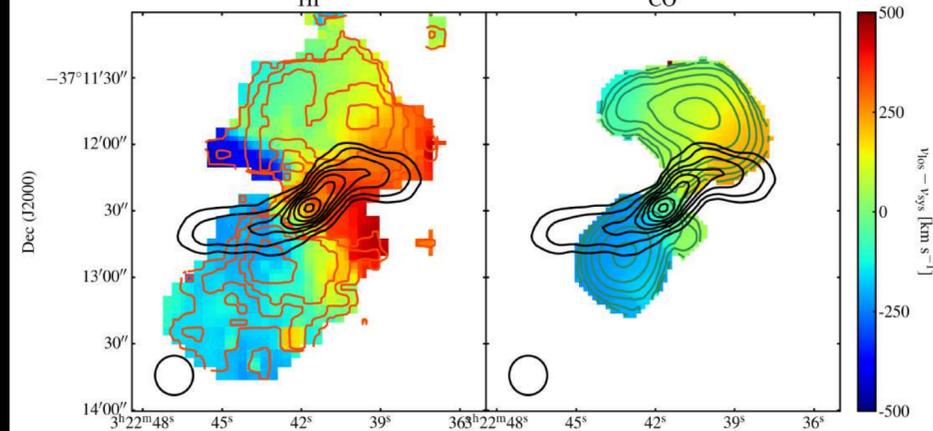
HI, CO (1-0) — 18 kpc fov



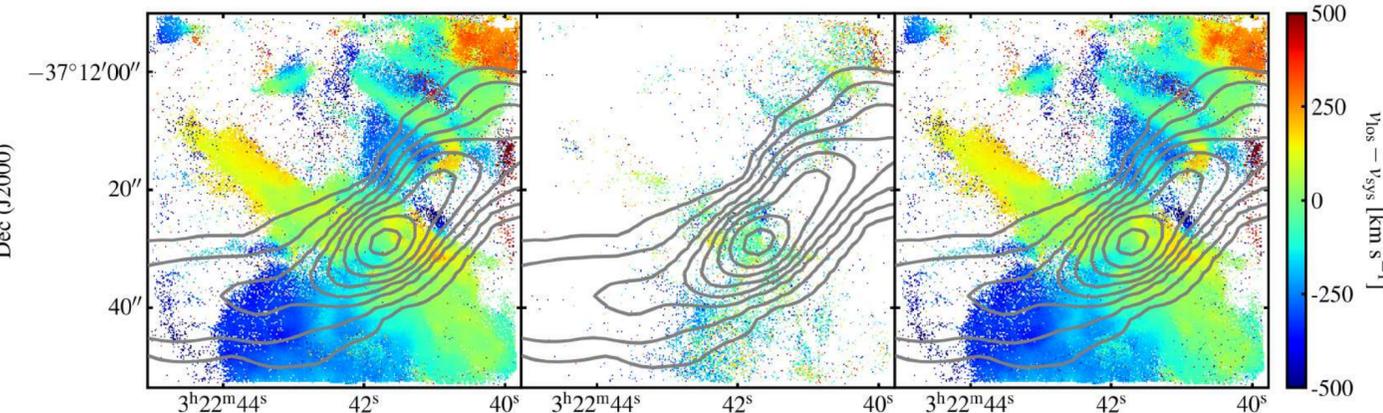
Ionised gas (MUSE) — 6 kpc fov



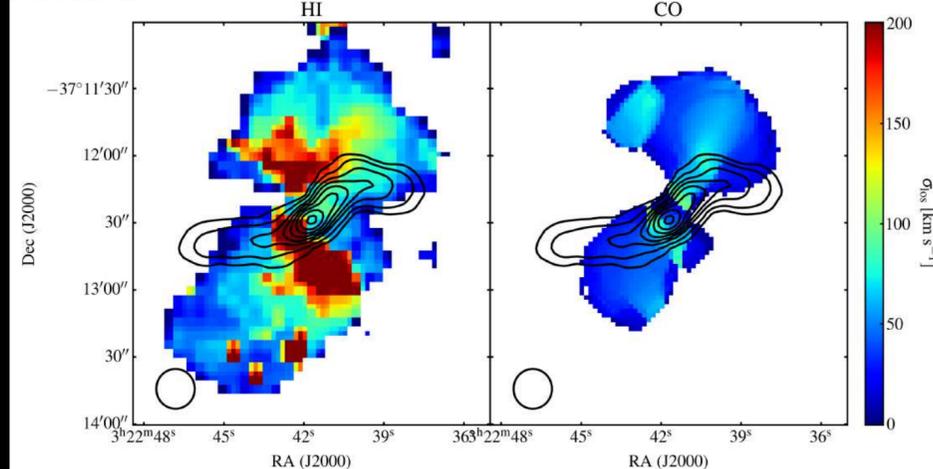
Mom 1



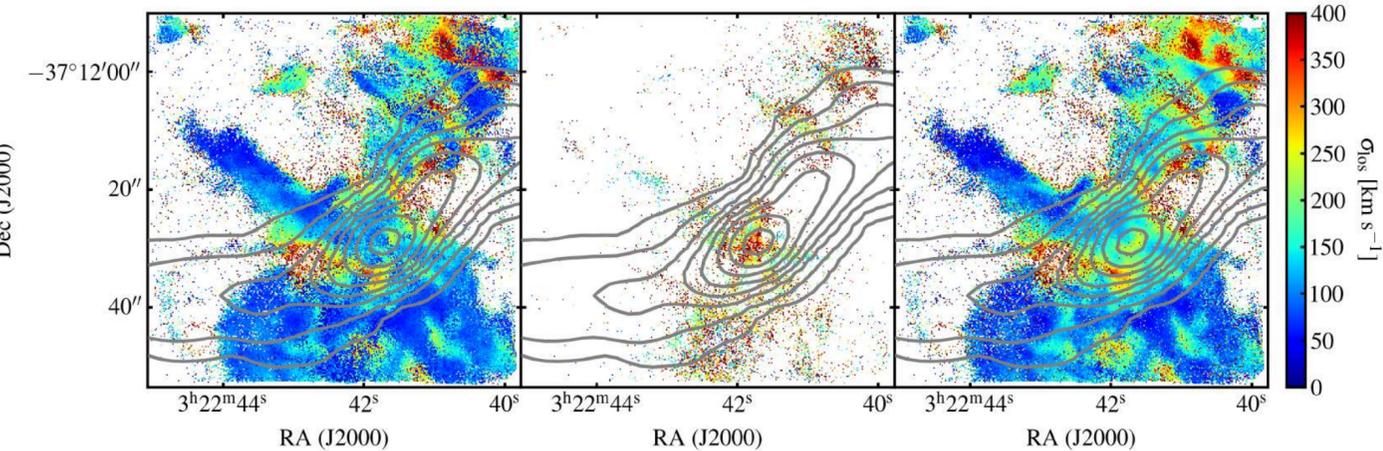
Mom 1



Mom 2



Mom 2

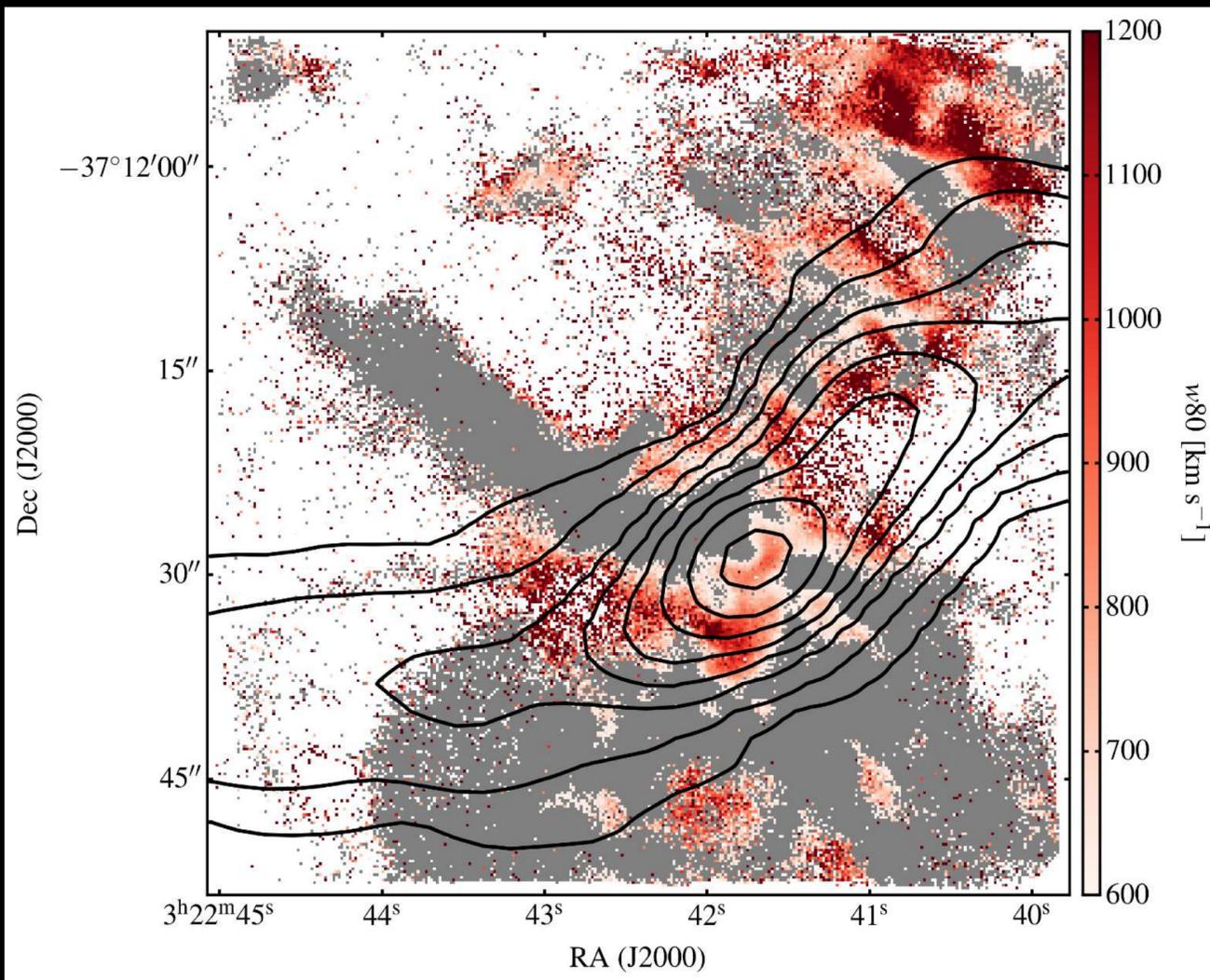


Rotation axis of the gas (NW-SE) perpendicular to the stellar body

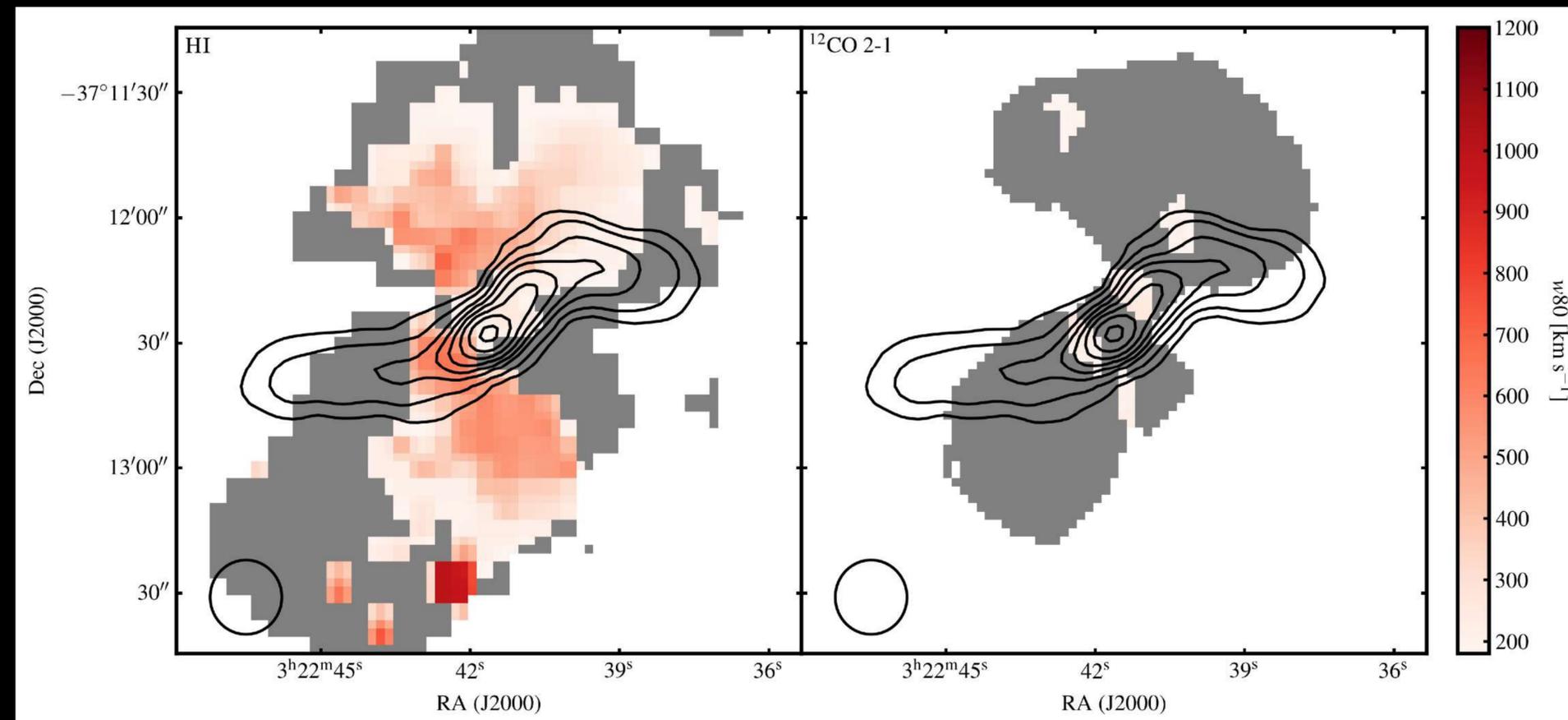
Several deviations from rotation

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

Multi-phase outflow in Fornax A



- 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

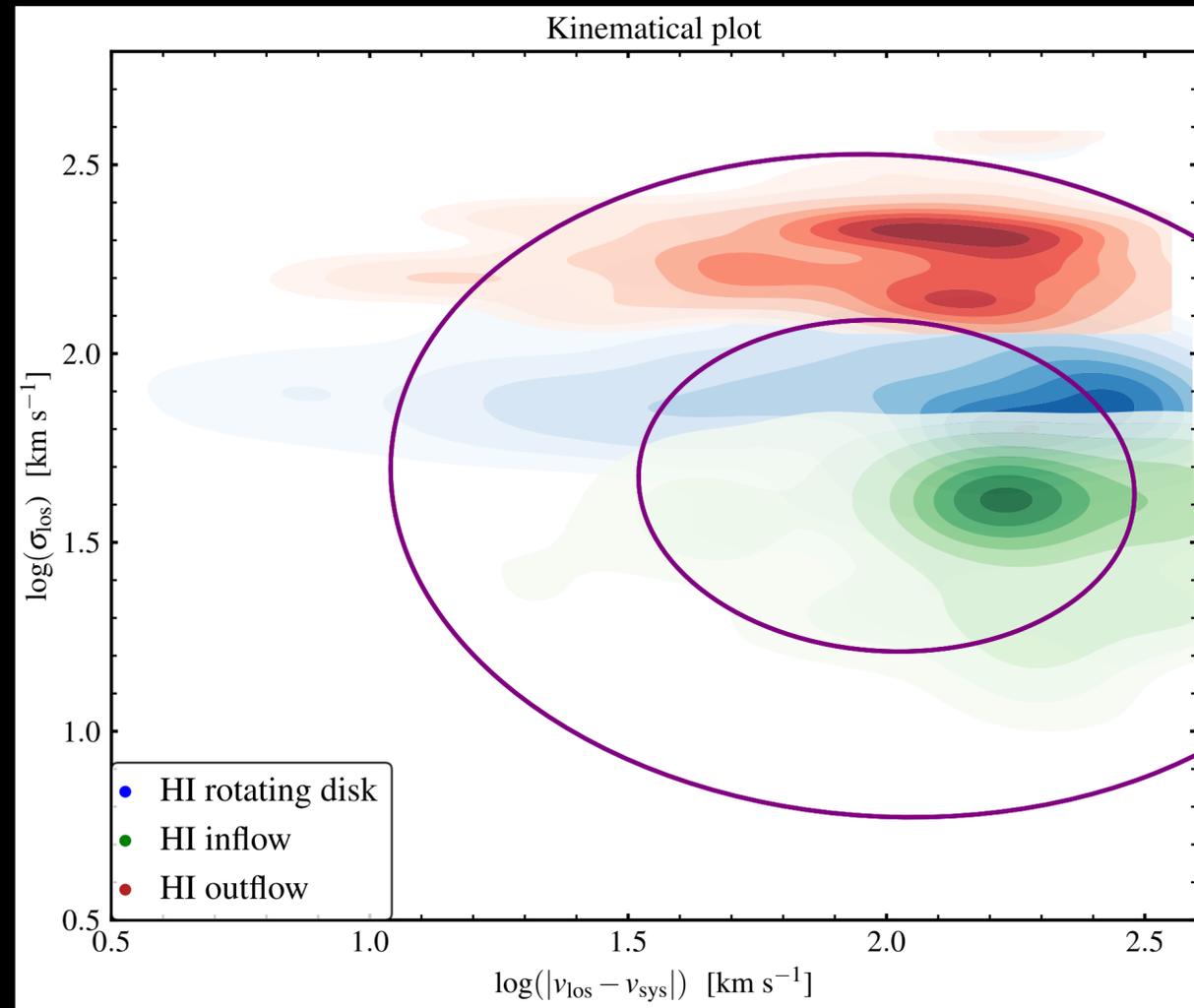


At its outflow velocity (2000 km s^{-1})
the outer ring would have reached its
distance from the centre in $\sim 3 \text{ Myr}$

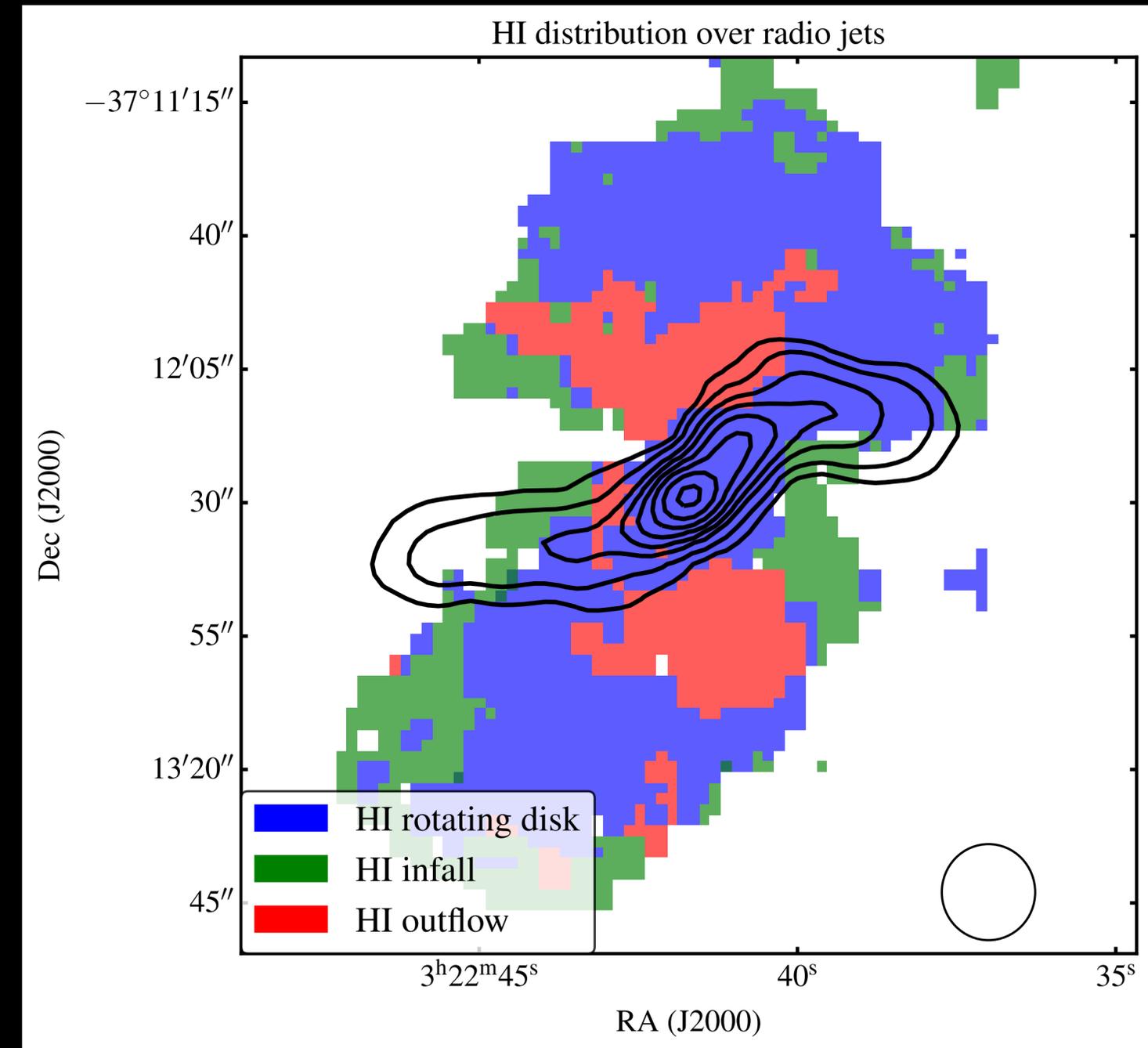
==

Age of the radio jets

Regions with similar kinematics



Kinematical plot — naturally identifies loci with similar kinematics

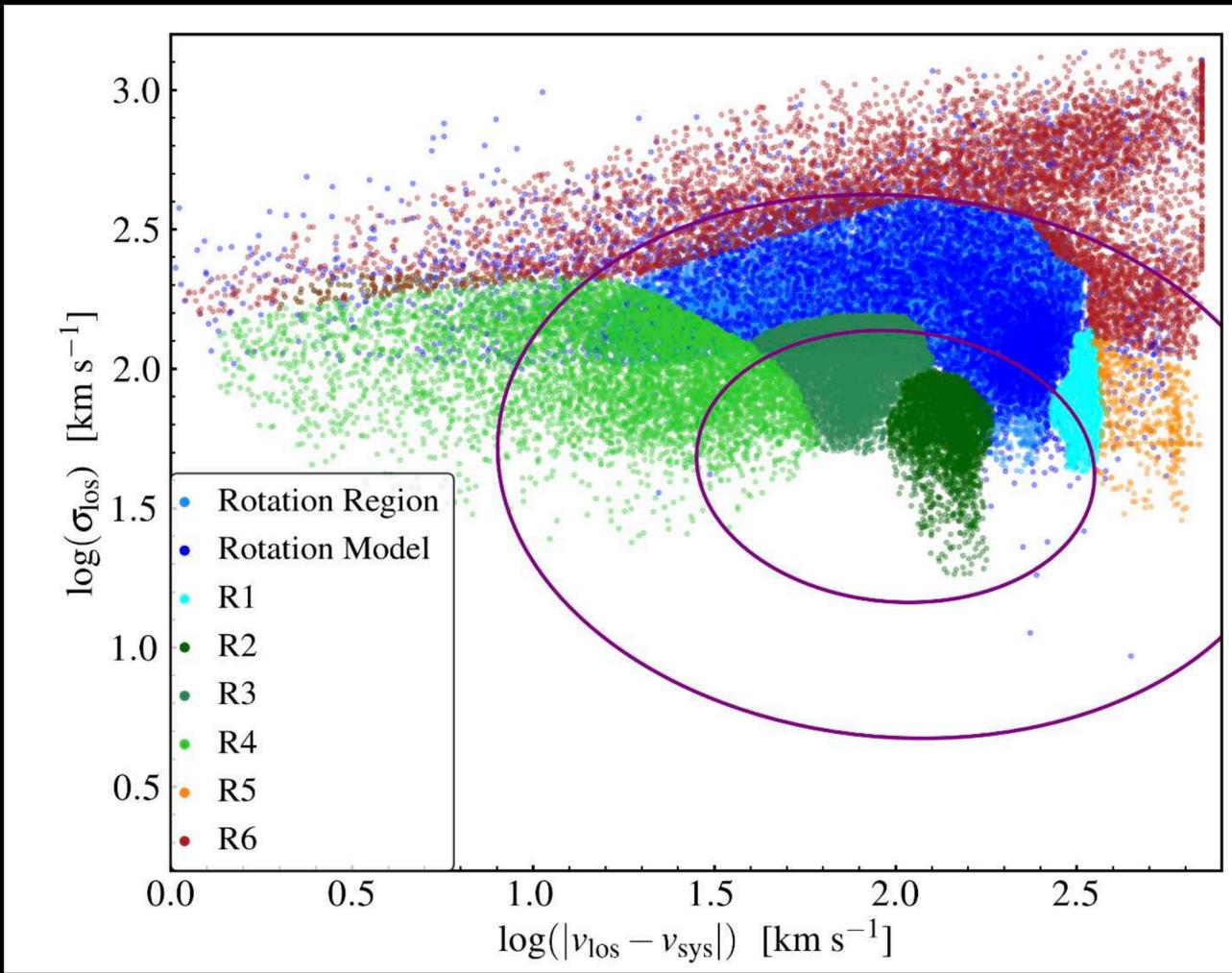


broad line-widths (R6) -> outflow in the wake of the radio jet

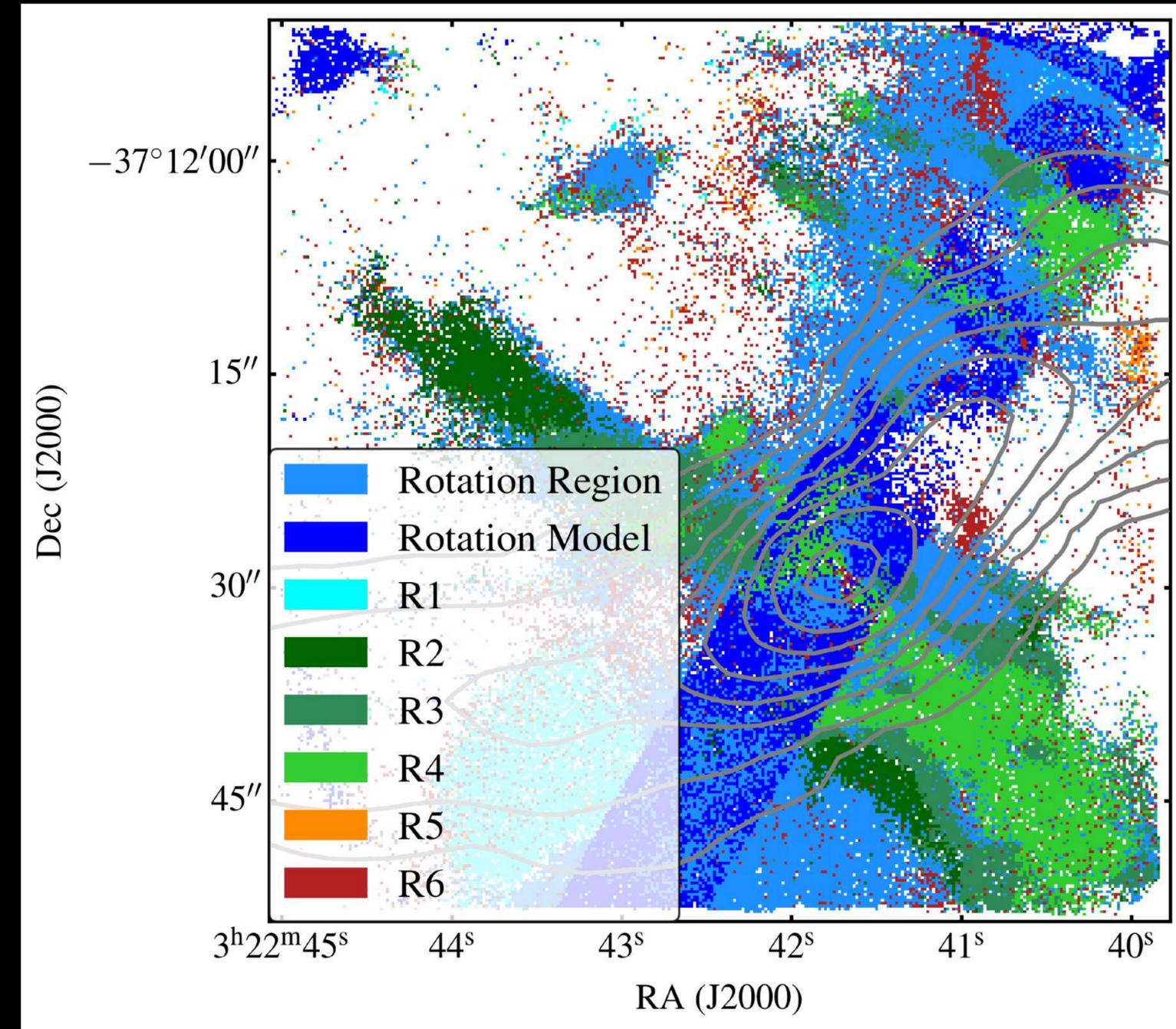
narrow line-widths -> EW stripe and filament and stripes

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

Ionised gas shows same kinematical structure



Kinematical plot — naturally identifies loci with similar kinematics

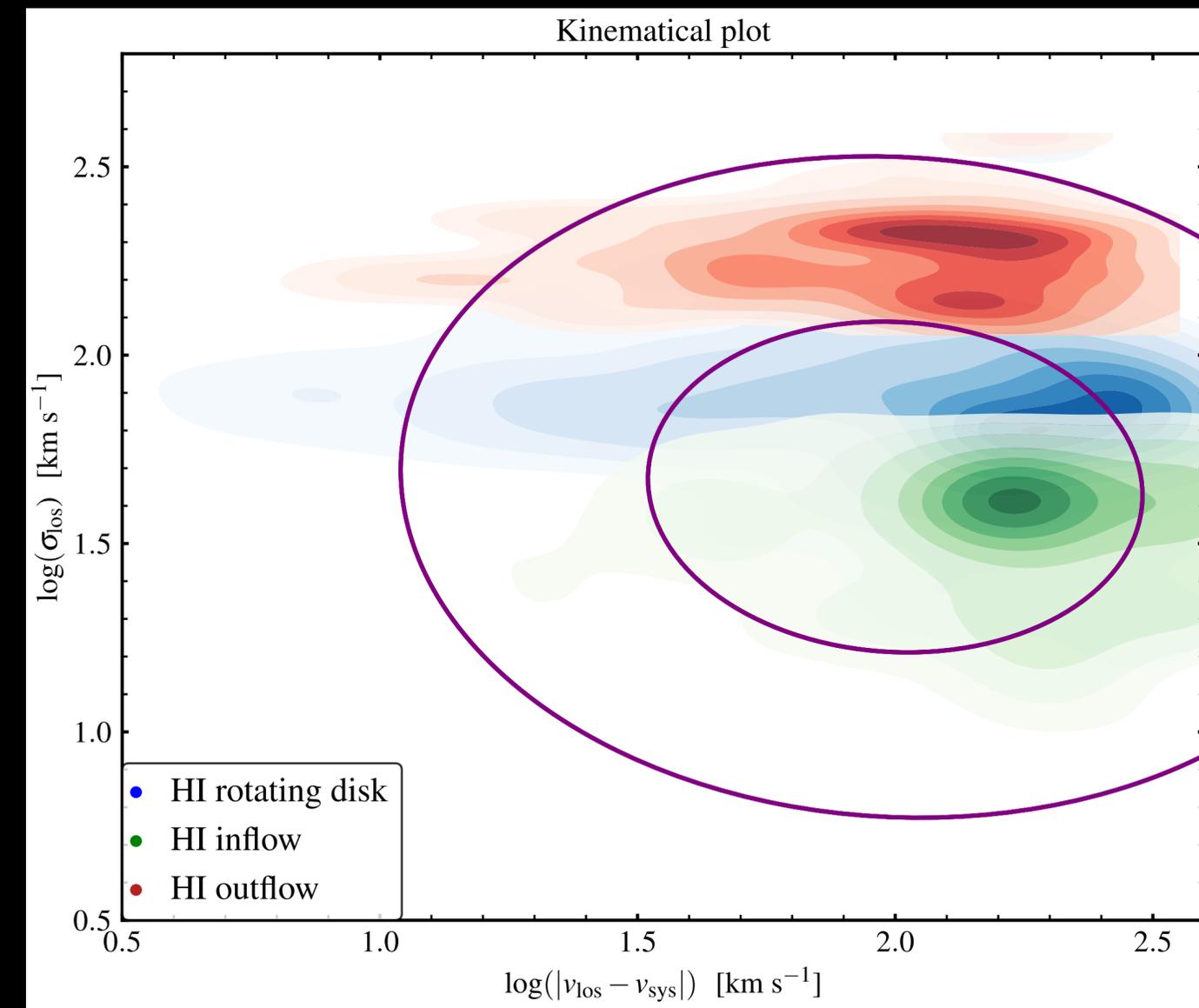


broad line-widths (R6) -> outflow in the wake of the radio jet

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

K-plot of HI and CO show the same properties

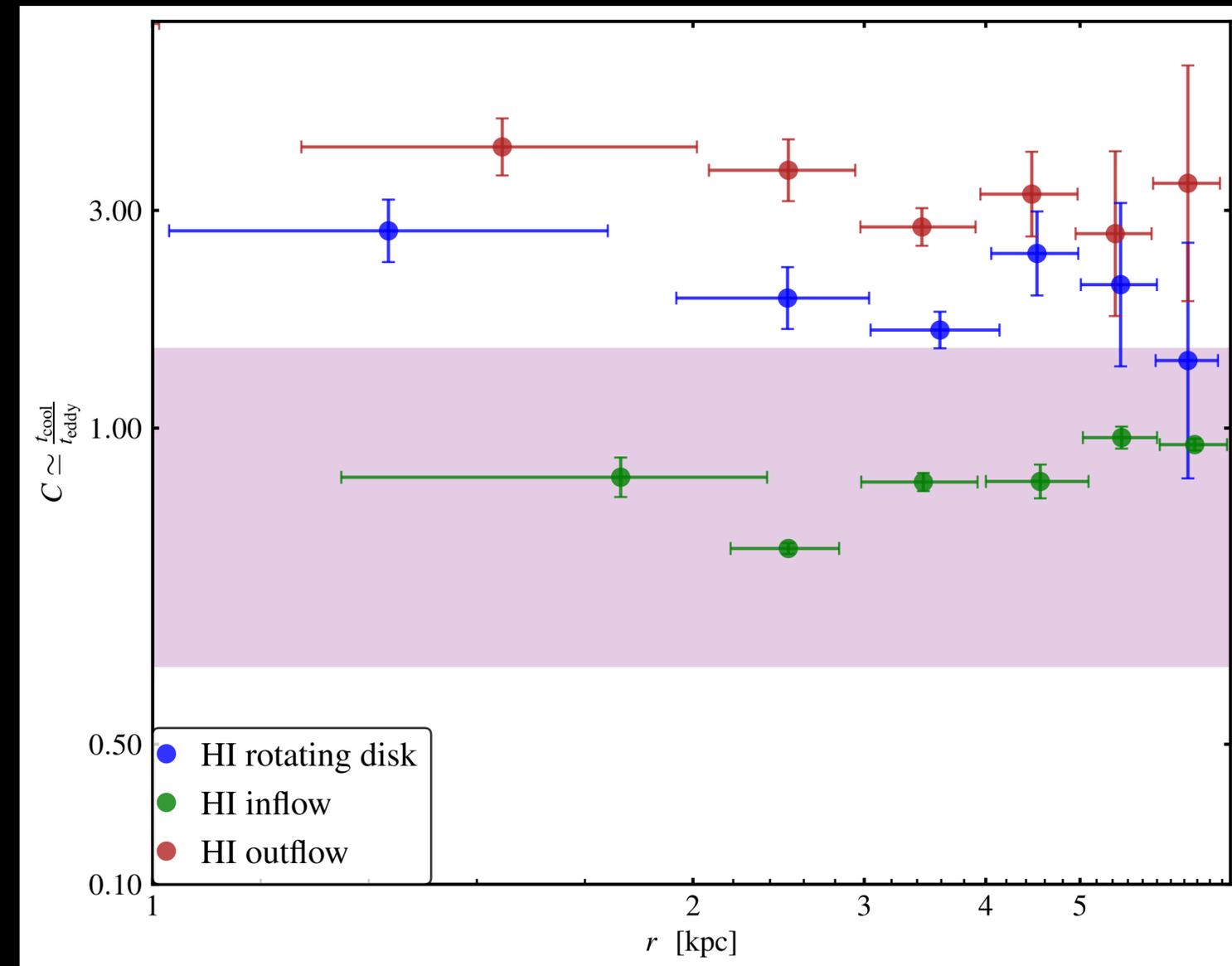
AGN feeding in Fornax A



- Purple ellipsis

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

The EW stripe and filaments may be feeding the AGN



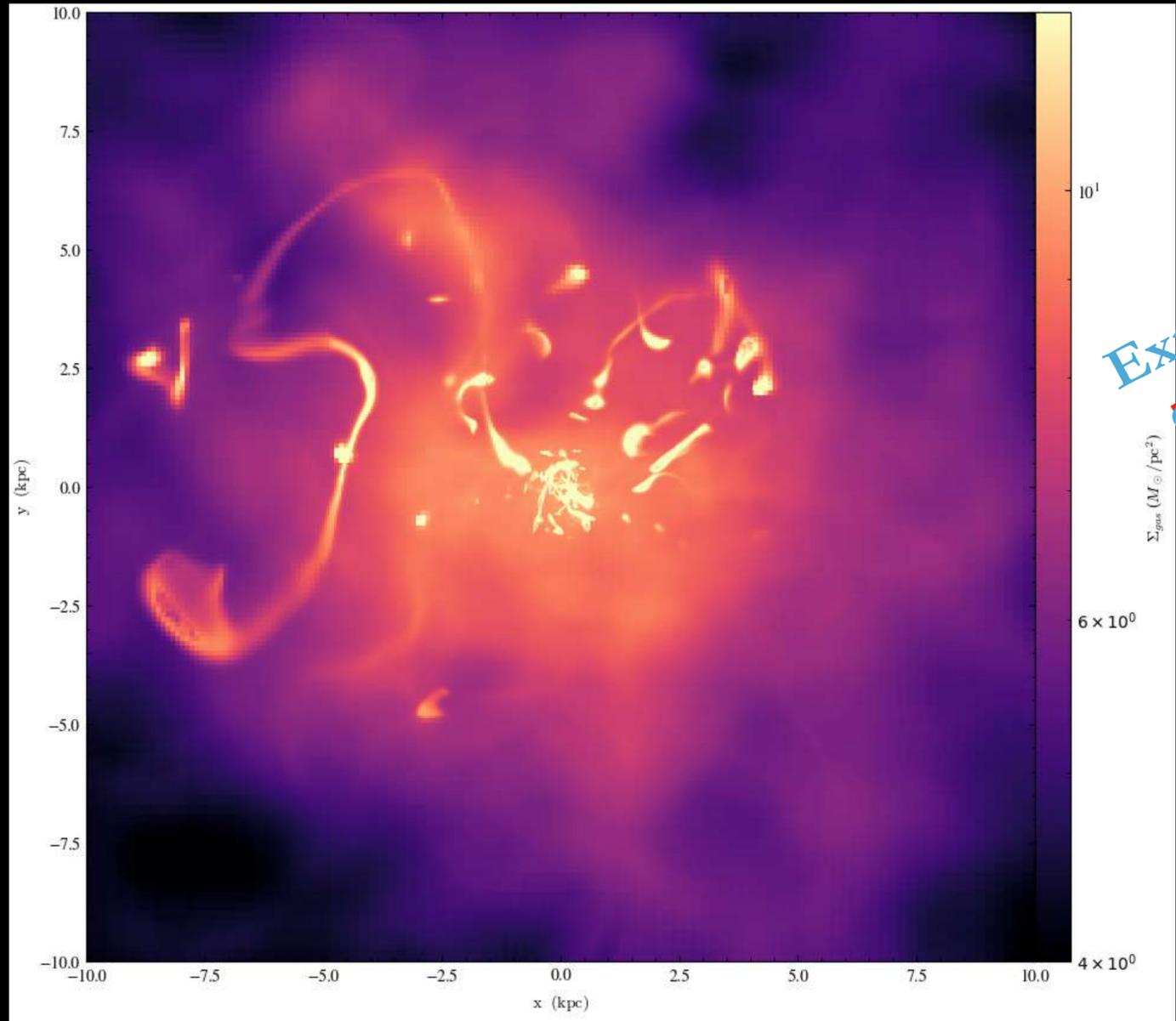
C-Ratio — cooling time / eddy turnover time
measures the role of turbulence causing condensation of the gas

EW filaments: turbulence may cause cooling and infall

Outflow: very different physical conditions

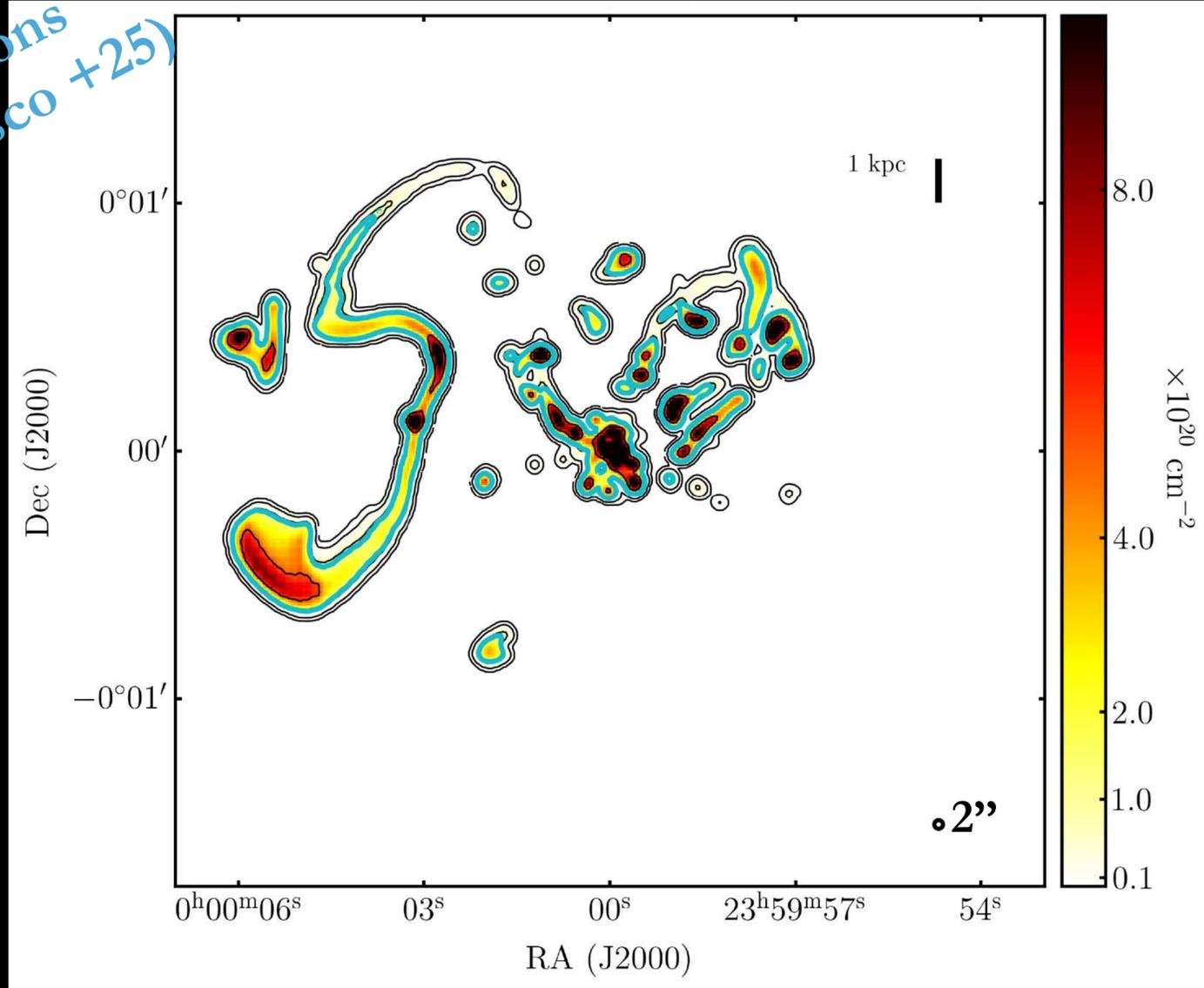
Chaotic Cold Accretion

Chaotic Cold Accretion: turbulence in the hot medium causes condensation into cold gas and consequent rapid & recursive accretion onto the SMBH (see Gaspari + 13,17,18 / King & Nixon 15)



Extracting HI with caveats
on neutral hydrogen and
atomic fractions
(see also Marasco +25)

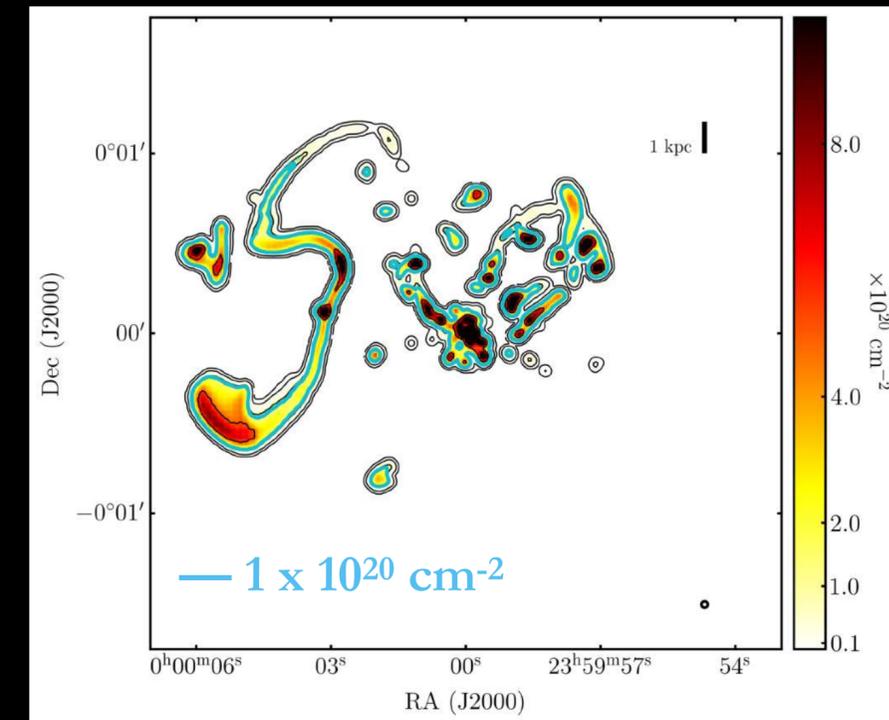
HI : 100-10⁴ K
6.6 x 10⁷ M_⊙



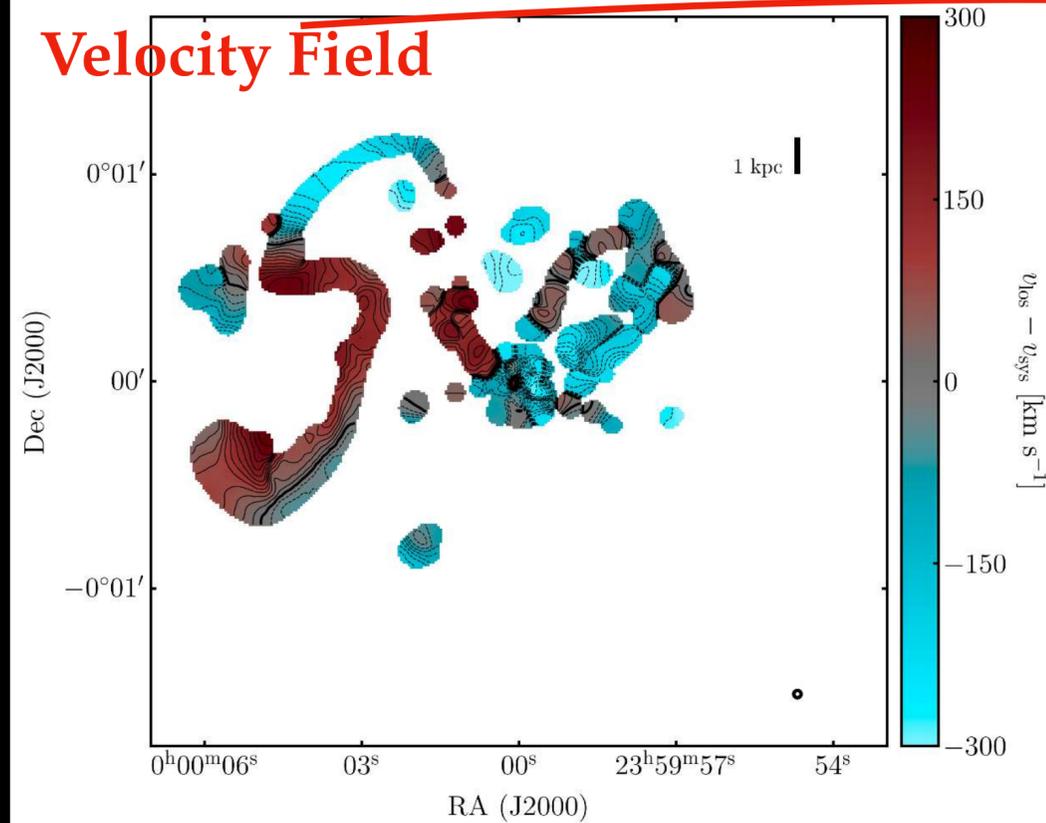
snapshot of multi-phase CCA rain within
8 kpc from the SMBH [Gaspari+17]

HI in Chaotic Cold Accretion

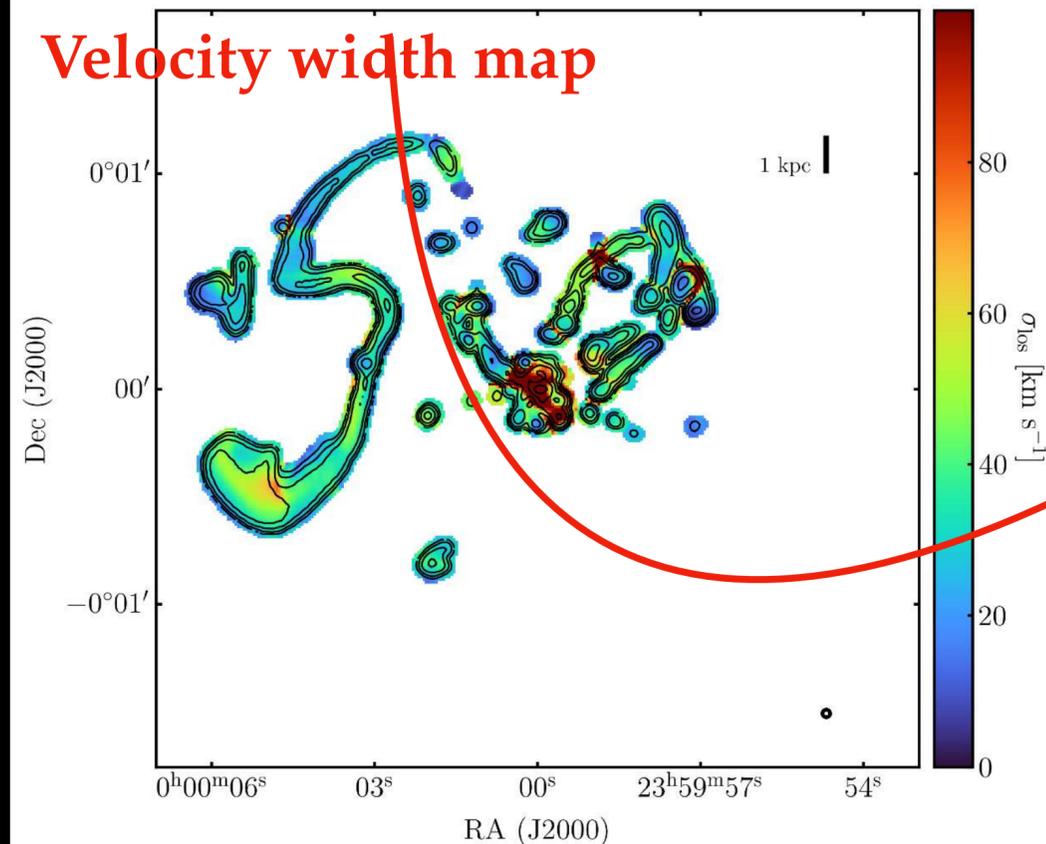
HI column density map



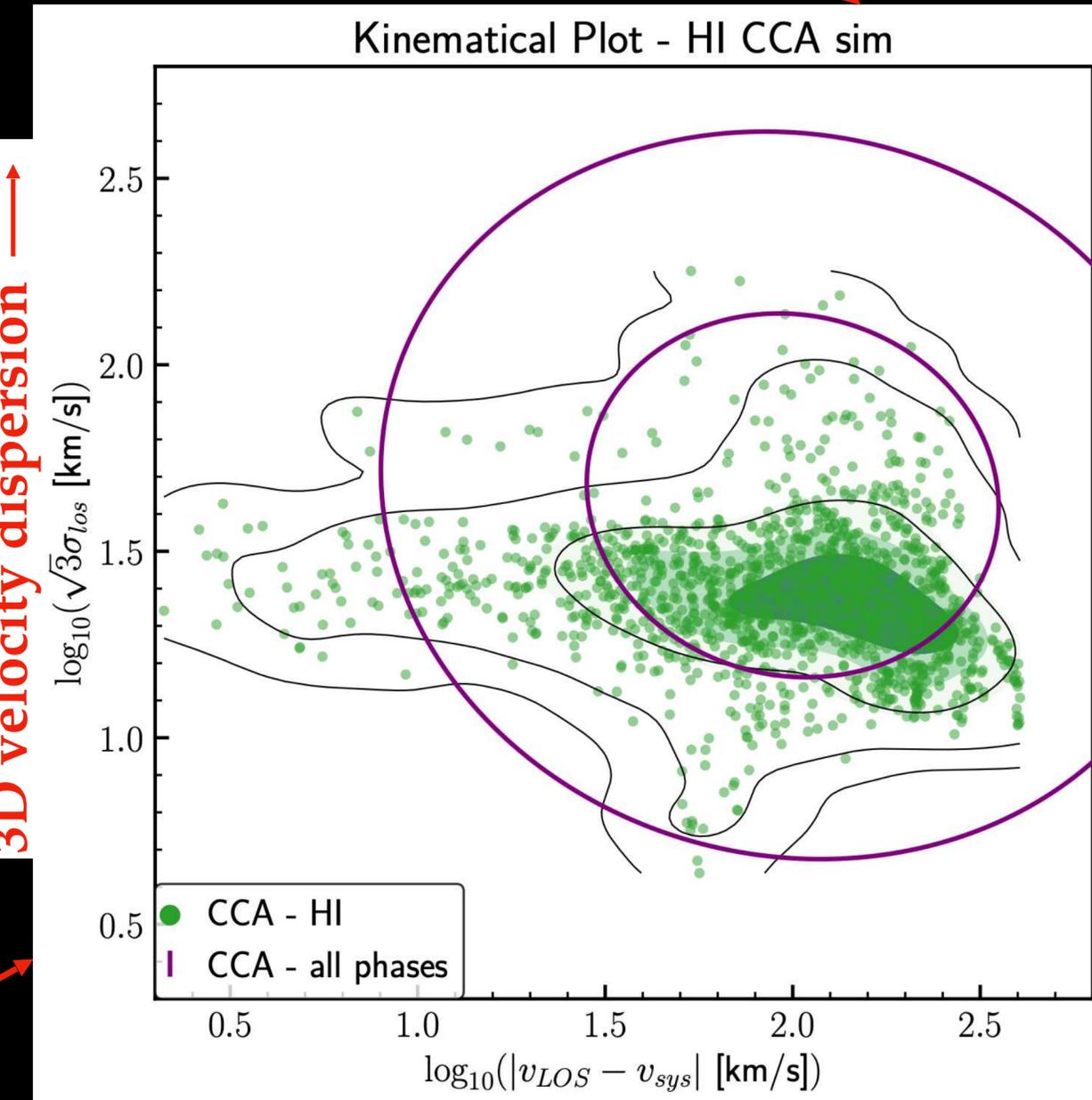
Velocity Field



Velocity width map



Kinematical Plot



Kinematical plot

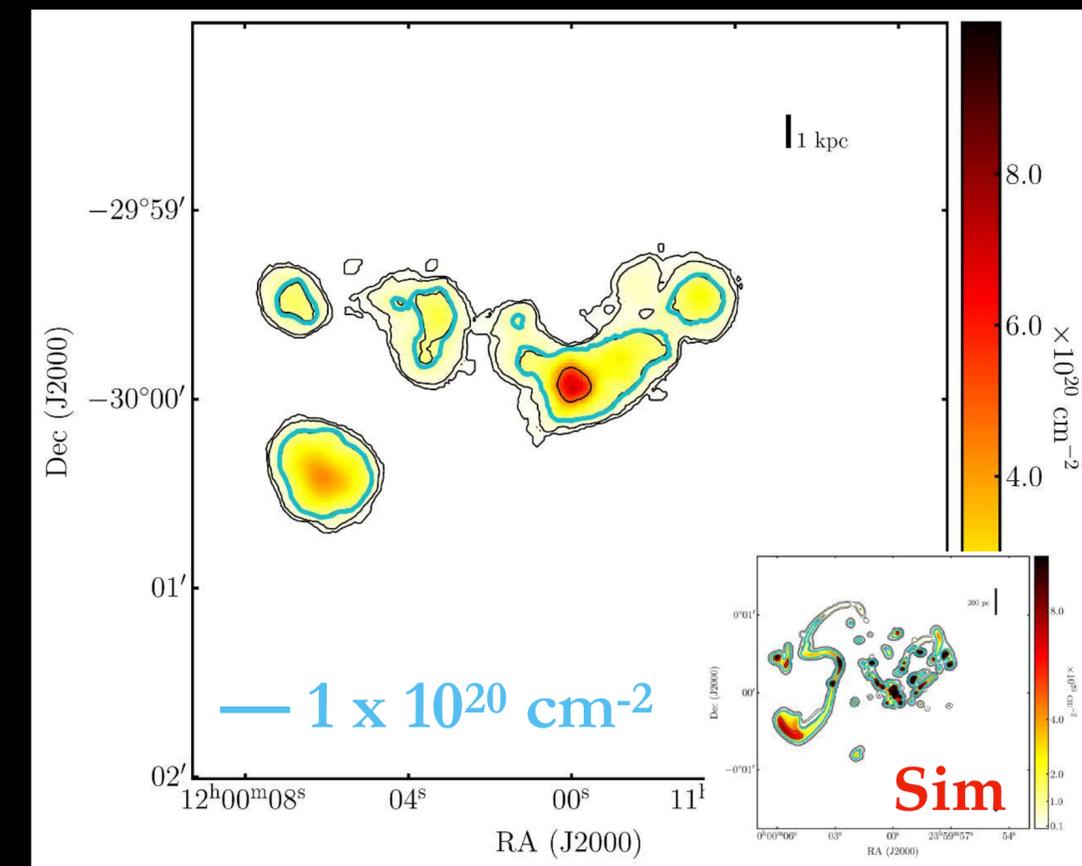
naturally identifies loci with similar kinematics

3D velocity dispersion \uparrow

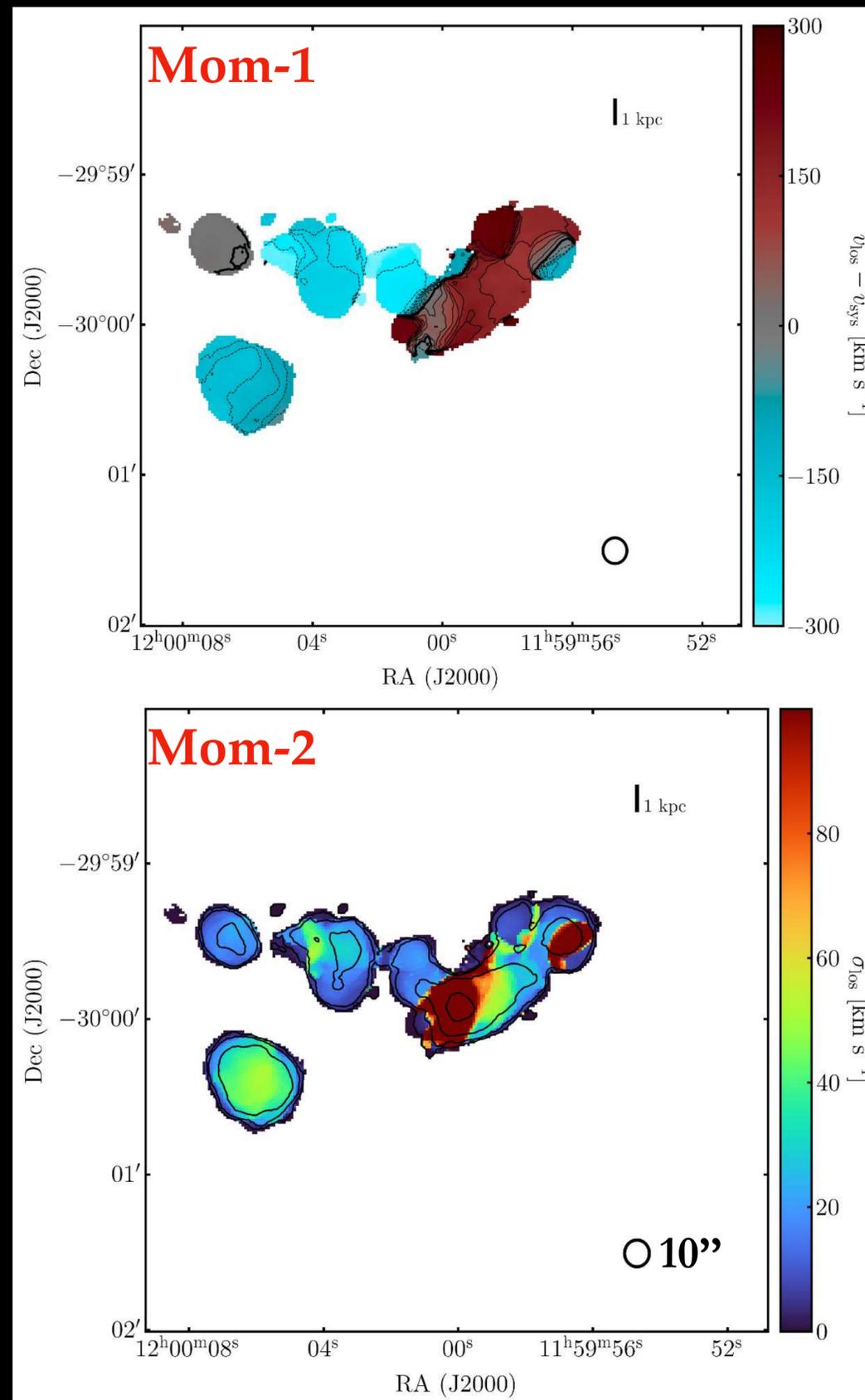
velocity shift w.r.t systemic \rightarrow

SKA-MID - CCA in Fornax A observed in 6 hrs

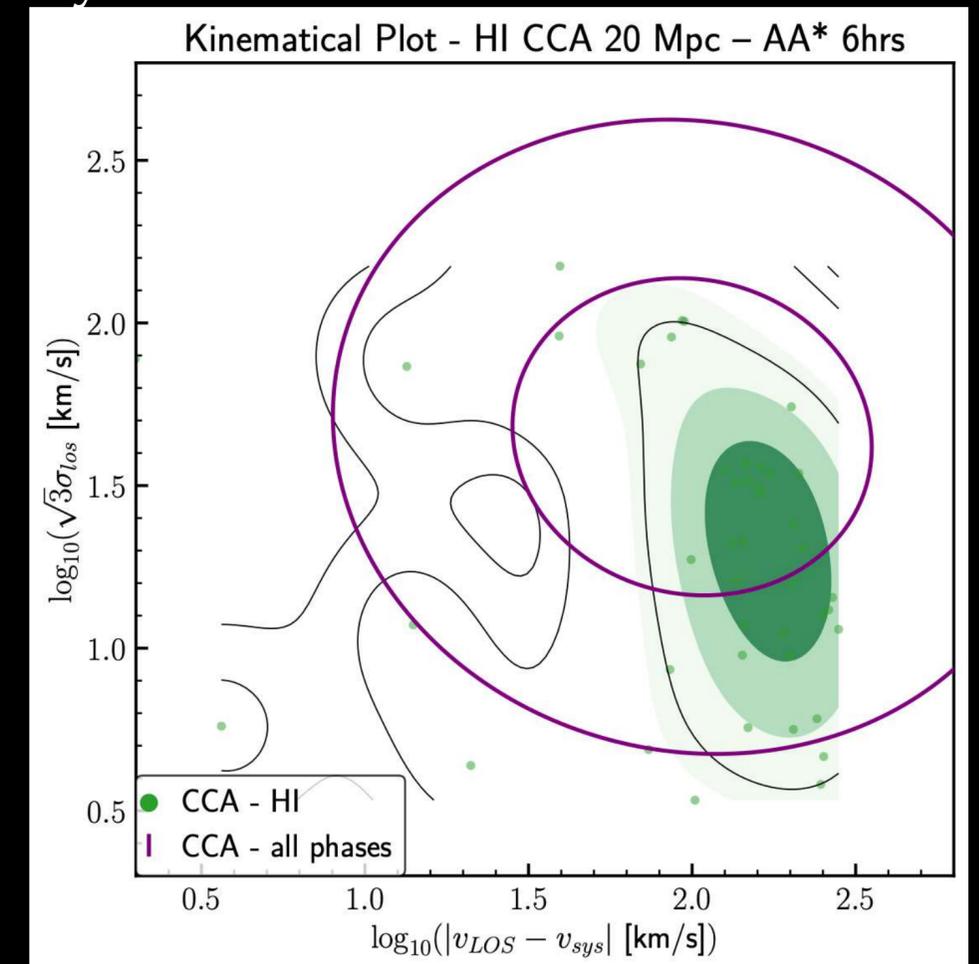
Synthetic SKA-MID AA*
observation of neutral hydrogen
 from CCA simulation
 $M_{\text{HI}} = 6.6 \times 10^7 M_{\odot}$ (as in Fornax A)
 $D = 3.4 \text{ Mpc}$



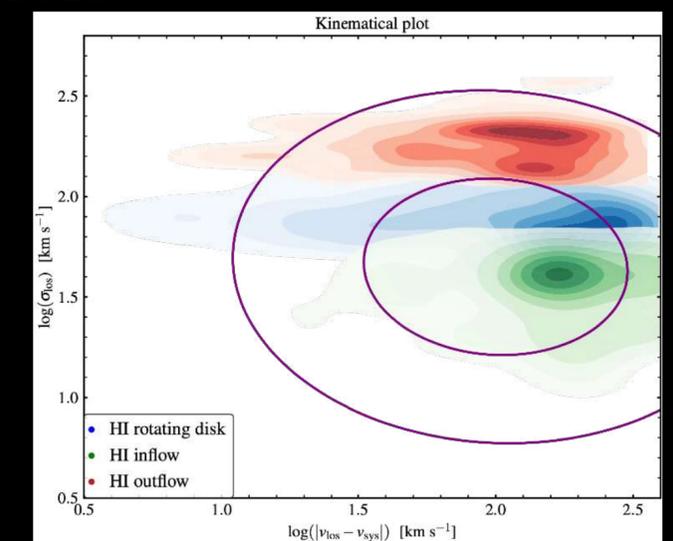
**Deconvolution, HI cleaning and
 source finding with same
 pipeline of MFS**



Synthetic Observation

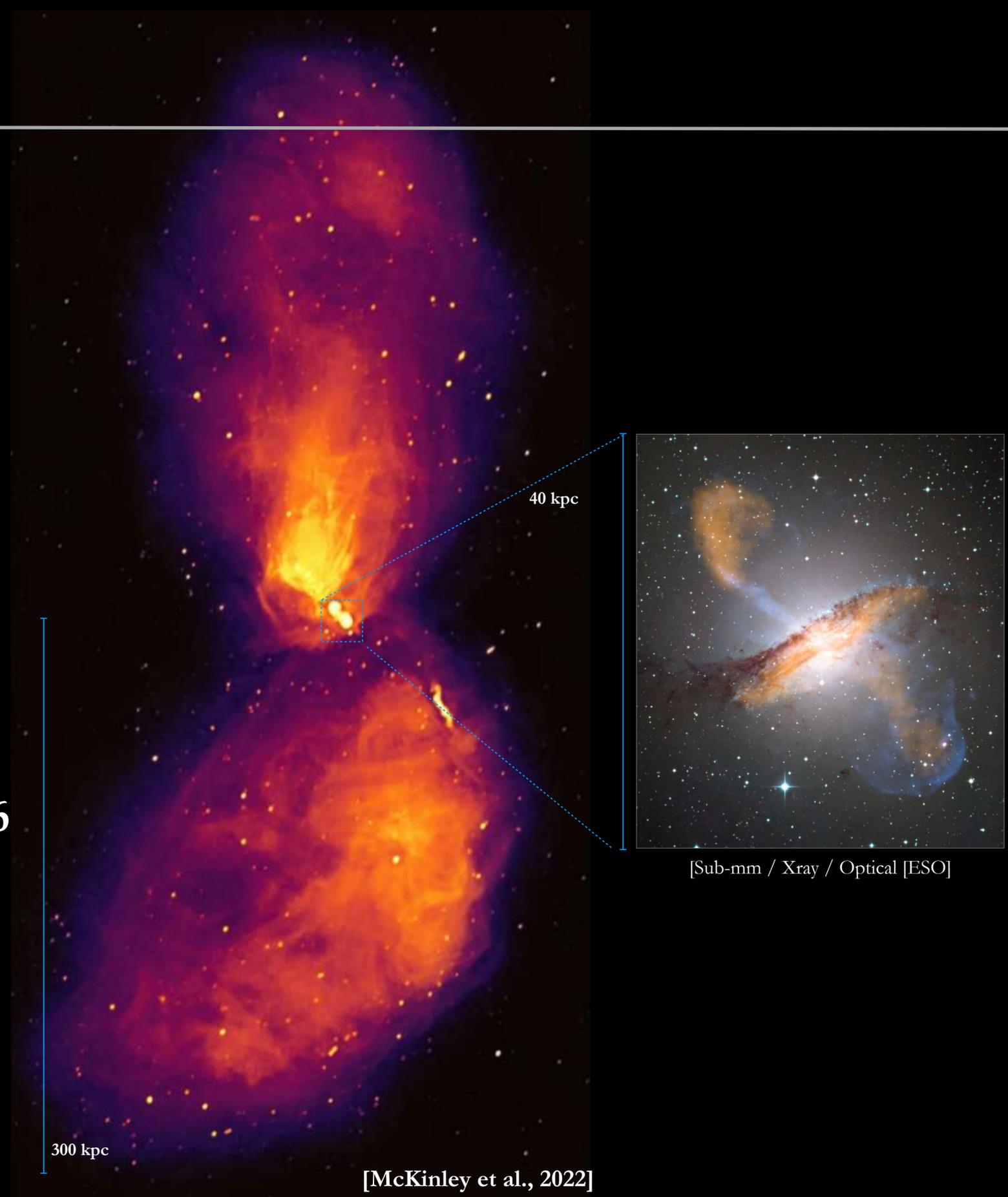


Observation



Centaurus A

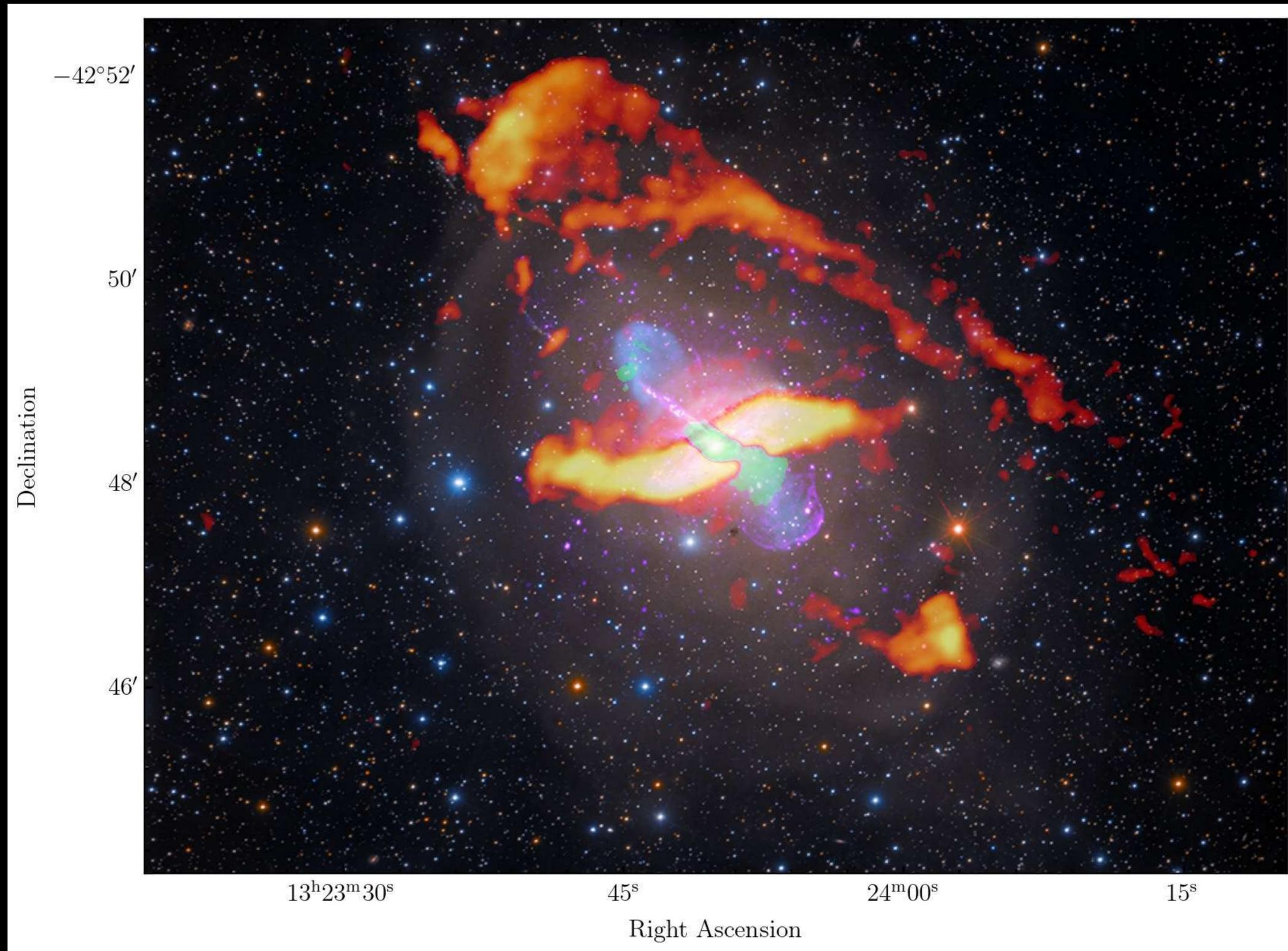
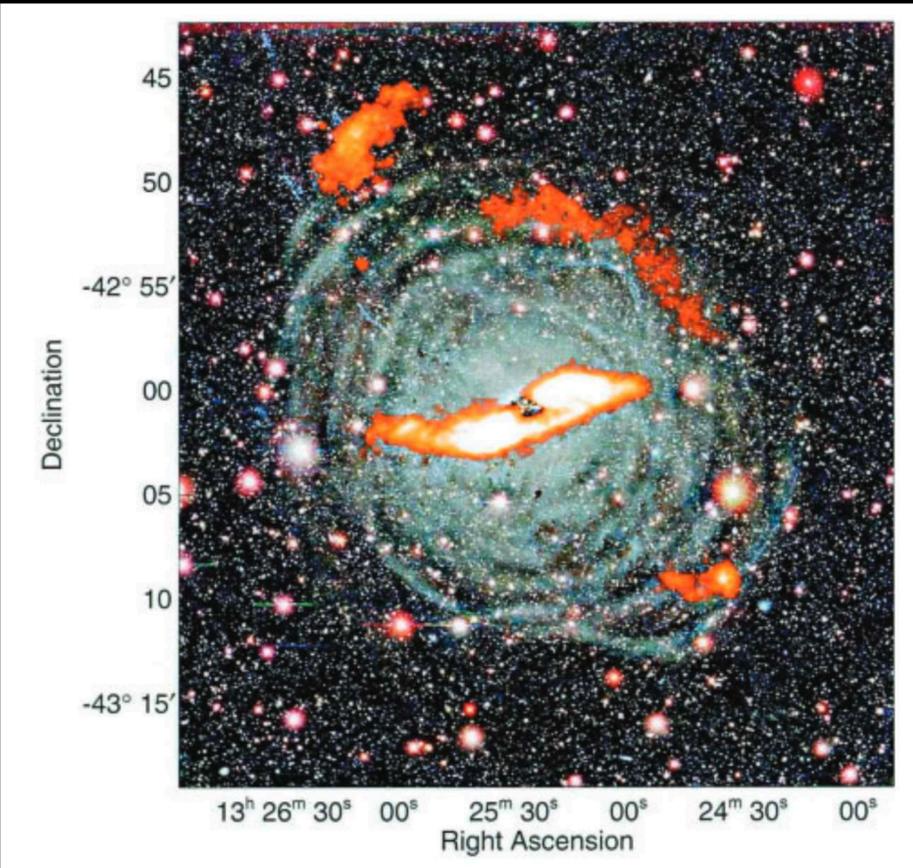
- AGN structures within the stellar body (< 25 kpc)
 - Jets & filament
 - Lobes
 - Bubbles
 - Circumnuclear dusty disk ($r \sim 6$ kpc)
- Regions of AGN-triggered star formation
 - Outer Filament (20 kpc from centre): Santoro+2016
 - Inner Filament (7 kpc from centre): Crockett+2015



Feedback - HI clouds unsettled by AGN

ATCA [Morganti 2010]

MeerKAT [Maccagni, McKinley in prep.]



-Radio continuum

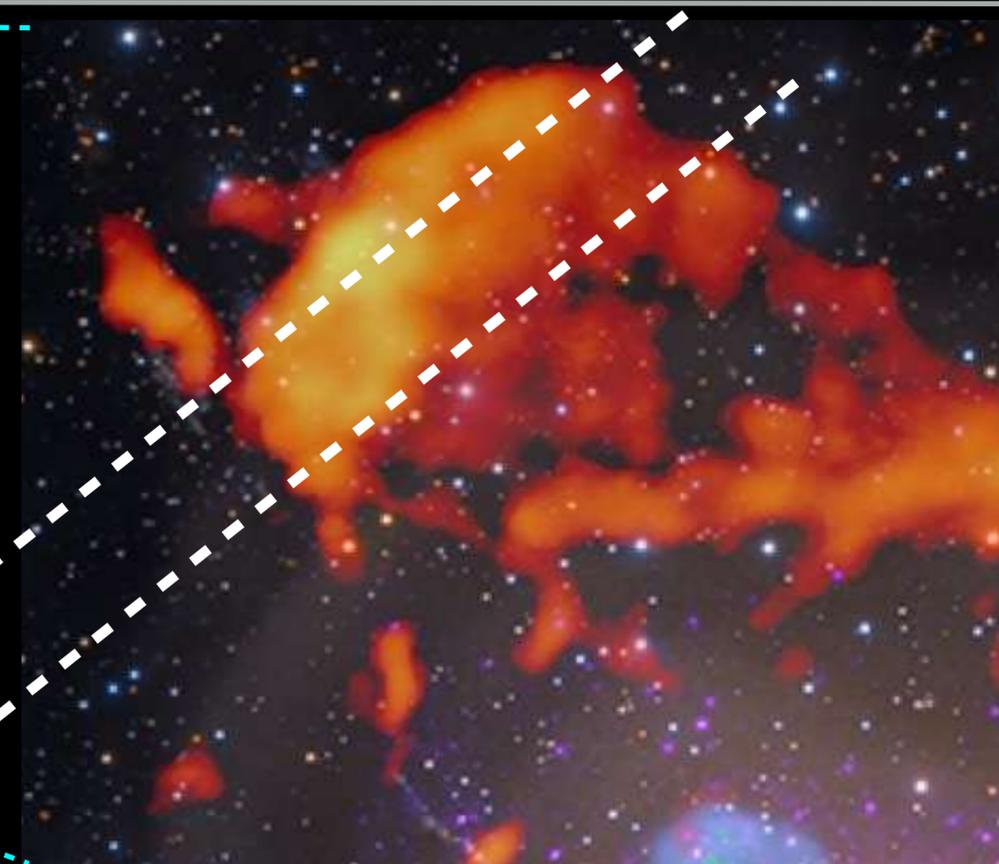
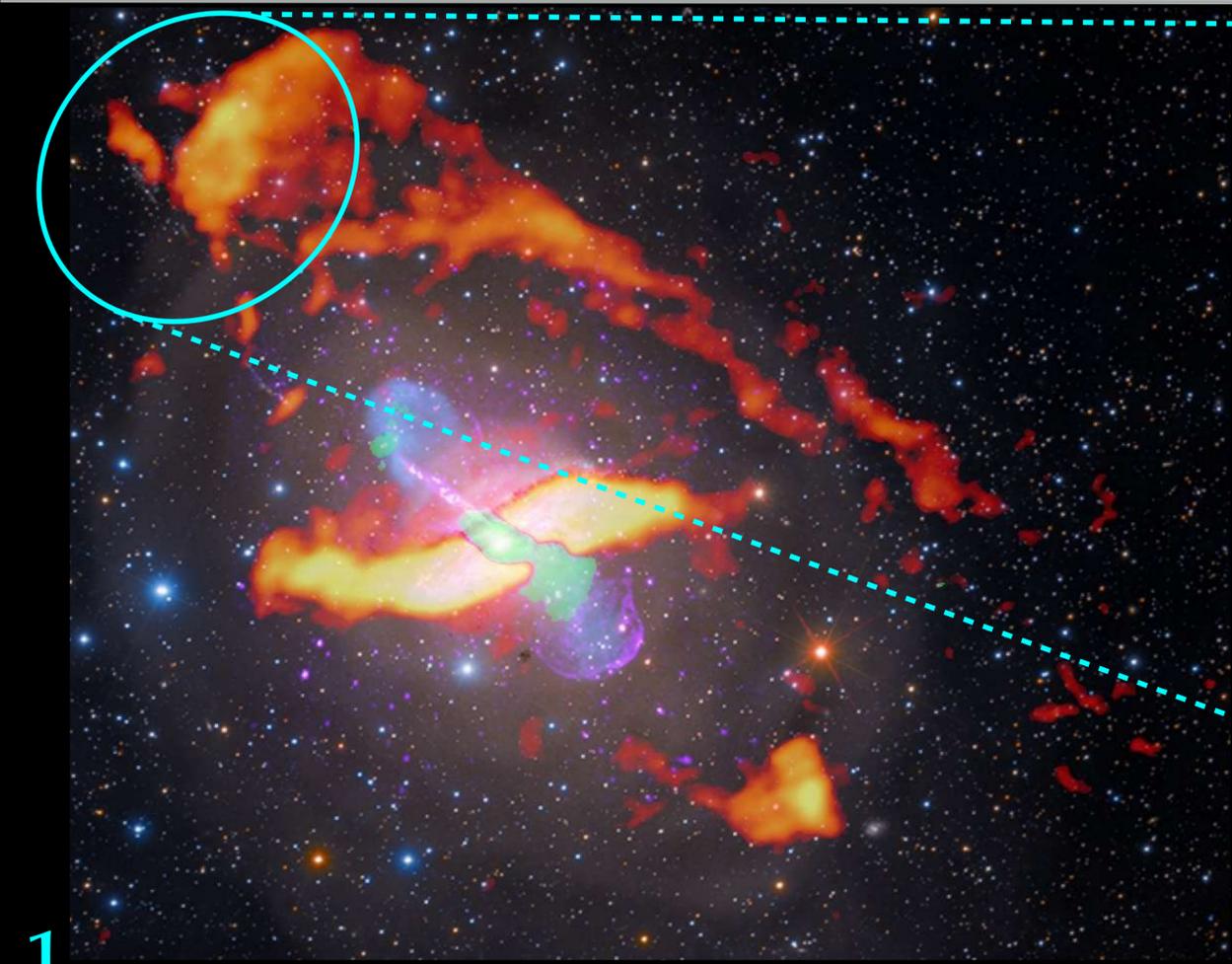
-HI emission

-HI absorption

HI clouds along the jets and filaments of ionised gas

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

Feedback - HI clouds unsettled by AGN

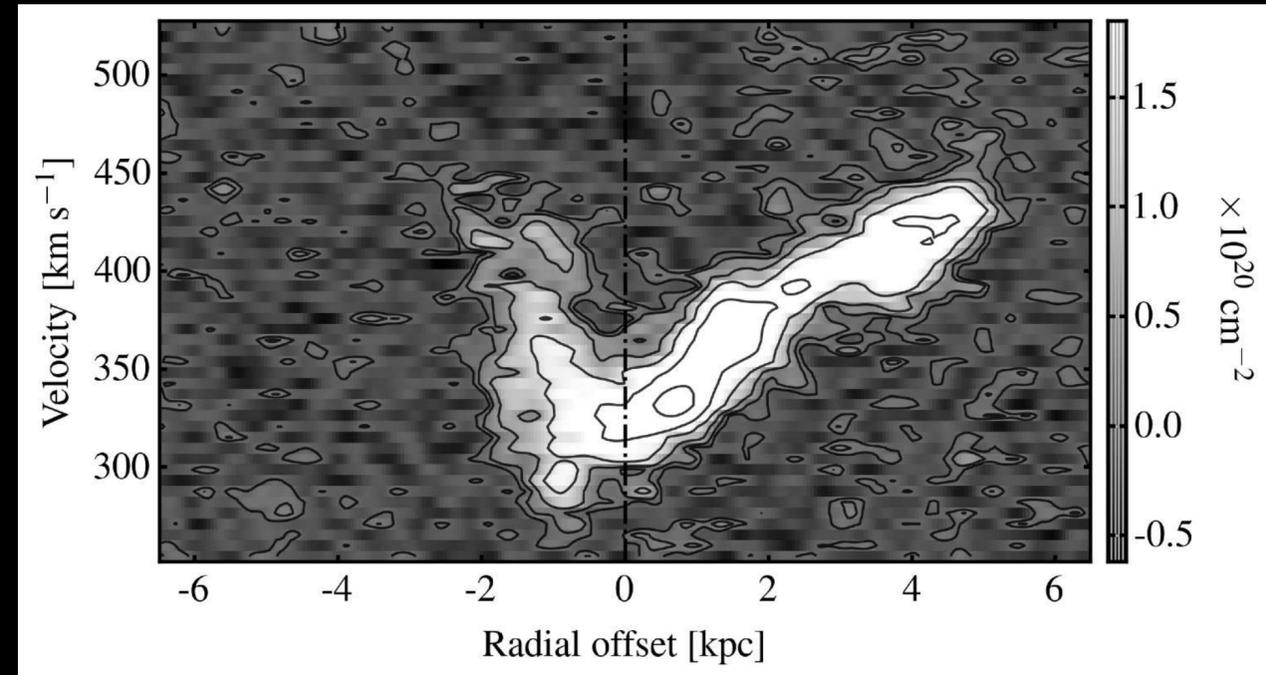
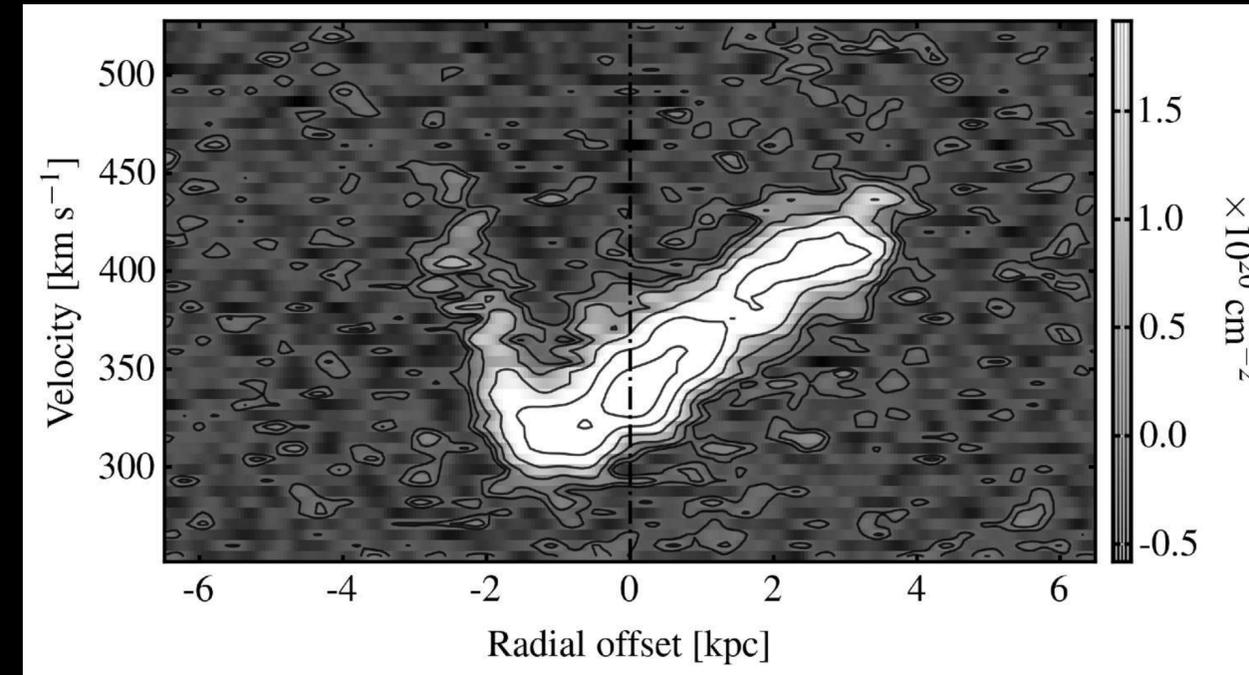


1st shown in
Oosterloo et al. 2005
(ATCA data)

AGN feedback is gently
unsettling the gas.

1

2



NGC
1371



Optical (DESI)

Little star formation in the center (feedback?)

Star forming ring

Optical (DESI)
+
UV (GALEX)

5 kpc

HI hole

Intra-arm
star forming
filaments

Optical (DESI)
+
UV (GALEX)
+
HI (MeerKAT)

Low-
column
density gas



Bipolar nuclear bubbles

$L_{1.4 \text{ GHz}} \sim 10^{20} \text{ W Hz}^{-1}$

AGN Jet?

$L_{1.4 \text{ GHz}} \sim 10^{21} \text{ W Hz}^{-1}$

AGN core?

$L_{1.4 \text{ GHz}} < 10^{20} \text{ W Hz}^{-1}$

Optical (DESI)

+

UV (GALEX)

+

HI (MeerKAT)

+

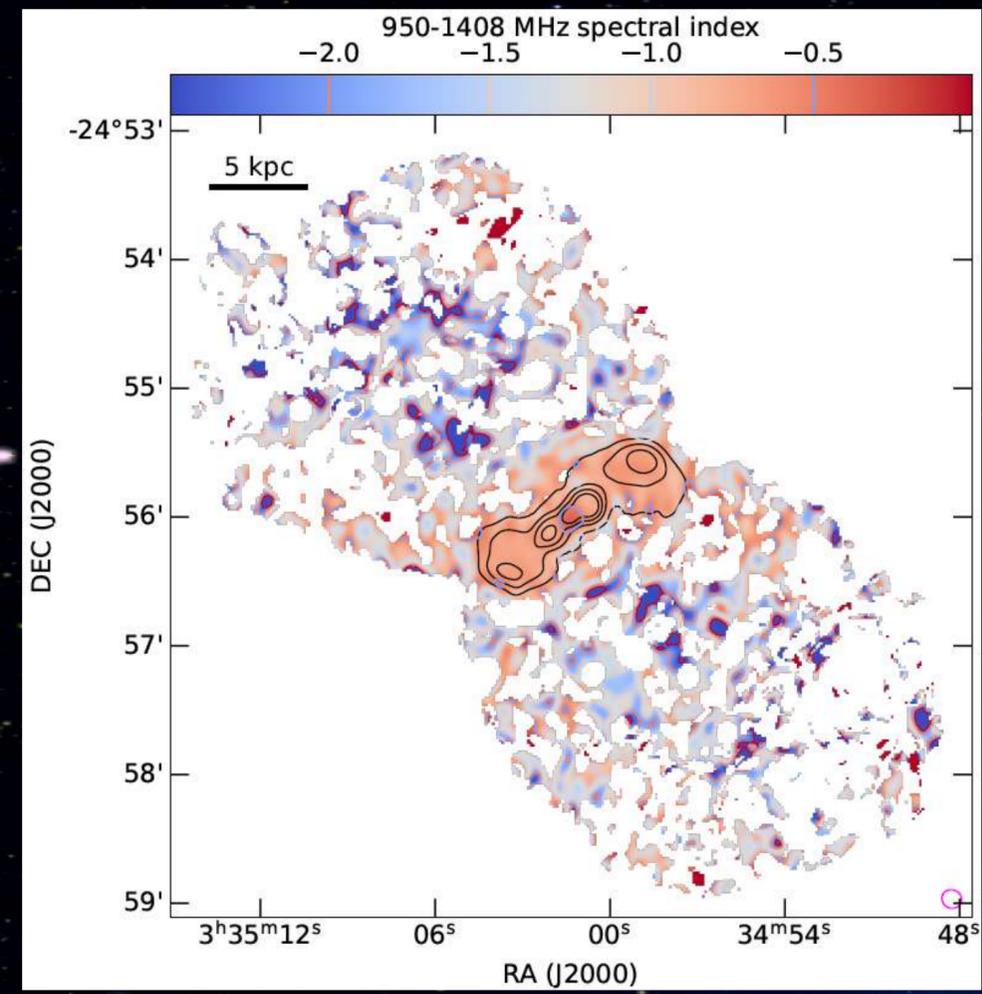
1.4 GHz continuum (MeerKAT)

No other known
bubbles with
similar properties
(size, luminosity
and shape)

Ulvestad+99, Owen00, Hota+06,
Harrison+15, Li+22, Zeng+23

Few examples of
radio AGN in
late-type
galaxies

(Ledlow+98, Abdo+09,
Morganti+11, Doi+12, Bagchi+14,
Sing+15)

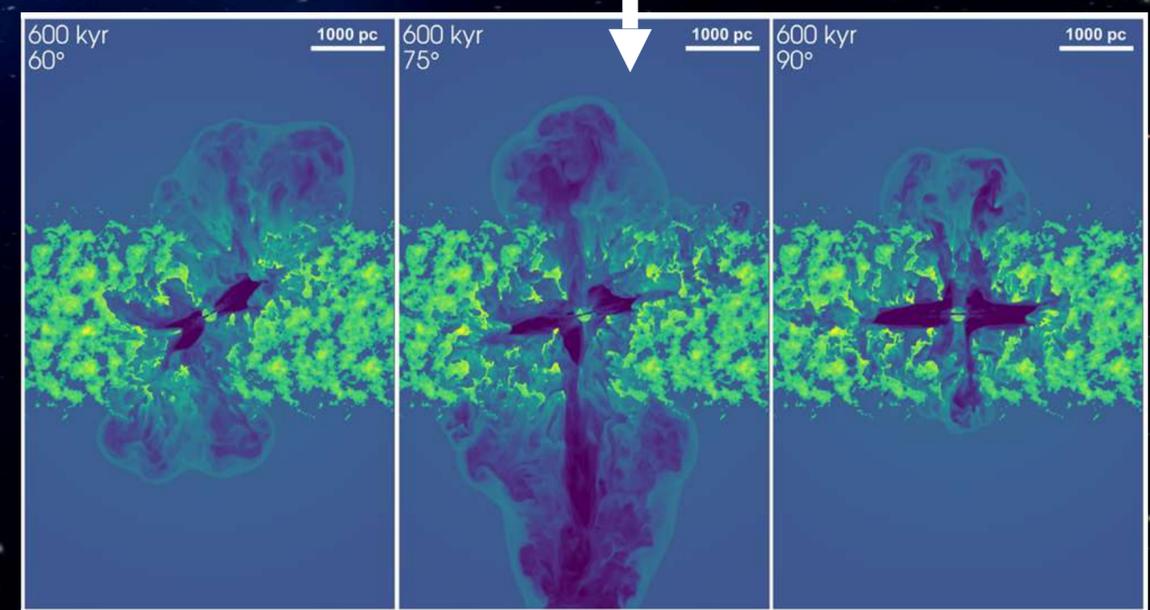


Veronese et al.
(submitted)

5 kpc

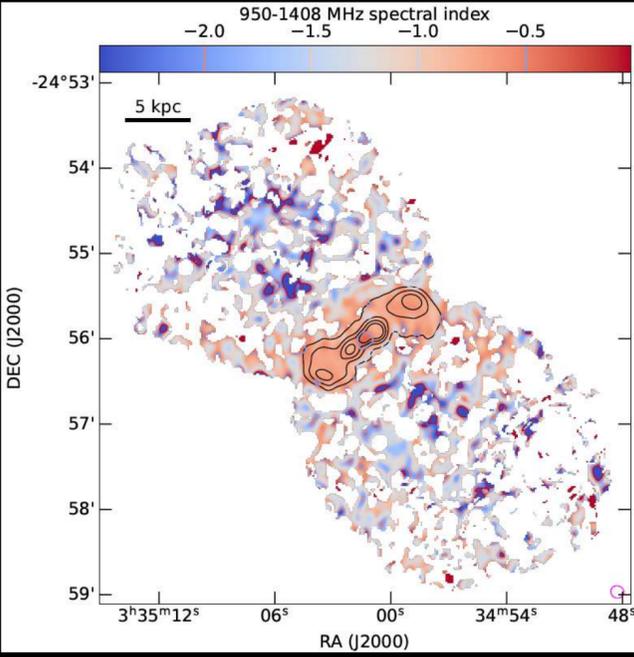
Spectral index consistent
with AGN emission

Bubbles results
from tilted jet-ISM
interaction
Tanner et al. (2022)



SKA-MID - Low-power radio jets & bubbles

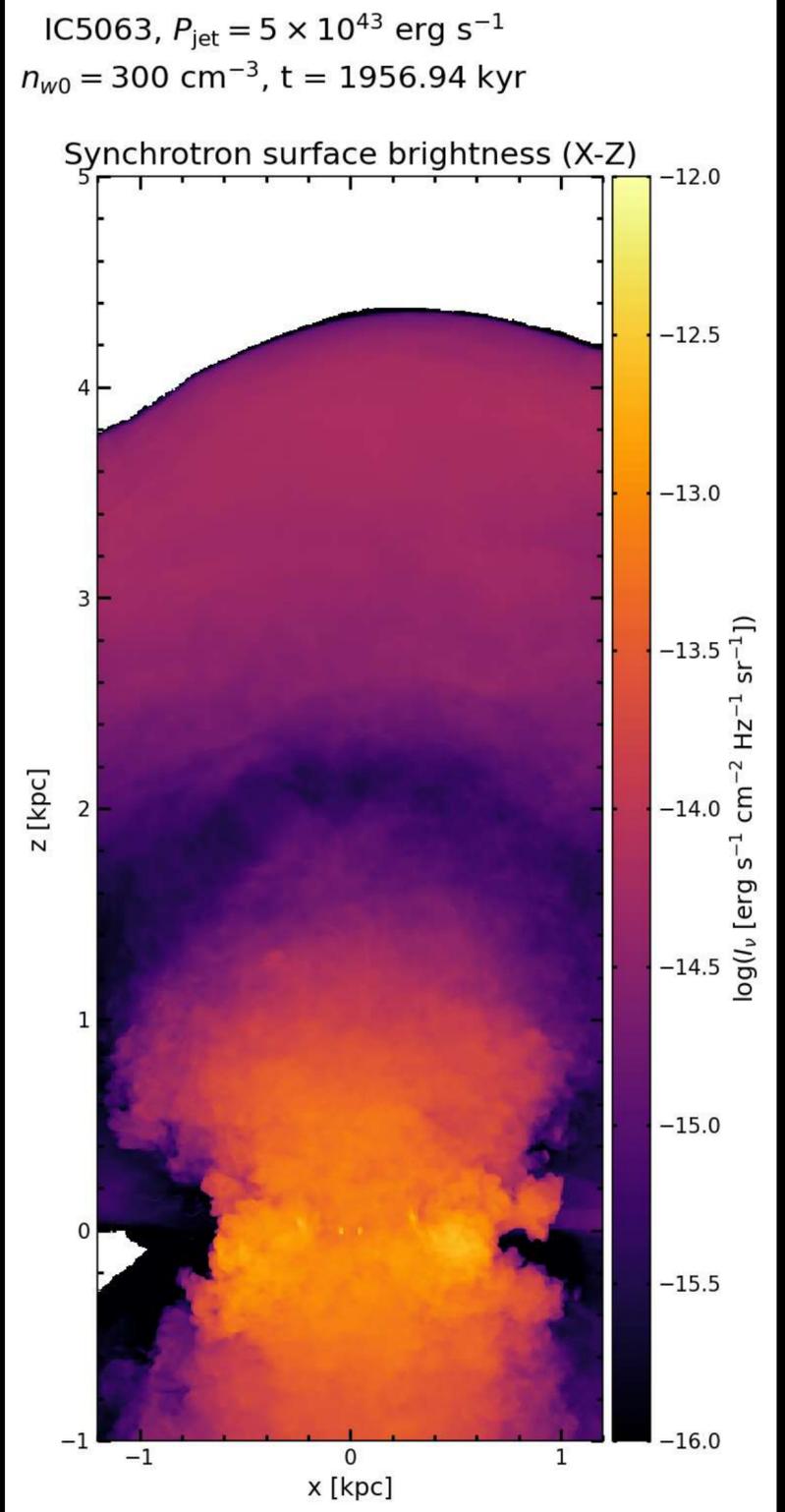
Observation



Low-power jets and bubbles exist in a few LTGs

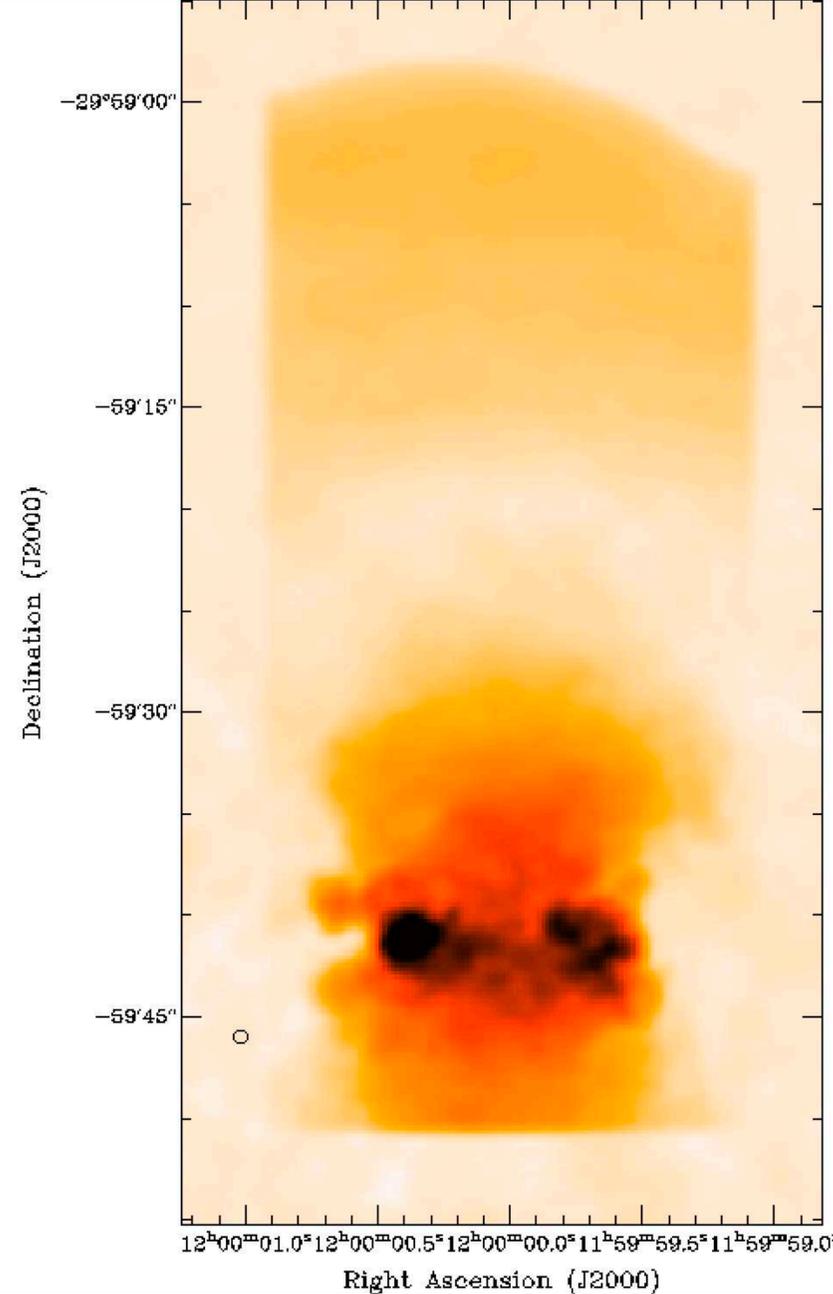
[Ledlow+98, Abdo+09, Morganti+11, Doi+12, Bagchi+14, Sing+15]

Simulation [Mukherjee+18]

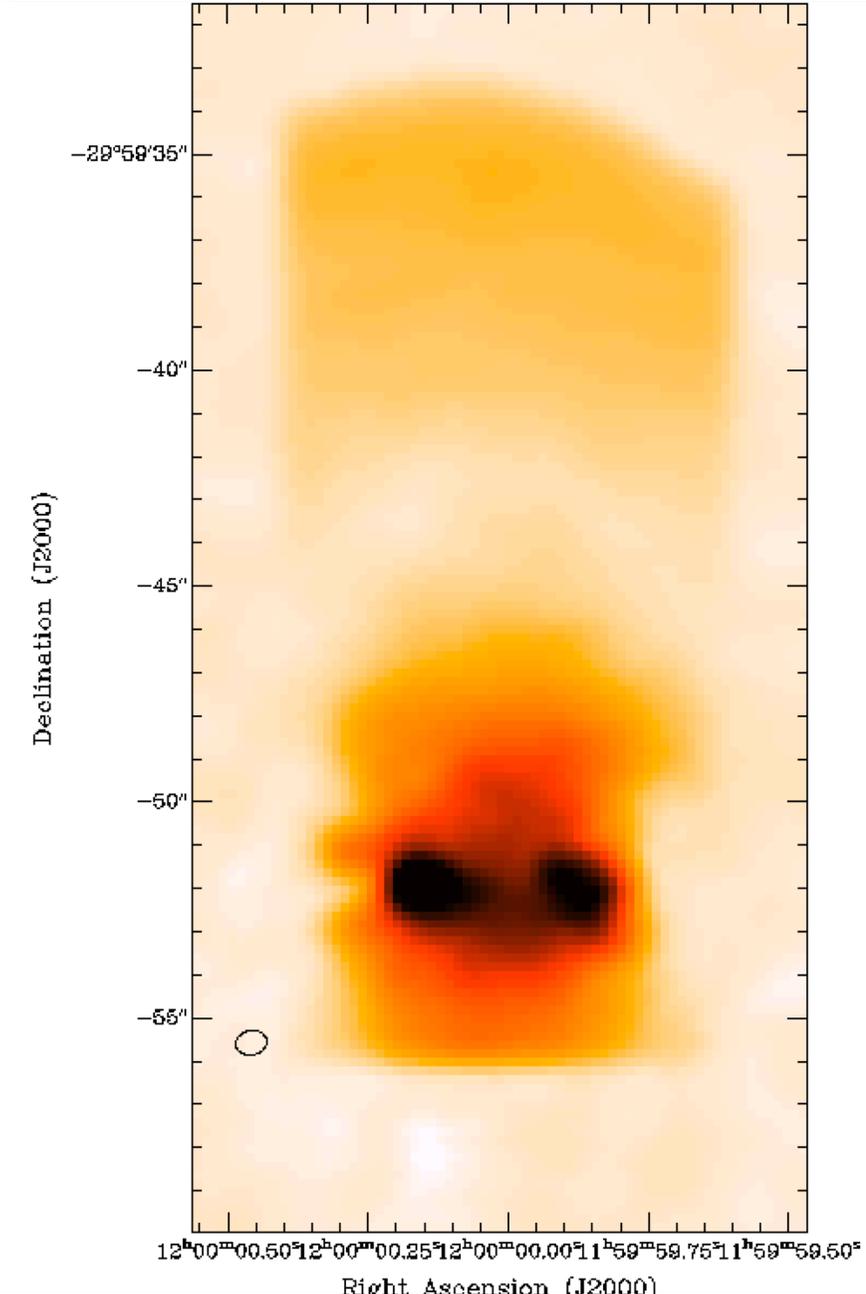


SKA-MID AA4 1.4 GHz 10hrs

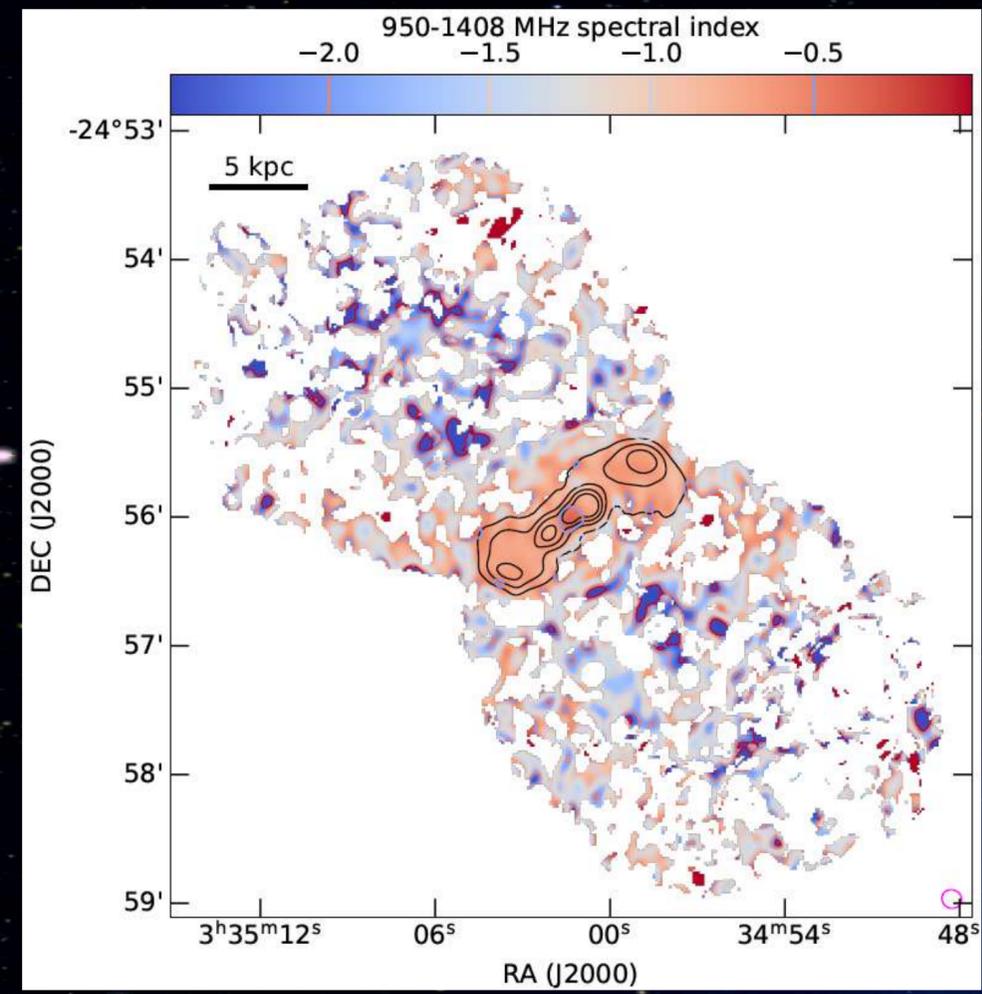
IC5063 @ 20Mpc



IC5063 @ 50Mpc



[Maccagni, Mainieri+ in prep]

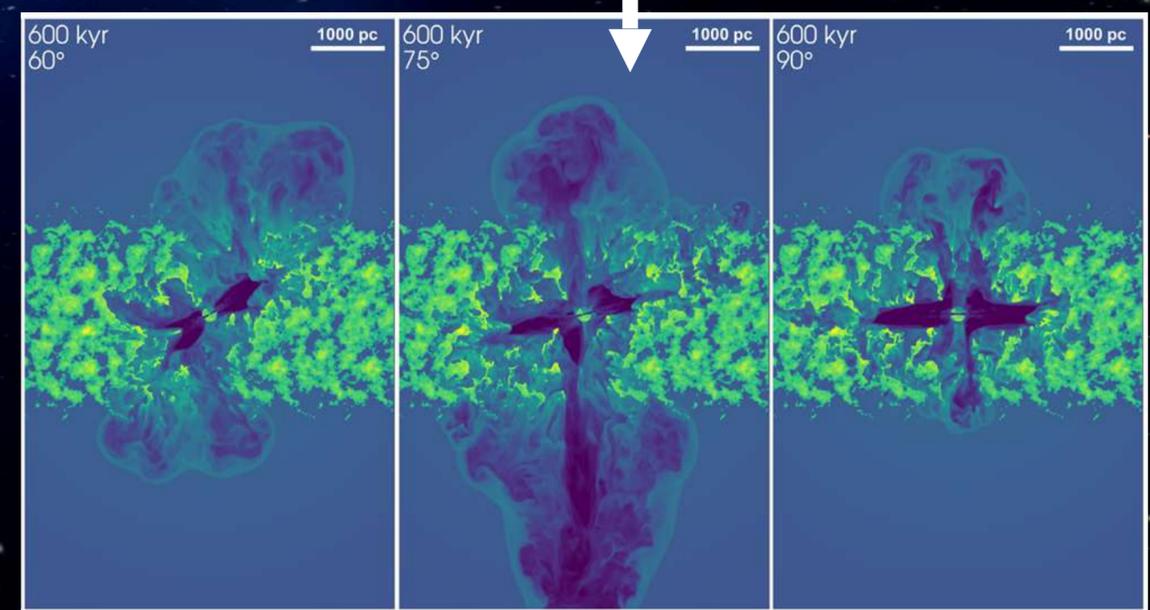


Veronese+2025

5 kpc

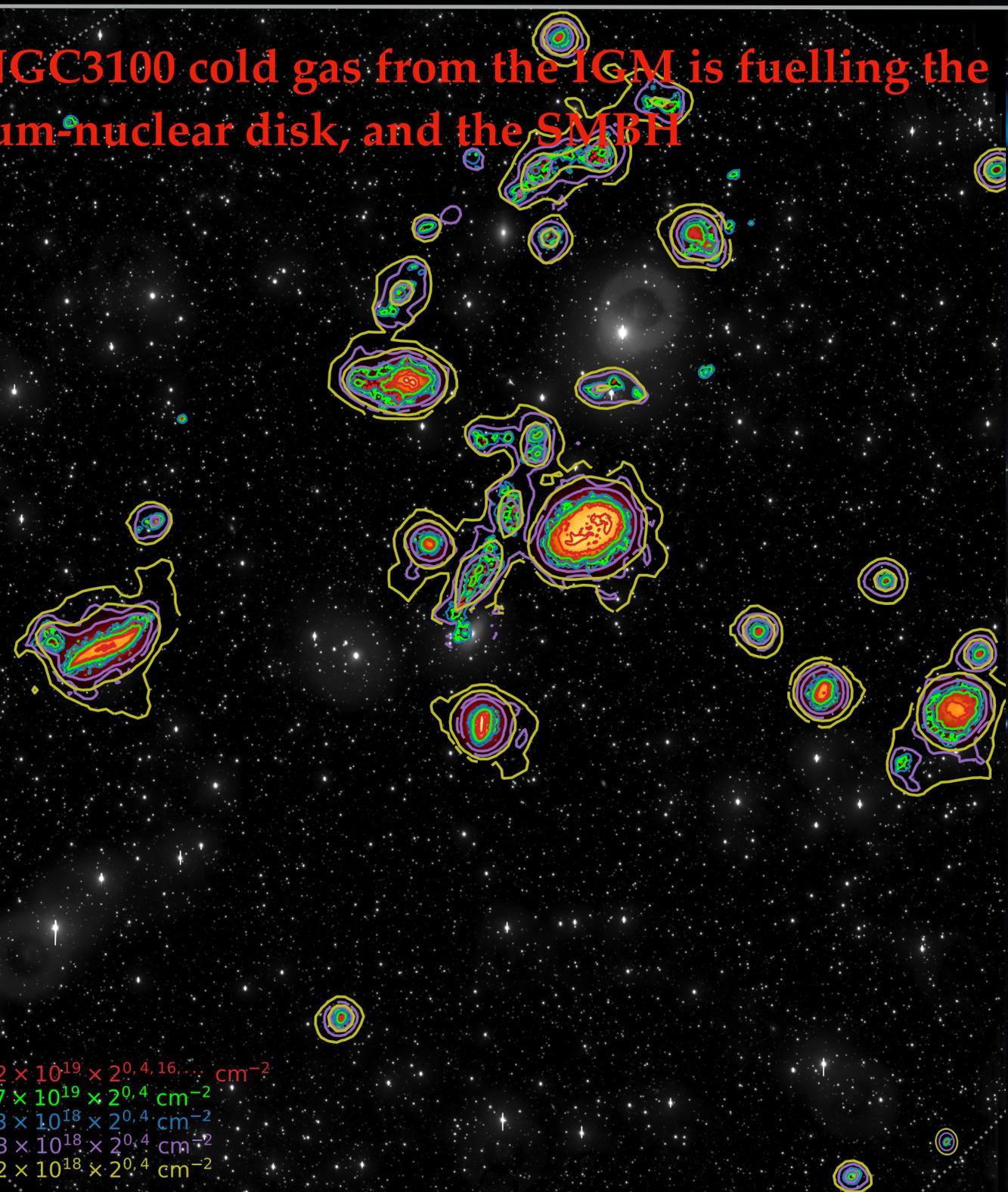
Spectral index consistent with AGN emission

Bubbles results from tilted jet-ISM interaction
Tanner et al. (2022)



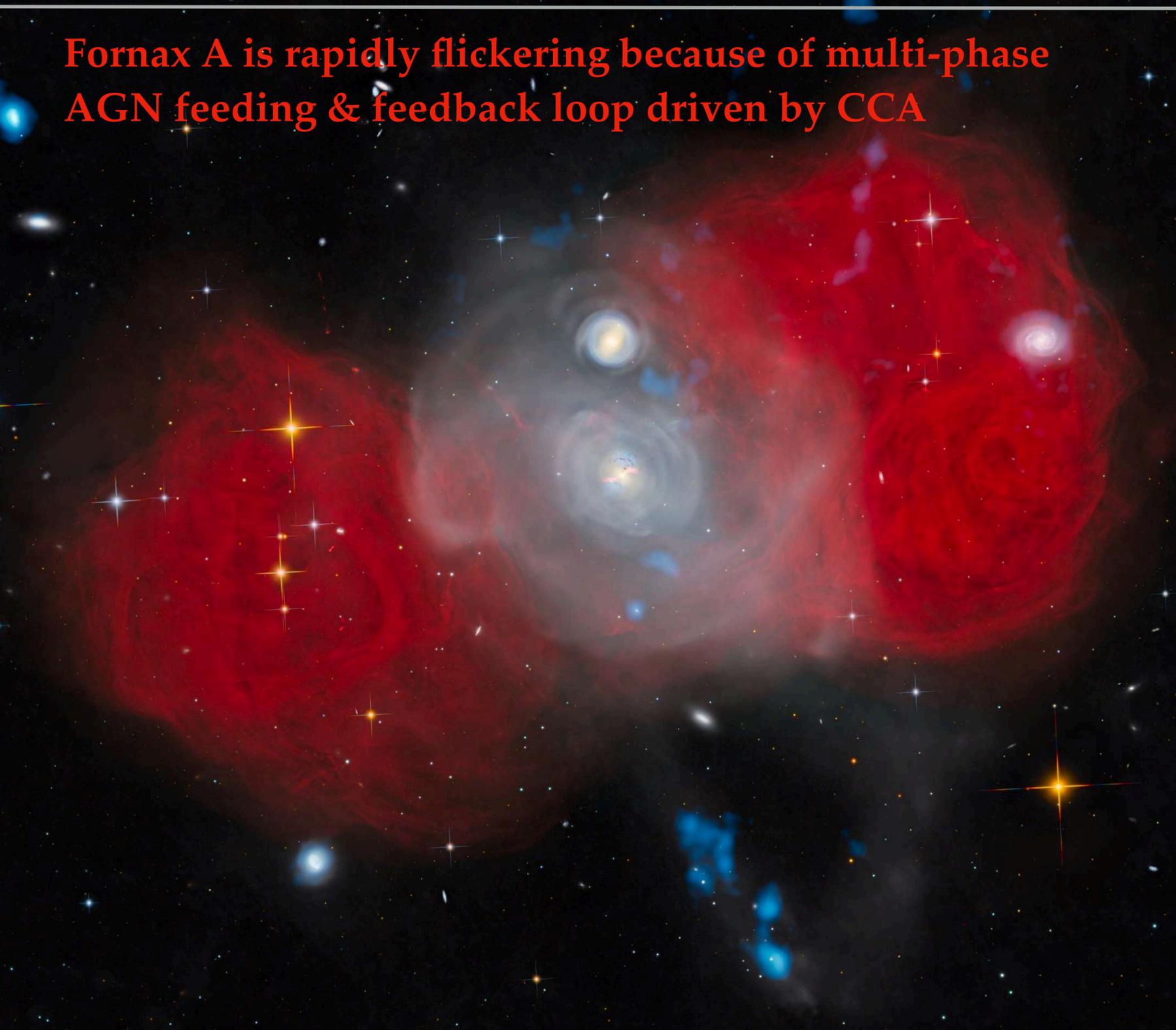
AGN and CGM a radio view - Conclusions

In NGC3100 cold gas from the IGM is fuelling the circum-nuclear disk, and the SMBH

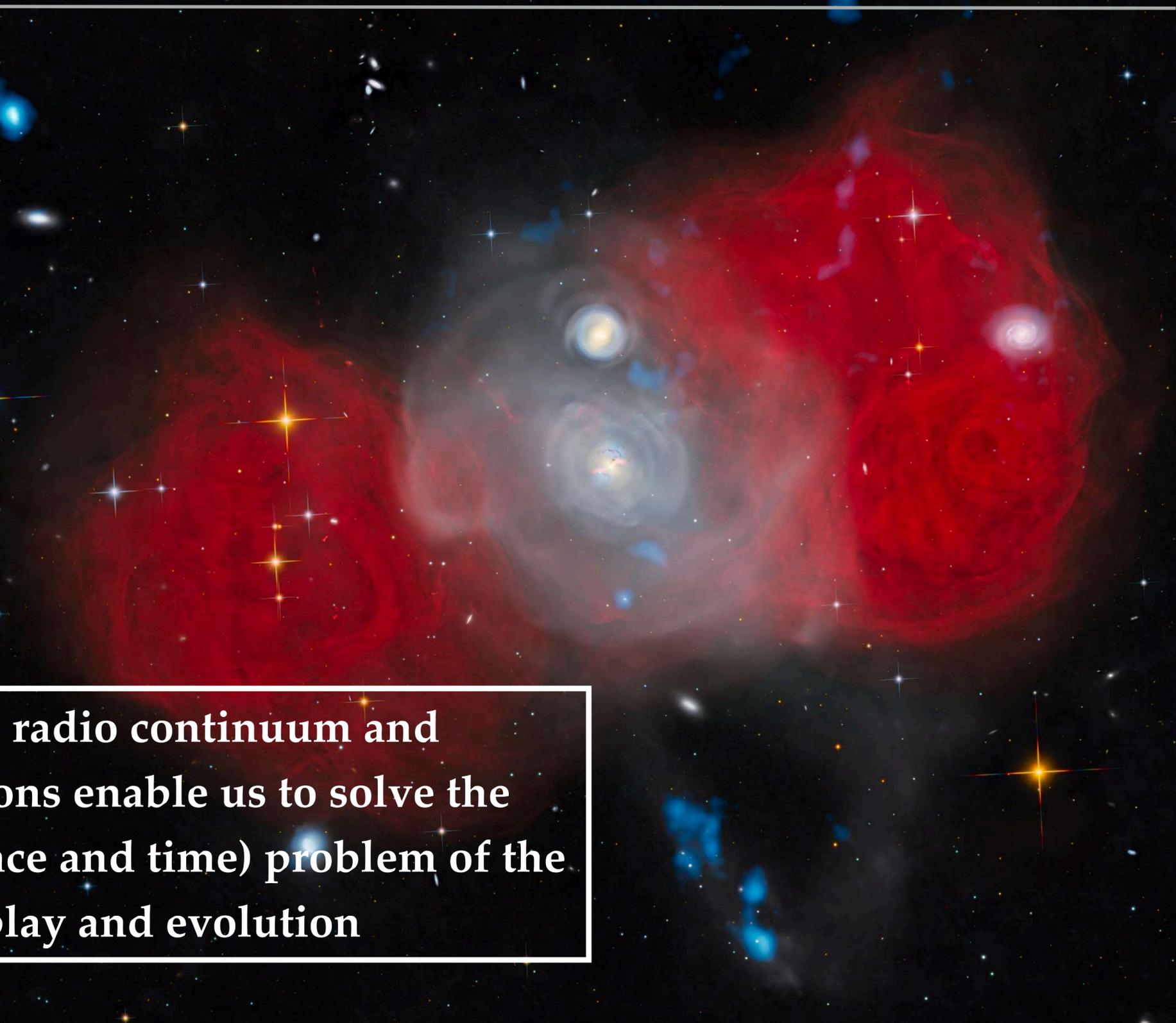
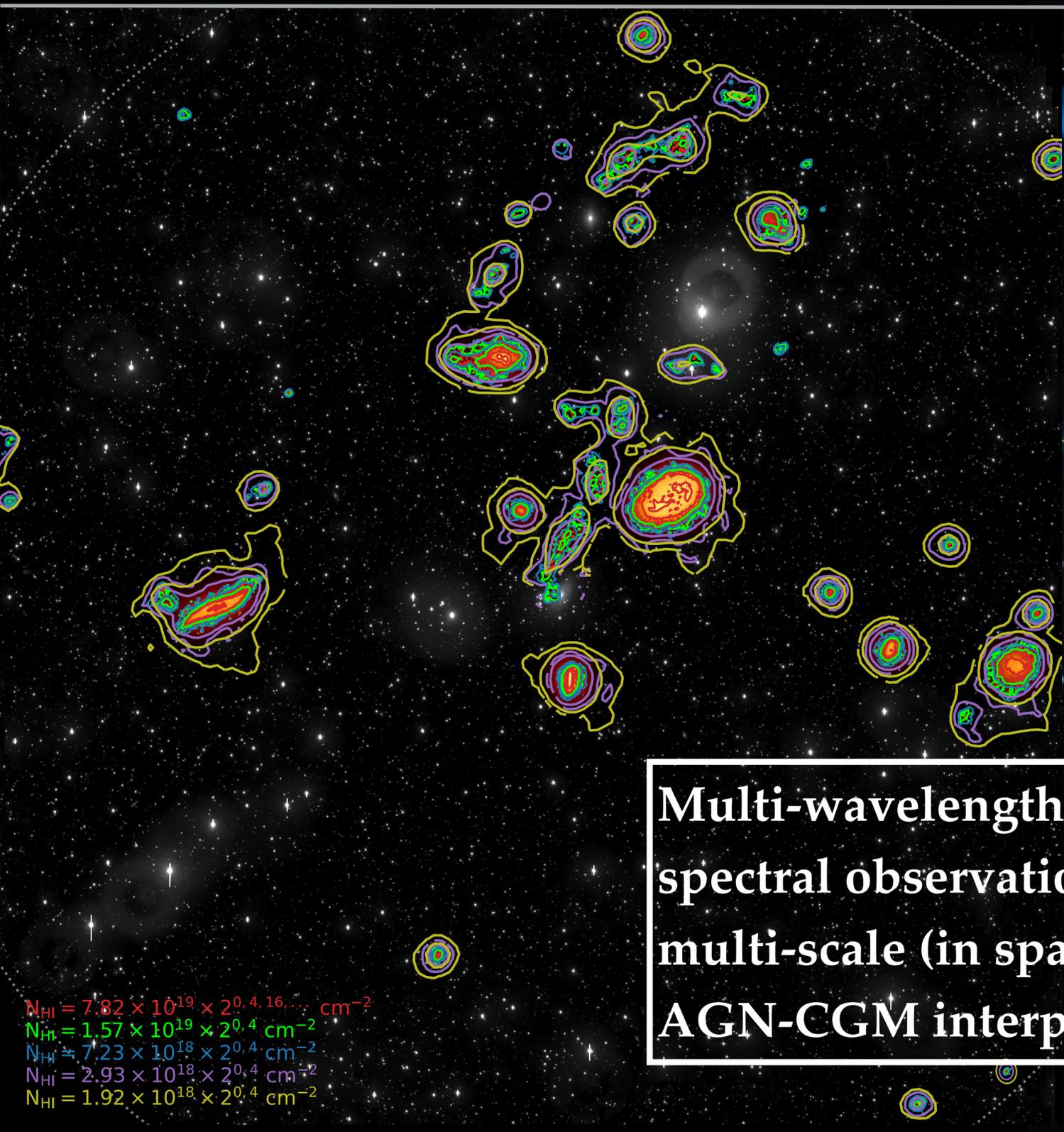


$N_{\text{HI}} = 7.82 \times 10^{19} \times 2^{0,4,16,\dots} \text{ cm}^{-2}$
 $N_{\text{HI}} = 1.57 \times 10^{19} \times 2^{0,4} \text{ cm}^{-2}$
 $N_{\text{HI}} = 7.23 \times 10^{18} \times 2^{0,4} \text{ cm}^{-2}$
 $N_{\text{HI}} = 2.93 \times 10^{18} \times 2^{0,4} \text{ cm}^{-2}$
 $N_{\text{HI}} = 1.92 \times 10^{18} \times 2^{0,4} \text{ cm}^{-2}$

Fornax A is rapidly flickering because of multi-phase AGN feeding & feedback loop driven by CCA



AGN and CGM a radio view - Conclusions



Multi-wavelength radio continuum and spectral observations enable us to solve the multi-scale (in space and time) problem of the AGN-CGM interplay and evolution

$N_{\text{HI}} = 7.82 \times 10^{19} \times 2^{0.4, 16, \dots} \text{ cm}^{-2}$
 $N_{\text{HI}} = 1.57 \times 10^{19} \times 2^{0.4} \text{ cm}^{-2}$
 $N_{\text{HI}} = 7.23 \times 10^{18} \times 2^{0.4} \text{ cm}^{-2}$
 $N_{\text{HI}} = 2.93 \times 10^{18} \times 2^{0.4} \text{ cm}^{-2}$
 $N_{\text{HI}} = 1.92 \times 10^{18} \times 2^{0.4} \text{ cm}^{-2}$



Per Bianca,
la mia Mamma

