INAF ISTITUTO NAZIONALE DI ASTROFISICA

Osservatorio Astronomico di Cagliari

AGN feeding and feedback processes revealed in detail by MeerKAT and the SKA

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Erwin de Blok - **MHONGOOSE** - ASTRON

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

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Max Gaspari - UNIMORE

Vincenzo Mainieri - ESO

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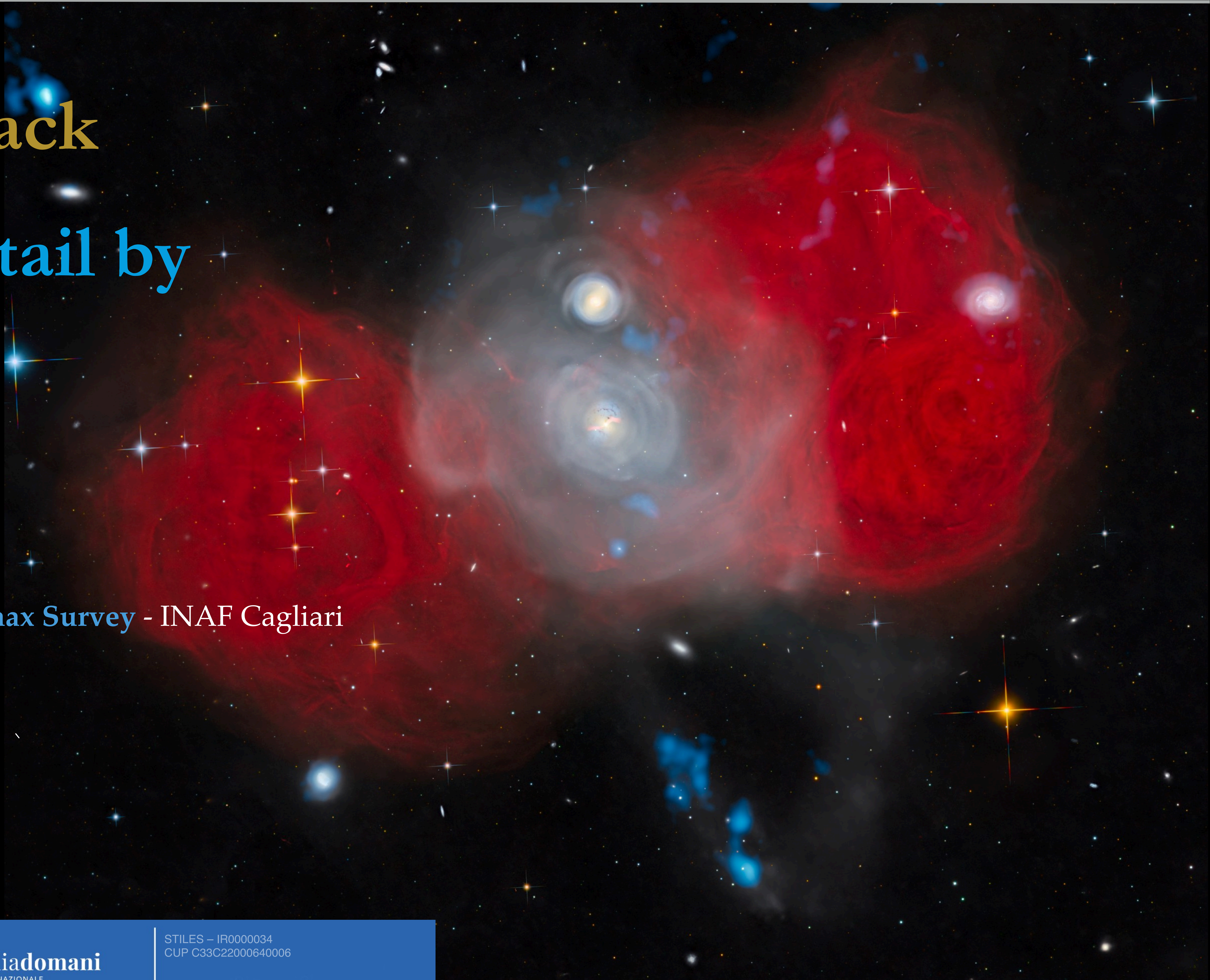

F.Maccagni, P.Serra, F.Enriques; INAF, SARAO

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Italiadomani PIANO NAZIONALE DI RIPRESA E RESILIENZA

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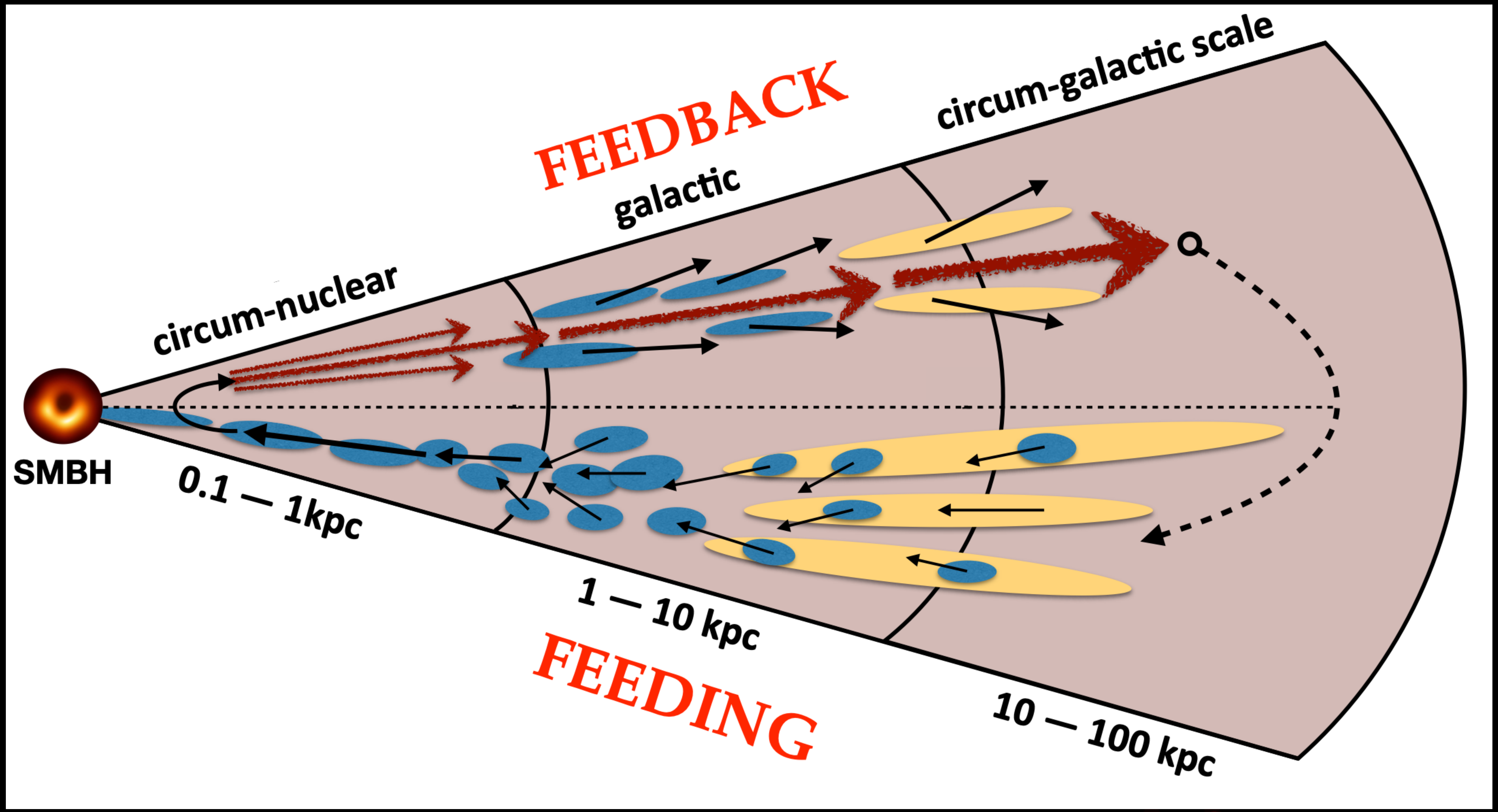
CUP C33C22000640006

From micro to macro - AGN Feeding and Feedback

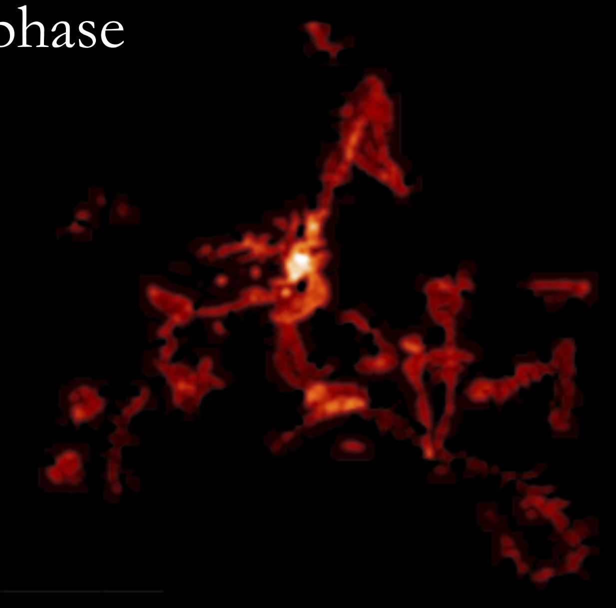
AGN feeding & feedback is a MULTI-SCALE phenomenon in SPACE and TIME

- SPACE
  - link between 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

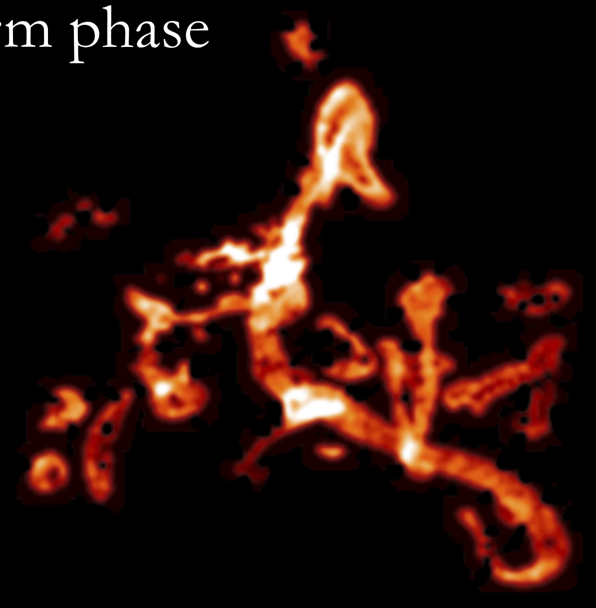


- MULTI-PHASE
  - hot, warm and cold gas co-exist and contribute over all spatial scales

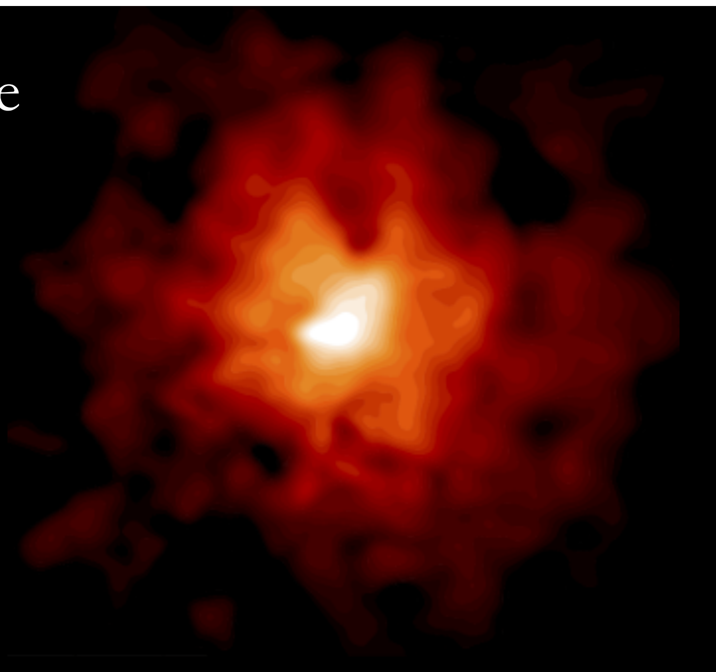
cold phase



warm phase



hot phase



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

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

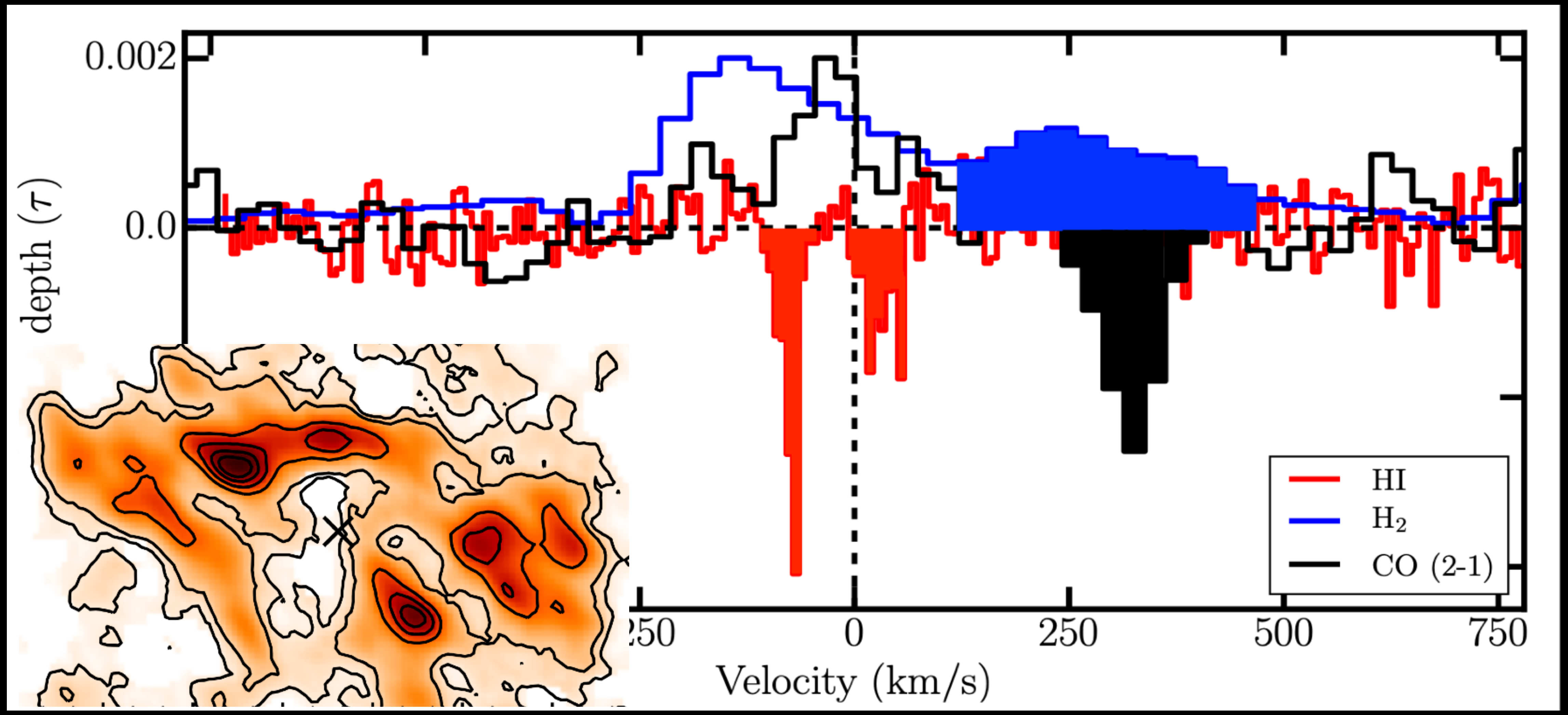
absorption studies (MICRO)

low resolution & sensitivity emission studies (MACRO)

BECAUSE cold gas in F&F has LOW column density: **< 1×10^{20} cm^{-2}**

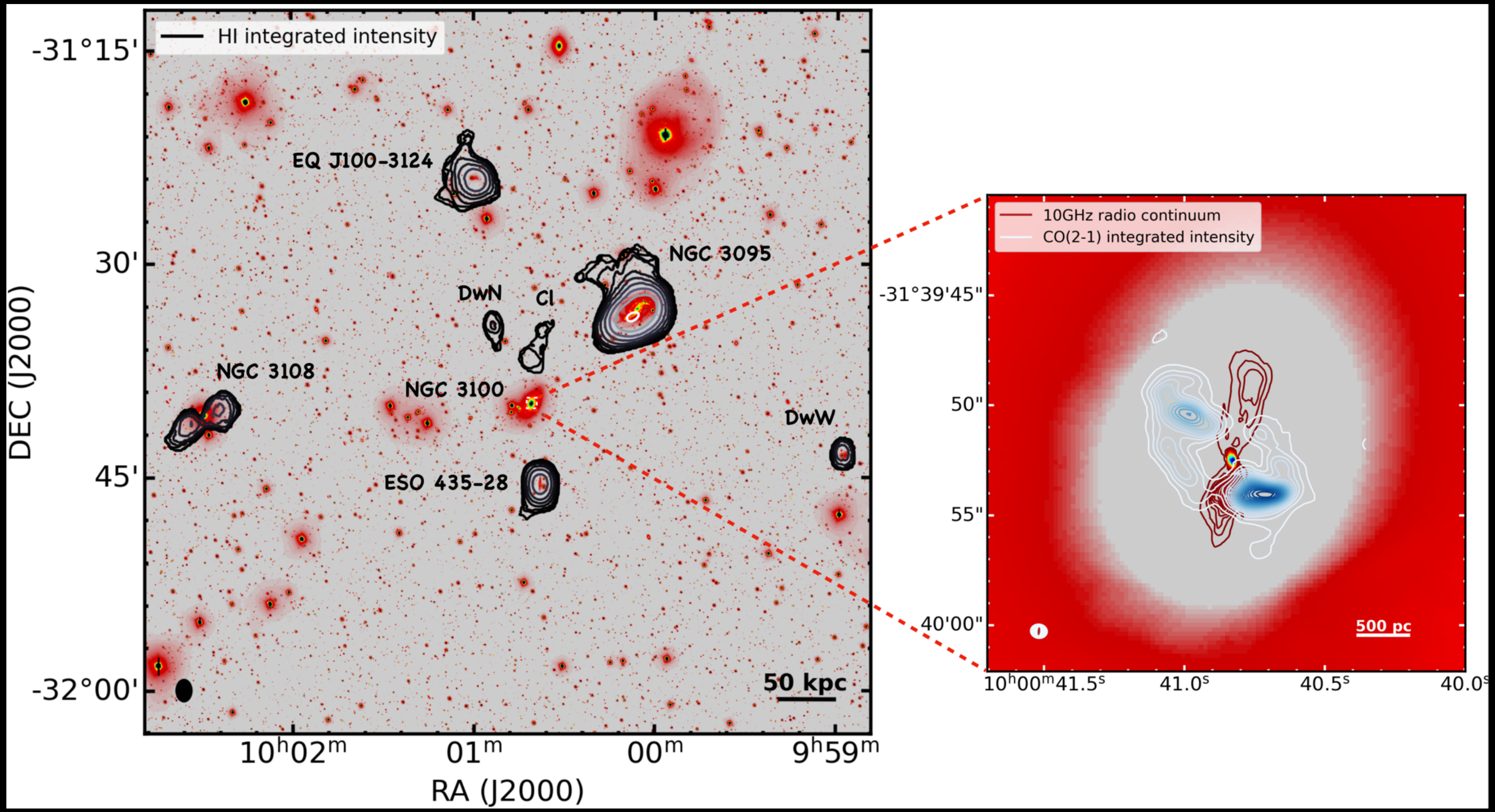
FEEDING

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



PKS1718-649, Maccagni+ 14,16,18

HI cloud fuelling circum-nuclear disk from the galaxy halo



NGC3100, Maccagni+ 23

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

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

absorption studies (MICRO)

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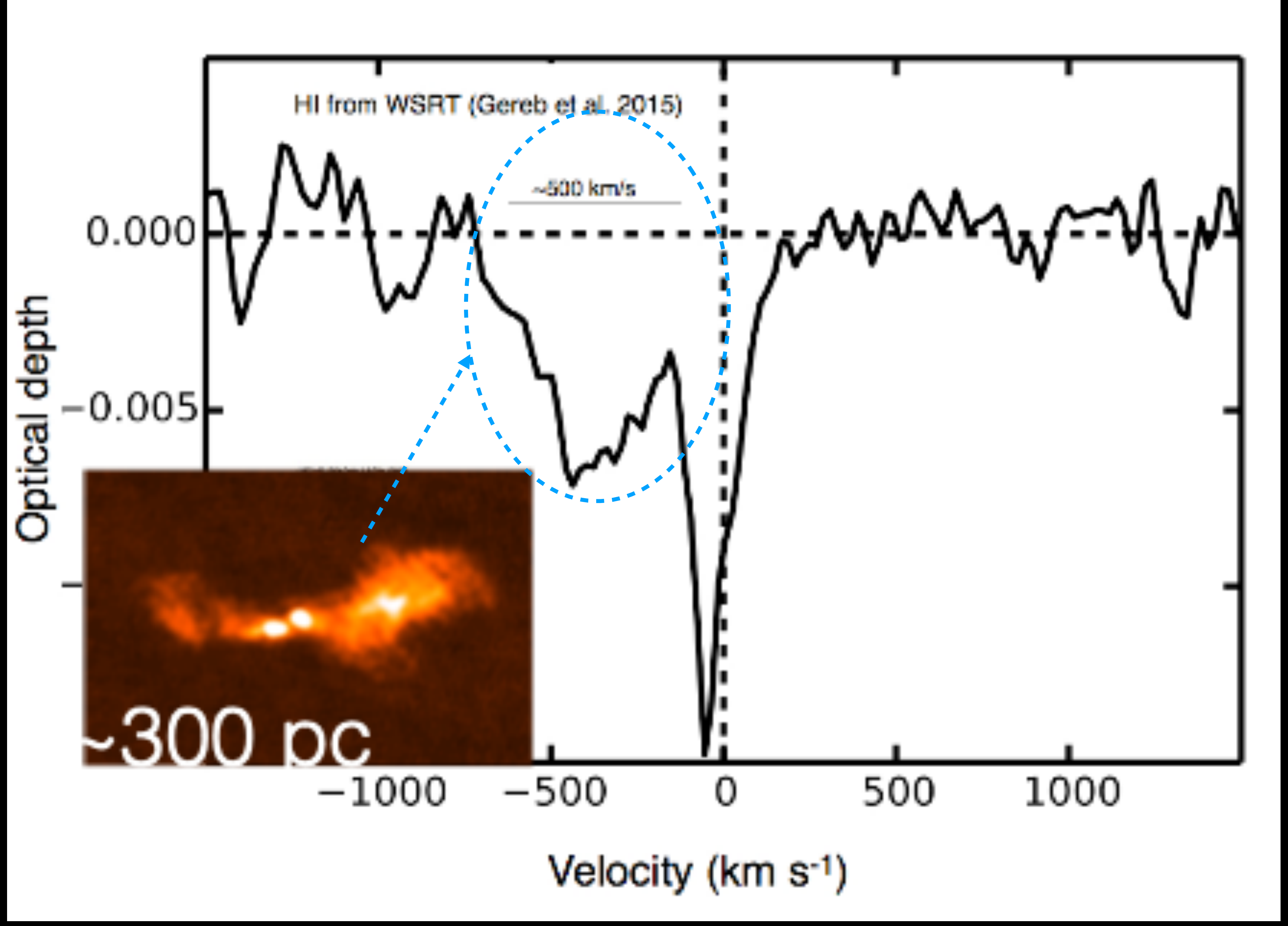
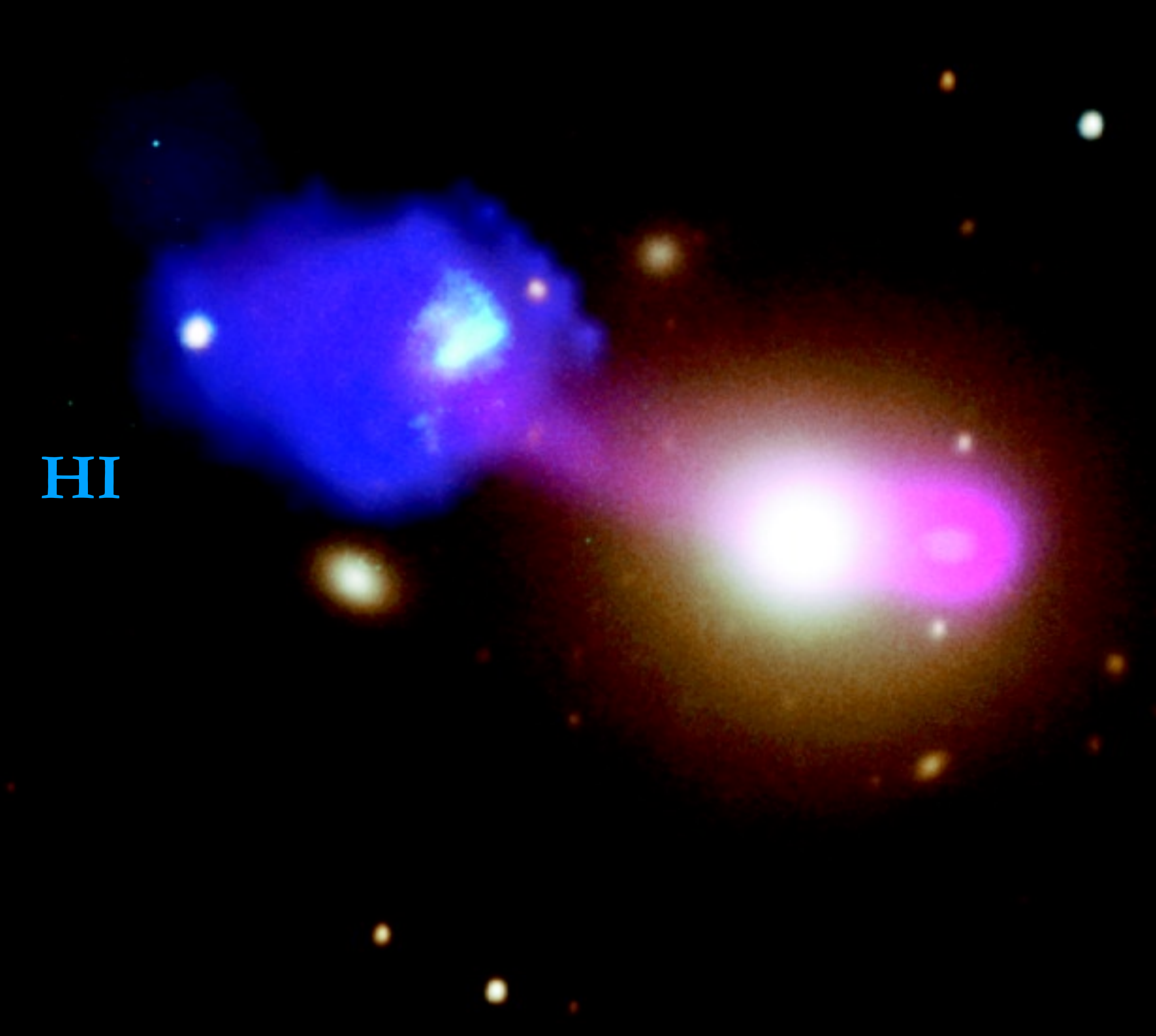
FEEDBACK

HI outflows on circum-nuclear scales



Positive feedback on circum-galactic scales

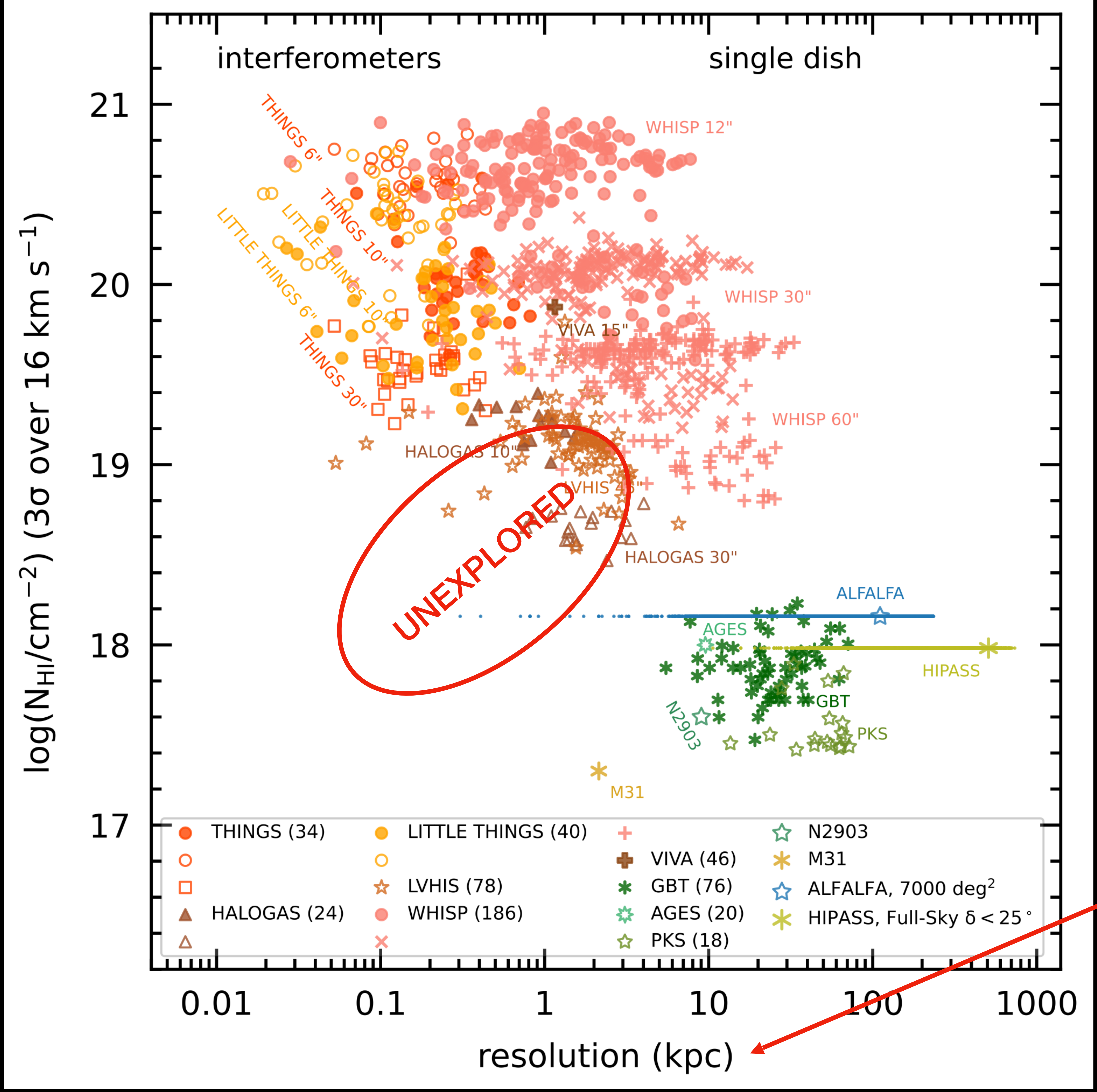


Minkowski object Croft et al. 2006

Centaurus A - Morganti 2011; Santoro+15; Salomé-

Past HI surveys

column density sensitivity

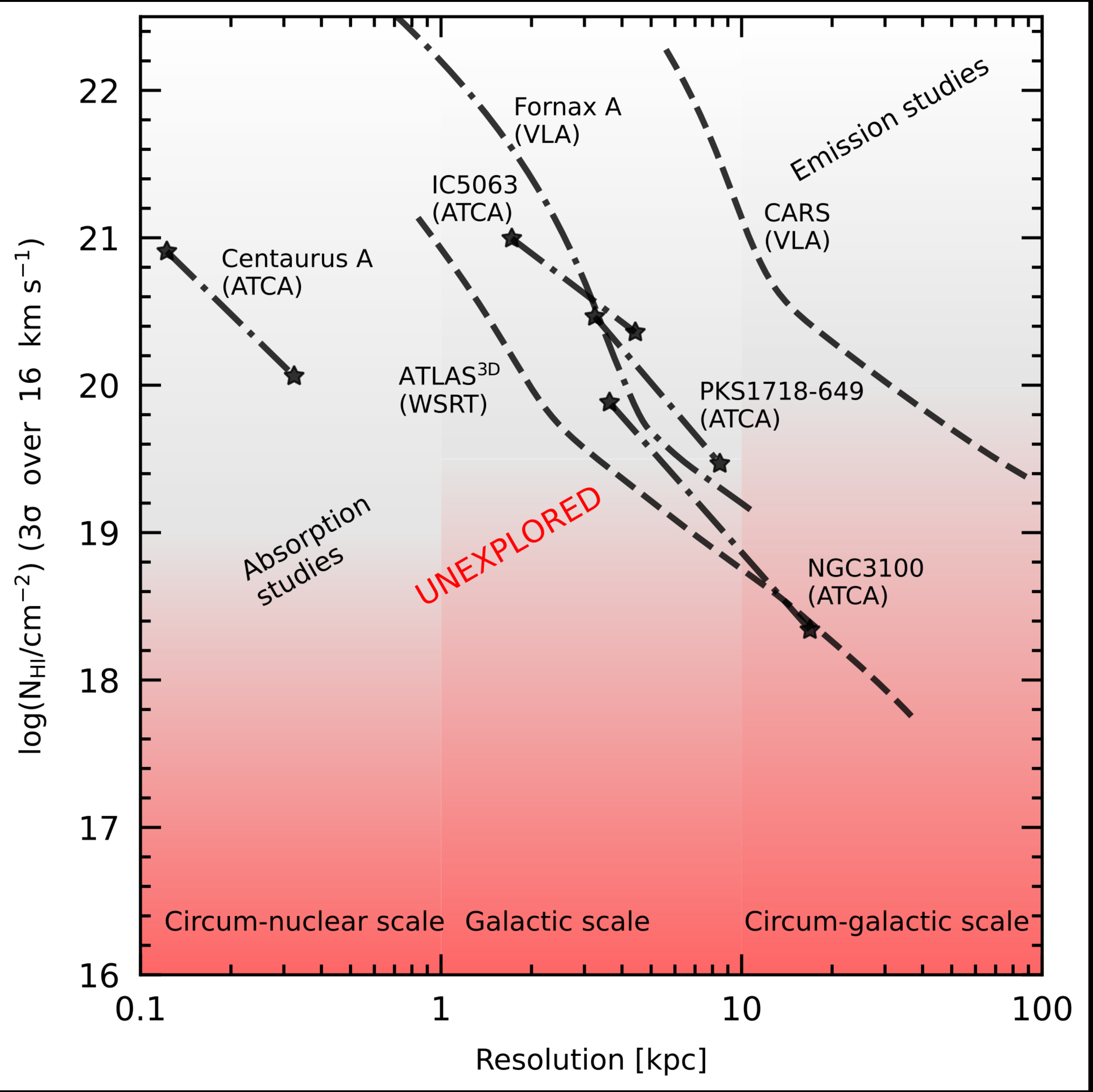


Physical resolution at the distance of the sources

[Maccagni & de Blok 2024]

Past HI studies in AGN

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



(non-exhaustive list)

nevertheless, 1/3 of ETGs has HI…

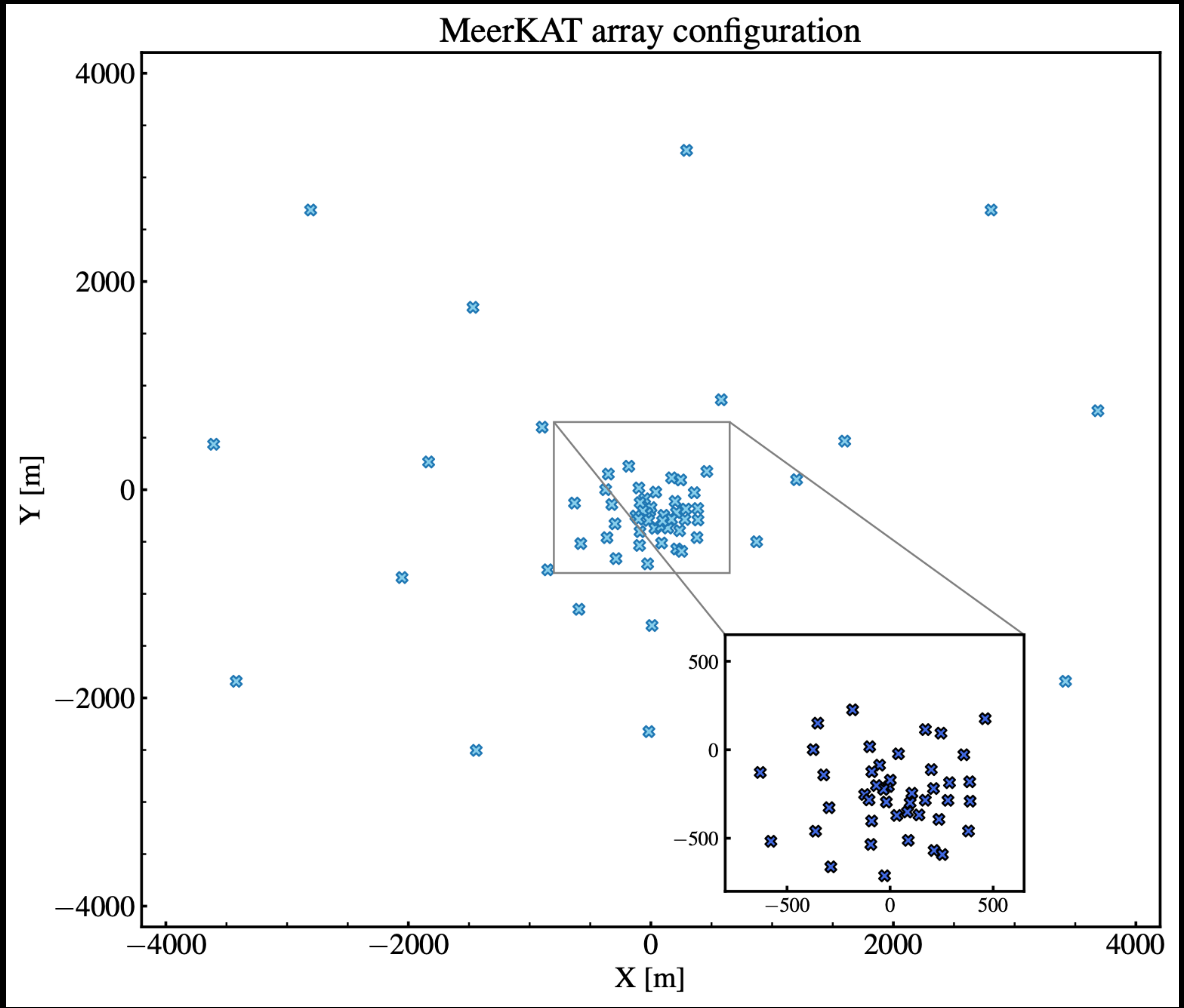
[Serra et al. 2012]

stacking shows low-column density HI in ETGs

[Maccagni et al. 2017]

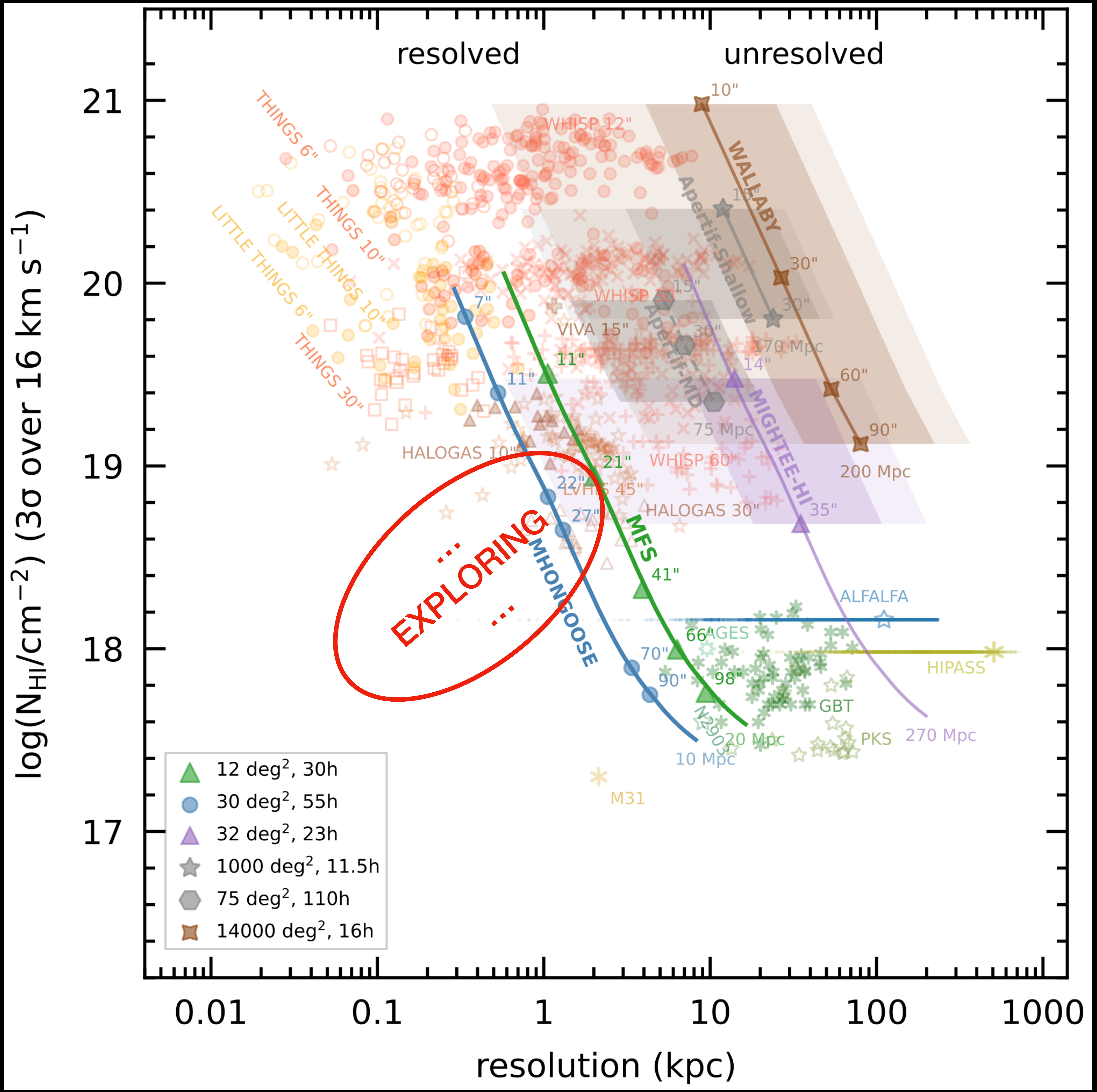
MeerKAT - telescope specs

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



MeerKAT - great sensitivity and resolution

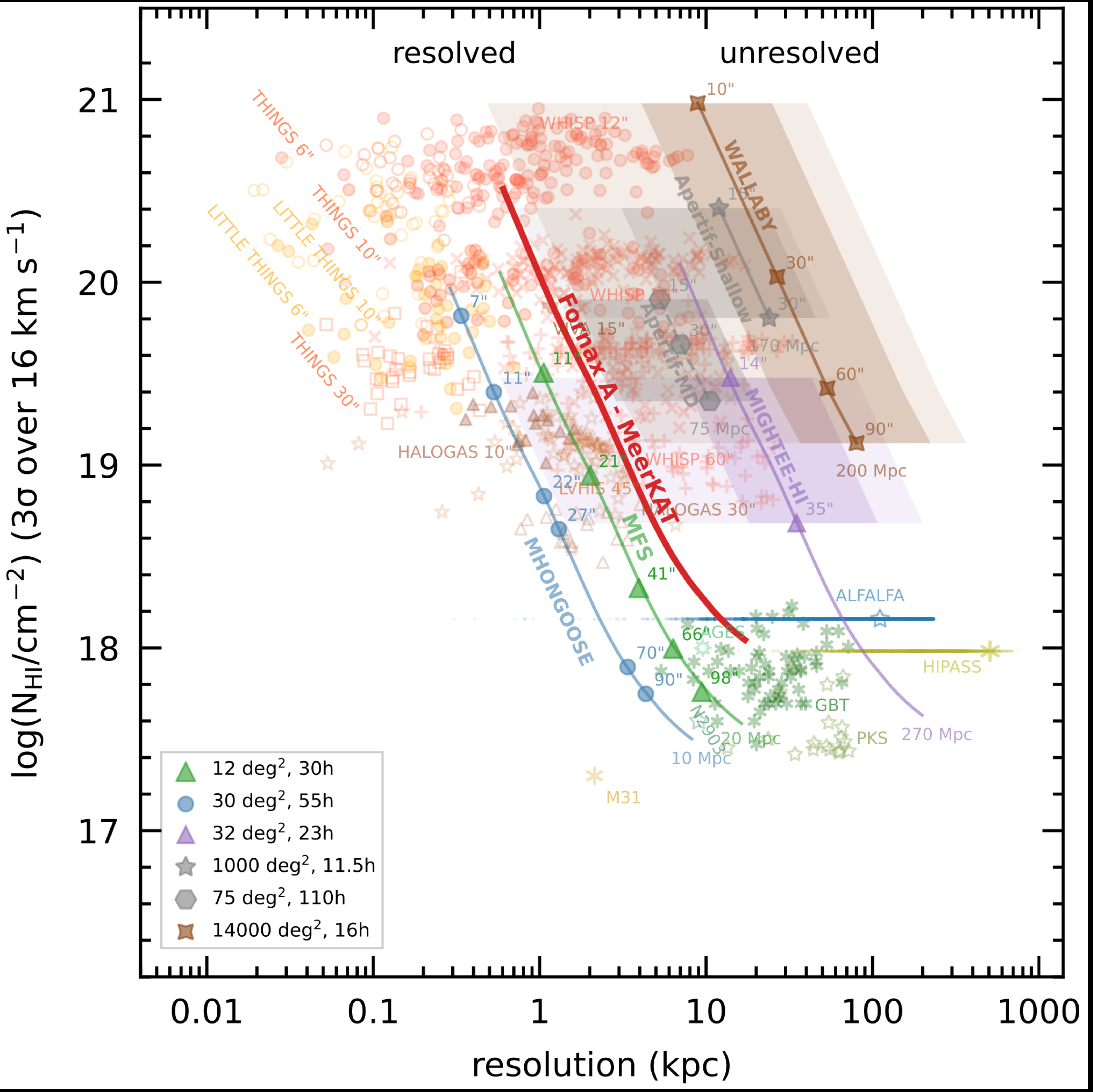
MeerKAT LSPs of nearby galaxies reach $N_{HI} < 10^{20}$ cm^{-2} with <kilo-parsec resolution



MeerKAT - great sensitivity and resolution

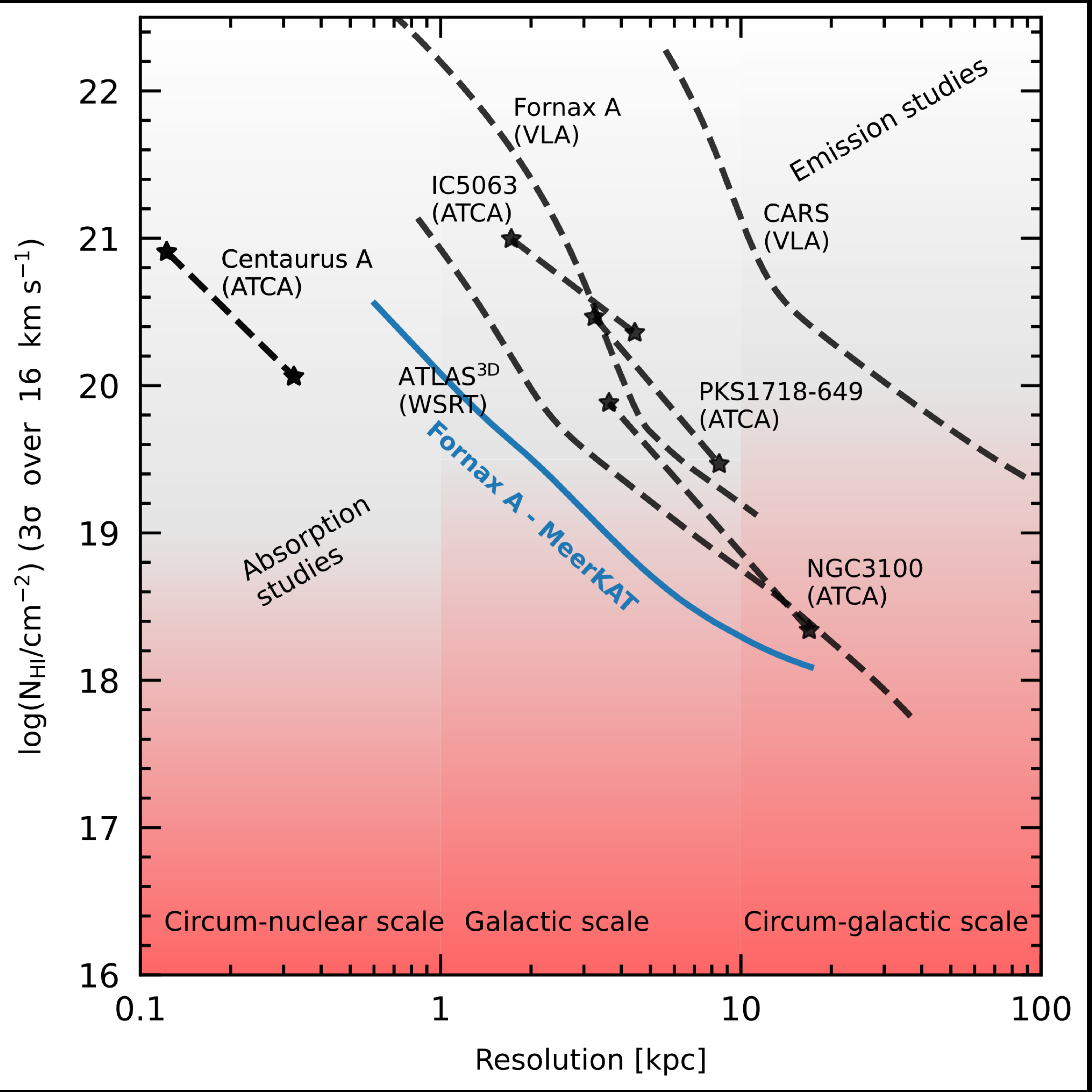
Fornax A - MeerKAT

- commissioning
- Δv = 44 km/s
- 10 hrs



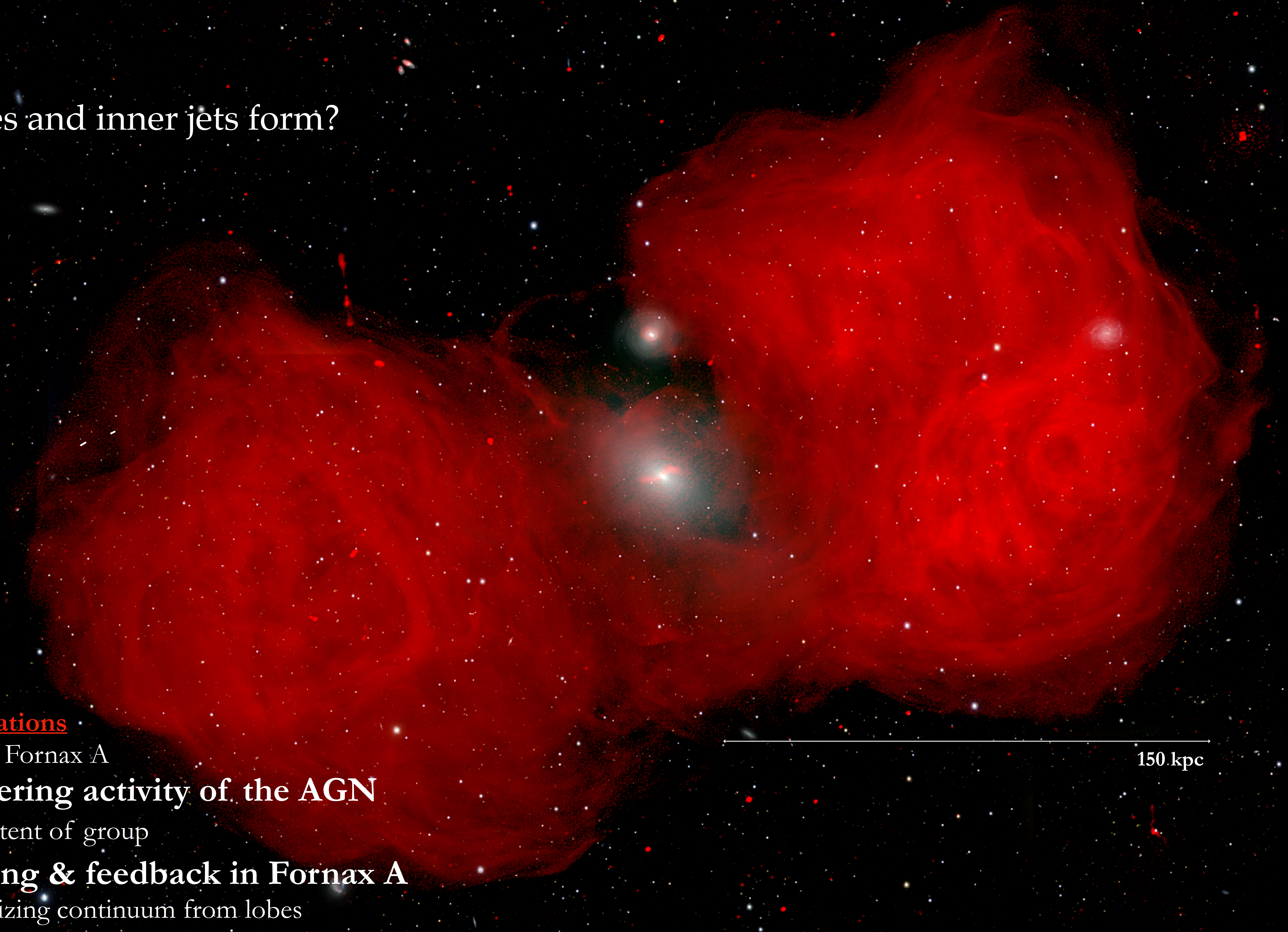
MeerKAT - great sensitivity and resolution

Opening a new parameter space of observations in AGN



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 Hα content of group

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

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

The flickering activity of Fornax A

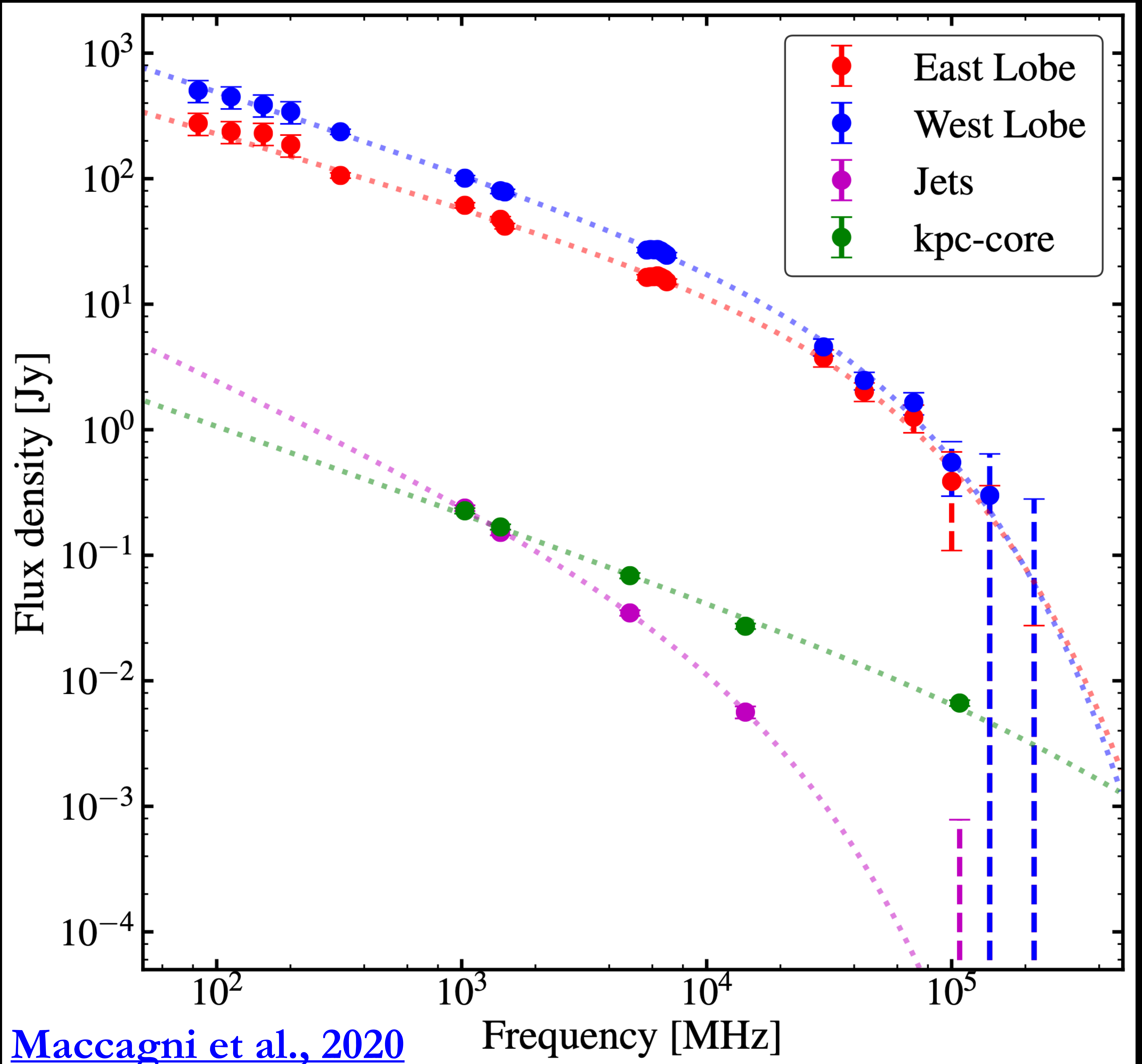
- Phase 1 — Lobes
- 24 Myr ago began the **last** injection of the lobes
- 12 Myr ago AGN switch-off

- Phase 2 — Jets
- 3 Myr ago AGN formed the jets
- 1 Myr ago AGN switch-off

- Phase 3 — Core
- kpc-core 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



Maccagni et al., 2020

The flickering activity of Fornax A

SKA will do this in only a few observations:

SKA-Low

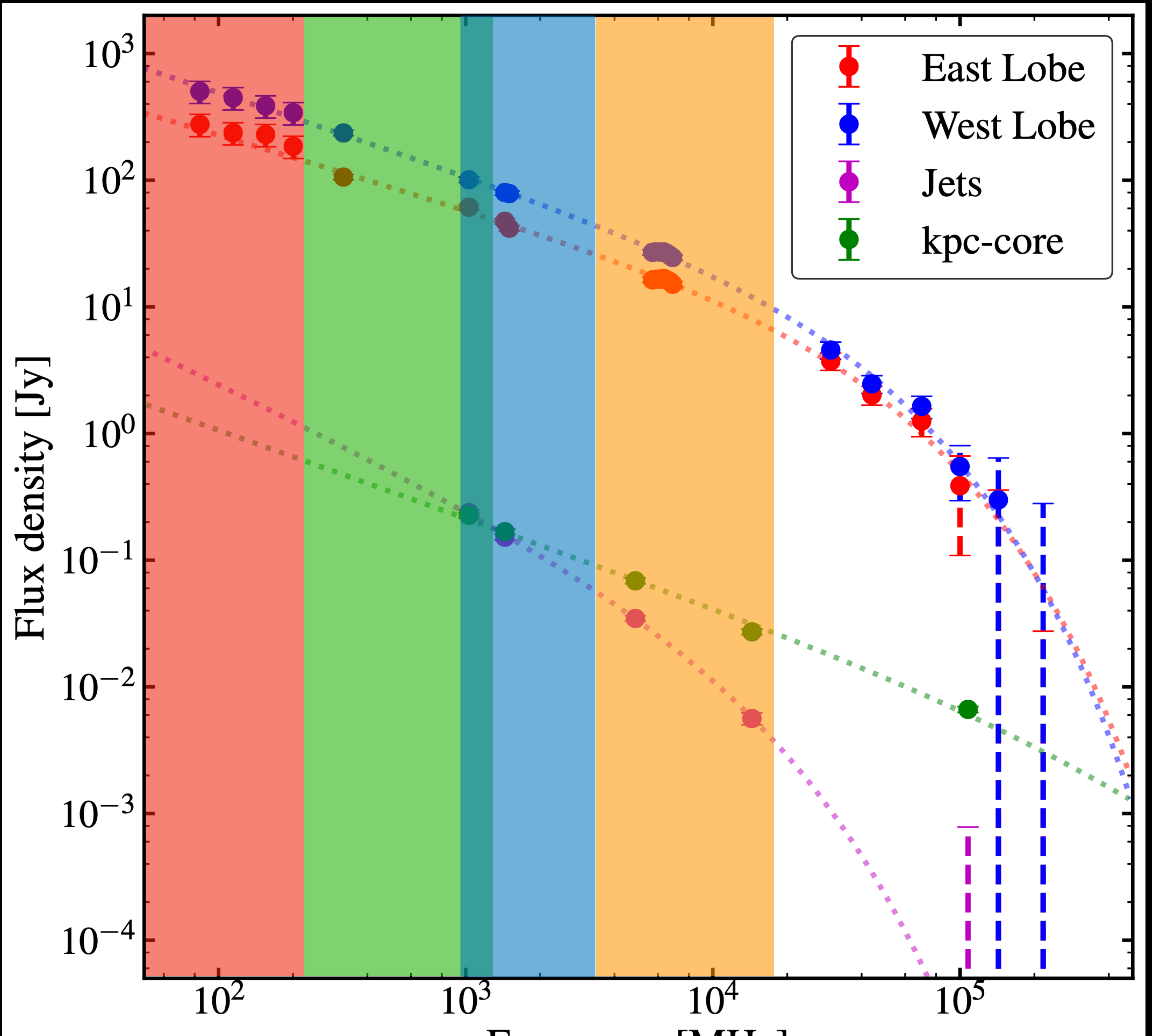
50-300 MHz broadband observation

SKA-Mid

Band 1: 0.35 - 1.09 GHz

Band 2: 0.95 - 1.76 GHz

Band 5,ab: 4.6 - 16.4 GHz



Maccagni et al., 2020

Fornax A & HI

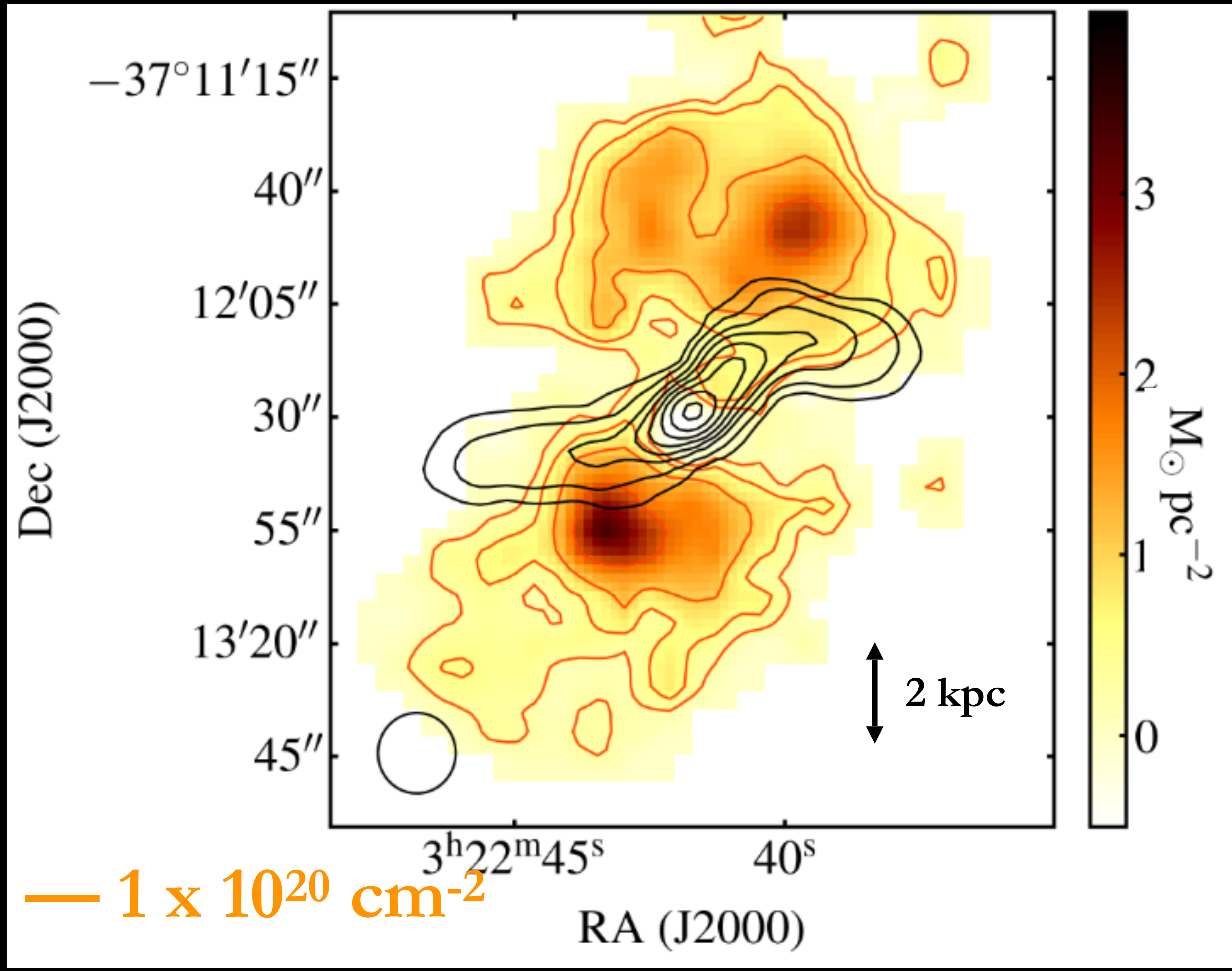
- What is fuelling and sustaining the rapid duty cycle of the AGN?
- Is AGN feedback changing the conditions of the ISM and IGM?

<u>MeerKAT commissioning observations</u>

Serra et al. 2019 : merger history of Fornax A
Maccagni et al. 2020 : flickering activity of the AGN
Kleiner et al. 2021 : HI and Hα content of group
Maccagni et al. 2021 : feeding & feedback in Fornax A
Loi et al. 2022 : HI and Hα depolarizing continuum from lobes

HI distribution in the innermost 8 kpc

HI Surface Brightness

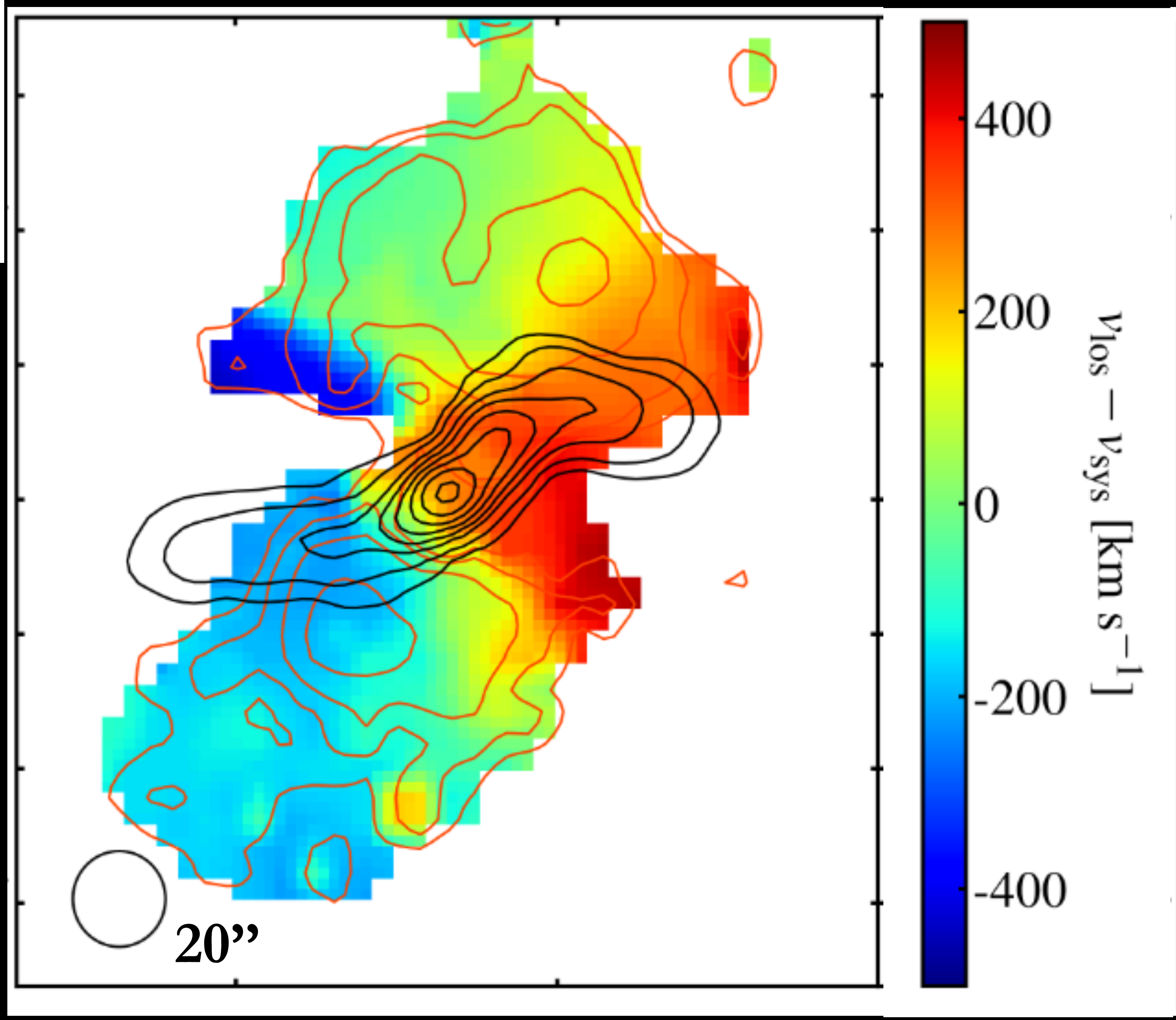


Rotation axis of the gas (NW-SE) perpendicular to the stellar body

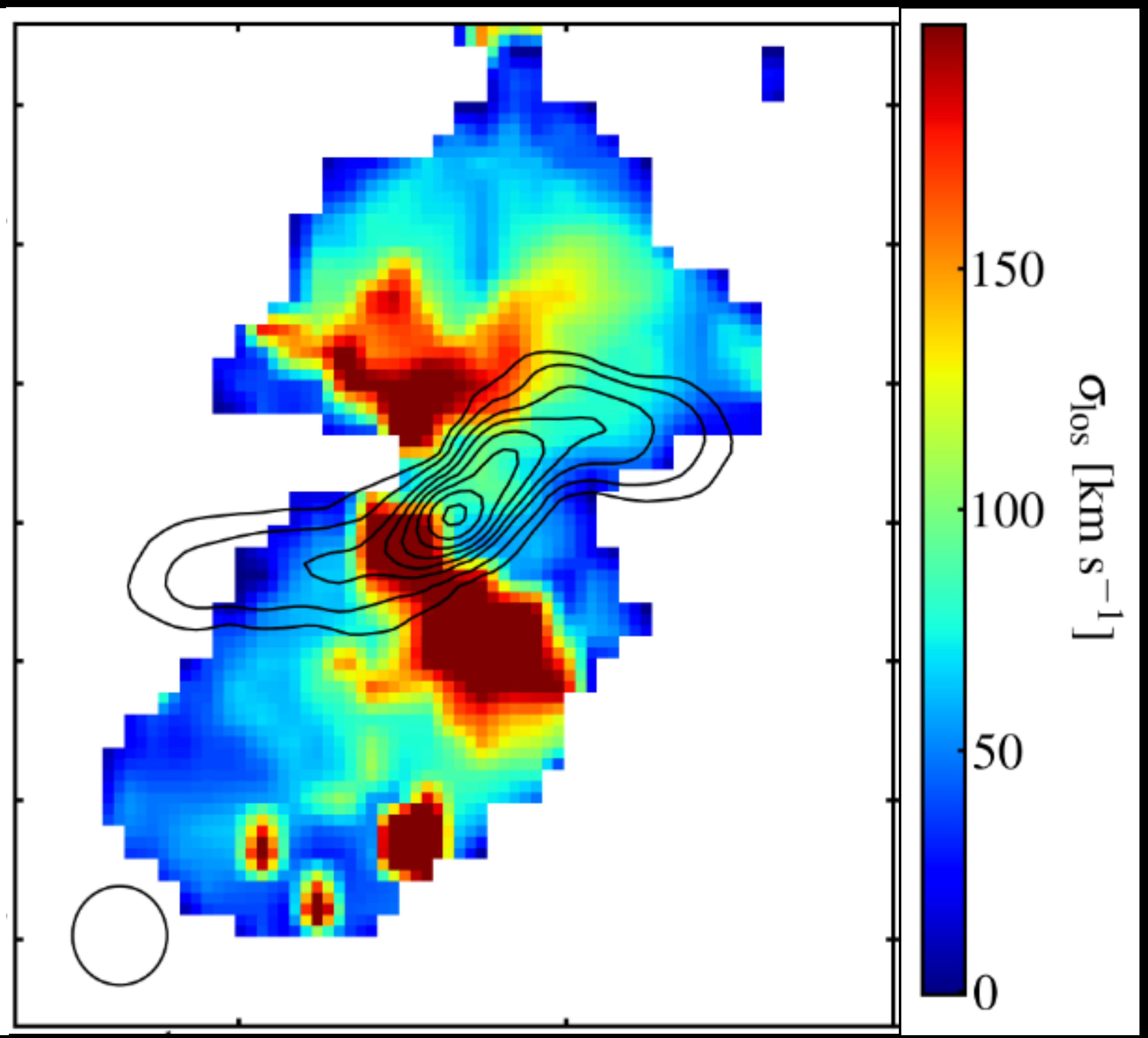
Several deviations from rotation

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

Velocity Field



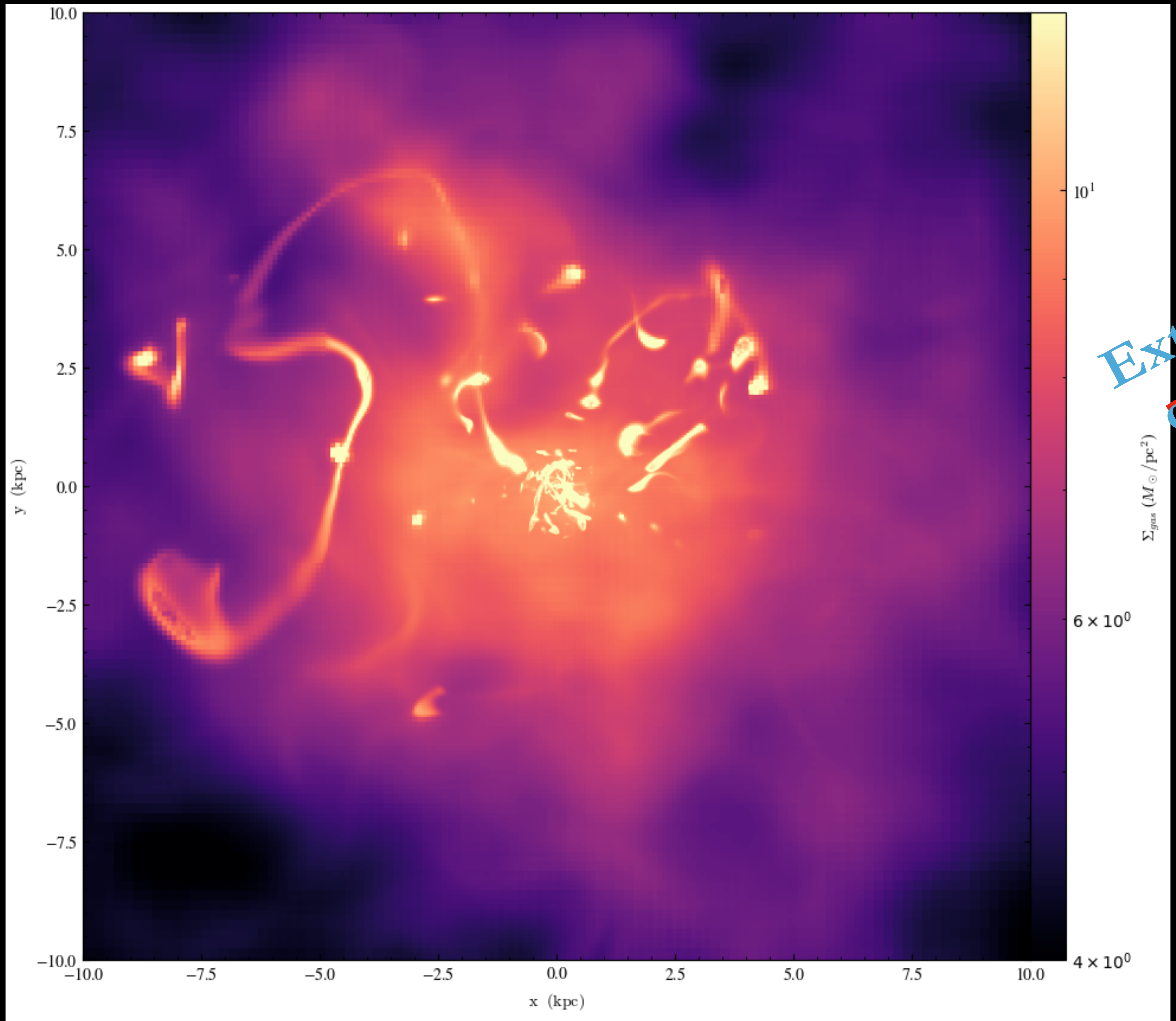
Velocity width map



Maccagni et al., 2021

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)

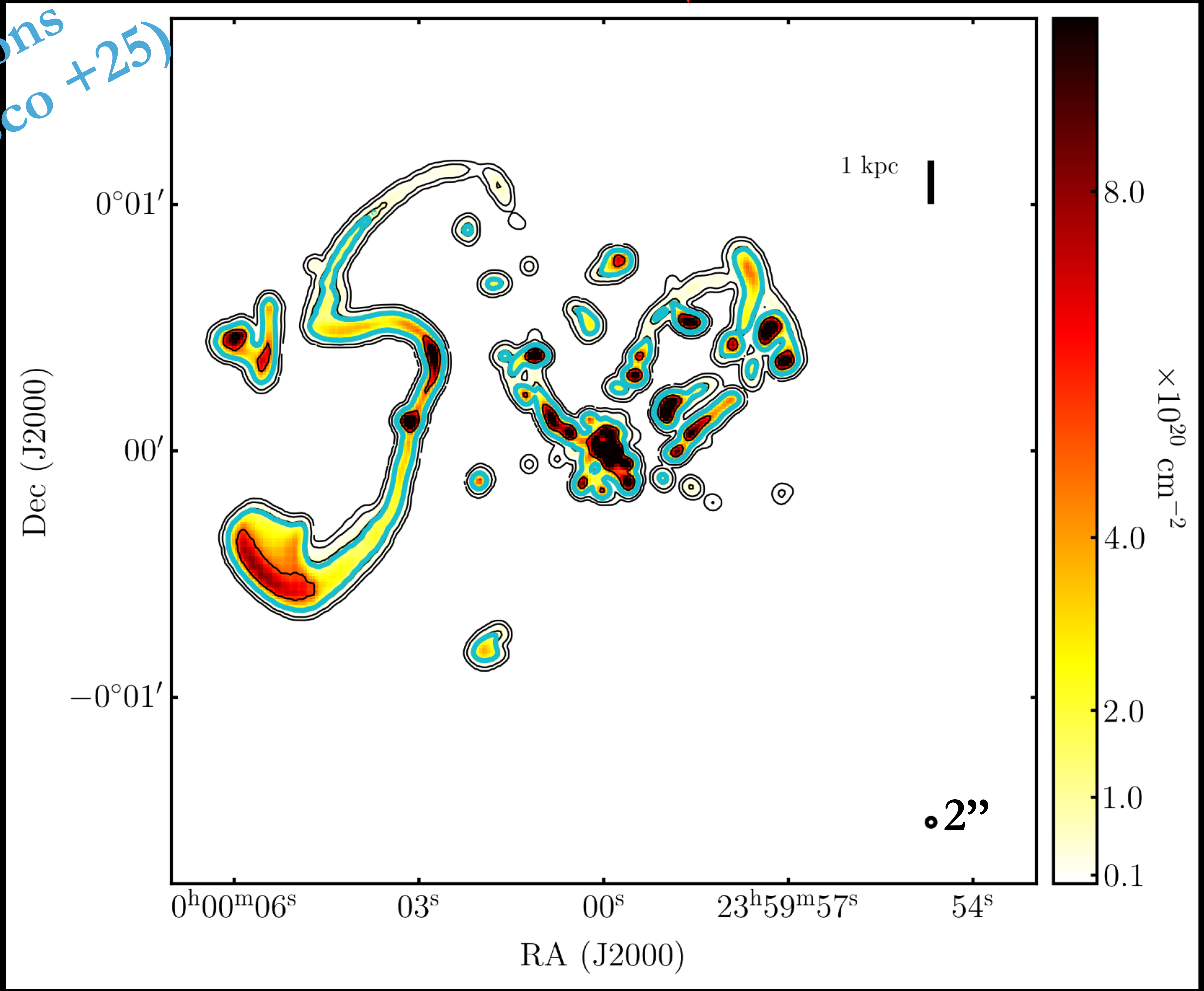


snapshot of multi-phase CCA rain within 8 kpc from the SMBH [Gaspari+17, courtesy of ERC-funded BHW]

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

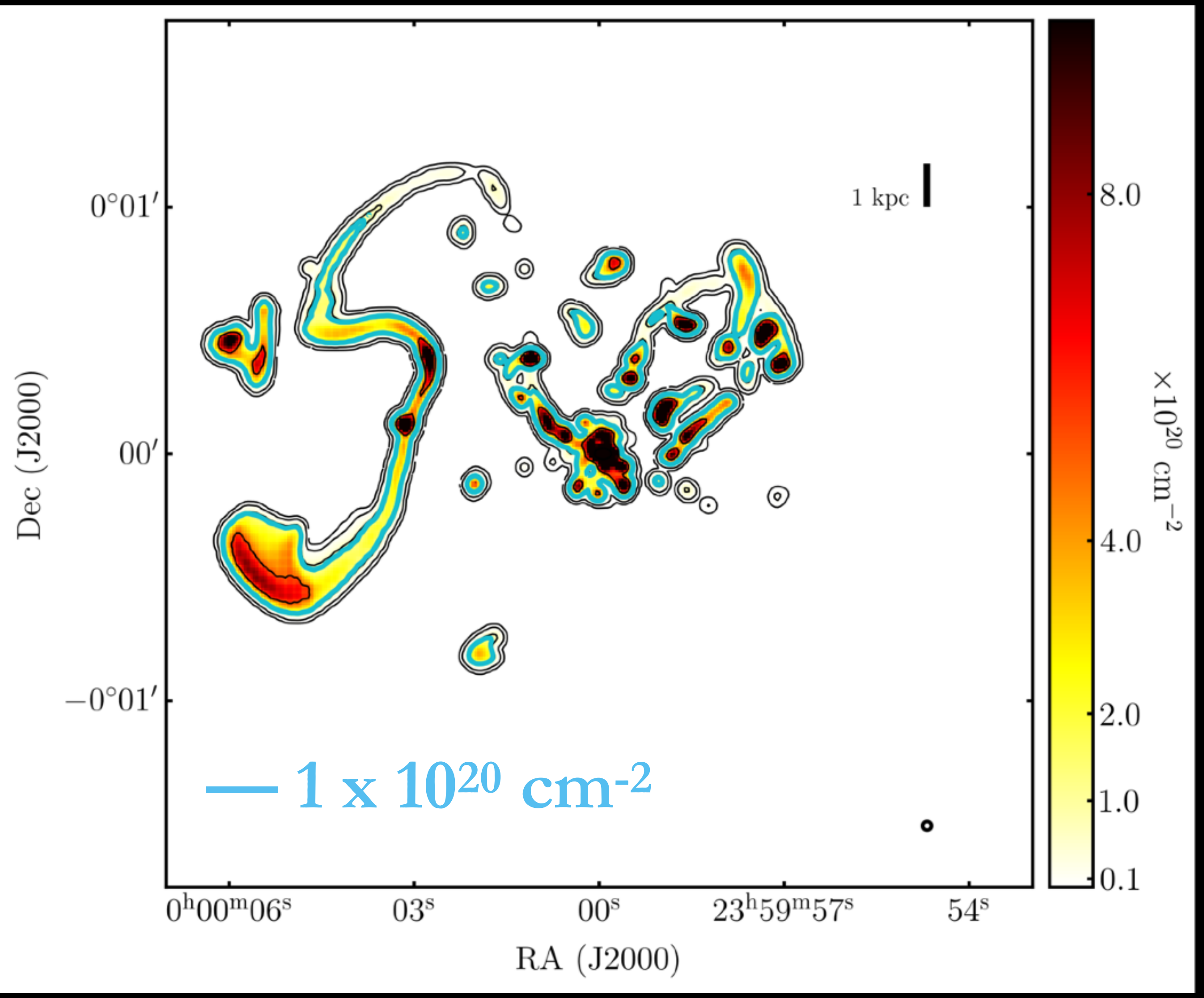
HI : 100-10^4 K

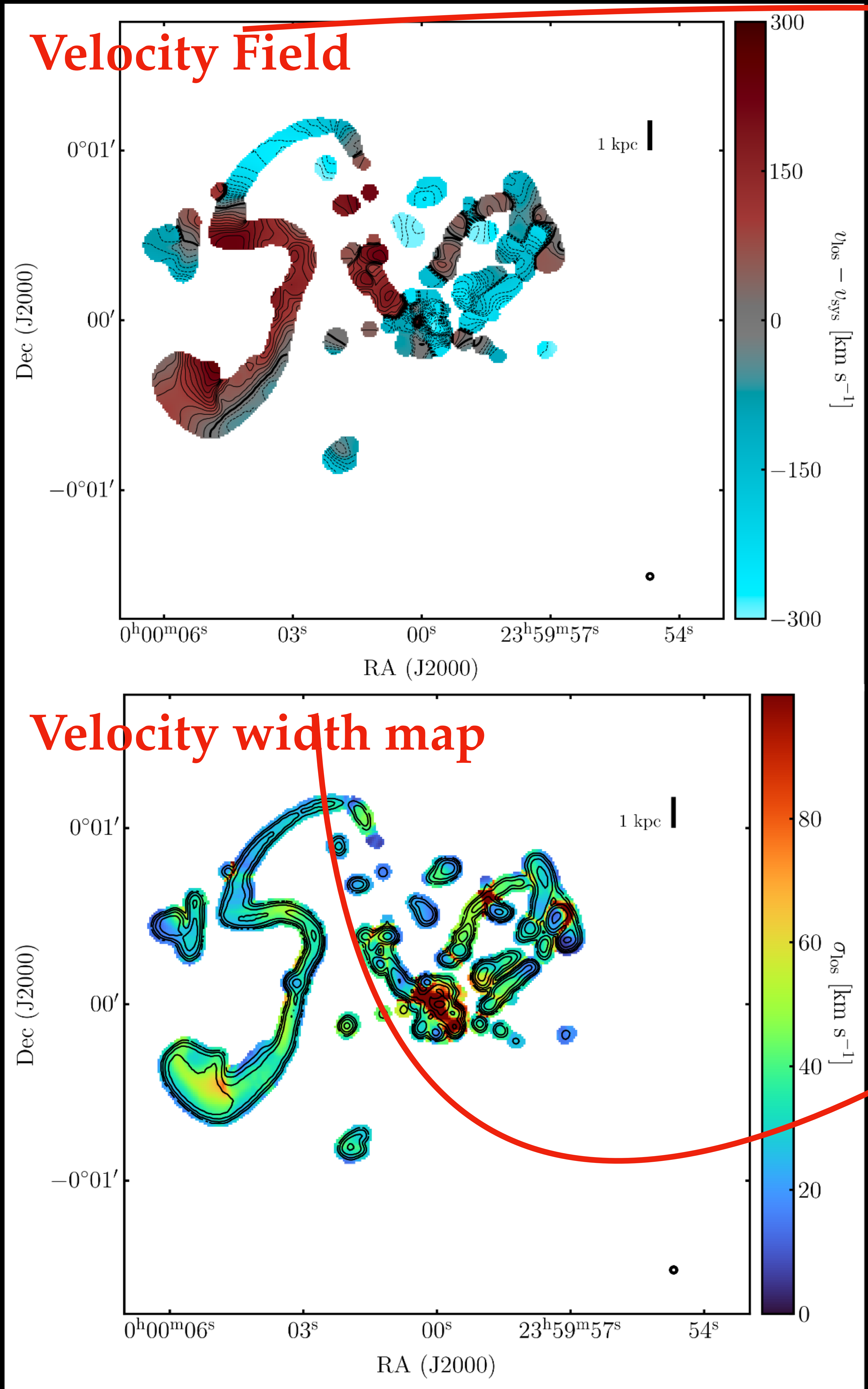
6.6 x 10^7 $M_\odot$



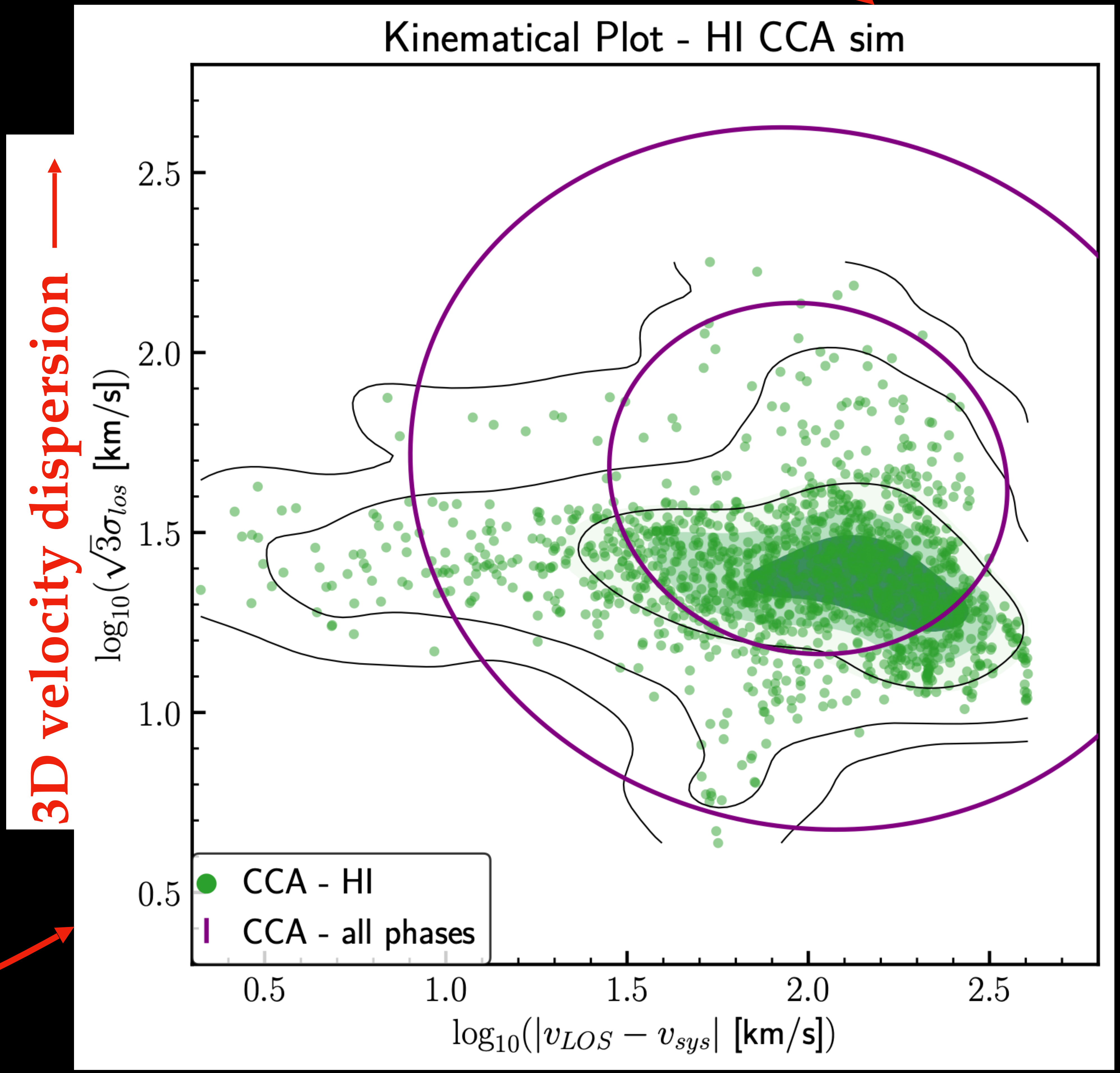
HI in Chaotic Cold Accretion

HI column density map





Kinematical Plot

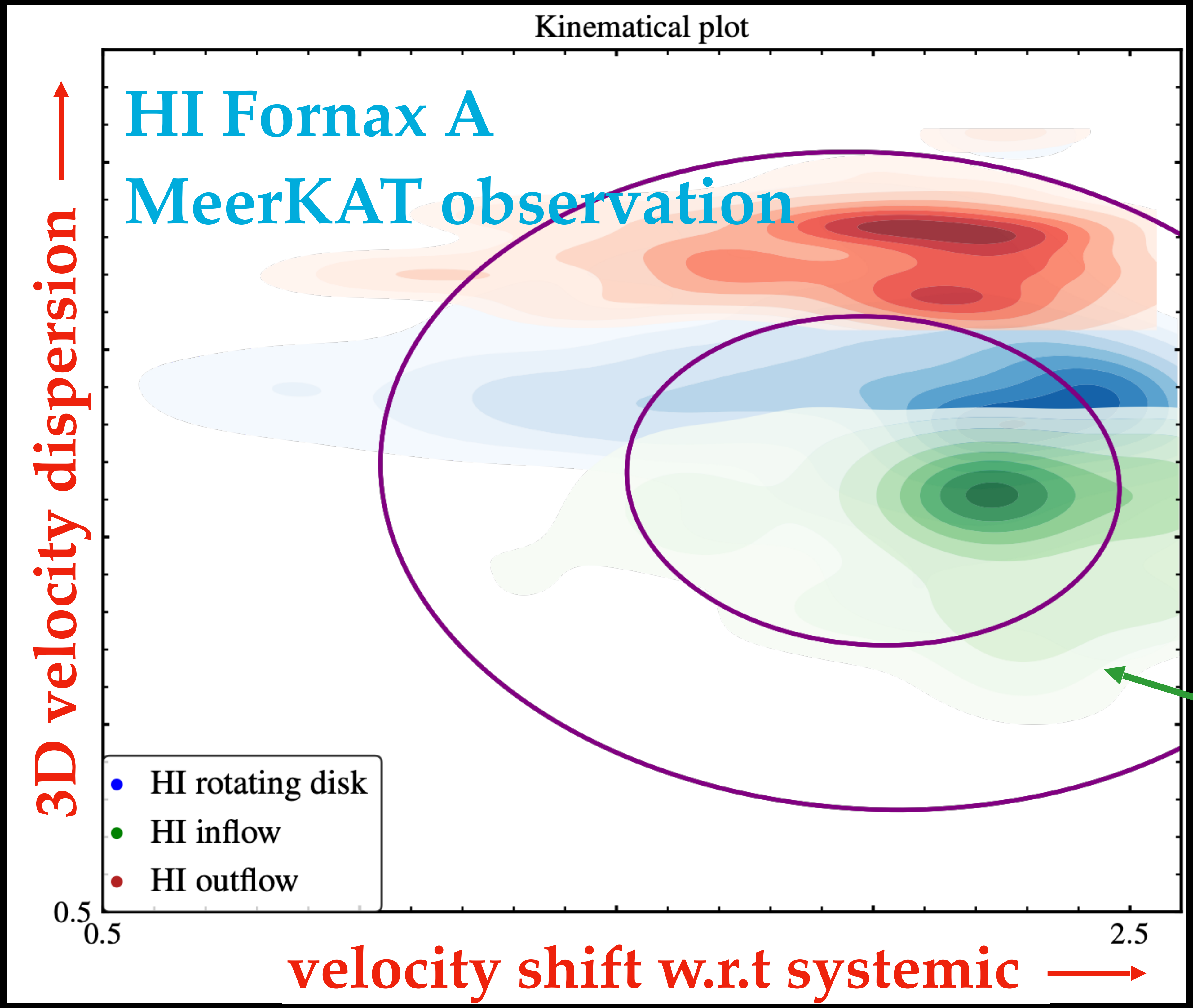


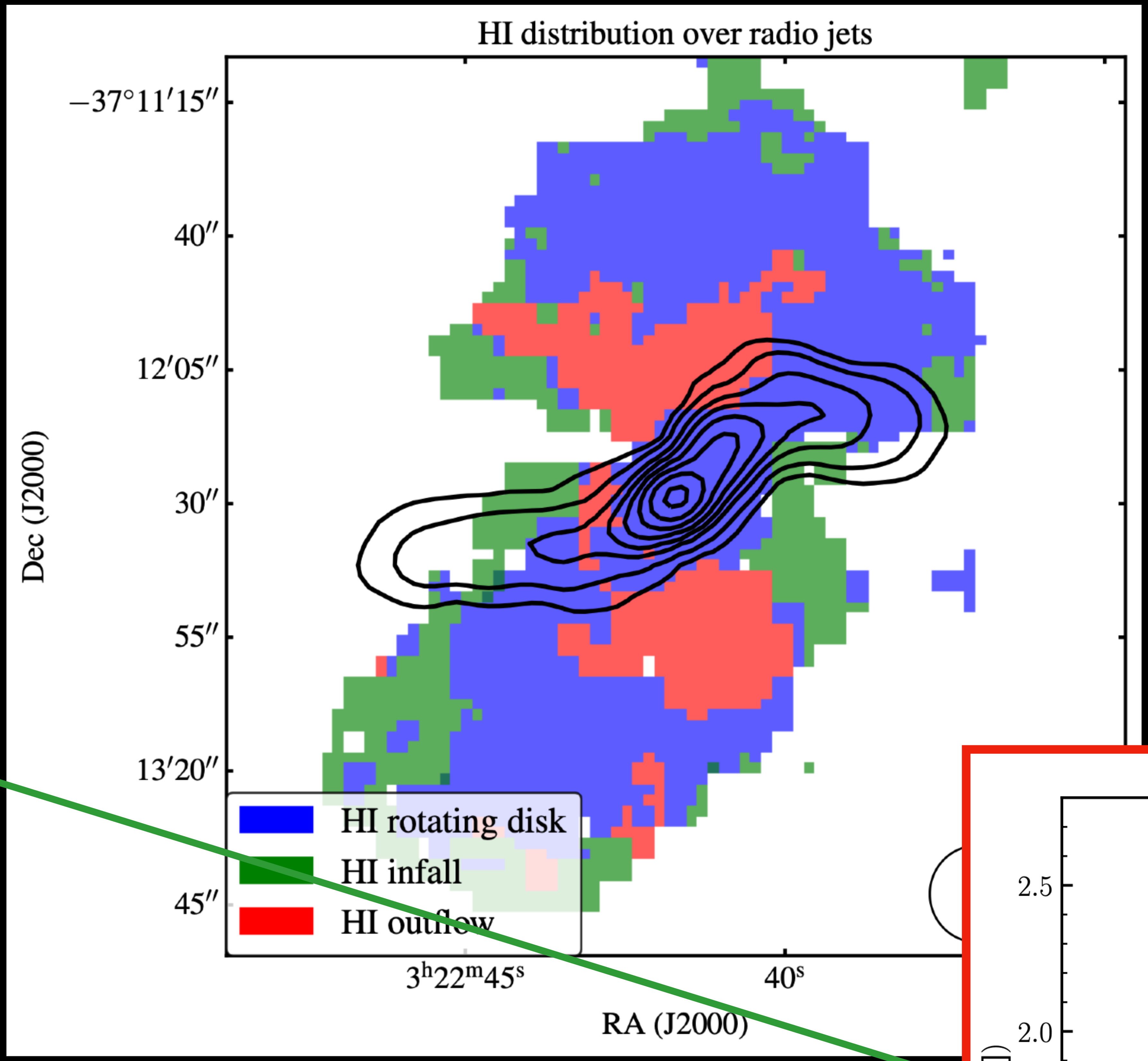
velocity shift w.r.t systemic ⟶

Kinematical plot

naturally identifies loci with similar kinematics

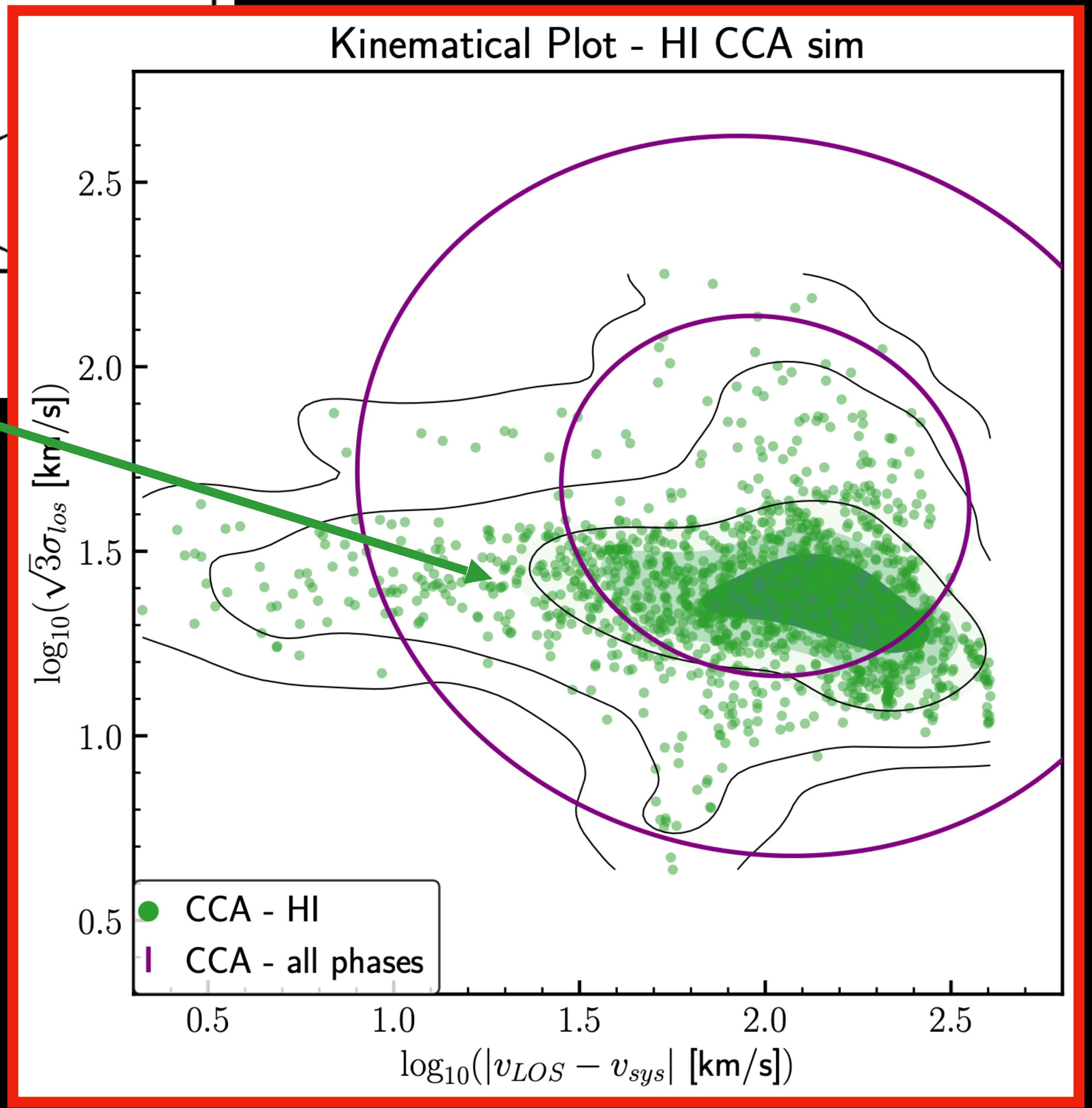
K-plot: Regions with similar kinematics





!!! CAVEATS !!!

- Low resolution and image quality
- Difficult comparison with simulations



intermediate line-widths: rotating gas (from 3D modelling)

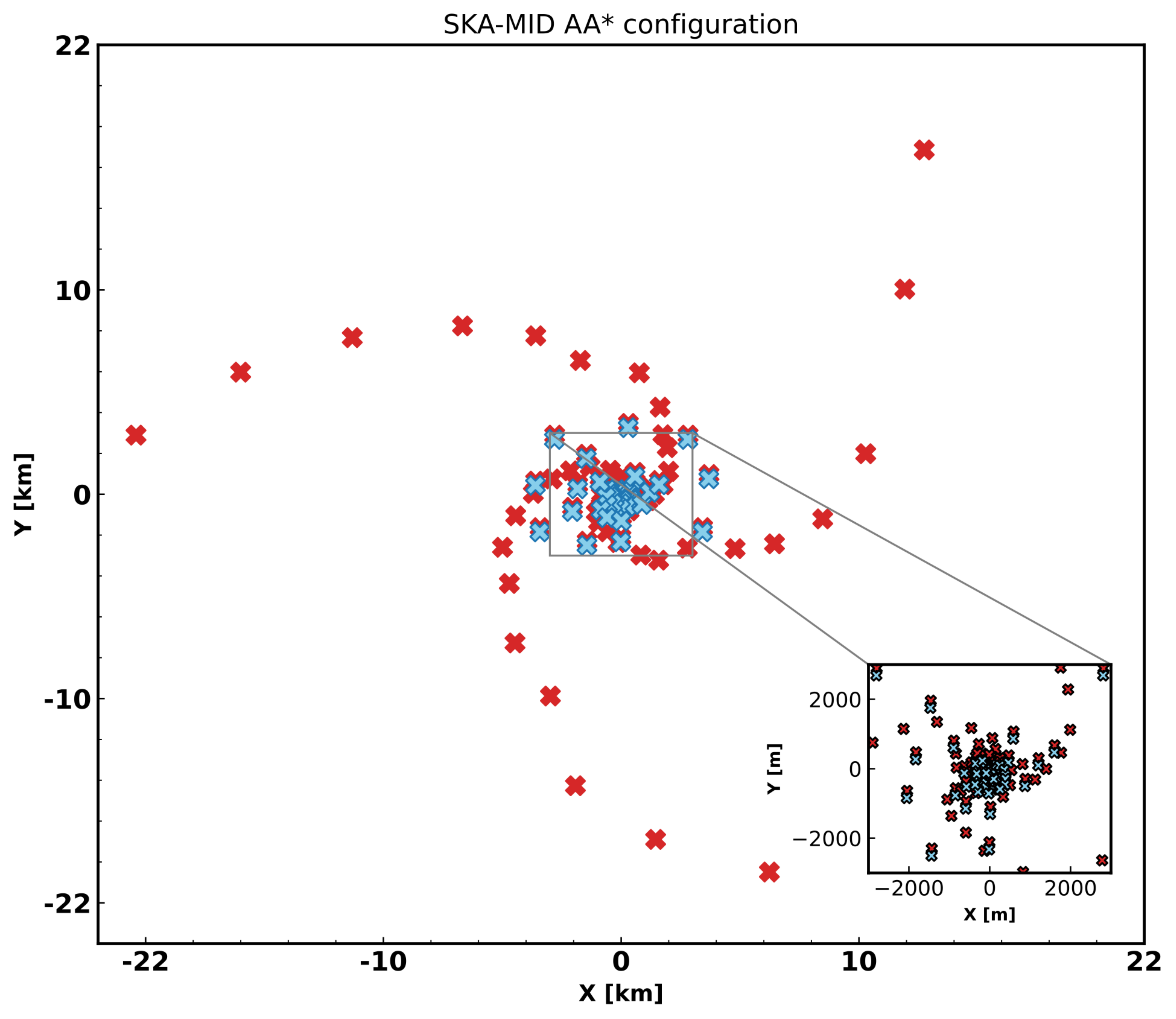
broad line-widths: outflow in the wake of the radio jet

narrow line-widths: EW stripe, **kinematics consistent with CCA**

<u>K-plot of ionised gas (MUSE) and CO (ALMA) show the same properties</u>

SKA-MID AA* - telescope specs

- **64 dishes of 13.5m** + **80 dishes of 15m**
- baselines 29m-36km

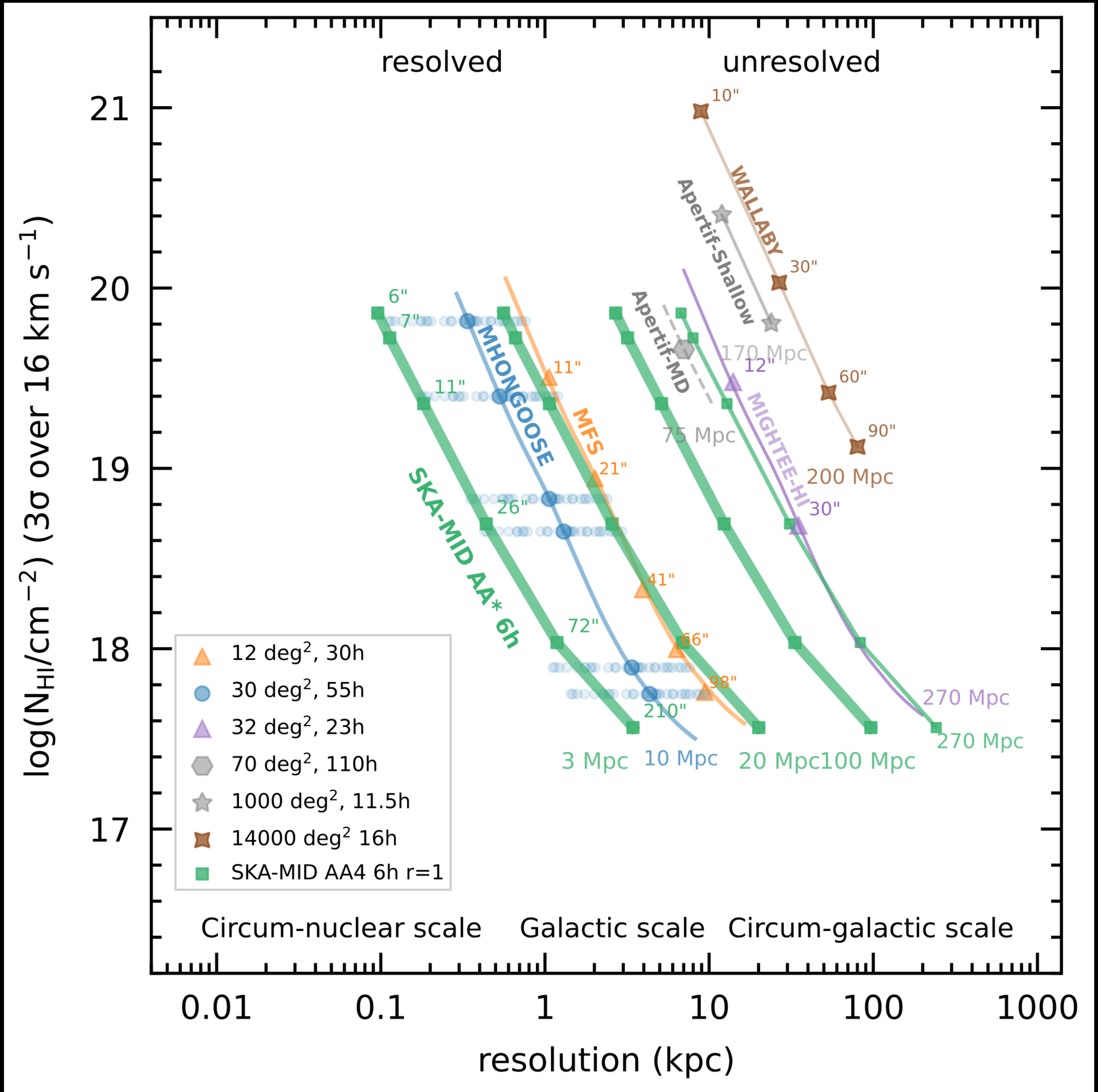


SKA AA* - 5 times faster than MeerKAT

MFS in 6 hours/pointing

r = 1

resolution: > 6″

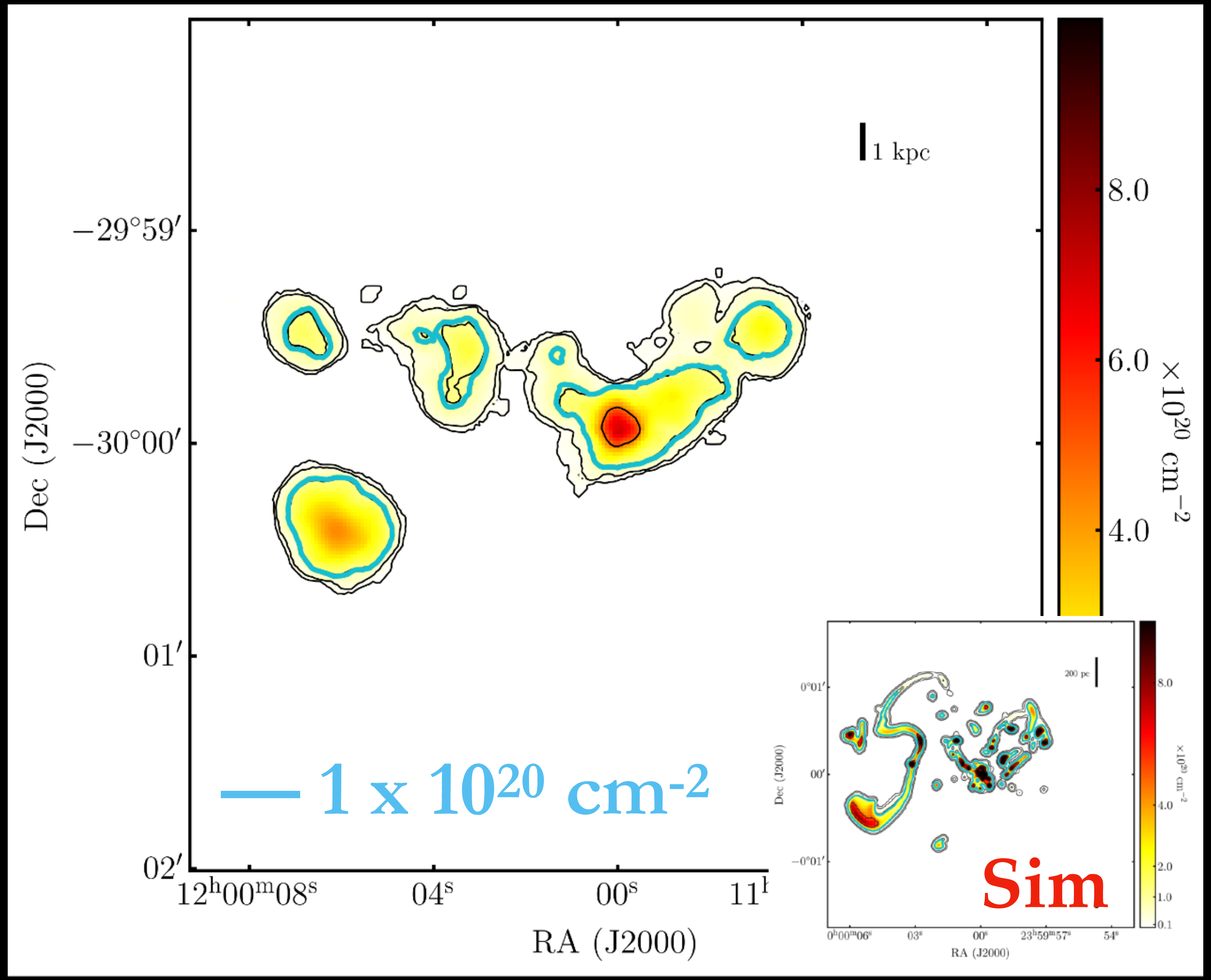


SKA AA* - CCA in Fornax A observed in 6 hrs

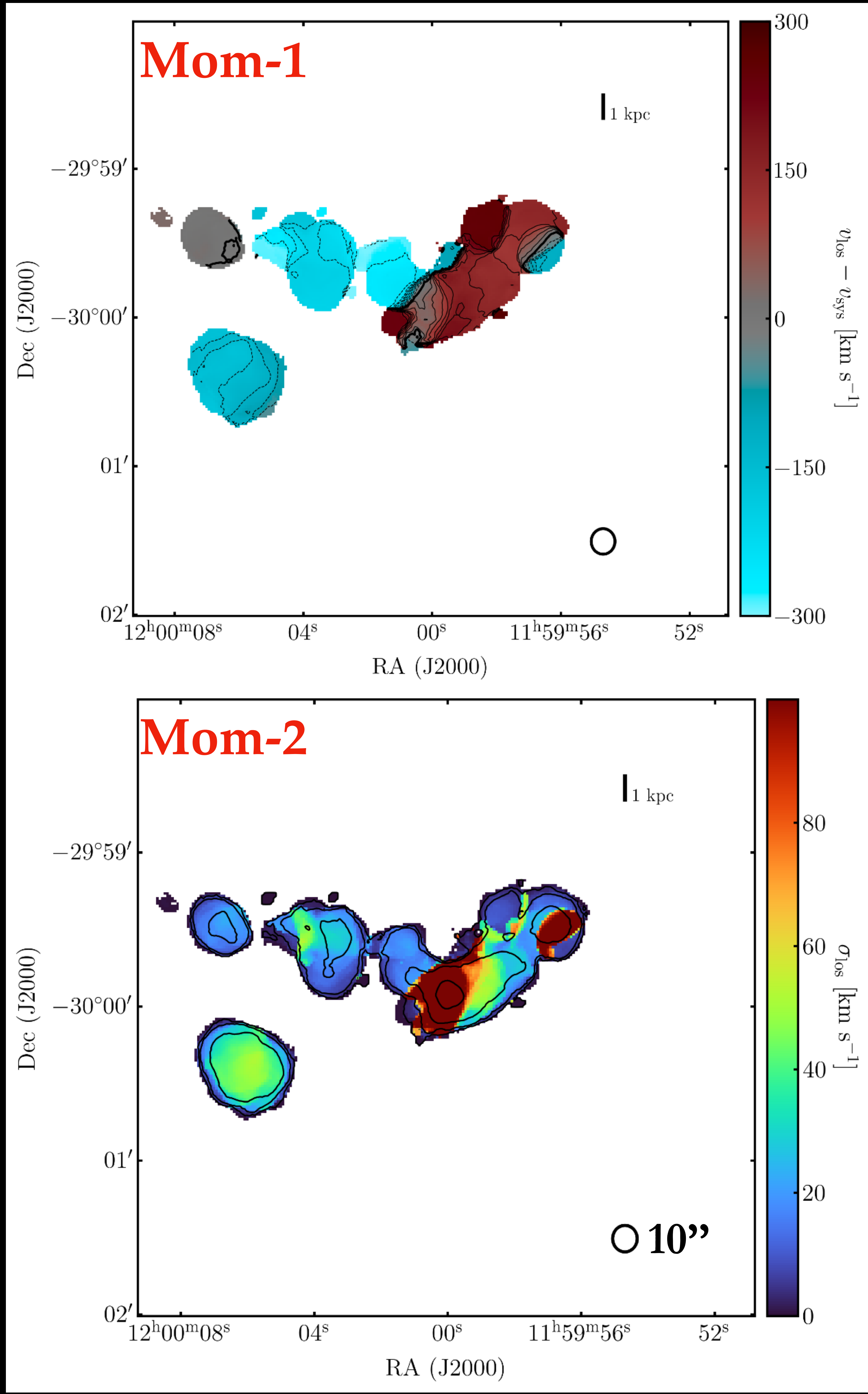
Synthetic SKA-MID AA* observation of neutral hydrogen from CCA simulation

$M_{HI} = 6.6 \times 10^7\ M_\odot$ (as in Fornax A)

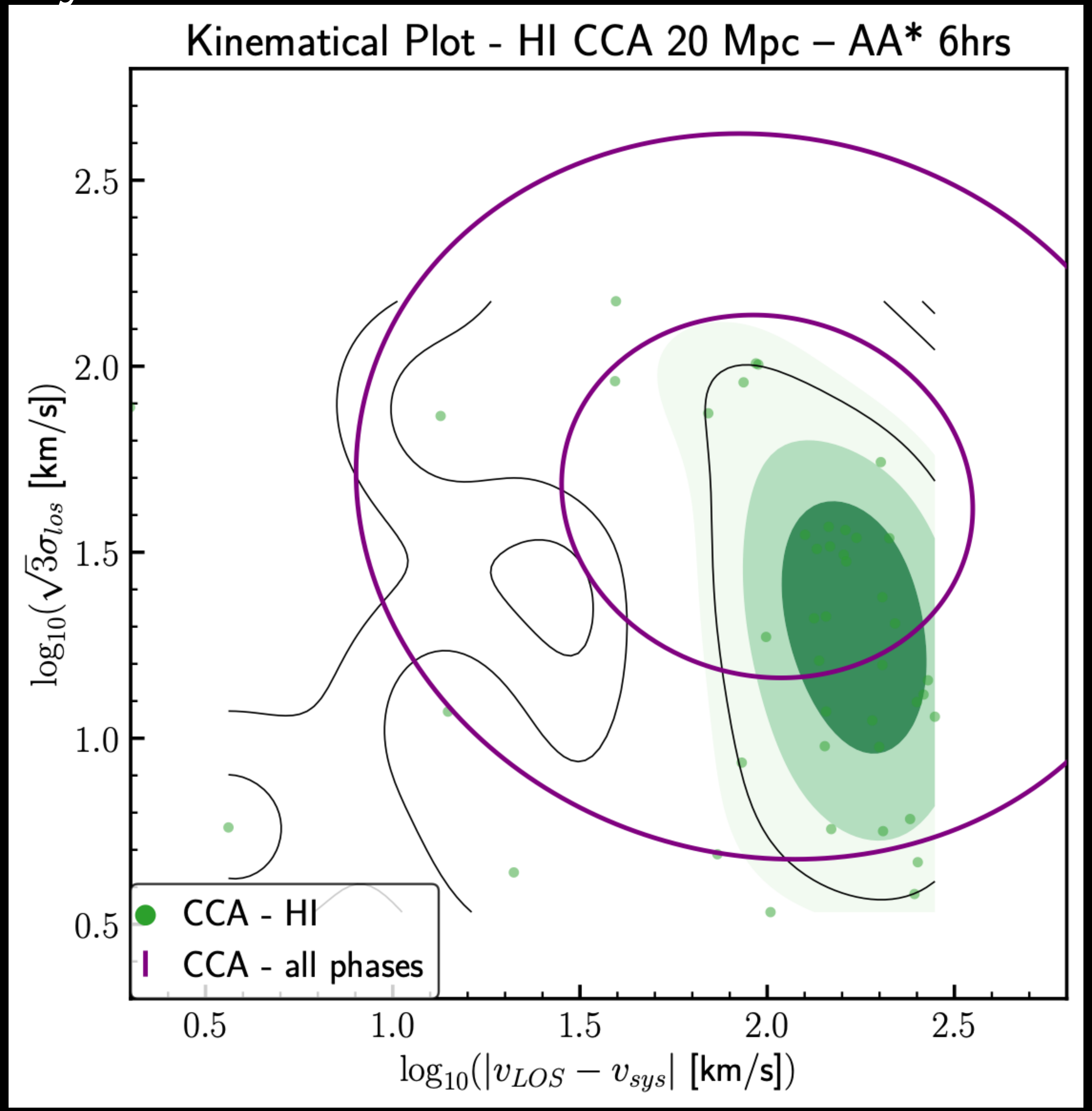
D = 3.4 Mpc



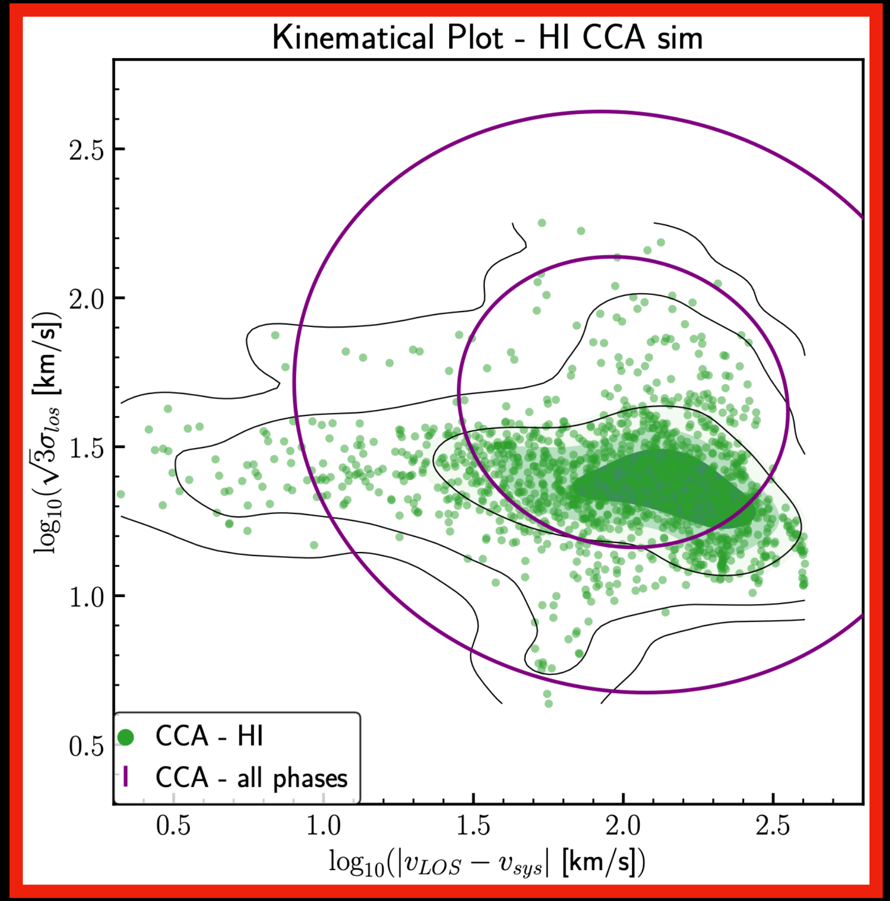
Deconvolution, HI cleaning and source finding with same pipeline of MFS



Synthetic Observation



Simulation



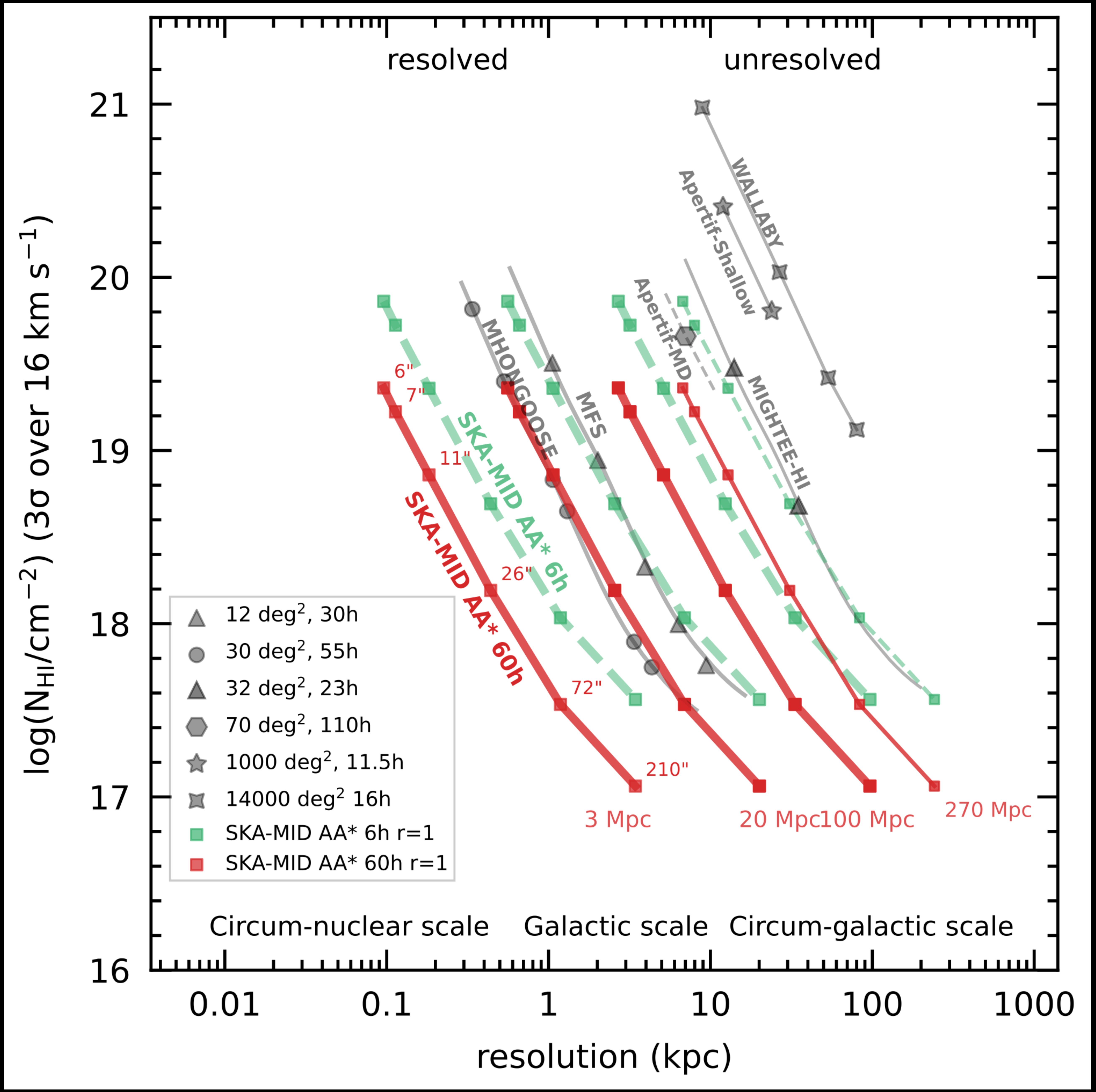
SKA AA* Deep - Exploring a new space of AGN F&F

60 hours (r=1):

HI ~10^{19} cm^{-2}

@ kilo-parsec

resolution

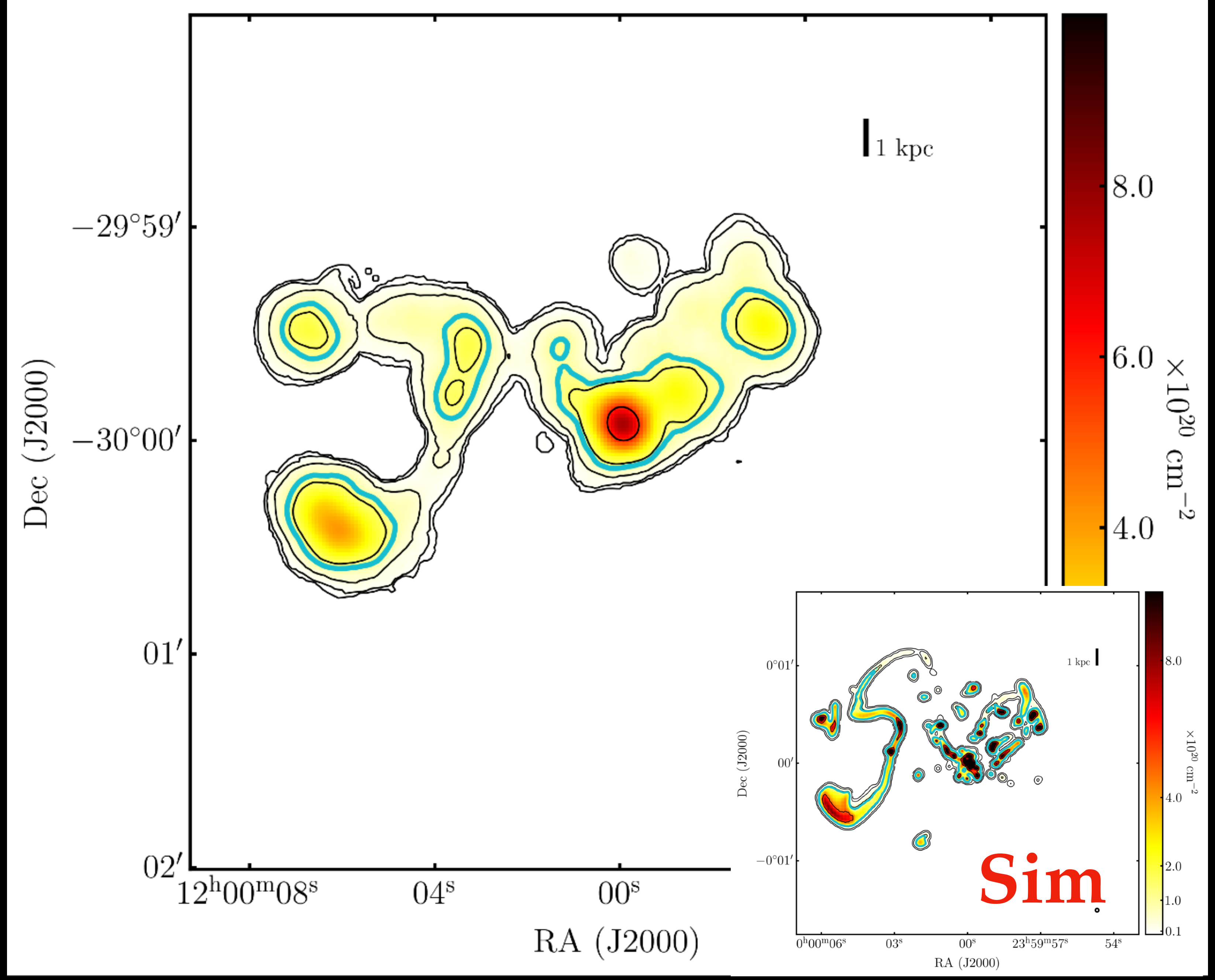


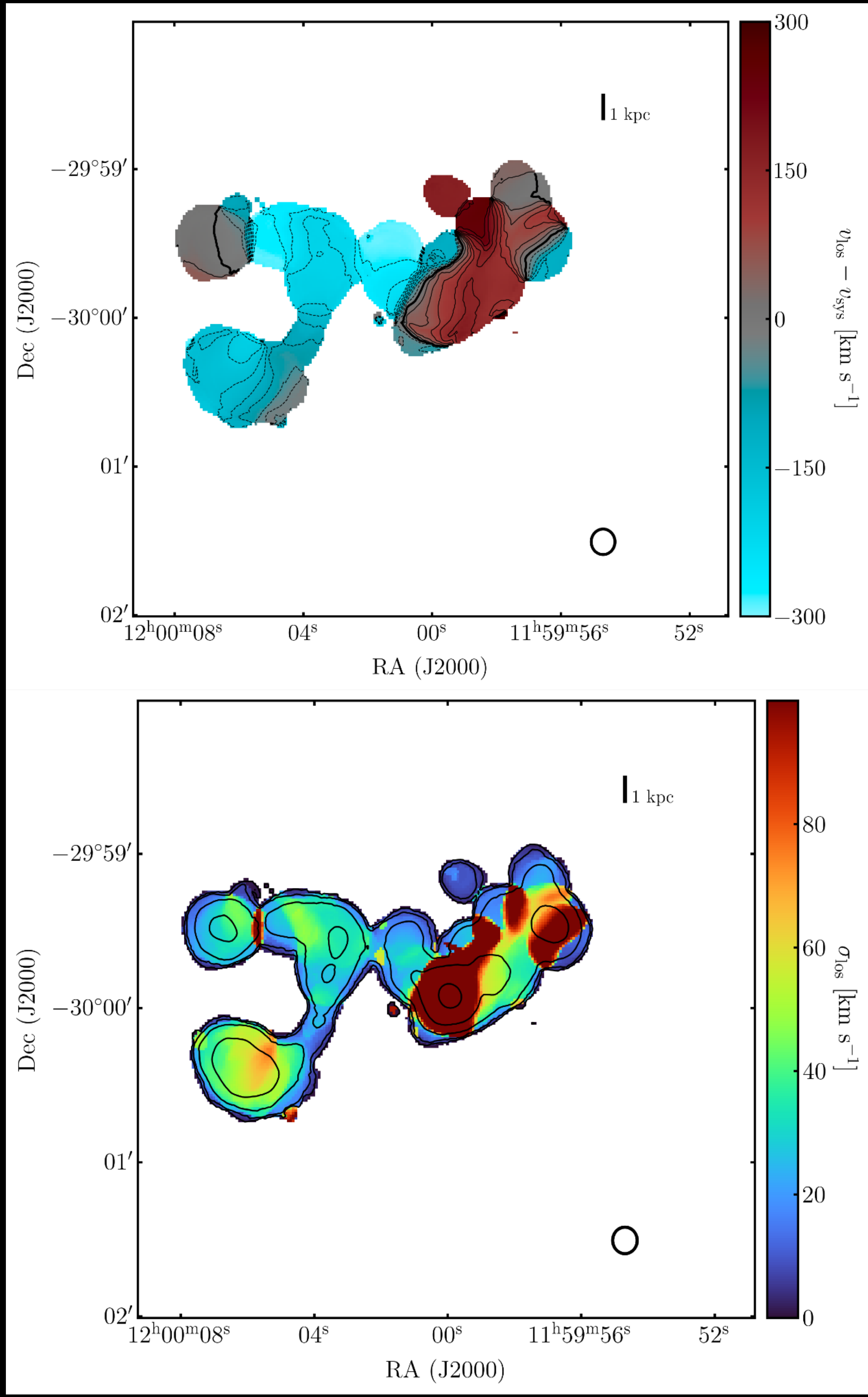
SKA AA* - CCA in Fornax A observed in 60 hrs

Synthetic SKA AA* HI observation

$M_{HI} = 6.6 \times 10^7 M_\odot$ (as in Fornax A)

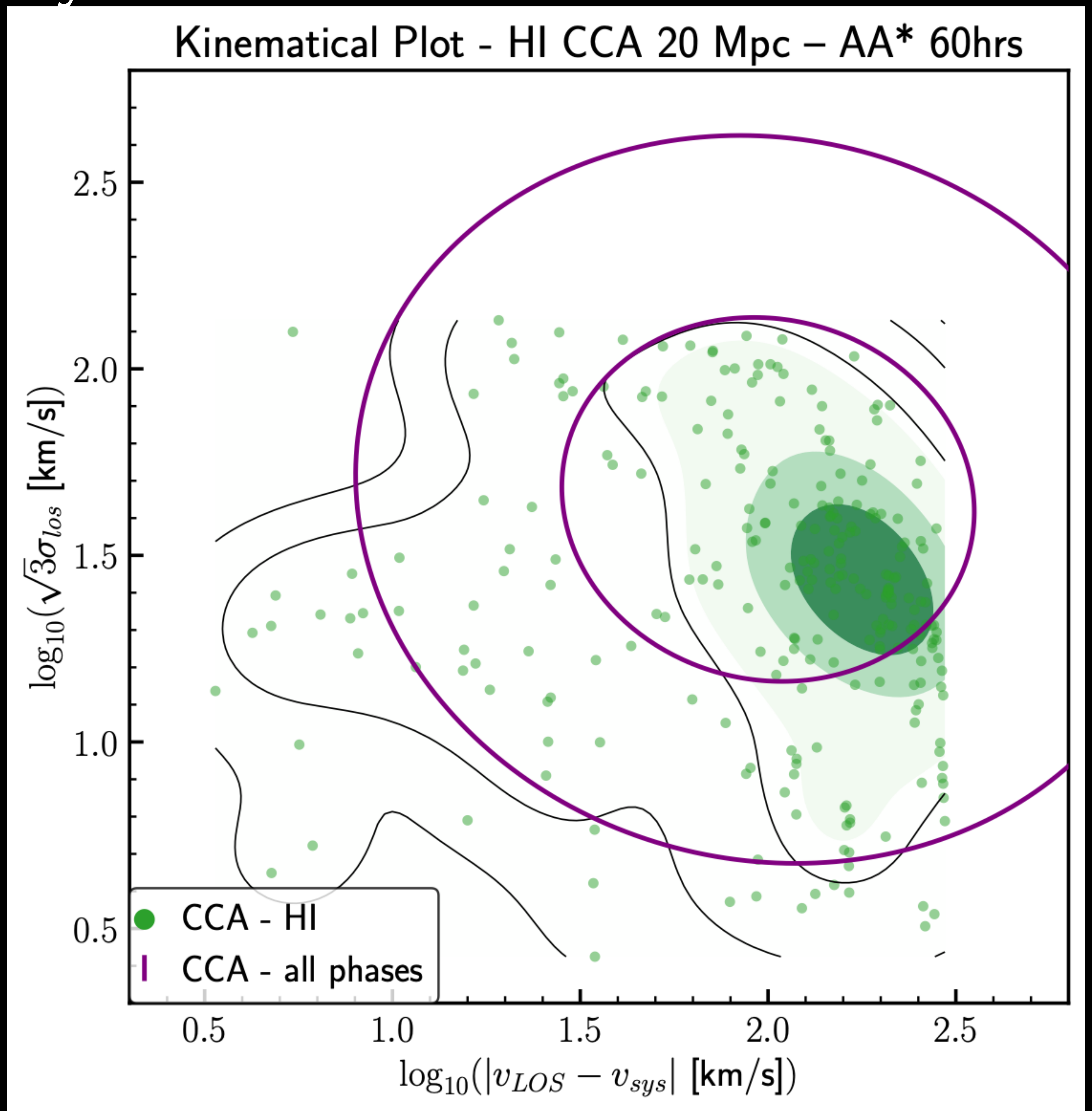
D = 20 Mpc



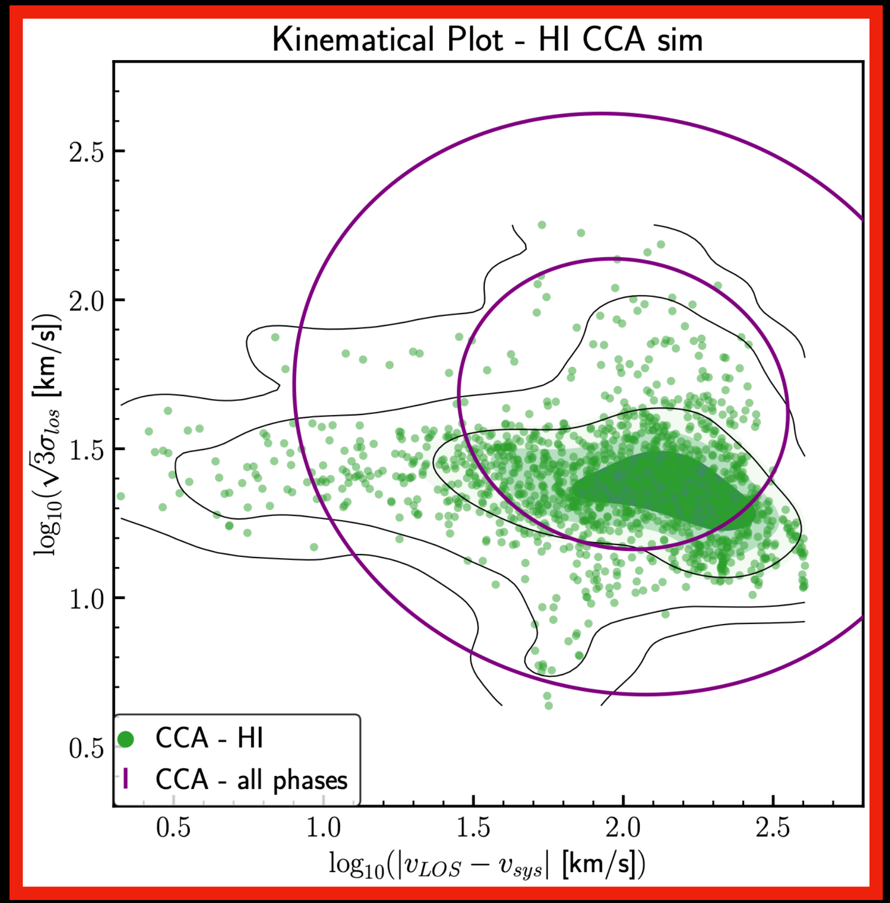


Deconvolution, HI cleaning, source finding with same pipeline of MFS

Synthetic Observation

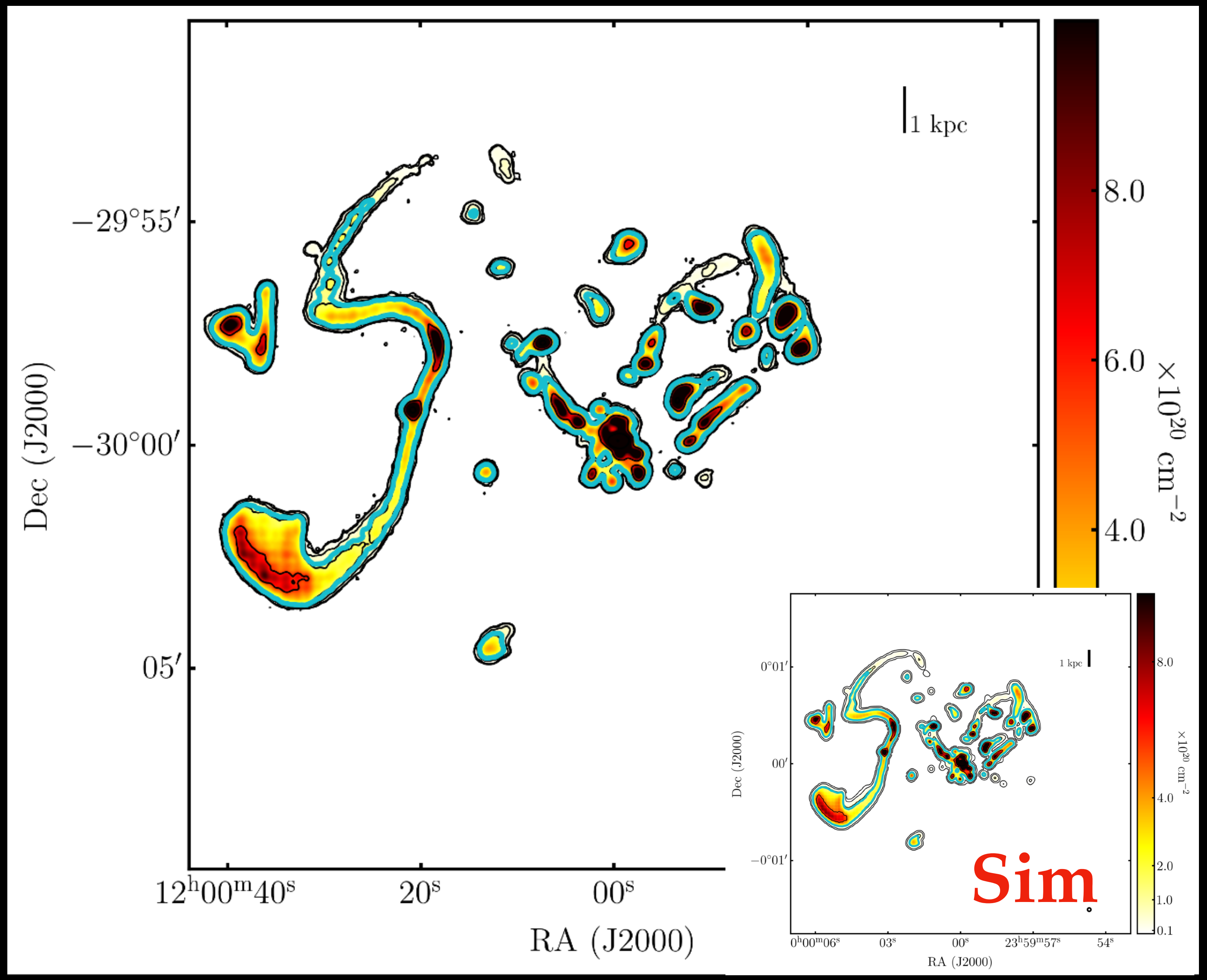


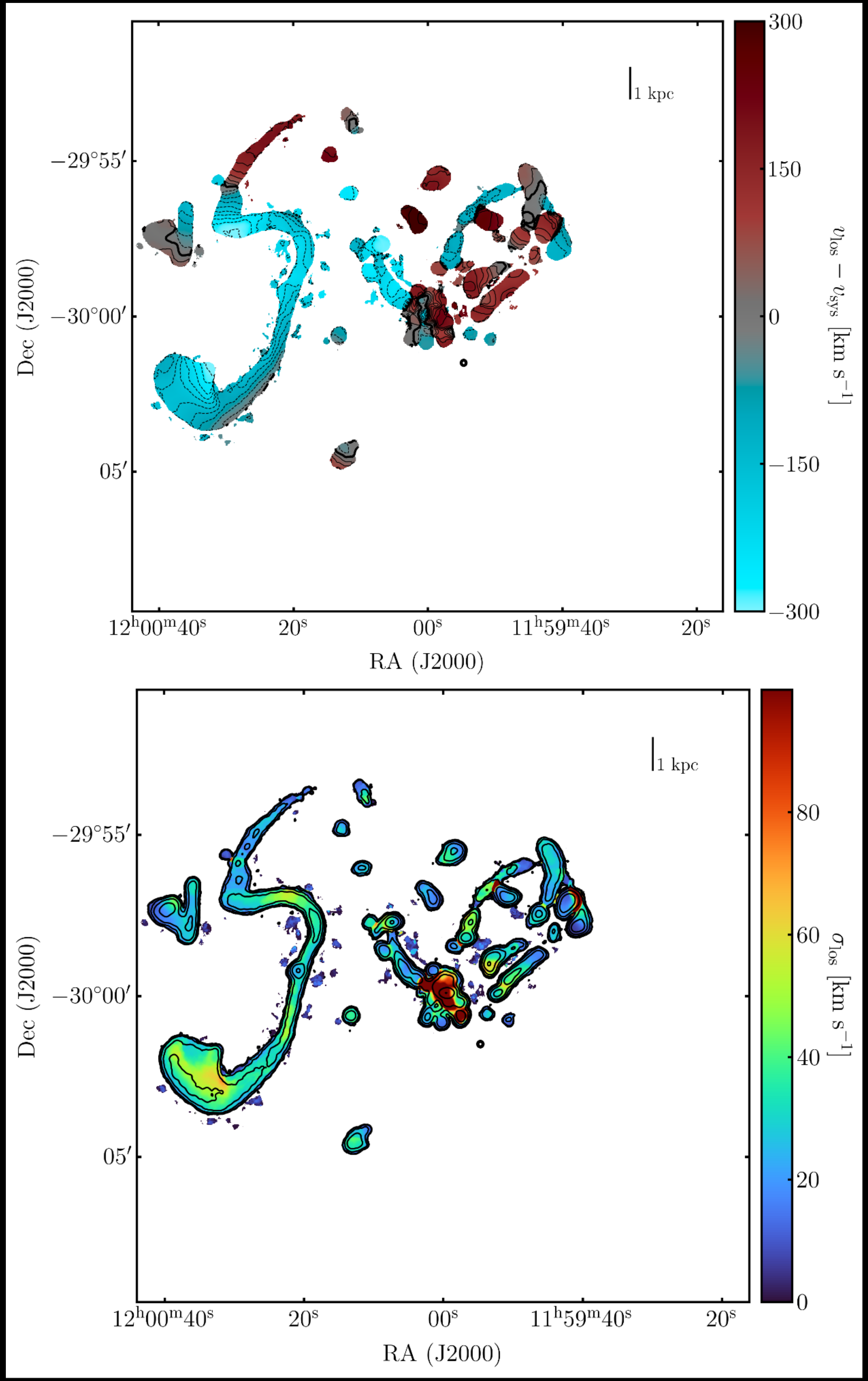
Simulation



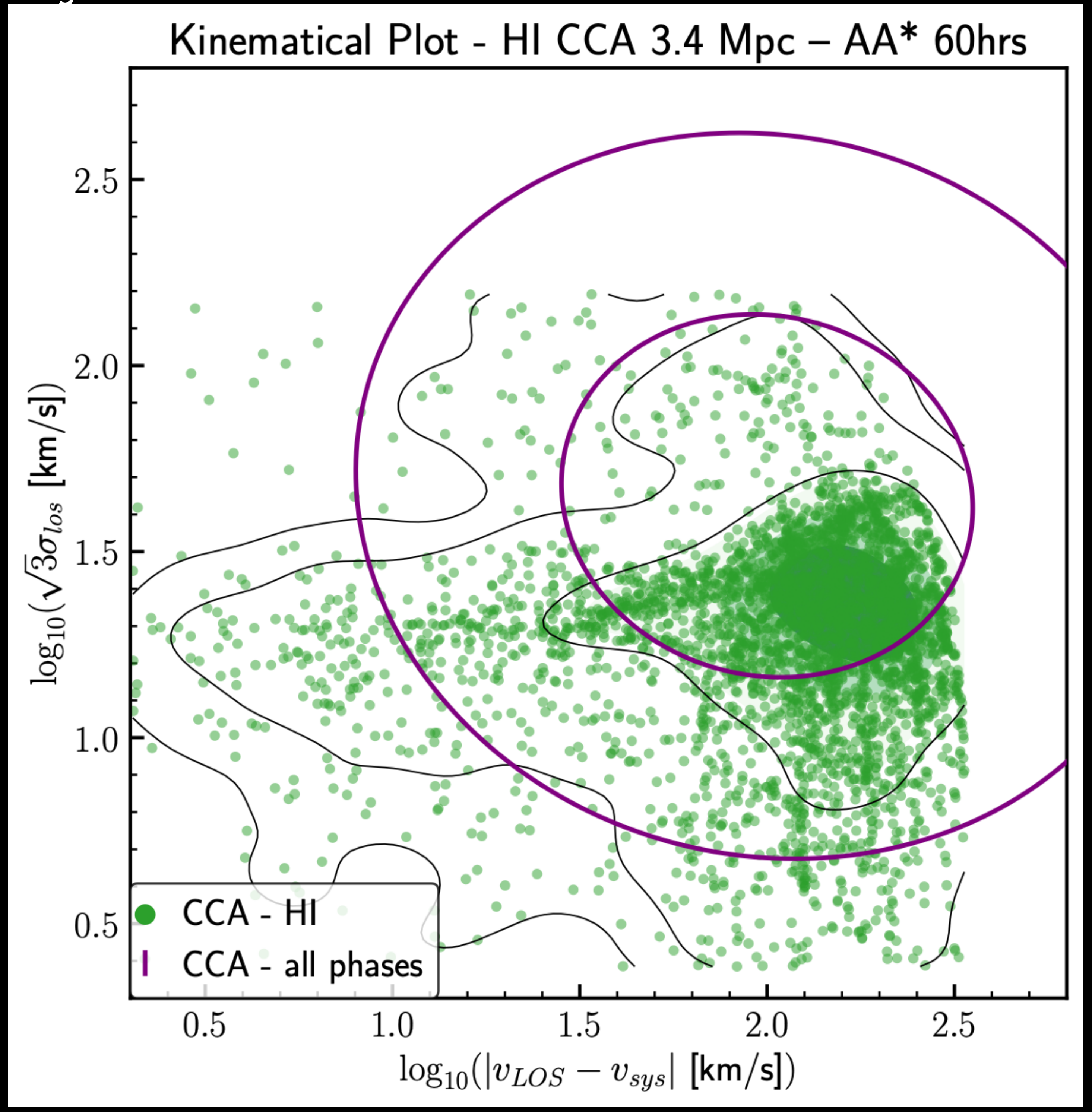
SKA AA* - CCA in Centaurus A observed in 60 hrs

Synthetic SKA AA* HI observation
M_{HI} = 6.6x10^7 $M_\odot$ (as in Fornax A)
D = 3.4 Mpc

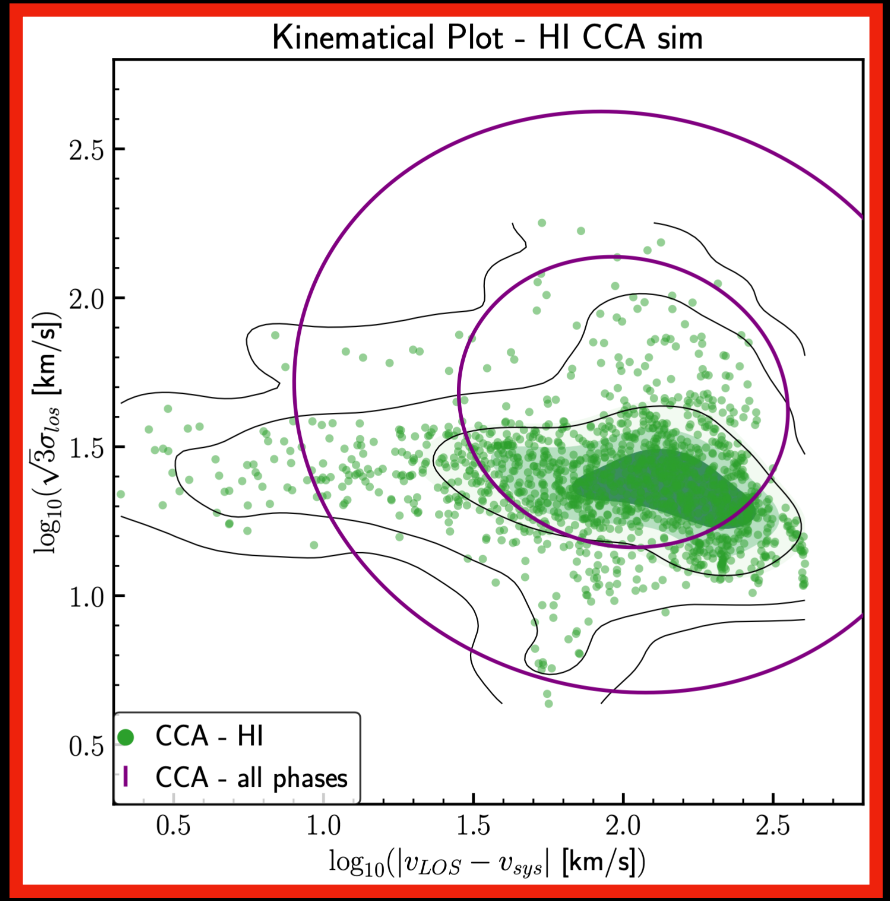




Synthetic Observation

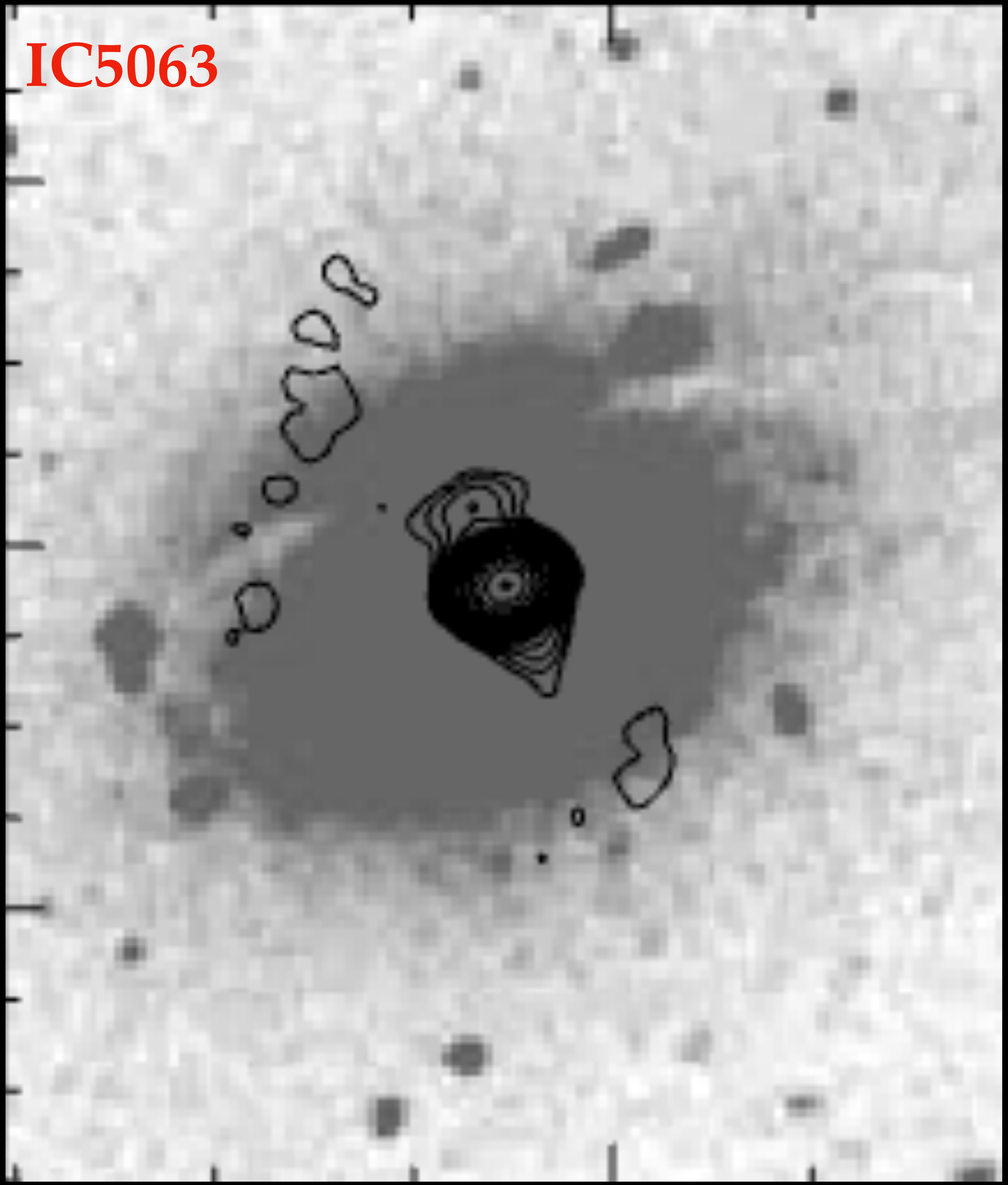


Simulation



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

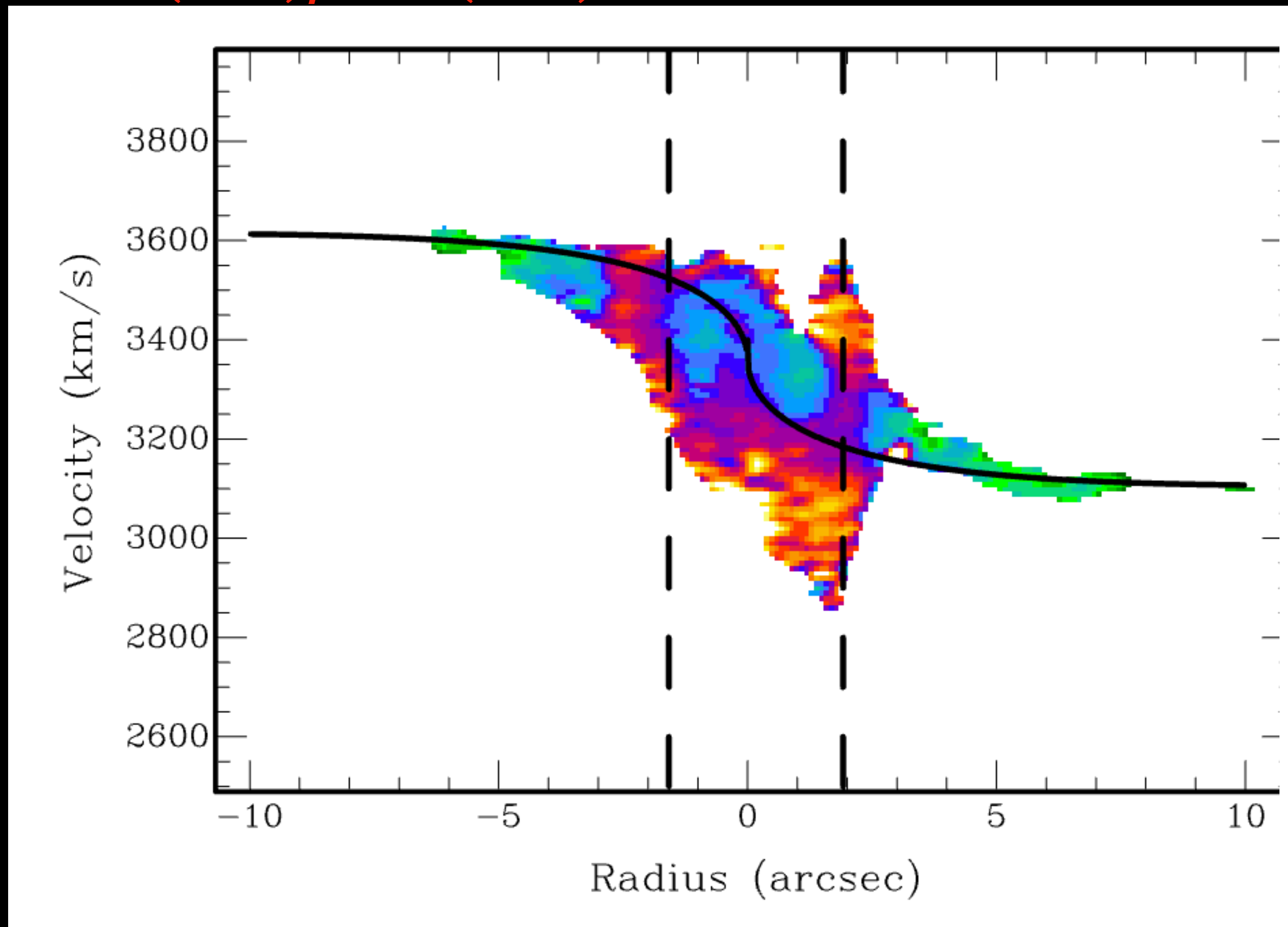
Radio continuum - jets and lobes at Low and Mid frequencies



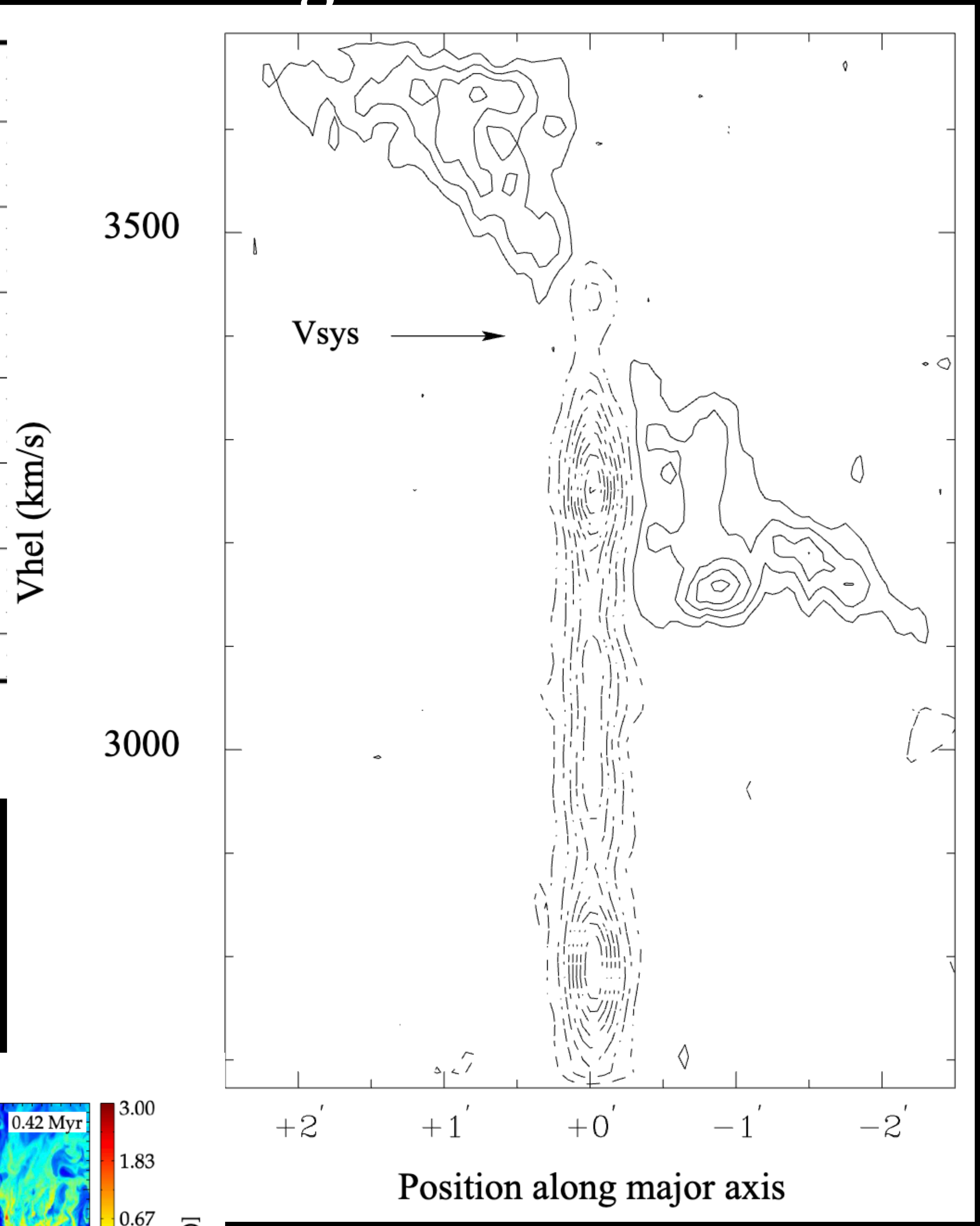
Morganti+98

Jets entrain an HI and CO outflow across the disk

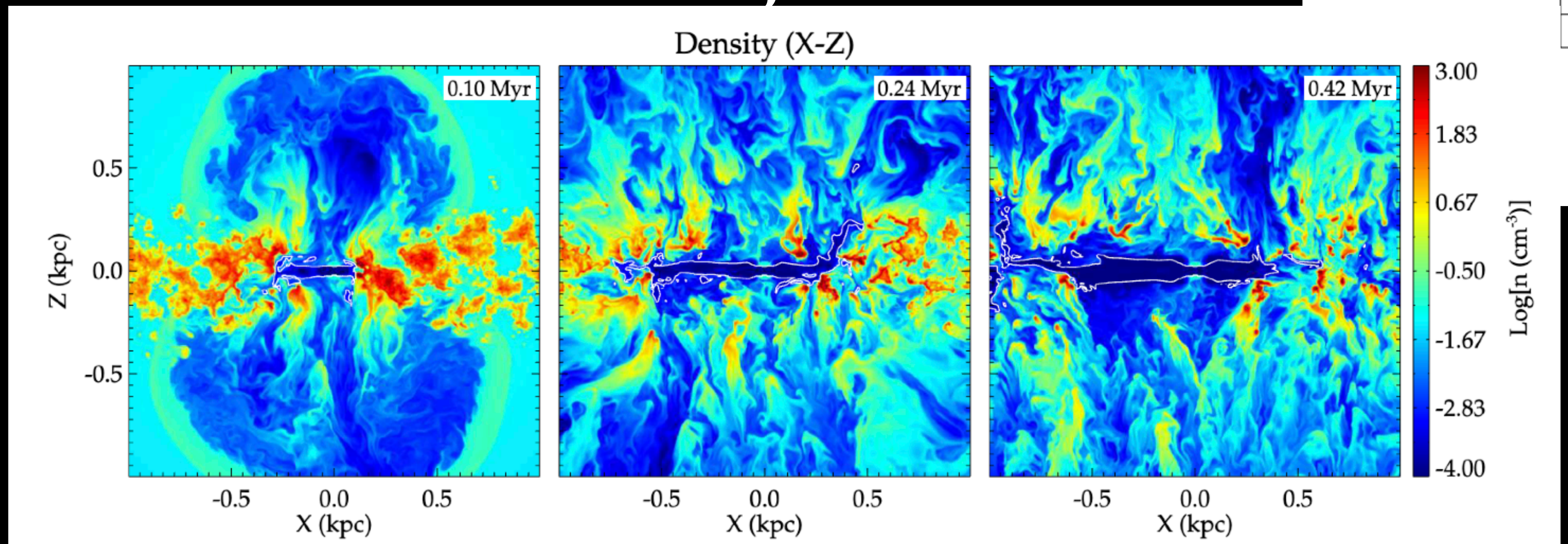
CO (3-2)/CO(2-1) - Oosterloo+17



HI - Morganti+98

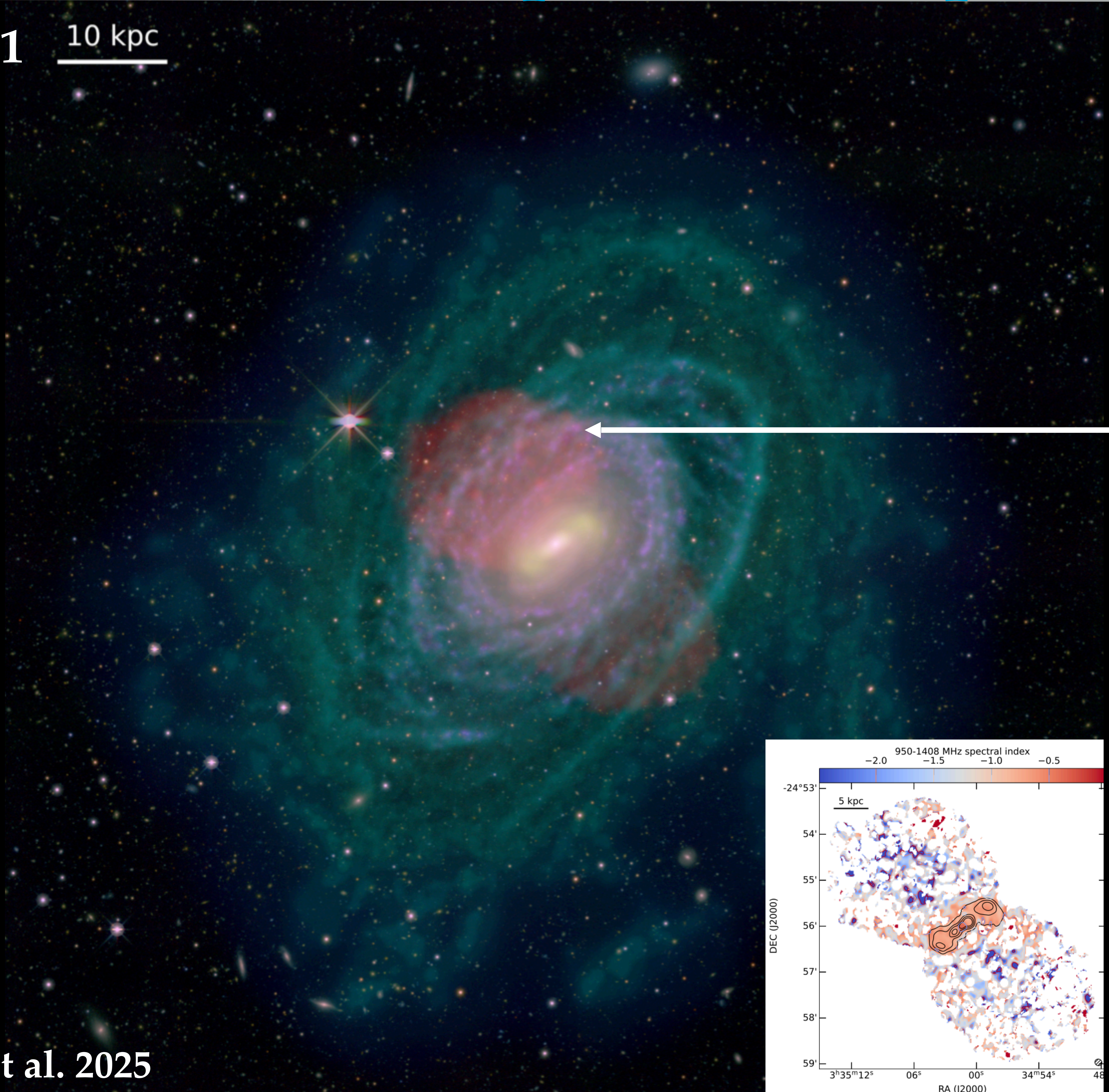


Simulation - Mukherjee+18

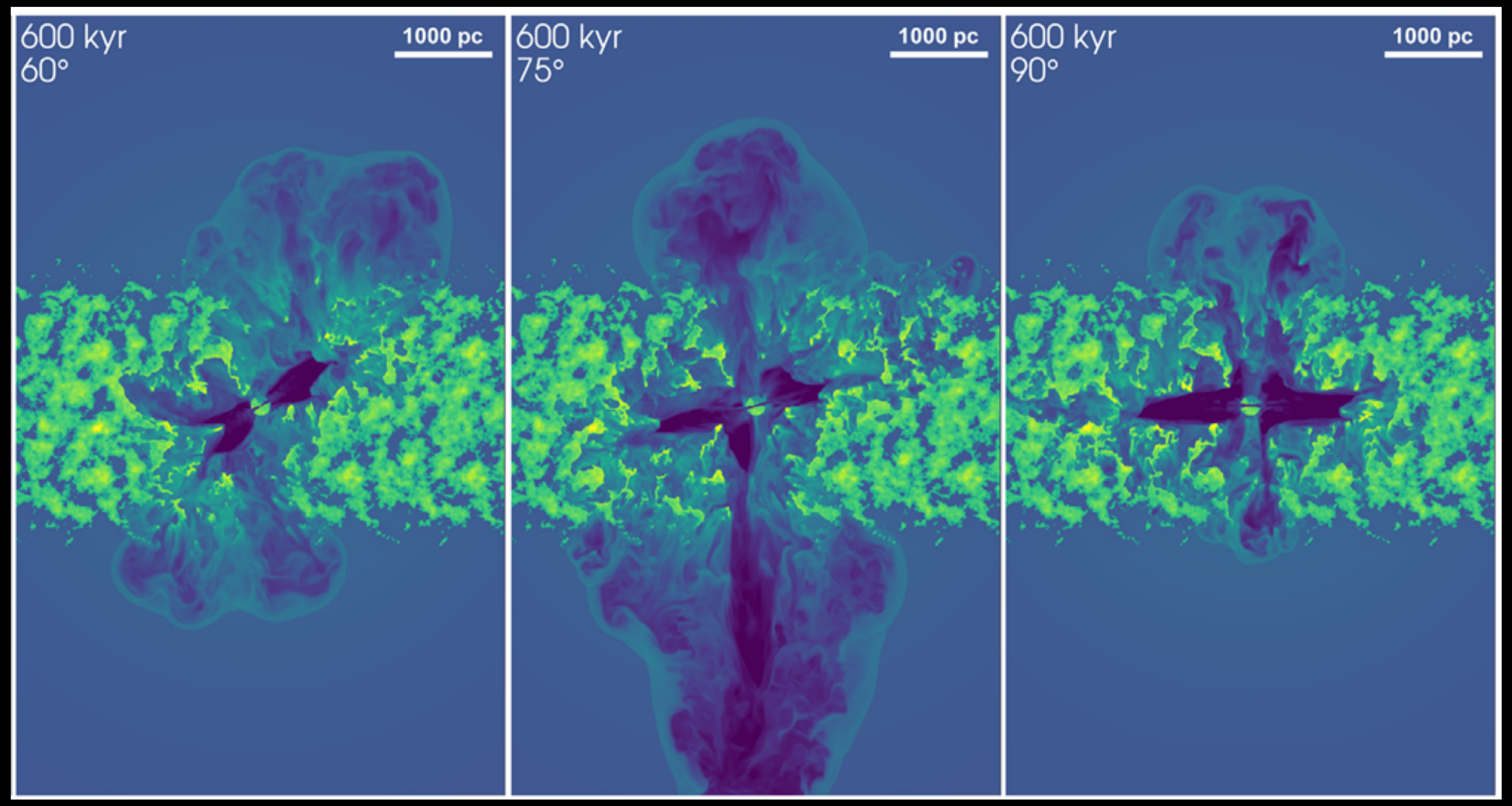


Radio continuum - impact of low-power jets and lobes

NGC1371



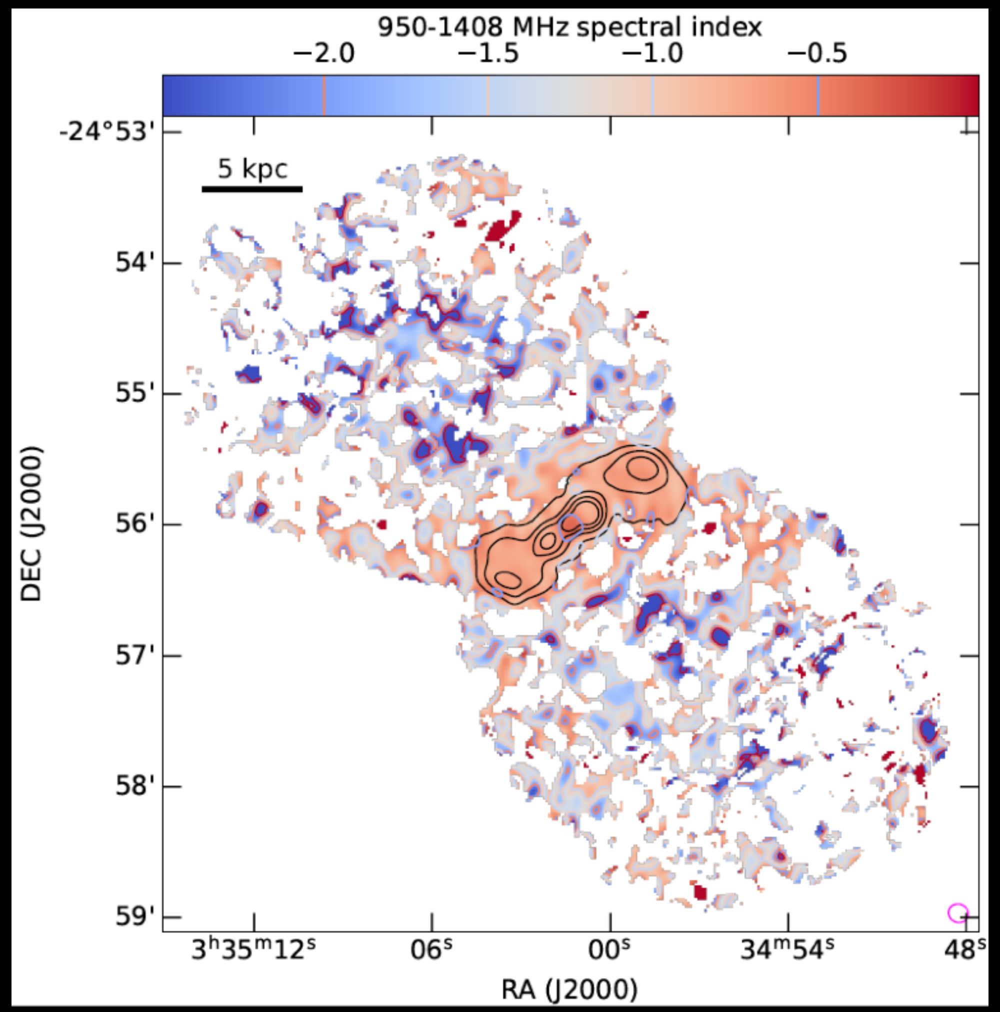
Bubbles results from tilted jet-ISM interaction
Tanner et al. (2022)



Veronese et al. 2025

SKA-MID - Low-power radio jets & bubbles

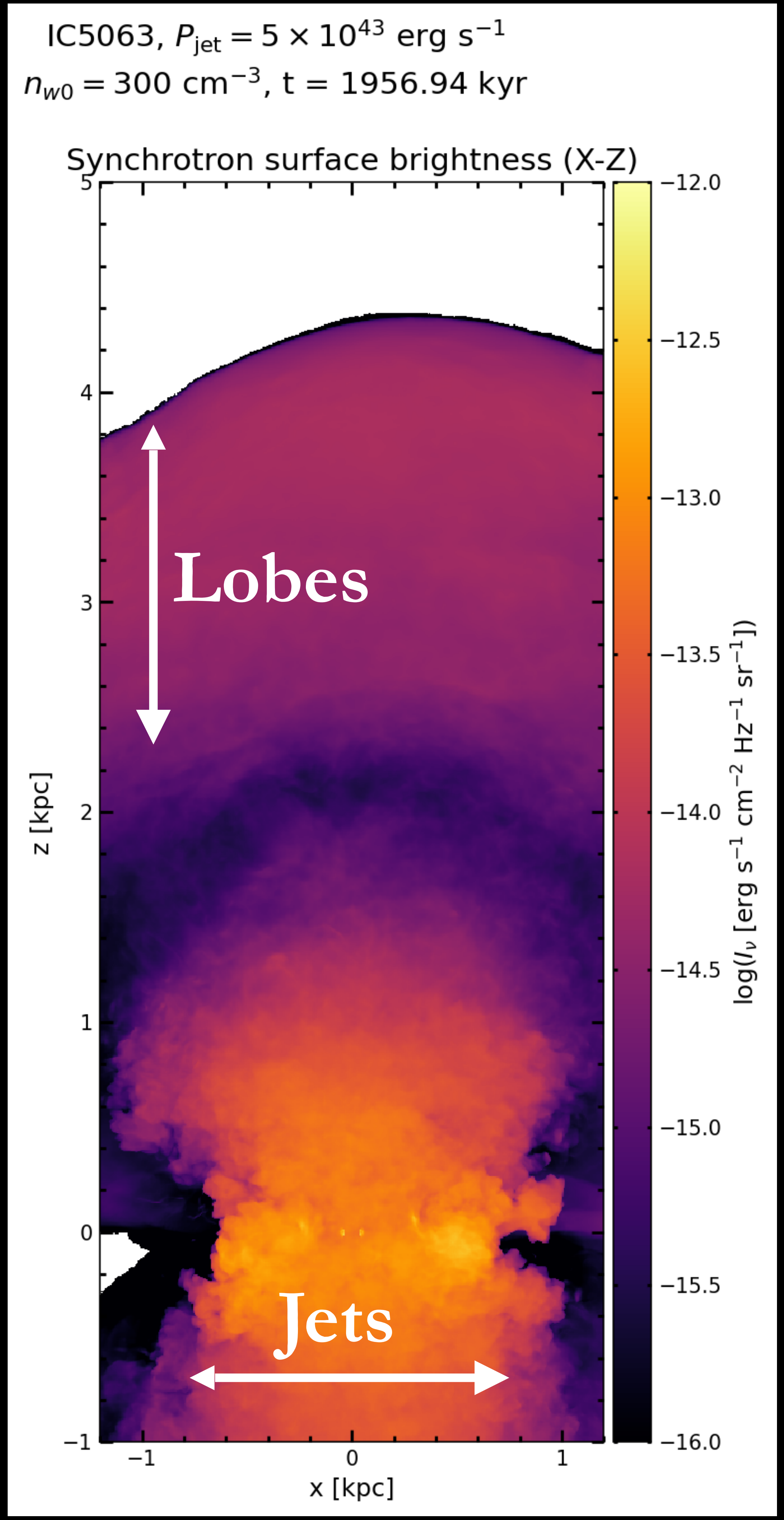
Observation



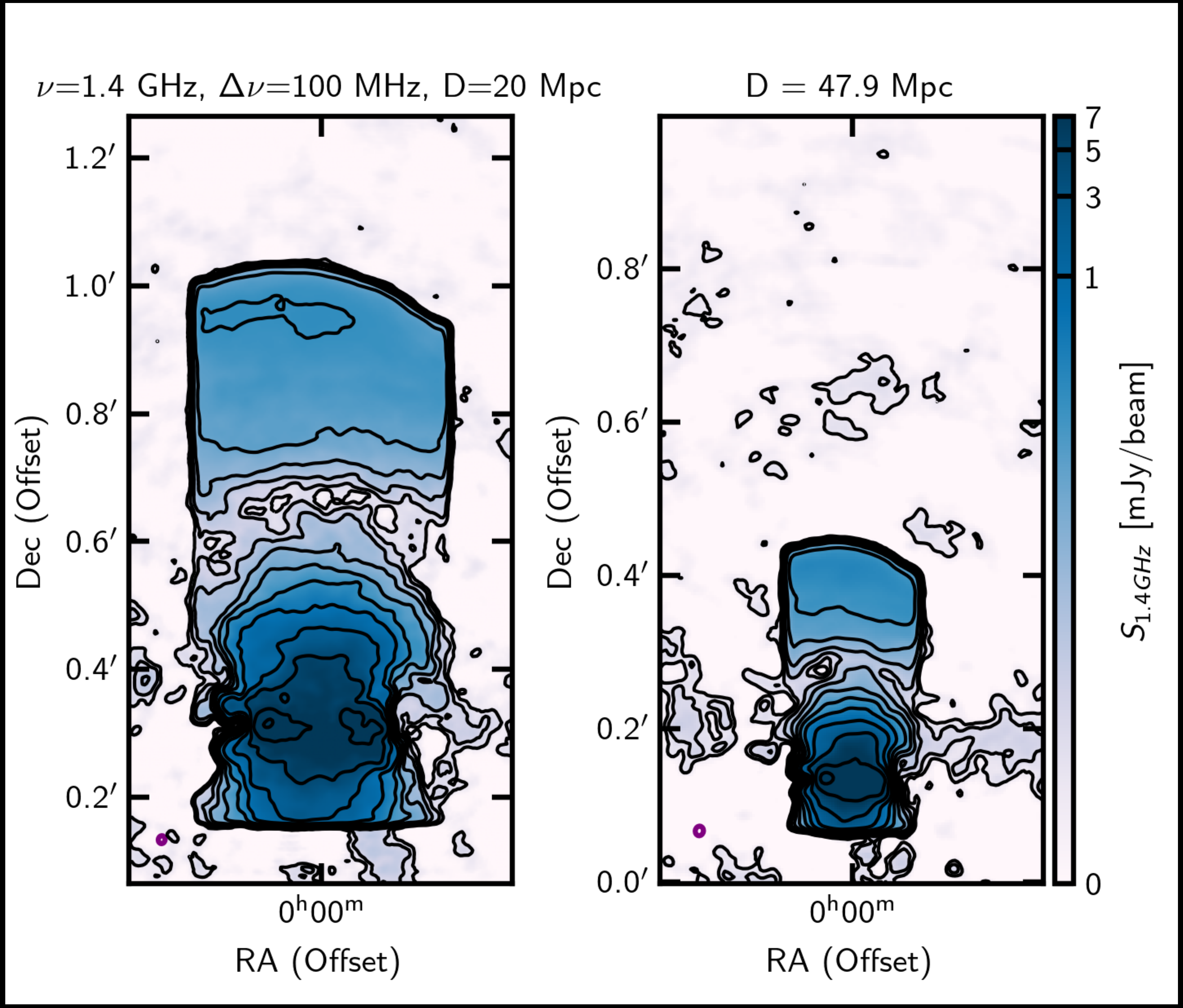
Low-power jets and bubbles exist in a few LTGs

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

Simulation [Mukherjee+18]

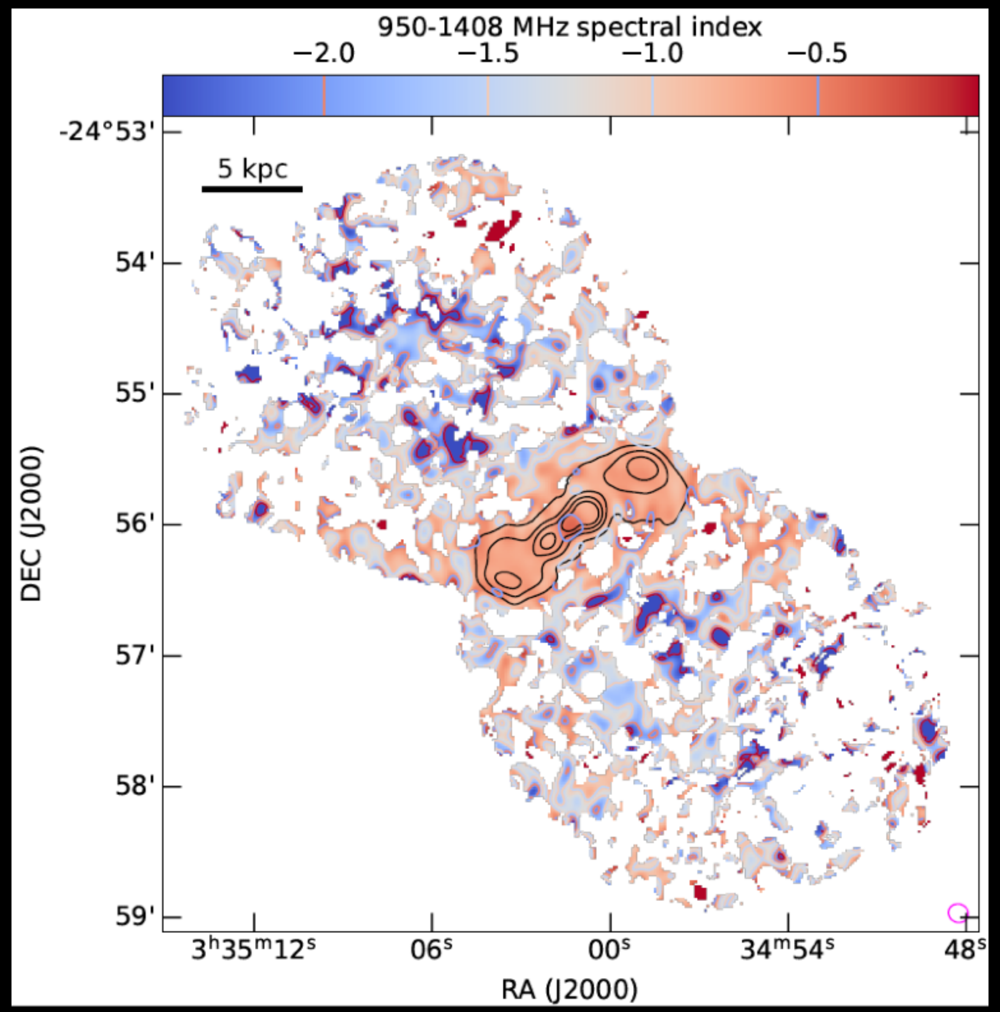


SKA-MID AA4 6hrs observation

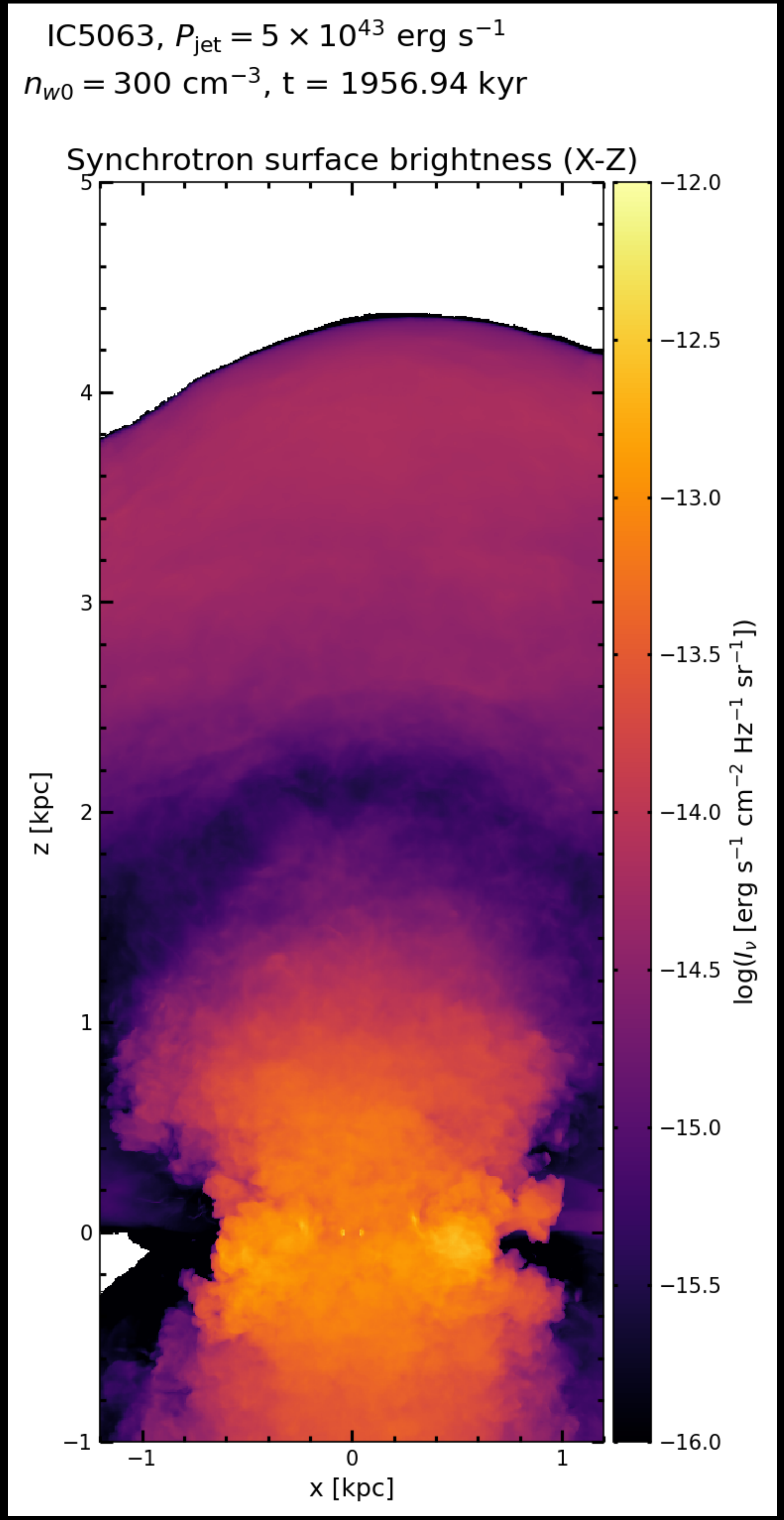


SKA-MID - Low-power radio jets & bubbles

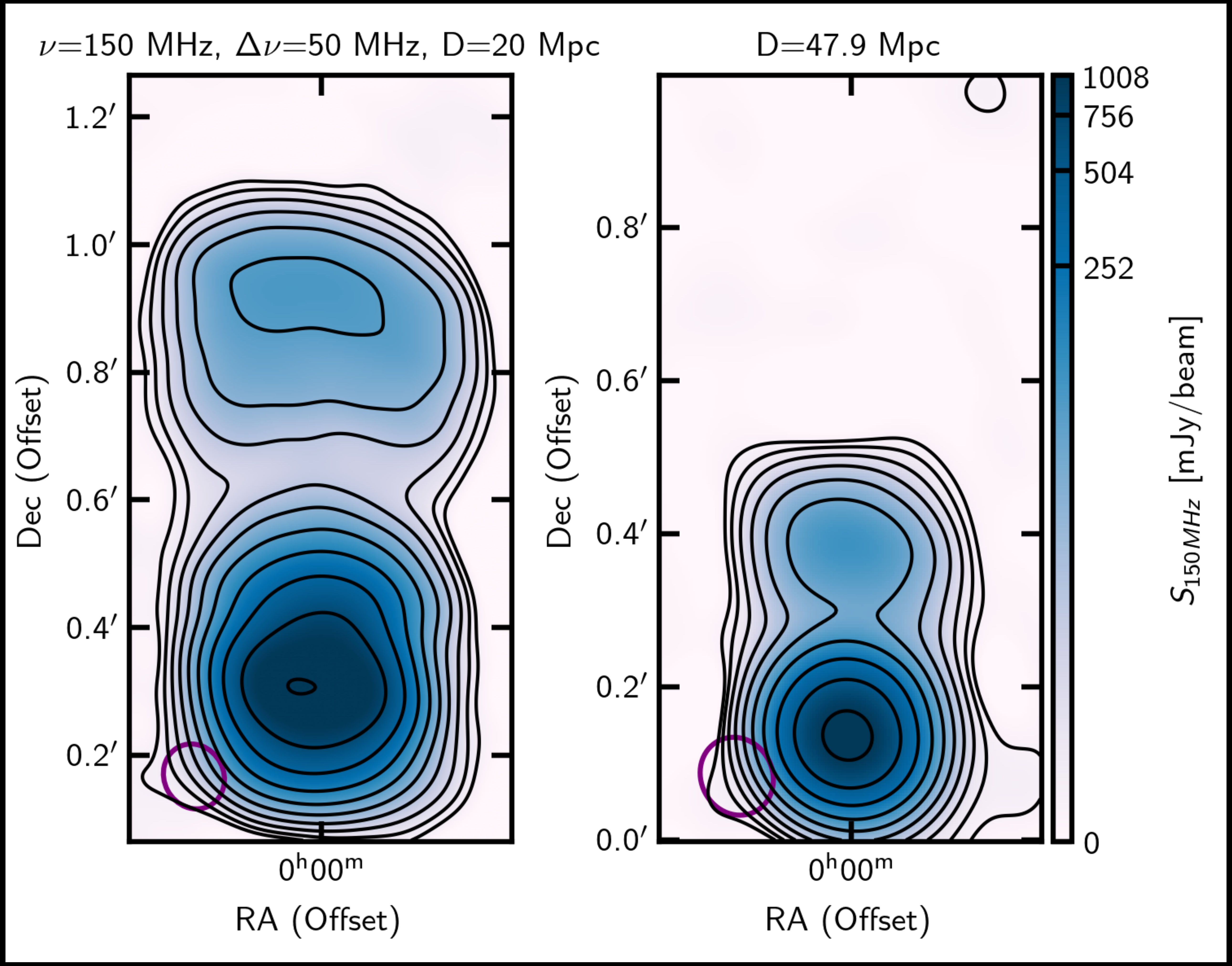
Observation



Simulation [Mukherjee+18]



SKA-Low AA4 6hrs observation

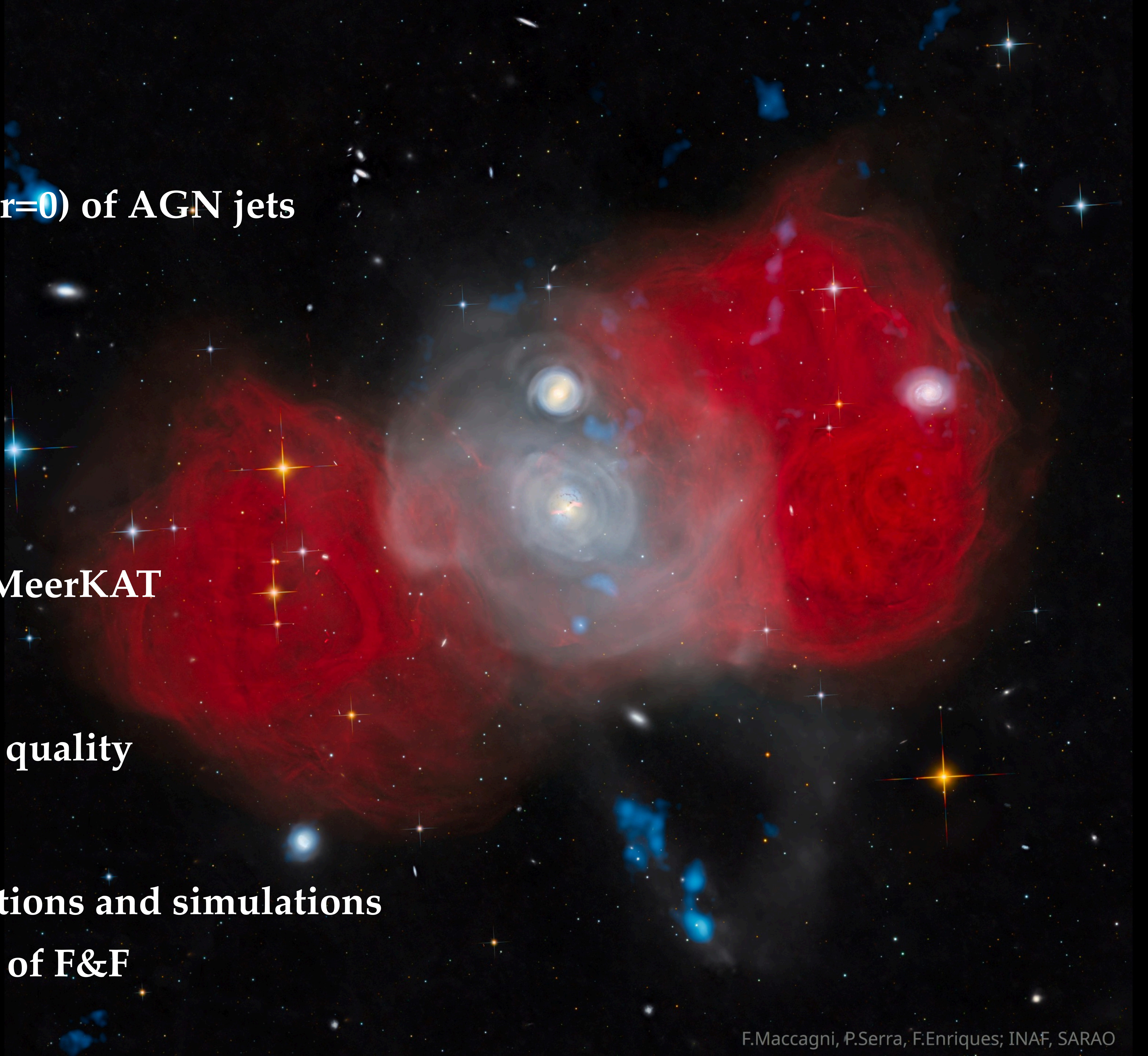


Low-power jets and bubbles exist in a few LTGs

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

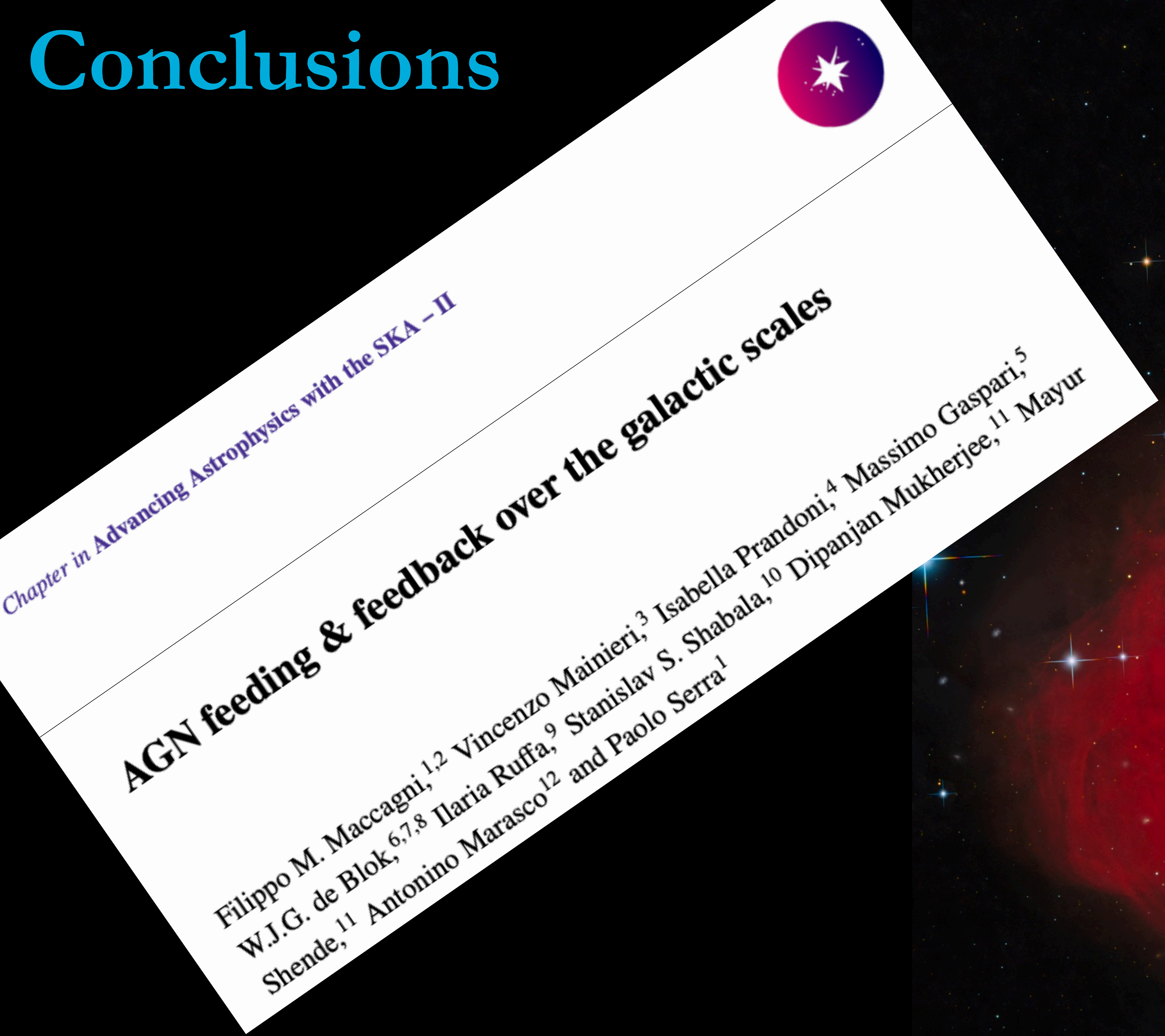
Conclusions

- Continuum
  - SKA LOW+MID: detailed view (8″, r=0) of AGN jets
    - Spectral index analysis
      - Timescale of AGN
    - Impact of low-power jets on ISM
- HI
  - SKA-MID AA*: 5 times faster than MeerKAT
    - MFS depth in 6 hrs / pointing (r=1)
  - Improved resolution (6″) and image quality
- SKA-MID AA* Deep (60 hrs)
  - Direct comparison between observations and simulations of F&F in nearby AGN with models of F&F



F.Maccagni, P.Serra, F.Enriques; INAF, SARAO

Conclusions



Chapter in Advancing Astrophysics with the SKA – II

AGN feeding & feedback over the galactic scales

Filippo M. Maccagni,[1,2] Vincenzo Mainieri,[3] Isabella Prandoni,[4] Massimo Gaspari,[5] W.J.G. de Blok,[6,7,8] Ilaria Ruffa,[9] Stanislav S. Shabala,[10] Dipanjan Mukherjee,[11] Mayur Shende,[11] Antonino Marasco[12] and Paolo Serra[1]

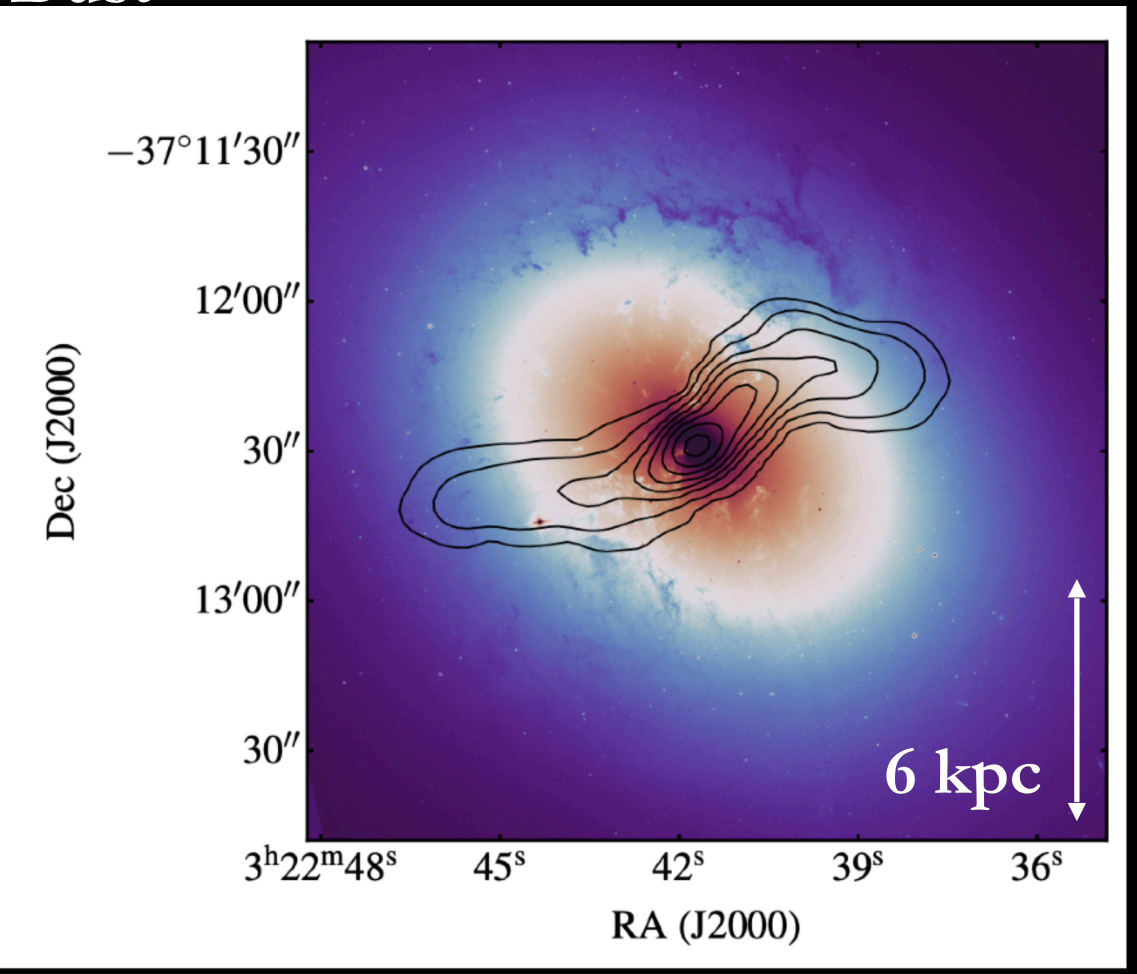
MeerKAT - a dense core of antennas

MeerKAT's dense core of antennas guarantees

constant sensitivity over all scales

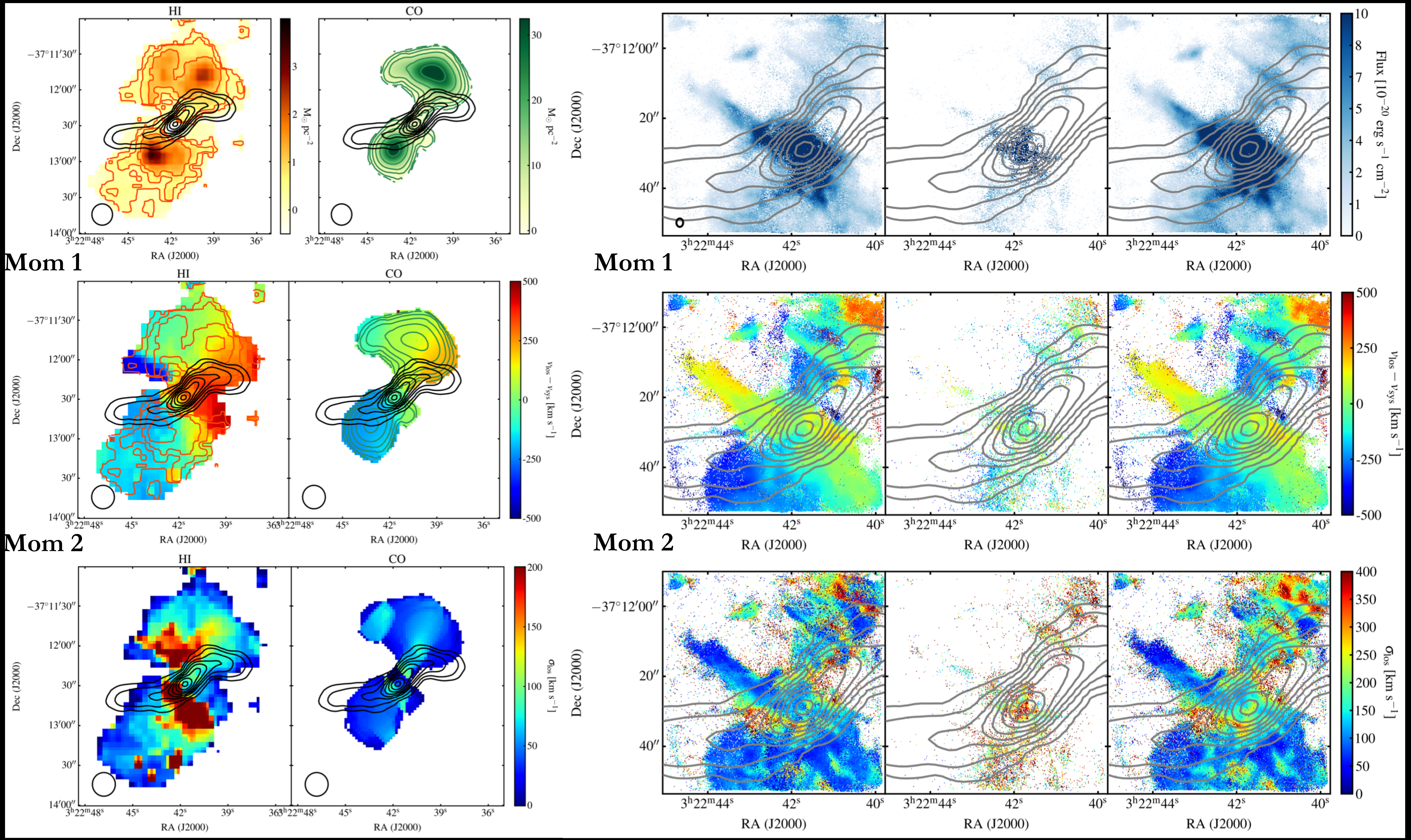
Cold gas distribution and kinematics in the centre

Dust



HI, CO (1-0) — 18 kpc fov

Ionised gas (MUSE) — 6 kpc fov



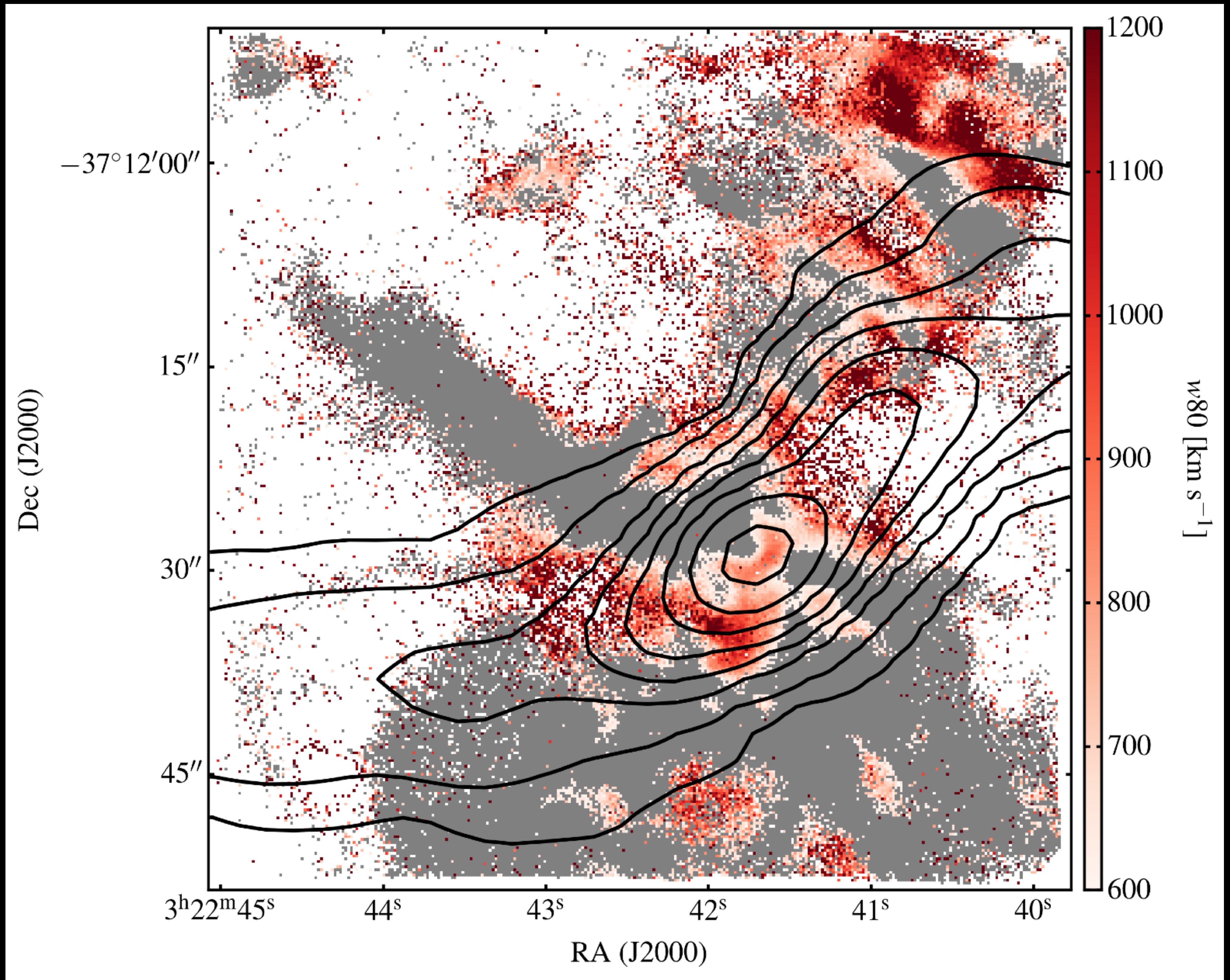
Rotation axis of the gas (NW-SE) perpendicular to the stellar body

Several deviations from rotation

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

[Maccagni et al., 2021]

Multi-phase outflow in Fornax A

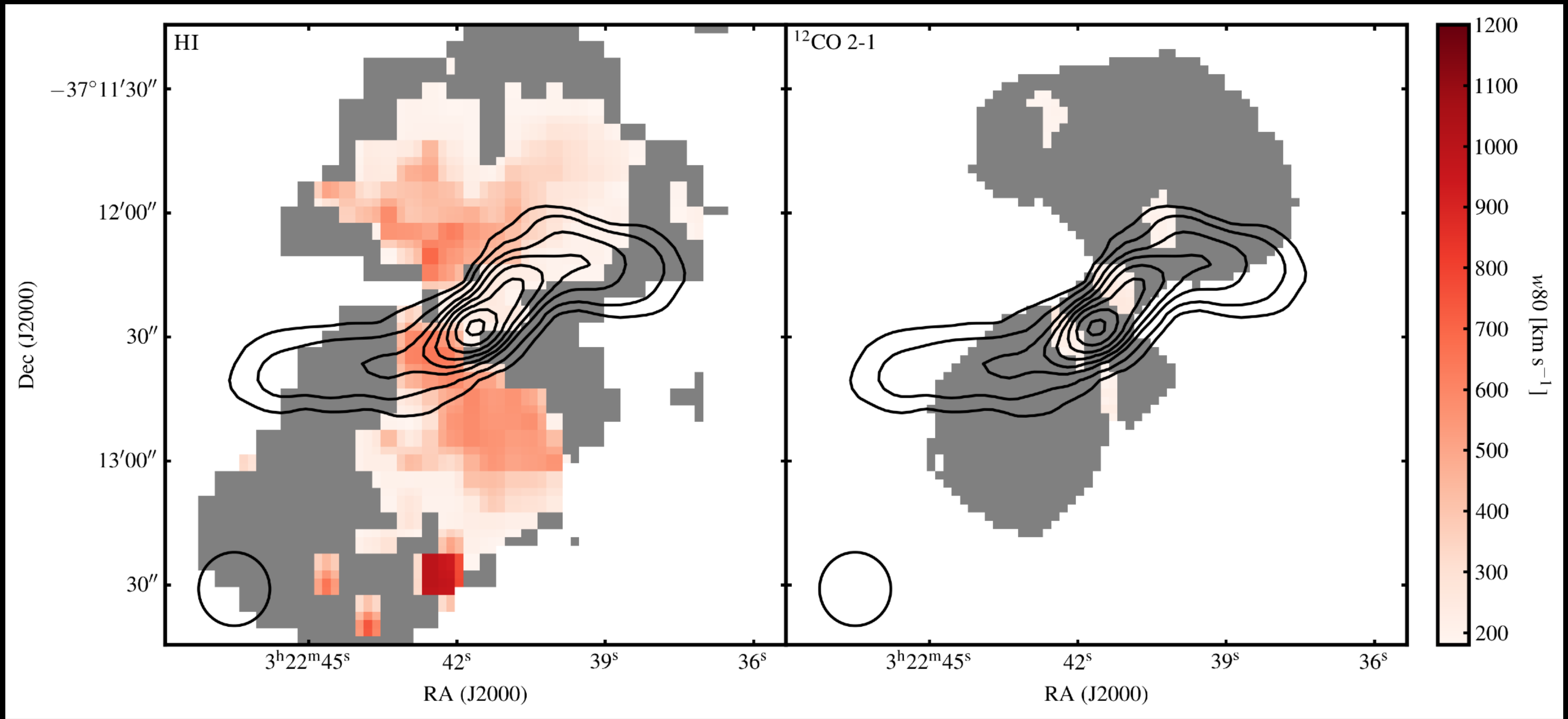


- Ionised gas
  - w80 > 600 km s^{-1} in the wake of the radio jets
- Cold gas
  - w80 > 600 km s^{-1} along the jets and in the outer ring

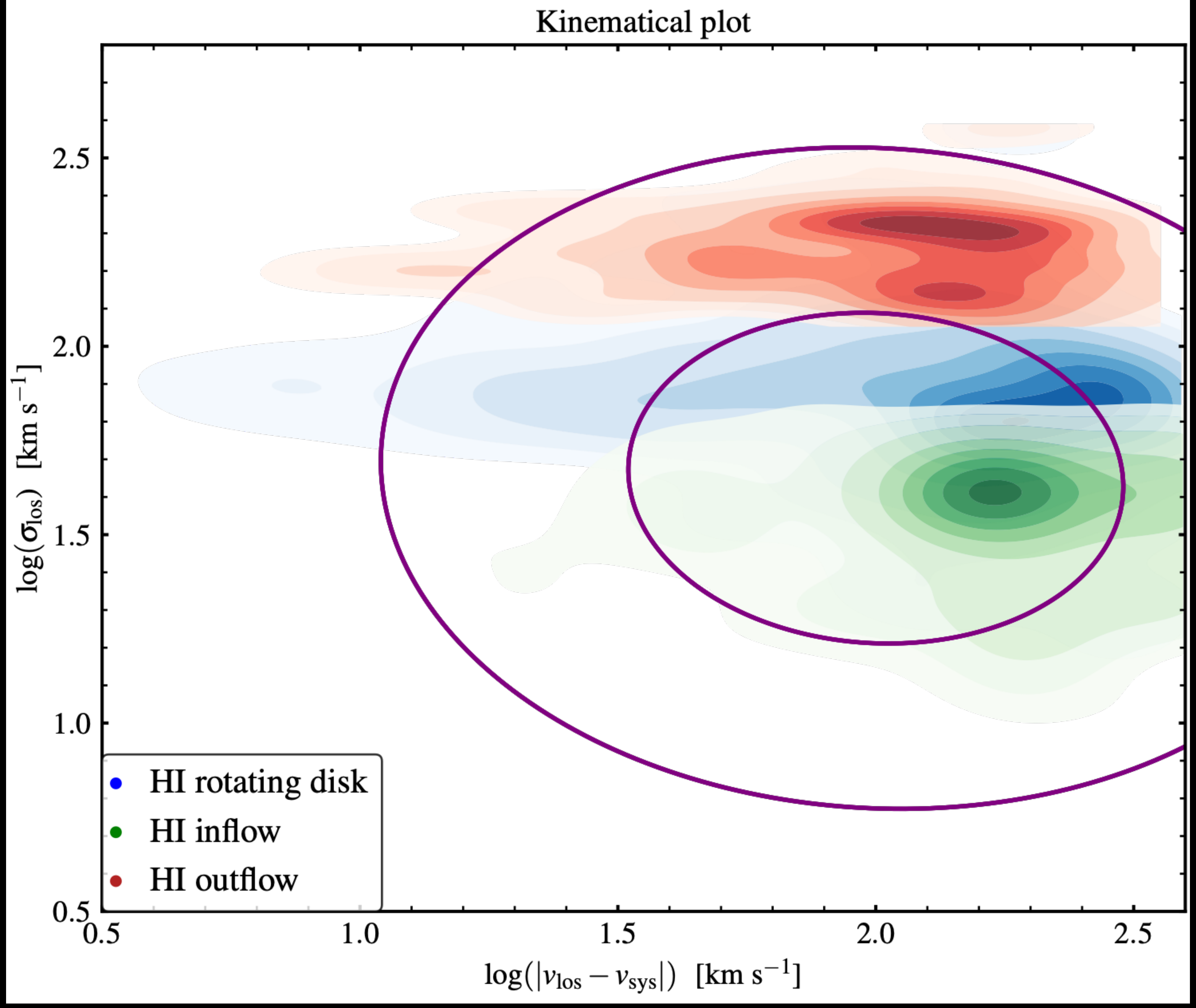
At its outflow velocity (2000 km s^{-1}) the outer ring would have reached its distance from the centre in ~ 3 Myr

==

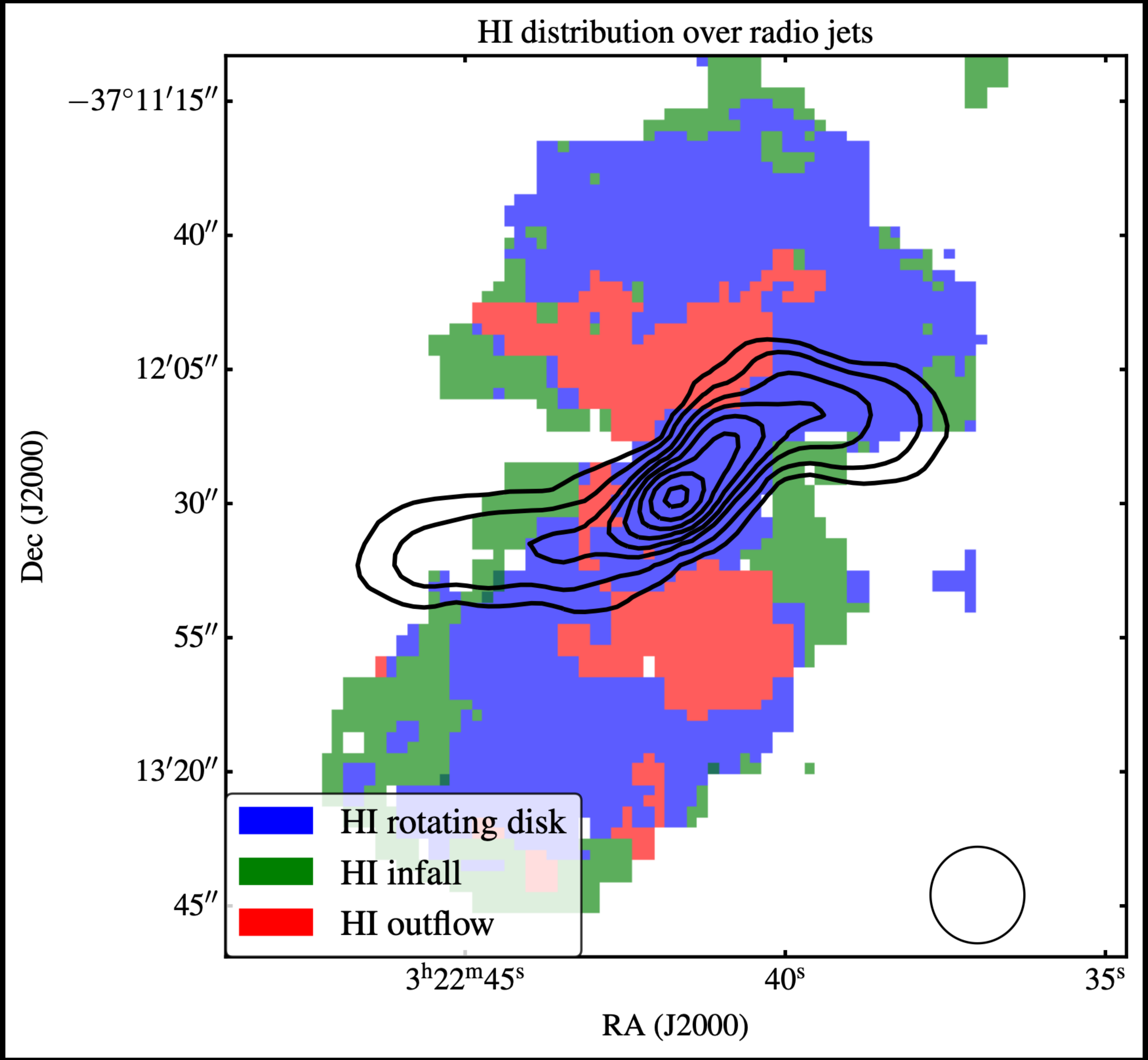
Age of the radio jets



Regions with similar kinematics



Kinematical plot — naturally identifies loci with similar kinematics

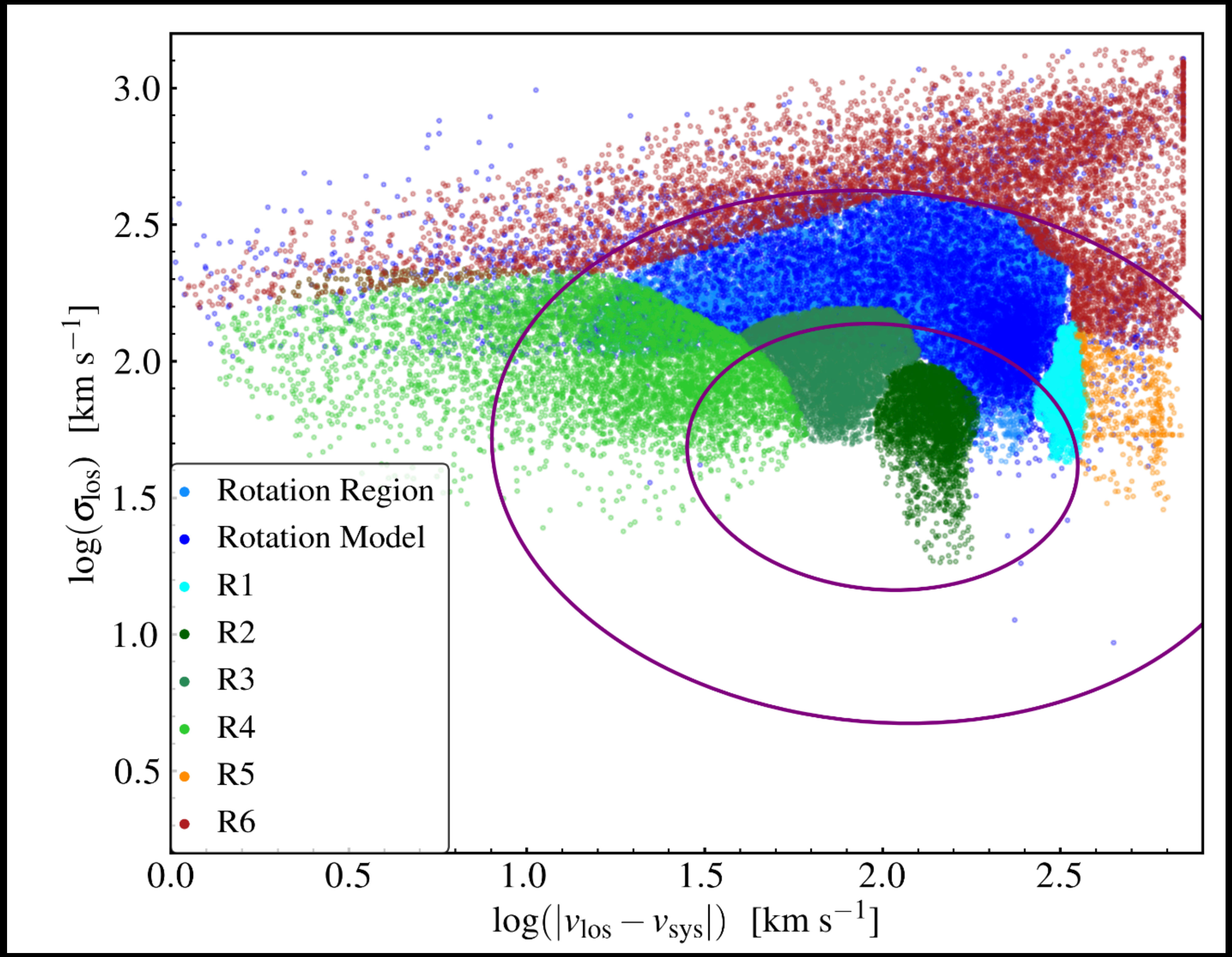


broad line-widths (R6) -> outflow in the wake of the radio jet

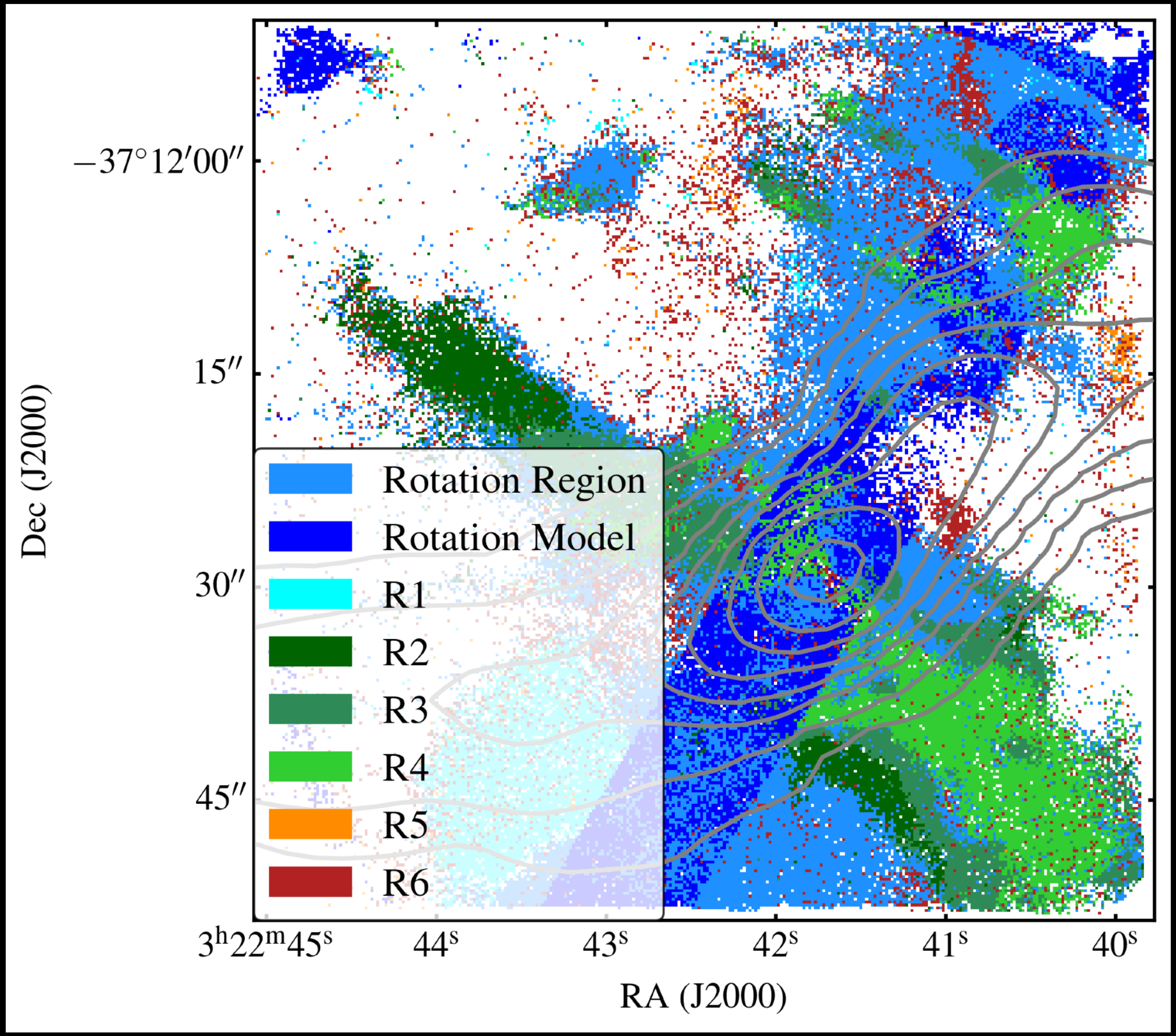
narrow line-widths -> EW stripe and filament and stripes

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

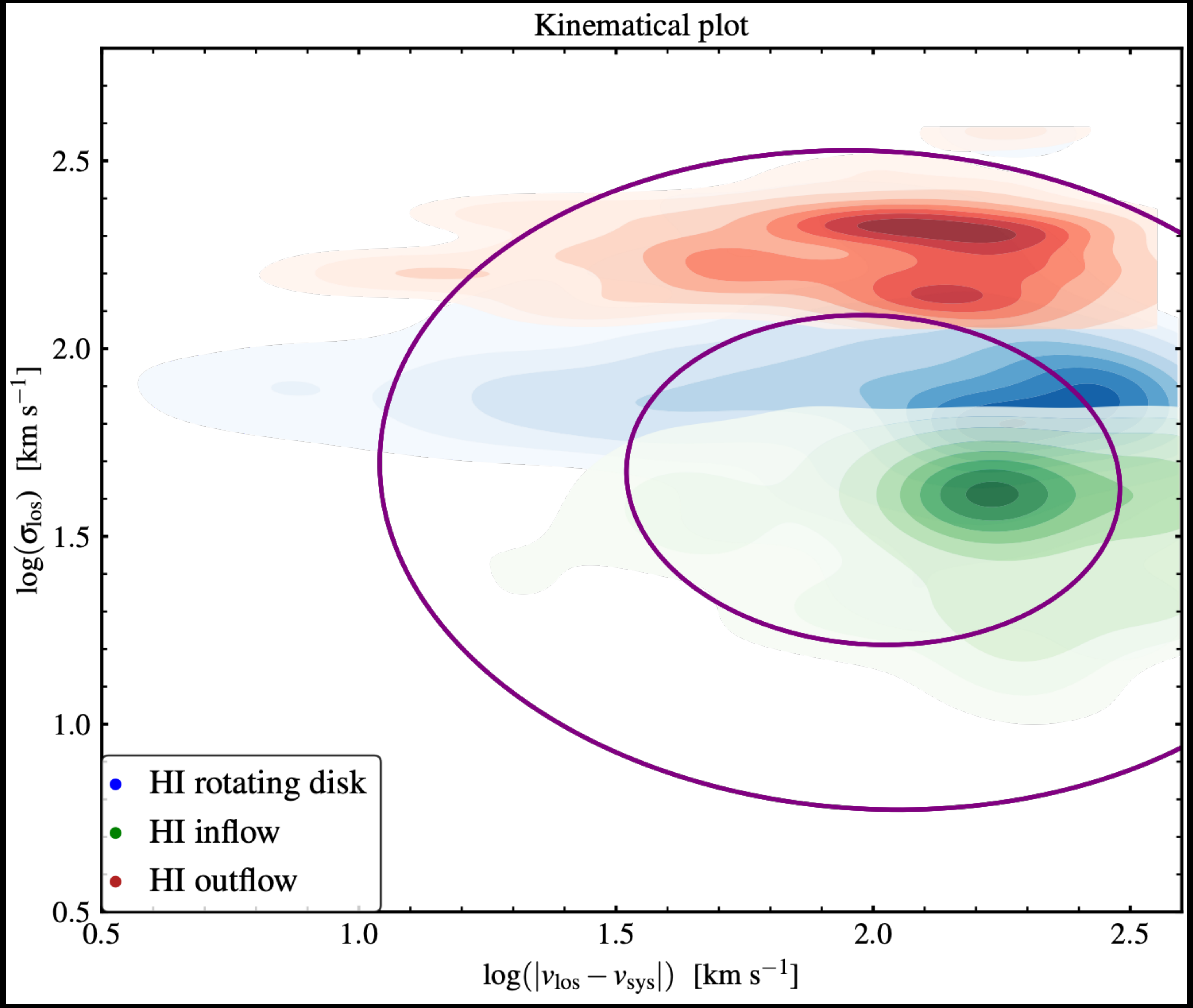


broad line-widths (R6) -> outflow in the wake of the radio jet

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

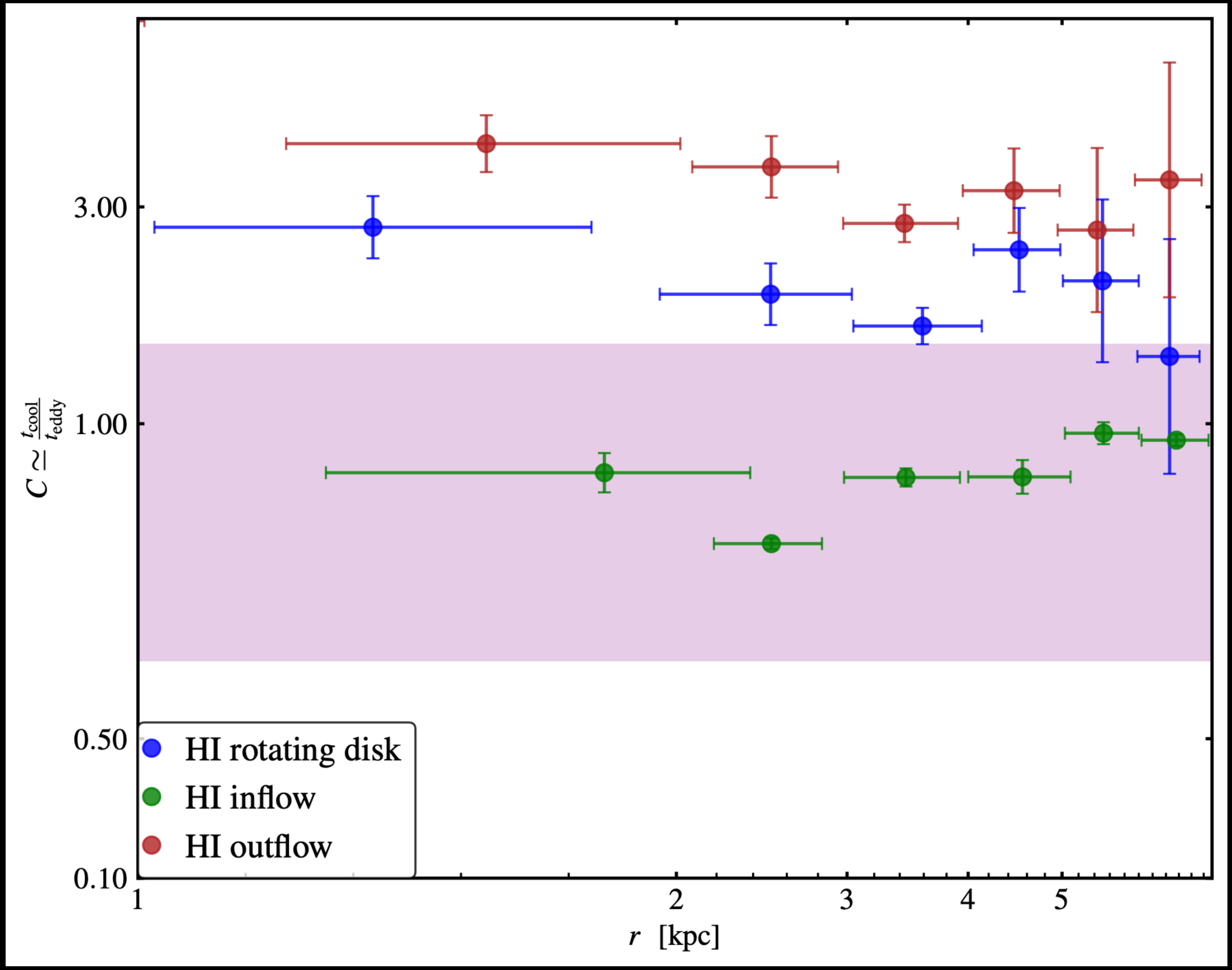
K-plot of HI and CO show the same properties

AGN feeding in Fornax A



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

The EW stripe and filaments may be feeding the AGN

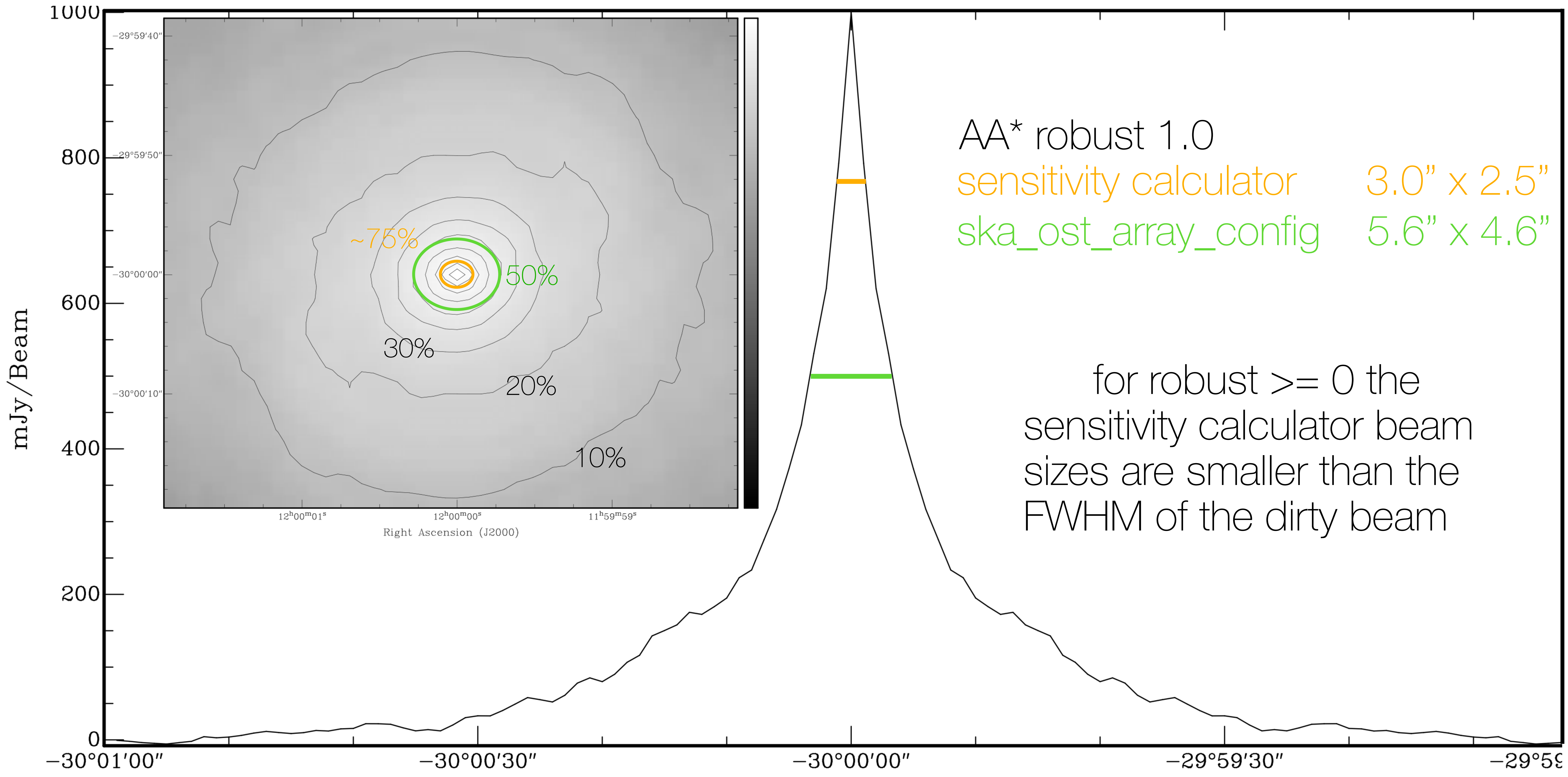


C-Ratio — cooling time / eddy turnover time
measures the role of turbulence causing condensation of the gas

EW filaments: turbulence may cause cooling and infall
Outflow: very different physical conditions

[Maccagni et al., 2021]

SKA-MID beam sizes



AA* robust 1.0

sensitivity calculator 3.0" x 2.5"

ska_ost_array_config 5.6" x 4.6"

for robust >= 0 the sensitivity calculator beam sizes are smaller than the FWHM of the dirty beam

courtesy of E. de Blok

SKA-MID beam sizes

- But what is the correct beam size to choose for restoring beam?
- Generally if the beam is approximately Gaussian at > 0.5 x peak an unambiguous beam size can be determined
- One option: choose a weighting tapering combination that gives you this (at the desired sensitivity)
- Also an issue with MeerKAT, but more prominent with AA*/AA4
- Critical for survey design (a factor 3.4 in beam area in this case)

courtesy of E. de Blok