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The future is here!
ORC's and other new wonders of radio surveys.

Mysterious Odd Radio Circle near the Large Magellanic Cloud -- An Intergalactic Supernova Remnant?

Lord of the Rings, Recollimators, RaRiGx, pre-SN1987A & Dancing Ghosts

Miroslav Filipovic

THANKS: A lot of people … about 50+ BUT special THANKS to: my PhD students Rami, Velibor & Neda

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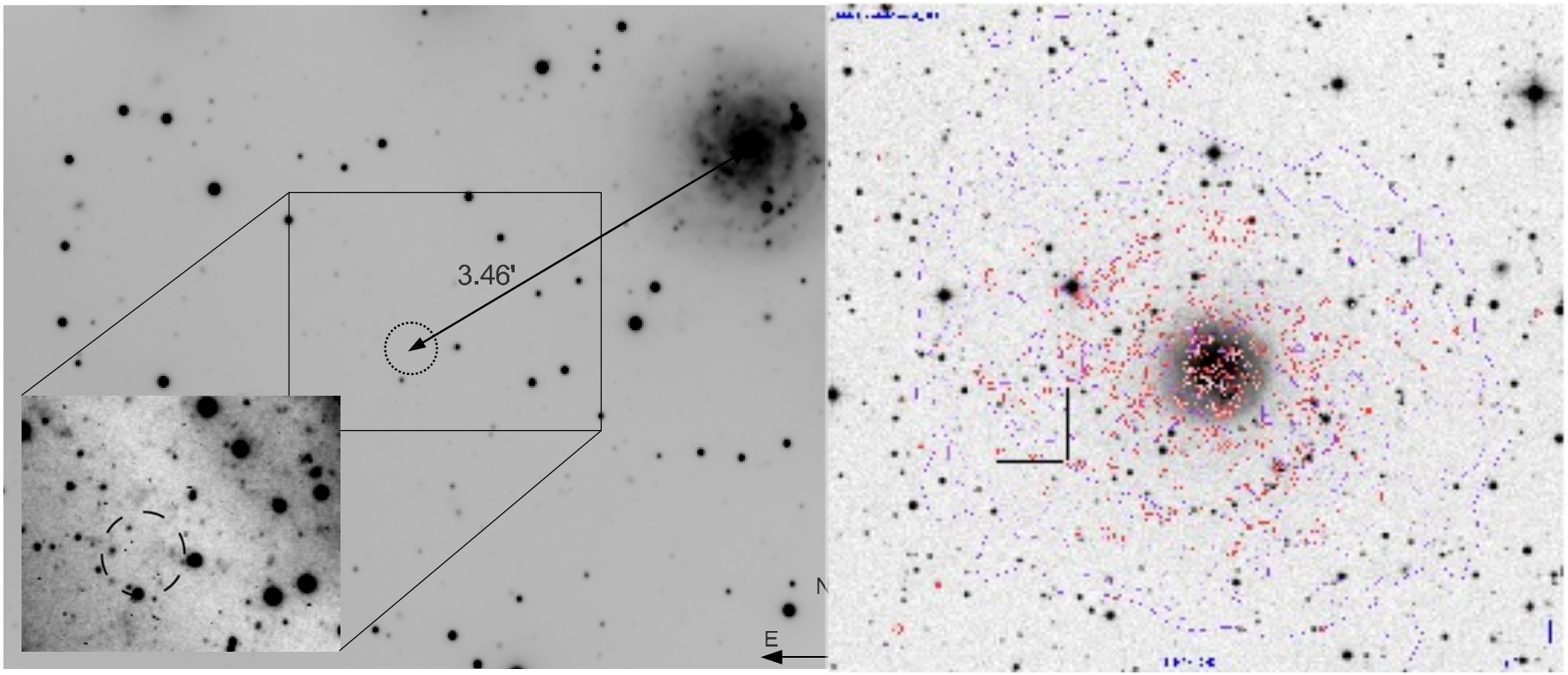
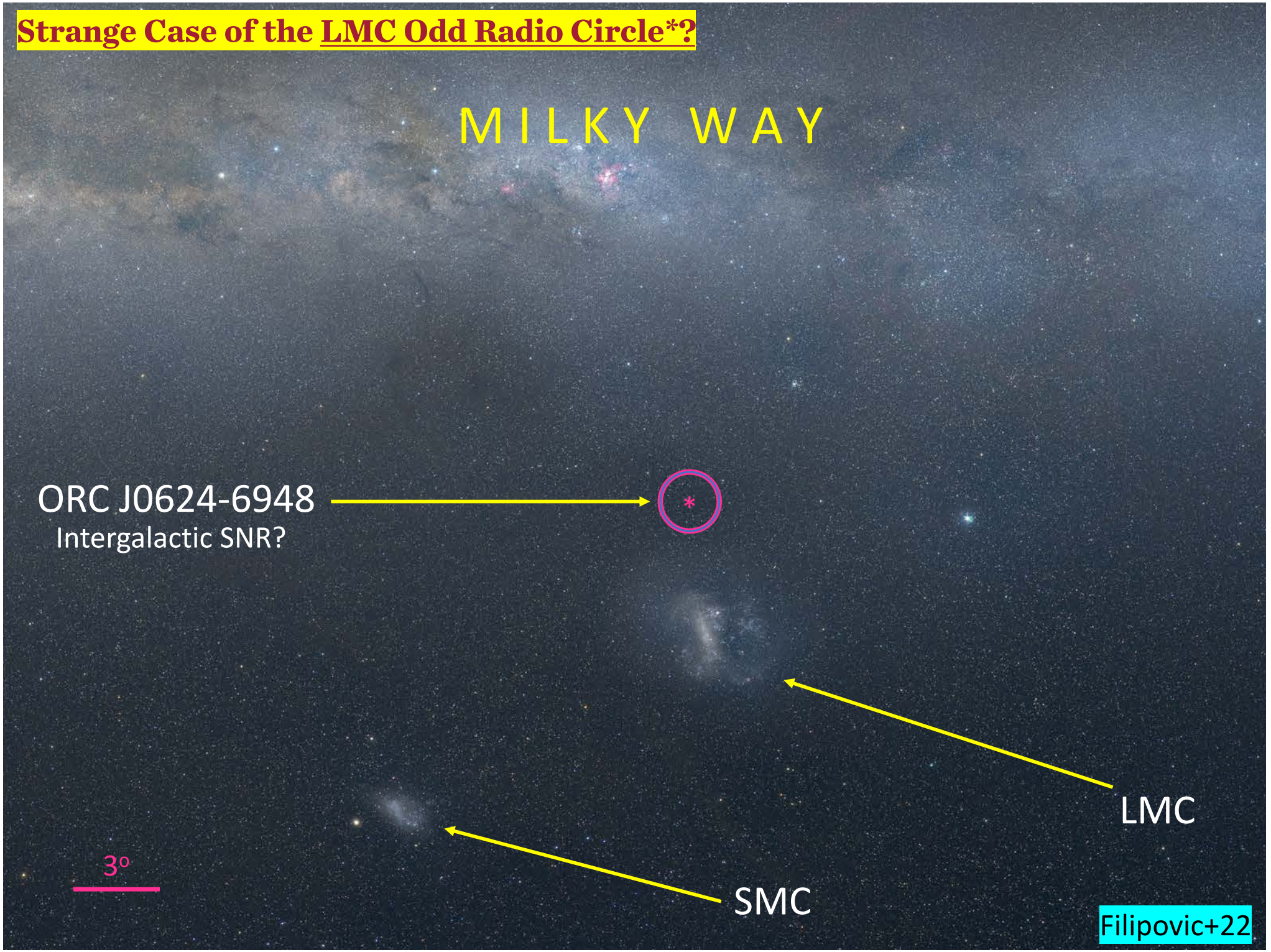
Host-less intergalactic SNe

NGC 1058



Zinn+2011


Strange Case of the LMC Odd Radio Circle*?
MILKY WAY
ORC J0624-6948
Intergalactic SNR?
*
LMC
SMC
3°
Filipovic+22

GASS & HI4PI and J0624-6948

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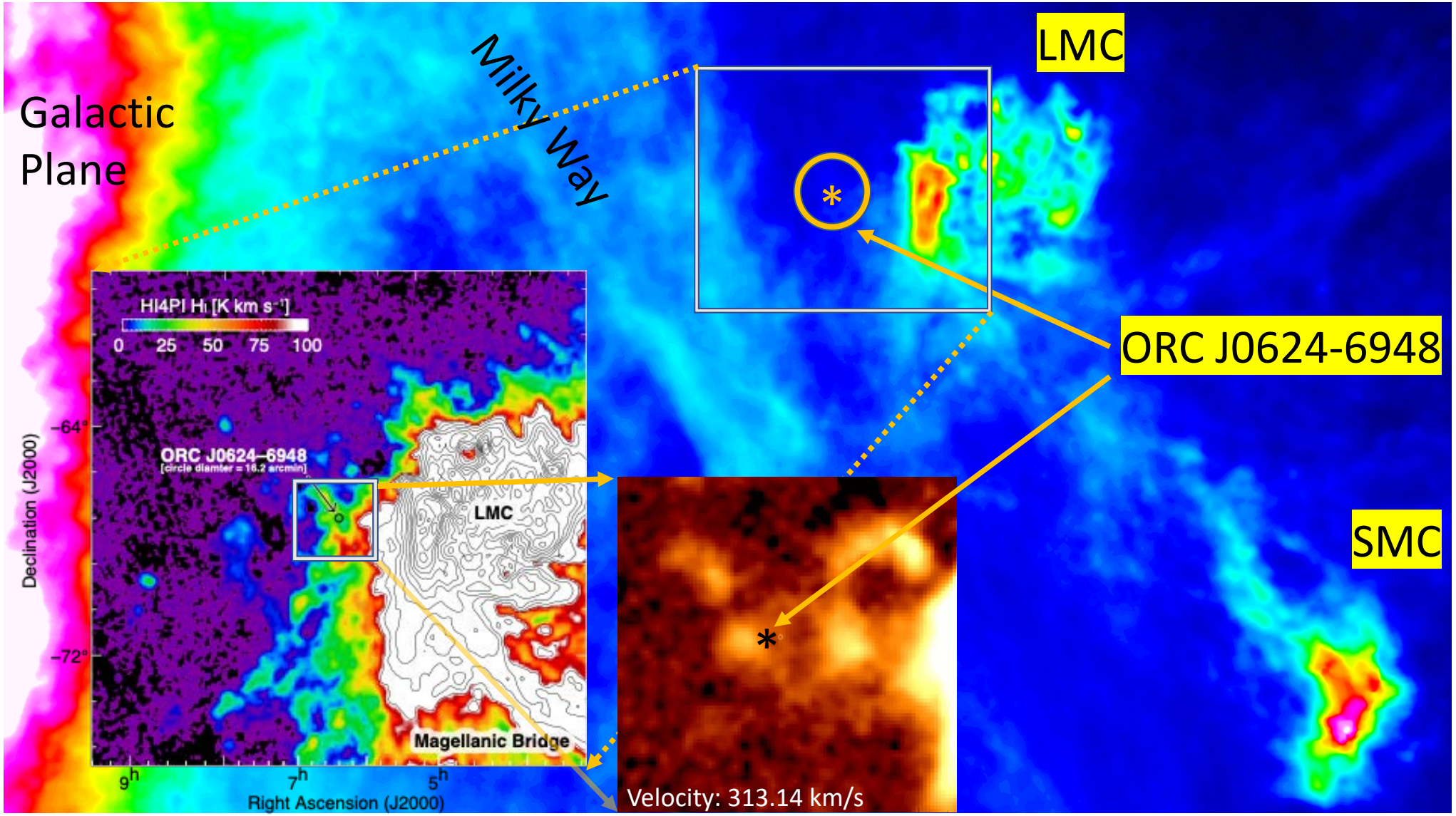

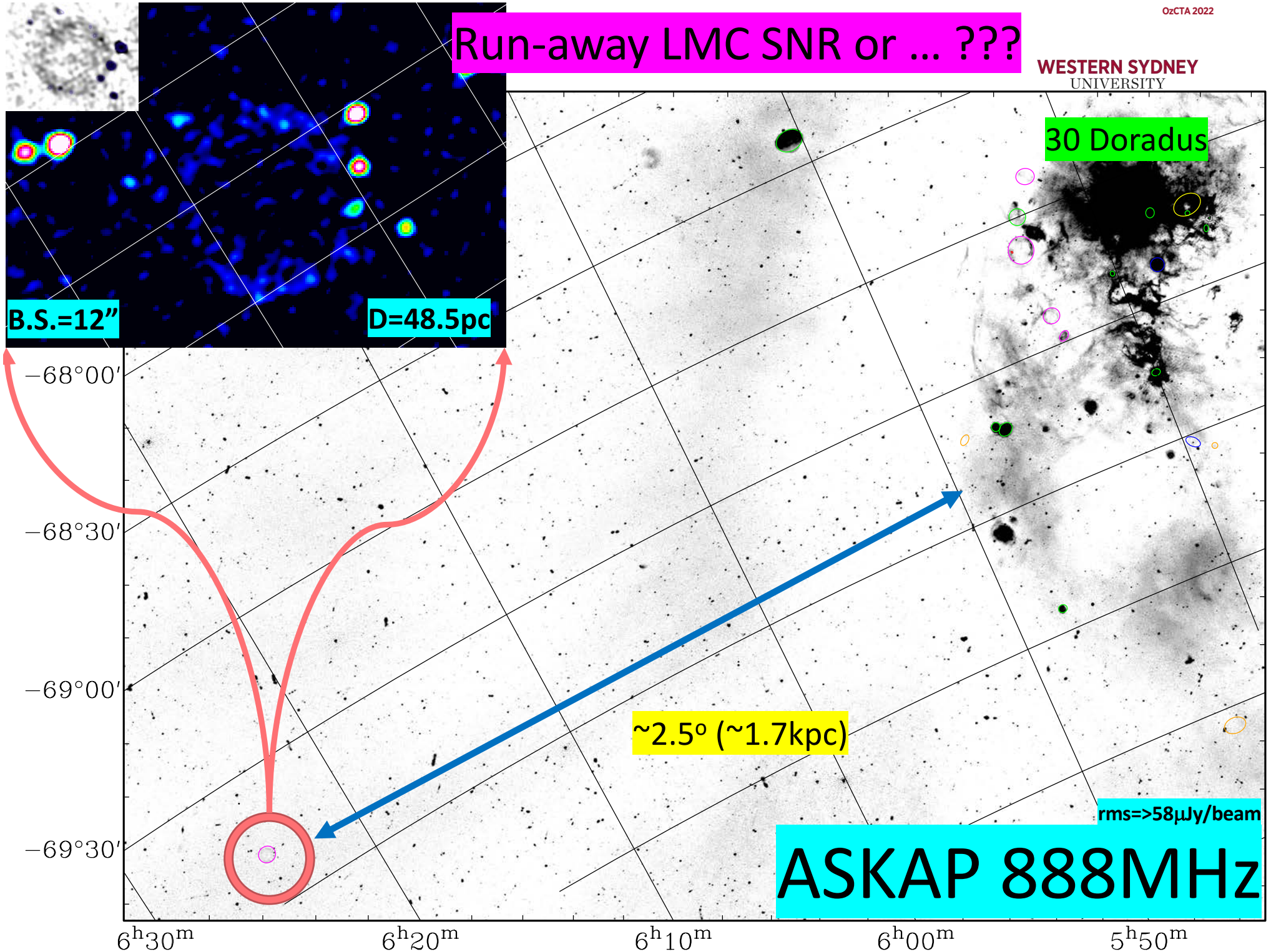
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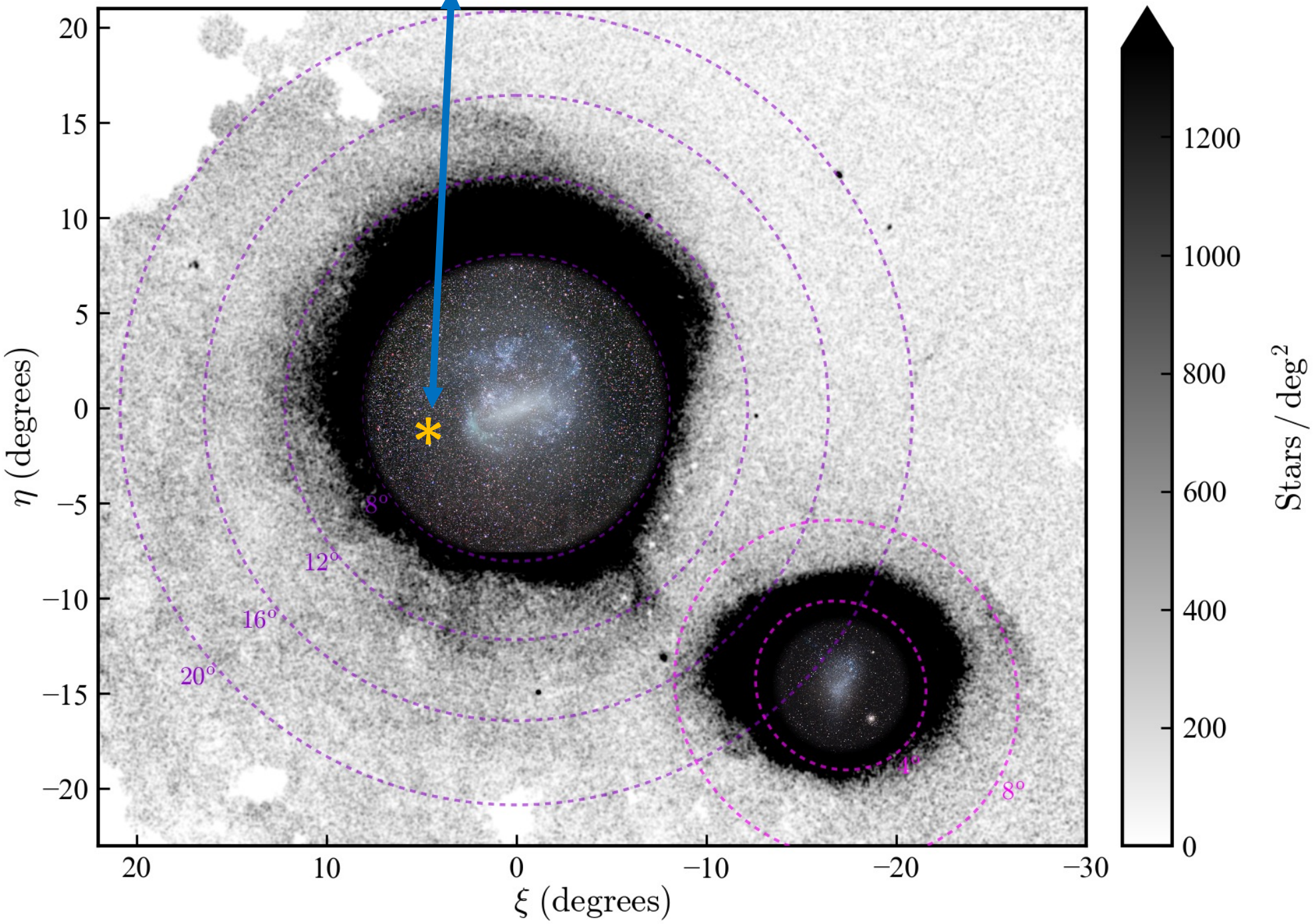
Run-away LMC SNR or … ???
30 Doradus
B.S.=12”
D=48.5pc
~2.5° (~1.7kpc)
rms=>58μJy/beam
ASKAP 888MHz
−68°00′
−68°30′
−69°00′
−69°30′
6h30m
6h20m
6h10m
6h00m
5h50m

LMC ORC 0624-6948

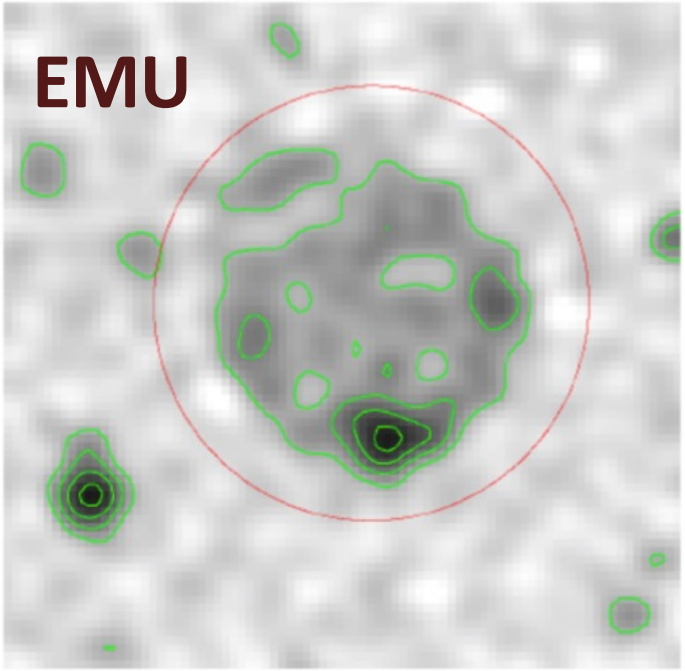
Courtesy of D. Mackey

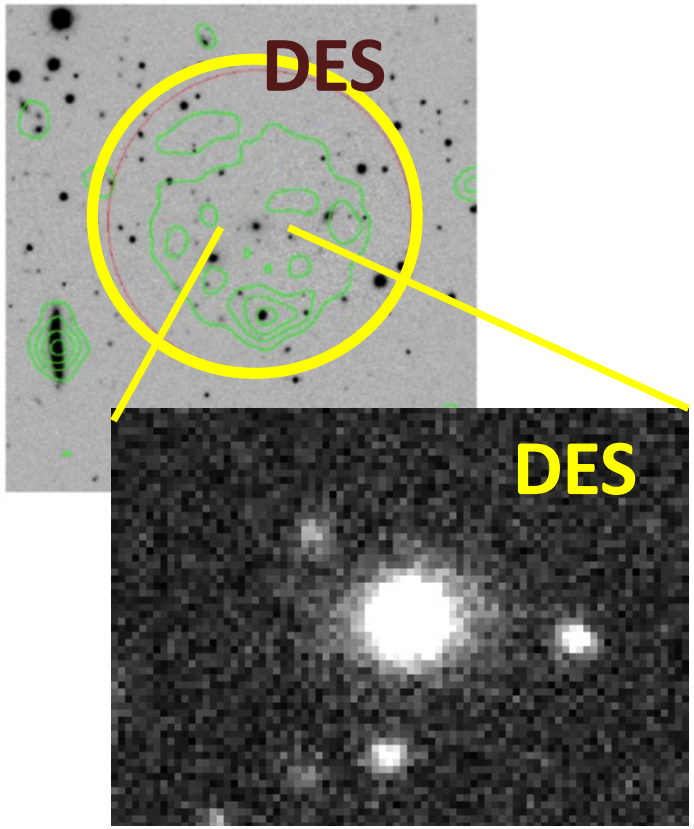


Odd Radio Circles –ORC's

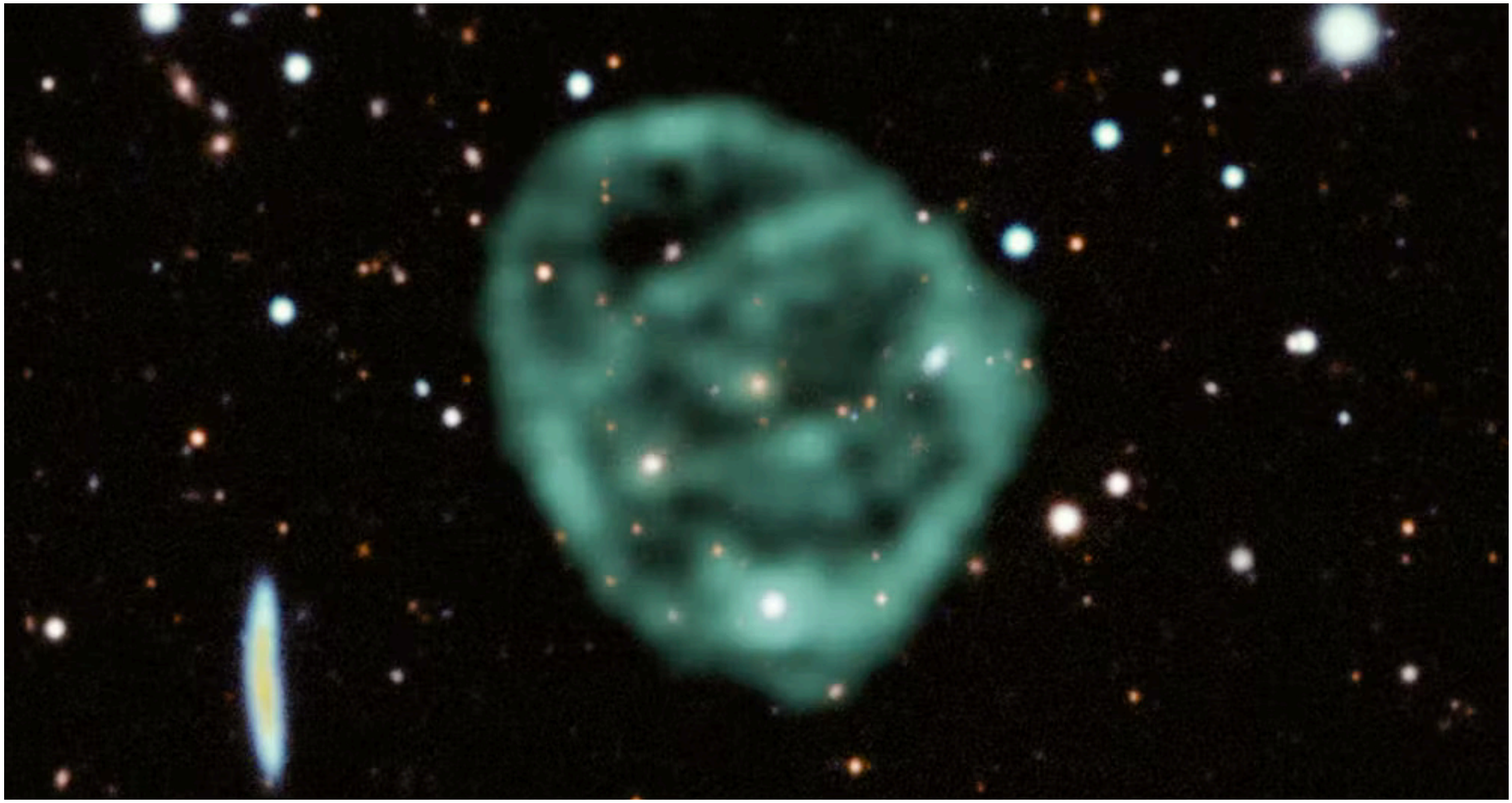
- No corresponding optical diffuse emission. Faint red object at centre is probably a galaxy
- NOT an artefact!
- Is it… SNR, planetary nebula, starburst ring, gravitational lens, bent-tail galaxy, pulsar wind nebula, end-on BL Lac, Einstein ring, cluster halo, etc
- So WTF? Consistent with edge-brightened sphere. Spherical shock from something that went bang?
- Now finding other examples in the EMU pilot data
- Not seen before in radio surveys because (a) rare, (b) low-surface brightness
- Several other examples have now been found in the pilot survey
- A new phenomenon – shock from an explosion?

Norris+20, Koribalski+21





Odd Radio Circles (ORCs)



MeerKAT, Norris+22

ASKAP 888 MHz; B.S.=13”

2.1 GHz; B.S.=15”

ATCA

Run-away LMC SNR or … ???

D=198”

ATCA

5.5 GHz; B.S.=10”

ATCA

9.0 GHz; B.S.=10”

DEC (J2000)

RA (J2000)

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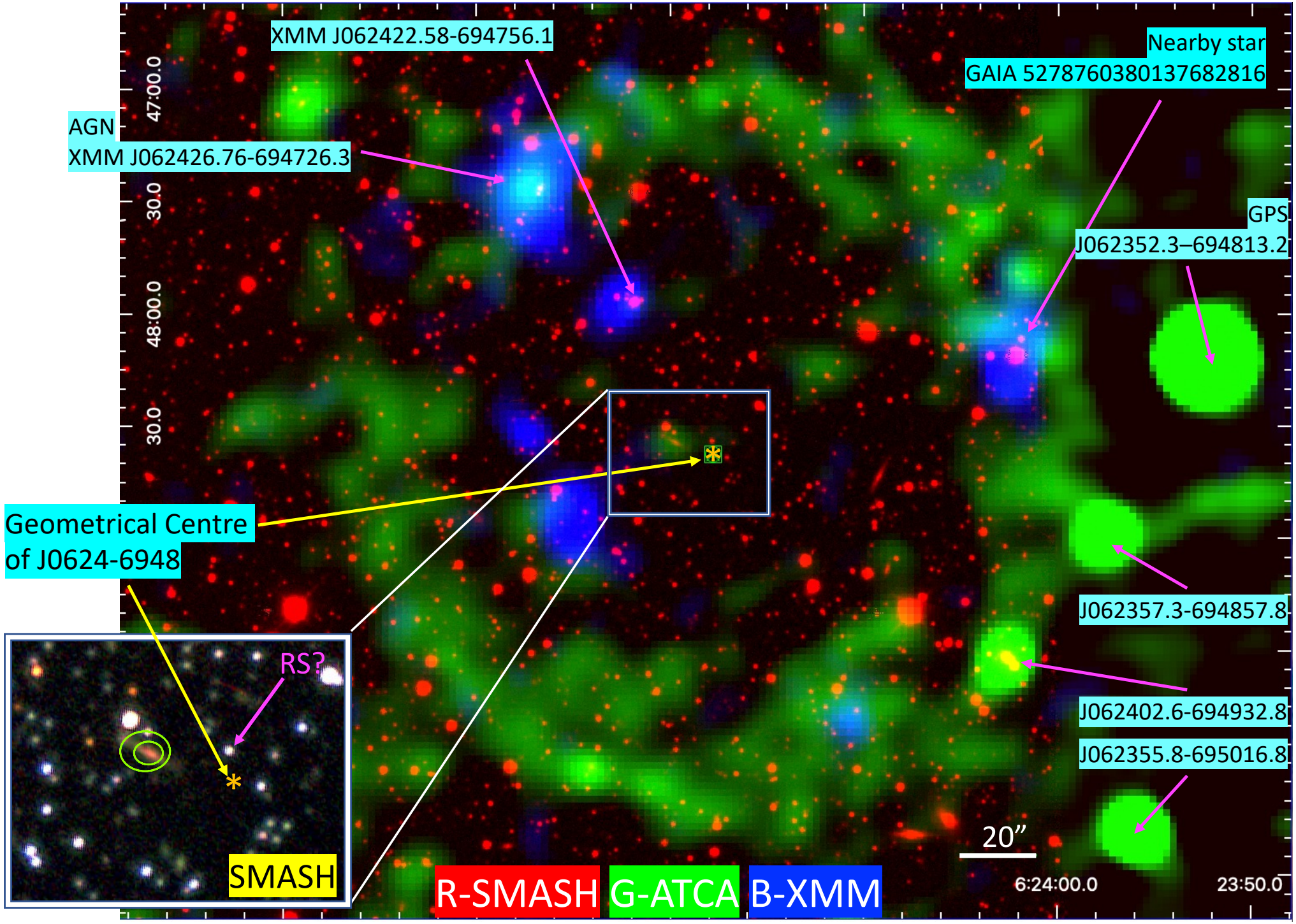
XMM J062422.58-694756.1
Nearby star
GAIA 5278760380137682816
AGN
XMM J062426.76-694726.3
GPS
J062352.3–694813.2
47:00.0
30.0
48:00.0
30.0
Geometrical Centre
of J0624-6948
J062357.3-694857.8
RS?
J062402.6-694932.8
J062355.8-695016.8
SMASH
20”
R-SMASH
G-ATCA
B-XMM
6:24:00.0
23:50.0

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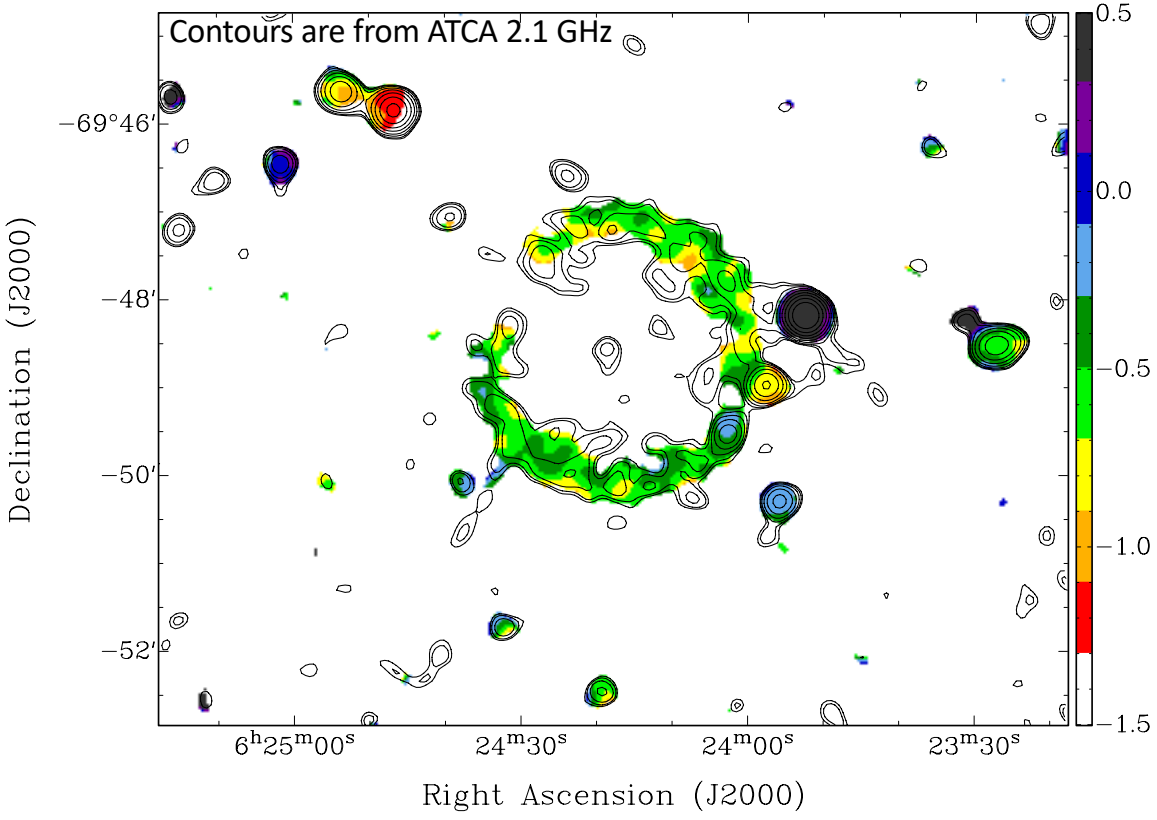
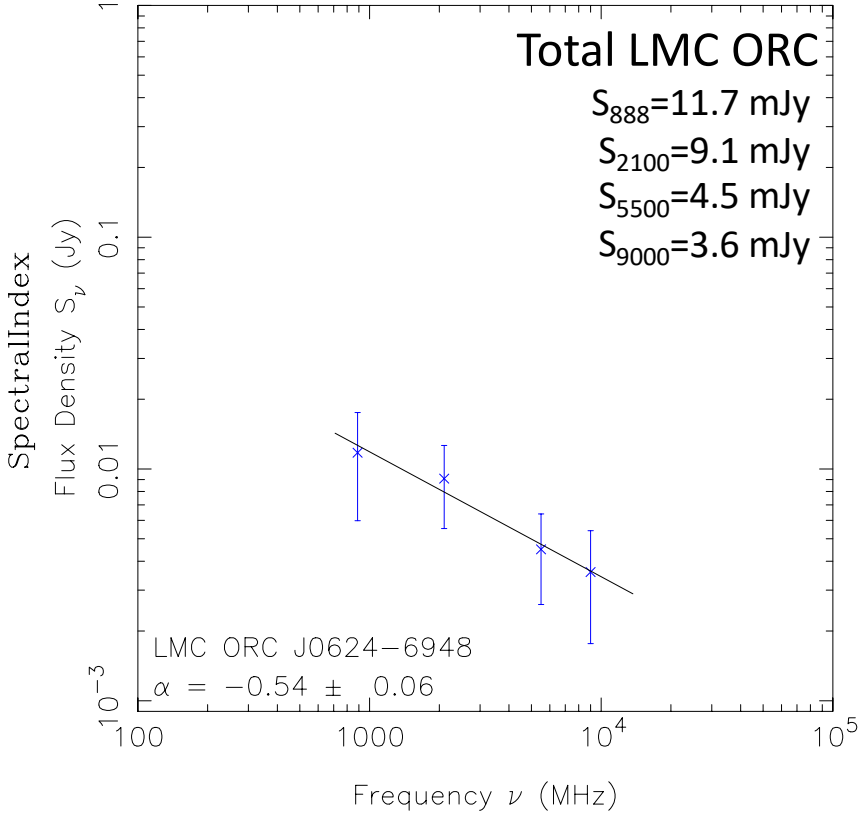
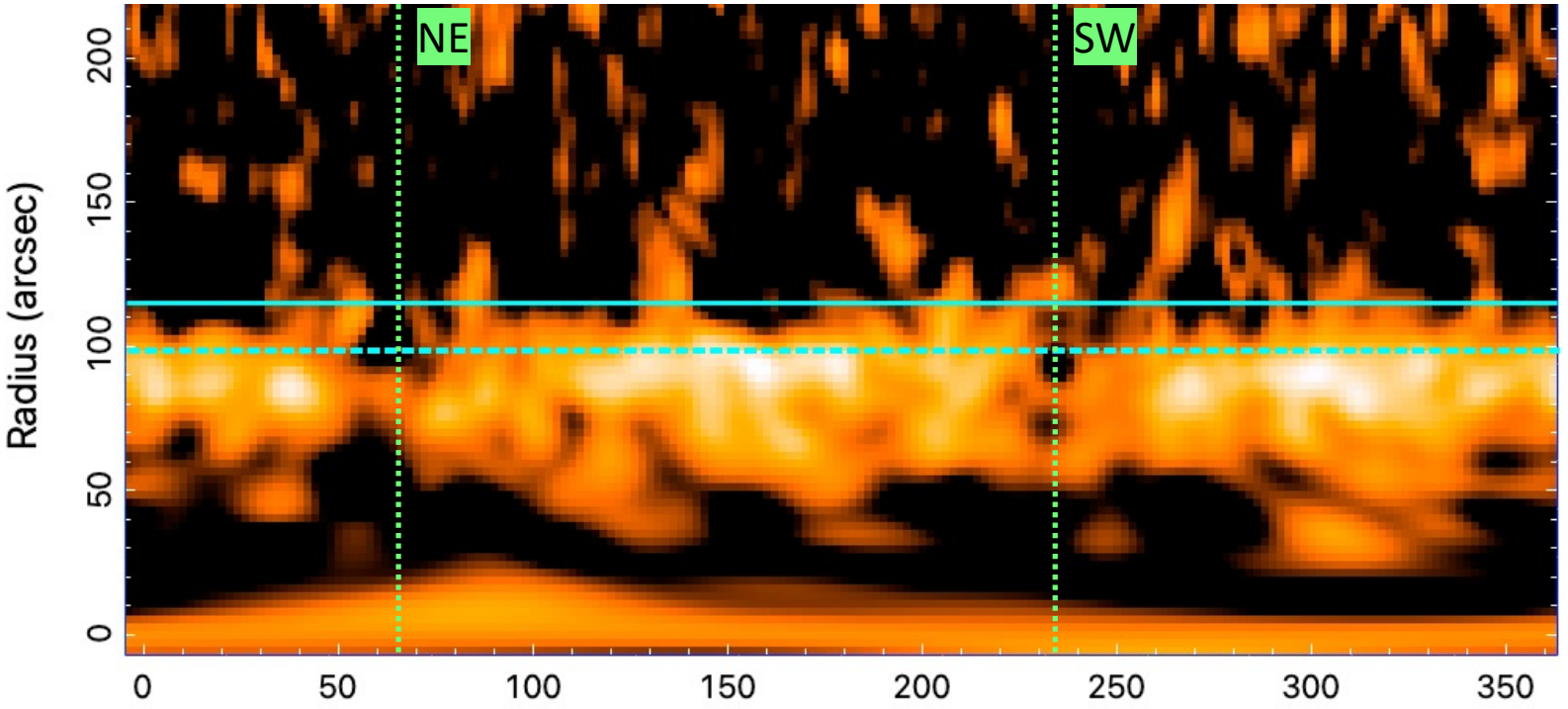
LMC_ORC_0 J0624-6948

Spectral index: -0.4 < α < -0.75 → same spectral age





Radio point-like sources in the field have distinctively different α



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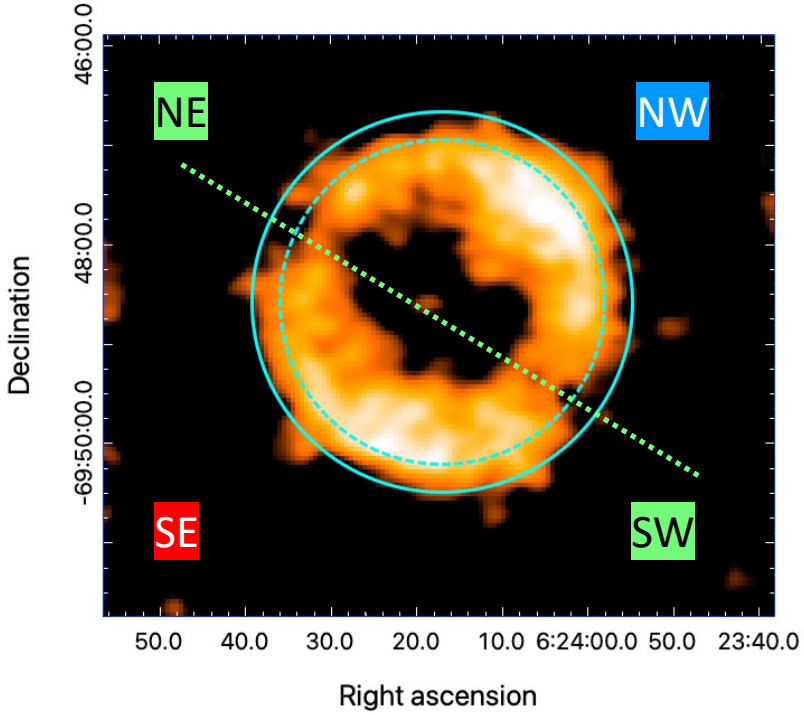
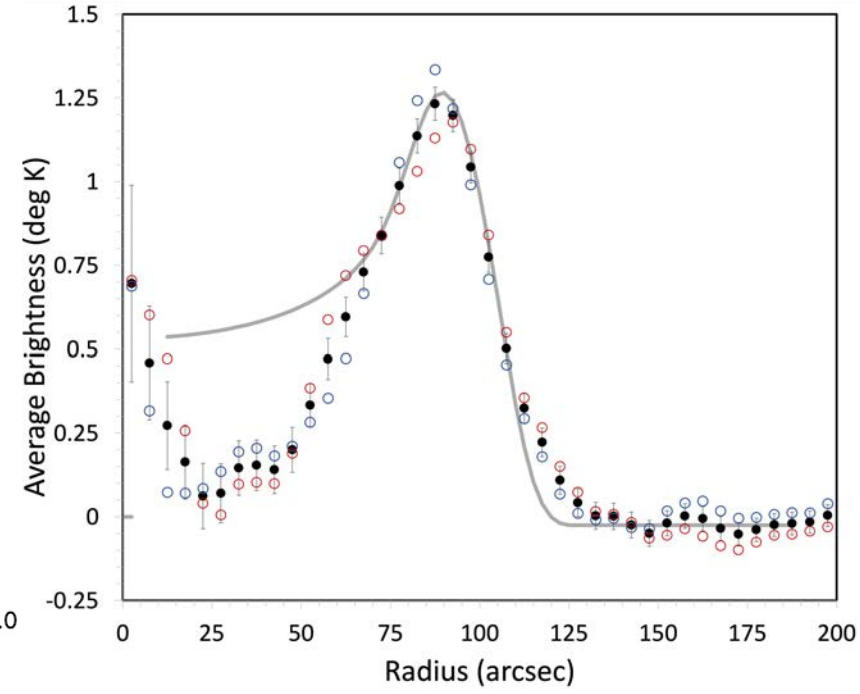
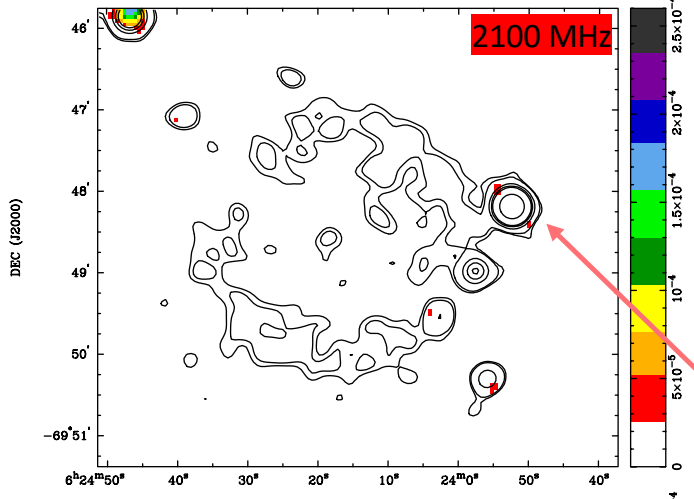
Effective 10-cm map

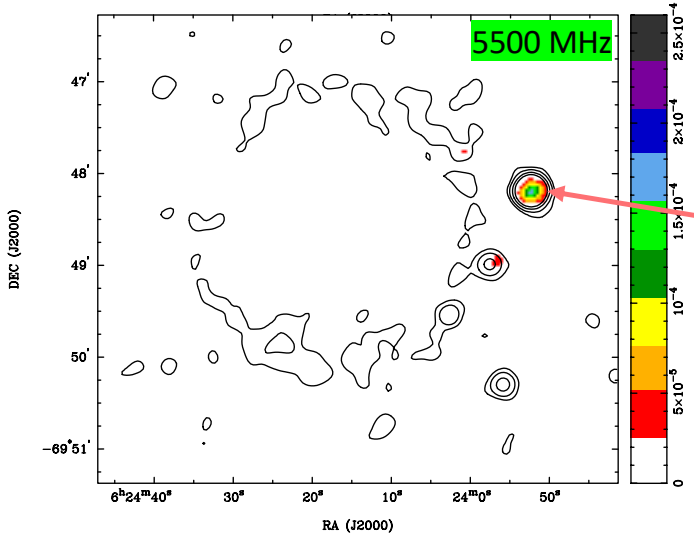
Thickness of the ring ~30”

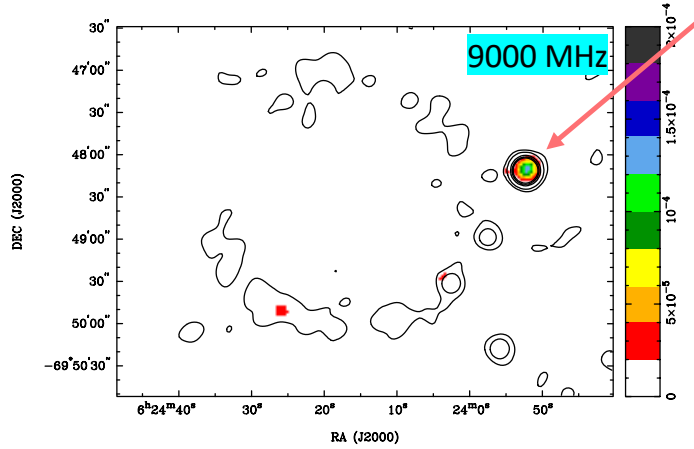




D~198”

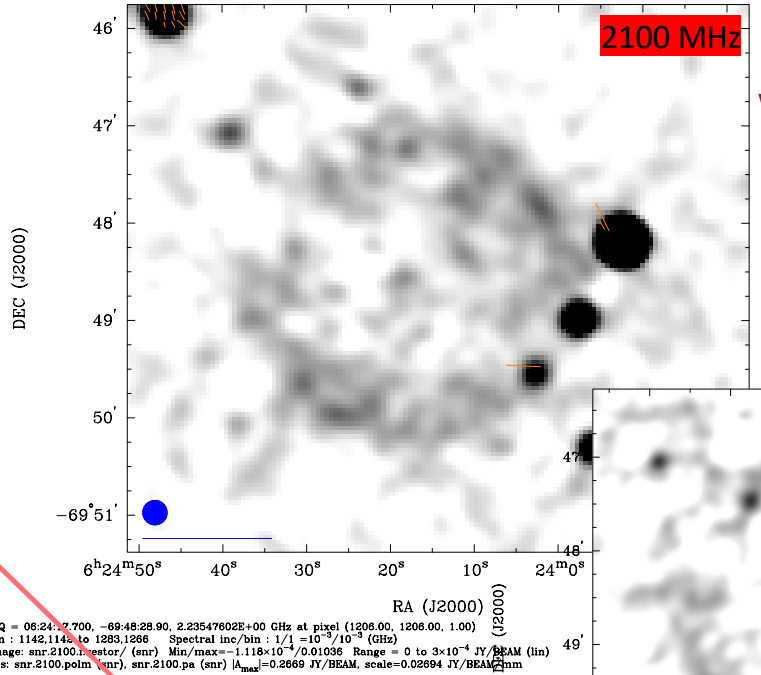






Polarisation

GPS



RA, DEC, FREQ = 06:24:17.700, −69:48:28.90, 2.23547602E+00 GHz at pixel (1206.00, 1206.00, 1.00)
Spatial region : 1142,1142 to 1283,1266 Spectral inc/bin : 1/1 =10^{-9}/10^{-9} (GHz)
Pixel map image: snr.2100.i.restor/ (snr) Min/max=−1.118×10^{-4}/0.01036 Range = 0 to 3×10^{-4} JY/BEAM (lin)
Vector images: snr.2100.polm (snr), snr.2100.pa (snr) $|A_{max}|$=0.2669 JY/BEAM, scale=0.02694 JY/BEAM/mm

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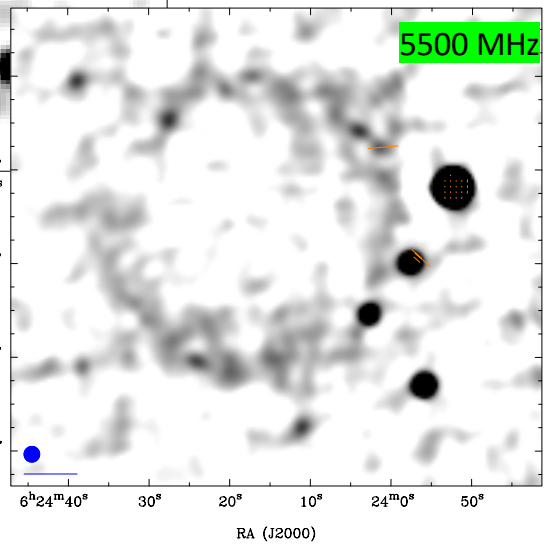
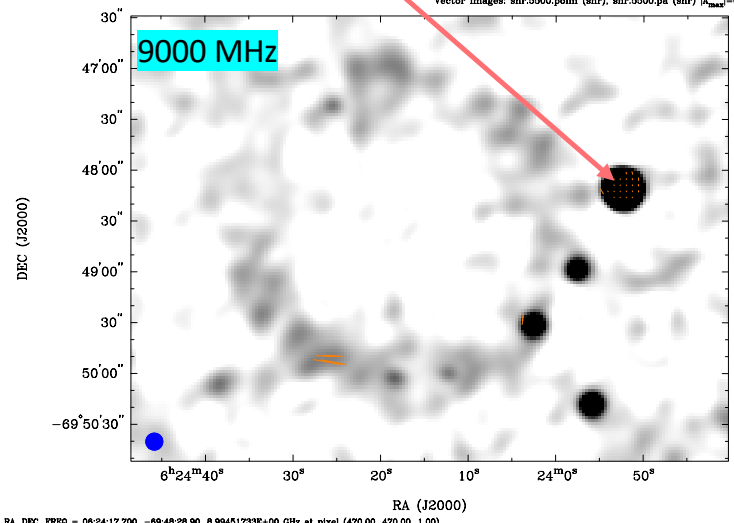
LMC_ORC



RA, DEC, FREQ = 06:24:17.700, −69:48:28.90, 5.46705246E+00 GHz at pixel (737.00, 737.00, 1.00)
Spatial region : 653,641 to 841,810 Spectral inc/bin : 1/1 =10^{-9}/10^{-9} (GHz)
Pixel map image: snr.5500.i.restor/ (snr) Min/max=−6.793×10^{-5}/0.0127 Range = 0 to 10^{-4} JY/BEAM (lin)
Vector images: snr.5500.polm (snr), snr.5500.pa (snr) $|A_{max}|$=0.5654 JY/BEAM, scale=0.05708 JY/BEAM/mm



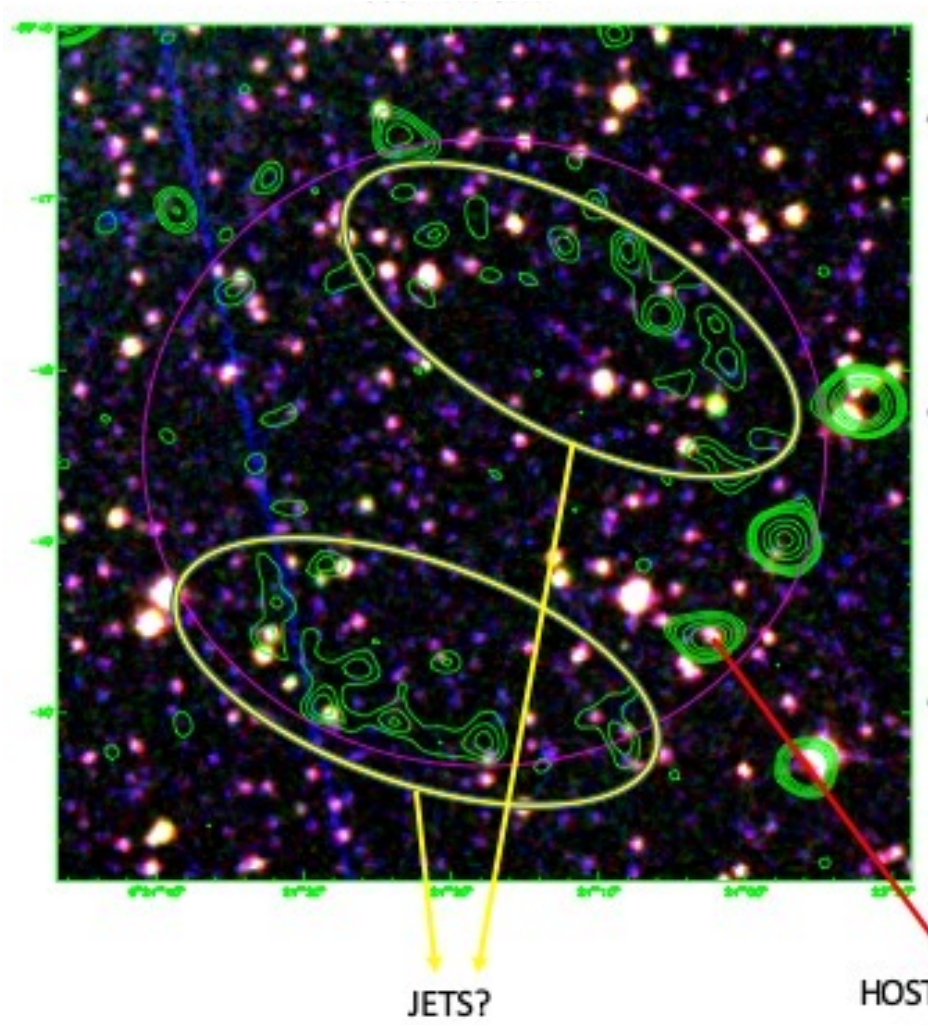
RA, DEC, FREQ = 06:24:17.700, −69:48:28.90, 8.99451733E+00 GHz at pixel (470.00, 470.00, 1.00)
Spatial region : 382,391 to 577,536 Spectral inc/bin : 1/1 =10^{-9}/10^{-9} (GHz)
Pixel map image: snr.9000.i.restor/ (snr) Min/max=−5.763×10^{-5}/7.7×10^{-3} Range = 0 to 10^{-4} JY/BEAM (lin)
Vector images: snr.9000.polm (snr), snr.9000.pa (snr) $|A_{max}|$=0.7685 JY/BEAM, scale=0.07759 JY/BEAM/mm

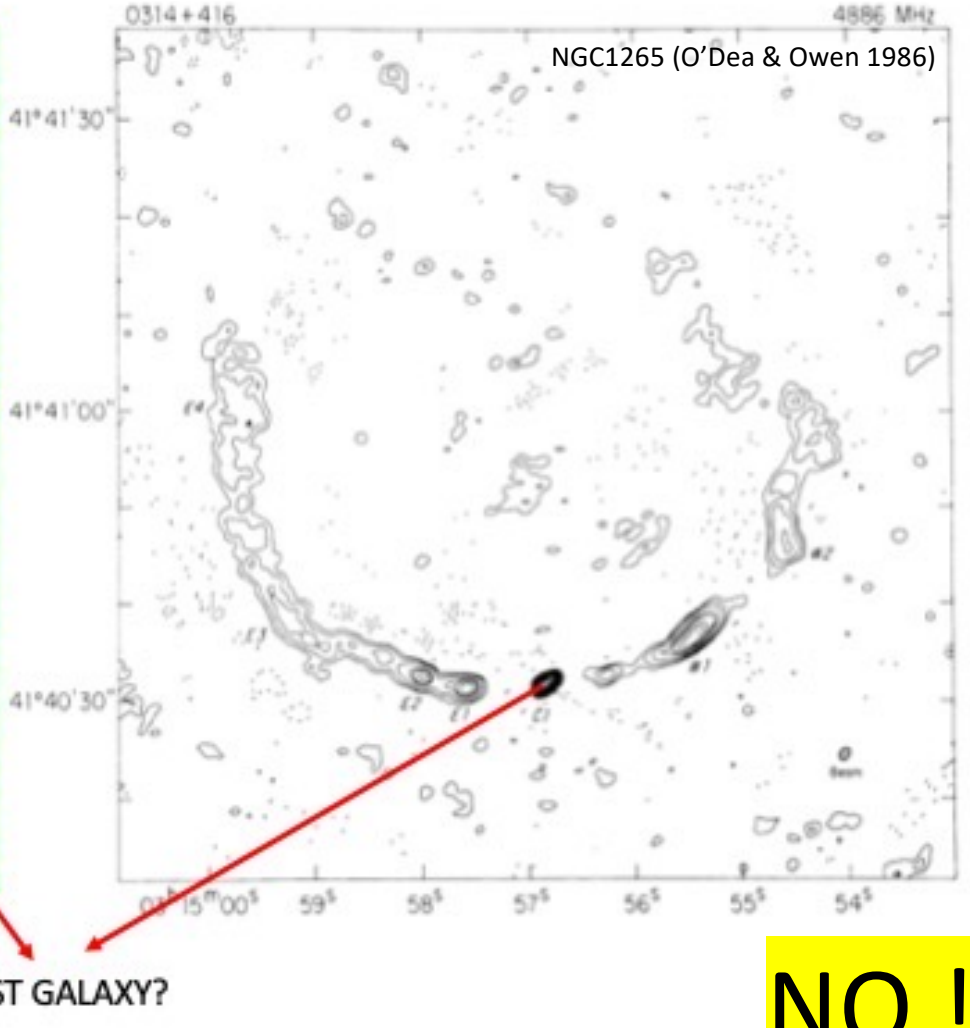
No Pol >1% !

J0624-6948 as Uruk-Hai ?

To be or NOT to be… ORC?

Case for AGN (NAT) ???

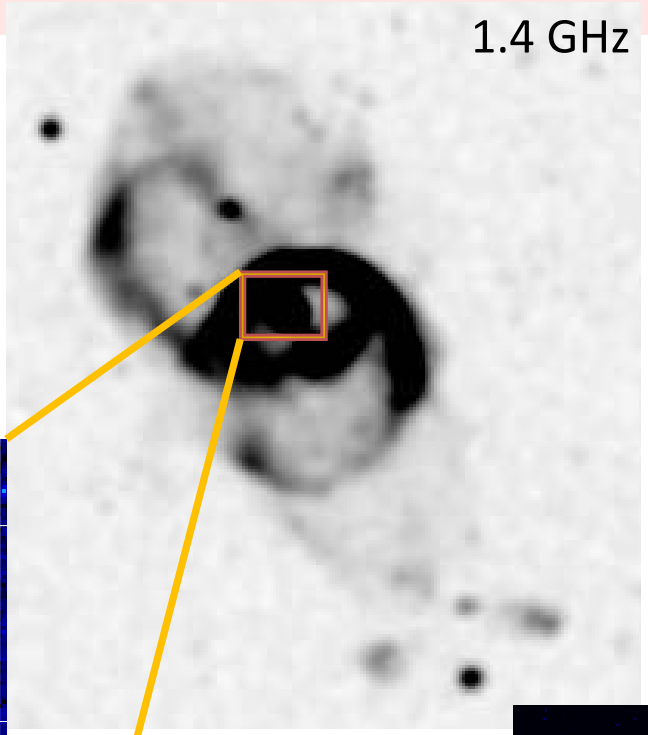


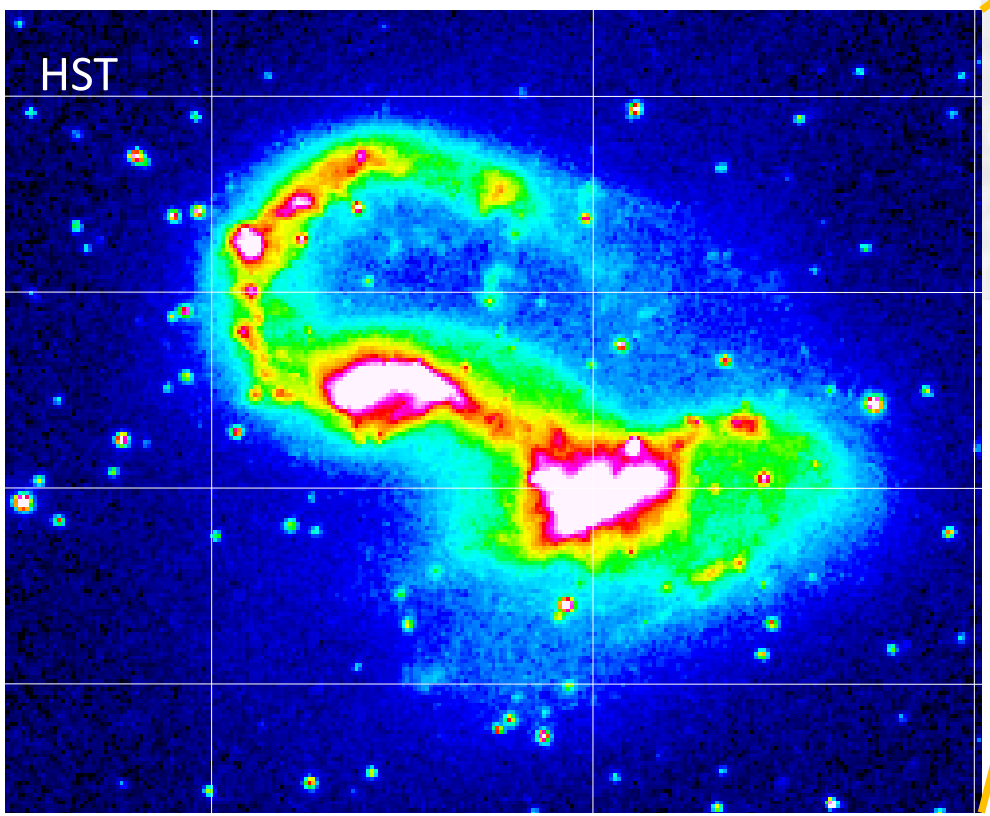


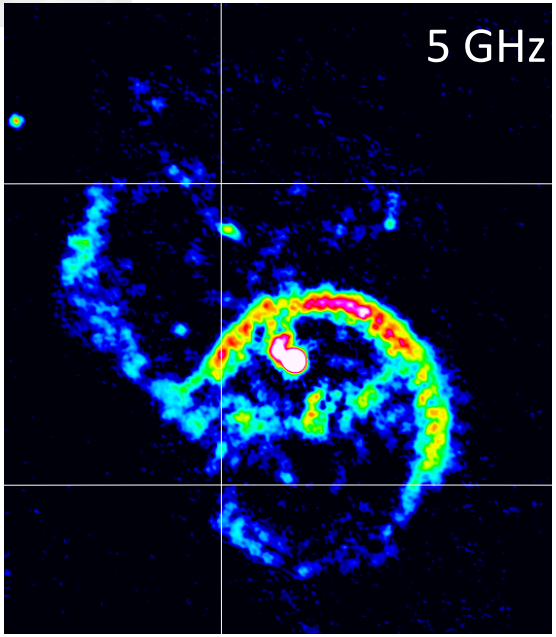
NO !!!

Radio JETS are synchrotron i.e. also steep radio spectra

To be or NOT to be... ORC?







To be or NOT to be…

is J0624-6948 an ORC?

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It is circular/ring!

But…

Much bigger (3’ vs. 1’)

Different spectral index (-0.54 vs -1.0)

No (obvious) central source (engine?)

No polarisation

To be or NOT to be…
Run-away LMC SNR or ORC

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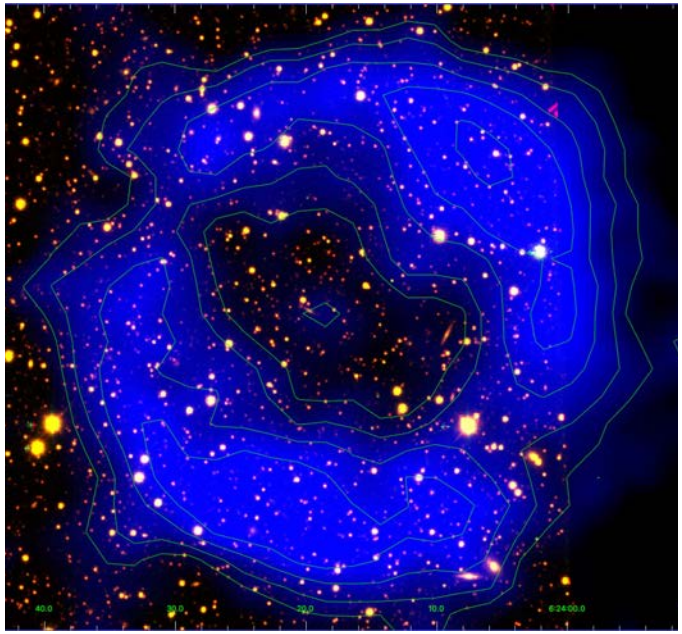
Case for ”run-away” LMC (or MW) SNR

- Located “between LMC and MW”. ~2.1º from the LMC.
- NO OBVIOUS OPTICAL or X-ray counterpart (good reasons for that)!!!
- Typical LMC SNR size with diam*=47.5pc where $d_{lmc\ av}$=41pc
- Perfect(?) D=198"±2" ring with thickness of ~30”
- ”classical SNR” bi-lateral shape
- But NO polarisation!



* Using distance to LMC of 50kpc

To be or NOT to be… Run-away LMC SNR or ORC

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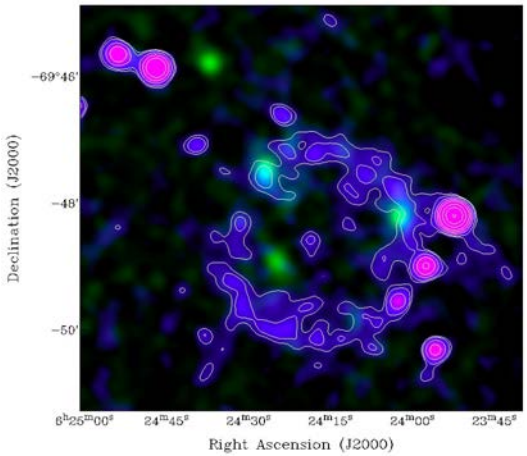
Case for ”run-away” LMC (or MW) SNR

PART 2



- SN(R) progenitor
  - Likely Type Ia, but
  - CC shouldn’t be ruled out either!!!
  - From LMC but also possible from MW

  From High Velocity Star(s) ?
- Evolving/Expanding in rarified environment – like MW Loops?
- S_{1GHz}=0.0119 Jy; Σ=1.54x10^{-22} W/(m^2 Hz SR); $L_{10MHz-100GHz}$=6.3x10^{25} W
- Evolving in very low ambient ISM → n_H~0.008 cm^{-3} → “ideal SNR”
- α=–0.54±0.06 → typical for mid-age SNR with low Σ
- Age: 4000-9000 yrs (ejecta dominated to Sedov phase)
- Assuming above D, α, S_{888}, $dist_{lmc}$, and filling factor of 0.875 Equipartition give us: B=7.5μGa and E_{min}=5.65 x 10^{48} ergs

* Using distance to LMC of 50kpc

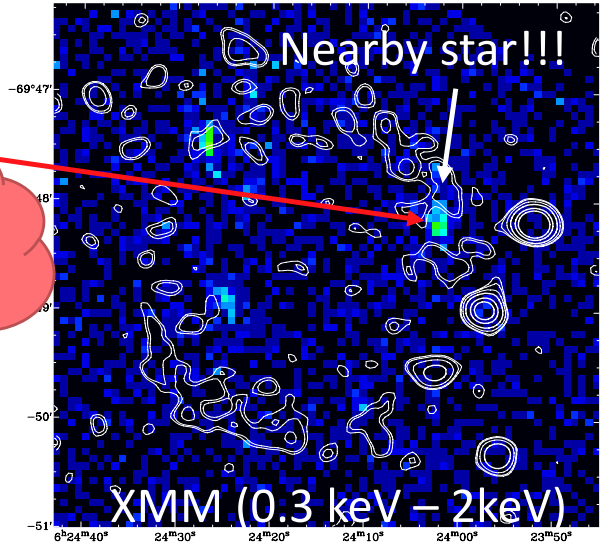
To be or NOT to be...
remnant of stellar super-flare (RSSF) or ORC_0 ?

Baby ORC?

What if it is nearby Remnant of Stellar Super-Flare?

- Distance from Gaia -- 58.5pc (p=17.0781)
  - M-dwarf class star (Gaia EDR3 5278760380137682816)
  - Size of shell ~ 0.186 ly (0.0578pc)
  - Age of 55-550 yrs if we assume
    - V_{exp} ~ 50-500 km/s
  - Proper motion in Dec=46.087mas/yr !
- Flare stars are known X-ray objects!
- Modelling E:
  - E_{CME} = >2x10^{36} erg $M/(1x10^{21}\ g)\ (v_{CME}/(450\ km/s))^2$
  - $M_{ejection}$ >2x10^{22}g = 1x10^{-11} M_{Sun} = 3x10^{-6} M_{Earth}

A CME on the Sun can travel Alfven speed (282.1 km/s) which would give an age of the ORC_0 of ONLY ~100yrs (t=s/v; s=d/2=0.0285pc=8.8^11km)



Fun fact:
M-dwarf A.K.A.:
Ultracool Dwarf (UCD) stars, and
UV-Ceti type stars.

Active Star HR 9024 (Argiroffi+19):
E_{CME} = 5.2×10^{34} erg
$M_{ejection}$ 1.2×10^{21} g

NOT PN or SN event!
"Maybe it's more like the ejection of a whole shell of stuff?"
Not just one side (flare) eruption!
Or maybe a multiple simultaneous eruptions?

If RSSF then proper motion will be observable!

CME = Coronal Mass Ejection; non-thermal origin as mag field produce them.

To be or NOT to be…
WHAT is J0624-6948 ?

Mid-age run-away LMC SNR (TN vs CC) -- 45%

or

Old-ish run-away Galactic SNR (TN vs CC) – 40%

or

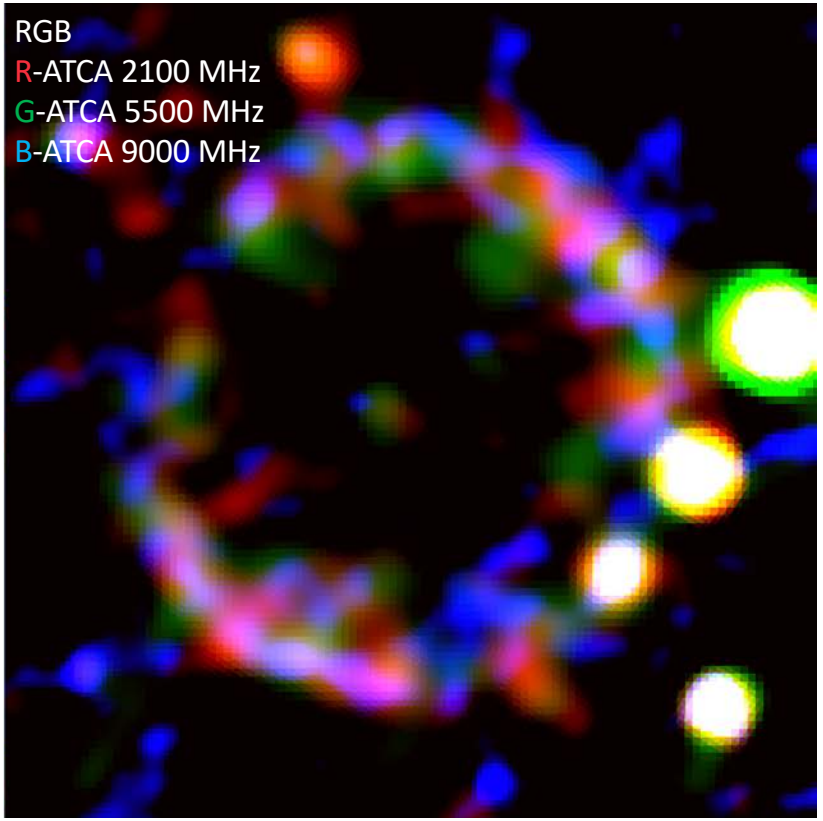
Nearby star super-flare???!! – 5%

or

…or precessing “BL-Lac” ??? –5%

or

something else ? -- 5%



To be or NOT to be...

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J0624-6948 as Unique SNR?

What is next?

- Parkes (search for PSR)
- Optical narrow-bands (Halpha, [SII] and [OIII])
- MeerKAT
- ?

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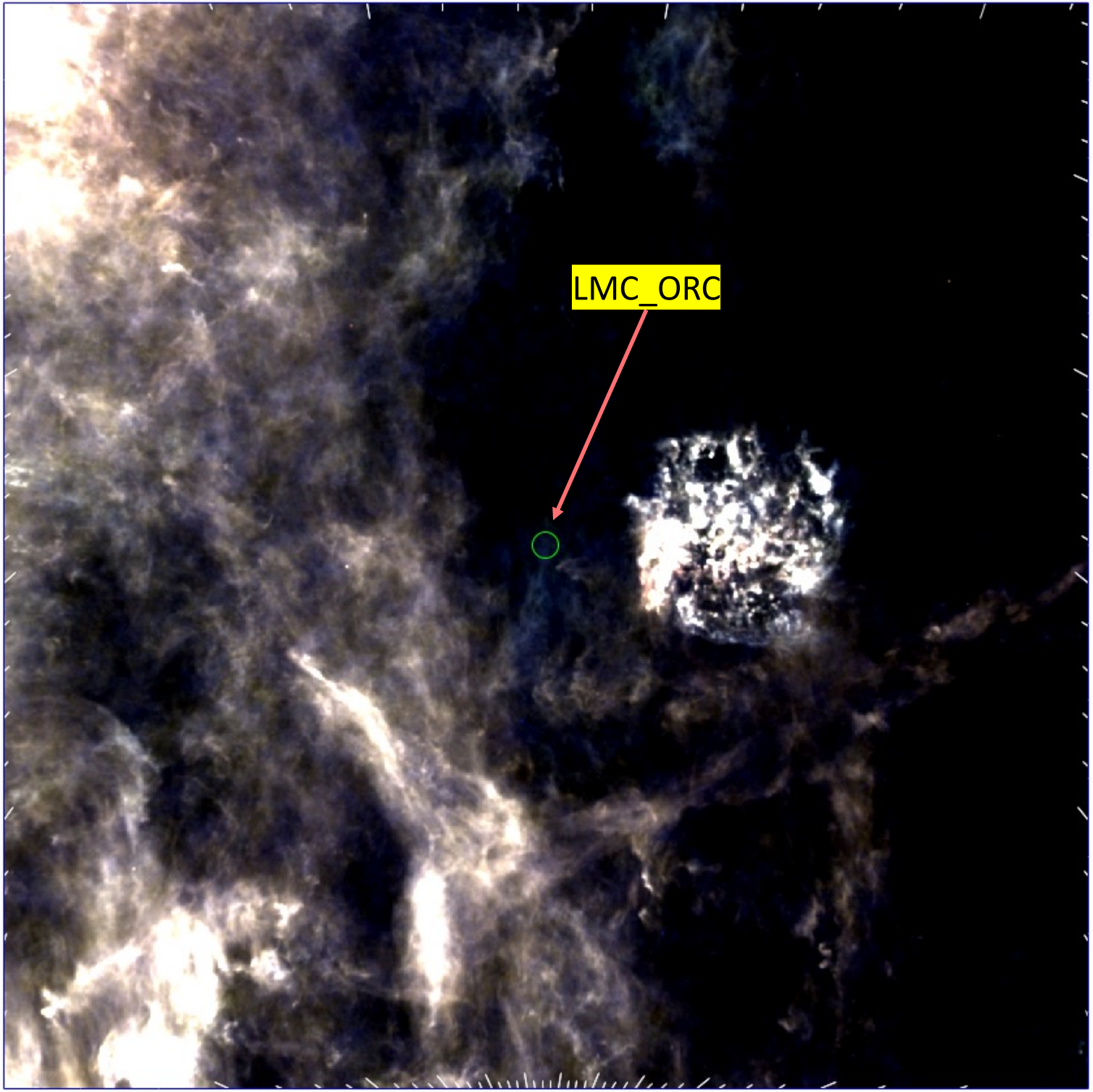

?

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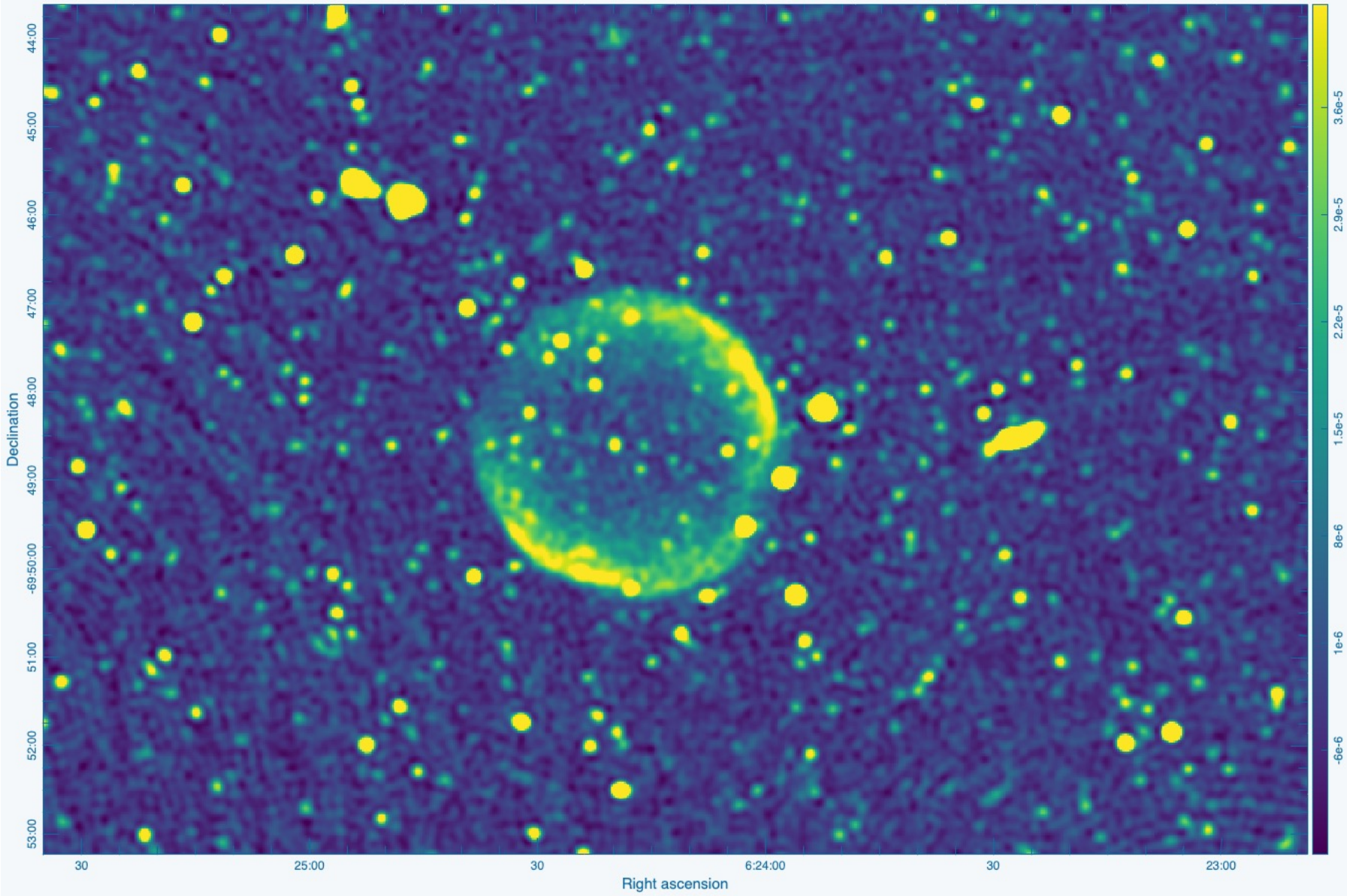
LMC ORC with MeerKAT



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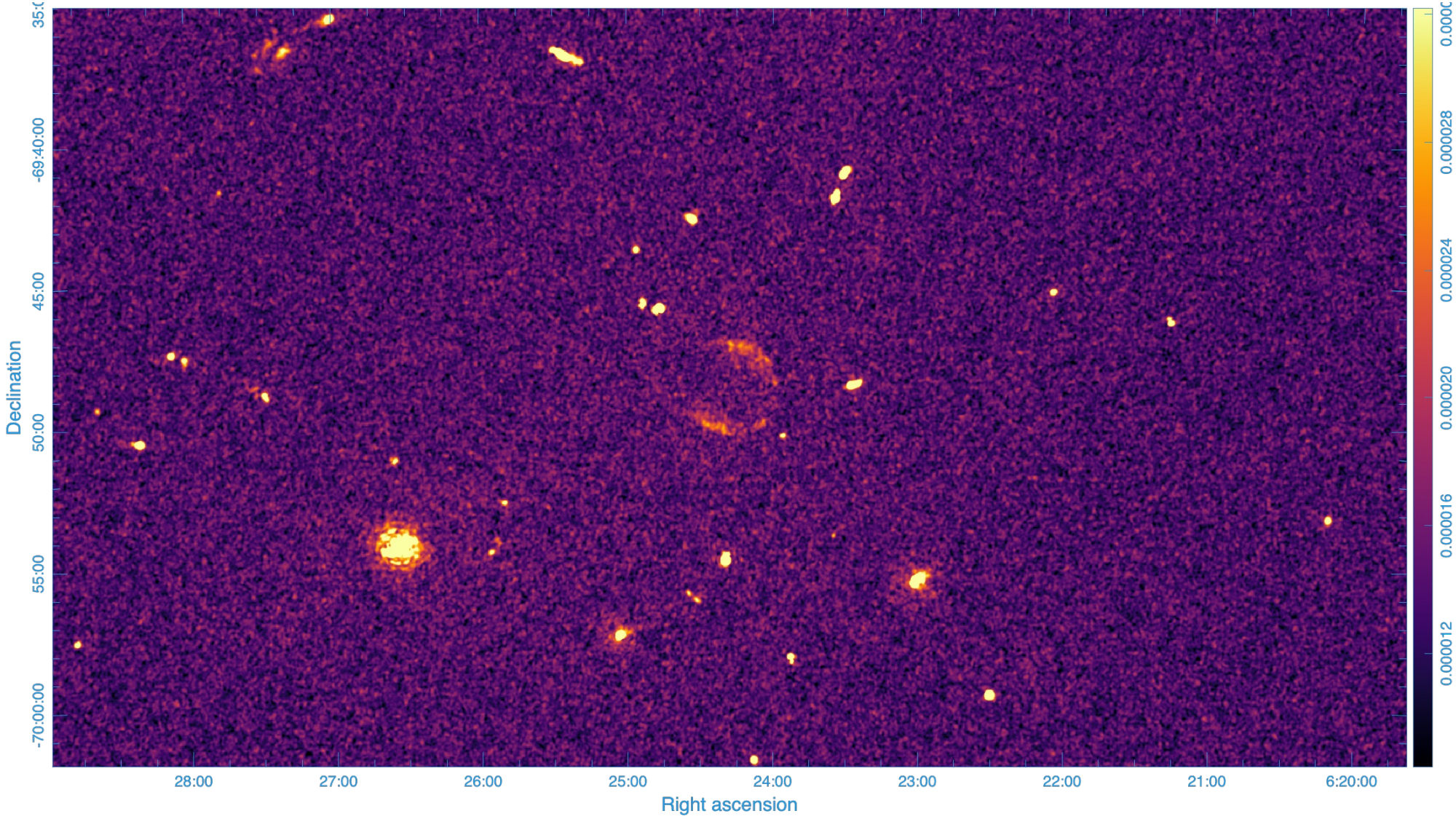
LMC ORC with MeerKAT



Not even a trace of Hα (CTIO 4m)

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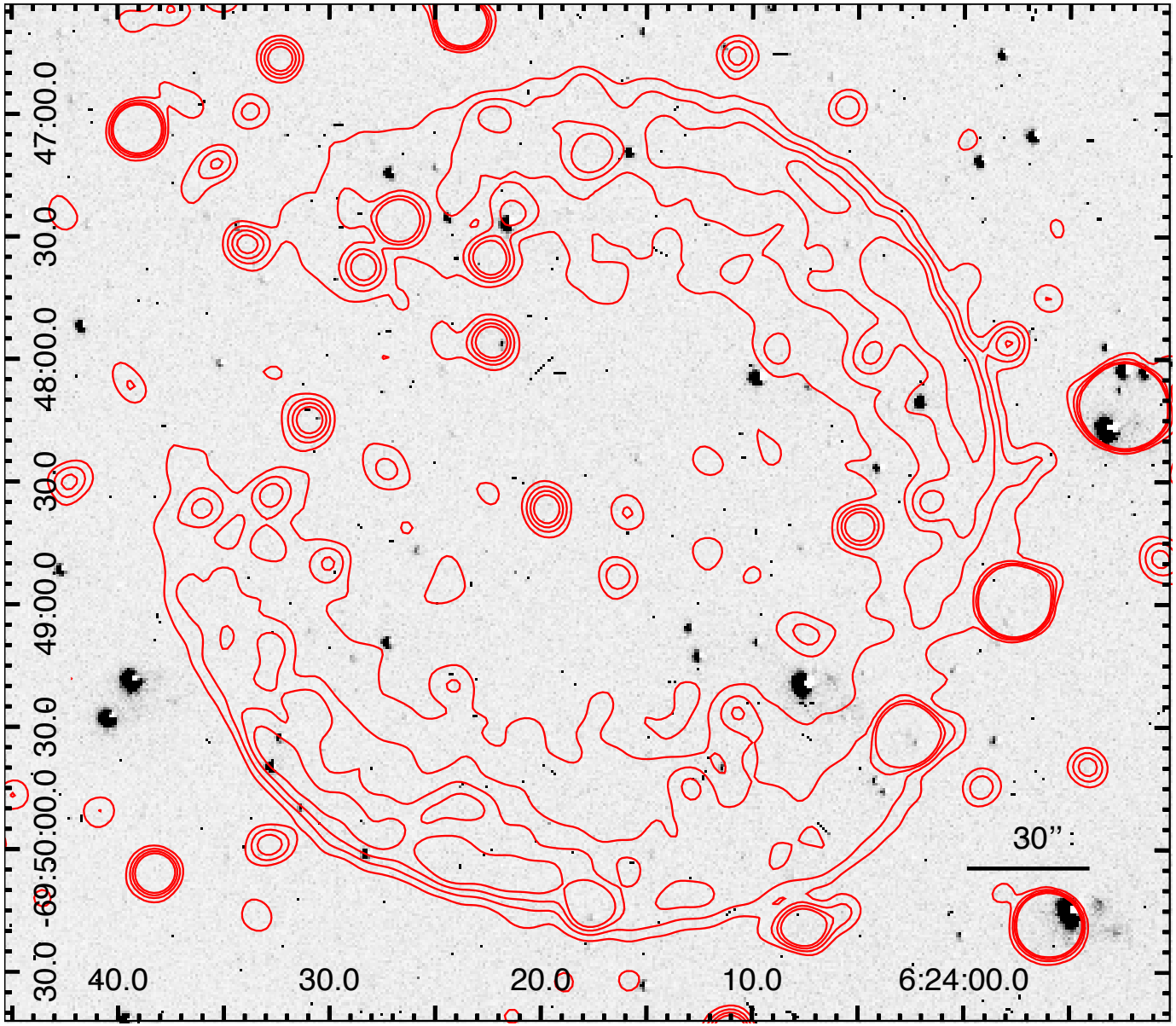
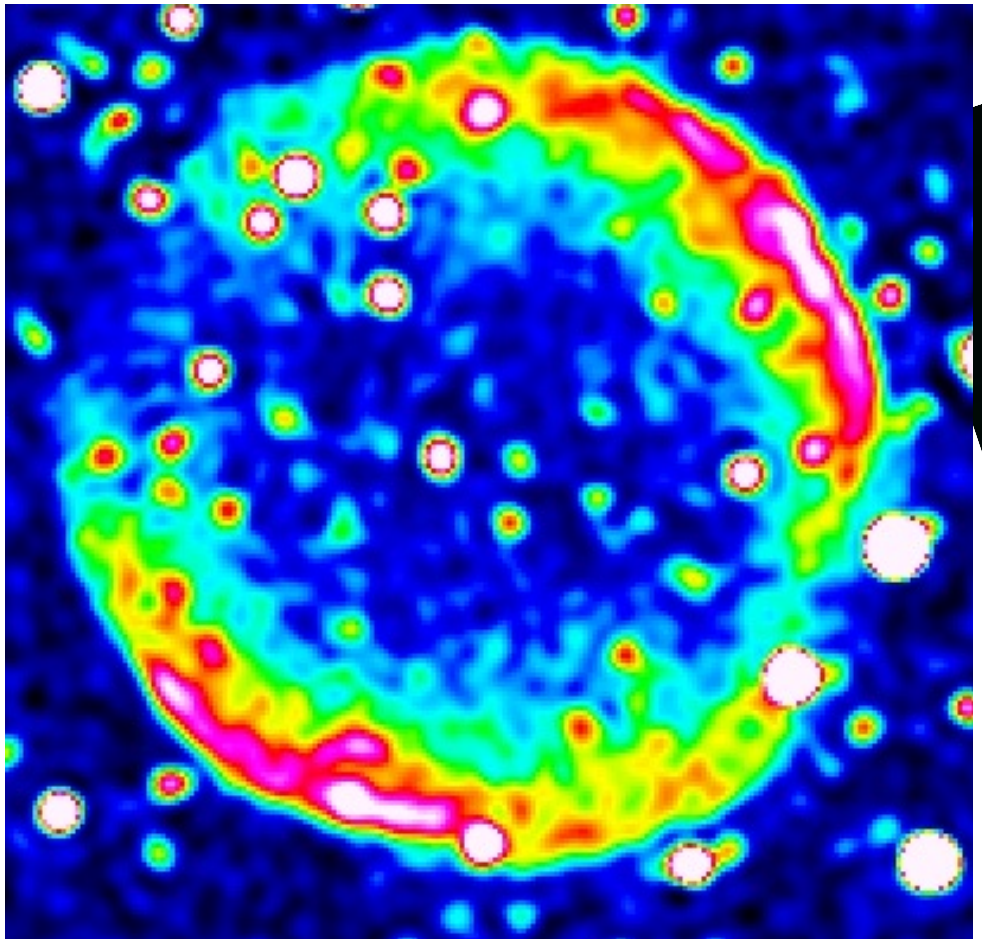
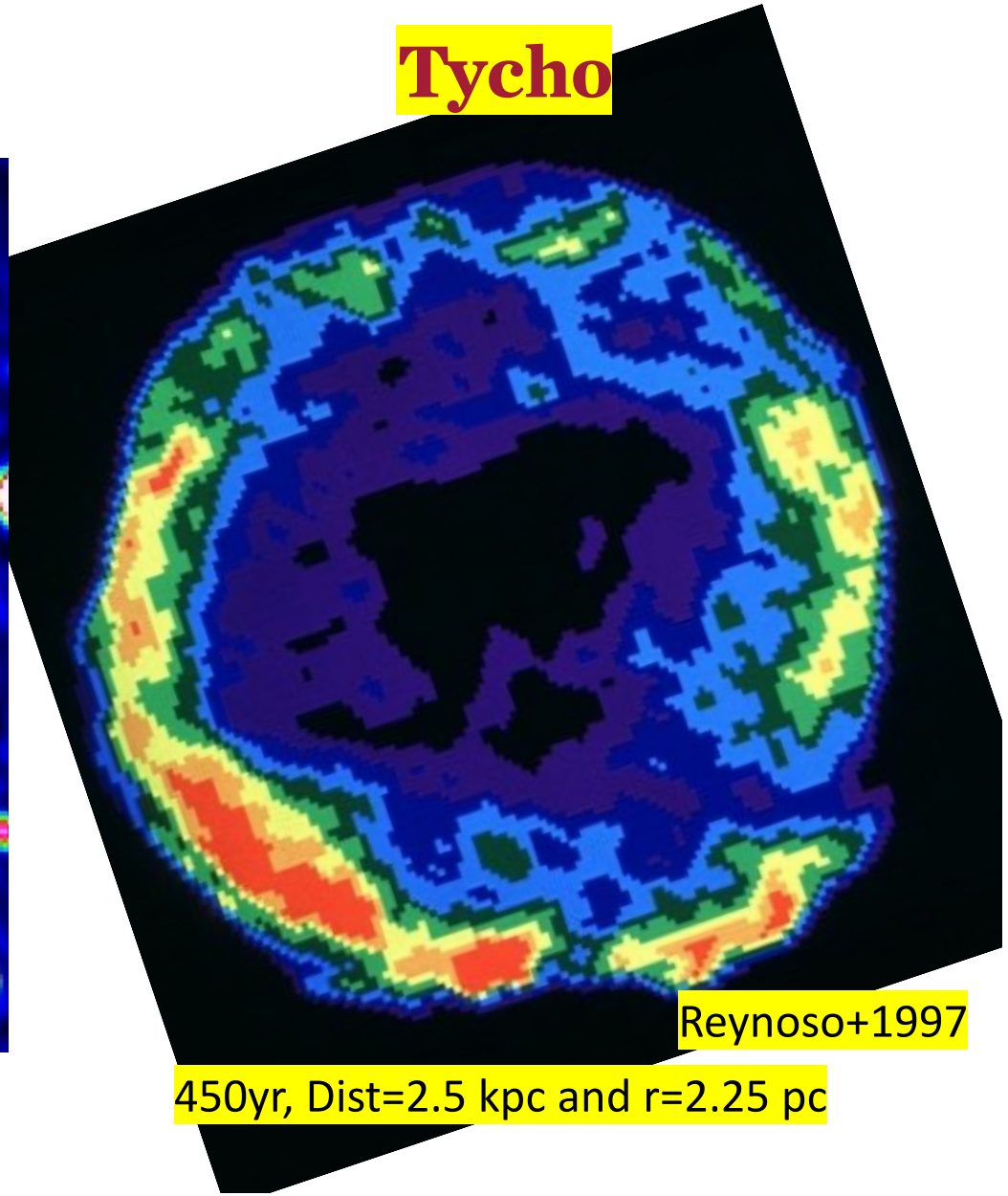


LMC_ORC



>4000yr, Dist=50 kpc and r=24 pc

Tycho



Reynoso+1997

450yr, Dist=2.5 kpc and r=2.25 pc

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WORK IN PROGRESS

RaRiGx (Radio Ring Galaxies)

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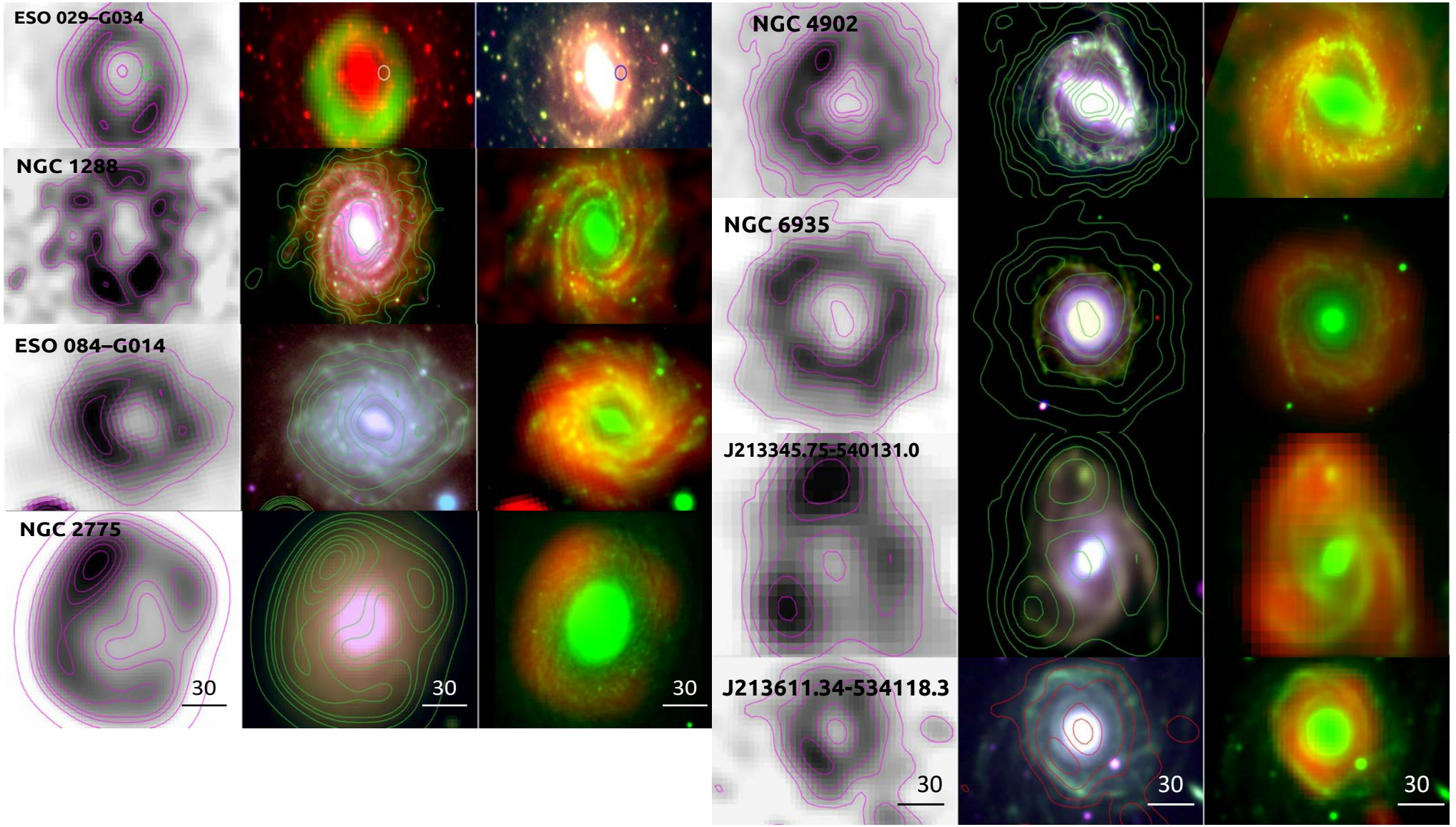
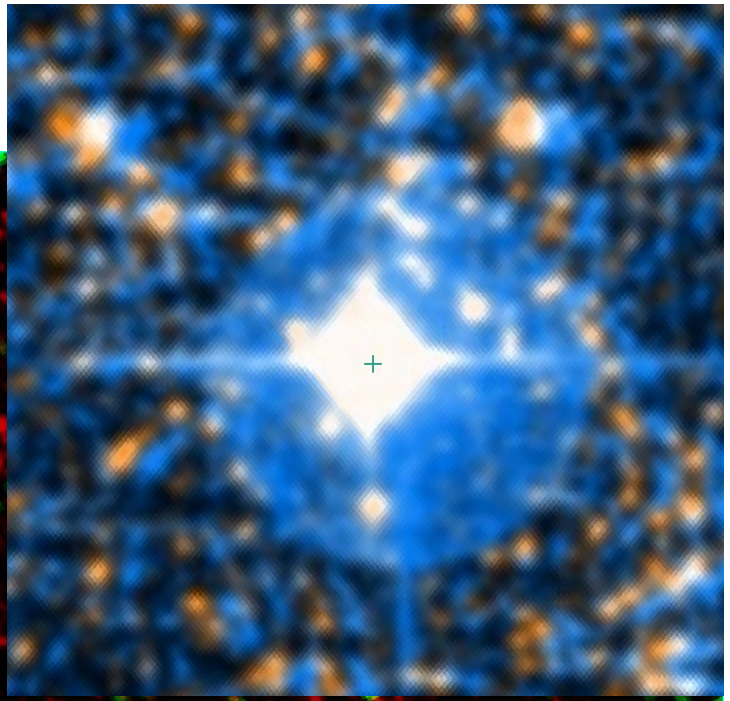


Pre-SN1987a????



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51:00.0
52:00.0
53:00.0
54:00.0
55:00.0
56:00.0
7:00.0
05.0
18:03:00.0
55.0
50.0
45.0
40.0
35.0
30.0
25.0
02:20.0

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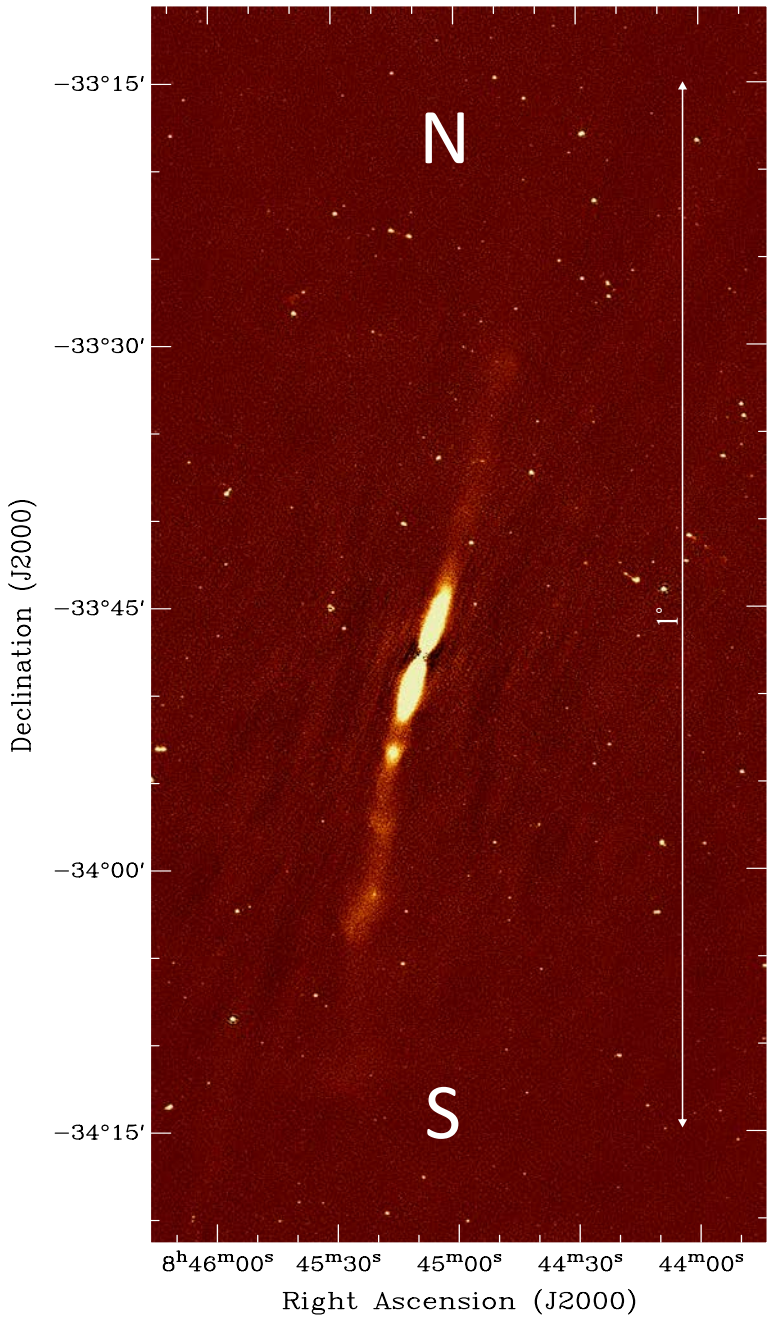
Curious case of NGC 2663

- Possible first case of observed recollimation phenomenon detected on kpc phenomenon on kpc scales?
- Positioned in extremely poor environment
- Very large galaxy in the nearby universe (< 200 Mpc) with jets about 350 kpc at 28.5 Mpc.
- Unusual fractional polarization
- SMBH might be offset
- First of many to come from EMU Survey?



Velovic+22

Recollimation shocks on kpc-scale

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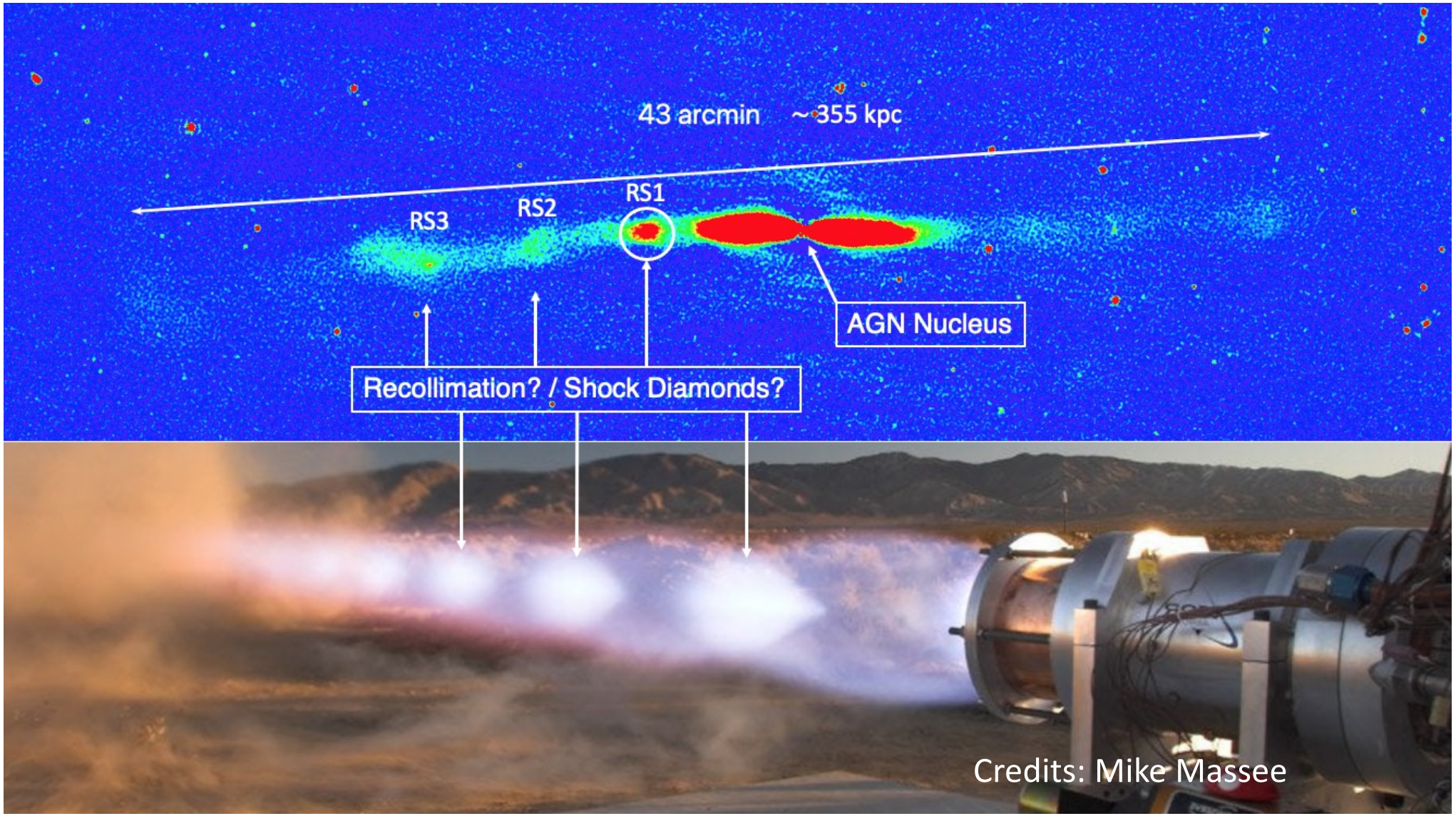

Pressure mismatch between the jet and the ambient medium.

Jet narrows and brightens up.

Multi frequency radio observations

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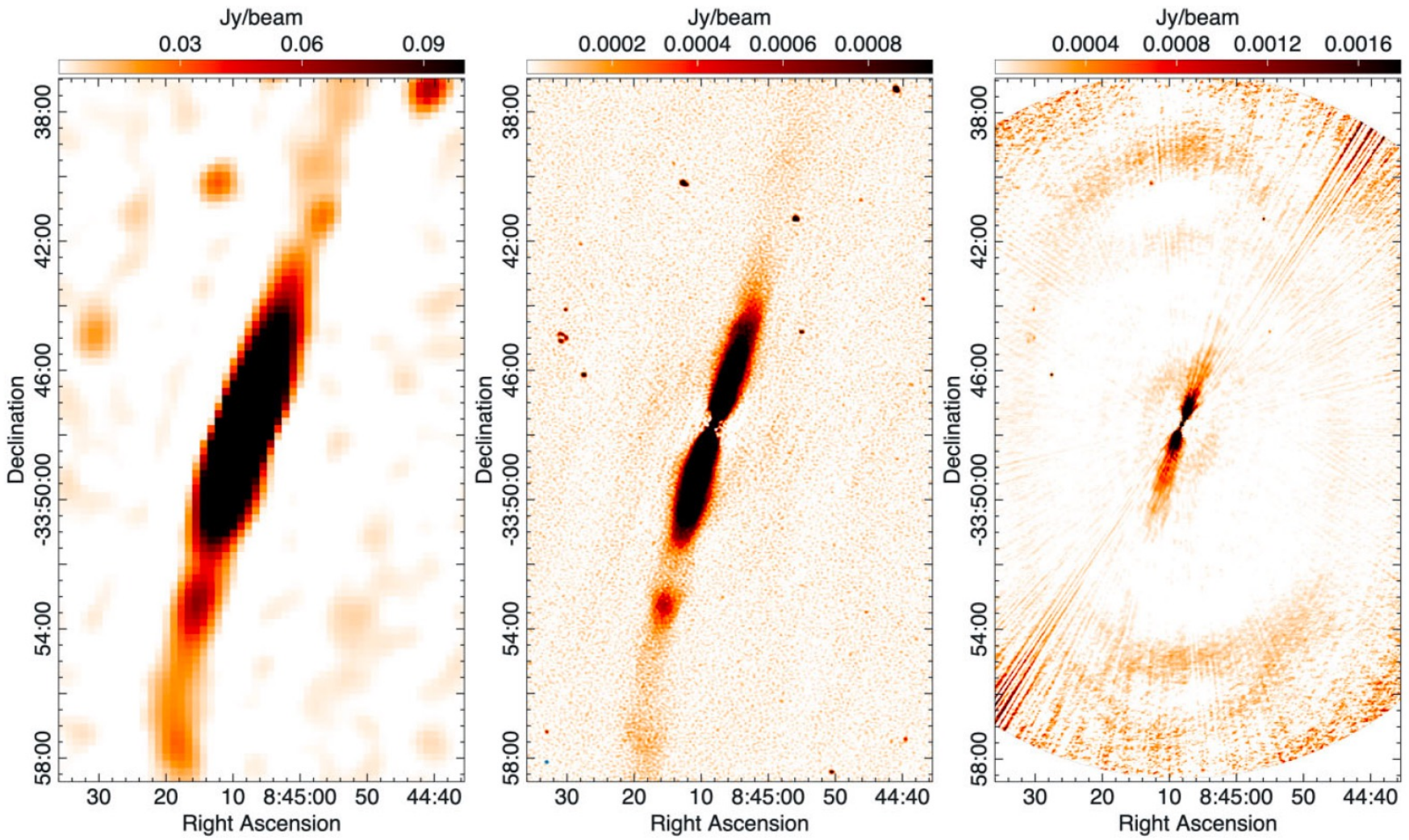
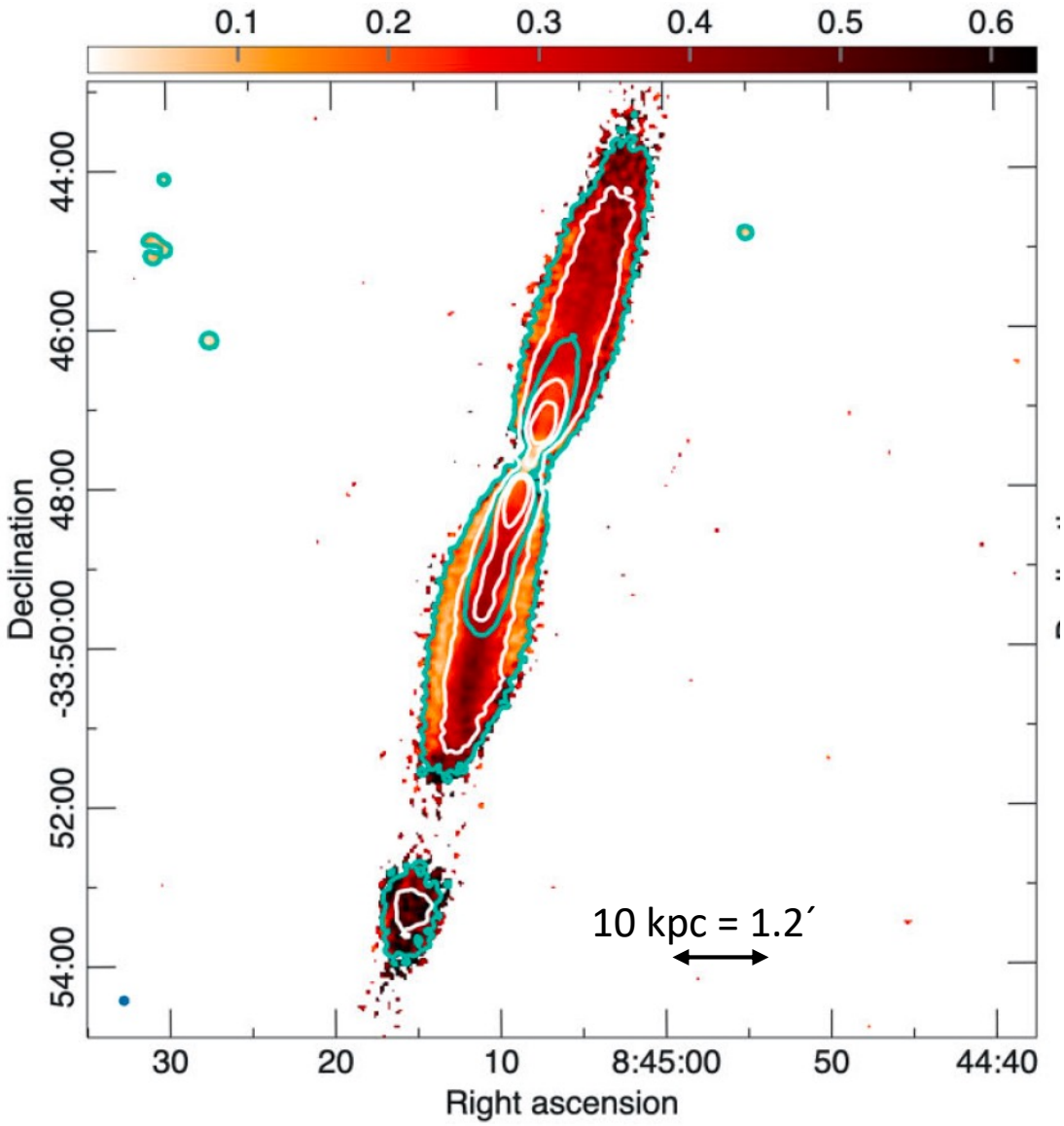


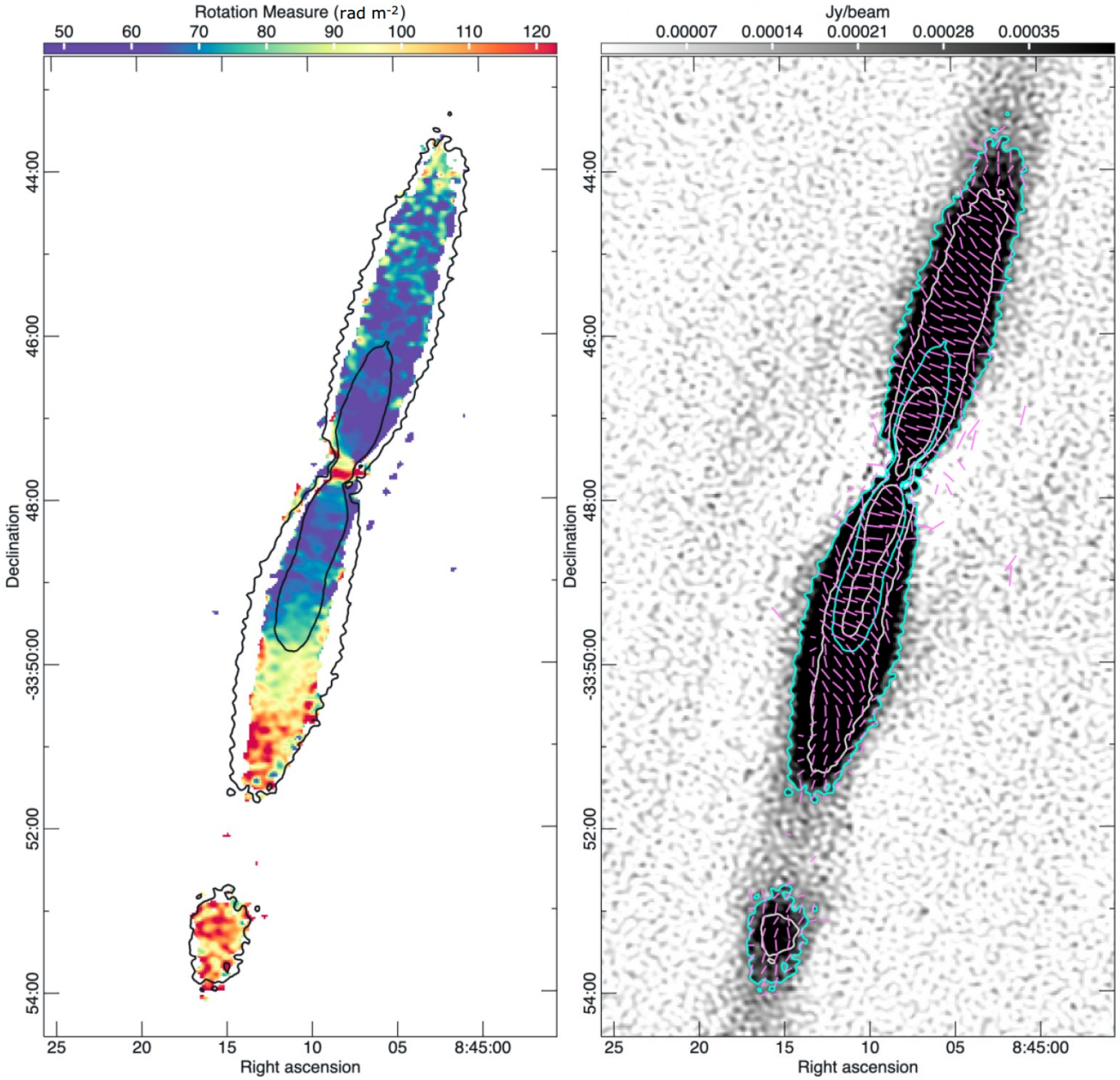
Frequency:	200 MHz	1520 MHz	2368 MHz
Resolution:	128´´x 105 ´´	6 ´´	9.6´´x 3.6´´
FOV:	25˚	25˚	16´

NGC 2663 polarization

- Fractional polarization is strongest along the ridge line and dropping towards the edges.
- Non-uniform cross-section - Coaxial *spine/sheath* jet structure.
- The inner spine of the jet has linear polarization.
- Toroidal field dominance in the outer sheath.



ASKAP 1520 MHz



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RM colour map - corresponding to peak polarization intensity after RM Synthesis.

Angled jets:
Northern jet is closer to the observer than the southern jet.

Magnetic field vectors change direction in the recollimation knot.

ASKAP 1520 MHz

Recollimation?

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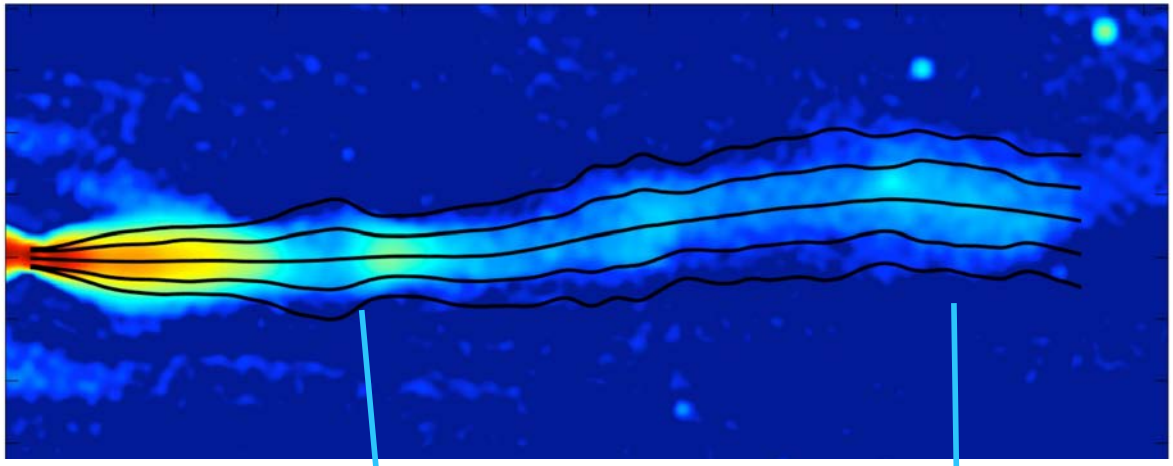
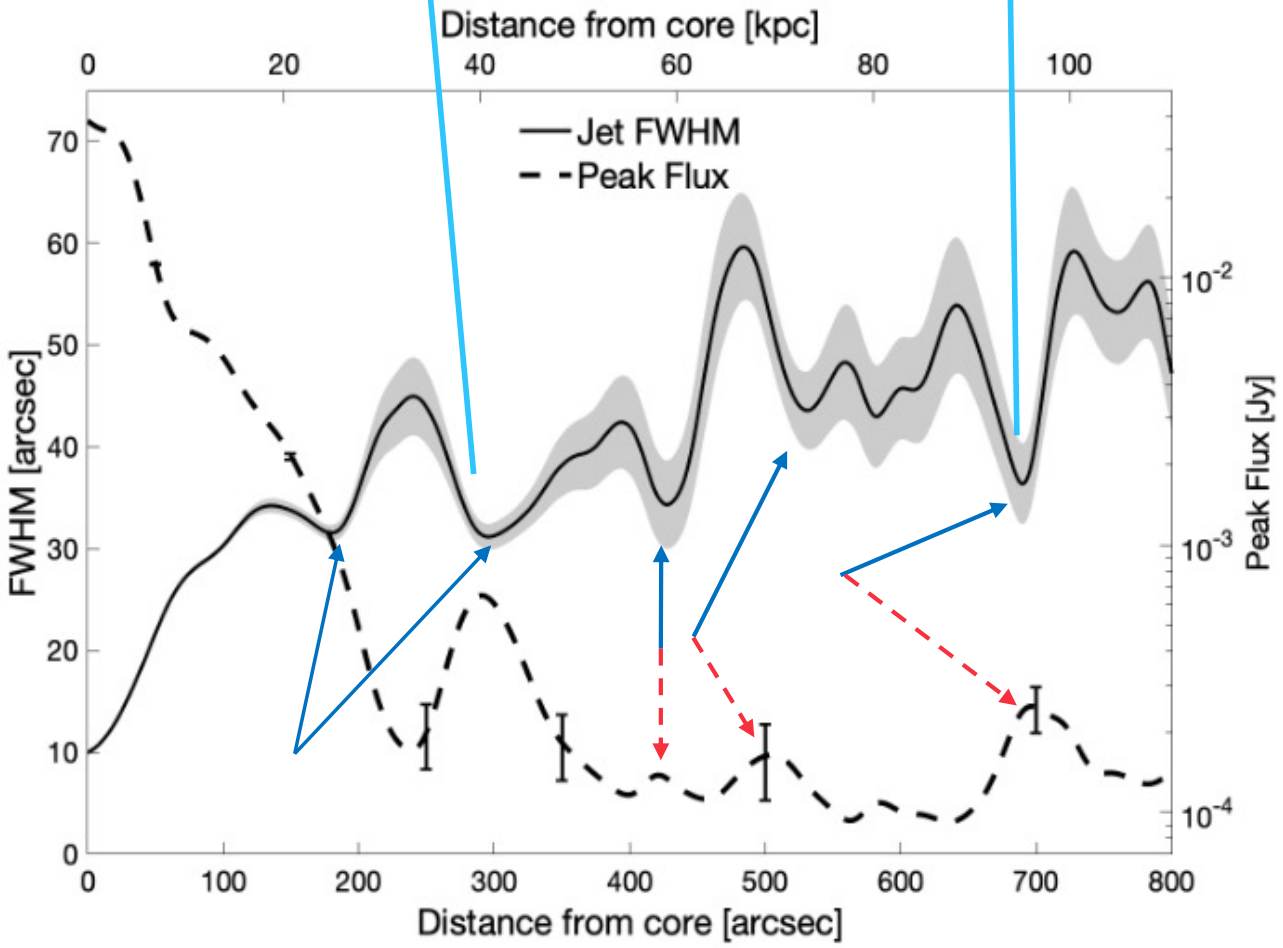
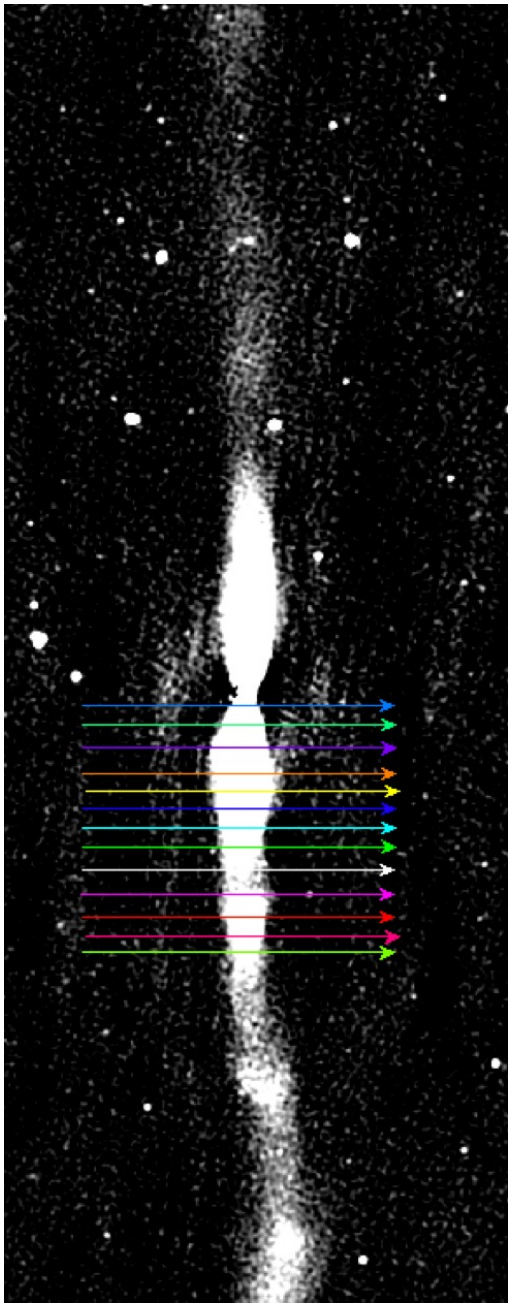
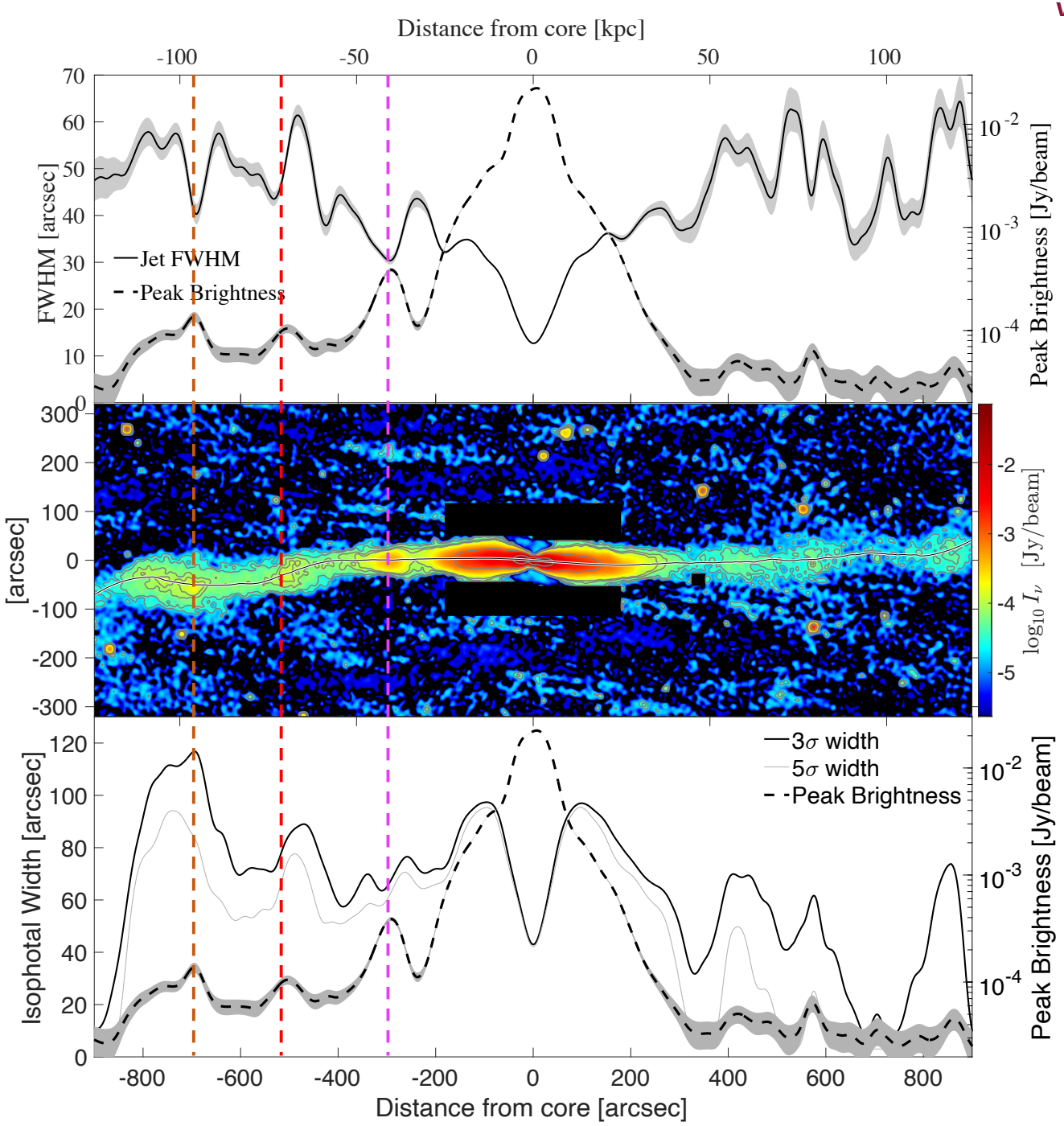






Recollimation?



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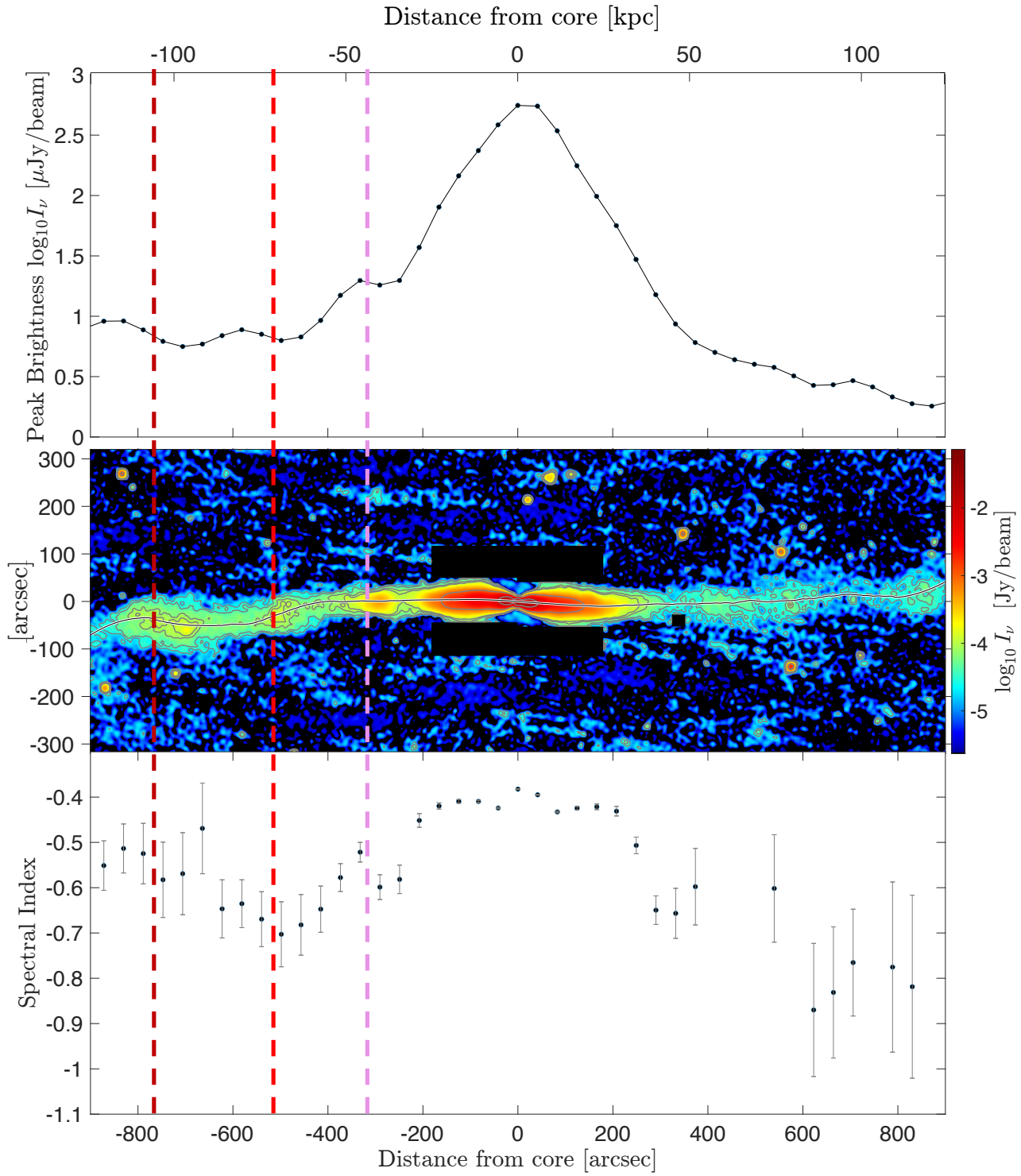

Chandra x-ray

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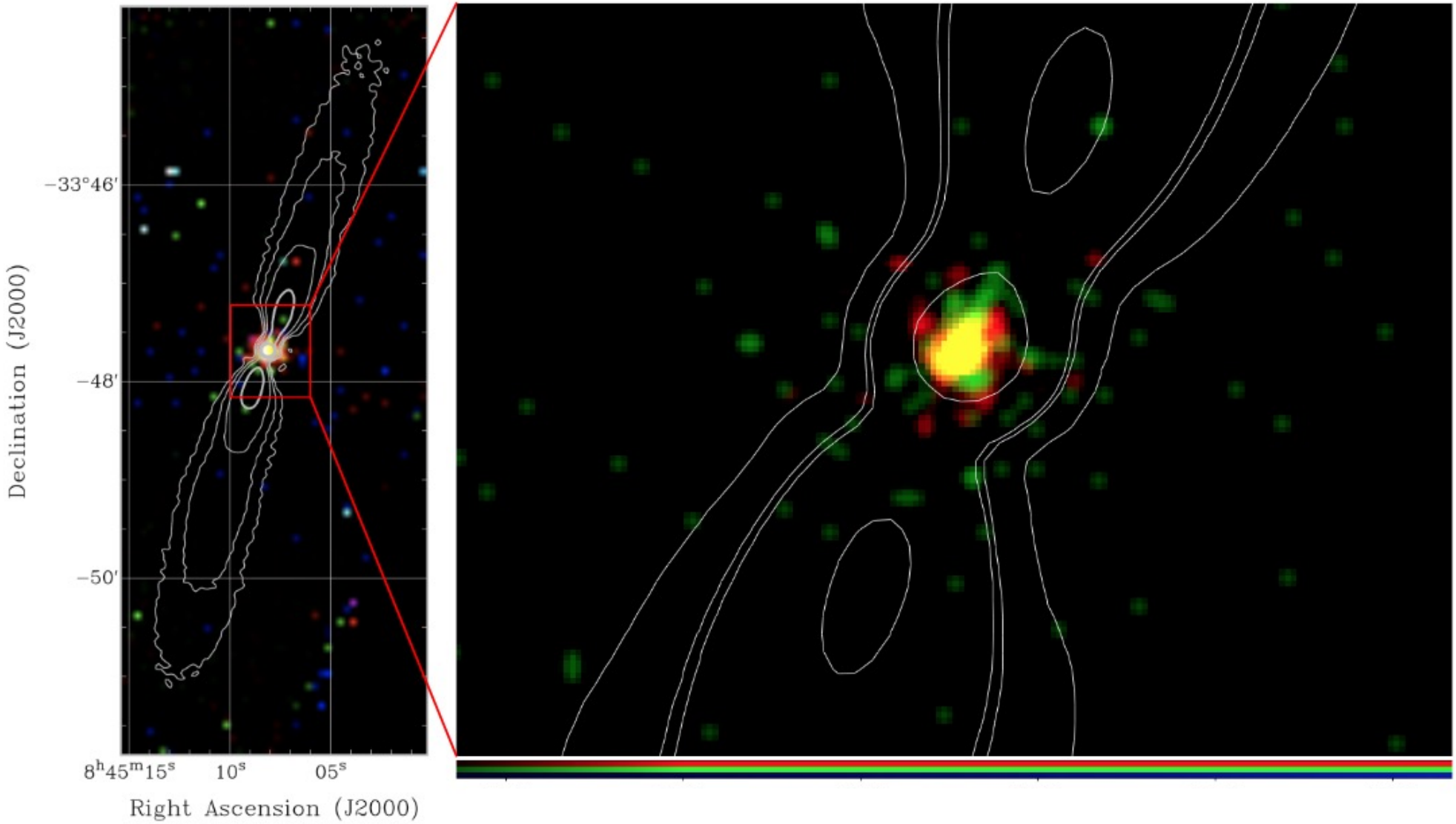
RGB image overlaid with ASKAP contours



R.G,B: soft (0.5 - 1.2 keV), medium (1.2 - 2.0 keV) and hard (2.0 - 7.0 keV) X-ray emission.

Other Candidates:

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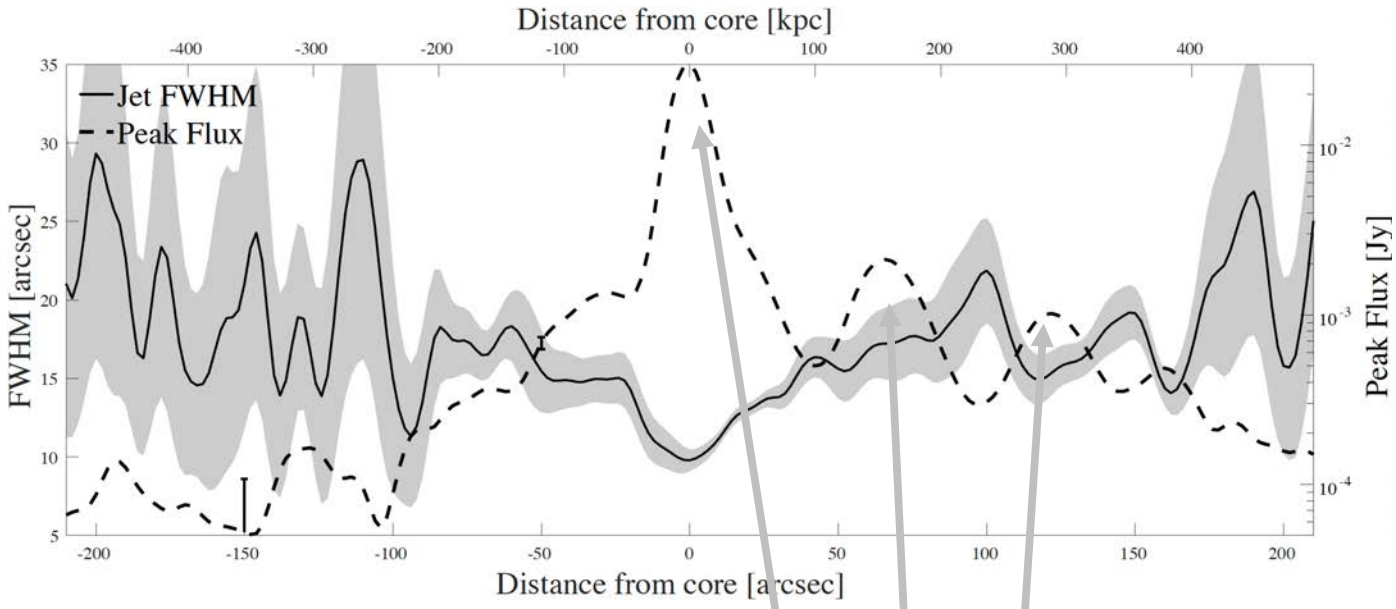
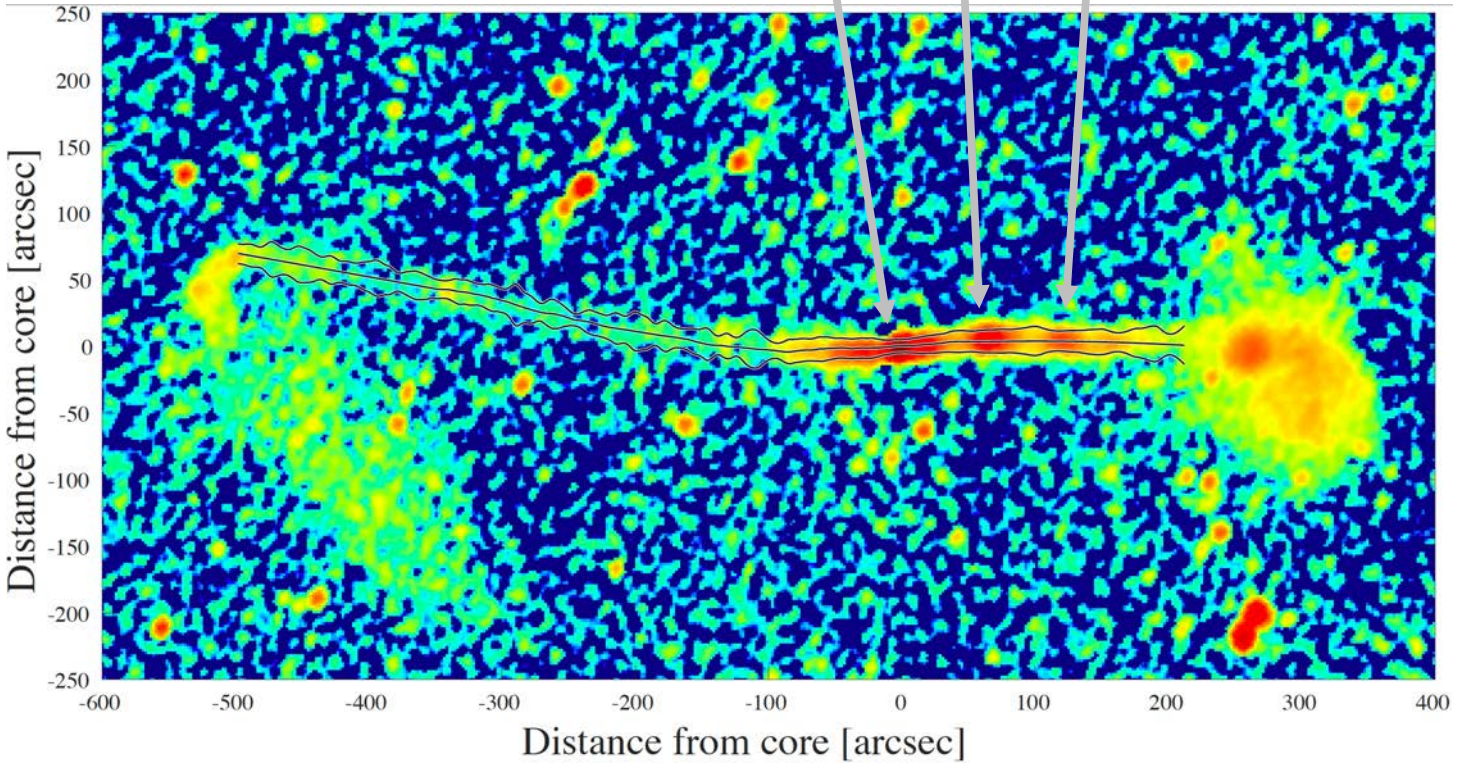




WISEA J052643.14-604210.5

D: ~490 Mpc

Angular size: ~ 22 arcmin

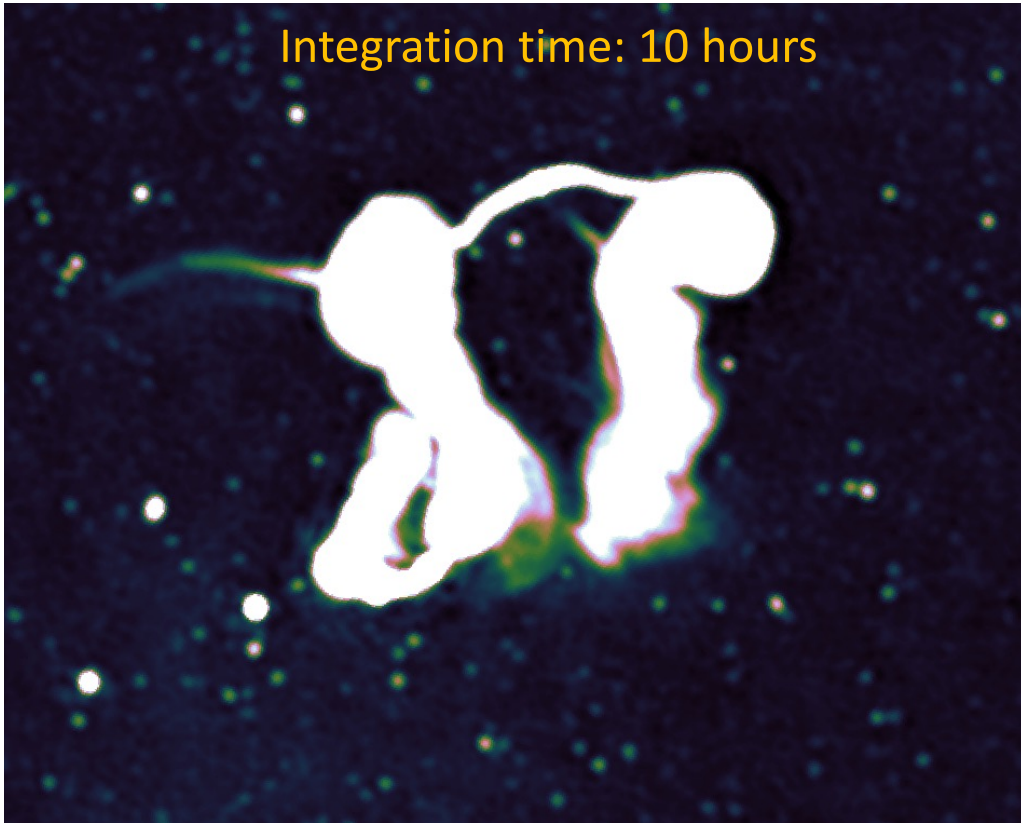
Size: ~ 2.6 Mpc

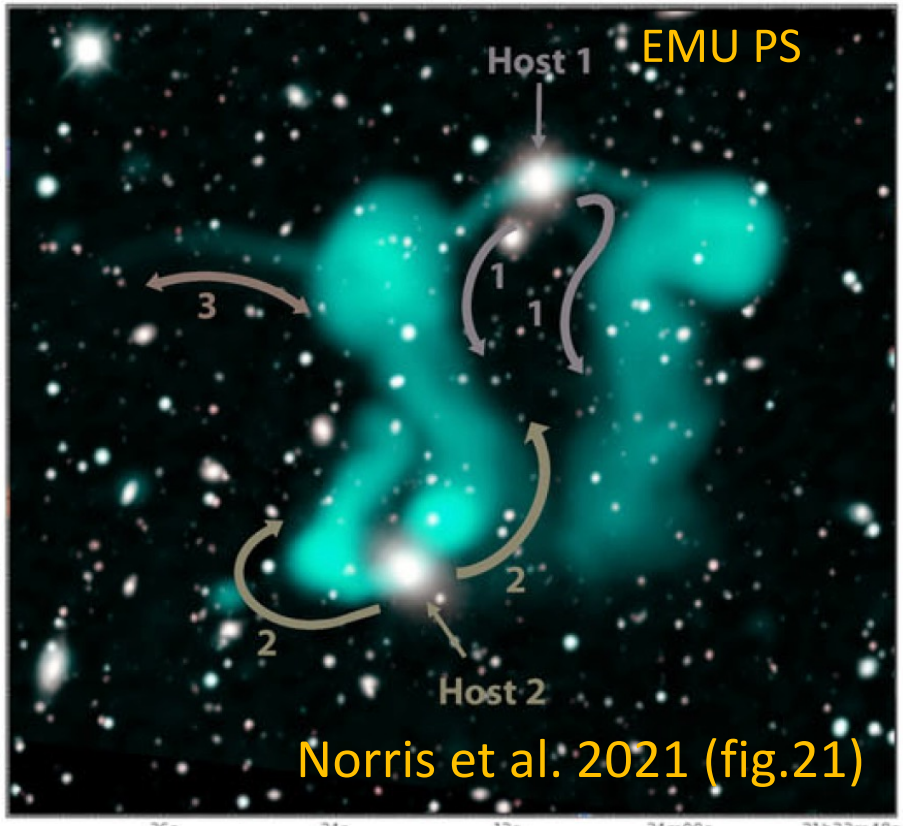
Summary

- **Possible first detection of a kpc-scale recollimating jets.**
- **Recollimation region is distinctive at all wavelengths and has been detected with different instruments.**
- **Unusual polarization behavior of the jet.**
- **Extremely rarified environment**
- **More data with new instruments and surveys.**


The Dancing Ghosts
1 arcmin
Dec
R.A.

MeerKAT vs ASKAP observations





MeerKAT observations:
Frequency: 1284 MHz
Beam size: 7.5˝ x 7.1˝

ASKAP observations:
Frequency: 943 MHz
Beam size: 14.0˝ x 10.9˝

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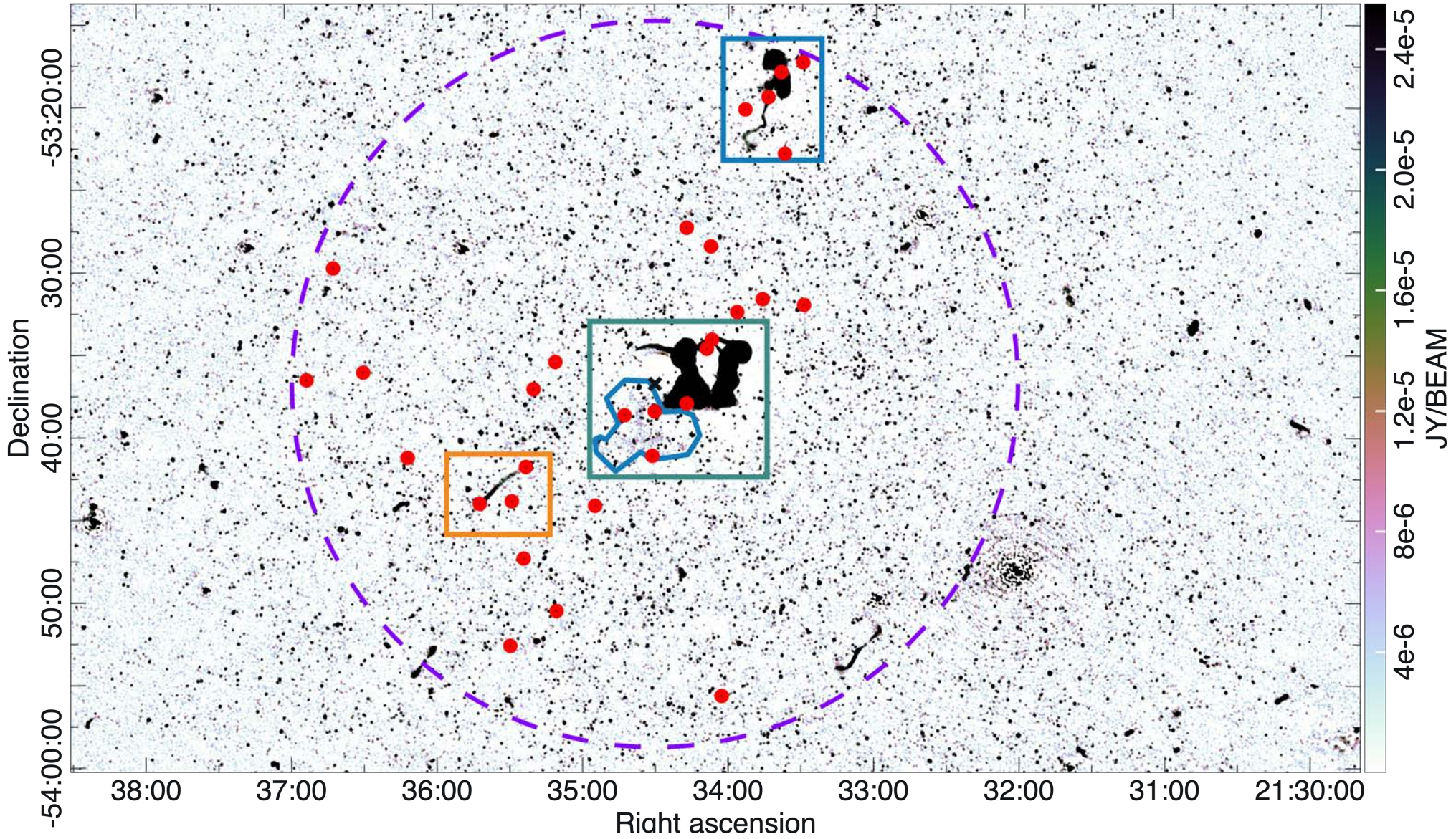
Cluster radius: ~22 arcmin
30 members, including PKS2130-538 complex



Abell 3785; z = 0.077 ~ 335 Mpc

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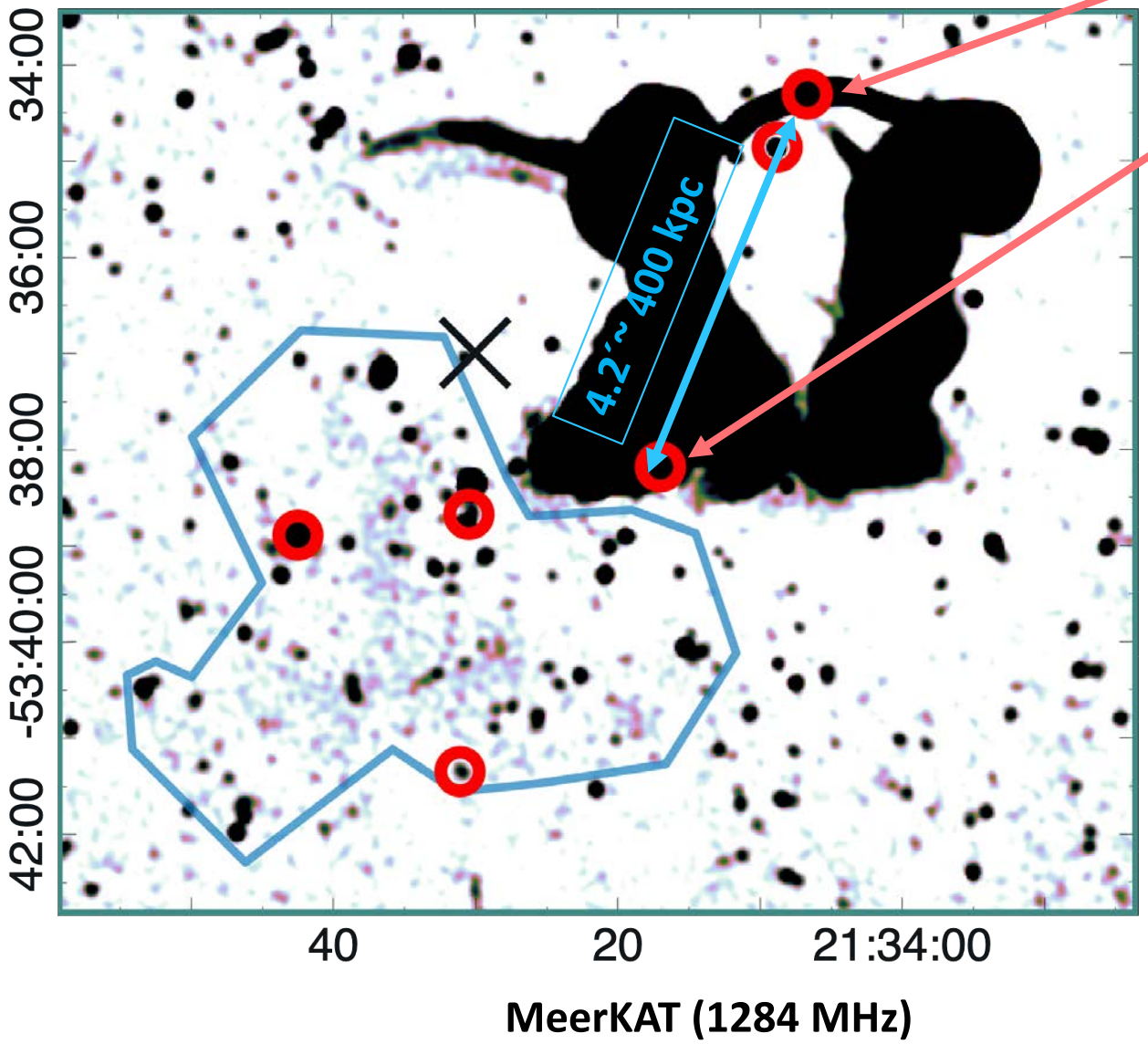
J213406
z = 0.0785 ~ 346 Mpc

J213417
z = 0.0765 ~ 338 Mpc



Detected 30 members of Abell 3785 galaxy cluster (red circles).

Low diffuse emission ~ 5´

X marks the centre

Distance Between two hosts:
Angular: 4.2´~ 400 kpc
Radial: ~ 8 Mpc

Dissection of the ghosts

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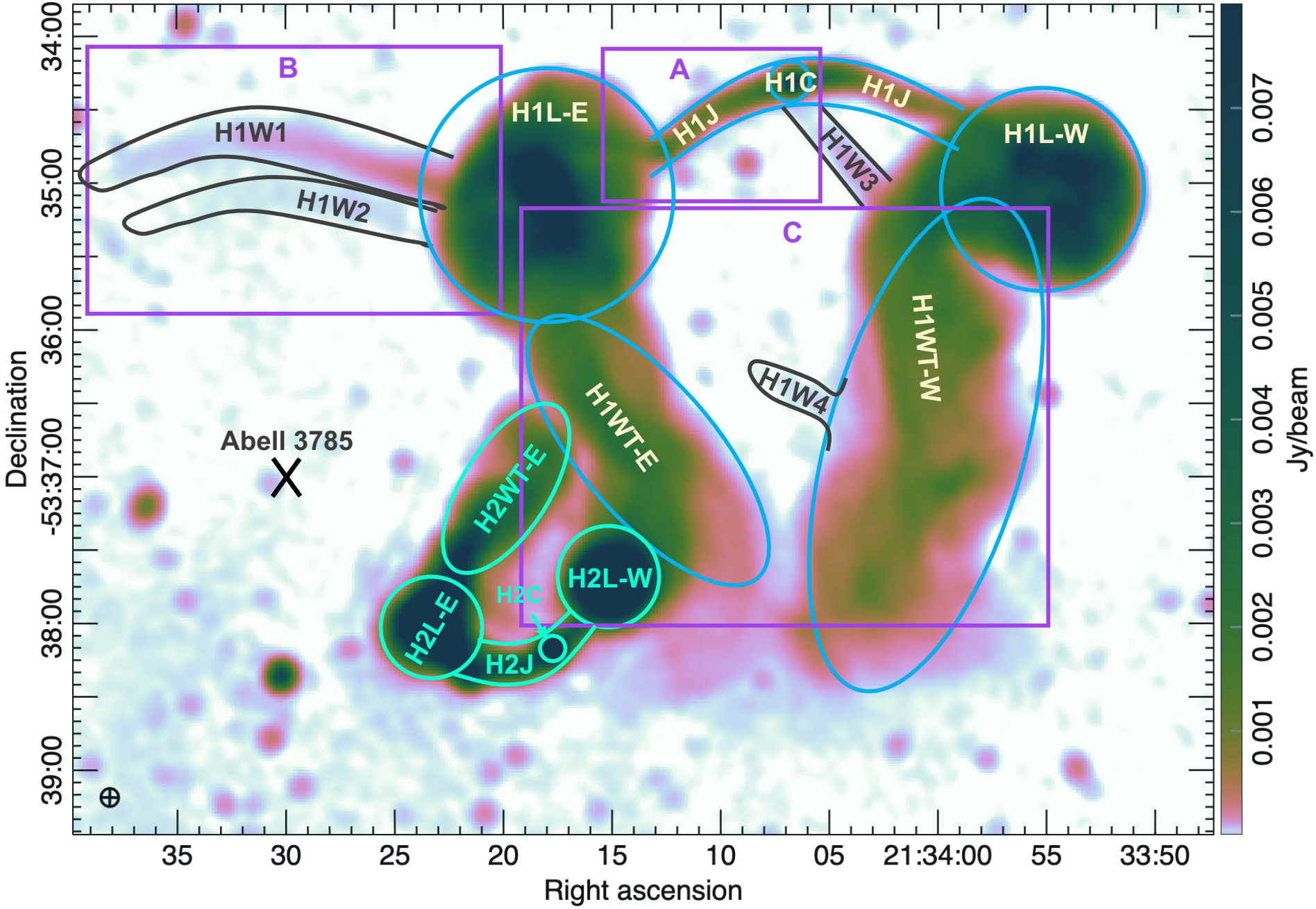

MeerKAT – ASKAP comparison

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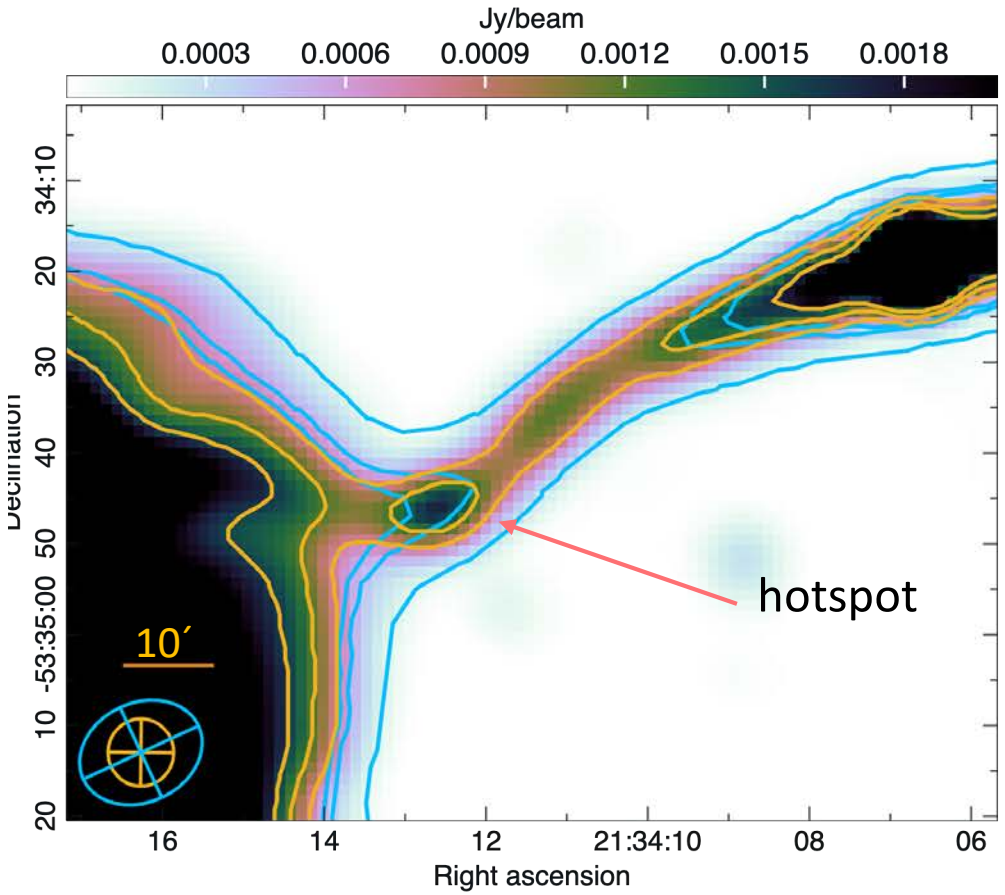
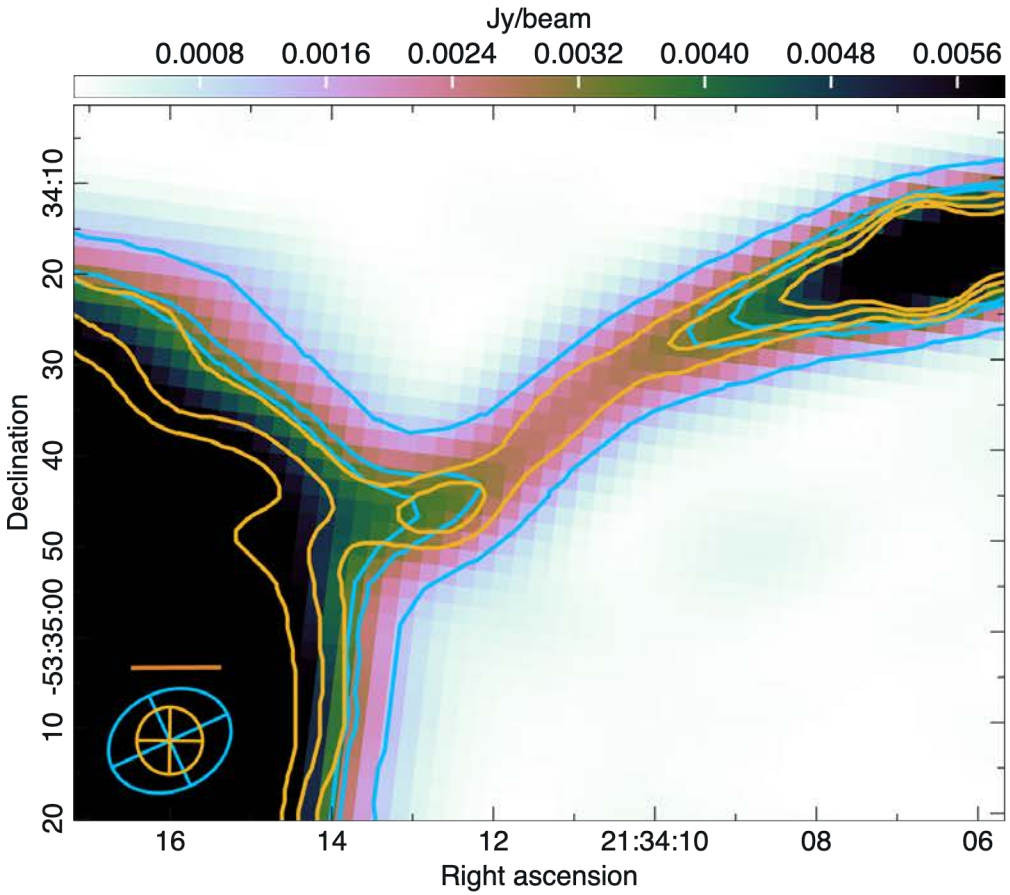
Region A





MeerKAT

ASKAP

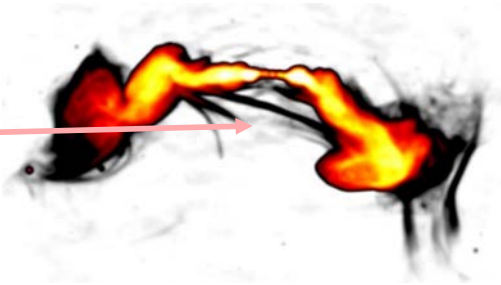
Hotspot prior to lobe creation is revealed in MeerKAT

MeerKAT – ASKAP comparison

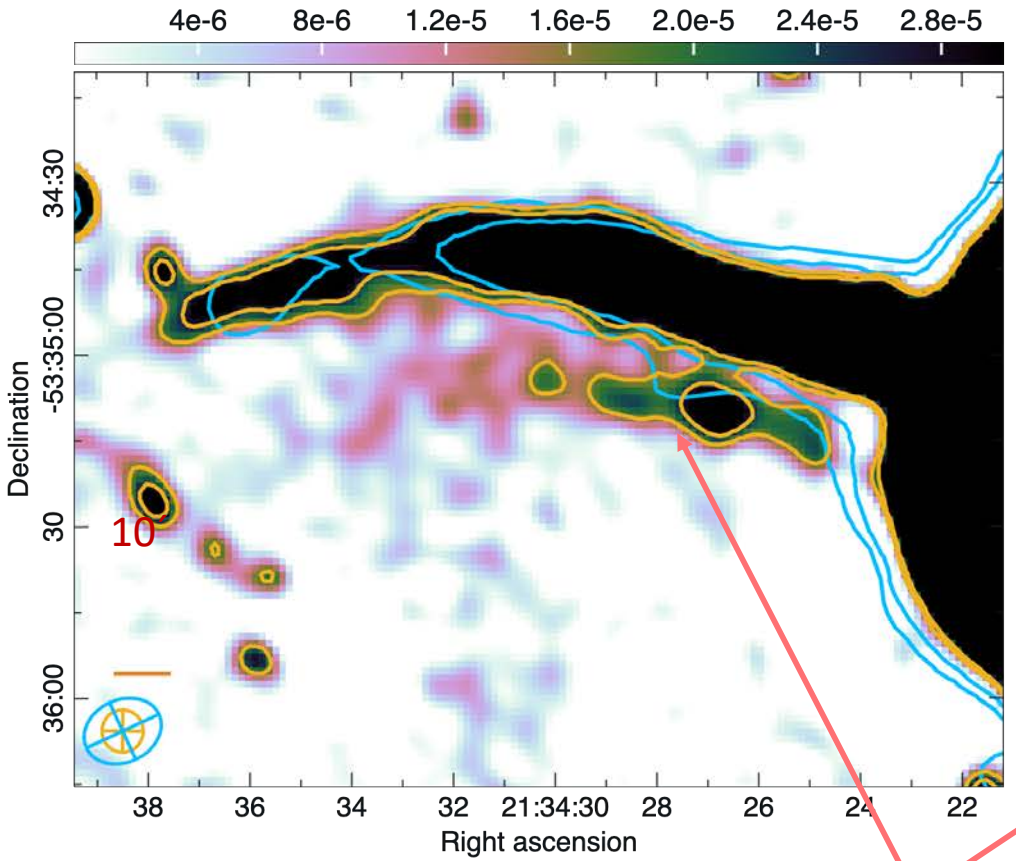
Thin stream of low surface brightness structures – Wisps

Collimated Synchrotron Threads (CST)?

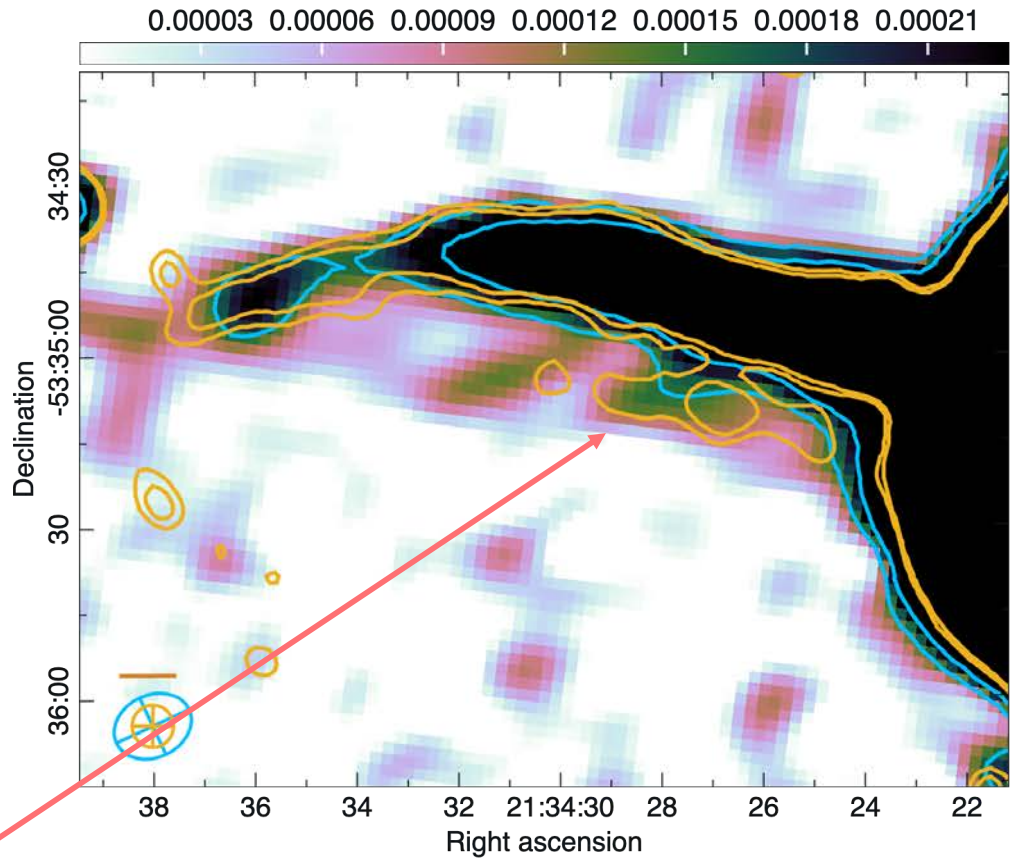
Ramatsoku et al. 2020



Region **B**



MeerKAT



ASKAP

Additional wisp is revealed with MeerKAT observation.

MeerKAT – ASKAP comparison

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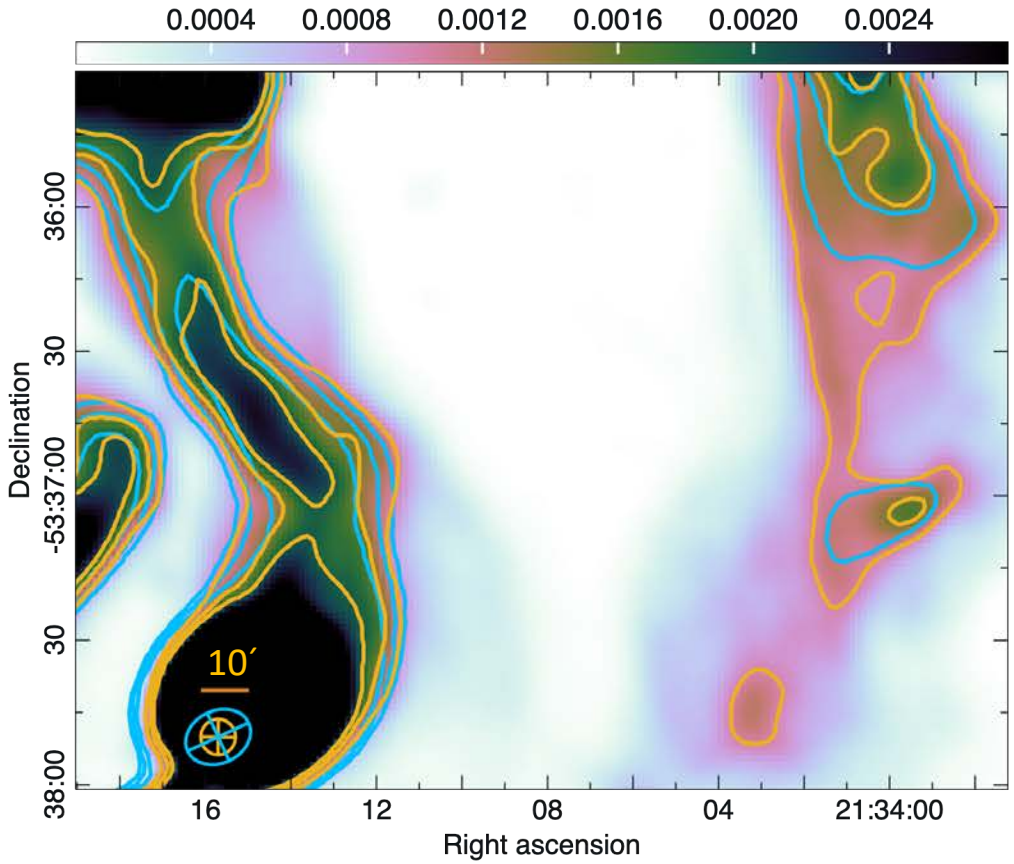
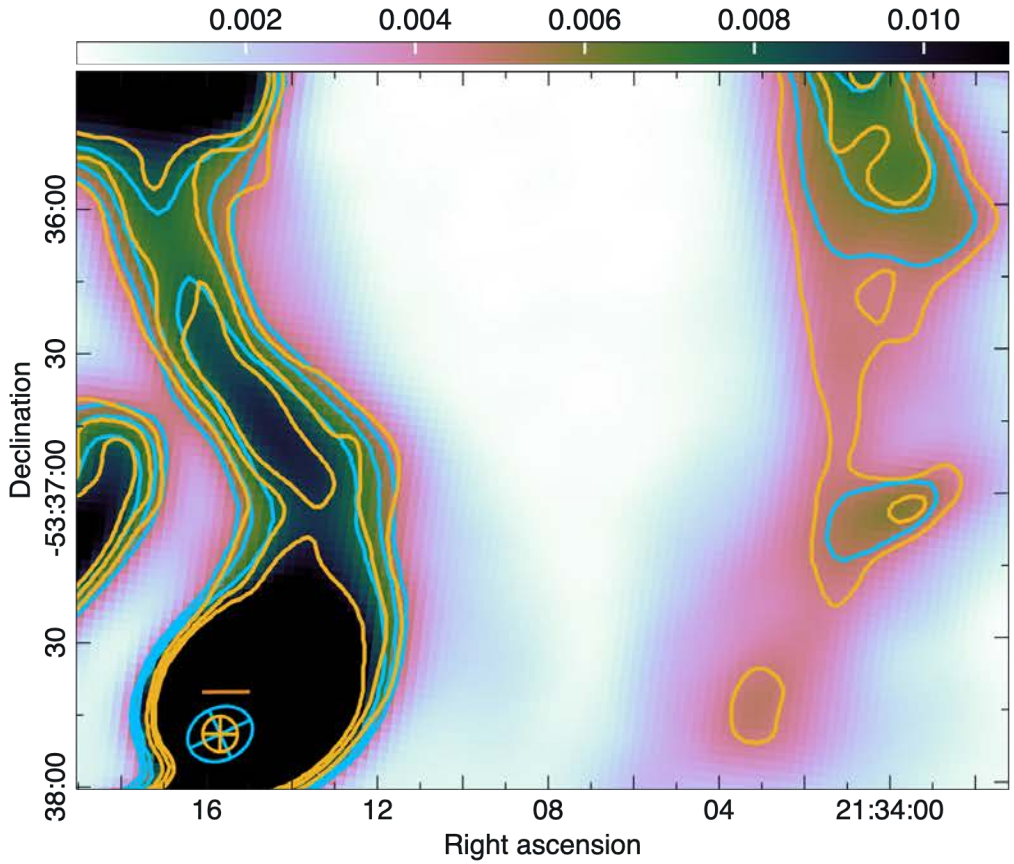
Region C



MeerKAT



ASKAP

MeerKAT reveals more low surface brightness structure

MeerKAT (1284 MHz)

OzCTA 2022

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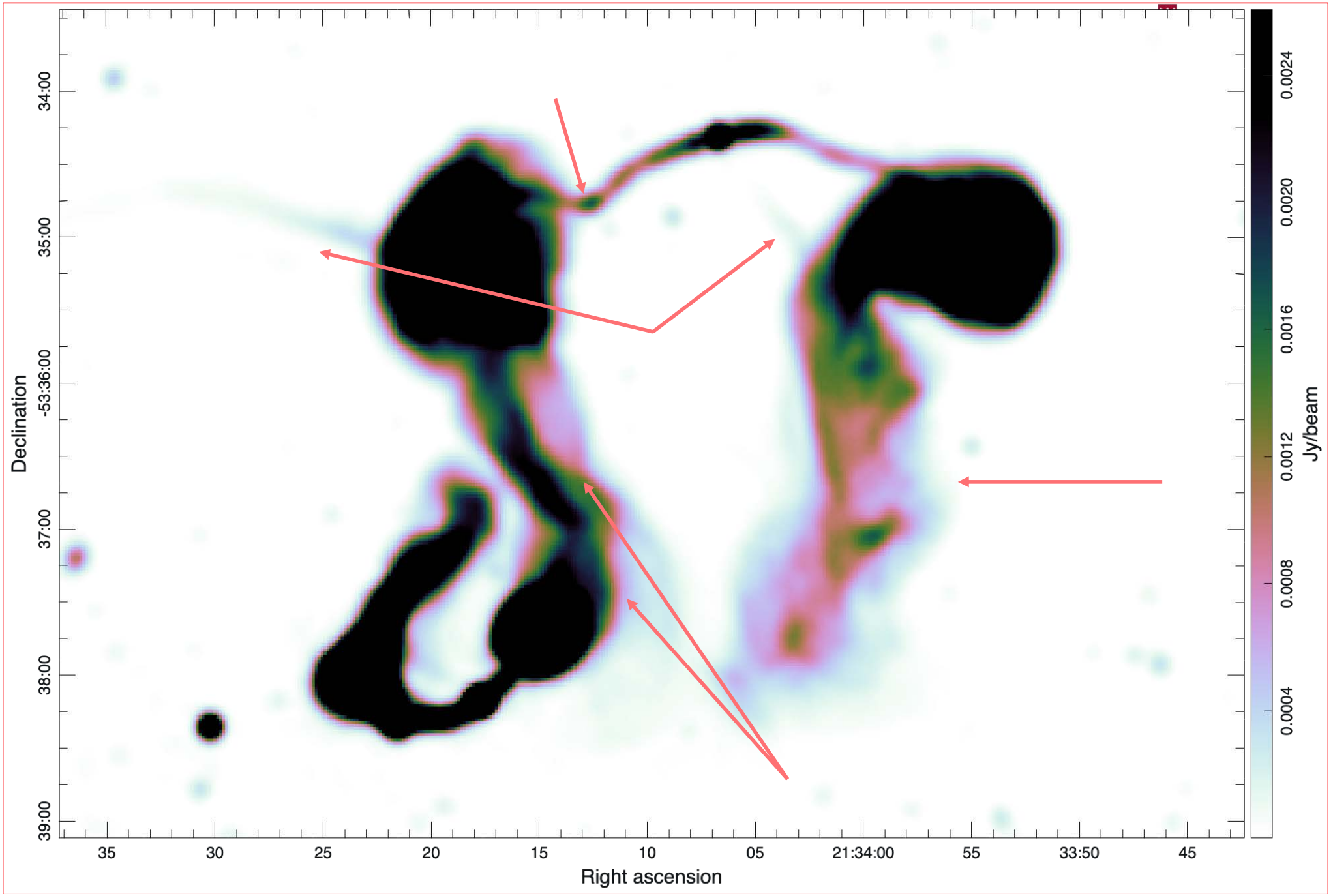

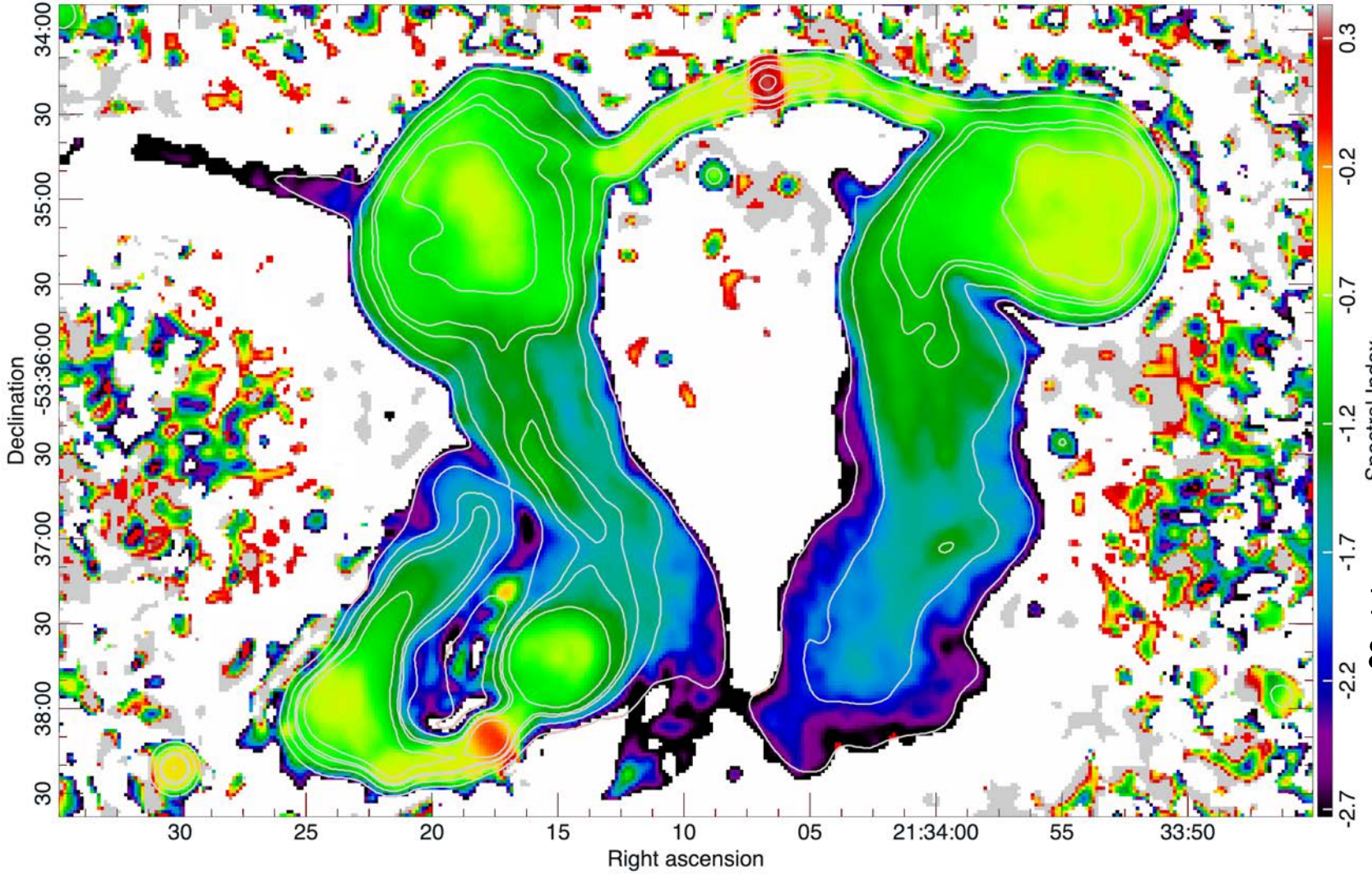

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14 channels:
860-1860 MHz

MeerKAT 1284MHz Spectral index

Cores: N(0.25) / S (−0.2)
Jets: − 0.6 to −0.7.
Lobes: –0.7 to –1.1
Wide tails: −1.7 to –2.3
Wisps: <−2.4

ASKAP Spectral index (Norris et al. 2021)

Cores: ~ 0
Jets: −0.4 to −0.5
Lobes: –0.6 to –0.7
Wide tails: −1.5
Wisps: −2.1

MeerKAT - Fractional polarization intensity at 1284 MHz

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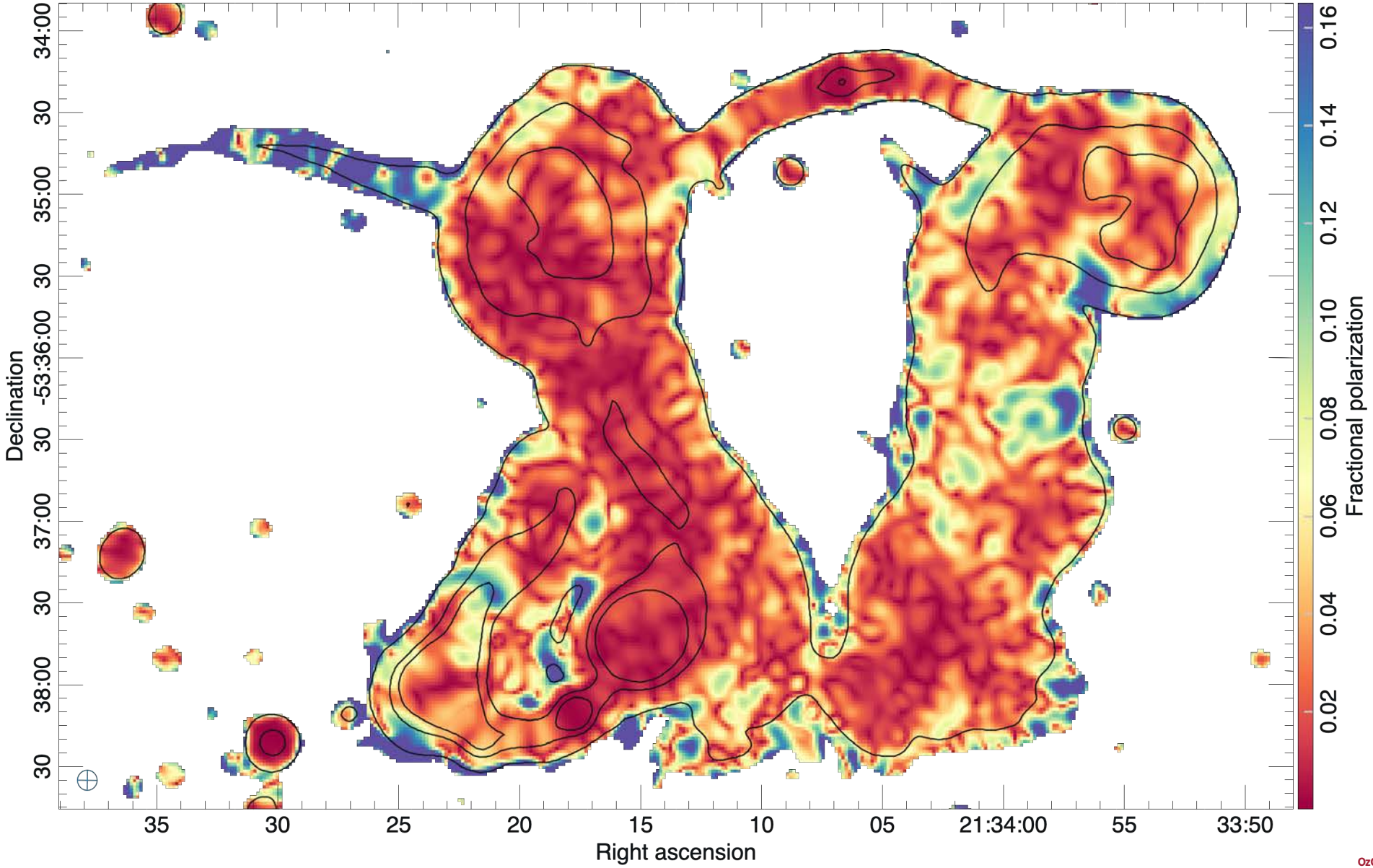
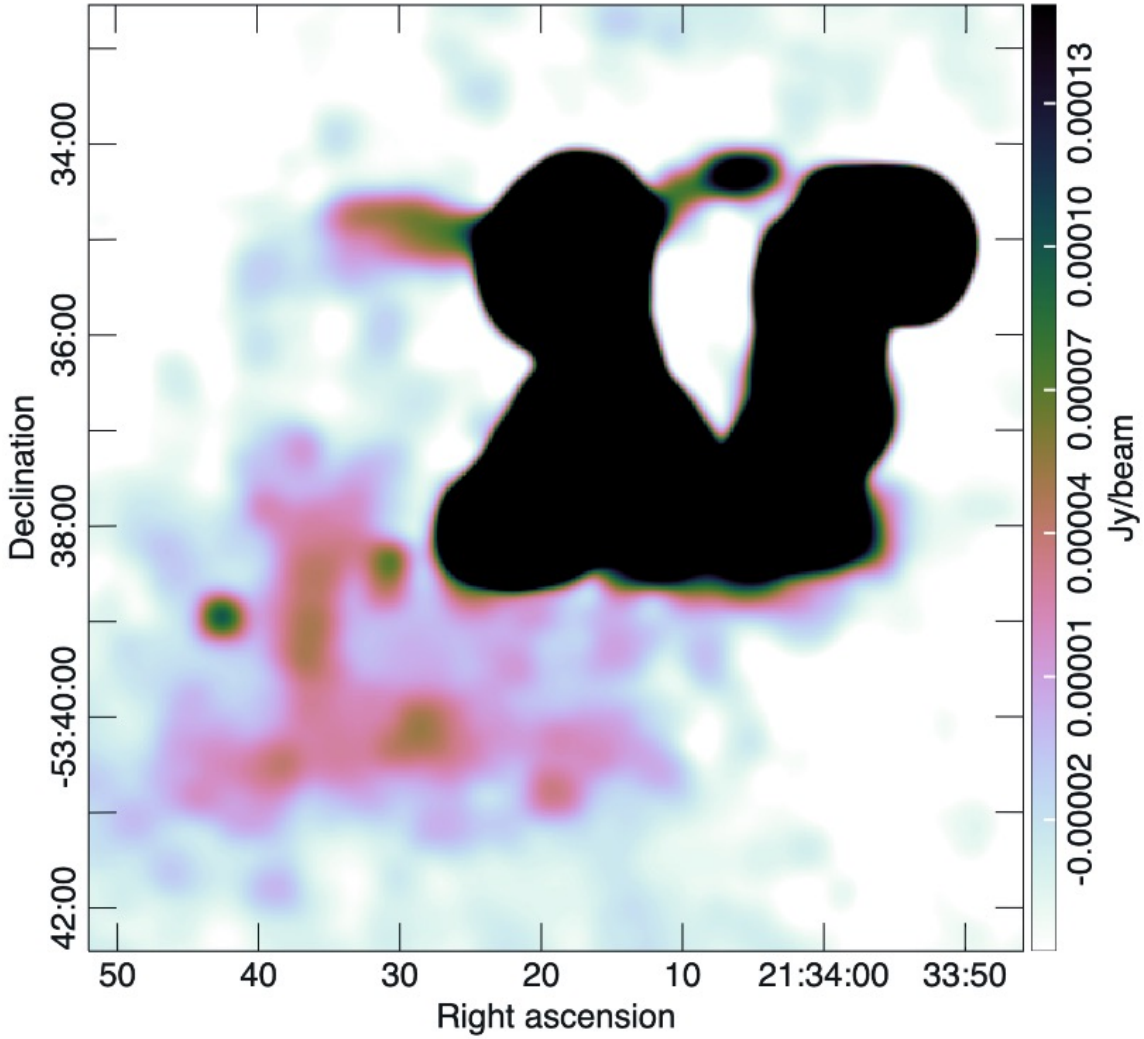
- Faint or no polarization in the hosts.
- Highest polarization in the wisp(s) and lobes



3 key questions to answer:

- Do we see signs of interaction in the Dancing Ghosts?
- What is the nature of the associated diffuse emission?
- What is the nature of wisps?

Diffuse emission



- Radio halo?

In the vicinity of the cluster centre; recent merger?
-Does not have halo-shape.

- Very steep SI ~ -2.4

indicates relic-type origin
- Close to the cluster centre.

- Ancient emission

originating from the hosts

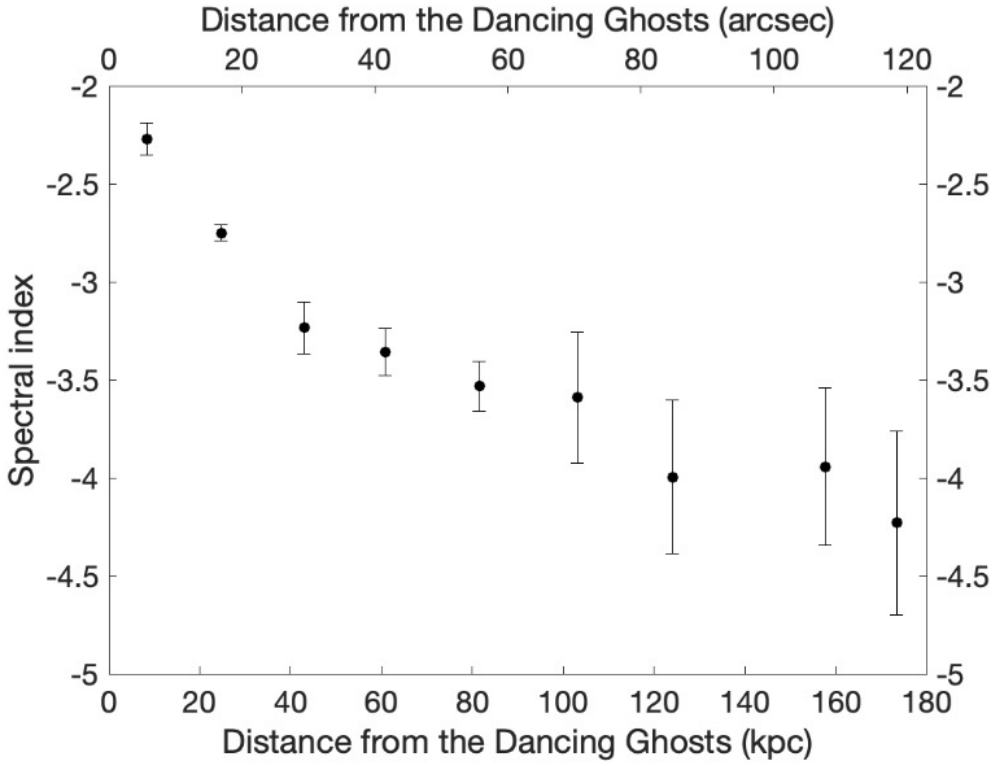
Wisps - Synchrotron Filaments

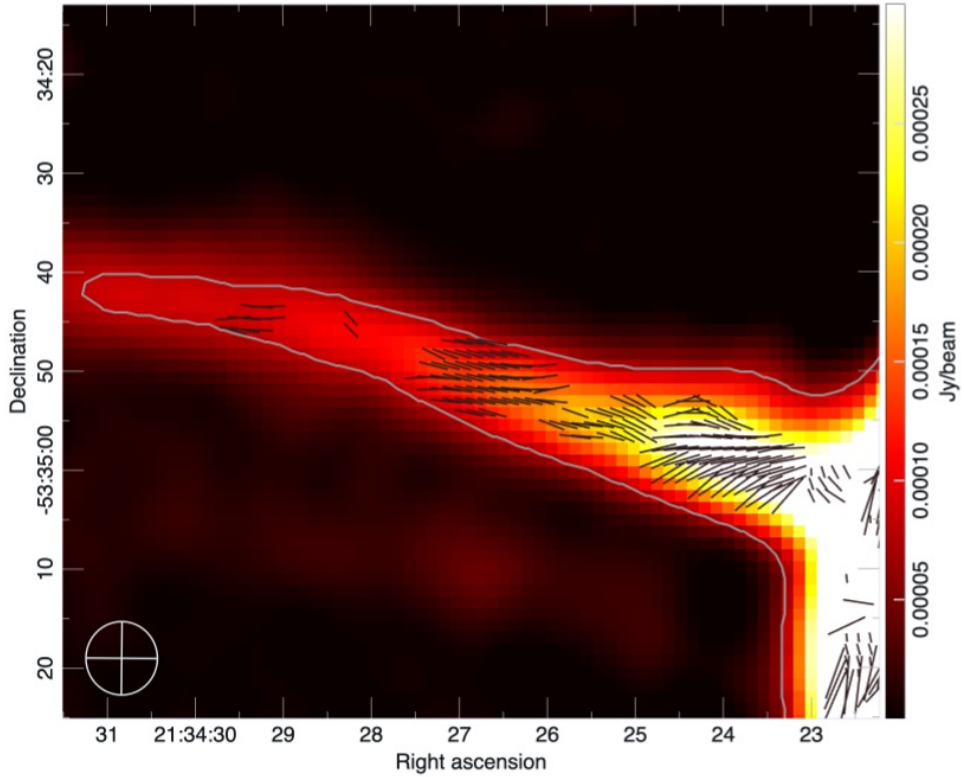
Magnetic filaments, being stretched during interaction with ICM (SI)

Interaction of Jet and a dense cloud (Jet bending)

Cosmic ray re-acceleration (External source of energy or reconnection)

- The magnetic field vectors are oriented along the structure
- The spectral index steepens with the distance from the lobe of the Dancing Ghost.





MeerKAT 1248MHz – Region of possible interaction

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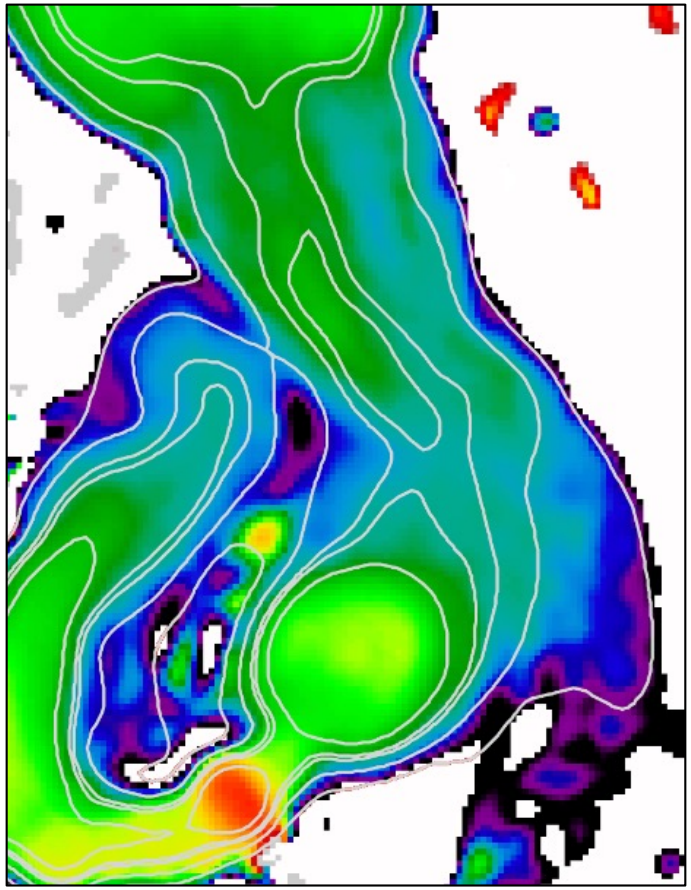
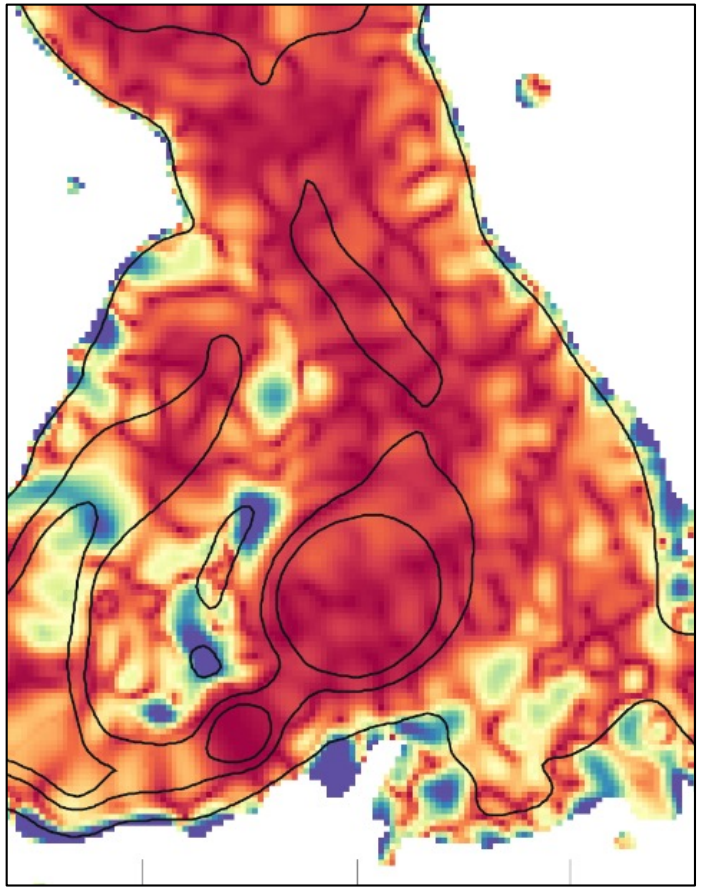
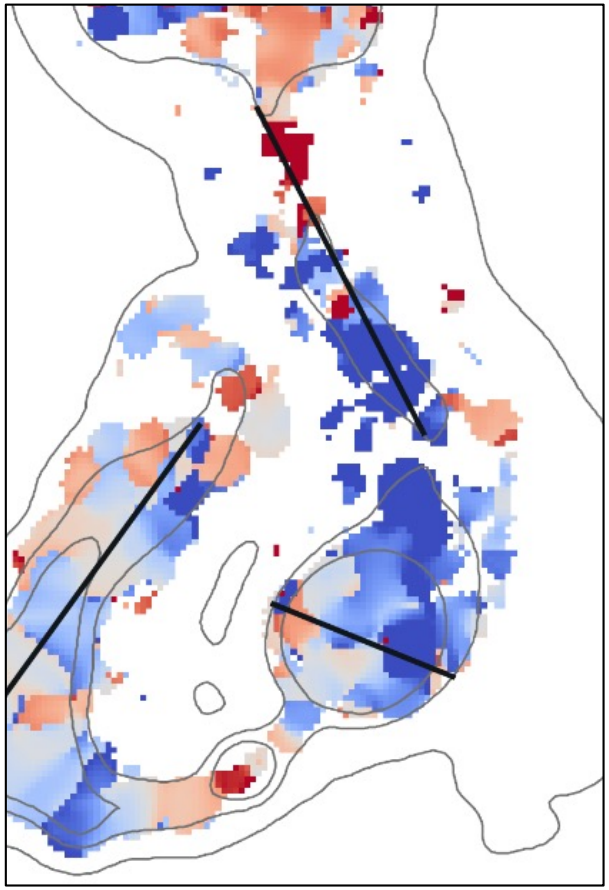
No discontinuity!



Spectral Index



Fractional Polarization



Rotation Measure

Summary

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- New features showing in meerkat images (hotspots, wisps, low surface brightness structure)
- Diffuse emission near the dancing ghost may represent radio halo, radio relics or ancient emission originating from the dancing ghosts.
- Spectral Index – inverted core, flat jets and steep lobes, extremely steep wisps and diffuse emission.
- Complex polarization, dominant in lobes.
- 30 detected sources from Abell 3785

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