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A STUDY OF THE LOBES OF RADIO GALAXY HYDRA A USING MEERKAT OBSERVATIONS

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Image: Optical image of Hydra A
Credit: Canada-France-Hawaii-Telescope/DSS

Hydra A

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- Hydra A the brightest radio galaxy in Abell 780 located at its center
- High-luminosity FRI radio galaxy
- The pair of hundred-kiloparsec diameter radio lobes in Hydra A are powered by the closest cluster-scale AGN outburst, which is one of the three most powerful AGN outbursts known to date
- Hydra A has been observed in optical, radio, X-ray and gamma-rays

Previous observations of Hydra A

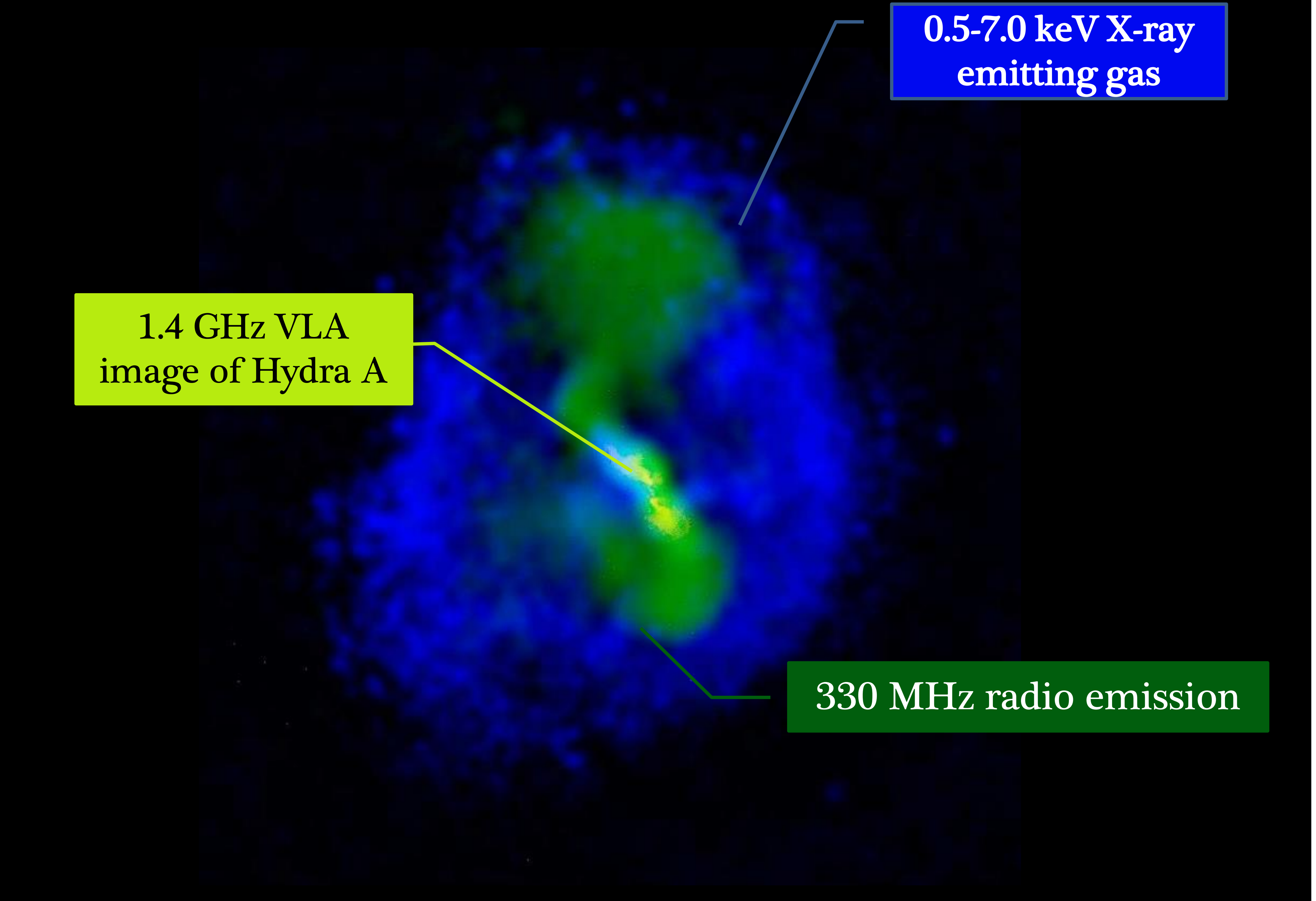

Figure*: Composite color image of Hydra A which illustrates the close connection between the observed, large X-ray cavity system (shown in blue) and the low frequency, 330 MHz radio emission (shown in green). The 330 MHz radio data is from Lane et al. (2004). 1.4 GHz VLA image of Hydra A is also shown in the core in yellow.

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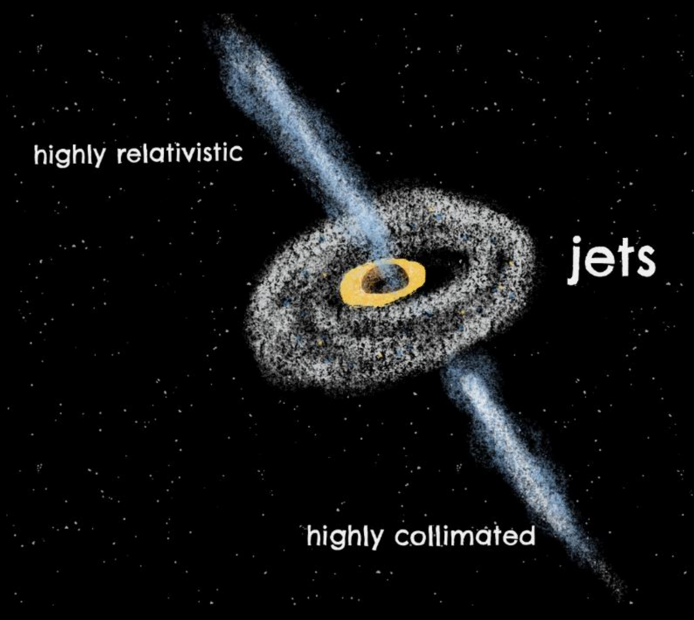
* *X-ray Supercavities in the Hydra A Cluster and the Outburst History of the Central Galaxy's Active Nucleus*, M. W. Wise, B. R. McNamara, P. E. J. Nulsen, J. C. Houck, L. P. David, **Astrophys.J. 659:1153-1158, 2007**

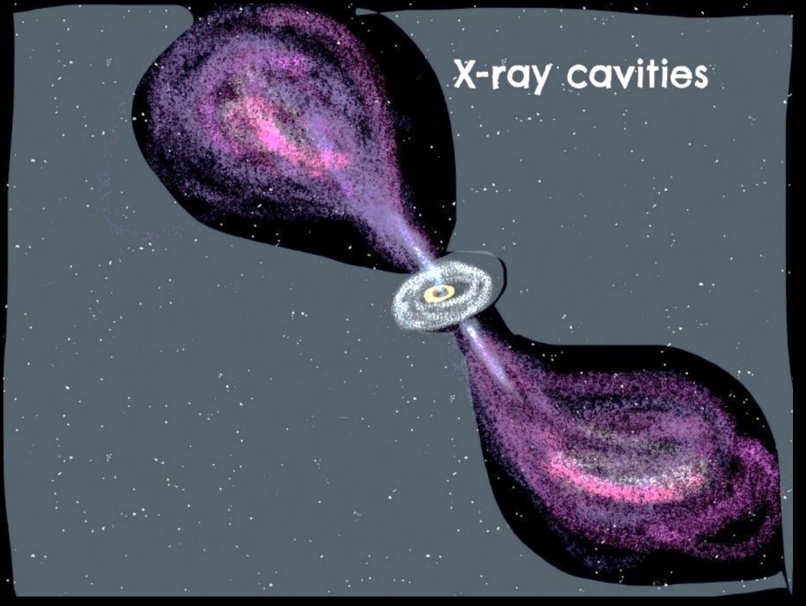
Structure and formation of Hydra A

- Central supermassive black hole (experienced 3 generations of outbursts)
- Jets



- 2 inner radio lobes (generated by the more recent AGN activity)
- 2 giant outer radio lobes (generated by earlier AGN activity)

- X-ray cavities surrounding radio lobes



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The Data

- Observations made using the MeerKAT telescope
- MeerKAT is an array consisting of 64 antennas 13.5 m in diameter each. It has a max baseline of 8 km
- Four observation epochs of 30 minutes each were accumulated with the full array
  - Frequency range: 856 MHz- 1712 MHz
- The CARACal (Jozsa et al. 2020) pipeline was used for the data reduction
- We derive fluxes from the radio maps obtained with CARACal.

Image: A single receptor that forms part of the MeerKAT telescope
Credit: South African Radio Astronomy Observatory (SARAO)

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CARACAL

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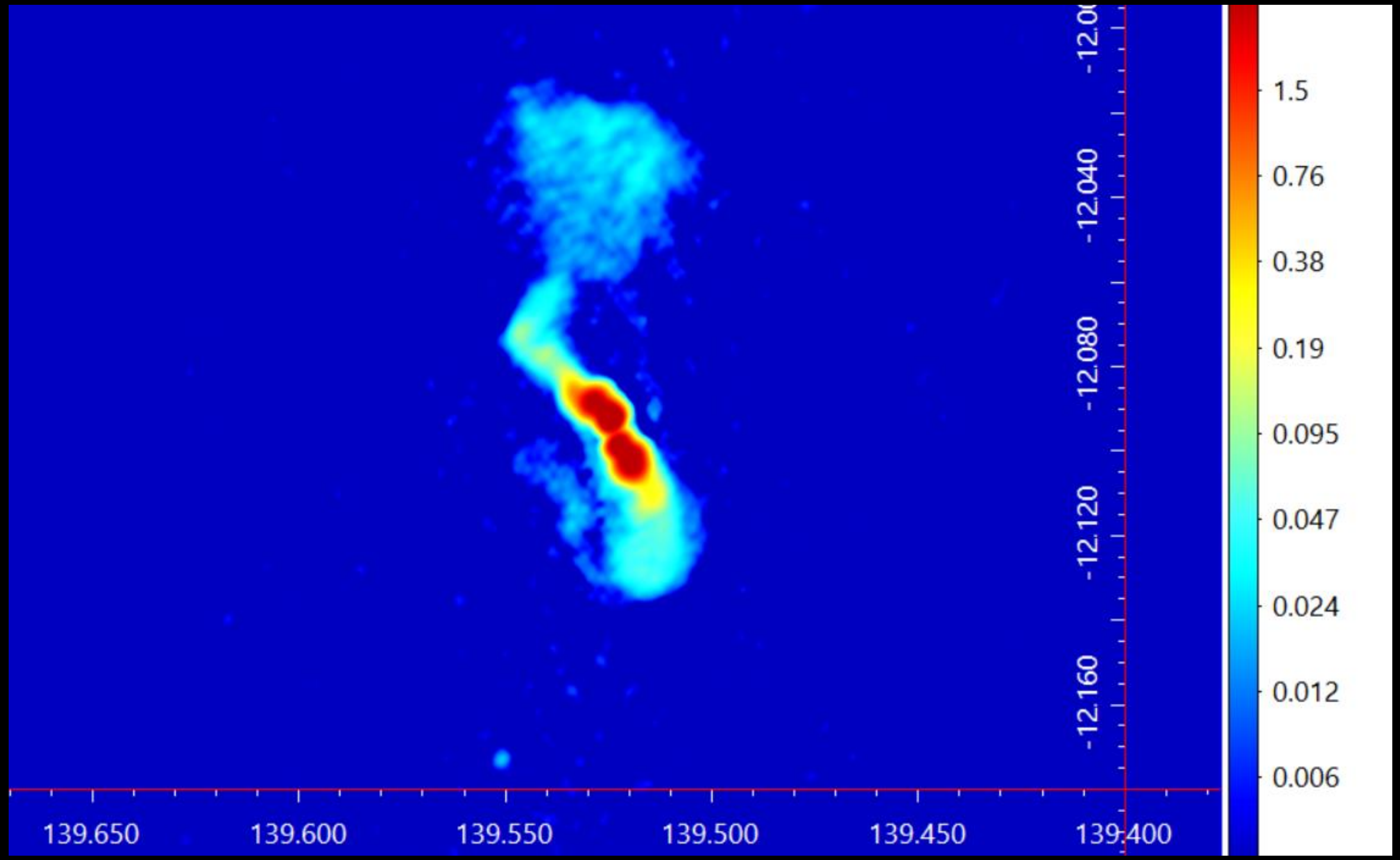
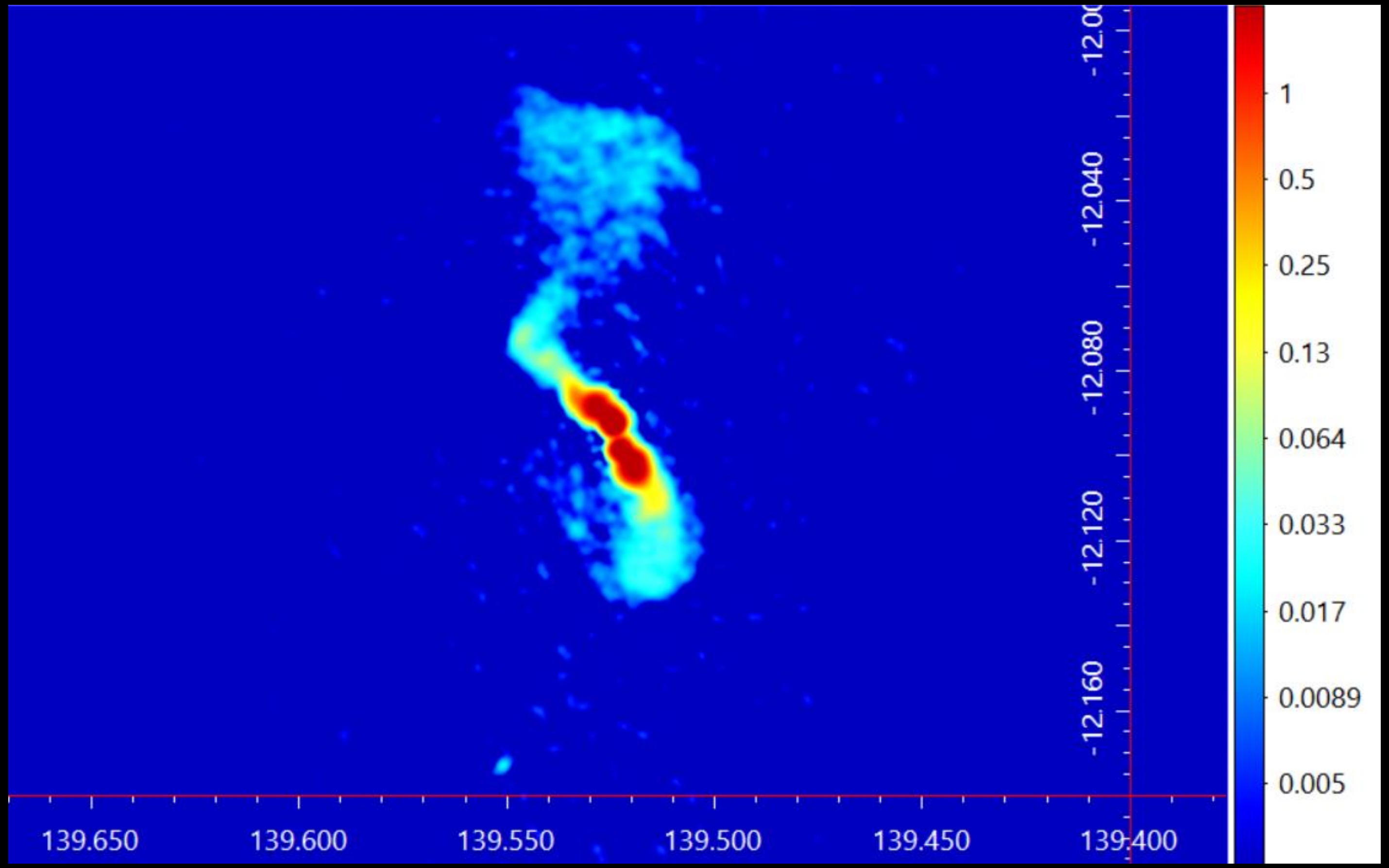
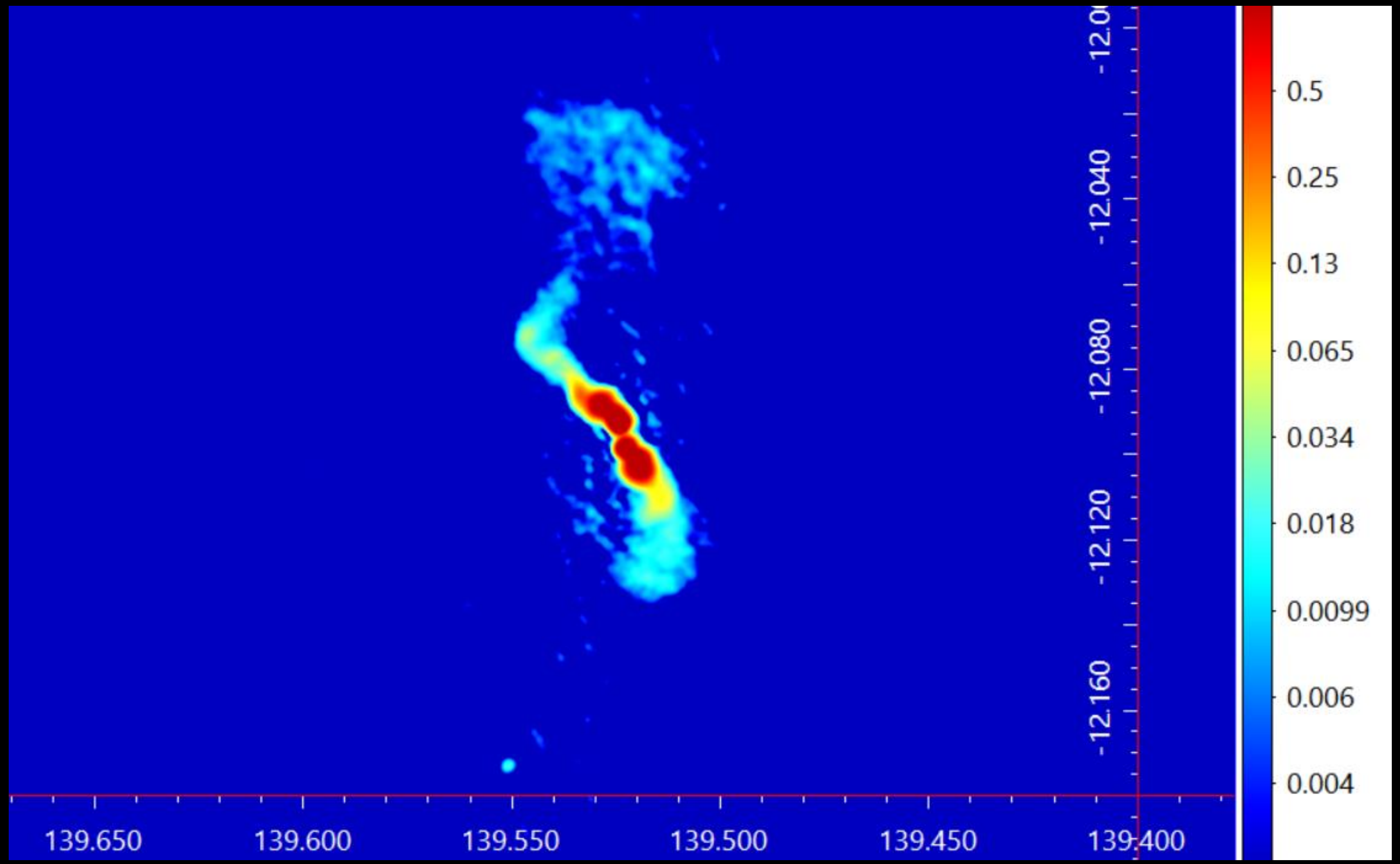
*Bandwidth of all images is 80 MHz



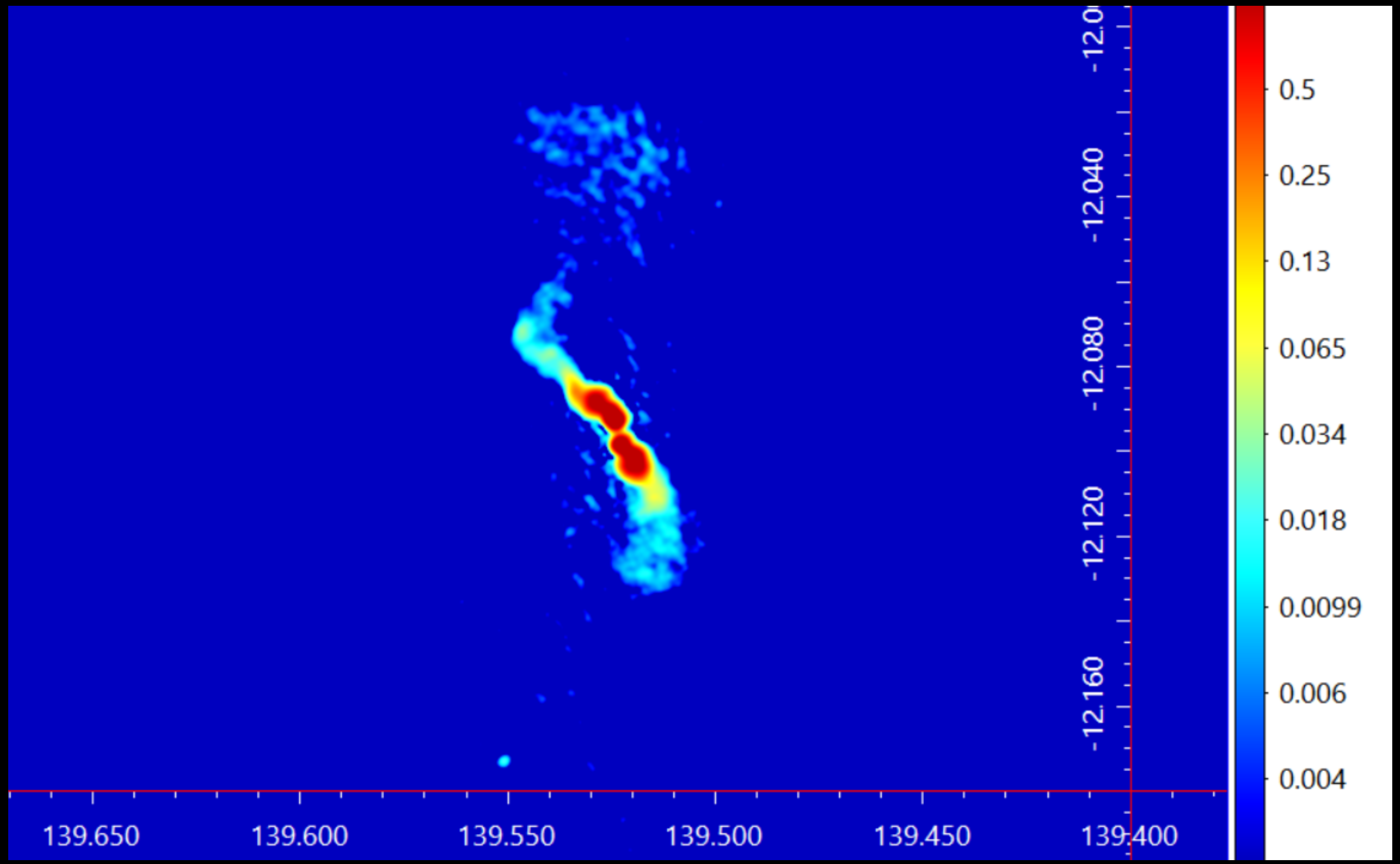
Preliminary image of Hydra A at 1000 MHz



Preliminary image of Hydra A at 1100 MHz



Preliminary image of Hydra A at 1330 MHz



Preliminary image of Hydra A at 1485 MHz

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Radio Morphology

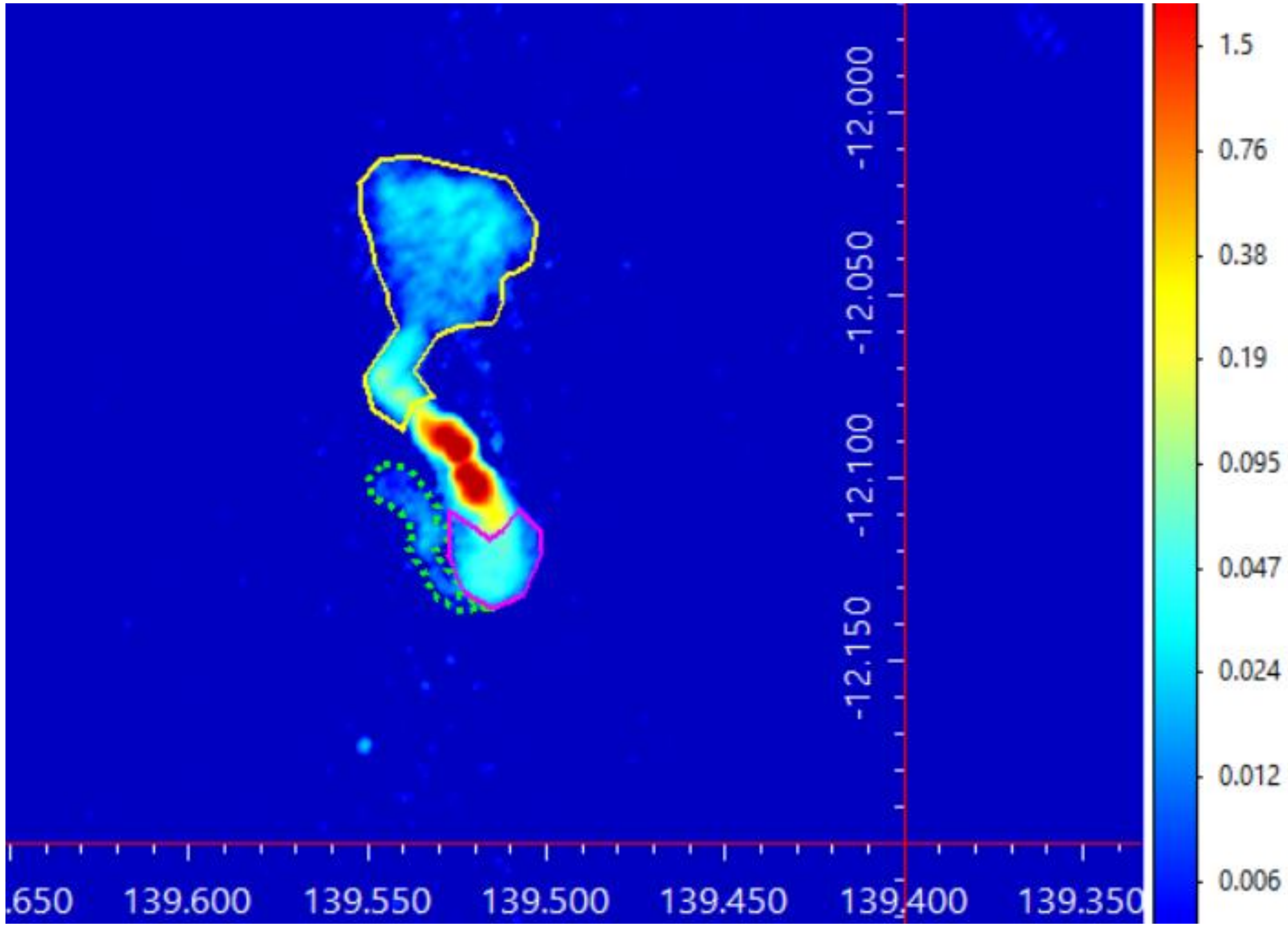
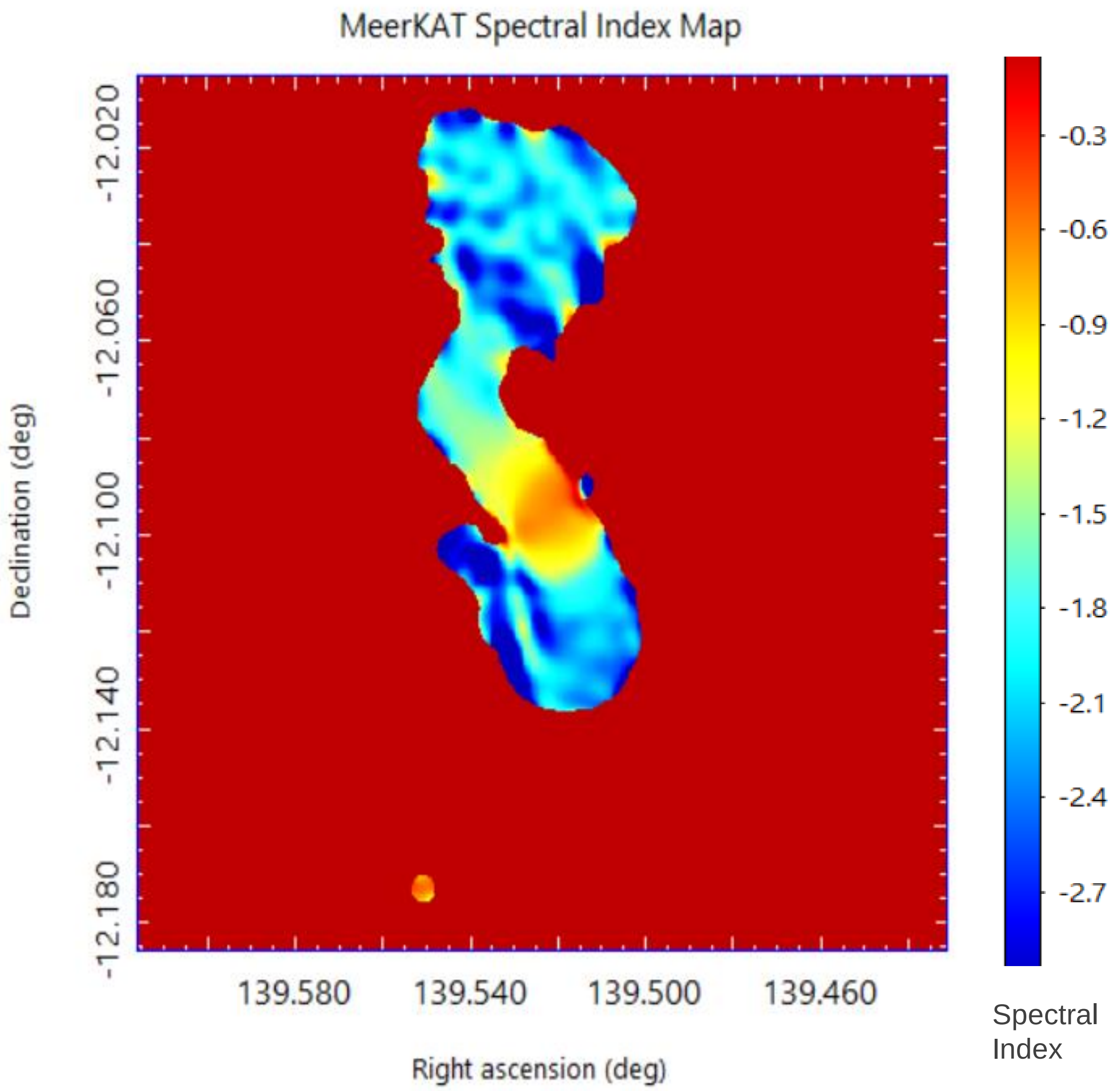


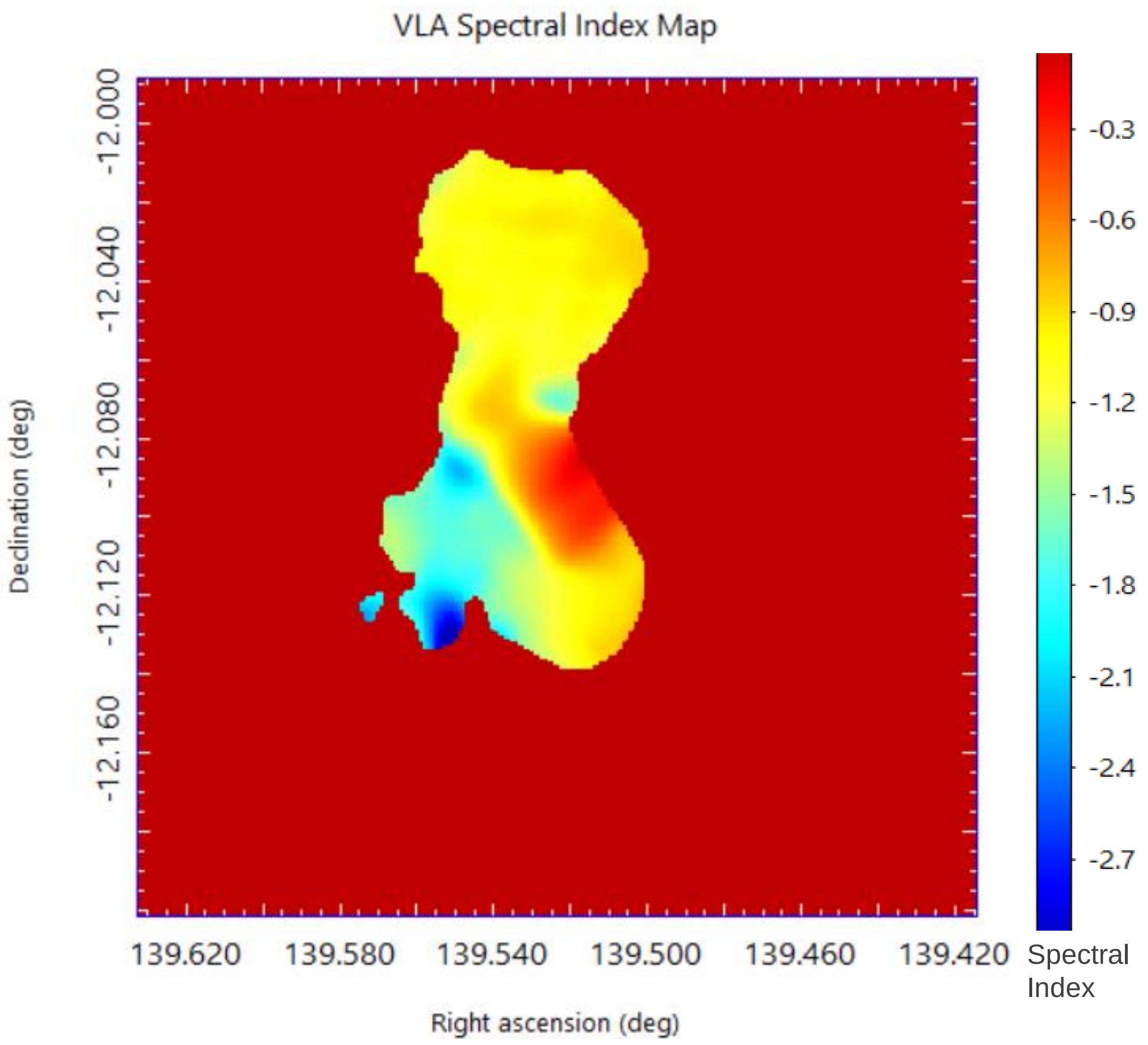
Figure: Radio map of Hydra A at 1000 MHz shown in equatorial coordinates of right ascension (deg) and declination (deg.). The colour bar represents the radio intensity in units of Jy/beam.

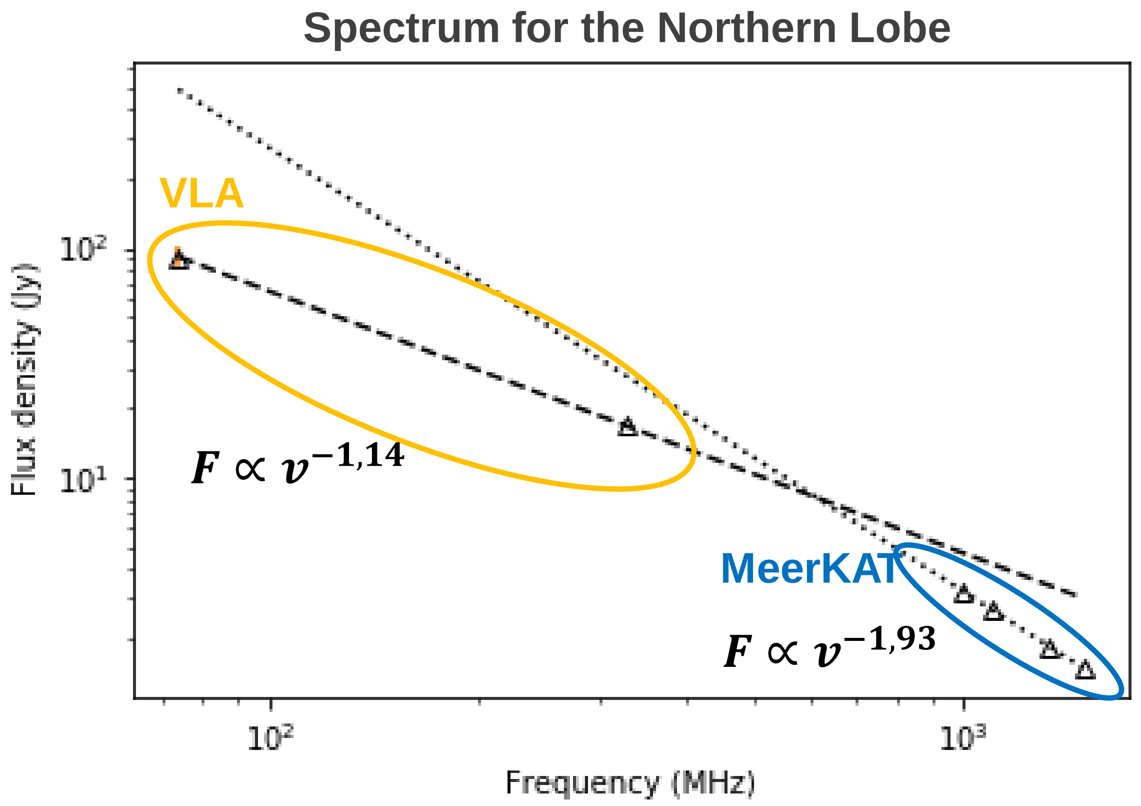
- 2 bright inner lobes
- 2 large diffuse radio lobes extending in the northern and southern directions
- A tail-like region extending from the southern outer lobe
- S-shape symmetry
  - Lobe bending due to dense ICM?
  - The galaxy is precessing and the tail is a remnant from an earlier generation of AGN activity?

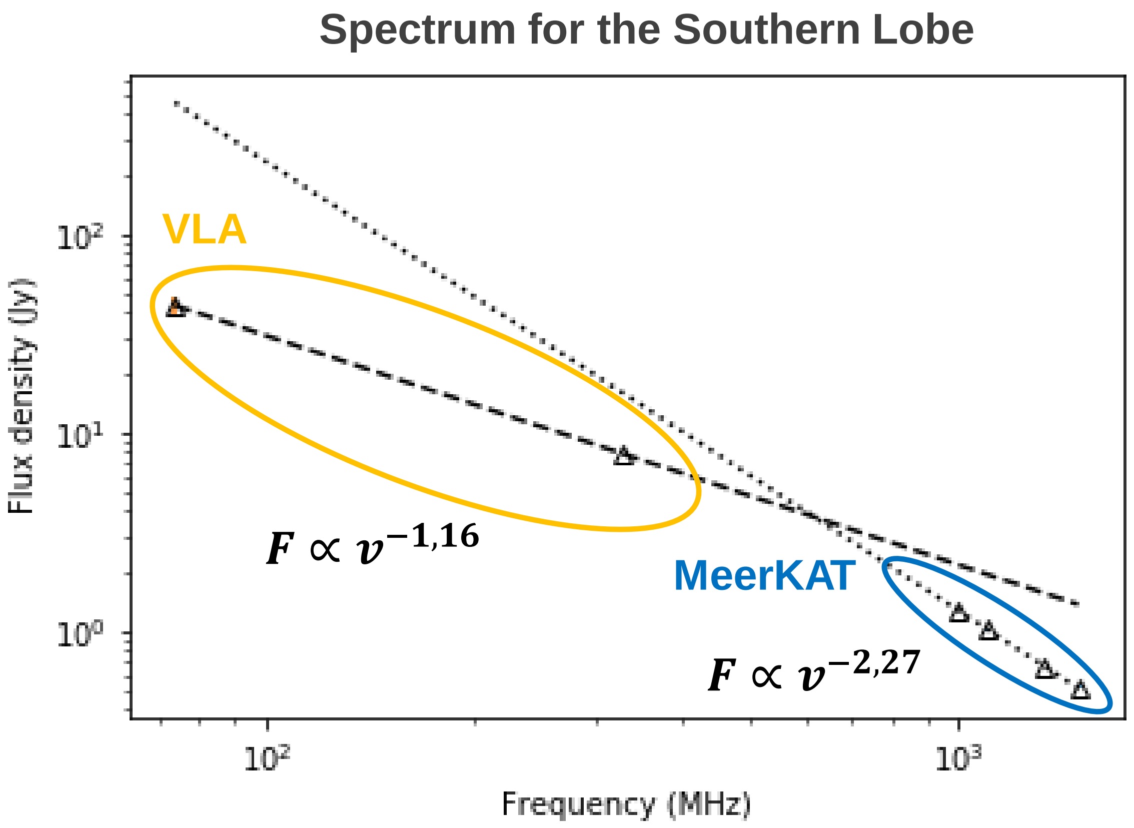
Spectral Analysis

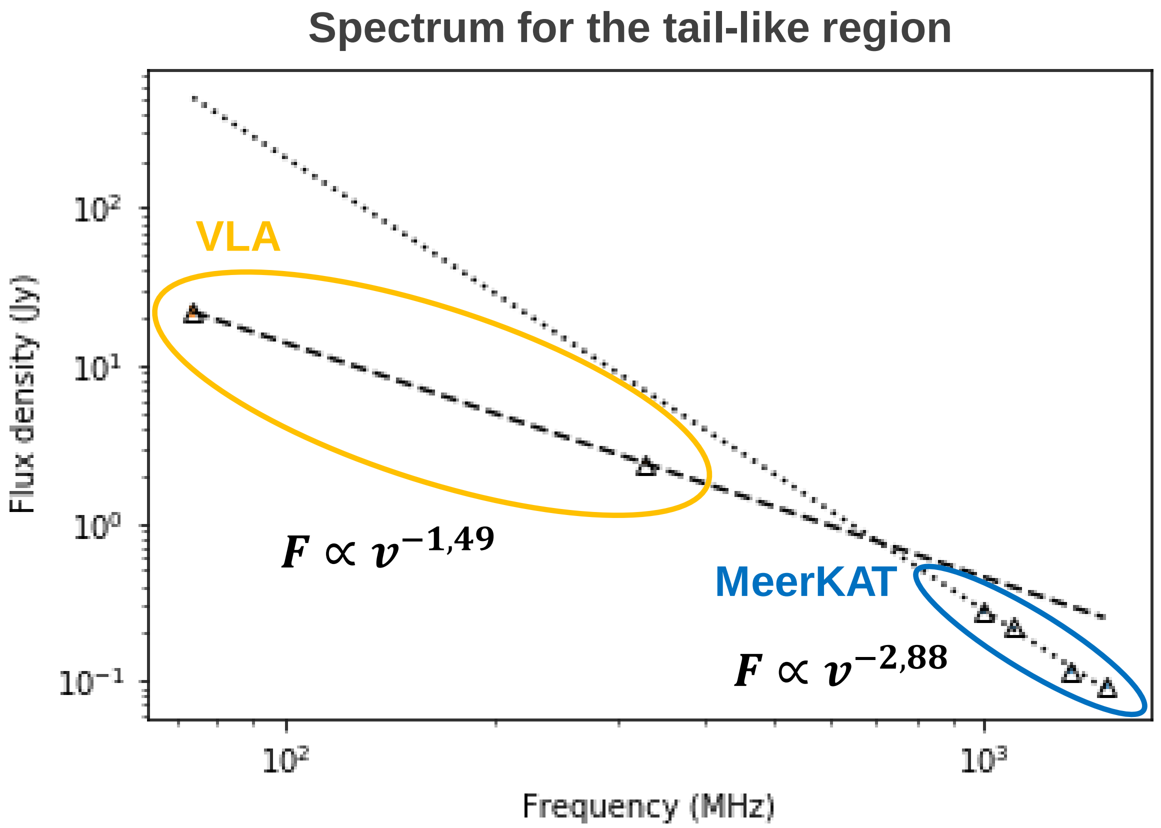
- Flux densities computed within MeerKAT frequency range and VLA Frequency range
- Steep spectrum in the MeerKAT frequency range
- We see a spectral break but not a single power law
- The Tail-like region has the steepest spectral index, suggesting it has undergone the most spectral aging.
  - Is the mechanism responsible for this emission the same as in the northern and southern lobes?











Modelling the radio spectrum in Hydra A

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- Due to the presence of the spectral break, we used the **Standard Kardashev-Pacholczyk (KP) model (1970)** to model the radio spectrum.

  - Assumptions
    - Electrons have an injection spectrum in the form of a power law

      $$N(E) = k_0 E^{-\gamma}$$

    - Electrons are interacting with a magnetic field B
    - Electrons evolve for a time T (age of the system)
    - Electrons experience Energy losses due to:
      - Synchrotron (with the magnetic field)
      - Inverse Compton (with the CMB photons)
    - Each electron keeps a constant pitch angle with the magnetic field direction during its lifetime (KP model)

The Best-fit Values of the Age and Magnetic field

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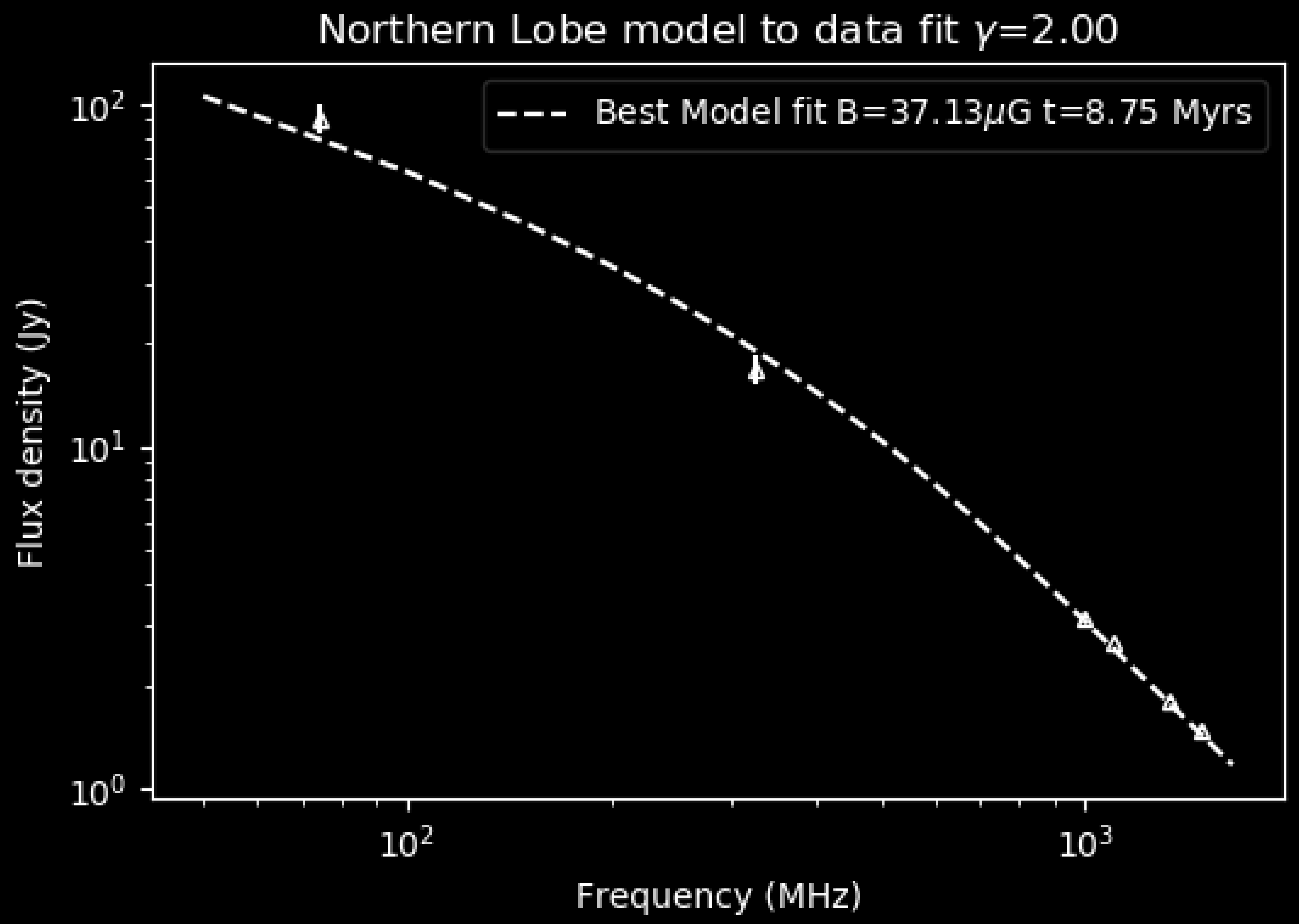
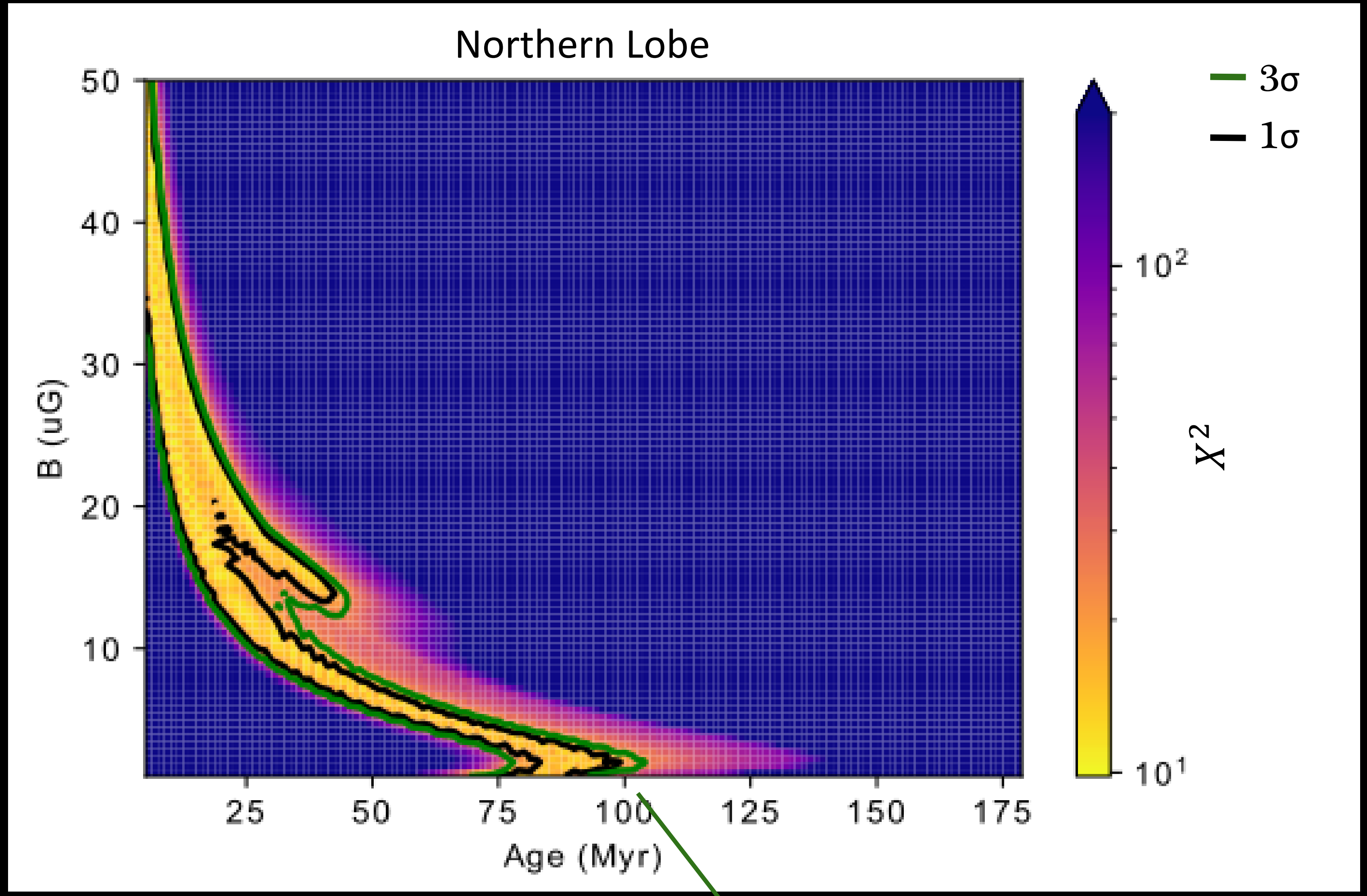


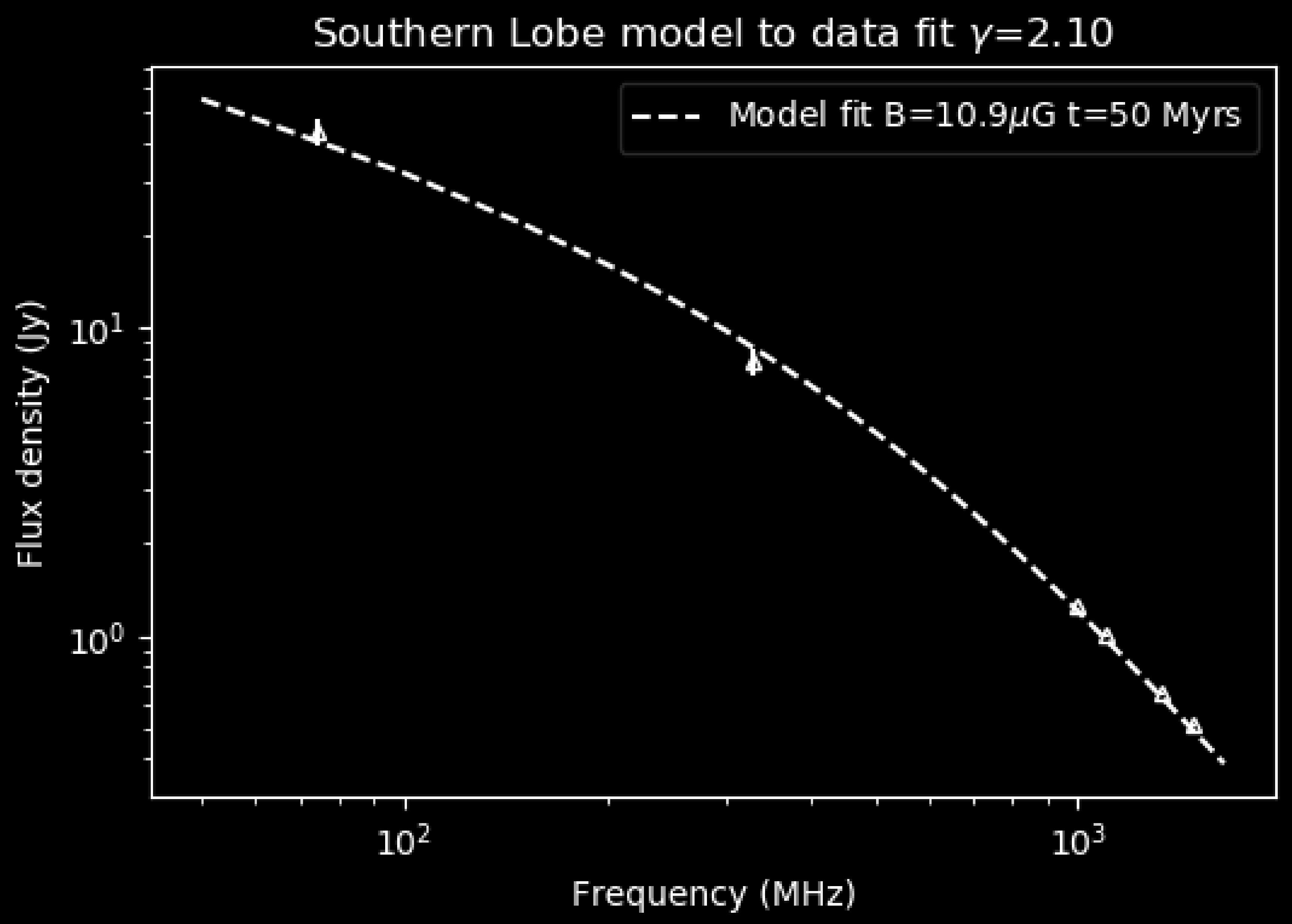


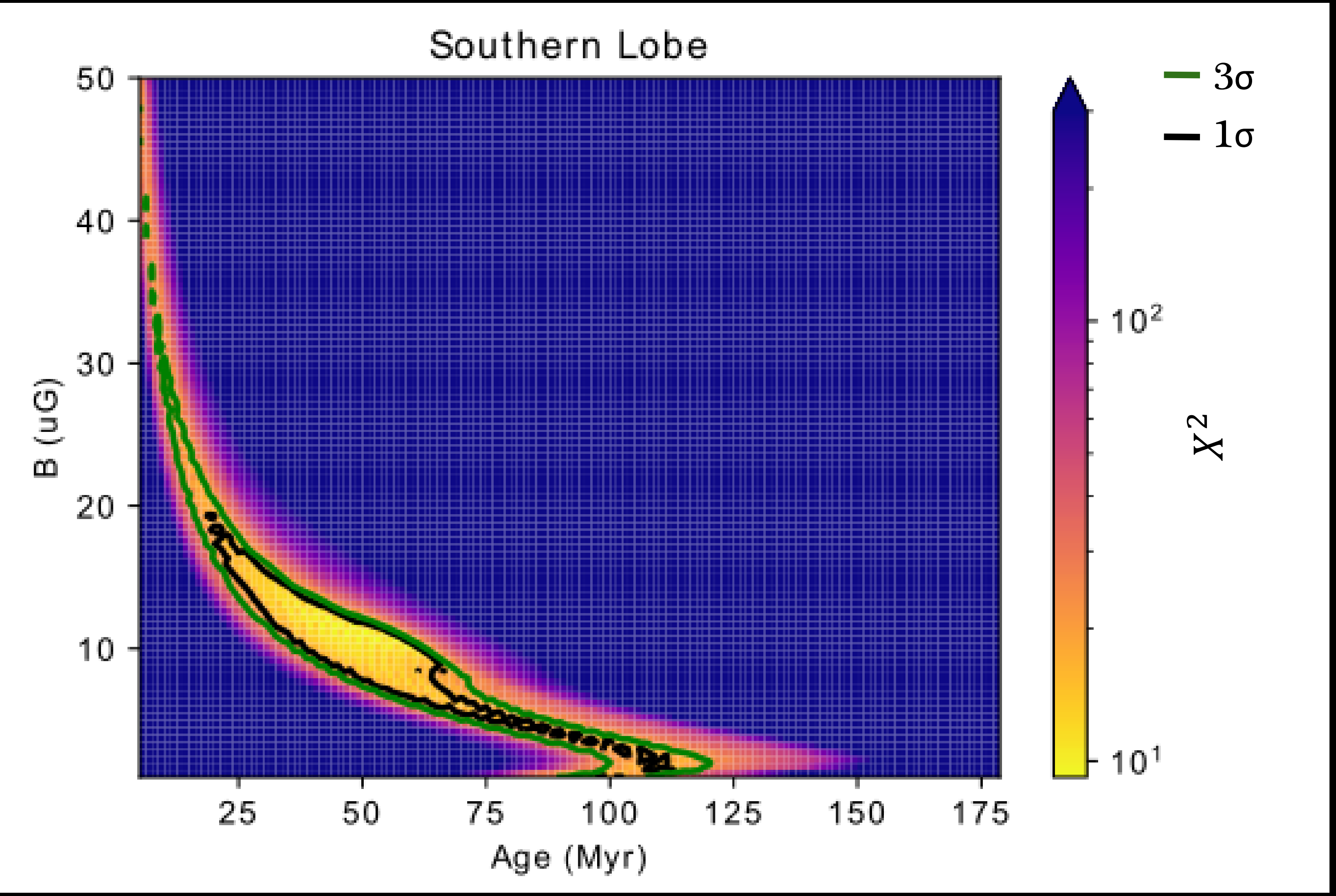
Cut-off around ~100 Myrs due to the CMB

- 3 sigma contours are quite broad
  - ➢ Possible to have age ~ 100 Myrs with a small magnetic field (possibly an underestimate)
  - ➢ Northern lobe appears to be youngest region- More mixing of electron populations?
    - Northern lobe still connected to jets

*values of the age and magnetic field found by minimizing the chi-squared statistic

The Best-fit Values of the Age and Magnetic field

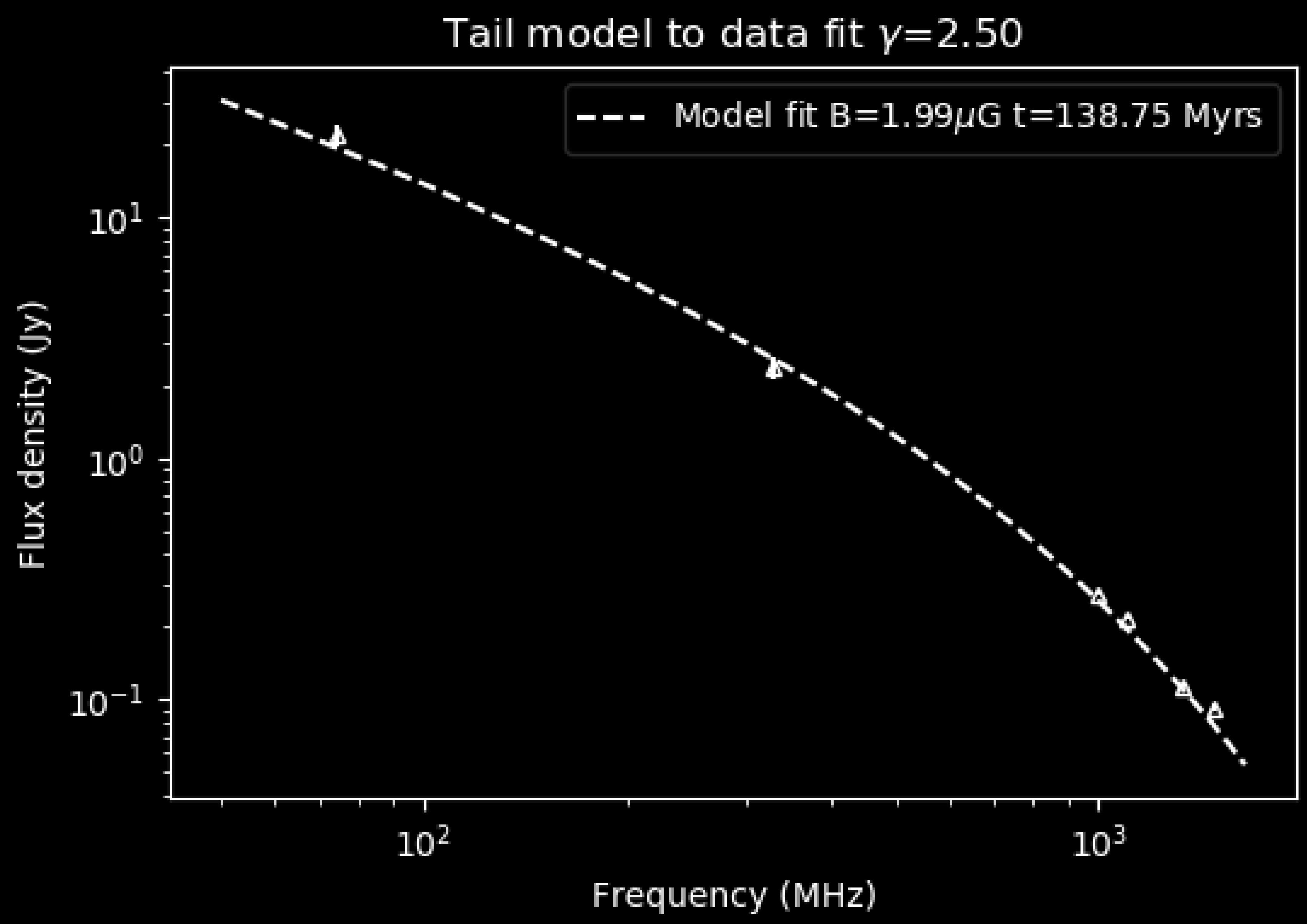


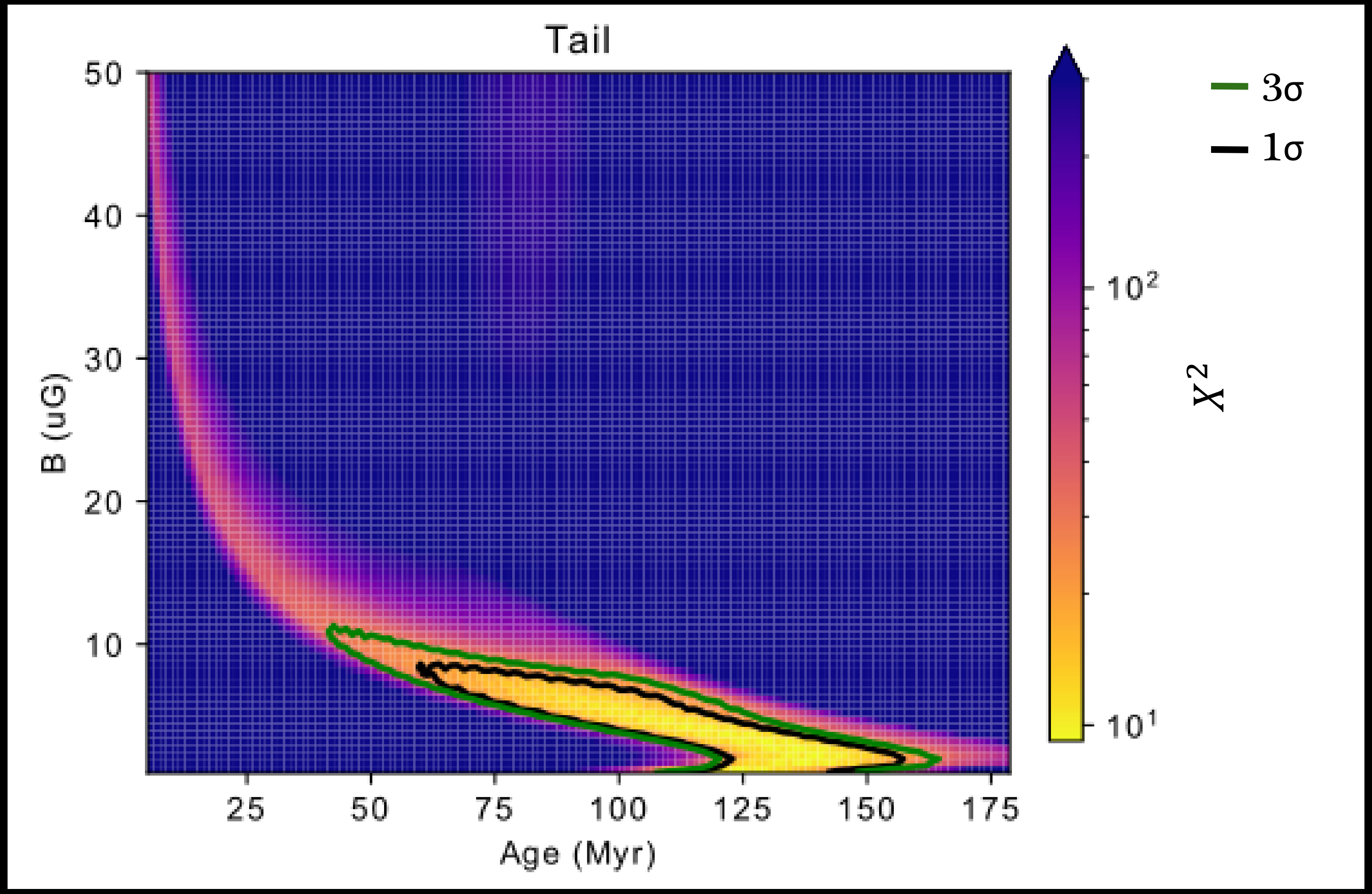


- 3 sigma contours:
  - Possible to have age ~ 120 Myr

*values of the age and magnetic field found by minimizing the chi-squared statistic

The Best-fit Values of the Age and Magnetic field





- 3 sigma contours :
  - ➢ Possible to have age ~ 160 Myrs with a small magnetic field
  - ➢ The tail region being the oldest suggests again that this region of emission is a result of an earlier generation of AGN activity (tail region already detached from the jets)

*values of the age and magnetic field found by minimizing the chi-squared statistic

Spectral age estimate vs previous age estimates

- We estimate the spectral age of Hydra A to be ~139 Myrs

- Spherical explosion model set an age estimate of ~ 140 Myrs
  [Nulsen et al. (2005) [1]]

- Dynamical age is estimated to be between 200 – 500 Myrs
  [Wise et al. (2007) [2]]

Dynamical age: The time required for cavity to rise the projected distance from the radio core to its present position at the speed of sound

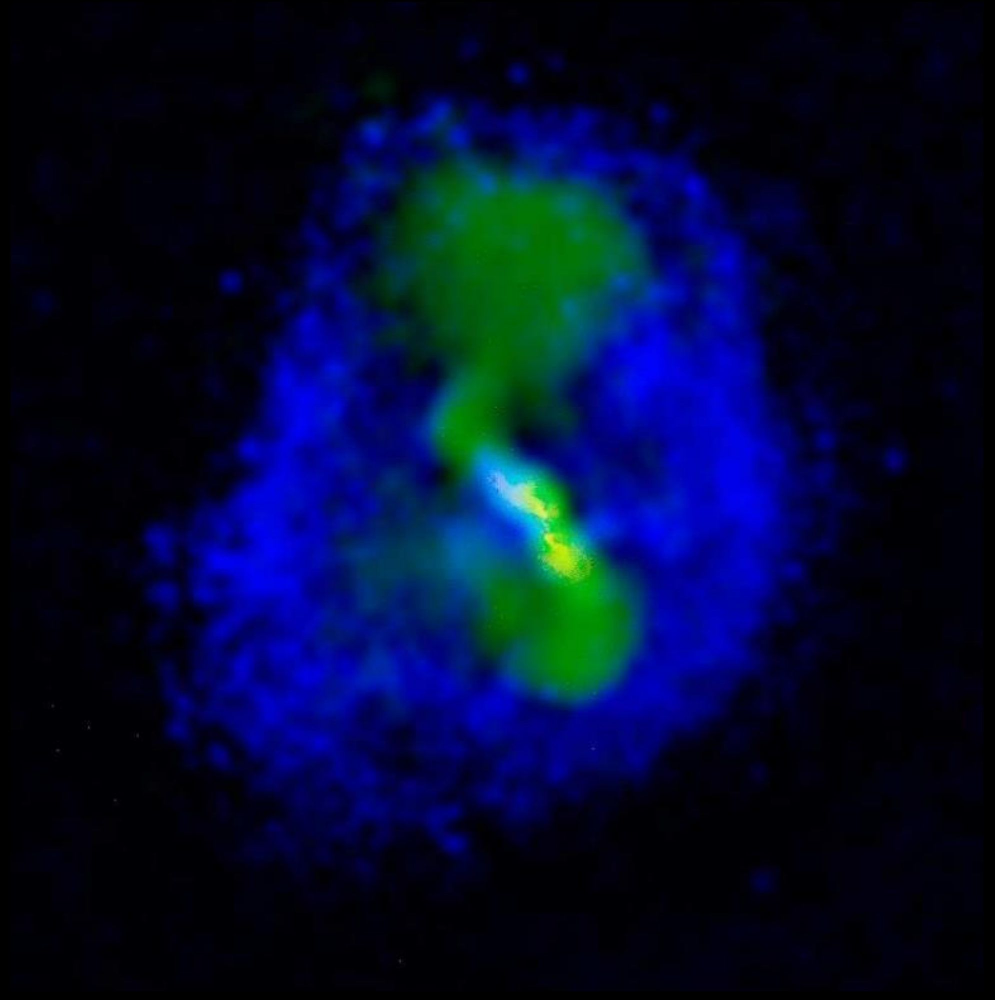


Figure: Composite color image of Hydra A which illustrates the close connection between the observed, large X-ray cavity system (shown in blue) and the low frequency, 330 Mhz radio emission (shown in green). The 330 Mhz radio data is from Lane et al. (2004). 1.4 GHz VLA image of Hydra A is also shown in the core in yellow.

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1 *The Cluster Scale AGN Outburst in Hydra A*, P. E. J. Nulsen, B. R. McNamara, M. W. Wise,4 and L. P. David, **Astrophys.J. 628:629 – 636, 2005**

2. *X-ray Supercavities in the Hydra A Cluster and the Outburst History of the Central Galaxy's Active Nucleus*, M. W. Wise, B. R. McNamara, P. E. J. Nulsen, J. C. Houck, L. P. David, **Astrophys.J. 659:1153-1158, 2007**

The H.E.S.S. Collaboration

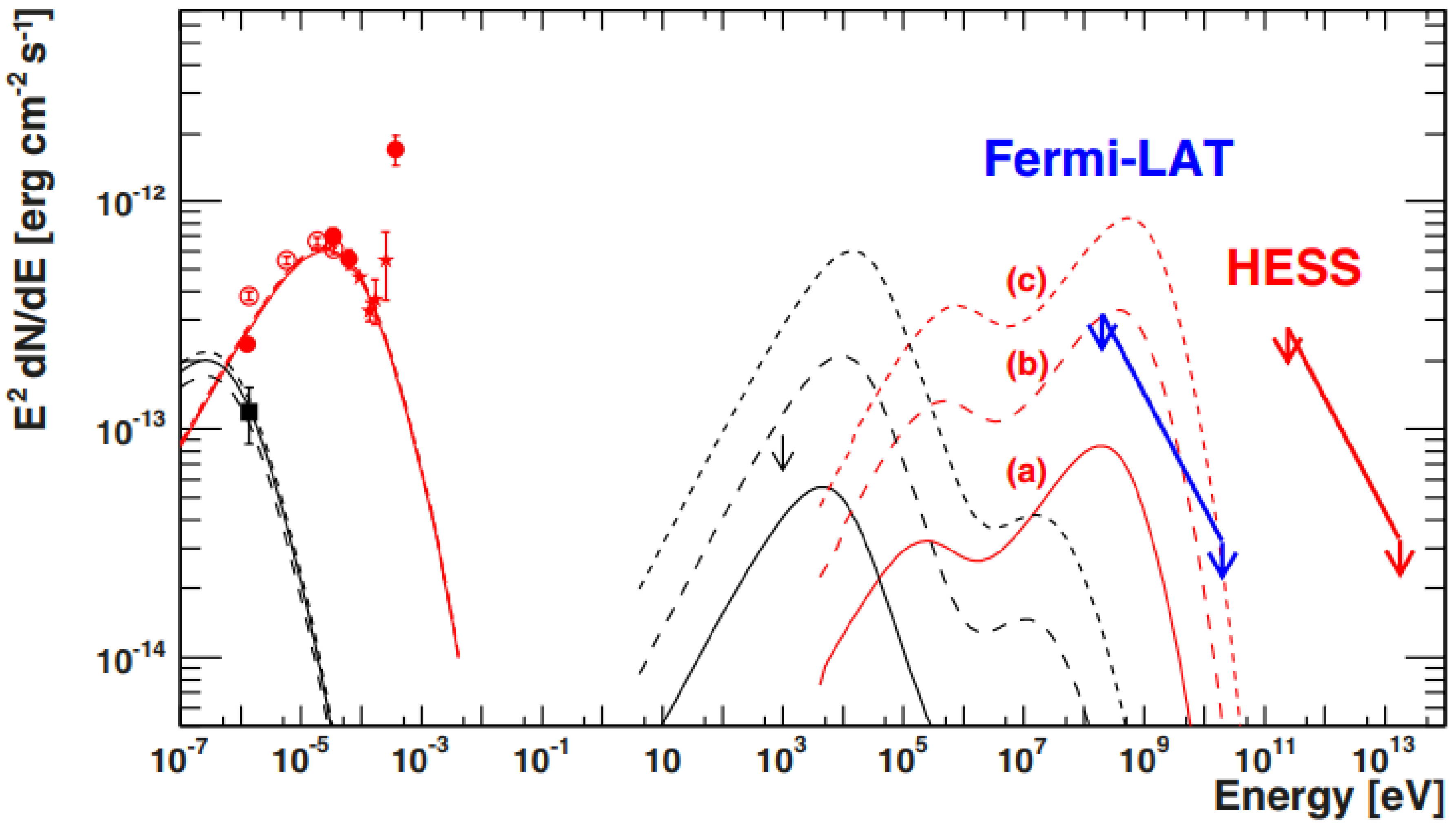

Figure: Synchrotron and expected corresponding IC emission for the inner and outer lobes of Hydra A. The experimental data for the inner lobes are shown as red open circles, red filled circles, and red stars. The radio flux for the outer lobes is indicated by black squares. Additionally the upper limit for the power-law emission at 1 keV for the outer (Northern) lobe (black arrow) is included. The red curves correspond to the emission of the inner lobes, and the black curves represent the outer lobes. The solid curves illustrate model (a), the dashed curve model (b) and the dotted curve is for model (c) from Table 2. Fermi and H.E.S.S. limits are shown for Γ = 2.5.

Gamma Rays?

- No signal has been found in either HESS or Fermi-LAT data set*
- At a confidence level of 95% an upper limit of $F_\gamma(>240\ \text{GeV}) < 7.9\times10^{-13}\ \text{cm}^{-2}\text{s}^{-1}$ for a powerlaw of the form $dN/dE \propto E^{-\Gamma}$ with an assumed photon index $\Gamma = 2.5$ is found.
- The fluxes we computed for the outer lobes are consistent with the outer lobe curve presented
- Given the steepening of the spectrum for the outer lobes, the non-detection of gamma rays is expected

*<u>*Constraints on the gamma-ray emission from the cluster-scale AGN outburst in the Hydra A galaxy cluster*, HESS Collaboration, **A&A. 545:A103, 2012**</u>

Summary and Conclusions

- From our radio observations we see the inner and outer lobes as well as an interesting tail like feature that exhibits an unusual bend
- Our spectral analysis reveals a steepening in the MeerKAT frequency range & a spectral break
- The modelling reveals that the tail is the oldest region of the galaxy
    - This suggest that the northern and southern lobes may still connected to the jet and being injected with younger electrons
    - The age of the tail suggests that the tail is completely disconnected from jets and is a remnant of an older generation of AGN activity
- We estimate the age for the system to be ~160 Myrs (consistent with previous age estimates)

Acknowledgments

- Our study has made use of data obtained from the MeerKAT telescope that has been provided by the South African Radio Astronomy Observatory (SARAO)- which is a facility of the National Research Foundation, an agency of the Department of Science and Technology.