Probing jet formation and acceleration at event horizon scales

Ainara Saiz Pérez, Christian M. Fromm, Felix Glaser, Raoul Kinadeter, Wladislaw Schulga, Florian Maul

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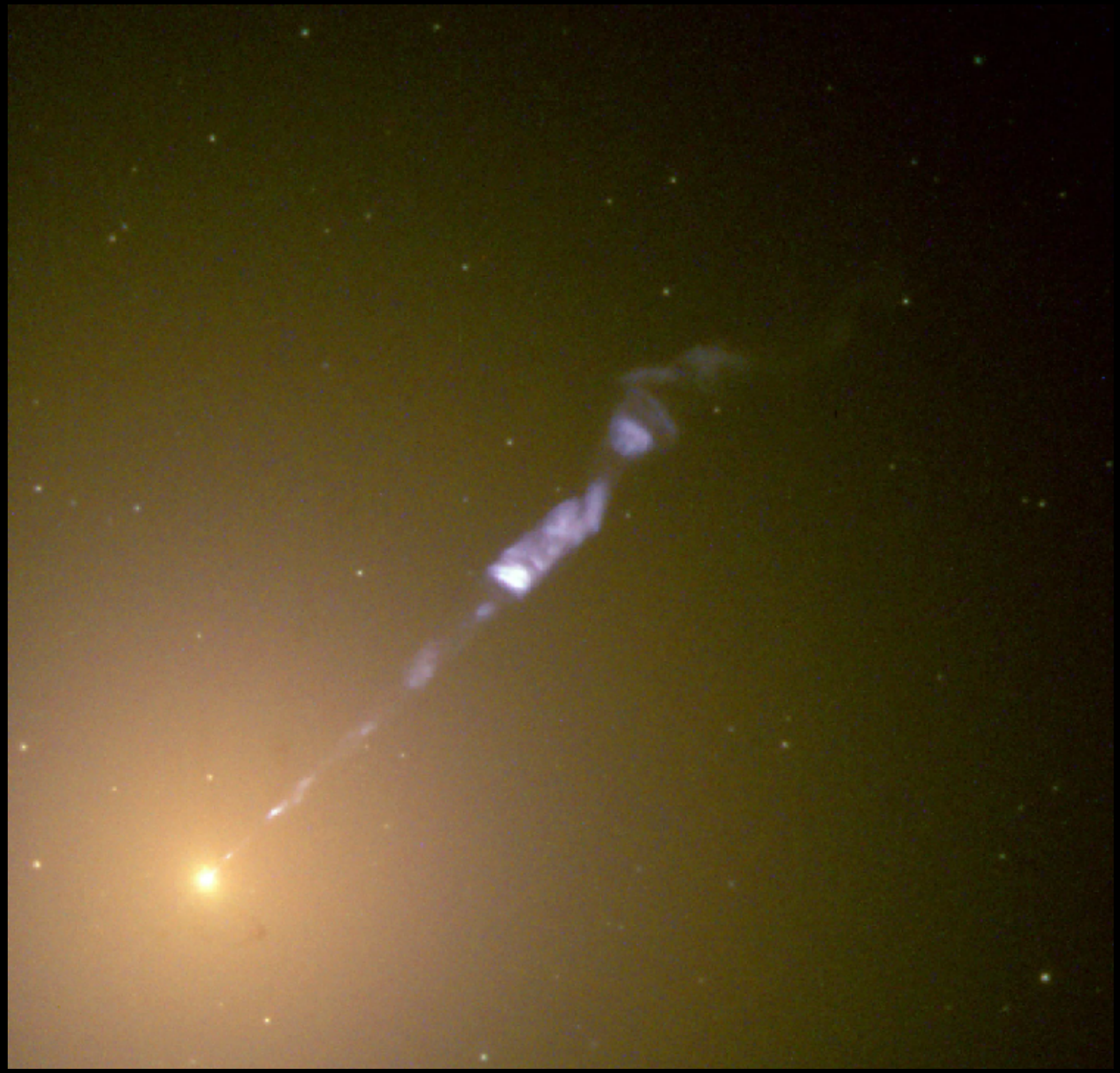
Jet-disk coupling

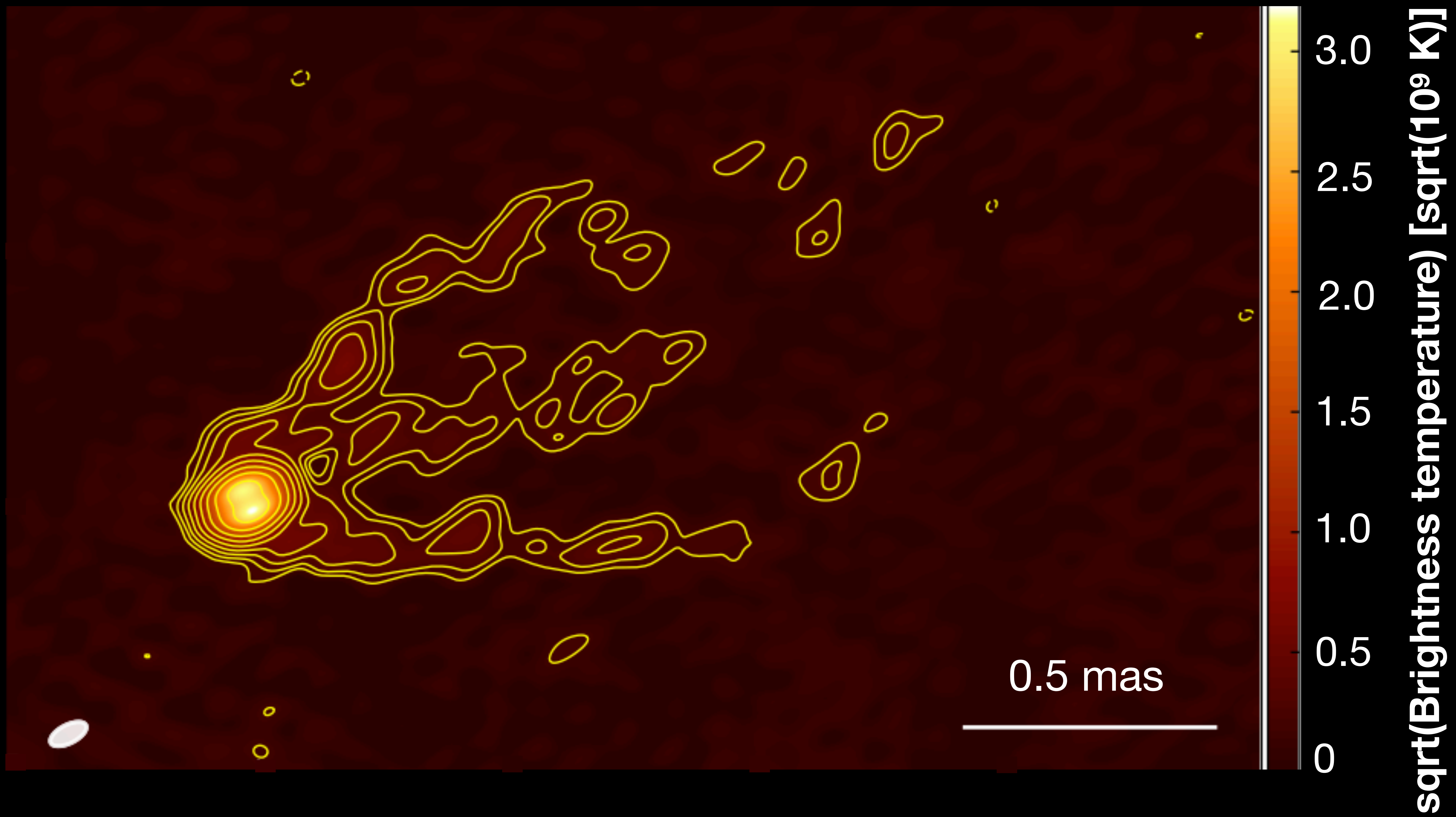
- Understanding how the disk and the jet of active galactic nuclei (AGN) couple to each other
- With our current resolution, M87 is the only source where the horizon scales and jet emission are simultaneously observed



AGN jet (blue) and clusters of stars (yellow) in the galaxy M87
(NASA and the Hubble Heritage Team)

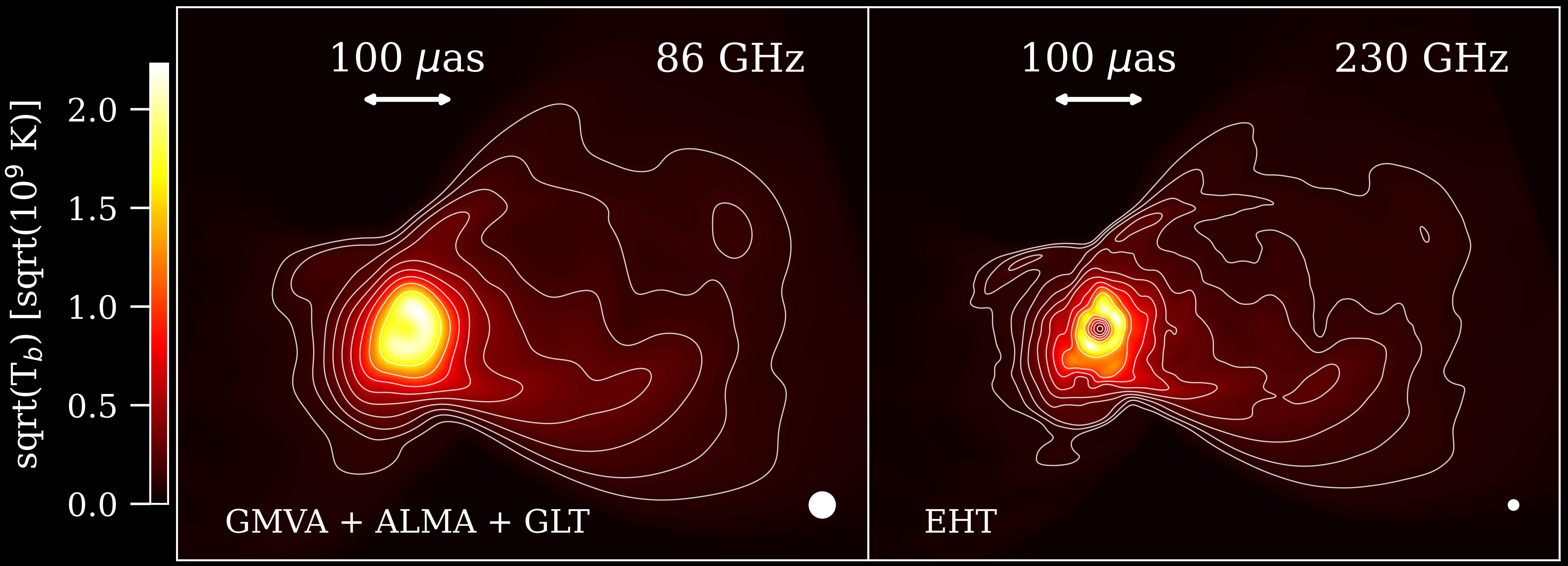
Jet-disk coupling

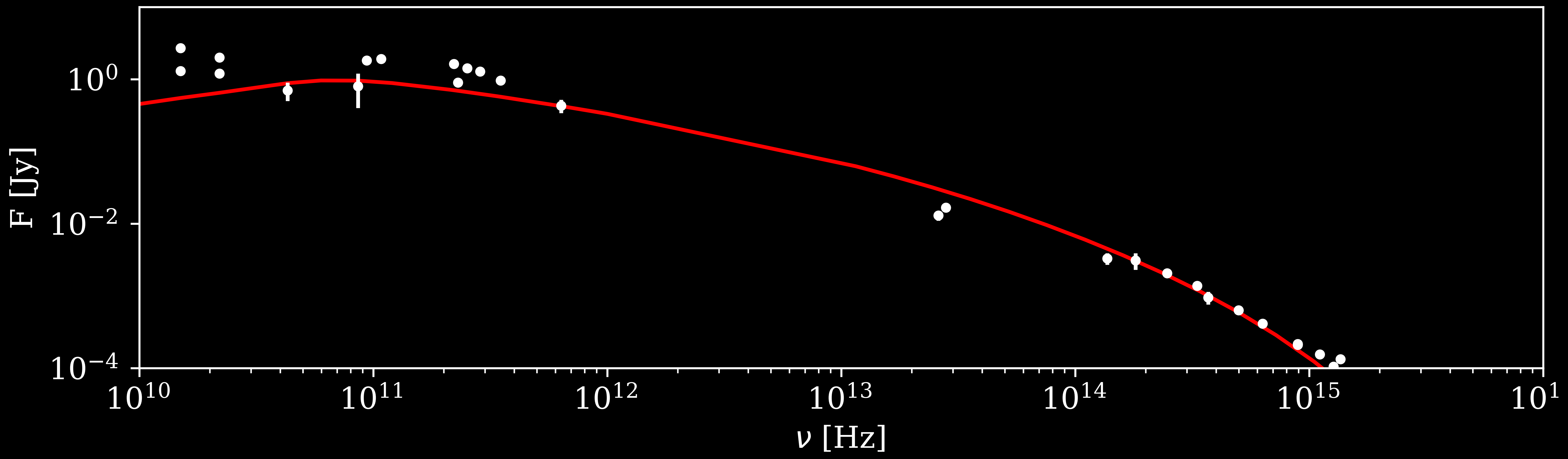
- Understanding how the disk and the jet of active galactic nuclei (AGN) couple to each other
- With our current resolution, M87 is the only source where the horizon scales and jet emission are simultaneously observed
- 3.5 mm observations: radio core + triple ridged jet



Adapted from
Lu, Ru-Sen, et al. "A ring-like accretion structure in M87 connecting its black hole and jet." Nature 616.7958 (2023): 686-690.

Results





- Our input theoretical model: result of 3D General Relativistic Magnetohydrodynamics + Radiative Transfer calculations: jet launching scenario

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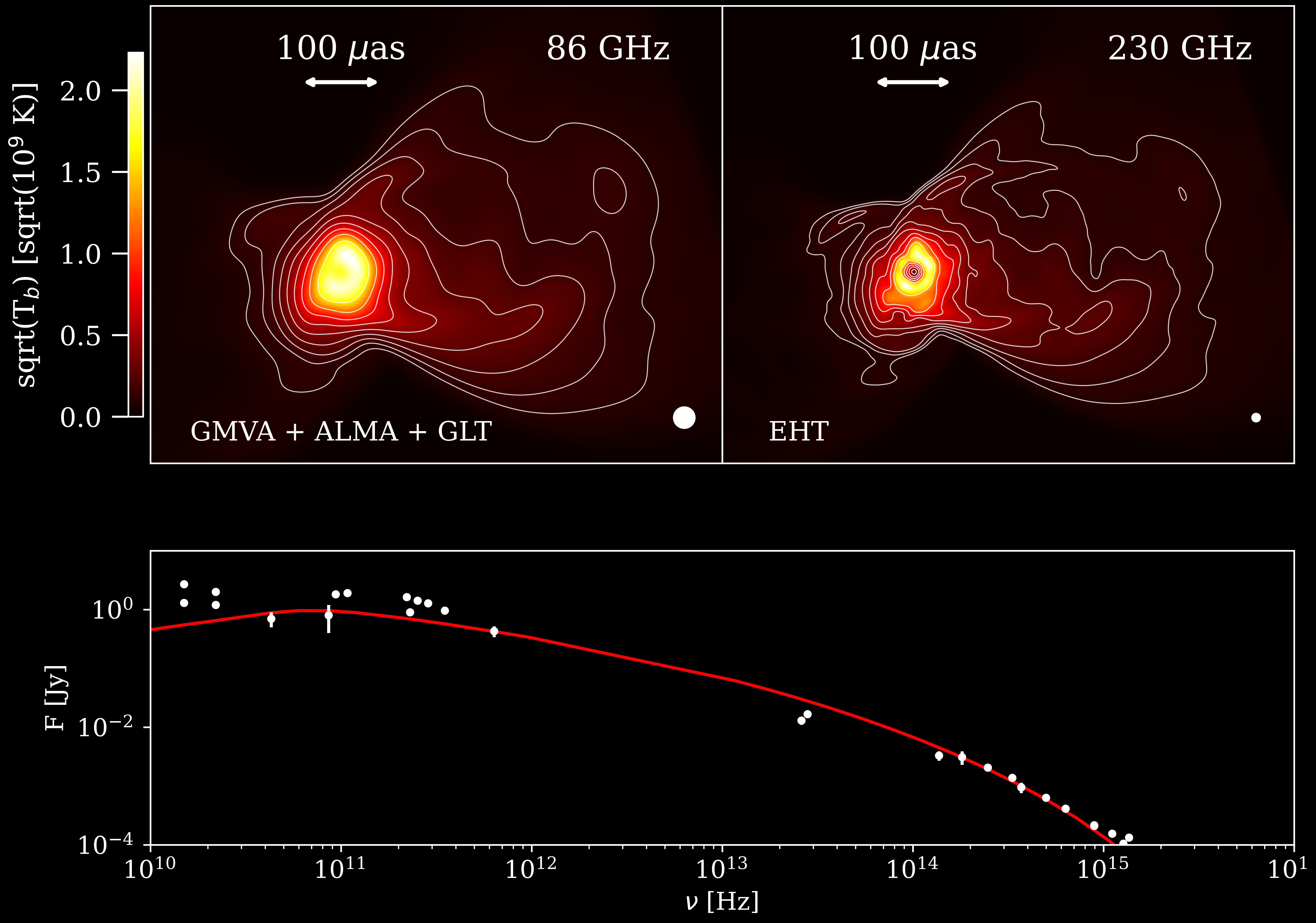

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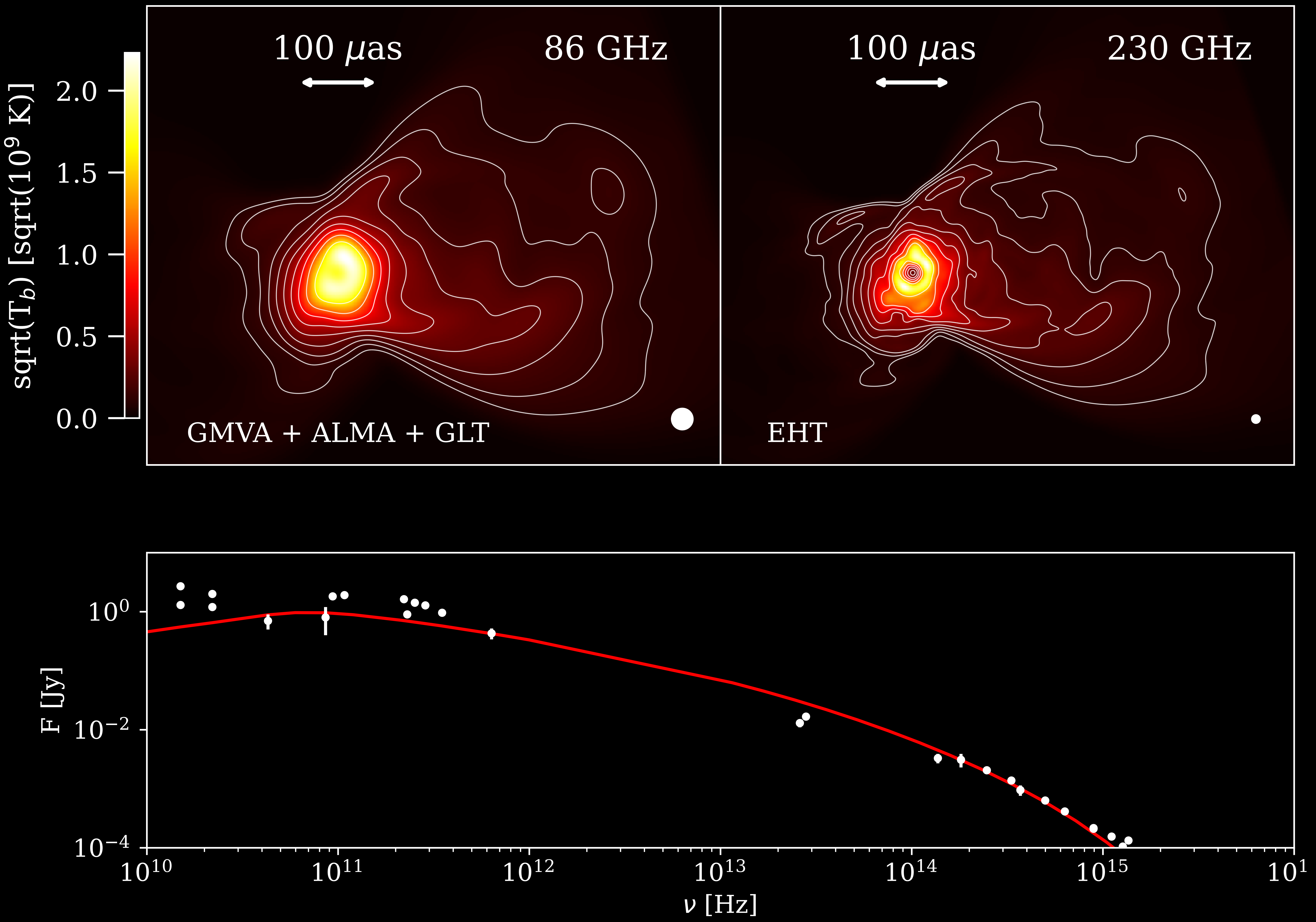

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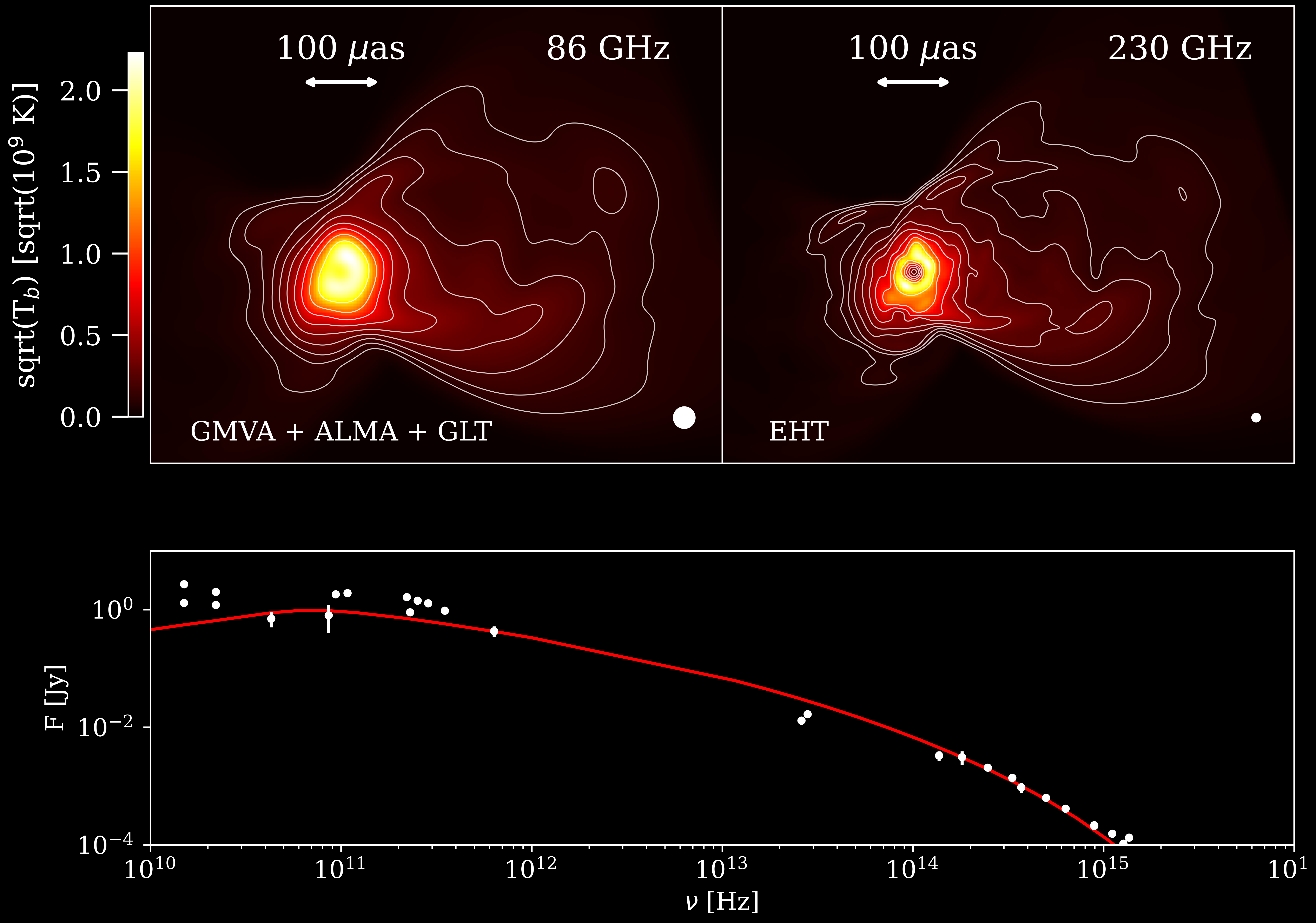

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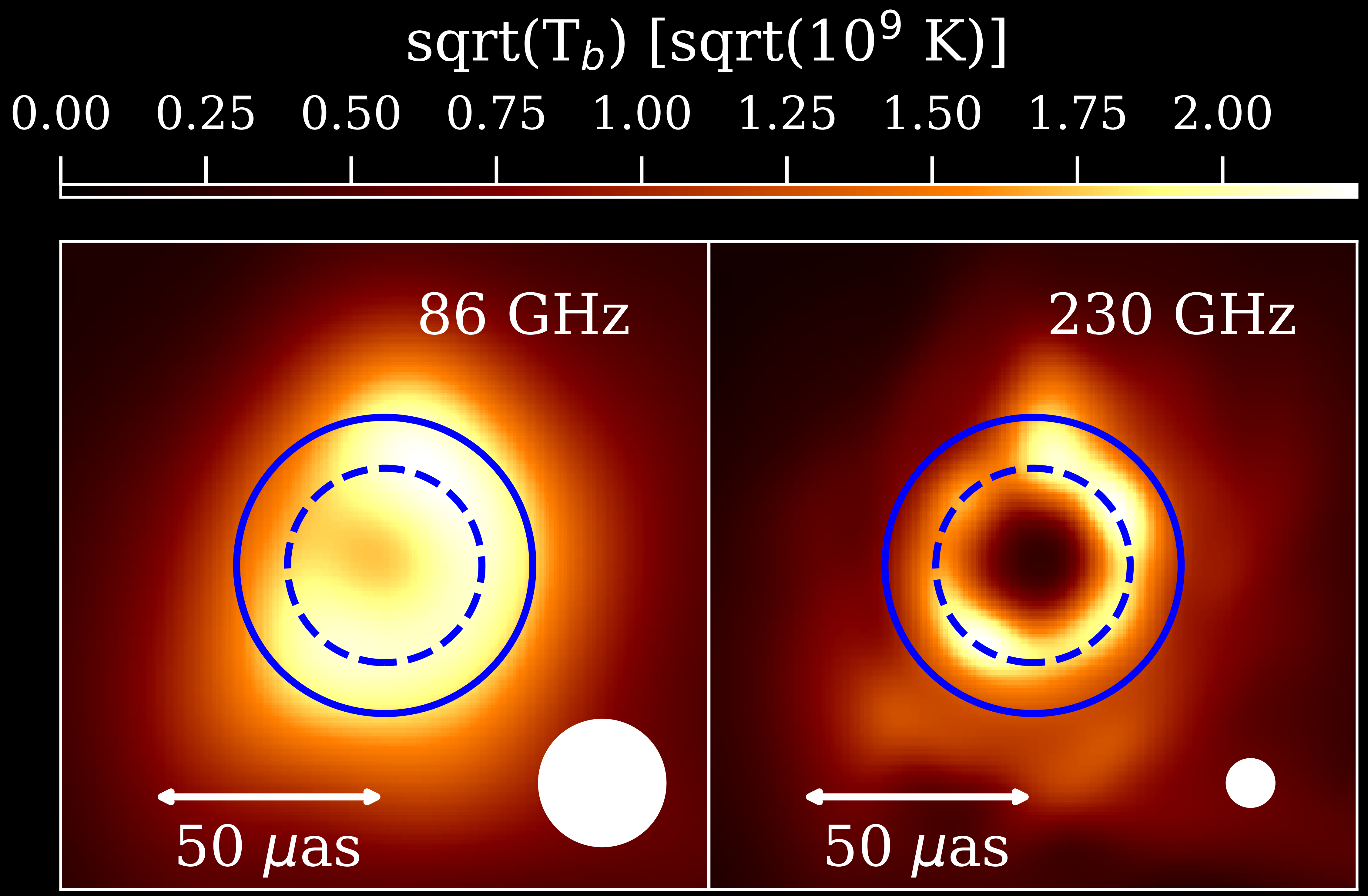
- Spin -0.5 (counterrotating)
- Emission model: mixed thermal and non thermal emission in ratios derived from magnetisation

Results - Horizon scale



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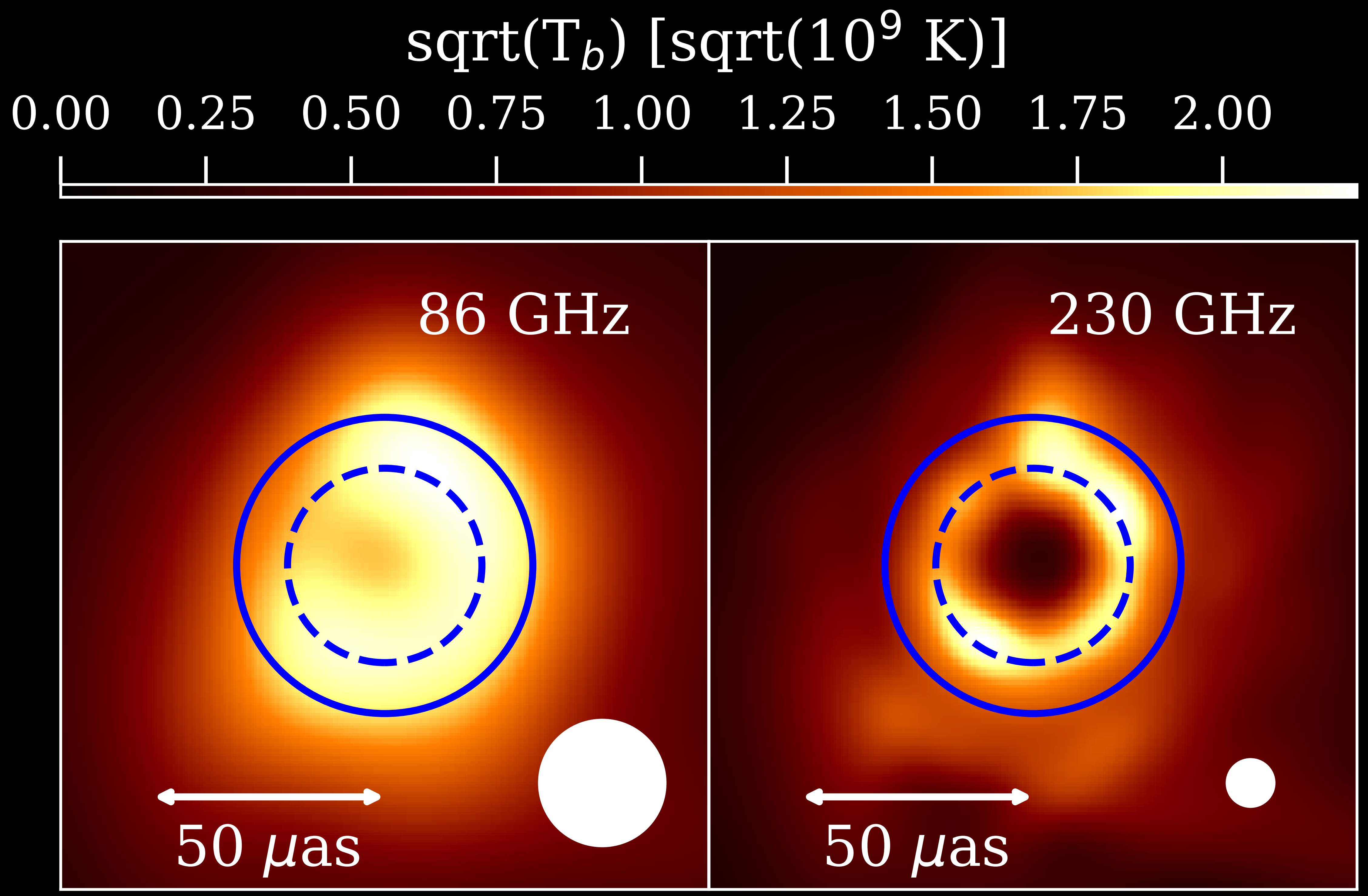
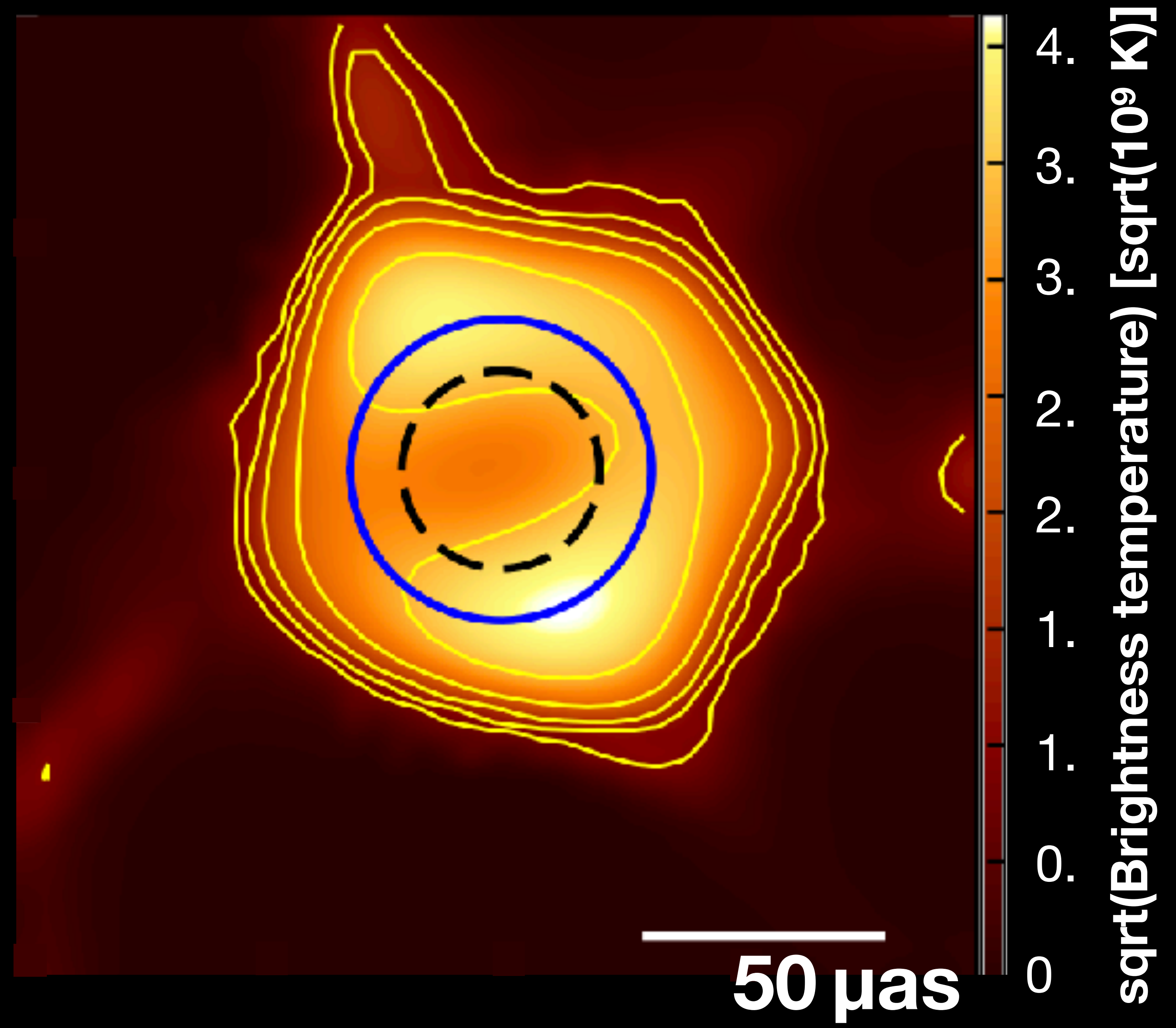


Comparison to validation source



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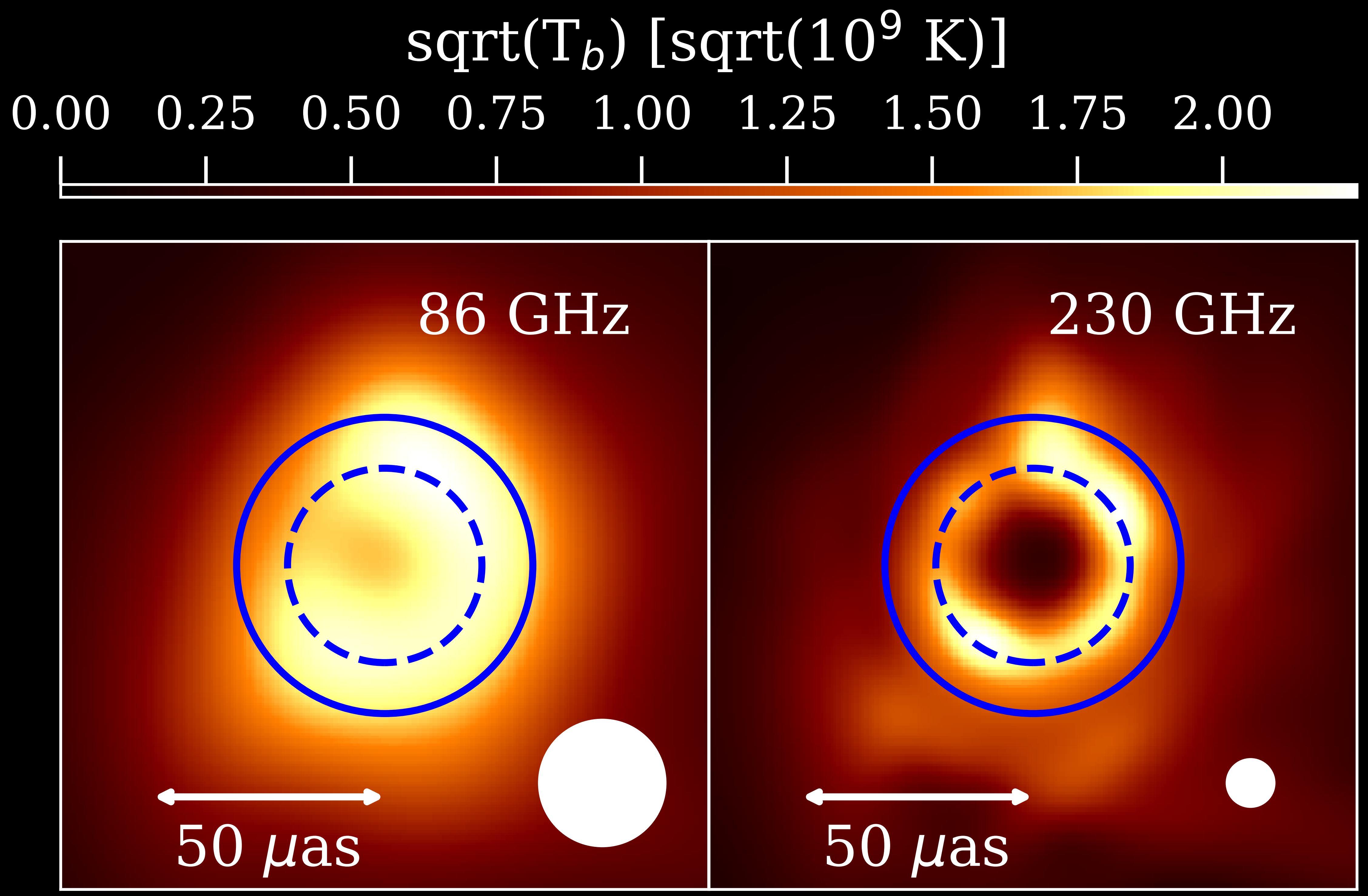

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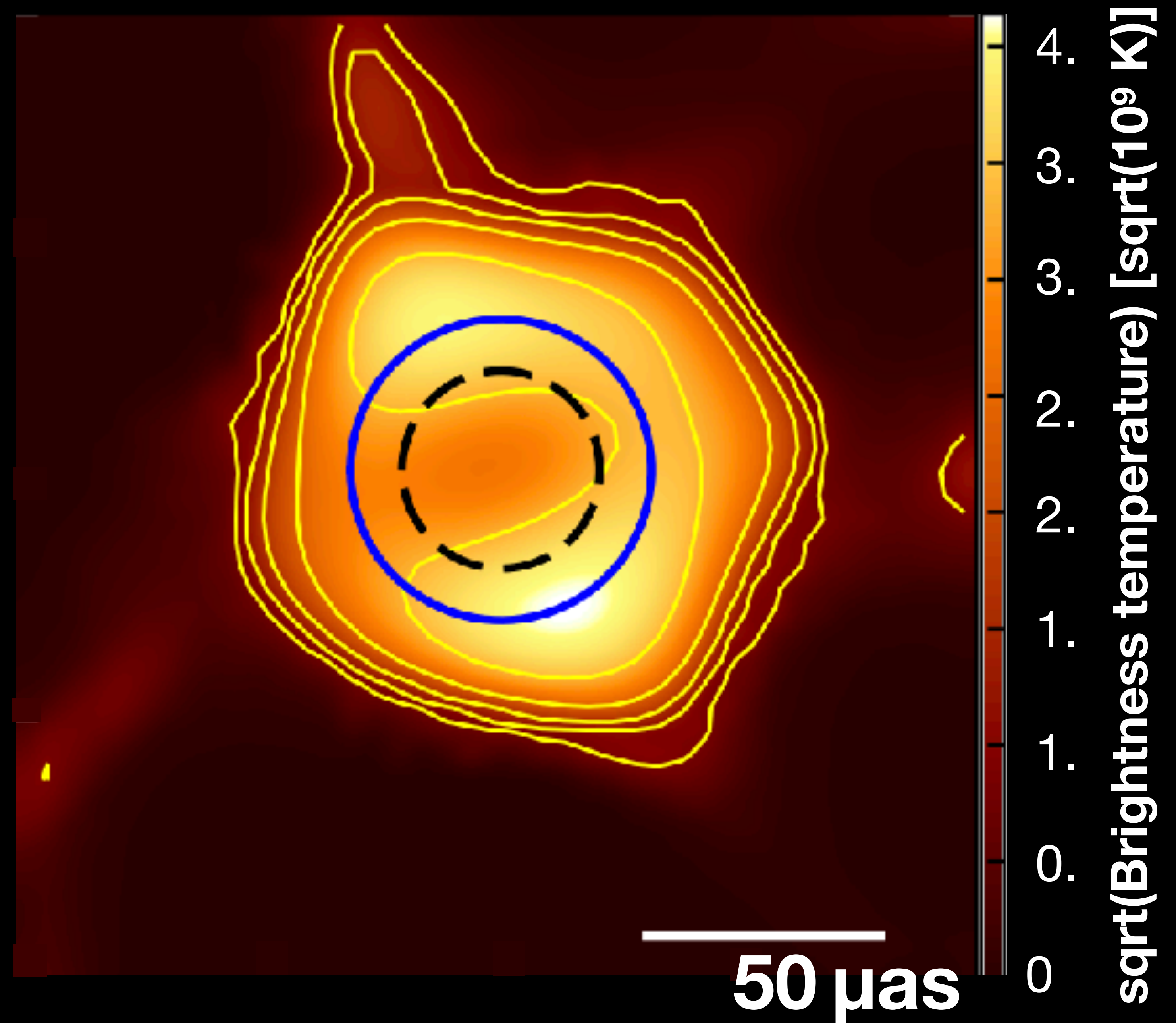

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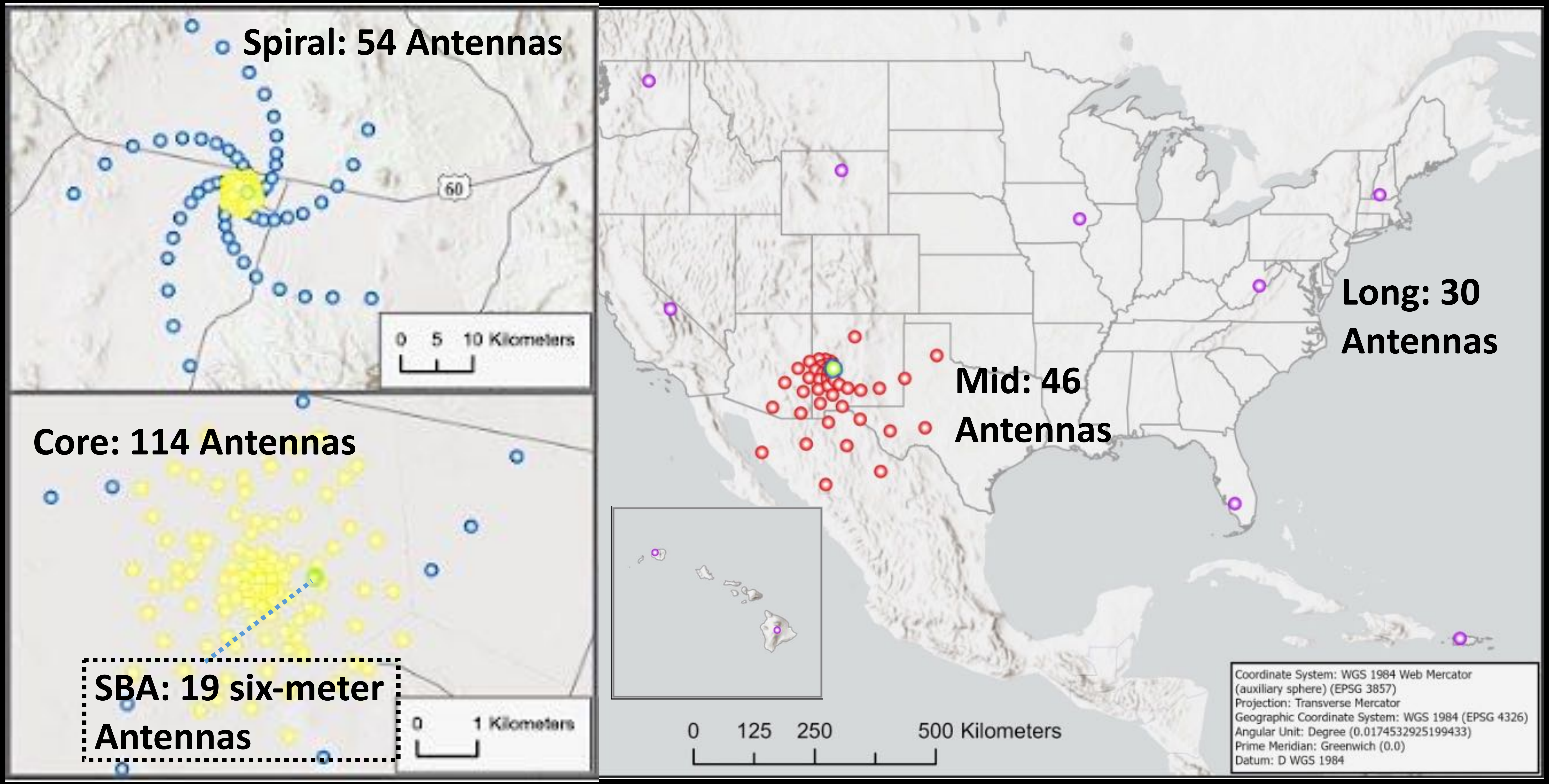
→ How could we improve our results with ngVLA?

Next-generation Very Large Array

27 antennas ⟶ 263 antennas, sensitivity improved tenfold



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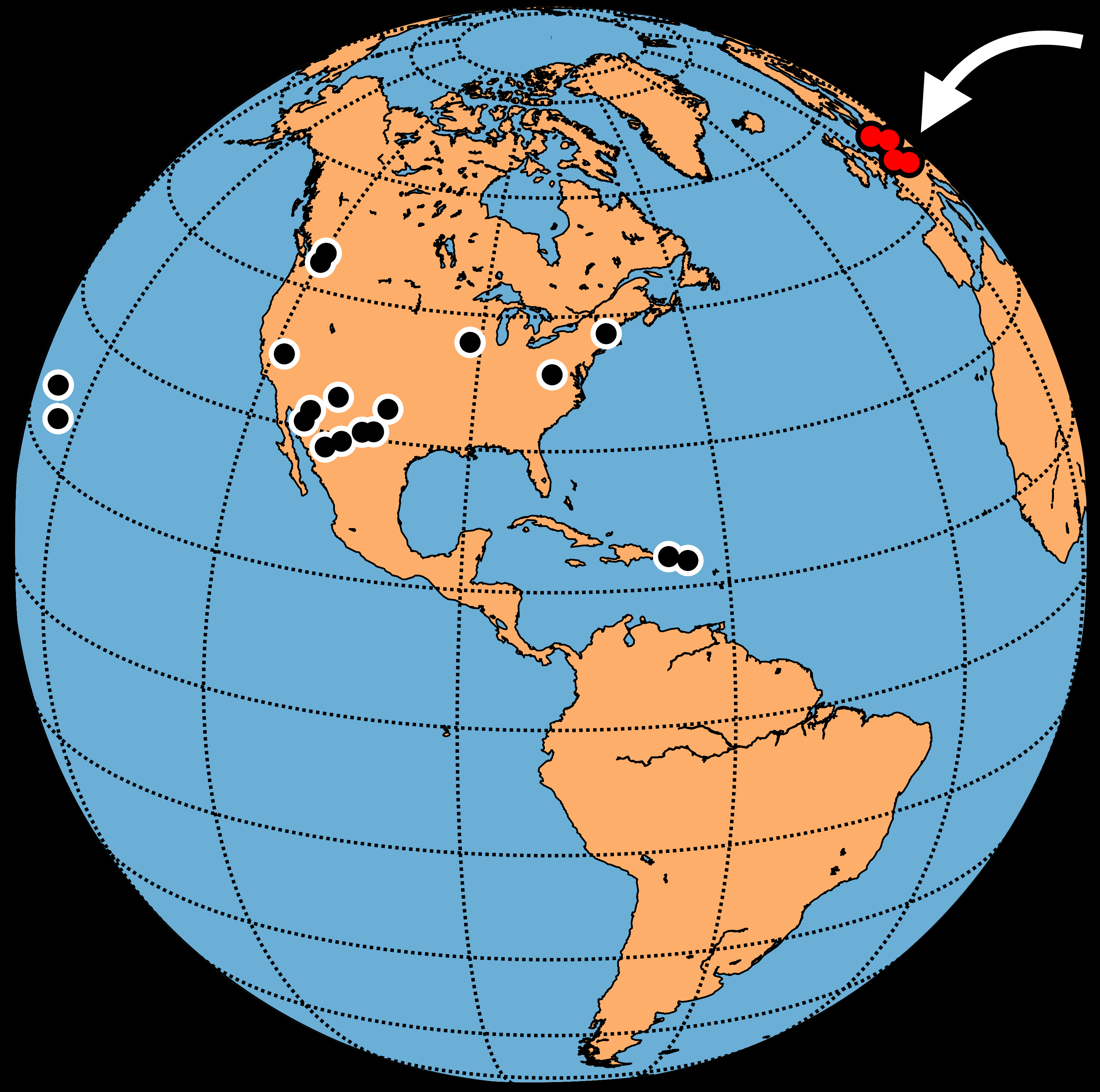
LEVERAGE (Long-baseline Extension in next-generation VLBI Experiments and Rapid-response Array Germany + Europe)



2-4 clusters, 18m dishes in sites with research infastructure: 4 proposed in Germany

Next-generation Very Large Array

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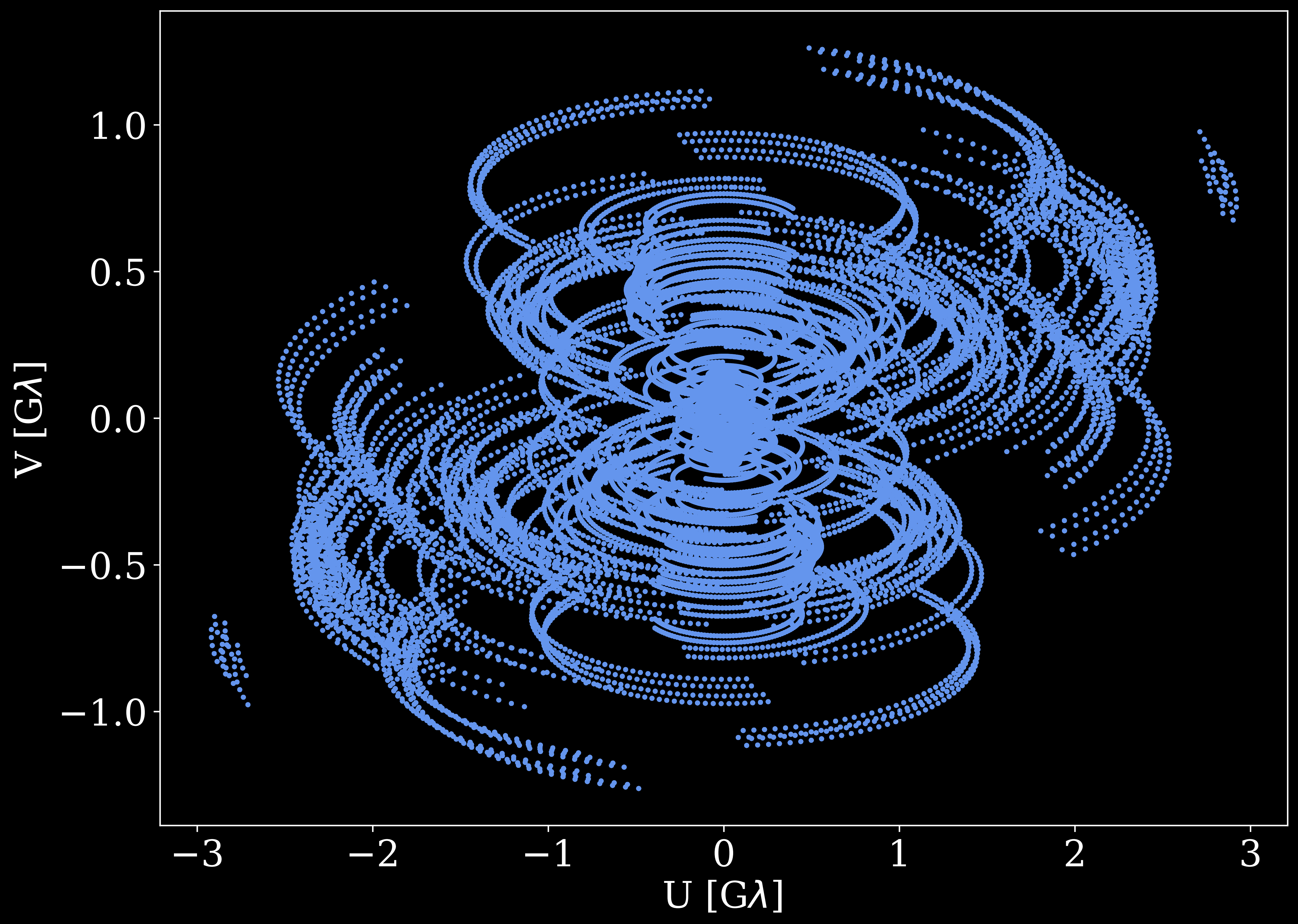
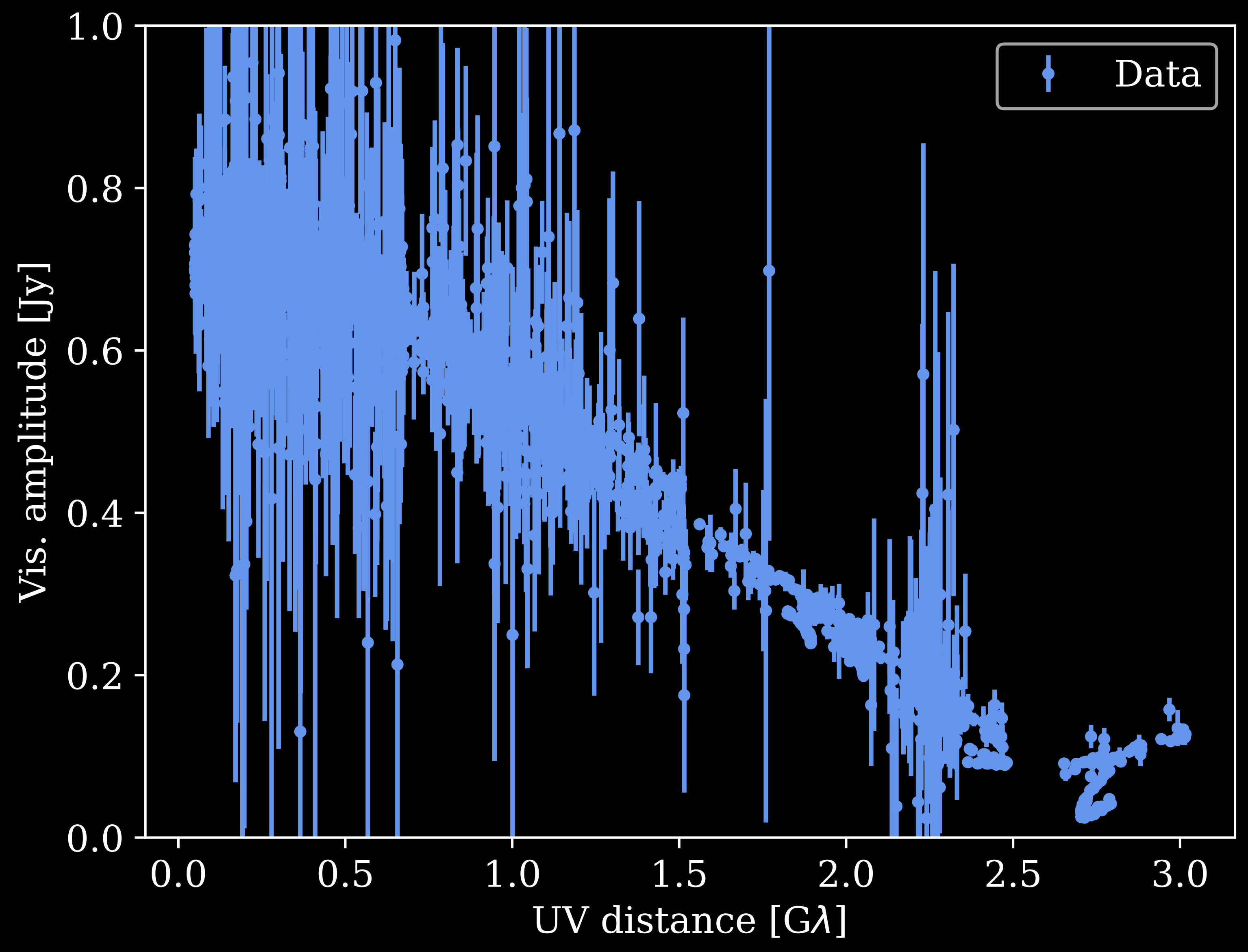
LEVERAGE (Long-baseline Extension in next-generation VLBI Experiments and Rapid-response Array Germany + Europe)

→ Computing synthetic baselines + sampling and Fourier transforming our theoretical model, we can study different observing arrays



M-ring fitting



- More realistic approach: make synthetic data from real observations: M87 at 86 GHz by GMVA + ALMA + GLT

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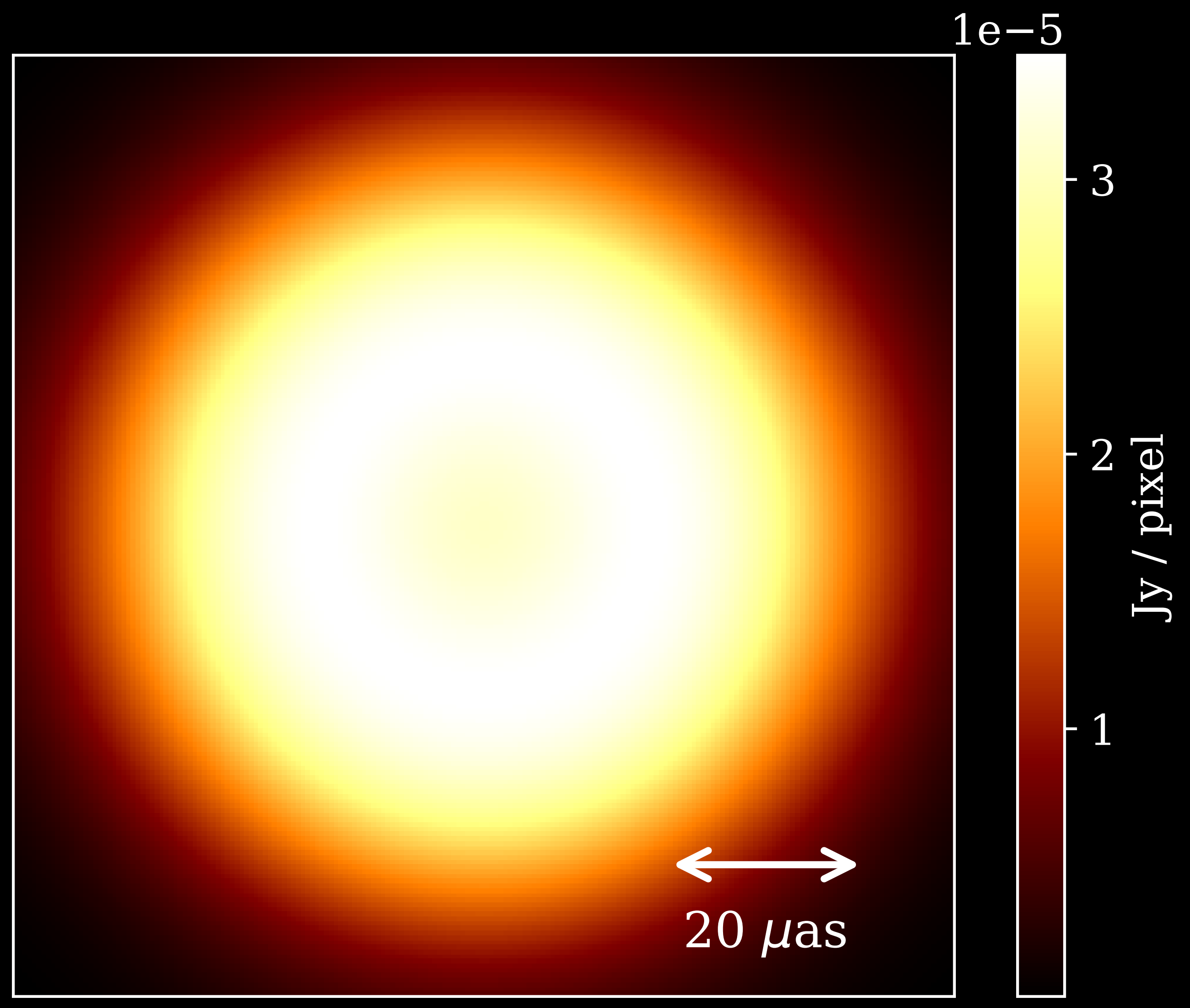

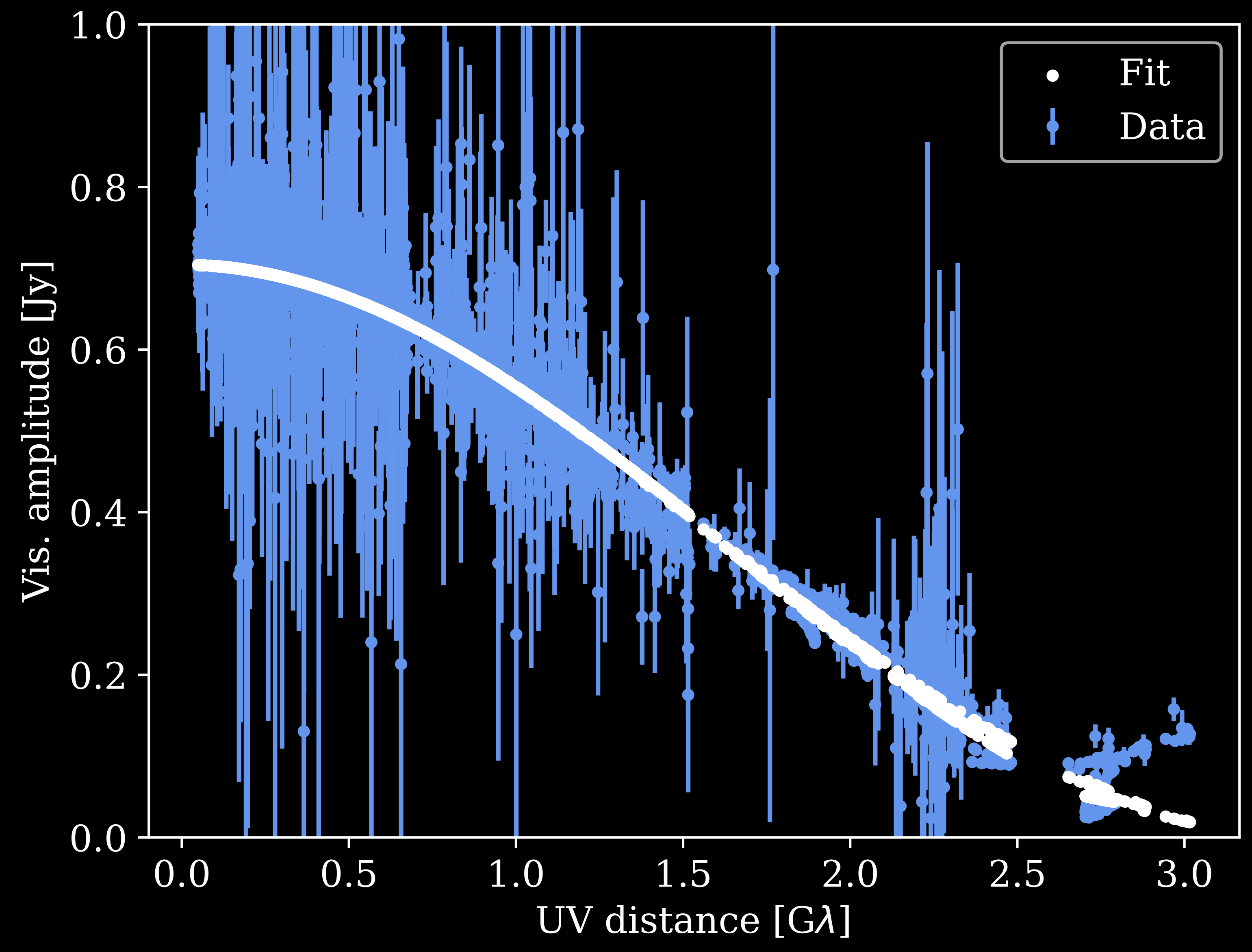

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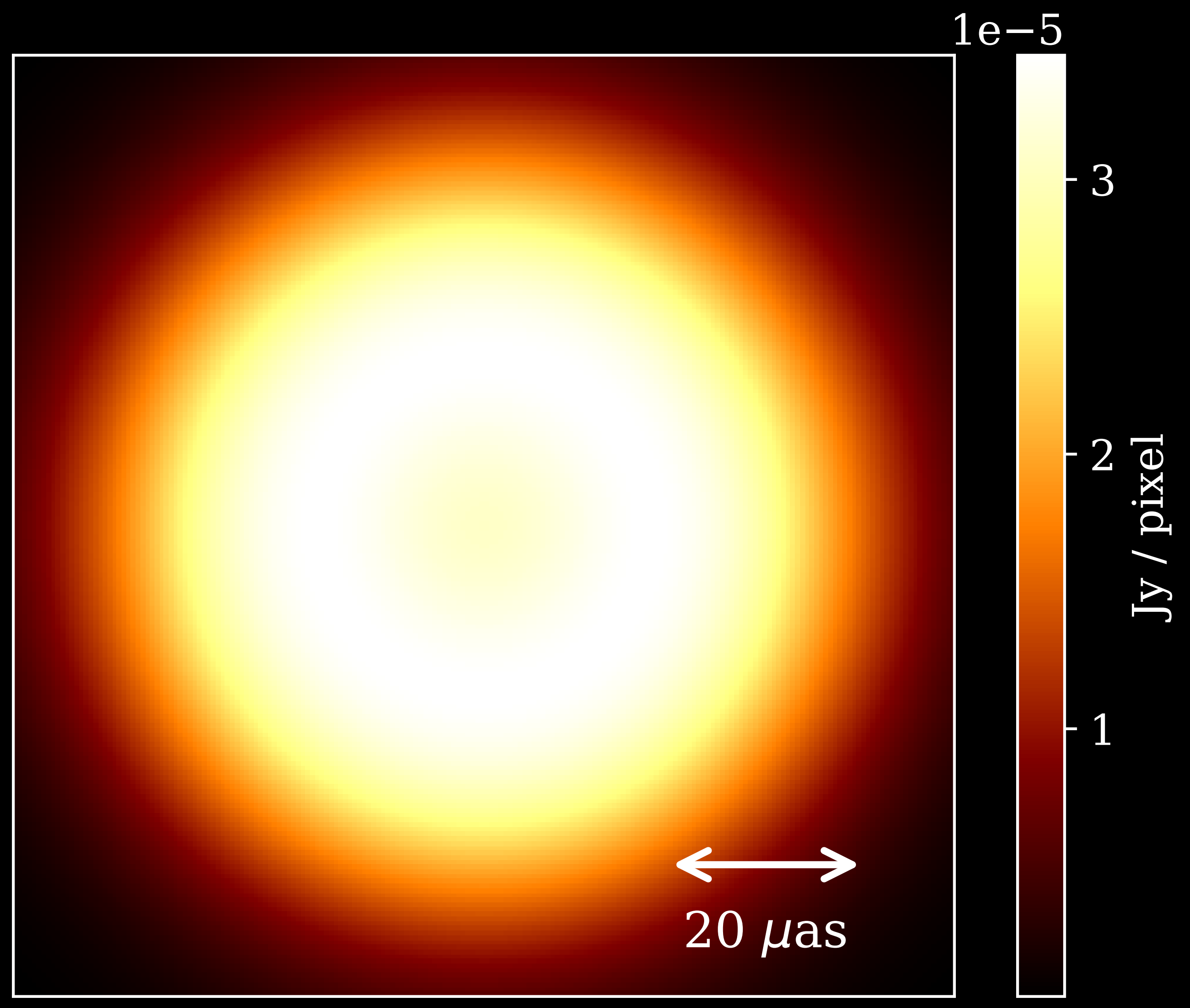

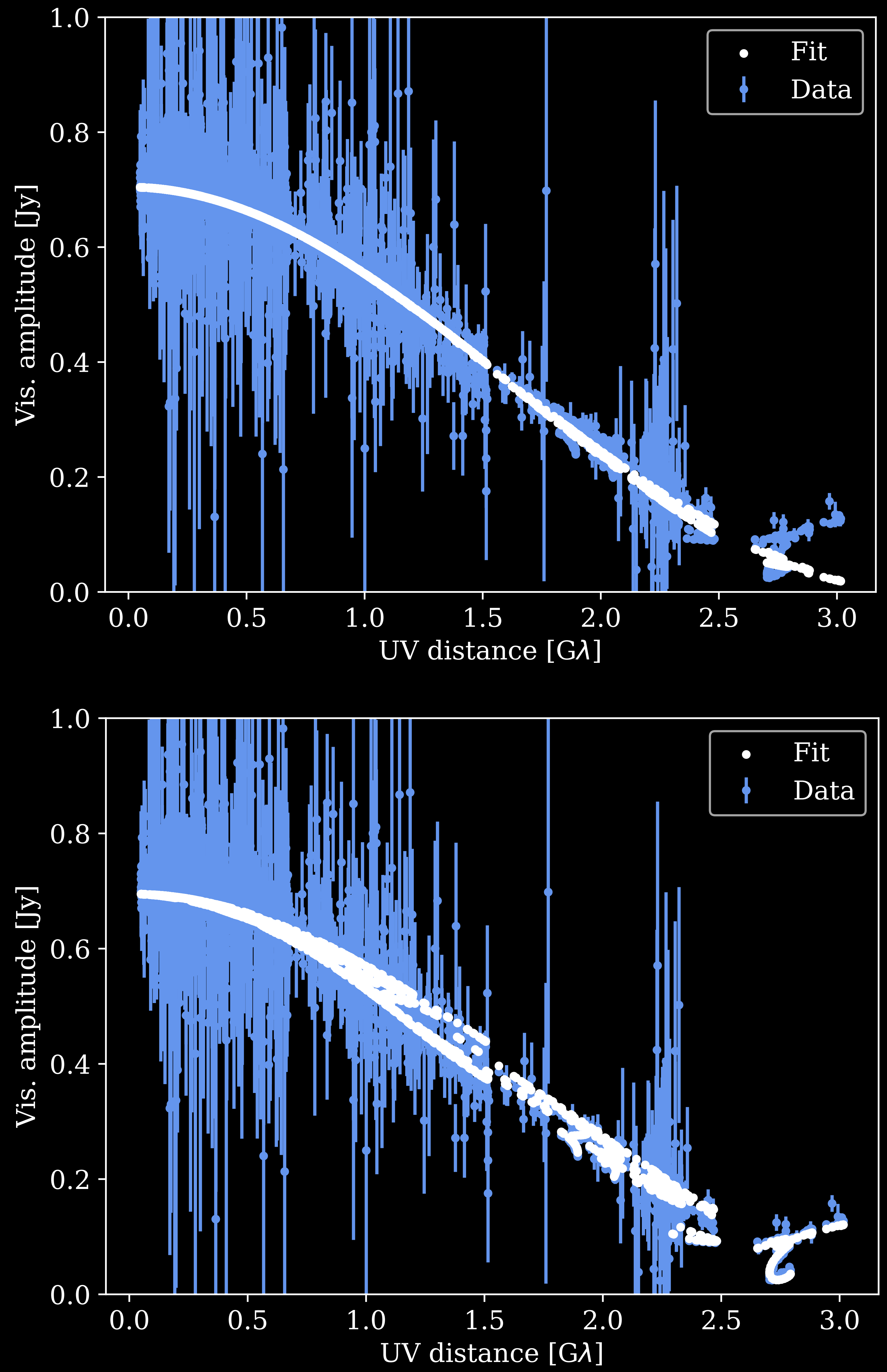

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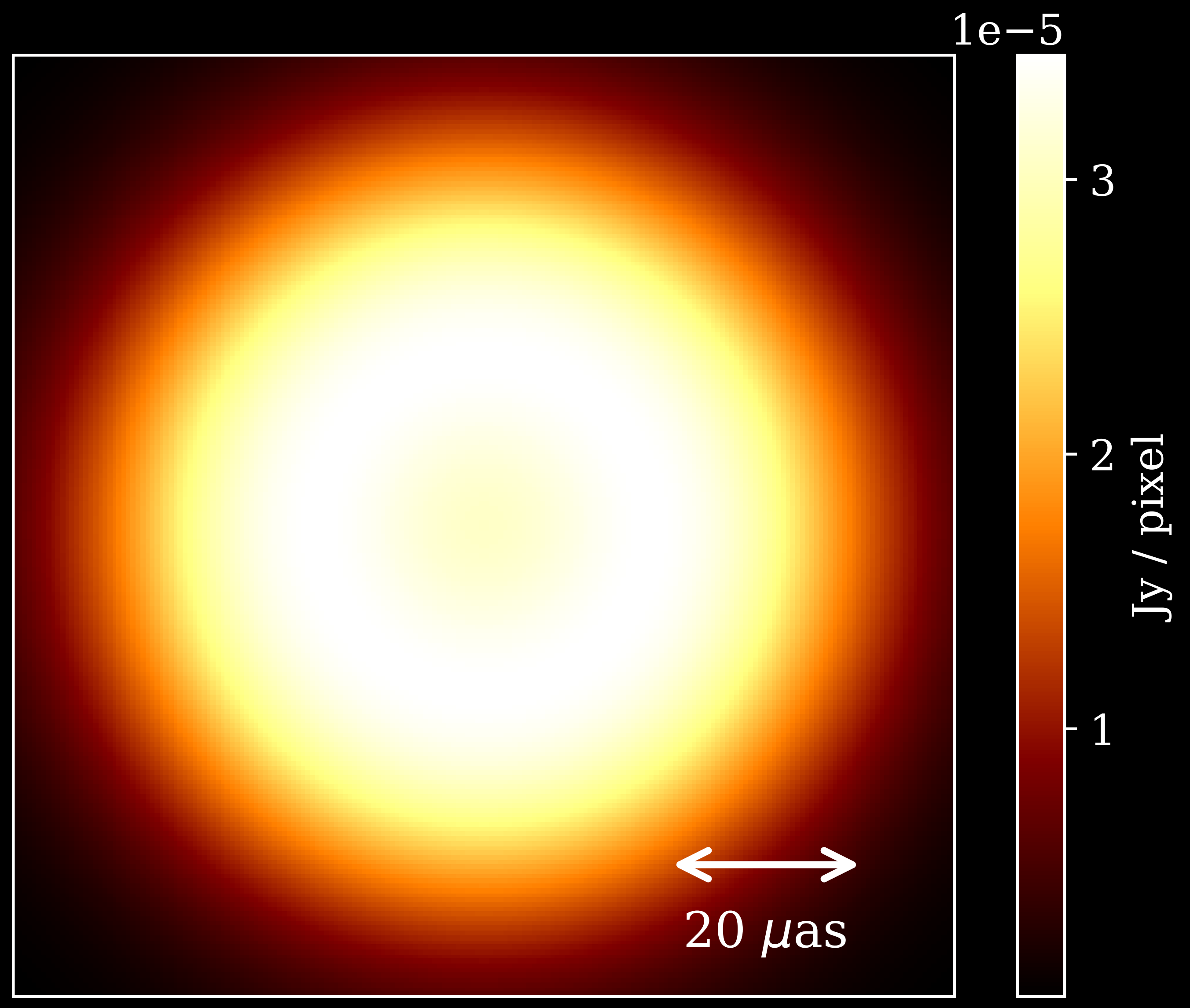
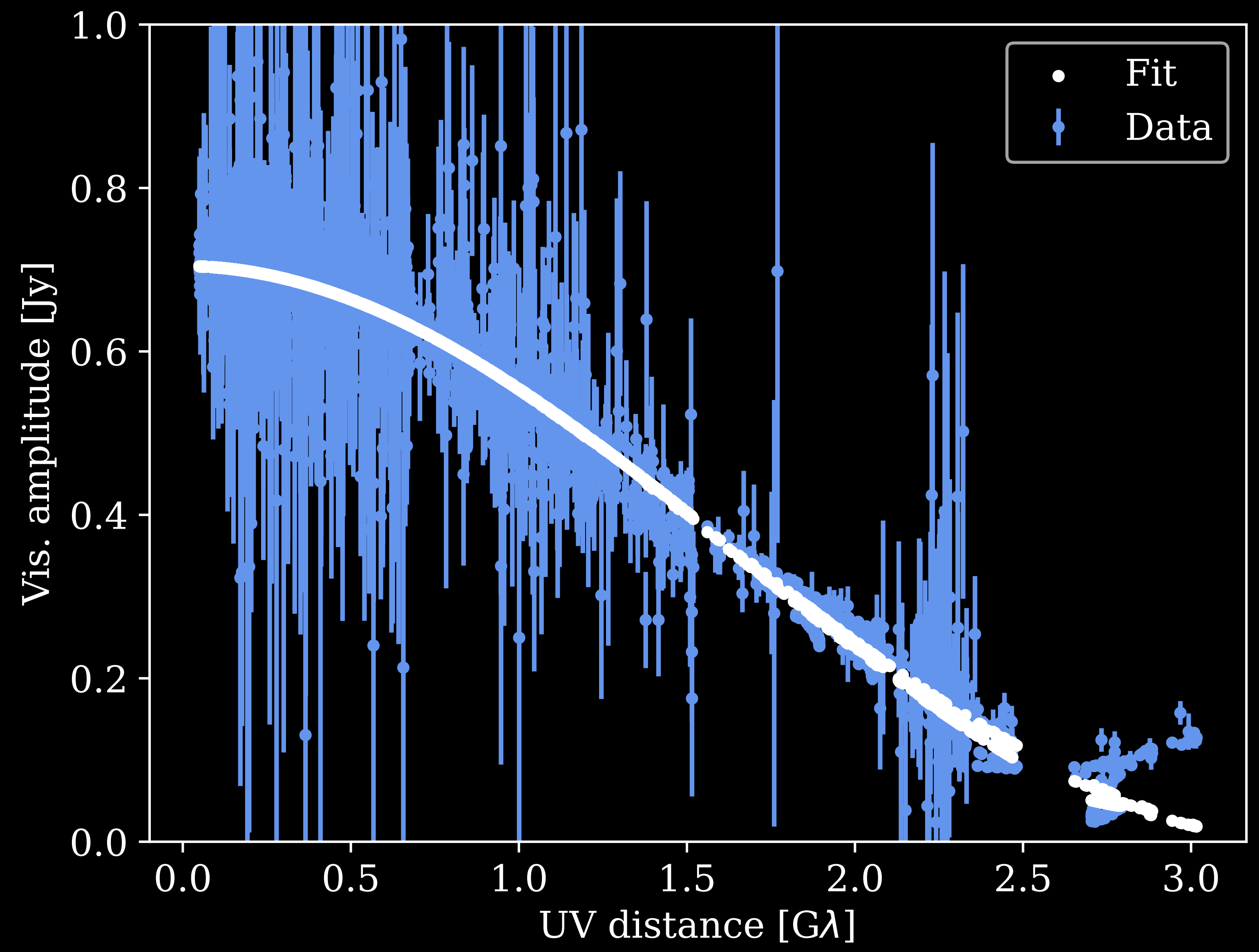
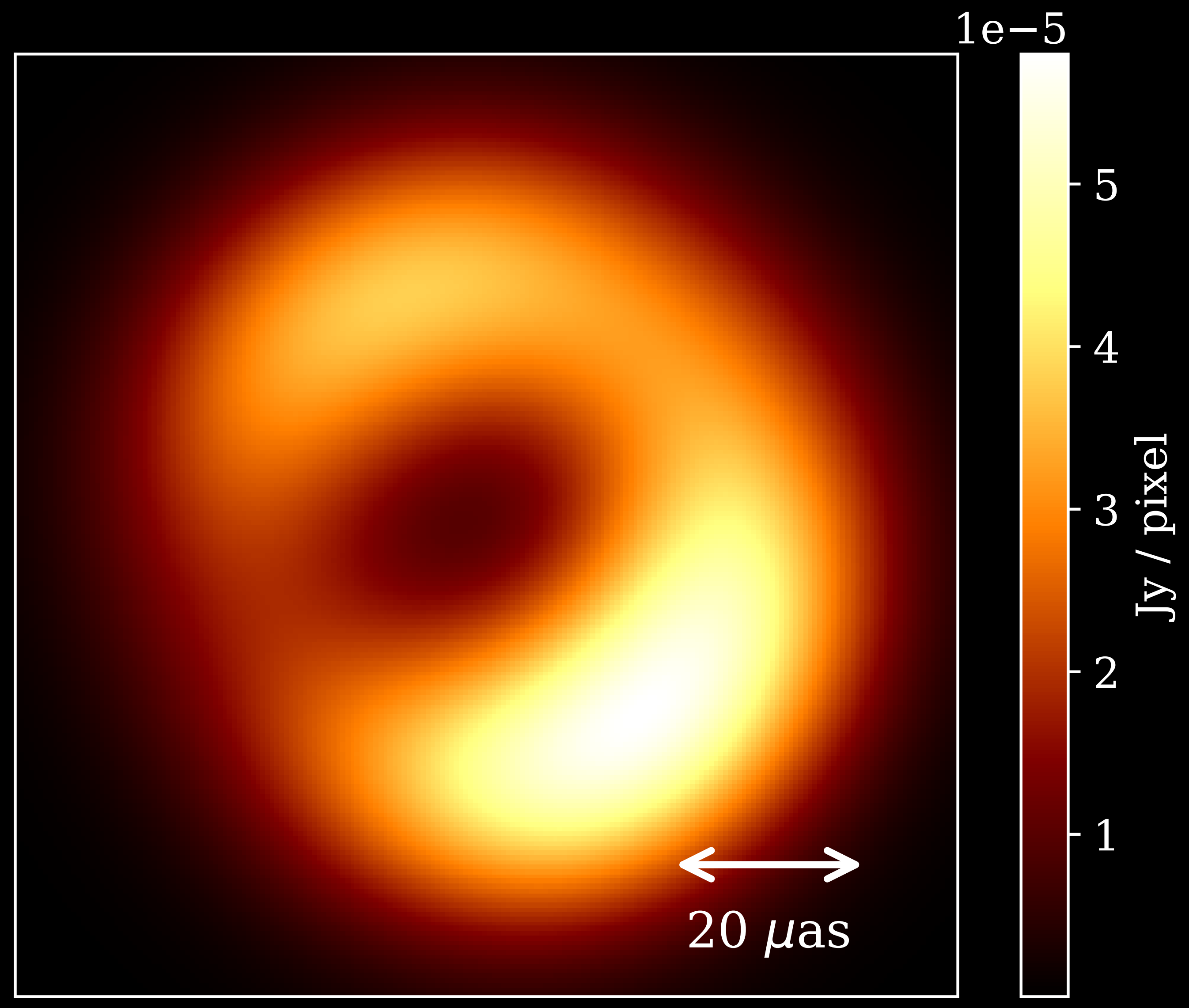
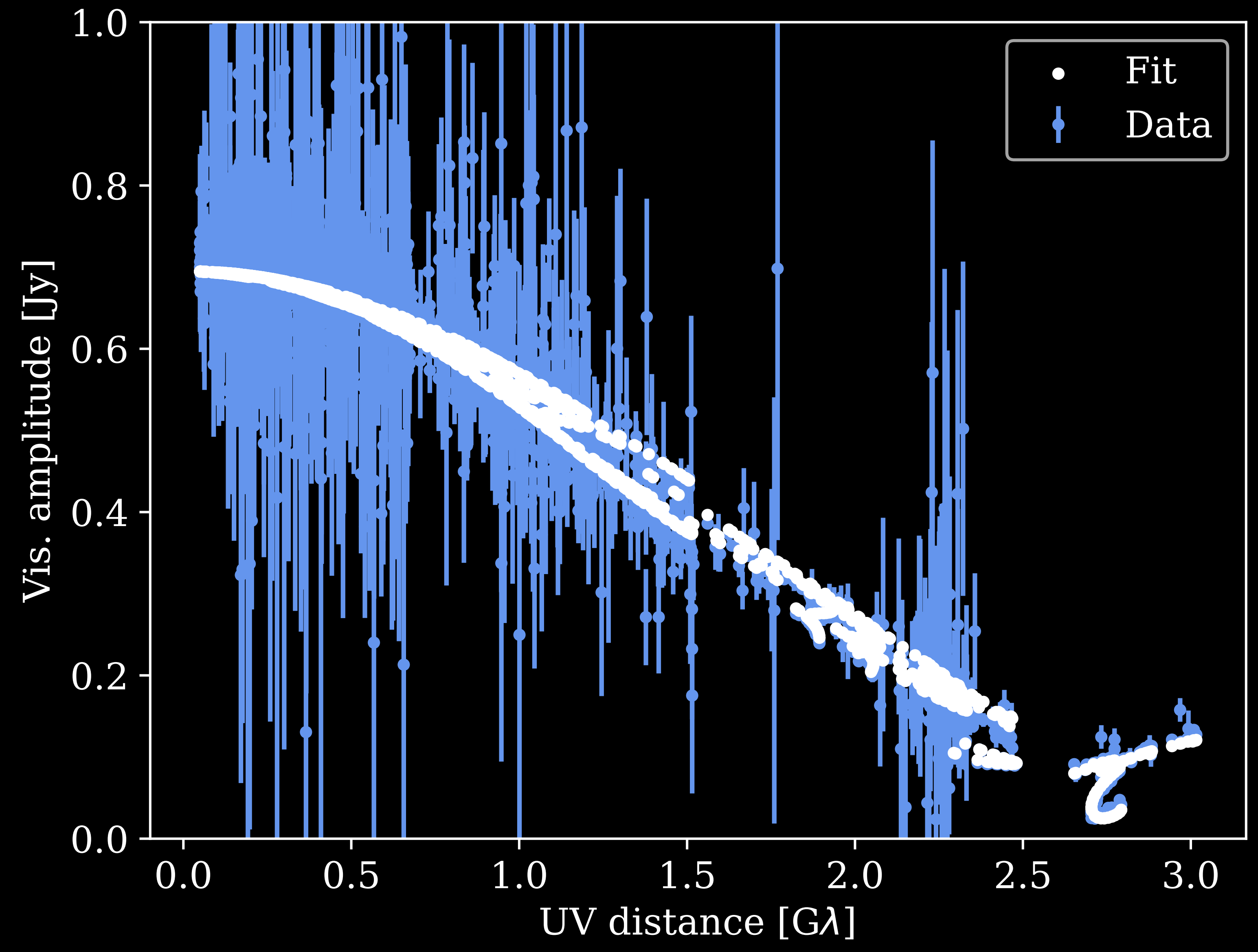


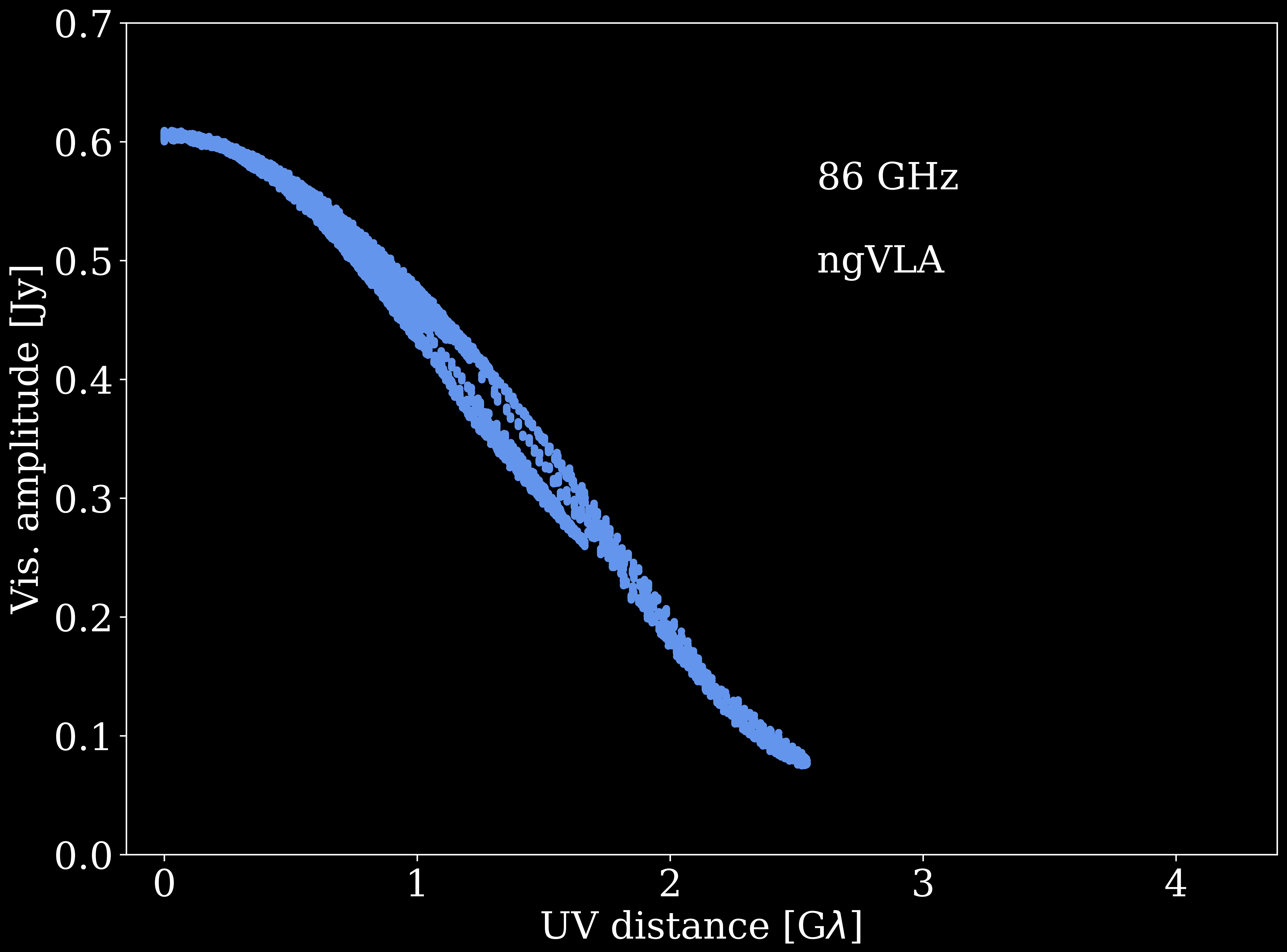






- More realistic approach: make synthetic data from real observations: M87 at 86 GHz by GMVA + ALMA + GLT
- Fitting a thick m-ring (no azimuthal symmetry) model to our data improves results compared to a symmetric thick ring
  - First and second null locations reveal ring diameter and thickness: missing second null

ngVLA and the morphology of M87



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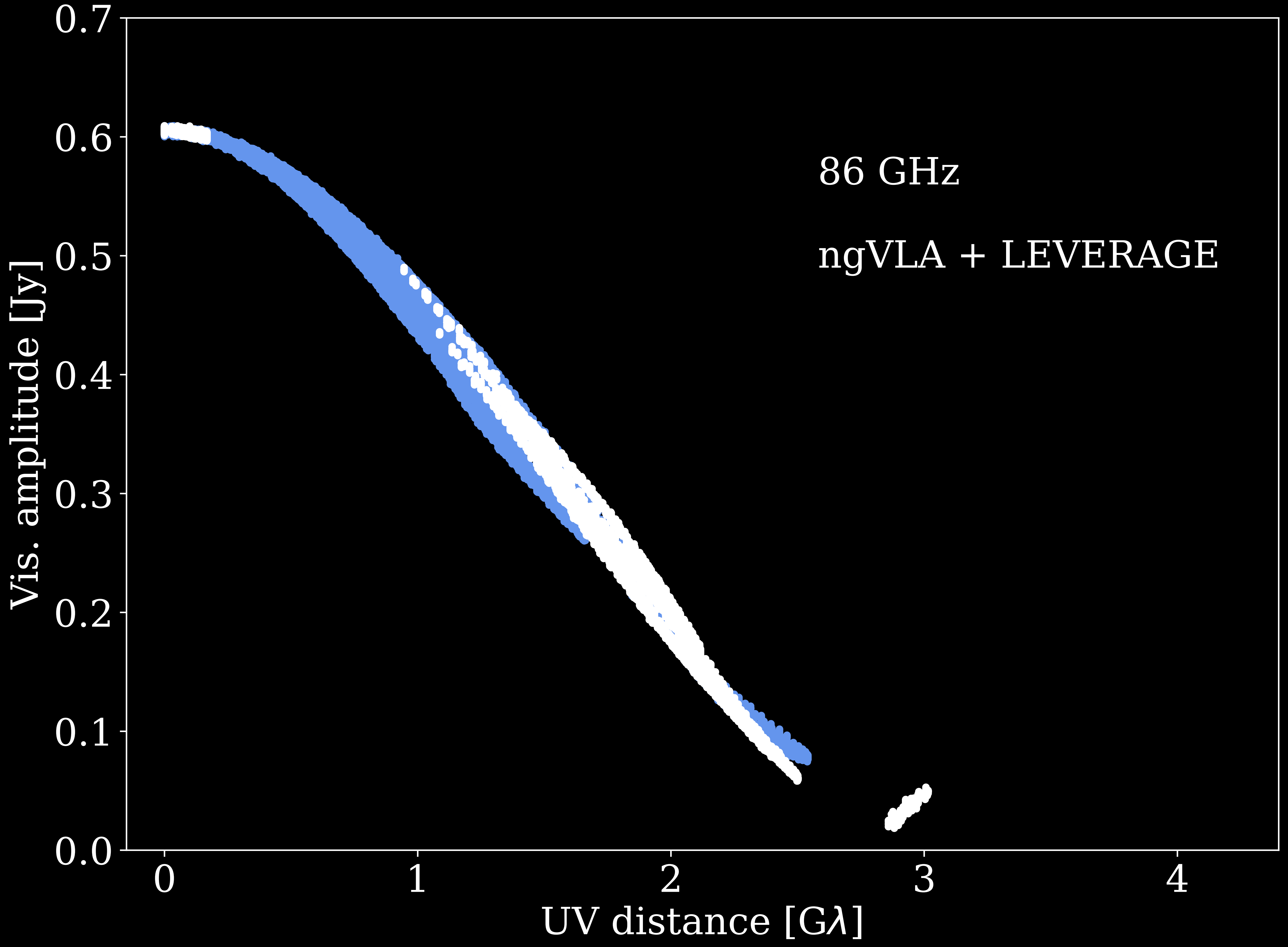

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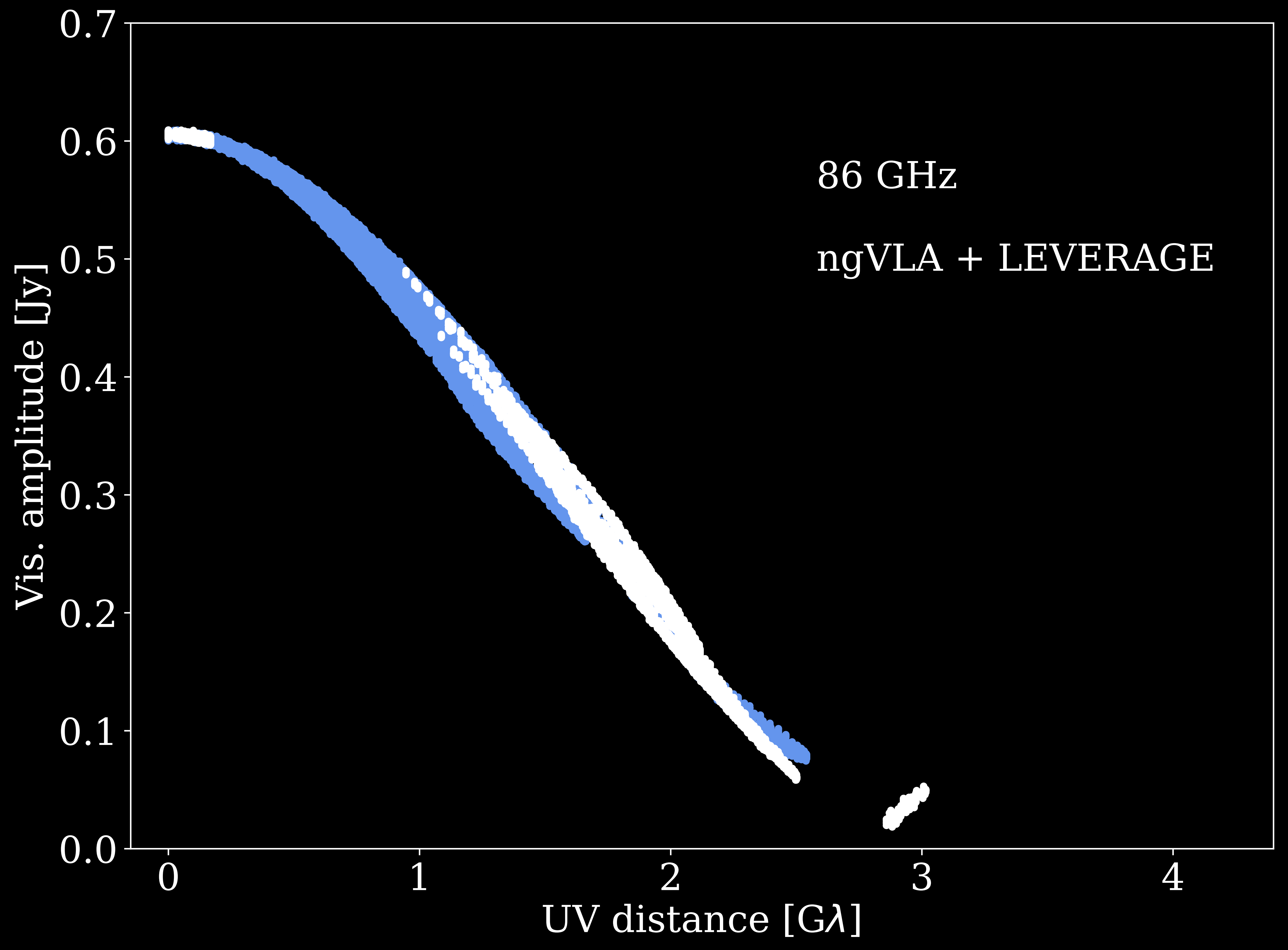
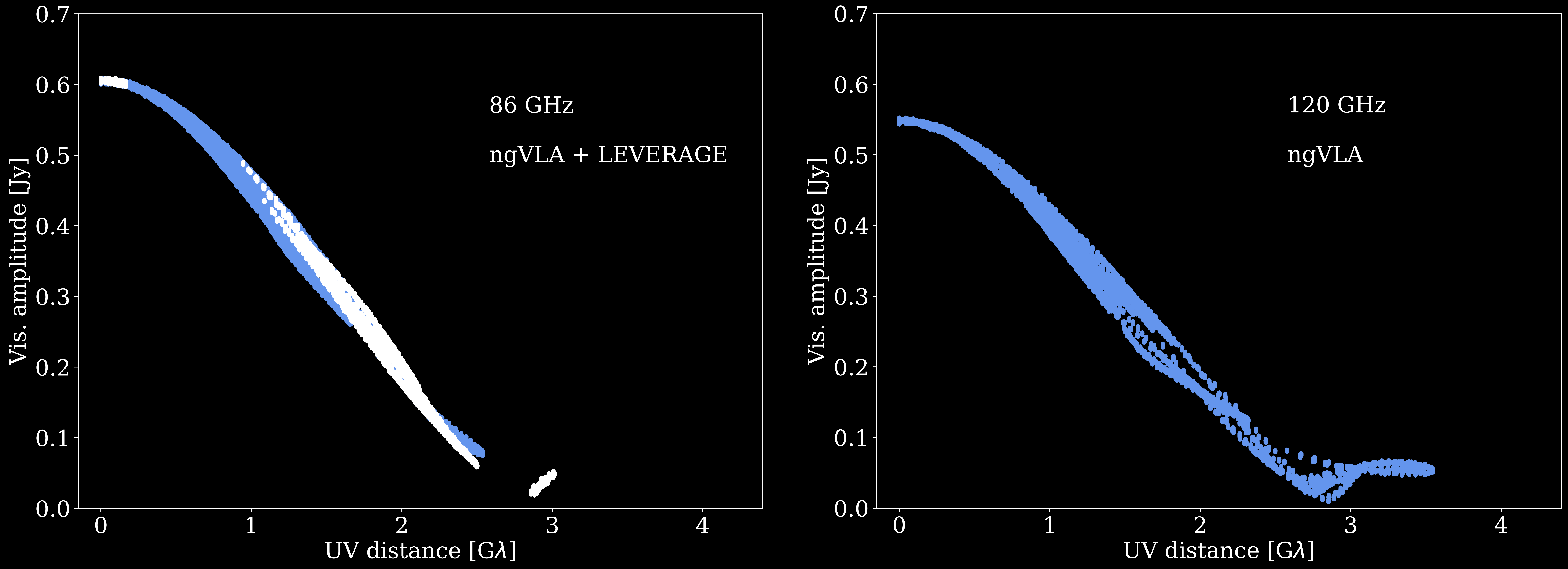


Band #	f_L GHz	f_M GHz	f_H GHz
1	1.2	2.0	3.5
2	3.5	6.6	12.3
3	12.3	15.9	20.5
4	20.5	26.4	34.0
5	30.5	39.2	50.5
6	70.0	90.1	116.0

ngVLA and the morphology of M87



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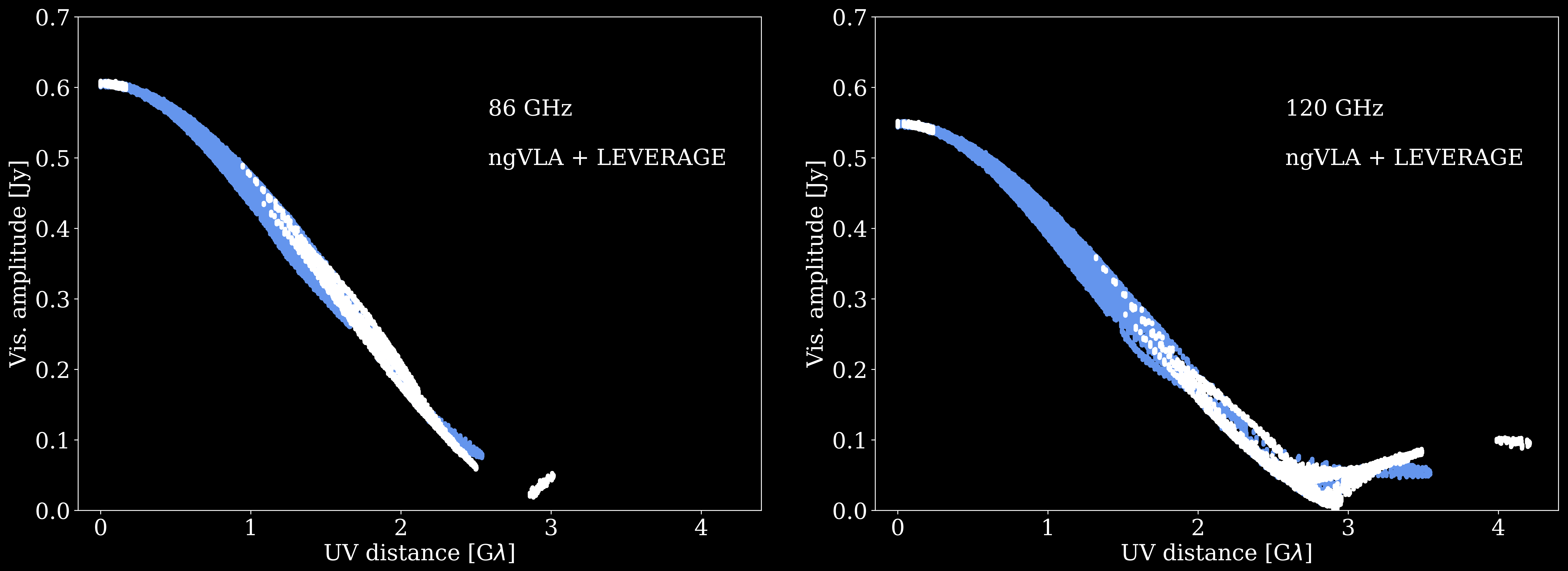
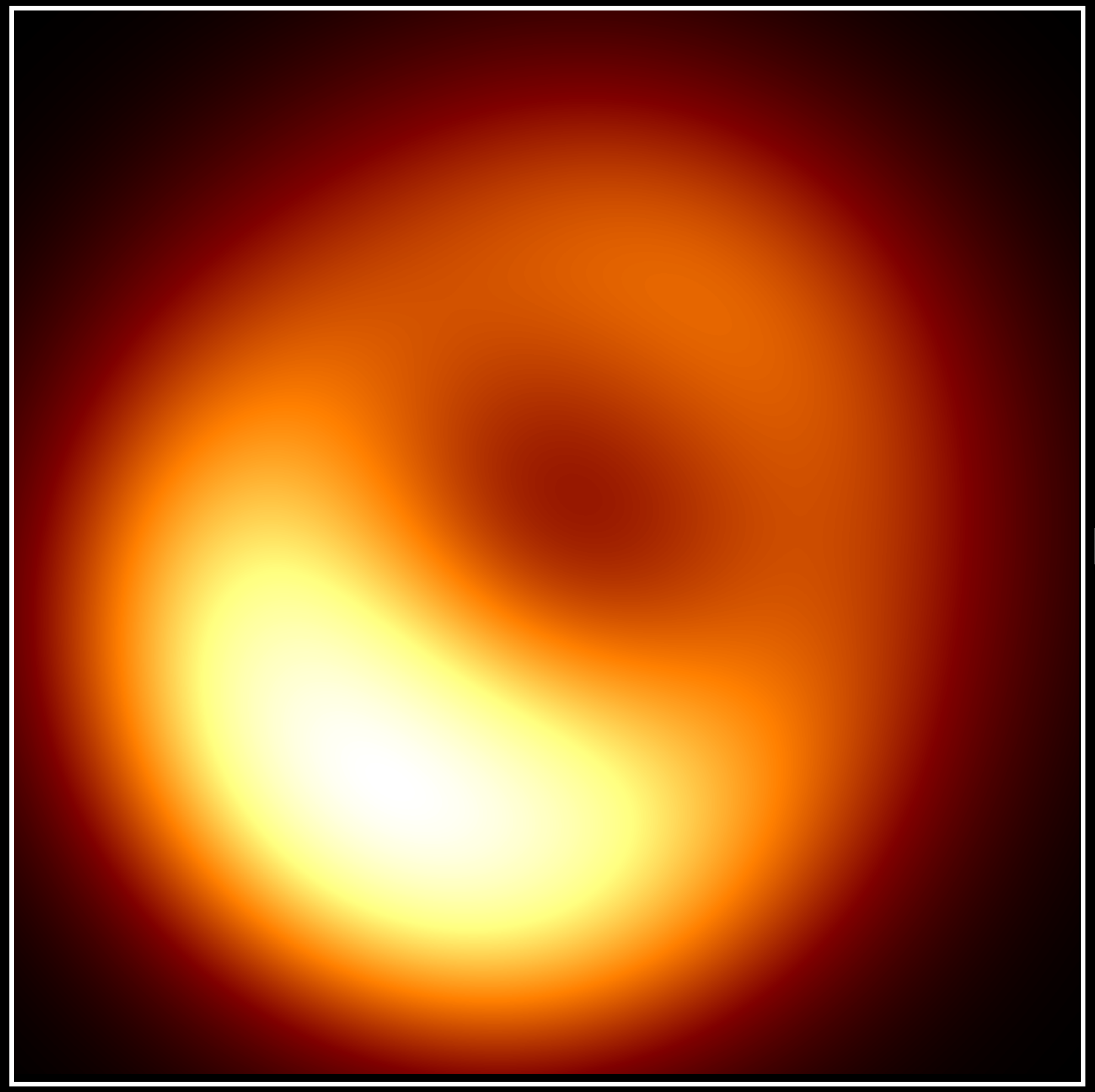


First null location clearly visible, second null location can be estimated with improved certainty

ngVLA and the morphology of M87

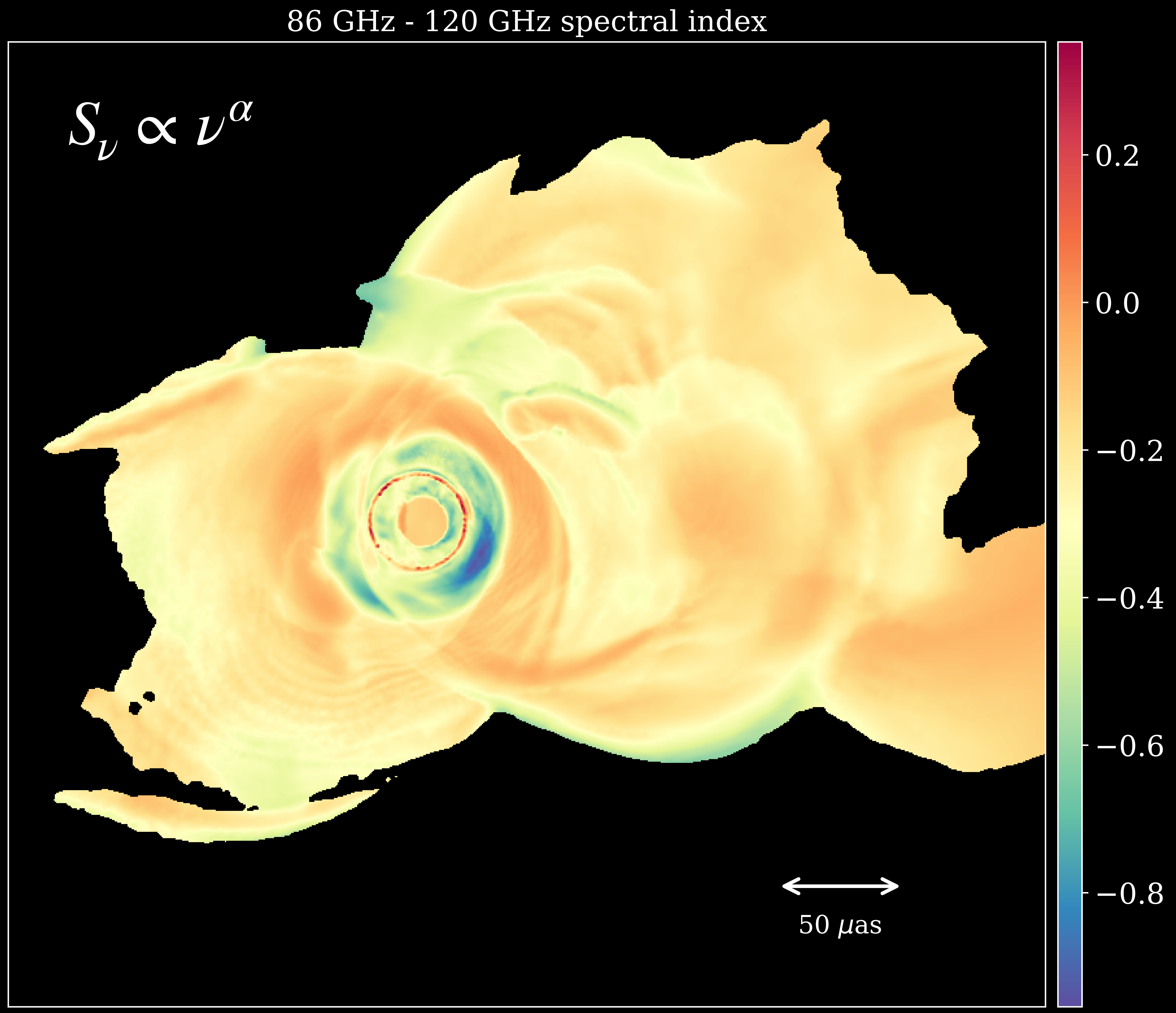


Model fit to our synthetic GMVA + ALMA + GLT data (86 GHz)

Model fit to our synthetic ngVLA + LEVERAGE data (86 GHz)

- Preliminary results show great improvement of our Bayesian fit to the data
- For some time steps (shown left), the quality of the posterior sampling, and thus the certainty of parameters such as the thickness, is improved
- For other time steps, these longer baselines are essential to correctly fit the asymmetric structure of the ring

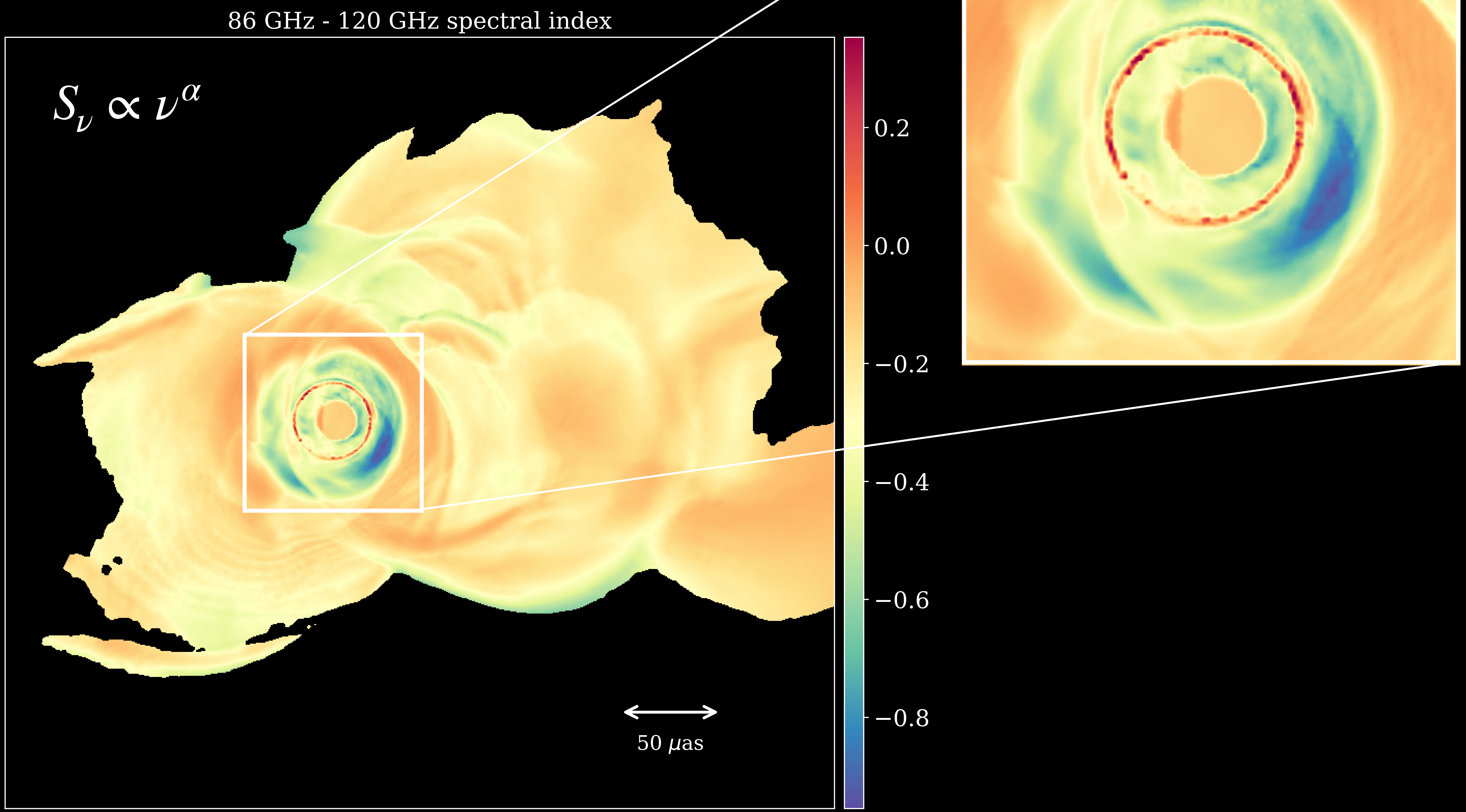
Spectral index



Flat at large scales

Transition zone in the horizon region

Spectral index



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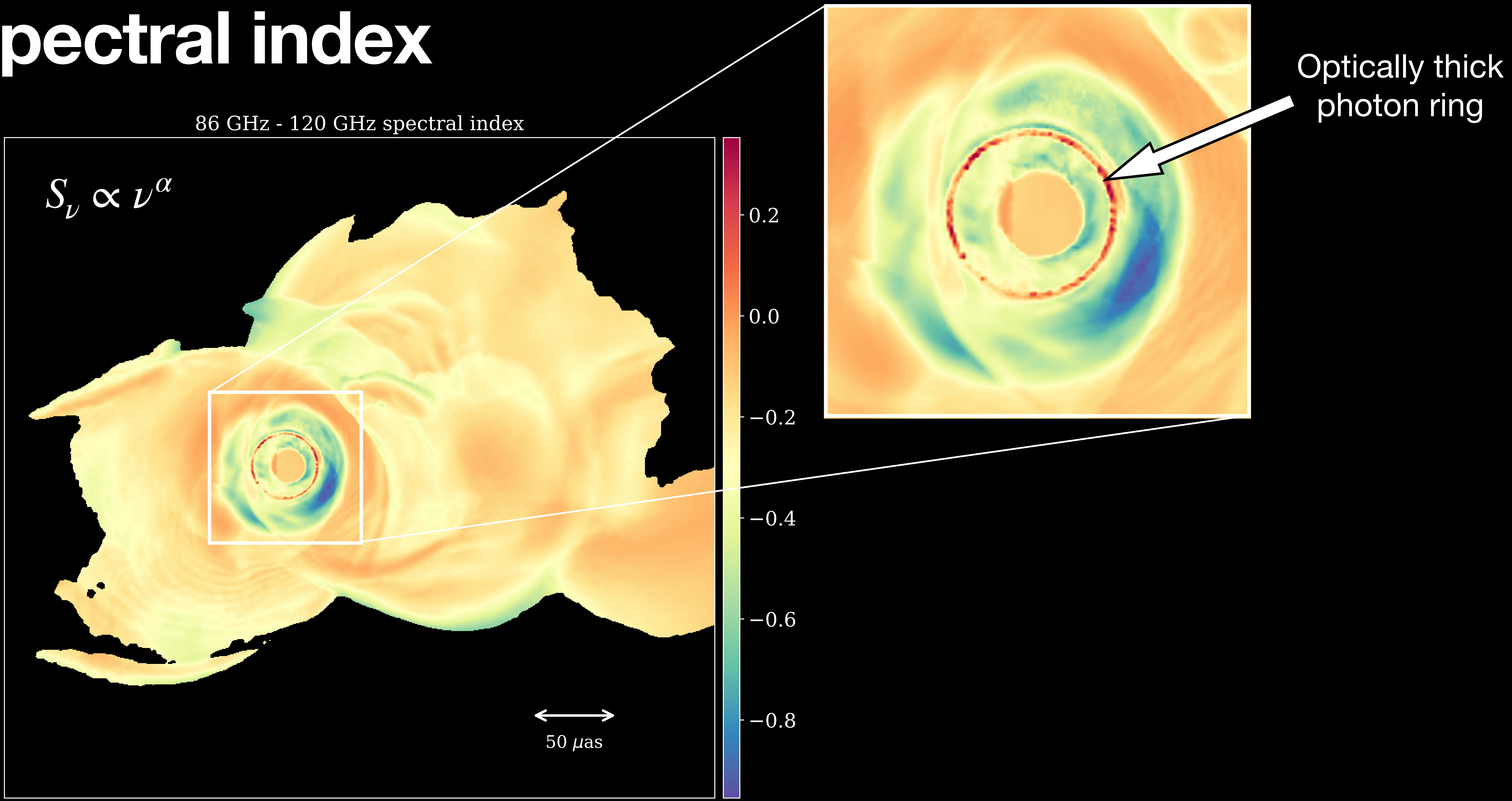
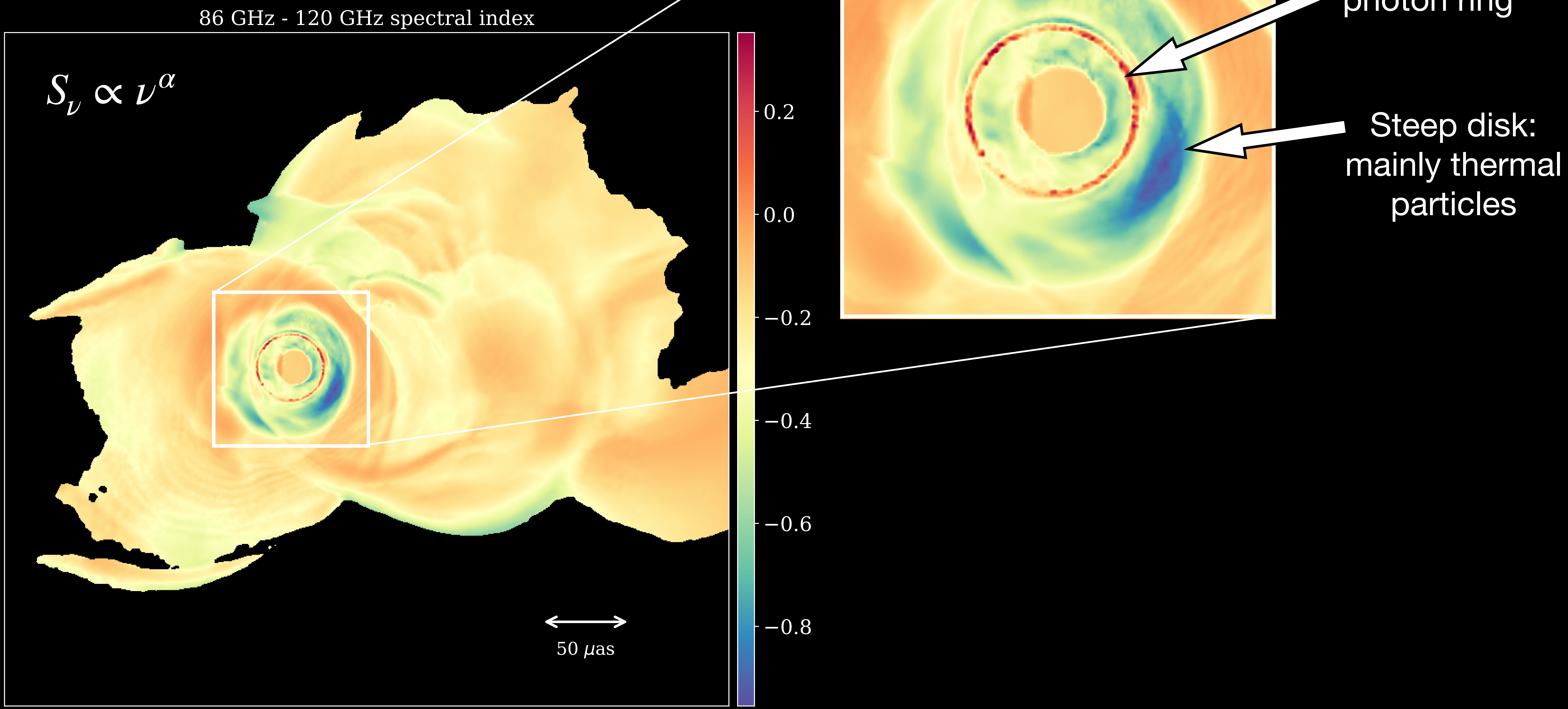


Spectral index



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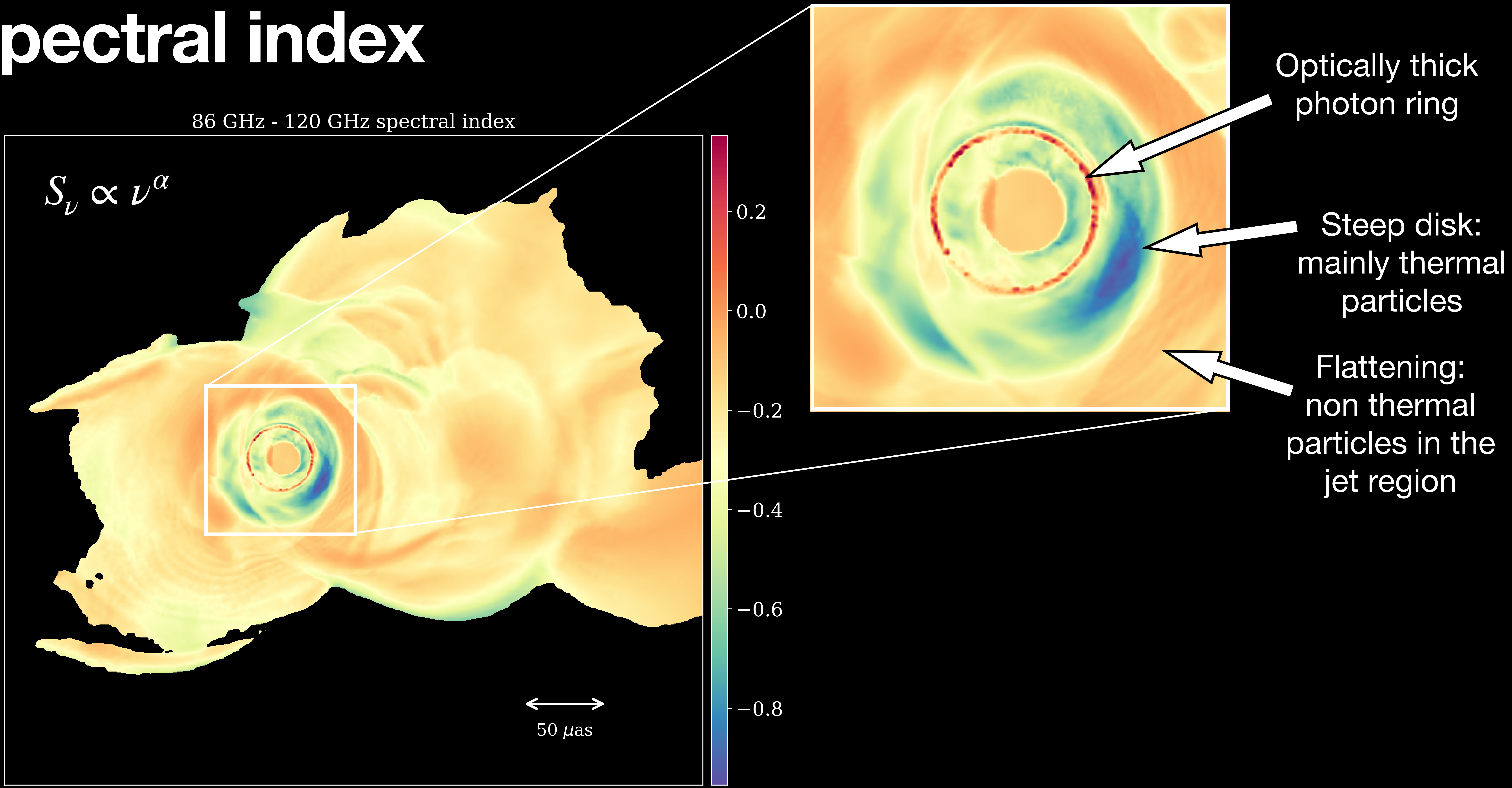

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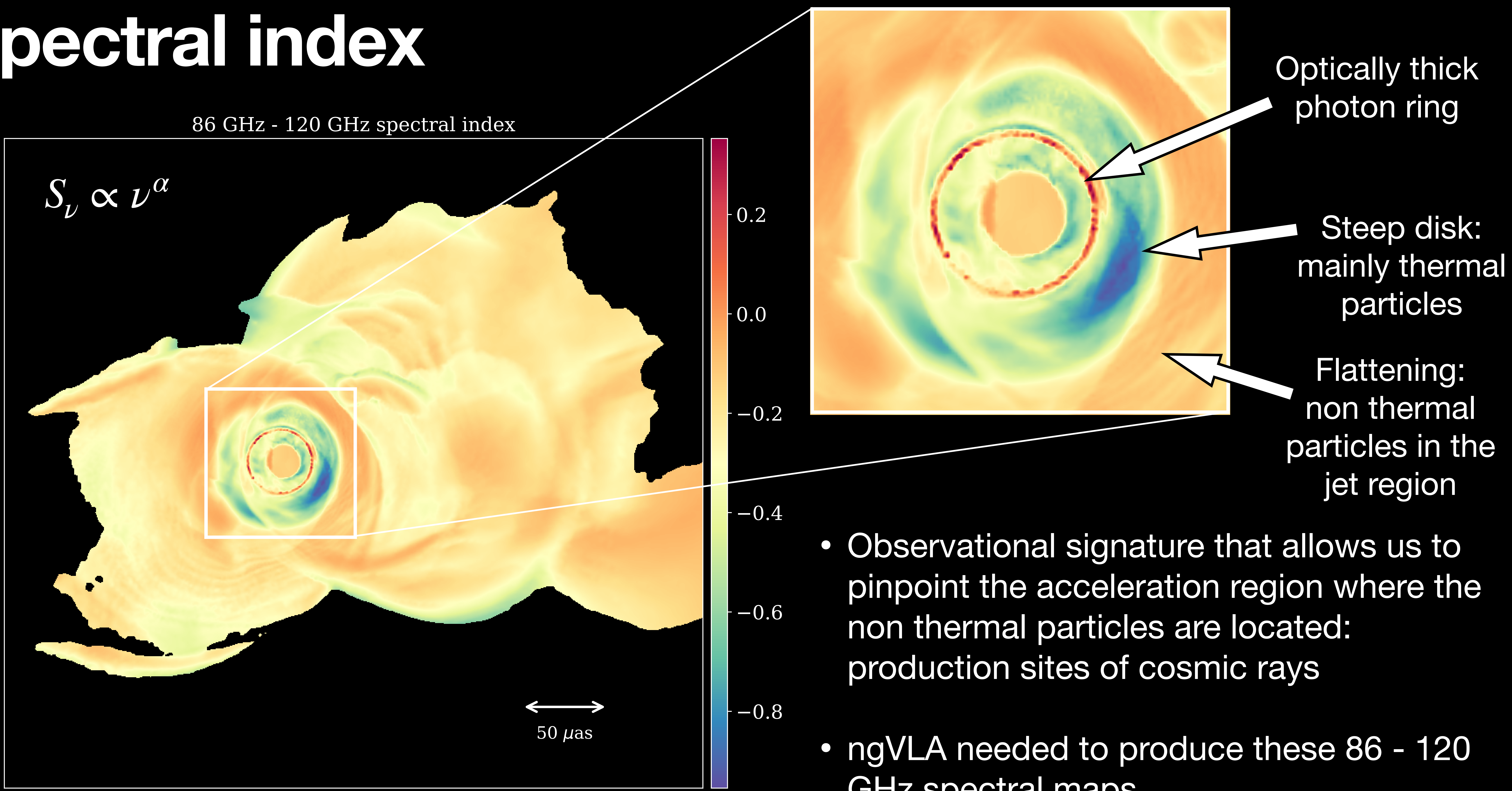
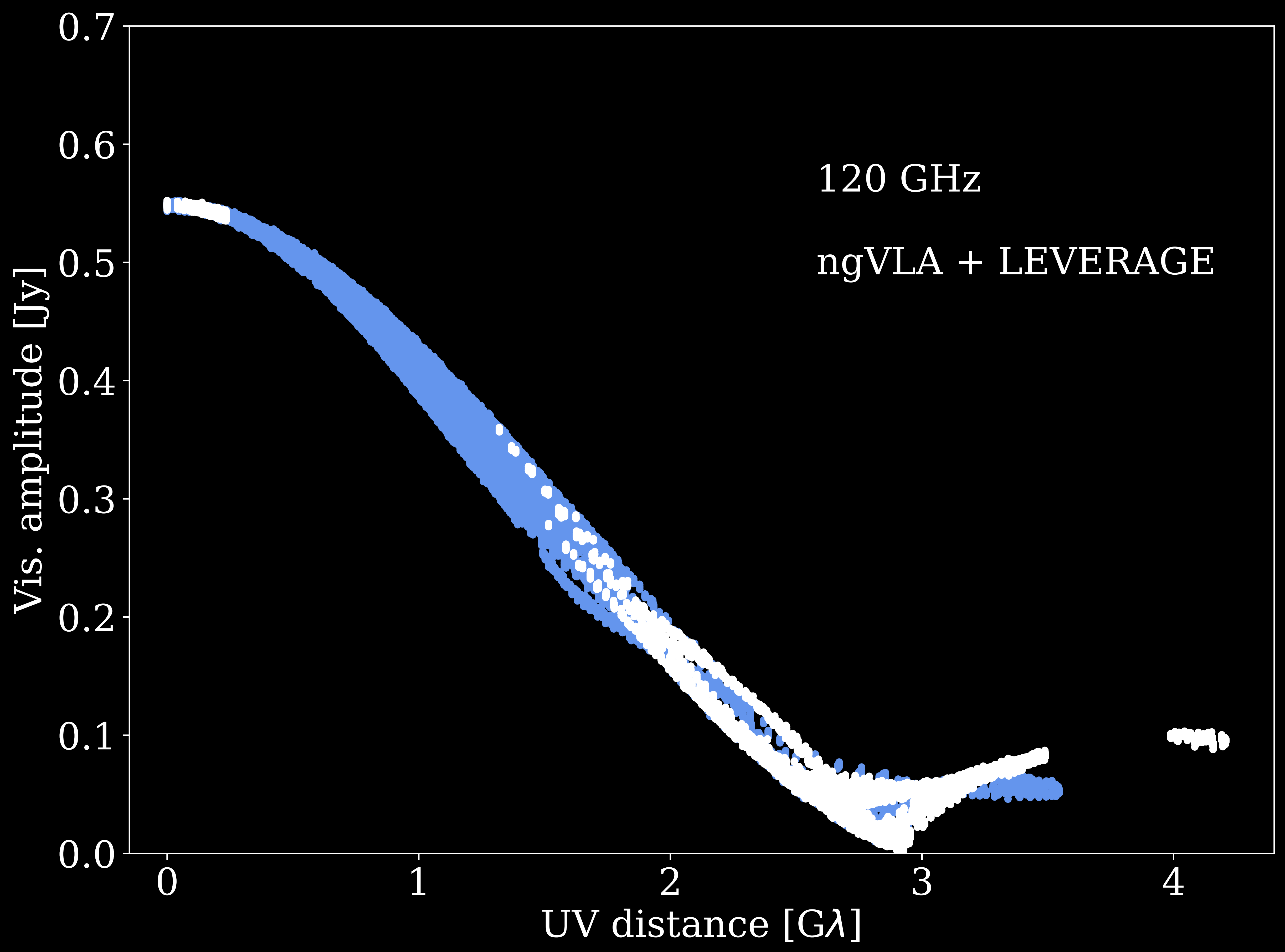


- Observational signature that allows us to pinpoint the acceleration region where the non thermal particles are located: production sites of cosmic rays

- ngVLA needed to produce these 86 - 120 GHz spectral maps

Conclusions

- The improved capabilities of the ngVLA will give us a clearer than ever before picture of the innermost morphology of the AGN of M87
- This improved resolution would allow us to probe the regions of particle injection and acceleration, painting a picture of the non thermal universe
- Future work: incorporating polarisation into our model



Thank you for your attention!

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SMBH spin

Flux	a_*	R_{low}	R_{high}	Summary
MAD	−0.94	1	160	fail
MAD	−0.94	10	1	fail
MAD	−0.94	10	10	fail
MAD	−0.94	10	20	fail
MAD	−0.94	10	40	fail
MAD	−0.94	10	80	fail
MAD	−0.94	10	160	**pass**
MAD	−0.5	1	1	fail
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MAD	0.0	10	1	fail
MAD	0.0	10	10	fail
MAD	0.0	10	20	fail
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MAD	0.0	10	80	fail
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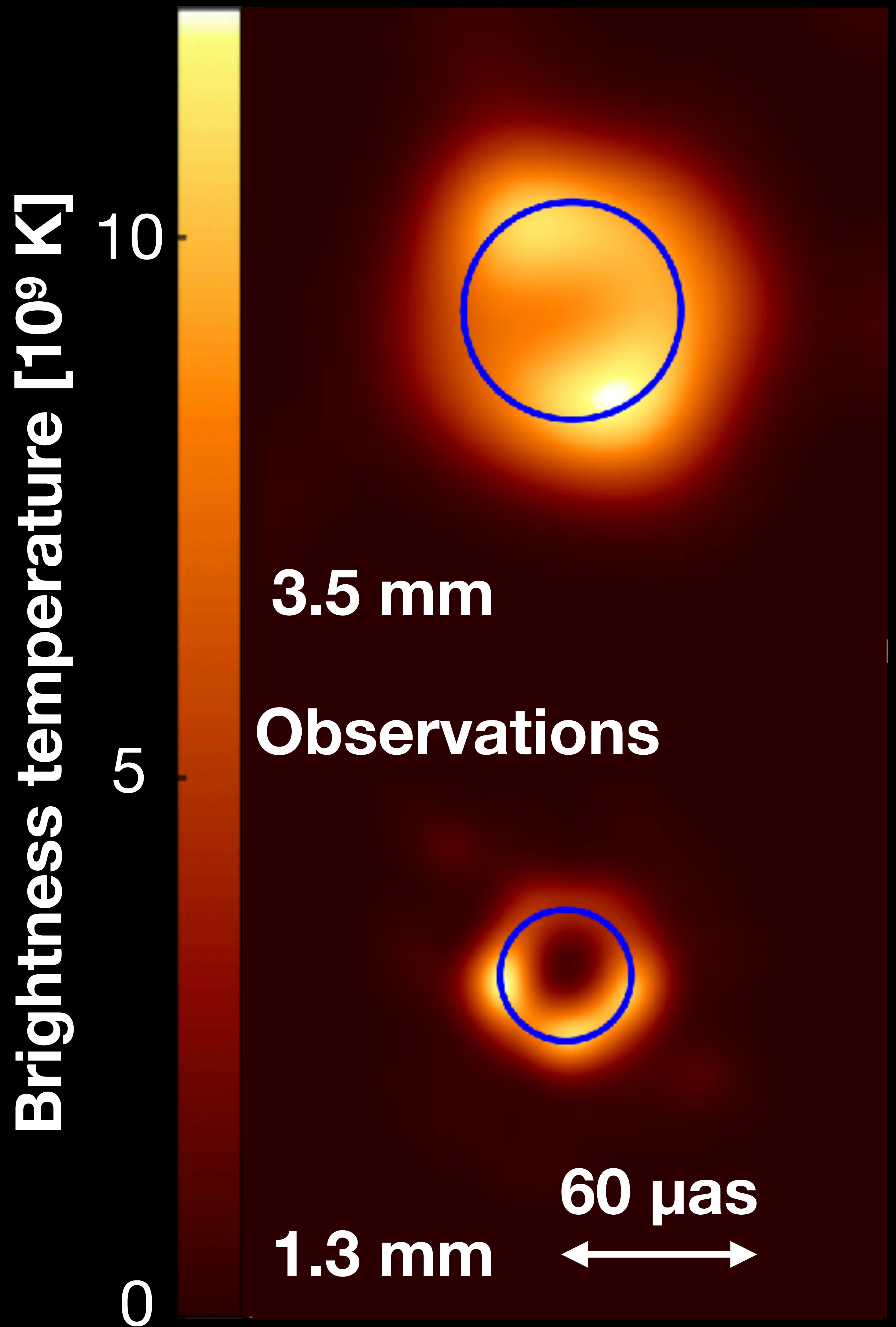
Cropped from
Akiyama, Kazunori, Juan Carlos Algaba, Antxon Alberdi, Walter Alef, Richard Anantua, Keiichi Asada, Rebecca Azulay et al. "First M87 event horizon telescope results. VIII. Magnetic field structure near the event horizon." *The Astrophysical Journal Letters* 910, no. 1 (2021): L13.

Emission modelling



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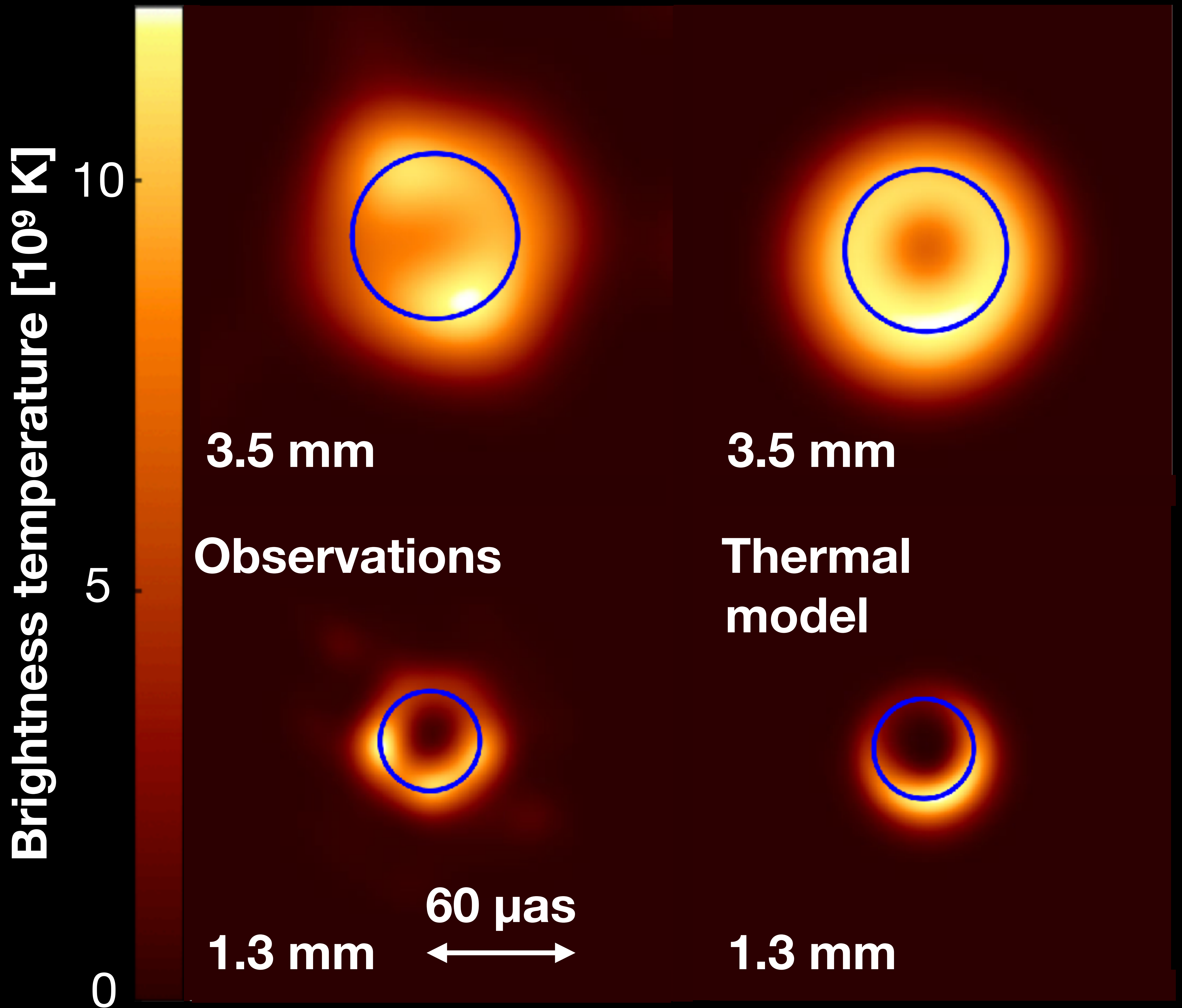

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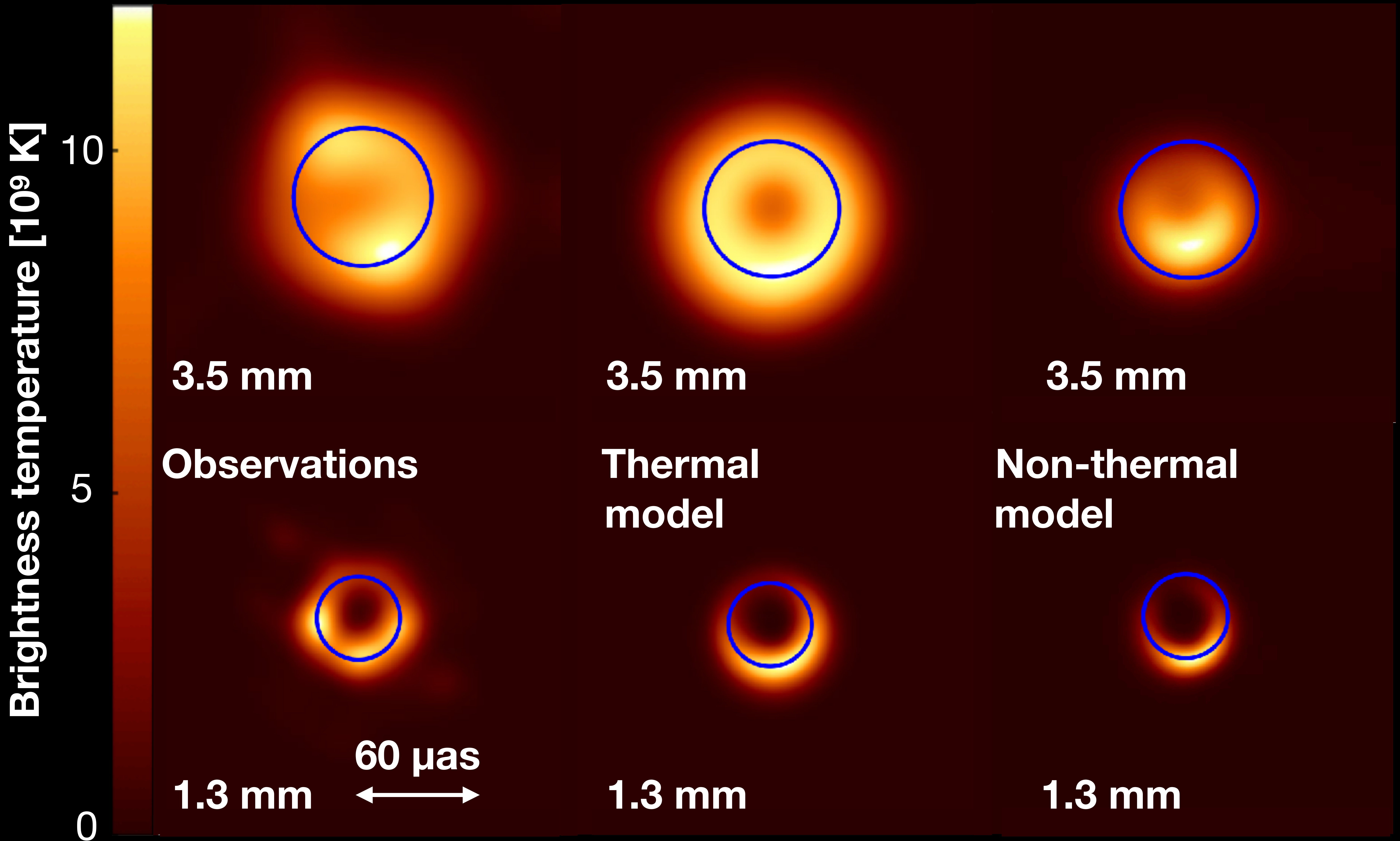

- Non-thermal model too small for 3.5 mm
- Black hole spin = 0.9

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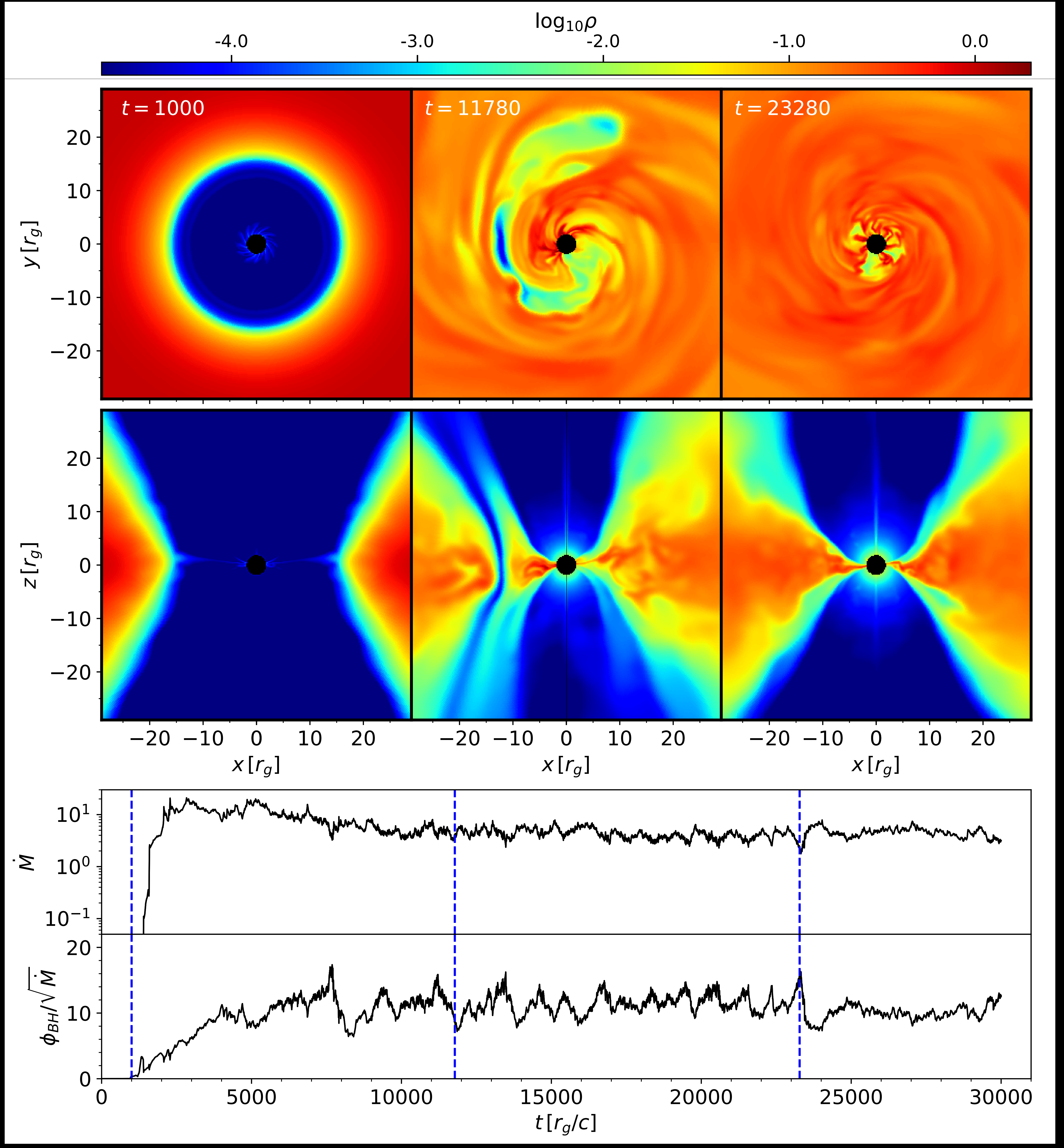
Our simulation - GRMHD

- 3D GRMHD code BHAC [1,2]
- MAD disk around a counterrotating black hole: a = -0.5
- From GRMHD quantities, description of the gas:

Plasma magnetisation	$\sigma = b^2/\rho$
Plasma beta	$\beta = p/b^2$
Gas temperature	$T = p/\rho$
Lorentz factor	Γ

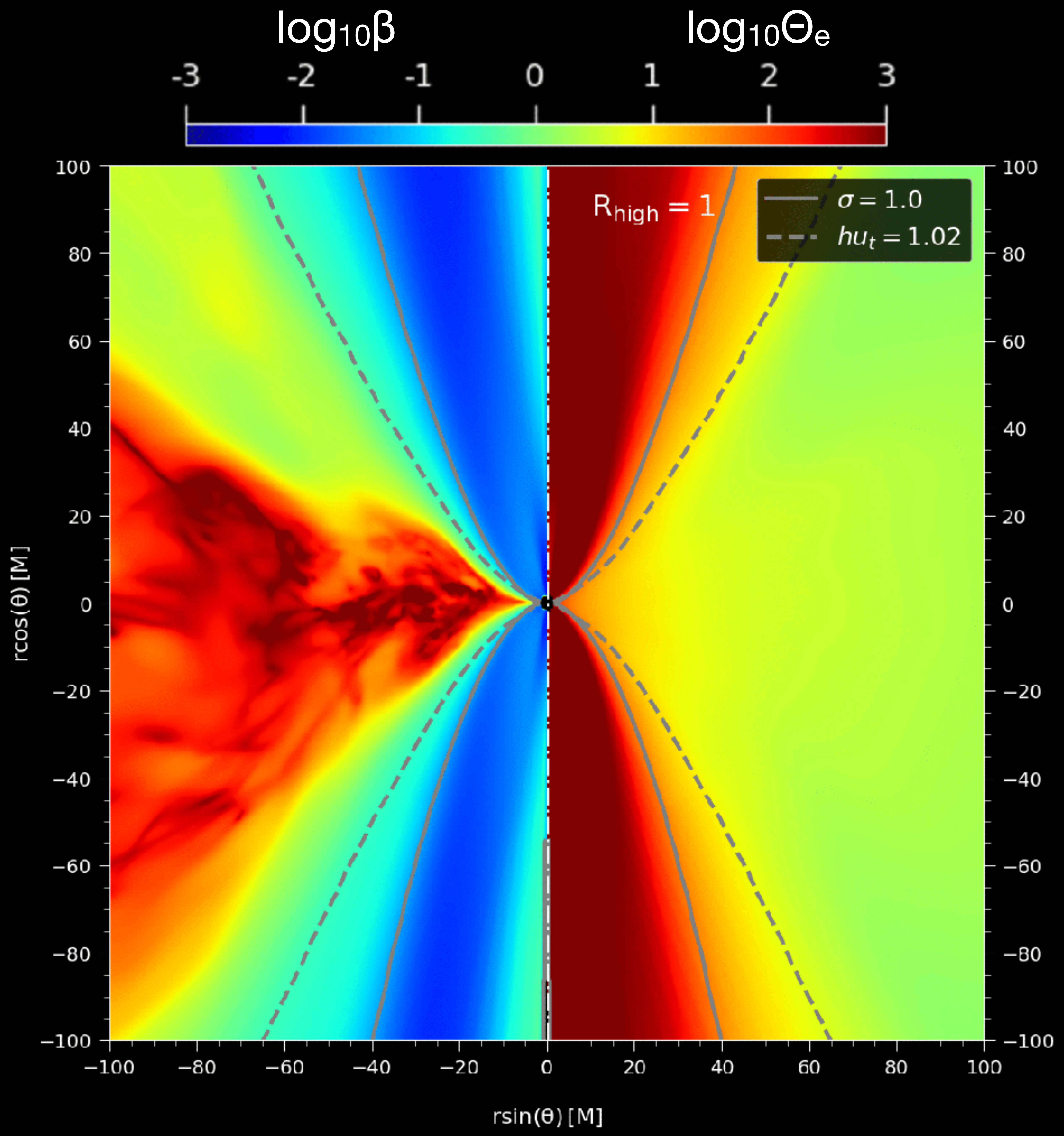


1. Porth, O., Olivares, H., Mizuno, Y., Younsi, Z., Rezzolla, L., Moscibrodzka, M., Falcke, H., Kramer, M. (2017). The Black Hole Accretion Code. Computational Astrophysics and Cosmology, 4(1), 1. https://doi.org/10.1186/s40668-017-0020-2

2. Olivares, H., Porth, O., Davelaar, J., Most, E. R., Fromm, C. M., Mizuno, Y., Younsi, Z., Rezzolla, L. (2019). Constrained transport and adaptive mesh refinement in the Black Hole Accretion Code. Astronomy & Astrophysics, 629, A61. https://doi.org/10.1051/0004-6361/201935559

Our simulation - GRRT

- Radiative transfer equations solved with GRRT code BHOSS [1]



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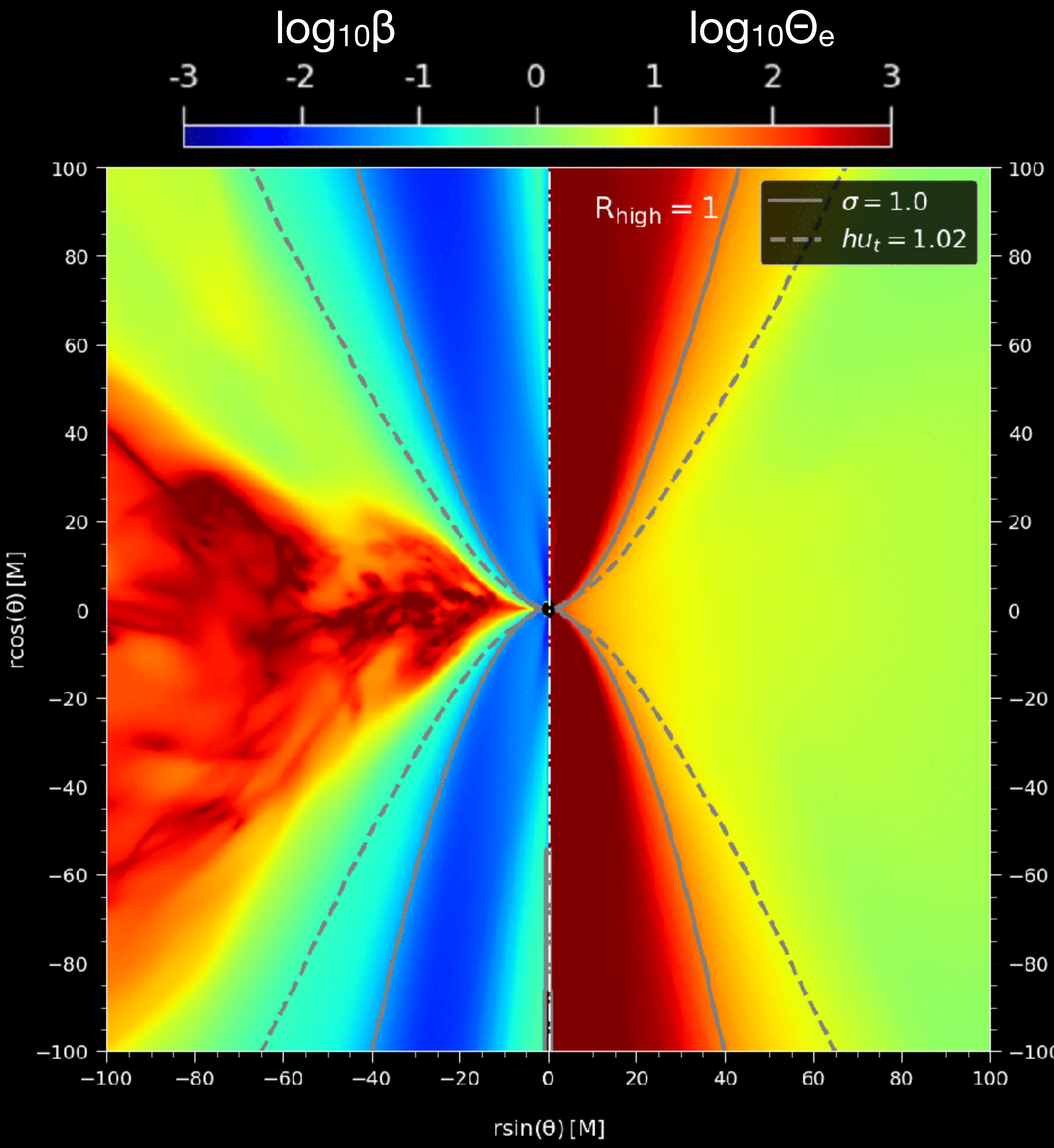
$$\frac{T_{\rm p}}{T_{\rm e}} = \frac{R_{\rm low} + \beta^2 R_{\rm high}}{1+\beta^2}, \quad \Theta_{\rm e} = \frac{p m_{\rm p}/m_{\rm e}}{\rho T_{\rm ratio}}$$



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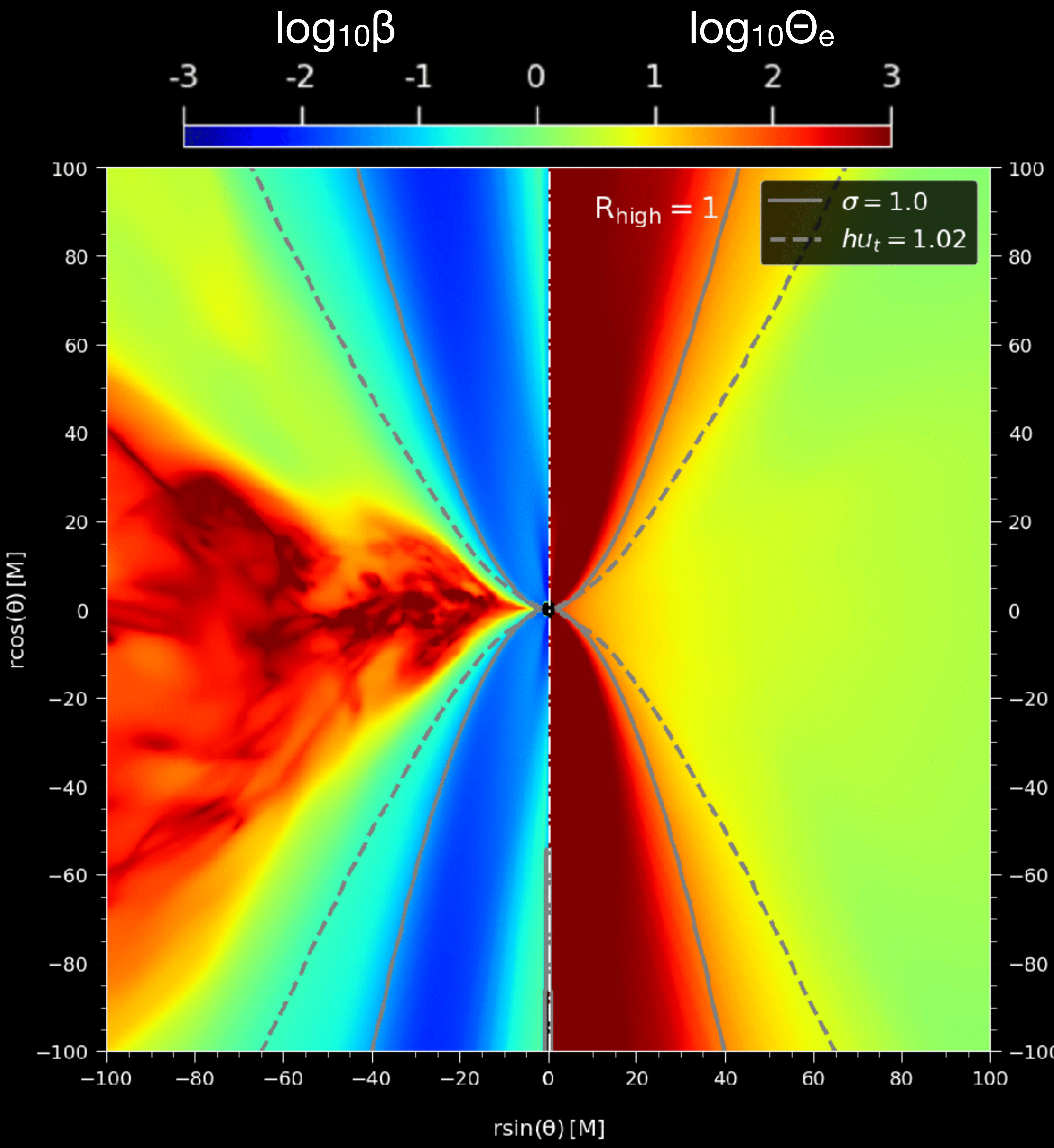

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Our simulation - GRRT

- Mix of thermal (Maxwell-Jüttner) and non-thermal (kappa) distributions; κ computed via particle-in-cell recipes

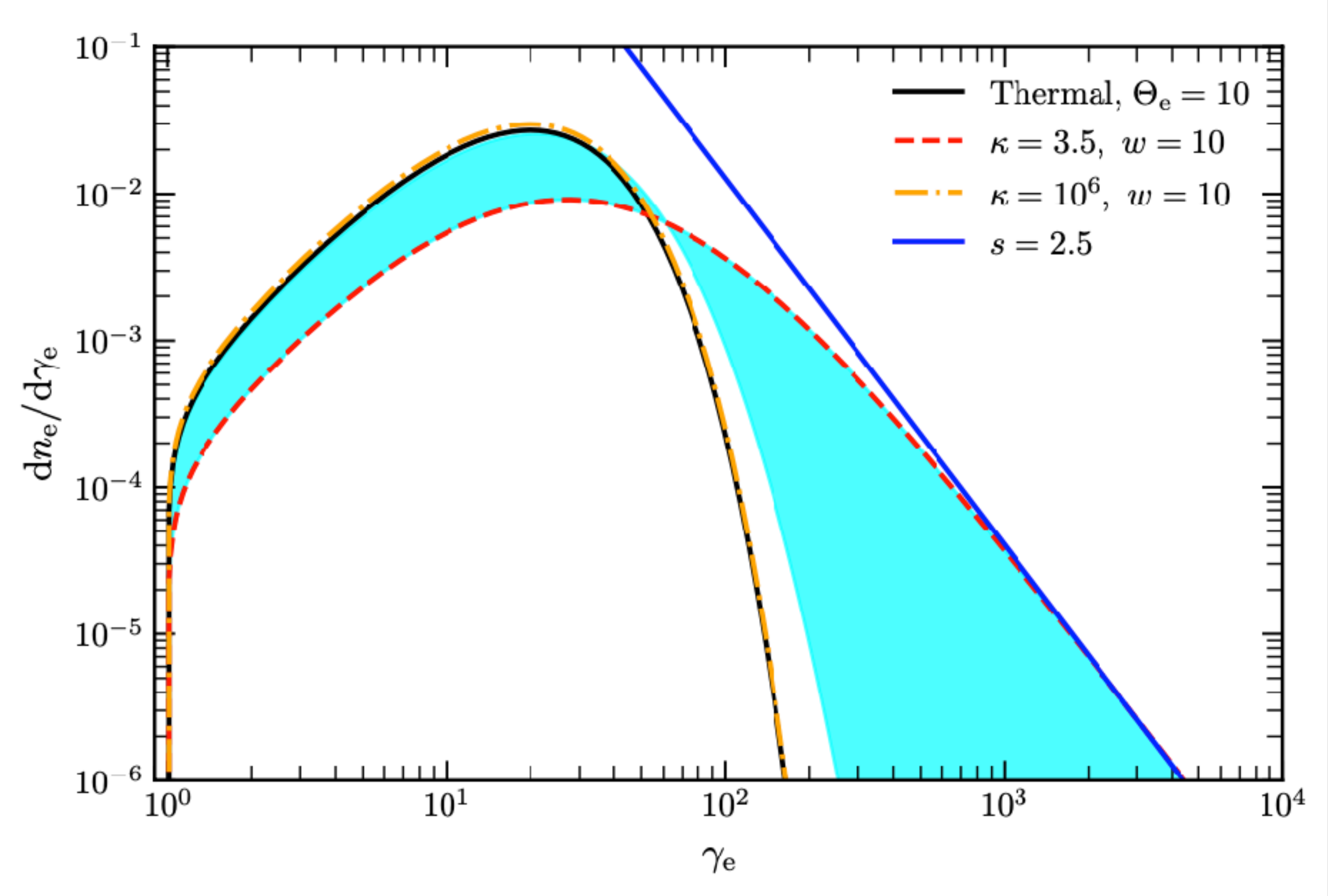
$$\kappa = 2.8 + 0.7\sigma^{-1/2} + 3.7\sigma^{-0.19}\tanh\left(23.4\sigma^{0.26}\beta\right)$$ [1]

$$w = \frac{\kappa - 3}{\kappa}\Theta_{\rm e} + \frac{\epsilon}{2}\left[1 + \tanh\left(r - r_{\rm inj}\right)\right]\frac{\kappa - 3}{6\kappa}\frac{m_{\rm p}}{m_{\rm e}}\sigma$$

- Mixed efficiency model for the emissivity and absorptivity coefficients

$$\tilde{\epsilon} = \epsilon_{\rm eff}\left[1 - e^{-1/\beta^2}\right]\left[1 - e^{-\left(\sigma/\sigma_{\rm min}\right)^2}\right]$$

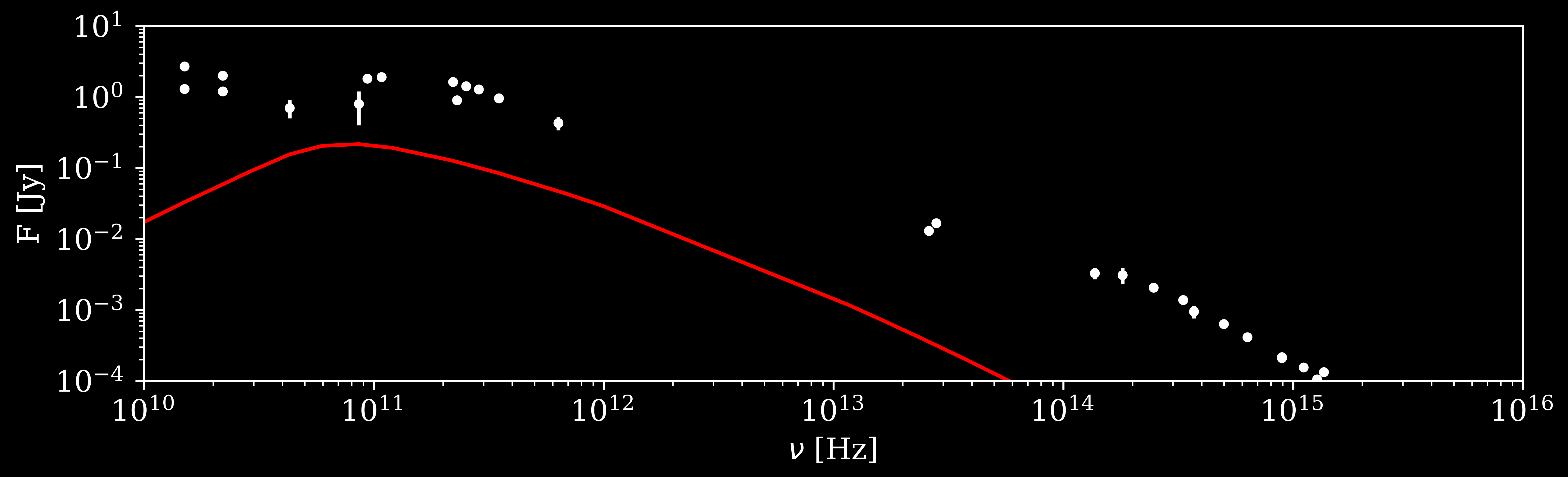
$$j_{\nu,tot} = (1 - \tilde{\epsilon})j_{\nu,thermal} + \tilde{\epsilon}j_{\nu,\kappa}$$



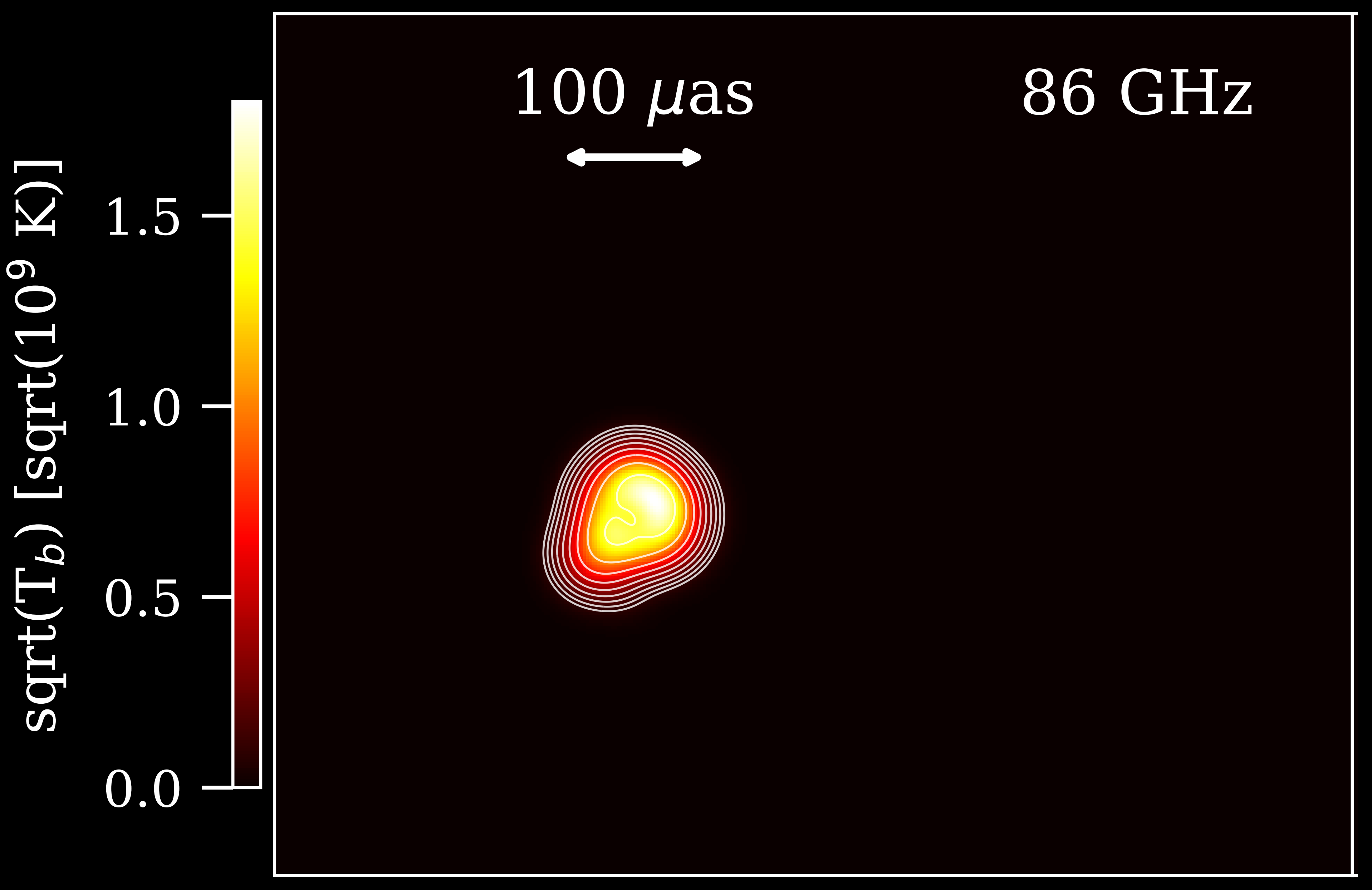
Fromm, Christian M., et al. "Impact of non-thermal particles on the spectral and structural properties of M87." Astronomy & Astrophysics 660 (2022): A107.

1. Ball, David, Lorenzo Sironi, and Feryal Özel. "Electron and proton acceleration in trans-relativistic magnetic reconnection: dependence on plasma beta and magnetization." *The Astrophysical Journal* 862, no. 1 (2018): 80.

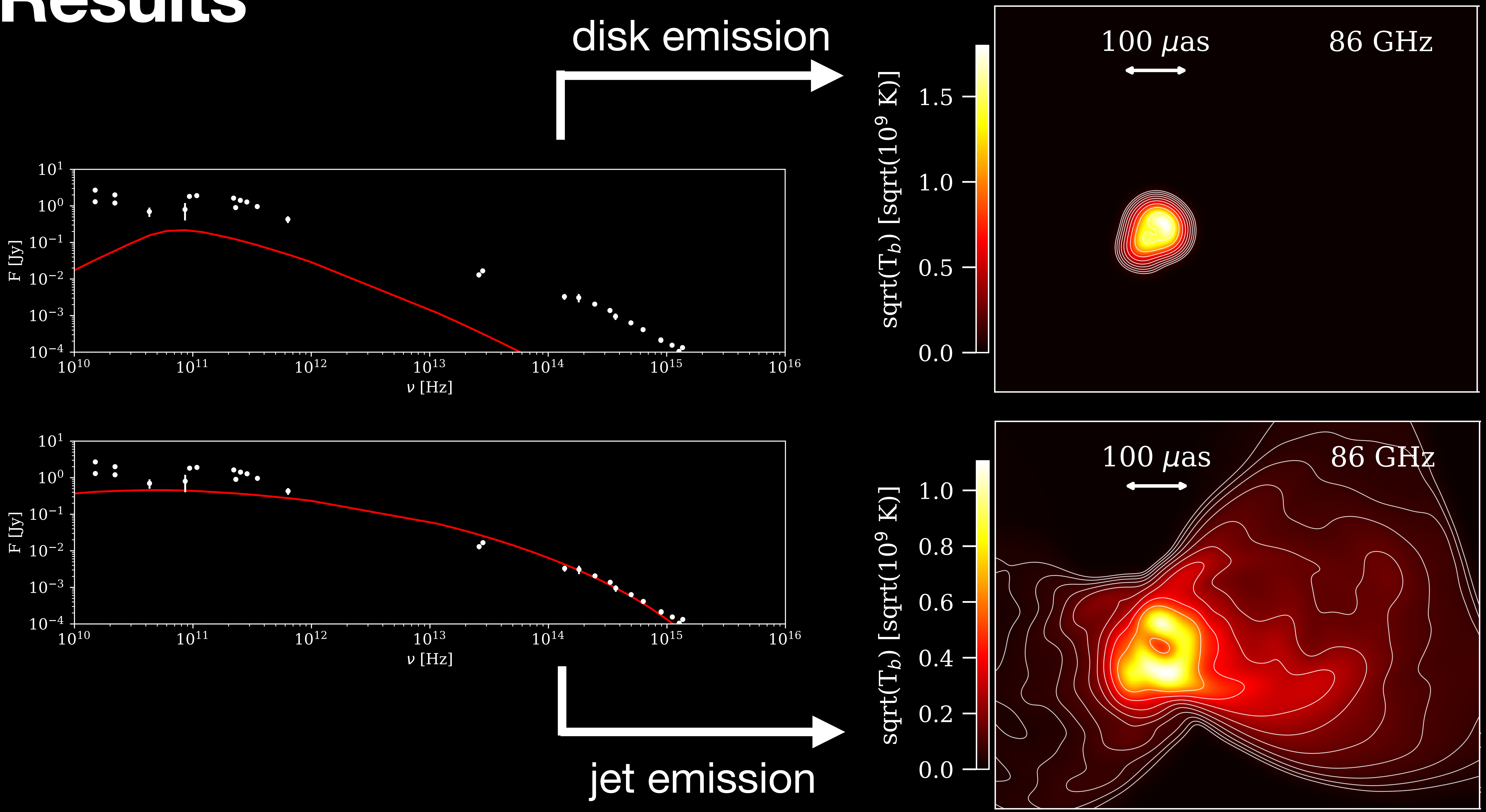
Results



disk emission

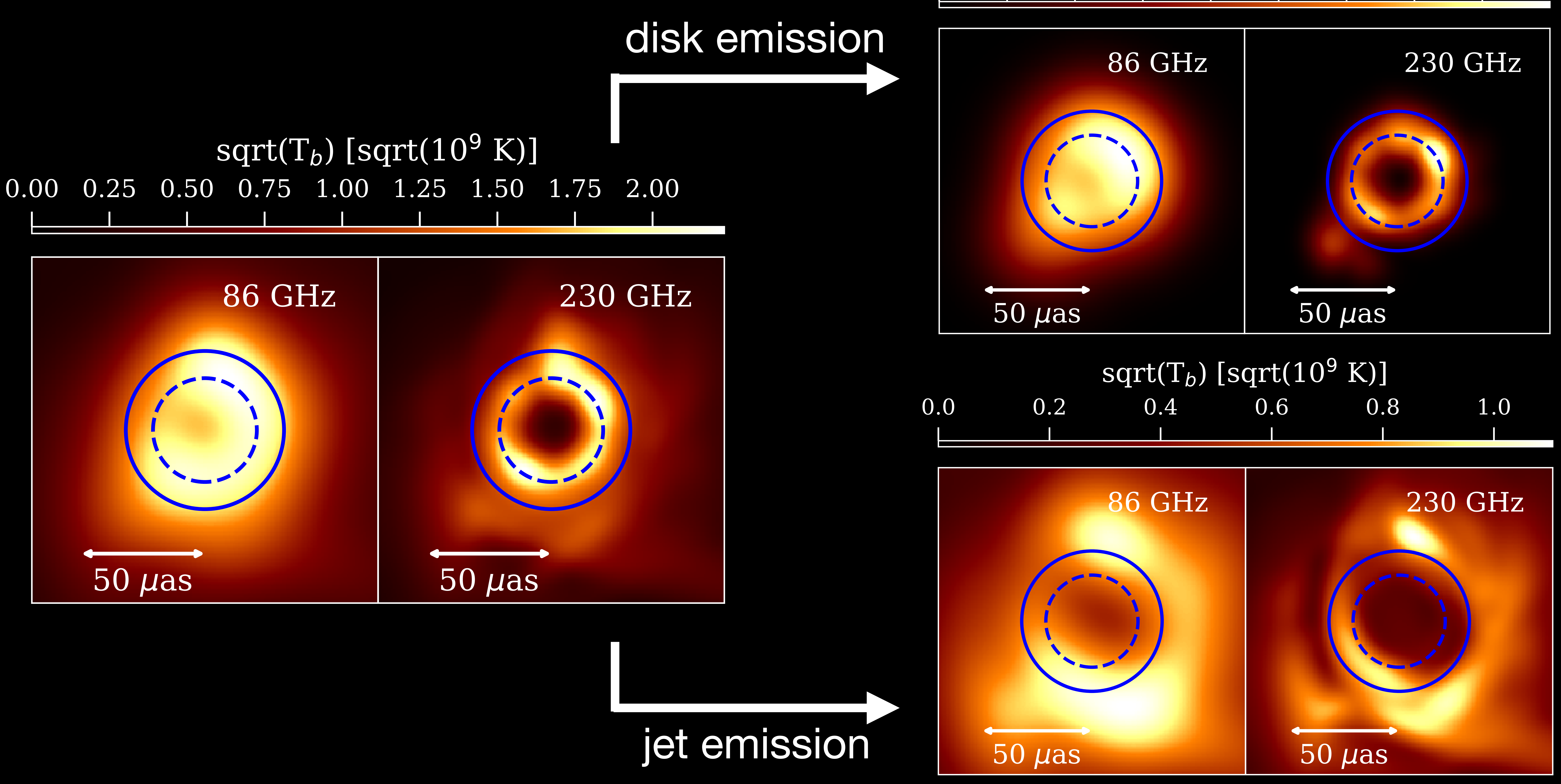


Results

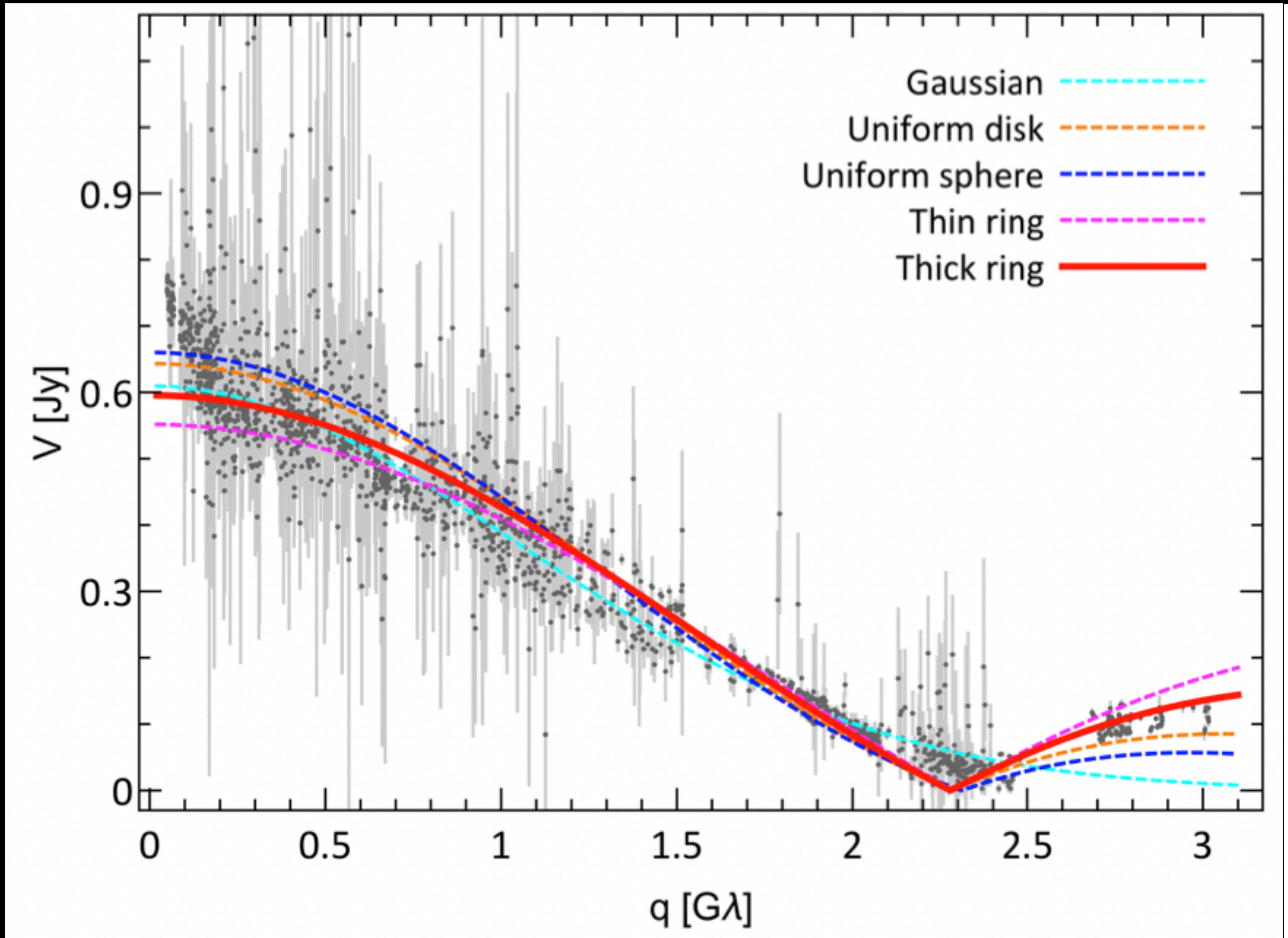


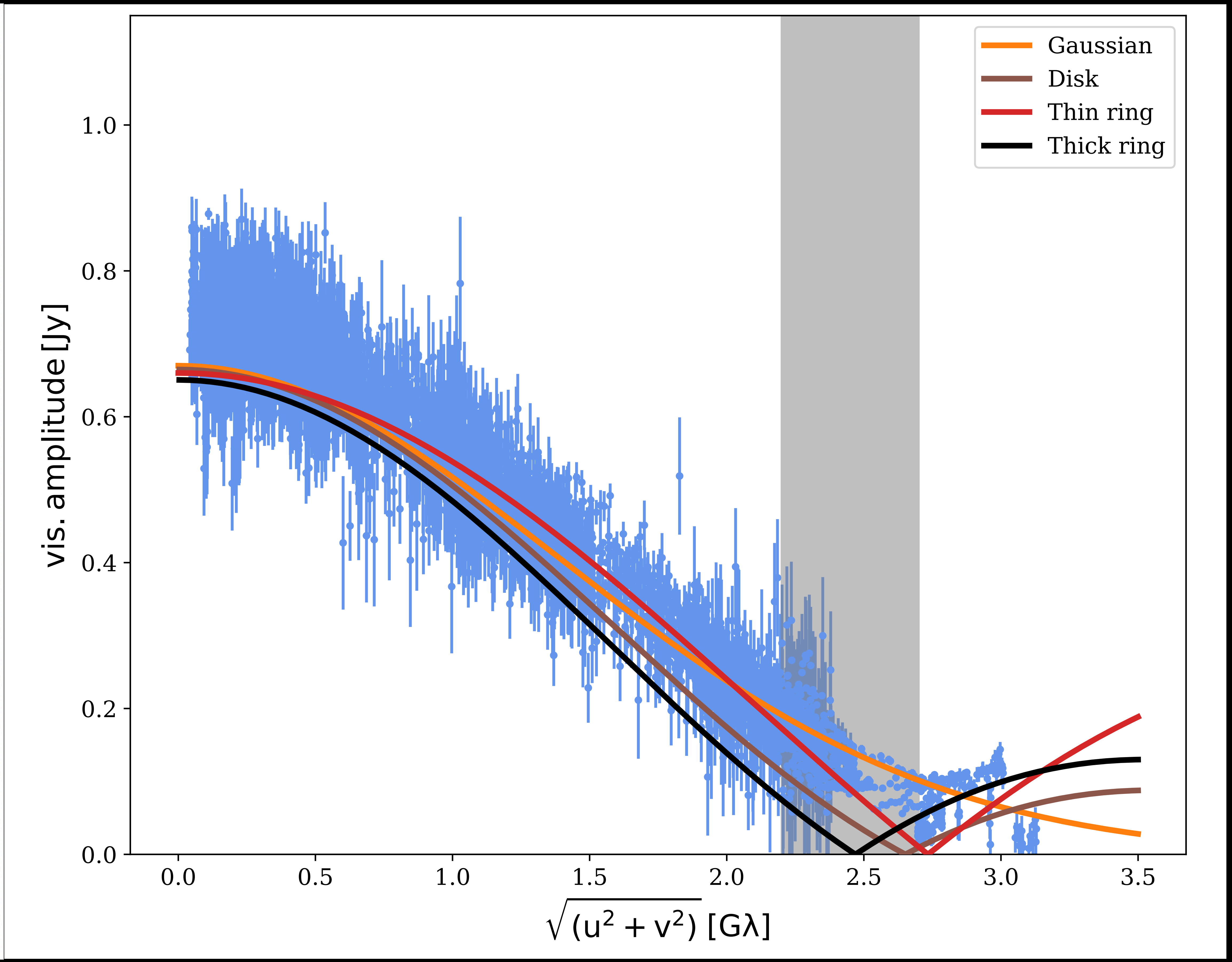
disk emission
jet emission
F [Jy]
ν [Hz]
100 μas
86 GHz
sqrt(T_b) [sqrt(10^9 K)]

Results - Horizon scale



Visibility fitting





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Preliminary results

Evolution over time