



Bundesministerium
für Bildung
und Forschung

VARIABLE STRUCTURES IN M87* FROM SPACE, TIME AND FREQUENCY RESOLVED INTERFEROMETRY

DYNAMIC VLBI IMAGING WITH INFORMATION FIELD THEORY

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REFERENCES

-  Kazunori Akiyama, Antxon Alberdi, Walter Alef, Keiichi Asada, Rebecca Azulay, Anne-Kathrin Bacsko, David Ball, Mislav Baloković, John Barrett, Dan Bintley, et al.
First M87 Event Horizon Telescope Results. IV. Imaging the Central Supermassive Black Hole.
The Astrophysical Journal Letters, 875(1):L4, April 2019.
-  Philipp Arras, Philipp Frank, Philipp Haim, Jakob Knollmüller, Reimar Leike, Martin Reinecke, and Torsten Enßlin.
Variable structures in m87* from space, time and frequency resolved interferometry.
Nature Astronomy, pages 1–11, 2022.

STARTING SITUATION: WORK BY THE EHT COLLABORATION

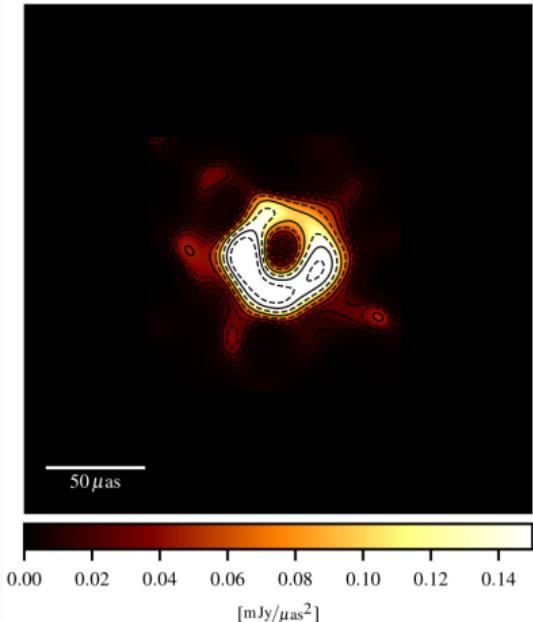
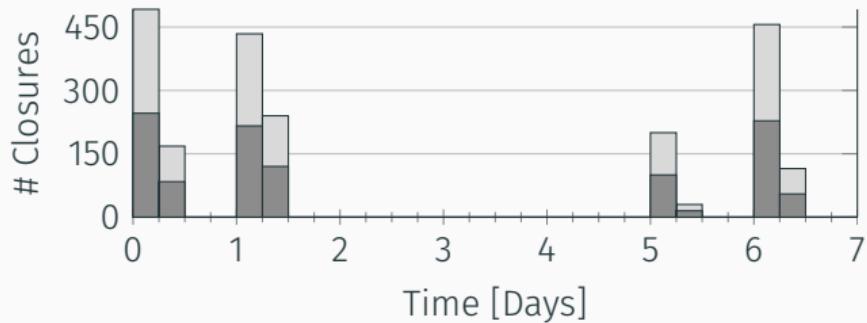


Figure 1: M87* on day 0 imaged with `ehtimaging` [AAA⁺¹⁹]. Saturated color bar.

- Uncertainty quantification via multiple independent imaging teams
- Independent imaging for each observing day



Product Rule of Probabilities

aka Bayes' theorem

$$\mathcal{P}(s|d) = \frac{\mathcal{P}(d|s) \mathcal{P}(s)}{\mathcal{P}(d)}$$

$\mathcal{P}(A|B)$: conditional probability,
s: parameters, d: data.

(Some) assumptions

- The brightness is strictly positive.
- The source features correlation in spatial, temporal and frequency direction.
⇒ Encoded in $\mathcal{P}(s)$.

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In our case:

- Correlation structure → full 4d-movie: sky brightness has shape (2, 28, 256, 256).
- The posterior $\mathcal{P}(s|d)$ is a ridiculously high-dimensional function:

$$\begin{cases} \mathbb{R}^{7,500,000} & \rightarrow \mathbb{R}^{\geq 0} \\ s & \mapsto \mathcal{P}(s|d) \end{cases}$$

- This function encodes our knowledge on M87* including uncertainties.

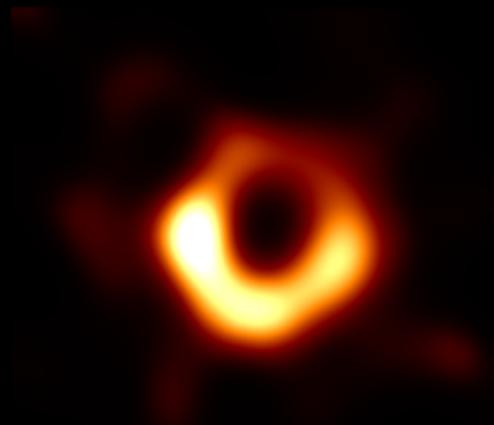
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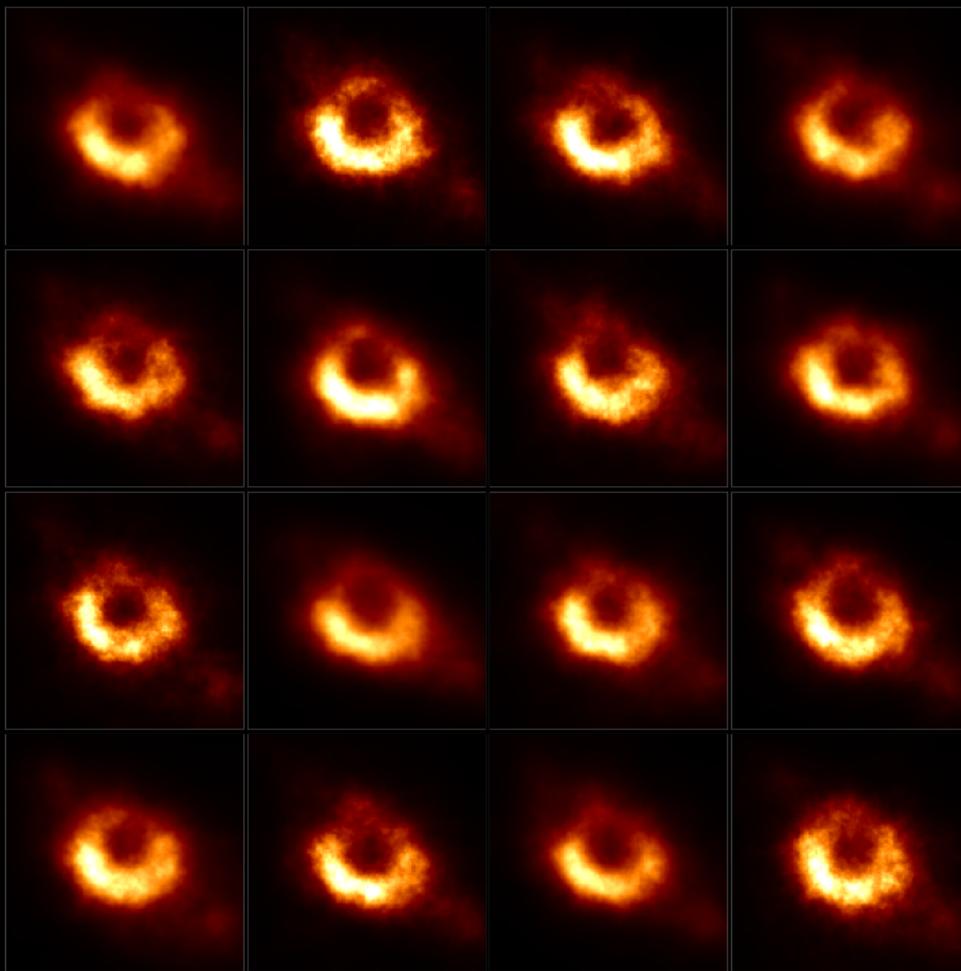












vlbi-resolve, [AFH⁺22], 16 posterior samples.

DATA CONSISTENCY

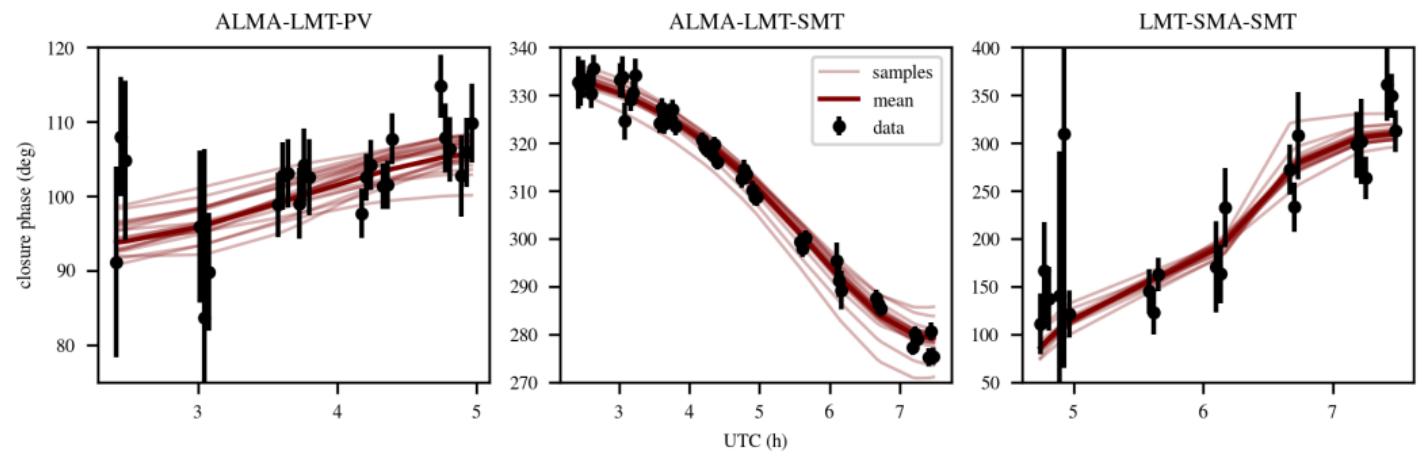


Figure 2: Three closure phases for triples of antennas as a function of time.

THE FUTURE: NEXT-GENERATION EVENT HORIZON TELESCOPE

NGEHT ANALYSIS CHALLENGE

Analysis Challenge by Freek Rolofs, Lindy Blackburn (CfA Harvard University) and many more.

<https://challenge.ngeht.org/challenge2/>

Workflow

1. Simulate M87*-like black hole (with GRMHD)
2. Simulate EHT 2022 / ngEHT observation → (realistic) data
3. Reconstruct sky model of M87*

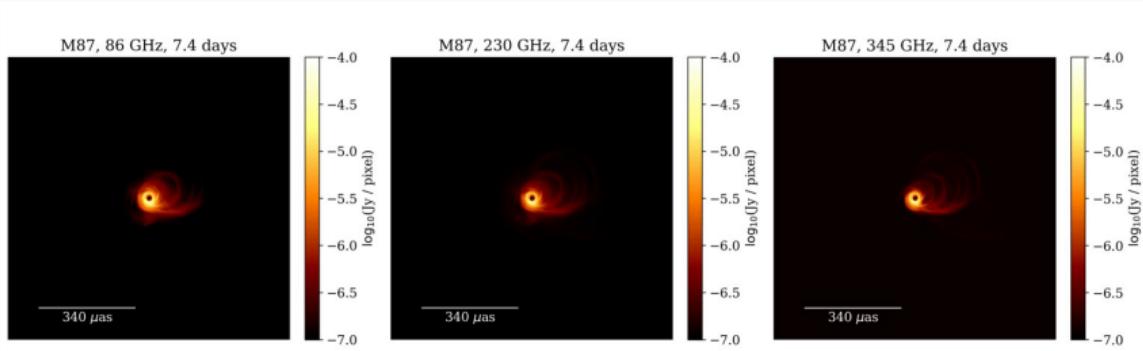


Figure 3: Ground truth

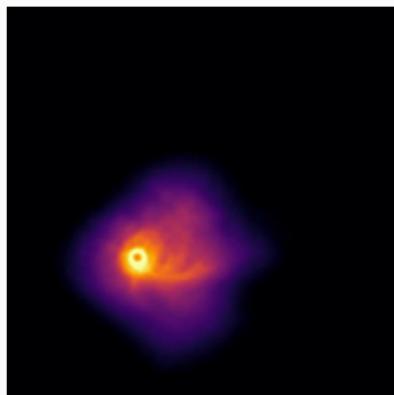


Figure 4: Log. reconstruction (eht2022)

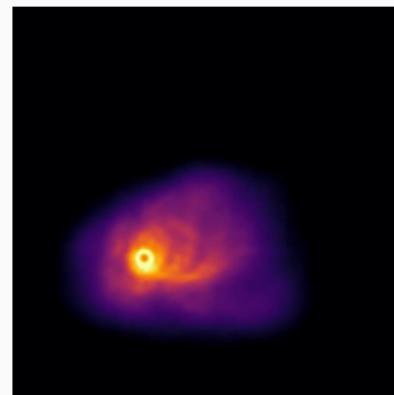


Figure 5: Log. reconstruction (ngeht)

PRIOR

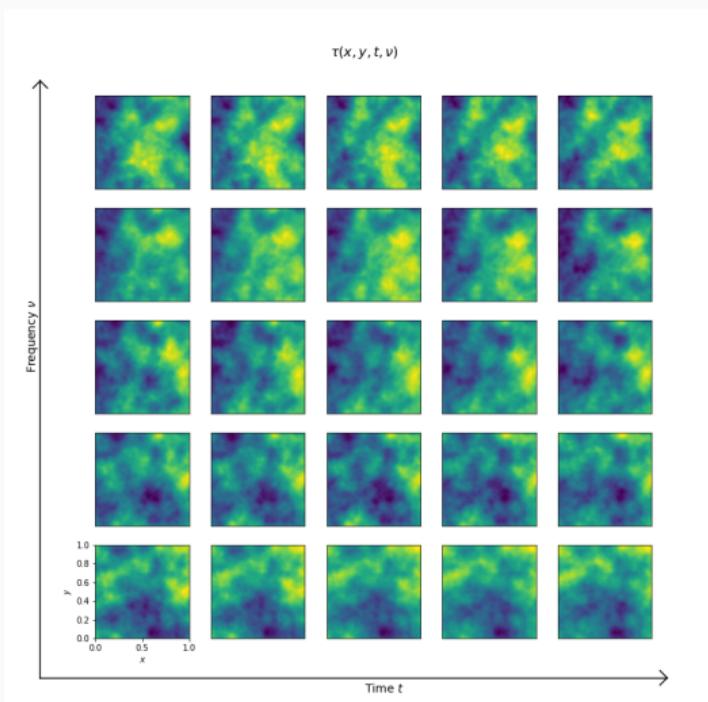


Figure 6: Exemplary sample 1 (log)

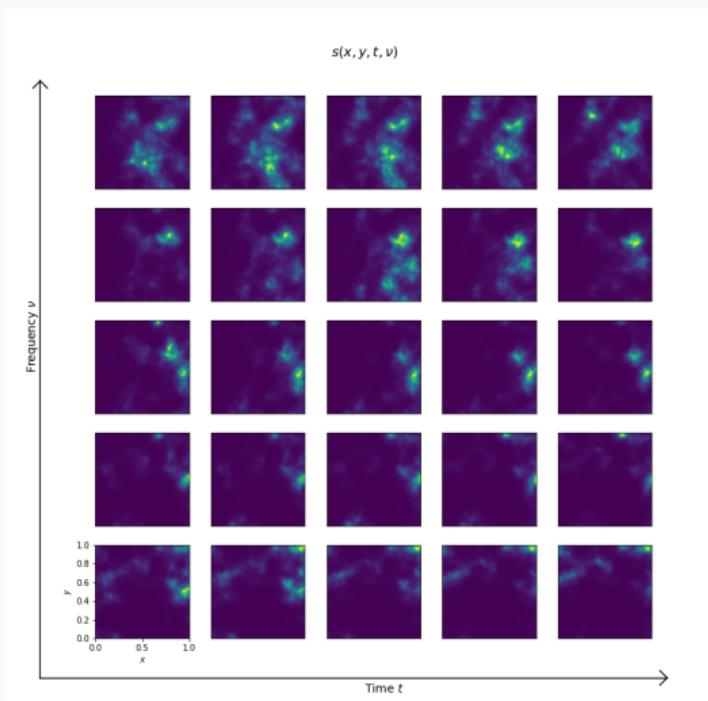


Figure 6: Exemplary sample 1

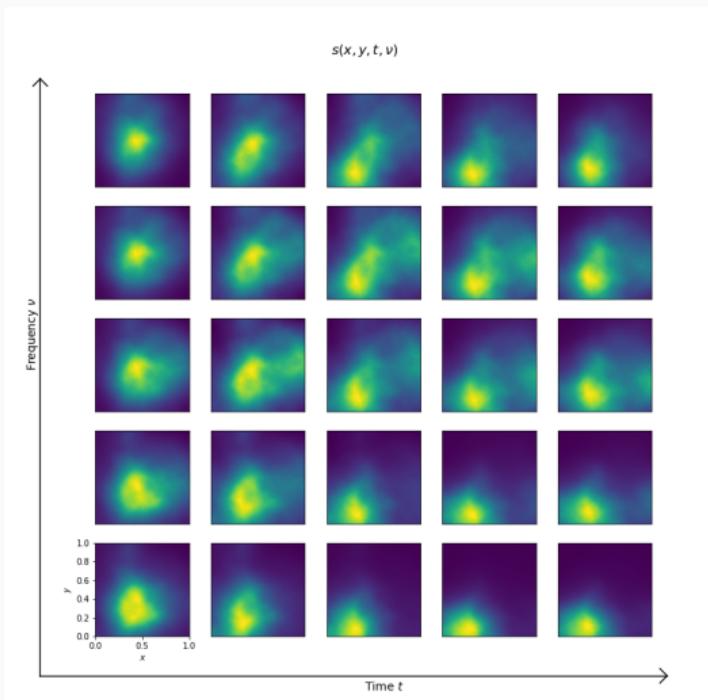


Figure 6: Exemplary sample 2

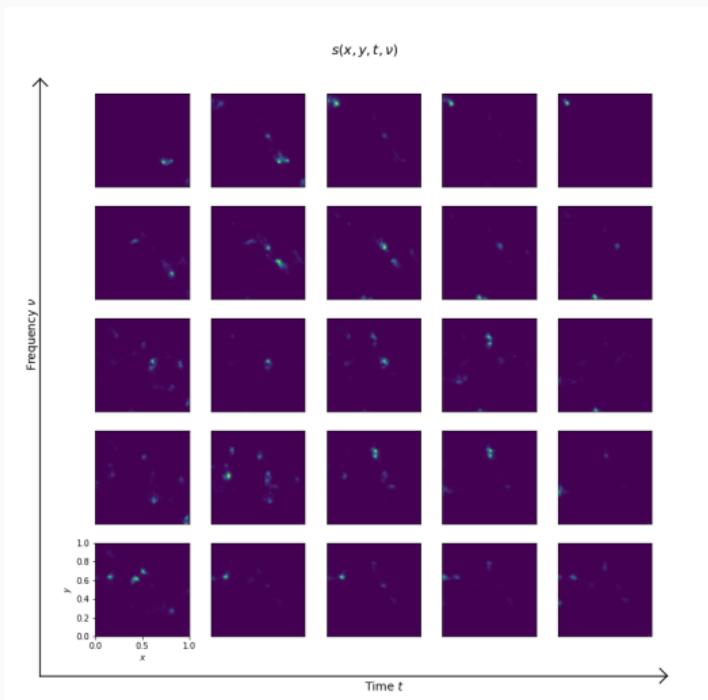
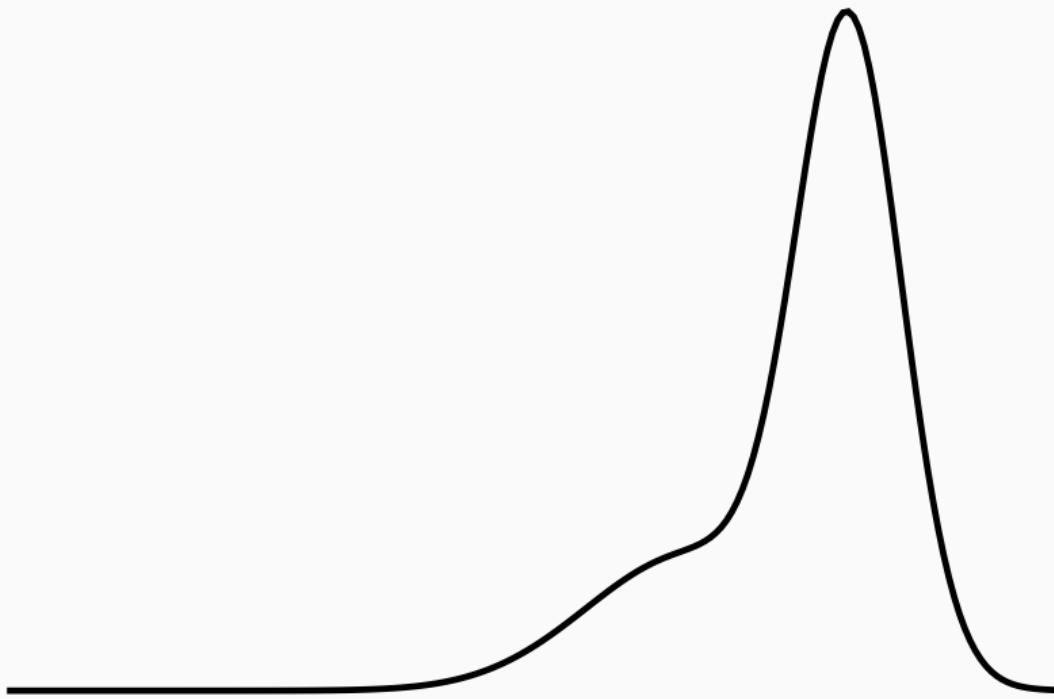


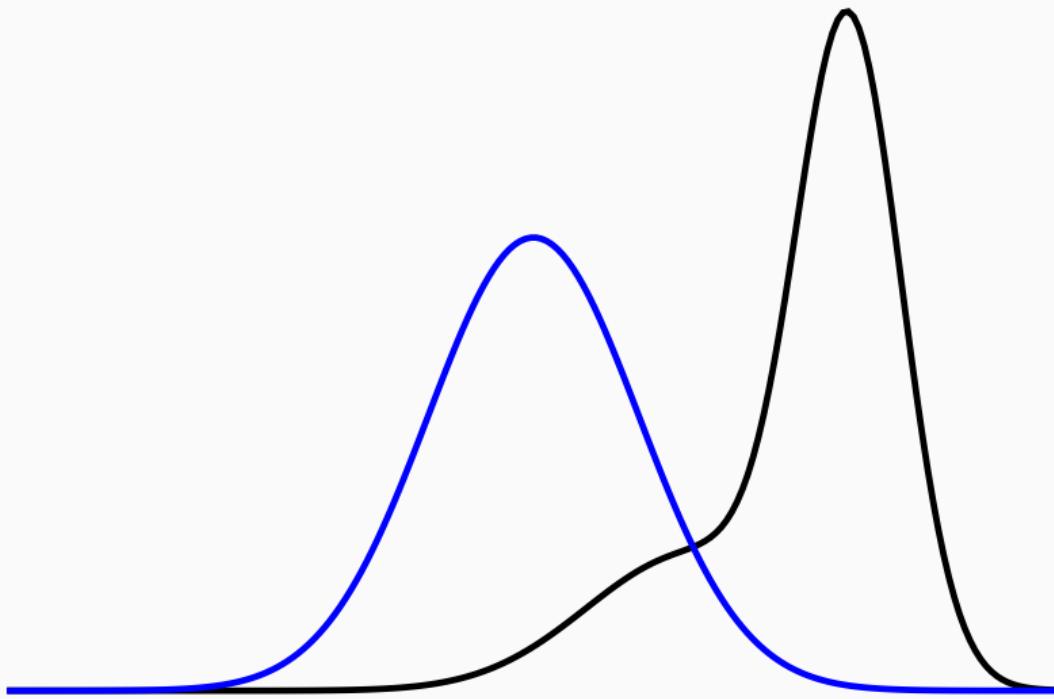
Figure 6: Exemplary sample 3

APPROXIMATE THE POSTERIOR

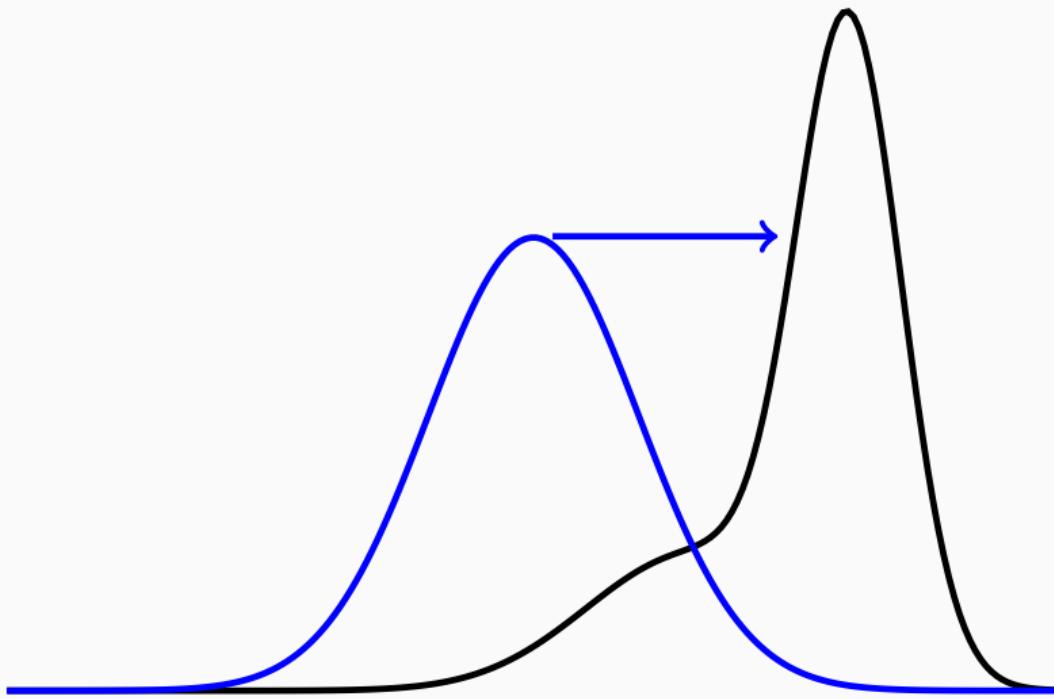
VARIATIONAL INFERENCE (→ KULLBACK-LEIBLER DIVERGENCE)



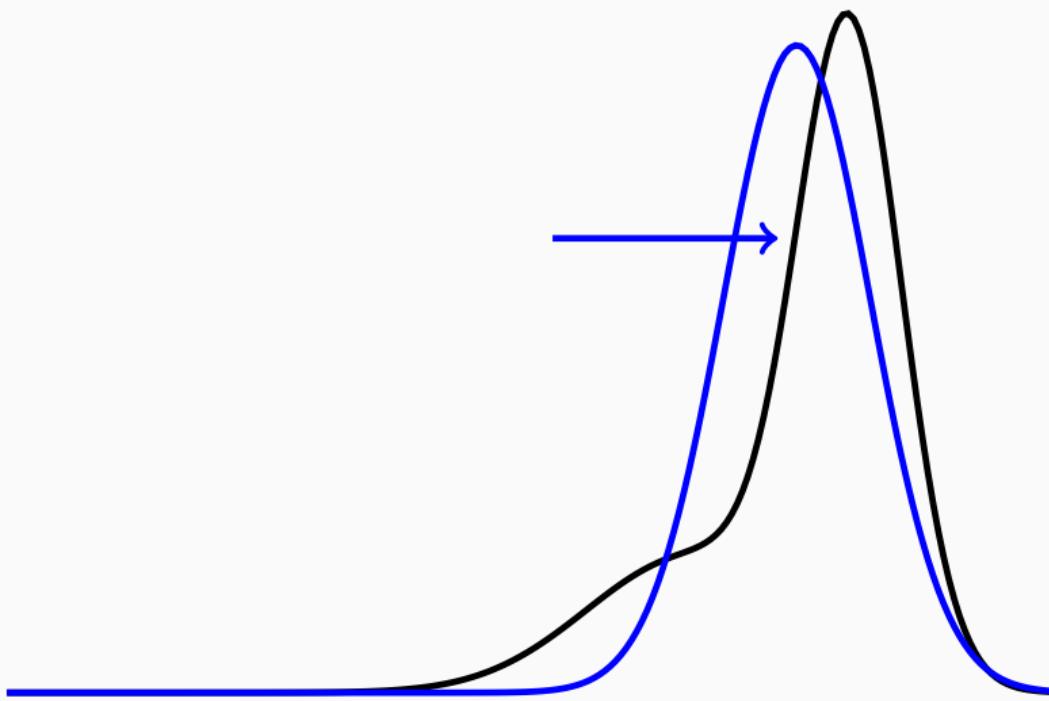
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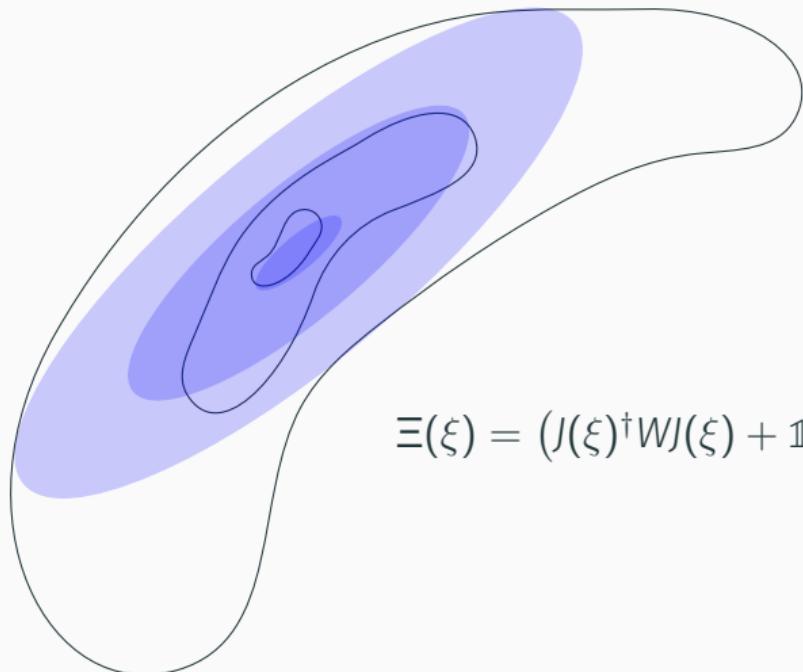
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- Metric Gaussian Variational Inference

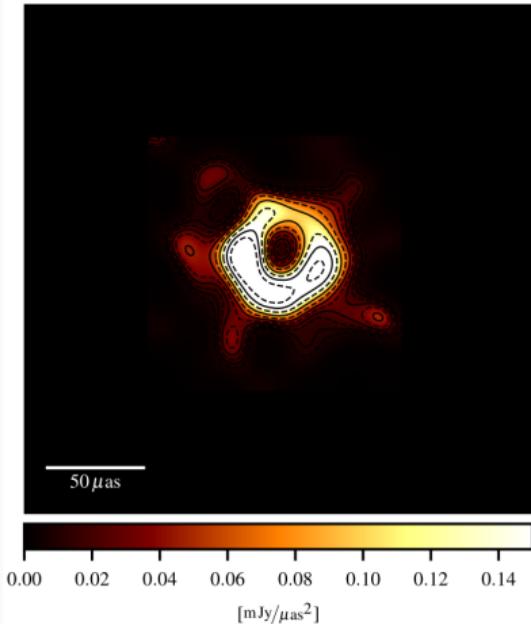
$$\Xi = (J(\xi)^\dagger W J(\xi) + \mathbb{1})^{-1}$$

with: J : Jacobian of the forward model, $W = \text{diag}(\text{weights})$.

METRIC GAUSSIAN VARIATIONAL INFERENCE



CONCLUSION

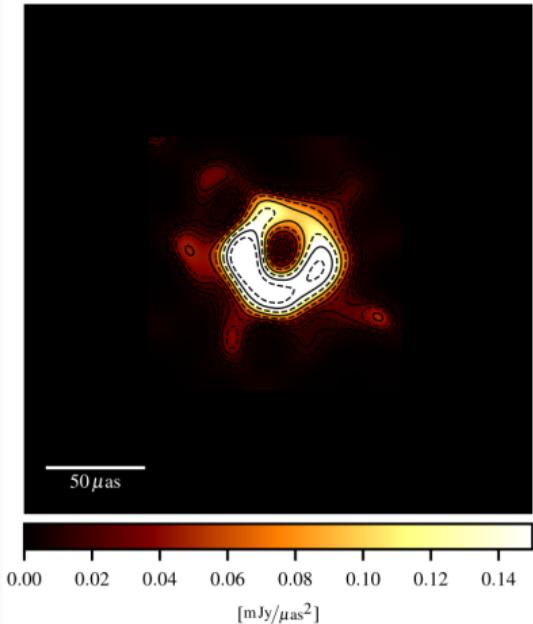


Differences to [AAA⁺19]

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Figure 7: M87* on day 0 imaged with ehtimaging [AAA⁺19]. Saturated color bar.

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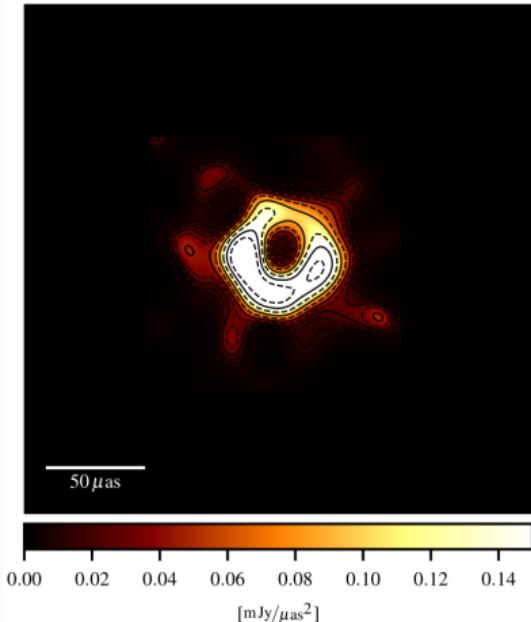


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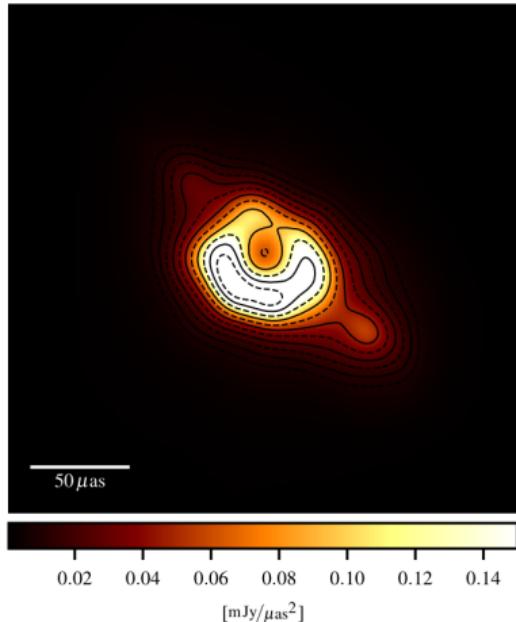


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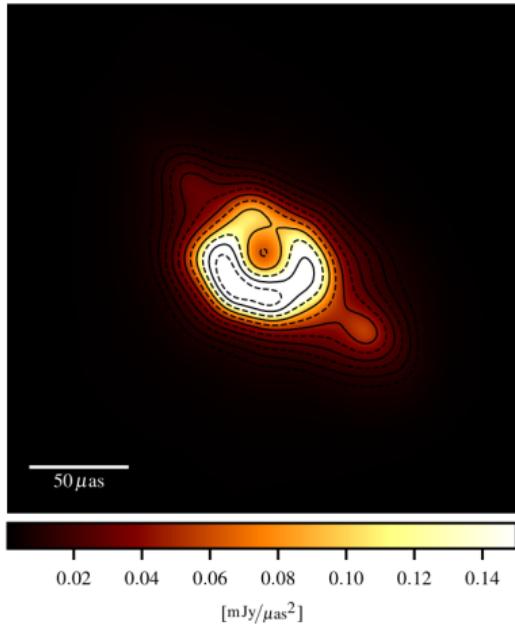


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Some aspects

- **Four-dimensional** (time, frequency, space) reconstruction of M87*
- **Bayesian** treatment despite huge problem size ($> 10^7$ dofs)