Black Hole and Exoplanet Imaging with Information Field Theory

BASP Frontiers 2025

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presenting the work of the IFT group led by Torsten Enßlin

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MAX-PLANCK-INSTITUT FÜR ASTROPHYSIK

Introduction to IFT

IFT

- information theory on fields
- inference framework
- imaging methodology

Signal and Data

signal: s, data: d

$$\mathcal{P}(s|d) = \underbrace{\mathcal{P}(d|s)}_{\text{data acquisition}} \underbrace{\mathcal{P}(s)}_{\text{model prior}} / \underbrace{\mathcal{P}(d)}_{\text{normalisation}} \tag{1}$$

reconstruct probability distribution $\implies$ uncertainty for free!

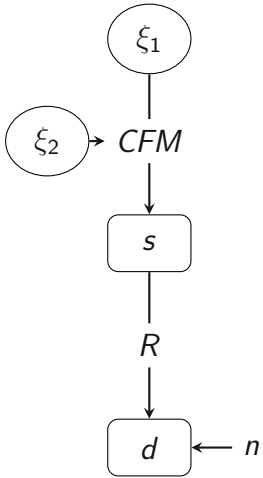
Forward Model

Forward Model

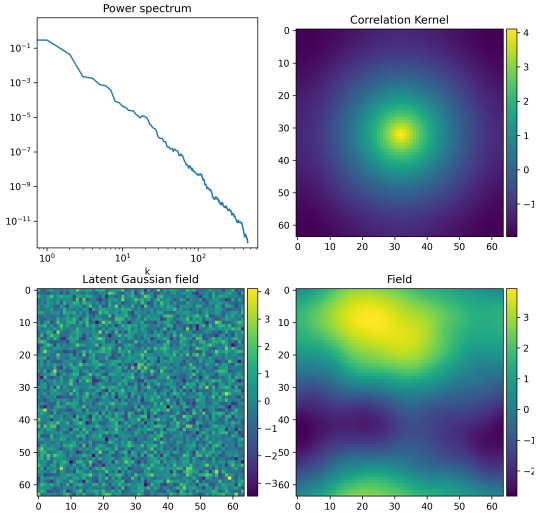
$$d = R(s) + n \tag{2}$$

$$s = CFM(\xi) \tag{3}$$

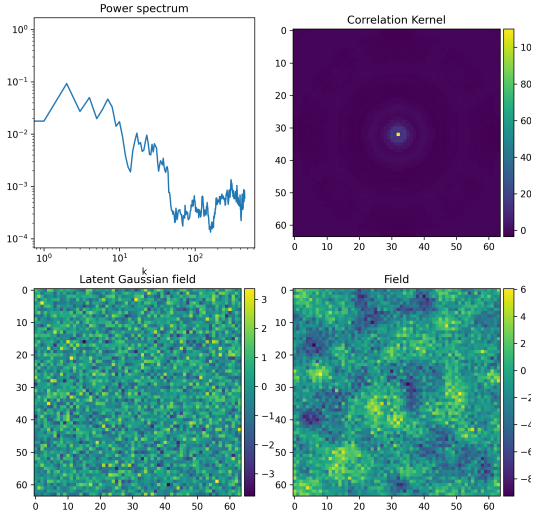
- smooth
- statistically homogenous, isotropic



$\xi \to s$


Power spectrum
k
Correlation Kernel
Latent Gaussian field
Field

$\xi \to s$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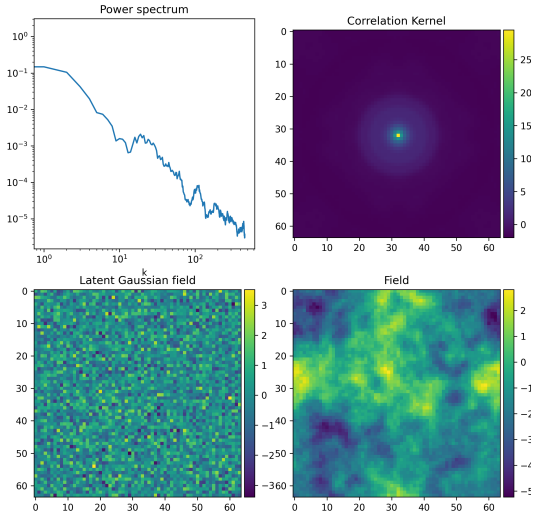
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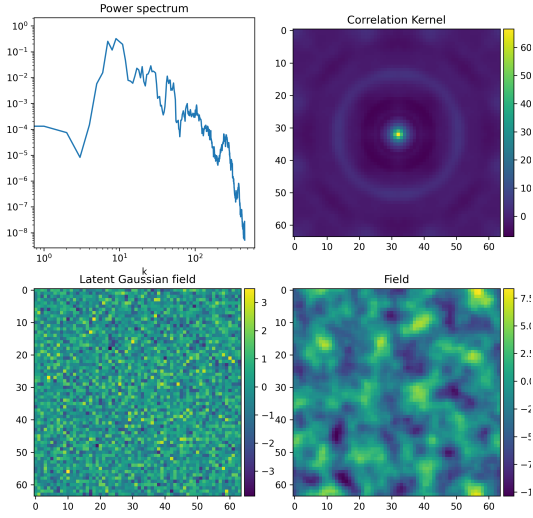
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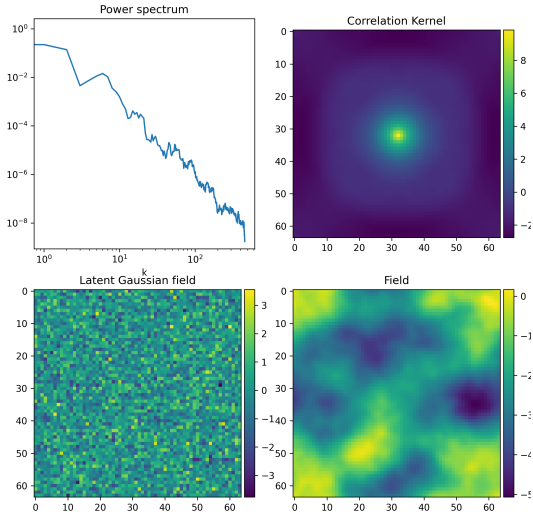
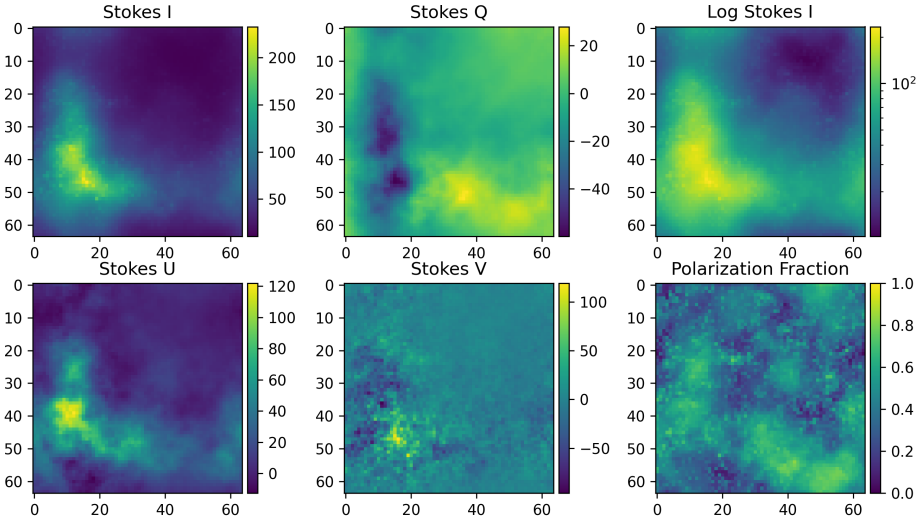

Power spectrum
k
Correlation Kernel
Latent Gaussian field
Field

Other Constraints

- enforce positivity $\Longleftarrow$ exponentiate the output
- enforce polarization constraints
  - $I > 0$
  - $I^2 \geq Q^2 + U^2 + V^2$

Polarization Constraint



$s \rightarrow d$

many possible data acquisition techniques:

- radio radio
- X ray
- neutrino
- infrared
- medical ...

$s \rightarrow d$: an Example

using small field approximation

$$\underbrace{V(u,v)}_{d} = \int e^{2\pi i(ul+vm)} \underbrace{B(l,m)}_{s} \, dldm + n \tag{4}$$

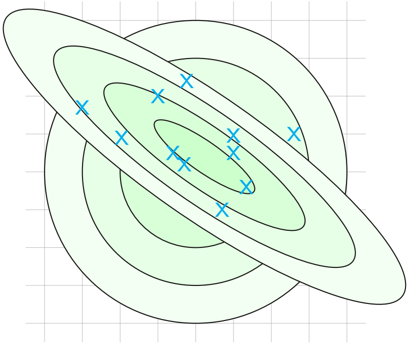
Inversion

Inversion

$$\mathcal{P}(\xi|d) = \frac{\mathcal{P}(\xi, d)}{\mathcal{P}(d)} \quad (5)$$

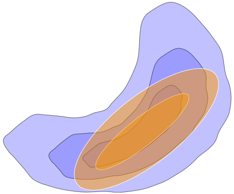
$$\approx \mathcal{G}(\xi - m, D) \quad (6)$$

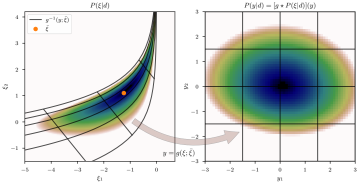
variational inference



Inversion

Metric Gaussian Variational Inference	Geometric Variational Inference
Knollmüller & Enßlin (arXiv:1901.11033)	Frank, Leike, & Enßlin (arXiv:2105.10470)





see Knollmüller and Ensslin [KE19] and Frank, Leike, and Enßlin [FLE21]

Similarity to Regularization

Tikhonov regularization:

$$\text{argmin}_{\beta}(X\beta - y)^{\dagger}(X\beta - y) + \lambda\beta^{\dagger}\beta \rightarrow (X^{\dagger}X + \lambda\mathbb{1})^{-1}X^{\dagger}y \tag{7}$$

IFT:

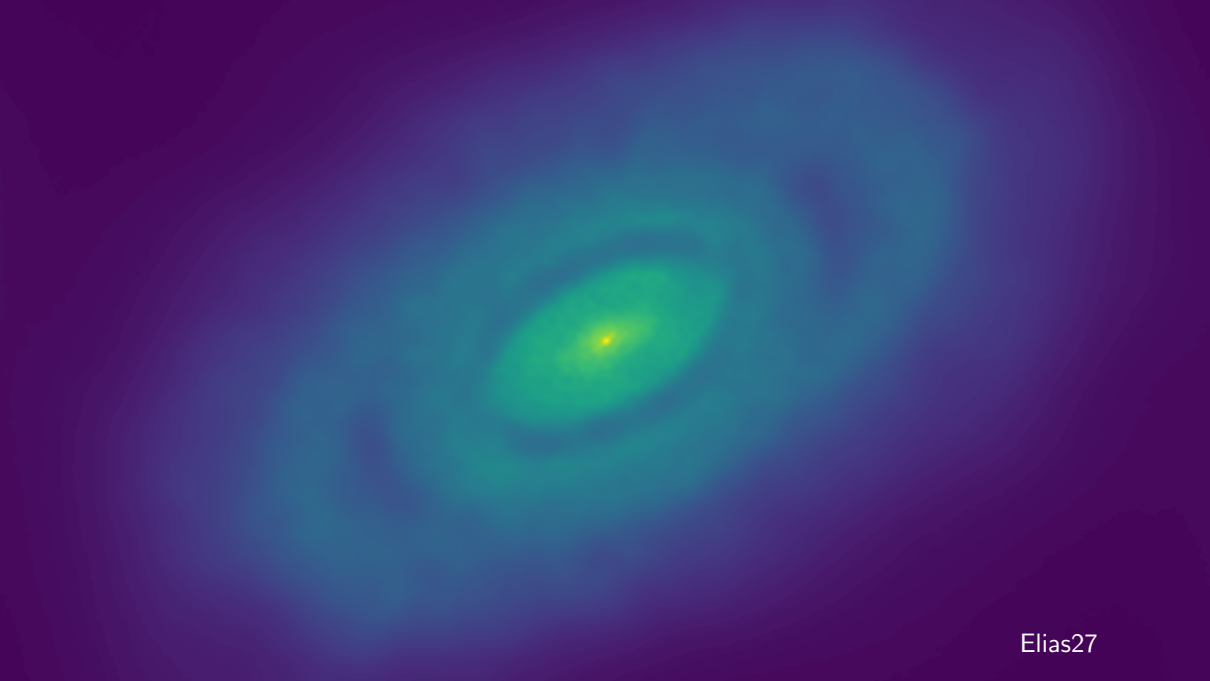
$$d - Rs = n \hookleftarrow \mathcal{G}(n, N) \tag{8}$$

$$s \hookleftarrow \mathcal{G}(s, S) \tag{9}$$

$$\mathcal{P}(s|d) \propto \mathcal{G}(d - Rs, N)\mathcal{G}(s, S) \tag{10}$$

$$\text{argmin}_{s}(Rs - d)^{\dagger}N^{-1}(Rs - d) + s^{\dagger}S^{-1}s \rightarrow (R^{\dagger}N^{-1}R + S^{-1})^{-1}R^{\dagger}N^{-1}d \tag{11}$$

Showcase


Elias27

Elias27

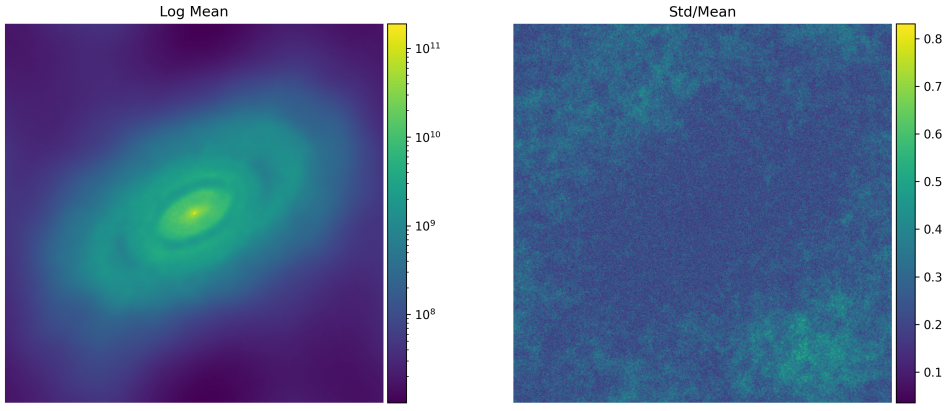
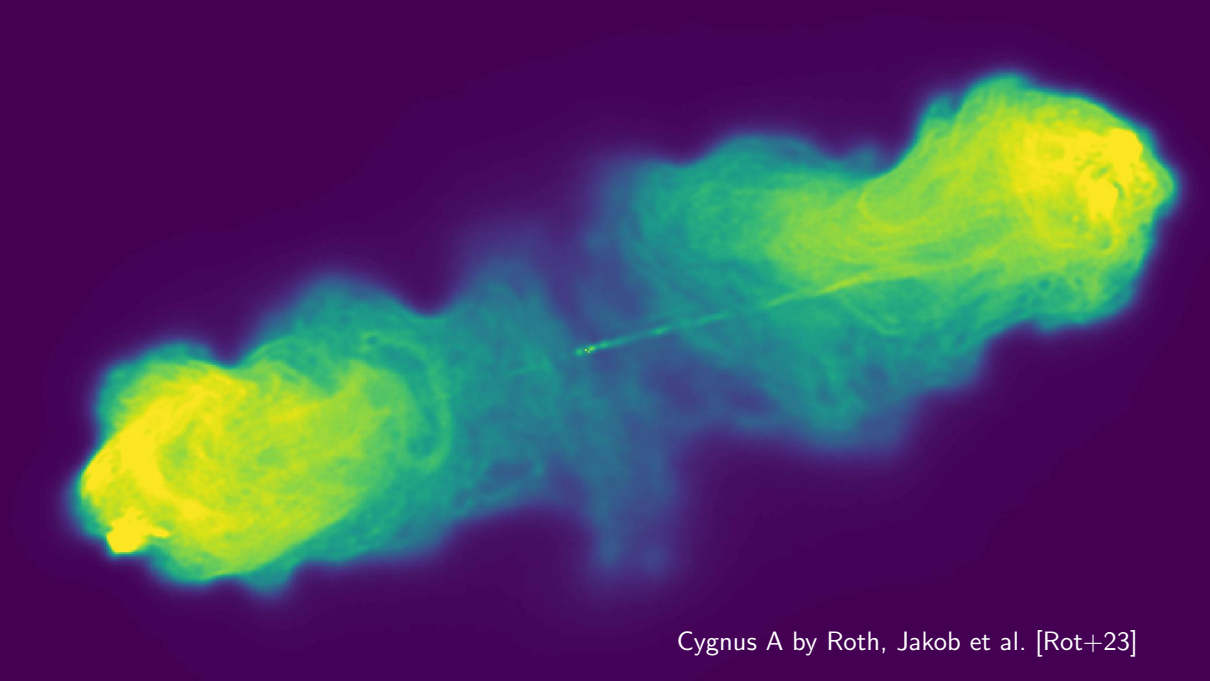
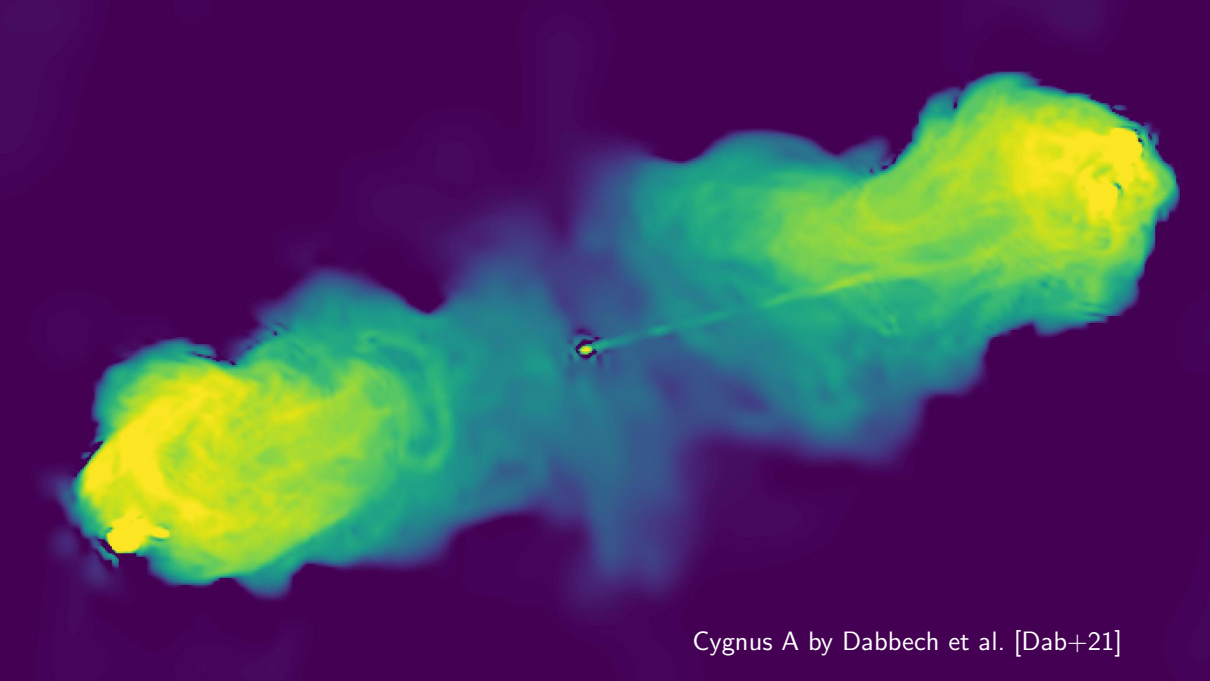
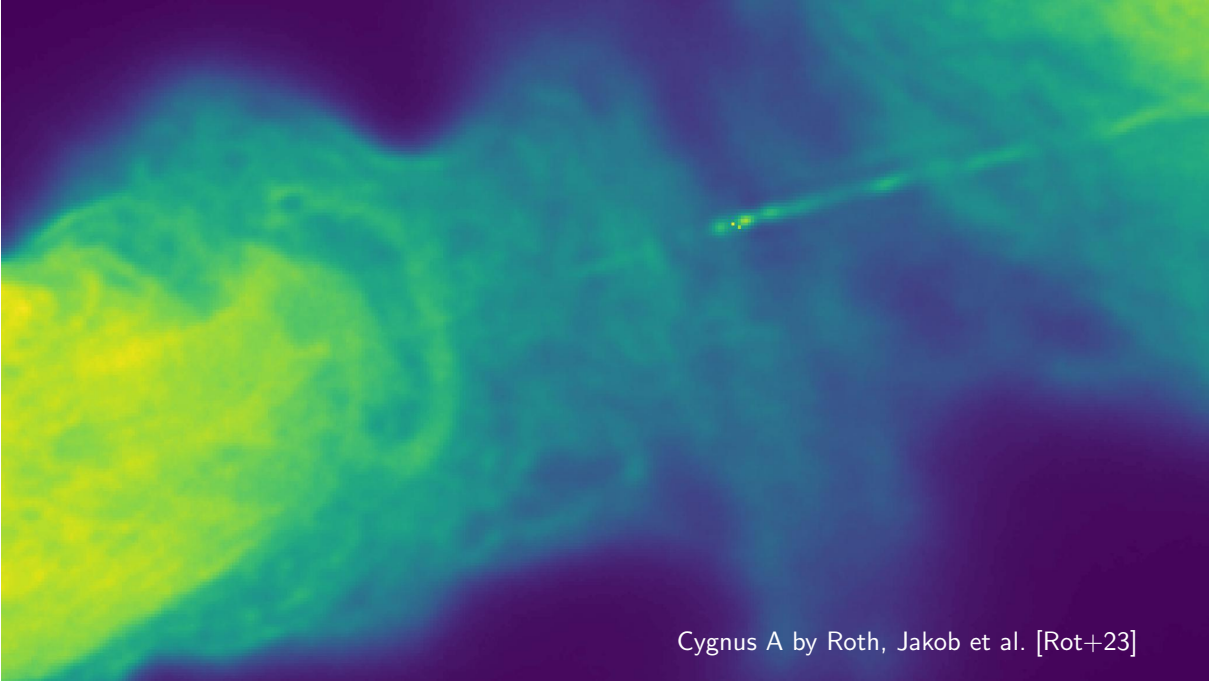


Figure 7: Mean and CoV for Elias27.



Cygnus A by Roth, Jakob et al. [Rot+23]


Cygnus A by Dabbech et al. [Dab+21]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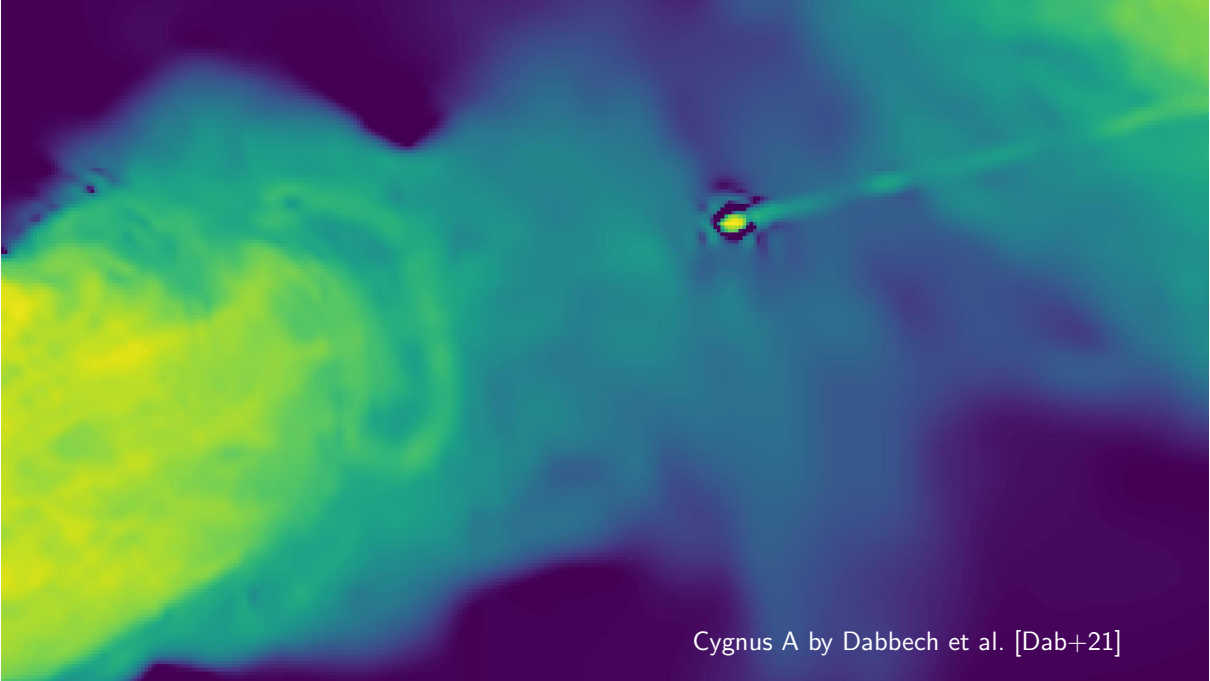
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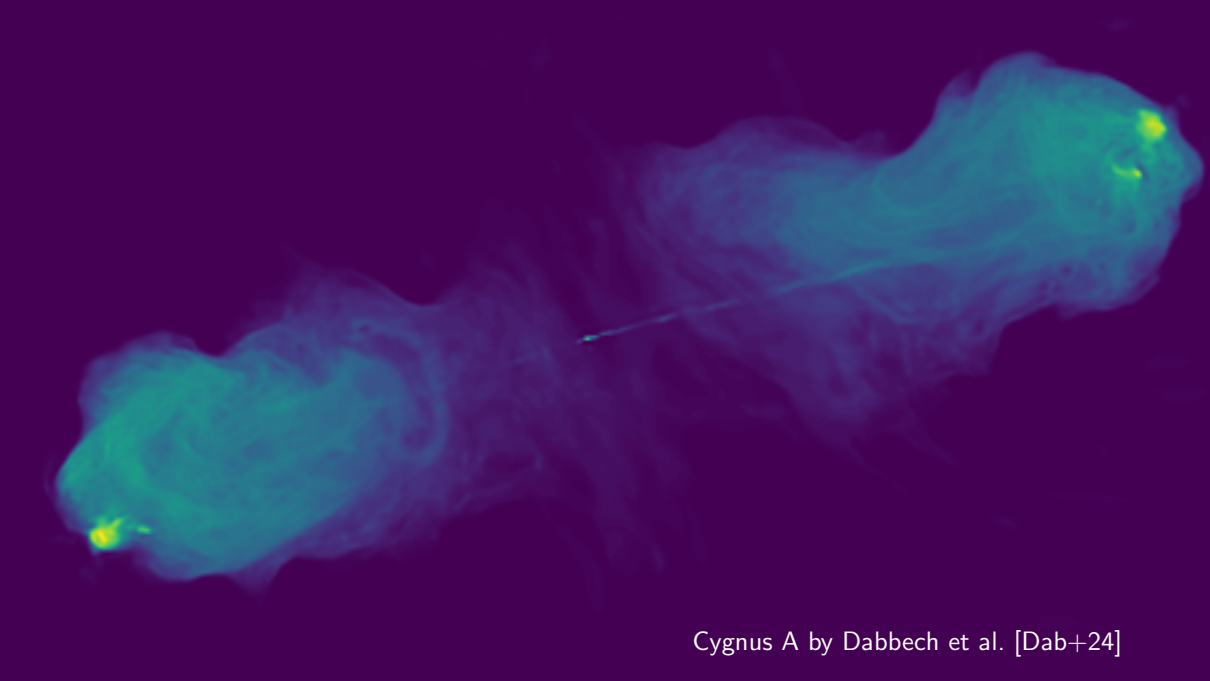
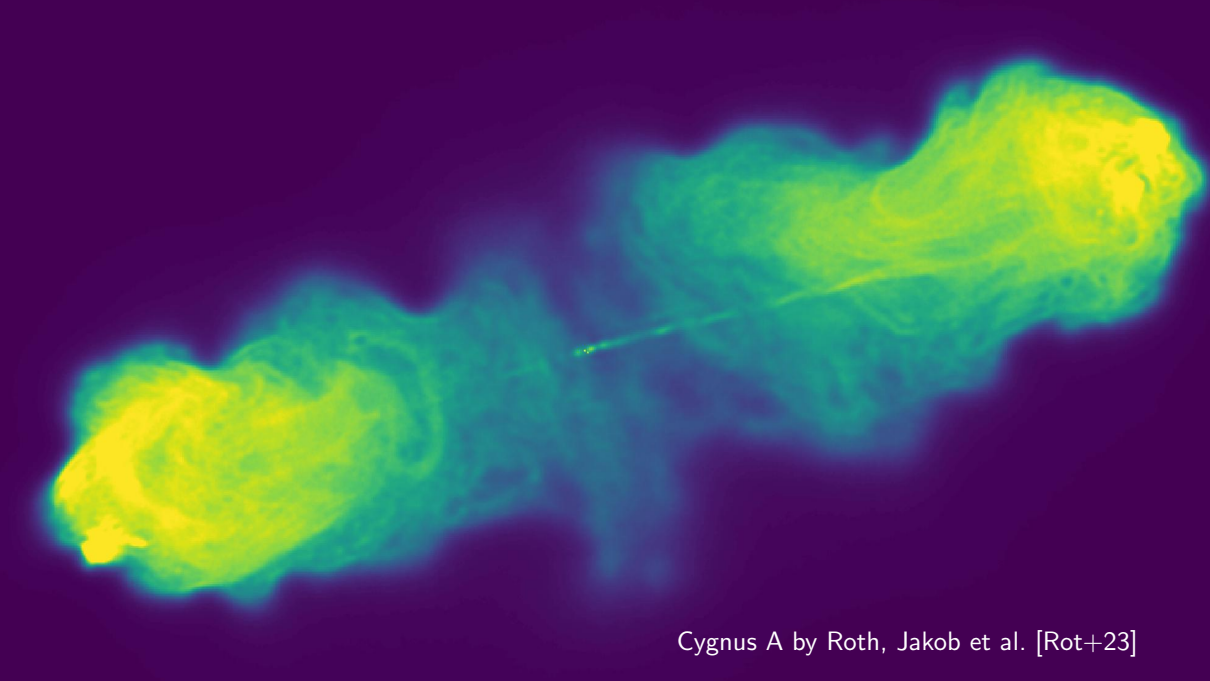


Cygnus A by Dabbech et al. [Dab+24]



Cygnus A by Roth, Jakob et al. [Rot+23]

M87 by Arras et al. [Arr+20]

Summary

Summary

- prior knowledge encoded
- statistical
- inference network

try it out:

NIFTy

gitlab.mpcdf.mpg.de/ift/nifty

resolve

gitlab.mpcdf.mpg.de/ift/resolve

Thanks! Any questions?

References

[KE19] Jakob Knollmüller and Torsten A. Ensslin. **"Metric Gaussian Variational Inference".** In: *ArXiv* abs/1901.11033 (2019).

[FLE21] Philipp Frank, Reimar Leike, and Torsten A. Enßlin. **"Geometric Variational Inference".** In: *Entropy* 23.7 (2021). ISSN: 1099-4300. DOI: 10.3390/e23070853.

[Rot+23] Roth, Jakob et al. **"Bayesian radio interferometric imaging with direction-dependent calibration".** In: *A&A* 678 (2023), A177. DOI: 10.1051/0004-6361/202346851.

[Dab+21] A Dabbech et al. **"Cygnus A jointly calibrated and imaged via non-convex optimization from VLA data".** In: *Monthly Notices of the Royal Astronomical Society* 506.4 (July 2021), pp. 4855–4876. ISSN: 0035-8711. DOI: 10.1093/mnras/stab1903.

[Dab+24] Arwa Dabbech et al. **"CLEANing Cygnus A deep and fast with R2D2".** English. In: *Astrophysical Journal Letters* 966.2 (2024). ISSN: 2041-8205. DOI: 10.3847/2041-8213/ad41df.

[Arr+20] Philipp Arras et al. **"Variable structures in M87* from space, time and frequency resolved interferometry".** In: *Nature Astronomy* 6 (2020), pp. 259 –269.

[KAE23] Jakob Knollmuller, Philipp Arras, and Torsten A. Enßlin. **"Resolving Horizon-Scale Dynamics of Sagittarius A*".** In: 2023.

[Rot+23] J. Roth et al. **"Fast-cadence High-contrast Imaging with Information Field Theory".** In: *The Astronomical Journal* 165.3 (Feb. 2023), p. 86. ISSN: 1538-3881. DOI: 10.3847/1538-3881/acabc1.

Backup

Exoplanet Imaging

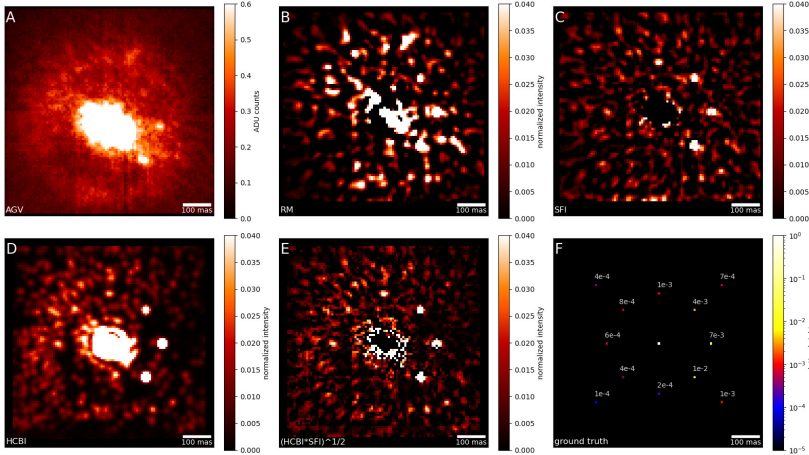


Figure 8: Exoplanet imaged using IFT methods [Rot+23].

Polarization

$$\begin{pmatrix} I+Q & U+iV \\ U-iV & I-Q \end{pmatrix} = \exp \begin{pmatrix} a+d & b+ic \\ b-ic & a-d \end{pmatrix} \tag{12}$$