Bayesian statistics approach to interferometry

RESOLVE meets ALMA

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Fabrizia Guglielmetti, Philipp Arras, Torsten Enßlin, Eric Villard

Observational astrophysics 101

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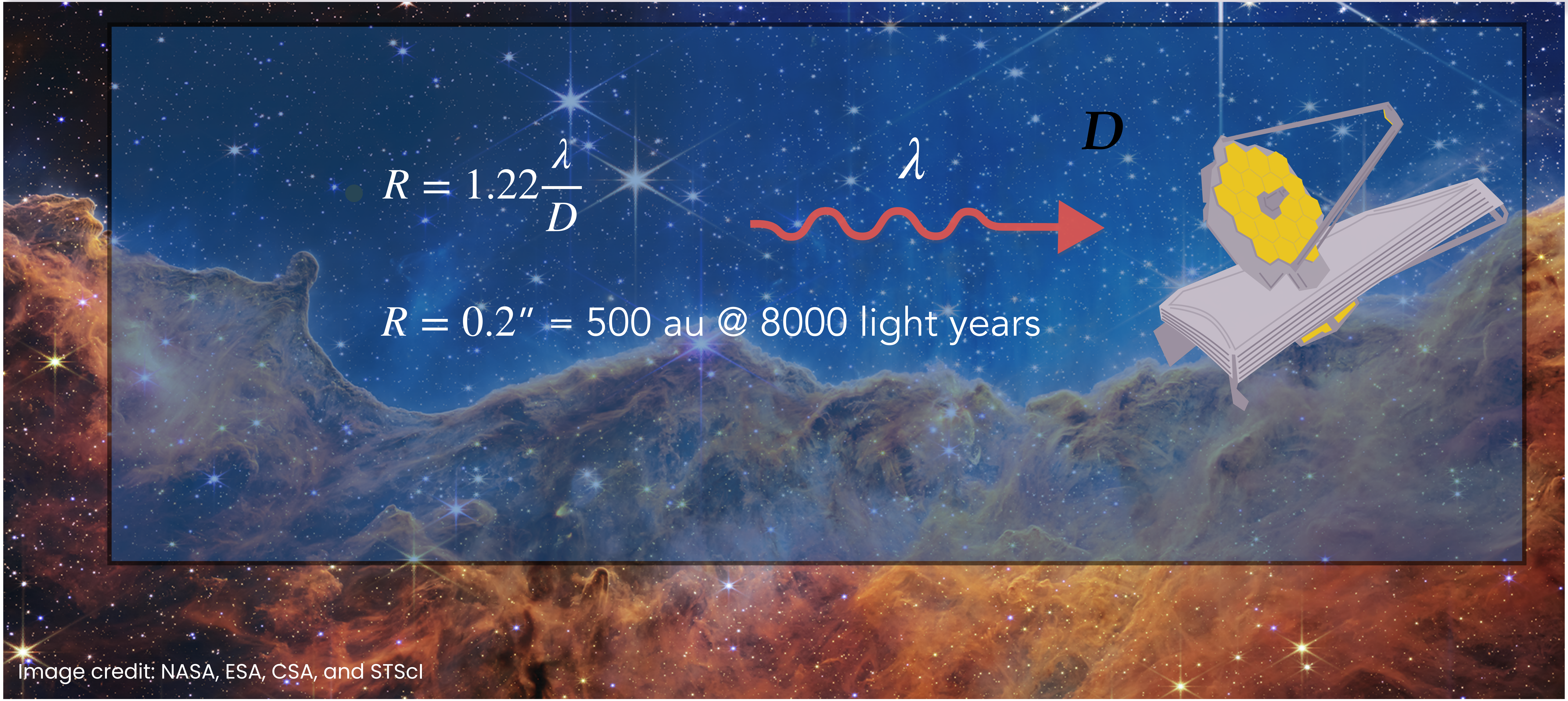

$$R = 1.22\frac{\lambda}{D}$$

$R = 0.2''$ = 500 au @ 8000 light years

Longer wavelengths: peering into the cooler universe

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For longer wavelengths we need bigger telescopes...

Old Green Bank Telescope (90 m)

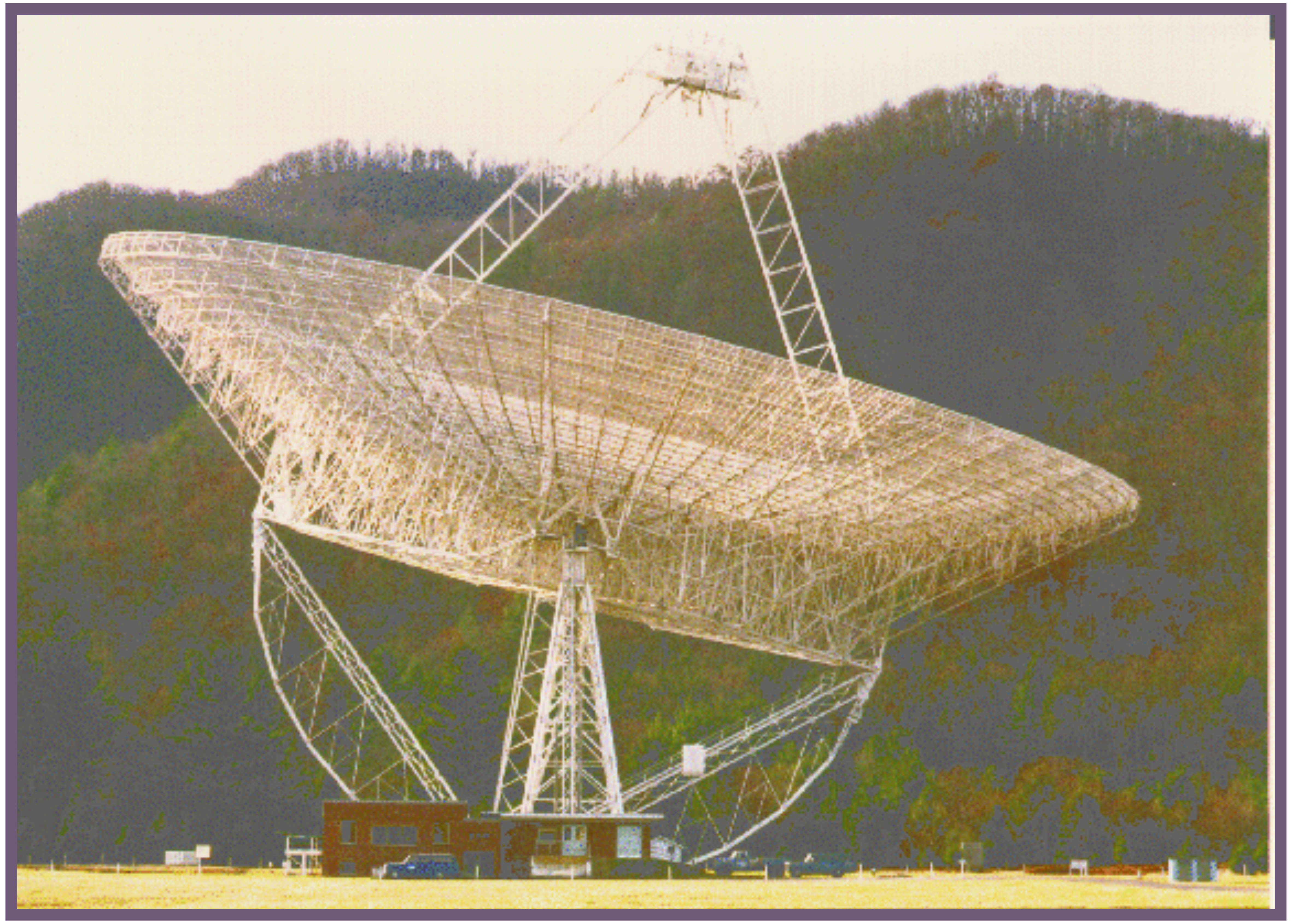

Image credit: Richard Porcas/NRAO

$$R = 1.22\frac{\lambda}{D}$$

$$R = 30'' = 80\,000 \text{ au @ } 8000 \text{ light years}$$

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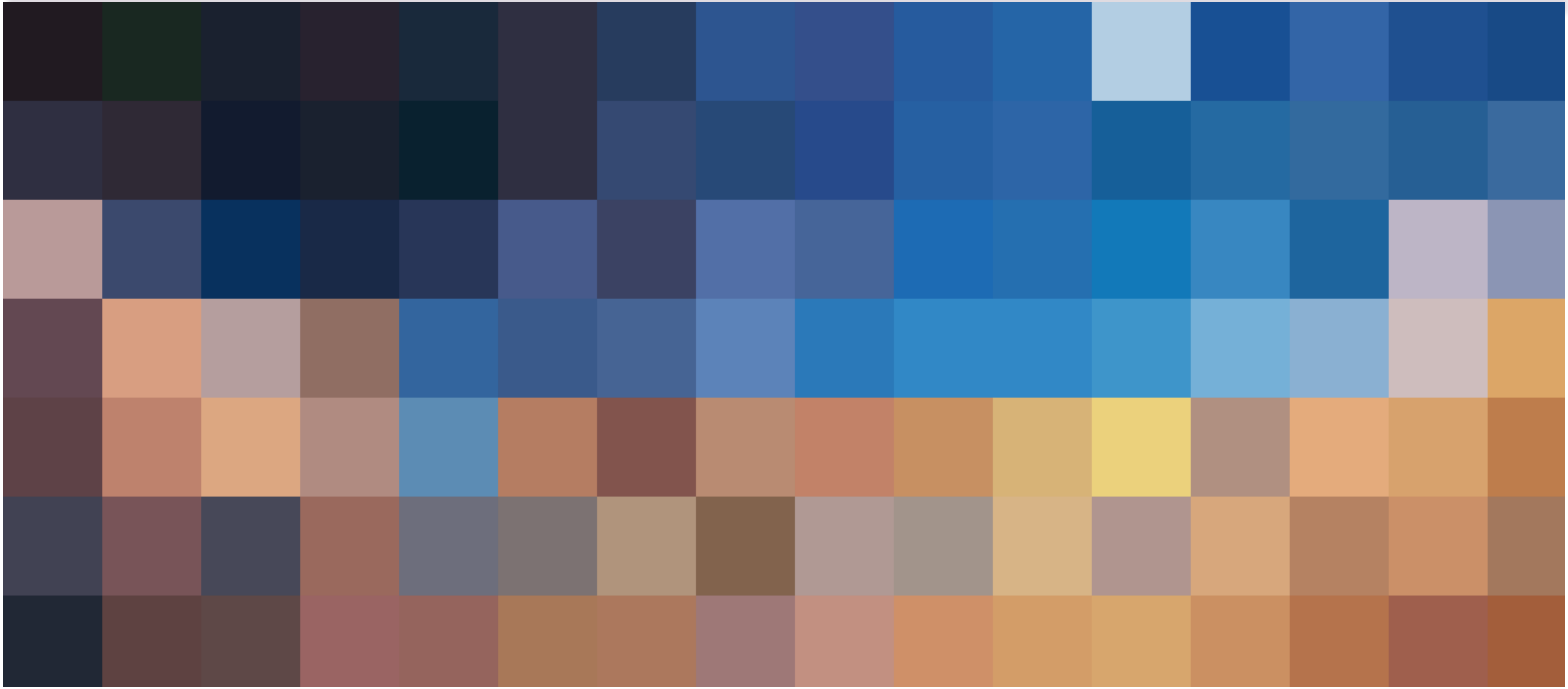

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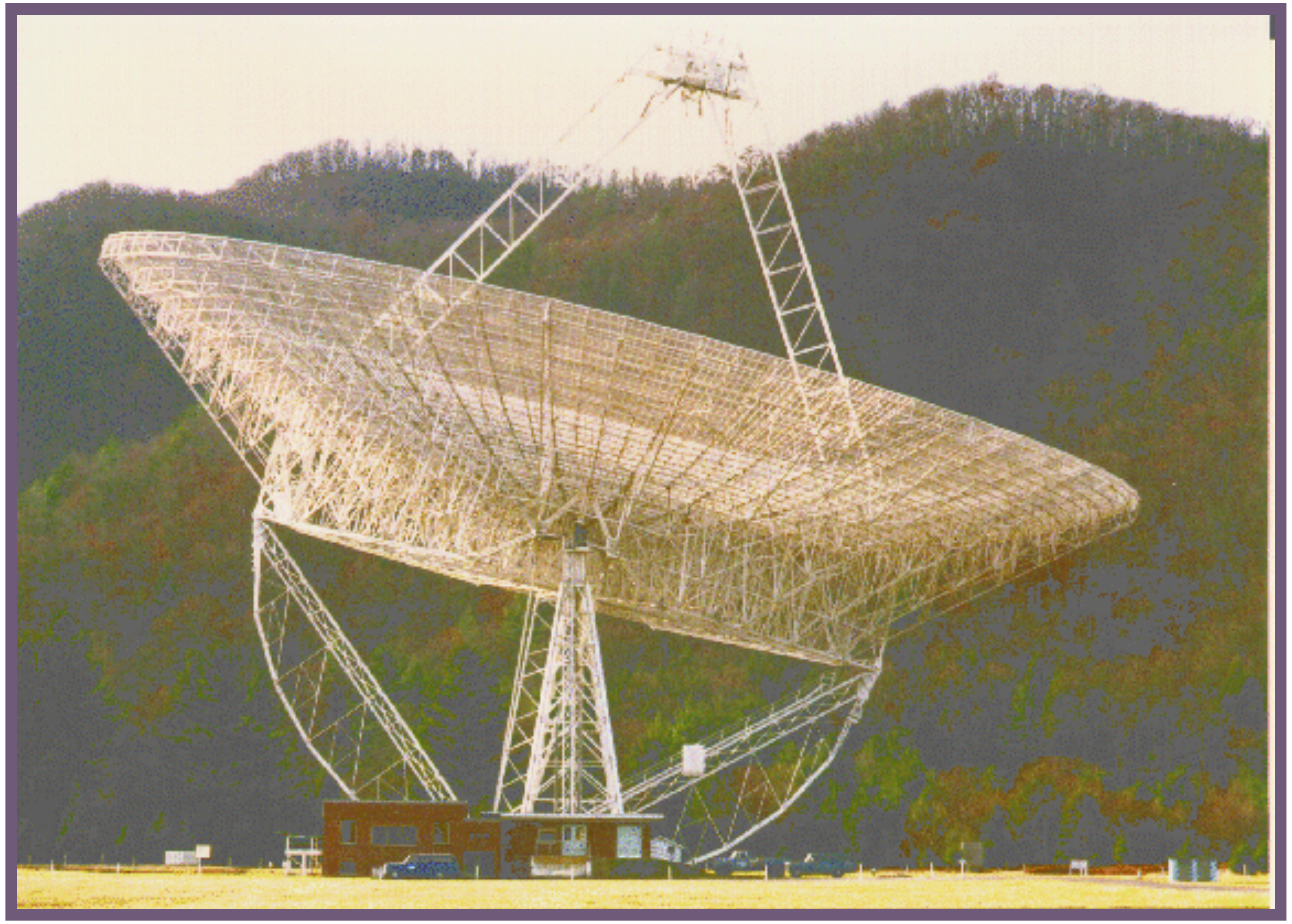

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...and building big telescopes is hard!

Old Green Bank Telescope (0 m)

Image credit: Richard Porcas/NRAO

...and building big telescopes is hard!

Old Green Bank Telescope (0 m)

Image credit: Richard Porcas/NRAO

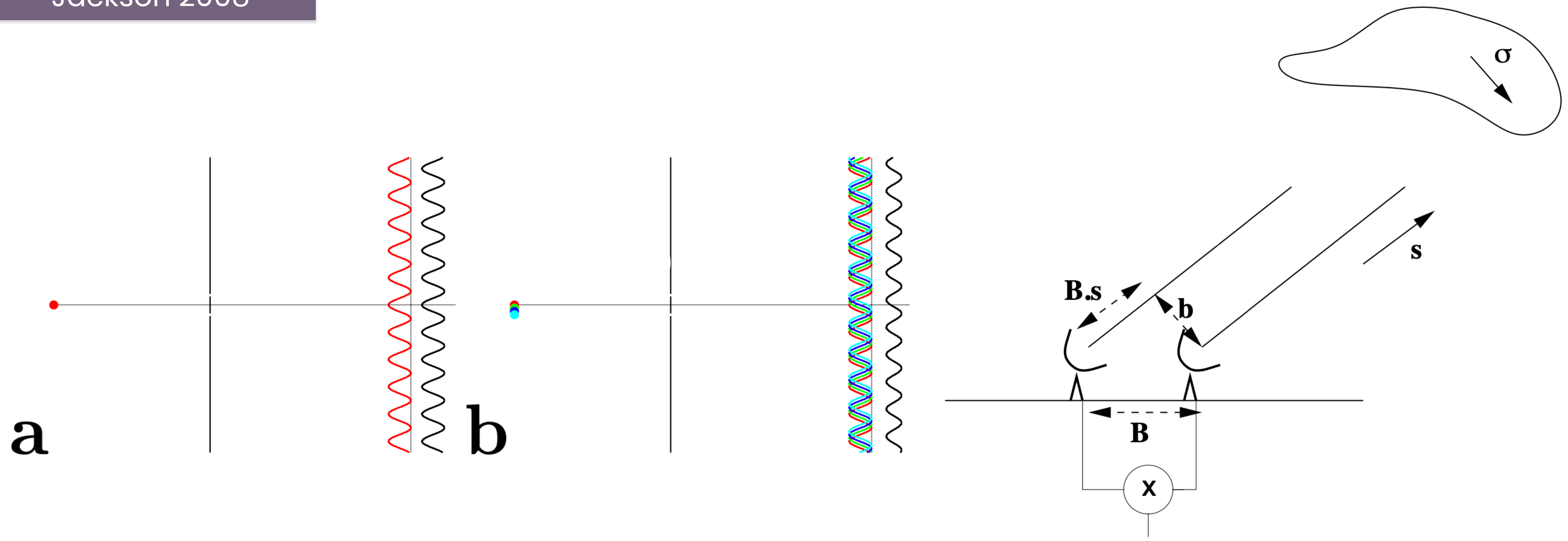
Very Large Array (25 m)

Image credit: NRAO

We can use many small telescopes as one big array!

Young experiment – principle of interferometry

Jackson 2008



Interferometry - using wave properties of light to overcome technical limitations

Atacama Large Millimeter/submillimeter Array (ALMA)

5000 m.a.s.l at Atacama Plateau - one of the driest places on Earth

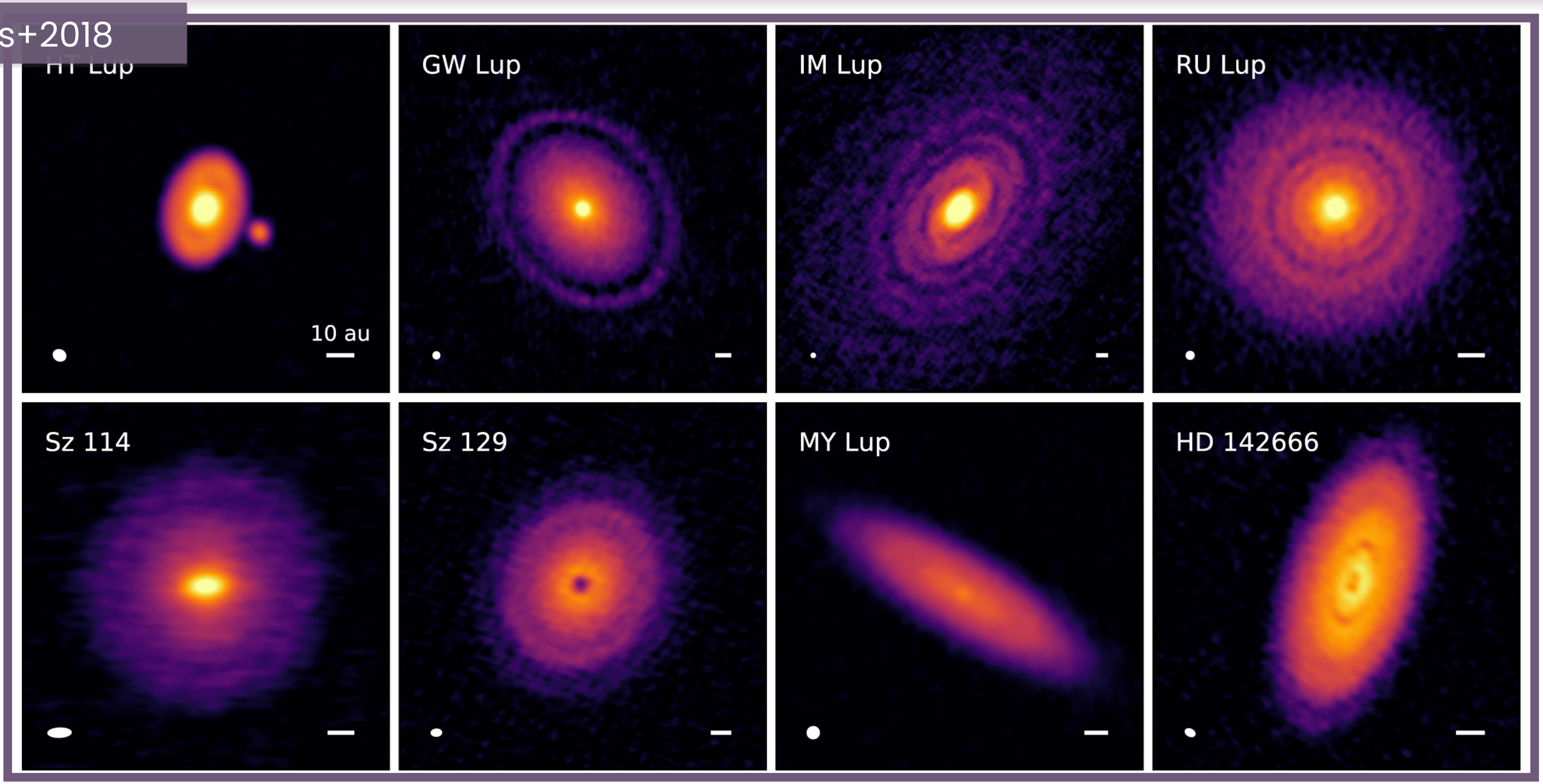
66 antennas (12 and 7 metres diameter)

Configurations from 160 m to 16 km max. baseline

Image credit: ALMA

Revolution of interferometry – ALMA

Andrews+2018



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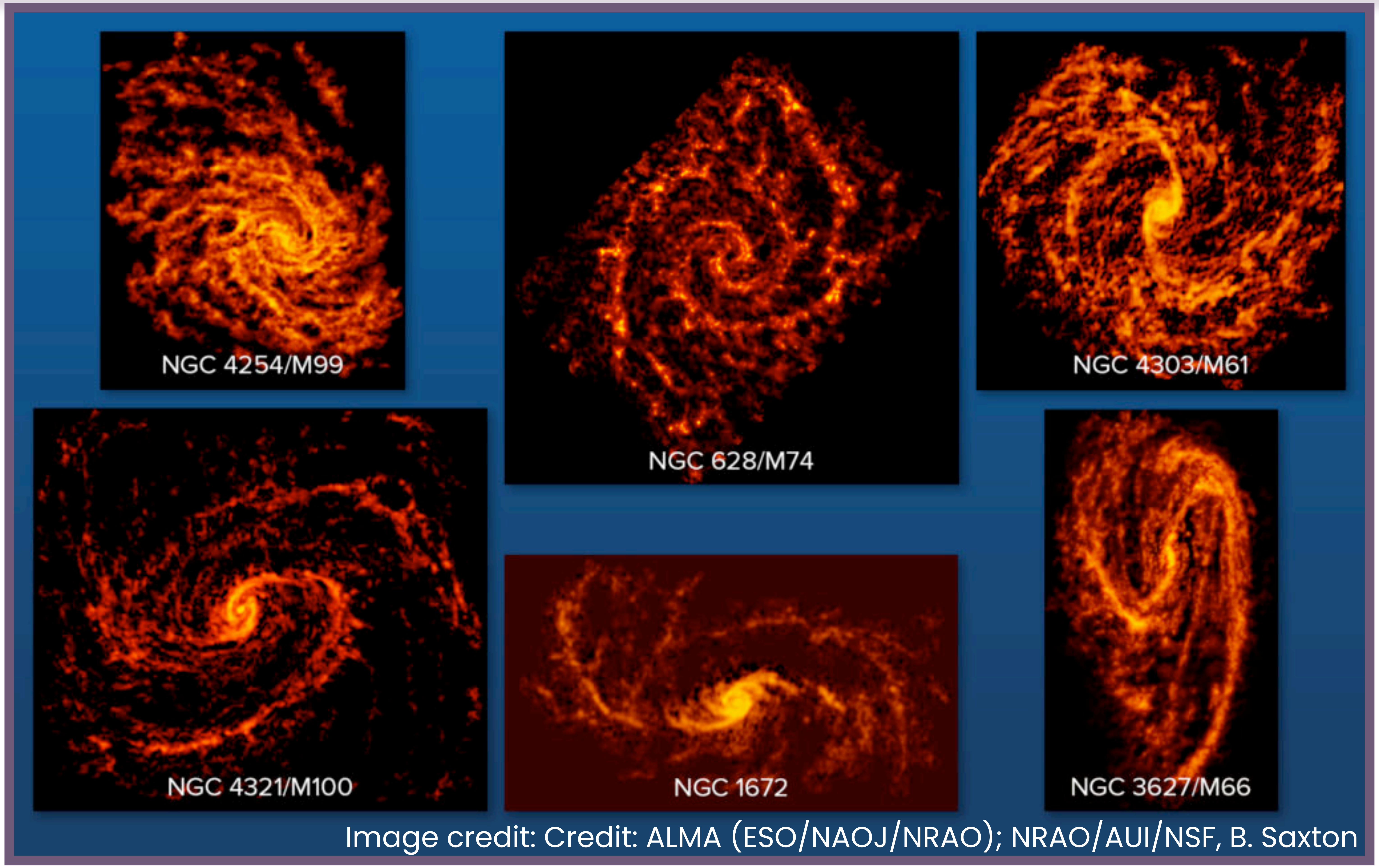
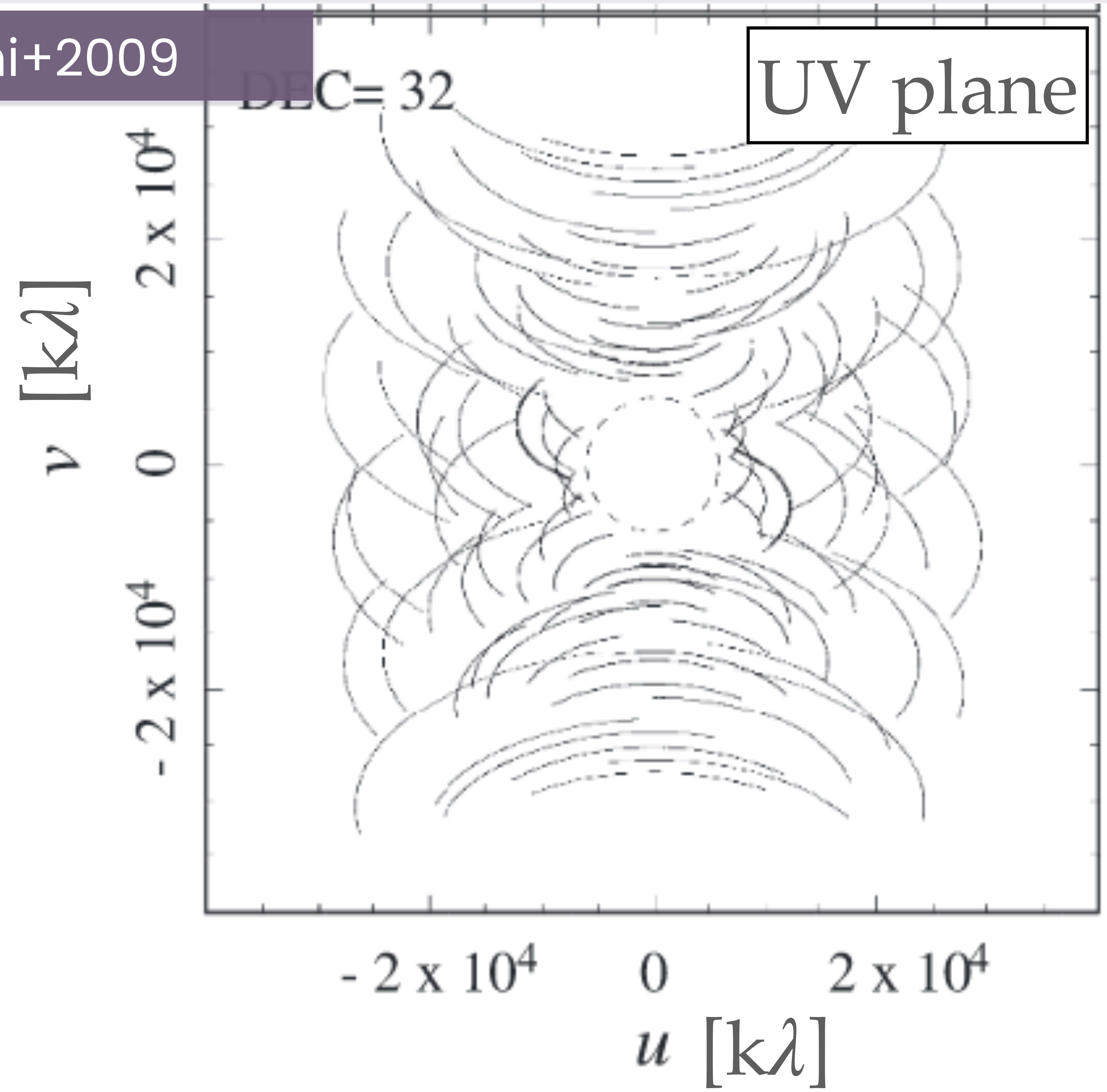
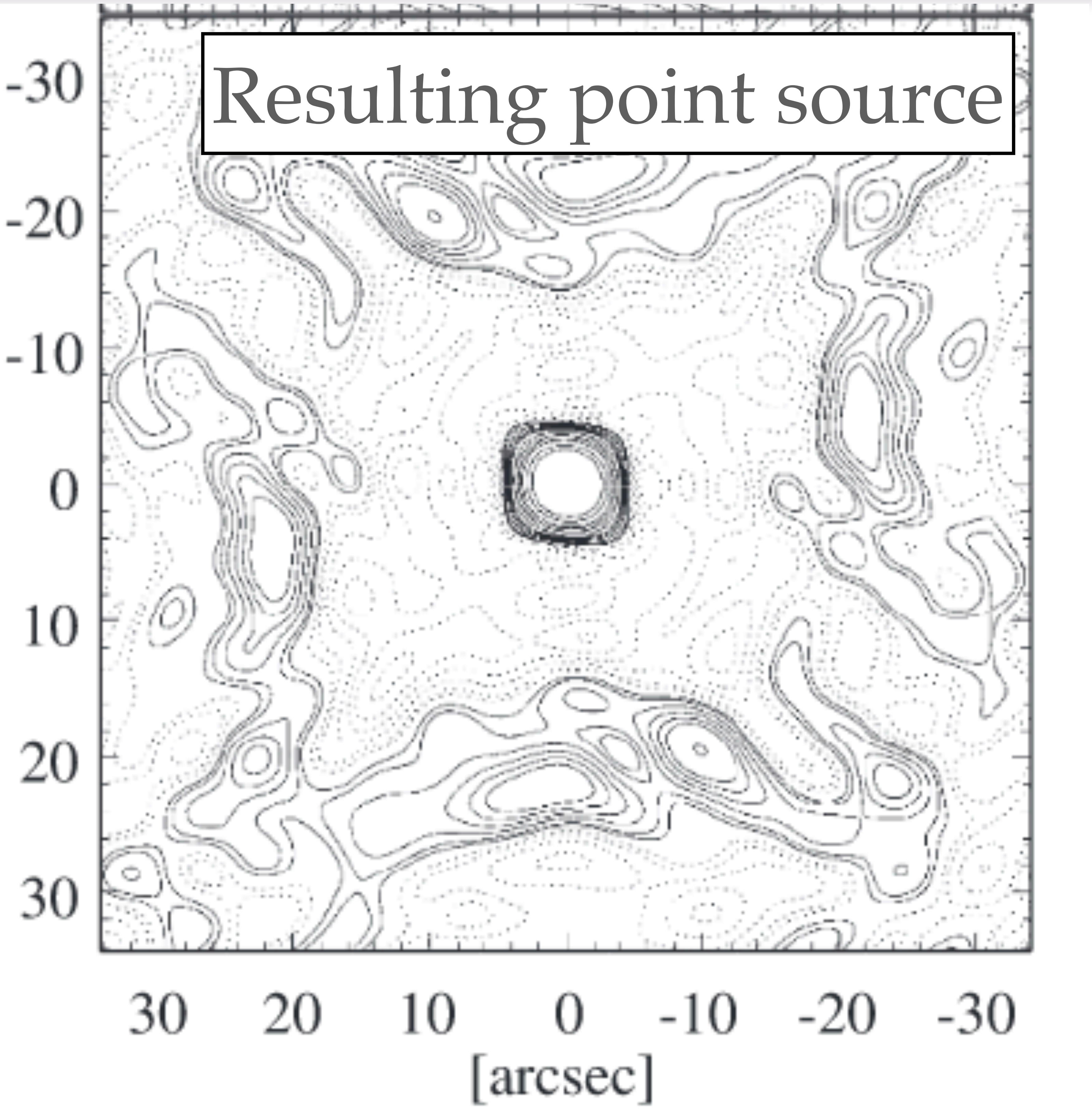


ALMA delivered stunning images at various cosmic scales

Missing information problem in interferometry

Iguchi+2009

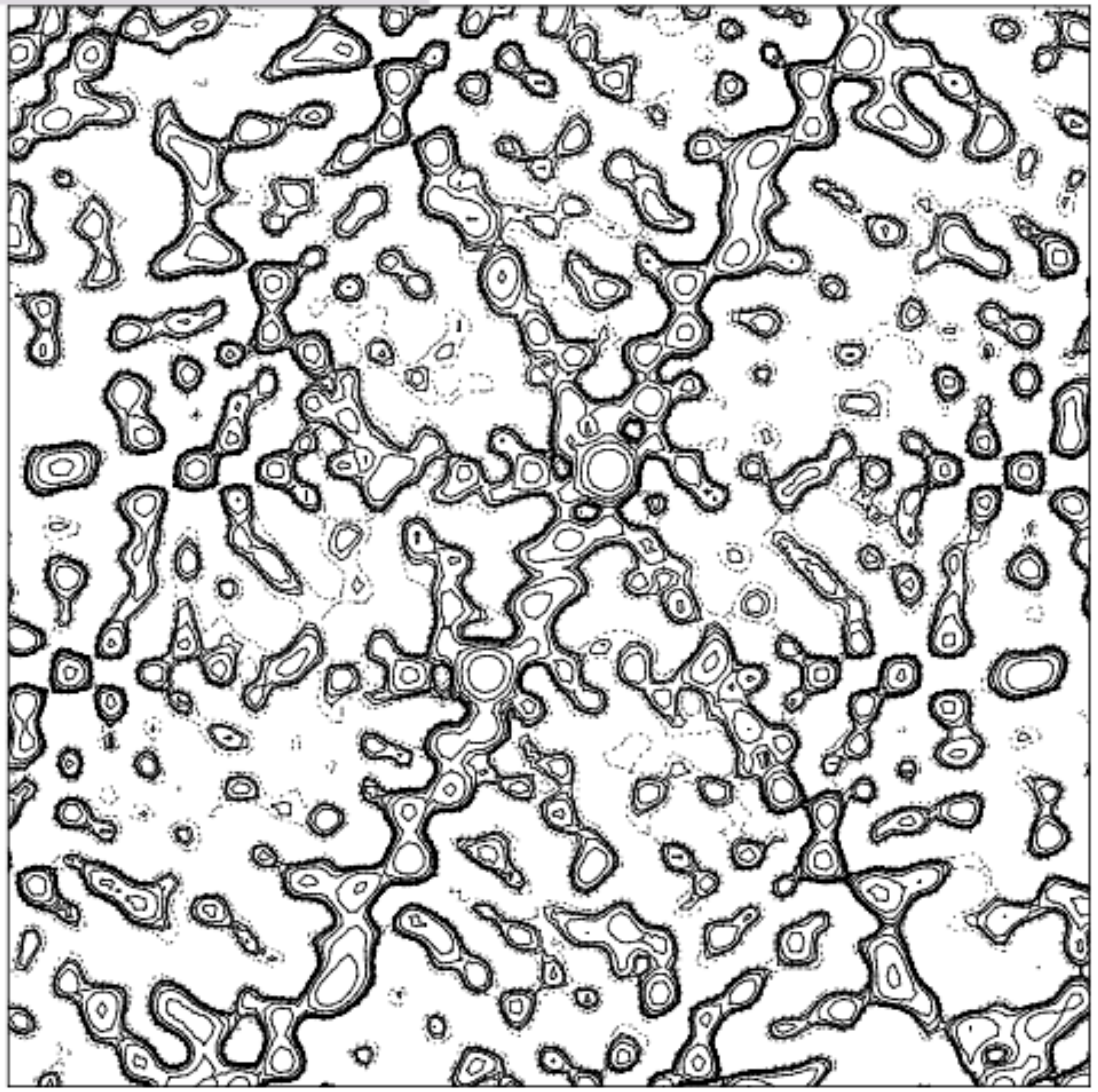




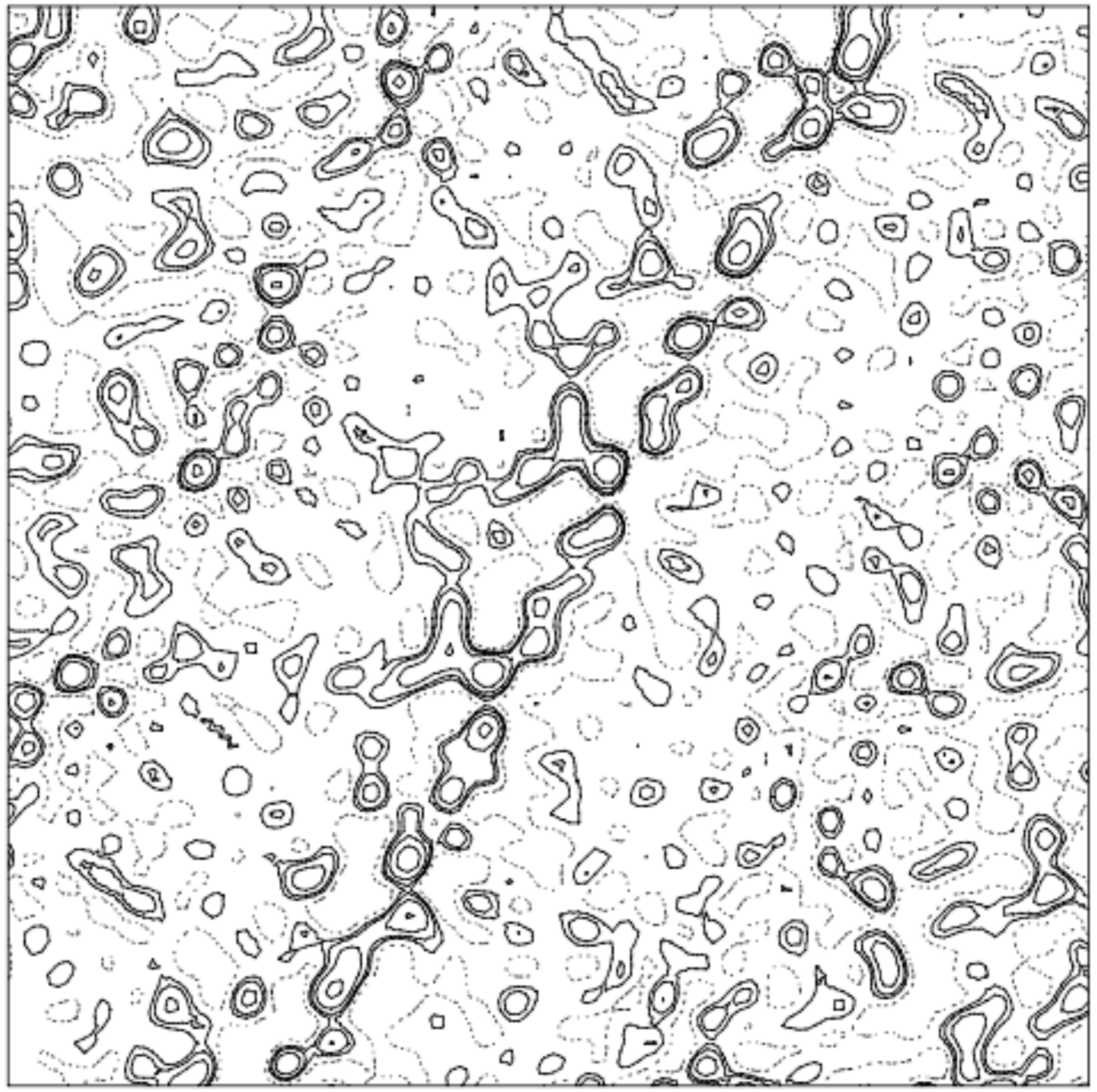
Superior resolution comes with a cost - we cannot sample all scales equally

CLEAN fundamentals

Jackson 2008



remove PSF



CLEAN fundamentals

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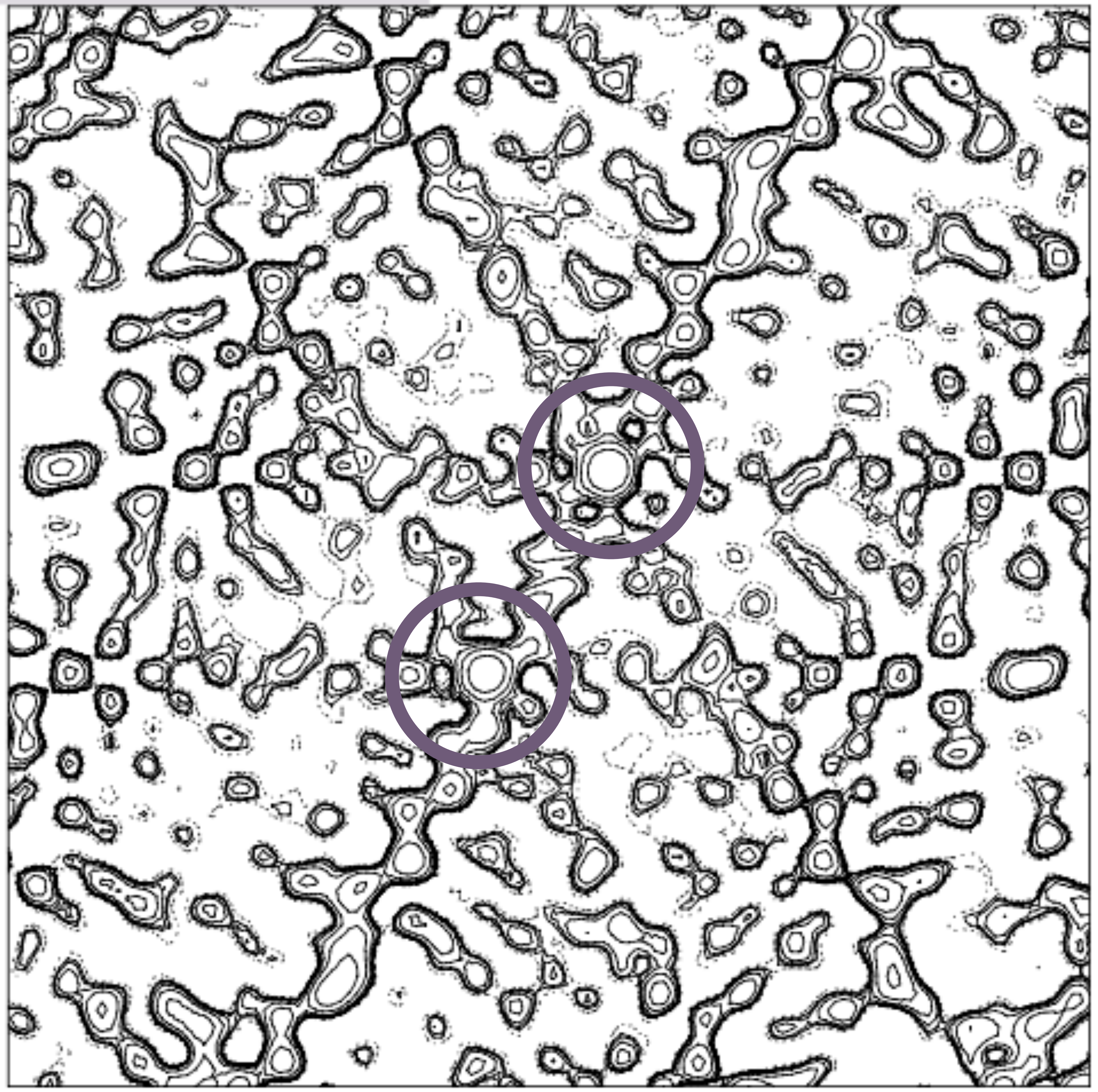

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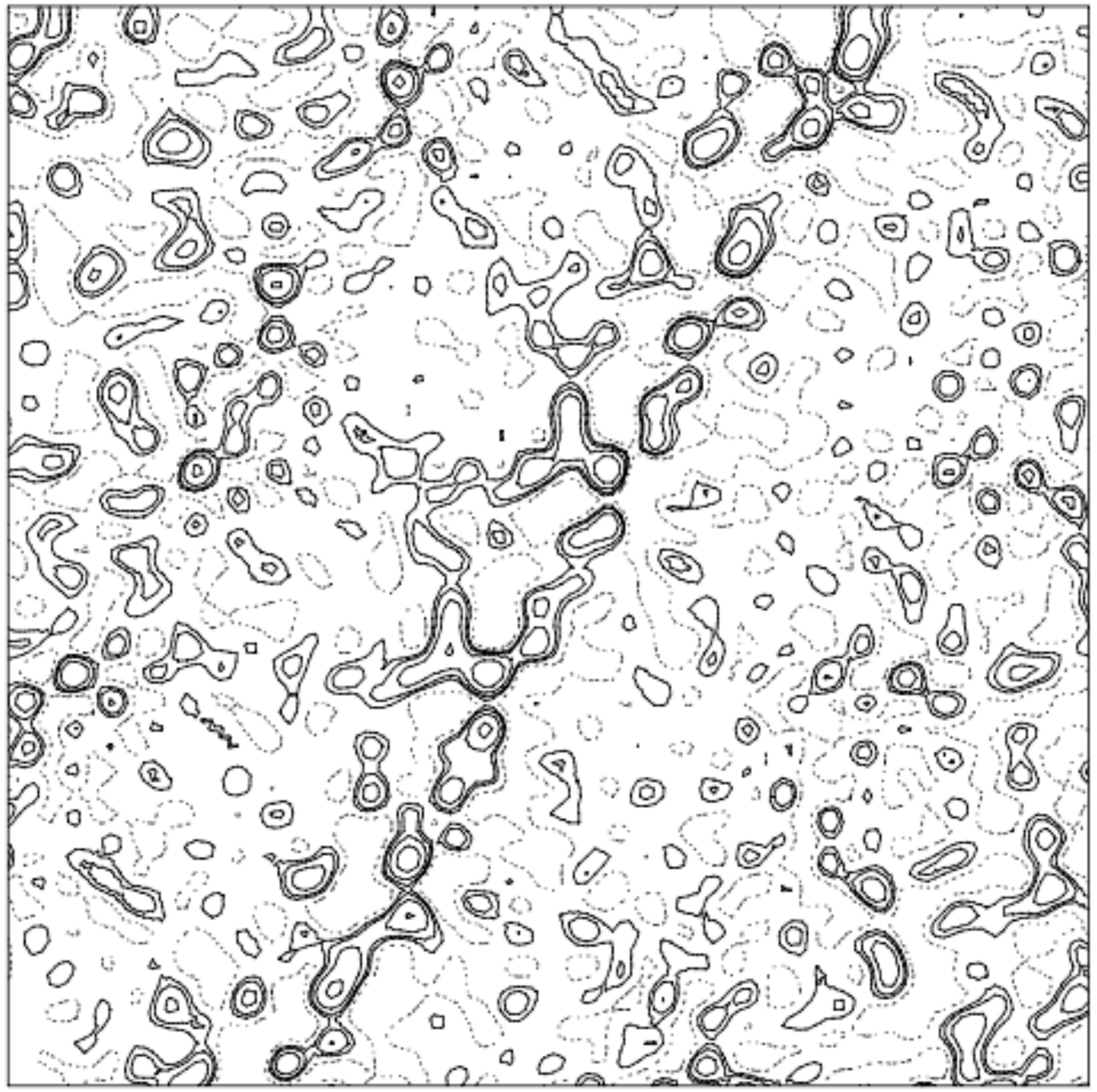

CLEAN fundamentals

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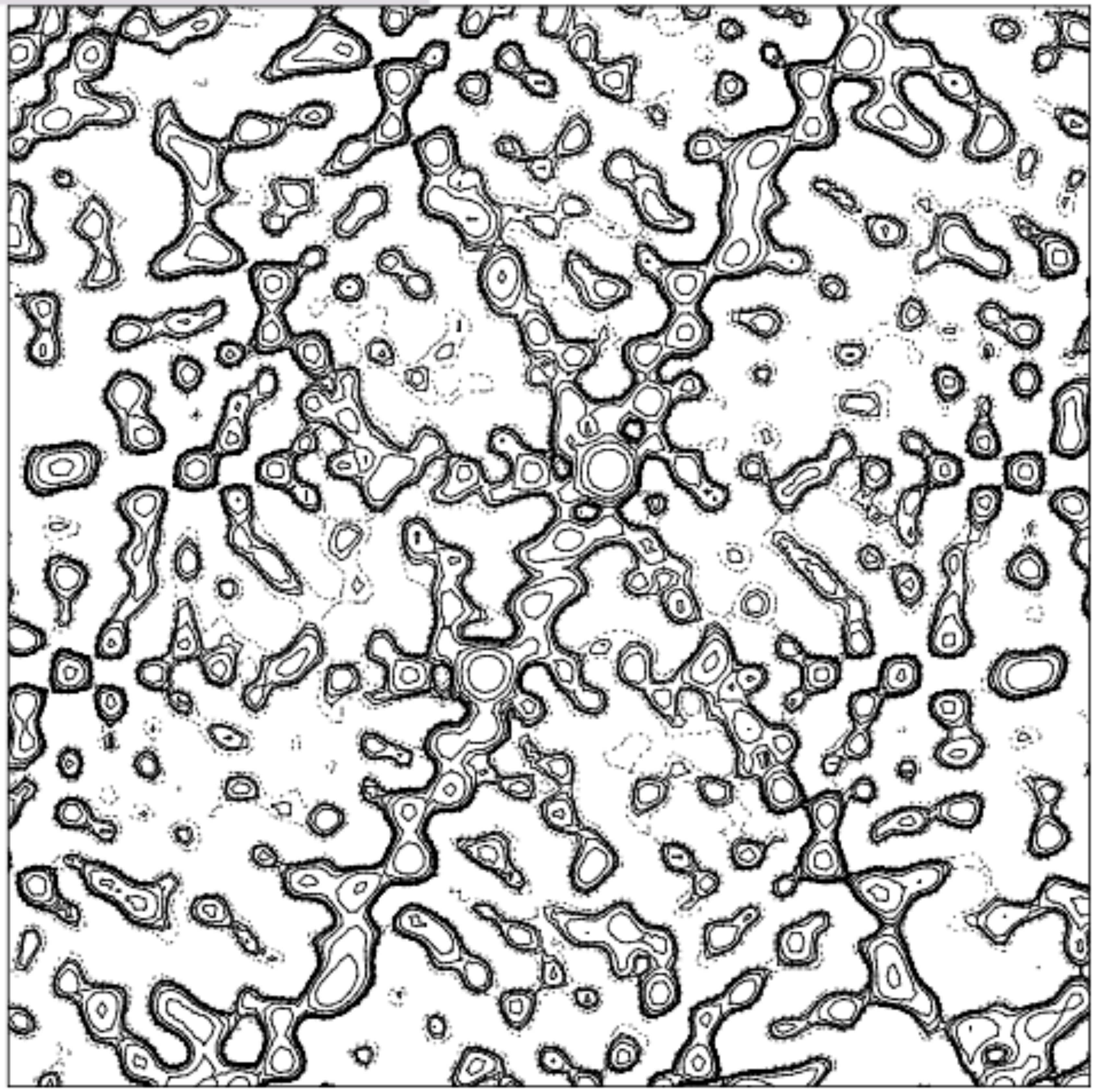
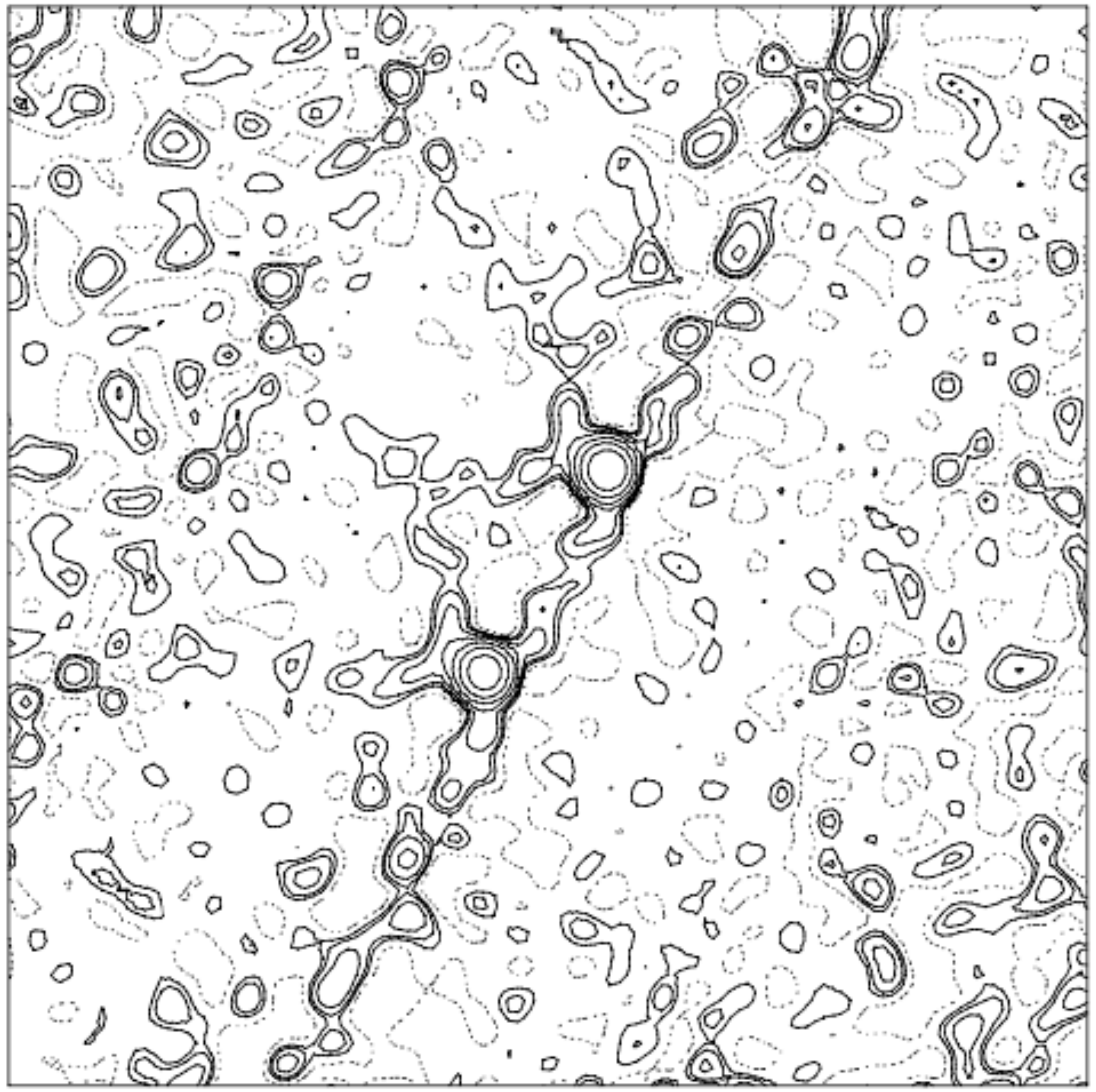
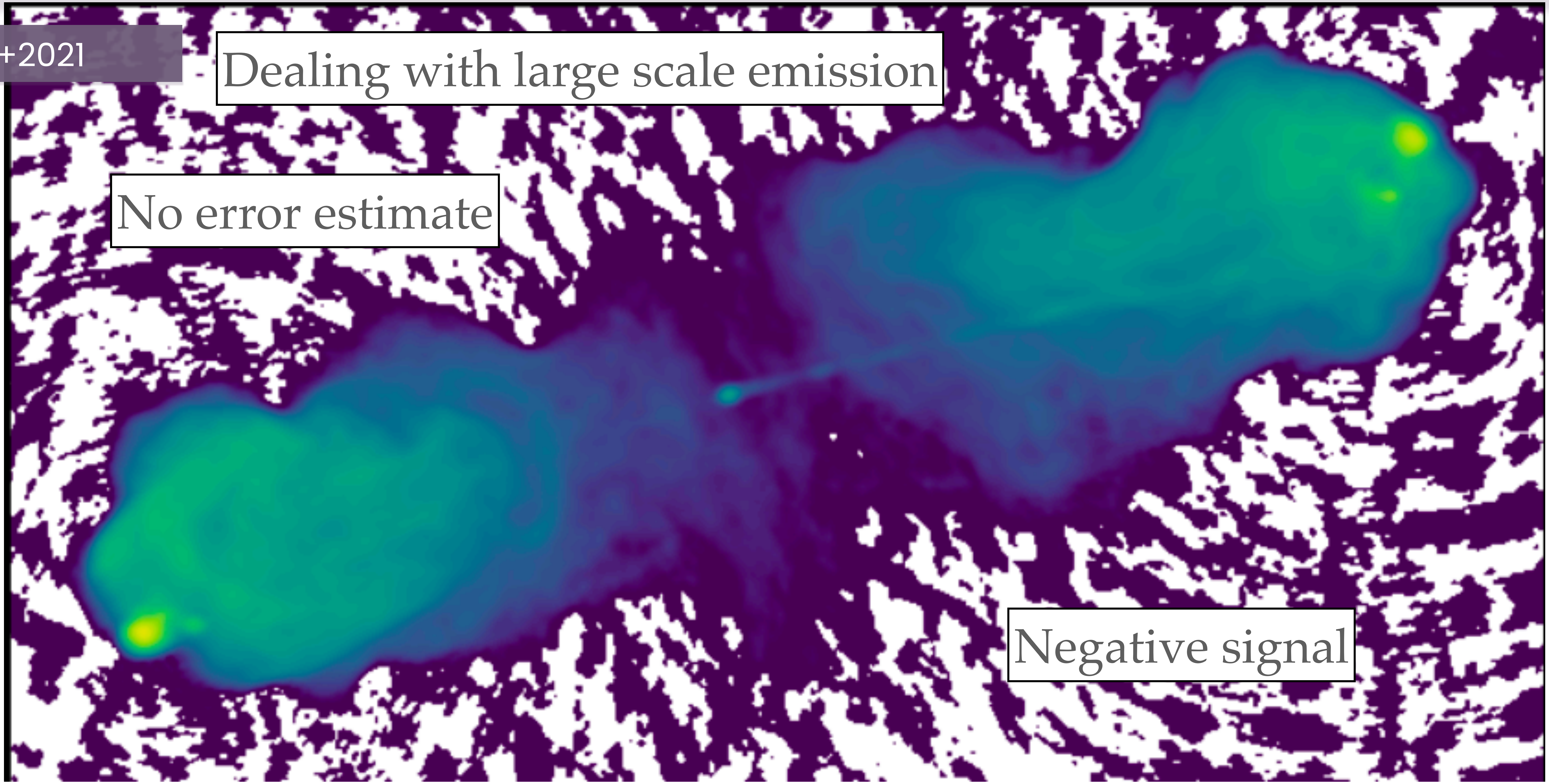




Limitations of CLEAN

Arras+2021



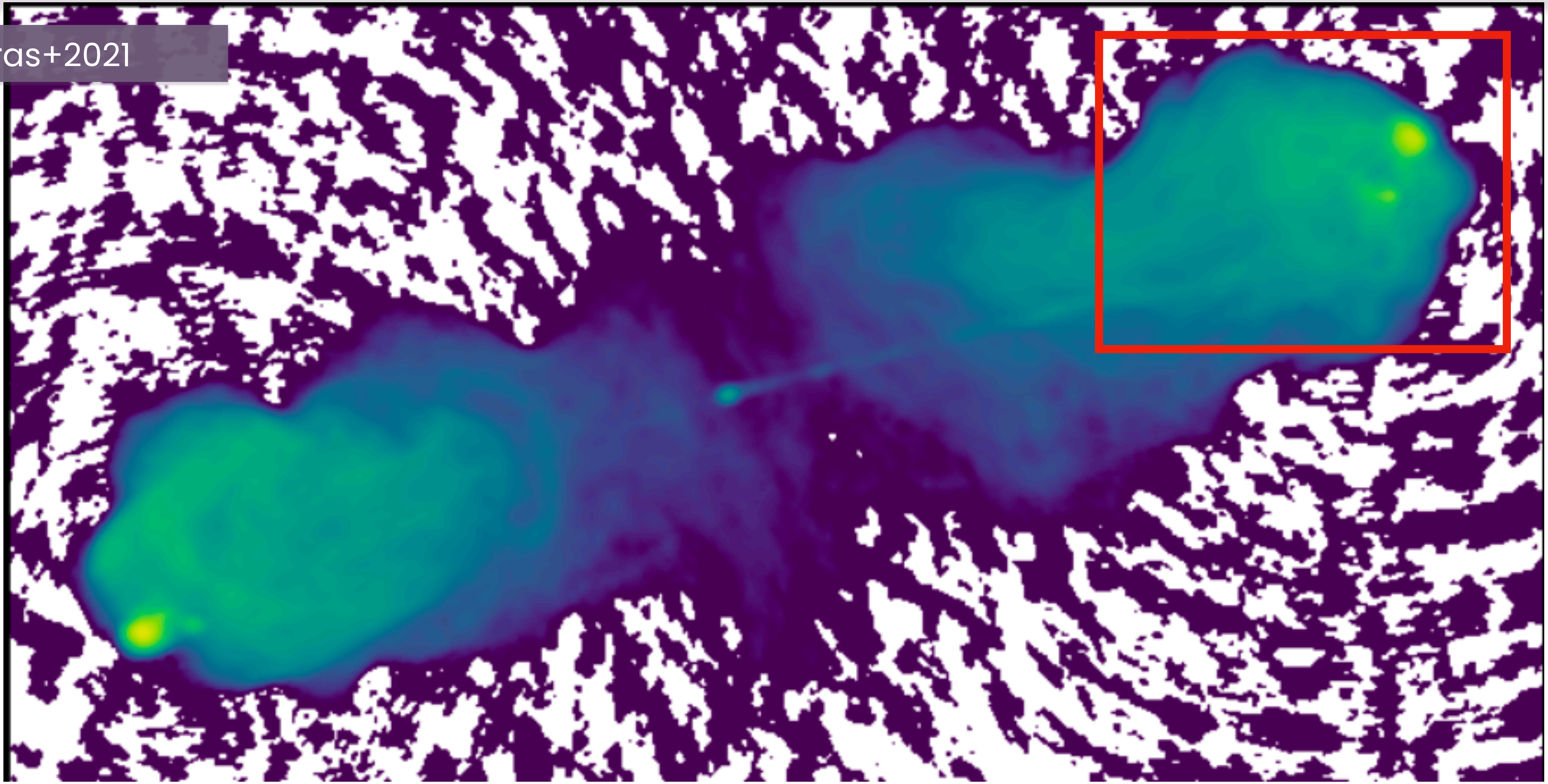
$$\mathcal{P}(s|d) = \frac{\mathcal{P}(d|s)\mathcal{P}(s)}{\mathcal{P}(d)}$$

RESOLVE algorithm

Enßlin+2009, Junklewitz+2014, Arras+2018

Comparison of RESOLVE and CLEAN algorithms – VLA test

Arras+2021



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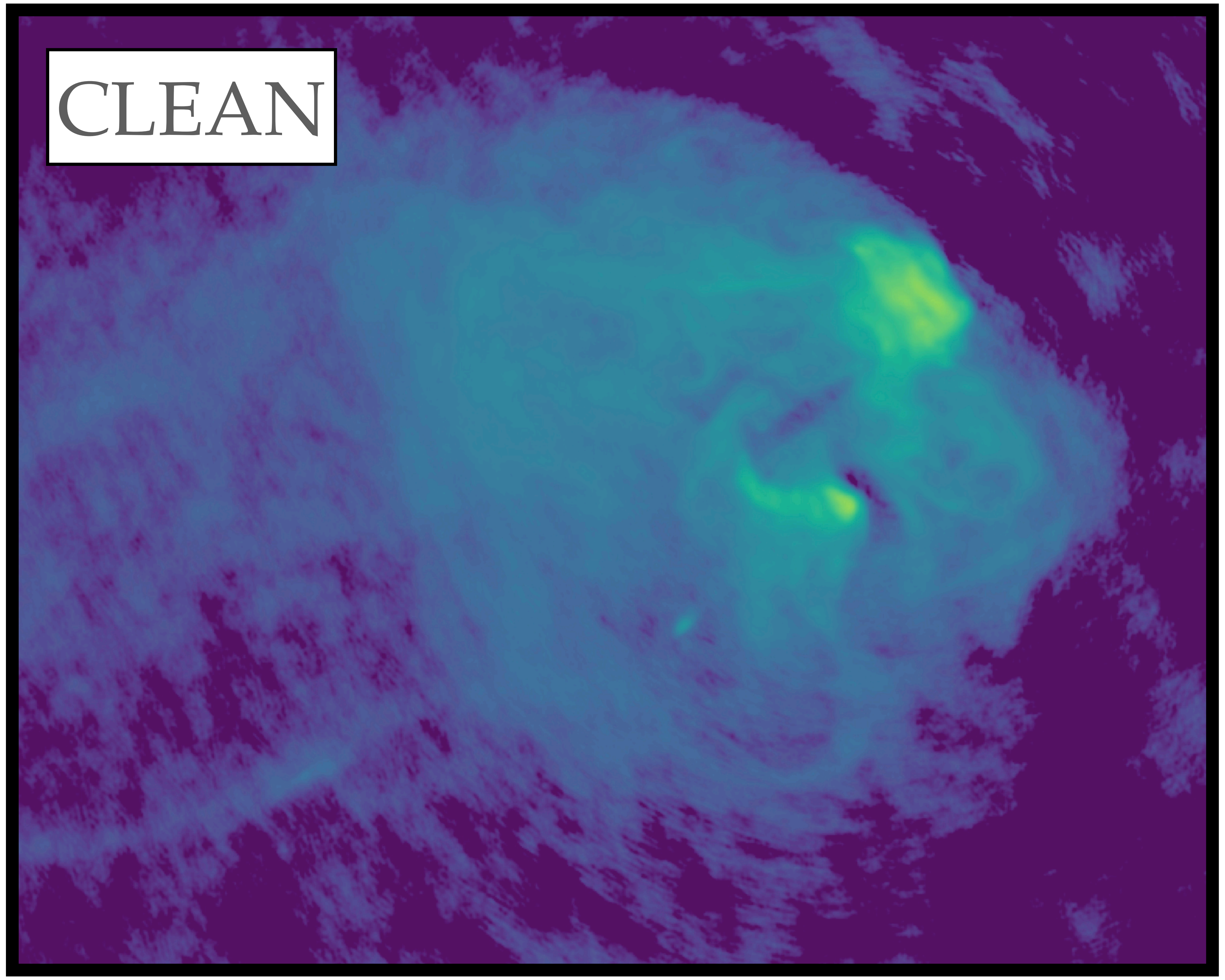
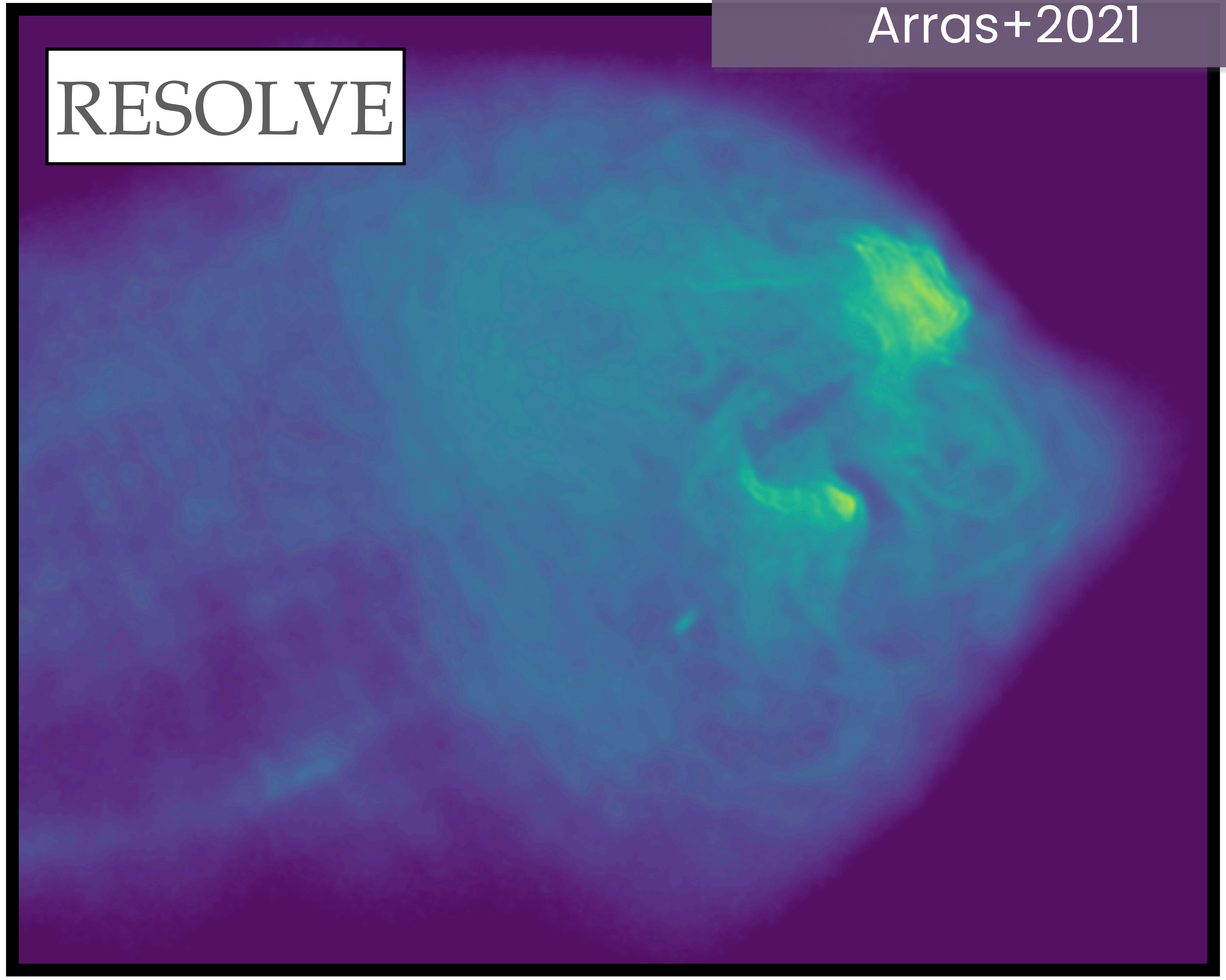
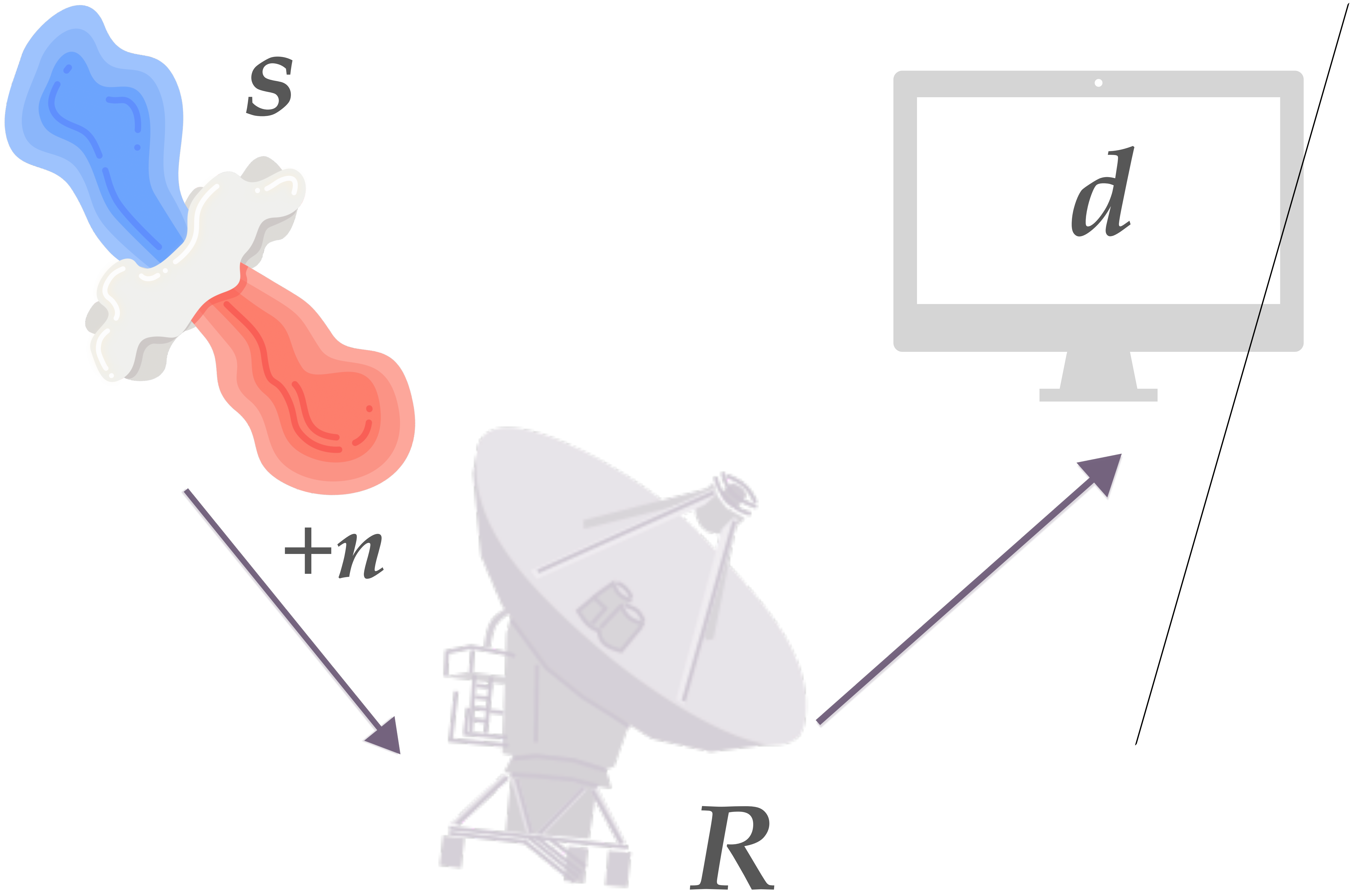




RESOLVE excels in retrieving large-scale emission

Astronomical signal inference



$$d = Rs + n$$

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

Information Field Theory (IFT)

Enßlin+2009

- Enables to use Bayesian inference in the context of field theory
- Treats field as a continuous object (no pixelisation)
- Allows for field theory formalism
- Well fitted to the context of inference of sky brightness from interferometric observation
- Practically: NIFTy python package (Reinecke+2018, Selig+2013, Arras+2019)

Minimum information on the field

1. Emitting sources have some unknown spatial correlation structure

2. Signal field is strictly positive

3. There is orders of magnitude difference in brightness within the field

Minimum information on the field

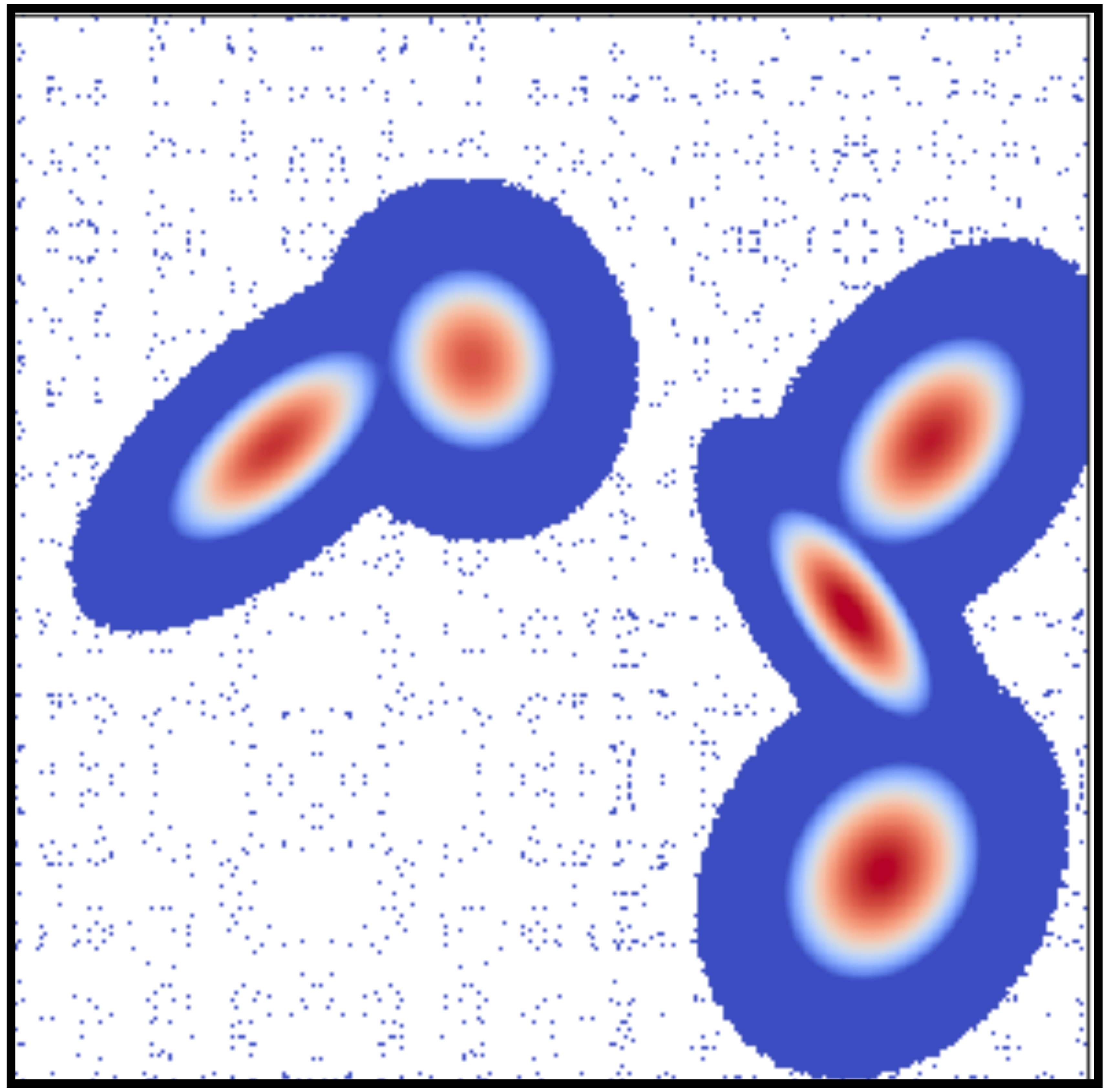
Junklewitz+2014

1. Emitting sources have some unknown spatial correlation structure → (*MaxEnt*) *Gaussian probability distribution*

2. Signal field is strictly positive

3. There is orders of magnitude difference in brightness within the field → *Logarithm of the signal field is Gaussian*

$$d = RI + n = RI_0 e^s + n$$

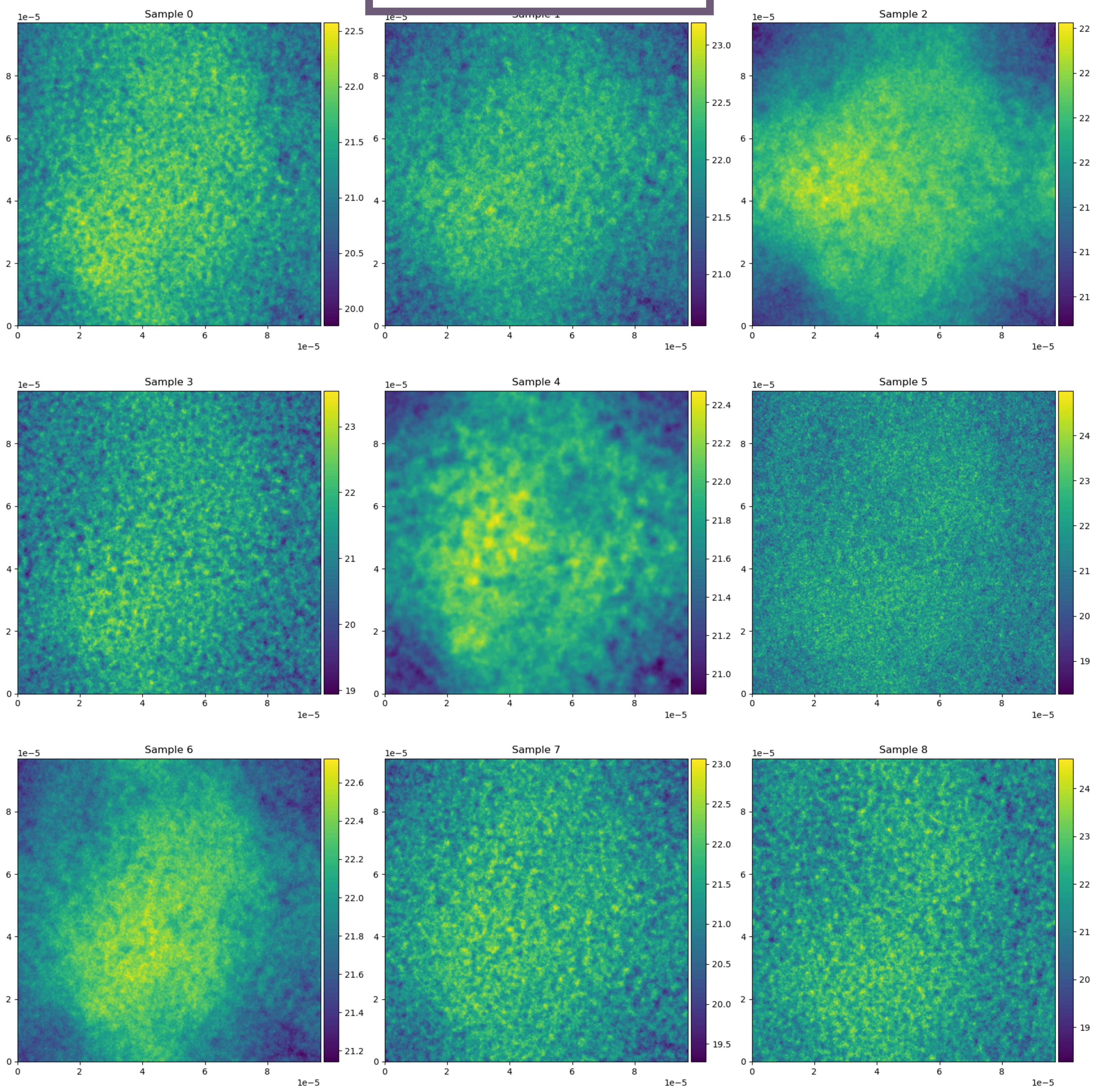


RESOLVE application to simulated dataset

A simulation of Gaussian continuum sources

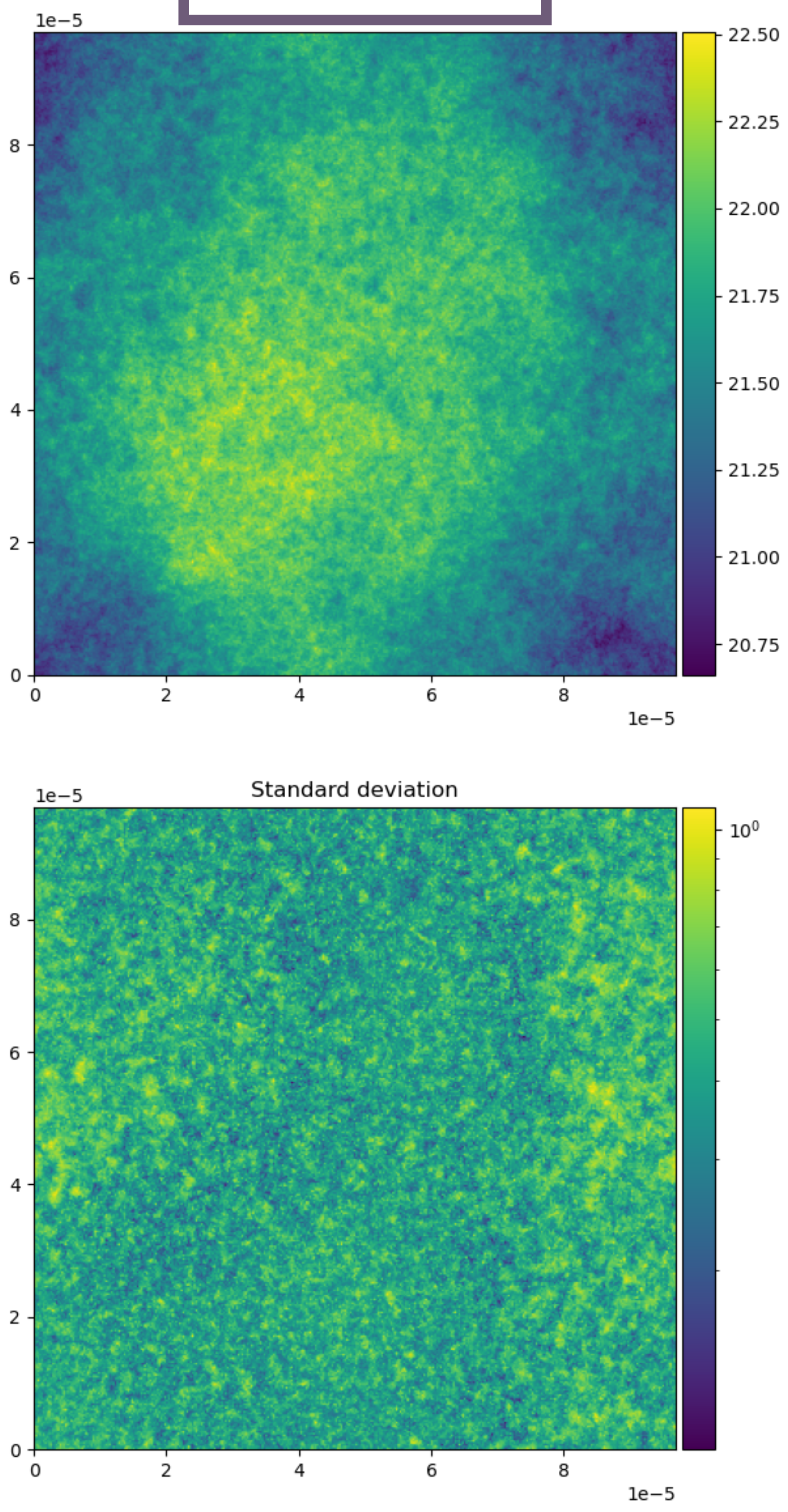
Iterations of RESOLVE

Samples

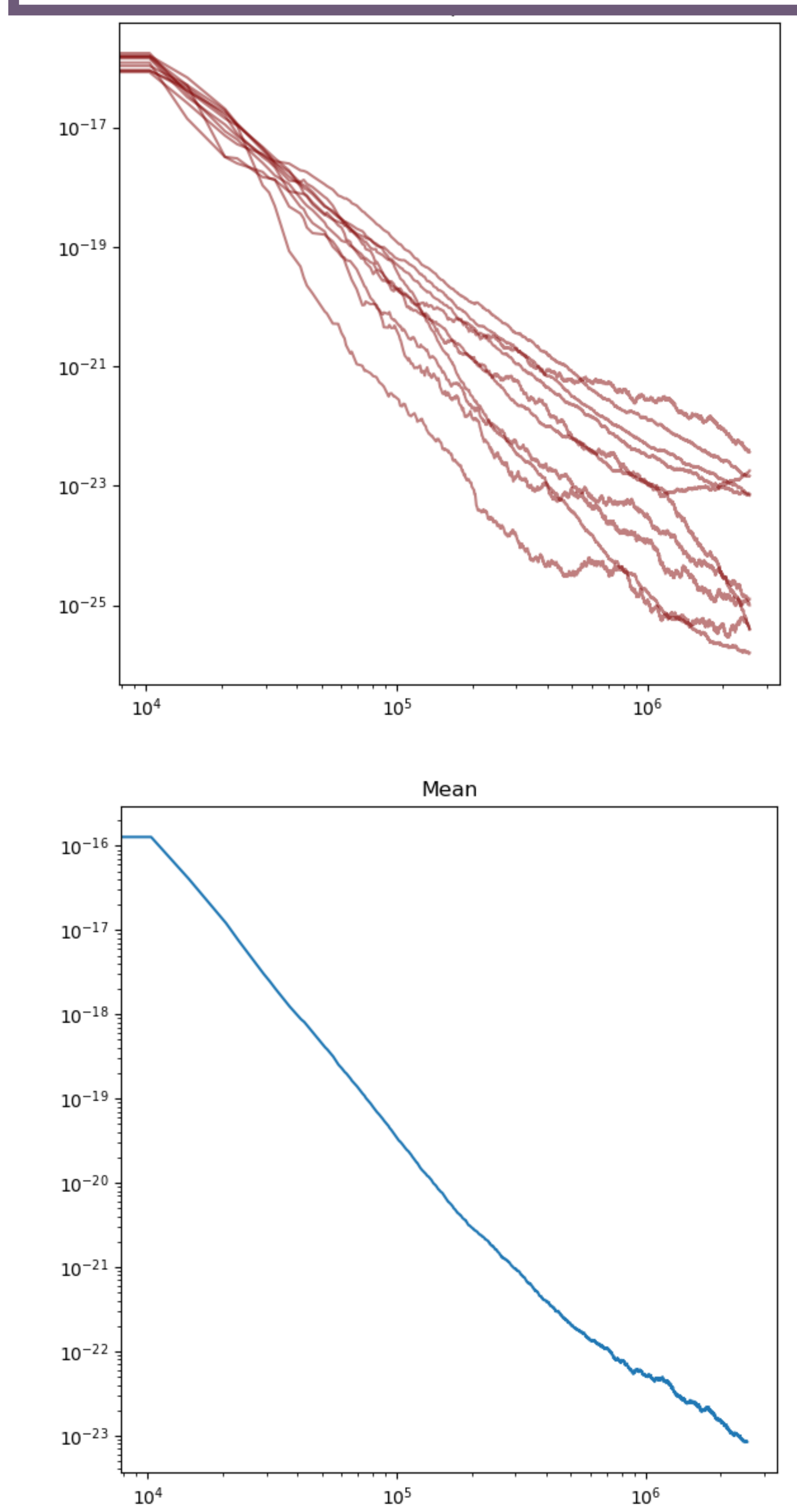


log(F) [MJy / sr]

Means



Power spectrum



Iterations of RESOLVE

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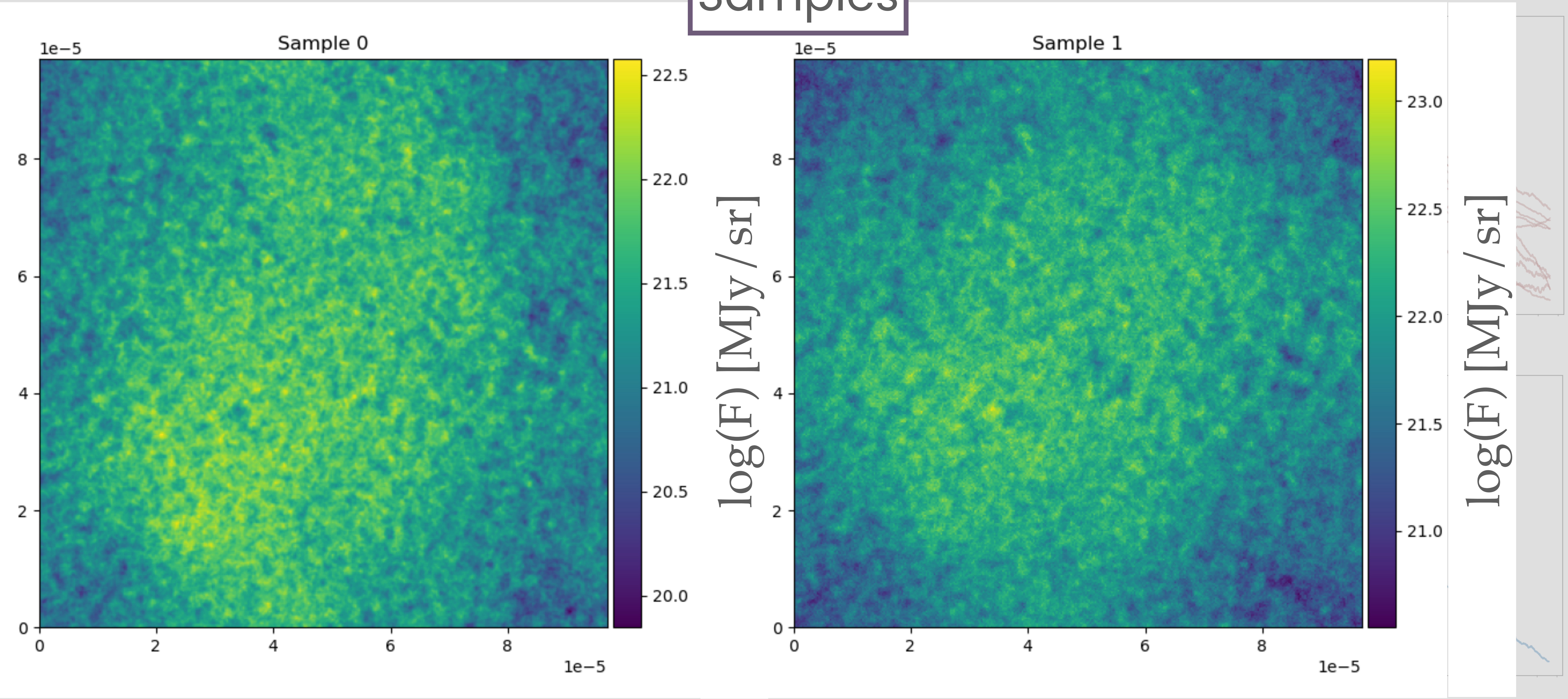

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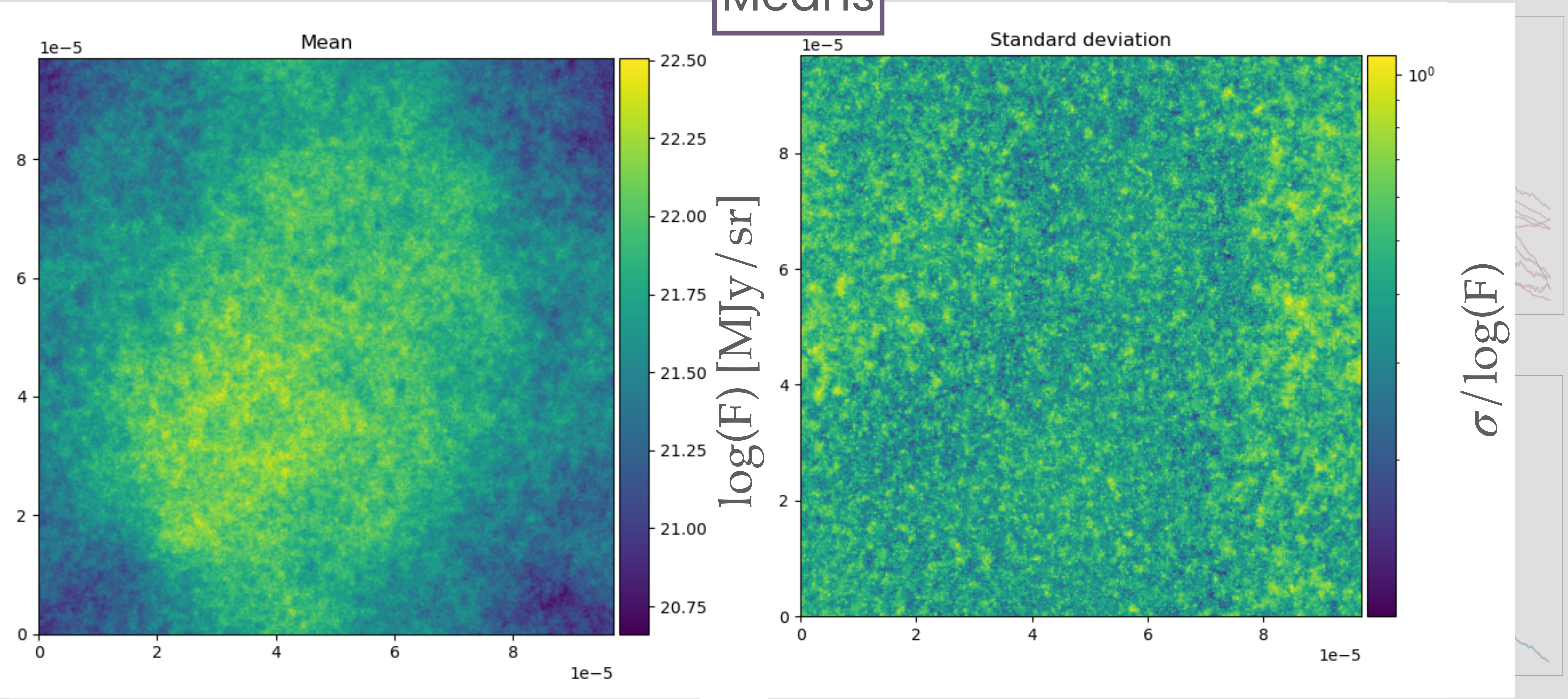
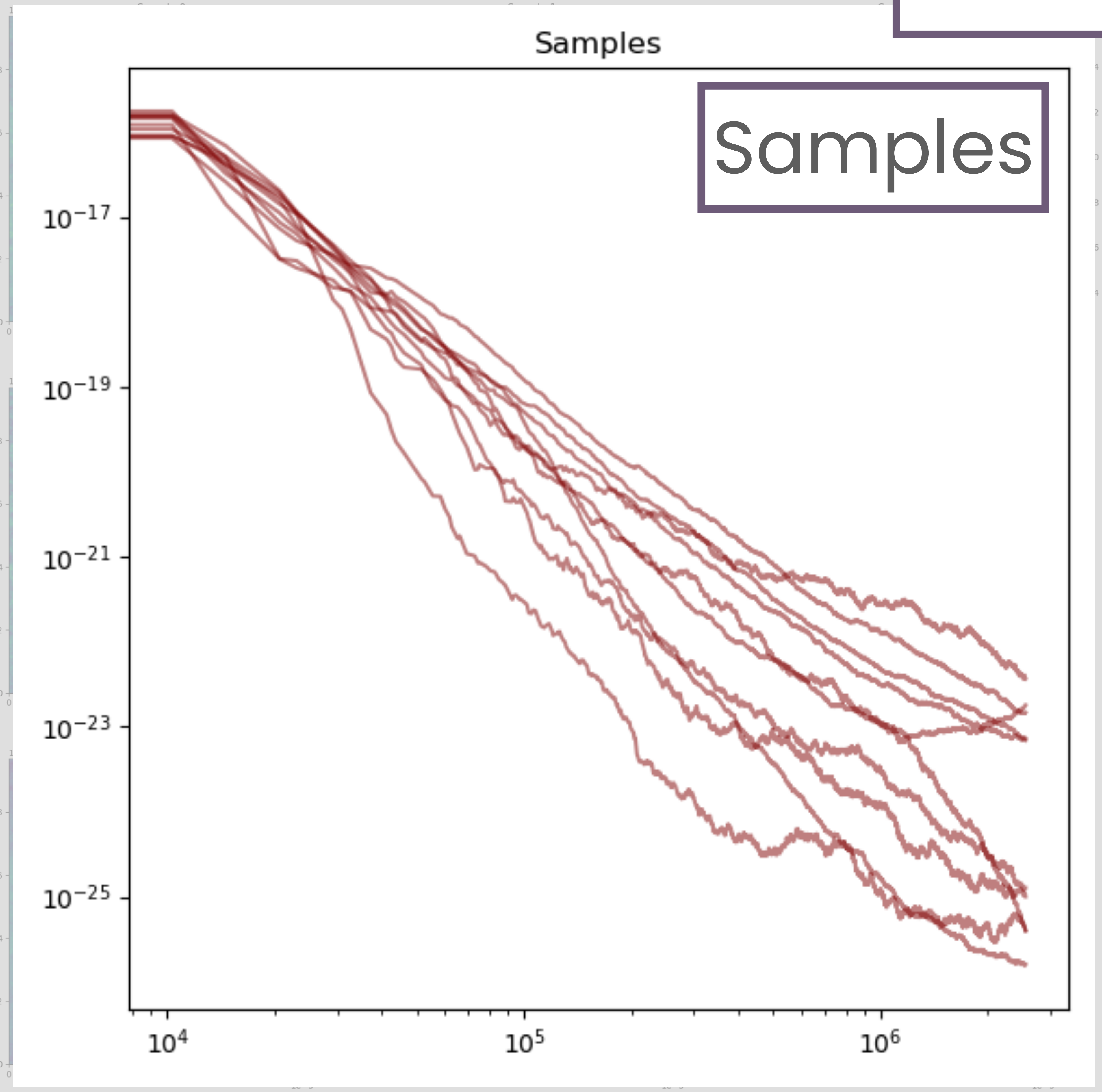
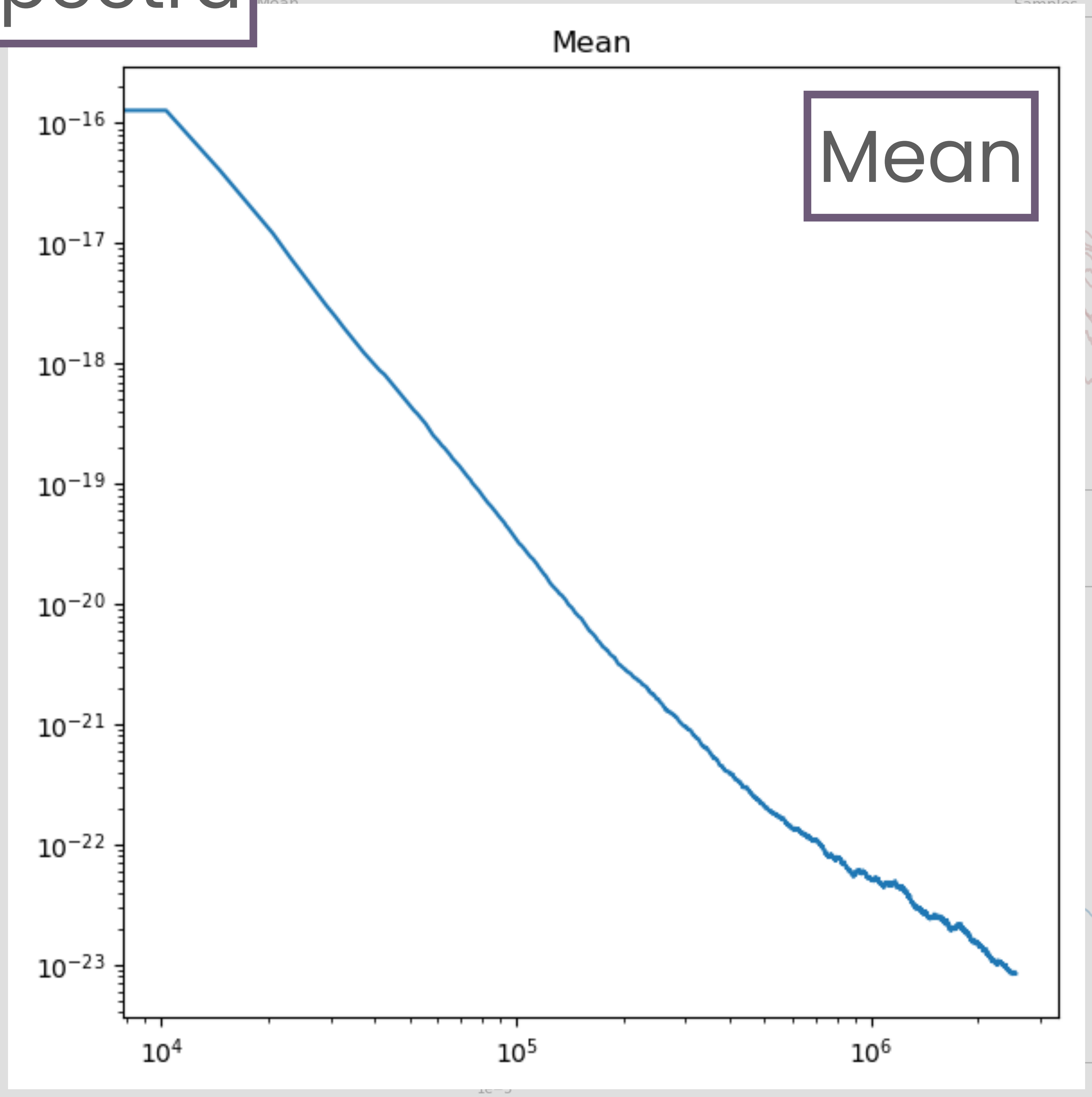


Iterations of RESOLVE

Power spectra

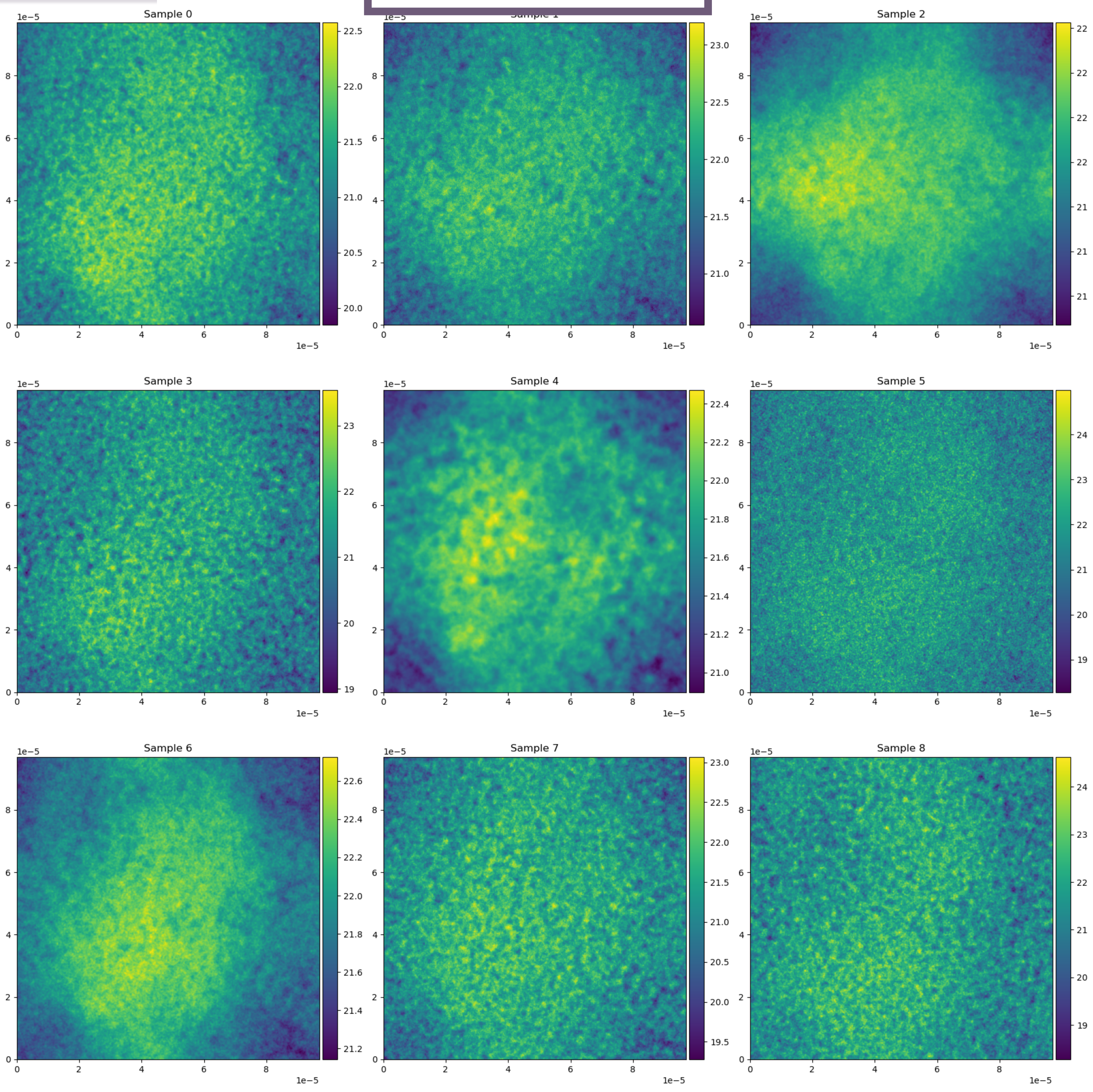




Iterations of RESOLVE

Iter = 0

Samples



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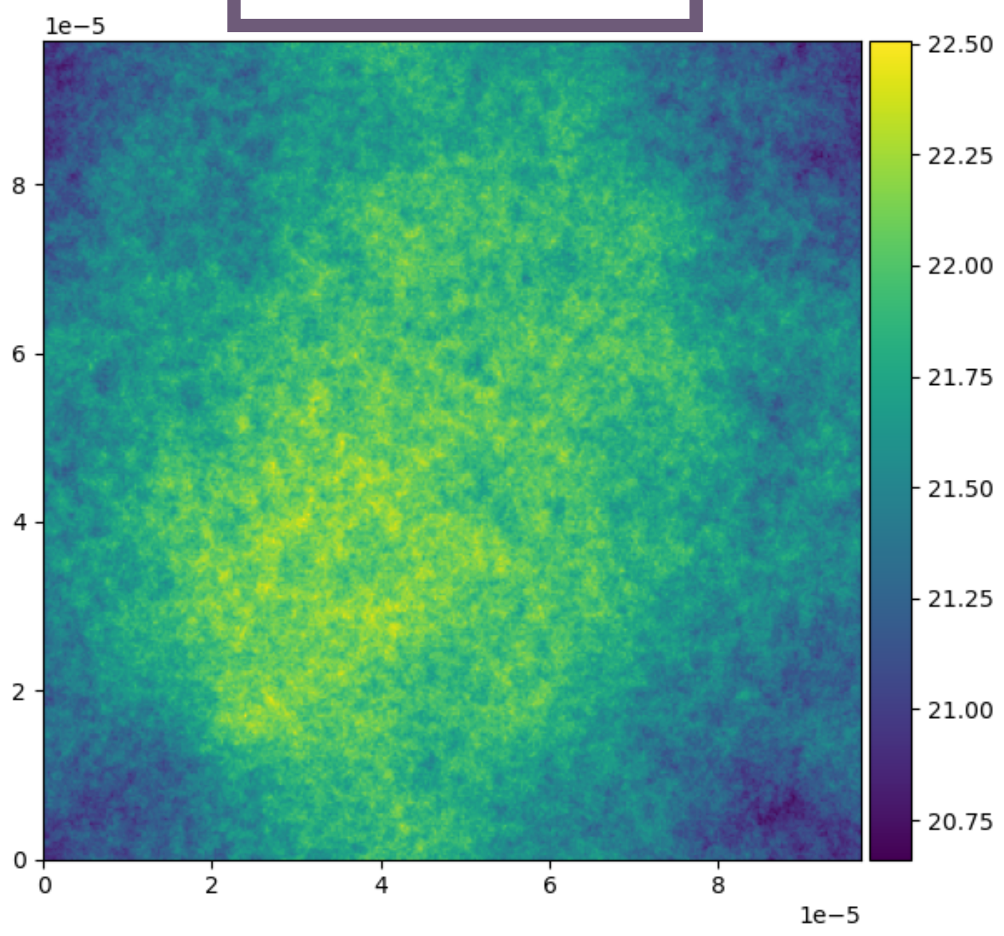
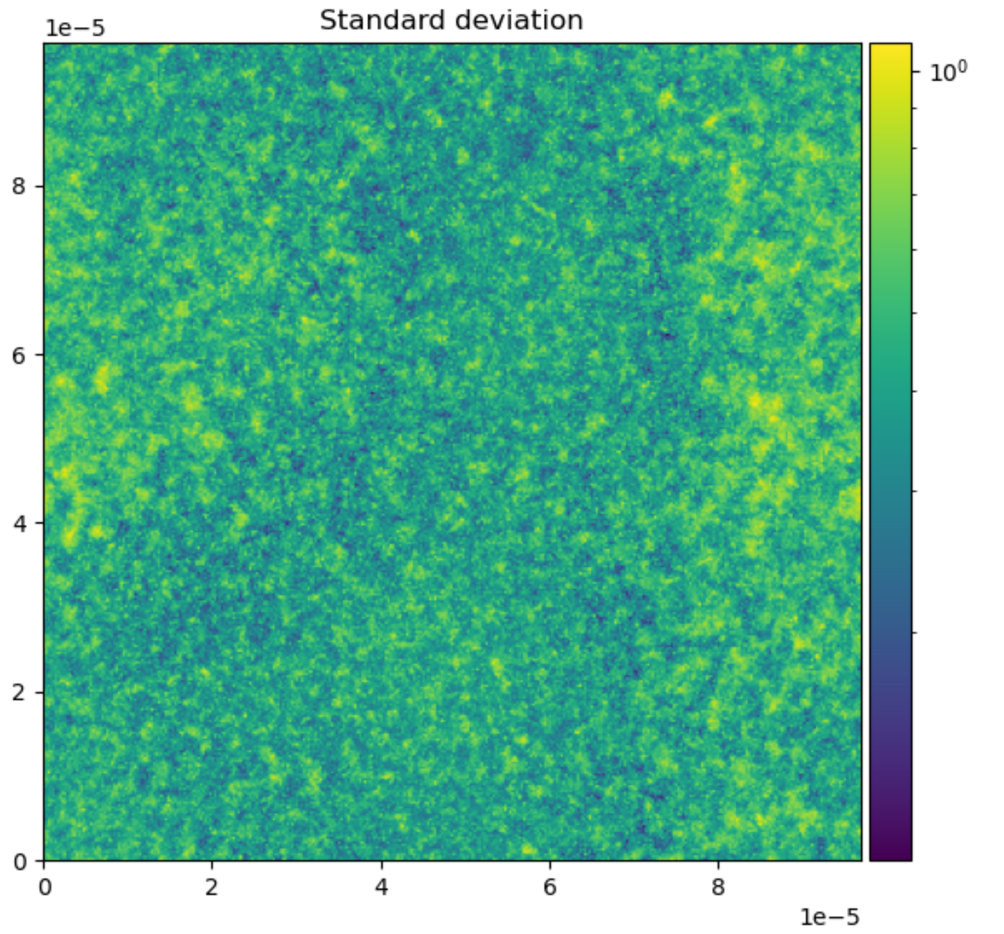
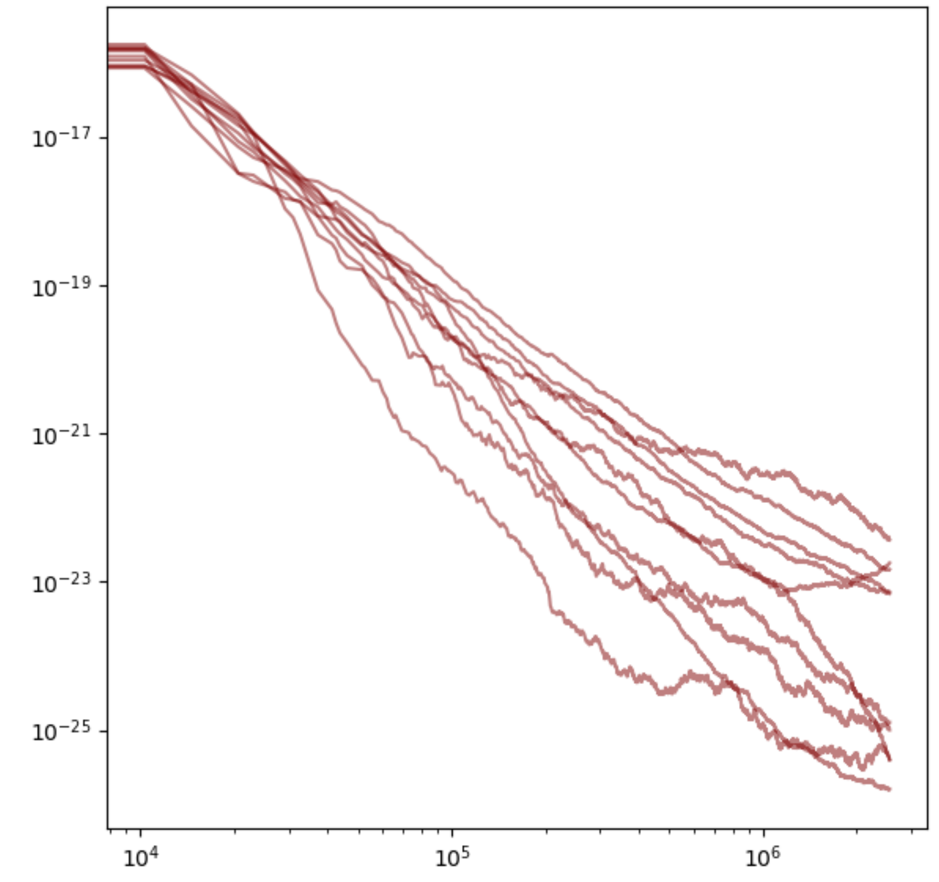
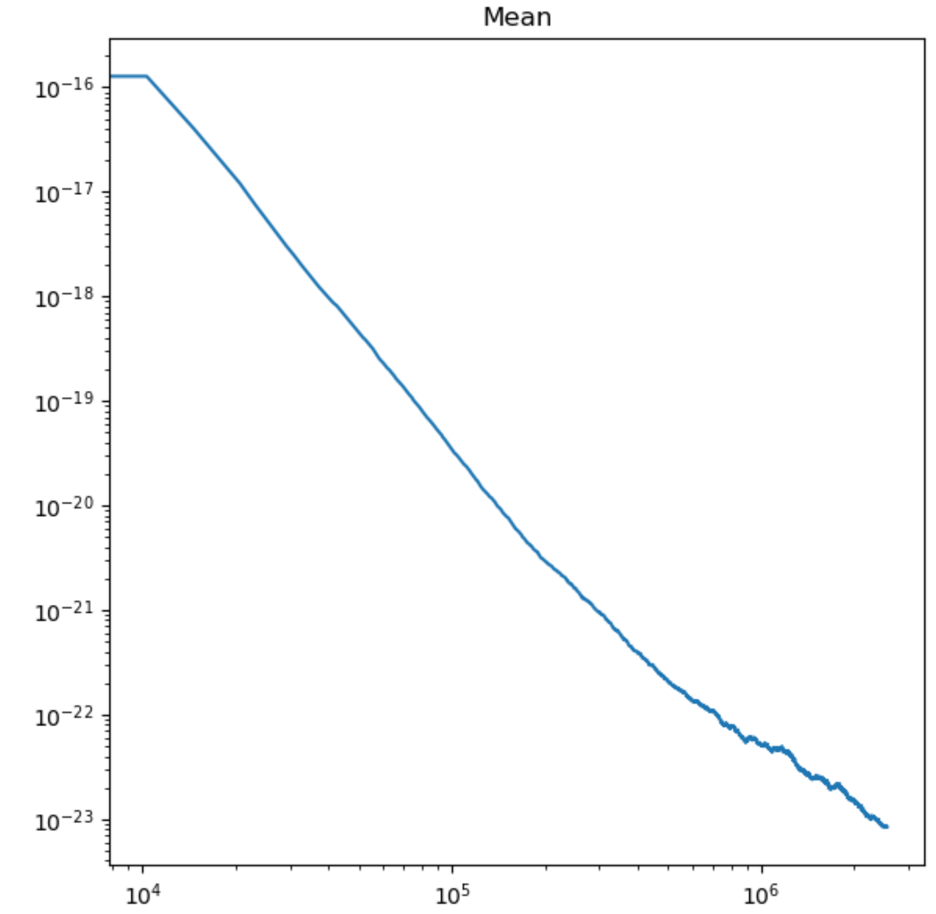




Power spectrum

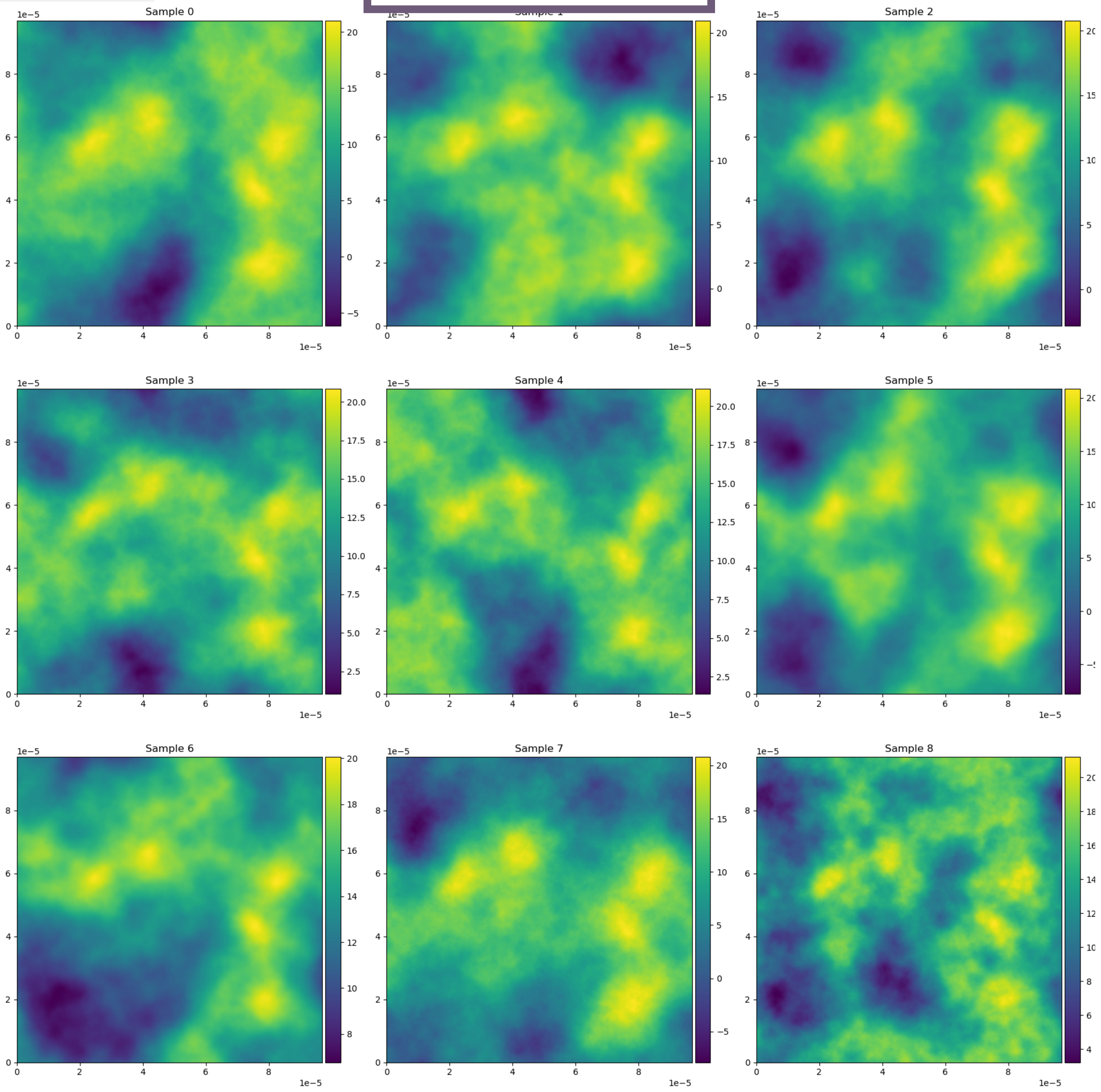




Iterative process

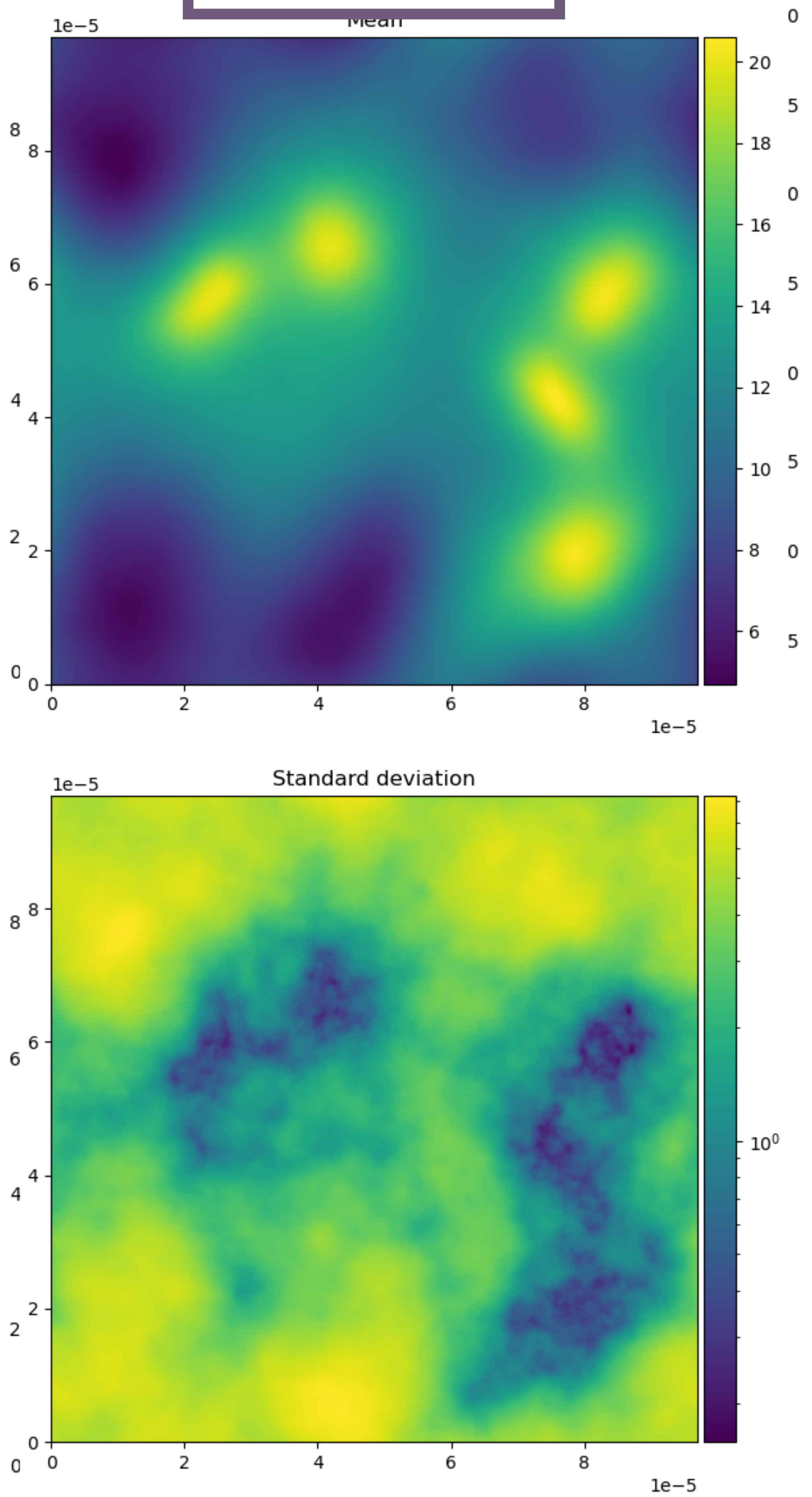
Iter = 5

Samples

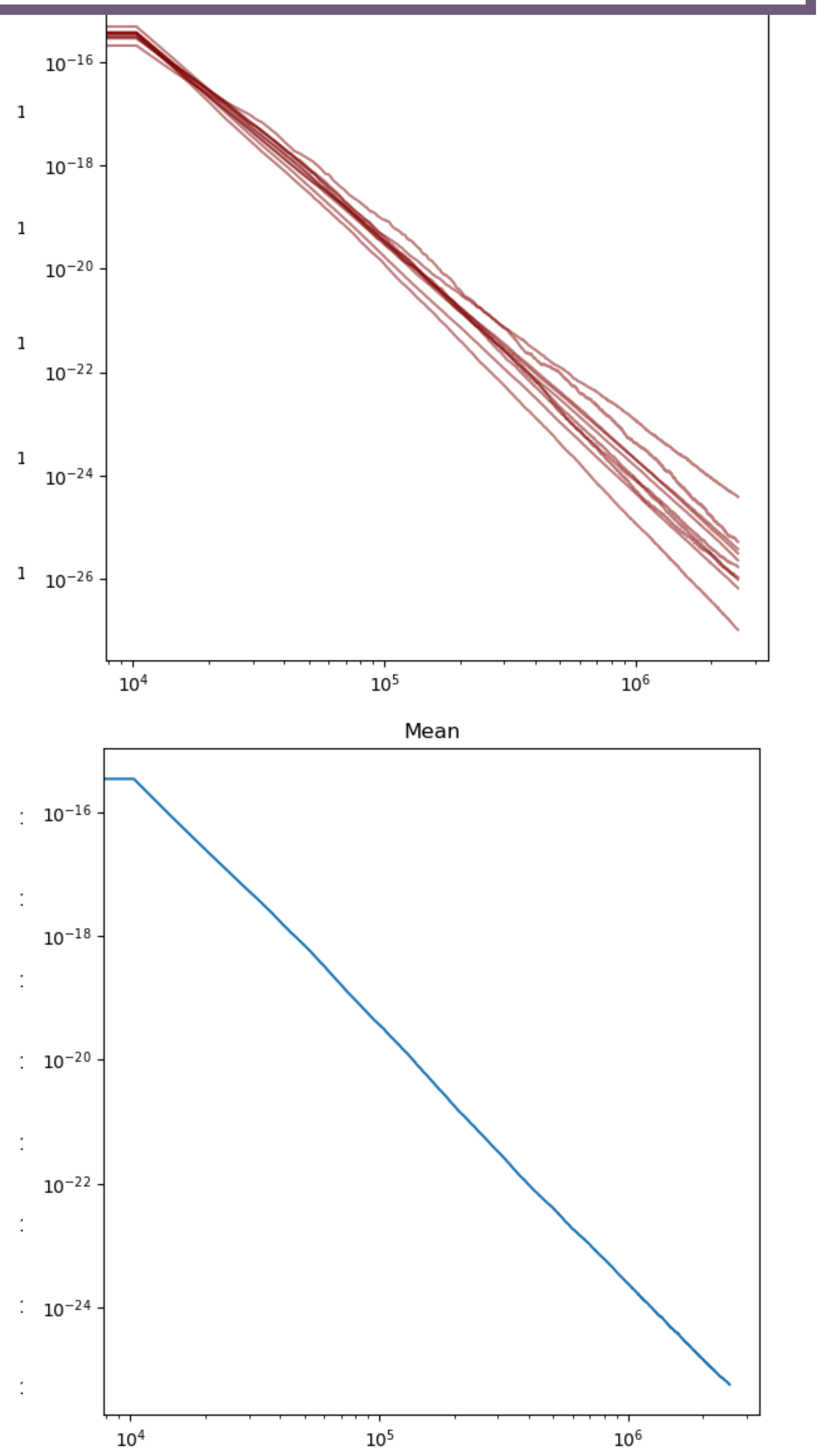


log(F) [MJy / sr]

Means



Power spectrum



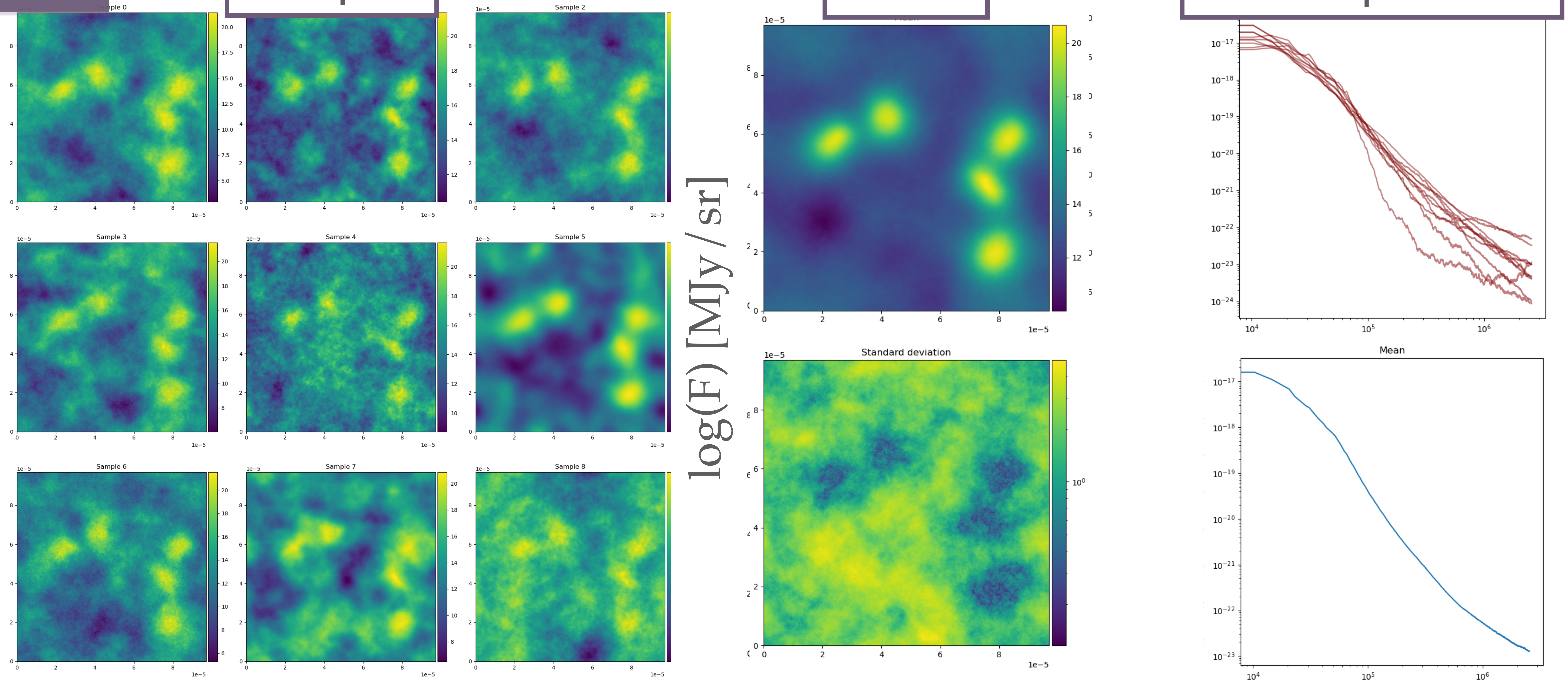
Iterative process

Iter = 23

Samples

Means

Power spectrum



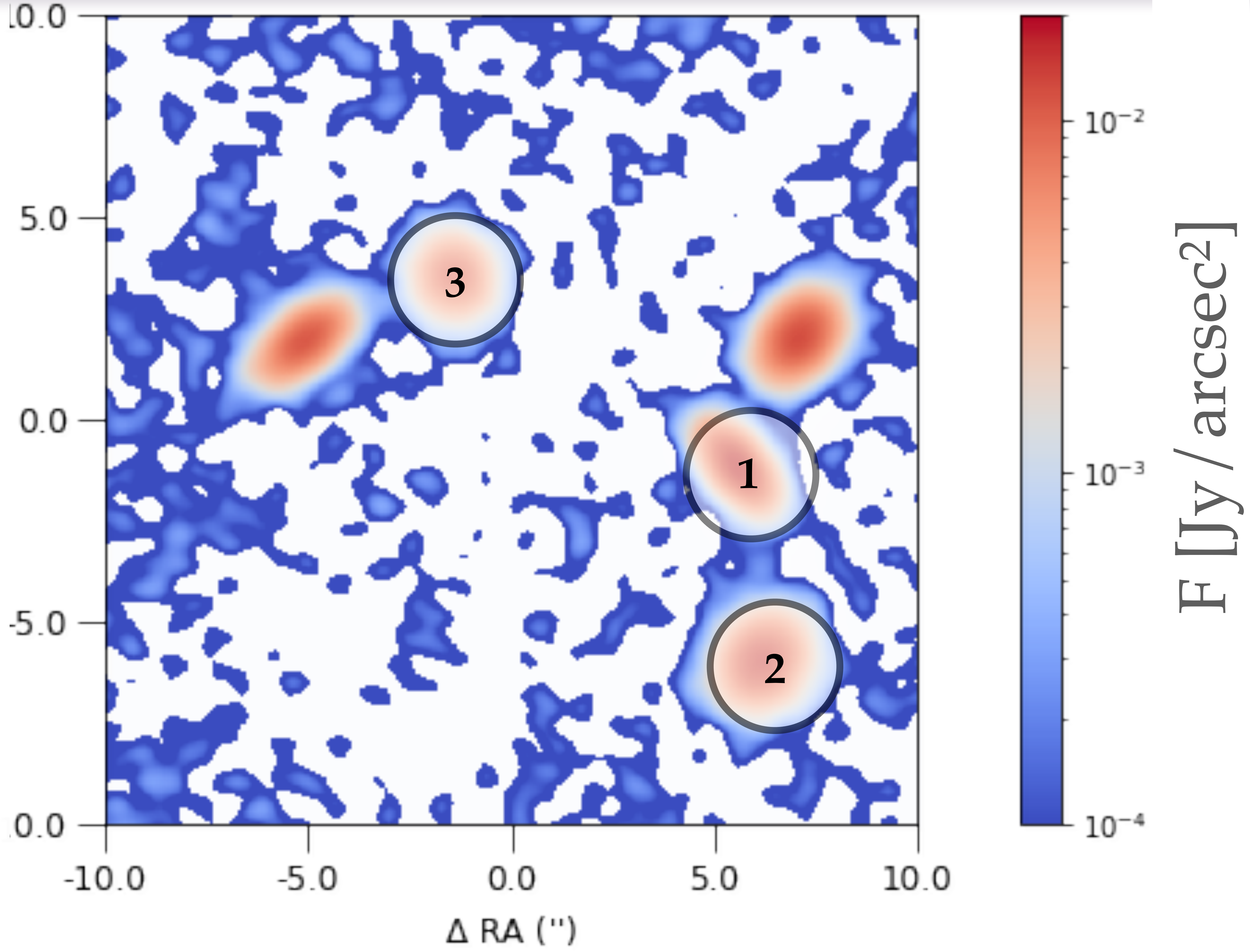
Final results of RESOLVE imaging

Five sources are recovered and uncertainty map is obtained

Direct comparison of imaging for simulated datasets

Note only positive emission in RESOLVE image

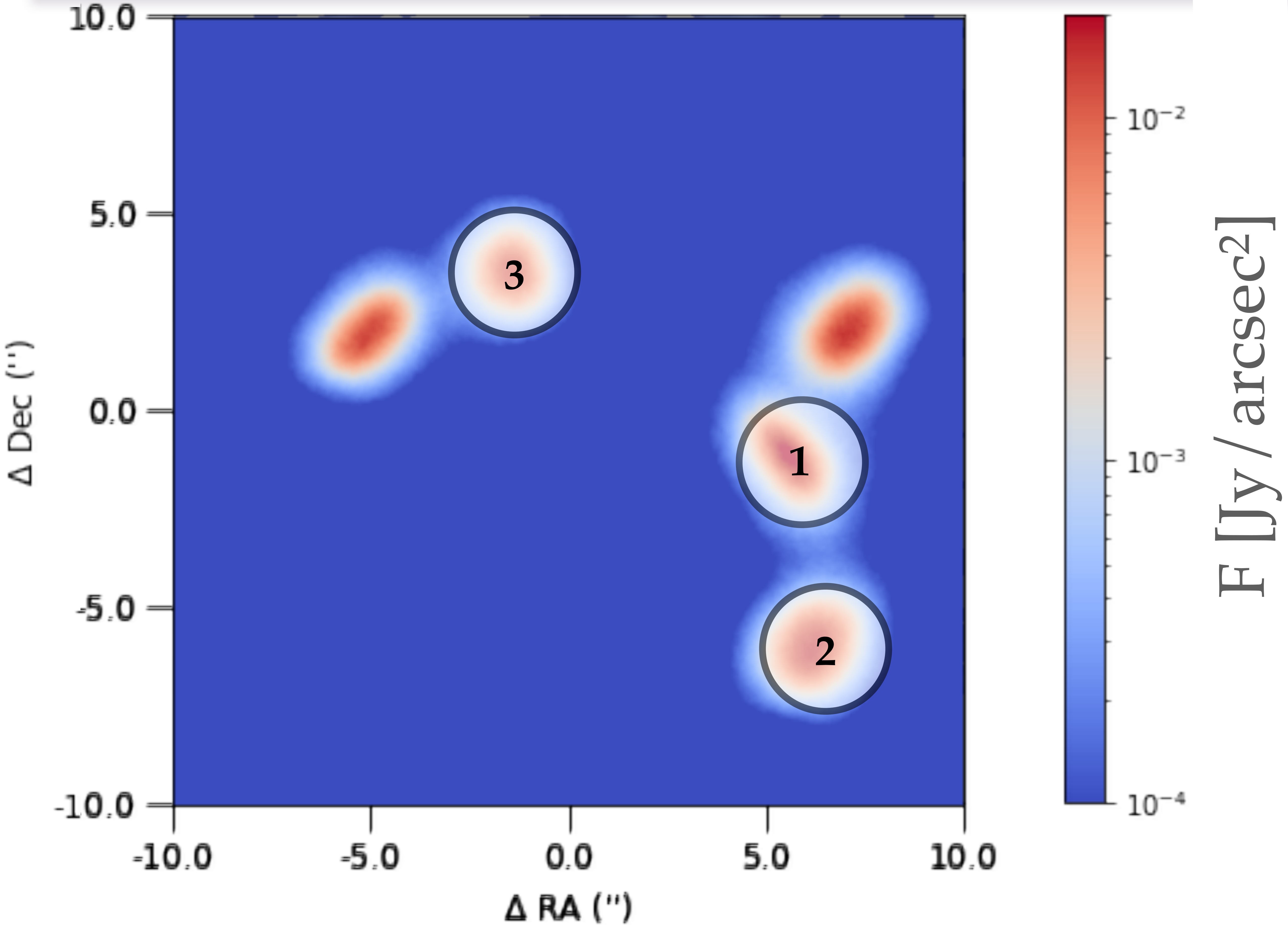
Recovery of flux by CLEAN and RESOLVE



Source	CLEAN Flux [mJy]	RESOLVE Flux [mJy]	Model Flux [mJy]
1	24.96	26.68	34.11
2	23.59	23.59	23.31
3	17.82	17.82	16.69

Comparable fluxes retrieved by CLEAN and RESOLVE

Recovery of flux by CLEAN and RESOLVE



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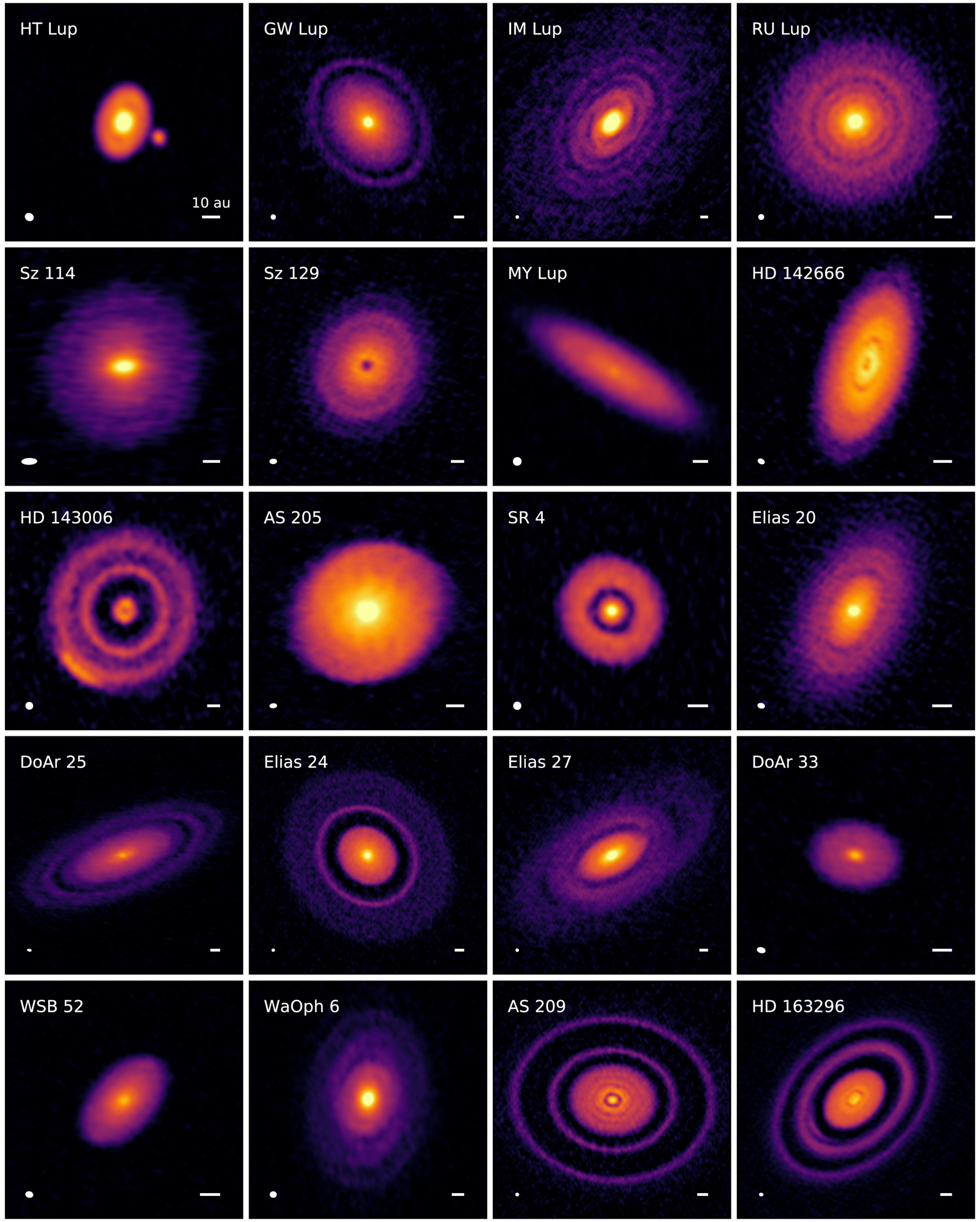
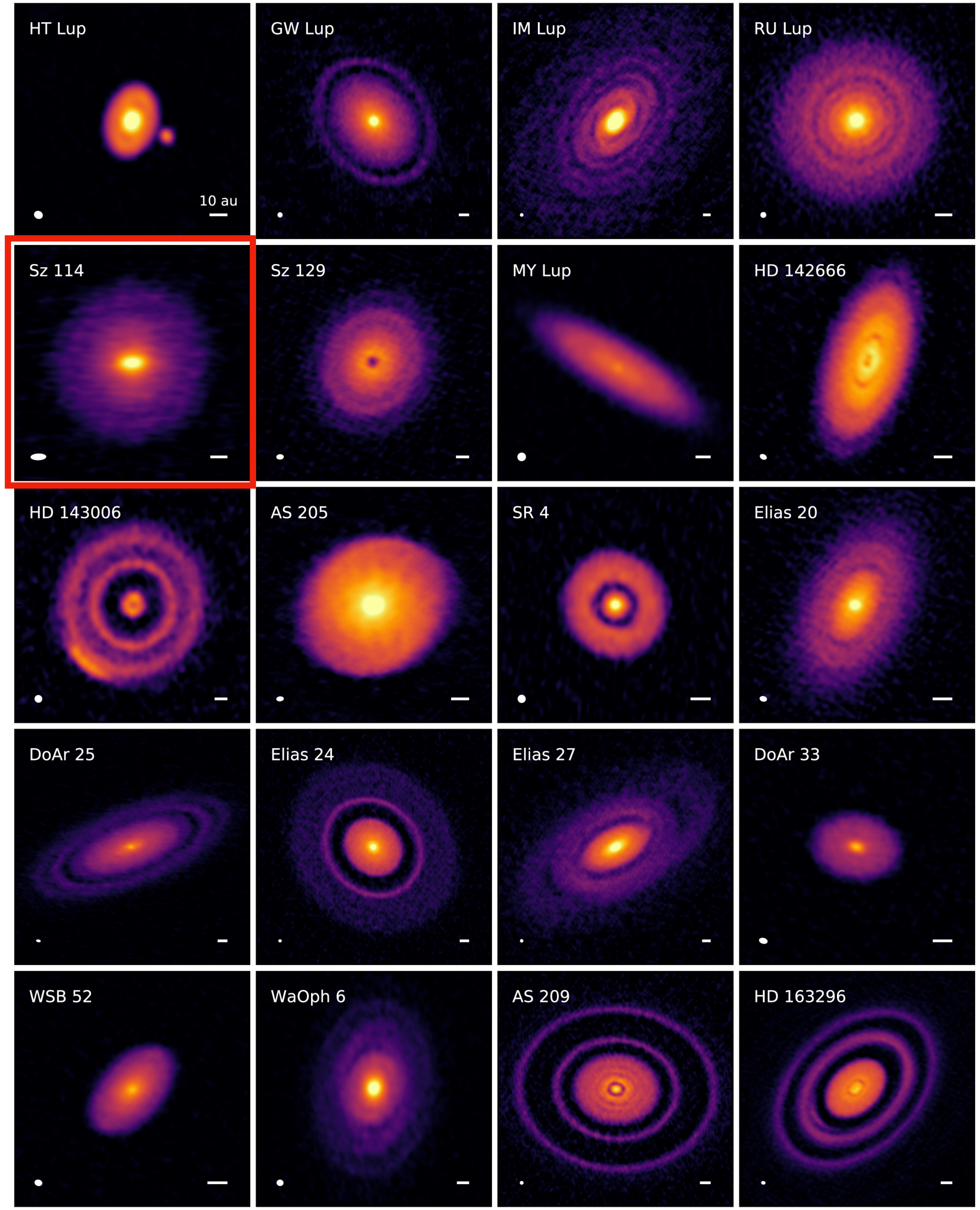


RESOLVE application to real data

Dust emission from planet-forming disk



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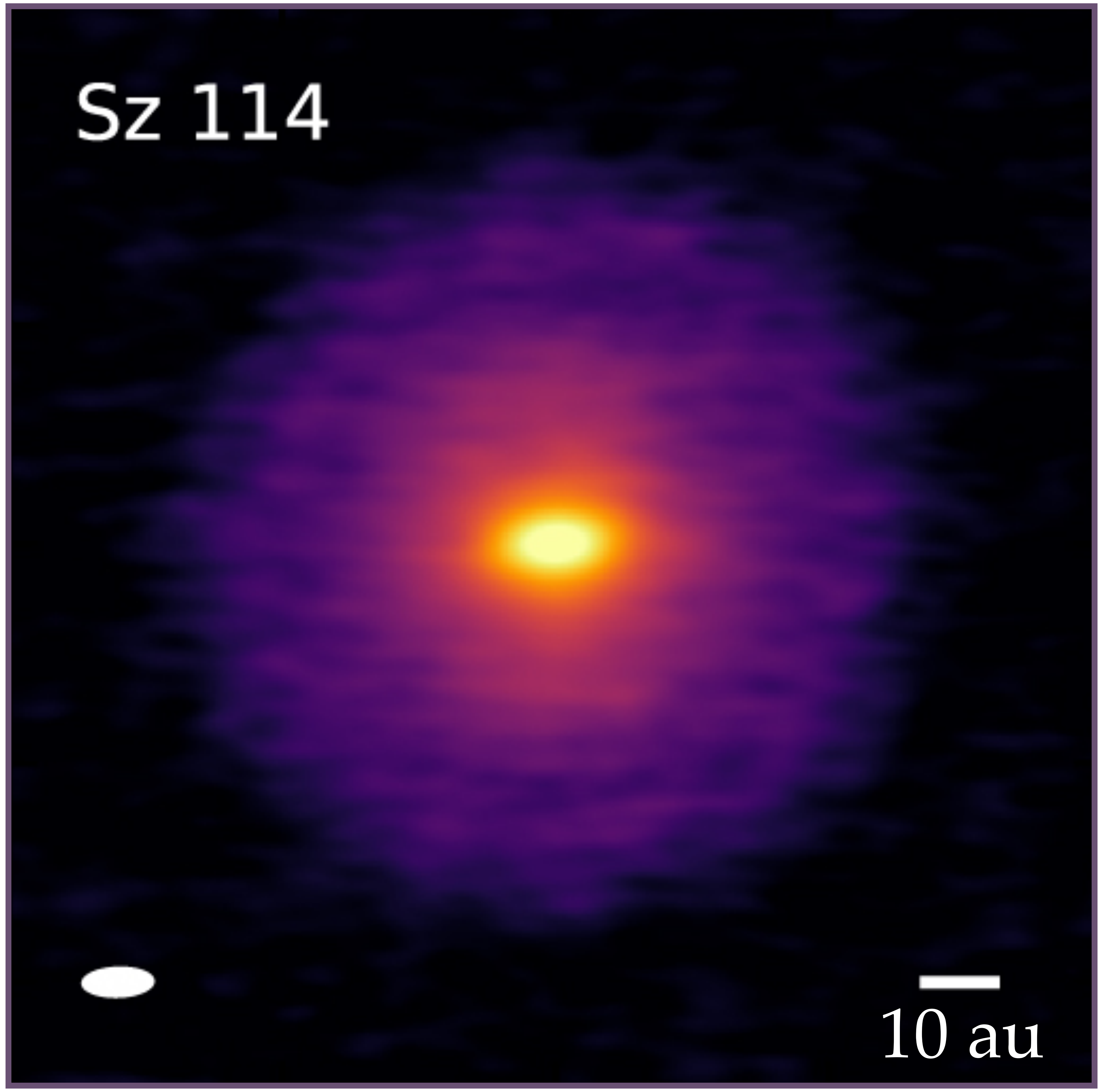

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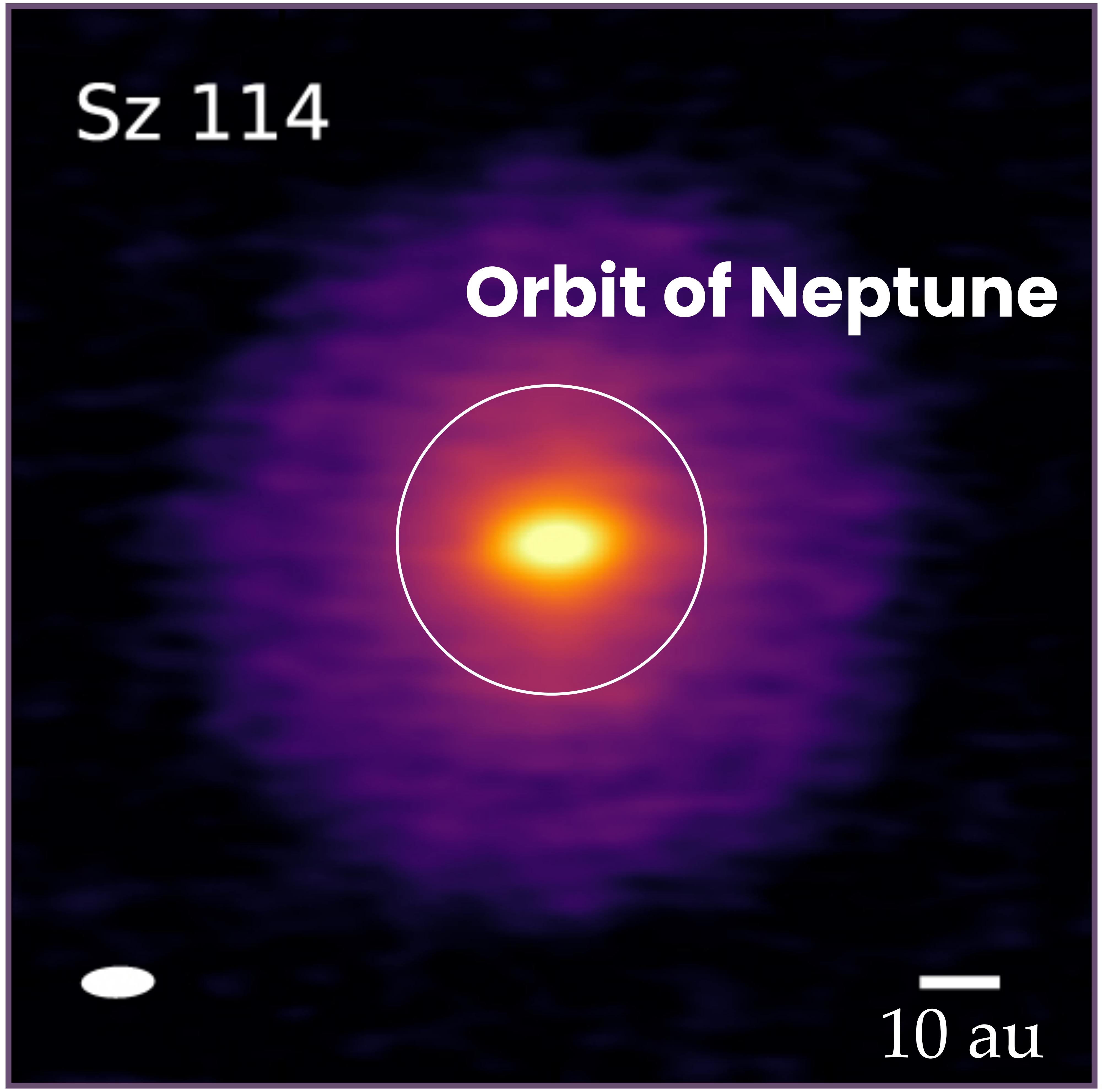

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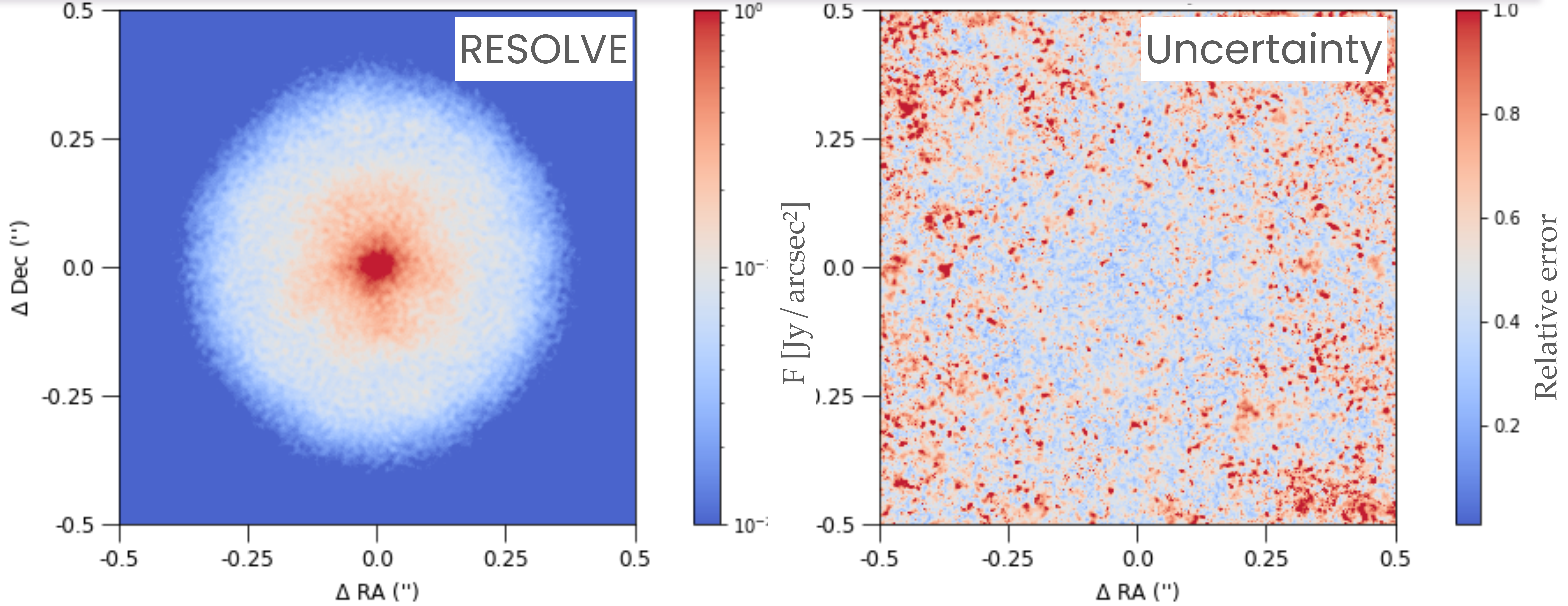
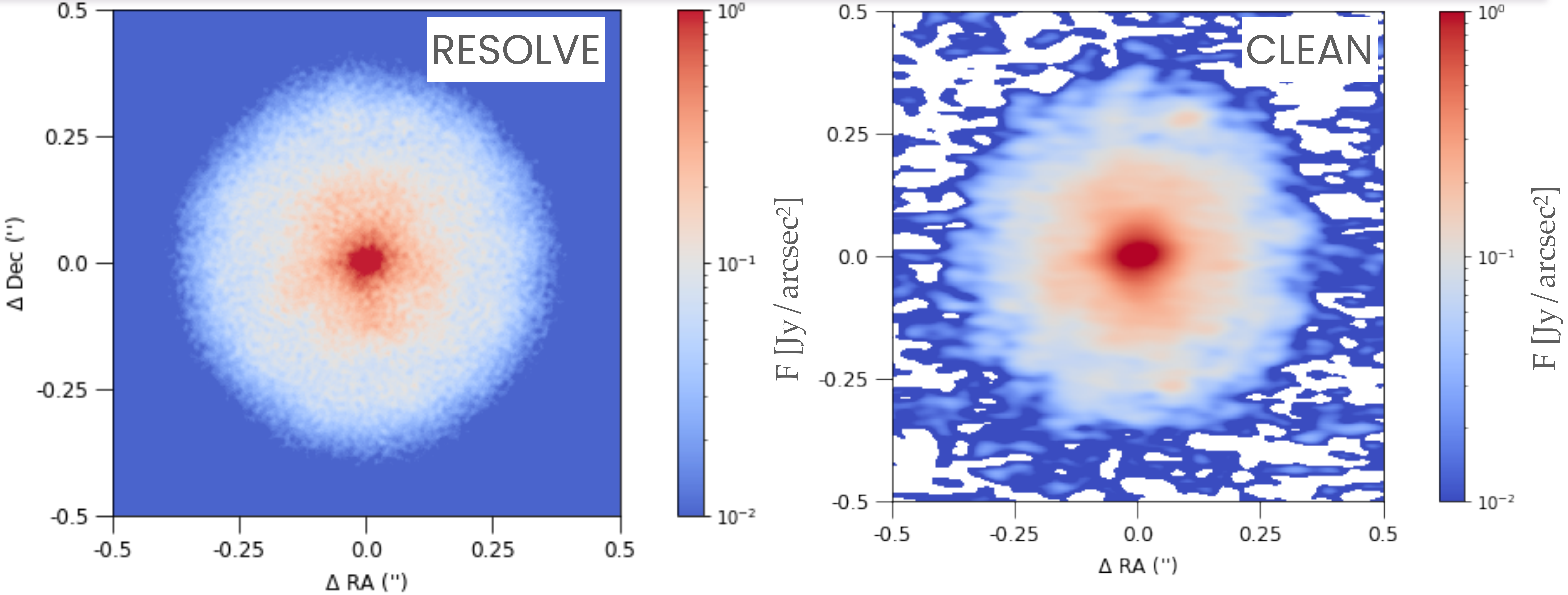
Final image and uncertainty for Sz114 disk



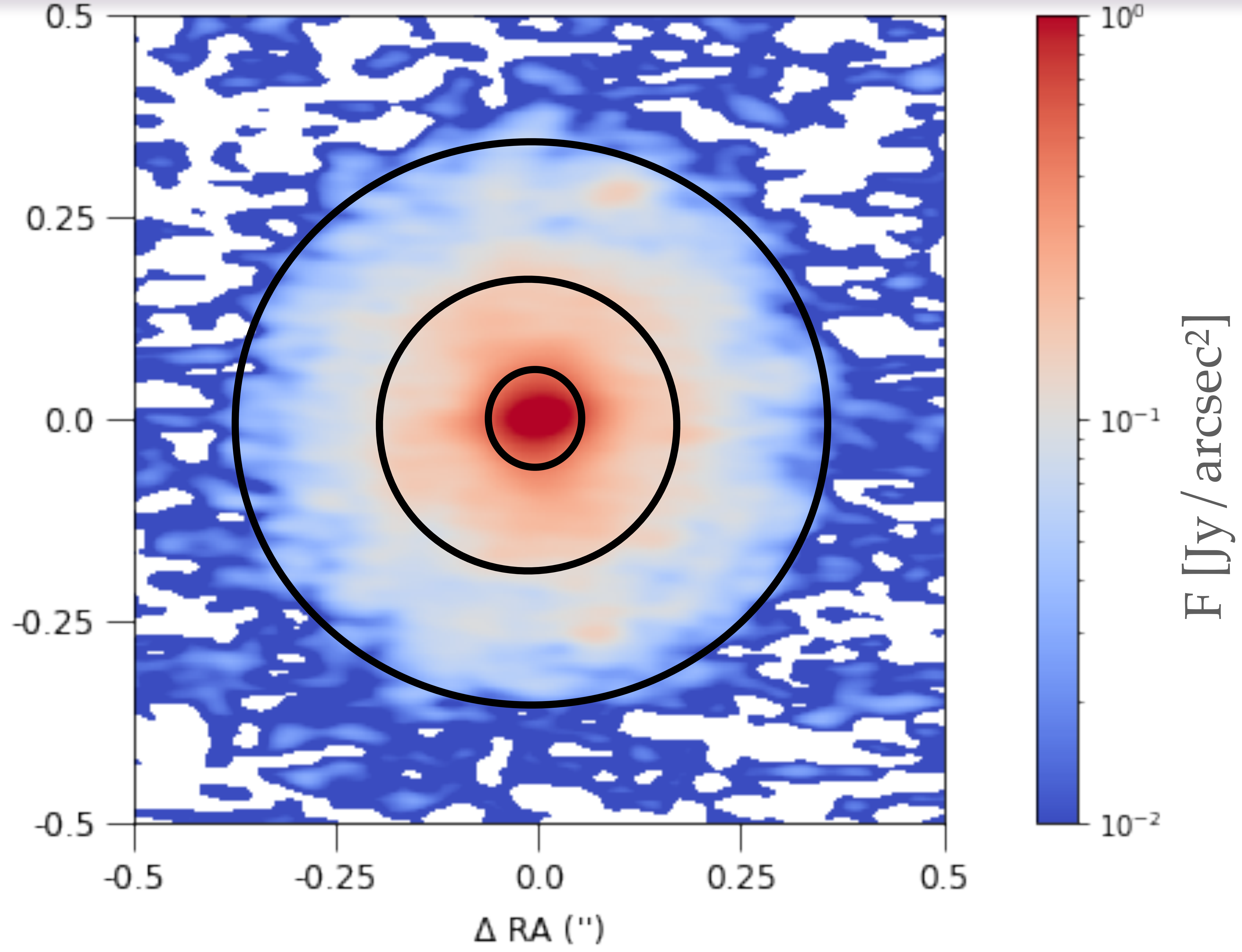
High-quality map of dust in protoplanetary disk obtained by RESOLVE

Direct comparison of results for Sz 114 protoplanetary disk



RESOLVE reveals potential for 'super-resolution'

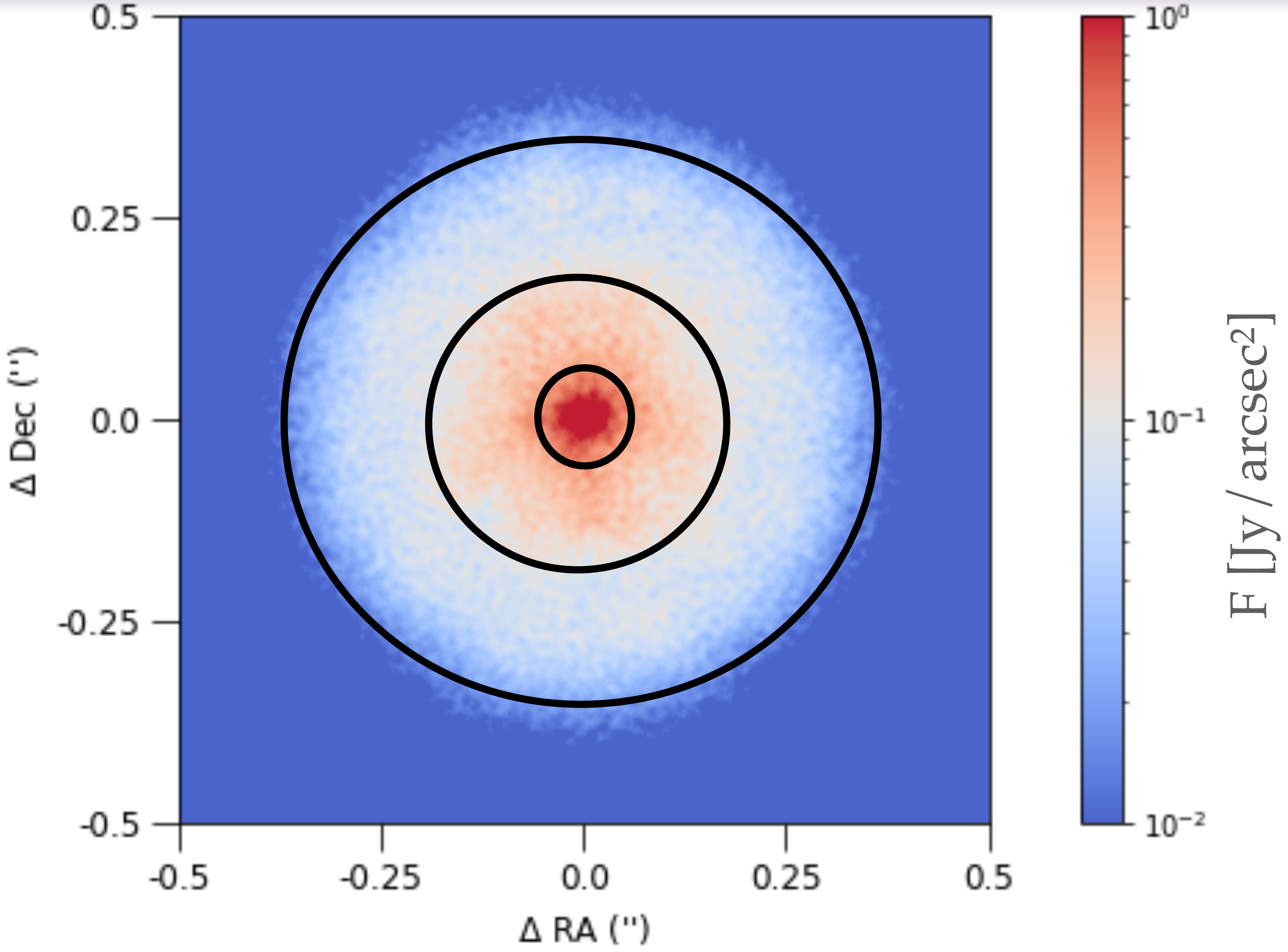
Flux comparison of results for Sz 114 protoplanetary disk



r	CLEAN Flux [mJy]	RESOLVE Flux [mJy]	CLEAN/RESOLVE
0.06"	8.95	9.48	95 %
0.15"	22.53	23.21	97 %
0.35"	47.24	47.24	100 %

Comparable fluxes retrieved by CLEAN and RESOLVE

Flux comparison of results for Sz 114 protoplanetary disk



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- RESOLVE recovers flux with comparable accuracy to CLEAN in simulated data and real ALMA observations
- We achieve super-resolution image of planet-forming disk with RESOLVE along with uncertainty map
- RESOLVE presents a potential to push forward imaging procedures of interferometric observations and enhance/support capabilities of CLEAN