

Final project: Very-long-baseline Interferometry

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The background is a deep purple space scene. A large, dark planet with a thin blue ring is visible in the upper right. The sky is filled with numerous small white stars and faint purple nebulae.

01 Understanding

Understanding, running, and modifying the code

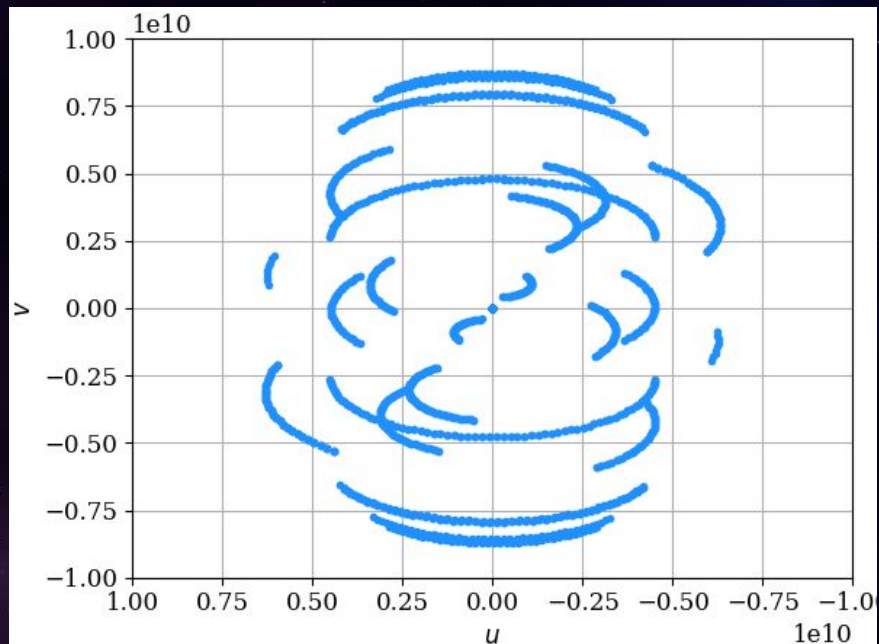
Input Image

```
1 # SRC: M87
2 # RA: 12 h 30 m 49.4234 s
3 # DEC: 12 deg 23 m 28.0439 s
4 # MJD: 48277.0000
5 # RF: 230.0000 GHz
6 # FOVX: 100 pix 0.000182 as
7 # FOVY: 100 pix 0.000182 as
8 # -----
9 # x (as)      y (as)      I (Jy/pixel)  Q (Jy/pixel)  U (Jy/pixel)
10 0.0000891800 0.0000891800 0.0000017870 -0.0000003144 0.0000002609
11 0.0000873600 0.0000891800 0.0000021787 -0.0000003004 0.0000003130
12 0.0000855400 0.0000891800 0.0000026383 -0.0000002713 0.0000003709
13 0.0000837200 0.0000891800 0.0000031731 -0.0000002242 0.0000004338
14 0.0000819000 0.0000891800 0.0000037904 -0.0000001568 0.0000005006
15 0.0000800800 0.0000891800 0.0000044970 -0.0000000660 0.0000005695
16 0.0000782600 0.0000891800 0.0000053005 0.0000000501 0.0000006385
17 0.0000764400 0.0000891800 0.0000062074 0.0000001942 0.0000007052
18 0.0000746200 0.0000891800 0.0000072253 0.0000003678 0.0000007669
19 0.0000728000 0.0000891800 0.0000083602 0.0000005727 0.0000008197
20 0.0000709800 0.0000891800 0.0000096197 0.0000008102 0.0000008604
```

What do I, Q, U, V represent?

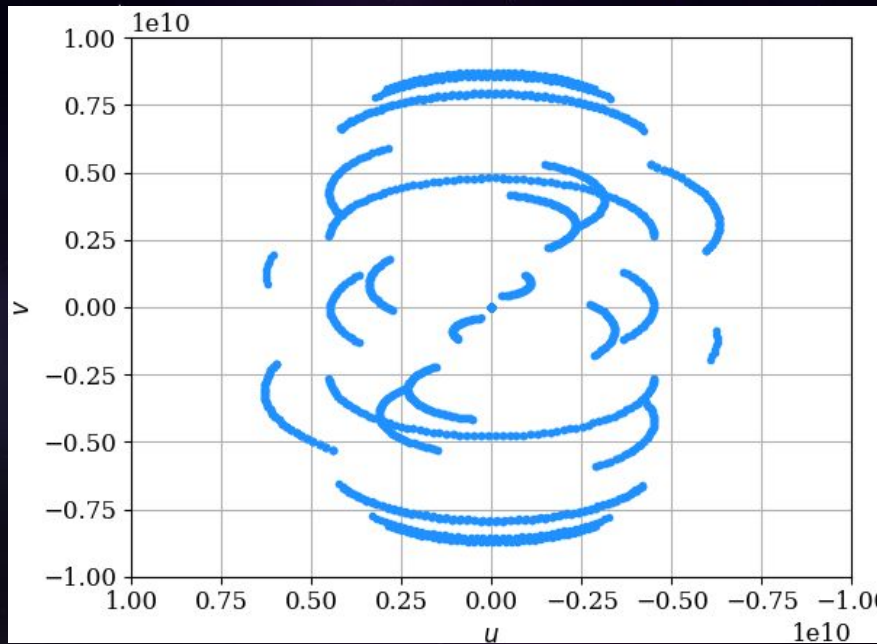
$$\begin{aligned}
 I &= \left(\begin{array}{c} \text{Image with horizontal double-headed arrow} + \text{Image with vertical double-headed arrow} \\ + \text{Image with diagonal double-headed arrow (bottom-left to top-right)} + \text{Image with diagonal double-headed arrow (top-left to bottom-right)} \end{array} \right) / 2 \\
 &= \text{Image with clockwise circular arrow} + \text{Image with counter-clockwise circular arrow}
 \end{aligned}
 \qquad
 \begin{aligned}
 Q &= \text{Image with horizontal double-headed arrow} - \text{Image with vertical double-headed arrow} \\
 U &= \text{Image with diagonal double-headed arrow (bottom-left to top-right)} - \text{Image with diagonal double-headed arrow (top-left to bottom-right)} \\
 V &= \text{Image with clockwise circular arrow} - \text{Image with counter-clockwise circular arrow (on a red background)}
 \end{aligned}$$

U-V coverage

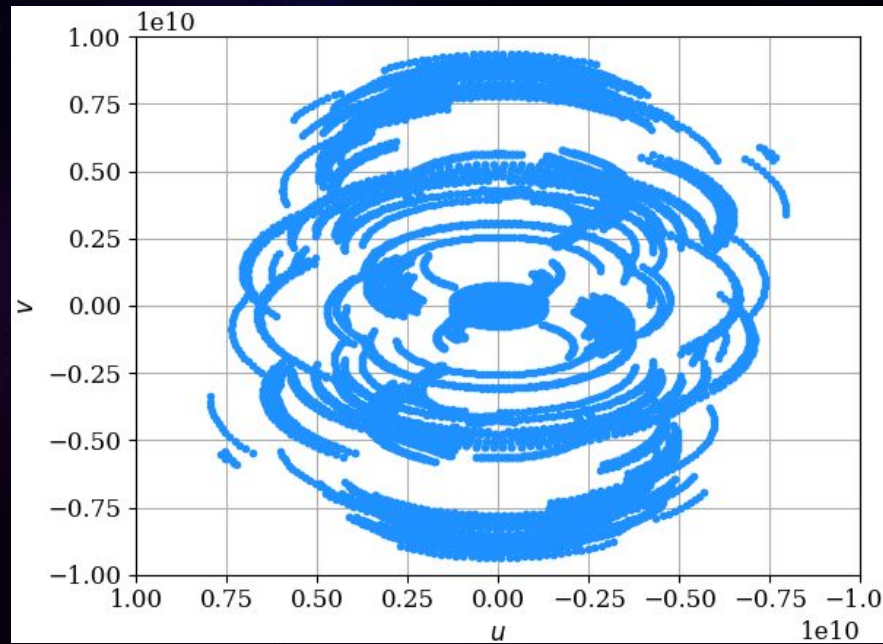


EHT2017_m87

Switching arrays

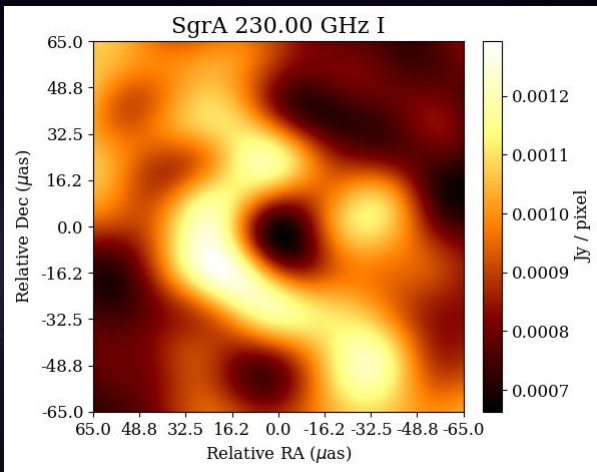


EHT2017_m87

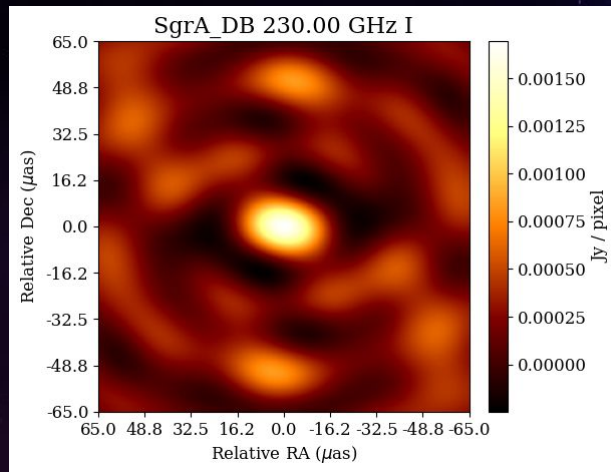


EHTII

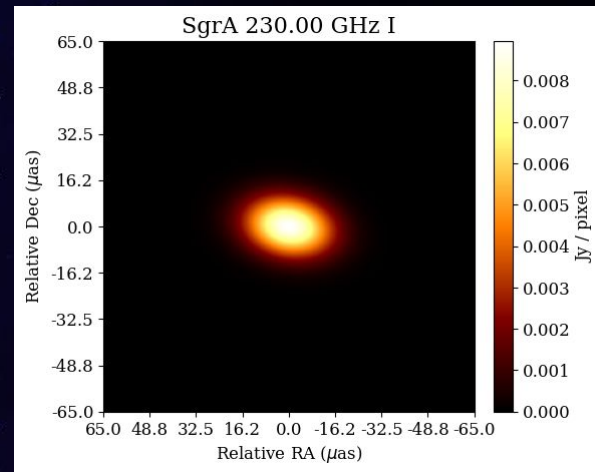
Dirty image and dirty beam



Dirty image



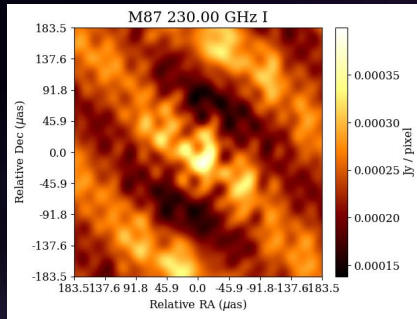
Dirty beam



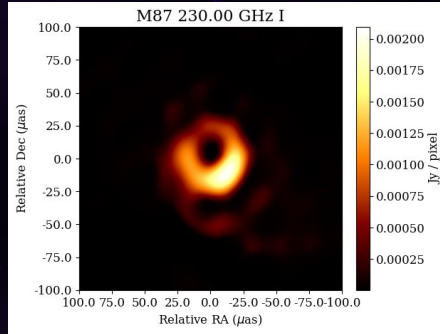
Clean beam

Experiments (Easier celestial object)

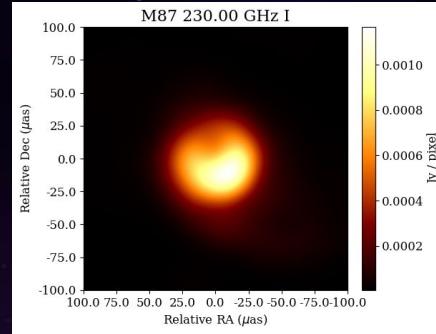
rowan_m87 (default)



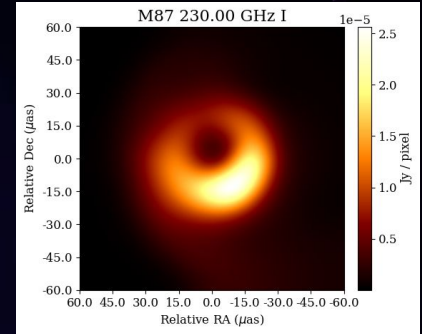
dirty image



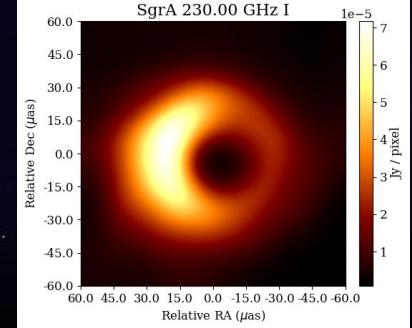
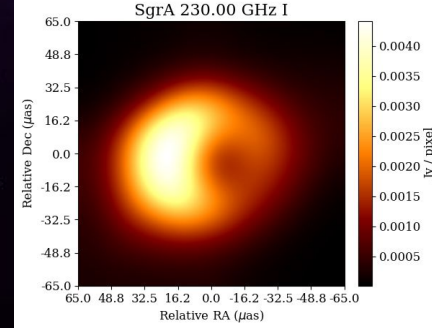
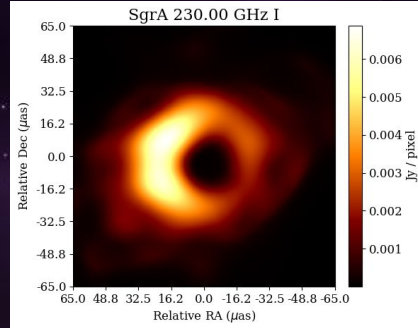
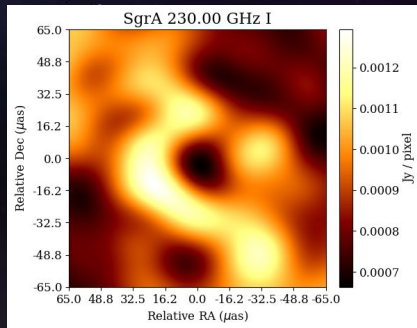
clean image



clean image (blurred)

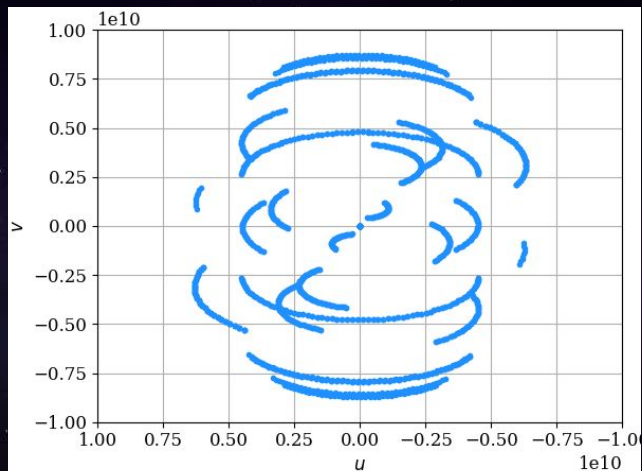


GT image

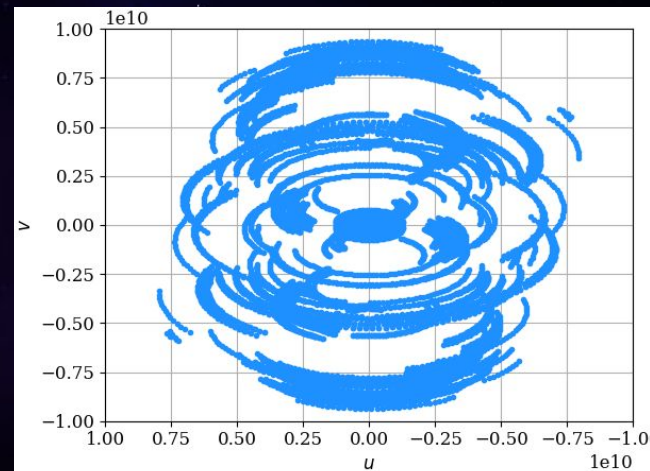


jason_mad_eofn

Experiments (Larger telescope array)

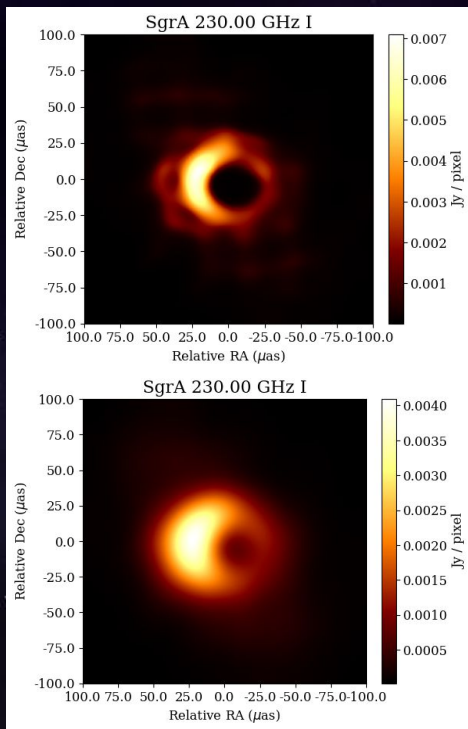


EHT2017_m87

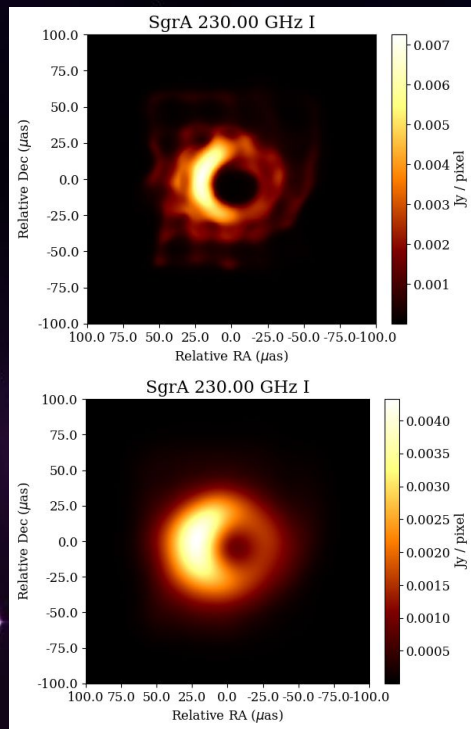


EHTII

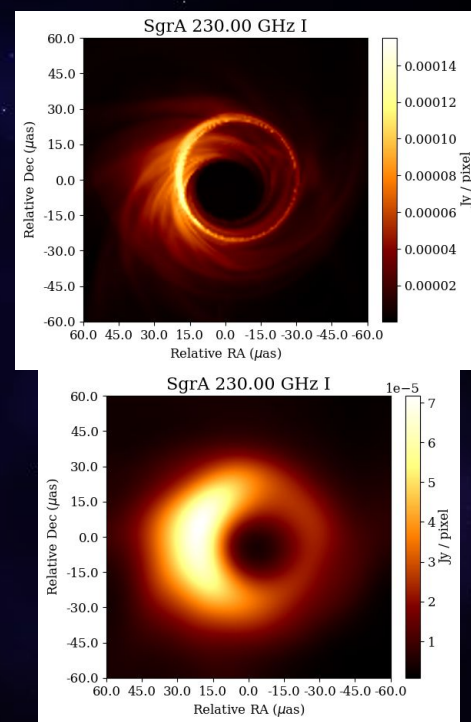
Experiments (Larger telescope array)



EHT2017_m87

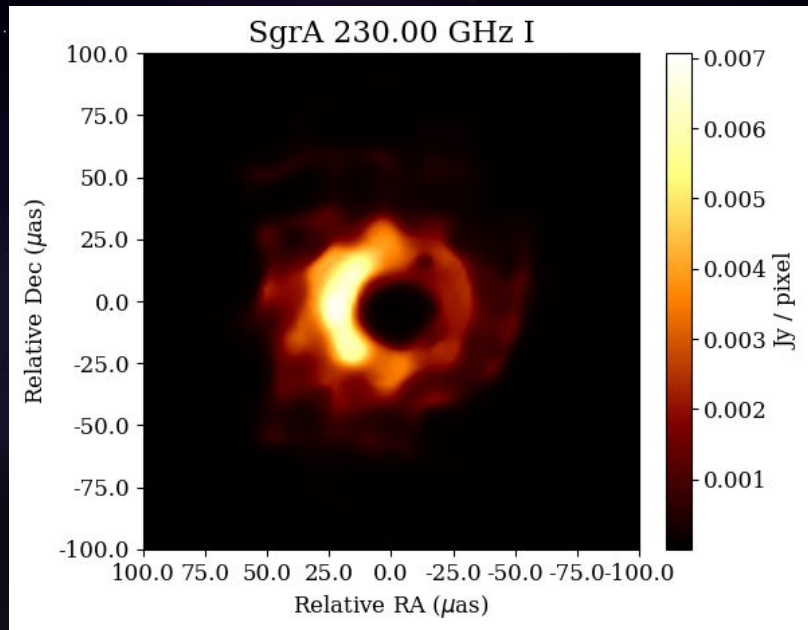


EHTII

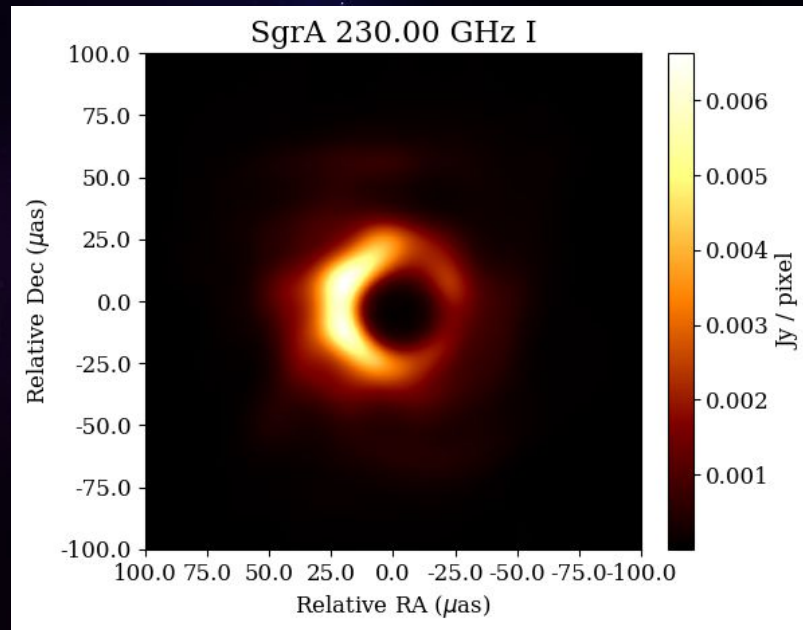


GT

Experiments (Computational priors and regularizers)

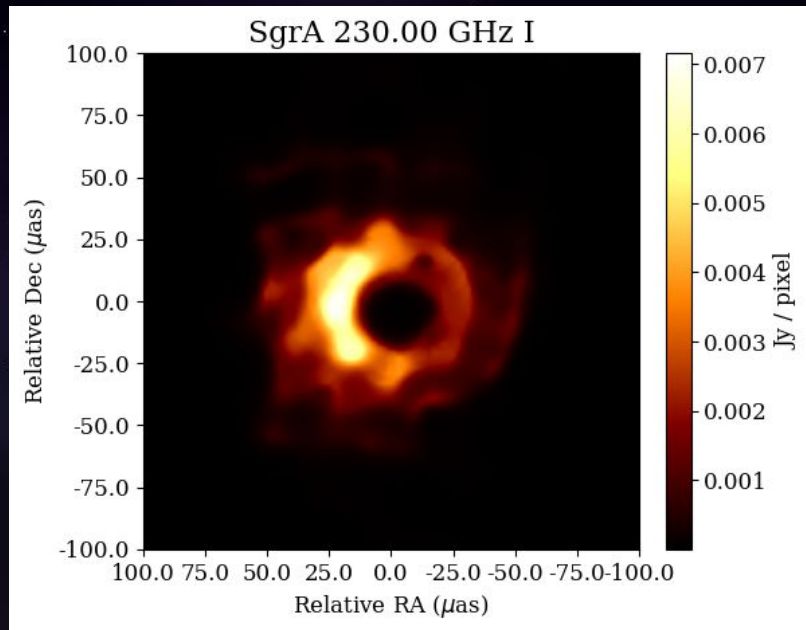


'simple': 0

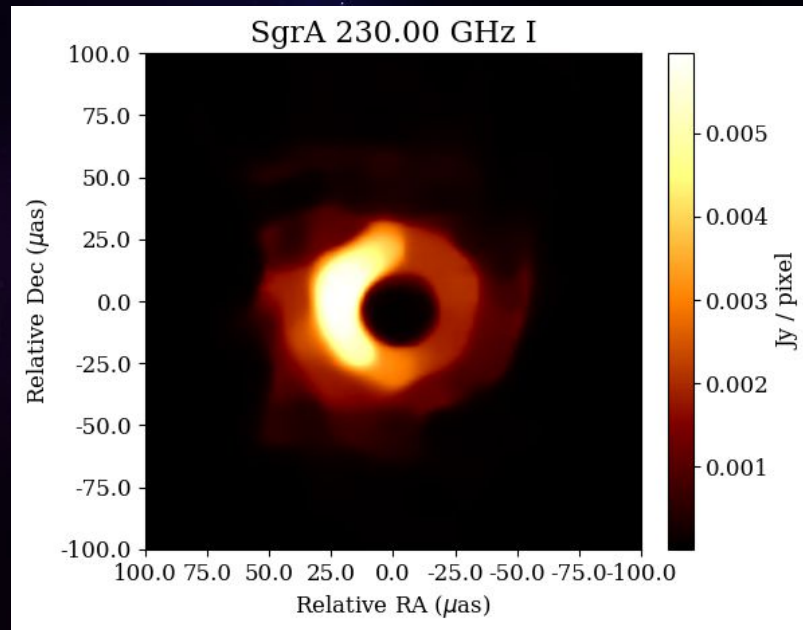


'simple': 1000

Experiments (Computational priors and regularizers)

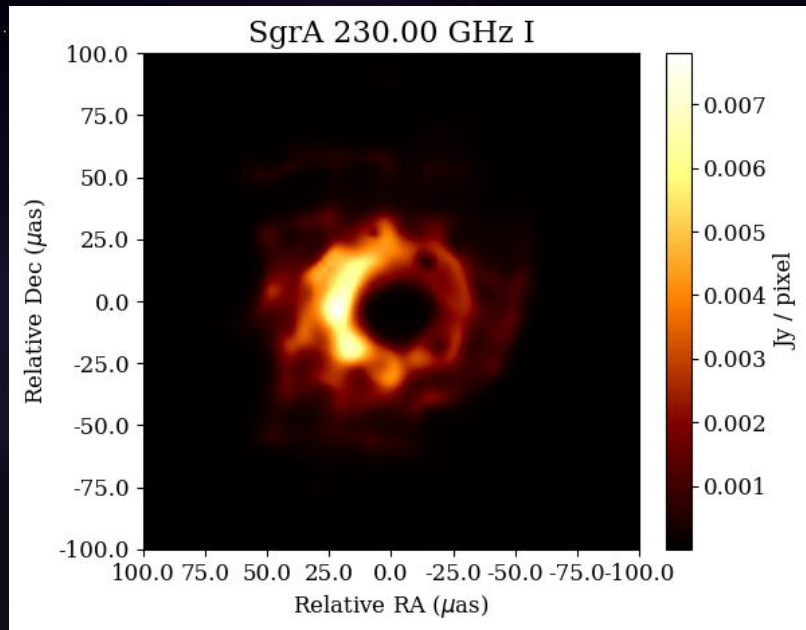


'tv': 1

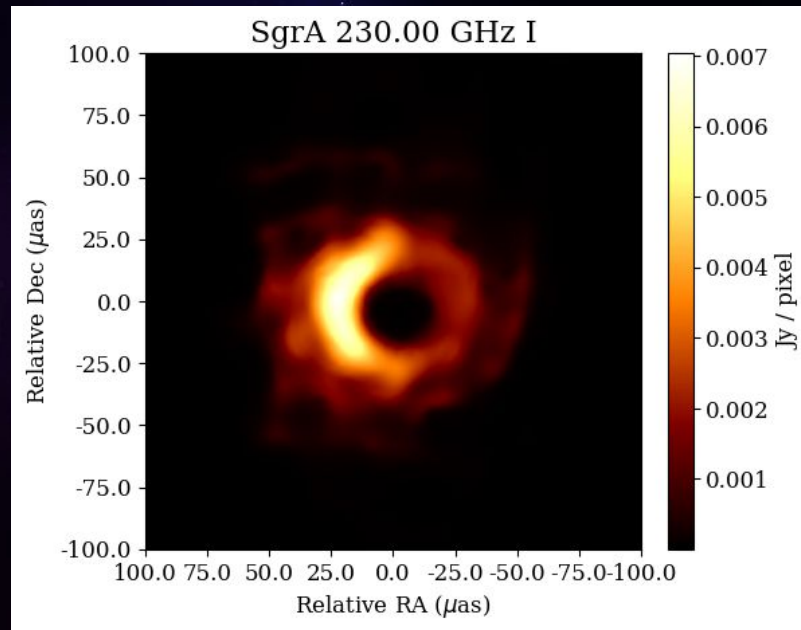


'tv': 10

Experiments (Computational priors and regularizers)

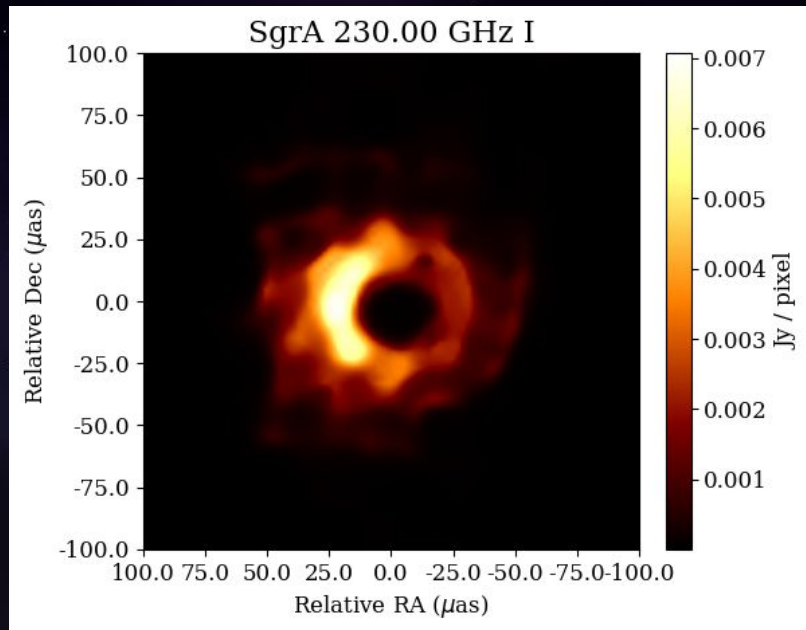


'tv2': 1

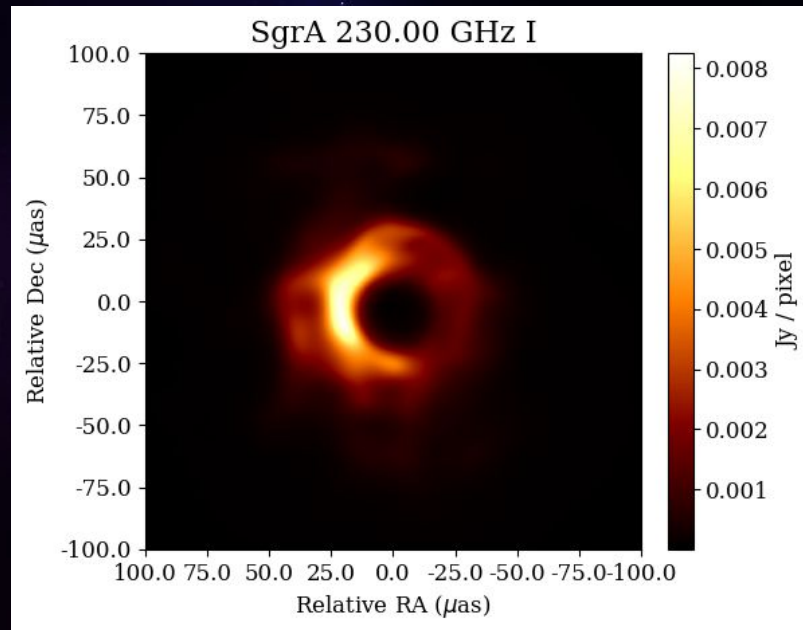


'tv2': 10

Experiments (Computational priors and regularizers)

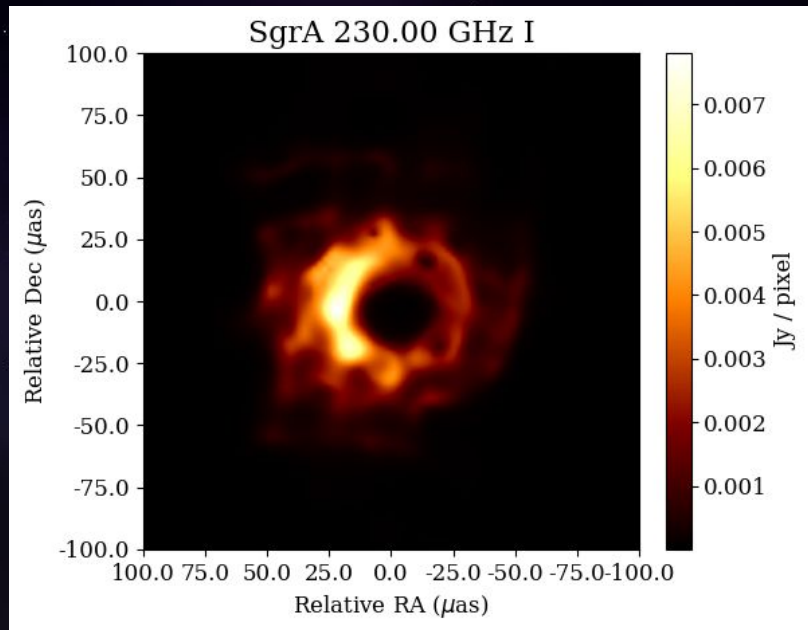


'flux': 1

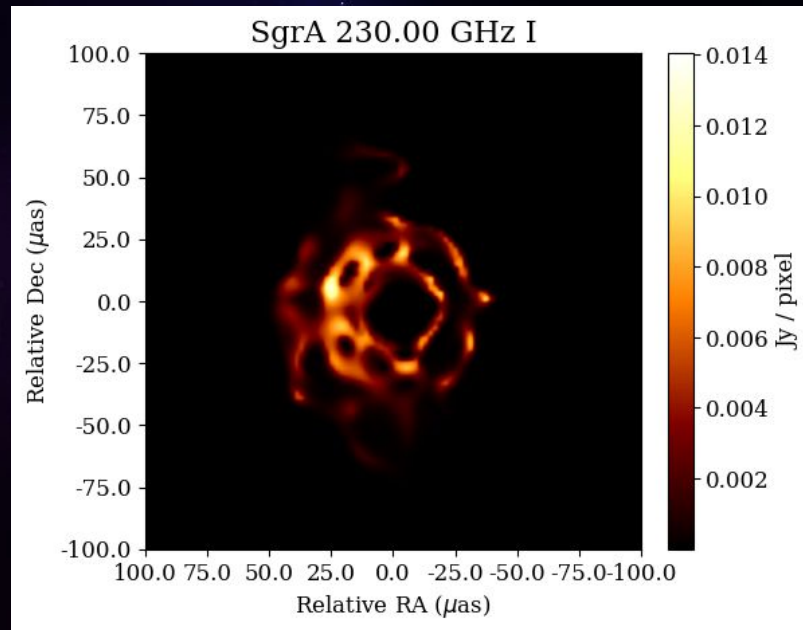


'flux': 1e8

Experiments (Computational priors and regularizers)



'l1': 0.1



'l1': 1e5

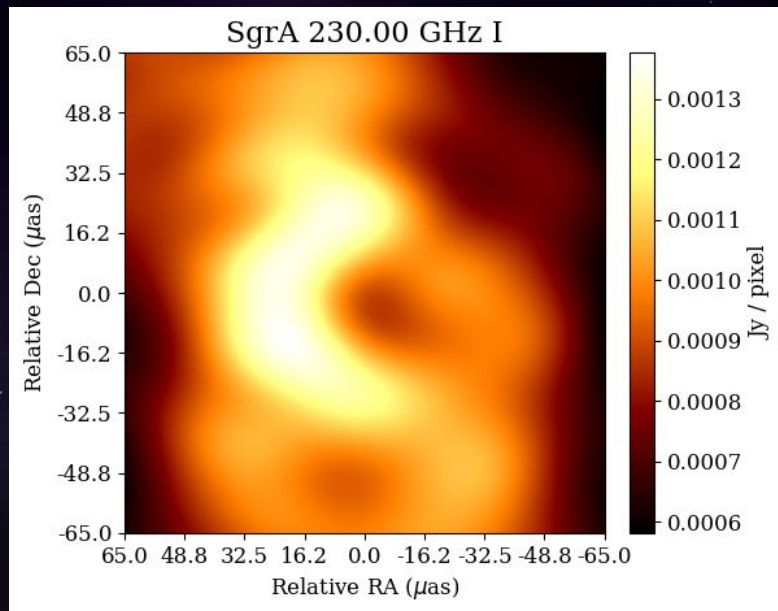
The background is a deep blue space filled with numerous small, distant stars. Several larger, more prominent stars are visible, some with distinct diffraction spikes. On the left and right sides, there are large, glowing, ethereal structures resembling nebulae or gas clouds in shades of blue and purple. The overall effect is a sense of vastness and cosmic wonder.

02

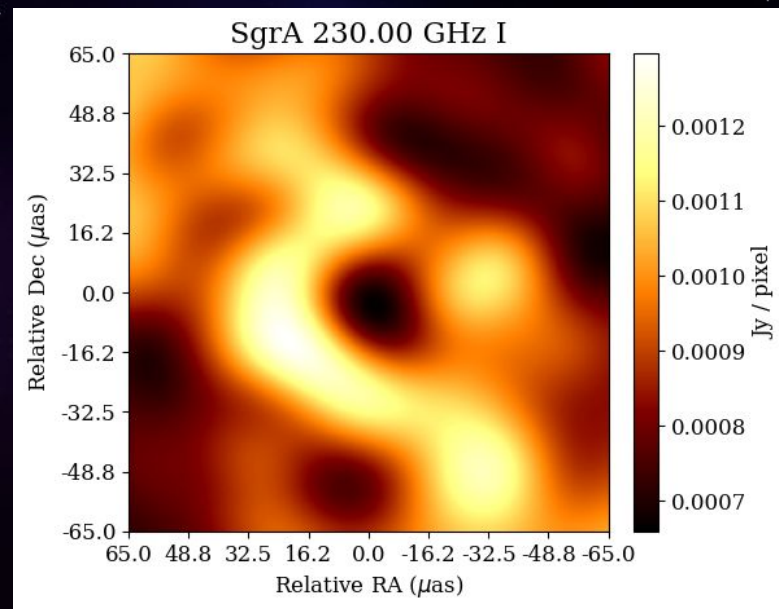
Telescopes obs

Forward model: Telescope observations

Add different amounts of noise

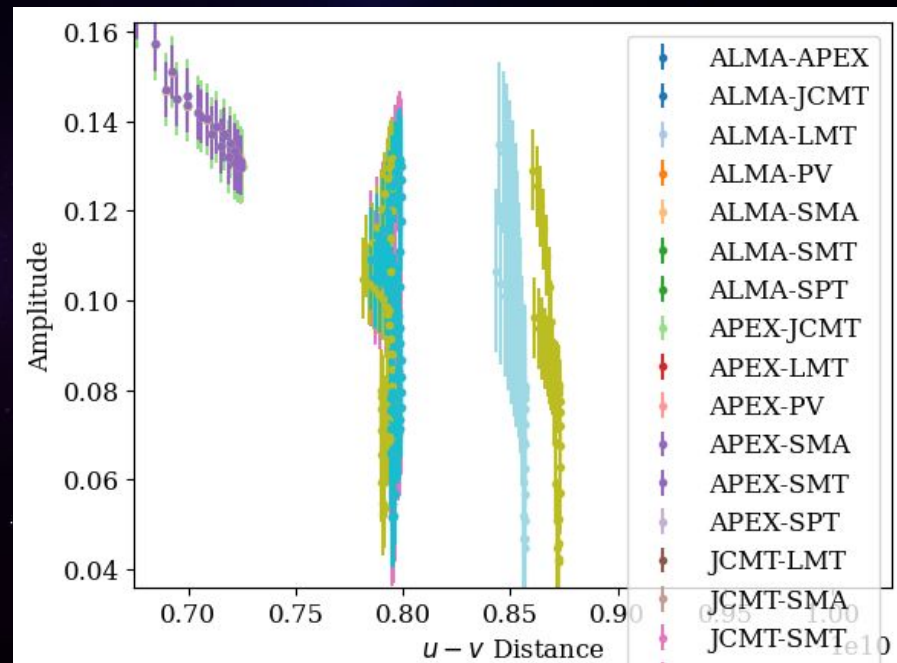
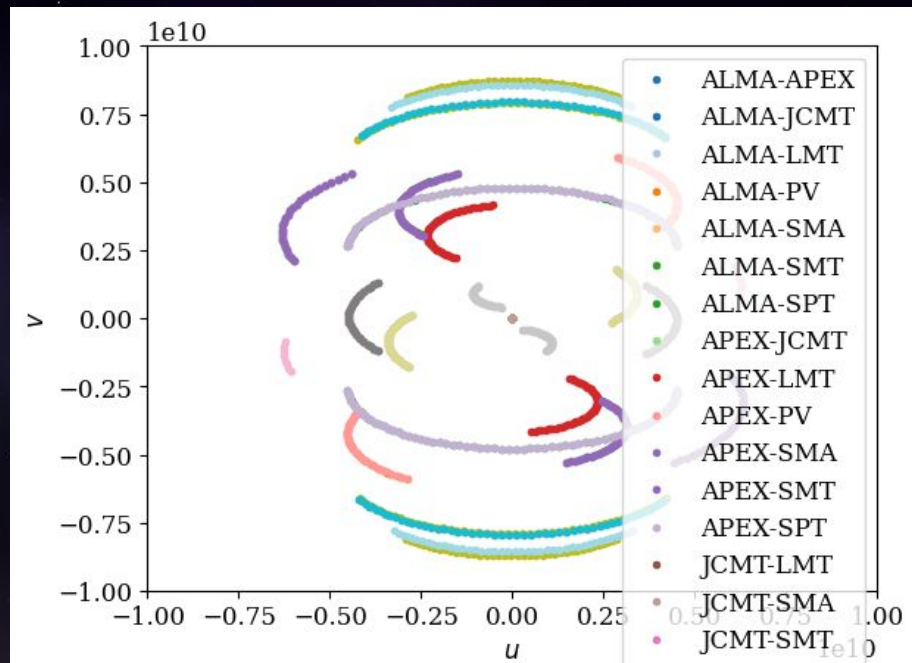


add_th_noise = False



add_th_noise = True

Compute frequencies by each pair of telescopes at a time



Add telescopes to maximize frequency coverage



Add telescopes to maximize frequency coverage



Add telescopes to maximize frequency coverage



Add telescopes to maximize frequency coverage



Add telescopes to maximize frequency coverage



Add telescopes to maximize frequency coverage



Add telescopes to maximize frequency coverage



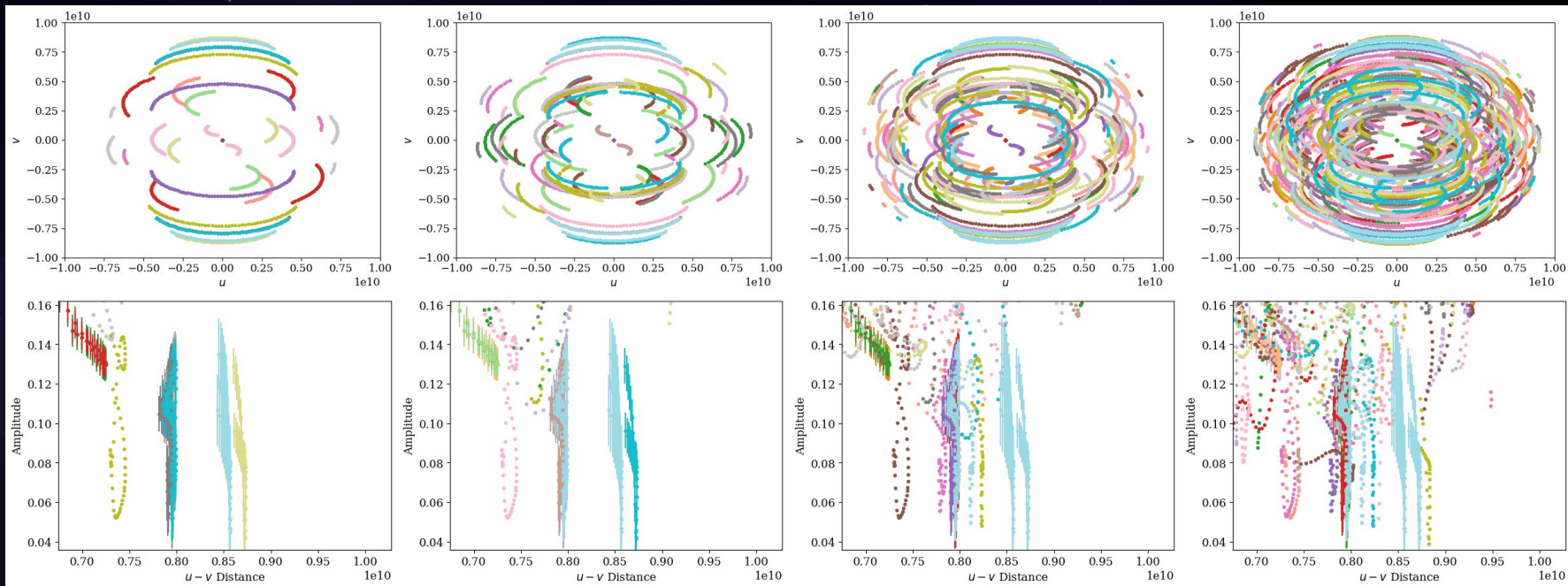
Add telescopes to maximize frequency coverage



Add telescopes to maximize frequency coverage



Add telescopes to maximize frequency coverage



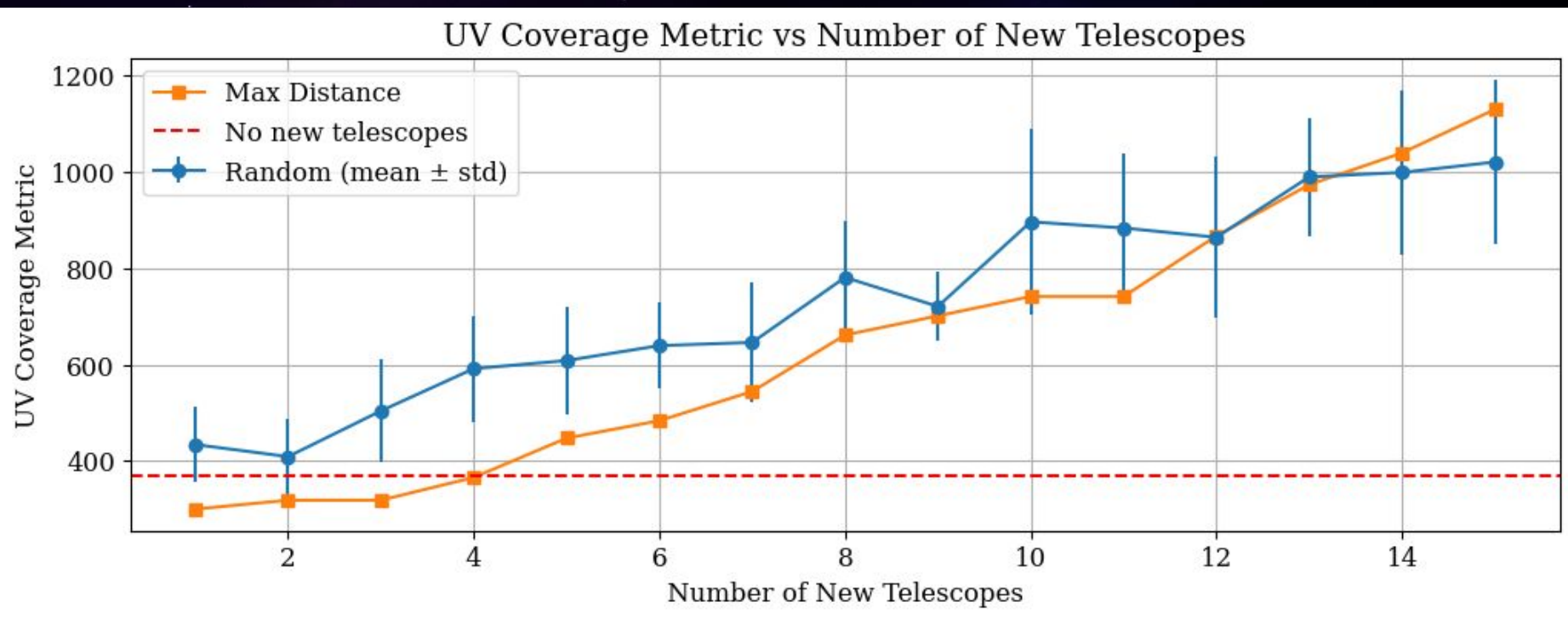
1 new telescope

5 news telescopes

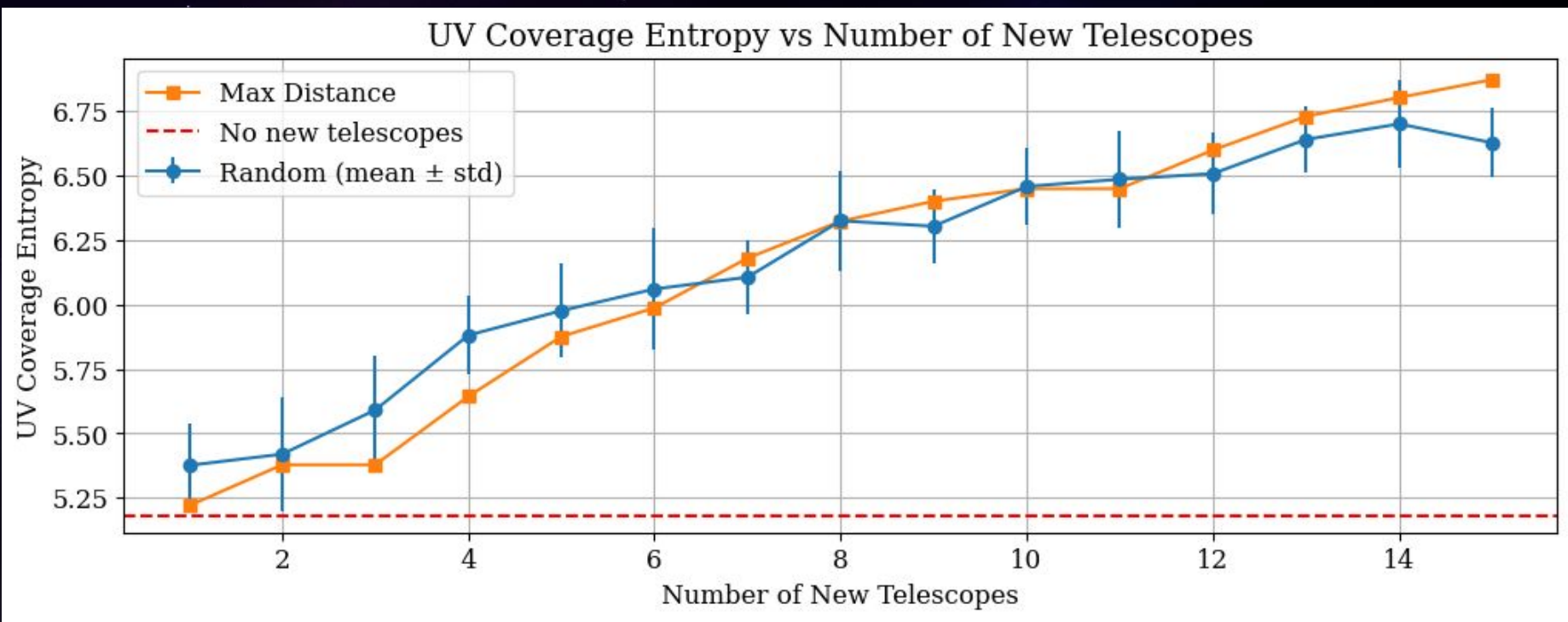
10 news telescopes

20 news telescopes

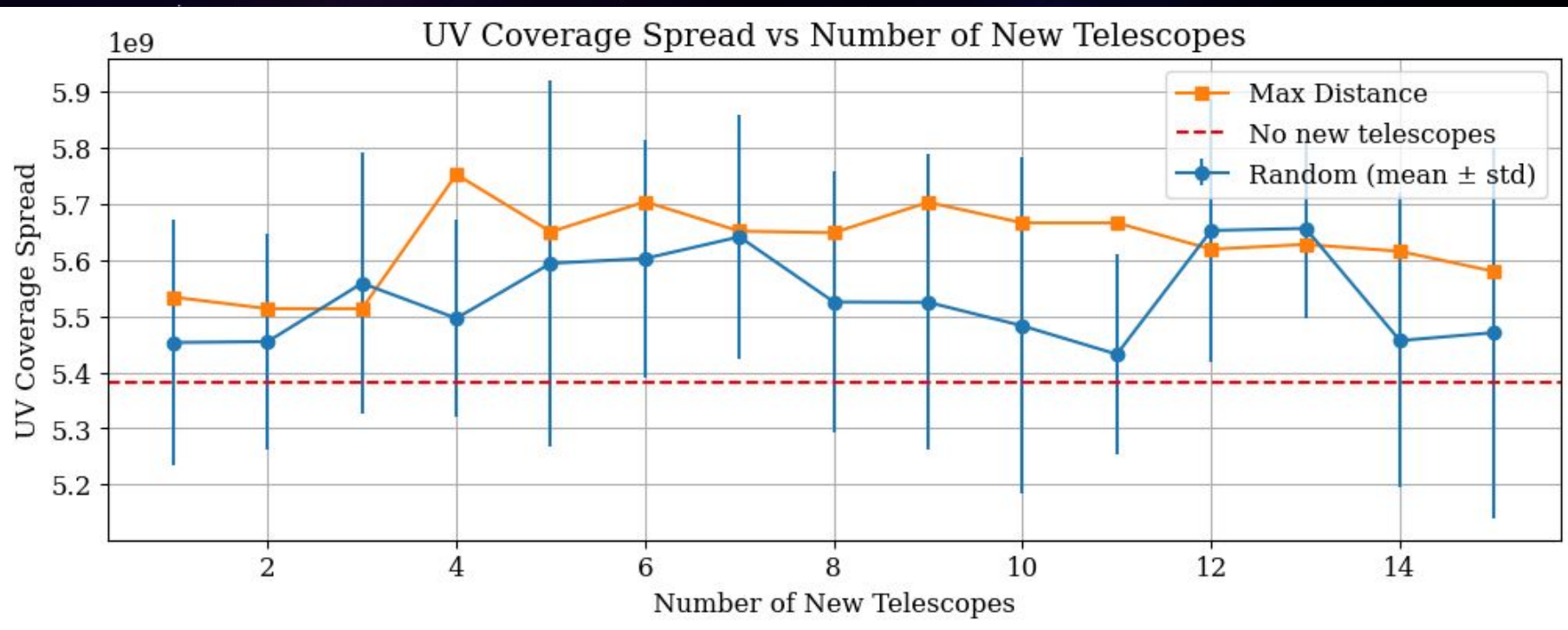
Add telescopes - Metrics (density-uniformity)



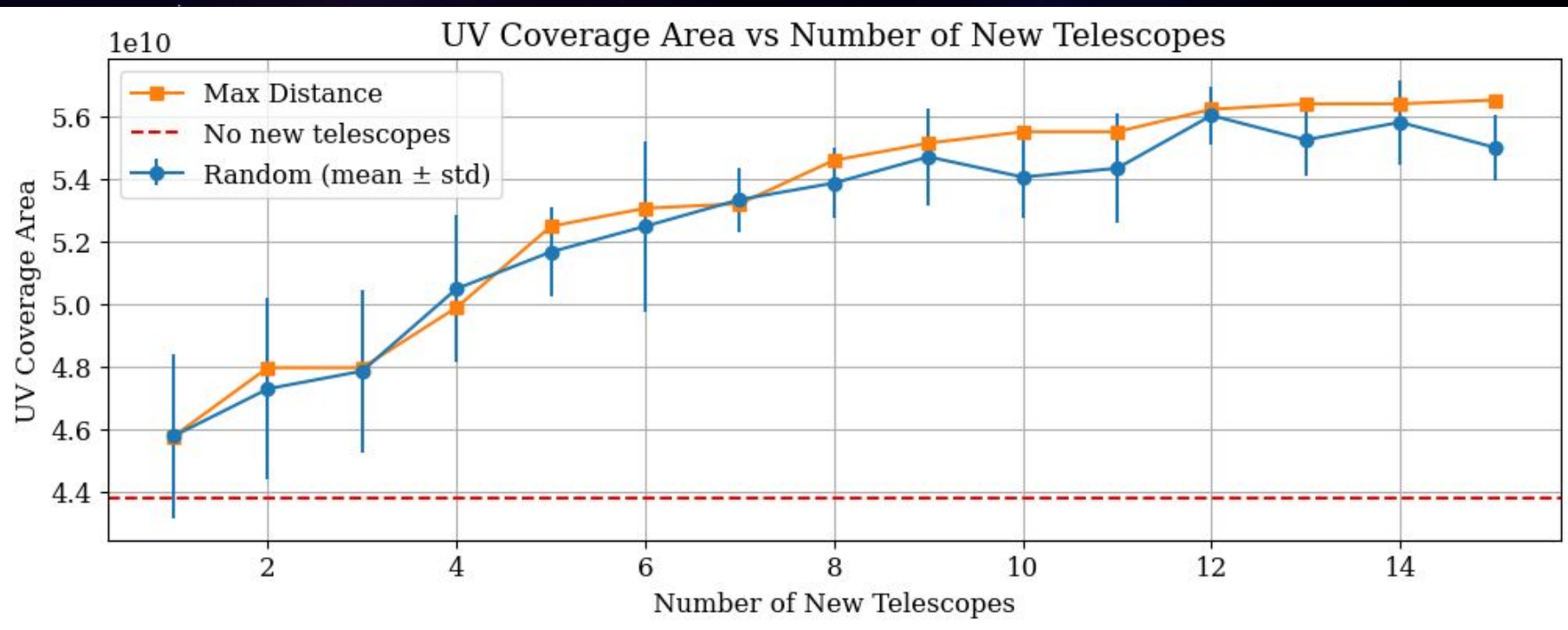
Add telescopes - Metrics (entropy)



Add telescopes - Metrics (spread)

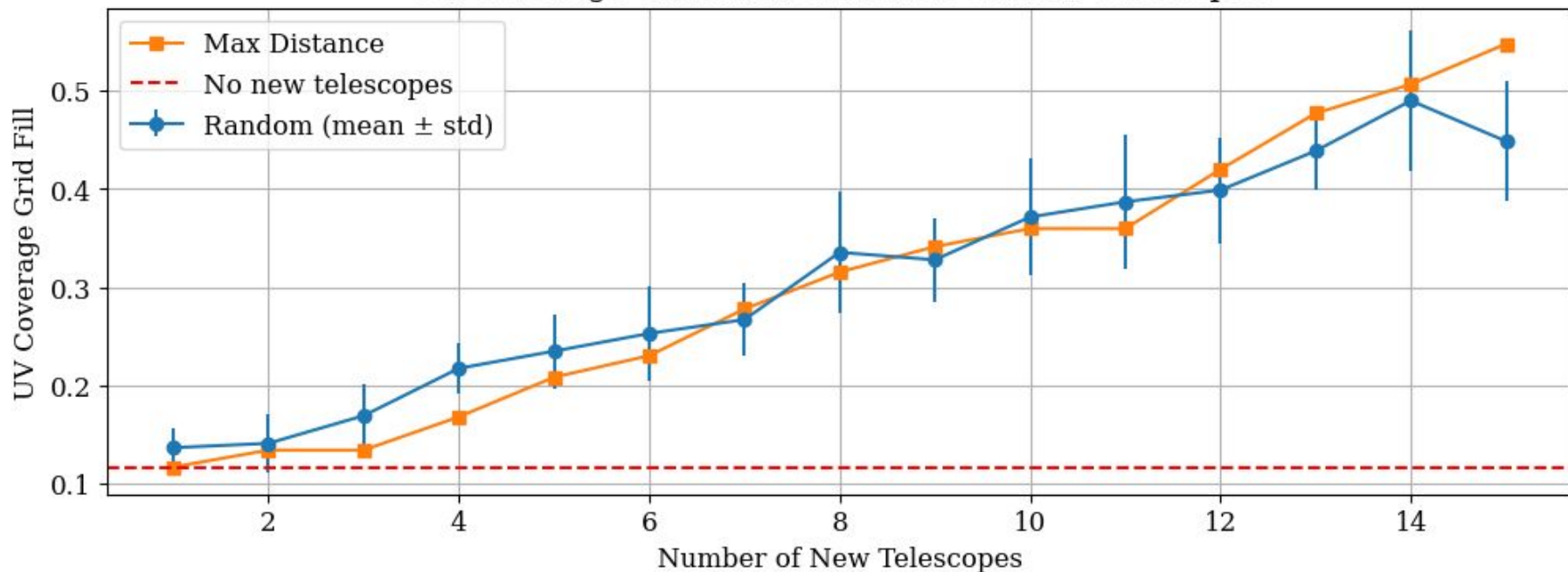


Add telescopes - Metrics (area)



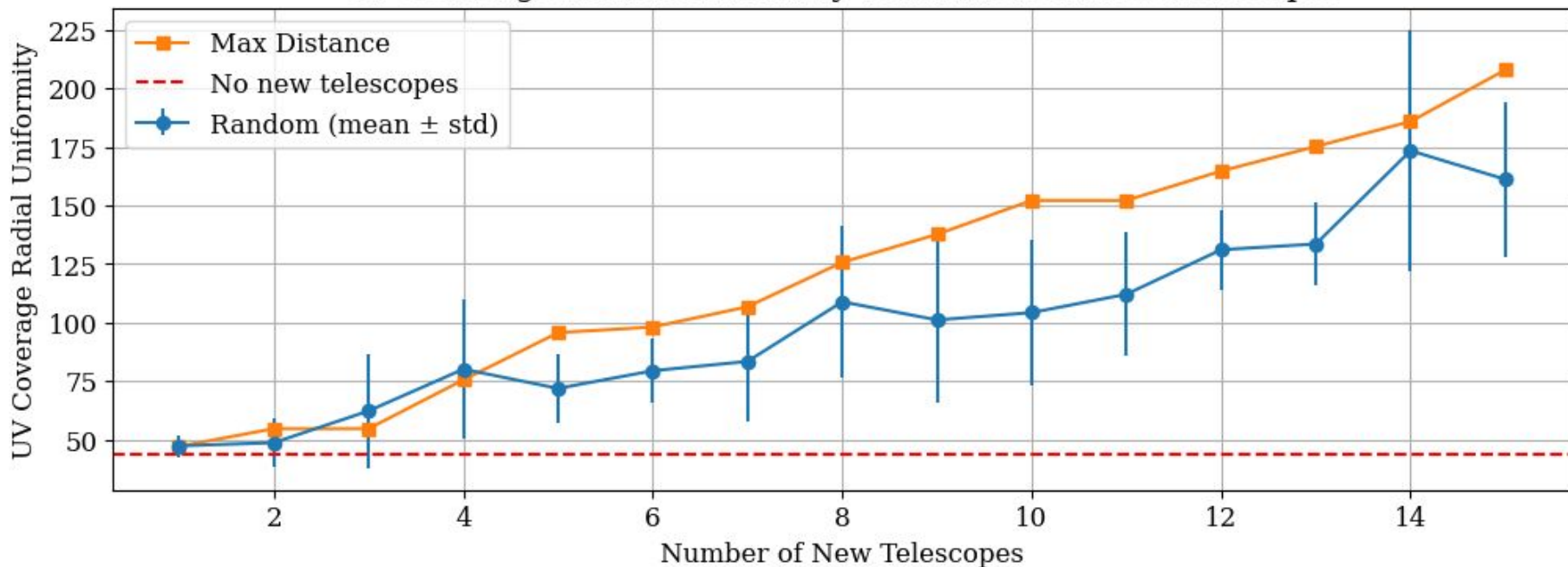
Add telescopes - Metrics (grid fill)

UV Coverage Grid Fill vs Number of New Telescopes

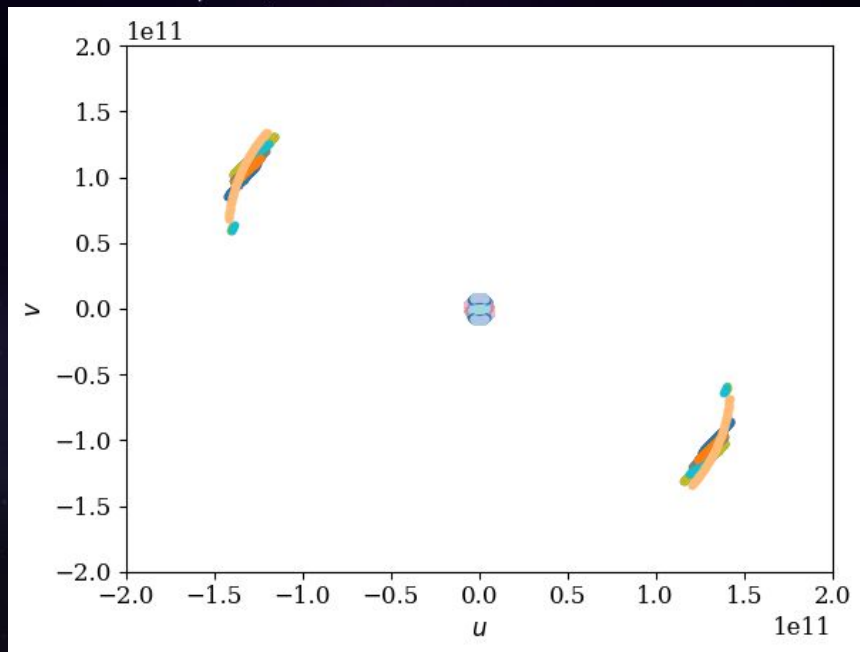


Add telescopes - Metrics (radial uniformity)

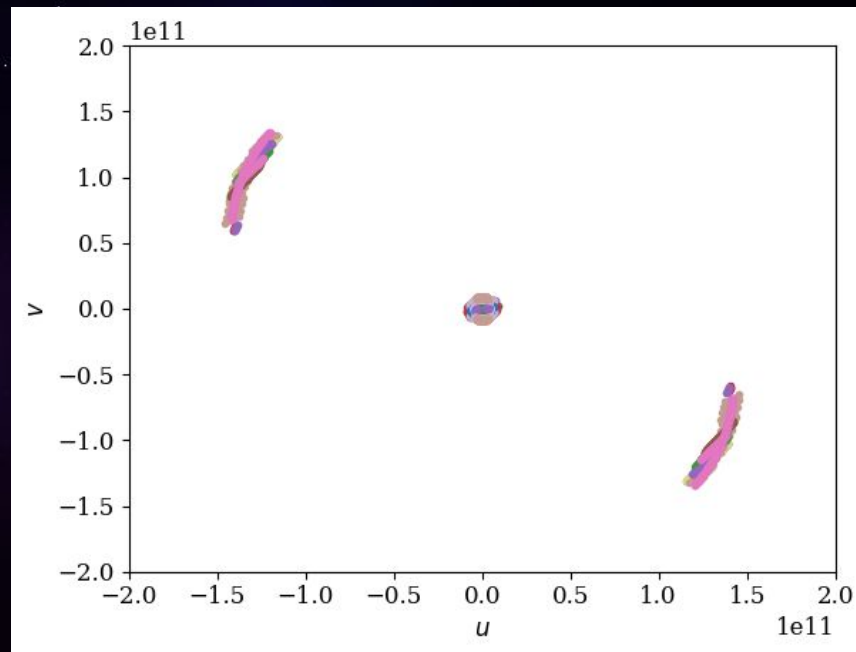
UV Coverage Radial Uniformity vs Number of New Telescopes



Evaluate the effect of satellite telescopes

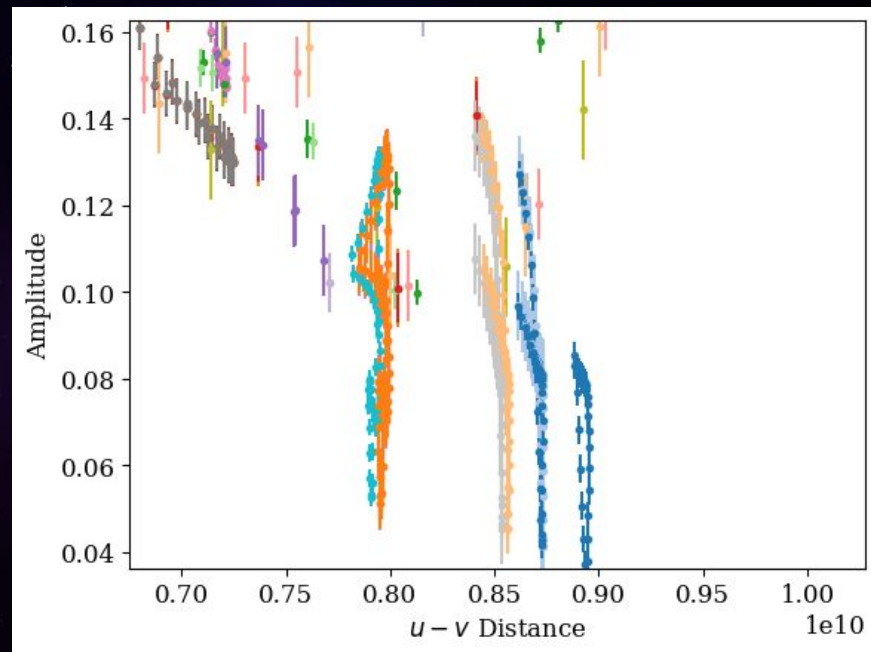
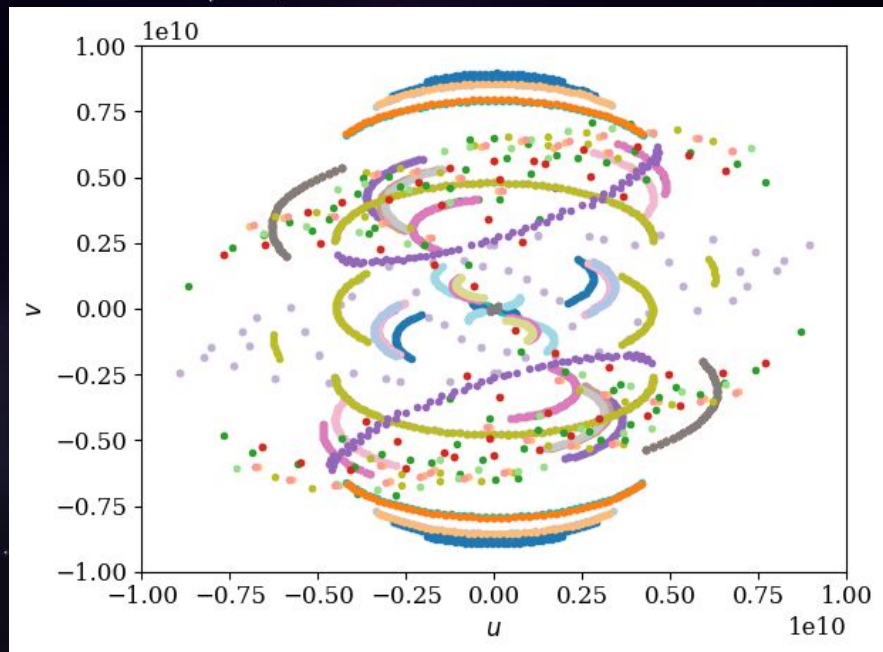


EHT2025wTESS



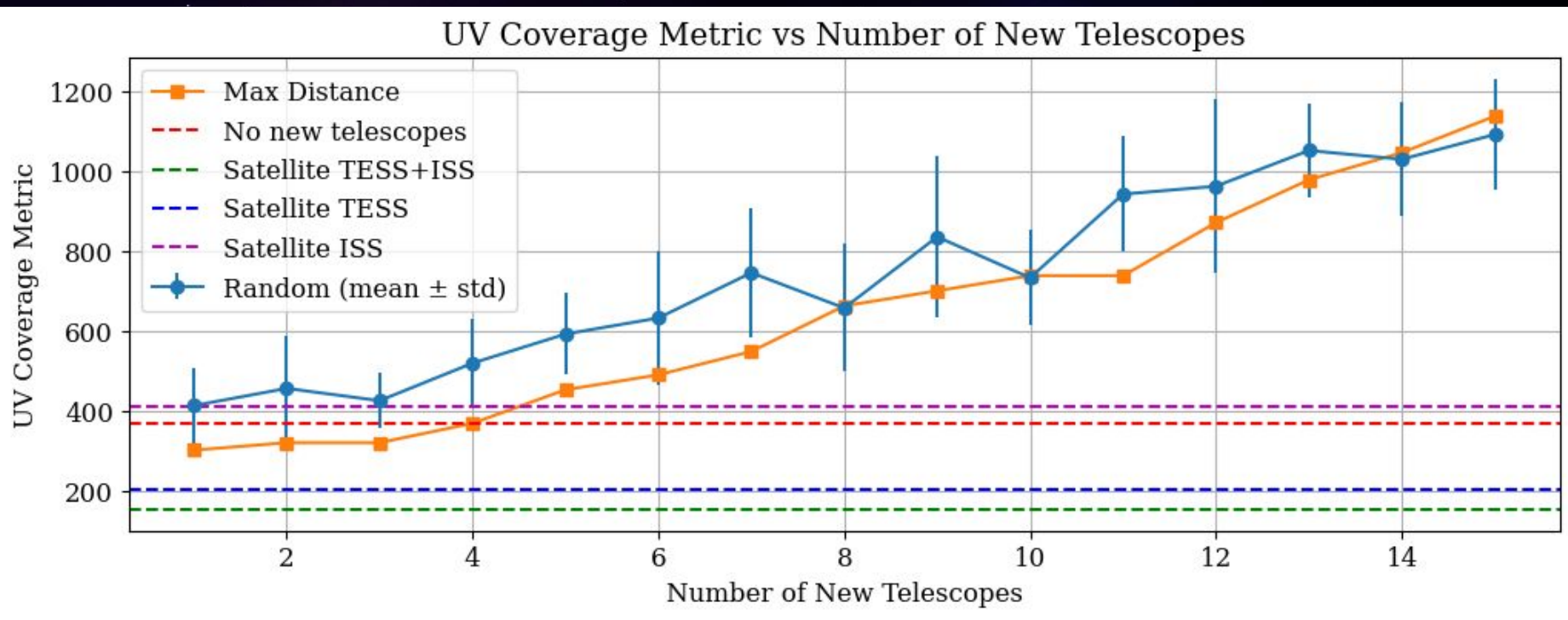
EHT2025wTESS&ISS

Evaluate the effect of satellite telescopes



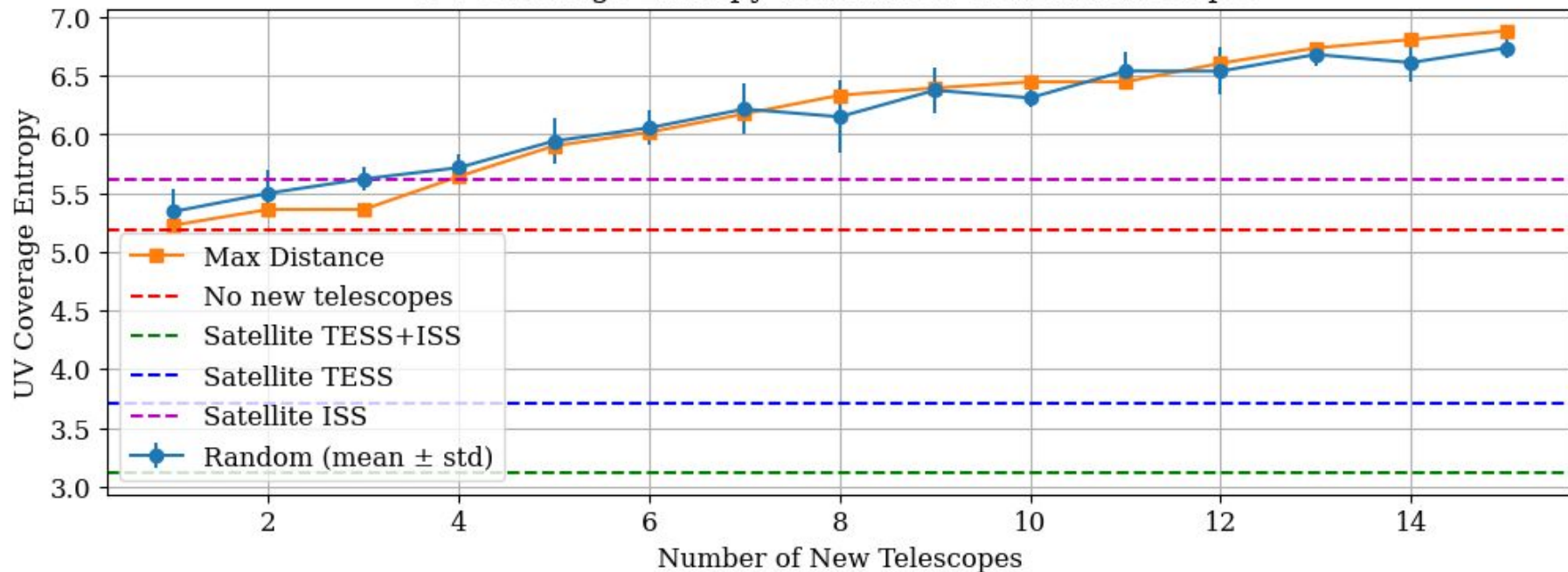
EHT2025wISS from close view

Satellite telescopes - Metrics (density-uniformity)

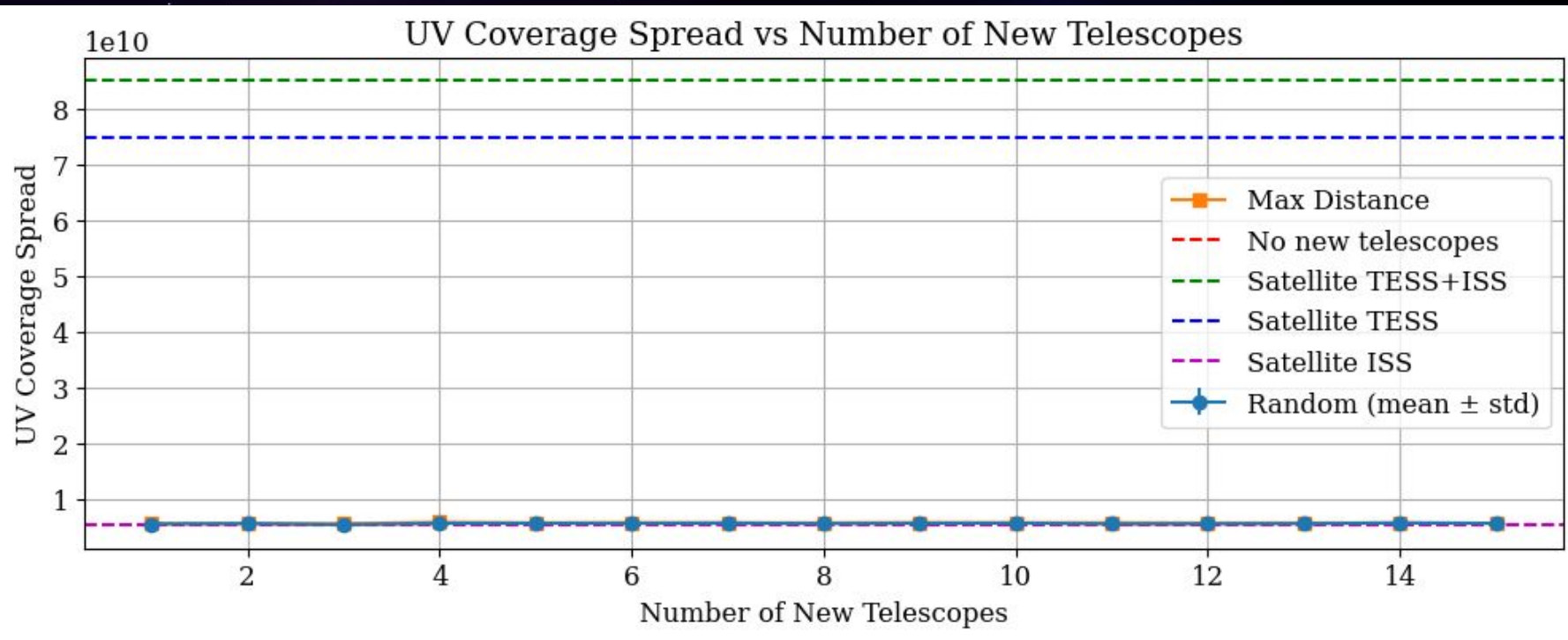


Satellite telescopes - Metrics (entropy)

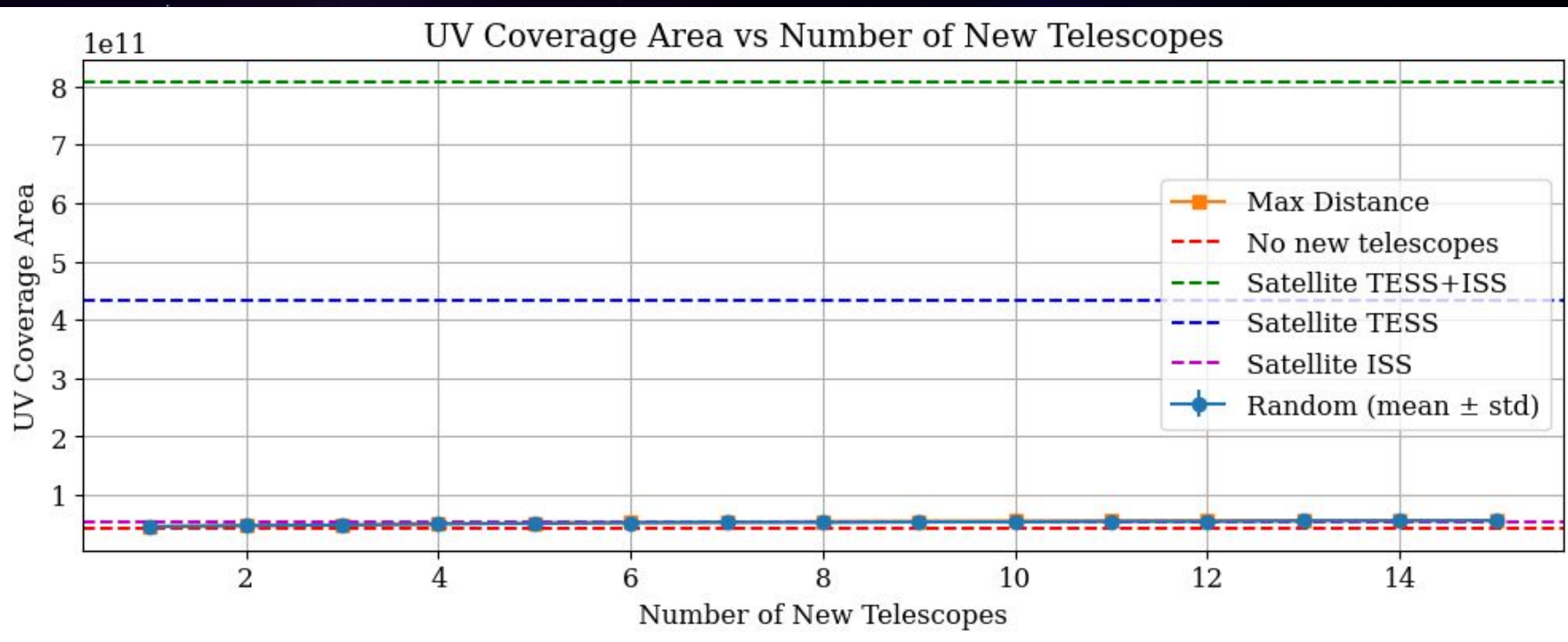
UV Coverage Entropy vs Number of New Telescopes



Satellite telescopes - Metrics (spread)

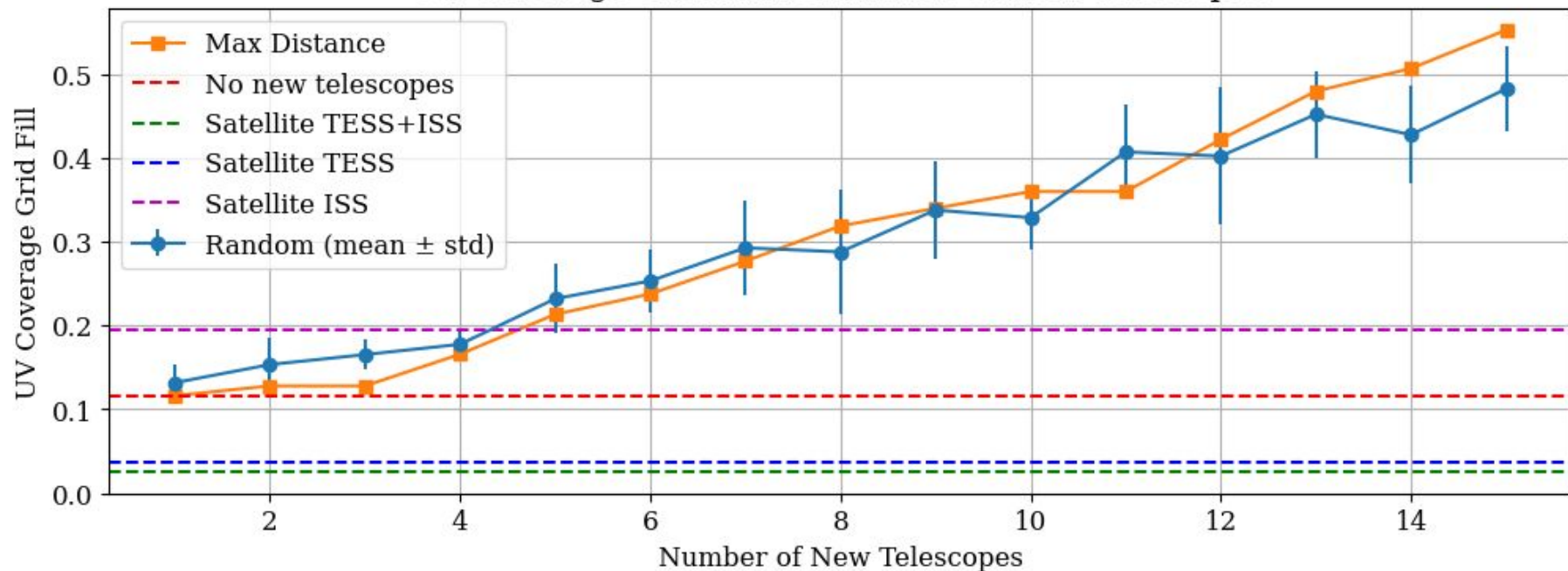


Satellite telescopes - Metrics (area)



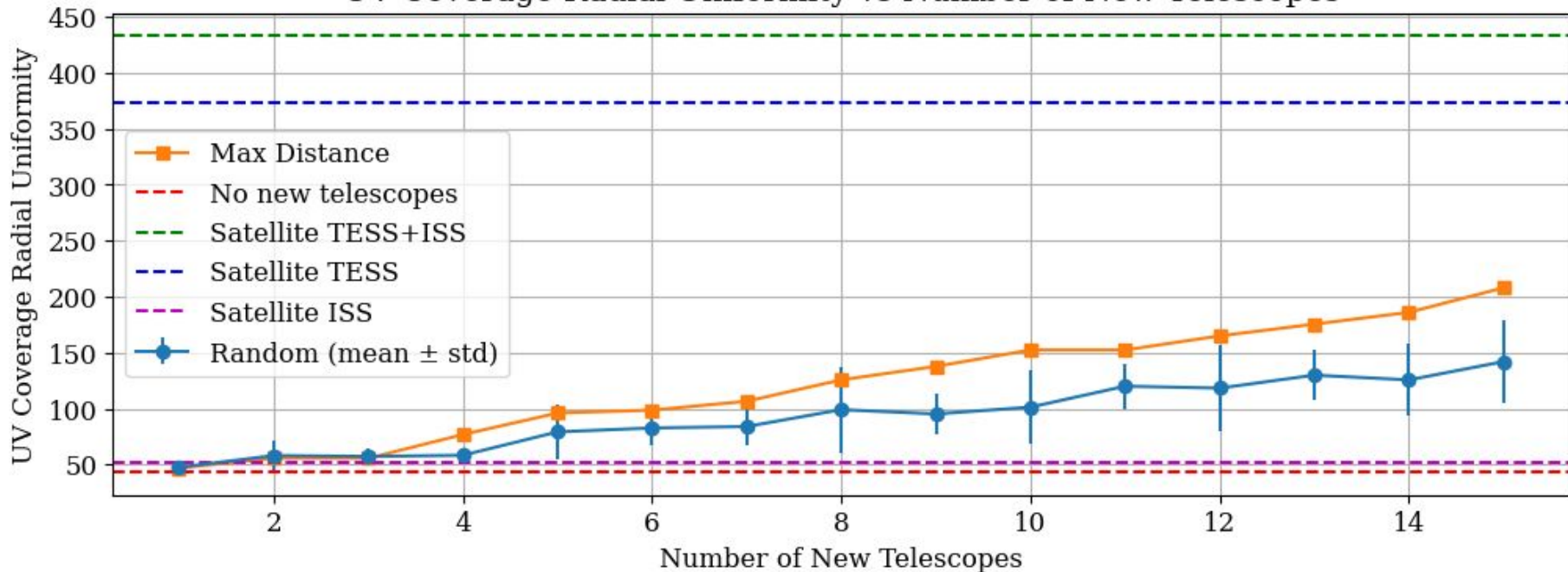
Satellite telescopes - Metrics (grid fill)

UV Coverage Grid Fill vs Number of New Telescopes



Satellite telescopes - Metrics (radial uniformity)

UV Coverage Radial Uniformity vs Number of New Telescopes



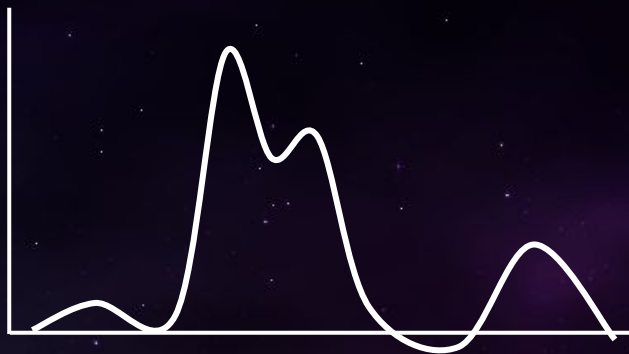


03

VLBI Imaging

VLBI Imaging: Estimating an image of a
celestial object

CLEAN algorithm

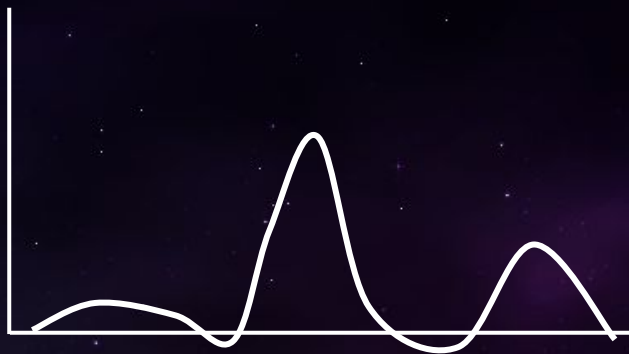


Dirty Image



Model Image

CLEAN algorithm



Dirty Image



Model Image

CLEAN algorithm



Dirty Image



Model Image

CLEAN algorithm



Thermal noise



Model Image

CLEAN algorithm



Model Image

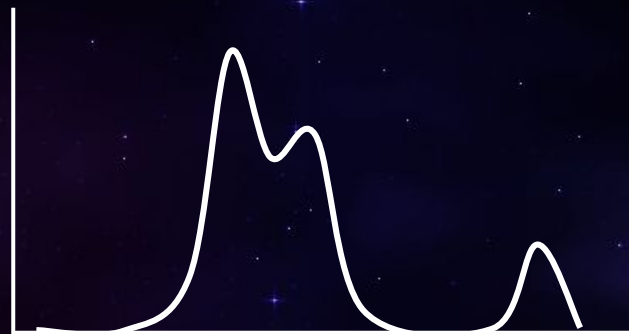


Clean beam (Gaussian beam)

CLEAN algorithm



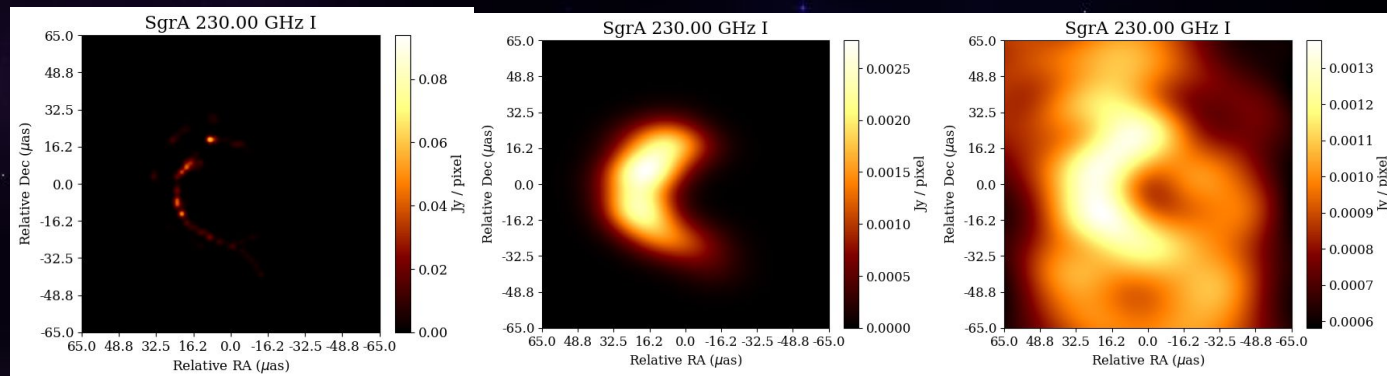
Model Image



Cleaned Image

Results

gain = 0.001
threshold = $4e-4$



gain = 0.1
threshold = $4e-4$

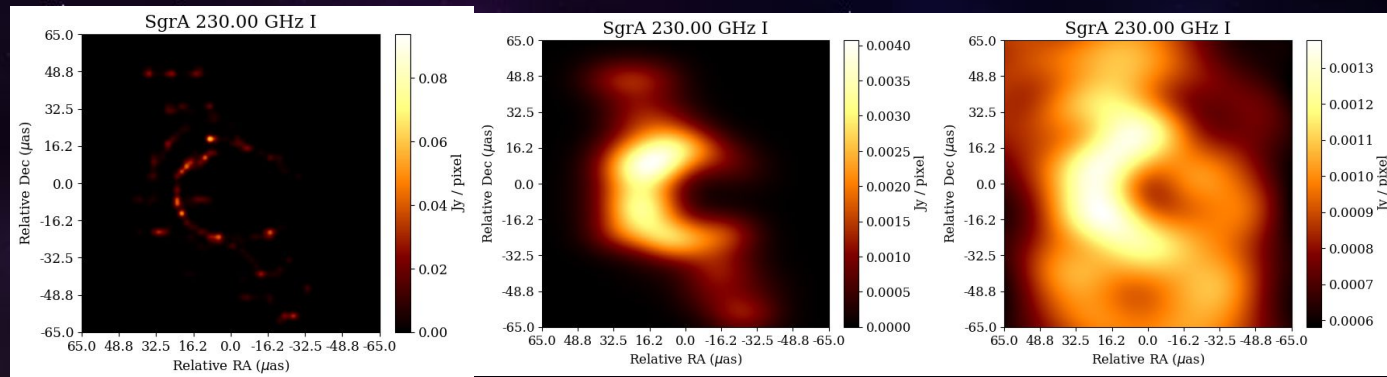


Image model

CLEANed image

Dirty image

The background is a deep blue space scene. It features two large, glowing blue galaxies on the right side, one in the upper right and one in the lower right. The rest of the background is filled with numerous small, distant stars of various colors (blue, orange, white) and a few faint, wispy nebulae. A thin white circle is centered on the left side of the image, containing the text.

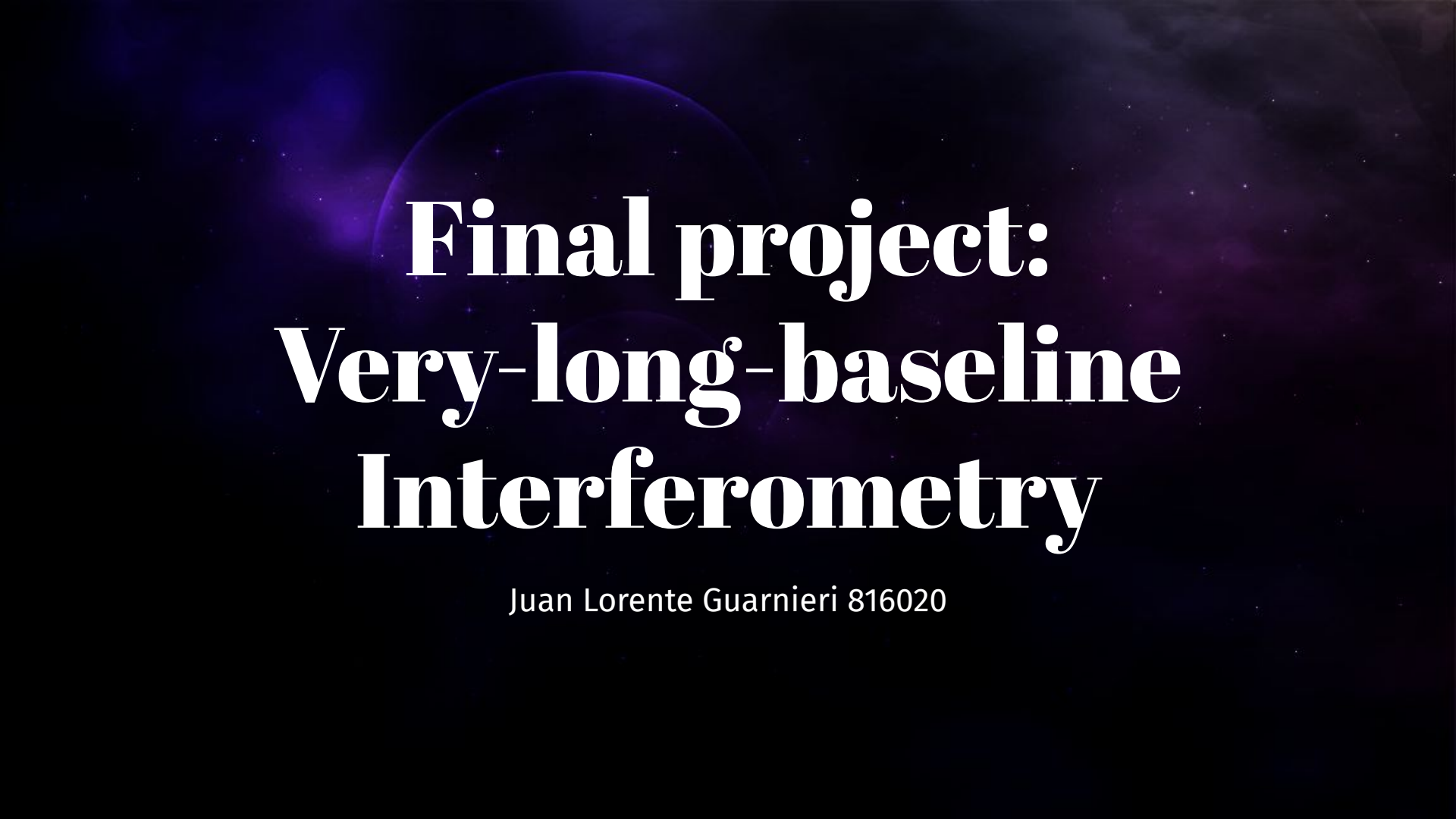
04

Summary

Things done

Summary

- ✔ Code (Section 2)
- ✔ Forward modeling (Section 3)
 - ✔ Add different amounts of noise
 - ✔ Compute frequencies by each pair of telescopes at a time
 - ✔ Add telescopes to maximize frequency coverage
 - ✔ Evaluate the effect of satellite telescopes
- ? VLBI imaging (Section 4)
 - ✔ Using the dirty image and dirty beam (CLEAN)
 - ✘ Using directly the frequency data



Final project: Very-long-baseline Interferometry

Juan Lorente Guarnieri 816020