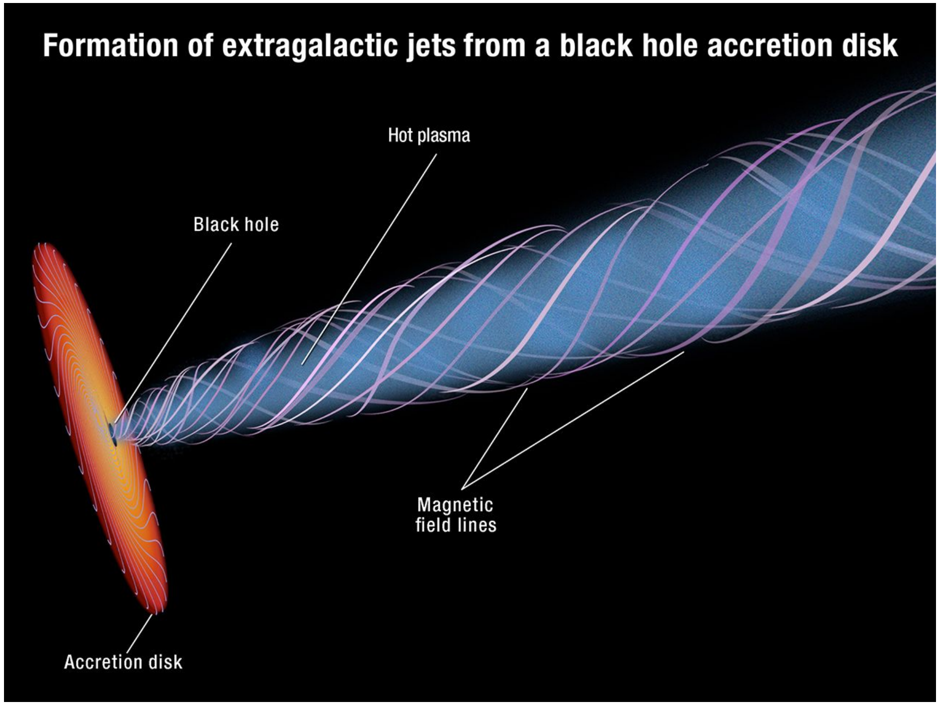
# VLA Radio Observations of Blazar TXS 0506+056

Phys 499 Presentation
Dalton J. Ronan
Supervisor: Gregory Sivakoff

# Background

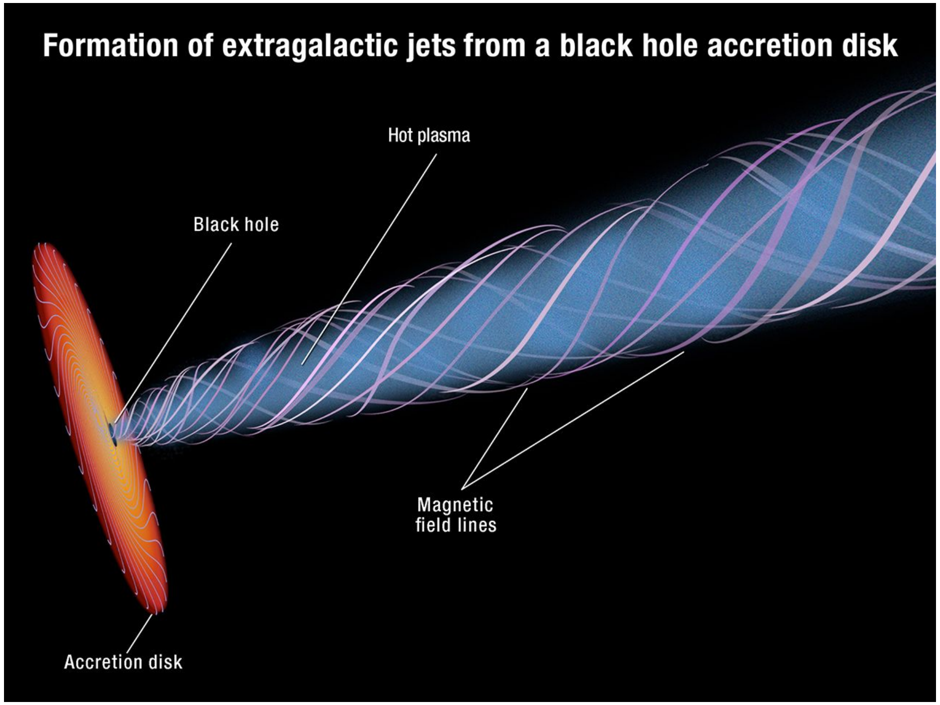
- Blazars ideal candidate for the study of jet physics
    - sources for high energy $\gamma$-rays and cosmic rays




http://hubblesite.org/image/918/category/49-elliptical-galaxies

# Background

- Blazars ideal candidate for the study of jet physics
  - sources for high energy $\gamma$-rays and cosmic rays
- Associated with neutrinos
  - Chargless & weakly interacting



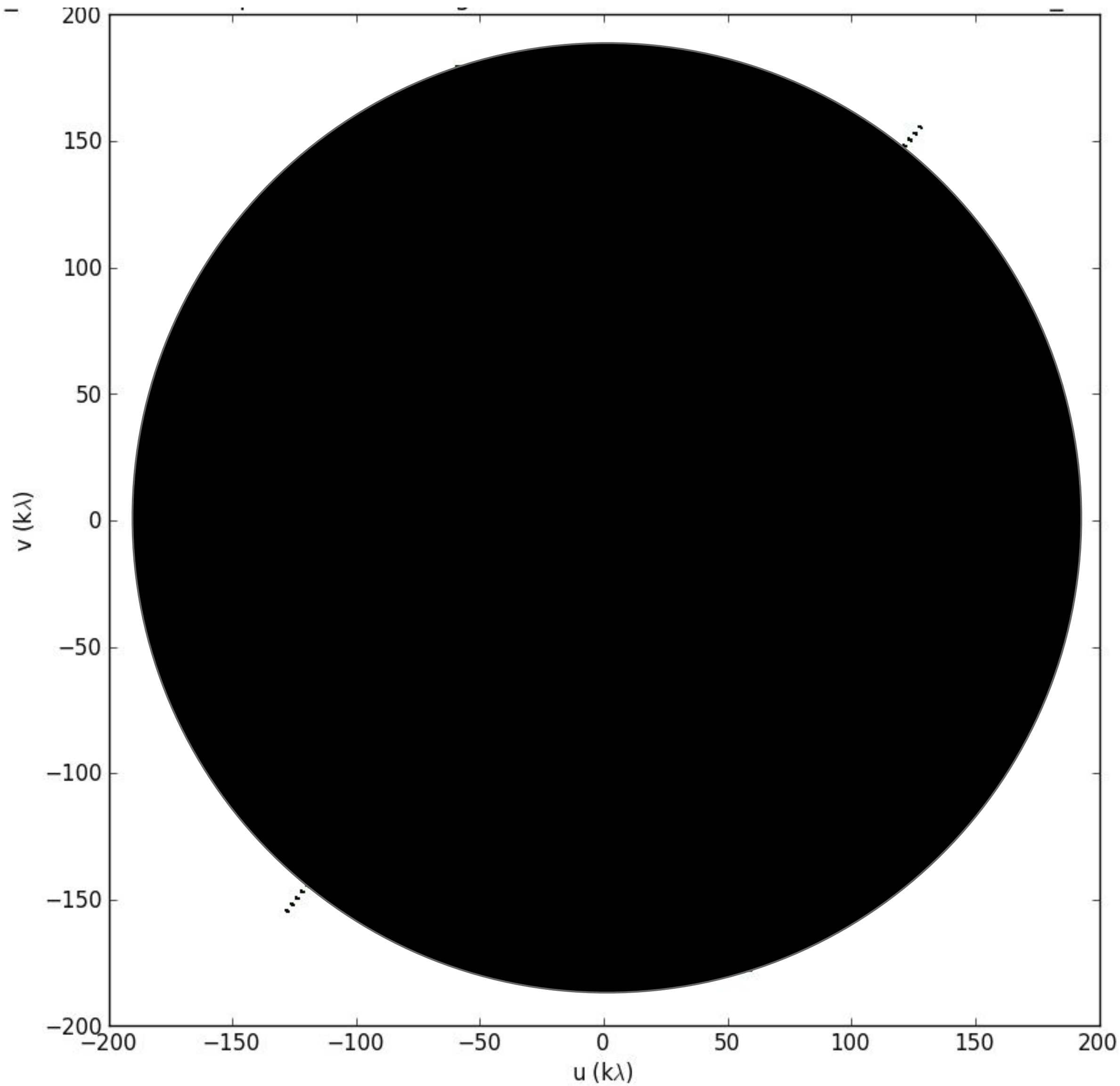

http://hubblesite.org/image/918/category/49-elliptical-galaxies

# The Project

- IceCube Neutrino Observatory detected neutrino on 22 September 2017
    - associated with blazar TXS 0506+056 at a 3.0 σ
- Observe blazar with Karl G. Jansky Very Large Array (VLA)
    - 7 epochs
        - October 05, 06, 09, 12, 24
        - November 21
        - March 04
    - ~11 minute observations on target
    - 4-8 GHz and 9-12 GHz bands
- Is blazar variable/evolving?
- Connection to neutrino detection?

# Radio Interferometry and Synthesis Imaging

# Radio Interferometry and Synthesis Imaging



# Radio Interferometry and Synthesis Imaging

- To achieve high angular resolution, need large telescope (~kms for radio): $\theta \sim \frac{\lambda}{D}$

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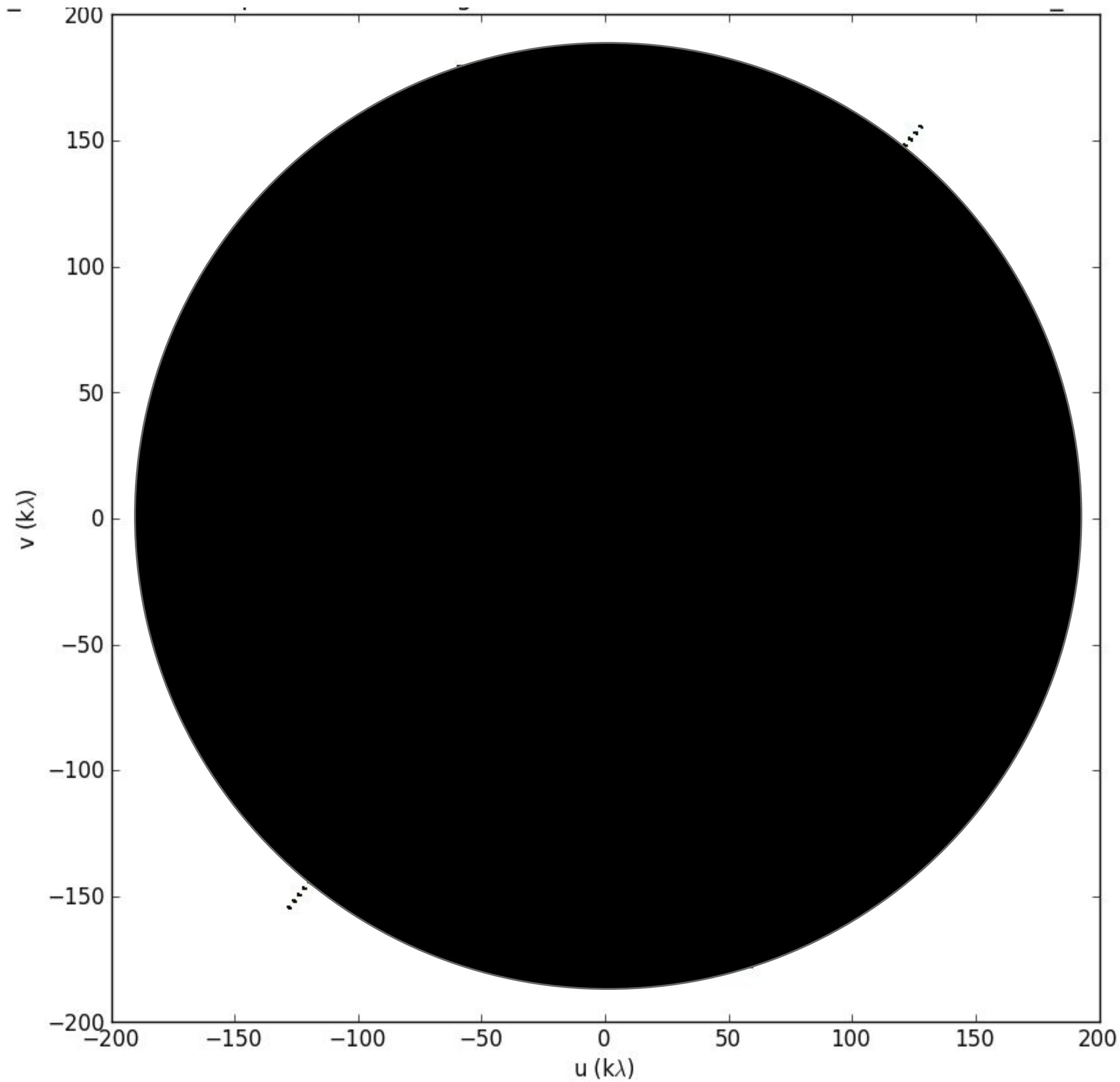

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- **Interferometry:** use many small apertures to *synthesize* a larger one

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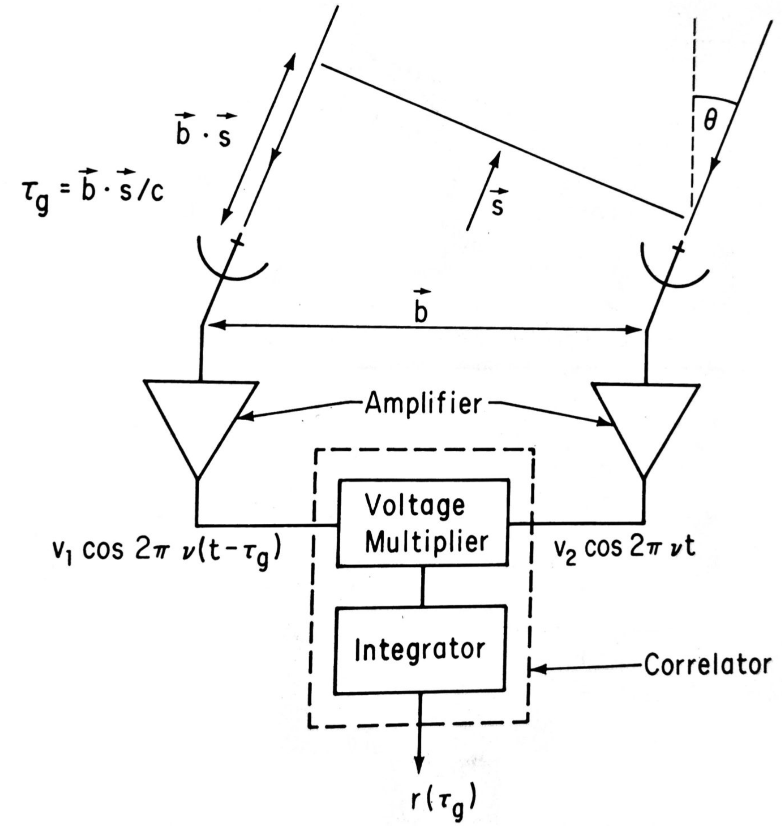


*Synthesis imaging in Radio Astronomy*, ASP conference series vol. 6

VLA in D configuration,
https://www.cv.nrao.edu/course/astr534/Interferometers2.html

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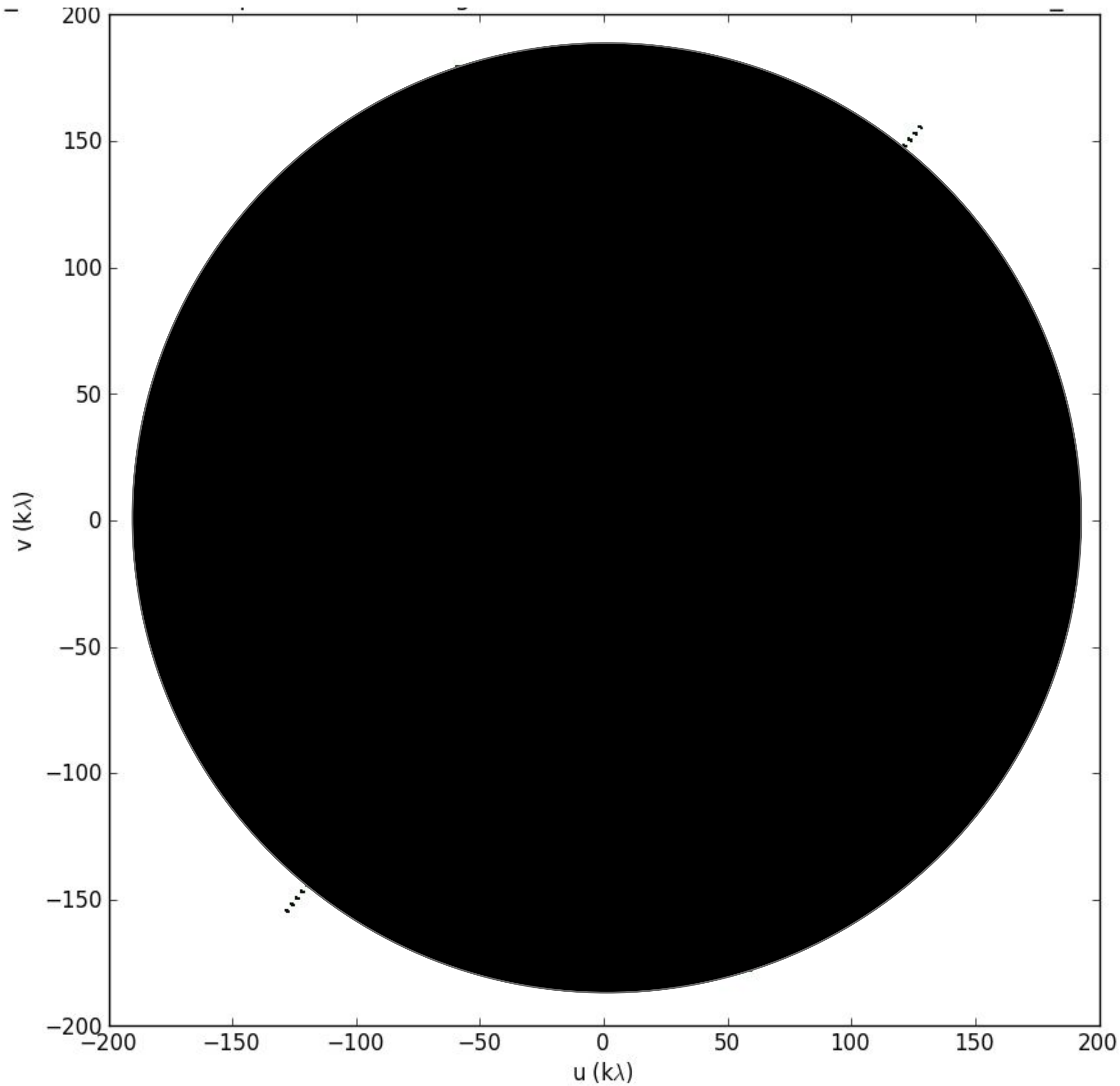

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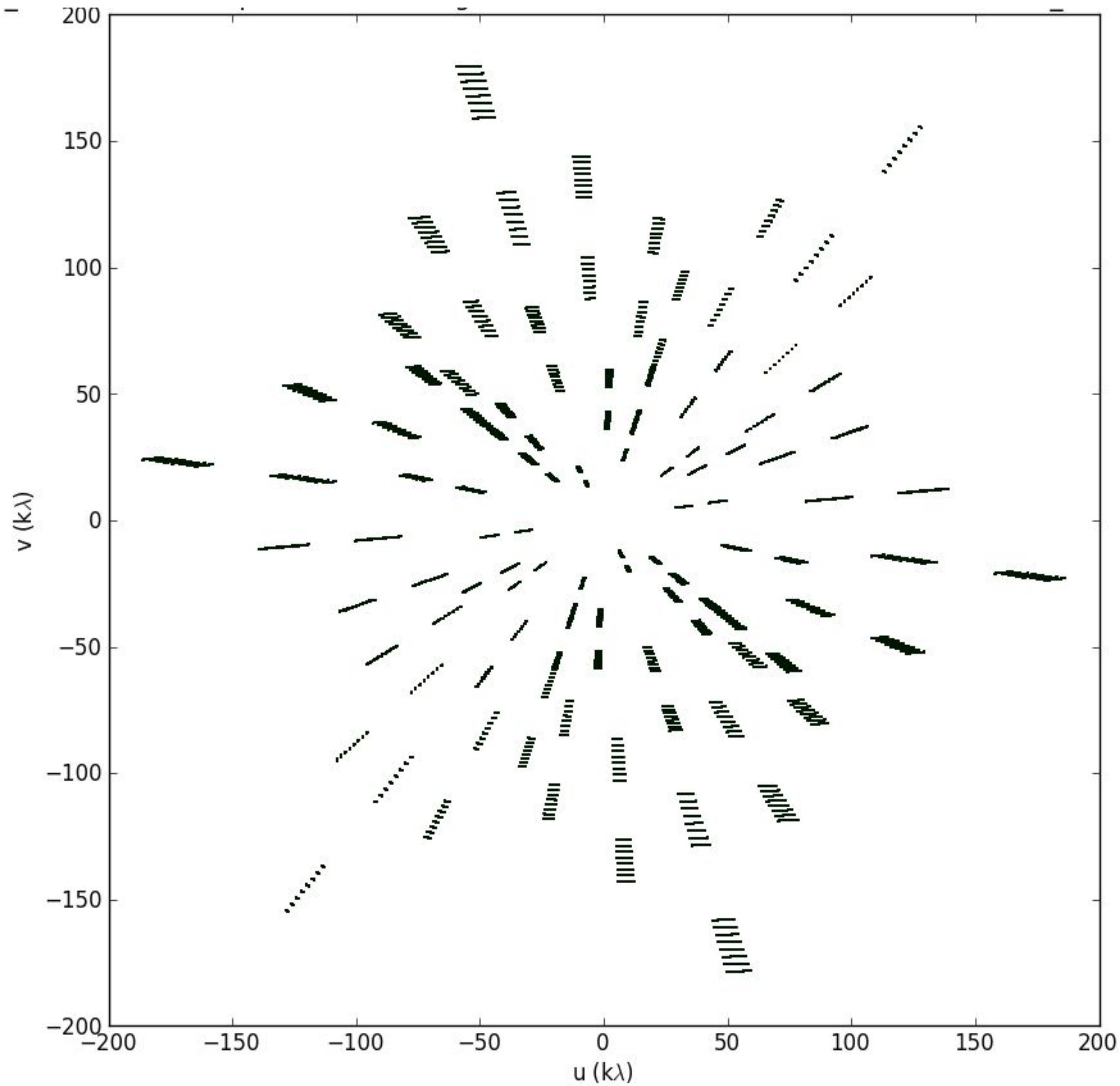

# Data Reduction Process

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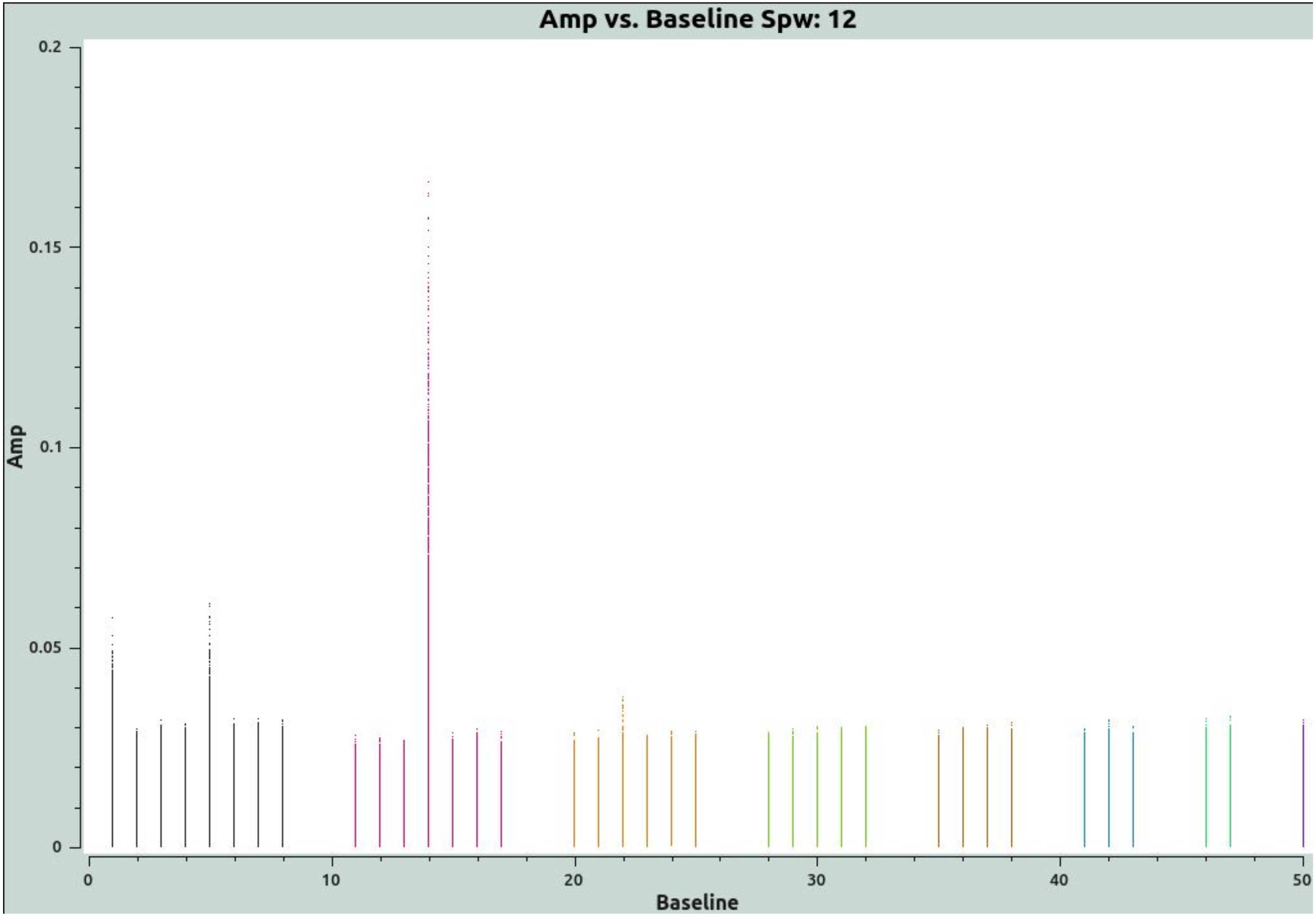
**Flagging**

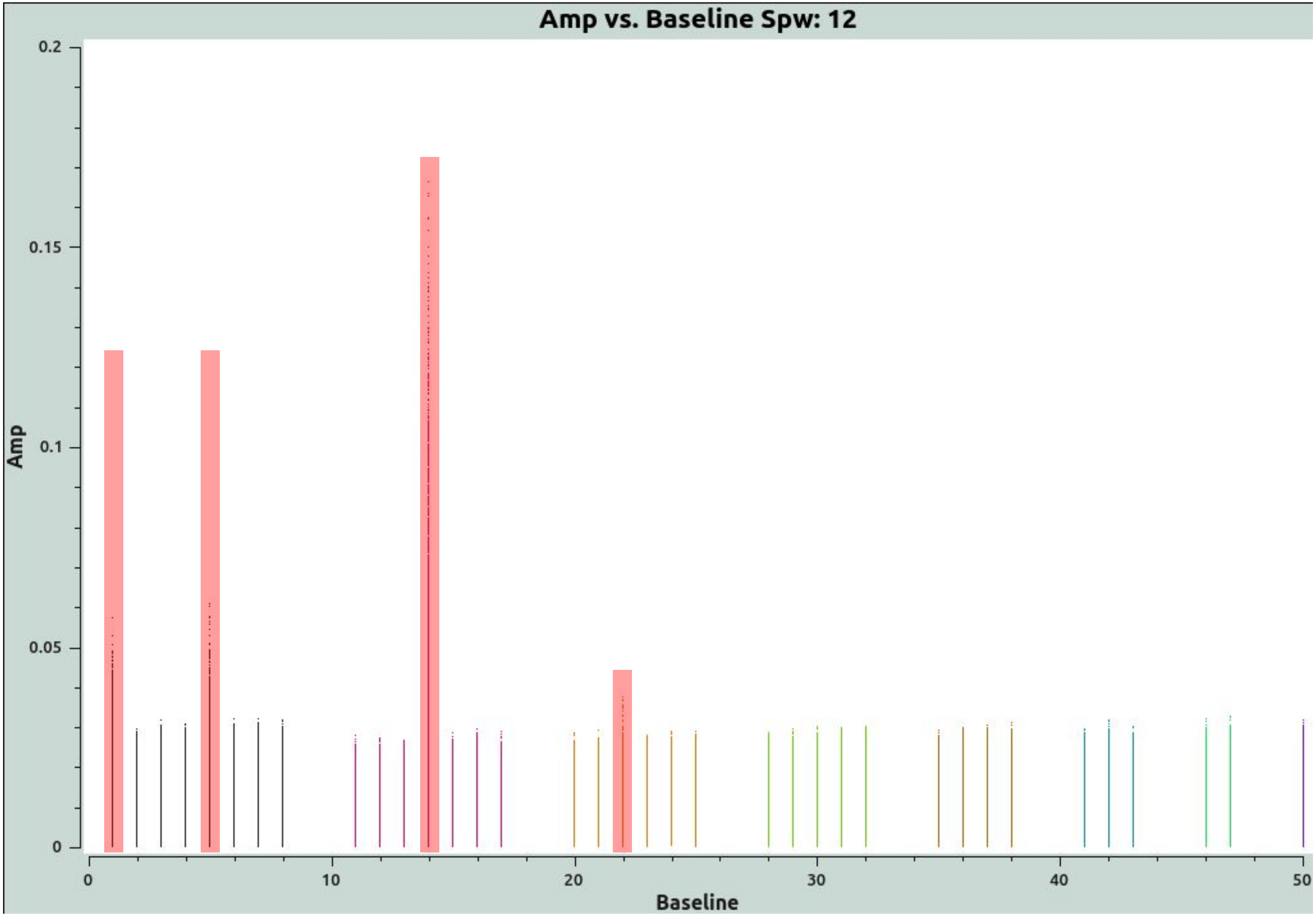
- Remove obvious bad data (from system errors) that can't be corrected
- Examine data looking for inconsistencies
  - Amplitude spikes
  - Phase scattering
  - RFI
  - A priori flags

# Data Reduction Process




Amplitude vs. Baseline in spectral window 12 (10.9 GHz), epoch 2

# Data Reduction Process




Amplitude vs. Baseline in spectral window 12 (10.9 GHz), epoch 2

# Reduction Process

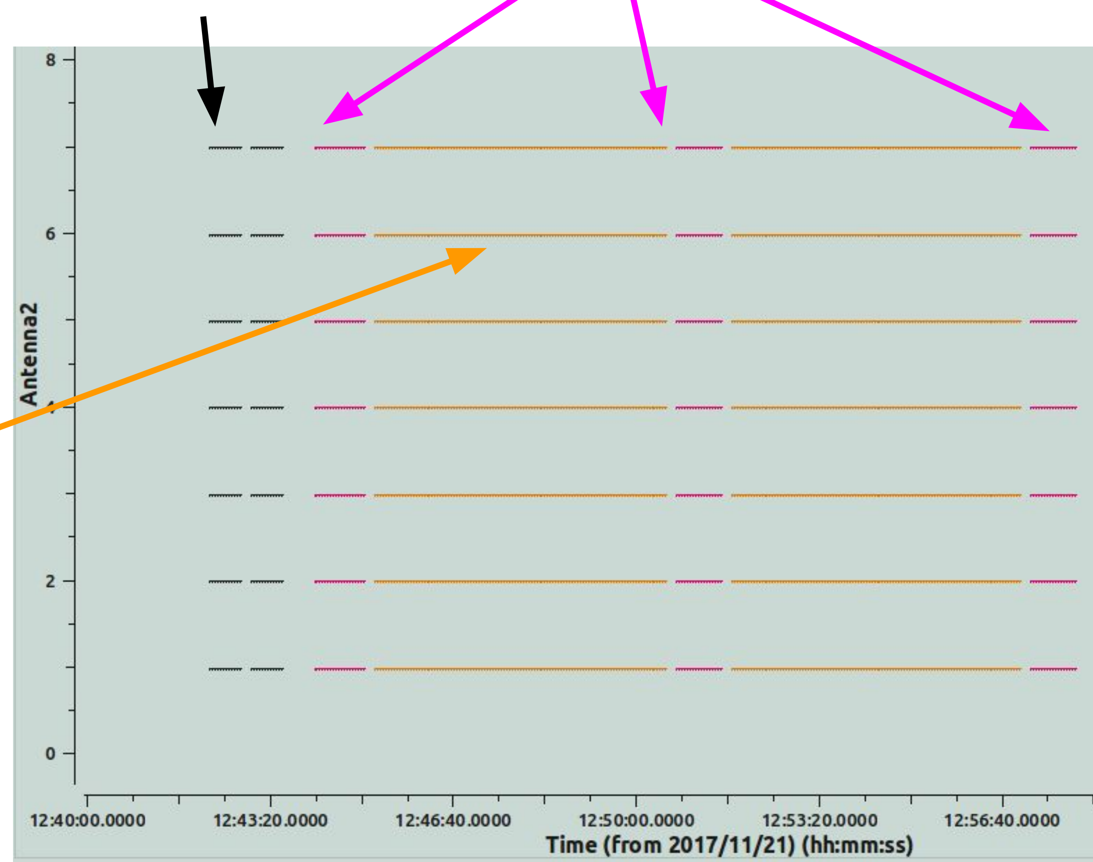
## Calibration

- Convert voltage response to flux density (Janskys)
- correct for effects due to the instrument and/or local temporary conditions
  - Atmospheric fluctuations
  - Delay
  - etc.

# Reduction Process

## Calibration

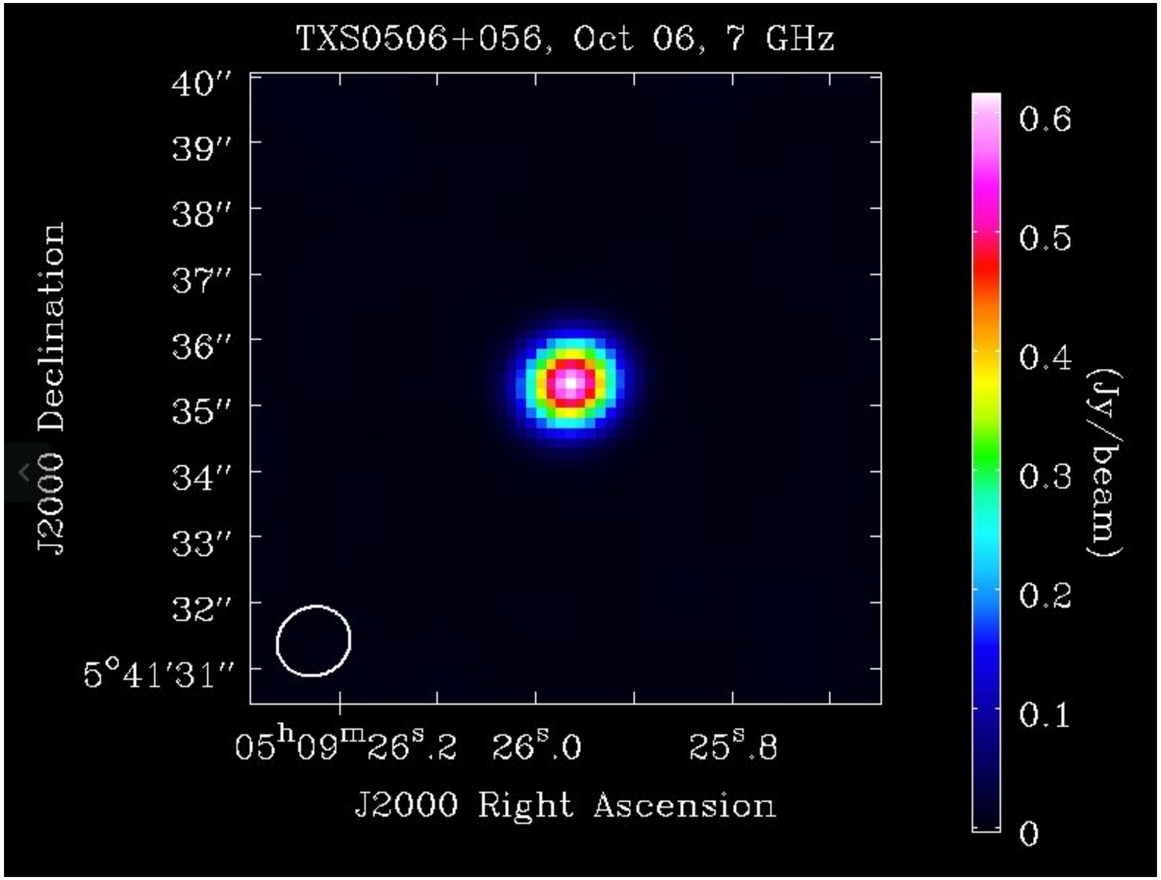
- Observe known sources
- Compare array response to models
- Calibrate data to match model
- Apply calibrations to target observations



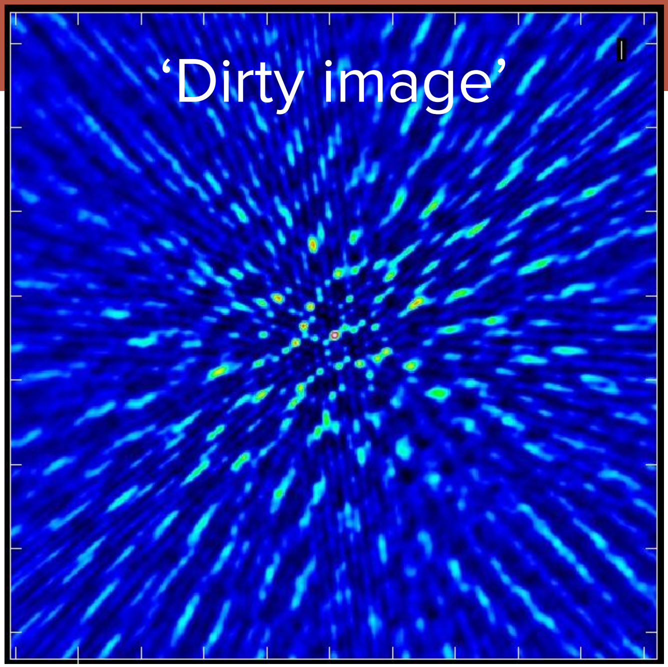

Array data feed during epoch 2 observation

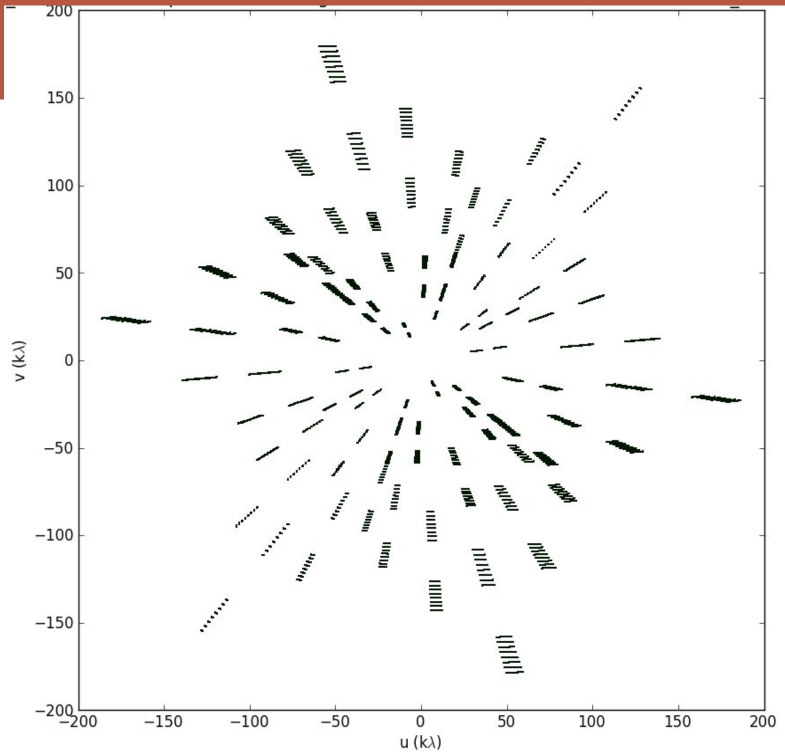
# Imaging

- Image true sky brightness from data (2D Fourier Transform)
- Create model of true sky brightness
  - "CLEAN" algorithm (Högbom, 1974)

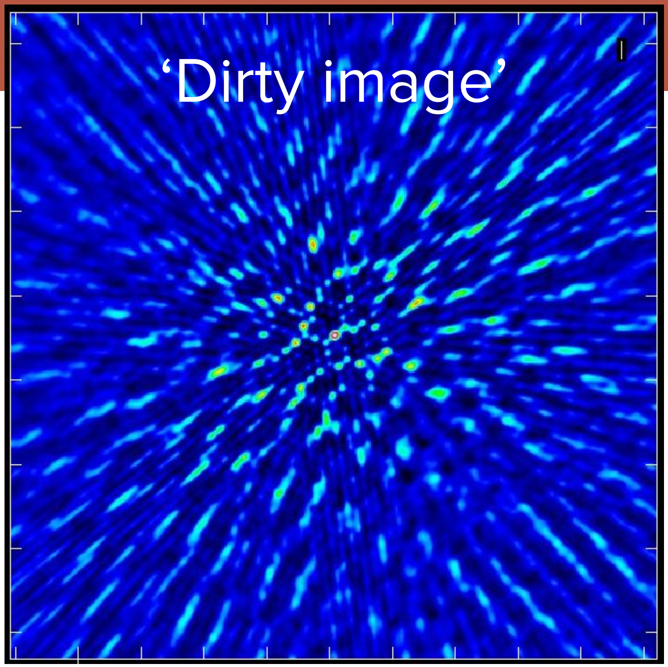


# CLEAN

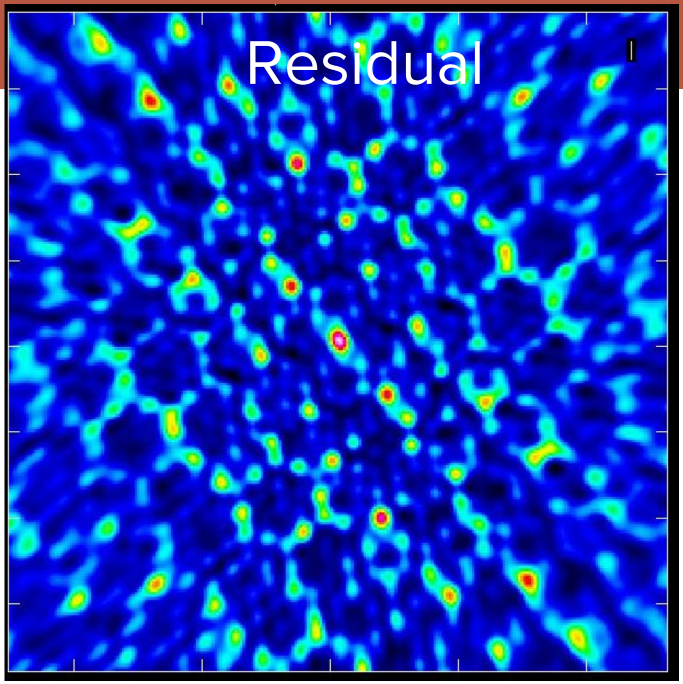

‘Dirty image’


v (kλ)
u (kλ)
200
150
100
50
0
−50
−100
−150
−200
−200
−150
−100
−50
0
50
100
150
200

# CLEAN




Subtract Peak



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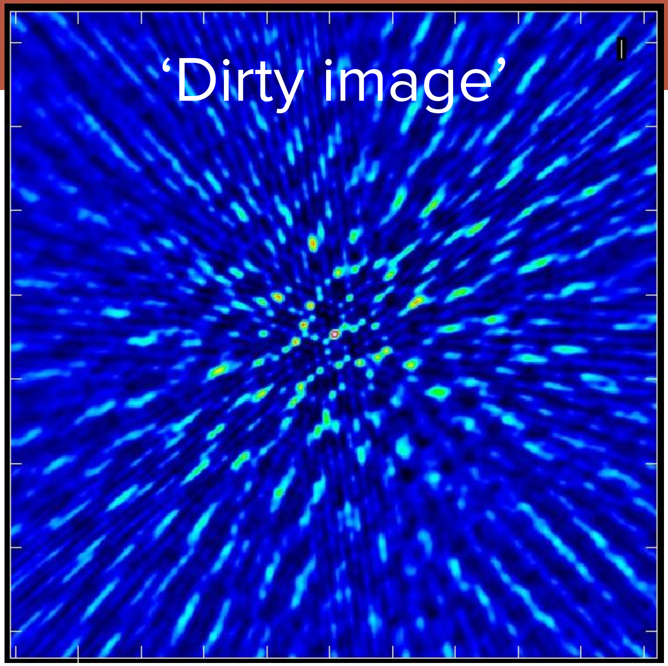


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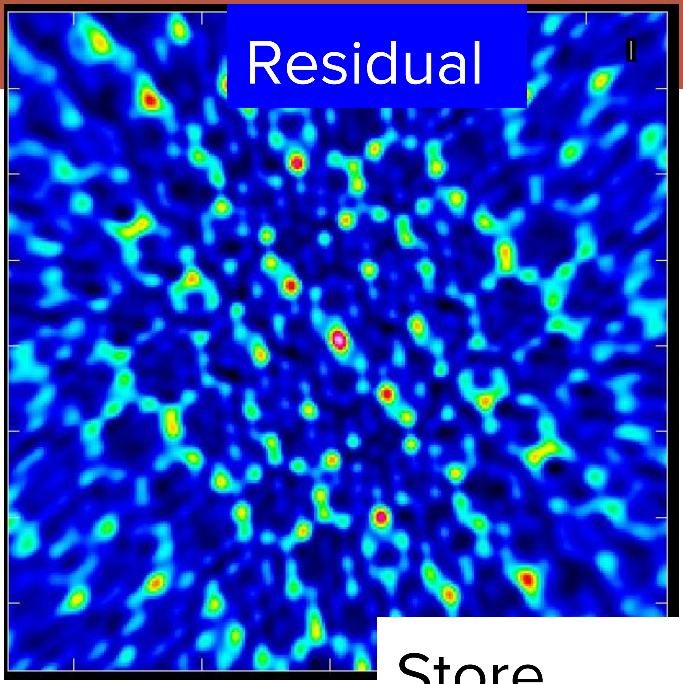
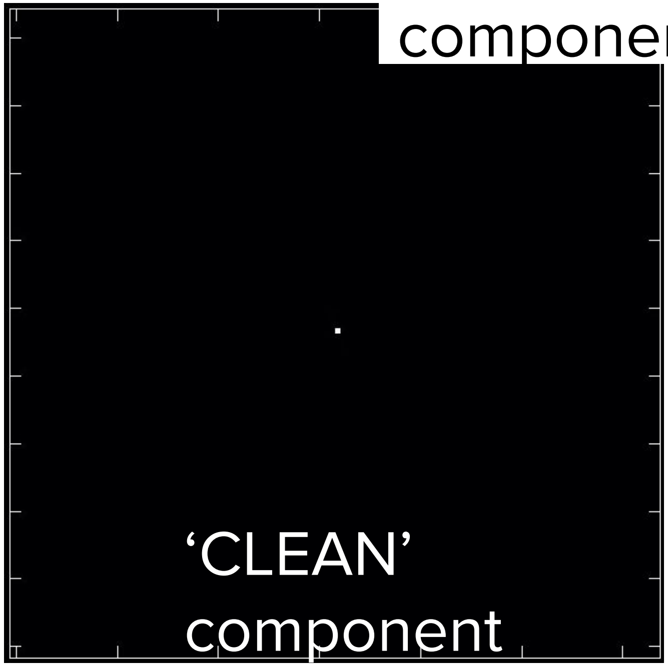



Store component



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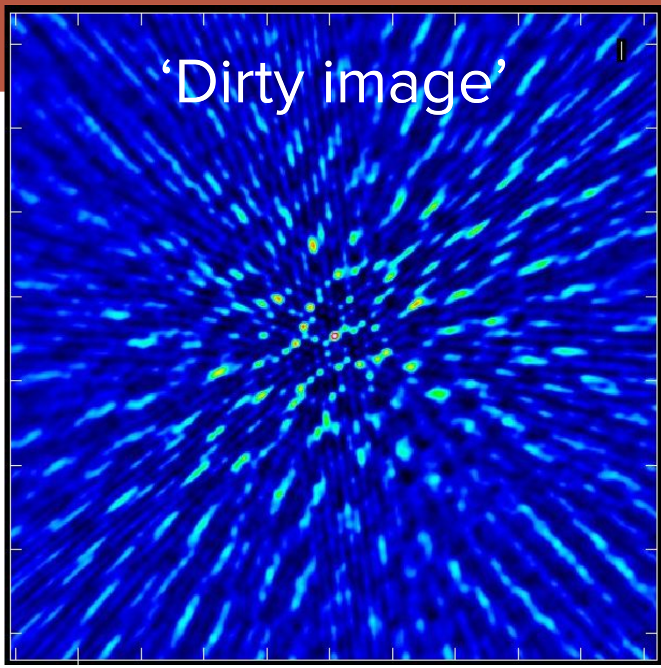


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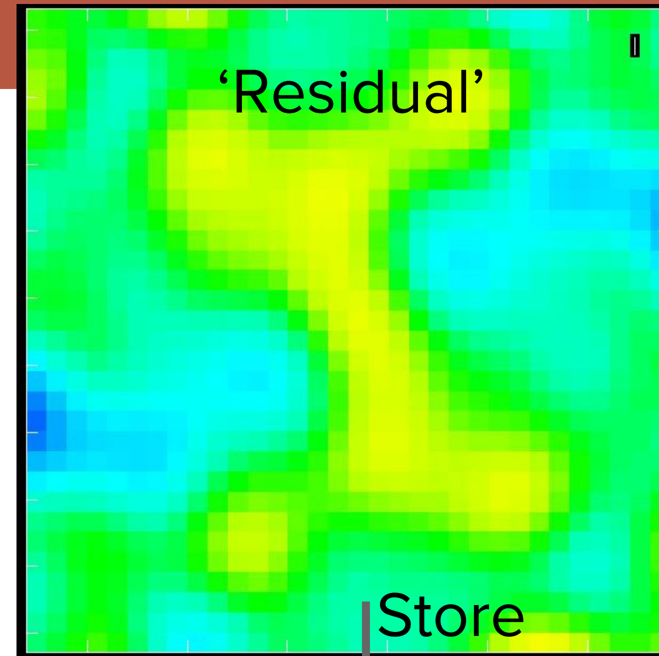


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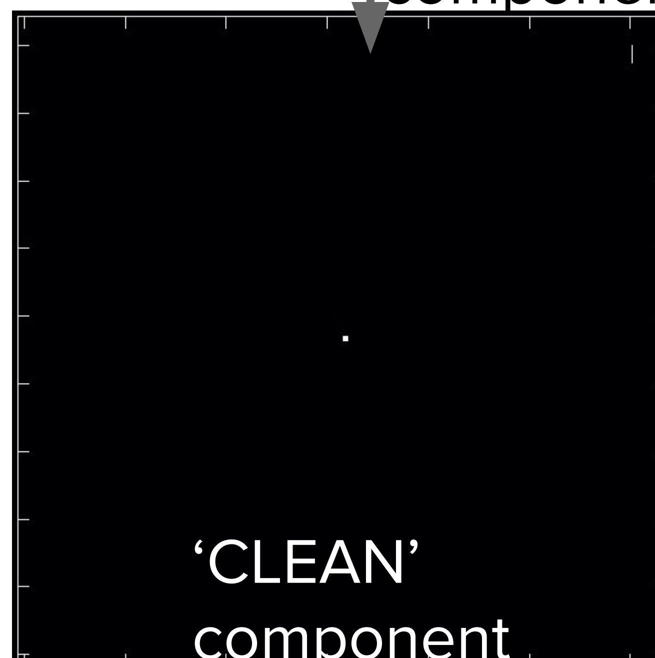
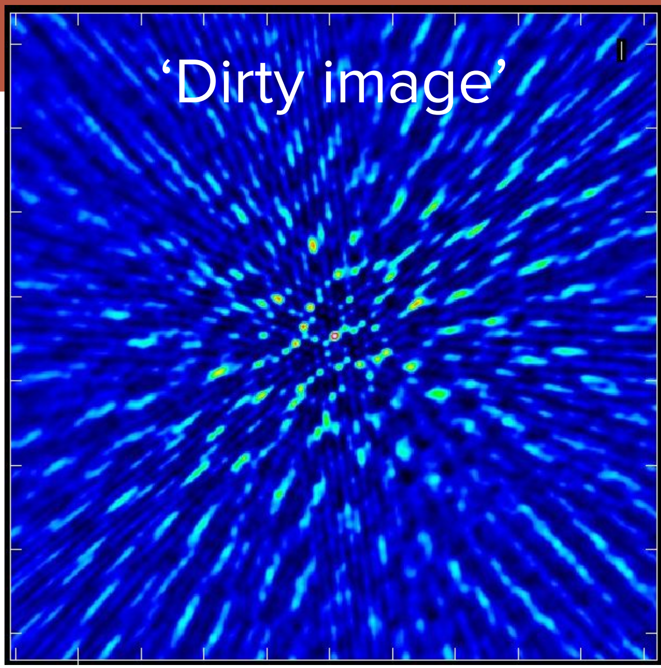



$$\times N$$

# CLEAN

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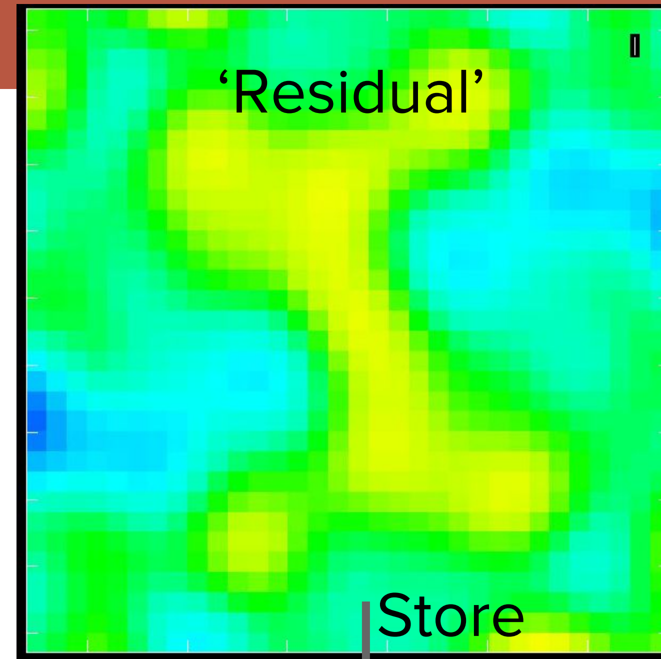
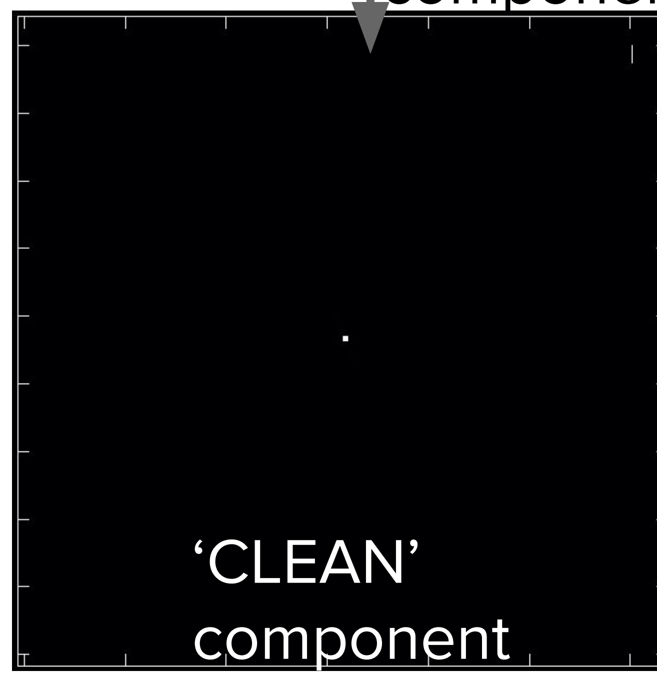
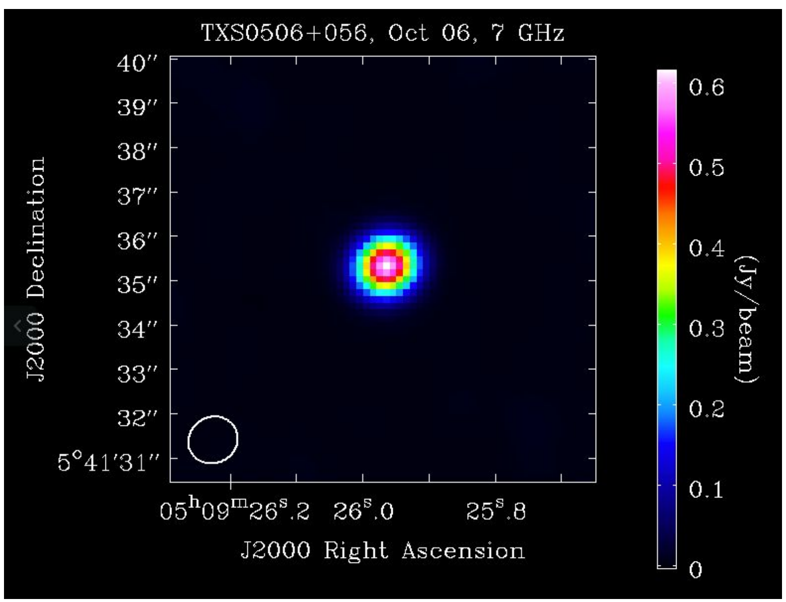


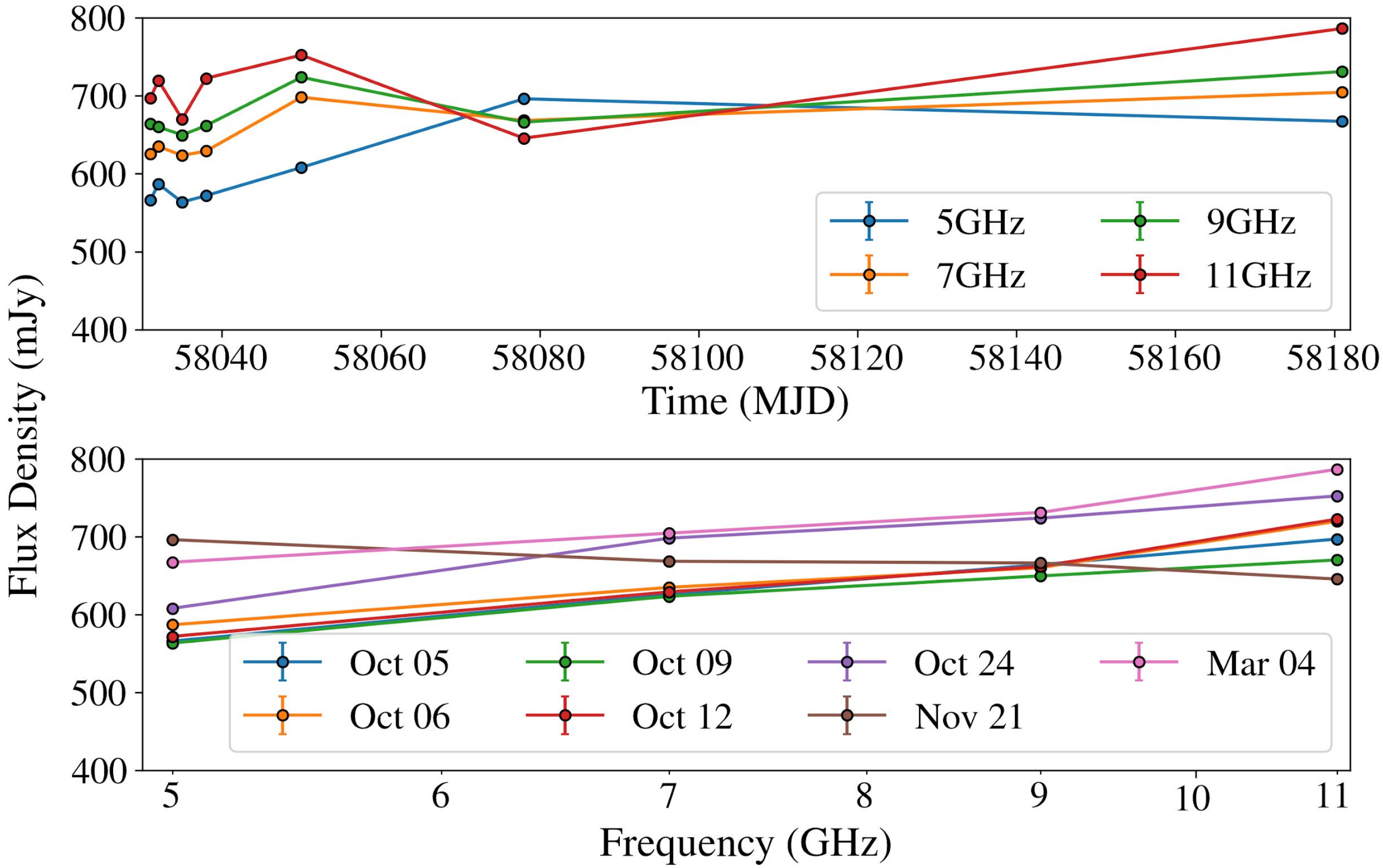

Store component




Reconvolve



# Initial Light Curve and SED




Light curve (top): flux density vs time

Spectral Energy Distribution [SED](bottom): flux density vs. frequency

# Spectral Index

- Split baseband into 32 bins of $\Delta\nu$=32 MHz
- Analyze each base-band to find spectral index, $\alpha$:

$$S_\nu = A\left(\frac{\nu}{\nu_0}\right)^\alpha$$

- Linearized to find $\alpha$

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- Split baseband into 32 bins of Δν=32 MHz
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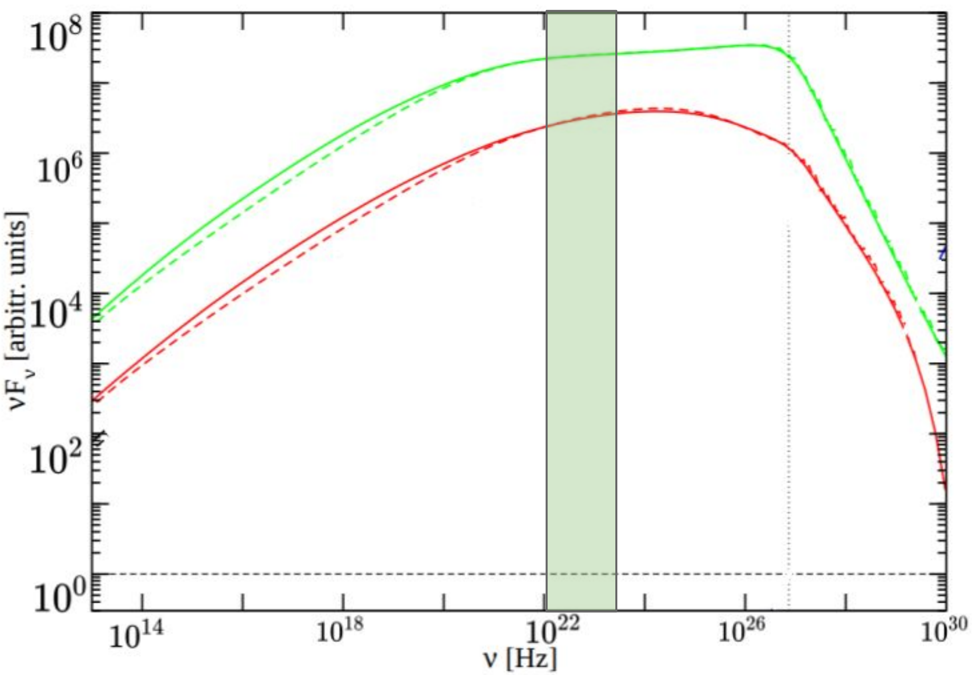
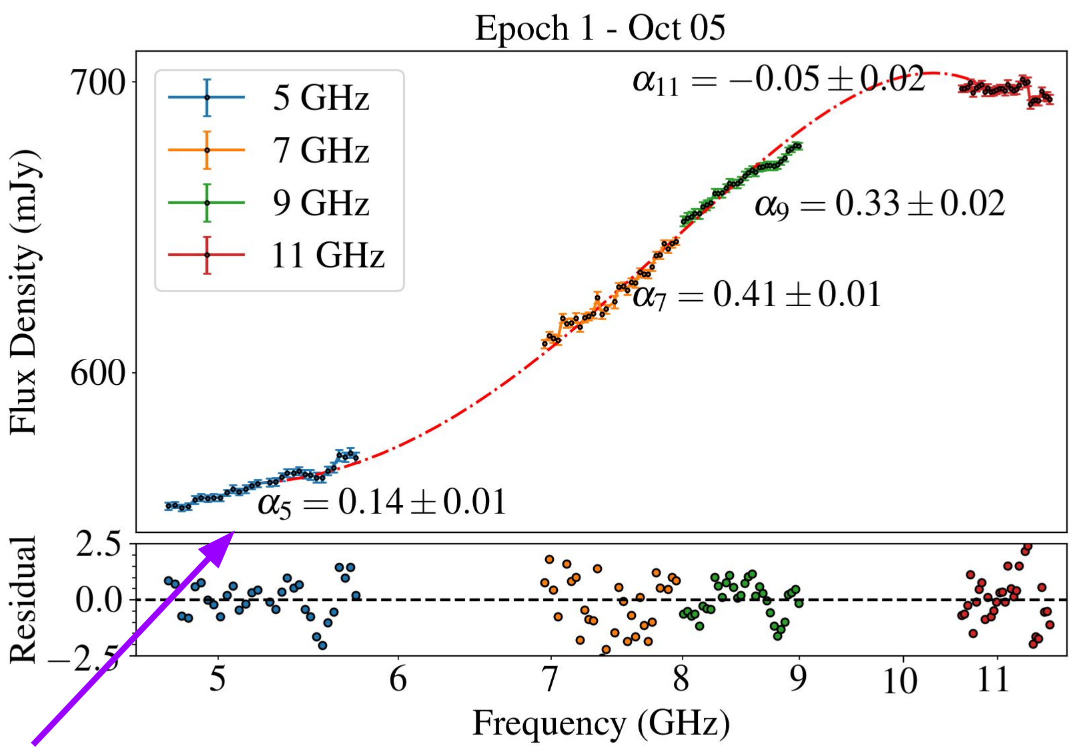
$$S_\nu = A\left(\frac{\nu}{\nu_0}\right)^{\alpha}$$

- Linearized to find α
- Expect flat radio spectrum




Adapted from Böttcher, Reimer, Sweeney, & Prakash (2013), ApJ, 768, 1 Figure 2

# Spectral Index

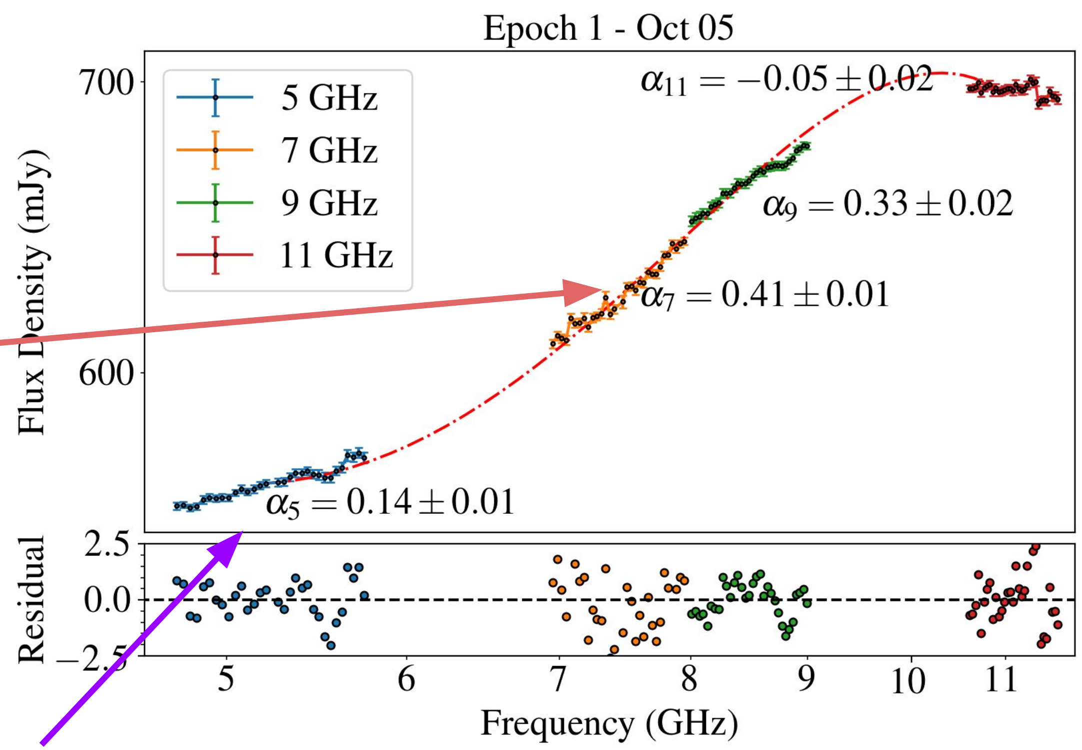



- Observe flatter at lower ν

# Spectral Index

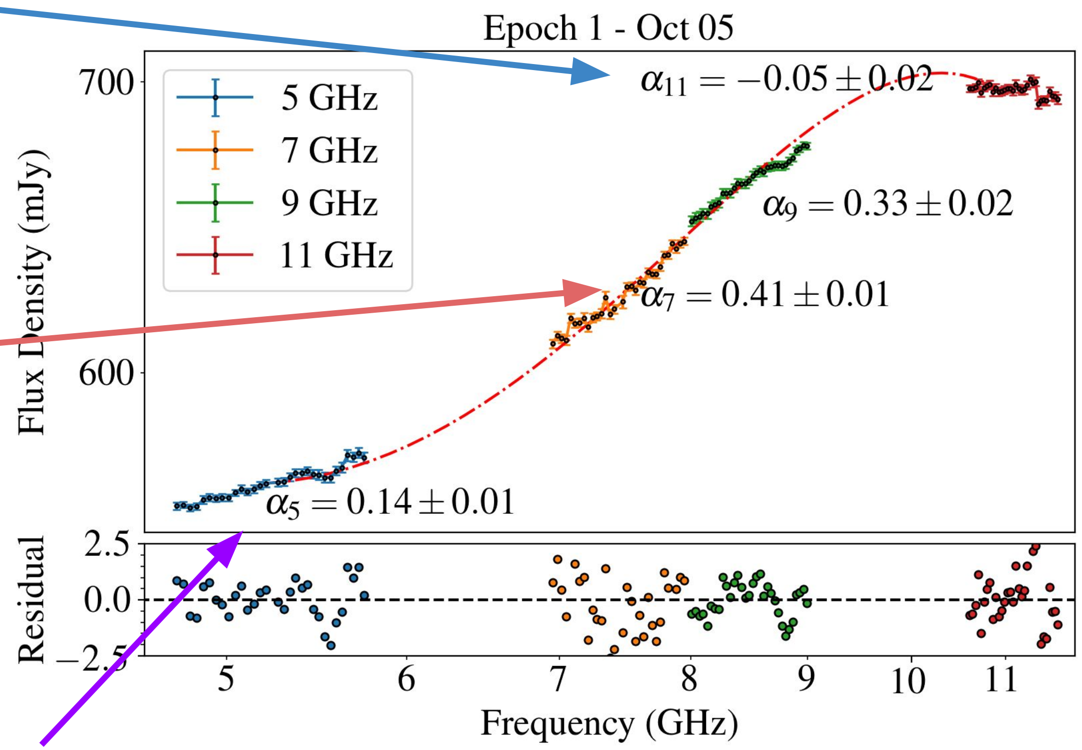
- Steeping

- Observe flatter at lower ν



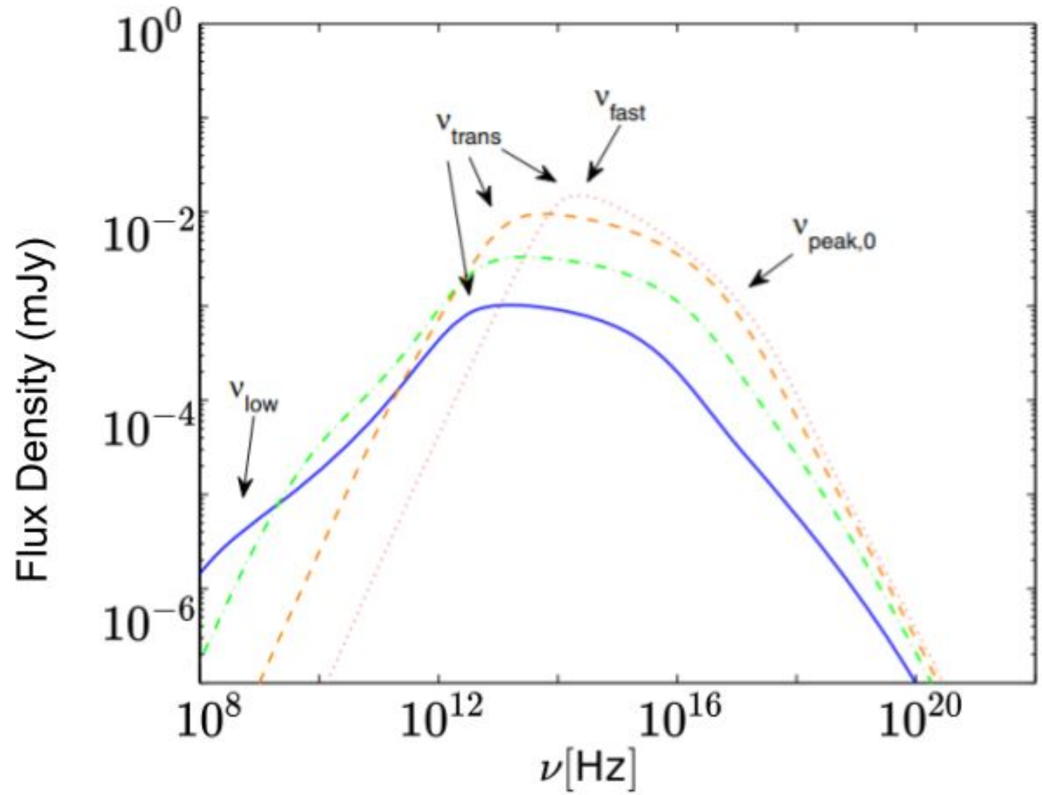
# Spectral Index

- Flattening again
- Steeping
- Observe flatter at lower ν



# Emission model

- Consistent with emission model of
    - single acceleration event
    - Synchrotron losses
    - And **adiabatic losses**
- **Pe’er & Casella 2009**




Pe’er & Casella (2009) ApJ, 699, 2, Figure 9

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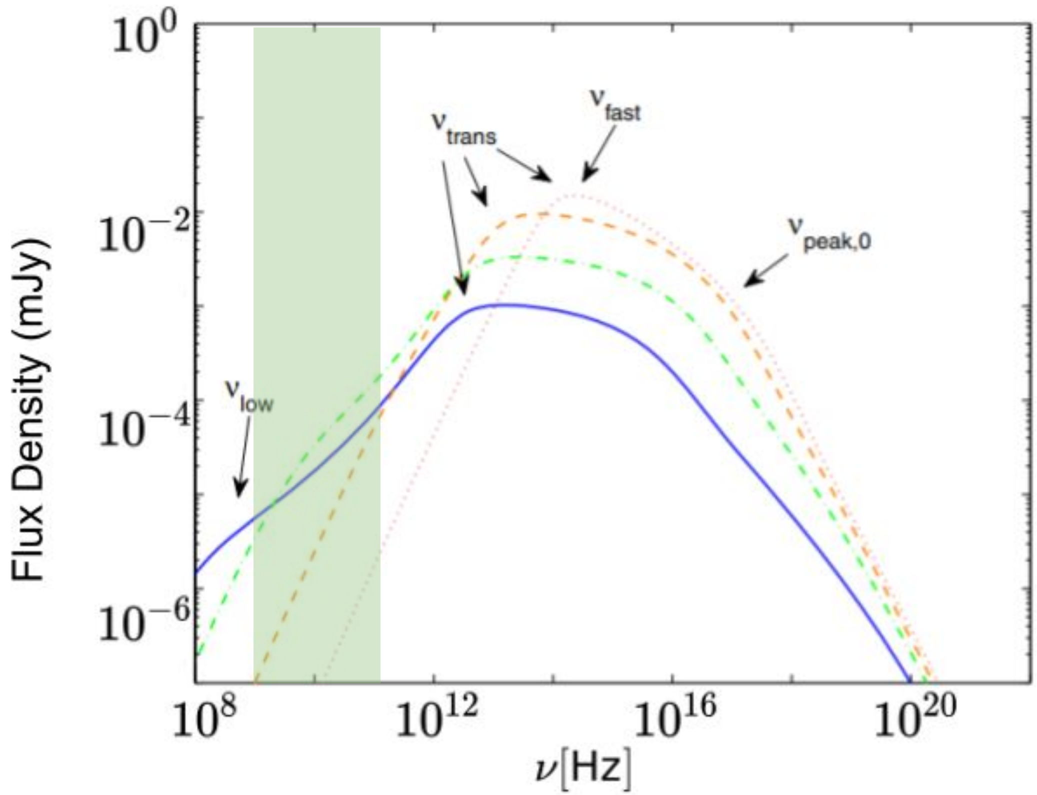
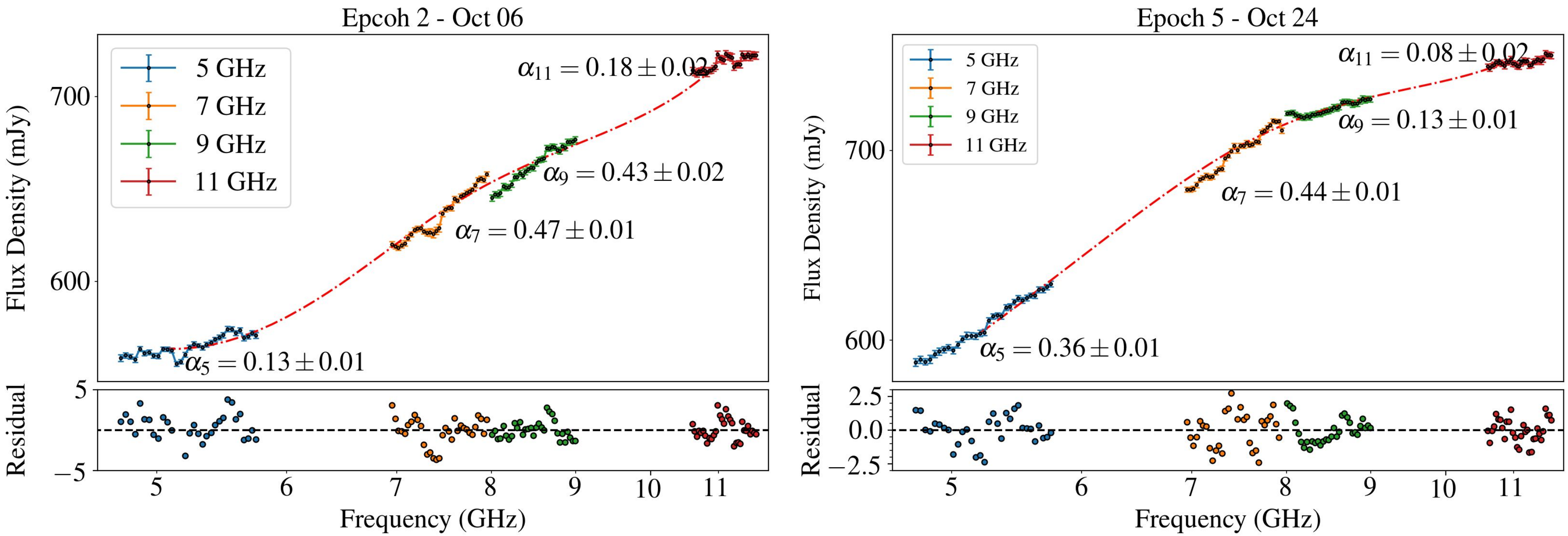



Pe’er & Casella (2009) ApJ, 699, 2, Figure 9

# Evidence of changing magnetic field

- Shape of SED changing observation to observation:



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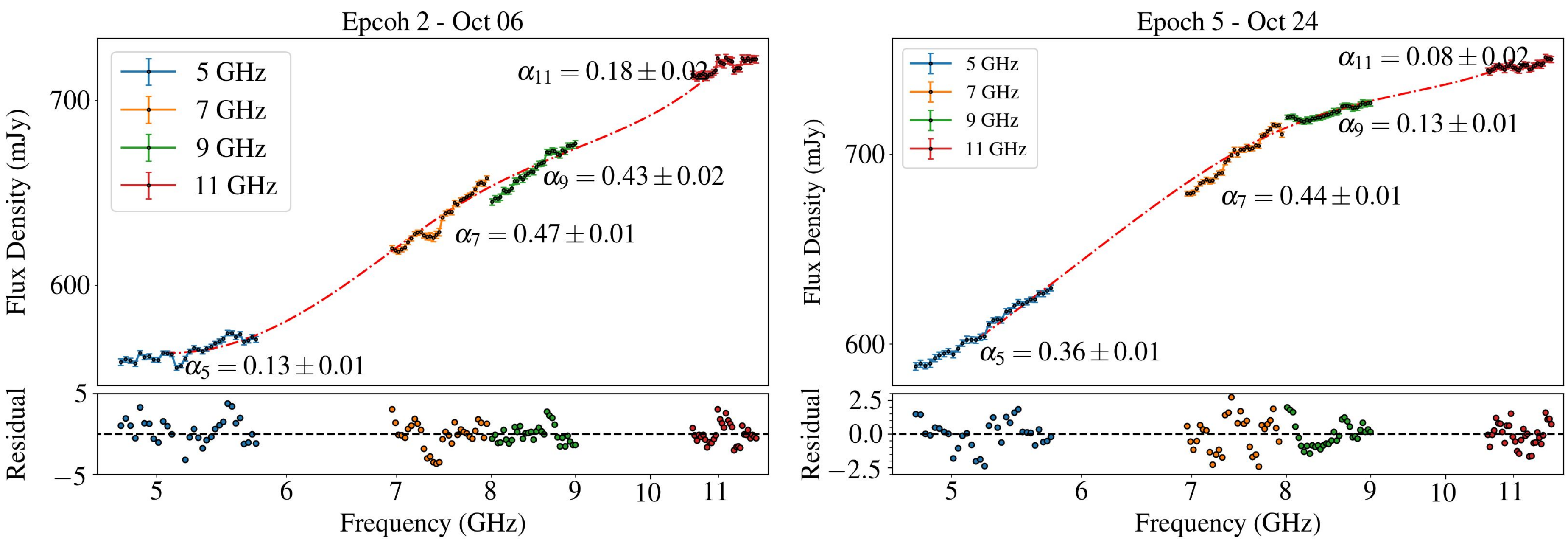


- Possible evidence of changing **B** field
  - Affect radio spectrum in non-trivial manner (Pe’er & Casella)

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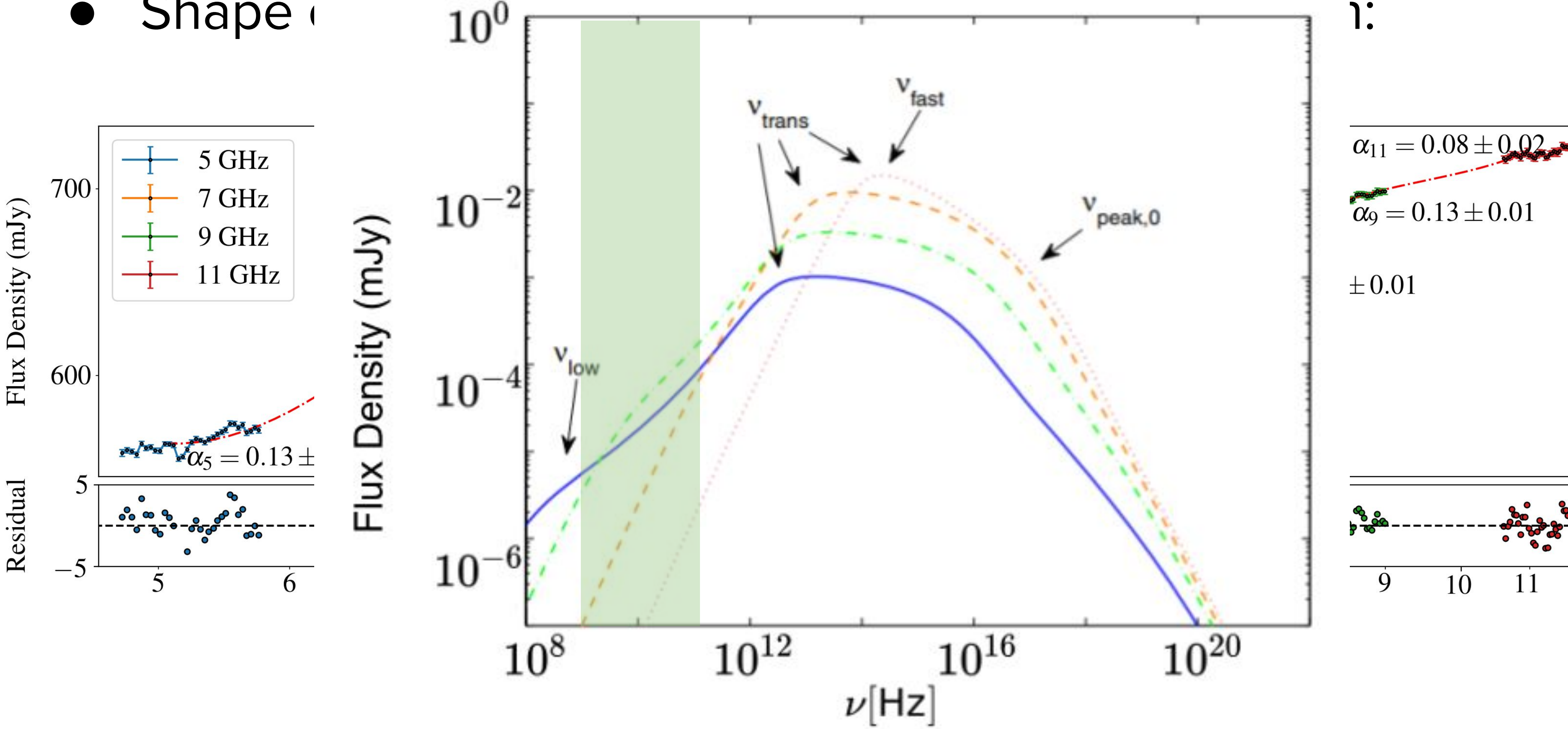


- Possible evidence of changing **B** field
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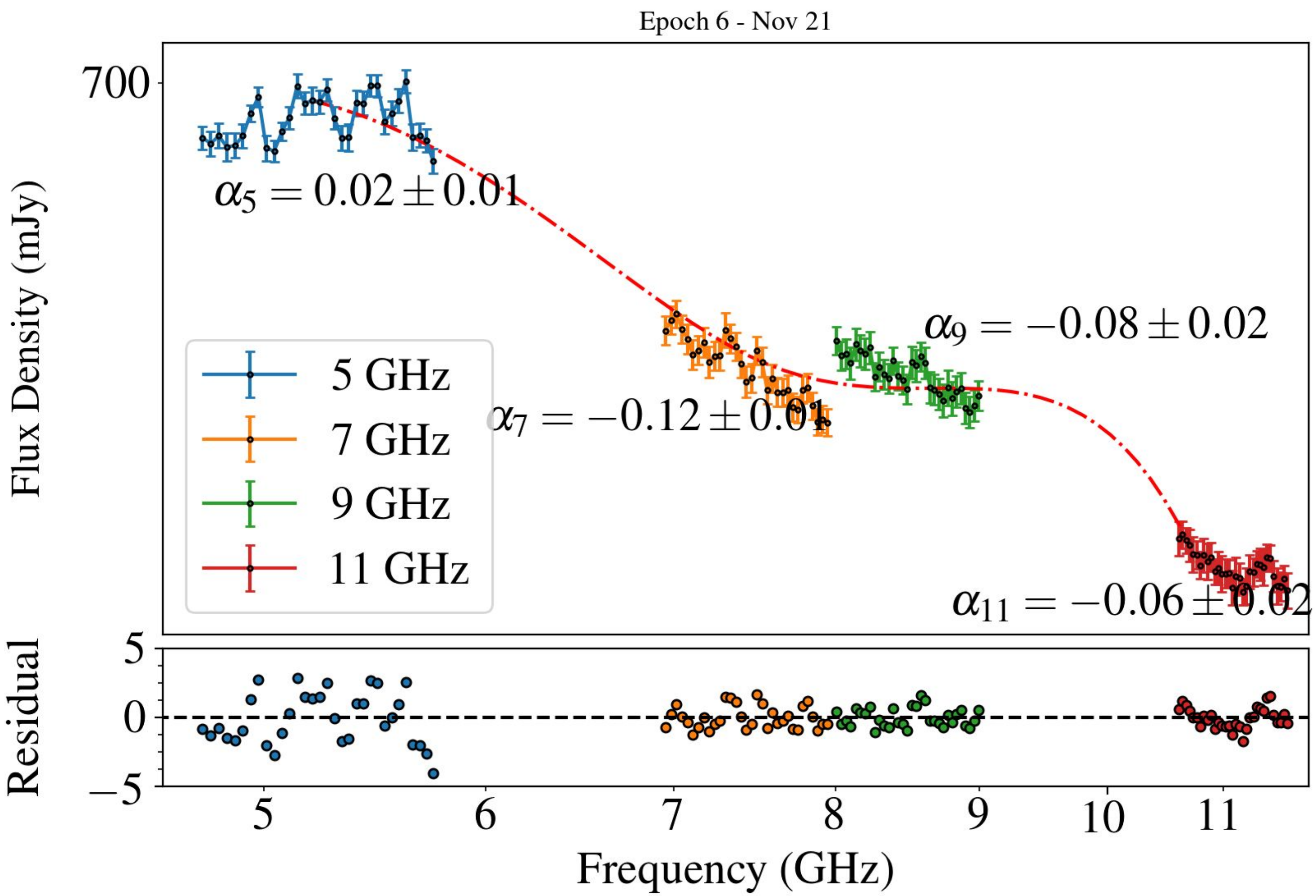
# Changing Jet Geometry

- Significant difference in epoch 6



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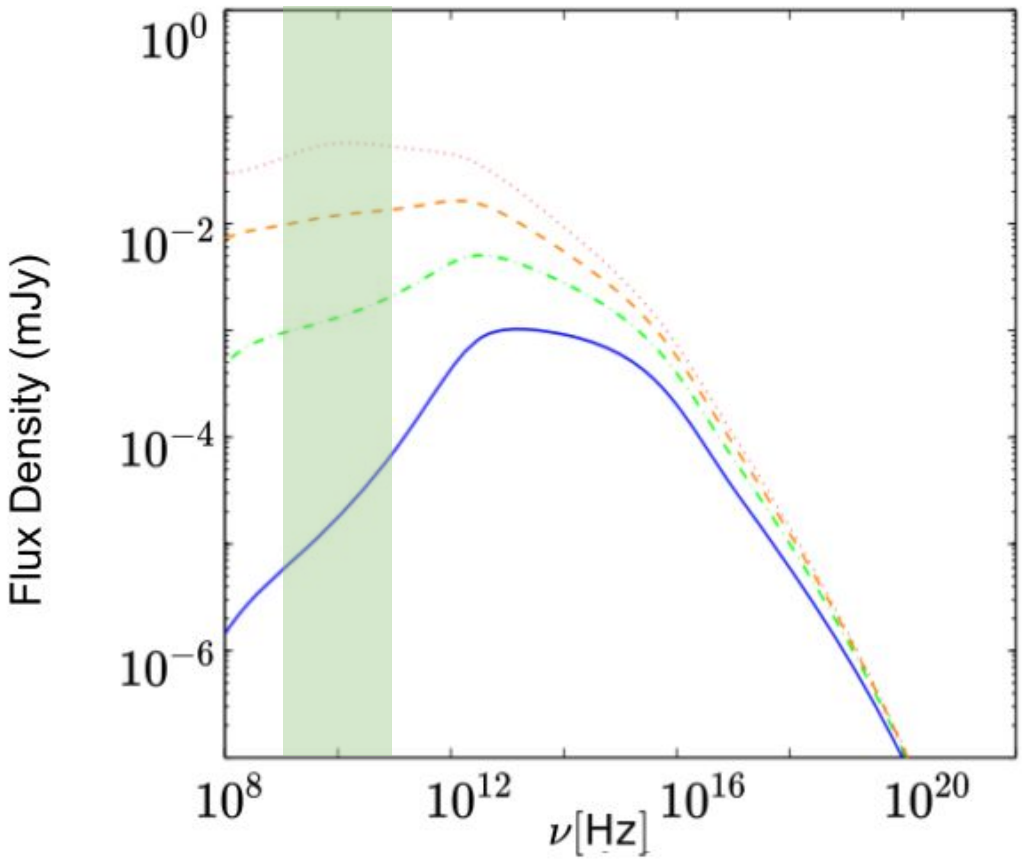


Pe’er & Casella (2009) ApJ, 699, 2, Figure 10

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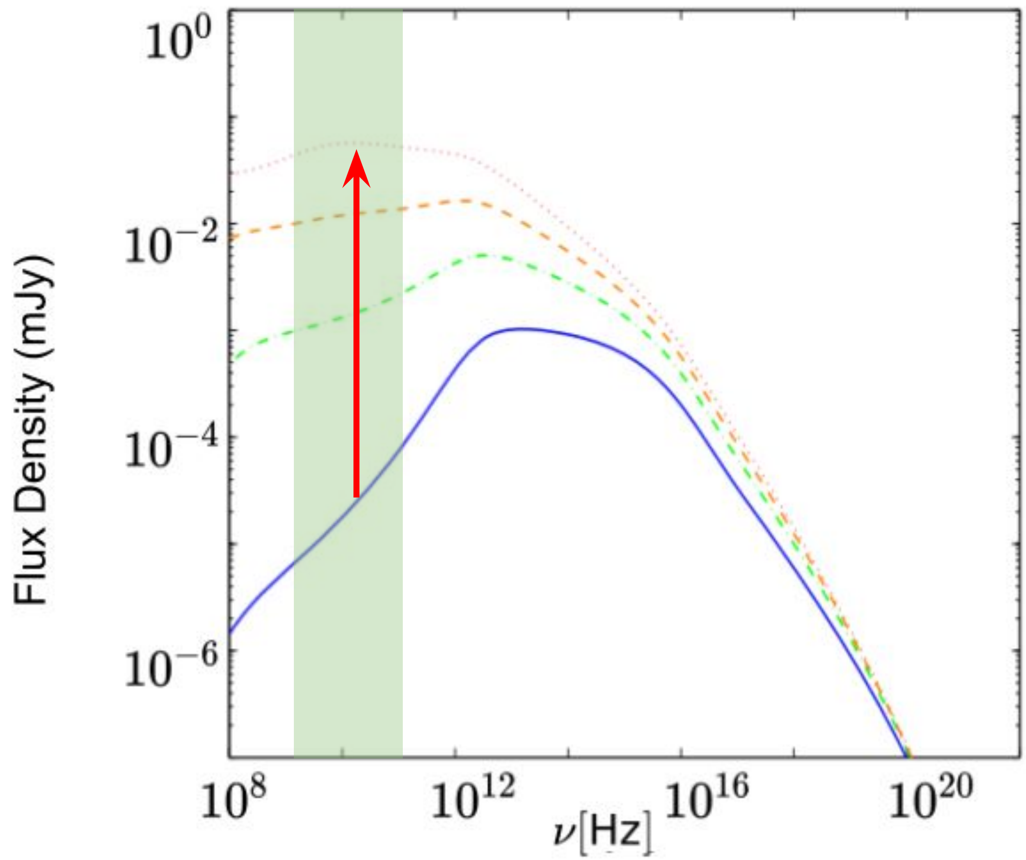


Pe'er & Casella (2009) ApJ, 699, 2, Figure 10

- Possibly explained by jet structure changing

# Variability

- Measure variability of jet in each base-band
- Determine flux density on 10 second interval

$$\chi_i^2 = \Sigma \frac{(S_i - S_{i,\mathrm{mean}})^2}{S_{i,\mathrm{mean}}}$$

$$\%\mathrm{rms} = \sqrt{\frac{\sigma_{\mathrm{XS}}}{S_{i,\mathrm{mean}}}} \times 100$$

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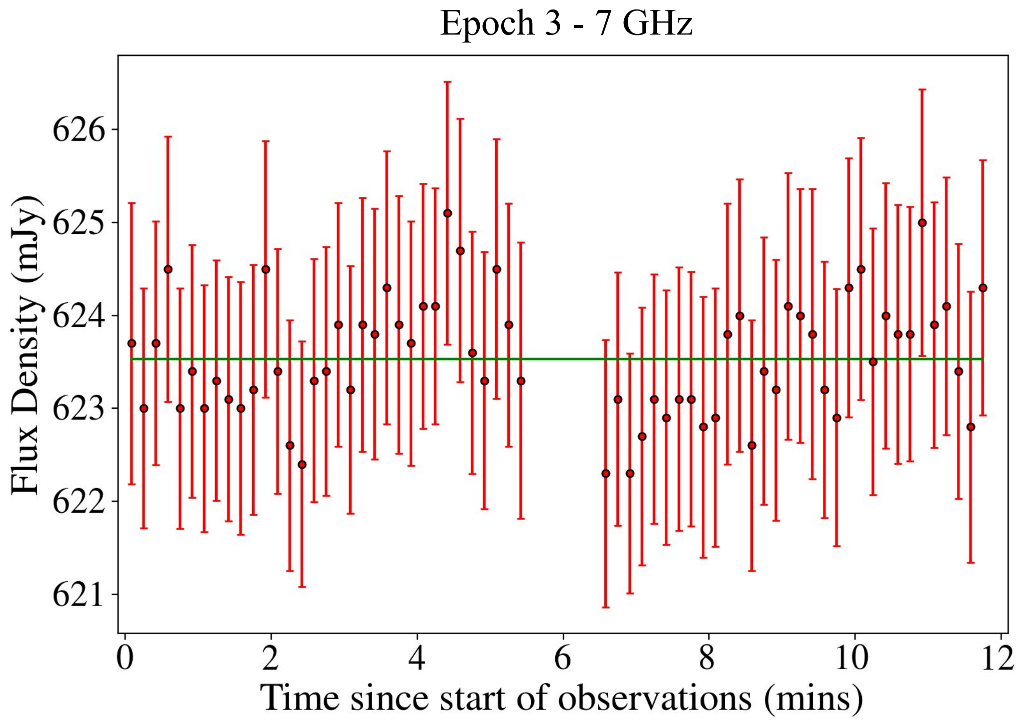

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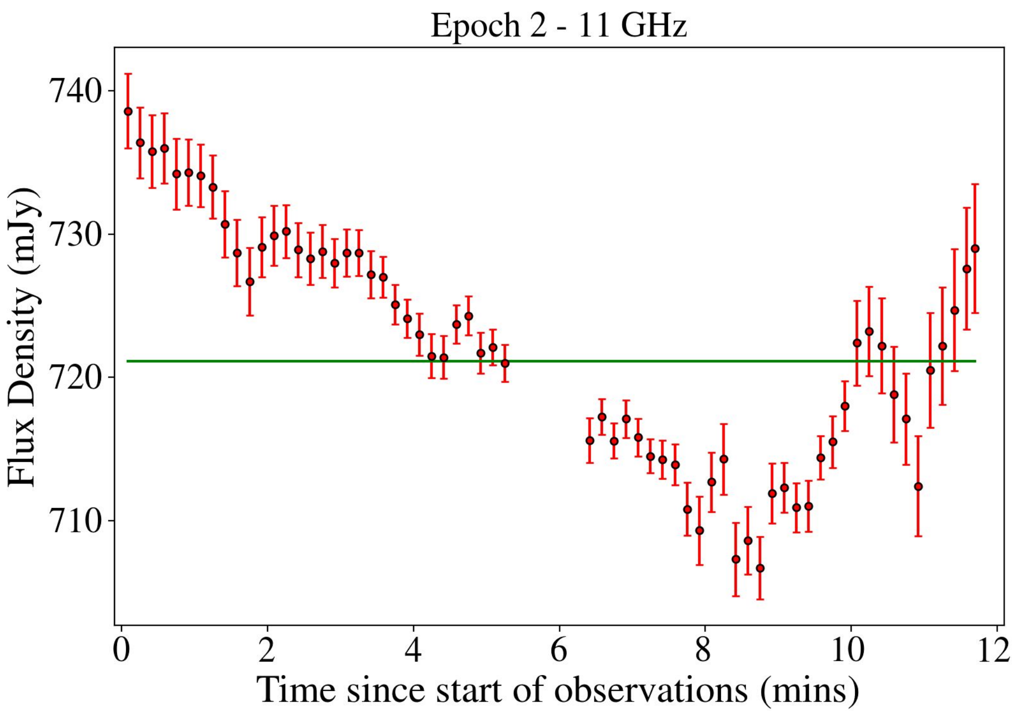

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| | | $\chi^2$ total | % rms |
|---|---|---|---|
| epoch 1 | 5 GHz | 78.8 | 0.0443 |
| | 7 GHz | 128.82 | -12.75 |
| | 9 GHz | 10.76 | ... |
| | 11 GHz | 46.74 | ... |
| epoch 2 | 5 GHz | 542.37 | 0.349 |
| | 7 GHz | 605.34 | 0.665 |
| | 9 GHz | 390.7 | 0.649 |
| | 11 GHz | 1030 | 1.09 |
| epoch 3 | 5 GHz | 12.02 | ... |
| | 7 GHz | 13.8 | ... |
| | 9 GHz | 15.24 | ... |
| | 11 GHz | 32.36 | ... |
| epoch 4 | 5 GHz | 21.19 | ... |
| | 7 GHz | 6.49 | ... |
| | 9 GHz | 27.2 | ... |
| | 11 GHz | 129 | 0.161 |
| epoch 5 | 5 GHz | 15.93 | ... |
| | 7 GHz | 21.97 | ... |
| | 9 GHz | 9.91 | ... |
| | 11 GHz | 33.38 | ... |
| epoch 6 | 5 GHz | 20.87 | ... |
| | 7 GHz | 47.31 | ... |
| | 9 GHz | 15.58 | ... |
| | 11 GHz | 716.44 | ... |
| epoch 7 | 5 GHz | 92.28 | 0.121 |
| | 7 GHz | 2780 | 1.85 |
| | 9 GHz | 484.7 | 0.290 |
| | 11 GHz | 446.6 | 0.493 |

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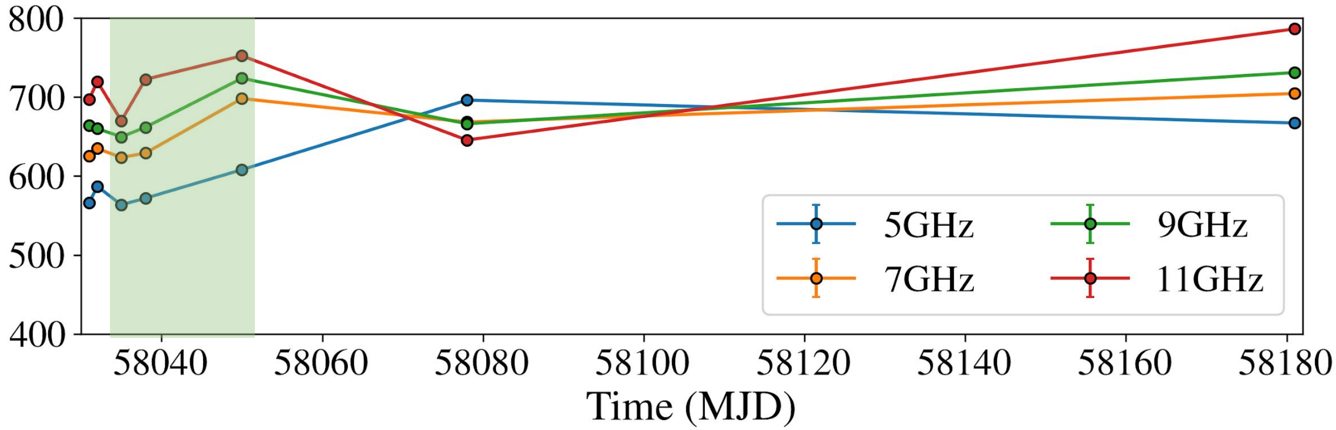
# Variability

- Epochs 3,4,5 show less activity over observations, but between epochs flux density is increasing
    - Long flaring state?



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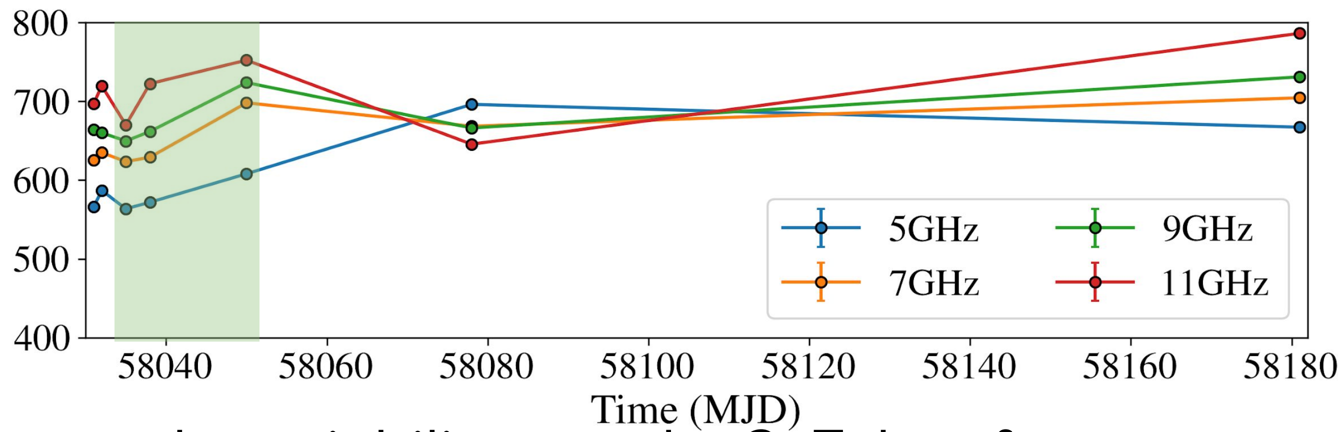
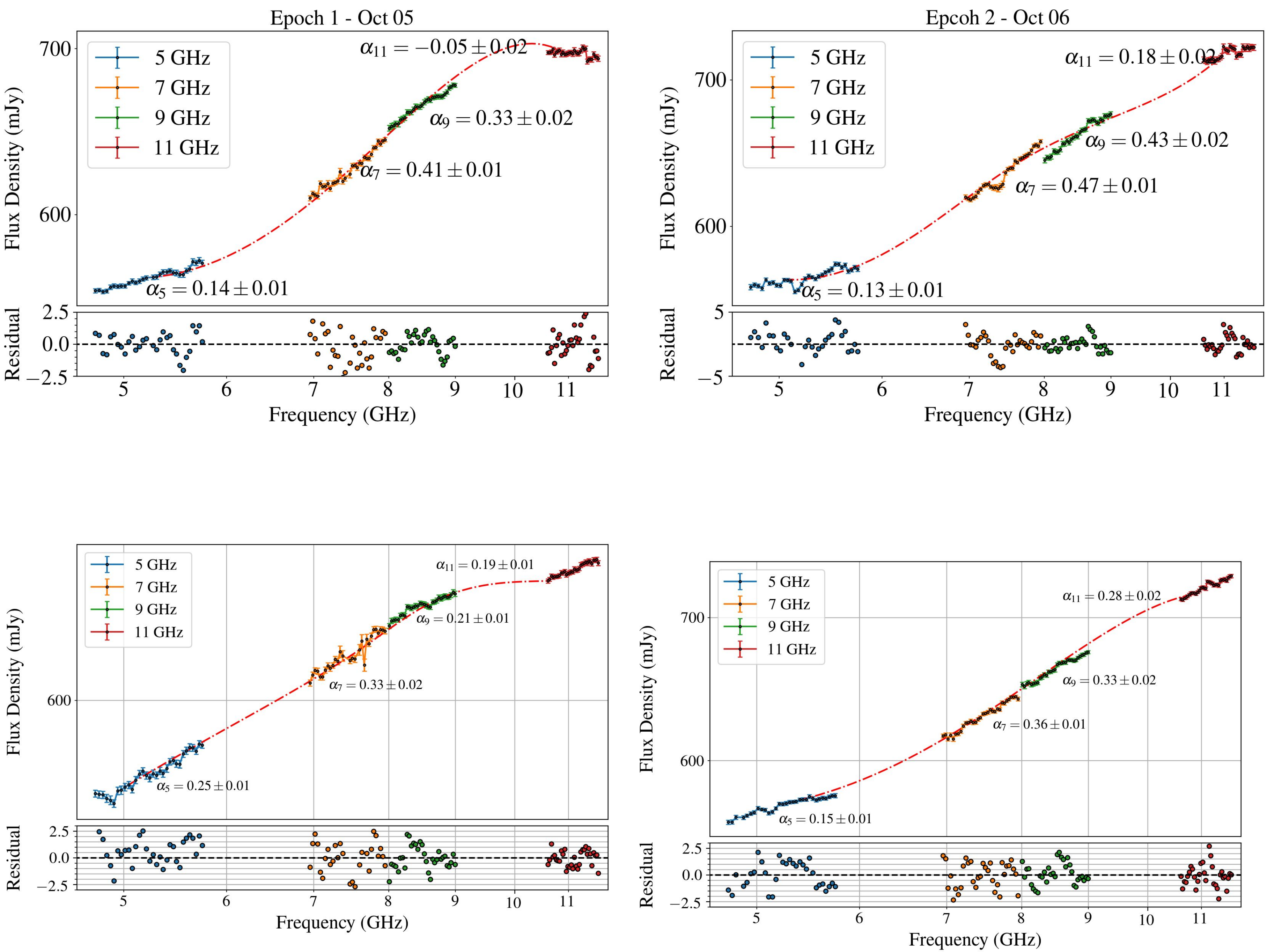


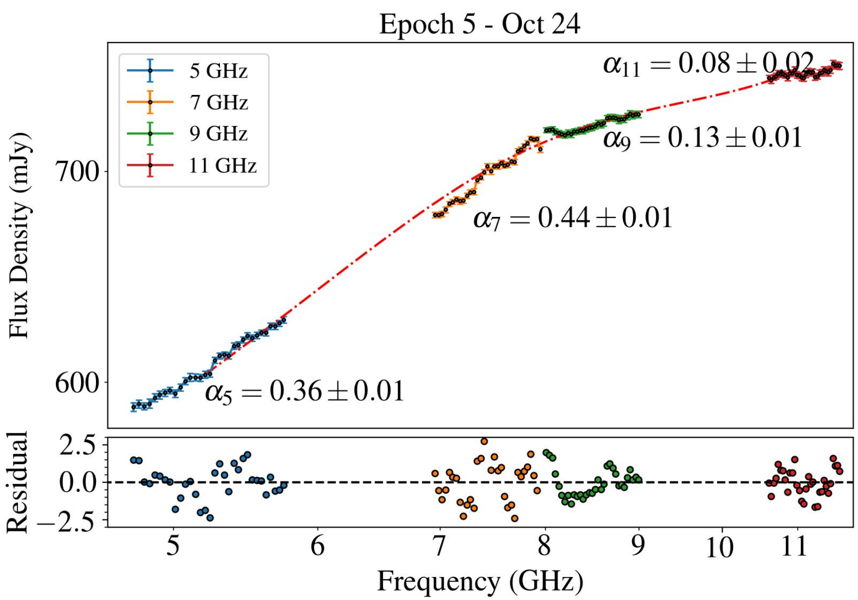

- Short scale variability epochs 2, 7, low frequency bands of epoch 1, and 11 GHz of epoch 4
    - More active:
        - ongoing particle injection, acceleration and cooling
        - Shocks developing in jet changing outflow

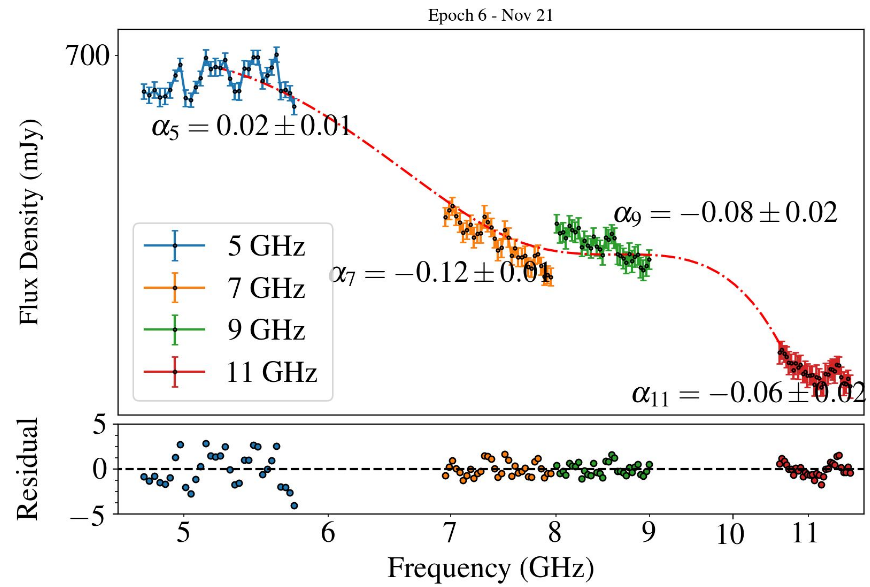
# Conclusions

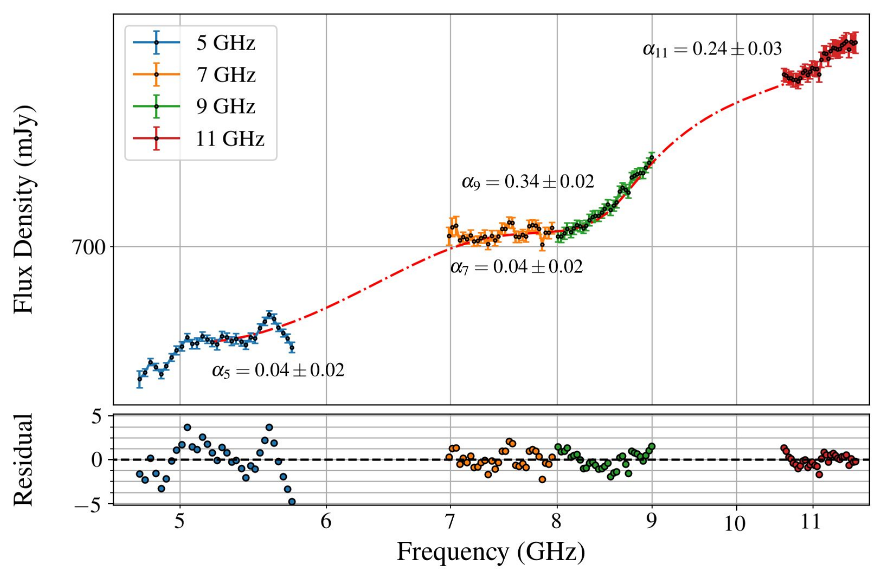
- Blazar indeed variable and evolving
  - SEDs:
    - Evidence of changing magnetic field
    - Changing geometry?
    - Adiabatic processes important
  - Light curves:
    - Evidence of variability on short (minute) ~ long (days)
- No definite connection to neutrino
- Future research: observe more blazars at this frequency; difference between neutrino counterparts and those no associated with neutrinos?

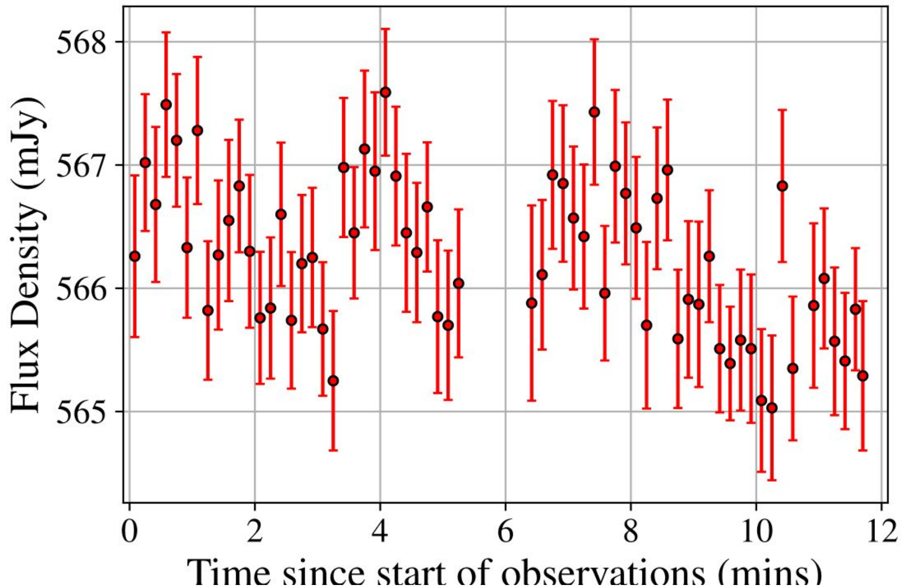


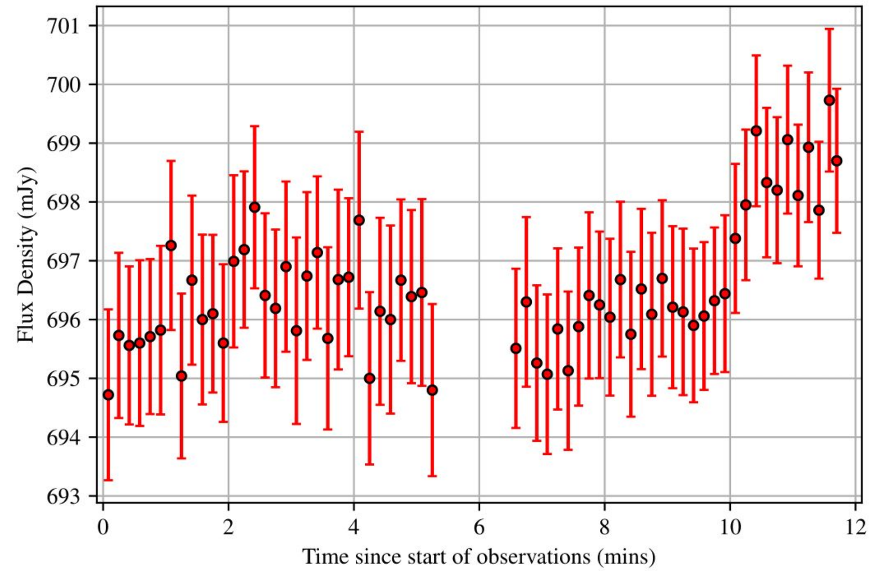
Epoch 1 - Oct 05
Epcoh 2 - Oct 06
5 GHz
7 GHz
9 GHz
11 GHz
$\alpha_{11} = -0.05 \pm 0.02$
$\alpha_9 = 0.33 \pm 0.02$
$\alpha_7 = 0.41 \pm 0.01$
$\alpha_5 = 0.14 \pm 0.01$
$\alpha_{11} = 0.18 \pm 0.02$
$\alpha_9 = 0.43 \pm 0.02$
$\alpha_7 = 0.47 \pm 0.01$
$\alpha_5 = 0.13 \pm 0.01$
$\alpha_{11} = 0.19 \pm 0.01$
$\alpha_9 = 0.21 \pm 0.01$
$\alpha_7 = 0.33 \pm 0.02$
$\alpha_5 = 0.25 \pm 0.01$
$\alpha_{11} = 0.28 \pm 0.02$
$\alpha_9 = 0.33 \pm 0.02$
$\alpha_7 = 0.36 \pm 0.01$
$\alpha_5 = 0.15 \pm 0.01$
Flux Density (mJy)
Residual
Frequency (GHz)

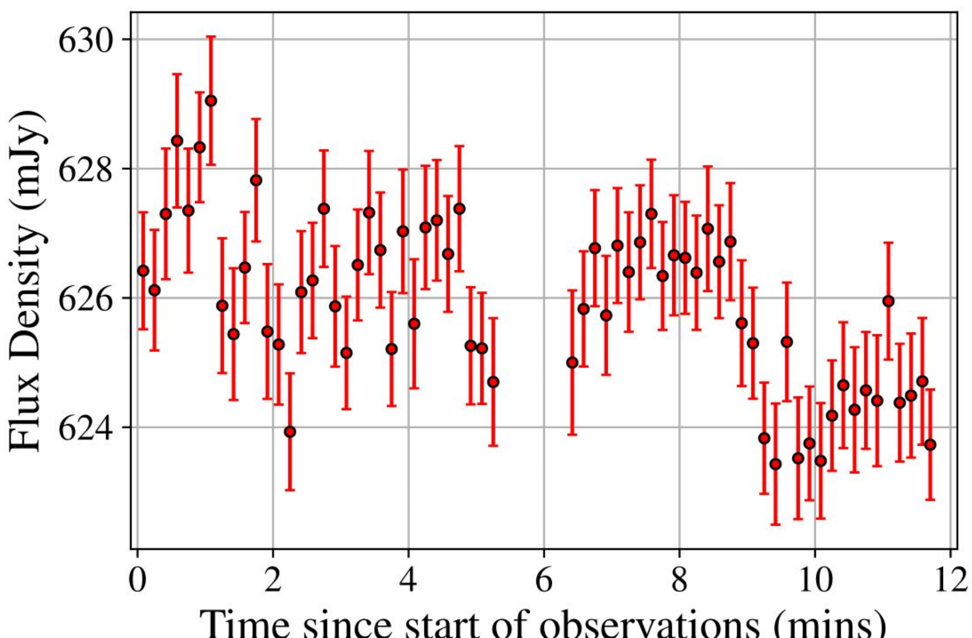

Epoch 5 - Oct 24
5 GHz
7 GHz
9 GHz
11 GHz
$\alpha_{11} = 0.08 \pm 0.02$
$\alpha_9 = 0.13 \pm 0.01$
$\alpha_7 = 0.44 \pm 0.01$
$\alpha_5 = 0.36 \pm 0.01$
Flux Density (mJy)
700
600
Residual
2.5
0.0
−2.5
5
6
7
8
9
10
11
Frequency (GHz)

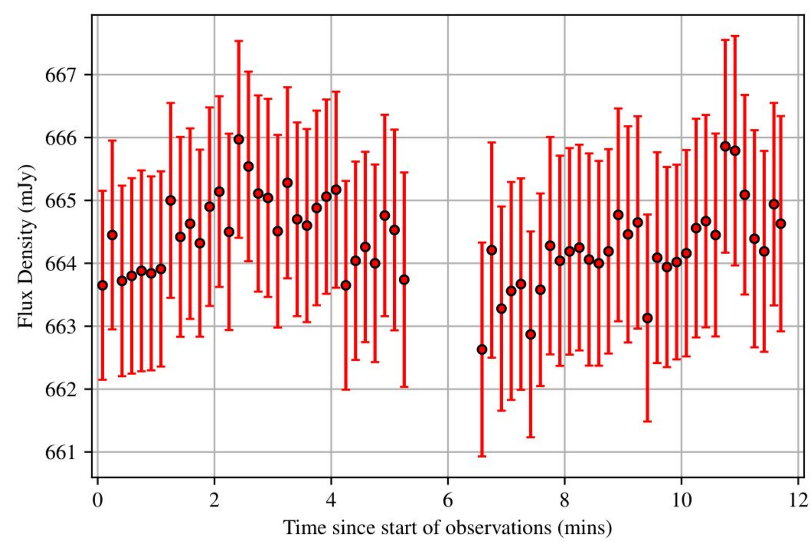

Epoch 6 - Nov 21
700
$\alpha_5 = 0.02 \pm 0.01$
5 GHz
7 GHz
9 GHz
11 GHz
$\alpha_9 = -0.08 \pm 0.02$
$\alpha_7 = -0.12 \pm 0.01$
$\alpha_{11} = -0.06 \pm 0.02$
Flux Density (mJy)
Residual
5
0
−5
5
6
7
8
9
10
11
Frequency (GHz)

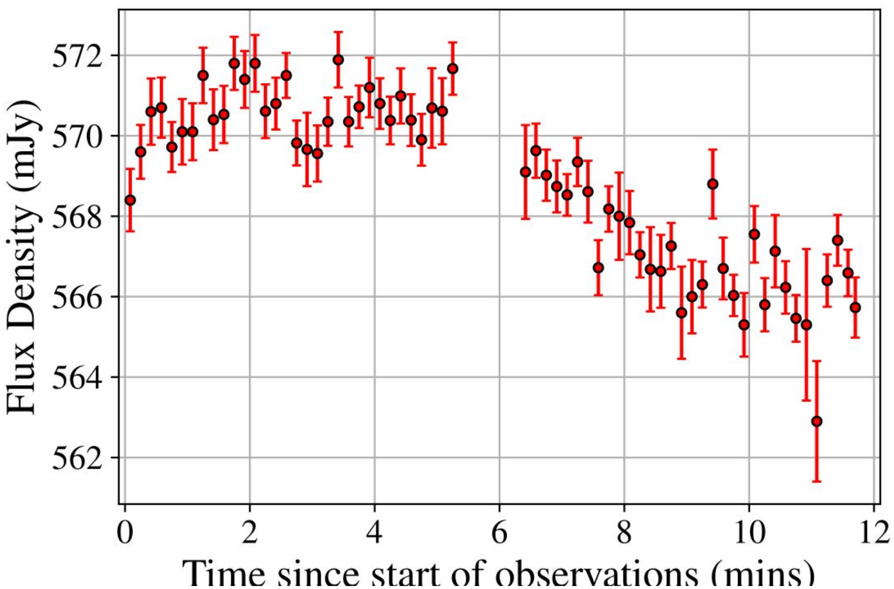

5 GHz
7 GHz
9 GHz
11 GHz
$\alpha_{11} = 0.24 \pm 0.03$
$\alpha_9 = 0.34 \pm 0.02$
$\alpha_7 = 0.04 \pm 0.02$
$\alpha_5 = 0.04 \pm 0.02$
Flux Density (mJy)
700
Residual
5
0
−5
5
6
7
8
9
10
11
Frequency (GHz)

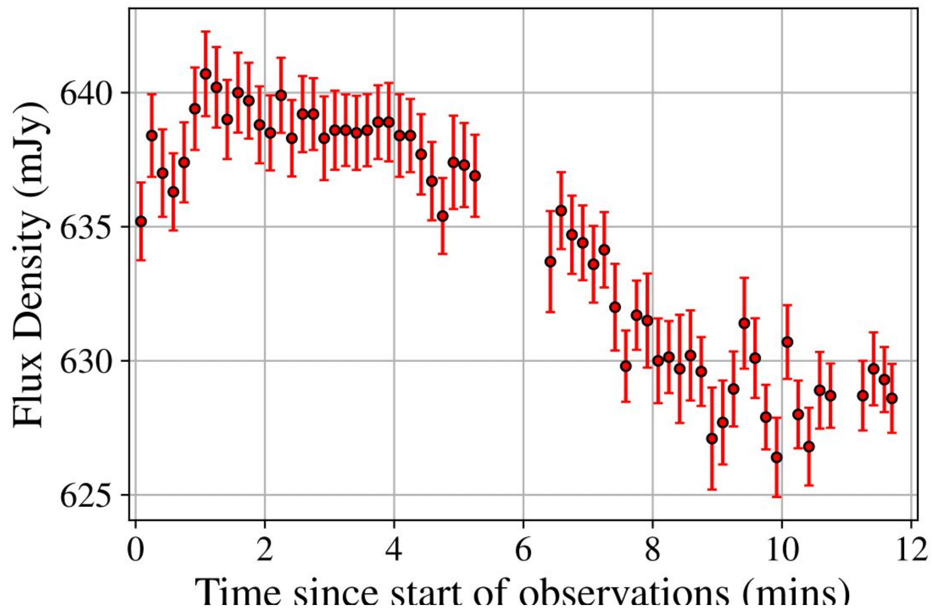

Flux Density (mJy)
568
567
566
565
0
2
4
6
8
10
12
Time since start of observations (mins)

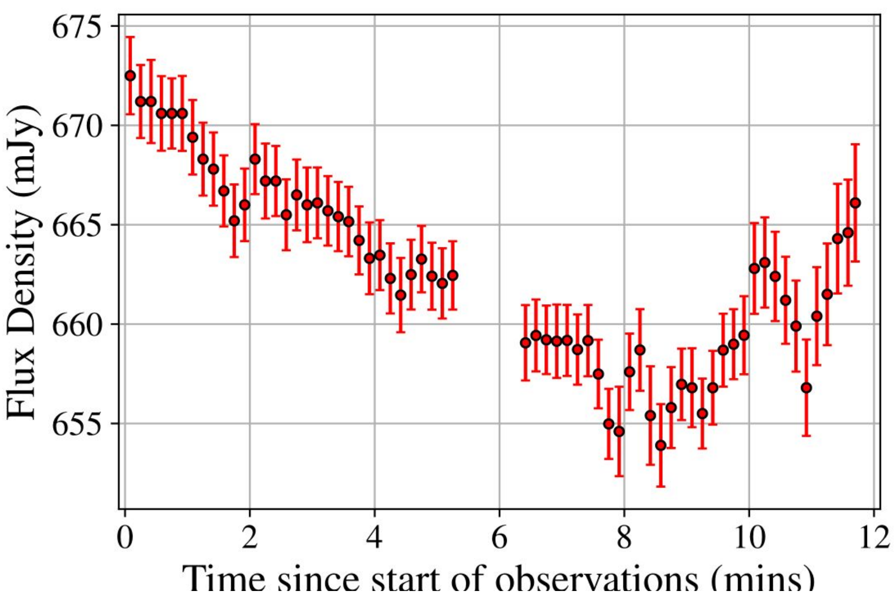

Flux Density (mJy)
701
700
699
698
697
696
695
694
693
0
2
4
6
8
10
12
Time since start of observations (mins)

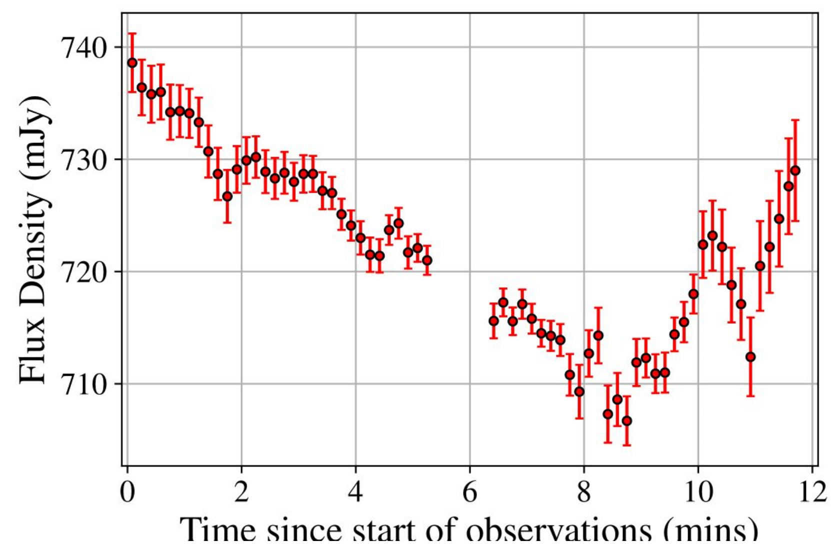

Flux Density (mJy)
630
628
626
624
0
2
4
6
8
10
12
Time since start of observations (mins)

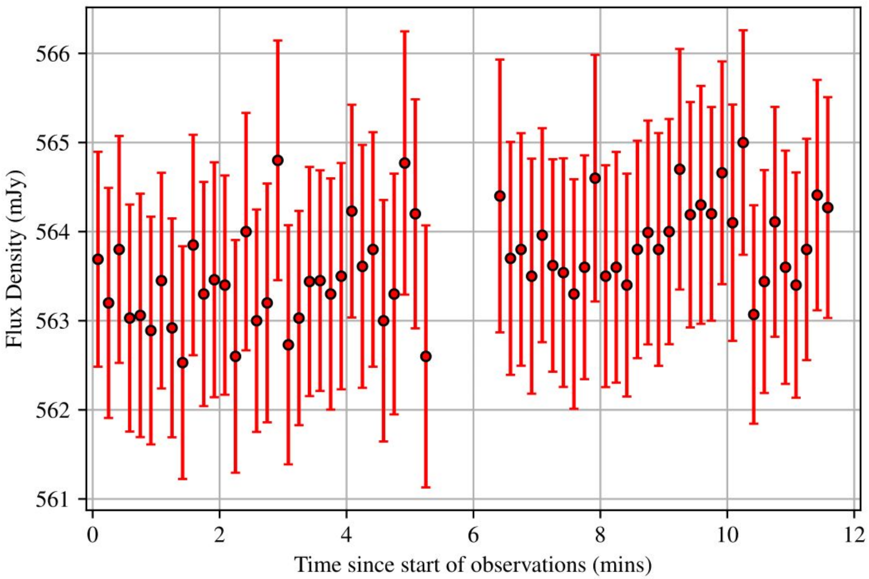
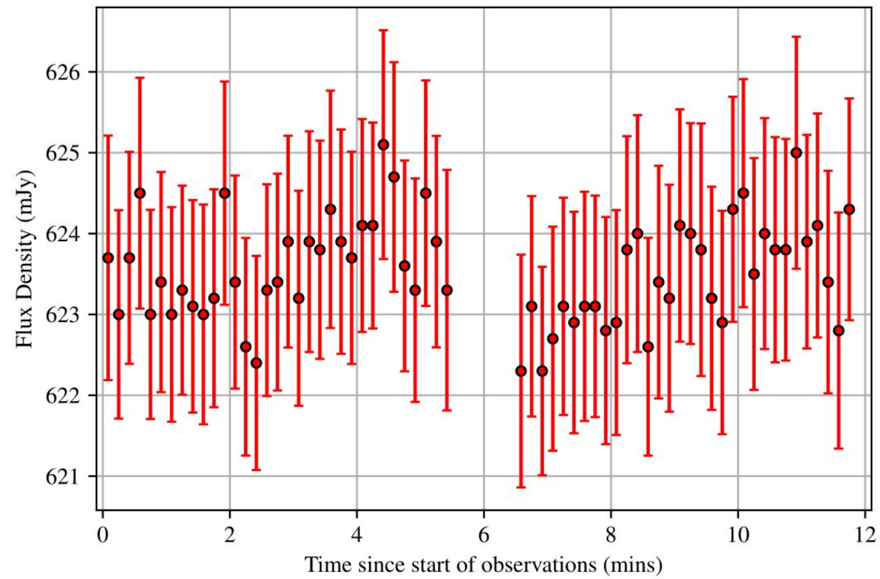
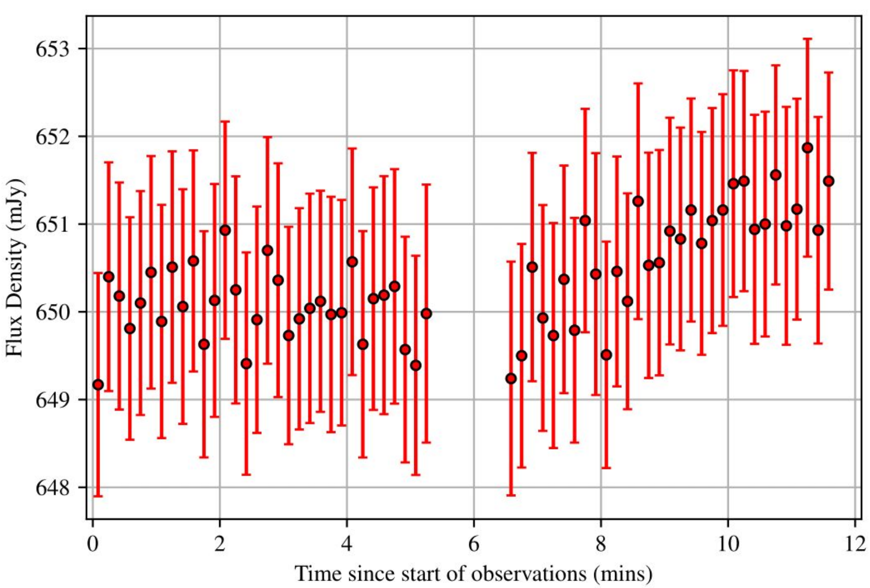
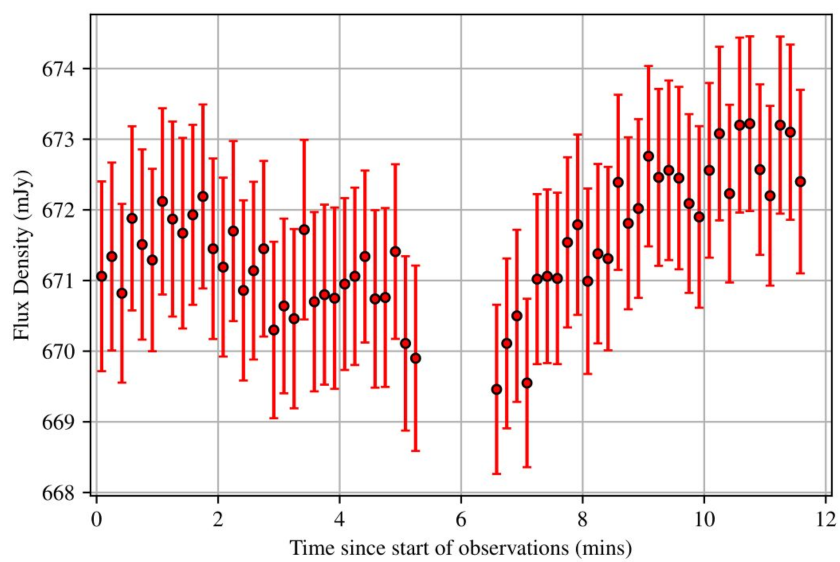

Flux Density (mJy)
667
666
665
664
663
662
661
0
2
4
6
8
10
12
Time since start of observations (mins)


Flux Density (mJy)
Time since start of observations (mins)
572
570
568
566
564
562
0
2
4
6
8
10
12


Flux Density (mJy)
Time since start of observations (mins)
640
635
630
625
0
2
4
6
8
10
12


Flux Density (mJy)
Time since start of observations (mins)
675
670
665
660
655
0
2
4
6
8
10
12


Flux Density (mJy)
Time since start of observations (mins)
740
730
720
710
0
2
4
6
8
10
12


Flux Density (mJy)
561
562
563
564
565
566
0
2
4
6
8
10
12
Time since start of observations (mins)

Flux Density (mJy)
621
622
623
624
625
626
0
2
4
6
8
10
12
Time since start of observations (mins)

Flux Density (mJy)
648
649
650
651
652
653
0
2
4
6
8
10
12
Time since start of observations (mins)

Flux Density (mJy)
668
669
670
671
672
673
674
0
2
4
6
8
10
12
Time since start of observations (mins)