Characterizing the Radio Transient Sky with MeerKAT

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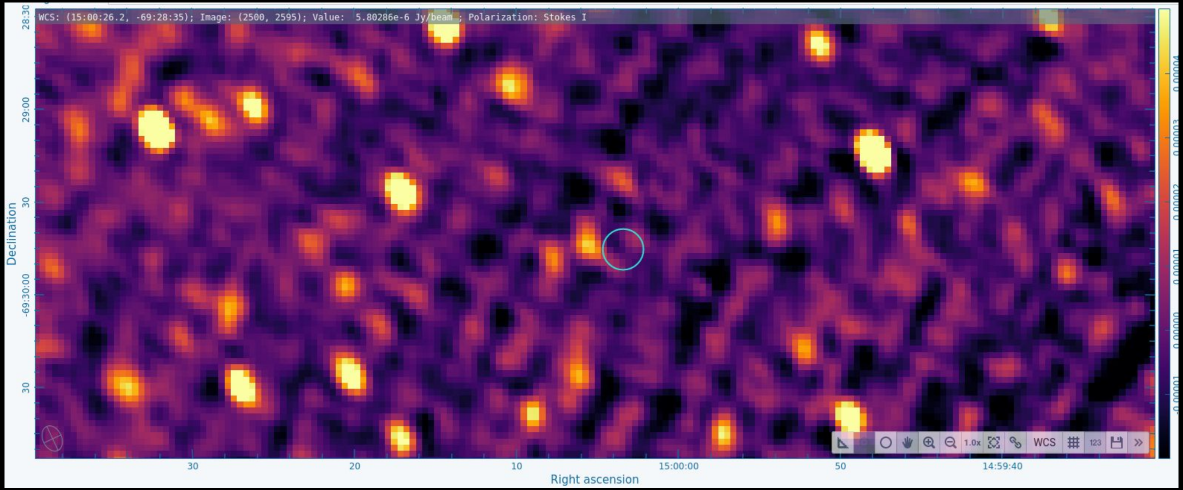
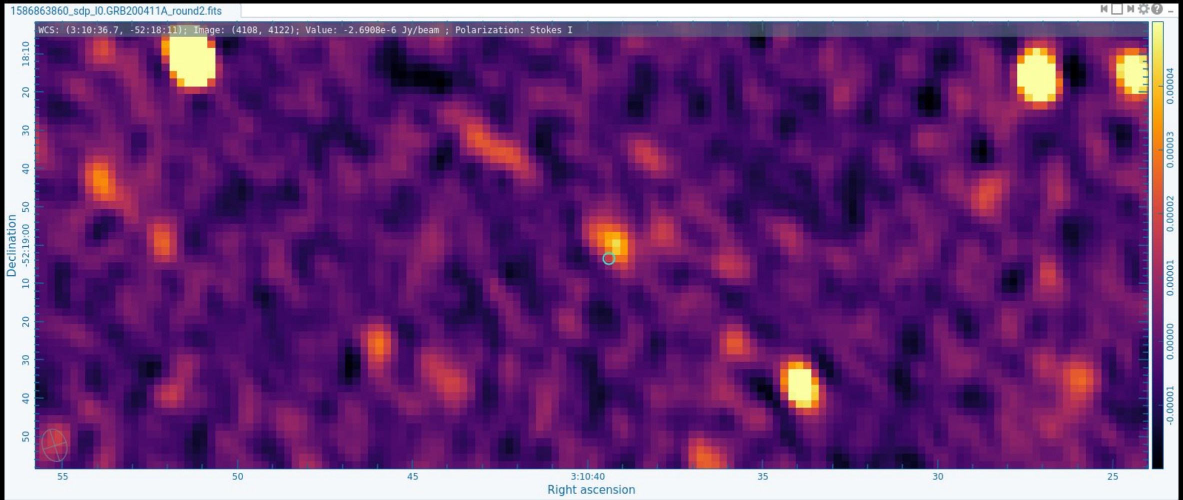
A New Era in Radio Astronomy: MeerKAT Radio Telescope

- Started operations in summer 2018
- Operates in 3 bands spanning 544 MHz and 3499 MHz with excellent sensitivity
  - L-band (856-1711 MHz)
- Field of view of almost 2 square degrees
- Excellent for transient searches

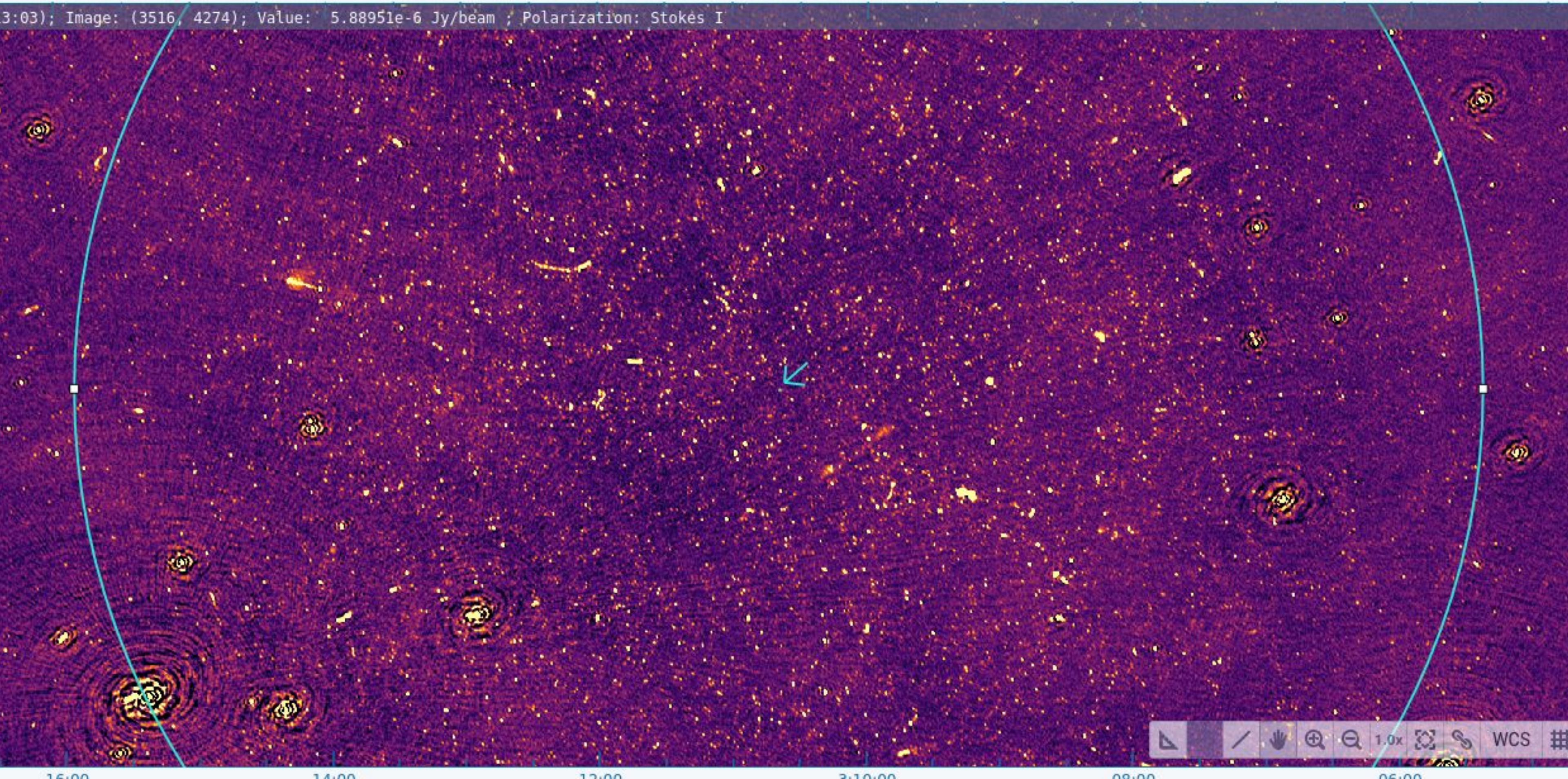
Observations of Short GRB fields with ThunderKAT

- ThunderKAT
  - Large Survey Project using MeerKAT
  - Studying radio transients
    - SGRB follow-up
    - Commensal searches
- 43 Observations of 10 different fields
- Deep limits





Commensal Searches



Commensal Searches

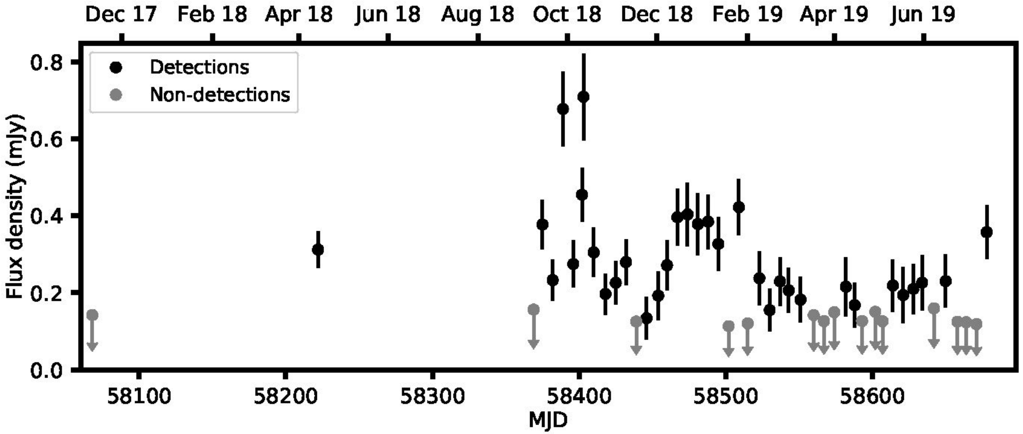
- 8 Short GRB Fields, 30 observations
  - Multiple timescales
    - 4 hour
    - 15 minute
    - 8 seconds
- Supernovae and Short GRB Fields
  - 30 Minutes
  - Ongoing searches at shorter timescales

An Immense Amount of Data!

- MeerKAT Images
  - ~1 Degree radius FOV
- First dataset:
  - 43,964 8 second images
    - Shown in background
    - 150 to 200 μJy noise for good examples
    - High positional error, reimaged for corrected position
  - 406 15 minute images
    - High correlated noise
    - 20 to 30 μJy noise for good examples
  - 30 ~4 hour images
    - 1 single field only
    - 6 to 7 μJy noise for good examples

Search Strategy

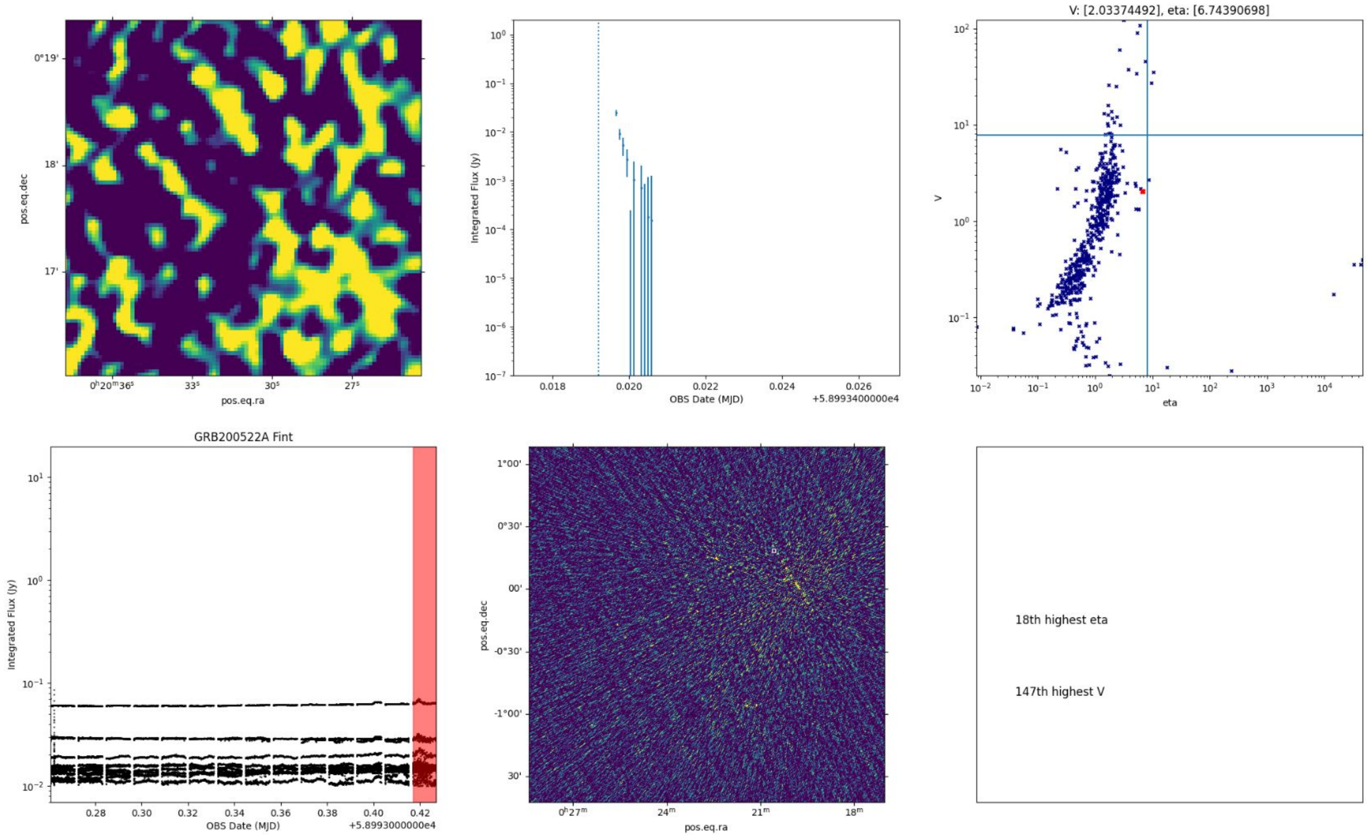
- LOFAR Transients Pipeline (TraP)[1]
  - Light curves
  - V and η, variability statistics
  - Large search radius
  - Low threshold
- Further restrictions
  - Threshold
  - Source Density
  - η cuts
- Make animations



MKT J170456.2-482100 found in the GX-339 field by L. Driessen [1]

[1]Swinbank et al. "The LOFAR Transients Pipeline" Astronomy and Computing. vol. 11, June 2015

Dataset 185, Date: 58993.41919835517



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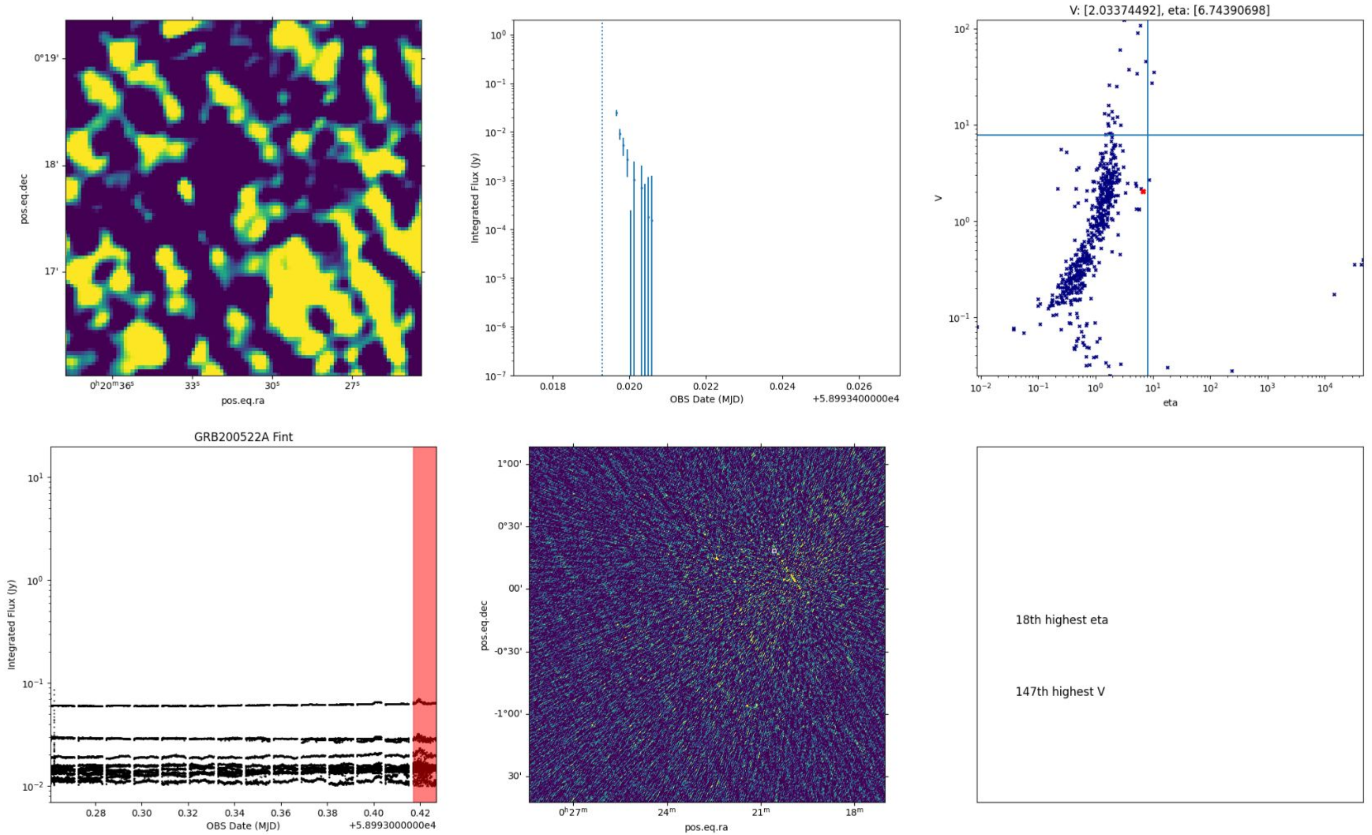

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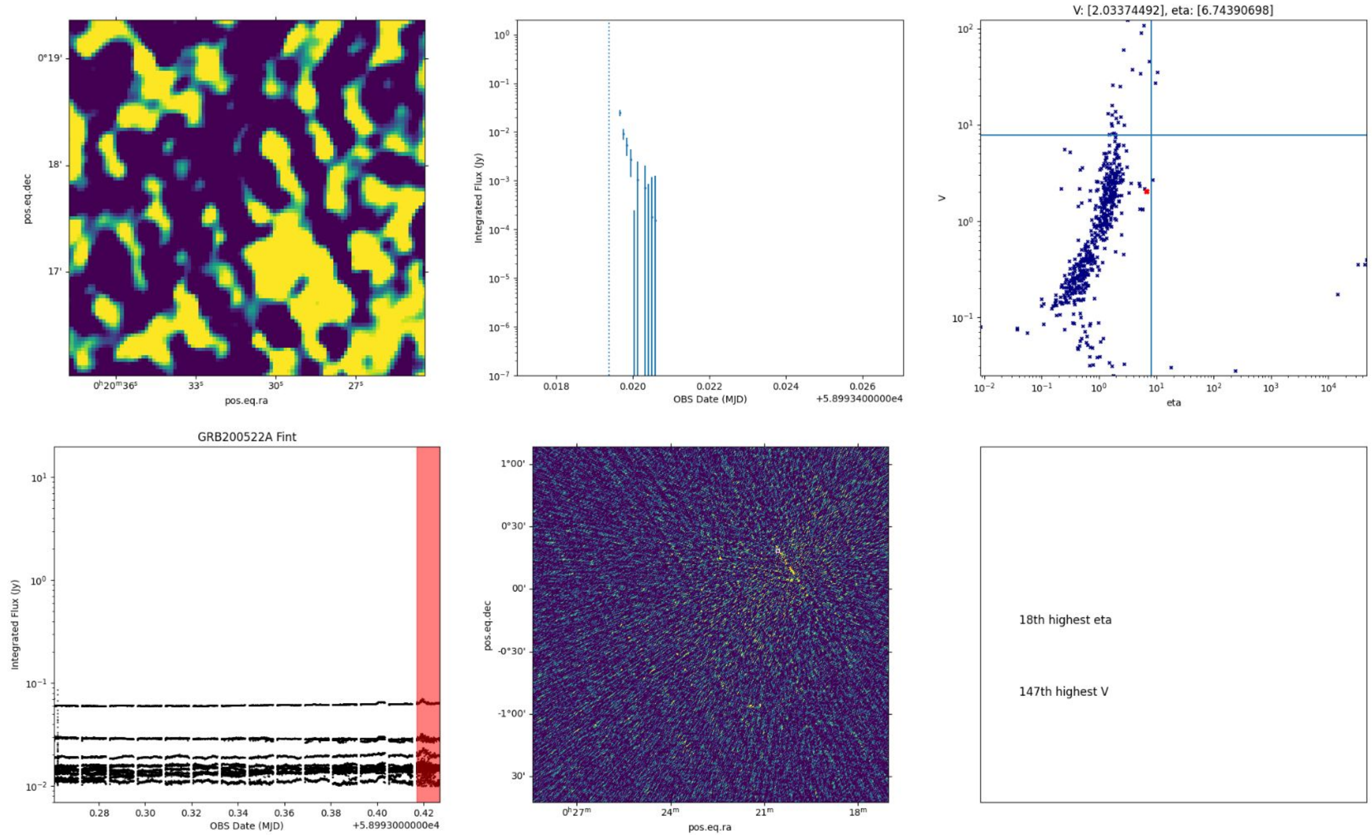

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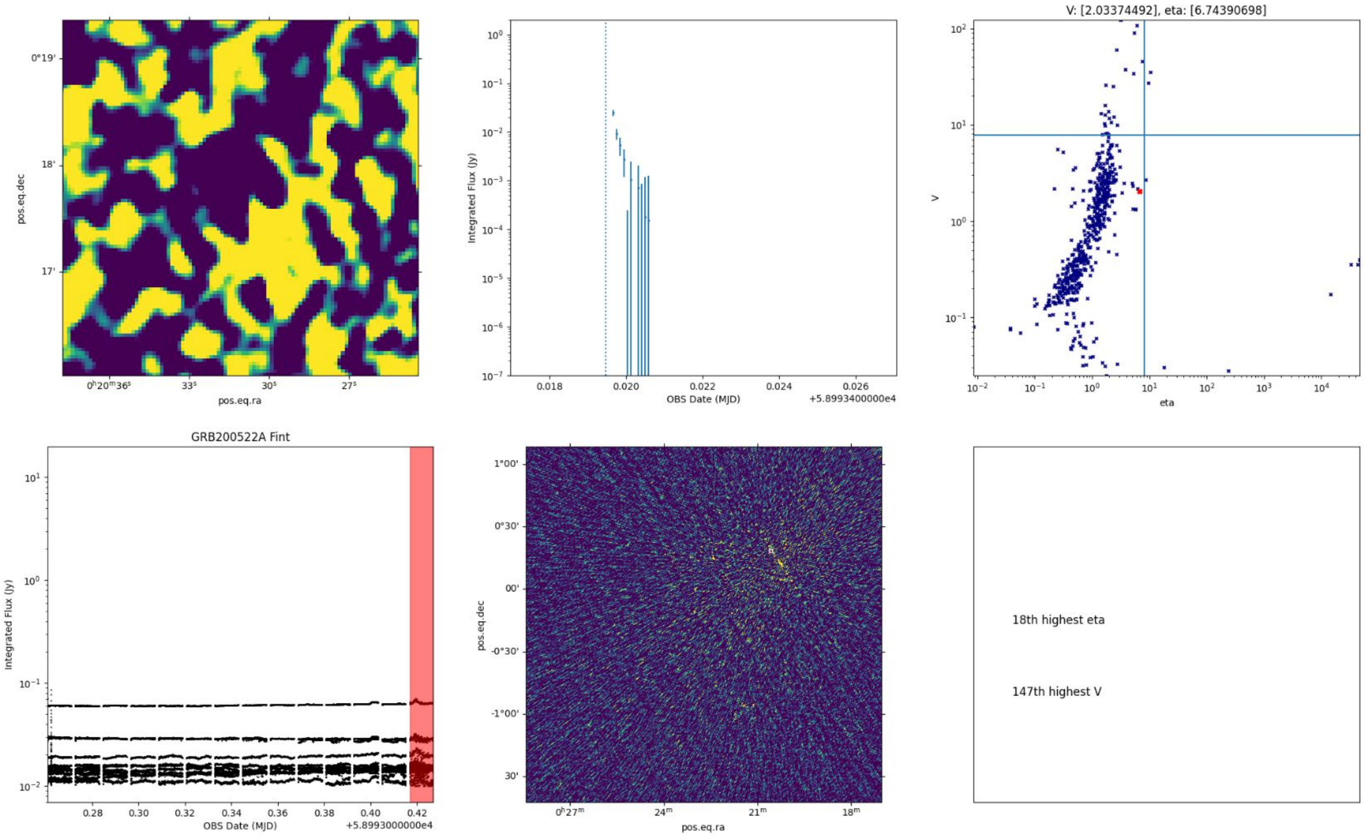

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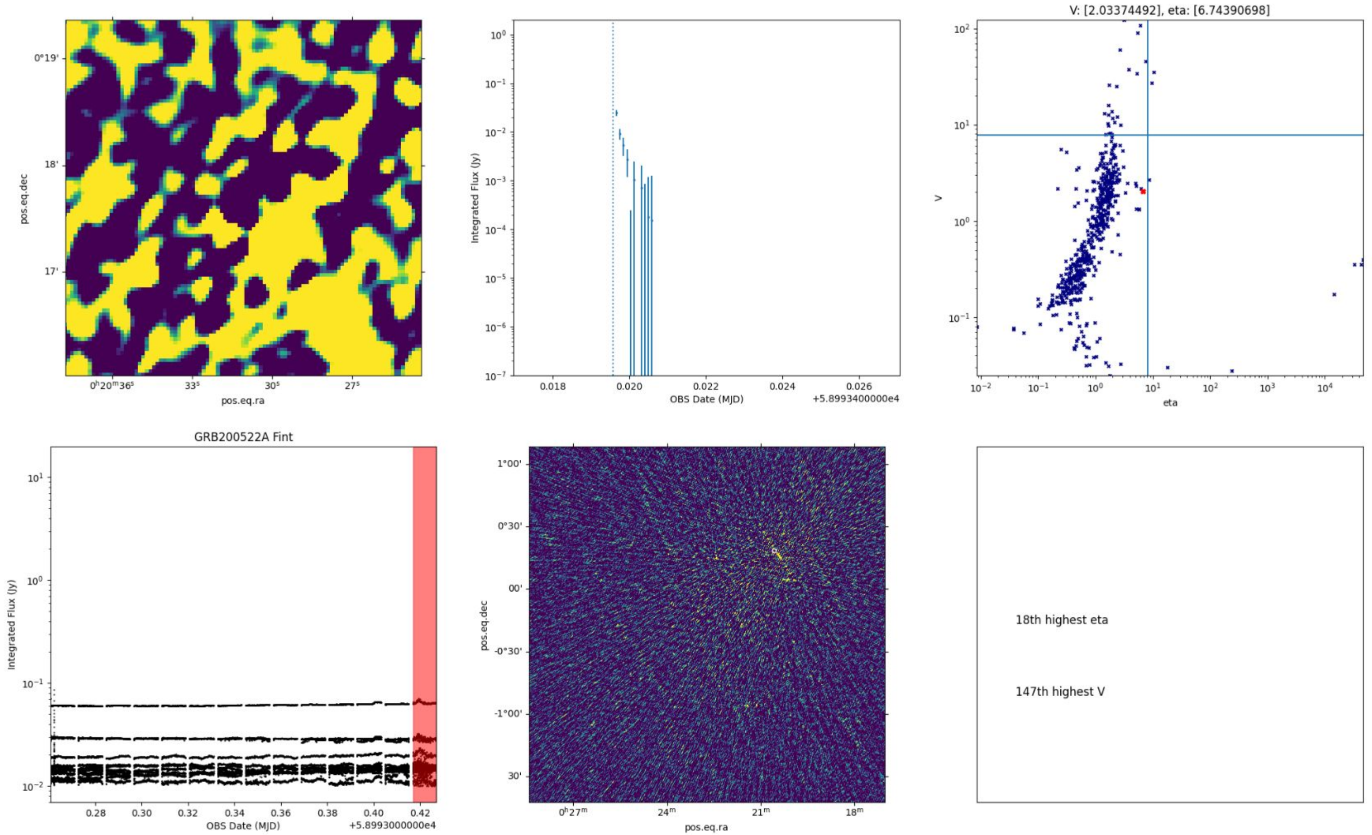

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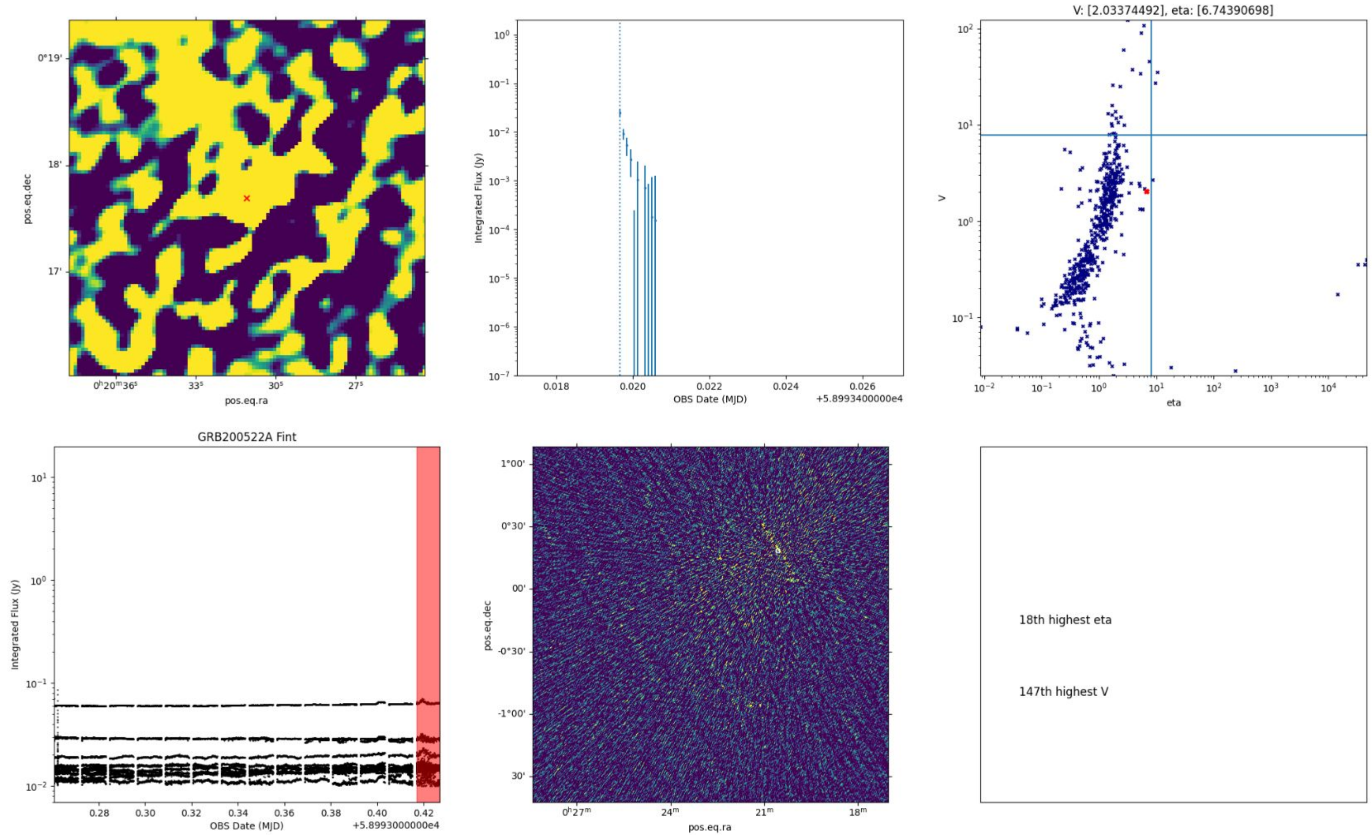

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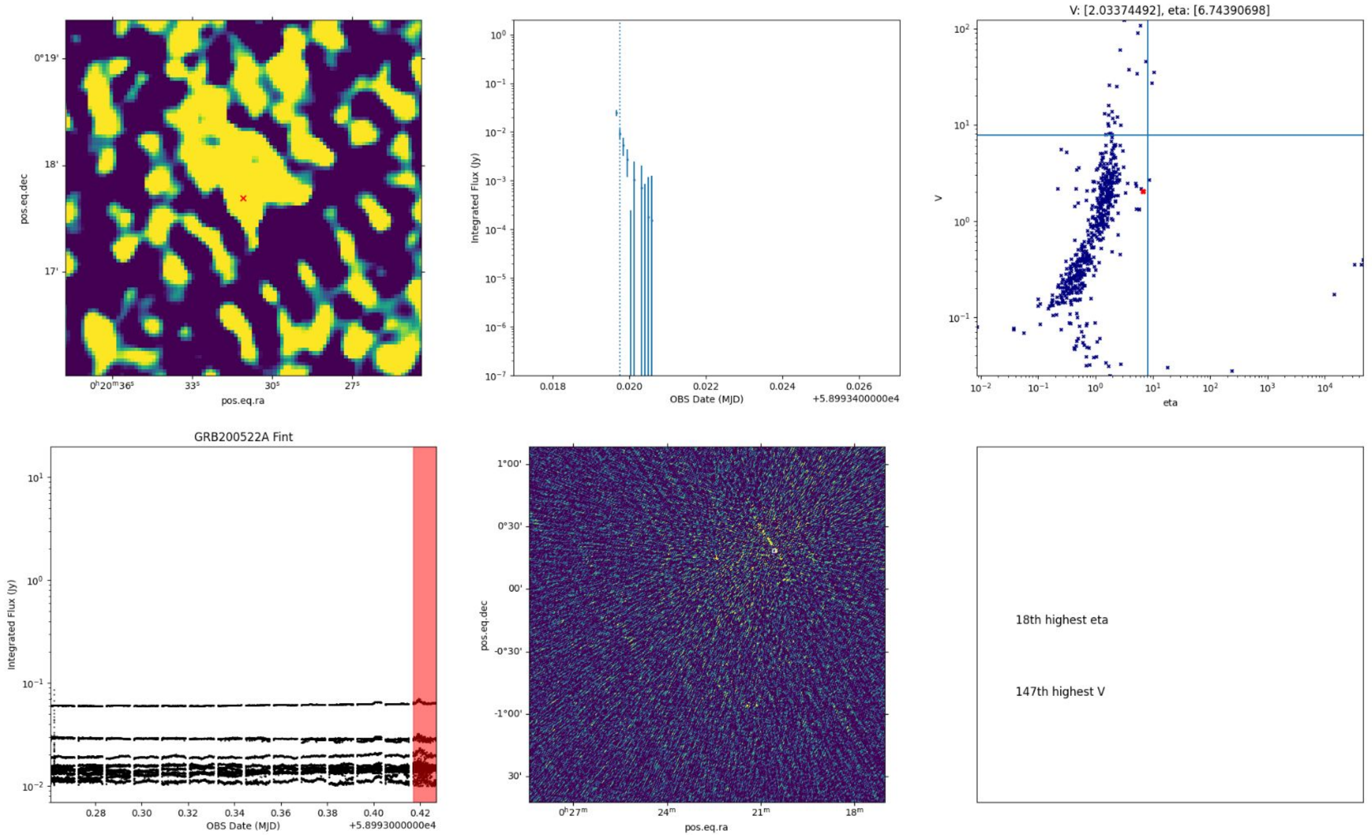

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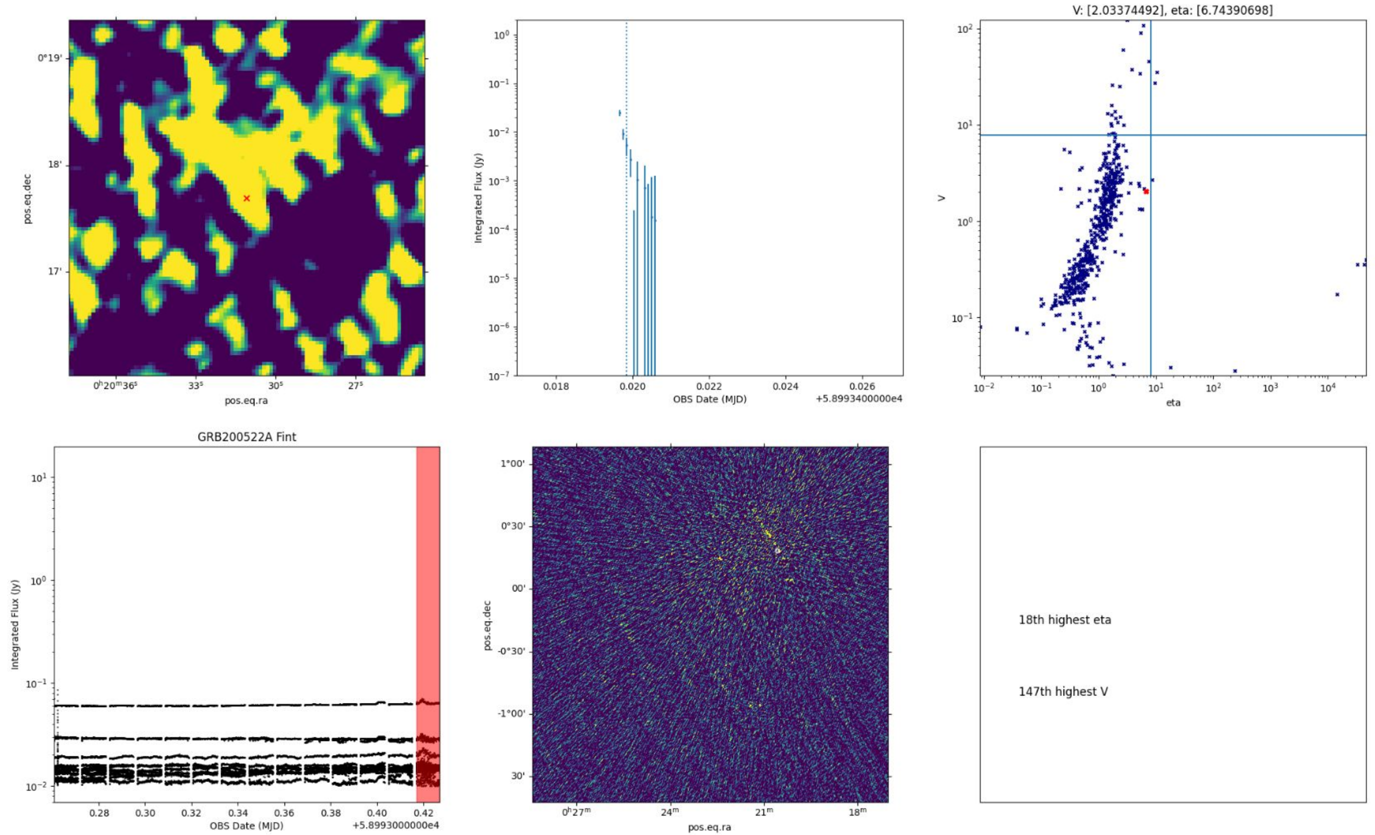

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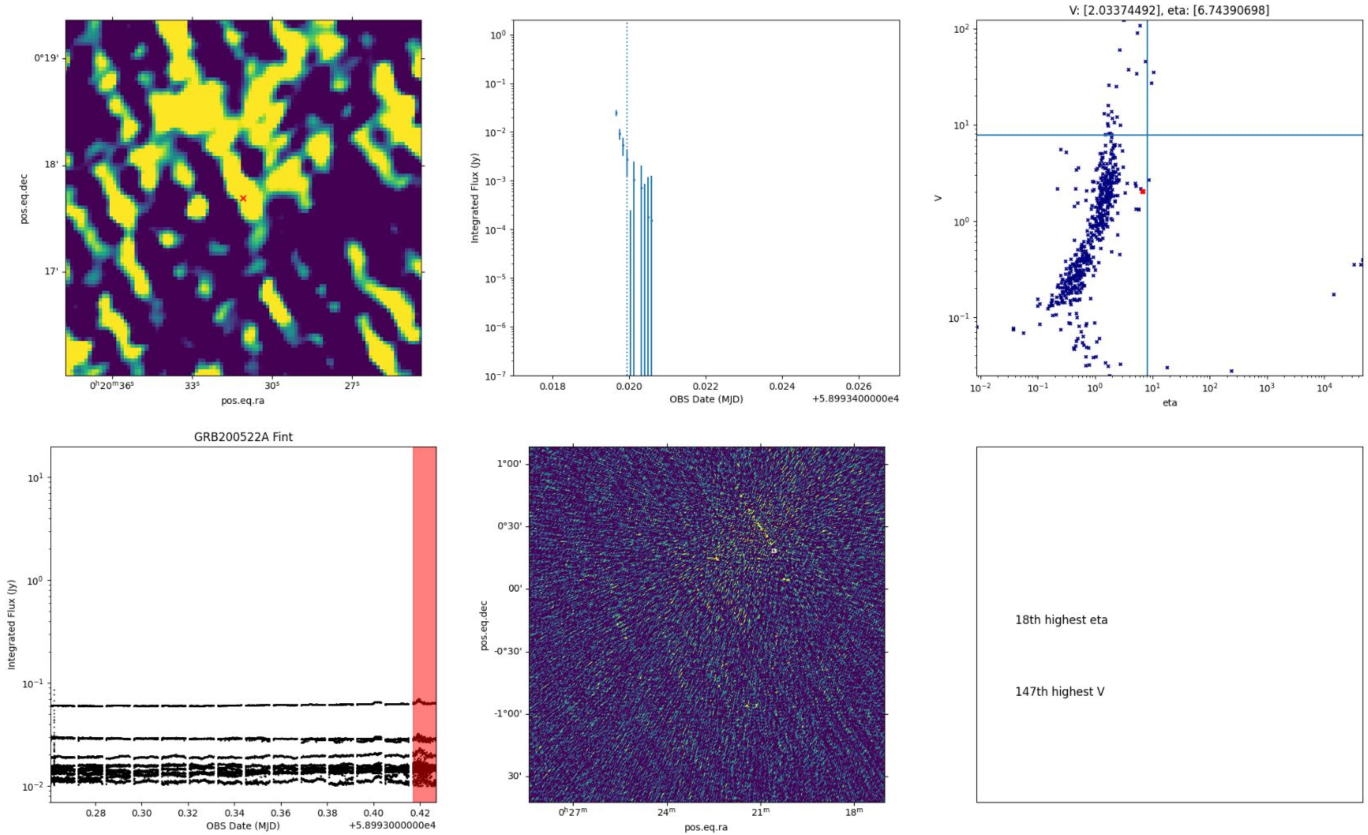

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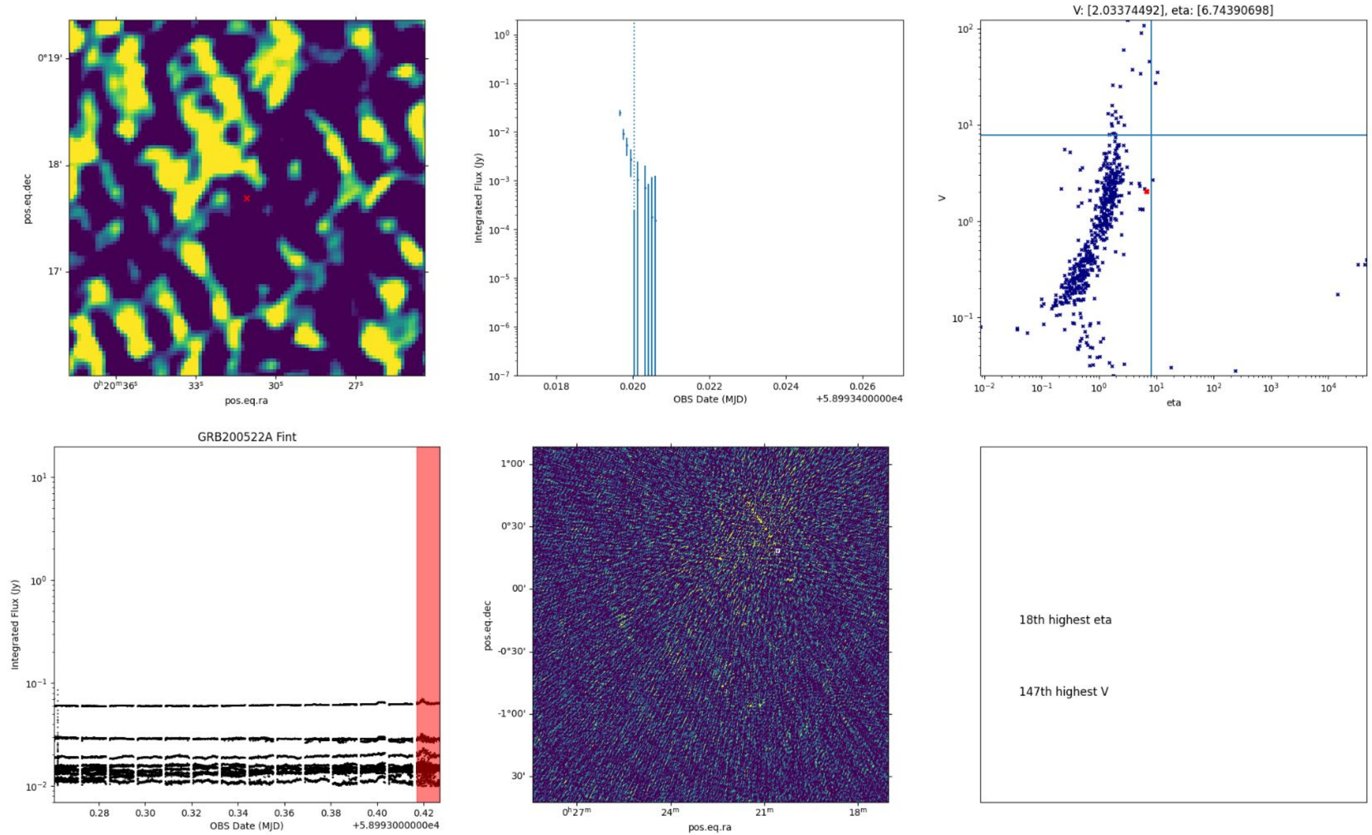

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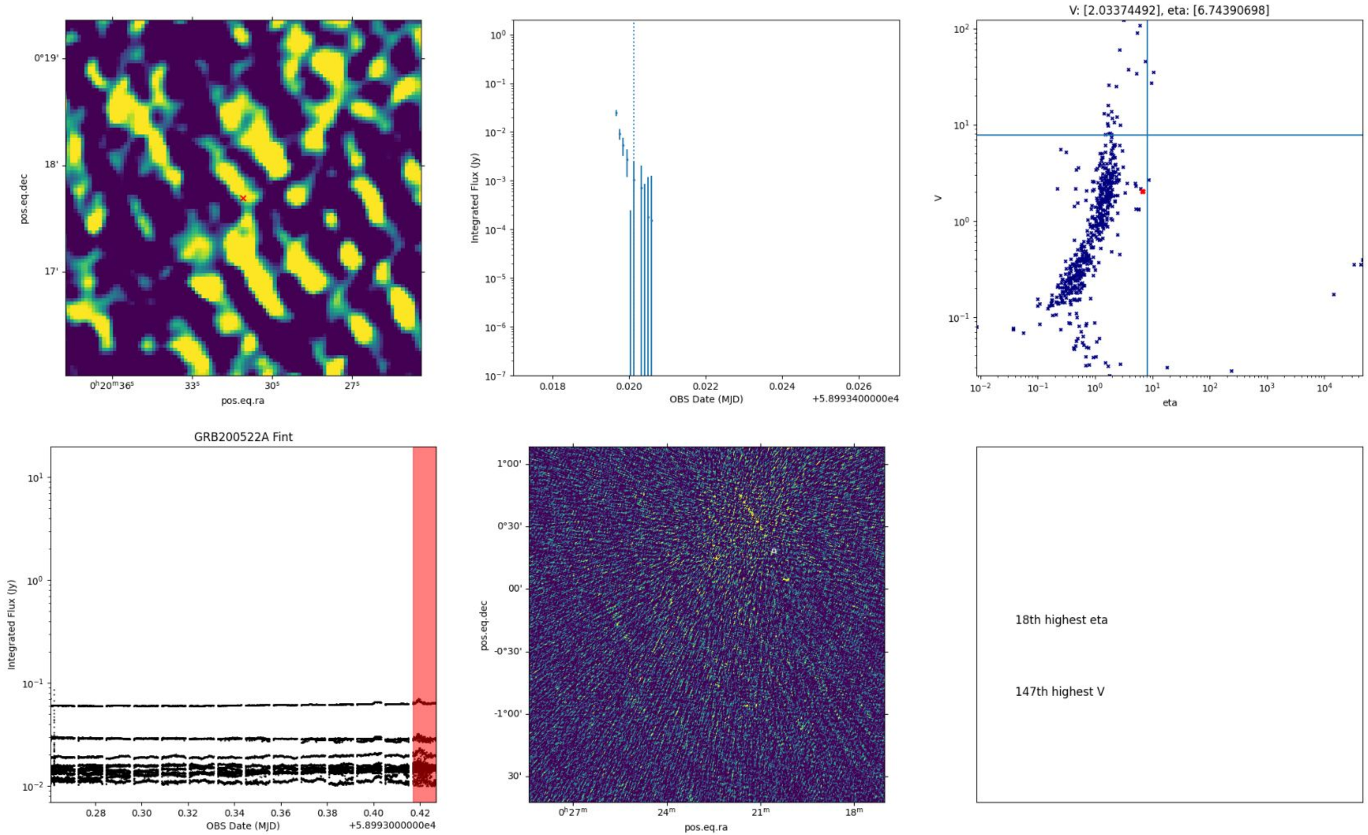

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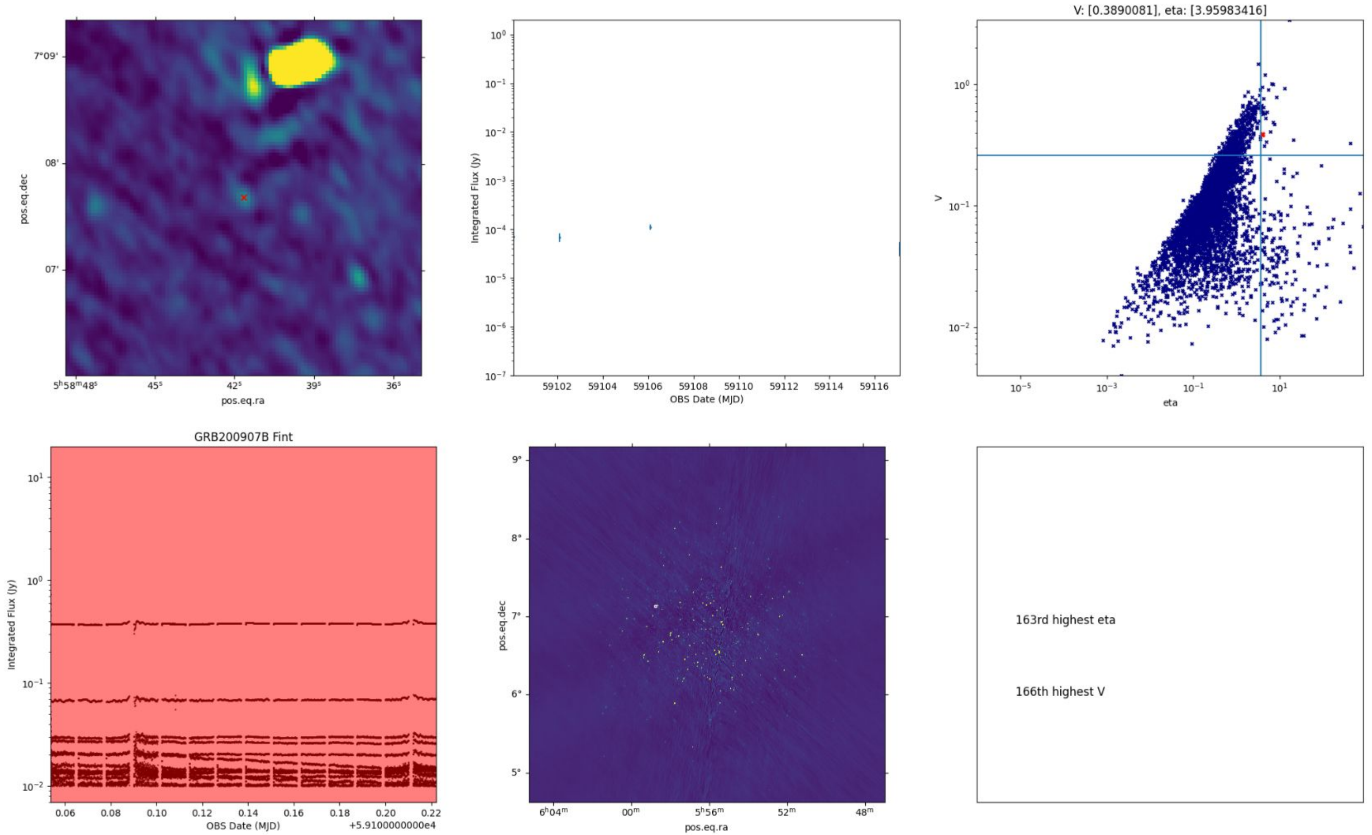

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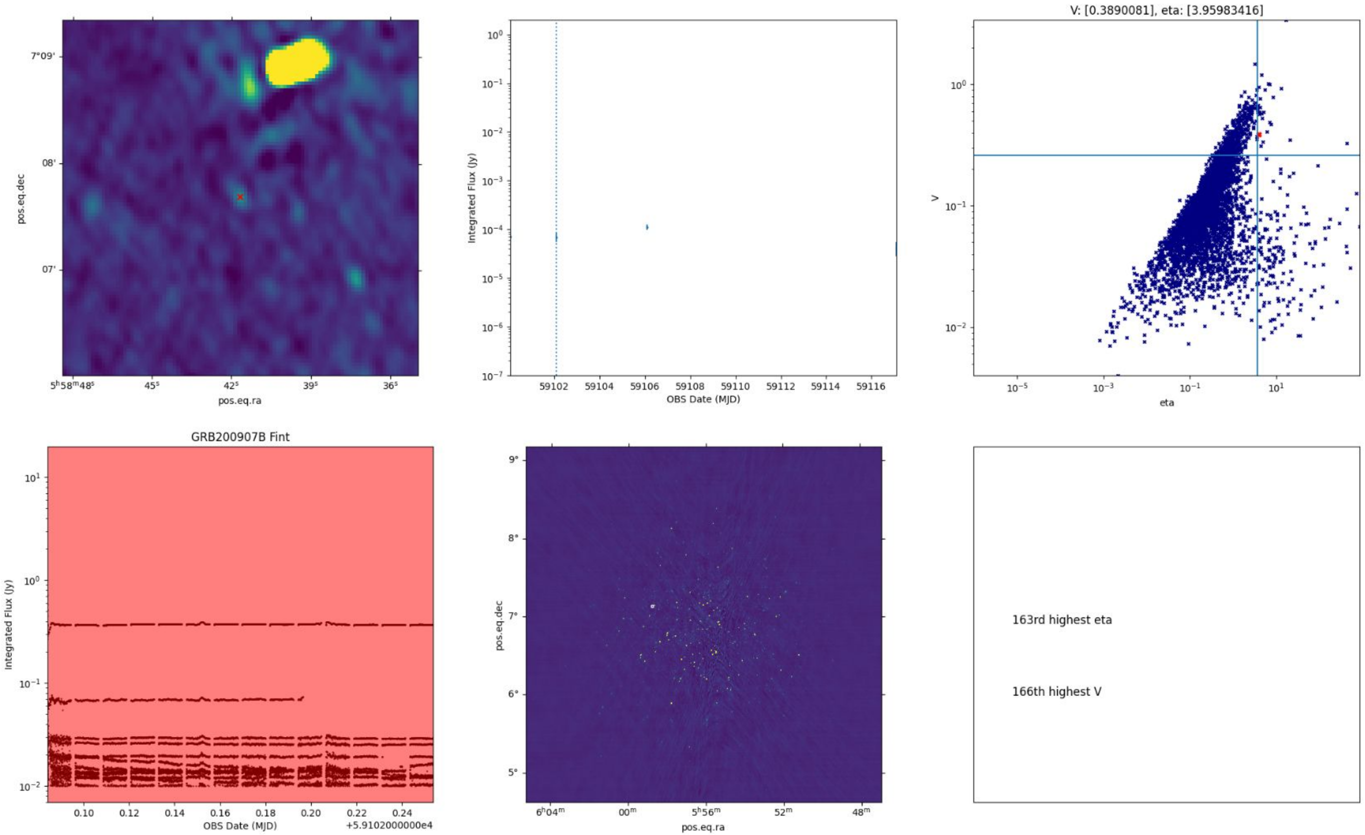

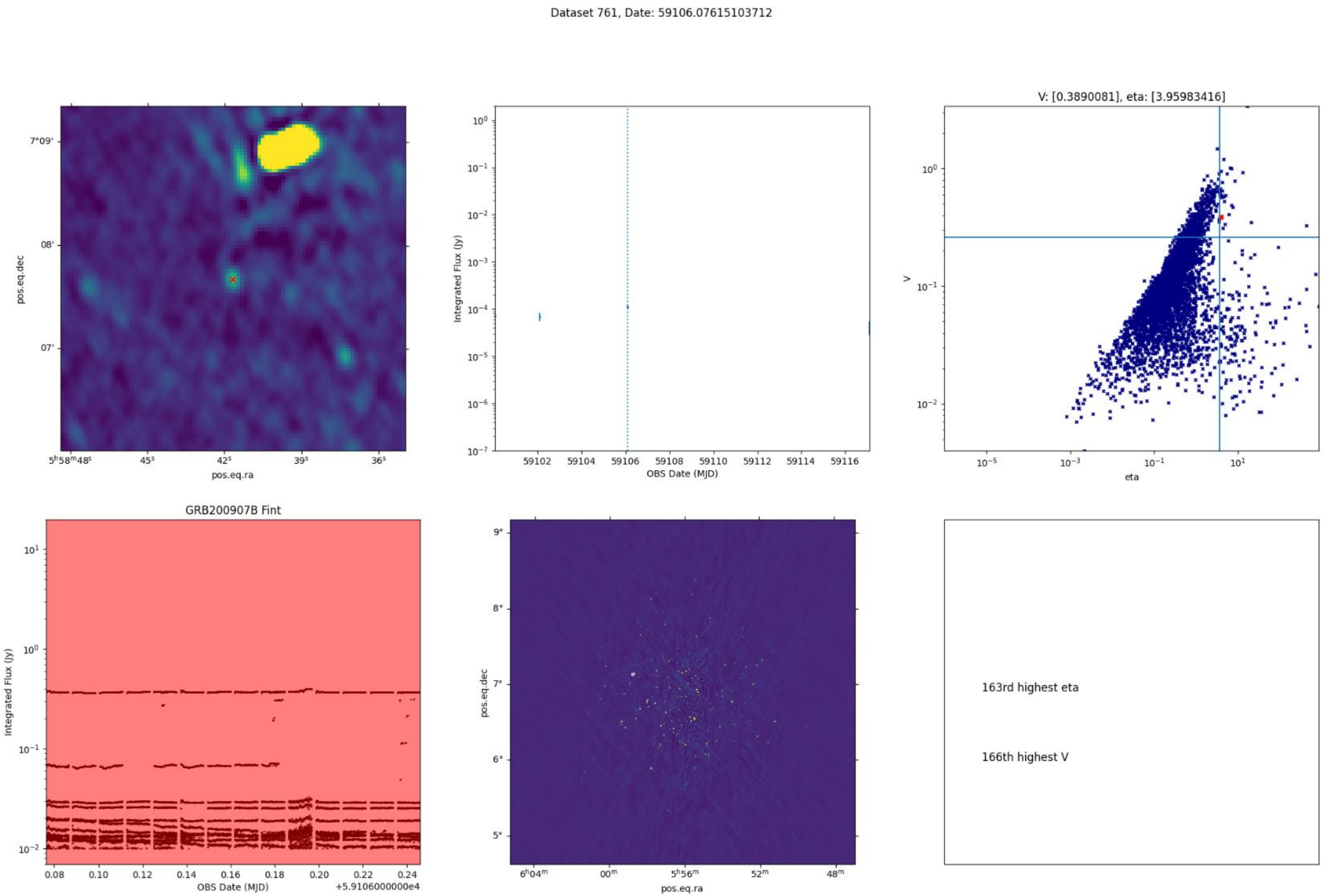

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pos.eq.ra
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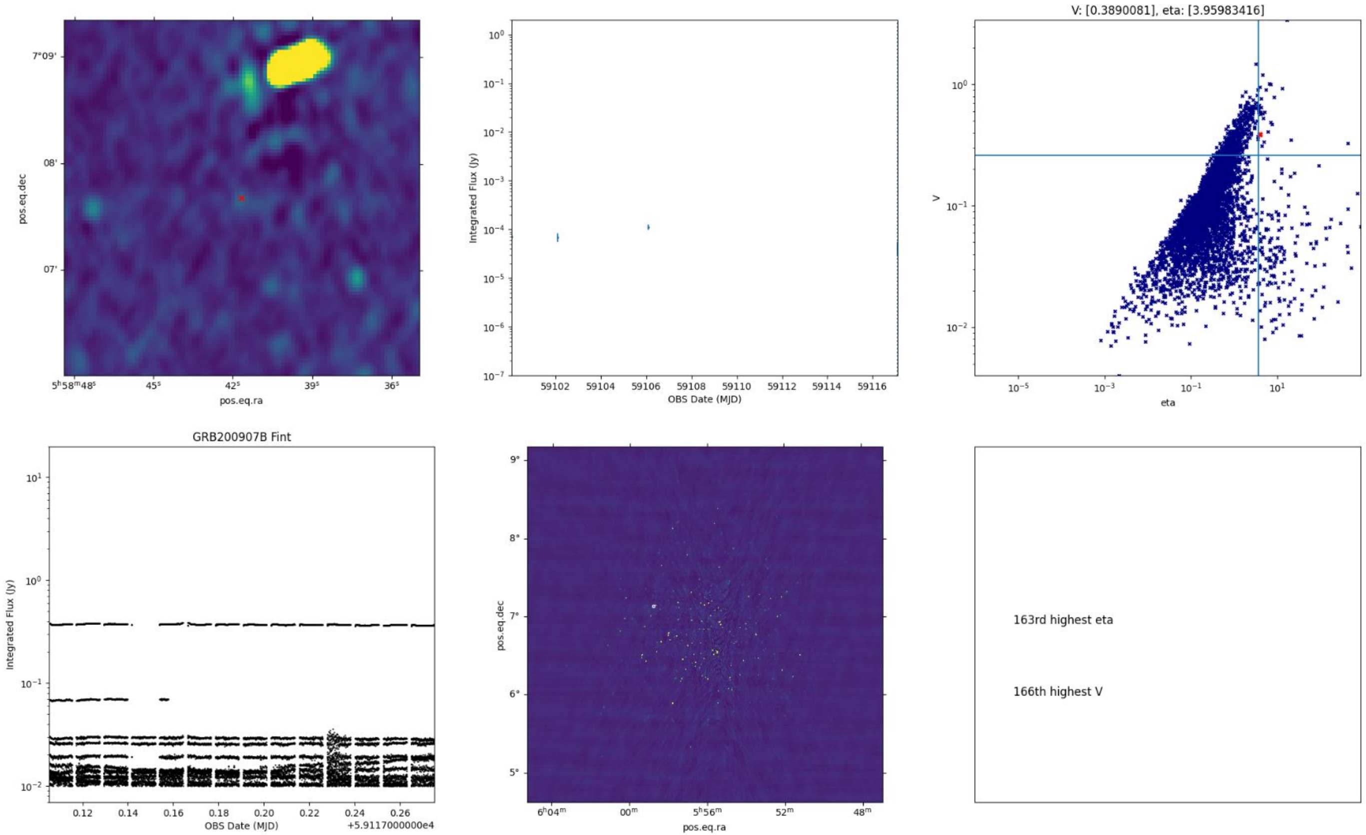
08'
07'
5h58m48s
45s
42s
39s
36s
Integrated Flux (Jy)
OBS Date (MJD)
59102
59104
59106
59108
59110
59112
59114
59116
V: [0.3890081], eta: [3.95983416]
V
eta
GRB200907B Fint
Integrated Flux (Jy)
OBS Date (MJD)
+5.9106000000e4
0.08
0.10
0.12
0.14
0.16
0.18
0.20
0.22
0.24
pos.eq.dec
pos.eq.ra
9°
8°
7°
6°
5°
6h04m
00m
5h56m
52m
48m
163rd highest eta
166th highest V

Dataset 761, Date: 59117.10503745871

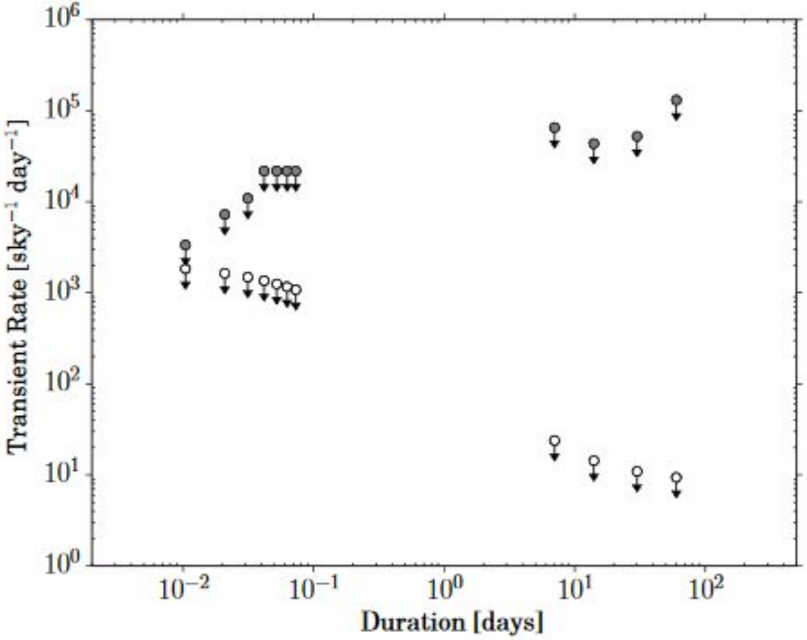


Transients and Variables

- 120 variables in the first search on the longest timescales
  - 52 are likely scintillating known AGN
  - 66 likely scintillating, likely AGN
  - 2 cannot be explained by interstellar scintillation, might be stellar flares
- Excellent limits on transient rates
  - 8 SGRB fields: 2×10^{-4} transients per day per sq degree at ~200 days

Calculating Transient Rates: Why Simulate Transients?

- Need to accurately determine transient rates [1]
  - Traditional methods do not account for multiple timescales or gaps in observations
  - Limited by the worst observation sensitivity
- Monte-Carlo Simulations allow for making these corrections [2]



Filled circles are with applying correction for gaps, open are without

[1] Carbone, D., et al. "New Methods to Constrain the Radio Transient Rate: Results from a Survey of Four Fields with LOFAR". MNRAS, 459, 3161-3174 (2016)

[2] Carbone, D., van der Horst, A. J., Wijers, R. A. M. J., and Rowlinson, A. "Calculating Transient Rates from Surveys". MNRAS, 465, 4106-4117 (2017)

Inputs

- Observing times
- Observation duration
- Image sensitivity
- Pointings on the sky
- Radius of the field of view
- Gaps in observations

In addition, this information can be generated using a provided script and extracted from the metadata

```
2020-02-27T17:50:08.822598+00:00,8,0.00032490346295863342,342.6375833333333,-59.1199444444445,False,1.5
2020-02-27T17:50:16.819214+00:00,8,0.00036999755874516445,342.6375833333333,-59.1199444444445,False,1.5
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```

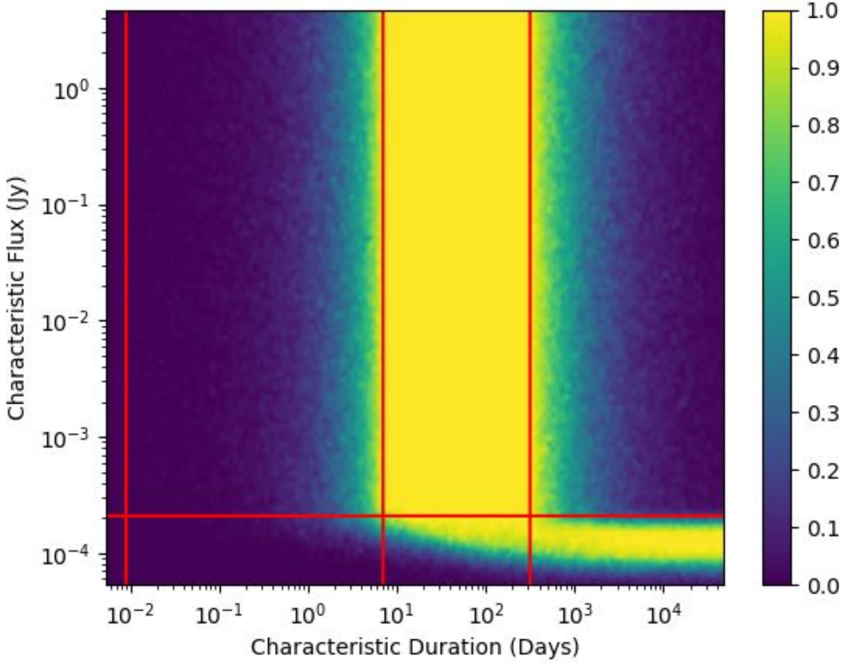
Chastain, S. I.; van der Horst, A. J.; Carbone, D. "Transient Simulations for Radio Surveys." Astronomy and Computing. vol. 40, July 2022

How Transients are Simulated

1. Config and observation files are read in
2. Source info generated via numpy random number generator (log10)
3. Iterate over observations, testing integrated flux for detection
4. Aggregate number of detections / simulations, generate probabilities

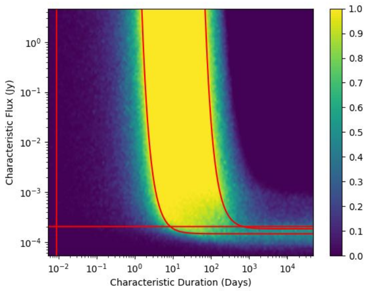
Chastain, S. I.; van der Horst, A. J.; Carbone, D. "Transient Simulations for Radio Surveys." Astronomy and Computing. vol. 40, July 2022

Output: Probability Contours

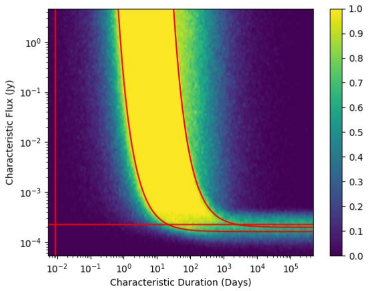


Tophat

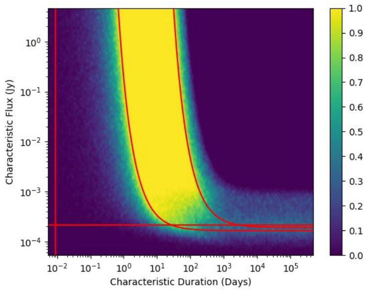
- Shows probability of detection
- Variety of light curves included
- Easily extendable to new light curves



Gaussian

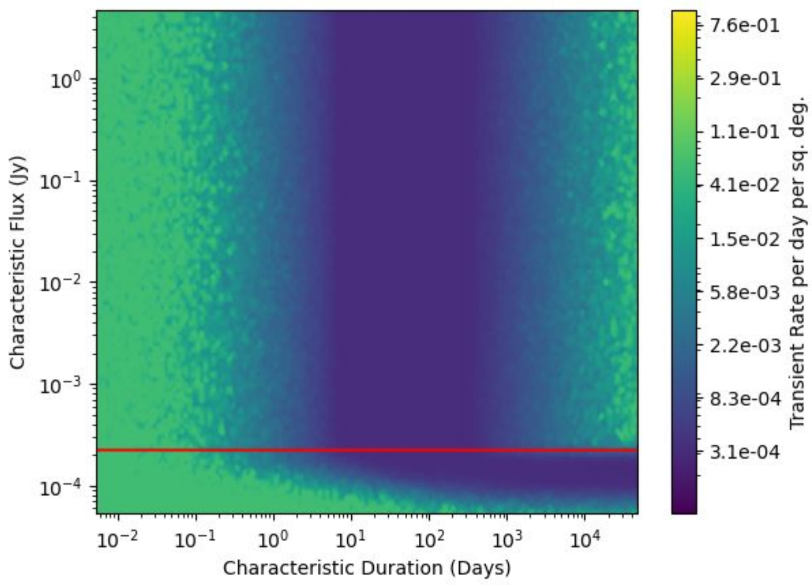


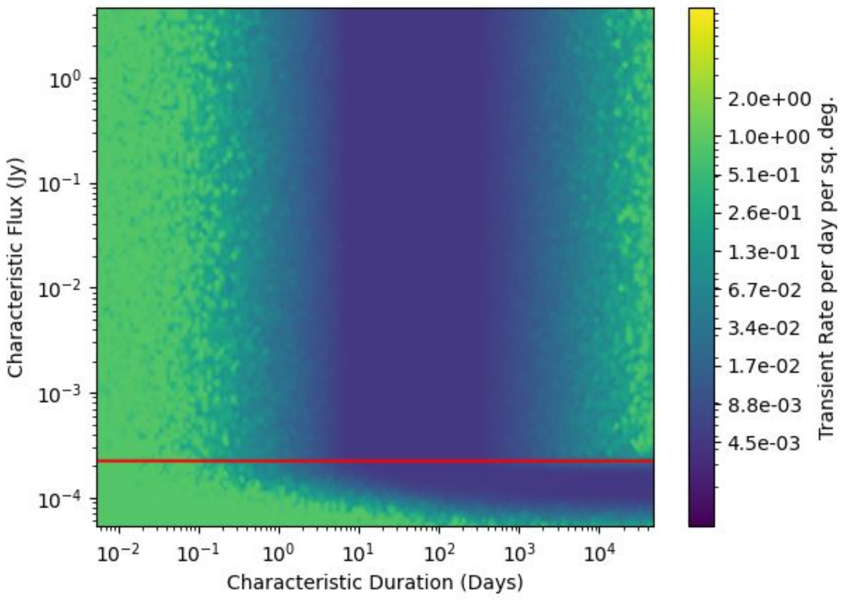
Fast Rise Exponential Decay



Exponential Rise Exponential Decay

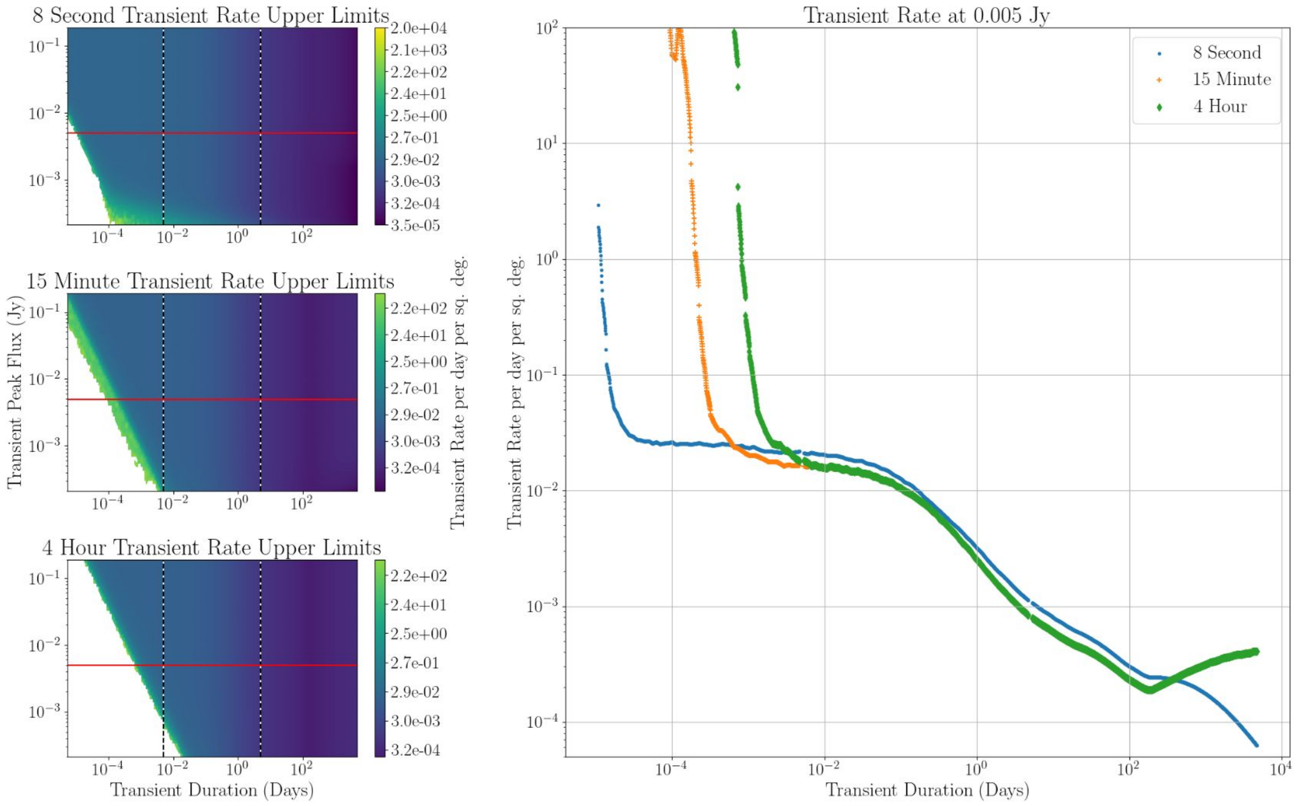
Outputs: Transient Rate Contour Plot





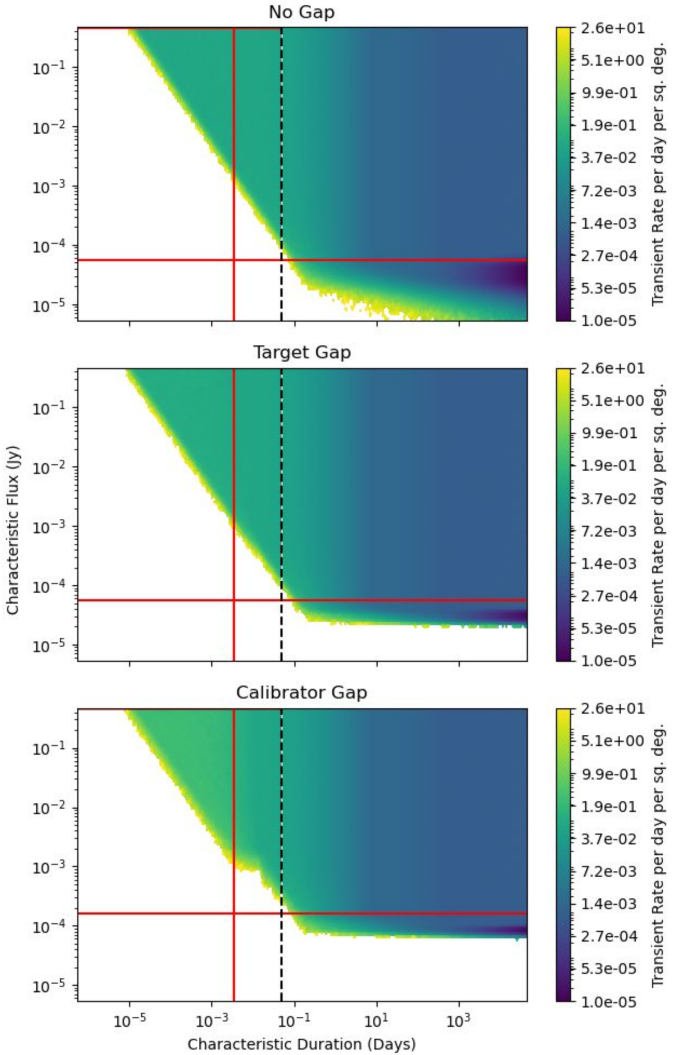
From probability contours, a transient rate can be calculated
Assumes transients follow Poisson distribution
If there are detections, plots lower (left) and upper (right) limits, if no detections upper limits only

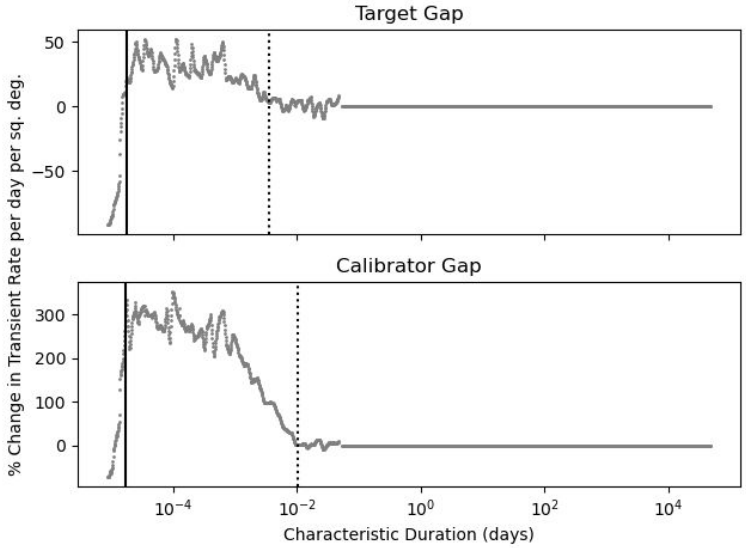
Outputs: Transient Rate Contour Plot



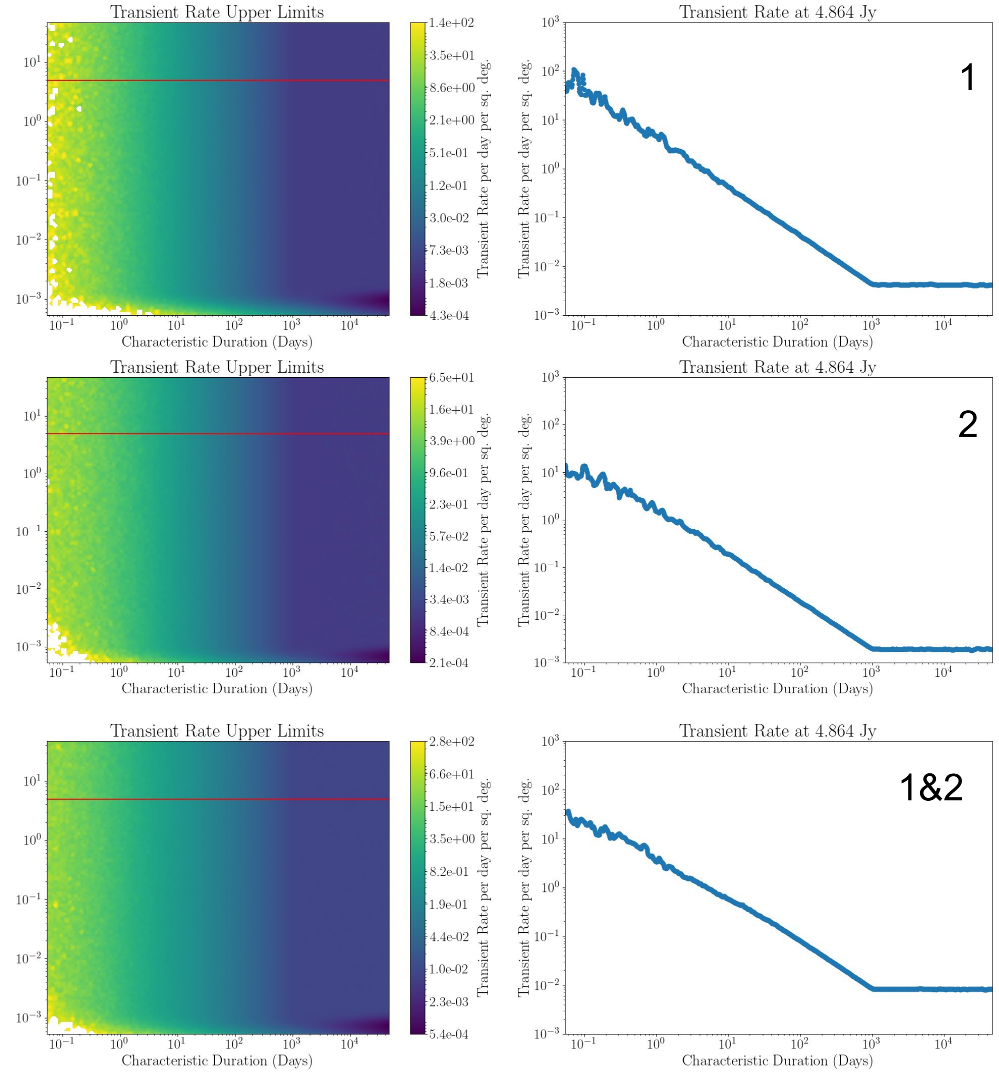
Gaps in Observations

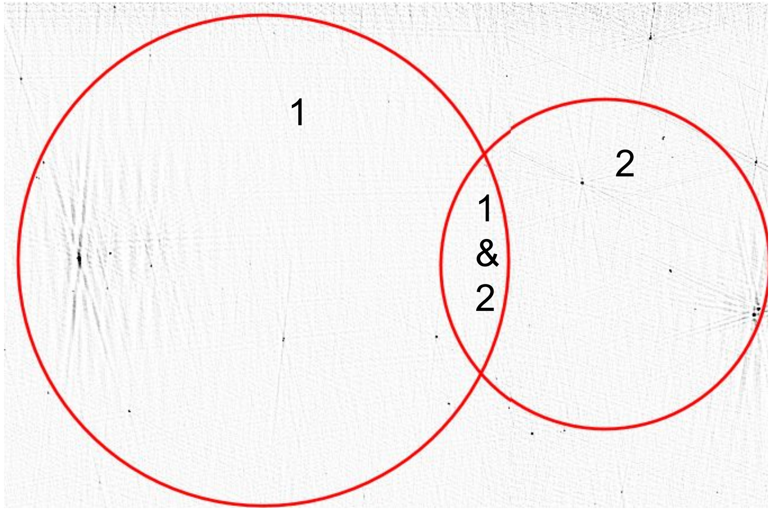
- Real radio observations contain gaps
- Results in different transient rates
- Calibration loop of 5 minutes on calibrator and 15 minutes on target





VLASS Survey Timescales





- Overlap between two tiles
- Now multiple timescales
- Can probe various timescales with calibrator field searches as in Bower & Saul 2011

Overview

- Commensally searching for transients
  - Upper limits on transient rates
  - 133 variables on longest timescale
  - 130 scintillating, 3 possibly intrinsic variability
  - Efficient short timescale searches may start detecting coherent emitters
- Characterizing transient rates
  - Accurate and flexible transient rate calculations
  - Many realistic effects accounted for
  - New features can make this even more accurate
  - Chastain, S. I., van der Horst, A. J., & Carbone, D. 2022, Astrophysics Source Code Library. ascl:2204.007. https://github.com/dentalfloss1/transients-simulations

Chastain, S. I.; van der Horst, A. J.; Carbone, D. "Transient Simulations for Radio Surveys." Astronomy and Computing. vol. 40, July 2022

email:sarahchastain1@unm.edu

Additional Materials

Characterizing the Radio Sky

- Following up on transients
  - Deep upper limits
  - Marginal detection: Similar astrophysical parameters to long GRBs
  - Non-detections: Low density environments, similar efficiencies
  - New instruments (SKA) should be able to distinguish between scenarios
- Commensally searching for transients
  - Upper limits on transient rates
  - 133 variables on longest timescale
  - 130 scintillating, 3 possibly intrinsic variability
  - Efficient short timescale searches may start detecting coherent emitters
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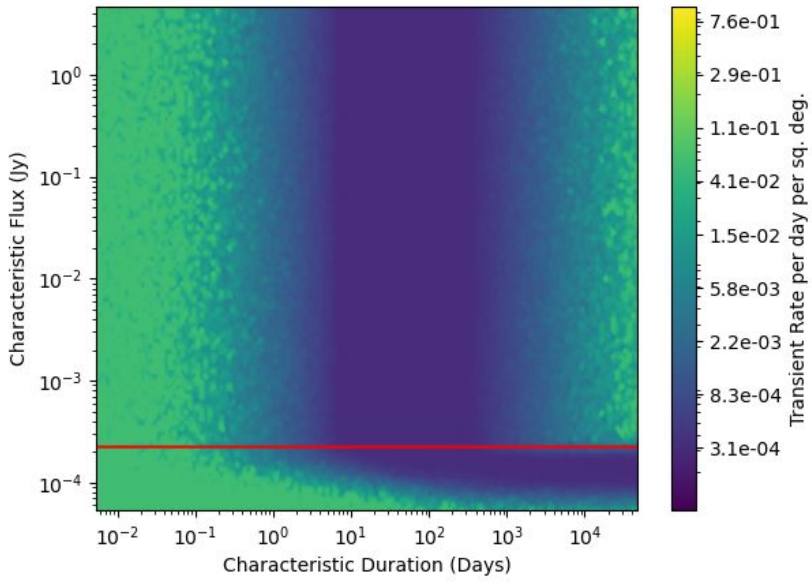
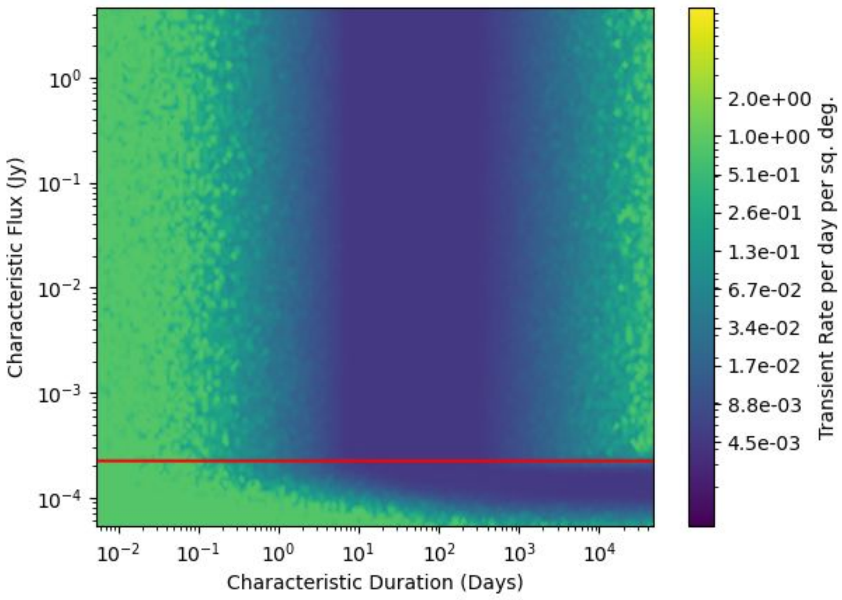
Outputs: Transient Rate Contour Plot





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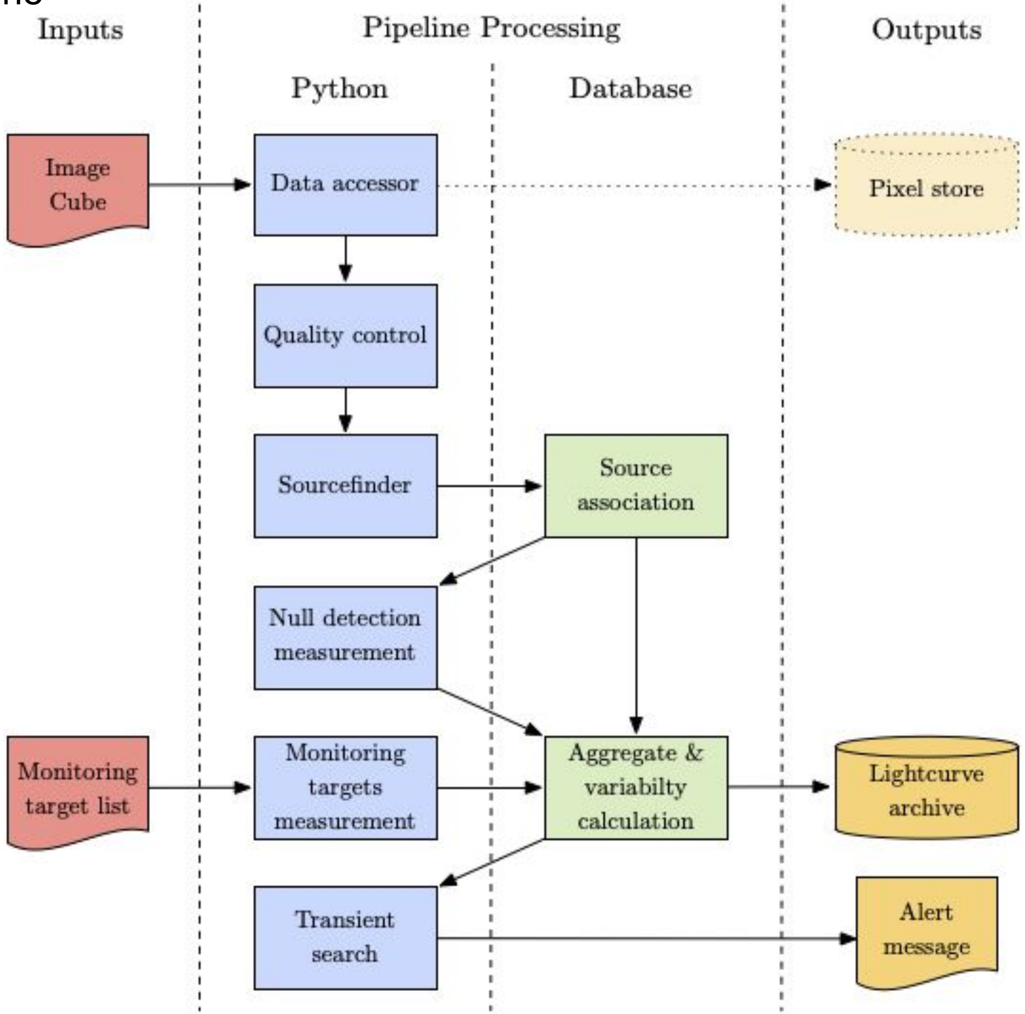
The Transients Pipeline



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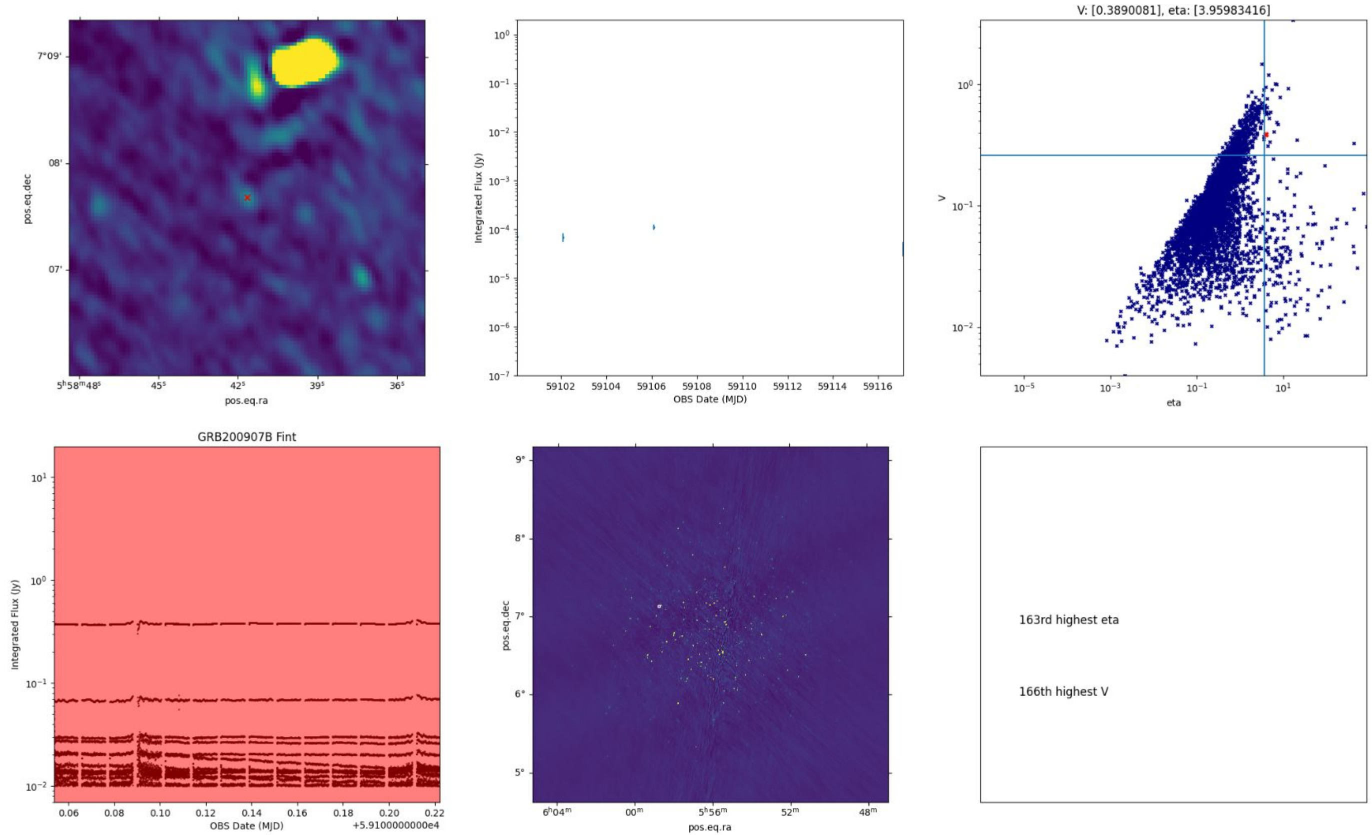

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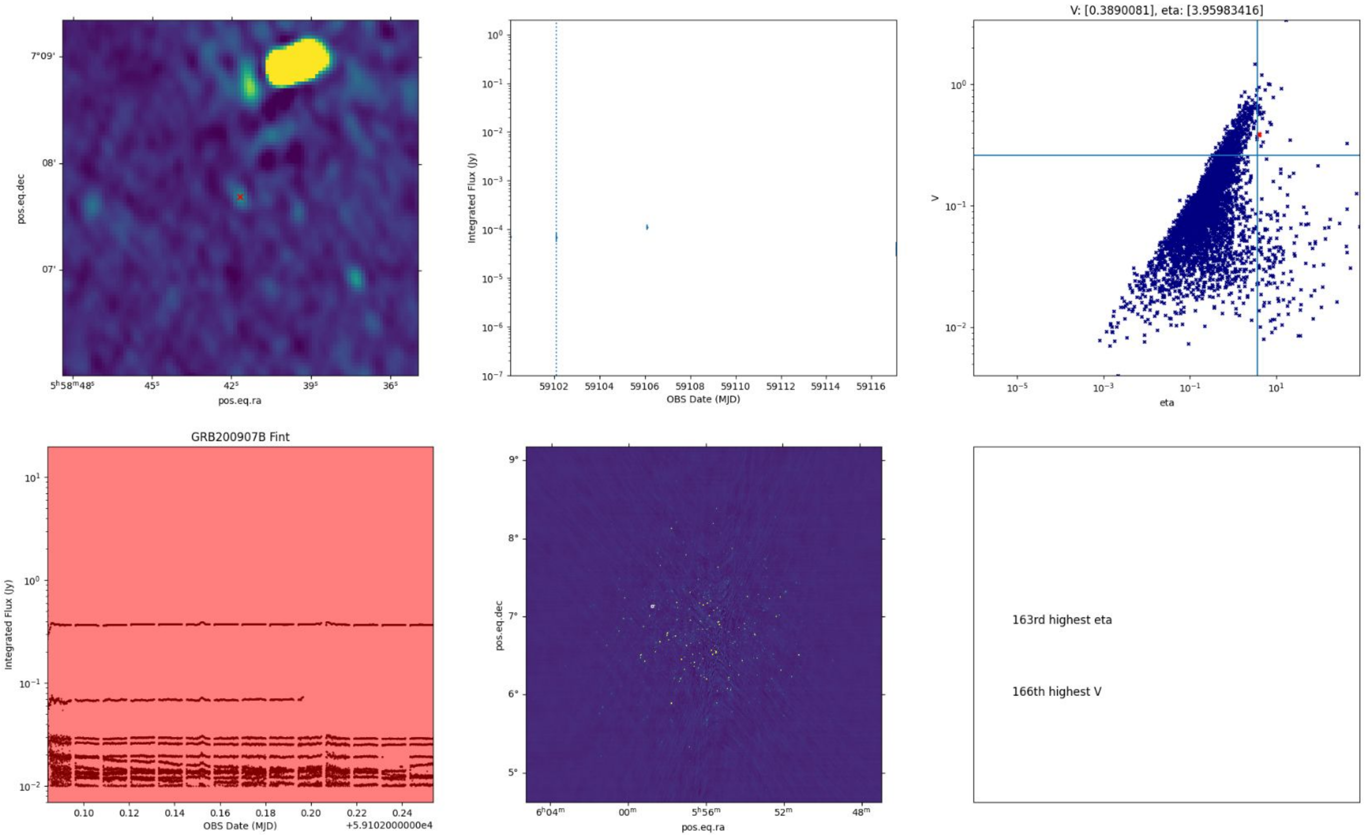

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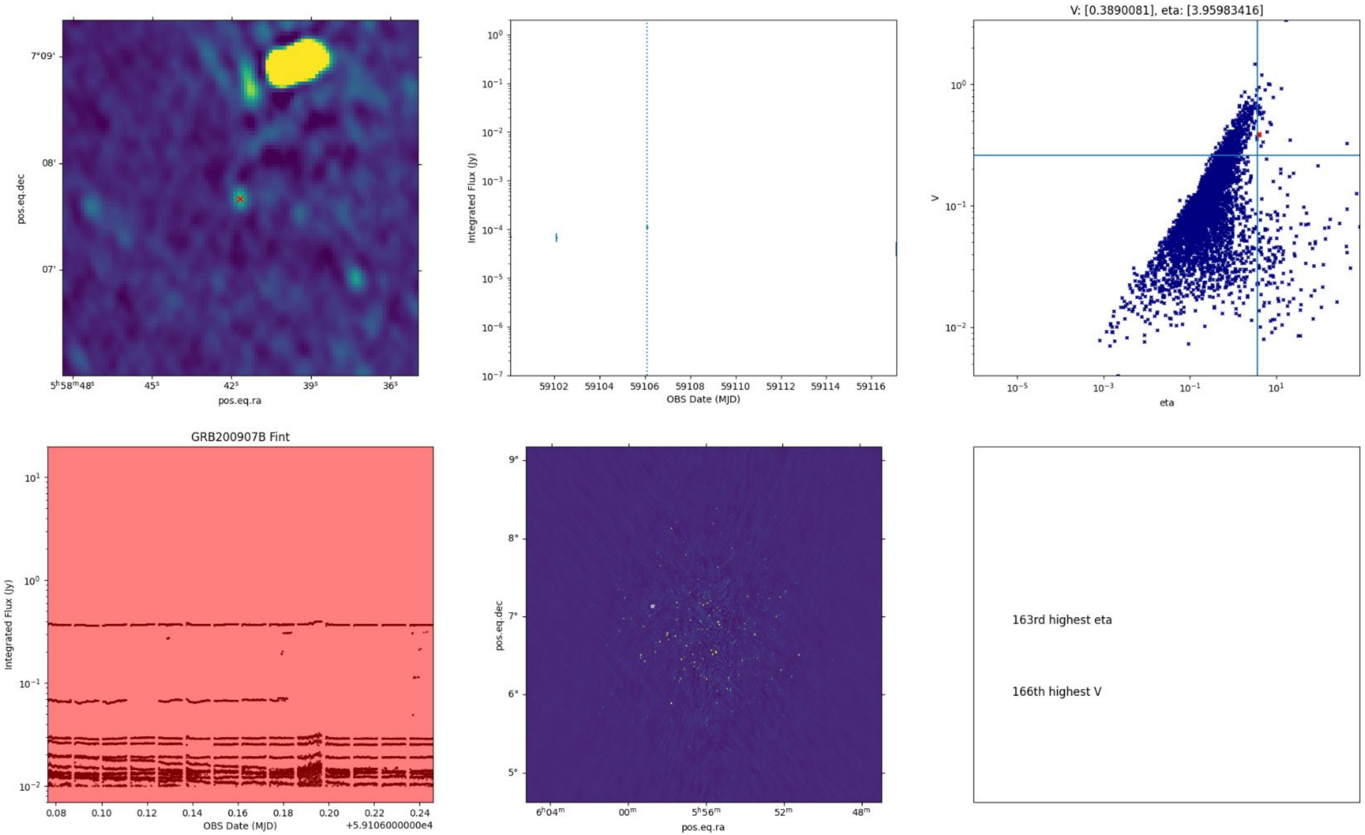

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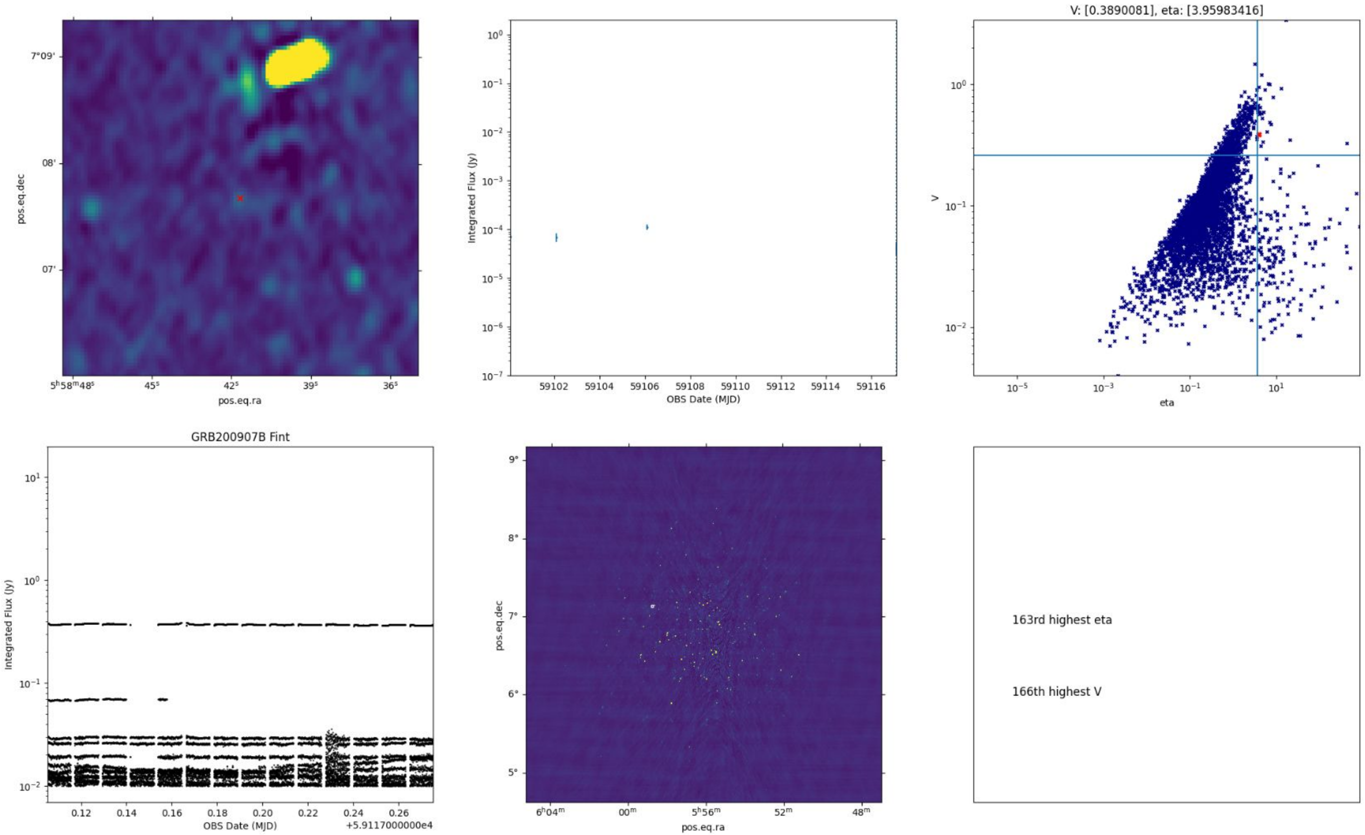


Further Reduction

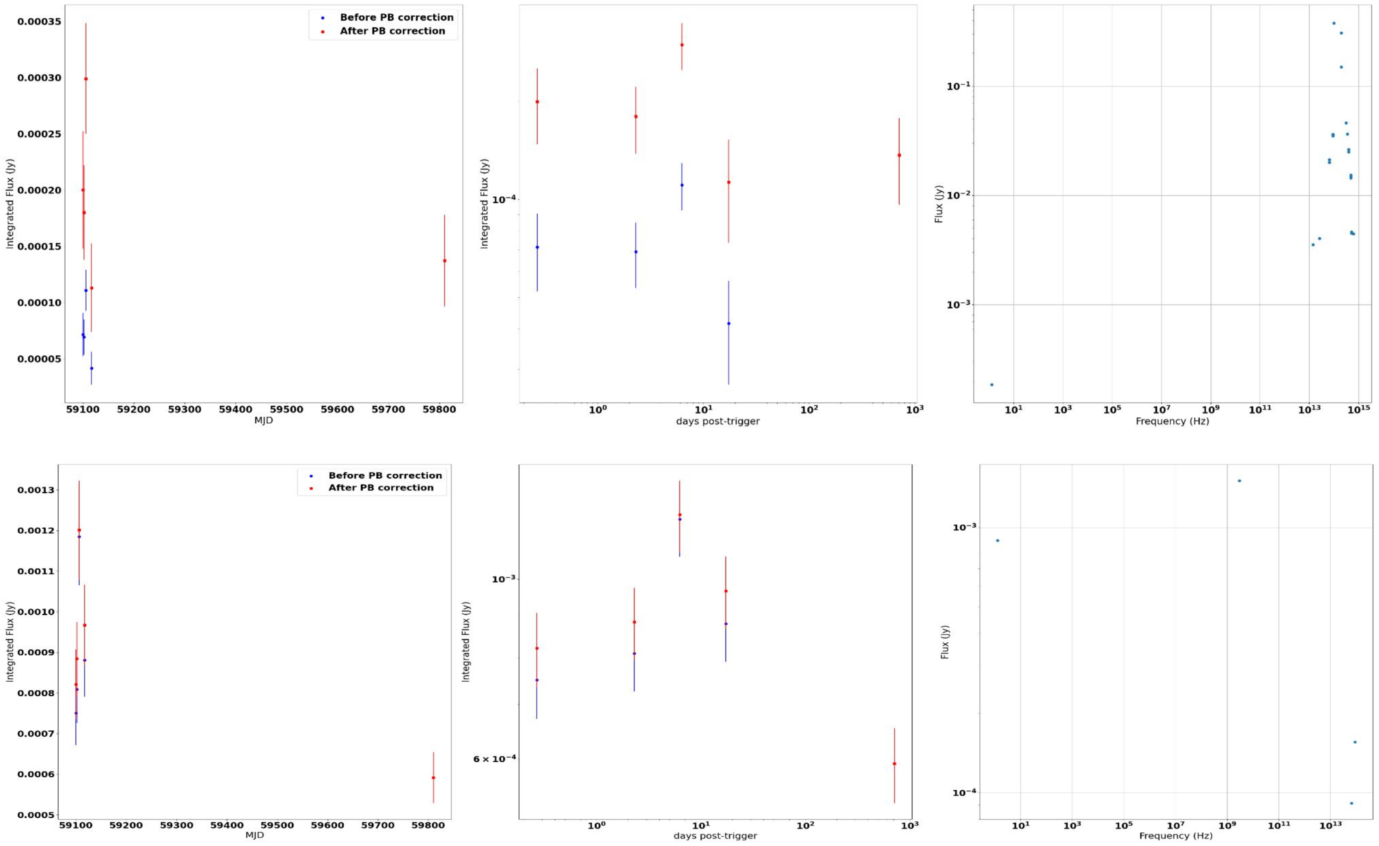
- 214 sources on 8 second timescale
  - 3 sources after visual examination
- 306 sources on 15 minute timescale
  - 19 sources after visual examination
- 278 sources on 4 hour timescale
  - 227 sources after visual examination

Testing Sources

- Force fit
- Position corrected
- Primary beam
- Recalculate variability
- Only 4 hour image remained
    - 122 sources, all variables
    - Variable on timescales from weeks to months

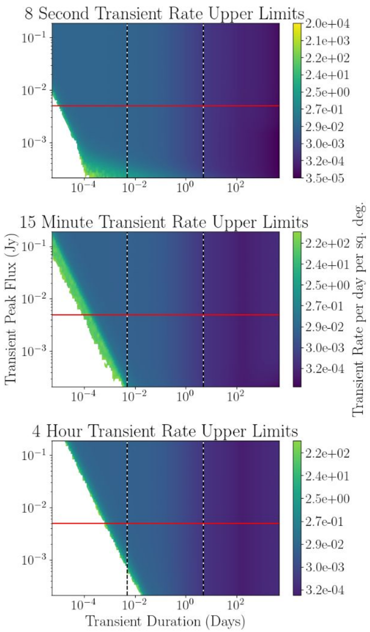
Variable Sources

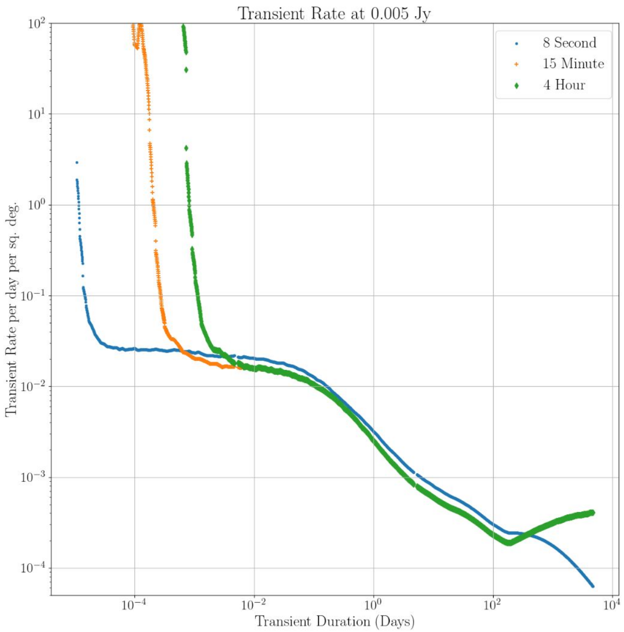
- Match catalogs in Vizier
  - 99 sources with a catalog match
  - No x-ray or gamma-ray matches
- Scintillation
  - Ionized ISM
  - Refractive and Diffractive
  - 2 sources not explained



Examining Variables

- Transient rate limits
  - Min fluence: 10 Jy ms
    - 0.03 transients day^{-1} sq. deg^{-1}
  - Fluence: 9×10^3 Jy ms
    - 2×10^{-4} transients day^{-1} sq. deg^{-1}





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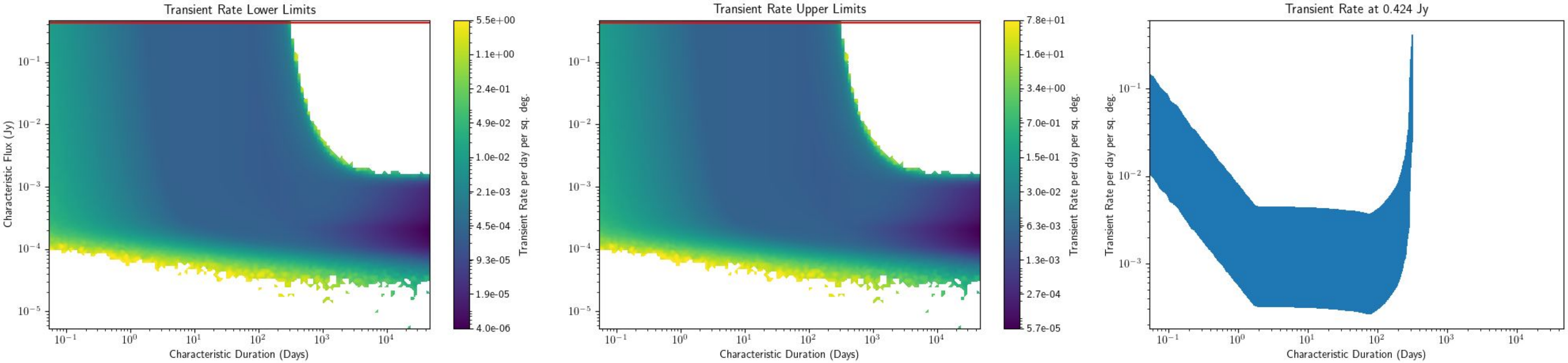
```


Chastain, S. I.; van der Horst, A. J.; Carbone, D. "Transient Simulations for Radio Surveys." Astronomy and Computing. vol. 40, July 2022

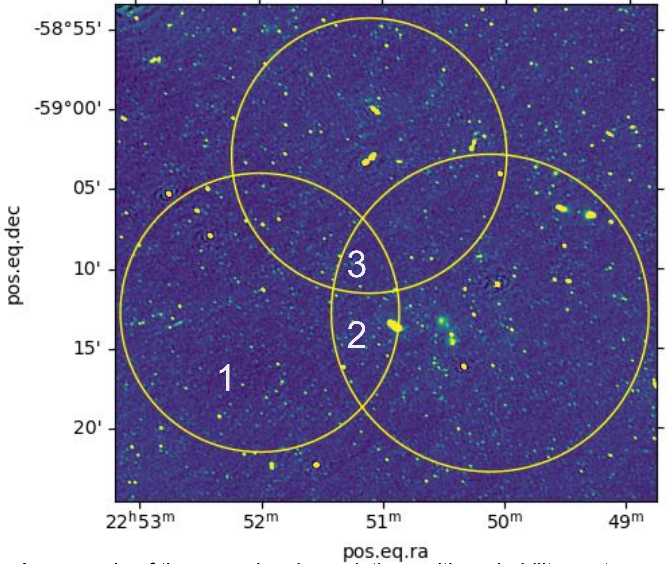
Outputs: Transient Rate Contour Plot



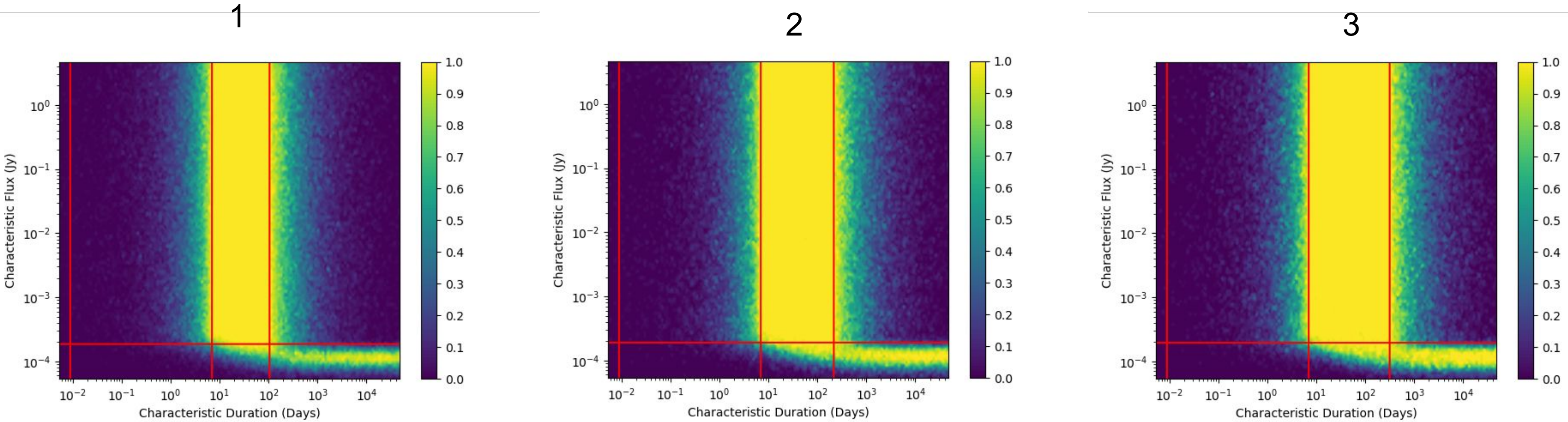
Another, more detailed example. This time with a Gaussian light curve

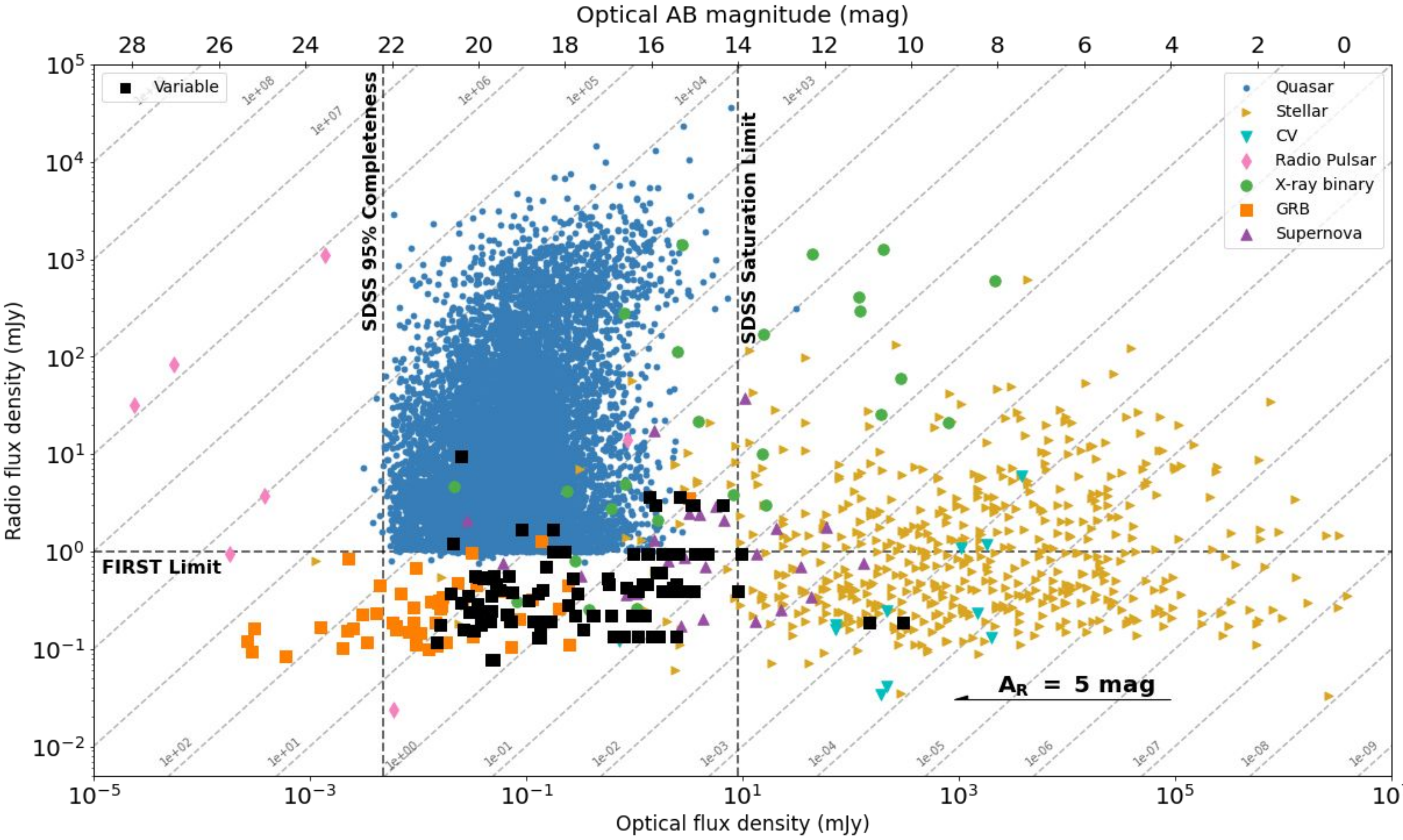
Overlapping Pointings

- Calculates double and triple overlapping regions
- Fully accurate area calculations accounting for spherical geometry



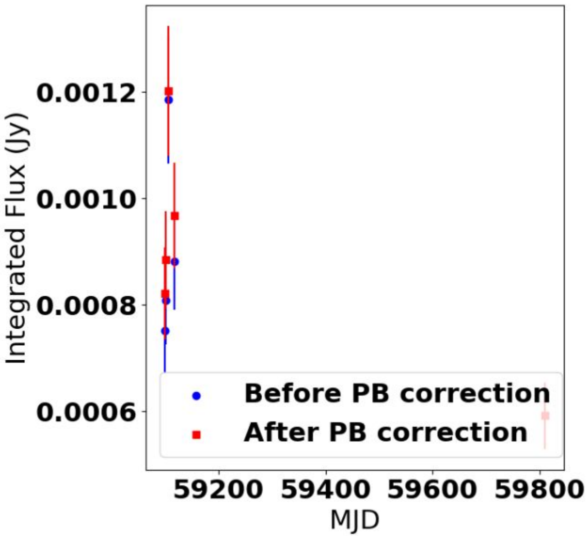
An example of three overlapping pointings with probability contours

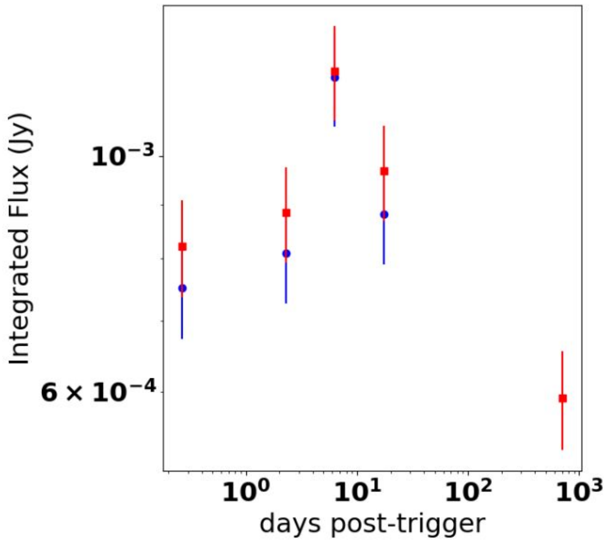


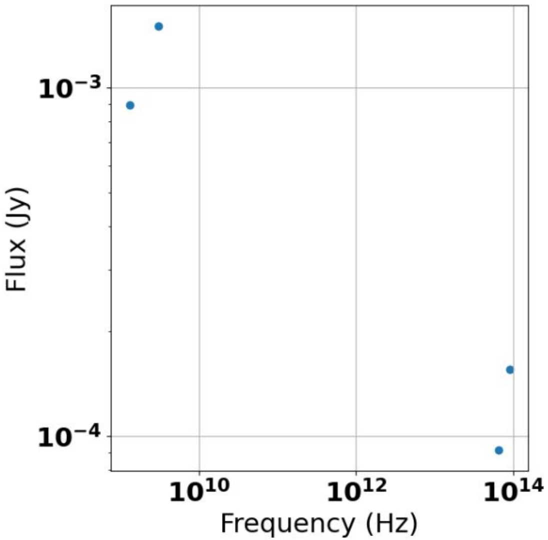


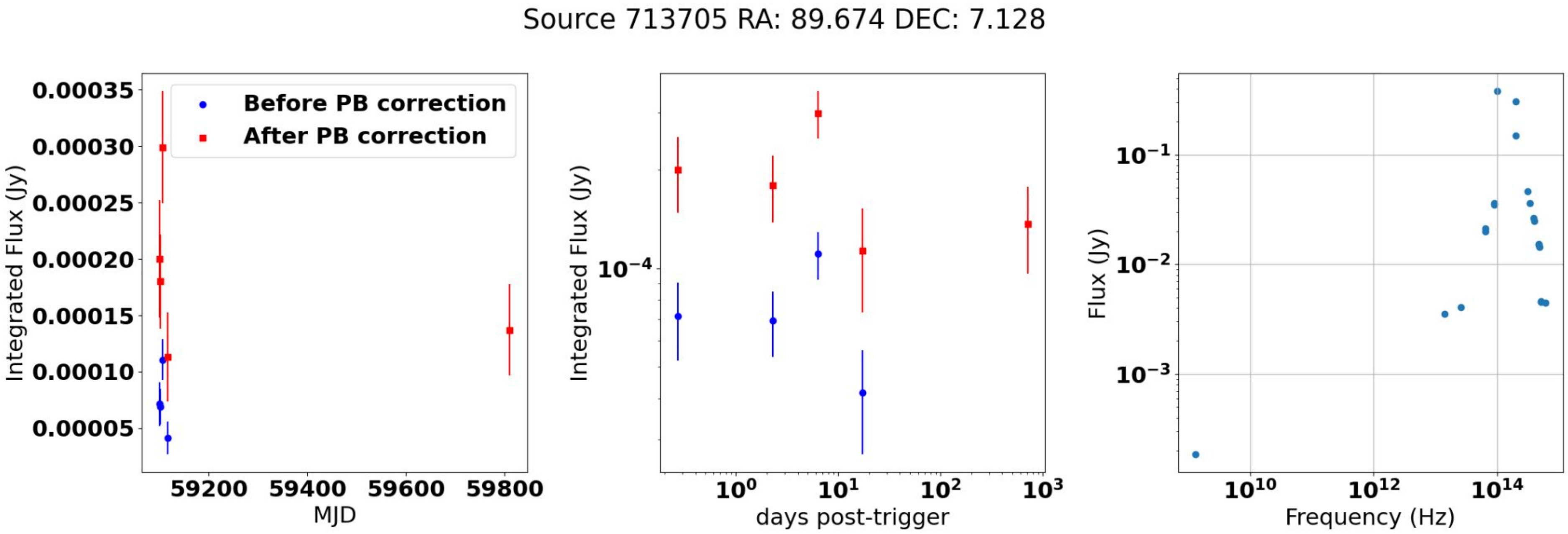
Optical AB magnitude (mag)
28 26 24 22 20 18 16 14 12 10 8 6 4 2 0
Variable
Quasar
Stellar
CV
Radio Pulsar
X-ray binary
GRB
Supernova
SDSS 95% Completeness
SDSS Saturation Limit
FIRST Limit
A_R = 5 mag
1e+08 1e+07 1e+06 1e+05 1e+04 1e+03
1e+02 1e+01 1e+00 1e-01 1e-02 1e-03 1e-04 1e-05 1e-06 1e-07 1e-08 1e-09
Radio flux density (mJy)
10^5 10^4 10^3 10^2 10^1 10^0 10^{-1} 10^{-2}
Optical flux density (mJy)
10^{-5} 10^{-3} 10^{-1} 10^1 10^3 10^5 10^7

Source 715880 RA: 88.854 DEC: 7.023








Source 713705 RA: 89.674 DEC: 7.128
Before PB correction
After PB correction
Integrated Flux (Jy)
0.00035
0.00030
0.00025
0.00020
0.00015
0.00010
0.00005
59200
59400
59600
59800
MJD
Integrated Flux (Jy)
10^{-4}
10^0
10^1
10^2
10^3
days post-trigger
Flux (Jy)
10^{-1}
10^{-2}
10^{-3}
10^{10}
10^{12}
10^{14}
Frequency (Hz)

Summary of Simulations

- Accounts for real world conditions
    - Overlapping pointings
    - Variety of observation sensitivity
    - Multiple light curves
- Fairly easy to adapt and extend to other uses
- Now publicly available: https://github.com/dentalfloss1/transients-simulations

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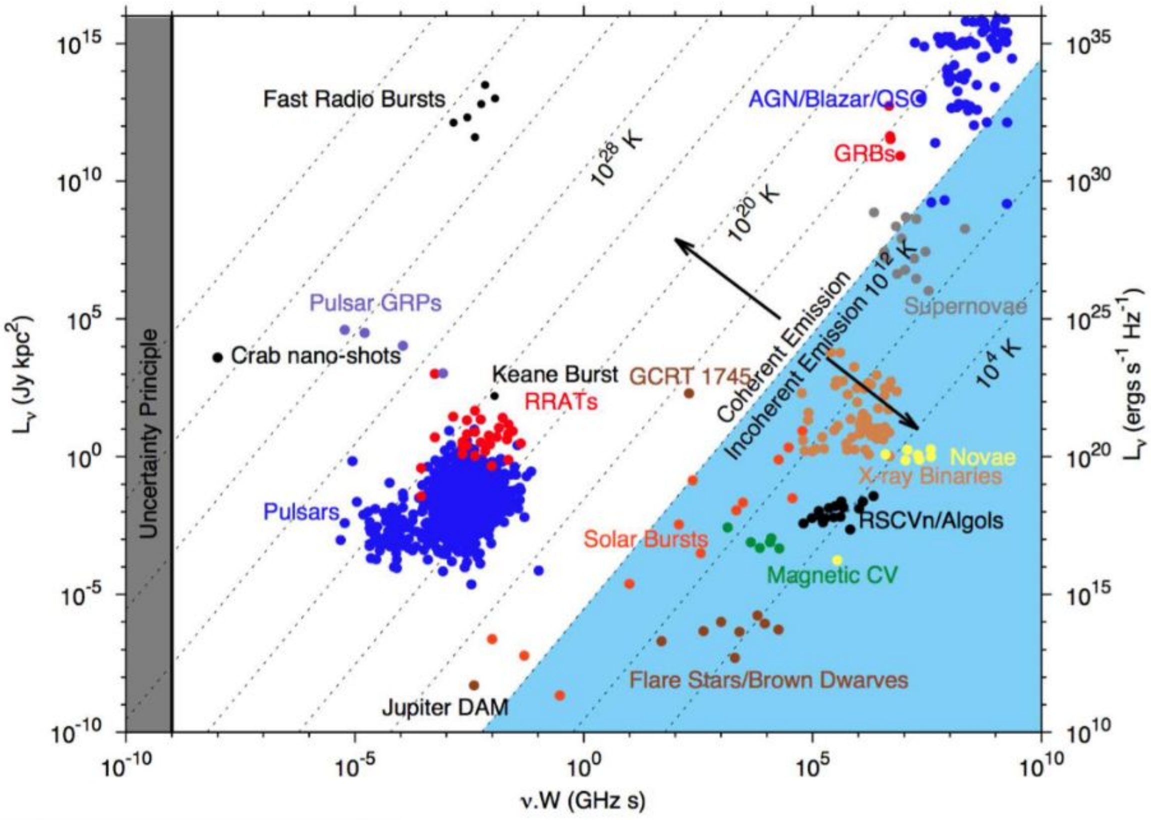
A Review of Radio Transients

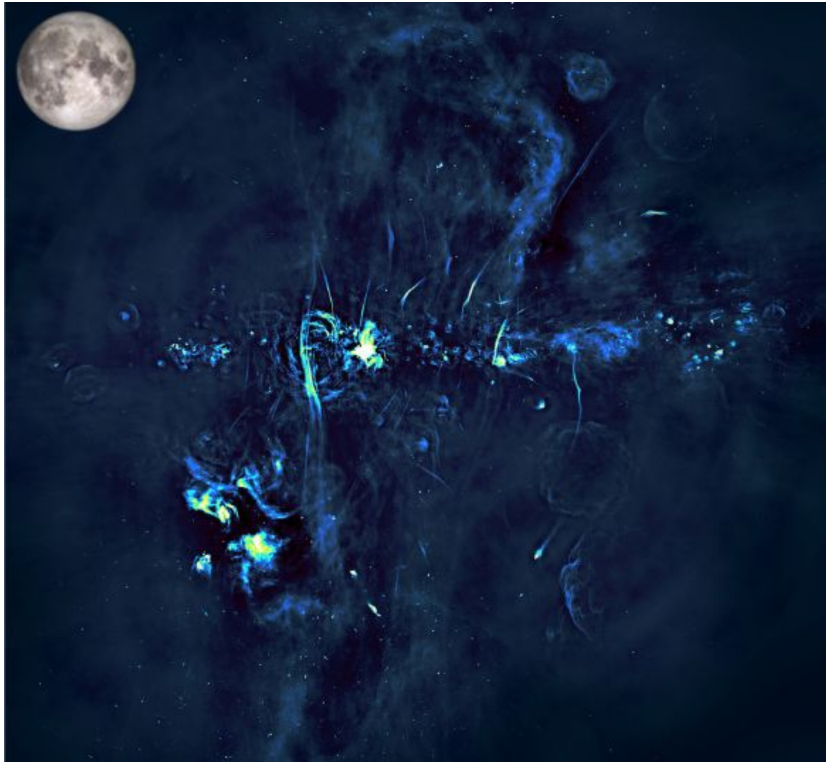
- Zoo of Transients
- Wide span of brightness and timescales
- How often?



M. Pietka, R. P. Fender, and E. F. Keane. “The variability time-scales and brightness temperatures of radio flares from stars to supermassive black holes”. MNRAS 446.4 (Feb. 2015), pp. 3687–3696

MeerKAT

- Started operations in summer 2018
- Better sensitivity than VLA between 1 and 2 GHz
- FOV > 1 sq. deg.
- Excellent for transient searches

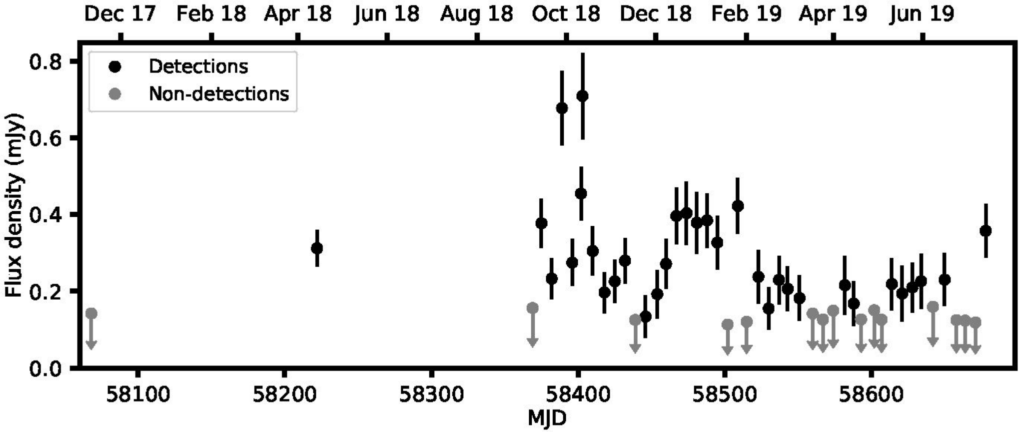


Made from 4 MeerKAT images, angular resolution of VLA is at most 0.5 deg

I. Heywood, F. Camilo, W.D. Cotton, et al. “Inflation of 430-parsec bipolar radio bubbles in the Galactic Centre by anenergetic event”.Nature573 (Sept. 2019), pp. 235–237 with Moon overlaid

Why Simulate Transients?

- Already found multiple transients in MeerKAT data
  - GX-339 field
  - MAXI J1820 field [2]
- Abundance of Data

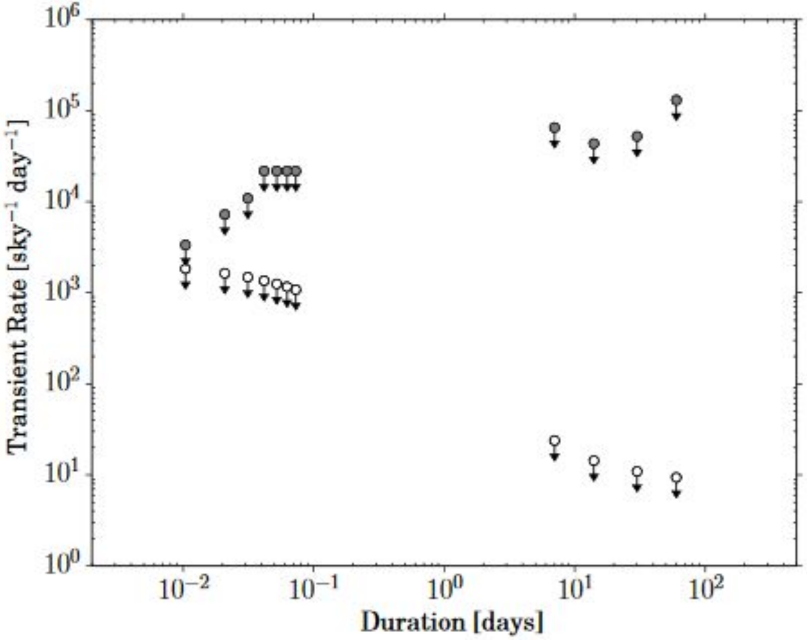


MKT J170456.2-482100 found in the GX-339 field by L. Driessen [1]

[1] Driessen, L. N.; McDonald, I.; Buckley, D. A. H.; Caleb, M. et al. “MKT J170456.2–482100: the first transient discovered by MeerKAT“. MNRAS, Volume 491, Issue 1, p.560-575 (2020)
[2] Rowlinson, A.; Meijn J.; van der Horst, A. J.; Chastain, S.; et al. "Search and identification of transient and variable radio sources using MeerKAT observations: a case study on the MAXI J1820+070 field"

Why Simulate Transients?

- Need to accurately determine transient rates [1]
  - Traditional methods do not account for multiple timescales or gaps in observations
  - Limited by the worst observation sensitivity
- Monte-Carlo Simulations allow for making these corrections [2]



Filled circles are without applying correction for gaps, open are with

[1] Carbone, D., et al. "New Methods to Constrain the Radio Transient Rate: Results from a Survey of Four Fields with LOFAR". MNRAS, 459, 3161-3174 (2016)
[2] Carbone, D., van der Horst, A. J., Wijers, R. A. M. J., and Rowlinson, A. "Calculating Transient Rates from Surveys". MNRAS, 465, 4106-4117 (2017)

Inputs

- Observing times
- Observation duration
- Image sensitivity
- Pointings on the sky
- Radius of the field of view
- Gaps in observations

In addition, this information can be generated using a provided script and extracted from the metadata

```
2020-02-27T17:50:08.822598+00:00,8,0.000324903462958634 2,342.6375833333333,-59.1199444444445,False,1.5
2020-02-27T17:50:16.819214+00:00,8,0.00036999755874516445,342.6375833333333,-59.1199444444445,False,1.5
2020-02-27T17:50:24.815832+00:00,8,0.0003751831812065452,342.6375833333333,-59.1199444444445,False,1.5
2020-02-27T17:50:32.812449+00:00,8,0.0003754194640878536,342.6375833333333,-59.1199444444445,False,1.5
2020-02-27T17:50:40.809067+00:00,8,0.0003727546266772708,342.6375833333333,-59.1199444444445,False,1.5
2020-02-27T17:50:48.805683+00:00,8,0.0003931288435233283,342.6375833333333,-59.1199444444445,False,1.5
2020-02-27T17:50:56.802301+00:00,8,0.0003832641595985016,342.6375833333333,-59.1199444444445,False,1.5
2020-02-27T17:51:04.798918+00:00,8,0.00037349760564495767,342.6375833333333,-59.1199444444445,False,1.5
2020-02-27T17:51:12.795536+00:00,8,0.00044303651649668587,342.6375833333333,-59.1199444444445,False,1.5
2020-02-27T17:51:16.793844+00:00,8,0.0004257181610628061,342.6375833333333,-59.1199444444445,False,1.5
```

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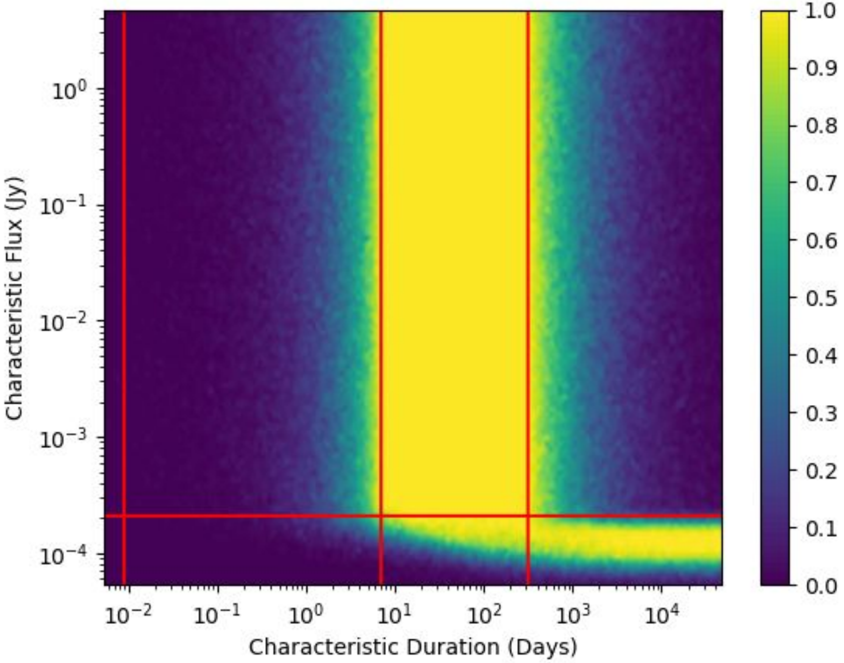
How Transients are Simulated

1. Config and observation files are read in
2. Source info generated via numpy random number generator (log10)
3. Iterate over observations, testing integrated flux for detection
4. Aggregate number of detections / simulations, generate probabilities

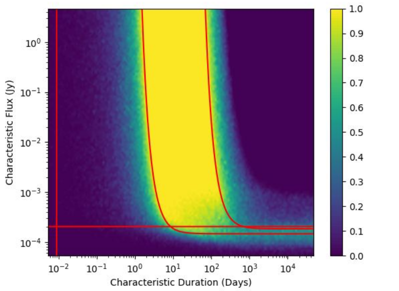
Chastain, S. I.; van der Horst, A. J.; Carbone, D. "Transient Simulations for Radio Surveys." Astronomy and Computing. vol. 40, July 2022

Output: Probability Contours

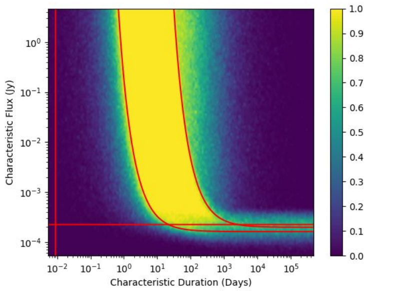


Tophat

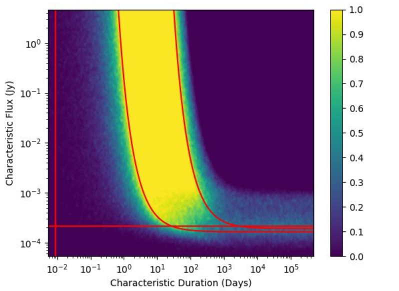
- Shows probability of detection
- Variety of light curves included
- Easily extendable to new light curves



Gaussian



Fast Rise Exponential Decay



Exponential Rise Exponential Decay

From Probabilities to Realistic Transient Rates

$$P(k, N_{det}) = \frac{N_{det}^k}{k!} e^{-N_{det}}$$

Model transients with a Poisson distribution

$$\rho_{all}(F,T) = \frac{\rho_{det}}{Prob(F,T)}$$

$$\rho_{sim}(F,T) = \frac{N_{sim}(F,T)}{(T_{surv}+T)\Omega}$$

We simulated this rate

$$\rho_{all}(F,T) = \frac{N_{det}}{Prob(F,T) \times (T_{surv}+T) \times \Omega}$$

$$\frac{N_{sim,det}(F,T)}{N_{sim}(F,T)} = \frac{N_{det}(F,T)}{N_{all}(F,T)}$$

$$\rho_{all}(F,T) = \frac{-\ln(1-\alpha)}{Prob(F,T) \times (T_{surv}+T) \times \Omega}$$

Assume the simulations are realistic, left side are probabilities

When k=0, Poisson distribution is easy to solve

$$\frac{\rho_{sim,det}(F,T)}{\rho_{sim}(F,T)} = \frac{\rho_{det}}{\rho_{all}(F,T)}$$

Johnson, Norman L.; Kemp, Adrienne W.; Kotz, Samuel , "Poisson Distribution", Univariate Discrete Distributions (3rd ed.), New York, NY, USA: John Wiley & Sons, Inc., pp. 156–207, (2005)

Carbone, D., van der Horst, A. J., Wijers, R. A. M. J., and Rowlinson, A. "Calculating Transient Rates from Surveys". MNRAS, 465, 4106-4117 (2017)

From Probabilities to Realistic Transient Rates

$$P(k, N_{det}) = \frac{N_{det}^k}{k!} e^{-N_{det}}$$

Model transients with a Poisson distribution

$$F^{-1}(\alpha/2; k, 1) \leq \mu \leq F^{-1}(1 - \alpha/2; k+1, 1)$$

But μ=λ and $\lambda = N_{det}$

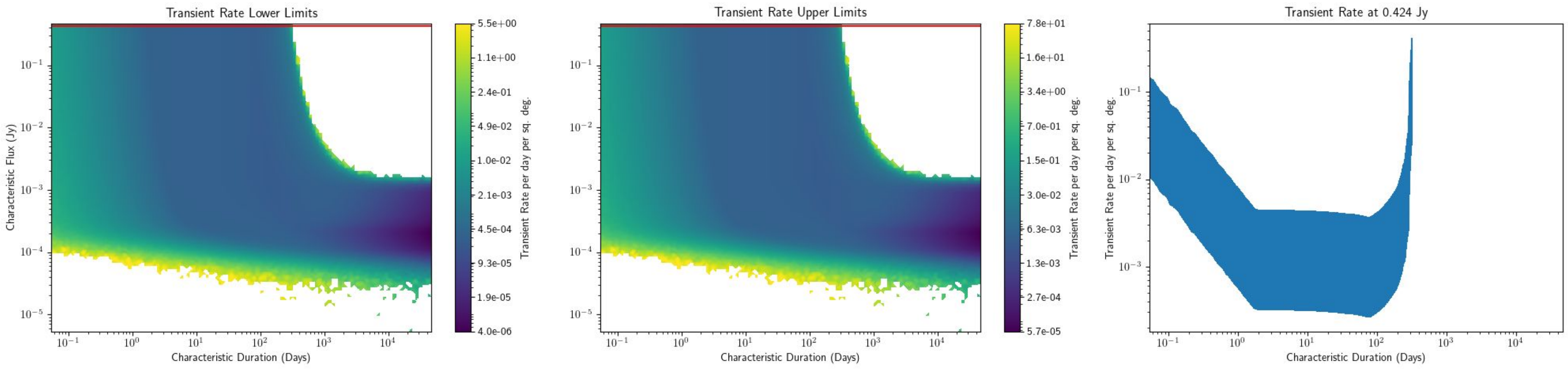
$$F^{-1}(\alpha/2; k, 1) \leq N_{det} \leq F^{-1}(1 - \alpha/2; k+1, 1)$$

$$\rho_{all}(F, T) = \frac{N_{det}}{Prob(F, T) \times (T_{surv} + T) \times \Omega}$$

Sub for N_{det}

[1] Johnson, Norman L.; Kemp, Adrienne W.; Kotz, Samuel , "Poisson Distribution", Univariate Discrete Distributions (3rd ed.), New York, NY, USA: John Wiley & Sons, Inc., pp. 156–207, (2005)

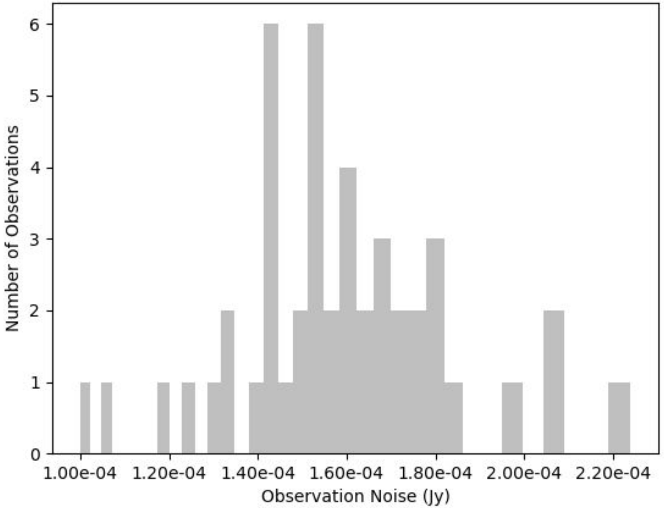
Outputs: Transient Rate Contour Plot

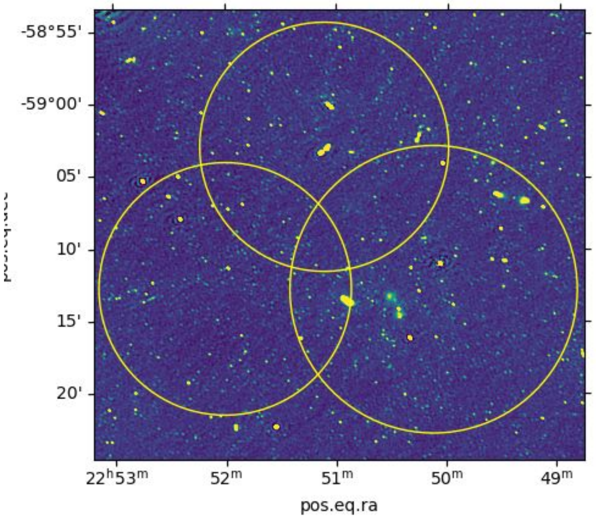


Another, more detailed example. This time with a Gaussian light curve

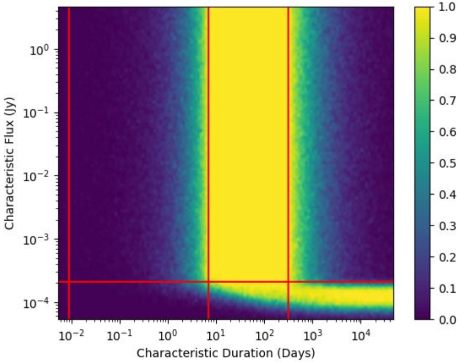
Accounting for Realistic Scenarios

- Varying observation sensitivity
- Variety of light curves
- Multiple overlapping pointings

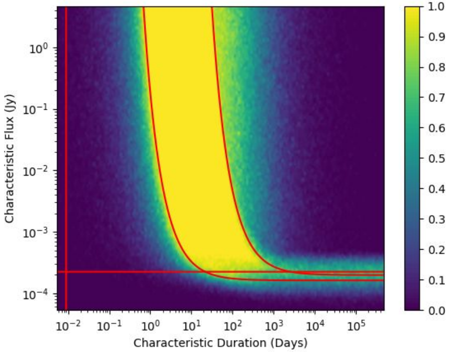




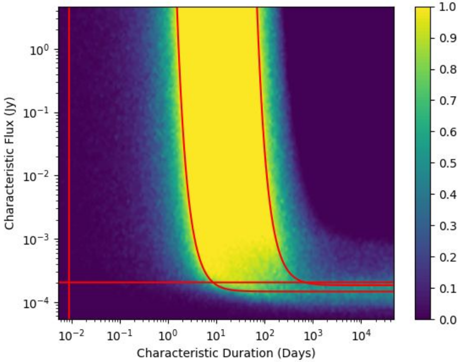
Tophat



FRED

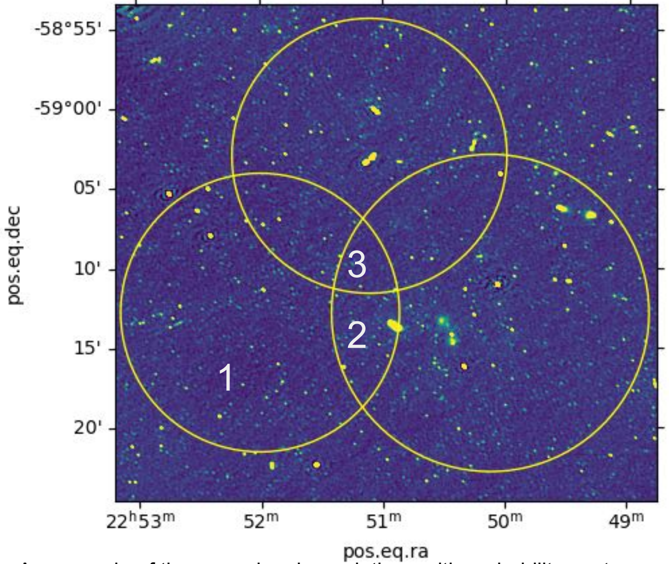


Gaussian



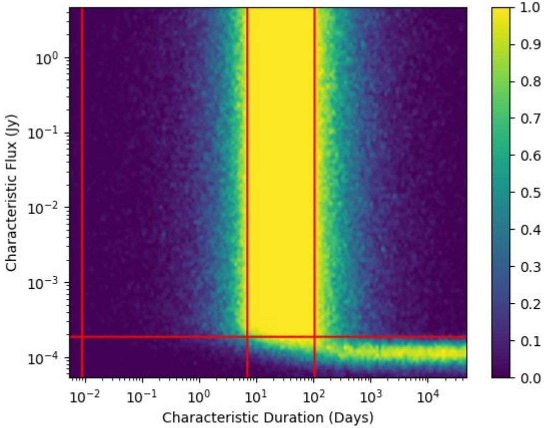
Overlapping Pointings

- Calculates double and triple overlapping regions
- Fully accurate area calculations accounting for spherical geometry

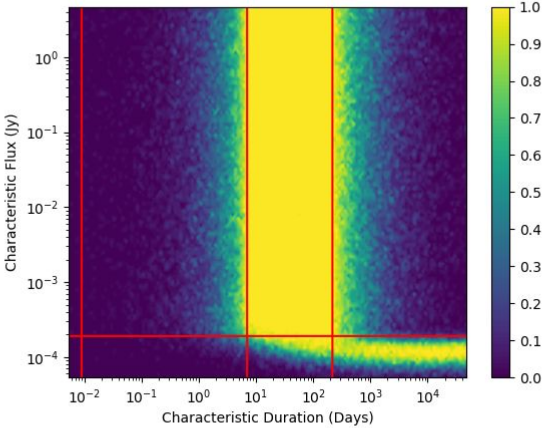


An example of three overlapping pointings with probability contours

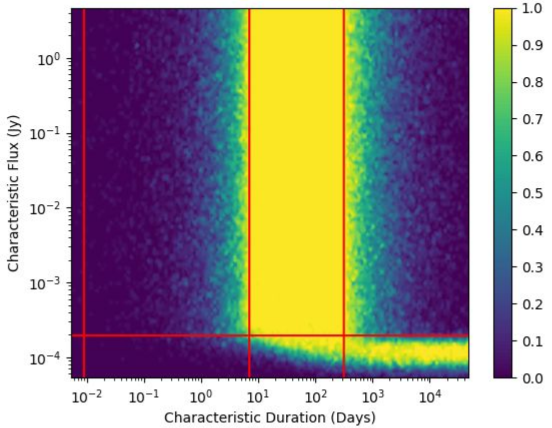
1



2

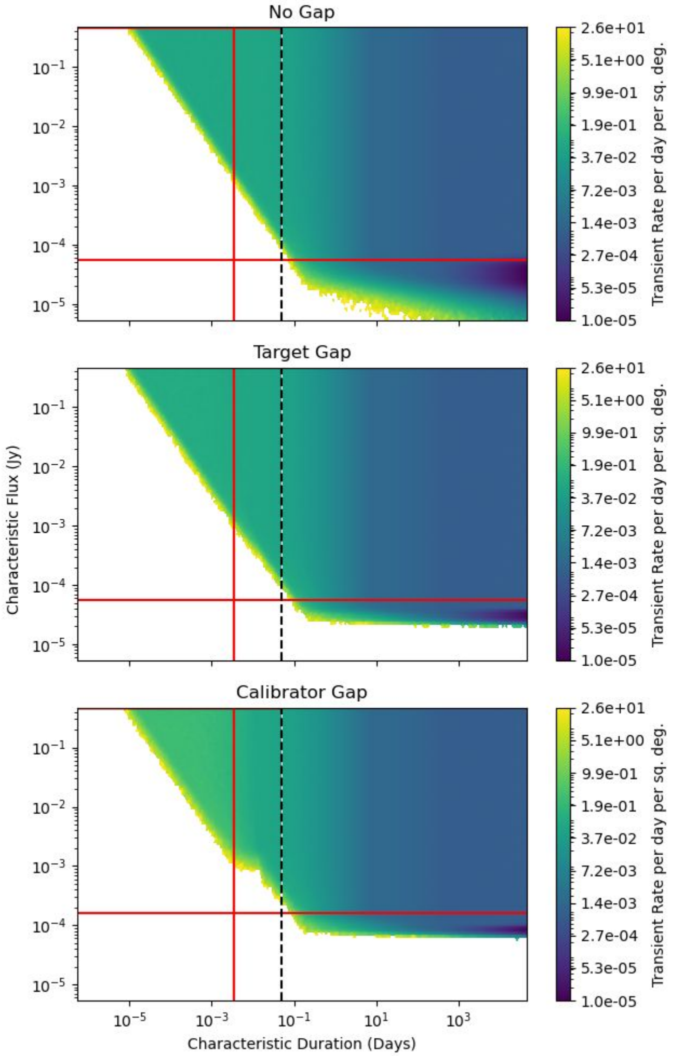


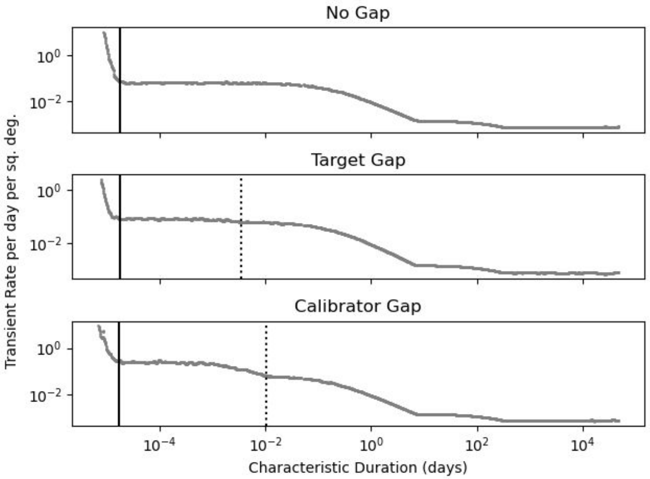
3

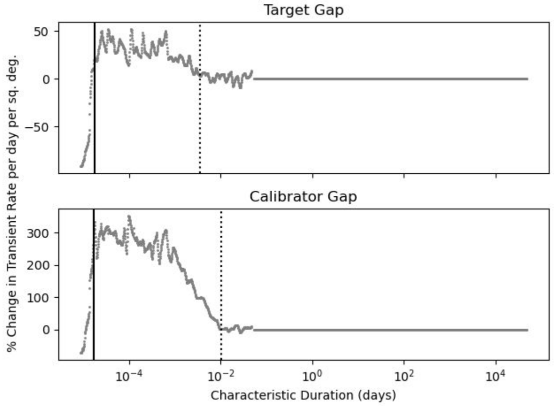


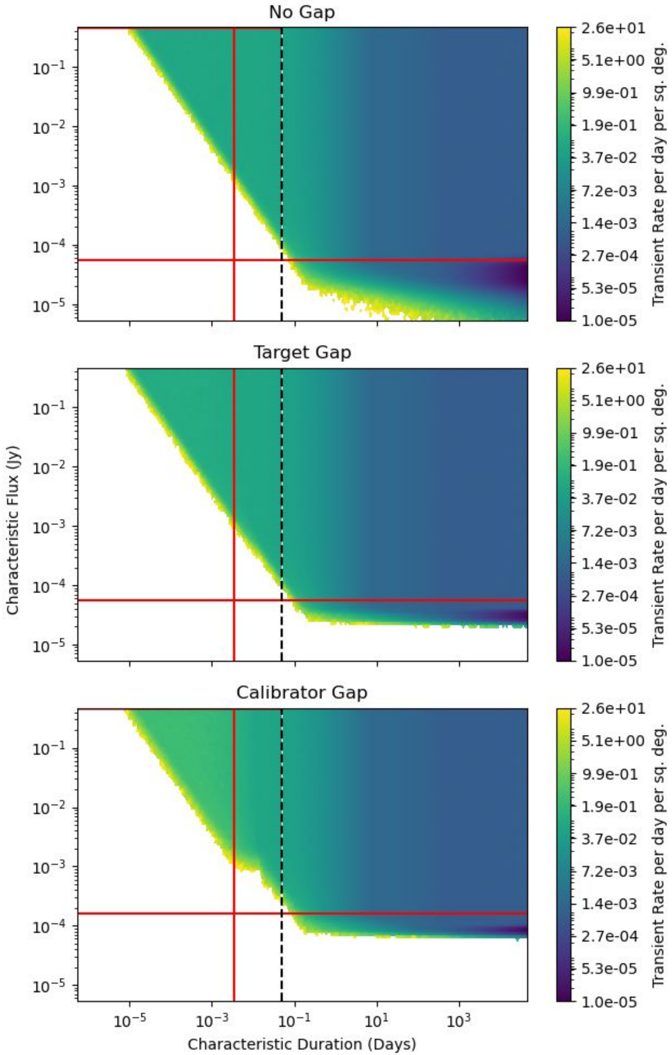
Gaps in Observations

- Real radio observations contain gaps
- Results in different transient rates
- This example simulates a target-gain calibration loop of 5 minutes on calibrator and 15 minutes on target









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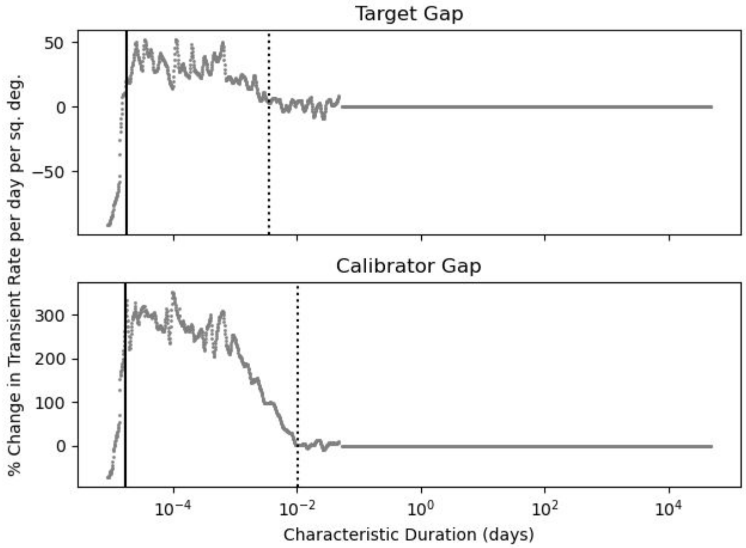
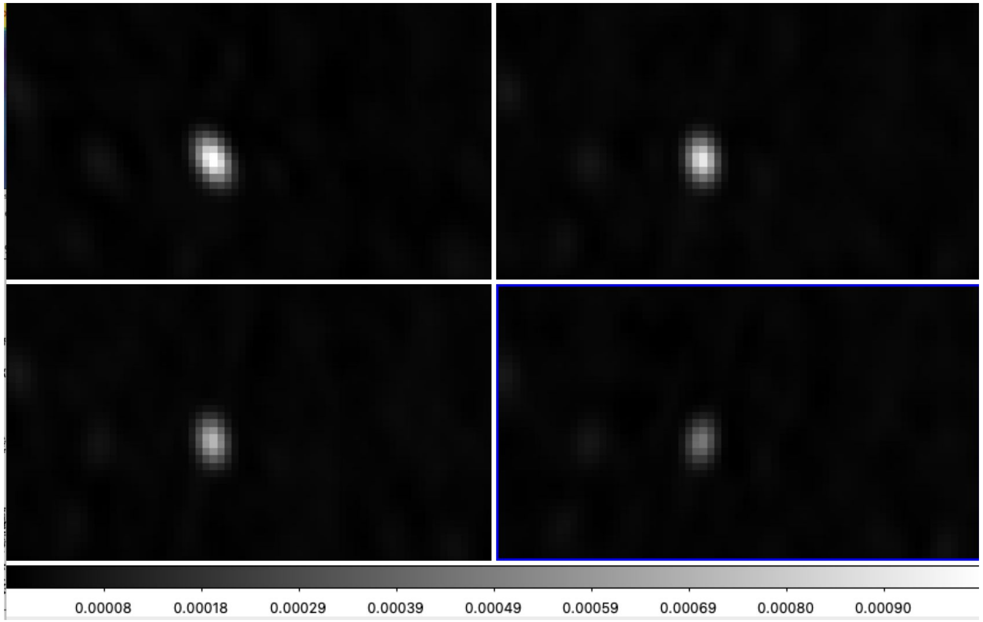
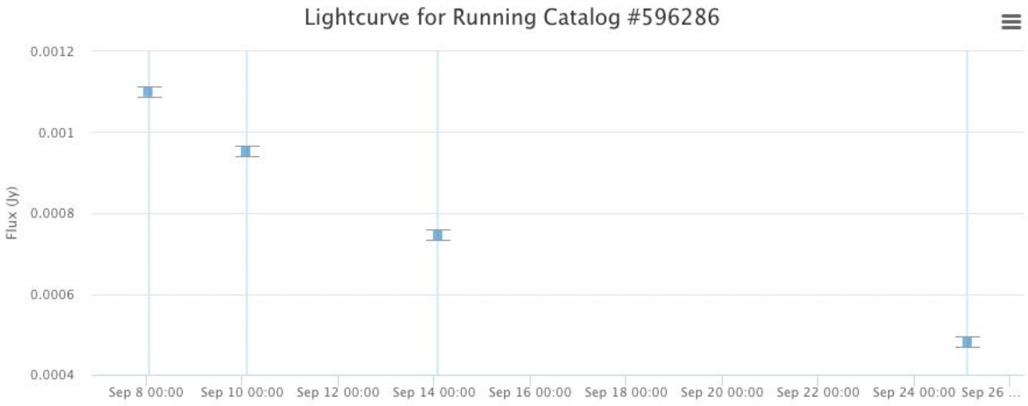


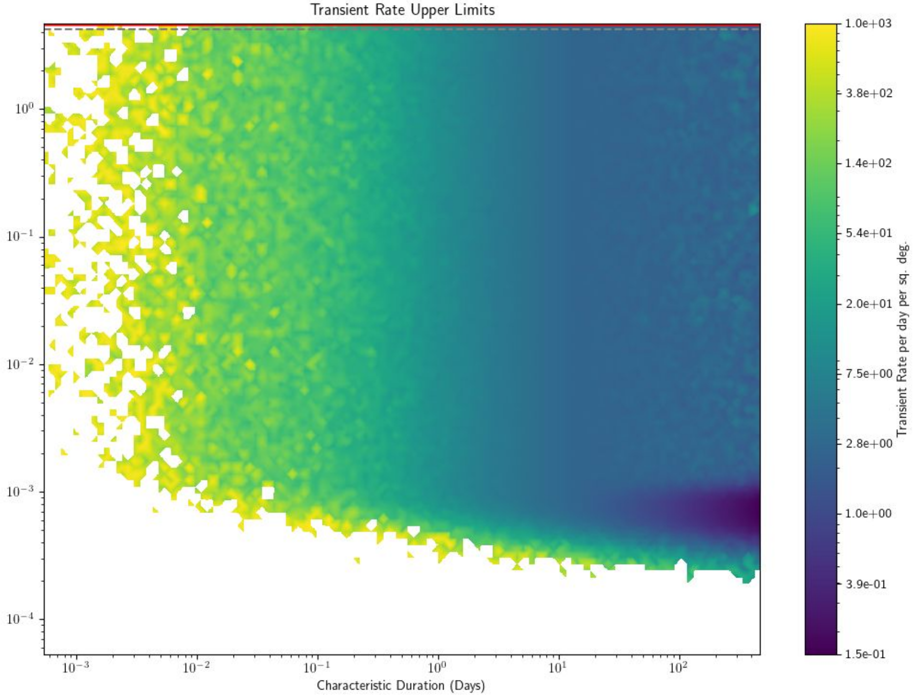
Commensal Searches in MeerKAT

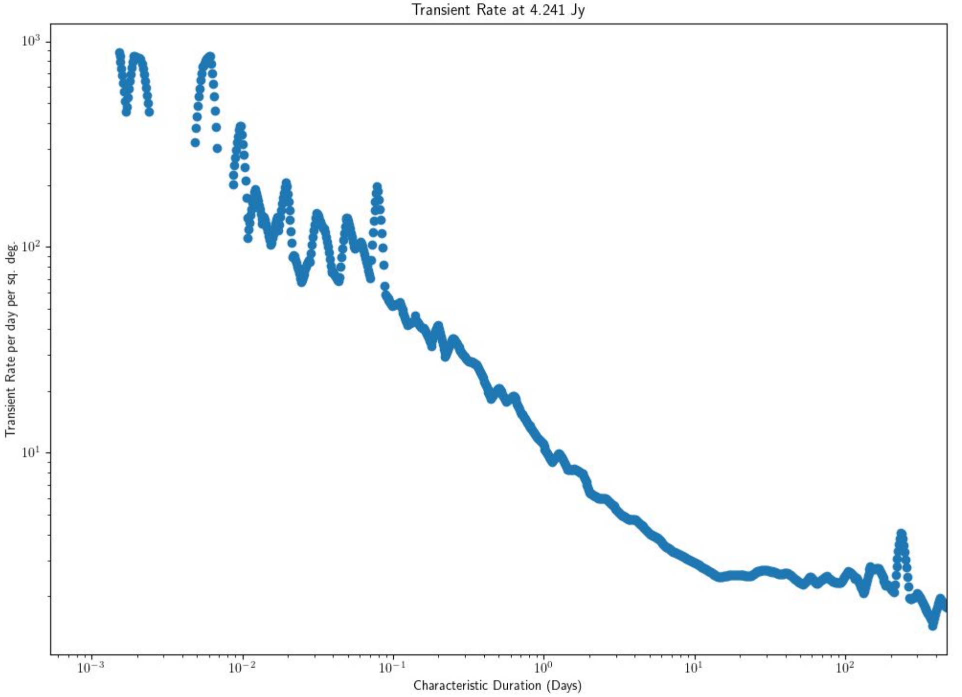
- Short GRB fields
- Some overlap with VLASS
- Also multiple timescales
    - 4 hour images
    - 15 minute images
    - 8 second images
- Interesting variables on long timescales
- One of many commensal search efforts





Application to VLASS: Calibrator Field Transients

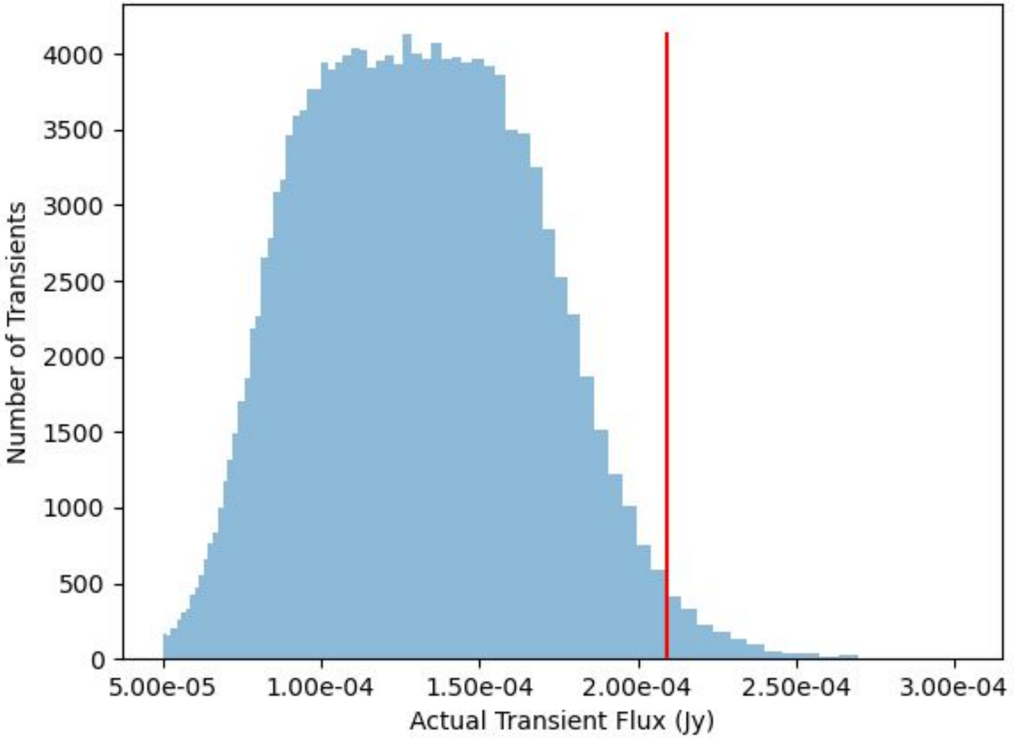


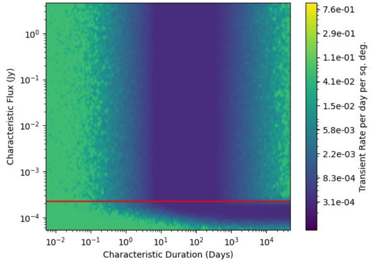


2018-02-03T22:05:05.100000+00:00,2018-02-03T22:06:28.400000+00:00,0.00018984238468117343,15.468287916666664,-28.522346108333334,False,0.11666666666666667
2018-02-16T20:52:56.100000+00:00,2018-02-16T20:54:18.900000+00:00,0.00010097123663625877,15.468287916666664,-28.522346108333334,False,0.11666666666666667
2018-02-16T21:12:40.100000+00:00,2018-02-16T21:13:41.700000+00:00,0.00026700172571445934,15.468287916666664,-28.522346108333334,False,0.11666666666666667
2018-02-16T21:32:10.500000+00:00,2018-02-16T21:33:15.800000+00:00,0.00021652559487489846,15.468287916666664,-28.522346108333334,False,0.11666666666666667
2018-02-16T21:51:53.100000+00:00,2018-02-16T21:53:01.500000+00:00,0.00014155826103482463,15.468287916666664,-28.522346108333334,False,0.11666666666666667
2018-02-16T22:08:43.800000+00:00,2018-02-16T22:09:56.300000+00:00,0.00017080008094357075,15.468287916666664,-28.522346108333334,False,0.11666666666666667
2018-02-16T22:25:44.900000+00:00,2018-02-16T22:26:57.800000+00:00,0.0001921937217774543,15.468287916666664,-28.522346108333334,False,0.11666666666666667

Outputs: False Detections Plot

- False detections show up as a tail in surface plots
- Occur due to simulated measurement error
- Mitigating with an analytic solution is impractical
- False detections depend on a large number of variables, not a simple distribution
- Solution is to simulate constant sources and set a limit in peak flux below which transients cannot be reliably detected



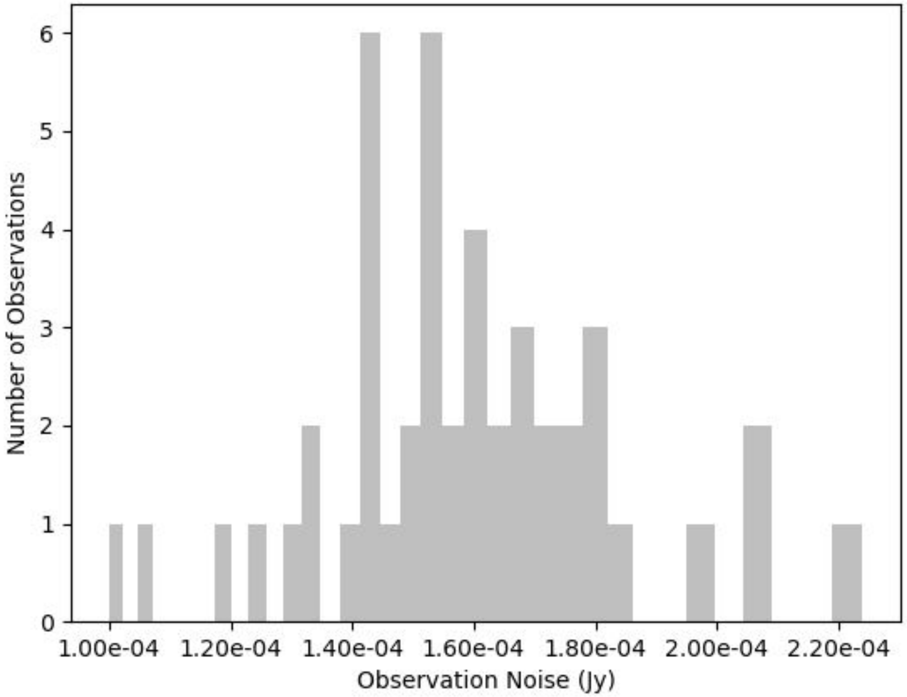


Other Outputs

- Observations histogram
- Numpy arrays for investigation

Design Notes

- Written in python3
- Runs on a laptop
- Easy to add new light curves
- Will be made public



Overview

- Several transient detections
- Accounts for real world conditions
  - Overlapping pointings
  - Variety of observation sensitivity
  - Multiple light curves
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Overview

- Several transient detections
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    - Overlapping pointings
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    - Multiple light curves
- Fairly easy to adapt and extend to other uses
- Will be publicly available
- Happy to collaborate, feel free to contact schastain@gwu.edu