BatAnalysis: A Comprehensive Python Pipeline for Swift BAT Data Analysis

Tyler Parsotan & BAT Team

Outline

- Introduction to Swift and BAT
- BAT Survey Data
  - Overview of the data
  - Past Analyses
  - Usefulness
- The BatAnalysis Python Package
  - How to analyze BAT survey data
  - Verifying with the Crab Nebula Pulsar
- Example Analyses of:
  - NGC 2992
  - MAXI J0637-430
  - GRB 221009A

The Neil Gehrels Swift Observatory

- Launched in 2004
- Overview of operations:

    1. BAT detects a Gamma Ray Burst (GRB)
    2. Autonomous slewing to the GRB
    3. XRT and UVOT observe the field to detect afterglow counterparts

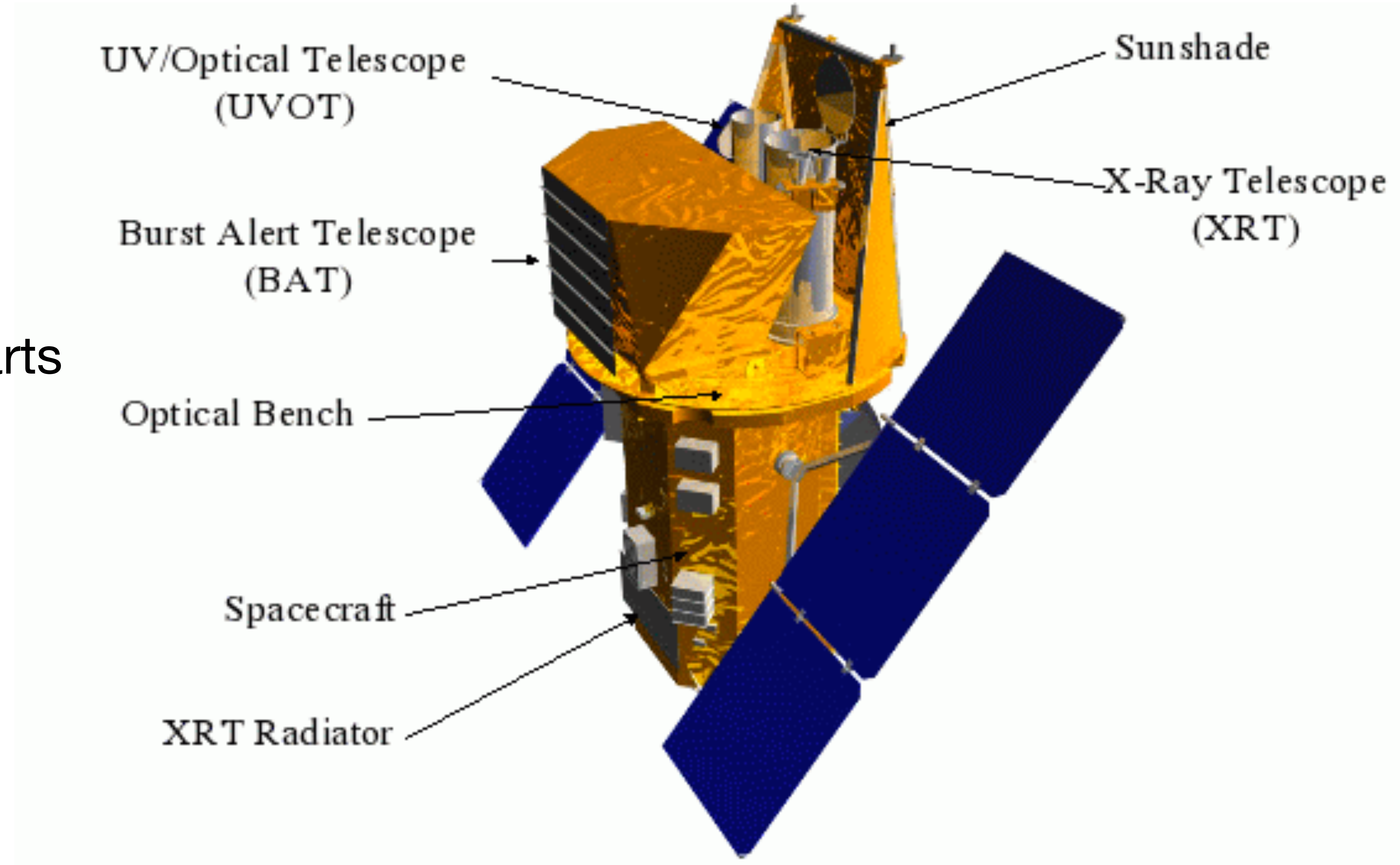
OR

    1. There is a ToO/many point plan for XRT/UVOT to observe a source
    2. BAT is pointed towards that source too collecting survey data

OR

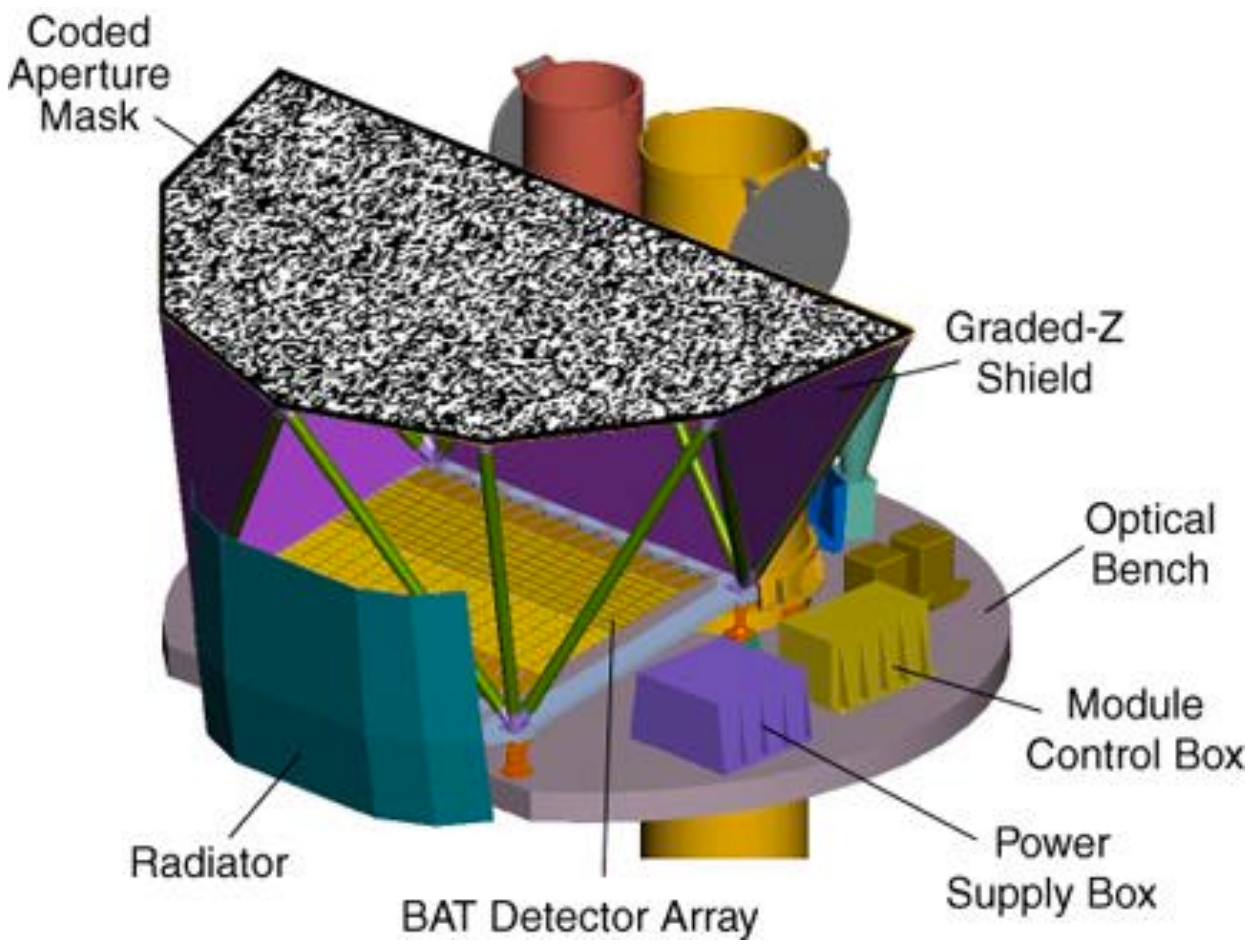
    1. BAT is surveying the sky normally, collecting survey data in between slews

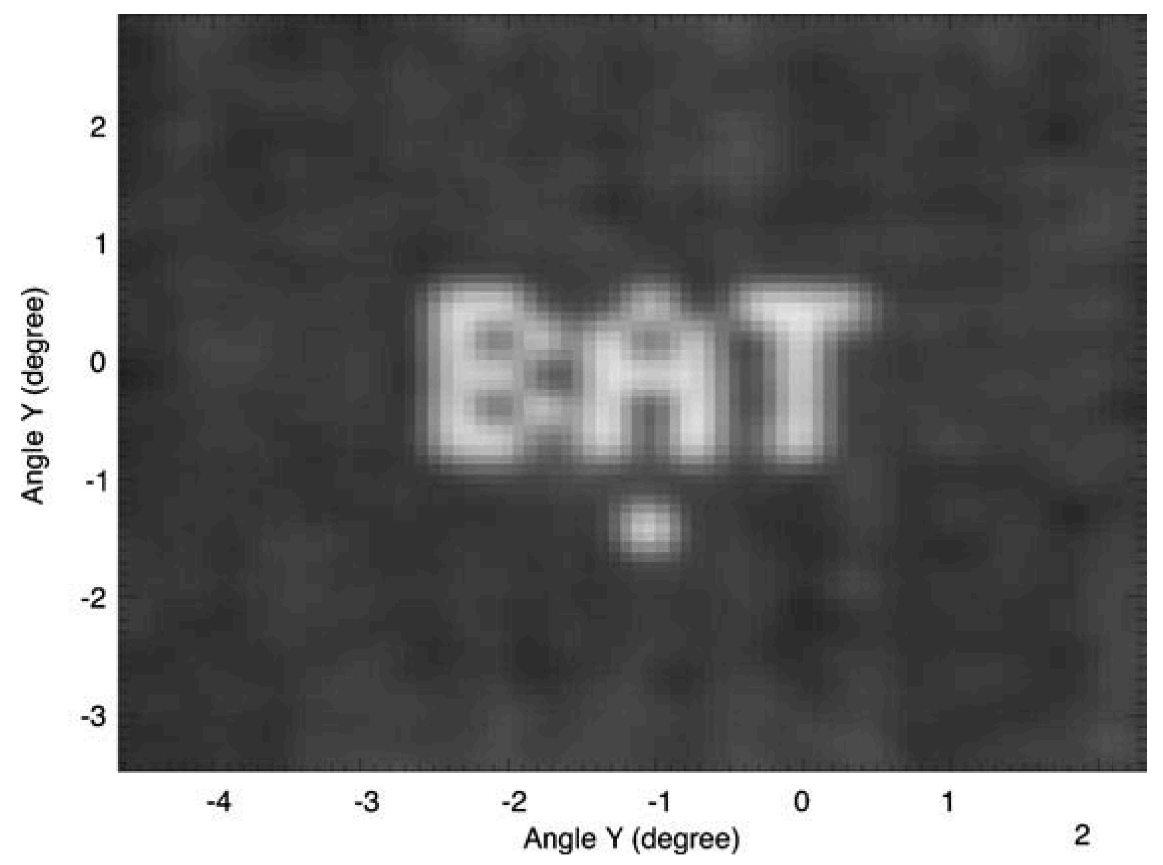
- Over 1500 GRBs have been detected



The BAT

- Uses coded mask techniques to maximize:
    - FOV (~60x120^{o})
    - Localization Capabilities of GRBs (~3 arcmin)
- GRBs → time tagged event (TTE) data
    - The highest quality data of each photon's direction and energy
    - Intensive to store and transfer to the ground
- Event data can be used to localize transients even if they do not trigger BAT or are located outside of the BAT FOV





Barthelmy+ 2005

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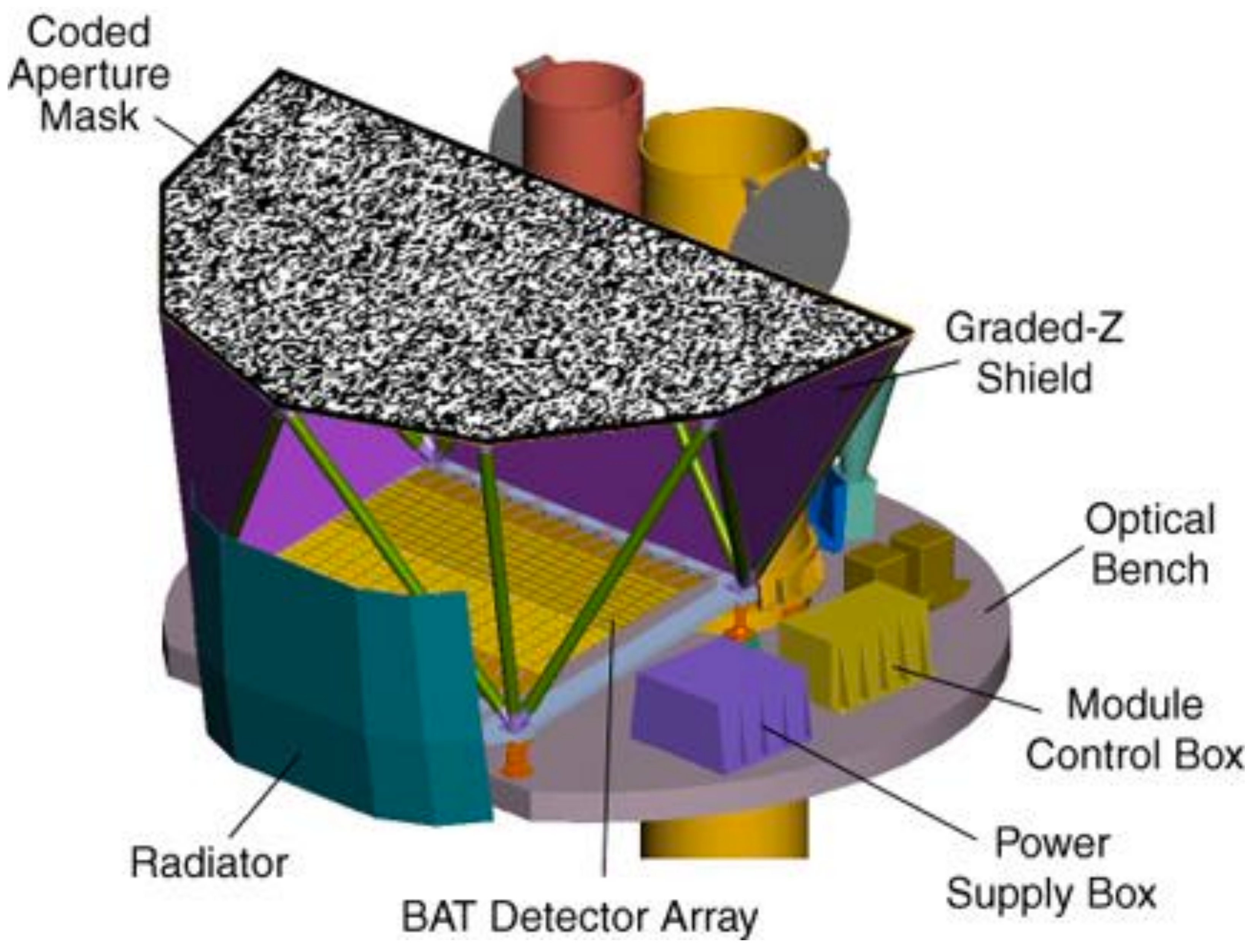
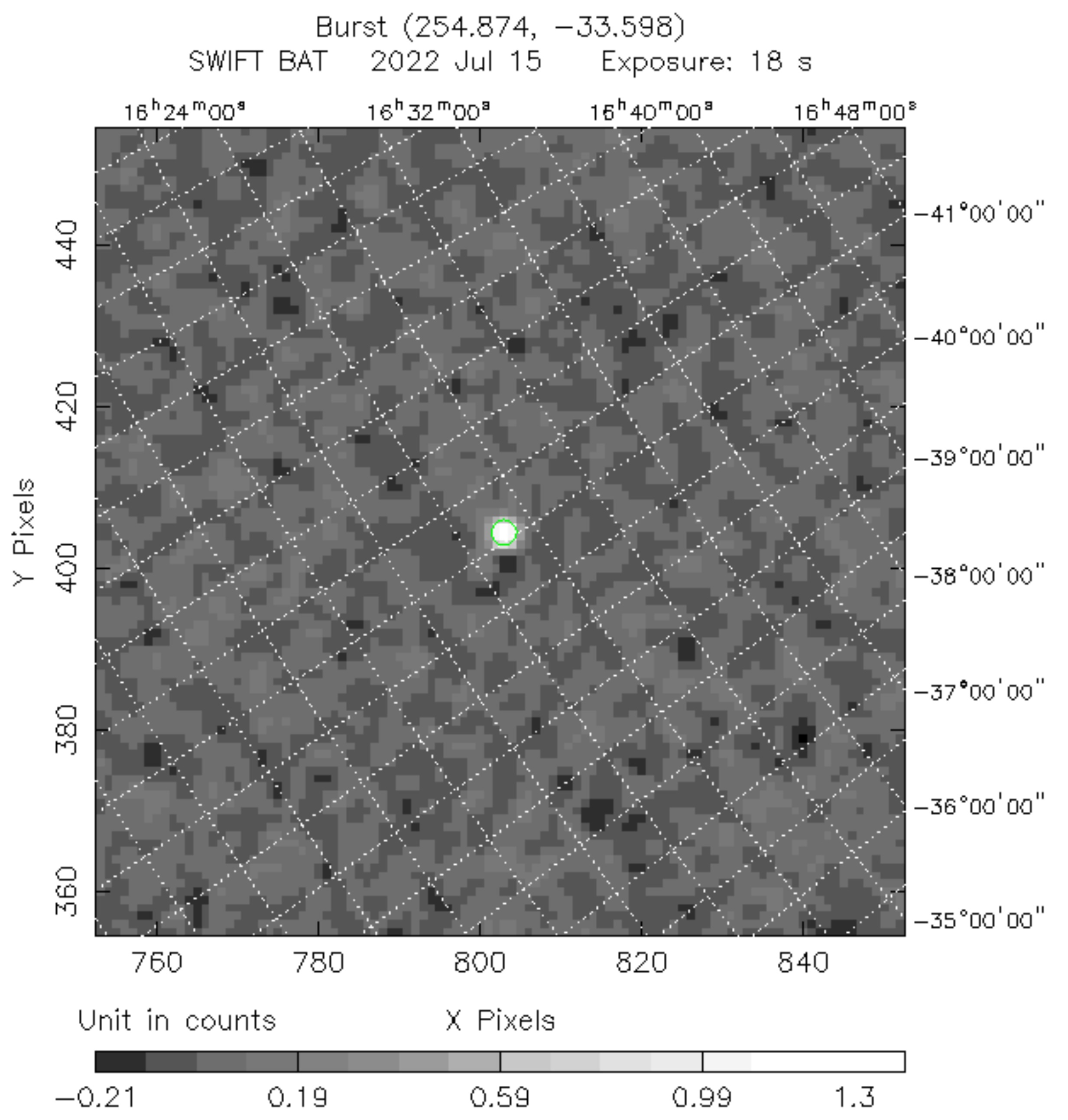
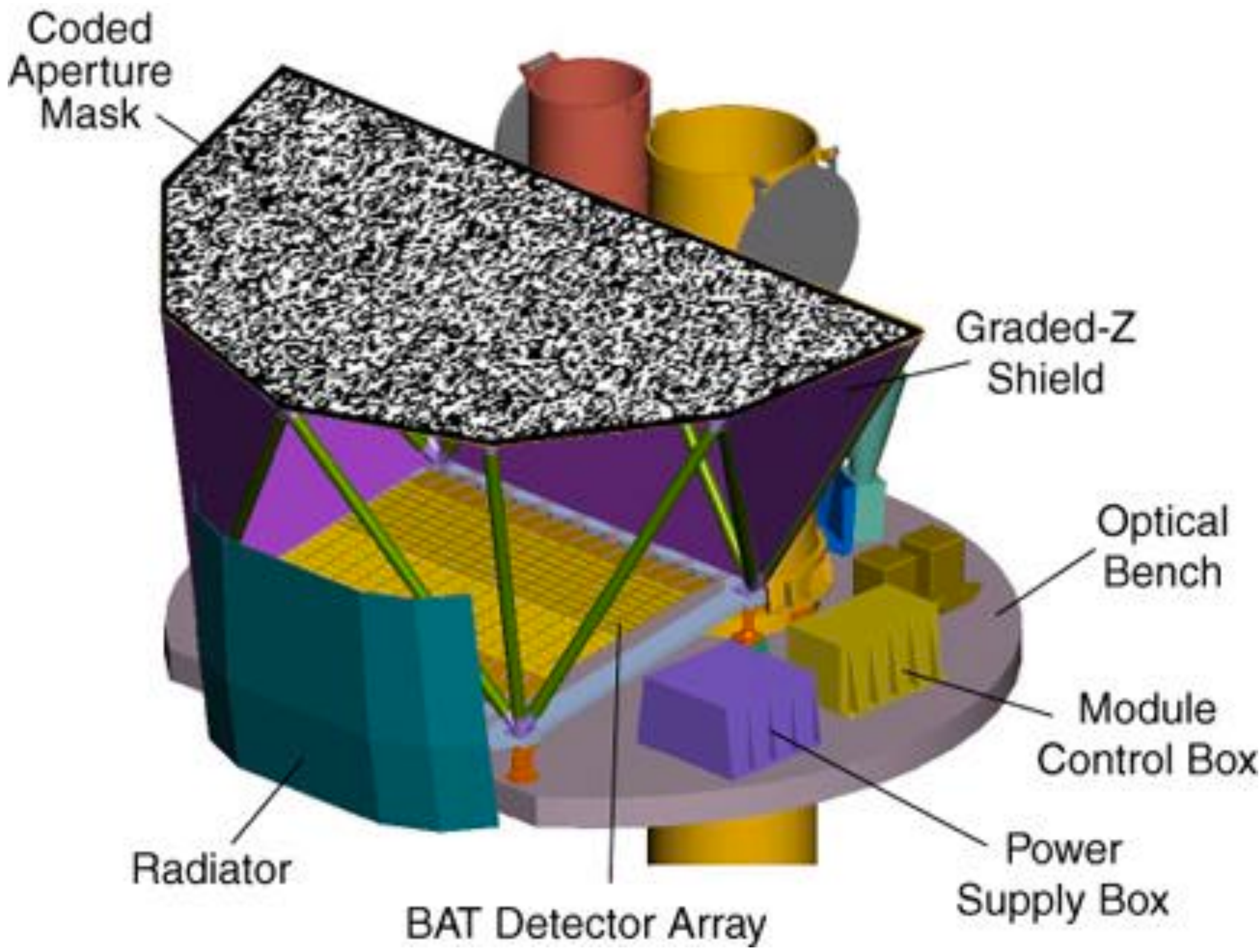




Barthelmy+ 2005

The BAT

- When its not triggering on GRBs BAT is surveying the sky in the 14-195 keV energy range
- Cannot store all the event data, therefore we compress it
- Create Detector Plane Histograms (DPHs)
  - 80 channel histograms of photon counts
- Accumulates DPHs in time intervals of ~300 seconds



Barthelmy+ 2005

BAT survey data is >90% of all the data produced by BAT, by volume.

It is the least used and has tons of possibilities

BAT TTE data is collected when:

1) BAT triggers

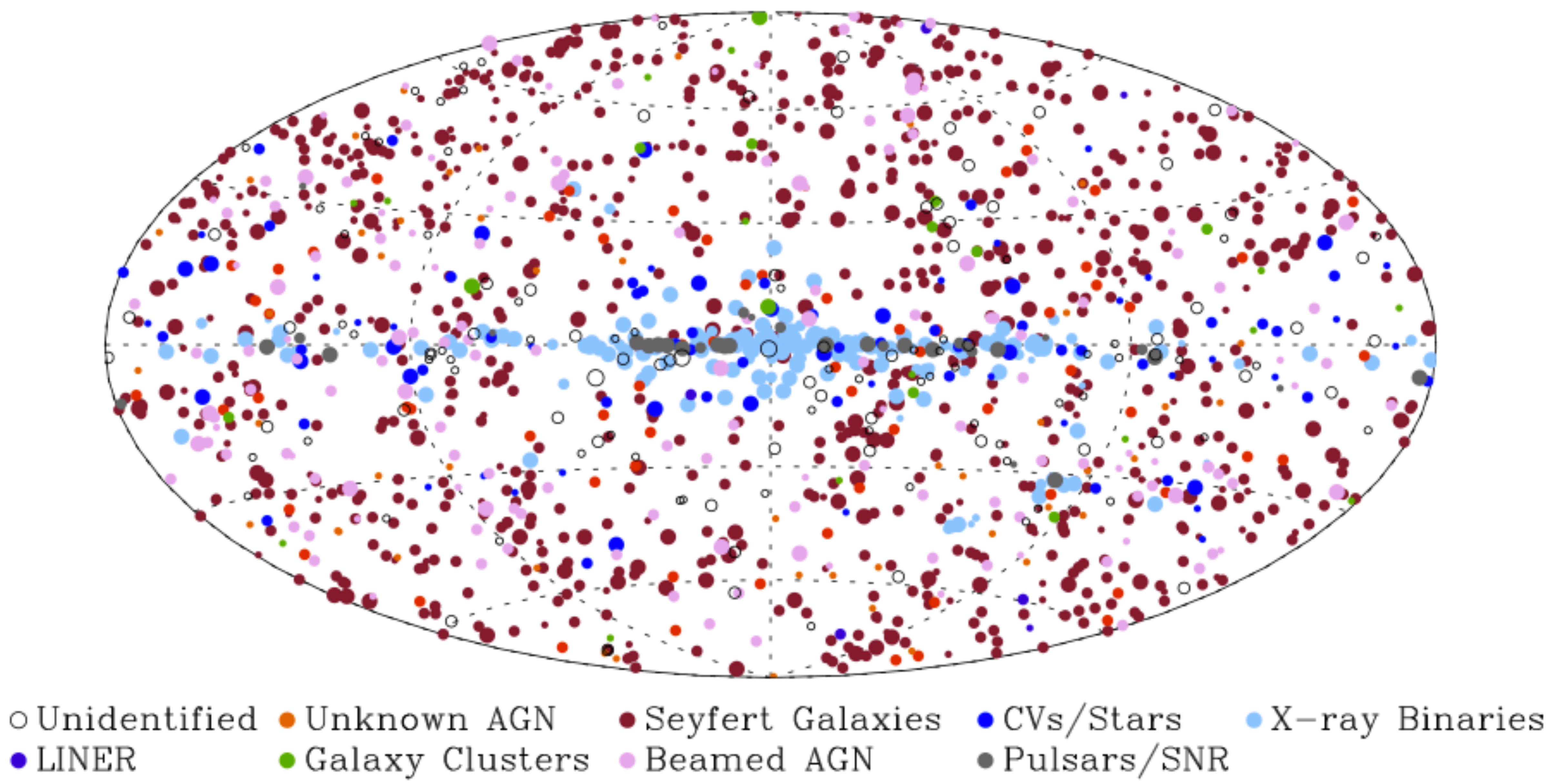
OR

2) when there is an external trigger and we can tell BAT to save the data around that time period

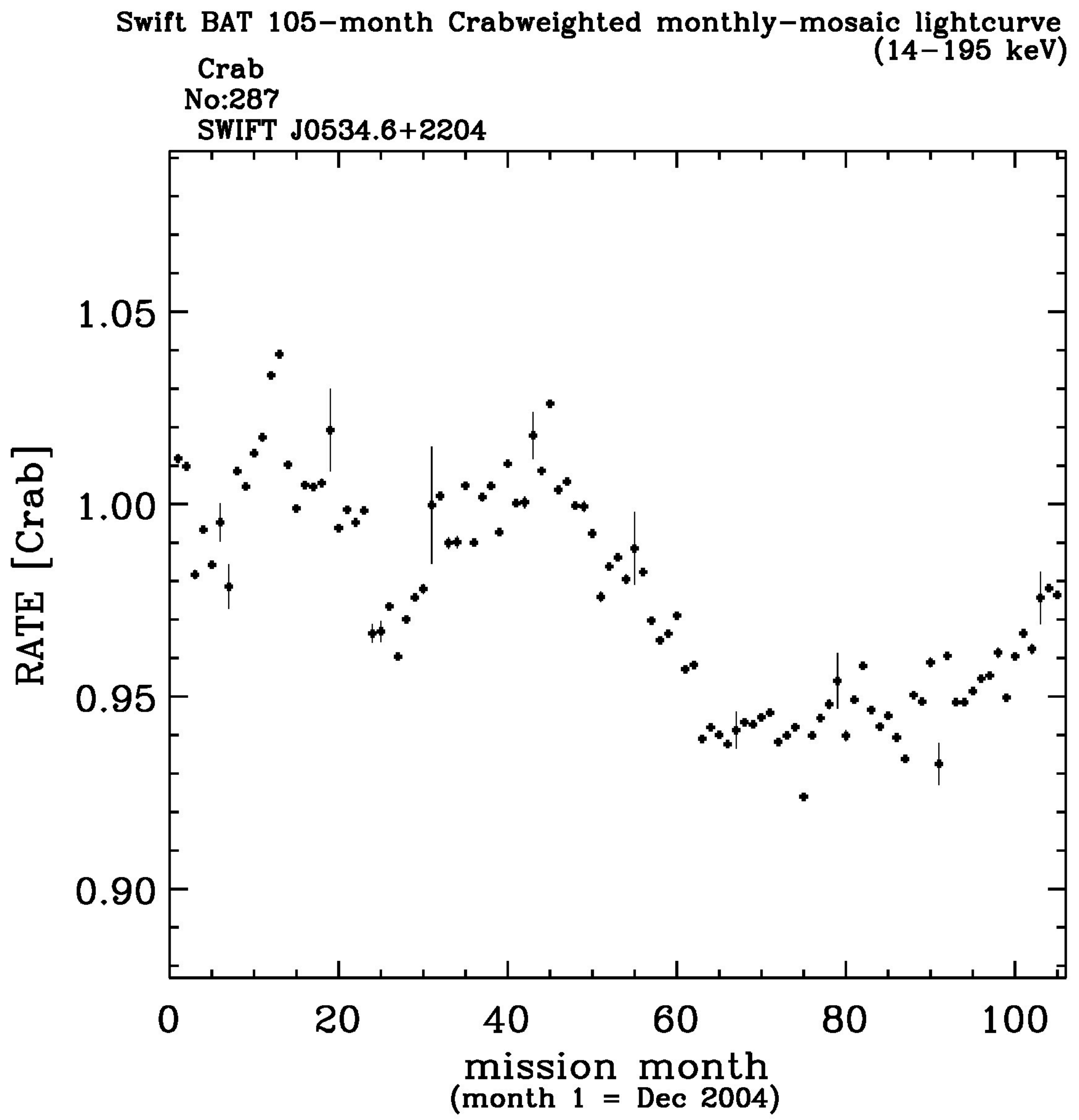
N-Month Survey Catalog
where N={22, 70, 105, 157}

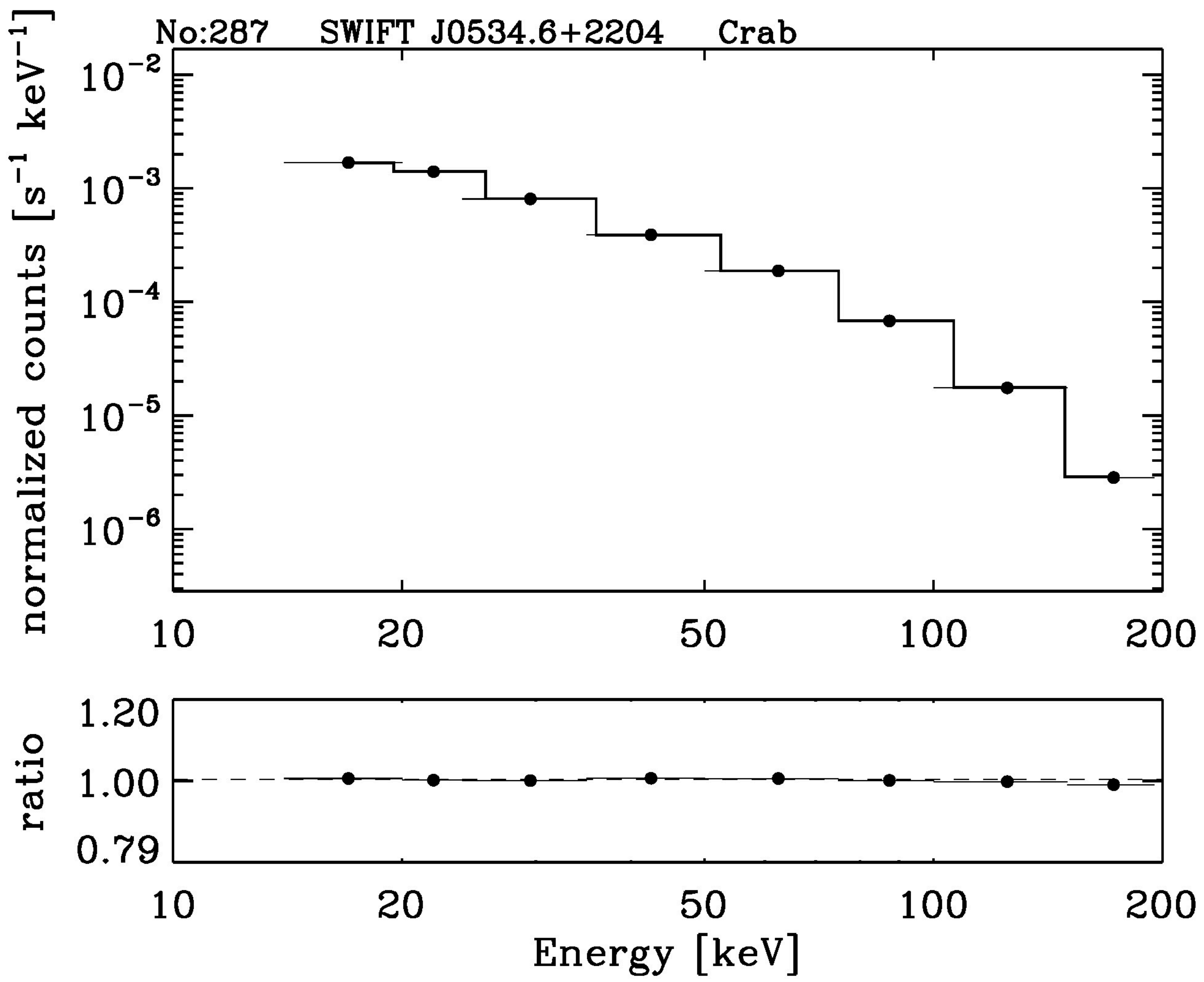
- Systematic analyses of BAT Survey data
- Analyze known sources to produce
  - Monthly mosaiced light curves
  - N-month mosaiced Spectra
- Discover new sources and (attempt to) identify them based on multi-wavelength follow-up

http://swift.gsfc.nasa.gov/results/bs22mon/
http://swift.gsfc.nasa.gov/results/bs70mon/
http://swift.gsfc.nasa.gov/results/bs105mon/



There are a total of 1632 sources identified in the 105 month survey where 422 are new detections



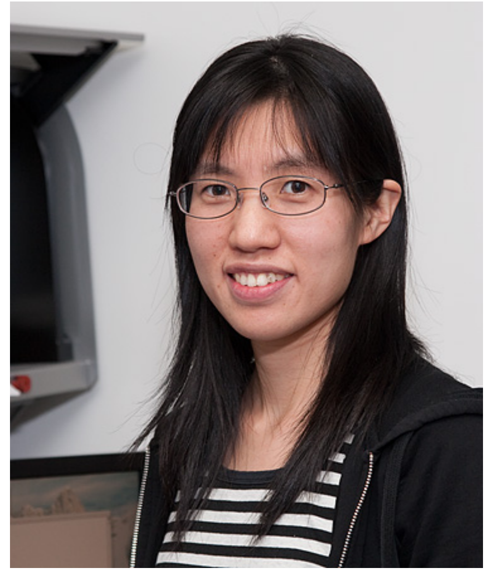


Tueller+ 2010, Baumgartner+ 2013, Oh+ 2018, Lien+ in Prep

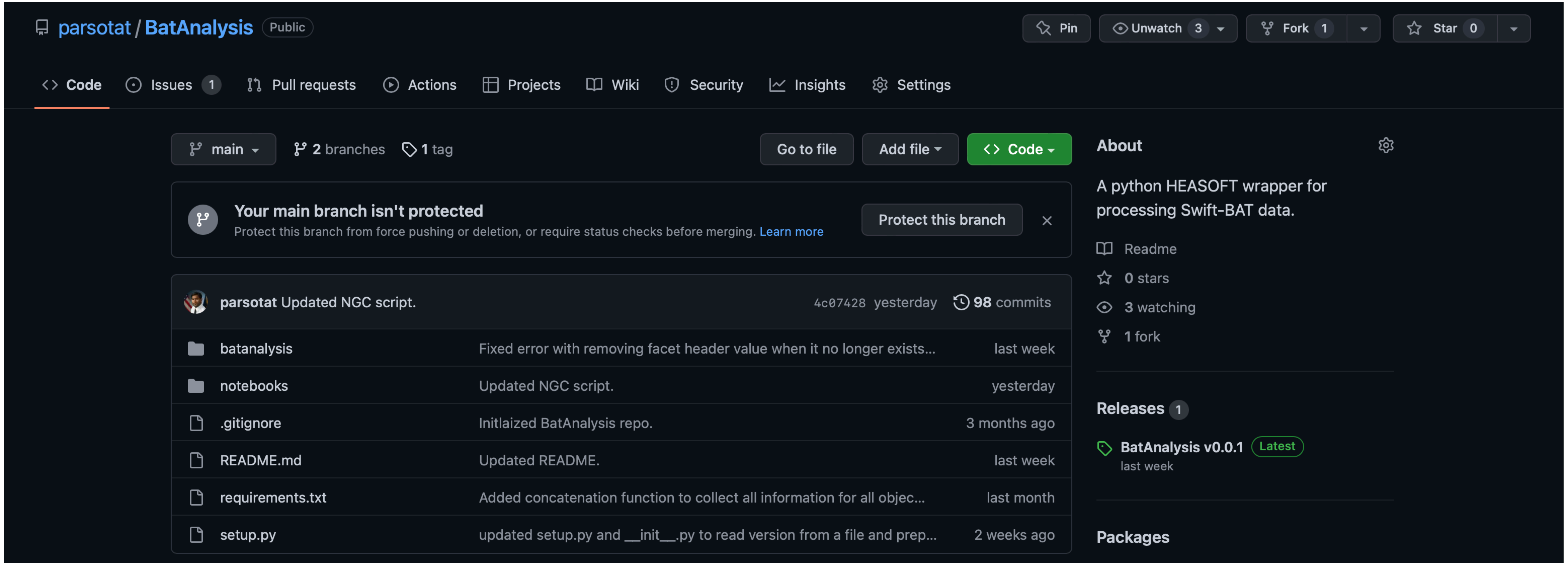
What if we want to analyze a source on a different time scale?

What if we want to look in archival data to place upper limits on a newly detected transient?

The BAT ANALYSIS Package

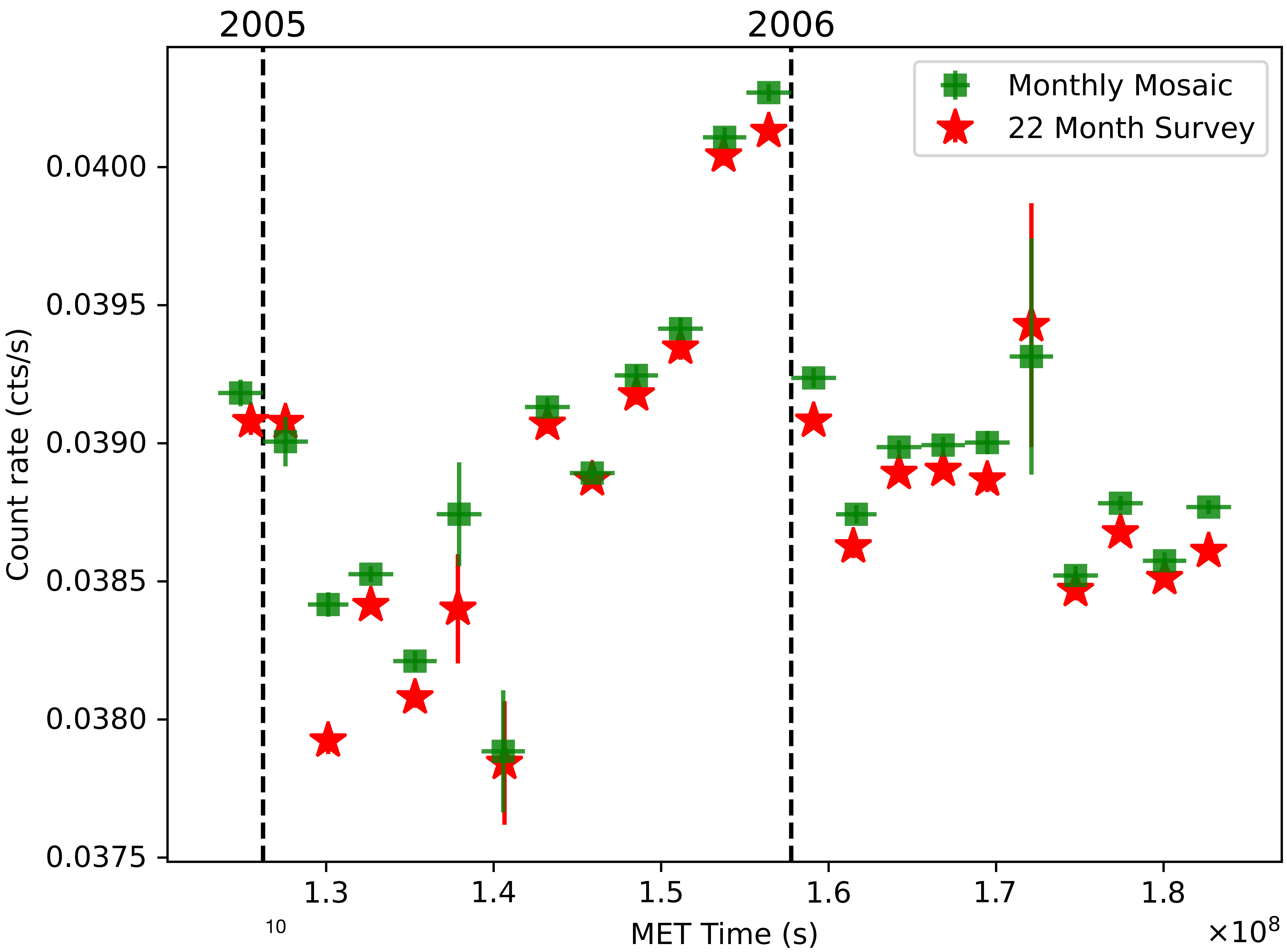




github.com/parsotat/BatAnalysis



The BatAnalysis Code Reproduces Prior Survey Catalog Results

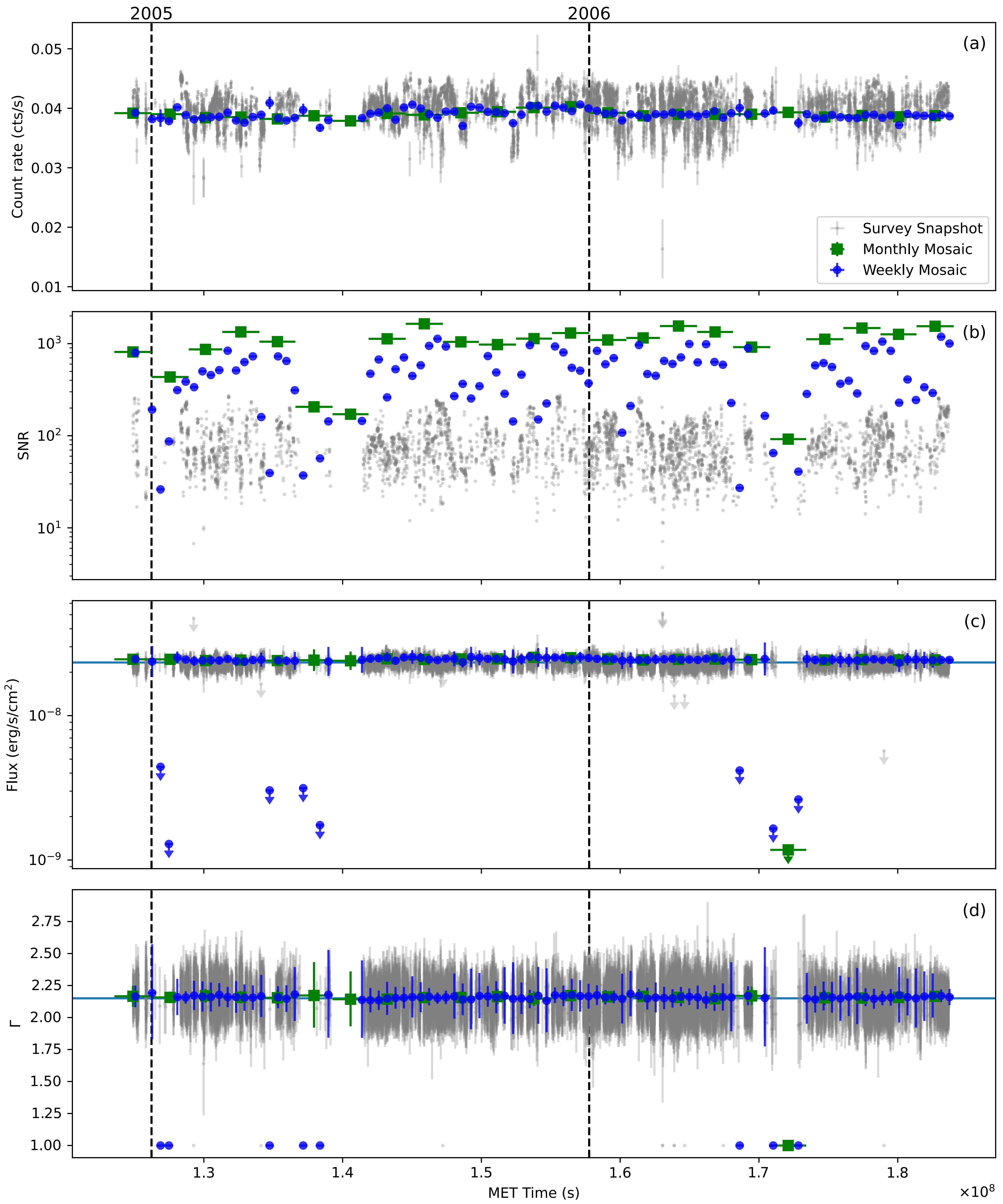
- 22 month survey:
  - Creates mosaic images from all survey data from Dec 2004 to Oct 2006
- BatAnalysis
  - Queries HEASARC for data
  - Filters data for ones where the Crab is "seen" by 1000 cm^2 of the BAT (~19% partial coding)



Tueller+ 2010, Parsotan+ 2023

The BatAnalysis Code Allows for a More Comprehensive Picture

- BatAnalysis
  - Can fit each survey/mosaic spectrum with a simple power law
  - If spectra are not well fit or if a detection is not obtained, the spectra are used to calculate upper limits

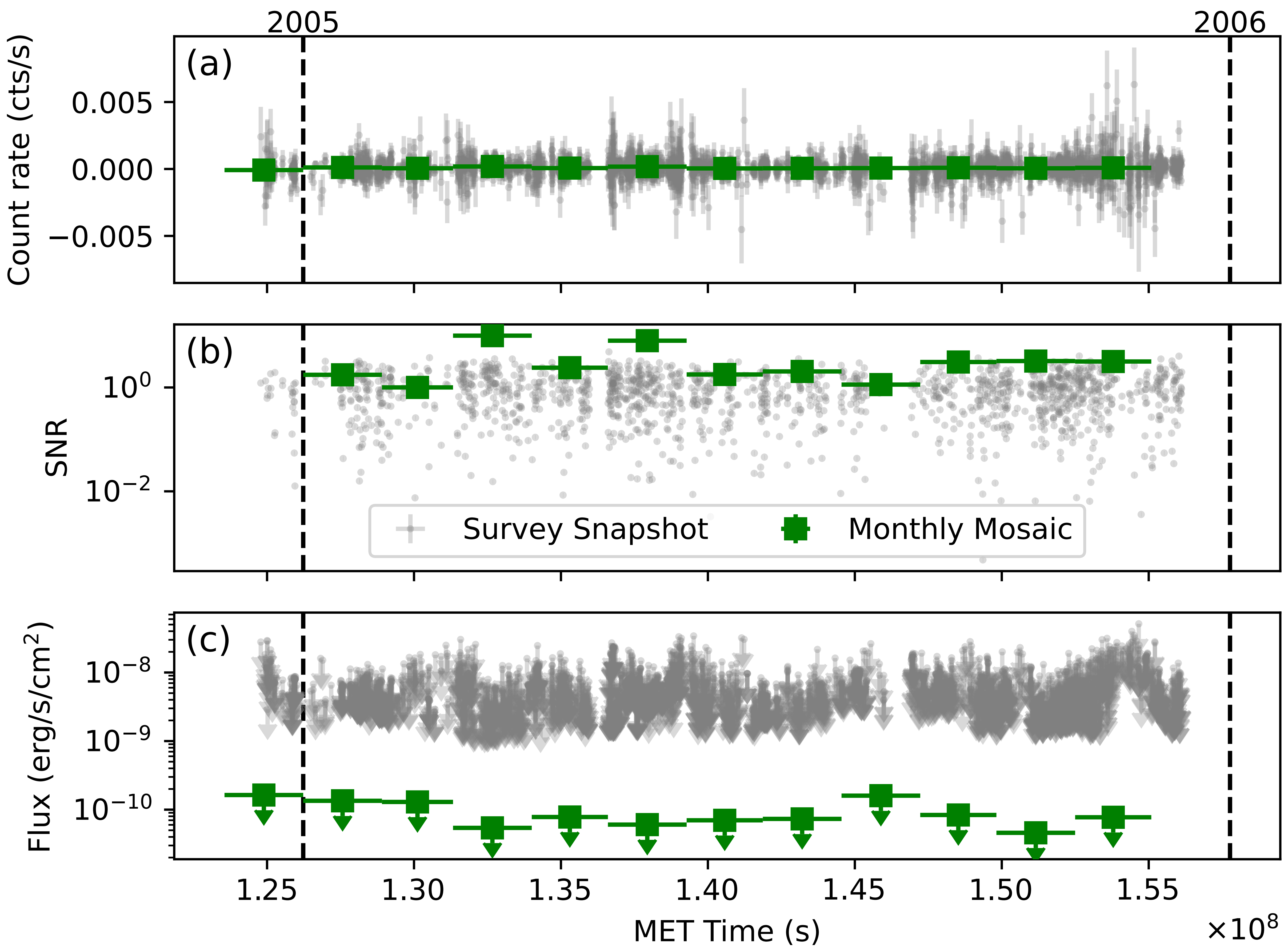


Parsotan+ 2023

BatAnalysis Allows for Custom Mosaicing

AGN NGC 2992

- Analyzed data from Dec 2004 - Dec 2005
- Obtained upper limits for each individual survey dataset and the monthly mosaics
- The year long mosaic image has a detection of SNR~12 in 14-195 keV energy band



Parsotan+ 2023

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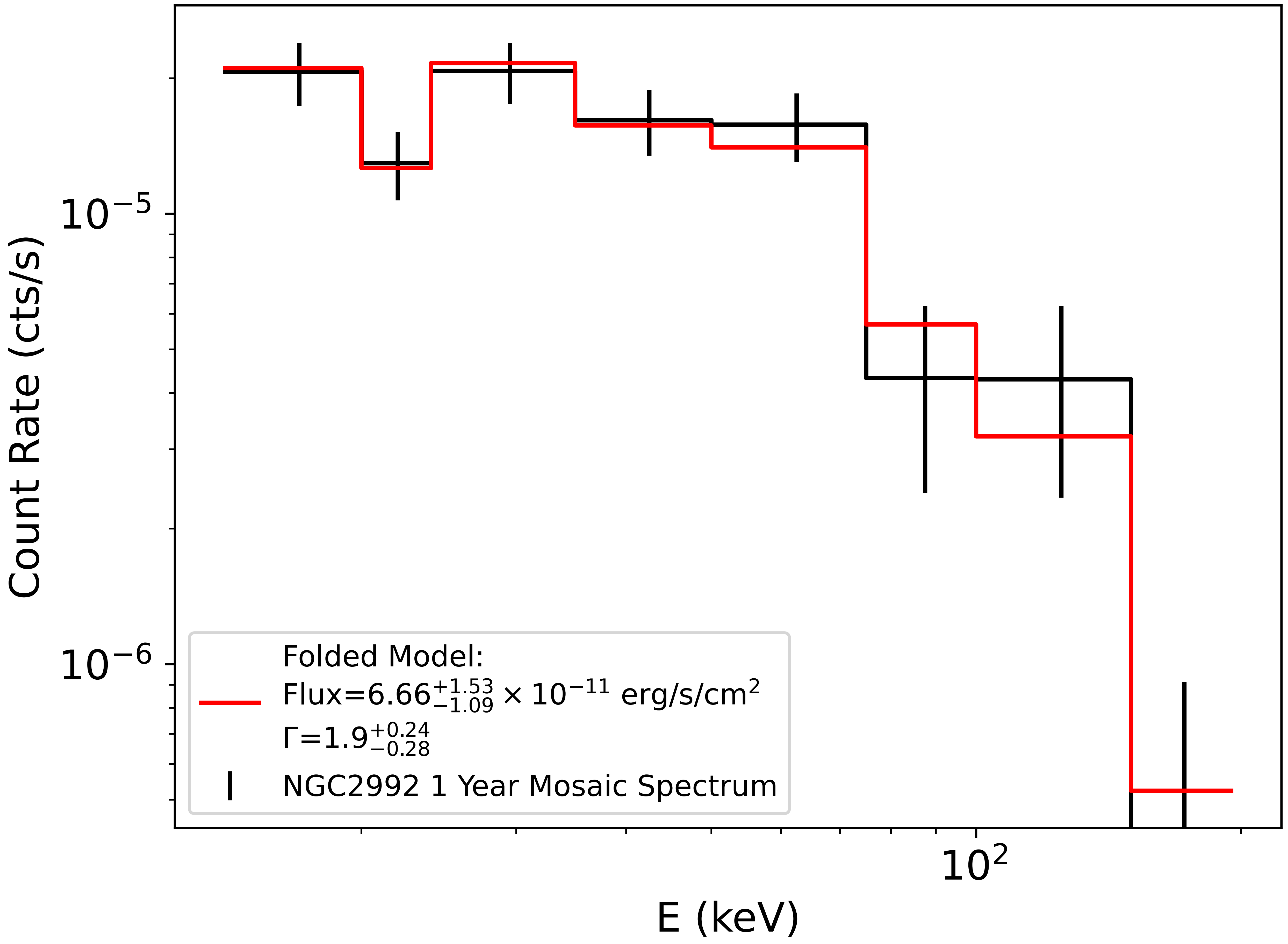
- The spectral fit show agreement with prior analyses

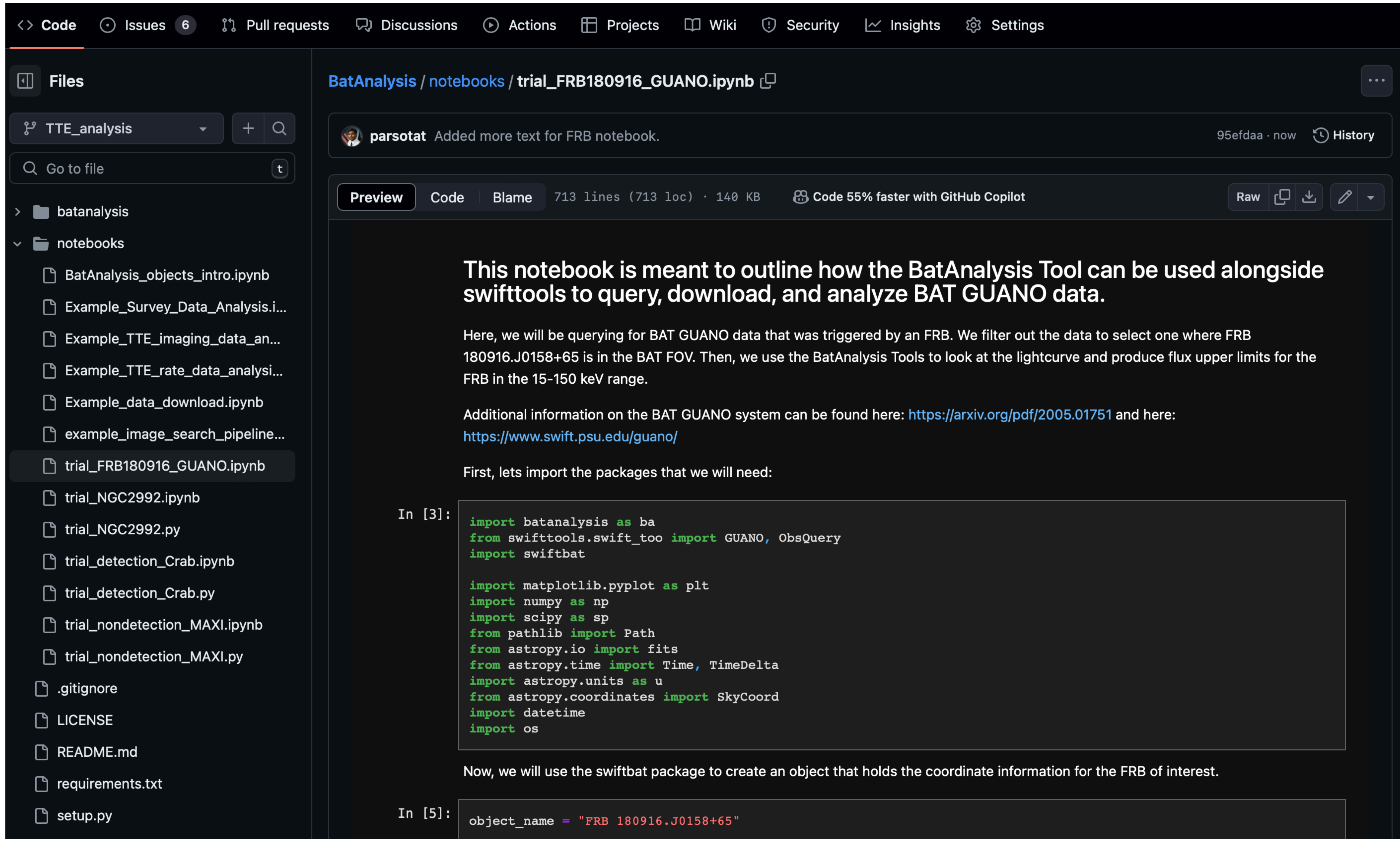


Parsotan+ 2023

BETA: BatAnalysis Allows for Custom Event Data Analysis

BAT GUANO Data

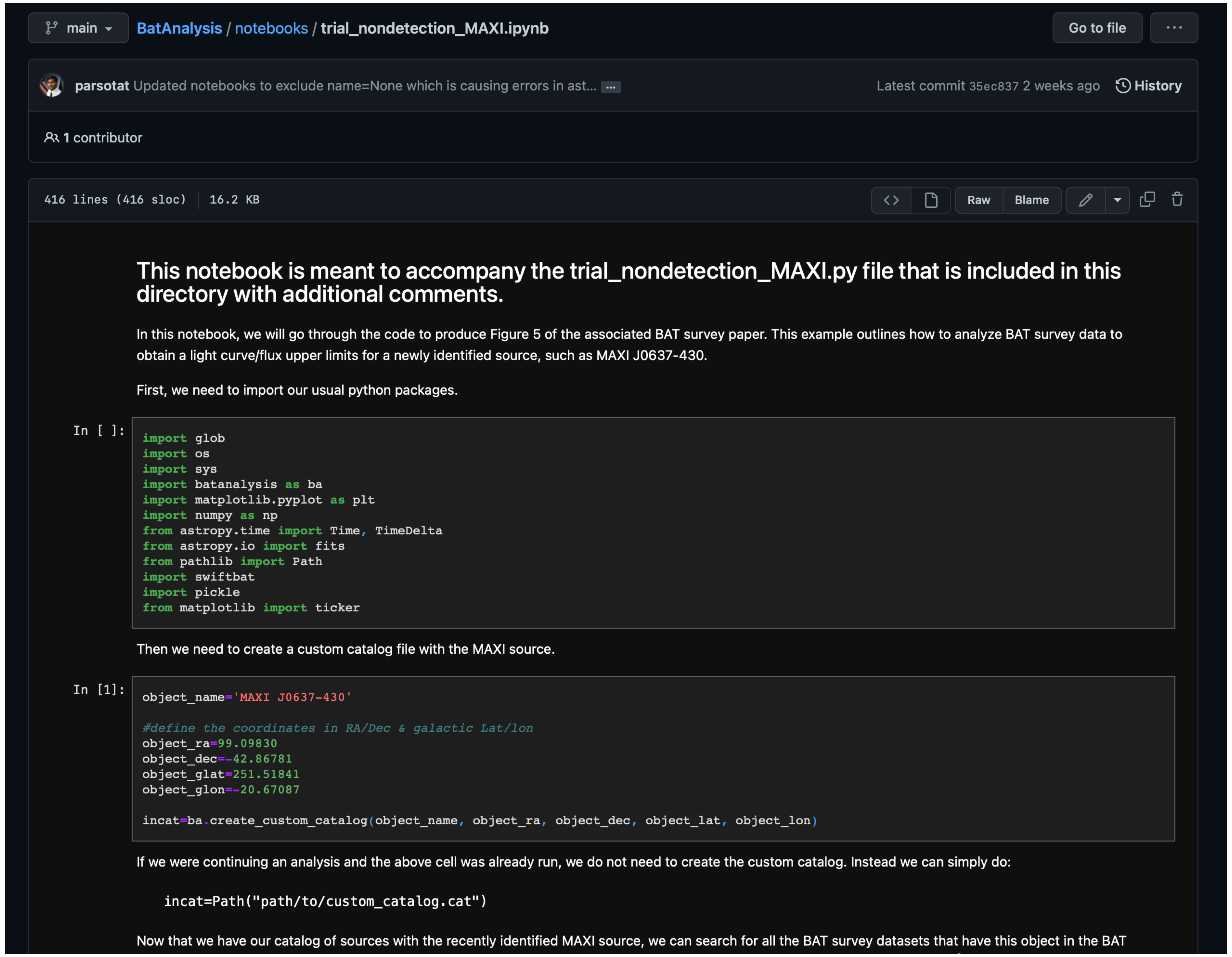
- Currently working on this portion of the package
- The beta version is available for testing with only one example analysis.
- There are notebooks that give a general overview of BAT event data files and ways to manipulate the data



BatAnalysis Survey Documentation

https://github.com/parsotat/BatAnalysis/tree/main/notebooks

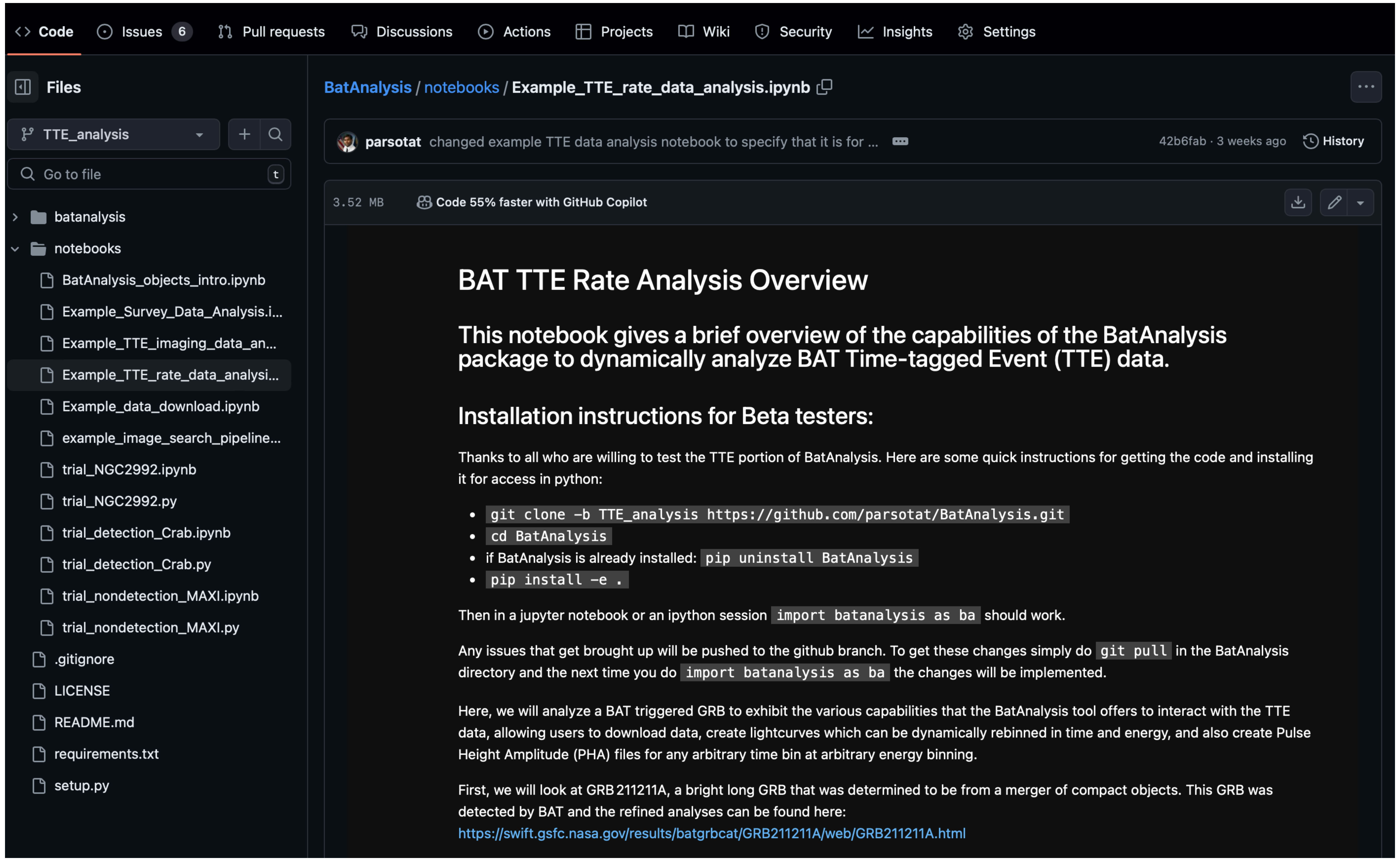
- Documentation is currently provided as Jupyter notebooks
  - Allow the results to be reproduced
  - Broadly explains what each step of an analysis is doing
  - A word of caution:
    - Some of these analyses can take a VERY large amount of space (eg the full 22 month Crab data & BatAnalyses produced files are ~2.5 TB in total)
    - The NGC analysis takes up ~815 GB
    - The MAXI analysis takes up ~330 GB
    - The BOAT analysis takes up ~60 GB of storage
    - The parallelized mosaic analyses capability can use a lot of memory at ~10 GB per process



BatAnalysis TTE Documentation

https://github.com/parsotat/BatAnalysis/tree/TTE_analysis/notebooks

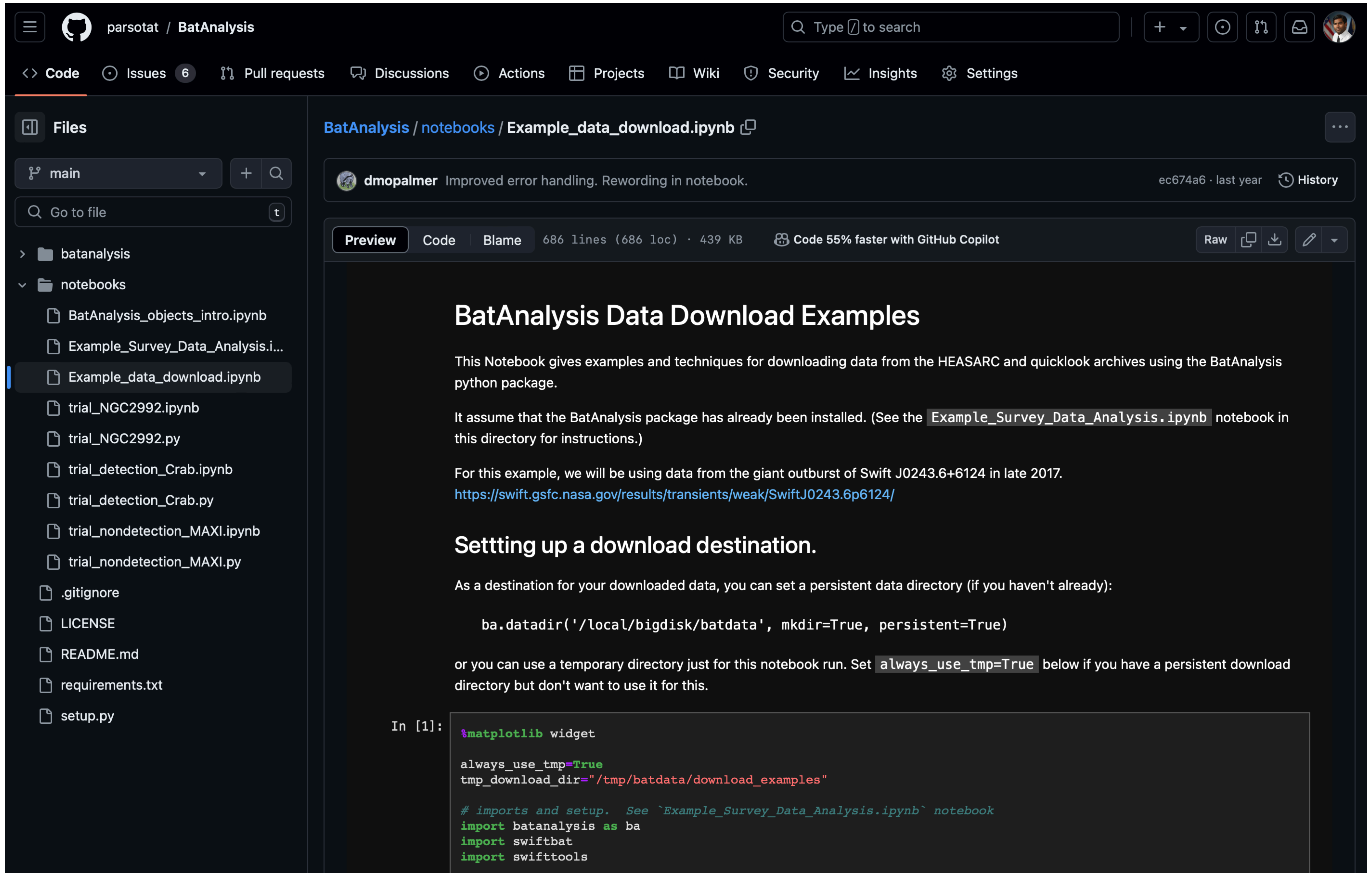
- Documentation is currently provided as Jupyter notebooks
    - 2 Primary Notebooks outlining the imaging capabilities and the traditional rate capabilities
- This is still the beta version and development is ongoing so be wary of any bugs.



Data Querying and Download Documentation

https://github.com/parsotat/BatAnalysis/blob/main/notebooks/Example_data_download.ipynb

- Various Examples show different ways to query data programmatically
- This notebook walks through the use of swifttools and various files that can be downloaded
- Additional documentation can be found on the swifttools website: https://www.swift.psu.edu/too_api/

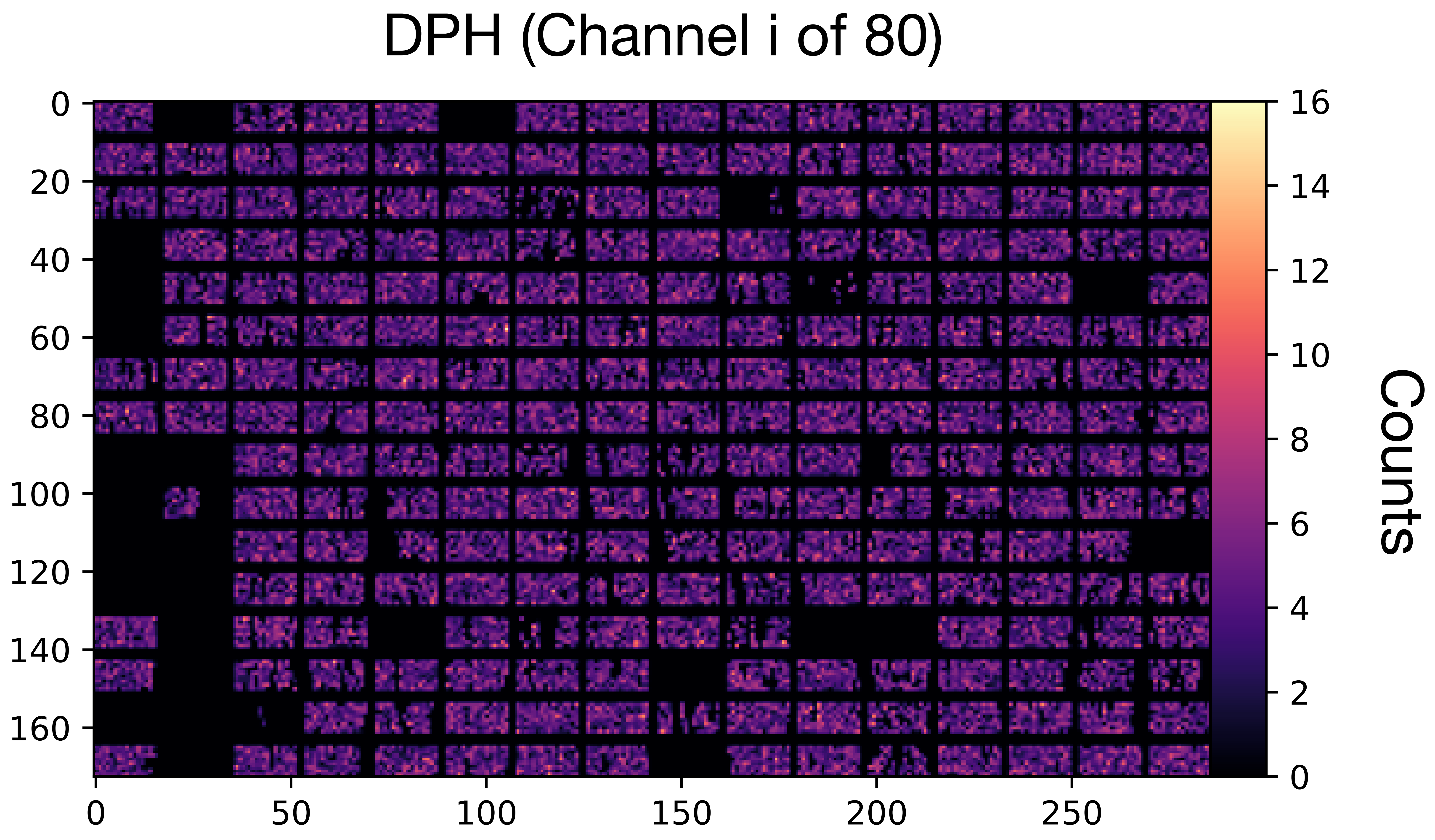


Summary

- The BatAnalysis package unlocks the potential of BAT data for a number of different analyses
- The package is open source and can be used by anyone
- Software such as this is dependent on other open source efforts including:
  - Swifttools (https://www.swift.psu.edu/too_api/)
  - The swift_bat package (https://github.com/lanl/swiftbat_python)
  - HEASoftpy
  - Astropy & Astroquery
  - Feedback from users such as yourselves
    - If issues are encountered users should open a GitHub issue outlining the problem and any relevant code
    - If the documentation is not clear please let me know by opening an GitHub issue as well so we can clarify things

Survey Observation Processing Steps

1. Raw Data Processing



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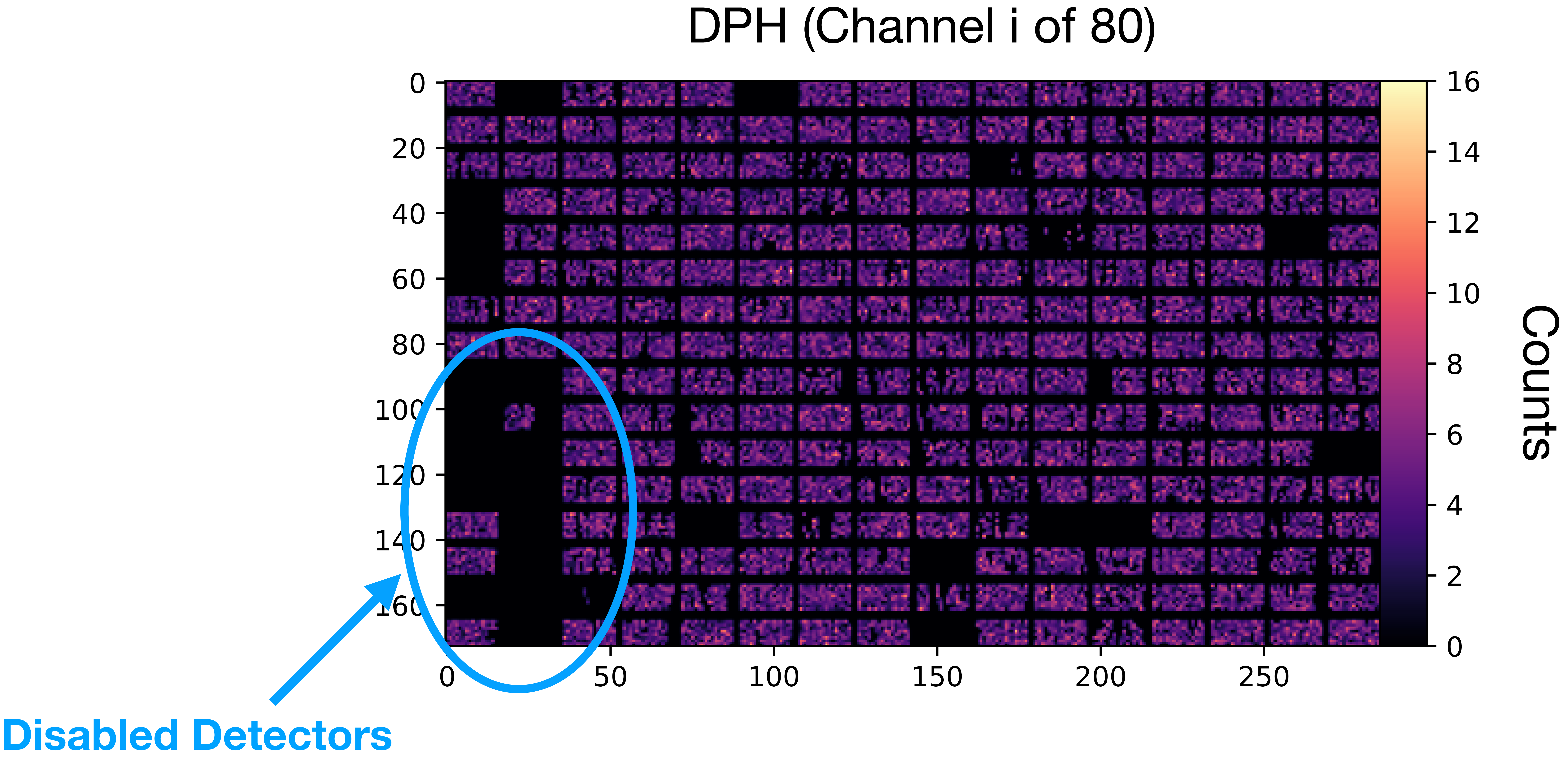

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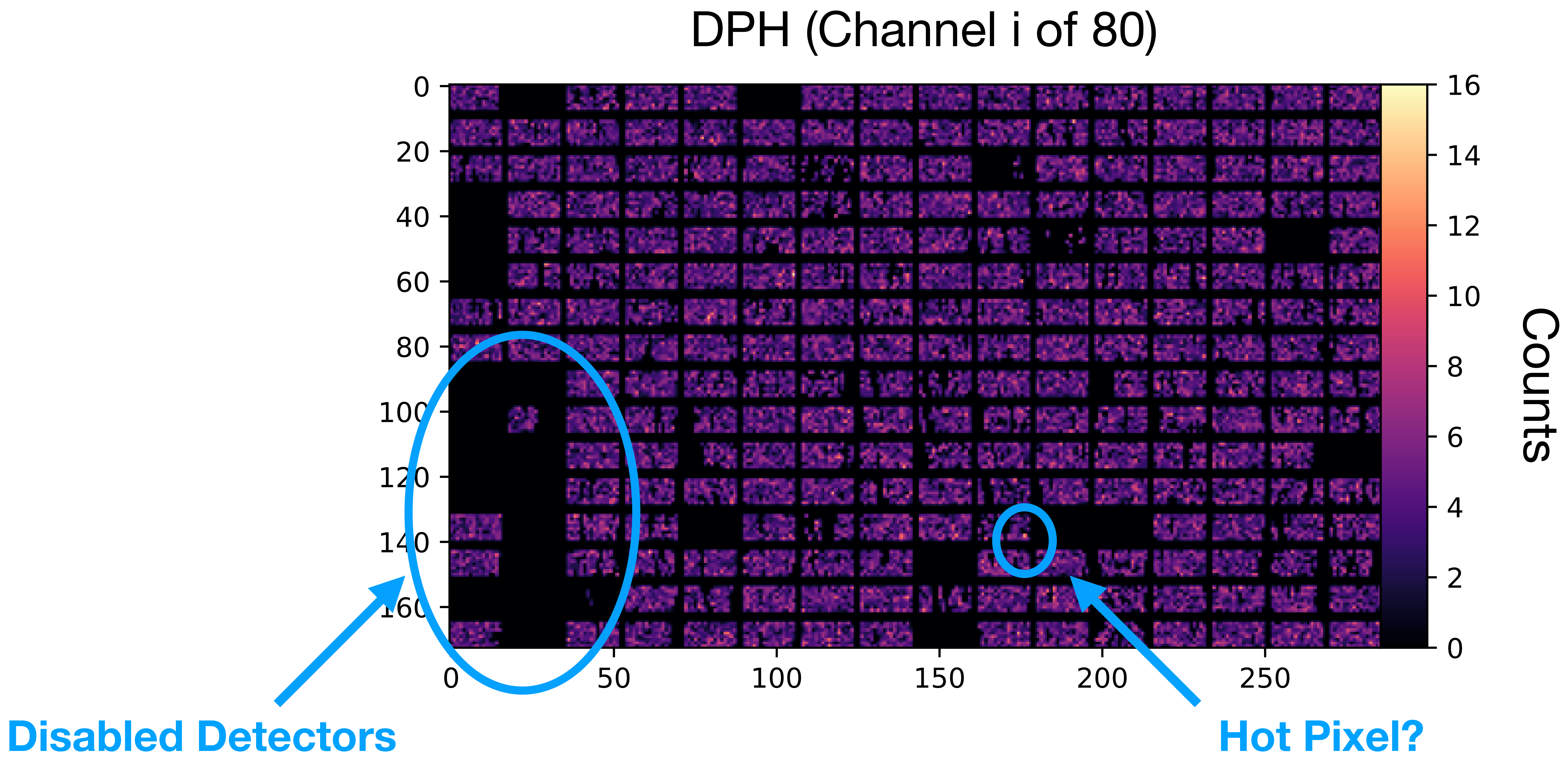
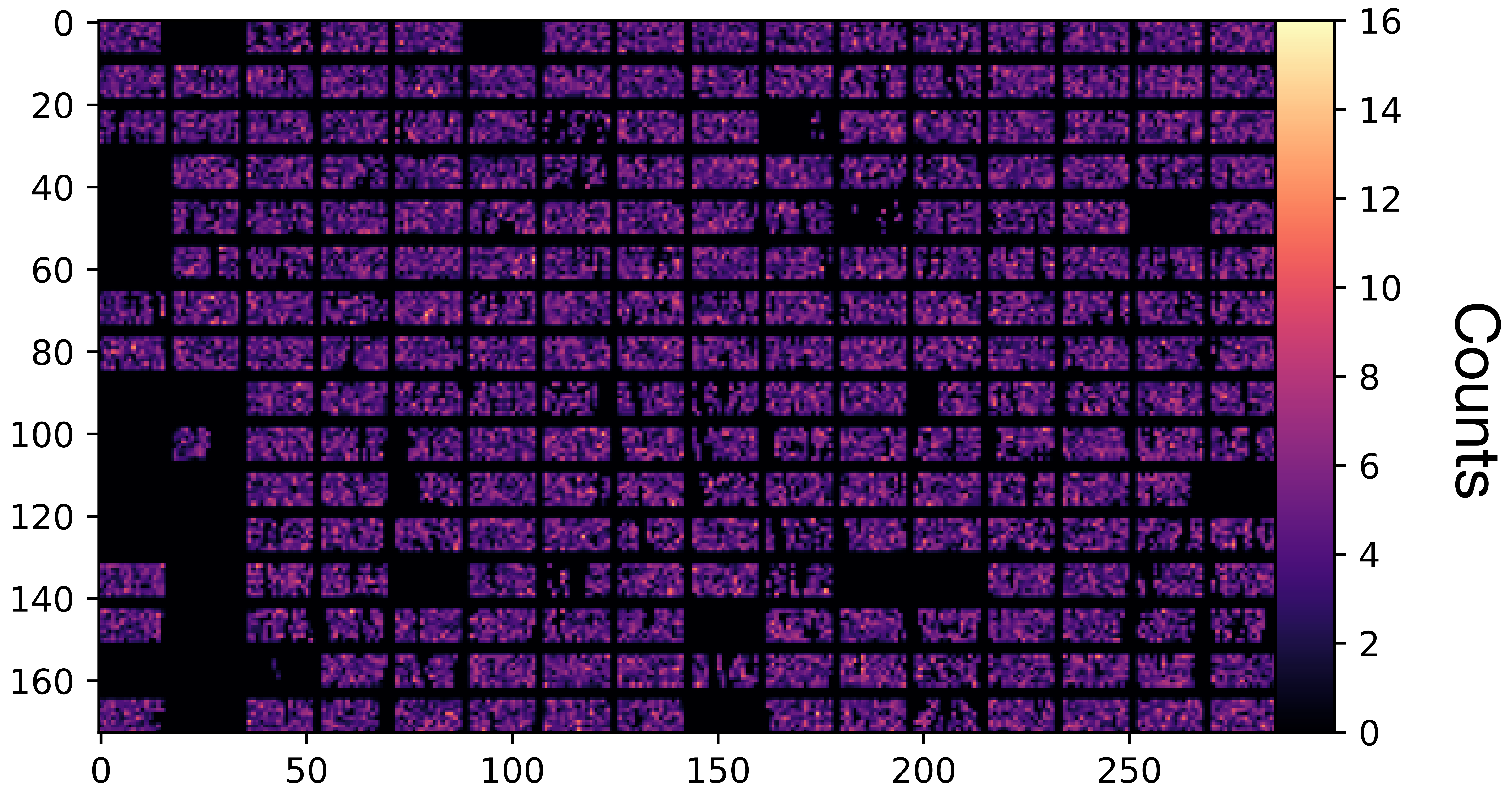


Survey Observation Processing Steps

1. Raw Data Processing

DPH (Channel i of 80)



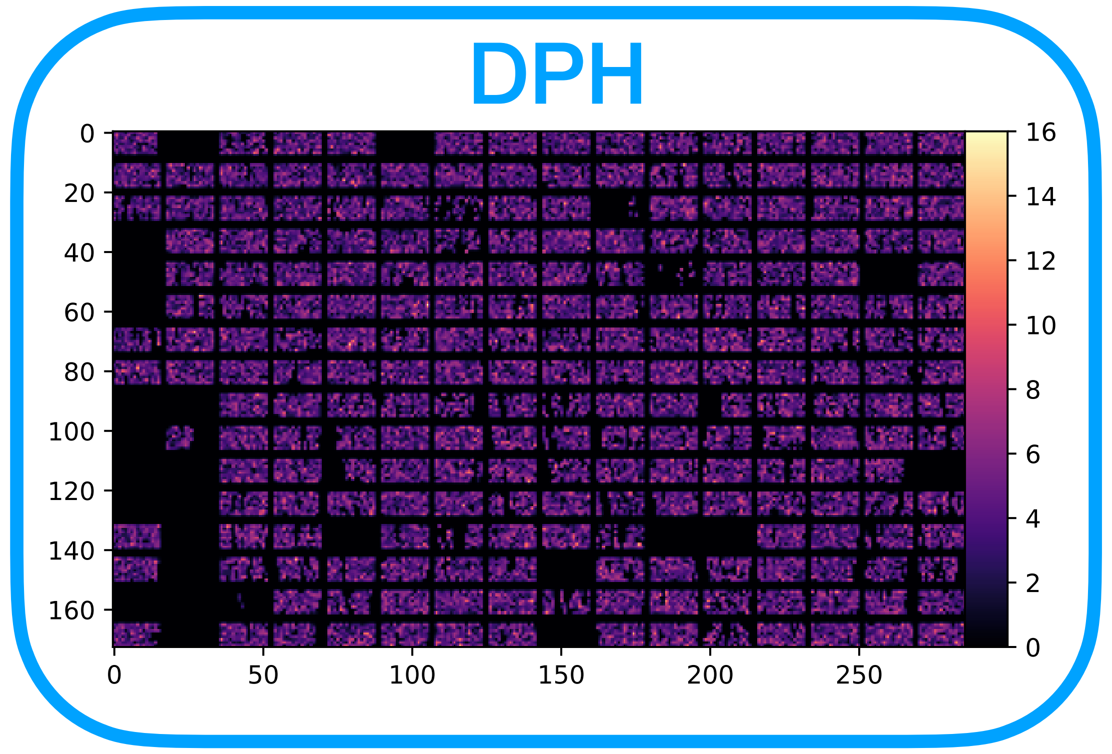
Survey Observation Processing Steps

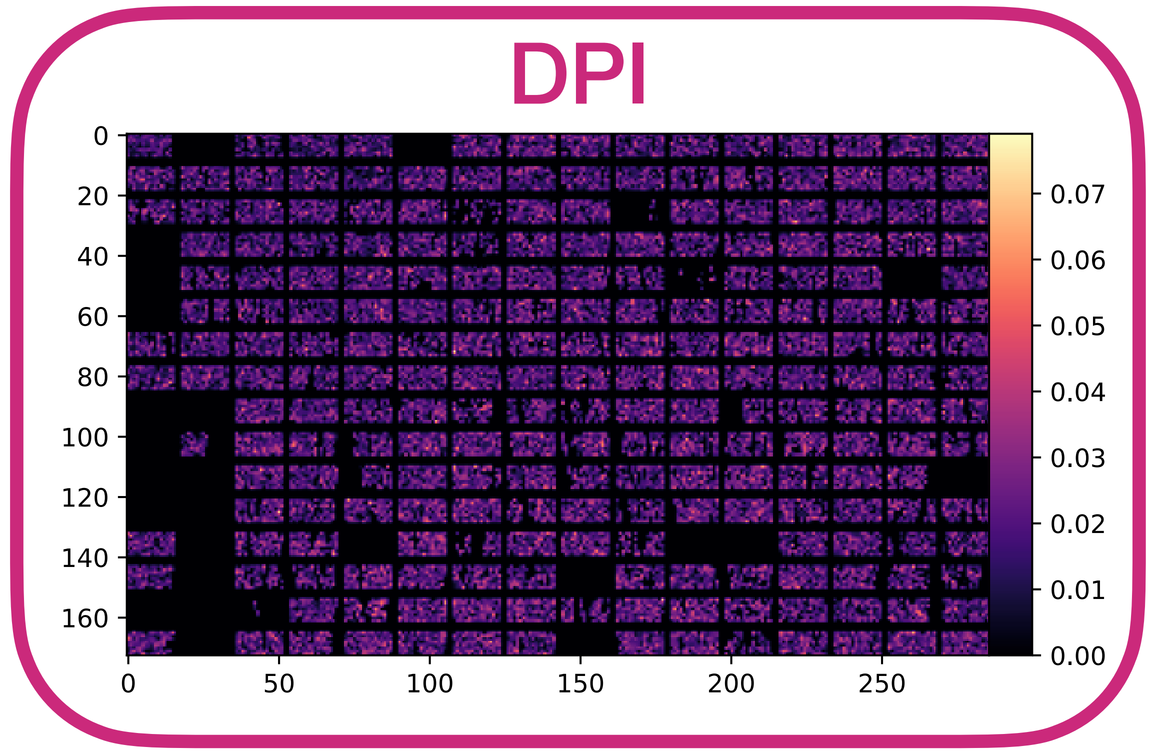
1. Raw Data Processing

- Rebin data into 8 energy bins: 20-24, 24-35, 35-50, 50-75, 75-100, 100-150, & 150-195 keV

Survey Observation Processing Steps

1. Raw Data Processing





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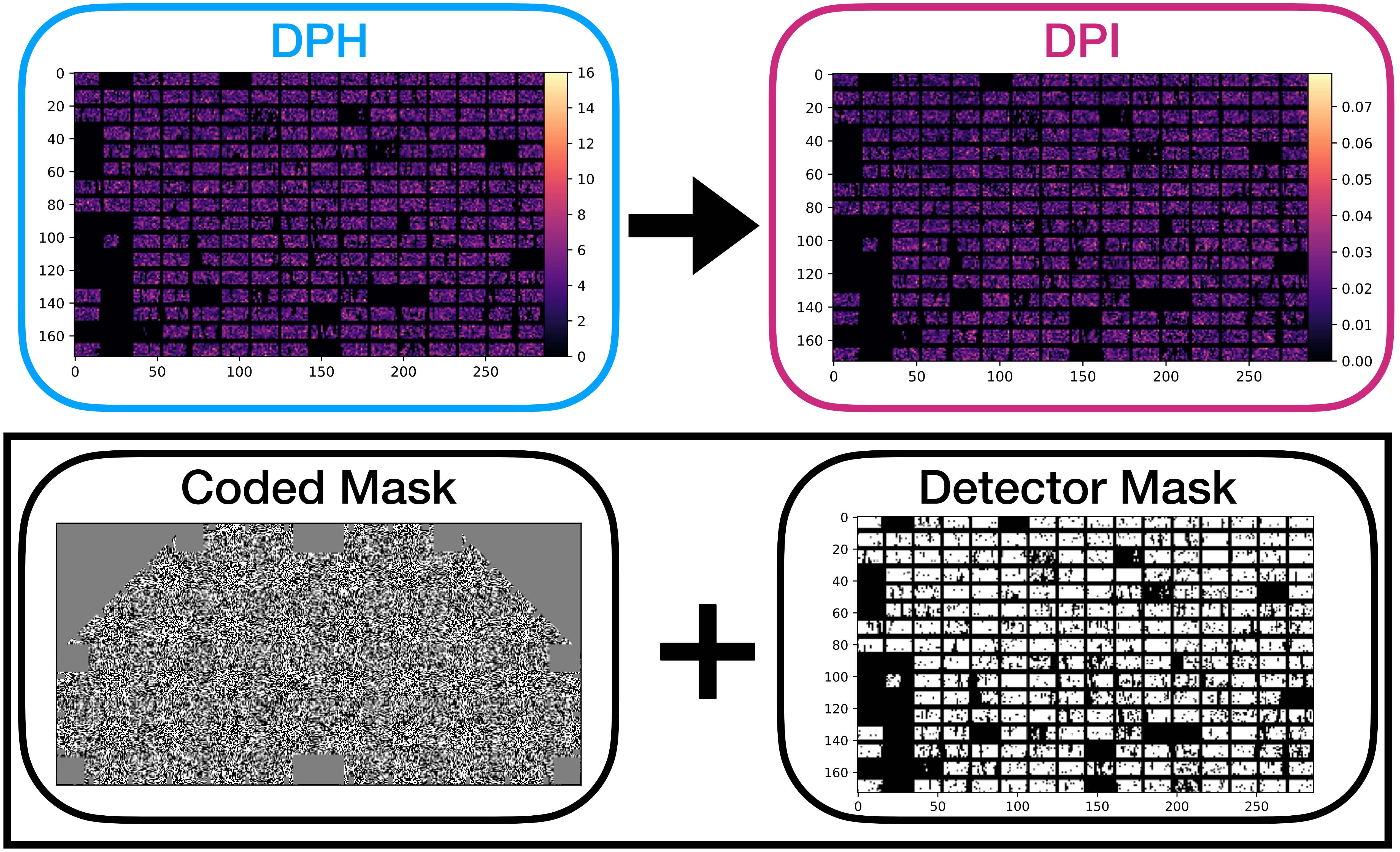

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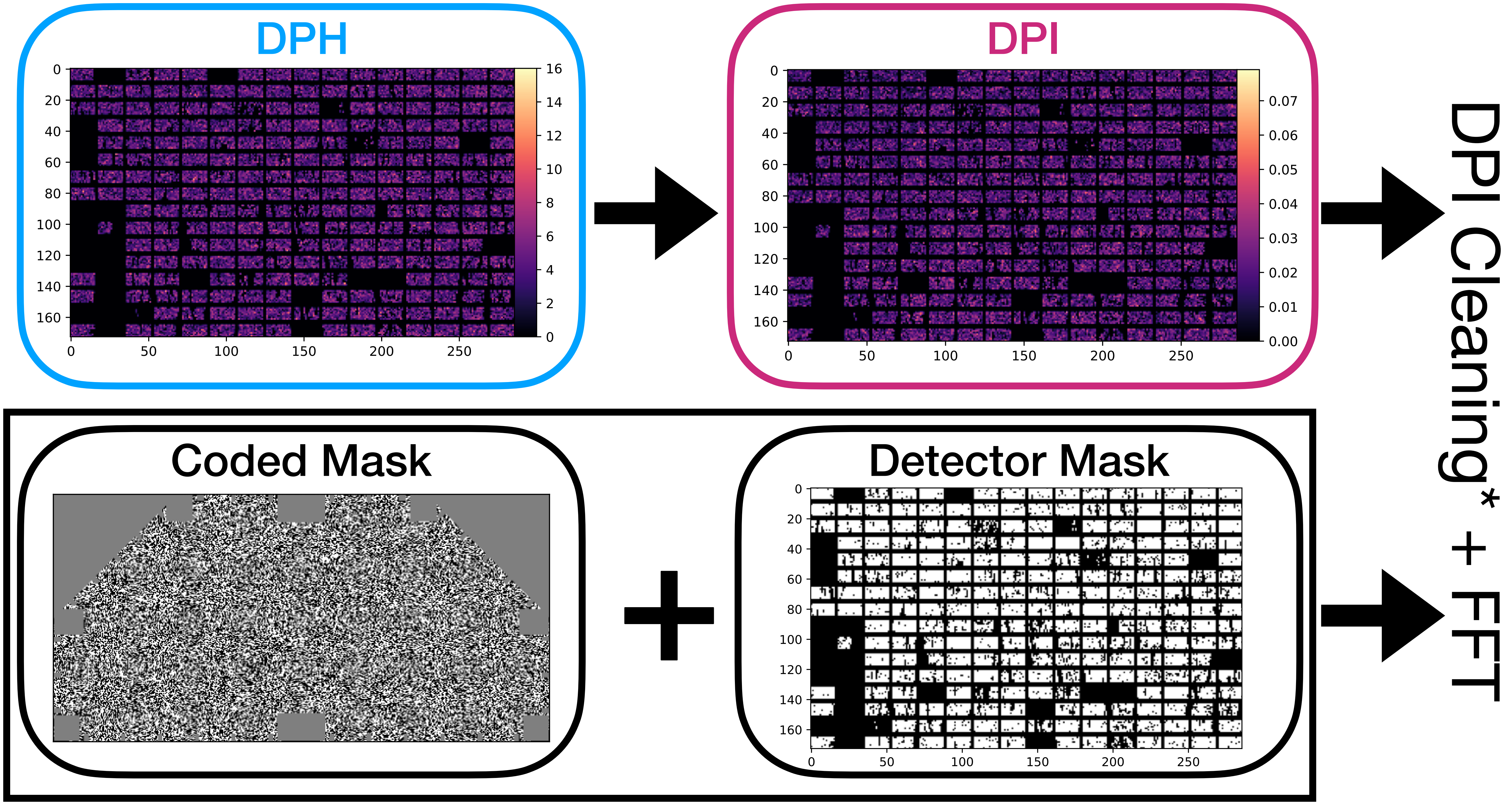

Survey Observation Processing Steps

1. Raw Data Processing

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DPI Cleaning:

- Cleans counts from bright sources with ray tracing
- Cleans noisy pixels from DPIs

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DPI Cleaning:
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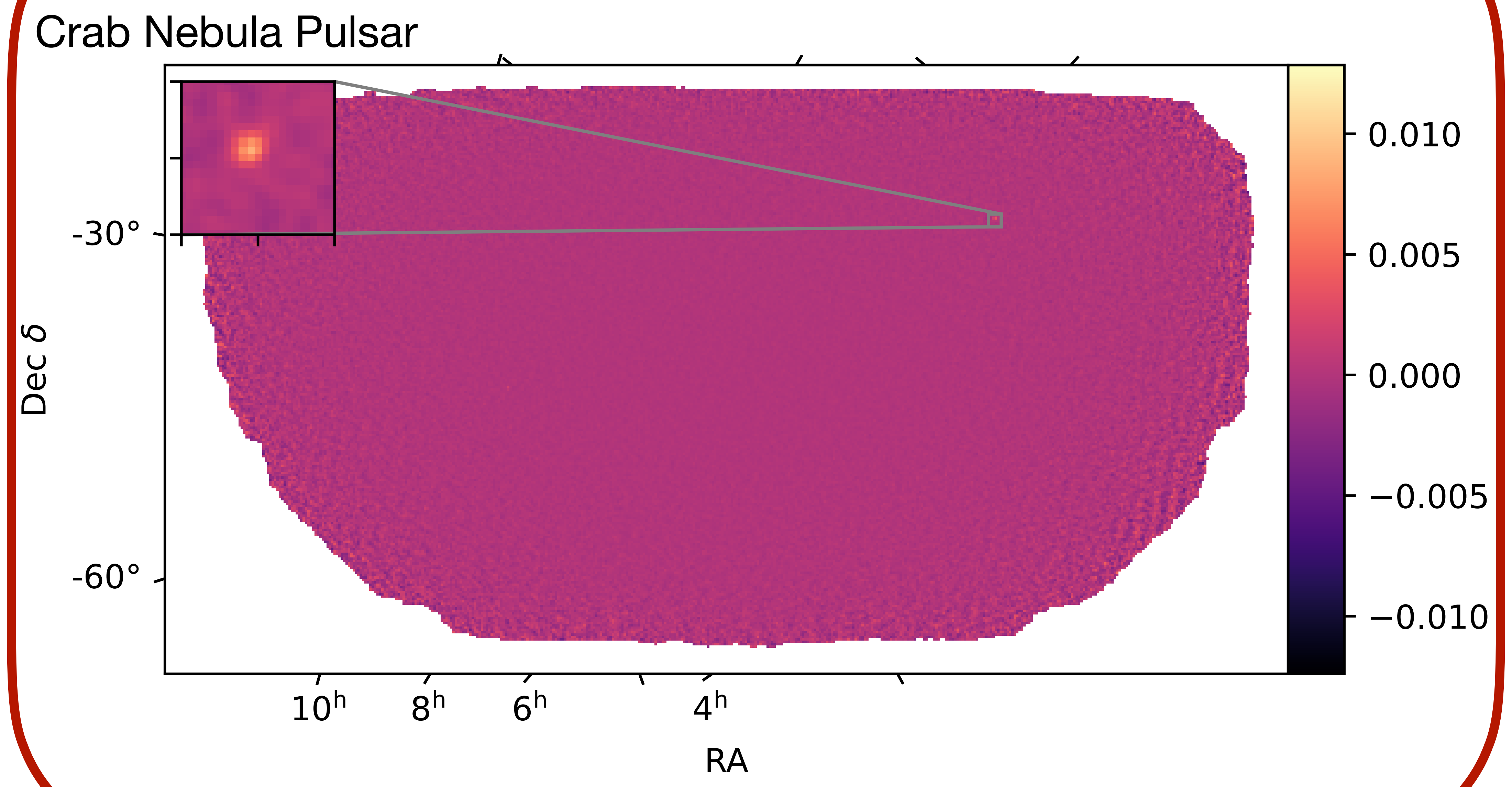
Pattern Noise Map Subtraction:
- Subtracts off persistent detector noise that builds up over time

Survey Observation Processing Steps

2. Image Processing - Individual Survey Datasets

Sky/Background Variance/etc. Images



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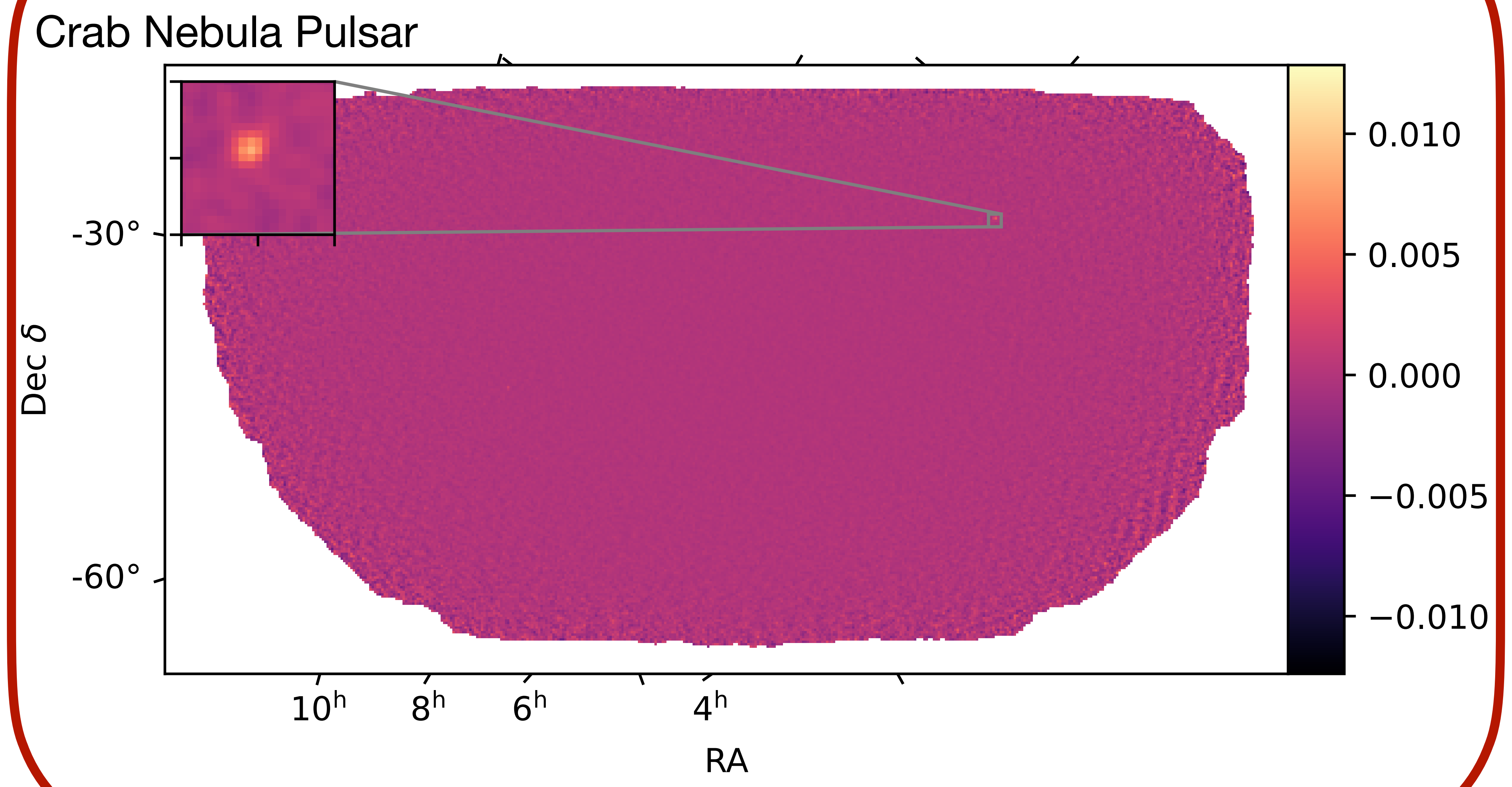

batcelldetect

Survey Observation Processing Steps

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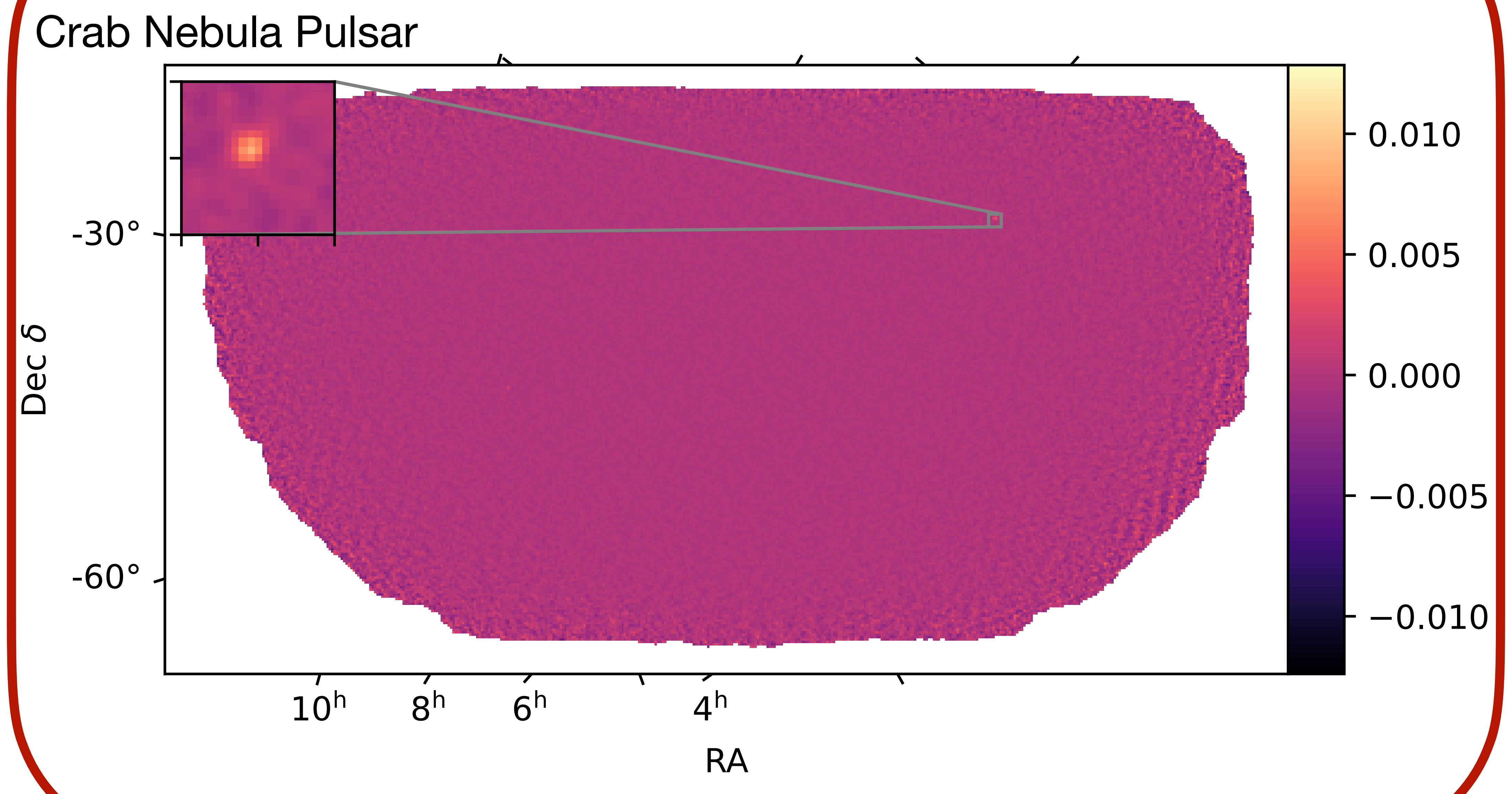
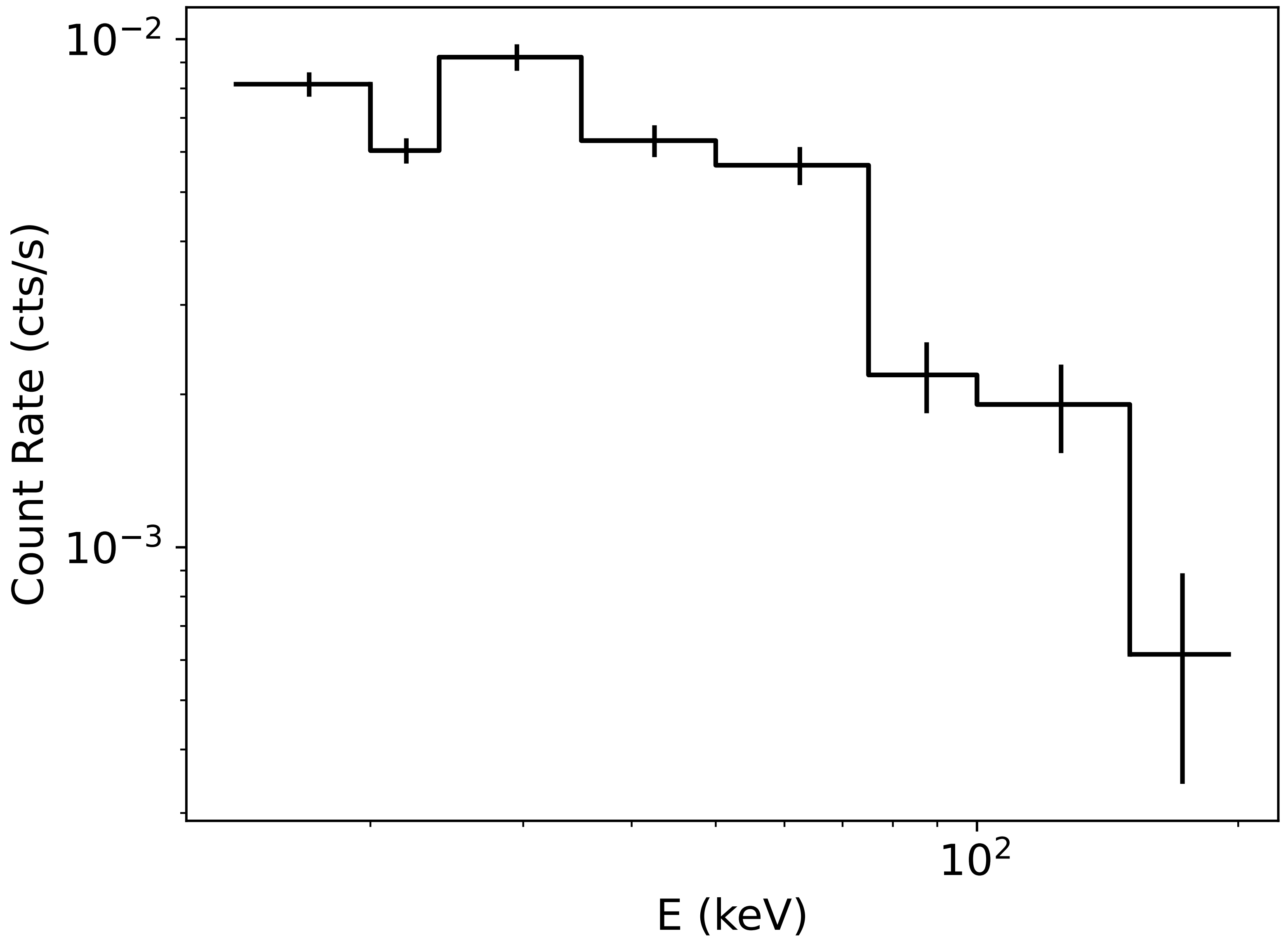


batcelldetect

- For Each Source that may be found:
  - Count rate in each energy bin
  - SNR of the detection
  - Local background variation



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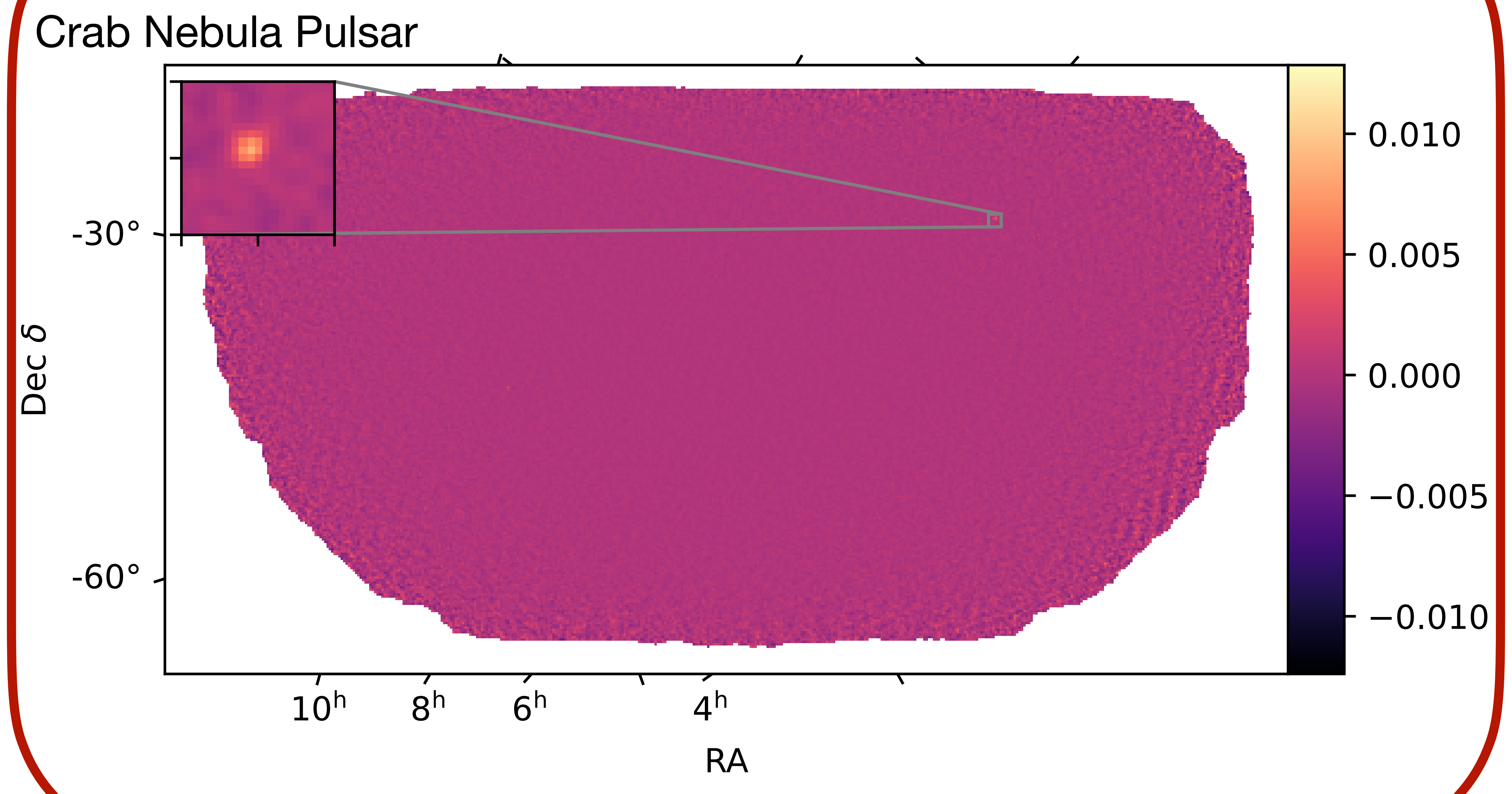

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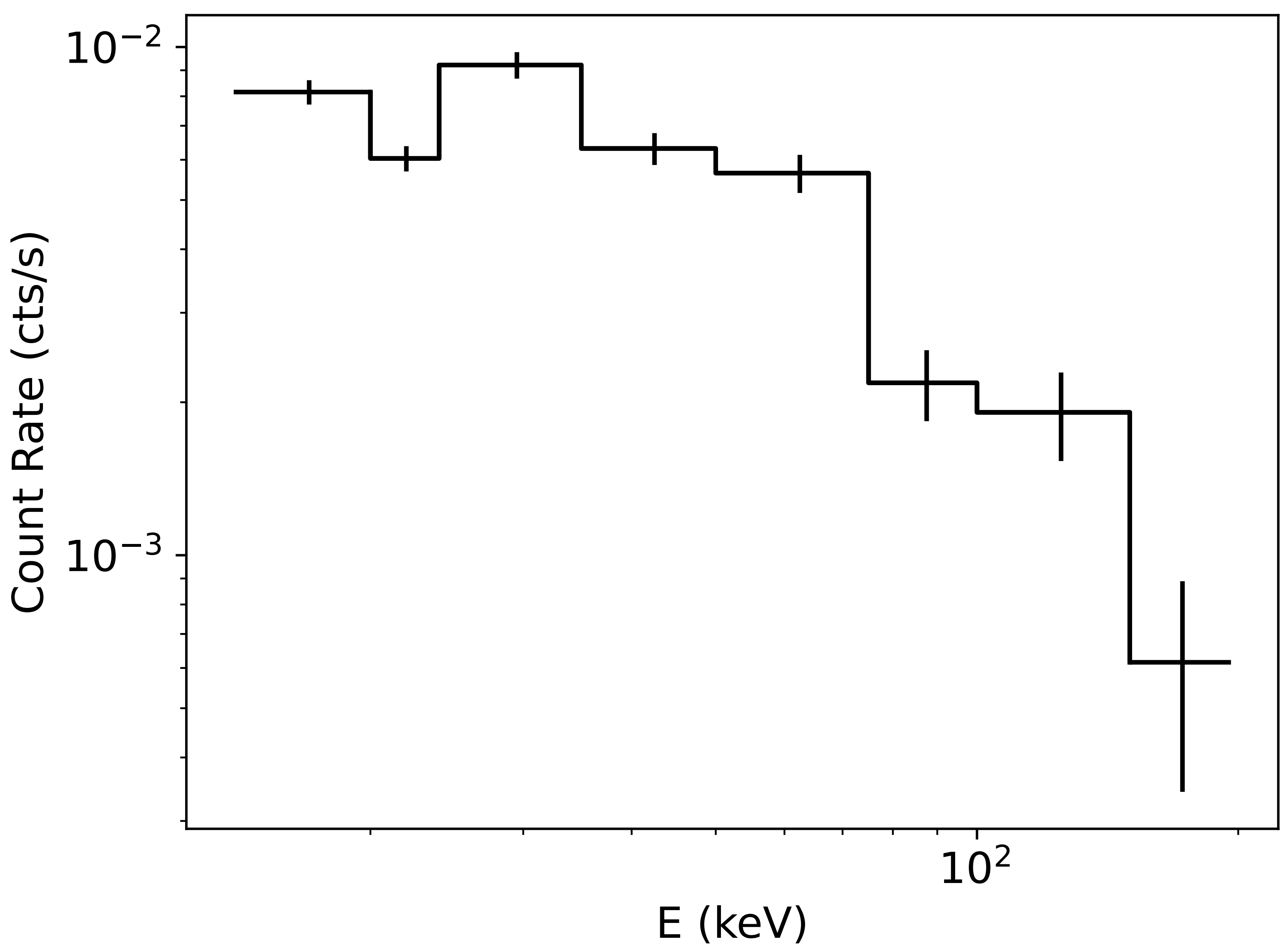


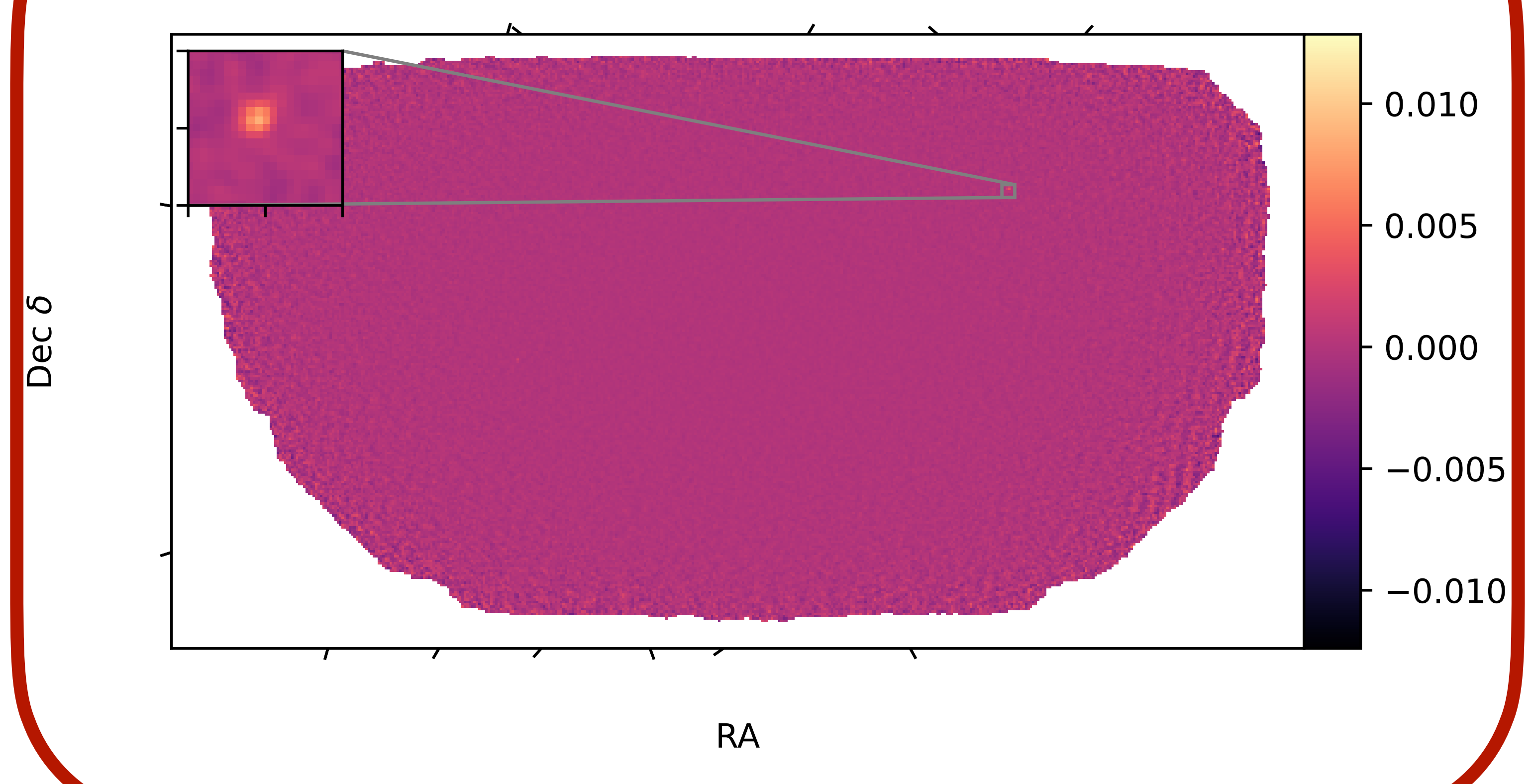
Batcelldetect: Uses a sliding annulus to detect sources and measure the local background counts

Survey Observation Processing Steps

2. Image Processing - Mosaic Survey Datasets

Observation 1

Images



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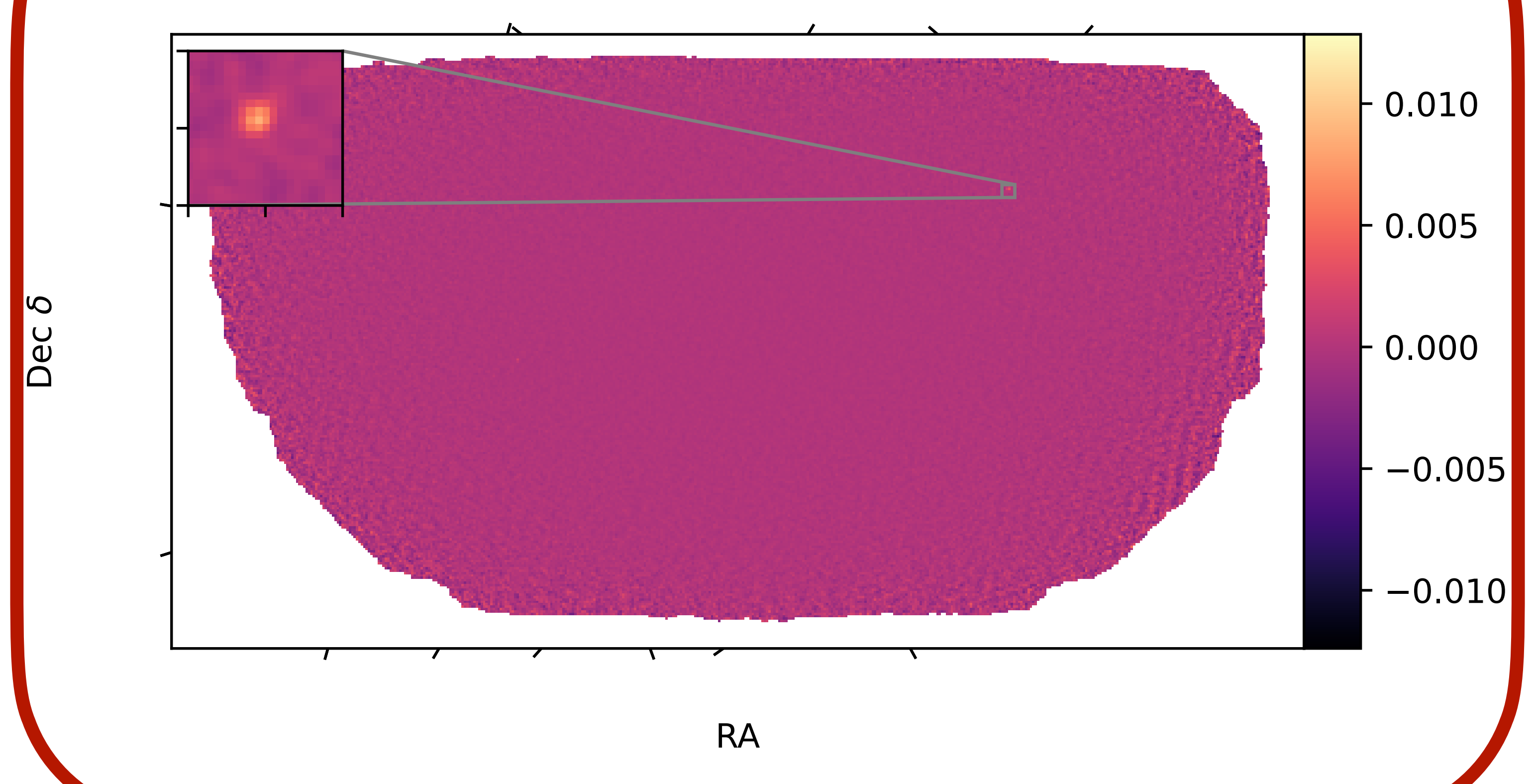
Observation 2

Images



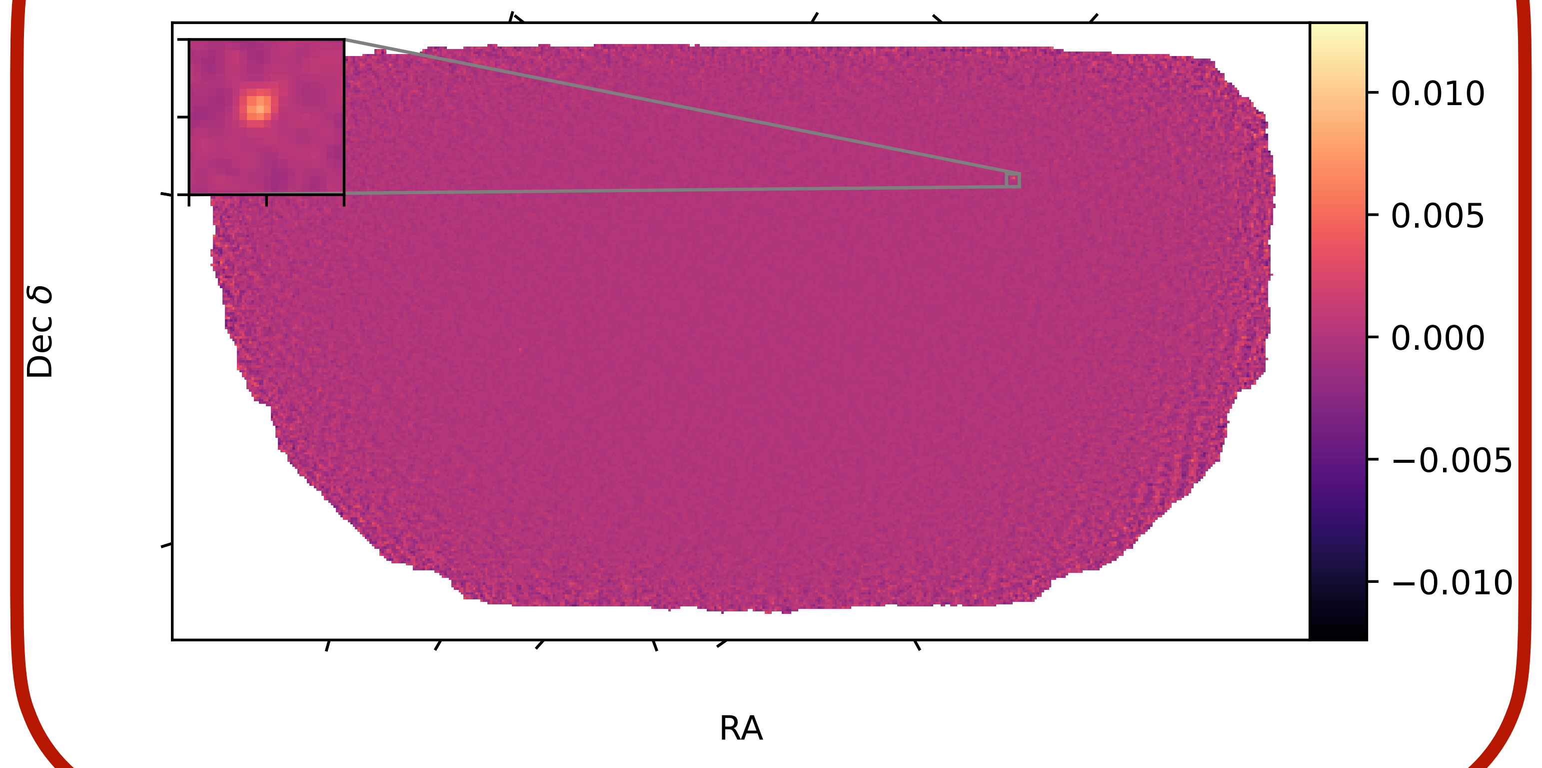
Survey Observation Processing Steps

2. Image Processing - Mosaic Survey Datasets

Observation 1

Images

$w_{i,j} \times$



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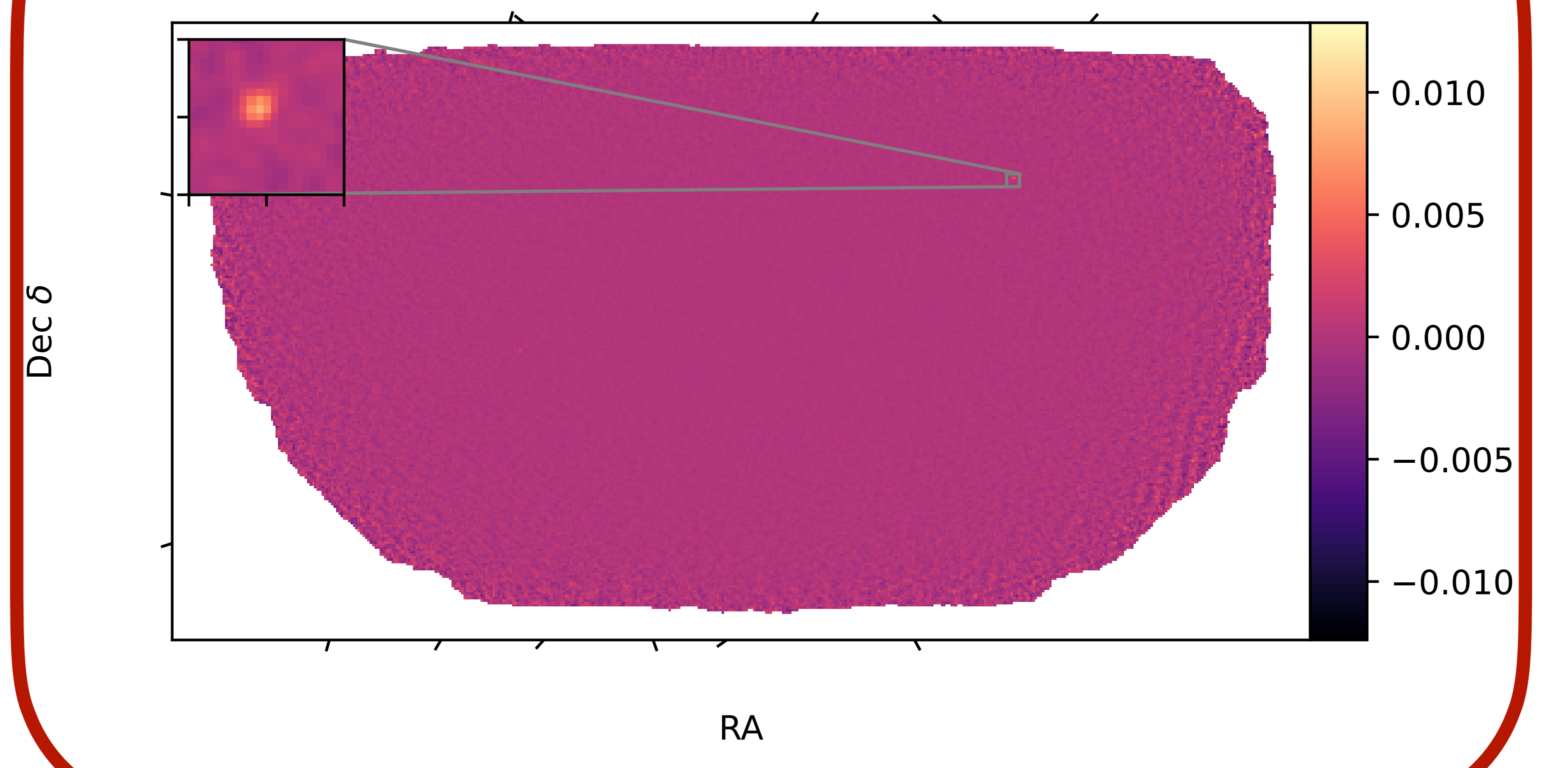


$$w_{i,j} \propto \sigma_{i,j}^{-2}$$

This suppresses counts in noisy images

Survey Observation Processing Steps

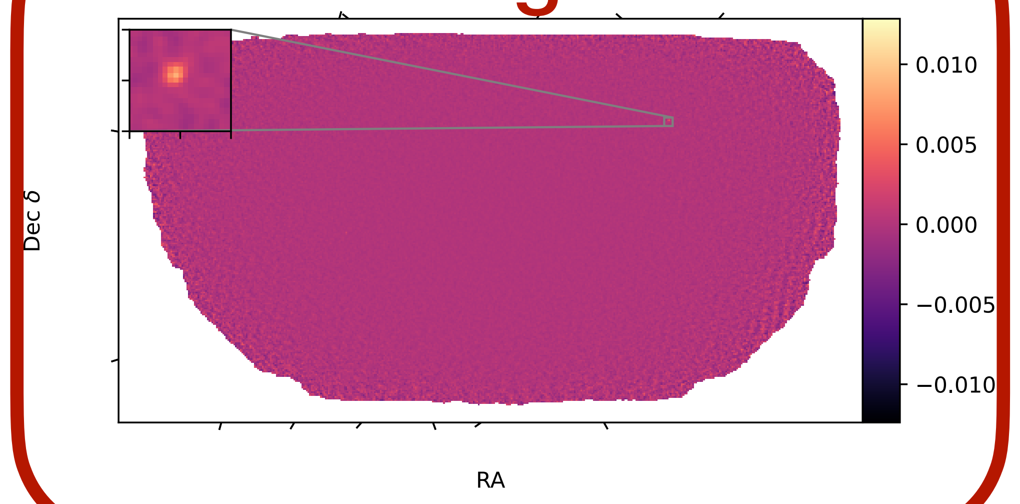
2. Image Processing - Mosaic Survey Datasets

Observations within some time bin

Observation 1

$w_{i,j} \times$

Images



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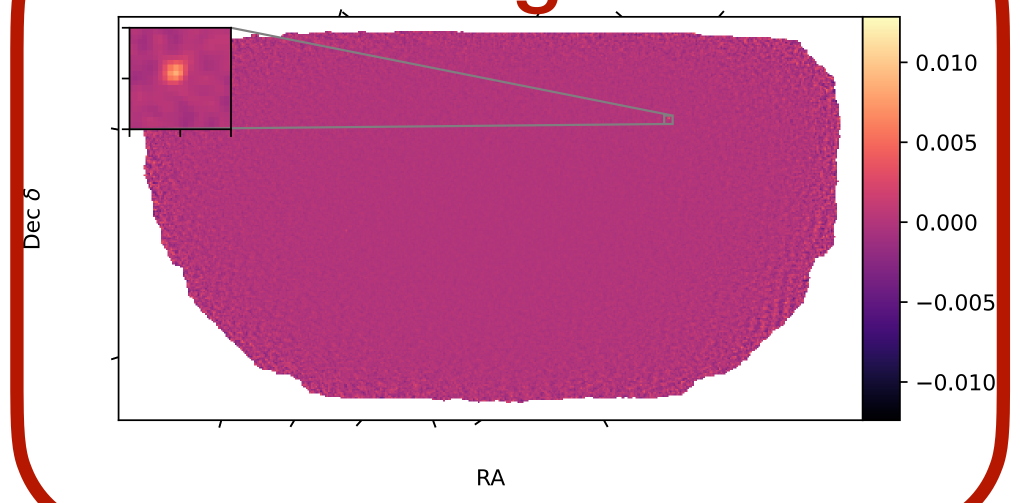
Observation N

$w_{i,j} \times$

Images



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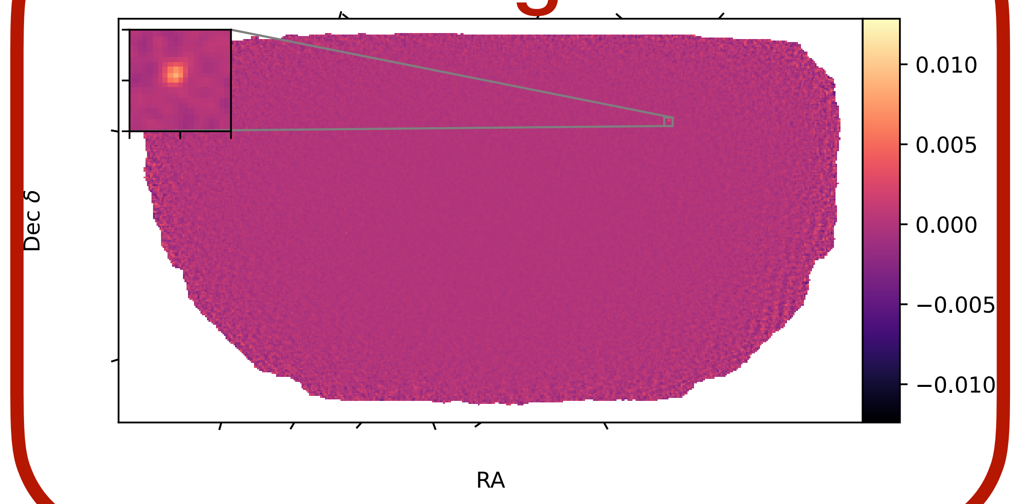
$w_{i,j} \times$ 

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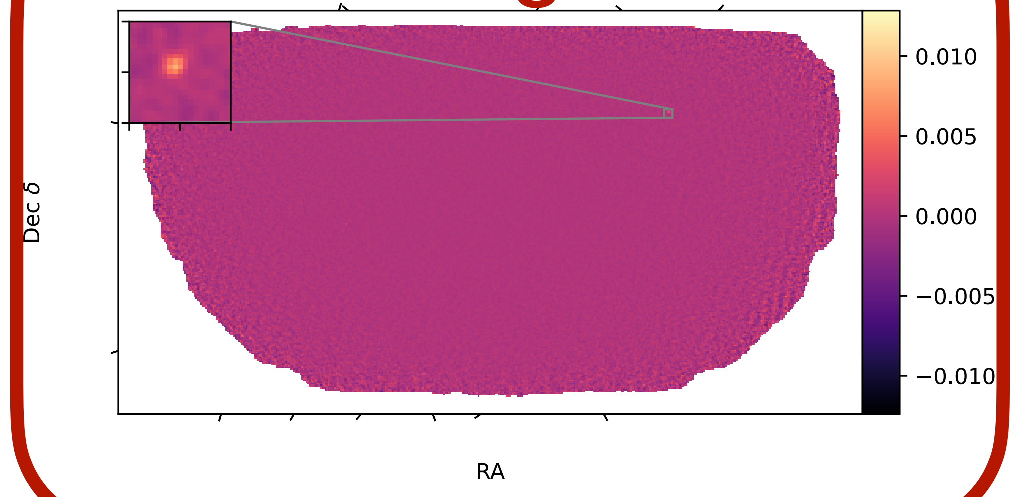
$w_{i,j} \times$ 

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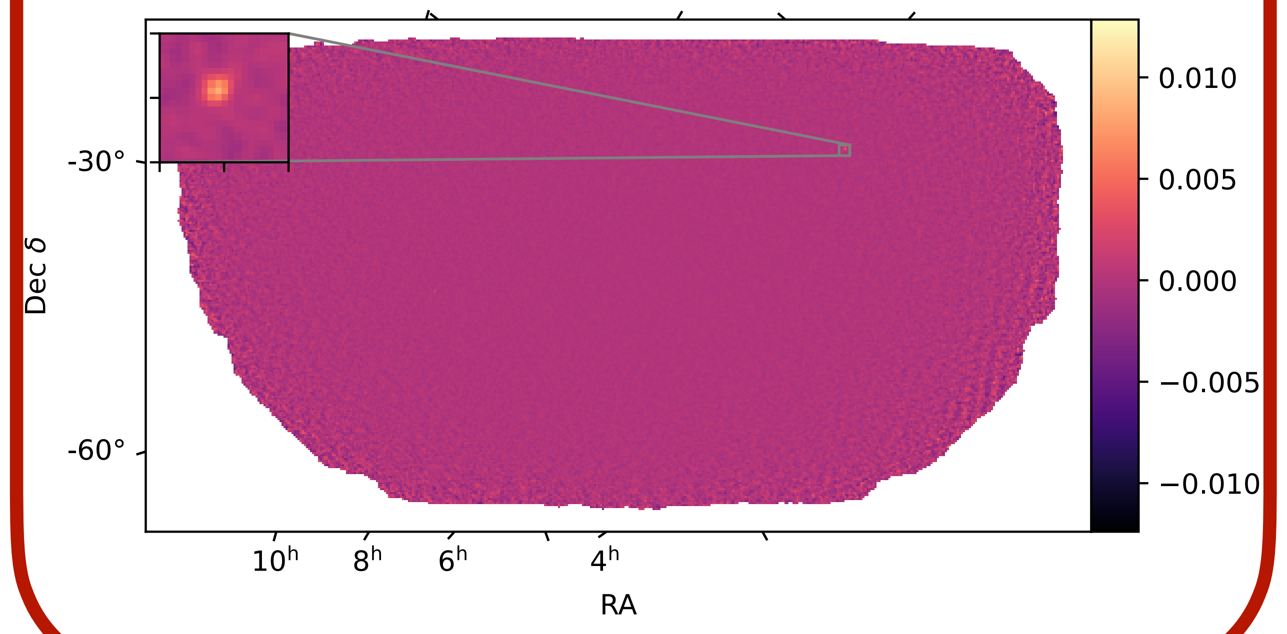
Time Bin Mosaic

Sky/Background
Variance/etc. Images



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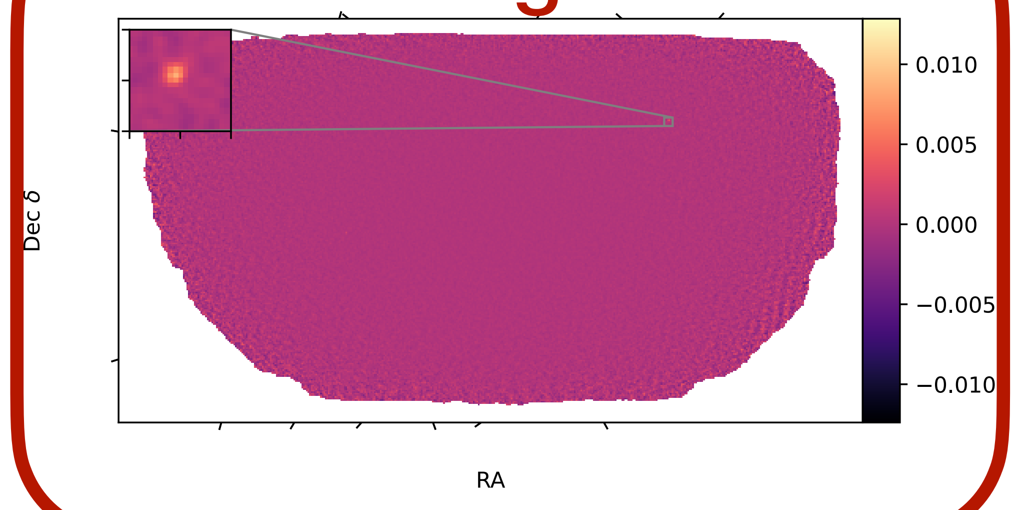

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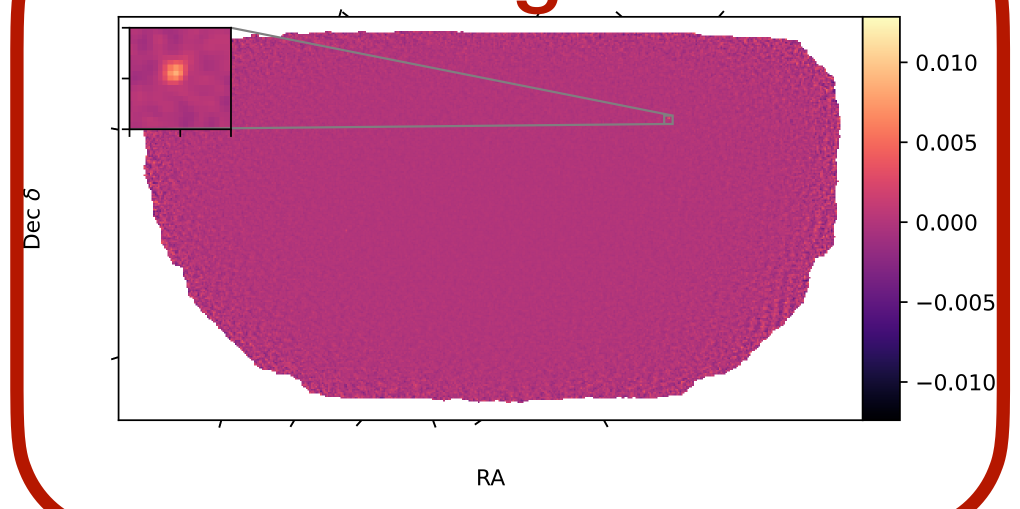

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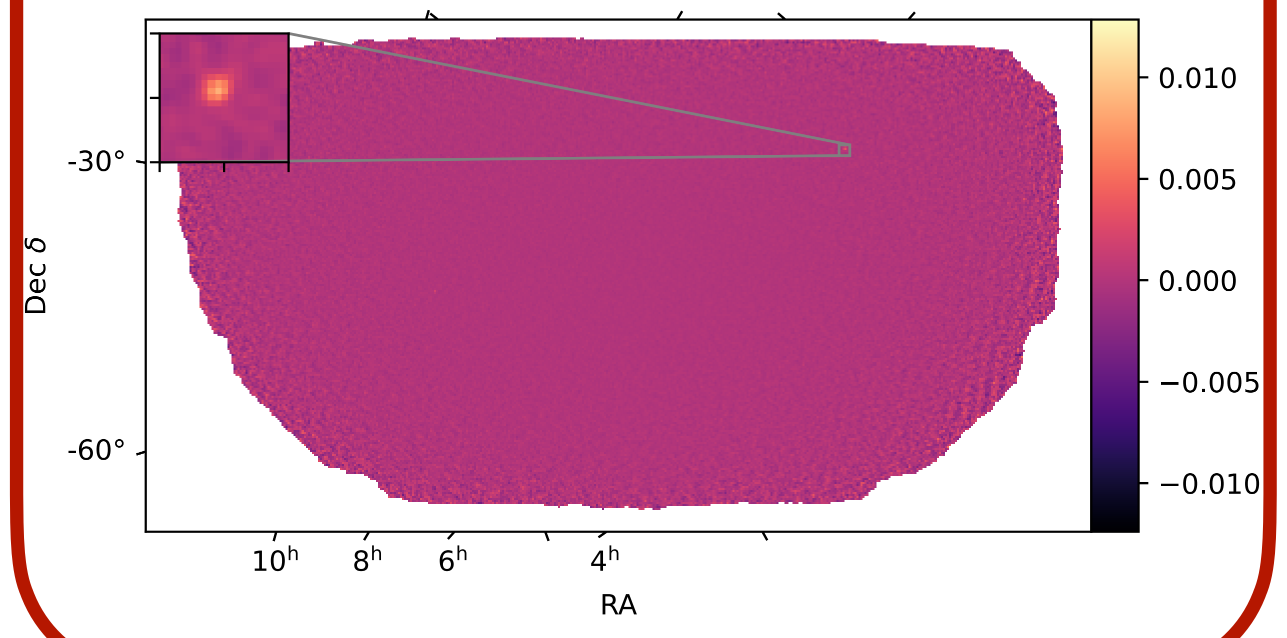

batcelldetect →

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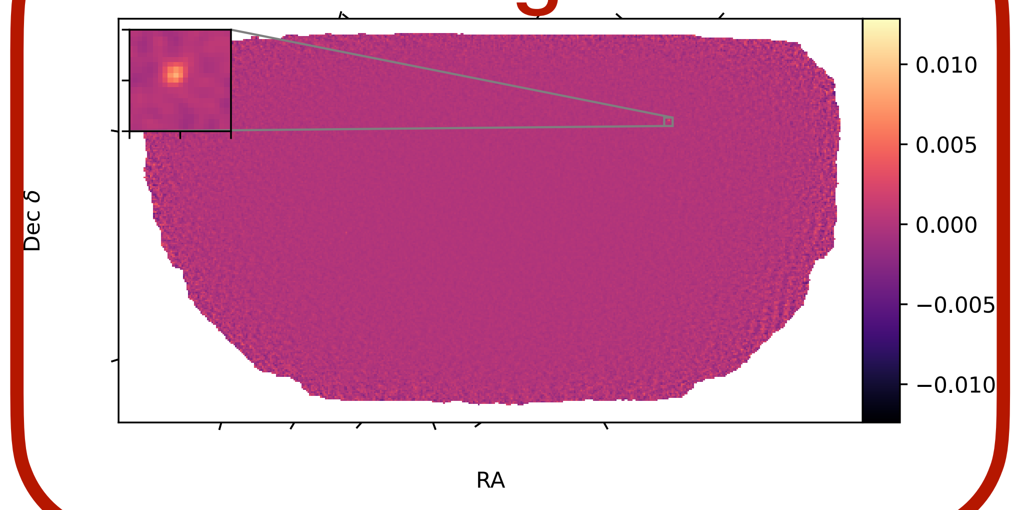
$w_{i,j} \times$ 

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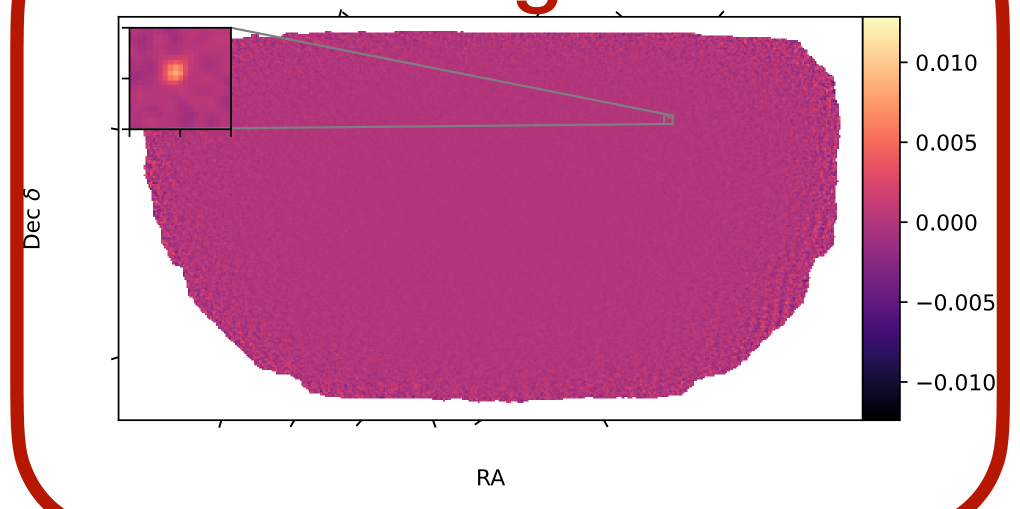
$w_{i,j} \times$ 

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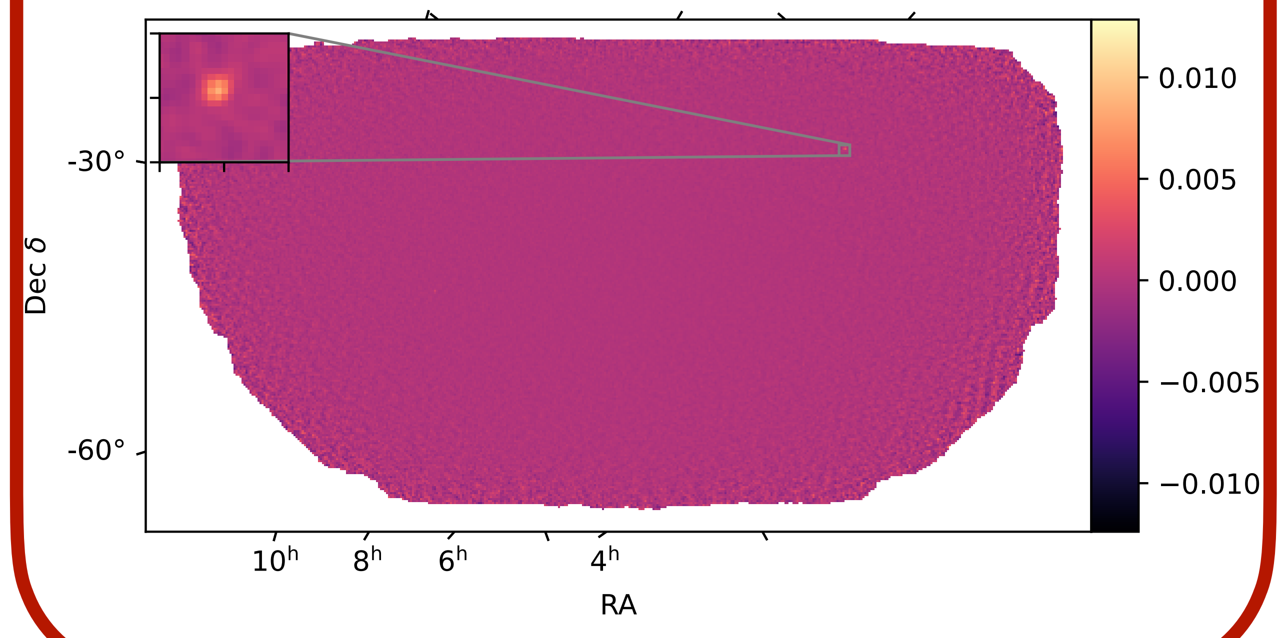

batcelldetect →