VARIABILITY ANALYSIS OF TEV BLAZAR MARKARIAN 421 WITH SIMULATED CTAO DATA

Nevis REU Final Presentations, 7/31/25

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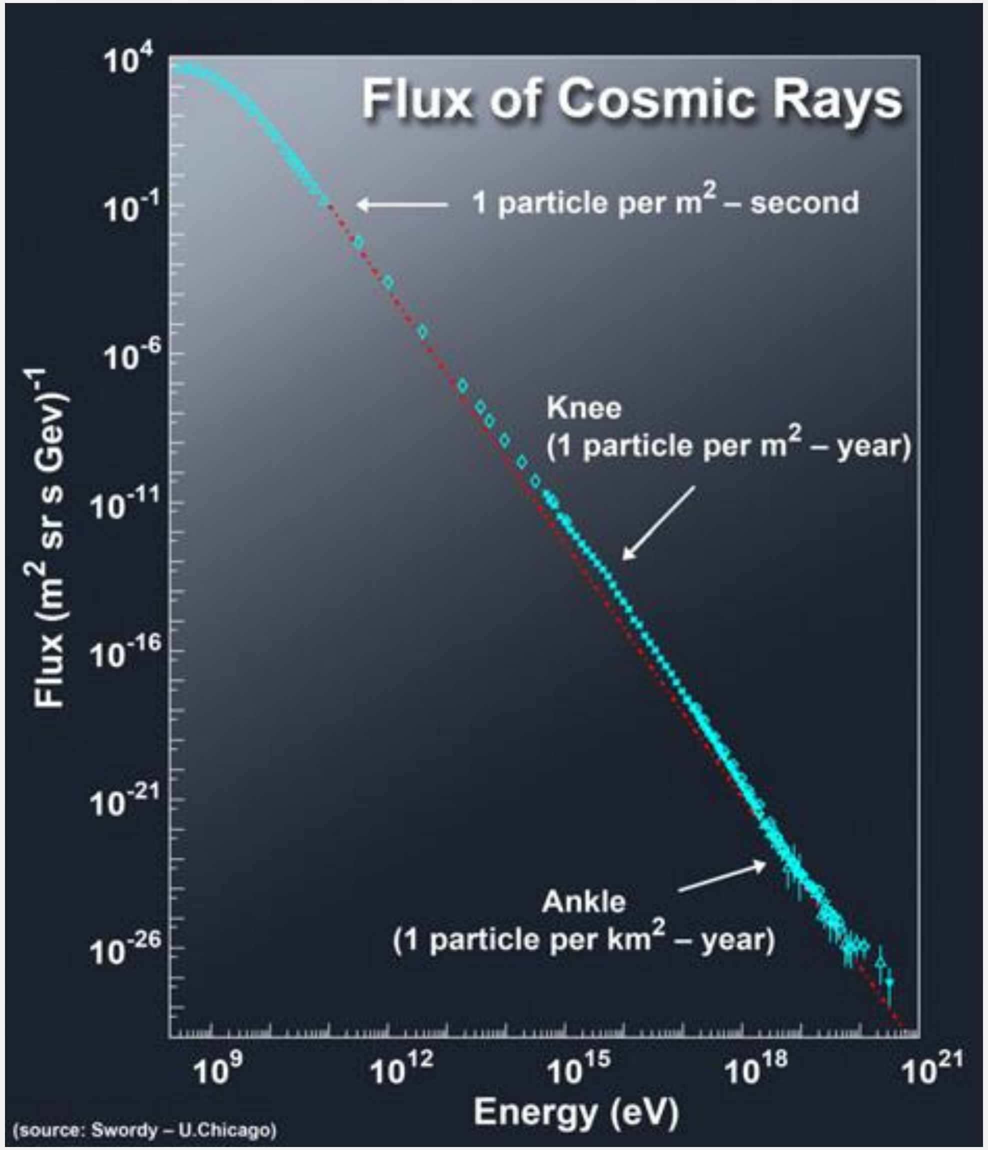
GAMMA-RAY ASTRONOMY

- High-level motivation: to understand the highest-energy objects/events in the universe
- In particular, understand where high-energy cosmic rays come from
- Cosmic Particle Accelerators!
- We cannot use cosmic rays to study these, need to look at charge-neutral messengers like photons and neutrinos



DOI: 10.1051/epjconf/201714510001

THE TEV SKY

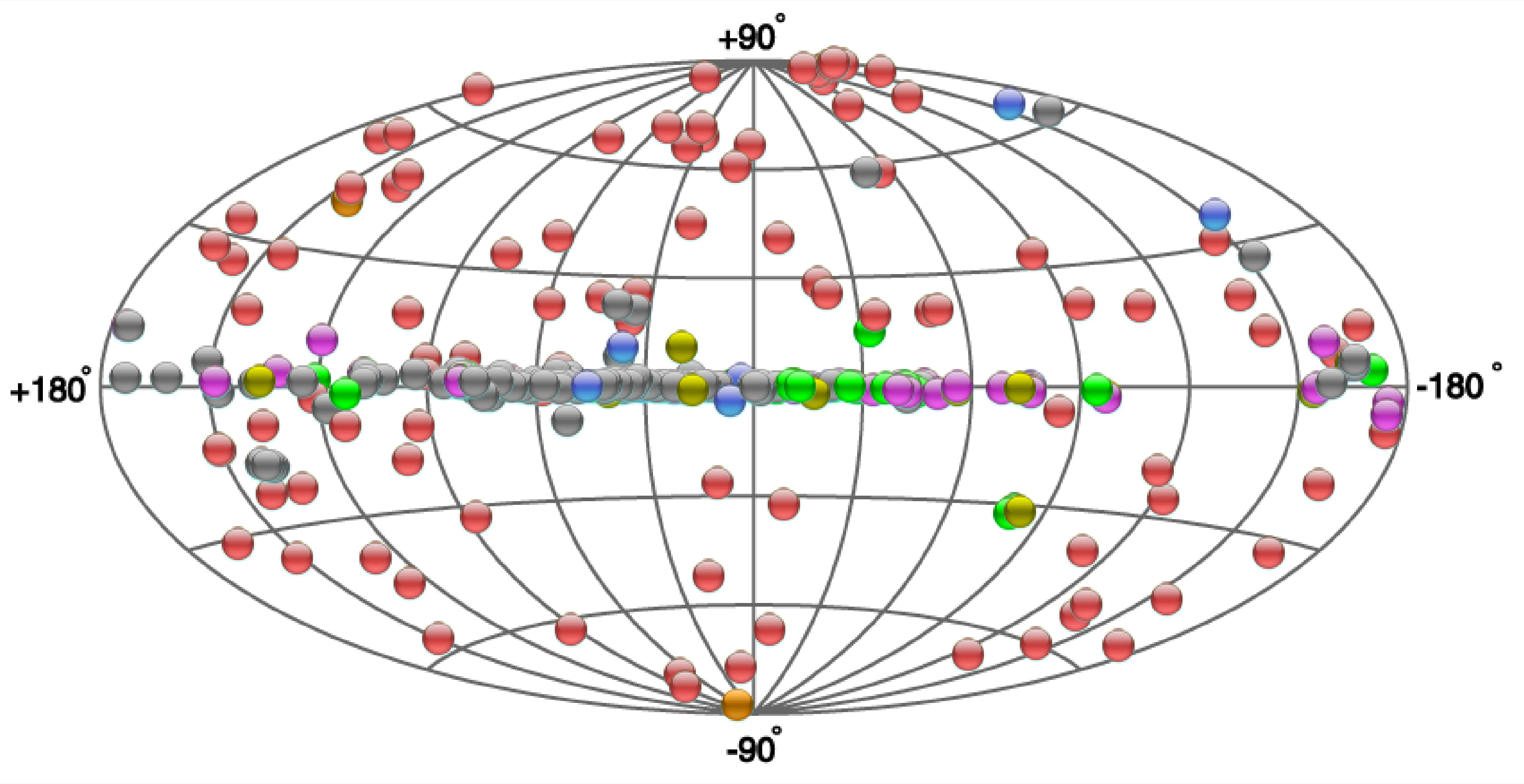
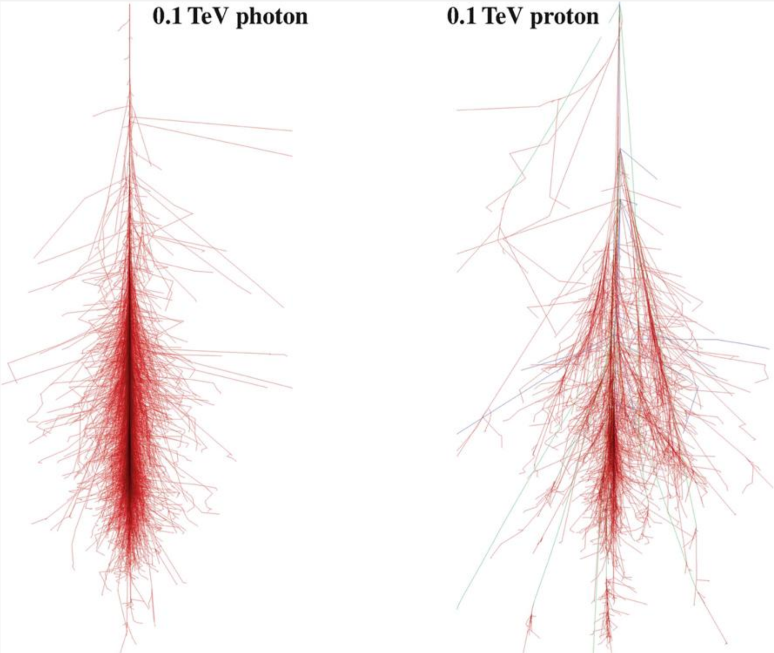


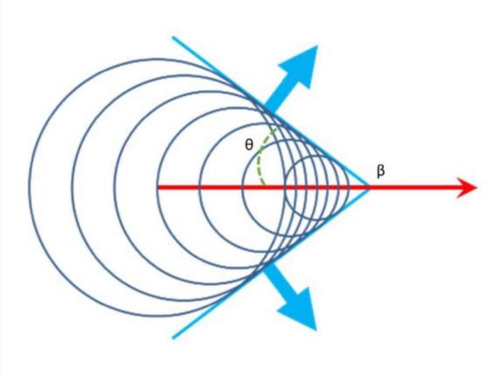
Image via TeVCat

Source Types

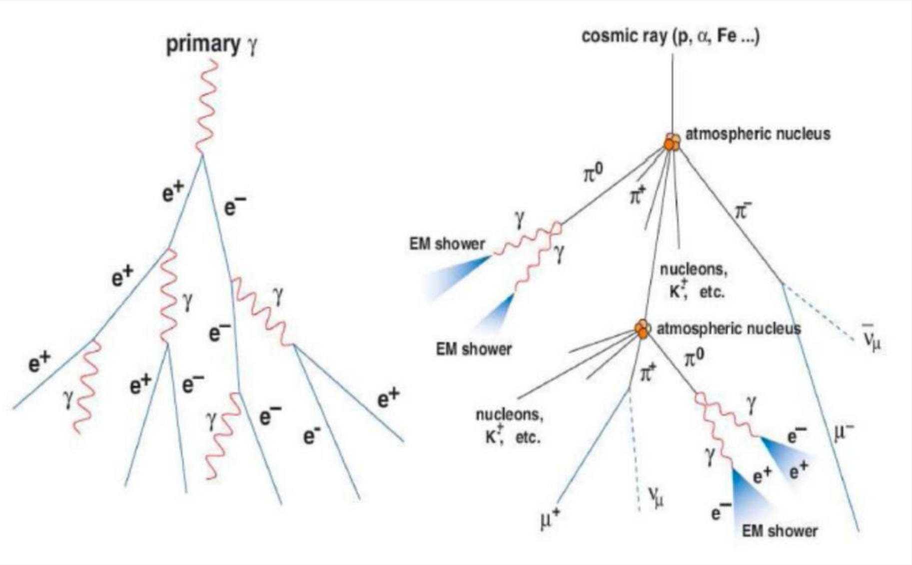
- Starburst
- XRB Nova Gamma BIN Binary PSR
- FRI HBL FSRQ LLAGN Blazar AGN (unknown type) LBL IBL GRB
- DARK UNID Other
- SNR/Molec. Cloud SNR Superbubble Shell Giant Molecular Cloud Composite SNR
- PWN TeV Halo Candidate PWN/TeV Halo TeV Halo
- Globular Cluster BL Lac (class unclear) Cat. Var. BIN Star Forming Region WR Microquasar Massive Star Cluster

IMAGING ATMOSPHERIC CHERENKOV TELESCOPES (IACTS)





https://www.seramarkoff.com/



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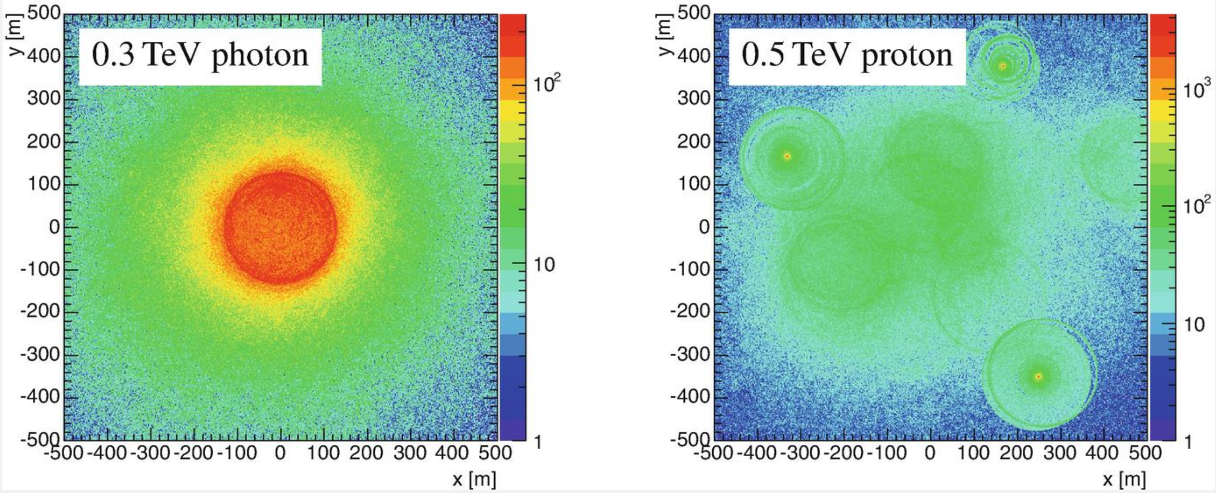
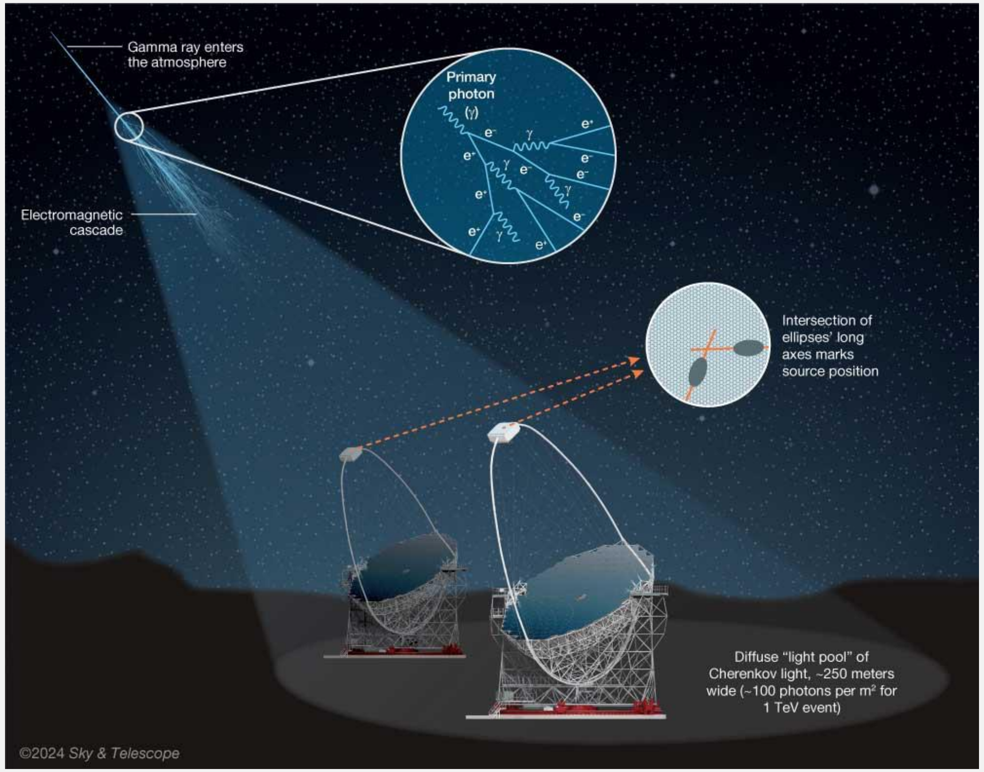
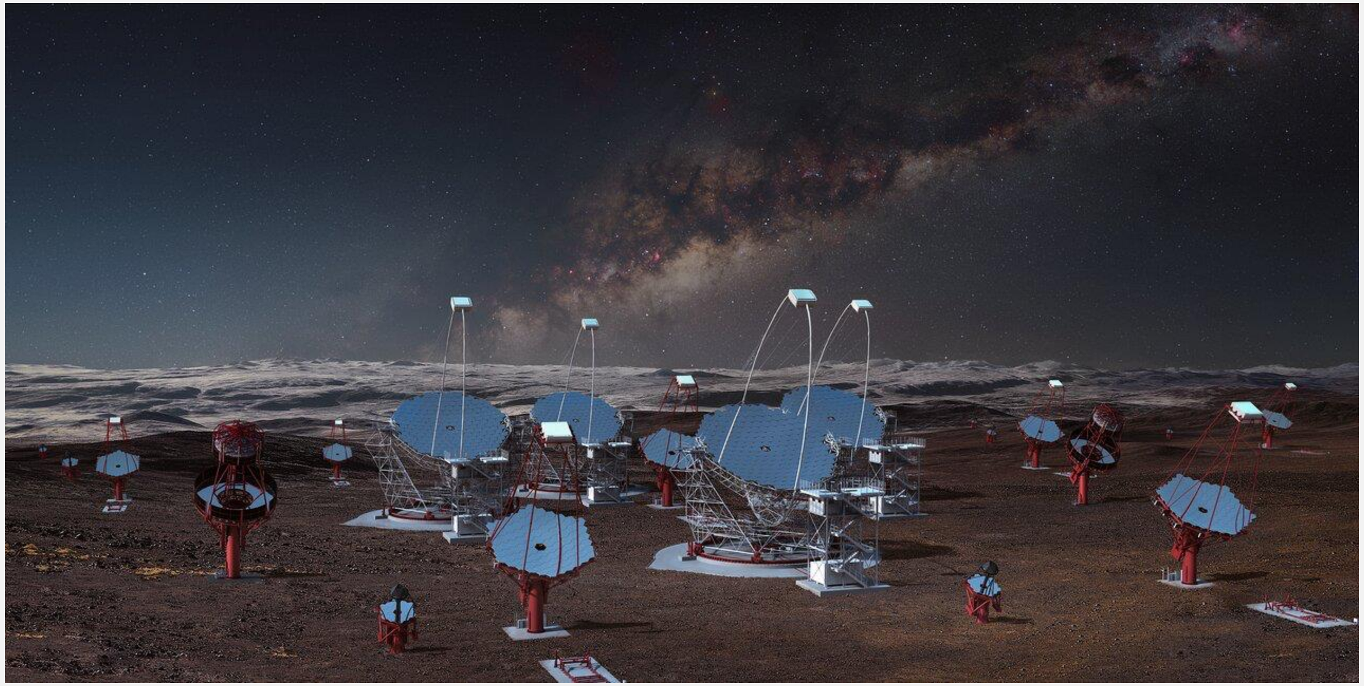


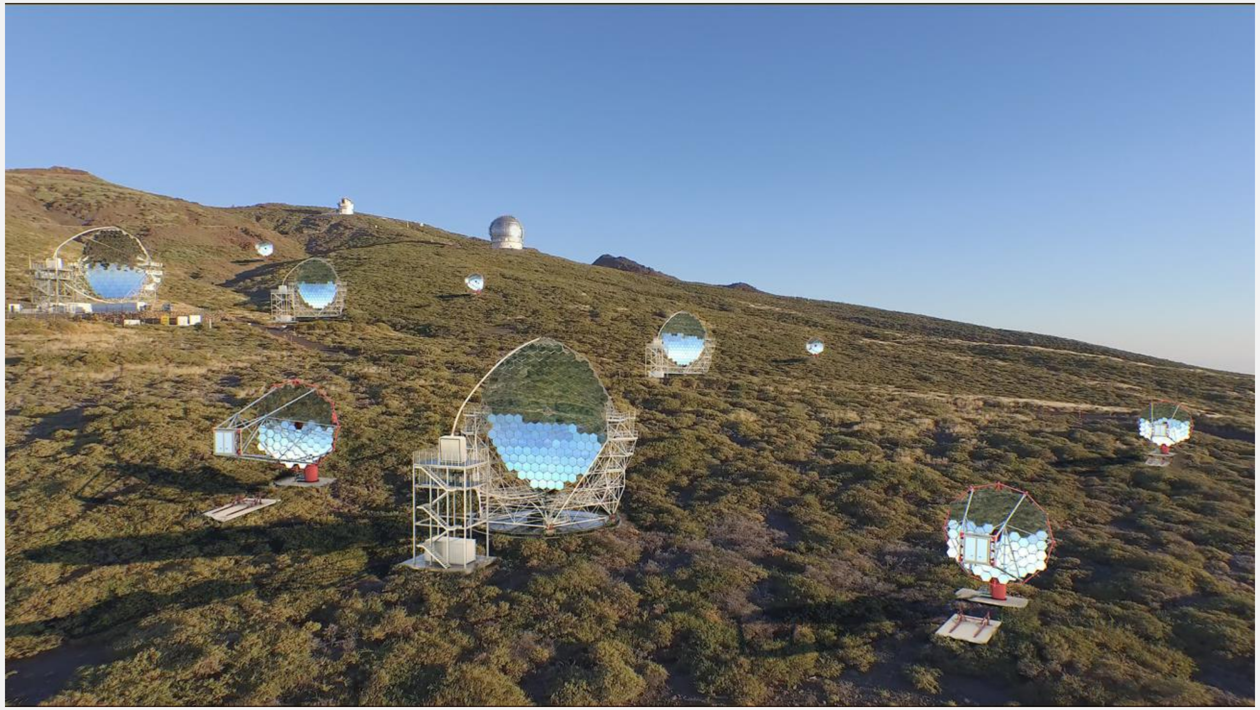
DOI: 10.1007/978-981-16-4544-0_61-1



CTAO

- The next generation IACT
- Currently under construction
- Small, medium, and large-sized telescopes with varied energy ranges
- Two arrays for full-sky coverage
- Factor of 10 higher sensitivity than last-generation instruments

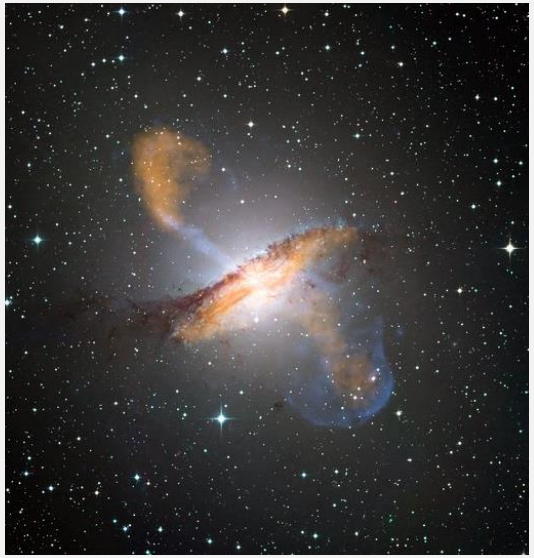




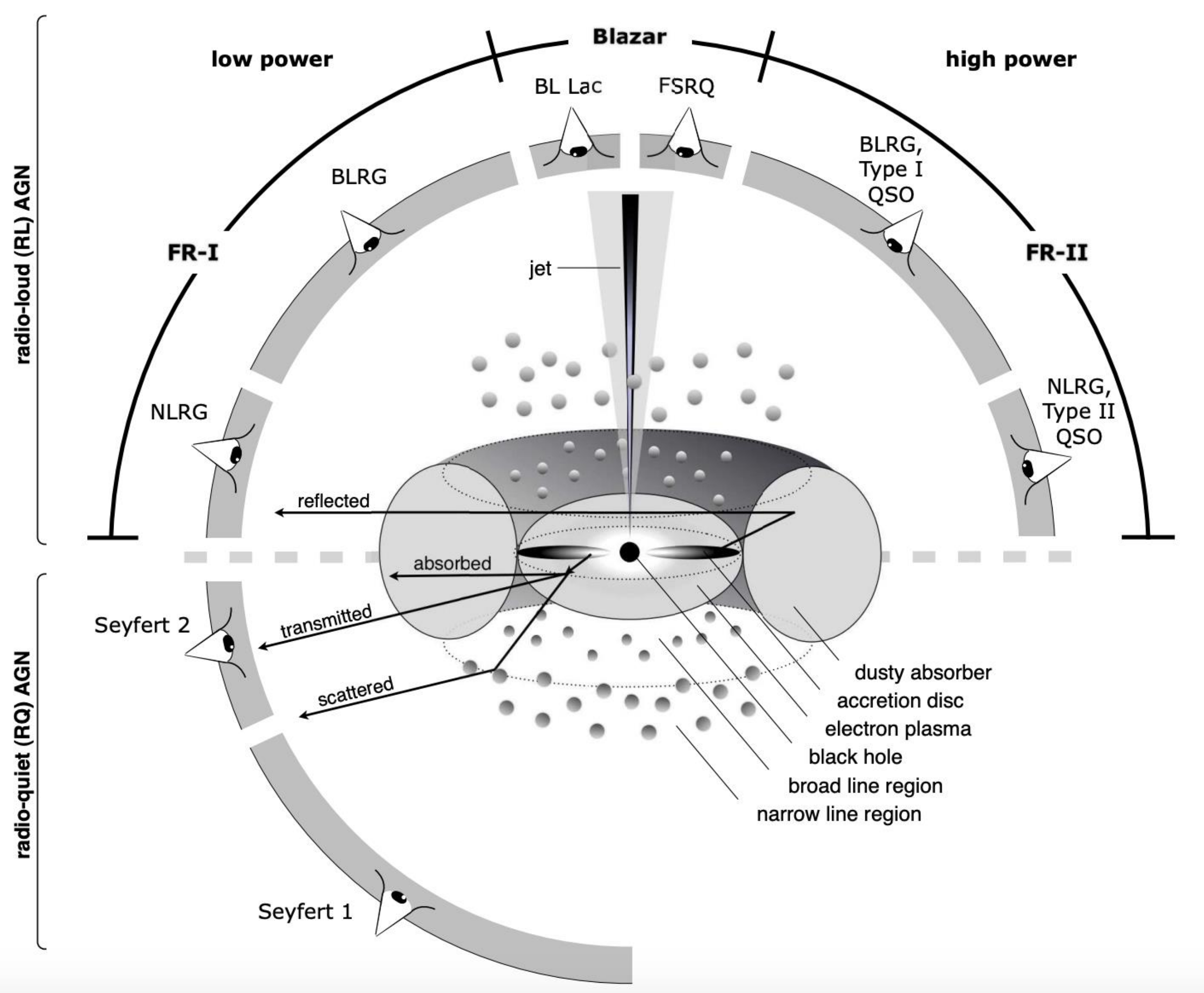
Images from CTAO Artistic Renderings

BLAZARS: COMMON SOURCES OF TEV GAMMA-RAYS

- Active Galactic Nuclei (AGN) are black holes at the center of galaxies that are actively accreting matter
- Depending on the viewing angle, presence of jets, and accretion rate, we see variety of different objects
- When the relativistic jet is pointed directly at an observer, the observer sees a **blazar**



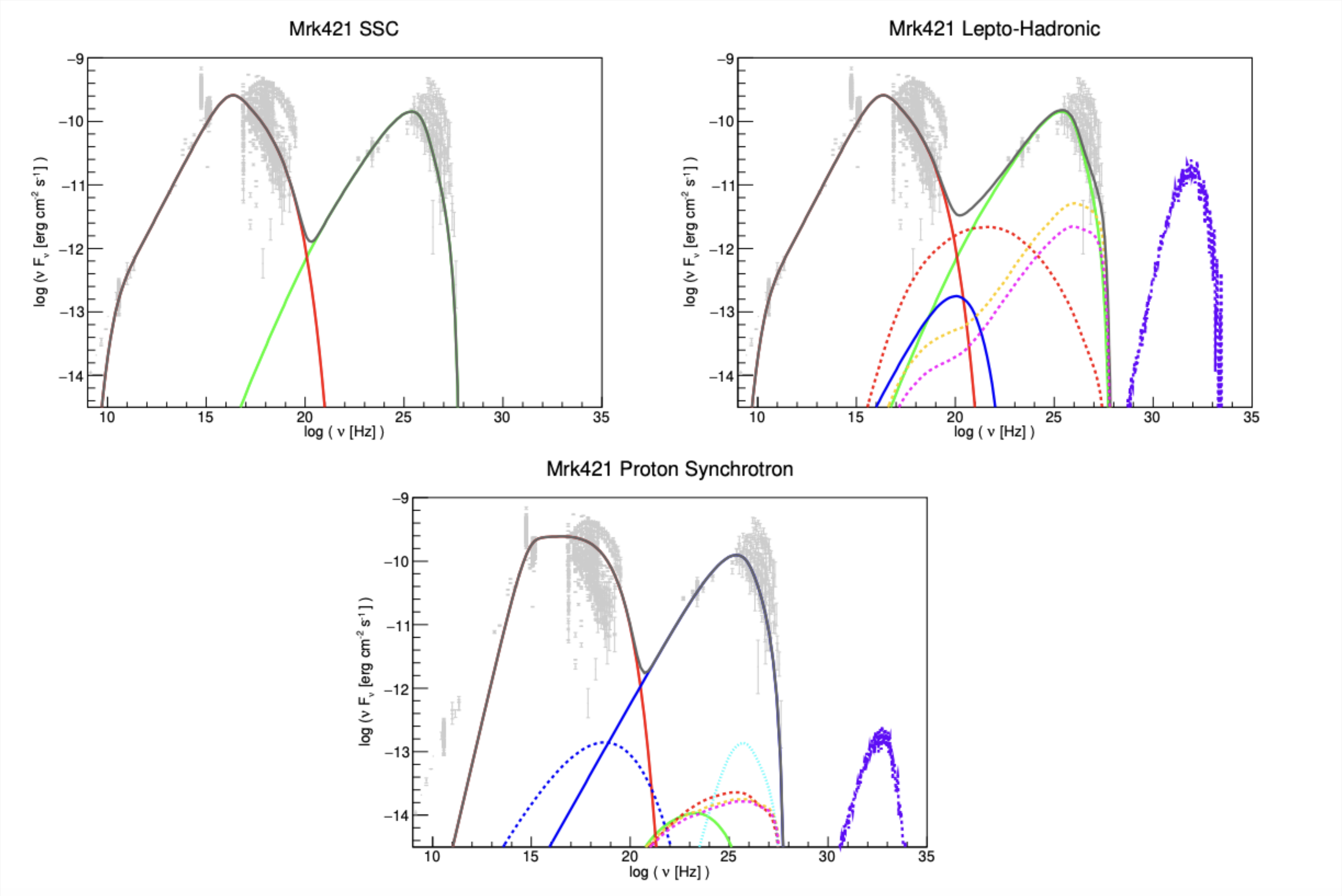
https://www.eso.org/public/images/eso0903a



arXiv:1302.1397

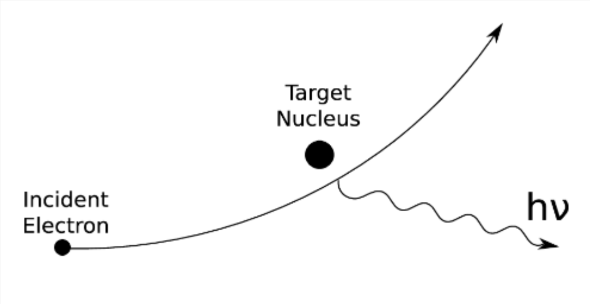
BLAZAR GAMMA RAY EMISSION

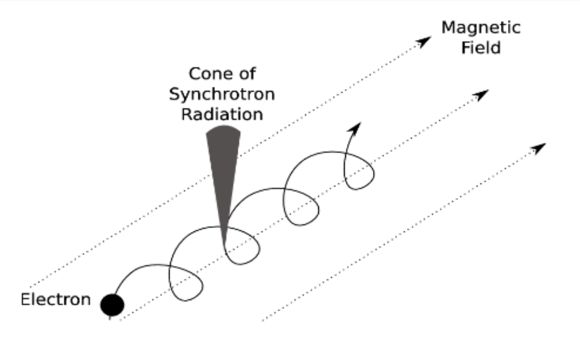
- Blazars have broad spectral energy distributions (SEDs) with two peaks
- Non-thermal emission
- Lower energy peak in UV to X-ray from synchrotron emission
- High energy peak in gamma rays
- Can be from leptonic or hadronic processes, or a mix of the two (not always clear)

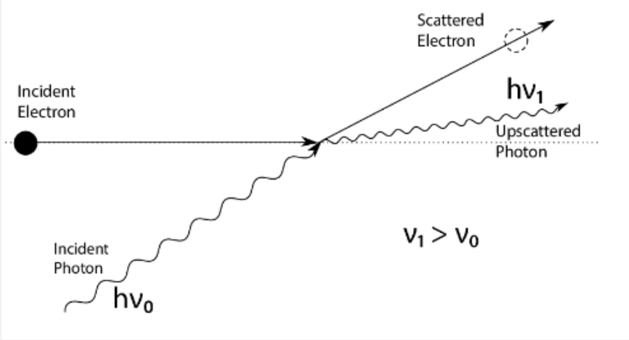


BLAZAR GAMMA RAY EMISSION

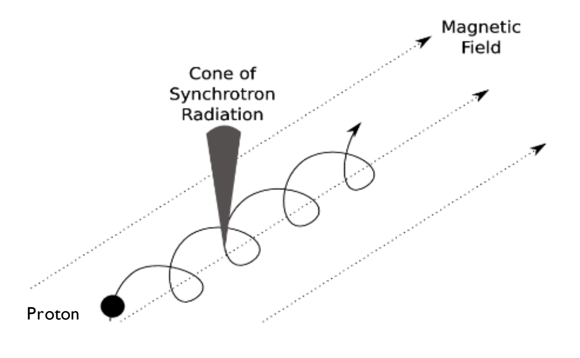
- Leptonic:
  - Electron Synchrotron Emission
  - Bremsstrahlung
  - Inverse Compton Scattering

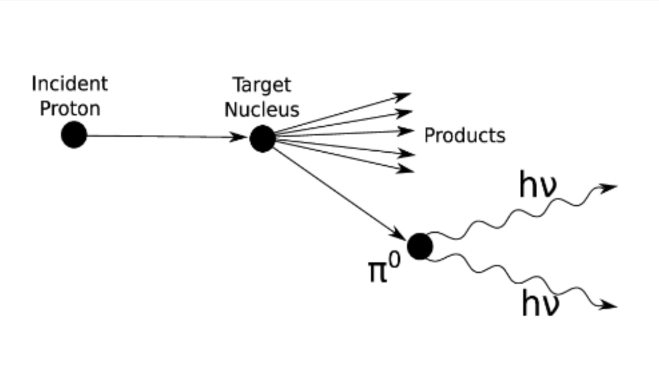






- Hadronic:
  - Proton Synchrotron Emission
  - Neutral pion decay, processes that produce pions also produce neutrinos





Images from Colin Adams' thesis defense, July 2024

BLAZAR GAMMA RAY EMISSION

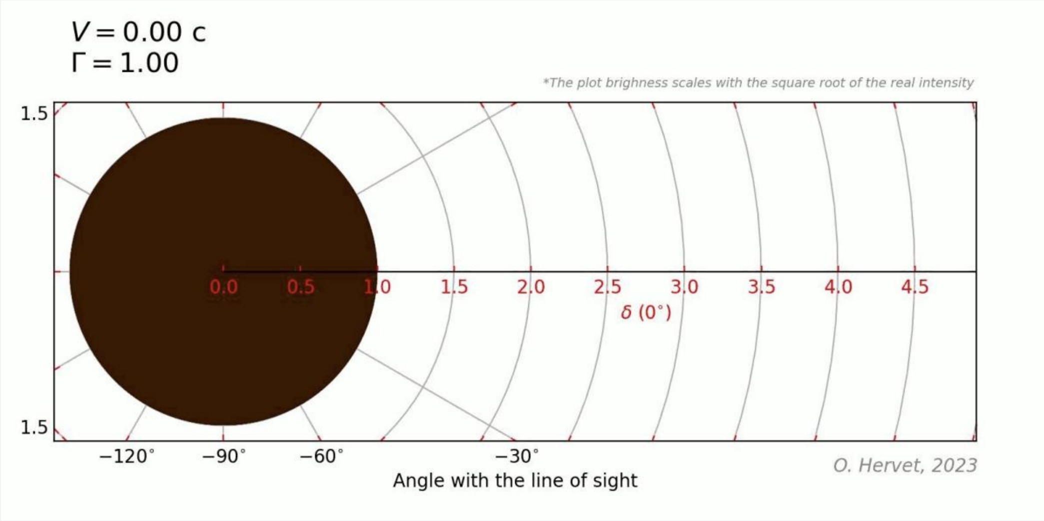
- Non-thermal emission from AGNs comes from processes in the relativistic jets
- Spherical emission "blob" moving at relativistic speeds
- Leads to Doppler boosting
- Quantified by a doppler factor δ

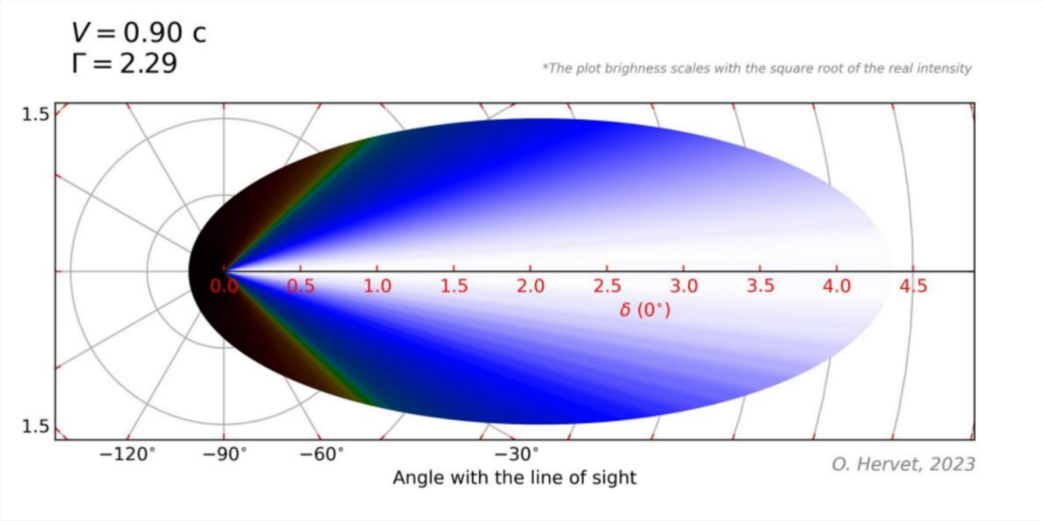
Lorentz Factor:

$$\Gamma = \frac{1}{\sqrt{1-\beta^2}}, \beta = \frac{v}{c}$$

Doppler Factor:

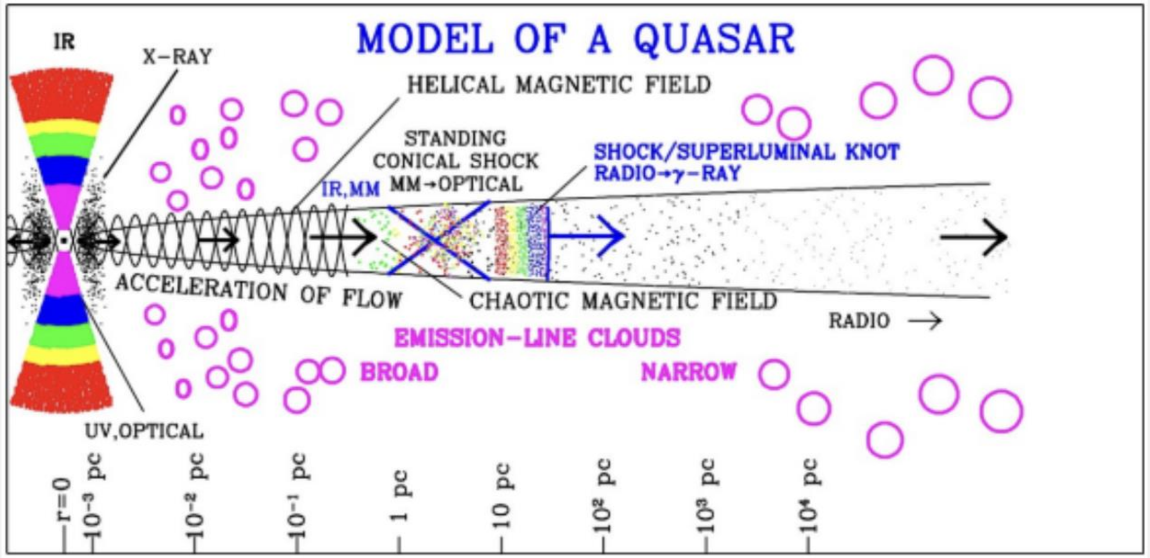
$$\delta = \frac{1}{\Gamma(1-\beta\cos\theta)}$$



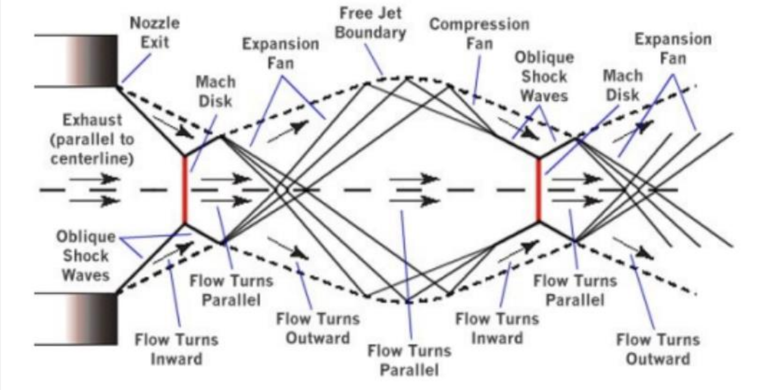


SOURCES OF PARTICLE ACCELERATION (AND VARIABILITY)

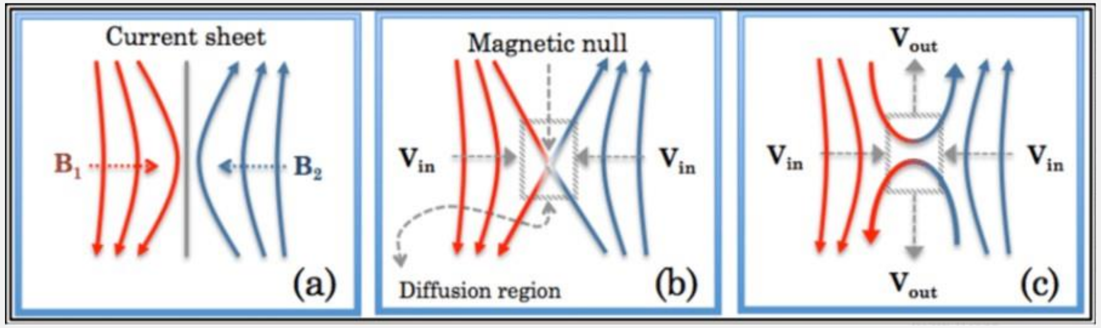
Shocks:



Mascher and Gear 1985



Magnetic Reconnection:



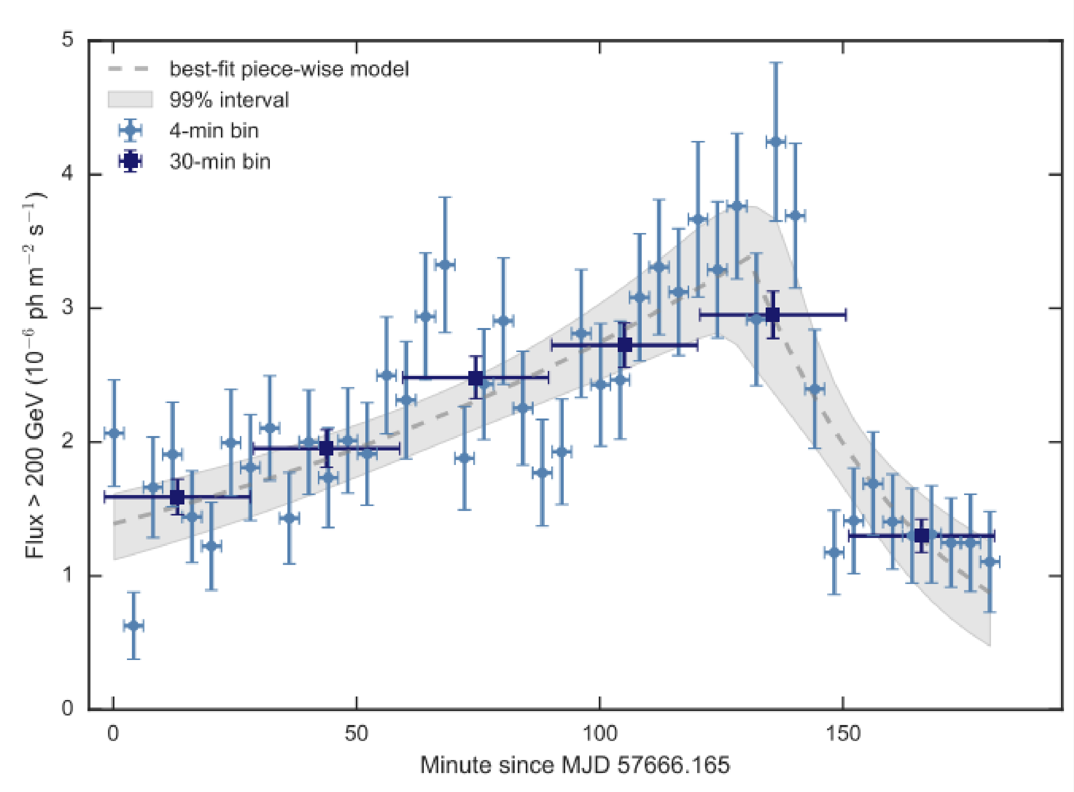
Genestreti et al. 2012

- Processes within the jets can accelerate particles, although they are not clear
- Shocks have more supporting evidence, but cannot explain min-scale variability
- Magnetic reconnections can explain short-timescale variability, but are less well-established

SHORT-TIMESCALE VARIABILITY

- We have observed minute-scale variability from a variety of blazars
- We still do not know what exactly causes variability on such short timescales
- Motivation: we want to maximize our opportunities to observe these flares and understand them better
- Understanding the short-timescale flaring activity of blazars can help us to understand VHE emission mechanisms/regions
- For example, flare timescales put limits on the doppler factor, δ and size, R, of the emitting region.

$$R \leq \frac{ct_{var}\delta}{1+z}$$



arXiv:1802.10113

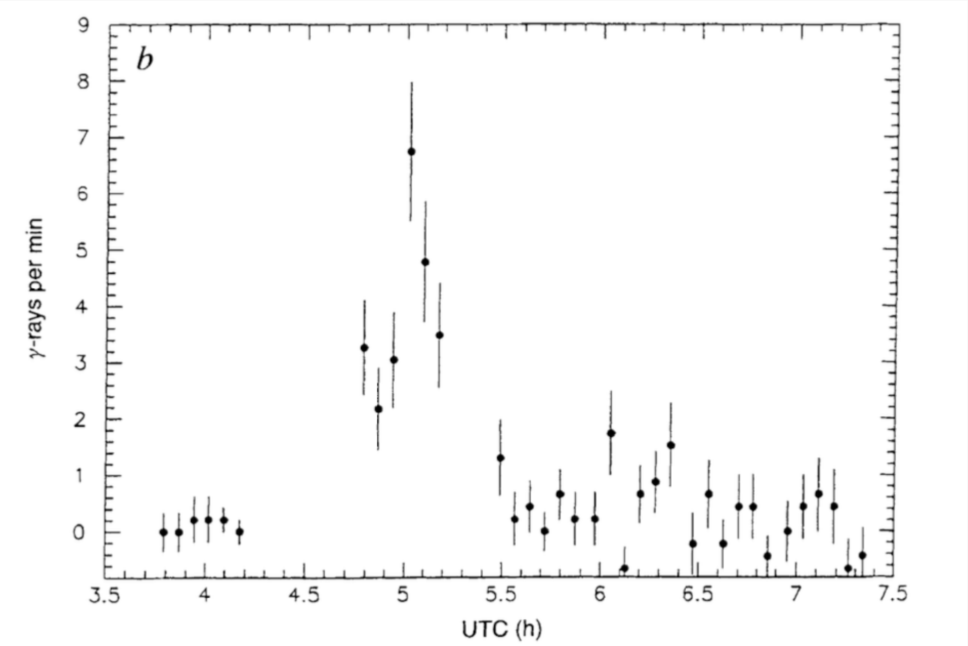
CTAO SCIENCE DATA CHALLENGE AND MY DATA

- While CTAO is being built, collaboration released the SDC
- Develop analysis methods using Gammapy
- My Dataset:
  - Simulated CTAO LTM data from Markarian 421
  - Stored as DL3 FITS files
  - Half-hour observing runs (divided into 4 7.5-minute segments)
  - Once a week for a year

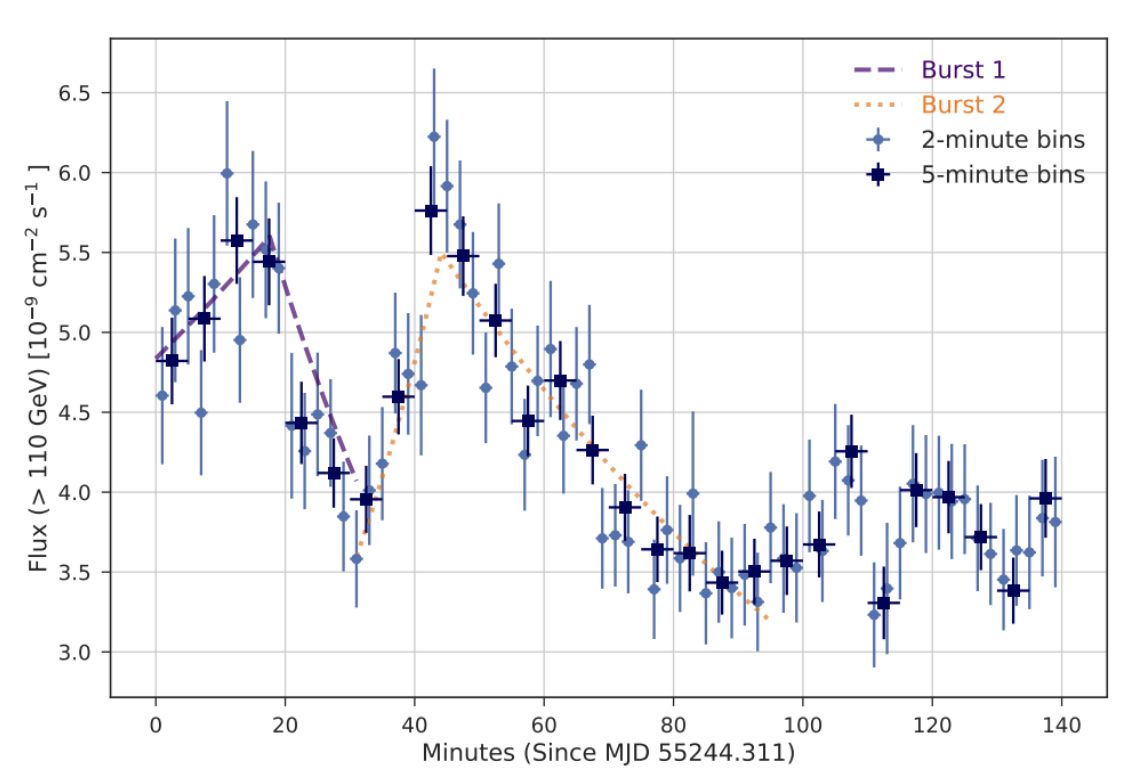
https://en.wikipedia.org/wiki/Markarian_421

MARKARIAN 421

- Nearby (z = 0.031) BL Lac
- First Extragalactic TeV source detected
- History of very short-timescale variability



https://www.nature.com/articles/383319a0

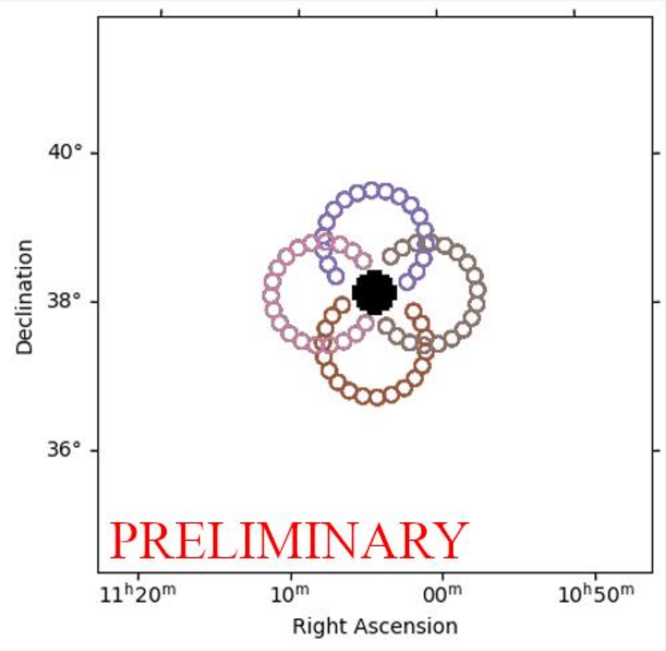


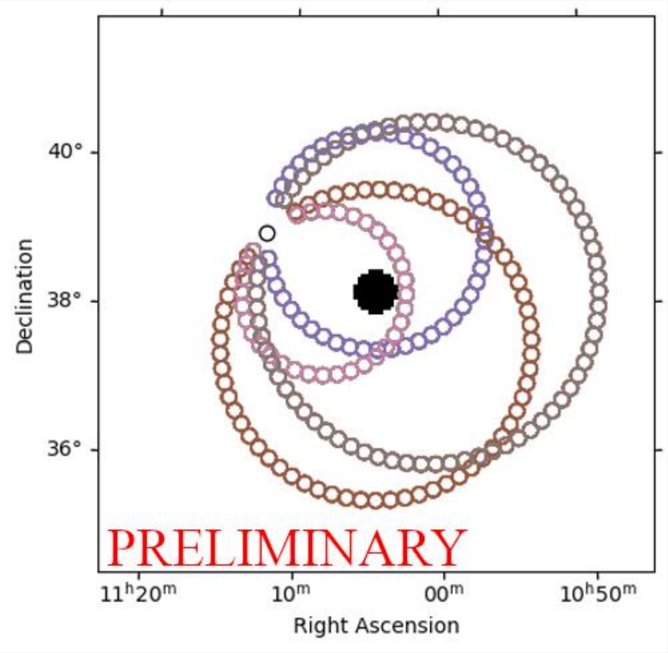
arXiv:2002.03567

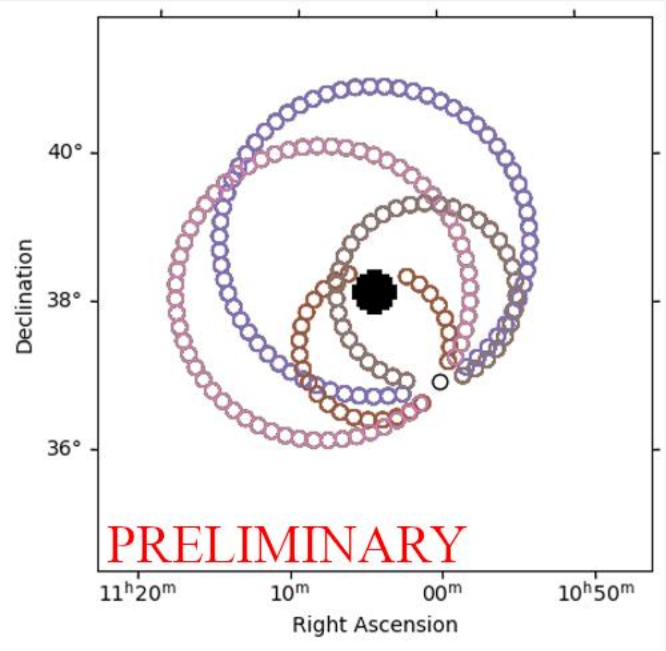
1D ANALYSIS – BACKGROUND VALIDATION

- Reflected Regions background method
- Background validated by placing the on region off the source

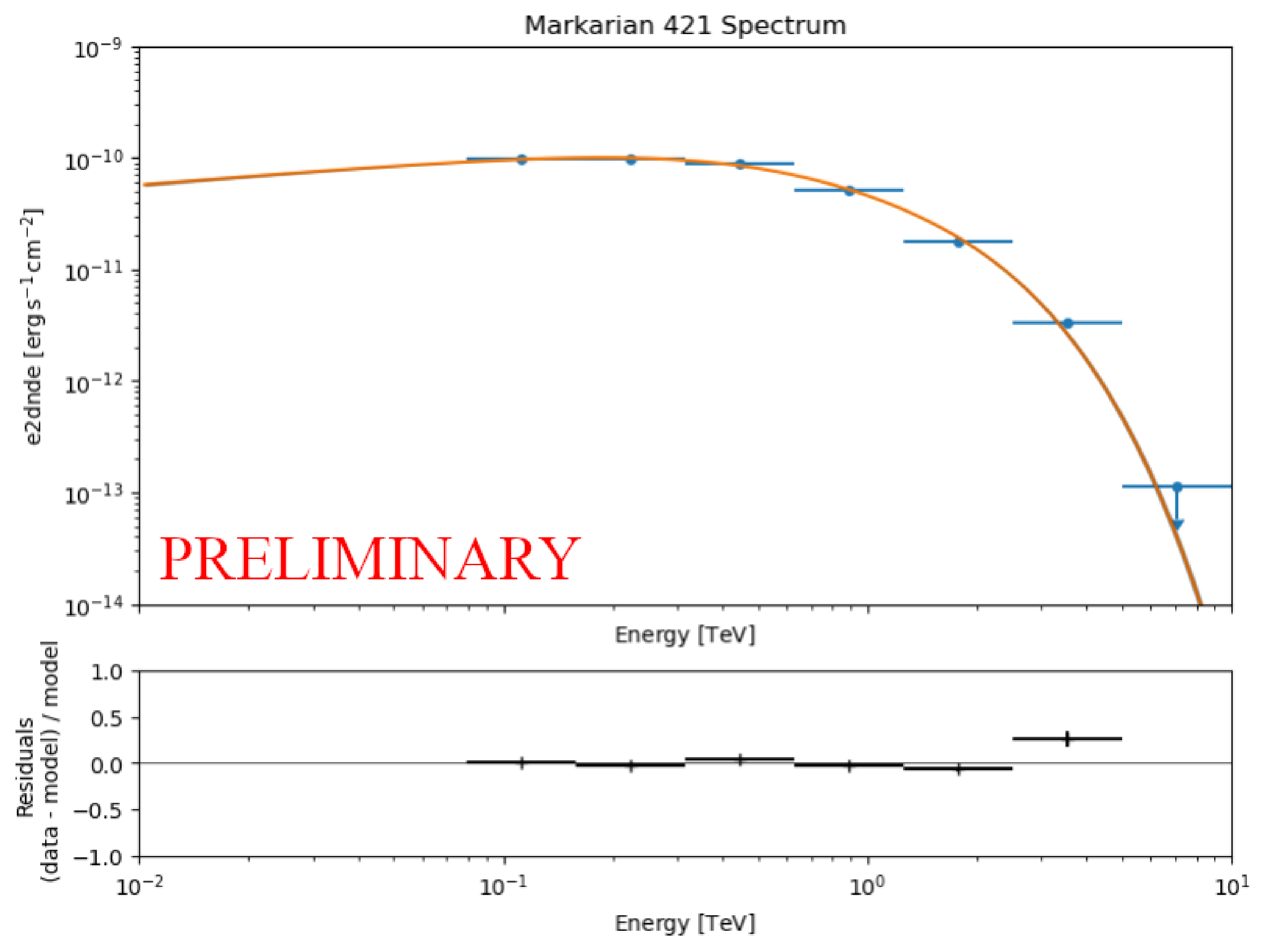
On Source?	Counts	Background	Excess	Significance
Yes	31286	652.895	30633.105	368.0327
No	626	617.024	8.976	0.357
No	620	621.732	-1.732	-0.0688







1D ANALYSIS - SPECTRUM



- After ensuring that the background was appropriately accounted for, I continued with my analysis
- Generated a spectrum between 10 GeV and 10 TeV
  - Fit with a Power law with an exponential cutoff, also accounting for the EBL

$$\phi(E) = \phi_0 \cdot \left(\frac{E}{E_0}\right)^{-\Gamma} \cdot \exp(-(\lambda E)^{\alpha})$$

Fit parameters:

$\phi_0 = (1.0847 \pm 0.0320) \cdot 10^{-10} \frac{photons}{TeV\ s\ cm^2}$

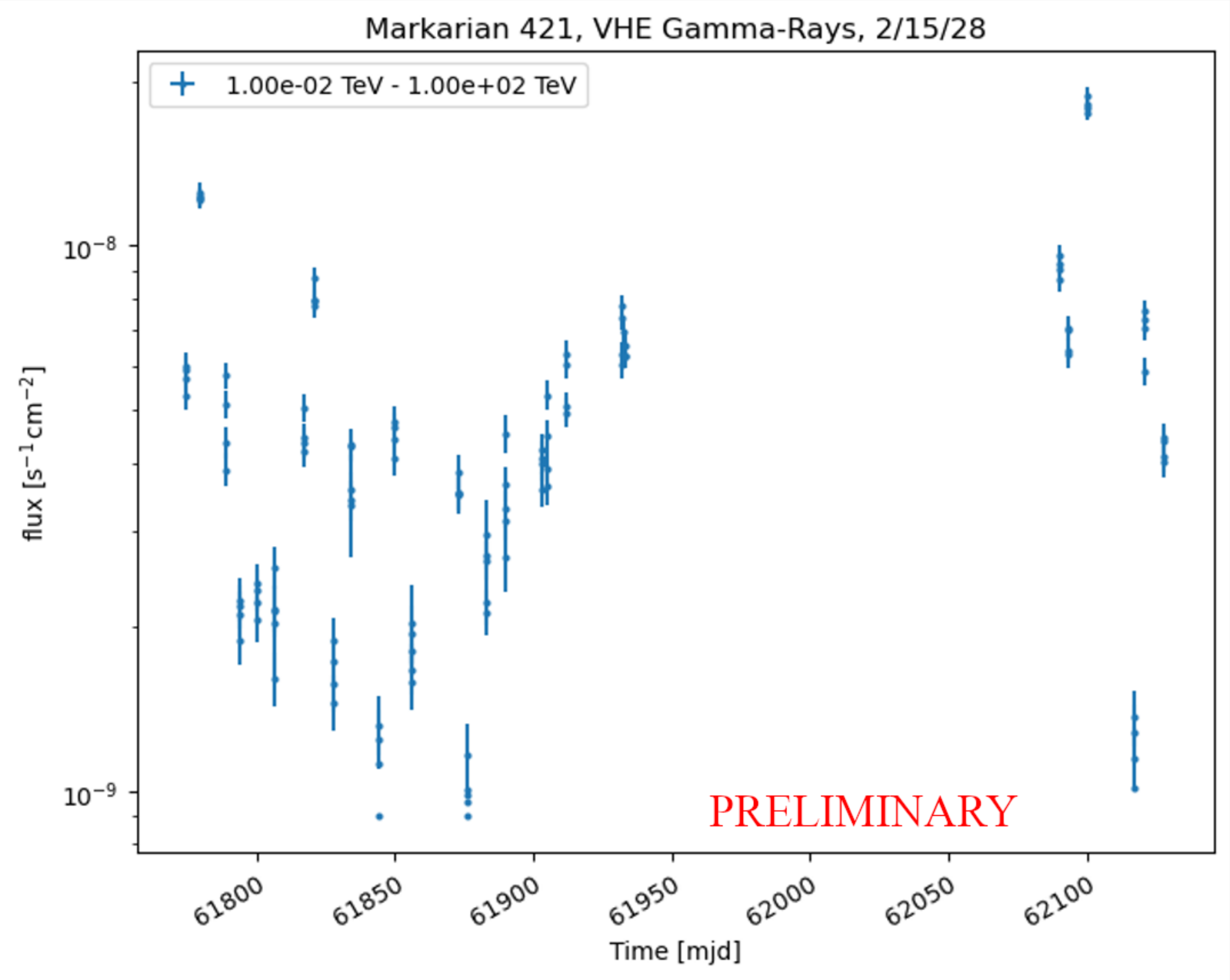
$E_0 = 1\ TeV$ (frozen)

$\Gamma = (1.8004 \pm 0.0154)$

$\lambda = (1.0350 \pm 0.0278) \frac{1}{TeV}$

$\alpha = 1$ (frozen)

1D ANALYSIS – 1-YEAR LIGHT CURVE



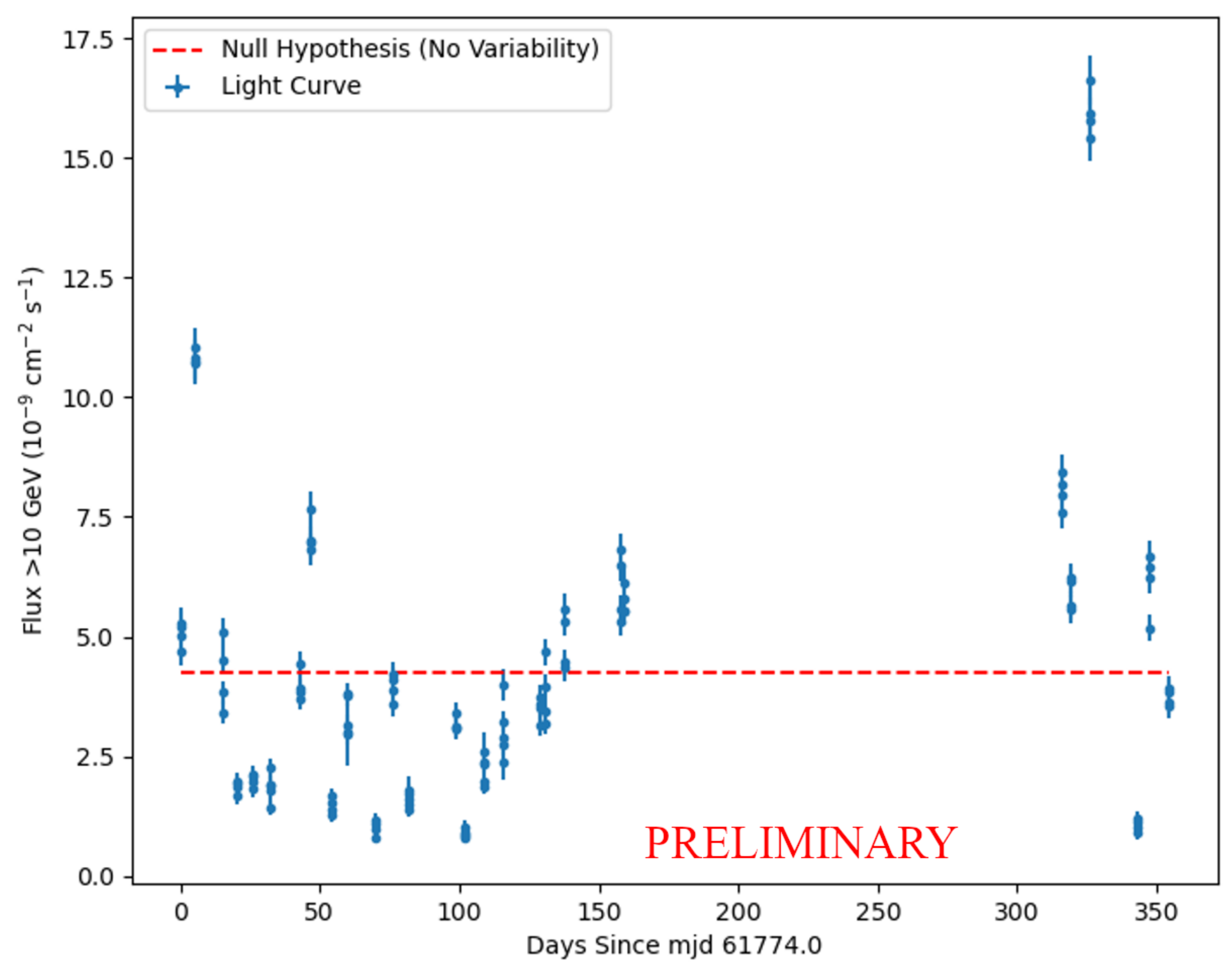
- We can clearly see there's some variability
- Variability analysis goals: test for variability over many timescales, determine the smallest timescale over which CTAO will detect significant variability

TESTING FOR VARIABILITY

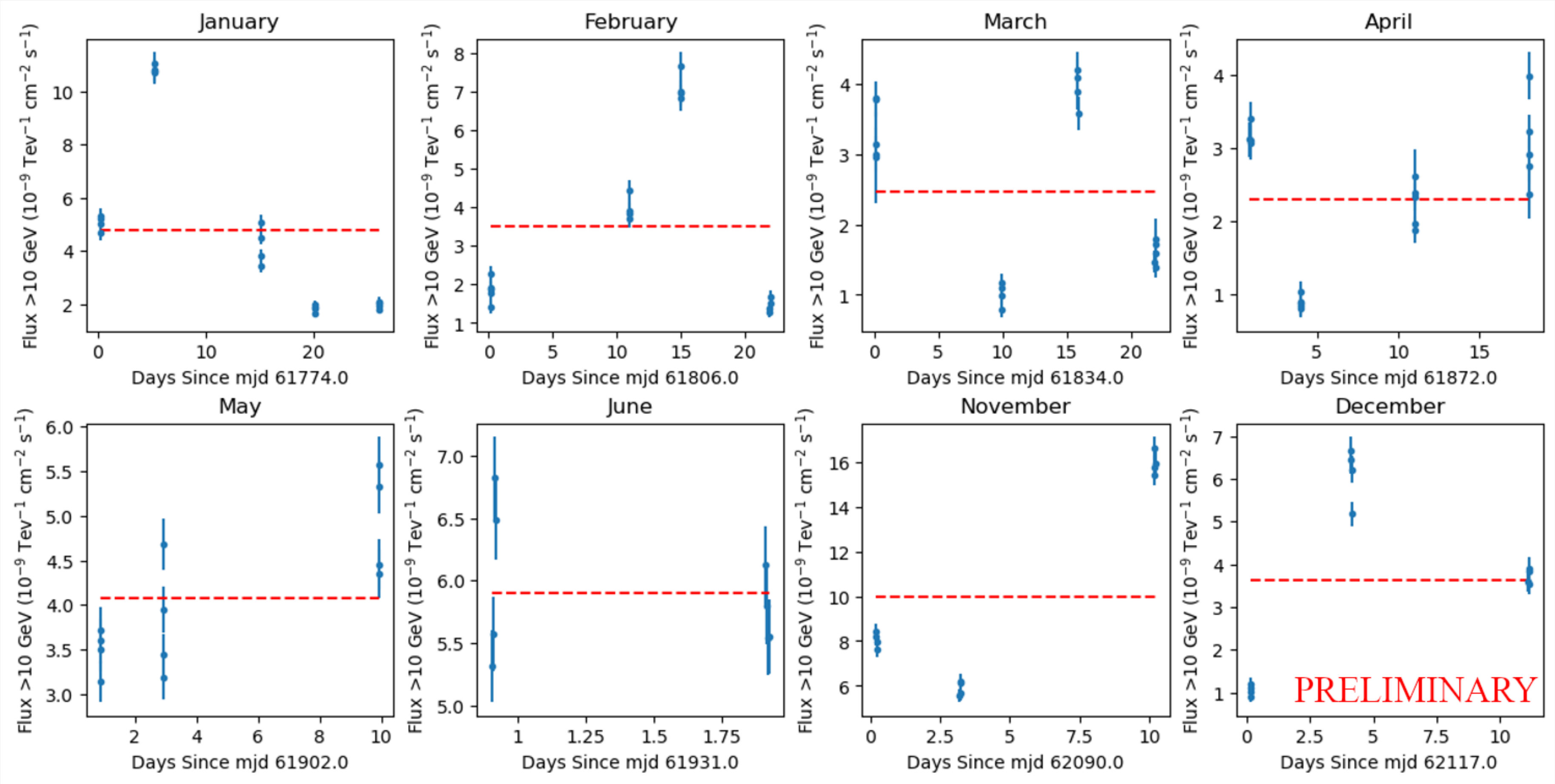
- Determining Variability Probability:
  - Chi^2 test performed on flat-line fit (avg flux)

$$\chi^2 = \frac{1}{(N-1)} \sum_{i=0}^{N} \frac{(F_i - \langle F \rangle)^2}{{\sigma_i}^2}$$

  - 1 – P-value is the variability probability
- Measured Avg Variability Probability over decreasing time intervals
- 1 year:
  - $\chi^2 = 17557.7$
  - Variability Probability is effectively 1



MONTH-SCALE VARIABILITY

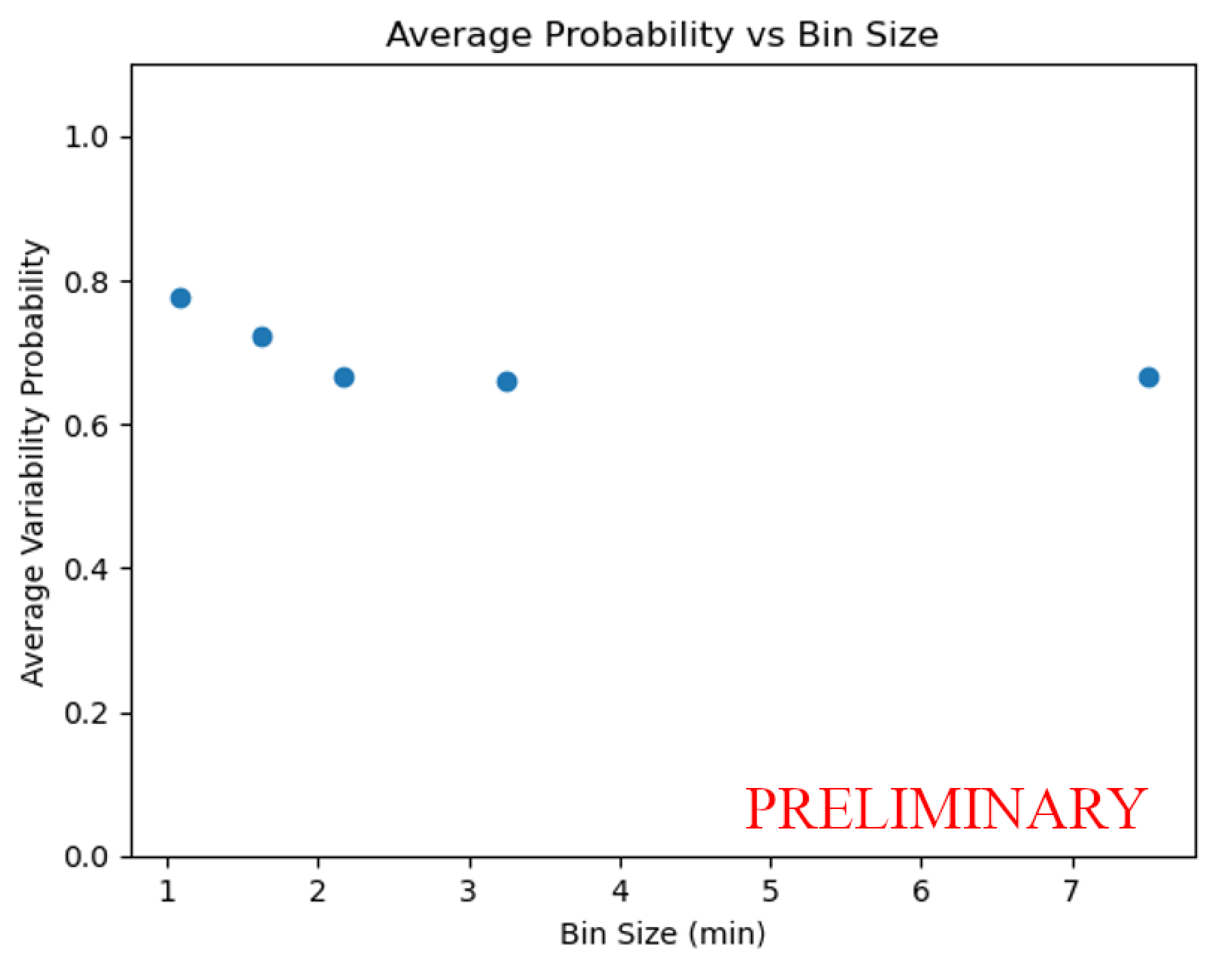


On average:

- $\chi^2 = 1153.4$
- Variability Probability = 0.99937

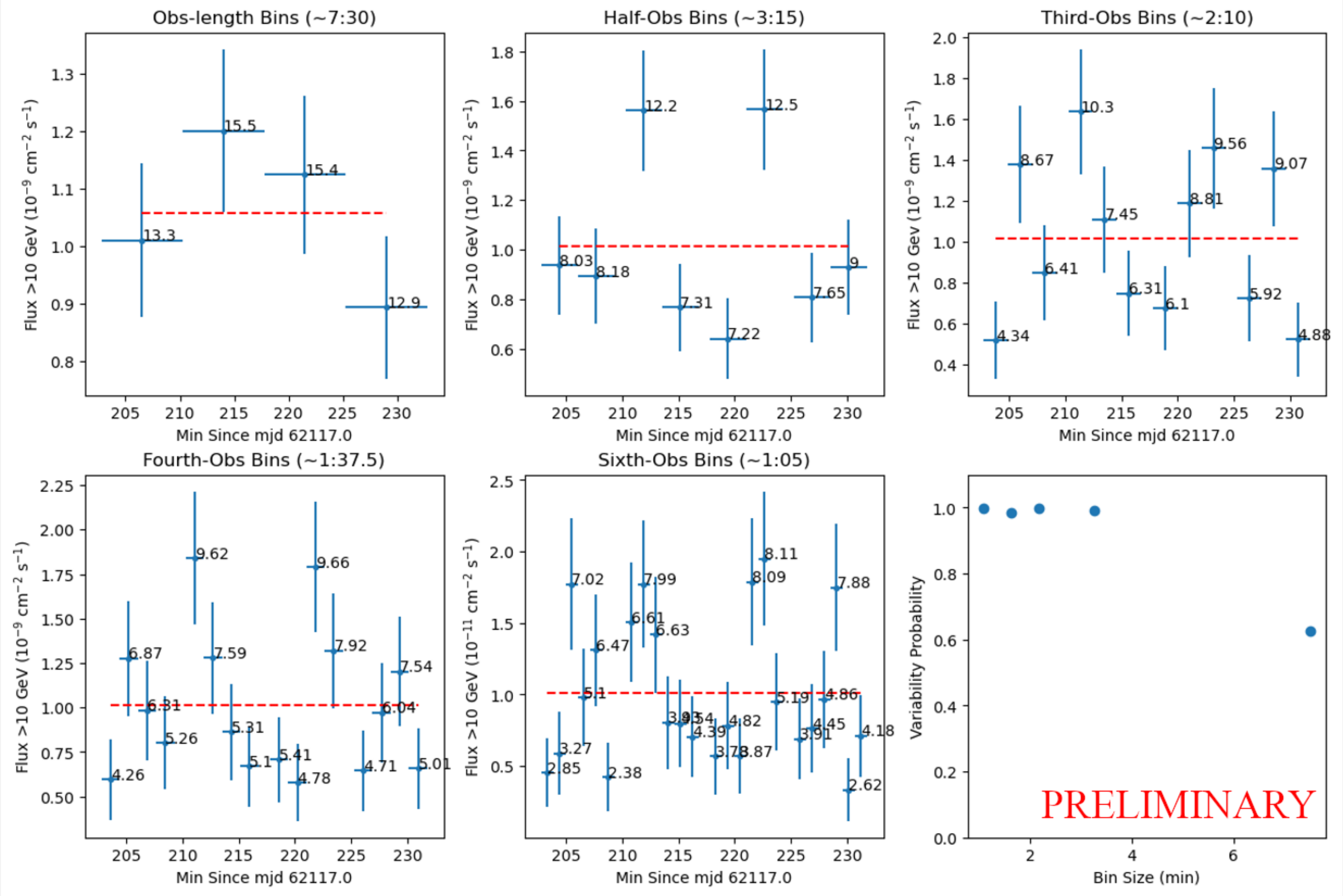
30-MIN OR LESS SCALE

- On a short timescale, decreasing the bin size increases the variability probability on average
- Smaller bin sizes can reveal shorter-timescale variability
- Bins also have less counts, so smaller significances
- Optimal bin size is then the smallest bin size than also fits a significance criteria
- Done for all time intervals with ≤1 full observing run (30 mins, four observations)
- Time intervals tested: 30 mins, 15 mins, 7.5 mins



OPTIMAL BINNING

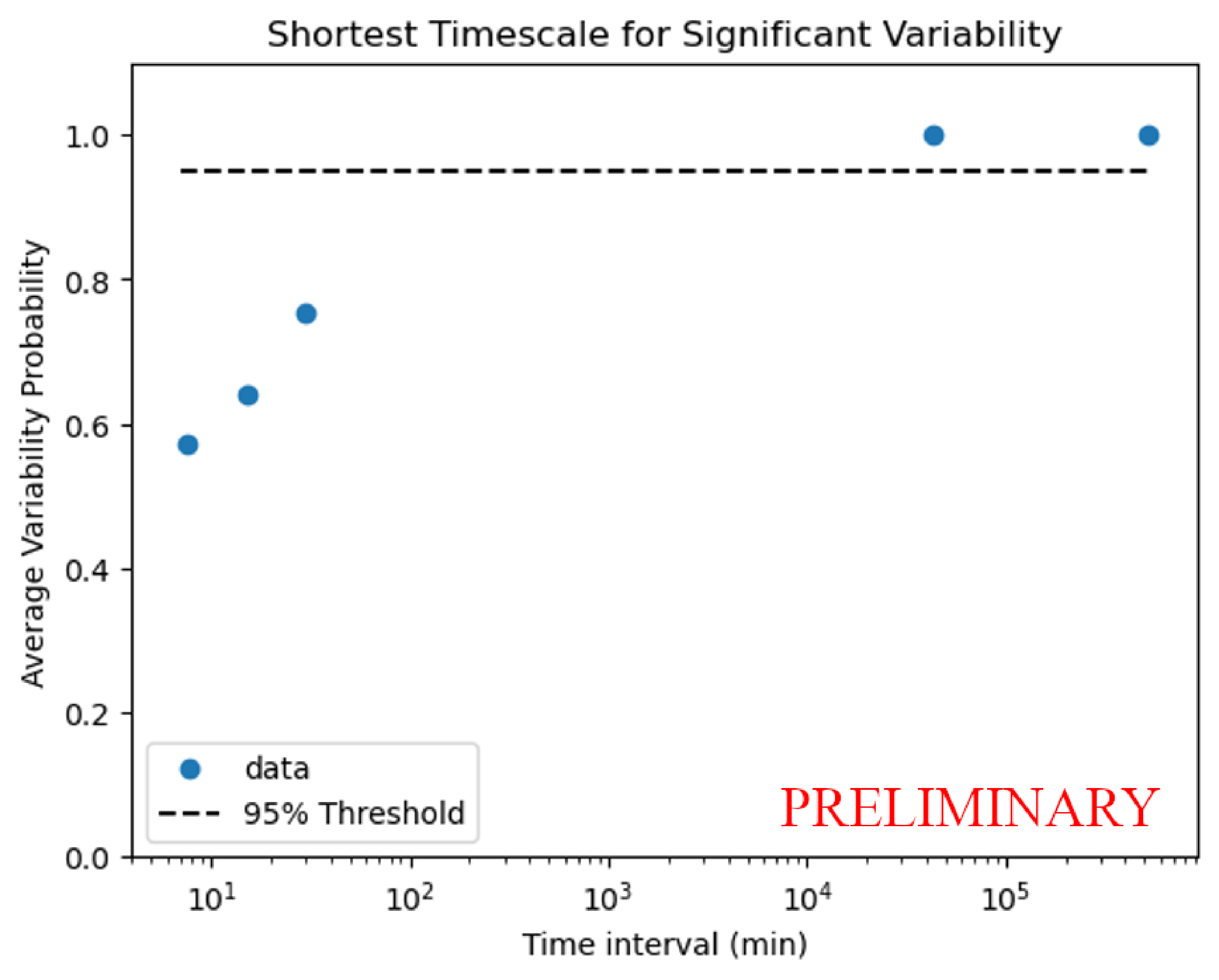
- Optimal bin size is the smallest bin size than also fits a significance criteria
- At least 80% of points must be over 5 sigma
- Bin Sizes: Full observations (7.5 mins), half-observations (3:15), third-observations (2:10), fourth-observations (1:37.5), and sixth-observations (1:05)
- Method:
  - Smallest bin size tested for significance criteria
  - If it passes, the probability is calculated
  - If it fails, the next largest bin size is tested



Example with one full observing run

RESULTS

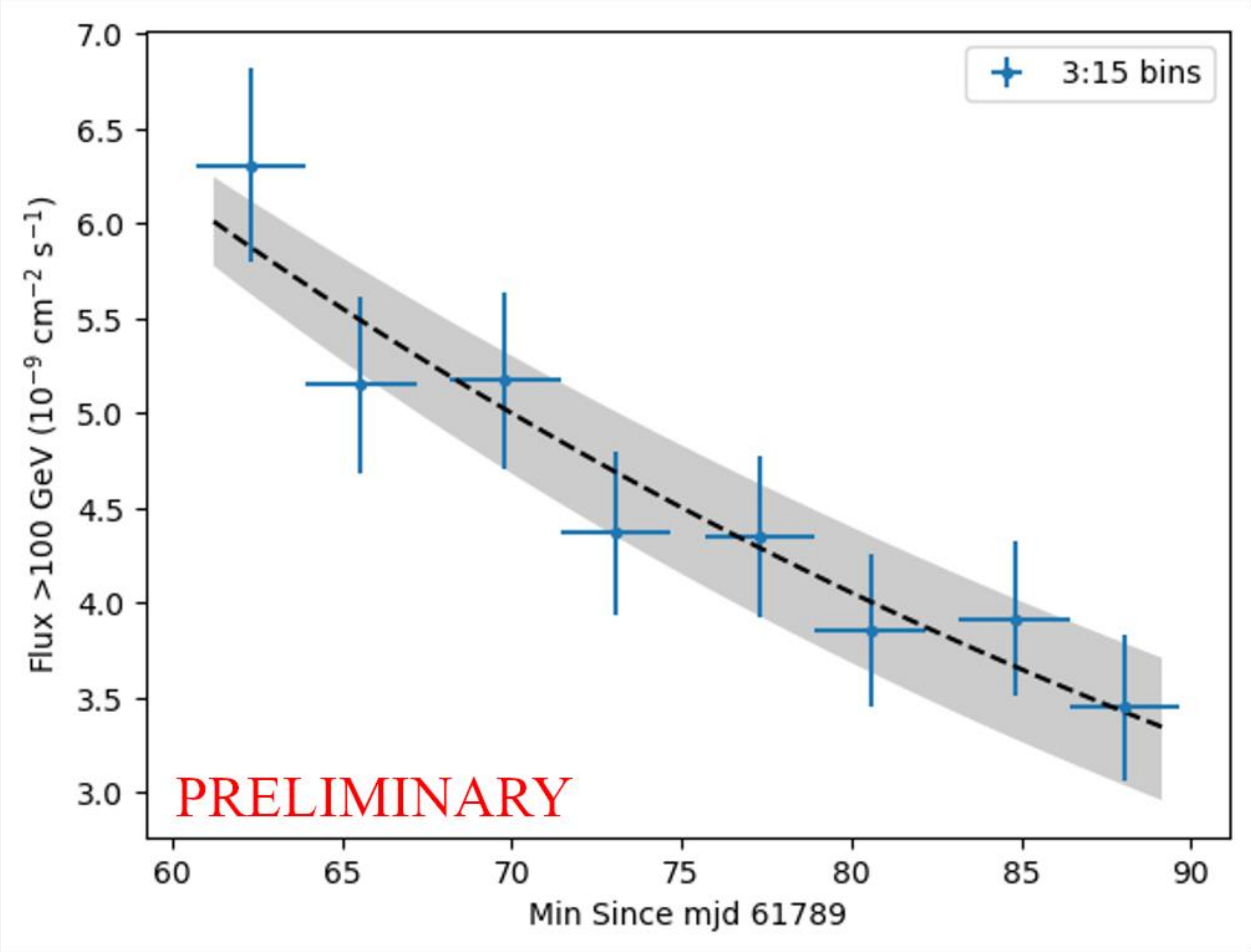
- For large time intervals, the variability probability was very high (~1)
- For shorter time intervals, the average probability dropped below 95% the threshold for significance
- Unfortunately, this dataset is too sparse to determine an accurate threshold for significance
- Therefore, if CTAO wants to observe short-timescale variability for Markarian 421, they should observe for more than for 30 minutes a week



SPECIAL CASES

- Despite the average variability probability for single observing runs being below the significance threshold, there are a few runs with significant variability
- Of those, a couple indicated possible flaring activity
- Flaring activity is indicated by:
  - Variability Probability >95%
  - Rise and fall behavior, or one of the two

01/19/2028



Function for fall:

$$F(t) = F_0 e^{\frac{-(t-t_0)}{t_{decay}}}$$

t_0 set as time of first observation, F_0 and t_{decay} set as fit parameters

Fit Results:

$F_0 = (3.434 \pm 0.134) \times 10^{-9} \frac{photons}{s\,cm^2}$

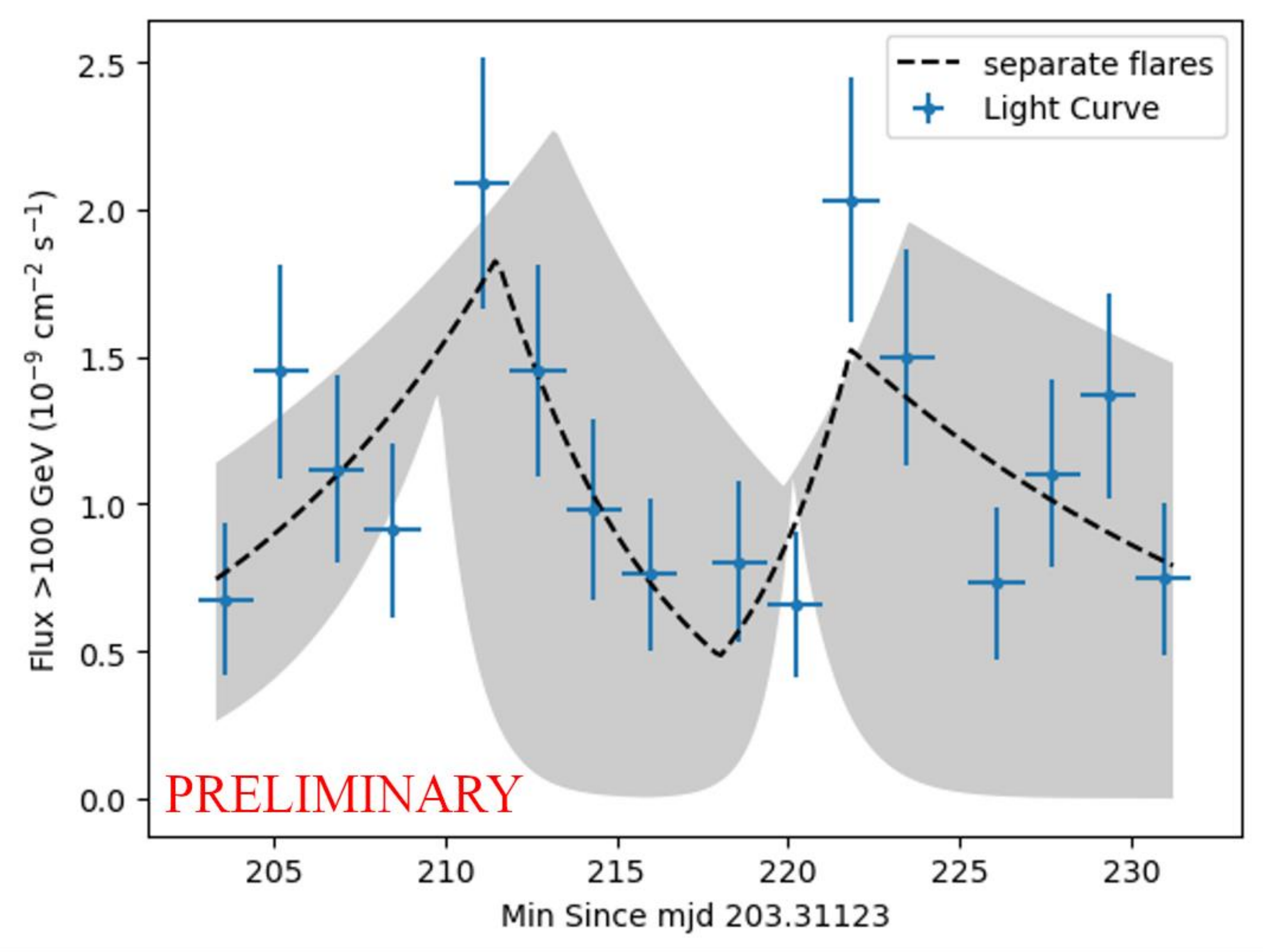
$t_{decay} = (47.708 \pm 5.933)\ min$

$\sqrt{TS} = 1.954$

$$\frac{R}{\delta} \leq \frac{ct_{var}}{1+z}$$

$$\frac{R}{\delta} \leq 8.9329 \times 10^{11}\ m = 2.699 \times 10^{-5}\ parsecs$$

12/12/2028



Function for double rise and fall:

$$F(t) = \begin{cases} F_0 e^{\frac{(t-t_{peak0})}{t_{rise0}}} & t < t_{peak0} \\ F_0 e^{\frac{-(t-t_{peak0})}{t_{decay0}}} & t_{peak0} \leq t < t_{split} \\ F_1 e^{\frac{(t-t_{peak1})}{t_{rise1}}} & t_{split} \leq t < t_{peak0} \\ F_1 e^{\frac{-(t-t_{peak1})}{t_{decay1}}} & t \geq t_{peak1} \end{cases}$$

Fit Results: t_{split} = 218.0 min $\sqrt{TS} = 1.660$

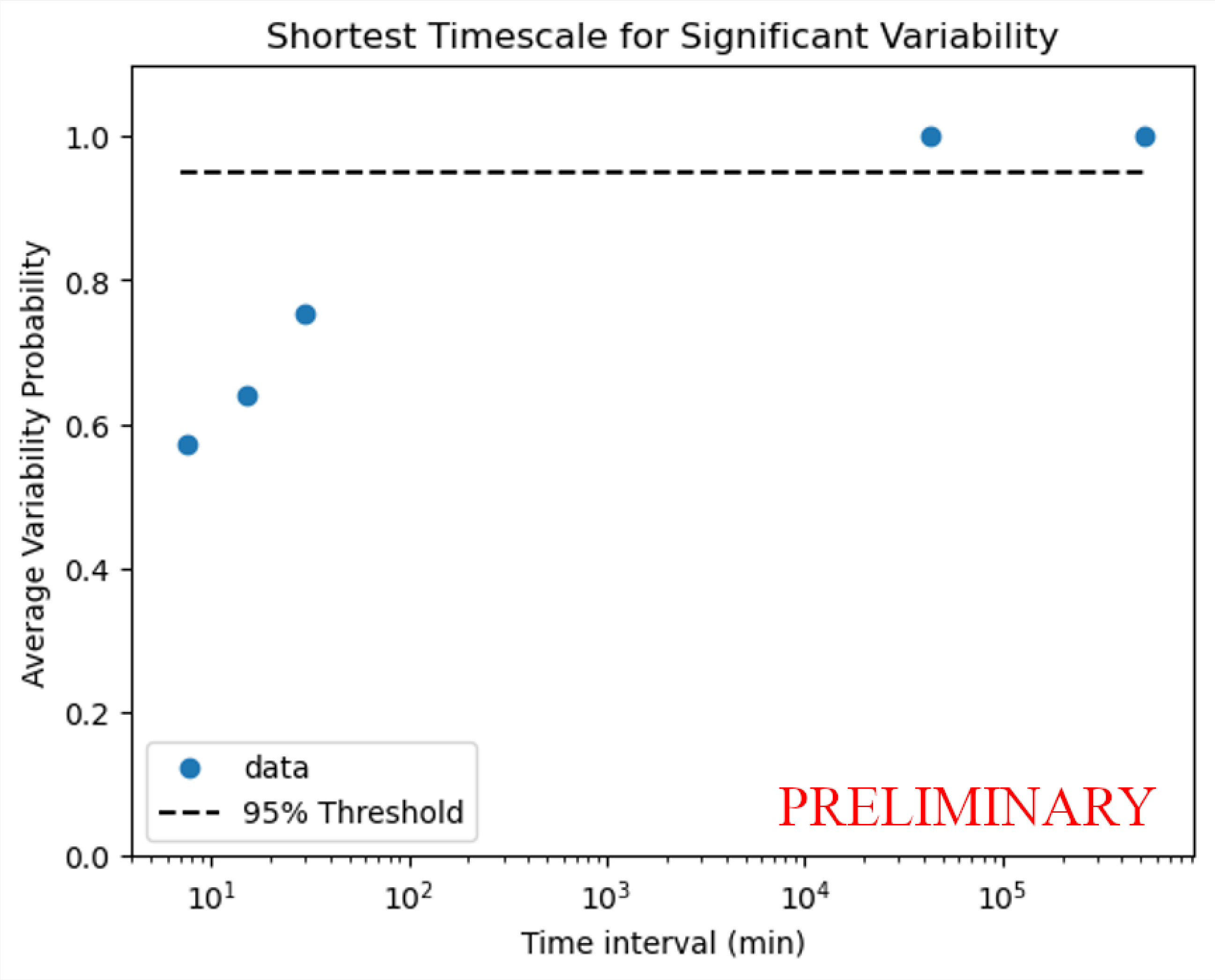
First Flare			
F_0	1.837	± 0.442	$\times 10^{-9} \frac{photons}{s\ cm^2}$
t_{peak0}	211.509	± 1.684	min
t_{rise0}	9.079	± 5.178	min
t_{decay0}	4.860	± 3.86	min
Second Flare			
F_1	1.524	± 0.435	$\times 10^{-9} \frac{photons}{s\ cm^2}$
t_{peak1}	221.832	± 1.687	min
t_{rise1}	3.322	± 2.597	min
t_{decay1}	14.316	± 13.087	min

Largest: $\frac{R}{\delta} \leq 2.499 \times 10^{11}\ m = 8.010 \times 10^{-6}\ parsecs$

Smallest: $\frac{R}{\delta} \leq 5.799 \times 10^{10}\ m = 1.879 \times 10^{-6}\ parsecs$

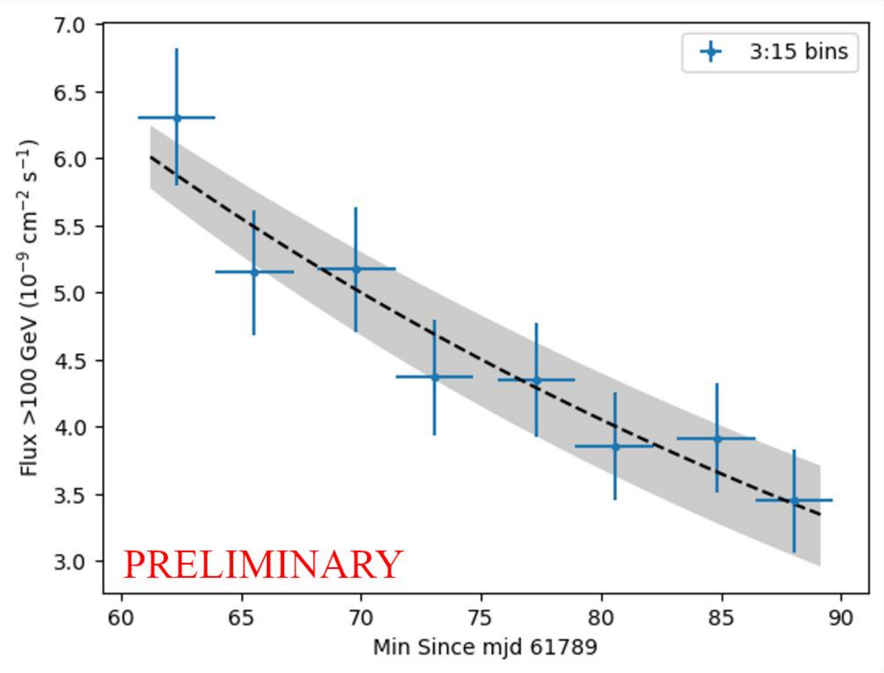
CONCLUSIONS: VARIABILITY STUDY

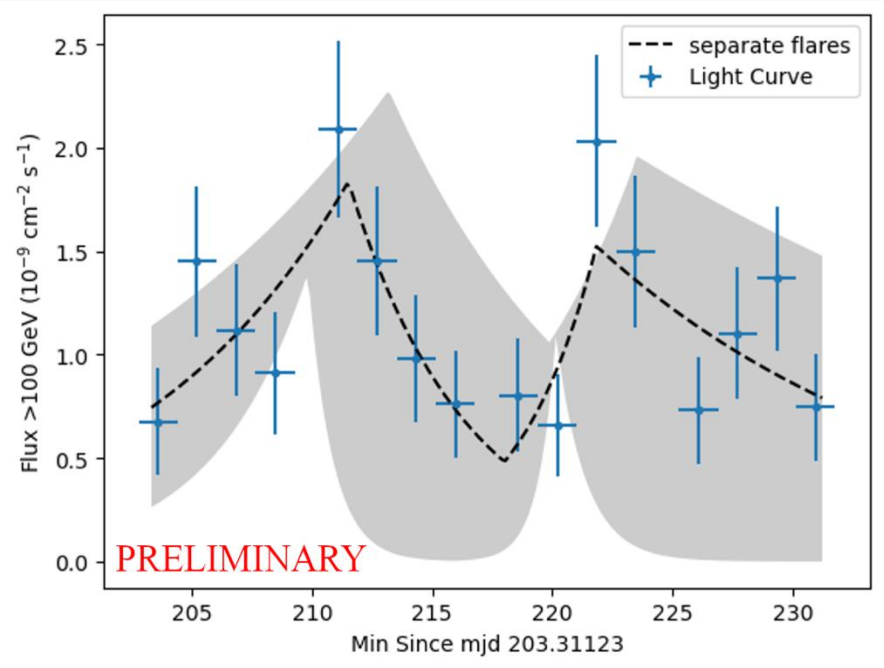
- Conducted a variability analysis of 1 year of simulated CTAO data
- On average, the probability that a light curve displays variability decreases over smaller time intervals
- For small intervals, the variability probability increases on average with decreasing bin size
- If CTAO wants to observe short-timescale variability in Markarian 421, they should observe more than 30 mins per week



DISCUSSION: FAST FLARES

- For some observing runs with significant variability, light curves were fit with exponential functions
- Timescales are short and the
  - Small emission regions,
  - Associated with the jet
- Longer cooling timescale
  - Exponential fall
  - Radiative losses, Inverse Compton Scattering
  - Leptonic model
- Double peaked light curve
  - First peak, longer rise than fall
  - Injection of high-energy particles
  - Second peak, shorter rise than fall
  - In situ acceleration, longer cooling timescale than dynamical timescale
  - Steep particle-energy distribution





ACKNOWLEDGEMENTS

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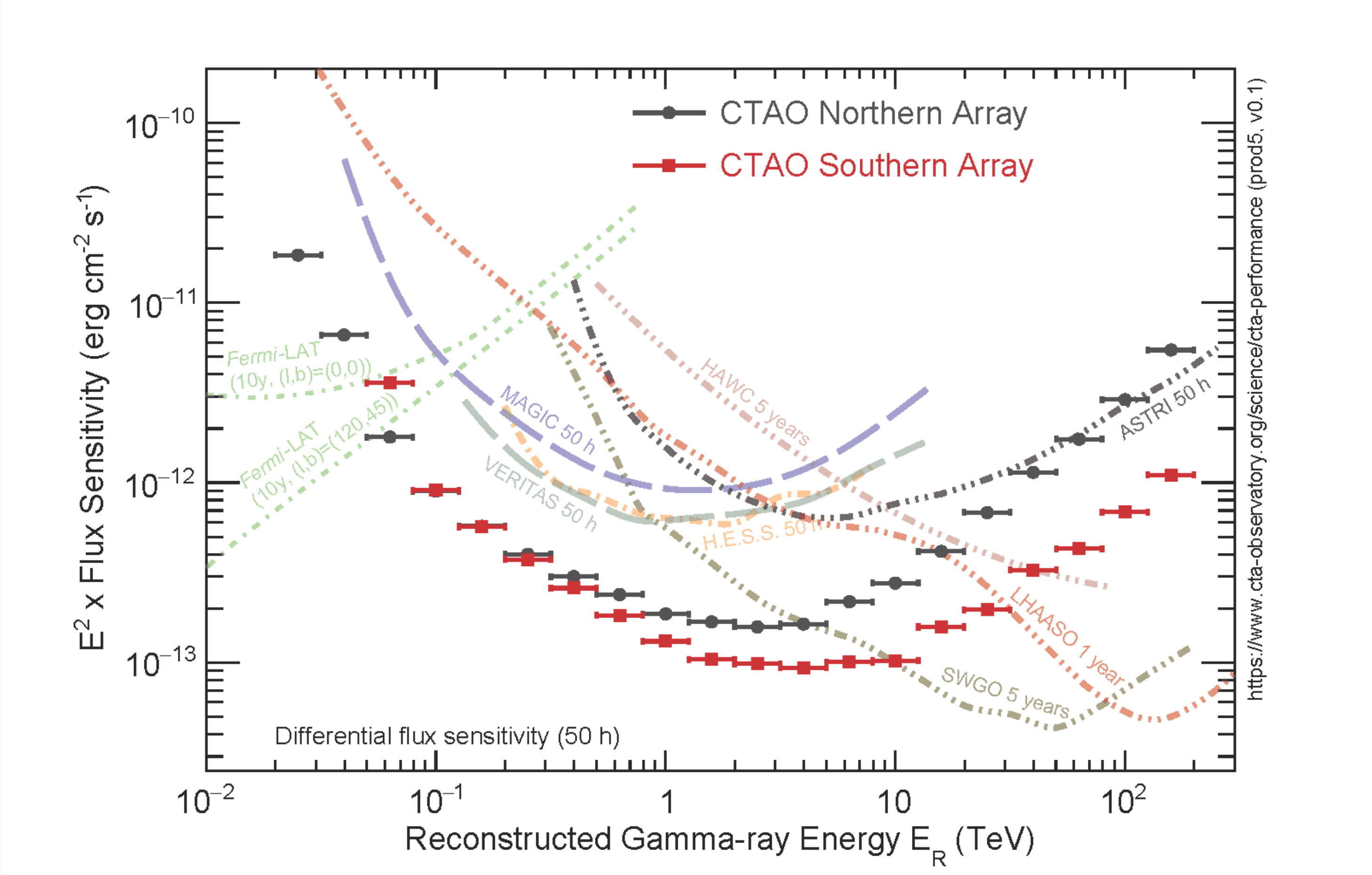
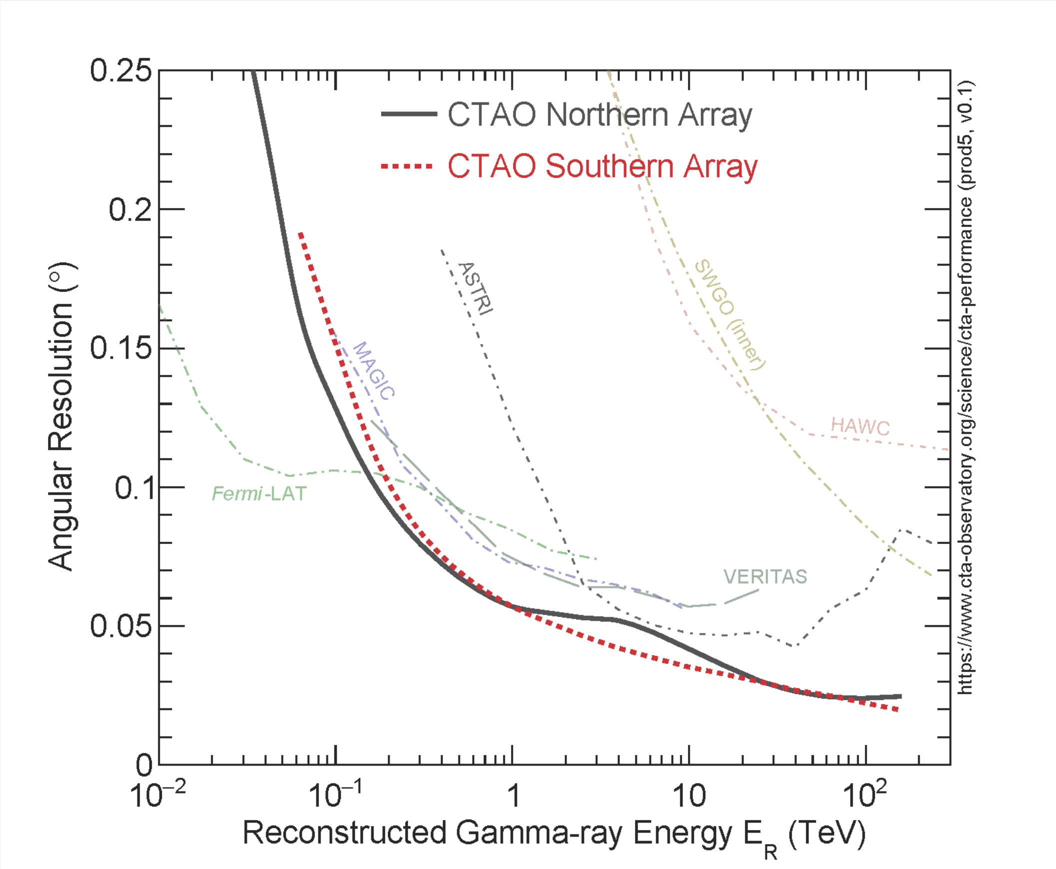
I would like to thank Professor Reshmi Mukherjee and Dr. Ruo yu Shang for their support and guidance on this project, as well as the rest of the VERITAS/CTAO group at Nevis

I would also like to thank Georgia, Reshmi, Amy, and the rest of the Nevis team for running a great REU program

BACKUP

CTAO PERFORMANCE





https://www.ctao.org/for-scientists/performance/

WHAT WE CAN LEARN FROM VARIABILITY

- Timescale: tells us about the size of the emission region and doppler factor.
- Smaller emission regions and shorter timescales favor magnetic reconnections in plasmoids, as passing through a shock multiple times takes too long
- Flare profile: slow rise and quick fall suggests particle injection, while quick rise and short fall suggests in situ acceleration
- In the plasmoid MR model, a slower fall than rise can also mean that the plasmoid has reached its peak velocity
- Flare decay timescales can tell us about particle cooling mechanisms

2D ANALYSIS

- Continued from Alex Sidler's work in Summer 2024
- Ring Background Method to create 2D datasets
- Significance Map and Distribution to confirm detection