Variability Analysis of Fermi-LAT data to improve prospects with CTAO

CTAO Summer School - Bertinoro & La Palma - 19/June/2024

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Universidade de São Paulo

Image credit: NASA - Jet Propulsion Laboratory, California Institute of Technology

Variability Analysis of Fermi-LAT data to improve prospects with CTAO

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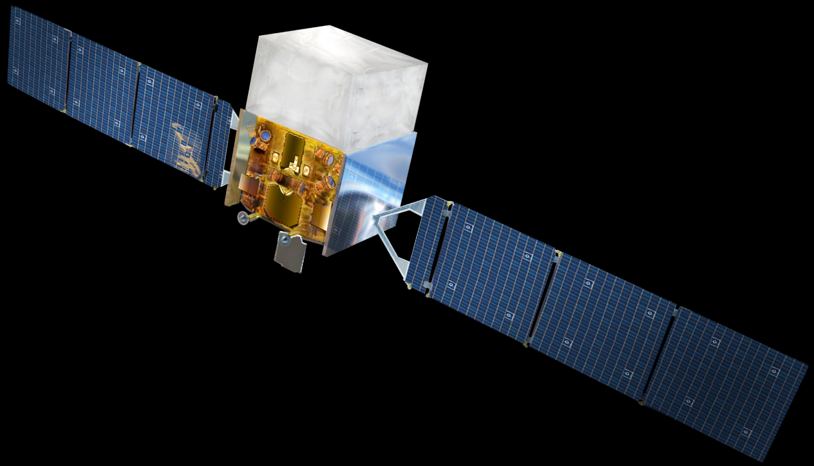
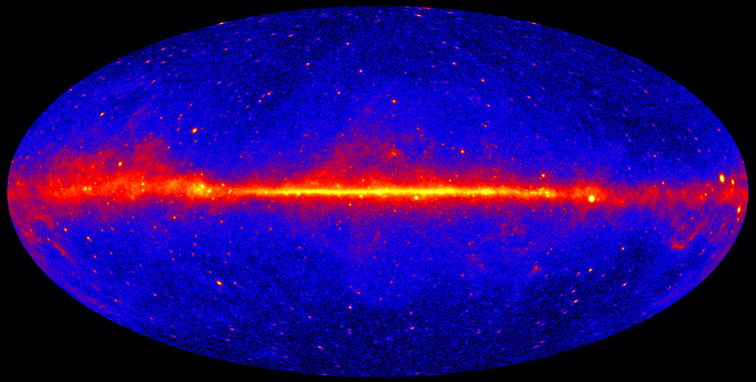
Fermi-LAT (Large Area Telescope)





- NASA's Fermi Gamma-ray Space Telescope
- Observing X-rays and Gamma-rays from low Earth orbit since 2008!

  → energy range: 20 MeV to 300 GeV

Image credits: By NASA - https://science.nasa.gov/toolkits/spacecraft-icons, Public Domain, https://commons.wikimedia.org/w/index.php?curid=58291732
By NASA/DOE/Fermi LAT Collaboration - https://svs.gsfc.nasa.gov/11342 , Public Domain, https://commons.wikimedia.org/w/index.php?curid=72966833

Introduction

- Procedure: Study through the data using the 4FGL Catalog
  - Light curves and Spectrum;
  - Fractional Variability;
  - Normalized Excess Variance.

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- Motivation:
  - Use public Fermi-LAT data to evaluate AGN daily variability;
  - Estimate the impact of including this variability on AGN populations detectability with CTAO.

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  - Light curves and Spectrum;
  - Fractional Variability;
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- Motivation:
  - Use public Fermi-LAT data to evaluate AGN daily variability;
  - Estimate the impact of including this variability on AGN populations detectability with CTAO.
- In summary:
  - Look for “Variability Trends“ (correlation) throughout different cadences;
  - "How does variability affect the AGN population we might observe?";
  - Extrapolate light curves to CTAO's energy range (AGN Long-Term Monitoring).

- 4FGL: the Fourth Fermi LAT Source Catalog of γ-ray detection
- Energy range: from 50 MeV to 300 GeV

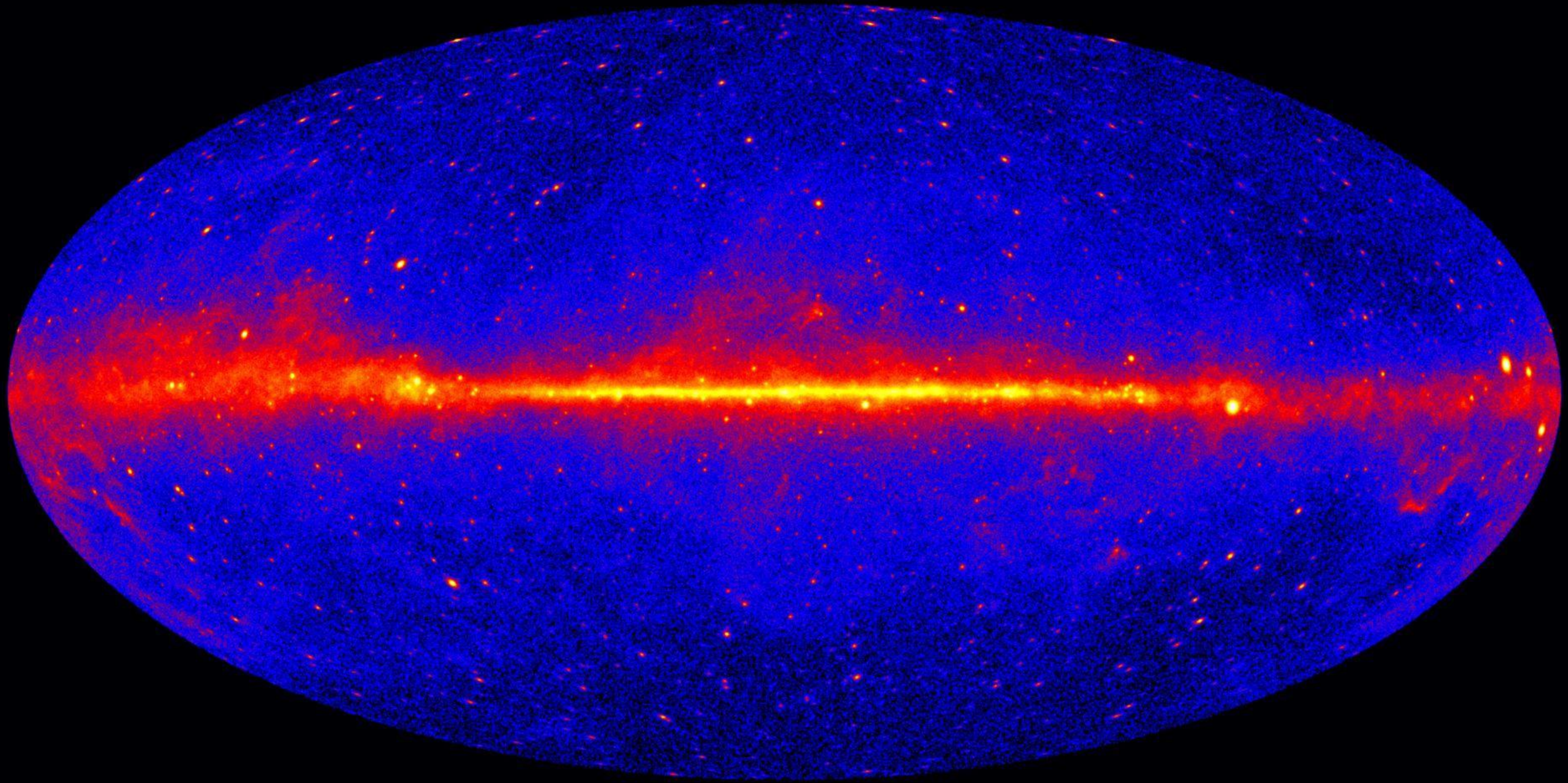


Image credit: https://svs.gsfc.nasa.gov/11342

Fermi LAT 60-month image

Most of the sources are blazars!

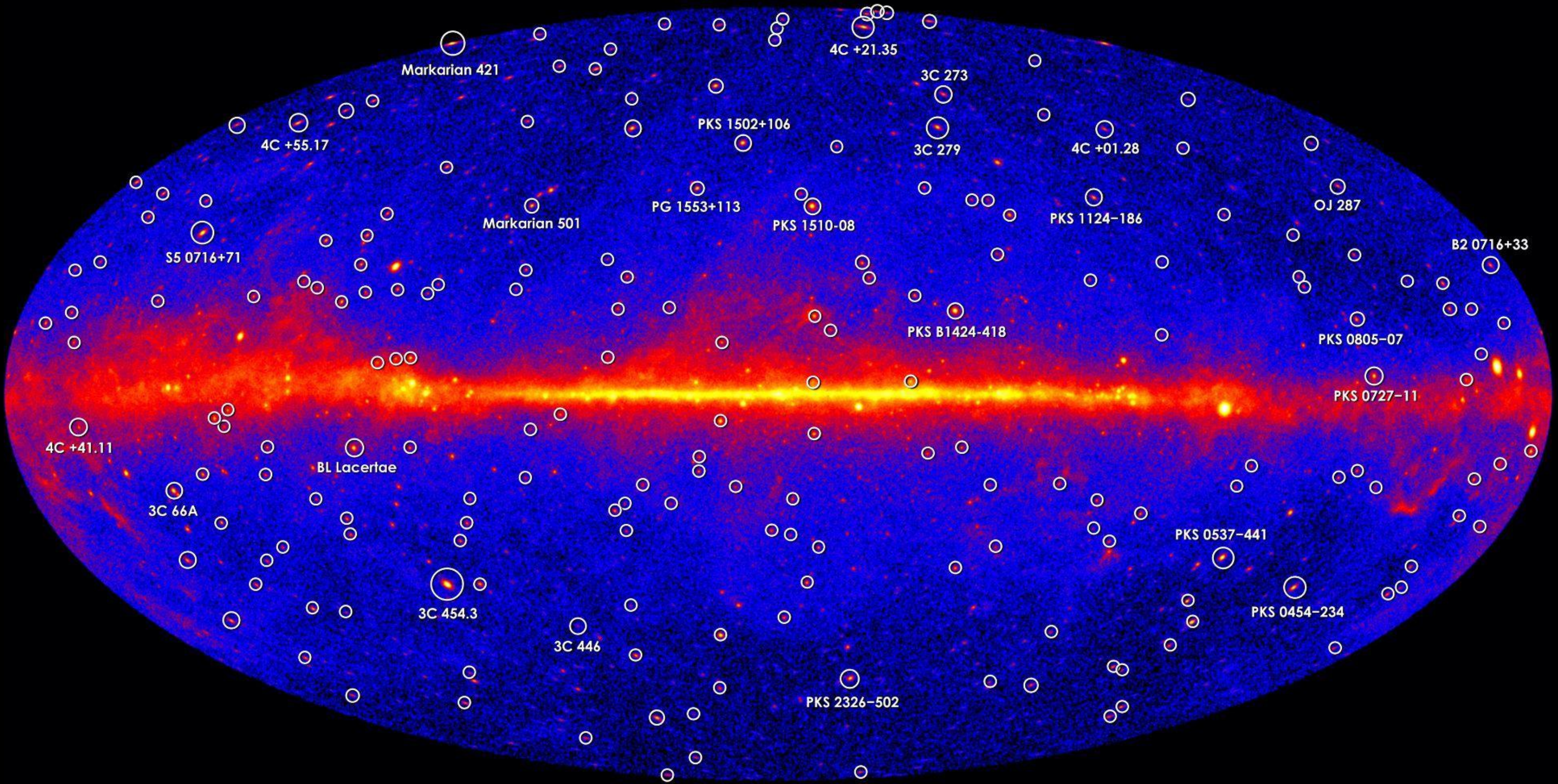


Image credit: https://svs.gsfc.nasa.gov/11342

Blazars

➡ Active Galactic Nuclei (AGN)

➡ Jet pointed towards our line of sight

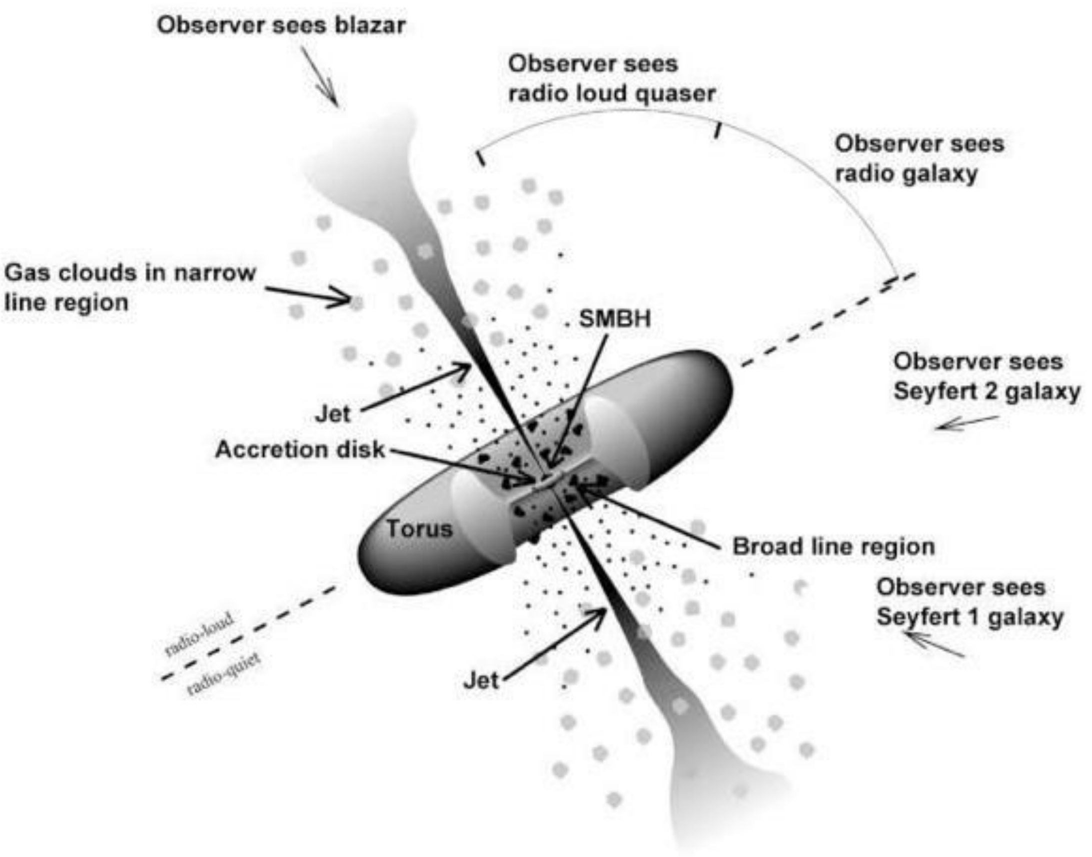


Image credit: https://fermi.gsfc.nasa.gov/science/eteu/agn/

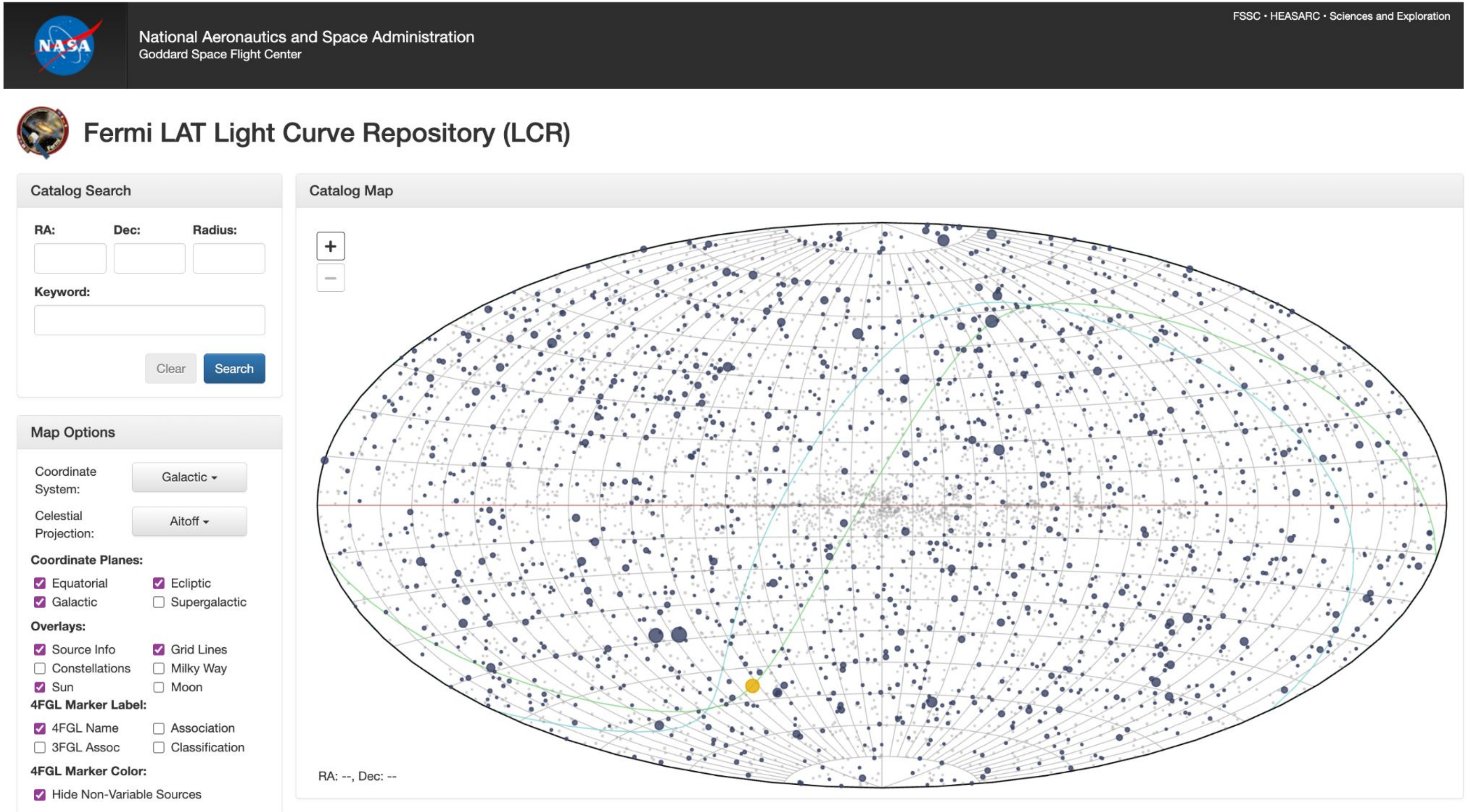


Image credit: https://fermi.gsfc.nasa.gov/ssc/data/access/lat/LightCurveRepository/

Catalog divided into 3 blazar classes

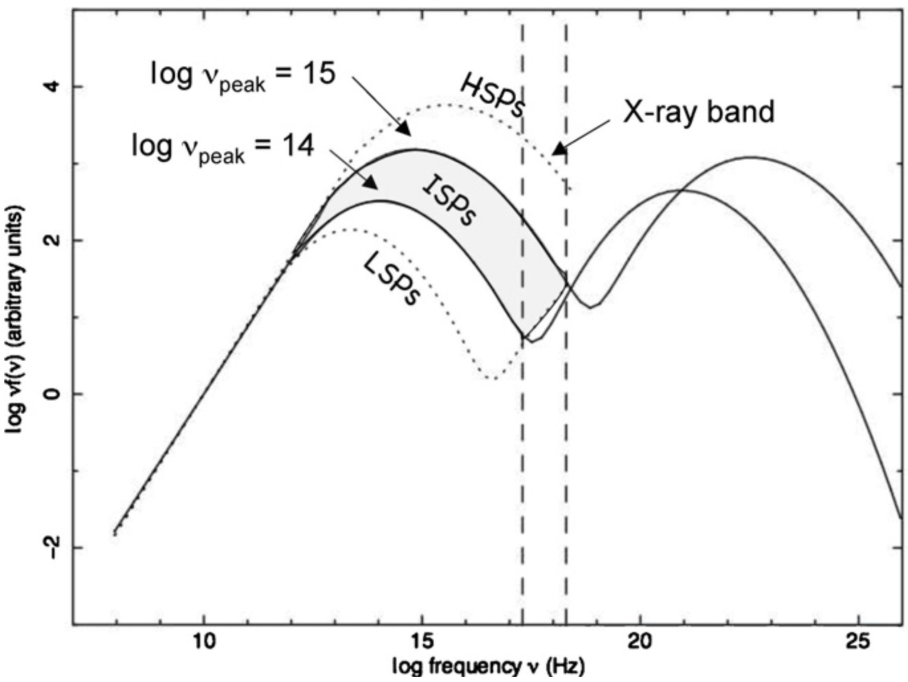


Image credit: Abdo et al. 2010

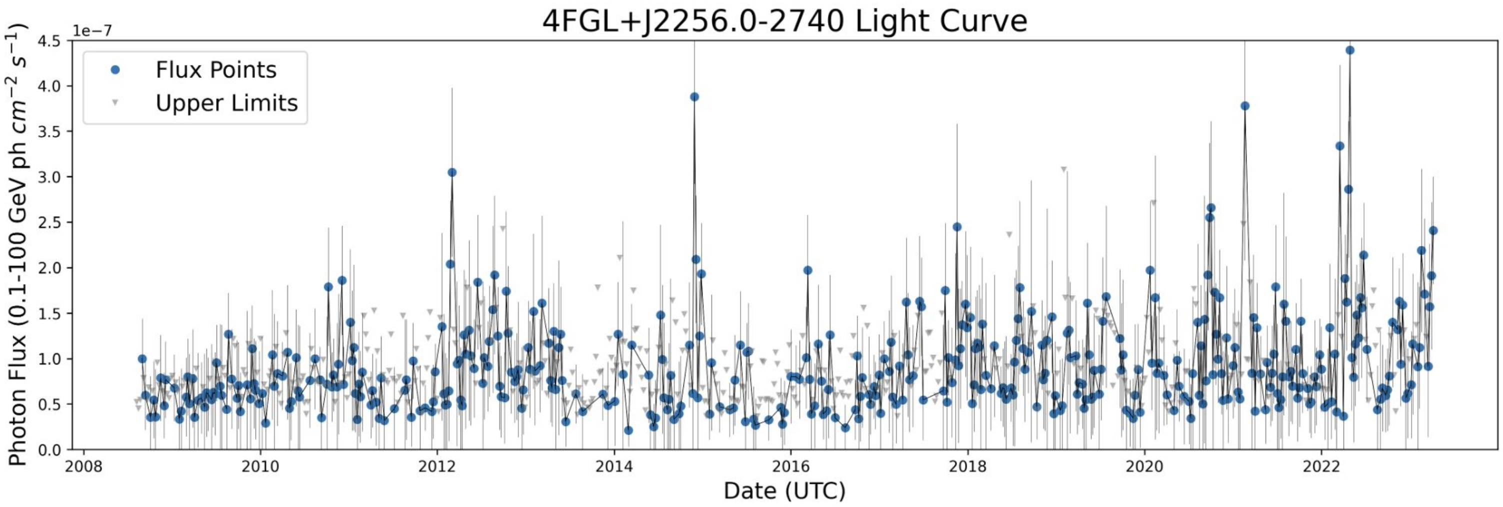
DR3 Catalog with 3814 sources

- Low Synchrotron Peak: 1699
- Intermediate Synchrotron Peak: 536
- High Synchrotron Peak: 590

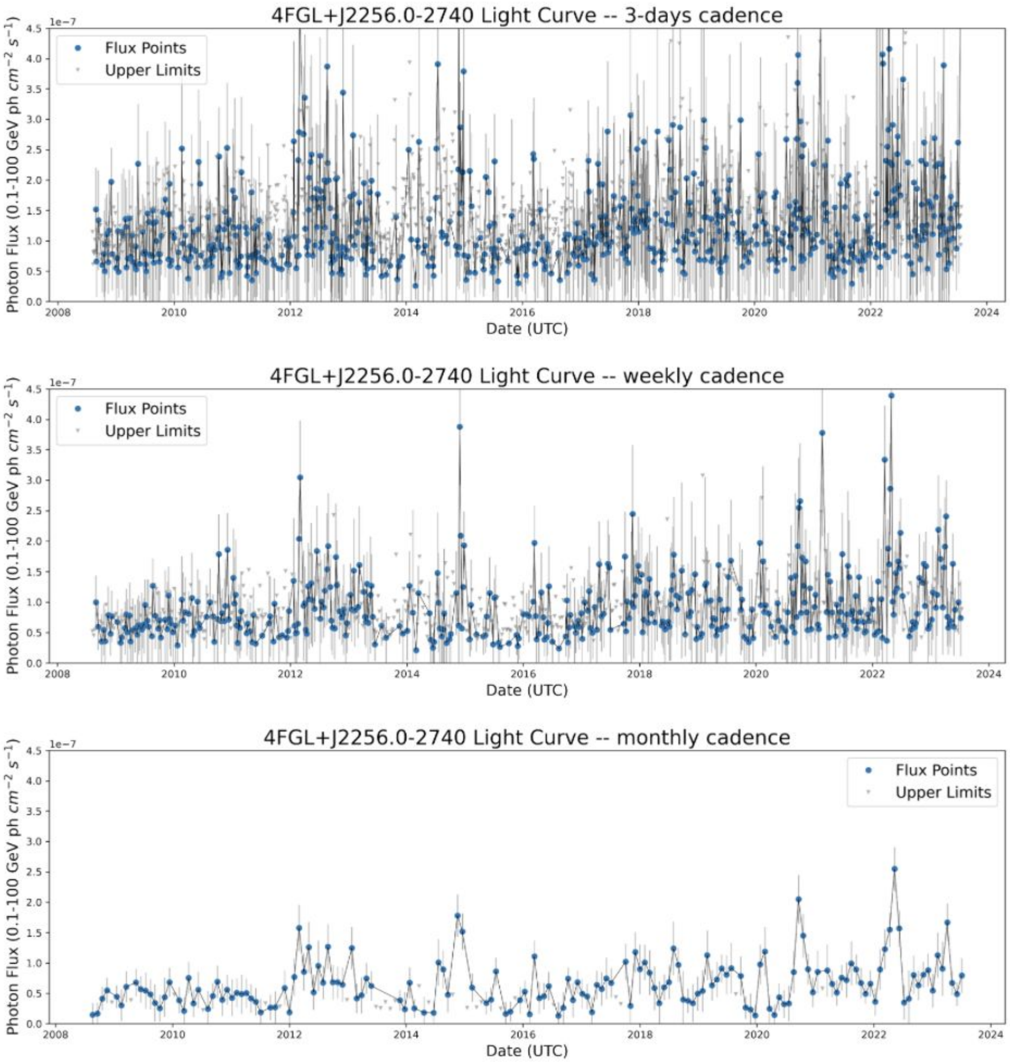
that totalize 2825 sources with a Synchrotron Peak label

Downloaded 1429 valid light curves !

Variability in Blazars



- Particles are being accelerated and emits radiation from magnetically dominated processes in the inner region of the jet;
- Blazars are one of the most variable extragalactic object: strong broad-band emission ranging from radio to TeV energies!


4FGL+J2256.0-2740 Light Curve -- 3-days cadence
Flux Points
Upper Limits
Photon Flux (0.1-100 GeV ph cm^{-2} s^{-1})
1e−7
Date (UTC)
4FGL+J2256.0-2740 Light Curve -- weekly cadence
Flux Points
Upper Limits
Photon Flux (0.1-100 GeV ph cm^{-2} s^{-1})
1e−7
Date (UTC)
4FGL+J2256.0-2740 Light Curve -- monthly cadence
Flux Points
Upper Limits
Photon Flux (0.1-100 GeV ph cm^{-2} s^{-1})
1e−7
Date (UTC)

Fractional Variability Parameter

$$F_{\mathrm{var}} = \sqrt{\frac{1}{{F_{av}}^{2}}\left[\frac{1}{N-1}\sum_{i=1}^{N}(F_i - F_{av})^2 - \frac{1}{N}\sum_{i=1}^{N}\sigma^2_{\mathrm{err,i}}\right]}$$

$$err(F_{\mathrm{var}}) = \sqrt{\left(\sqrt{\frac{1}{2N}}\frac{\overline{\sigma^2_{\mathrm{err}}}}{{F_{av}}^{2}\,F_{\mathrm{var}}}\right)^2 + \left(\sqrt{\frac{\overline{\sigma^2_{\mathrm{err}}}}{N}}\frac{1}{F_{av}}\right)^2}$$

Vaughan et. al 2003

Normalized Excess Variance

$$\sigma^2_{\mathrm{NXS}} = \frac{1}{{F_{av}}^2}\left[\frac{1}{N-1}\sum_{i=1}^{N}(F_i - F_{av})^2 - \frac{1}{N}\sum_{i=1}^{N}\sigma^2_{\mathrm{err,i}}\right]$$

$$err(\sigma^2_{\mathrm{NXS}}) = \sqrt{\left(\sqrt{\frac{2}{N}}\cdot\frac{\overline{\sigma^2_{\mathrm{err}}}}{{F_{av}}^2}\right)^2 + \left(\sqrt{\frac{\overline{\sigma^2_{\mathrm{err}}}}{N}}\cdot\frac{2F_{\mathrm{var}}}{F_{av}}\right)^2}$$

Vaughan et. al 2003

Selecting bright sources & Treating outliers points

- Remove the sources (monthly timescale) with
    - n° Upper Limits > n° flux measurements

- Remove, from the .json file of each source, the flux points in which
    - flux_error = 0
    - fit_convergence !=0

- Make the point an Upper Limit if
    - TS < 10

  (minimal Test Statistic: significance of the detection)

Selection of Sources

- Selection of sources which show significant variability on a monthly timescale

$$\sigma^2_{NXS}(\mathrm{monthly}) - 3 * err[\sigma^2_{NXS}](\mathrm{monthly}) > 0$$

- Verification of 3-day timescale variability against monthly timescale variability

Selection of Sources

- Selection of sources which show significant variabi... y on a monthly timescale

σ^2_{NXS} ... $) > 0$

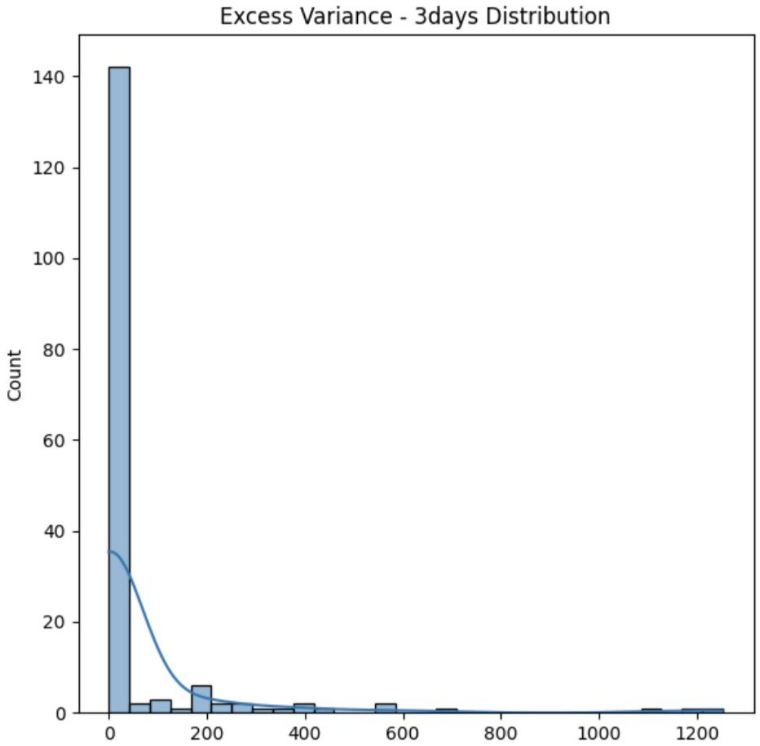
- Veri... nthly time...

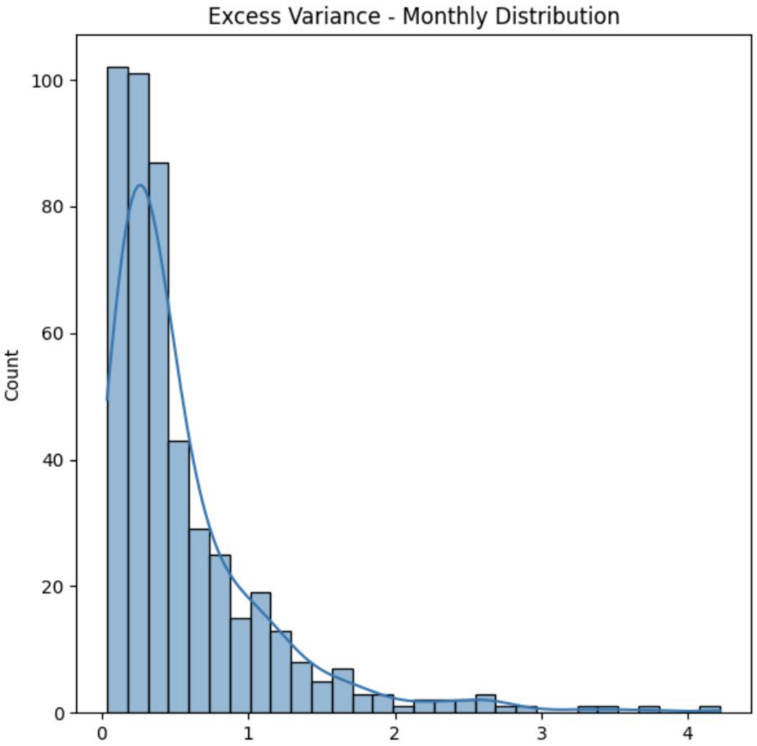
Selected 476 sources!

including the brightest known TeV blazars

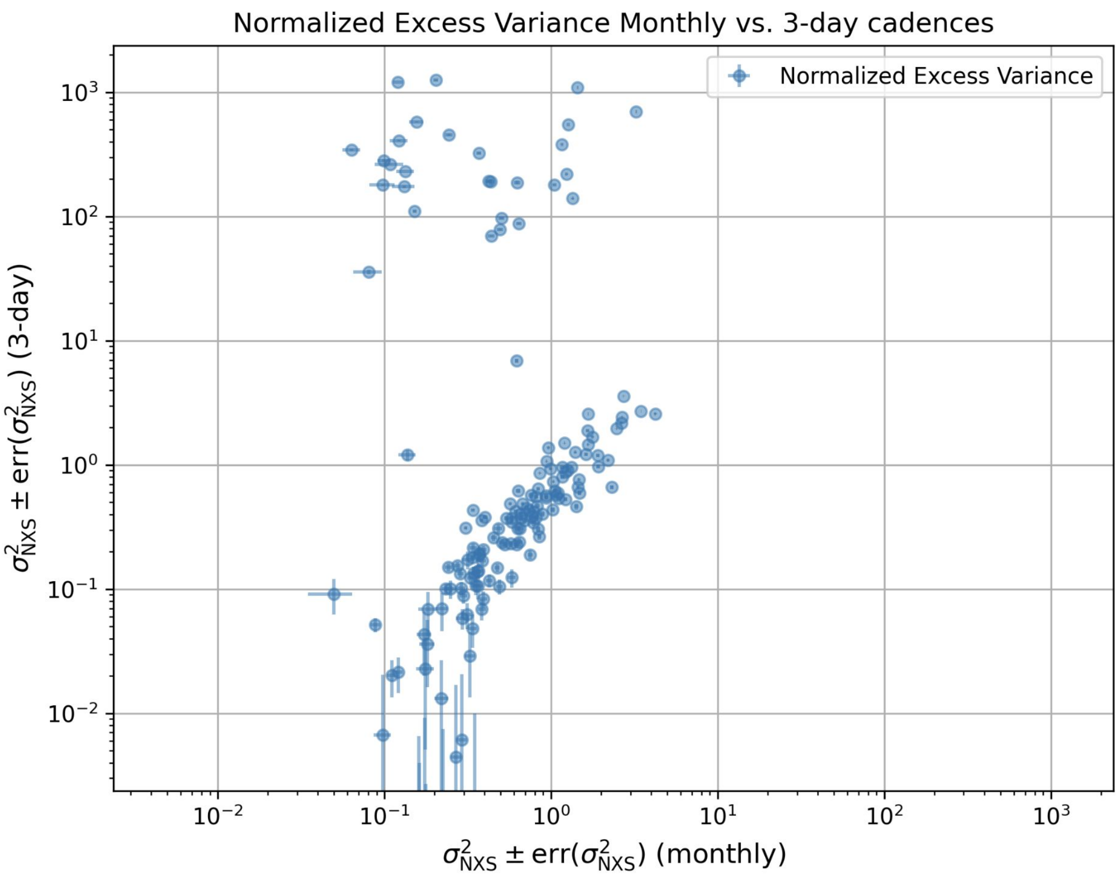
(e.g. Mkn 421, Mkn 501,
PKS 2155-304 & PG 1553-113)

Preliminary Results

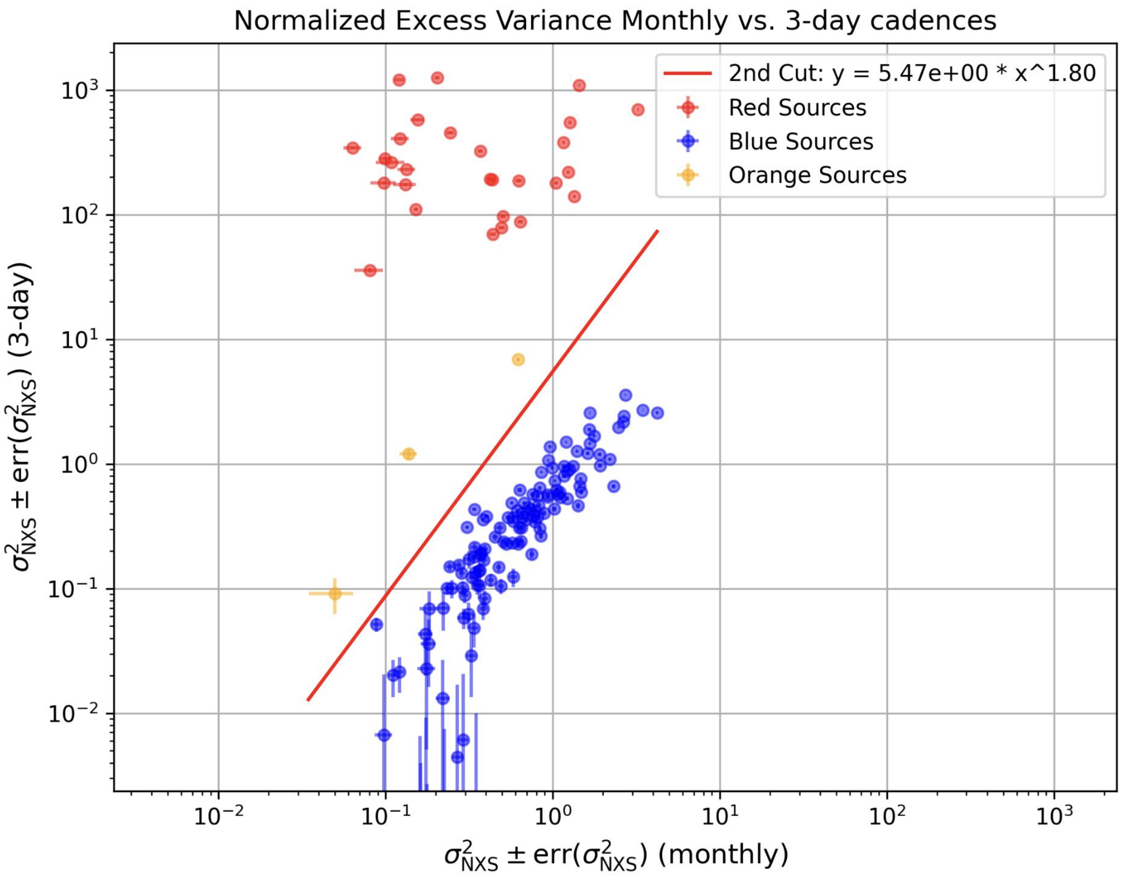




Preliminary Results



Dividing into subgroups



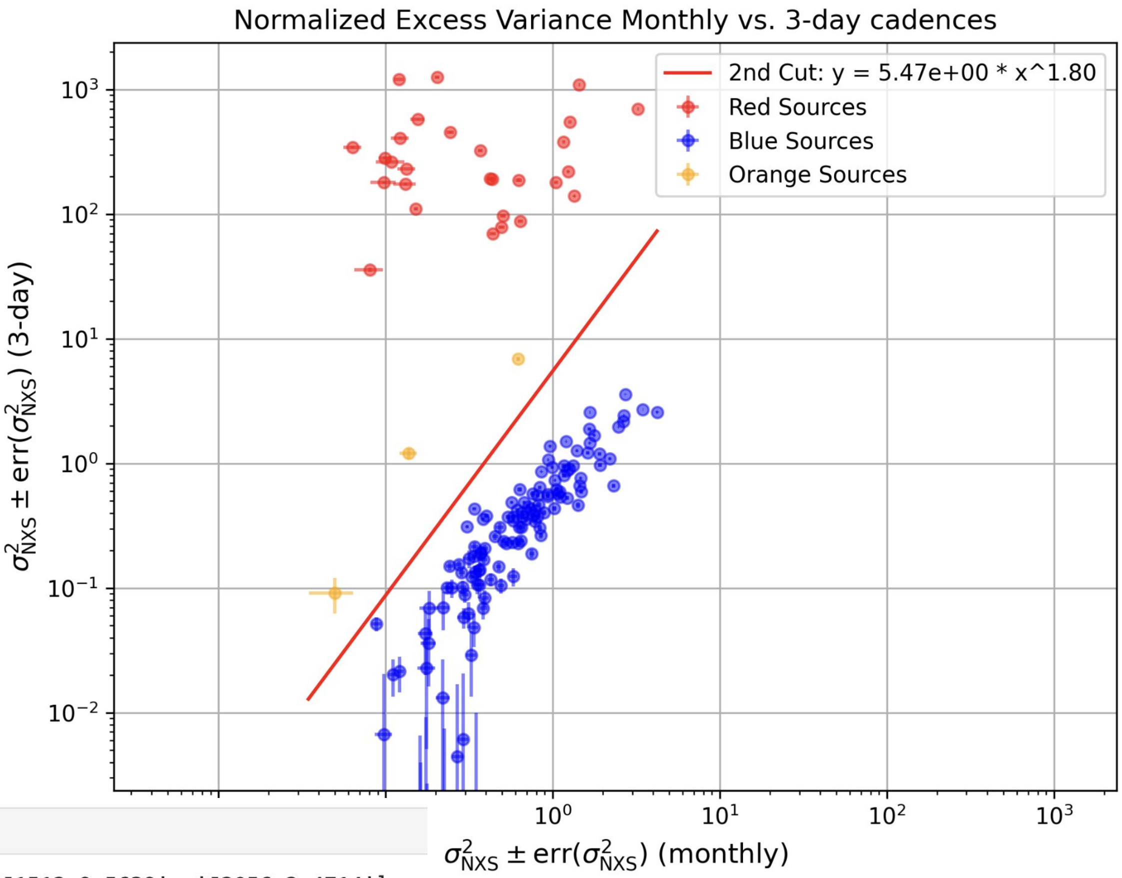
Look more careful into the lightcurves!

```
[95]: len(red_sources)

[95]: 28

[96]: red_sources

[96]: ['J0102.8+5824',
       'J0137.0+4751',
       'J0221.1+3556',
       'J0222.6+4302',
       'J0237.8+2848',
       'J0238.6+1637',
       'J0303.6+4716',
       'J0533.3+4823',
       'J0607.4+4739',
       'J0818.2+4222',
       'J0921.6+6216',
       'J1015.0+4926',
       'J1033.9+6050',
       'J1037.7+5711',
       'J1058.6+5627',
       'J1104.4+3812',
       'J1159.5+2914',
       'J1248.3+5820',
       'J1329.0-5607',
       'J1517.7-2422',
       'J1650.3-5045',
       'J1733.0-1305',
       'J1911.2-2006',
       'J1941.3-6210',
       'J2009.4-4849',
       'J2158.8-3013',
       'J2236.5-1433',
       'J2329.3-4955']
```



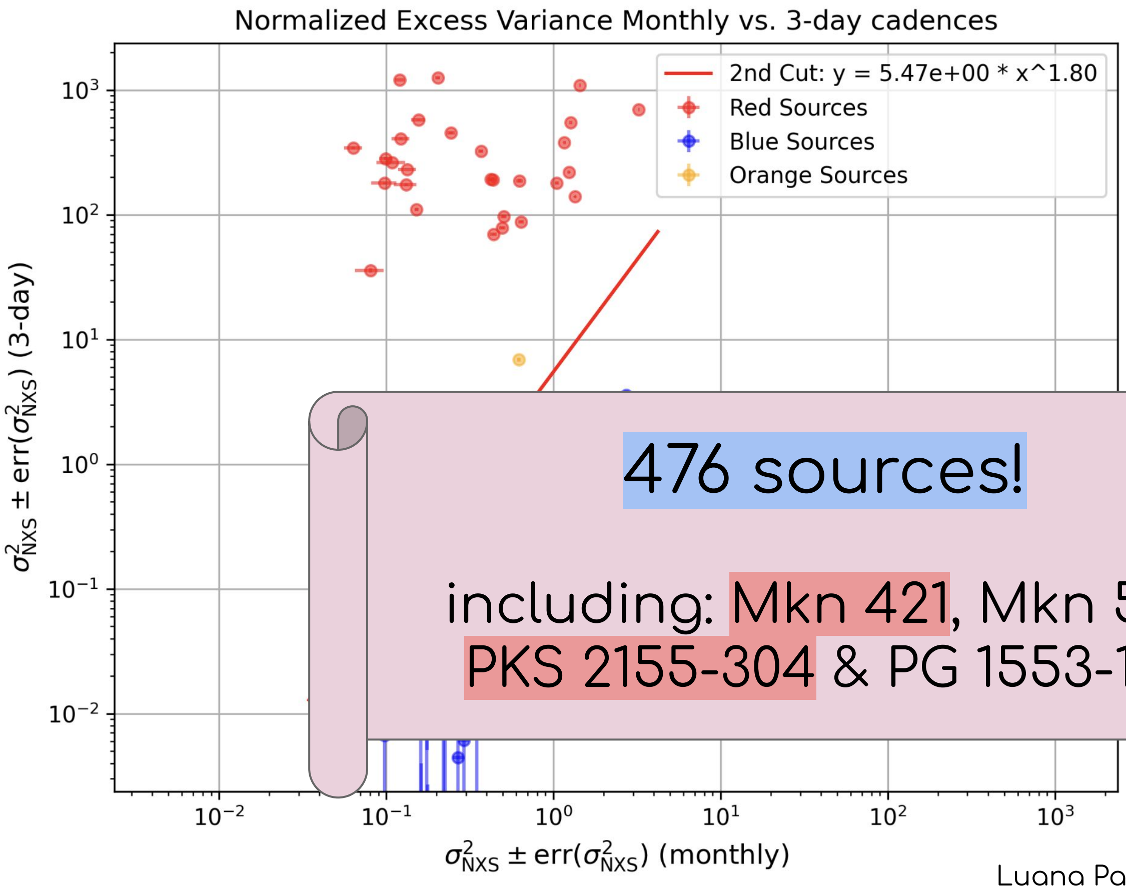

```
orange_sources

['J1132.7+0034', 'J1512.9-5639', 'J2056.2-4714']
```

Deviation includes important information

```
[95]: len(red_sources)
[95]: 28
[96]: red_sources
[96]: ['J0102.8+5824',
       'J0137.0+4751',
       'J0221.1+3556',
       'J0222.6+4302',
       'J0237.8+2848',
       'J0238.6+1637',
       'J0303.6+4716',
       'J0533.3+4823',
       'J0607.4+4739',
       'J0818.2+4222',
       'J0921.6+6216',
       'J1015.0+4926',
       'J1033.9+6050',
       'J1037.7+5711',
       'J1104.4+3812',
       'J1248.3+5820',
       'J1329.0-5607',
       'J1517.7-2422',
       'J1650.3-5045',
       'J1733.0-1305',
       'J1911.2-2006',
       'J1941.3-6210',
       'J2158.8-3013',
       'J2329.3-4955']
```

Mkn 421

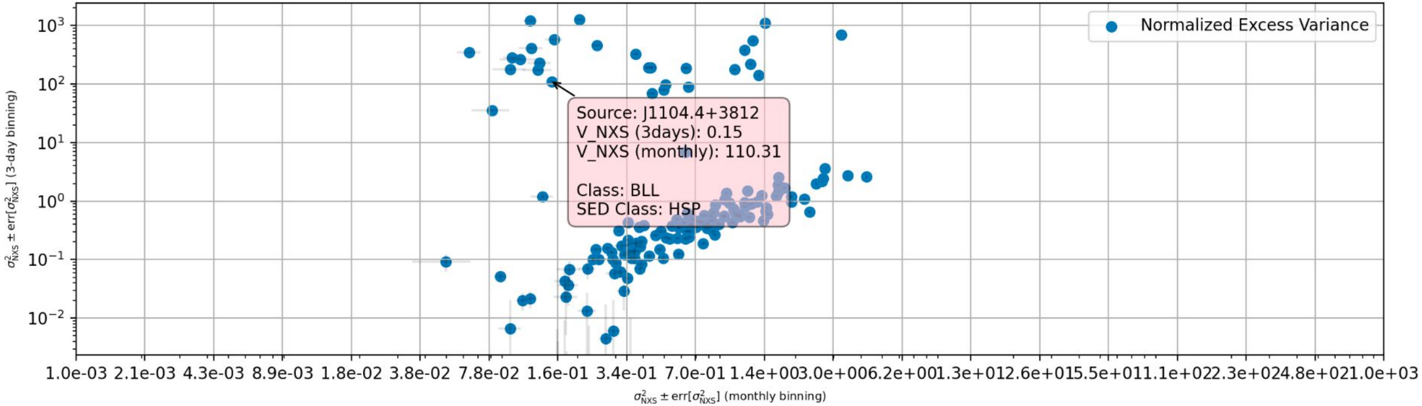


476 sources!

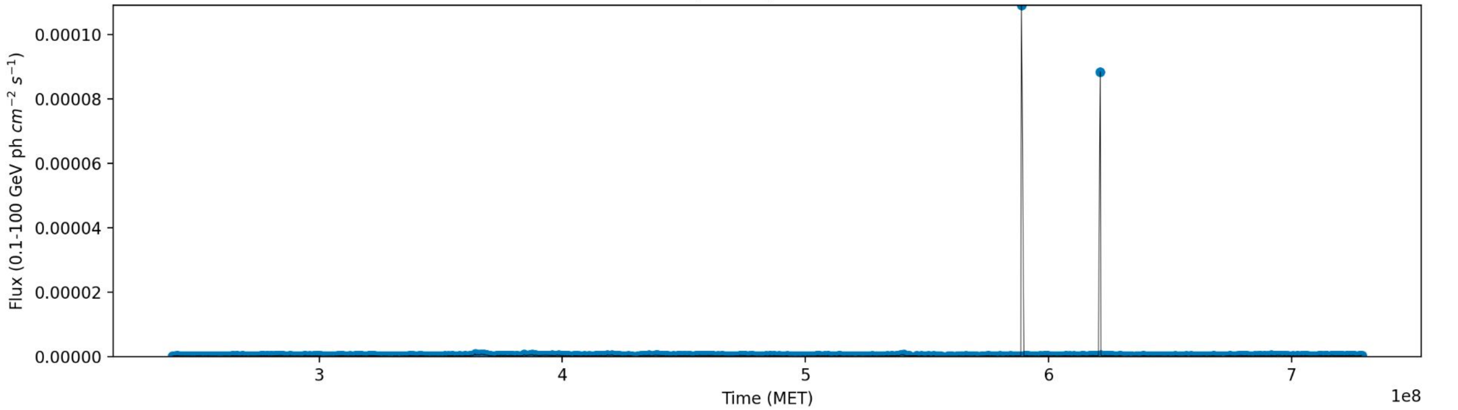
including: Mkn 421, Mkn 501, PKS 2155-304 & PG 1553-113

Deviation includes important information

Mkn 421



Lightcurve for J1104.4+3812



Selecting the blue sources

```
[95]: len(red_sources)

[95]: 28

[96]: red_sources

[96]: ['J0102.8+5824',
       'J0137.0+4751',
       'J0221.1+3556',
       'J0222.6+4302',
       'J0237.8+2848',
       'J0238.6+1637',
       'J0303.6+4716',
       'J0533.3+4823',
       'J0607.4+4739',
       'J0818.2+4222',
       'J0921.6+6216',
       'J1015.0+4926',
       'J1033.9+6050',
       'J1037.7+5711',
       'J1058.6+5627',
       'J1104.4+3812',
       'J1159.5+2914',
       'J1248.3+5820',
       'J1329.0-5607',
       'J1517.7-2422',
       'J1650.3-5045',
       'J1733.0-1305',
       'J1911.2-2006',
       'J1941.3-6210',
       'J2009.4-4849',
       'J2158.8-3013',
       'J2236.5-1433',
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```
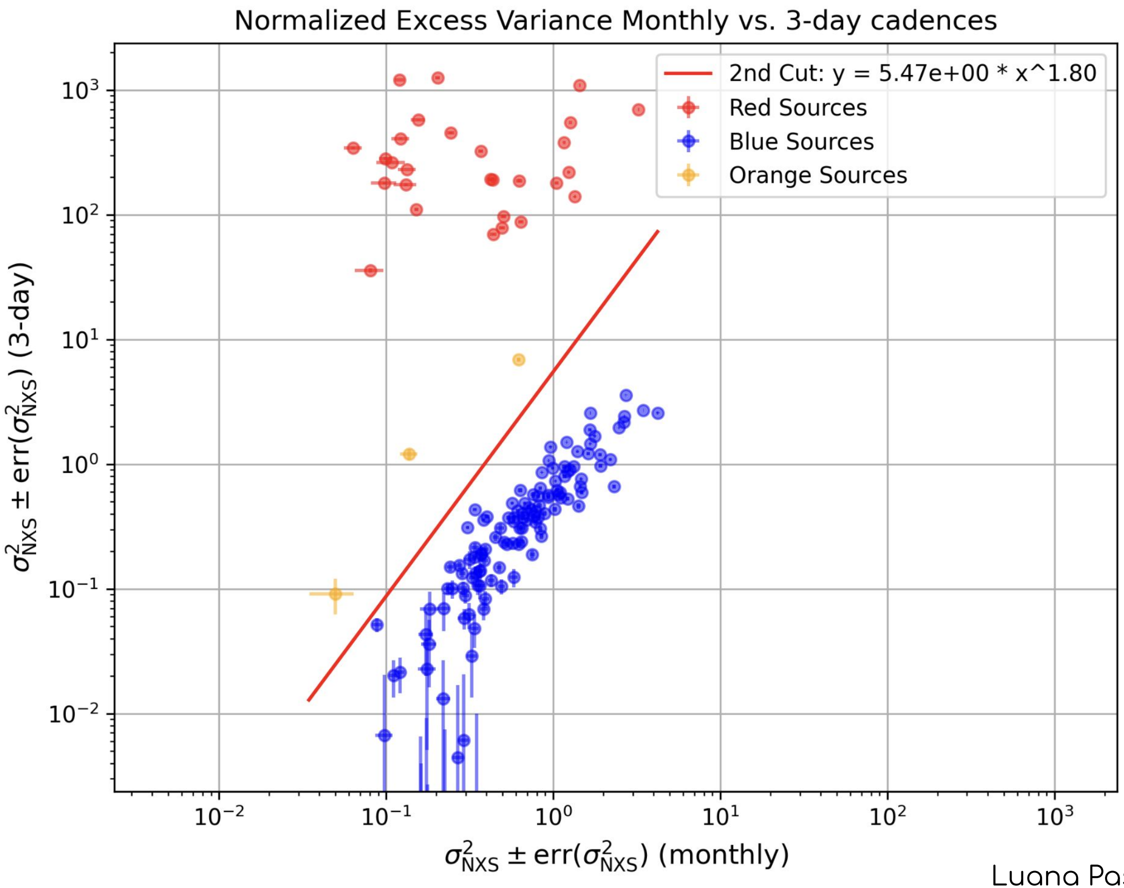
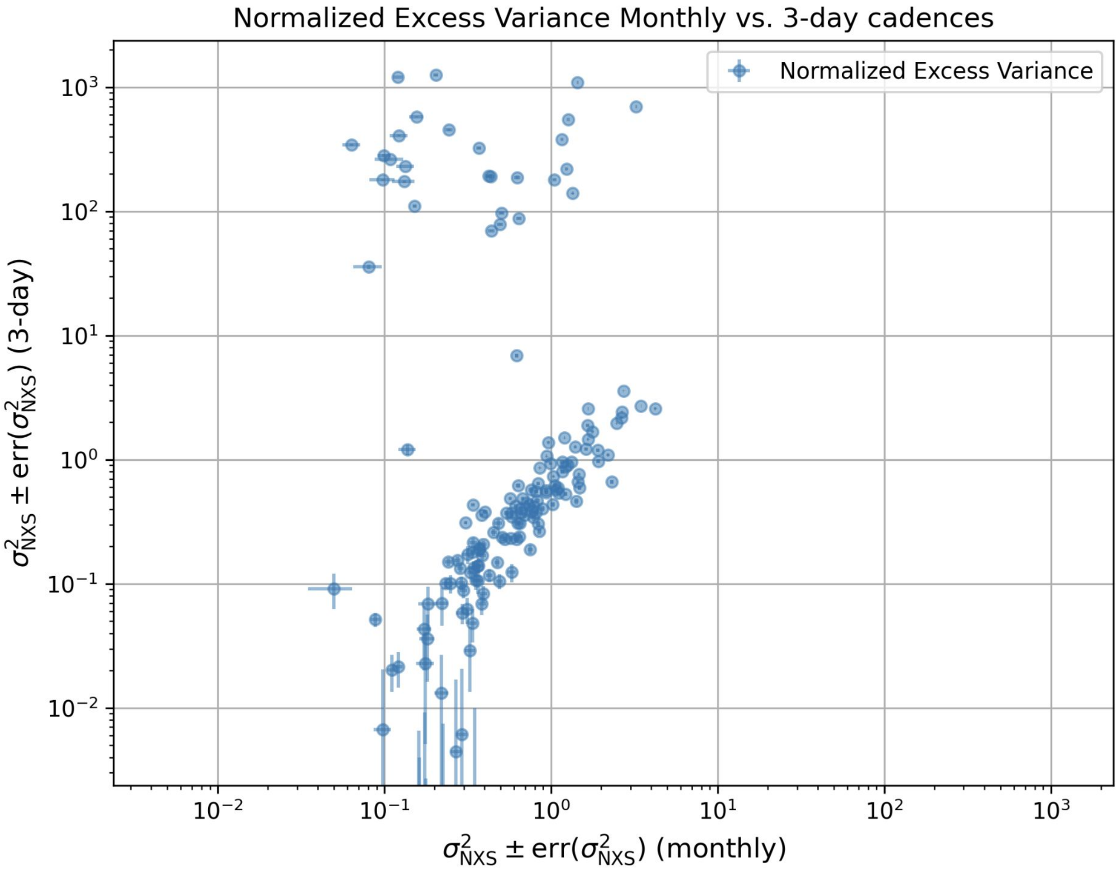
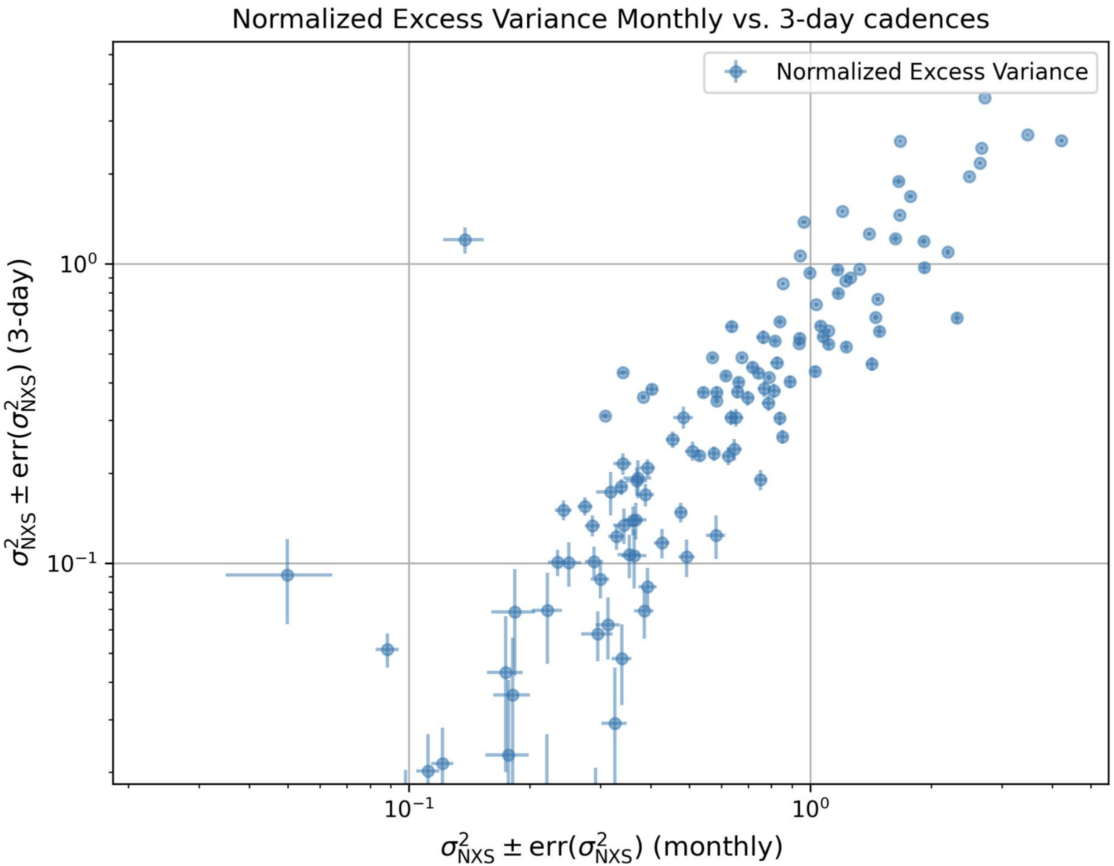



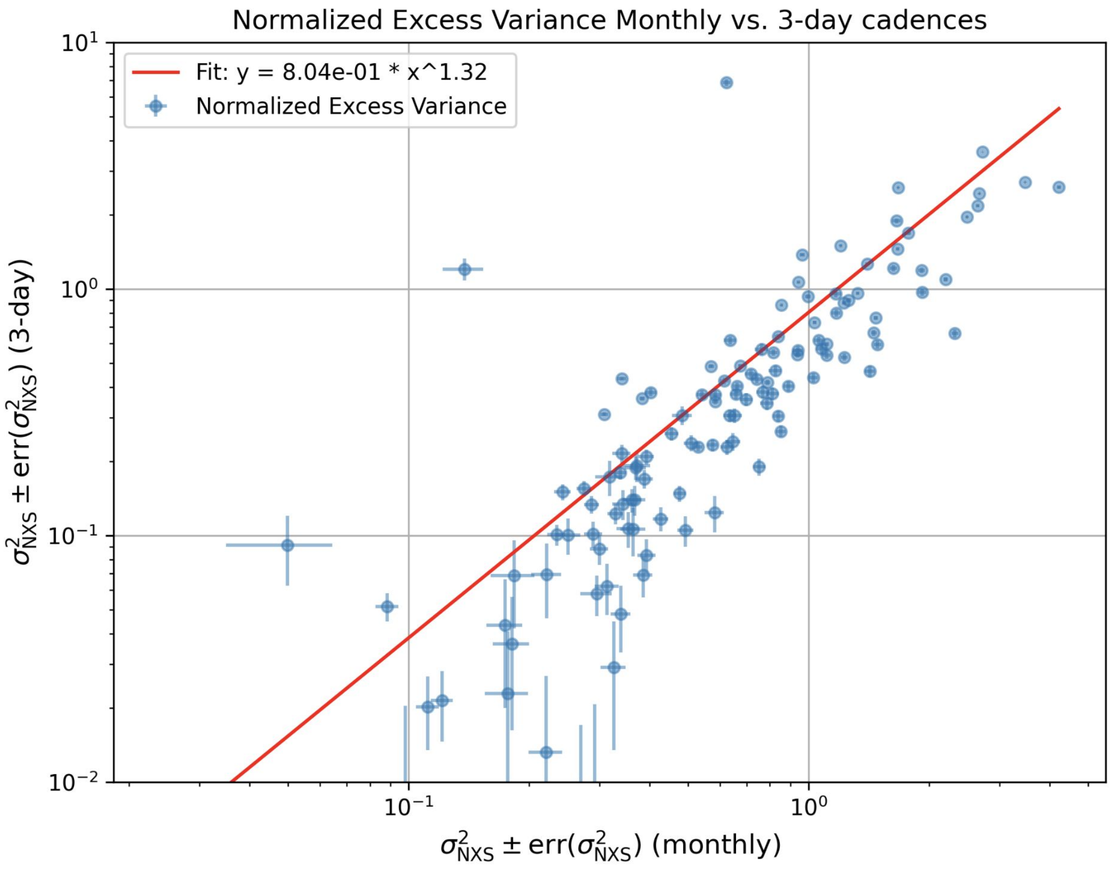
Preliminary Results



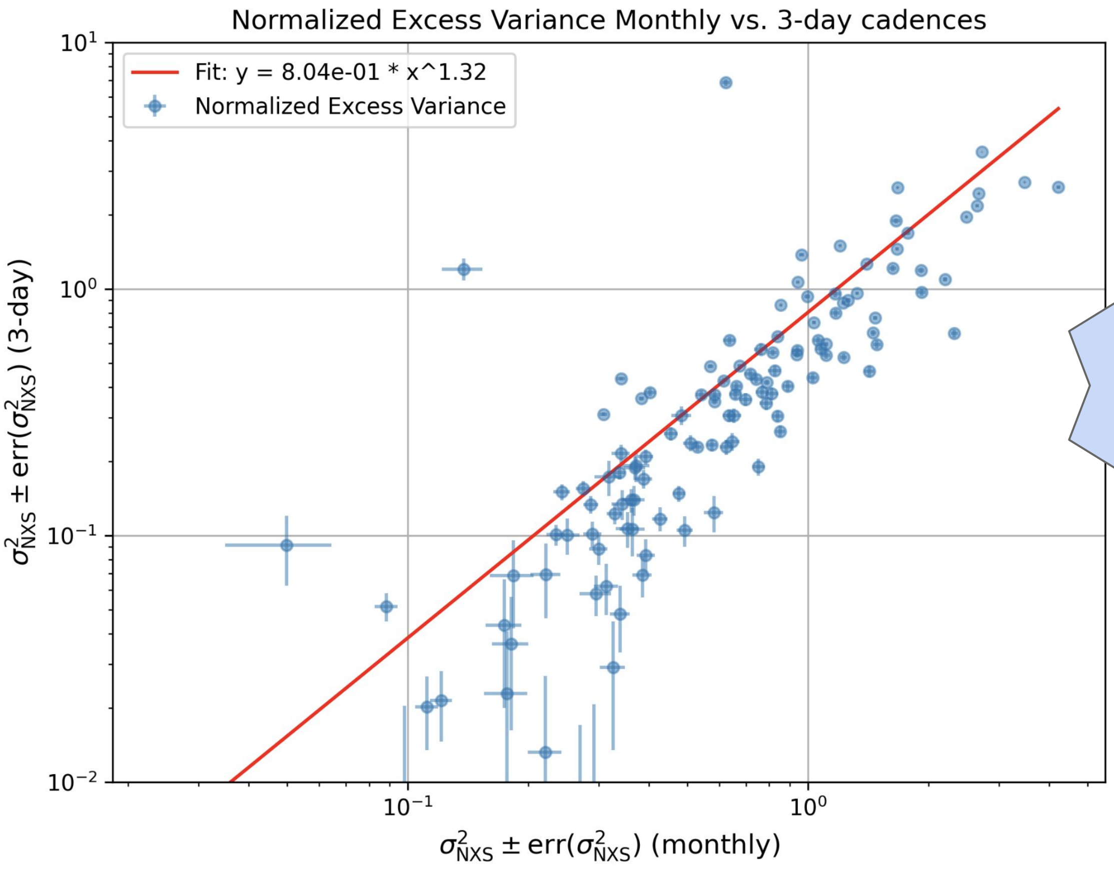
For y < 10


Normalized Excess Variance Monthly vs. 3-day cadences
Normalized Excess Variance
$\sigma^2_{NXS} \pm err(\sigma^2_{NXS})$ (3-day)
$\sigma^2_{NXS} \pm err(\sigma^2_{NXS})$ (monthly)
10^0
10^{-1}
10^{-1}
10^0

Try to set a correlation fit

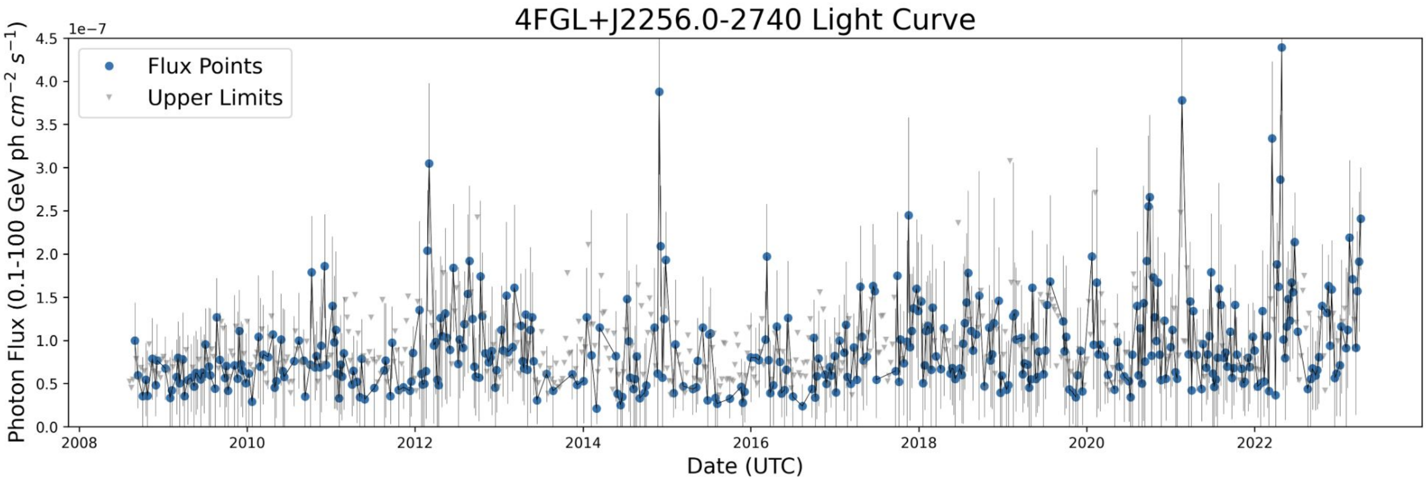


Try to set a correlation fit



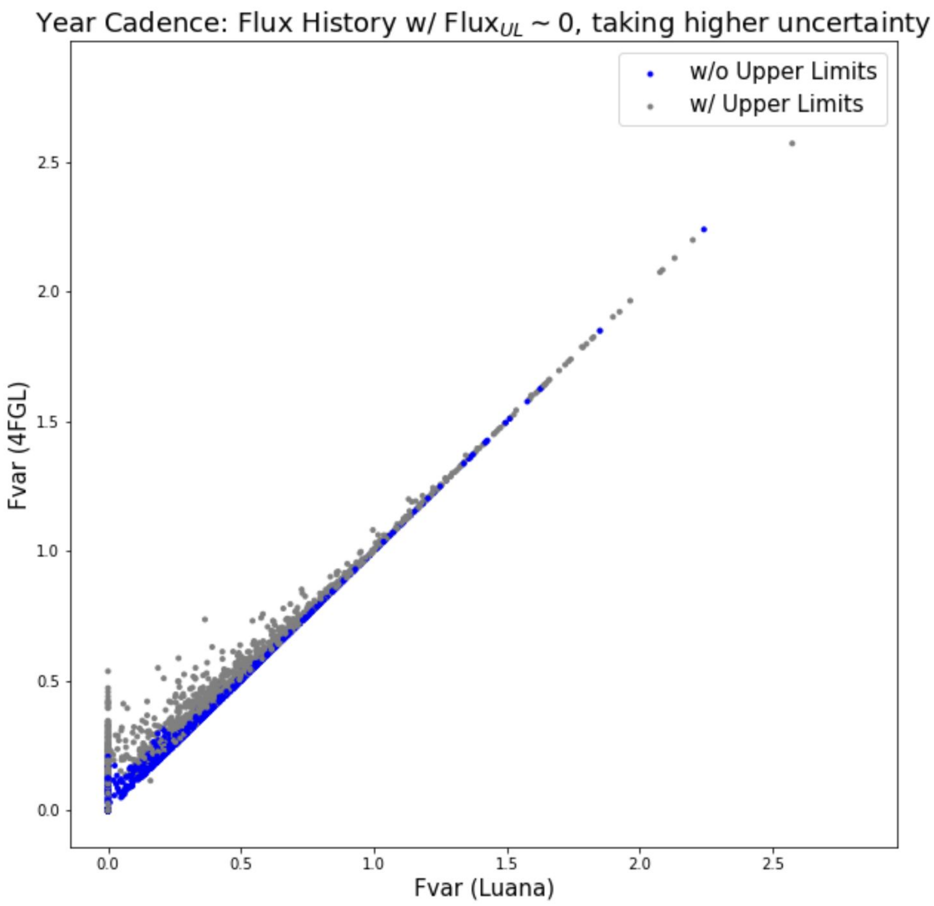
Almost there!

Summary of results until now



- Fermi-LAT only has made available the F_var calculations for the Year cadence
- We have F_var calculations for 3-day, Weekly and Monthly cadences
- To Cross-Check: We are using the History-Flux from the 4FGL to simulate their F_var calculated for year cadence as in S. Abdollahi et al 2020 (ApJS 247 33).

Cross-Check of F_var in Year cadence



- Using the Flux History from the 4FGL to compare our calculations with their year F_var
- Consistent results for Year Variability!
- Until now we have only used actual Flux Measurements
- We are treating and analyzing how to include Upper Limits in the analysis

Next Steps

- Look more careful into the lightcurve of the sources that deviate;
- Include Upper Limits in the analysis;
- Look for a correlation of the variability with:
  - Free Index;
  - Synchrotron Peak;
- Extrapolate the light curves using Gammapy in the AGN Long-Term Monitoring task force;
- In order to:
  - Find the observing time that CTAO will need for each source
  - Estimate what CTA will be able to detect and how variability affects the size of the population we identify

NGC 1068
(Messier 77)

Filtros BVR

Thanks!

Questions ?

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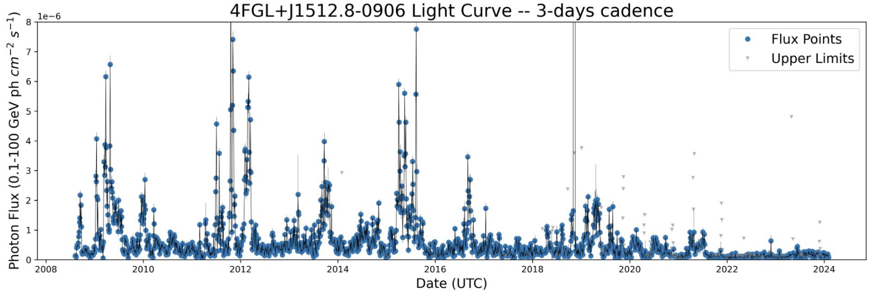
luana.passosreis@cta-consortium.org

Claikson Benedito
&
Luana Reis
Observatório Pico dos Dias (MG) - Jun/2023

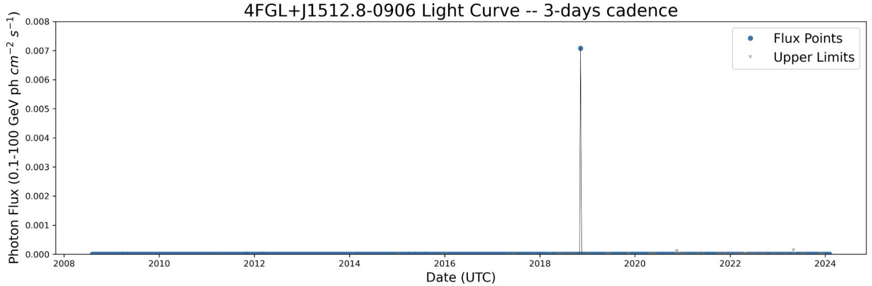
Back-up

Before and After Outlier Treatment

```
[40]: plot_lc('4FGL+J1512.8-0906.json', 8e-6, '3-days')
```

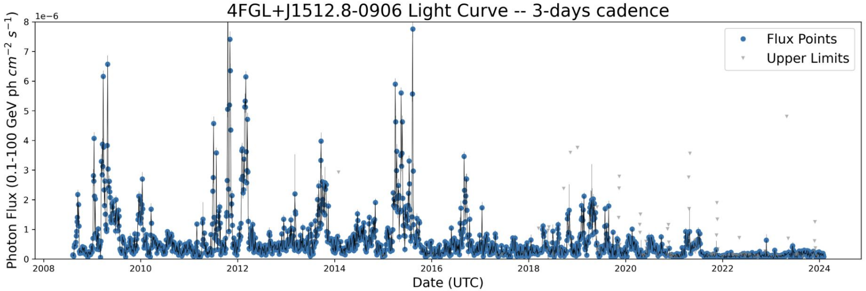



```
[41]: plot_lc('4FGL+J1512.8-0906.json', 8e-3, '3-days')
```

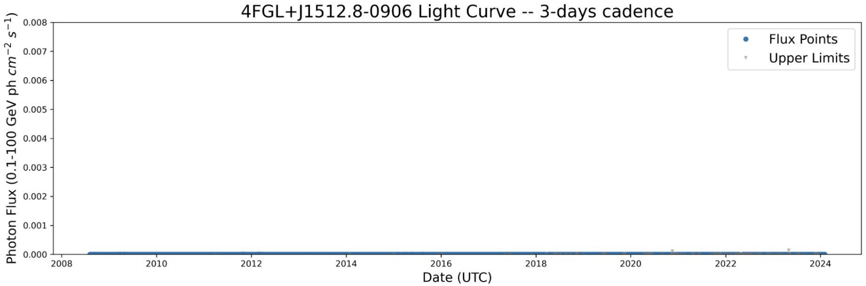


before

```
[40]: plot_lc('4FGL+J1512.8-0906.json', 8e-6, '3-days')
```



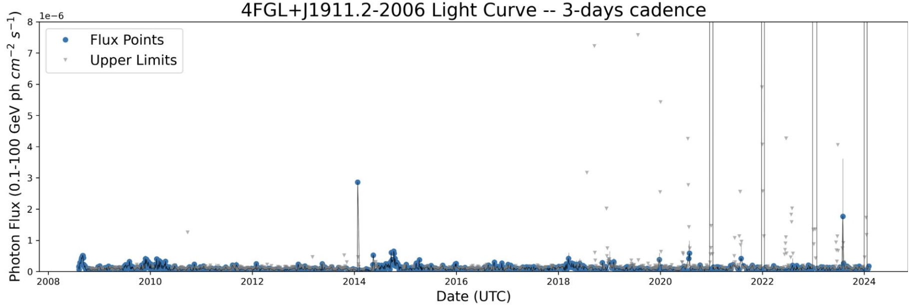

```
[41]: plot_lc('4FGL+J1512.8-0906.json', 8e-3, '3-days')
```



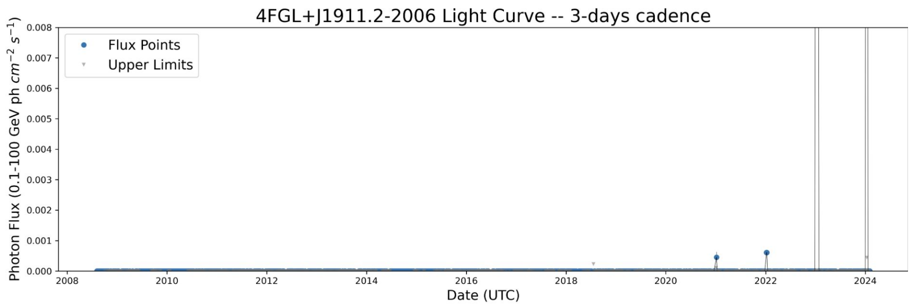
after

Before and After Outlier Treatment

```
[44]: plot_lc('4FGL+J1911.2-2006.json', 8e-6, '3-days')
```

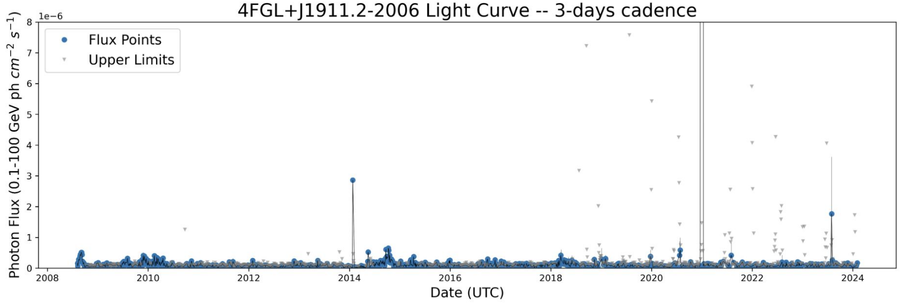



```
[45]: plot_lc('4FGL+J1911.2-2006.json', 8e-3, '3-days')
```

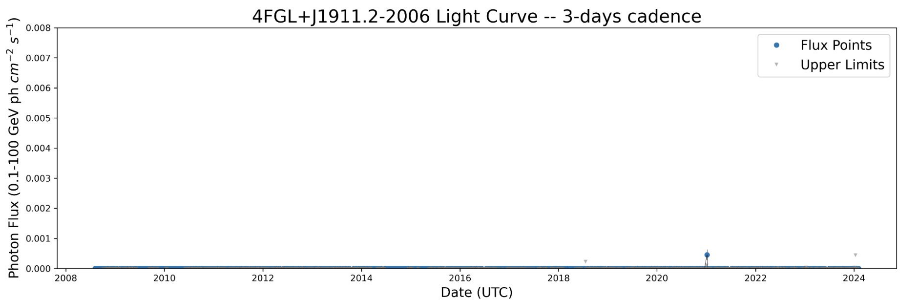


before

```
[44]: plot_lc('4FGL+J1911.2-2006.json', 8e-6, '3-days')
```

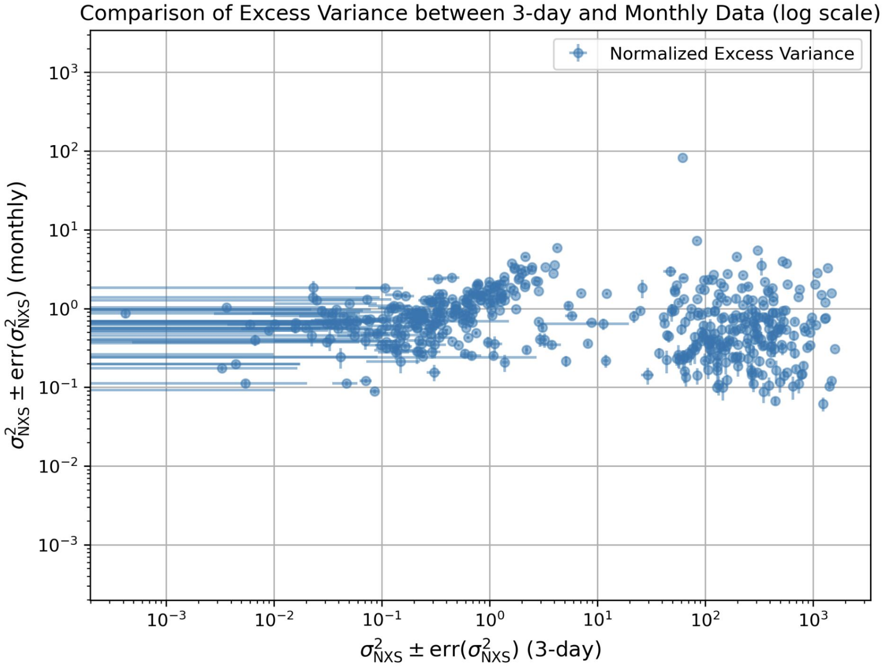



```
[45]: plot_lc('4FGL+J1911.2-2006.json', 8e-3, '3-days')
```

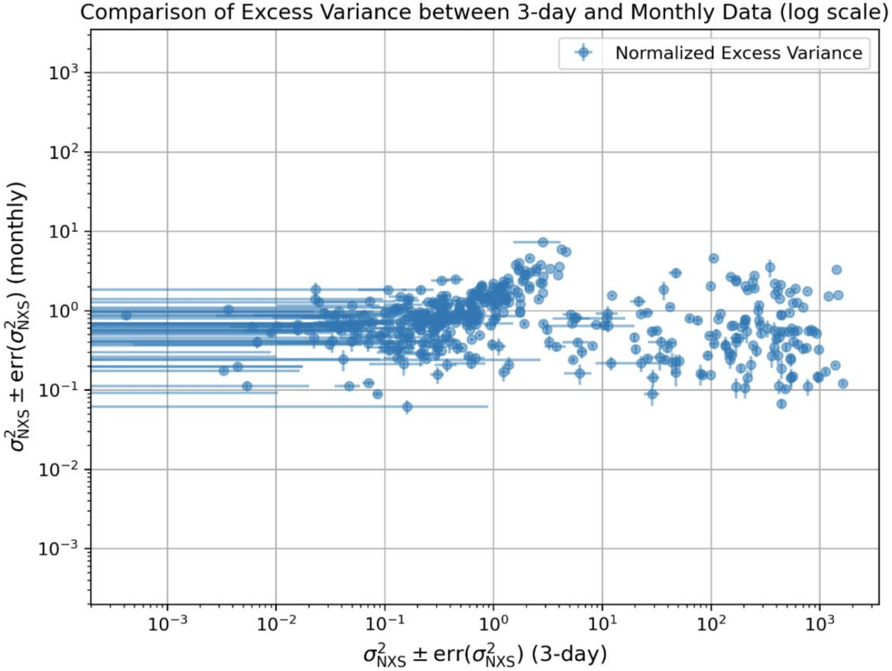


after

Preliminary Analysis

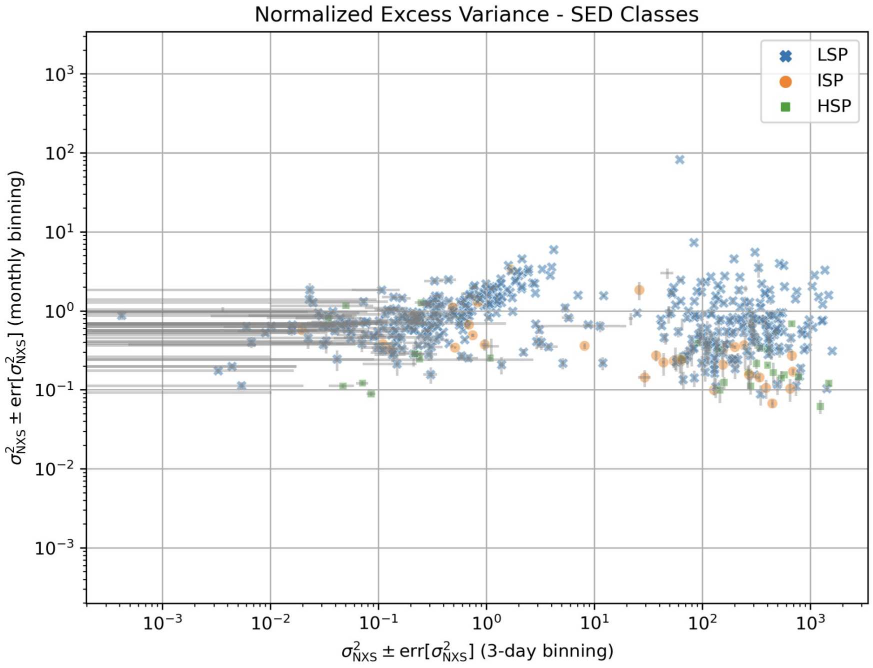


before

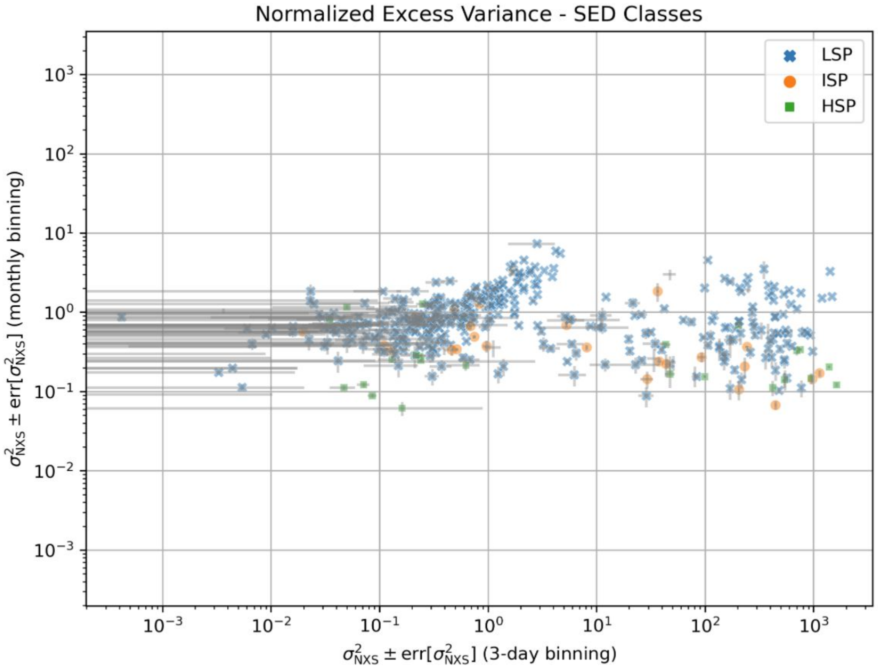


after

Preliminary Analysis

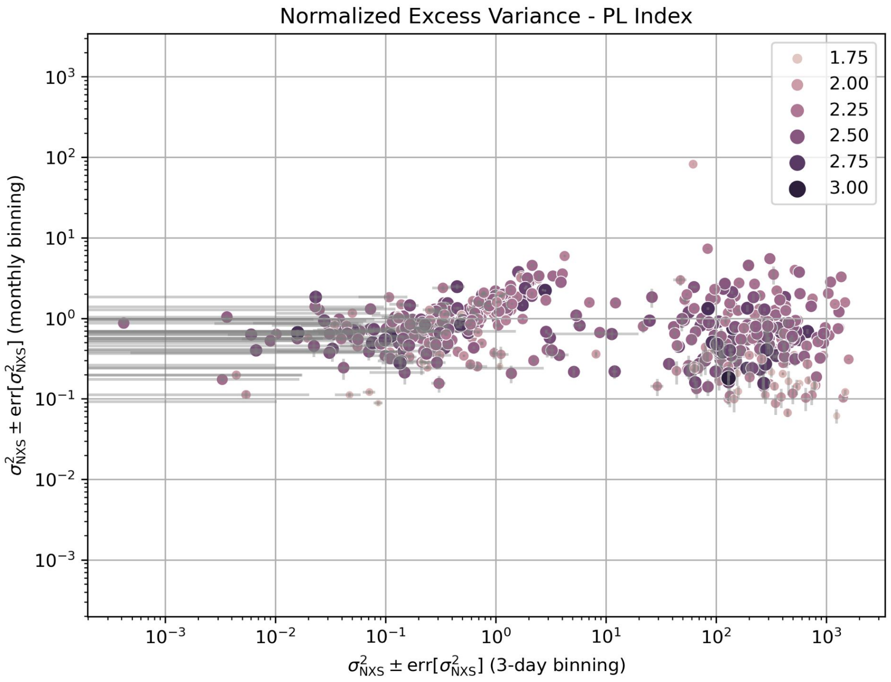


before

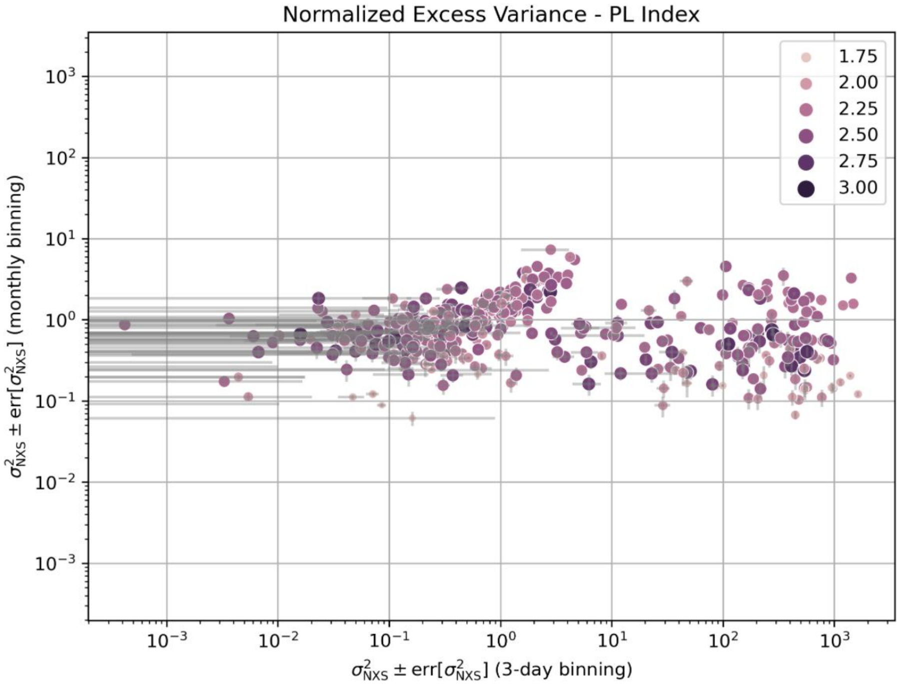


after

Preliminary Analysis



before



after

Bonus

MHD simulations and particle acceleration:

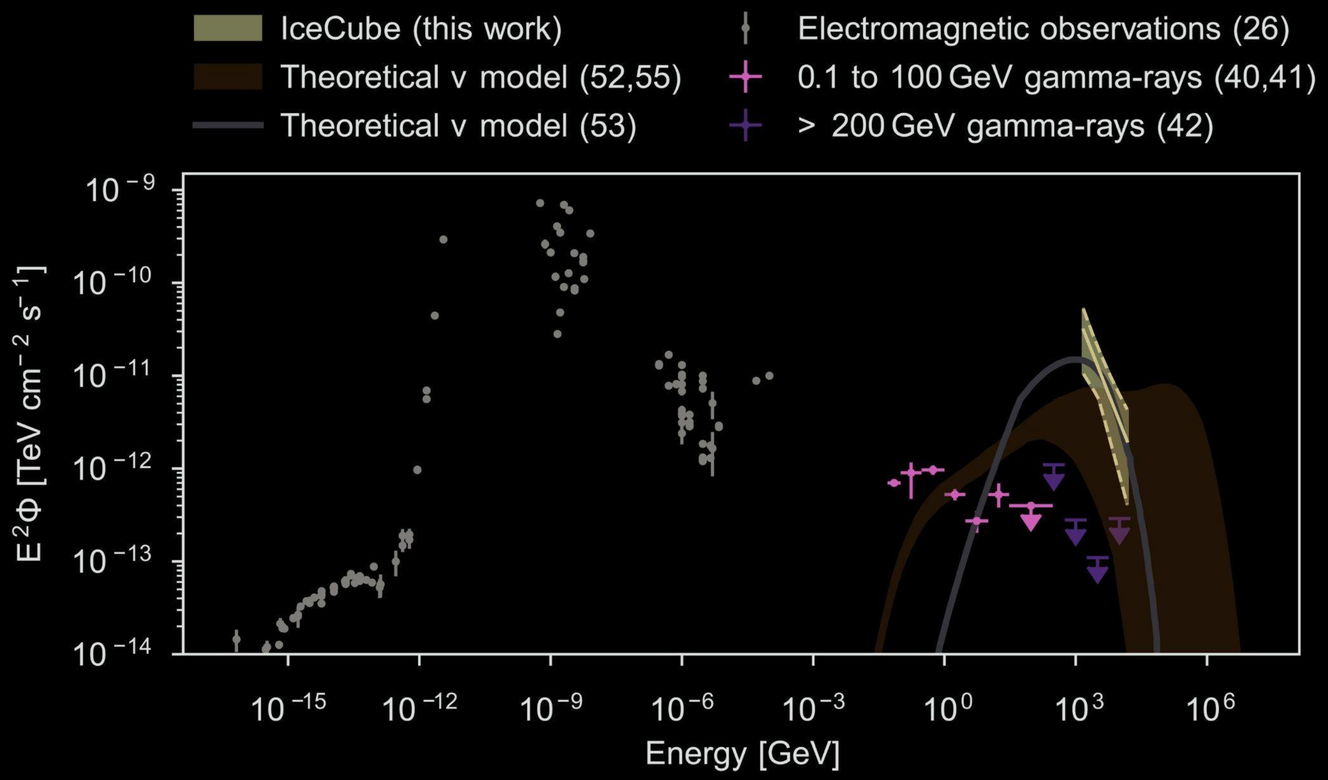
special case of NGC 1068

Filtros BVR, Luana e Claikson, OPD - MG - Jun/2023

Luana Passos Reis

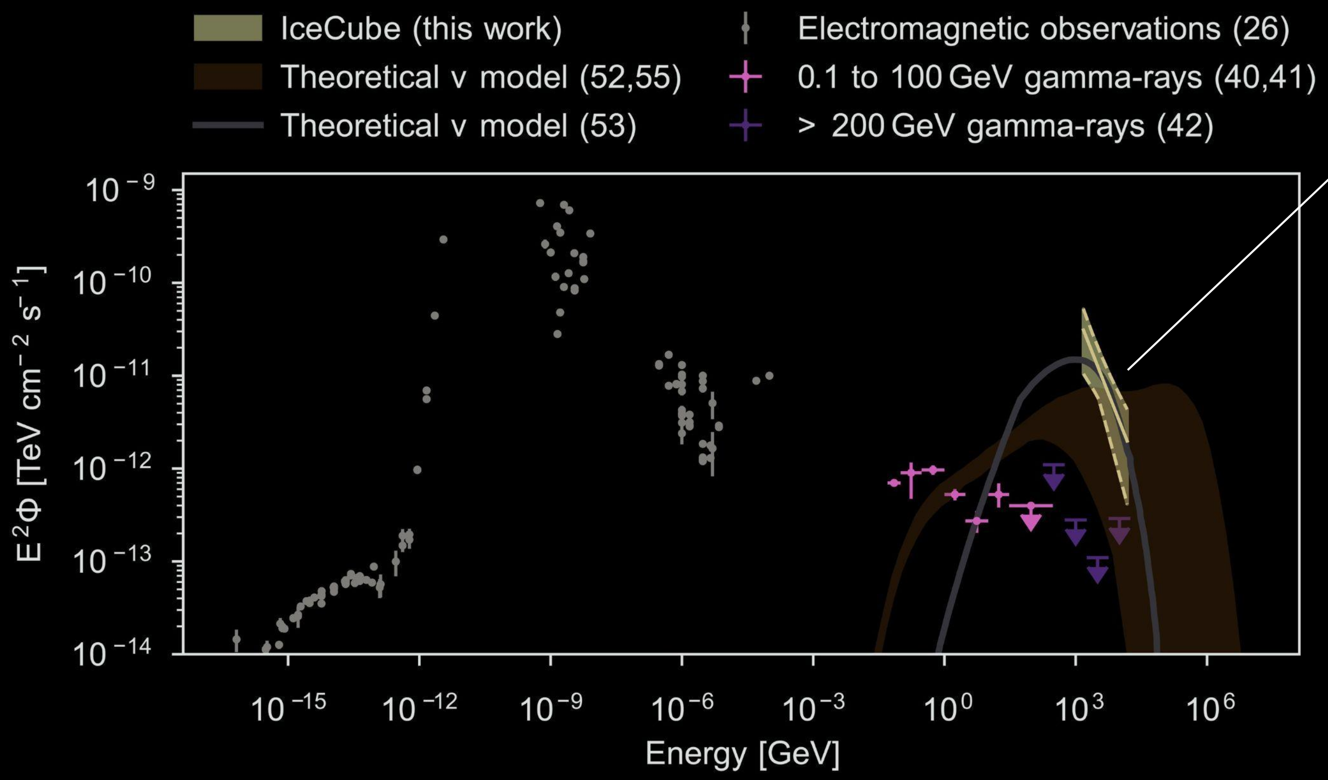
Elisabete M. de Gouveia Dal Pino
Giovani Heizen Vicentin
Chandra B. Singh

Neutrino VS gamma-ray flux from NGC1068



(IceCube Collaboration, 2022, Science)

Neutrino VS gamma-ray flux from NGC1068



Neutrinos, a clue for the acceleration of protons to relativistic velocities

(IceCube Collaboration, 2022, Science)

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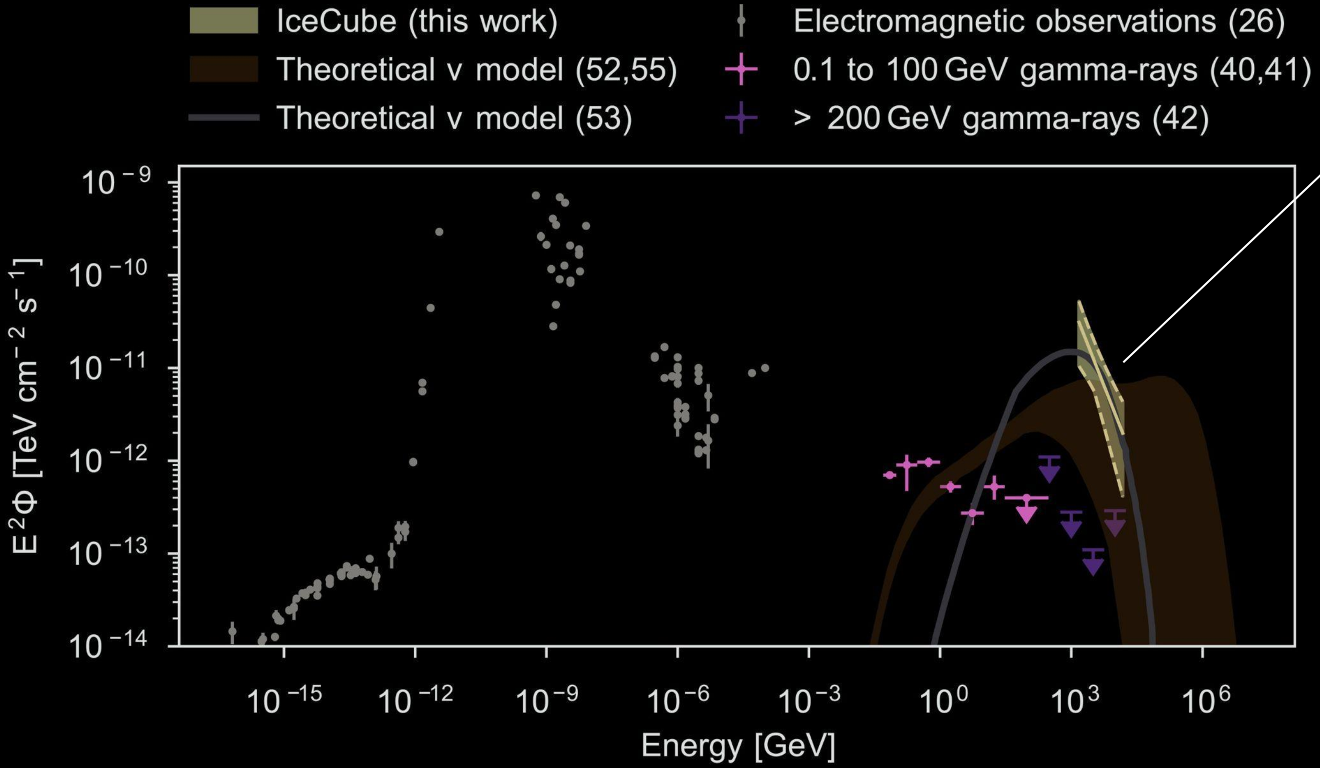

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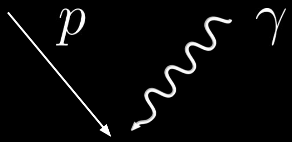

photopion ($\pi^{\pm}$ component)

(IceCube Collaboration, 2022, Science)

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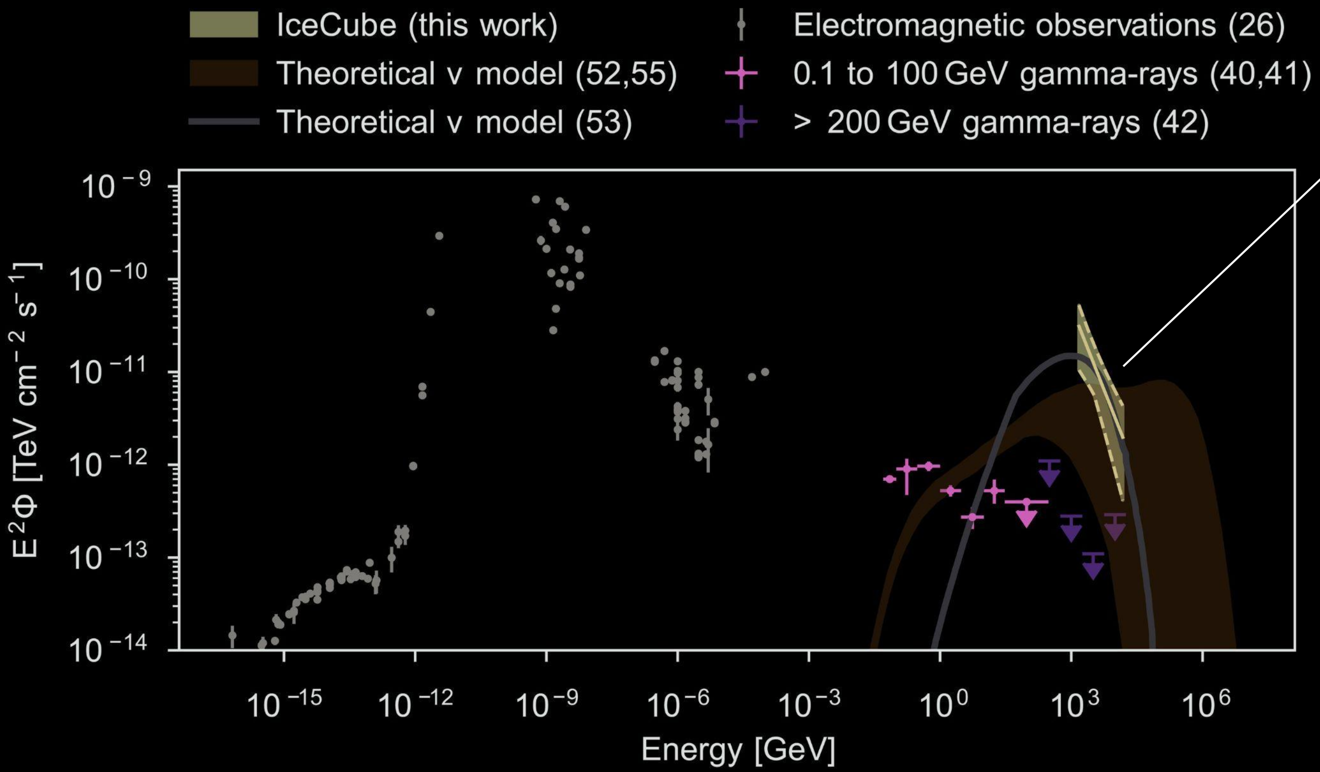

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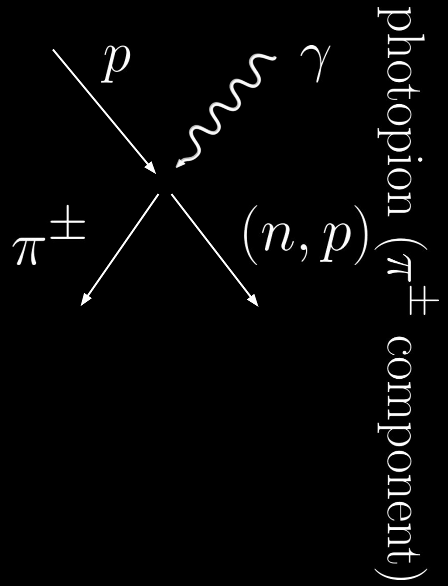

(IceCube Collaboration, 2022, Science)

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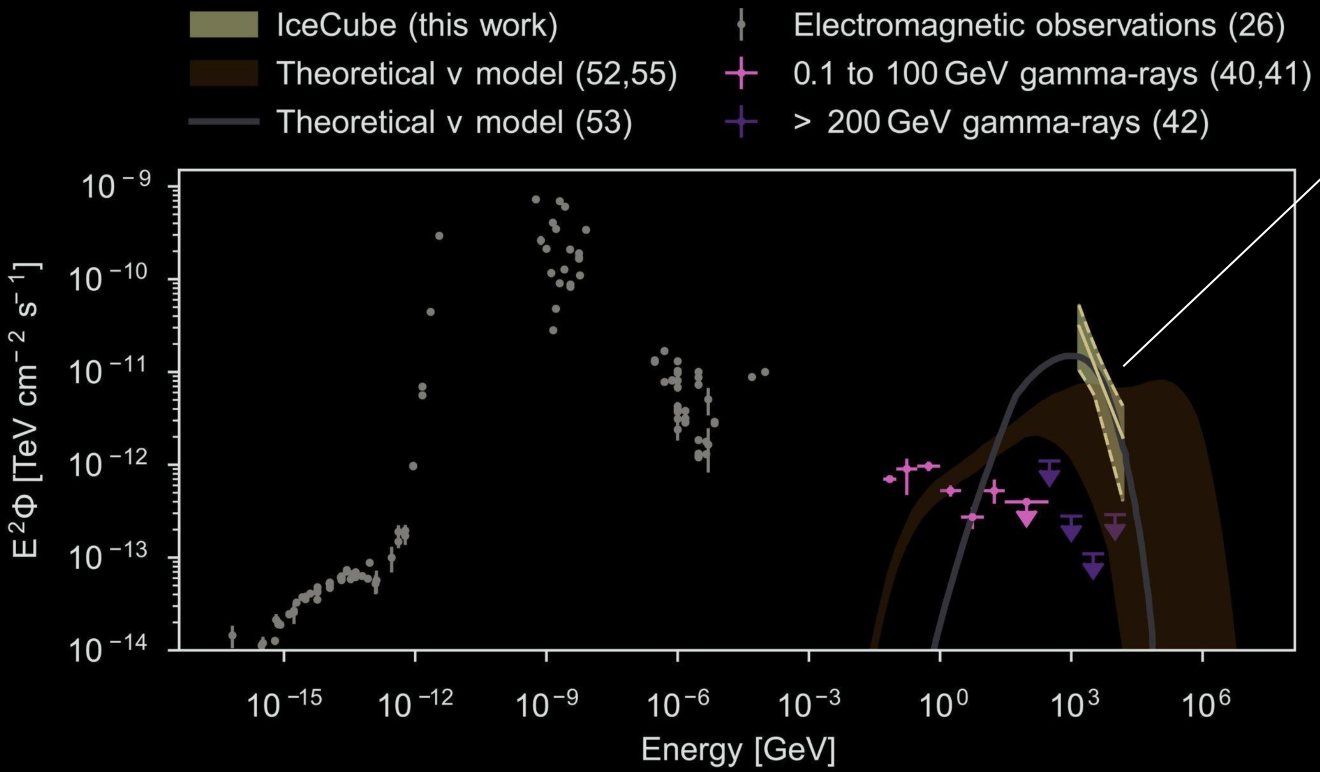

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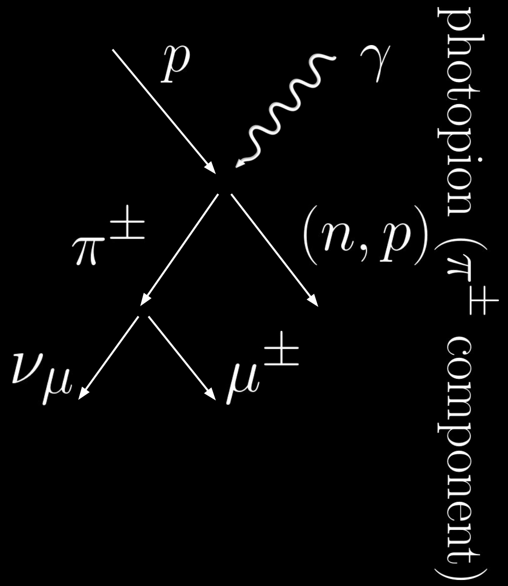

(IceCube Collaboration, 2022, Science)

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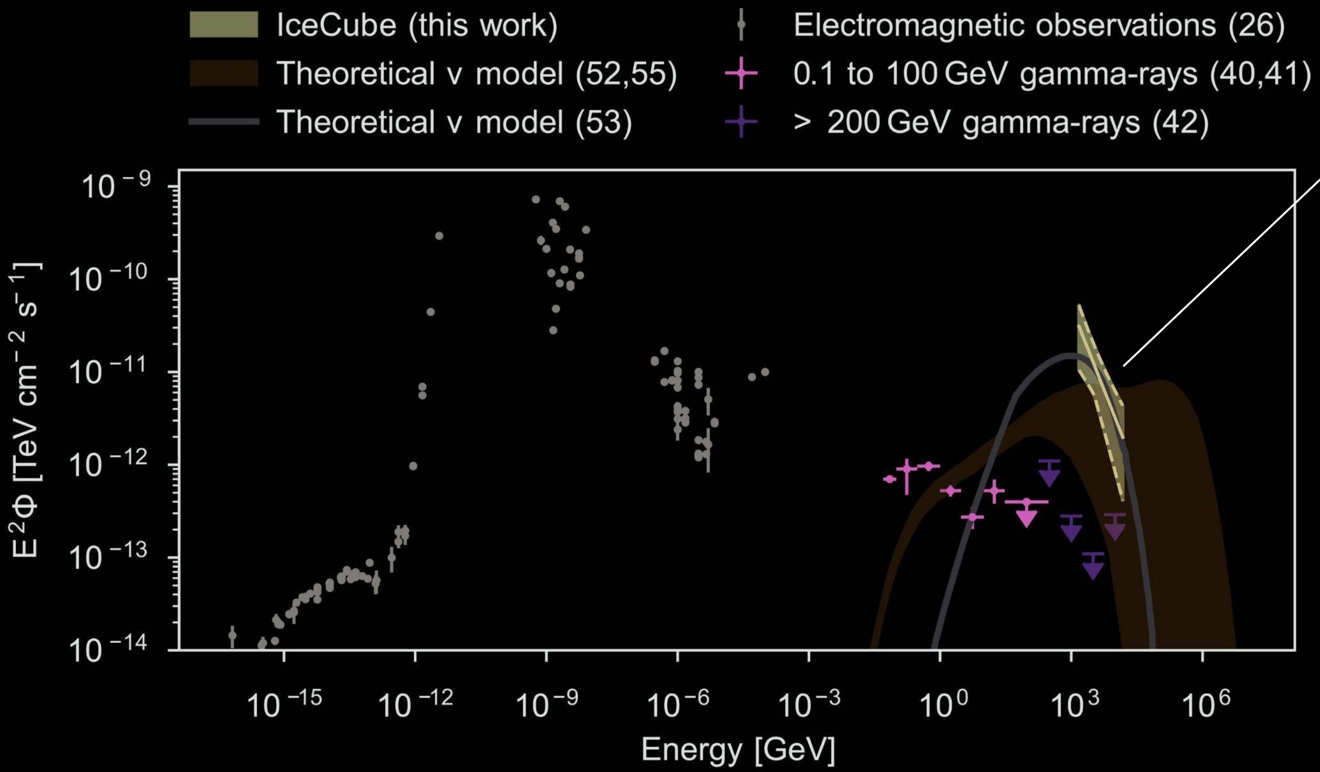

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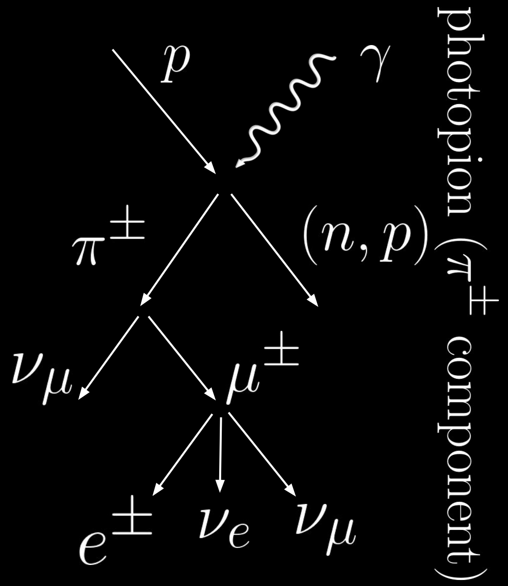

(IceCube Collaboration, 2022, Science)

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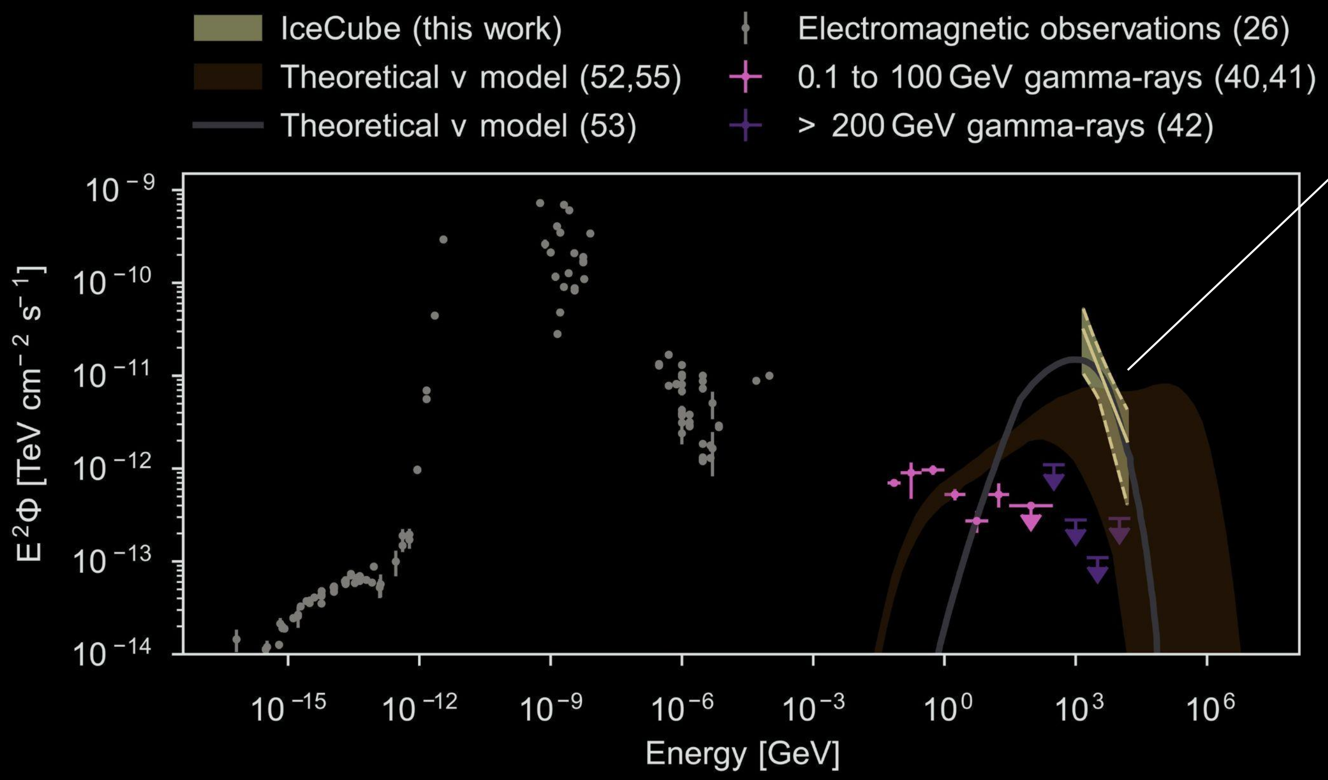

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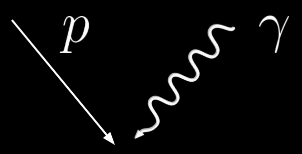

photopion (π^0 component)

(IceCube Collaboration, 2022, Science)

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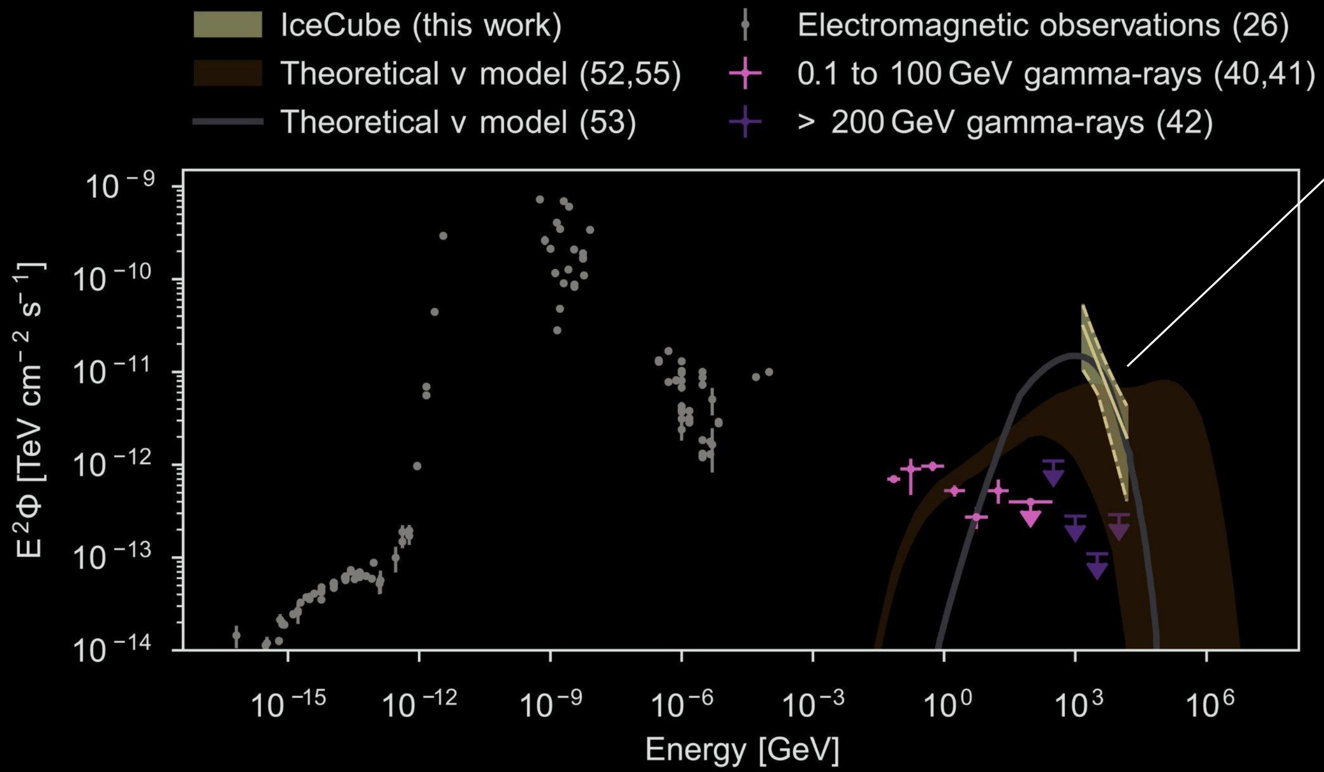

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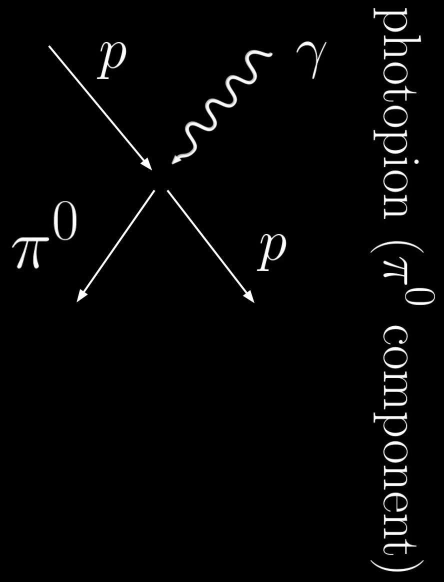

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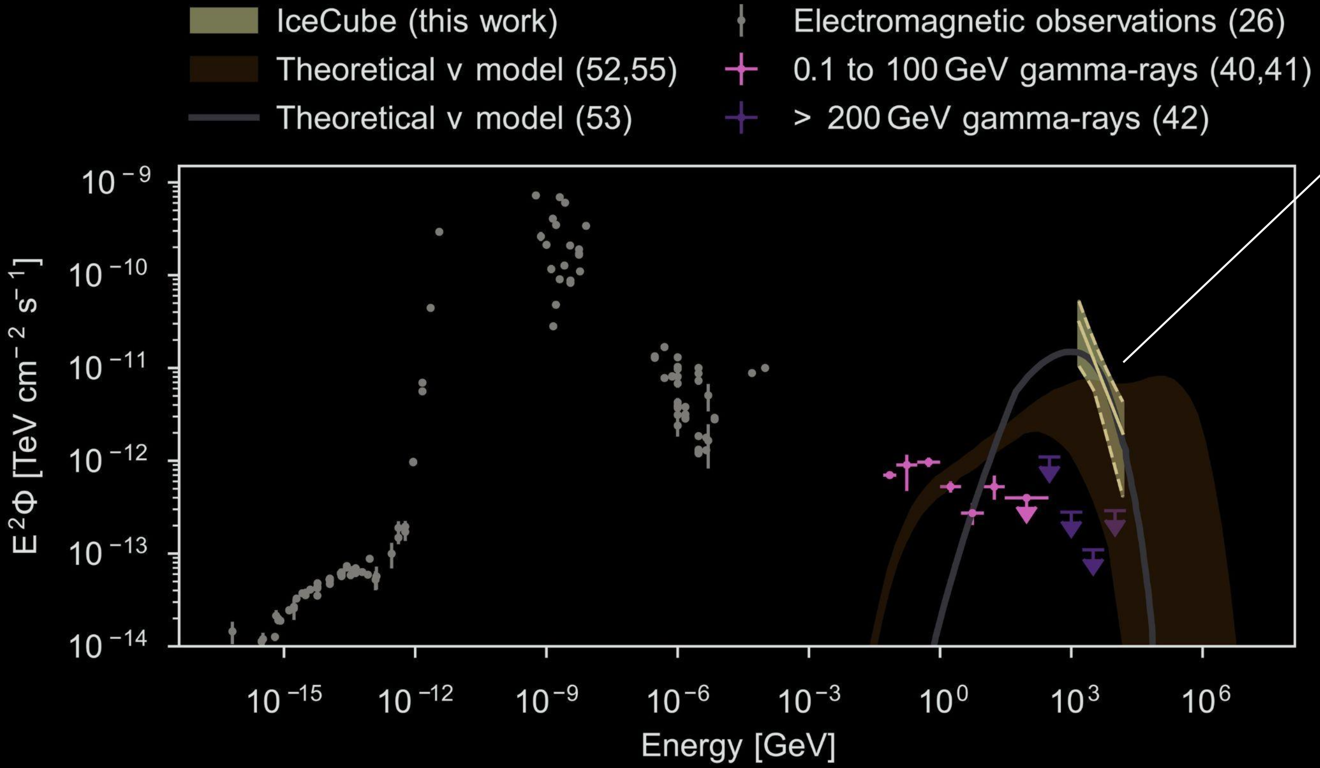

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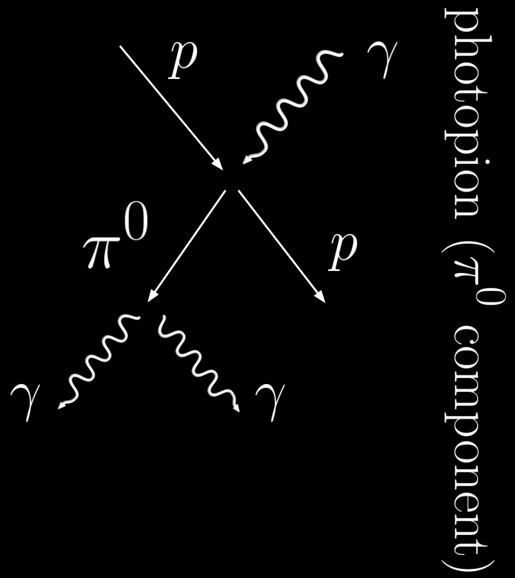

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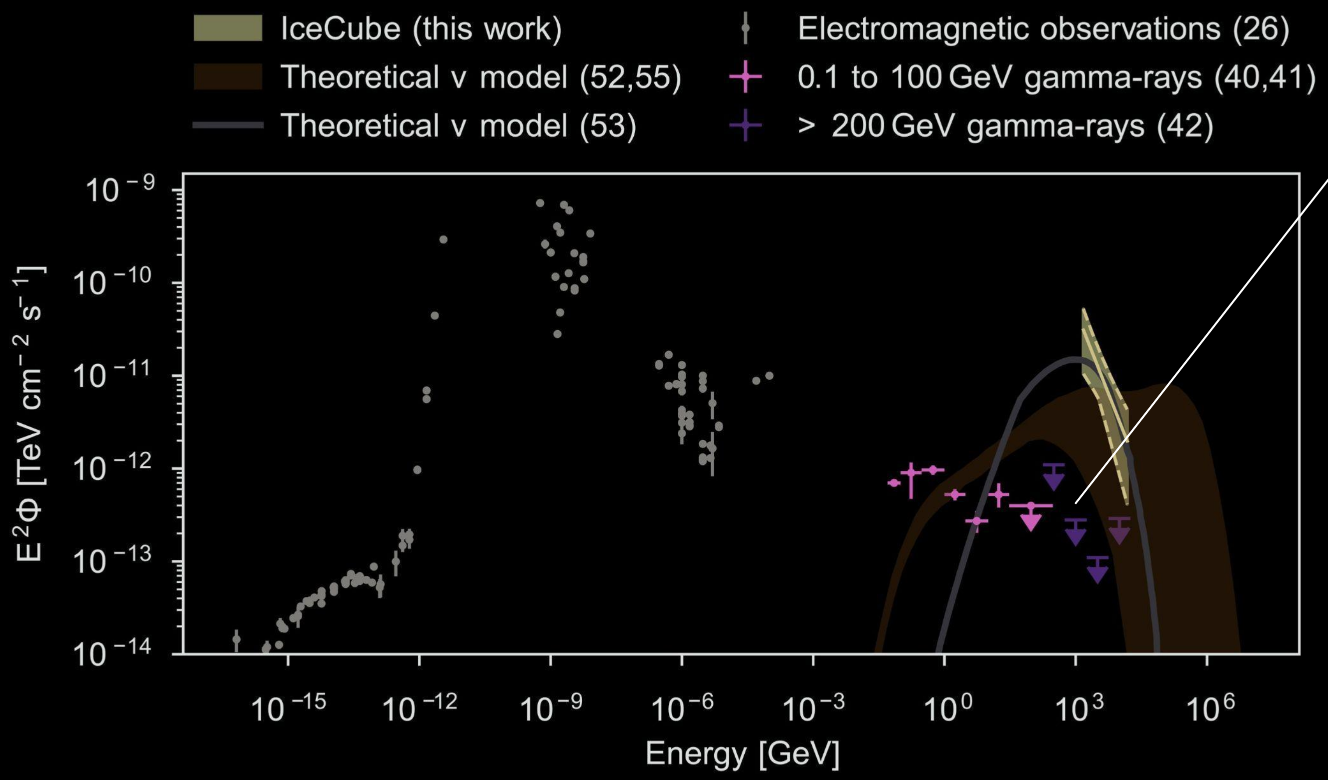
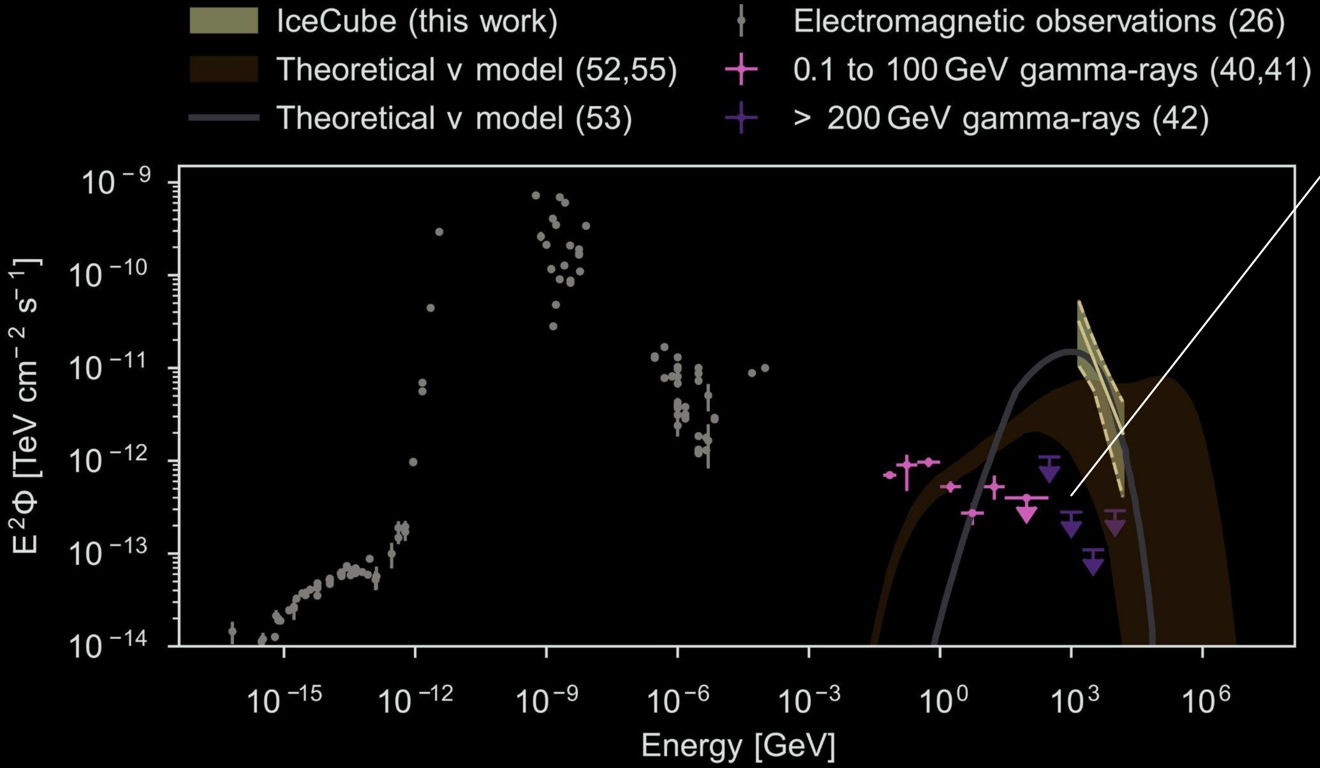


The absence of γ rays indicates auto-absorption due to a dense photon field

(IceCube Collaboration, 2022, Science)

Neutrino VS gamma-ray flux from NGC1068



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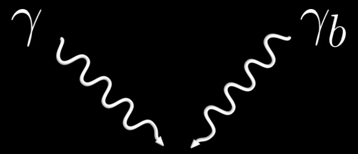
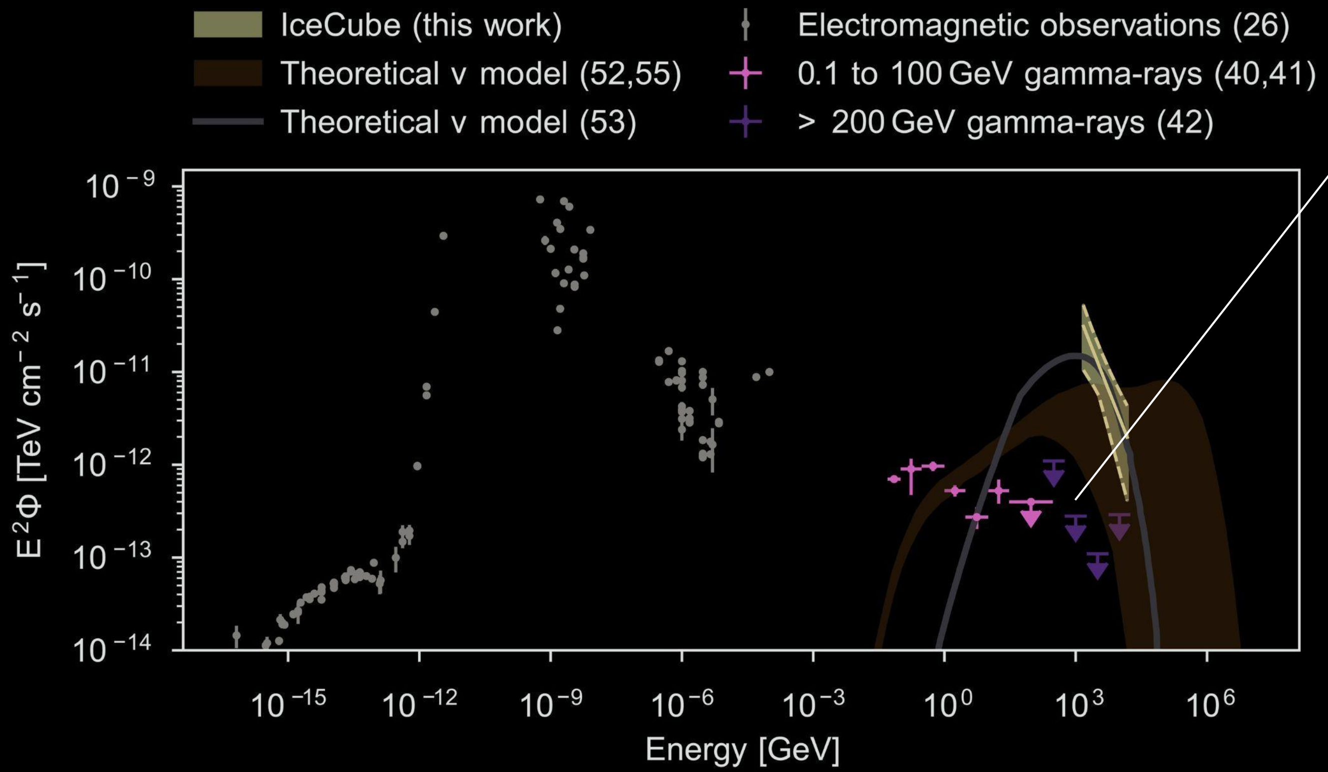


pair production

(IceCube Collaboration, 2022, Science)

Neutrino VS gamma-ray flux from NGC1068



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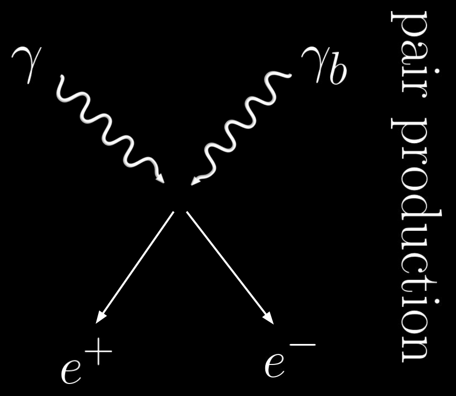

(IceCube Collaboration, 2022, Science)

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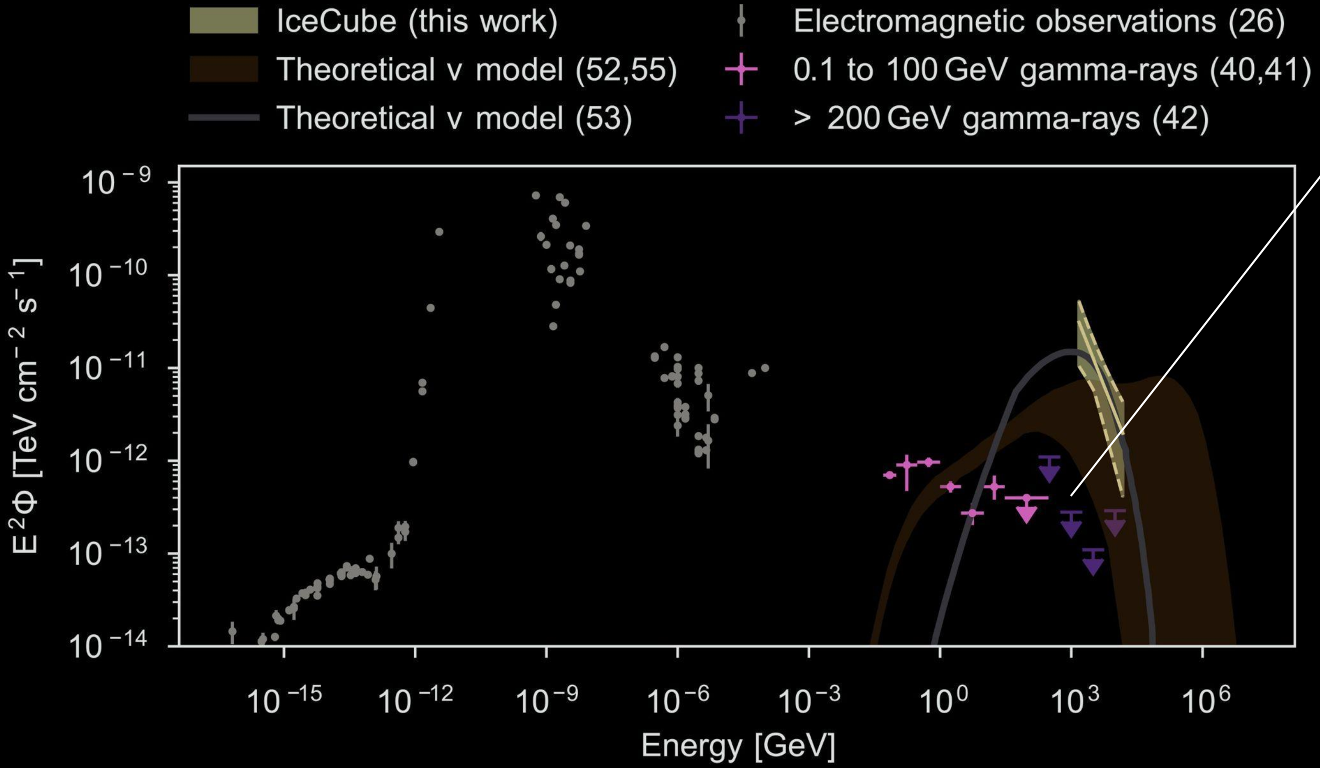

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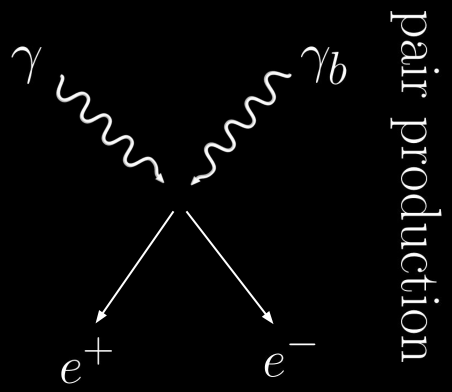
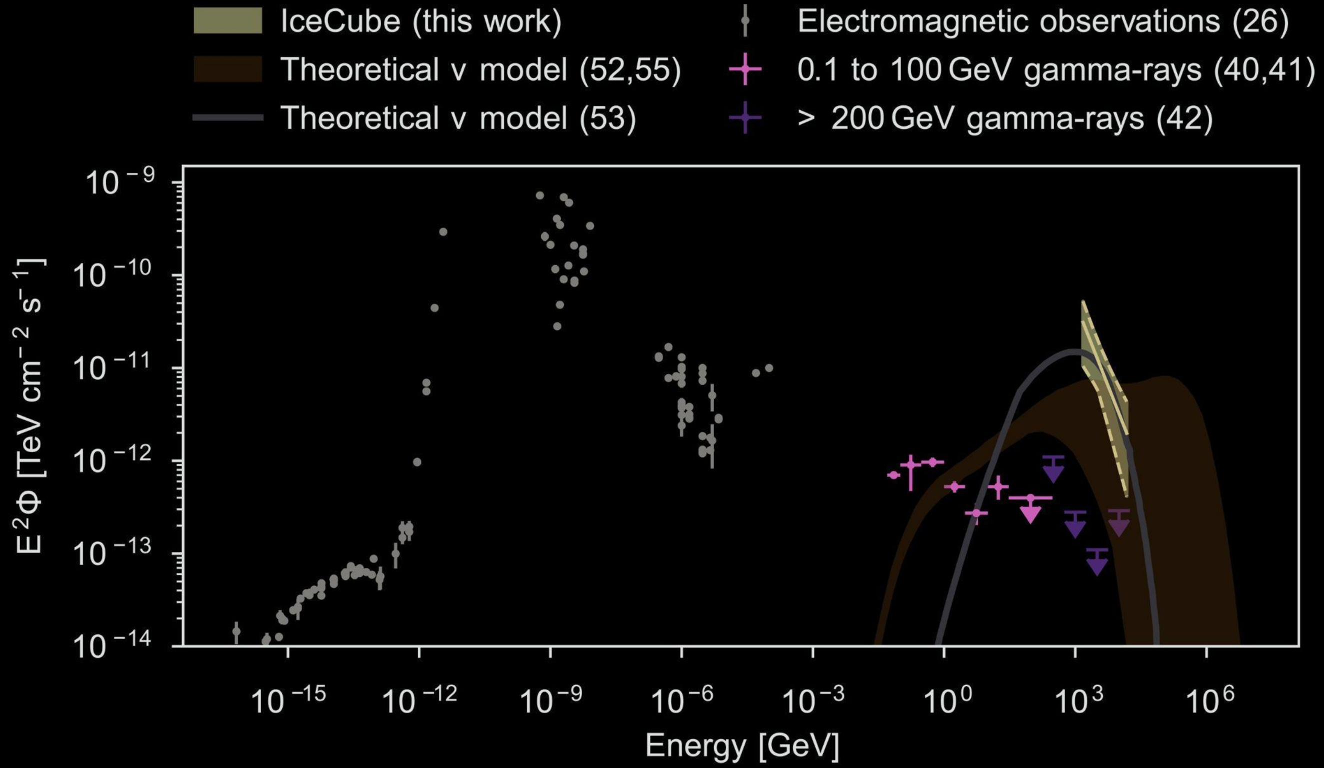


$\therefore$ The emission may become from the inner part of the AGN!

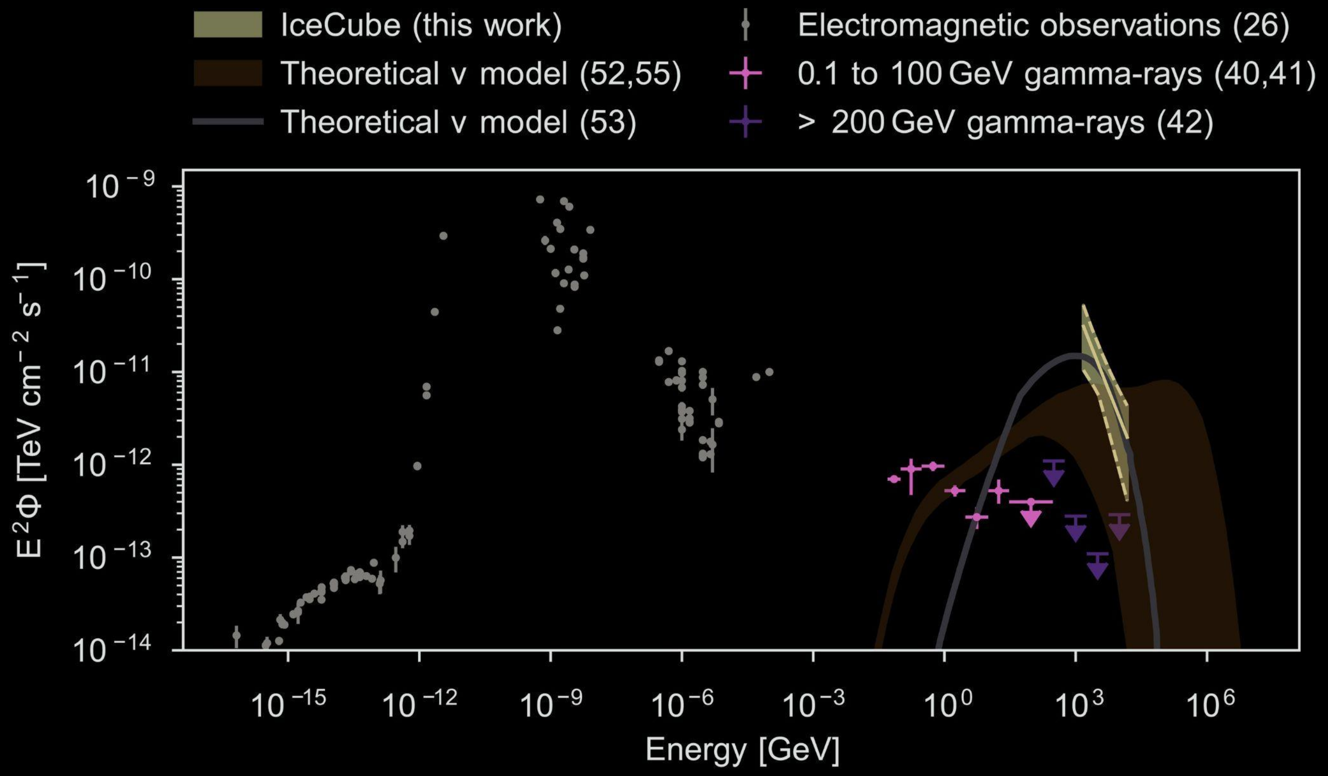
Neutrino VS gamma-ray flux from NGC1068



(IceCube Collaboration, 2022, Science)

What may accelerate these protons in the surroundings of the SMBH?

Neutrino VS gamma-ray flux from NGC1068



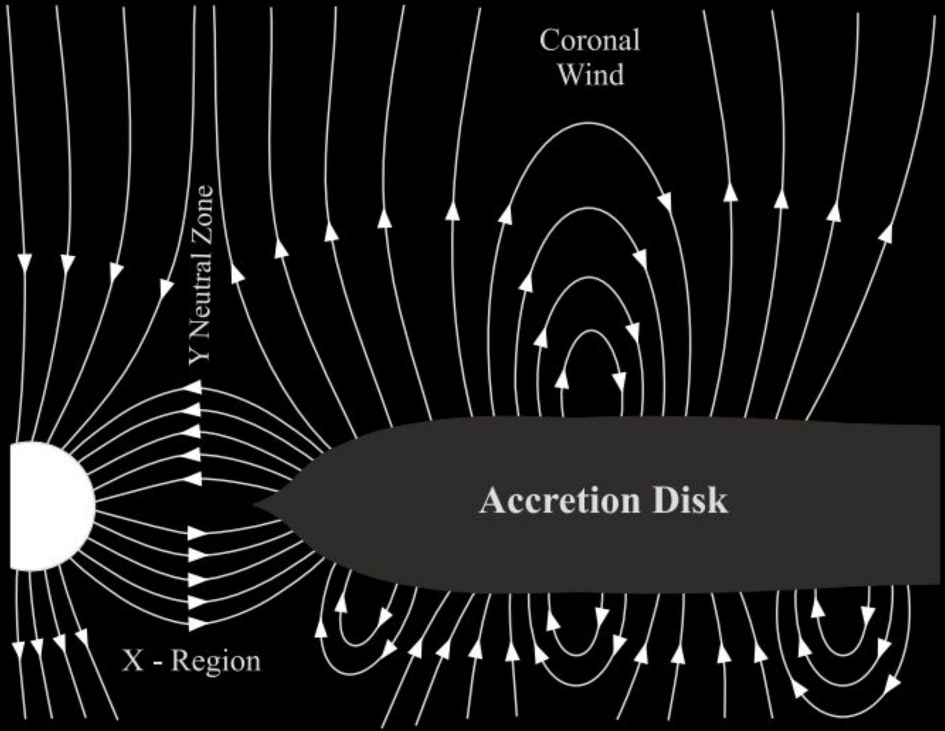
What may accelerate these protons in the surroundings of the SMBH?

Magnetic Reconnection!

(IceCube Collaboration, 2022, Science)

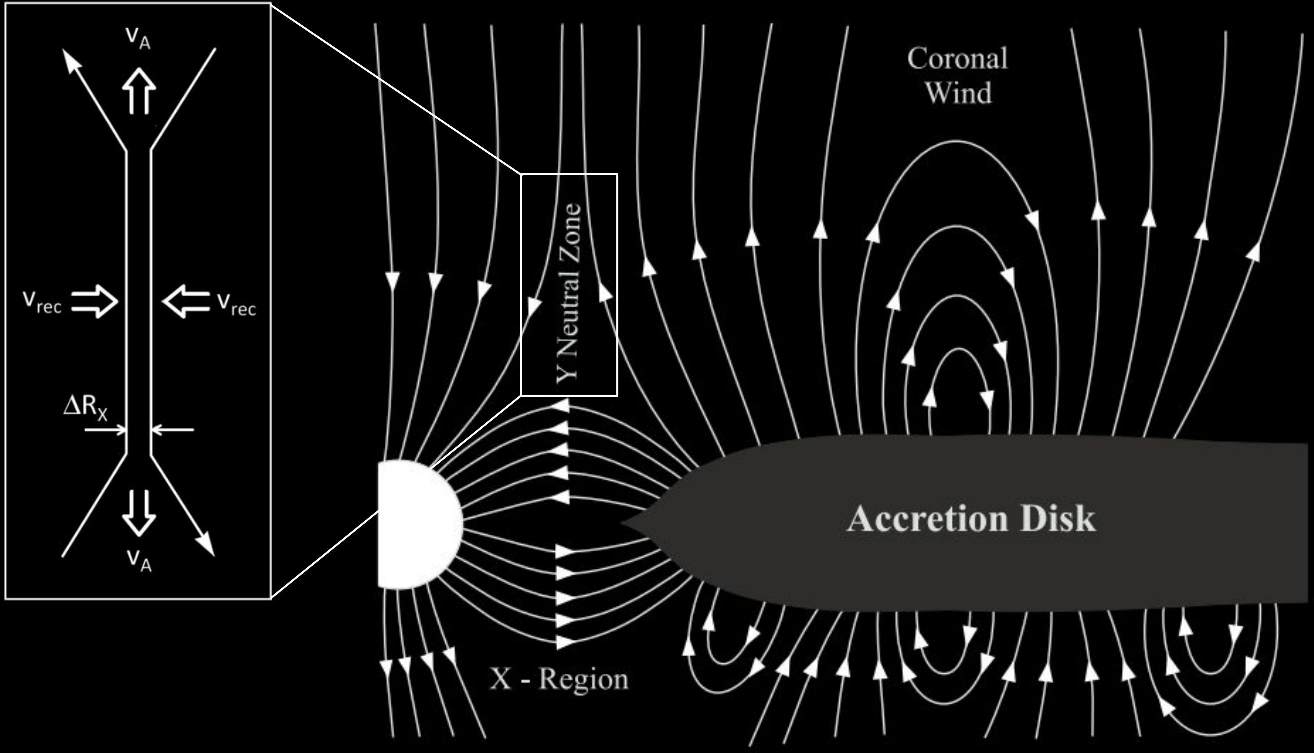
Magnetic Reconnection around Black Holes

Possible configuration of the magnetic field lines for an accretion flow into a black hole



(de Gouveia Dal Pino & Lazarian, 2005, A&A)

Magnetic Reconnection around Black Holes

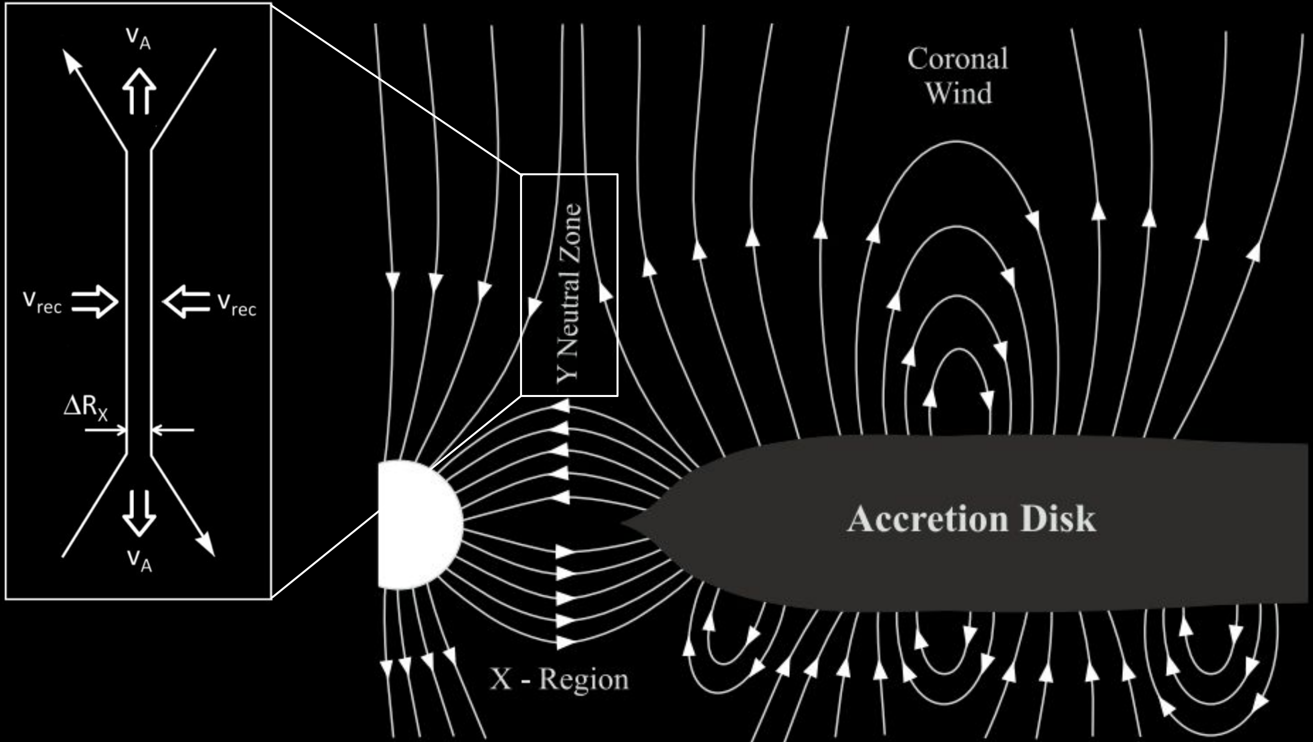


(de Gouveia Dal Pino & Lazarian, 2005, A&A)

Magnetic Reconnection around Black Holes

Particles can be accelerated in the magnetic discontinuity according to a first-order Fermi process:

$$\left\langle \frac{\Delta E}{E} \right\rangle \sim \frac{V_{\rm rec}}{c}$$



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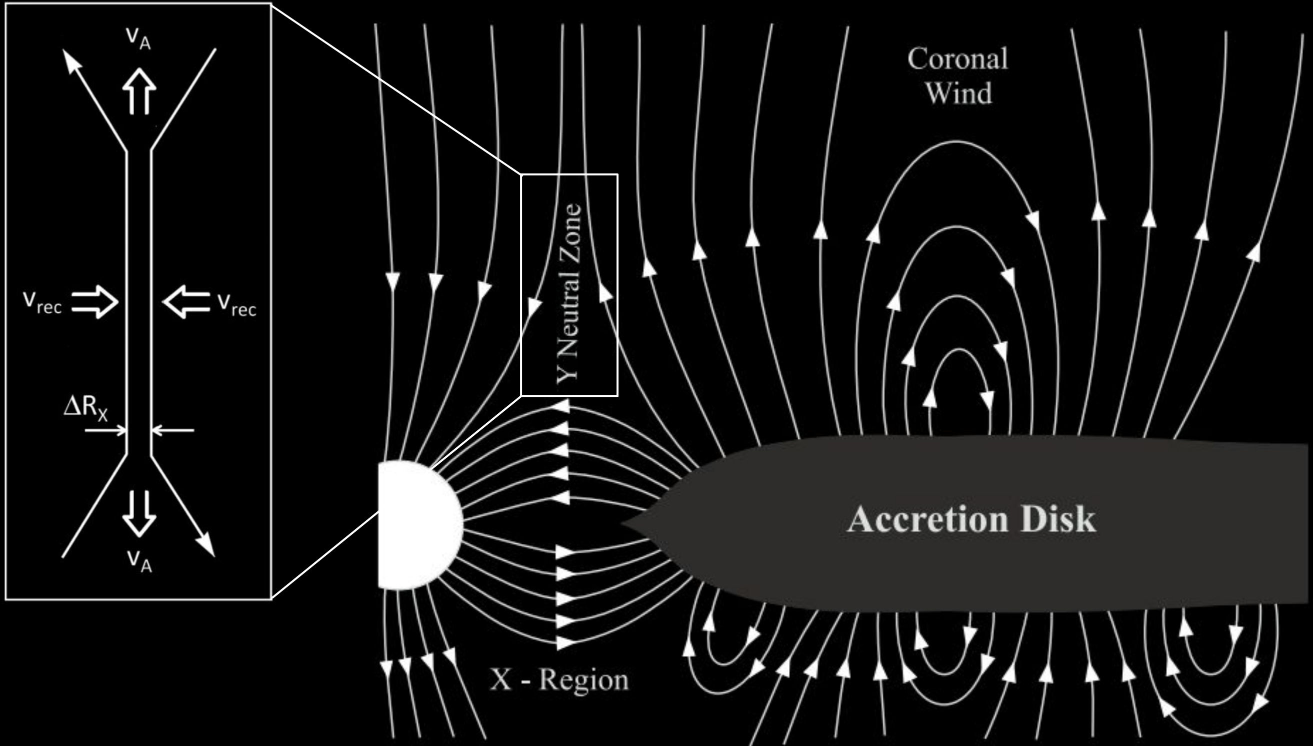
Magnetic Reconnection around Black Holes

$$\left\langle \frac{\Delta E}{E} \right\rangle \sim \frac{V_{\rm rec}}{c}$$

Implies an exponential growth of the energy with time!



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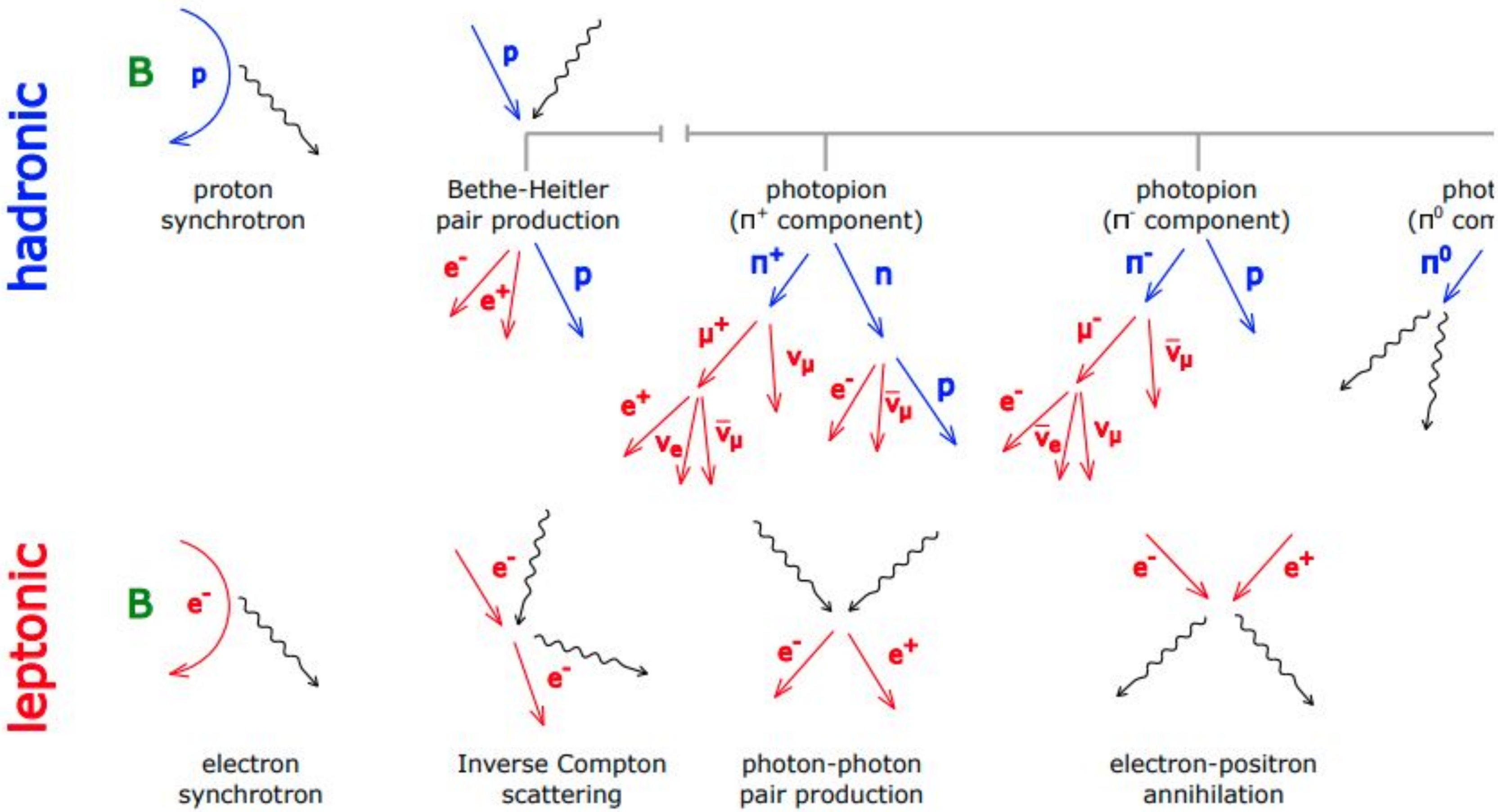

Mastichiadis 2016