AGN Studies: Variability Analysis of Fermi-LAT data for the Cherenkov Telescope Array & MHD simulations

High-Energy Astrophysics in the Multi-Messenger Era - IFSC - April/2024

Luana Passos Reis

PhD Student at IAG-USP

Universidade de São Paulo

Advisor: Elisabete M. de Gouveia Dal Pino

About me

São Paulo

About me

Osasco

About me

Lafayette, Louisiana - USA

About me

Bachelor in Physics

(IFUSP)

About me

Love to travel

About me

PhD Student in Astronomy (IAG/USP) since 2023

About me

2019 - 2022

About me

INCLOUDE

Technical Training I

About me

INCLOUDE

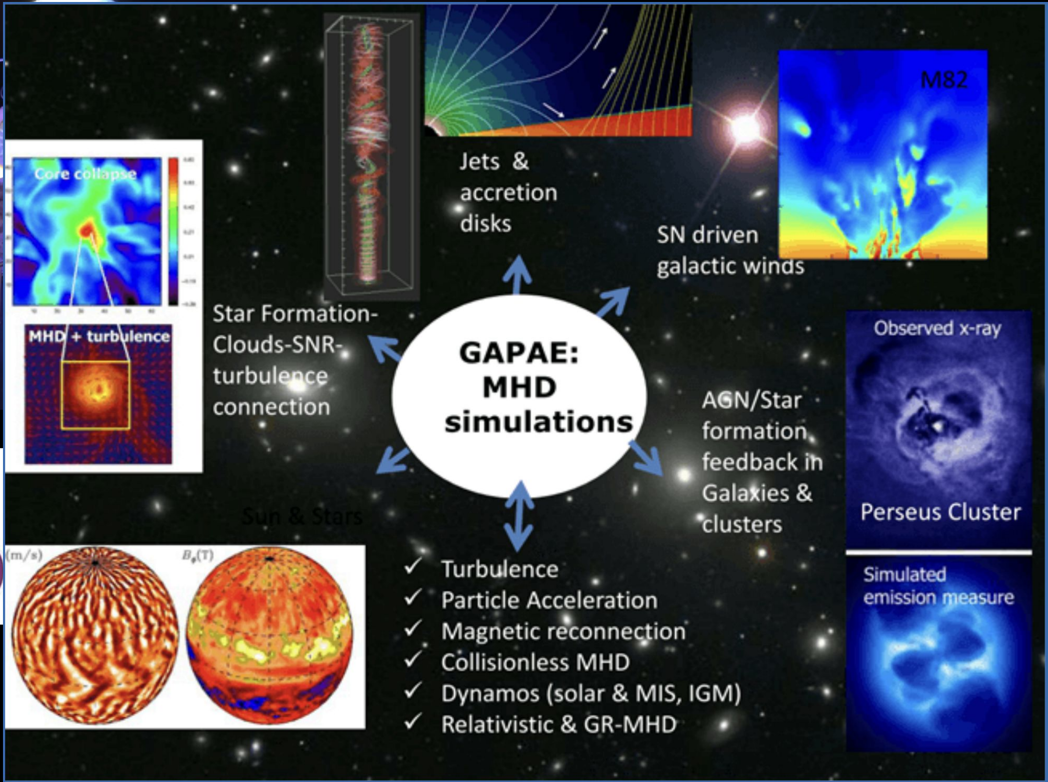
Outreach

About me

GAPAE:

Plasma & High Energy

Astrophysics



About me

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Plasma & High Energy

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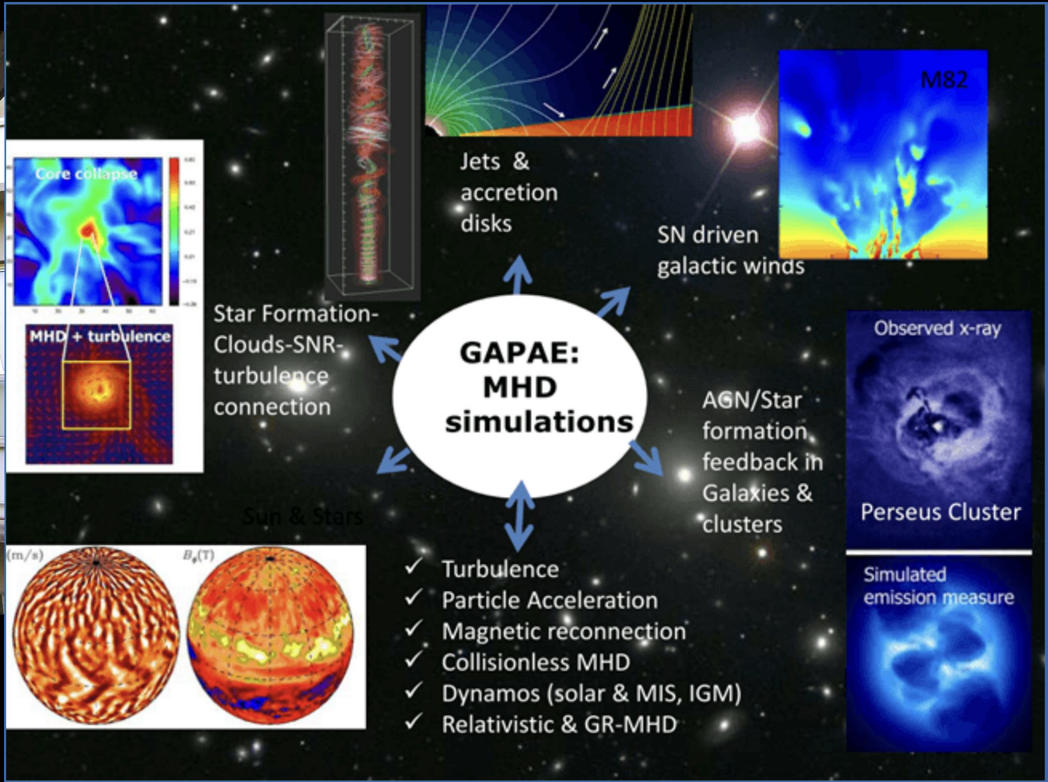


Variability Analysis of Fermi-LAT data to improve prospects with CTA

Luana Passos Reis*, Elisabete M. de Gouveia Dal Pino, Tarek Hassan, Jonathan Biteau, Santiago Pita, Jean-Philippe Lenain & Atreya Acharyya

* luana.passos.reis@usp.br / luana.passosreis@cta-consortium.org

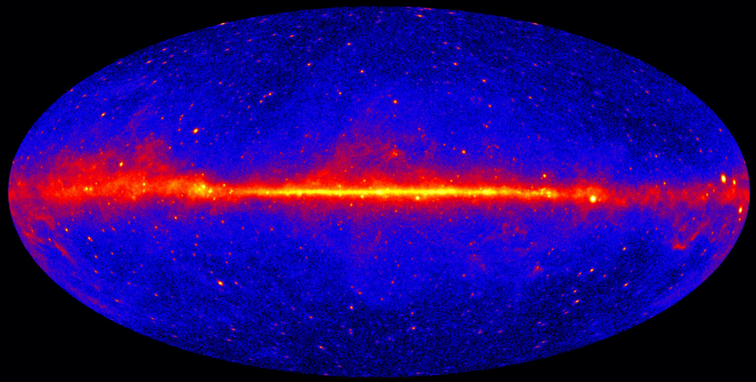
cherenkov telescope array

FUNDAÇÃO DE AMPARO À PESQUISA DO ESTADO DE SÃO PAULO

Universidade de São Paulo

INSTITUTO DE ASTRONOMIA, GEOFÍSICA E CIÊNCIAS ATMOSFÉRICAS

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

CTA: Cherenkov Telescope Array

https://www.cta-observatory.org/

Cherenkov Telescope Array

- next generation ground-based instrument for gamma-ray astronomy at very-high energies

- 64 telescopes located in the northern (La Palma, Canary Islands) and southern (ESO's Paranal Observatory, Chile) hemispheres

- First open ground-based gamma-ray observatory, multinational, worldwide project to build a new generation of gamma-ray instrument in the energy range extending from some tens of GeV to about 300 TeV

https://www.cta-observatory.org/

Introduction

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

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  - Estimate the impact of including this variability on AGN populations detectability with CTA.

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    - Fractional Variability;
    - Normalized Excess Variance.
- Motivation:
    - Use public Fermi-LAT data to evaluate AGN variability;
    - Estimate the impact of including this variability on AGN populations detectability with CTA.
- In order to:
    - Look for “Variability Trends“ (or bias) at the CTA energy range;
    - "How does variability affect the population we might observe?";
    - Extrapolate light curves to CTA'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

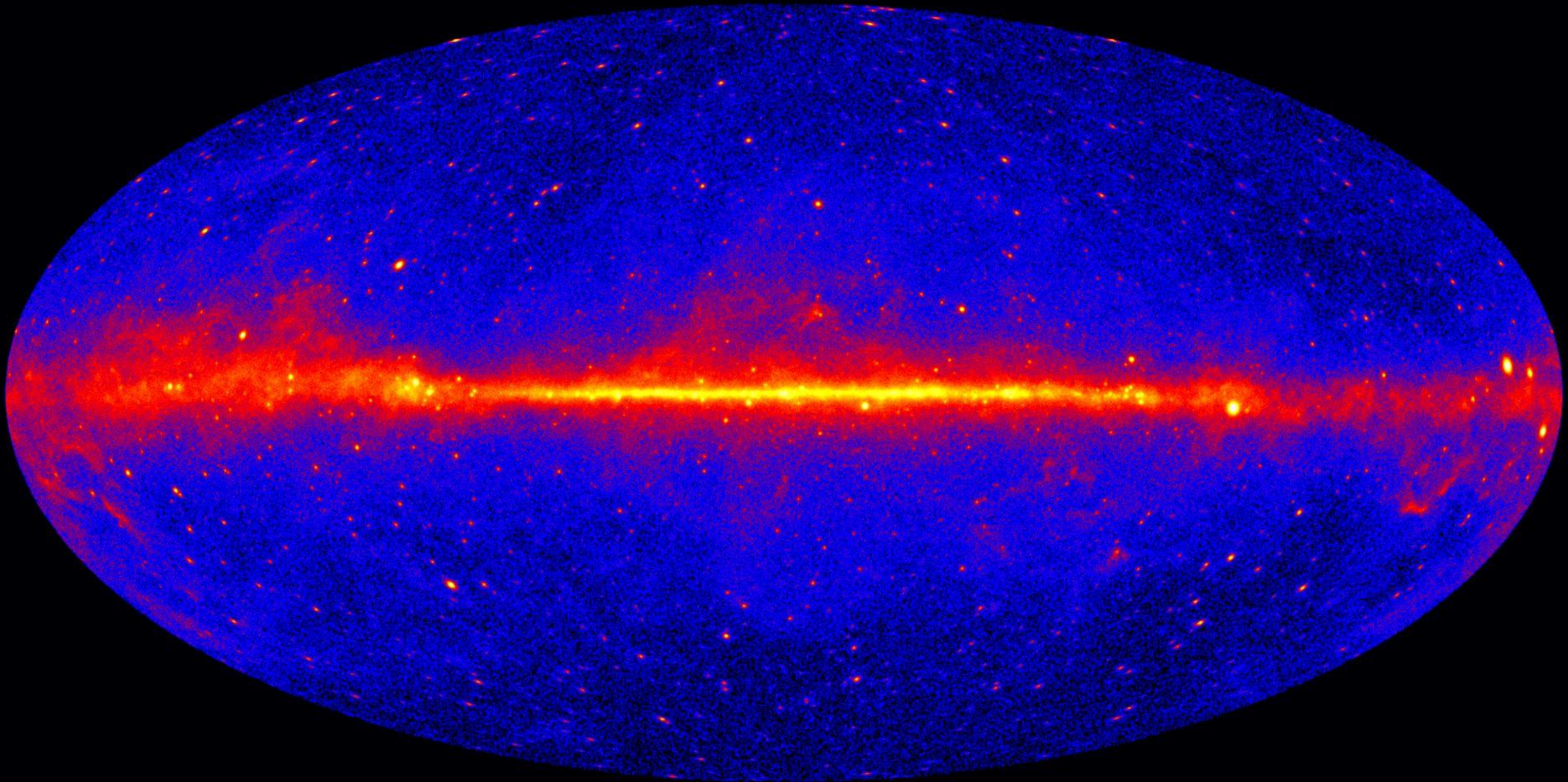


Image credit: https://svs.gsfc.nasa.gov/11342

Fermi LAT 60-month image

Most of the sources are blazars!

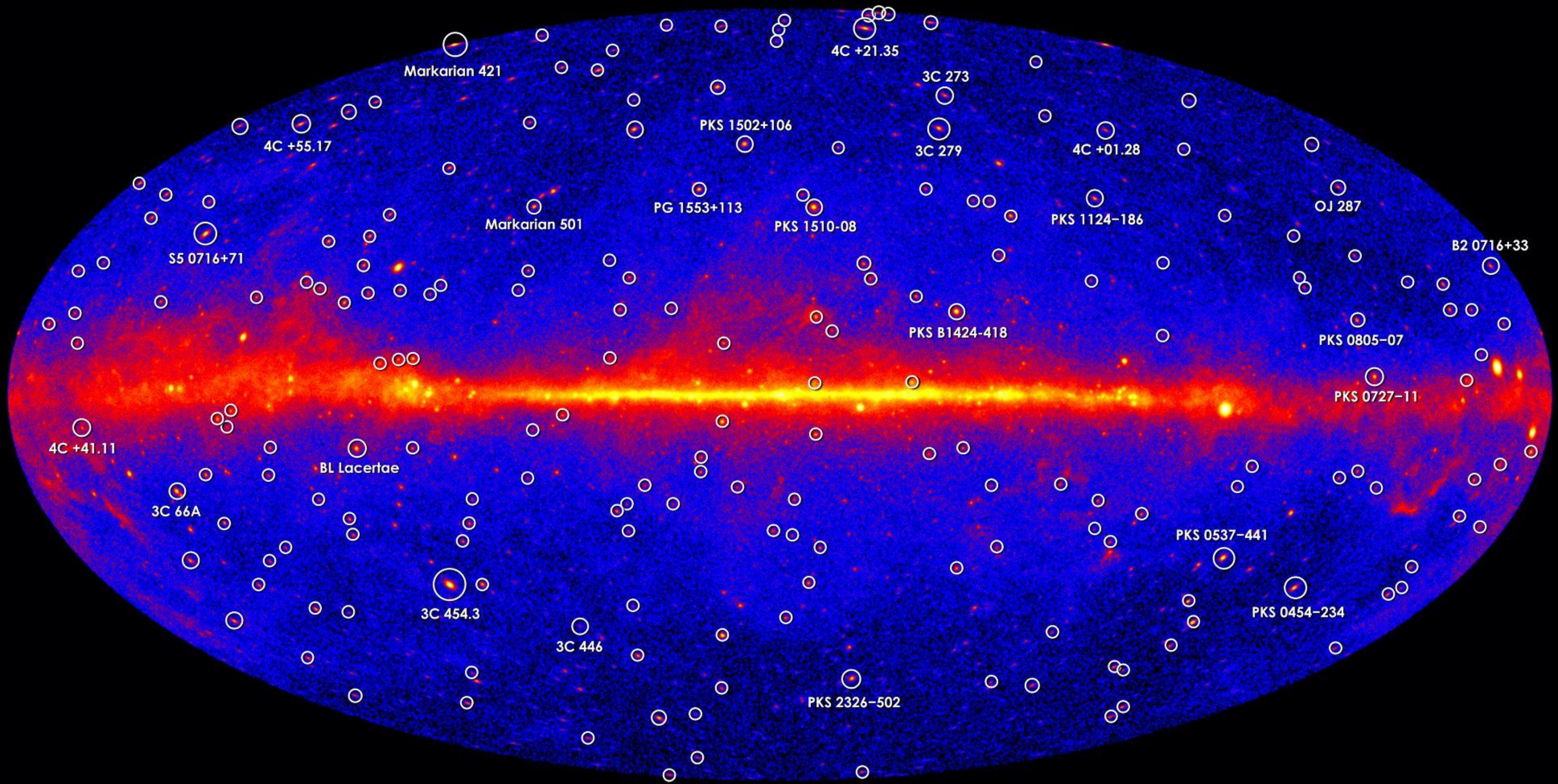


Image credit: https://svs.gsfc.nasa.gov/11342

Blazars

- ➡ Active Galactic Nuclei (AGN)

- ➡ Jet pointed towards our line of sight

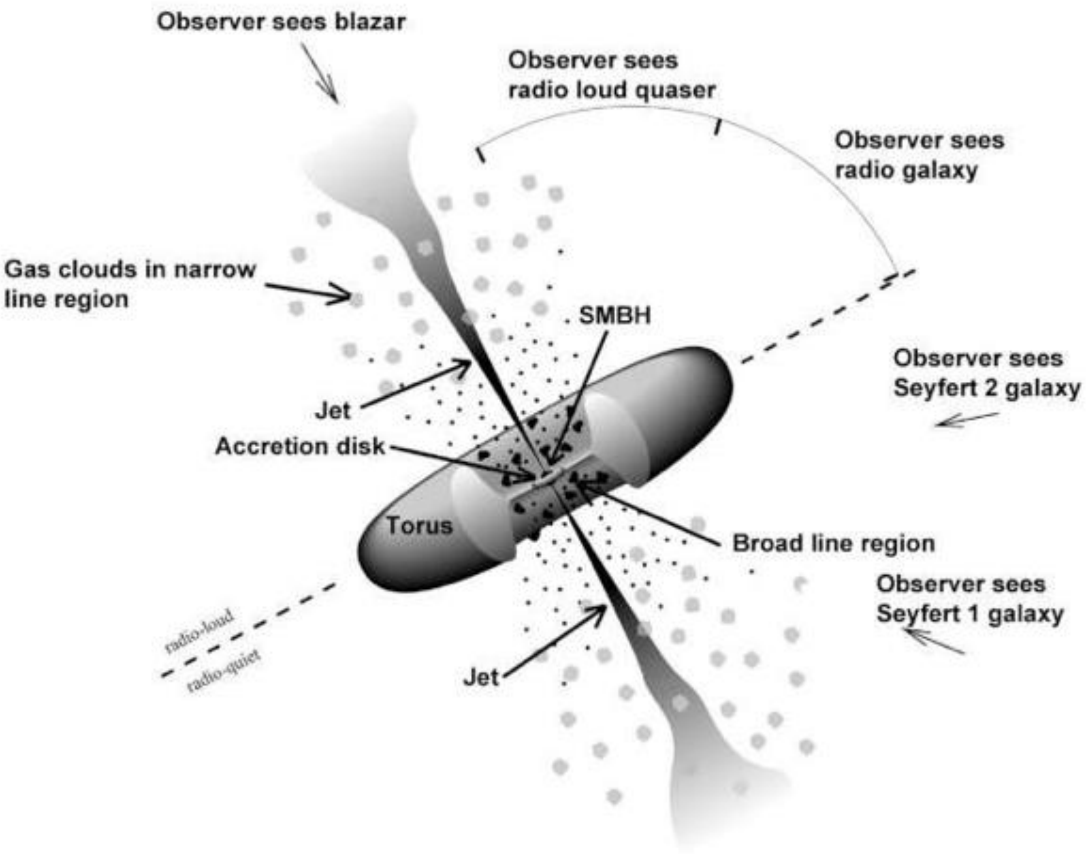


Image credit: https://fermi.gsfc.nasa.gov/science/eteu/agn/

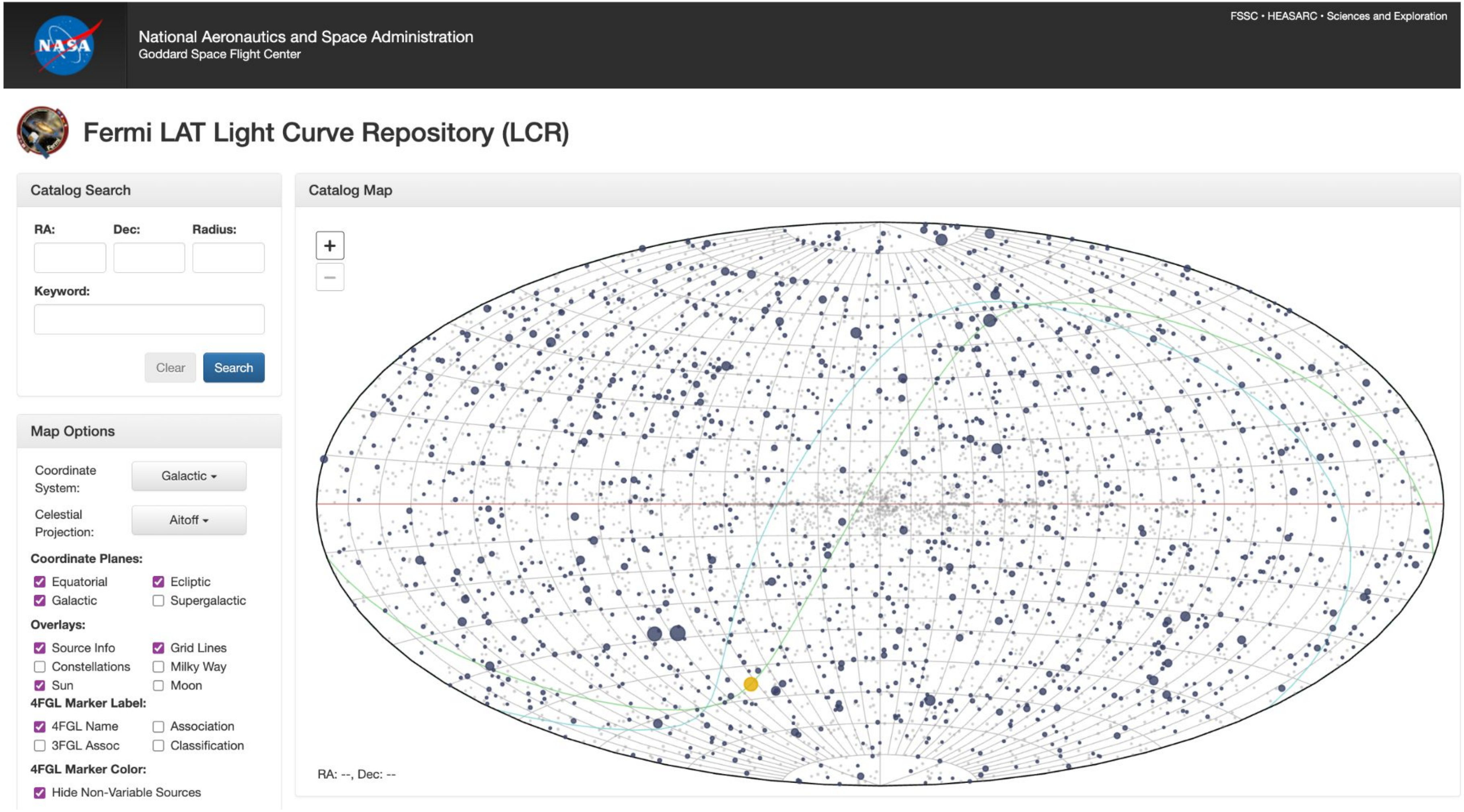


Image credit: https://fermi.gsfc.nasa.gov/ssc/data/access/lat/LightCurveRepository/

Catalog divided into 3 blazar classes

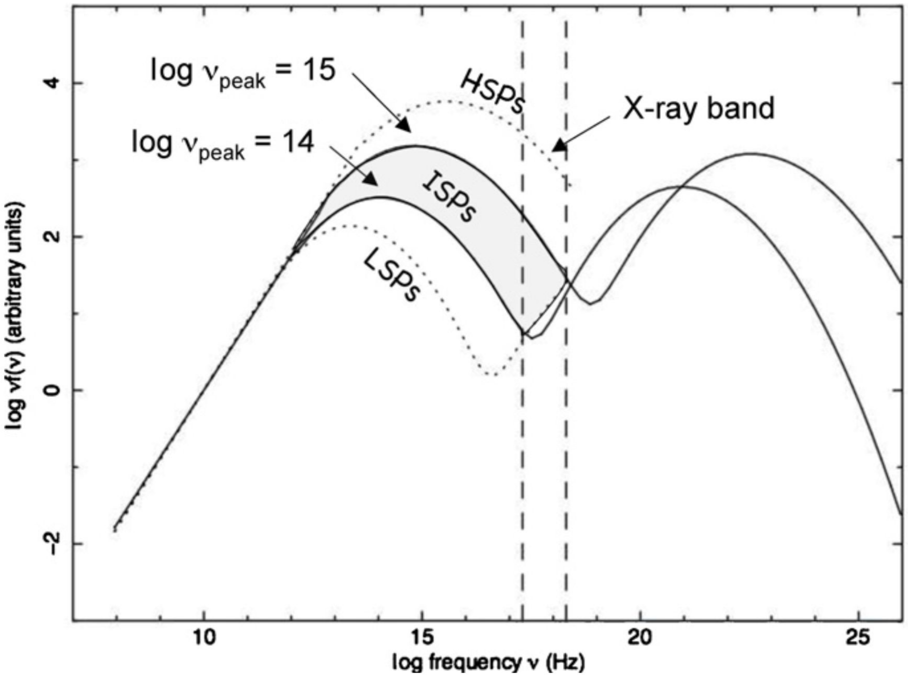


Image credit: Abdo et al. 2010

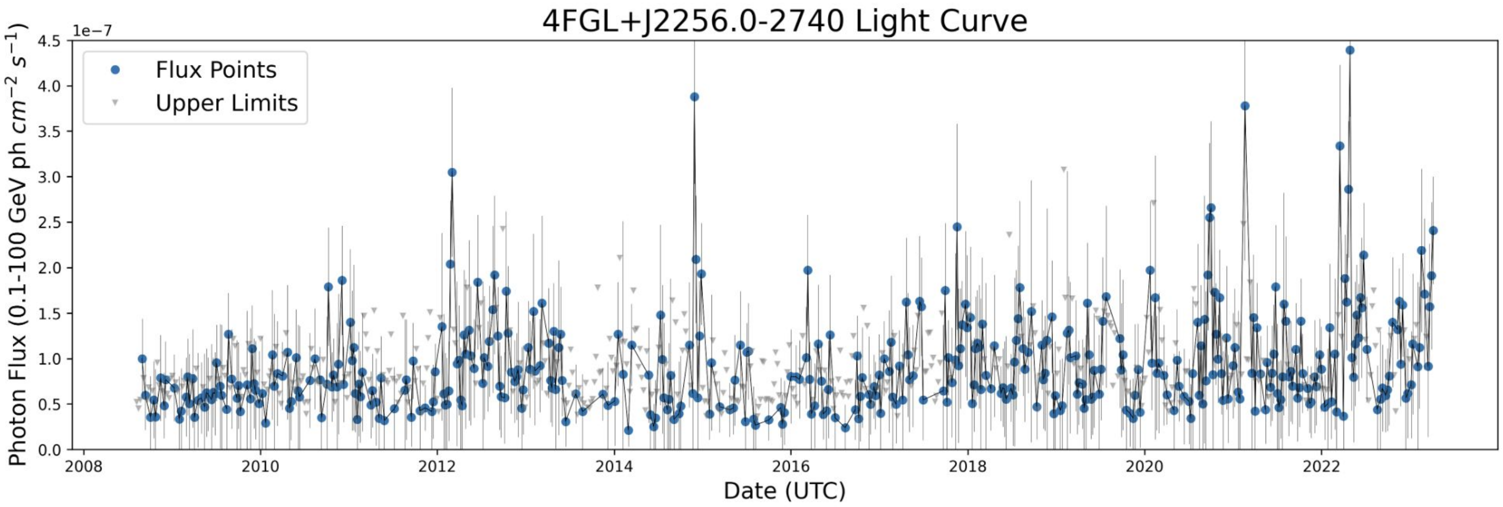
DR3 Catalog with 3814 sources

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

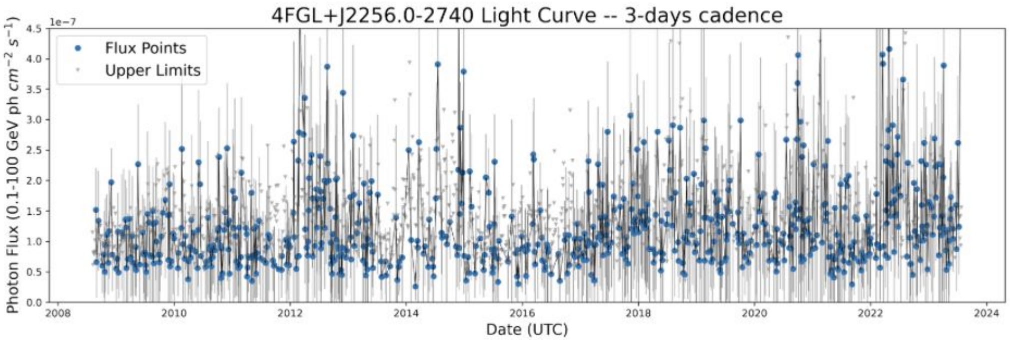
that totalize 2825 sources with a Synchrotron Peak label

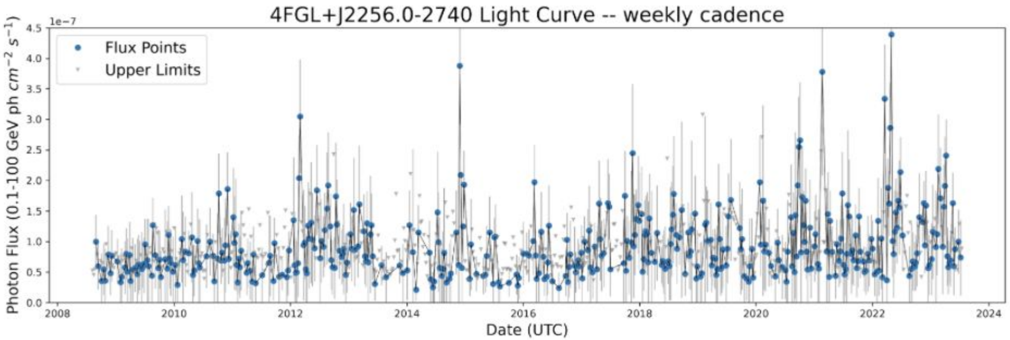
Downloaded 1429 valid light curves !

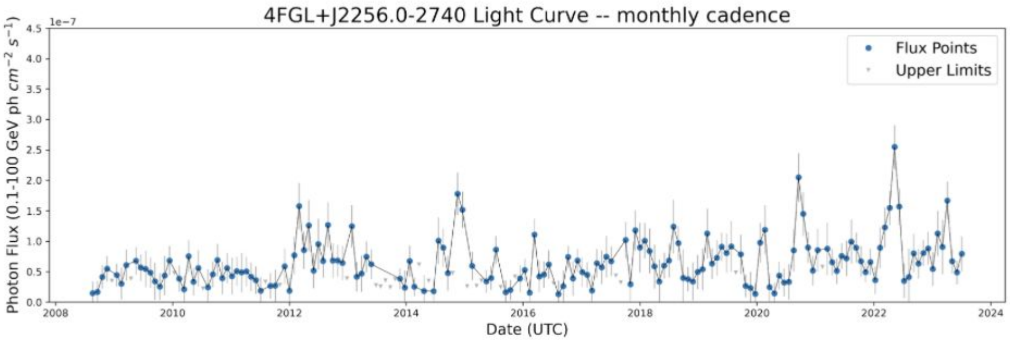
Variability in Blazars



- 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

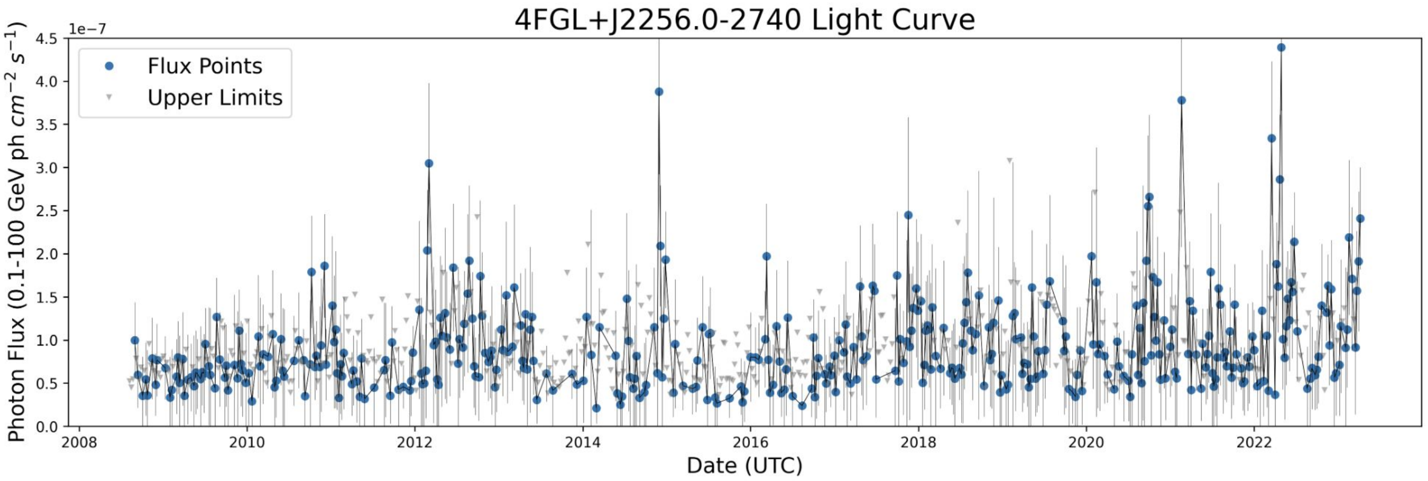
Selection of Sources

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

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

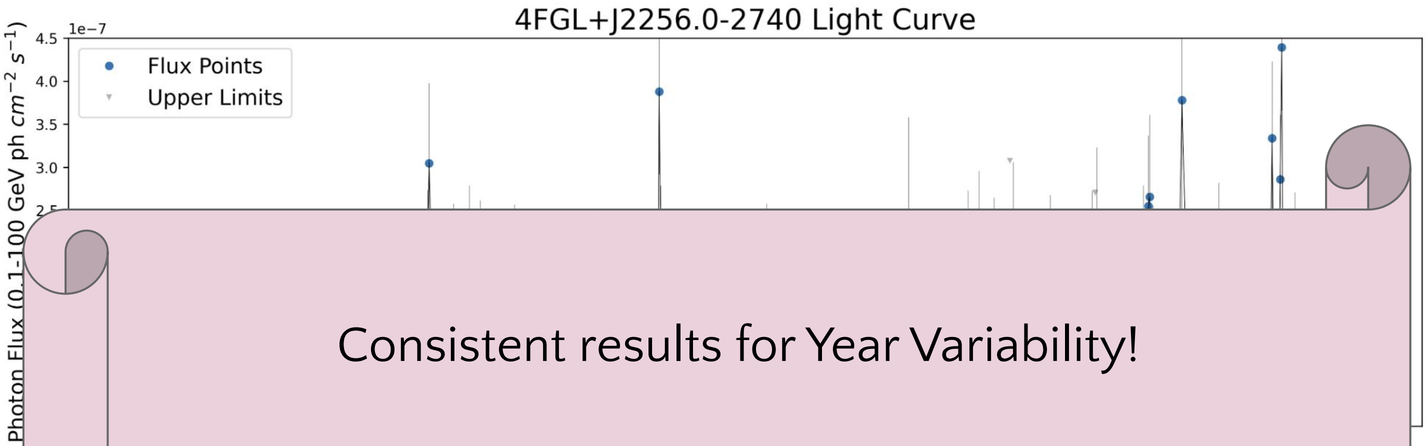
- Verification of 3-day timescale variability against monthly timescale variability

Fractional Variability Calculations



- 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).

Fractional Variability Calculations



Consistent results for Year Variability!

Now:
We are treating and analyzing outliers that are creating a huge bias in the Weekly and 3-day bins!

- Fermi ... r caden
- We ho
- To Cro 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).

Next Steps

- Refine the analysis treating the outliers

- Extrapolate the light curves using Gammapy
  - By defining
    - a variability threshold
    - which cadence is more relevant (3-day/ weekly/ monthly)

- In order to:
  - Find the observing time that CTA will need for each source
  - Correlation of the variability with
    - Free Index
    - Synchrotron Peak

  - Estimate what CTA will be able to detect and how variability affects the size of the population we identify

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

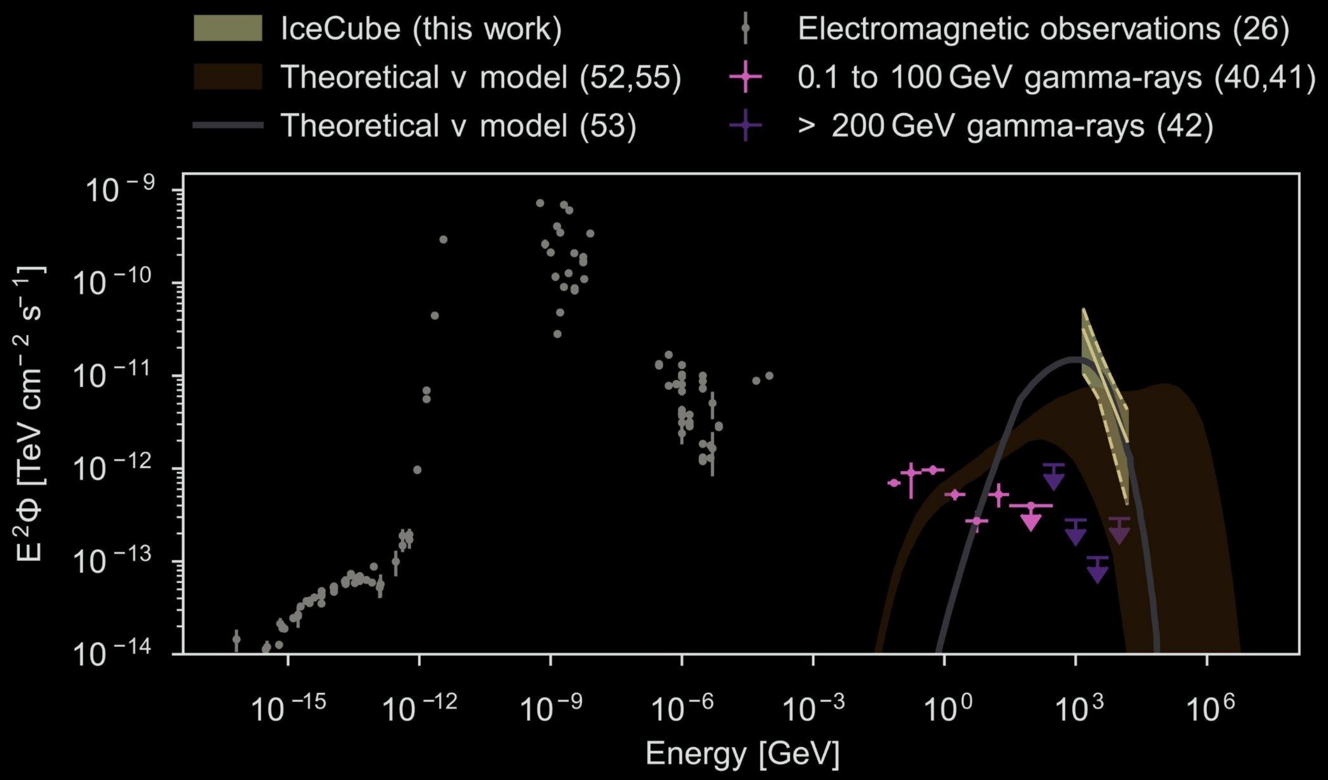
MHD simulations and particle acceleration:

special case of NGC 1068

Luana Passos Reis

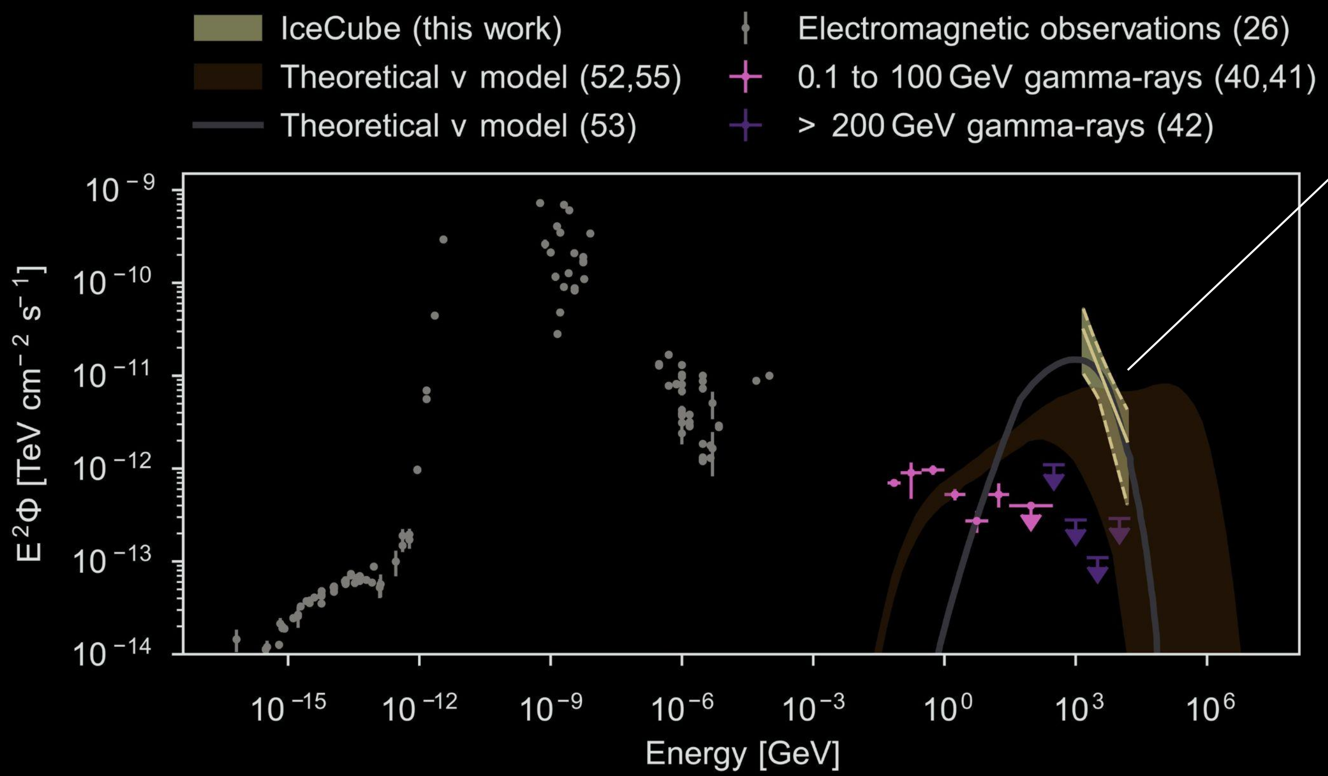
Elisabete M. de Gouveia Dal Pino
Giovani Heizen Vicentin
Chandra B. Singh

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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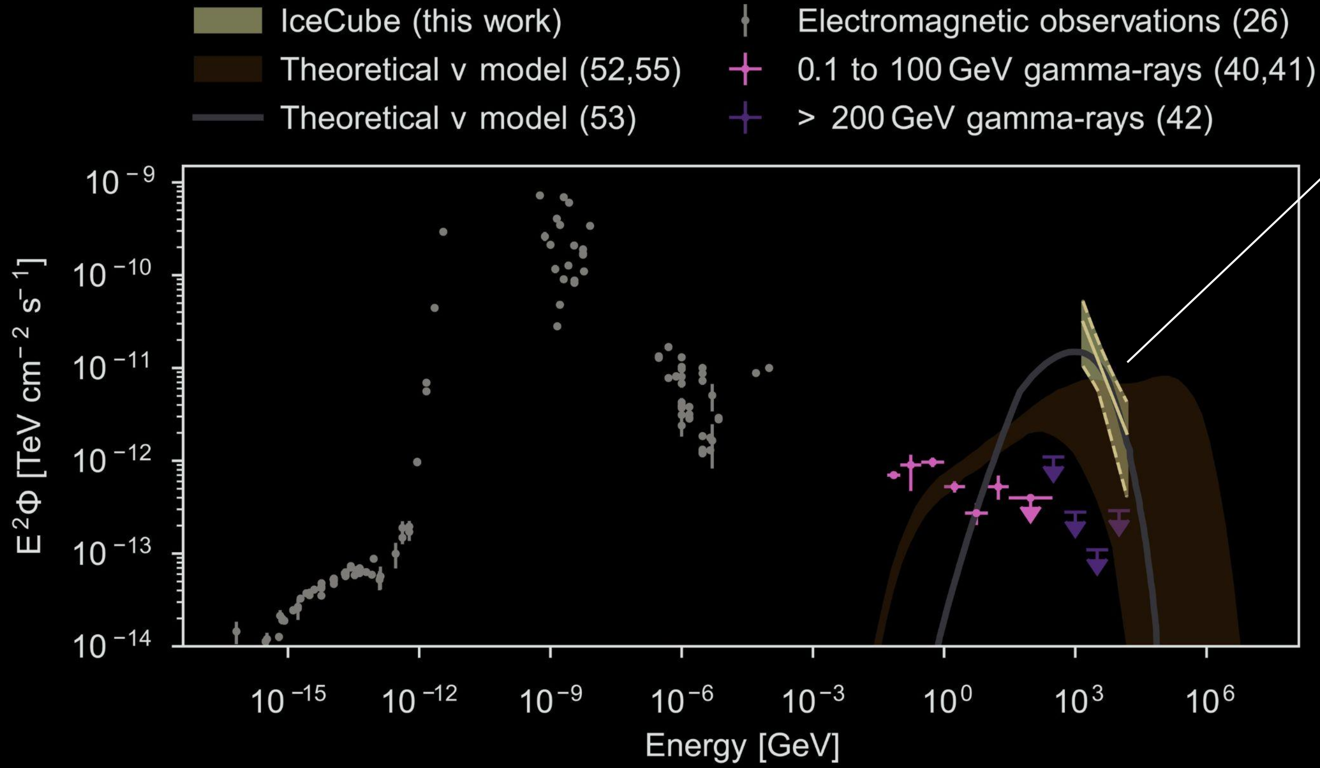

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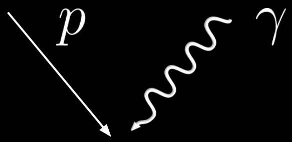
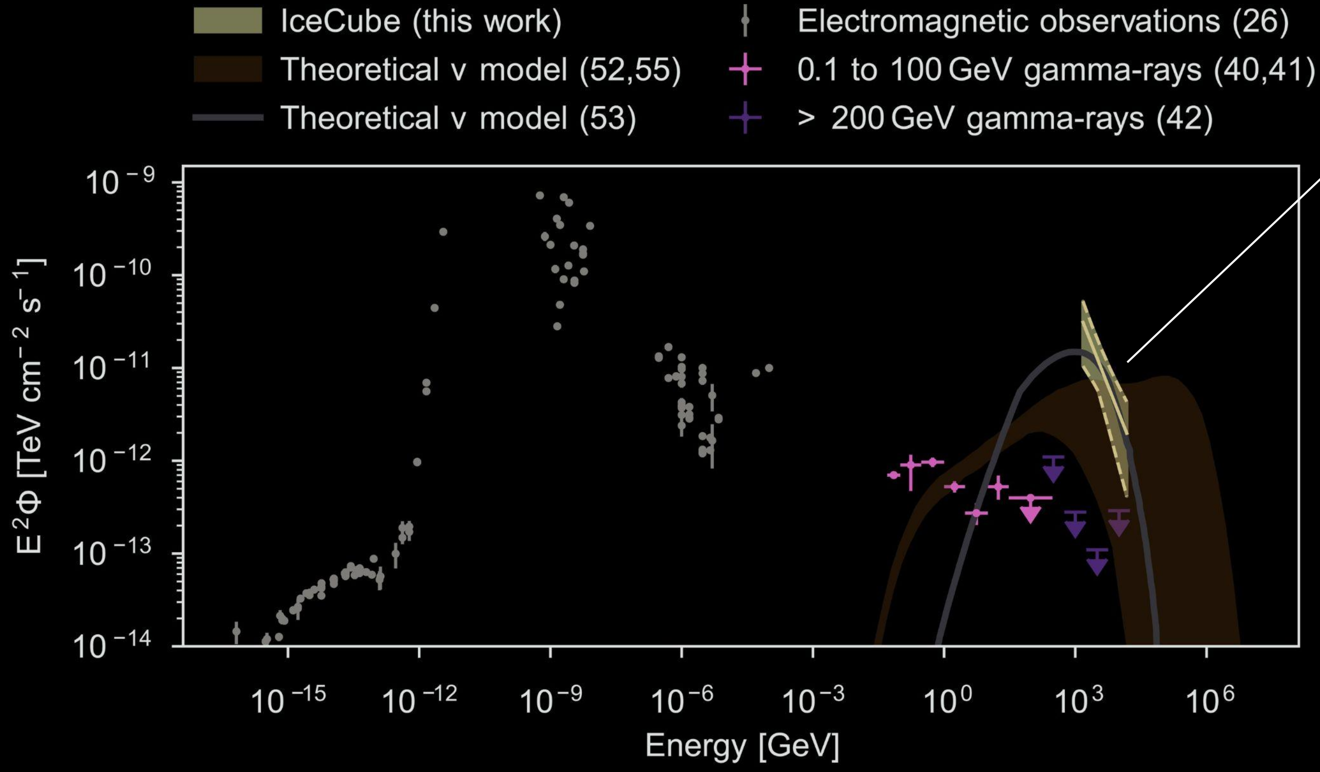


photopion ($\pi^{\pm}$ component)

Neutrino VS gamma-ray flux from NGC1068



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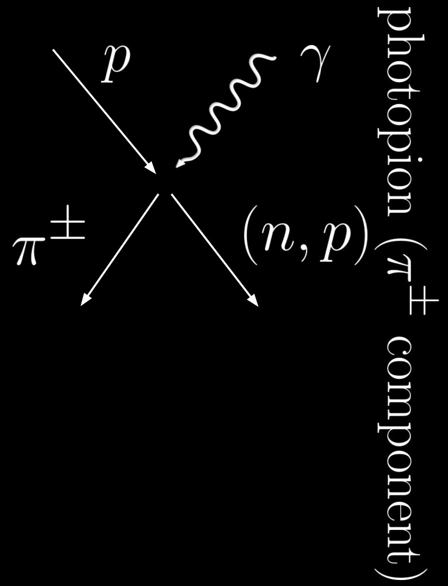

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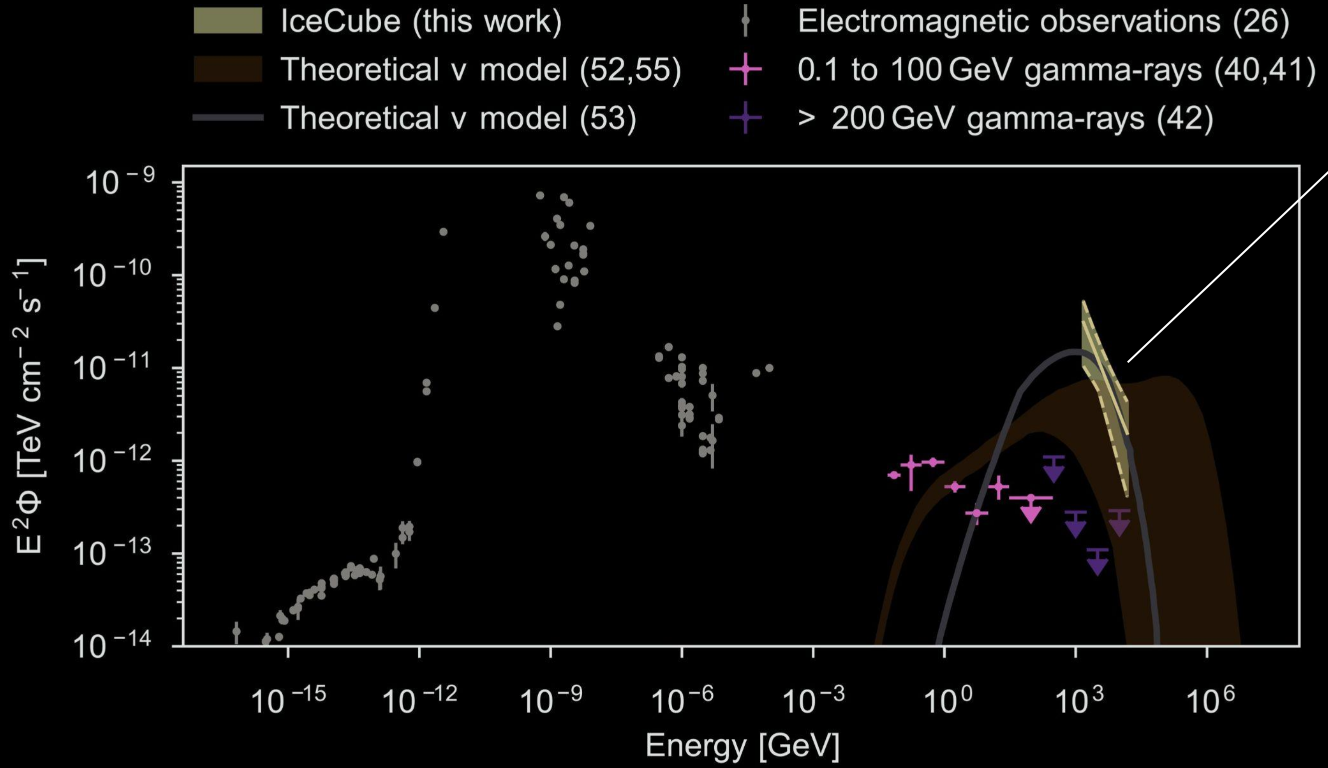

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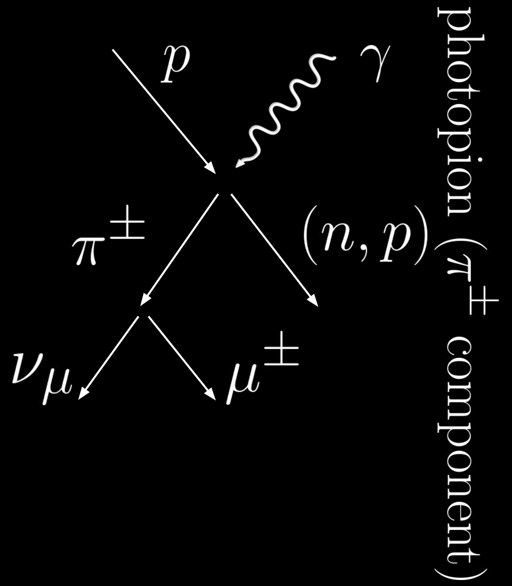

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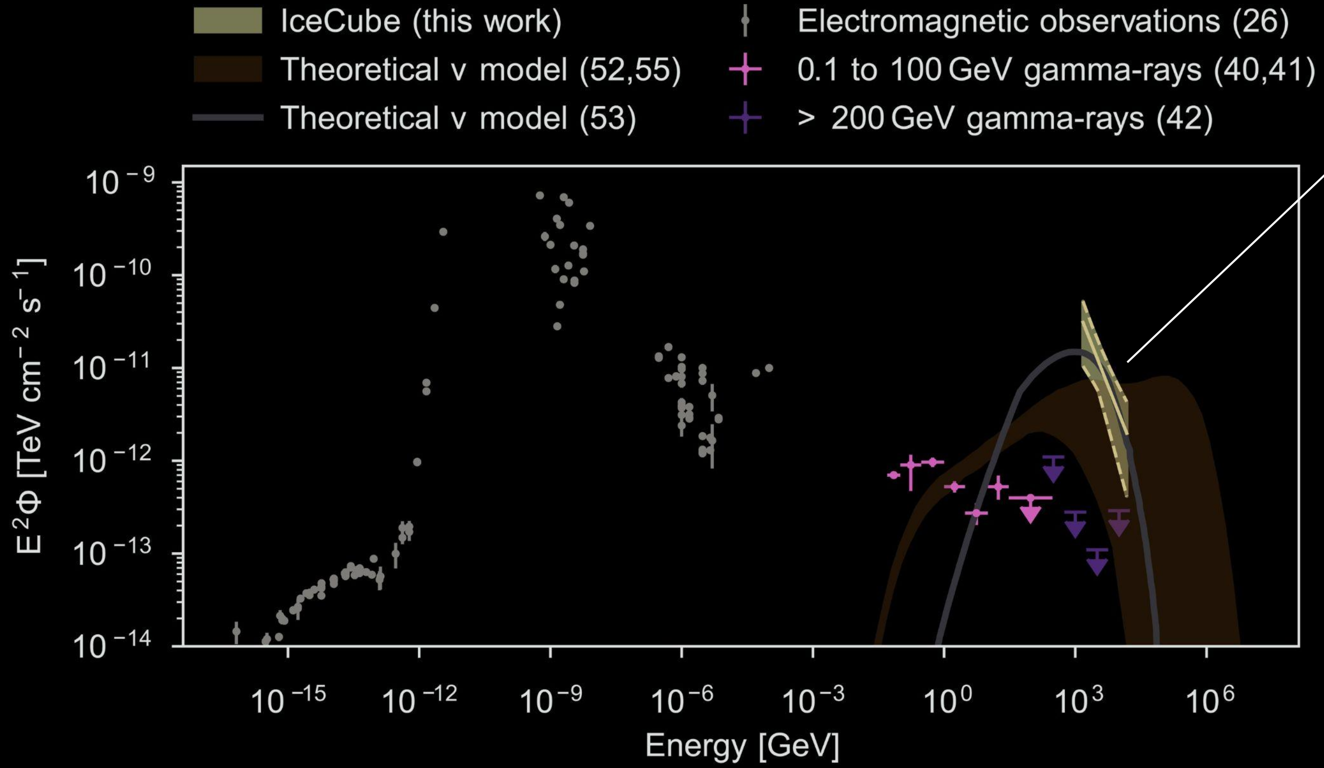

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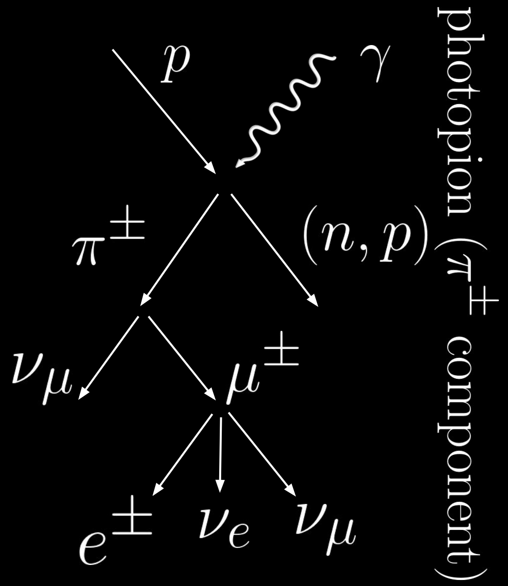

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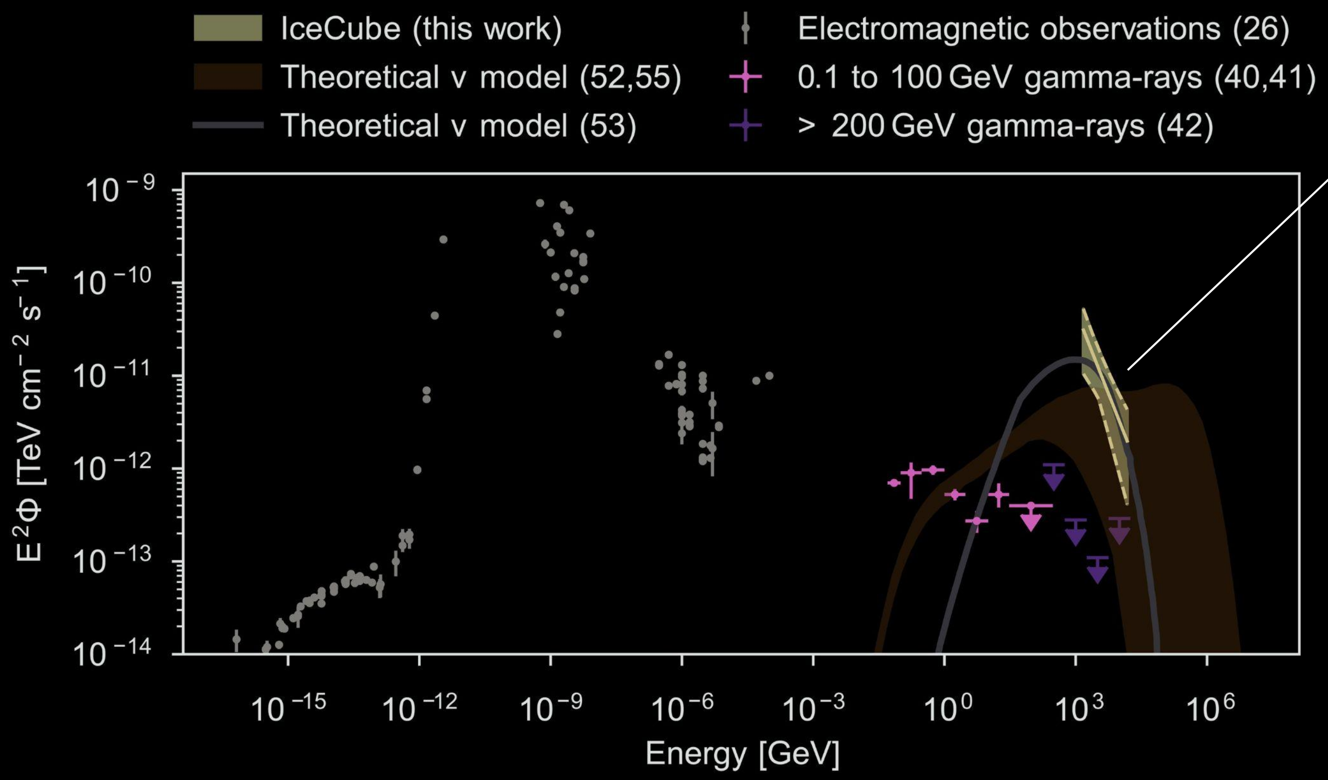

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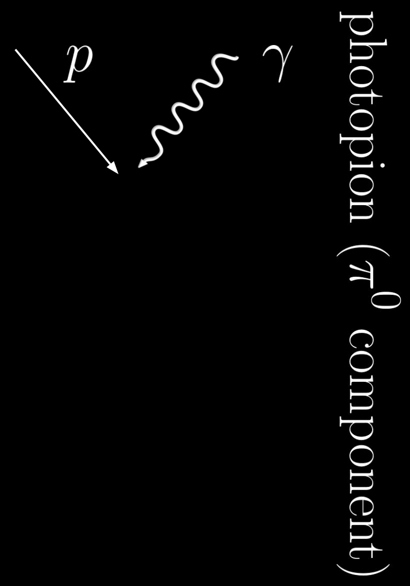

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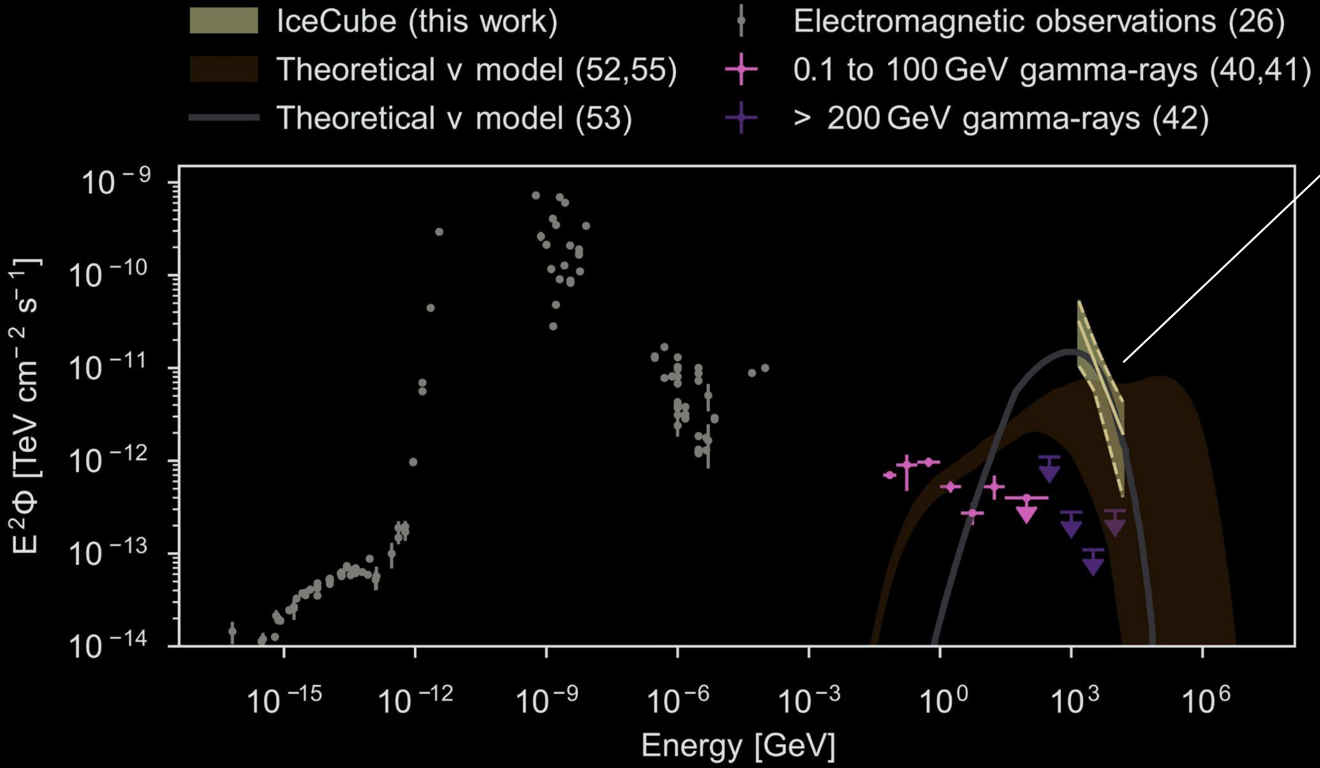

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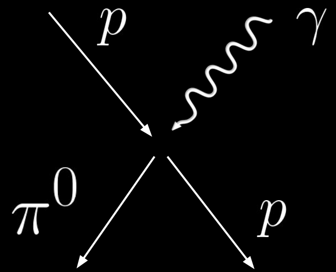

photopion (π^0 component)

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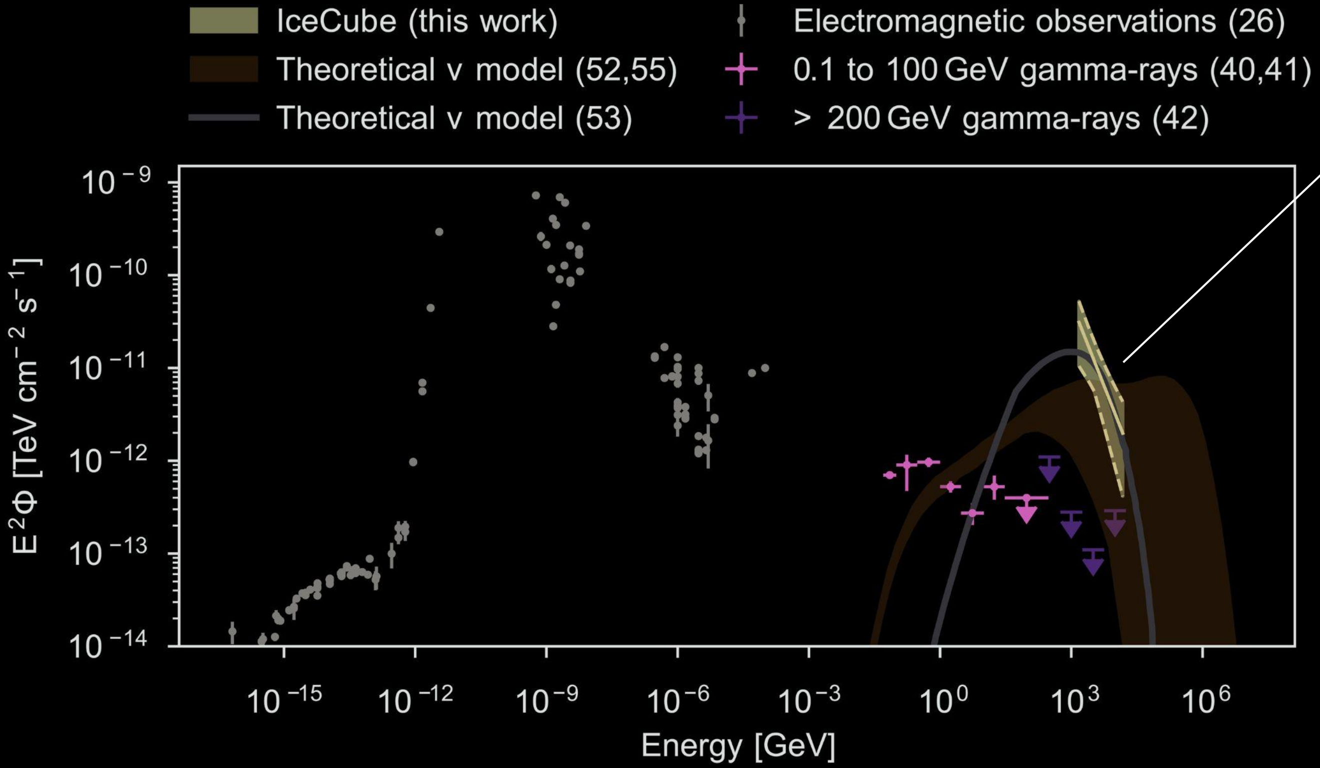

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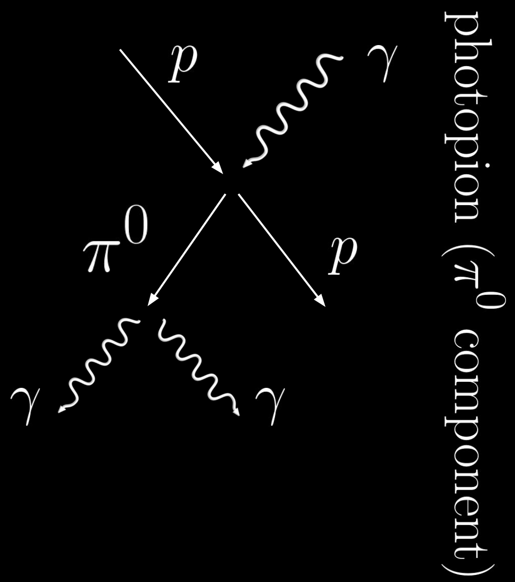

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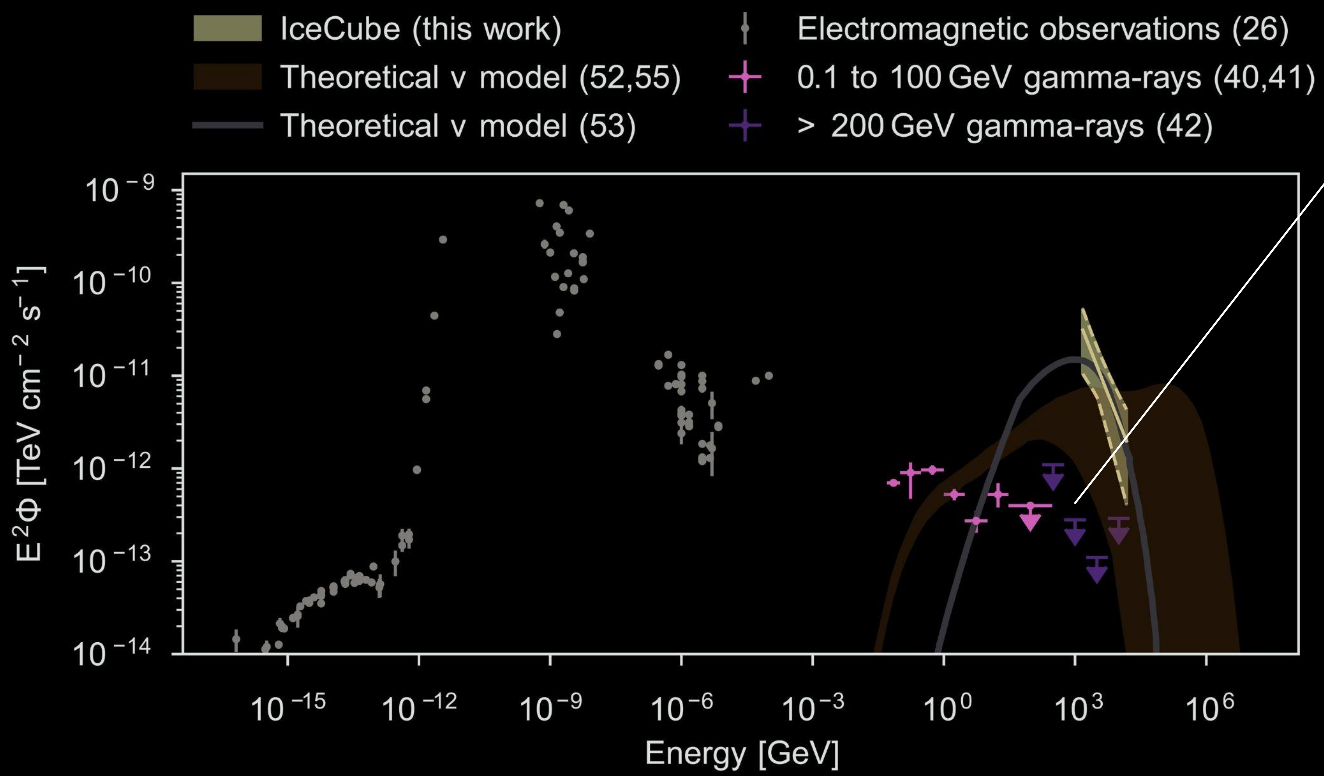
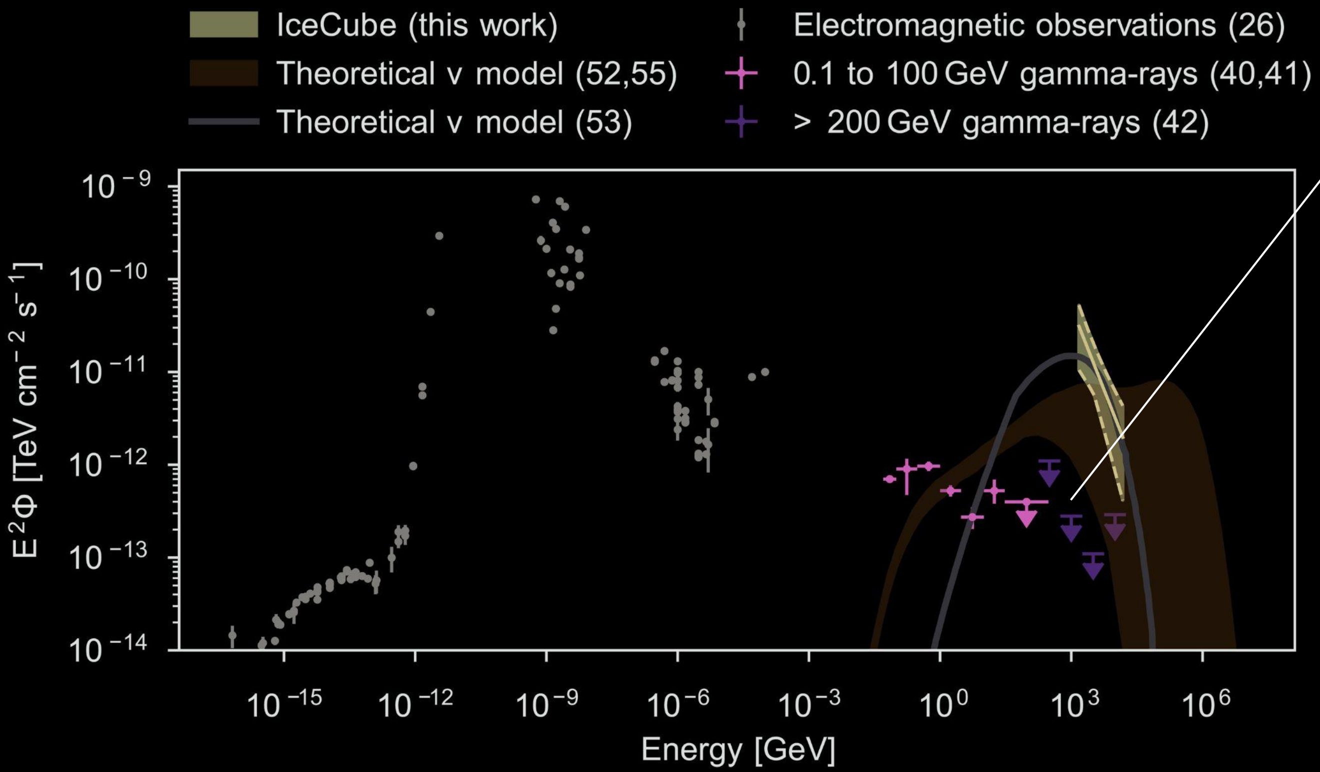


The absence of γ rays indicates auto-absorption due to a dense photon field

(IceCube Collaboration, 2022, Science)

Neutrino VS gamma-ray flux from NGC1068



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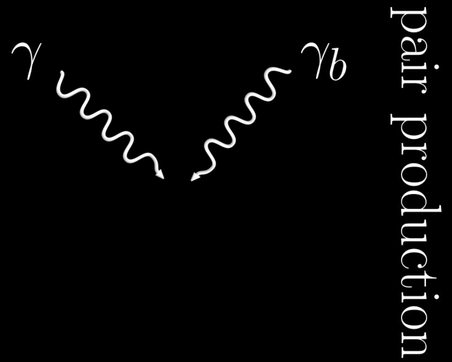

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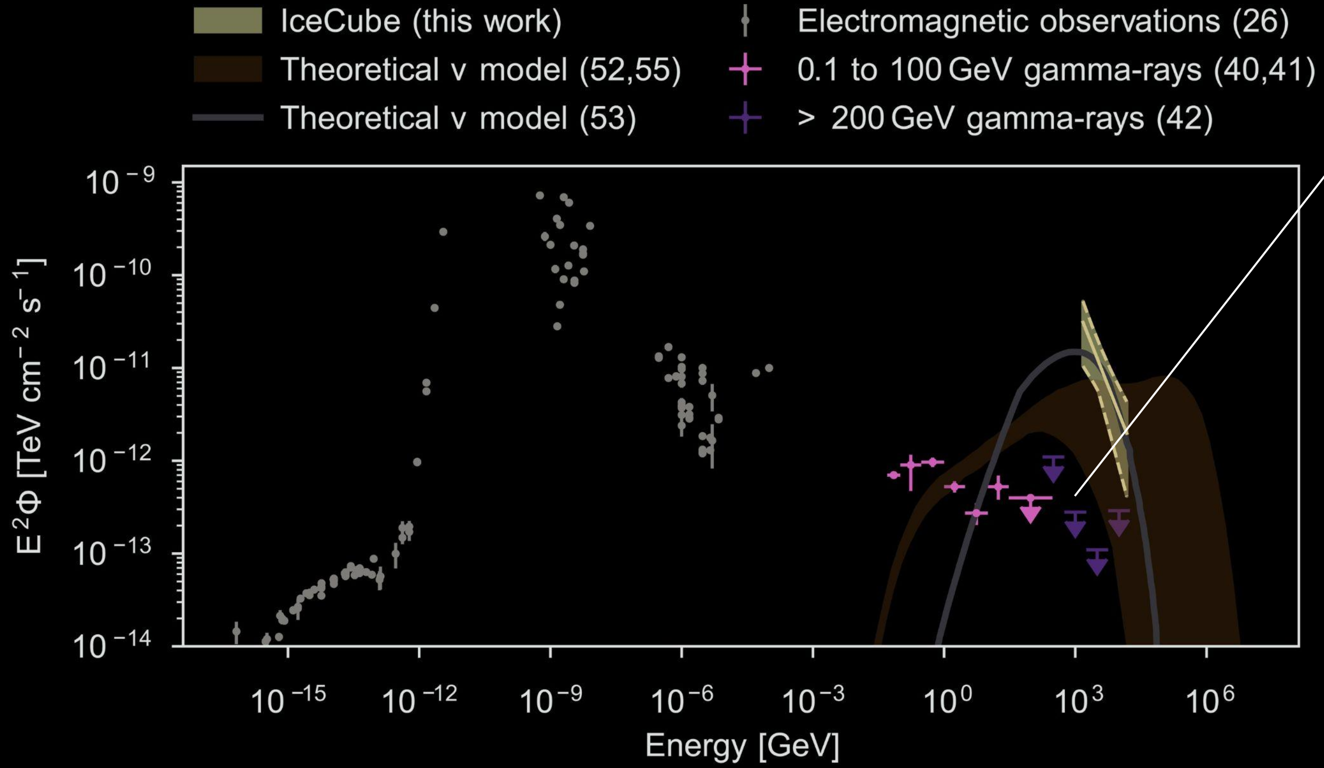

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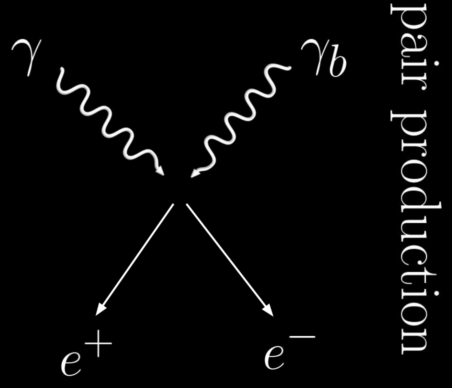
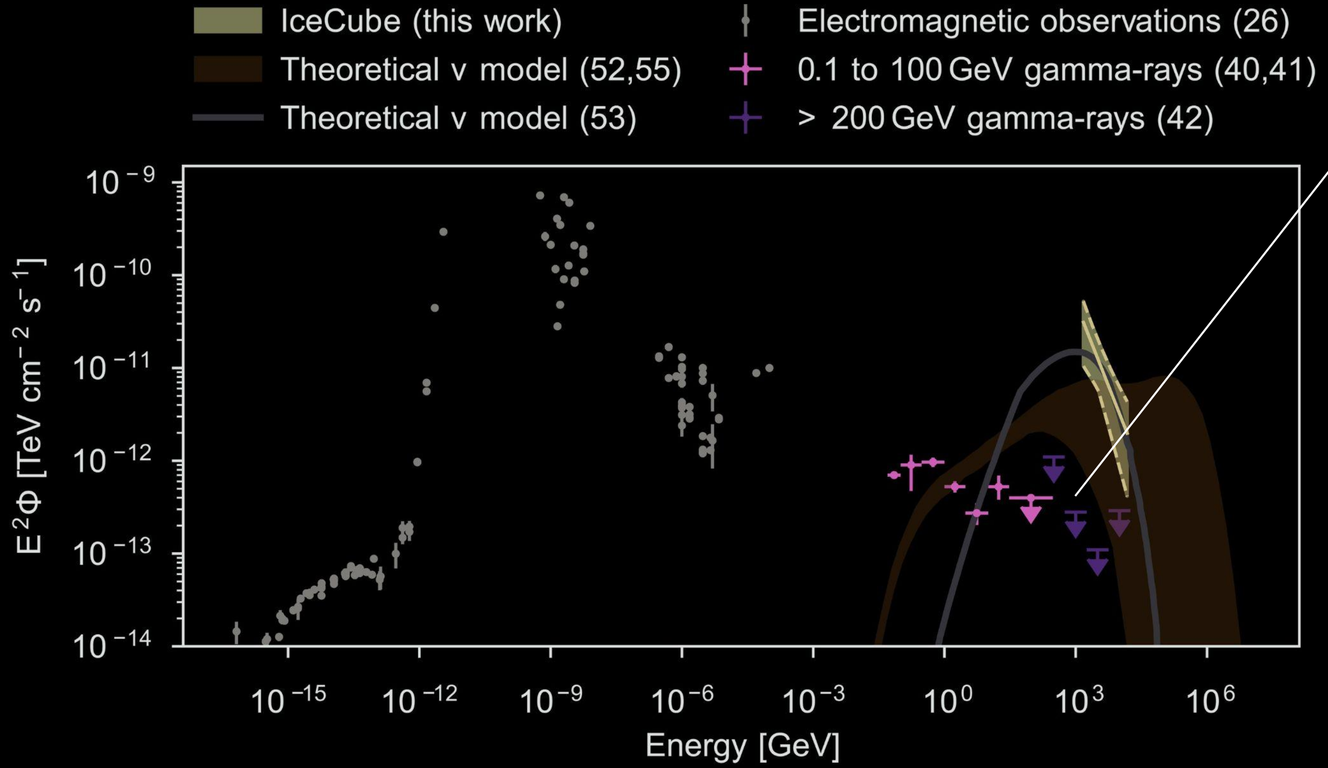


(IceCube Collaboration, 2022, Science)

Neutrino VS gamma-ray flux from NGC1068



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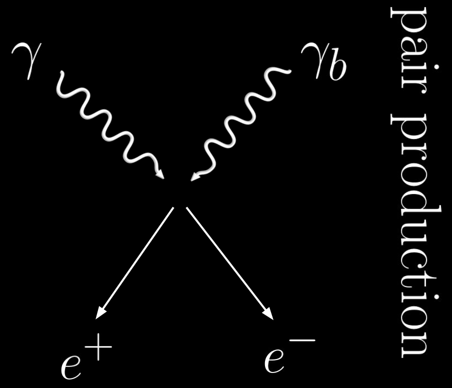
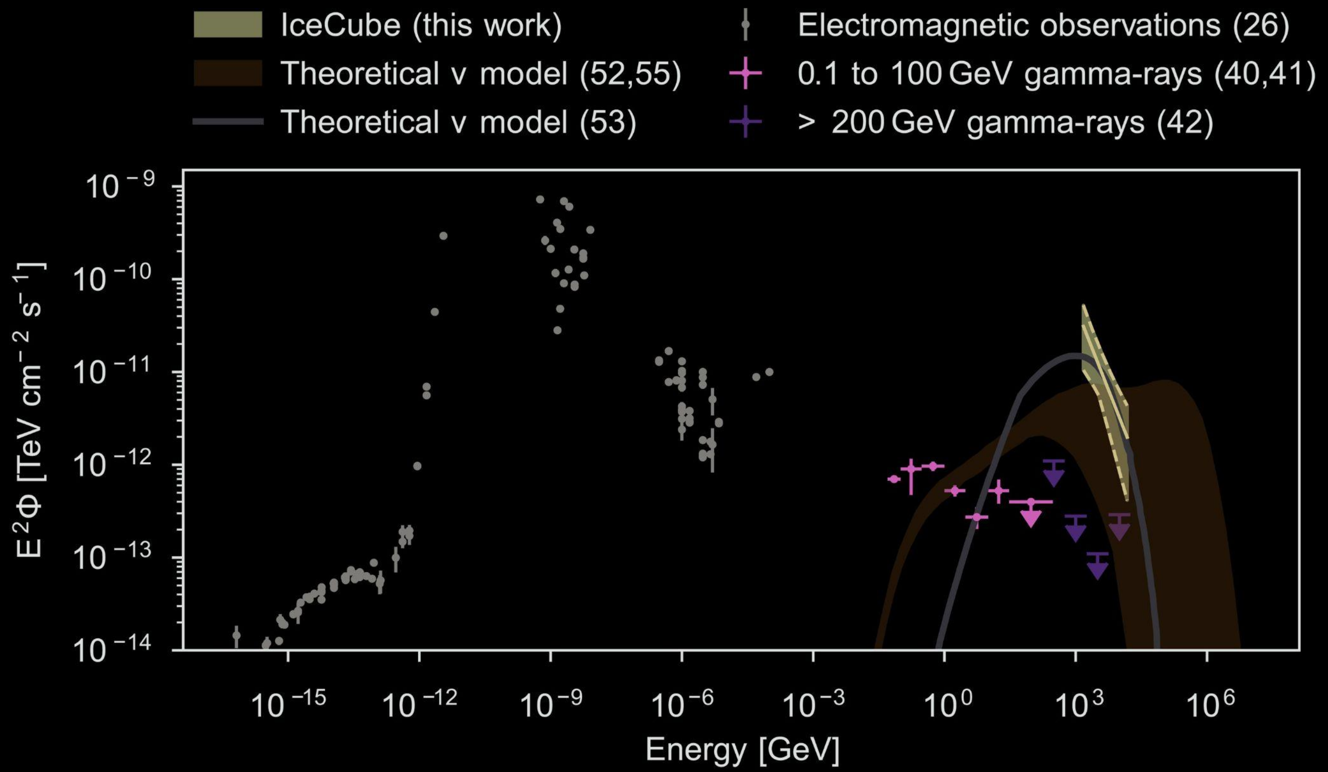


$\therefore$ The emission may become from the inner part of the AGN!

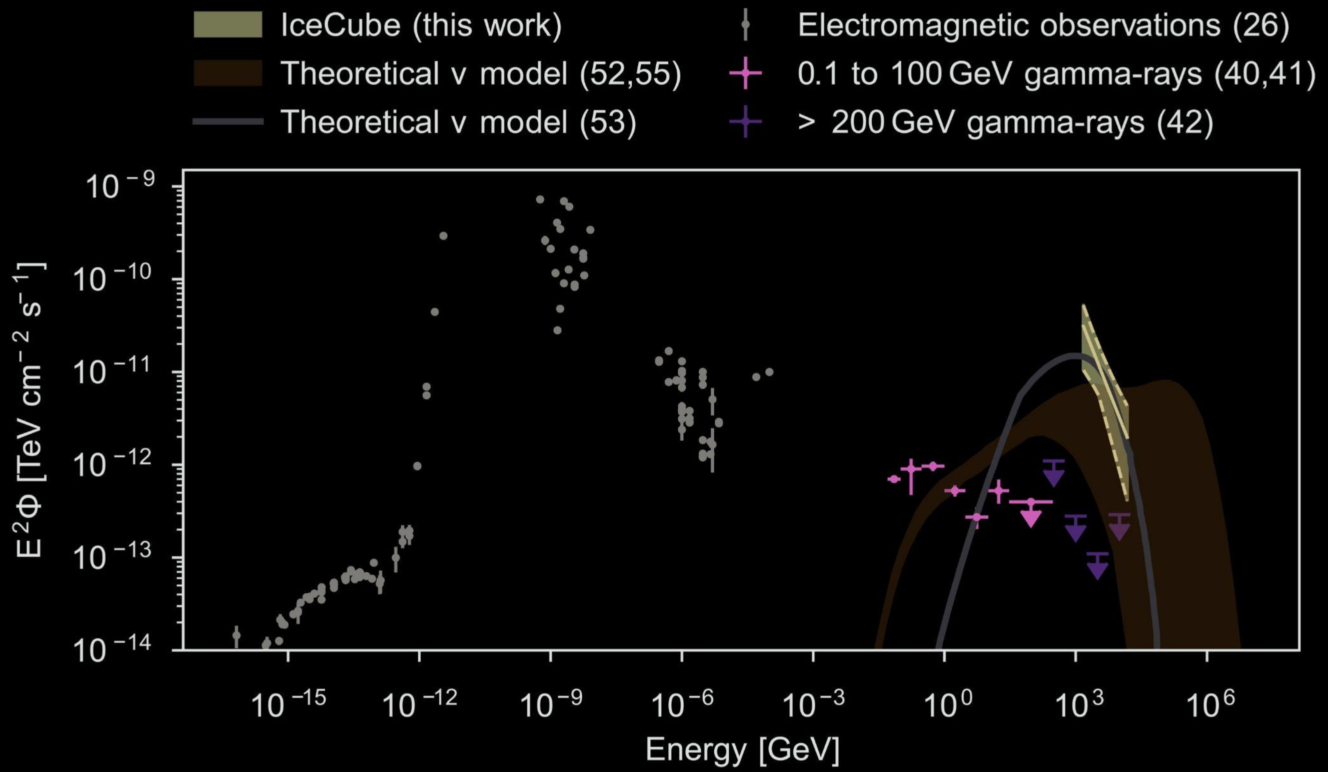
Neutrino VS gamma-ray flux from NGC1068



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

(IceCube Collaboration, 2022, Science)

Neutrino VS gamma-ray flux from NGC1068



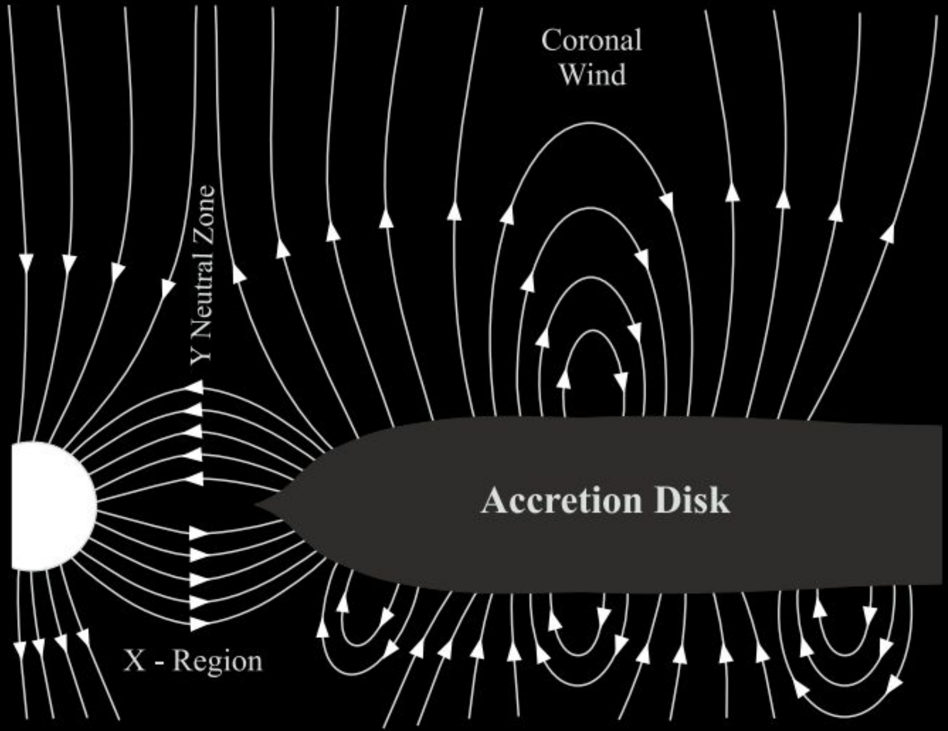
What may accelerate these protons in the surroundings of the SMBH?

Magnetic Reconnection!

(IceCube Collaboration, 2022, Science)

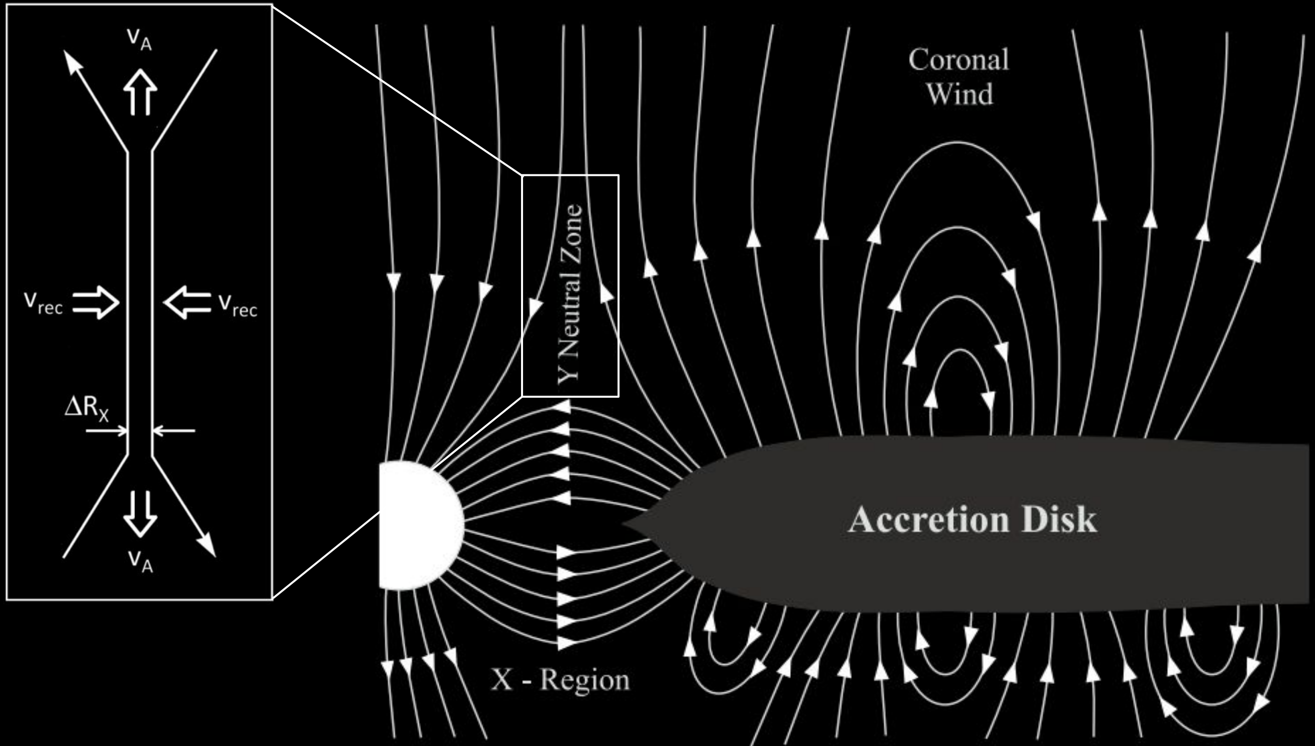
Magnetic Reconnection around Black Holes

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

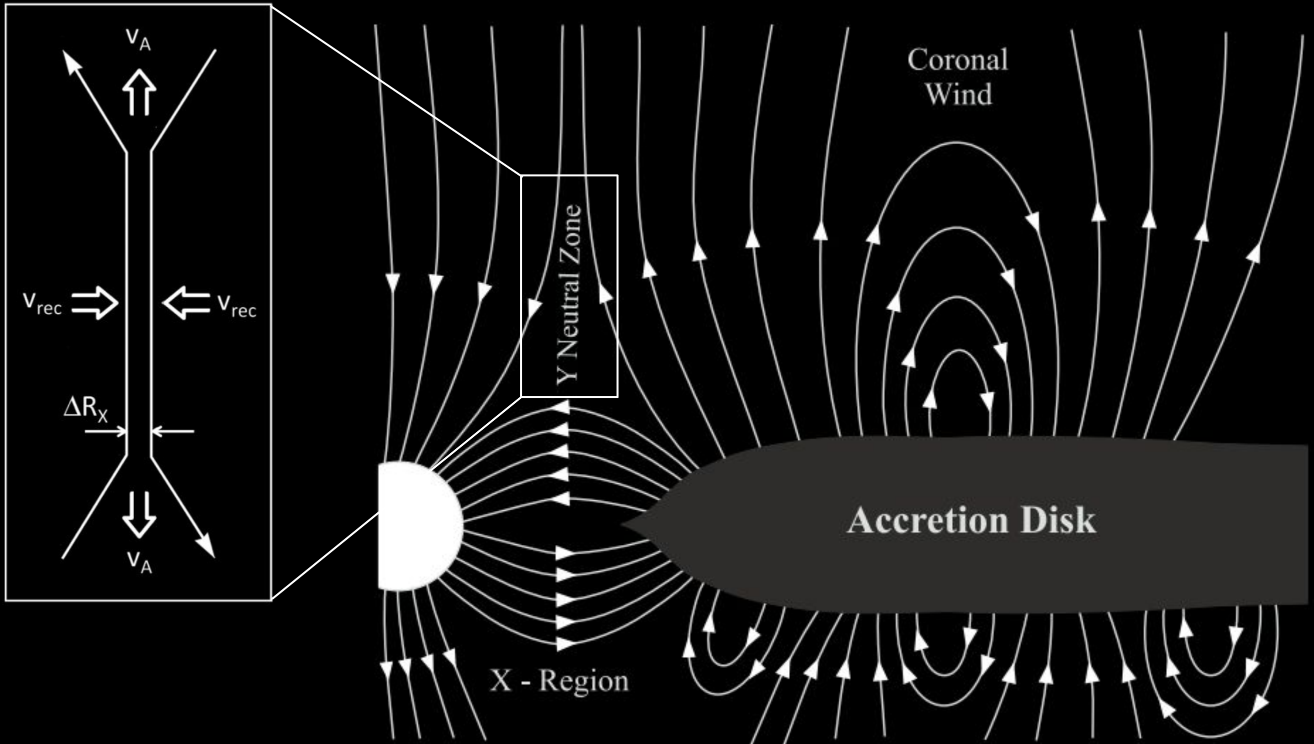


(de Gouveia Dal Pino & Lazarian, 2005, A&A)

Magnetic Reconnection around Black Holes

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

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

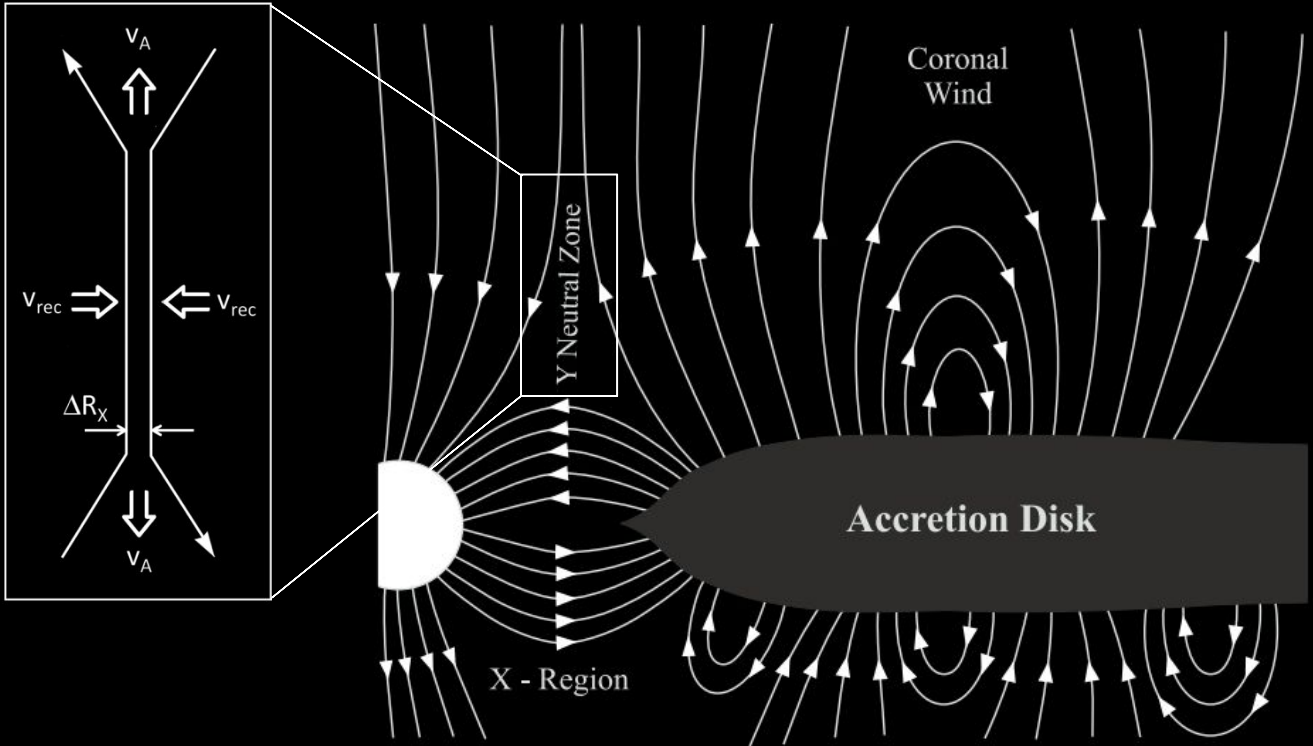


(de Gouveia Dal Pino & Lazarian, 2005, A&A)

Magnetic Reconnection around Black Holes

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

Implies an exponential growth of the energy with time!



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

NGC 1068
(Messier 77)

Filtros BVR

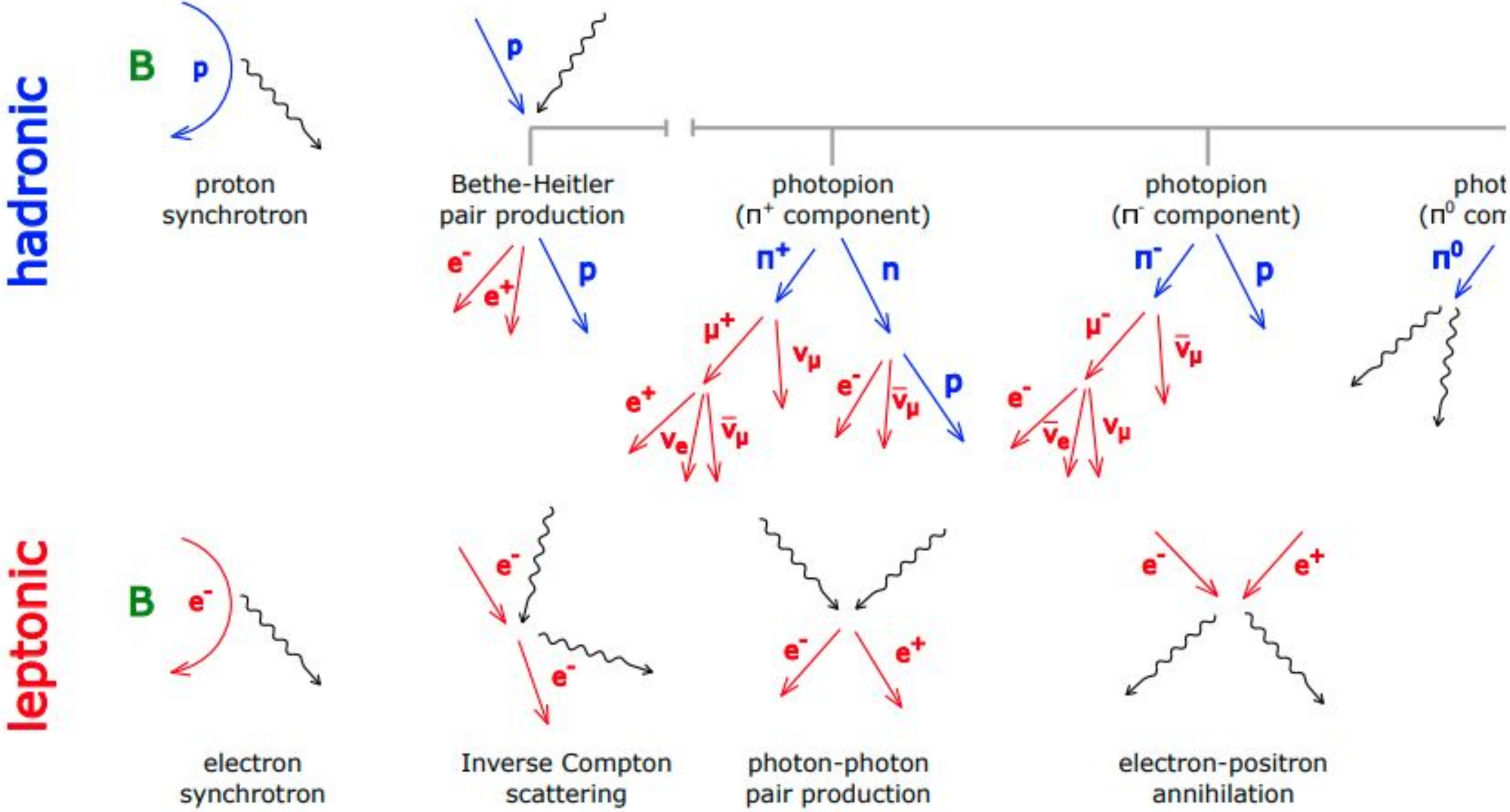
Thanks!

Questions ?

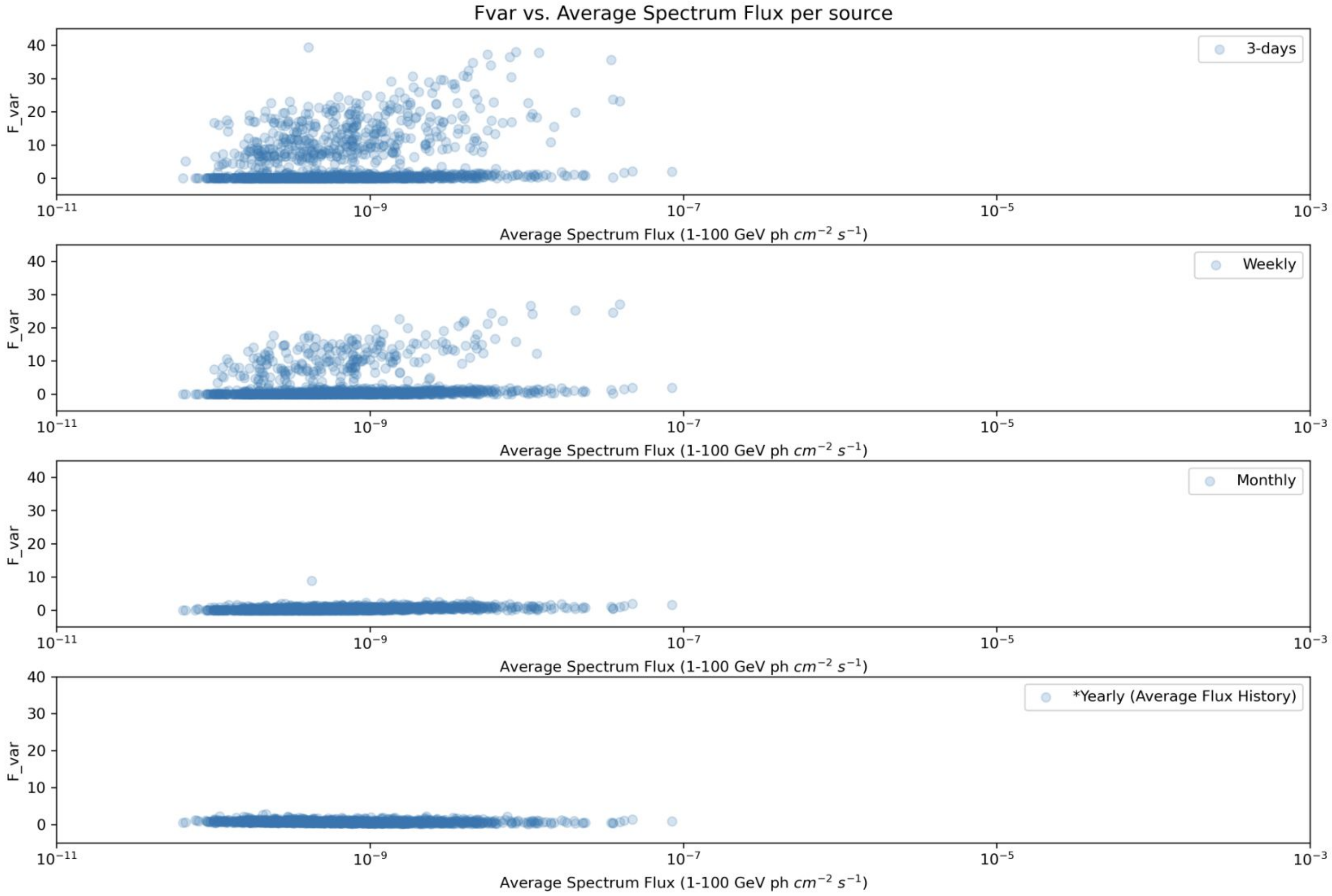
luana.passos.reis@usp.br
luana.passosreis@cta-consortium.org

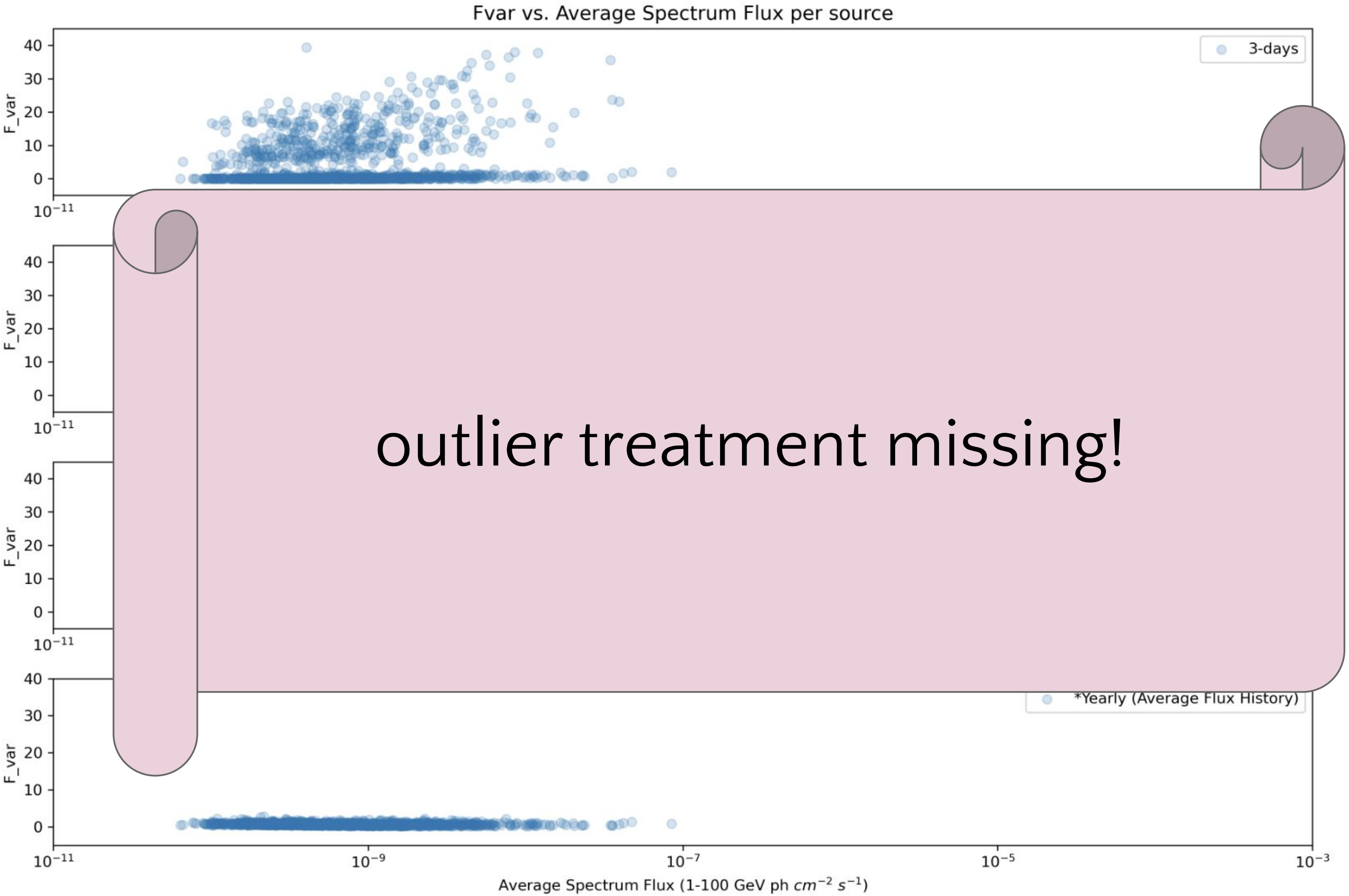
Claikson Benedito
&
Luana Reis
Observatório Pico dos Dias (MG) - Jun/2023

Back-up



Mastichiadis 2016


Fvar vs. Average Spectrum Flux per source
F_var
3-days
Weekly
Monthly
*Yearly (Average Flux History)
Average Spectrum Flux (1-100 GeV ph cm^{-2} s^{-1})
40
30
20
10
0
10^{-11}
10^{-9}
10^{-7}
10^{-5}
10^{-3}



outlier treatment missing!

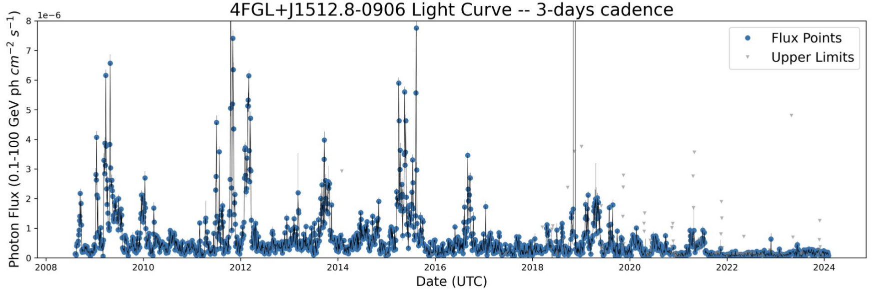
Removing flux_points that are outliers

- Remove, from the .json file of each source, the flux points in which

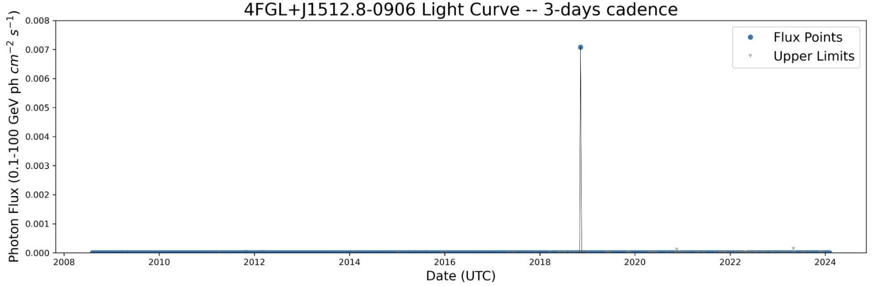
    - flux_error = 0
    - fit_convergence !=0
    - .... ?

Before and After Outlier Treatment

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

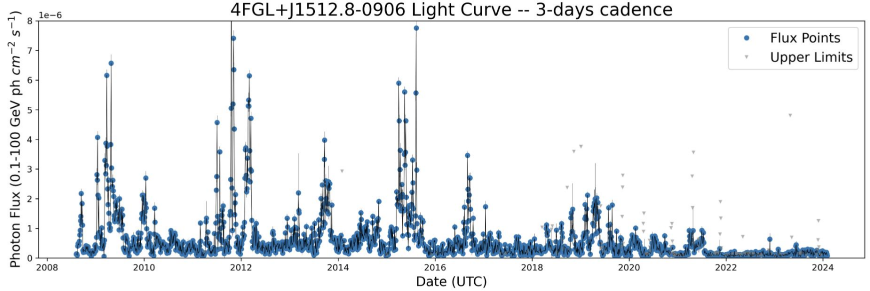



```
[41]: plot_lc('4FGL+J1512.8-0906.json', 8e-3, '3-days')
```

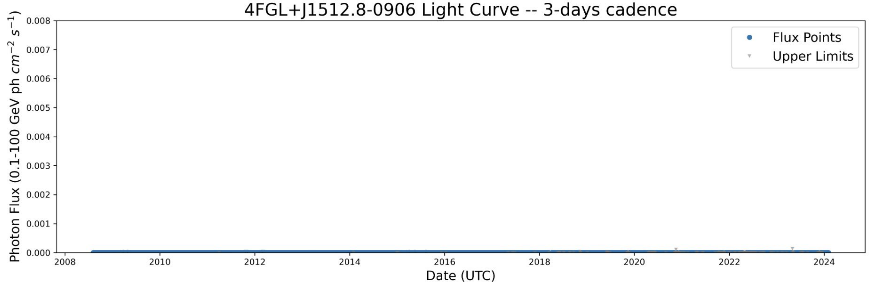


before

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



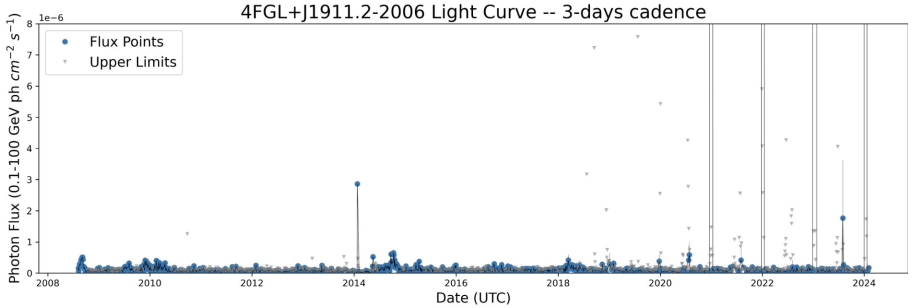

```
[41]: plot_lc('4FGL+J1512.8-0906.json', 8e-3, '3-days')
```



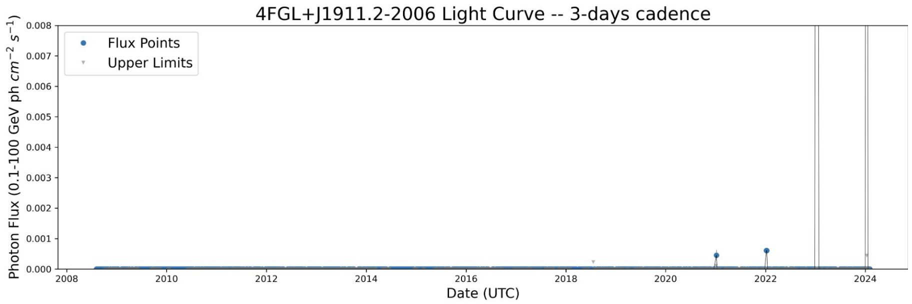
after

Before and After Outlier Treatment

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

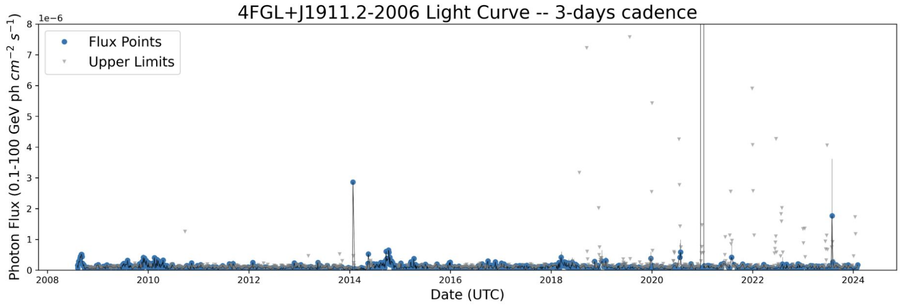



```
[45]: plot_lc('4FGL+J1911.2-2006.json', 8e-3, '3-days')
```

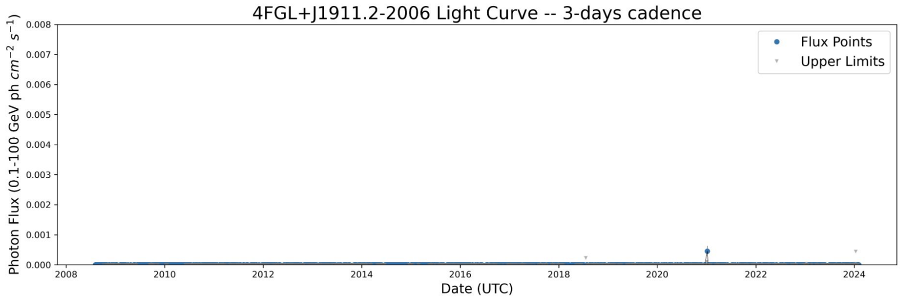


before

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

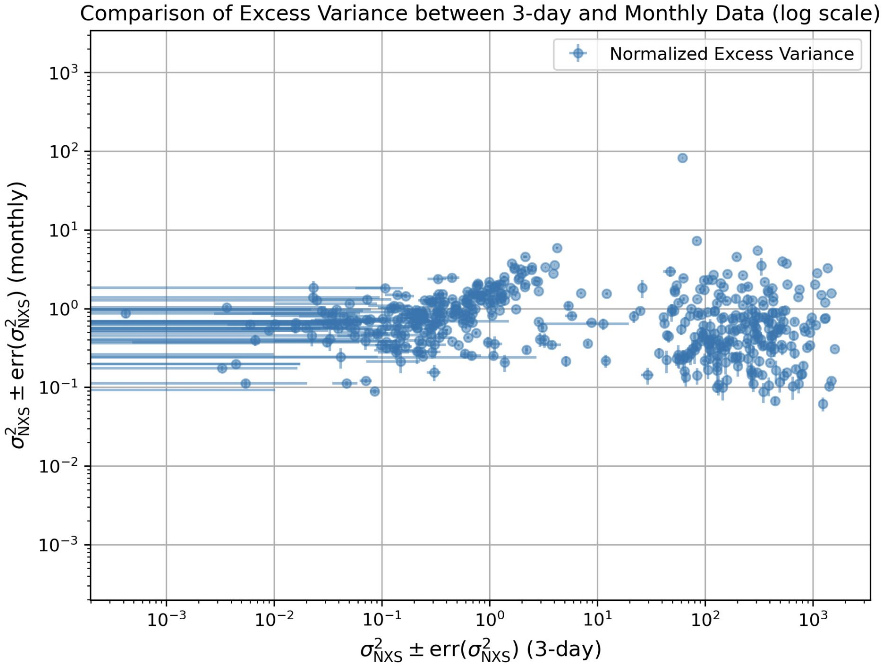



```
[45]: plot_lc('4FGL+J1911.2-2006.json', 8e-3, '3-days')
```

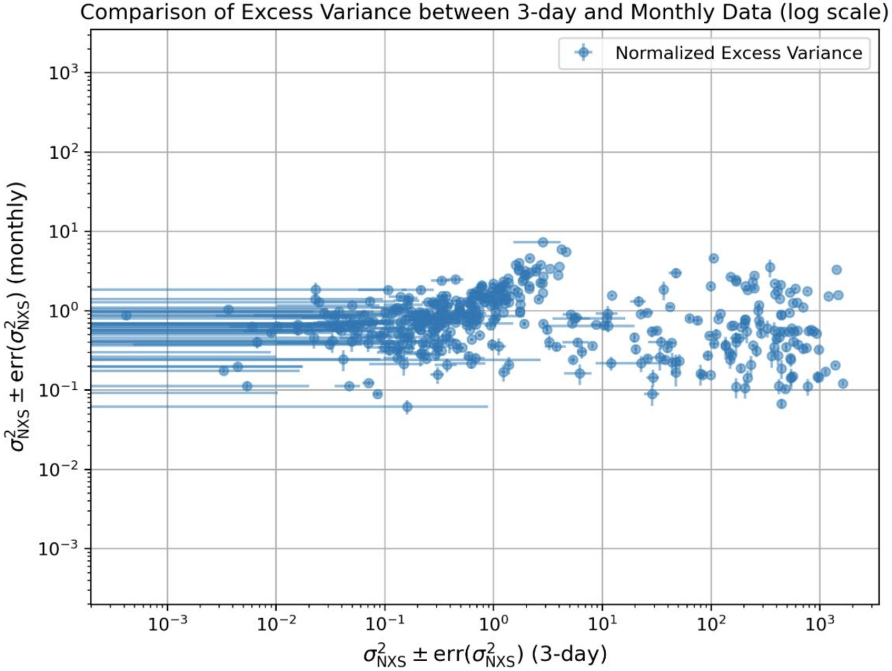


after

Preliminary Analysis

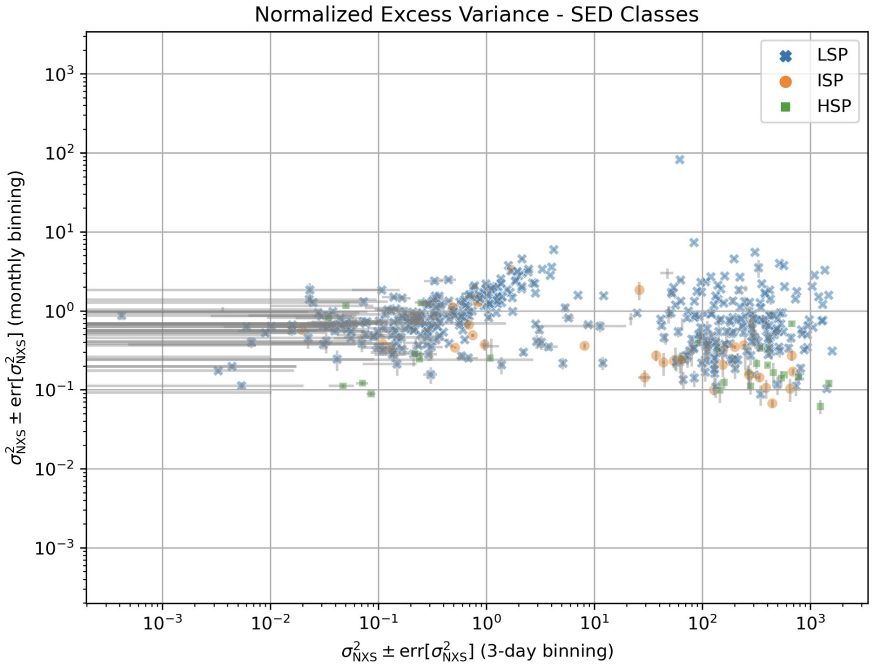


before

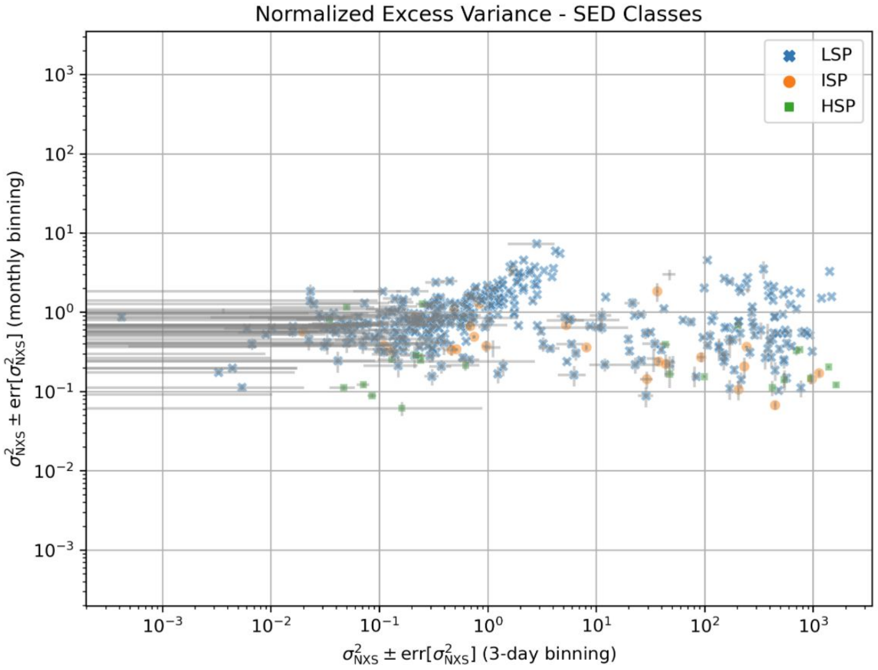


after

Preliminary Analysis

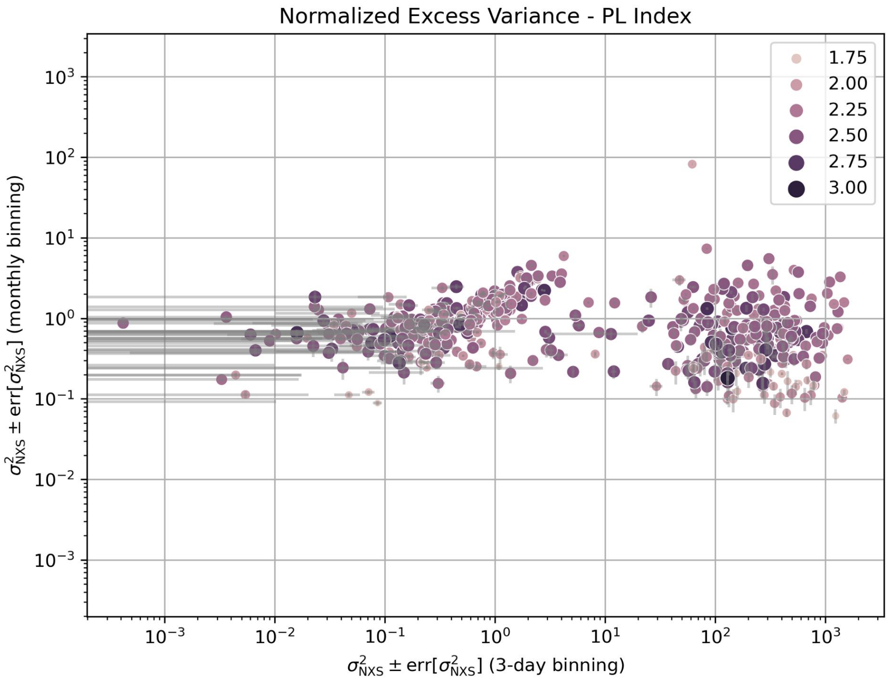


before

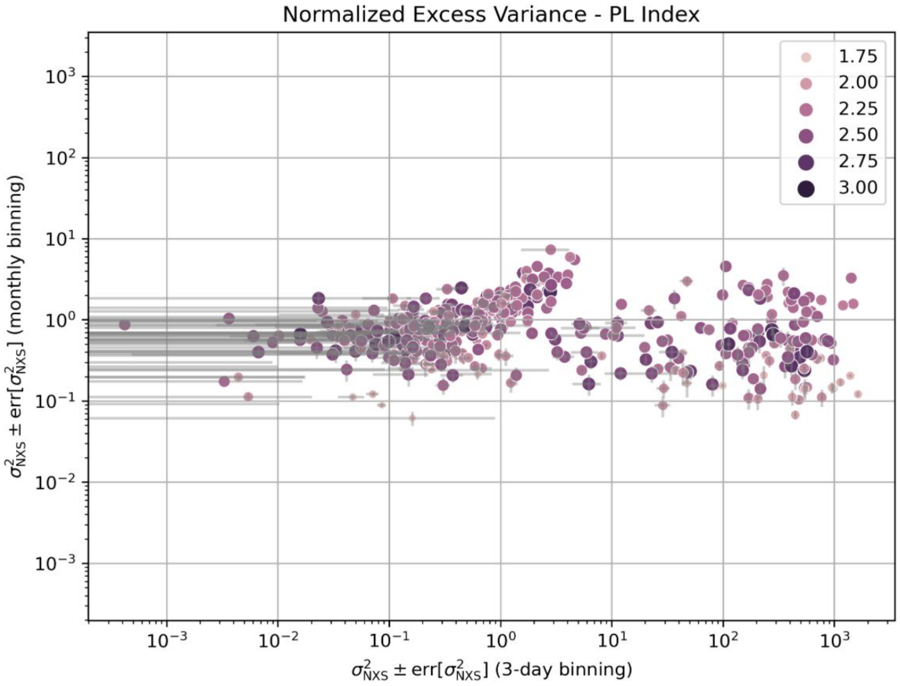


after

Preliminary Analysis



before



after