

# Markarian Multiwavelength Data Center (MMDC) Modeling blazar broadband emission with convolutional neural networks



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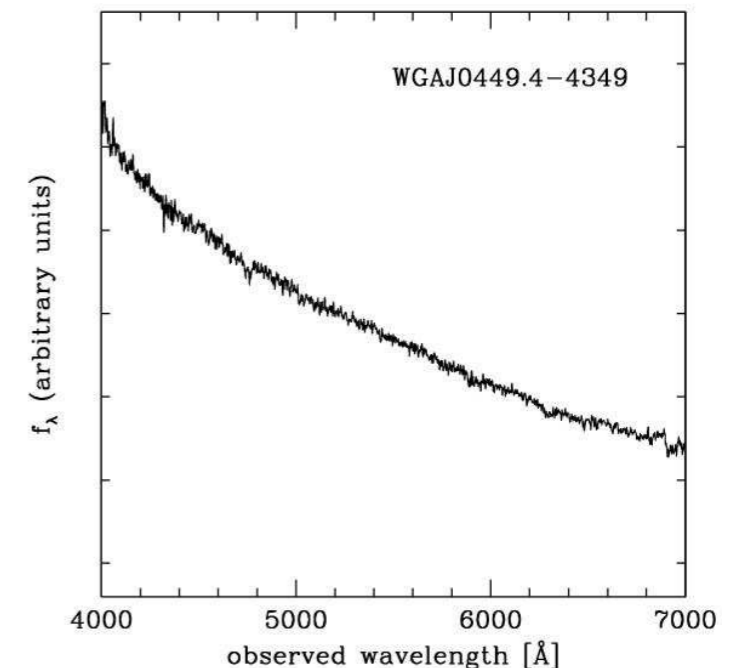
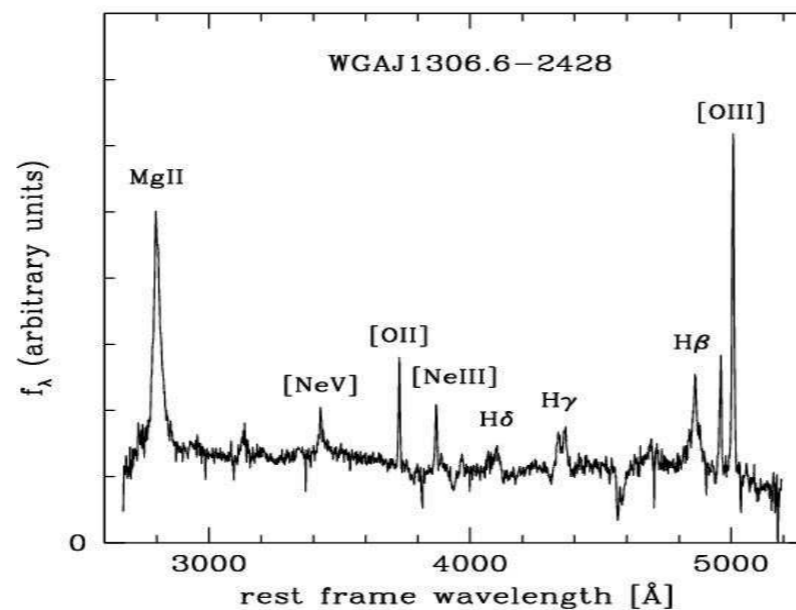
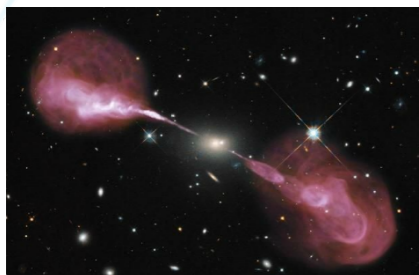
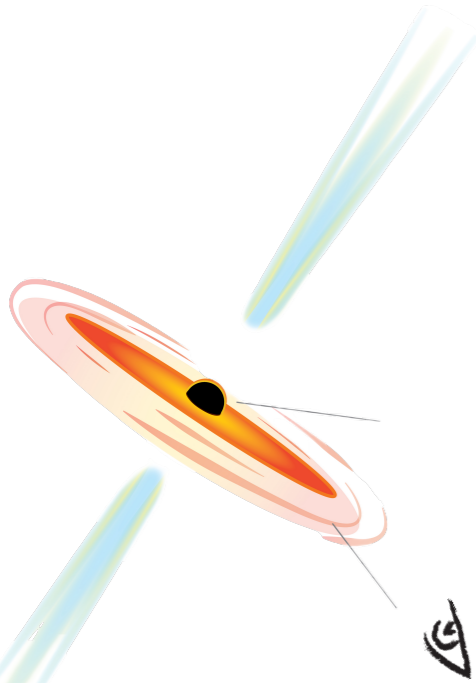
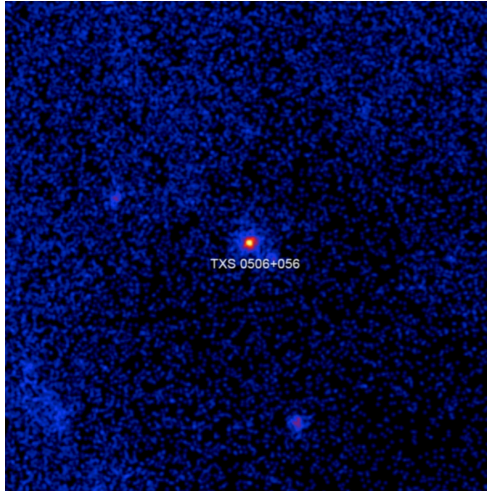
# Blazars: powerful and rare objects

The common model for blazar emission is that these sources are quasars in which a relativistic jet is pointing at the observer, or very close to the observer's line of sight.

Blazars are rare objects. Even when combining data from multiple surveys, only about 6,000 sources exhibit blazar-like features among estimated 100 to 200 billion galaxies.

Why blazars are interesting ?

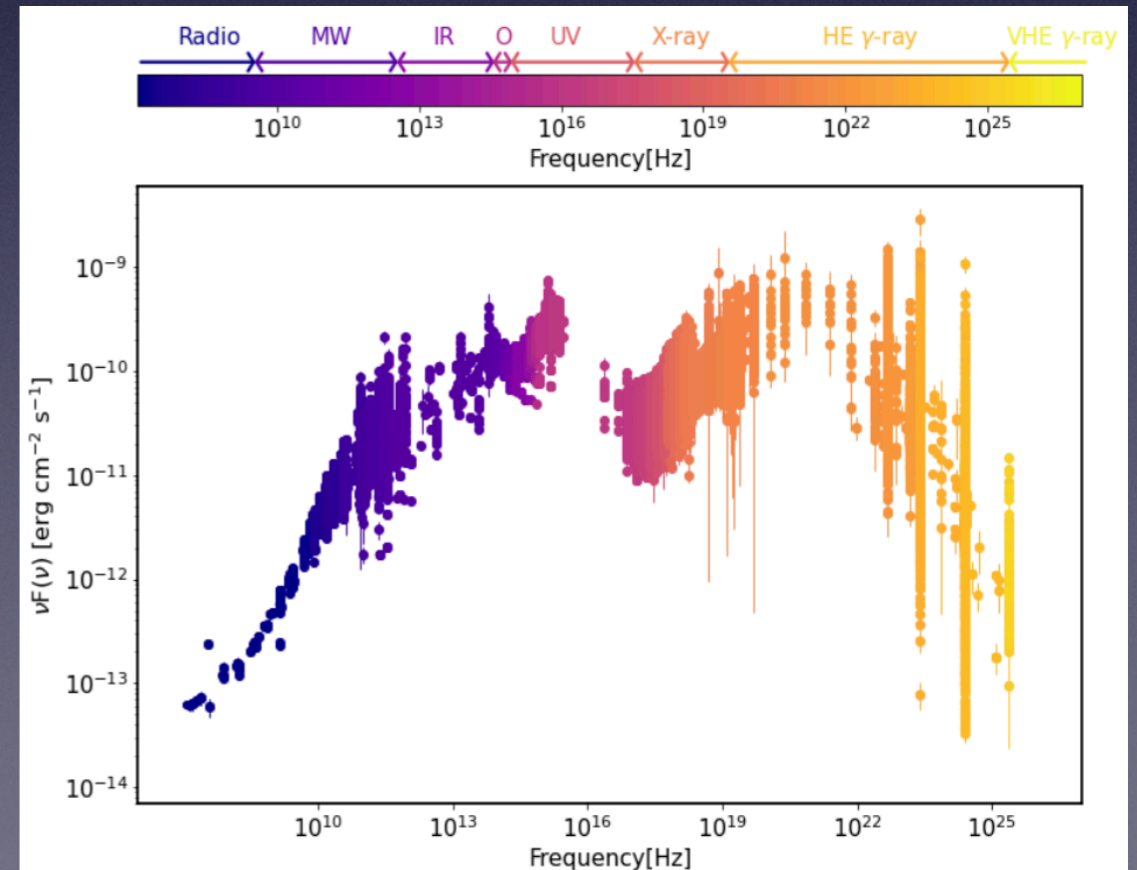
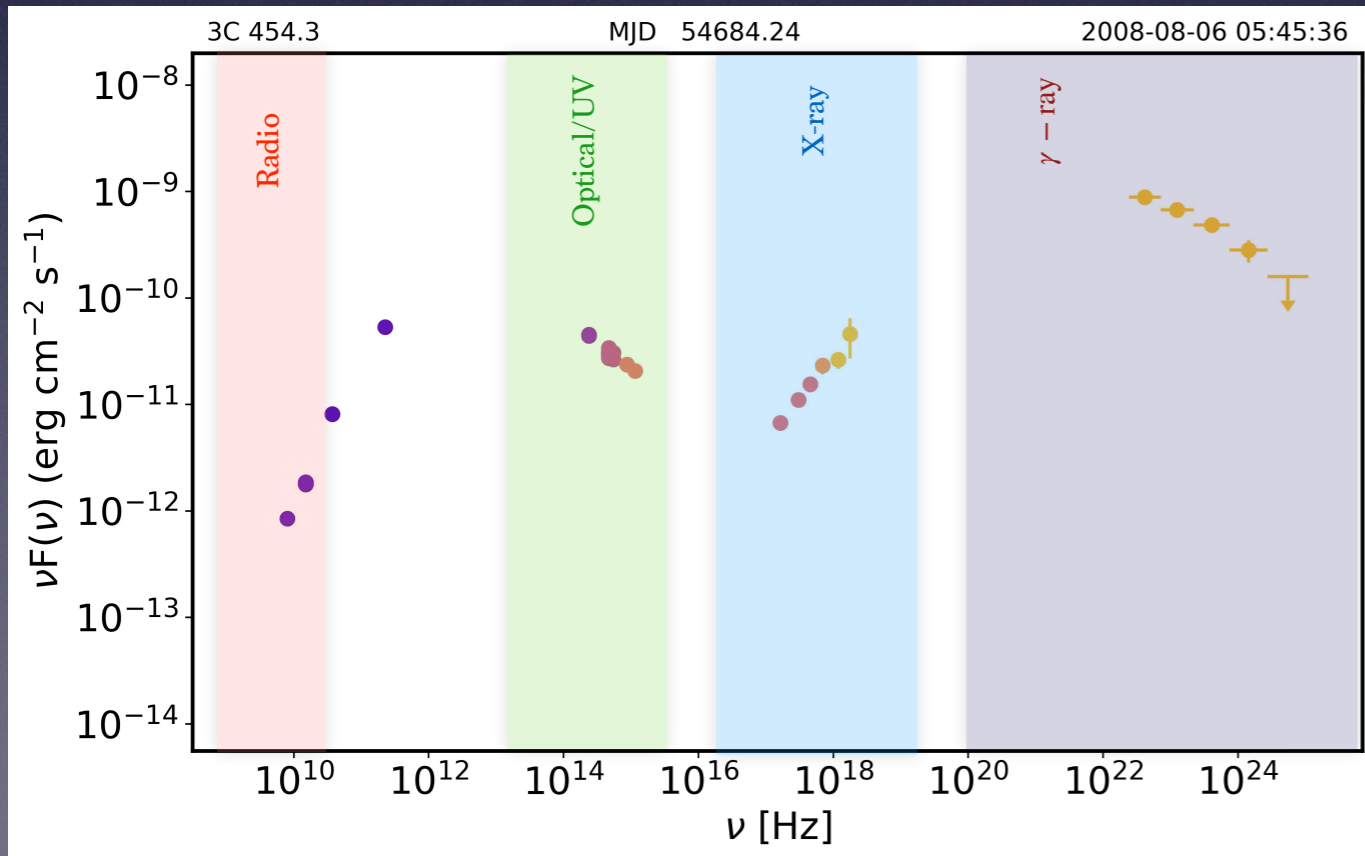
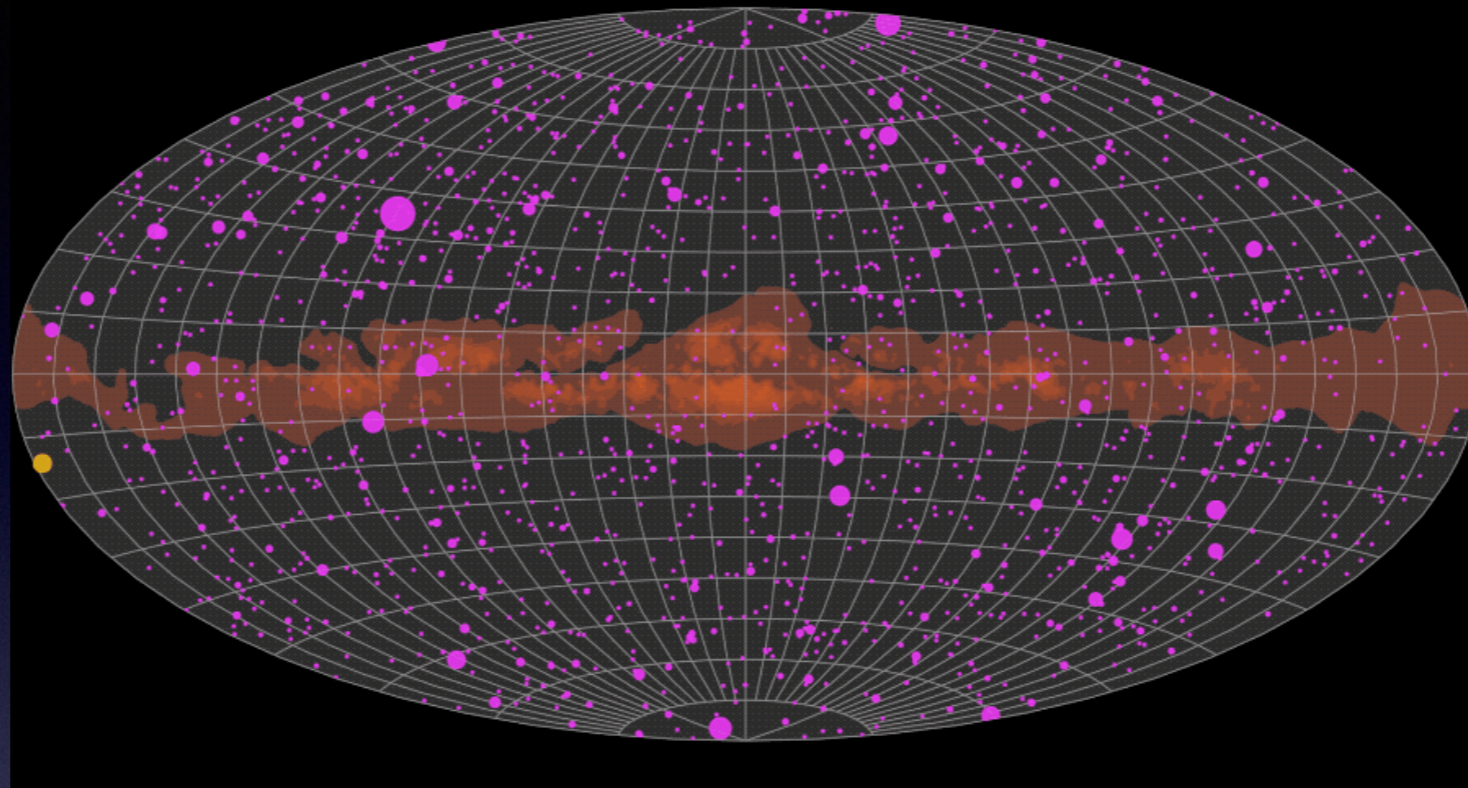
- High powers: most powerful “non-explosive” sources in the Universe ( $\sim 10^{49}$  erg/s)
- Fast variability/small emitting region;  $R \leq c t_{\text{var}}/(1+z)$
- Broadband emission: from radio to VHE  $\gamma$ -ray, neutrinos
- Dominant sources in HE  $\gamma$ -ray sky:  $\sim 55\%$  of 4FGL-DR3 sources are blazars.



# High amplitude fast variability

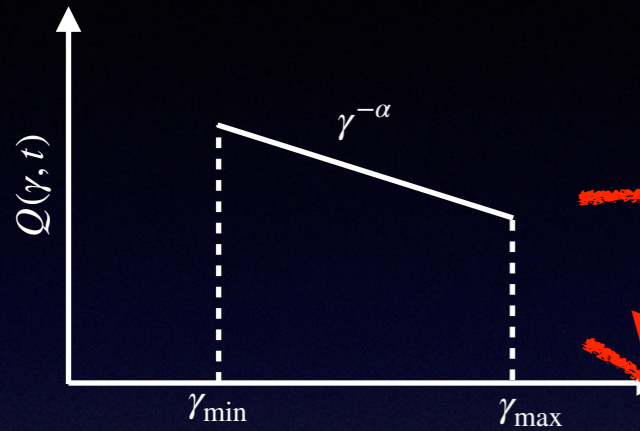
$\gamma$ -ray band

Abdollahi et al., ApJ, 2023

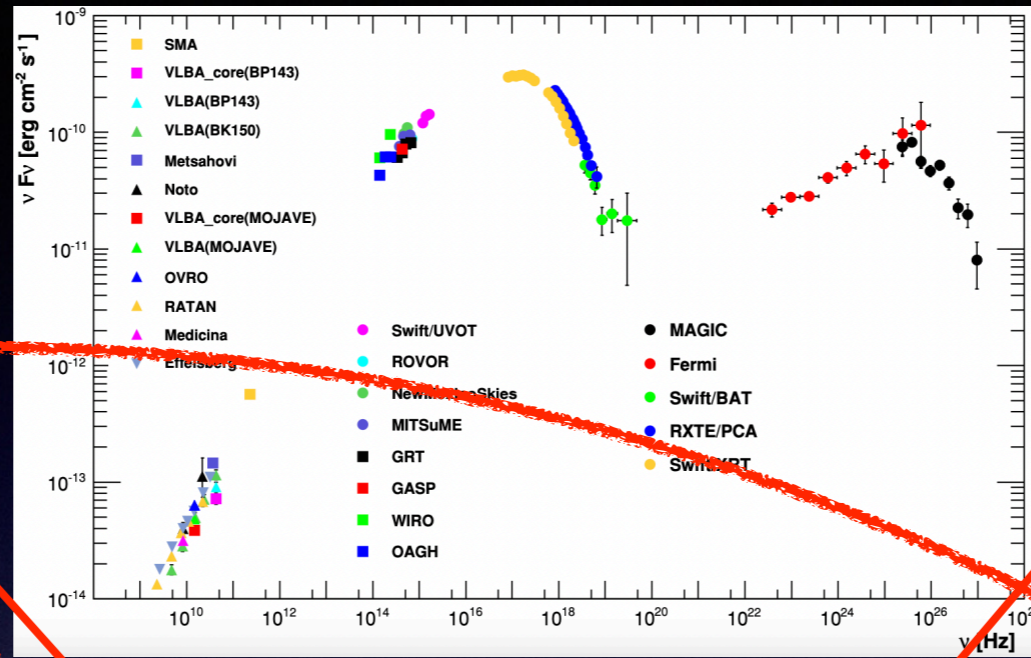


# The origin of emission

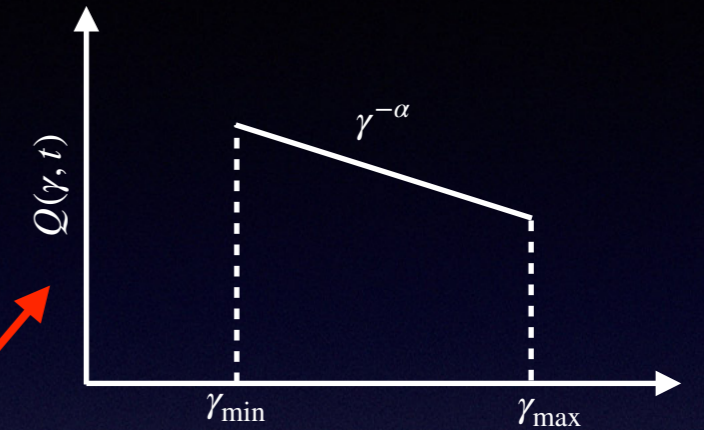
Injection or acceleration of electrons



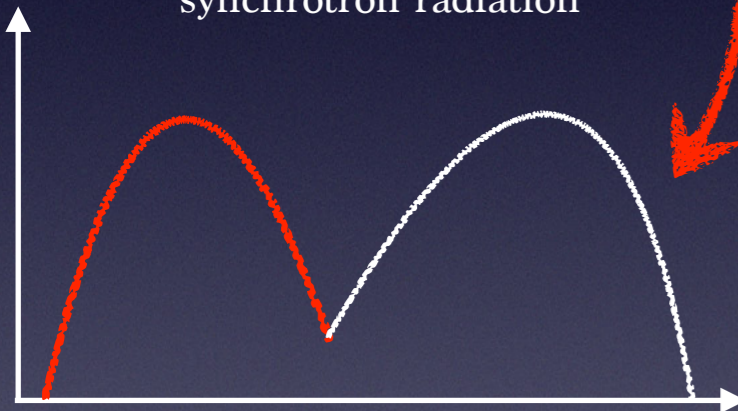
Fermi, MAGIC 2011



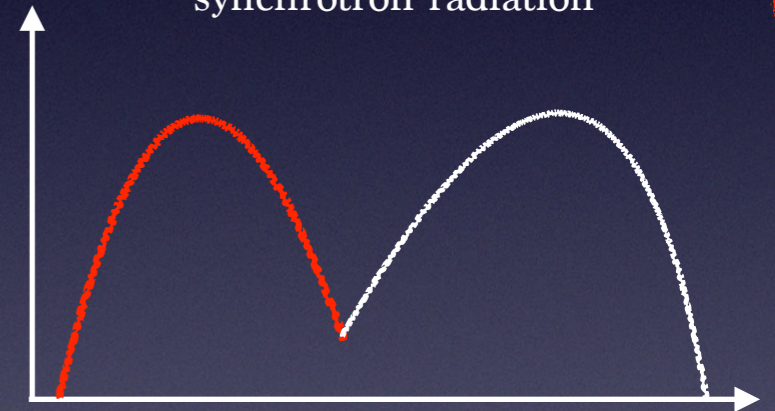
Injection or acceleration of protons



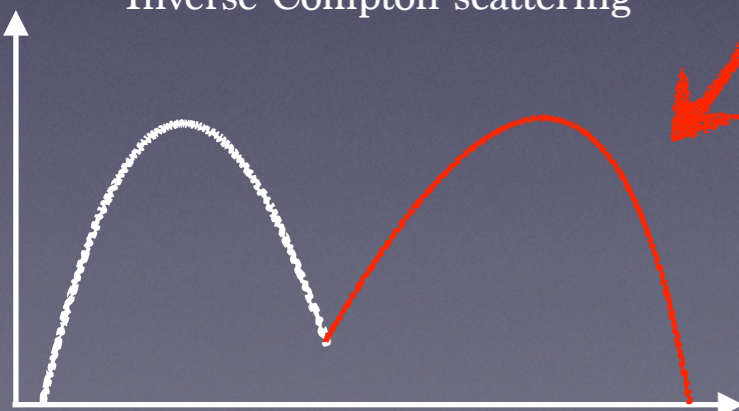
synchrotron radiation



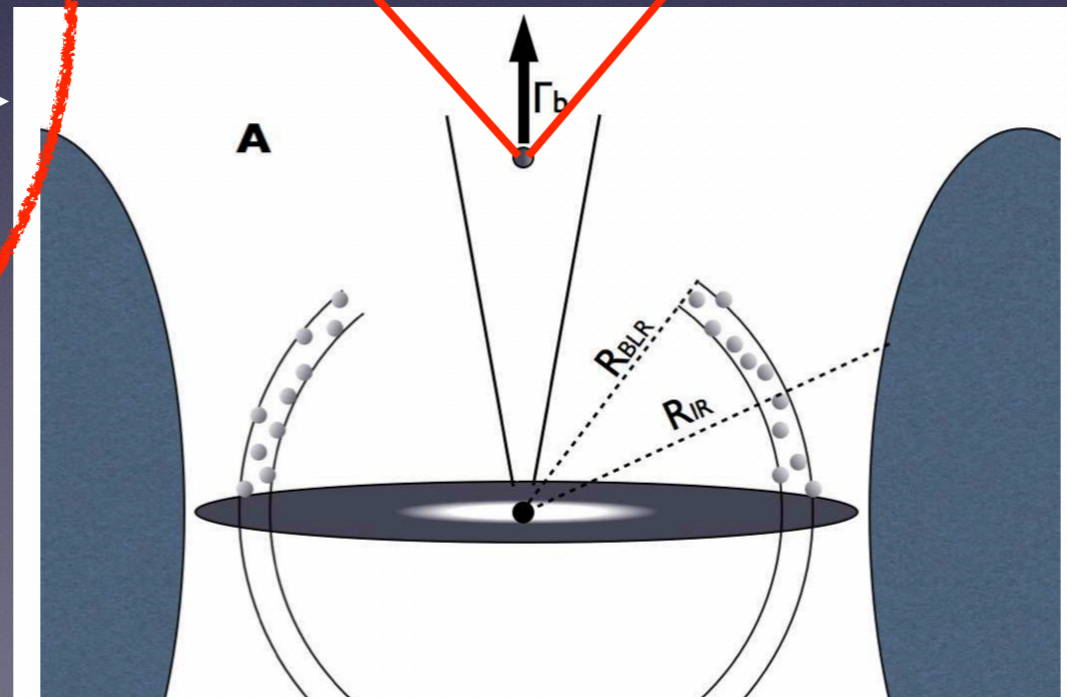
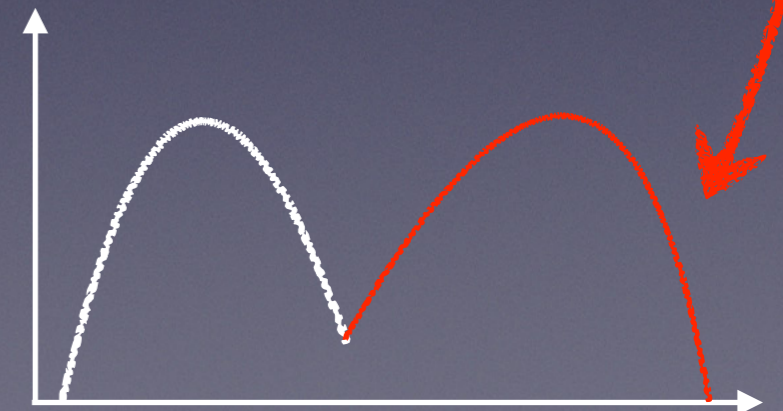
synchrotron radiation



Inverse Compton scattering

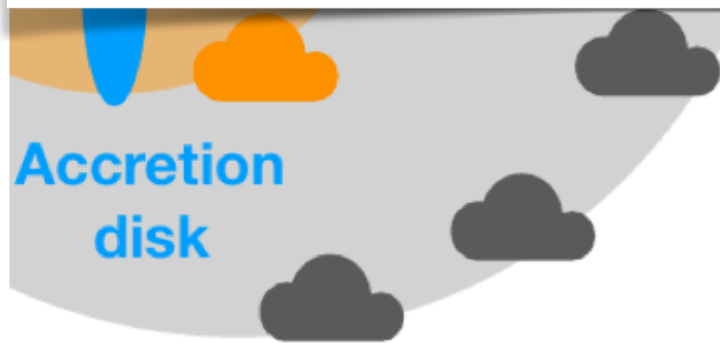
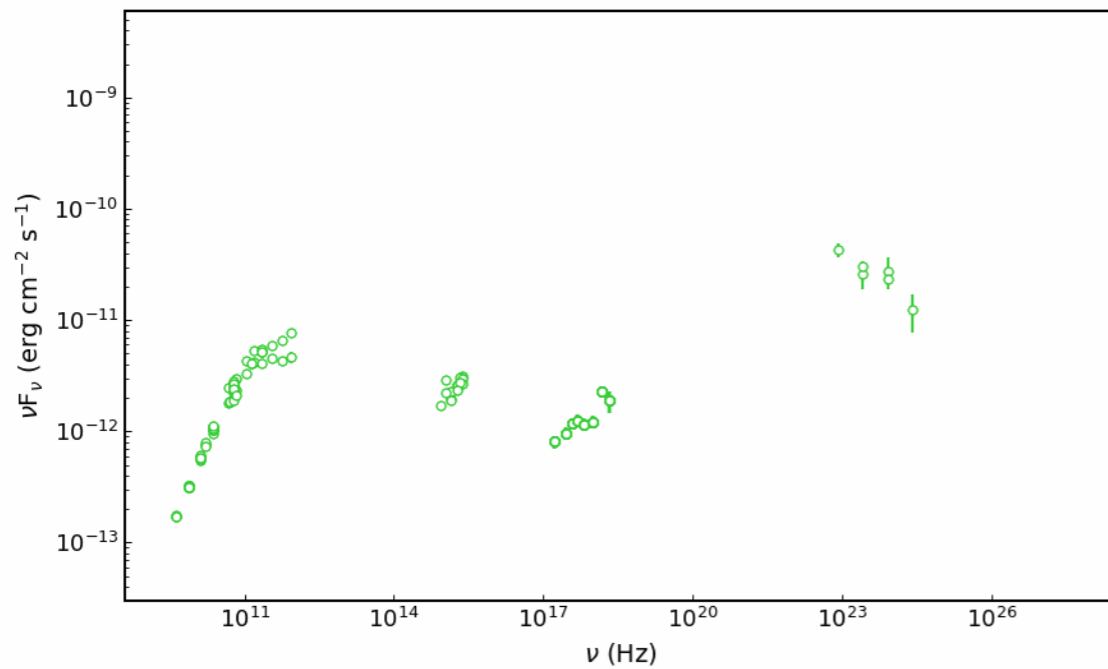
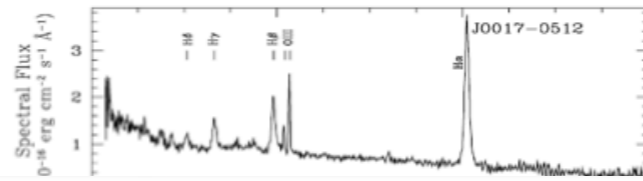


Proton emission

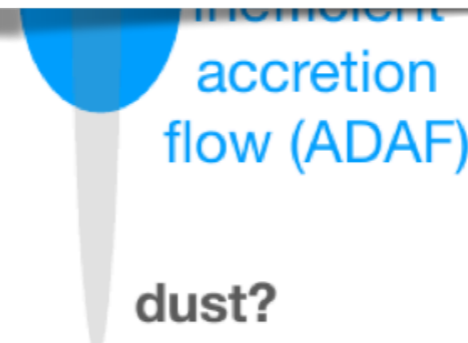
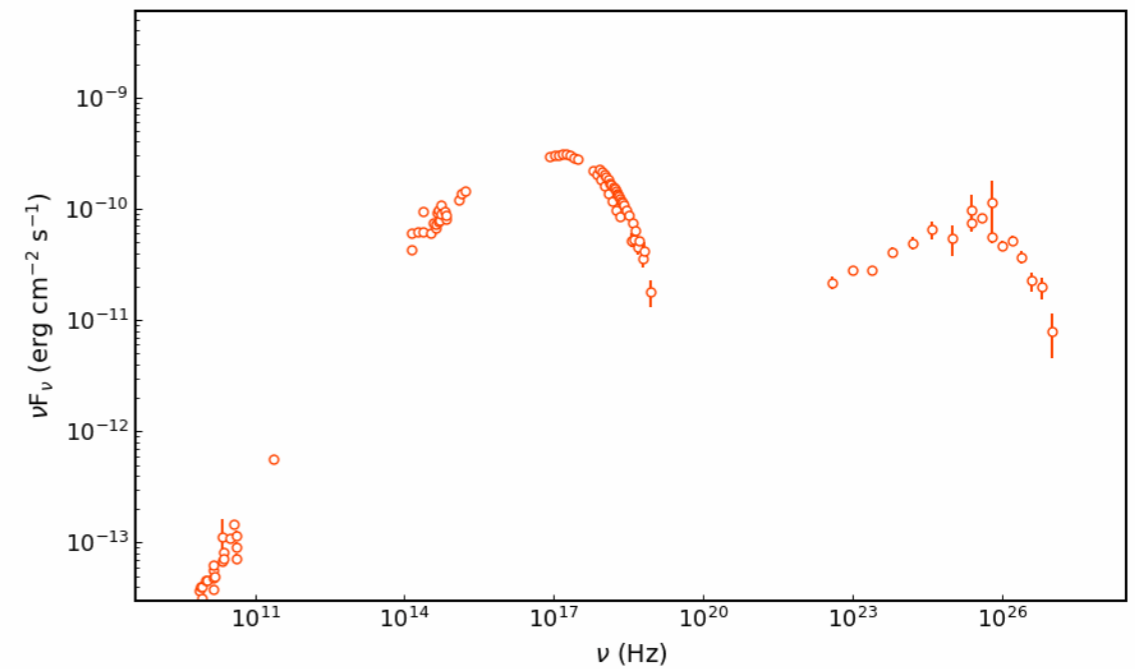
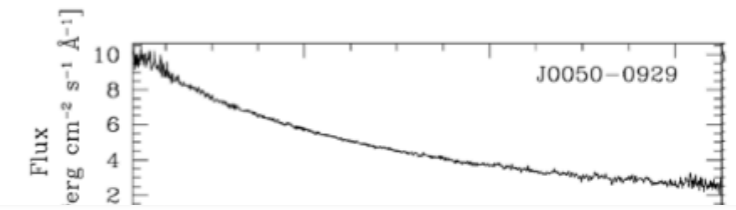


# Origin of Emission: leptonic

## FSRQs

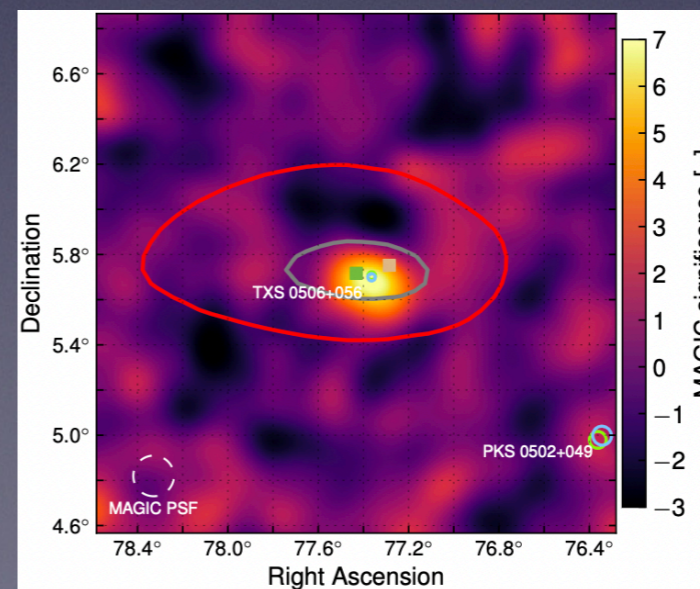
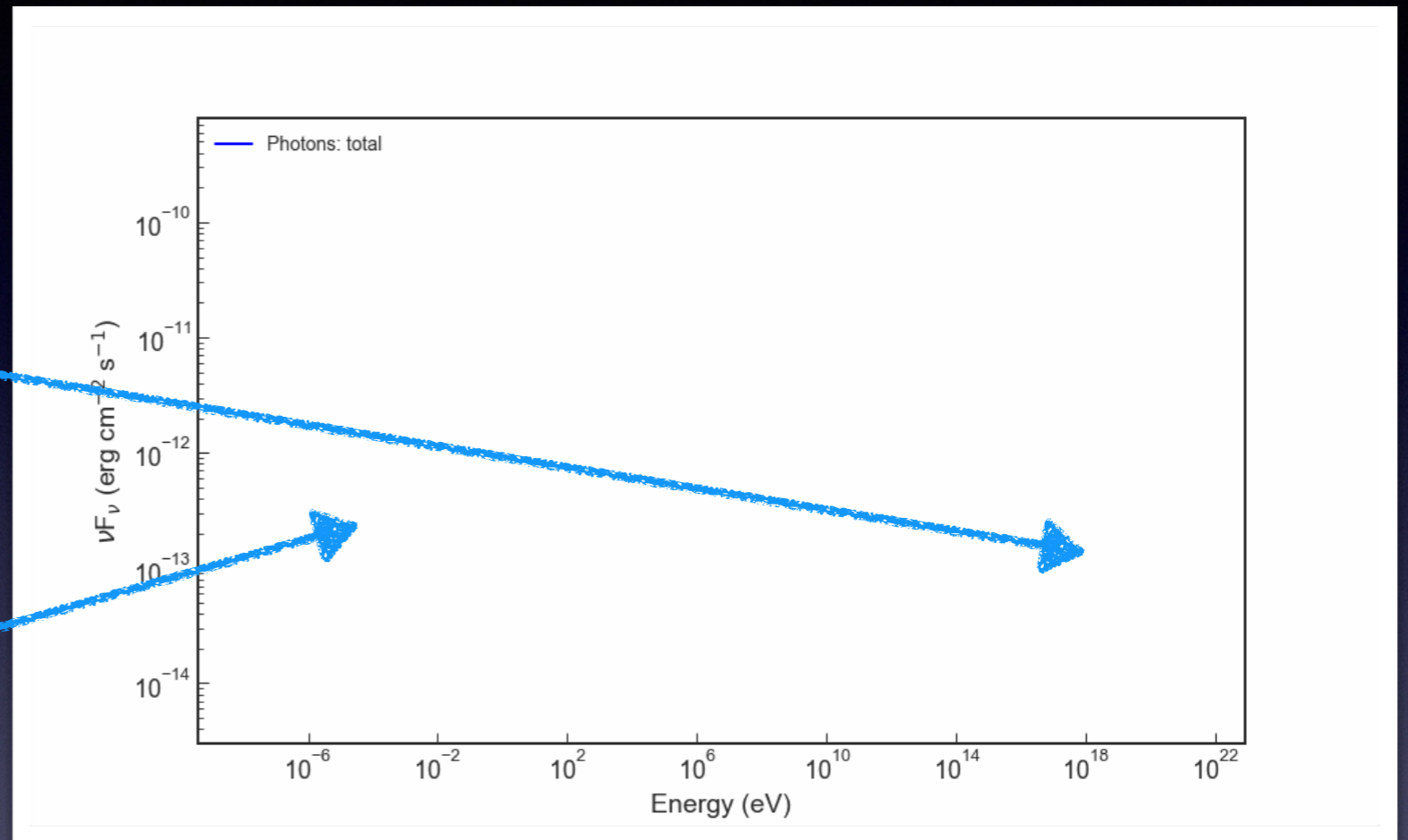
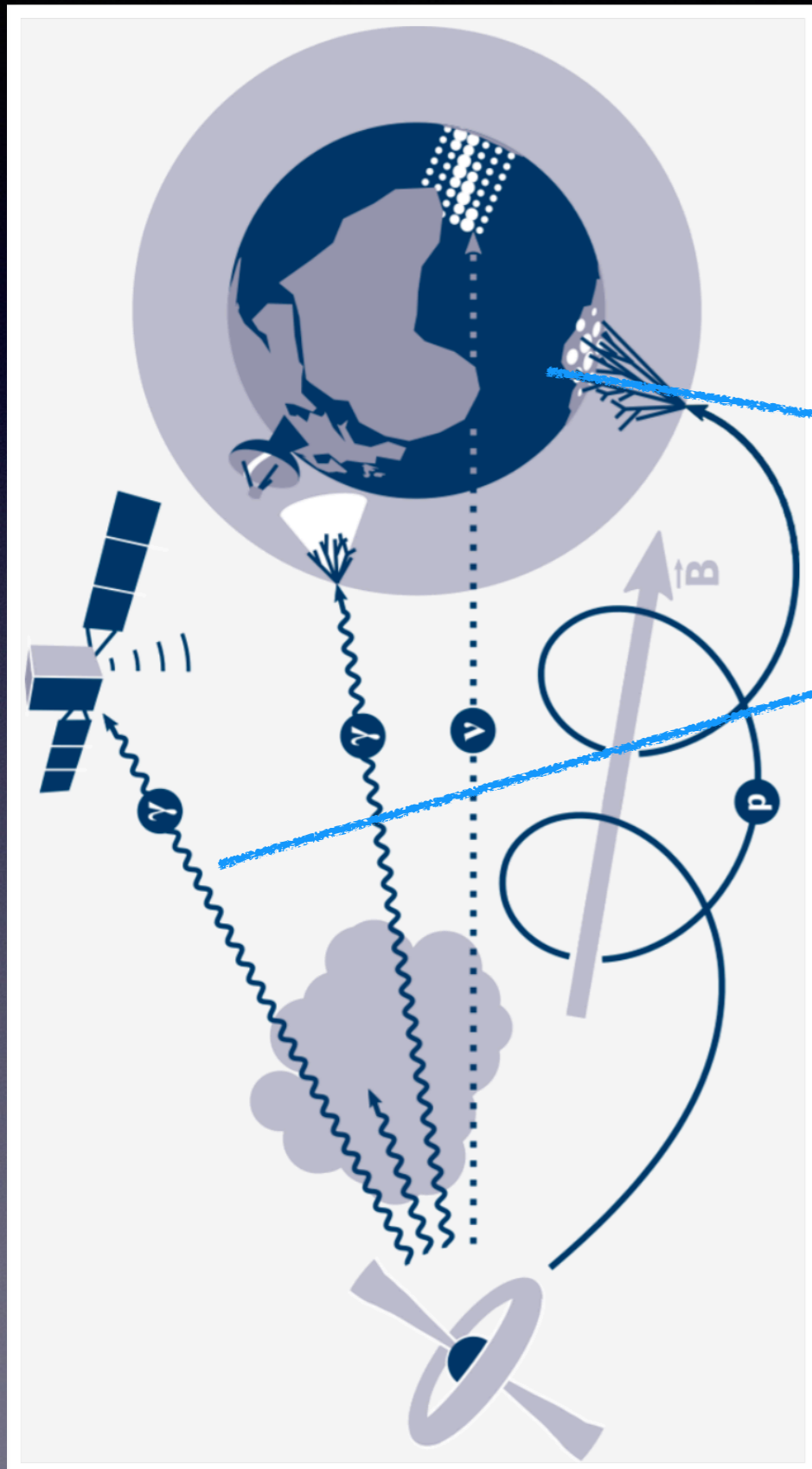


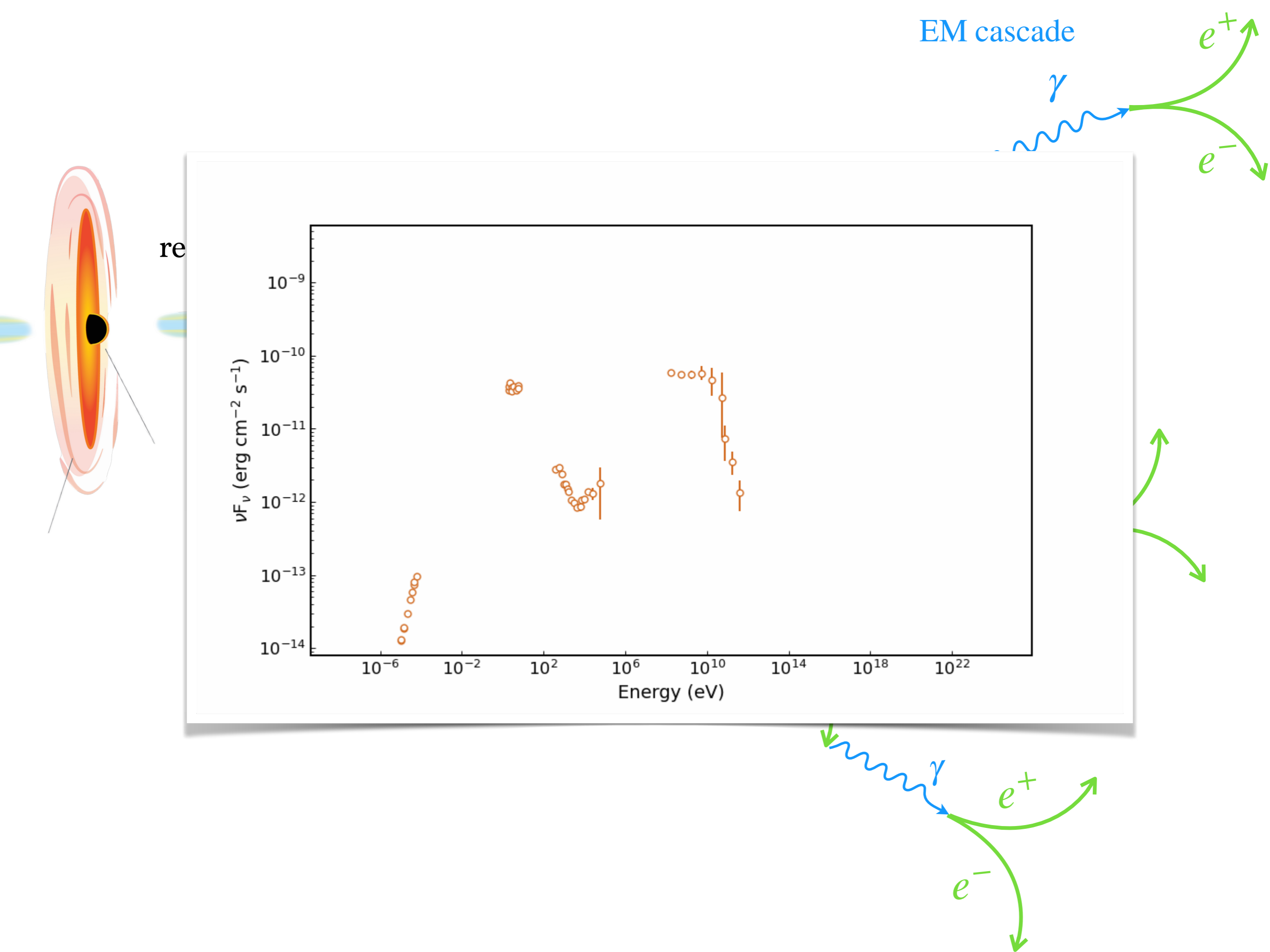
## BL Lacs

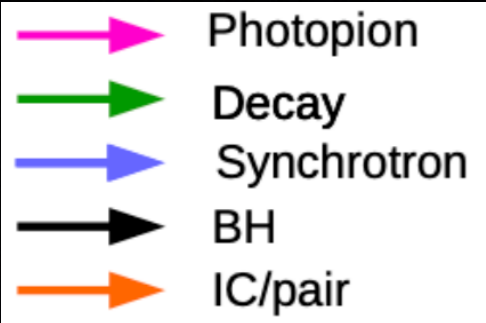


Credit: F. Oikonomou

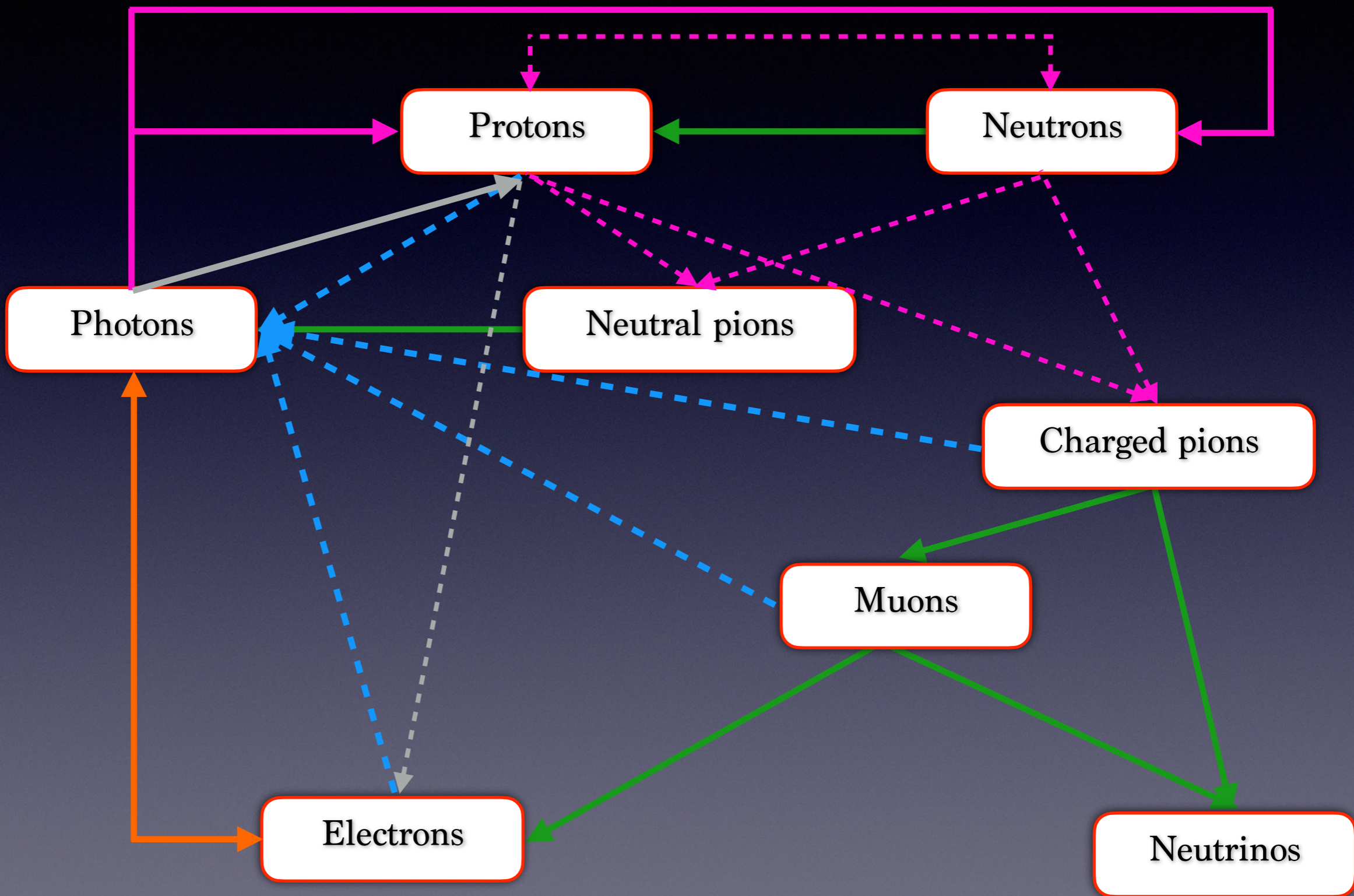
# Origin of Emission: protons







# Simulator Of Processes in Relativistic AstroNomical Objects (SOPRANO): Interaction chart





# Evolution of the particle distribution

$$\frac{\partial N_p}{\partial t} = C_{p\gamma \rightarrow p\pi} + C_{p\gamma \rightarrow e^+e^-} + C_{\text{synch}} - S_{\gamma p \rightarrow n\pi} + Q_{\gamma n \rightarrow p\pi}$$

$$\frac{\partial N_\mu}{\partial t} = Q_{\pi^\pm} - S_\mu + C_{\text{synch}}$$

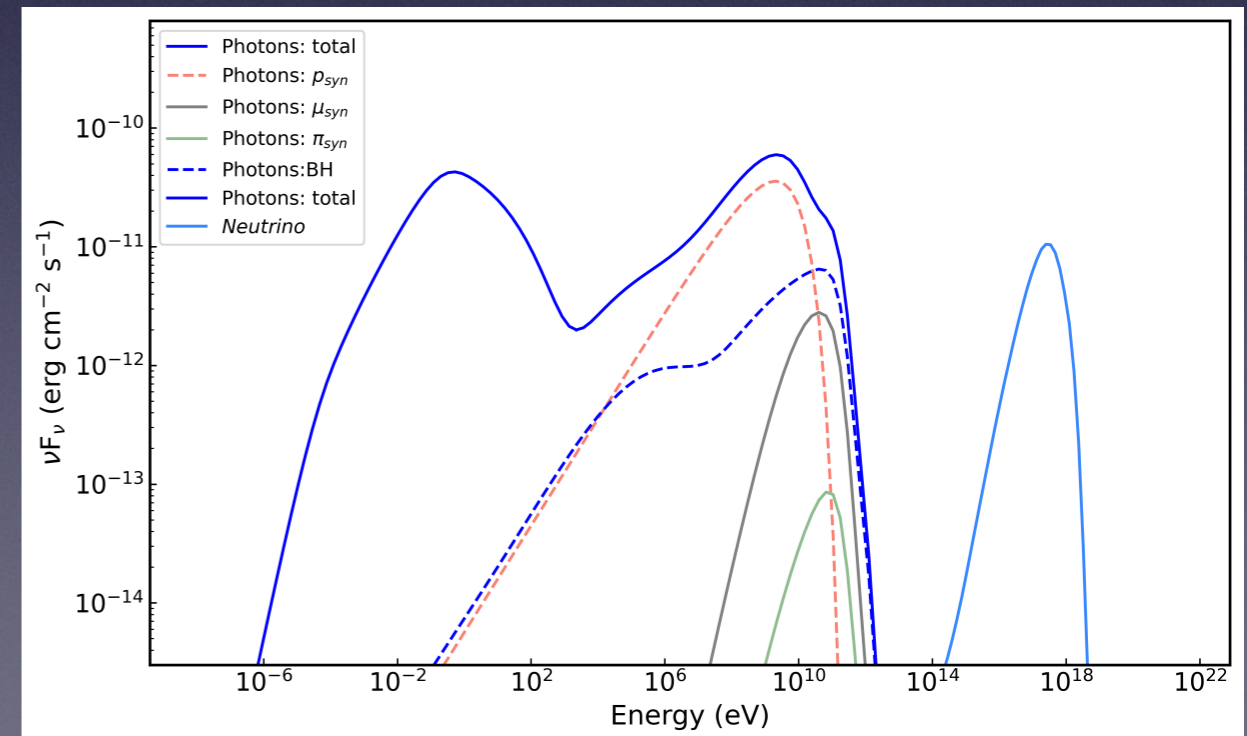
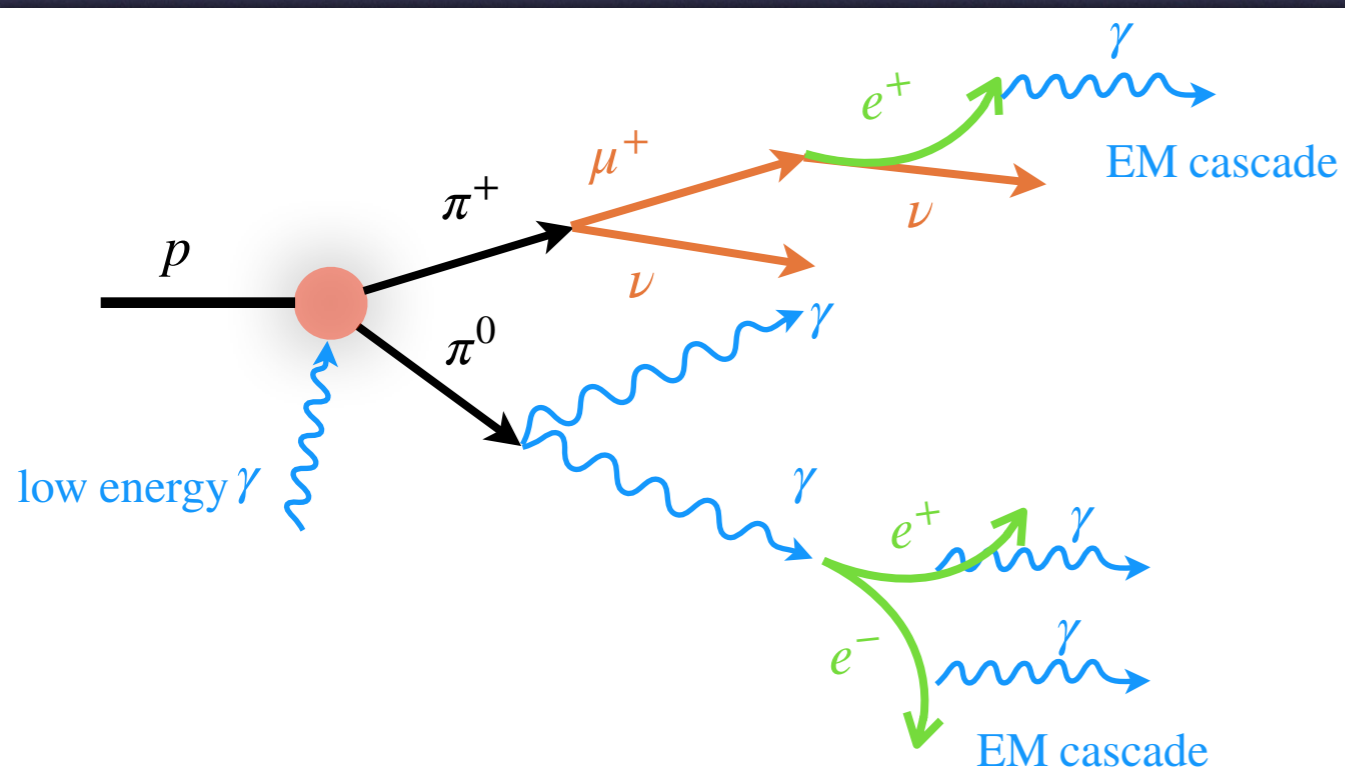
$$\frac{\partial N_n}{\partial t} = -S_{n\gamma \rightarrow p\pi} + Q_{p\gamma \rightarrow n\pi} + C_{n\gamma \rightarrow n\pi}$$

Q: sink term  
S: source term  
C: cooling term

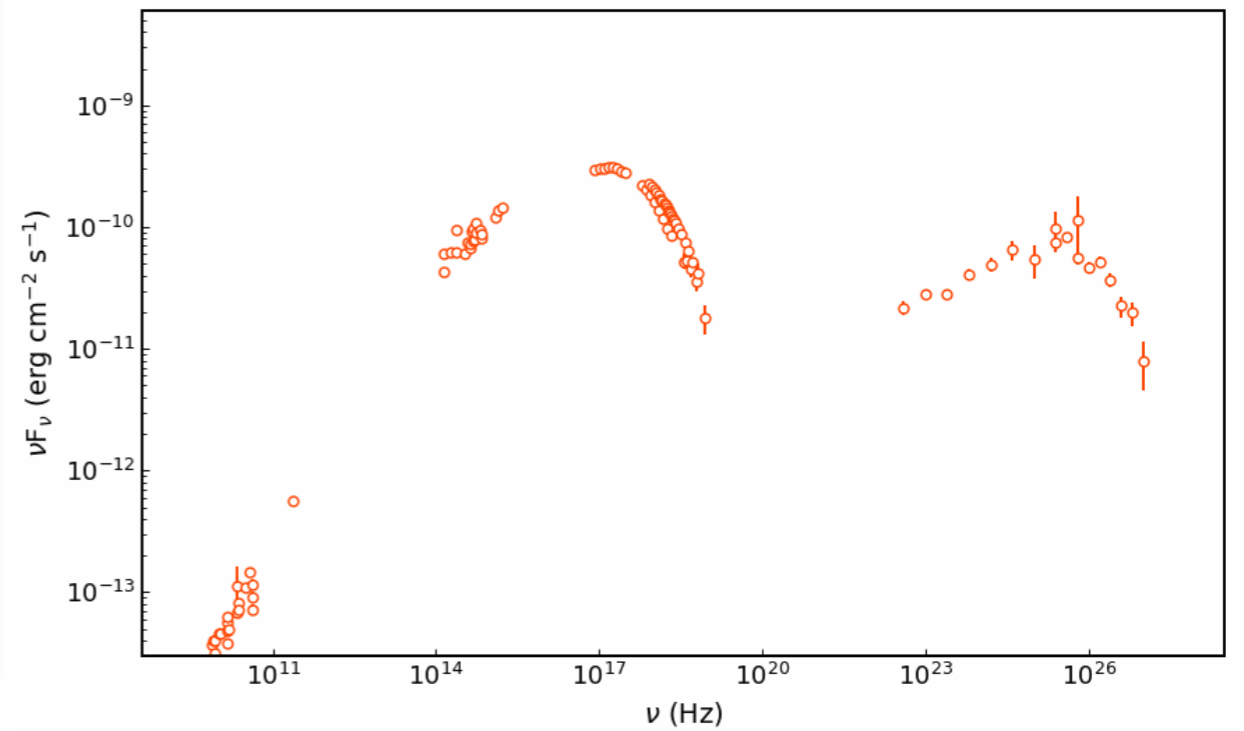
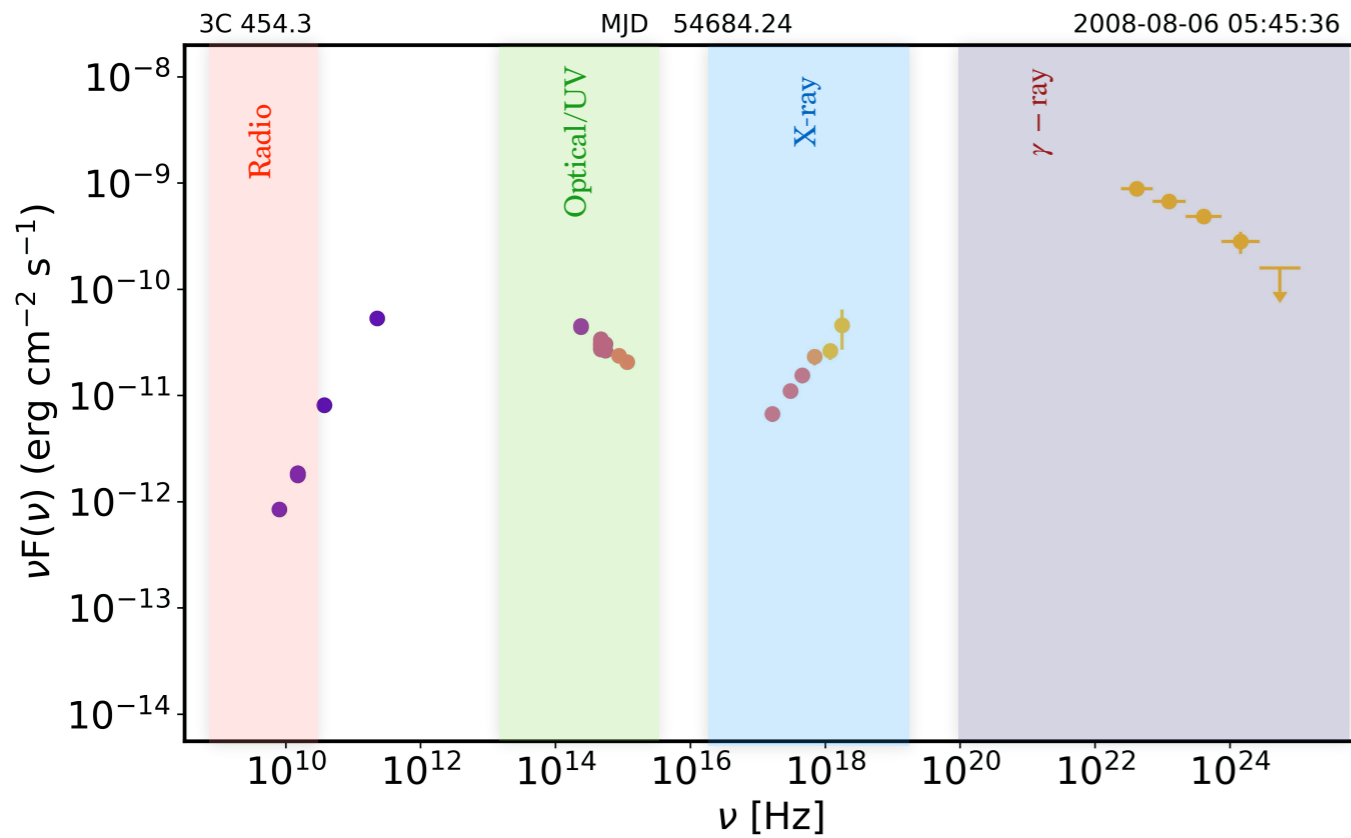
$$\frac{\partial N_{\nu,\zeta}}{\partial t} = Q_{\pi^\pm} + Q_\mu$$

$$\frac{\partial N_{\pi^\pm}}{\partial t} = Q_{p\gamma \rightarrow \pi} + Q_{n\gamma \rightarrow \pi} - S_\pi + C_{\text{synch}}$$

$$\frac{\partial N_{e^\pm}}{\partial t} = Q_\mu + Q_{p\gamma \rightarrow e^+e^-} + Q_{\gamma\gamma \rightarrow e^+e^-} C_{\text{IC}} + C_{\text{synch}}$$



# Data—Modeling



# MMDC

MMDC

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## WELCOME TO MMDC

Markarian Multiwavelength Data Center (MMDC): a platform for building and analyzing multiwavelength SEDs.

GET STARTED

# Interesting story

## L'Osservatorio del Tuscolo e "i telescopi di Mussolini"

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<sup>2</sup> INAF · Osservatorio Astronomico di Roma

<sup>3</sup> St. Petersburg Filial of Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation · Russian Academy of Science

### Introduzione

L'OSSERVATORIO Astronomico di Roma (OAR-INAF) nasce nel 1938, ereditando la tradizione scientifica e il patrimonio dei due osservatori astronomici pubblici che erano presenti all'epoca nella capitale: l'Osservatorio Astronomico del Collegio Romano e l'Osservatorio del Campidoglio.<sup>1</sup>

Il nuovo istituto, diretto e fortemente voluto da Giuseppe Armellini (1887-1958), fu inaugurato il 22 ottobre 1938 sulla collina di Monte Mario nella rinascimentale Villa Mellini.

L'attività di ricerca è stata condotta senza interruzione a Monte Mario fino al 1988, anno in cui la sede principale dell'Osservatorio fu spostata a Monte Porzio Catone sulle pendici del Tuscolo.

Anche l'idea di un grande osservatorio astronomico nazionale al Tuscolo, nacque negli anni Trenta, promossa da Emilio Bianchi (1875-1942), accademico d'Italia e direttore dell'Osservatorio Astronomico di Brera.

Fu proprio nel maggio 1938 che, nel corso della sua visita Roma, Adolf Hitler consegnò a Mussolini una pergamena nella quale si impegnava a donare all'Italia un osservatorio completo di tutta la strumentazione, che sarebbe stata prodotta dalla ditta Carl Zeiss di Jena.<sup>2</sup> In cambio l'Italia avrebbe donato alla Germania il Discobolo Lancellotti, copia di epoca romana della famosa scultura di Mirone (BUONANNO 2008; CARROL 2008; STROLLO 2008).

Lo scoppio della seconda guerra mondiale e i tragici eventi del 1943 posero fine al progetto. I lavori del nuovo osservatorio rimasero incompiuti e i telescopi promessi non giunsero mai in Italia: requisiti dall'Armata Rossa, finirono negli osservatori dell'Unione Sovietica.

<sup>1</sup> L'Osservatorio del Collegio Romano, va ricordato come il luogo ove, nella seconda metà del XIX sec., operò padre Angelo Secchi, fondatore dell'astrofisica stellare. Nello stesso periodo l'Osservatorio Universitario del Campidoglio era diretto da Lorenzo Respighi. (ALTAMORE e MAFFEO 2013).

<sup>2</sup> Dal discorso di Hitler: «Nella mia qualità di Führer e di Cancelliere del Reich germanico, prego Benito Mussolini, Duce del popolo che diede al mondo il grande inventore e scienziato Galileo Galilei, di gradire in dono un telescopio Zeiss ed insieme l'intero arredamento per un Osservatorio Astronomico, e ciò in segno di omaggio e di amicizia».



FIG. 1. L'Osservatorio Astronomico di Monte Porzio Catone.

Nel 1948 l'edificio fu assegnato all'Osservatorio Astronomico di Roma e da allora cominciò una lenta opera di ricostruzione che portò, nel giro di qualche decennio, al trasferimento della sede principale dell'OAR a Monte Porzio. Presso questa struttura oggi si svolge un'attività di ricerca astrofisica di punta, sia osservativa sia teorica, che spazia dallo studio del Sistema solare, alle stelle e ai sistemi stellari, alle galassie e alla cosmologia.

La grande cupola dell'edificio principale, opportunamente riadattata, oggi ospita una parte della grande biblioteca dell'istituto. Questo spazio è anche adibito a sala conferenze ed utilizzato per esposizioni. (FIG. 1)

### La sorte dei telescopi dopo il 1945

Nel maggio del 1945 gli astronomi sovietici Piotr Dobronravyn (1908-2000) and Andrei Severnii (1913-1987), futuro direttore dell'Osservatorio Astrofisico di Crimea, si recarono in Germania per cercare di recuperare la strumentazione sottratta all'osservatorio astronomico di Simeiz<sup>3</sup> dalle truppe tedesche. I telescopi furono trovati all'Osservatorio di

<sup>3</sup> L'Osservatorio di Simeiz in Crimea fu attivo fino alla metà degli anni Cinquanta del XX secolo; oggi è una stazione dell'Osservatorio Astrofisico di Crimea.

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## Il telescopio Schmidt

Al momento dell'arrivo a Jena delle truppe sovietiche, lo specchio del telescopio Schmidt era ancora in lavorazione; fu comunque trasportato alla LOMO di Leningrado ove, sotto la supervisione dell'accademico Victor A. Ambartsumian (1908-1996), fu completato. Dopo il completamento di tutte le parti meccaniche e ottiche, Ambartsumian ottenne che il telescopio fosse installato all'Osservatorio Astrofisico di Byurakan in Armenia, da lui fondato nel 1946 (AMBARTSUMIAN 2000).

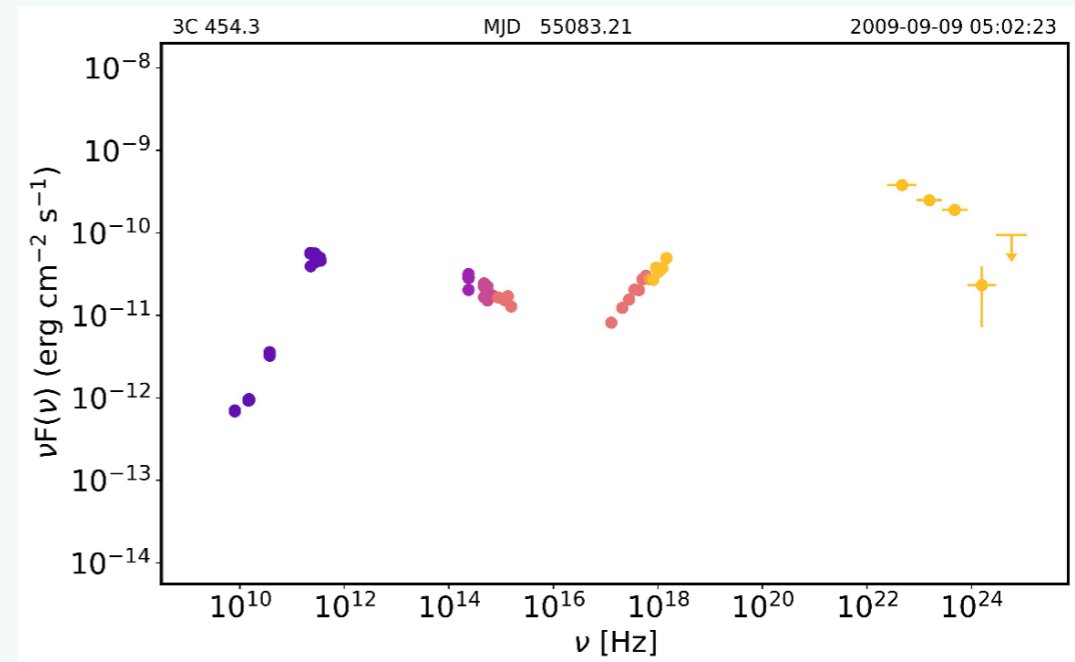
# New data

**MMDC is an innovative platform that facilitates comprehensive research on blazars by building and analyzing multiwavelength Spectral Energy Distributions (SEDs).**

*Blazars are a subtype of active galactic nuclei with relativistic jets directed almost exactly towards Earth. As powerful, long-lived extragalactic objects, they offer a unique window into the processes around supermassive black holes and the distant universe.*

- ✓ Originating near supermassive black holes, the relativistic jets of blazars produce intense emissions spanning from radio frequencies to gamma-rays.
- ✓ The broadband emission from blazars shows high variability across the electromagnetic spectrum, often manifesting on timescales of days or hours and displaying complex behavior.
- ✓ High-energy neutrino detection from blazars confirms hadronic processes within their jets, where protons interact with matter or radiation to create neutrinos. This makes blazars key targets for multi-messenger studies.

In this database, users can search for and construct detailed multi-wavelength SEDs of blazars. SEDs are interactively visualized, allowing data manipulation and time filtering. The SEDs are constructed by combining archival data from various catalogs (obtained through the [VOU-Blazar](#) tool) with time-resolved data across IR, optical, UV, X-ray, and gamma-ray bands.



## IR and optical/UV data

- IR Data: WISE/NEOWISE (3.4, 4.6, 12, 22  $\mu$ m)
- Optical Data: ASAS-SN (V, g-band), ZTF (g, r, i), UVOT (V, B, U)
- UV Data: UVOT (W1, M2, W2)

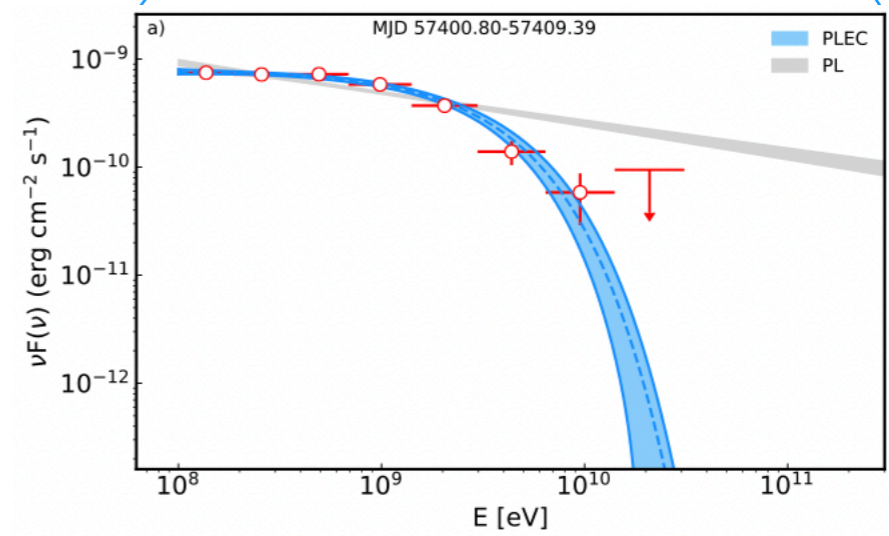
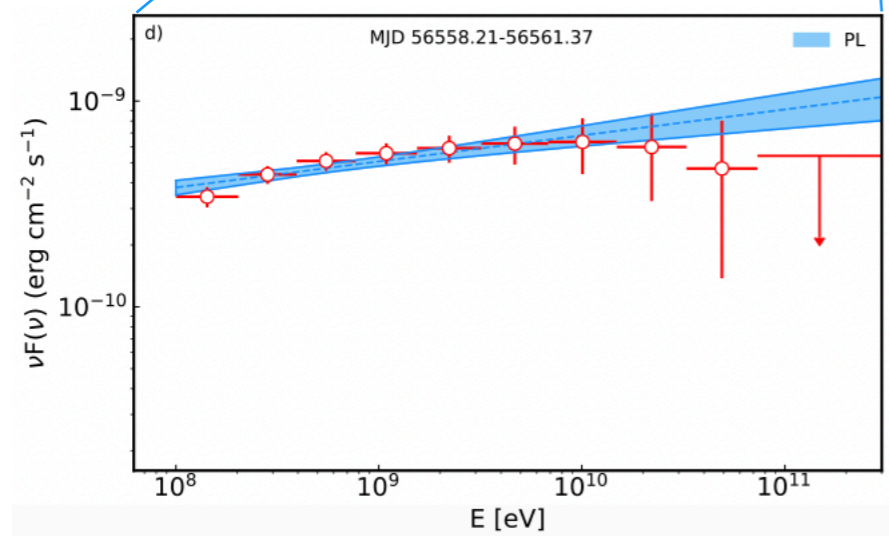
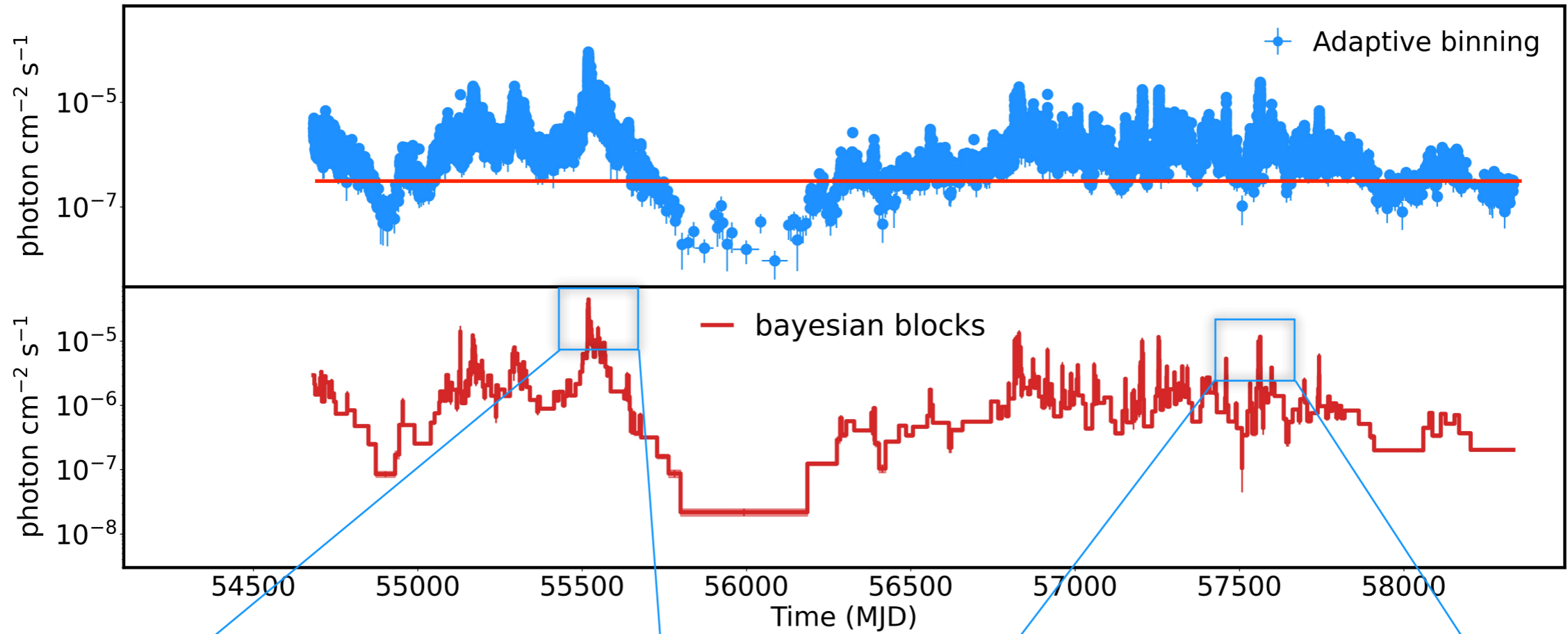
## X-ray data

- 0.3-10 keV from each XRT observation (ObsID)
- 3.0-79 keV from each NuSTAR observation (ObsID)

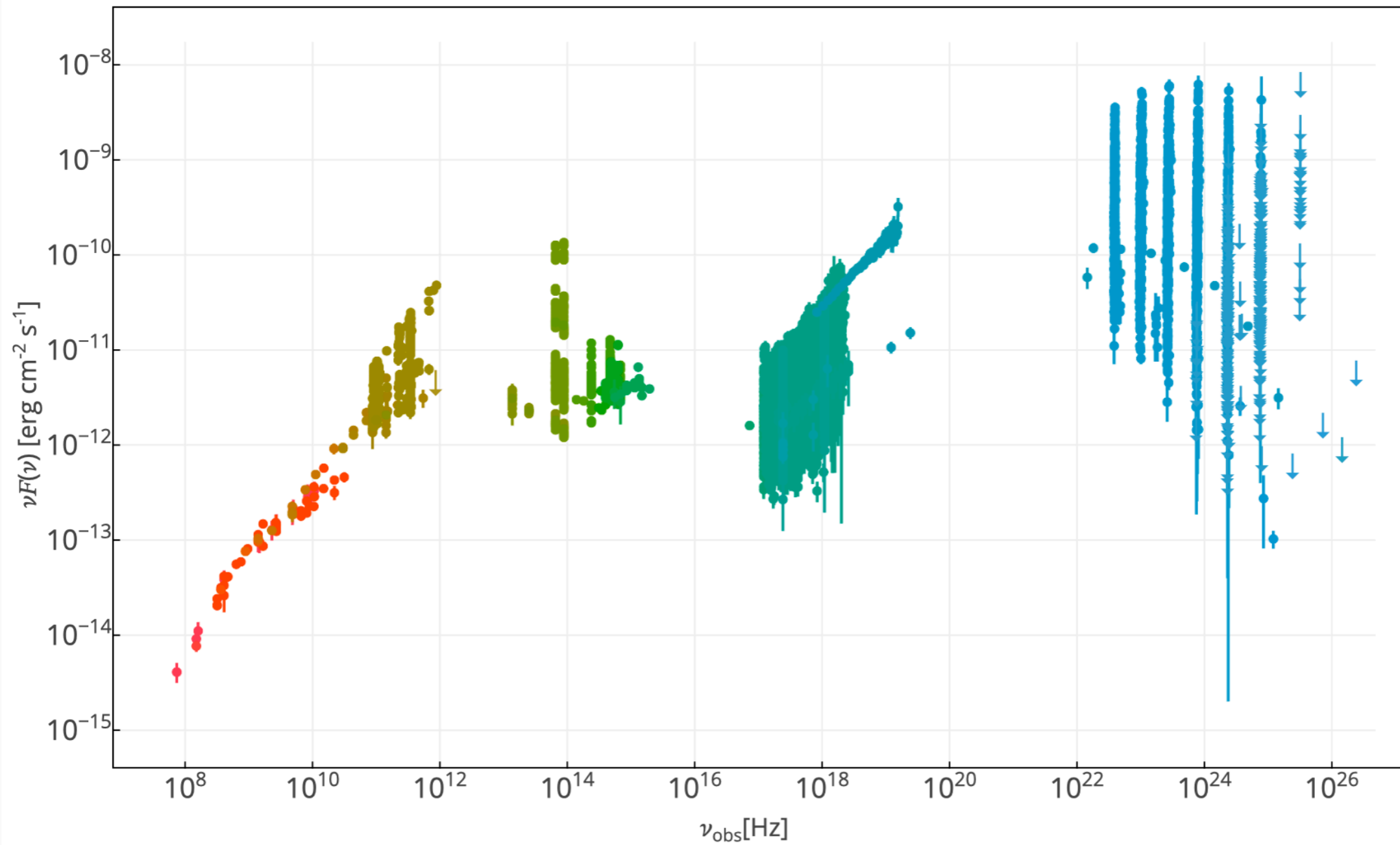
## Gamma-ray data

- Adaptively binned light curve computed for the period from 2008 to 2023.
- Divided into piece-wise constant Bayesian blocks.
- Spectral analysis applied to each interval.

# Gamma-ray data







> Time Filtering

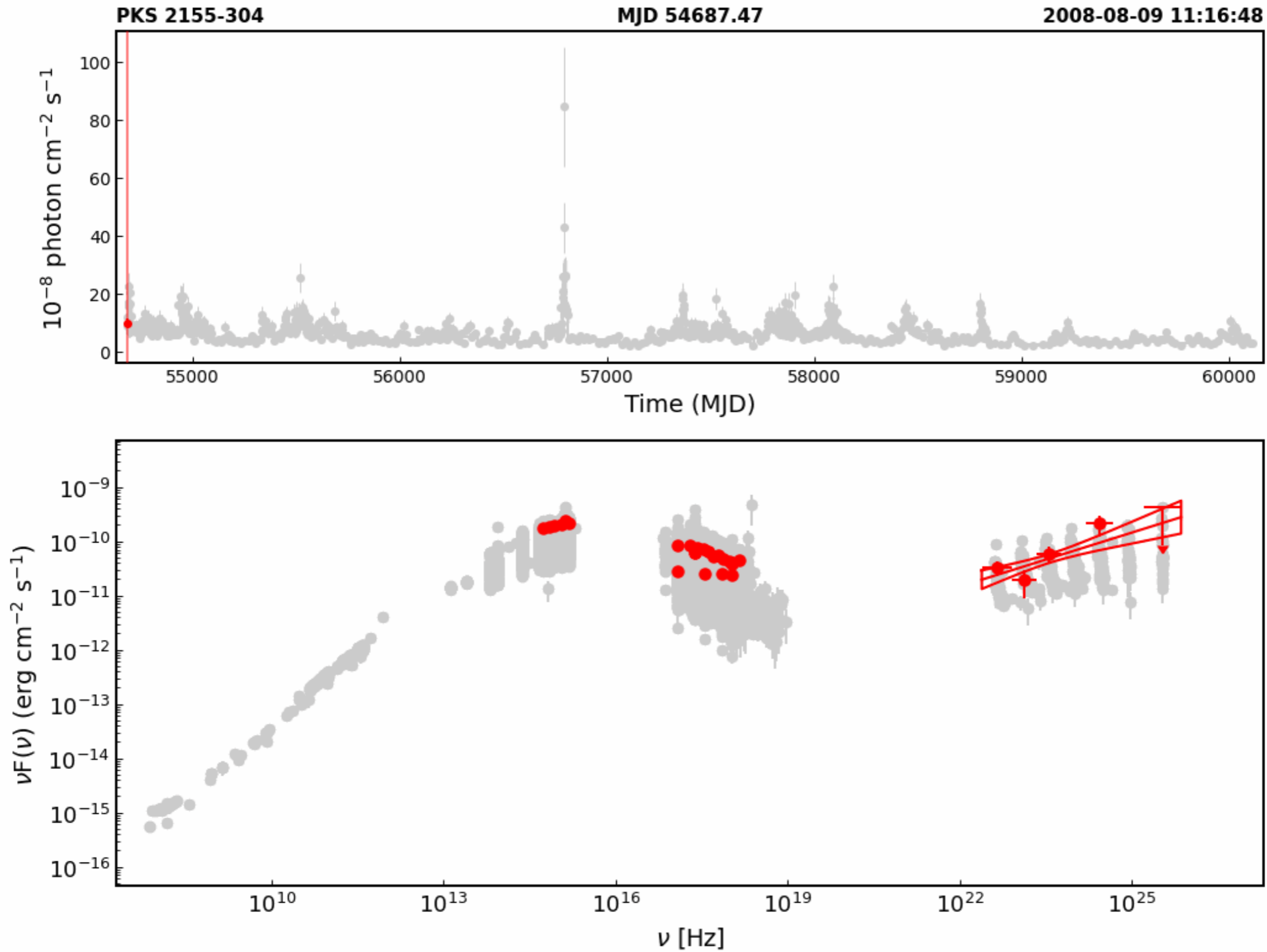
> Plot Options

> Energy Band

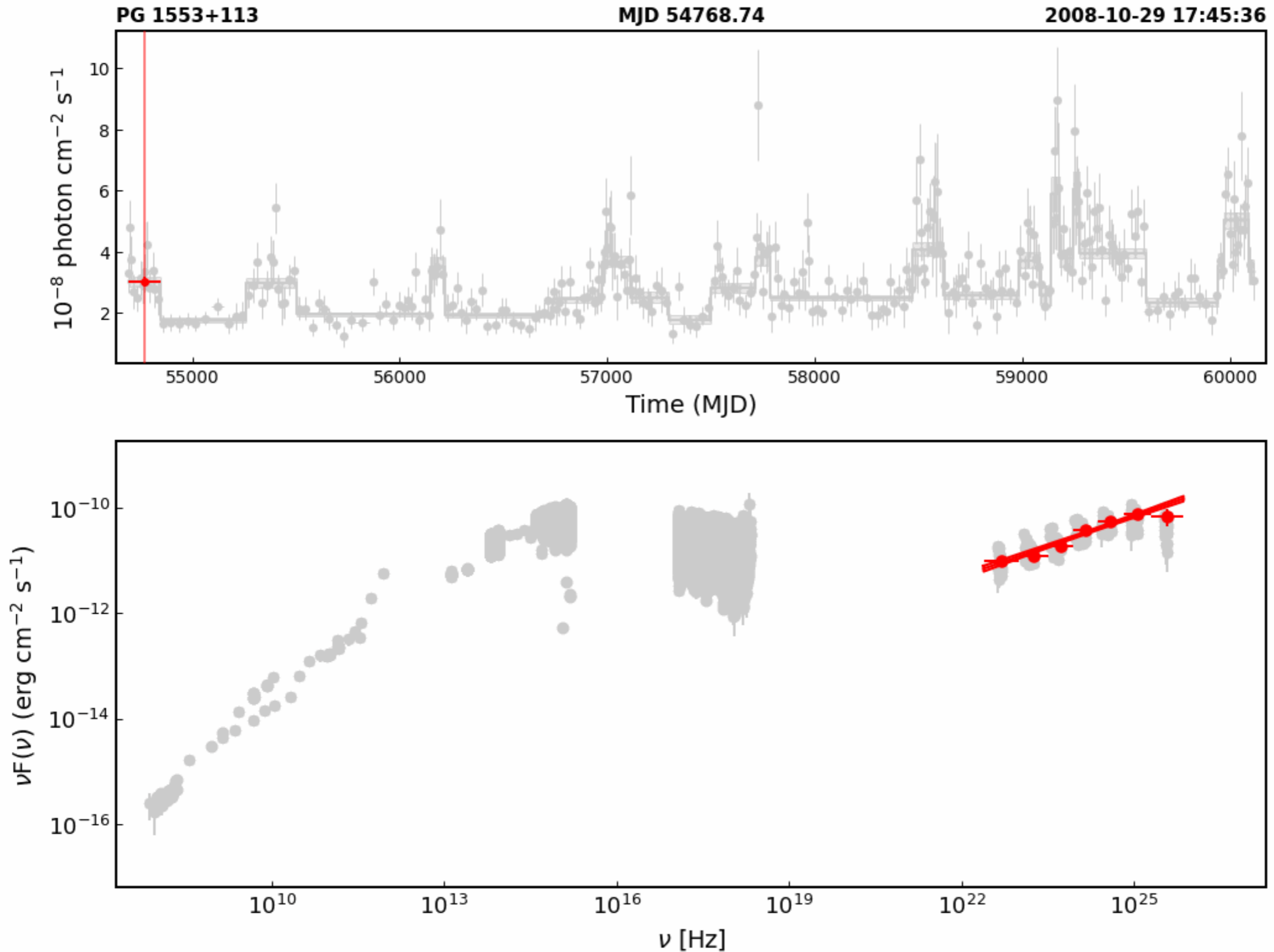
- >  Radio
- >  Infrared
- >  Optical
- >  Ultraviolet
- >  X-ray
- >  Gamma ray



# SED/LC animation

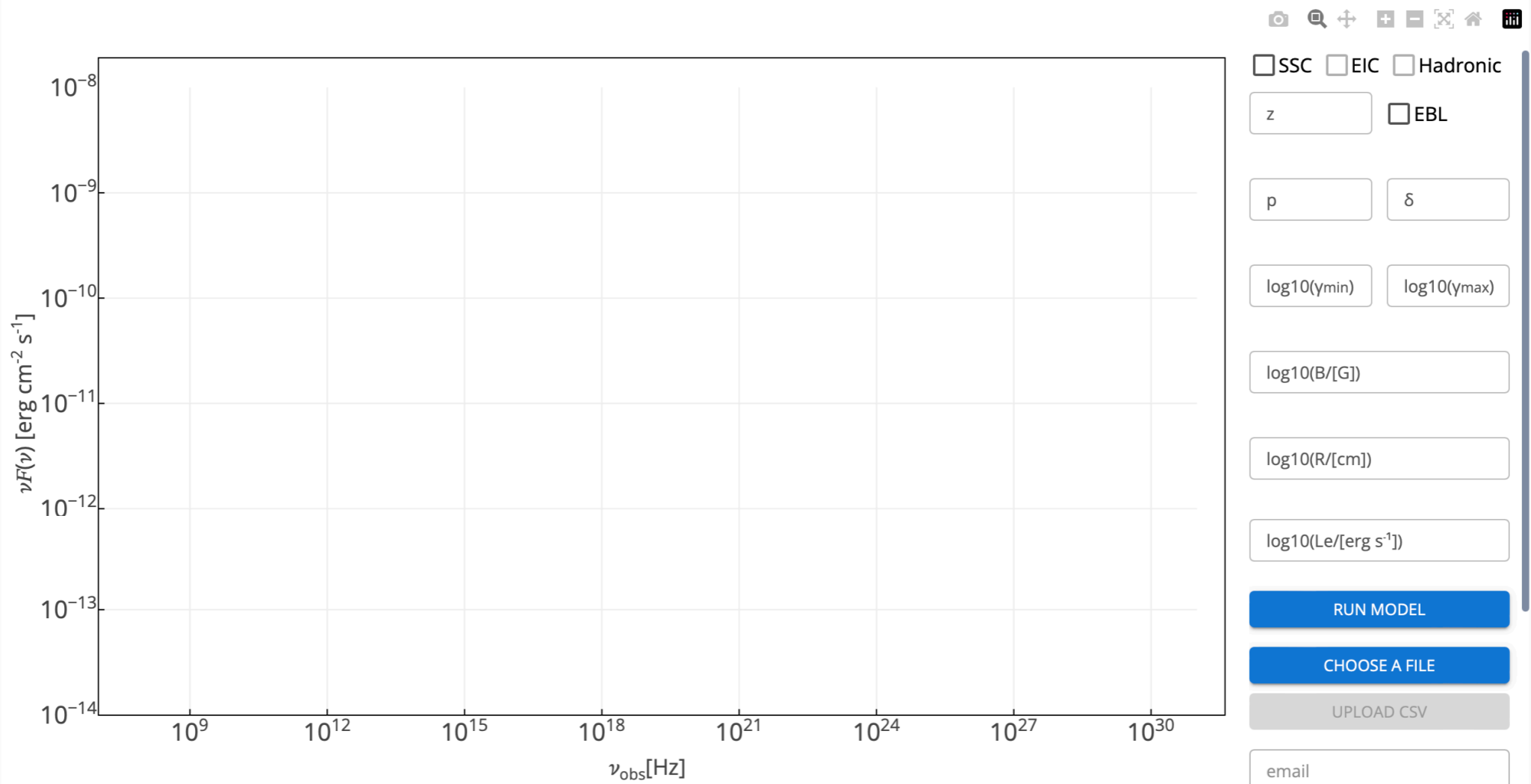


# SED/LC animation



# Modeling

## Modeling blazar broadband emission with convolutional neural networks



# Modeling

Monthly Notices

of the

ROYAL ASTRONOMICAL SOCIETY



MNRAS **509**, 2102–2121 (2022)

Advance Access publication 2021 September 29

<https://doi.org/10.1093/mnras/stab2688>

## Time-dependent lepto-hadronic modelling of the emission from blazar jets with *SOPRANO*: the case of TXS 0506 + 056, 3HSP J095507.9 + 355101, and 3C 279

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Typeset using L<sup>A</sup>T<sub>E</sub>X default style in AASTeX631

Modeling blazar broadband emission with convolutional neural networks - I. Synchrotron self-Compton model

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A. CASOTTO,<sup>8</sup> AND A. PE'ER<sup>1</sup>

# Electron energy distribution vs injection

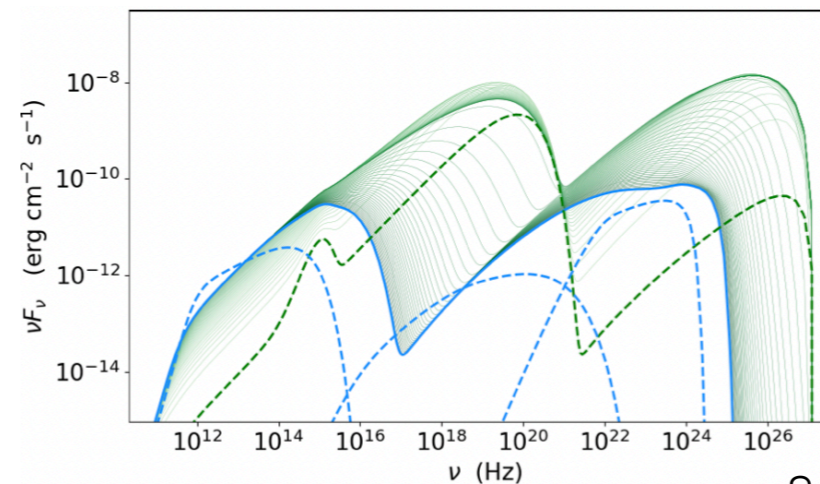
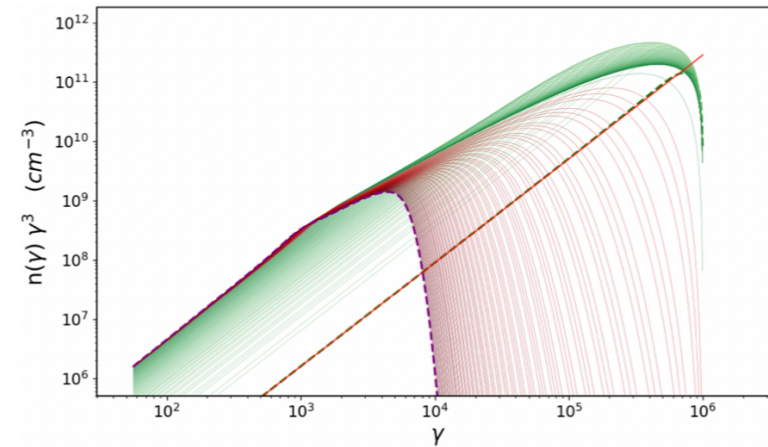
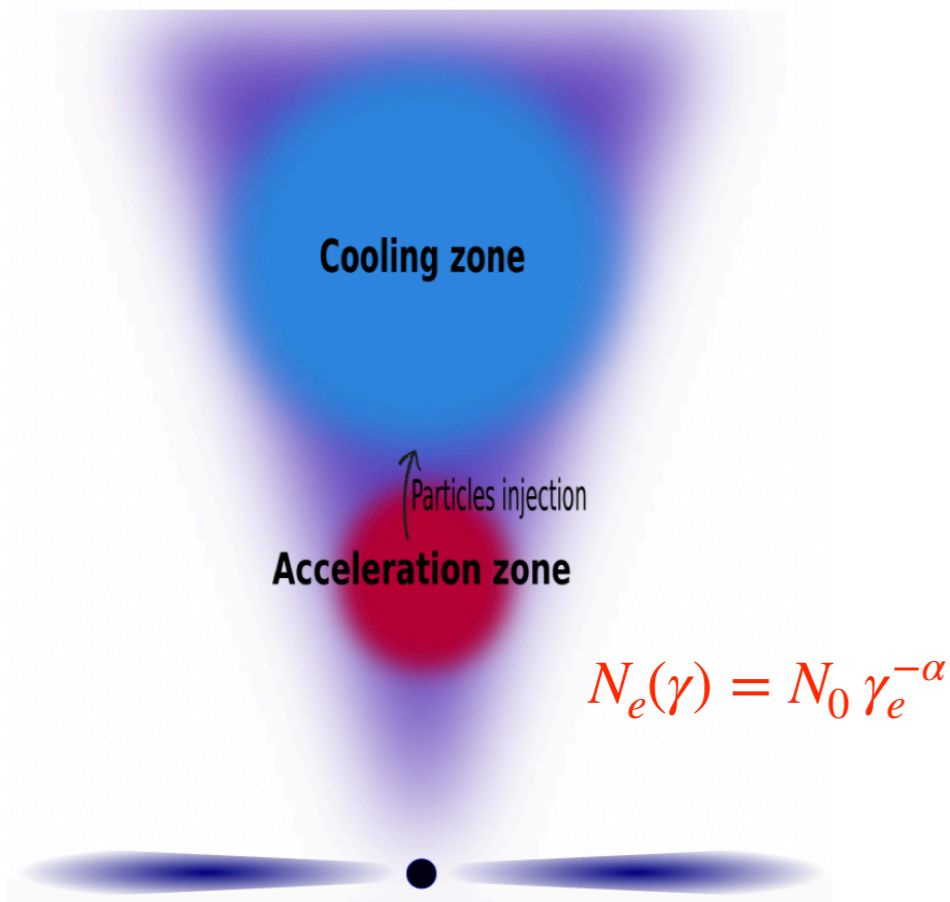
```
[2]: # electron energy distribution
n_e = BrokenPowerLaw(
    k=1e-8 * u.Unit("cm-3"),
    p1=2.02,
    p2=3.43,
    gamma_b=1e5,
    gamma_min=500,
    gamma_max=1e6,
)

# initialise the sherpa model
ssc_model = SynchrotronSelfComptonModel(n_e, backend="sherpa")
```

```
from jetset.obs_constrain import ObsConstrain
from jetset.model_manager import FitModel
sed_obspar=ObsConstrain(beaming=25,
                        B_range=[0.001,0.1],
                        distr_e='lppl',
                        t_var_sec=3*86400,
                        nu_cut_IR=1E12,
                        SEDShape=my_shape)
```

```
prefit_jet=sed_obspar.constrain_SSC_model(electron_distribution_log_v)
prefit_jet.save_model('prefit_jet.pkl')
```

$$\frac{\partial N_e(\gamma, t)}{\partial t} = \frac{\partial}{\partial \gamma}(\dot{\gamma}N_e(\gamma, t)) - \frac{N_e(\gamma, t)}{t_{esc}} + Q(\gamma, t)$$



# THE MODEL: SYNCHROTRON SELF-COMPTON

In the one-zone SSC model, it is assumed that the emission originates from a spherical region of the jet (referred to as a 'blob') with a comoving radius  $R$ , which moves with Lorentz factor  $\Gamma$ . We assume that the observers sees the jet at angle  $1/\Gamma$ , such that the Doppler boost factor  $\delta \equiv \Gamma$ . The magnetic field  $B$  inside this region is assumed to be homogeneous and constant. Electrons, once injected into this region, lose their energy under the effect of the magnetic field as well as by interacting with the local photon fields, ultimately generating the observed broadband spectrum.

Despite the likely presence of protons in the jet, for the SSC model, we assume that only electrons are accelerated and radiate once injected in the radiation zone. The injection function  $Q_e$  is assumed to be a cutoff power-law with index  $p$  for electrons with a Lorentz factor  $\gamma$  larger than a minimum Lorentz factor  $\gamma_{\min}$ , such that

$$Q_e = \begin{cases} Q_{e,0} \gamma^{-p} \exp\left(-\frac{\gamma}{\gamma_{\max}}\right) & \gamma \geq \gamma_{\min}, \\ 0 & \text{otherwise.} \end{cases} \quad (1)$$

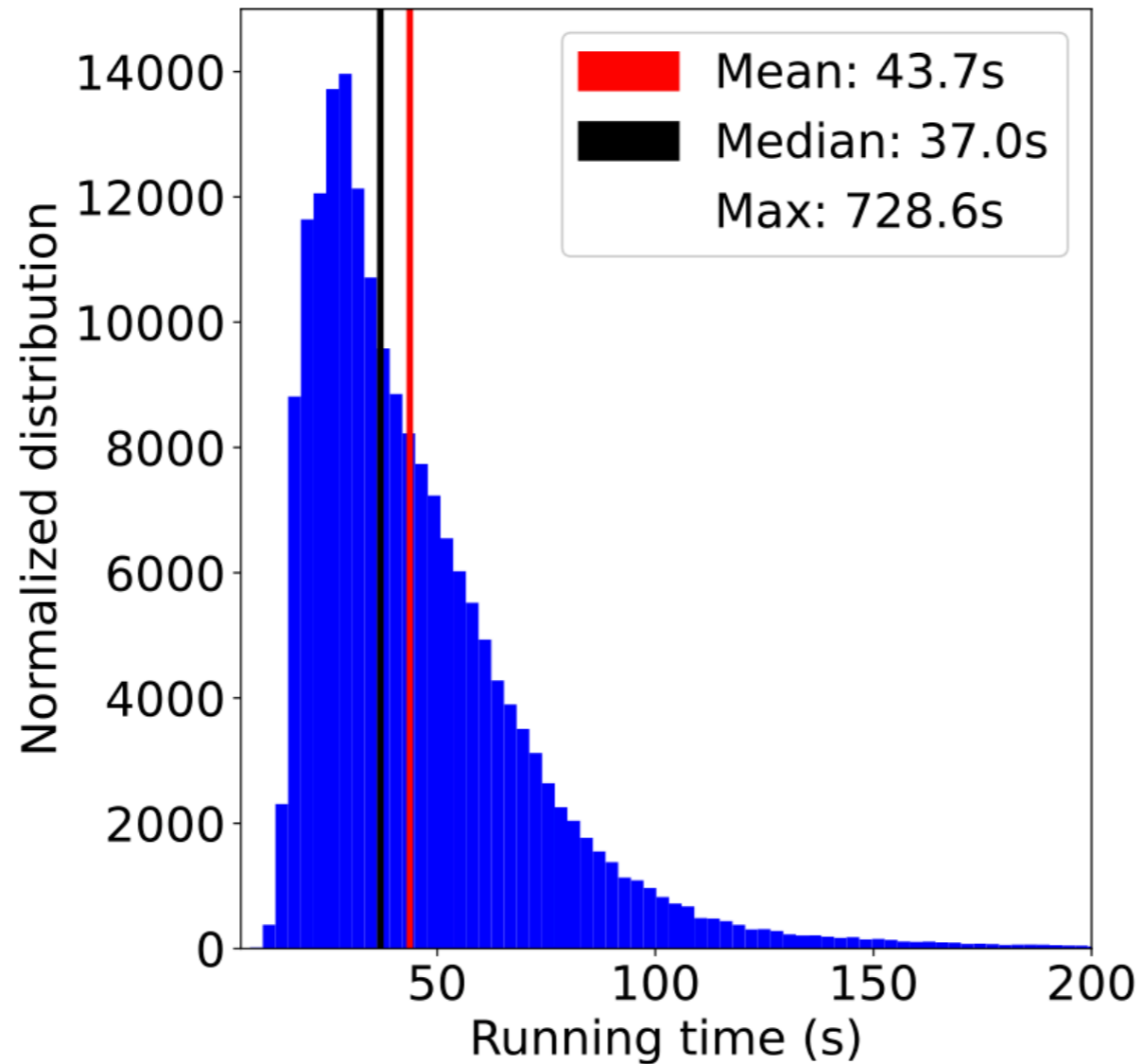
where  $\gamma_{\max}$  is the cutoff electron Lorentz factor. The normalization  $Q_{e,0}$  is set so that the electron luminosity  $L_e$  is determined by

$$L_e = \pi R^2 \delta^2 m_e c^3 \int_1^{\infty} \gamma Q_e d\gamma, \quad (2)$$

where  $m_e$  is the electron rest mass and  $c$  is the speed of light. The temporal evolution of the electron distribution is obtained by solving the Fokker-Planck diffusion equation, while the evolution of photons is described by an integro-differential equation. We label the distribution function of photons by  $N_\gamma$ , and that of electrons by  $N_e$ . With the photon energy denoted as  $x$ , the kinetic equations are

$$\begin{cases} \frac{\partial N_e}{\partial t}(\gamma) = \frac{N_e}{t_{\text{esc}}} + \frac{\partial}{\partial \gamma} [(C_{\text{IC}} N_\gamma + C_{\text{sync}}) N_e \times] + Q_{\gamma\gamma \rightarrow e^+e^-}, \\ \frac{\partial N_\gamma}{\partial t}(x) = \frac{N_\gamma}{t_{\text{esc}}} + Q_{\text{sync}} + R_{\text{IC}} N_\gamma - S_{\gamma\gamma \rightarrow e^+e^-}, \end{cases} \quad (3)$$

# Computational time



$$37 \times 15000 / 3600 / 24 = 6.4$$

# Table model

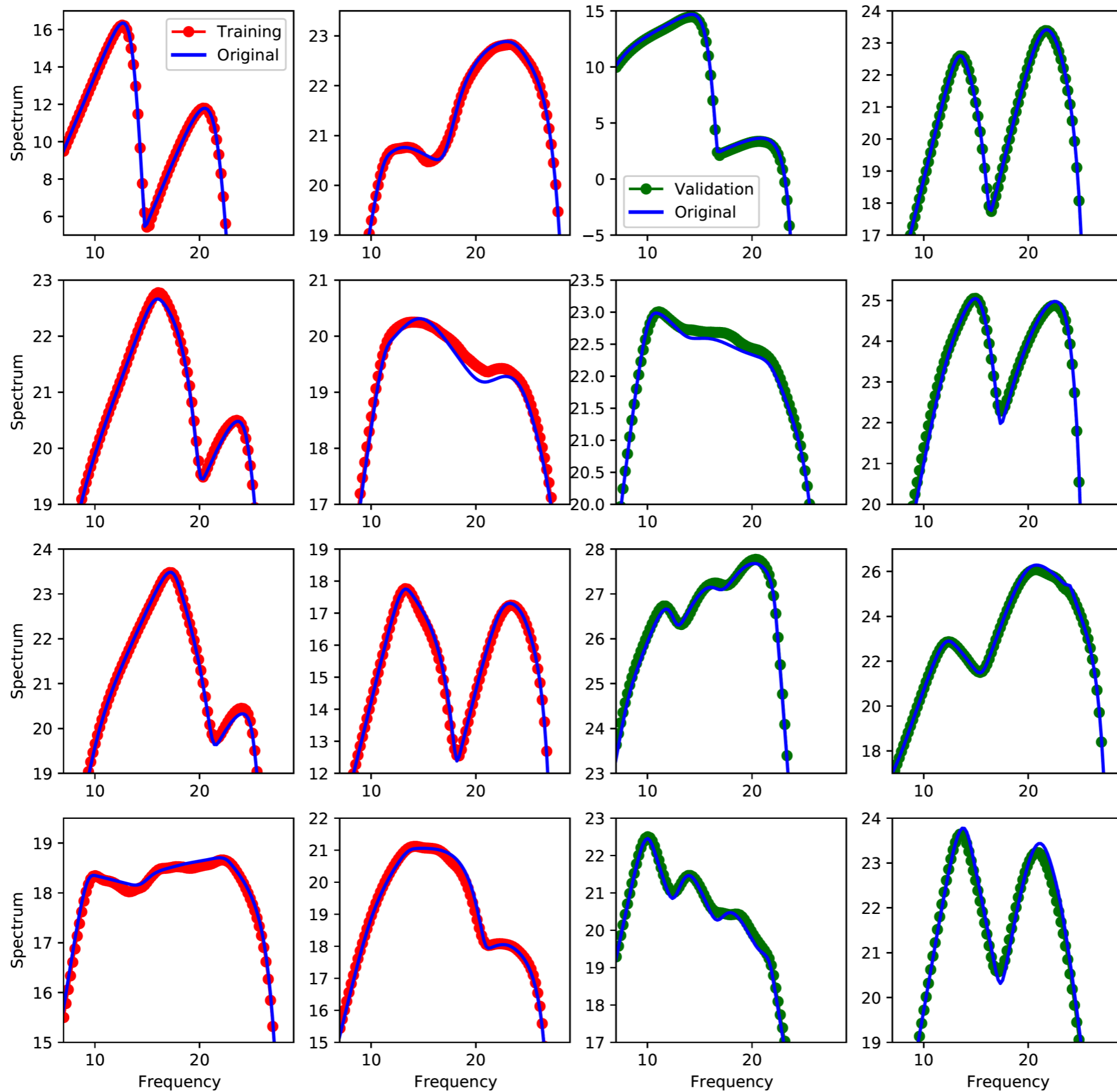
Parameter	Units	Symbol	Minimum	Maximum	Type of distribution
Doppler boost	-	$\delta$	3	50	Linear
Blob radius	cm	R	$10^{15}$	$10^{18}$	Logarithmic
Minimum electron injection Lorentz factor	-	$\gamma_{\min}$	$10^{1.5}$	$10^5$	Logarithmic
Maximum electron injection Lorentz factor	-	$\gamma_{\max}$	$10^2$	$10^8$	Logarithmic
Injection index	-	$p$	1.8	5	Linear
Electron luminosity	erg.s <sup>-1</sup>	$L_e$	$10^{42}$	$10^{48}$	Logarithmic
Magnetic field	G	$B$	$10^{-3}$	$10^2$	Logarithmic

**Table 1.** Characteristics of the dataset. For each parameter, we recall its unit (if any) and symbol, and we provide its range and the distribution of the discrete parameter values. The total number of spectra is set to  $2 \times 10^5$ .

Simulation of  $2 \times 10^5$  spectra



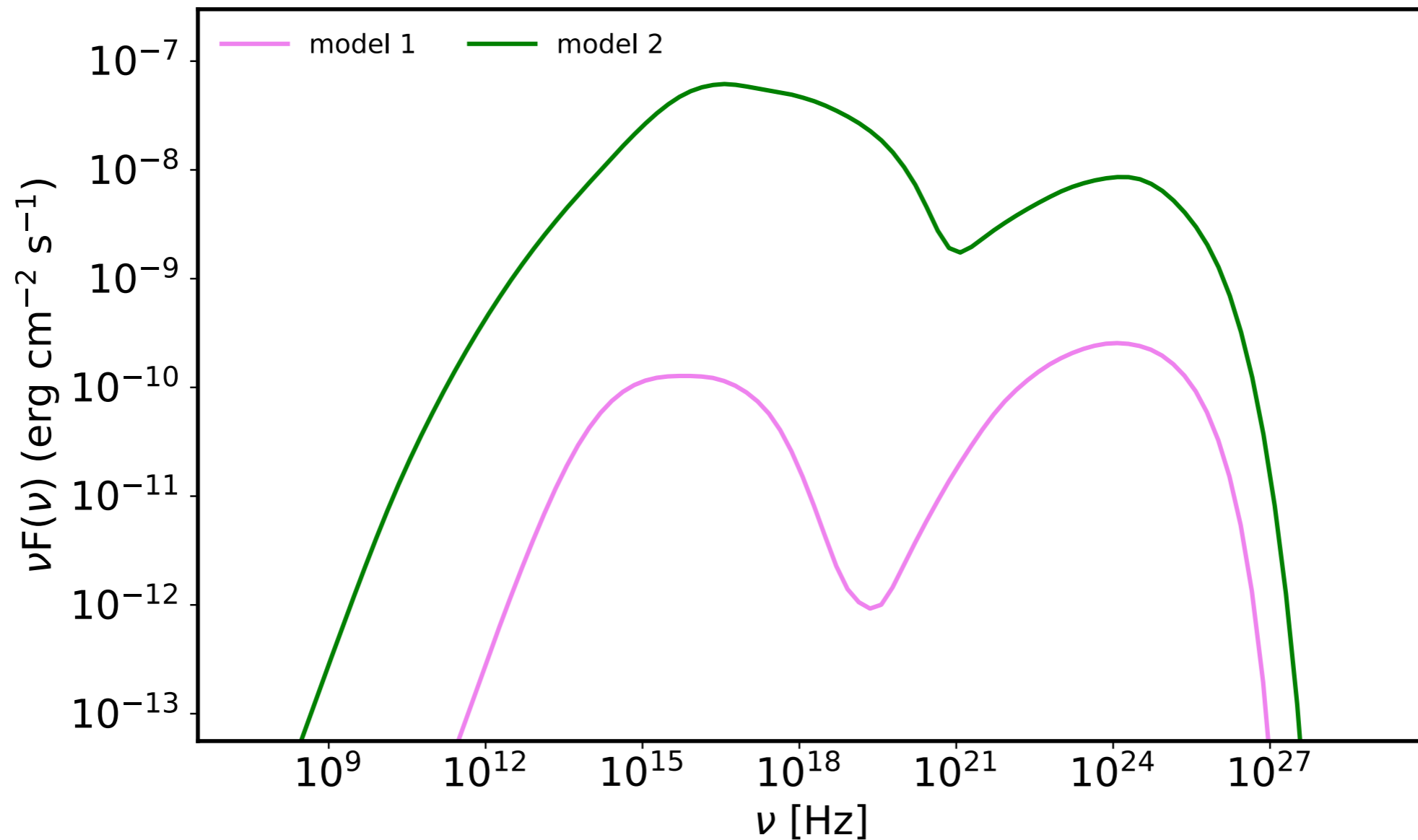
# Comparison between the spectra computed by the CNN (dotted line) and by SOPRANO



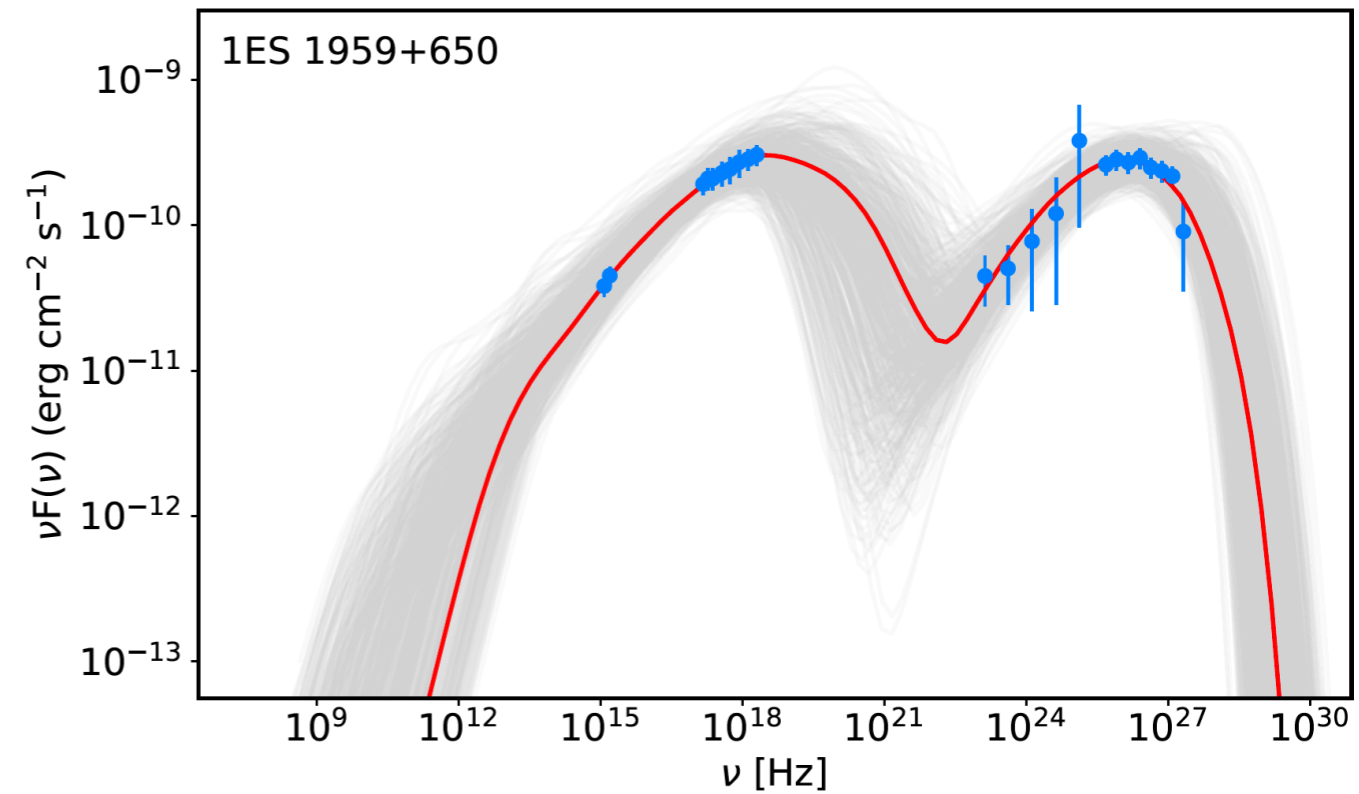
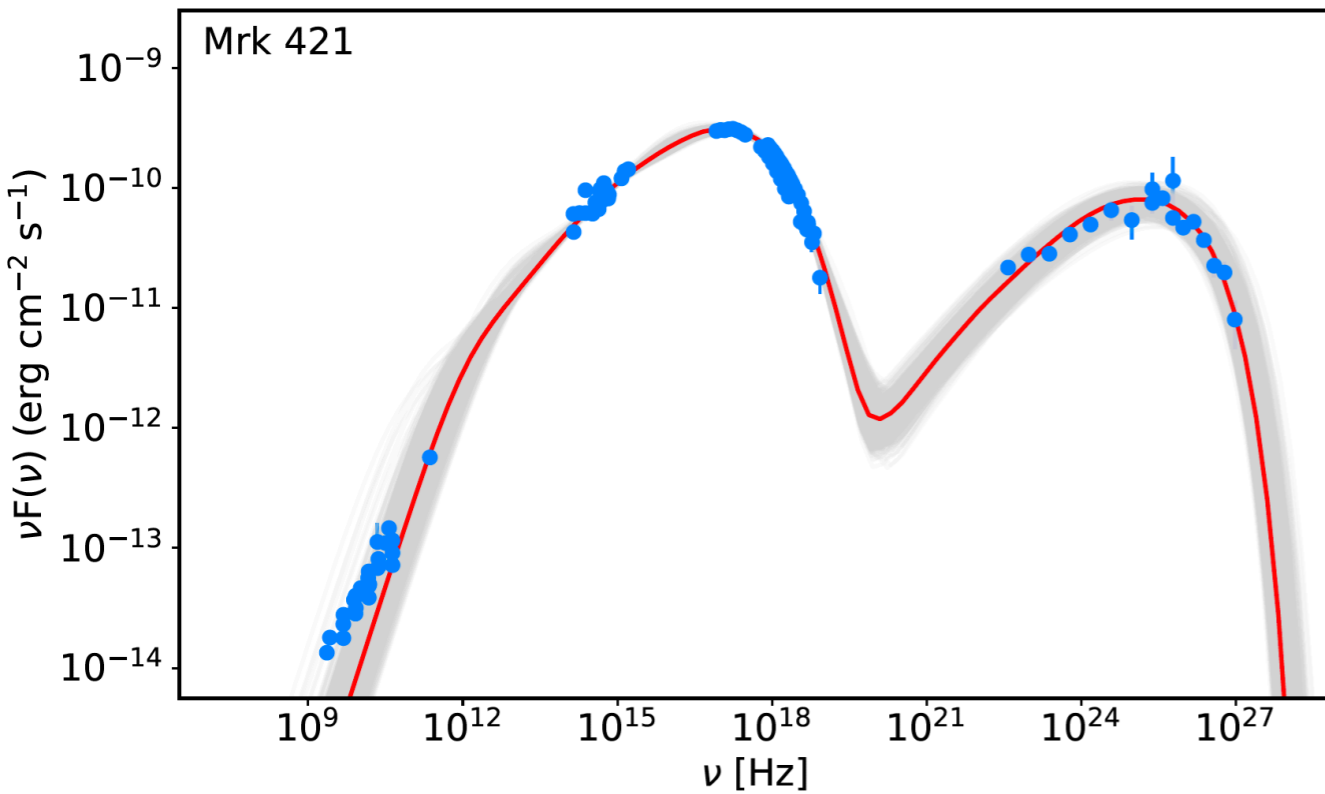
# CNN

```
param = {"log_B": -0.5, "log_electron_luminosity": 44.0, "log_gamma_cut": 4.4, "log_gamma_min": 3.2, "log_radius": 16, "lorentz_factor": 15, "spectral_index": 2.0 }
```

```
param2 = {"log_B": 1, "log_electron_luminosity": 45.0, "log_gamma_cut": 4.8, "log_gamma_min": 3.4, "log_radius": 16, "lorentz_factor": 25, "spectral_index": 2.3 }
```



# SED fitting



Parameters	Mrk 421	1ES 1959+650
$p$	$2.16 \pm 0.08$	$2.26 \pm 0.16$
$\log_{10}(\gamma_{\max})$	$4.87 \pm 0.16$	$6.41 \pm 0.45$
$\log_{10}(\gamma_{\min})$	$2.49 \pm 0.22$	$3.20 \pm 0.69$
$\delta$	$31.01 \pm 8.08$	$22.49 \pm 9.54$
$\log_{10}(B/[G])$	$-1.17 \pm 0.28$	$-1.62 \pm 0.38$
$\log_{10}(R/[cm])$	$16.43 \pm 0.44$	$16.82 \pm 0.38$
$\log_{10}(L_e/[erg s^{-1}])$	$43.32 \pm 0.18$	$43.71 \pm 0.32$
$\log_{10}(L_B/[erg s^{-1}])$	43.08	42.68
	All parameters free	All parameters free