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A HADRONIC SYNCHROTRON MIRROR MODEL FOR BLAZARS - APPLICATION TO 3C279

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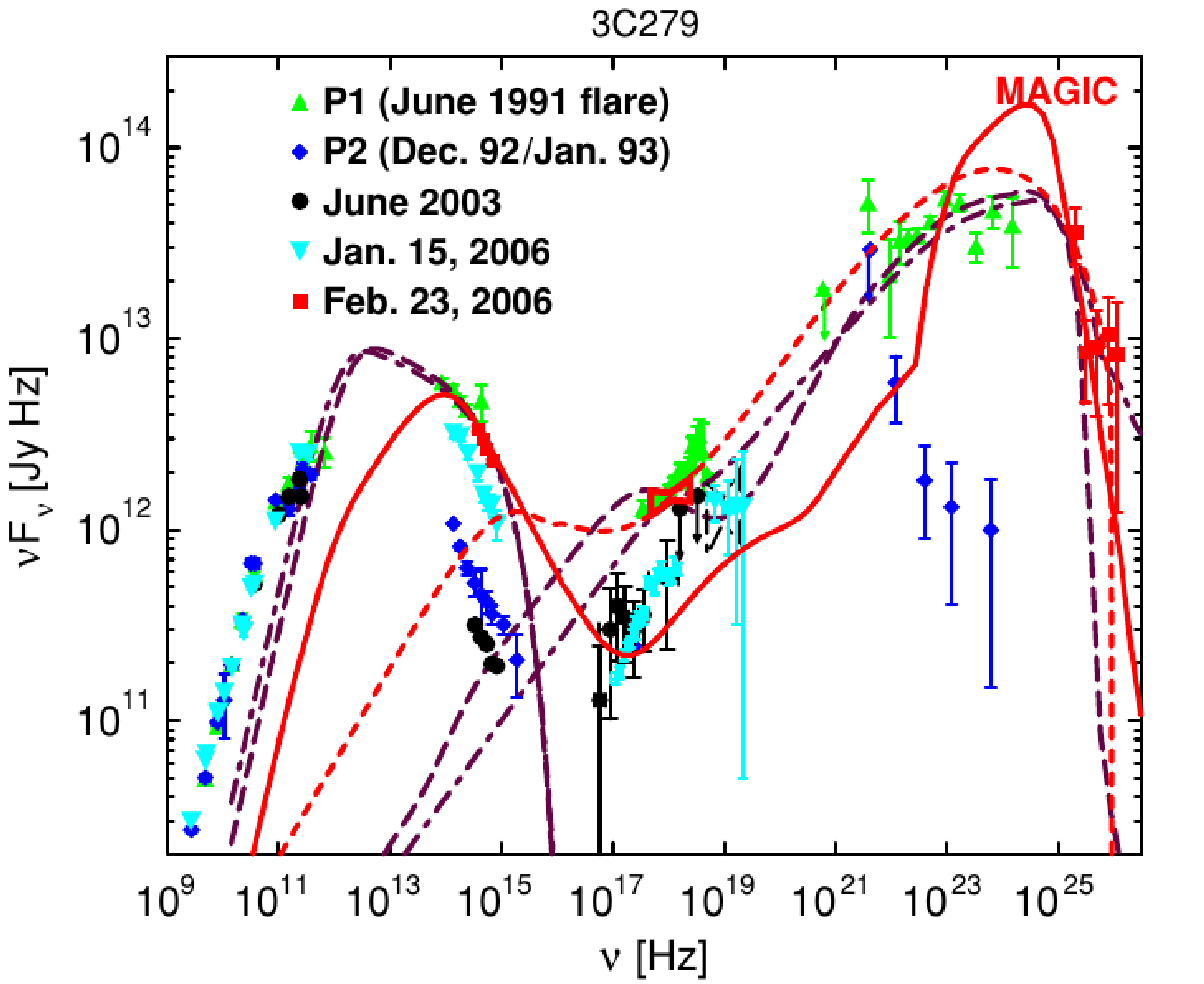
Aim

The motivation behind studying the orphan flares:

- What radiation mechanisms produce orphan TeV flares?
- Are protons accelerated to ultra-relativistic energies in the jets of blazars?
- Are hadronic interactions expected to be associated with the production of very-high-energy neutrinos?
- Why is the variability of 3C 279 sometimes correlated across the electromagnetic spectrum and sometimes not, as seen in other blazars as well?

SEDs



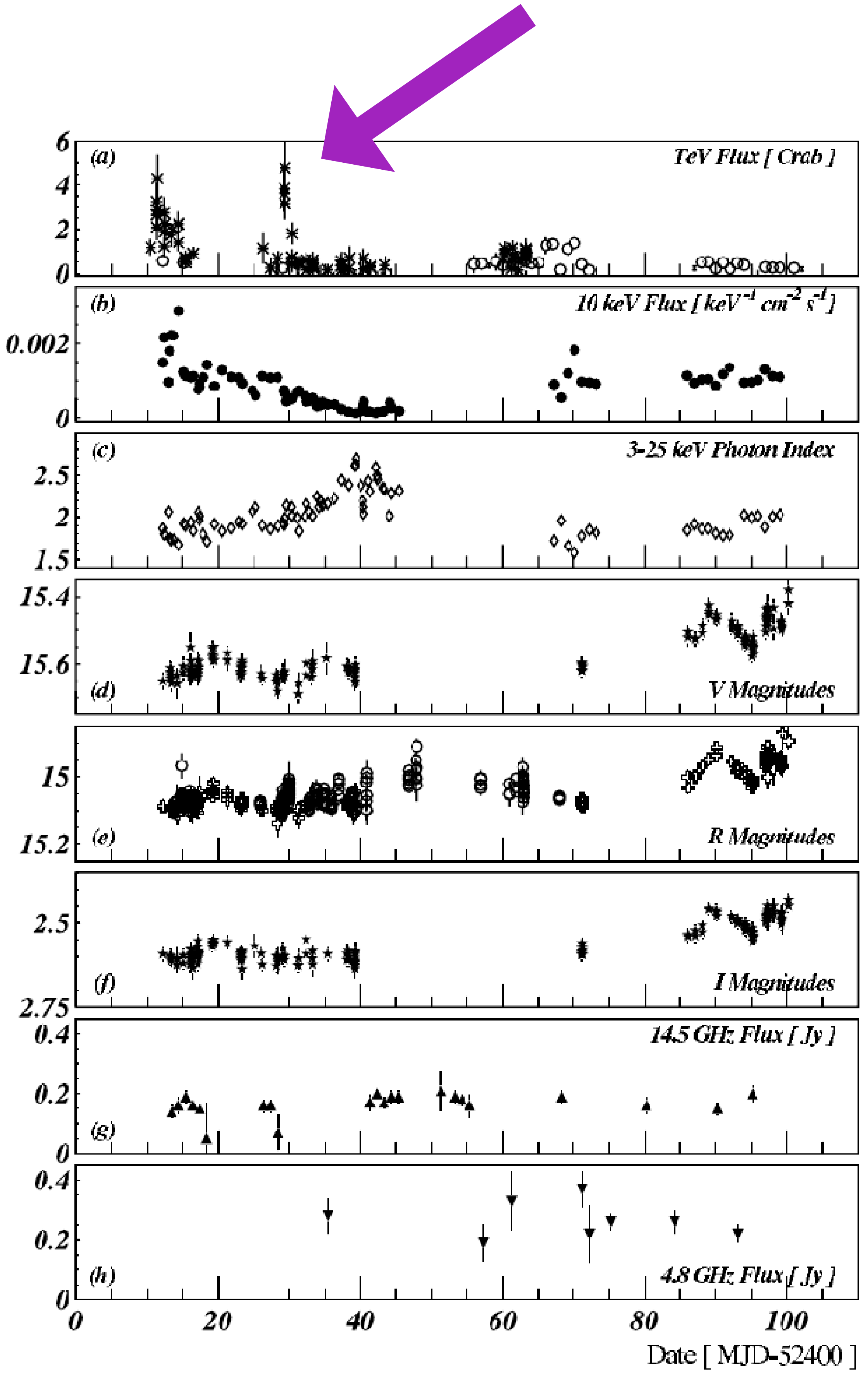
[BÖTTCHER ET AL., 2009]

- SEDs of blazars are characterised by two components
- First Component: Electron Synchrotron radiation
- Second Component: can be leptonic or hadronic:
  - Compton scattering
  - Proton synchrotron radiation
  - Photo-Pion Production

$$p + \gamma \rightarrow p + \pi^0 \rightarrow p + \gamma + \gamma$$
$$or \rightarrow n + \pi^+ \rightarrow n + \mu^+ + \nu_\mu \rightarrow n + e^+ + \nu_\mu + \nu_e + \overline{\nu}_\mu$$

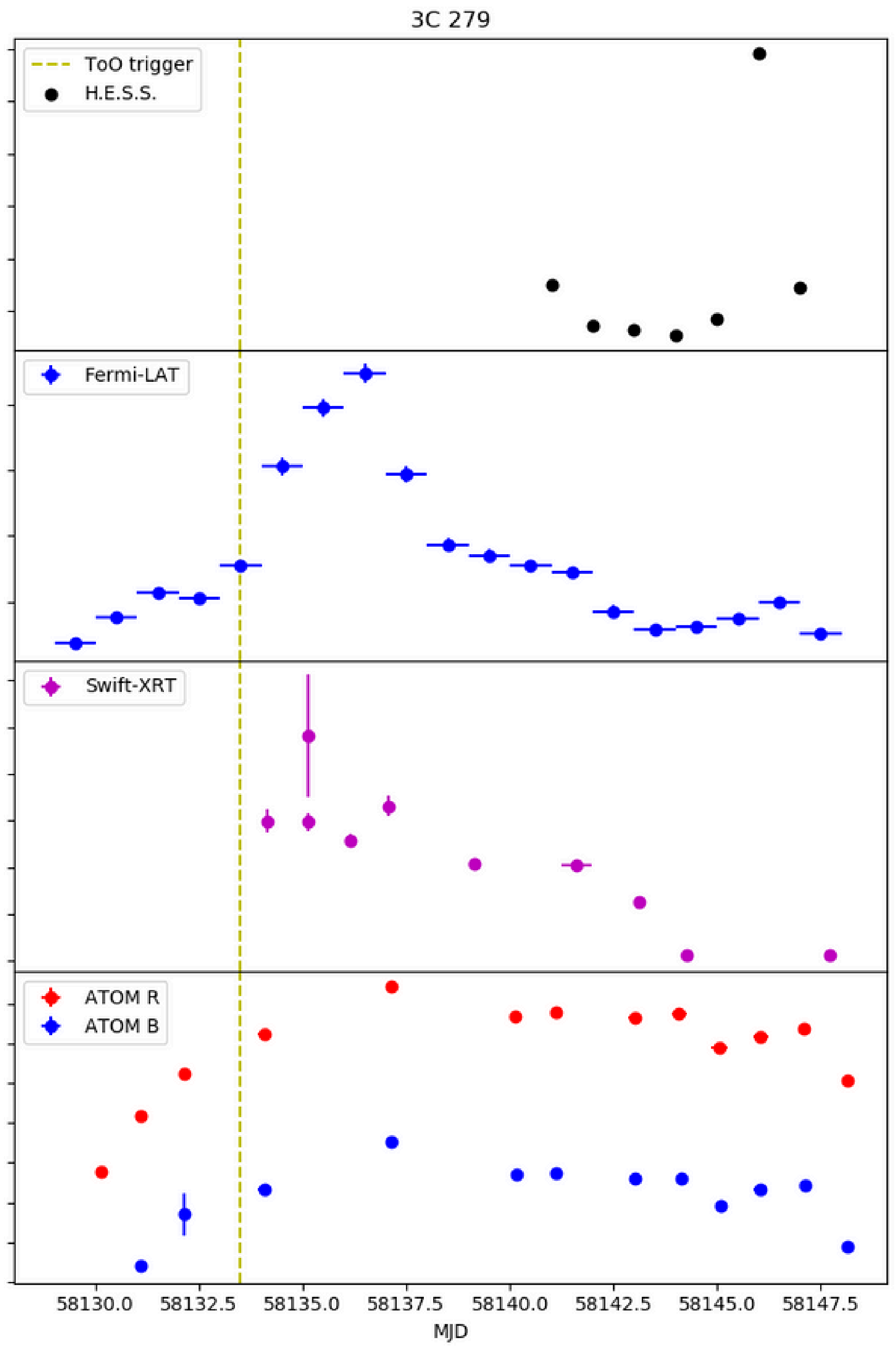
Orphan Flares

- Extreme variability and flaring in different bands
- Flaring in one frequency band unaccompanied by flaring in other bands
- Orphan flares are usually secondary flares



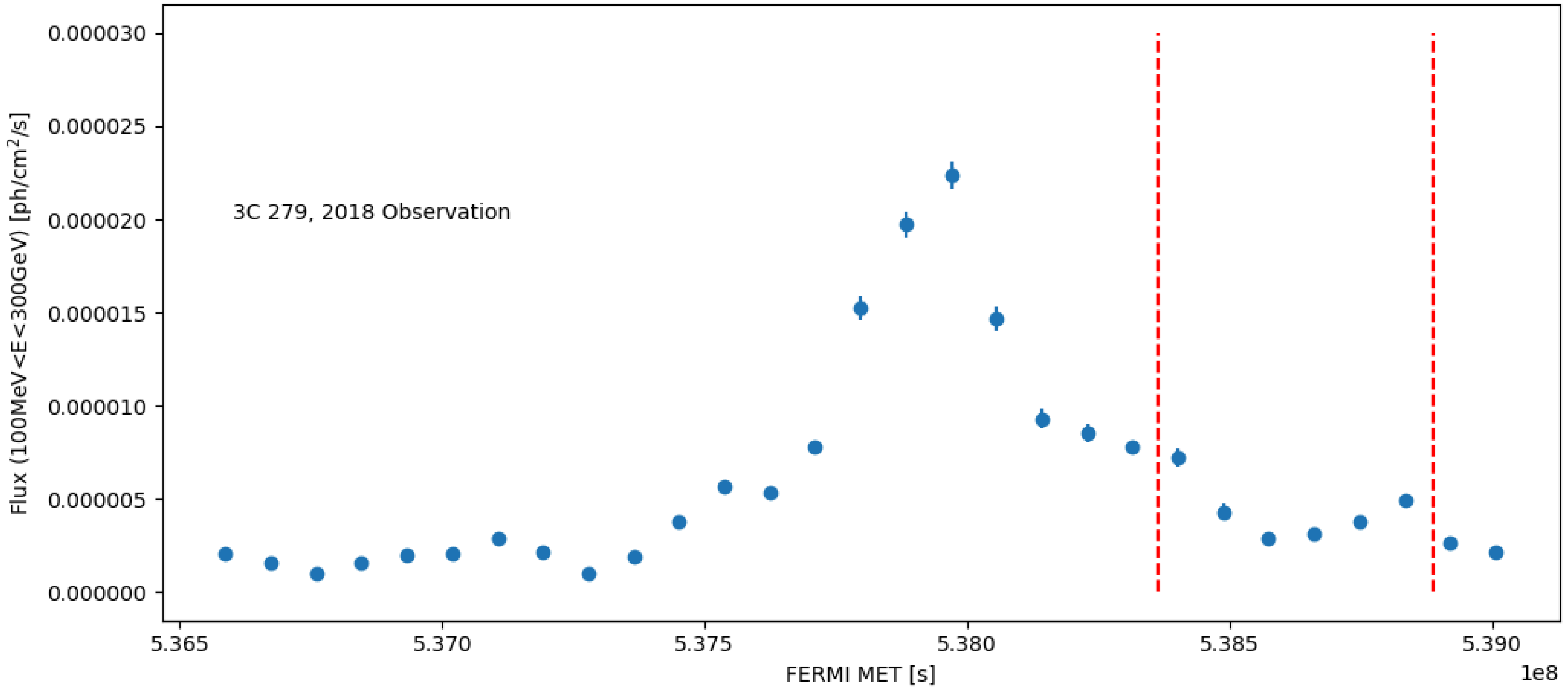
[KRAWCZYNSKI ET AL., 2004]

3C 279 Flare



The Orphan flare - reason for this study

On the 28th of January 2018, eleven days after a Fermi-LAT flare was observed with counterparts in the X-ray and optical bands, an orphan flare in the VHE γ-ray band was detected.



- 3C 279 is a FSRQ at a redshift of z = 0.536.
- H.E.S.S. data in period bounded by the red lines.
- ToO observations by Fermi, HESS, Swift-XRT and ATOM were ongoing triggered by the Fermi-LAT flare.

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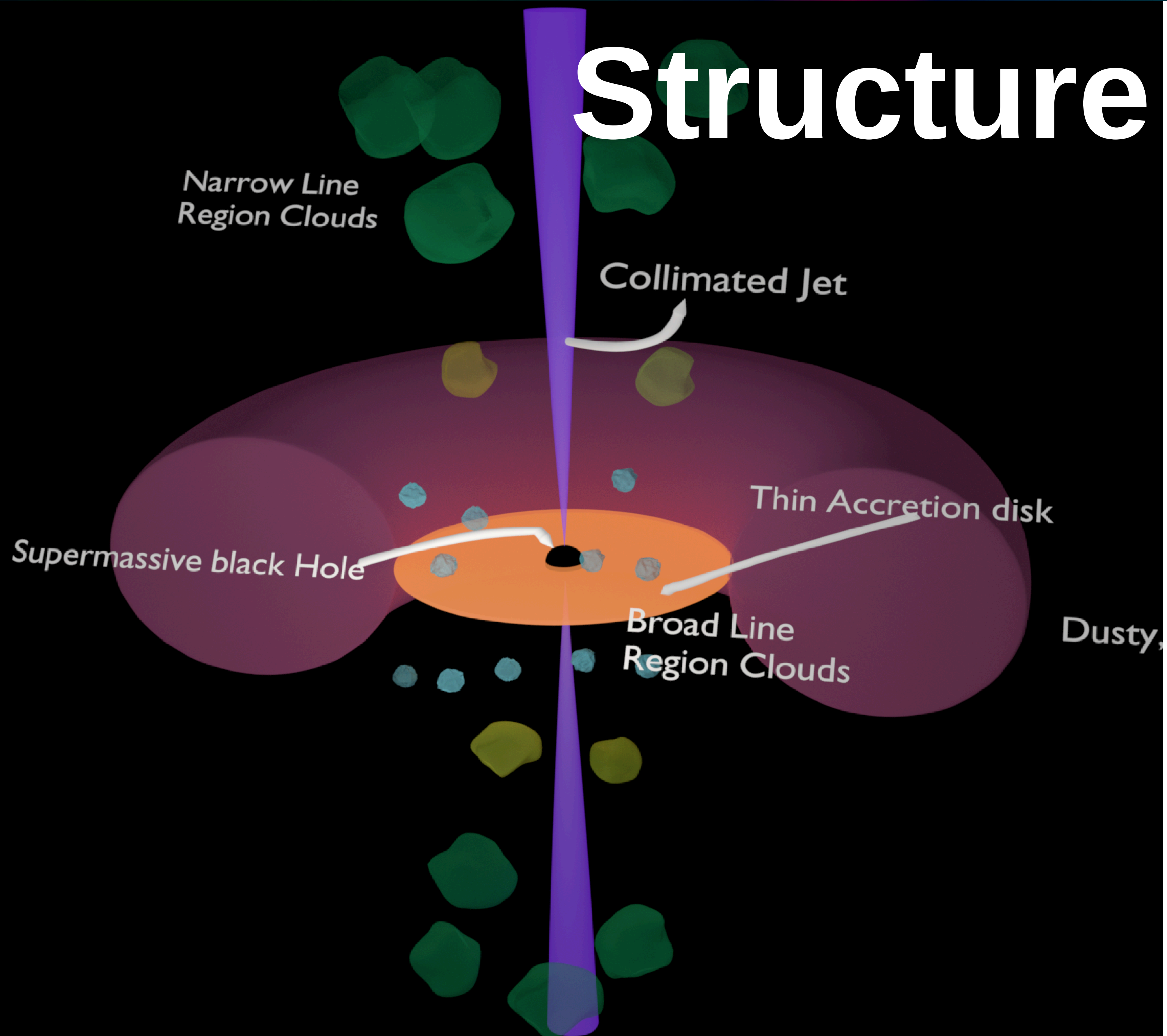
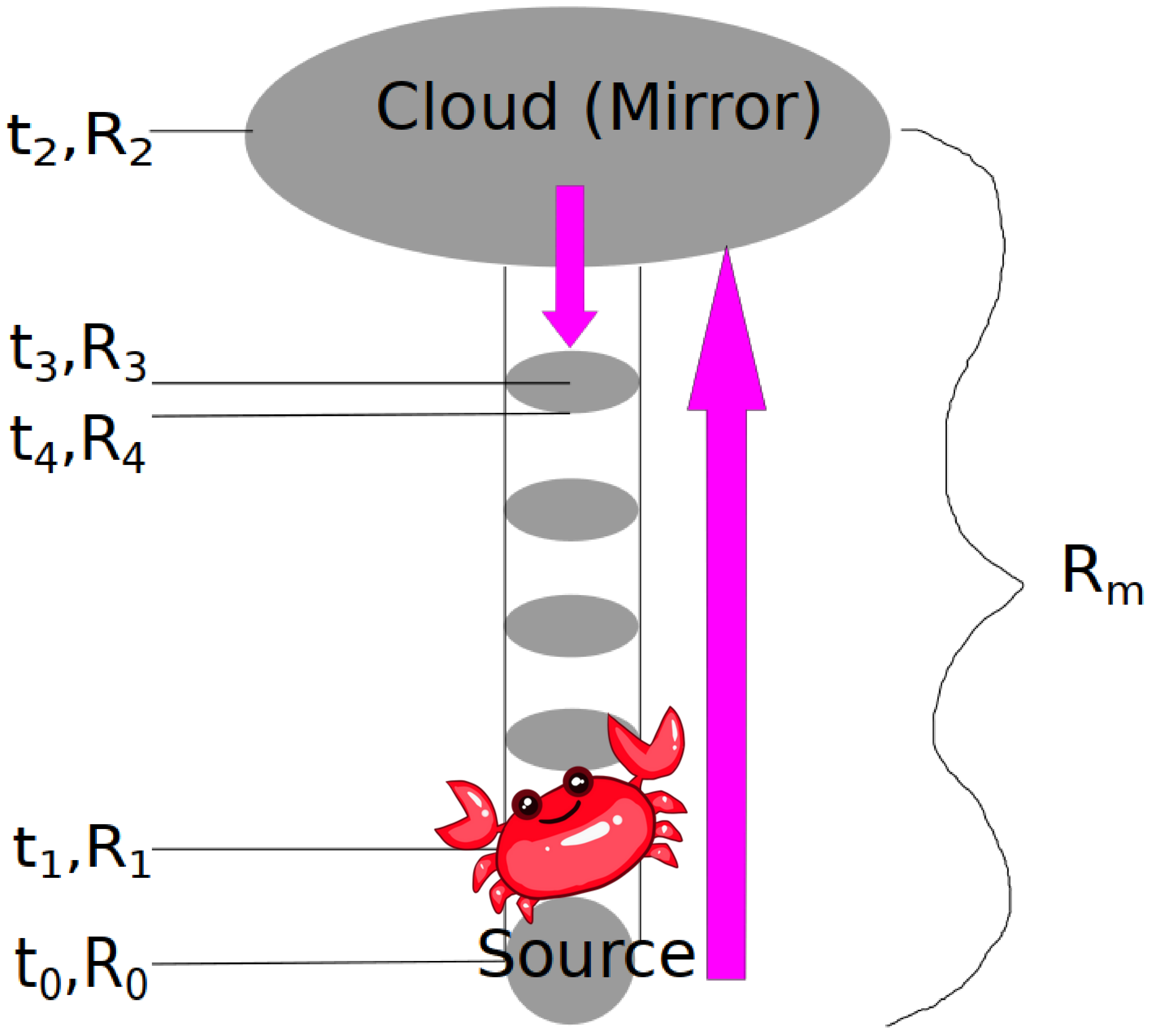
Motivation for Hadronic scenario

Why we chose a hadronic mirror scenario:

- Leptonic SSC models predict quasi-simultaneous flaring in other wavebands like X-ray and optical bands.
- Matter in blazar jets might be dynamically dominated by baryon content [Sikora & Madejski, 2000].
- We consider a hadronic mirror scenario.
- An example as done in [Böttcher, 2005] with the orphan flare of 1ES 1959+650.
- The mirror lowers the threshold of the proton energy required for photo-pion production.
- The orphan flare nature of the 28 January 2018 flare, requires something different from a standard one-zone model.

AGN and hadronic mirror Structure



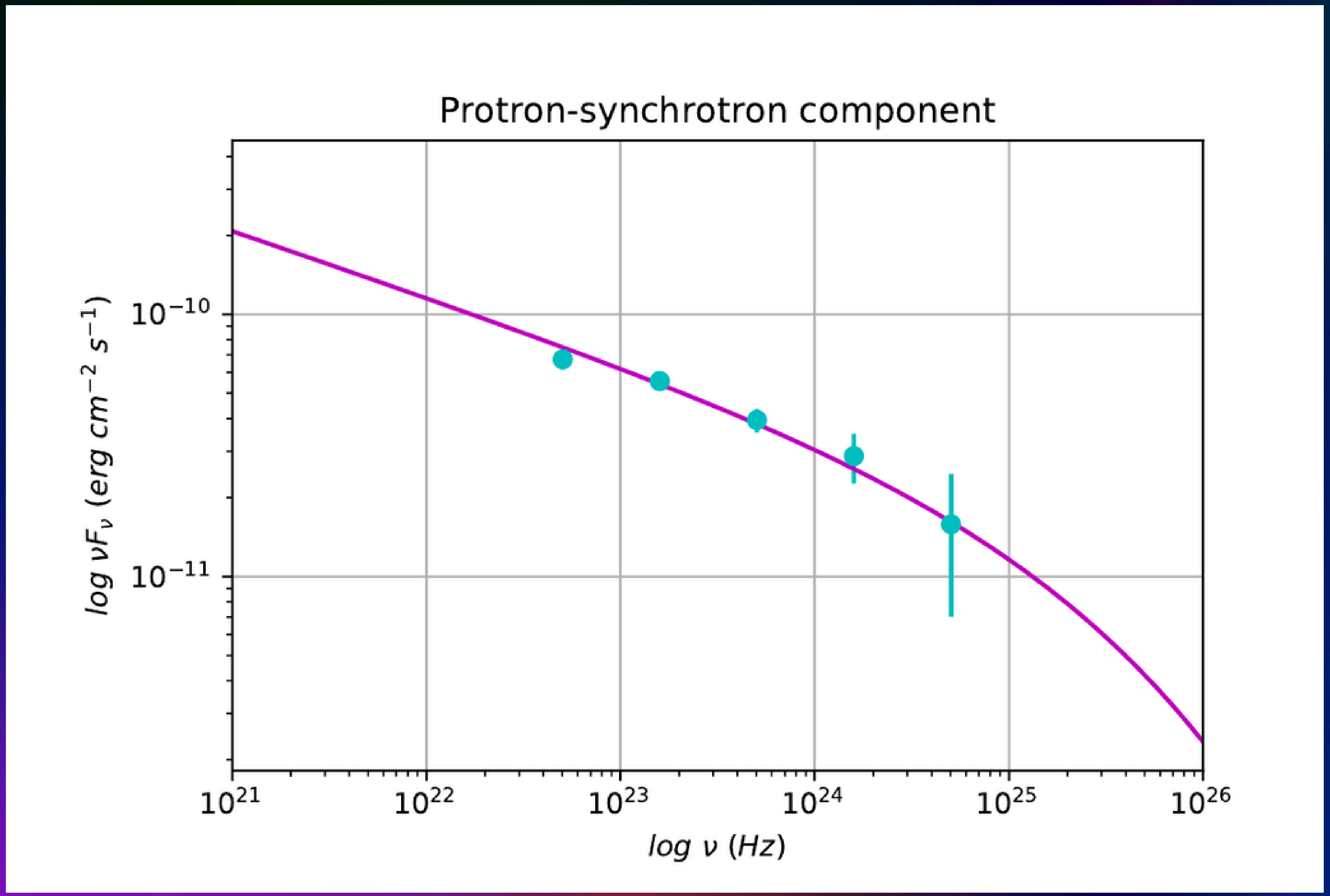


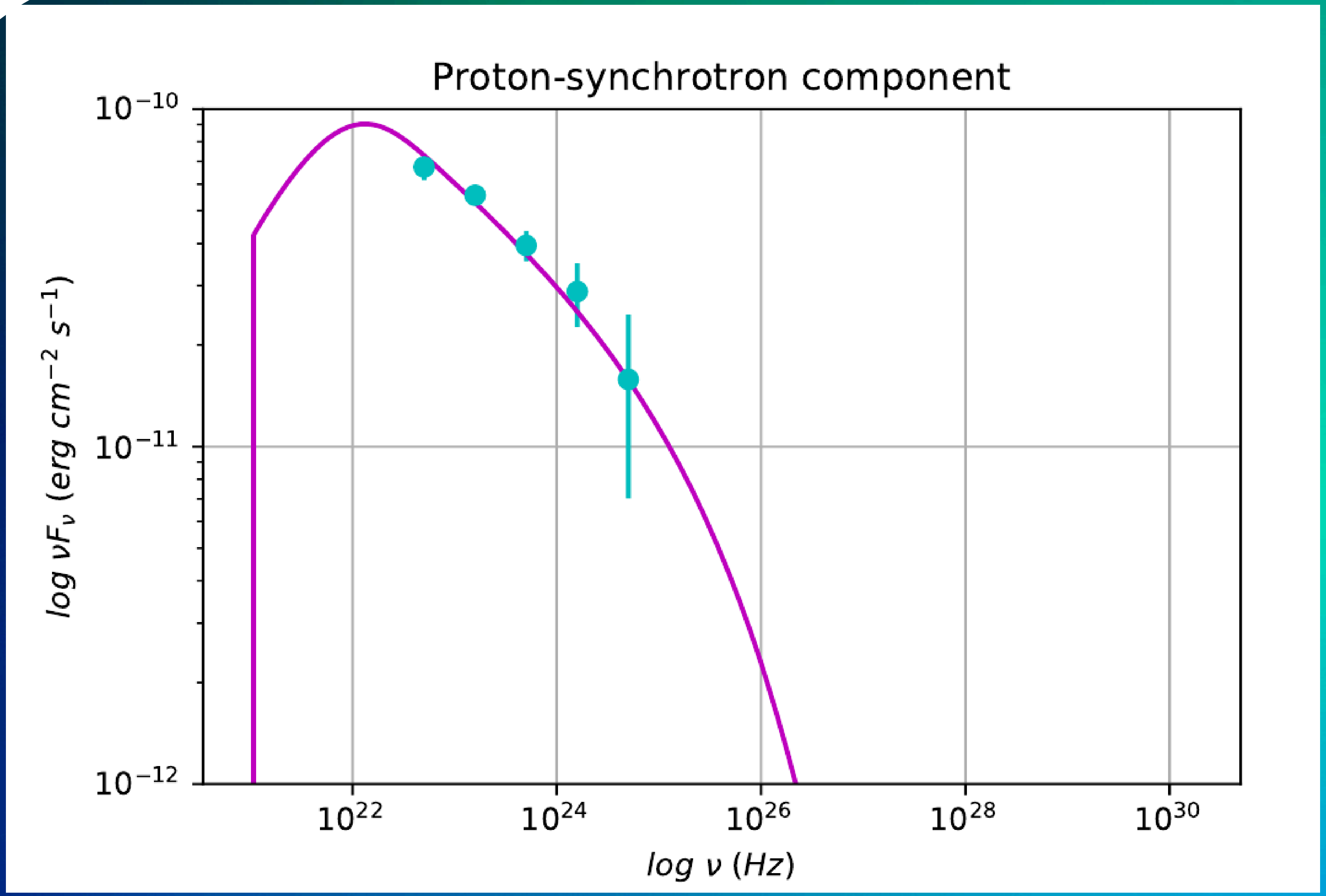
The Modelling Process

The programming steps:

- Get the parameters describing the relativistic proton population from a proton synchrotron fit to the Fermi-LAT gamma-ray spectrum.
- Numerical evaluation of the target photon field as a function of time.
- Pion production and pion-decay products.
- Calculate the $\gamma\gamma$-opacity.
- Calculate the resulting electromagnetic cascades to find the emerging SED.

Proton Spectrum

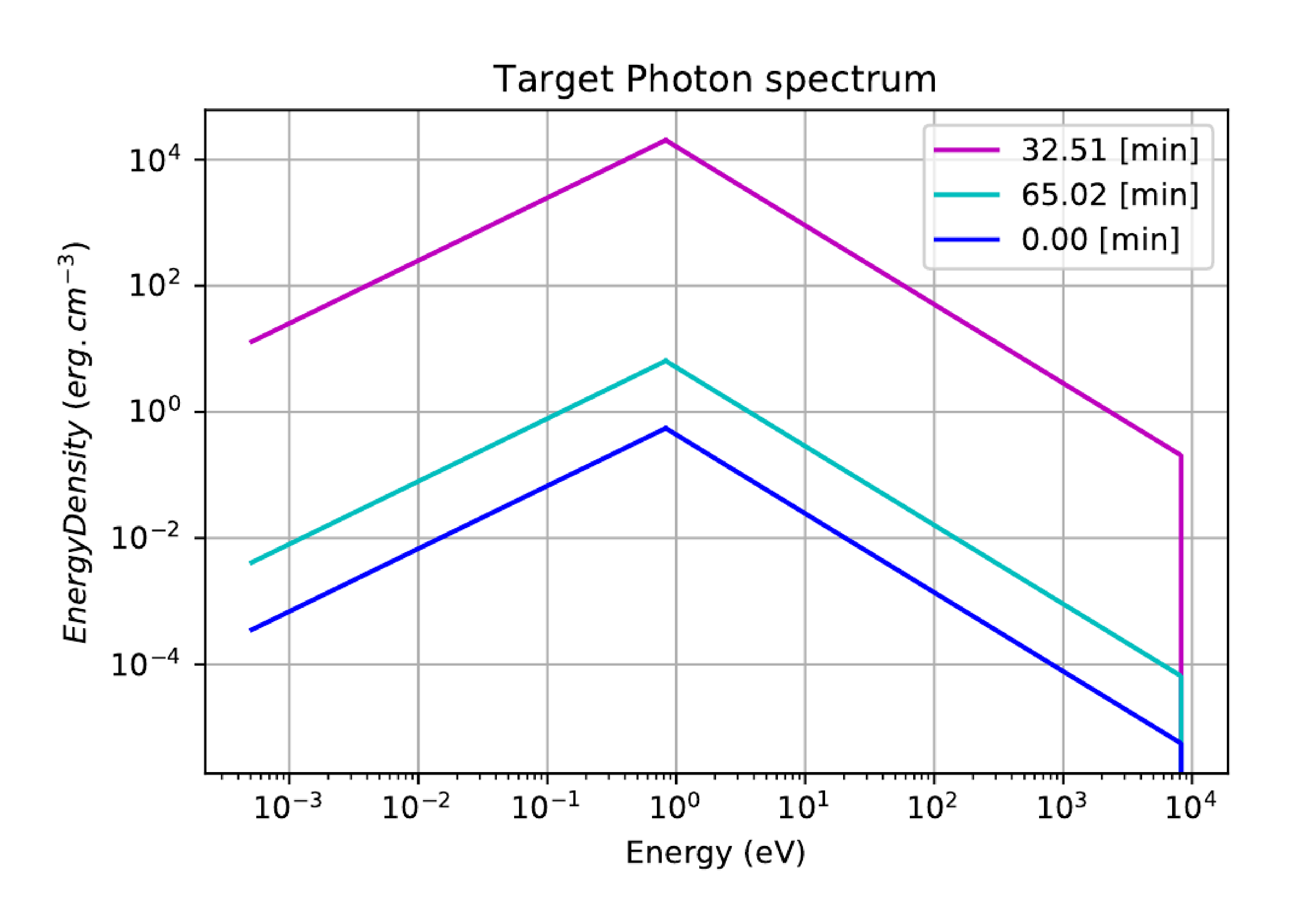




$$N_p(\gamma_p) = N_0 \gamma_p^{-p}$$

$$N_p(\gamma_p) = N_0 \left(\frac{\gamma_p}{\gamma_b}\right)^{-p_{1,2}} e^{-\frac{\gamma_p}{\gamma_c}}$$

Target photon spectrum



- The target photon spectrum at certain times since the onset of the orphan flare.
- We can see the energy density shoot up after some time passes and then come down again after more time passes.

Parameters

Important Parameters

- The normalisation of the proton spectrum
- Magnetic field
- The Lorentz factor that signifies the break in the spectrum
- Radius of the cloud
- Fraction of reflected photons
- The Doppler factor

N_0	2.5×10^{37}
B	$100\ G$
γ_b	9.8×10^{7}
R_{cl}	$5.5 \times 10^{15}\ cm$
τ	0.001
δ	10

A list of the model parameters.

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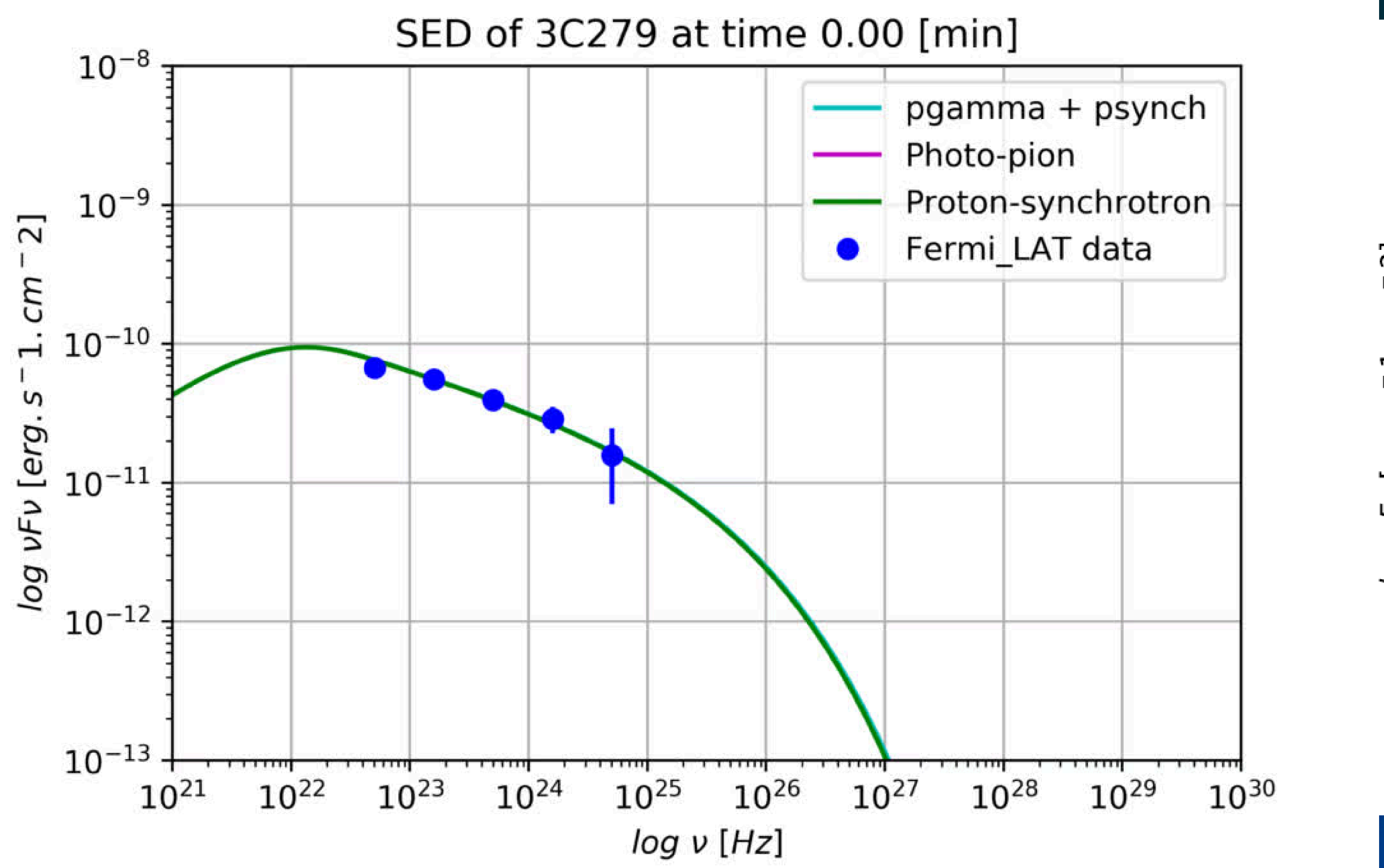
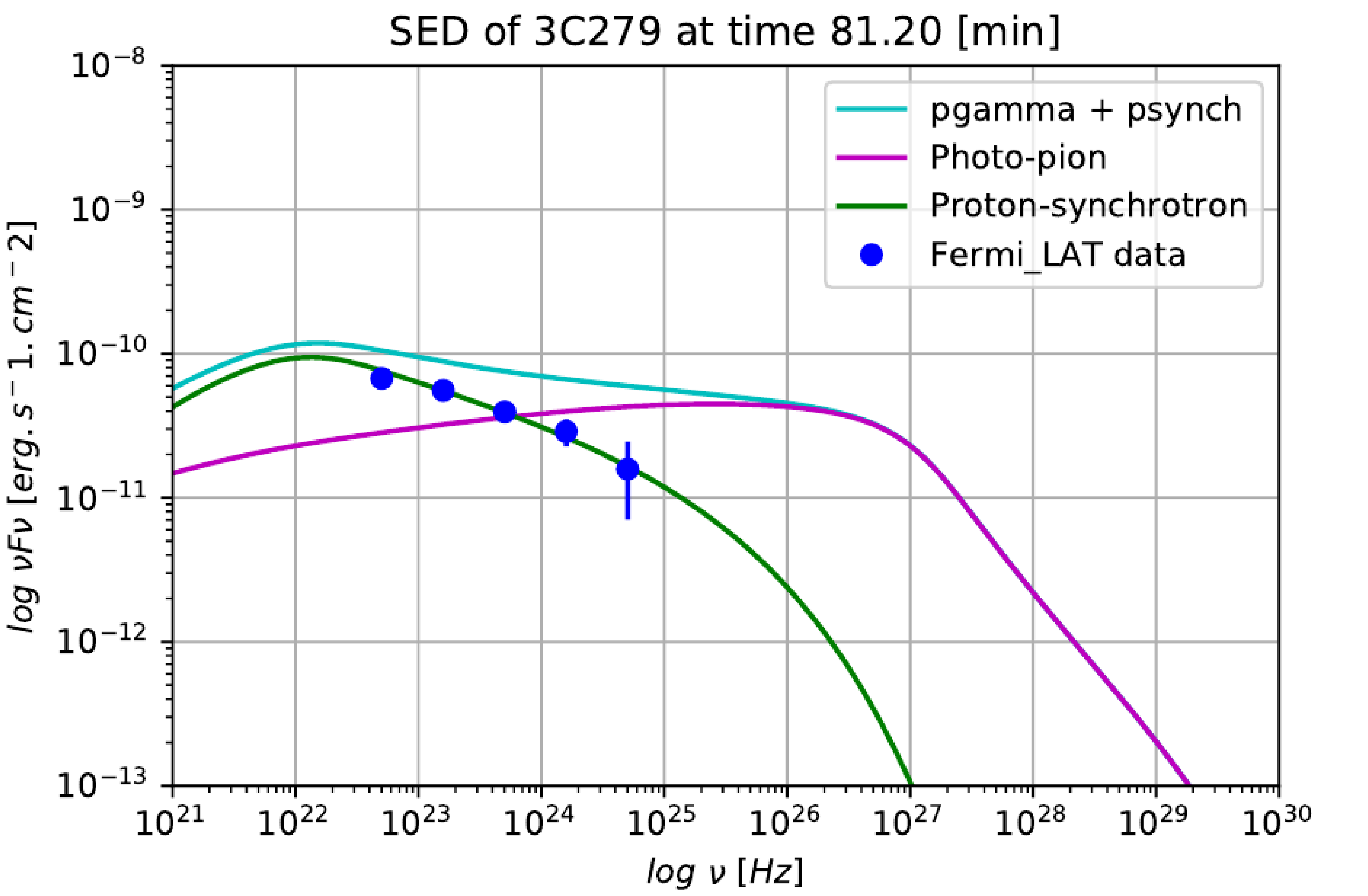
3C279 - SEDs

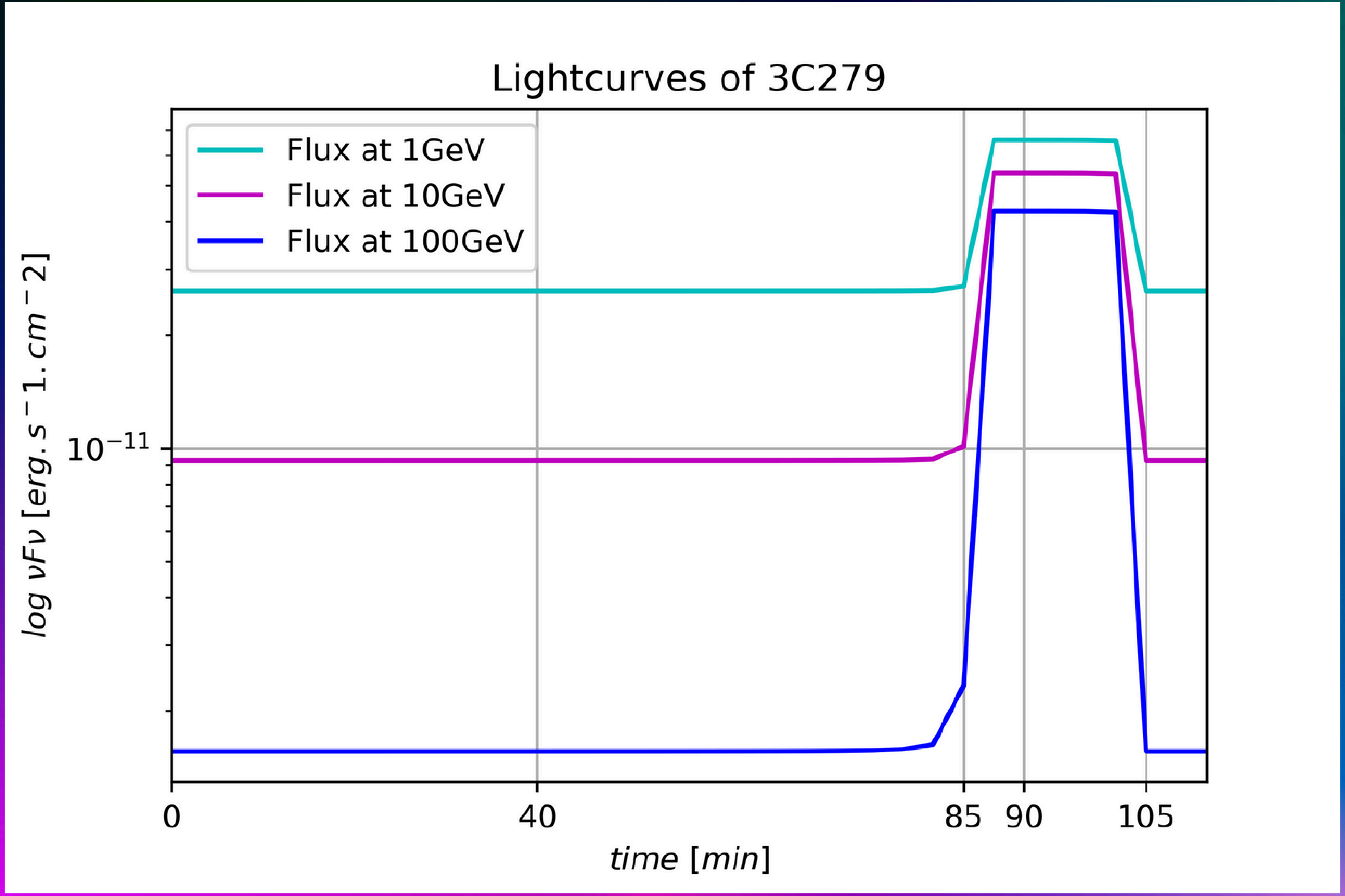




- The photons from the photo-pion decay products are injected at high energies into the jet and form pair cascades.
- The cascades cause pair production and are responsible for the synchrotron radiation.

$$N_e(\gamma) = \frac{1}{\nu_0 \gamma^2} \int_{\gamma}^{\infty} d\tilde{\gamma} \left\{ Q_e(\tilde{\gamma}) + \dot{N}_e^{\gamma\gamma}(\tilde{\gamma}) - \frac{N_e(\tilde{\gamma})}{t_{esc}} \right\}$$

Lightcurves



- The VHE flare is represented by the model flux at 100 GeV.
- There is a flare of a factor of 2 in flux at 1 GeV.
- The model predicts a significant flare of about 30 min duration.
- The observed time differs from the time in the AGN rest frame, because of light-travel-time effects.
- The light-travel-time effect leads to a contraction of the observed time.

$$t_{obs} = \frac{t_{AGN}}{\Gamma^2}$$

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Luminosities

For 3C279

Is the jet power proton or Poynting flux dominated?

- Close to equipartition
- Slightly proton dominated
- Jet power is a little bit larger than the Eddington luminosity.
- This can be explained by the fact that the jet is not in a steady state, so the jet power is only larger for the duration of the flare, and then reverts back to a lower value.

$$L_p \sim \pi R_b^2 c \Gamma^2 \gamma_b^2 m_p c^2 \frac{N_0}{V_b} \sim 2.1 \times 10^{47} \text{ erg.s}^{-1}$$

$$L_B \sim \pi R_b^2 c \Gamma^2 \frac{B^2}{(8\pi)} \sim 9.4 \times 10^{46} \text{ erg.s}^{-1}$$

$$L_{Edd} = 1.3 \times 10^{47} \text{ erg.s}^{-1}$$

Summary

Summary

- The synchrotron mirror scenario induces a dense enough target photon field.
- This model does predict a moderate flare in Fermi-LAT, but with a much smaller amplitude than that of the VHE flare.
- This suggests that protons are accelerated to ultra-relativistic energies.
- The flare duration is predicted to be about half an hour long, the runtime of one H.E.S.S. observational run.
- Fermi-LAT typically needs longer integration times than half an hour to get a significant detection of 3C279, which could explain why no flare was seen in the Fermi-LAT light curve.

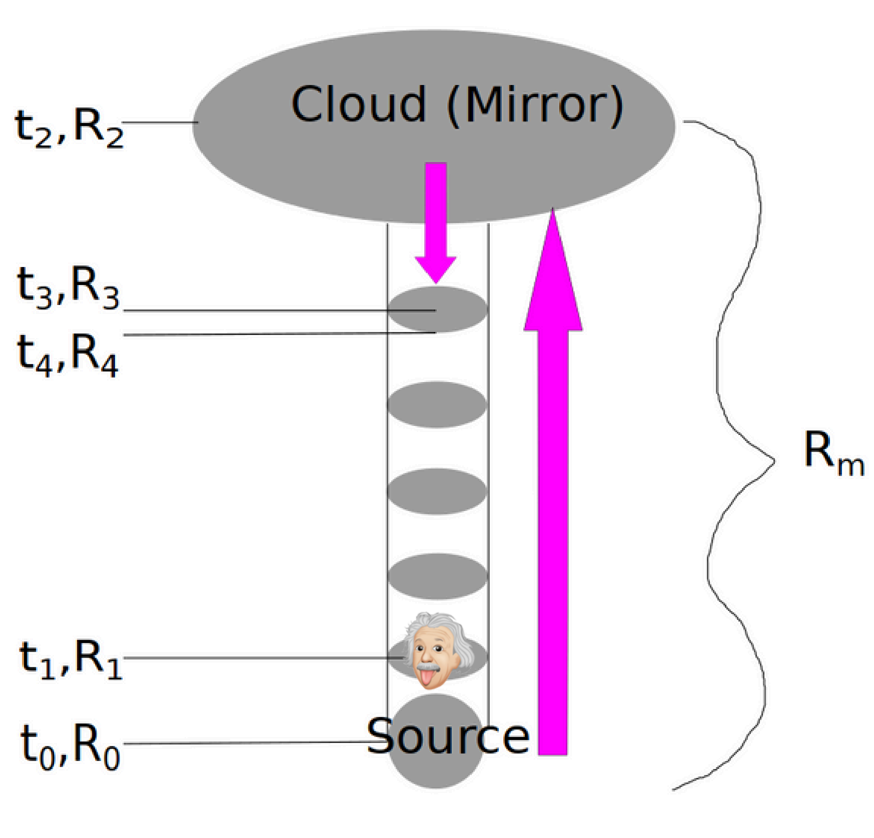
Ongoing work

- Do another parameter study to see if the jet power can be less than the Eddington luminosity.
- A comparative study of different models.
  - Combined lepto-hadronic - “Unified model”
  - Spine-sheath model - “Ring-of-fire”
- Search for neutrino signatures and emission.
- Detection of neutrino emission will also test the models.
- Preparation of article on the hadronic model results

Thank you!

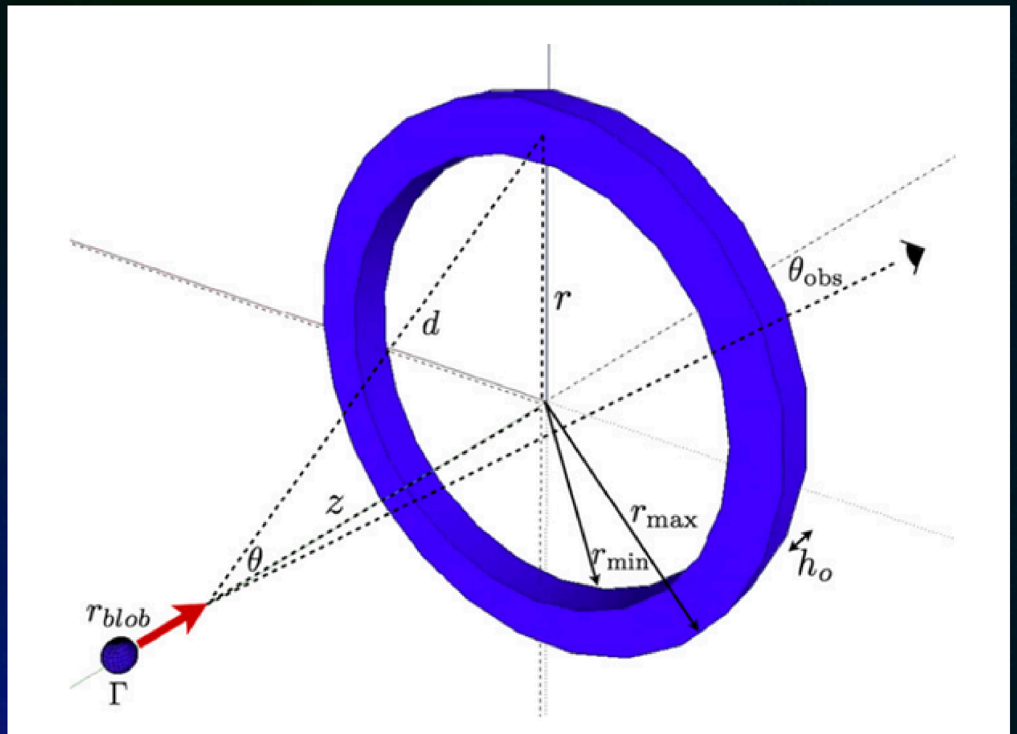
Feel free to ask if you have any questions.

Models
TO BE COMPARED



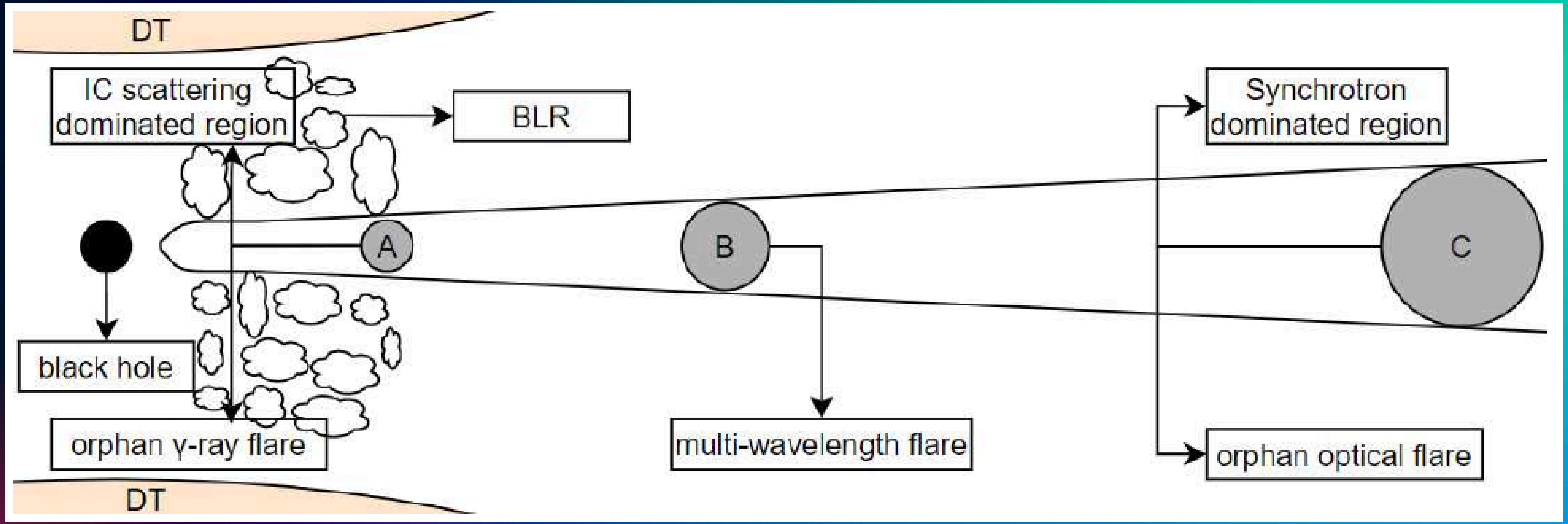
Hadronic Synchrotron Mirror Model

Laenita de Jonge
and
Prof Markus Böttcher



Ring-of-Fire Model

Nicholas R. MacDonald ,
Alan P. Marscher ,
Svetlana G. Jorstad , and
Manasvita Joshi



Stochastic Dissipation Model

Ze-Rui Wang, Ruo-Yu Liu, Maria Petropoulou, Foteini Oikonomou, Rui Xue, and Xiang-Yu Wang

Feasibility of the mirror model

Will the mirror model actually work?

- Semi-analytical approach
- Target photon density for photo-pion production calculated from basic principles.
- The expression for the energy density of the reflected synchrotron radiation:

$$\langle u'_{R,sy}(t_1)\rangle = \frac{4\Gamma^6 \nu F_\nu(sy) d_L^2 \tau R_{cl}^2}{3(R_m - R_b)} \int_0^{\frac{R_m - R_b}{\beta c}} \frac{dt_1}{(R_m - \beta c t_1)^2 (R_m - \frac{\beta c t_1}{2})^2}$$

- A standard integral was used to solve the integrand.
- After simplification a new expression is found where xf = α − tf is the time for photo-pion interactions to take place.
- α is the time it takes the blob to move to the centre of the cloud.
- tf is the total integration time.

$$\langle u'_{R,sy}\rangle = \frac{4\Gamma^6 \nu F_\nu(sy) d_L^2 \tau R_{cl}^2}{3(R_m - R_b)} \left(\frac{4}{(\beta c)^4}\left[\frac{1}{\alpha^2 x_f} + \frac{2}{\alpha^3}\ln\left(\frac{t_f}{2x_f}\right)\right]\right)$$

- By substituting in all the variables the predicted target photon density can be found

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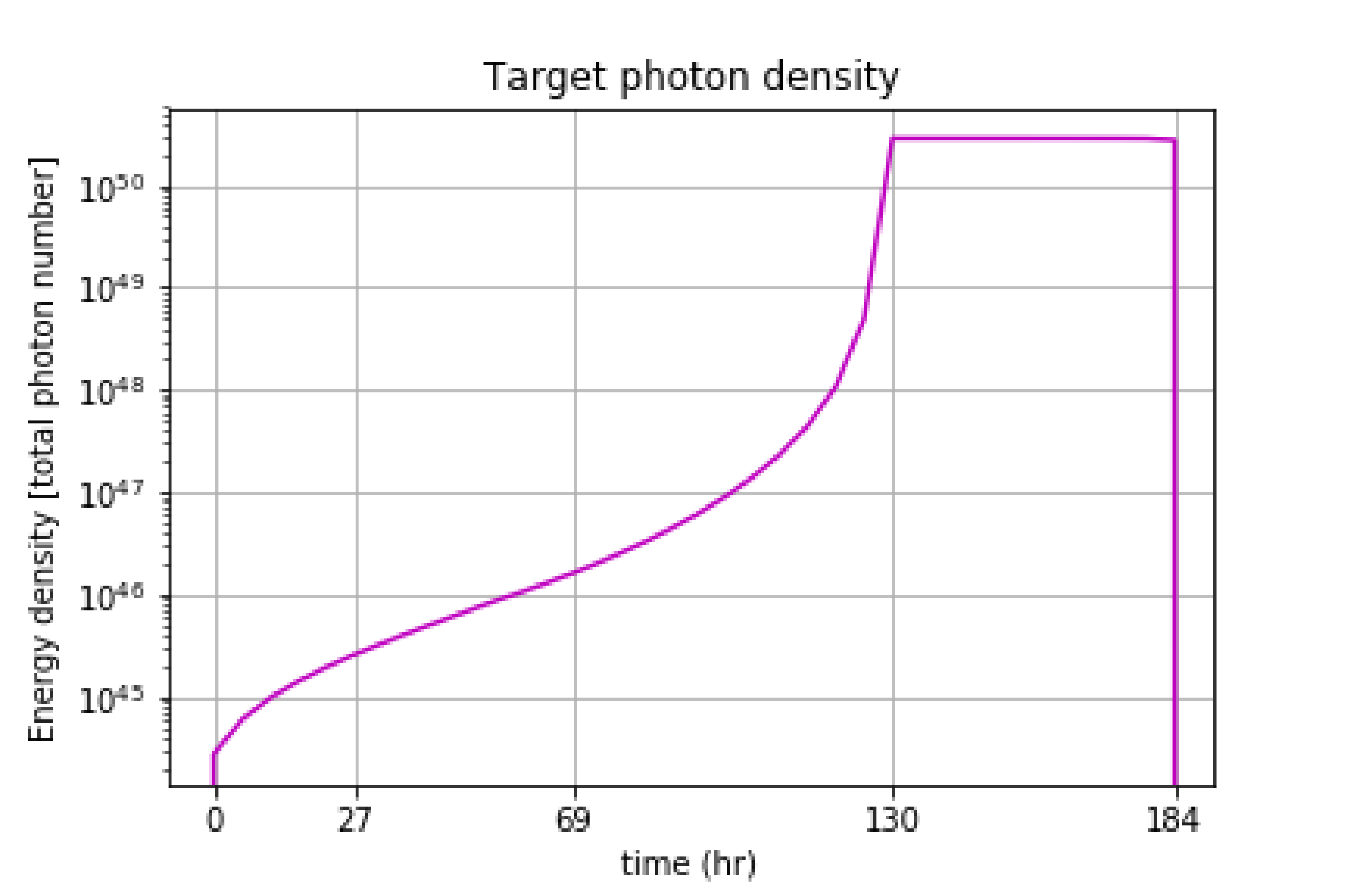
Target Photon Energy Density

Will the mirror model actually work?

- The required target photon energy density: 280 erg·cm−3.
- Estimated actual target photon energy density for standard parameters: 35.2 erg ·cm−3
- Order of magnitude difference.
- By calculating the Lorentz factor for the relativistic protons at the peak of the GEV Fermi-LAT spectrum using the synchrotron frequency.
- The Lorentz factor is used to calculate the synchrotron cooling rate which is compared to the photon-pion energy loss-rates from which the above calculated density is found.
- Conclusively, the target photon field was dense enough for photo-pion production to take place



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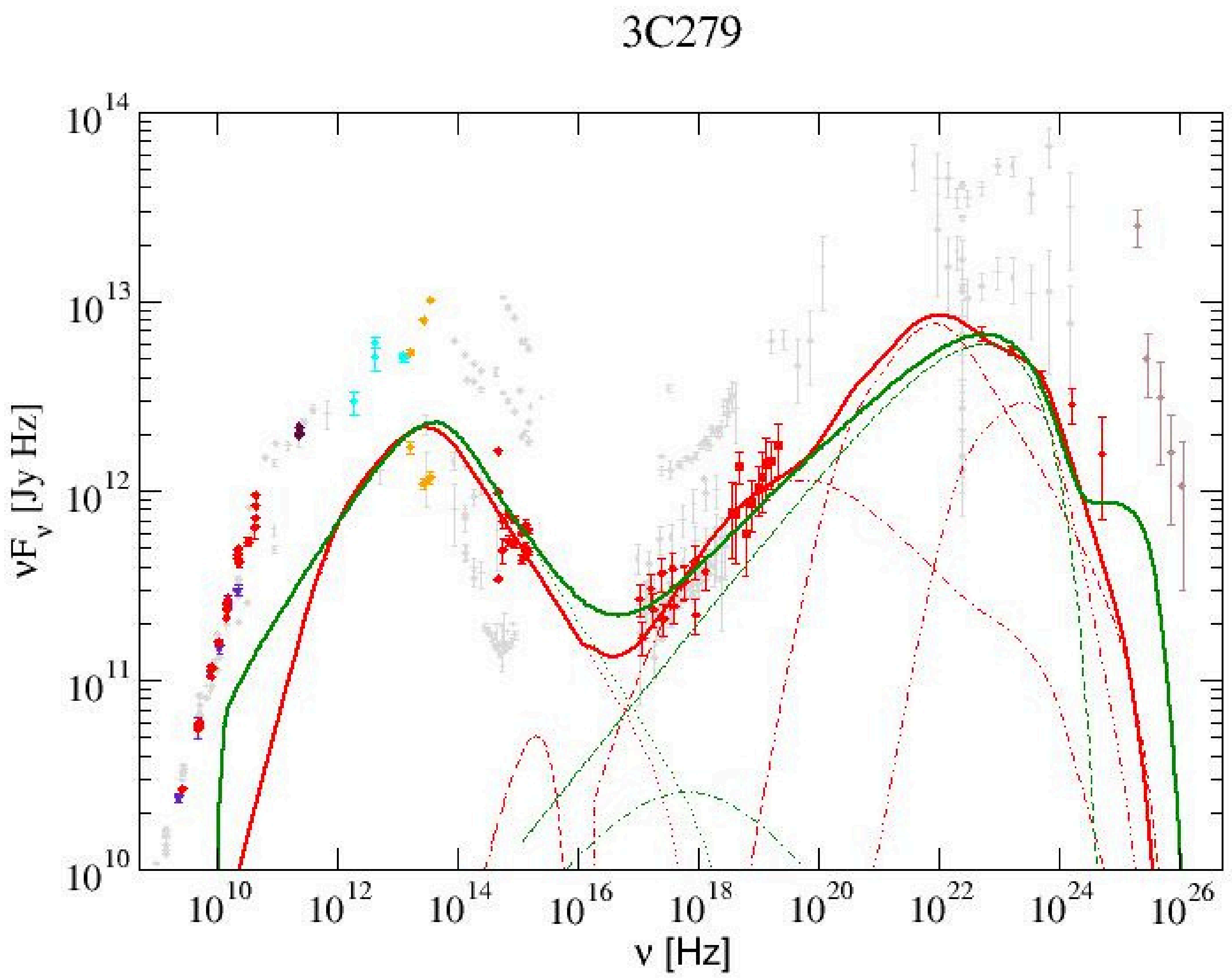
Motivation

- Leptonic fit - Redline
- Lepto-Hadronic fit - Greenline
- Electron synchrotron radiation - Component 1
- Proton synchrotron radiation - Component 2
- Photo-Pion Production - Component 3
- We investigate if the photo-pion component can be able to produce the VHE flare.



[BÖTTCHER, 2013]

Photo-pion production

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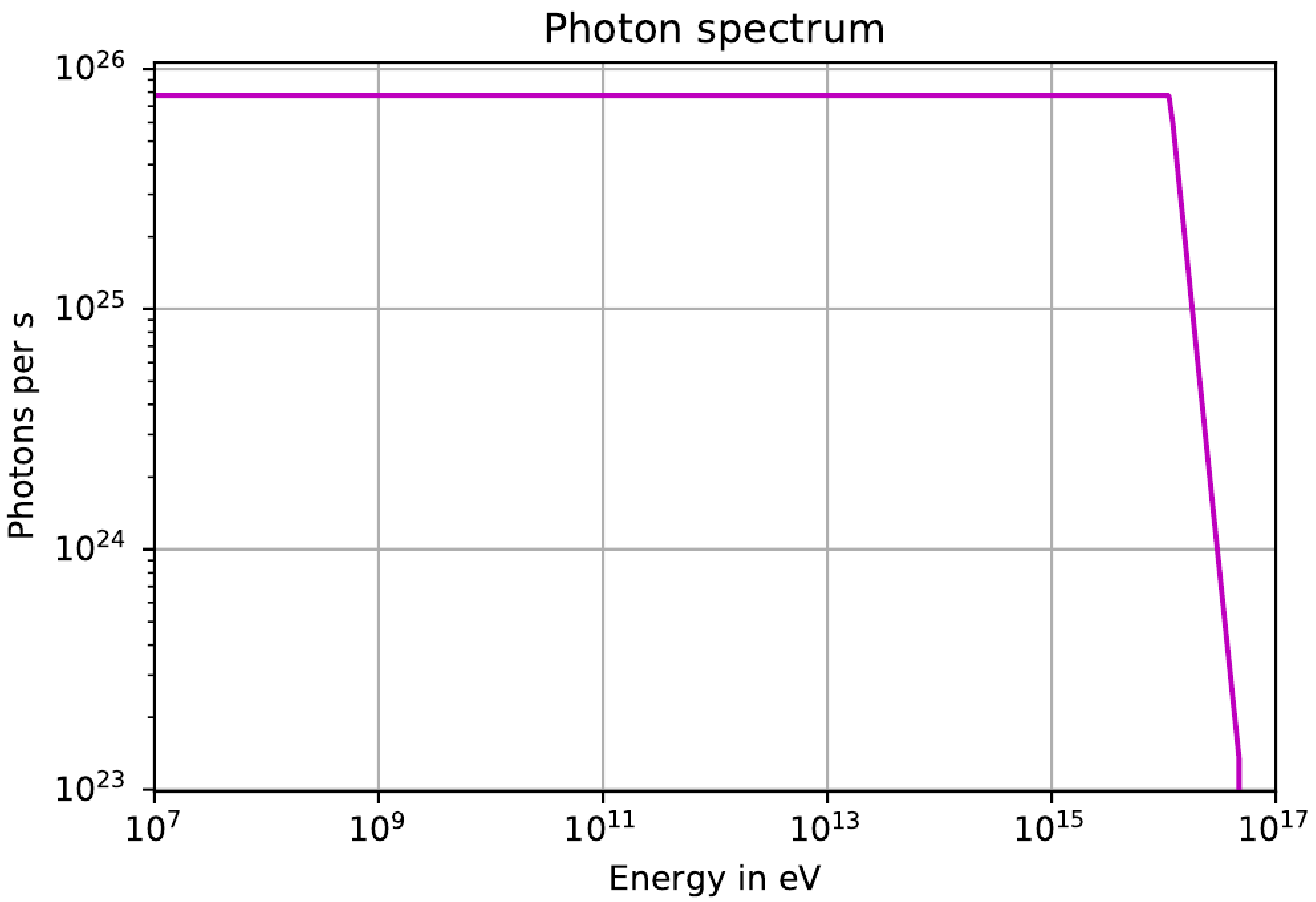
$$\dot{N}_{\gamma}^{\pi 0}(\epsilon) = \sigma_0 n_0 \frac{c N_0 E_\Delta}{2 m_\pi c^2 (\alpha + 1)} \times \int_{max[\epsilon \frac{m_e}{m_\pi}, \gamma_b, \frac{E_\Delta}{2\epsilon_2 m_e c^2}]}^{\gamma_{cr,max}} d\gamma_\pi \gamma_\pi^{-(2+s)} \left(max\left[\epsilon_1, \frac{E_\Delta}{2\gamma_\pi m_e c^2}\right] - \epsilon_2^{-(\alpha+1)} \right)$$

[BÖTTCHER AND DERMER, 1998]

- Photon number spectra
- Use σ_0 = 2 × 10−28 cm^2, the photo-pion differential cross-section, and EΔ = 330M eV, the energy at the threshold for the delta resonance, to find the number spectra.
- The pions are produced near-threshold energy in the proton's rest frame.
- γ_b represents the minimum Lorentz factor beyond which we have the power-law proton spectrum.



Magnetic Field

R_{cl}	$1 \times 10^{16}\ cm$
τ	0.01

N_0	3×10^{38}
B	varied
p	1.8
δ	10
R_b	$1 \times 10^{16}\ cm$

The Eddington Luminosity is: 1.3e+47

B=1:

The Proton Luminosity: 1e+49

The Poynting-flux Luminosity: 3.8e+43

B=25:

The Proton Luminosity: 4.2e+47

The Poynting-flux Luminosity: 2.3e+46

B=50:

The Proton Luminosity: 2.1e+47

The Poynting-flux Luminosity: 9.4e+46

B=75:

The Proton Luminosity: 1.4e+47

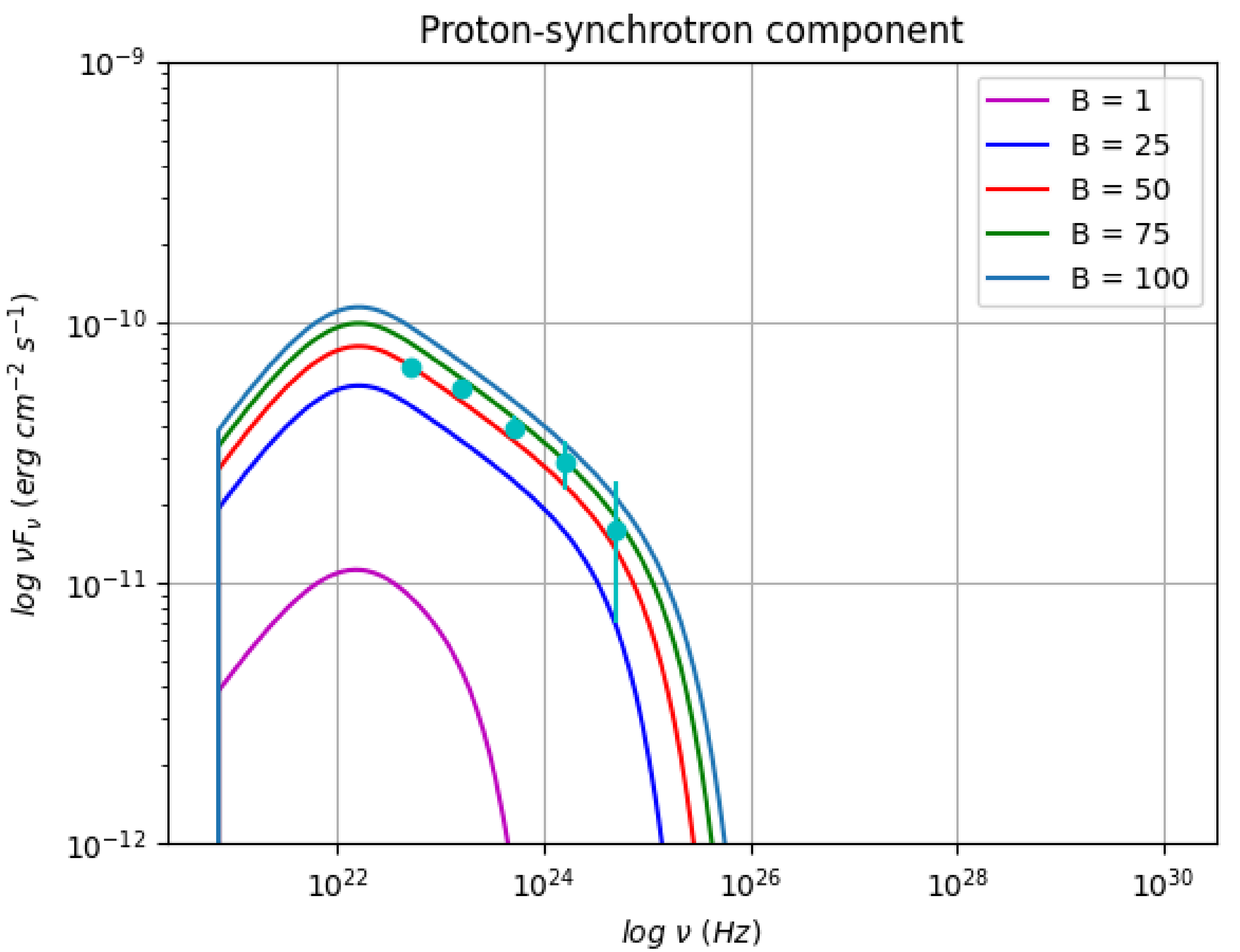
The Poynting-flux Luminosity: 2.1e+47

B=100:

The Proton Luminosity: 1e+47

The Poynting-flux Luminosity: 3.8e+47

- The proton Luminosity decreases as the magnetic field increases.
- The Poynting-flux Luminosity increases as the magnetic field does.
- Gammabreak decreases as the magnetic field does.



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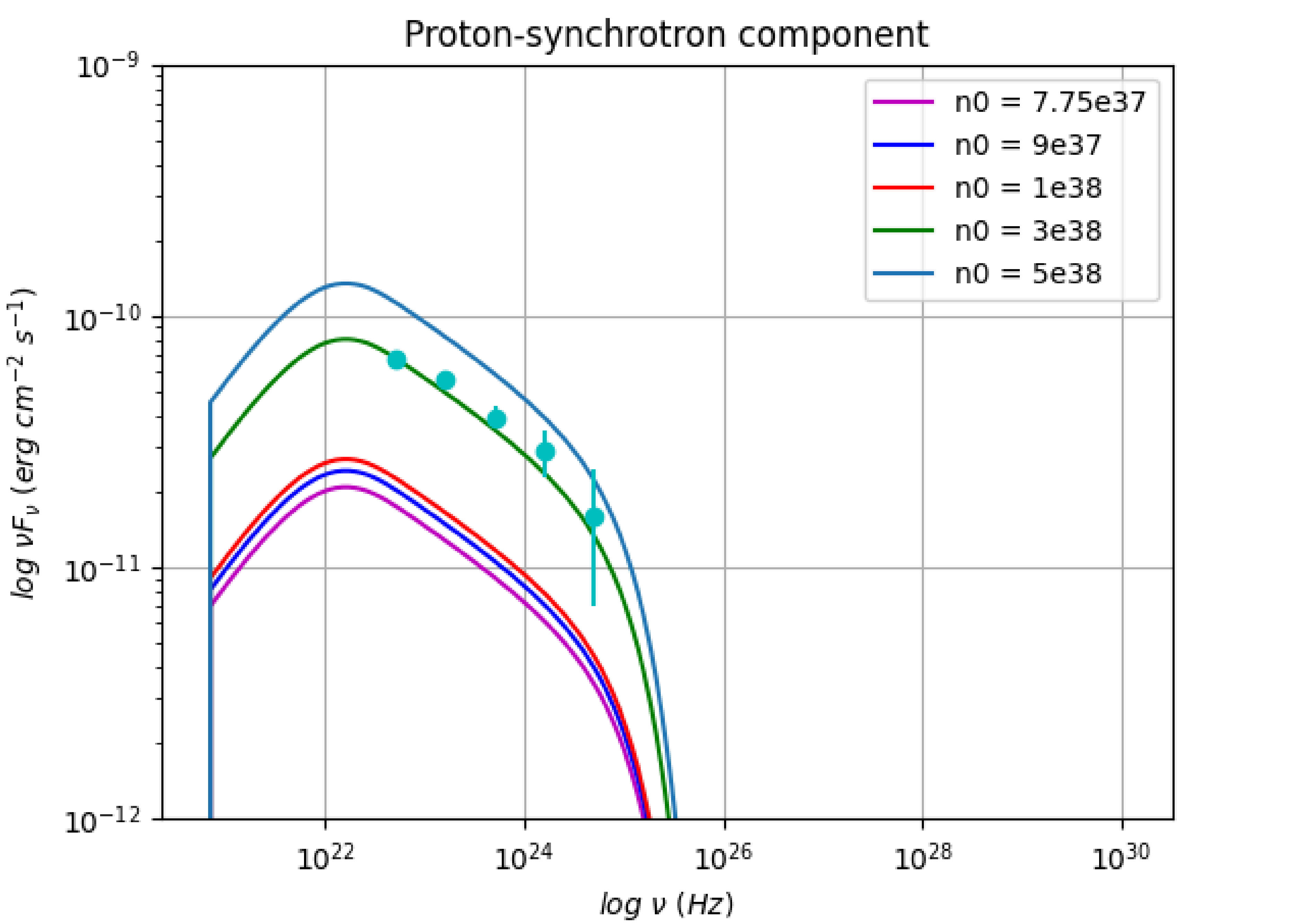
Normalisation

The Eddington Luminosity is: 1.3e+47
n0=7.75e37:
The Proton Luminosity: 5.4e+46
The Poynting-flux Luminosity: 9.4e+46
n0=9e37:
The Proton Luminosity: 6.3e+46
The Poynting-flux Luminosity: 9.4e+46
n0=1e38:
The Proton Luminosity: 6.9e+46
The Poynting-flux Luminosity: 9.4e+46
n0=3e38:
The Proton Luminosity: 2e+47
The Poynting-flux Luminosity: 9.4e+46
n0=5e38:
The Proton Luminosity: 3.5e+47
The Poynting-flux Luminosity: 9.4e+46

- The proton Luminosity increases as the normalisation increases.
- The Poynting-flux Luminosity stays stable as the normalisation is varied.
- Gammabreak stays stable as the normalisation varies.

R_{cl}	$1 \times 10^{16}\ cm$
τ	0.01

N_0	varied
B	$50\ G$
p	1.8
δ	10
R_b	$1 \times 10^{16}\ cm$



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