HEASA 2024

A STUDY OF THE HADRONIC SYNCHROTRON MIRROR MODEL

Laenita De Jonge
Supervisor: Markus Böttcher

4 October 2024

Aim - Questions to be answered

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?

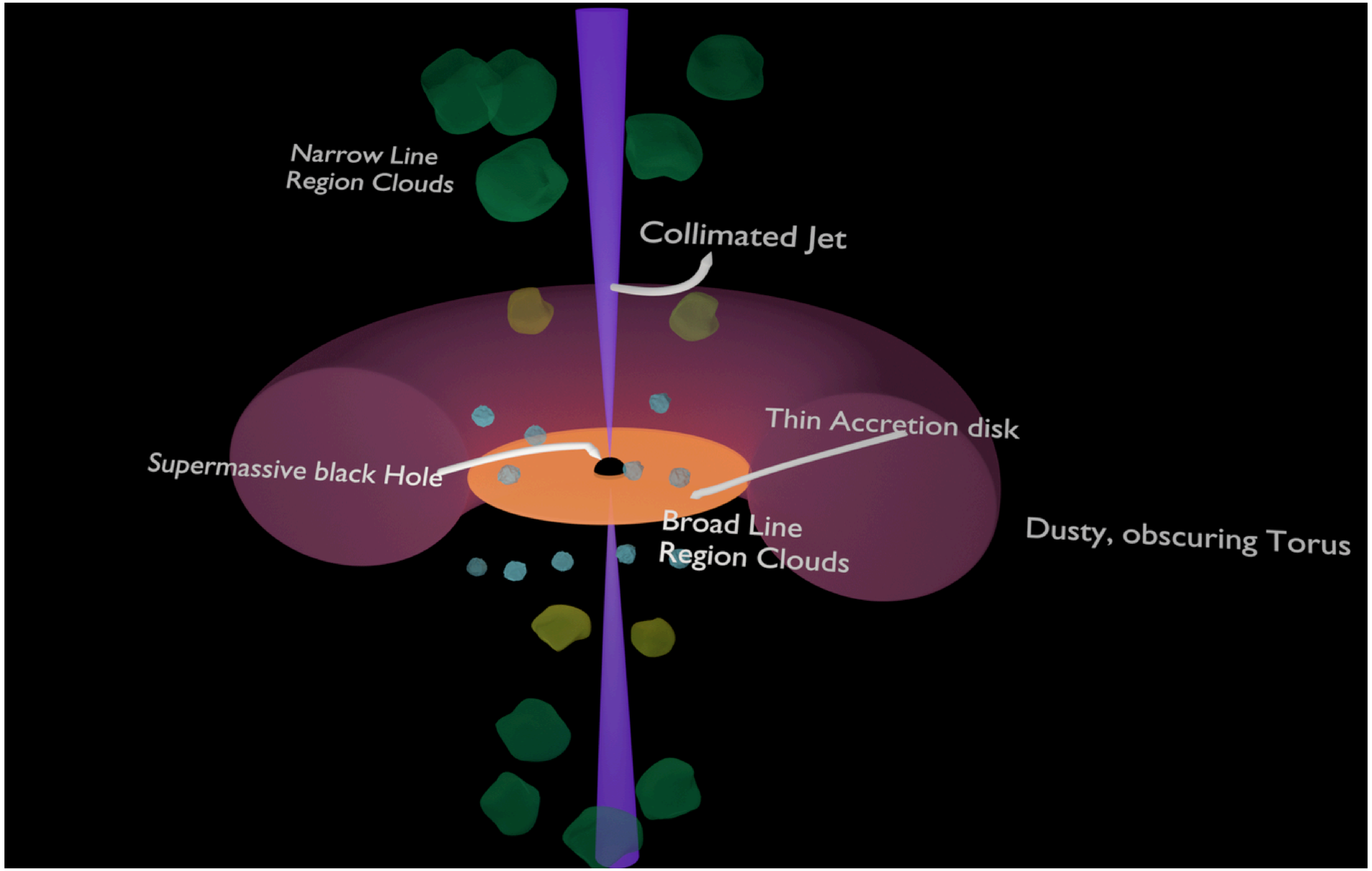
The motivation behind the parameter study:

- The proton jet power is greater than the Eddington luminosity.
- To see how some of the different parameters influence the model.

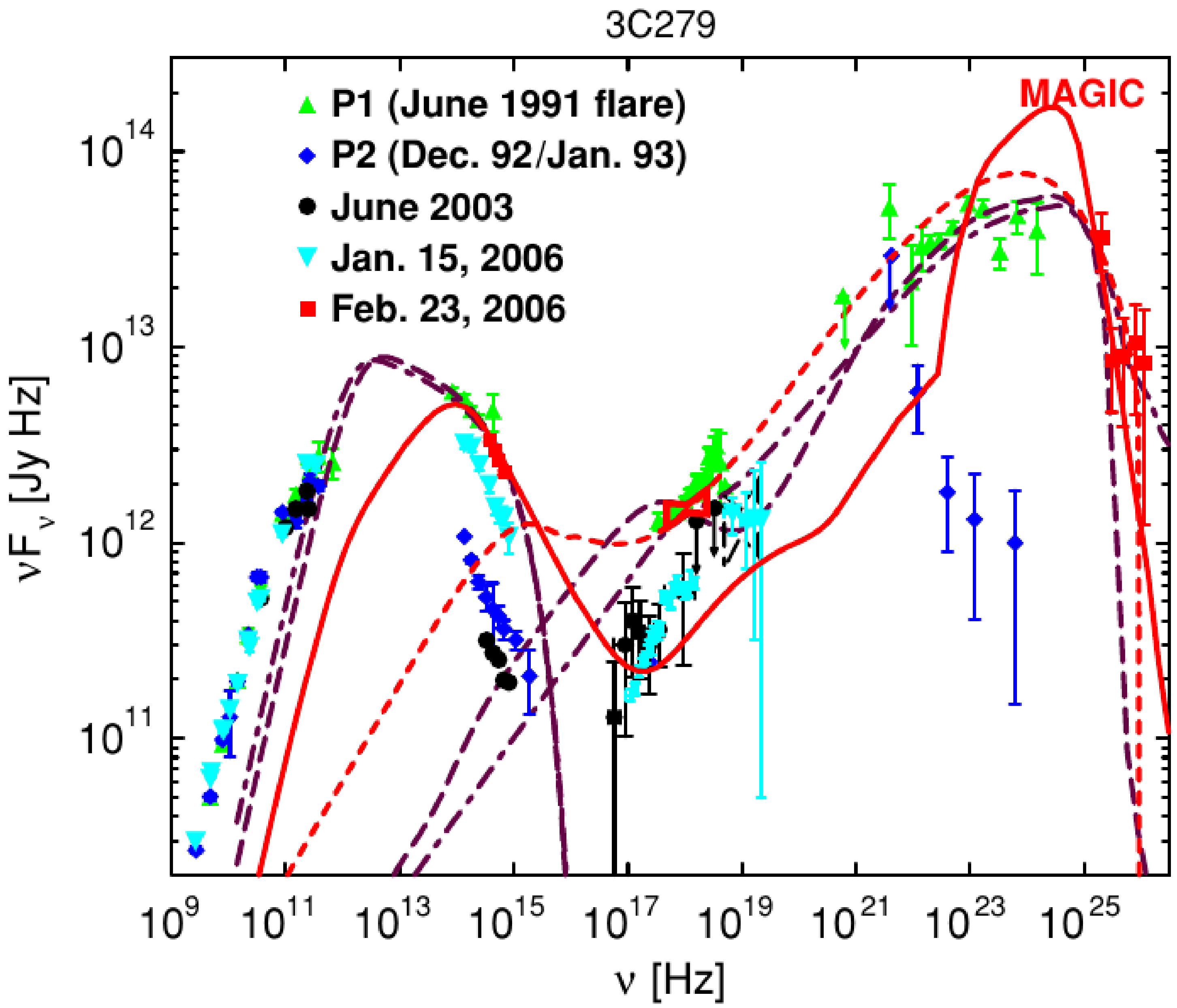
Outline

What this presentation covers

- Background
  - SED components
  - Orphan Flares
- The hadronic synchrotron mirror model
  - Motivation
  - Model
  - Results
- Parameter study - results
- Neutrino emission - preliminary results
- Summary and Future Work



SEDs

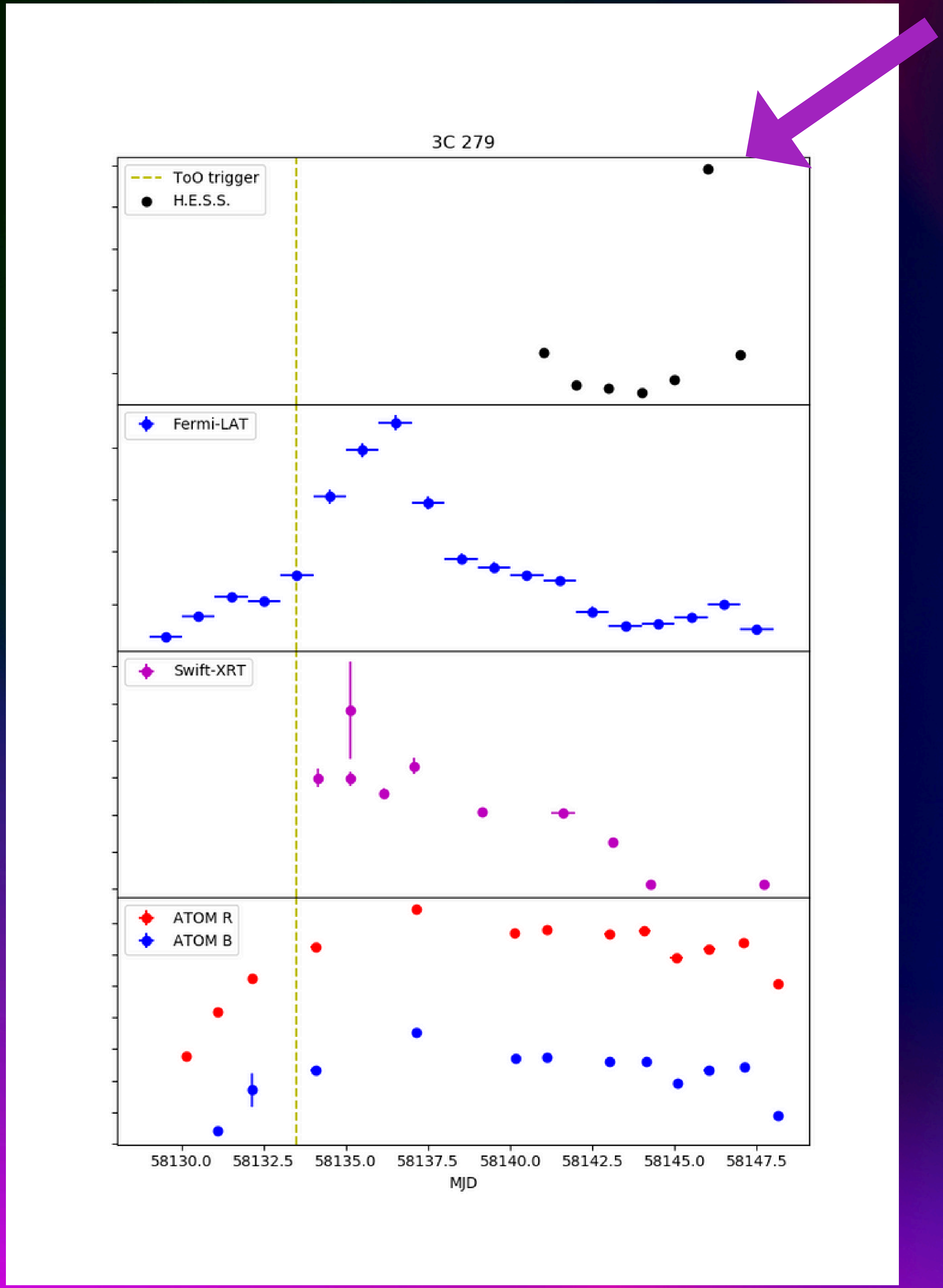


[BÖTTCHER ET AL., 2009]

- SED's 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 (can result from proton synchrotron radiation)

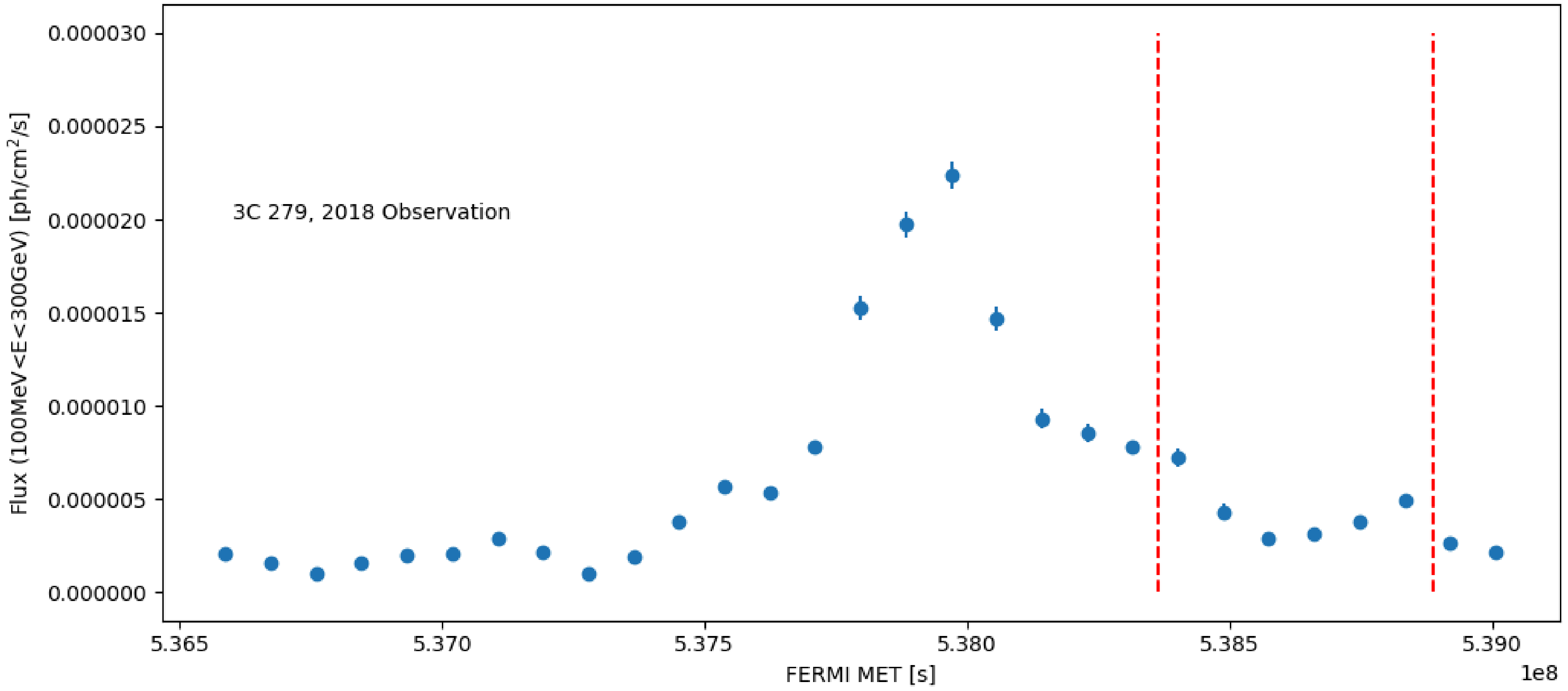
$$p + \gamma \rightarrow p + \pi^0 \rightarrow p + \gamma + \gamma$$
$$or \rightarrow n + \pi^+ \rightarrow n + \mu^+ + \nu_\mu \rightarrow n + e^+ + \nu_\mu + \nu_e + \overline{\nu}_\mu$$

Orphan Flares



Example of observed orphan flare

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

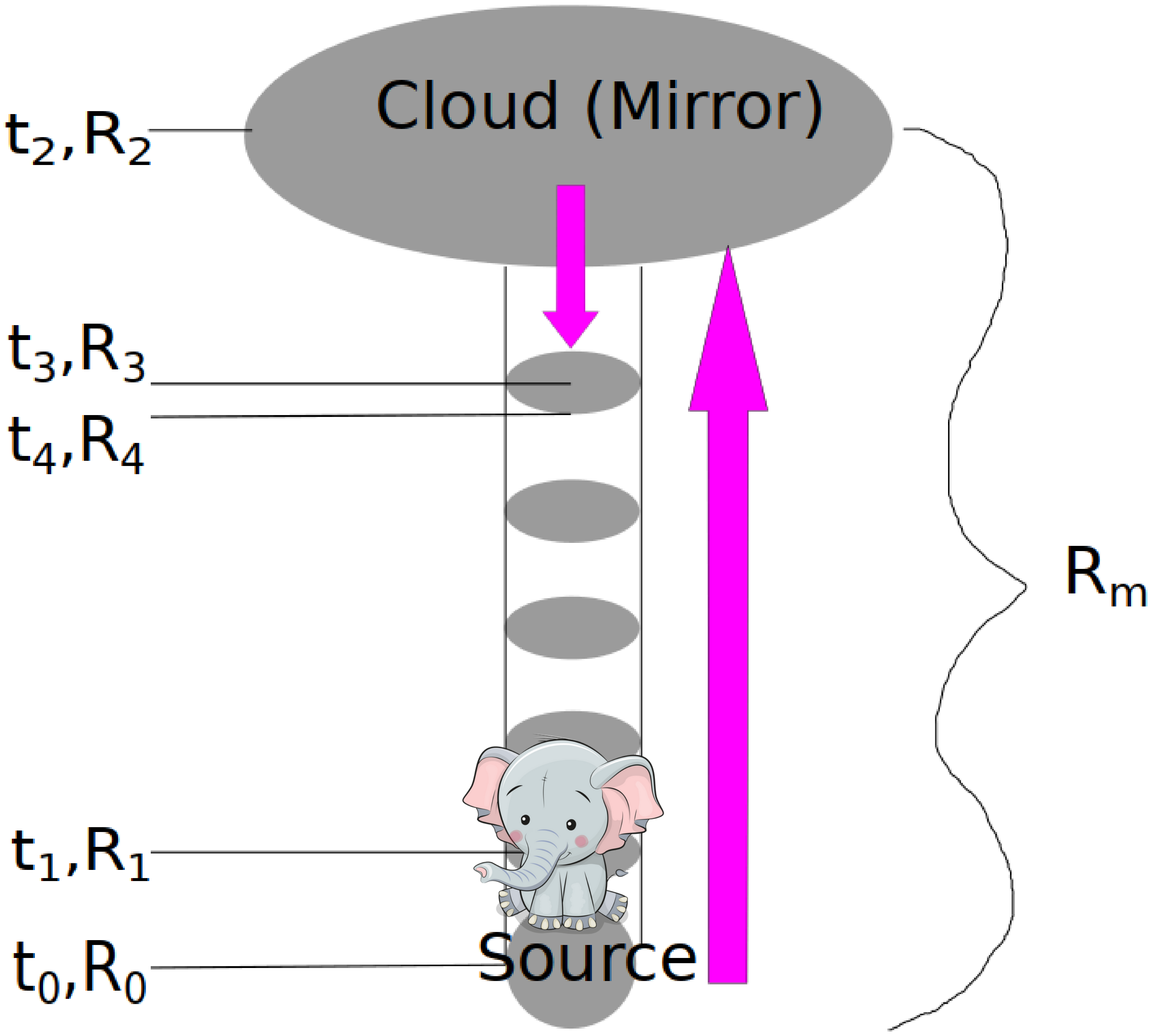


- 3C 279 is a FSRQ at a redshift of z = 0.536.
- 28th January 2018
- H.E.S.S. data in period bounded by the red lines.
- ToO observation was ongoing because of the Fermi-LAT flare by Fermi, HESS, Swift-XRT and ATOM.

Motivation for Hadronic scenario

Why we chose a hadronic mirror scenario:

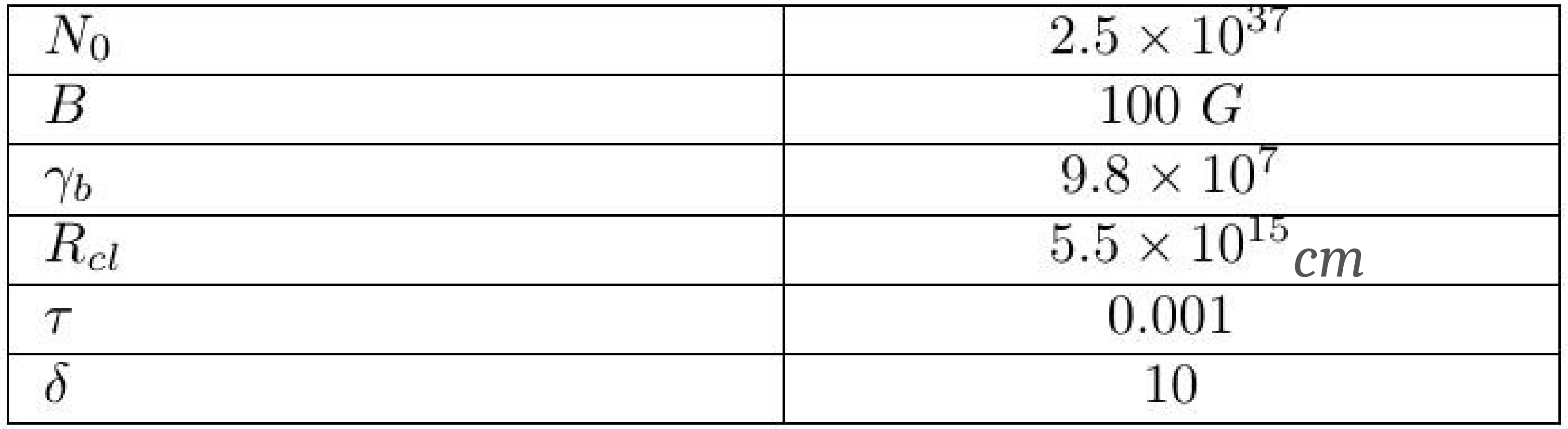
- Leptonic SSC models predict quasi-simultaneous flaring in other wavebands like X-ray and optical bands.
- Matter in blazar jets might be dynamically dominated by baryon content [Sikora & Madejski, 2000].
- We consider a hadronic mirror scenario.
- Example as done in [Böttcher, 2005] with the orphan 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 our mirror scenario.



Hadronic Synchrotron Mirror Model

Important Parameters

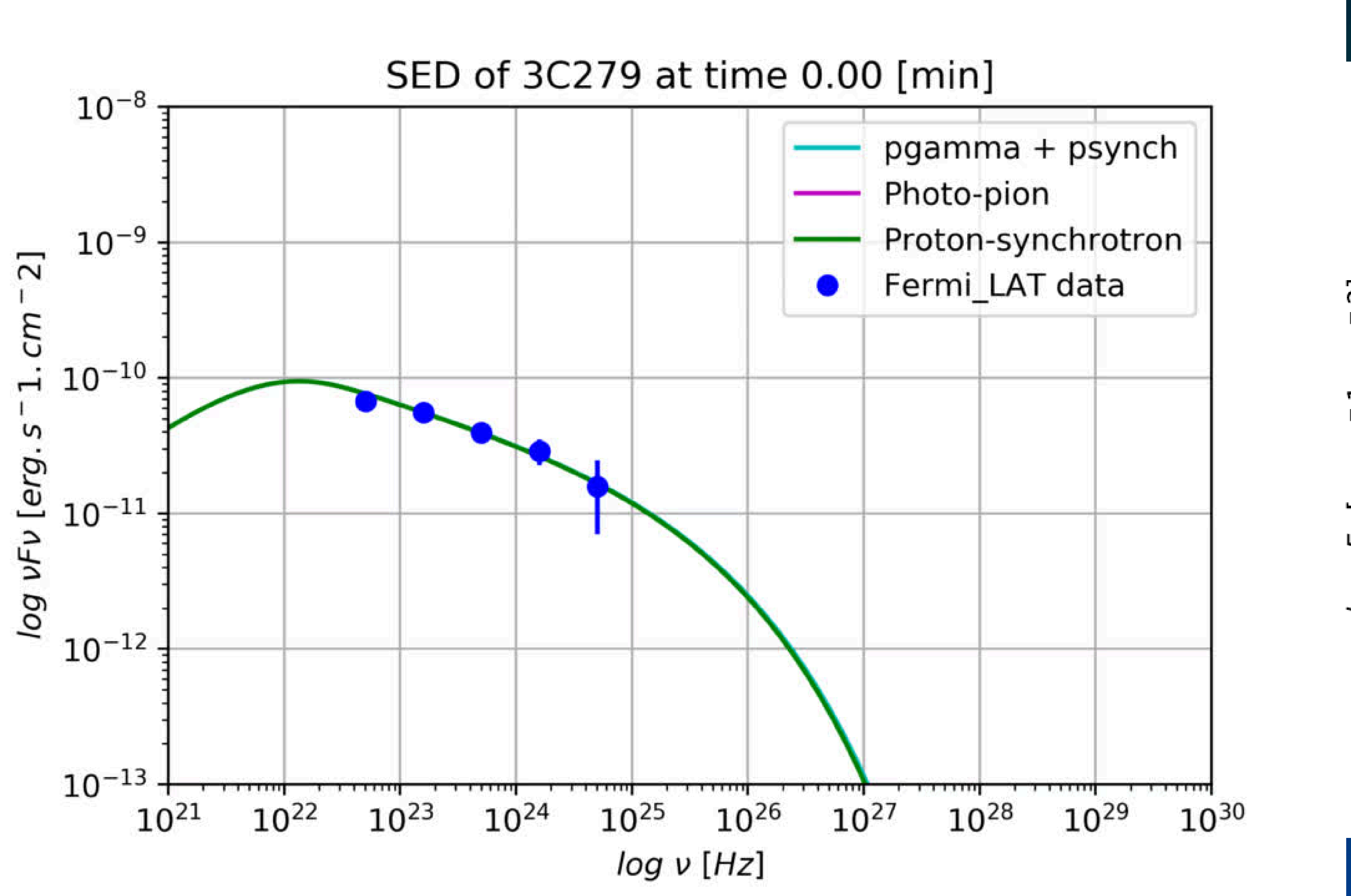
- The normalisation of the proton spectrum
- Magnetic field
- The Lorentz factor that signifies the break in the spectrum
- Radius of the cloud
- Fraction of reflected photons
- The Doppler factor

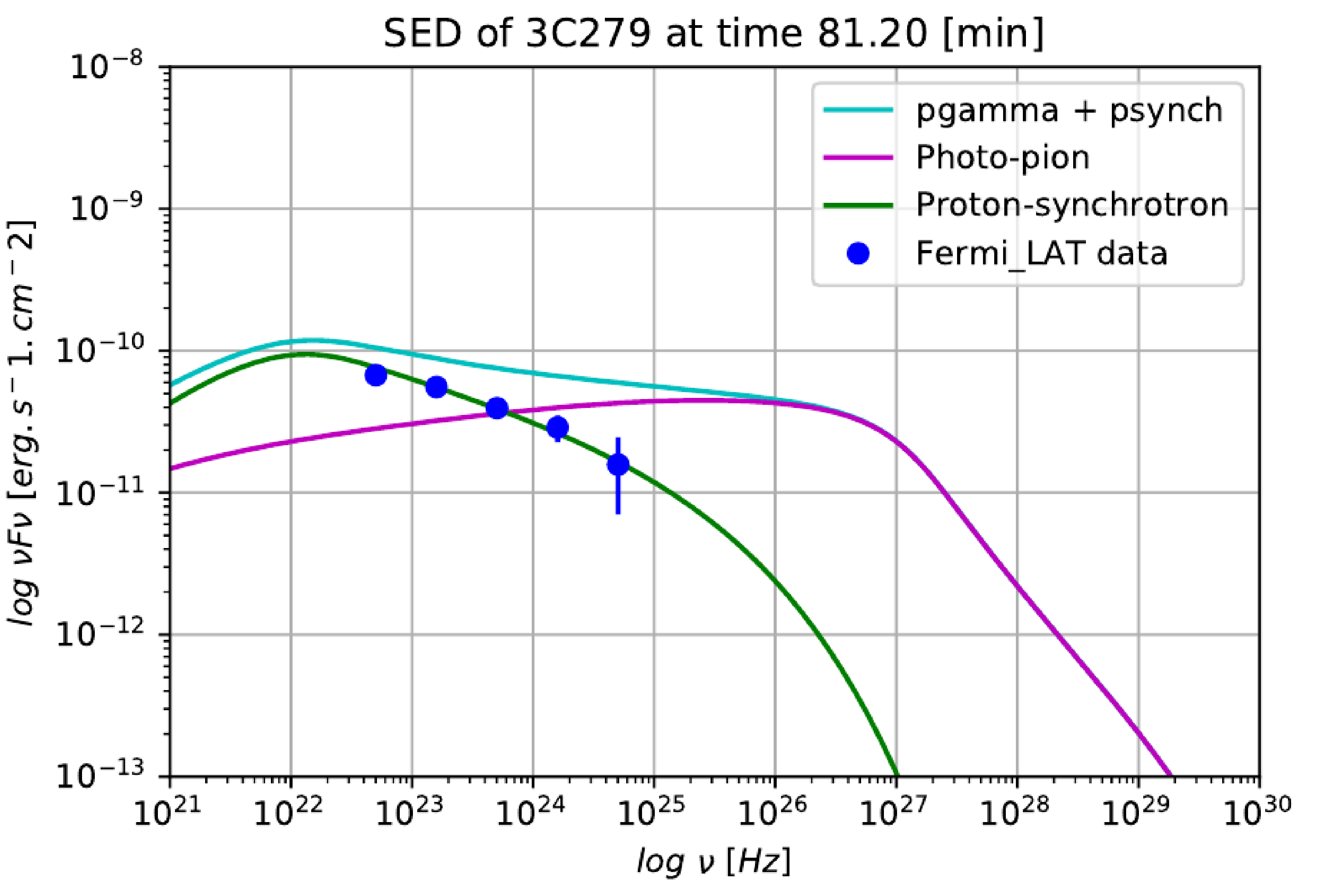


N_0	2.5×10^{37}
B	$100\ G$
γ_b	9.8×10^{7}
R_{cl}	$5.5 \times 10^{15} cm$
τ	0.001
δ	10

A list of the model parameters.

3C279 - SEDs

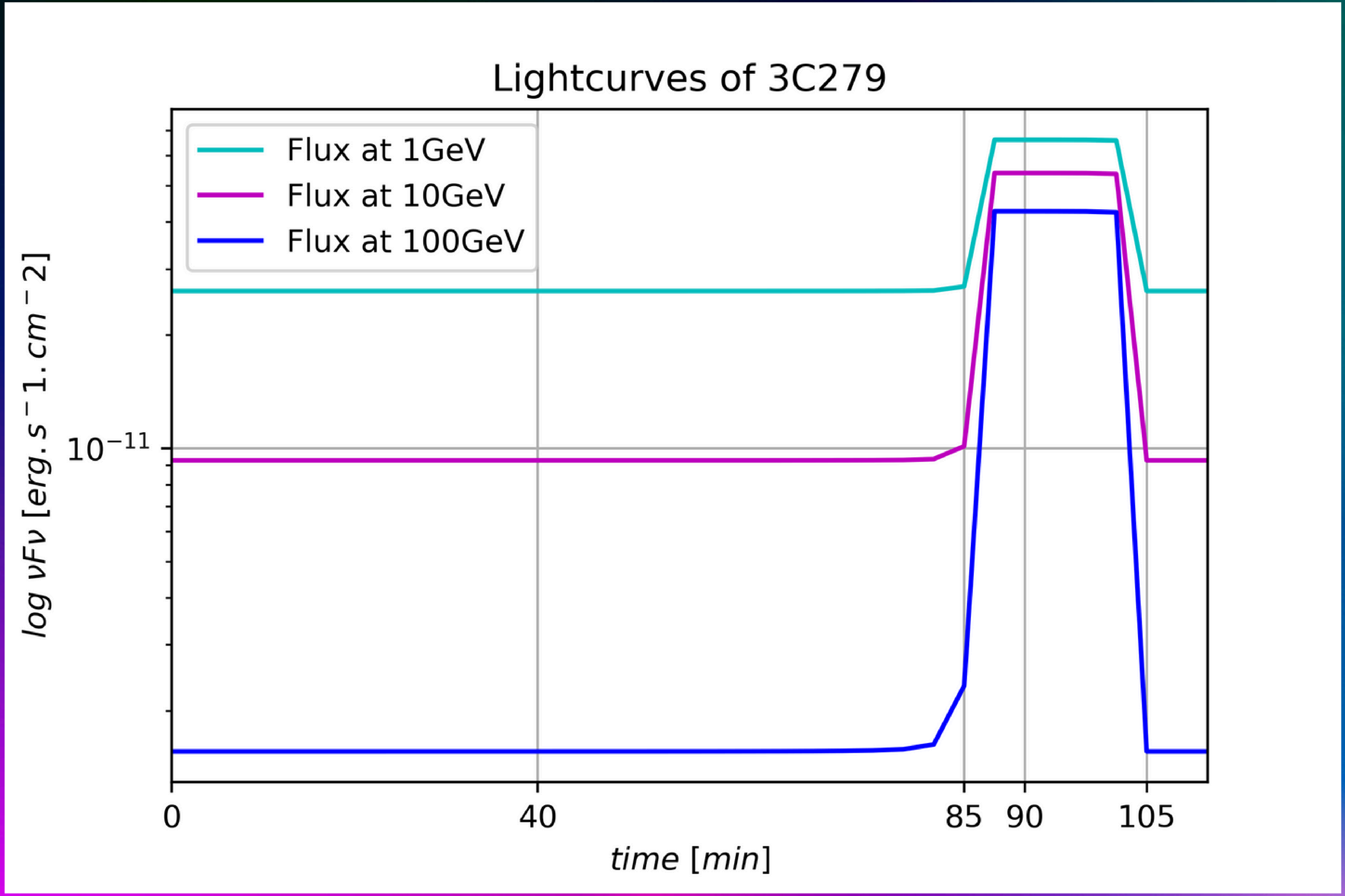




- The photons from the photo-pion decay products are injected at high energies into the jet and form pair cascades.
- The cascades cause pair production and are responsible for the synchrotron radiation.

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

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.

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

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.

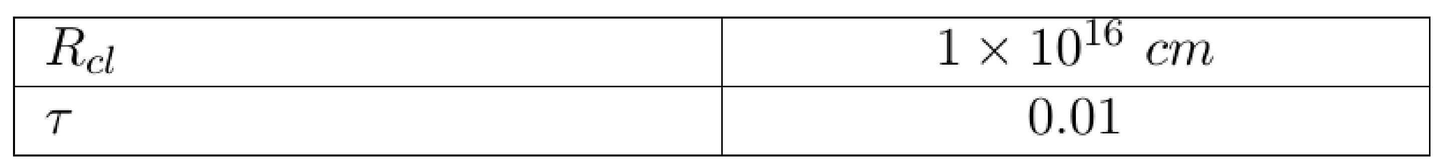
$$L_p \sim \pi R_b^2 c \Gamma^2 \gamma_b^2 m_p c^2 \frac{N_0}{V_b} \sim 2.1 \times 10^{47} \ \mathrm{erg.s}^{-1}$$

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

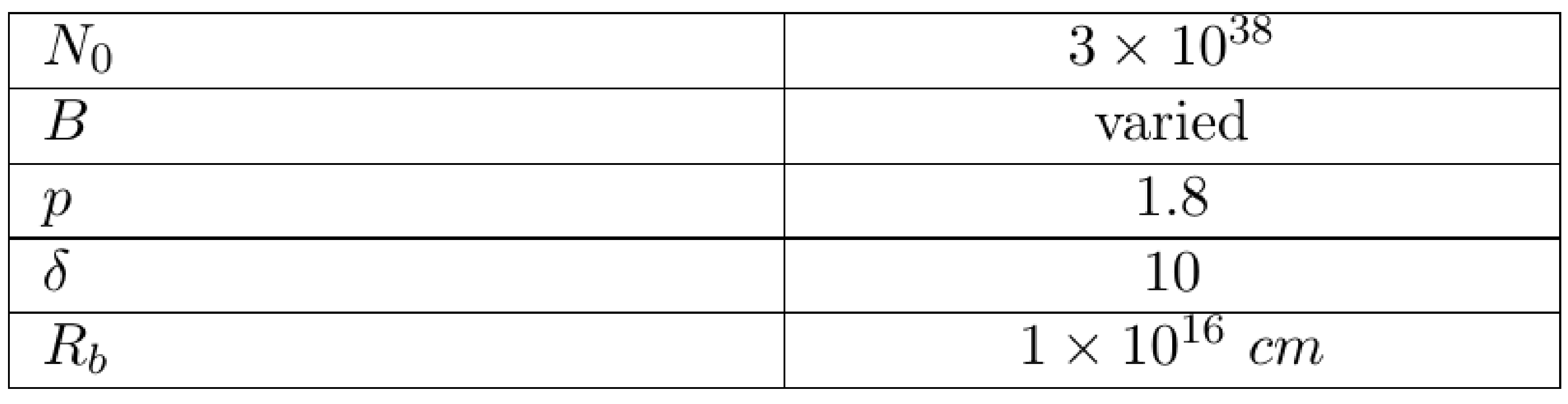
$$L_{Edd} = 1.3 \times 10^{47} \ \mathrm{erg.s}^{-1}$$

$$L_{Sum} \sim 3.04 \times 10^{47} \ erg.s^{-1}$$

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

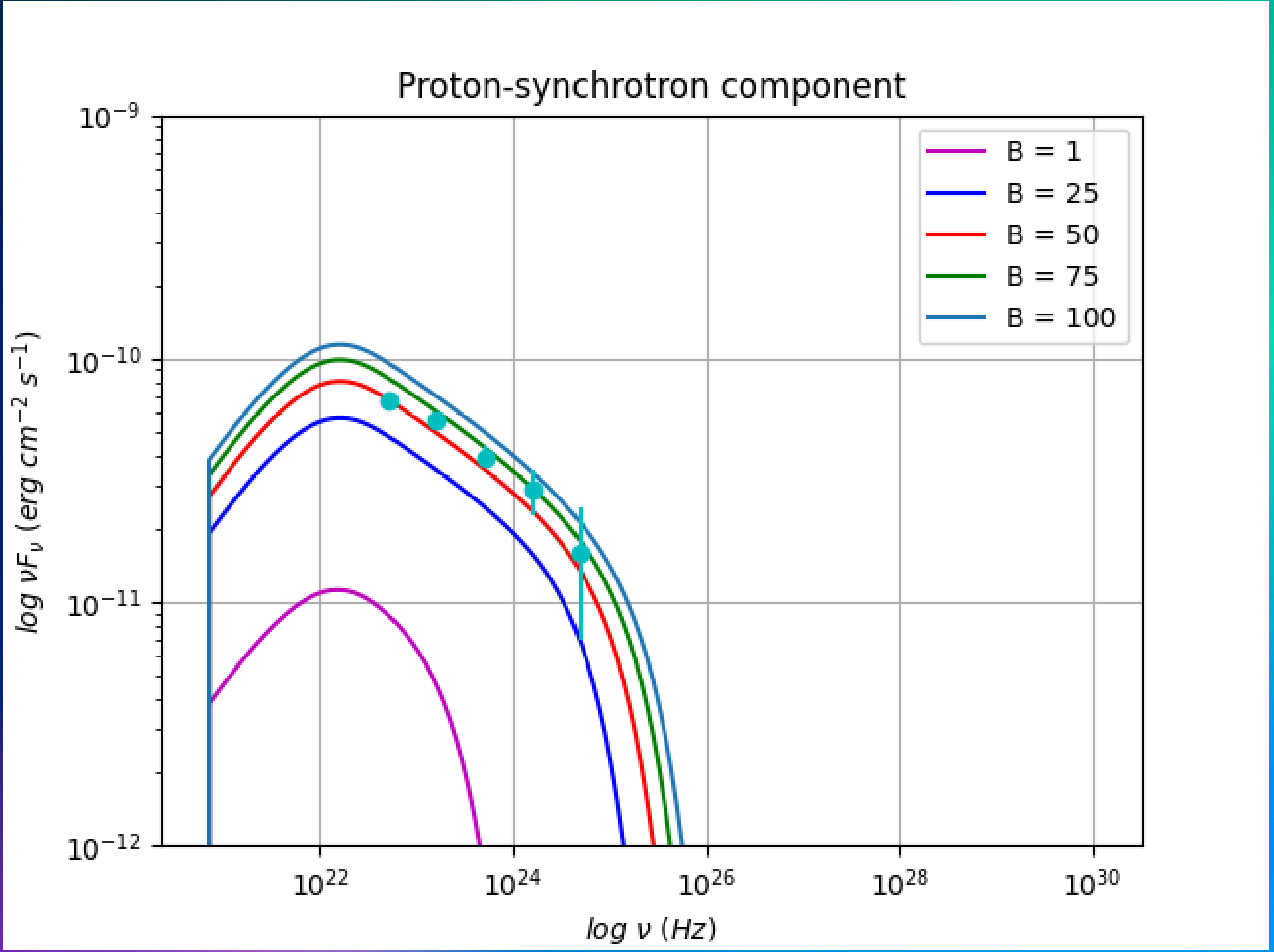
The Poynting-flux Luminosity: 2.1e+47

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.



Proton-synchrotron component

Normalisation

R_{cl}	$1 \times 10^{16}\ cm$
τ	0.01

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

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

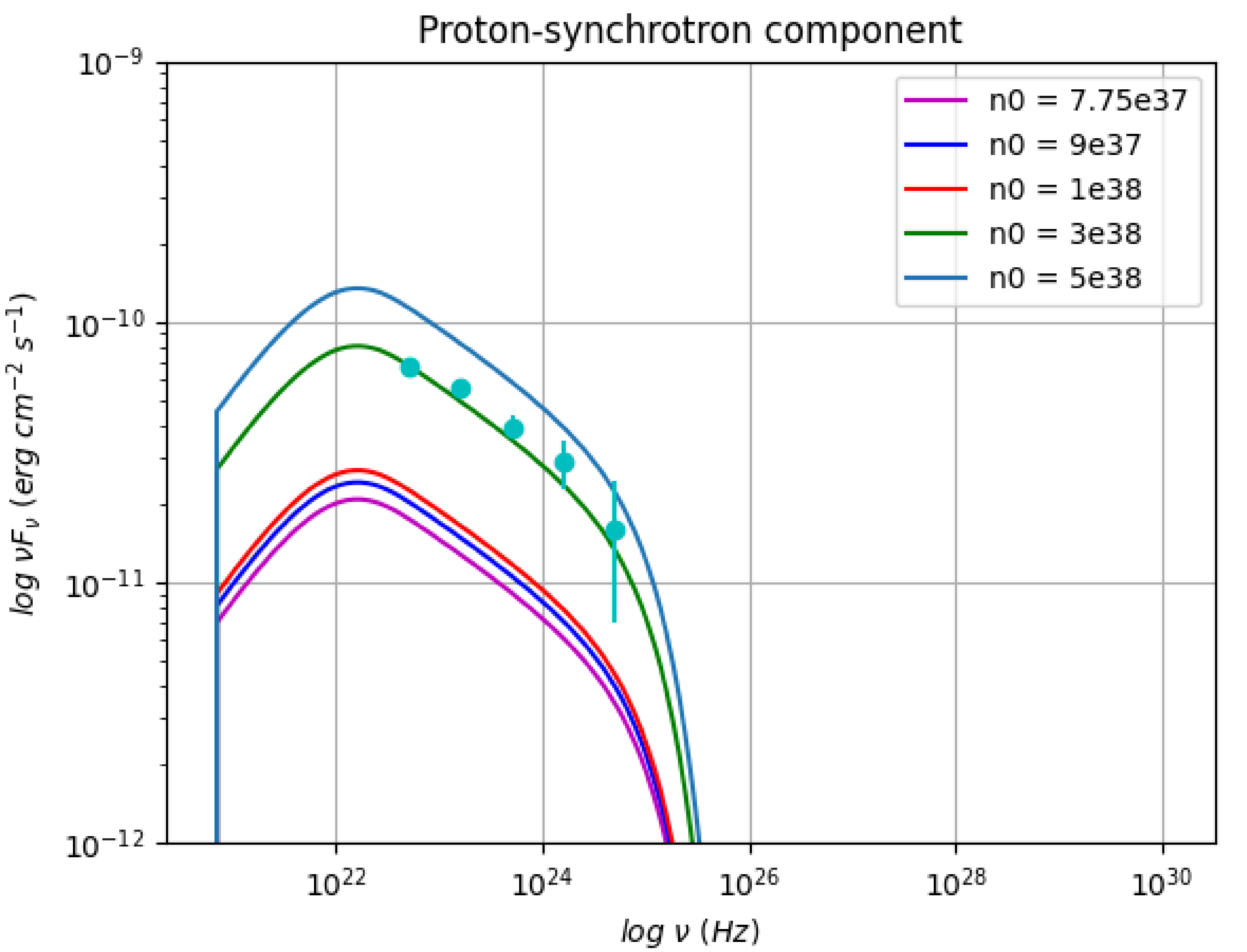
The Poynting-flux Luminosity: 9.4e+46

n0=5e38:

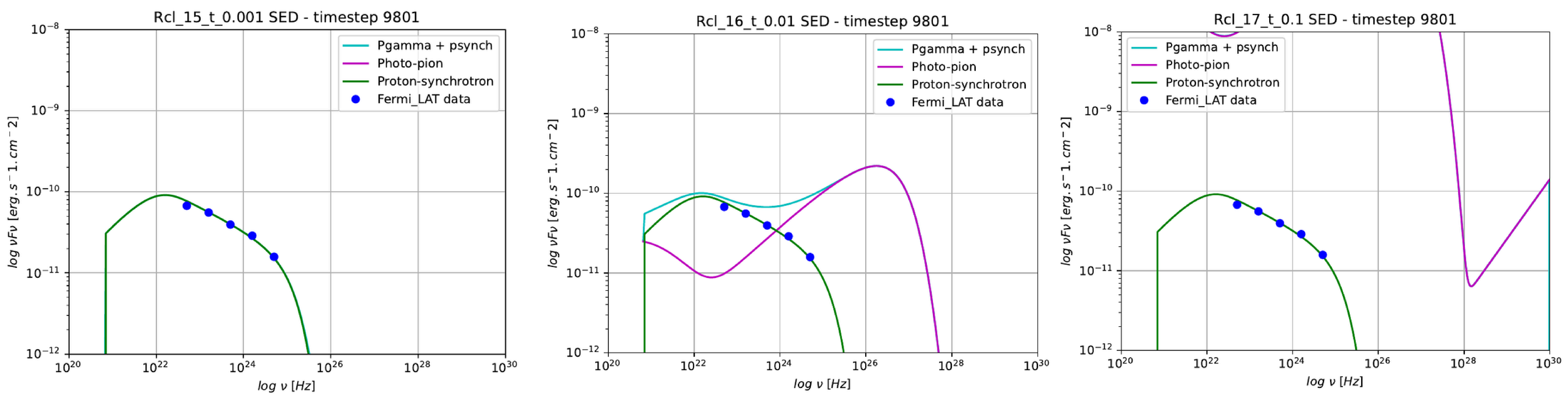
The Proton Luminosity: 3.5e+47

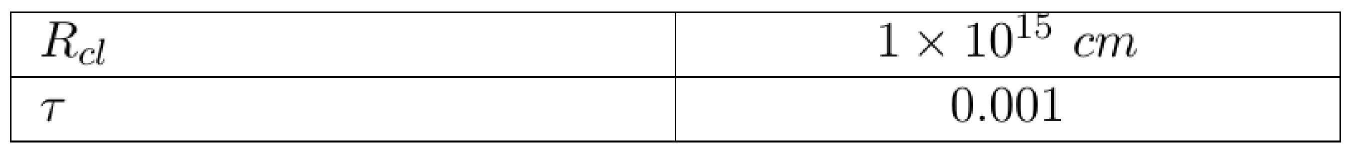
The Poynting-flux Luminosity: 9.4e+46

- 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.

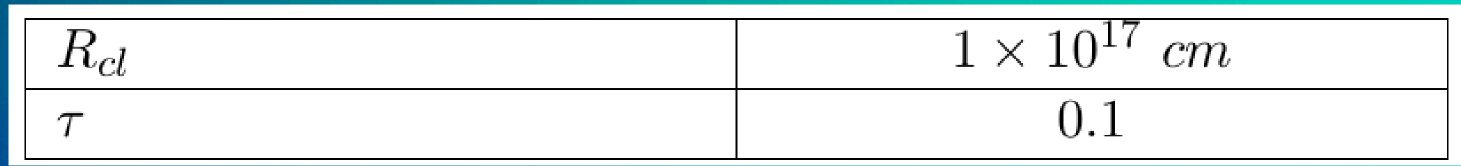


Cloud parameter

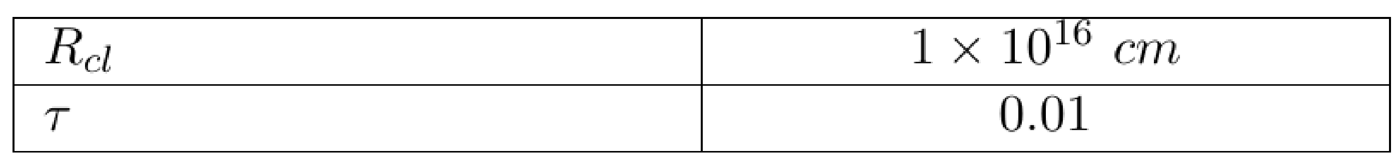




R_{cl}	$1 \times 10^{15}\ cm$
τ	0.001



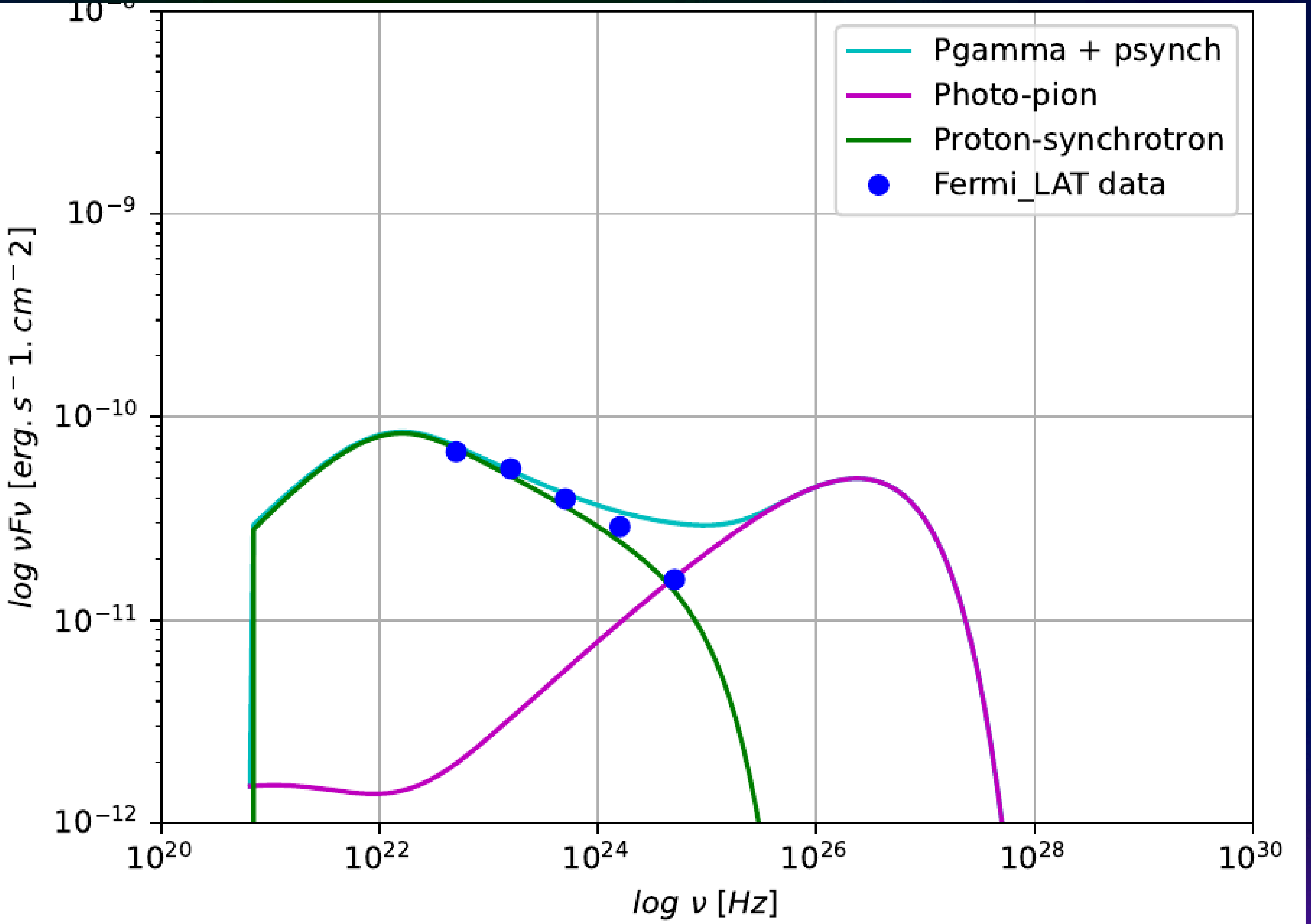
R_{cl}	$1 \times 10^{17}\ cm$
τ	0.1



R_{cl}	$1 \times 10^{16}\ cm$
τ	0.01

- The cloud parameter and fraction of reflected photons determine if the hadronic synchrotron mirror model is efficient enough to have significant emission.

Parameterstudy Results



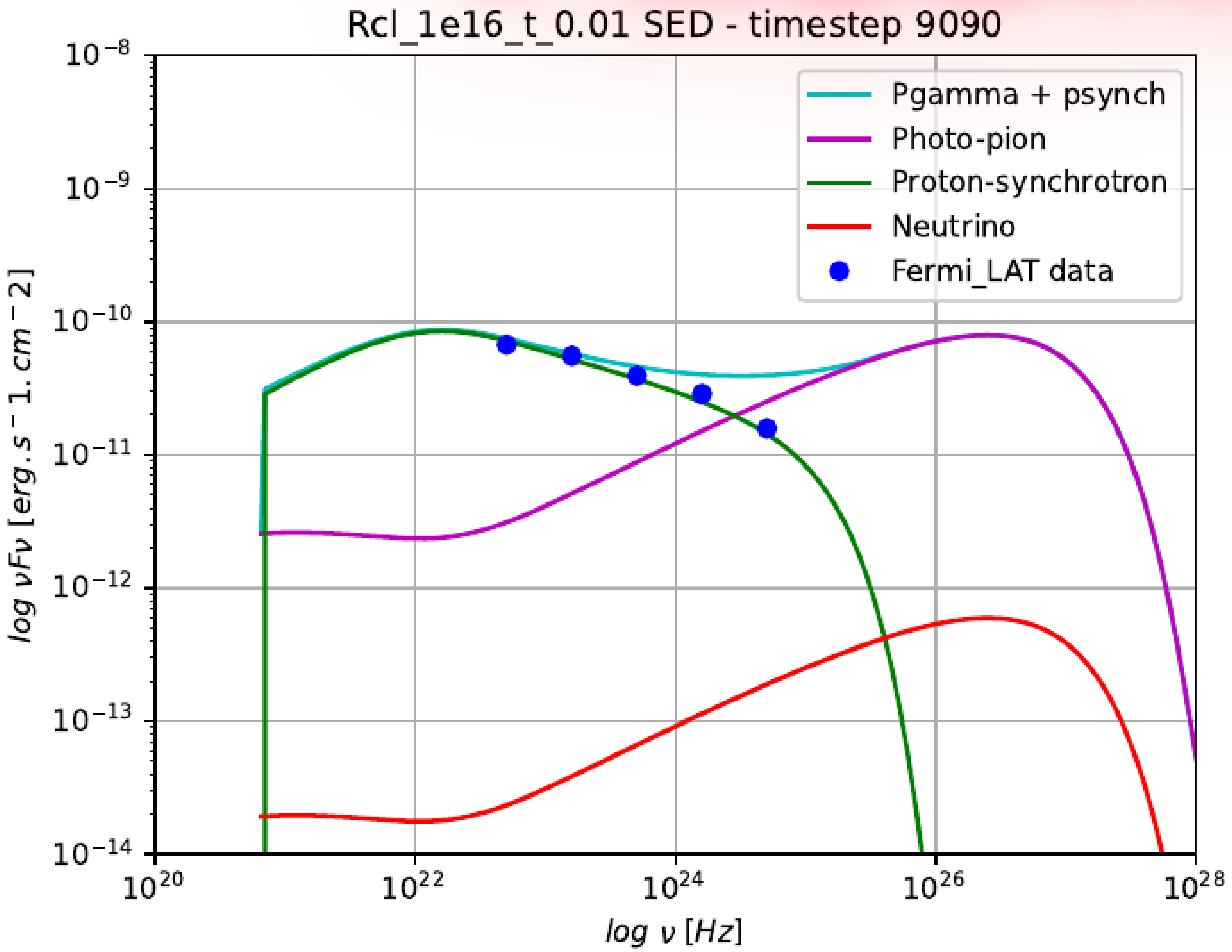
N_0	3×10^{38}
B	$53\ G$
p	1.8
δ	10
R_b	1×10^{16}

R_{cl}	$1 \times 10^{16}\ cm$
τ	0.01

$$L_{Sum} \sim 2.9 \times 10^{47}\ erg.s^{-1}$$

Neutrino Results

PRELIMINARY



Neutrino events

KM3NeT:

$$1.5 \times 10^{-6} \; events$$

IceCube:

$$1.4 \times 10^{-9} \; events$$

Summary

Summary

- The target photon field is dense enough for photo-pion interactions.
- 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.
- From the parameterstudy sub-Eddington jet powers were not found, but this can be explained by the jet power only being higher during the flare and reverting back to a sub-Eddington value during the quiescent state.
- Neutrino events are very few and would make detection hard.

Future work

- A comparative study of different models.
  - “Ring-of-fire” model.
  - Stochastic dissipation model.
- Application of the hadronic synchrotron mirror model on multiple orphan flares.

Thank you!

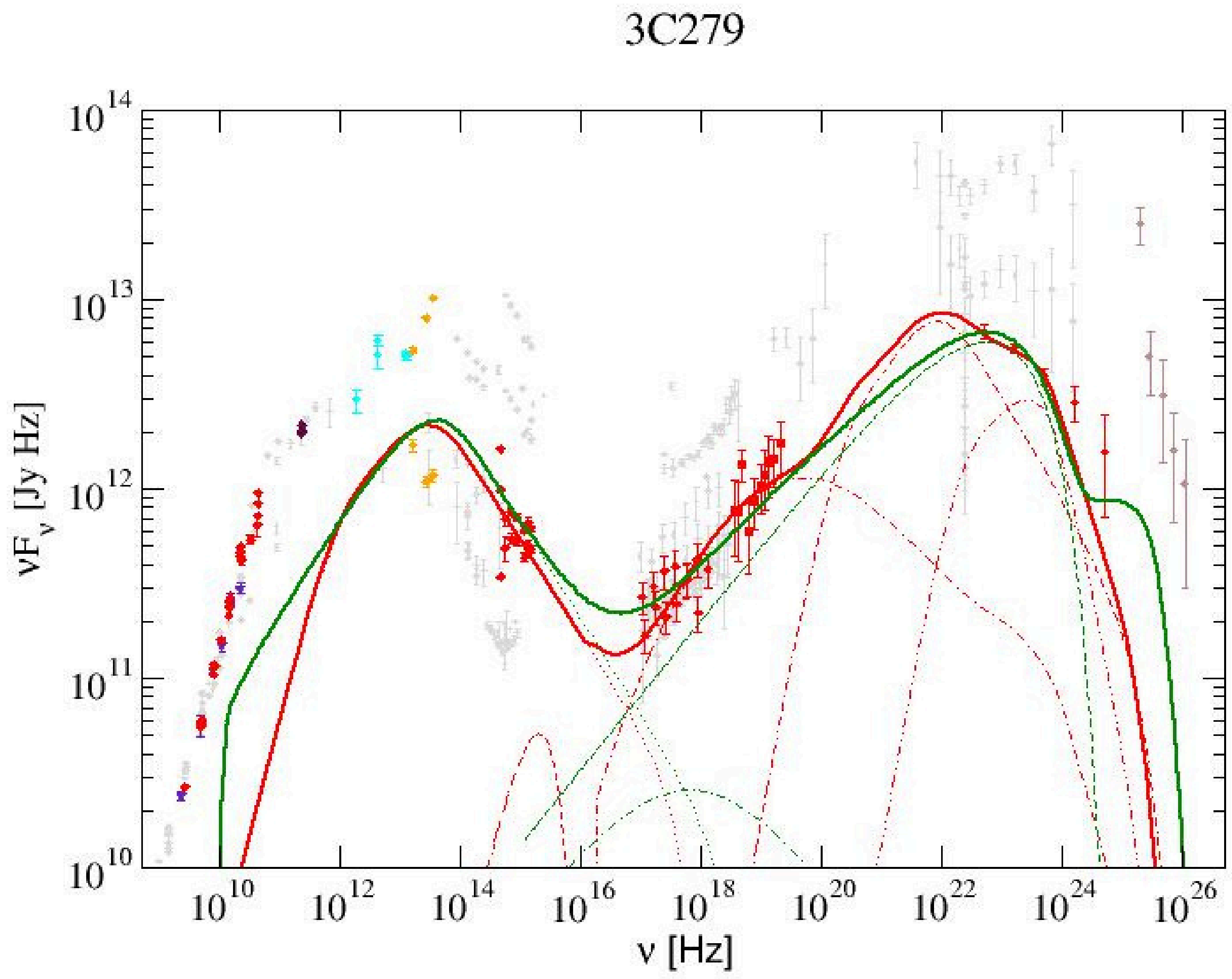
Feel free to ask if you have any questions.

Photo Credits: Cornelia Arcaro

Appendix

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]

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 γγ-opacity.
- Calculate the resulting electromagnetic cascades to find the emerging SED.

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:

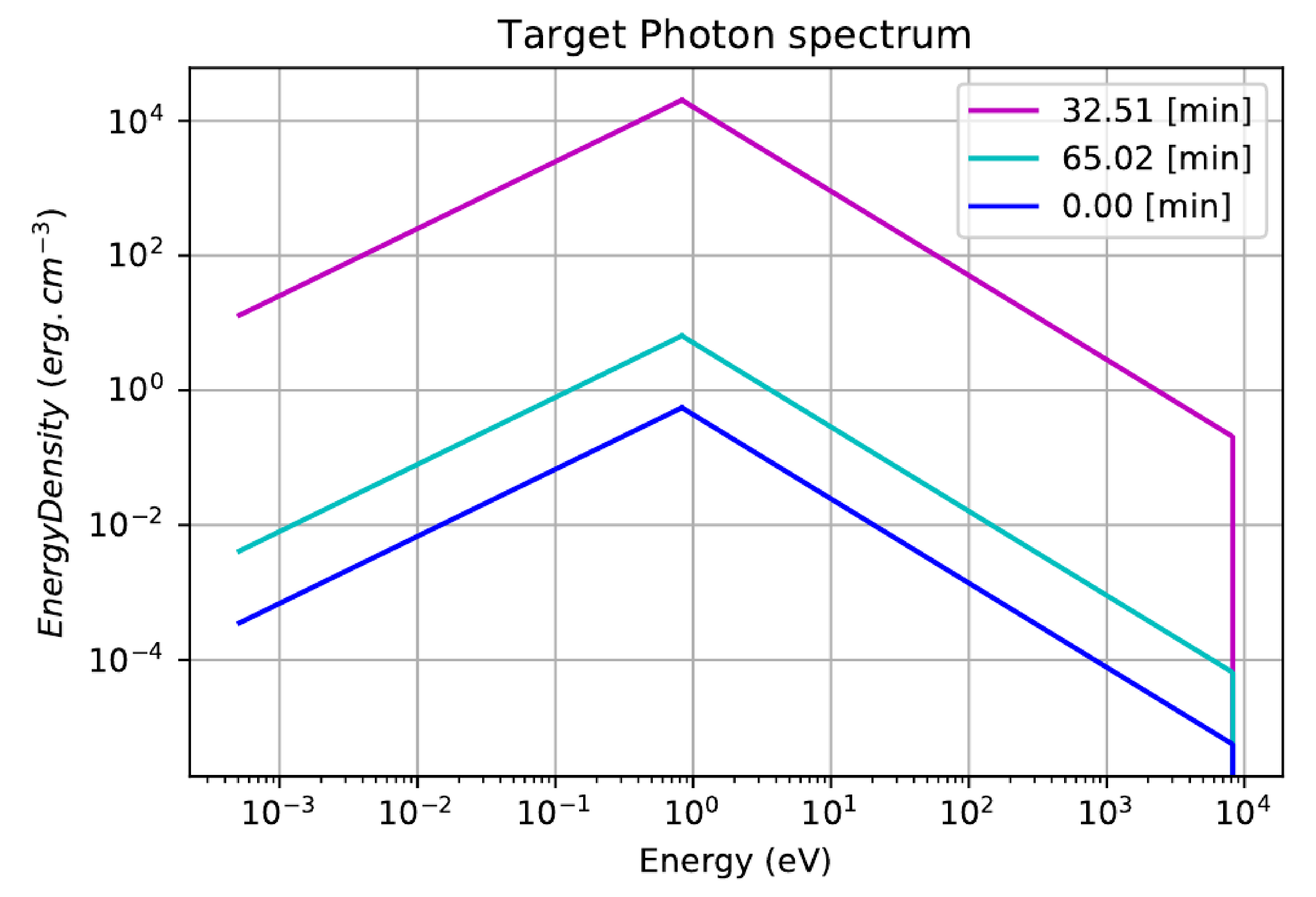
$$\langle u'_{R,sy}(t_1)\rangle = \frac{4\Gamma^6 \nu F_\nu(sy) d_L^2 \tau R_{cl}^2}{3(R_m - R_b)} \int_0^{\frac{R_m - R_b}{\beta c}} \frac{dt_1}{(R_m - \beta c t_1)^2 (R_m - \frac{\beta c t_1}{2})^2}$$

- 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

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.

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

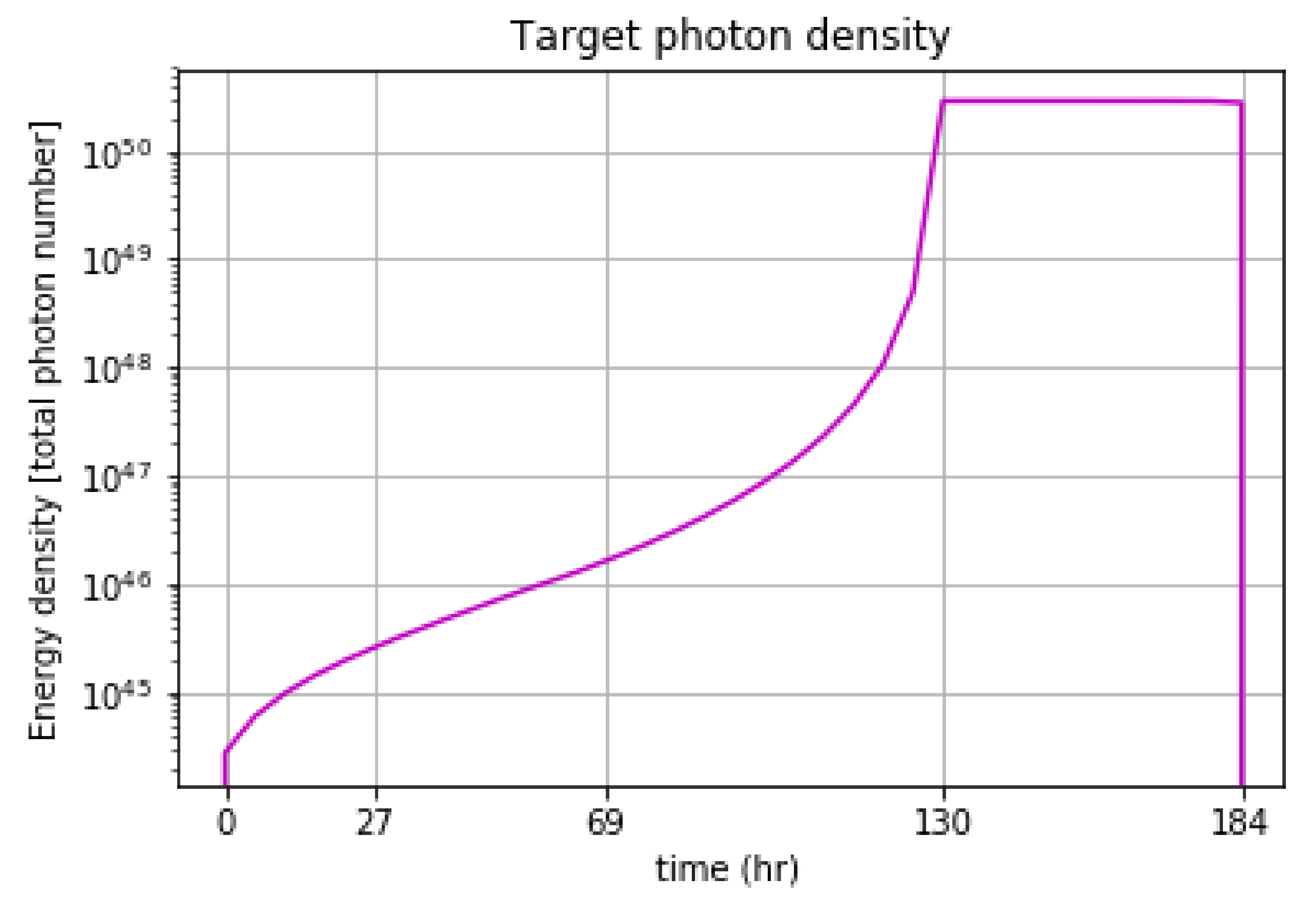
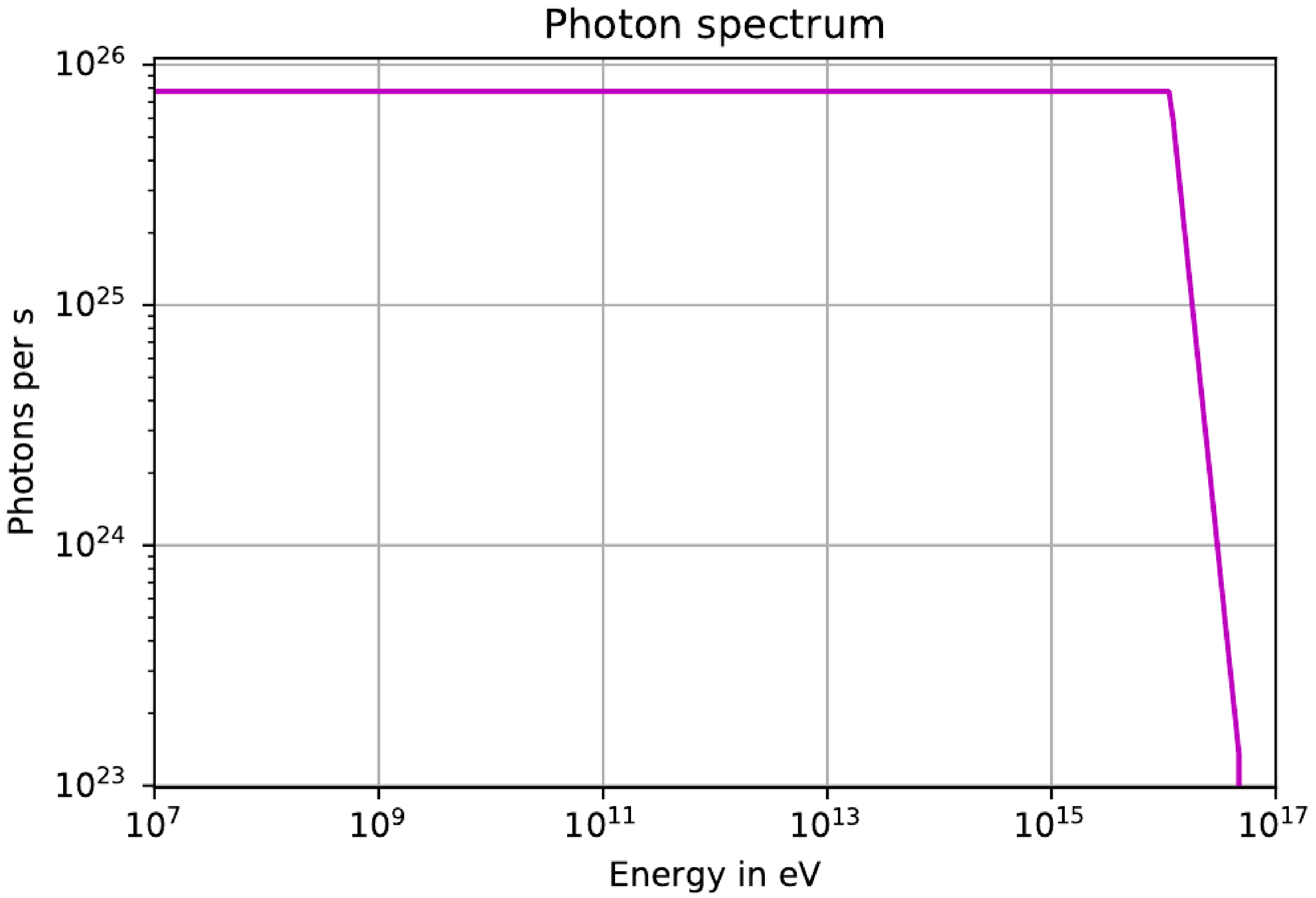


Photo-pion production

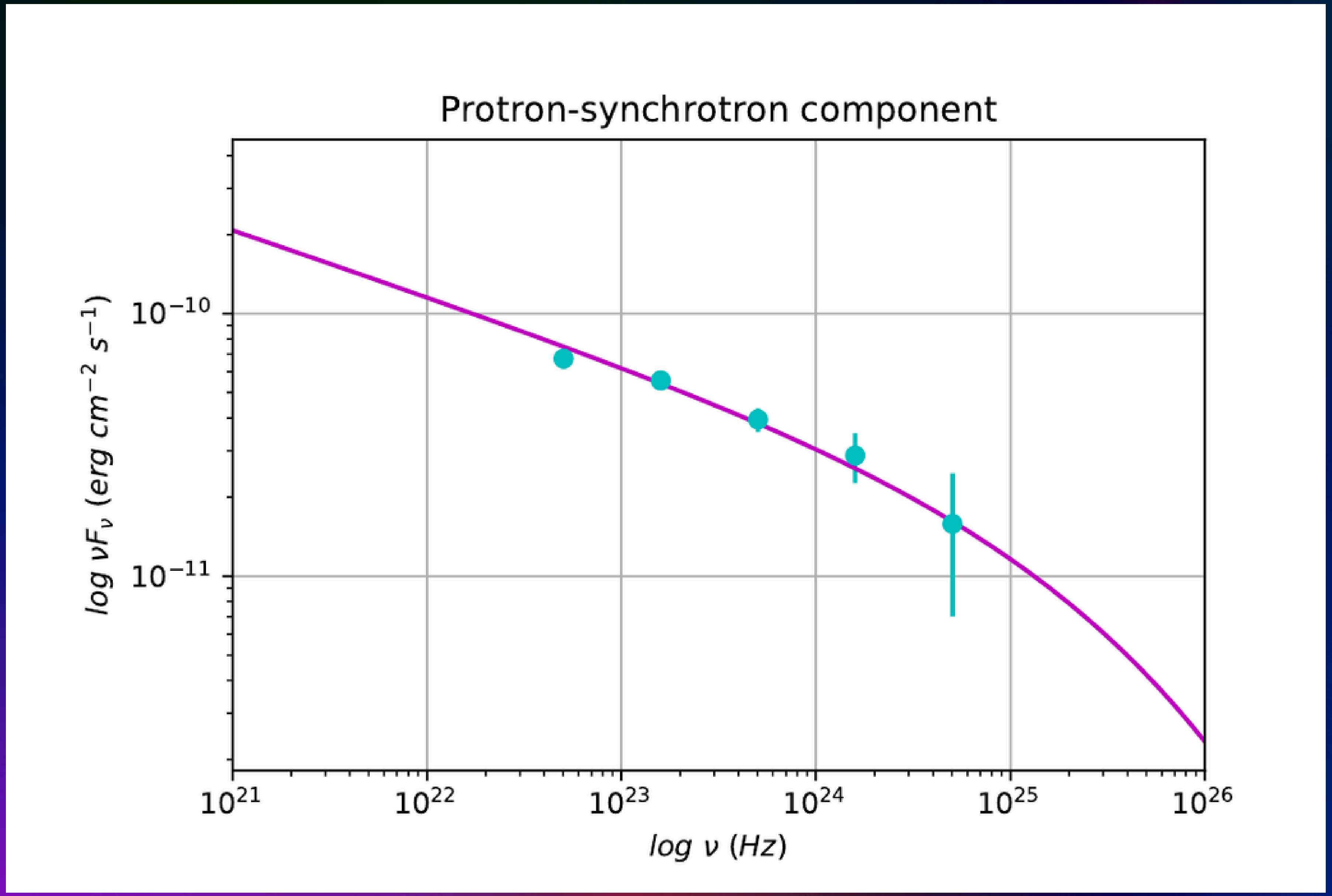
$$\dot{N}_{\gamma}^{\pi_0}(\epsilon) = \sigma_0 n_0 \frac{c N_0 E_\Delta}{2 m_\pi c^2 (\alpha + 1)} \times \int_{max[\epsilon \frac{m_e}{m_\pi}, \gamma_b, \frac{E_\Delta}{2\epsilon_2 m_e c^2}]}^{\gamma_{cr,max}} d\gamma_\pi \gamma_\pi^{-(2+s)} \left(max \left[\epsilon_1, \frac{E_\Delta}{2 \gamma_\pi m_e c^2} \right] - \epsilon_2^{-(\alpha+1)} \right)$$

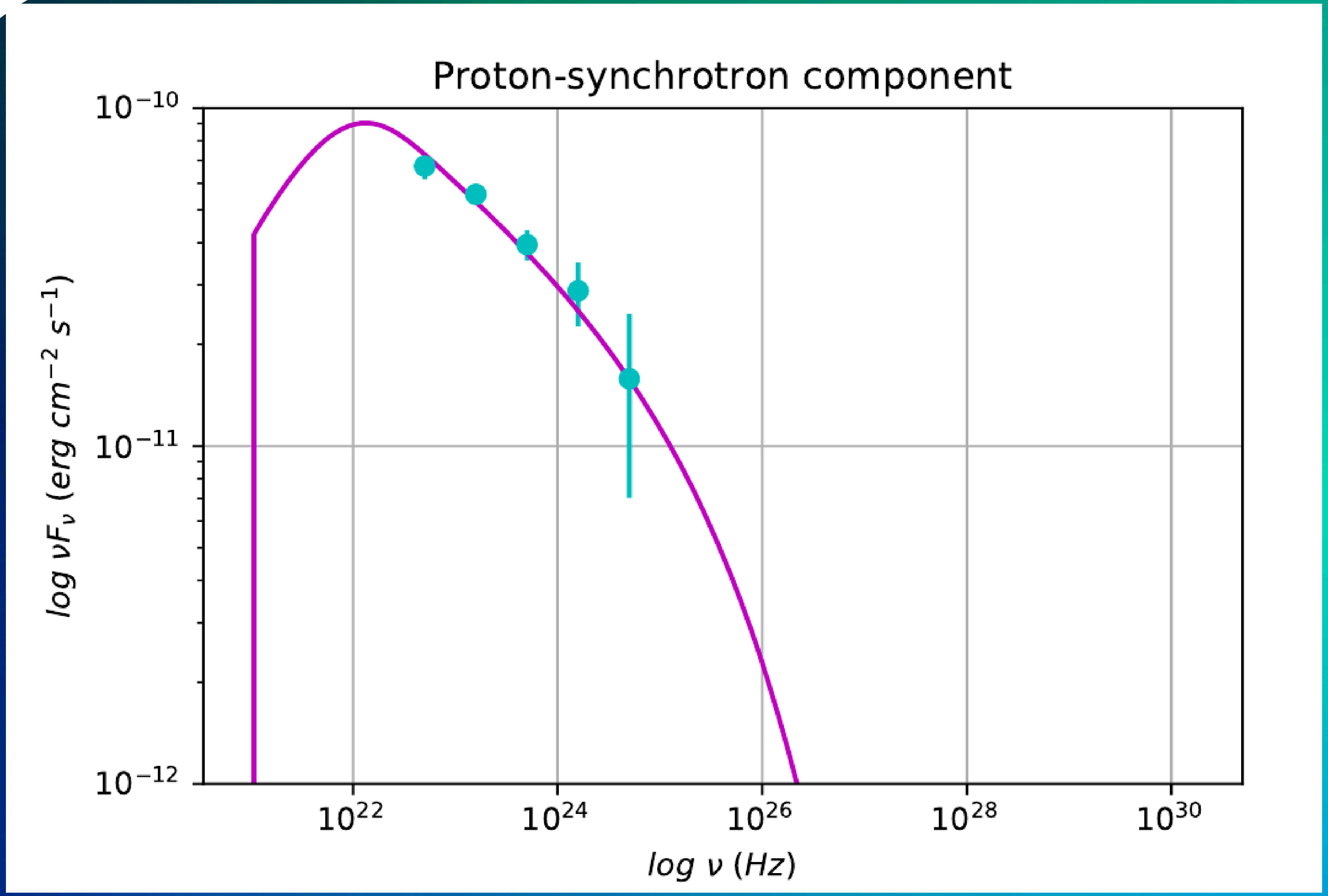
[BÖTTCHER AND DERMER, 1998]

- 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.



Proton Spectrum





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

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