# Neutral pion bumps in the TeV spectra of X-ray flaring blazars

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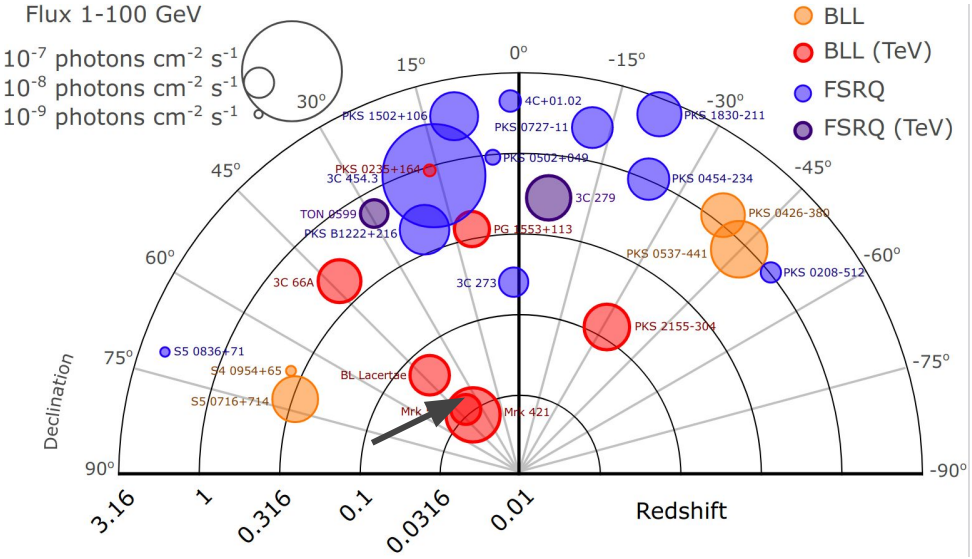
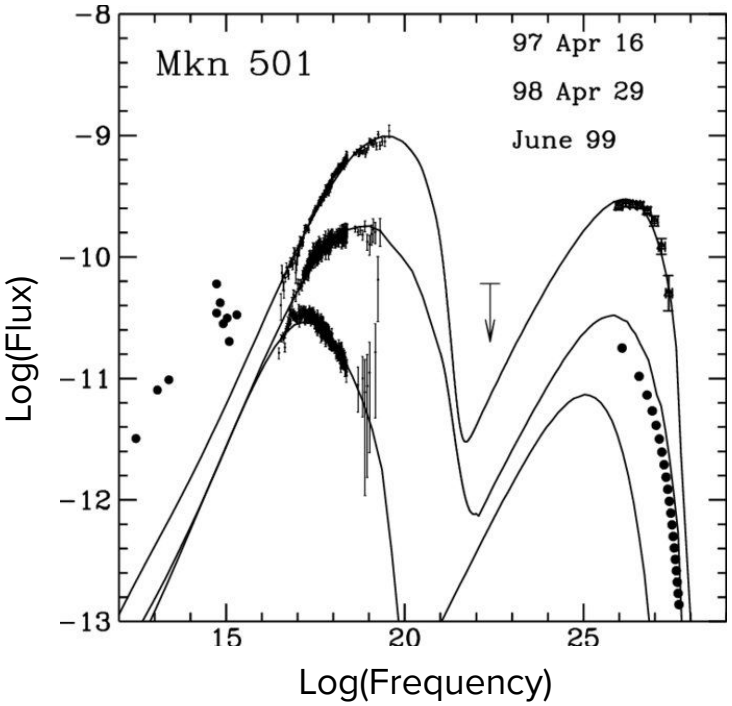
# Introduction to Mrk 501

- One of the nearest to Earth TeV blazars
- Hard X-ray flares ($E_{pk}$> 10 keV)
- Transient extreme blazar



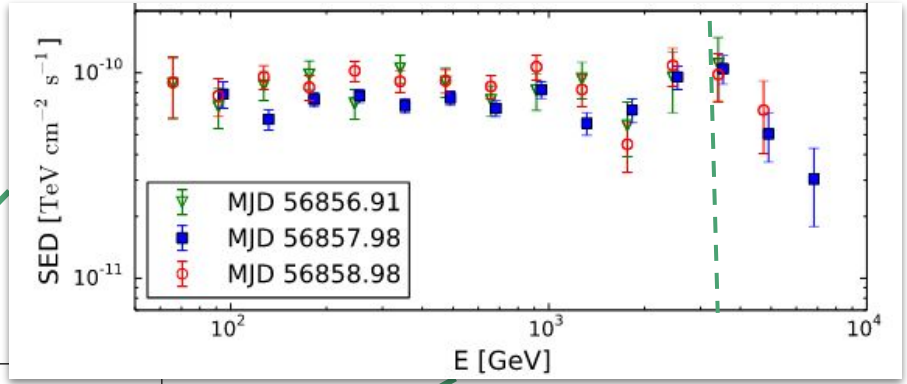

Credit: S. Dimitrakoudis

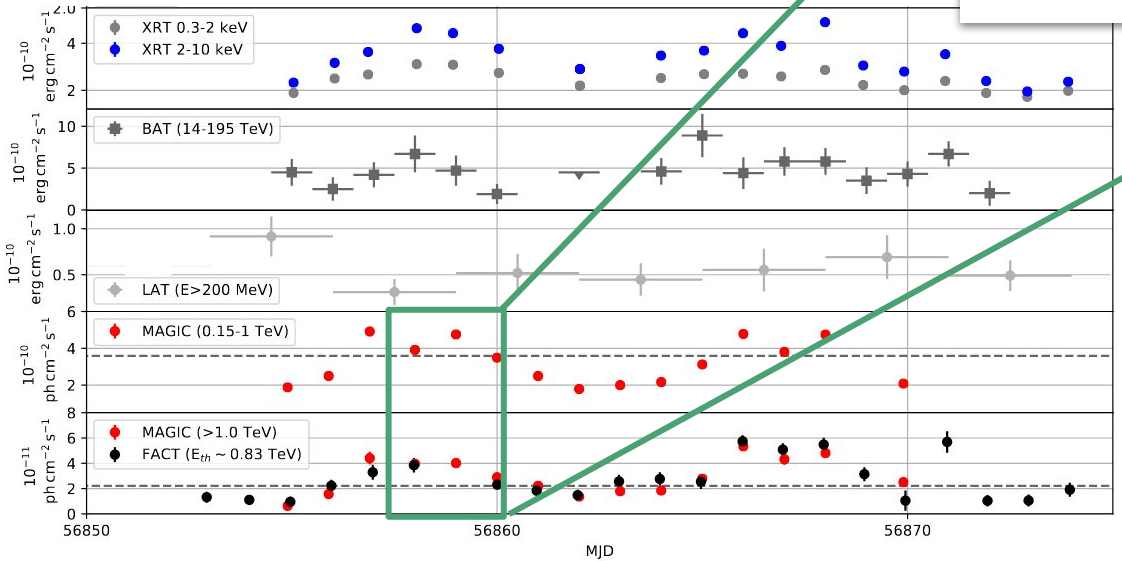
Tavecchio et al. 2008, ApJ



# Motivation

- X-ray & VHE flaring activity in July 2014
- Narrow spectral feature at ~ 3 TeV

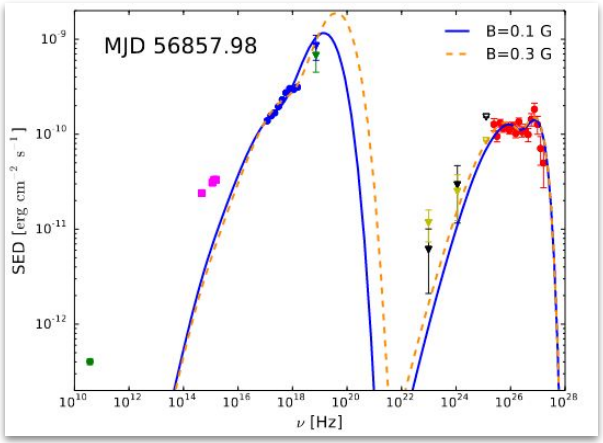



MAGIC Collaboration et al., 2020, A&A, 637, 86

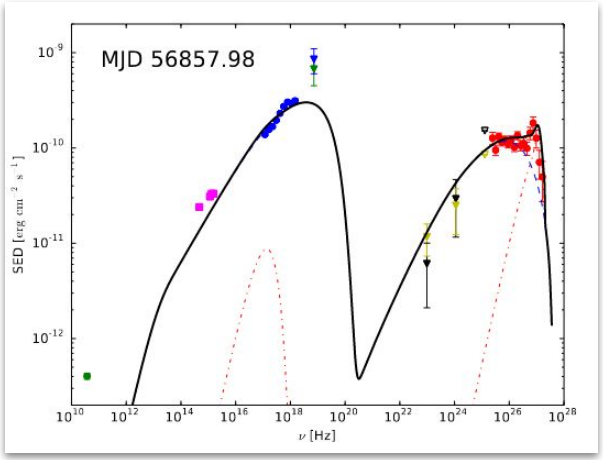
# Various interpretations of TeV feature

SSC from piled-up EED

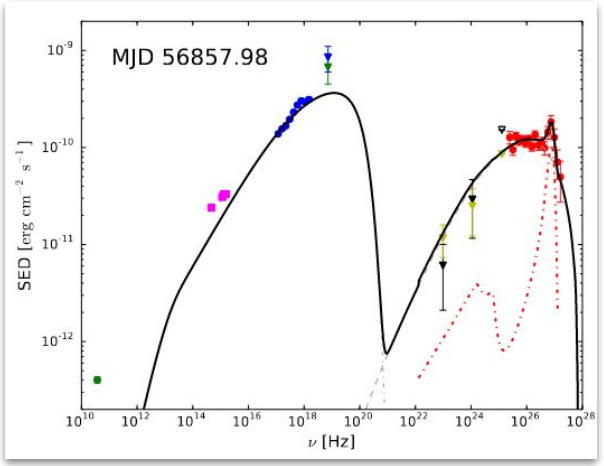



MAGIC Collaboration et al., 2020, A&A, 637, 86

SSC from 2 emitting regions

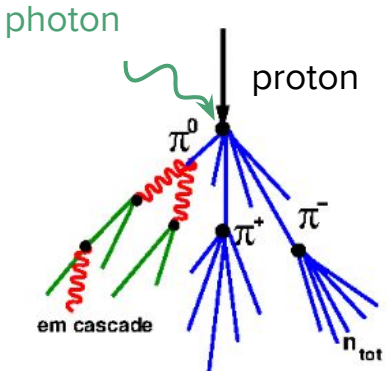



SSC + IC cascade model




(see also Wendel et al. 2021, A&A)

# An alternative scenario




- Narrow TeV spectral feature ➙ monoenergetic protons with tens of TeV energy

$$\varepsilon_p \approx 10\ \mathrm{TeV}\left(\frac{\varepsilon_\gamma}{1\ \mathrm{TeV}}\right)$$

- Energetic target photons needed for pion production

Interaction with jet photons

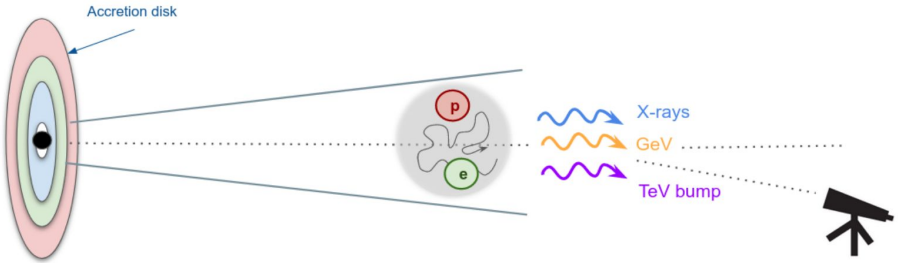
$$\left(\frac{\varepsilon_t}{0.5\ \mathrm{MeV}}\right)\left(\frac{\varepsilon_\gamma}{1\ \mathrm{TeV}}\right) \gtrsim 1.45\,(1+z)^{-2}\left(\frac{\delta}{10}\right)^2.$$

Interaction with external photons

$$\left(\frac{\varepsilon_t}{10\ \mathrm{keV}}\right)\left(\frac{\varepsilon_\gamma}{1\ \mathrm{TeV}}\right) \gtrsim 1.45\,(1+z)^{-2}.$$

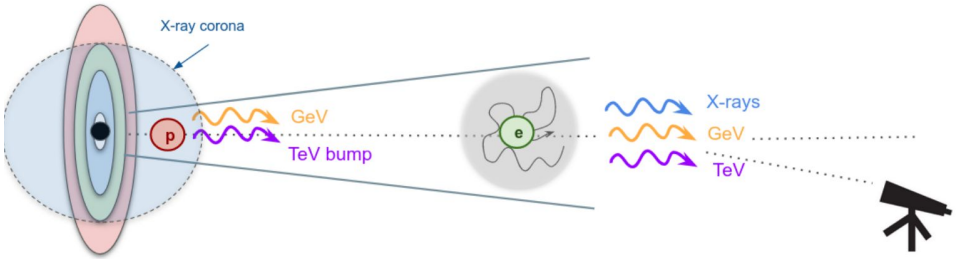
# A simple model for high-energy flares

Multi-wavelength flare produced in the same region down the jet




Photopion production on synchrotron jet photons

TeV flare produced in the inner jet regions (within X-ray coronal field)

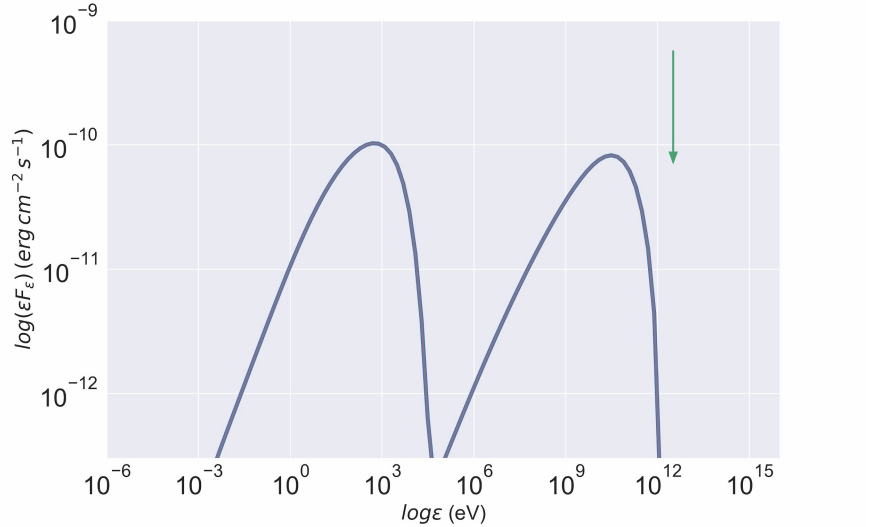



Photopion production on hard X-rays from corona

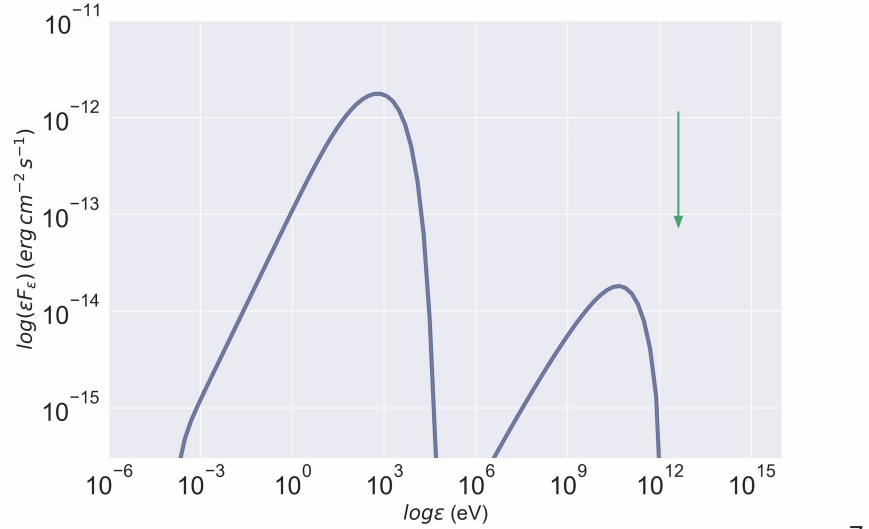
# X-ray jet photons: SEDs

$E_{e,max} = E_{p,max} =$ 32 TeV (Flare) and 1 TeV (Quiet)
Other parameters: se = sp = 1.9, B=0.86 G, R=1e15 cm, δ=20

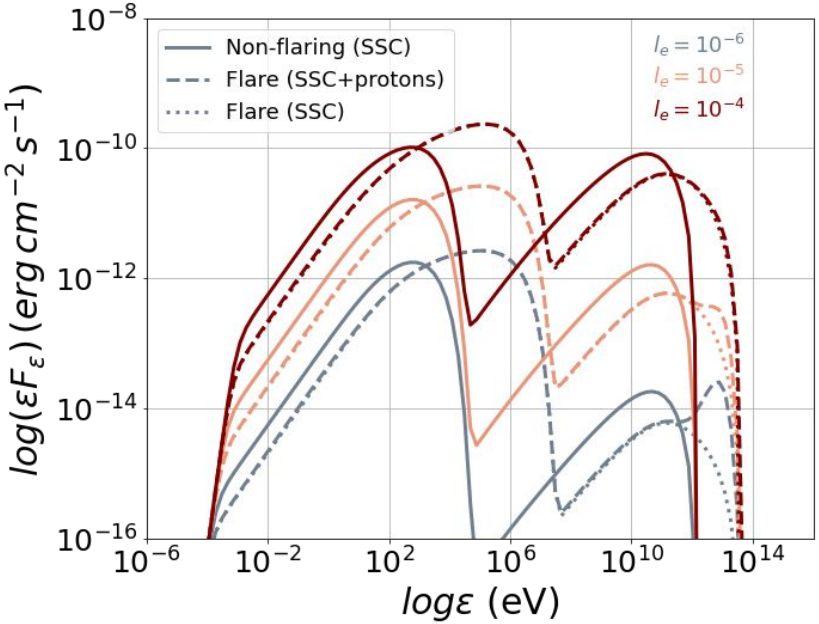
Hardening of TeV spectrum




Narrow TeV spectral feature

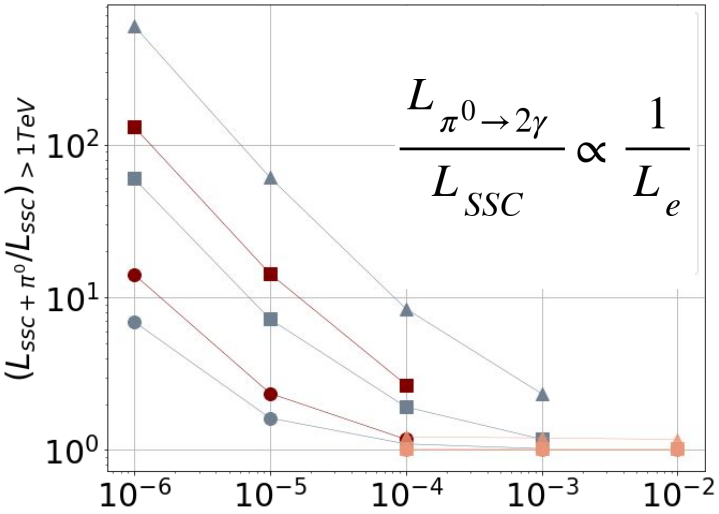


# X-ray jet photons: SSC vs. $\pi^0$ decay



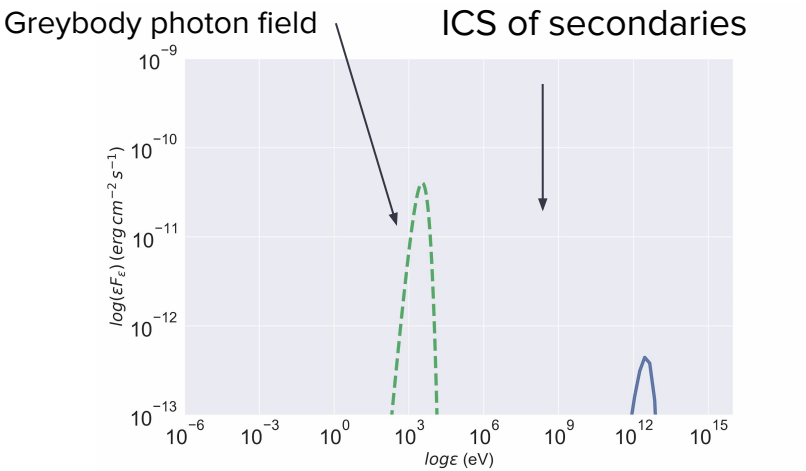

Other parameters: B=0.86 G, R=1e15 cm, δ=20

As the electron luminosity increases, the SSC component hides the $\pi^0$ bump:

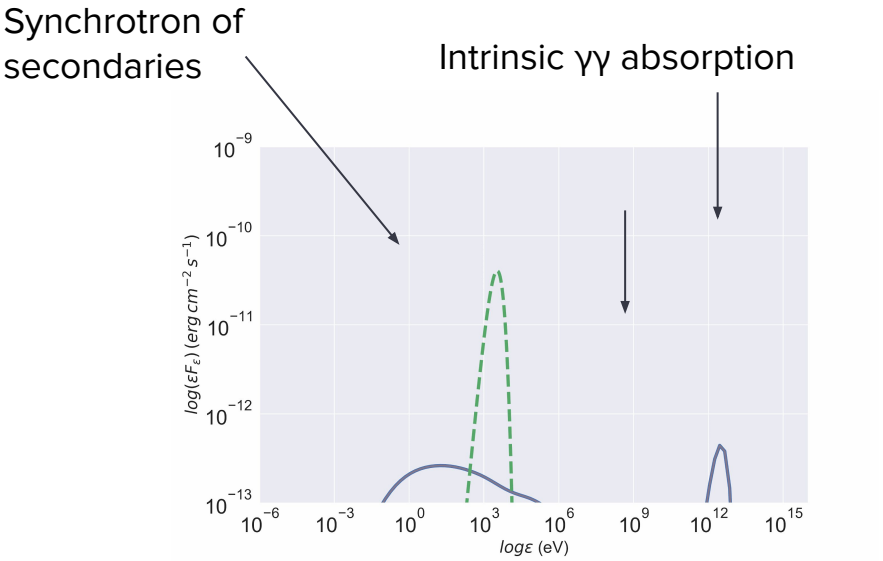


# X-ray ambient photons: SEDs

Weak magnetic field (B=0.1 mG)




Strong magnetic field (B=0.1 kG)

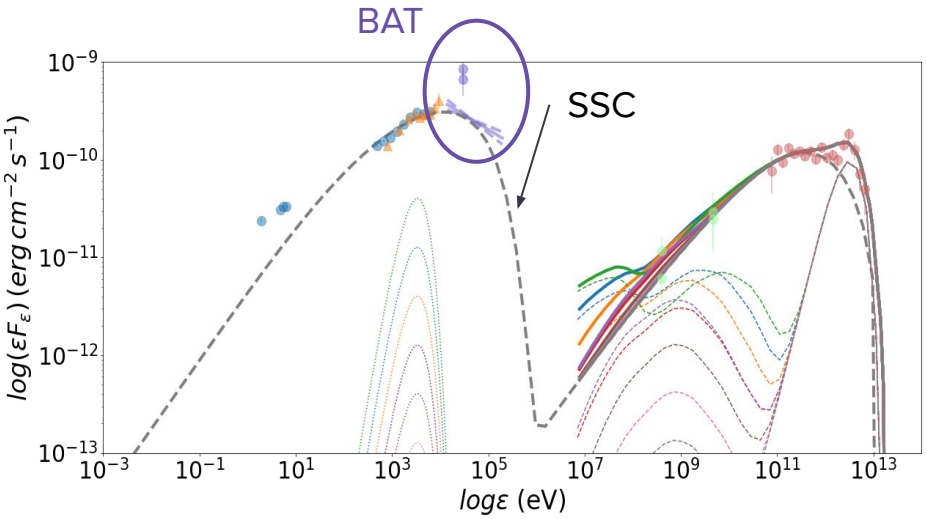



Other parameters: δ=10, R=1e15 cm, Lp,j = 1e49 erg/s

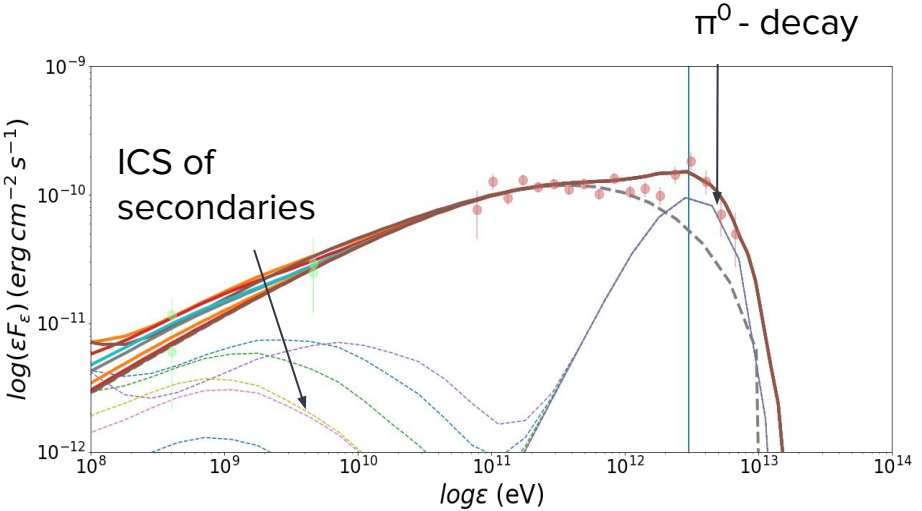
# Application to Mrk 501

preliminary

MJD 56857.98

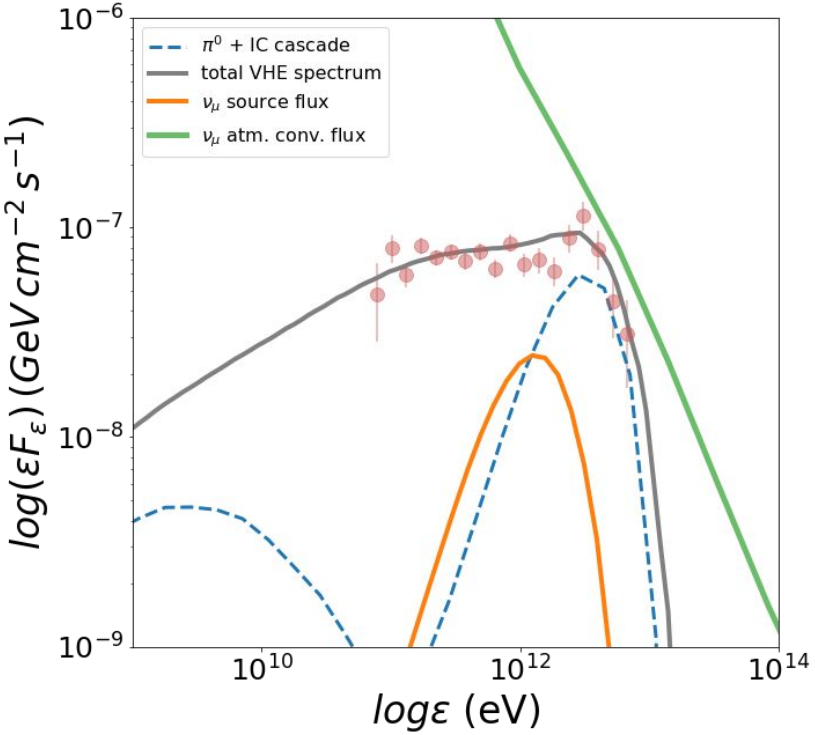



- Different combinations of $u_{ext}$ and $L_p$ can lead to the same $\pi^0$ γ-ray flux
- Limits on $u_{ext}/u_B$ can be placed using optical/UV + X-ray obs.




Data from MAGIC Collaboration et al., 2020, A&A

# Neutrinos from flaring Mrk 501 ?

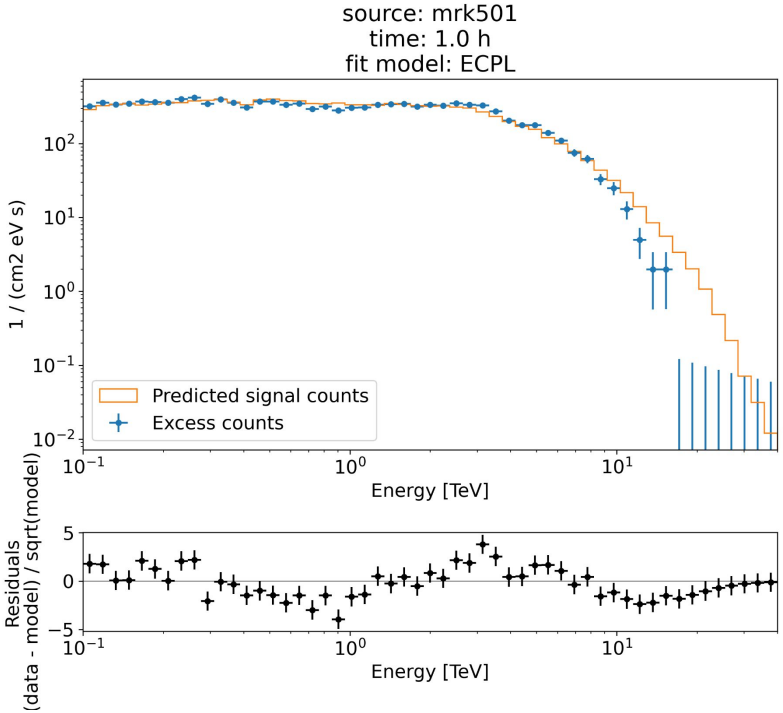


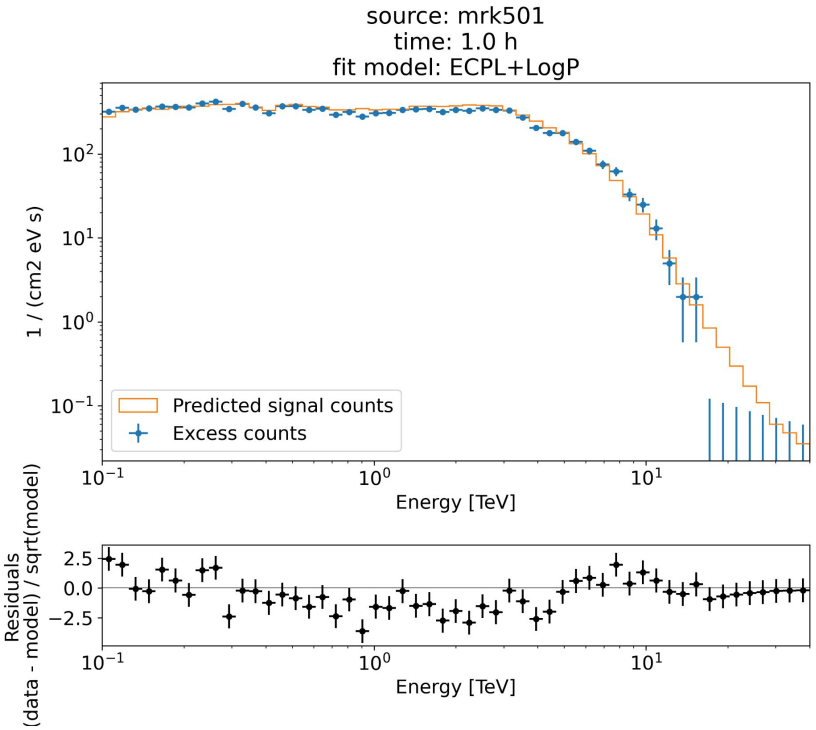

preliminary

- Atmospheric muon neutrino flux from Honda et al. (HKKMS2007) plotted assuming $\Delta\Omega = 1$ deg
- Source neutrino flux well hidden in the atmospheric background

# CTA: 1 hr exposure

Foivos Zanias
undergrad @ NKUA



# CTA: 0.1 hr exposure

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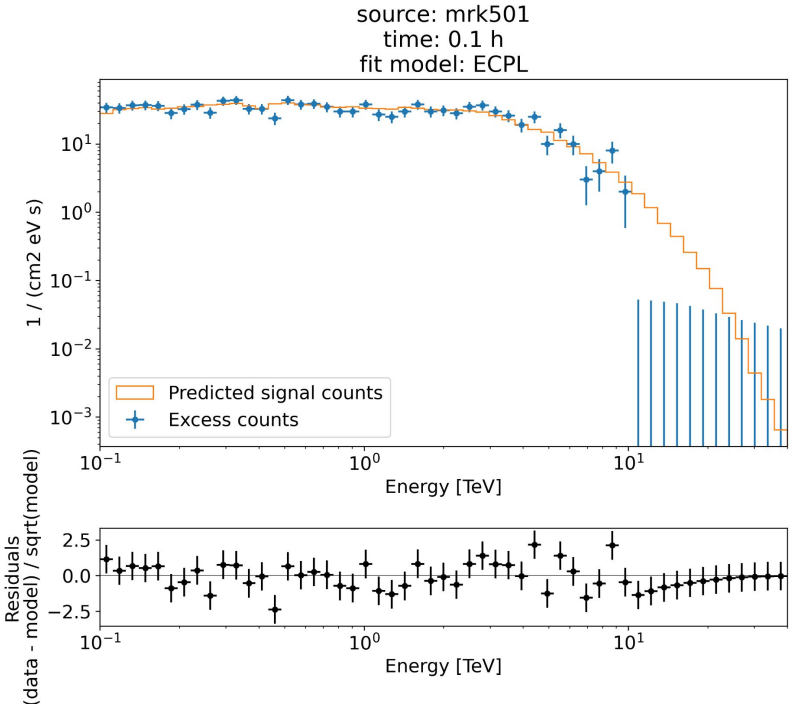
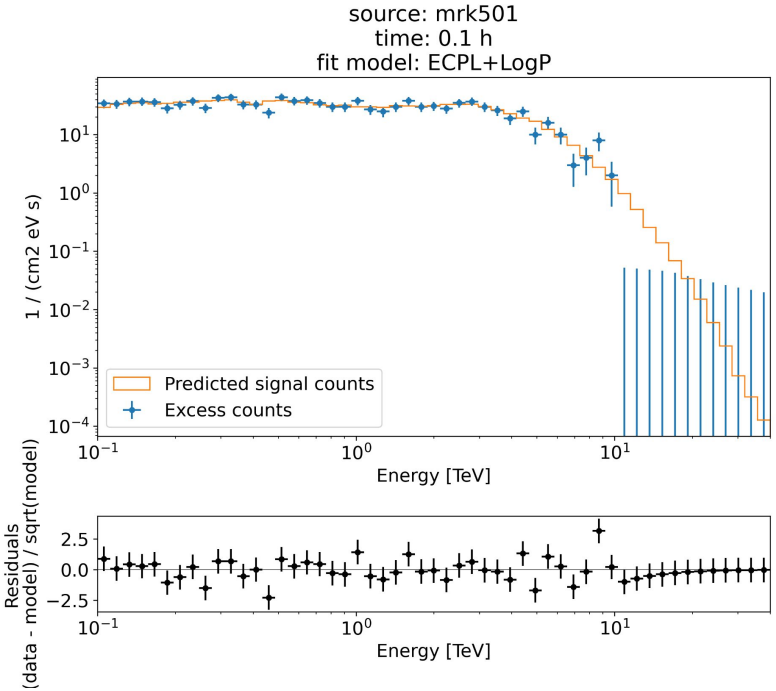
undergrad @ NKUA



# Conclusions

- Intermittent proton acceleration to tens of TeV in flaring blazars can lead to transient narrow TeV spectral features from $\pi^0$ decay
- Effectively mono-energetic proton distributions and hard X-ray / soft γ-ray photons are needed
- TeV neutrinos with similar flux as the VHE feature are expected. Neutrino signal hidden in the atmospheric background, unless bumps at E > 30 TeV are discovered!
- Preliminary application to the VHE data of Mrk 501 in July 2014 is promising
- CTA will be able to better resolve such features with exposure times < 1 hr and allow searches for time variability

Thank you!

Contact email: mpetropo@phys.uoa.gr

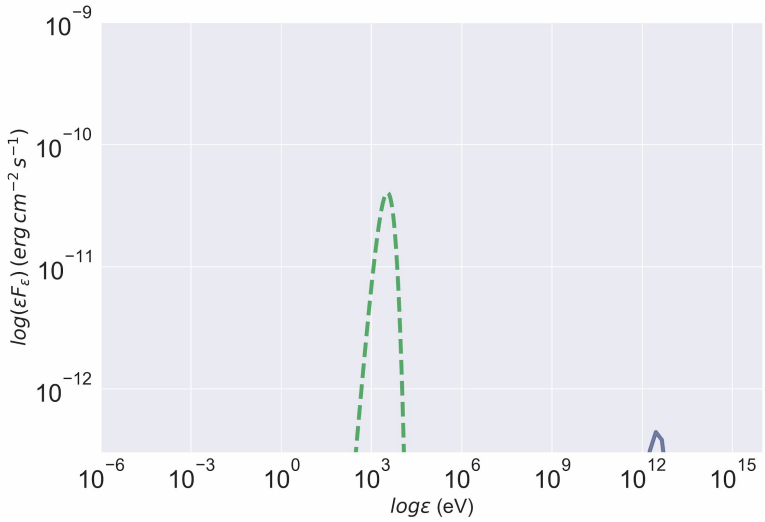
Petropoulou, Mastichiadis, Paneque et al., **in prep.**

# Back-up slides

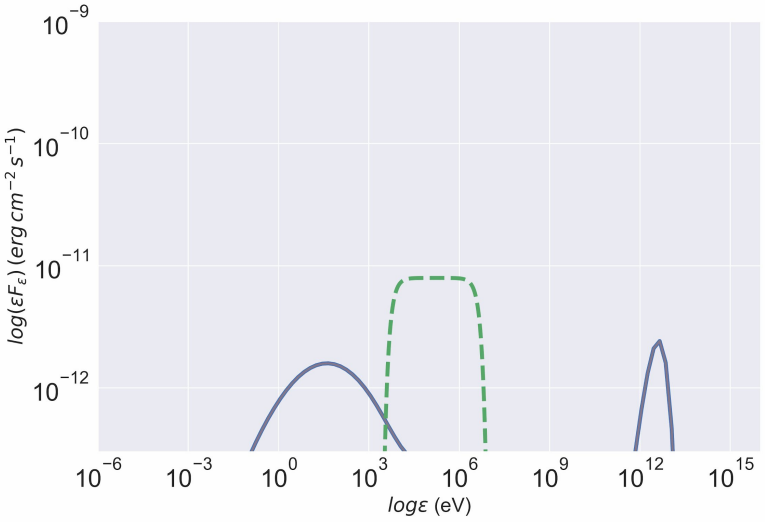
# X-ray ambient photons: SEDs - 2

Strong magnetic field (B=0.1 kG)

Grey-body photon field




Power-law photon field




Other parameters: δ=10, R=1e15 cm, Lp,j = 1e49 erg/s

# Comparison of composite models

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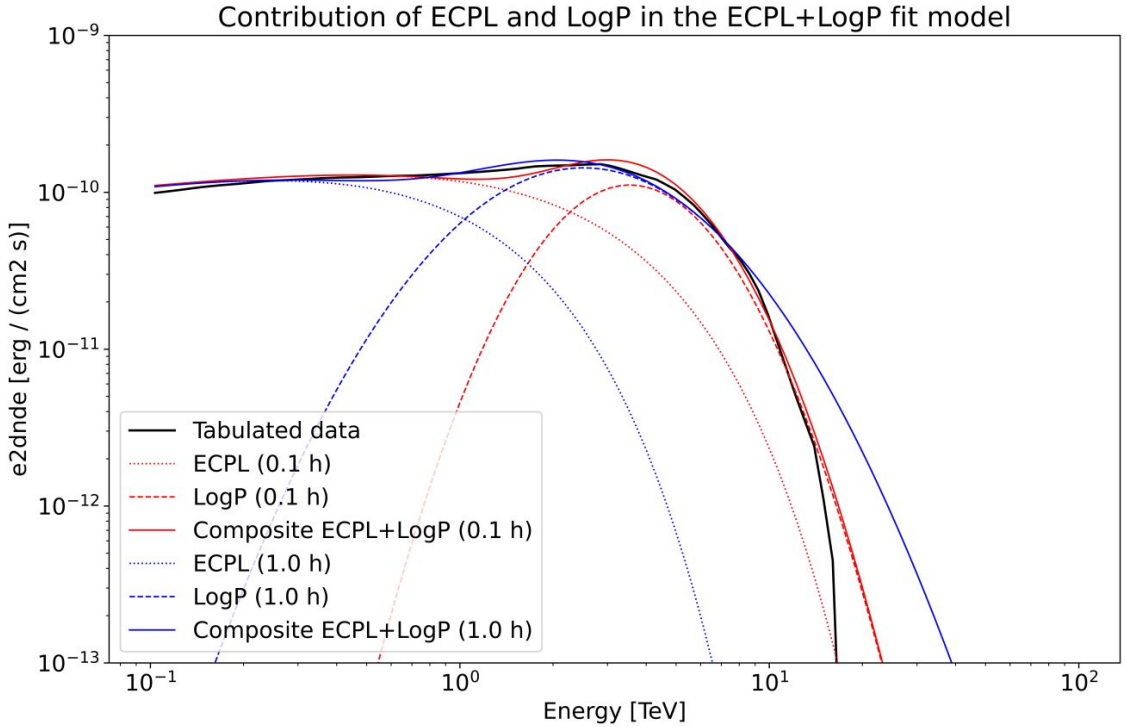
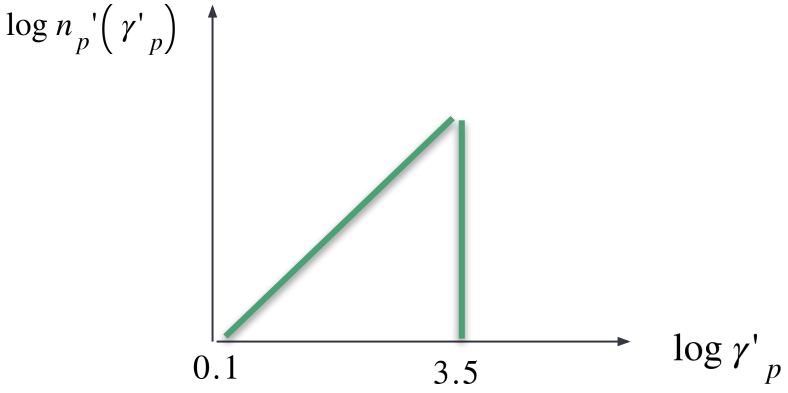


# Energetics

Power in relativistic protons: $L_{p,j} = 2\pi R^2 \Gamma^2 c\, u'_p \approx 2\pi R^2 \Gamma^2 c\, \langle \gamma'_p \rangle n'_p m_p c^2$

## Effectively monoenergetic proton distribution

$$\langle \gamma'_p \rangle \approx \begin{cases} 2000\ (Flare) \\ 2\ (Quiet) \end{cases} \qquad L_{p,j} \approx \begin{cases} 10^{49}\ erg/s\ (Flare) \\ 10^{46}\ erg/s\ (Quiet) \end{cases}$$




## Extended proton distribution

$$\langle \gamma'_p \rangle \approx \begin{cases} 13\ (Flare) \\ 3\ (Quiet) \end{cases} \qquad L_{p,j} \approx \begin{cases} 10^{49}\ erg/s\ (Flare) \\ 2.5 \cdot 10^{48}\ erg/s\ (Quiet) \end{cases}$$