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A Theoretical Model to Explain TeV Gamma-ray and X-ray Correlation in Blazars

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OUTLINE

- Observations: TeV and X-ray correlations and disconnections
- Theoretical model:
  - Generalities
  - Lepton model
  - Hadronic model
- Application to Mrk 421
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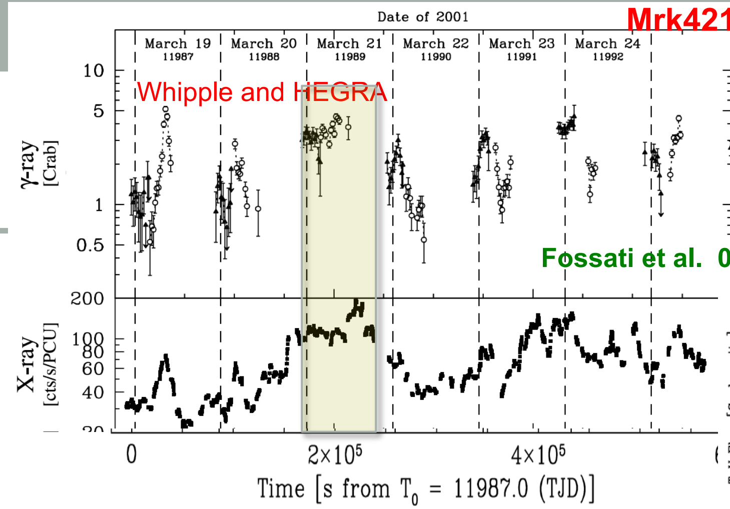
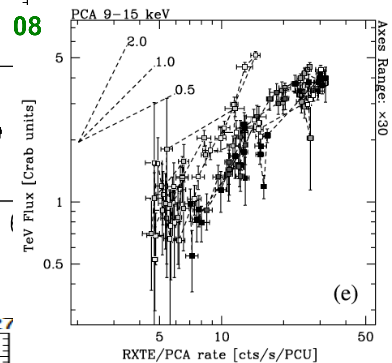
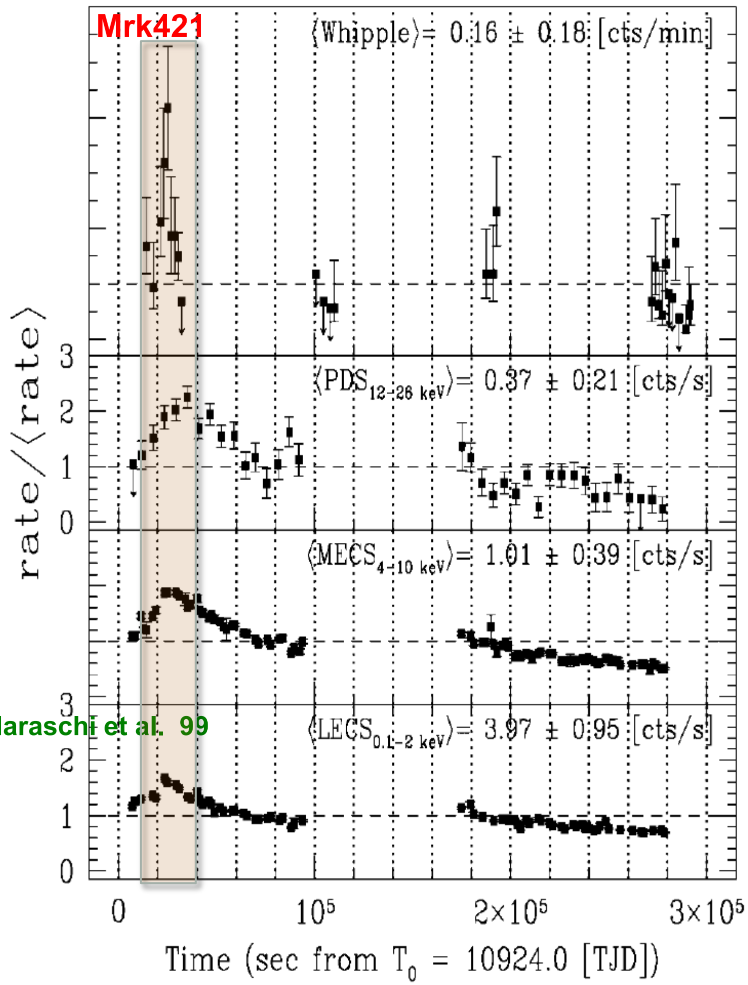
➢ Correlations

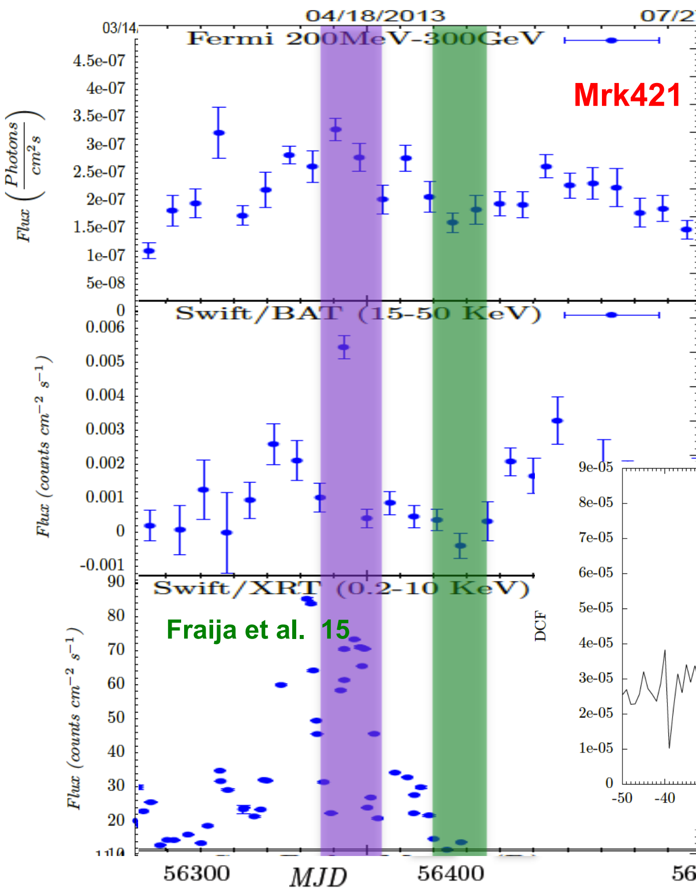


X-ray and TeV are highly correlated. (flaring activity 2001).

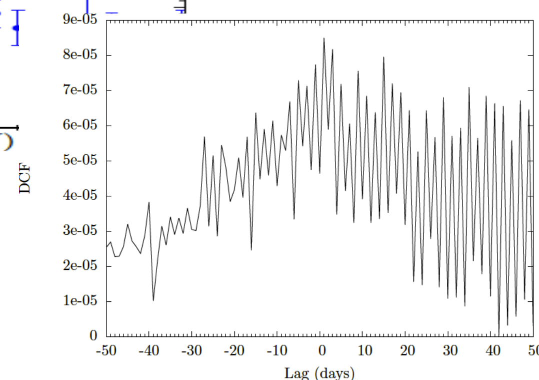




X-ray and TeV are well correlated on timescale of hours (flaring activity April/98).

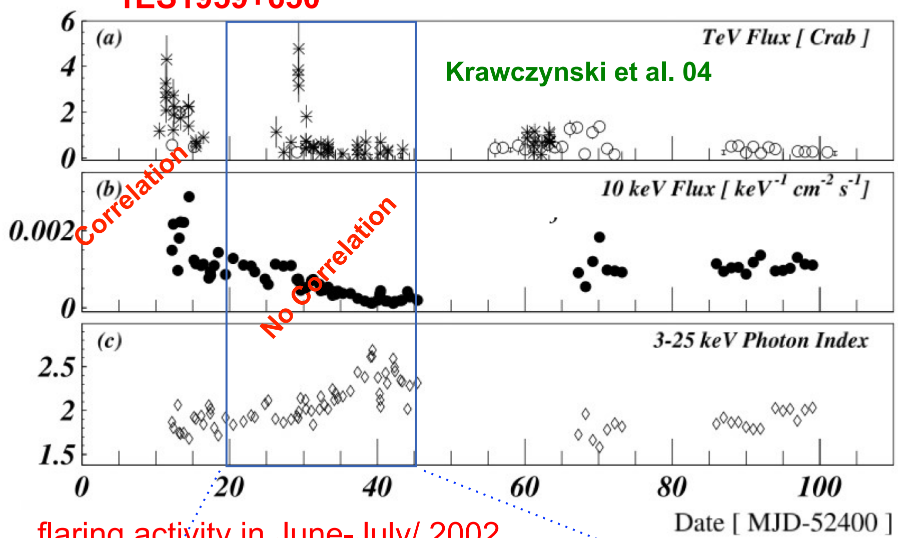


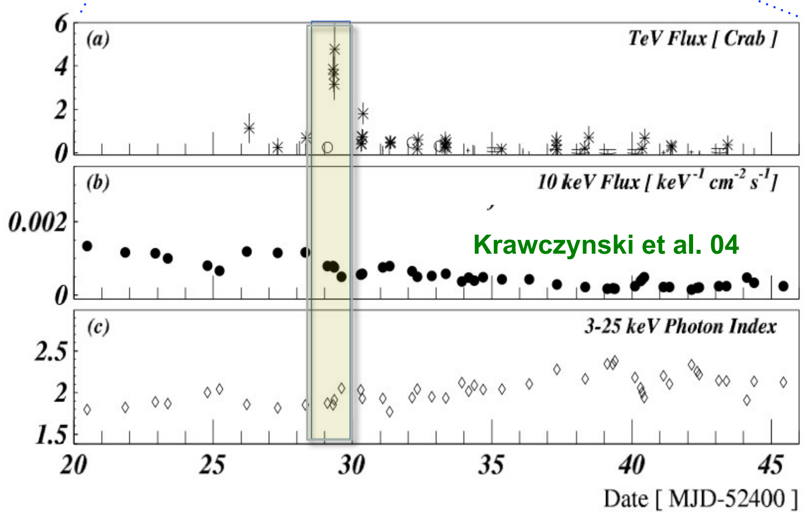
X-ray and TeV are correlated during the flare (flaring activity April/13).

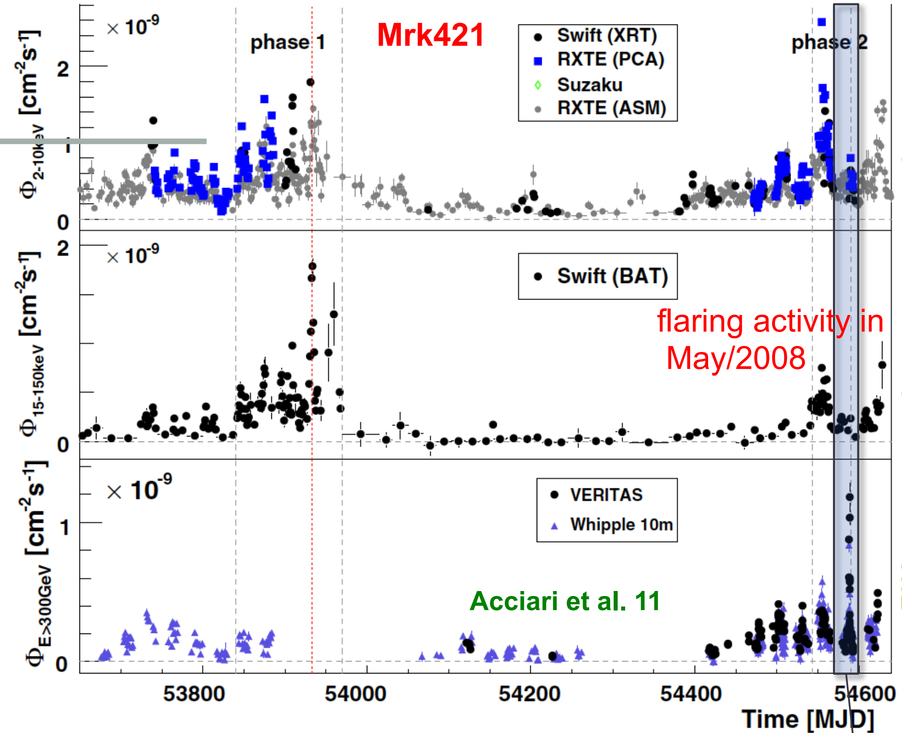


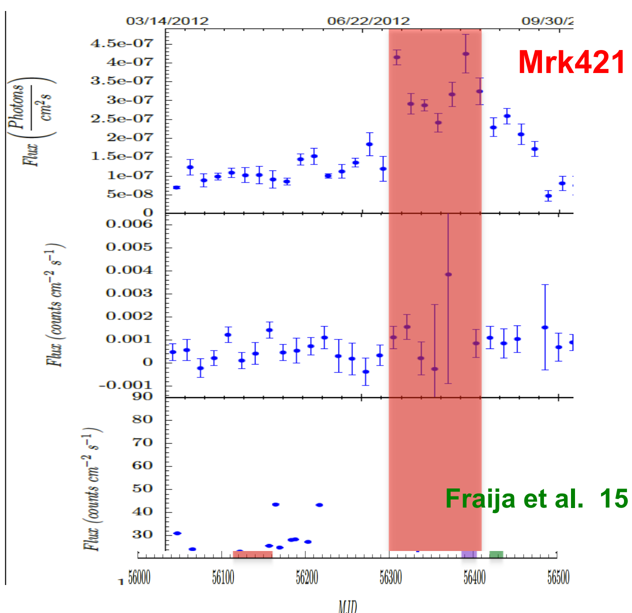
➢ Disconnections

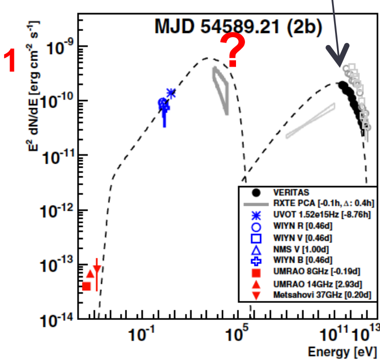
(Orphan Flares)











Flaring activity in August/2012

Is there a correlation between X-ray and TeV γ-ray emission ????

(hourly, daily, monthly, etc.)

If so, what is the origin ??

How could the orphan flares be explained ???

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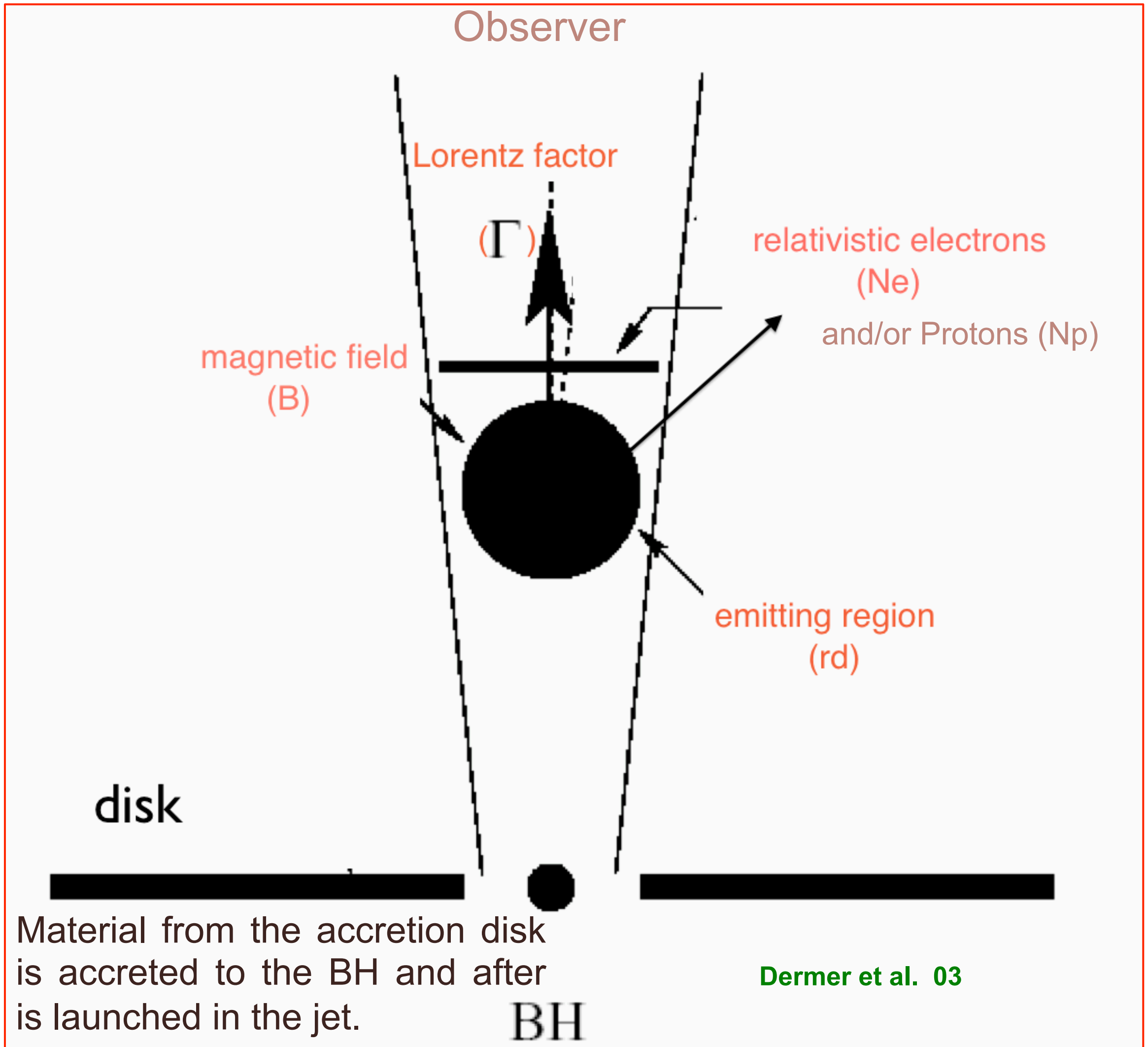
➢ Theoretical Model

Sketch of the basic model



Material from the accretion disk is accreted to the BH and after is launched in the jet.

Dermer et al. 03

We consider a spherical emitting region:

- Moving at relativistic speed with bulk Lorentz factor Γ.
- with a uniform particle densities (Ne and/or Np).
- with radius (rd).
- Endowed with a magnetic field B.

Leptonic model
Just 4 parameters
(B, Γ , rd and Ne(β))

Hadronic model
Additionally Np
(5 parameters)

(we will use natural unities $c=\hbar=1$ and prime quantities are in the comoving frame)

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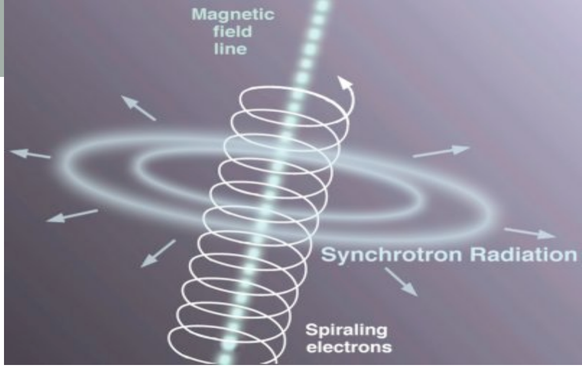
➢ Synchrotron radiation



By considering that a fraction of total energy is given

To accelerate electrons $U_e = m_e \int \gamma_e N_e(\gamma_e) d\gamma_e$ → minimum e⁻ Lorentz factor $\gamma_{e,m} = \frac{(\alpha-2)}{m_e(\alpha-1)} \frac{U_e}{N_e}$

To generate and/or amplify magnetic field $U_B = \frac{B^2}{8\pi}$ → Cooling Time scale $t'_c = \frac{3 m_e}{4\sigma_T} U_B^{-1} \gamma_e^{-1}$

→ cut-off e⁻ Lorentz factor $\gamma_{e,b} = \frac{3\, m_e}{4\, \sigma_T} (1+Y)^{-1} \Gamma U_B^{-1} r_d^{-1}$

Compton parameter $Y = U_e/U_B$

Acceleration time scale $t'_{acc} = \sqrt{\frac{\pi}{2} \frac{m_e}{q_e}} U_B^{-1} \gamma_e$ → Maximum e⁻ Lorentz factor $\gamma_{e,max} = \left(\frac{9\, q_e^2}{8\pi\, \sigma_T^2} \right)^{1/4} U_B^{-1/4}$

Photon energy released $\epsilon_\gamma^{obs}(\gamma_e) = \sqrt{\frac{8\pi q_e^2}{m_e^2}} \Gamma U_B^{1/2} \gamma_{e,i}^2$

Break synchrotron energies

$$\epsilon_{\gamma,m}^{obs} = \frac{\sqrt{8\pi}\, q_e (\alpha-2)^2}{m_e^3 (\alpha-1)^2} \Gamma U_B^{1/2} U_e^2 N_e^{-2},$$

$$\epsilon_{\gamma,c}^{obs} = \frac{9\sqrt{2\pi}\, q_e\, m_e}{8\, \sigma_T^2} (1+Y)^{-2} \Gamma^3 U_B^{-3/2} r_d^{-2},$$

$$\epsilon_{\gamma,max}^{obs} = \frac{3\, q_e^2}{m_e\, \sigma_T} \Gamma,$$

electron distribution

$$N_e(\gamma_e) \propto \begin{cases} \gamma_e^{-\alpha} & \gamma_{e,m} < \gamma_e < \gamma_{e,b}, \\ \gamma_{e,b}\gamma_e^{-(\alpha+1)} & \gamma_{e,b} \leq \gamma_e < \gamma_{e,max}, \end{cases}$$

Flux conservation

$$\epsilon_\gamma N_\gamma(\epsilon_\gamma) d\epsilon_\gamma \propto N_e(E_e) dE_e$$

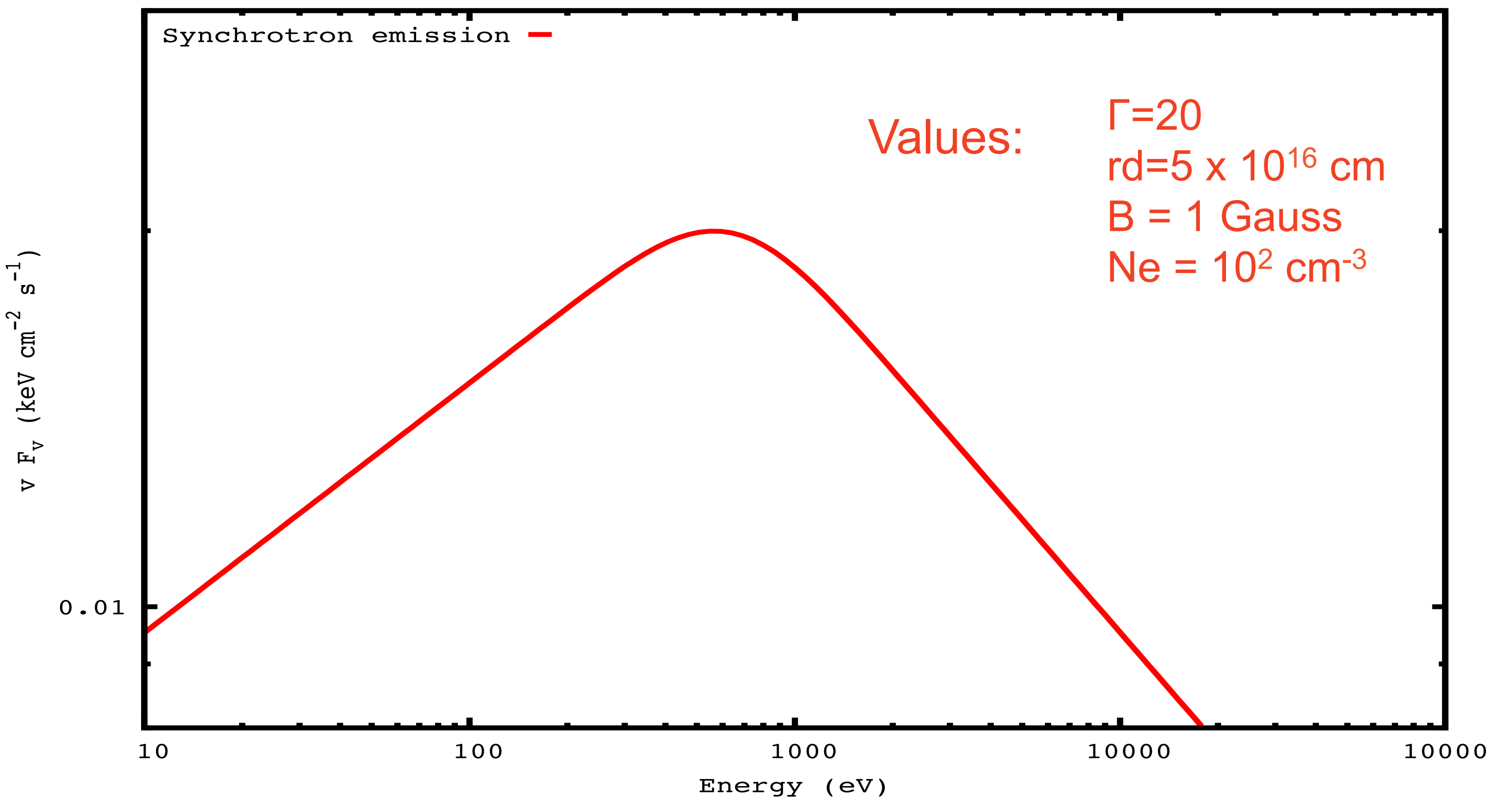
Electron Synchrotron spectrum

$$\epsilon_\gamma^2 N_\gamma(\epsilon_\gamma) = A_{syn,\gamma} \begin{cases} \left(\frac{\epsilon_\gamma}{\epsilon_{\gamma,m}}\right)^{4/3} & \epsilon_\gamma^{obs} < \epsilon_{\gamma,m}^{obs}, \\ \left(\frac{\epsilon_\gamma}{\epsilon_{\gamma,m}}\right)^{-(\alpha-3)/2} & \epsilon_{\gamma,m}^{obs} < \epsilon_\gamma^{obs} < \epsilon_{\gamma,c}^{obs}, \\ \left(\frac{\epsilon_{\gamma,c}}{\epsilon_{\gamma,m}}\right)^{-(\alpha-3)/2} \left(\frac{\epsilon_\gamma}{\epsilon_{\gamma,c}}\right)^{-(\alpha-2)/2}, & \epsilon_{\gamma,c}^{obs} < \epsilon_\gamma^{obs} < \epsilon_{\gamma,max}^{obs} \end{cases}$$

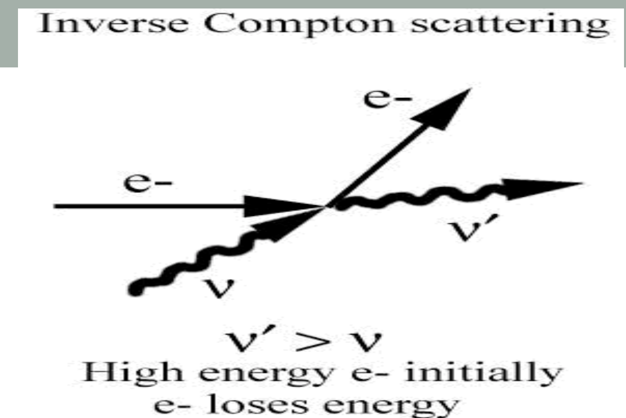
↔ $\beta=(\alpha+2)/2$

$$A_{syn,\gamma} = \frac{P_{\nu,max}^{obs} n_e}{4\pi d_z^2} \epsilon_{\gamma,c}^{obs} \simeq \frac{m_e^2}{4 q_e \sigma_T} d_z^{-2} \Gamma^5 U_B^{-1} N_e r_d$$

Milagro and Veritas (Low state)
Power index: $\beta = 2.3$



➢ Compton scattering



Synchrotron self-Compton relation

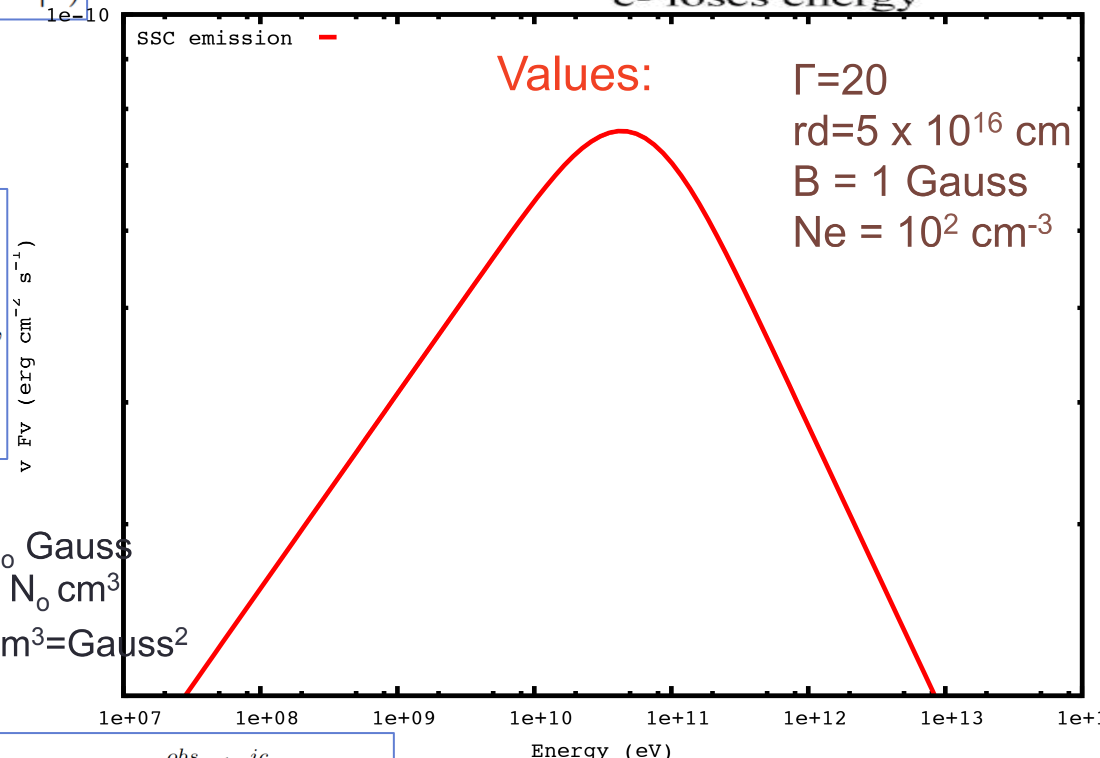
$$\epsilon^{ic}_{\gamma,(\mathrm{m}|\mathrm{c})} \simeq \gamma^2_{e,(\mathrm{m}|\mathrm{c})}\epsilon_{\gamma,(\mathrm{m}|\mathrm{c})}$$

Break Compton scattering energies

$$\epsilon^{ic}_{\gamma,m} = \frac{\sqrt{8\pi}\, q_e(\alpha-2)^4}{m_e^5\,(\alpha-1)^4}\,\Gamma\, U_B^{1/2}\, U_e^4 N_e^{-4},$$

$$\epsilon^{ic}_{\gamma,c} = \frac{81\sqrt{2\pi}\, q_e\, m_e^3}{128\,\sigma_T^4}\,(1+Y)^{-4}\,\Gamma^5\, U_B^{-7/2}\, r_d^{-4},$$

$$\epsilon^{ic}_{\gamma,max} = \frac{9\, q_e^3}{2\sqrt{2\pi}\, m_e\, \sigma_T^2}\,\Gamma\, U_B^{-1/2},$$



Compton parameter $Y = 2.06 \times 10^{-5}\, N_o/B_o^2$

B=B_o Gauss
Ne= N_o cm^3
erg/cm^3=$Gauss^2$

Compton scattering spectrum

$$\epsilon_\gamma^{ic\,2} N_\gamma(\epsilon_\gamma^{ic}) = Y\,(\epsilon_\gamma^2 N_\gamma)^{syn}_{max} \begin{cases} \left(\frac{\epsilon_\gamma^{ic}}{\epsilon^{ic}_{\gamma,m}}\right)^{4/3} & \epsilon_\gamma^{obs} < \epsilon^{ic}_{\gamma,m}, \\ \left(\frac{\epsilon_\gamma^{ic}}{\epsilon^{ic}_{\gamma,m}}\right)^{-(\alpha-3)/2} & \epsilon^{obs}_{\gamma,m} < \epsilon_\gamma^{ic} < \epsilon^{ic}_{\gamma,c}, \\ \left(\frac{\epsilon^{ic}_{\gamma,c}}{\epsilon^{ic}_{\gamma,m}}\right)^{-(\alpha-3)/2}\left(\frac{\epsilon_\gamma^{ic}}{\epsilon^{ic}_{\gamma,c}}\right)^{-(\alpha-2)/2}, & \epsilon^{ic}_{\gamma,c} < \epsilon_\gamma^{ic} < \epsilon^{ic}_{\gamma,max} \end{cases}$$

$$(\epsilon_\gamma^2 N_\gamma)^{syn}_{max} = A_{syn,\gamma}\left(\frac{9 m_e^4\,(\alpha-1)^2}{16\sigma_T^2\,(\alpha-2)^2}\Gamma^2\, U_B^{-2}\, U_e^{-2} N_e^2\, r_d^{-2}\right)^{-(\alpha-3)/2}$$

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➤ Pγ interactions

The target photon density

$$n_\gamma \simeq \frac{d_z^2}{r_d^2\,\epsilon_{\gamma,\mathrm{pk}}}(\nu F_\nu)$$

Charged and neutral pion production channels

$$p\,\gamma \longrightarrow \begin{cases} n\,\pi^+ & \text{fraction } 1/3, \\ p\,\pi^0 & \text{fraction } 2/3, \end{cases}$$

$$\pi^\pm \rightarrow \mu^\pm + \nu_\mu/\bar{\nu}_\mu$$

$$e^\pm + \nu_\mu/\bar{\nu}_\mu + \bar{\nu}_\mu/\nu_\mu + \nu_e/\bar{\nu}_e$$

$$\pi_0 \rightarrow \gamma\gamma$$

Photo pion cooling time,

$$t'^{-1}_{\pi^0} = \frac{1}{2\,\gamma_p^2}\int d\epsilon\,\sigma_\pi(\epsilon)\,\xi_{\pi^0}\,\epsilon\int dx\,x^{-2}\,\frac{dn_\gamma}{d\epsilon_\gamma}(\epsilon_\gamma = x)\,,$$

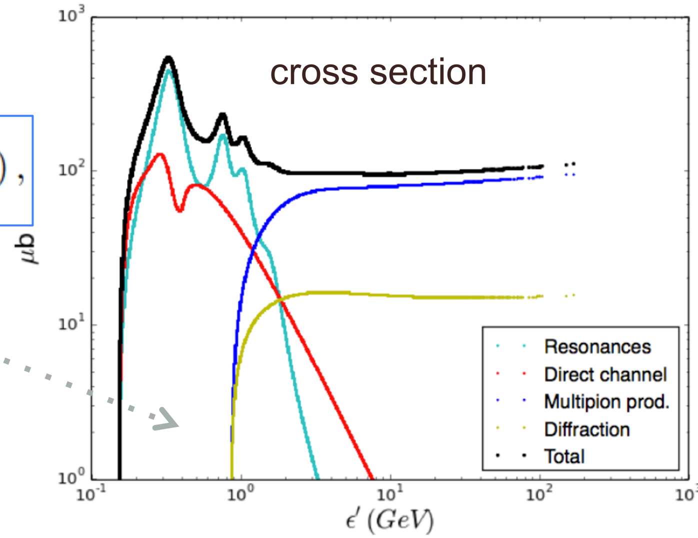


Photo pion efficency

$$f_{\pi^0} = \frac{t'_d}{t'_{\pi^0}}$$

Proton distribution

$$\frac{dN_p}{dE_p} = A_p\left(\frac{E_p}{\mathrm{GeV}}\right)^{-\alpha}$$

Photo pion spectrum:

$$\left(\epsilon^2\frac{dN}{d\epsilon}\right)_{\pi^0,\gamma} = \frac{6\,r_d\,\eta_\gamma\,\sigma_{peak}\,\Delta\epsilon_{peak}}{\Gamma^2\,\epsilon_{peak}\left(\frac{2}{\xi_{\pi^0}}\right)^{\alpha-1}}A_p\begin{cases}\left(\frac{\epsilon_{\pi^0,\gamma,c}}{\epsilon_0}\right)^{-1}\left(\frac{\epsilon_{\pi^0,\gamma}}{\epsilon_0}\right)^{-\alpha+3} & \epsilon_{\pi^0,\gamma} < \epsilon_{\pi^0,\gamma,c} \\ \left(\frac{\epsilon_{\pi^0,\gamma}}{\epsilon_0}\right)^{-\alpha+2} & \epsilon_{\pi^0,\gamma,c} < \epsilon_{\pi^0,\gamma},\end{cases}$$

➤ μ⁻, e± and proton synchrotron radiation

comparison

Photon energy $\epsilon'_\gamma = \frac{3\pi q_e B'}{8\, m_\mu^3} E'^2_\mu$

$t'_{syn,i} = 6\pi m_i^4 / (\sigma_T\, m_e^2\, B'^2\, E'_i)$

$t'_{\mu^+,dec} = \frac{E'_{\mu^+}}{m_{\mu^+}} \tau_{\mu^+}$

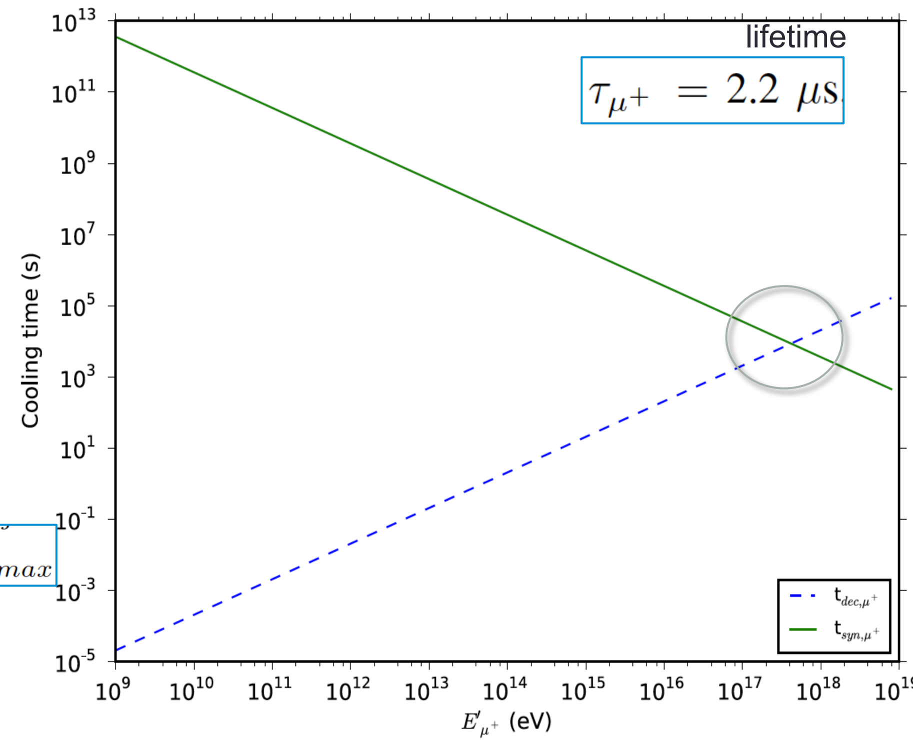
where muon Lorentz factor $\gamma_i = m_i^2 / m_e^2\, \gamma_e$

Aharonian 2000, Mannheim 1993

Break synchrotron energies

$$\epsilon_{\gamma,c} = \frac{m_i^5}{m_e^5} \epsilon_{\gamma,c-e}$$

$$\epsilon_{\gamma,max} = \frac{m_i}{m_e} \epsilon_{\gamma,max-e}$$



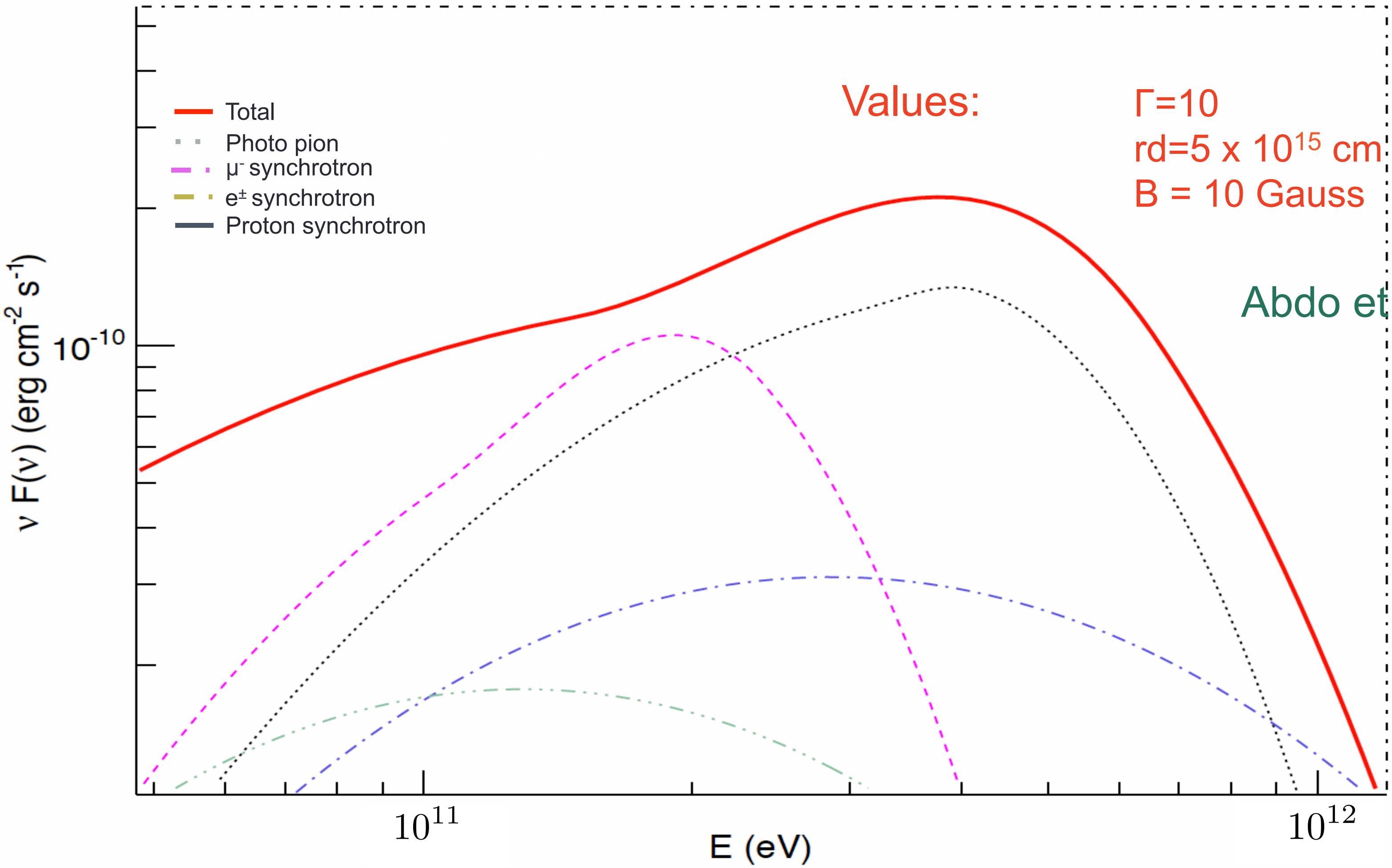
Muons are accelerated by a power law distribution

$N_i(\gamma_i)$: $\gamma_i^{-\alpha}$ for $\gamma_i < \gamma_{i,b}$ and $\gamma_{i,b}\gamma_i^{-(\alpha+1)}$ for $\gamma_{i,b} \le \gamma_i < \gamma_{i,max}$

Synchrotron spectrum of muons and secondary pairs

$$\left(\epsilon^2 \frac{dN}{d\epsilon}\right)_{syn,\gamma} = \frac{4\,\sigma_T\, m_i^4}{27\pi^2 q_e\, m_e^3} r_j^3\, D_z^{-2}\, \Gamma_j\, \epsilon_{\gamma,c-e}\, B'\, N_i \begin{cases} \left(\frac{\epsilon_{\gamma,c}}{\epsilon_0}\right)^{-1/2} \left(\frac{\epsilon_\gamma}{\epsilon_0}\right)^{-(\alpha-3)/2} & \epsilon_\gamma < \epsilon_{\gamma,c}, \\ \left(\frac{\epsilon_\gamma}{\epsilon_0}\right)^{-(\alpha-2)/2} & \epsilon_{\gamma,c} < \epsilon_\gamma < \epsilon_{\gamma,max} \end{cases}$$

➢ Summing up: the hadronic spectrum



Abdo et al. 2013

Models

Leptonic

Electron synchrotron spectrum → First peak ≈ 0.5 keV X-ray

Compton scattering spectrum → Second peak ≈ 200 GeV TeV γ-ray

There is correlation: X-ray ⟷ TeV γ-ray

Hadronic

Primary electron synchrotron spectrum → First peak ≈ 0.5 keV X-ray

Photo pion + Muon, secondary e± and proton synchrotron spectrum → Second peak ≈ 200 GeV TeV γ-ray

There is NOT correlation: X-ray ⟷̸ TeV γ-ray

Orphan flares could be explain!!

Botcher 2004

Fraija 2014

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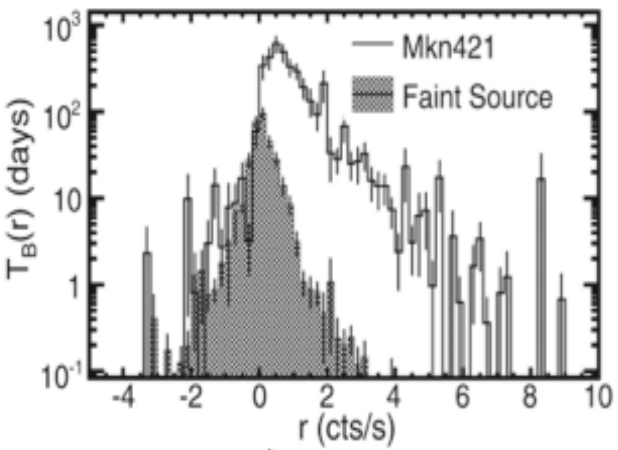
➢ Data sets

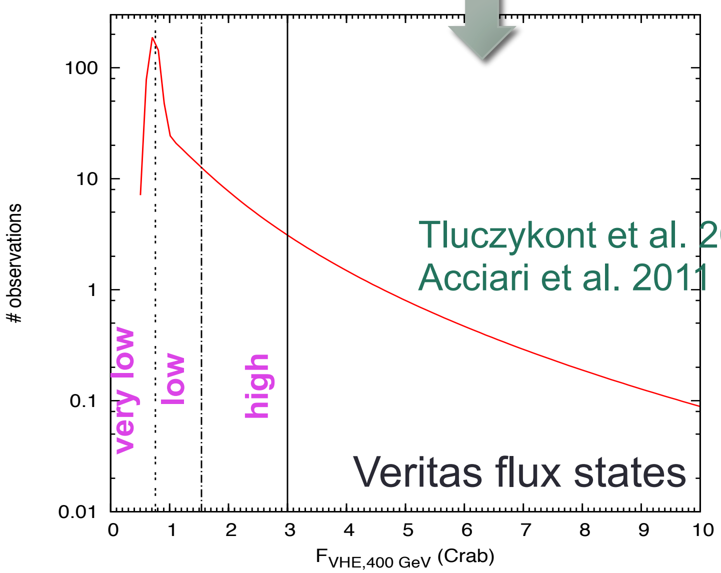
- Whipple - RXTE/ASM data (Acciari et al. 2014)
- **Milagro - RXTE/ASM data**
- HEGRA CT1 - RXTE/ASM (Aharonian et al. 2003)
- MAGIC/Whipple/VERITAS-XMM Newton data (Acciari et al. 2009)
- MAGIC-RXTE/ASM data (Albert et al. 2007)



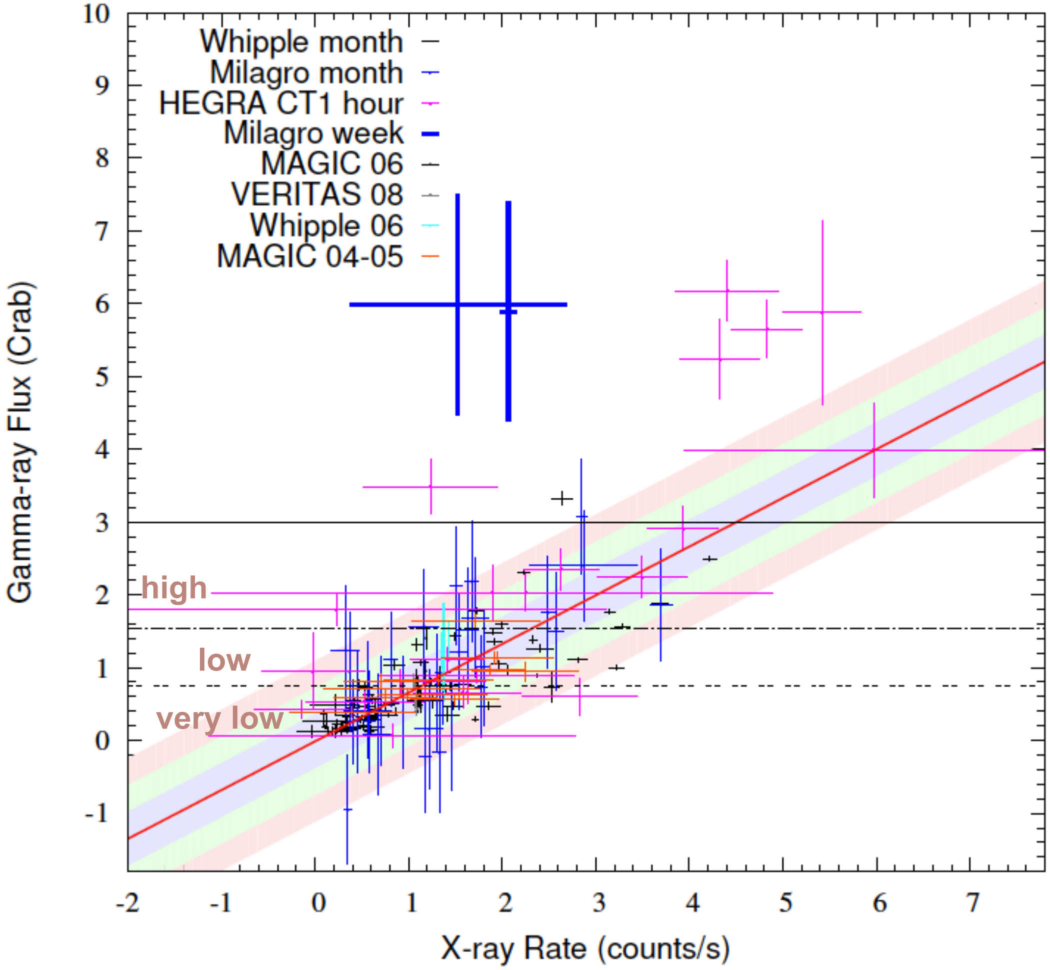
Resconi et al. 2009

RXTE/ASM >14 years
2-10 keV
Mean=0.5 counts/s
(distribution)

IACTs: MAGIC, H.E.S.S., Whipple/VERITAS, CAT, HEGRA
14 years E > 400 GeV
Mean=0.73 Crab
(distribution)



Tluczykont et al. 2010
Acciari et al. 2011



- R=0.73
- Linear fit: slope=0.67 ± 0.04
- Sigma: σ=0.37 ± 0.03

Patricelli et al 2015

➢ Considerations in our model

Values of parameters

$$\beta = 2.3$$
$$r_d = 5 \times 10^{16}\,\mathrm{cm}$$
$$\Gamma = 10$$

Acciari et al. 2011, 2014
Abdo et al. 2014

Values N_e and B are computed fitting data

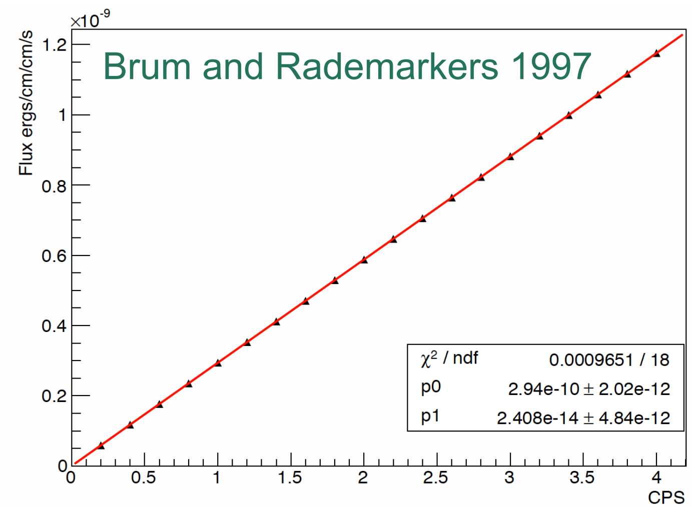
VHE gamma-ray fluxes was normalized to the Crab flux, as measured by VERITAS

$$1\,\mathrm{Crab} = 0.871 \times 10^{-10}\,\mathrm{erg/cm^2/s}$$

Unities of X-ray flux were changed
(with the online WebPIMMS tool)

$$\mathrm{erg/cm^2/s} \rightarrow \mathrm{CPS}$$

http://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3pimms/w3pimms_pro.pl



Kalberla et al 2005

Column density fixed to the Galactic value in the direction of Mrk 421: $1.61 \times 10^{20}\,\mathrm{cm^{-2}}$

➢ Comparison

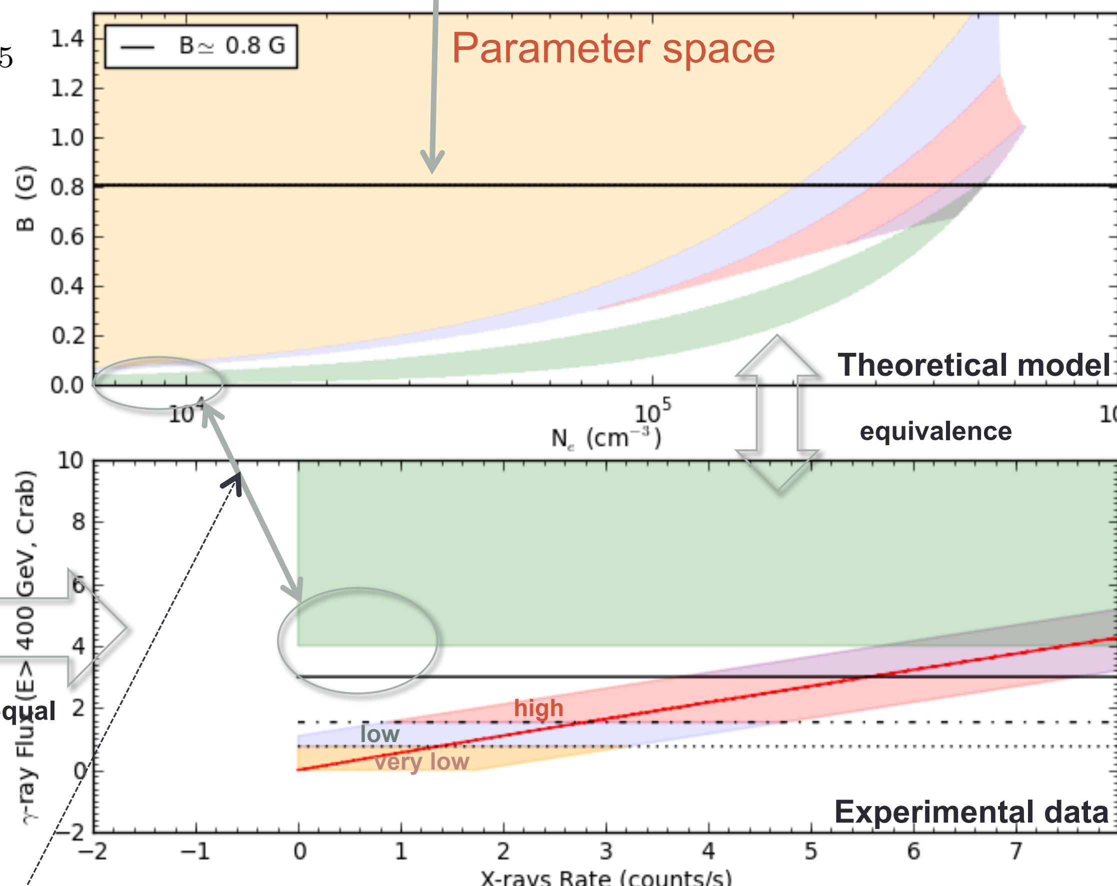
Unique correlation $B \simeq 0.8$ G

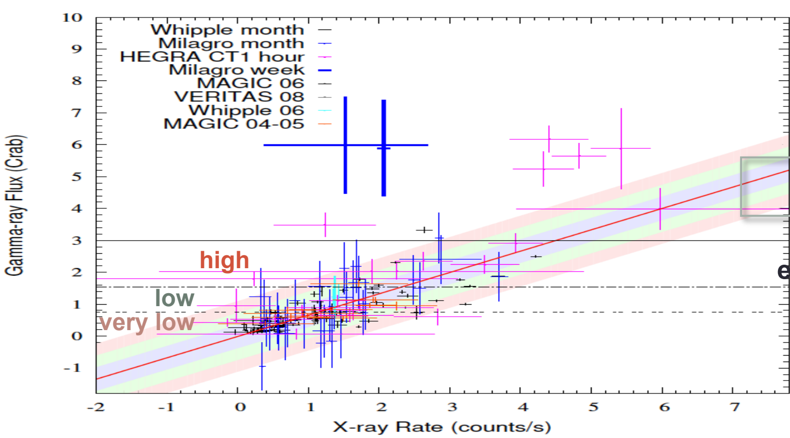
Magnetic field $0.01 \leq B\,(G) \leq 1.6$

Electron density $10^3 \leq N_e\,(\mathrm{cm}^{-3}) \leq 10^{5.5}$

As fluxes increase the set of parameters decreases.

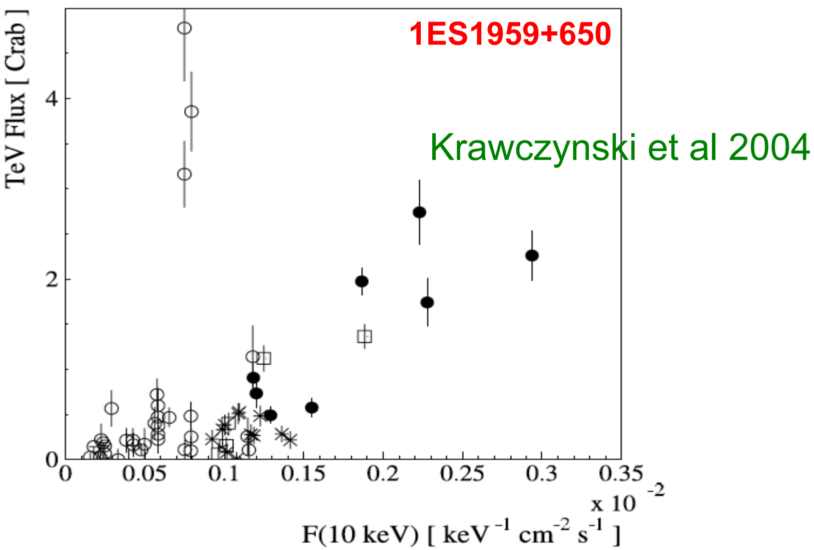
As fluxes decrease B decreases

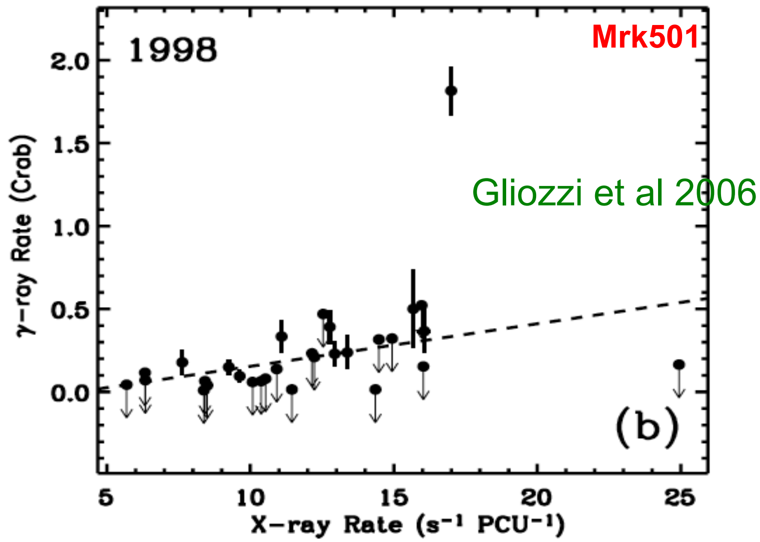


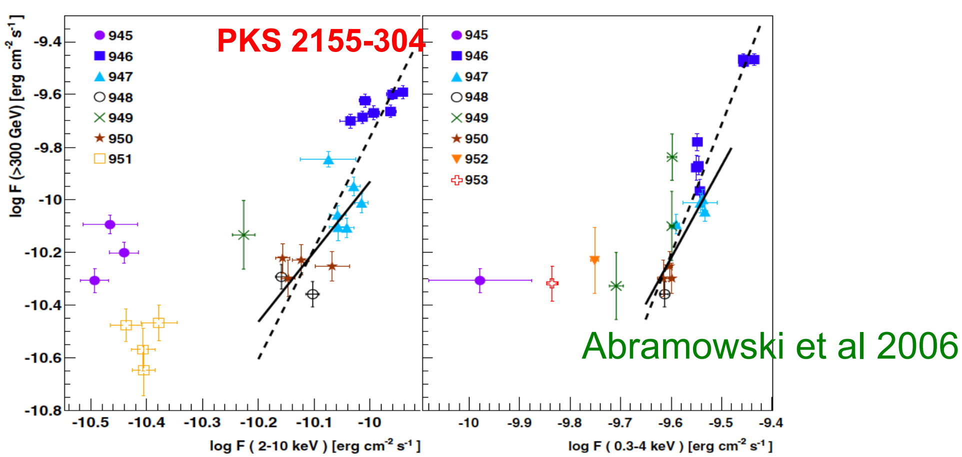


orphan flares

This model could be generalized to other blazars







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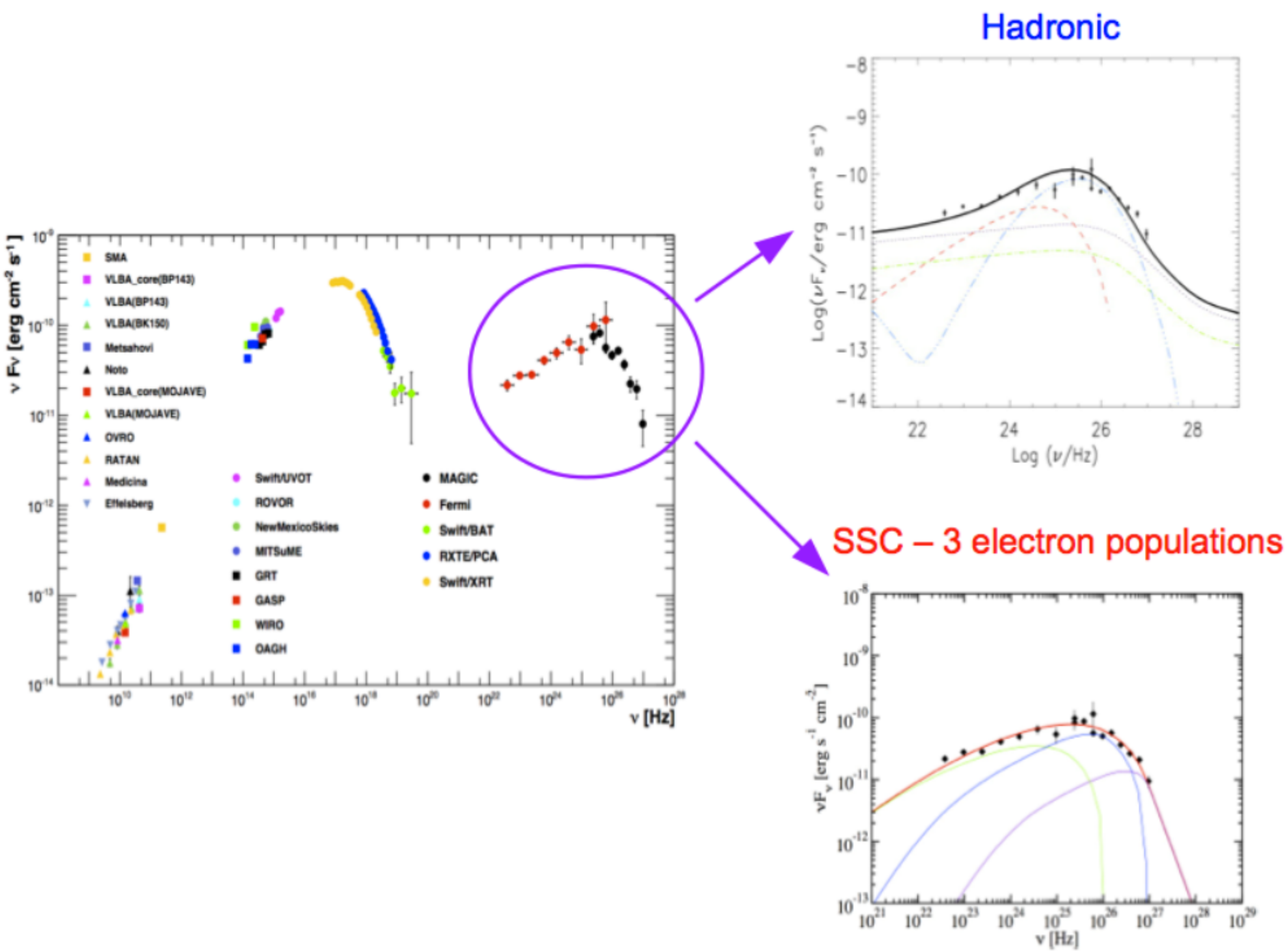
- ✓ Mrk421 shows a correlation between TeV γ-ray and X-ray emissions independent of time scales and instruments, although it seems to break at the highest γ-ray fluxes.

- ✓ The overall correlation can be interpreted as SSC scenario with a single value of magnetic field $\mathrm{B} \simeq 0.8\ \mathrm{G}$

- ✓ The "outliers" and orphan flares might be described within SSC framework for a set of values of N_e and B different from the ones characterizing the overall correlation.

- ✓ We have developed a theoretical model that can explain the correlation between TeV γ-ray and X-ray emissions of Mrk 421. Although the hadronic model can describe the SED, it can not explain the correlation.

Back up



Both leptonic and hadronic models describe well the SED