Theoretical models to explain TeV gamma-ray and X-ray correlations exhibited in Blazars

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OUTLINE

- Observations: TeV and X-ray correlations (variability and spectrum)
- Theoretical model:
  - Generalities
  - Lepton model
  - Hadronic model
- Application to Mrk 421
- Conclusions

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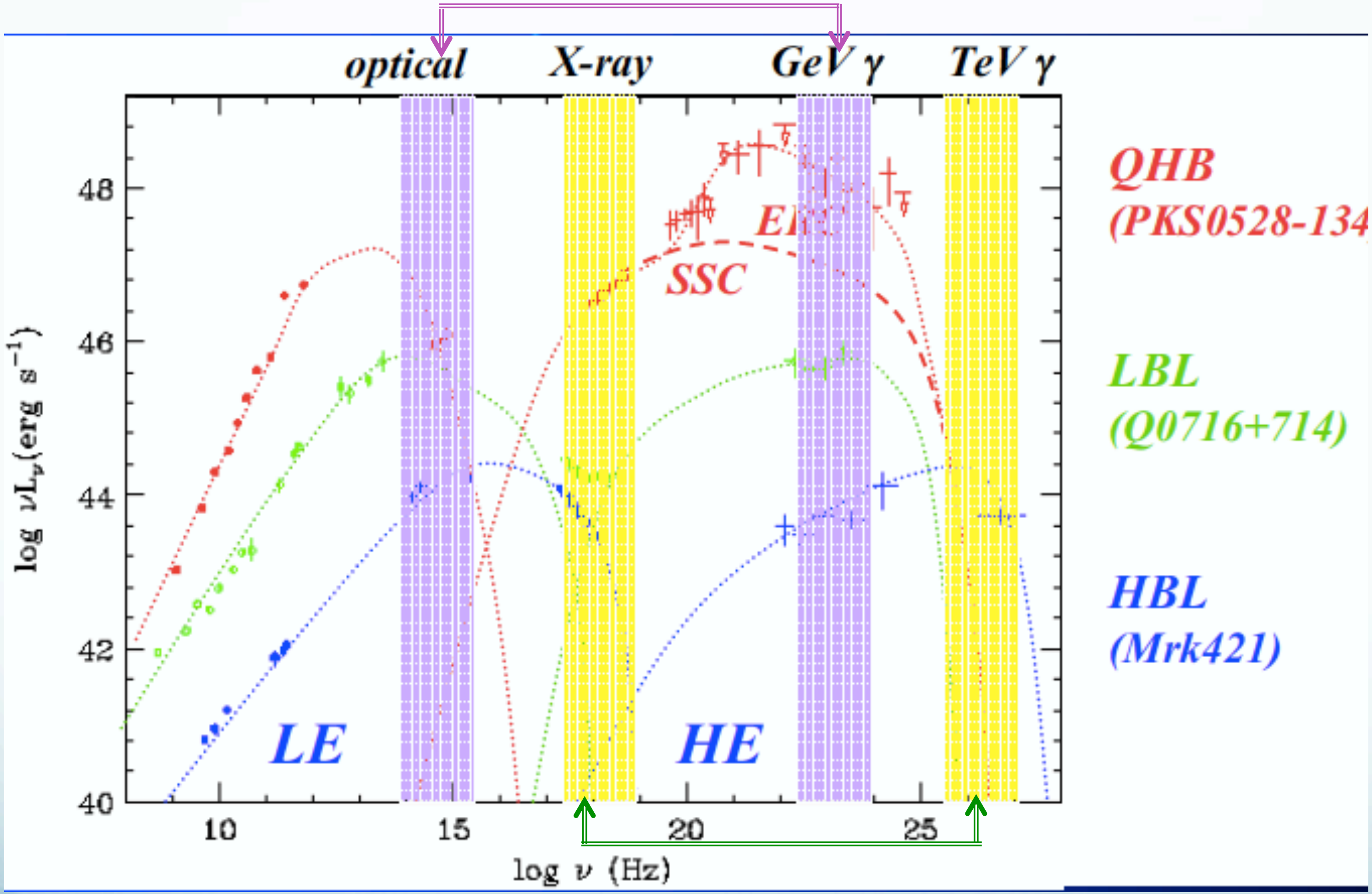
➢ Unified view of Blazars

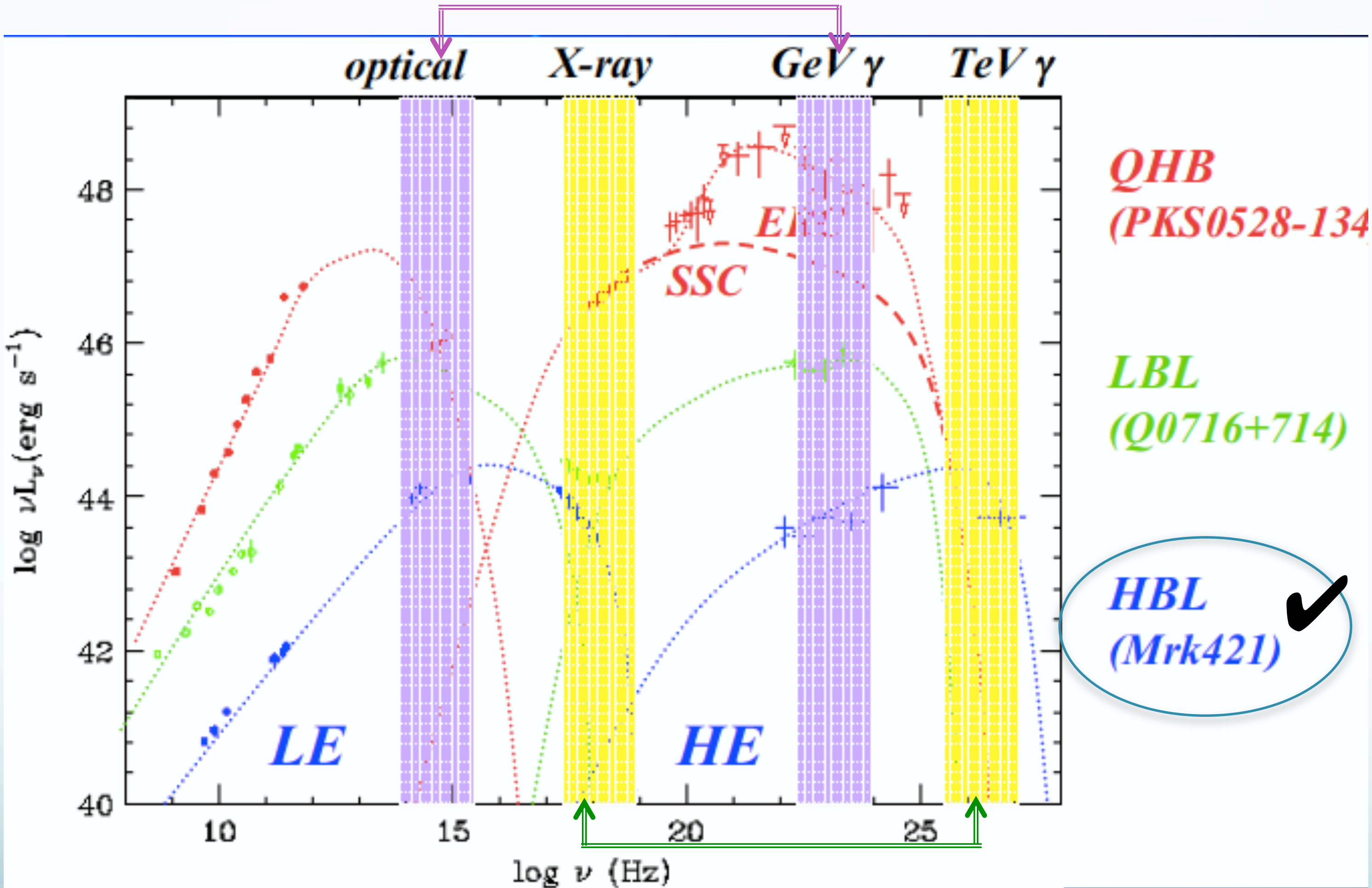


High energy end of emission components;

LE ..... X-ray (HBL) ⟺ Optical (QHB)

HE ... TeV γ-ray (HBL) ⟺ GeV γ-ray (QHB)

➢ Unified view of Blazars



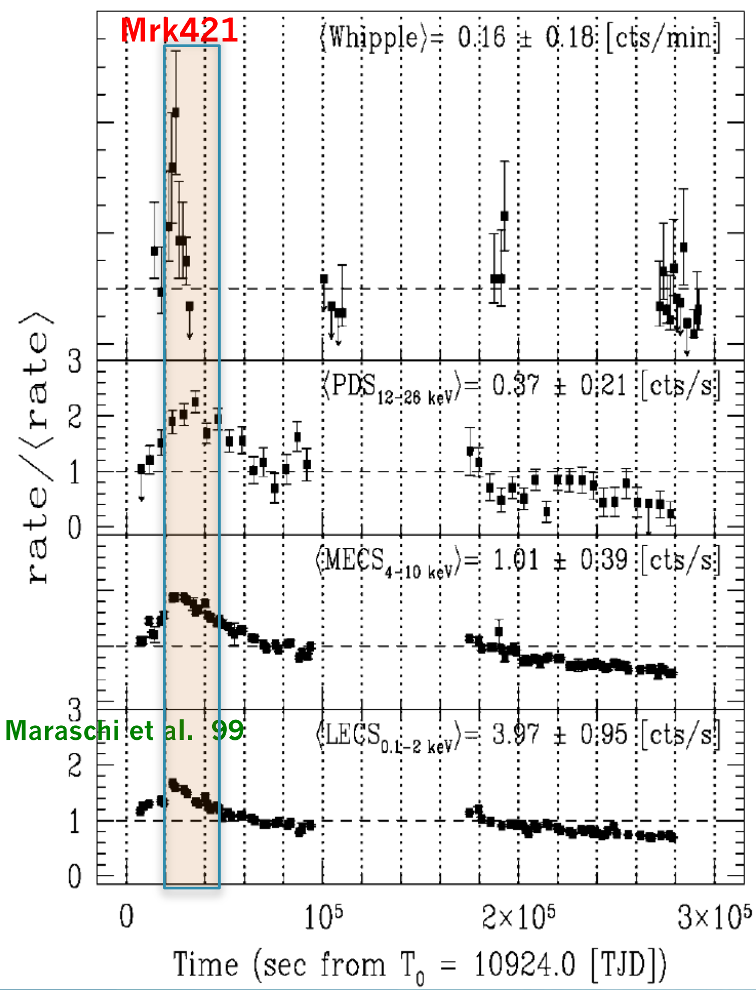
High energy end of emission components;

LE ..... X-ray (HBL) ⟺ Optical (QHB)

HE ... TeV γ-ray (HBL) ⟺ GeV γ-ray (QHB)

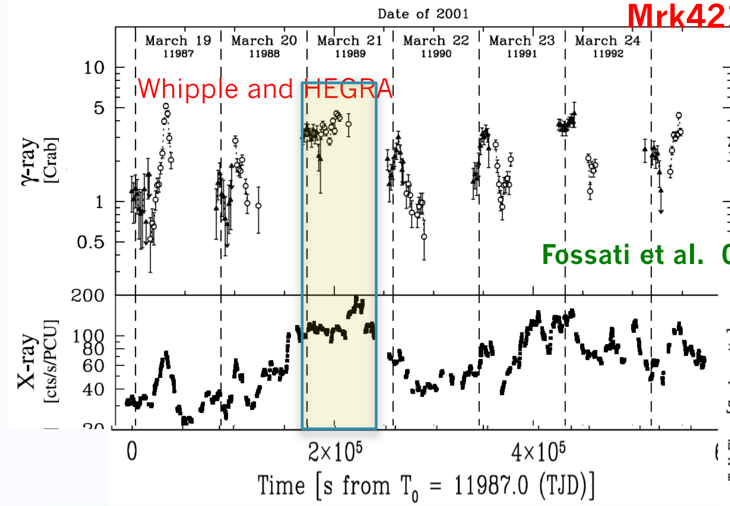
Fraija et al. 15

➢ Correlations (Variability)



Maraschi et al. 99

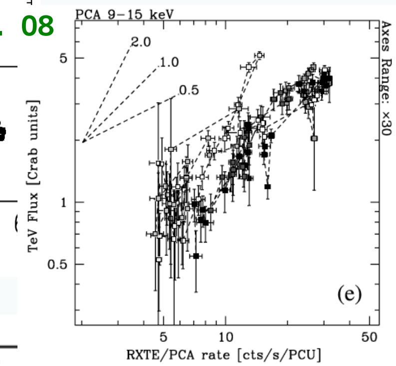
X-ray and TeV are well correlated on timescales of hours (flaring activity April/98).

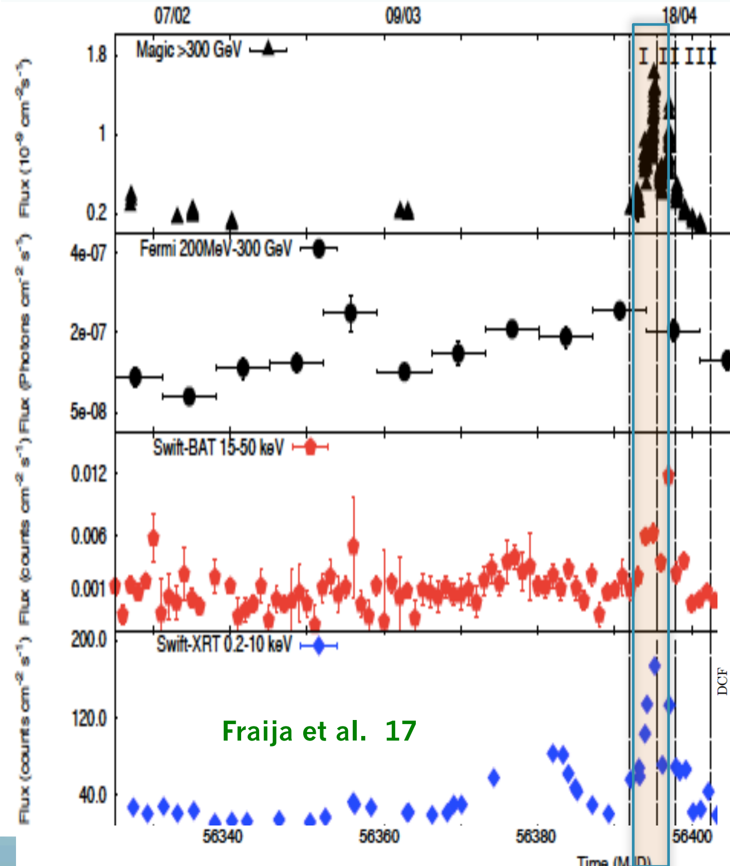


Mrk421

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

Fossati et al. 08

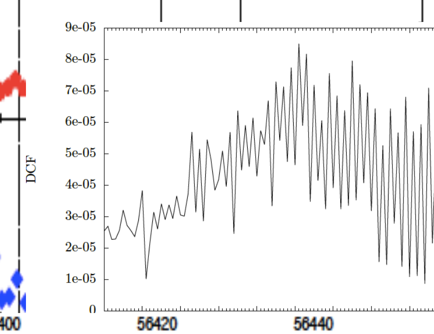




Mrk421

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

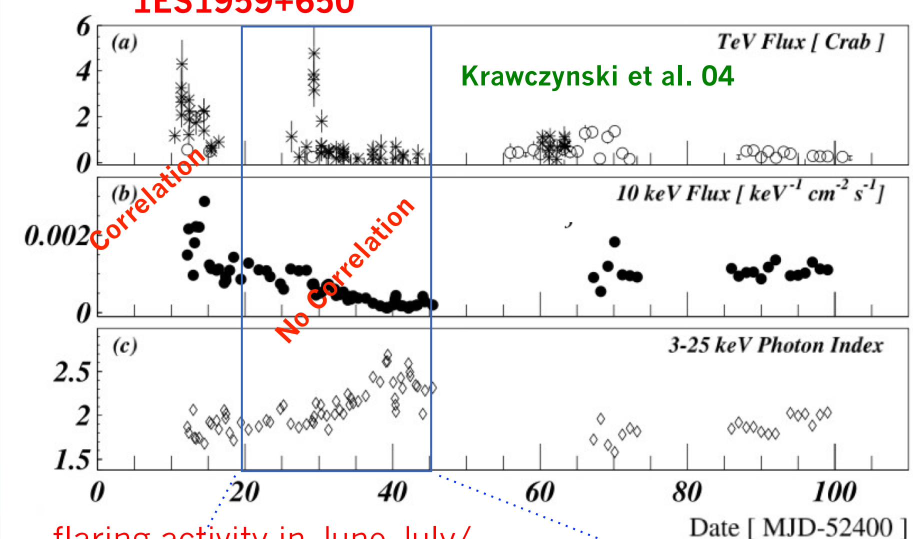
Fraija et al. 17



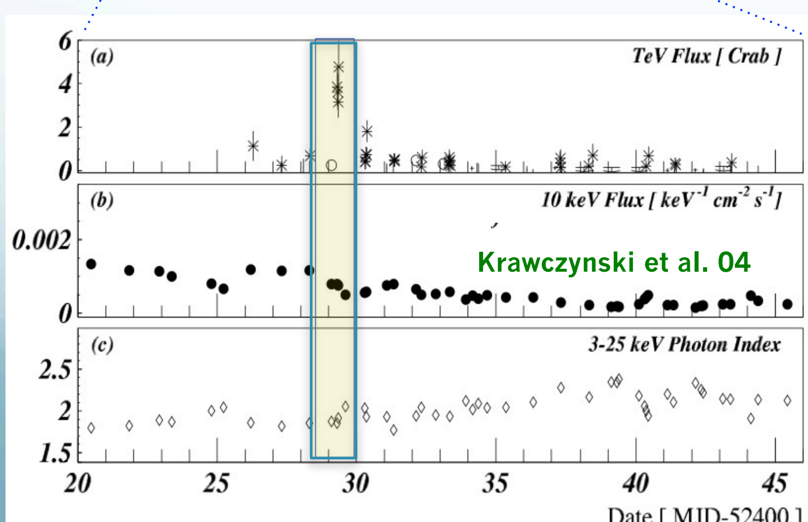
➢ No correlations (Variability)

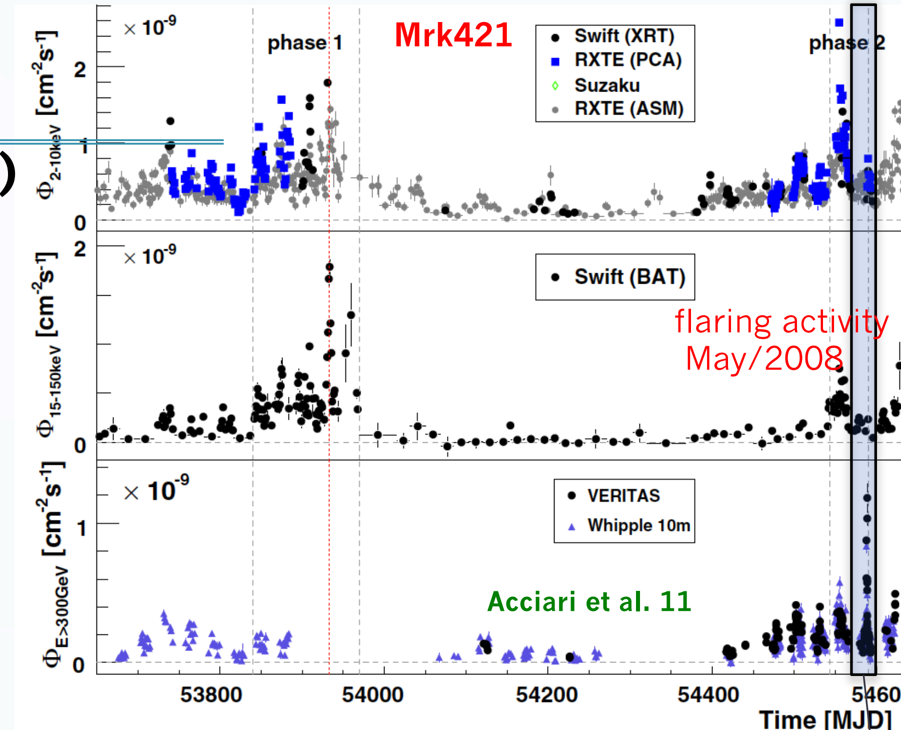
(Orphan Flares)

1ES1959+650

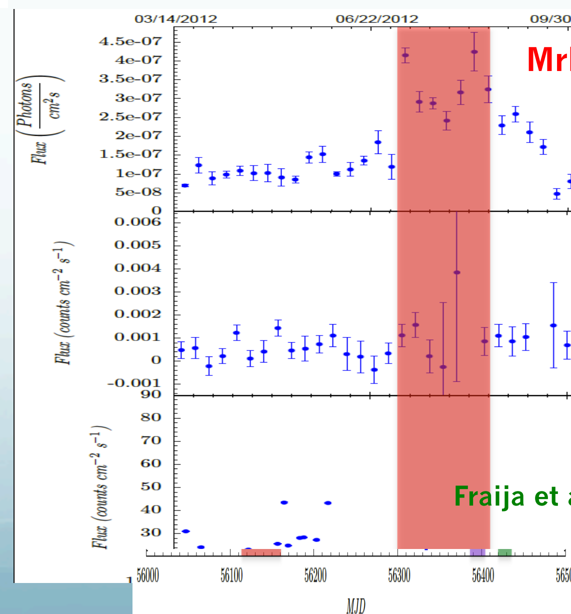


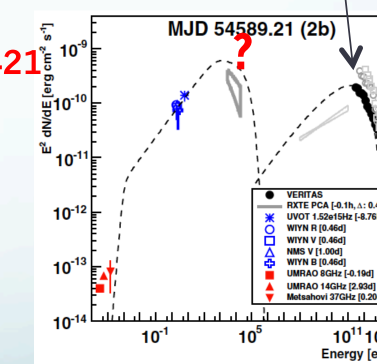
flaring activity in June-July/2002





flaring activity in May/2008

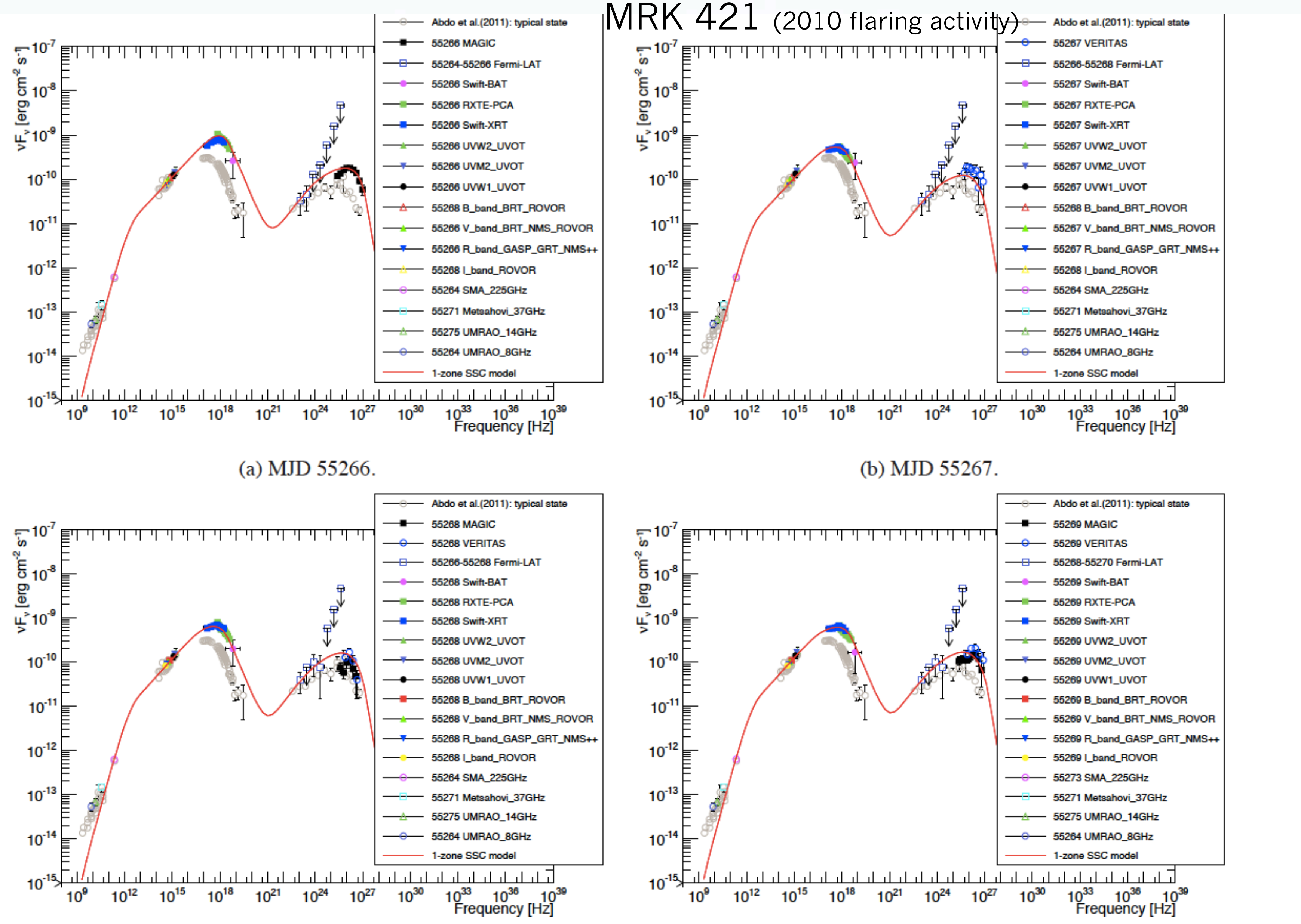




Flaring activity in August/2012

Spectral energy distribution (SSC Model)

MRK 421 (2010 flaring activity)



(a) MJD 55266.

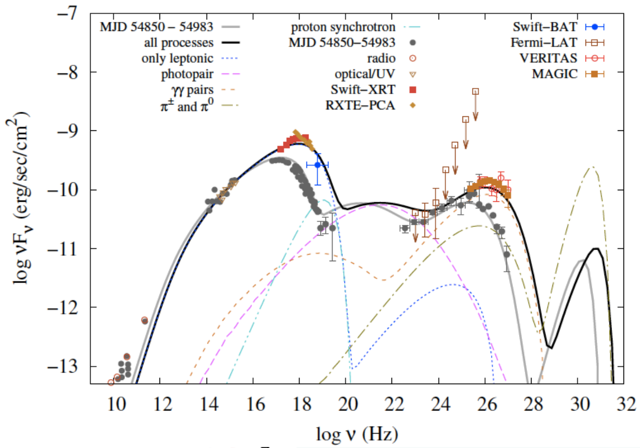
(b) MJD 55267.

(c) MJD 55268.

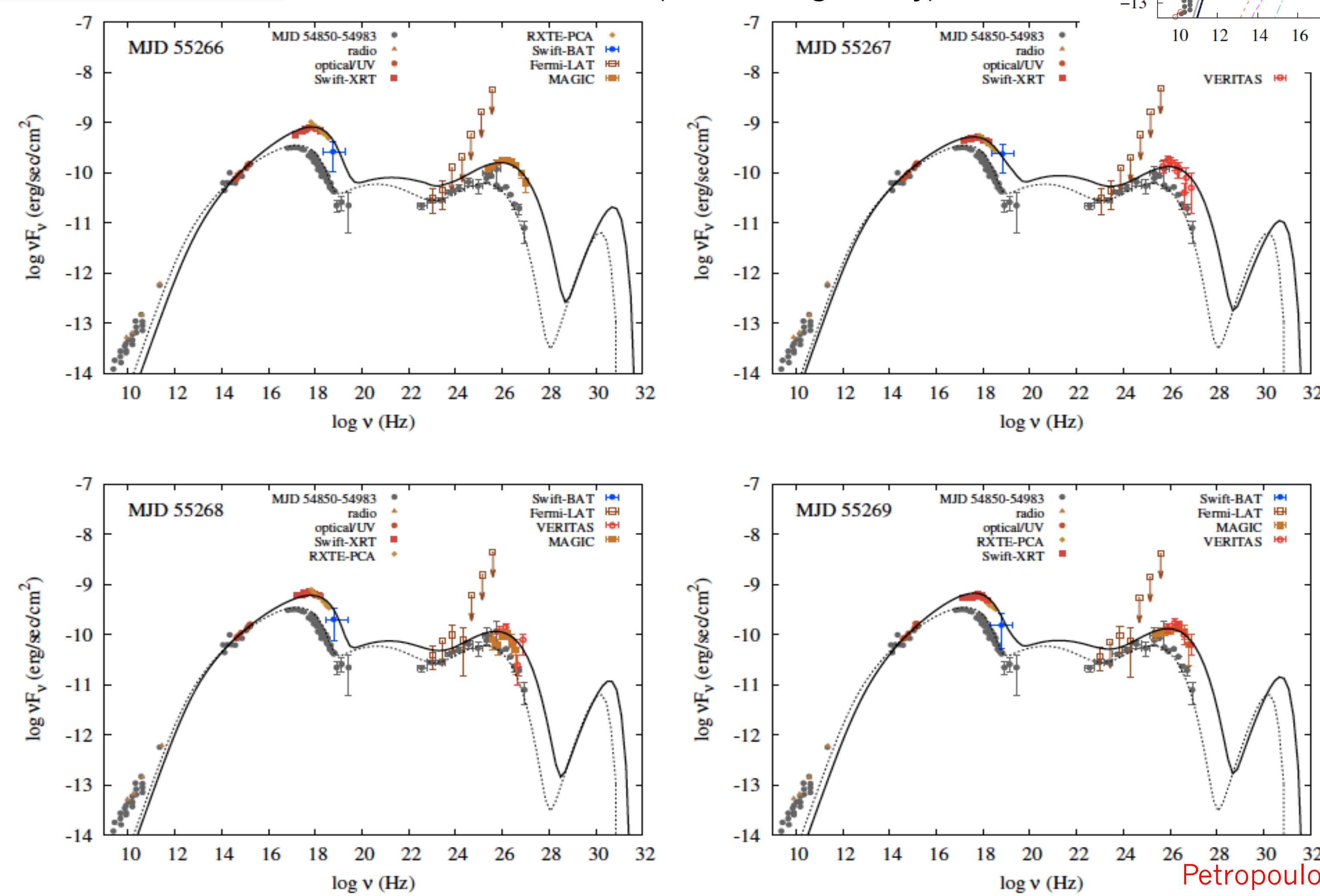
(d) MJD 55269.

Aleksic et al. 2015

Spectral energy distribution
(Hadronic Model)



MRK 421 (2010 flaring activity)



Petropoulou et al 2016

Is there a correlation between X-ray and TeV γ-ray emission ????
(hourly, daily, monthly, etc.)

If so, what is the origin ??

How could be explained the TeV γ-ray activity without the X-ray activity ???

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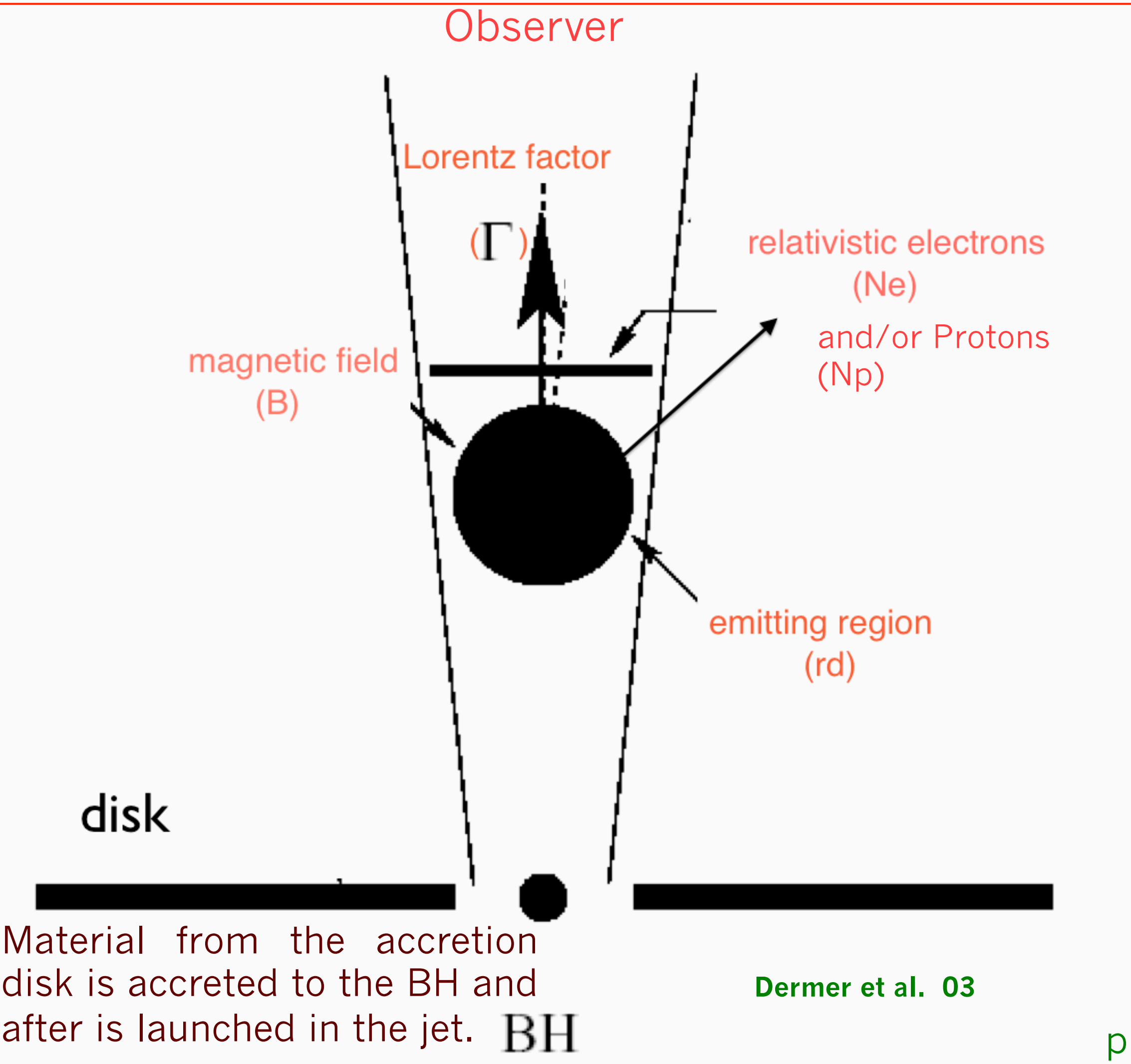
➢ Theoretical Model

Sketch of the basic model



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

We consider a spherical emitting region:

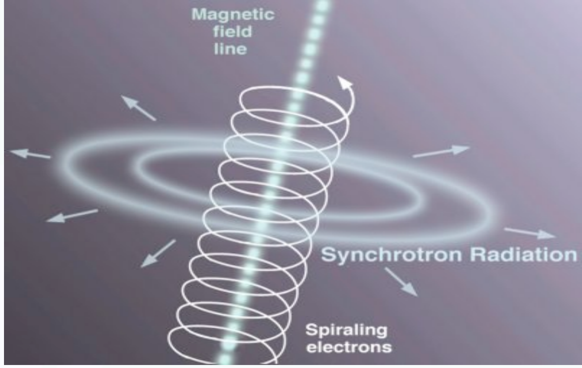
- moving at relativistic speed with bulk Lorentz factor Γ.
- with a uniform particle densities (Ne and/or Np).
- with radius (rd).
- endowed with a magnetic field B.

Leptonic model
only 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)

➢ 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 $t'_c = \frac{3m_e}{4\sigma_T} U_B^{-1} \gamma_e^{-1}$

→ 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

$$\epsilon^{obs}_{\gamma,m} = \frac{\sqrt{8\pi}\, q_e(\alpha-2)^2}{m_e^3\,(\alpha-1)^2} \Gamma\, U_B^{1/2}\, U_e^2 N_e^{-2},$$
$$\epsilon^{obs}_{\gamma,c} = \frac{9\sqrt{2\pi}\, q_e\, m_e}{8\, \sigma_T^2} (1+Y)^{-2} \Gamma^3 U_B^{-3/2} r_d^{-2},$$
$$\epsilon^{obs}_{\gamma,max} = \frac{3\, q_e^2}{m_e\, \sigma_T} \Gamma,$$

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

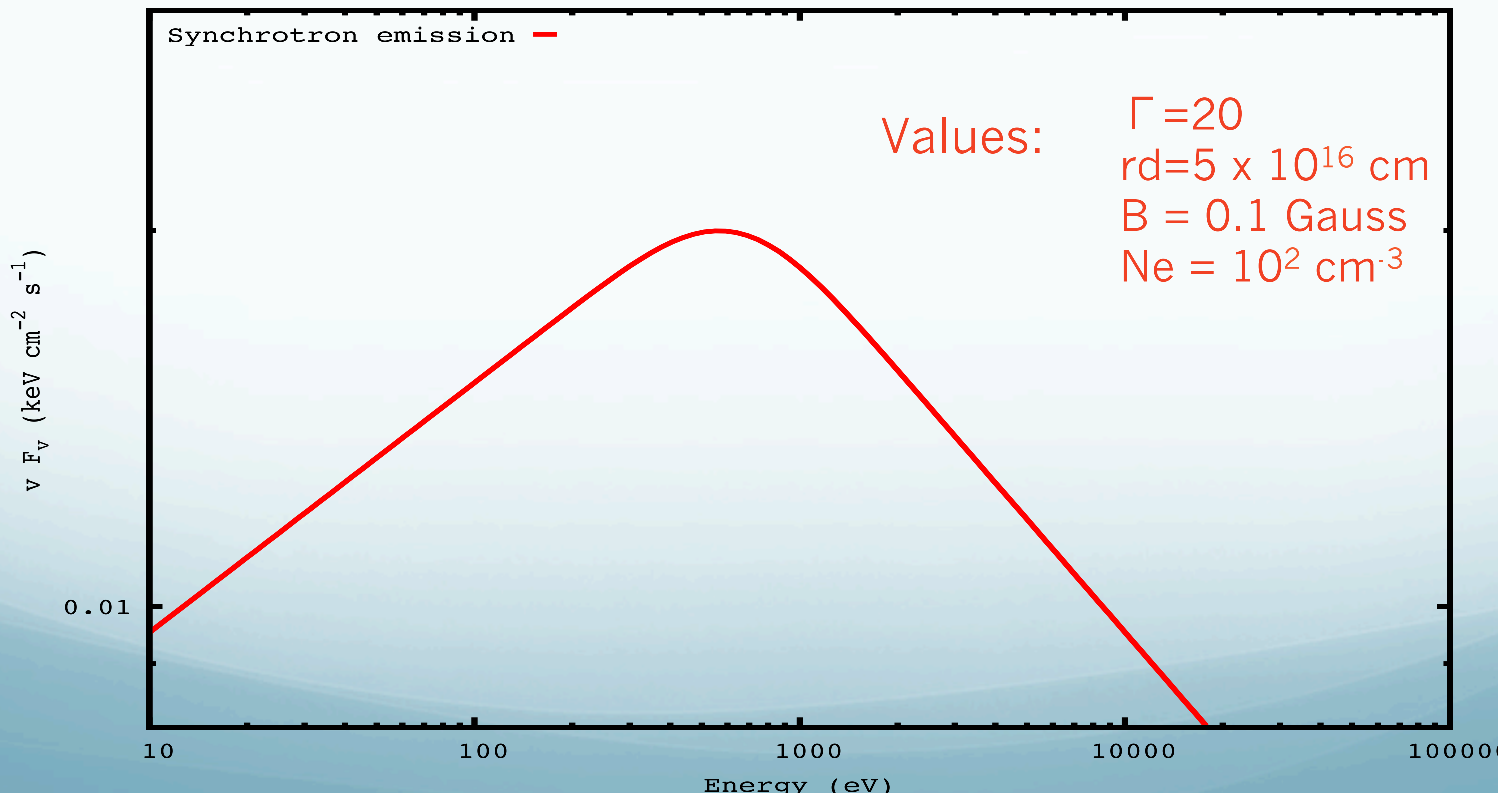
$$\epsilon_\gamma N_\gamma(\epsilon_\gamma) d\epsilon_\gamma \propto N_e(E_e) dE_e$$

Electron Synchrotron spectrum

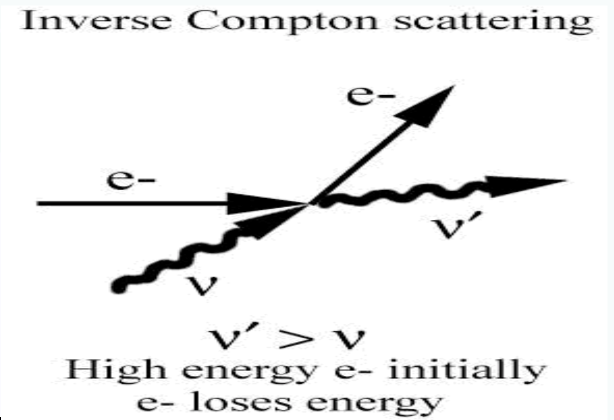
$$\epsilon_\gamma^2 N_\gamma(\epsilon_\gamma) = A_{syn,\gamma} \begin{cases} \left(\frac{\epsilon_\gamma}{\epsilon_{\gamma,m}}\right)^{4/3} & \epsilon_\gamma^{obs} < \epsilon_{\gamma,m}^{obs}, \\ \left(\frac{\epsilon_\gamma}{\epsilon_{\gamma,m}}\right)^{-(\alpha-3)/2} & \epsilon_{\gamma,m}^{obs} < \epsilon_\gamma^{obs}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

$\leftrightarrow$ $\beta = (\alpha + 2)/2$

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



➢ Inverse Compton scattering



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

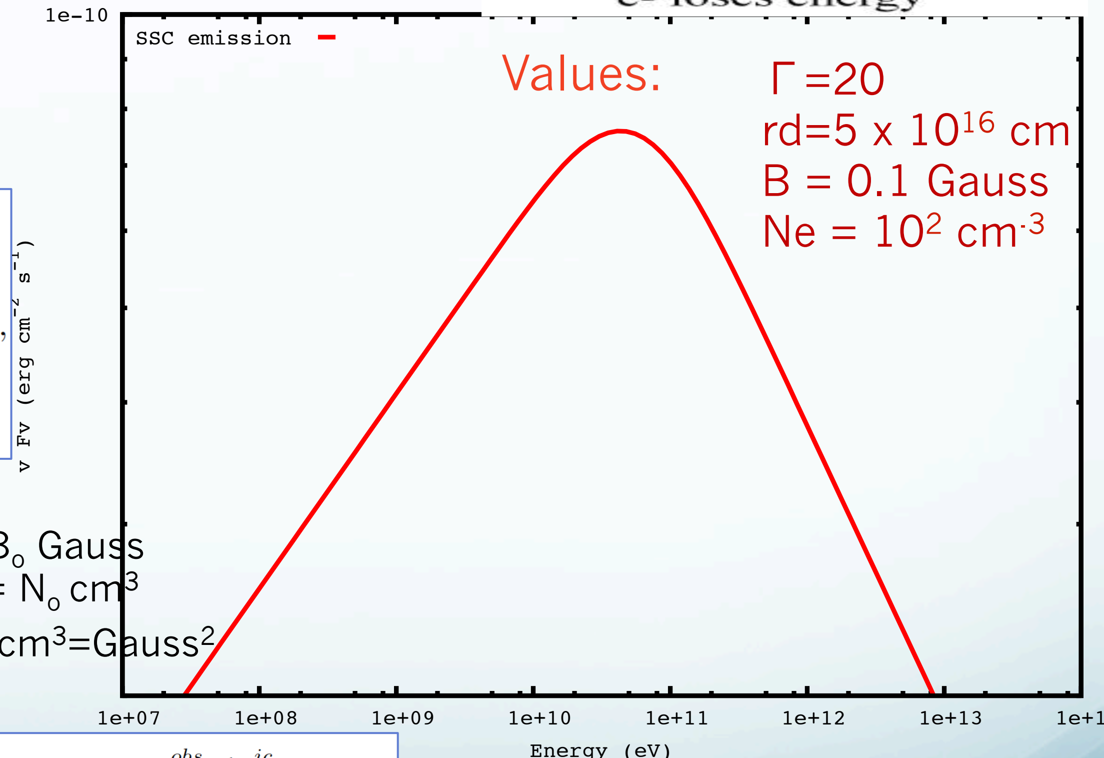
optical depth $$\tau_{\gamma\gamma} \simeq \sigma_T\, n(x) x r_d$$

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

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

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

Milagro and Veritas (Low state)
Power index: β = 2.3

➢ External inverse-Compton scattering

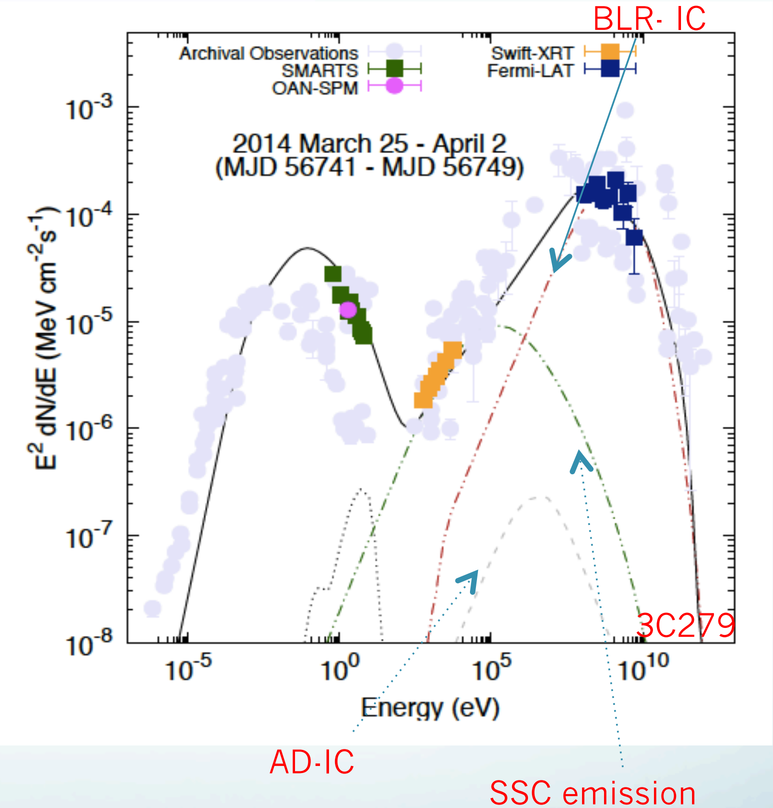
Up-scattered photons from BLR

Energy density BLR $$U'_{\rm BLR} \simeq \Gamma^2 \frac{L_{\rm BLR}}{4\pi r_{\rm BLR}^2}$$

Tarjet photon density BLR $$n'_\epsilon \delta\epsilon \simeq \Gamma^2 \frac{L_{\rm BLR}}{4\pi r_{\rm BLR}^2 \epsilon_{\rm BLR}}$$

Luminosity BLR $$L_{\rm BLR} = 10^{44}\,{\rm erg\,s^{-1}}\; f_{c,-1}\, L_{\rm AD,45}$$

Interaction region BLR $$R_{\rm BLR} \simeq 10^{17}\,{\rm cm}\; L_{\rm AD,45}^{1/2}$$



Up-scattered photons from accretion disk

Energy density AD $$U'_{\rm AD} \simeq \Gamma^2 \frac{\tau_{\rm sc}\, L_{\rm AD}}{4\pi r_{\rm BLR}^2}$$

Tarjet photon density AD $$n'_\epsilon \simeq \frac{\tau_{\rm sc}\, L_{\rm E'}}{4\pi r_{\rm BLR}^2 \epsilon'}$$

➢ P γ interactions

The target photon density

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

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

$$\Downarrow$$

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

neutrino production

Charged and neutral pion production channels

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

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

Photo-pion cooling time,

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

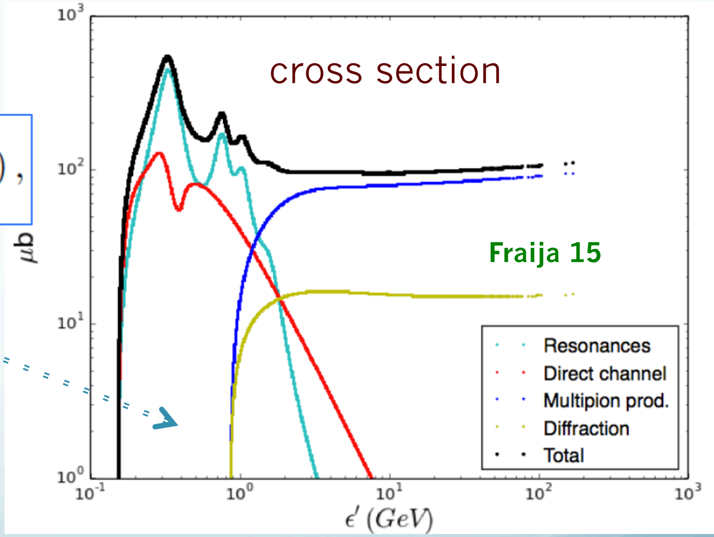


Photo pion efficency

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

Proton distribution

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

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 $\gamma_i = m_i^2/m_e^2\, \gamma_e$

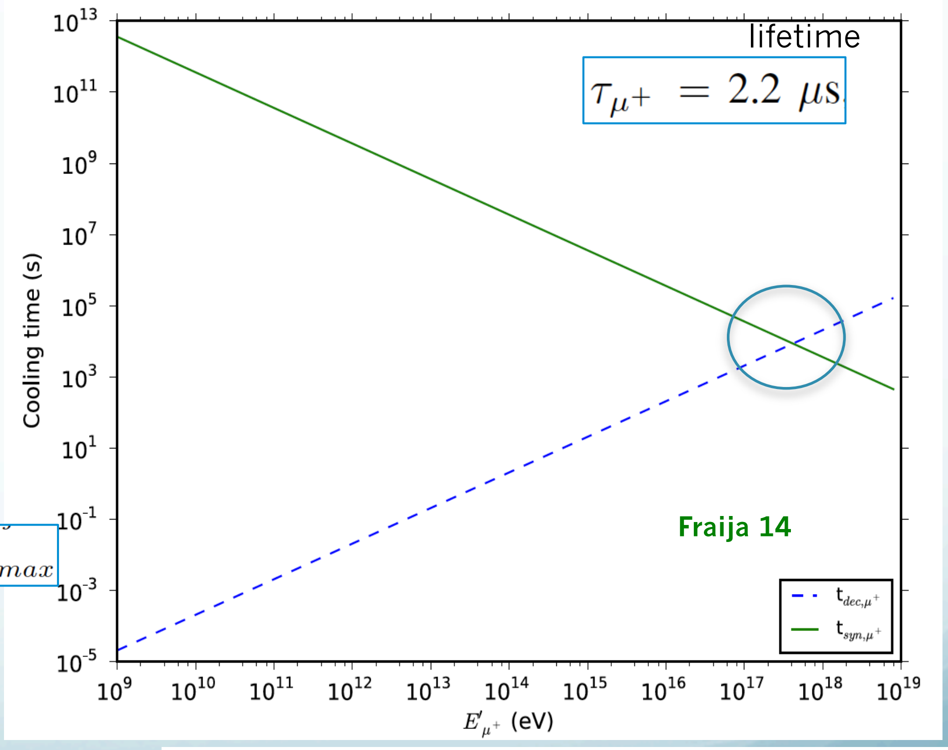
Aharonian 2000, Mannheim 1993

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 $\gamma_{i,b} \leq \gamma_i < \gamma_{i,max}$

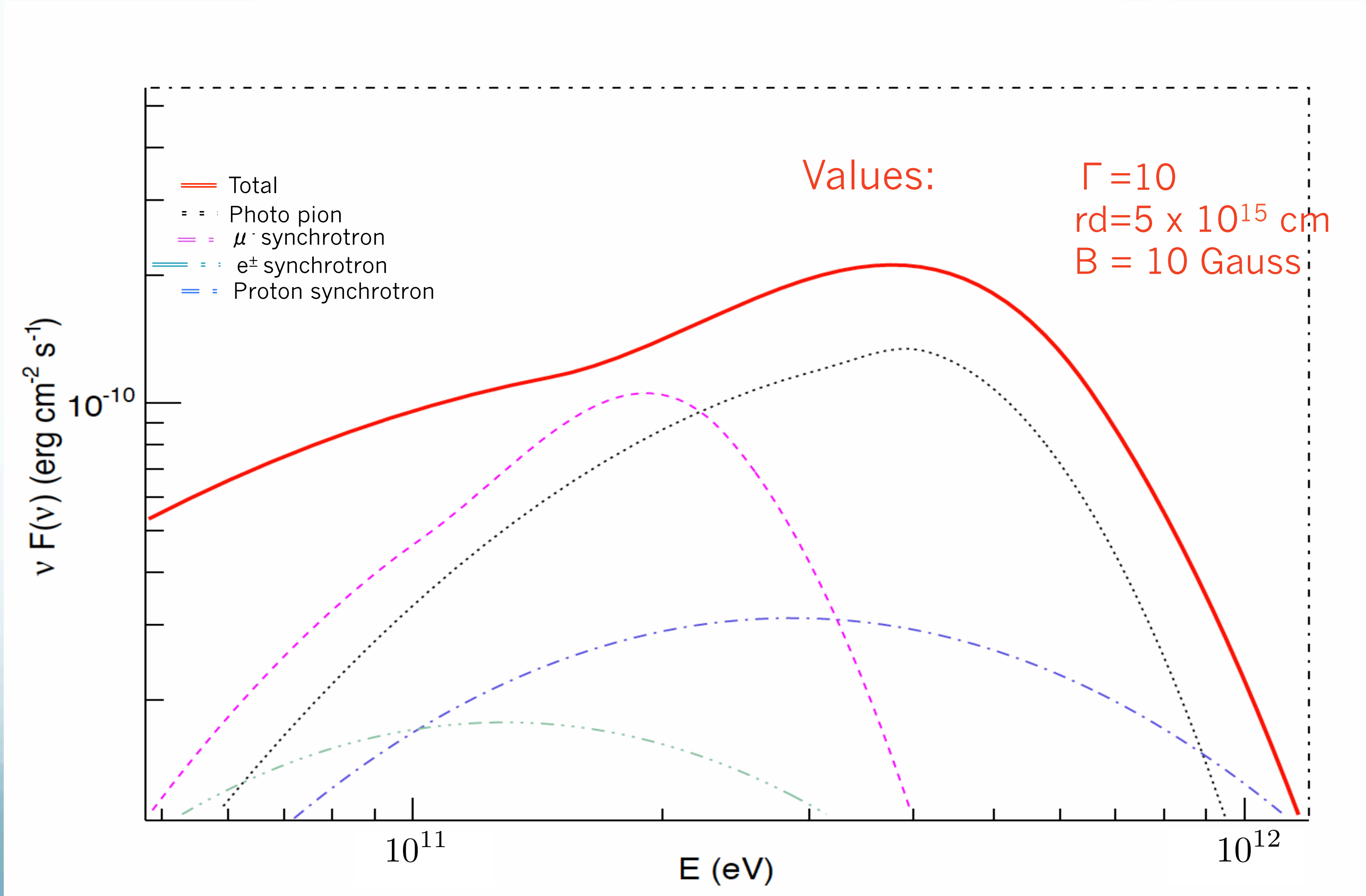
lifetime $\tau_{\mu^+} = 2.2\ \mu s$



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



➢ e± pair plasma

Initial electron density

$$n_{e,o} = \frac{1}{4\sigma_T G_N M}\,\frac{1}{\Gamma^2_{W,o}\,\beta_{W,o}\langle\gamma_{e,o}\rangle}\left(\frac{m_p}{m_e}\right)\left(\frac{r_g}{r_o}\right)^2\left(\frac{L_j}{L_{Edd}}\right)$$

Photon density

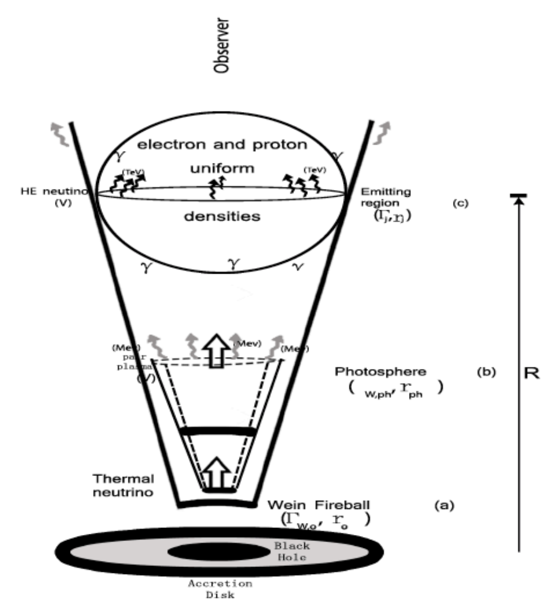
$$n_\gamma = \frac{\theta_0}{\theta_{ph}(1+2f(\theta_{ph}))}\,\frac{3L_\gamma}{4\pi r^2_{ph}\,\epsilon\,\Gamma^2_{W,ph}\,\beta_{W,ph}\,m_e\,\langle\gamma_{e,o}\rangle}$$

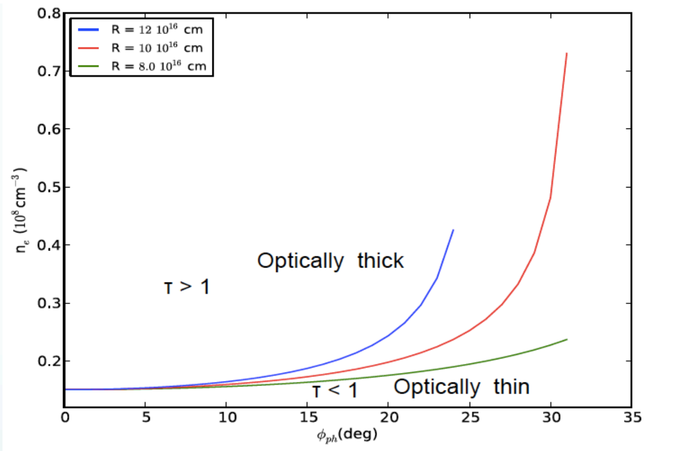
Optical thickness to pair creation

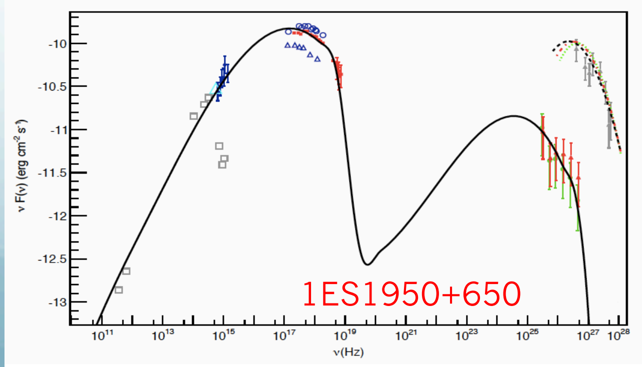
$$\tau_{\gamma\gamma} \simeq \frac{\sigma_T\,\epsilon_{\gamma b}\,r_{ph}}{4\,m_e\,\Gamma_{W,ph}}\,n_\gamma$$

Output spectrum of MeV photons

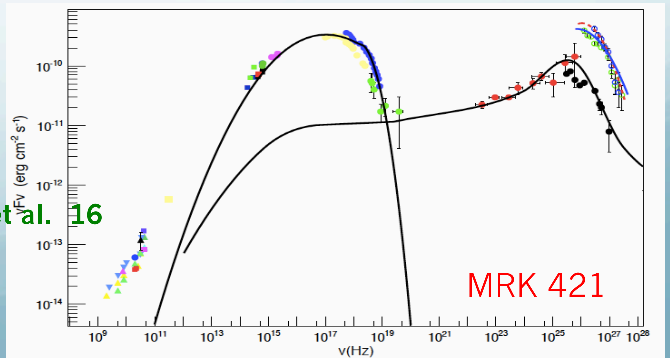
$$\frac{dn_\gamma(\epsilon_\gamma)}{d\epsilon_\gamma} \propto \begin{cases} (\epsilon_\gamma)^{-\beta_l}, & \text{if } \epsilon_\gamma < \epsilon_{\gamma b}, \\ (\epsilon_{\gamma b})^{-\beta_l+\beta_h}(\epsilon_\gamma)^{-\beta_h}, & \text{if } \epsilon_\gamma \geq \epsilon_{\gamma b}, \end{cases}$$







Fraija et al. 16



➢ Models

Leptonic

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

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

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

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

There is not 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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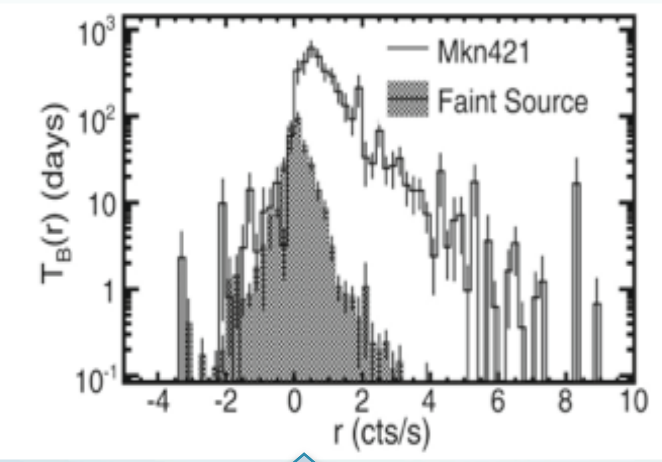
➢ Data sets

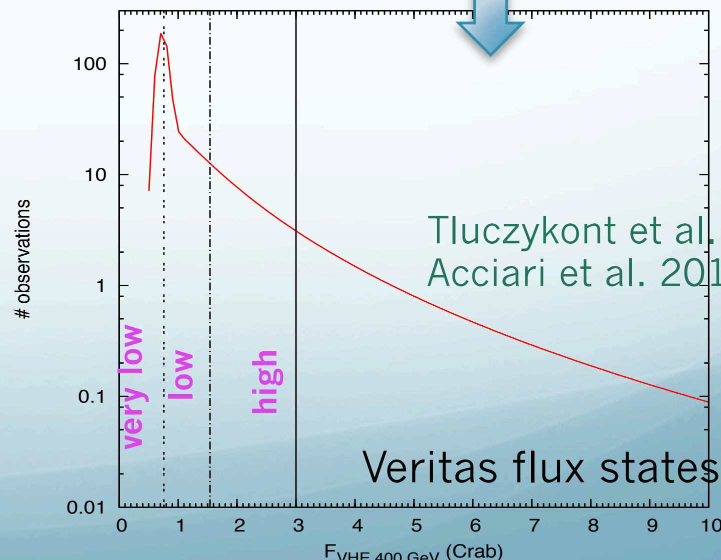
- Whipple - RXTE/ASM data (Acciari et al. 2014)
- **Milagro - RXTE/ASM data**
- HEGRA CT1 - RXTE/ASM (Aharonian et al. 2003)
- MAGIC/Whipple/VERITAS-XMM Newton data (Acciari et al. 2009)
- MAGIC-RXTE/ASM data (Albert et al. 2007)



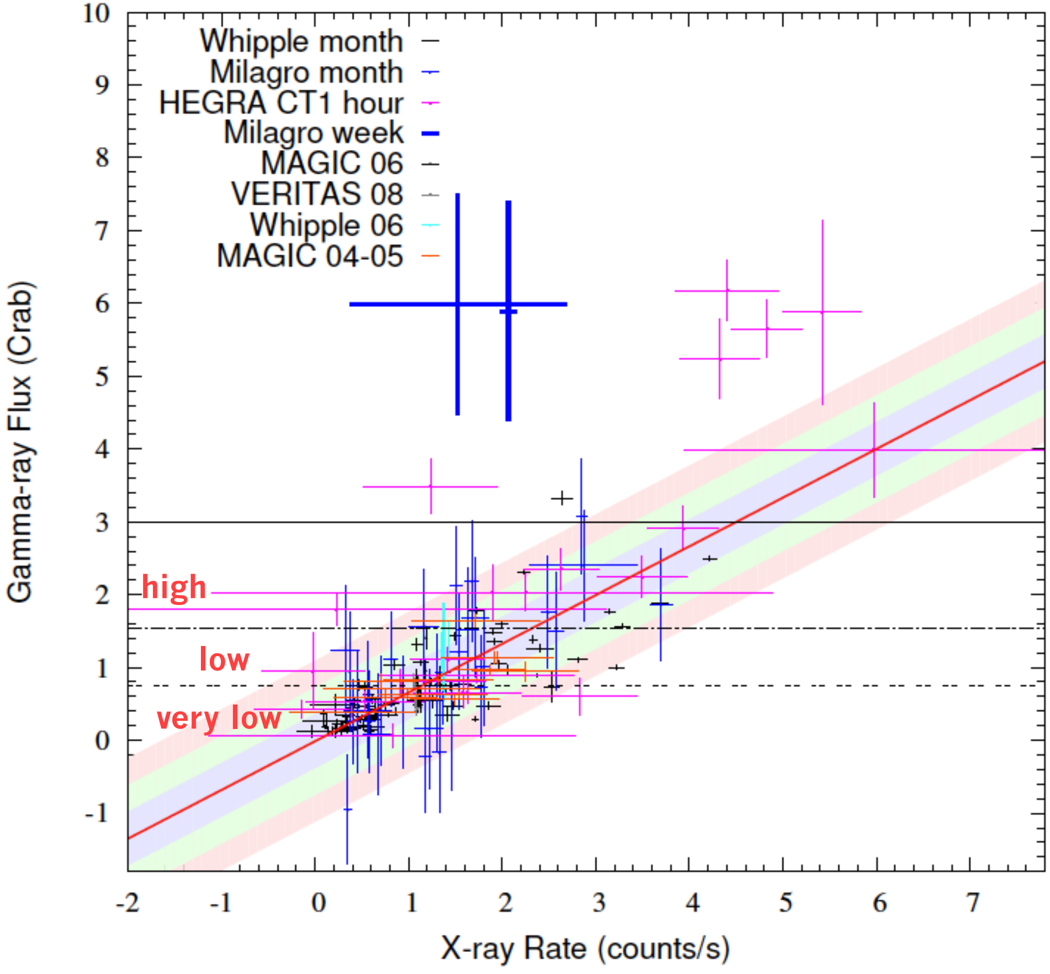
Resconi et al. 2009

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

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 $= 0.67 \pm 0.04$
- Sigma: $\sigma = 0.37 \pm 0.03$

Patricelli et al 2015
Gonzalez et al 2018

➢ 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

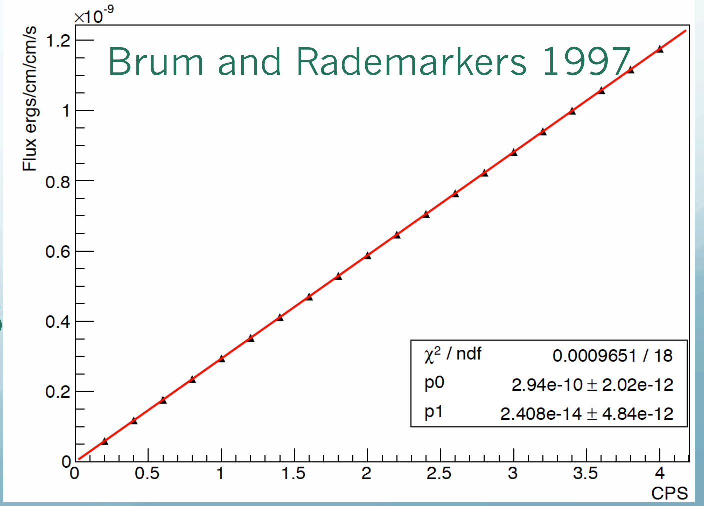
Values N_e and B are computed fitting data

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

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

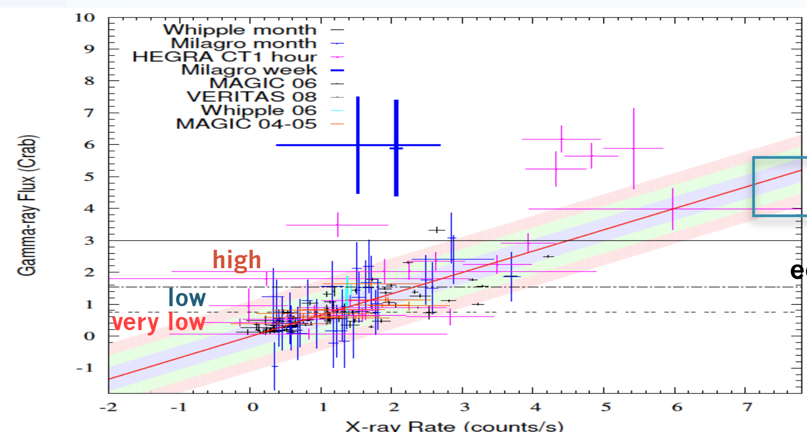
Electron density $10^3 \leq N_e\,(\mathrm{cm}^{-3}) \leq 10^{5.5}$

As fluxes increase the set of parameters decreases.

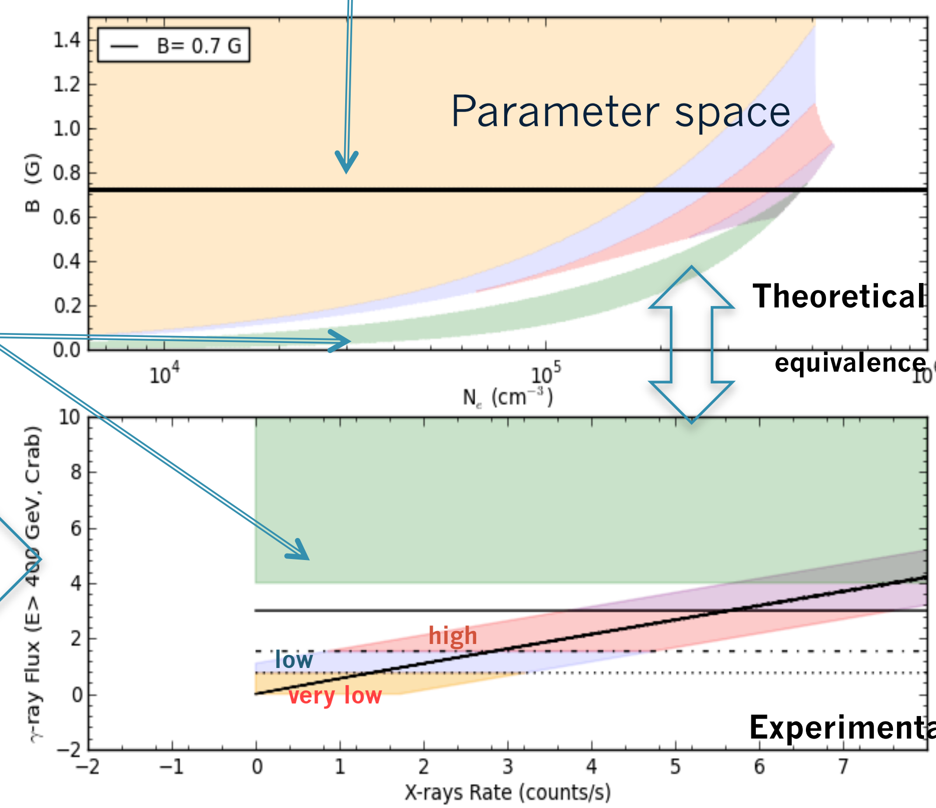
As fluxes decrease B decreases

Unique correlation

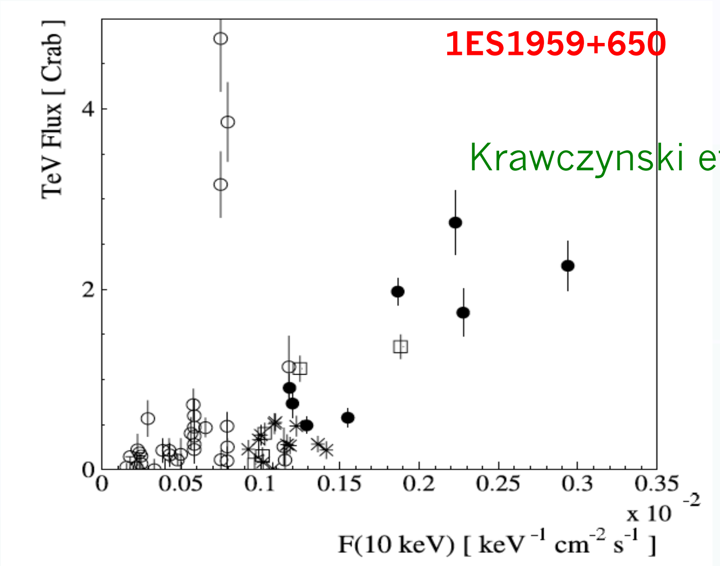
Orphan flares



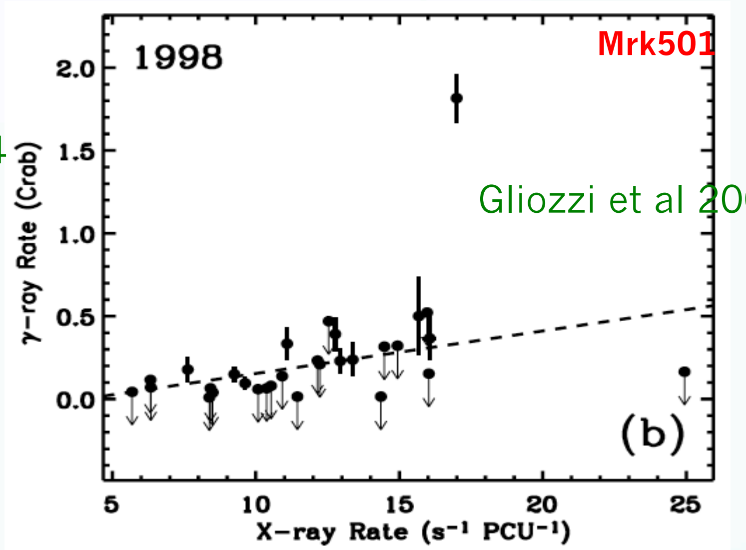
equal



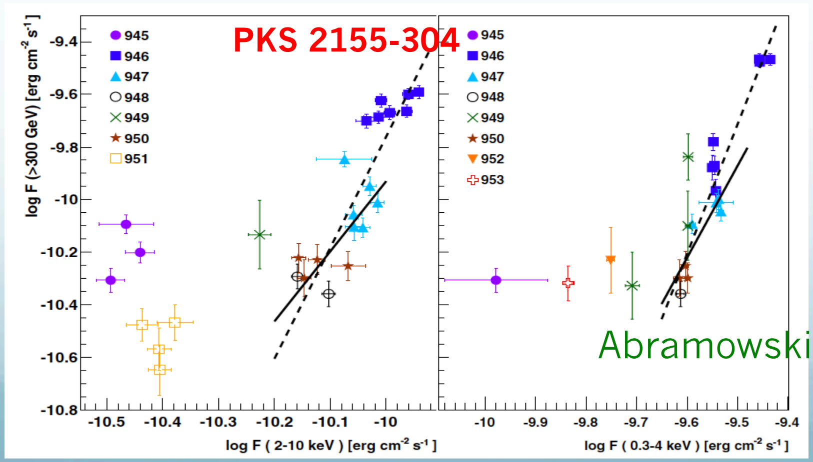
This model could be generalized to other blazars



Krawczynski et al 2004



Gliozzi et al 2006



Abramowski et al 2006

OUTLINE

- Observations: TeV and X-ray correlations (variability and spectrum)
- Theoretical model:
  - Generalities
  - Lepton model
  - Hadronic model
- Application to Mrk 421
- Conclusions

➢ Conclusions

- ✓ 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 0.6 < B< 0.8 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 and external inverse-Compton models can describe the SED, it can not explain the correlation.