A mechanism for producing intrinsic broken power-law γ-ray spectra in compact sources

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Outline

PART I

- Introduction to the instability of “automatic photon quenching”

- Critical conditions for the growth of the instability

- Steady-state γ-ray spectra

PART II

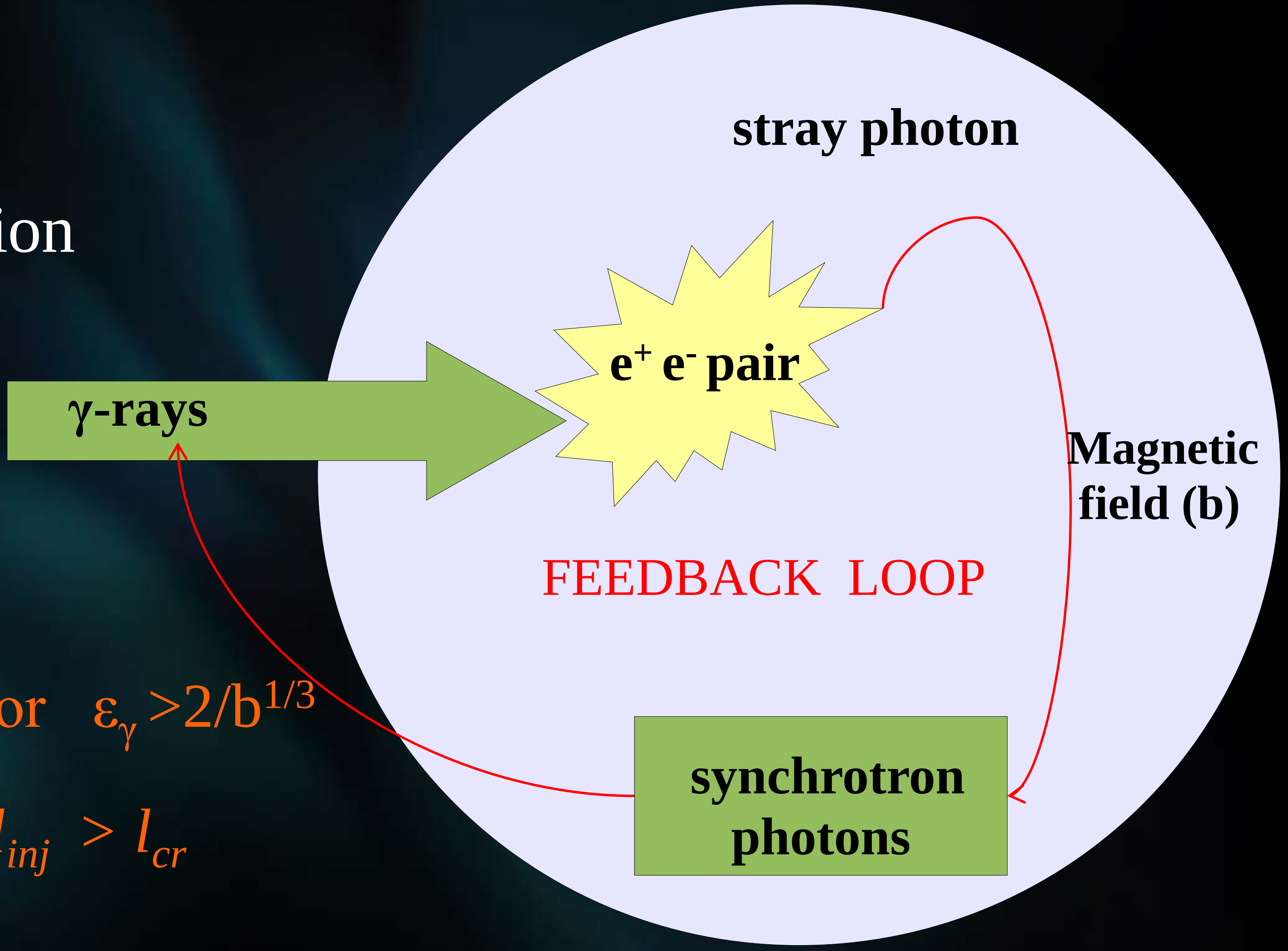
- Relevance to observations

- Application on γ-ray emitting blazar PKS 0447-439

Introduction -1

Processes:

1) $\gamma\gamma$ absorption
2) synchrotron emission



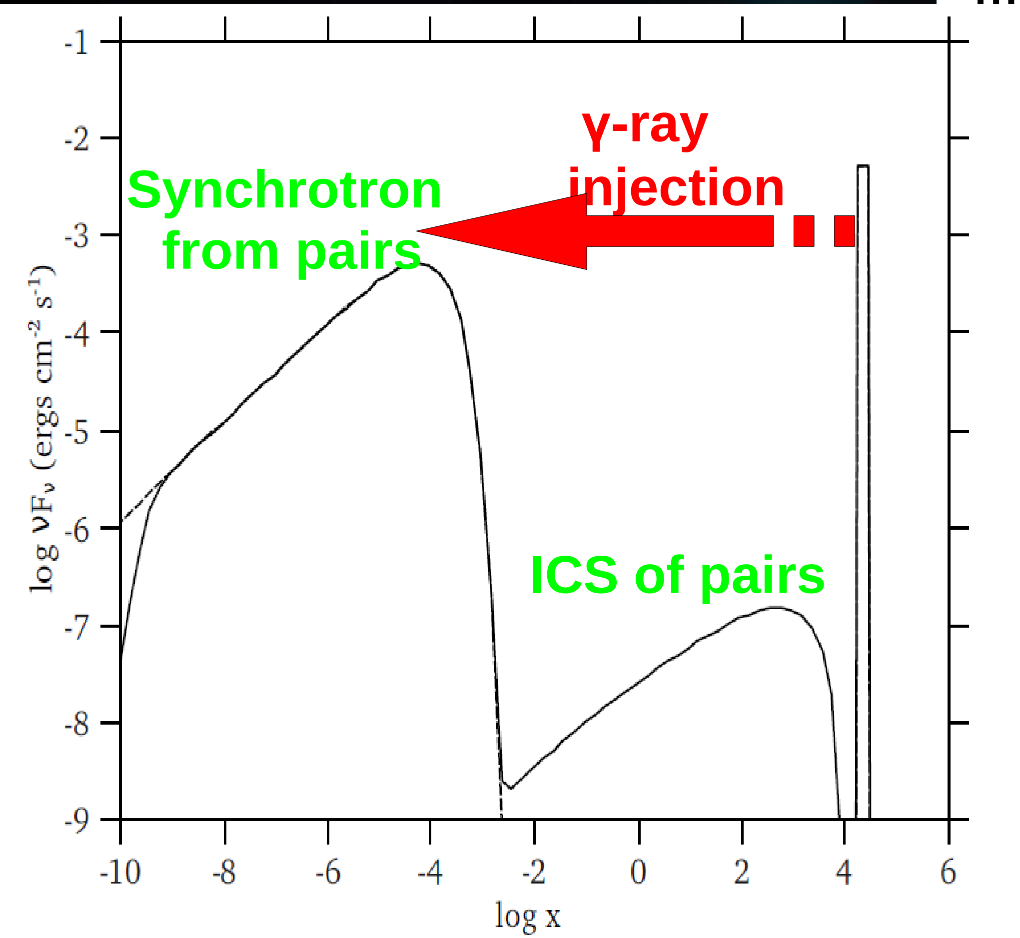
Criteria:

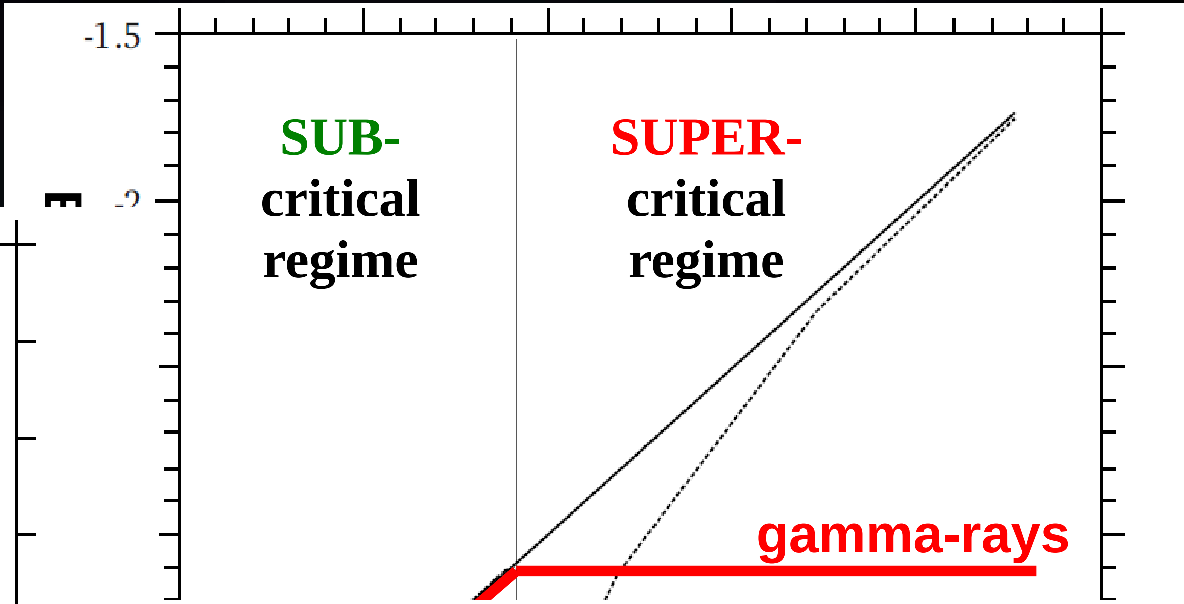
1)Feedback $x_s \varepsilon_\gamma > 2$ or $\varepsilon_\gamma > 2/b^{1/3}$

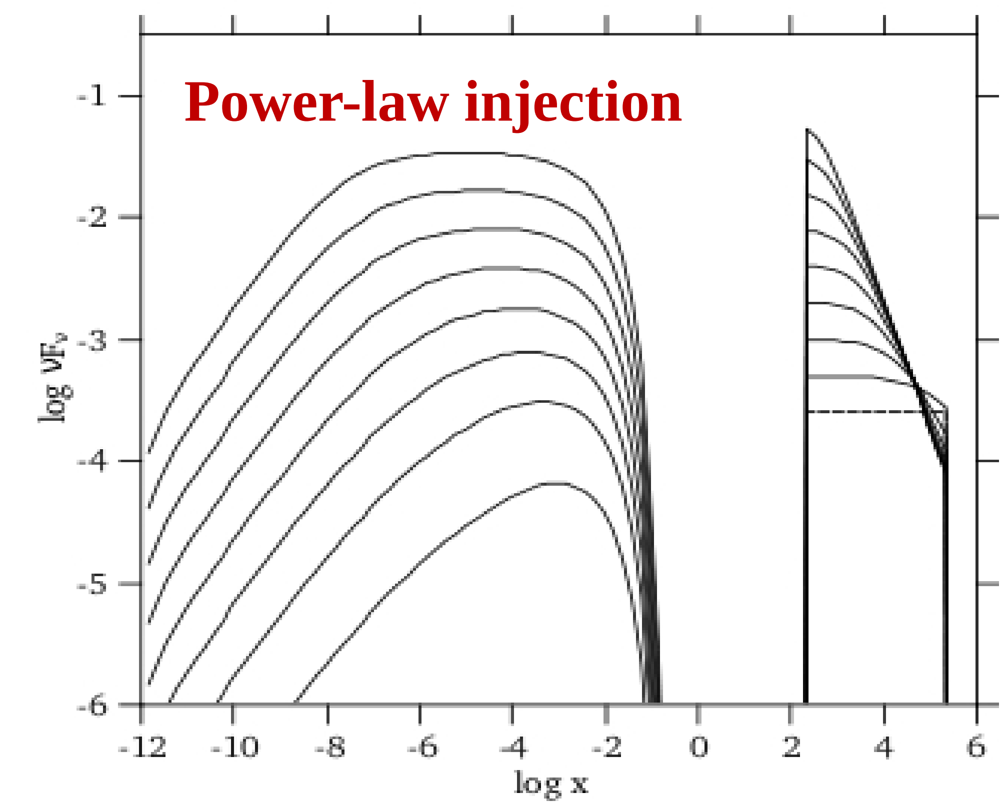
2) Marginal stability $l_{inj} > l_{cr}$

Stawarz & Kirk (2007)
Petropoulou & Mastichiadis (2011)

Introduction - 2

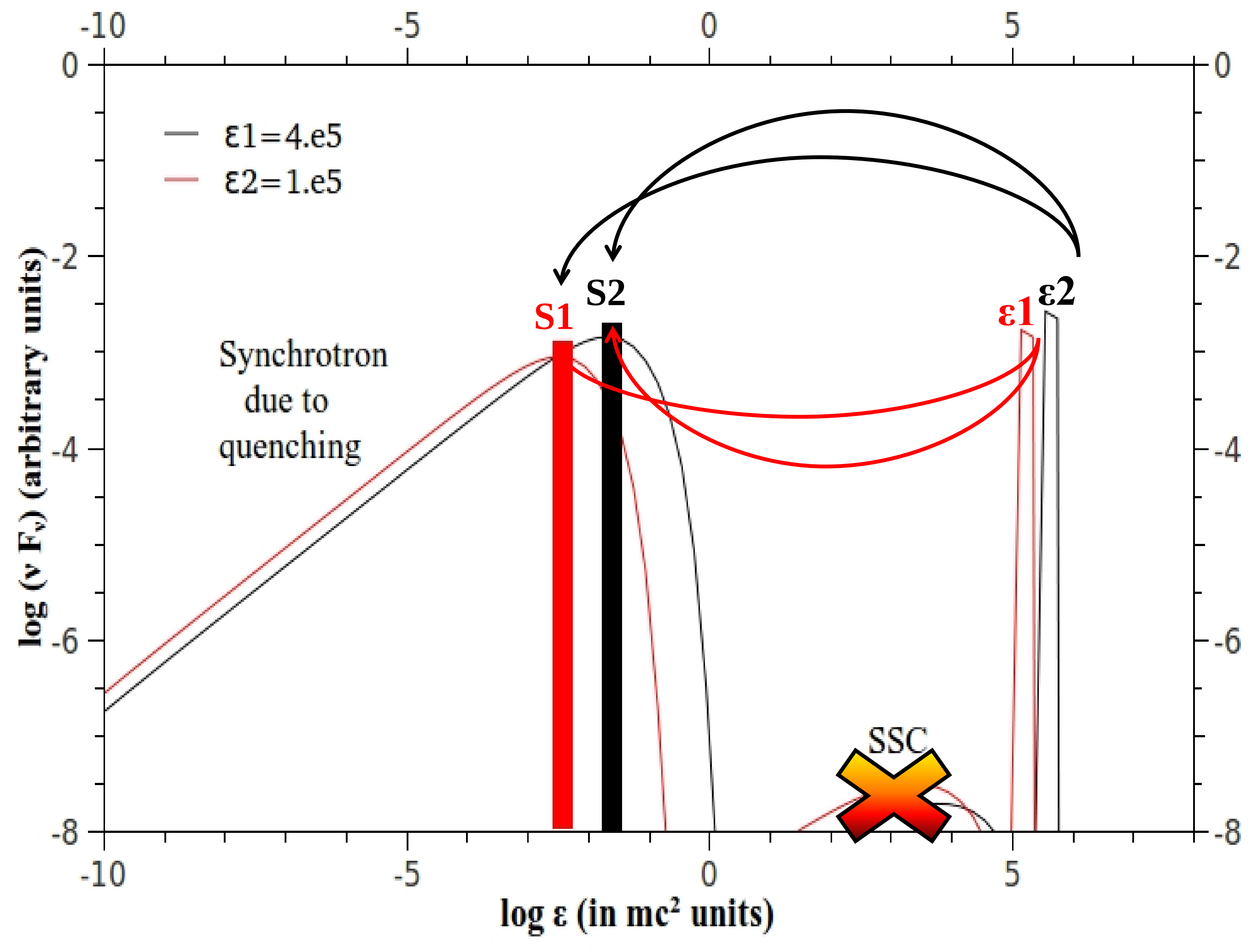






Petropoulou & Mastichiadis (2011)

Critical condition - 1



Critical condition - 2

For discrete injection of γ-rays

$$\sum_{i=1}^{N} \frac{Q_{\rm inj}^{(i)}}{\epsilon_i^4} \geq \frac{b^2}{16\sigma_0}.$$

For more details
see poster S2-01
by Dafni Arfani

For continuous injection of γ-rays

$$\ell_{\gamma,\rm cr} = \frac{b^2}{48\sigma_0} \begin{cases} \dfrac{(\Gamma+3)\left(\epsilon_{\rm min}^{-\Gamma+2} - \epsilon_{\rm max}^{-\Gamma+2}\right)}{(\Gamma-2)\left(\epsilon_{\rm M}^{-\Gamma-3} - \epsilon_{\rm max}^{-\Gamma-3}\right)}, & \text{for } \Gamma \neq 2 \\[2ex] \dfrac{(\Gamma+3)}{\left(\epsilon_{\rm M}^{-\Gamma-3} - \epsilon_{\rm max}^{-\Gamma-3}\right)} \ln\left(\dfrac{\epsilon_{\rm max}}{\epsilon_{\rm min}}\right), & \text{for } \Gamma = 2, \end{cases}$$

Steady state spectra - 1

METHOD :

- Use continuous instead of discrete energy distributions
- Write 3 equations for: γ-rays, pairs , soft photons
- Use continuous energy losses for pairs
- Find steady-state solutions

$$
\begin{aligned}
\boxed{n_\gamma(\epsilon)} &= Q_0 \epsilon^{-\Gamma} H(\epsilon - \epsilon_{\rm min}) H(\epsilon_{\rm max} - \epsilon)) - \boxed{n_\gamma(\epsilon)} \int_0^{x_{\rm max}} {\rm d}x \; \sigma_{\gamma\gamma}(x\epsilon) \boxed{n_{\rm s}(x),} \\
\boxed{n_{\rm s}(x)} &= \alpha_1 x^{-1/2} \boxed{n_{\rm e}\left(\sqrt{\frac{x}{b}}\right),} \\
\boxed{n_{\rm e}(\gamma)} &= +\alpha_2 \frac{\partial}{\partial \gamma} \boxed{\left(\gamma^2 n_{\rm e}\right)} + \boxed{4 n_\gamma(\epsilon)} \int_0^{x_{\rm max}} {\rm d}x \; \sigma_{\gamma\gamma}(x\epsilon) \boxed{n_{\rm s}(x)}
\end{aligned}
$$

Steady state spectra - 2

$$n_\gamma(\epsilon) = Q_0 \epsilon^{-\Gamma}, \quad \epsilon_{\rm min} \le \epsilon \le \epsilon_{\rm br}$$

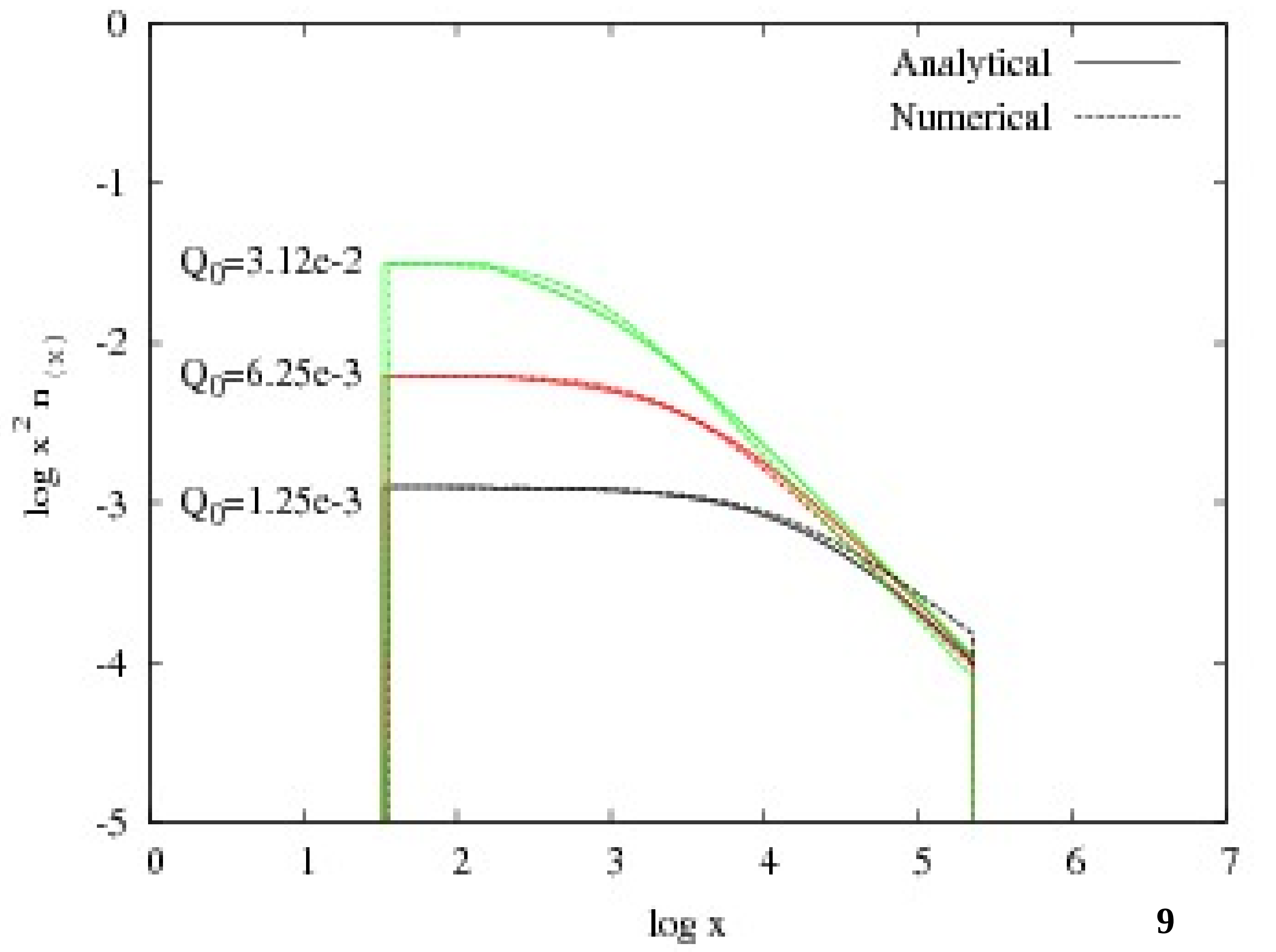
$$n_\gamma(\epsilon) = \frac{Q_0 \epsilon^{-\Gamma}}{1 + \frac{F}{\epsilon}\left(\left(\frac{2}{\epsilon}\right)^{-\Gamma/2-1} - x_{\rm max}^{-\alpha}\right)}, \quad \epsilon_{\rm br} < \epsilon \le \epsilon_{\rm max},$$

Depends on:

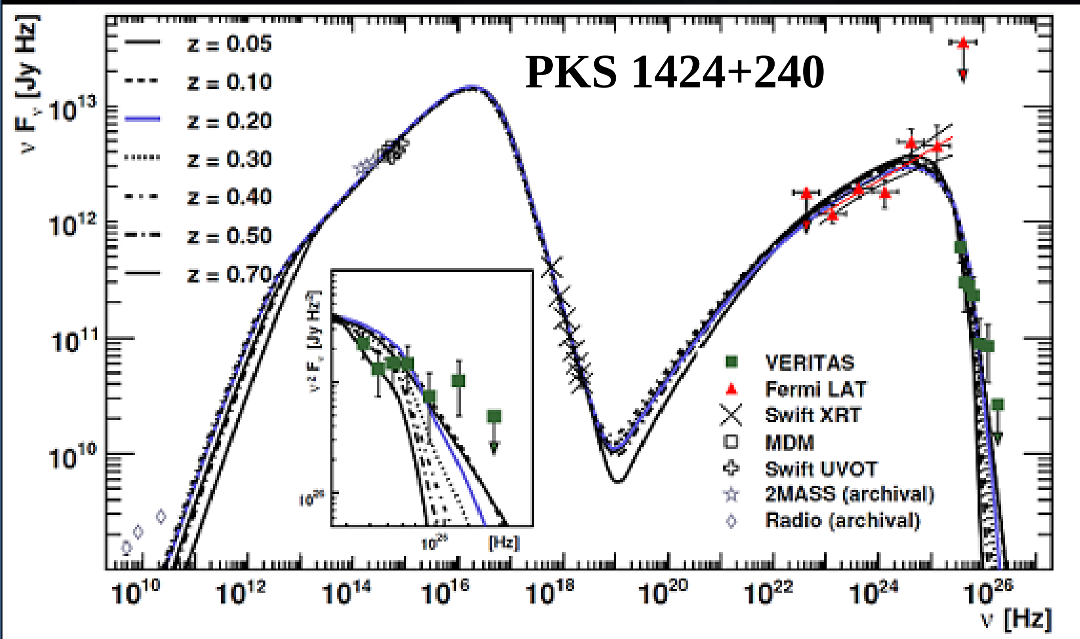
- Magnetic field
- Max γ-ray energy

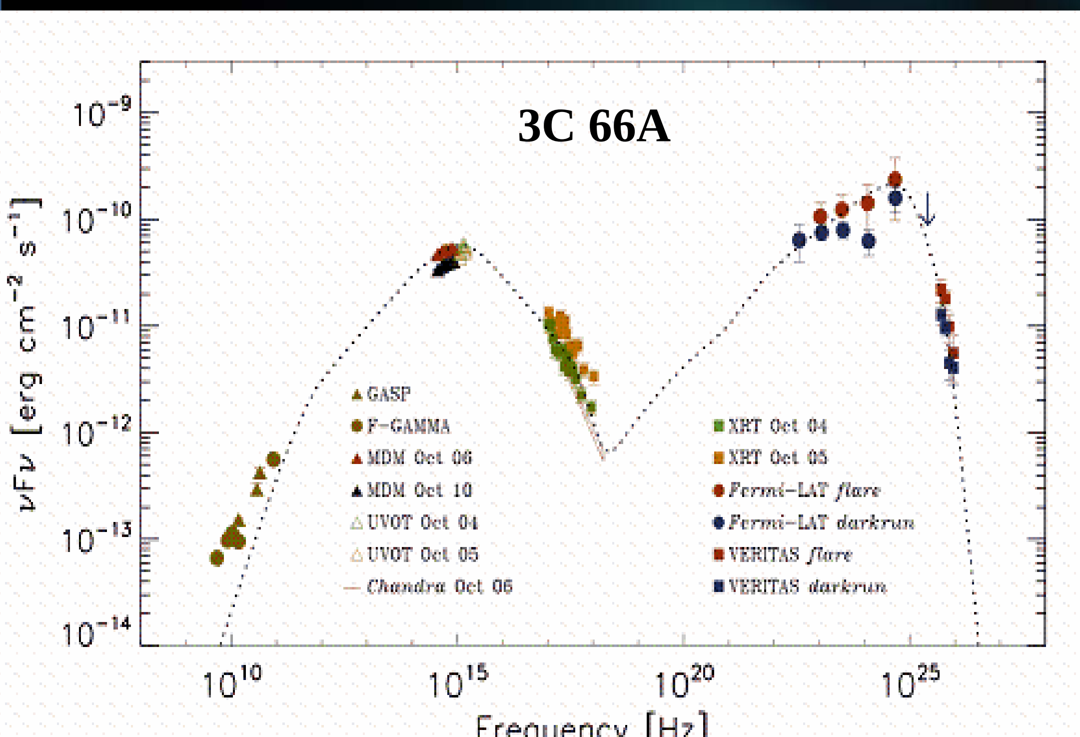
Asymptotic spectral break

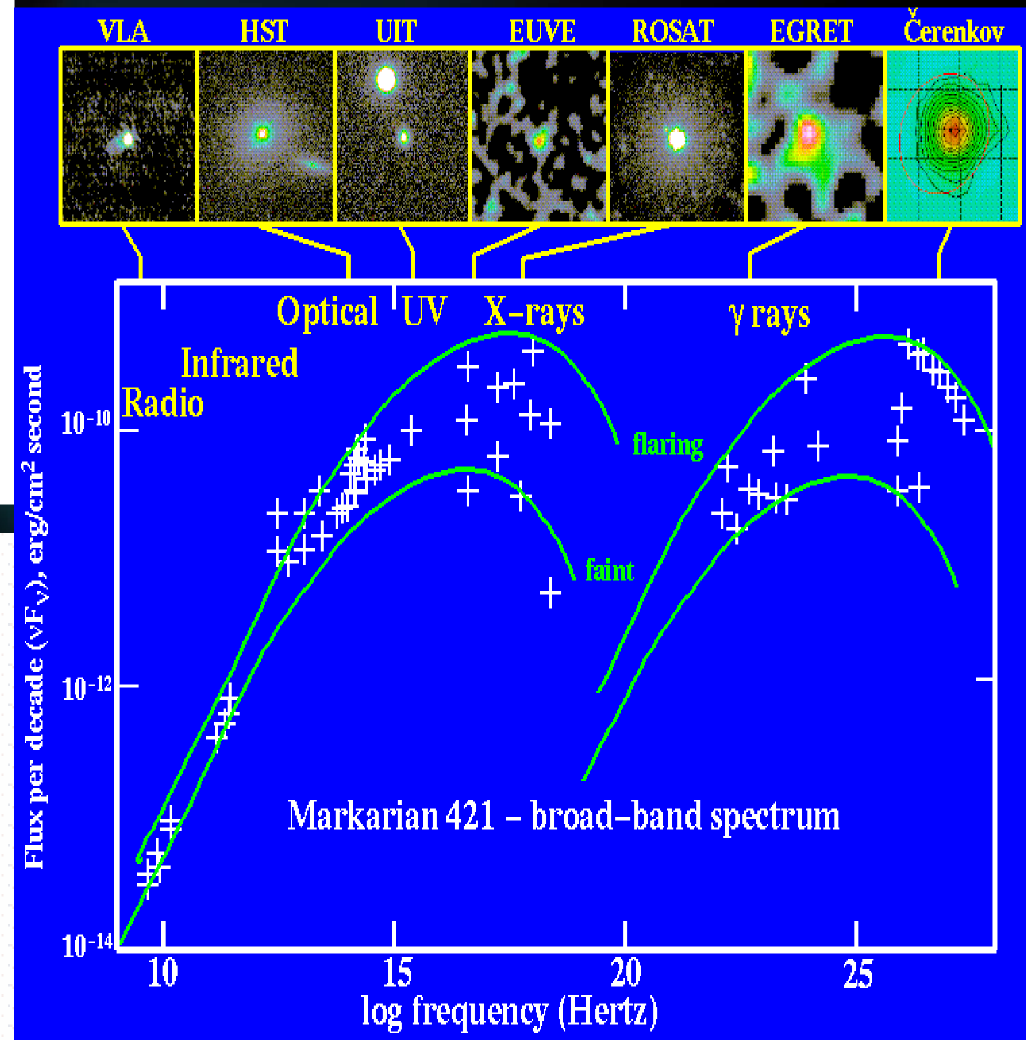
$\Gamma \longrightarrow 3\,\Gamma/2$



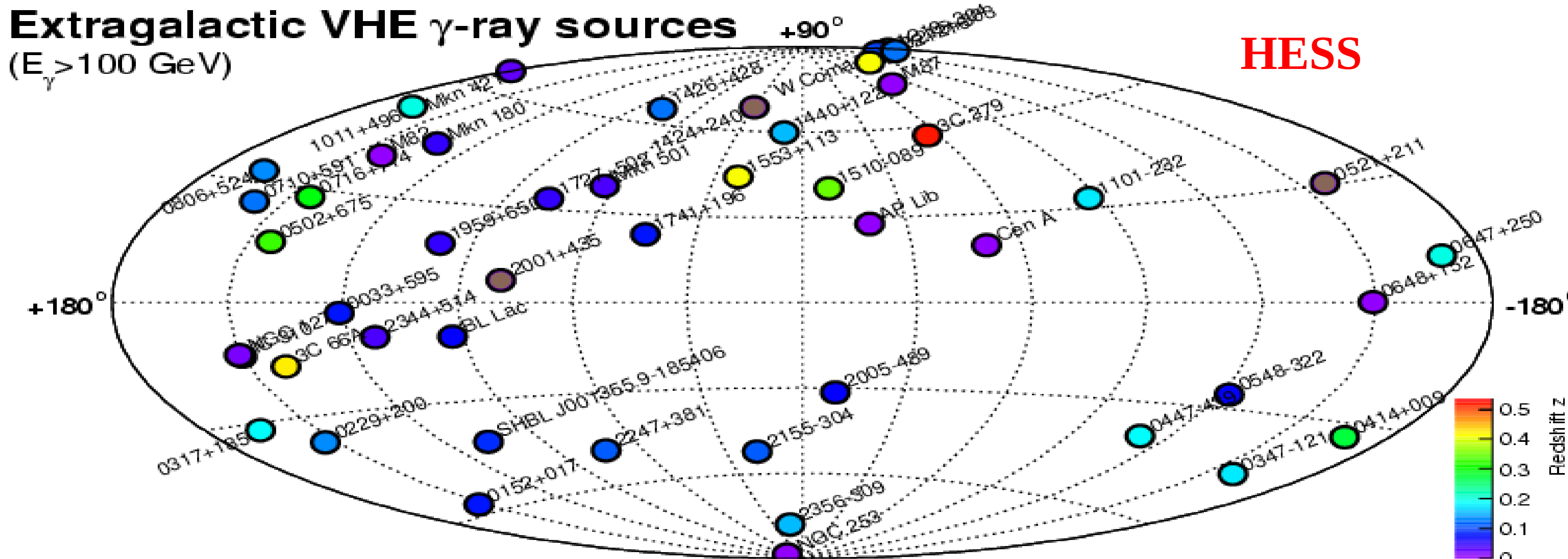
Relevance to observations - 1



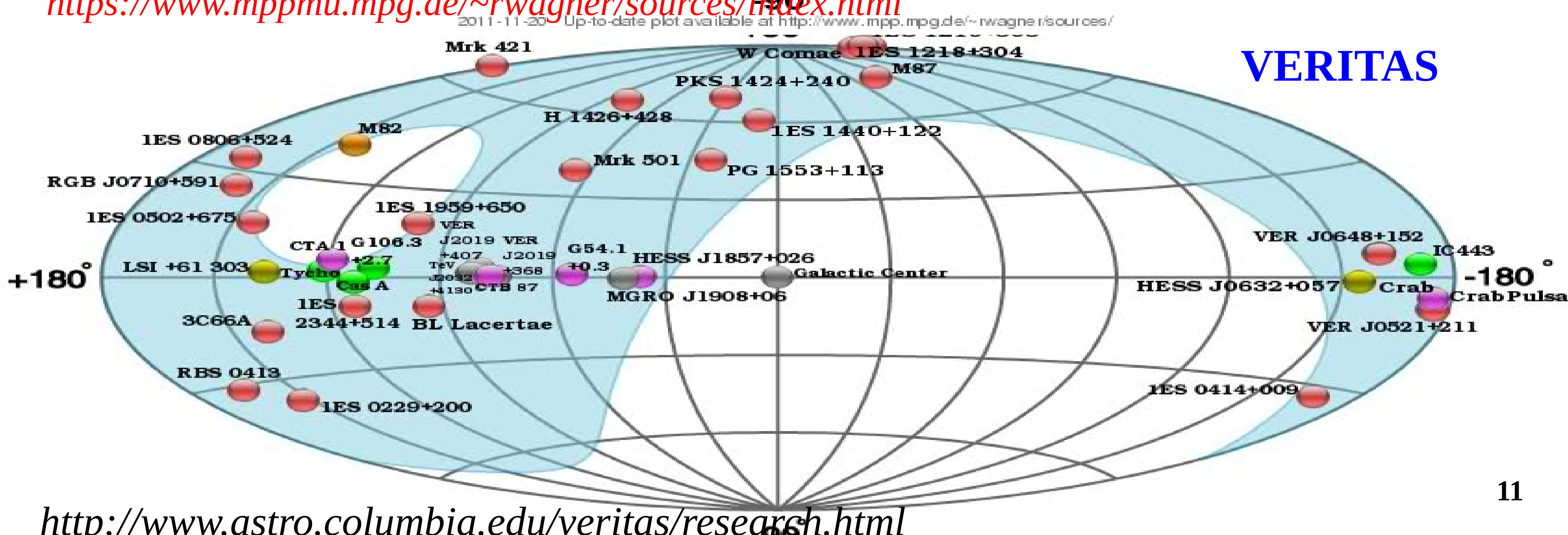




Relevance to observations - 2



https://www.mppmu.mpg.de/~rwagner/sources/index.html



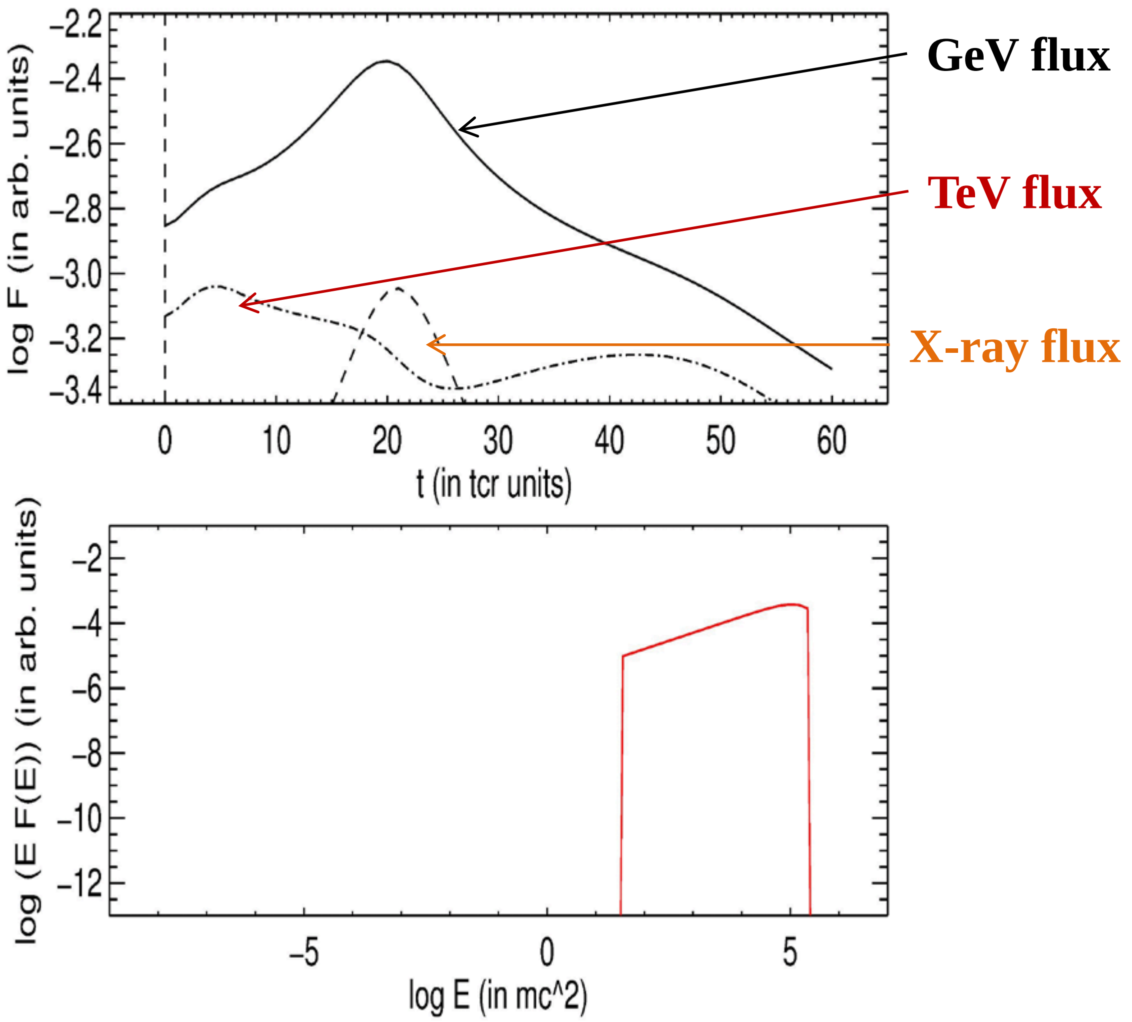
http://www.astro.columbia.edu/veritas/research.html

Predictions of our model

- Large spectral breaks : $\Delta\Gamma=\Gamma/2 > 0.5$
- Absorbed γ-ray luminosity appears in the X-ray band

$$E^{obs}_{s,max} = 0.5\,\delta^2(1+z)^{-2}\left(E^{obs}_{br,9}\right)^{-1} \text{ in keV}$$

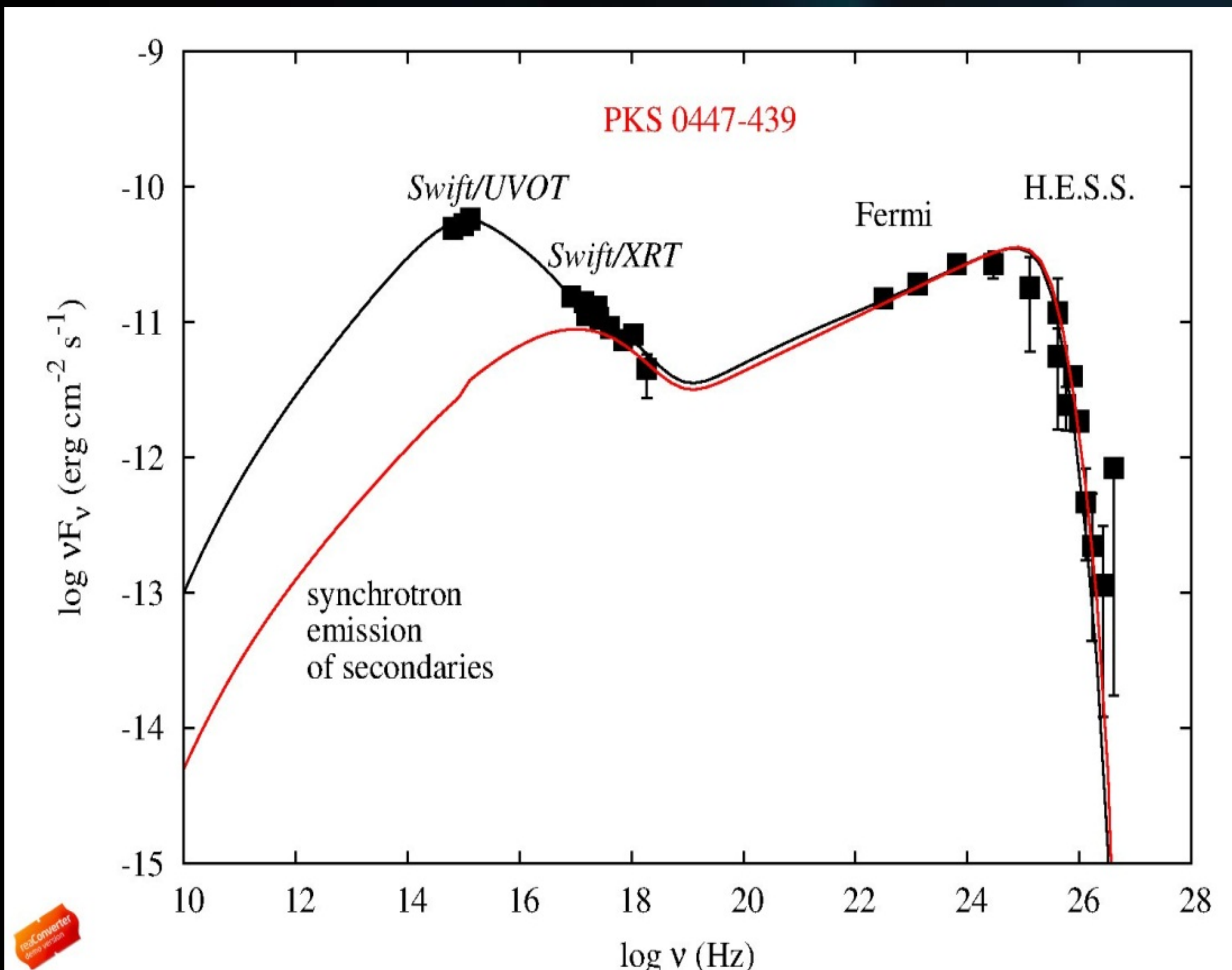
- X-ray/ GeV flux correlation



Credit: G. Vasilopoulos

Application on PKS 0447-439

- Recently detected in VHE γ-rays (Abramowski et al. 2013)
- Redshift z ~0.2 (but still disputable)
- Correlation of TeV/ X-ray variability: unknown



Parameter symbol	
R (cm)	8×10^{15}
B (G)	20
u_B (erg cm^{-3})	16
δ	11
ϵ_{max} $(m_e c^2)$	10^5
ϵ_{min} $(m_e c^2)$	10^{-6}
Γ	1.8
ℓ_{inj}	7.2×10^{-3}
$\ell_{\gamma,cr}$	2×10^{-3}
γ_{max}	8×10^3
γ_{min}	8×10^2
p	2.5
ℓ^e_{inj}	2×10^{-3}

Petropoulou et al. 2013

Summary

- Growth of the instability leads in internal absorption of γ-rays and in appearance of a soft photon component

- The critical condition for the onset of the instability depends on the minimum/maximum energies and the photon index of the γ-ray spectrum, as well as on the magnetic field

- Large spectral breaks ($\Delta\Gamma > 0.5$) are obtained if the system lies deep in the supercritical regime

- Magnetic field values ~ 10-50 G are required for breaks in the GeV energy range and cutoff energies ~ a few TeV.

- Tight correlation between the unabsorbed γ-ray flux and the soft synchrotron flux is predicted

See also poster S2-2 by S. Dimitrakoudis et al

Thank you