Gamma-ray signatures from pair cascades in recombination-line radiation fields

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In collaboration with J. Becerra González[2], A. Shukla[3], D. Paneque[4] and K. Mannheim[1]

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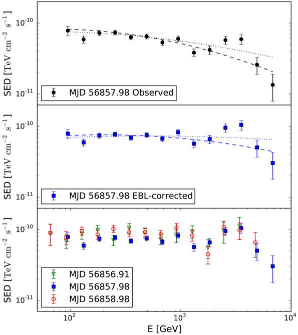
Peculiar feature in Markarian 501 – A hint to gap activity?



SED of Mrk 501 from 19.07.2014 (top and middle frame) and from 18. - 20.07.2014 (bottom), observed by the MAGIC telescopes.
Dotted lines: Best log-parabola fit
Dashed lines: Neglecting data above 1.5 TeV
Acciari, et al., 2020, A&A

PL, LP and ELP fit of MAGIC data:
Inconsistent at $> 3\sigma$

Likelihood ratio test:
Broad LP + narrow LP preferred at 4σ versus single LP

⇒ Talk #79 by J. Becerra González
Check the video talk!

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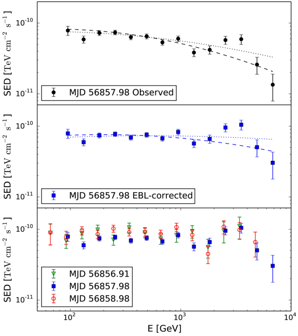

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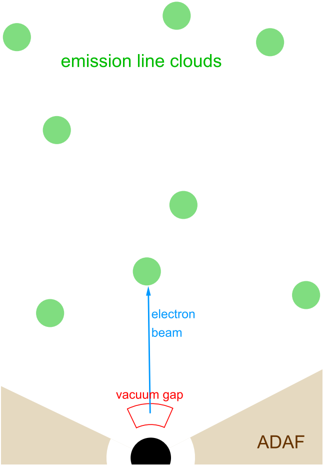
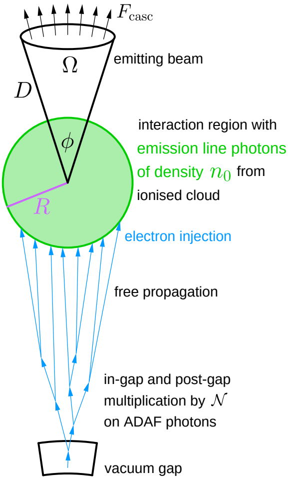
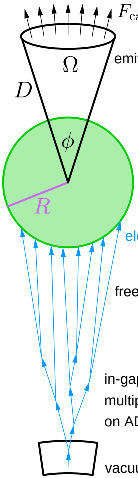


Interaction of electron beam with emission line photons



$$\dot{N}_{\mathrm{i}}(\gamma) = \begin{cases} \frac{K_{\mathrm{G}}}{\sigma\sqrt{(2\pi)}} \cdot \exp\left(-\frac{(\gamma-\gamma_{\mathrm{mean}})^2}{2\,\sigma^2}\right) & \text{if } \gamma_{\min} \leq \gamma \leq \gamma_{\max}, \\ 0 & \text{otherwise} \end{cases}$$

Interaction of electron beam with emission line photons



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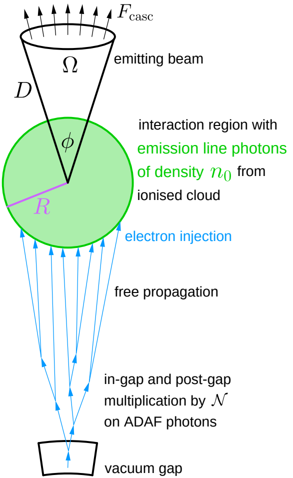
$$n_0(x) = K_{\mathrm{lines}} \cdot \sum_{i=1}^{4} \frac{K_{\mathrm{line},\,i}}{x_{0,\,i}} \cdot \delta_{\mathrm{Dirac}}\left(x - x_{0,\,i}\right)$$

i	Wavelength $\lambda_{0,\,i}$/nm	Relative flux density contribution $K_{\mathrm{line},\,i}$	Line
1	30.5	2.00	He II Lyman-α
2	93.0	0.17	H Lyman series
3	102.6	0.57	H Lyman-β
4	121.5	5.40	H Lyman-α

Interaction of electron beam with emission line photons



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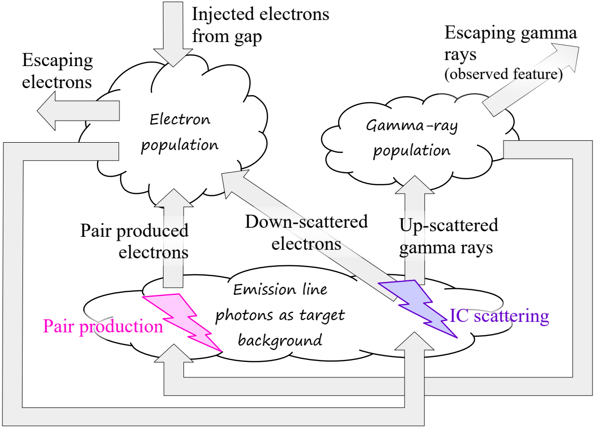
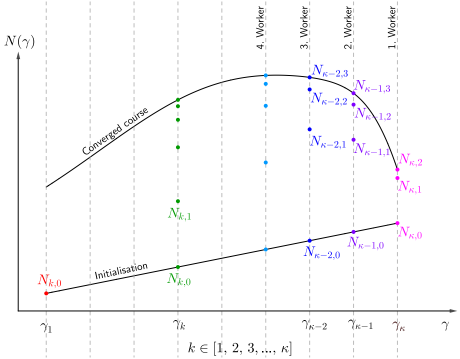
$$T_{\text{esc}} := \frac{R}{c}$$

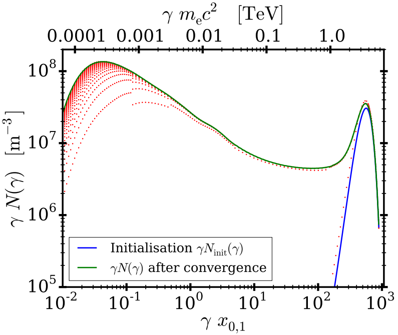
Interaction of electron beam with emission line photons
⇒ Evolution of IC pair cascade



Determine electron distribution

Input quantities, kinetic equations, steady state $\Rightarrow$ $N(\gamma_k) = \mathcal{F}(N(\gamma \geq \gamma_k, \gamma_k)$





Converged electron energy distribution versus product of the Lorentz-factor with the energy of the highest energetic line. At high energies, the distribution is shaped mainly due to the injected electrons. At low energies, escape gets more and more important. Wendel, et al., 2021, A&A

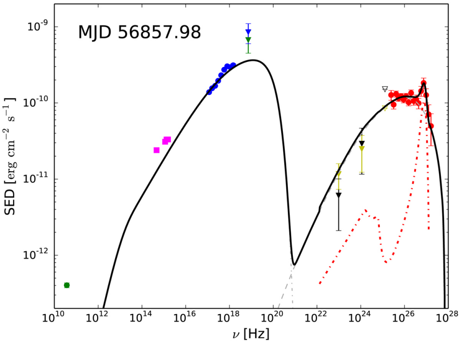
Fit to observational SED

- Electron distribution $\Rightarrow \; n_\gamma(x_\gamma)$
- $F_{\mathrm{casc}}(x_\gamma) = n_\gamma(x_\gamma) \cdot \dfrac{4\pi\, c\, R^2}{\Omega(\phi)\, D^2\, m_e c^2}$
- Add SSC component:

  $F(x_\gamma) = F_{\mathrm{casc}}(x_\gamma) + F_{\mathrm{SSC}}(x_\gamma)$

Quantity	Used value
γ_{min}	10^3
γ_{break}	$4.0 \cdot 10^5$
γ_{max}	$3.0 \cdot 10^6$
α_1	2.0
α_2	3.1
R	$2.9 \cdot 10^{13}$ m
B	$1.2 \cdot 10^{-5}$ T
δ	20
Electrons' number density	$2.1 \cdot 10^{10}\ \mathrm{m}^{-3}$

The SSC parameters used for fitting.



Broadband SED of Mrk 501 from 19.07.2014 (MJD 56857.98).
Red dots: MAGIC
Black / yellow triangles: Fermi LAT
Blue / green: Swift BAT / XRT
Pink: KVA / Swift UVOT
Green: Metsähovi
Grey lines: SSC emission
Red line: Cascaded emission
Black line: SSC + cascaded emission
Acciari, et al., 2020, A&A

Fit to observational SED

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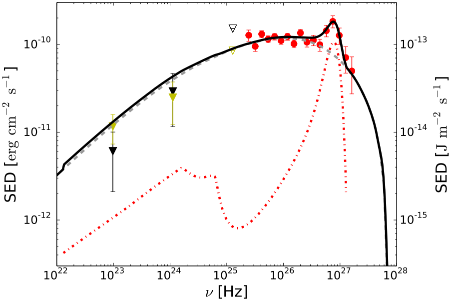
- Add SSC component:
  $F(x_\gamma) = F_{\text{casc}}(x_\gamma) + F_{\text{SSC}}(x_\gamma)$
- Fit peaky feature:

Quantity	Used value
ϕ	1.8°
R	$3.0 \cdot 10^{11}$ m
K_G	$3.3 \cdot 10^{4}\ \text{s}^{-1}\text{m}^{-3}$
K_{lines}	$9.7 \cdot 10^{12}\ \text{m}^{-3}$
γ_{mean}	$3.4 \cdot 10^{12}\ \text{eV}/(m_e c^2)$
σ	$0.23\ \gamma_{\text{mean}}$

The cascade parameters used for fitting.

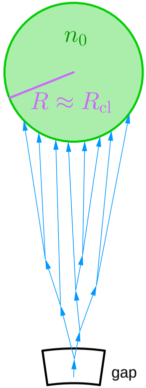


HE and VHE SED of Mrk 501 from 19.07.2014 (MJD 56857.98).
Red dots: MAGIC
Black / yellow triangles: Fermi LAT
Grey line: SSC emission
Red line: Cascaded emission
Black line: SSC + cascaded emission
Wendel, et al., 2021, A&A

Inferences about Mrk 501 – Emission line clouds

- Assume $N_{\mathrm{cl}} \approx 10$ clouds of size R_{cl}:
  $n_0,\ N_{\mathrm{cl}},\ R_{\mathrm{cl}} \ \Rightarrow\ L_{\mathrm{Ly}\,\alpha,\,\mathrm{mod}}$

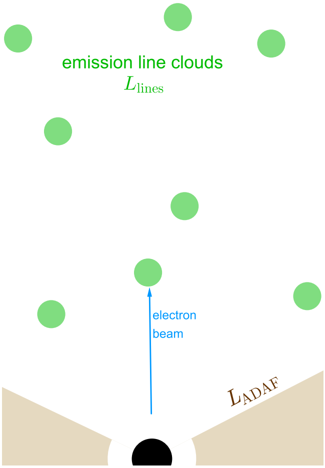
- $L_{\mathrm{Ly}\,\alpha,\,\mathrm{mod}} \overset{!}{=} L_{\mathrm{Ly}\,\alpha,\,\mathrm{obs}}$ (from Stocke, Danforth, Perlman, 2011, ApJ)
  $\Rightarrow\ R_{\mathrm{cl}} \approx 1.8 \cdot 10^{11}\ \mathrm{m} \approx R$



Inferences about Mrk 501 – Reprocessing of accretion flow luminosity

- n_0, N_{cl}, R_{cl} $\Rightarrow$ L_{lines}
- Determine accretion flow luminosity L_{ADAF}
  (from Mahadevan, 1997, ApJ)
- $L_{\mathrm{lines}} \overset{!}{=} \overbrace{0.01}^{\xi} L_{\mathrm{ADAF}}$

  Alternative: $\xi = 0.1$ or 0.001

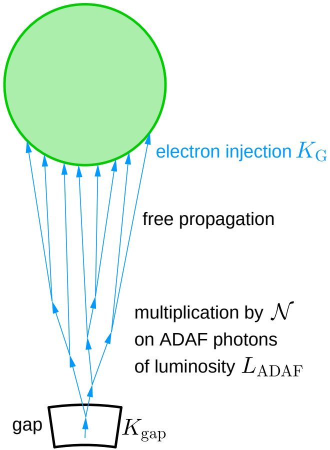


Inferences about Mrk 501 – Multiplication of electrons

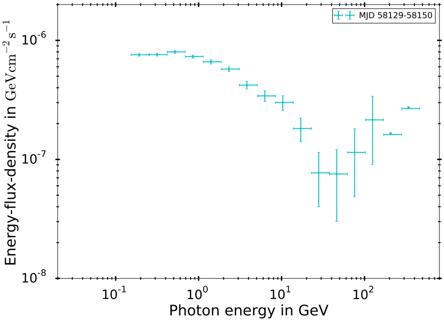
- Determine materialisation rate in gap
  $L_{\mathrm{ADAF}} \;\Rightarrow\; n_{\gamma,\,\mathrm{gap}} \;\Rightarrow\; K_{\mathrm{gap}}$
- $K_{\mathrm{gap}} \cdot \mathcal{N} \overset{!}{=} K_{\mathrm{G}}$
  $\Rightarrow\; \mathcal{N} \approx 10^6$
- Check: $e\,\Phi_{\mathrm{gap}}/\mathcal{N} \overset{!}{=} \gamma_{\max}\, m_{\mathrm{e}} c^2$

  $10^{19}\,\mathrm{eV}/\mathcal{N} \approx e\,\Phi_{\mathrm{gap}}/\mathcal{N} \overset{!}{=} \gamma_{\max}\, m_{\mathrm{e}} c^2 \approx 5.7 \cdot 10^{12}\,\mathrm{eV}$

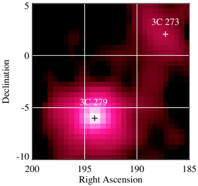
  Valid for $\xi = 0.01$
  Invalid for alternative $\xi = 0.1$ or 0.001



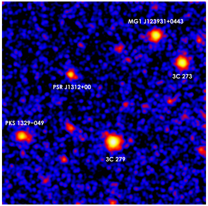
Gamma-ray emission from 3C 279



SED of 3C 279, observed by the Fermi LAT. Wendel, Shukla and Mannheim, accepted by ApJ

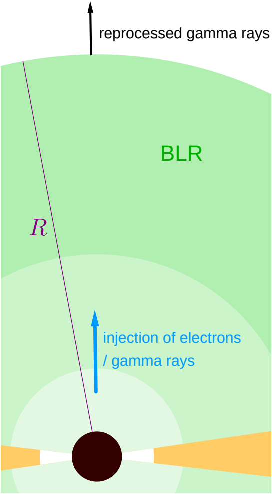


Sky map around 3C 279 and 3C 273. EGRET Team, 1991



5-year exposure at energies > 1 GeV. NASA/DOE/Fermi LAT Collaboration

Gamma-ray emission from 3C 279



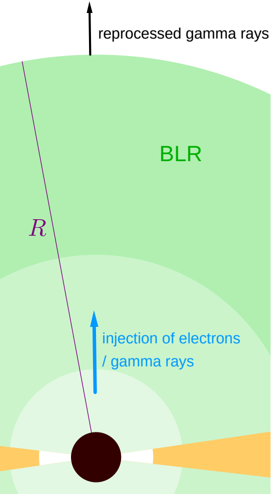
Case 1:	$\dot{N}_{\mathrm{i}}(\gamma)$:	Gaussian
	$\dot{n}_{\gamma,\mathrm{i}}(x_\gamma)$:	Power-law
Case 2:	$\dot{n}_{\gamma,\mathrm{i}}(x_\gamma)$:	Log-parabola
Case 3:	$\dot{N}_{\mathrm{i}}(\gamma)$:	Gaussian + power-law

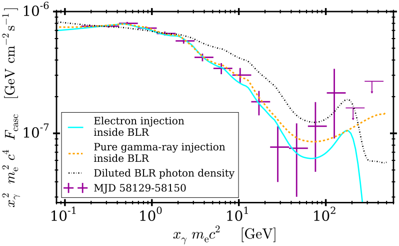
$n_0(x)$: Sum of emission lines

Most prominent lines: O VII, C V, Fe XVIII, Fe XXIII, He II Lyman-α, He I, H I Lyman-α

$$T_{\mathrm{esc}} := \frac{R}{c}$$

Gamma-ray emission from 3C 279





Fermi SED (MJD 58129 - 58150, violet markers) with cascade modeling fits.
Cyan and orange lines: Cascade in BLR photon field
Black dot-dashed lines: Cascade outside of BLR
Wendel, Shukla and Mannheim, accepted by ApJ

Fail to meet points for same R, diluted n_0 and non-extreme $\dot{N}_\mathrm{i}$ and $\dot{n}_{\gamma,\mathrm{i}}$

$\Rightarrow$ Emission not from outside of BLR

Summary

- Robust scheme to solve for steady-state cascaded N and n_γ.
- Markarian 501:
  - Hot (10^{10} K), low-accreting ($\dot{m} \approx$ few 10^{-4}) ADAF
    - Materialisation in gap and subsequent multiplication by $\mathcal{N} \approx 10^6$
    - Cloud reprocessing fraction $\xi \approx 0.01$
  - Electron beam + emission lines $\Rightarrow$ IC pair cascade
  - Escaping gamma rays can account for narrow SED feature
  - Narrow SED feature can indicate gap activity
- Dip in SED of 3C 279:
  Emission from edge of BLR preferred toward outside of BLR

Work performed by C. Wendel, J. Becerra González, A. Shukla, D. Paneque and K. Mannheim
$\Rightarrow$ Talk #79