

Multi-wavelength emission analysis from inverse-Compton initiated cascades

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② Motivation of study

③ Framework

④ Modelling

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⑥ Part 1

⑦ Conclusions

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Active galactic nuclei (AGNi)

- Compact regions at centres of galaxies
- Accrete matter onto a supermassive black hole ($m_{\text{BH}} \sim (10^6 - 10^{10}) M_{\odot}$)
- Power source: gravitational well of SMBH produces powerful radiation output
- Classified into different types

Schematics of active galactic nuclei with relativistic jet

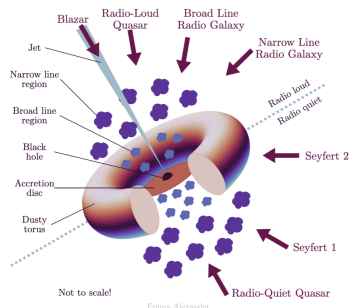


Image Credit: Emma Alexander, based on Urry and Padovani (1995)

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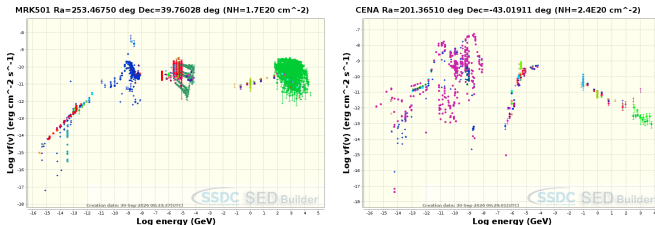
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Broadband spectral energy distribution (SED) of blazars and radio galaxies



Broadband SED of the blazar Mrk 501 (*left*) and radio galaxy Cen A (*right*)

- Emissions are Doppler boosted due to relativistic outflows in blazar jets, whereas in radio galaxies there is weak boosting
- Radio galaxies are the parent population of the blazars, so they must intrinsically produce high-energy (HE, $E > 100$ MeV) to very high-energy (VHE, $E > 100$ GeV) emissions. Hence, their SEDs are similar

Modelling SED of Radio Galaxies

- Roustazadeh and Böttcher (2010, 2011, 2012) and Sitarek and Bednarek (2010) explored inverse-Compton (IC) supported cascade emission as a viable mechanism to model SEDs of radio galaxies
- **Prev. works (RB)** used
 - Broad-line region (BLR) radiation field as the target photons for IC scattering
 - Oblique magnetic field
- Shakura and Sunyaev (1973) (SS) disk radiation field more dominant than BLR (at $R < R_{\text{BLR}}$, e.g. see Ghisellini and Tavecchio (2009))
- **This work** includes the radiation field of a accretion disk for IC scattering
 - SS radiation field as the target photons for IC scattering
 - Oblique magnetic field
 - Toroidal magnetic field* **NEW**



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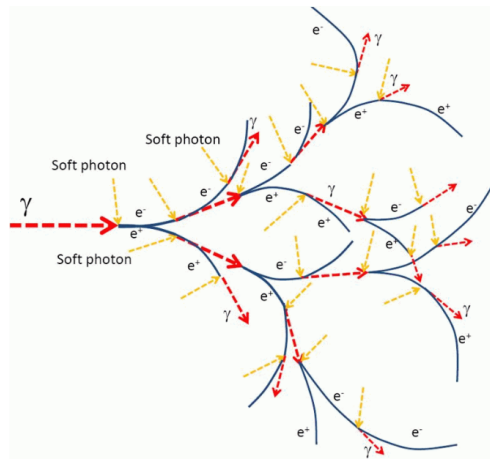
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Schematics of Monte-Carlo Cascade Emission

- Inject $\propto \epsilon_{\gamma}^{\pm\alpha}$, $\alpha = 2.5$, primary γ -rays along the jet axis
- $\gamma - \gamma \rightarrow e^{-} + e^{+}$ with either a disk or BLR photon
- $e^{+}e^{-}$ pairs follow trajectories from deflections by magnetic field lines and emit synchrotron radiation
- $e^{+}e^{-}$ pairs IC scatter a disk or BLR photon
- $\rightarrow$ cascade emission



Credit: Roustazadeh, 2012, PhD thesis

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Modelling

Cascade code input parameters

- Magnetic field strength B
- Magnetic field orientation: Oblique (θ_B w.r.t jet-axis) / Toroidal
- Supermassive black hole mass m_{BH}
- Disk luminosity L_d
- BLR size R_{BLR}
- Primary γ -ray spectral index α
- Primary γ -ray injection height z_0^γ
- BLR energy density u_{BLR}

Escape photons ($\epsilon, w, \mu, \phi, \text{time_stamp}$) $\rightarrow$ output file $\rightarrow$ analysis

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NGC 1275

- Centre of Perseus Cluster (Perseus A/3C 84) Deep sky corner
- Redshift = 0.0176
- $14^\circ < \theta < 17^\circ \implies 0.95 < \mu < 0.97$
- TeV γ -rays detected during 21 Dec 2022 flare (Godambe et al., 2024)

Fixed and free parameters simulate SED of NGC 1275 using our Monte-Carlo cascade code

Free parameters	Fixed parameters	Value
B	θ_B	11°
z_0^γ	m_{BH}	$10^8 M_\odot$
u_{BLR}	L_d	$1.88 \times 10^{43} \text{ erg s}^{-1}$
	R_{BLR}	10^{16} cm
	α	2.5

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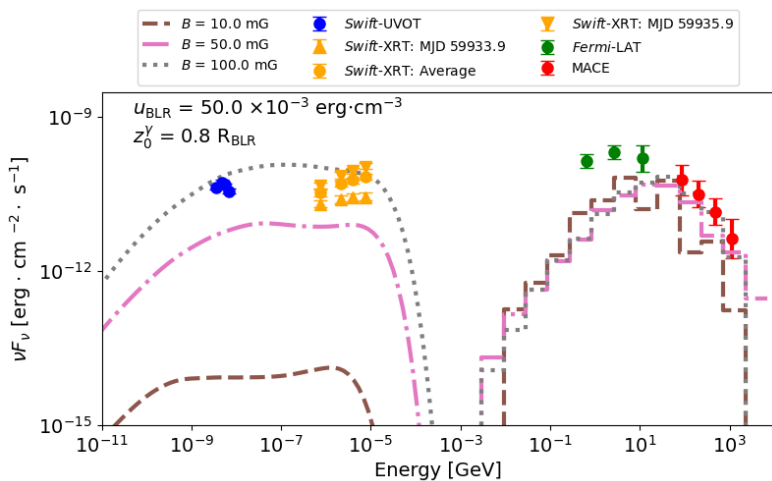
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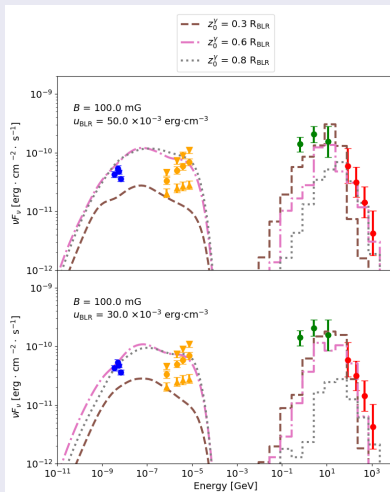
Results: SED Behaviour

Dependence on B , in case of $\theta_B = 11^\circ$



Results: SED Behaviour

Response to radiation energy density (z_0^γ and u_{BLR})



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Conclusions

- **Magnetic field (B)**
 - $\nu F_{\nu, \text{sy}}^{\text{peak}} \propto B^2$
 - $r_L \propto E_e/B$, drives efficiency of isotropization
 - Shapes cascade IC spectrum (broadness of IC spectrum)
 - Isotropizes $e^\pm$ pairs, enabling γ -rays to escape at off-axis directions
- **External radiation energy density**
 - Raises Synchrotron and IC flux, then suppresses them
 - Synchrotron decline due to external photon field suppression
 $L_{\text{sy}}/L_{\text{IC}} = u_B/u_{\text{ext}}$
 - IC "decline" due to optical thickness of photon field
- **γ -ray injection height**
 - Locates IC peak (tentative conclusion due to upper limits on optical/UV and X-rays)

Ntshatsha, Böttcher, and Razzaque (2026) accepted in MNRAS

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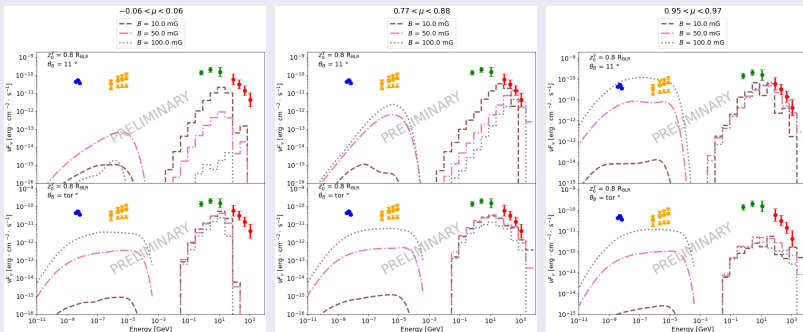
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Oblique vs Toroidal Magnetic field

Edge-on, Intermediate and Forward observers, respectively



Future work

Futher code refinements

- Helical B field.
- Cascade code needs Synchrotron self-Compton (SSC) of cascade $e^{\pm}$ pairs.

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Thanks!

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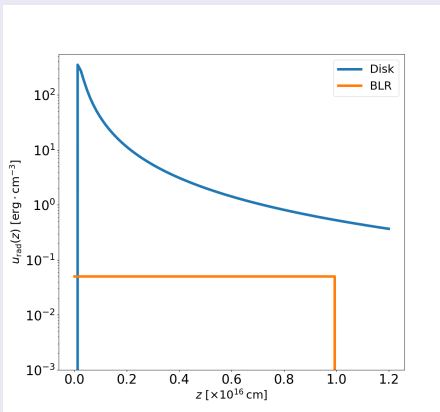
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Back-up Slide(s)

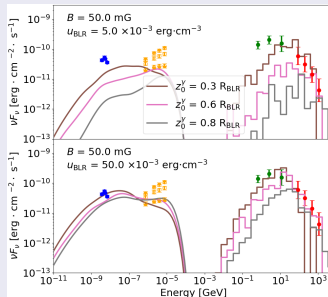
Results

Radiation energy density vs γ -ray injection height disk



Results: SED Behaviour

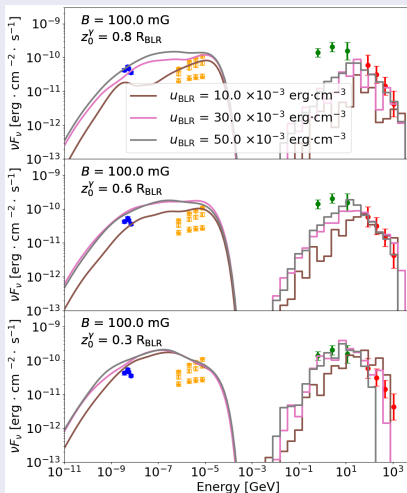
Dependence on γ -ray injection height (z_0^γ)



$$\frac{L_{\text{sy}}}{L_{\text{ext}}} = \frac{u_{\text{sy}}}{u_{\text{ext}}} \quad (2)$$

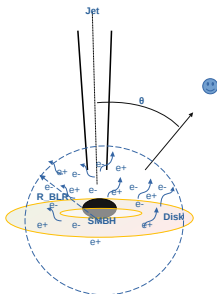
Results: SED Behaviour

Dependence on BLR energy density (u_{BLR})

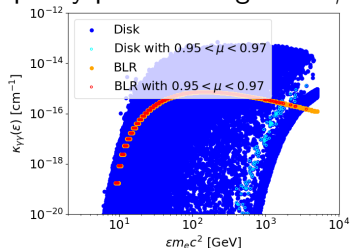


Code calibration ($\theta_{\text{esc}} = \theta_{\text{obs}} = \theta$)

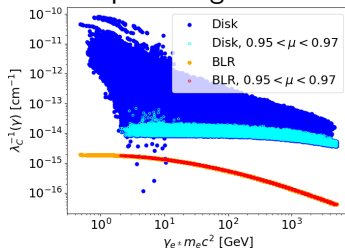
Cascade schematic



$\gamma\gamma$ opacity per unit length for γ -rays

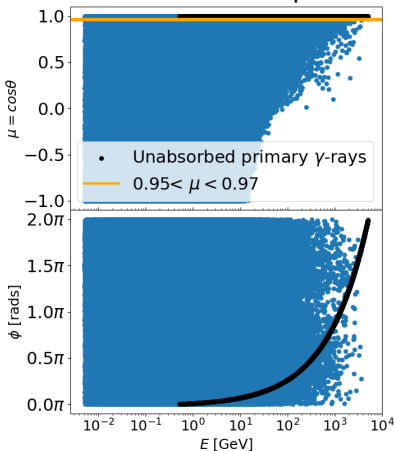
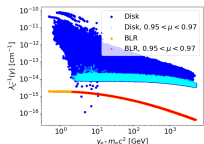
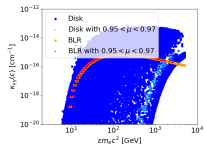


IC mean-free path lengths for $e^\pm$ pairs

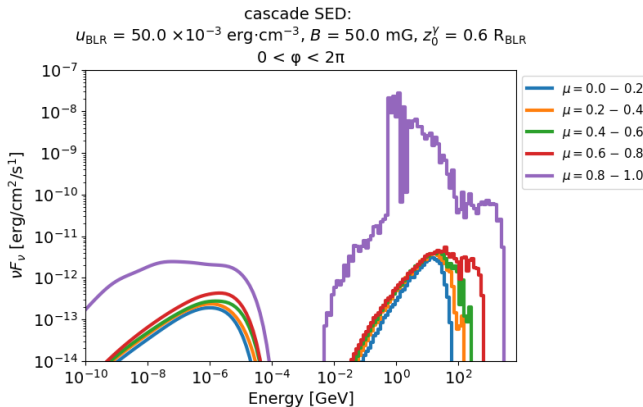


Code calibration

Angular (polar and azimuthal) distribution of cascade photons



Code calibration



SED model fit to NGC 1275 during 2022 flare

MJDs 59933.9(5.9) constrain B

