Gamma-Raying the Universe
Gamma-Ray Diagnostics of the Extragalactic Background Light, Intergalactic Magnetic Fields, and New Physics

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Active Galactic Nuclei (AGN)

- Spirals
- Ellipticals
- Seyferts
- Emission lines: Broad and narrow
- Seyfert 1
- Narrow Seyfert 2
- Radio loud
- Radio spectrum: Flat vs. Steep
- Jets viewed: Head-on vs. Side
- Radio quiet quasars
- Radio galaxies
- BL Lac Objects
- Flat Spectrum
- Radio Quasars
- 90% Thermal dominated
- 10% Non-Thermal (jet) dominated
- Gamma-Ray Loud AGN
Blazars

• Class of AGN consisting of BL Lac objects and gamma-ray bright quasars
• Rapidly (often intra-day) variable
Blazar Variability: Variability of PKS 2155-304

VHE γ-ray and X-ray variability often closely correlated

(Costamante et al. 2008)

VHE γ-ray variability on time scales as short as a few minutes!

(Aharonian et al. 2007)
Blazars

- Class of AGN consisting of BL Lac objects and gamma-ray bright quasars
- Rapidly (often intra-day) variable
- Strong gamma-ray sources
Blazar Spectral Energy Distributions (SEDs)

Non-thermal spectra with two broad bumps:

- Low-energy (probably synchrotron): radio-IR-optical(−UV-X-rays)
- High-energy (X-ray − γ-rays)
Blazar Classification

**Flat Spectrum Radio Quasars (FSRQs):**
- Low-frequency component from radio to optical/UV,
  \[ \nu_{\text{sy}} \leq 10^{14} \text{ Hz} \]
- High-frequency component from X-rays to \( \gamma \)-rays, often dominating total power

**High-frequency peaked BL Lacs (HBLs):**
- Low-frequency component from radio to UV/X-rays,
  \[ \nu_{\text{sy}} > 10^{15} \text{ Hz} \]
- Intermediate overall luminosity
- High-frequency component from hard X-rays to high-energy gamma-rays

**Low-frequency peaked / Intermediate BL Lacs (LBLs/IBLs):**
- Peak frequencies at IR/Optical and GeV gamma-rays,
  \[ 10^{14} \text{ Hz} < \nu_{\text{sy}} \leq 10^{15} \text{ Hz} \]
- Intermediate overall luminosity
  - Sometimes \( \gamma \)-ray dominated

(Hartman et al. 2000)  
(Abdo et al. 2011)  
(Acciari et al. 2009)
Blazars

- Class of AGN consisting of BL Lac objects and gamma-ray bright quasars
- Rapidly (often intra-day) variable
- Strong gamma-ray sources
- Radio and optical polarization
- Radio jets, often with superluminal motion
Faster than the speed of light?

(The MOJAVE Collaboration)
Relativistic Beaming / Boosting

In the co-moving frame of the emission region:

\[ \Gamma = (1 - \beta_\Gamma)^{-1/2} \]

Isotropic emission \( I'_\nu \) at frequency \( \nu' \)

Time interval \( t'_{\text{var}} \)

In the stationary (observer’s) frame:

\[ \delta = (\Gamma[1 - \beta_\Gamma \cos \theta])^{-1} \]

Doppler boosting factor

Beamed emission:

\[ I_\nu = \delta^3 I'_\nu \quad \nu = \delta \nu' \]

For power-law \( F_\nu \sim \nu^{-\alpha} \):

\[ F_\nu = \delta^{(3+\alpha)} F'_{\nu} \]

Time interval \( t_{\text{var}} = t'_{\text{var}} / \delta \)
Detecting Gamma-Rays with Fermi

Fermi Gamma-Ray Space Telescope: Launched June 11, 2008

- High-Energy $\gamma$-Ray
  $(30\text{ MeV} - 100\text{ GeV})$
The Fermi Gamma-Ray Sky

Plane of the Milky Way (diffuse emission)

LS I +61 303
(X-ray Binary)

NGC 1275
(radio galaxy)

PSR 1836+59
(pulsar)

3C454.3 (quasar)

Centaurus A
(radio galaxy)

PKS 1502+106
(quasar)

3C279
(quasar)

Geminga
(pulsar)

Crab
(SNR)

PKS 0528+134
(quasar)

~ 100 MeV – 30 GeV

Credit: NASA/DOE/Fermi LAT Collaboration
Redshifts of Fermi Blazars

Gamma-Ray Blazars (FSRQs) easily visible out to redshift of \(~ 3\).

(2\textsuperscript{nd} LAT AGN Catalog: Ackermann et al. 2011)
Detecting Very-High-Energy (> 100 GeV) Gamma-Rays with Cherenkov Telescopes

Cherenkov light from secondary particles (muons, electrons, positrons) in air showers initiated by very-high-energy gamma-rays in the atmosphere.
H.E.S.S.
High Energy Stereoscopic System

Khomas Highlands, near Windhoek, Namibia
The VHE Gamma-Ray Sky

• Over 140 VHE γ-ray sources
• Most extragalactic VHE sources are blazars
Progress of VHE Astronomy

Extragalactic VHE sources

Discovery year


Markarian 421
Markarian 501
1ES 2344+514
1ES 1959+650
1ES 2155-304
H 1426+428
H 1426+428
PKS 2005-689
PG 1553+113
1ES 0229+20
1ES 0347-121
BL Lacertae
1ES 1011+496
1ES 0806+524
1ES J0152+017
RGB J0710+591
RGB J0710+591
3C 66A
W Comae
PKS 0548-322
3C 279
RGB J0710+591
1ES 0716+714
Centaurus A
VER J0521+211
RGS 0413
1ES 0414+598
1ES 0502+670
PKS 0441-419
1ES 0441-419
1ES 0355+050
AP Lir
MAGIC J2001+432
AP Lir
MAGIC J2001+432

Note: The graph shows the progress of VHE astronomy from 1992 to 2010, indicating the discovery year of various extragalactic Very High Energy (VHE) sources.
Gamma-Gamma Absorpton / Pair production

The inverse process of pair annihilation can absorb $\gamma$-rays with energies $E > 511$ keV.

Threshold energy $E_{\text{thr}}$ for a $\gamma$-ray interacting with a background photon field of photons with characteristic photon energy $E_1$:

$$\varepsilon_{\text{thr}} \sim \frac{1}{\varepsilon_1}$$

$$\varepsilon = \frac{E_{\text{ph}}}{(m_e c^2)}$$

100 GeV – TeV photons are absorbed in intergalactic space by interacting with the Extragalactic Background Light (EBL)!
The Extragalactic Background Light (EBL)

- Carries the imprint of the star formation history of the Universe.
- Notoriously difficult to measure because of Galactic and solar-system foregrounds.
- Direct galaxy counts set lower limits; galaxy formation/evolution models needed to develop realistic estimates.
- Reasonably well known at low $z$, but very uncertain at high $z$. 

![Graph showing the relationship between frequency ($\nu$) and intensity ($I_{\nu}$) for different wavelengths ($\lambda$). The graph is labeled with various authors' names and years, indicating different studies and their findings. The x-axis represents the wavelength in micrometers ($\mu m$), while the y-axis shows the intensity in nW m$^{-2}$ sr$^{-1}$. The graph highlights the contributions from stars and dust in the extragalactic background light.]

Kneiske et al. 2004
Aharonian et al. 2006
Stecker et al. 2006
Franceschini et al. 2008
Dominguez et al. 2011
Gamma-Gamma Absorption by the EBL

Absorption optical depth $\tau_{\gamma\gamma}$

Franceschini et al. (2008)
The VHE Gamma-Ray Horizon

Don't expect any VHE blazars at $z > 0.5$
Gravitationally Lensed Blazar S3 0218+35 at $z = 0.944$

7 VHE blazars with unknown redshifts!
Redshift Lower Limits from EBL Absorption

- Assumption: intrinsic VHE spectrum is not harder than extrapolation from GeV (Fermi)
- Apply EBL correction to Fermi extrapolation to match the observed VHE spectrum -> UL on z

More precise methods take into account curvature of intrinsic spectrum (e.g. from detailed SED modeling)

(Georganopoulos et al. 2010)
Example:
PKS 1424+240 (z = ???)

First TeV blazar detection prompted by Fermi: IBL with hard GeV $\gamma$-ray spectrum ($\alpha_{\text{phot}} = 1.73$)

$\rightarrow$ Multiwavelength Observing Campaign in 2009

Biggest problem for theory interpretation: Unknown $z$:

SIMBAD: $z = 0.16$ (but no reference)

Sbarufatti et al. (2005): Limit from non-detection of host galaxy: $z > 0.67$

Extrapolated Fermi spectrum + EBL absorption: $z \lesssim 0.6$
PKS 1424+240

Model fits with pure SSC models for a variety of redshifts

PKS 1424+240
June 2009

$z = 0.10$

(Acciari et al. 2010)
Pure SSC models provide a reasonable fit; no EC component required.

For larger redshift, increasing discrepancy with VHE $\gamma$-ray spectral index $\rightarrow z \lesssim 0.3$

(Acciari et al. 2010)
... or maybe not ...

PKS 1424+240
\(z < 0.3\)

Firm lower limit on \(z\) from UV absorption-line systems:

\(z > 0.6035\)

Furniss et al. (2013)
Problems with EBL Absorption

PKS 1424+240
(z ≥ 0.6)

EBL de-absorption with lowest conceivable EBL level, for z = 0.6

=> Unphysical (?) upturn of the spectrum at the highest energies!
Lowering EBL Absorption Effects

1) Blazars = Cosmic-Ray Sources (?)
   => Cosmic-Rays interact with CMB

\[ p_{CR} + \gamma_{CMB} \rightarrow n + \pi^+ \quad \Rightarrow \quad \pi^+ \rightarrow \mu^+ + \nu_\mu \quad \Rightarrow \quad \mu^+ \rightarrow e^+ + \bar{\nu}_\mu + \nu_e \]

Compton scattering of EBL/CMB photons

=> Resulting VHE \( \gamma \)-ray spectra are almost independent of EBL!

(Essey & Kusenko 2010)
Lowering EBL Absorption Effects

2) Axion-like Particle (ALP) Conversion

=> ALPs not subject to EBL absorption!

\[ \gamma + B \rightarrow a \rightarrow \gamma + B \]

\[ \mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a \]

(D. Montanino)

(Tavecchio et al. 2012)
Lowering EBL Absorption Effects

3) Inhomogeneous EBL (?)
=> "VHE-like" blazars located preferentially behind low-density lines of sight (voids)

But not sufficient to solve EBL discrepancy:
For PKS 1424+240: $\Delta \tau_{\gamma\gamma} < \sim 10\%$

(Furniss et al. 2015)
Intergalactic Cascading and Magnetic Fields

EBL-absorption of VHE $\gamma$-rays produces $e^+e^-$ pairs $\rightarrow$ Compton scattering of EBL photons $\rightarrow$ GeV (Fermi) $\gamma$-rays

Upper limits on GeV emission $\rightarrow$ Lower limits on B
Intergalactic Cascading and Magnetic Fields

VHE $\gamma$-rays from pair cascades (not detected)

Fermi $\gamma$-rays from pair cascades (upper limits)

RGB J0710+591 (z=0.13) (Taylor et al. 2011)
Gravitational Lensing of Gamma-Ray Blazars

possible way of "imaging" gamma-ray emission regions in blazars!

Gravitational Lensing echoes observed in two blazars at GeV energies (Fermi) → Magnification of one of the images → Time Delay between two images

- What about $\gamma\gamma$-absorption?

PKS 1830-211 (Barnacka et al. 2011)
$\gamma\gamma$-Absorption in Gravitational Lenses?

- Intervening Lensing Galaxies (Macrolensing): $\gamma\gamma$ absorption negligible!

(Barnacka et al. 2014)
\(\gamma\gamma\)-Absorption in Gravitational Lenses?

- Stars in Intervening Galaxies (Microlensing):

\[
\text{Position of visible image always } > 2 \cdot 10^{16} \text{ cm } (M/M_0) \text{ from the lensing star!}
\]

(Barnacka et al. 2014)
**$\gamma\gamma$-Absorption in Gravitational Lenses?**

- **Stars in Intervening Galaxies (Microlensing):**

  \[ \varepsilon_{\gamma\gamma} \text{ absorption negligible!} \]

  \[ \text{(Barnacka et al. 2014)} \]
$\gamma\gamma$-Absorption in Gravitational Lenses?

• Stars in Intervening Galaxies (Microlensing):

Confirmed by Atel # 6349:
"Discovery of Very High Energy Gamma-Ray Emission From Gravitationally Lensed Blazar S3 0218+357 with the MAGIC Telescopes"!!!

Lensed \(\gamma\)-ray blazar at \(z = 0.94\)

(Barnacka et al. 2014)

\[=> \text{Gravitational lensing helps } \gamma\text{-rays avoid } \gamma\gamma\text{-absorption!} \]
Summary

1. The EBL carries the signature of the star formation history of the Universe, but is difficult to measure directly.

2. The EBL can be probed through its $\gamma\gamma$-absorption effect on VHE $\gamma$-rays → EBL absorption appears to be lower than predicted (from galaxy counts + galaxy evolution models).

3. Possible solutions: Cosmic-Ray induced $\gamma$-rays; ALP conversion; low-density LOS (not sufficient by itself).

4. EBL absorption – pair cascading can be used to set lower limits on the Intergalactic Magnetic Field ($B_{\text{IGMF}} > 10^{-17}$ G).

5. Gravitational lensing may help expand the VHE $\gamma$-ray horizon; $\gamma\gamma$-absorption by the radiation field of the lens will not interfere!
Blazar Variability: Example: The Quasar 3C279

(Böttcher et al. 2007)
Superluminal Motion

Apparent motion at up to ~ 40 times the speed of light!
Leptonic Blazar Model

Relativistic jet outflow with $\Gamma \approx 10$

Injection, acceleration of ultrarelativistic electrons

Radiative cooling $\leftrightarrow$ escape $\Rightarrow$

Seed photons:
- Synchrotron (within same region [SSC] or slower/faster earlier/later emission regions [decel. jet]), Accr. Disk, BLR, dust torus (EC)

$$\gamma^q \text{ or } \gamma^2$$

$$\gamma^{-q} \text{ or } \gamma^{-(q+1)}$$

$$Q_e(\gamma, t)$$

$$\gamma^-q$$
Hadronic Blazar Models

Relativistic jet outflow with $\Gamma \approx 10$

Injection, acceleration of ultrarelativistic electrons and protons

Synchrotron emission of primary $e^-$

Proton-induced radiation mechanisms:

- Proton synchrotron
  - $p \gamma \rightarrow p\pi^0$
  - $\pi^0 \rightarrow 2\gamma$

- $p \gamma \rightarrow n\pi^+$; $\pi^+ \rightarrow \mu^+\nu_\mu$
  - $\mu^+ \rightarrow e^+\nu_e\nu_\mu$

→ secondary $\mu^-$, e-synchrotron

- Cascades ...

$Q_{e,p}(\gamma, t)$

$\gamma^{-q}$

$\gamma_1$ $\gamma_2$ $\gamma$

$\nu F_\nu$

$\nu$

Sources of External Photons
(↔ Location of the Blazar Zone)

Direct accretion disk emission (Dermer et al. 1992, Dermer & Schlickeiser 1994)
→ $d < \text{few } 100 - 1000 \, R_s$

Optical-UV Emission from the BLR (Sikora et al. 1994)
→ $d < \sim \text{pc}$

Infrared Radiation from the Obscuring Torus (Blazejowski et al. 2000)
→ $d \sim 1 - 10\text{s of pc}$

Synchrotron emission from slower/faster regions of the jet (Georganopoulos & Kazanas 2003)
→ $d \sim \text{pc - kpc}$

Spine – Sheath Interaction (Ghisellini & Tavecchio 2008)
→ $d \sim \text{pc - kpc}$
Leptonic and Hadronic Model Fits Along the Blazar Sequence

3C66A (IBL)

Red = leptonic
Green = lepto-hadronic
Leptonic and Hadronic Model Fits along the Blazar Sequence

Red = Leptonic
Green = Hadronic

- Synchrotron
- Synchrotron self-Compton (SSC)
- External Compton of direct accretion disk photons (ECD)
- External Compton of emission from BLR clouds (ECC)
- Electron synchrotron
- Proton synchrotron

(Böttcher, Reimer et al. 2013)
The Blazar Sequence

Fermi - LAT

(100 MeV – 100 GeV)

VHE Blazar Candidates

(2nd LAT AGN Catalog: Ackermann et al. 2011)
# VHE $\gamma$-Ray Blazars

<table>
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<th>Class</th>
<th>z</th>
<th>Date</th>
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**Table:**

- **Name:** The name of the blazar.
- **Class:** The classification of the blazar.
- **z:** The redshift of the blazar.
- **Date:** The date of the observation.
### PKS 1424+240

**SSC fit parameters for a variety of redshifts**

<table>
<thead>
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</table>

$L_e = \text{kinetic power in relativistic electrons}$

$L_B = \text{Poynting flux}$

$\varepsilon_B = \frac{L_B}{L_e} = \text{magnetic-field equipartition fraction}$

$D = \text{Doppler factor}$

Fits for $z \geq 0.5$ require large Doppler factors