Blazar heating: physical mechanism and cosmological consequences

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in collaboration with

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The physics of blazar heating
- Introduction and motivation
- Propagation of TeV photons
- Plasma instabilities

Cosmological consequences
- Unifying blazars and quasars
- The intergalactic medium
- Formation of dwarf galaxies
Unified model of active galactic nuclei

- accretion disk
- dusty torus
- relativistic jet
- super-massive black hole
The blazar sequence

- continuous sequence from LBL–IBL–HBL
- TeV blazars are dim (very sub-Eddington)
- TeV blazars have rising spectra in the Fermi band ($\alpha < 2$)
- define TeV blazar = hard IBL + HBL

Ghisellini (2011), arXiv:1104.0006
There are several classes of TeV sources:

- **Galactic** - pulsars, BH binaries, supernova remnants
- **Extragalactic** - mostly blazars, two starburst galaxies

### VHE $\gamma$-ray Sky Map

$E_{\gamma} > 100$ GeV

![VHE $\gamma$-ray Sky Map](http://www.mpp.mpg.de/~nvagne/sources/)

Annihilation and pair production

$e^- + e^+ \rightarrow \text{blazar}$

extragalactic background light (infrared, eV)

TeV light (infrared, eV)
Annihilation and pair production

\[ \sqrt{s} = \sqrt{2E \epsilon_{\text{EBL}} (1 - \cos \theta)} > 2m_e c^2 \]

\[ \lambda_{\gamma\gamma} \sim (35 \ldots 700) \text{ Mpc for } z = 1 \ldots 0 \]
Inverse Compton cascades

\[ \lambda_{IC} \sim \lambda_{\gamma\gamma}/1000 \]

\[ \lambda_{\gamma\gamma} \sim (35\ldots700) \text{ Mpc for } z = 1\ldots0 \]

cosmic microwave background, \(10^{-3} \text{ eV}\)

extragalactic background light (infrared, eV)
Inverse Compton cascades

\[ \lambda_{IC} \sim \lambda_{\gamma\gamma}/1000 \]

\[ \lambda_{\gamma\gamma} \sim (35 \ldots 700) \text{ Mpc for } z = 1 \ldots 0 \]

→ each TeV point source should also be a GeV point source!
What about the cascade emission?

Every TeV source should be associated with a 1-100 GeV gamma-ray halo

![Graph showing expected cascade emission, TeV detections, and intrinsic spectra with data from Neronov & Vovk (2010).](image)
Every TeV source should be associated with a 1-100 GeV gamma-ray halo – **not seen!**
Inverse Compton cascades

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\[ \lambda_{\gamma\gamma} \sim (35 \ldots 700) \text{ Mpc for } z = 1 \ldots 0 \]

cosmic microwave background, $10^{-3}$ eV

extragalactic background light (infrared, eV)
Magnetic field deflection

Pair deflection in intergalactic magnetic field

Extragalactic background light (infrared, eV)

GeV

e^-

e^+

TeV

blazar

Light (infrared, eV)
Magnetic field deflection

- GeV point source diluted $\rightarrow$ weak "pair halo"
- stronger B–field implies more deflection and dilution, gamma–ray non–detection $\rightarrow B \gtrsim 10^{-16} \mu G$ – primordial fields?
The physics of blazar heating
Introduction and motivation
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Plasma instabilities

Magnetic field deflection

• problem for unified AGN model: blazars and quasars apparently do not share the same cosmological evolution (as otherwise, evolving blazars would overproduce the gamma–ray background)!
What else could happen?

- $e^-$
- $e^+$
- extragalactic background light (infrared, eV)
- TeV
- blazar

Christoph Pfrommer  Blazar heating
Plasma beam instabilities

*pair plasma beam propagating through the intergalactic medium*
How do $e^+/e^-$ beams propagate through the intergalactic medium (IGM)?

- Interpenetrating beams of charged particles are unstable to plasma instabilities.

- Consider the two-stream instability:

$$
\begin{align*}
& e^+, e^- \\
& e^+, e^- \\
& e^+, e^- \\
\end{align*}
$$
Two-stream instability: mechanism

consider wave-like perturbation in background plasma along the beam direction (Langmuir wave):

- initially homogeneous beam-\(e^-\): attractive (repulsive) force by potential maxima (minima)
- \(e^-\) attain lowest velocity in potential minima → bunching up
- \(e^+\) attain lowest velocity in potential maxima → bunching up
Two-stream instability: mechanism

consider wave-like perturbation in background plasma along the beam direction (Langmuir wave):

- beam-$e^+/e^-$ couple in phase with the background perturbation: enhances background potential
- stronger forces on beam-$e^+/e^-$ → positive feedback
- exponential wave-growth → instability
Two-stream instability: momentum transfer

- **Particles with** $v \gtrsim v_{\text{phase}}$:
  - Pair momentum $\rightarrow$ Plasma waves $\rightarrow$ Growing modes: Instability

- **Particles with** $v \lesssim v_{\text{phase}}$:
  - Plasma wave momentum $\rightarrow$ Pairs $\rightarrow$ Landau damping
Oblique instability

- \( \mathbf{k} \) oblique to \( \mathbf{v}_{\text{beam}} \): real word perturbations don’t choose “easy” alignment = \( \sum \) all orientations

- oblique grows faster than two-stream: \( E \)-fields can easier deflect ultra-relativistic particles than change their parallel velocities

(Nakar, Bret & Milosavljevic 2011)

Bret (2009), Bret+ (2010)
consider a light beam penetrating into relatively dense plasma

\[ \Gamma \simeq 0.4 \gamma \frac{n_{\text{beam}}}{n_{\text{IGM}}} \omega_p \]

Broderick, Chang, C.P. (2012), also Schlickeiser+ (2012)
Consider a light beam penetrating into relatively dense plasma.

The maximum growth rate is given by:

\[ \Gamma \approx 0.4 \gamma \frac{n_{\text{beam}}}{n_{\text{IGM}}} \omega_p \]

The oblique instability beats inverse Compton cooling by a factor of 10-100.

Assume that the instability grows at a linear rate up to saturation.

Broderick, Chang, C.P. (2012), also Schlickeiser+ (2012)
Outline

1. The physics of blazar heating
   - Introduction and motivation
   - Propagation of TeV photons
   - Plasma instabilities

2. Cosmological consequences
   - Unifying blazars and quasars
   - The intergalactic medium
   - Formation of dwarf galaxies
TeV emission from blazars – a new paradigm

\[ \gamma_{\text{TeV}} + \gamma_{\text{eV}} \rightarrow e^+ + e^- \rightarrow \{ \text{inv. Compton cascades} \rightarrow \gamma_{\text{GeV}} \]

\[ \text{plasma instabilities} \rightarrow \text{IGM heating} \]
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absence of $\gamma_{\text{GeV}}$’s has significant implications for . . .

- intergalactic magnetic field estimates
- unified picture of TeV blazars and quasars

intergalactic magnetic field estimates
unified picture of TeV blazars and quasars
collect luminosity of all 23 TeV blazars with good spectral measurements

account for the selection effects (sky coverage, duty cycle, galactic occultation, TeV flux limit)

TeV blazar luminosity density is a scaled version ($\eta_B \sim 0.2\%$) of that of quasars!
Quasars and TeV blazars are:

- regulated by the same mechanism
- contemporaneous elements of a single AGN population: TeV-blazar activity does not lag quasar activity

Broderick, Chang, C.P. (2012)
Quasars and TeV blazars are:

- regulated by the same mechanism
- contemporaneous elements of a single AGN population: TeV-blazar activity does not lag quasar activity

→ assume that they trace each other for all redshifts!

Broderick, Chang, C.P. (2012)
How many TeV blazars are there?

Hopkins+ (2007)
How many TeV blazars are there?

\[ \log[\Phi(z, M_B \leq -27)] \text{ [Mpc]}^{-3} \]

Fermi hard gamma-ray blazar counts

Hopkins+ (2007)
How many TeV blazars are there?

Fermi extragalactic gamma-ray background

Fermi hard gamma-ray blazar counts

Hopkins+ (2007)
Redshift distribution of *Fermi* hard $\gamma$-ray blazars

![Graph showing redshift distribution of Fermi hard $\gamma$-ray blazars with data points for 1LAC, Abdo et al. 2010 and 2LAC, Ackermann et al. 2011. The graph shows the evolving hard gamma-ray blazars above the Fermi flux limit.](image)

1LAC, Abdo et al. 2010
2LAC, Ackermann et al. 2011
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Redshift distribution of *Fermi* hard $\gamma$-ray blazars

$\rightarrow$ evolving (increasing) blazar population consistent with observed declining evolution (*Fermi* flux limit)!

\[ \frac{d\log N_{\gamma}}{dz} \]

1LAC, Abdo et al. 2010
2LAC, Ackermann et al. 2011

evolving hard gamma–ray blazars above the Fermi flux limit

Broderick, C.P.+ (in prep)
How many TeV blazars are there?

Fermi extragalactic gamma-ray background

Fermi hard gamma-ray blazar counts

Hopkins+ (2007)
Extragalactic gamma-ray background

- intrinsic spectrum for a TeV blazar:

\[
d\frac{N}{dE} = f \hat{F}_E = f \left[ \left( \frac{E}{E_b} \right)^{\Gamma_l} + \left( \frac{E}{E_b} \right)^{\Gamma_h} \right]^{-1},
\]

\( E_b = 1 \text{ TeV} \) is break energy, \( \Gamma_h = 3 \) is high-energy spectral index, \( \Gamma_l \) related to \( \Gamma_F \), which is drawn from observed distribution

- extragalactic gamma-ray background (EGRB):

\[
E^2 \frac{dN}{dE}(E, z) = \frac{1}{4\pi} \int_0^2 d\Gamma_l \int_\infty^\infty dV(z') \frac{\eta_B \tilde{\Lambda}_Q(z') \hat{F}_{E'}}{4\pi D_L^2} e^{-\tau_E(E', z')},
\]

\( E' = E(1 + z') \) is gamma-ray energy at emission, \( \tilde{\Lambda}_Q \) is physical quasar luminosity density, \( \eta_B \sim 0.2\% \) is blazar fraction, \( \tau \) is optical depth
Extragalactic gamma-ray background

The resolved hard blazars, \( z < 0.3 \)

unabsorbed

pair production

absorbed, after subtracting

the resolved hard blazars, \( z < 0.3 \)

PRELIMINARY

Abdo et al. (2010)

Ackermann et al. (in prep.)

absorbed by

pair production

E \( \geq 3 \) GeV

Broderick, C.P. (in prep.)

Dominated by soft sources
→ evolving population of hard blazars provides excellent match to latest EGRB by Fermi for $E \gtrsim 3$ GeV

**Extragalactic gamma-ray background**

**E$^2$ dN/dE (MeV s$^{-1}$ cm$^{-2}$ sr$^{-1}$)**

- Dominated by soft sources
- Absorbed, after subtracting the resolved hard blazars, $z < 0.3$
- Unabsorbed
- Absorbed by pair production

**Acknowledgments**

- PRELIMINARY
- Ackermann et al. (in prep.)
- Abdo et al. (2010)
- Broderick, C.P+ (in prep.)
The signal at 10 (100) GeV is dominated by redshifts $z \sim 1$ ($z \sim 0.8$)
TeV emission from blazars – a new paradigm

\[ \gamma_{\text{TeV}} + \gamma_{\text{eV}} \rightarrow e^+ + e^- \rightarrow \left\{ \begin{array}{l}
\text{inv. Compton cascades} \rightarrow \gamma_{\text{GeV}} \\
\text{plasma instabilities} \rightarrow \text{IGM heating}
\end{array} \right. \]

absence of \( \gamma_{\text{GeV}} \)'s has significant implications for . . .

- intergalactic magnetic field estimates
- unified picture of TeV blazars and quasars: explains *Fermi*’s \( \gamma \)-ray background and blazar number counts

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Blazar heating
TeV emission from blazars – a new paradigm

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Additional IGM heating has significant implications for . . .

- Thermal history of the IGM: Lyman-\( \alpha \) forest
- Late time structure formation: dwarf galaxies, galaxy clusters
Evolution of the heating rates

Heating Rates [eV Gyr$^{-1}$]

- HI, HeI−/HeII− reionization
- Blazar heating
- Photoheating

$10^3\quad 10^2\quad 10\quad 1\quad 0.1\quad 10^{-2}$

$10\quad 5\quad 2\quad 1 + z\quad 10\quad 2\quad 0.1\quad 10^{-2}$

Chang, Broderick, C.P. (2012)
Blazar heating vs. photoheating

- total power from AGN/stars vastly exceeds the TeV power of blazars
Blazar heating vs. photoheating

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- $T_{\text{IGM}} \sim 10^4$ K (1 eV) at mean density ($z \sim 2$)

\[
\varepsilon_{\text{th}} = \frac{kT}{m_p c^2} \sim 10^{-9}
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- radiative energy ratio emitted by BHs in the Universe (Fukugita & Peebles 2004)
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  \varepsilon_{\text{rad}} = \eta \Omega_{\text{bh}} \sim 0.1 \times 10^{-4} \sim 10^{-5}
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- Fraction of the energy energetic enough to ionize H I is $\sim 0.1$:
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- Photoheating efficiency \( \eta_{\text{ph}} \sim 10^{-3} \quad \rightarrow \quad kT \sim \eta_{\text{ph}} \varepsilon_{\text{UV}} \ m_p c^2 \sim \text{eV} \)
  (limited by the abundance of H I/He II due to the small recombination rate)
The physics of blazar heating
Cosmological consequences

Blazar heating vs. photoheating

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  (limited by the total power of TeV sources)
Thermal history of the IGM

C.P., Chang, Broderick (2012)
Evolution of the temperature-density relation

no blazar heating

\[ T \propto \frac{1}{\delta} \]
Evolution of the temperature-density relation

no blazar heating

- blazars and extragalactic background light are uniform:
  - \( \rightarrow \) blazar heating rate independent of density
Evolution of the temperature-density relation

- blazars and extragalactic background light are uniform:
  - blazar heating rate independent of density
  - makes low density regions *hot*
  - causes inverted temperature-density relation, $T \propto 1/\delta$
Evolution of the temperature-density relation

- Blazars and extragalactic background light are uniform:
  - → Blazar heating rate independent of density
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Chang, Broderick, C.P. (2012)
Blazars cause hot voids

no blazar heating

with blazar heating

Chang, Broderick, C.P. (2012)
Blazars cause hot voids

**no blazar heating**

**with blazar heating**

- blazars completely change the thermal history of the diffuse IGM and late-time structure formation
Entropy evolution

Temperature evolution

- only photoheating
- standard BLF
- optimistic BLF

Evolution of entropy, $K_e = kTn^{-2/3}$, governs structure formation.

Blazar heating: late-time, evolving, modest entropy floor.
Evolution of entropy, $K_e = kTn_e^{-2/3}$, governs structure formation.

Blazar heating: late-time, evolving, modest entropy floor.
Dwarf galaxy formation

- thermal pressure opposes gravitational collapse on small scales
- characteristic length/mass scale below which objects do not form
Dwarf galaxy formation

- thermal pressure opposes gravitational collapse on small scales
- characteristic length/mass scale below which objects do not form
- hotter intergalactic medium → higher thermal pressure
  → higher Jeans mass:

\[ M_J \propto \frac{c_s^3}{\rho^{1/2}} \propto \left( \frac{T_{\text{IGM}}^3}{\rho} \right)^{1/2} \]

\[ \frac{M_{J,\text{blazar}}}{M_{J,\text{photo}}} \approx \left( \frac{T_{\text{blazar}}}{T_{\text{photo}}} \right)^{3/2} \gtrsim 30 \]

→ blazar heating increases \( M_J \) by 30 over pure photoheating!
Dwarf galaxy formation

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  $\rightarrow$ blazar heating increases $M_J$ by 30 over pure photoheating!

- complications:
  - non-linear collapse,
  - delayed pressure response in expanding universe $\rightarrow$ concept of “filtering mass”

C.P., Chang, Broderick (2012)
Dwarf galaxy formation – Filtering mass

C.P., Chang, Broderick (2012)

Blazar heating

M_F \sim 10^{11} M_\odot
M_F \sim 10^{10} M_\odot

linear theory
only photoheating
non-linear theory

\frac{M_{F,\text{blazar}}}{M_F}

M_F [ h^{-1} M_\odot]
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Peebles’ void phenomenon explained?

<table>
<thead>
<tr>
<th>Mean Density</th>
<th>Void, $1 + \delta = 0.5$</th>
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<tbody>
<tr>
<td>$1 + \delta = 1, \ z_{\text{reion}} = 10$</td>
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<td>$M_f \ [h^{-1} M_\odot]$</td>
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<td>$10^6$</td>
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</tbody>
</table>

- blazar heating efficiently suppresses the formation of void dwarfs within existing DM halos of masses $< 3 \times 10^{11} M_\odot$ ($z = 0$)
- may reconcile the number of void dwarfs in simulations and the paucity of those in observations

C.P., Chang, Broderick (2012)
Substructures in cold DM simulations much more numerous than observed number of Milky Way satellites!
When do dwarfs form?

Dolphin+ (2005)

isochrone fitting for different metallicities $\rightarrow$ star formation histories
When do dwarfs form?

- red: $\tau_{\text{form}} > 10$ Gyr, $z > 2$

Dolphin+ (2005)
Milky Way satellites: formation history and abundance

Satellite formation time

late forming satellites (< 10 Gyr) not observed!

Maccio & Fontanot (2010)
Milky Way satellites: formation history and abundance

- blazar heating suppresses late satellite formation, may reconcile low observed dwarf abundances with CDM simulations

**satellite formation time**

late forming satellites (< 10 Gyr) not observed!

**satellite luminosity function**

Maccio & Fontanot (2010)

Maccio+ (2010)

- no blazar heating: linear theory
- non-linear theory
Galactic H I-mass function

- H I-mass function is too flat (i.e., gas version of missing dwarf problem!)
- photoheating and SN feedback too inefficient
- IGM entropy floor of $K \sim 15$ keV cm$^2$ at $z \sim 2 - 3$ successful!
Conclusions on blazar heating

**Blazar heating:** TeV photons are attenuated by EBL; their kinetic energy → heating of the IGM; it is *not* cascaded to GeV energies
Conclusions on blazar heating

**Blazar heating:** TeV photons are attenuated by EBL; their kinetic energy $\rightarrow$ heating of the IGM; it is *not* cascaded to GeV energies

- explains puzzles in gamma-ray astrophysics:
  - lack of GeV bumps in blazar spectra without IGM $B$-fields
  - *unified TeV blazar-quasar model* explains Fermi source counts and extragalactic gamma-ray background
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- novel mechanism; dramatically alters thermal history of the IGM:
  - uniform and $z$-dependent preheating
  - quantitative self-consistent picture of high-$z$ Lyman-$\alpha$ forest
Conclusions on blazar heating

**Blazar heating**: TeV photons are attenuated by EBL; their kinetic energy → heating of the IGM; it is *not* cascaded to GeV energies

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- novel mechanism; dramatically alters thermal history of the IGM:
  - uniform and $z$-dependent preheating
  - quantitative self-consistent picture of high-$z$ Lyman-\(\alpha\) forest

- significantly modifies late-time structure formation:
  - suppresses late dwarf formation (in accordance with SFHs): void phenomenon, “missing satellites” (?)
The physics of blazar heating
Unifying blazars and quasars
The intergalactic medium
Formation of dwarf galaxies

Literature for the talk


TeV photon absorption by pair production

*top*: intrinsic and observed SEDs of blazars at $z = 1$;
*bottom*: inferred $\Gamma_F$ for the spectra in the top panel;

*Fermi* data on BL Lacs and non-BL Lacs (mostly FSRQs)
Challenges to the Challenge

Challenge #1 (unknown unknowns): inhomogeneous universe

- universe is inhomogeneous and hence density of electrons change as function of position
- could lead to loss of resonance over length scale $\ll$ spatial growth length scale (Miniati & Elyiv 2012)
- growth length in oblique kinetic regime appears to be shorter than gradient $\rightarrow$ no instability quenching!
Challenges to the Challenge

Challenge #1 (unknown unknowns): **inhomogeneous universe**
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Challenge #2 (known unknowns): **non-linear saturation**
- we assume that the non-linear damping rate = linear growth rate
- effect of wave-particle and wave-wave interactions need to be resolved
- Miniati & Elyiv (2012) claim that the nonlinear Landau damping rate is $\ll$ linear growth rate, but need to scatter waves with $\Delta k/k \sim 50$
- this is in conflict with the theory of induced scattering! (Schlickeiser+ 2012)
Implications for $B$-field measurements
Fraction of the pair energy lost to inverse-Compton on the CMB: $f_{IC} = \Gamma_{IC}/(\Gamma_{IC} + \Gamma_{oblique})$

Broderick, Chang, C.P. (2012)
Conclusions on $B$-field constraints from blazar spectra

- it is thought that TeV blazar spectra might constrain IGM $B$-fields
- this assumes that cooling mechanism is IC off the CMB + deflection from magnetic fields
- beam instabilities may allow high-energy $e^+/e^-$ pairs to self scatter and/or lose energy
- isotropizes the beam – no need for $B$-field
- $\lesssim 1$–$10\%$ of beam energy to IC CMB photons
Conclusions on $B$-field constraints from blazar spectra

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- isotropizes the beam – no need for $B$-field
- $\lesssim 1$–$10\%$ of beam energy to IC CMB photons

→ TeV blazar spectra are not suitable to measure IGM $B$-fields (if plasma instabilities saturate close to linear rate)!