The Cosmological Impact of Blazars: from Plasma Instabilities to Structure Formation

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in collaboration with

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Outline

1. Physics of blazar heating
   - TeV emission from blazars
   - Plasma instabilities and magnetic fields
   - Extragalactic gamma-ray background

2. The intergalactic medium
   - Properties of blazar heating
   - Thermal history of the IGM
   - The Lyman-\(\alpha\) forest

3. Structure formation
   - Formation of dwarf galaxies
   - Puzzles in galaxy formation
   - Bimodality of galaxy clusters
The TeV gamma-ray sky

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 > 100 GeV)

2011-01-08 - Up-to-date plot available at http://www.mpp.mpg.de/~rwagner/sources/
Unified model of active galactic nuclei

- narrow line region
- broad line region
- dusty torus
- relativistic jet
- central SMBH
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
1 TeV photons can pair produce with 1 eV EBL photons:

\[ \gamma_{\text{TeV}} + \gamma_{\text{eV}} \rightarrow e^+ + e^- \]

- mean free path for this depends on the density of 1 eV photons:
  \[ \lambda_{\gamma\gamma} \sim (35 \ldots 700) \text{ Mpc for } z = 1 \ldots 0 \]
  pairs produced with energy of 0.5 TeV (\( \gamma = 10^6 \))
- these pairs inverse Compton scatter off the CMB photons:
  mean free path is \( \lambda_{\text{IC}} \sim \lambda_{\gamma\gamma}/1000 \)
  producing gamma-rays of \( \sim 1 \text{ GeV} \)

\[ E \sim \gamma^2 E_{\text{CMB}} \sim 1 \text{ GeV} \]

- 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 – not seen!

![Graph showing TeV spectra and TeV detections with Fermi constraints and expected cascade emission]
Measuring IGM $B$-fields from TeV/GeV observations

- TeV beam of $e^+/e^-$ are deflected out of the line of sight reducing the GeV IC flux $\rightarrow$ lower limit on $B$

- Larmor radius
  \[ r_L = \frac{E}{eB} \sim 30 \left( \frac{E}{3 \text{ TeV}} \right) \left( \frac{B}{10^{-16} \text{ G}} \right)^{-1} \text{ Mpc} \]

- IC mean free path
  \[ x_{\text{IC}} \sim 0.1 \left( \frac{E}{3 \text{ TeV}} \right)^{-1} \text{ Mpc} \]

- For the associated 10 GeV IC photons the *Fermi* angular resolution is $0.2^\circ$ or $\theta \sim 3 \times 10^{-3} \text{ rad}$

  \[ \frac{x_{\text{IC}}}{r_L} > \theta \rightarrow B \gtrsim 10^{-16} \text{ G} \]
How do beams of $e^+ / e^-$ propagate through the IGM?

- Plasma processes are important
- Interpenetrating beams of charged particles are unstable
- Consider the two-stream instability:

\[ \omega_p = \sqrt{\frac{4\pi e^2 n_e}{\gamma^2 m_e}}, \quad \lambda_p = \gamma \frac{c}{\omega_p} \sim 10^{14} \text{ cm} \times \left( \frac{\gamma}{10^6} \right) \bigg|_{\bar{\rho}(z=0)} \]
Two-stream instability: mechanism

wave-like perturbation with $k \parallel \mathbf{v}_{\text{beam}}$, longitudinal charge oscillations in background plasma (Langmuir wave):

- initially homogeneous beam-$e^-$:
  - attractive (repulsive) force by potential maxima (minima)
- $e^-$ attain lowest velocity in potential minima $\rightarrow$ bunching up
- $e^+$ attain lowest velocity in potential maxima $\rightarrow$ bunching up

\[ e^+, e^- \]
Two-stream instability: mechanism

wave-like perturbation with $k \parallel \mathbf{v}_{\text{beam}}$, longitudinal charge oscillations in background plasma (Langmuir wave):

- beam-$e^+ / e^-$ couple in phase with the background perturbation: enhances background potential
- stronger forces on beam-$e^+ / e^-$ $\rightarrow$ positive feedback
- exponential wave-growth $\rightarrow$ instability

\[ e^+, e^- \]
Two-stream instability: energy transfer

- particles with $v \gtrsim v_{\text{phase}}$:
  - pair energy $\rightarrow$ plasma waves $\rightarrow$ growing modes

- particles with $v \lesssim v_{\text{phase}}$:
  - plasma wave energy $\rightarrow$ pairs $\rightarrow$ damped modes
Oblique instability

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

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

maximum growth rate

$\sim 0.4 \gamma \frac{n_{\text{beam}}}{n_{\text{IGM}}} \omega_p$

oblique instability beats IC by two orders of magnitude
Beam physics – complications . . .

non-linear saturation:

- non-linear evolution of these instabilities at these density contrasts is not known
- expectation from PIC simulations suggest substantial isotropization of the beam
- **assume** that they grow at linear rate up to saturation

→ plasma instabilities dissipate the beam’s energy, no (little) energy left over for inverse Compton scattering off the CMB
TeV emission from blazars – a new paradigm

\[ \gamma_{\text{TeV}} + \gamma_{\text{eV}} \rightarrow e^+ + e^- \rightarrow \begin{cases} \text{IC off CMB} \rightarrow \gamma_{\text{GeV}} \\ \text{plasma instabilities} \rightarrow \text{heating IGM} \end{cases} \]

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

- intergalactic \( B \)-field estimates
- \( \gamma \)-ray emission from blazars: spectra, background

additional IGM heating has significant implications for . . .

- thermal history of the IGM: Lyman-\( \alpha \) forest
- late time structure formation: dwarfs, galaxy clusters
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. (2011)
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

→ TeV blazar spectra are not suitable to measure IGM $B$-fields!
TeV blazar luminosity density: today

- 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!

Broderick, Chang, C.P. (2011)
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!
How many TeV blazars are there?

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

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

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

Fermi extragalactic gamma-ray background

Fermi hard gamma-ray blazar counts

Hopkins+ (2007)
**Fermi** number count of “TeV blazars”

- number evolution of TeV blazars that are expected to have been observed by *Fermi* vs. observed evolution
- colors: different flux (luminosity) limits connecting the *Fermi* and the TeV band:

\[
L_{\text{TeV, min}}(z) = \eta L_{\text{Fermi, min}}(z)
\]

- evolving (increasing) blazar population consistent with observed declining evolution (*Fermi* flux limit)!
How many TeV blazars are there at high-$z$?

Hopkins+ (2007)
Fermi probes “dragons” of the gamma-ray sky

Fermi LAT Extragalactic Gamma-ray Background

Energy (GeV)
Intensity (GeV photons per cm² per sec per steradian)

Background accounted for by unresolved AGN
Unknown contributors
Extragalactic gamma-ray background

- assume all TeV blazars have identical intrinsic spectra:

\[ F_E = L \hat{F}_E \propto \frac{1}{(E/E_b)^{\alpha_L-1} + (E/E_b)^{\alpha-1}} , \]

\( E_b \) is break energy,
\( \alpha_L < \alpha \) are low and high-energy spectral indexes

- extragalactic gamma-ray background:

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

\( E' = E(1 + z') \) is gamma-ray energy at emission,
\( \tilde{\Lambda}_Q \) is physical quasar luminosity density,
\( \tau \) is optical depth
Extragalactic gamma-ray background: varying $\alpha$

- **dotted**: unabsorbed EGRB due to TeV blazars
- **dashed**: absorbed EGRB due to TeV blazars
- **solid**: absorbed EGRB, after subtracting the resolved TeV blazars ($z < 0.25$)

Broderick, Chang, C.P. (2011)
Extragalactic gamma-ray background: varying $\alpha_L$

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Broderick, Chang, C.P. (2011)

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Blazar heating
Extragalactic gamma-ray background: varying $E_b$

- **dotted**: unabsorbed EGRB due to TeV blazars
- **dashed**: absorbed EGRB due to TeV blazars
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Broderick, Chang, C.P. (2011)
Conclusions on extragalactic gamma-ray background

- the TeV blazar luminosity density is a scaled version of the quasar luminosity density at $z = 0.1$
- assuming that TeV blazars trace quasars for all $z$ and adopting typical spectra, we can match the *Fermi*-LAT extragalactic gamma-ray background
- evolving blazars do not overproduce EGRB since the absorbed energy is not reprocessed to GeV energies
- fraction of absorbed energy is greater at higher energies
Evolution of the heating rates

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

- HI, HeI$^-$/HeII$^-$ reionization
- Blazar heating
- Photoheating

10x larger heating

Chang, Broderick, C.P. (2011)
Blazar heating vs. photoheating

- total power from AGN/stars vastly exceeds the TeV power of blazars
- \( T_{\text{IGM}} \sim 10^4 \) K (1 eV) at mean density \((z \sim 2)\)
  \[
  \varepsilon_{\text{th}} = \frac{kT}{m_p c^2} \sim 10^{-9}
  \]
- radiative energy ratio emitted by BHs in the Universe \((\text{Fukugita} \& \text{Peebles 2004})\)
  \[
  \varepsilon_{\text{rad}} = \eta \Omega_{\text{bh}} \sim 0.1 \times 10^{-4} \sim 10^{-5}
  \]
- fraction of the energy energetic enough to ionize H I is \(\sim 0.1:\)
  \[
  \varepsilon_{\text{UV}} \sim 0.1 \varepsilon_{\text{rad}} \sim 10^{-6} \rightarrow kT \sim \text{keV}
  \]
- photoheating efficiency \(\eta_{\text{ph}} \sim 10^{-3}\)
  \[
  kT \sim \eta_{\text{ph}} \varepsilon_{\text{UV}} m_p c^2 \sim \text{eV}
  \]
  (limited by the abundance of H I/He II due to the small recombination rate)
- blazar heating efficiency \(\eta_{\text{bh}} \sim 10^{-3}\)
  \[
  kT \sim \eta_{\text{bh}} \varepsilon_{\text{rad}} m_p c^2 \sim 10 \text{ eV}
  \]
  (limited by the total power of TeV sources)
Chang, Broderick, C.P. (2011)
blazars and extragalactic background light are uniform:
→ blazar heating rate independent of density
→ makes low density regions hot
→ causes inverted temperature-density relation, $T \propto 1/\delta$
Blazars cause hot voids

- blazars completely change the thermal history of the diffuse IGM and late-time structure formation.
Simulations with blazar heating

Puchwein, C.P., Springel, Broderick, Chang (2011):

- $L = 15h^{-1}\text{Mpc}$ boxes with $2 \times 384^3$ particles
- one reference run without blazar heating
- three with blazar heating at different levels of efficiency (address uncertainty)
- used an up-to-date model of the UV background (Faucher-Giguère+ 2009)
Temperature-density relation

Puchwein, C.P., Springel, Broderick, Chang (2011)
Ly-$\alpha$ spectra

- Transmitted flux fraction $e^{-\tau}$
  - No blazar heating
  - Intermediate b. h.

Velocity [km s$^{-1}$]

$\Delta e^{-\tau}$

Puchwein+ (2011)
Physics of blazar heating
The intergalactic medium
Structure formation

Properties of blazar heating
Thermal history of the IGM
The Lyman-α forest

The end of fudged Ly-α simulations

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Effective optical depth $\tau_{\text{eff}}$ vs. redshift $z$

- No blazar heating
- Weak blazar heating
- Intermediate blazar heating
- Strong blazar heating

Viel et al. 2004
Tytler et al. 2004
FG '08

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Photoionization rate $\Gamma_{\text{HI}} \times 10^{-12}$ s$^{-1}$ vs. redshift $z$

- No blazar heating
- Weak blazar heating
- Intermediate blazar heating
- Strong blazar heating

FG '08
FG '08, inv. EOS
FG '09 model

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$\Delta \Gamma_{\text{HI}} / \sigma_{\Gamma_{\text{HI}}}$ vs. redshift $z$

Puchwein+ (2011)
Ly-α flux PDFs and power spectra

self-consistent UV background

10^1
10^0
10^-1
10^-2

PDF of transmitted flux fraction

z = 2.52

z = 2.94

transmitted flux fraction

Puchwein+ (2011)
decomposing Lyman-α forest into individual Voigt profiles
allows studying the thermal broadening of absorption lines
Voigt profile decomposition – line width distribution

PDF of $b \, [\text{km} \, \text{s}^{-1}]$

- $N_{\text{HI}} > 10^{13} \, \text{cm}^{-2}$
- $2.75 < z < 3.05$
- no blazar heating
- weak blazar heating
- intermediate blazar heating
- strong blazar heating

Kirkman & Tytler '97

Puchwein+ (2011)
improvement in modelling the Lyman-\(\alpha\) forest is a direct consequence of the peculiar properties of blazar heating:

- **heating rate independent of IGM density** → naturally produces the inverted \(T–\rho\) relation that Lyman-\(\alpha\) forest data demand

- **recent and continuous nature of the heating** needed to match the redshift evolutions of all Lyman-\(\alpha\) forest statistics

- **magnitude of the heating rate required by Lyman-\(\alpha\) forest data** \(\sim\) the total energy output of TeV blazars (or equivalently \(\sim 0.2\%\) of that of quasars)
Entropy evolution

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

C.P., Chang, Broderick (2011)
Dwarf galaxy formation – Jeans mass

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

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

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

\[ \rightarrow \text{depends on instantaneous value of } c_s \]

- “filtering mass” depends on full thermal history of the gas: accounts for delayed response of pressure in counteracting gravitational collapse in the expanding universe

- apply corrections for non-linear collapse
Dwarf galaxy formation – Filtering mass

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

\[ 1 + \delta = 1, \quad z_{\text{reion}} = 10 \]

\[ M_{F, \text{blazar}} / M_F \]

C.P., Chang, Broderick (2011)

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Blazar heating
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
When do dwarfs form?

Dolphin et al. (2005)

isochrone fitting for different metallicities → star formation histories
When do dwarfs form?

\[ \tau_{\text{form}} > 10 \text{ Gyr}, z > 2 \]
“Missing satellite” problem in the Milky Way

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

![Diagram showing satellite formation time and luminosity function](image)

- Late forming satellites (< 10 Gyr) not observed!

![Linear theory vs. non-linear theory](image)

- No blazar heating: linear theory
- Non-linear theory

Maccio & Fontanot (2010)

Maccio+ (2010)

Blazar heating
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 $K \sim 15 \text{ keV cm}^2$ at $z \sim 2 - 3$ successful!
When do clusters form?

- **mass accretion history**

- **mass accretion rates**

- Most cluster gas accretes after $z = 1$, when blazar heating can have a large effect (for late forming objects)!

C.P., Chang, Broderick (2011)
Do optical and X-ray/Sunyaev-Zel’dovich cluster observations probe the same population? (Hicks+ 2008, Planck Collaboration 2011)
Entrophy profiles: effect of blazar heating

**varying formation time**

![Graph showing entropy profiles with varying formation time](image)

**varying cluster mass**

![Graph showing entropy profiles with varying cluster mass](image)

**assume**

big fraction of intra-cluster medium collapses from IGM:

- redshift-dependent entropy excess in cores
- greatest effect for late forming groups/small clusters
Gravitational reprocessing of entropy floors

- greater initial entropy $K_0$
  - $\rightarrow$ more shock heating
  - $\rightarrow$ greater increase in $K_0$
  - over entropy floor
- net $K_0$ amplification of 3-5
- expect:
  - median $K_{e,0} \sim 150$ keV cm$^2$
  - max. $K_{e,0} \sim 600$ keV cm$^2$
Cool-core versus non-cool core clusters

Cavagnolo+ (2009)
Cool-core versus non-cool core clusters

- time-dependent preheating + gravitational reprocessing
  → CC-NCC bifurcation (two attractor solutions)

- need hydrodynamic simulations to confirm this scenario
How efficient is heating by AGN feedback?

\[ E_{\text{cav}} = 4PV_{\text{tot}} \times 10^{58} \text{erg} \]

\[ K_{e,0} \text{ [keV cm}^2\text{]} \]

C.P., Chang, Broderick (2011)

AGNs cannot transform CC to NCC clusters (on a buoyancy timescale)

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Blazar heating
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Cool cores vs. non-cool cores

C.P., Chang, Broderick (2011)

\[ E_{b,2500}(kT_X = 0.7 \text{ keV}) \]
\[ E_{b,2500}(kT_X = 1.2 \text{ keV}) \]

AGNs cannot transform CC to NCC clusters (on a buoyancy timescale)
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Cool cores

Non-cool cores

\( E_{b,2500}(kT_X = 0.7 \text{ keV}) \)

\( E_{b,2500}(kT_X = 1.2 \text{ keV}) \)

\( E_{b,2500}(kT_X = 2.0 \text{ keV}) \)

\( E_{b,2500}(kT_X = 3.5 \text{ keV}) \)

\( E_{b,2500}(kT_X = 5.9 \text{ keV}) \)

C.P., Chang, Broderick (2011)
How efficient is heating by AGN feedback?

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cool cores
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Christoph Pfrommer

Blazar heating
How efficient is heating by AGN feedback?

AGNs cannot transform CC to NCC clusters (on a buoyancy timescale)

C.P., Chang, Broderick (2011)
Conclusions on blazar heating

- explains puzzles in high-energy 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

- novel mechanism; dramatically alters thermal history of the IGM:
  - uniform and $z$-dependent preheating
  - rate independent of density $\rightarrow$ inverted $T-\rho$ relation
  - quantitative self-consistent picture of high-$z$ Lyman-$\alpha$ forest

- significantly modifies late-time structure formation:
  - suppresses late dwarf formation (in accordance with SFHs): “missing satellites”, void phenomenon, $\text{H} \, \text{I}$-mass function
  - group/cluster bimodality of core entropy values
Ly-$\alpha$ flux PDFs and power spectra

Puchwein+ (2011)