The Physics and Cosmology of TeV Blazars

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in collaboration with

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Jan 10, 2014 / Königstuhl Colloquium
The Hitchhiker’s Guide to . . . Blazar Heating

- **Blazar Physics**
  - black holes and jets
  - propagation $\gamma$ rays
  - plasma physics
The Hitchhiker’s Guide to . . . Blazar Heating

**Blazar Physics**
- black holes and jets
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**Cosmological Consequences**
- intergalactic magnetic fields
- unification of blazars and AGN
- gamma-ray background
The Hitchhiker’s Guide to . . . Blazar Heating

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  - black holes and jets
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  - plasma physics

- **Cosmological Consequences**
  - intergalactic magnetic fields
  - unification of blazars and AGN
  - gamma-ray background
  - thermal history of the Universe
  - Lyman-$\alpha$ forest
  - formation of dwarf galaxies
Outline

1. Blazars
   - Black hole jets
   - Propagating $\gamma$ rays
   - Plasma instabilities

2. Gamma-ray sky
   - Magnetic fields
   - Blazar-AGN unification
   - Gamma-ray background

3. Structure formation
   - Properties of blazar heating
   - The Lyman-$\alpha$ forest
   - Dwarf galaxies
Black hole jets - nearby

Centaurus A in X-rays: closest active galaxy with a super-massive black hole

Messier 87 in the radio: closest active cluster galaxy in the Virgo cluster: $M_{\text{bh}} \approx 6 \times 10^9 M_\odot$
Black hole jets - at cosmological distances

Quasar 3C175: 1 million light years across

Giant radio galaxy B1545-321: relic radio plasma and new jet activity
Unified model of active galactic nuclei

- Blazars
- Gamma-ray sky
- Structure formation
- Black hole jets
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- Plasma instabilities

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- Accretion disk
- Dusty torus
- Relativistic jet
- Super-massive black hole
The blazar sequence

- continuous sequence from FSRQ–LBL–IBL–HBL
- TeV blazars ($\nu \gtrsim 10^{26}$ Hz) are dim: very sub-Eddington
- TeV blazars have rising energy spectra in the Fermi band
- define TeV blazar = hard IBL + HBL

Donato+ (2001)
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 γ-ray Sky Map
(E\(>100\) GeV)
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Annihilation and pair production

Blazars
Gamma-ray sky
Structure formation

Black hole jets
Propagating $\gamma$ rays
Plasma instabilities

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

TeV
blazar

Pfrommer

$e^-$
$e^+$
extragalactic background light (infrared, eV)
Annihilation and pair production

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

extragalactic background light (infrared, eV)

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

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

Extragalactic background light (infrared, eV)

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

- Cosmic microwave background, $10^{-3}$ eV
- Extragalactic background light (infrared, eV)
- GeV
- $\lambda_{IC} \sim \lambda_\gamma/1000$
- $\lambda_\gamma \sim (35 \ldots 700) \text{ Mpc for } z = 1 \ldots 0$

→ 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.

Neronov & Vovk (2010) expected cascade emission, TeV detections, and intrinsic spectra.
What about the cascade emission?

Every TeV source should be associated with a 1-100 GeV gamma-ray halo – not seen!

Neronov & Vovk (2010)

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Inverse Compton cascades

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

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

Pair deflection in intergalactic magnetic field

extragalactic background light (infrared, eV)

GeV

e

blazar

TeV

γ-rays

Plasma instabilities

Structure formation

Gamma-ray sky

Black hole jets

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Magnetic field deflection

- GeV point source diluted \(\rightarrow\) weak "pair halo"
- stronger B-field implies more deflection and dilution, gamma-ray non-detection \(\rightarrow\) \(B \gtrsim 10^{-16}\) G – primordial fields?
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?

Extragalactic background light (infrared, eV)
Plasma beam instabilities

→ pair plasma beam propagating through the intergalactic medium
Interlude: plasma physics

How do $e^+/e^-$ beams propagate through the intergalactic medium?

- interpenetrating beams of charged particles are unstable to plasma instabilities
- consider the two-stream instability:

\[
\begin{align*}
\text{e}^+, \text{e}^- & \quad \longrightarrow \quad \text{p}, \text{e}^- \\
\text{e}^+, \text{e}^- & \quad \longrightarrow \quad \text{p}, \text{e}^- \\
\text{e}^+, \text{e}^- & \quad \longrightarrow \quad \text{p}, \text{e}^-
\end{align*}
\]

- one frequency (timescale) and one length in the problem:

\[
\omega_p = \sqrt{\frac{4\pi e^2 n_e}{m_e}}, \quad \lambda_p = \left. \frac{c}{\omega_p} \right|_{\bar{\rho}(z=0)} \sim 10^8 \text{ cm}
\]
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-\(e^+/e^-\) \(\rightarrow\) positive feedback
- exponential wave-growth \(\rightarrow\) 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**

- $k$ oblique to $v_{\text{beam}}$: 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

maximum growth rate

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

Broderick, Chang, C.P. (2012), also Schlickeiser+ (2012)
Beam physics – growth rates

- consider a light beam penetrating into relatively dense plasma
- maximum growth rate
  \[ \Gamma \approx 0.4 \gamma \frac{n_{\text{beam}}}{n_{\text{IGM}}} \omega_p \]
- oblique instability beats inverse Compton cooling by factor 10-100
- assume that instability grows at linear rate up to saturation

Broderick, Chang, C.P. (2012), also Schlickeiser+ (2012)
TeV emission from blazars – a new paradigm

\[ \gamma_{\text{TeV}} + \gamma_{\text{eV}} \rightarrow e^+ + e^- \rightarrow \begin{cases} \text{inv. Compton cascades} & \rightarrow \gamma_{\text{GeV}} \\ \text{plasma instabilities} & \end{cases} \]
TeV emission from blazars – a new paradigm

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

\[ \text{plasma instabilities} \]

absence of $\gamma_{\text{GeV}}$’s has significant implications for . . .

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

1. Blazars
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3. Structure formation
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   - Dwarf galaxies
Implications for intergalactic magnetic fields

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

\{ inv. Compton cascades \rightarrow \gamma_{\text{GeV}} \\
plasma instabilities \}

- competition of rates: \( \Gamma_{\text{IC}} \) vs. \( \Gamma_{\text{oblique}} \)
- fraction of the pair energy lost to inverse-Compton on the CMB:
  \( f_{\text{IC}} = \Gamma_{\text{IC}} / (\Gamma_{\text{IC}} + \Gamma_{\text{oblique}}) \)
- plasma instability dominates for more luminous blazars

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 allow high-energy $e^+/e^-$ pairs to self scatter and/or lose energy.
- Isotropizes the beam – no need for $B$-field.
- $\lesssim 1\text{–}10\%$ 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)!

Broderick, Chang, C.P. (2012), Schlickeiser, Krakau, Supsar (2013), Chang+ (in prep.)
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. (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
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?

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

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

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

![Graph showing redshift distribution of Fermi hard $\gamma$-ray blazars.]

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

Evolving hard gamma-ray blazars above the Fermi flux limit.

Broderick, C.P.+ (2013)
Redshift distribution of *Fermi* hard $\gamma$-ray blazars

\[ \text{dlog} N_B / \text{dz} \]

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

evolving hard gamma–ray blazars above the Fermi flux limit

→ evolving (increasing) blazar population consistent with observed declining evolution (*Fermi* flux limit)!
log $\mathcal{N}$ – log $S$ distribution of *Fermi* hard $\gamma$-ray blazars

Broderick, C.P. + (2013) → predicted and observed flux distributions of hard *Fermi* blazars between 10 GeV and 500 GeV are indistinguishable!
log $N$ – log $S$ distribution of *Fermi* hard $\gamma$-ray blazars

→ predicted and observed flux distributions of hard *Fermi* blazars between 10 GeV and 500 GeV are indistinguishable!
How many TeV blazars are there?

Hopkins+ (2007)
TeV photon absorption by pair production

intrinsic and observed SEDs of blazars at $z = 1$

$\gamma$-ray attenuation by annihilation and pair producing on the EBL

inferred spectral index $\Gamma_F$ for the spectra in the top panel;
overlay of Fermi data on BL Lacs and non-BL Lacs (mostly FSRQs)
Extragalactic gamma-ray background

• intrinsic spectrum for a TeV blazar:

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

\(E_b = 1\) 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):

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

\(E' = E(1 + z')\) 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 by Ackermann et al. (in prep.)
- Absorbed, after subtracting Abdo et al. (2010)

Broderick, C.P. (2013) → evolving population of hard blazars provides excellent match to latest EGRB by Fermi for $E \gtrsim 3$ GeV

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Extragalactic gamma-ray background

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

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the signal at 10 (100) GeV is dominated by redshifts $z \sim 1.2$ ($z \sim 0.6$)
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TeV emission from blazars – a new paradigm

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

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
TeV emission from blazars – a new paradigm

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

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

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additional IGM heating has significant implications for . . .

- thermal history of the IGM: Lyman-\( \alpha \) forest
- late-time formation of dwarf galaxies
Evolution of the heating rates

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

10^3
10^2
10
1
0.1
10^{-2}
10^{-3}
10^{-4}
1 + z

HI, HeI−/HeII− reionization
blazar heating
photoheating
10x larger heating

Chang, Broderick, C.P. (2012)
total power from AGN/stars vastly exceeds the TeV power of blazars
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 ($z \sim 2$)

\[
\varepsilon_{\text{th}} = \frac{kT}{m_p c^2} \sim 10^{-9}
\]
total power from AGN/stars vastly exceeds the TeV power of blazars

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radiative energy ratio emitted by BHs in the Universe (Fukugita & Peebles 2004)

\[ \varepsilon_{\text{rad}} = \eta \Omega_{\text{bh}} \sim 0.1 \times 10^{-4} \sim 10^{-5} \]
Blazar heating vs. photoheating

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- radiative energy ratio emitted by BHs in the Universe \(\varepsilon_{\text{rad}} = \eta \Omega_{\text{bh}} \sim 0.1 \times 10^{-4} \sim 10^{-5}\)
- fraction of the energy energetic enough to ionize \(\text{H} \, \text{I}\) is \(\sim 0.1\):
  \[ \varepsilon_{\text{UV}} \sim 0.1 \varepsilon_{\text{rad}} \sim 10^{-6} \rightarrow kT \sim \text{keV} \]
Blazar heating vs. photoheating

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  \[
  \varepsilon_{\text{rad}} = \eta \Omega_{\text{bh}} \sim 0.1 \times 10^{-4} \sim 10^{-5}
  \]
- fraction of the energy energetic enough to ionize \( \text{H I} \) is \(\sim 0.1\):
  \[
  \varepsilon_{\text{UV}} \sim 0.1\varepsilon_{\text{rad}} \sim 10^{-6} \quad \rightarrow \quad kT \sim \text{keV}
  \]
- 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 \( \text{H I}/\text{He II} \) due to the small recombination rate)
total power from AGN/stars vastly exceeds the TeV power of blazars

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

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radiative energy ratio emitted by BHs in the Universe \( (\text{Fukugita & Peebles 2004}) \)

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fraction of the energy energetic enough to ionize H I is \( \sim 0.1 \):

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photoheating efficiency \( \eta_{\text{ph}} \sim 10^{-3} \rightarrow kT \sim \eta_{\text{ph}} \varepsilon_{\text{UV}} m_p c^2 \sim \text{eV} \)

(limited by the abundance of H I/He II due to the small recombination rate)

blazar heating efficiency \( \eta_{\text{bh}} \sim 10^{-3} \rightarrow kT \sim \eta_{\text{bh}} \varepsilon_{\text{rad}} m_p c^2 \sim 10 \text{ eV} \)

(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

\begin{figure}
\centering
\includegraphics[width=\textwidth]{plot.png}
\caption{Evolution of the temperature-density relation with and without blazar heating.}
\end{figure}
Evolution of the temperature-density relation

- blazars and extragalactic background light are uniform:
  $\rightarrow$ blazar heating rate independent of density
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 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

no blazar heating

with blazar heating

Chang, Broderick, C.P. (2012)

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Blazars cause hot voids

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

Blazars completely change the thermal history of the diffuse IGM and late-time structure formation.

Chang, Broderick, C.P. (2012)

Viel et al. (2009)

Chang, Broderick, C.P. (2012)
Simulations with blazar heating

Puchwein, C.P., Springel, Broderick, Chang (2012):

- $L = 15h^{-1}\text{Mpc}$ 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)
The intergalactic medium
Temperature-density relation

\[ \log_{10}\left(\frac{T}{K}\right) = \log_{10}\left(\frac{N_{HI}}{N_{HJ}}\right) = -8 \]

\[ \log_{10}\left(\frac{M_{\text{pix}}}{(h^{-1} M_\odot)}\right) \]

Puchwein, C.P., Springel, Broderick, Chang (2012)

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The Lyman-\(\alpha\) forest
The observed Lyman-\(\alpha\) forest

![Graph showing the Lyman-\(\alpha\) forest and Lyman Alpha Emission](image-url)
The simulated Ly-$\alpha$ forest

- Transmitted flux fraction $e^{-\tau}$
- Velocity [km s$^{-1}$]

Puchwein+ (2012)

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The Physics and Cosmology of TeV Blazars
Optical depths and temperatures

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

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

Redshift evolutions of effective optical depth and IGM temperature match data only with additional heating, e.g., provided by blazars!
Optical depths and temperatures

Redshift evolutions of effective optical depth and IGM temperature match data only with additional heating, e.g., provided by blazars!
Ly-$\alpha$ flux PDFs and power spectra

- Tuned UV background
- PDF of transmitted flux fraction
- Transmitted flux fraction
- z = 2.52
- z = 2.94

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

Kim et al. 2007
Ly-\(\alpha\) flux PDFs and power spectra

**Tuned UV background**

- no blazar heating
- weak blazar heating
- intermediate blazar heating
- strong blazar heating

*Kim et al. 2007*

PDF of transmitted flux fraction

- **z = 2.52**
- **z = 2.94**

*Puchwein+ (2012)*

Power spectrum \( \mathcal{P}_B(k) \)

- **z = 2.07**
- **z = 2.52**

*Viel et al. 2004*

*Kim et al. 2004*
Voigt profile decomposition

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

- PDF of $b$ [skm$^{-1}$]
- $N_{HI} > 10^{13}$ cm$^{-2}$
- $2.75 < z < 3.05$
- no blazar heating
- weak blazar heating
- intermediate blazar heating
- strong blazar heating

Kirkman & Tytler '97

Puchwein+ (2012)

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improvement in modelling the Lyman-α 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-α forest data demand
- recent and continuous nature of the heating needed to match the redshift evolutions of all Lyman-α forest statistics
- magnitude of the heating rate required by Lyman-α forest data $\sim$ the total energy output of TeV blazars (or equivalently $\sim 0.2\%$ of that of quasars)
Entropy evolution

temperature evolution

\[ T \text{ [K]} \]

- only photoheating
- standard BLF
- optimistic BLF

\[ K_e = kTn^{\frac{5}{3}} \]

evolved of entropy, structure formation

blazar heating: late-time, evolving, modest entropy floor
Entropy evolution

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

C.P., Chang, Broderick (2012)
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 $\rightarrow$ higher thermal pressure
  $\rightarrow$ higher Jeans mass:

$$M_J \propto \frac{c_s^3}{\rho^{1/2}} \propto \left( \frac{T_{\text{IGM}}^3}{\rho} \right)^{1/2} \rightarrow \frac{M_{J,\text{blazar}}}{M_{J,\text{photo}}} \approx \left( \frac{T_{\text{blazar}}}{T_{\text{photo}}} \right)^{3/2} \gtrsim 30$$

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

\[ M_J \propto \frac{c_s^3}{\rho^{1/2}} \propto \left( \frac{T_{IGM}^3}{\rho} \right)^{1/2} \rightarrow \frac{M_{J,\text{blazar}}}{M_{J,\text{photo}}} \approx \left( \frac{T_{\text{blazar}}}{T_{\text{photo}}} \right)^{3/2} \gtrsim 30 \]

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

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

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

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

C.P., Chang, Broderick (2012)
Peebles’ void phenomenon explained?

- 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

\[1 + \delta = 0.5, \ z_{\text{reion}} = 10\]

C.P., Chang, Broderick (2012)
Lu, Mo, Lu, Katz, et al. (2013): constructing merger tree-based model of galaxy formation that matches

- observed stellar mass function (different $z$)
- luminosity function of local cluster galaxies

→ star formation histories of dark matter halos (different $z$)
→ strong quenching of star formation efficiency for $z \lesssim 2$ in low-mass halos ($M < 10^{11} \, h^{-1} M_\odot$) → blazar heating?
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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  - 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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- significantly modifies late-time structure formation:
  - suppresses late dwarf formation (in accordance with SFHs)
  - void phenomenon, “missing satellites” (?)


Challenges to the Challenge

Challenge #1 (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
- using slow collisional scattering (reactive regime), Miniati & Elyiv (2012) claim that the nonlinear Landau damping rate is \( \ll \) linear growth rate
- also accounting for much faster collisionless scattering (kinetic regime) → powerful instability, faster than IC cooling (Schlickeiser+ 2013, Chang+ in prep.)
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Challenge #2 (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! (Chang+ in prep.)
Simulations of the beam-plasma instability

- \( \alpha \gamma = 3 \) in simulation: beam energy density dominates rest frame energy density of background plasma
- \( \alpha \gamma \sim 10^{-12} \) in reality: background dominates by far

\[
\alpha = \frac{n_{\text{beam}}}{n_{\text{IGM}}}, \quad \text{Sironi & Giannios (2013)}
\]
Simulations of the beam-plasma instability

- $\alpha \gamma = 3$ in simulation: beam energy density dominates rest frame energy density of background plasma
- $\alpha \gamma \sim 10^{-12}$ in reality: background dominates by far
- Extrapolation with Lorentz force argument:
  \[ \frac{\Delta p_{\text{beam},\perp}}{\Delta t} \sim eE_{\perp} \]
- However: coherent field $E_{\perp}$ causes beam deflection, not broadening of momentum distribution

$\alpha = \frac{n_{\text{beam}}}{n_{\text{IGM}}}$, Sironi & Giannios (2013)
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 → star formation histories
When do dwarfs form?

red: $\tau_{\text{form}} > 10$ Gyr, $z > 2$
Milky Way satellites: formation history and abundance

late forming satellites (< 10 Gyr) not observed!

Maccio & Fontanot (2010)

Christoph Pfrommer
The Physics and Cosmology of TeV Blazars
**Milky Way satellites: formation history and abundance**

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

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

Maccio & Fontanot (2010)

Maccio+ (2010)
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!