The Physics and Cosmology of TeV Blazars

Christoph Pfrommer

in collaboration with

Avery E. Broderick, Phil Chang, Ewald Puchwein, Volker Springel

1 Heidelberg Institute for Theoretical Studies, Germany
2 Perimeter Institute/University of Waterloo, Canada
3 University of Wisconsin-Milwaukee, USA

Jul 11, 2012 / Meeting, DFG Research Unit FOR 1254
Physics of blazar heating
The intergalactic medium
Structure formation

The Hitchhiker’s Guide to . . . Blazar Heating

- the extragalactic TeV Universe
- plasma physics for cosmologists
The Hitchhiker’s Guide to . . . Blazar Heating

- the extragalactic TeV Universe
- plasma physics for cosmologists
- consequences for
  - intergalactic magnetic fields
  - extragalactic gamma-ray background
  - thermal history of the Universe
  - Lyman-α forest
  - “missing dwarf galaxies”
  - H I mass function
  - galaxy cluster bimodality
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
   - Conclusions
TeV gamma-ray astronomy

H.E.S.S.

MAGIC I

VERITAS

MAGIC II
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
($E_{\gamma} > 100$ GeV)

Unified model of active galactic nuclei

- Narrow line region
- Broad line region
- Dusty torus
- Relativistic jet
- Central SMBH

Christoph Pfrommer
The Physics and Cosmology of TeV Blazars
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:

\[ \gamma_{\text{TeV}} + \gamma_{\text{eV}} \rightarrow e^+ + e^- \]
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 ($\gamma = 10^6$)
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 \(\sim 1 \text{ GeV}\)

\[ E \sim \gamma^2 E_{\text{CMB}} \sim 1 \text{ GeV} \]
Propagating of TeV photons

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:
  \[ \lambda_{\gamma\gamma} \sim (35 \ldots 700) \text{ Mpc for } z = 1 \ldots 0 \]
  \[ \text{pairs produced with energy of } 0.5 \text{ TeV (} \gamma = 10^6 \)\]

- these pairs inverse Compton scatter off the CMB photons:
  \[ \lambda_{\text{IC}} \sim \lambda_{\gamma\gamma}/1000 \]
  \[ \text{producing gamma-rays of } \sim 1 \text{ GeV} \]

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

- 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 expected cascade emission against Fermi constraints for different TeV sources. Neronov & Vovk (2010) references are indicated.]
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

\[
    r_L = \frac{E}{eB} \sim 30 \left( \frac{E}{3 \text{ TeV}} \right) \left( \frac{B}{10^{-16} \text{ G}} \right)^{-1} \text{ Mpc}
\]
TeV beam of $e^+/e^-$ are deflected out of the line of sight reducing the GeV IC flux → 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

$$x_{IC} \sim 0.1 \left( \frac{E}{3 \text{ TeV}} \right)^{-1} \text{ Mpc}$$

for the associated 10 GeV IC photons the $Fermi$ angular resolution is 0.2° or $\theta \sim 3 \times 10^{-3}$ rad

$$\frac{x_{IC}}{r_L} > \theta \rightarrow B \gtrsim 10^{-16} \text{ G}$$
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:

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

wave-like perturbation with \( \mathbf{k} \parallel \mathbf{v}_{\text{beam}} \), 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-\( e^+/e^- \) → positive feedback
- exponential wave-growth → 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 $v_{beam}$: real word perturbations don’t choose “easy” alignment $= \sum$ all orientations

Bret (2009), Bret+ (2010)
Beam physics – growth rates

- 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

Broderick, Chang, C.P. (2012)
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
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

\[ \gamma_{\text{TeV}} + \gamma_{\text{eV}} \rightarrow e^+ + e^- \rightarrow \{ \begin{align*} \text{IC off CMB} & \rightarrow \gamma_{\text{GeV}} \\ \text{plasma instabilities} & \rightarrow \text{heating IGM} \end{align*} \]
TeV emission from blazars – a new paradigm

\[ \gamma_{\text{TeV}} + \gamma_{\text{eV}} \rightarrow e^+ + e^- \rightarrow \left\{ \begin{align*}
\text{IC off CMB} & \rightarrow \gamma_{\text{GeV}} \\
\text{plasma instabilities} & \rightarrow \text{heating IGM}
\end{align*} \right. \]

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

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

- 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

$\rightarrow$ **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. (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

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?

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

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

Broderick, Chang, C.P. (2012)
**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:
  \[ L_{\text{TeV},\text{min}}(z) = \eta L_{\text{Fermi},\text{min}}(z) \]

\[ \eta = 0.8, \ 1.6, \ 3.1 \]

\( d\log N_{\beta} / dz \)

Broderick, Chang, C.P. (2012)

→ 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 cm$^2$ per sec per steradian)

Background accounted for by unresolved AGN

Unknown contributors

Christoph Pfrommer
The Physics and Cosmology of TeV Blazars
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 (EGRB):

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

\( E' = E(1 + z') \) 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

- **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. (2012)
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
   - Conclusions
Evolution of the heating rates

Chang, Broderick, C.P. (2012)

Christoph Pfrommer

The Physics and Cosmology of TeV Blazars
Blazar heating vs. photoheating

- 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 ($z \sim 2$)

$$\varepsilon_{\text{th}} = \frac{kT}{m_p c^2} \sim 10^{-9}$$
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 ($z \sim 2$)
  \[ \varepsilon_{\text{th}} = \frac{kT}{m_pc^2} \sim 10^{-9} \]
- radiative energy ratio emitted by BHs in the Universe (Fukugita & Peebles 2004)
  \[ \varepsilon_{\text{rad}} = \eta \Omega_{\text{bh}} \sim 0.1 \times 10^{-4} \sim 10^{-5} \]
total power from AGN/stars vastly exceeds the TeV power of blazars

\[ T_{\text{IGM}} \sim 10^4 \text{ K (1 eV)} \] 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 (Fukugita & 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 \( \sim 0.1 \):

\[ \varepsilon_{\text{UV}} \sim 0.1 \varepsilon_{\text{rad}} \sim 10^{-6} \rightarrow kT \sim \text{keV} \]
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 (Fukugita & 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 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 (Fukugita & 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 $\sim 0.1$:
  \[
  \varepsilon_{\text{UV}} \sim 0.1 \varepsilon_{\text{rad}} \sim 10^{-6} \quad \rightarrow \quad kT \sim \text{keV}
  \]
- 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 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)
Thermal history of the IGM

Chang, Broderick, C.P. (2012)

Christoph Pfrommer

The Physics and Cosmology of TeV Blazars
Evolution of the temperature-density relation

no blazar heating
no blazar heating

- blazars and extragalactic background light are uniform:
  → 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
  → makes low density regions hot
  → causes inverted temperature-density relation, $T \propto 1/\delta$

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

no blazar heating

with blazar heating

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

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

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)
Temperature-density relation

\[ \log_{10}(T/\text{K}) = -8 \]

\[ \log_{10}(N_{\text{HI}}/N_{\text{H}}) = \]

\[ \log_{10}(\rho/\langle \rho \rangle) = -2 -1 0 1 2 3 \]

\[ \log_{10}(M_{\text{pix}}/(h^{-1}M_{\odot})) = 5 6 7 8 9 10 \]

Viel et al. 2009, F=0.1-0.8

Viel et al. 2009, F=0-0.9

Puchwein, C.P., Springel, Broderick, Chang (2012)
Ly-\(\alpha\) spectra

\begin{figure}
\centering
\includegraphics[width=\textwidth]{ly-alpha-spectra}
\end{figure}

\textit{Puchwein+ (2012)
Optical depths and temperatures

\[ \text{effective optical depth } \tau_{\text{eff}} \]

\[ \text{redshift } z \]

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

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

\[ T(\Delta)/(10^4 \text{K}) \]

- Becker et al. 2011

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

Puchwein+ (2012)
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

$N_{HI} > 10^{13}\text{cm}^{-2}$
$2.75 < z < 3.05$

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

Kirkman & Tytler '97

Puchwein+ (2012)

Christoph Pfrommer
The Physics and Cosmology of TeV Blazars
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)
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-α forest

3. Structure formation
   - Formation of dwarf galaxies
   - Puzzles in galaxy formation
   - Conclusions
Entropy evolution

Temperature evolution

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

- 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.
Entropy evolution

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

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

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

→ depends on instantaneous value of $c_s$
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 $\rightarrow$ higher IGM pressure $\rightarrow$ higher Jeans mass:

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

$\rightarrow$ 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

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

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

C.P., Chang, Broderick (2012)
“Missing satellite” problem in the Milky Way

Substructures in cold DM simulations much more numerous than observed number of Milky Way satellites!

Dolphin+ (2005)

Springel+ (2008)

Christoph Pfrommer

The Physics and Cosmology of TeV Blazars
When do dwarfs form?

Dolphin+ (2005)

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

\[ \tau_{\text{form}} > 10 \text{ Gyr}, \ z > 2 \]

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

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) are not observed!

Satellite luminosity function:
- No blazar heating: linear theory vs. non-linear theory

Maccio & Fontanot (2010)
Galactic H I-mass function

- The 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!
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
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
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, $\text{H I}$-mass function
  - group/cluster bimodality of core entropy values
When do clusters form?

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

C.P., Chang, Broderick (2012)
Entropy floor in clusters

Cluster entropy profiles

\[ K \text{[keV cm}^2\text{]} \]

\[ R \text{[kpc]} \]

Cavagnolo+ (2009)

Entropy floor in clusters

Cluster entropy profiles

\[ K \text{[keV cm}^2\text{]} \]

\[ R \text{[kpc]} \]

Cavagnolo+ (2009)
Do optical and X-ray/Sunyaev-Zel’dovich cluster observations probe the same population? (Hicks+ 2008, Planck Collaboration 2011)
**Entropy profiles: effect of blazar heating**

**varying formation time**

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

**varying cluster mass**

![Graph showing entropy profiles for 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

C.P., Chang, Broderick (2012)
greater initial entropy $K_0$ 
→ more shock heating 
→ greater increase in $K_0$ over entropy floor

- net $K_0$ amplification of 3-5
- expect: 
  median $K_{e,0} \sim 150 \text{ keV cm}^2$
  max. $K_{e,0} \sim 600 \text{ keV cm}^2$
Cool-core versus non-cool core clusters

![Graph showing cool-core and hot-core clusters]

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

**Early forming**, \( t_{\text{merger}} > t_{\text{cool}} \)

**Late forming**, \( t_{\text{merger}} < t_{\text{cool}} \)

Cavognolo+ (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

Cavagnolo+ (2009)
How efficient is heating by AGN feedback?

![Graph showing the relationship between $E_{\text{cav}} = 4PV_{\text{tot}}$ and $K_{e,0}$. The graph distinguishes between cool cores and non-cool cores.](image)

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

C.P., Chang, Broderick (2011)

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

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

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

Christoph Pfrommer

The Physics and Cosmology of TeV Blazars
How efficient is heating by AGN feedback?

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

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

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

Cool cores vs. non-cool cores

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

C.P., Chang, Broderick (2011)

$E_{\text{cav}} = 4P V_{\text{tot}} [10^{58} \text{erg}]$

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

cool cores non-cool cores

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

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

AGNs cannot transform CC to NCC clusters

(on a buoyancy timescale)
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)

\[ E_{b,2500}(kT_X = 0.7 \text{ keV}) \]
\[ E_{b,2500}(kT_X = 1.2 \text{ keV}) \]
\[ E_{b,2500}(kT_X = 2.0 \text{ keV}) \]
\[ E_{b,2500}(kT_X = 3.5 \text{ keV}) \]
\[ E_{b,2500}(kT_X = 5.9 \text{ keV}) \]

AGNs cannot transform CC to NCC clusters (on a buoyancy timescale)
How efficient is heating by AGN feedback?

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

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

C.P., Chang, Broderick (2011)

- \( E_{b,2500}(kT_X = 0.7 \text{ keV}) \)
- \( E_{b,2500}(kT_X = 1.2 \text{ keV}) \)
- \( E_{b,2500}(kT_X = 2.0 \text{ keV}) \)
- \( E_{b,2500}(kT_X = 3.5 \text{ keV}) \)
- \( E_{b,2500}(kT_X = 5.9 \text{ keV}) \)

Cool cores vs. non-cool cores
How efficient is heating by AGN feedback?

C.P., Chang, Broderick (2011)

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

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

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

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

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

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

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

cool cores

non-cool cores

AGNs cannot transform CC to NCC clusters (on a buoyancy timescale)
How efficient is heating by AGN feedback?

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