The Physics and Cosmology of TeV Blazars

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in collaboration with

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Blazar Physics

- black holes and jets
- TeV photon propagation
- plasma physics
The Hitchhiker’s Guide to . . . Blazar Heating

- **Blazar Physics**
  - black holes and jets
  - TeV photon propagation
  - plasma physics

- **Cosmological Consequences** for
  - intergalactic magnetic fields
  - gamma-ray background
The Hitchhiker’s Guide to . . . Blazar Heating

- **Blazar Physics**
  - black holes and jets
  - TeV photon propagation
  - plasma physics

- **Cosmological Consequences** for
  - intergalactic magnetic fields
  - gamma-ray background
  - thermal history of the Universe
  - Lyman-\(\alpha\) forest
  - formation of dwarf galaxies
  - galaxy cluster thermodynamics
Outline

1. Physics of blazar heating
   - Black hole jets
   - Plasma instabilities
   - Gamma-ray sky

2. The intergalactic medium
   - Properties of blazar heating
   - Thermal history of the IGM
   - The Lyman-α forest

3. Structure formation
   - Formation of dwarf galaxies
   - Galaxy cluster thermodynamics
   - Conclusions
Black hole
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: $M_{bh} \approx 6 \times 10^9 M_\odot$
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

- Relativistic jet
- Accretion disk
- Dusty torus
- Supermassive 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
Annihilation and pair production

\[ e^- + e^+ \rightarrow \text{blazar} + \text{extragalactic background light (infrared, eV)} \]

\[ \text{TeV light} \]
Annihilation and pair production

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

extragalactic backgroud 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)

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

Cosmic microwave background, $10^{-3} \text{eV}$

TeV light (infrared, eV)
Inverse Compton cascades

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

GeV

$\lambda_{IC} \sim \lambda_{\gamma\gamma}/1000$

extragalactic background light (infrared, eV)

$\lambda_{\gamma\gamma} \sim (35 \ldots 700)$ 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.
What about the cascade emission?

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

Neronov & Vovk (2010)

Fermi constraints

expected cascade emission

TeV detections

intrinsic spectra

Neronov & Vovk (2010)
Inverse Compton cascades

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

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

extragalactic background light (infrared, eV)

Magnetic field deflection
Magnetic field deflection

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

\[ \omega_p = \sqrt{\frac{4\pi e^2 n_e}{m_e}}, \quad \lambda_p = \frac{c}{\omega_p} \bigg|_{\bar{\rho}(z=0)} \sim 10^8 \text{ cm} \]
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 $\rightarrow$ bunching up
- $e^+$ attain lowest velocity in potential maxima $\rightarrow$ 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 $\mathbf{v}_{\text{beam}}$: 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

maximum growth rate

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

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

maximum growth rate

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

oblique instability beats inverse Compton cooling by factor 10-100

**assume** that instability grows at linear rate up to saturation
TeV emission from blazars – a new paradigm

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

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

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

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

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→ 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?

Fermi hard gamma-ray blazar counts

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

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

Broderick, C.P.+ (2013)

- Evolving hard gamma-ray blazars above the Fermi flux limit
- 1LAC, Abdo et al. 2010
- 2LAC, Ackermann et al. 2011

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The Physics and Cosmology of TeV Blazars
Redshift distribution of *Fermi* hard $\gamma$-ray blazars

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

Broderick, C.P.+ (2013)
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:

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

\(E_b = 1\) 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

Dominated by soft sources

absorbed, after subtracting the resolved hard blazars, \( z < 0.3 \)

Abdo et al. (2010)

Ackermann et al. (in prep.)

unabsorbed

absorbed by pair production

\( E \gtrsim 3 \) GeV

Broderick, C.P.+ (2013)

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

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The Physics and Cosmology of TeV Blazars
→ evolving population of hard blazars provides excellent match to latest EGRB by *Fermi* for $E \gtrsim 3$ GeV

*Christoph Pfrommer*  
The Physics and Cosmology of TeV Blazars
Extragalactic gamma-ray background

→ 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

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

- inv. Compton cascades \(\rightarrow\) \(\gamma_{\text{GeV}}\)
- plasma instabilities \(\rightarrow\) IGM heating

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

- intergalactic magnetic field estimates
- unified picture of TeV blazars and quasars: explains \textit{Fermi's} \(\gamma\)-ray background and blazar number counts
TeV emission from blazars – a new paradigm

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

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

$10^2$

$10^3$

$10$

$0.1$

$10^{-2}$

$10^{-3}$

$1 + z$

$10$

$5$

$2$

$1$

$10^{-1}$

$10^0$

Chang, Broderick, C.P. (2012)

10x larger heating

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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

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

$$\varepsilon_{\text{th}} = \frac{kT}{m_pc^2} \sim 10^{-9}$$
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radiative energy ratio emitted by BHs in the Universe (Fukugita & Peebles 2004)

\[ \varepsilon_{\text{rad}} = \eta \Omega_{\text{bh}} \sim 0.1 \times 10^{-4} \sim 10^{-5} \]
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  \varepsilon_{\text{UV}} \sim 0.1 \varepsilon_{\text{rad}} \sim 10^{-6} \rightarrow kT \sim \text{keV}
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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 \( \text{H I}/\text{He II} \) due to the small recombination rate)
Blazar heating vs. photoheating

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  \[
  kT \sim \eta_{\text{bh}} \varepsilon_{\text{rad}} m_p c^2 \sim 10 \text{ eV}
  \]
  (limited by the total power of TeV sources)
Thermal history of the IGM

C.P., Chang, Broderick (2012)

- only photoheating
- standard BLF
- optimistic BLF
Evolution of the temperature-density relation

no blazar heating
blazars and extragalactic background light are uniform:
→ blazar heating rate independent of density
Physics of blazar heating
The intergalactic medium
Structure formation
Properties of blazar heating
Thermal history of the IGM
The Lyman-\(\alpha\) forest

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

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  - 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):

- $L = 15 h^{-1} \text{Mpc}$ 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

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

Puchwein, C.P., Springel, Broderick, Chang (2012)
The Lyman-α forest
The observed Lyman-α forest

![Lyman-α forest graph](image.png)
The simulated Ly-α forest

Puchwein+ (2012)
Optical depths and temperatures

![Graph showing optical depths versus redshift for different levels of blazar heating. The graph includes data points and lines for no blazar heating, weak blazar heating, intermediate blazar heating, and strong blazar heating. The legend also includes data from Viel et al. 2004, Tytler et al. 2004, and FG '08.](image-url)
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)

![Graph showing Ly-\(\alpha\) flux PDFs and power spectra](image)

- **PDF of transmitted flux fraction**
  - Log scale on the y-axis.
  - X-axis: transmitted flux fraction.
  - Different lines represent different levels of blazar heating.
  - Z values show the evolution with redshift.

- **Power spectrum**
  - Log scale on both axes.
  - X-axis: wavenumber (k [s km\(^{-1}\)]).
  - Y-axis: power spectrum \(\xi \times P_D(k)\).

**Legend**
- No blazar heating
- Weak blazar heating
- Intermediate blazar heating
- Strong blazar heating

**References**
- Kim et al. 2007
- 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

\[ b \text{[km s}^{-1}] \]

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

\( \text{PDF of } b \text{[km s}^{-1}] \)

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

Kirkman & Tytler ’97

Puchwein+ (2012)
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)
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Entropy evolution

Temperature evolution

\[ T[K] \]

only photoheating
standard BLF
optimistic BLF

\[ T[K] \]

20 10 5 2 1
1 +z
10^3
10^4
10^5

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entropy evolution

\[ K_e = kTn_e^{-2/3} \]

evolution of entropy, \( K_e \) 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 → higher thermal pressure
  → higher Jeans mass:

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

→ 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 $\rightarrow$ 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!

- 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

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

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

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)

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

$1 + \delta = 1, z_{\text{reion}} = 10$
“Missing satellite” problem in the Milky Way

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

satellite formation time

Maccio & Fontanot (2010)

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

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

Maccio & Fontanot (2010)

Maccio+ (2010)
Galactic 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!
When do clusters form?

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

Cluster entropy profiles

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

**varying formation time**

![Graph showing entropy profiles for different formation times and cluster masses.](image)

**varying cluster mass**

![Graph showing entropy profiles for different cluster masses and formation times.](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)
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 $K_{e,0} \sim 150 \text{ keV cm}^2$
  - max. $K_{e,0} \sim 600 \text{ keV cm}^2$
Cool-core versus non-cool core clusters

\[ \text{Number of clusters} \]

\[ \text{Fractional number of clusters} \]

\[ K_0 \text{ [keV cm}^2\text{]} \]

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

![Diagram showing the distribution of cool and hot clusters with respect to $K_0$ (keV cm$^{-2}$)].

- **Cool core clusters** ($t_{\text{merger}} > t_{\text{cool}}$)
- **Hot core clusters** ($t_{\text{merger}} < t_{\text{cool}}$)

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

Cavagnolo+ (2009)
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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The Physics and Cosmology of TeV Blazars
How efficient is heating by AGN feedback?

C.P., Chang, Broderick (2011)

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

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

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

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

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

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

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

cool cores

non-cool cores
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

**Blazar heating:** TeV photons are attenuated by EBL; their kinetic energy $\rightarrow$ heating of the IGM; it is *not* cascaded to GeV energies
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- significantly modifies late-time structure formation:
  - suppresses late dwarf formation (in accordance with SFHs): void phenomenon, “missing satellites” (?)
  - group/cluster bimodality of core entropy values

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The Physics and Cosmology of TeV Blazars


Additional slides
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)

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Broderick, C.P.+ (2013)
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.)