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

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

Structure formation
- Entropy evolution
- Formation of dwarf galaxies
- Bimodality of galaxy clusters
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TeV gamma-ray astronomy

H.E.S.S.

MAGIC I

VERITAS

MAGIC II

Christoph Pfrommer

Blazar heating
high-energy $\gamma$-ray impacts the Earth’s atmosphere and sets off an electro-magnetic cascade in the vicinity of a nucleus

$e^+/e^-$ travel faster than the speed of light in the atmosphere $\rightarrow$ emission of a cone of blue Čerenkov light
Imaging air Čerenkov telescopes – the technique

- primary $\gamma$-rays and hadrons cause different shower characteristics $\rightarrow$ separation of $\gamma$-rays from ‘background’ events
- opening angle and shower location in the shower image allows reconstructing the initial energy and direction of the $\gamma$-ray
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)
Unified model of active galactic nuclei

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

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Christoph Pfrommer
Blazar heating
The blazar sequence

Ghisellini (2011)
1 TeV photons can pair produce with 1 eV photons:

$$\gamma + \gamma \rightarrow e^+ + e^-$$

mean free path for this depends on the density of 1 eV photons:
→ typically $\sim (35 \ldots 700)$ 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 $\sim (45 \ldots 700)$ kpc
→ producing gamma-rays of $\sim 1$ 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!**

TeV spectra

TeV detections

Fermi constraints

expected cascade emission

Neronov & Vovk (2010)
TeV beam of $e^+/e^-$ are deflected out of the line of sight reducing the GeV IC flux:

- 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 angular resolution is $0.2^\circ$ or $\theta \sim 3 \times 10^{-3} \text{ rad}$

$$\frac{x_{\text{IC}}}{r_L} > \theta \rightarrow B \gtrsim 10^{-16} \text{ G}$$
Missing plasma physics?

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:

\[ \frac{\omega_p}{\gamma} = \sqrt{\frac{4\pi e^2 n_e}{\gamma^2 m_e}} \]

\[ \lambda_p = \frac{\gamma c}{\omega_p} \]

- one frequency (timescale) and one length in the problem:
Two-stream instability: mechanism

wave-like perturbation with $k \parallel v_{beam}$, 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

\[ e^+, e^- \]

\[ \Phi \]

\[ p \]

\[ e^- \]

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

wave-like perturbation with $k \parallel v_{\text{beam}}$, 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
Two-stream instability: energy transfer

- Energy is transferred to the plasma wave from particles with $v \gtrsim v_{\text{phase}} \rightarrow$ growing modes
- Energy is transferred from the plasma wave to particles with $v \lesssim v_{\text{phase}} \rightarrow$ 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

Broderick, Chang, C.P. (2011)
Beam physics – growth rates

- non-linear evolution of these instabilities at these density contrasts is not known
- expectation from PIC simulations suggest substantial isotropization of the beam
- no need for intergalactic magnetic field to deflect pairs
- plasma instabilities dissipate the beam’s energy, no energy left over for inverse Compton scattering off the CMB
Implications for $B$-field measurements

Broderick, Chang, C.P. (2011)
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

$\sim 1$–$10\%$ of beam energy to IC CMB photons

TeV blazar spectra are not suitable to measure IGM $B$-fields
TeV blazar luminosity density

- collect luminosity of all 23 TeV blazars with good spectral measurements
- account for the selection effects
- TeV blazar luminosity density is a scaled version ($\eta_B \sim 0.2\%$) of that of quasars!
- assume that they trace each other for all $z$

Broderick, Chang, C.P. (2011)
**Fermi number count of “TeV blazars”**

- number evolution of TeV blazars that are expected to have been observed by *Fermi* vs. observed evolution
- different colors correspond to different spectra connecting the *Fermi* and the TeV-energy band

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

Broderick, Chang, C.P. (2011)
Fermi probes “dragons” of the gamma-ray sky

Fermi LAT Extragalactic Gamma-ray Background

Energy (GeV)
0.1 1
10^{-6}
100
Intensity (GeV photons per cm^2 per sec per steradian)
10^{-7}
10^{-8}
10^{-9}

Unknown contributors
Background accounted for by unresolved AGN

Christoph Pfrommer

Blazar heating
Extragalactic gamma-ray background

- assume all TeV blazars have identical intrinsic spectra:

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

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

- spectrum of the extragalactic gamma-ray background:

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

where \( E' = E(1 + z') \), \( \tilde{\Lambda}_Q \) is the physical quasar luminosity density, and \( \tau(E, z) \) is the optical depth to TeV-gamma rays emitted with energy \( E \) from an object located at \( z \).
Extragalactic gamma-ray background: varying $\alpha_L$

- **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 $E_b$

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

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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 larger at higher $z$ and energies
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Evolution of the heating rates

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

- HI, HeI$^{-}$/HeII$^{-}$-reionization
- photoheating
- blazar heating
- 10x larger heating

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

- total power from AGN/stars vastly exceeds the TeV power of blazars
- $T_{\text{IGM}} \sim 10^4 \text{ K} \ (1 \text{ eV})$ 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 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. (2011)
blazars and extragalactic background light are uniform
→ blazar heating independent of density
→ causes inverted temperature-density relation, $T \propto 1/\delta$

blazars completely change the thermal history of the diffuse IGM and late-time structure formation
Evolution of the temperature-density relation

no blazar heating

blazar heating

- Blazars and extragalactic background light are uniform → blazar heating independent of density → causes inverted temperature-density relation, $T \propto 1/\delta$

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

Chang, Broderick, C.P. (2011)
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 (to account for uncertainties in the expected blazar-heating rate)
- used an up-to-date model of the UV background (Faucher-Giguère et al. 2009)
Temperature-density relation

Puchwein, C.P., Springel, Broderick, Chang (2011)
Ly-α spectra

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

- PDF of transmitted flux fraction
- Power spectrum $\xi(k) \times P_{1D}(k)$

$z = 2.07$
- No blazar heating
- Weak blazar heating
- Intermediate blazar heating
- Strong blazar heating

$z = 2.52$
- No blazar heating
- Weak blazar heating
- Intermediate blazar heating
- Strong blazar heating

Puchwein+ (2011)

Viel et al. 2004

Kim et al. 2004

Christoph Pfrommer  Blazar heating
Voigt profile decomposition

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

$N_{\text{HI}} > 10^{13} \text{cm}^{-2}$

$2.75 < z < 3.05$

- Dotted line: no blazar heating
- Blue dashed line: weak blazar heating
- Green dash-dotted line: intermediate blazar heating
- Red dashed-dotted line: strong blazar heating

Kirkman & Tytler '97

Puchwein+ (2011)

PDF of $b$ [km$^{-1}$]

Puchwein+ (2011)
impressive 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)
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evolution of the entropy, $K_e = kTn_e^{-2/3}$, at mean density

- blazar heating substantially increases the entropy floor ($z \lesssim 2$)
Evolution of the entropy-density relation

- blazar heating substantially increases the entropy in voids
- scatter is also increased → larger stochasticity of structure formation

C.P., Chang, Broderick (2011)
Jeans mass

- on small enough scales, the thermal pressure can oppose gravitational collapse of the gas
- characteristic length scale below which objects will not form
- Jeans wavenumber and mass is obtained by balancing the sound crossing and free-fall timescales

\[
k_J(a) \equiv \frac{a}{c_s(a)} \sqrt{4\pi G \bar{\rho}(a)}
\]

\[
M_J(a) \equiv \frac{4\pi}{3} \bar{\rho}(a) \left( \frac{2\pi a}{k_J(a)} \right)^3 = \frac{4\pi^{5/2}}{3} \frac{c_s^3(a)}{G^{3/2} \bar{\rho}^{1/2}(a)}
\]

- blazar heating increases the IGM temperature by $\sim 10$:

\[
\frac{M_J,\text{blazar}}{M_J,\text{photo}} = \left( \frac{c_s,\text{blazar}}{c_s,\text{photo}} \right)^3 = \left( \frac{T_{\text{blazar}}}{T_{\text{photo}}} \right)^{3/2} \gtrsim 30
\]
Filtering mass – dwarf formation

C.P., Chang, Broderick (2011)
Peebles’ void phenomenon explained?

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

C.P., Chang, Broderick (2011)
"Missing satellite" problem in the Milky Way

- **Satellite formation time**
  - Late forming satellites (< 10 Gyr) not observed!
  - Maccio & Fontanot (2010)

- **Satellite luminosity function**
  - Maccio+ (2010)

- Blazar heating suppresses late satellite formation, reconciling low observed dwarf abundances with CDM simulations.
Blazar heating is an amalgam of pre-heating and AGN feedback:

- **blazar heating is not localized** (≠ AGN feedback)
  → may change initial conditions for forming groups (but provides no stability for cool cores, CCs)

- **blazar heating generates time-dependent entropy floor** (≠ pre-heating)
  → may solve the classical problems of pre-heating (z ≈ 3):
    - provides a physical mechanism
    - does not starve galaxy formation for z ≲ 3
    - early forming groups can cool and develop observed low-\(K_e\) cores
Mass accretion history of groups/clusters

- Peak entropy injection from blazar heating ($z \sim 1$) matches formation time of groups.
- Early forming groups are unaffected and develop cool cores.
- Late forming groups may have an elevated entropy core.

C.P., Chang, Broderick (2011)
Entropy profiles: effect of blazar heating

varying formation time

varying cluster mass

If significant fraction of intra-group medium collapses from IGM:

- $z$-dependent excess entropy in cores (no cooling)
- largest effect for late forming, small objects
Scenario for the bimodality of cluster core entropies?

- Entropy core, $K_{e,0}$, immediately after formation is set by the $z$-dependent blazar heating.

- Only late forming groups ($z \lesssim 1$) are directly affected by blazar (pre-)heating.

- If the cooling time, $t_{\text{cool}}$, is shorter than the time period to the successive merger, $t_{\text{merger}}$, the group will radiate away the elevated core entropy and evolve into a CC.

- If $t_{\text{cool}} > t_{\text{merger}}$, merger shocks can gravitationally reprocess the entropy cores and amplify them → potentially those forming clusters evolve into non-cool core (NCC) systems.
Gravitational reprocessing of entropy floors

- Larger $K_{e,0}$ of a merging cluster facilitates shock heating $\rightarrow$ increase of $K_{e,0}$ over entropy floor
- Entropy floor of 100 keV cm$^2$ at $z = 3$ in non-radiative simulation:
  - Net entropy amplification factor $\sim$ 3–5 for clusters and groups (Borgani+ 2005)
- Expect median of $K_{e,0} \sim 150$ keV cm$^2$; maximum $K_{e,0} \sim 600$ keV cm$^2$

Borgani+ (2005)
Bimodality of cluster core entropies

- *Chandra* observations match blazar heating expectations!
- Need hydrodynamic simulations to confirm this scenario
Conclusions on blazar heating

- explains puzzles in high-energy astrophysics:
  - TeV blazars can evolve like quasars
  - extragalactic gamma-ray background at $E \gtrsim 10$ GeV
  - invalidates intergalactic $B$-constraints from blazar spectra

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

- significantly modifies late-time structure formation:
  - suppresses late formation of dwarfs:
    - “missing satellite” problem, void phenomenon
  - group/cluster bimodality of core entropy values
How efficient is heating by AGN feedback?

- **cavity enthalpy**
  \[ E_{\text{cav}} = 4 P V_{\text{tot}} \]

- **in some cases**
  \[ E_{\text{cav}} \gtrsim E_{\text{bind}}(R_{2500}) \]

- **cavity energy** only couples weakly into ICM, but prevents cooling catastrophe

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

- **cool cores**
- **non-cool cores**

C.P., Chang, Broderick (2011)

- on a buoyancy timescale, no AGN outburst transforms a CC to a non-cool core (NCC) cluster!

Christoph Pfrommer  |  Blazar heating