30,000 foot view of blazar heating

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with

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Feedback over 44 orders of magnitude, Perimeter Institute – 2016
Motivation
A new link between high-energy astrophysics and cosmological structure formation

Introduction to Blazars
- active galactic nuclei (AGN)
- propagating gamma rays
- plasma physics

Cosmological Consequences
- unifying blazars with AGN
- gamma-ray background
- thermal history of the Universe
- Lyman-α forest
- formation of dwarf galaxies
Active galactic nucleus (AGN)

- **AGN**: compact region at the center of a galaxy, which dominates the luminosity of its electromagnetic spectrum.
- AGN emission is most likely caused by mass accretion onto a supermassive black hole and can also launch relativistic jets.
Active galactic nucleus at a cosmological distance

- AGN: compact region at the center of a galaxy, which dominates the luminosity of its electromagnetic spectrum.
- AGN emission is most likely caused by mass accretion onto a supermassive black hole and can also launch relativistic jets.
- AGNs are among the most luminous sources in the universe → discovery of distant objects.

Quasar 3C175 at $z \sim 0.8$:
jet extends $10^6$ light years across.
Unified model of active galactic nuclei

- Blazars
- Gamma-ray sky
- Structure formation
- Active galactic nuclei
- Propagating $\gamma$ rays
- Plasma instabilities

- accretion disk
- dusty torus
- relativistic jet
- super−massive black hole

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Unified model of active galactic nuclei

Blazar: jet aligned with line-of-sight
TeV gamma-ray observations

MAGIC

VERITAS

H.E.S.S.

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The TeV gamma-ray sky

There are several classes of TeV sources:

- Galactic - pulsars, BH binaries, supernova remnants
- Extragalactic - mostly blazars, two starburst galaxies

Source Types

- PWN
- Binary XRB PSR Gamma BIN
- HBL IBL FRI FSRO
- Blazar LBL AGN (unknown type)
- Shell SNR Molec. Cloud Composite SNR Superbubble
- Starburst
- DARK UNID Other
- uQuasar Star Forming Region Globular Cluster Cat. Var. Massive Star Cluster BIN SL Lec (class unclear) WR

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Annihilation and pair production

\[ e^- + e^+ \rightarrow \text{blazar} \]

extragalactic background light (infrared, eV)
Annihilation and pair production

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

extragalactic background light (infrared, eV)

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

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

extragalactic background light (infrared, eV)

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

\[ \gamma \text{rays} \rightarrow \text{e}^{-} + \text{e}^{+} \]

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

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

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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)
What about the cascade emission?

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

![Graph showing expected cascade emission, TeV detections, and intrinsic spectra with Fermi exclusion region.](image-url)
Inverse Compton cascades

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

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

The diagram illustrates the process of inverse Compton scattering, where an electron and positron interact with cosmic microwave background and extragalactic background light (infrared, eV) to produce gamma rays. The energy transfer is depicted with arrows showing the direction of energy flow. The equation \( \lambda_{\text{IC}} \sim \lambda_{\gamma\gamma}/1000 \) relates the inverse Compton scattering length to the gamma-ray wavelength, indicating the scale of the process. The range \( \lambda_{\gamma\gamma} \sim (35 \ldots 700) \text{ Mpc for } z = 1 \ldots 0 \) gives the expected gamma-ray wavelength for a redshift range, reflecting the cosmic origin of the gamma rays.
Extragalactic magnetic fields?

pair deflection in intergalactic magnetic field

extragalactic background light (infrared, eV)

TeV

blazar

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Extragalactic magnetic fields?

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

- problem for unified AGN model: no increase in comoving blazar density with redshift allowed (as seen in other AGNs) since otherwise, extragalactic GeV background would be overproduced!
What else could happen?

Blazars
Gamma-ray sky
Structure formation
Active galactic nuclei
Propagating $\gamma$ rays
Plasma instabilities

What else could happen?

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

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Plasma instabilities

Pair plasma beam propagating through the intergalactic medium
Plasma instabilities

- pair beam
  - intergalactic medium (IGM)

  $e^+, e^-$  $p, e^-$
  $e^+, e^-$  $p, e^-$
  $e^+, e^-$  $p, e^-$

- this configuration is unstable to plasma instabilities

- characteristic frequency and length scale of the problem:

$$\omega_p = \sqrt{\frac{4\pi e^2 n_e}{m_e}}, \quad \lambda_p = \frac{c}{\omega_p} \left| \bar{\rho}(z=0) \right| \sim 10^8 \text{cm}$$
Two-stream instability

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

\[ \Phi \\
\]

\[ e^+, e^- \]

\[ p \]

$e^-$ $e^-$
Two-stream instability

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-$e^+/e^-$ → positive feedback
- exponential wave-growth → instability

\[ e^+, e^- \]
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

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**Oblique instability**

- \( \mathbf{k} \) 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)

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**Beam flow**

Beam (\( \mathbf{k} = \frac{c}{\omega_p} \))
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

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

plasma instabilities

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

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

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Implications for intergalactic magnetic fields

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

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

Broderick, Chang, C.P. (2012)

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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

$\rightarrow$ **TeV blazar spectra are not suitable to measure IGM $B$-fields** (if plasma instabilities saturate close to linear rate)!

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

→ assume that they trace each other for all redshifts!
How many TeV blazars are there?

→ use all-sky survey of the GeV gamma-ray sky: *Fermi* gamma-ray space telescope
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

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

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

Broderick, C.P.+ (2013)
Extragalactic gamma-ray background

- intrinsic spectrum for a TeV blazar:

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

- \( E_b = 1 \text{ TeV} \) 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):

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

- \( E' = E(1 + z') \) is gamma-ray energy at emission,
- \( \tilde{\Lambda}_Q \) is physical quasar luminosity density,
- \( \eta_B \sim 0.2\% \) is blazar fraction, \( \tau \) is optical depth
Extragalactic gamma-ray background

→ evolving population of hard blazars provides excellent match to latest EGRB by Fermi for $E \gtrsim 3$ GeV
→ the signal at 10 (100) GeV is dominated by redshifts $z \sim 1.2$ ($z \sim 0.6$)
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 . . .

- 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 formation of dwarf galaxies
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 \( \eta_{\text{ph}} \sim 10^{-3} \) \( \rightarrow kT \sim \eta_{\text{ph}} \varepsilon_{\text{UV}} m_p c^2 \sim \text{eV} \)
  (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)

→ increased temperature at mean density!

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no blazar heating

with blazar heating

- blazars and extragalactic background light are uniform:
  → blazar heating rate independent of density
  → makes low density regions *hot*
  → causes inverted temperature-density relation, $T \propto 1/\delta$
Blazars cause hot voids

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

Chang, Broderick, C.P. (2012)
Cosmological hydrodynamical simulations

- include predicted volumetric heating rate in cosmological hydrodynamical simulations
- study:
  - thermal properties of intergalactic medium
  - Lyman-α forest
Temperature-density relation

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

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The Lyman-\(\alpha\) forest
The observed Lyman-α forest
The simulated Ly-\(\alpha\) forest

Puchwein, C.P.+ (2012)
**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, C.P.+ (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** is 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)
“Missing satellite” problem in the Milky Way

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

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

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

$\rightarrow$ 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)
blazar heating suppresses the formation of late-forming dwarfs within existing dark matter halos of masses $< 10^{11} M_\odot$

→ introduces new time and mass scale to galaxy formation!
When do dwarfs form?

Dolphin+ (2005)

Isochrone fitting for different metallicities → star formation histories

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When do dwarfs form?

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

- Blazars
- Gamma-ray sky
- The Lyman-α forest
- Structure formation
- Dwarf galaxies

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**Satellite formation time**

Maccio & Fontanot (2010)

late forming satellites (< 10 Gyr) not observed!

**Satellite luminosity function**

Maccio+ (2010)

- no blazar heating: linear theory
- non-linear theory

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

- explains puzzles in gamma-ray 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
  - quantitative self-consistent picture of high-$z$ Lyman-$\alpha$ forest

- significantly modifies late-time structure formation:
  - suppresses late dwarf formation
  - void phenomenon, “missing satellites” (?)
Literature for the talk

Additional slides
Empirical model for star formation histories (1)

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 ($M < 10^{11} \, h^{-1} M_\odot$) $\rightarrow$ blazar heating?
**Galactic H I-mass function**

- H I-mass function is too flat (i.e., gas version of missing dwarf problem!)
- photoheating and SN feedback too inefficient
- IGM entropy floor of $K \sim 15 \text{keV cm}^2$ at $z \sim 2 - 3$ successful!

Mo+ (2005)