The physics of propagating TeV gamma-rays: From plasma instabilities to cosmological structure formation

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with

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**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-$\alpha$ 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.

Centaurus A

The physics of propagating TeV gamma-rays
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

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

The physics of propagating TeV gamma-rays
TeV gamma-ray observations

The physics of propagating TeV gamma-rays
The TeV gamma-ray sky

There are several classes of TeV sources:

- Galactic - pulsars, BH binaries, supernova remnants
- Extragalactic - mostly blazars, two starburst galaxies
The physics of propagating TeV gamma-rays
Annihilation and pair production

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

\[ \lambda_{\gamma\gamma} \sim (35 \ldots 700) \text{ Mpc for } z = 1 \ldots 0 \]
Blazars
Gamma-ray sky
Structure formation
Active galactic nuclei
Propagating γ rays
Plasma instabilities

Inverse Compton cascades

The physics of propagating TeV gamma-rays

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

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

\[ \lambda_{\text{IC}} \sim \lambda_{\gamma\gamma}/1000 \]
\[ \lambda_{\gamma\gamma} \sim (35 \ldots 700) \text{ Mpc for } z = 1 \ldots 0 \]

→ 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!**

- **expected cascade emission**
- **Fermi exclusion region**
- **TeV detections**
- **intrinsic spectra**

Neronov & Vovk (2010)
Inverse Compton cascades

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

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

The physics of propagating TeV gamma-rays
Extragalactic magnetic fields?

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

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Plasma instabilities

Pair plasma beam propagating through the intergalactic medium

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Plasma instabilities

- pair beam

This configuration is unstable to plasma instabilities

Characteristic frequency and length scale of the problem:

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

- $k$ oblique to $\mathbf{v}_{beam}$: 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)

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

- 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 \textit{linear} rate up to saturation

Broderick, Chang, C.P. (2012), also Schlickeiser+ (2012)
Challenges to the Challenge

Challenge #1: quenching of linear growth & non-linear saturation

- quenching of linear growth at small level \((10^{-3} - 10^{-2}) \epsilon_e\)
- cold beam: slow secular growth with non-linear saturation
  only \(\sim 10\%\) of the beam energy transferred to the IGM

PIC simulations: \(\alpha = n_{\text{beam}}/n_{\text{IGM}},\)
1D: black – two-stream & green – oblique,
2D: red – oblique (Sironi & Giannios 2013)
Plasma simulations: resolution

Shalaby+ (2016)

- **Spatial resolution:**
  - 
  - 

- **Momentum resolution:**
  - 
  - 

- **Spectral resolution:**
  - 
  - 
  - 

The physics of propagating TeV gamma-rays
The physics of propagating TeV gamma-rays

The graph shows the growth rate \( \Gamma/\omega_p \) as a function of wave number \( kc/\omega_p \), where \( c \) is the speed of light and \( \omega_p \) is the plasma frequency. The growth rate is plotted on a log-log scale, with the wave number on a linear scale.

Key points from the graph:
- The growth rate increases significantly as the wave number approaches 1.0.
- The graph starts from a growth rate of \( 10^{-5} \) at a wave number of 0.2 and rises sharply.

The data is based on plasma simulations from Shalaby+ (2016).
Plasma simulations: resolution

Shalaby+ (2016)

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The physics of propagating TeV gamma-rays
Challenge #2: inhomogeneous universe

- Universe is inhomogeneous
  - Electron density changes as a function of position
- Could lead to loss of resonance over length scale $\ll$ length scale for instability growth

Condition for linear growth to occur is claimed (Miniati & Elyiv 2013)

\[
\frac{\text{few}}{\Gamma_m} < \frac{\Delta k_{||}}{|dk/dt|} \quad \text{electrostatic modes (1D)} \quad \frac{\gamma_b}{\alpha} \frac{c\lambda_{||}}{\omega_p} < 1,
\]

Where $\lambda_{||} \equiv |n/\nabla n|$. 

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Background inhomogeneity effects

**Condition** \[ \left( \frac{\gamma_b}{\alpha} \right) \left( \frac{c \lambda_{||}}{\omega_p} \right) < 1 \]

**Simulation** \[ \left( \frac{\gamma_b}{\alpha} \right) \left( \frac{c \lambda_{||}}{\omega_p} \right) \sim 10^7 \]

Shalaby+ (2016): 1D PIC simulation shows linear wave growth at lower growth rate, more energy lost by the beam than for uniform case.
Challenges to the Challenge

Challenge #3: induced scattering (non-linear Landau damping)

- we assume that the non-linear damping rate = linear growth rate
- 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
- accounting for much faster collisionless scattering (kinetic regime) \( \rightarrow \) powerful instability, faster than IC cooling

(Schlickeiser+ 2013, Chang+ 2014)
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
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)
Unified TeV blazar-quasar model

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

The physics of propagating TeV gamma-rays
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)

Fermi extragalactic gamma-ray background

Fermi hard gamma-ray blazar counts

log[ \Phi(z, M_B > -27)] [Mpc^{-3}]
Redshift distribution of *Fermi* hard $\gamma$-ray blazars

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

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

Hopkins+ (2007)
Extragalactic gamma-ray background

→ evolving population of hard blazars provides excellent match to latest EGRB by *Fermi* for $E \gtrsim 3$ GeV
Extragalactic gamma-ray background

→ 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
Thermal history of the IGM

C.P., Chang, Broderick (2012)

→ increased temperature at mean density!
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)
The Lyman-α forest
The observed Lyman-$\alpha$ forest

![Graph showing Lyman-\(\alpha\) forest and Lyman Alpha Emission]

**TOTAL COUNTS**

**VACUUM HELIOCENTRIC WAVELENGTH (ANGSTROM)**

Q1159+123
The simulated Ly-\(\alpha\) forest

Puchwein, C.P.+ (2012)

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Ly-α 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** ∼ the total energy output of TeV blazars (or equivalently ∼ 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:

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

$\rightarrow$ 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 suppressed

- 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!
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

- 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” (?)
CRAGSMAN: The Impact of Cosmic RAys on Galaxy and CluSter ForMAtion

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The physics of propagating TeV gamma-rays
Literature for the talk


