The Physics and Cosmology of TeV Blazars

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in collaboration 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
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- **Cosmological Consequences**
  - unifying blazars with AGN
  - gamma-ray background
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- **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.

- AGNs are the most luminous sources in the universe → discovery of distant objects.
Active galactic nucleus at a cosmological distance

Quasar 3C175 at $z \sim 0.8$:
jet extends $10^6$ light years across

- AGN: compact region at the center of a galaxy, which dominates the luminosity of its electromagnetic spectrum.
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- AGNs are the most luminous sources in the universe → discovery of distant objects.
Unified model of active galactic nuclei

- Relativistic jet
- Accretion disk
- Dusty torus
- 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

VHE $\gamma$-ray Sky Map
(E $> 100$ GeV)

2011-01-08 - Up-to-date plot available at http://www.mpp.mpg.de/~nvagneis/sources/
Annihilation and pair production

\[ e^- + e^+ \rightarrow \gamma \]

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

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

extragalactic background light (infrared, eV)

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

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

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Inverse Compton cascades

\( \lambda_{IC} \sim \lambda_{\gamma\gamma}/1000 \)

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

→ 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!

Neronov & Vovk (2010)

expected cascade emission

Fermi exclusion region

TeV detections

intrinsic spectra
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?

pair deflection in intergalactic magnetic field

GeV light (infrared, eV)

extragalactic background light (infrared, eV)

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Extragalactic magnetic fields?

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

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

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Plasma instabilities

Pair plasma beam propagating through the intergalactic medium

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The Physics and Cosmology of TeV Blazars
Plasma instabilities

- pair beam

\begin{align*}
\text{pair beam} & \\
e^+, e^- & \quad \longrightarrow \quad \text{intergalactic medium (IGM)} \\
e^+, e^- & \quad \longrightarrow \quad p, e^- \\
e^+, e^- & \quad \longrightarrow \quad p, e^- \\
e^+, e^- & \quad \longrightarrow \quad p, e^- \\
\end{align*}

- this configuration is unstable to plasma instabilities

- characteristic frequency and length scale of the problem:

\begin{align*}
\omega_p &= \sqrt{\frac{4\pi e^2 n_e}{m_e}}, \\
\lambda_p &= \left. \frac{c}{\omega_p} \right|_{\bar{\rho}(z=0)} \sim 10^8 \text{ cm}
\end{align*}
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

\[ e^+, e^- \]
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
Two-stream instability: momentum transfer

- **Particles with** $v \gtrsim v_{\text{phase}}$:
  - Pair momentum $\to$ plasma waves $\to$ growing modes: instability

- **Particles with** $v \lesssim v_{\text{phase}}$:
  - Plasma wave momentum $\to$ pairs $\to$ 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)
Oblique instability

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(Nakar, Bret & Milosavljevic 2011)

Bret (2009), Bret+ (2010)
consider a light beam penetrating into relatively dense plasma

maximum growth rate

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

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

maximum growth rate

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

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

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

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

The absence of \( \gamma_{\text{GeV}} \)'s has significant implications for . . .
- intergalactic magnetic field estimates
- unified picture of TeV blazars and quasars
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:
  \[ f_{\text{IC}} = \frac{\Gamma_{\text{IC}}}{\left( \Gamma_{\text{IC}} + \Gamma_{\text{oblique}} \right)} \]
- plasma instability dominates for more luminous blazars

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.)
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

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Quasars and TeV blazars are:

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→ 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?

Fermi hard gamma-ray blazar counts

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

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

Broderick, C.P.+ (2013)

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

...evolving hard gamma–ray blazars above the Fermi flux limit!
Redshift distribution of *Fermi* hard $\gamma$-ray blazars

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

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

- extragalactic gamma-ray background (EGRB):

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

- $E_b = 1$ TeV is break energy, $\Gamma_h = 3$ is high-energy spectral index,
- $\Gamma_i$ related to $\Gamma_F$, which is drawn from observed distribution
- $\eta_B \sim 0.2\%$ is blazar fraction, $\tau$ is optical depth
Extragalactic gamma-ray background

Dominated by soft sources

\[ E^2 \frac{dN}{dE} \text{ (MeV s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1}) \]

\[ 10^{-3} \]

\[ 10^{-4} \]

\[ 10^{-5} \]

\[ 10^{-2} \]

\[ 10^{-1} \]

\[ 1 \]

\[ 10 \]

\[ 10^2 \]

\[ 10^3 \]

\[ 10^4 \]

\[ E (\text{GeV}) \]

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

Absorbed by pair production

Unabsorbed

Abdo et al. (2010)

Ackermann et al. (in prep.)

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

→ evolving population of hard blazars provides excellent match to latest EGRB by Fermi for $E \gtrsim 3$ GeV

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Extragalactic gamma-ray background

→ the signal at 10 (100) GeV is dominated by redshifts $z \sim 1.2$ ($z \sim 0.6$)

Broderick, C.P.+ (2013)
TeV emission from blazars – a new paradigm

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additional IGM heating has significant implications for . . .

- thermal history of the IGM: Lyman-\( \alpha \) forest
- late-time formation of dwarf galaxies
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
- $T_{\text{IGM}} \sim 10^4 \text{ K (1 eV)}$ at mean density ($z \sim 2$)

\[
\varepsilon_{\text{th}} = \frac{kT}{m_p c^2} \sim 10^{-9}
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Blazar heating vs. photoheating

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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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  \[ kT \sim \eta_{\text{ph}} \varepsilon_{\text{UV}} m_p c^2 \sim \text{eV} \]
  (limited by the abundance of H I/He II due to the small recombination rate)
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- \( T_{IGM} \sim 10^4 \, \text{K} \) (1 eV) at mean density \((z \sim 2)\)

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- Blazar heating efficiency \( \eta_{bh} \sim 10^{-3} \) \( \rightarrow \) \( kT \sim \eta_{bh} \varepsilon_{rad} m_p c^2 \sim 10 \, \text{eV} \)
  (limited by the total power of TeV sources)
Thermal history of the IGM

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

- HI, HeI−/HeII− reionization
- Photoheating
- Blazar heating

\[ 10^3, 10^4, 10^5 \]

\[ 1 + z = 10, 20 \]

\[ \text{temperature } 10 \times \text{ higher} \]

\[ \text{increased temperature at mean density!} \]

C.P., Chang, Broderick (2012)
Evolution of the temperature-density relation

no blazar heating

\[ T \propto \frac{1}{\delta} \]
no blazar heating

\begin{itemize}
  \item blazars and extragalactic background light are uniform:
  \item blazar heating rate independent of density
\end{itemize}
Evolution of the temperature-density relation

- blazars and extragalactic background light are uniform:
  \( \rightarrow \) blazar heating rate independent of density
  \( \rightarrow \) makes low density regions \textit{hot}
  \( \rightarrow \) 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)

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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

\[
\log_{10}\left(\frac{\rho}{\langle\rho\rangle}\right) = -2 -1 0 1 2 3 \\
\log_{10}(T/K) = -8 -7 -6 -5 -4 -3 -2 5 6 7 8 9 10
\]

no blazar heating

intermediate blazar heating

Viel et al. 2009, F=0.1-0.8
Viel et al. 2009, F=0-0.9

Puchwein, C.P., Springel, Broderick, Chang (2012)
The Lyman-\(\alpha\) forest
The observed Lyman-\(\alpha\) forest
Optical depths and temperatures

- Effective optical depth $\tau_{\text{eff}}$ vs. redshift $z$
- Lines represent different levels of blazar heating:
  - No blazar heating
  - Weak blazar heating
  - Intermediate blazar heating
  - Strong blazar heating
- Data points from:
  - Viel et al. 2004
  - Tytler et al. 2004
  - FG '08

Redshift evolutions of effective optical depth and IGM temperature match data only with additional heating, e.g., provided by blazars!
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Ly-α flux PDFs and power spectra

- Tuned UV background

- z = 2.52

- z = 2.94

PDF of transmitted flux fraction

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

Kim et al. 2007

- Transmitted flux fraction

- 10^(-1) to 10^1

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Ly-$\alpha$ flux PDFs and power spectra

Puchwein, C.P+ (2012)
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

PDF of $b$ [skm$^{-1}$] for $N_{HI} > 10^{13}$ cm$^{-2}$

- $2.75 < z < 3.05$
- no blazar heating
- weak blazar heating
- intermediate blazar heating
- strong blazar heating

Kirkman & Tytler ‘97

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!

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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:

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

→ blazar heating increases \( M_J \) by 30 over pure photoheating!
Dwarf galaxy formation

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- characteristic length/mass scale below which objects do not form
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- complications:
  - non-linear collapse,
  - delayed pressure response in expanding universe → 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!

C.P., Chang, Broderick (2012)
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
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
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- novel mechanism; dramatically alters thermal history of the IGM:
  - uniform and $z$-dependent preheating
  - quantitative self-consistent picture of high-$z$ Lyman-α forest
Conclusions on blazar heating

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


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) \( \rightarrow \) powerful instability, faster than IC cooling (Schlickeiser+ 2013, Chang+ in prep.)
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.)

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.)
Simulations of the beam-plasma instability

- $\alpha \gamma = 3$ in simulation: beam energy density dominates rest frame energy density of background plasma
- $\alpha \gamma \sim 10^{-12}$ in reality: background dominates by far

$\alpha = \frac{n_{\text{beam}}}{n_{\text{IGM}}}$, Sironi & Giannios (2013)
Simulations of the beam-plasma instability

- $\alpha \gamma = 3$ in simulation: beam energy density dominates rest frame energy density of background plasma
- $\alpha \gamma \sim 10^{-12}$ in reality: background dominates by far
- Extrapolation with Lorentz force argument:
  $$\frac{\Delta p_{\text{beam}, \perp}}{\Delta t} \sim eE_{\perp}$$
- However: coherent field $E_{\perp}$ causes beam deflection, not broadening of momentum distribution

$\alpha = \frac{n_{\text{beam}}}{n_{\text{IGM}}}$, Sironi & Giannios (2013)
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 $z$)
Empirical model for star formation histories (2)

→ strong quenching of star formation efficiency for $z \lesssim 2$ in low-mass halos ($M < 10^{11} h^{-1} M_\odot$) → blazar heating?
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)

Blazars
Gamma-ray sky
Structure formation

Properties of blazar heating
The Lyman-α forest
Dwarf galaxies

The Physics and Cosmology of TeV Blazars

Christoph Pfrommer

HITS
Milky Way satellites: formation history and abundance

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**Blazars**
**Gamma-ray sky**
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**The Lyman-\(\alpha\) forest**
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**satellite formation time**

Maccio & Fontanot (2010)

late forming satellites (< 10 Gyr)
not observed!

**satellite luminosity function**

Maccio+ (2010)

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