30,000 foot view of blazar heating

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with

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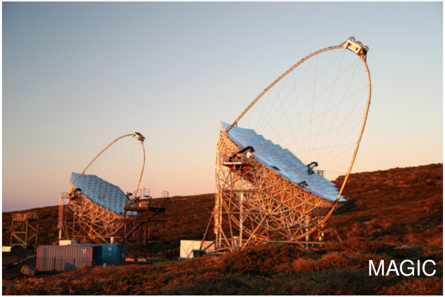
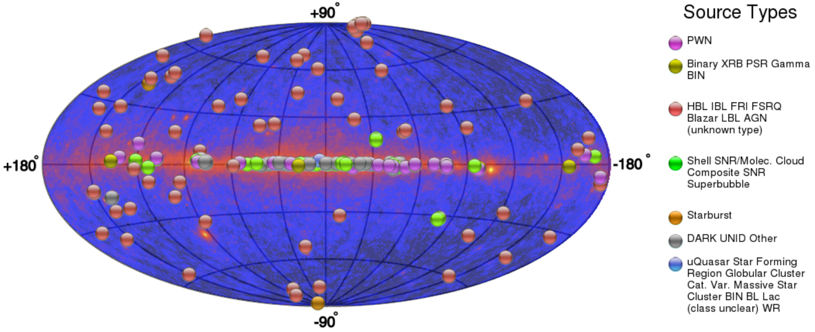
TeV gamma-ray observations



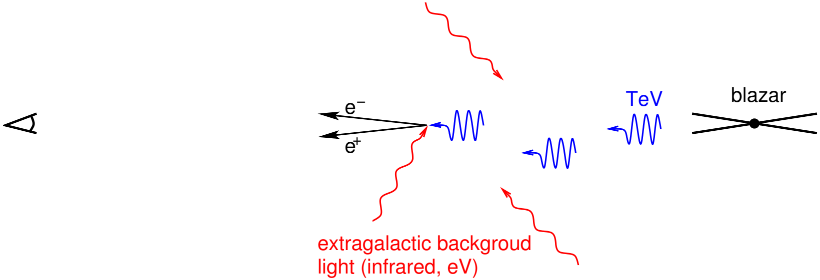
The TeV gamma-ray sky

There are several classes of TeV sources:

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

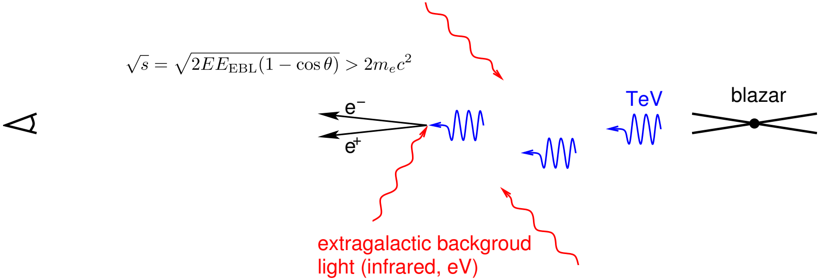


Annihilation and pair production



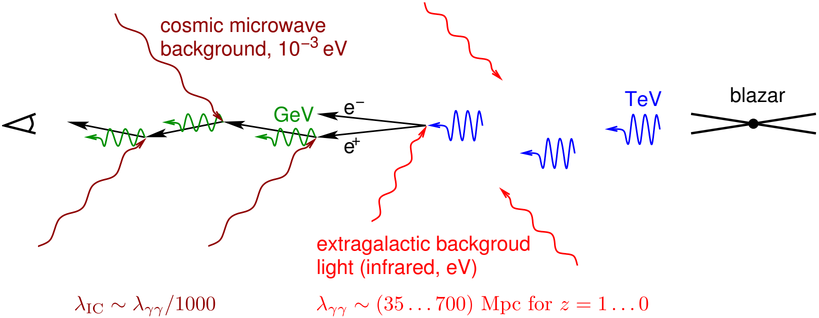
Annihilation and pair production

$$\sqrt{s} = \sqrt{2EE_{\mathrm{EBL}}(1-\cos\theta)} > 2m_e c^2$$

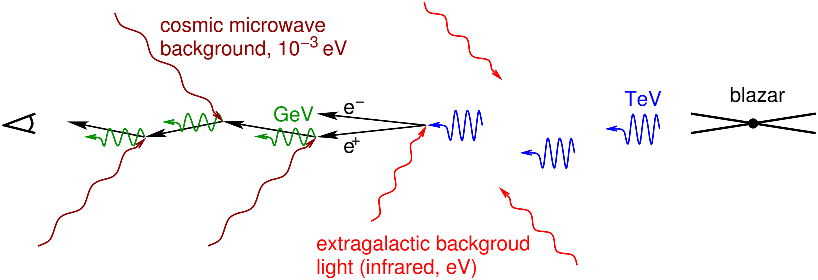


$\lambda_{\gamma\gamma} \sim (35\ldots700)$ Mpc for $z = 1\ldots0$

Inverse Compton cascades



Inverse Compton cascades

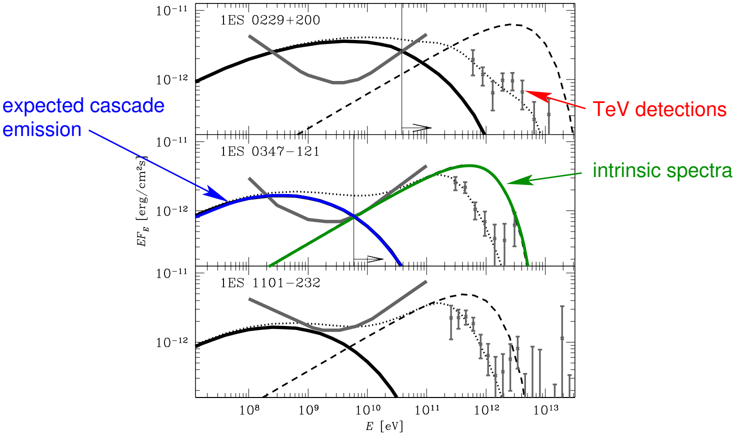


$\lambda_{\rm IC} \sim \lambda_{\gamma\gamma}/1000$ $\qquad$ $\lambda_{\gamma\gamma} \sim (35\ldots700)$ Mpc for $z = 1\ldots0$

$\longrightarrow$ each TeV point source should also be a GeV point source!

What about the cascade emission?

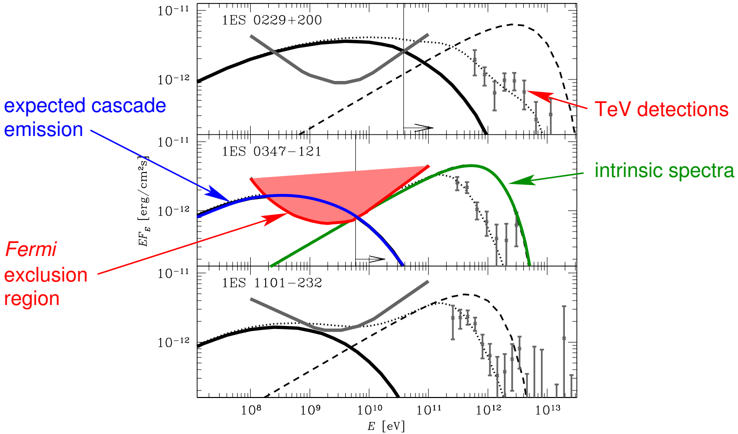
Every TeV source should be associated with a 1-100 GeV gamma-ray halo



Neronov & Vovk (2010)

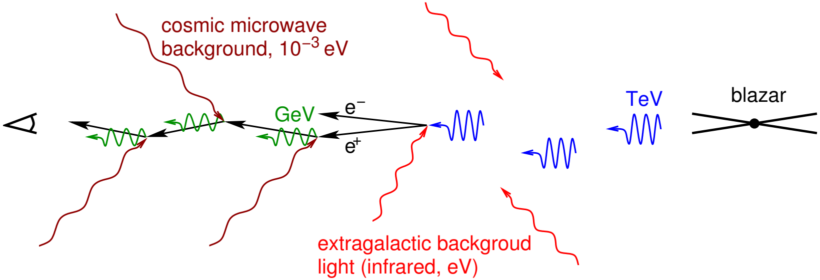
What about the cascade emission?

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



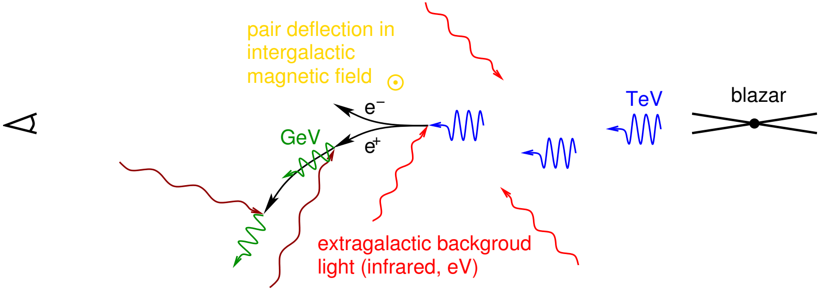
Neronov & Vovk (2010)

Inverse Compton cascades

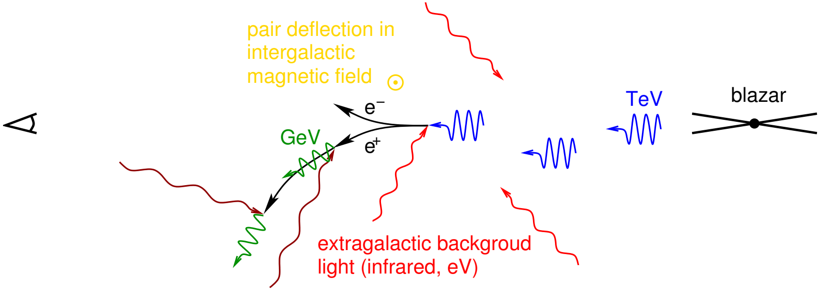


$\lambda_{\mathrm{IC}} \sim \lambda_{\gamma\gamma}/1000$ $\lambda_{\gamma\gamma} \sim (35 \ldots 700)$ Mpc for $z = 1 \ldots 0$

Extragalactic magnetic fields?

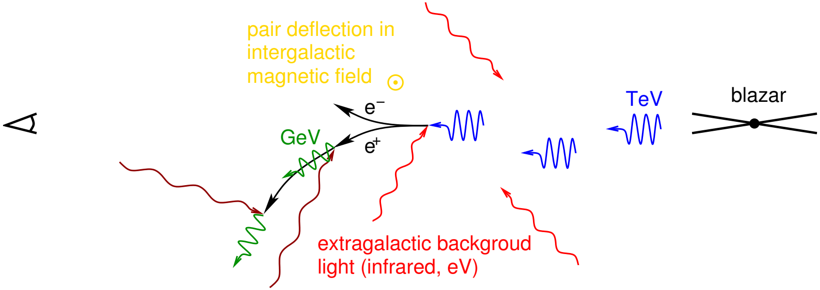


Extragalactic magnetic fields?



- GeV point source diluted $\longrightarrow$ weak "pair halo"
- stronger B–field implies more deflection and dilution,
  gamma–ray non–detection $\longrightarrow$ $B \gtrsim 10^{-16}\,\mathrm{G}$ – 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 other–wise, extragalactic GeV background would be overproduced!

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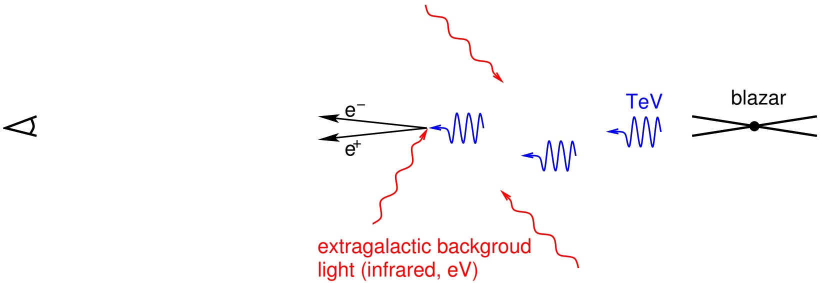
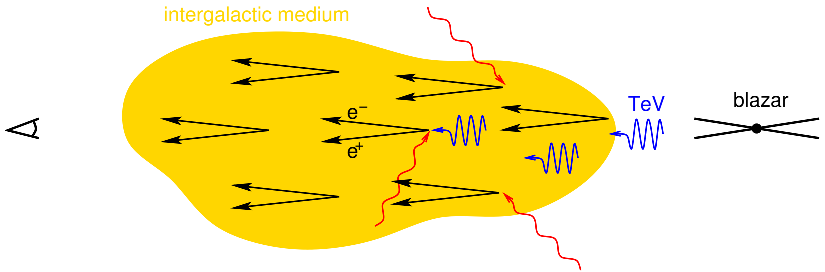
What else could happen?



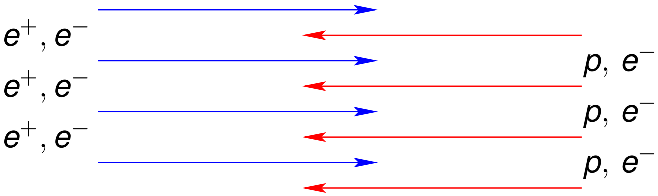
Plasma instabilities



→ pair plasma beam propagating through the intergalactic medium

Plasma instabilities

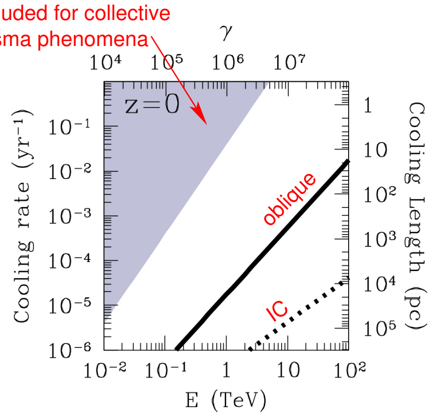
- pair beam intergalactic medium (IGM)



- this configuration is unstable to plasma instabilities
- characteristic frequency and length scale of the problem:

$$\omega_p = \sqrt{\frac{4\pi e^2 n_e}{m_e}}, \qquad \lambda_p = \frac{c}{\omega_p}\bigg|_{\bar{\rho}(z=0)} \sim 10^8\,\mathrm{cm}$$

Beam physics – growth rates



Broderick, Chang, CP (2012), also Schlickeiser+ (2012)

- consider a light beam penetrating into relatively dense plasma
- maximum growth rate

$$\Gamma \simeq 0.4\,\gamma\,\frac{n_{\mathrm{beam}}}{n_{\mathrm{IGM}}}\,\omega_p$$

- 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

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

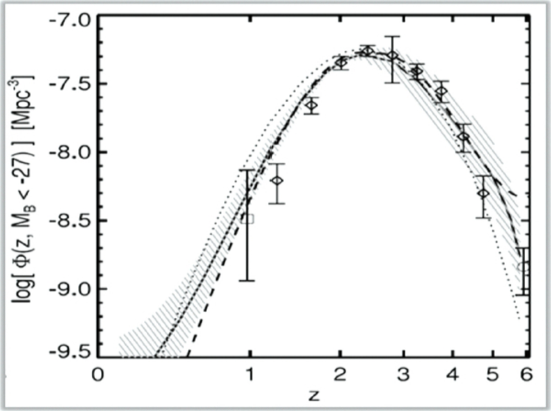
absence of γ_{GeV}'s has significant implications for ...

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

How many TeV blazars are there?

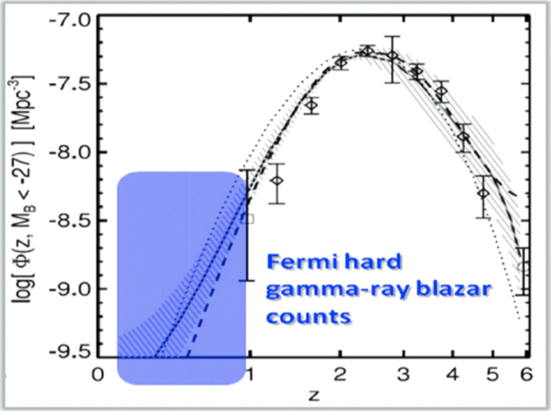
→ use all-sky survey of the GeV gamma-ray sky: *Fermi* gamma-ray space telescope

How many TeV blazars are there?



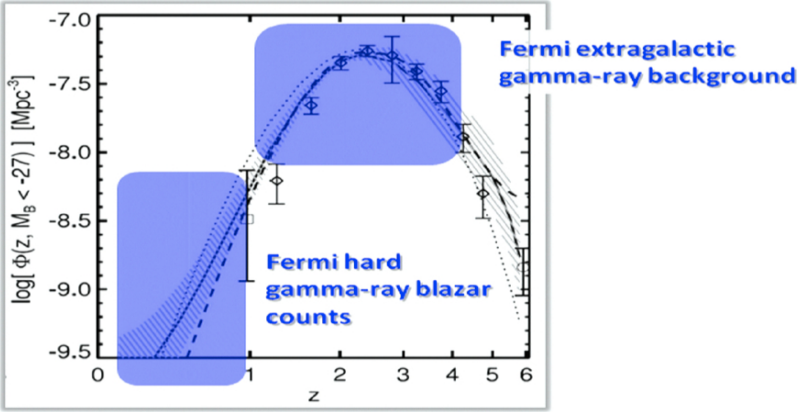
Hopkins+ (2007)

How many TeV blazars are there?



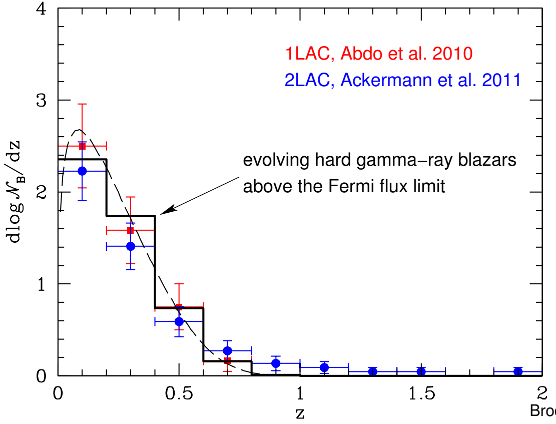
Hopkins+ (2007)

How many TeV blazars are there?



Hopkins+ (2007)

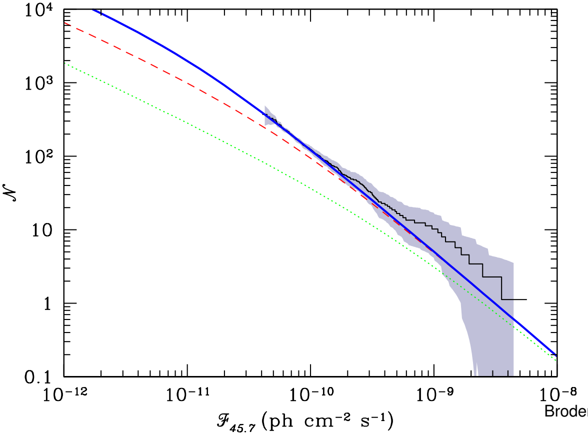
Redshift distribution of *Fermi* hard γ-ray blazars



Broderick, CP+ (2013)

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

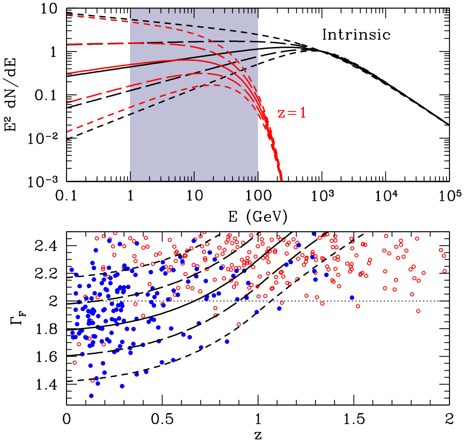
$\log \mathcal{N} - \log S$ distribution of *Fermi* hard γ-ray blazars



Broderick, CP+ (2013)

→ predicted and observed flux distributions of hard *Fermi* blazars between 10 GeV and 500 GeV are indistinguishable!

TeV photon absorption by pair production

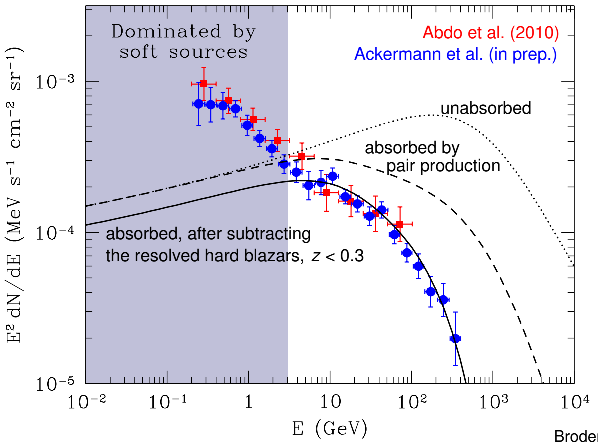


Broderick, CP+ (2013)

intrinsic and observed SEDs of blazars at $z = 1$
$\rightarrow$ γ-ray attenuation by annihilation and pair producing on the EBL

inferred spectral index Γ_F for the spectra in the top panel; overlay of *Fermi* data on BL Lacs and non-BL Lacs (mostly FSRQs)

Extragalactic gamma-ray background



Broderick, CP+ (2013)

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

TeV emission from blazars – a new paradigm

$$\gamma_{\mathrm{TeV}} + \gamma_{\mathrm{eV}} \;\rightarrow\; e^{+} + e^{-} \;\rightarrow\; \begin{cases} \text{inv. Compton cascades} & \rightarrow \quad \gamma_{\mathrm{GeV}} \\ \text{plasma instabilities} & \rightarrow \quad \text{IGM heating} \end{cases}$$

absence of γ_{GeV}'s has significant implications for ...

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

additional IGM heating has significant implications for ...

- thermal history of the IGM: Lyman-α forest
- late-time formation of dwarf galaxies

Blazar heating vs. photoheating

- total power from AGN/stars vastly exceeds the TeV power of blazars
- $T_{\mathrm{IGM}} \sim 10^4$ K (1 eV) at mean density ($z \sim 2$)

$$\varepsilon_{\mathrm{th}} = \frac{kT}{m_{\mathrm{p}} c^2} \sim 10^{-9}$$

- radiative energy ratio emitted by BHs in the Universe (Fukugita & Peebles 2004)

$$\varepsilon_{\mathrm{rad}} = \eta\, \Omega_{\mathrm{bh}} \sim 0.1 \times 10^{-4} \sim 10^{-5}$$

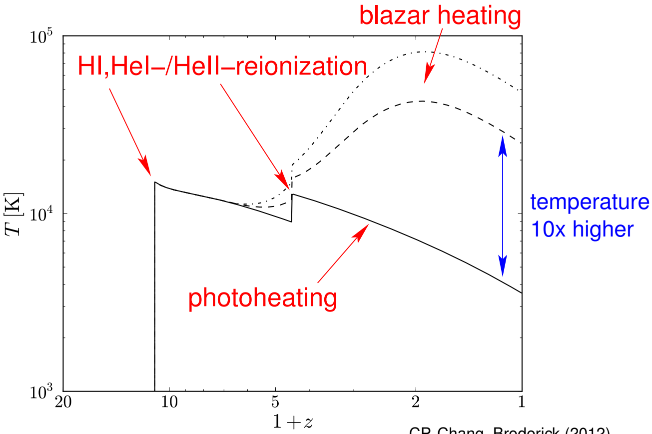
- fraction of the energy energetic enough to ionize H I is ~ 0.1:

$$\varepsilon_{\mathrm{UV}} \sim 0.1 \varepsilon_{\mathrm{rad}} \sim 10^{-6} \quad \rightarrow \quad kT \sim \mathrm{keV}$$

- photoheating efficiency $\eta_{\mathrm{ph}} \sim 10^{-3} \quad \rightarrow \quad kT \sim \eta_{\mathrm{ph}}\, \varepsilon_{\mathrm{UV}}\, m_{\mathrm{p}} c^2 \sim \mathrm{eV}$
  (limited by the abundance of H I/He II due to the small recombination rate)
- blazar heating efficiency $\eta_{\mathrm{bh}} \sim 10^{-3} \quad \rightarrow \quad kT \sim \eta_{\mathrm{bh}}\, \varepsilon_{\mathrm{rad}}\, m_{\mathrm{p}} c^2 \sim 10\,\mathrm{eV}$
  (limited by the total power of TeV sources)

AIP

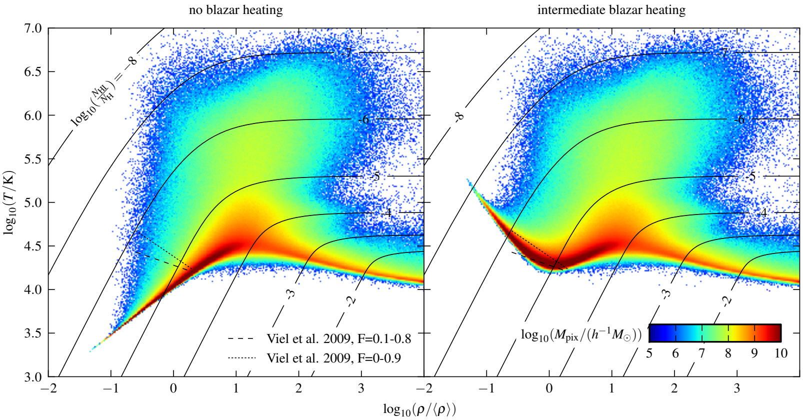
Thermal history of the IGM



CP, Chang, Broderick (2012)

→ increased temperature at **mean** density!

Temperature-density relation



Puchwein, CP, Springel, Broderick, Chang (2012)

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
- dramatically alters thermal history of the IGM:
  - uniform and z-dependent preheating
  - no clear sign in Lyman-α forest at $z > 2$
- only modifies late-time structure formation:
  - suppresses late dwarf formation
  - void phenomenon (?)

Literature for the talk

- Broderick, Chang, Pfrommer, *The cosmological impact of luminous TeV blazars I: implications of plasma instabilities for the intergalactic magnetic field and extragalactic gamma-ray background*, ApJ, 752, 22, 2012.
- Chang, Broderick, Pfrommer, *The cosmological impact of luminous TeV blazars II: rewriting the thermal history of the intergalactic medium*, ApJ, 752, 23, 2012.
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