The Physics and Cosmology of TeV Blazars

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in collaboration with

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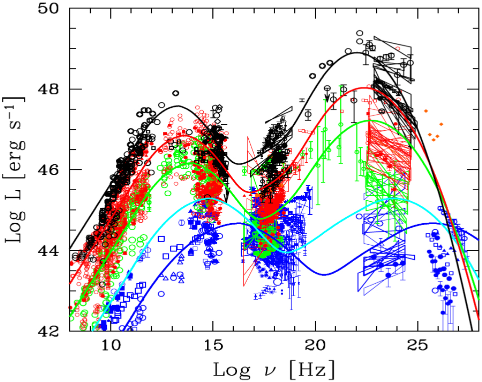
Jul 12, 2012 / Gamma2012 Heidelberg

The blazar sequence



Ghisellini (2011), arXiv:1104.0006

- continuous sequence from LBL–IBL–HBL
- TeV blazars are dim (very sub-Eddington)
- TeV blazars have rising spectra in the Fermi band ($\alpha < 2$)
- define TeV blazar = hard IBL + HBL

Propagation of TeV photons

- 1 TeV photons can pair produce with 1 eV EBL photons:

$$\gamma_{\text{TeV}} + \gamma_{\text{eV}} \rightarrow e^+ + e^-$$

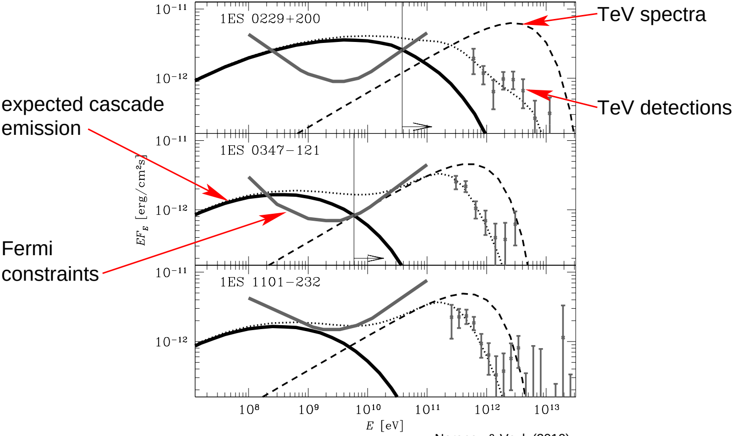
- mean free path for this depends on the density of 1 eV photons:
  $\rightarrow \lambda_{\gamma\gamma} \sim (35 \ldots 700)$ Mpc for $z = 1 \ldots 0$
  $\rightarrow$ pairs produced with energy of 0.5 TeV ($\gamma = 10^6$)
- these pairs inverse Compton scatter off the CMB photons:
  $\rightarrow$ mean free path is $\lambda_{\text{IC}} \sim \lambda_{\gamma\gamma}/1000$
  $\rightarrow$ 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!** → **limits on extragalactic magnetic fields?**

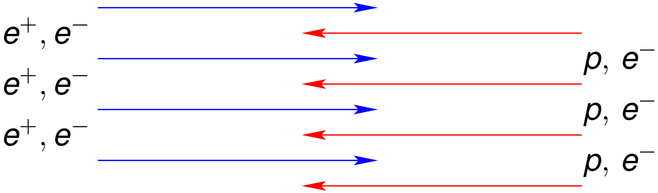


Neronov & Vovk (2010)

Missing plasma physics?

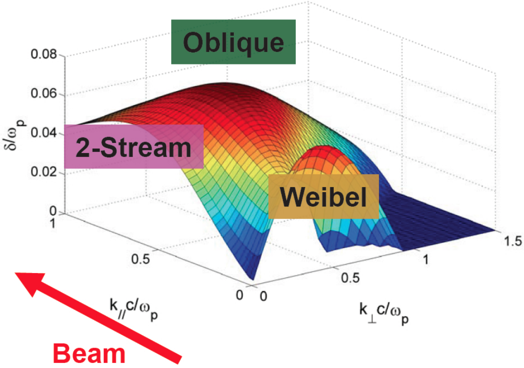
How do beams of e^+/e^- propagate through the IGM?

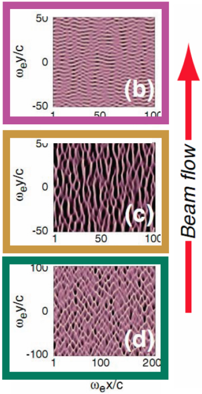
- plasma processes are important
- interpenetrating beams of charged particles are unstable



Oblique instability

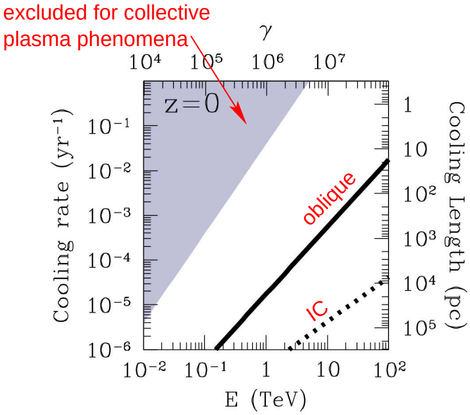
k oblique to $\boldsymbol{v}_{\rm beam}$: real word perturbations don't choose "easy" alignment $= \sum$ all orientations





Bret (2009), Bret+ (2010)

Beam physics – growth rates



Broderick, Chang, C.P. (2012)

- 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 factor 10-100
- **assume** that instability grows at linear rate up to saturation

TeV emission from blazars – a new paradigm

$$\gamma_{\rm TeV} + \gamma_{\rm eV} \;\rightarrow\; e^+ + e^- \;\rightarrow\; \begin{cases} \text{IC off CMB} & \rightarrow \;\gamma_{\rm GeV} \\ \text{plasma instabilities} & \rightarrow \;\text{heating IGM} \end{cases}$$

absence of $\gamma_{\rm GeV}$'s has significant implications for ...

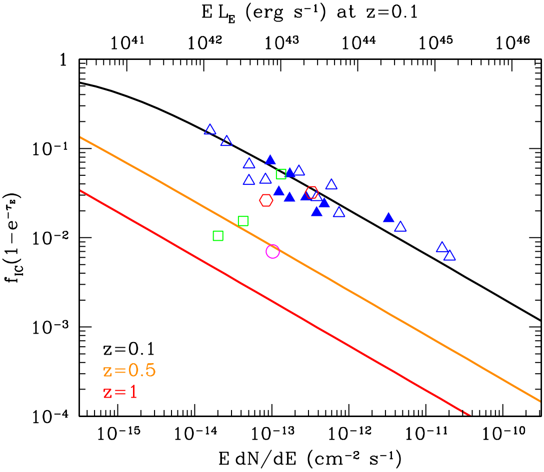
- intergalactic *B*-field estimates
- γ-ray emission from blazars: spectra, background

additional IGM heating has significant implications for ...

- thermal history of the IGM: Lyman-α forest
- late time structure formation: dwarfs, galaxy clusters

Implications for *B*-field measurements

Fraction of the pair energy lost to inverse-Compton on the CMB: $f_{\rm IC} = \Gamma_{\rm IC}/(\Gamma_{\rm IC} + \Gamma_{\rm oblique})$



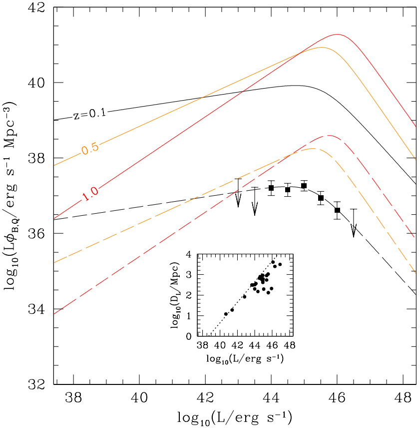
Broderick, Chang, C.P. (2012)

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 may 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 at linear rate)!**

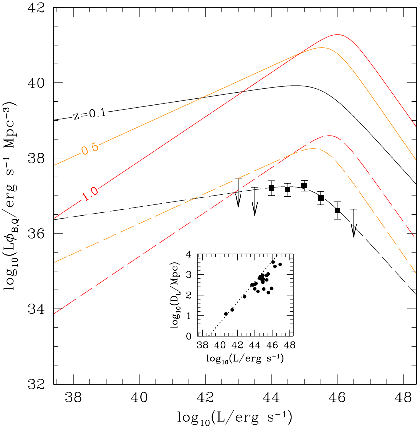
TeV blazar luminosity density: today



Broderick, Chang, C.P. (2012)

- 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!

Unified TeV blazar-quasar model



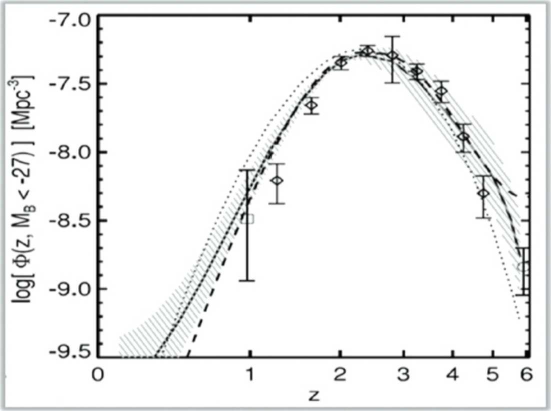
Broderick, Chang, C.P. (2012)

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?



Hopkins+ (2007)

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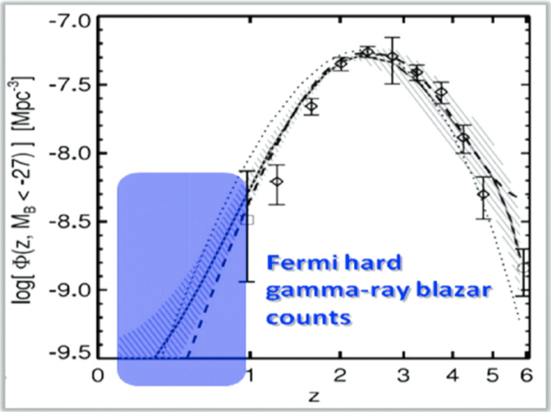

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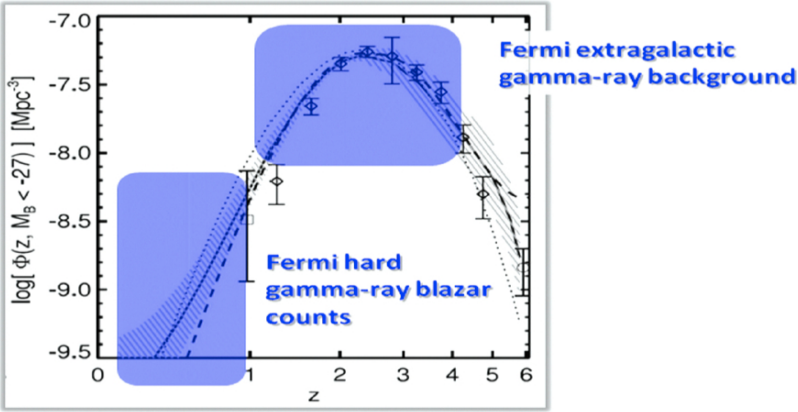
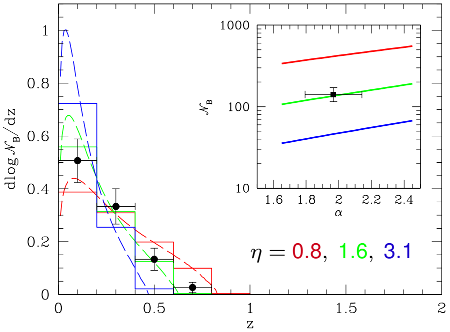


Hopkins+ (2007)

Fermi number count of "TeV blazars"



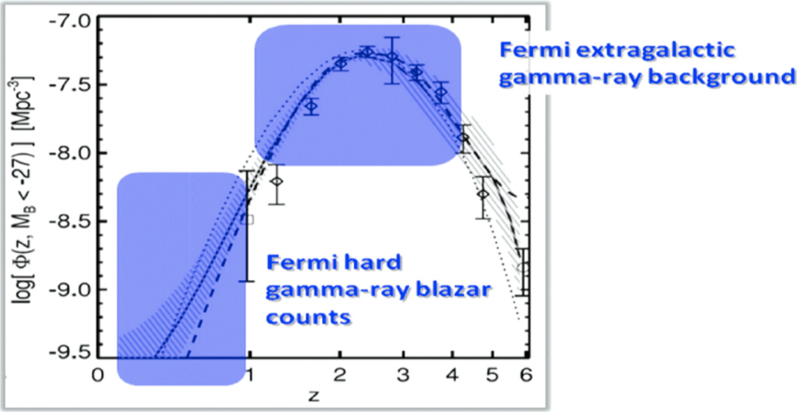
Broderick, Chang, C.P. (2012)

- TeV blazar evolution: model vs. *Fermi* number counts
- colors: different flux (luminosity) limits connecting the *Fermi* and the TeV band:

$$L_{\mathrm{TeV,min}}(z) = \eta\, L_{\mathrm{Fermi,min}}(z)$$

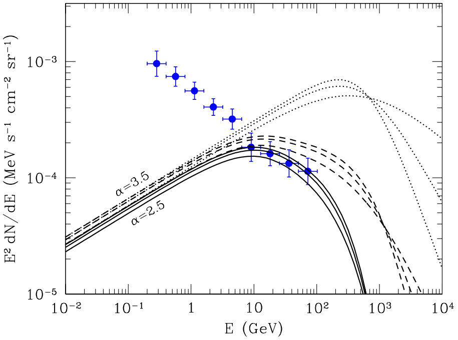
→ **evolving (increasing) blazar population consistent with observed declining evolution (*Fermi* flux limit)!**

How many TeV blazars are there at high-z?



Hopkins+ (2007)

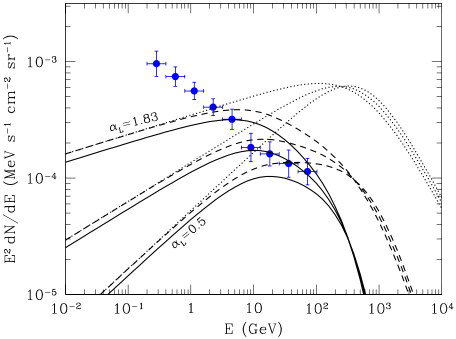
Extragalactic gamma-ray background: varying α



Broderick, Chang, C.P. (2012)

- *dotted:* unabsorbed EGRB due to TeV blazars
- *dashed:* absorbed EGRB due to TeV blazars
- *solid:* absorbed EGRB, after subtracting the resolved TeV blazars ($z < 0.25$)

Extragalactic gamma-ray background: varying α_L



Broderick, Chang, C.P. (2012)

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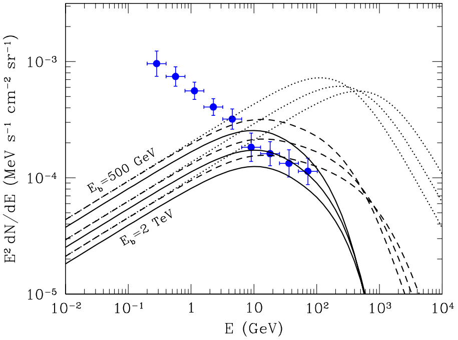
Extragalactic gamma-ray background: varying E_b



Broderick, Chang, C.P. (2012)

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Conclusions on blazar heating

- explains puzzles in high-energy 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
  - rate independent of density $\rightarrow$ inverted T–ρ relation
  - quantitative self-consistent picture of high-*z* Lyman-α forest
- significantly modifies late-time structure formation:
  - suppresses late dwarf formation (in accordance with SFHs): "missing satellites", void phenomenon, H I-mass function
  - group/cluster bimodality of core entropy values

Lorentz boosting the pair distribution function

- the beam temperature T is defined by the distribution function:

$$f \sim \exp[-(E - vp_{\|})/kT] \tag{1}$$

  E, $p_{\|}$, and v are the IGM-frame energy, parallel momentum component, and average beam velocity ($c = 1$)

- the pair-frame pair energies (E') are related to that in the IGM frame (E) by the standard Lorentz transformation:

$$E' = \gamma(E - vp) \quad \rightarrow \quad E - vp = E'/\gamma \tag{2}$$

  where $\gamma = 1/\sqrt{1 - v^2} \sim 10^6$ (for pairs with $E \sim$ TeV)

- since the distribution function is a Lorentz scalar (due to the invariance of the phase space volume element), eq. (1) implies that in the pair frame the distribution function is given by

$$f \sim \exp(-E'/\gamma kT) \equiv \exp(-E'/kT') \rightarrow kT \sim kT'/\gamma \sim \text{eV}, \tag{3}$$

  where $T' = \gamma T$ is the pair temperature in the pair frame