Blazar heating: physical mechanism and cosmological consequences

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in collaboration with

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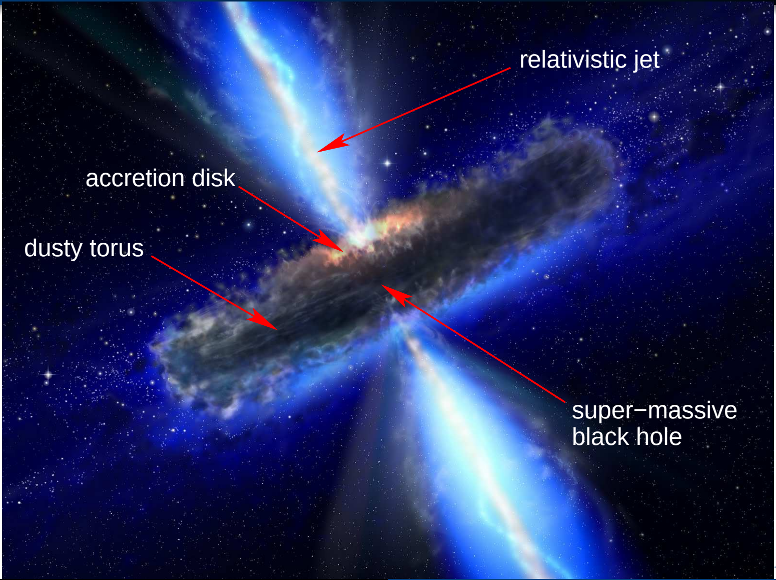
Outline

1. The physics of blazar heating
   - Introduction and motivation
   - Propagation of TeV photons
   - Plasma instabilities

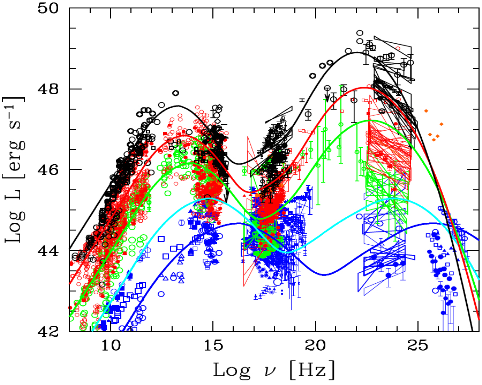
2. Cosmological consequences
   - Unifying blazars and quasars
   - The intergalactic medium
   - Formation of dwarf galaxies

Outline

Unified model of active galactic nuclei



The blazar sequence



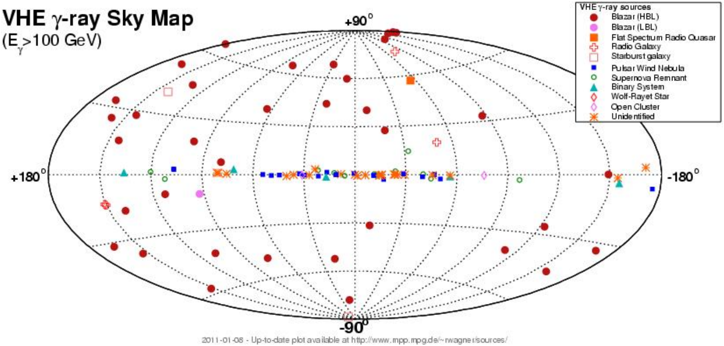
Ghisellini (2011), arXiv:1104.0006

- 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

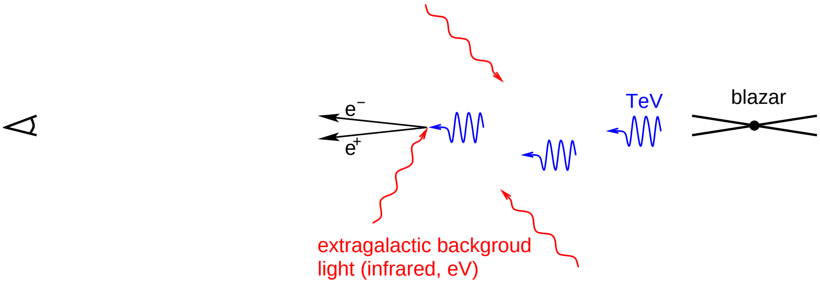
The TeV gamma-ray sky

There are several classes of TeV sources:

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



Annihilation and pair production



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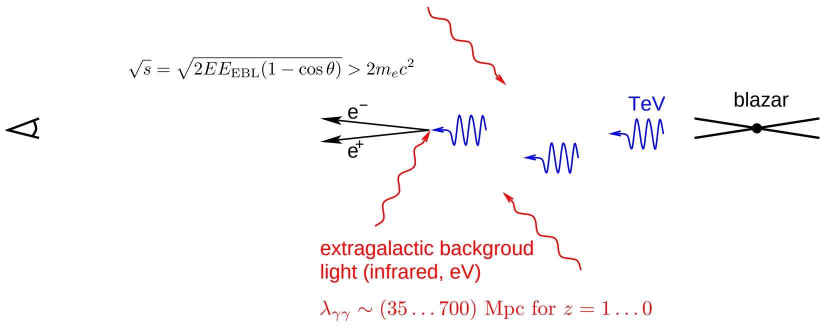
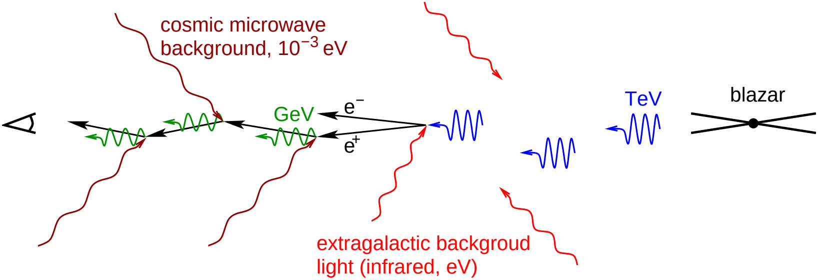


Inverse Compton cascades



$\lambda_{\mathrm{IC}} \sim \lambda_{\gamma\gamma}/1000$

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

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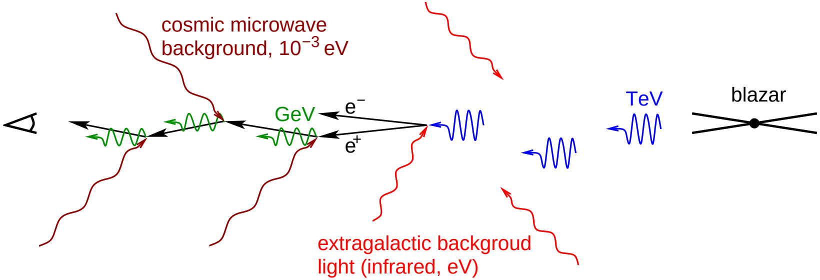
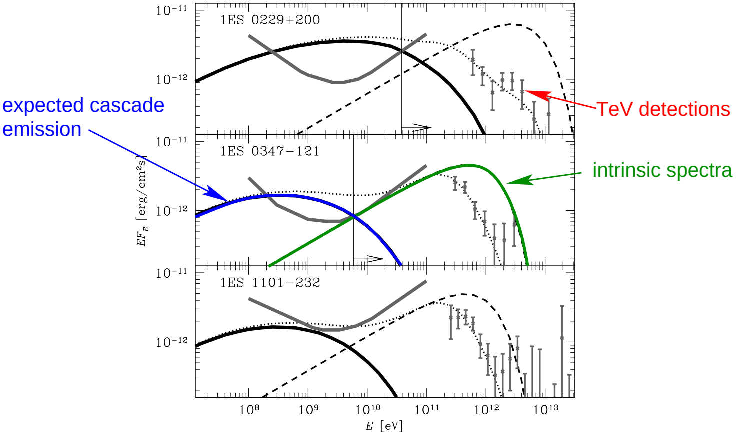


$\lambda_{\rm IC} \sim \lambda_{\gamma\gamma}/1000$ $\quad$ $\lambda_{\gamma\gamma} \sim (35\ldots700)$ Mpc for $z = 1\ldots0$

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

What about the cascade emission?

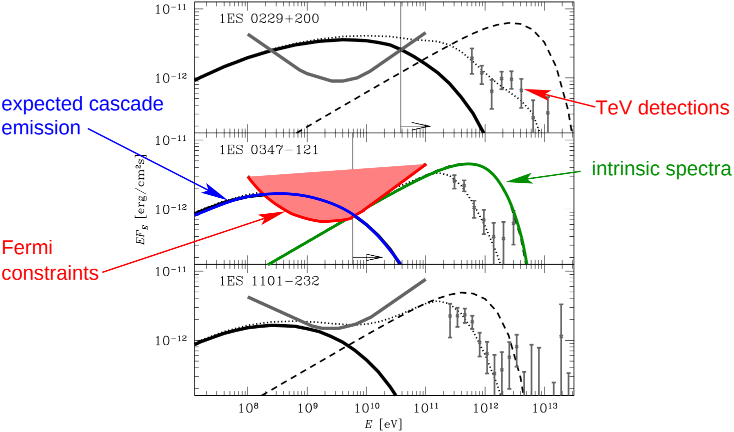
Every TeV source should be associated with a 1-100 GeV gamma-ray halo



Neronov & Vovk (2010)

What about the cascade emission?

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



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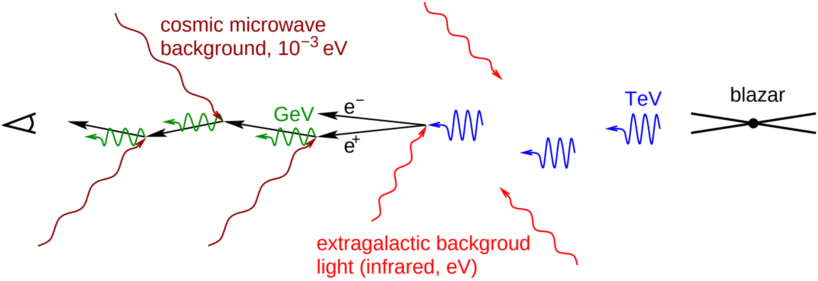

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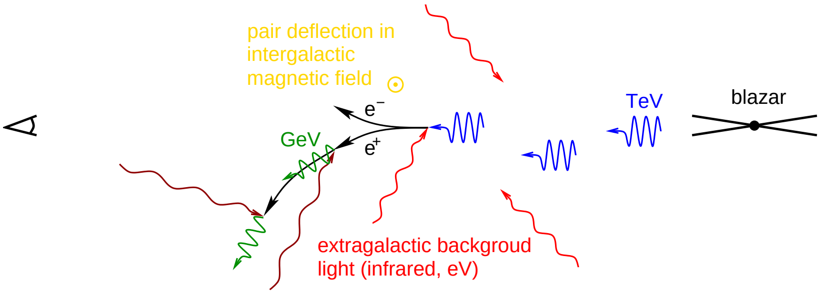
Magnetic field deflection



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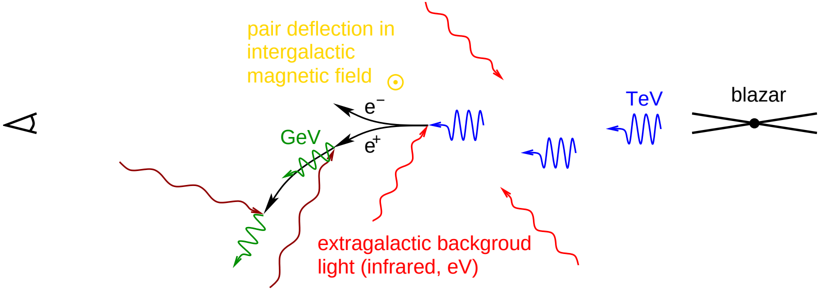
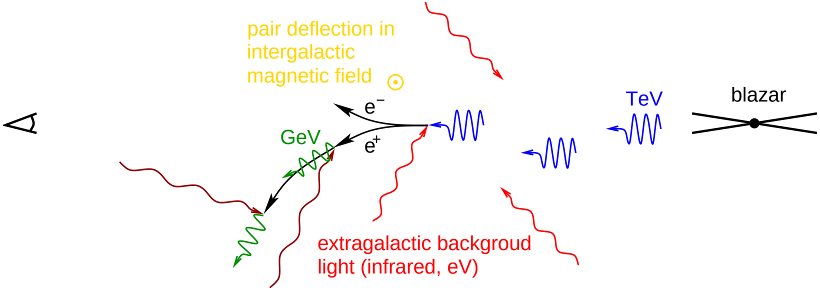


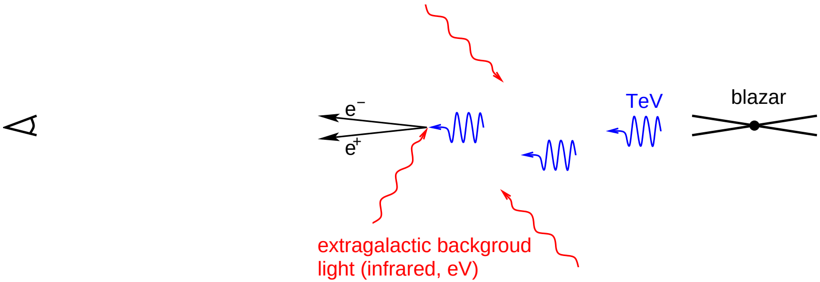
- GeV point source diluted ⟶ weak "pair halo"
- stronger B−field implies more deflection and dilution,
  gamma−ray non−detection ⟶ $B \gtrsim 10^{-16}\,\mu\mathrm{G}$ − primordial fields?

Magnetic field deflection

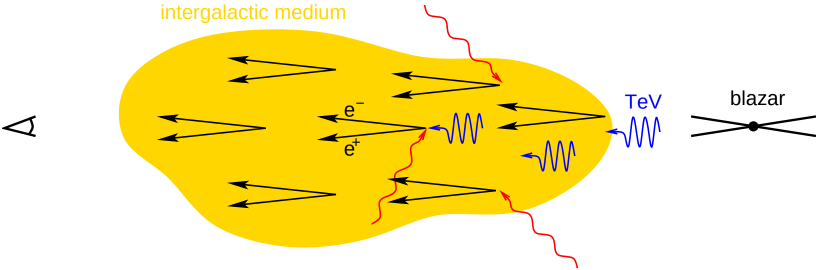


- problem for unified AGN model: blazars and quasars apparently do not share the same cosmological evolution (as otherwise, evolving blazars would overproduce the gamma−ray background)!

What else could happen?



Plasma beam instabilities

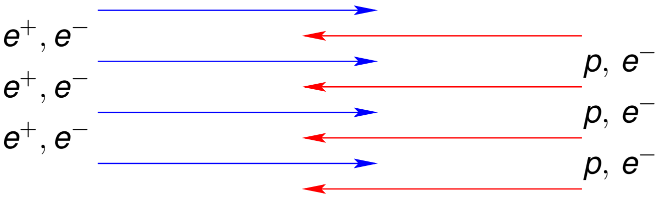


→ pair plasma beam propagating through the intergalactic medium

Interlude: plasma physics

How do e^+/e^- beams propagate through the intergalactic medium (IGM)?

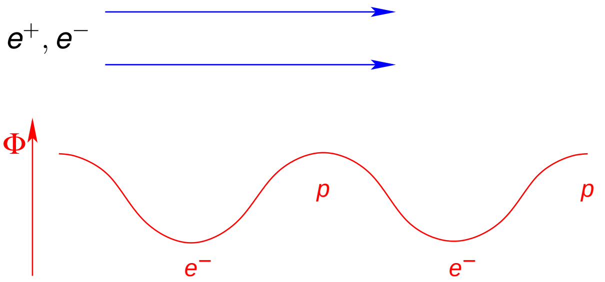
- interpenetrating beams of charged particles are unstable to plasma instabilities
- consider the two-stream instability:



Two-stream instability: mechanism

consider wave-like perturbation in background plasma along the beam direction (Langmuir wave):

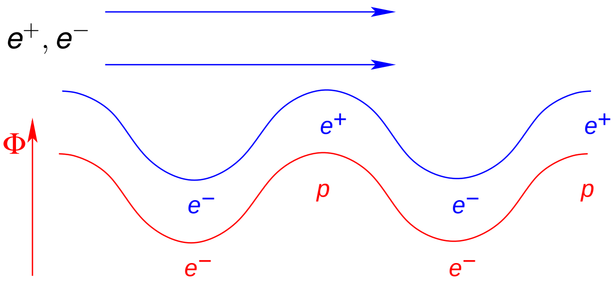
- initially homogeneous beam-e^-:
  attractive (repulsive) force by potential maxima (minima)
- e^- attain lowest velocity in potential minima $\rightarrow$ bunching up
- e^+ attain lowest velocity in potential maxima $\rightarrow$ bunching up



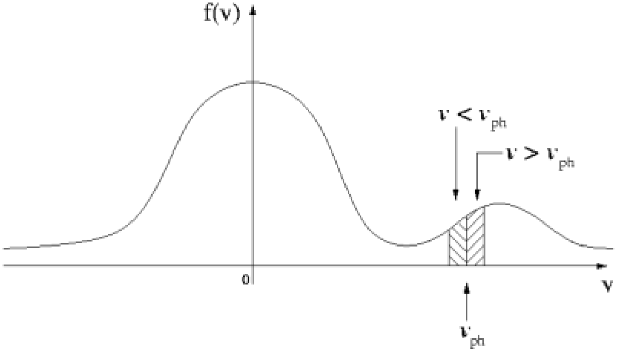
Two-stream instability: mechanism

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^- $\rightarrow$ positive feedback
- exponential wave-growth $\rightarrow$ instability



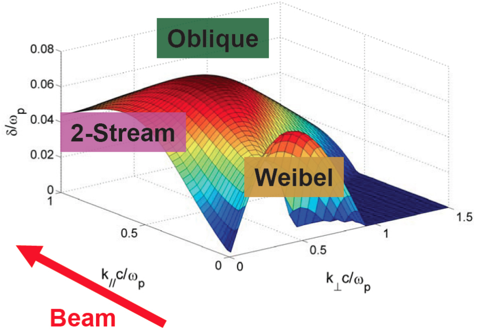
Two-stream instability: momentum transfer

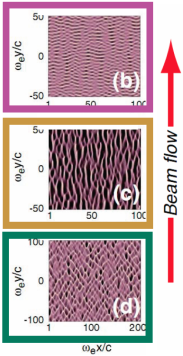


- particles with $v \gtrsim v_{\text{phase}}$:
  pair momentum → plasma waves → growing modes: instability
- particles with $v \lesssim v_{\text{phase}}$:
  plasma wave momentum → pairs → Landau damping

Oblique instability

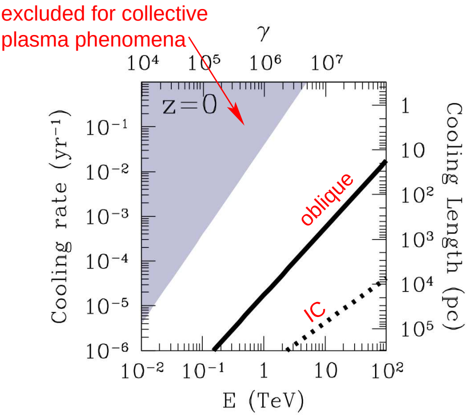
- $\boldsymbol{k}$ oblique to $\boldsymbol{v}_{\rm beam}$: real word perturbations don't choose "easy" alignment $= \sum$ all orientations
- oblique grows faster than two-stream: E-fields can easier deflect ultra-relativistic particles than change their parallel velocities
(Nakar, Bret & Milosavljevic 2011)





Bret (2009), Bret+ (2010)

Beam physics – growth rates



Broderick, Chang, C.P. (2012), also Schlickeiser+ (2012)

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

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

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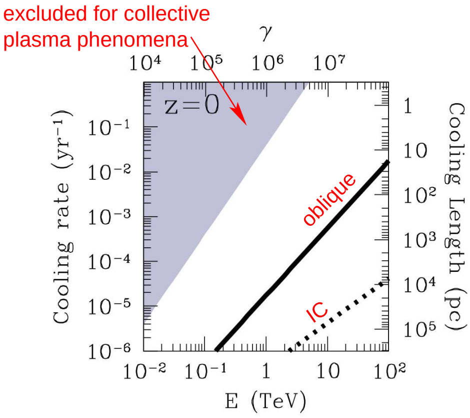

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- oblique instability beats inverse Compton cooling by factor 10-100
- **assume** that instability grows at linear rate up to saturation

Outline

TeV emission from blazars – a new paradigm

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

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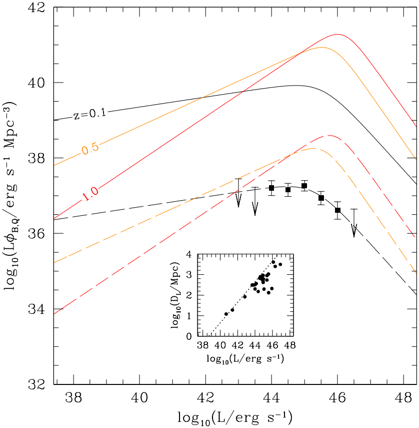
absence of γ_{GeV}'s has significant implications for ...

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

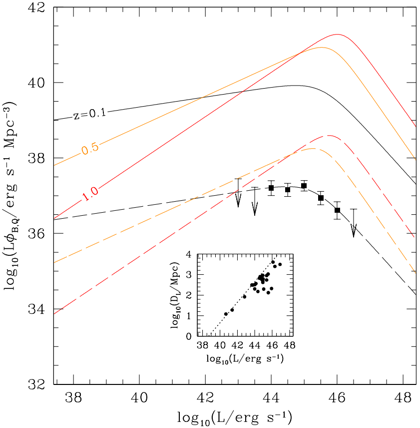
TeV blazar luminosity density: today



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



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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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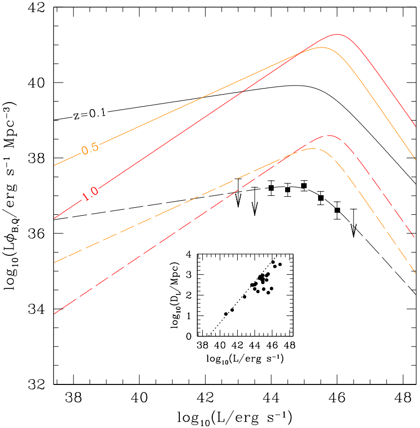

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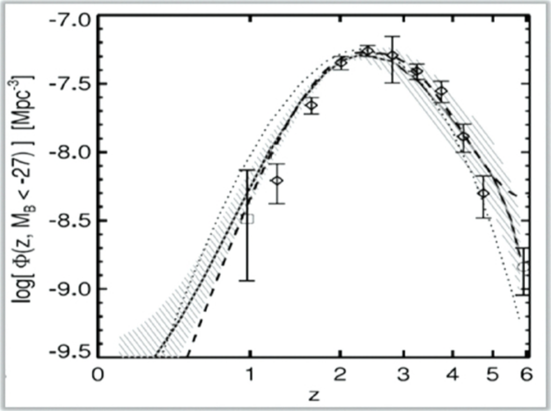
→ **assume that they trace each other for all redshifts!**

How many TeV blazars are there?



Hopkins+ (2007)

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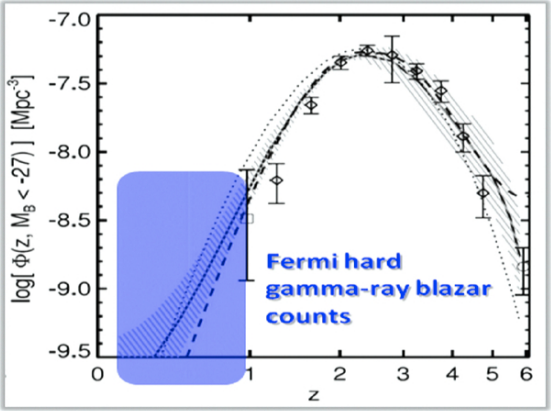

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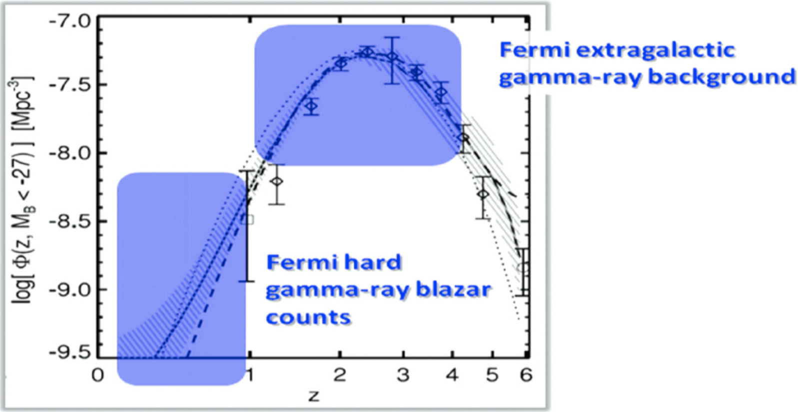

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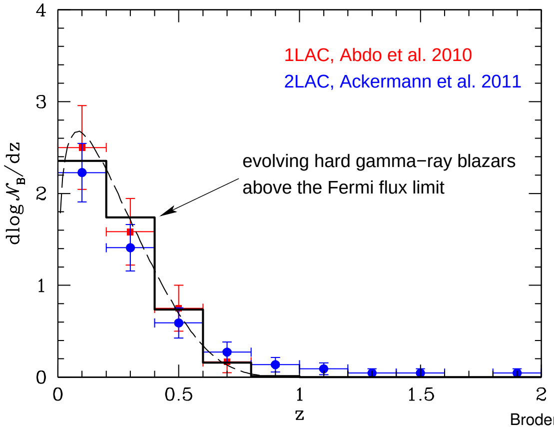
Redshift distribution of *Fermi* hard γ-ray blazars



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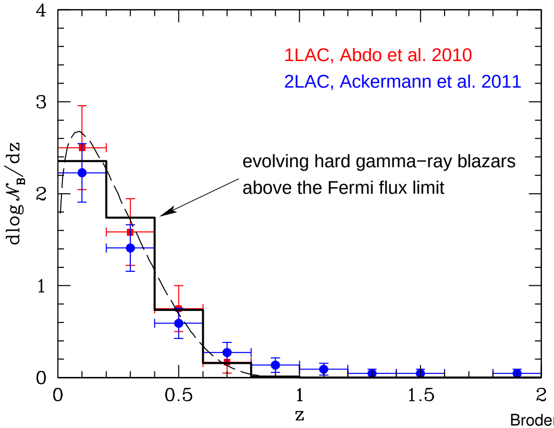

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→ evolving (increasing) blazar population consistent with observed declining evolution (*Fermi* flux limit)!

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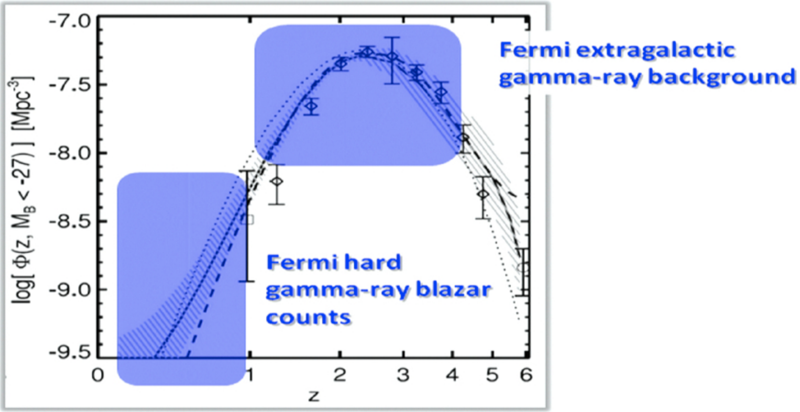


Hopkins+ (2007)

Extragalactic gamma-ray background

- intrinsic spectrum for a TeV blazar:

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

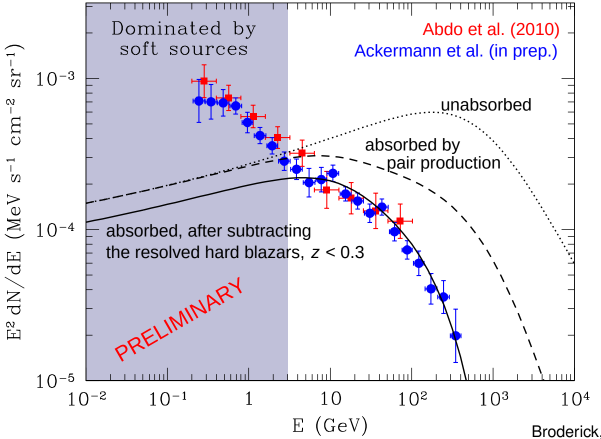
$E_b = 1$ TeV is break energy, $\Gamma_h = 3$ is high-energy spectral index,
Γ_l related to Γ_F, which is drawn from observed distribution

- extragalactic gamma-ray background (EGRB):

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

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

Extragalactic gamma-ray background



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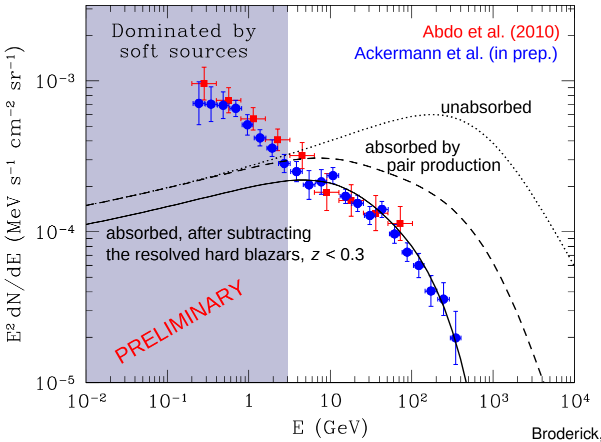
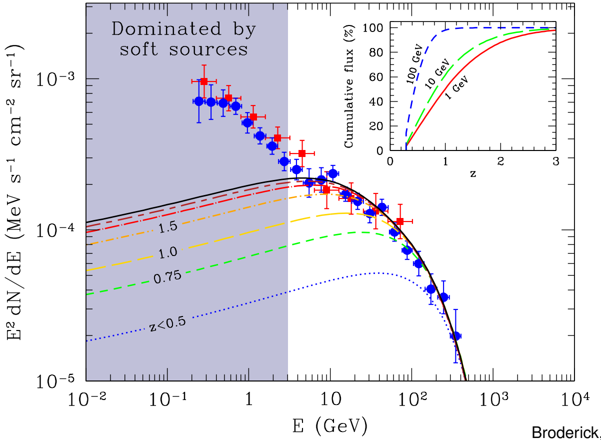


Broderick, C.P.+ (in prep.)

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

Extragalactic gamma-ray background



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→ **the signal at 10 (100) GeV is dominated by redshifts $z \sim 1$** ($z \sim 0.8$)

TeV emission from blazars – a new paradigm

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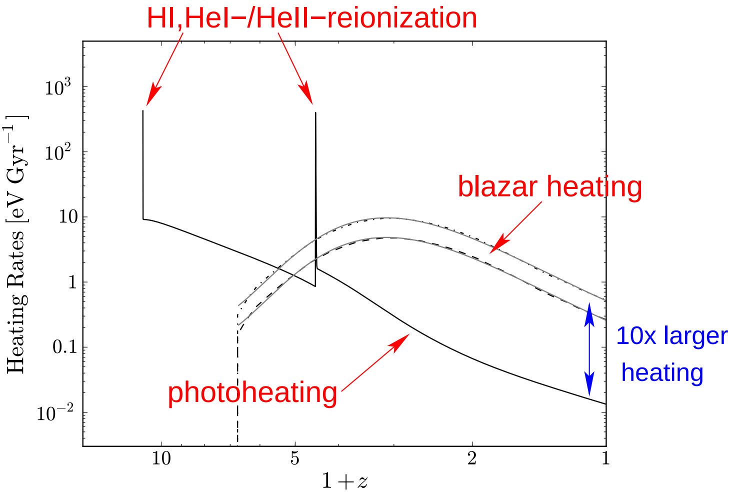
additional IGM heating has significant implications for ...

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

Evolution of the heating rates



Chang, Broderick, C.P. (2012)

Blazar heating vs. photoheating

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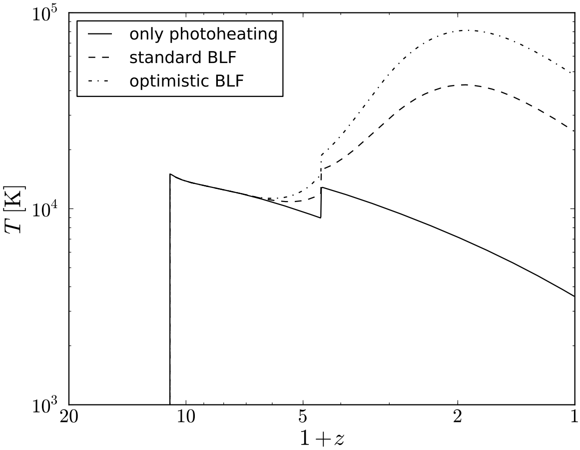
  (limited by the total power of TeV sources)

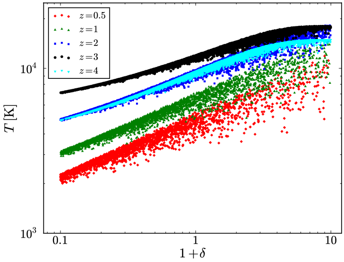
Thermal history of the IGM



C.P., Chang, Broderick (2012)

Evolution of the temperature-density relation

no blazar heating



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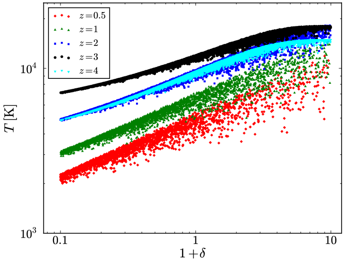

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  $\rightarrow$ blazar heating rate independent of density

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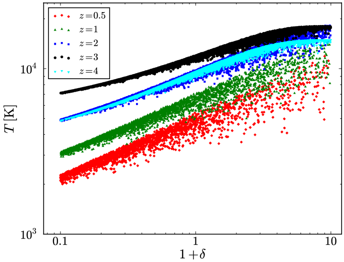

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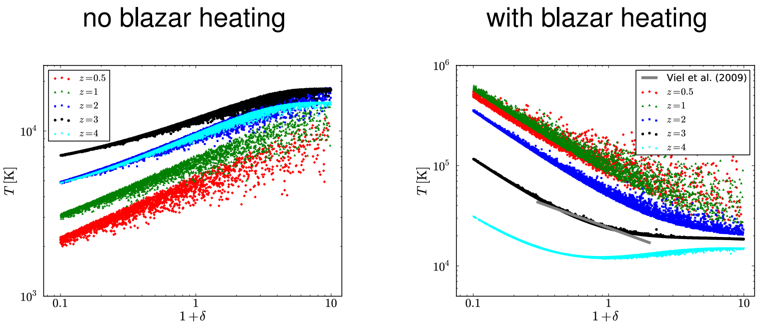
  $\rightarrow$ makes low density regions *hot*
  $\rightarrow$ causes inverted temperature-density relation, $T \propto 1/\delta$

Evolution of the temperature-density relation



Chang, Broderick, C.P. (2012)

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Blazars cause hot voids

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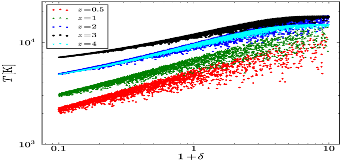
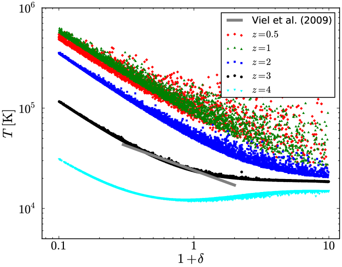


with blazar heating



Chang, Broderick, C.P. (2012)

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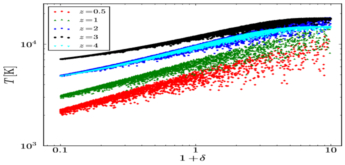
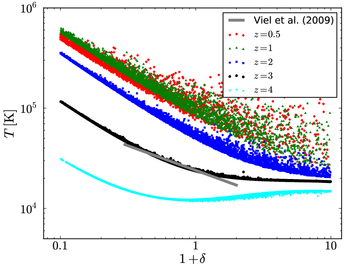


with blazar heating

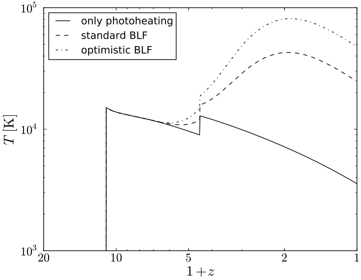


Chang, Broderick, C.P. (2012)

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

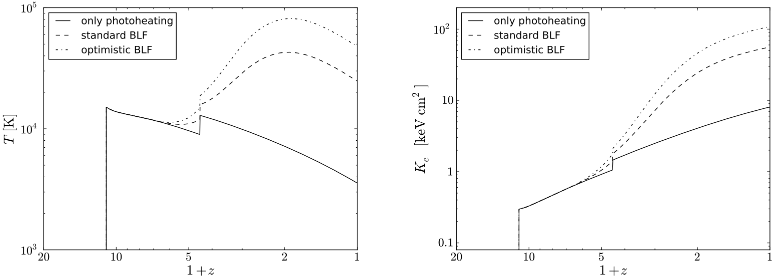
Entropy evolution

temperature evolution



Entropy evolution

temperature evolution | entropy evolution



C.P., Chang, Broderick (2012)

- evolution of entropy, $K_e = kTn_e^{-2/3}$, governs structure formation
- blazar heating: late-time, evolving, modest entropy floor

Dwarf galaxy formation

- thermal pressure opposes gravitational collapse on small scales
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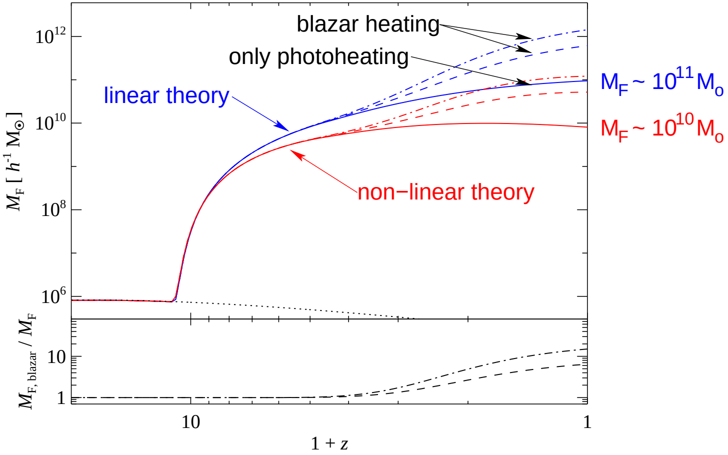
  $\rightarrow$ blazar heating increases M_J by 30 over pure photoheating!
- complications:
  non-linear collapse,
  delayed pressure response in expanding universe $\rightarrow$ concept of "filtering mass"

C.P., Chang, Broderick (2012)

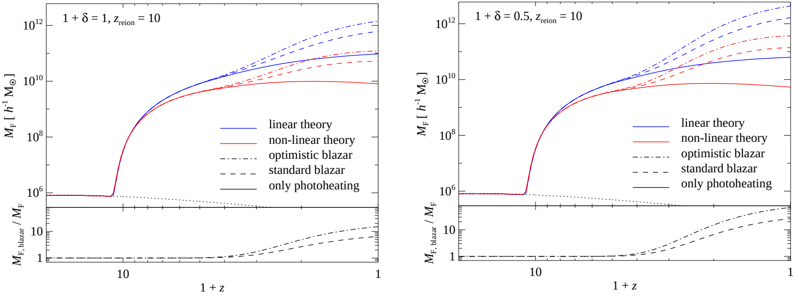
Dwarf galaxy formation – Filtering mass



C.P., Chang, Broderick (2012)

Peebles' void phenomenon explained?

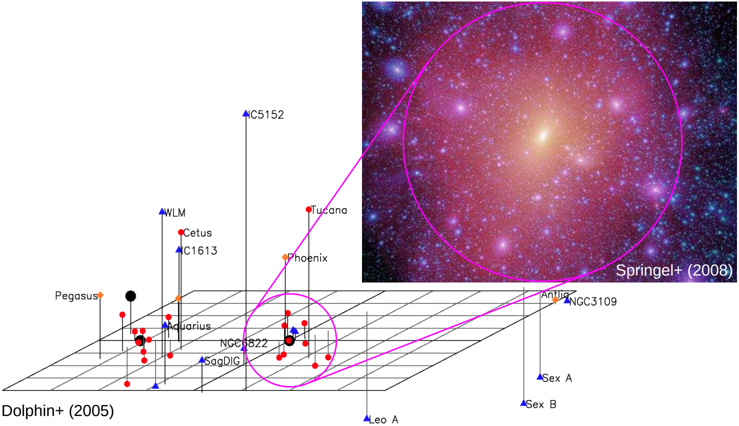
mean density | void, $1 + \delta = 0.5$



C.P., Chang, Broderick (2012)

- blazar heating efficiently suppresses the formation of void dwarfs within existing DM halos of masses $< 3 \times 10^{11}$ $M_\odot$ ($z = 0$)
- may reconcile the number of void dwarfs in simulations and the paucity of those in observations

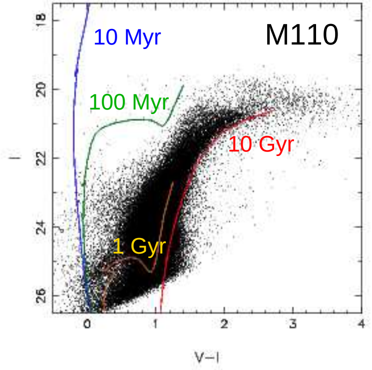
"Missing satellite" problem in the Milky Way



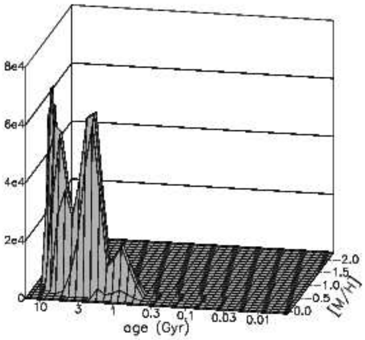
Dolphin+ (2005)

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

When do dwarfs form?

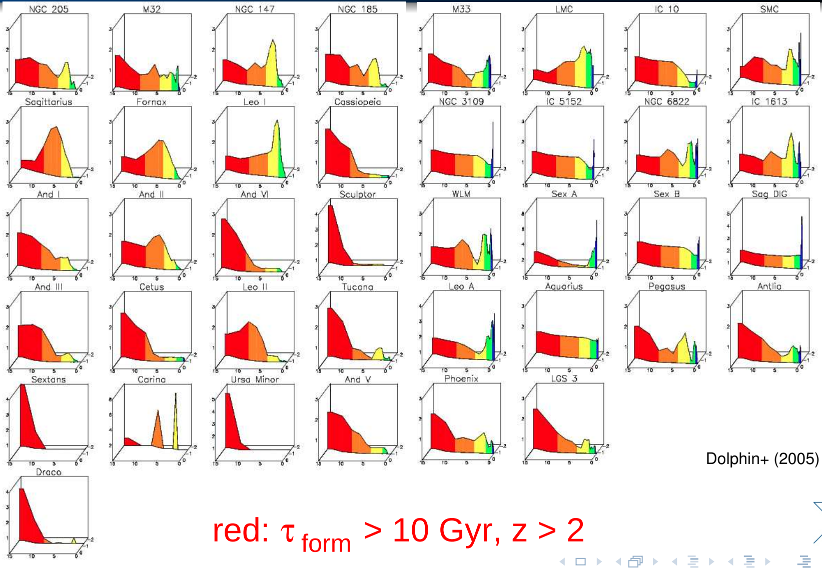


Dolphin+ (2005)



isochrone fitting for different metallicities → star formation histories

When do dwarfs form?

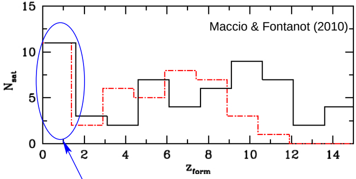


Dolphin+ (2005)

red: $\tau_{\rm form} > 10$ Gyr, $z > 2$

Milky Way satellites: formation history and abundance

satellite formation time



late forming satellites (< 10 Gyr)
not observed!

Milky Way satellites: formation history and abundance

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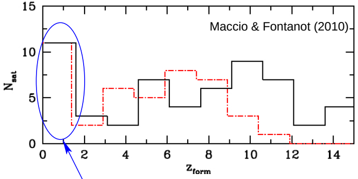
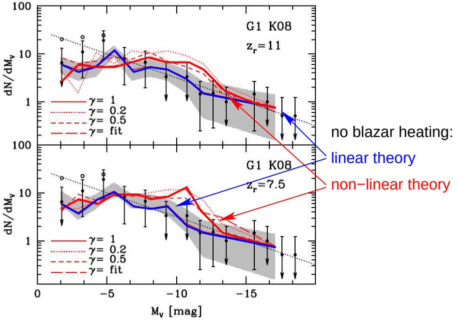


satellite luminosity function

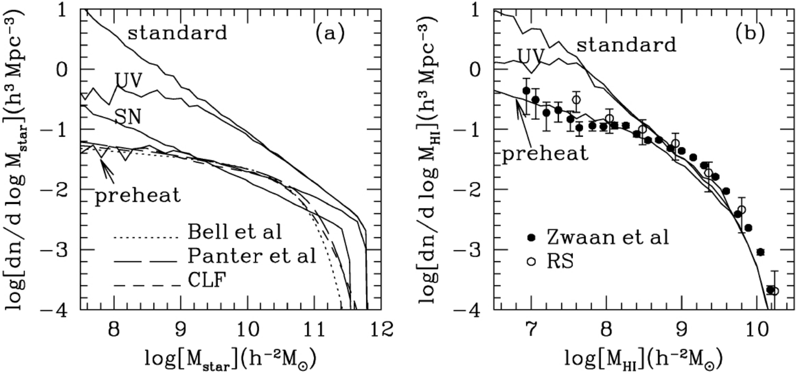


Maccio+ (2010)

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

Galactic H I-mass function

Mo+ (2005)



- 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 $K \sim 15\,\mathrm{keV\,cm}^2$ at $z \sim 2-3$ successful!

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Blazar heating: TeV photons are attenuated by EBL; their kinetic energy → heating of the IGM; it is *not* cascaded to GeV energies

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  - quantitative self-consistent picture of high-z Lyman-α forest
- significantly modifies late-time structure formation:
  - suppresses late dwarf formation (in accordance with SFHs): void phenomenon, "missing satellites" (?)

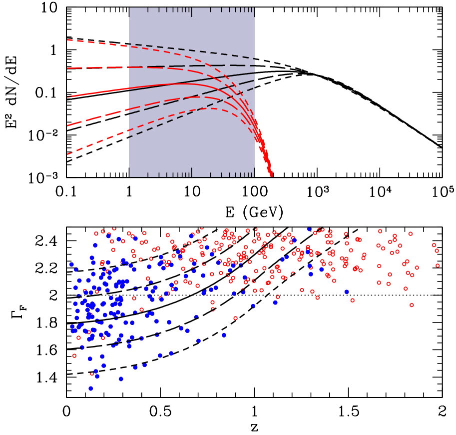
Literature for the talk

- 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.
- Pfrommer, Chang, Broderick, *The cosmological impact of luminous TeV blazars III: implications for galaxy clusters and the formation of dwarf galaxies*, ApJ, 752, 24, 2012.
- Puchwein, Pfrommer, Springel, Broderick, Chang, *The Lyman-α forest in a blazar-heated Universe*, MNRAS, 423, 149, 2012.

Additional slides

TeV photon absorption by pair production

top: intrinsic and observed SEDs of blazars at z = 1;
bottom: inferred Γ_F for the spectra in the top panel;
Fermi data on BL Lacs and non-BL Lacs (mostly FSRQs)



Broderick, C.P.+ (in prep)

Challenges to the Challenge

Challenge #1 (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!

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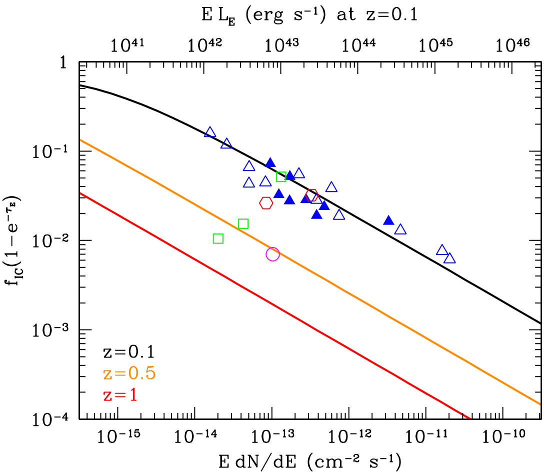
Challenge #2 (known unknowns): **non-linear saturation**

- we assume that the non-linear damping rate = linear growth rate
- effect of wave-particle and wave-wave interactions need to be resolved
- Miniati & Elyiv (2012) claim that the nonlinear Landau damping rate is $\ll$ linear growth rate, but need to scatter waves with $\Delta k/k \sim 50$
- this is in conflict with the theory of induced scattering! (Schlickeiser+ 2012)

Implications for *B*-field measurements

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



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

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