The Plasma Physics and Cosmological Impact of TeV Blazars

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Outline

- Propagation of TeV photons and Cascade Emission
- Plasma instabilities in beams and TeV blazars
- Heating by TeV Blazars - TeV Feedback
- Cosmological Impact of Heating
  - Hotter IGM -- inverted temperature-density profile
  - Suppression of dwarfs -- missing satellite/void phenomenon
- Strong evolution consistent with Fermi observations
- Summary

Broderick, PC, & Pfrommer (2012) ApJ, 752, 22
PC, Broderick & Pfrommer (2012) ApJ, 752, 23
Pfrommer, PC, Broderick (2012) ApJ, 752, 24
Puchwald, Pfrommer, Springel, Broderick, & P.C. (2012) MNRAS, 423, 149
Broderick, Pfrommer, Puchwein, PC (2013ab) arXiv:1308.0015, arXiv:1308:0340

Propagation of TeV photons

- 1 TeV photons that meet 1 eV photons have a c.o.m. energy of 1 MeV

$$\gamma + \gamma \rightarrow e^+ + e^-$$

- Typical Length scale for this depends on the density of 1 eV photons
    - But it is typically ~100 Mpc
    - Produce pairs with energy of 1 TeV

- These pairs inverse Compton scatter off the CMB photons
    - mean free path is roughly 300 kpc.
    - Producing gamma-rays of ~1 GeV

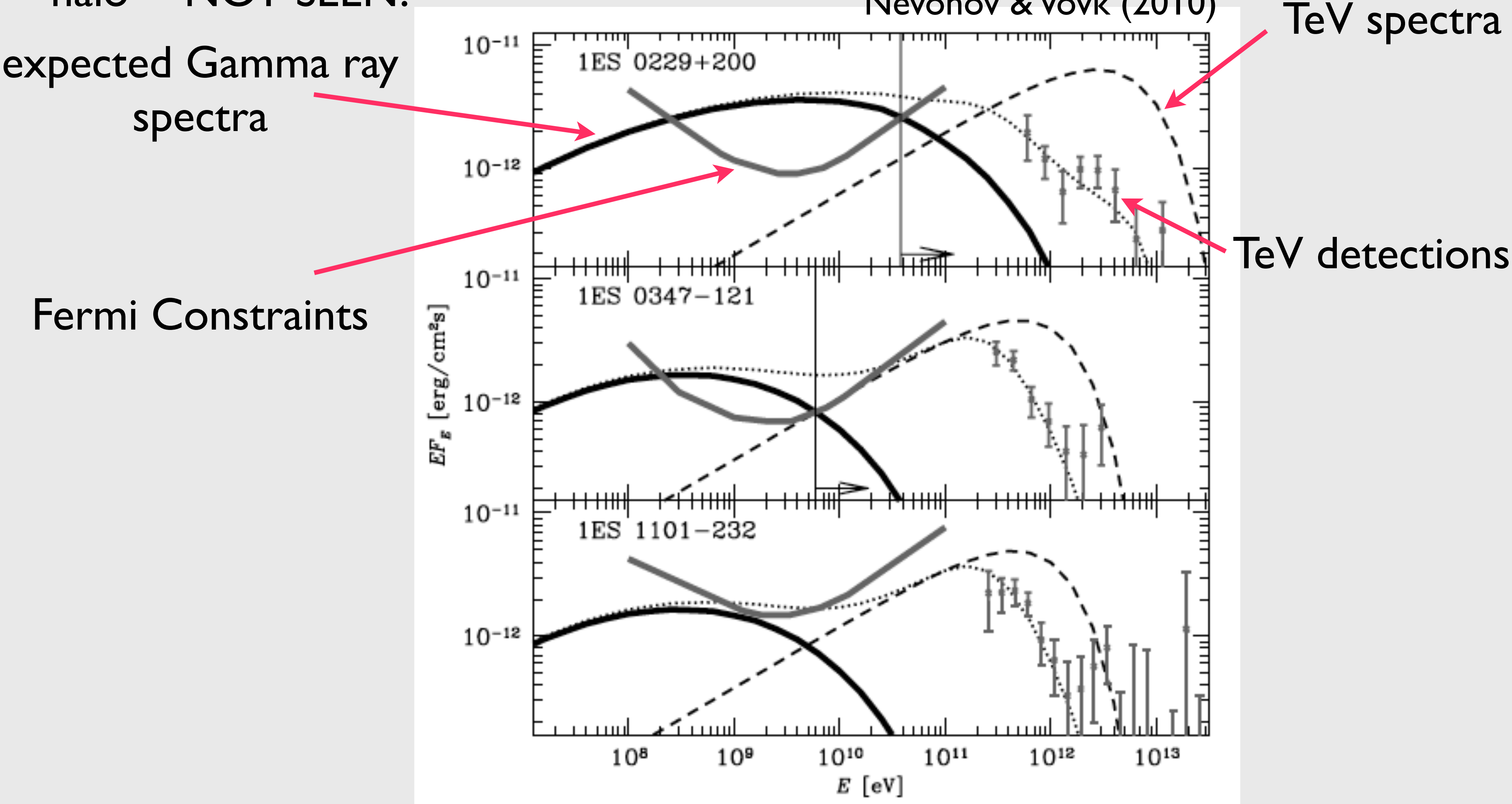
$$E \sim \Gamma^2 E_{\rm CMB} \sim 1\,{\rm GeV}$$

- TeV energies get downgraded to GeV energies -- GeV calorimeter of the TeV universe

Where is the inverse Compton emission?

- Every TeV source should be associated with a 1-100 GeV gamma-ray halo -- NOT SEEN!

Nevonov & Vovk (2010)



- Magnetic fields? or missing plasma physics
- Charged particle beams are violently unstable -- two-stream, weibel, oblique

Measuring the intergalactic mangetic field from TeV/GeV Observations

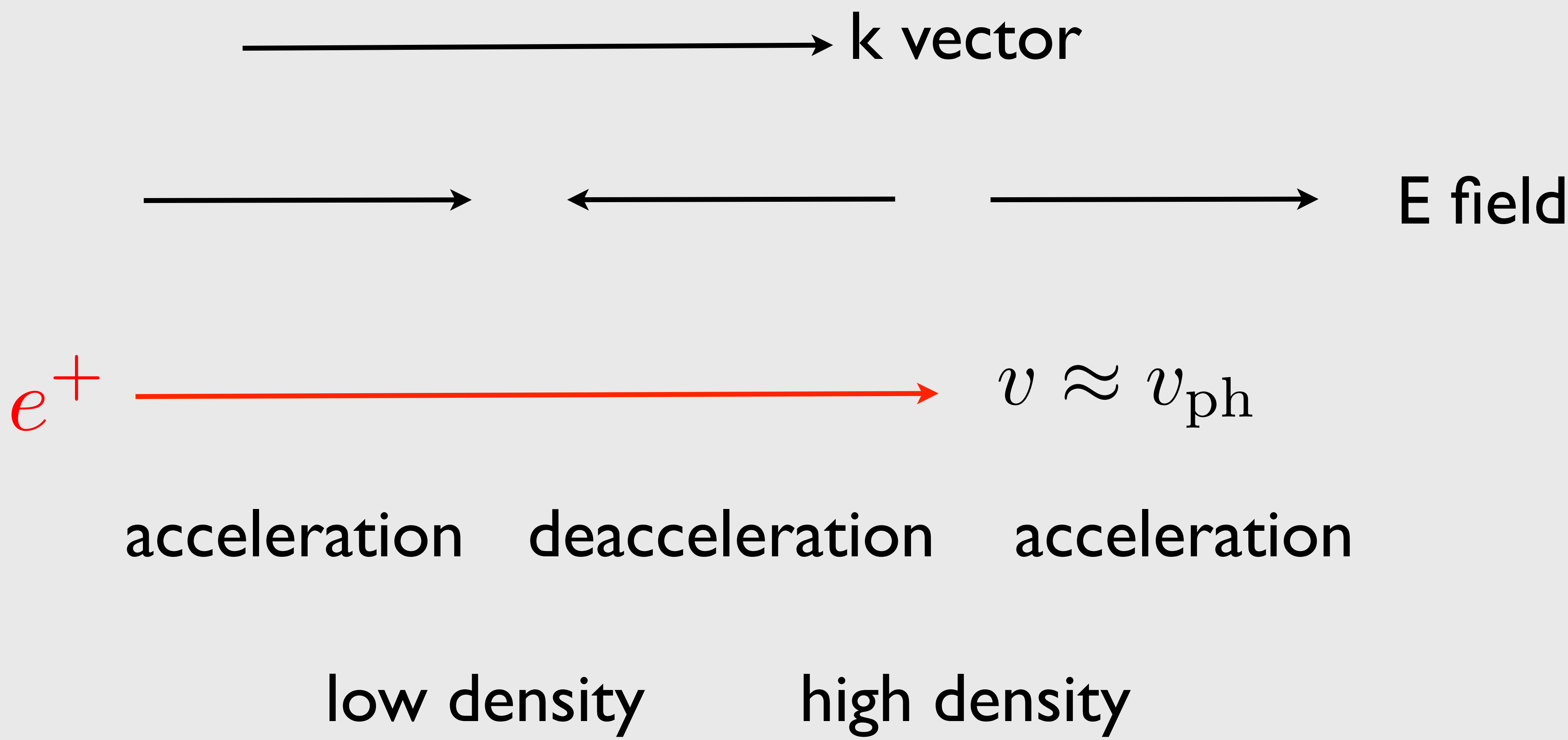
- TeV beam of electrons and positions are deflected out of the line of sight reducing the GeV IC flux.
- Larmor radius: $r_{\rm L} = \frac{E}{eB} \sim 30 \left(\frac{E}{3\,{\rm TeV}}\right)\left(\frac{B}{10^{-16}\,{\rm G}}\right)^{-1}\ {\rm Mpc}$
- IC distance: $x_{\rm IC} \sim 0.1 \left(\frac{E}{3\,{\rm TeV}}\right)^{-1}\ {\rm Mpc}$
- For the associated 10 GeV IC photons angular resolution is 0.2 degrees or

$$\theta \sim 3 \times 10^{-3}\,{\rm rads}$$

- $\frac{x_{\rm IC}}{r_{\rm L}} > \theta \to B \gtrsim 10^{-16}\,{\rm G}$

Beam-Plasma (two-stream) Instability: Intuitive Picture

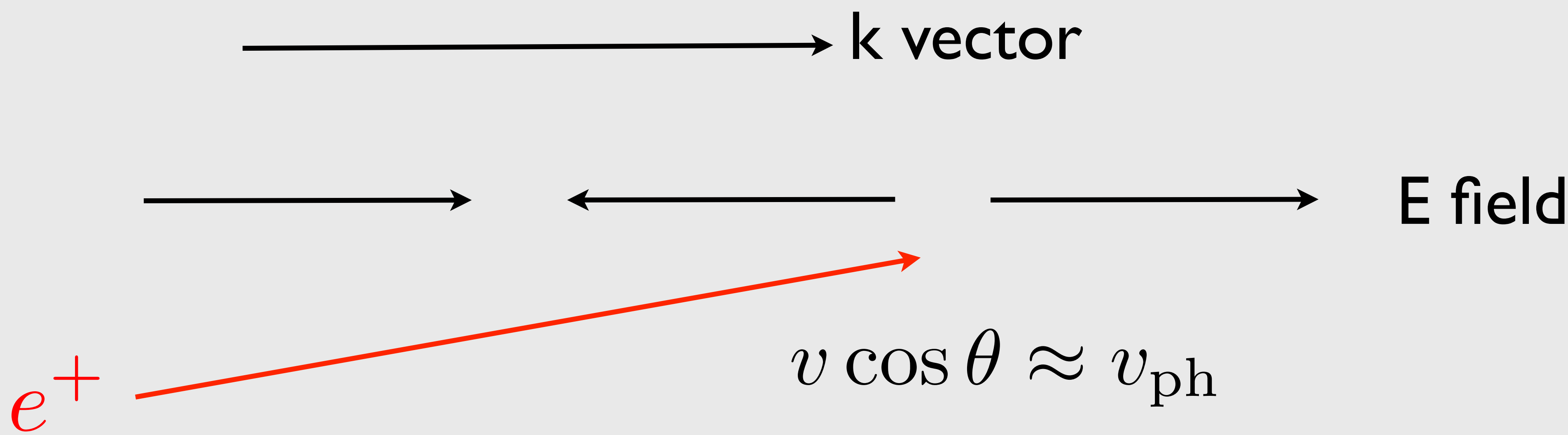
- Basically an overstable Langmuir wave (plasma oscillation)
- Move to the reference frame of the wave



Oblique Instability: Intuitive Picture

- Almost the same as beam plasma

- Move to the reference frame of the wave

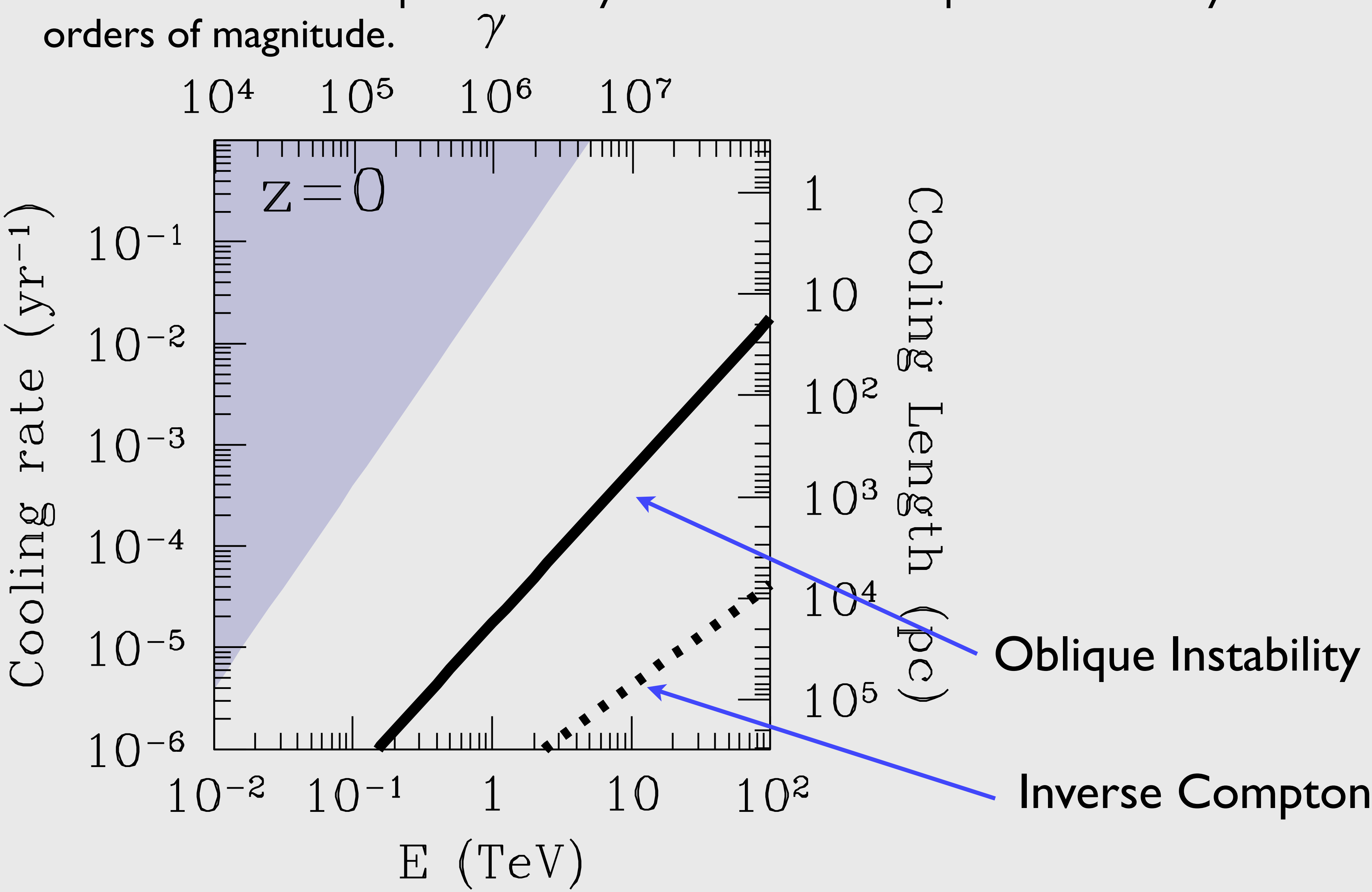


- Deflections of particle trajectory instead of particle straight-line velocity

- Greater growth rate than two-stream because ultrarelativistic particles are easier to deflect than to change their parallel velocities (Nakar, Bret & Milosavljevic 2011).

missing plasma physics?

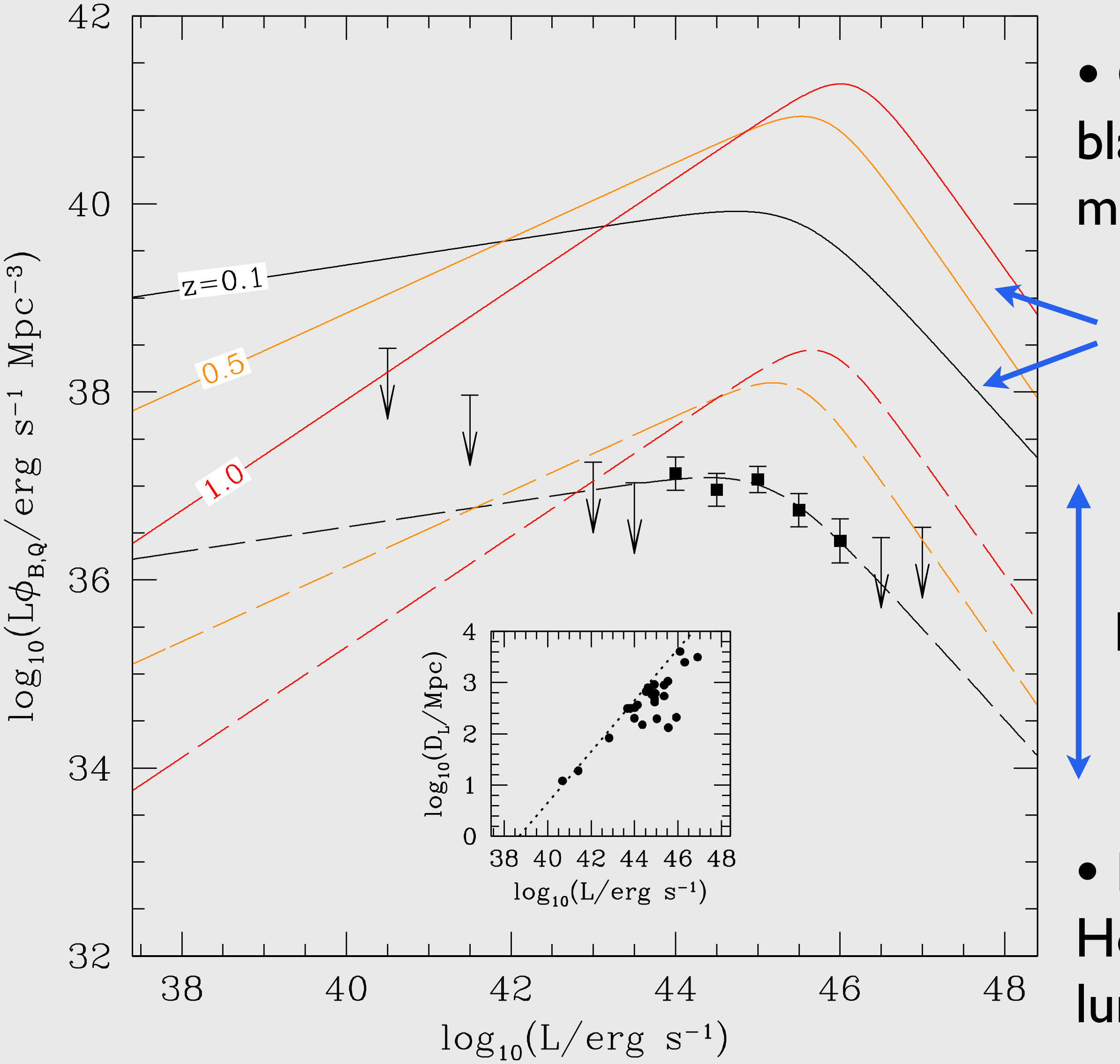
Growth rate of Oblique instability beats inverse Compton off CMB by orders of magnitude.



The TeV Blazar Luminosity Function

- Sum over the flux of 28 TeV blazars with good spectral measurements.
  - Account for the selection effects.

Broderick, PC & Pfrommer (2012)



- Construct a BLF using the 28 blazars with good spectral measurements.

- Fits a rescaled version of Hopkin et al (2007) quasar luminosity function.

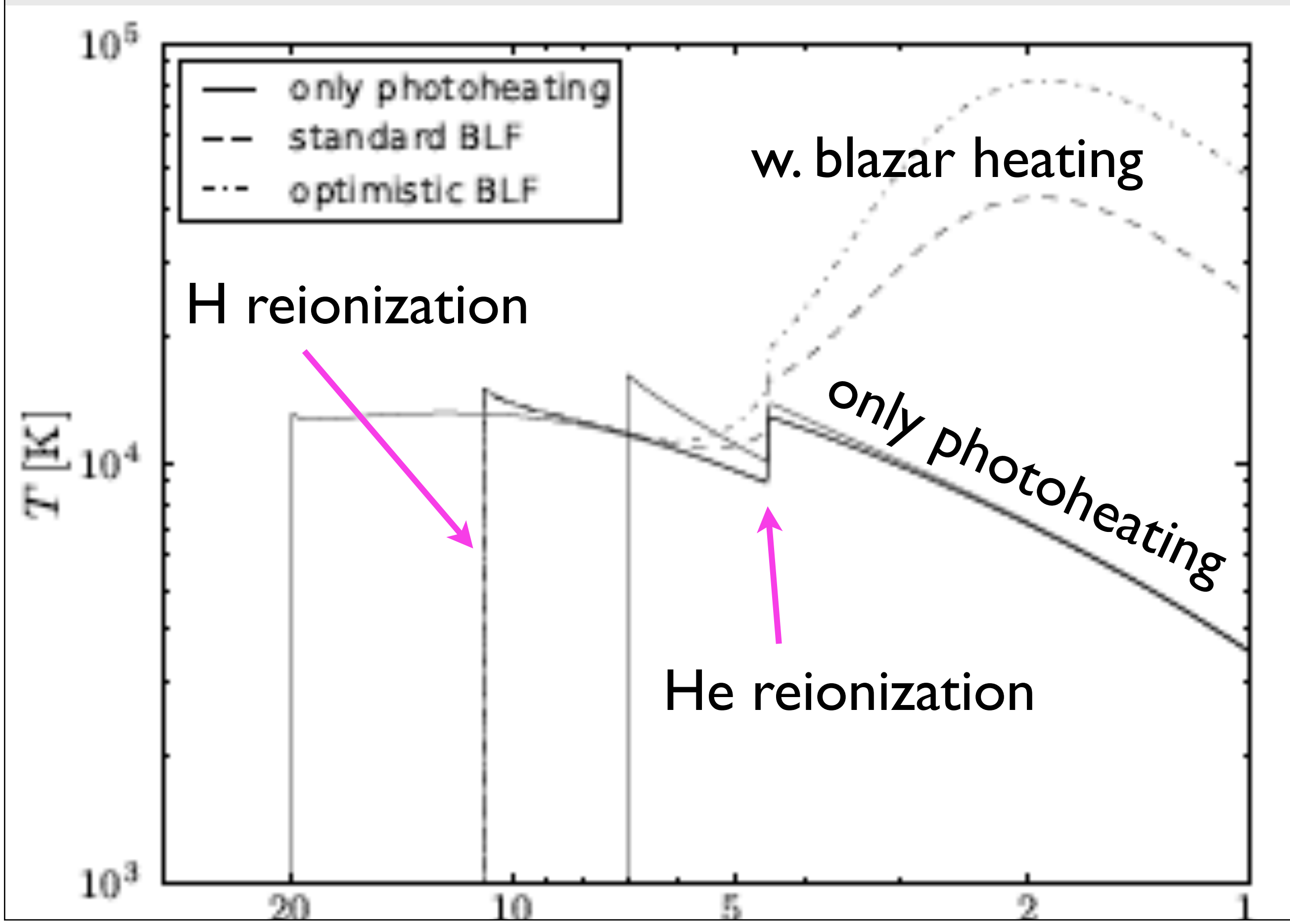
TeV Blazar Heating Rate

- Best estimate for the amount of blazar heating at z=0.

$$\dot{Q} = 7 \times 10^{-8}\,\mathrm{eV\,cm^{-3}\,Gyr^{-1}}$$

- We rescale this to z>0 using Hopkins et al (2007) QLD.

PC, Broderick & Pfrommer (2012)



- Blazar heating is volumetrically constant!

Increased by factor of ~7

It Is All About the Efficiency

• Recombination rate of H is of order the Hubble time (at present) and is instantly ionized with excess energy of 4 eV. So every proton in the universe gets:

$$E_{\mathrm{ph}} = 4\,\mathrm{eV}$$

• Cosmic baryon fraction in BHs is 0.01%

• $\epsilon_{\mathrm{rad,BH}} = 10^{-5}$

• BLD is 0.4% of the quasar luminosity density.

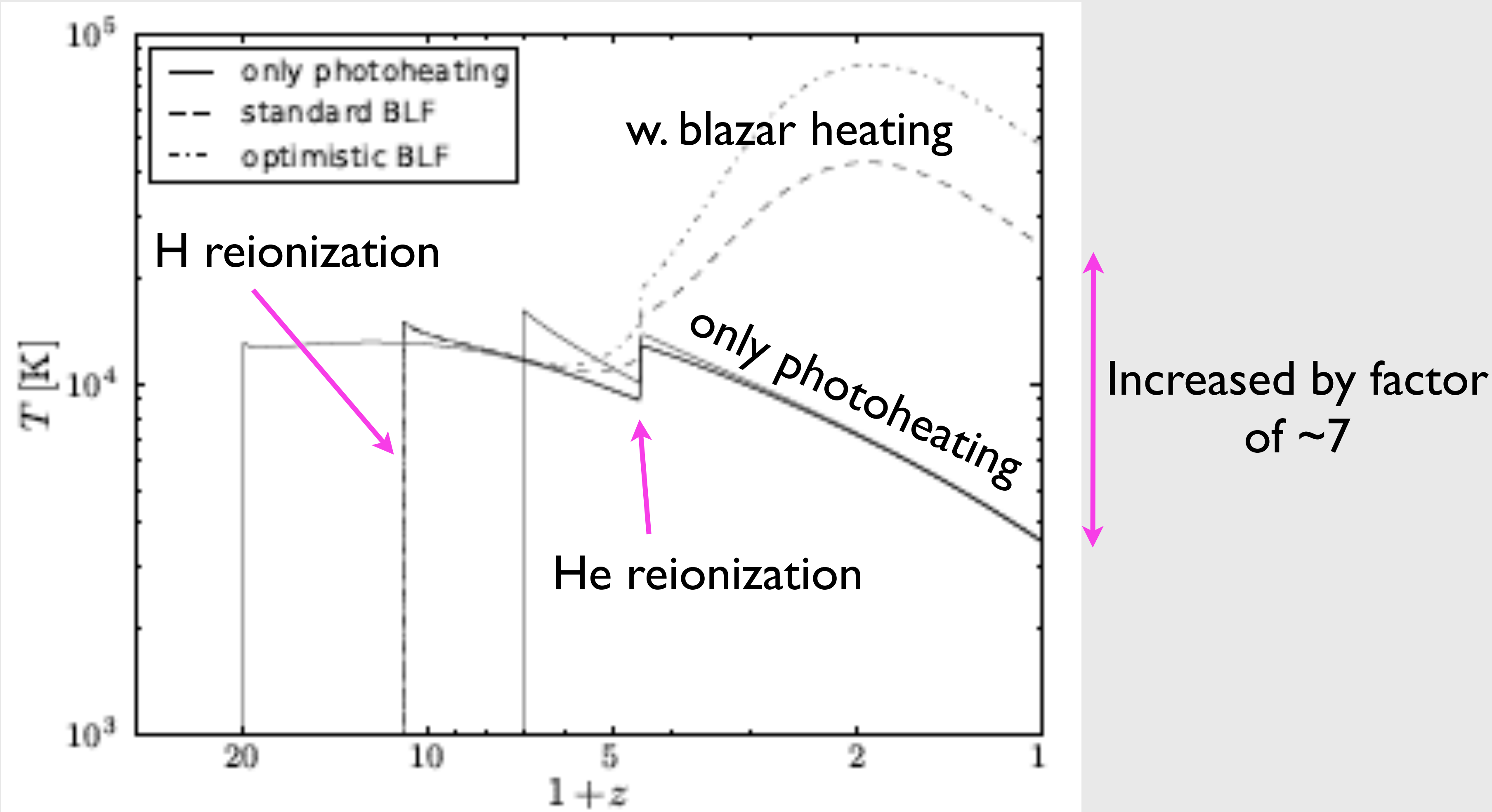
$$E_{\mathrm{TeV}} = 4 \times 10^{-3} \times \epsilon_{\mathrm{rad,BH}} \times m_p c^2 = 40\,\mathrm{eV}$$

• factor of 10 larger than photoheating.

• Efficiency of plasma heating make up for their relative lack of power of TeV blazars

Thermal History of the intergalactic medium

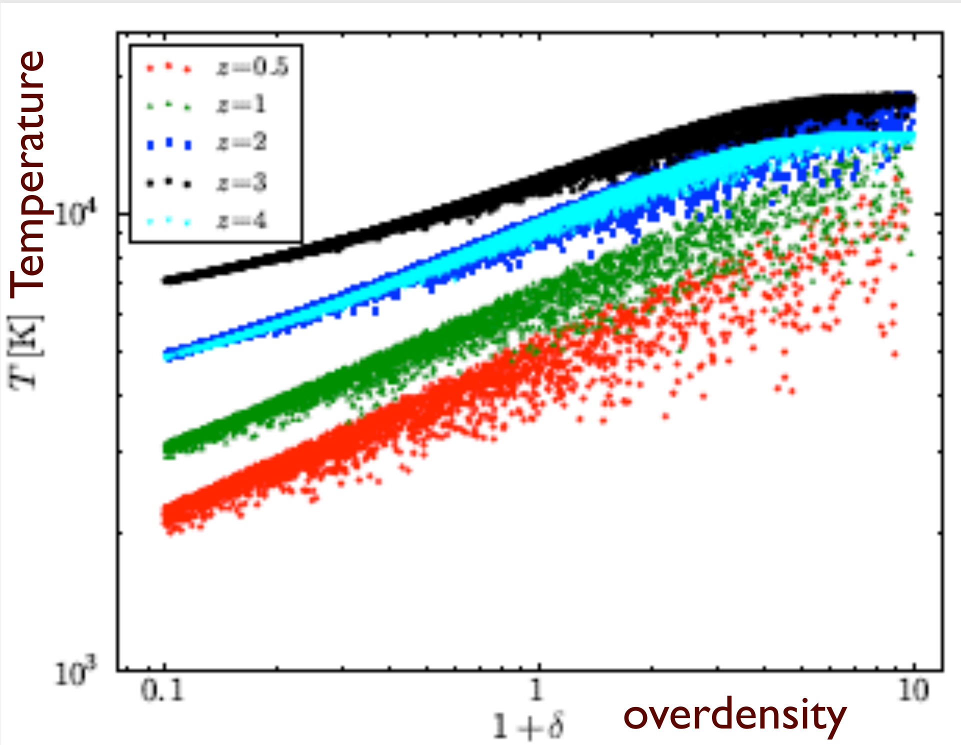
PC, Broderick & Pfrommer (2012)



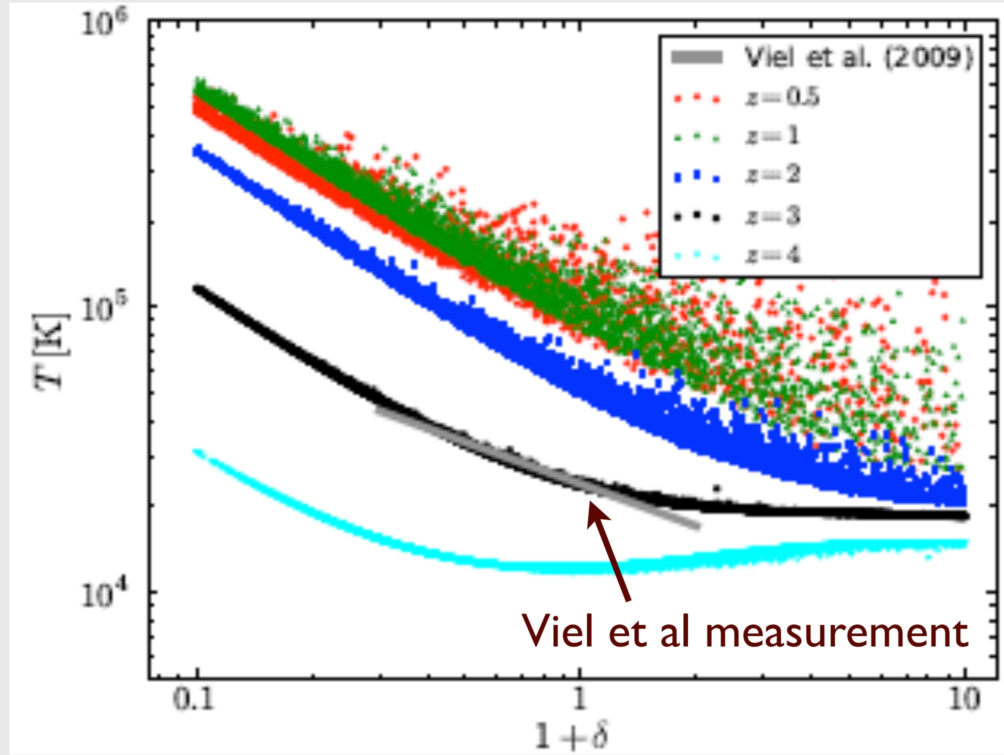
- Blazars completely change the thermal history of the diffuse IGM
- Changes the history of structure formation of the IGM.

Thermal History of the IGM

PC, Broderick & Pfrommer (2012)



only photoheating

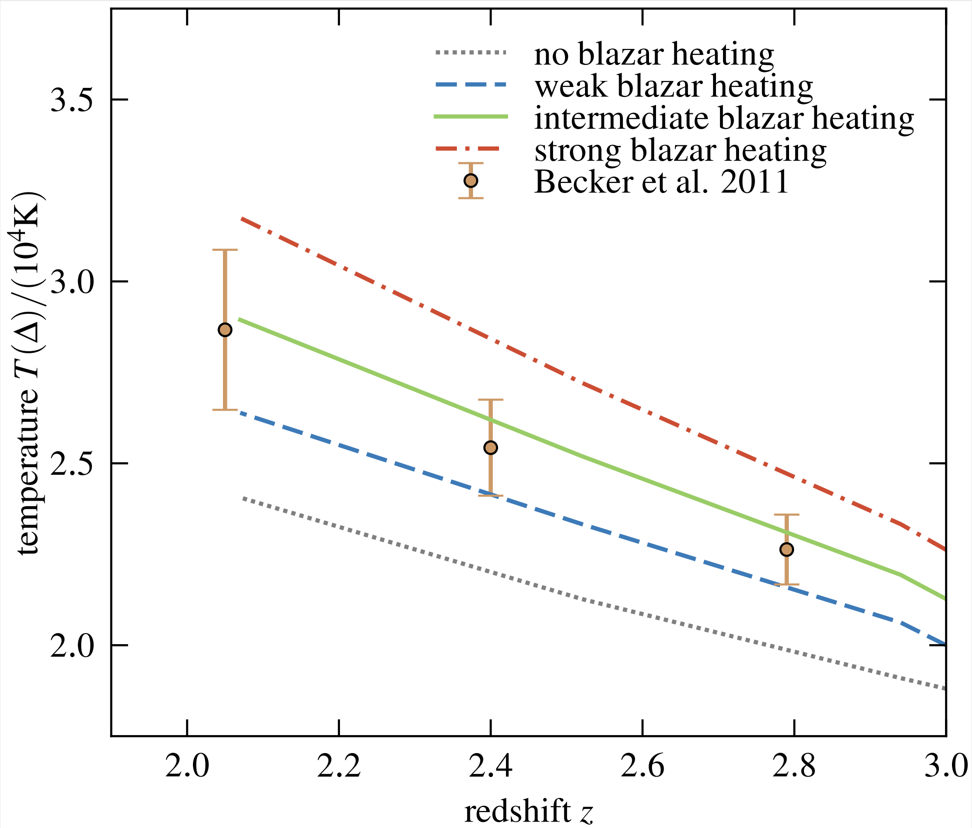


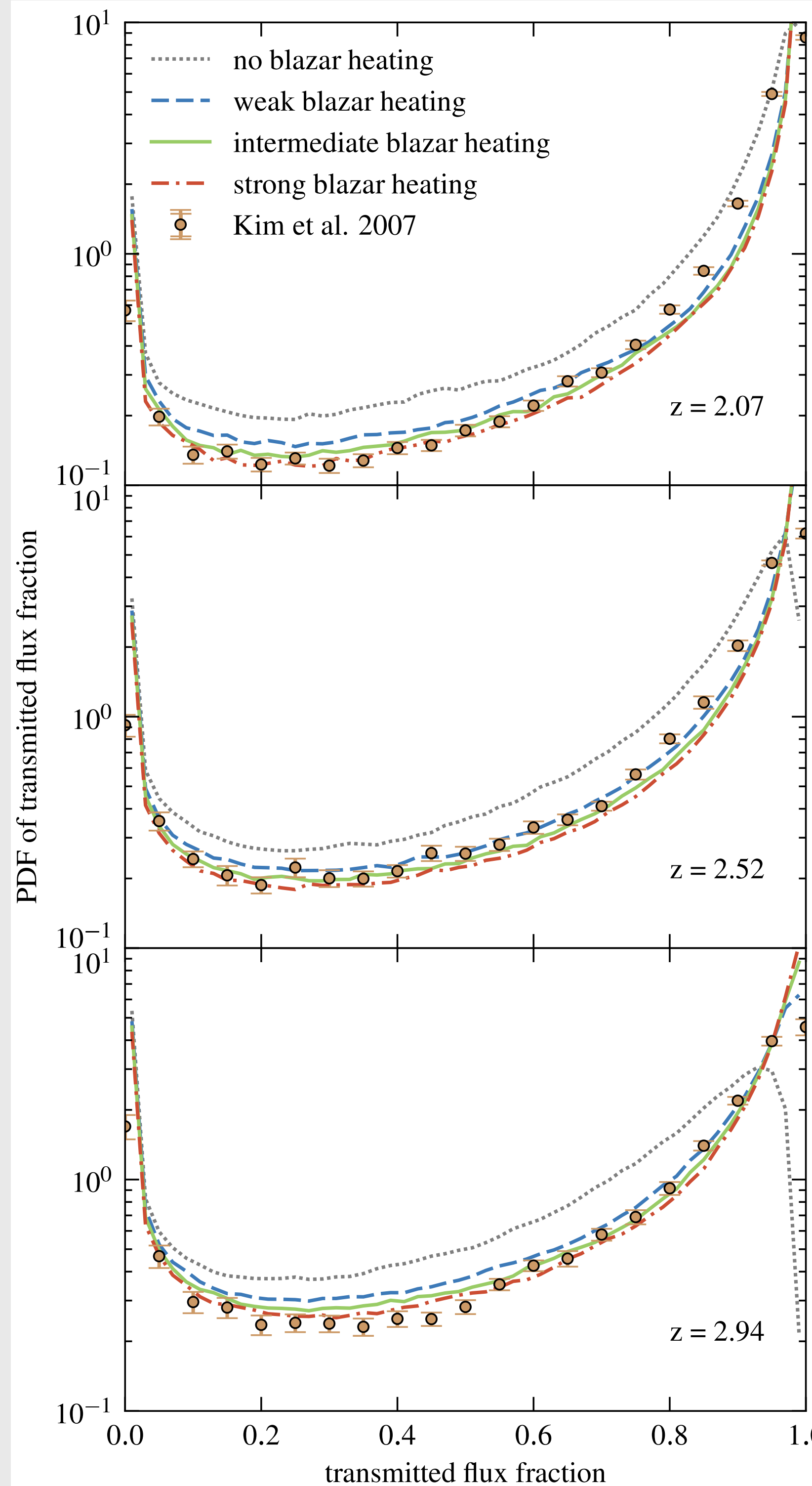
Blazar heating increased by 50% (optimistic model)

- Because heating is constant per volume -- T increase is largest in voids.
- Naturally produces inverted equation of state.
  - Which is otherwise difficult to do in standard heating models.
- Increases low density regions to a $\mathrm{few} \times 10^5\,\mathrm{K}$

Comparison with Observations

Puchwein et al 2012





- Measured temperature of the mean IGM in better agreement with blazar heating.

- High transmitted flux fraction in much better agreement with blazars -- makes IGM hotter, so less recombinations

Strong Evolution of TeV Blazars - Comparison with Fermi

Volume

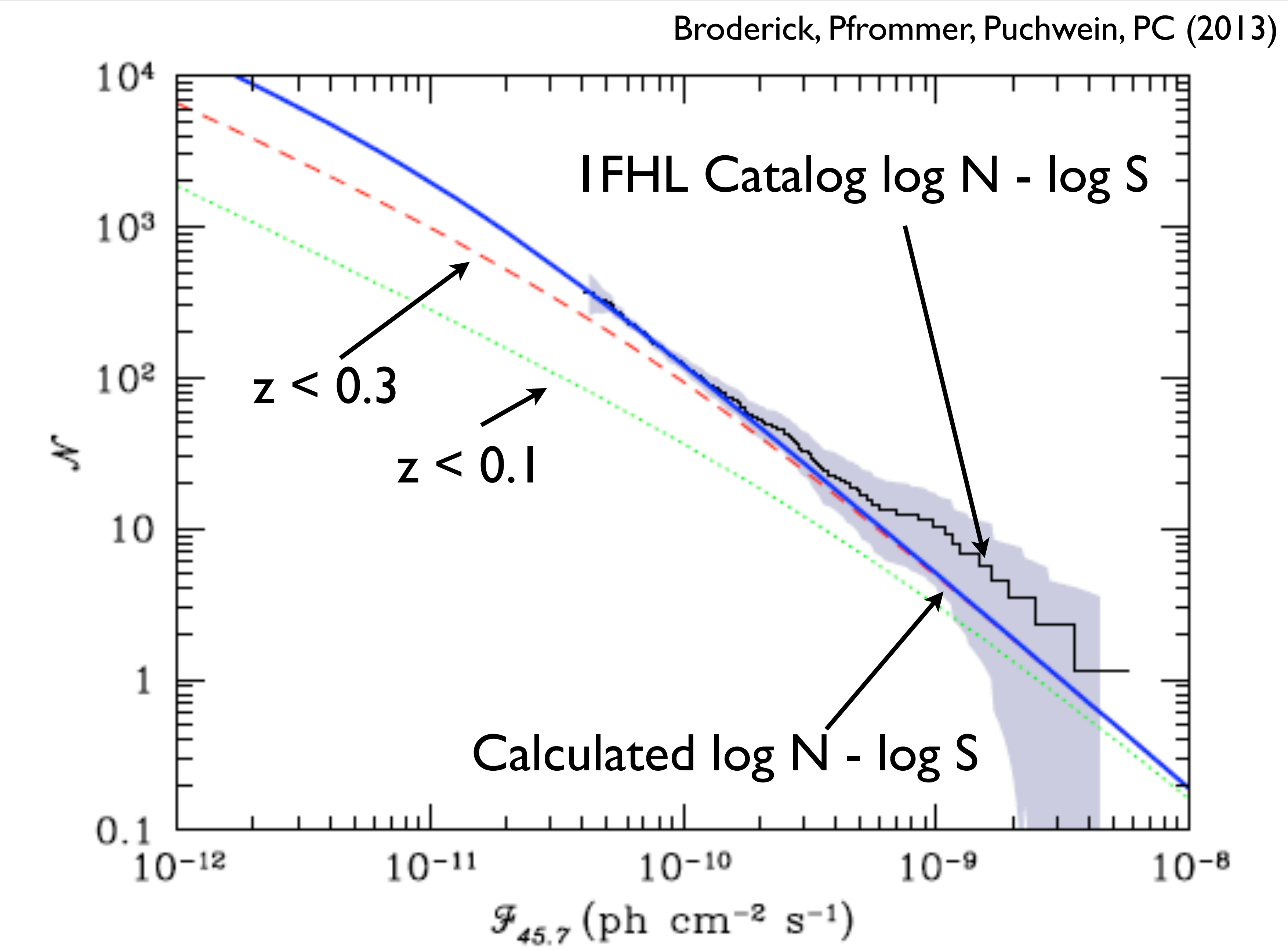
$$\mathcal{N}(>S) = \int_0^2 d\Gamma \int \frac{dV}{dz} dz \int_{L(F=S,z)}^{\infty} dL \phi_B\left(z, L, \Gamma\right)$$

Spectral Index

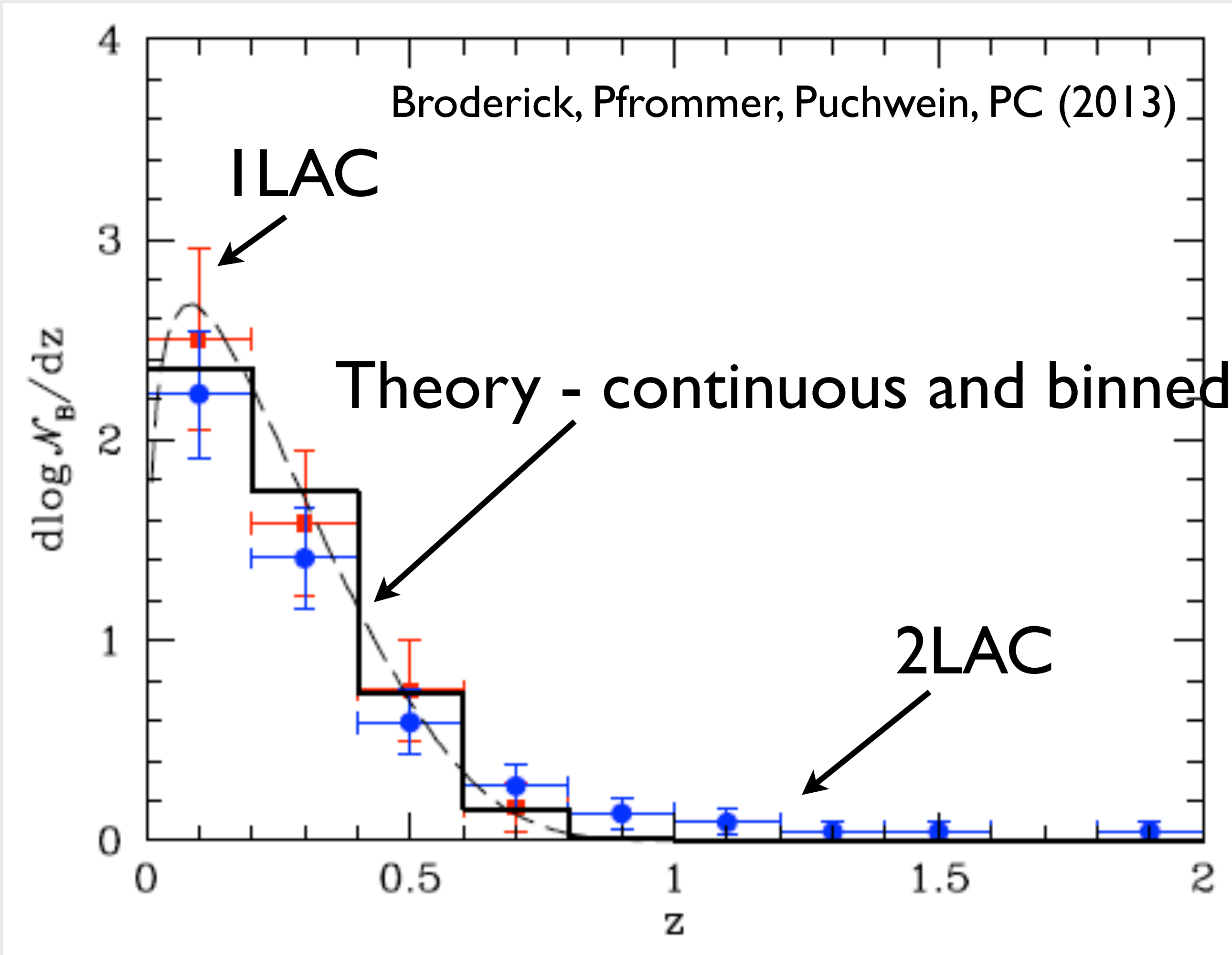
Instrinsic L

- Instrinsic L contains the effects of absorption
- Integral over spectral index only includes hard Fermi sources: spectral index < 2
- $\phi_B(z, L, \Gamma)$ contains the rescaled quasar luminosity function with an empirical spectral index constructed from Fermi data.

Strong Evolution - consistent with log N - log S



Strong Evolution - consistent with hard blazar redshift distribution



Strong evolutions is consistent with the observed falloff in numbers of hard blazars with redshift - due to flux limit

Summary

- Plasma Physics is important for the propagation of TeV pair beams.
  - Beams are violently unstable to the “oblique” and beam-plasma instability.

- TeV blazars dominate the heating of the IGM at $z < 2$-3
  - Beats photoheating by an order of magnitude

- Changes the temperature structure of the IGM

- Implications for structure formation - dwarfs and clusters

- Strong evolution is consistent with Fermi observations