

# The Physics and Cosmology of TeV Blazars

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in collaboration with

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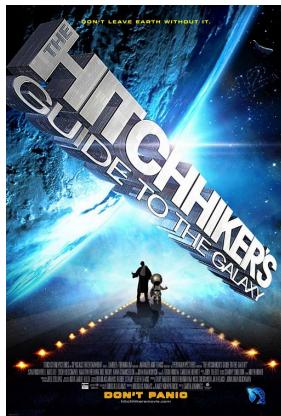
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Oct 29, 2012 / Physics Colloquium Bochum

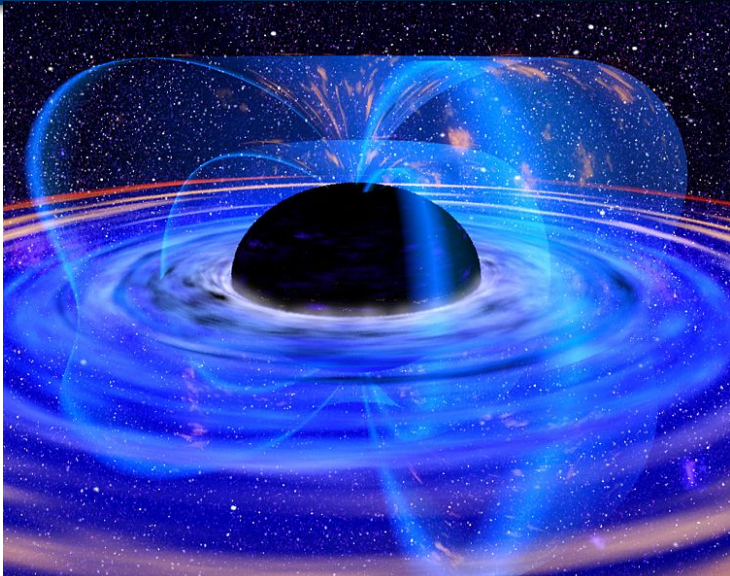


# The Hitchhiker's Guide to ... Blazar Heating

- **Blazar Physics**
  - black holes and jets
  - TeV photon propagation
  - plasma physics
- **Cosmological Consequences** for
  - intergalactic magnetic fields
  - gamma-ray background
  - thermal history of the Universe
  - Lyman- $\alpha$  forest
  - formation of dwarf galaxies
  - galaxy cluster thermodynamics



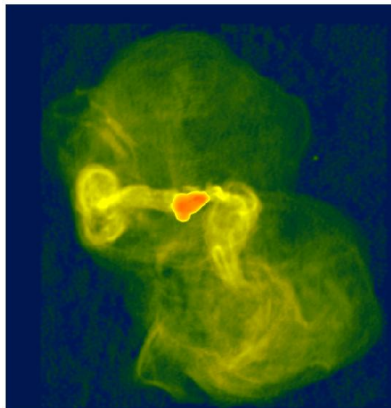
# Black hole



## Black hole jets - nearby



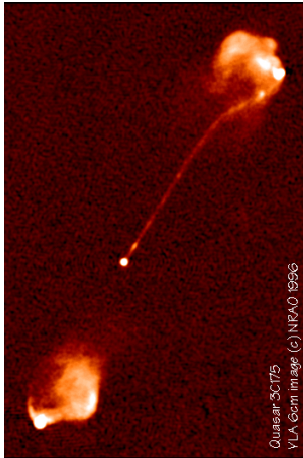
Centaurus A in X-rays:  
closest active galaxy with a  
super-massive black hole



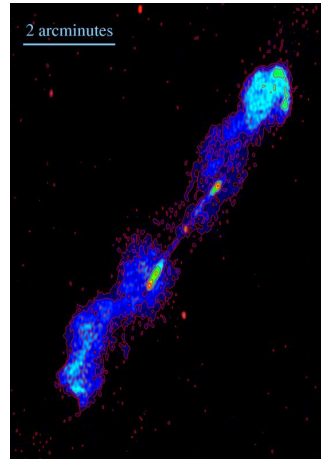
Messier 87 in the radio:  
closest active cluster galaxy in  
the Virgo cluster:  $M_{\text{bh}} \simeq 6 \times 10^9 M_{\odot}$



# Black hole jets - at cosmological distances



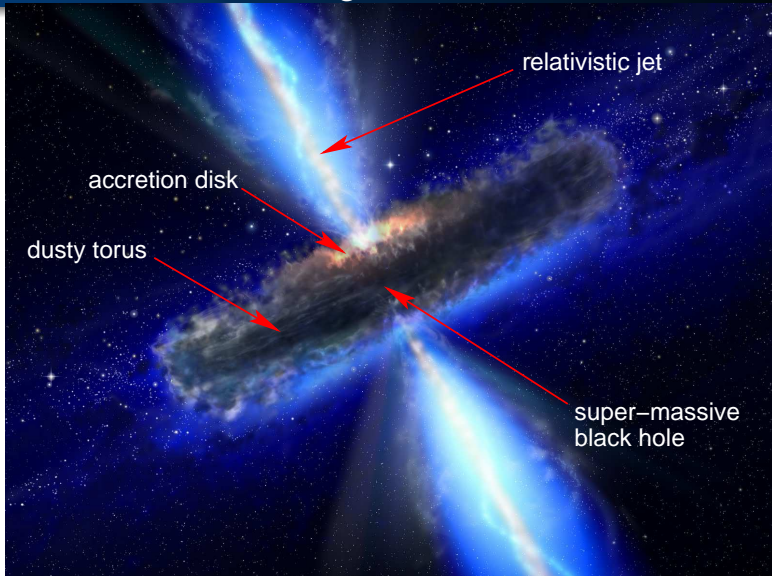
Quasar 3C175:  
1 million light years across



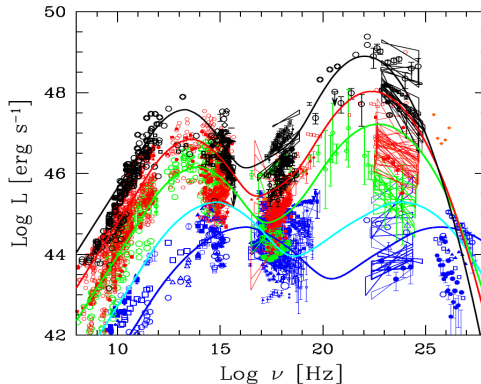
Giant radio galaxy B1545-321:  
relic radio plasma and new jet activity



# Unified model of active galactic nuclei



# The blazar sequence



Ghisellini (2011), arXiv:1104.0006

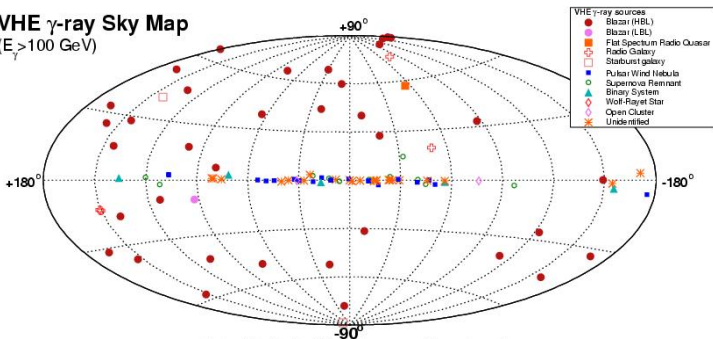
- continuous sequence from **LBL**–**IBL**–**HBL**
- TeV blazars are dim (very sub-Eddington)
- TeV blazars have rising spectra in the Fermi band ( $\alpha < 2$ )
- define TeV blazar = **hard IBL** + **HBL**

# The TeV gamma-ray sky

There are several classes of TeV sources:

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

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

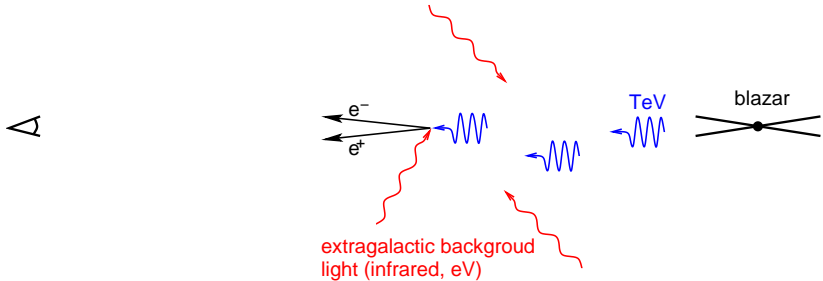


2011-01-08 - Up-to-date plot available at <http://www.inpp.mpg.de/~rwagne/sources/>

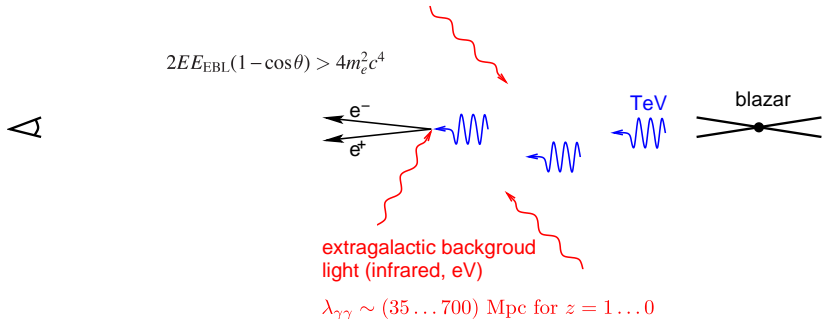




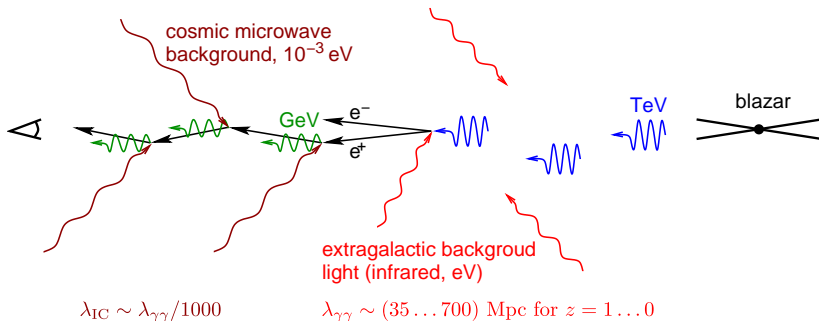
# Annihilation and pair production



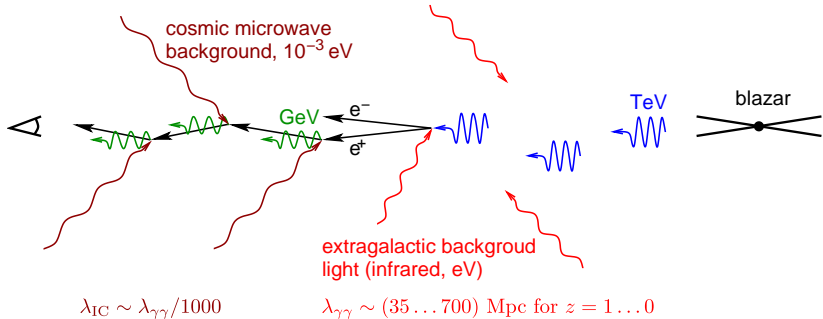
# Annihilation and pair production



# Inverse Compton cascades



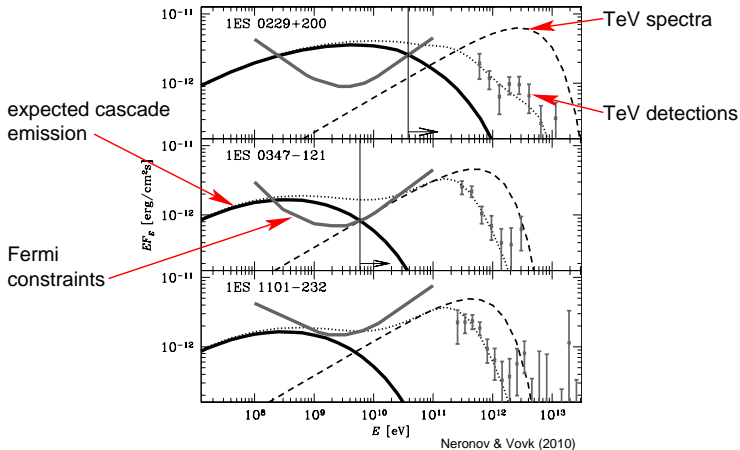
# Inverse Compton cascades



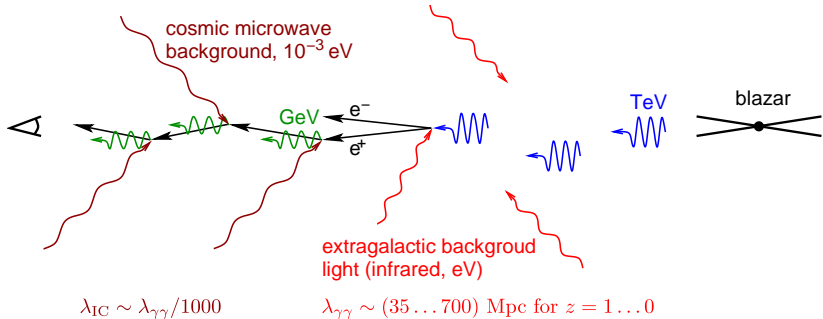
→ each TeV point source should also be a GeV point source!

# What about the cascade emission?

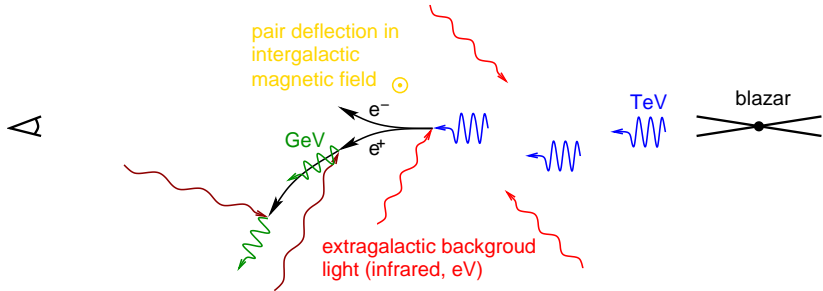
Every TeV source should be associated with a 1-100 GeV gamma-ray halo – **not seen!**



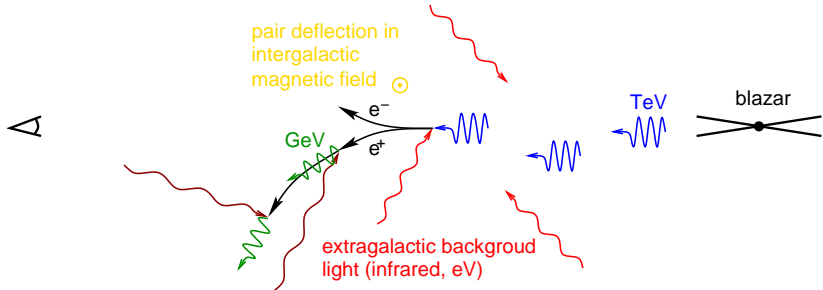
# Inverse Compton cascades



# Magnetic field deflection



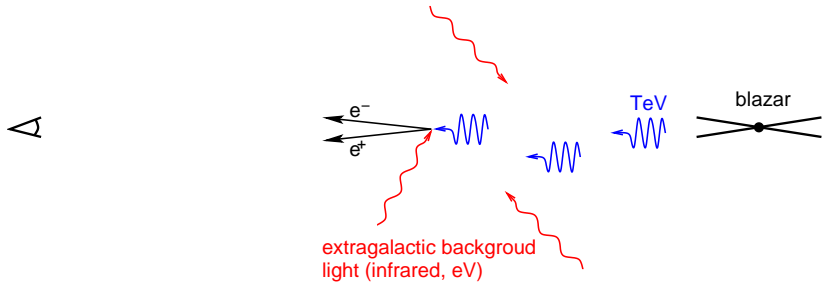
# Magnetic field deflection



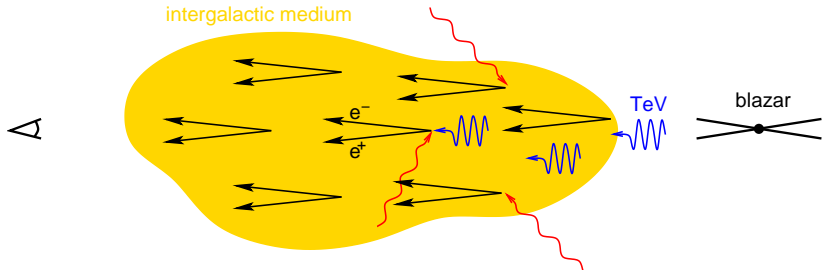
- GeV point source diluted  $\rightarrow$  weak "pair halo"
- stronger B-field implies more deflection and dilution, gamma-ray non-detection  $\rightarrow B \gtrsim 10^{-16} \mu\text{G}$  – primordial fields?



# What else could happen?



# Plasma beam instabilities

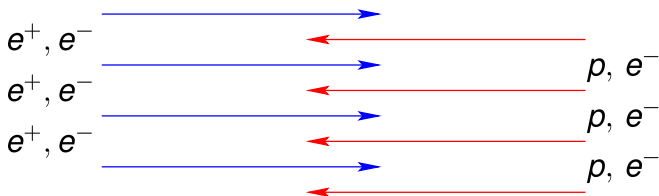


→ pair plasma beam propagating through the intergalactic medium

## Missing plasma physics?

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

- plasma processes are important
- interpenetrating beams of charged particles are unstable
- consider the two-stream instability:



- one frequency (timescale) and one length in the problem:

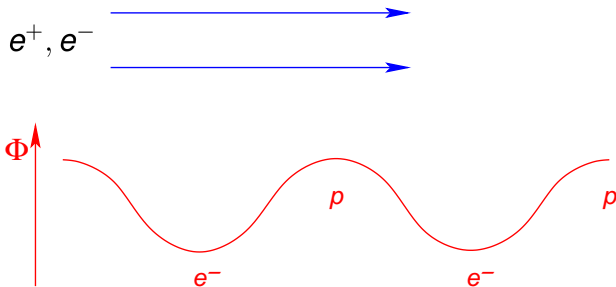
$$\omega_p = \sqrt{\frac{4\pi e^2 n_e}{m_e}}, \quad \lambda_p = \frac{c}{\omega_p} \Big|_{\bar{\rho}(z=0)} \sim 10^8 \text{ cm}$$



# Two-stream instability: mechanism

wave-like perturbation with  $\mathbf{k} \parallel \mathbf{v}_{\text{beam}}$ , longitudinal charge oscillations in background plasma (Langmuir wave):

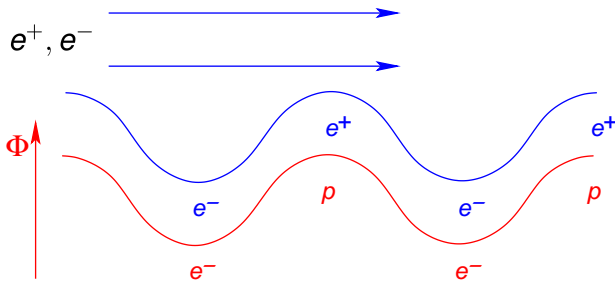
- initially homogeneous beam- $e^-$ :  
attractive (repulsive) force by potential maxima (minima)
- $e^-$  attain lowest velocity in potential minima  $\rightarrow$  bunching up
- $e^+$  attain lowest velocity in potential maxima  $\rightarrow$  bunching up



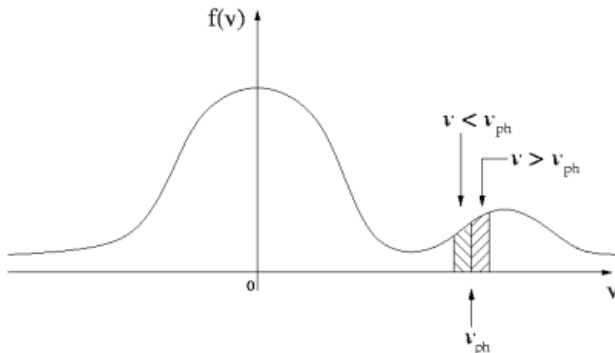
## Two-stream instability: mechanism

wave-like perturbation with  $\mathbf{k} \parallel \mathbf{v}_{\text{beam}}$ , longitudinal charge oscillations in background plasma (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

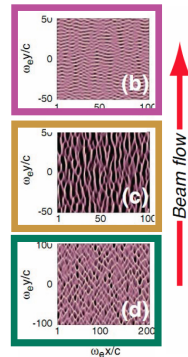
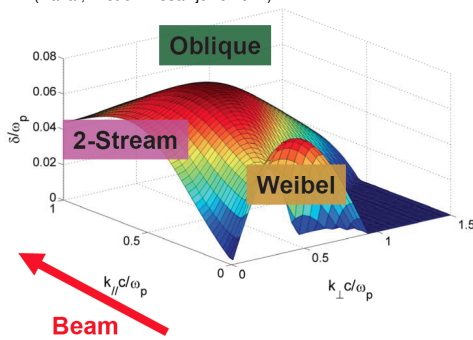


- particles with  $v \gtrsim v_{\text{phase}}$ :  
pair momentum  $\rightarrow$  plasma waves  $\rightarrow$  growing modes: instability
- particles with  $v \lesssim v_{\text{phase}}$ :  
plasma wave momentum  $\rightarrow$  pairs  $\rightarrow$  Landau damping



# Oblique instability

- $\mathbf{k}$  oblique to  $\mathbf{v}_{\text{beam}}$ : real world 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)

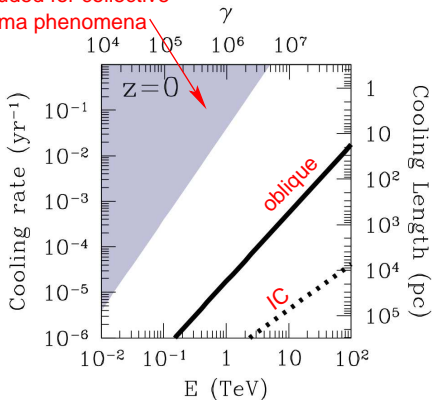


Bret (2009), Bret+ (2010)



# Beam physics – growth rates

excluded for collective  
plasma phenomena



- 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 two orders of magnitude

Broderick, Chang, C.P. (2012)





## Beam physics – complications . . .

non-linear saturation:

- non-linear evolution of these instabilities at these density contrasts is not known
- expectation from PIC simulations suggest substantial isotropization of the beam
- **assume** that they grow at linear rate up to saturation

→ plasma instabilities dissipate the beam's energy, no (little) energy left over for inverse Compton scattering off the CMB



# TeV emission from blazars – a new paradigm

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

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

- intergalactic  $B$ -field estimates
- $\gamma$ -ray emission from blazars: spectra, background

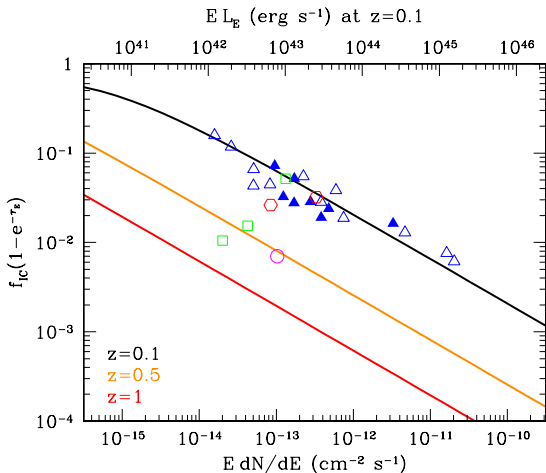
additional IGM heating has significant implications for ...

- thermal history of the IGM: Lyman- $\alpha$  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:  $f_{IC} = \Gamma_{IC}/(\Gamma_{IC} + \Gamma_{oblique})$



Broderick, Chang, C.P. (2012)



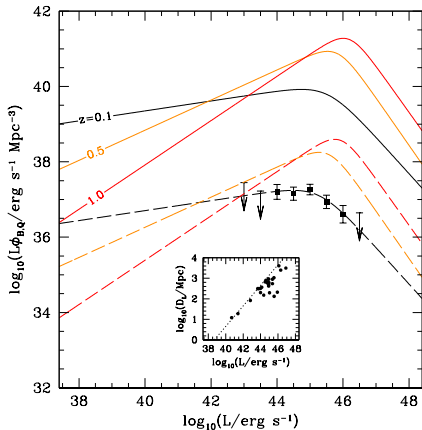
## Conclusions on $B$ -field constraints from blazar spectra

- 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
- $\lesssim 1\text{--}10\%$  of beam energy to IC CMB photons

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



# TeV blazar luminosity density: today

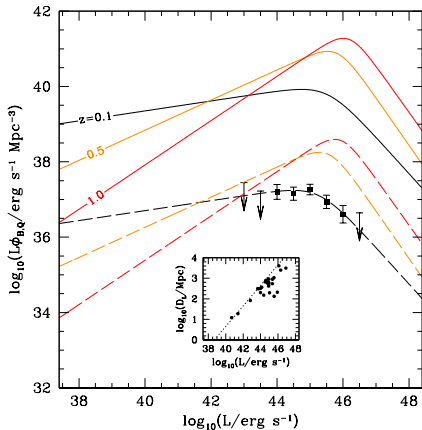


Broderick, Chang, C.P. (2012)

- 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)

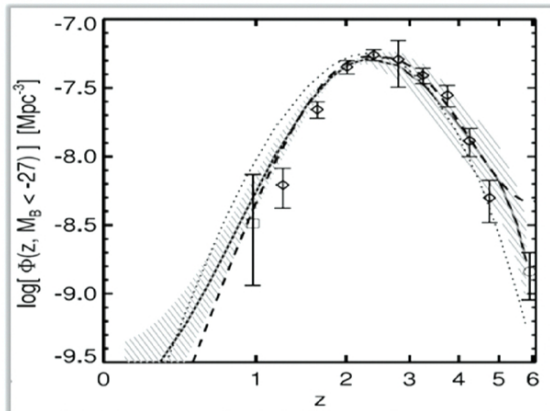
Quasars and TeV blazars are:

- 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!**



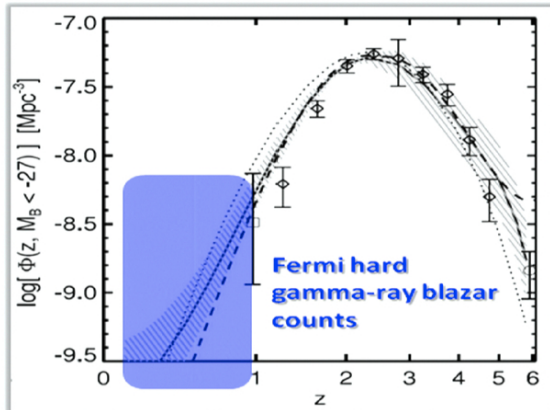
# How many TeV blazars are there?



Hopkins+ (2007)



# How many TeV blazars are there?

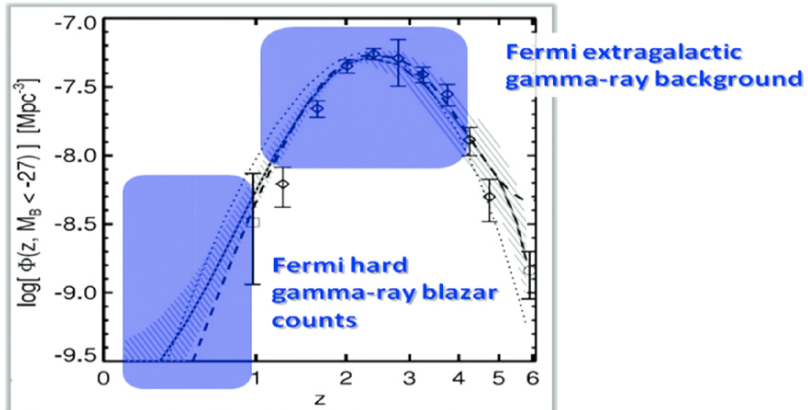


Hopkins+ (2007)





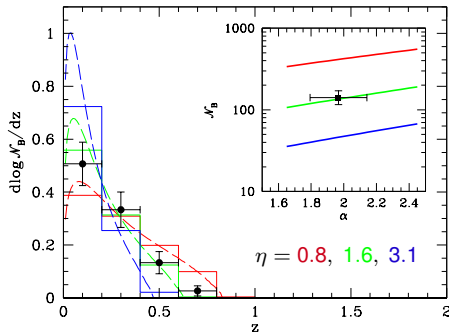
# How many TeV blazars are there?



Hopkins+ (2007)



# Fermi number count of “TeV blazars”



Broderick, Chang, C.P. (2012)

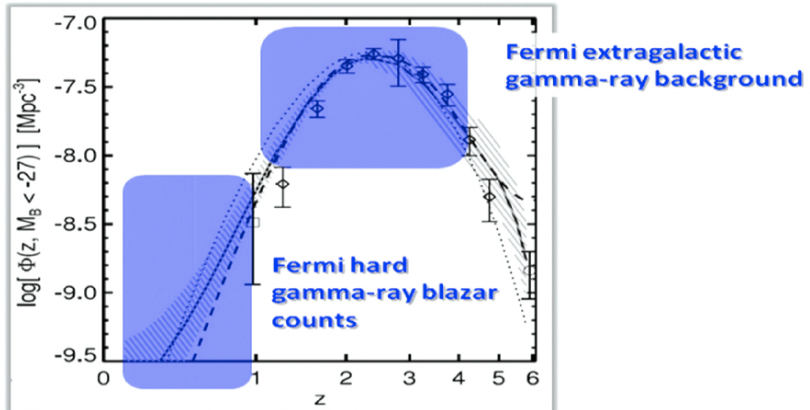
- TeV blazar evolution: model vs. *Fermi* number counts
- colors: different flux (luminosity) limits connecting the *Fermi* and the TeV band:

$$L_{\text{TeV},\text{min}}(Z) = \eta L_{\text{Fermi},\text{min}}(Z)$$

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



# How many TeV blazars are there at high- $z$ ?

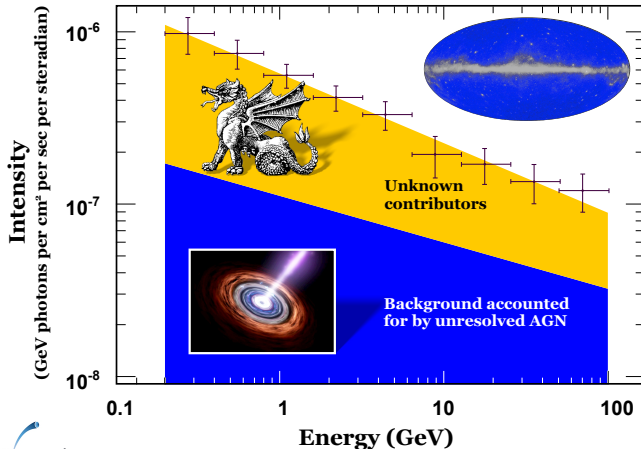


Hopkins+ (2007)



# Fermi probes “dragons” of the gamma-ray sky

## Fermi LAT Extragalactic Gamma-ray Background



# Extragalactic gamma-ray background

- assume all TeV blazars have identical intrinsic spectra:

$$F_E = L\hat{F}_E \propto \frac{1}{(E/E_b)^{\alpha_L-1} + (E/E_b)^{\alpha-1}},$$

$E_b$  is break energy,

$\alpha_L < \alpha$  are low and high-energy spectral indexes

- extragalactic gamma-ray background (EGRB):

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

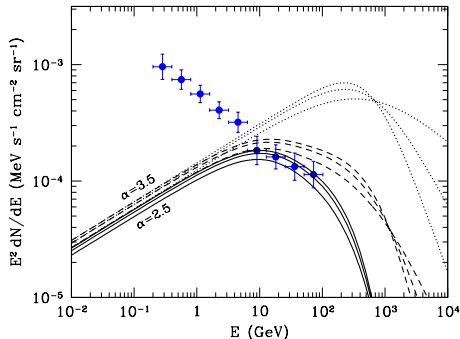
$E' = E(1 + z')$  is gamma-ray energy at *emission*,

$\tilde{\Lambda}_Q$  is physical quasar luminosity density,

$\eta_B \sim 0.2\%$  is blazar fraction,  $\tau$  is optical depth



# Extragalactic gamma-ray background: varying $\alpha$

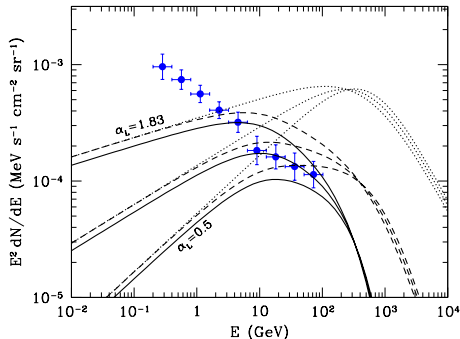


Broderick, Chang, C.P. (2012)

- *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 $\alpha_L$

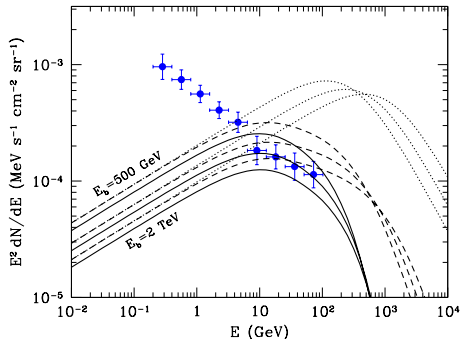


Broderick, Chang, C.P. (2012)

- *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 $E_b$



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 ( $z < 0.25$ )



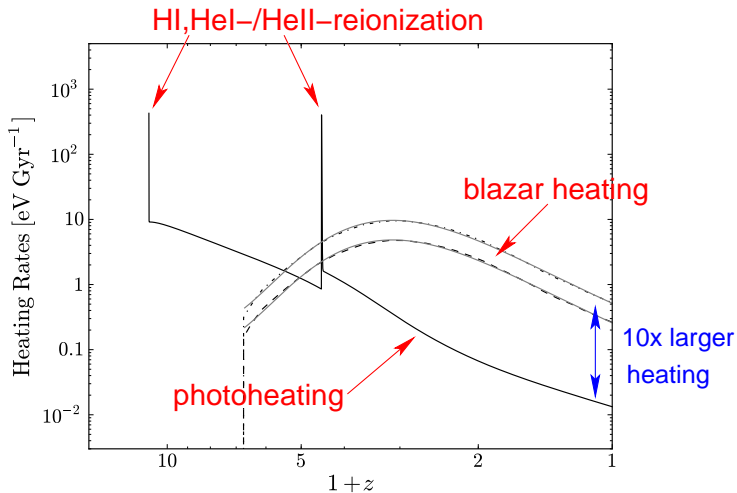


## Conclusions on extragalactic gamma-ray background

- the TeV blazar luminosity density is a scaled version of the quasar luminosity density at  $z = 0.1$
- assuming that quasars trace TeV blazars for all  $z$  and adopting typical spectra, **we can match the *Fermi*-LAT blazar number counts *and* the EGRB!**
- evolving blazars do not overproduce EGRB since the absorbed energy is not reprocessed to GeV energies
- fraction of absorbed energy is greater at higher energies



# Evolution of the heating rates



Chang, Broderick, C.P. (2012)



# Blazar heating vs. photoheating

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

$$\varepsilon_{\text{th}} = \frac{kT}{m_p c^2} \sim 10^{-9}$$

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

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

- fraction of the energy energetic enough to ionize H I is  $\sim 0.1$ :

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

- photoheating efficiency  $\eta_{\text{ph}} \sim 10^{-3} \quad \rightarrow \quad kT \sim \eta_{\text{ph}} \varepsilon_{\text{UV}} m_p c^2 \sim \text{eV}$

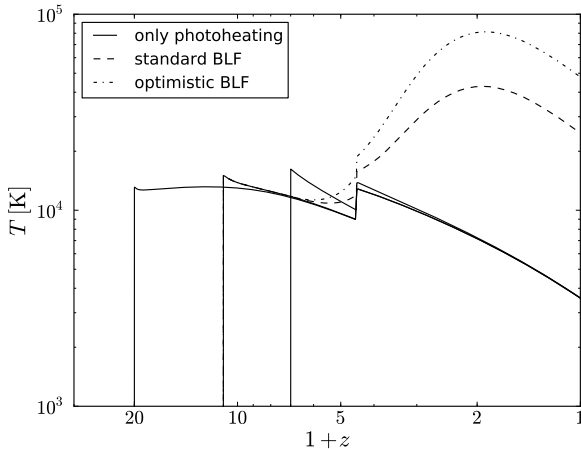
(limited by the abundance of H I/He II due to the small recombination rate)

- blazar heating efficiency  $\eta_{\text{bh}} \sim 10^{-3} \quad \rightarrow \quad kT \sim \eta_{\text{bh}} \varepsilon_{\text{rad}} m_p c^2 \sim 10 \text{ eV}$

(limited by the total power of TeV sources)



# Thermal history of the IGM

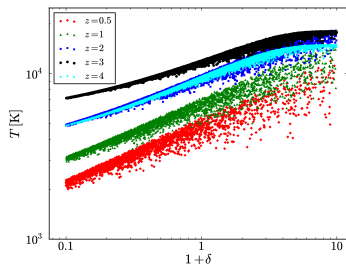


Chang, Broderick, C.P. (2012)

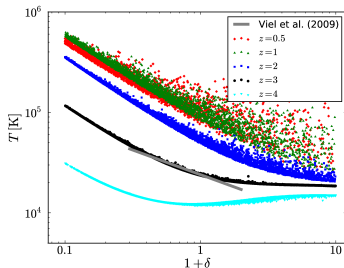


# Evolution of the temperature-density relation

no blazar heating



with blazar heating



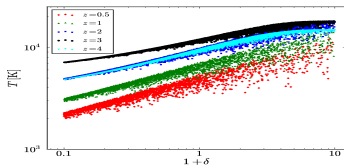
Chang, Broderick, C.P. (2012)

- blazars and extragalactic background light are uniform:
  - blazar heating rate independent of density
  - makes low density regions *hot*
  - causes inverted temperature-density relation,  $T \propto 1/\delta$

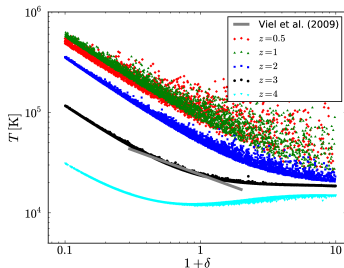


# Blazars cause hot voids

no blazar heating



with blazar heating



Chang, Broderick, C.P. (2012)

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



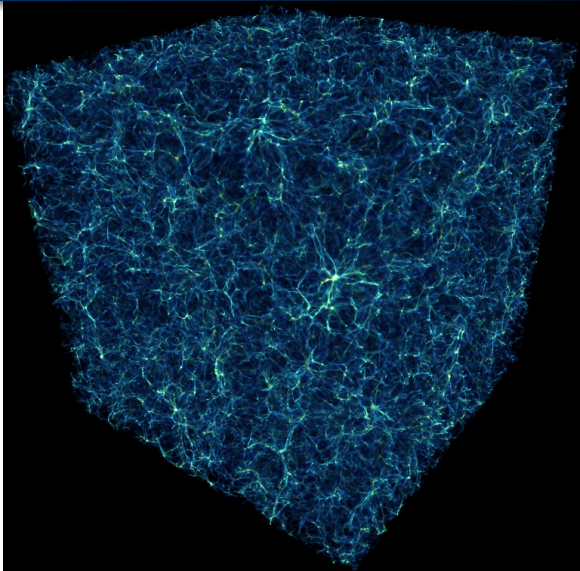
# Simulations with blazar heating

Puchwein, C.P., Springel, Broderick, Chang (2012):

- $L = 15h^{-1}$  Mpc boxes with  $2 \times 384^3$  particles
- one reference run without blazar heating
- three with blazar heating at different levels of efficiency  
(address uncertainty)
- used an up-to-date model of the UV background (Faucher-Giguère+ 2009)

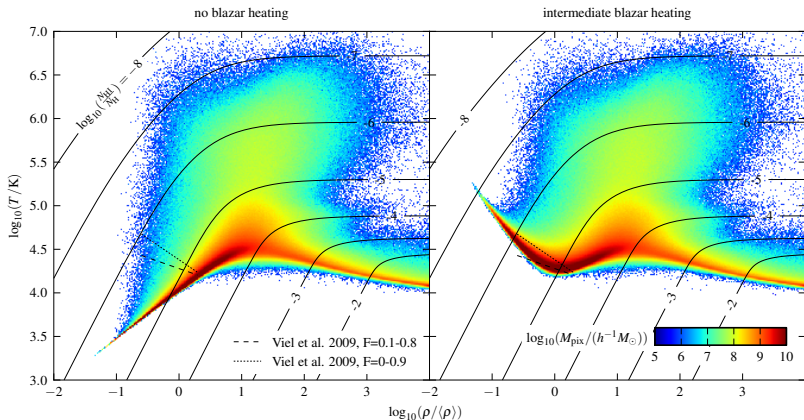


# The intergalactic medium





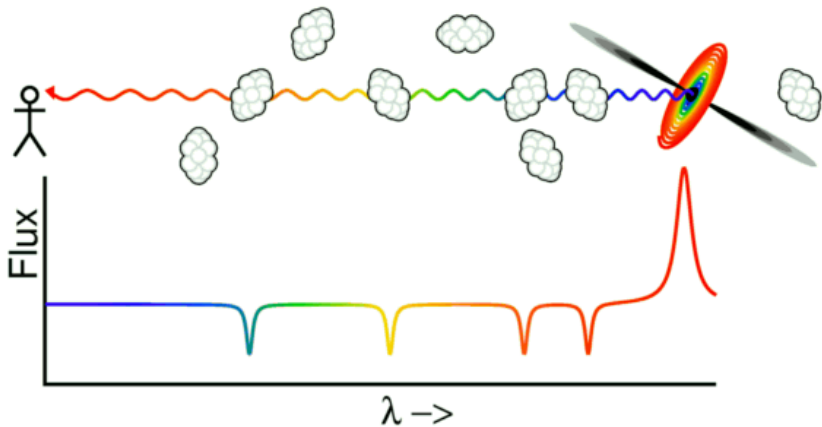
# Temperature-density relation



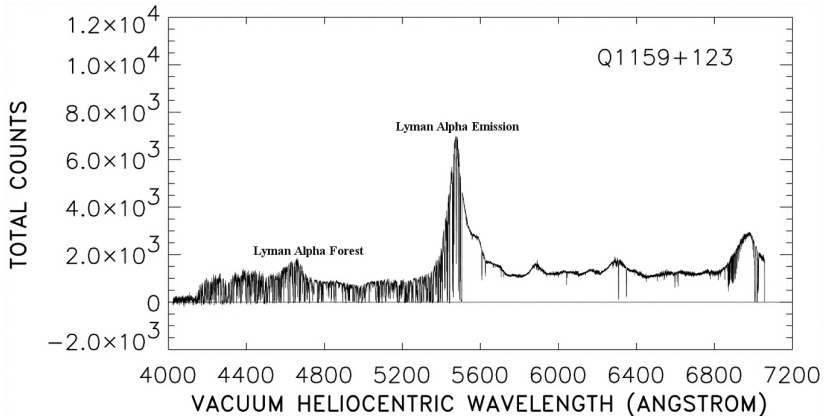
Puchwein, C.P., Springel, Broderick, Chang (2012)



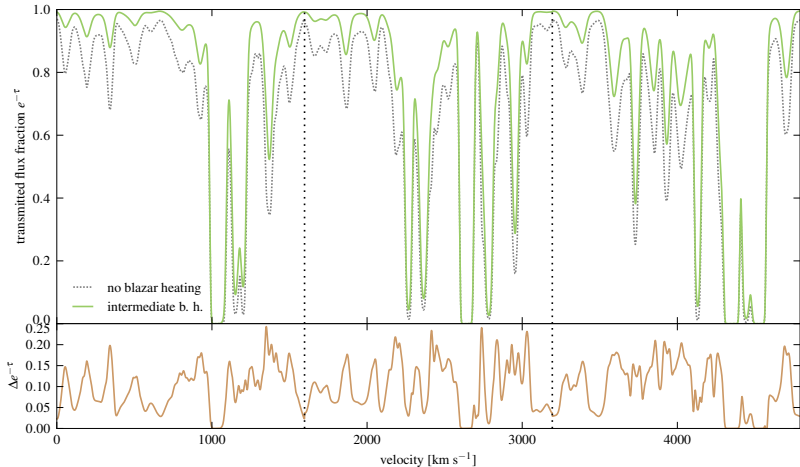
# The Lyman- $\alpha$ forest



# The observed Lyman- $\alpha$ forest



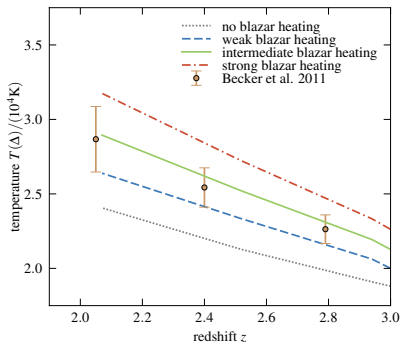
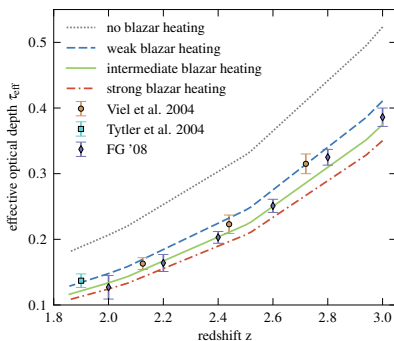
# The simulated Ly- $\alpha$ forest



Puchwein+ (2012)



# Optical depths and temperatures

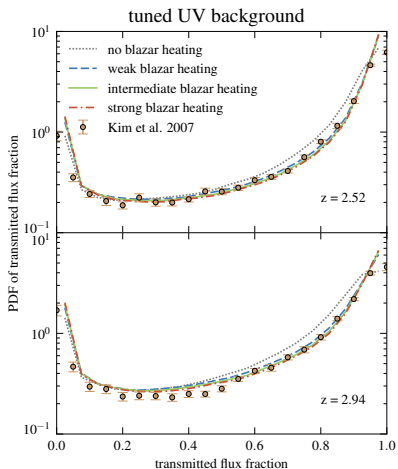


Puchwein+ (2012)

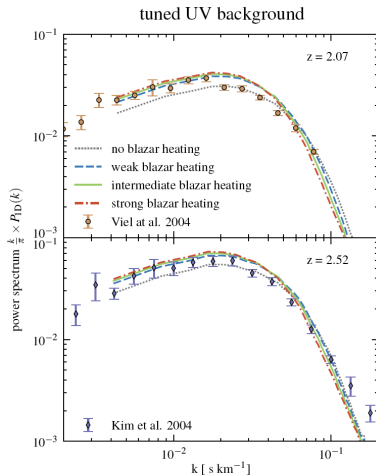
Redshift evolutions of effective optical depth and IGM temperature match data only with additional heating, e.g., provided by blazars!



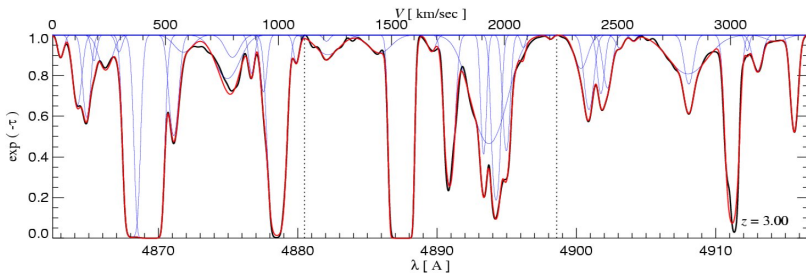
# Ly- $\alpha$ flux PDFs and power spectra



Puchwein+ (2012)



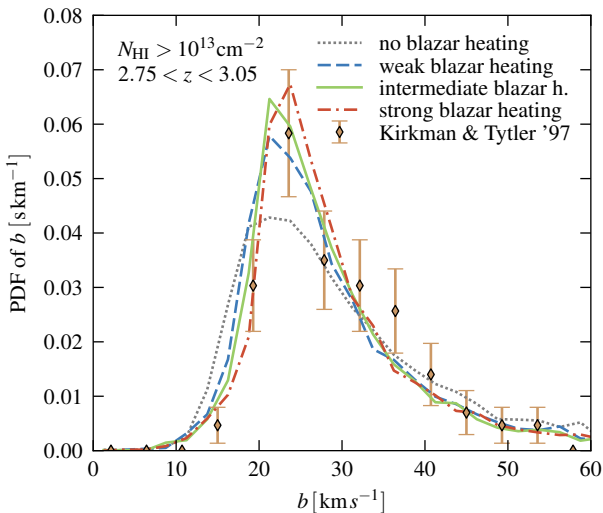
# Voigt profile decomposition



- decomposing Lyman- $\alpha$  forest into individual Voigt profiles
- allows studying the thermal broadening of absorption lines



# Voigt profile decomposition – line width distribution



Puchwein+ (2012)





# Lyman- $\alpha$ forest in a blazar heated Universe

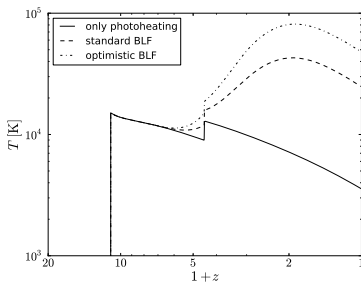
improvement in modelling the Lyman- $\alpha$  forest is a direct consequence of the peculiar properties of blazar heating:

- **heating rate independent of IGM density**  $\rightarrow$  naturally produces the inverted  $T-\rho$  relation that Lyman- $\alpha$  forest data demand
- **recent and continuous nature of the heating** needed to match the redshift evolutions of all Lyman- $\alpha$  forest statistics
- **magnitude of the heating rate required by Lyman- $\alpha$  forest data**  
 $\sim$  **the total energy output of TeV blazars** (or equivalently  $\sim 0.2\%$  of that of quasars)

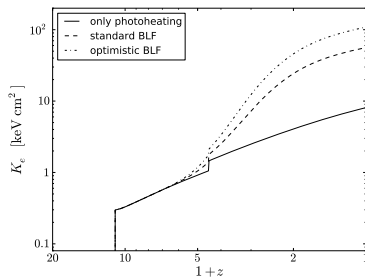


# Entropy evolution

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 – Jeans mass

- thermal pressure opposes gravitational collapse on small scales
- characteristic length/mass scale below which objects do not form
- hotter IGM  $\rightarrow$  higher IGM pressure  $\rightarrow$  **higher Jeans mass**:

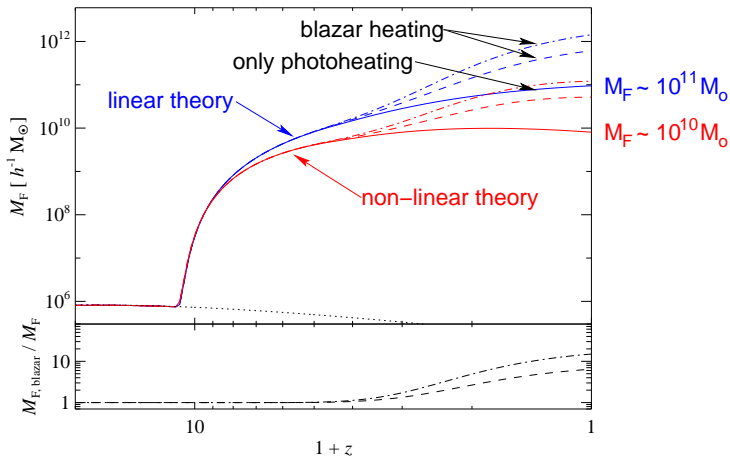
$$M_J \propto \frac{c_s^3}{\rho^{1/2}} \propto \left( \frac{T_{\text{IGM}}^3}{\rho} \right)^{1/2} \rightarrow \frac{M_{J,\text{blazar}}}{M_{J,\text{photo}}} \approx \left( \frac{T_{\text{blazar}}}{T_{\text{photo}}} \right)^{3/2} \gtrsim 30$$

$\rightarrow$  depends on instantaneous value of  $c_s$

- “**filtering mass**” depends on full thermal history of the gas: accounts for delayed response of pressure in counteracting gravitational collapse in the expanding universe
- apply corrections for **non-linear collapse**



# Dwarf galaxy formation – Filtering mass

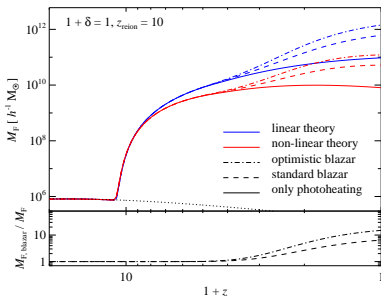


C.P., Chang, Broderick (2012)

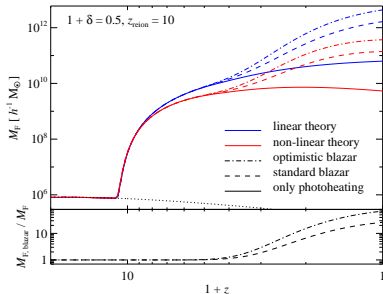


# Peebles' void phenomenon explained?

mean density



void,  $1 + \delta = 0.5$

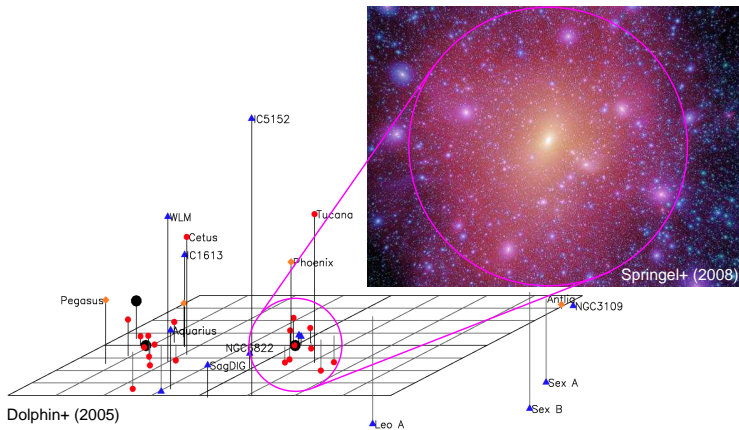


C.P., Chang, Broderick (2012)

- 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



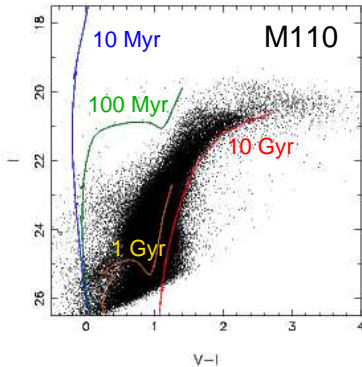
# “Missing satellite” problem in the Milky Way



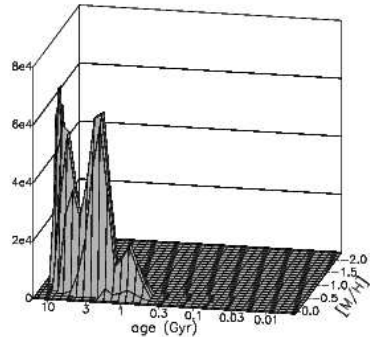
Substructures in cold DM simulations much more numerous than observed number of Milky Way satellites!



# When do dwarfs form?



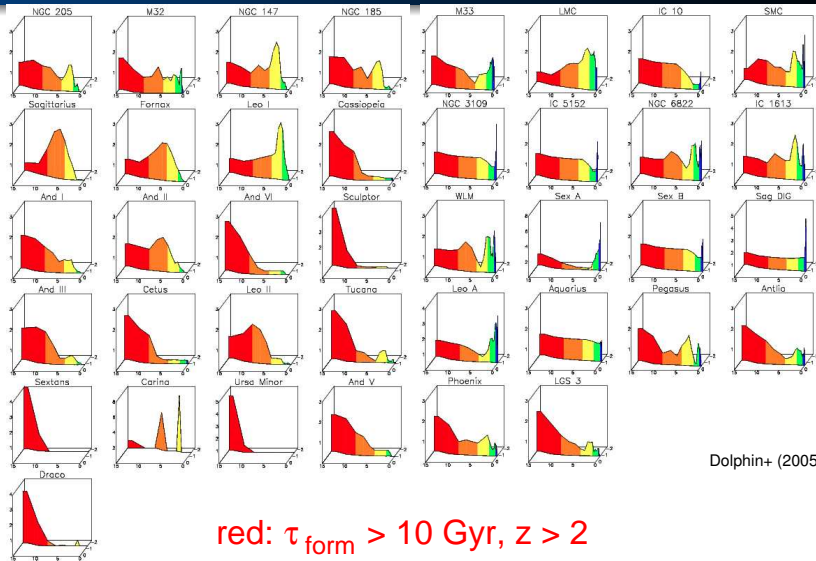
Dolphin+ (2005)



isochrone fitting for different metallicities → star formation histories



# When do dwarfs form?



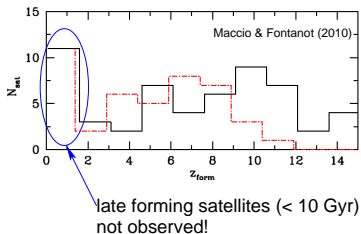
Dolphin+ (2005)



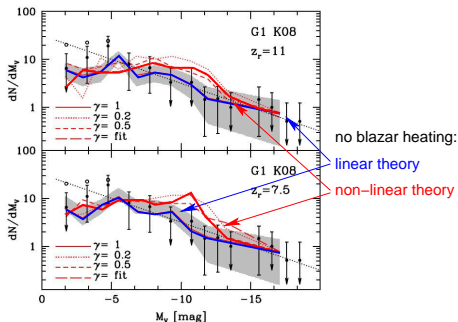


# Milky Way satellites: formation history and abundance

satellite formation time



satellite luminosity function

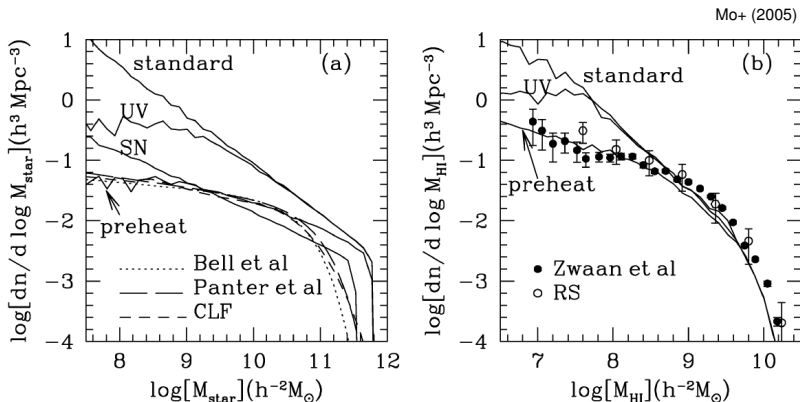


Maccio+ (2010)

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



# Galactic H I-mass function

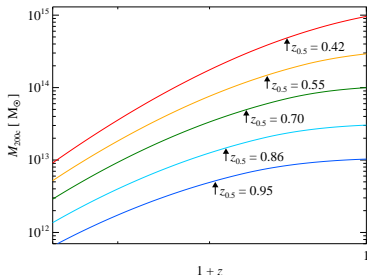


- H I-mass function is too flat (i.e., gas version of missing dwarf problem!)
- photoheating and SN feedback too inefficient
- IGM entropy floor of  $K \sim 15 \text{ keV cm}^2$  at  $z \sim 2 - 3$  successful!

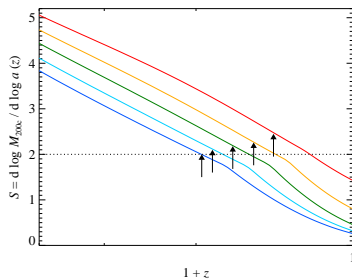


# When do clusters form?

mass accretion history



mass accretion rates



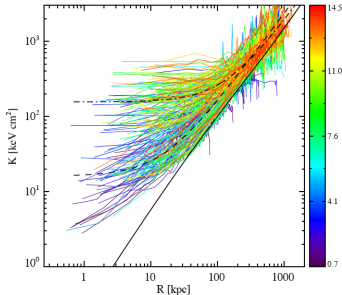
C.P., Chang, Broderick (2012)

- most cluster gas accretes after  $z = 1$ , when blazar heating can have a large effect (for late forming objects)!



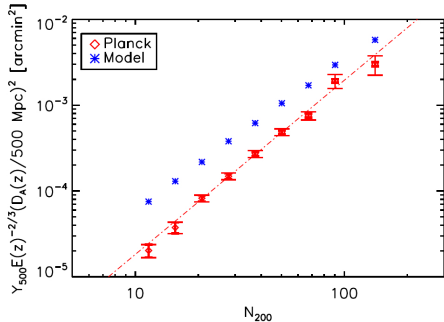
# Entropy floor in clusters

Cluster entropy profiles



Cavagnolo+ (2009)

Planck stacking of optical clusters



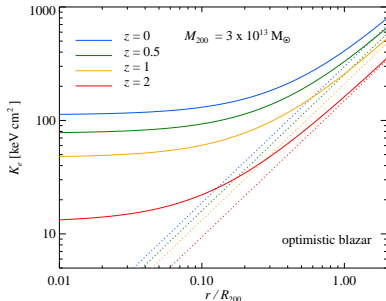
Planck Collaboration (2011)

- Do optical and X-ray/Sunyaev-Zel'dovich cluster observations probe the same population? (Hicks+ 2008, Planck Collaboration 2011)

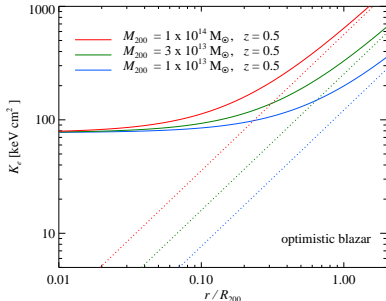


# Entropy profiles: effect of blazar heating

varying formation time



varying cluster mass



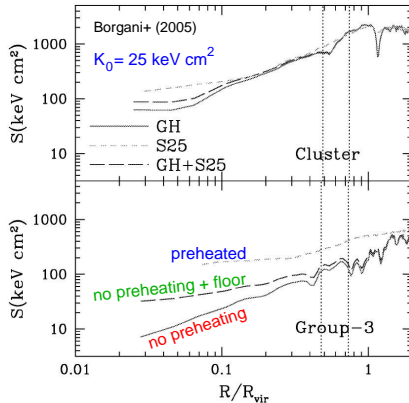
C.P., Chang, Broderick (2012)

**assume** big fraction of intra-cluster medium collapses from IGM:

- redshift-dependent entropy excess in cores
- greatest effect for late forming groups/small clusters



# Gravitational reprocessing of entropy floors

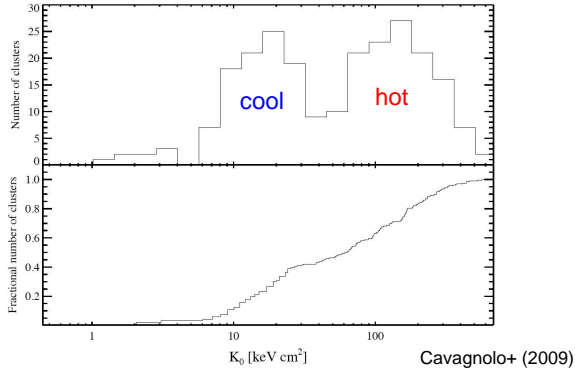


Borgani+ (2005)

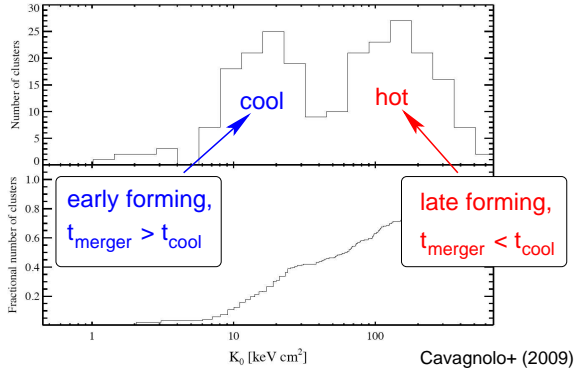
- greater initial entropy  $K_0$   
 → more shock heating  
 → greater increase in  $K_0$   
 over entropy floor
- net  $K_0$  amplification of 3-5
- expect:  
 median  $K_{e,0} \sim 150 \text{ keV cm}^2$   
 max.  $K_{e,0} \sim 600 \text{ keV cm}^2$



# Cool-core versus non-cool core clusters



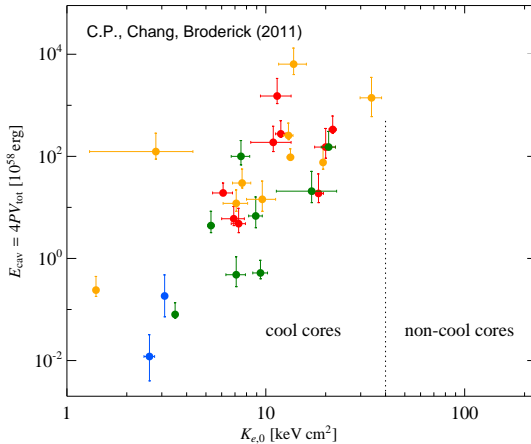
# Cool-core versus non-cool core clusters



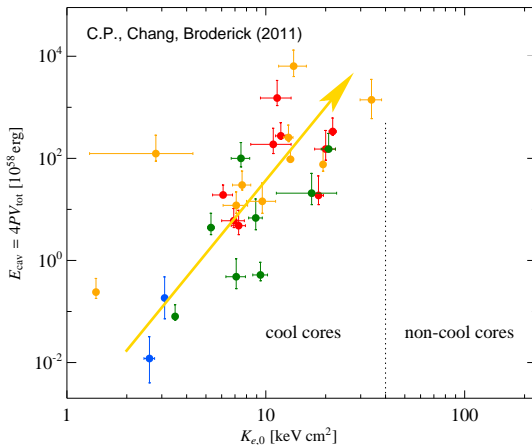
- time-dependent preheating + gravitational reprocessing  
→ CC-NCC bifurcation (two attractor solutions)
- need hydrodynamic simulations to confirm this scenario



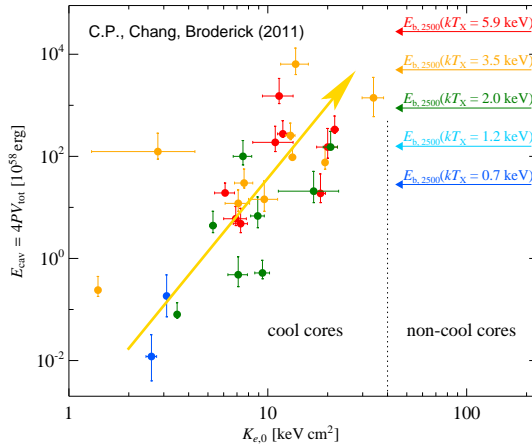
# How efficient is heating by AGN feedback?



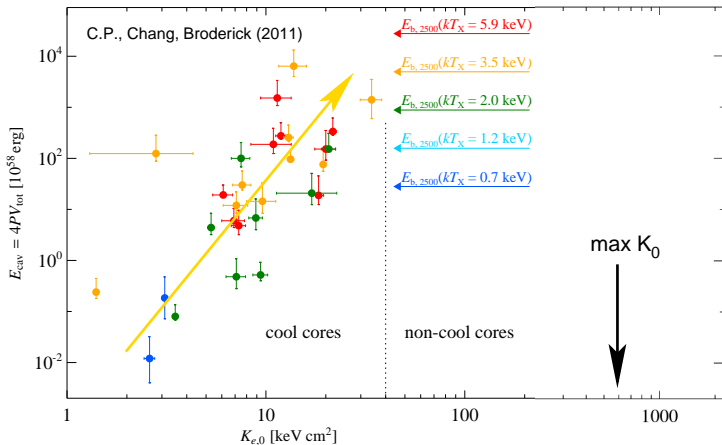
# How efficient is heating by AGN feedback?



# How efficient is heating by AGN feedback?



# How efficient is heating by AGN feedback?



**AGNs cannot transform CC to NCC clusters** (on a buoyancy timescale)



# 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  $T-\rho$  relation
  - quantitative self-consistent picture of high- $z$  Lyman- $\alpha$  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



# 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- $\alpha$  forest in a blazar-heated Universe*, MNRAS, 423, 149, 2012.



# Additional slides



# 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!**

## 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!**





# Measuring IGM $B$ -fields from TeV/GeV observations

- TeV beam of  $e^+ / e^-$  are deflected out of the line of sight reducing the GeV IC flux  $\rightarrow$  **lower limit on  $B$**
- Larmor radius

$$r_L = \frac{E}{eB} \sim 30 \left( \frac{E}{3 \text{ TeV}} \right) \left( \frac{B}{10^{-16} \text{ G}} \right)^{-1} \text{ Mpc}$$

- IC mean free path

$$x_{\text{IC}} \sim 0.1 \left( \frac{E}{3 \text{ TeV}} \right)^{-1} \text{ Mpc}$$

- for the associated 10 GeV IC photons the *Fermi* angular resolution is  $0.2^\circ$  or  $\theta \sim 3 \times 10^{-3}$  rad

$$\frac{x_{\text{IC}}}{r_L} > \theta \rightarrow B \gtrsim 10^{-16} \text{ G}$$

