The Cosmological Impact of Blazars: from Plasma Instabilities to Structure Formation

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in collaboration with

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Outline

1. Physics of blazar heating
   - TeV emission from blazars
   - Plasma instabilities and magnetic fields
   - Extragalactic gamma-ray background
2. The intergalactic medium
   - Properties of blazar heating
   - Thermal history of the IGM
   - The Lyman-α forest
3. Structure formation
   - Entropy evolution
   - Formation of dwarf galaxies
   - Bimodality of galaxy clusters

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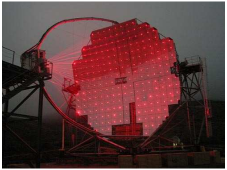
TeV gamma-ray astronomy

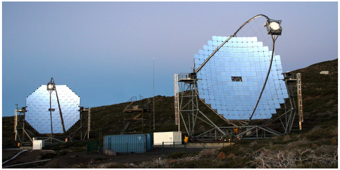
H.E.S.S.

MAGIC I

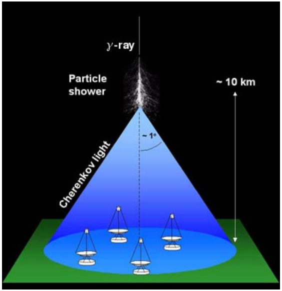


VERITAS

MAGIC II

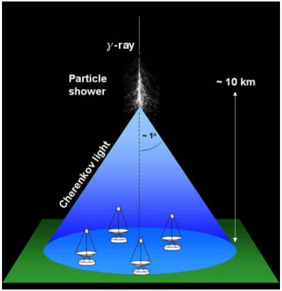


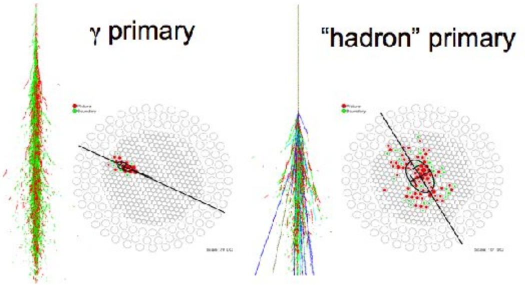
Imaging air Čerenkov telescopes – the technique



- high-energy γ-ray impacts the Earth's atmosphere and sets off an electro-magnetic cascade in the vicinity of a nucleus
- e^+/e^- travel faster than the speed of light in the atmosphere $\rightarrow$ emission of a cone of blue Čerenkov light

Imaging air Čerenkov telescopes – the technique



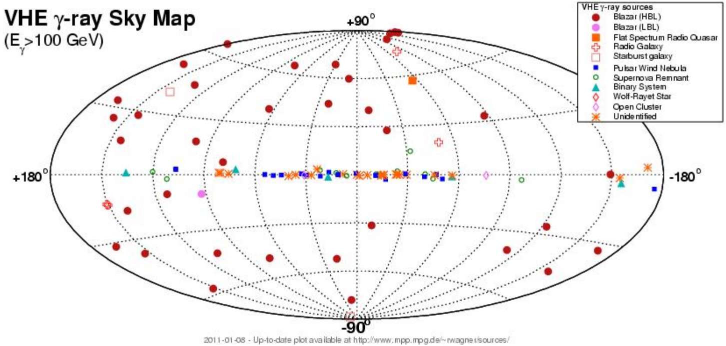


- primary γ-rays and hadrons cause different shower characteristics $\rightarrow$ separation of γ-rays from 'background' events
- opening angle and shower location in the shower image allows reconstructing the initial energy and direction of the γ-ray

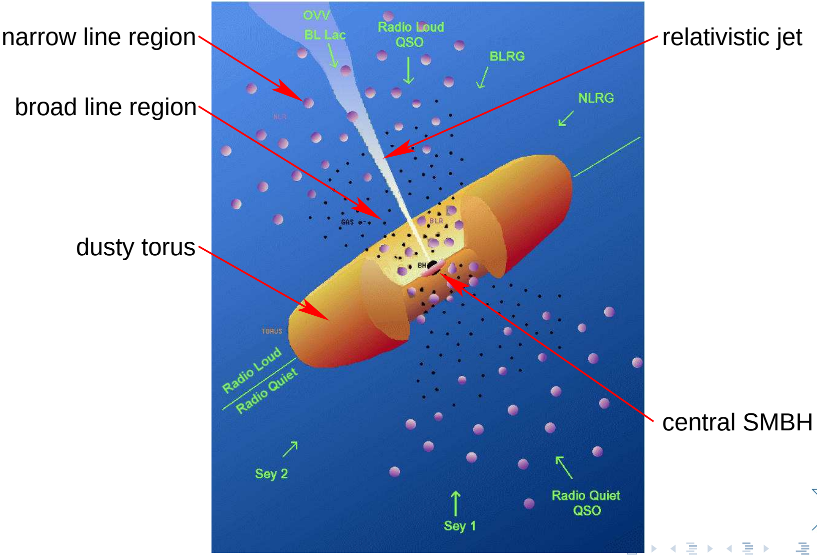
The TeV gamma-ray sky

There are several classes of TeV sources:

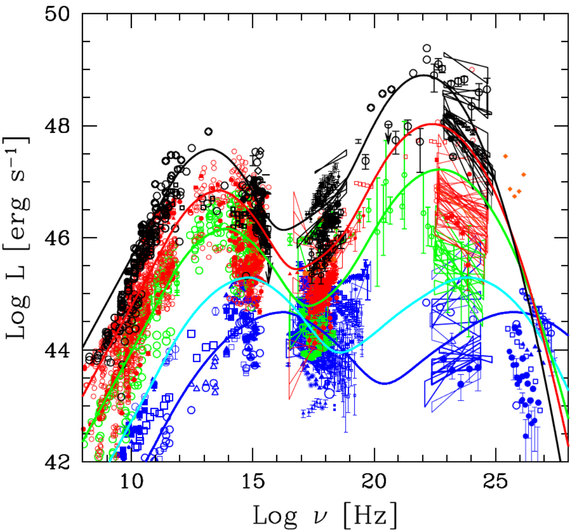
- Galactic - pulsars, BH binaries, supernova remnants
- Extragalactic - **mostly** blazars, two starburst galaxies



Unified model of active galactic nuclei



The blazar sequence



Ghisellini (2011)

Propagation of TeV photons

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

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

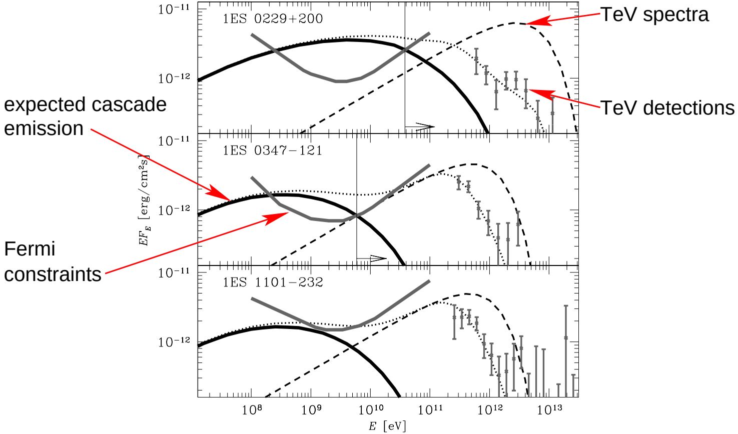
- mean free path for this depends on the density of 1 eV photons:
  $\rightarrow$ typically $\sim (35 \ldots 700)$ Mpc for $z = 1 \ldots 0$
  $\rightarrow$ pairs produced with energy of 0.5 TeV ($\gamma = 10^6$)
- these pairs inverse Compton scatter off the CMB photons
  $\rightarrow$ mean free path is $\sim (45 \ldots 700)$ kpc
  $\rightarrow$ producing gamma-rays of $\sim$ 1 GeV

$$E \sim \gamma^2 E_{\rm CMB} \sim 1\ \mathrm{GeV}$$

- 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!**



Neronov & Vovk (2010)

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:
- Larmor radius

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

- IC mean free path

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

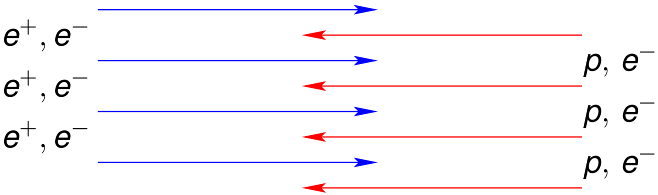
- for the associated 10 GeV IC photons angular resolution is 0.2° or $\theta \sim 3 \times 10^{-3}$ rad

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

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:



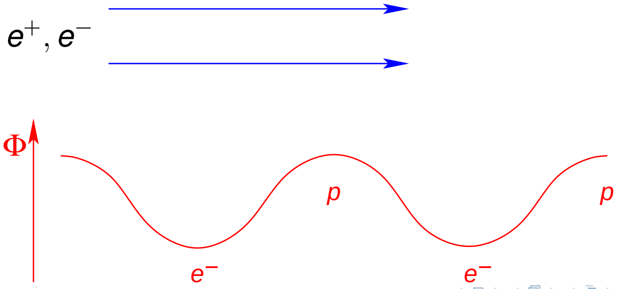
- one frequency (timescale) and one length in the problem:

$$\frac{\omega_p}{\gamma} = \sqrt{\frac{4\pi e^2 n_e}{\gamma^2 m_e}} \qquad \lambda_p = \frac{\gamma c}{\omega_p}$$

Two-stream instability: mechanism

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

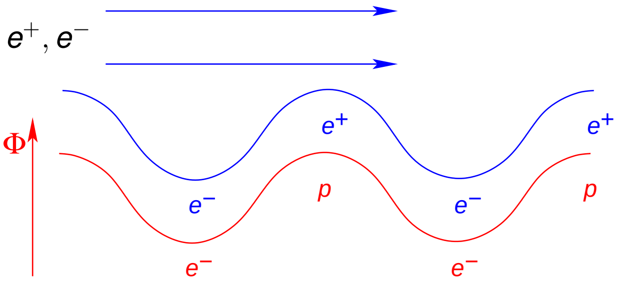
- initially homogeneous beam-e^-:
  attractive (repulsive) force by potential maxima (minima)
- e^- attain lowest velocity in potential minima → bunching up
- e^+ attain lowest velocity in potential maxima → bunching up



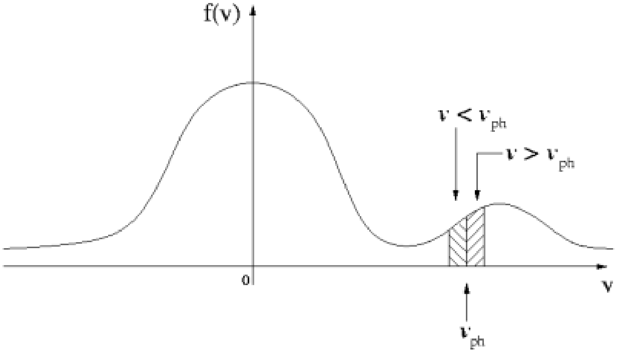
Two-stream instability: mechanism

wave-like perturbation with $\boldsymbol{k} || \boldsymbol{v}_{\text{beam}}$, 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^- → positive feedback
- exponential wave-growth → instability



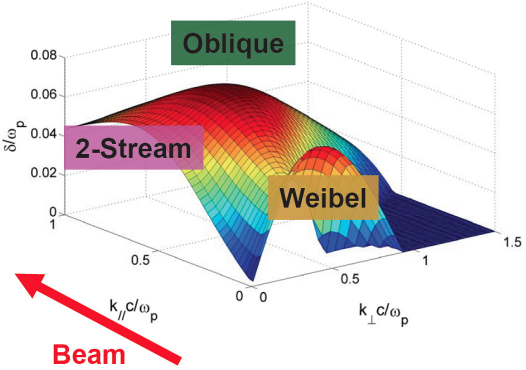
Two-stream instability: energy transfer

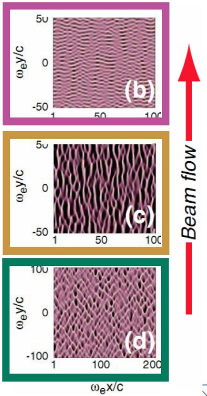


- energy is transferred to the plasma wave from particles with $v \gtrsim v_{\text{phase}} \rightarrow$ growing modes
- energy is transferred from the plasma wave to particles with $v \lesssim v_{\text{phase}} \rightarrow$ damped modes

Oblique instability

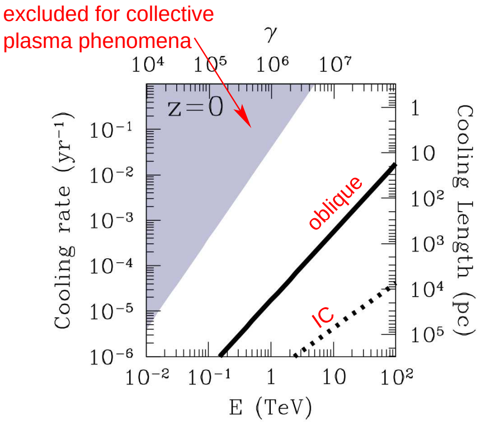
k oblique to $\boldsymbol{v}_{\text{beam}}$: real word perturbations don't choose "easy" alignment $= \sum$ all orientations





Bret (2009), Bret+ (2010)

Beam physics – growth rates



Broderick, Chang, C.P. (2011)

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

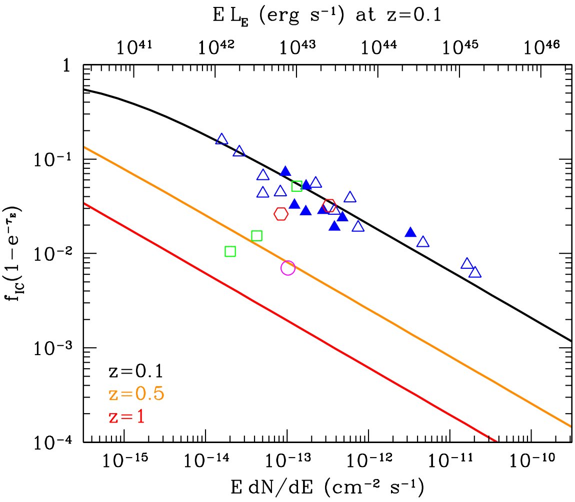
$$\sim 0.4\,\gamma\,\frac{n_{\mathrm{beam}}}{n_{\mathrm{IGM}}}\,\omega_p$$

- oblique instability beats IC by two orders of magnitude

Beam physics – growth rates

- non-linear evolution of these instabilities at these density contrasts is not known
- expectation from PIC simulations suggest substantial isotropization of the beam
- no need for intergalactic magnetic field to deflect pairs
- plasma instabilities dissipate the beam's energy, no energy left over for inverse Compton scattering off the CMB

Implications for *B*-field measurements

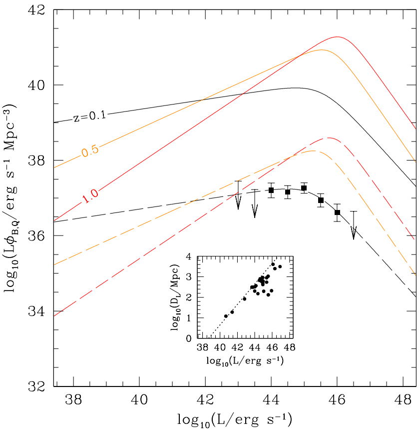


Broderick, Chang, C.P. (2011)

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
- $\sim$ 1–10% of beam energy to IC CMB photons
- TeV blazar spectra are not suitable to measure IGM *B*-fields

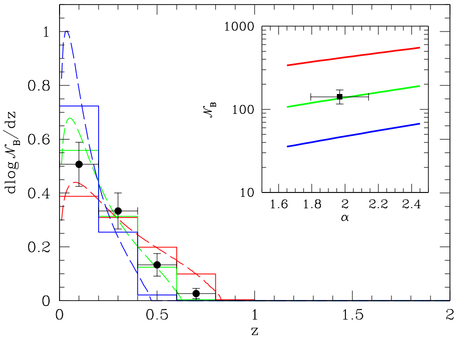
TeV blazar luminosity density



Broderick, Chang, C.P. (2011)

- collect luminosity of all 23 TeV blazars with good spectral measurements
- account for the selection effects
- TeV blazar luminosity density is a scaled version ($\eta_B \sim 0.2\%$) of that of quasars!
- assume that they trace each other for all z

Fermi number count of "TeV blazars"

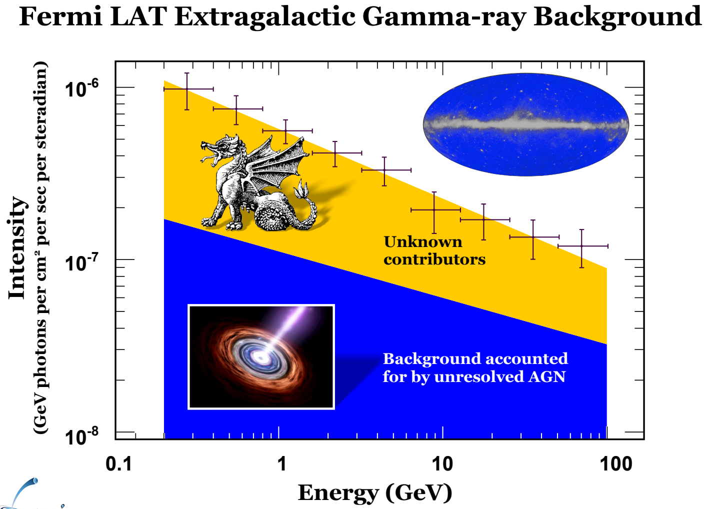


Broderick, Chang, C.P. (2011)

- number evolution of TeV blazars that are expected to have been observed by *Fermi* vs. observed evolution
- different colors correspond to different spectra connecting the *Fermi* and the TeV-energy band

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

Fermi probes "dragons" of the gamma-ray sky



Extragalactic gamma-ray background

- assume all TeV blazars have identical intrinsic spectra:

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

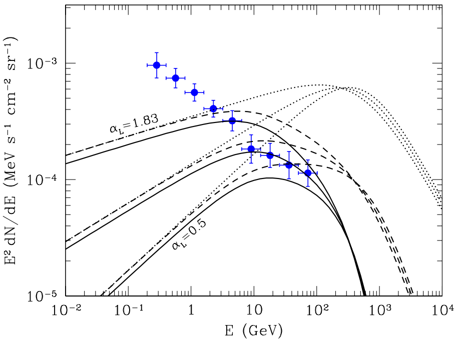
  where E_b is the energy of the spectral break, and $\alpha_L < \alpha$ are the low and high-energy spectral indexes

- spectrum of the extragalactic gamma-ray background:

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

  where $E' = E(1 + z')$, $\tilde{\Lambda}_Q$ is the physical quasar luminosity density, and $\tau(E, z)$ is the optical depth to TeV-gamma rays emitted with energy E from an object located at z

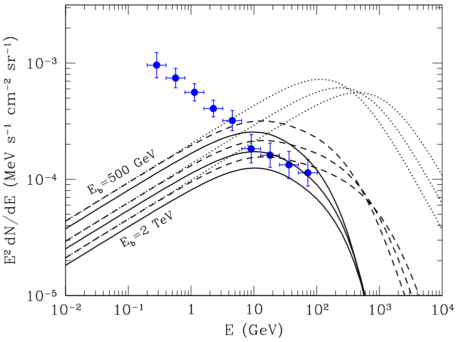
Extragalactic gamma-ray background: varying α_L



Broderick, Chang, C.P. (2011)

- *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. (2011)

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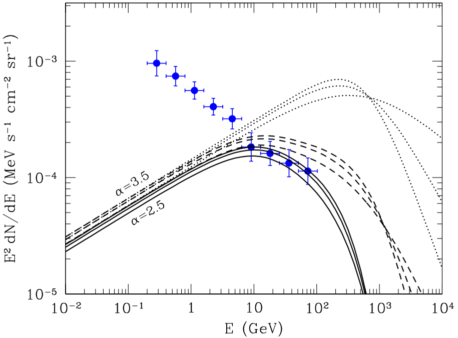

Broderick, Chang, C.P. (2011)

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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 TeV blazars trace quasars for all z and adopting typical spectra, we can match the *Fermi*-LAT extragalactic gamma-ray background
- evolving blazars do not overproduce EGRB since the absorbed energy is not reprocessed to GeV energies
- fraction of absorbed energy is larger at higher z and energies

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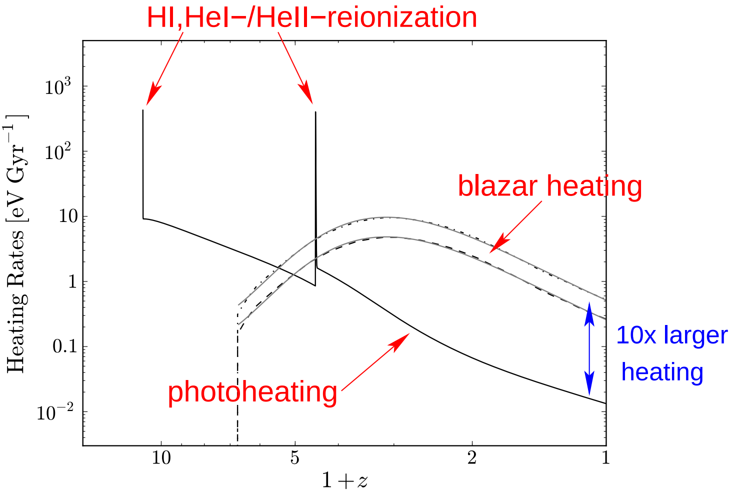
Evolution of the heating rates



Chang, Broderick, C.P. (2011)

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)

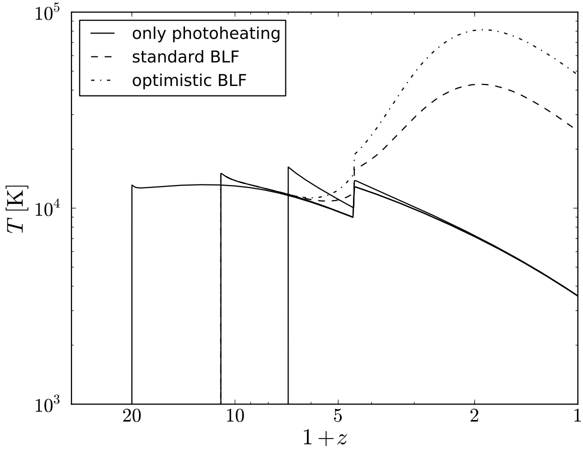
$$\varepsilon_{\mathrm{rad}} = \eta\, \Omega_{\mathrm{bh}} \sim 0.1 \times 10^{-4} \sim 10^{-5}$$

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

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

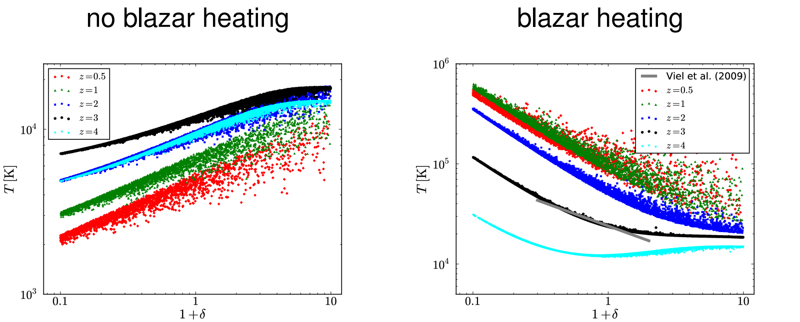
- photoheating efficiency $\eta_{\mathrm{ph}} \sim 10^{-3} \quad \rightarrow \quad kT \sim \eta_{\mathrm{ph}}\, \varepsilon_{\mathrm{UV}}\, m_{\mathrm{p}} c^2 \sim \mathrm{eV}$
  (limitted by the abundance of H I/He II due to the small recombination rate)
- blazar heating efficiency $\eta_{\mathrm{bh}}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

Thermal history of the IGM



Chang, Broderick, C.P. (2011)

Evolution of the temperature-density relation



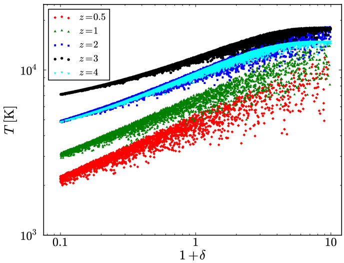
Chang, Broderick, C.P. (2011)

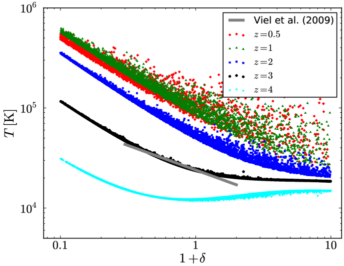
- blazars and extragalactic background light are uniform
  $\rightarrow$ blazar heating independent of density
  $\rightarrow$ causes inverted temperature-density relation, $T \propto 1/\delta$
- blazars completely change the thermal history of the diffuse IGM and late-time structure formation

Evolution of the temperature-density relation

no blazar heating

blazar heating





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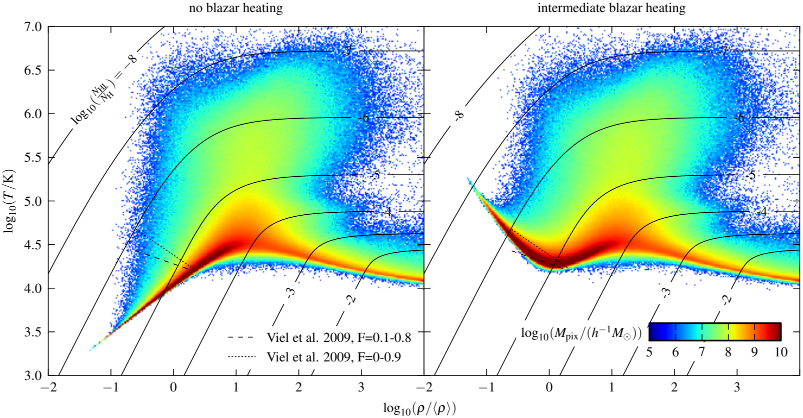
Simulations with blazar heating

Puchwein, C.P., Springel, Broderick, Chang (2011):

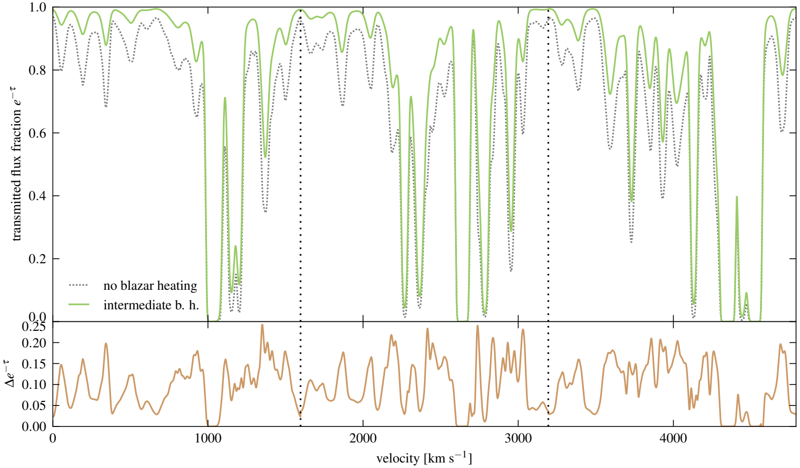
- $L = 15h^{-1}\mathrm{Mpc}$ boxes with 2×384^3 particles
- one reference run without blazar heating
- three with blazar heating at different levels of efficiency (to account for uncertainties in the expected blazar-heating rate)
- used an up-to-date model of the UV background (Faucher-Giguère et al. 2009)

Temperature-density relation



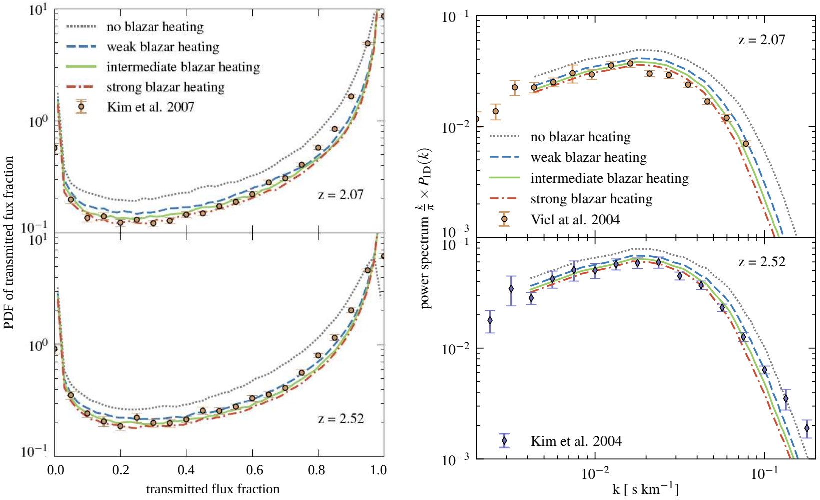
Puchwein, C.P., Springel, Broderick, Chang (2011)

Ly-α spectra



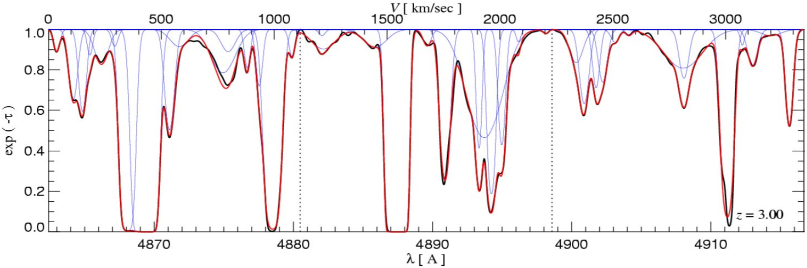
Puchwein+ (2011)

Ly-α flux PDFs and power spectra



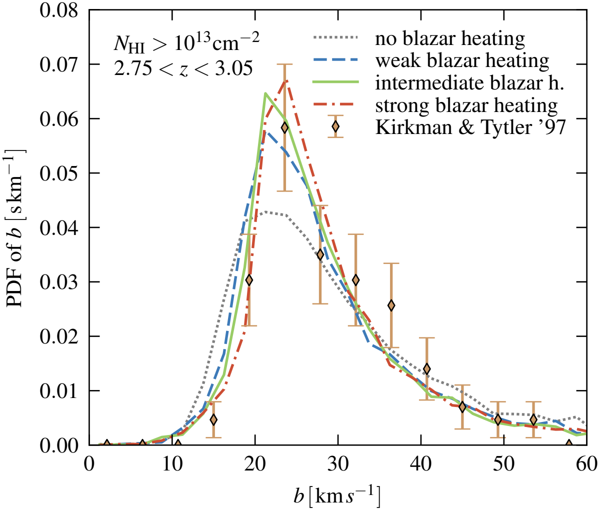
Puchwein+ (2011)

Voigt profile decomposition



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

Voigt profile decomposition – line width distribution



Puchwein+ (2011)

Lyman-α forest in a blazar heated Universe

impressive improvement in modelling the Lyman-α forest is a direct consequence of the peculiar properties of blazar heating:

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

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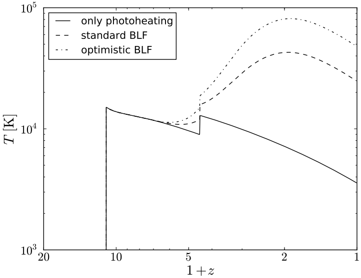
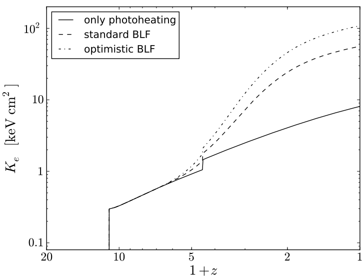
Entropy evolution

temperature evolution



entropy evolution

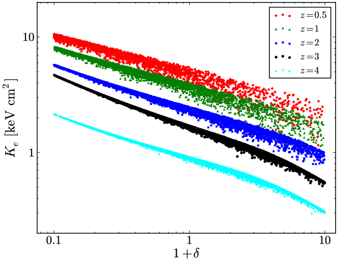


C.P., Chang, Broderick (2011)

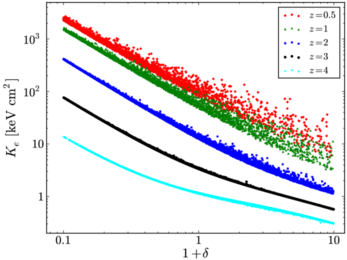
- evolution of the entropy, $K_\mathrm{e} = kTn_\mathrm{e}^{-2/3}$, at mean density
- blazar heating substantially increases the entropy floor ($z \lesssim 2$)

Evolution of the entropy-density relation

no blazar heating



blazar heating



C.P., Chang, Broderick (2011)

- blazar heating substantially increases the entropy in voids
- scatter is also increased → larger stochasticity of structure formation

HITS

Jeans mass

- on small enough scales, the thermal pressure can oppose gravitational collapse of the gas
- characteristic length scale below which objects will not form
- Jeans wavenumber and mass is obtained by balancing the sound crossing and free-fall timescales

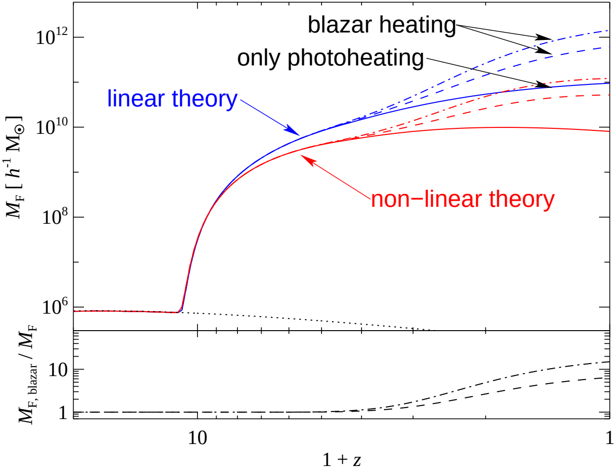
$$k_J(a) \equiv \frac{a}{c_s(a)} \sqrt{4\pi G\bar{\rho}(a)}$$

$$M_J(a) \equiv \frac{4\pi}{3}\,\bar{\rho}(a) \left(\frac{2\pi a}{k_J(a)}\right)^3 = \frac{4\pi^{5/2}}{3}\,\frac{c_s^3(a)}{G^{3/2}\bar{\rho}^{1/2}(a)}$$

- blazar heating increases the IGM temperature by ~ 10:

$$\frac{M_{J,\mathrm{blazar}}}{M_{J,\mathrm{photo}}} = \left(\frac{c_{\mathrm{s,blazar}}}{c_{\mathrm{s,photo}}}\right)^3 = \left(\frac{T_{\mathrm{blazar}}}{T_{\mathrm{photo}}}\right)^{3/2} \gtrsim 30$$

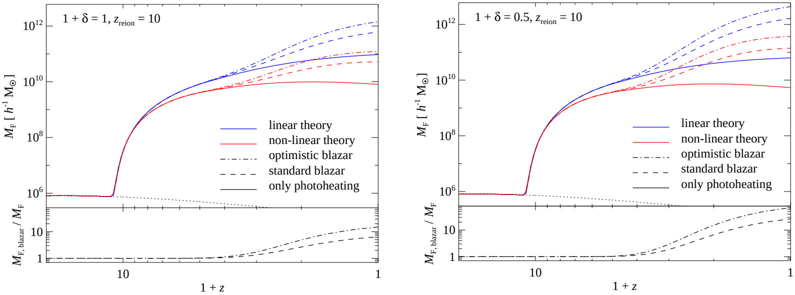
Filtering mass – dwarf formation



C.P., Chang, Broderick (2011)

Peebles' void phenomenon explained?

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

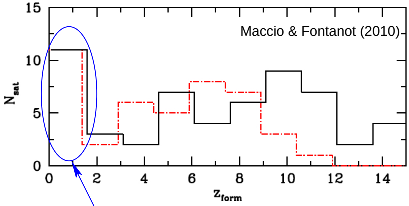


C.P., Chang, Broderick (2011)

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

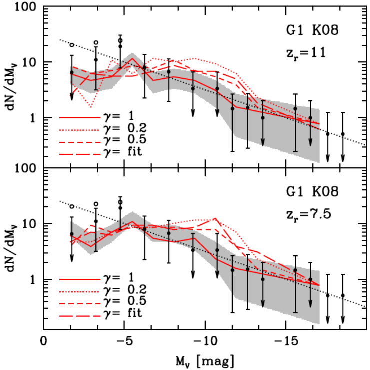
"Missing satellite" problem in the Milky Way

satellite formation time



late forming satellites (< 10 Gyr) not observed!

satellite luminosity function



Maccio+ (2010)

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

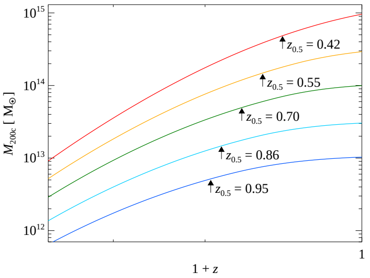
Blazar heating: AGN feedback vs. pre-heating

Blazar heating is an amalgam of pre-heating and AGN feedback:

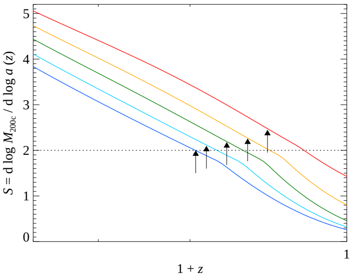
- blazar heating is not localized ($\neq$ AGN feedback)
  $\rightarrow$ may change initial conditions for forming groups (but provides no stability for cool cores, CCs)
- blazar heating generates time-dependent entropy floor ($\neq$ pre-heating)
  $\rightarrow$ may solve the classical problems of pre-heating ($z \sim 3$):
  - provides a physical mechanism
  - does not starve galaxy formation for $z \lesssim 3$
  - early forming groups can cool and develop observed low-K_e cores

Mass accretion history of groups/clusters

mass accretion history



mass accretion rates

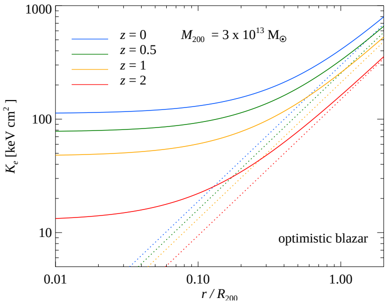


C.P., Chang, Broderick (2011)

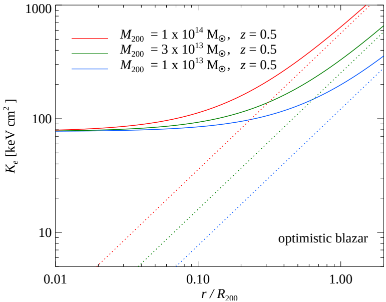
- peak entropy injection from blazar heating ($z \sim 1$) matches formation time of groups
- early forming groups are unaffected and develop cool cores
- late forming groups may have an elevated entropy core

Entropy profiles: effect of blazar heating

varying formation time



varying cluster mass



C.P., Chang, Broderick (2011)

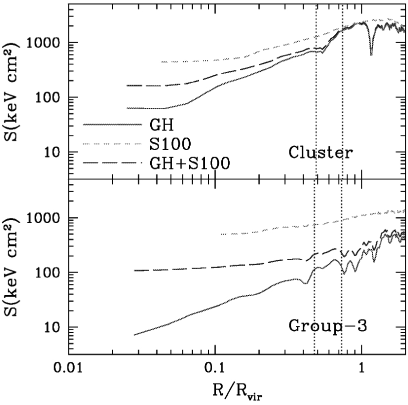
If significant fraction of intra-group medium collapses from IGM:

- z-dependent excess entropy in cores (no cooling)
- largest effect for late forming, small objects

Scenario for the bimodality of cluster core entropies?

- entropy core, $K_{e,0}$, immediately after formation is set by the z-dependent blazar heating
- only late forming groups ($z \lesssim 1$) are directly affected by blazar (pre-)heating
- if the cooling time, t_{cool}, is shorter than the time period to the successive merger, t_{merger}, the group will radiate away the elevated core entropy and evolve into a CC
- if $t_{cool} > t_{merger}$, merger shocks can gravitationally reprocess the entropy cores and amplify them → potentially those forming clusters evolve into non-cool core (NCC) systems

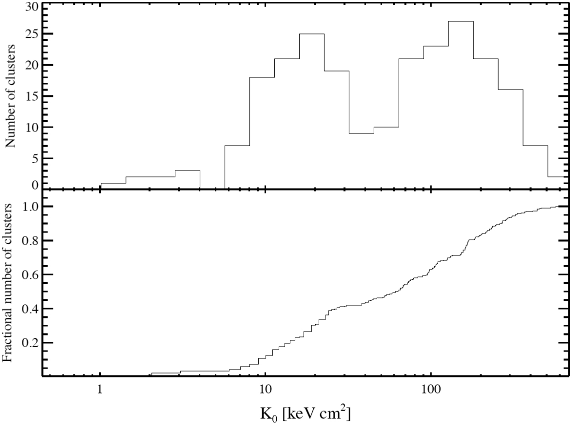
Gravitational reprocessing of entropy floors



Borgani+ (2005)

- larger $K_{e,0}$ of a merging cluster facilitates shock heating $\rightarrow$ increase of $K_{e,0}$ over entropy floor
- entropy floor of 100 keV cm^2 at $z = 3$ in non-radiative simulation: net entropy amplification factor $\sim$ 3–5 for clusters and groups (Borgani+ 2005)
- expect median of $K_{e,0} \sim 150$ keV cm^2; maximum $K_{e,0} \sim 600$ keV cm^2

Bimodality of cluster core entropies



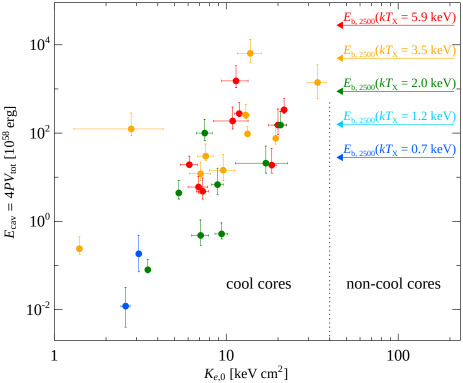
Cavagnolo+ (2009)

- *Chandra* observations match blazar heating expectations!
- need hydrodynamic simulations to confirm this scenario

Conclusions on blazar heating

- explains puzzles in high-energy astrophysics:
  - TeV blazars can evolve like quasars
  - extragalactic gamma-ray background at $E \gtrsim 10$ GeV
  - invalidates intergalactic B-constraints from blazar spectra
- novel mechanism; dramatically alters thermal history of the IGM:
  - uniform and z-dependent preheating
  - rate independent of density $\rightarrow$ inverted T–ρ relation
  - consistent picture of Lyman-α forest
- significantly modifies late-time structure formation:
  - suppresses late formation of dwarfs: "missing satellite" problem, void phenomenon
  - group/cluster bimodality of core entropy values

How efficient is heating by AGN feedback?



C.P., Chang, Broderick (2011)

- cavity enthalpy

$$E_{cav} = 4\,PV_{tot}$$

- in some cases

$$E_{cav} \gtrsim E_{bind}(R_{2500})$$

- cavity energy only couples weakly into ICM, but prevents cooling catastrophe

- on a buoyancy timescale, no AGN outburst transforms a CC to a non-cool core (NCC) cluster!

HITS