The Physics and Cosmology of TeV Blazars

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in collaboration with

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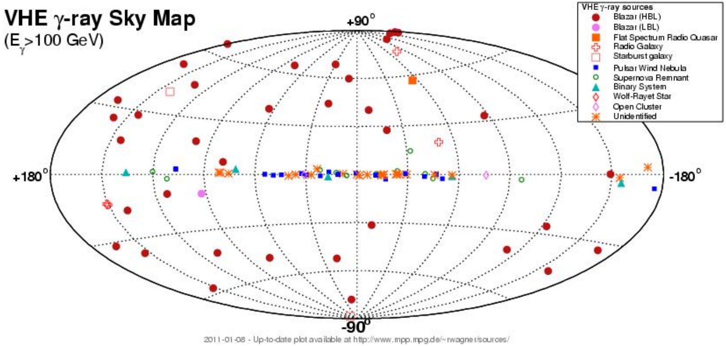
Outline

The TeV gamma-ray sky

There are several classes of TeV sources:

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



Propagation of TeV photons

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

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

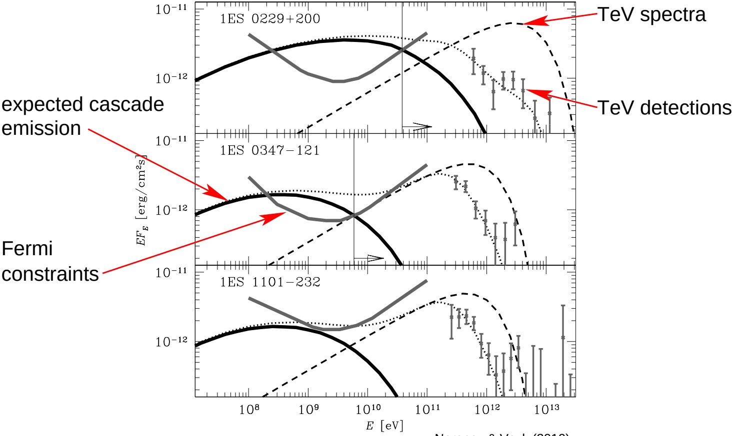
- mean free path for this depends on the density of 1 eV photons:
  $\rightarrow \lambda_{\gamma\gamma} \sim (35 \ldots 700)$ Mpc for $z = 1 \ldots 0$
  $\rightarrow$ pairs produced with energy of 0.5 TeV ($\gamma = 10^6$)
- these pairs inverse Compton scatter off the CMB photons:
  $\rightarrow$ mean free path is $\lambda_{\mathrm{IC}} \sim \lambda_{\gamma\gamma}/1000$
  $\rightarrow$ producing gamma-rays of $\sim$ 1 GeV

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

- 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!** → **limits on extragalactic magnetic fields?**

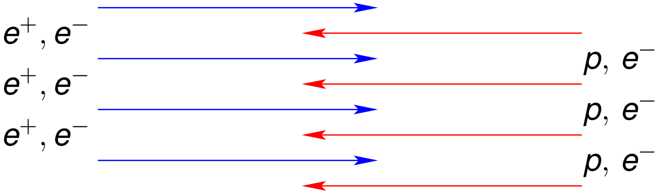


Neronov & Vovk (2010)

Missing plasma physics?

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

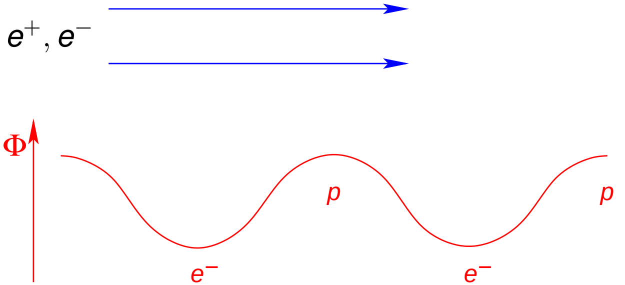
- plasma processes are important
- interpenetrating beams of charged particles are unstable



Two-stream instability: mechanism

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

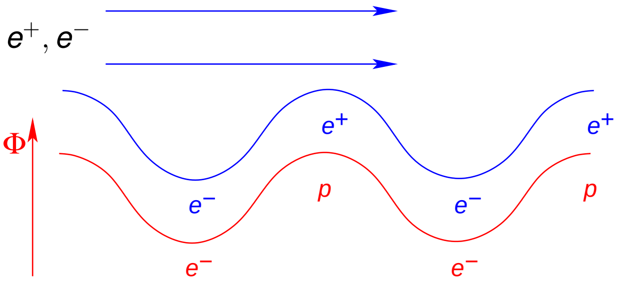
- initially homogeneous beam-e^-:
  attractive (repulsive) force by potential maxima (minima)
- e^- attain lowest velocity in potential minima $\rightarrow$ bunching up
- e^+ attain lowest velocity in potential maxima $\rightarrow$ bunching up



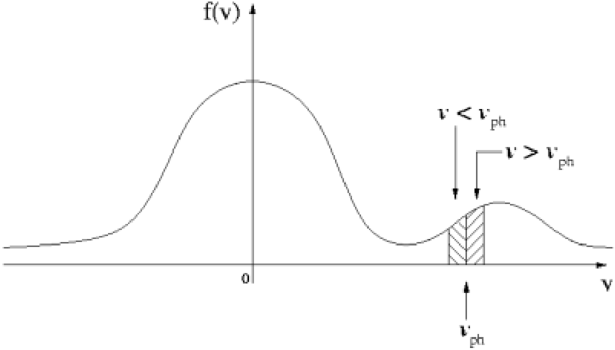
Two-stream instability: mechanism

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



Two-stream instability: momentum transfer

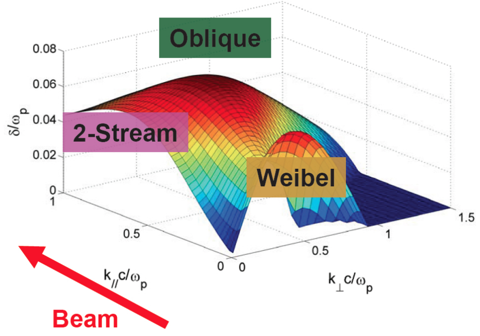


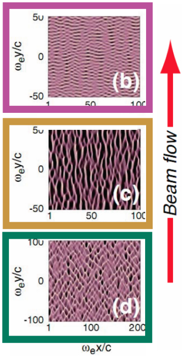
- particles with $v \gtrsim v_{\rm phase}$:
  pair momentum → plasma waves: growing modes/instability
- particles with $v \lesssim v_{\rm phase}$:
  plasma wave momentum → pairs: damping (Landau damping)

Oblique instability

- $\boldsymbol{k}$ oblique to $\boldsymbol{v}_{\text{beam}}$: real word perturbations don't choose "easy" alignment $= \sum$ all orientations
- greater growth rate than two-stream: ultra-relativistic particles are easier to deflect than to change their parallel velocities

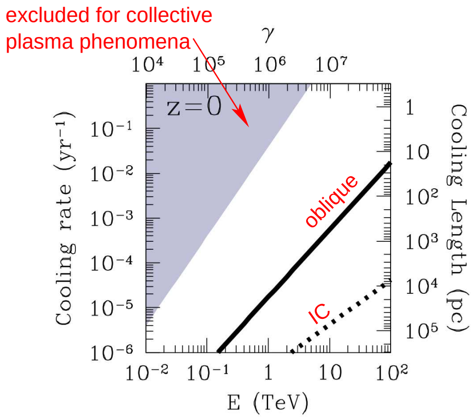
(Nakar, Bret & Milosavljevic 2011)





Bret (2009), Bret+ (2010)

Beam physics – growth rates



Broderick, Chang, C.P. (2012)

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

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

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

TeV emission from blazars – a new paradigm

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

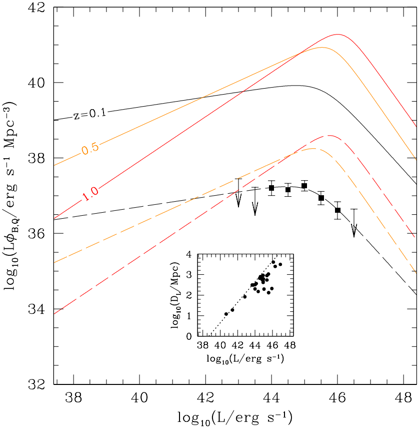
absence of $\gamma_{\rm GeV}$'s has significant implications for . . .

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

additional IGM heating has significant implications for . . .

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

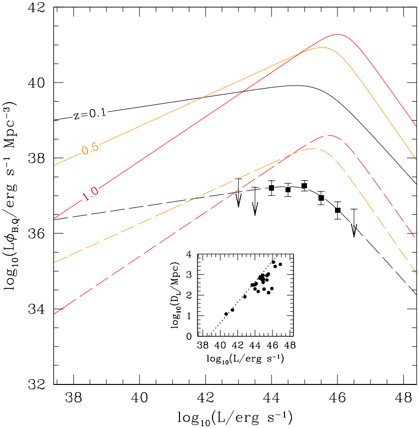
TeV blazar luminosity density: today



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



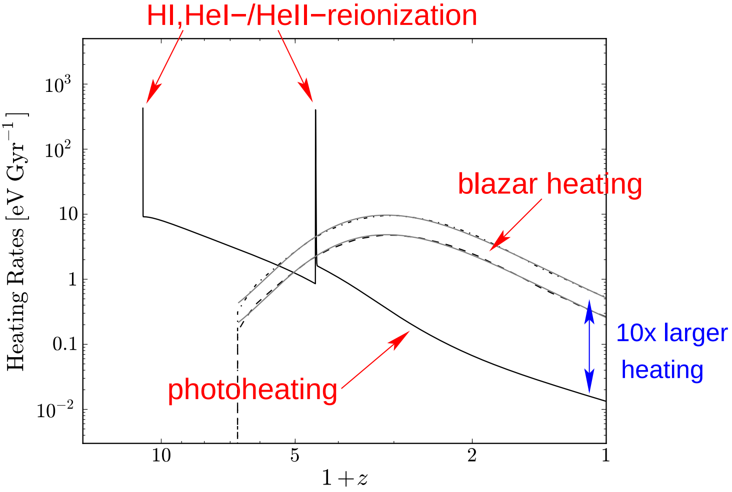
Broderick, Chang, C.P. (2012)

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!**

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
- $T_{\mathrm{IGM}} \sim 10^4$ 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)

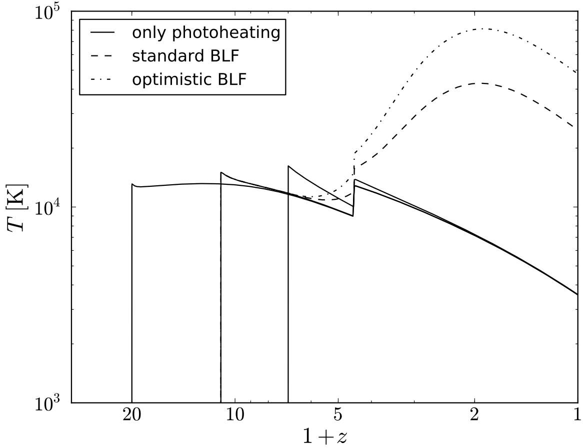
$$\varepsilon_{\mathrm{rad}} = \eta \, \Omega_{\mathrm{bh}} \sim 0.1 \times 10^{-4} \sim 10^{-5}$$

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

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

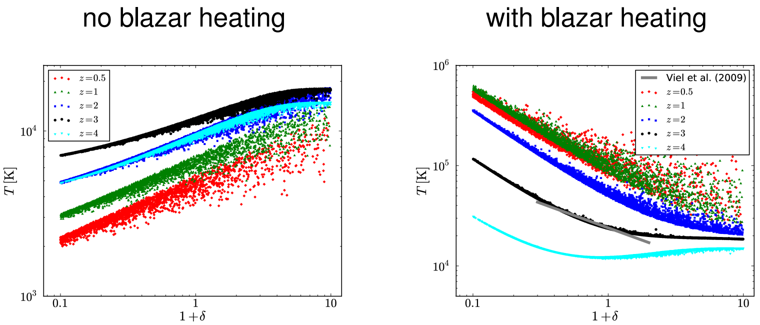
- photoheating efficiency $\eta_{\mathrm{ph}} \sim 10^{-3} \quad \rightarrow \quad kT \sim \eta_{\mathrm{ph}} \, \varepsilon_{\mathrm{UV}} \, m_{\mathrm{p}} c^2 \sim \mathrm{eV}$
  (limited by the abundance of H I/He II due to the small recombination rate)
- blazar heating efficiency $\eta_{\mathrm{bh}}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

Thermal history of the IGM



Chang, Broderick, C.P. (2012)

Evolution of the temperature-density relation

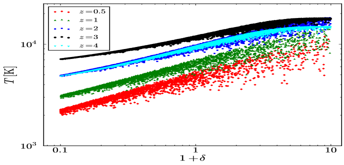


Chang, Broderick, C.P. (2012)

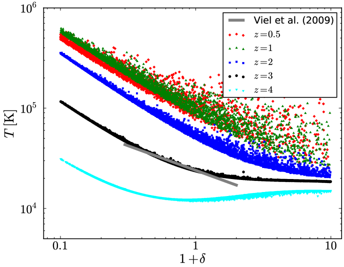
- blazars and extragalactic background light are uniform:
  $\rightarrow$ blazar heating rate independent of density
  $\rightarrow$ makes low density regions *hot*
  $\rightarrow$ causes inverted temperature-density relation, $T \propto 1/\delta$

Blazars cause hot voids

no blazar heating



with blazar heating

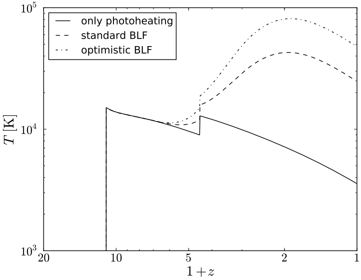


Chang, Broderick, C.P. (2012)

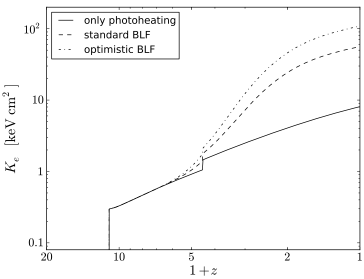
- blazars completely change the thermal history of the diffuse IGM and late-time structure formation

Entropy evolution

temperature evolution



entropy evolution



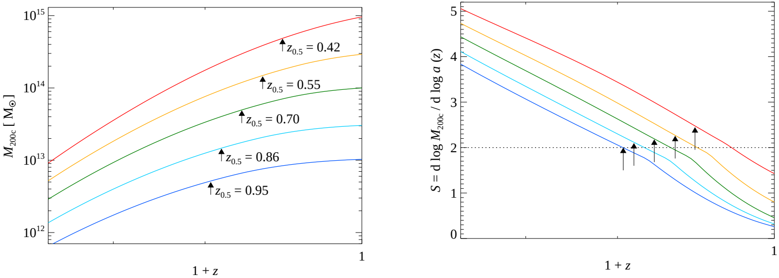
C.P., Chang, Broderick (2012)

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

When do clusters form?

mass accretion history

mass accretion rates

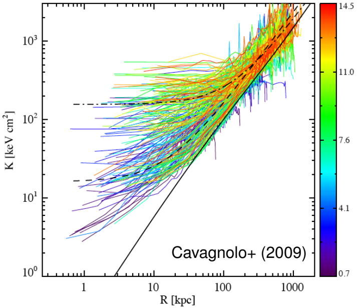


C.P., Chang, Broderick (2012)

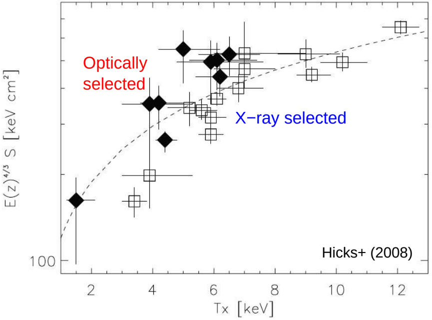
- most cluster gas accretes after $z = 1$, when blazar heating can have a large effect (for late forming objects)!

Entropy floor in clusters

Cluster entropy profiles



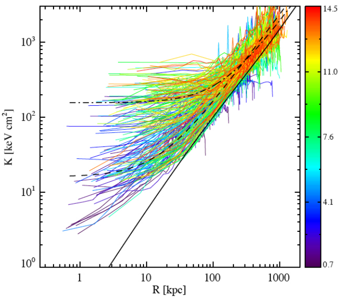
ICM entropy at $0.1R_{200}$:



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

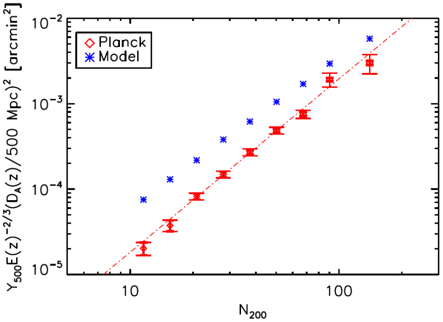
Entropy floor in clusters

Cluster entropy profiles



Cavagnolo+ (2009)

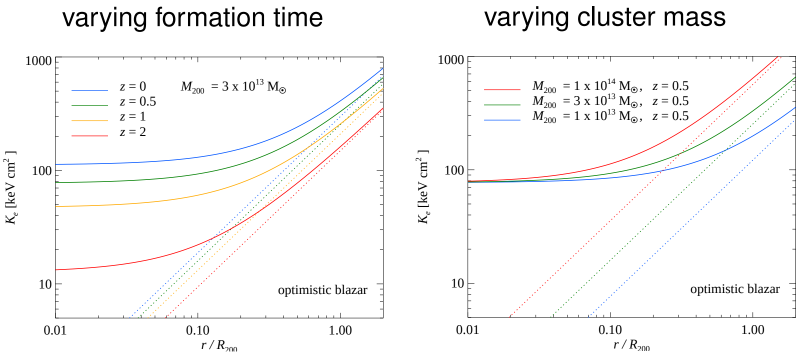
Planck stacking of optical clusters



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

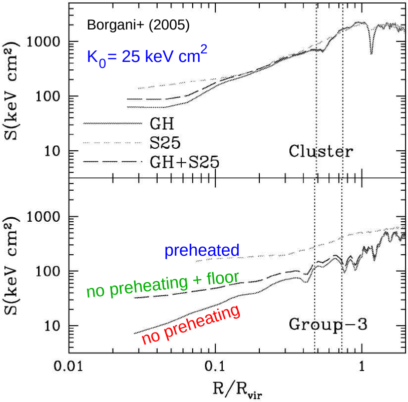


C.P., Chang, Broderick (2012)

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



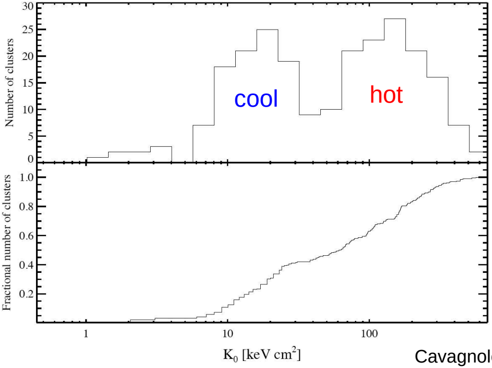
Borgani+ (2005)

- greater initial entropy K_0
  $\rightarrow$ more shock heating
  $\rightarrow$ greater increase in K_0 over entropy floor
- net K_0 amplification of 3-5
- expect:

  median $K_{e,0} \sim 150\,\mathrm{keV\,cm}^2$

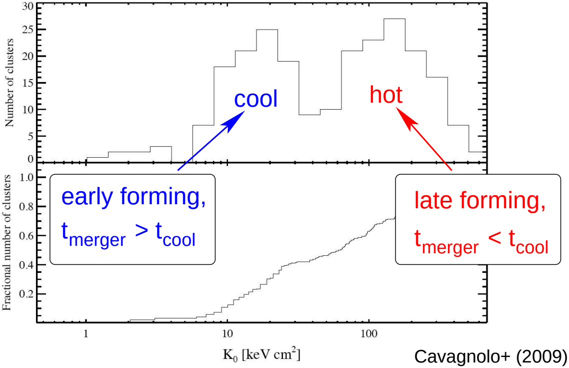
  max. $K_{e,0} \sim 600\,\mathrm{keV\,cm}^2$

Cool-core versus non-cool core clusters



Cavagnolo+ (2009)

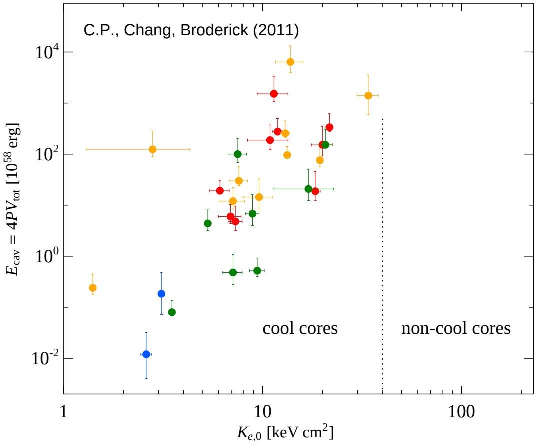
Cool-core versus non-cool core clusters



Cavagnolo+ (2009)

- 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?



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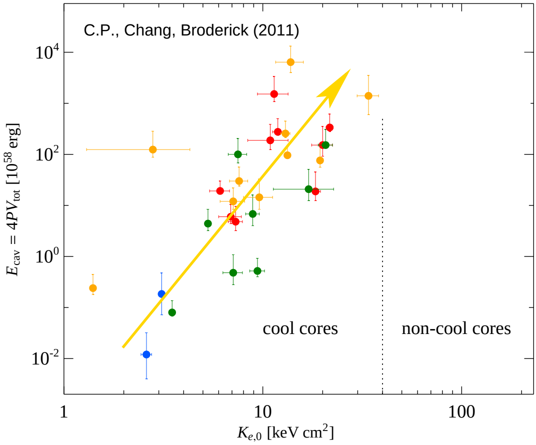

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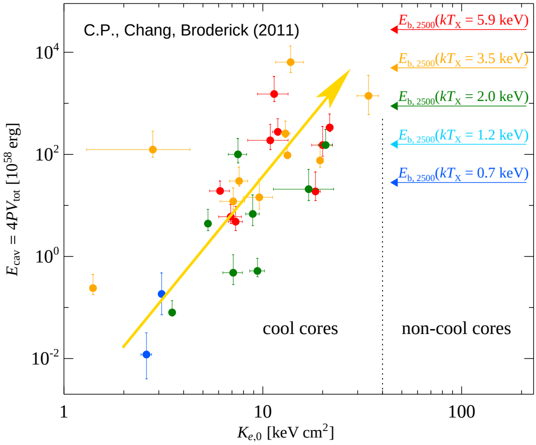

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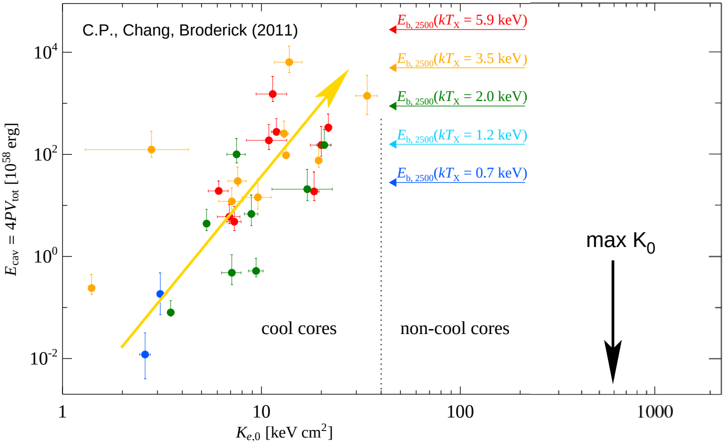
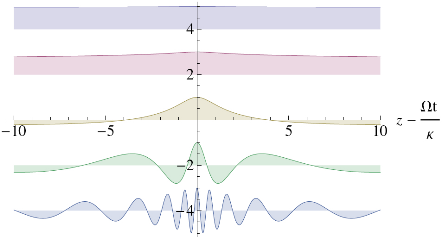


AGNs cannot transform CC to NCC clusters (on a buoyancy timescale)

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)
- we have reasons to believe that the instability is not appreciably slowed in the presence of even dramatic inhomogeneities



plasma eigenmodes for the Lorentzian background case

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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 and Elyiv (2012) claim that the nonlinear damping rate is $\ll$ linear growth rate

Conclusions on blazar heating

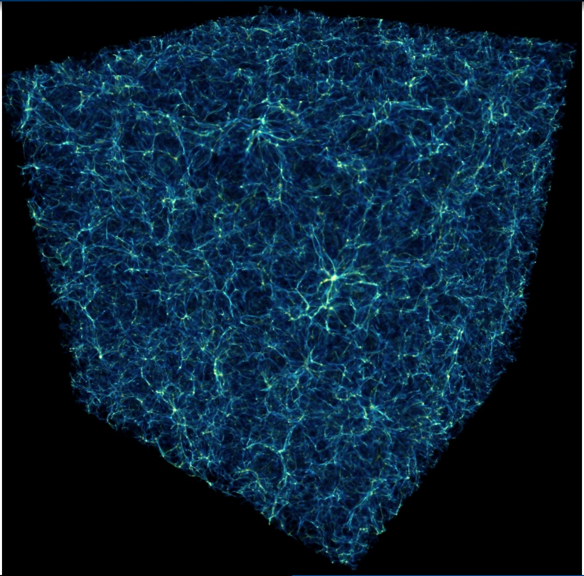
- explains puzzles in high-energy astrophysics:
  - lack of GeV bumps in blazar spectra without IGM *B*-fields
  - *unified TeV blazar-quasar model* explains Fermi source counts and extragalactic gamma-ray background
- novel mechanism; dramatically alters thermal history of the IGM:
  - uniform and z-dependent preheating
  - rate independent of density $\to$ inverted T–ρ relation
  - quantitative self-consistent picture of high-z Lyman-α forest
- significantly modifies late-time structure formation:
  - group/cluster bimodality of core entropy values
  - suppresses late dwarf formation (in accordance with SFHs): "missing satellites", void phenomenon, H I-mass function

Simulations with blazar heating

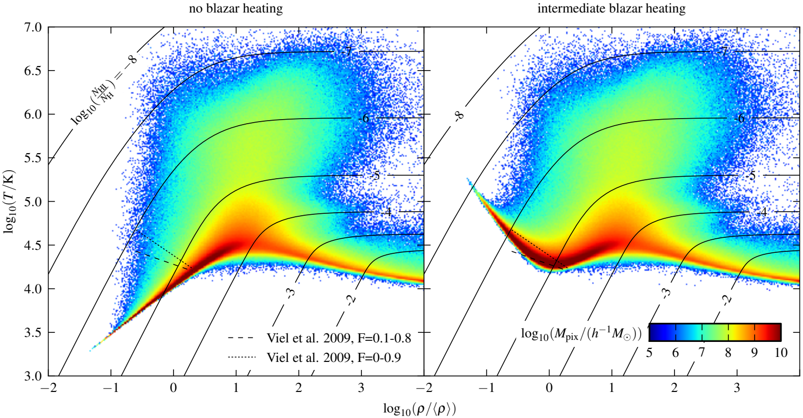
Puchwein, C.P., Springel, Broderick, Chang (2012):

- $L = 15h^{-1}$Mpc boxes with 2×384^3 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

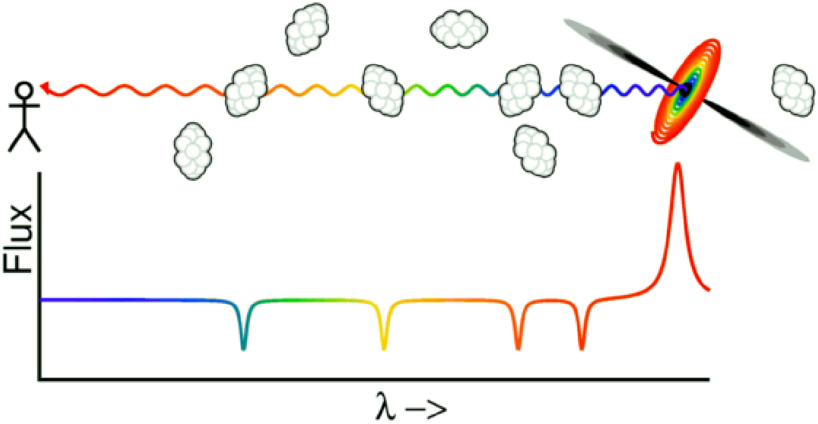


Temperature-density relation

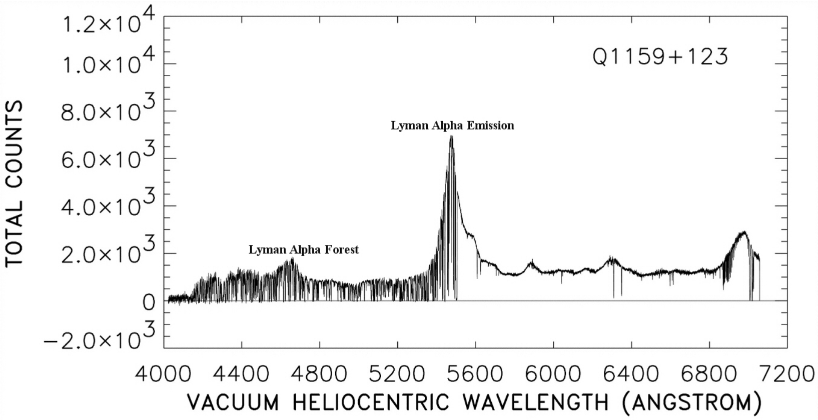


Puchwein, C.P., Springel, Broderick, Chang (2012)

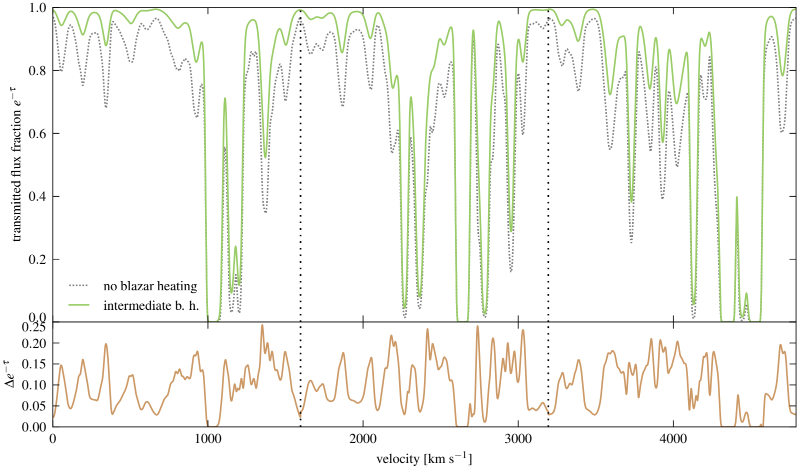
The Lyman-α forest



The observed Lyman-α forest

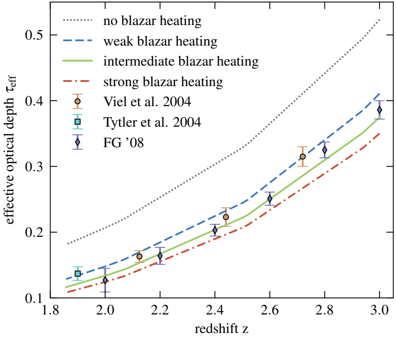


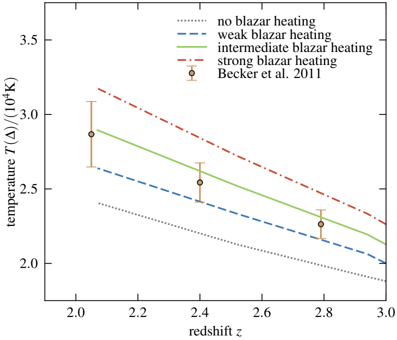
The simulated Ly-α forest



Puchwein+ (2012)

Optical depths and temperatures

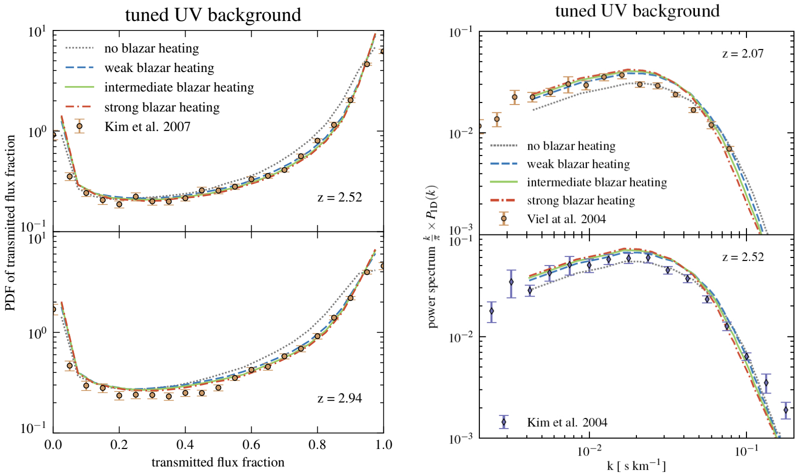




Puchwein+ (2012)

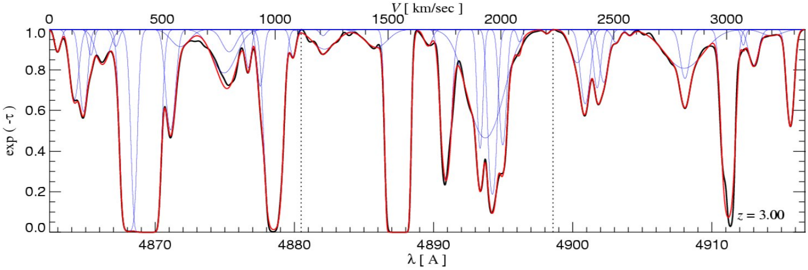
Redshift evolutions of effective optical depth and IGM temperature match data only with additional heating, e.g., provided by blazars!

Ly-α flux PDFs and power spectra



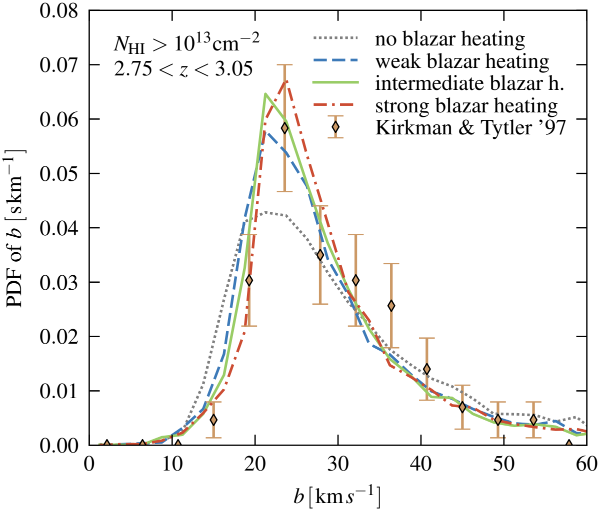
Puchwein+ (2012)

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+ (2012)

Lyman-α forest in a blazar heated Universe

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)

Dwarf galaxy formation – Jeans mass

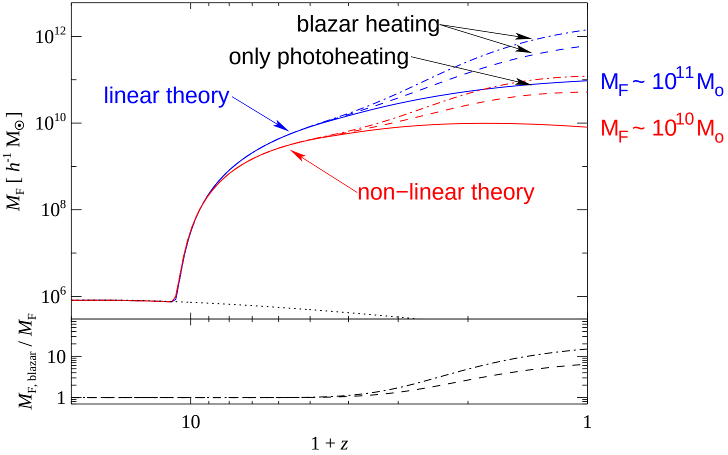
- thermal pressure opposes gravitational collapse on small scales
- characteristic length/mass scale below which objects do not form
- hotter IGM → higher IGM pressure → higher Jeans mass:

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

  → 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

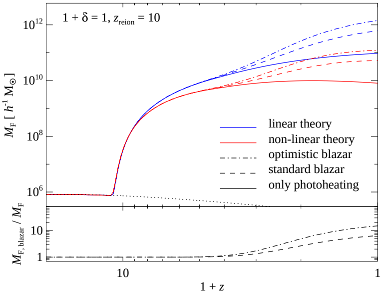
Dwarf galaxy formation – Filtering mass



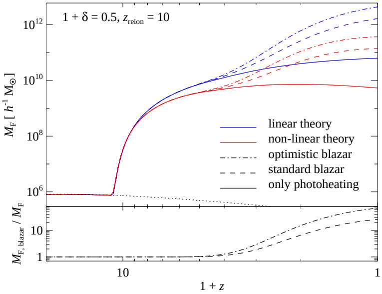
C.P., Chang, Broderick (2012)

Peebles' void phenomenon explained?

mean density



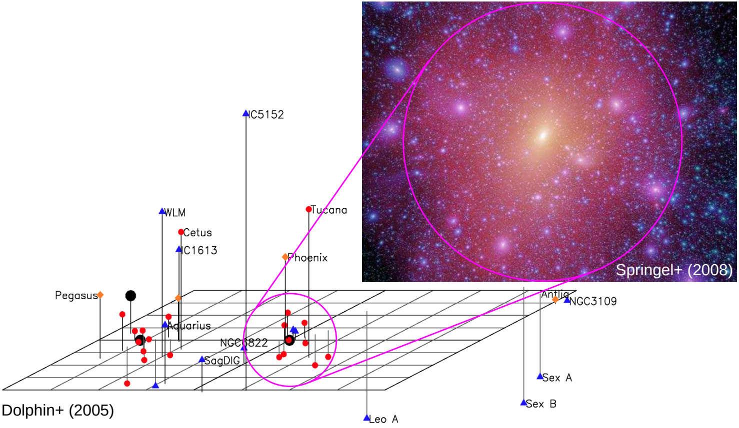
void, $1 + \delta = 0.5$



C.P., Chang, Broderick (2012)

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

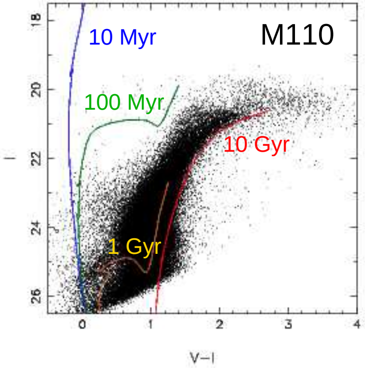
“Missing satellite” problem in the Milky Way



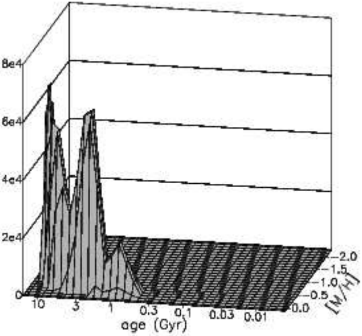
Dolphin+ (2005)

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

When do dwarfs form?

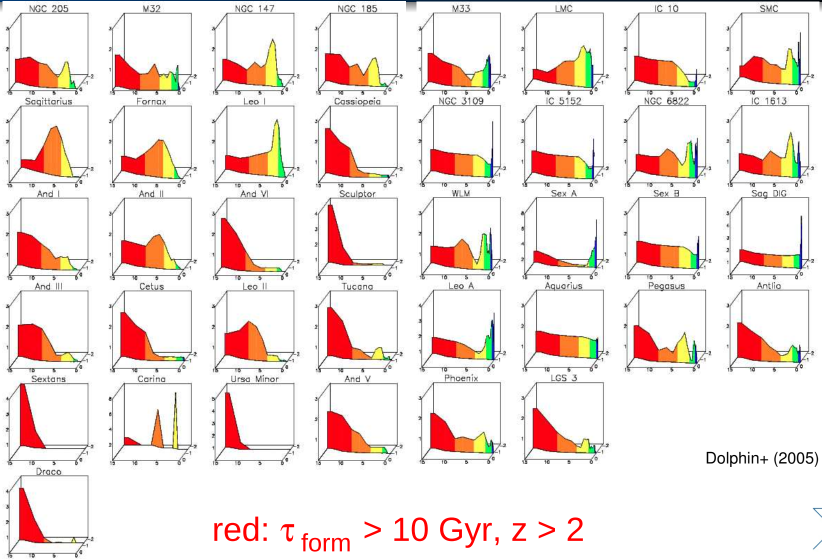


Dolphin+ (2005)



isochrone fitting for different metallicities → star formation histories

When do dwarfs form?

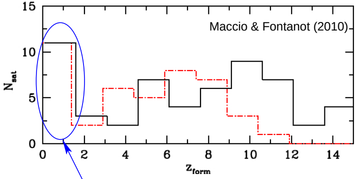


Dolphin+ (2005)

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

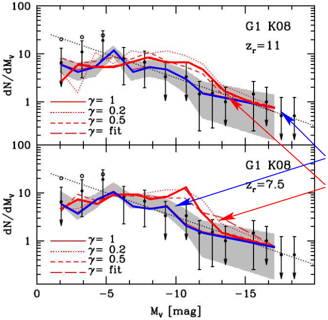
Milky Way satellites: formation history and abundance

satellite formation time



late forming satellites (< 10 Gyr) not observed!

satellite luminosity function



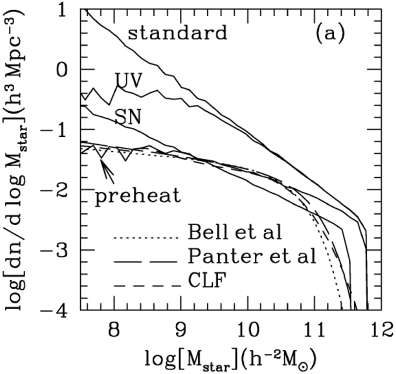
no blazar heating:
linear theory
non−linear theory

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!