The Physics and Cosmology of TeV Blazars

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in collaboration with

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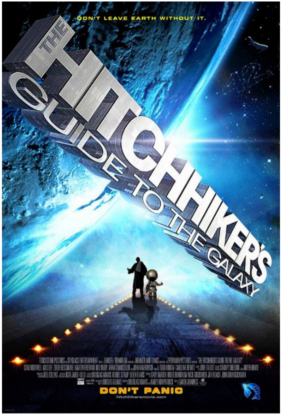
The Hitchhiker's Guide to . . . Blazar Heating

- **Blazar Physics**
  - black holes and jets
  - propagation γ rays
  - plasma physics



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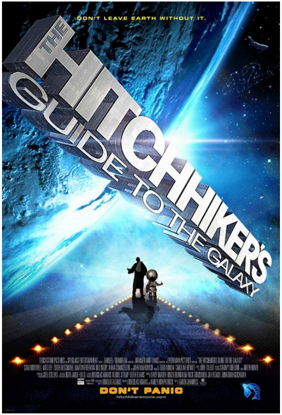
- **Cosmological Consequences**
    - intergalactic magnetic fields
    - unification of blazars and AGN
    - gamma-ray background



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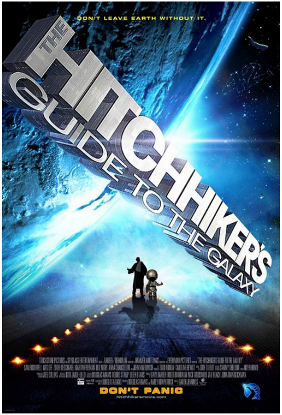
  - unification of blazars and AGN
  - gamma-ray background
  - thermal history of the Universe
  - Lyman-α forest
  - formation of dwarf galaxies

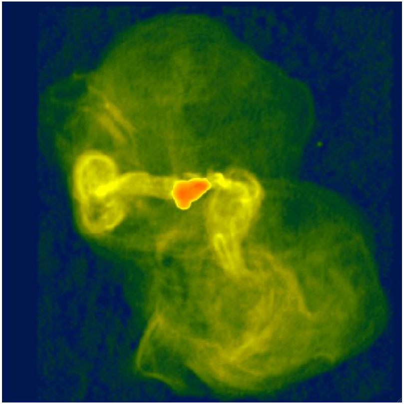


Outline

1. Blazars
   - Black hole jets
   - Propagating γ rays
   - Plasma instabilities
2. Gamma-ray sky
   - Magnetic fields
   - Blazar-AGN unification
   - Gamma-ray background
3. Structure formation
   - Properties of blazar heating
   - The Lyman-α forest
   - Dwarf galaxies

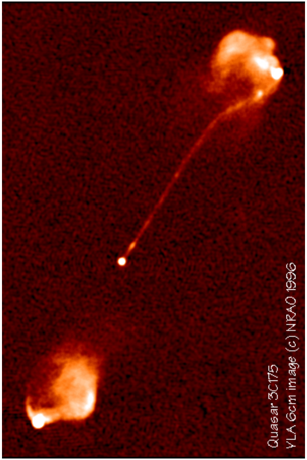
Black hole jets - nearby

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



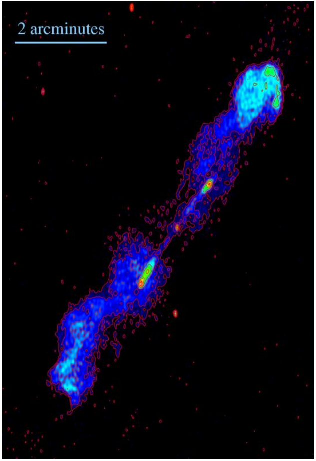
Messier 87 in the radio:
closest active cluster galaxy in
the Virgo cluster: $M_{\mathrm{bh}} \simeq 6 \times 10^9 \mathrm{M}_\odot$

Black hole jets - at cosmological distances



Quasar 3C175:

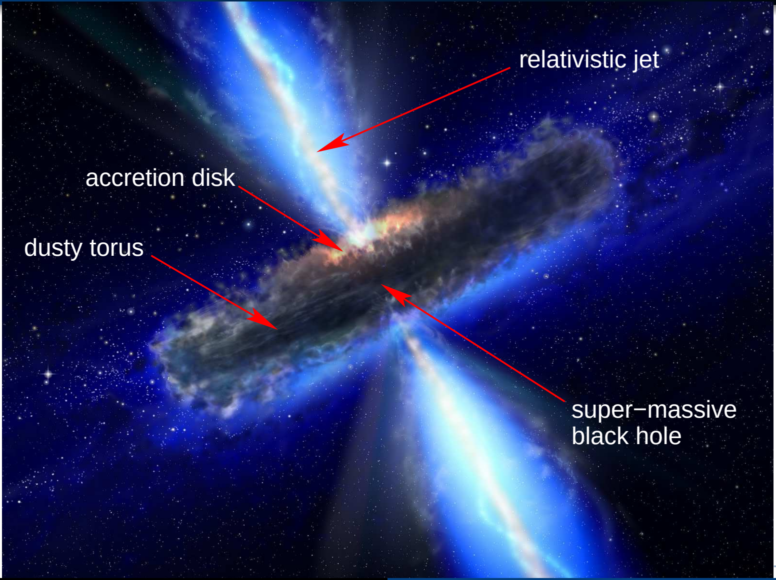
1 million light years across



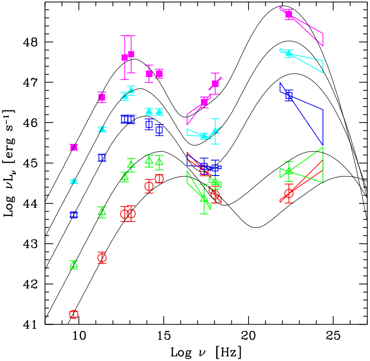
Giant radio galaxy B1545-321:

relic radio plasma and new jet activity

Unified model of active galactic nuclei



The blazar sequence



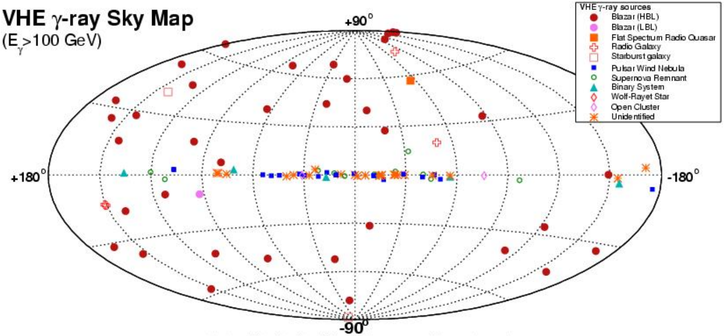
Donato+ (2001)

- continuous sequence from FSRQ–LBL–IBL–HBL
- TeV blazars ($\nu \gtrsim 10^{26}$ Hz) are dim: very sub-Eddington
- TeV blazars have rising energy spectra in the Fermi band
- define TeV blazar = hard IBL + HBL

The TeV gamma-ray sky

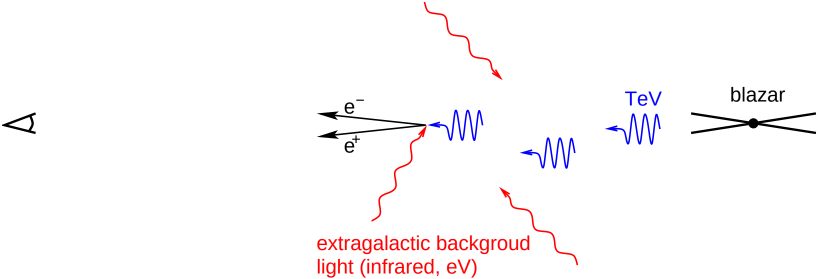
There are several classes of TeV sources:

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



2011-01-08 - Up-to-date plot available at http://www.mpp.mpg.de/~rwagner/sources/

Annihilation and pair production



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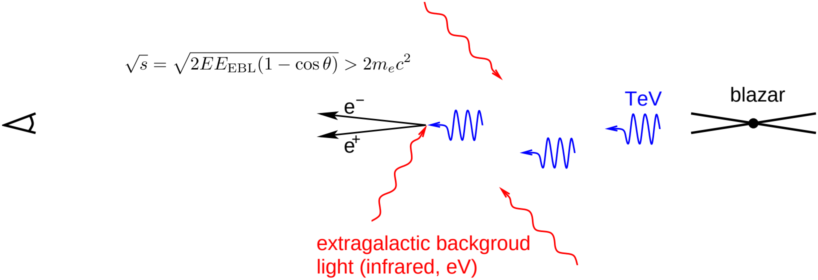
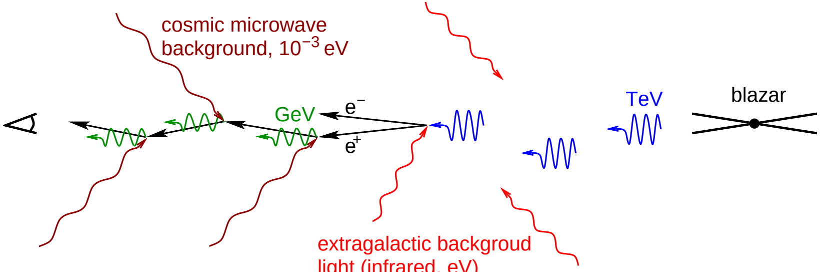


$$\sqrt{s} = \sqrt{2EE_{\mathrm{EBL}}(1-\cos\theta)} > 2m_e c^2$$

extragalactic backgroud light (infrared, eV)

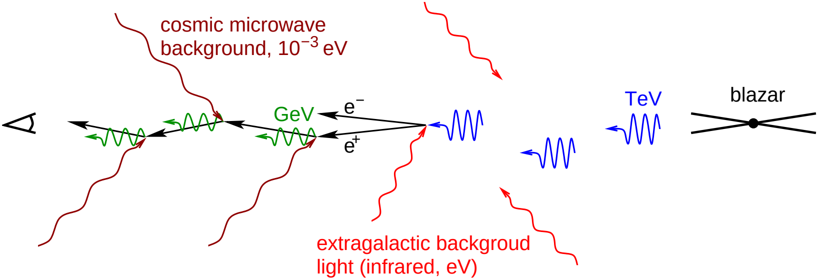
$$\lambda_{\gamma\gamma} \sim (35\ldots700)\ \mathrm{Mpc\ for}\ z = 1\ldots0$$

Inverse Compton cascades



$\lambda_{\rm IC} \sim \lambda_{\gamma\gamma}/1000$ $\lambda_{\gamma\gamma} \sim (35\dots700)$ Mpc for $z = 1\dots0$

Inverse Compton cascades



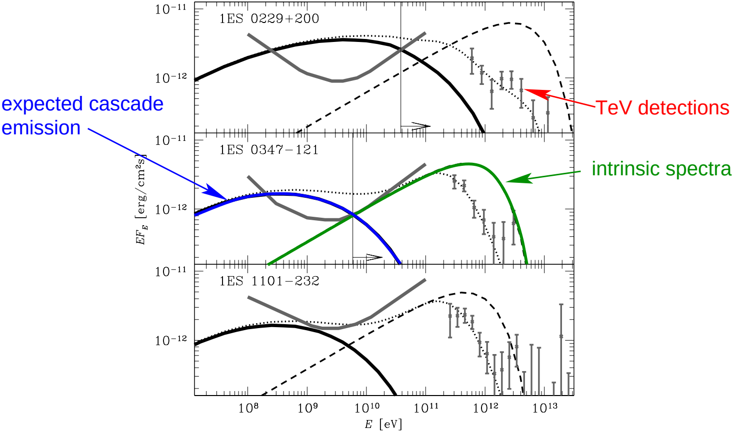
$\lambda_{\mathrm{IC}} \sim \lambda_{\gamma\gamma}/1000$

$\lambda_{\gamma\gamma} \sim (35 \ldots 700)\ \mathrm{Mpc\ for}\ z = 1 \ldots 0$

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

What about the cascade emission?

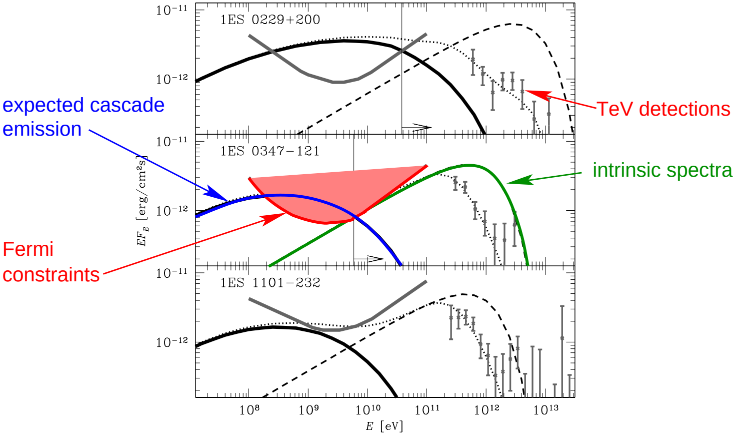
Every TeV source should be associated with a 1-100 GeV gamma-ray halo



Neronov & Vovk (2010)

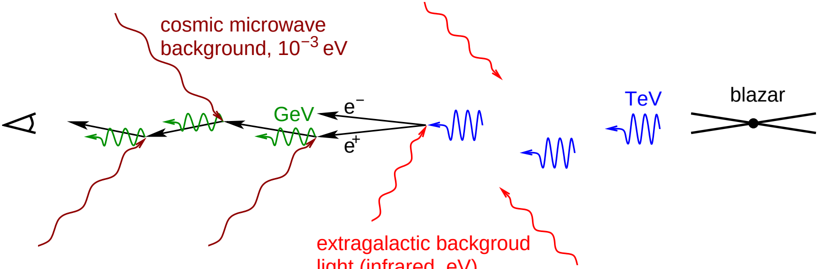
What about the cascade emission?

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



Neronov & Vovk (2010)

Inverse Compton cascades



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

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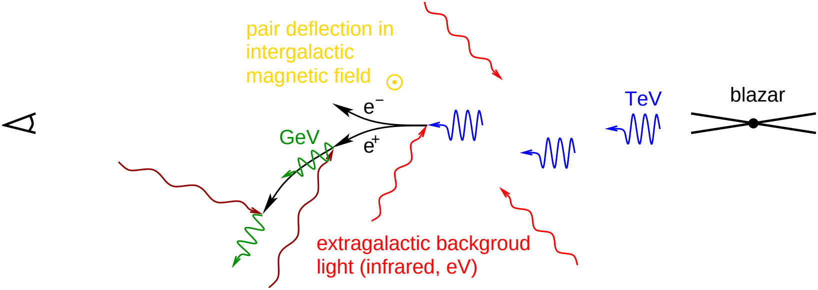
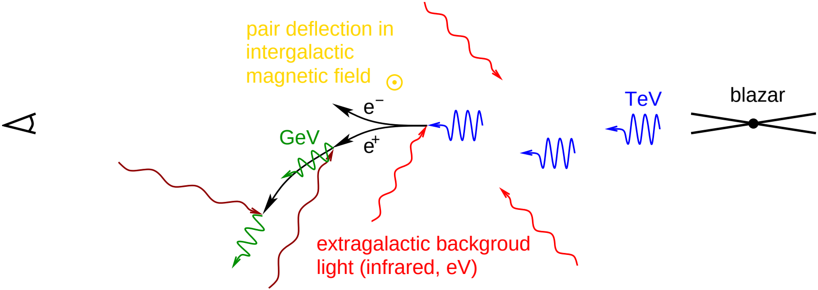
Magnetic field deflection

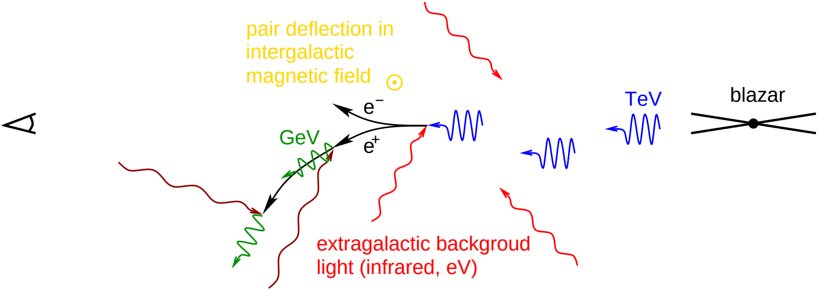


Magnetic field deflection



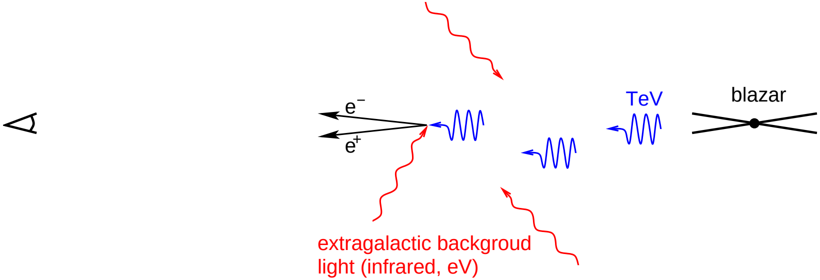
- GeV point source diluted ⟶ weak "pair halo"
- stronger B−field implies more deflection and dilution, gamma−ray non−detection ⟶ $B \gtrsim 10^{-16}\,\mathrm{G}$ − primordial fields?

Magnetic field deflection

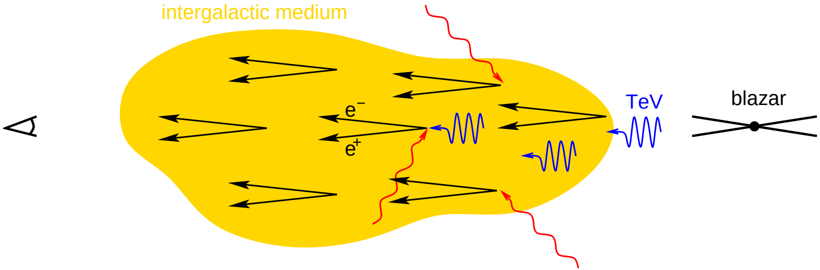


- problem for unified AGN model: blazars and quasars apparently do not share the same cosmological evolution (as otherwise, evolving blazars would overproduce the gamma−ray background)!

What else could happen?



Plasma beam instabilities

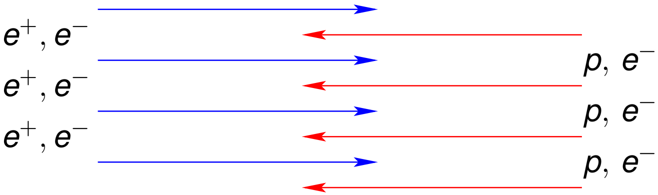


- pair plasma beam propagating through the intergalactic medium

Interlude: plasma physics

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

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



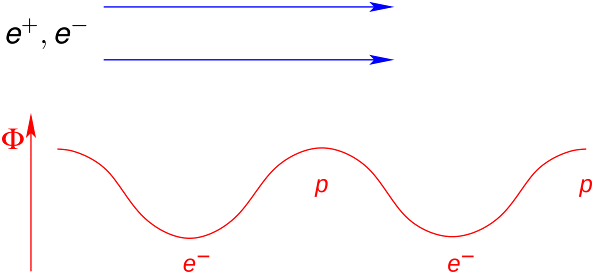
- one frequency (timescale) and one length in the problem:

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

Two-stream instability: mechanism

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

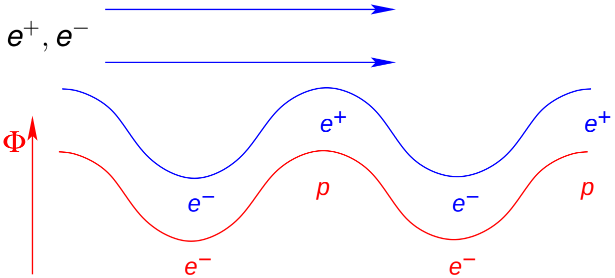
- initially homogeneous beam-e^-:
  attractive (repulsive) force by potential maxima (minima)
- e^- attain lowest velocity in potential minima → bunching up
- e^+ attain lowest velocity in potential maxima → bunching up



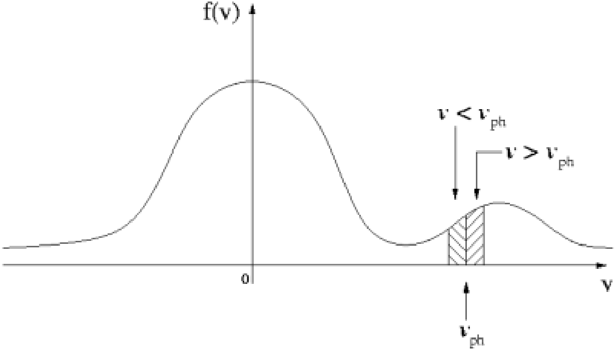
Two-stream instability: mechanism

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

- beam-e^+/e^- couple in phase with the background perturbation: enhances background potential
- stronger forces on beam-e^+/e^- → positive feedback
- exponential wave-growth → instability



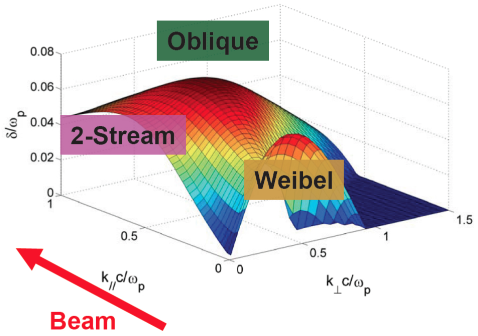
Two-stream instability: momentum transfer



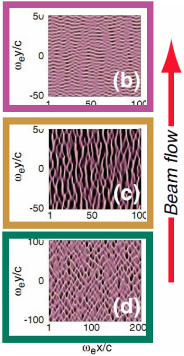
- particles with $v \gtrsim v_{\mathrm{phase}}$:
  pair momentum → plasma waves → growing modes: instability
- particles with $v \lesssim v_{\mathrm{phase}}$:
  plasma wave momentum → pairs → Landau damping

Oblique instability

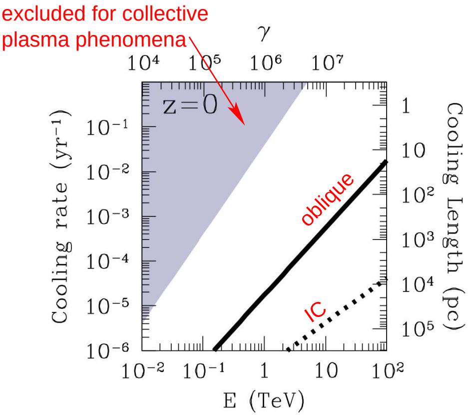
- ***k*** oblique to $\boldsymbol{v}_{\text{beam}}$: real word perturbations don’t choose “easy” alignment $= \sum$ all orientations
- oblique grows faster than two-stream: *E*-fields can easier deflect ultra-relativistic particles than change their parallel velocities
  (Nakar, Bret & Milosavljevic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



Bret (2009), Bret+ (2010)



Beam physics – growth rates

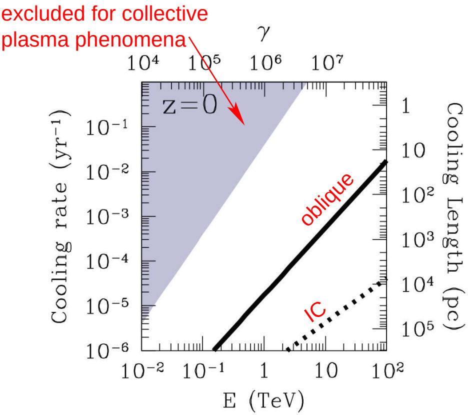


Broderick, Chang, C.P. (2012), also Schlickeiser+ (2012)

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

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

Beam physics – growth rates



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- consider a light beam penetrating into relatively dense plasma
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$$\Gamma \simeq 0.4\,\gamma\,\frac{n_{\mathrm{beam}}}{n_{\mathrm{IGM}}}\,\omega_p$$

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

TeV emission from blazars – a new paradigm

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

TeV emission from blazars – a new paradigm

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

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

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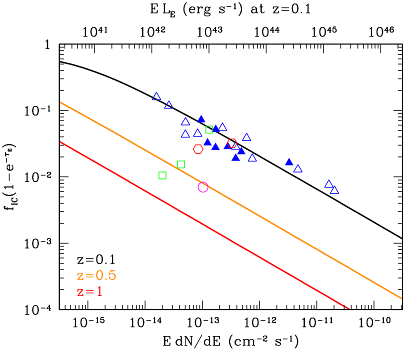
    - Dwarf galaxies

Implications for intergalactic magnetic fields

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

- competition of rates: $\Gamma_{\rm IC}$ vs. $\Gamma_{\rm oblique}$
- fraction of the pair energy lost to inverse-Compton on the CMB: $f_{\rm IC} = \Gamma_{\rm IC}/(\Gamma_{\rm IC} + \Gamma_{\rm oblique})$
- **plasma instability dominates for more luminous blazars**



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 allow high-energy e^+/e^- pairs to self scatter and/or lose energy
- isotropizes the beam – no need for *B*-field
- $\lesssim$ 1–10% of beam energy to IC CMB photons

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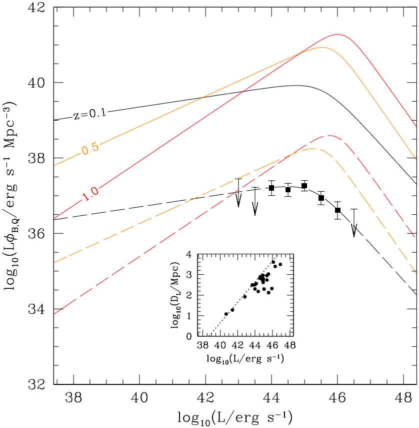
→ **TeV blazar spectra are not suitable to measure IGM *B*-fields**
(if plasma instabilities saturate close to linear rate)!

Broderick, Chang, C.P. (2012), Schlickeiser, Krakau, Supsar (2013), Chang+ (in prep.)

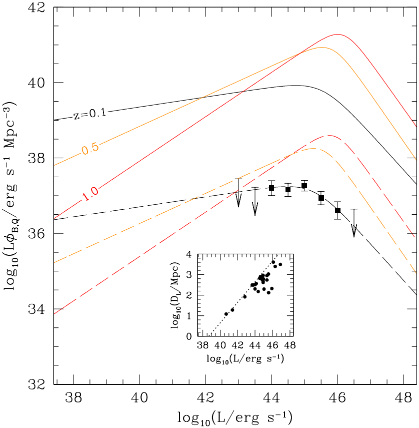
TeV blazar luminosity density: today



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

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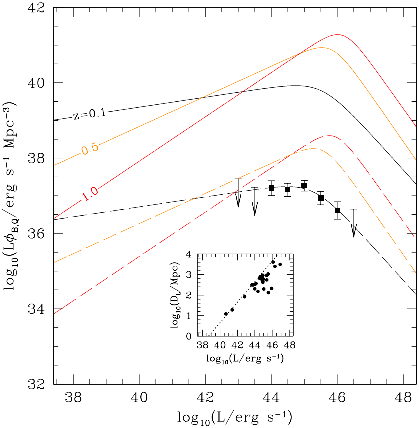

Broderick, Chang, C.P. (2012)

Quasars and TeV blazars are:

- regulated by the same mechanism
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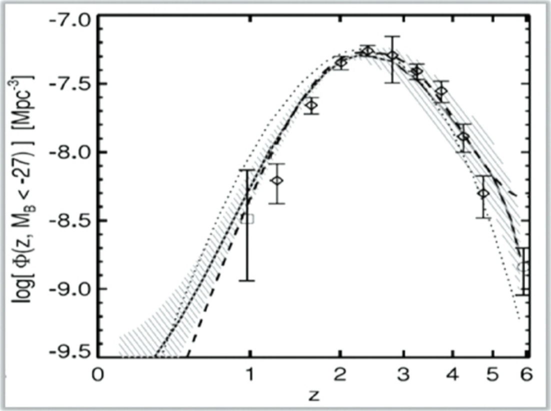
→ **assume that they trace each other for all redshifts!**

How many TeV blazars are there?



Hopkins+ (2007)

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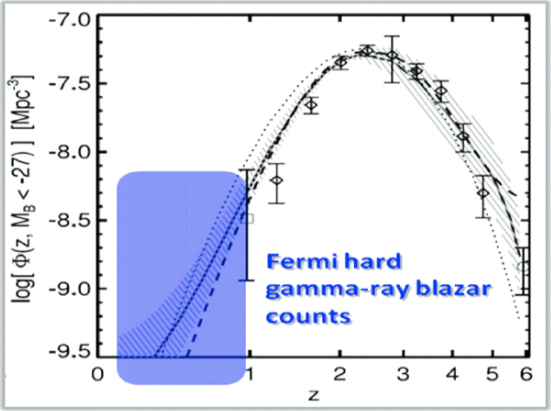

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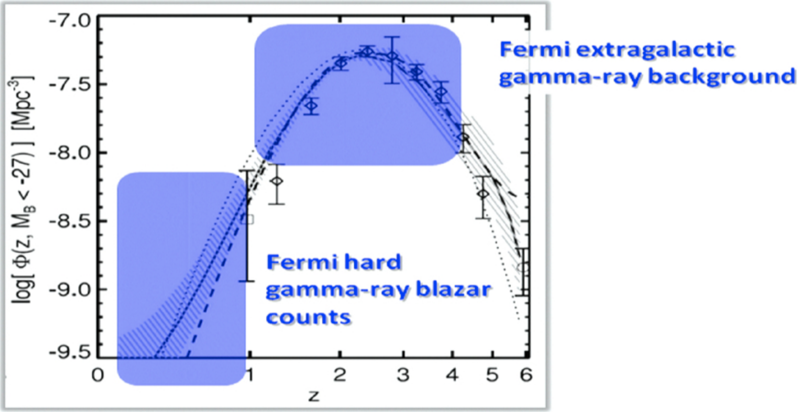
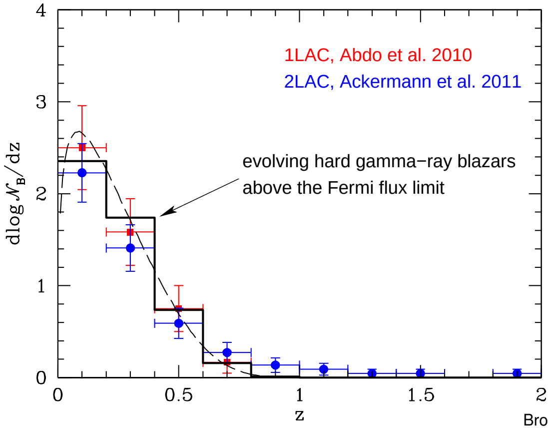


Hopkins+ (2007)

Redshift distribution of *Fermi* hard γ-ray blazars



Broderick, C.P.+ (2013)

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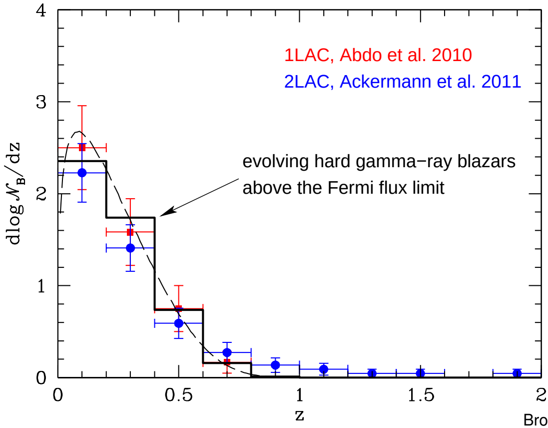
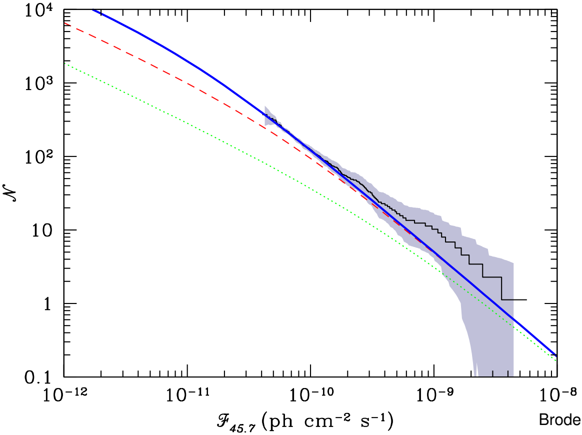


Broderick, C.P.+ (2013)

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

$\log \mathcal{N} - \log S$ distribution of *Fermi* hard γ-ray blazars



Broderick, C.P.+ (2013)

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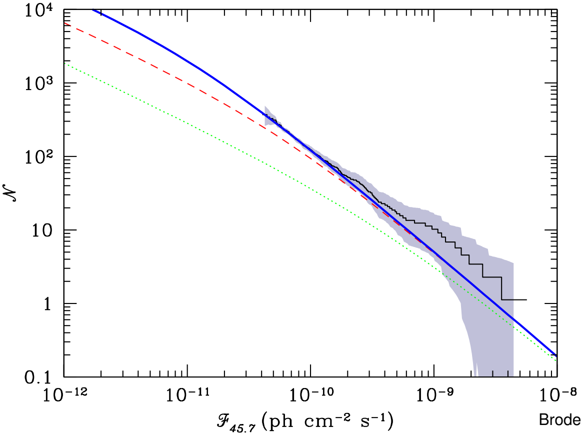

Broderick, C.P.+ (2013)

→ predicted and observed flux distributions of hard *Fermi* blazars between 10 GeV and 500 GeV are indistinguishable!

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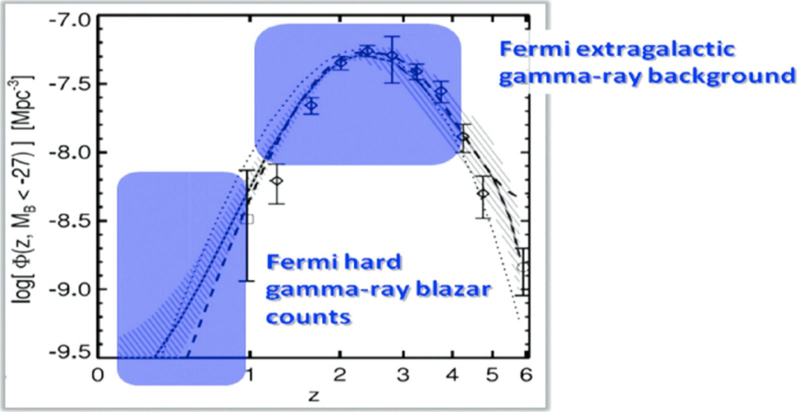
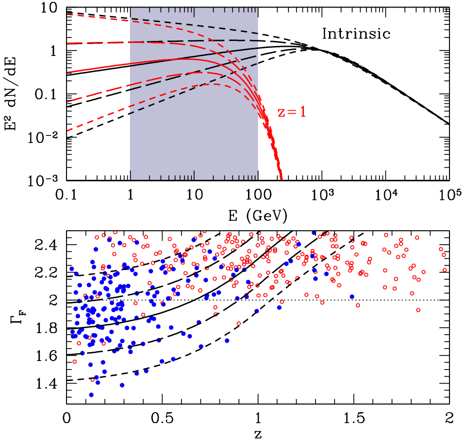


Hopkins+ (2007)

TeV photon absorption by pair production



Broderick, C.P.+ (2013)

intrinsic and observed SEDs of blazars at $z = 1$ → γ-ray attenuation by annihilation and pair producing on the EBL

inferred spectral index Γ_F for the spectra in the top panel; overlay of *Fermi* data on BL Lacs and non-BL Lacs (mostly FSRQs)

Extragalactic gamma-ray background

- intrinsic spectrum for a TeV blazar:

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

$E_b = 1$ TeV is break energy, $\Gamma_h = 3$ is high-energy spectral index,

Γ_l related to Γ_F, which is drawn from observed distribution

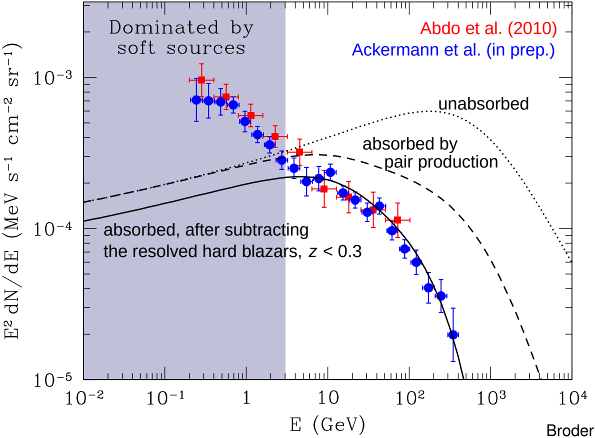
- extragalactic gamma-ray background (EGRB):

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

$E' = E(1+z')$ is gamma-ray energy at *emission*,
$\tilde{\Lambda}_Q$ is physical quasar luminosity density,

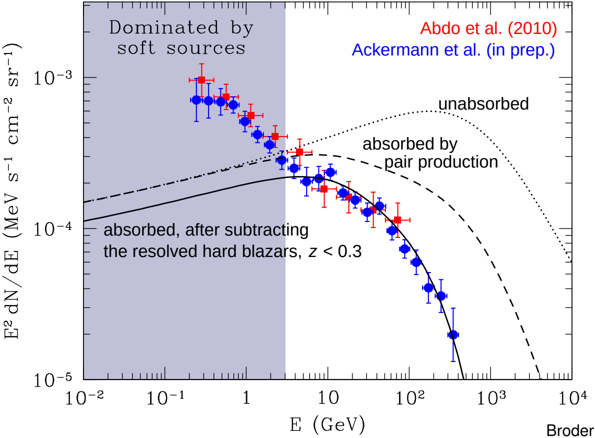
$\eta_B \sim 0.2\%$ is blazar fraction, τ is optical depth

Extragalactic gamma-ray background



Broderick, C.P.+ (2013)

Extragalactic gamma-ray background



Broderick, C.P.+ (2013)

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

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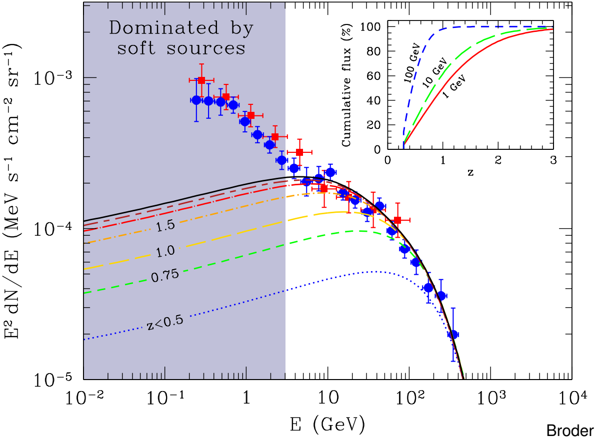

Broderick, C.P.+ (2013)

→ the signal at 10 (100) GeV is dominated by redshifts $z \sim 1.2$ ($z \sim 0.6$)

Outline

1. Blazars
   - Black hole jets
   - Propagating γ rays
   - Plasma instabilities
2. Gamma-ray sky
   - Magnetic fields
   - Blazar-AGN unification
   - Gamma-ray background
3. Structure formation
   - Properties of blazar heating
   - The Lyman-α forest
   - Dwarf galaxies

TeV emission from blazars – a new paradigm

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

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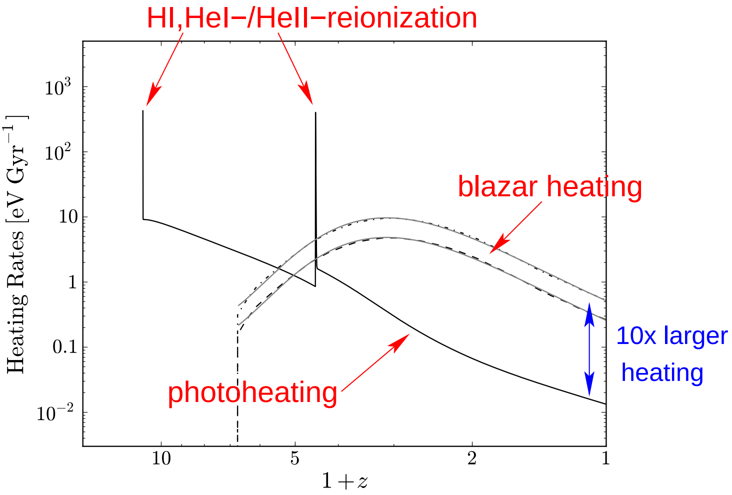
additional IGM heating has significant implications for . . .

- thermal history of the IGM: Lyman-α forest
- late-time formation of dwarf galaxies

Evolution of the heating rates



Chang, Broderick, C.P. (2012)

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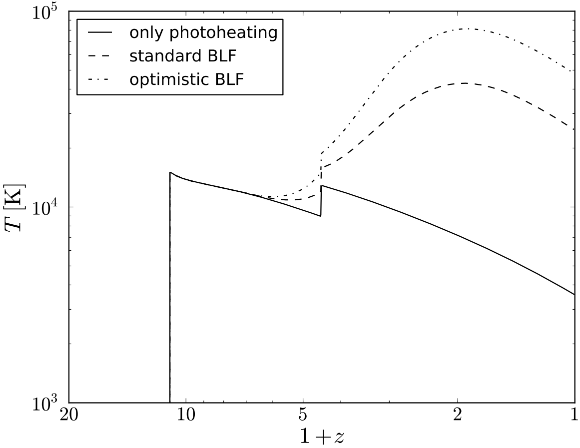
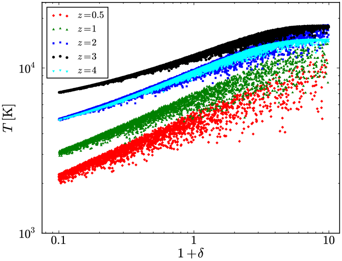
Thermal history of the IGM



C.P., Chang, Broderick (2012)

Evolution of the temperature-density relation

no blazar heating



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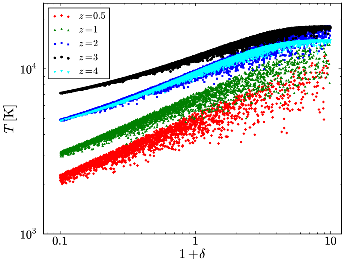

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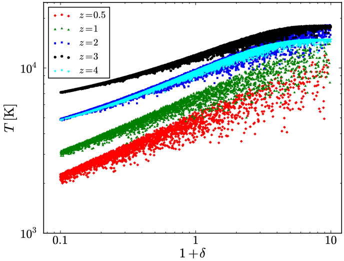

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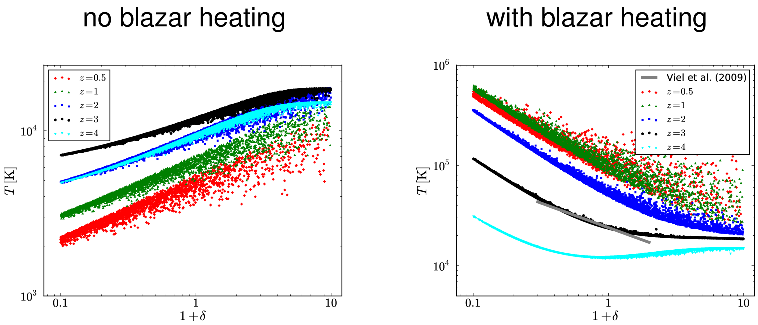

Chang, Broderick, C.P. (2012)

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Blazars cause hot voids

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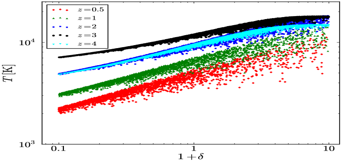
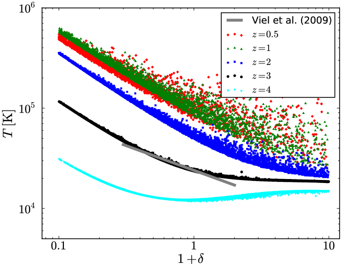


with blazar heating



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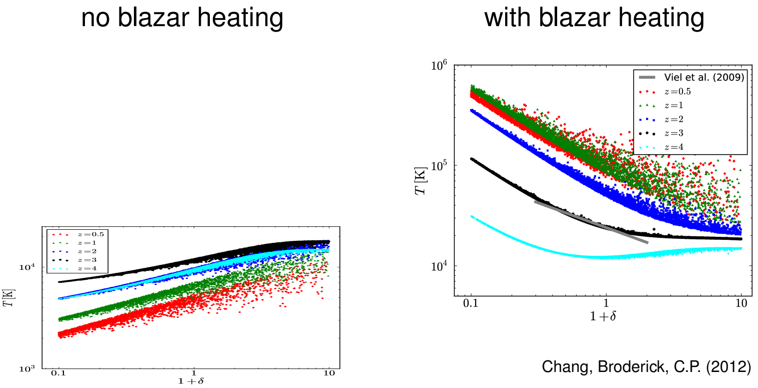


Chang, Broderick, C.P. (2012)

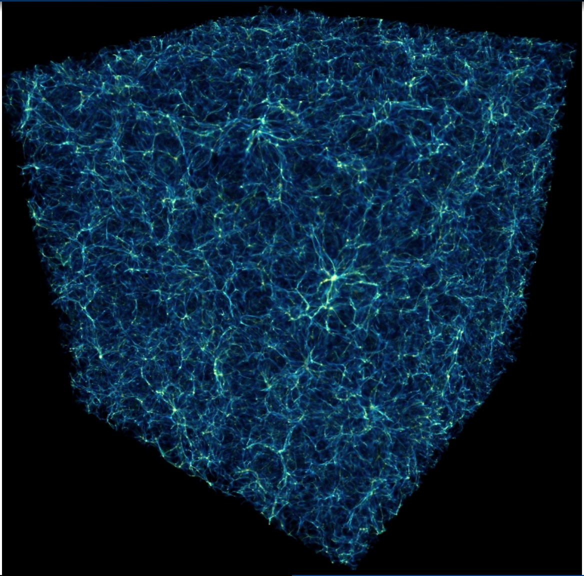
- blazars completely change the thermal history of the diffuse IGM and late-time structure formation

Simulations with blazar heating

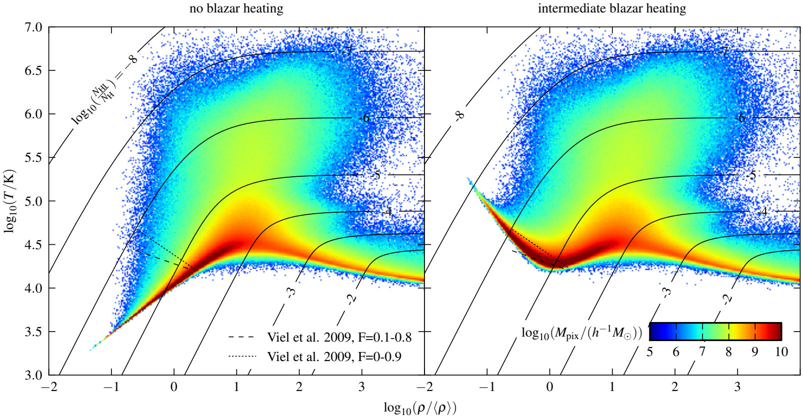
Puchwein, C.P., Springel, Broderick, Chang (2012):

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

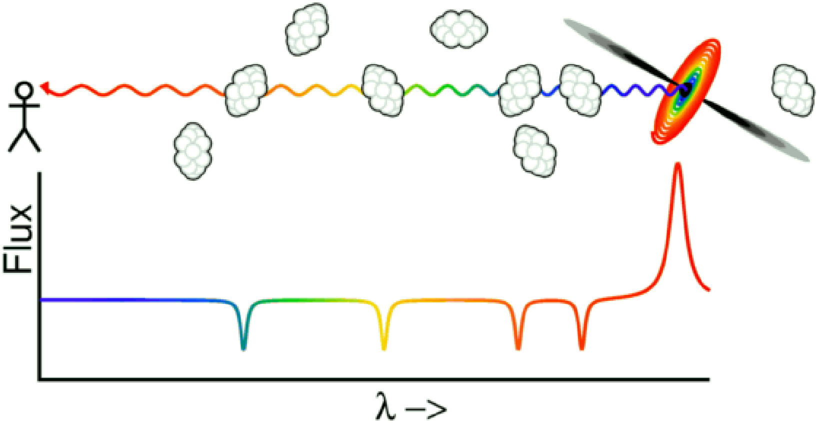


Temperature-density relation

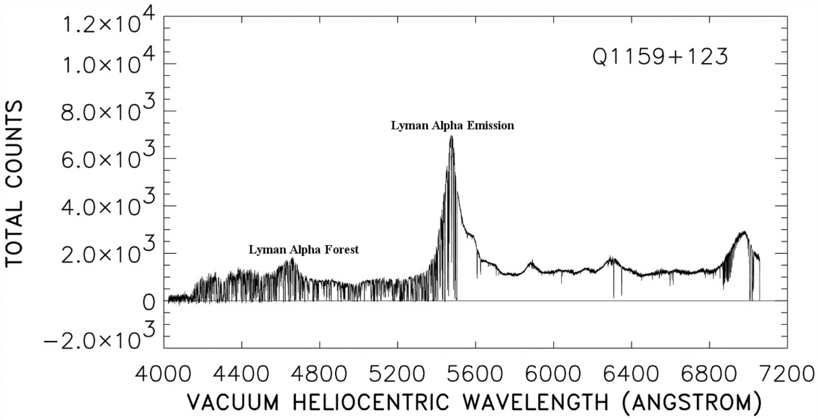


Puchwein, C.P., Springel, Broderick, Chang (2012)

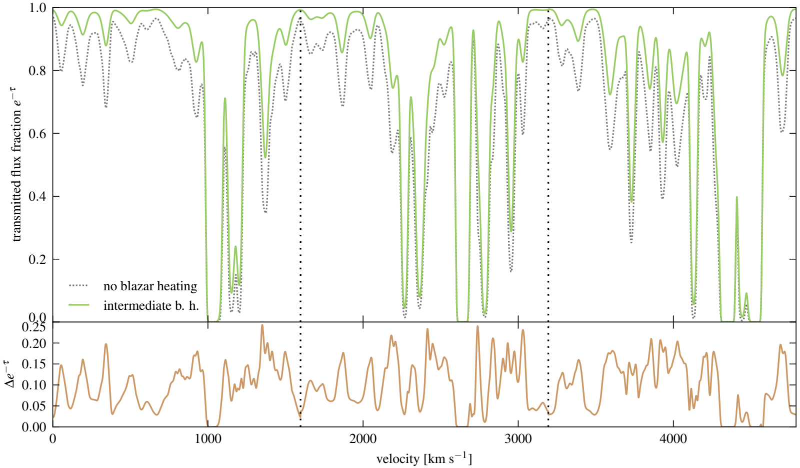
The Lyman-α forest



The observed Lyman-α forest

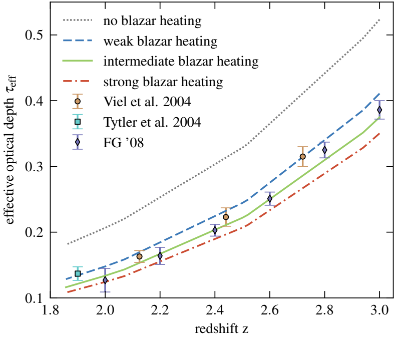


The simulated Ly-α forest



Puchwein+ (2012)

Optical depths and temperatures



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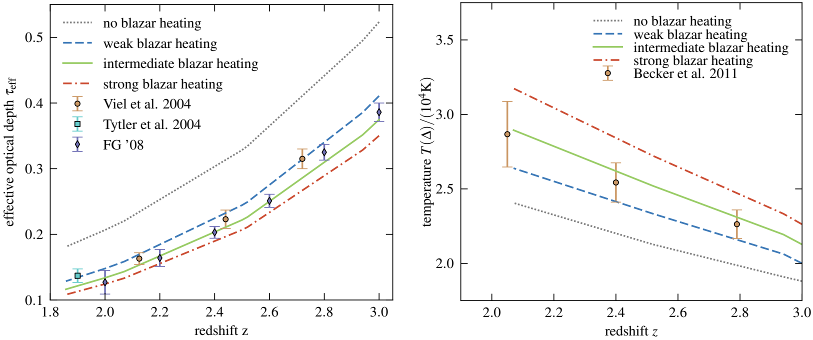
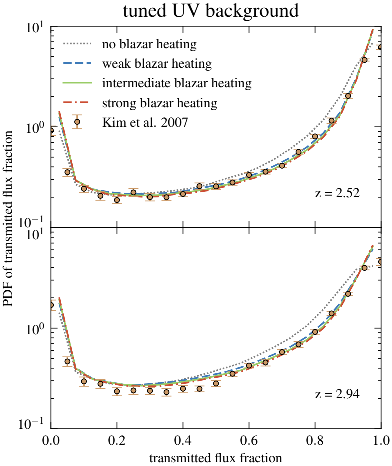


Puchwein+ (2012)

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



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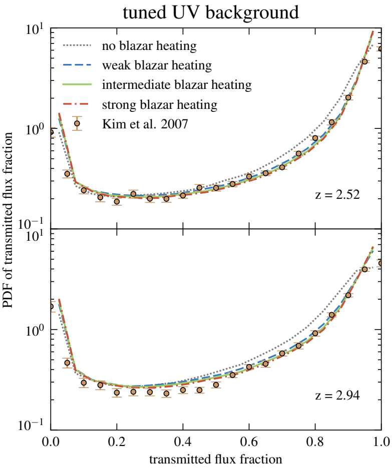
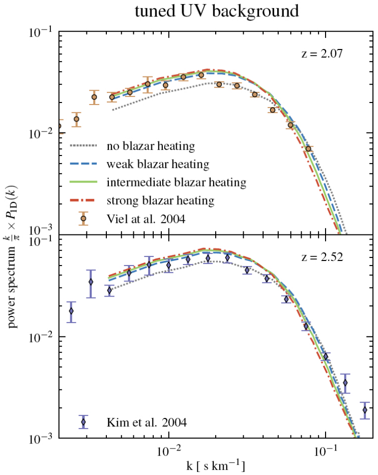
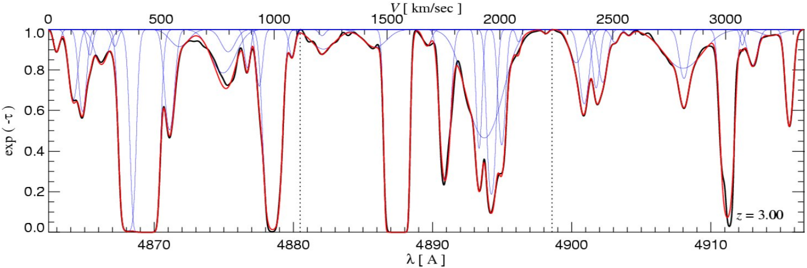




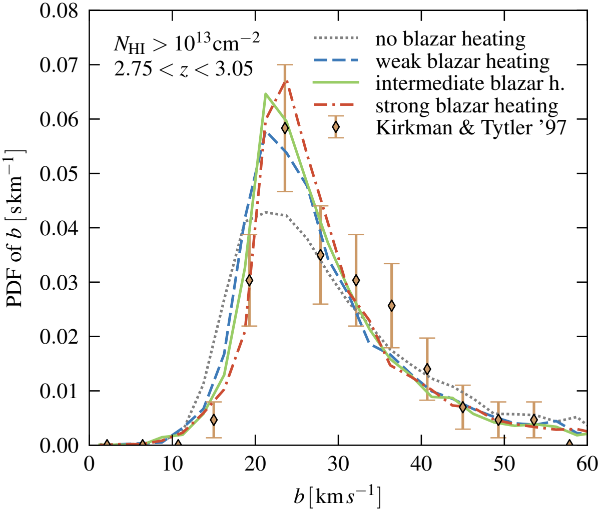
Puchwein+ (2012)

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)

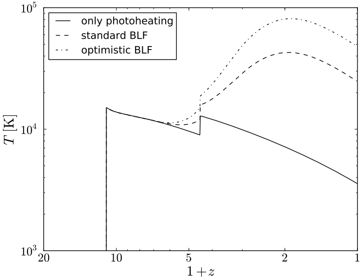
Lyman-α forest in a blazar heated Universe

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

- heating rate independent of IGM density → 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)

Entropy evolution

temperature evolution



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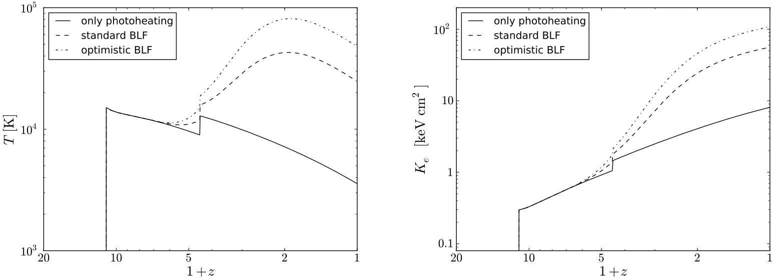

temperature evolution

entropy evolution

C.P., Chang, Broderick (2012)

- evolution of entropy, $K_\mathrm{e} = kTn_\mathrm{e}^{-2/3}$, governs structure formation
- blazar heating: late-time, evolving, modest entropy floor

Dwarf galaxy formation

- thermal pressure opposes gravitational collapse on small scales
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→ blazar heating increases M_J by 30 over pure photoheating!

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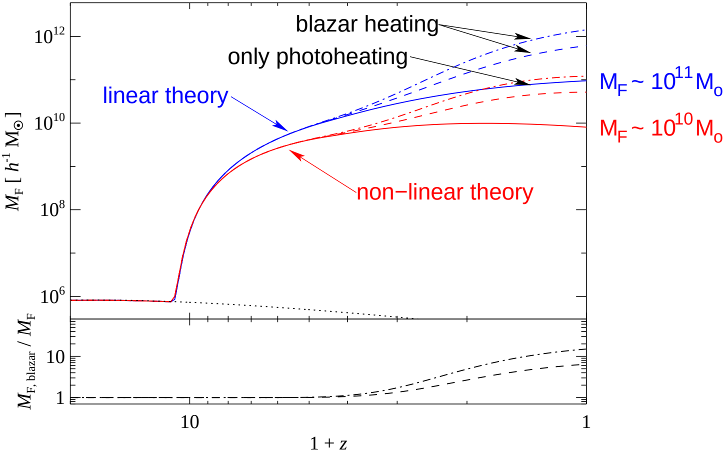
- complications:
  non-linear collapse,
  delayed pressure response in expanding universe → concept of "filtering mass"

C.P., Chang, Broderick (2012)

Dwarf galaxy formation – Filtering mass

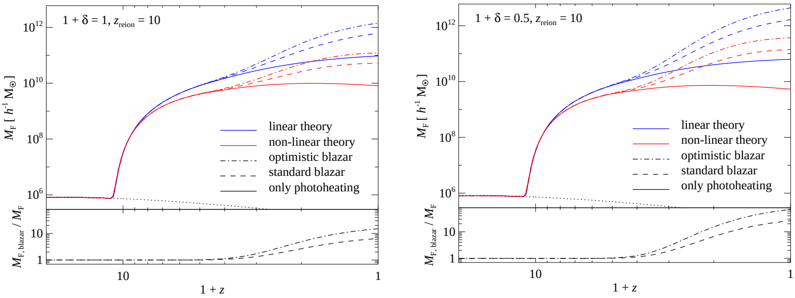


C.P., Chang, Broderick (2012)

Peebles' void phenomenon explained?

mean density

void, $1 + \delta = 0.5$



C.P., Chang, Broderick (2012)

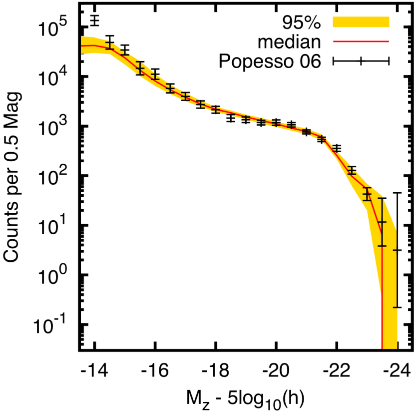
- blazar heating efficiently suppresses the formation of void dwarfs within existing DM halos of masses $< 3 \times 10^{11}$ $M_\odot$ $(z = 0)$
- may reconcile the number of void dwarfs in simulations and the paucity of those in observations

Empirical model for star formation histories (1)

Lu, Mo, Lu, Katz, et al. (2013): constructing merger tree-based model of galaxy formation that matches

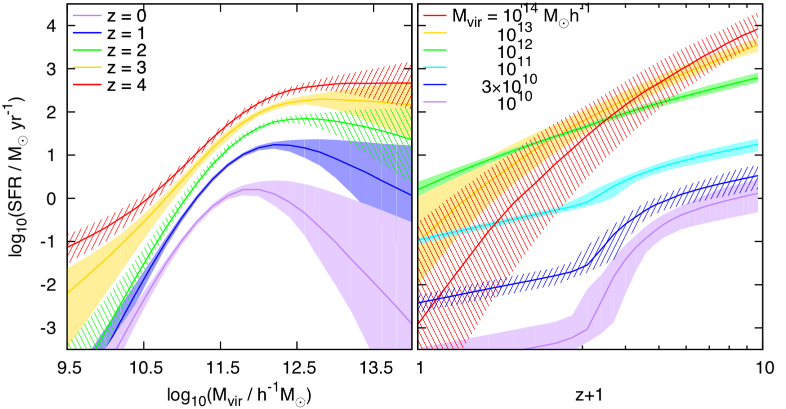
- observed stellar mass function (different *z*)
- luminosity function of local cluster galaxies

→ star formation histories of dark matter halos (different *z*)



Lu+ (2013)

Empirical model for star formation histories (2)



Lu+ (2013)

→ strong quenching of star formation efficiency for $z \lesssim 2$ in low-mass halos ($M < 10^{11}\, h^{-1} \mathrm{M}_\odot$) → blazar heating?

Conclusions on blazar heating

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

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

Literature for the talk

- Broderick, Chang, Pfrommer, *The cosmological impact of luminous TeV blazars I: implications of plasma instabilities for the intergalactic magnetic field and extragalactic gamma-ray background*, ApJ, 752, 22, 2012.
- Chang, Broderick, Pfrommer, *The cosmological impact of luminous TeV blazars II: rewriting the thermal history of the intergalactic medium*, ApJ, 752, 23, 2012.
- Pfrommer, Chang, Broderick, *The cosmological impact of luminous TeV blazars III: implications for galaxy clusters and the formation of dwarf galaxies*, ApJ, 752, 24, 2012.
- Puchwein, Pfrommer, Springel, Broderick, Chang, *The Lyman-α forest in a blazar-heated Universe*, MNRAS, 423, 149, 2012.
- Broderick, Pfrommer, Chang, Puchwein, *Implications of plasma beam instabilities for the statistics of the Fermi hard gamma-ray blazars and the origin of the extragalactic gamma-ray background*, ApJ, subm., 2013.
- Broderick, Pfrommer, Chang, Puchwein, *Lower limits upon the anisotropy of the extragalactic gamma-ray background implied by the 2FGL and 1FHL catalogs*, ApJ, subm., 2013.

Additional slides

Challenges to the Challenge

Challenge #1 (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
- using slow *collisional scattering* (reactive regime), Miniati & Elyiv (2012) claim that the nonlinear Landau damping rate is $\ll$ linear growth rate
- also accounting for much faster *collisionless scattering* (kinetic regime) $\rightarrow$ powerful instability, faster than IC cooling (Schlickeiser+ 2013, Chang+ in prep.)

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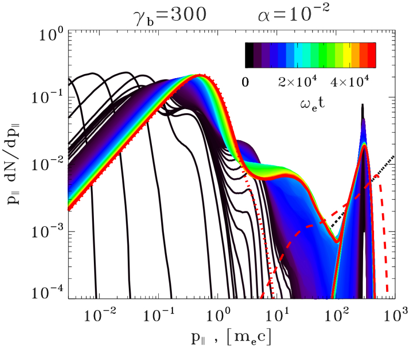
Challenge #2 (unknown unknowns): **inhomogeneous universe**

- 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 → no instability quenching! (Chang+ in prep.)

Simulations of the beam-plasma instability



$\alpha = n_{\mathrm{beam}}/n_{\mathrm{IGM}}$, Sironi & Giannios (2013)

- $\alpha\gamma = 3$ in simulation: beam energy density dominates rest frame energy density of background plasma
- $\alpha\gamma \sim 10^{-12}$ in reality: background dominates by far

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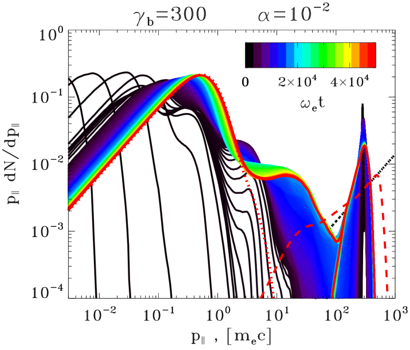

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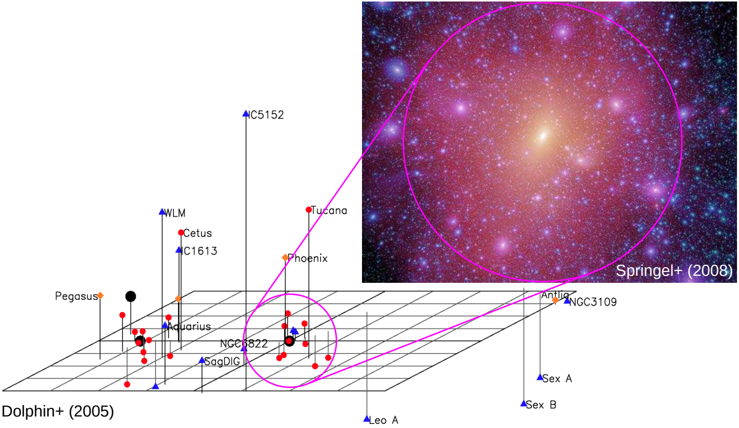
- $\alpha\gamma = 3$ in simulation: beam energy density dominates rest frame energy density of background plasma
- $\alpha\gamma \sim 10^{-12}$ in reality: background dominates by far
- extrapolation with Lorentz force argument:

$$\frac{\Delta p_{\text{beam},\perp}}{\Delta t} \sim eE_\perp$$

- **however:** coherent field $E_\perp$ causes beam deflection, not broadening of momentum distribution

“Missing satellite” problem in the Milky Way

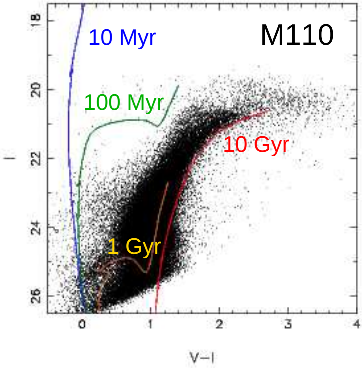


Springel+ (2008)

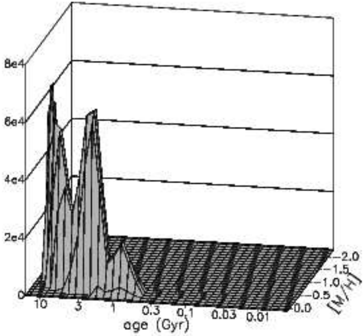
Dolphin+ (2005)

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

When do dwarfs form?

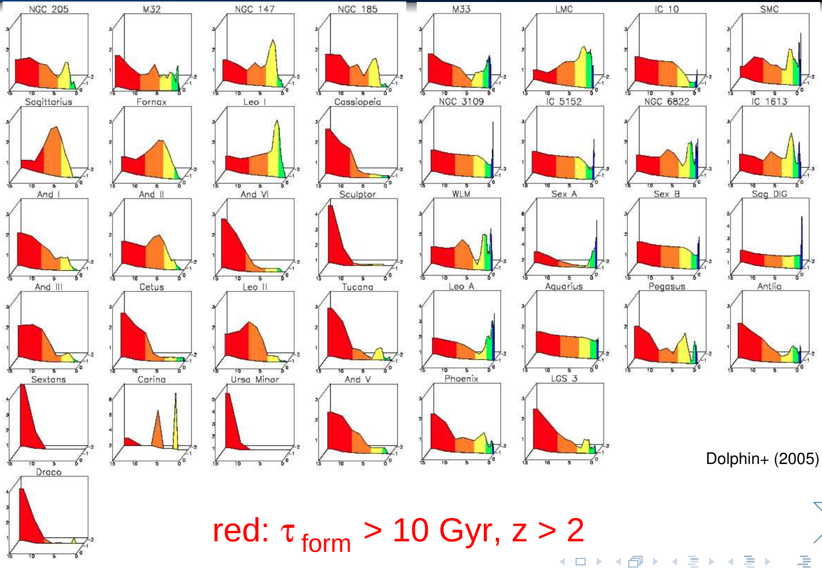


Dolphin+ (2005)



isochrone fitting for different metallicities → star formation histories

When do dwarfs form?

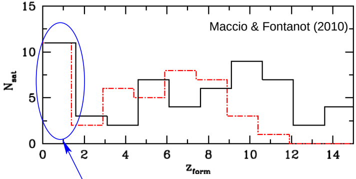


Dolphin+ (2005)

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

Milky Way satellites: formation history and abundance

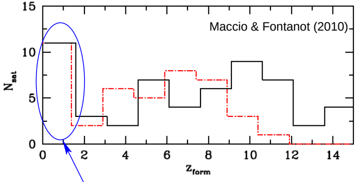
satellite formation time



late forming satellites (< 10 Gyr)
not observed!

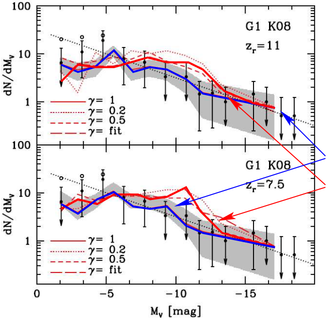
Milky Way satellites: formation history and abundance

satellite formation time



late forming satellites (< 10 Gyr)
not observed!

satellite luminosity function



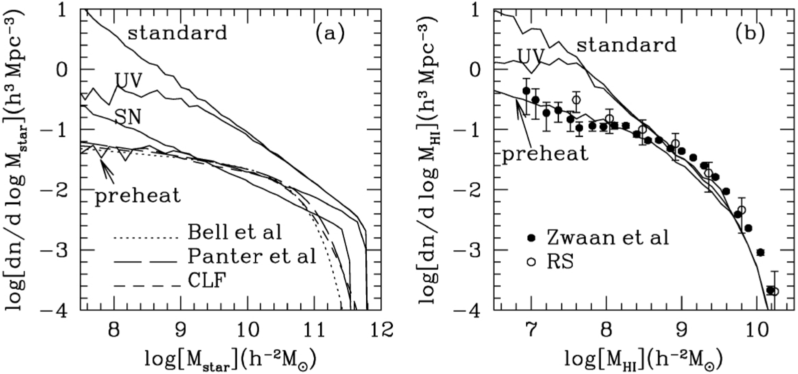
no blazar heating:
linear theory
non−linear theory

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!