The Physics and Cosmology of TeV Blazars

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in collaboration with

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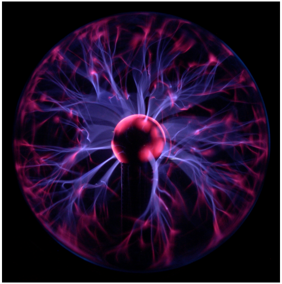
HITS

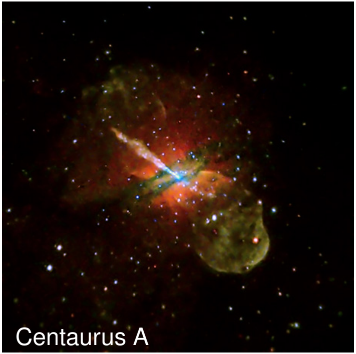
Motivation

A new link between high-energy astrophysics and cosmological structure formation



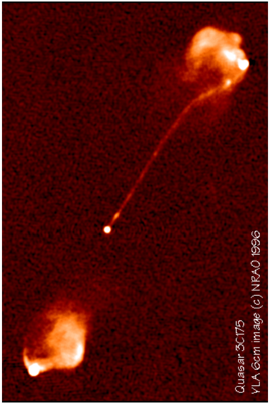
- **Introduction to Blazars**
  - active galactic nuclei (AGN)
  - propagating gamma rays
  - plasma physics
- **Cosmological Consequences**
  - unifying blazars with AGN
  - gamma-ray background
  - thermal history of the Universe
  - Lyman-α forest
  - formation of dwarf galaxies

Active galactic nucleus (AGN)


Centaurus A

- AGN: compact region at the center of a galaxy, which dominates the luminosity of its electromagnetic spectrum
- AGN emission is most likely caused by mass accretion onto a supermassive black hole and can also launch relativistic jets

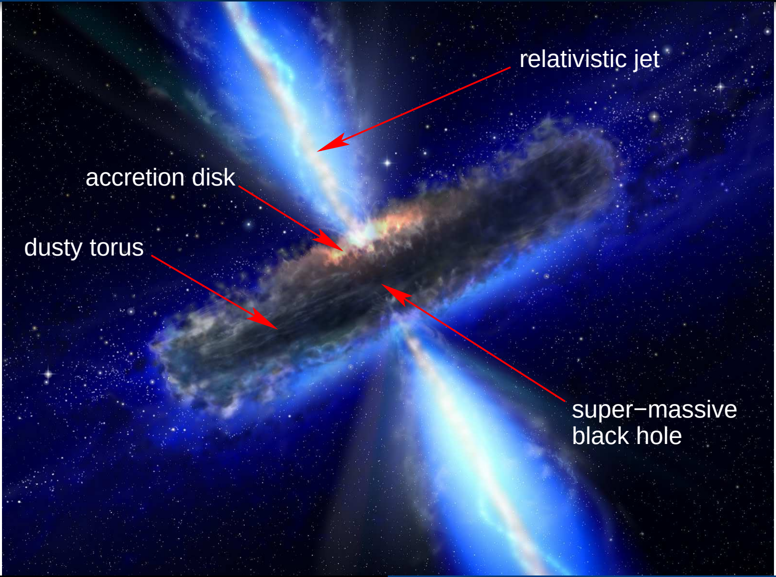
Active galactic nucleus at a cosmological distance



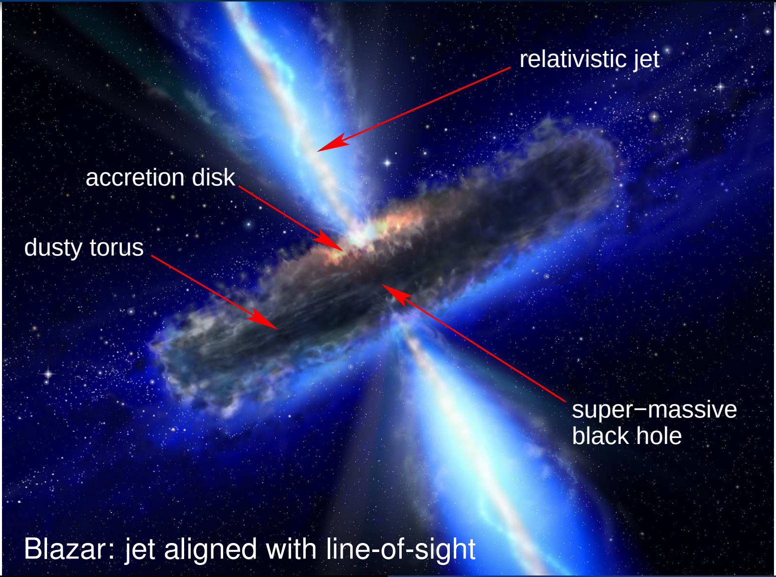
Quasar 3C175 at $z \simeq 0.8$:
jet extends 10^6 light years across

- AGN: compact region at the center of a galaxy, which dominates the luminosity of its electromagnetic spectrum
- AGN emission is most likely caused by mass accretion onto a supermassive black hole and can also launch relativistic jets
- AGNs are among the most luminous sources in the universe $\rightarrow$ discovery of distant objects

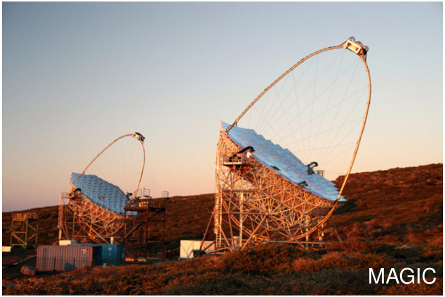
Unified model of active galactic nuclei



Unified model of active galactic nuclei



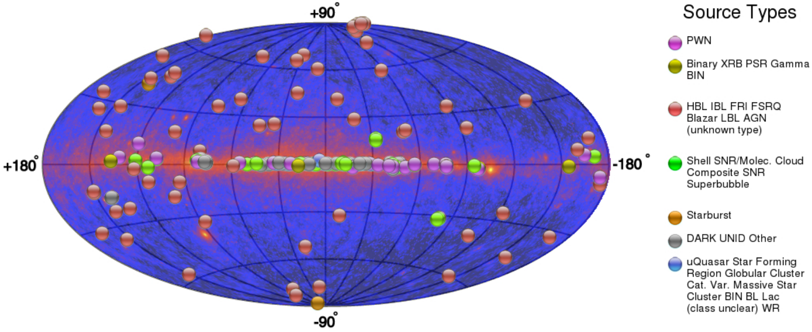
TeV gamma-ray observations



The TeV gamma-ray sky

There are several classes of TeV sources:

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



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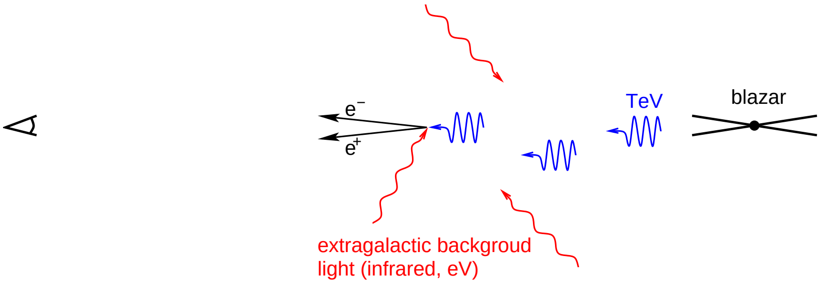
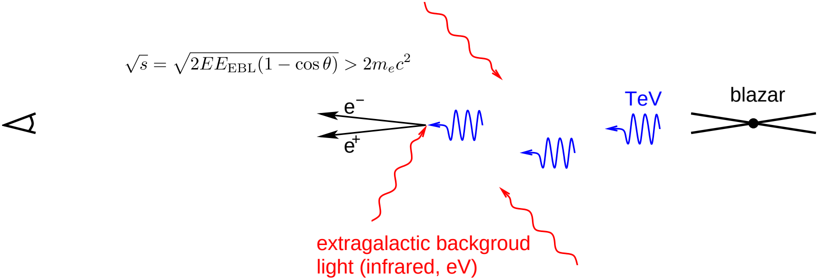
Annihilation and pair production



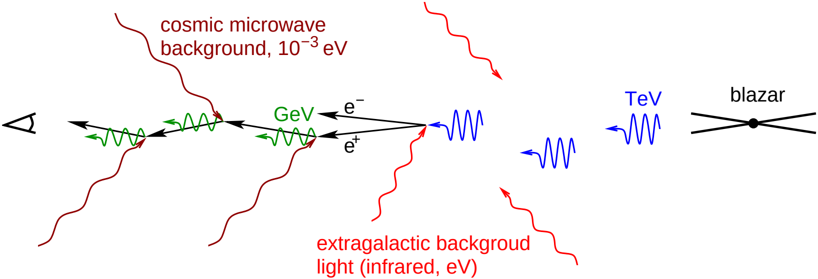
Annihilation and pair production

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



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

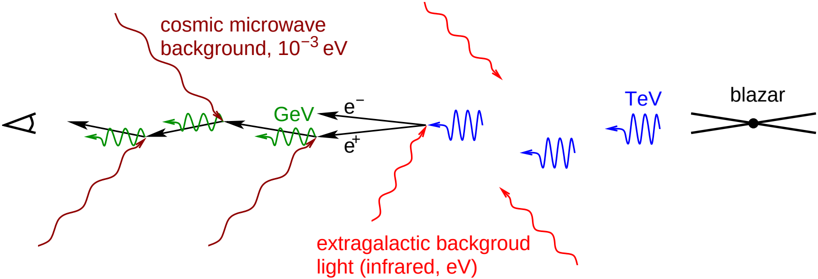
Inverse Compton cascades



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

$\lambda_{\gamma\gamma} \sim (35\dots700)\ \mathrm{Mpc\ for}\ z = 1\dots0$

Inverse Compton cascades

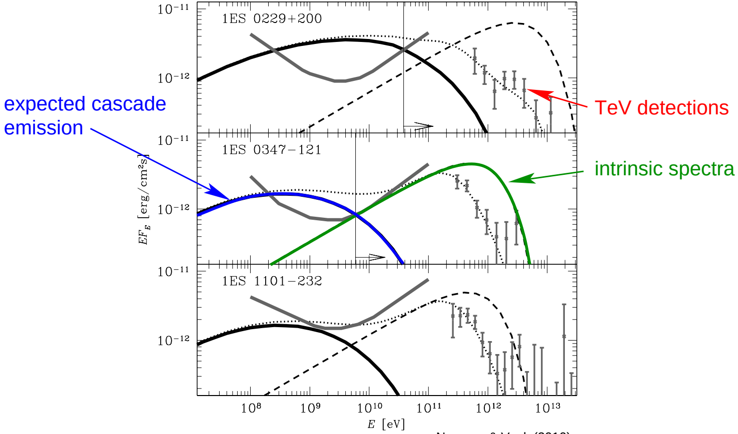


$\lambda_{\mathrm{IC}} \sim \lambda_{\gamma\gamma}/1000$ $\qquad$ $\lambda_{\gamma\gamma} \sim (35 \ldots 700)$ Mpc for $z = 1 \ldots 0$

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

What about the cascade emission?

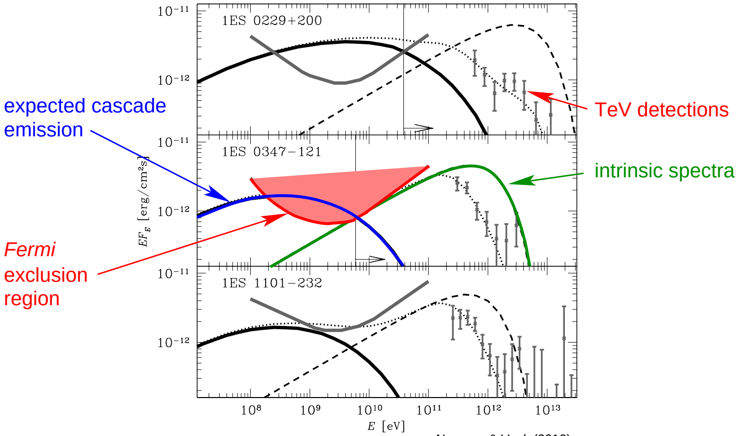
Every TeV source should be associated with a 1-100 GeV gamma-ray halo



Neronov & Vovk (2010)

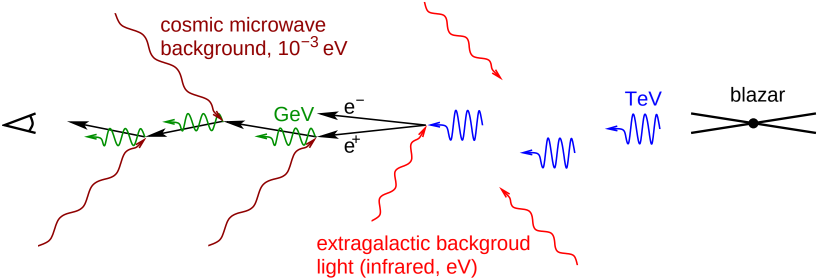
What about the cascade emission?

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



Neronov & Vovk (2010)

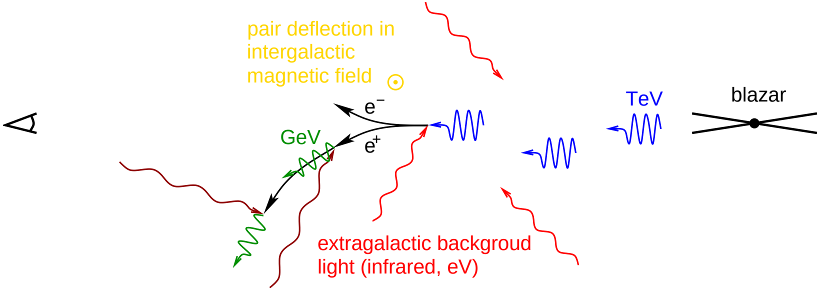
Inverse Compton cascades



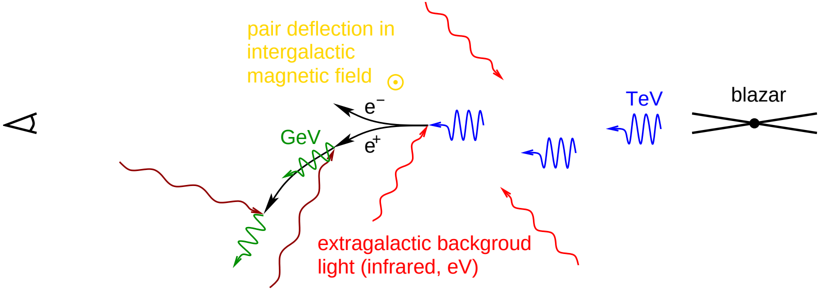
$\lambda_{\rm IC} \sim \lambda_{\gamma\gamma}/1000$

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

Extragalactic magnetic fields?

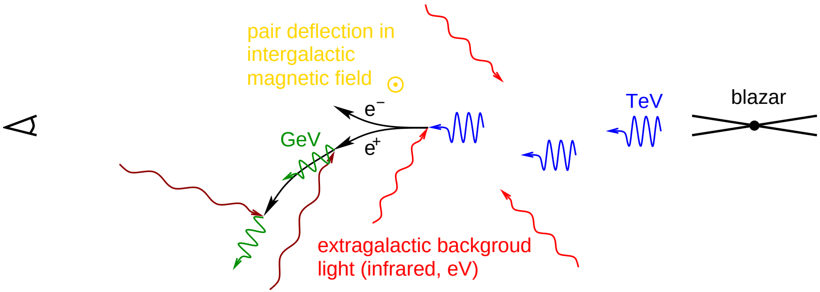


Extragalactic magnetic fields?



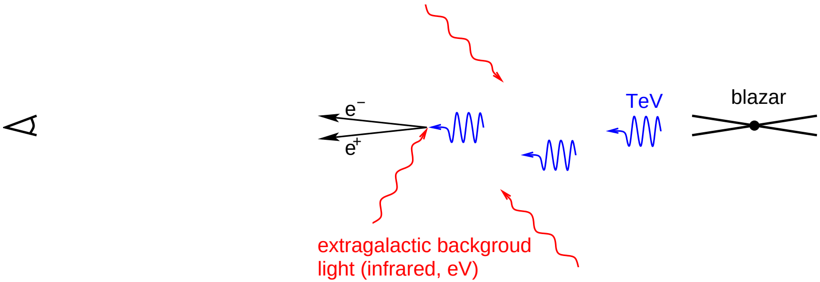
- GeV point source diluted ⟶ weak "pair halo"
- stronger B−field implies more deflection and dilution,
  gamma−ray non−detection ⟶ $B \gtrsim 10^{-16}\,\mathrm{G}$ − primordial fields?

Extragalactic magnetic fields?

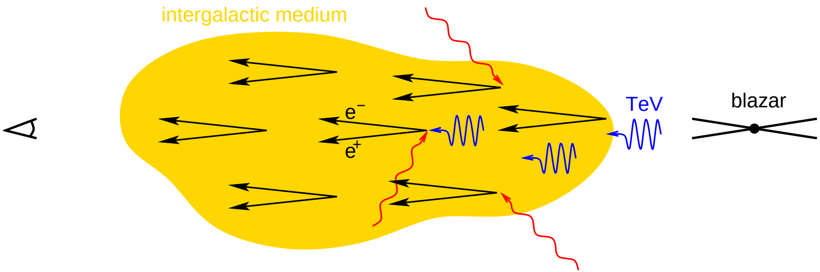


- problem for unified AGN model: no increase in comoving blazar density with redshift allowed (as seen in other AGNs) since other−wise, extragalactic GeV background would be overproduced!

What else could happen?



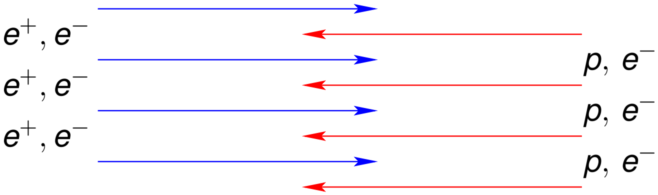
Plasma instabilities



→ pair plasma beam propagating through the intergalactic medium

Plasma instabilities

- pair beam — intergalactic medium (IGM)



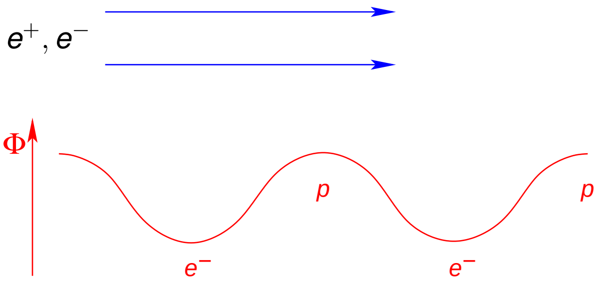
- this configuration is unstable to plasma instabilities
- characteristic frequency and length scale of the problem:

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

Two-stream instability

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

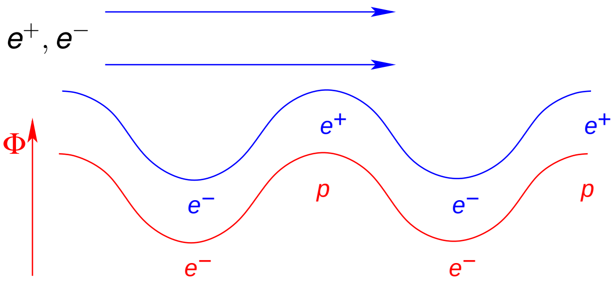
- initially homogeneous beam-e^-:
  attractive (repulsive) force by potential maxima (minima)
- e^- attain lowest velocity in potential minima $\rightarrow$ bunching up
- e^+ attain lowest velocity in potential maxima $\rightarrow$ bunching up



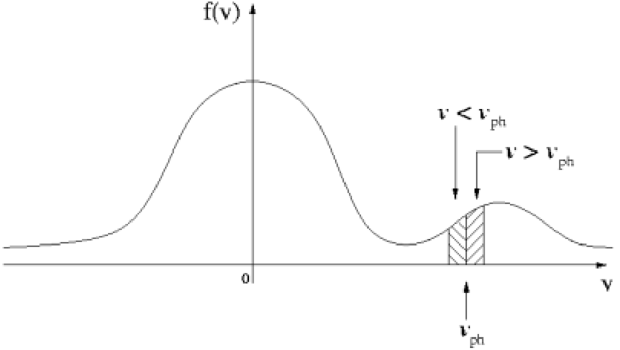
Two-stream instability

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^- $\rightarrow$ positive feedback
- exponential wave-growth $\rightarrow$ instability



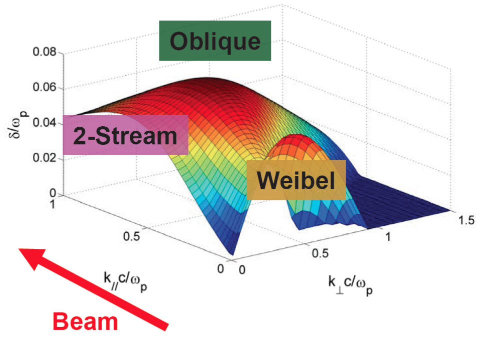
Two-stream instability: momentum transfer

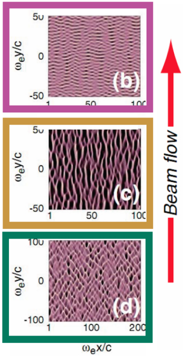


- particles with $v \gtrsim v_{\text{phase}}$:
  pair momentum → plasma waves → growing modes: instability
- particles with $v \lesssim v_{\text{phase}}$:
  plasma wave momentum → pairs → Landau damping

Oblique instability

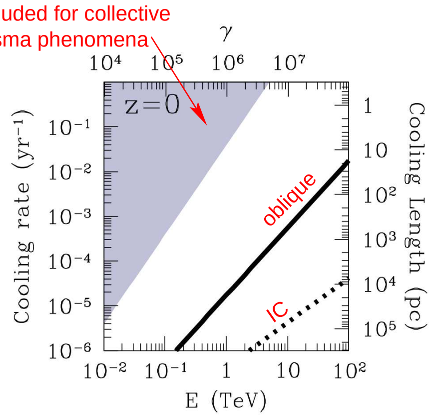
- $\boldsymbol{k}$ oblique to $\boldsymbol{v}_{\mathrm{beam}}$: real word perturbations don't choose "easy" alignment $= \sum$ all orientations
- oblique grows faster than two-stream: E-fields can easier deflect ultra-relativistic particles than change their parallel velocities (Nakar, Bret & Milosavljevic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

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

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

Challenges to the Challenge

Challenge #1: **inhomogeneous universe**

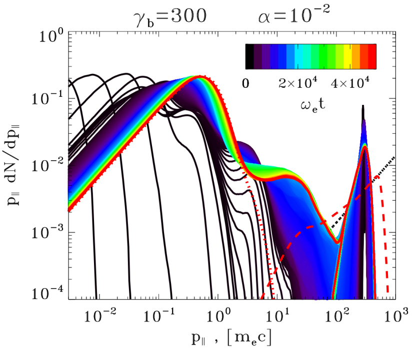
- universe is inhomogeneous $\to$ electron density changes with position
- could lead to loss of resonance over length scale $\ll$ spatial growth length scale $\lambda \equiv v_{\text{phase}}\tau_{\text{growth}}$ (Miniati & Elyiv 2012)
- plasma instabilities grow *locally*; information can only propagate with $v_{\text{group}} = 3v_{\text{th,e}}^2/v_{\text{phase}} \approx 1\,\text{km/s}$ (*causality*) $\to$ no instability quenching!

Challenge #2: **non-linear scattering**

- 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) $\to$ powerful instability, faster than IC cooling (Schlickeiser+ 2013, Chang+ 2014)

Simulations of the beam-plasma instability

Challenge #3: **non-linear saturation**



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

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

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

- **however:**
(1) coherent field $E_\perp$ causes beam deflection, no broadening of momentum distribution
(2) simulations do not conserve energy: numerical heating may quench instability

TeV emission from blazars – a new paradigm

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

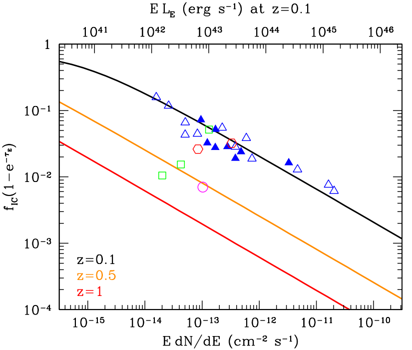
absence of γ_{GeV}'s has significant implications for ...

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

Implications for intergalactic magnetic fields

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

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



Broderick, Chang, C.P. (2012)

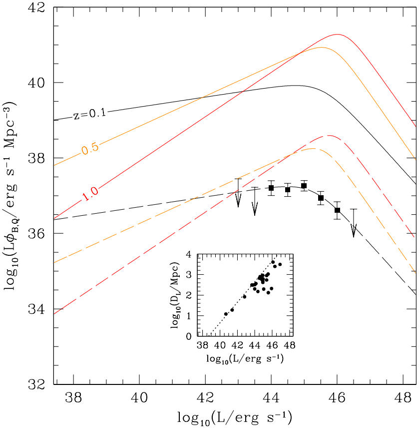
Conclusions on *B*-field constraints from blazar spectra

- 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

$\rightarrow$ **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+ (2014)

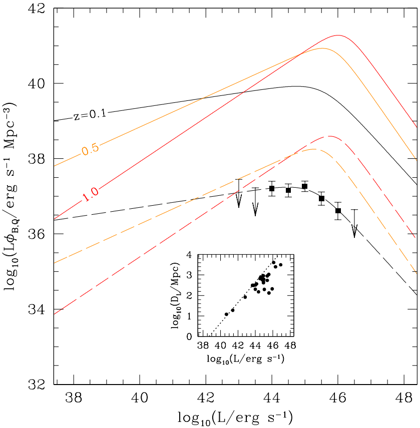
TeV blazar luminosity density: today



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:

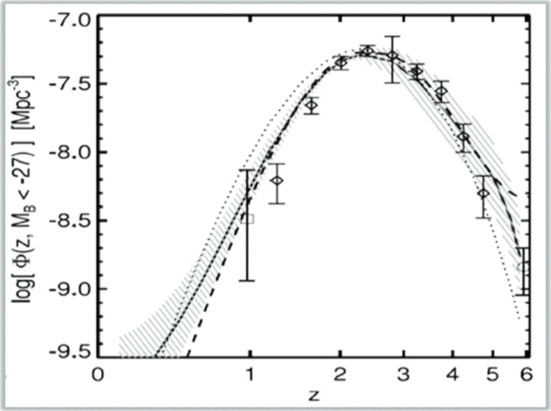
- regulated by the same mechanism
- contemporaneous elements of a single AGN population: TeV-blazar activity does not lag quasar activity

→ **assume that they trace each other for all redshifts!**

How many TeV blazars are there?

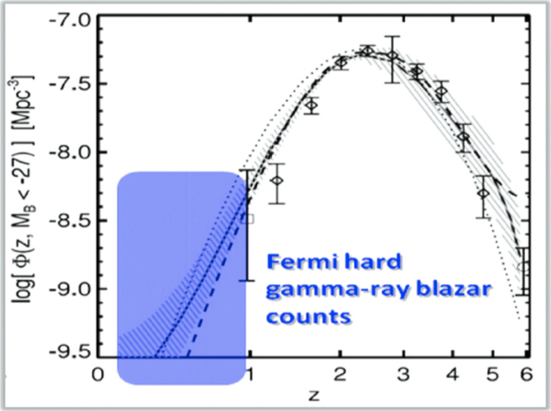
→ use all-sky survey of the GeV gamma-ray sky: *Fermi* gamma-ray space telescope

How many TeV blazars are there?



Hopkins+ (2007)

How many TeV blazars are there?



Hopkins+ (2007)

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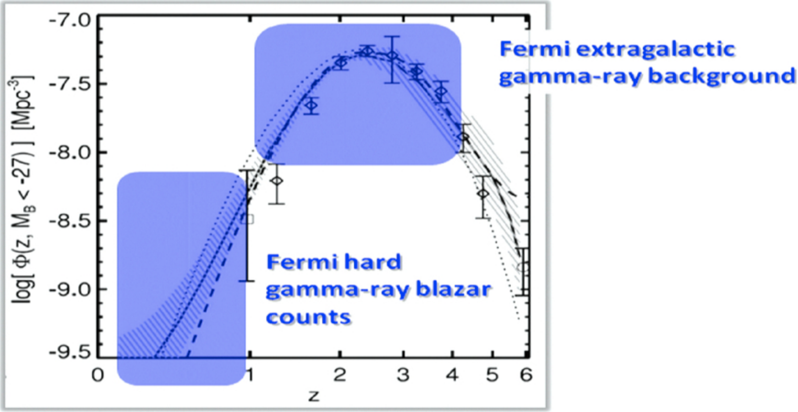
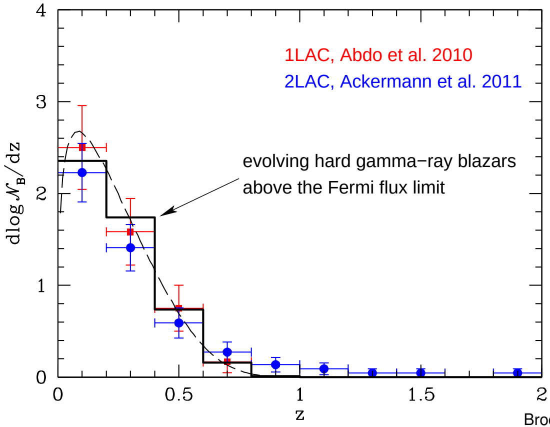


Hopkins+ (2007)

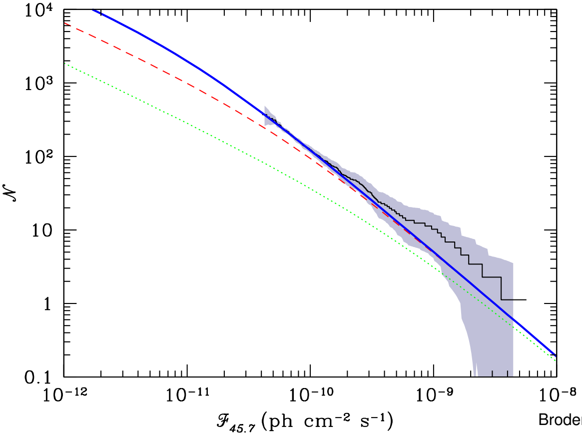
Redshift distribution of *Fermi* hard γ-ray blazars



Broderick, C.P.+ (2013)

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

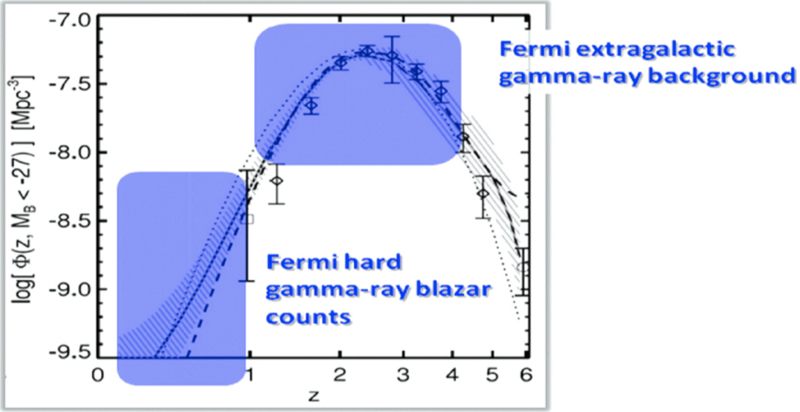
$\log \mathcal{N} - \log S$ distribution of *Fermi* hard γ-ray blazars



Broderick, C.P.+ (2013)

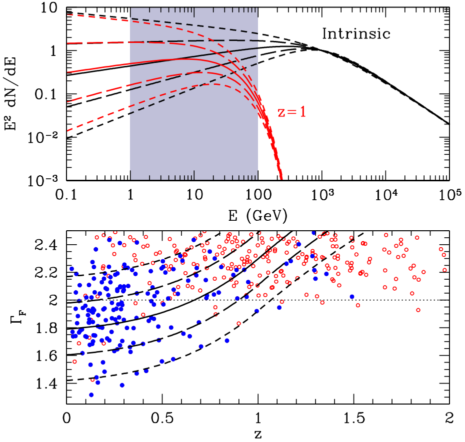
$\rightarrow$ predicted and observed flux distributions of hard *Fermi* blazars between 10 GeV and 500 GeV are indistinguishable!

How many TeV blazars are there?



Hopkins+ (2007)

TeV photon absorption by pair production



Broderick, C.P.+ (2013)

intrinsic and observed SEDs of blazars at $z = 1$
$\rightarrow$ 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:

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

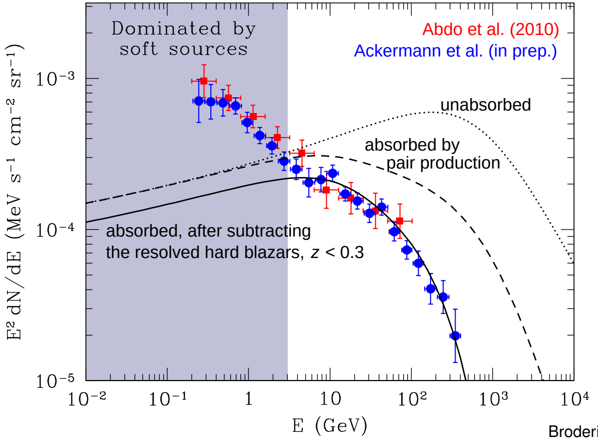
$E_b = 1$ TeV is break energy, $\Gamma_h = 3$ is high-energy spectral index,
Γ_l related to Γ_F, which is drawn from observed distribution

- extragalactic gamma-ray background (EGRB):

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

$E' = E(1+z')$ 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

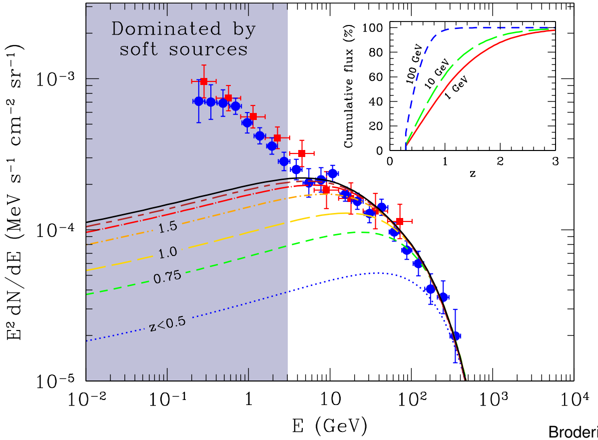
Extragalactic gamma-ray background



Broderick, C.P.+ (2013)

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

Extragalactic gamma-ray background



Broderick, C.P.+ (2013)

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

TeV emission from blazars – a new paradigm

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

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

- intergalactic magnetic field estimates
- unified picture of TeV blazars and quasars: explains *Fermi's* γ-ray background and blazar number counts

additional IGM heating has significant implications for . . .

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

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)

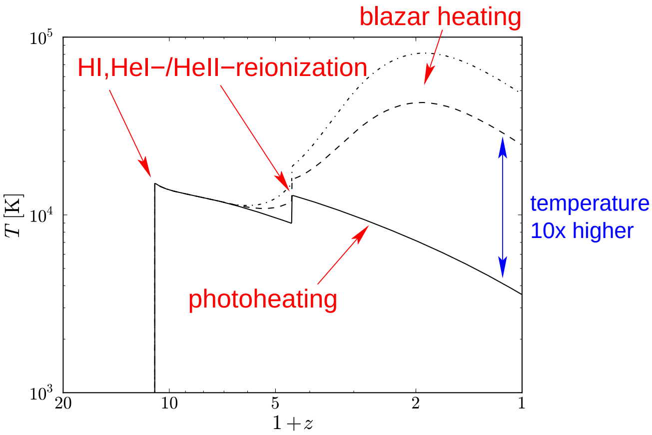
$$\varepsilon_{\mathrm{rad}} = \eta\, \Omega_{\mathrm{bh}} \sim 0.1 \times 10^{-4} \sim 10^{-5}$$

- 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)

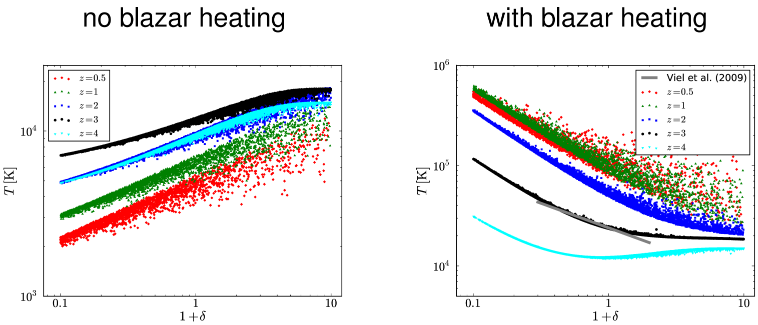
Thermal history of the IGM



C.P., Chang, Broderick (2012)

$\rightarrow$ increased temperature at **mean** density!

Evolution of the temperature-density relation

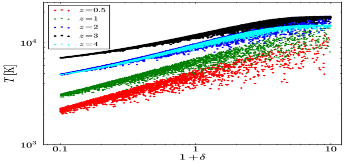


Chang, Broderick, C.P. (2012)

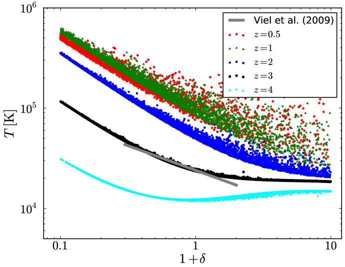
- blazars and extragalactic background light are uniform:
  $\rightarrow$ blazar heating rate independent of density
  $\rightarrow$ makes low density regions *hot*
  $\rightarrow$ causes inverted temperature-density relation, $T \propto 1/\delta$

Blazars cause hot voids

no blazar heating



with blazar heating

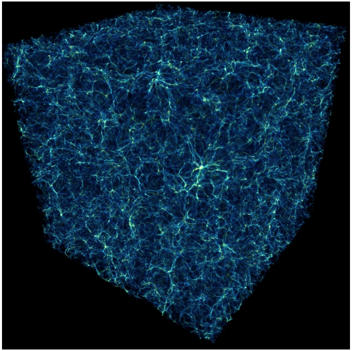


Chang, Broderick, C.P. (2012)

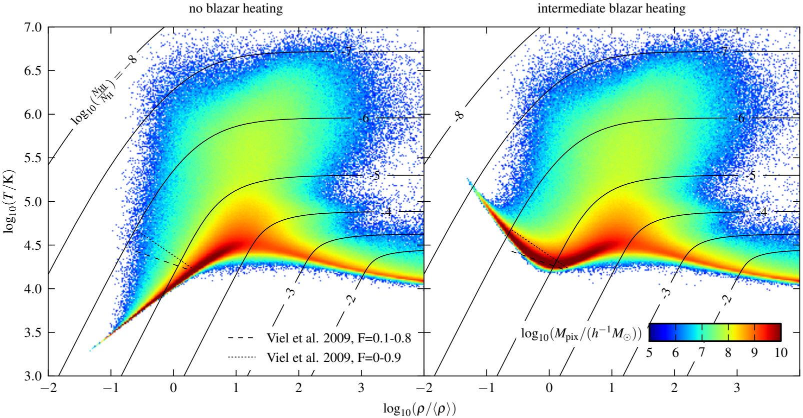
- blazars completely change the thermal history of the diffuse IGM and late-time structure formation

Cosmological hydrodynamical simulations

- include predicted volumetric heating rate in cosmological hydrodynamical simulations
- study:
  - thermal properties of intergalactic medium
  - Lyman-α forest

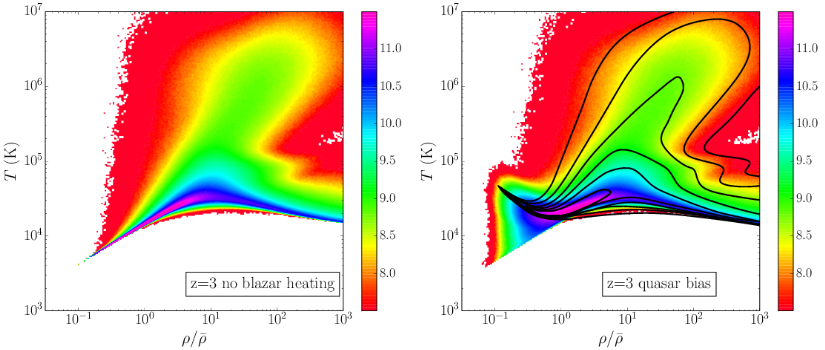


Temperature-density relation



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

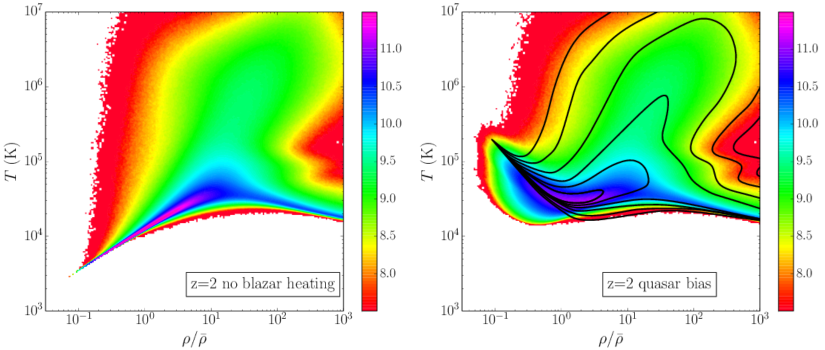
Temperature-density relation: patchy blazar heating



Lamberts, Chang, C.P., Puchwein, Broderick, Shalaby (2015)

→ patchy blazar heating diversifies the thermal history of the IGM

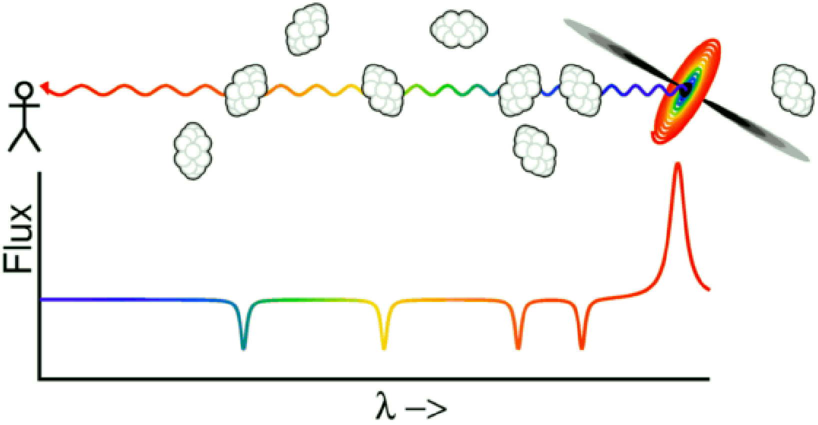
Temperature-density relation: patchy blazar heating



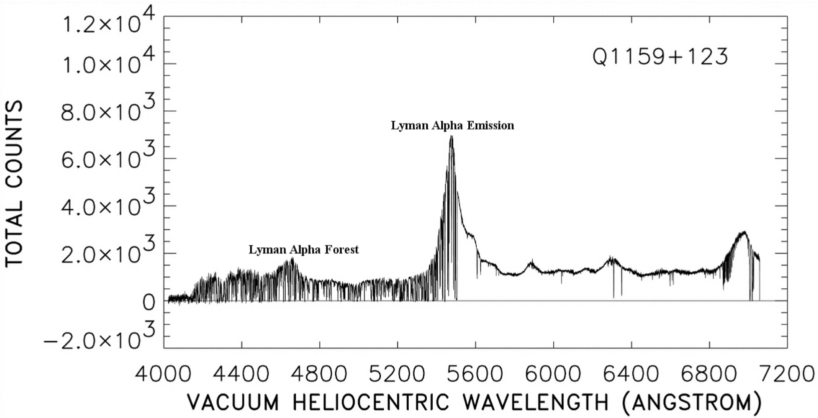
Lamberts, Chang, C.P., Puchwein, Broderick, Shalaby (2015)

→ patchy blazar heating diversifies the thermal history of the IGM

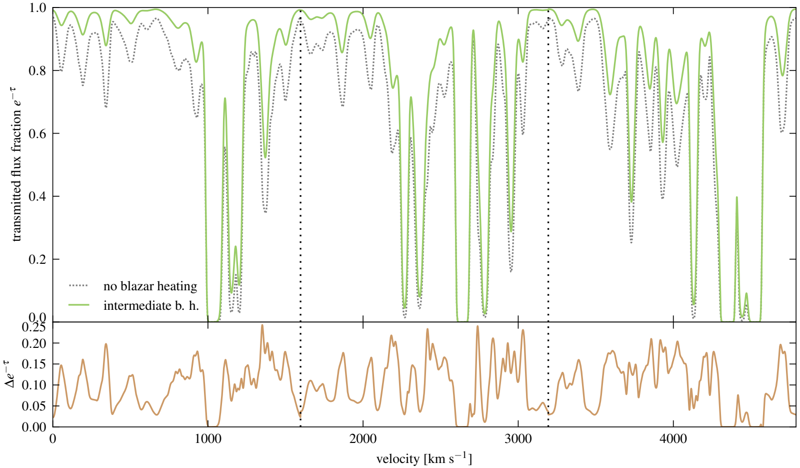
The Lyman-α forest



The observed Lyman-α forest

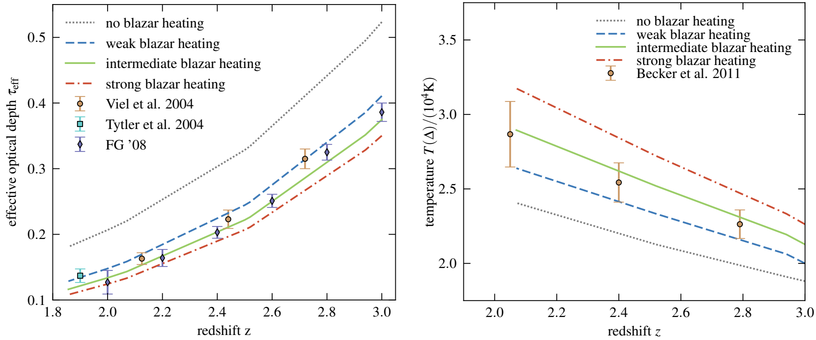


The simulated Ly-α forest



Puchwein, C.P.+ (2012)

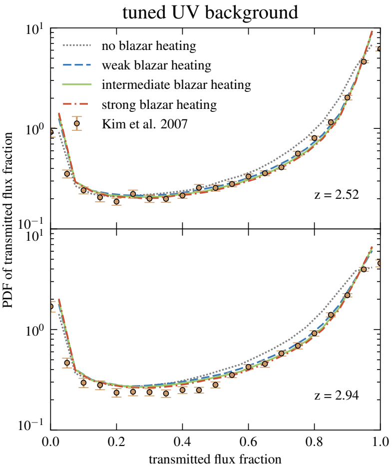
Optical depths and temperatures

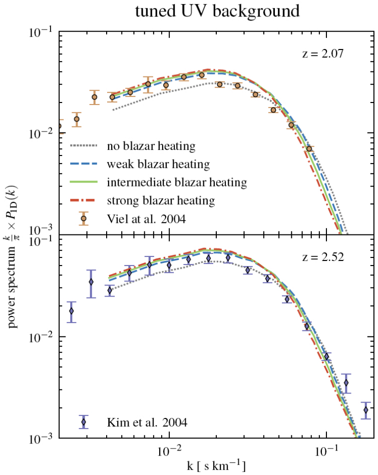


Puchwein, C.P.+ (2012)

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

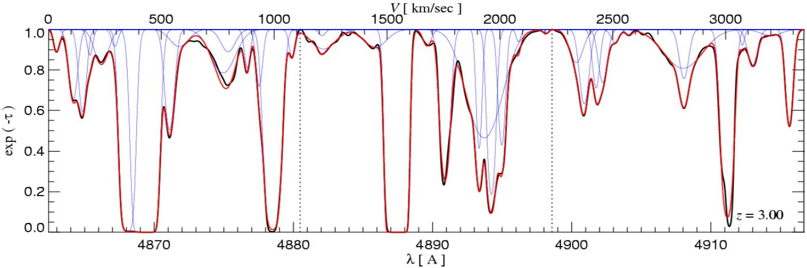
Ly-α flux PDFs and power spectra





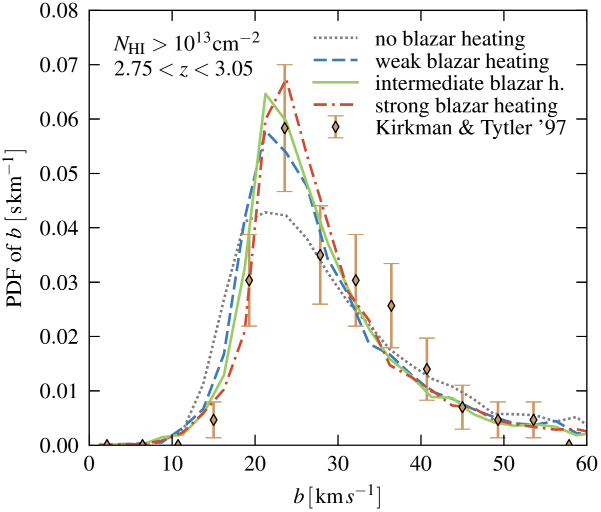
Puchwein, C.P.+ (2012)

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



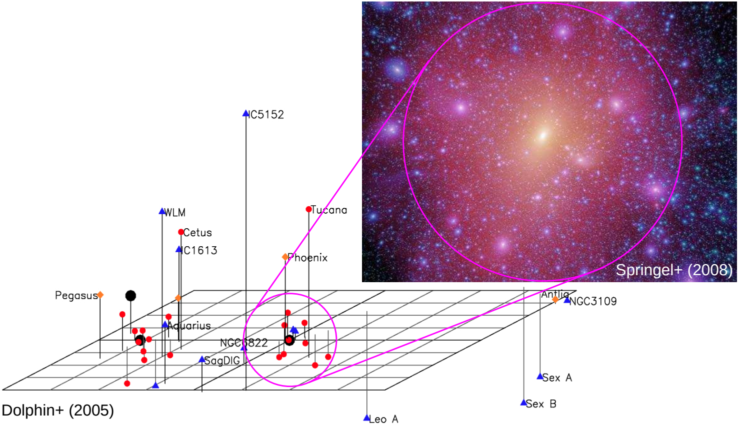
Puchwein, C.P.+ (2012)

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 is 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)

“Missing satellite” problem in the Milky Way



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

Dwarf galaxy formation

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

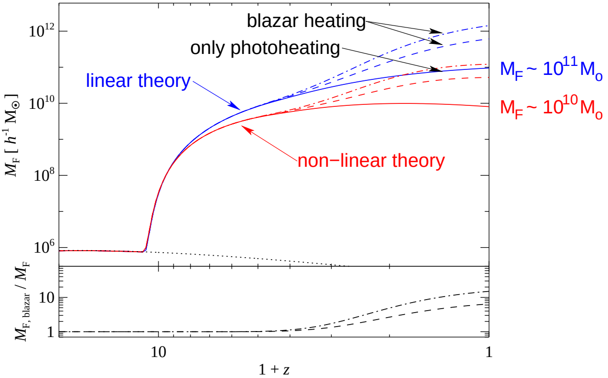
$$M_J \propto \frac{c_s^3}{\rho^{1/2}} \propto \left(\frac{T_{\rm IGM}^3}{\rho}\right)^{1/2} \quad \rightarrow \quad \frac{M_{J,\rm blazar}}{M_{J,\rm photo}} \approx \left(\frac{T_{\rm blazar}}{T_{\rm photo}}\right)^{3/2} \gtrsim 30$$

  → blazar heating increases M_J by 30 over pure photoheating!
- complications:
  non-linear collapse,
  delayed pressure response in expanding universe → concept of "filtering mass"

C.P., Chang, Broderick (2012)

HITS

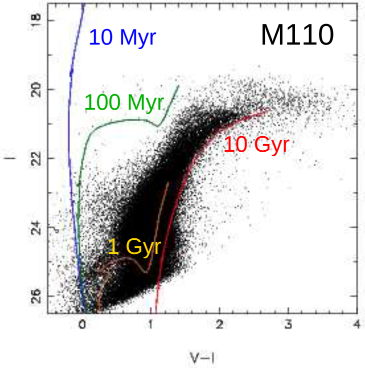
Dwarf galaxy formation suppressed



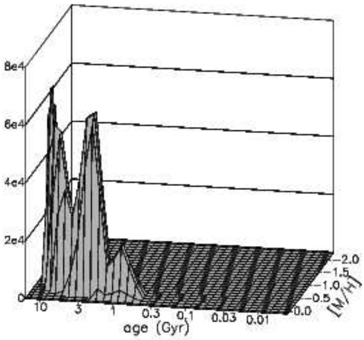
C.P., Chang, Broderick (2012)

- blazar heating suppresses the formation of late-forming dwarfs within existing dark matter halos of masses $< 10^{11}\ \mathrm{M}_\odot$
  $\rightarrow$ introduces new time and mass scale to galaxy formation!

When do dwarfs form?

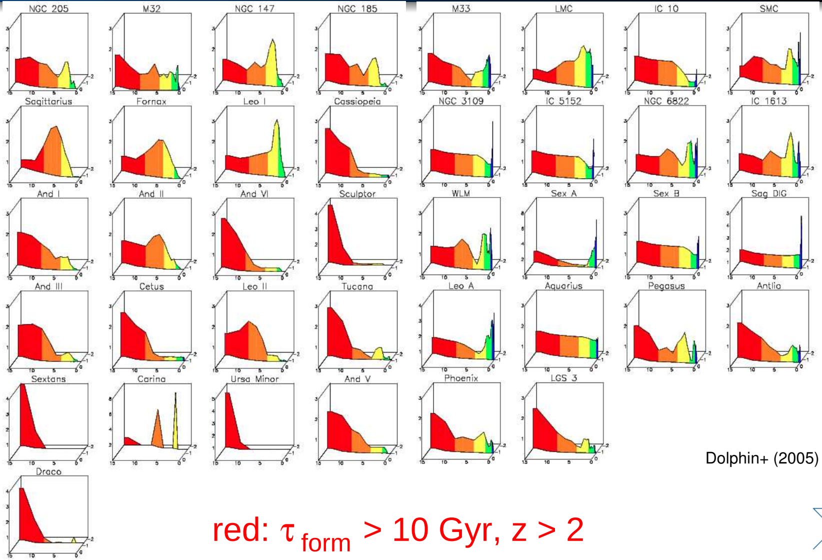


Dolphin+ (2005)



isochrone fitting for different metallicities → star formation histories

When do dwarfs form?



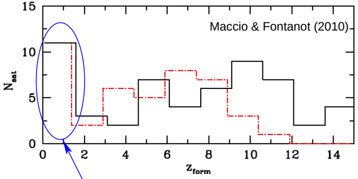
Dolphin+ (2005)

red: τ_{form} > 10 Gyr, z > 2

HITS

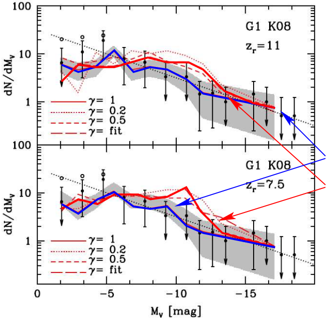
Milky Way satellites: formation history and abundance

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

Conclusions on blazar heating

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

- explains puzzles in gamma-ray 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
  - quantitative self-consistent picture of high-z Lyman-α forest
- significantly modifies late-time structure formation:
  - suppresses late dwarf formation
  - 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, 790, 137, 2014.
- Chang, Broderick, Pfrommer, Puchwein, Lamberts, Shalaby, *The effect of nonlinear Landau damping on ultrarelativistic beam plasma instabilities*, ApJ, 2014, 797, 110.
- Lamberts, Chang, Pfrommer, Puchwein, Broderick, Shalaby, *Patchy blazar heating: diversifying the thermal history of the intergalactic medium*, 2015, submitted, arXiv:1502.07980.

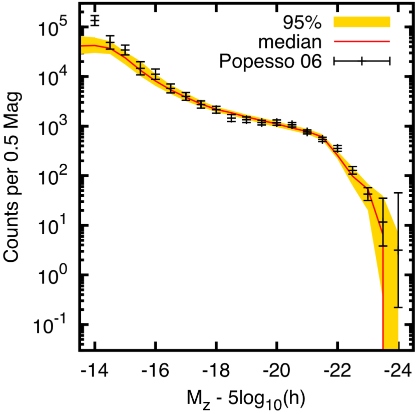
Additional slides

Empirical model for star formation histories (1)

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

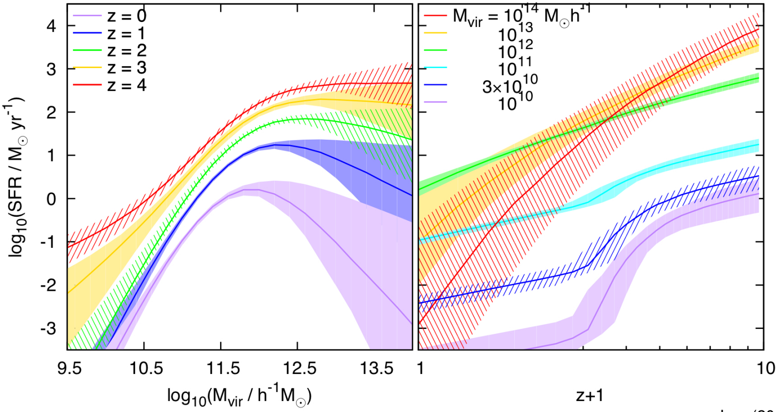
- observed stellar mass function (different z)
- luminosity function of local cluster galaxies

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



Lu+ (2013)

Empirical model for star formation histories (2)

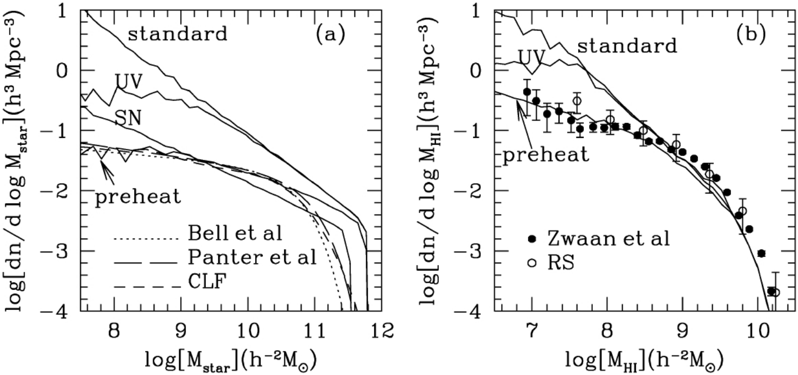


Lu+ (2013)

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

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!