The Physics of Propagating TeV Gamma-rays: from Plasma Instabilities to Cosmological Structure Formation

Christoph Pfrommer[1]

in collaboration with

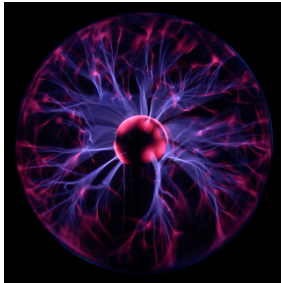Avery E. Broderick, Phil Chang, Ewald Puchwein, Volker Springel

[1] Heidelberg Institute for Theoretical Studies, Germany

Mar 24, 2014 / DPG Frühjahrstagung, Mainz

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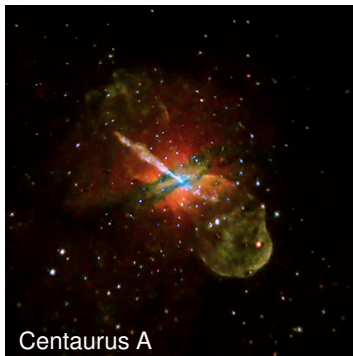A new link between high-energy astrophysics and cosmological structure formation

- **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
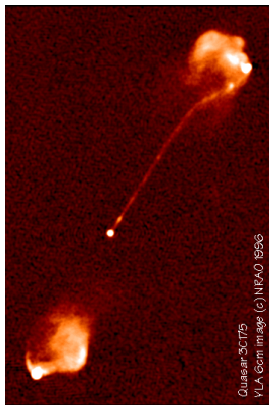 - formation of dwarf galaxies

Blazars
Gamma-ray sky
Structure formation

Active galactic nuclei
Propagating γ rays
Plasma instabilities

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

- AGNs are the most luminous sources in the universe
  $\rightarrow$ discovery of distant objects

HITS

Blazars
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Active galactic nucleus at a cosmological distance

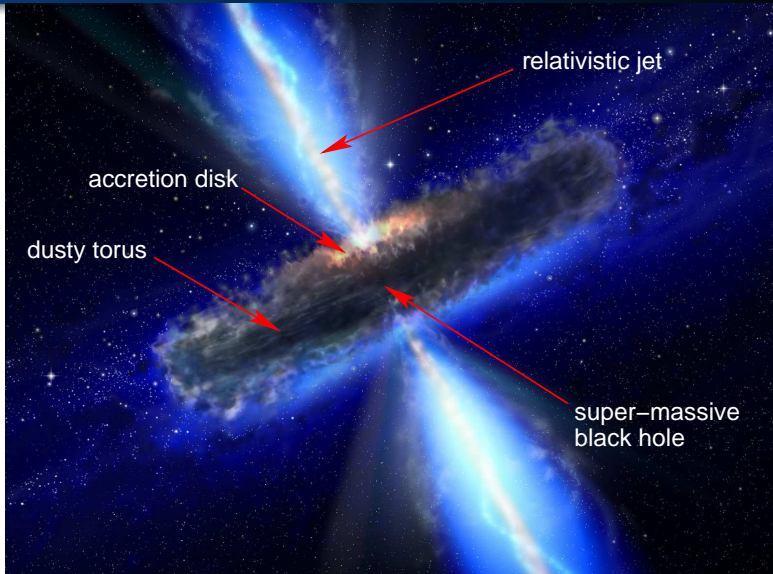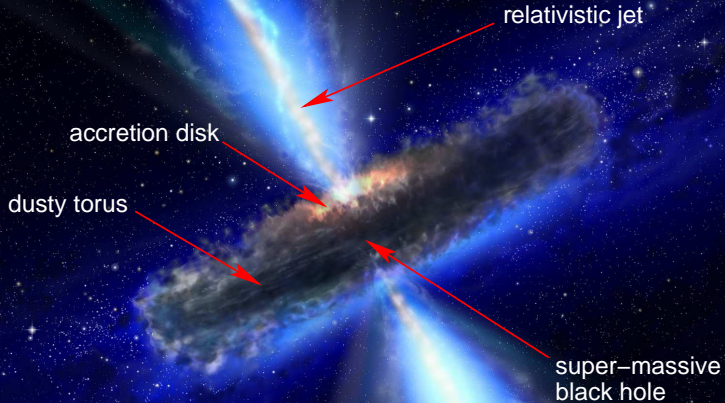Quasar 3C175 at $z \simeq 0.8$:
jet extends 10^6 light years across

- 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 the most luminous sources in the universe
  $\rightarrow$ discovery of distant objects

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Unified model of active galactic nuclei

relativistic jet

accretion disk

dusty torus

super–massive
black hole

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Unified model of active galactic nuclei

relativistic jet

accretion disk

dusty torus

super–massive
black hole

Blazar: jet aligned with line-of-sight

Blazars
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TeV gamma-ray observations

MAGIC

VERITAS

H.E.S.S.

HITS

Blazars
Gamma-ray sky
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Active galactic nuclei
Propagating γ rays
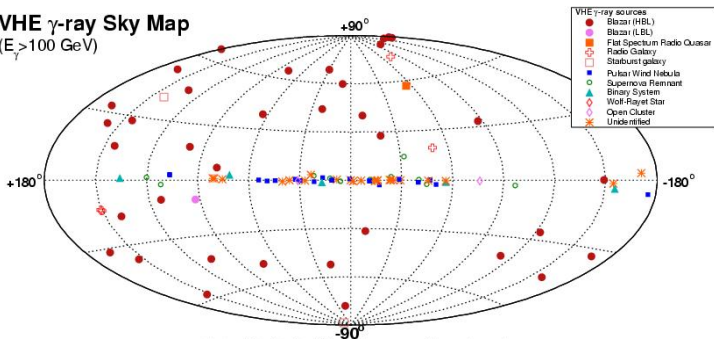Plasma instabilities
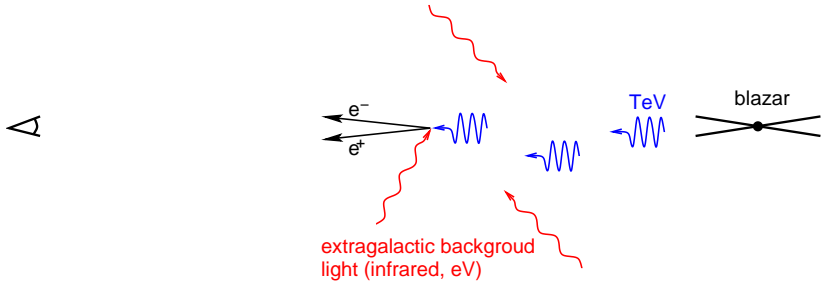
The TeV gamma-ray sky

There are several classes of TeV sources:

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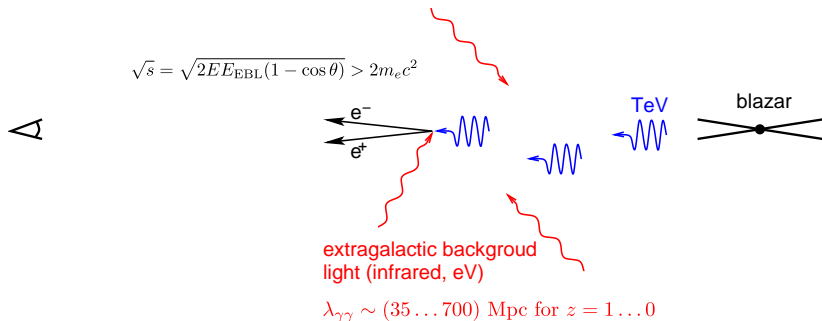- Extragalactic - **mostly** blazars, two starburst galaxies

VHE γ-ray Sky Map
(E_γ >100 GeV)

VHE γ-ray sources
- Blazar (HBL)
- Blazar (LBL)
- Flat Spectrum Radio Quasar
- Radio Galaxy
- Starburst galaxy
- Pulsar Wind Nebula
- Supernova Remnant
- Binary System
- Wolf-Rayet Star
- Open Cluster
- Unidentified

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

Blazars
Gamma-ray sky
Structure formation

Active galactic nuclei
Propagating γ rays
Plasma instabilities

Annihilation and pair production

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Annihilation and pair production

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

e⁻

e⁺

TeV

blazar

extragalactic backgroud
light (infrared, eV)

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

Blazars
Gamma-ray sky
Structure formation

Active galactic nuclei
Propagating γ rays
Plasma instabilities

Inverse Compton cascades

cosmic microwave
background, 10^{-3} eV

GeV

e^-

e^+

TeV

blazar

extragalactic background
light (infrared, eV)

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

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

Blazars
Gamma-ray sky
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Plasma instabilities

Inverse Compton cascades

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

Blazars
Gamma-ray sky
Structure formation

Active galactic nuclei
Propagating γ rays
Plasma instabilities

What about the cascade emission?

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

Neronov & Vovk (2010)

Blazars
Gamma-ray sky
Structure formation

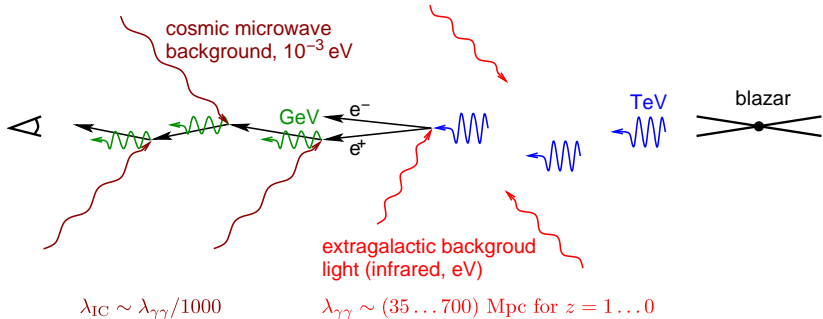Active galactic nuclei
Propagating γ rays
Plasma instabilities
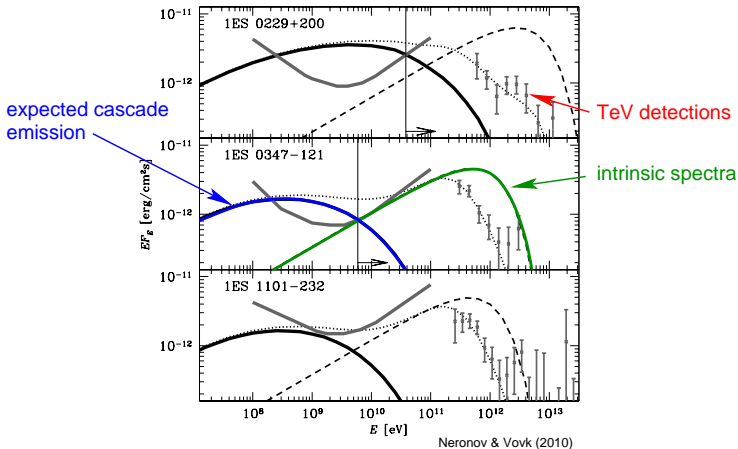
What about the cascade emission?

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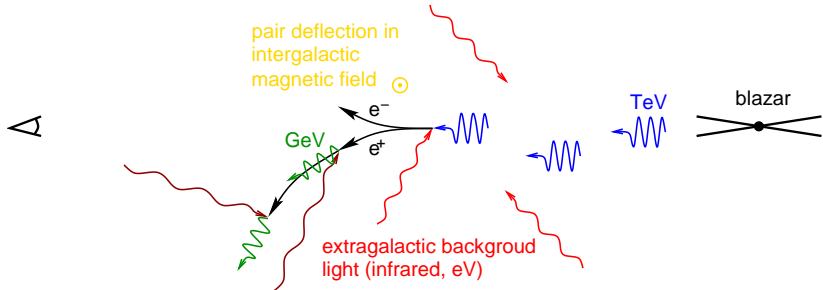

expected cascade emission
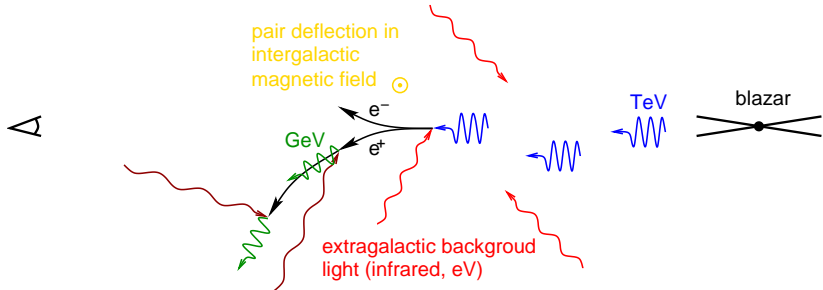
Fermi exclusion region

TeV detections

intrinsic spectra

Neronov & Vovk (2010)

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Inverse Compton cascades

cosmic microwave
background, 10^{-3} eV

GeV

e^-

e^+

extragalactic background
light (infrared, eV)

TeV

blazar

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

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

HITS

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Plasma instabilities

Extragalactic magnetic fields?

pair deflection in
intergalactic
magnetic field ⊙

e^-

GeV

e^+

TeV

blazar

extragalactic backgroud
light (infrared, eV)

HITS

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Plasma instabilities

Extragalactic magnetic fields?

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

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Extragalactic magnetic fields?

pair deflection in
intergalactic
magnetic field ⊙

e^-

GeV

e^+

TeV

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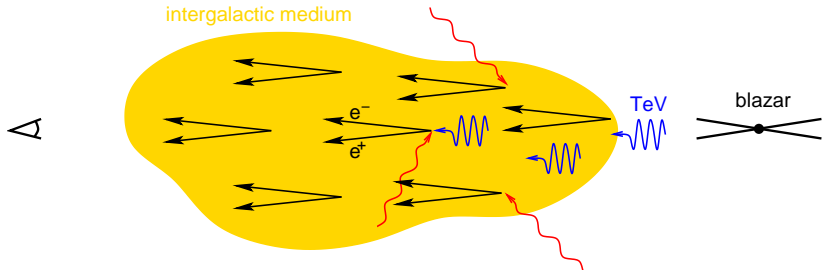
extragalactic backgroud
light (infrared, eV)
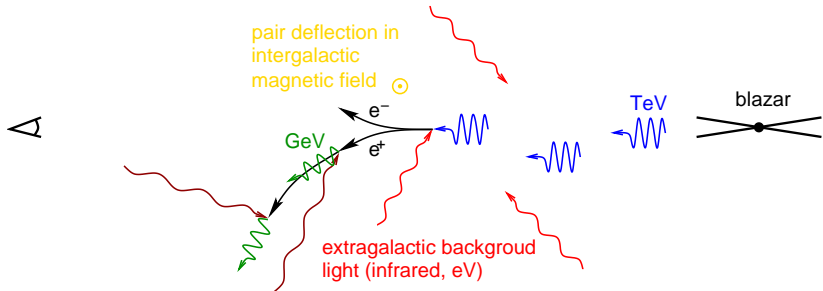
- **problem for unified AGN model:** no increase in comoving blazar density with redshift allowed (as seen in other AGNs) since other–wise, extragalactic GeV background would be overproduced!

HITS

Blazars
Gamma-ray sky
Structure formation

Active galactic nuclei
Propagating γ rays
Plasma instabilities

What else could happen?

extragalactic backgroud
light (infrared, eV)

Blazars
Gamma-ray sky
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Active galactic nuclei
Propagating γ rays
Plasma instabilities

Plasma instabilities

intergalactic medium

e^-

e^+

TeV

blazar

$\triangleleft$

→ pair plasma beam propagating
through the intergalactic medium

Blazars
Gamma-ray sky
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Active galactic nuclei
Propagating γ rays
Plasma instabilities

Plasma instabilities

- pair beam   intergalactic medium (IGM)
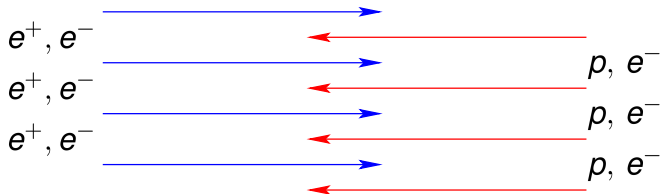
- this configuration is unstable to plasma instabilities
- characteristic frequency and length scale of the problem:

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

Blazars
Gamma-ray sky
Structure formation

Active galactic nuclei
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Plasma instabilities

Two-stream instability

consider wave-like perturbation in background plasma along the beam direction (Langmuir wave):
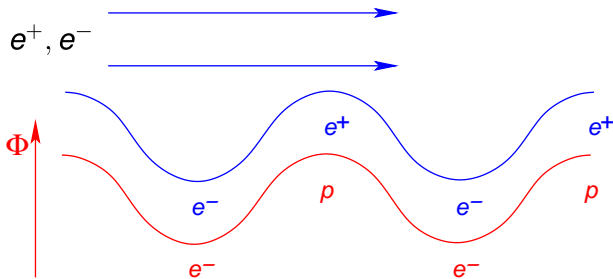
- initially homogeneous beam-e^-:
  attractive (repulsive) force by potential maxima (minima)
- e^- attain lowest velocity in potential minima $\rightarrow$ bunching up
- e^+ attain lowest velocity in potential maxima $\rightarrow$ bunching up
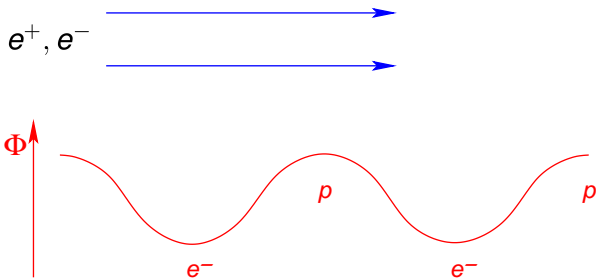
Blazars
Gamma-ray sky
Structure formation

Active galactic nuclei
Propagating γ rays
Plasma instabilities
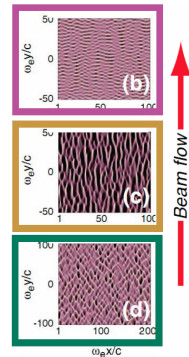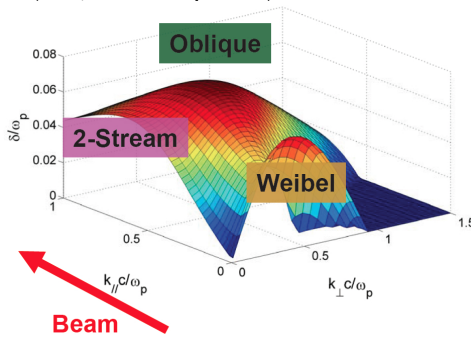
Two-stream instability

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

Blazars
Gamma-ray sky
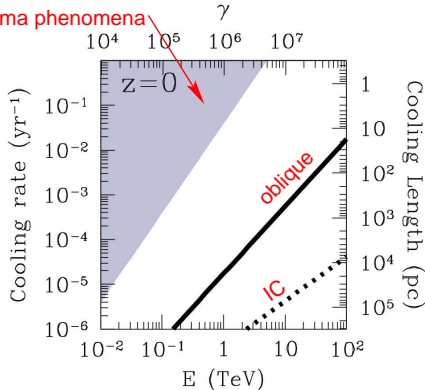Structure formation

Active galactic nuclei
Propagating γ rays
Plasma instabilities

Oblique instability

- **k** oblique to **v_{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)

Blazars
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Structure formation

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Beam physics – growth rates

excluded for collective
plasma phenomena

γ

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

- consider a light beam penetrating into relatively dense plasma

- maximum growth rate

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

- oblique instability beats inverse Compton cooling by factor 10-100

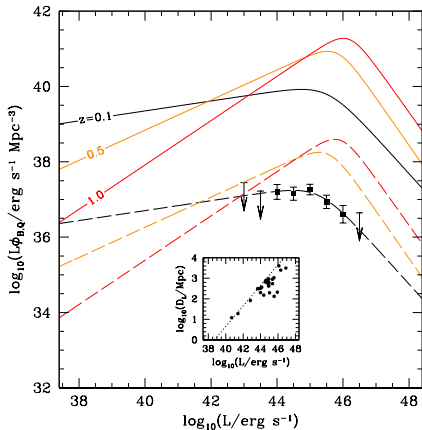- **assume** that instability grows at linear rate up to saturation

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TeV emission from blazars – a new paradigm

$$\gamma_{\text{TeV}} + \gamma_{\text{eV}} \; \rightarrow \; e^+ + e^- \; \rightarrow \; \begin{cases} \text{inv. Compton cascades} \quad \rightarrow \quad \gamma_{\text{GeV}} \\[2ex] \text{plasma instabilities} \end{cases}$$

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

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

Blazars
Gamma-ray sky
Structure formation

Unified scenario
Blazar evolution
Gamma-ray background
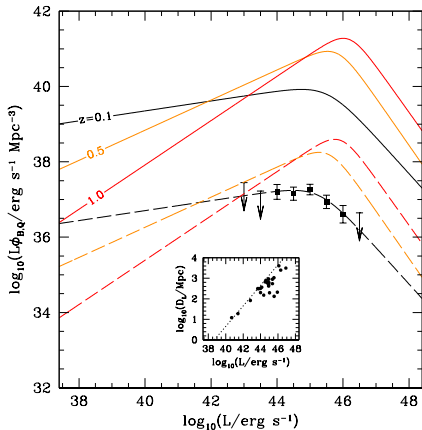
TeV blazar luminosity density: today

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!

Blazars
Gamma-ray sky
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Unified scenario
Blazar evolution
Gamma-ray background

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

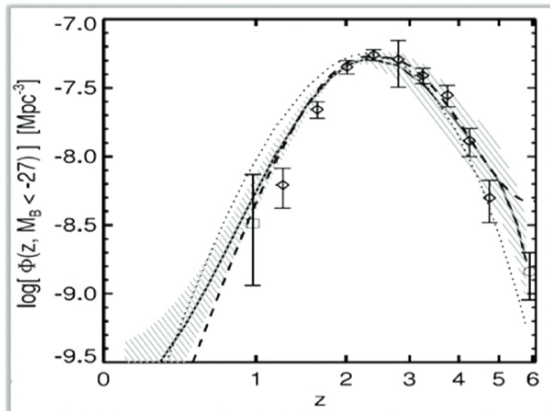→ **assume that they trace each other for all redshifts!**

Blazars
Gamma-ray sky
Structure formation

Unified scenario
Blazar evolution
Gamma-ray background

How many TeV blazars are there?

$\rightarrow$ use all-sky survey of the GeV gamma-ray sky: *Fermi* gamma-ray space telescope

Blazars
Gamma-ray sky
Structure formation

Unified scenario
Blazar evolution
Gamma-ray background

How many TeV blazars are there?

Hopkins+ (2007)

Blazars
Gamma-ray sky
Structure formation

Unified scenario
Blazar evolution
Gamma-ray background

How many TeV blazars are there?

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How many TeV blazars are there?

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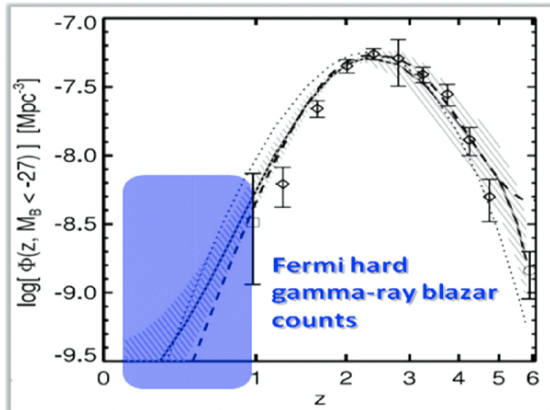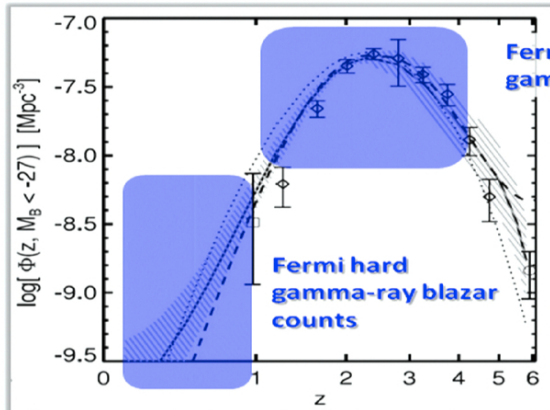
Redshift distribution of *Fermi* hard γ-ray blazars

1LAC, Abdo et al. 2010
2LAC, Ackermann et al. 2011

evolving hard gamma–ray blazars
above the Fermi flux limit

Broderick, C.P.+ (2013)
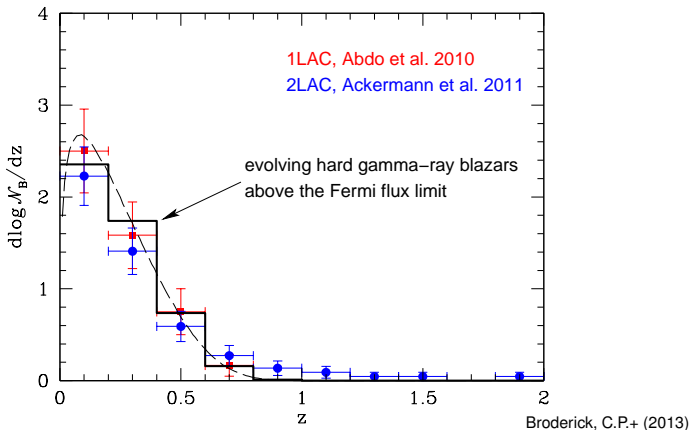
$\rightarrow$ evolving (increasing) blazar population consistent with observed
declining evolution (*Fermi* flux limit)!

Blazars
Gamma-ray sky
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Unified scenario
Blazar evolution
Gamma-ray background

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

Broderick, C.P.+ (2013)
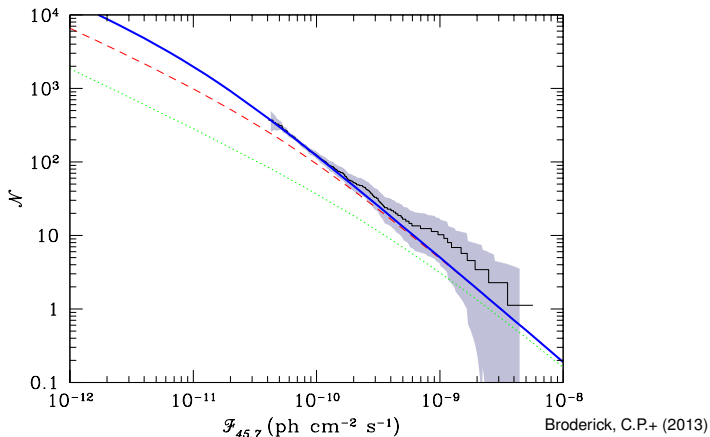
$\rightarrow$ predicted and observed flux distributions of hard *Fermi* blazars between 10 GeV and 500 GeV are indistinguishable!

Blazars
Gamma-ray sky
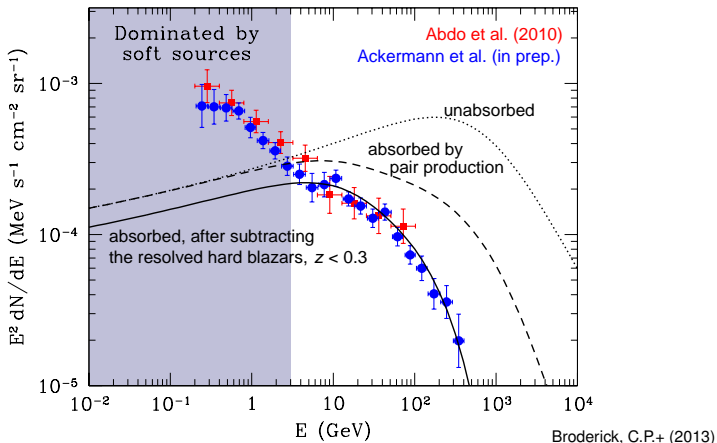Structure formation

Unified scenario
Blazar evolution
Gamma-ray background

How many TeV blazars are there?

Hopkins+ (2007)

Blazars
Gamma-ray sky
Structure formation

Unified scenario
Blazar evolution
Gamma-ray background

Extragalactic gamma-ray background

Dominated by soft sources

Abdo et al. (2010)
Ackermann et al. (in prep.)

unabsorbed

absorbed by pair production

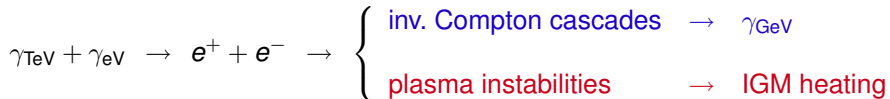absorbed, after subtracting the resolved hard blazars, $z < 0.3$

Broderick, C.P.+ (2013)
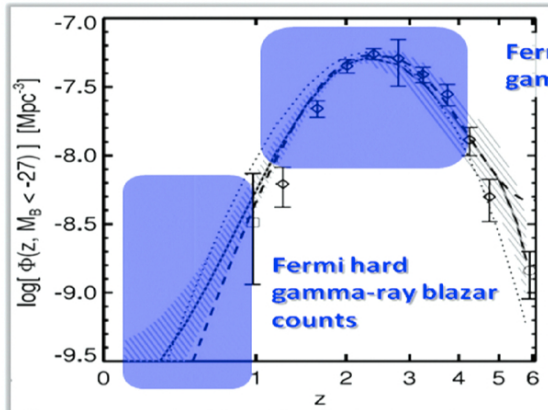
$\rightarrow$ evolving population of hard blazars provides excellent match to latest EGRB by *Fermi* for $E \gtrsim 3$ GeV

Blazars
Gamma-ray sky
Structure formation

Properties of blazar heating
The Lyman-α forest
Dwarf galaxies

TeV emission from blazars – a new paradigm

$$\gamma_{\text{TeV}} + \gamma_{\text{eV}} \;\rightarrow\; e^+ + e^- \;\rightarrow\; \begin{cases} \text{inv. Compton cascades} & \rightarrow & \gamma_{\text{GeV}} \\[2mm] \text{plasma instabilities} & \rightarrow & \text{IGM heating} \end{cases}$$

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

HITS

Blazars
Gamma-ray sky
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Properties of blazar heating
The Lyman-α forest
Dwarf galaxies

Blazar heating vs. photoheating

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

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

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

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

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

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

- photoheating efficiency $\eta_{ph} \sim 10^{-3} \quad \rightarrow \quad kT \sim \eta_{ph} \, \varepsilon_{UV} \, m_p c^2 \sim eV$
  (limited by the abundance of H I/He II due to the small recombination rate)

- blazar heating efficiency $\eta_{bh} \sim 10^{-3} \quad \rightarrow \quad kT \sim \eta_{bh} \, \varepsilon_{rad} \, m_p c^2 \sim 10 \, eV$
  (limited by the total power of TeV sources)

Blazars
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Thermal history of the IGM
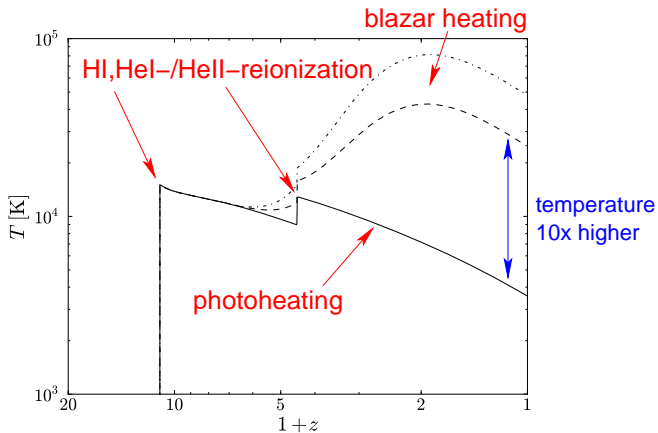
C.P., Chang, Broderick (2012)

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

Blazars
Gamma-ray sky
Structure formation
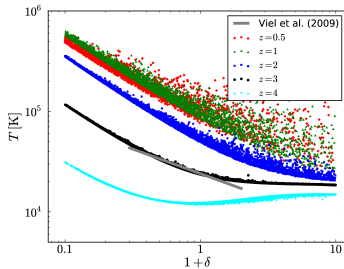
Properties of blazar heating
The Lyman-α forest
Dwarf galaxies

Evolution of the temperature-density relation

no blazar heating
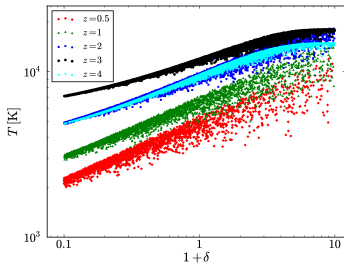
with blazar heating

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
Gamma-ray sky
Structure formation

Properties of blazar heating
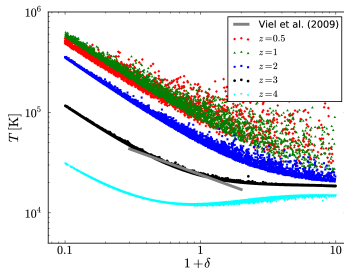The Lyman-α forest
Dwarf galaxies

Blazars cause hot voids

no blazar heating
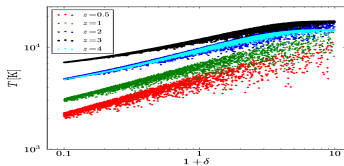
with blazar heating

Chang, Broderick, C.P. (2012)

- blazars completely change the thermal history of the diffuse IGM and late-time structure formation
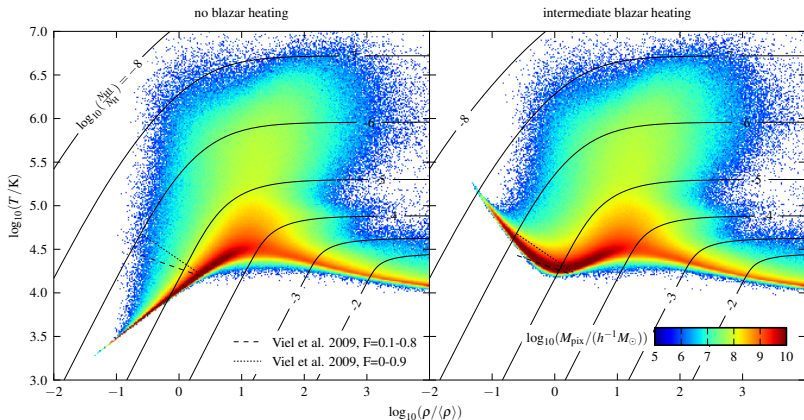
Blazars
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Properties of blazar heating
The Lyman-α forest
Dwarf galaxies

Cosmological hydrodynamical simulations

- include predicted volumetric heating rate in cosmological hydrodynamical simulations

- study:
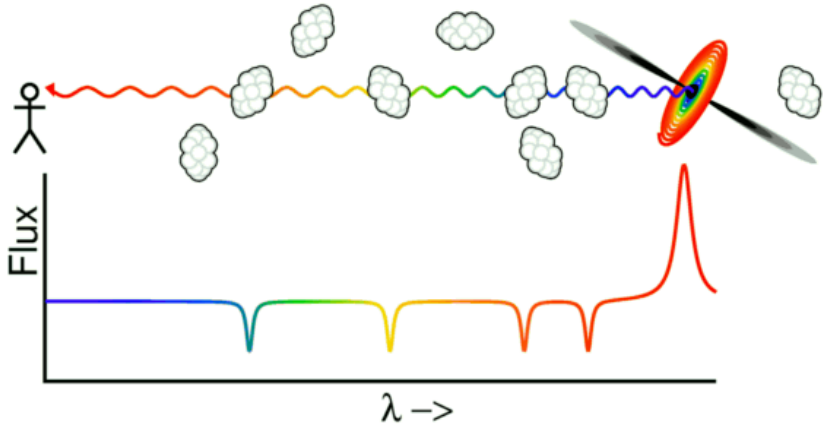 - thermal properties of intergalactic medium
  - Lyman-α forest

Blazars
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Properties of blazar heating
The Lyman-α forest
Dwarf galaxies
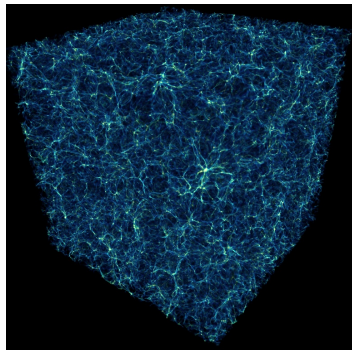
Temperature-density relation

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

HITS

Blazars
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Properties of blazar heating
The Lyman-α forest
Dwarf galaxies

The Lyman-α forest

Blazars
Gamma-ray sky
Structure formation

Properties of blazar heating
The Lyman-α forest
Dwarf galaxies

The simulated Ly-α forest

Puchwein, C.P.+ (2012)

Blazars
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Properties of blazar heating
The Lyman-α forest
Dwarf galaxies
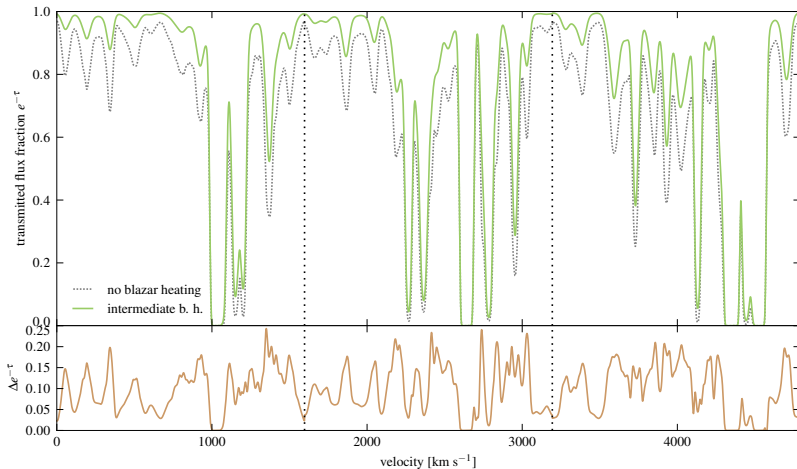
Ly-α flux PDFs and power spectra

Puchwein, C.P.+ (2012)

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Structure formation

Properties of blazar heating
The Lyman-α forest
Dwarf galaxies
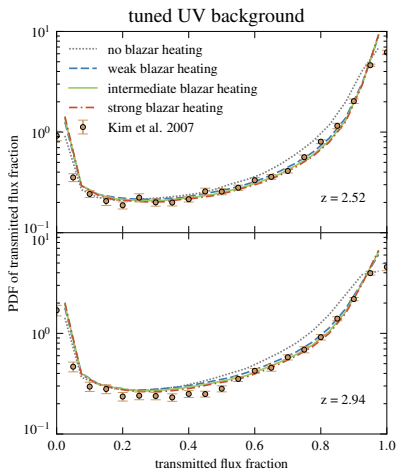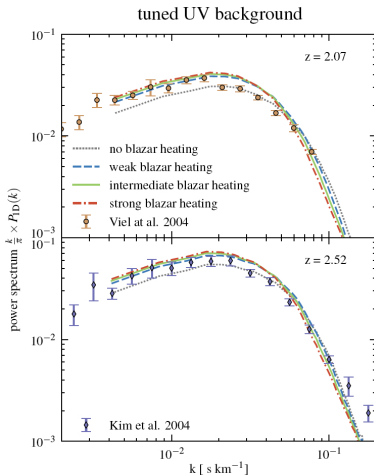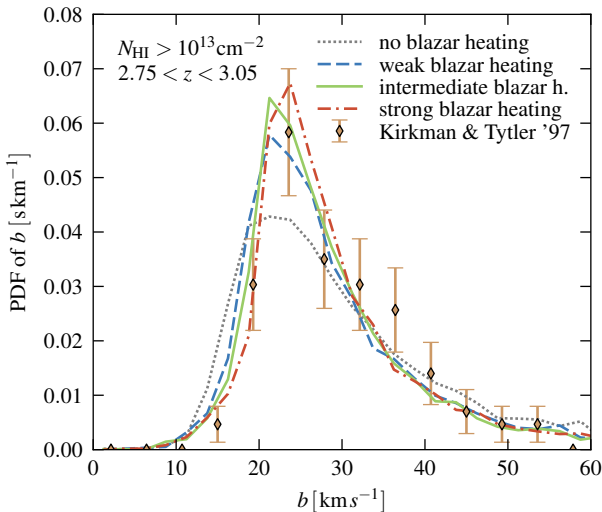
Voigt profile decomposition
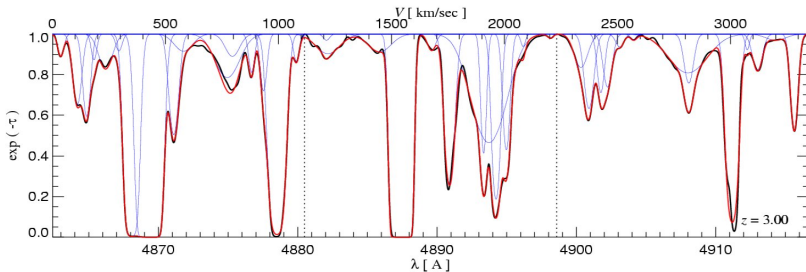
- decomposing Lyman-α forest into individual Voigt profiles
- allows studying the thermal broadening of absorption lines

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Voigt profile decomposition – line width distribution

Puchwein, C.P.+ (2012)

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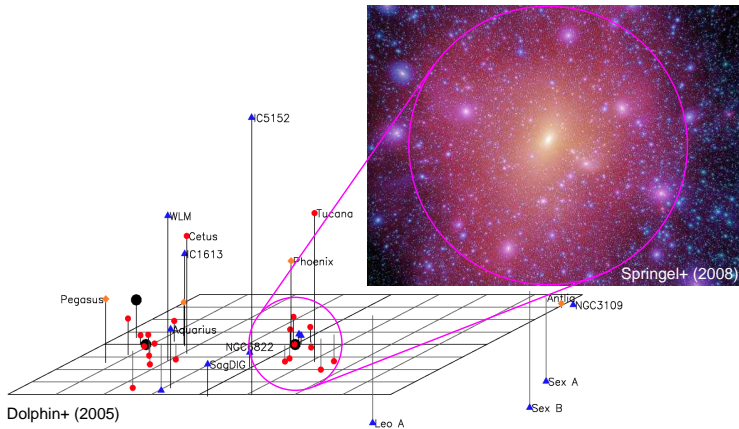The Lyman-α forest
Dwarf galaxies

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)

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"Missing satellite" problem in the Milky Way

Springel+ (2008)

C5152

WLM

Tucana

Cetus
C1613

Phoenix

Pegasus

Antlia
NGC3109

Aquarius

NGC3822

SagDIG

Sex A

Sex B

Leo A

Dolphin+ (2005)

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

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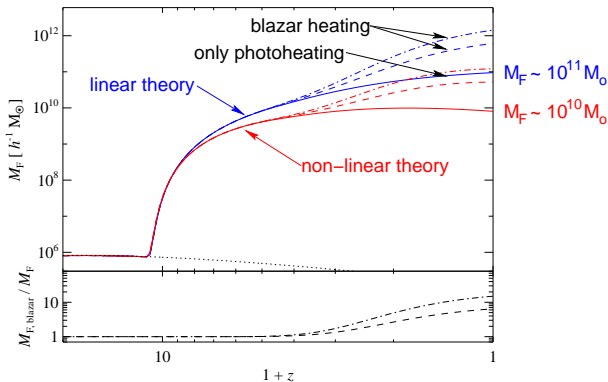The Lyman-α forest
Dwarf galaxies

Dwarf galaxy formation

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

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

  $\rightarrow$ blazar heating increases M_J by 30 over pure photoheating!

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

C.P., Chang, Broderick (2012)

HITS

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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 $< 10^{11}\,M_\odot$
  $\rightarrow$ introduces new time and mass scale to galaxy formation!

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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" (?)

HITS

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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.

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Additional slides

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Challenges to the Challenge
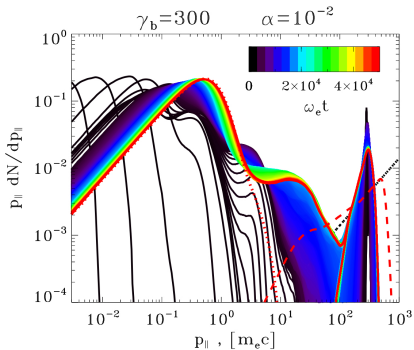
Challenge #1 (known unknowns): **non-linear saturation**

- 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.)

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 $\rightarrow$ no instability quenching! (Chang+ in prep.)

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Simulations of the beam-plasma instability

$\gamma_b = 300$ $\alpha = 10^{-2}$

$0 \quad 2\times10^4 \quad 4\times10^4$

$\omega_e t$

$\alpha = n_{\text{beam}}/n_{\text{IGM}}$,   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

- extrapolation with Lorentz force argument:

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

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

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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)
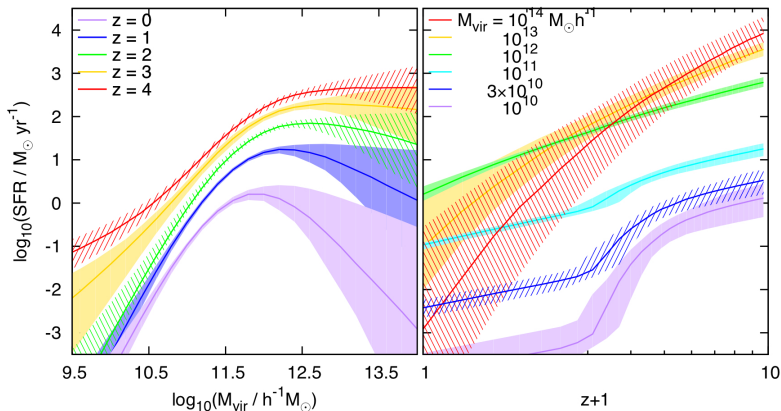
- luminosity function of local cluster galaxies

$\rightarrow$ star formation histories of dark matter halos (different z)

Lu+ (2013)

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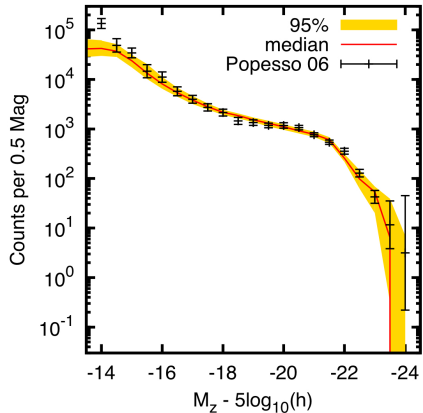
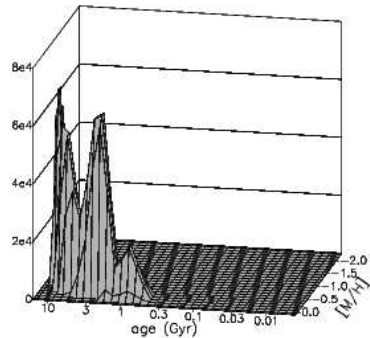# Empirical model for star formation histories (2)

Lu+ (2013)

$\rightarrow$ strong quenching of star formation efficiency for $z \lesssim 2$ in low-mass halos ($M < 10^{11}\, h^{-1} M_\odot$) $\rightarrow$ blazar heating?
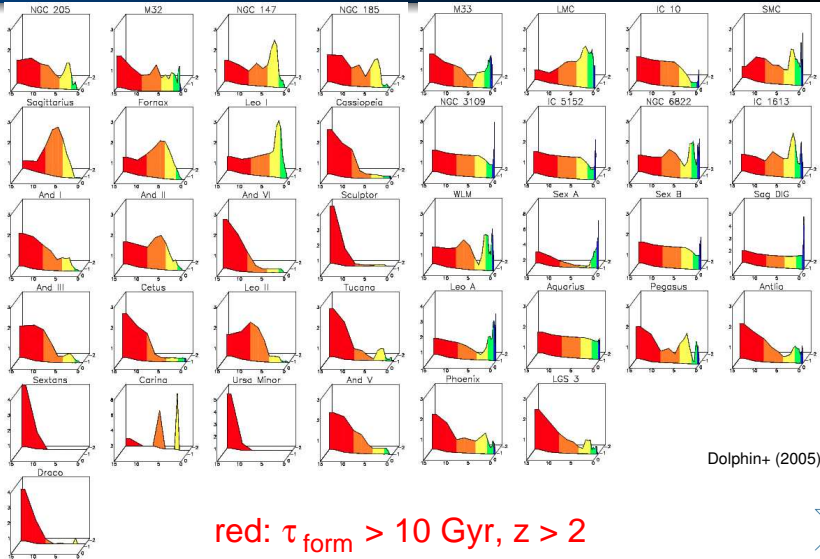
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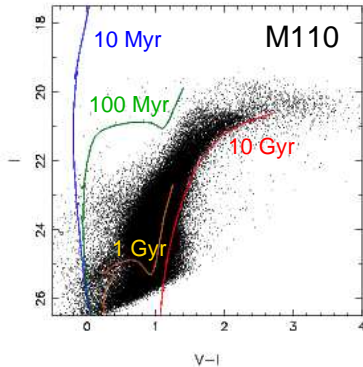
When do dwarfs form?

Dolphin+ (2005)

isochrone fitting for different metallicities $\rightarrow$ star formation histories

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When do dwarfs form?

Dolphin+ (2005)

red: τ_{form} > 10 Gyr, z > 2

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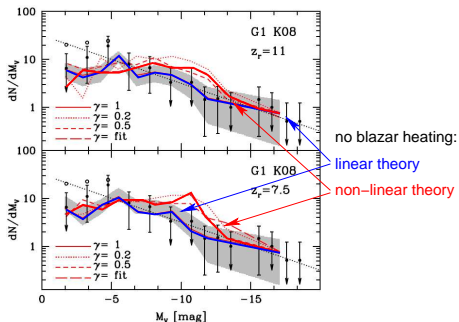The Lyman-α forest
Dwarf galaxies

Milky Way satellites: formation history and abundance

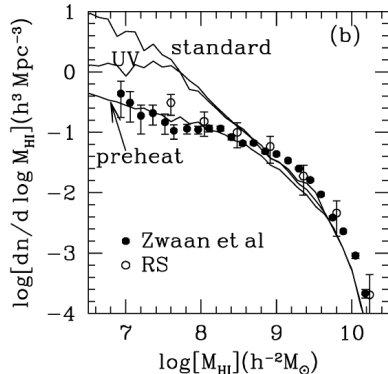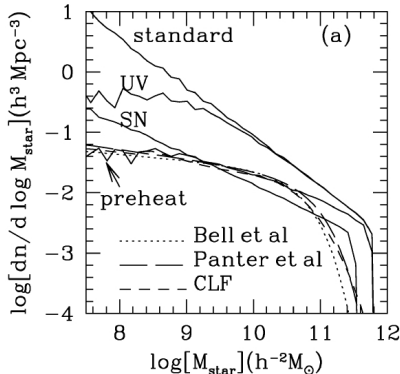satellite formation time   satellite luminosity function
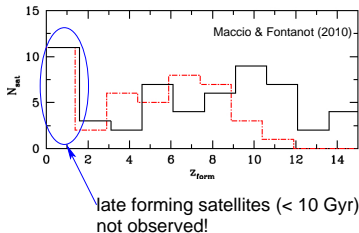
Maccio+ (2010)

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

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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!