Introduction to extragalactic sources of very high-energy photons

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Very High Energy Phenomena in the Universe

HITS

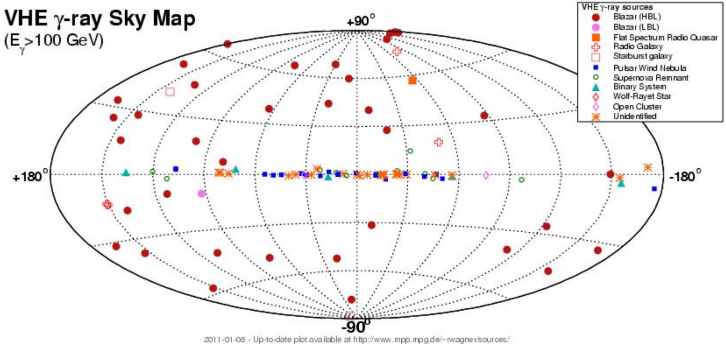
Outline

1. Gamma-ray emission
   - The gamma-ray sky
   - The main questions
   - Gamma-ray emission
2. Extragalactic gamma-ray sources
   - Radio galaxies and blazars
   - Galaxies and clusters
   - Fundamental physics
3. The physics and cosmology of TeV blazars
   - Propagation of TeV photons
   - Plasma instabilities
   - Cosmological consequences

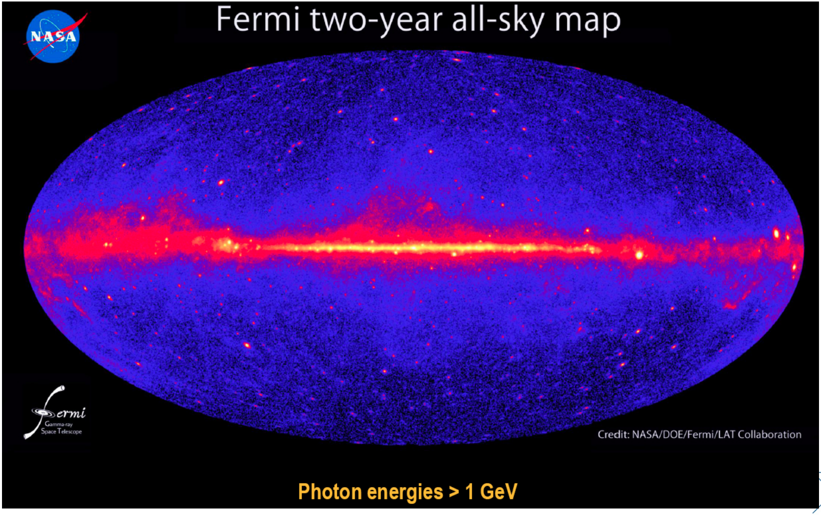
The TeV gamma-ray sky

There are several classes of TeV sources:

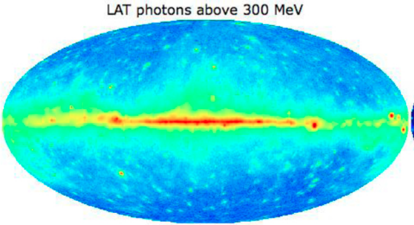
- Galactic - pulsars, BH binaries, supernova remnants
- Extragalactic - **mostly** blazars, two starburst galaxies

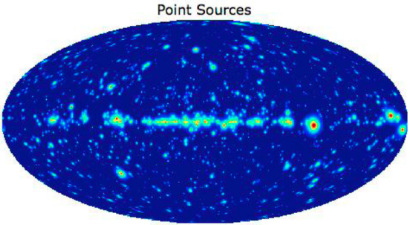


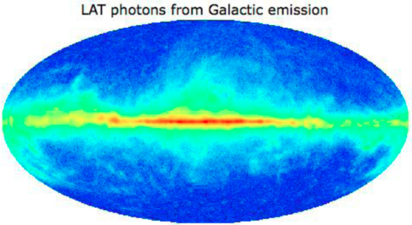
The GeV gamma-ray sky



The GeV gamma-ray sky: decomposition







Anisotropic features on large angular scales associated with **Galactic diffuse emission** and **resolved sources**

The Questions

Probing physics and cosmology with the extragalactic gamma-ray sky

- **which objects can we see?**
  active galactic nuclei (blazars, radio galaxies), starburst galaxies, gamma-ray bursts, diffuse radiation
  $\rightarrow$ astronomy: characterization, population studies
- **what underlying physics can we probe?**
  most extreme physics laboratories of the cosmos:
  particle acceleration, magnetic fields (origin, amplification)
  $\rightarrow$ high-energy astrophysics, plasma physics
- **what fundamental physics can we hope to learn?**
  galaxy formation, dark matter, structure of space time
  $\rightarrow$ structure formation, particle physics, cosmology

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Gamma-ray emission induced by cosmic rays

Complementary information to cosmic rays: gamma rays point back to origin

hadronic processes:

- pion decay:

$$\mathrm{p+ion} \rightarrow \begin{cases} \pi^0 & \rightarrow \quad \gamma\gamma \\ \pi^\pm & \rightarrow \quad \mathrm{e}^\pm + 3\nu \end{cases}$$

- photo-meson production:

$$\mathrm{p}+\gamma \rightarrow \begin{cases} \pi^0 & \rightarrow \quad \gamma\gamma \\ \pi^\pm & \rightarrow \quad \mathrm{e}^\pm + 3\nu \end{cases}$$

- Bethe-Heitler pair production:

$$\mathrm{p} + \gamma \rightarrow \mathrm{p} + e^+ + e^-$$

leptonic processes:

- inverse Compton:

$$\mathrm{e}^* + \gamma \rightarrow \mathrm{e} + \gamma^*$$

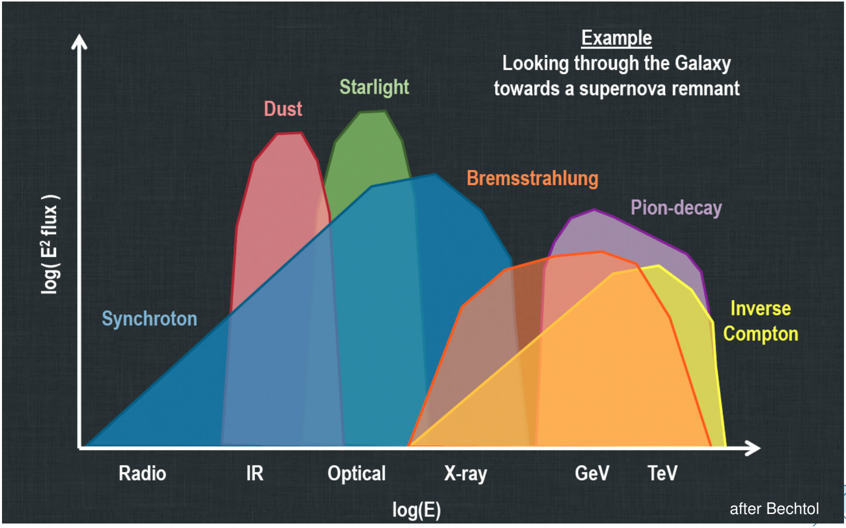
- synchrotron radiation:

$$\mathrm{e}^* + B \rightarrow \mathrm{e} + B + \gamma^*$$

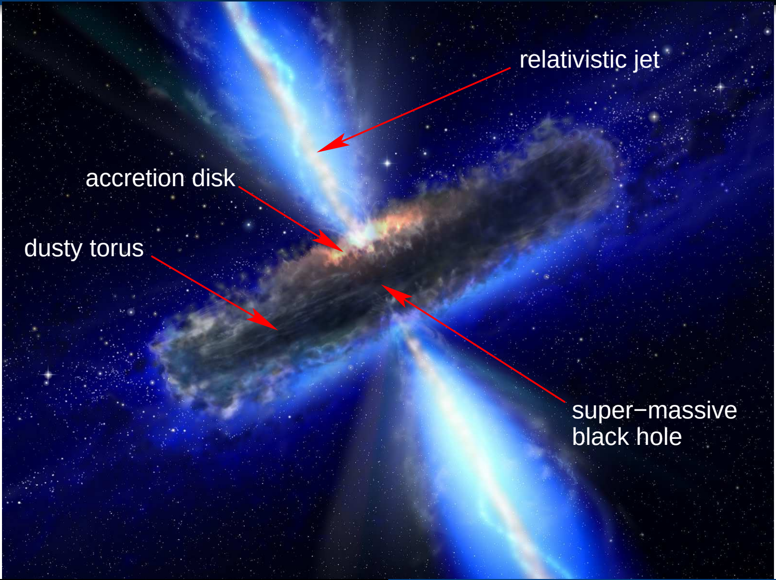
- bremsstrahlung:

$$\mathrm{e}^* + \mathrm{ion} \rightarrow \mathrm{e} + \mathrm{ion} + \gamma^*$$

A sketch of the nonthermal emission

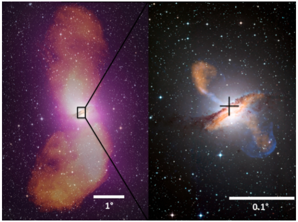


Unified model of active galactic nuclei

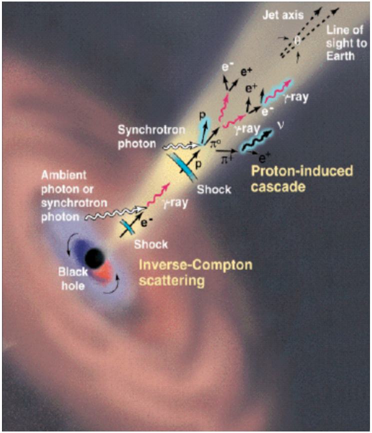


Active galactic nuclei

- active galactic nuclei (AGN)
  - relativistic jets powered by accretion onto supermassive black holes
  - particle acceleration
  - radio lobes push ambient plasma around
  - AGN feedback heating: *solution* to cluster "cooling flow problem" and mitigating massive galaxy formation
- example: Cen A (3.7 Mpc)
  "AGN under the microscope"
  - GeV emission from giant radio lobes *(Fermi)*
  - TeV emission from nucleus/inner jet (H.E.S.S.)

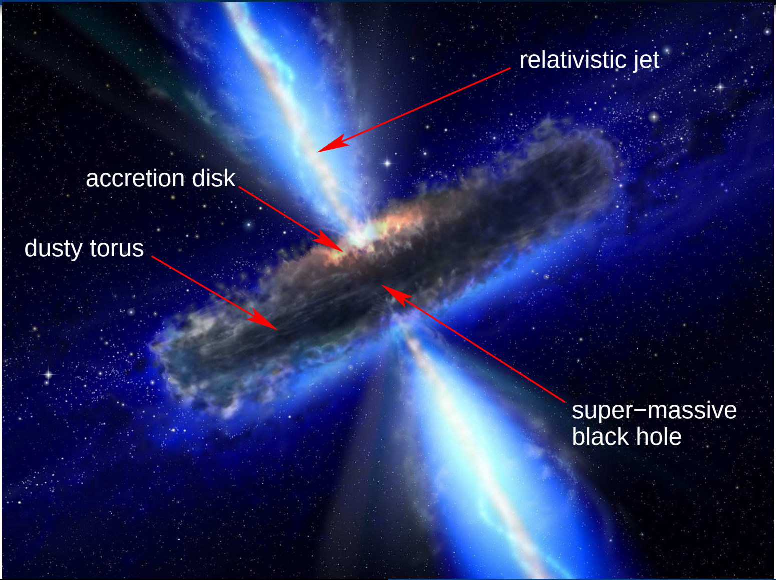


Active galactic nuclei: paradigm and open questions

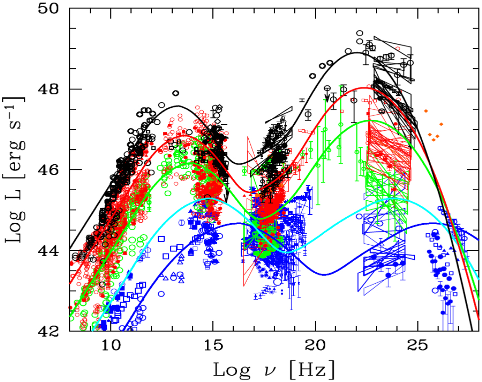


- current paradigm:
  - synchrotron self Compton
  - external Compton
  - proton-induced cascades
  - proton synchrotron
- open questions:
  - energetics
  - mechanisms for jet formation and collimation
  - plasma composition (leptonic vs. hadronic, 1-zone vs. spine-layer)
  - acceleration mechanisms
- TeV "flares" may sign instabilities in the accretion of matter onto the central supermassive black hole

Unified model of AGN: blazars



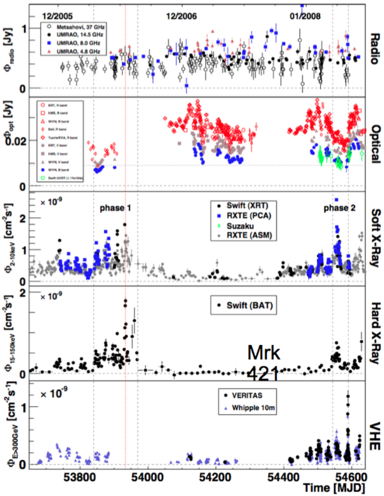
The blazar sequence



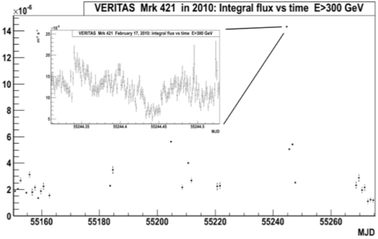
Ghisellini (2011)

- continuous sequence from LBL–IBL–HBL
- TeV blazars are dim (very sub-Eddington)
- TeV blazars have rising spectra in the Fermi band ($\Gamma_F < 2$)

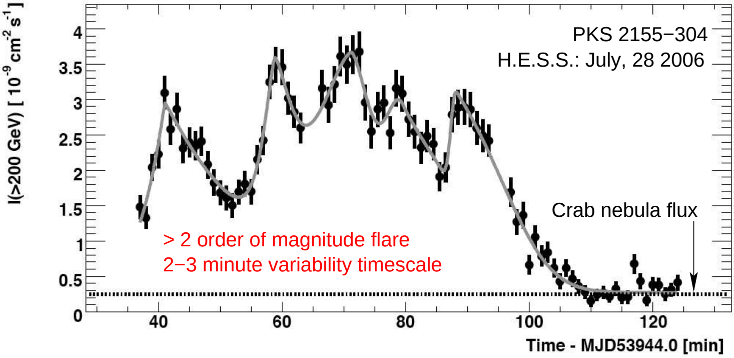
Blazar variability



- complex multi-wavelength behaviour challenges simple models
- extreme variability, e.g., in Mk 421:



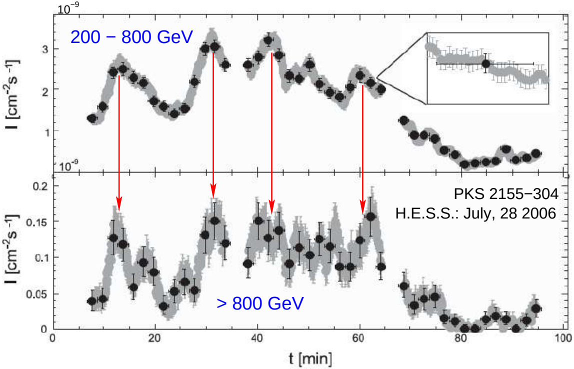
Blazar variability: causality



variability timescale is $\Delta t_{\mathrm{var}} \sim 0.01 R_s c$:

- causality requires $R < c\Delta t_{\mathrm{var}}\gamma \rightarrow$ very small emission region
- implies bulk motion w/ Lorentz factor $\gamma > 50$ (Begelmann, Fabian, Rees 2008)

Blazar variability: Quantum Gravity constraints

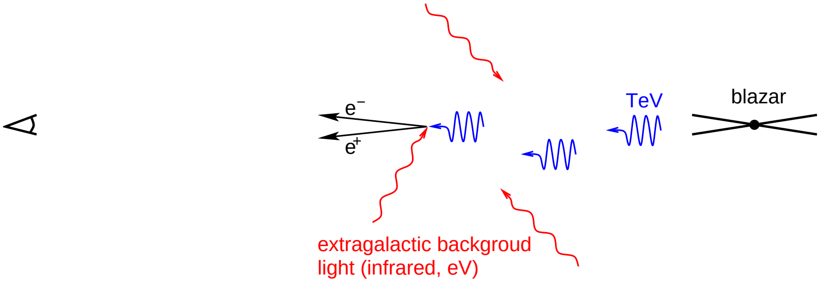


no observable time delay between low and high energy photons!

→ constraints on energy-dependent violation of Lorentz invariance (energy-dependent speed of light) as predicted in various models of Quantum Gravity

Observational gamma-ray cosmology

Annihilation and pair production



Observational gamma-ray cosmology

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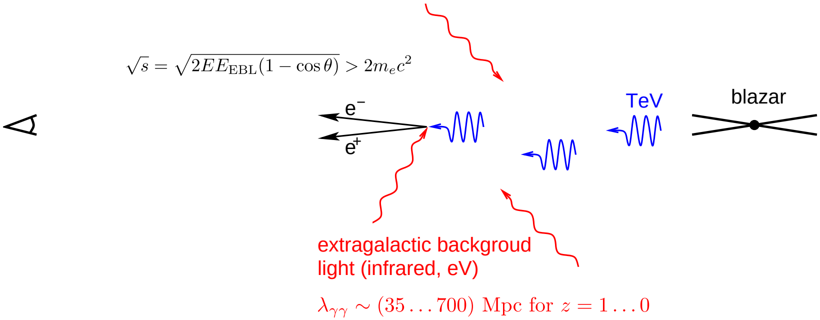
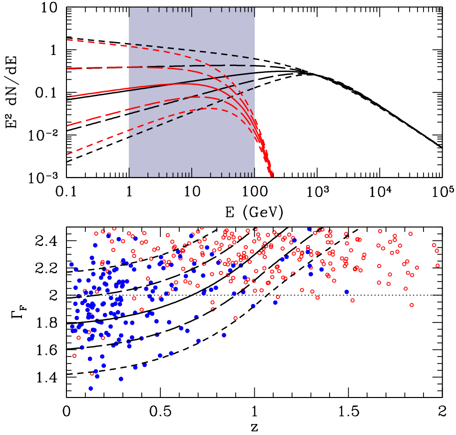


TeV photon absorption by pair production

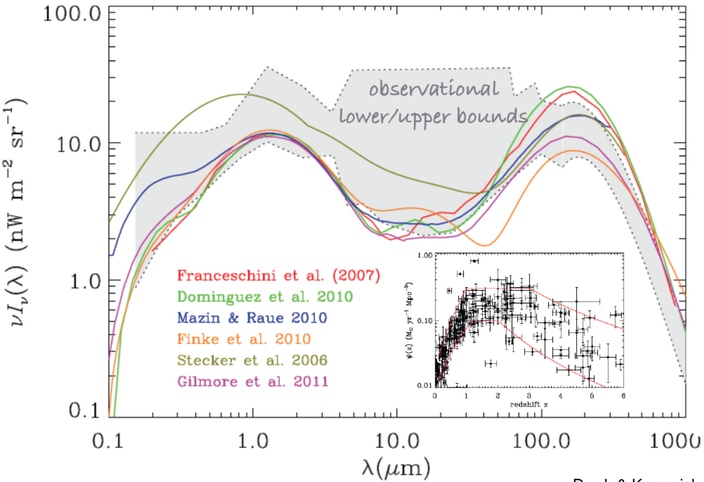
top: intrinsic and observed SEDs of blazars at z = 1;
bottom: inferred Γ_F for the spectra in the top panel;
Fermi data on BL Lacs and non-BL Lacs (mostly FSRQs)



Broderick, C.P.+ (in prep)

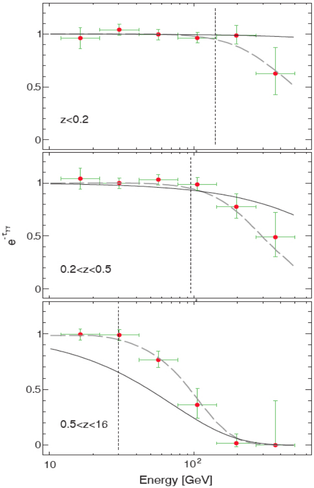
Extragalactic background light

Unique probe of the integrated star formation rate



Dwek & Krennrich (2012)

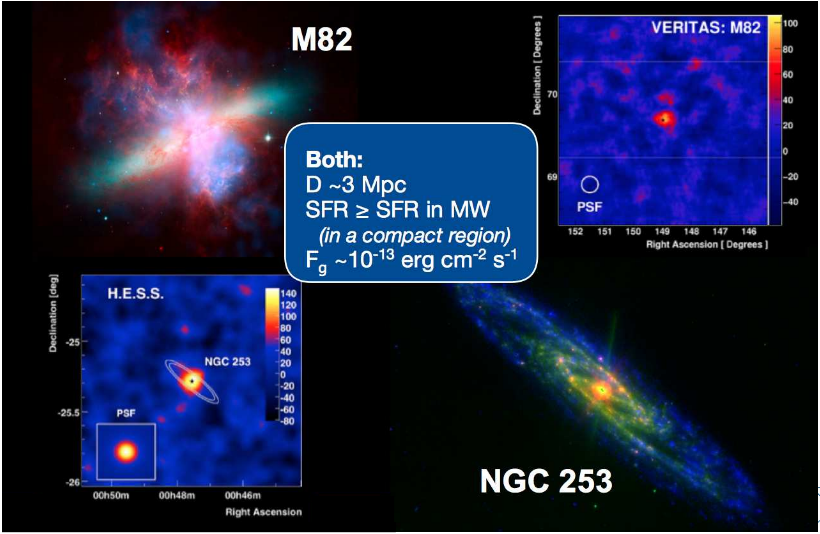
The *Fermi* gamma-ray horizon



Ackermann+ (2012)

- 150 significantly detected BL Lac blazars above 3 GeV
- $0.03 < z < 1.6$: spectrum unabsorbed for $E < 25$ GeV
- absorption feature moves to lower E for higher source redshifts (propagation distances) due to attenuation of gamma rays by EBL (optical/UV)
- $UV(> 5\,\mathrm{eV})$ EBL intensity: $3(\pm 1)\mathrm{nW\ m^{-2} sr^{-1}}$ at $z \sim 1$

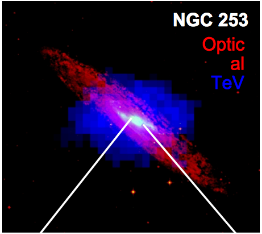
Starburst galaxies

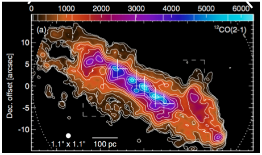


Cosmic rays and star formation

the picture: star formation → supernova remnants → proton acceleration → pion decay induced by p-p interactions

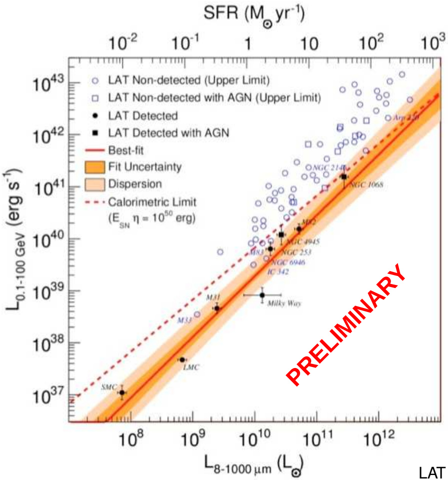
- **dense material in starburst region**
  - $\langle n \rangle \sim 250\ \mathrm{cm}^{-3}$
  - $t_{\mathrm{pp}} \sim t_{\mathrm{esc}}$
  - approaching the calorimetric limit
  - large NT bremsstrahlung and B: efficient electron emission
- **FIR – radio correlation**
  - implies universal conversion: SF → CR → synchrotron
  - now: FIR – gamma-ray correlation





FIR – gamma-ray correlation

Universal conversion: SF → CR → gamma rays



LAT Collaboration (in prep)

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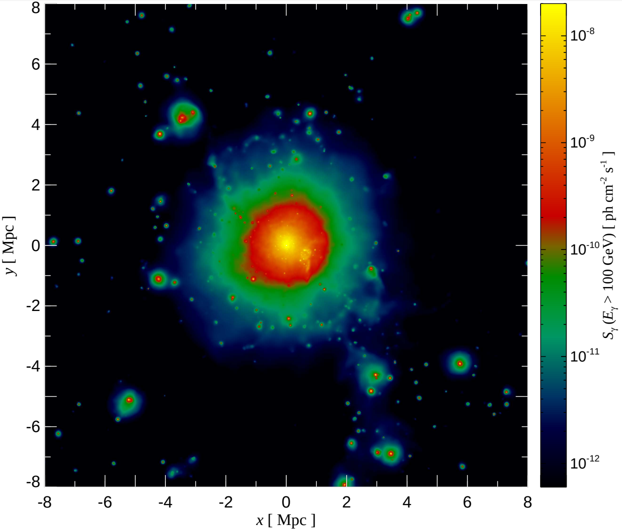
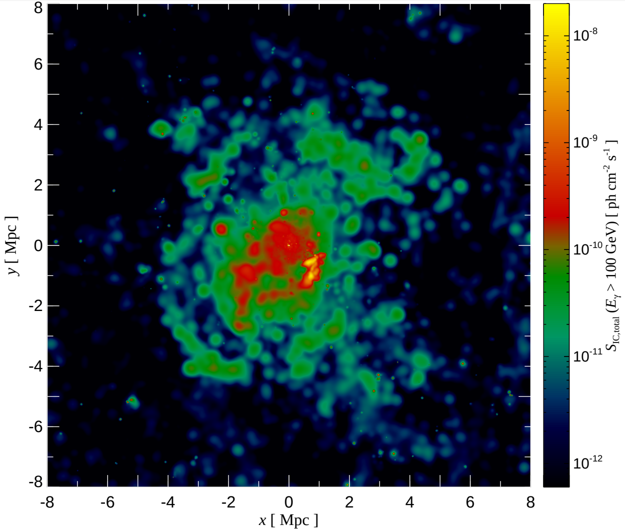
Galaxy clusters: pion decay

CR protons, accelerated in formation shocks, accumulate in clusters over Hubble time



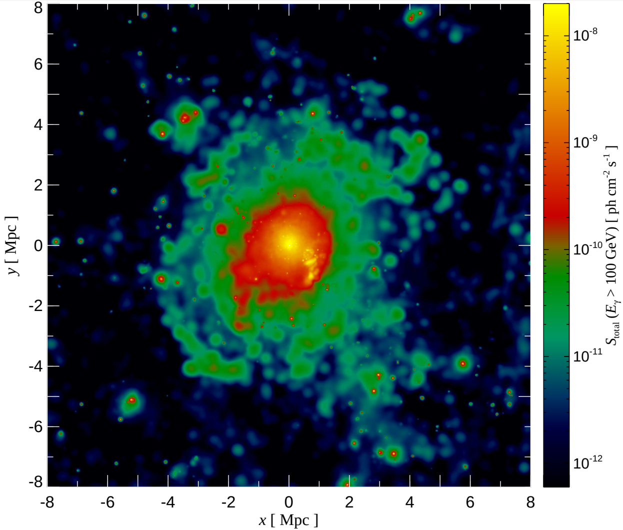
Galaxy clusters: inverse Compton

Primary, shock-accelerated electrons

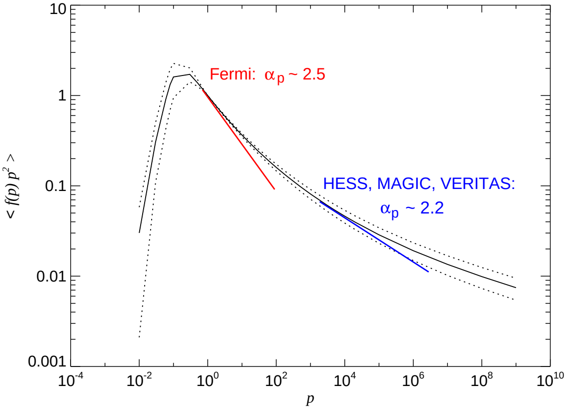


Galaxy clusters: total γ-ray emission

Dominated by hadronically induced pion decay



Universal CR spectrum in clusters (Pinzke & C.P. 2010)



normalized CR spectrum shows universal concave shape across clusters:
during the hierarchical assembly, every fluid element experienced on average the same history of shock strengths, responsible for shaping the CR spectrum

Constraining CR physics with γ-ray observations

- non-observations of γ rays constrain CR-to-thermal pressure to $P_{\rm CR}/P_{\rm th} < 1.7\%$ in Coma and Perseus
- constrains maximum shock acceleration efficiency to $< 50\%$
- hydrostatic cluster masses not significantly biased by CRs: important for cluster cosmology!

Indirect DM searches: modeling

- **assume:** supersymmetric particles are Majorana particles
  → annihilate and produce gamma rays

$$N_\gamma = \left[\int_{\mathrm{LOS}} \rho_\chi^2 \,\mathrm{d}l_\chi\right] \frac{\langle\sigma v\rangle}{2M_\chi^2} \left[\int_{E_{\mathrm{th}}}^{M_\chi} \left(\frac{\mathrm{d}N_\gamma}{\mathrm{d}E}\right)_{\mathrm{SUSY}} A_{\mathrm{eff}}(E)\,\mathrm{d}E\right] \frac{\Delta\Omega}{4\pi}\,\tau_{\exp}$$

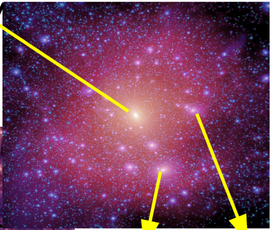
- astrophysics: contains the uncertainty about the DM profile with its central behavior and the substructure distribution
- particle physics: assuming DM is supersymmetric, there is the uncertainty about the cross section, neutralino mass, and decay channels
- detector properties: energy dependent effective area, detector response, scanning strategy, . . .

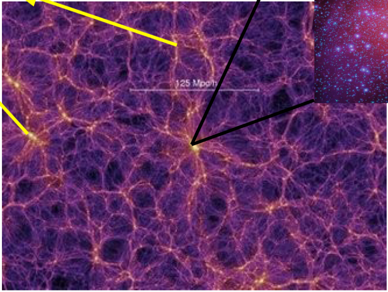
Indirect DM searches: sources

Galactic center:
Good statistics, but source confusion and diffuse background

Milky Way halo:
Very good statistics, but diffuse background

Galaxy clusters:
Low background, but low statistics



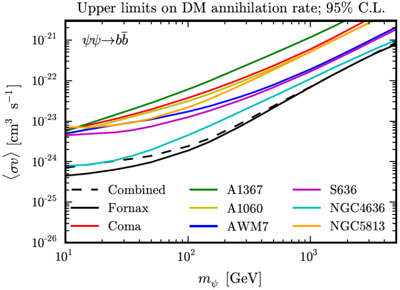


Satellites:
Low background, but low statistics

Extra galactic:
Very good statistics, but astrophysics and galactic diffuse foregrounds

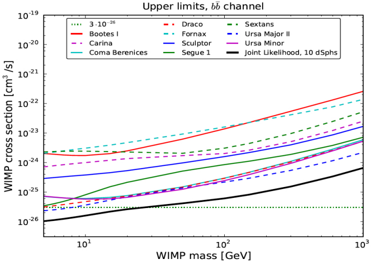
DM searches in clusters vs. dwarfs

Galaxy clusters:



Huang et al. 2011 (see also Ando & Nagai 2012)

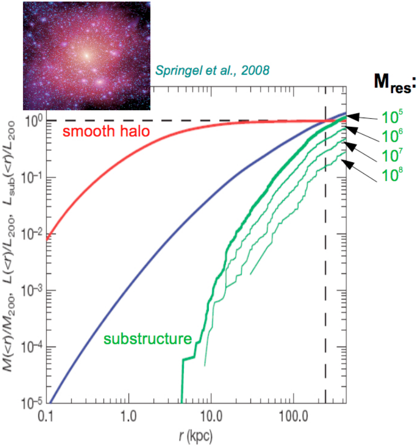
Dwarf galaxies:



Ackermann et al. (Fermi-LAT) 2011

- combined limits for dwarf galaxies $\sim$ 20 times more constraining
- high-resolution CDM simulations predict substructures that boost the γ-ray flux $\rightarrow$ clusters should outshine dwarfs by $\gtrsim$ 10
  (e.g., Pinzke, C.P., Bergström 2011; Gao et al. 2011)

Enhancement from DM substructures



Constant offset in the luminosity from substructures between different mass resolutions in the simulation (M_{res}).

$$\mathrm{Norm} \propto M_{res}^{-0.226}$$

Extrapolate to the minimal mass of dark matter halos (M_{min}) that can form.

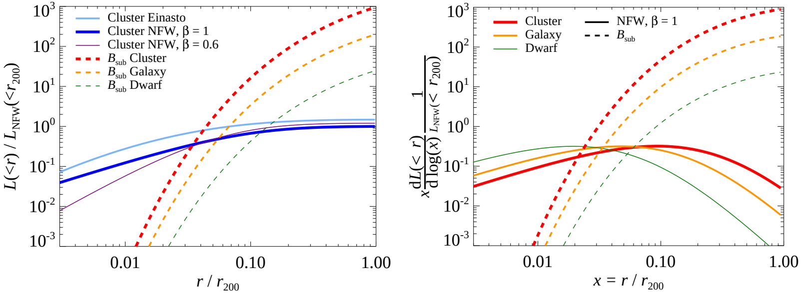
The cold dark matter scenario suggests $M_{min} \sim 10^{-6}\,M_\odot$.

Hofmann, Schwarz and Stöcker, 2008
Green, Hofmann and Schwarz, 2005

$$L_{sub}(<r) \propto (M_{200} / M_{res})^{0.226}$$

Luminosity boosted by ~1000 in clusters
Pinzke et al. 2011, Gao et al 2011

Spatial DM distribution

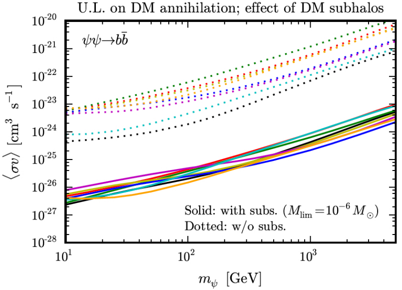


Pinzke, C.P., Bergström 2011

- form of smooth density profile only important for central region, majority of smooth flux accumulates around $r \simeq r_s/3$
- emission from substructures dominated by outer regions $\rightarrow$ spatially extended
- large boost in clusters (~ 1000); smaller boost in dwarf satellites (~ 20), much smaller if outskirts are tidally stripped

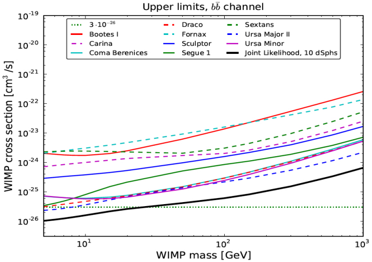
DM searches in clusters vs. dwarfs

Clusters with substructures:



Huang et al. 2011 (see also Ando & Nagai 2012)

Dwarf galaxies:



Ackermann et al. (Fermi-LAT) 2011

- galaxy clusters $\sim$ 10 times more constraining than dwarf satellites when accounting for substructures!

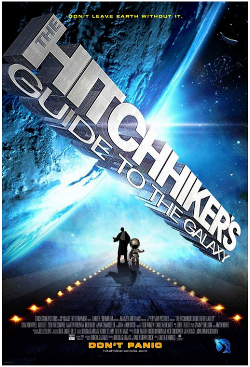
Conclusions on extragalactic γ-ray astrophysics

- the non-thermal universe revealed by high energy radiation provides new probes of fundamental physics and cosmology
- we are currently entering a fascinating era of multi-frequency experiments: no shortage of data and puzzles $\rightarrow$ new ideas and theories
- mind the unseen (dark matter, galaxy clusters,...): what can it teach us?

"In the fields of observation chance favors only the prepared mind!" (Louis Pasteur)

The Hitchhiker's Guide to . . . Blazar Heating

- **High-energy Astrophysics**
  - TeV photon propagation
  - plasma physics
- **Cosmological Consequences** for
  - intergalactic magnetic fields
  - gamma-ray background
  - thermal history of the Universe
  - Lyman-α forest
  - formation of dwarf galaxies



Collaboration members:

Broderick, Chang, Pfrommer, Puchwein, Springel

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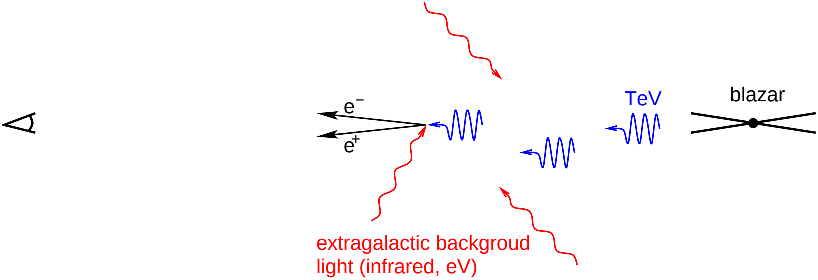
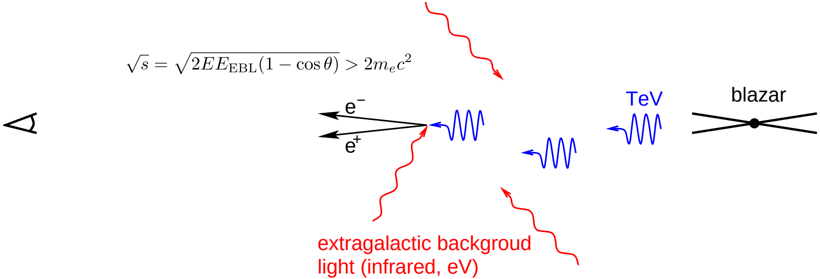
Annihilation and pair production



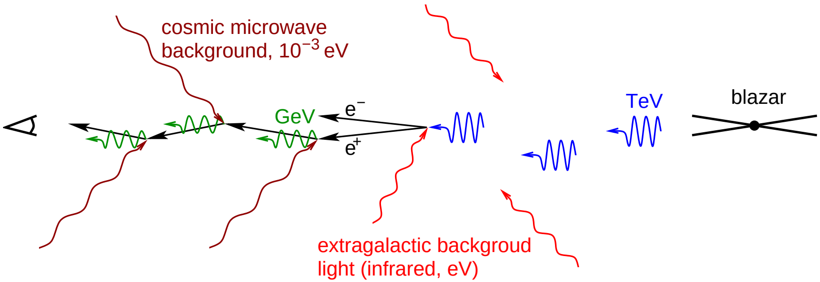
Annihilation and pair production

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



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

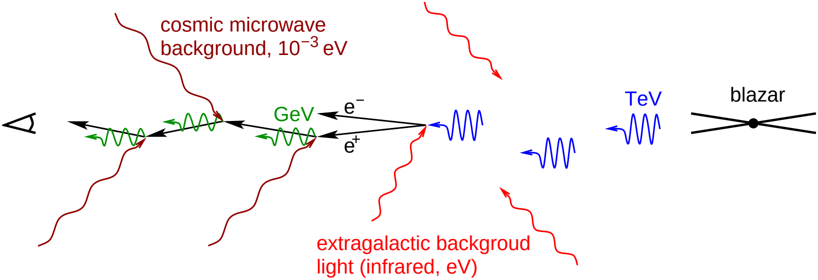
Inverse Compton cascades



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

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

Inverse Compton cascades

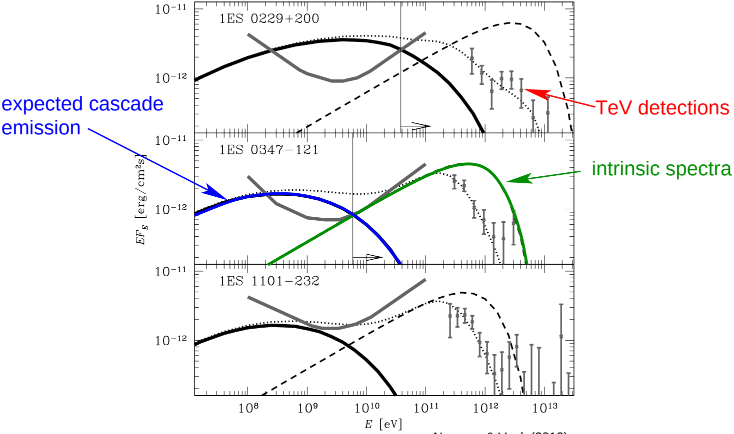


$\lambda_{\mathrm{IC}} \sim \lambda_{\gamma\gamma}/1000$ $\lambda_{\gamma\gamma} \sim (35 \ldots 700)\ \mathrm{Mpc\ for}\ z = 1 \ldots 0$

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

What about the cascade emission?

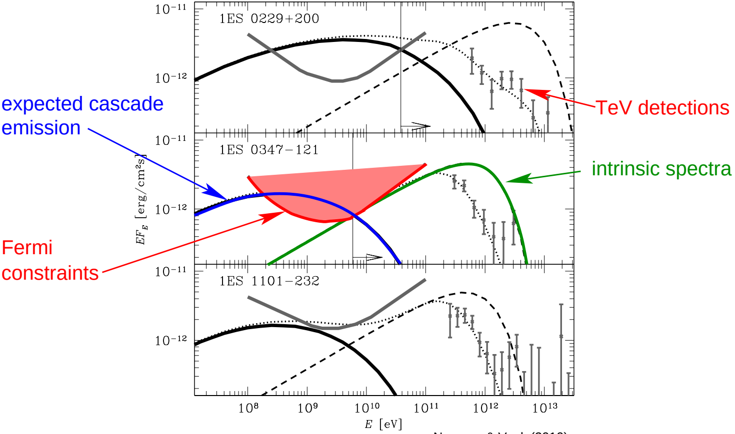
Every TeV source should be associated with a 1-100 GeV gamma-ray halo



Neronov & Vovk (2010)

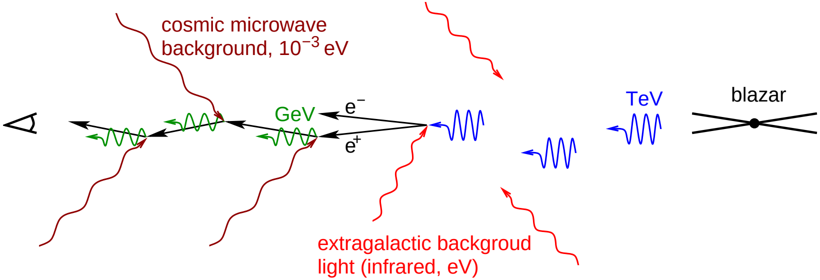
What about the cascade emission?

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



Neronov & Vovk (2010)

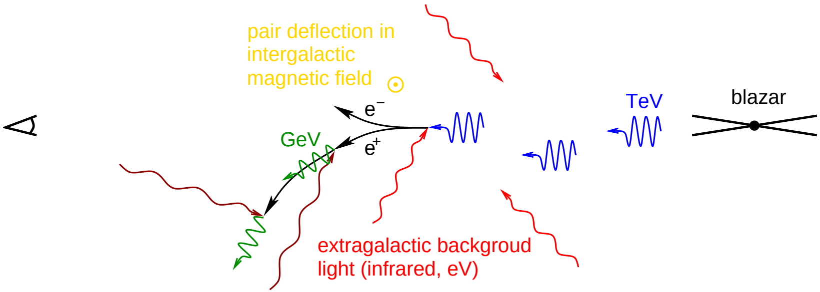
Inverse Compton cascades



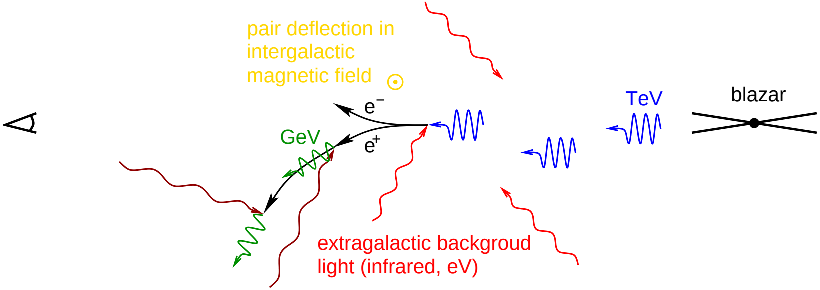
$\lambda_{\rm IC} \sim \lambda_{\gamma\gamma}/1000$

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

Magnetic field deflection

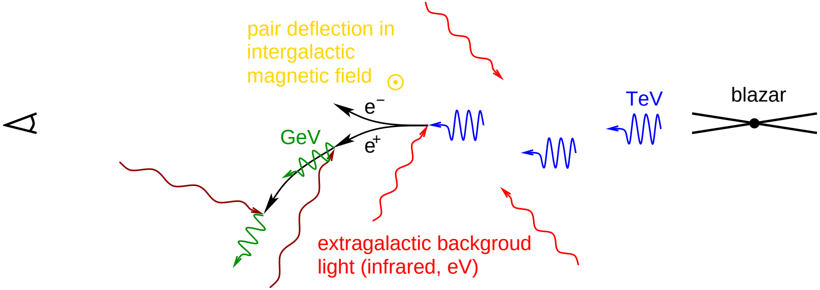


Magnetic field deflection



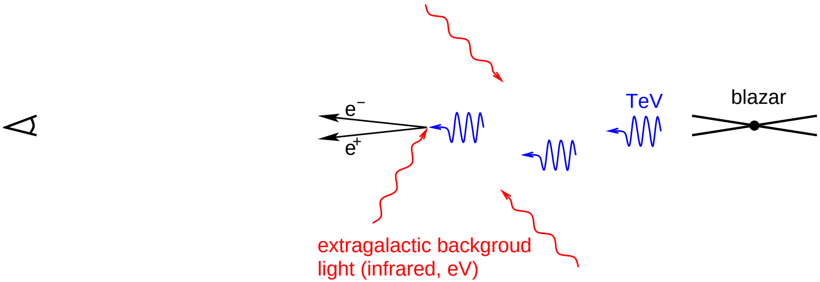
- GeV point source diluted ⟶ weak "pair halo"
- stronger B−field implies more deflection and dilution,
  gamma−ray non−detection ⟶ $B \gtrsim 10^{-16}\,\mu\mathrm{G}$ − primordial fields?

Magnetic field deflection

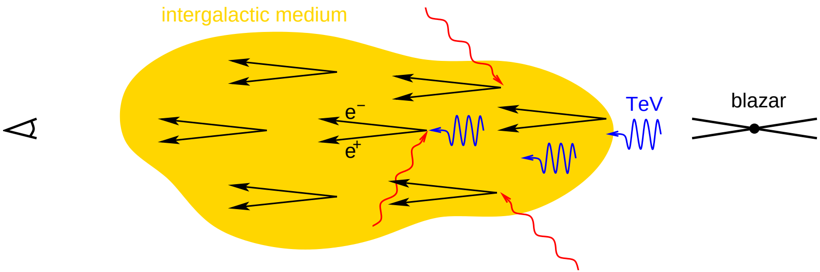


- problem for unified AGN model: blazars and quasars apparently do not share the same cosmological evolution (as otherwise, evolving blazars would overproduce the gamma−ray background)!

What else could happen?



Plasma beam instabilities

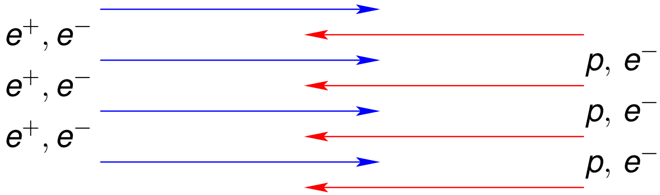


→ pair plasma beam propagating through the intergalactic medium

Interlude: plasma physics

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

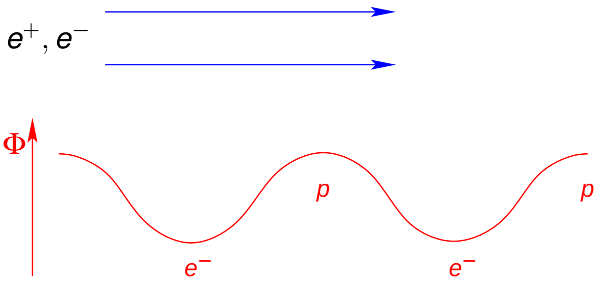
- interpenetrating beams of charged particles are unstable to plasma instabilities
- consider the two-stream instability:



Two-stream instability: mechanism

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

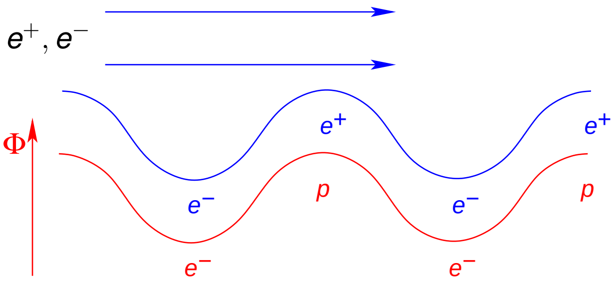
- initially homogeneous beam-e^-:
  attractive (repulsive) force by potential maxima (minima)
- e^- attain lowest velocity in potential minima $\rightarrow$ bunching up
- e^+ attain lowest velocity in potential maxima $\rightarrow$ bunching up



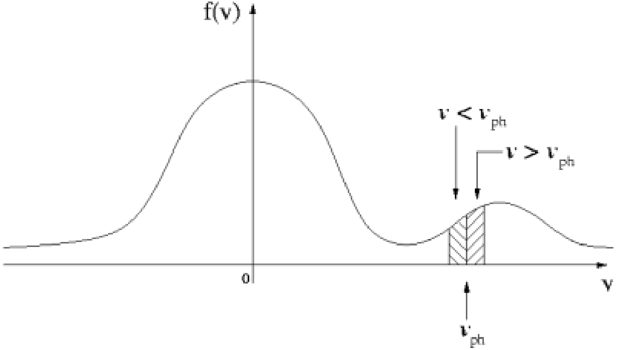
Two-stream instability: mechanism

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



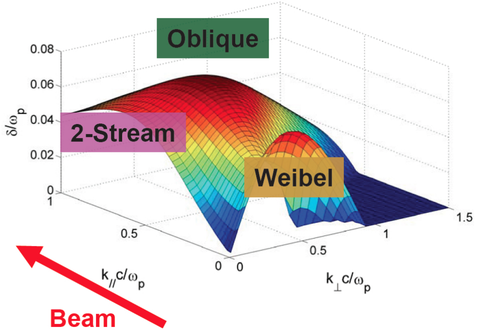
Two-stream instability: momentum transfer

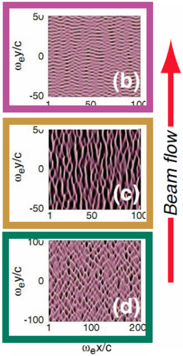


- particles with $v \gtrsim v_{\rm phase}$:
  pair momentum → plasma waves → growing modes: instability
- particles with $v \lesssim v_{\rm phase}$:
  plasma wave momentum → pairs → Landau damping

Oblique instability

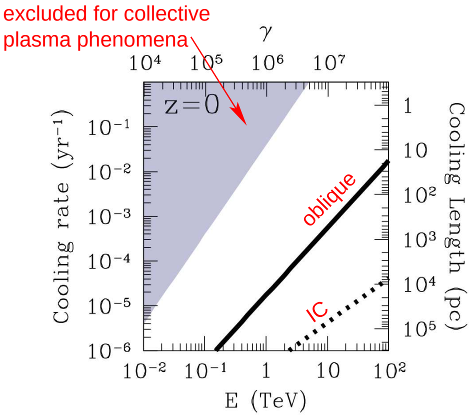
- ***k*** oblique to $\boldsymbol{v}_{\rm beam}$: real word perturbations don't choose "easy" alignment $= \sum$ all orientations
- oblique grows faster than two-stream: E-fields can easier deflect ultra-relativistic particles than change their parallel velocities
  (Nakar, Bret & Milosavljevic 2011)





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

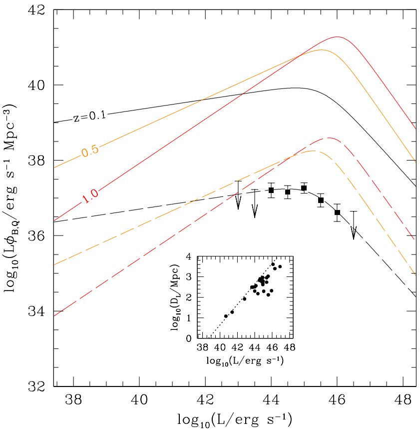
TeV emission from blazars – a new paradigm

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

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

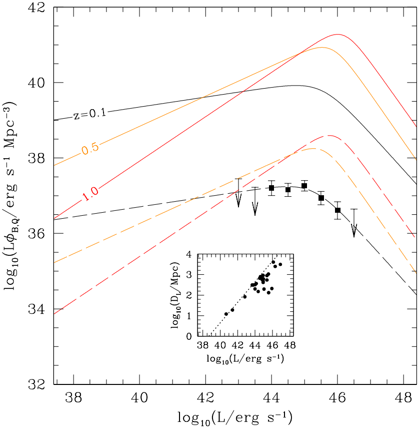
TeV blazar luminosity density: today



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



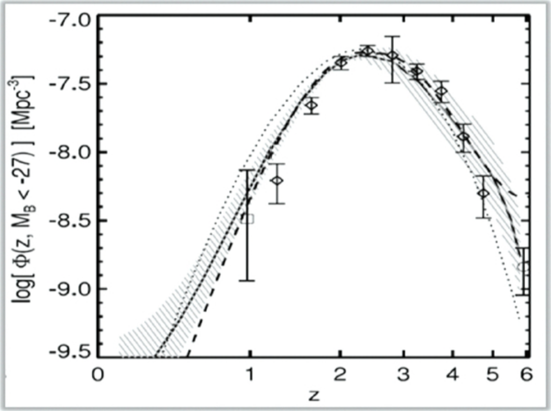
Broderick, Chang, C.P. (2012)

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

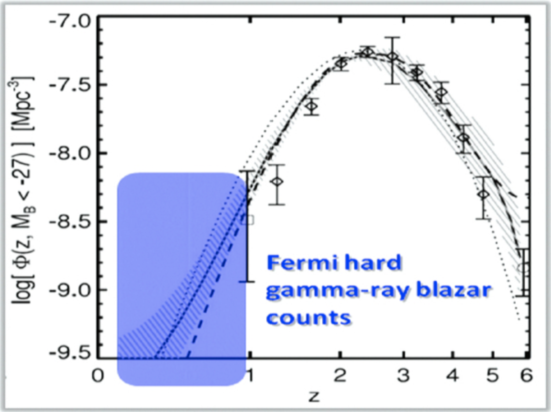
→ **assume that they trace each other for all redshifts!**

How many TeV blazars are there?



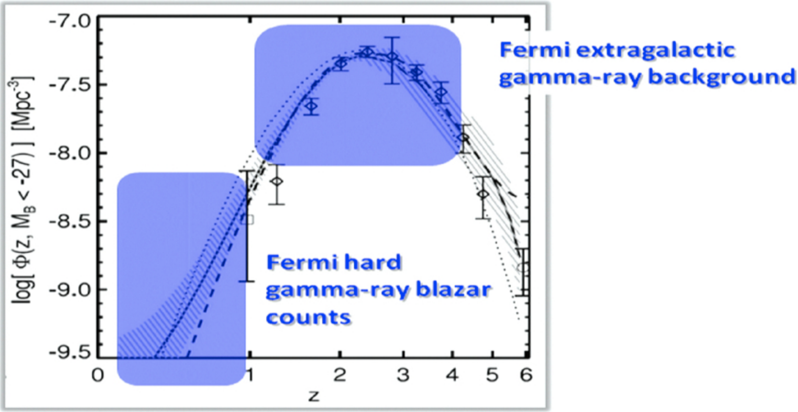
Hopkins+ (2007)

How many TeV blazars are there?



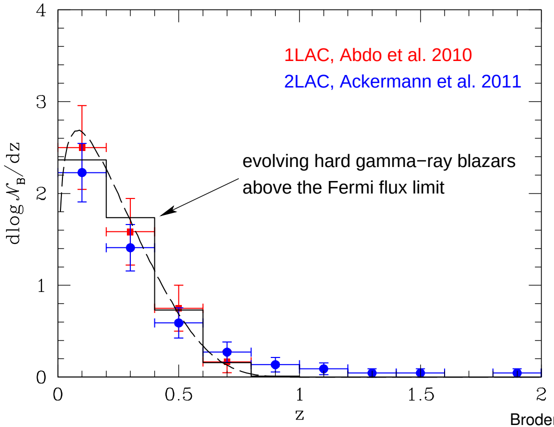
Hopkins+ (2007)

How many TeV blazars are there?



Hopkins+ (2007)

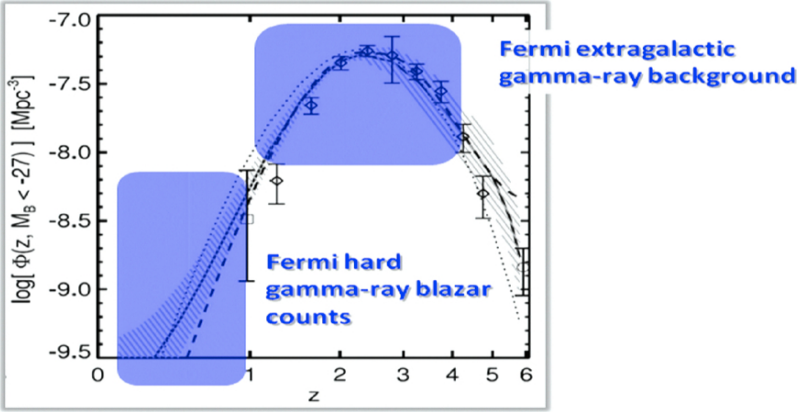
Redshift distribution of *Fermi* hard γ-ray blazars



Broderick, C.P.+ (in prep)

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

How many TeV blazars are there?



Hopkins+ (2007)

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

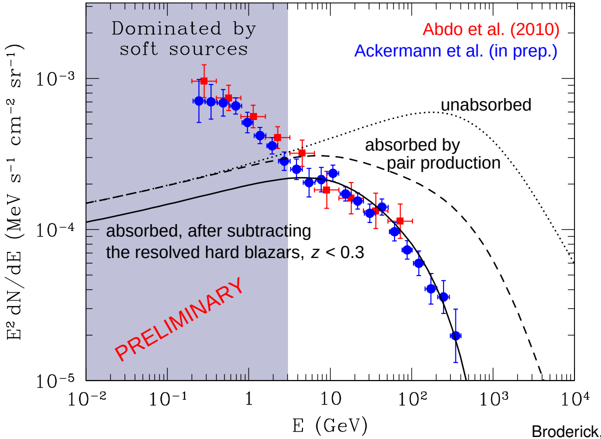
- extragalactic gamma-ray background (EGRB):

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

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

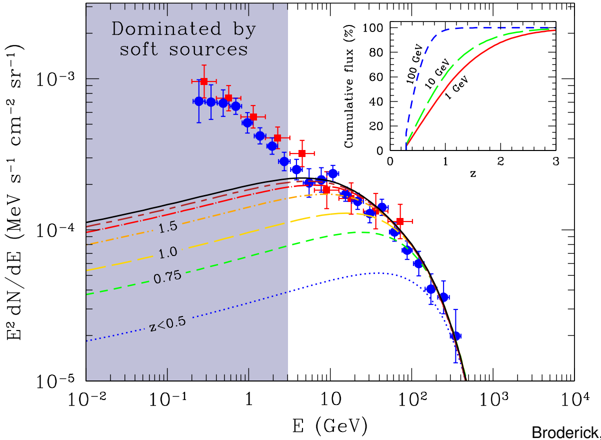
Extragalactic gamma-ray background



Broderick, C.P.+ (in prep.)

→ **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.+ (in prep.)

→ **the signal at 10 (100) GeV is dominated by redshifts $z \sim 1$ ($z \sim 0.8$)**

TeV emission from blazars – a new paradigm

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

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

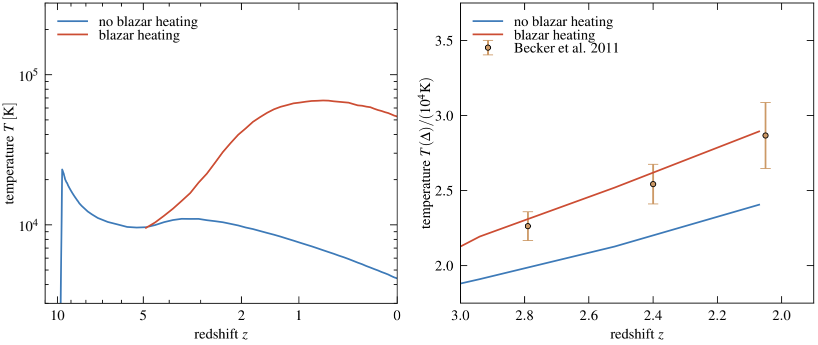
- intergalactic magnetic field estimates
- unified picture of TeV blazars and quasars: explains *Fermi's* γ-ray background and blazar number counts

additional IGM heating has significant implications for ...

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

TeV blazars heat the intergalactic medium

$T(z)$ at mean density ($\Delta = 0$) observed $T[z(\Delta)]$



Puchwein, C.P.+ (2012)

- every region in the universe is heated by at least one blazar
- TeV blazars increase temperatures at mean density ($\Delta = 0$) by a factor 10 today

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:

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

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

  → expect slight reduction: $M_{J,\mathrm{blazar}}/M_{J,\mathrm{photo}} \approx 10$

C.P., Chang, Broderick (2012)

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 (in accordance with SFHs): “missing satellites”, void phenomenon(?)

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.

Additional slides

Challenges to the Challenge

Challenge #1 (unknown unknowns): **inhomogeneous universe**

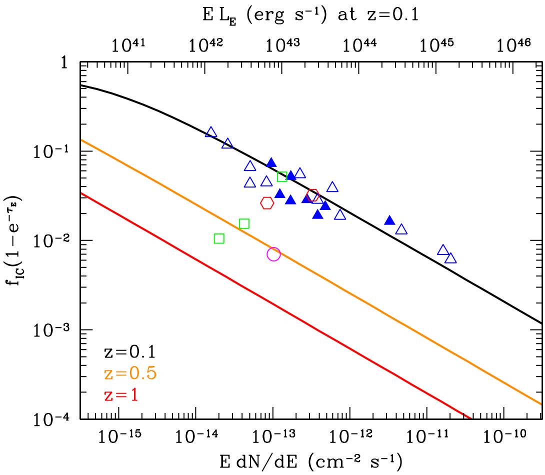
- universe is inhomogeneous and hence density of electrons change as function of position
- could lead to loss of resonance over length scale $\ll$ spatial growth length scale (Miniati & Elyiv 2012)
- growth length in oblique kinetic regime appears to be shorter than gradient $\rightarrow$ no instability quenching!

Challenge #2 (known unknowns): **non-linear saturation**

- we assume that the non-linear damping rate = linear growth rate
- effect of wave-particle and wave-wave interactions need to be resolved
- Miniati & Elyiv (2012) claim that the nonlinear Landau damping rate is $\ll$ linear growth rate, but need to scatter waves with $\Delta k/k \sim 50$
- this is in conflict with the theory of induced scattering! (Schlickeiser+ 2012)

Implications for *B*-field measurements

Fraction of the pair energy lost to inverse-Compton on the CMB: $f_{IC} = \Gamma_{IC}/(\Gamma_{IC} + \Gamma_{oblique})$



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 may 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

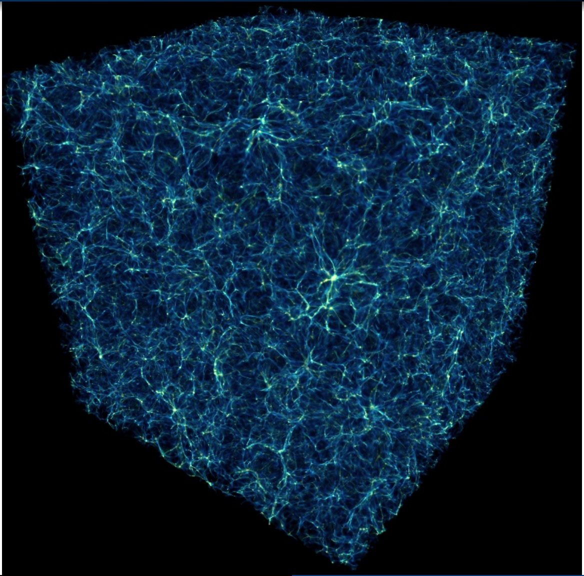
$\rightarrow$ **TeV blazar spectra are not suitable to measure IGM *B*-fields (if plasma instabilities saturate close to linear rate)!**

Simulations with blazar heating

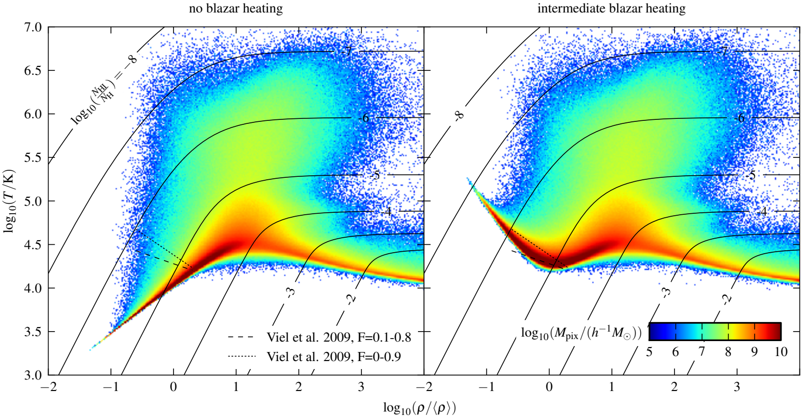
Puchwein, C.P., Springel, Broderick, Chang (2012):

- $L = 15h^{-1}$Mpc boxes with 2×384^3 particles
- one reference run without blazar heating
- three with blazar heating at different levels of efficiency
  (address uncertainty)
- used an up-to-date model of the UV background (Faucher-Giguère+ 2009)

The intergalactic medium

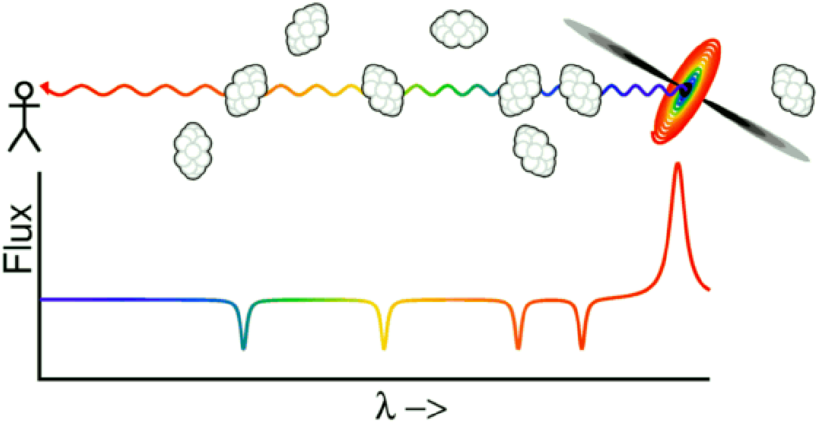


Temperature-density relation

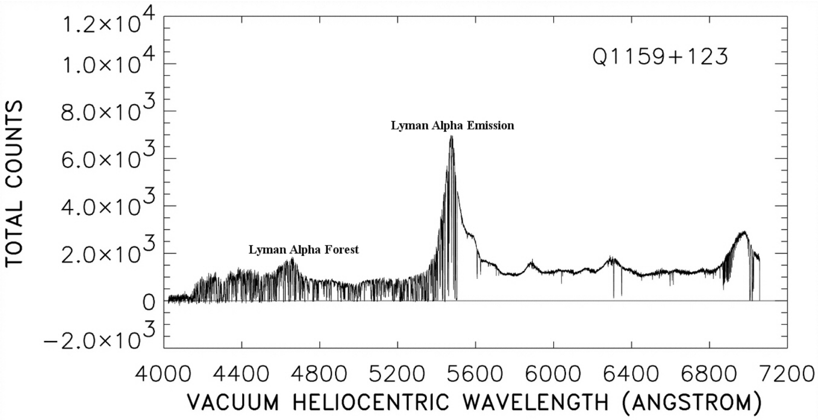


Puchwein, C.P., Springel, Broderick, Chang (2012)

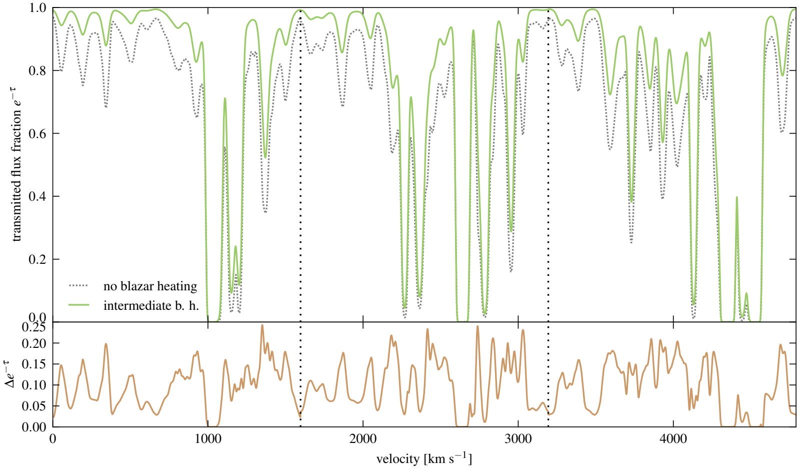
The Lyman-α forest



The observed Lyman-α forest

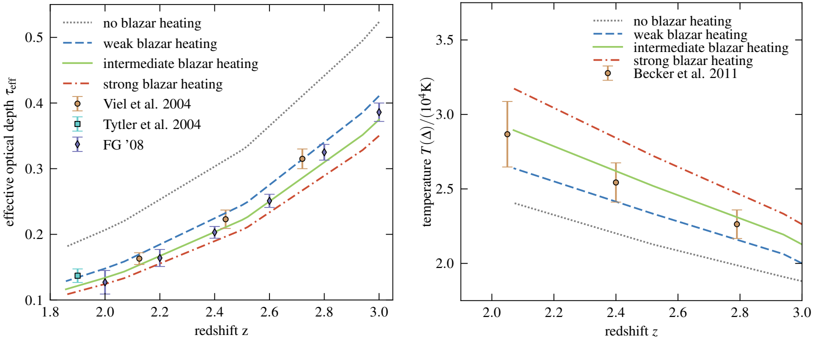


The simulated Ly-α forest



Puchwein+ (2012)

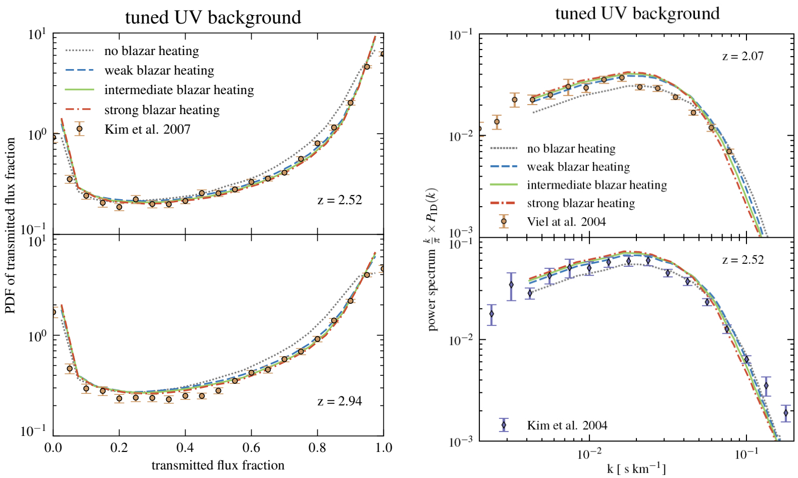
Optical depths and temperatures



Puchwein+ (2012)

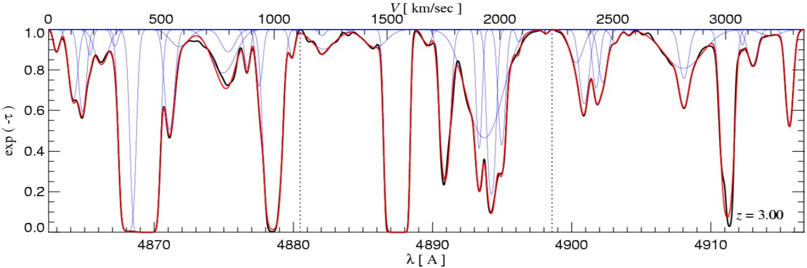
Redshift evolutions of effective optical depth and IGM temperature match data only with additional heating, e.g., provided by blazars!

Ly-α flux PDFs and power spectra



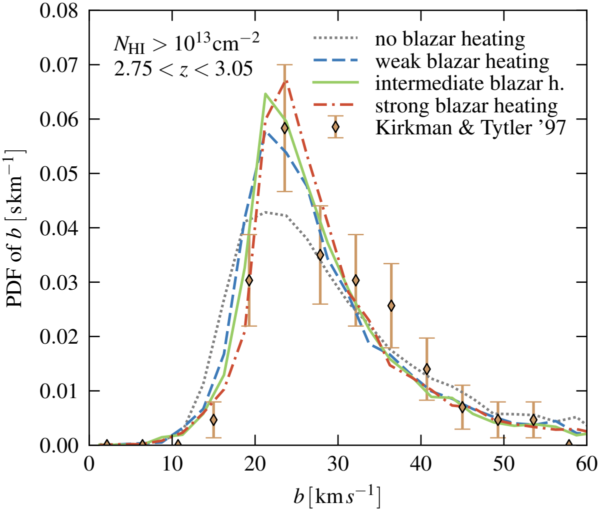
Puchwein+ (2012)

Voigt profile decomposition



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

Voigt profile decomposition – line width distribution



Puchwein+ (2012)

Lyman-α forest in a blazar heated Universe

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

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