Suppression of the TeV Pair-beam–Plasma Instability by a Tangled Weak Intergalactic Magnetic Field

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Cosmic Magnetism in Voids and Filaments
23 -27 Jan 2023
Bologna

University of Potsdam & DESY

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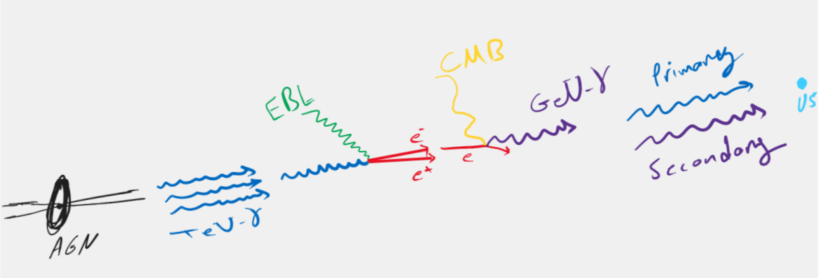
Introduction

Introduction

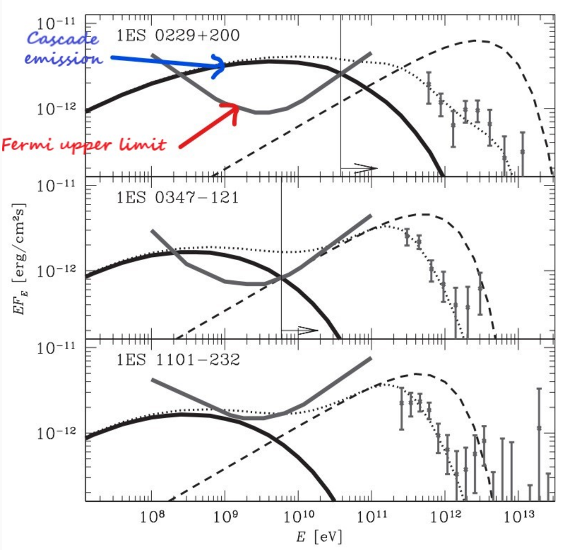
- Blazars are AGN's with a jet oriented along the line of sight.
- Some population of blazars (BL Lacs, in particular) shows an intense emission γ-ray at TeV energies.
- Along with the primary TeV emission we expected to detect an electromagnetic cascade in the GeV energy band due to the attenuation in the IGM:



The electromagnetic cascade is missing in the observations

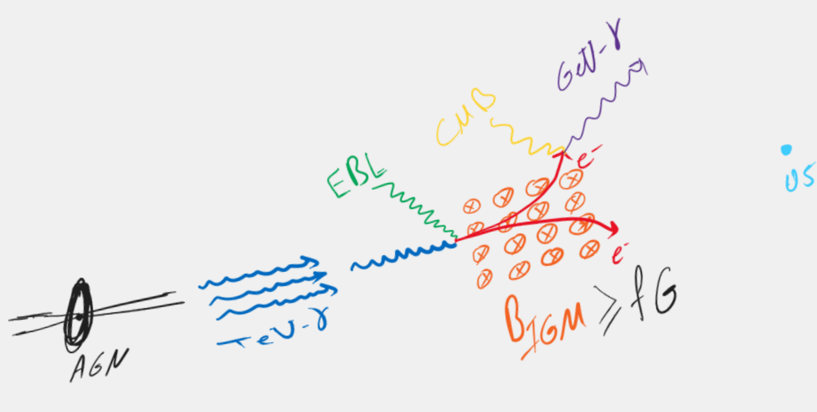
- Some of the observed blazars arriving energy fluxes in the GeV band are under the predicted flux from the full electromagnetic cascade.

Neronov and Vovk (2010)



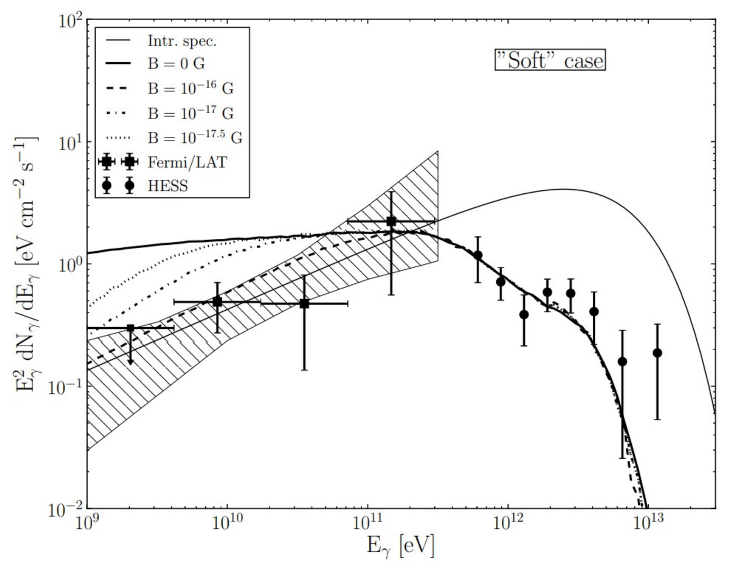
First possible explanation

- Deflection by the IGM magnetic fields.



Neronov and Vovk (2010) Taylor et al. (2011)

1ES 0229+200 and IGMF

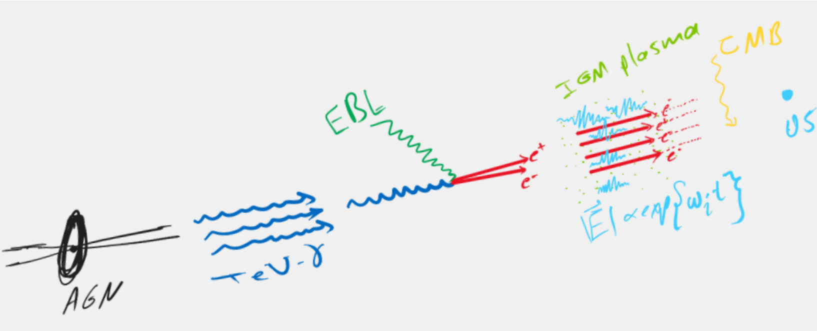


Taylor et al. (2011)

Second possible explanation

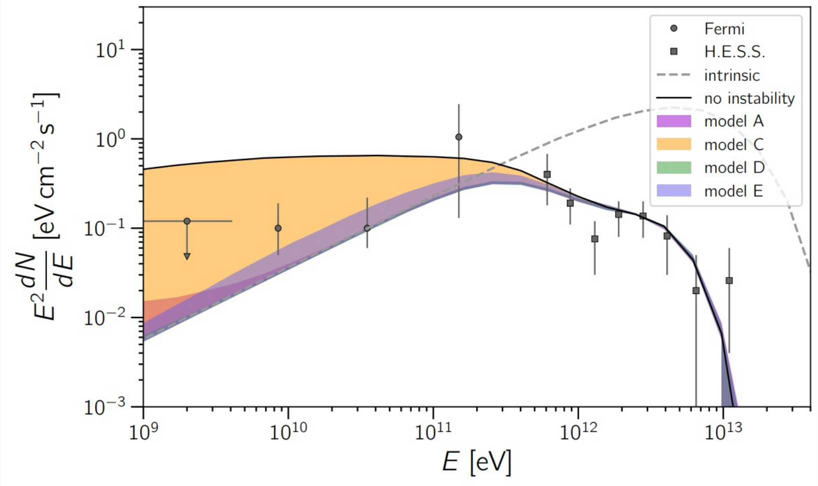
- Energy loss due to the Beam-plasma instabilities.

$$\omega_i \sim 10^{-8} Sec^{-1} \xrightarrow{\text{Waves evolution}} \tau_{\text{loss}} \sim 10^{12} Sec << \tau_{\text{IC}} \sim 10^{14} Sec$$



Broderick et al. (2012) Brejzman and Ryutov (1974)

1ES 0229+200 and Beam-plasma instability



Rafael Alves Batista talk

Alves Batista et al. (2019)

The Question

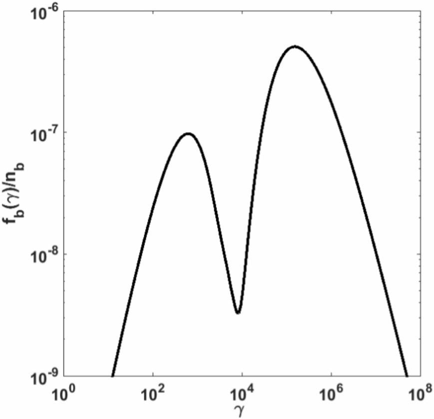
- **The plasma instability was calculated neglecting the IGM magnetic fields. How the IGM magnetic fields will impact the instability if it were there?**

Artwork by Sandbox Studio, Chicago

IGMF effect on Pair-beam electrostatic instability

Pair beam particles' distribution function

- Primary VHE gamma-rays: $dN/dE \sim E^{-1.8}$.
- Attenuation with the EBL at z =0.2 from Finke et al (2010).
- Pair spectrum at 50 Mpc from the source:



$$f_b(p,\theta) = f_{b,p}(p) f_{b,\theta}(p,\theta),$$
$$f_{b,\theta}(p,\theta) \approx \frac{1}{\pi\Delta\theta_s} \exp\left\{-\frac{\theta^2}{\Delta\theta_s^2}\right\},$$
$$\Delta\theta_s \approx \frac{m_e c}{p}$$

Vafin et al. (2018)

Pair-Beam and IGM parameters

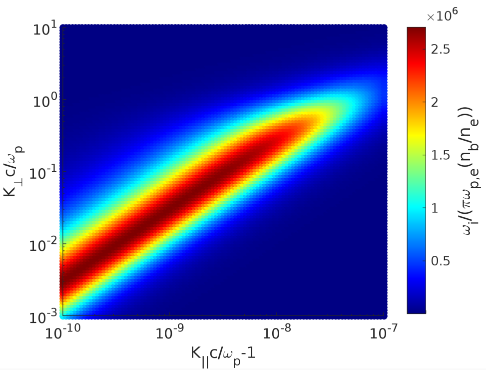
- Total pair-beam particles density at 50 Mpc: $n_b = 3 \times 10^{-22} \text{cm}^{-3}$.
- Pair-beam mean Lorentz factor at 50 Mpc: $\gamma_b = 4 \times 10^6$.
- The IGM plasma density: $n_e = 10^{-7}(1+z)^3 \text{cm}^{-3}$.
- The IGM temperature: $T_e = 10^4$ K.

Linear growth rate of the electrostatic instability without IGMF

- The linear electrostatic growth rate is the key quantity of the plasma instability (Brejzman and Ryutov, 1974):

$$\omega_i(\boldsymbol{k}) = \omega_p \frac{2\pi^2 e^2}{k^2} \int d^3\boldsymbol{p} \left(\boldsymbol{k} \cdot \frac{\partial f}{\partial \boldsymbol{p}}\right) \delta(\boldsymbol{k} \cdot \boldsymbol{v} - \omega_p).$$

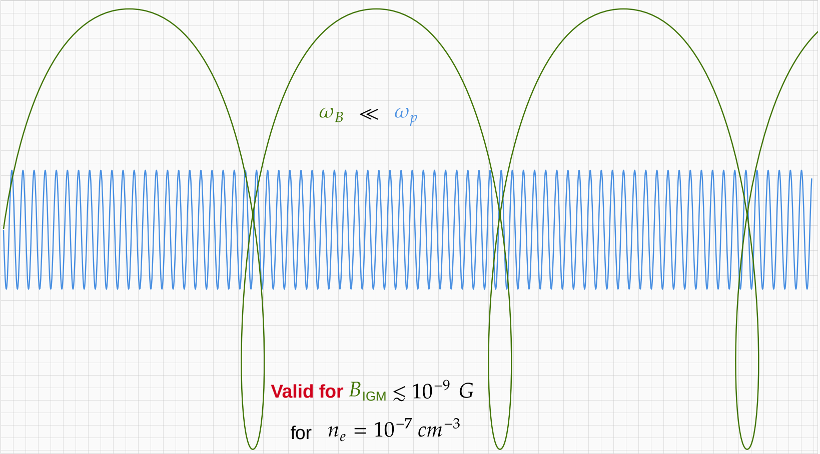
- Maximum growth rate: $\omega_{i,\max}^{-1} \approx 10^8$ Sec.
- Inverse Compton scattering $\sim 10^{14}$ Sec.



Vafin et al. (2018)

Weak IGMFs don't change the beam-plasam linear analysis

- The intergalactic magnetic fields do not change the electrostatic dispersion relation used to derive the linear growth rate.

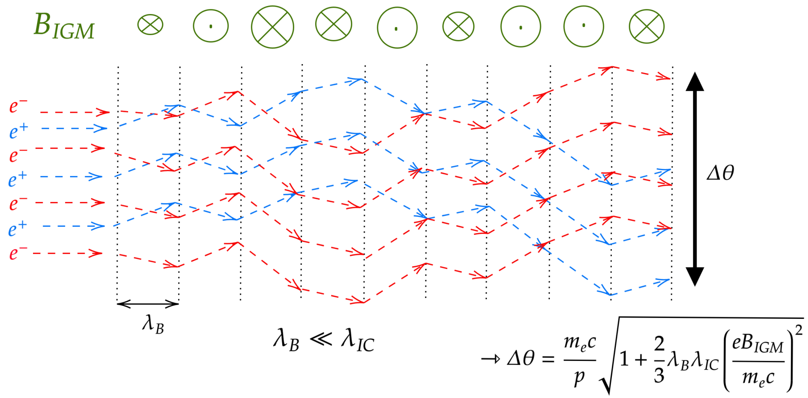


Valid for $B_{\text{IGM}} \lesssim 10^{-9}\ G$

for $n_e = 10^{-7}\ cm^{-3}$

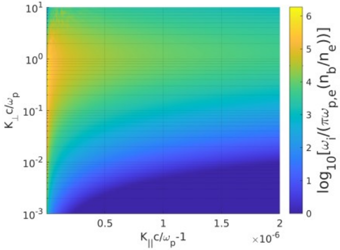
Weak Intergalactic Magnetic Fields effect on the Linear Growth Rate of Electrostatic Instability

- The intergalactic magnetic fields cause stochastic deflections of the electrons and positrons increasing the angular distribution function of the pair beam as a Gaussian with the angler spread

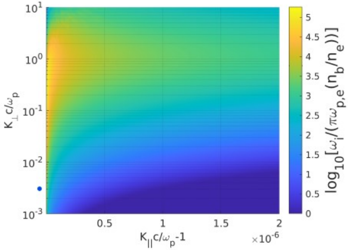


$$\rightarrow \Delta\theta = \frac{m_e c}{p}\sqrt{1 + \frac{2}{3}\lambda_B \lambda_{IC}\left(\frac{eB_{IGM}}{m_e c}\right)^2}$$

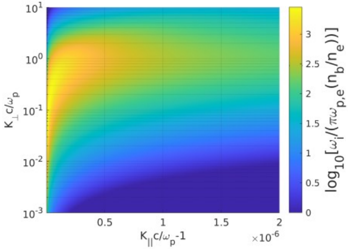
Weak IGMFs effect on the Linear Growth Rate $\omega_i(\Delta\theta(B_{\mathbf{IGM}}, \lambda_{\mathbf{B}}))$



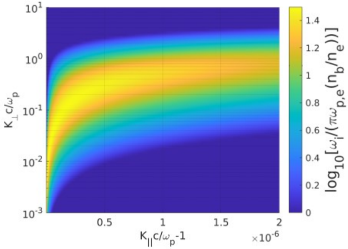
(a) $B_{\text{IGM}} = 10^{-18}$ Gauss and $\lambda_B = 1$ pc



(b) $B_{\text{IGM}} = 10^{-17}$ Gauss and $\lambda_B = 1$ pc

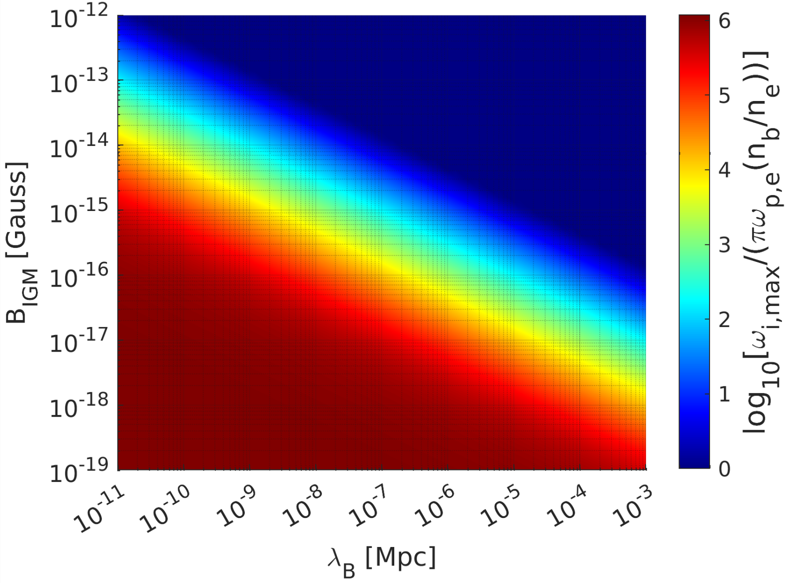


(c) $B_{\text{IGM}} = 10^{-16}$ Gauss and $\lambda_B = 1$ pc.



(d) $B_{\text{IGM}} = 10^{-15}$ Gauss and $\lambda_B = 1$ pc

Strong reduction of the instability growth rate peak with IGMF



Energy loss time of the beam-plasma instability

- Lower instability growth rate yields longer energy loss time of the instability

  $$\tau_{\mathrm{loss}}^{-1} = 2\delta\omega_{i,\mathrm{max}},$$

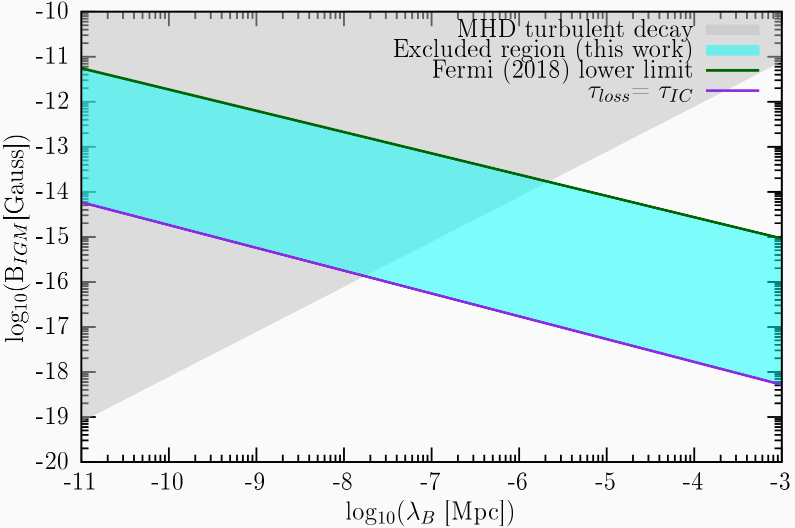
  where $\delta = U_{\mathrm{ES}}/U_{\mathrm{beam}}$ is the normalized wave energy density at the equilibrium level.

- We consider the energy loss time in Vafin et al. (2018) that is about one order of magnitude less than the IC energy loss time at redshift 0.2:

  $$\frac{\tau_{\mathrm{loss}}}{\tau_{\mathrm{IC}}} = 0.026 \tag{1}$$

- The weak intergalactic magnetic field increases the energy loss time of the beam-plasma instability suppressing it after a certain limit.

Plasma instability limit compared to the time delay limit Alawashra and Pohl (2022)



Blazar-induced Pair beam plasma instability current statue

Blazar-induced Pair beam plasma instability current statue

- We know that the linear growth rate is **much faster** than the inverse Compton scattering.

  Broderick et al. (2012); Vafin et al. (2018)

- Non-linear evolution of the instability which includes the waves-particle scattering, wave-wave interaction and the background inhomogeneity effect is **still uncertain**.

  Schlickeiser et al. (2012); Miniati and Elyiv (2013); Vafin et al. (2019)

- Feedback of the instability on the pair beam might include an angular spread that suppress the instability linear growth rate as well. **No significant energy loss**.

  Perry and Lyubarsky (2021)

Summary

Summary

- Weak intergalactic magnetic fields slow down the linear electrostatic instability.
- This suppression is effective for fields with a factor of a thousand weaker than those needed for magnetic deflection of the cascade emission.
- Back-reaction of the instability on the pair beam may include widening of the beam which also could suppress the instability (See Perry and Lyubarsky (2021)).

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Linear analysis of the beam-plasma instability

- To describe the full system of the beam-plasma particles we need Maxwell's equation and Vlasov's equation

$$\left[\frac{\partial}{\partial t} + \mathbf{v} \cdot \frac{\partial}{\partial \mathbf{r}} + q_a \left(\mathbf{E} + \frac{\mathbf{v} \times \mathbf{B}}{c}\right) \cdot \frac{\partial}{\partial \mathbf{p}}\right] f_a = 0 \tag{2}$$

$$\boldsymbol{\nabla} \cdot \mathbf{E} = 4\pi\rho \tag{3}$$

$$\boldsymbol{\nabla} \cdot \mathbf{B} = 0 \tag{4}$$

$$\boldsymbol{\nabla} \times \mathbf{E} = -\frac{1}{c}\frac{\partial \mathbf{B}}{\partial t} \tag{5}$$

$$\boldsymbol{\nabla} \times \mathbf{B} = \frac{4\pi}{c}\mathbf{J} + \frac{1}{c}\frac{\partial \mathbf{E}}{\partial t} \tag{6}$$

- Taking the average quantities plus a perturbation part $f_a = f_{a0} + \delta f_a$, $\mathbf{E} = \mathbf{E}_0 + \delta\mathbf{E}$ and $\mathbf{B} = \mathbf{B}_0 + \delta\mathbf{B}$.

Blazar-induced pair beam electrostatic instability

- Neglect the external magnetic field and its perturbation ($\mathbf{B} = \mathbf{B}_0 + \delta\mathbf{B} = 0$).
- Zero average electric field ($\mathbf{E}_0 = 0$).
- Take Fourier-Laplace transform of **E** fluctuations

$$\delta\mathbf{E} = (2\pi)^{-4} \int\int \delta\mathbf{E}_{k,w} e^{i\mathbf{kr}-i\omega t} d^3k d\omega. \tag{7}$$

- Using Maxwell-Vlasov equations leads to an equation link ω with k called the dispersion relation.
- Solve for the imaginary part of $\omega(k)$: $\omega_i > 0$ leads to an instability growing ,$\omega_i < 0$ leads to decaying.
- For Blazar-induced pair beams the dominant modes are the **electrostatic** ($\delta\mathbf{E} \parallel \mathbf{k}$).