Suppression of the TeV pair-beam plasma instability by a tangled weak intergalactic magnetic field

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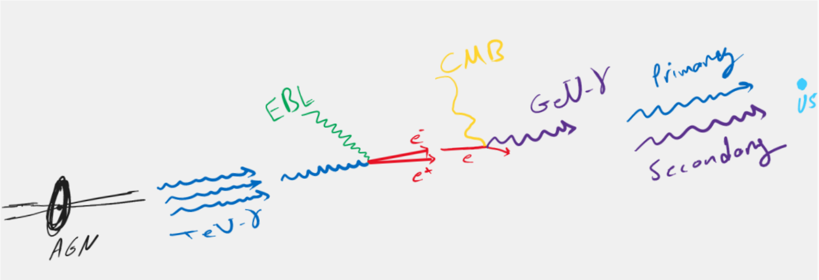
DESY.

HELMHOLTZ WEIZMANN RESEARCH SCHOOL MULTIMESSENGER ASTRONOMY

Introduction

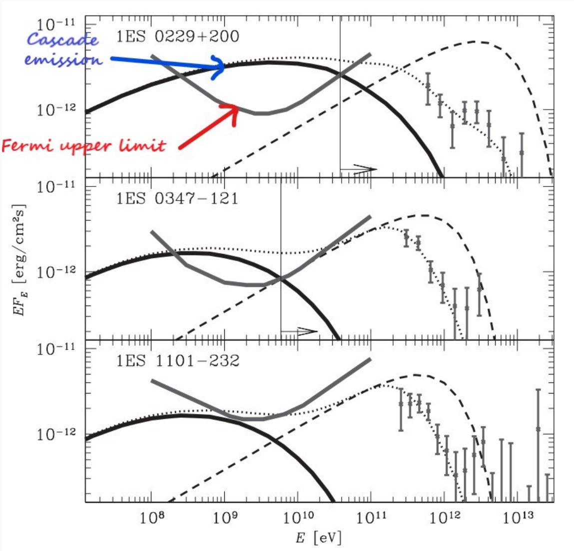
- Blazars are AGN's with a jet oriented along the line of sight.
- Some population of blazars (BL Lacs, in particular) shows an intense emission γ-ray at TeV energies.
- Along with the primary TeV emmision we expected to detect an electromagnetic cascade in the GeV energy band due to the attenuation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



The electromagnetic cascade is missing in the observations

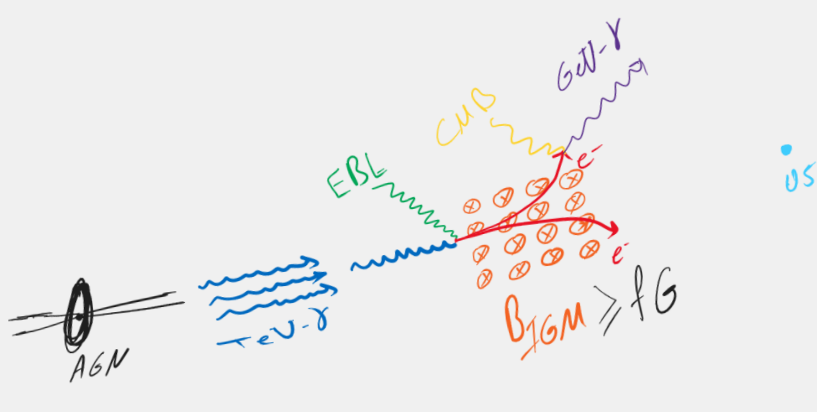
- Some of the observed blazars arriving energy fluxes in the GeV band are under the predicted flux from the full electromagnetic cascade.

Neronov and Vovk (2010)



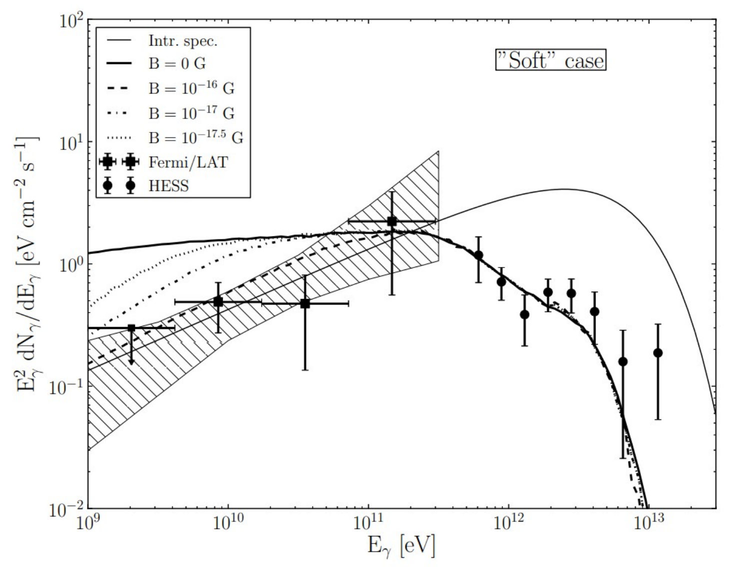
First possible explanation

- Deflection by the IGM magnetic fields.



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

1ES 0229+200 and IGMF

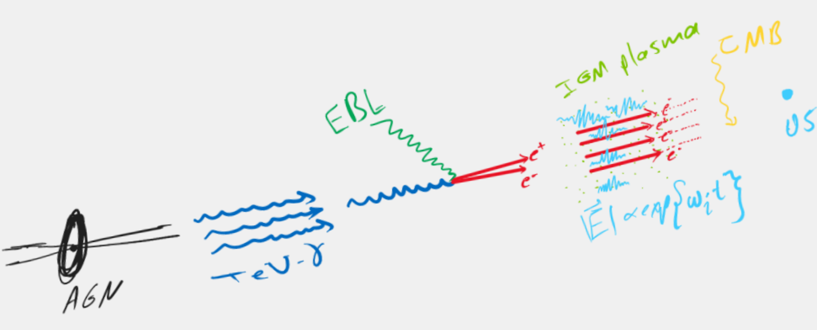


Vovk et al. (2012)

Second possible explanation

- Energy loss due to the Beam-plasma instabilities.

$$\omega_i \sim 10^{-7} Sec^{-1} \xrightarrow{\textit{Waves evolution}} \tau_{\text{loss}} \sim 10^{12} Sec << \tau_{\text{IC}} \sim 10^{13} Sec$$



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

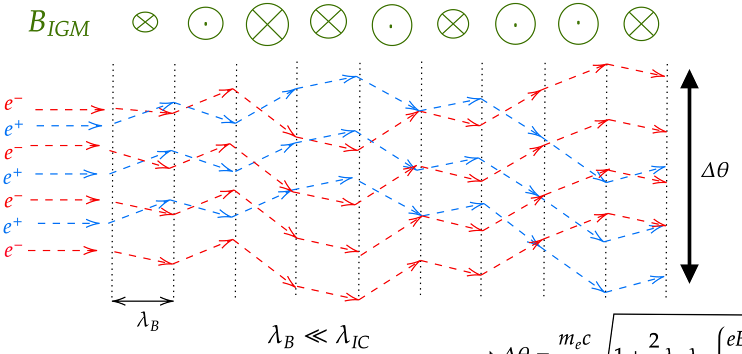
The question

- **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

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

- This angular spread slows down the linear growth rate of the instability

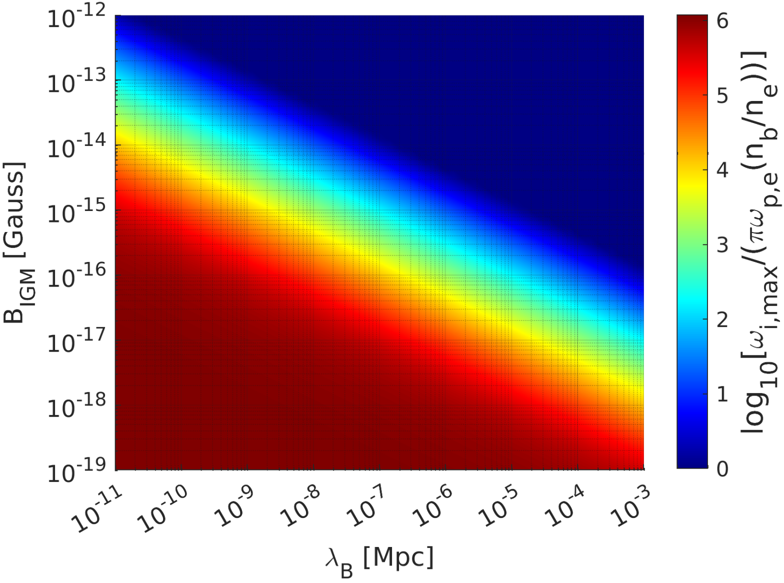
$$\omega_i(\boldsymbol{k}) = \omega_p \frac{2\pi^2 e^2}{k^2} \int d^3\boldsymbol{p} \left(\boldsymbol{k} \cdot \frac{\partial f}{\partial \boldsymbol{p}} \right) \delta(\omega_p - \boldsymbol{k} \cdot \boldsymbol{v}).$$

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

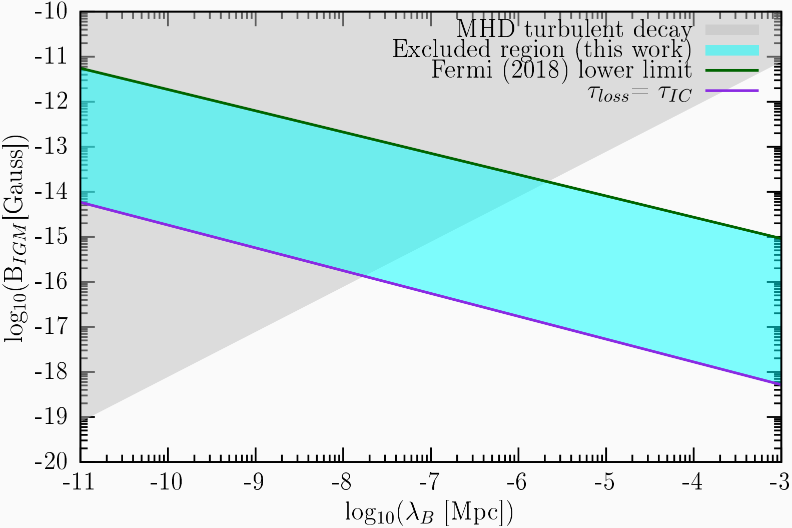
$$\tau_{\text{loss}}^{-1} = 2\delta\omega_{i,\text{max}},$$

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

Strong reduction of the instability growth rate peak with IGMF



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



Summary

- Weak intergalactic magnetic fields slow down the linear electrostatic instability.
- This suppression is effective for fields 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 still unclear, but it may include widening of the beam which also could suppress the instability (See Perry and Lyubarsky (2021)).

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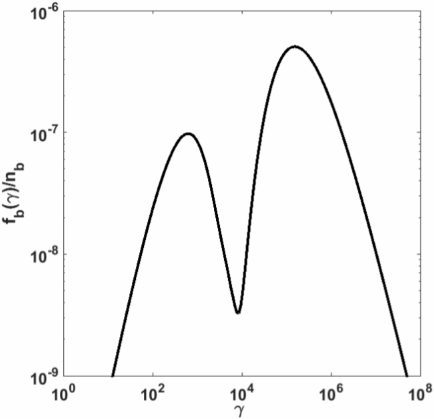
Pair beam particle distribution

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

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

Vafin et al. (2018)



Pair-Beam parameters

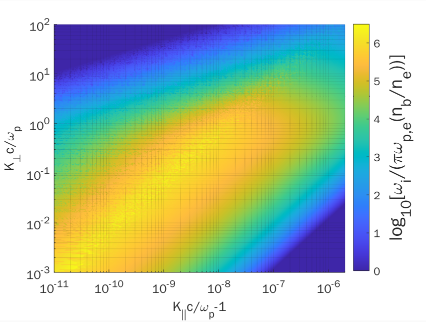
- Total pair-beam particles density at 50 Mpc: $n_b = 3 \times 10^{-22}\mathrm{cm}^{-3}$.
- Pair-beam mean Lorentz factor at 50 Mpc: $\gamma_b = 4 \times 10^6$.
- The IGM plasma density: $n_e = 10^{-7}(1 + z)^3\mathrm{cm}^{-3}$.
- The IGM temperature: $T_e = 10^4$ K.

Linear growth rate of electrostatic instability for a blazar induced beam

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

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

- Maximum growth rate: $\omega_{i,\max}^{-1} \approx 10^7$ Sec.
- Inverse Compton scattering $\sim 10^{13}$ Sec.



Vafin et al. (2018)

Back-reaction on the pair beam

- The back-reaction is given by the diffusion equation

$$\frac{\partial f(p,\theta)}{\partial t} = \frac{1}{p^2 \sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta D_{\theta\theta}\frac{\partial f}{\partial\theta}\right) + \frac{1}{p\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta D_{\theta p}\frac{\partial f}{\partial p}\right) + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p D_{\theta p}\frac{\partial f}{\partial\theta}\right) + \frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_{pp}\frac{\partial f}{\partial p}\right), \quad (1)$$

  where the resonant momentum-diffusion tensor defined by

$$D_{\alpha\beta} = \pi e^2 \int d^3\boldsymbol{k} W(\boldsymbol{k}, t)\frac{k_\alpha k_\beta}{k^2}\delta(\boldsymbol{k}\cdot\boldsymbol{v} - \omega_p), \quad (2)$$

  where k_α is the wavenumber projection to the α component of the beam, for example, $k_p = k$ and $k_\theta = \boldsymbol{k}\cdot\hat{\boldsymbol{\theta}} = k[\sin\theta'\cos\theta\cos\varphi' - \cos\theta'\sin\theta]$.

- Perry and Lyubarsky (2021) solved only the first part of the right hand side of this equation.

Perry and Lyubarsky (2021) result

- Perry and Lyubarsky (2021) used the approximation

$$\begin{aligned}
&\frac{1}{p^2 \sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta D_{\theta\theta}\frac{\partial f}{\partial\theta}\right) \sim \left(\frac{\theta'}{\Delta\theta}\right)^2 \\
&\frac{1}{p \sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta D_{\theta p}\frac{\partial f}{\partial p}\right) \sim \left(\frac{\theta'}{\Delta\theta}\right) \\
&\frac{1}{p^2}\frac{\partial}{\partial p}\left(p D_{\theta p}\frac{\partial f}{\partial\theta}\right) \sim \left(\frac{\theta'}{\Delta\theta}\right) \\
&\frac{1}{p^2}\frac{\partial}{\partial p}\left(p^2 D_{pp}\frac{\partial f}{\partial p}\right) \sim 1
\end{aligned} \tag{3}$$

where the intergalactic beam is narrow $\Delta\theta \sim 10^{-5}$ and the beam energy spread is large $\Delta p \sim p$. θ' is the angle of the waves propagation, they consider only $\theta' \sim 1$.

- Scattering is stronger than the energy loss, scattering suppresses the instability energy loss.
- Will the argument hold if we include $\theta' << 1$?