Impact of Plasma Instability on Constraint of the Intergalactic Magnetic Field

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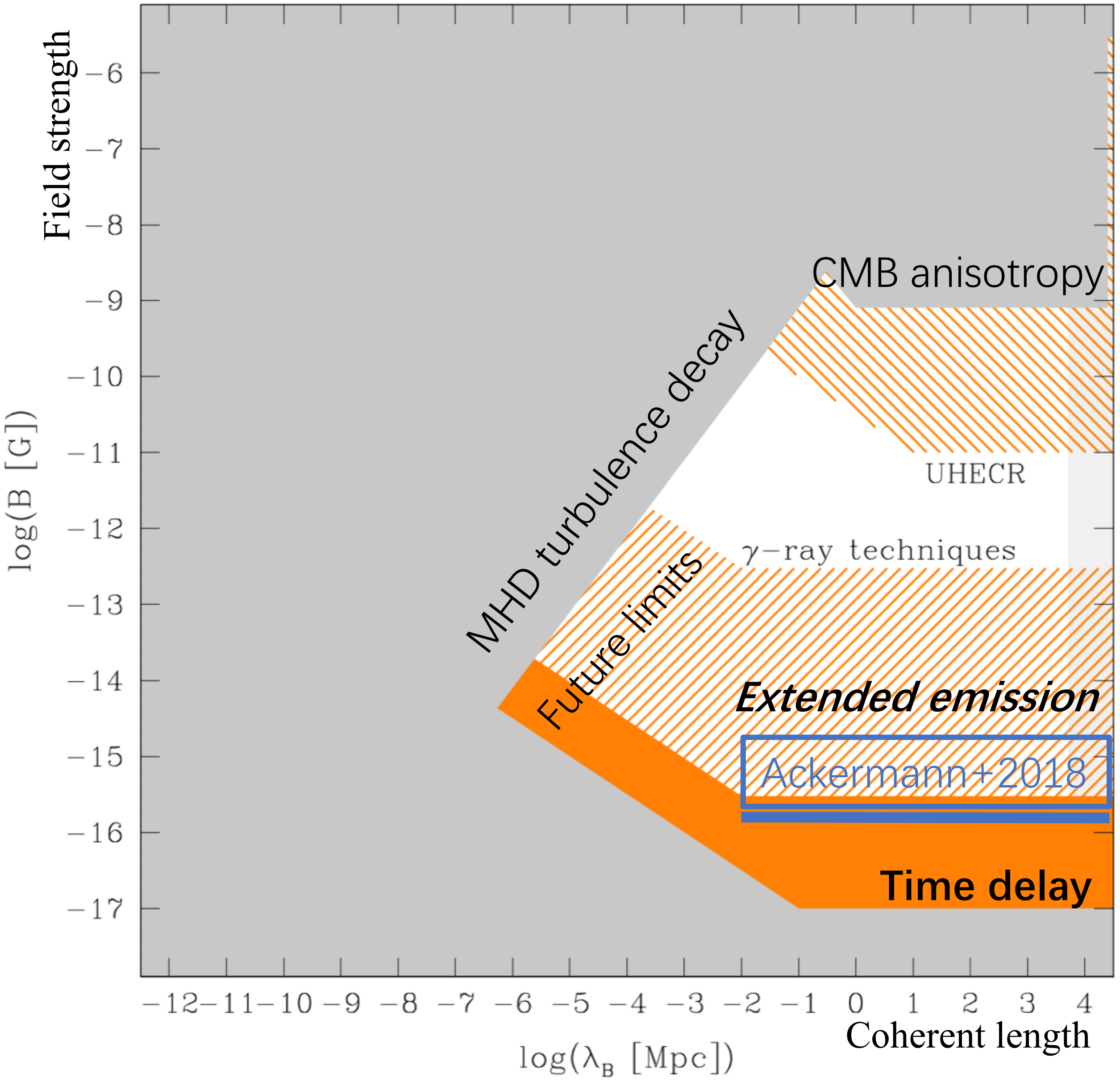


Durrer&Neronov 2013

Gamma-ray astronomy:

providing a tool to probe IGMF

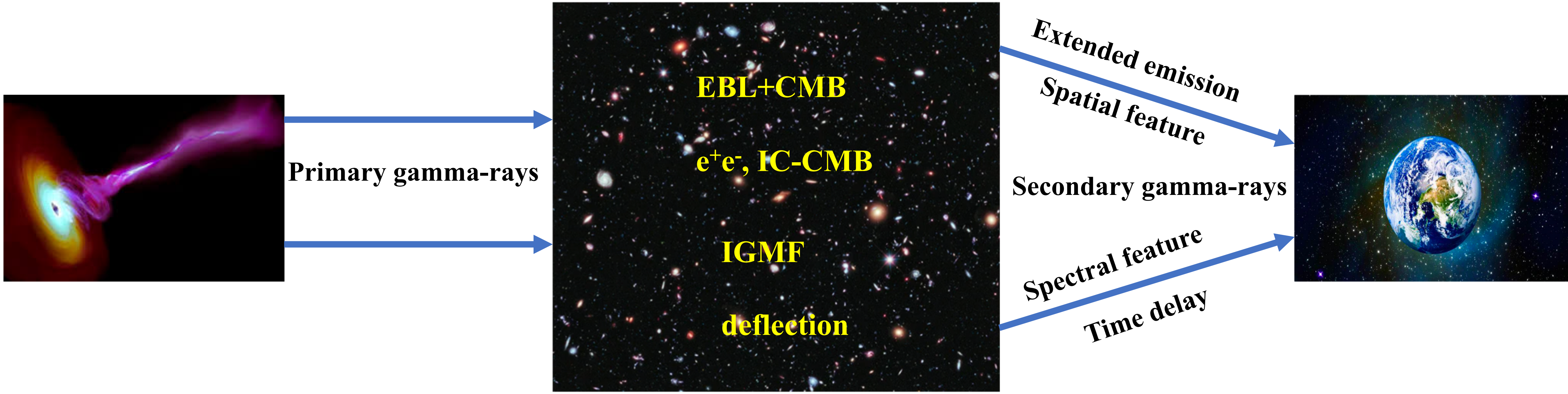
Origin of IGMF:

astrophysical: galaxy formation

cosmological: early universe physics

IGMF measurements through gamma-ray data

e.g., Aharonian et al. 1994; Elyiv et al. 2009

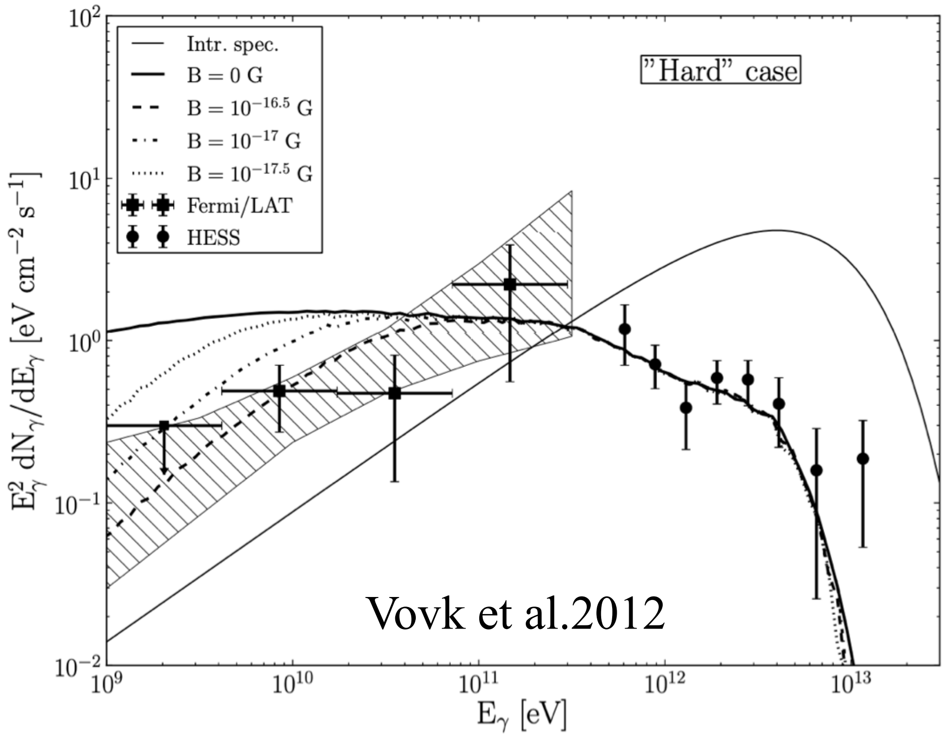


e.g., plaga 1995; Dai et al. 2002; Murase et al. 2008

IGMF measurements through gamma-ray data

e.g., Aharonian et al. 1994; Elyiv et al. 2009

Primary gamma-ray



d emission

gamma-rays

e delay

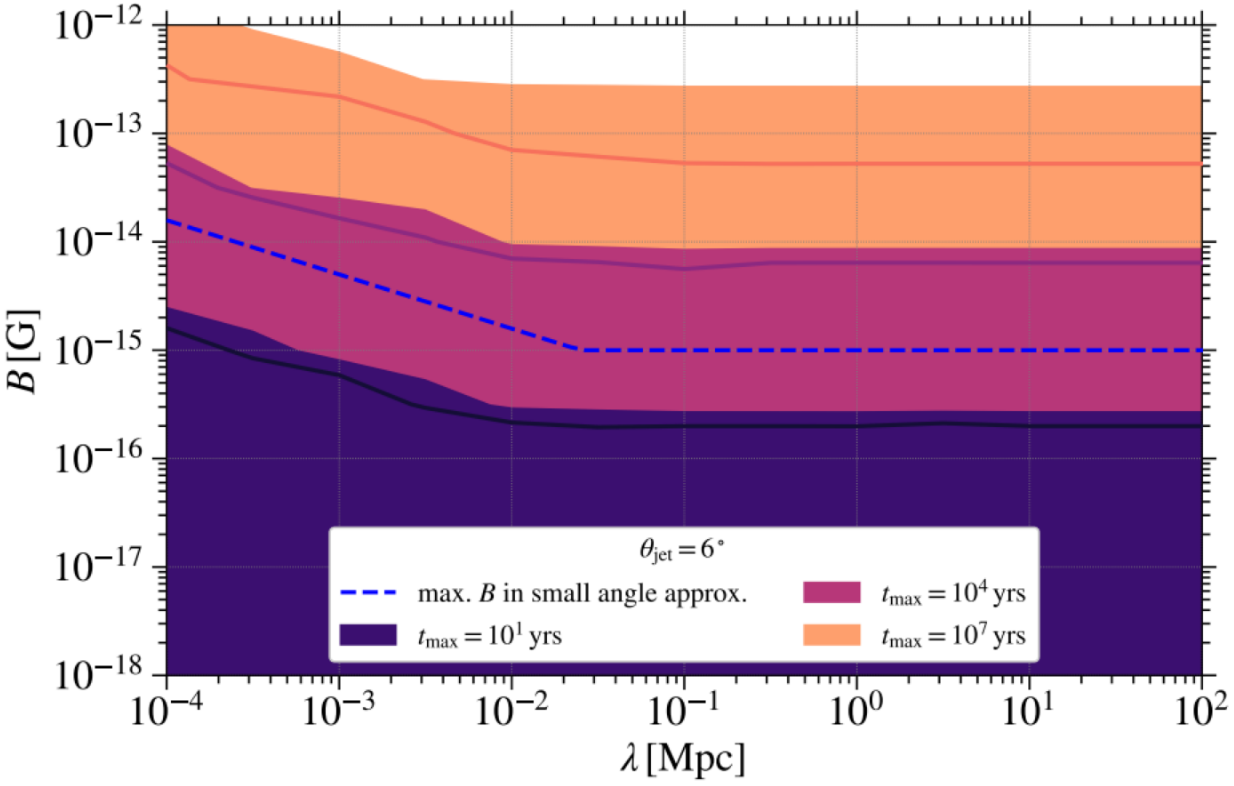
e.g., plaga 1995; Dai et al. 2002; Murase et al. 2008

IGMF measurements through gamma-ray data

- **Constraints from Fermi-LAT observations:**
- Neronov&Vovk 2010
- Tavecchio et al. 2010
- Taylor et al. 2011
- Dermer et al. 2011
- Vovk et al. 2012
- Finke et al. 2015
- Ackermann et al. 2018
- ……………….

Ackermann et al. 2018

No evidence for extended emission in individual sources or in stacked source samples.



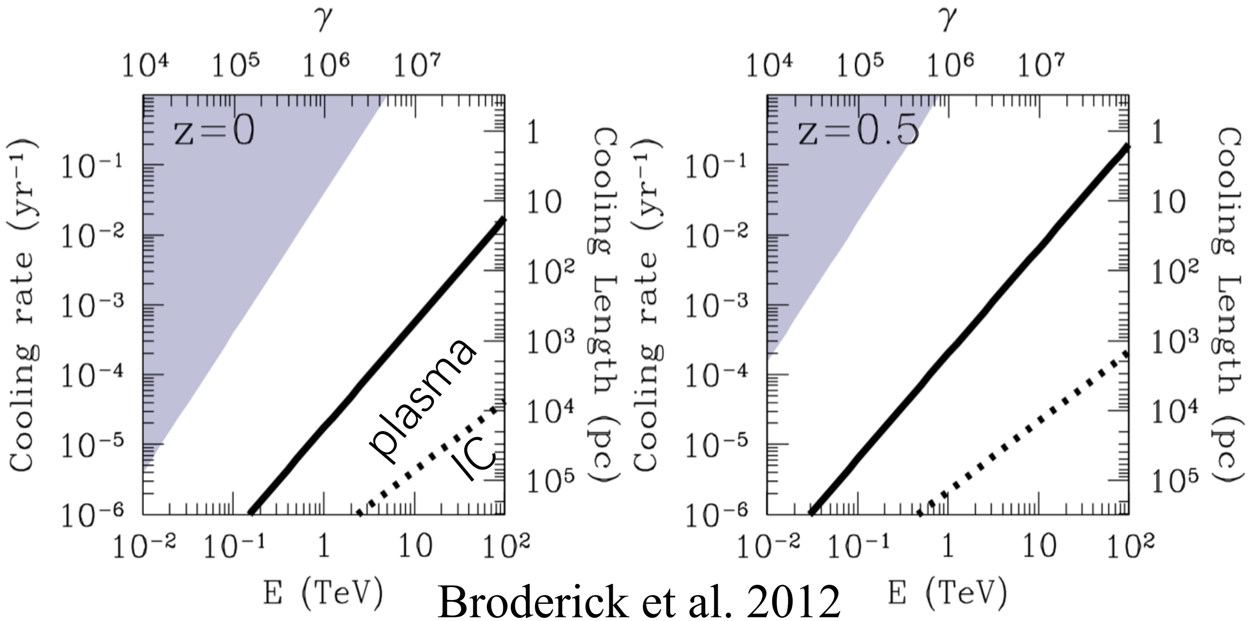
However……,

the above results are based on the assumption that the dominant cooling process for e^+e^- is IC-CMB.

What else could happen?

e^+e^- beam propagating through the intergalactic medium

→ **plasma instabilities (Broderick et al. 2012)**



Broderick et al. 2012

Two competing processes:

$$\gamma_{\rm TeV} + \gamma_{\rm eV} \rightarrow e^+ + e^- \rightarrow$$

- IC → secondary gamma-rays
- Plasma instabilities → IGM heating

Plasma instabilities: very complicated physics problem

Many authors made efforts to study this problem through analytical method and PIC simulations:

e.g., Schlickeiser et al. 2012a, 2012b, 2013; Miniati & Elyiv 2013; Chang et al. 2014; Sironi & Giannios 2014; Kempf et al. 2016; Shalaby et al. 2018; Vafin et al. 2018…

However, the fate of the pair's evolution is still under debate.

A simple analysis including plasma instability cooling

$$\frac{\partial}{\partial\gamma}[\dot{\gamma}n_e(\gamma)] = \dot{n}_e(\gamma),$$

The steady-state electron continuity equation that governs the pair evolution, no escape and advection.

The solution:

$$n(\gamma) = \frac{1}{\dot{\gamma}}\int_{\gamma}^{\infty} d\gamma' \dot{n}_e(\gamma').$$

$$\dot{n}_e(\gamma) = \frac{16\pi d_L^2 f_\epsilon}{m_e c^2 \epsilon^2}[1 - e^{-\tau_{\gamma\gamma}(\epsilon,z)}],\ \epsilon = 2\gamma;$$

Pair injection rate

$$f_\epsilon = F(E) = F_0\left(\frac{E}{E_0}\right)^{2-\Gamma} e^{-E/E_{\rm cut}},\ E = m_e c^2 \epsilon;$$

Primary gamma-ray spectrum

Cooling rate:

$$-\dot{\gamma}_{\rm T} = \frac{4}{3}c\sigma_{\rm T}\frac{u_{\rm CMB}}{m_e c^2}\gamma^2 = \nu_{\rm T}\gamma^2,$$

IC cooling

$$-\dot{\gamma}_{\rm M,K} = \nu_{\rm M,k}\gamma^2.$$

Plasma oblique instability cooling

$$\dot{\gamma} = \dot{\gamma}_{\rm M,K} + \dot{\gamma}_{\rm T} = \nu_{\rm T}(1+b)\gamma^2 \qquad b = \nu_{\rm M,k}/\nu_{\rm T}$$

Secondary gamma-ray flux (the formula of Dermer et al. 2011)

$$f_{\epsilon_s} = \frac{1}{1+b} \frac{3}{2}\left(\frac{\epsilon_s}{\epsilon_0}\right)^2 \int_{\max\left[\sqrt{\frac{\epsilon_s}{4\epsilon_0}},\gamma_{dfl},\gamma(\Delta t)\right]}^{\infty} d\gamma\, \gamma^{-4}\left(1-\frac{\epsilon_s}{4\gamma^2\epsilon_0}\right),$$

$$\times \int_{\gamma}^{\infty} d\gamma_i\, \frac{f_\epsilon \left\{\exp[\tau_{\gamma\gamma}(\epsilon, z)]-1\right\}}{\epsilon^2},$$

$$\gamma_{dfl} = \begin{cases} \sqrt{\frac{eB}{\theta_j m_e c \nu_{\rm T}}}, & \gamma_{dfl} > \frac{c}{\nu_{\rm T}\lambda_{coh}} \\ \left(\frac{c\lambda_{coh}}{\nu_{\rm T}}\right)^{1/3} \left(\frac{eB}{m_e c^2 \theta_j}\right)^{2/3}, & \gamma_{dfl} < \frac{c}{\nu_{\rm T}\lambda_{coh}} \end{cases}$$

$$\gamma(\Delta t) = \begin{cases} \sqrt{\frac{eB}{m_e c \nu_{\rm T}}} \left(\frac{\lambda_{tot}}{2c\Delta t}\right)^{1/4} \cong \frac{9.9\times 10^9 \lambda_{100}^{1/4} B_{-15}^{1/2}}{[\Delta t({\rm s})]^{1/4}}, & \frac{7.5\times 10^5}{\lambda_{coh}({\rm Mpc})} < \gamma \\ \left(\frac{eB}{m_e c^2}\right)^{2/3} \left(\frac{\lambda_{tot}\lambda_{coh}}{2\nu_{\rm T}\Delta t}\right)^{1/3} \cong \frac{2.3\times 10^{11} \lambda_{100}^{1/3} B_{-15}^{2/3} \lambda_{coh}^{1/3}({\rm Mpc})}{[\Delta t({\rm s})]^{1/3}}, & \gamma < \frac{7.5\times 10^5}{\lambda_{coh}({\rm Mpc})} \end{cases}$$

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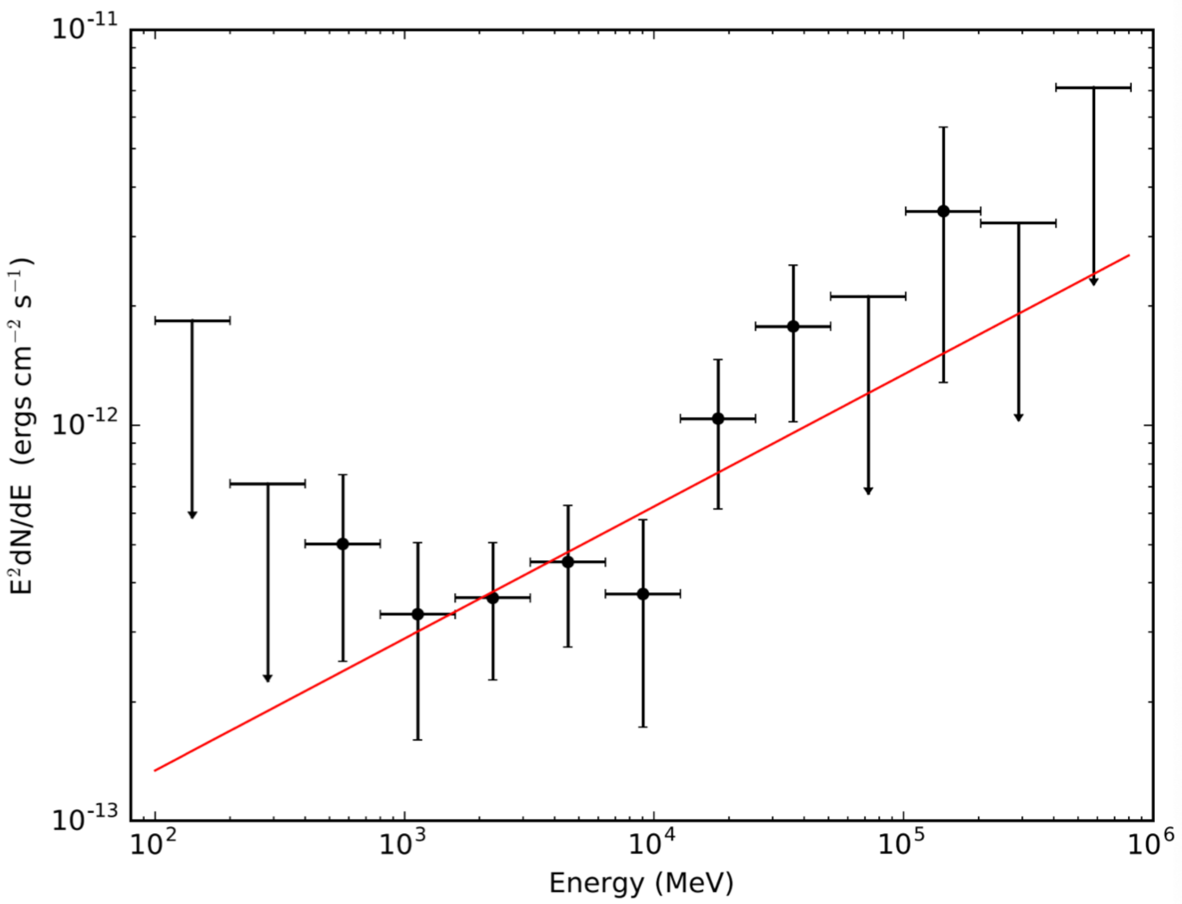
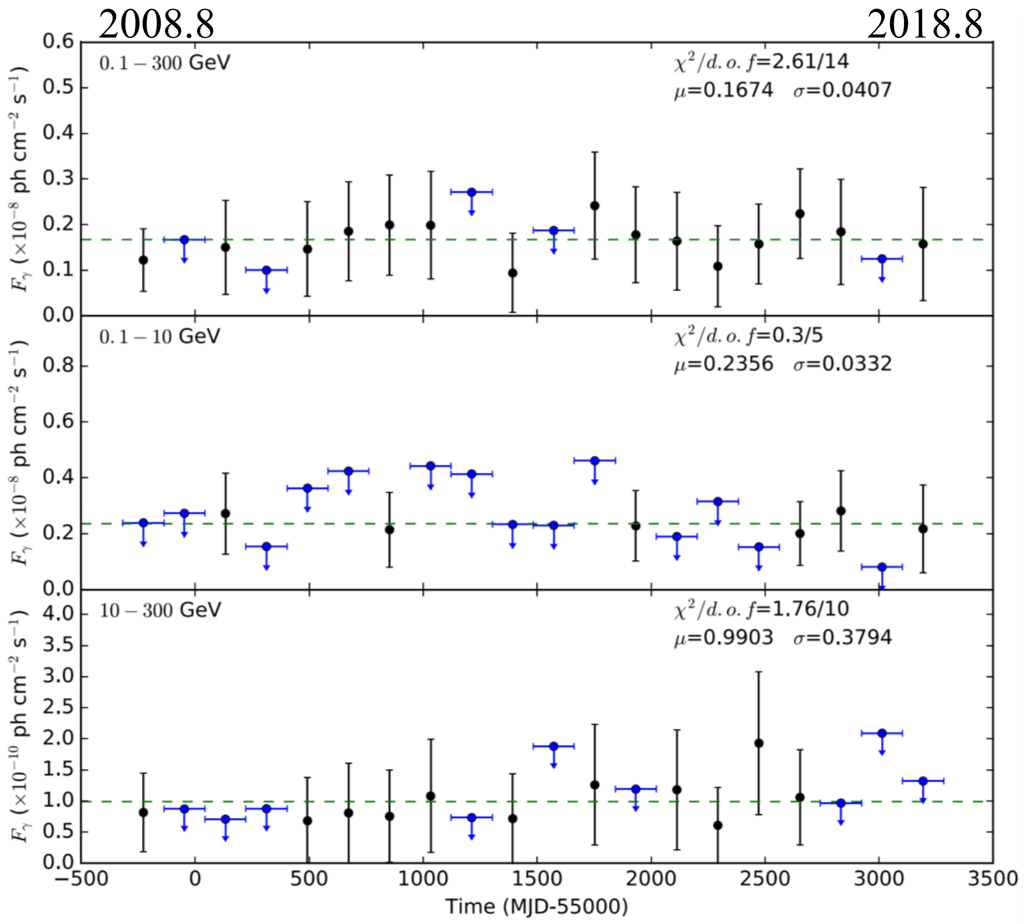
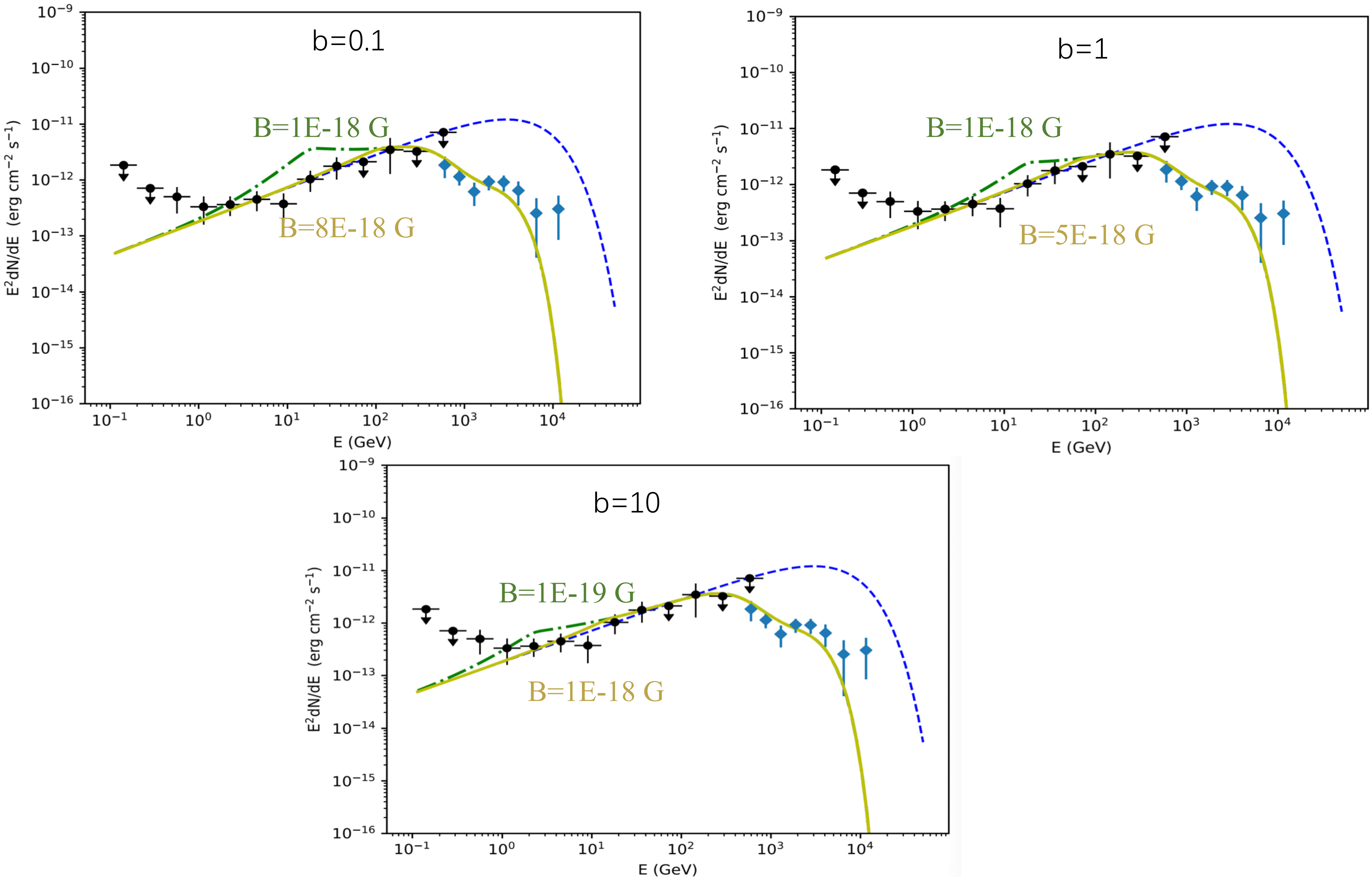


10^{-11}
10^{-12}
10^{-13}
E^2dN/dE (ergs cm^{-2} s^{-1})
10^2
10^3
10^4
10^5
10^6
Energy (MeV)



2008.8
2018.8
$0.1-300$ GeV
$\chi^2/d.o.f$=2.61/14
μ=0.1674 σ=0.0407
$0.1-10$ GeV
$\chi^2/d.o.f$=0.3/5
μ=0.2356 σ=0.0332
$10-300$ GeV
$\chi^2/d.o.f$=1.76/10
μ=0.9903 σ=0.3794
F_γ ($\times10^{-8}$ ph cm^{-2} s^{-1})
F_γ ($\times10^{-8}$ ph cm^{-2} s^{-1})
F_γ ($\times10^{-10}$ ph cm^{-2} s^{-1})
Time (MJD-55000)



b=0.1
B=1E-18 G
B=8E-18 G
b=1
B=1E-18 G
B=5E-18 G
b=10
B=1E-19 G
B=1E-18 G
E^2dN/dE (erg cm^{-2} s^{-1})
E (GeV)

Conclusion

- Our results suggest that the gamma-ray data still put effective constraints on IGMF, even if the oblique instability cooling is strongly dominating over the IC cooling.

Thanks for your attention!