

# **morphological properties of blazar-induced gamma-ray haloes**

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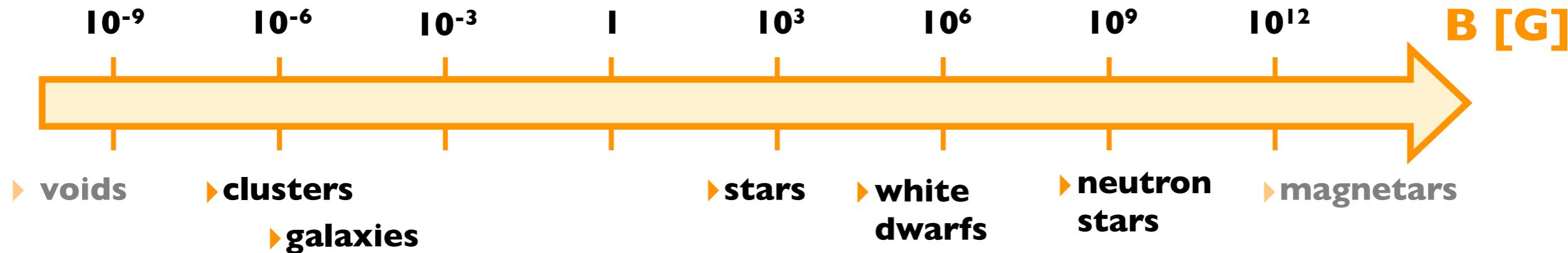
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*<sup>2</sup> Immanuel Kant Baltic Federal University, Institute of Physics, Mathematics and Information Technology*

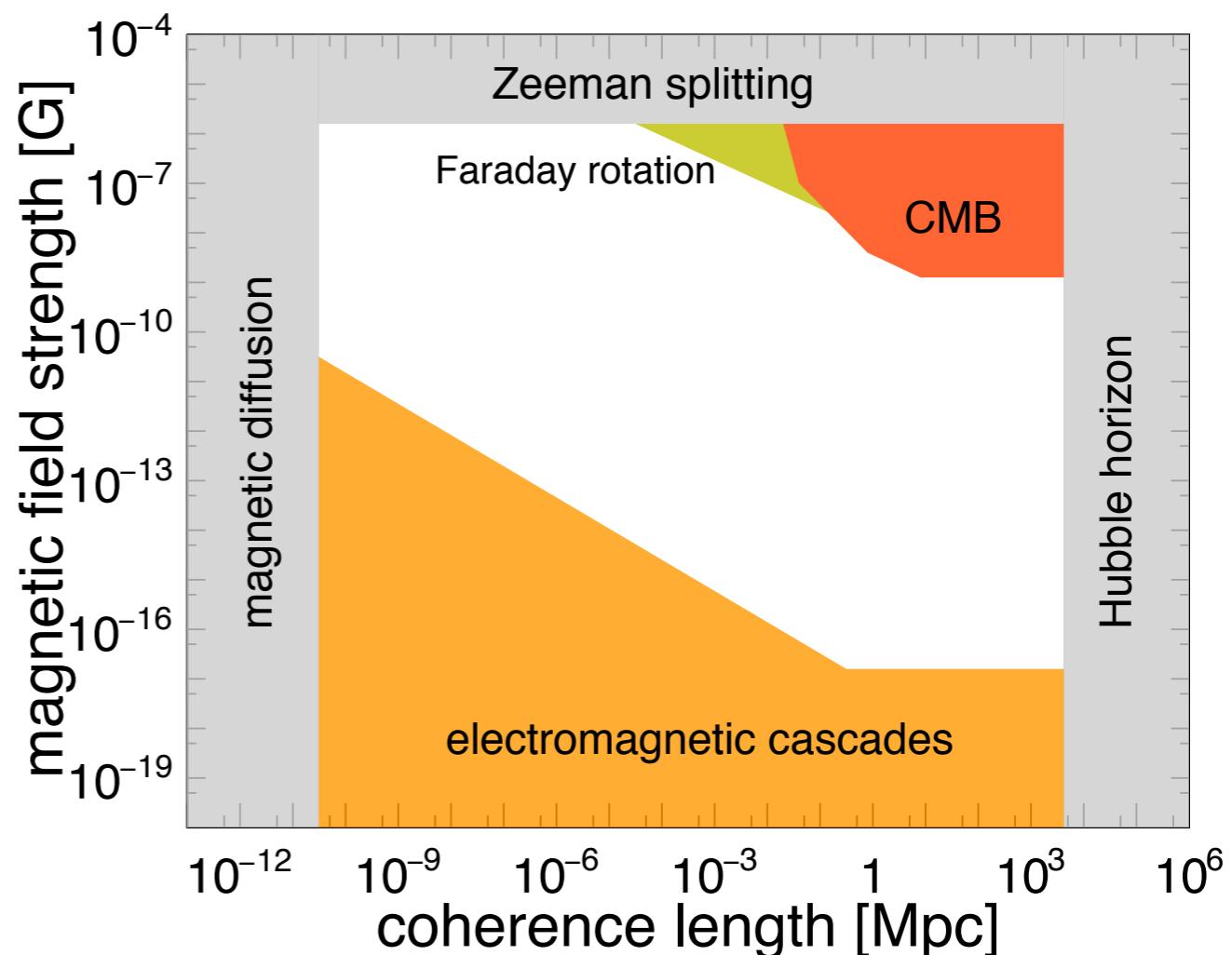
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International Cosmic Ray Conference (ICRC2017)  
Busan, South Korea  
July/2017

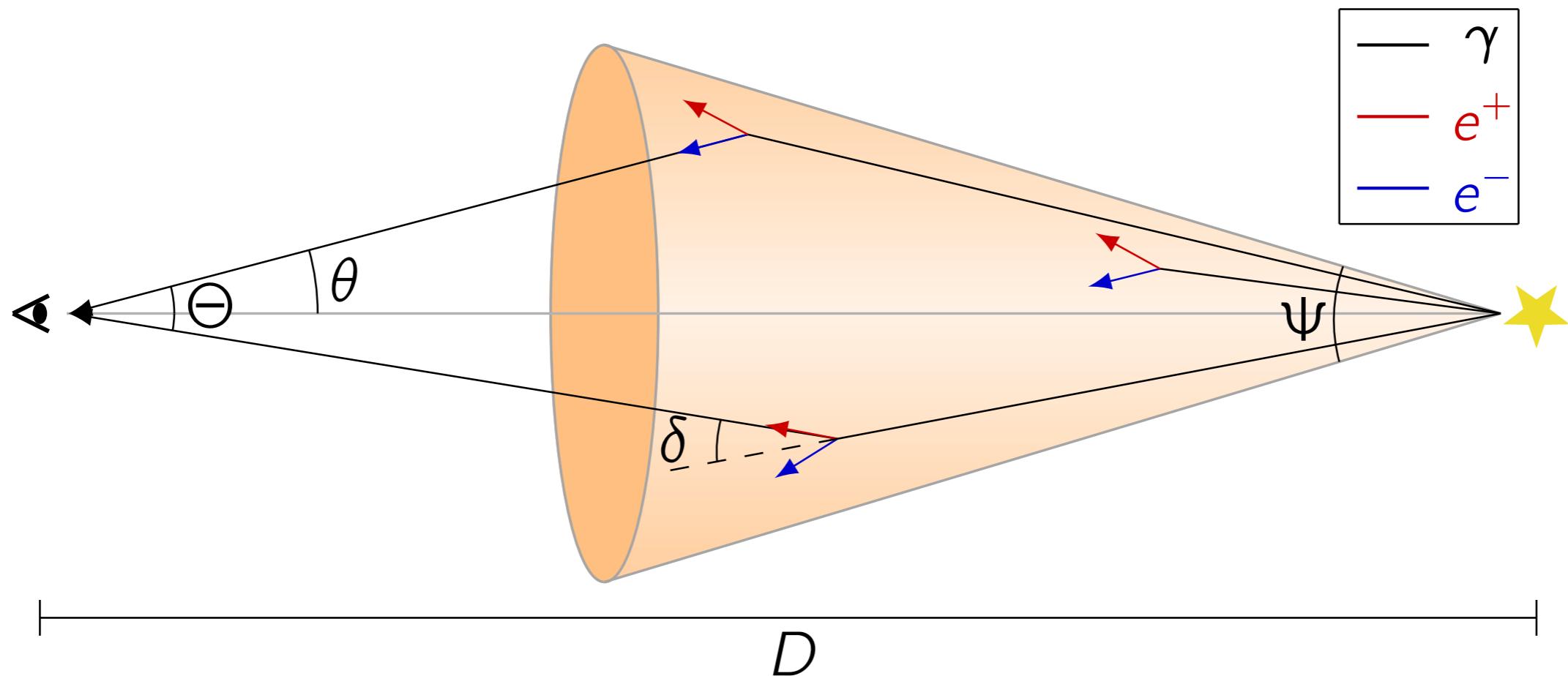
# intergalactic magnetic fields



- are there cosmological magnetic fields?
- how did the magnetic fields in the universe originate? astrophysical vs cosmological origin
- we have upper and lower bounds, but parameter space is still large
- upper limit from CMB:  $\sim n$  G  
[Planck Collaboration. A&A 594 (2016) A19]
- lower limit from cascades:  $\sim 10$  aG  
[Neronov & Vovk. Science 328 (2010) 72]

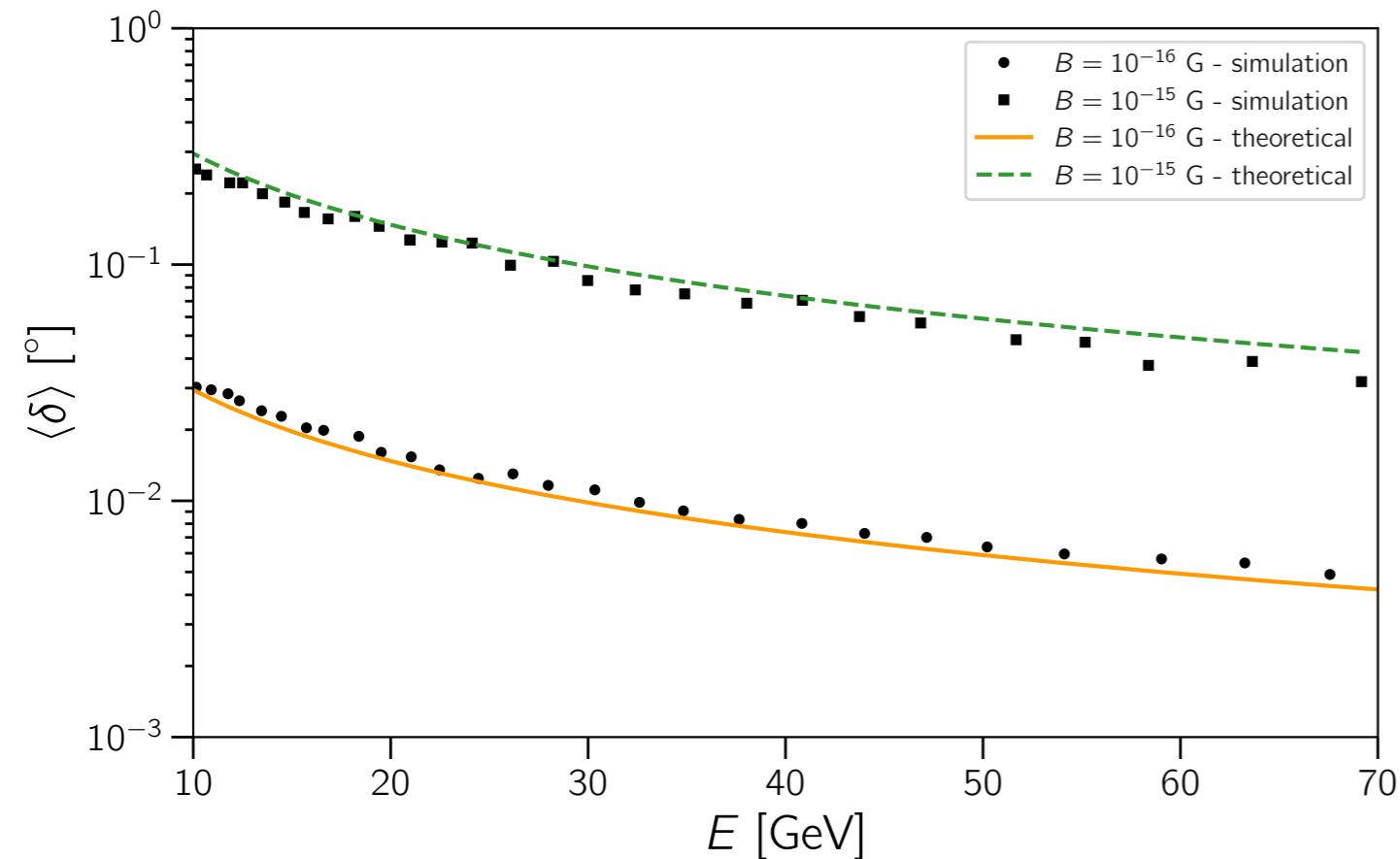


# electromagnetic cascades



- ▶ pair production generates electrons and positrons whose opening angle is proportional to the strength of the magnetic field; secondary gamma rays are produced via inverse Compton scattering
- ▶ point-like sources will appear extended for sufficiently high magnetic fields
- ▶ the charged component of the cascade is sensitive to the **strength** and **structure** of intervening magnetic fields

# code description & performance



- ▶ code adapted from CRPropa 3, with weighted sampling [*R. Alves Batista et al. JCAP 05 (2016) 038*]
- ▶ computational setup is tested by comparing with theoretical predictions
- ▶ interactions and energy losses: pair production, inverse Compton scattering, synchrotron emission, redshift losses
- ▶ stochastic magnetic fields defined on a grid
- ▶ performance:  $10^5$  initial photons, takes about 4 hours on 12 cores at 2.3 GHz (for  $B=10^{-15}$  G and  $z=0.14$ )

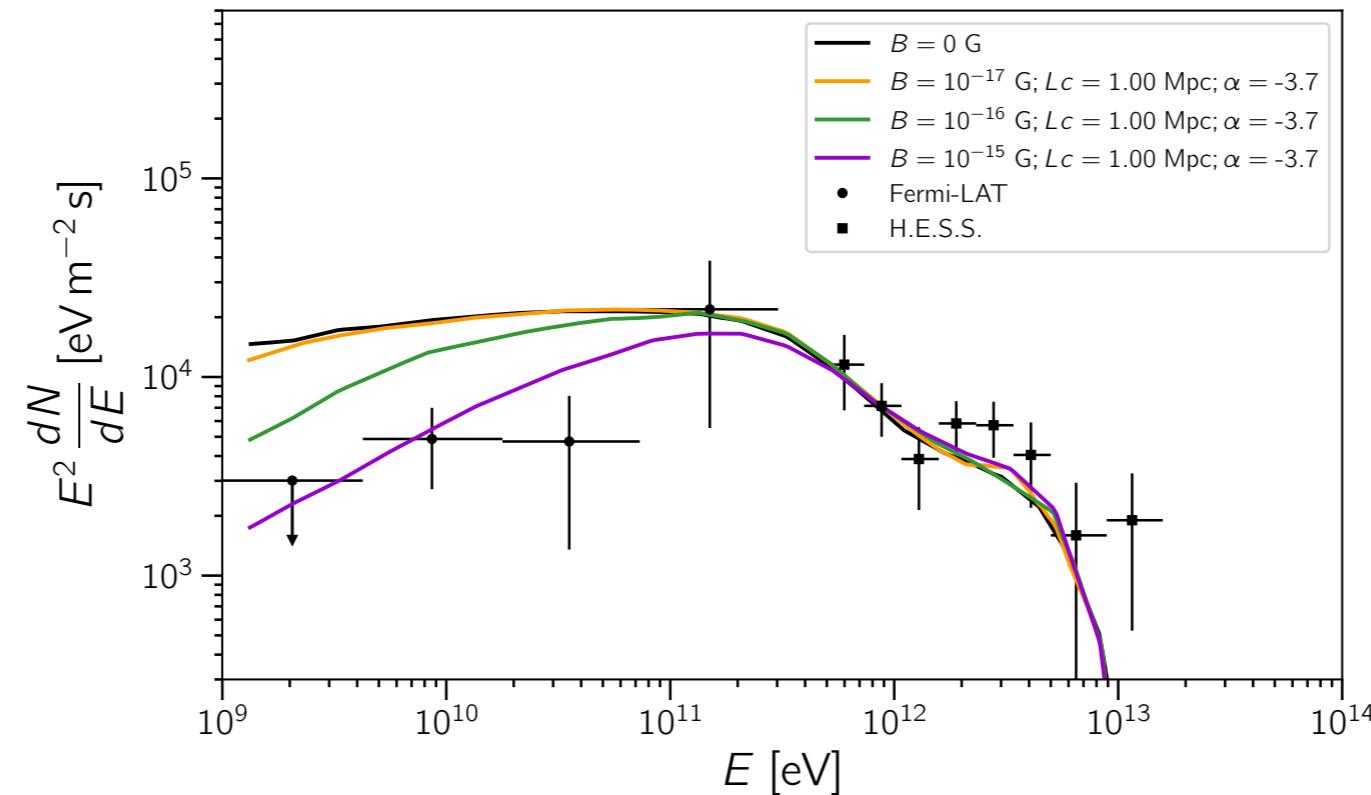
## theoretical prediction

Neronov & Semikoz. PRD 80 (2009) 123012.

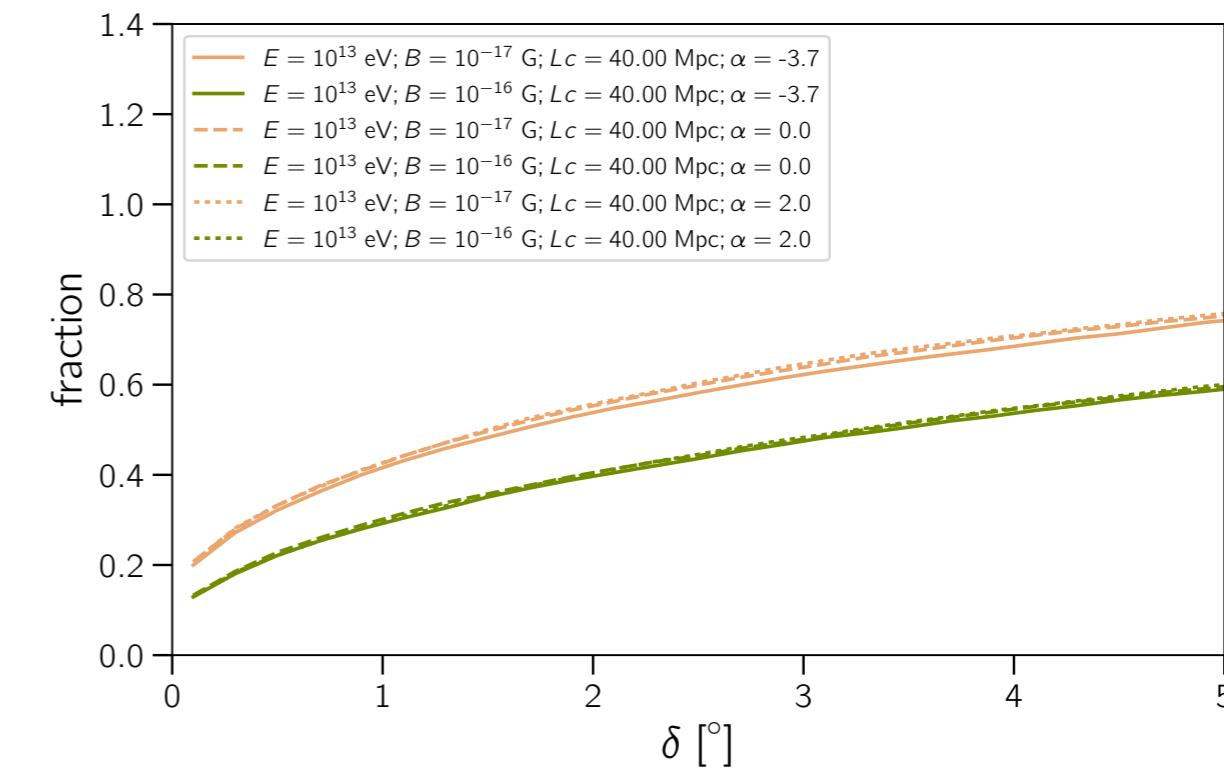
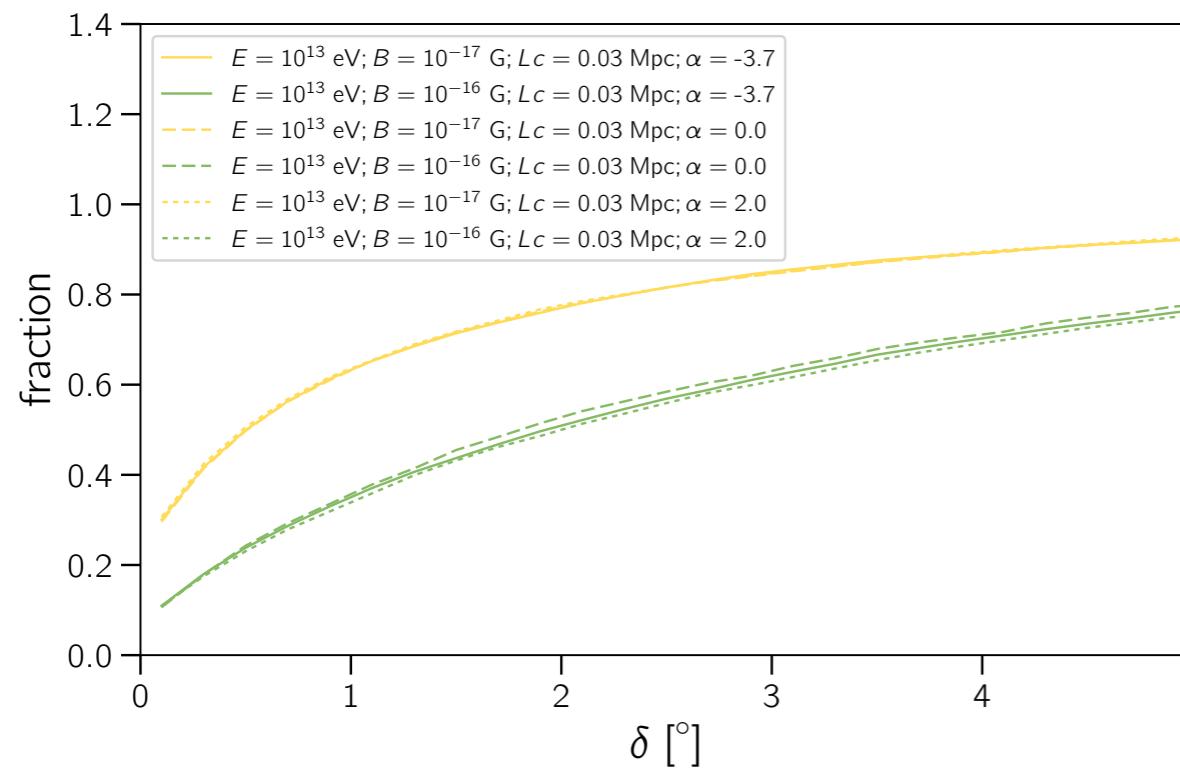
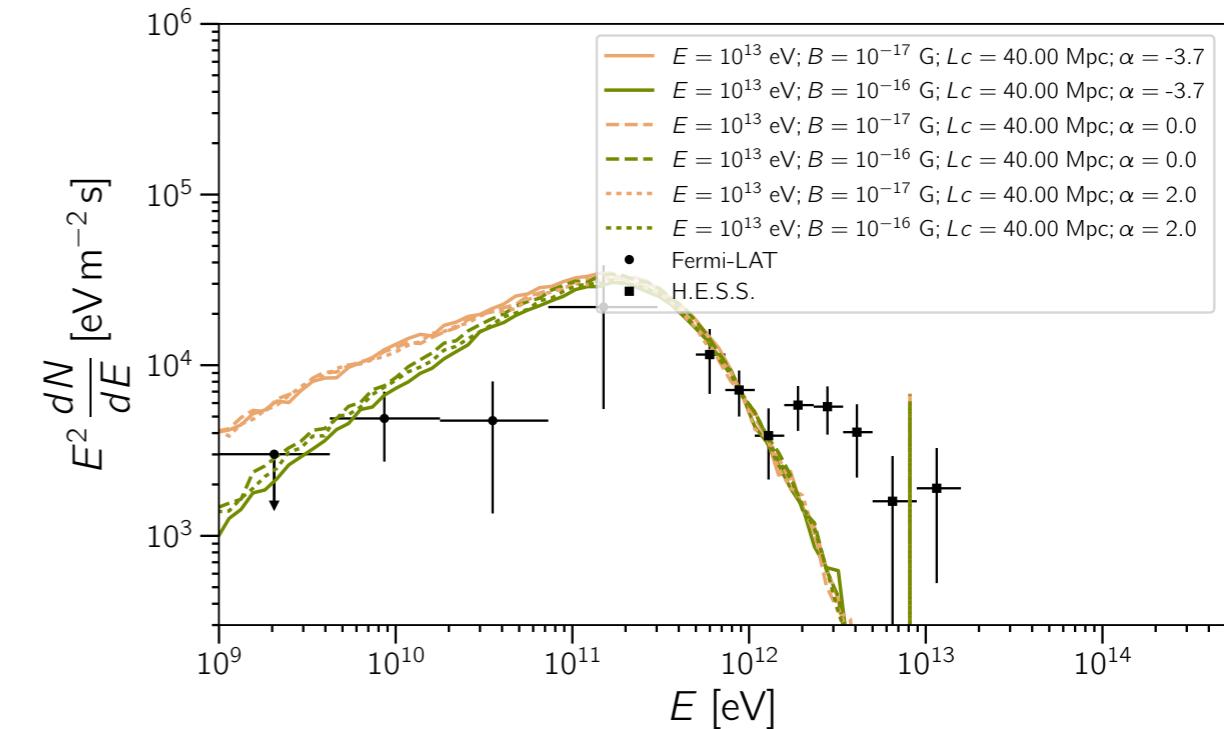
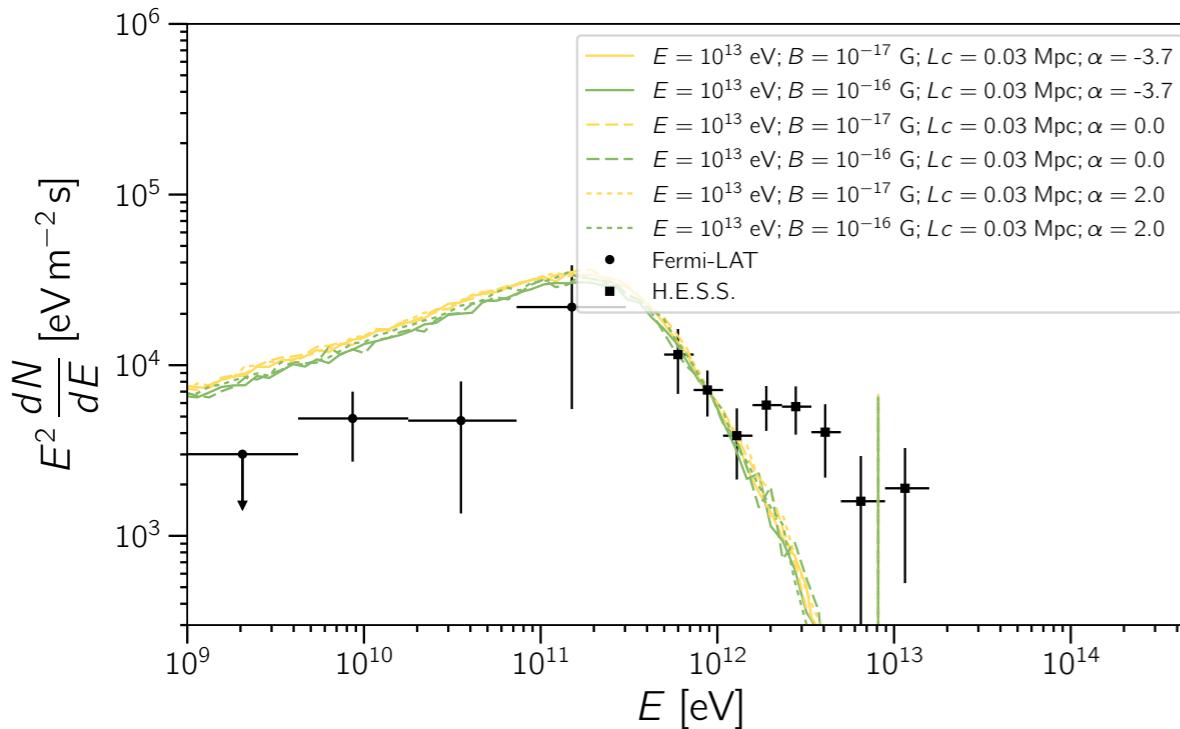
$$\theta(E_\gamma) \simeq 0.05^\circ \kappa (1 + z_s)^{-4} \left( \frac{B}{\text{fG}} \right) \left( \frac{E_\gamma}{0.1 \text{ TeV}} \right)^{-1} \left( \frac{D_s}{\text{Gpc}} \right)^{-1} \left( \frac{E_{\text{TeV}}}{10 \text{ TeV}} \right)^{-1}$$

# simulations - part I

- ▶ goal: to investigate the effects of properties of magnetic fields (strength, power spectrum, ...) on gamma-ray observables (spectrum, arrival directions)
- ▶ source: IES 0229+200 ( $z = 0.14$ ,  $D \sim 600$  Mpc)
- ▶ monochromatic injection spectrum
- ▶ magnetic power spectrum of stochastic fields:  $B(k) \propto k^\alpha$ , where  $\alpha = -11/3$  for Kolmogorov spectrum, and  $\alpha = 2$  for Batchelor spectrum
- ▶ magnetic fields induce a suppression in the flux for sub-TeV energies (see figure)
- ▶ we consider haloes in the source's frame, with coordinate system  $(\alpha, \beta)$

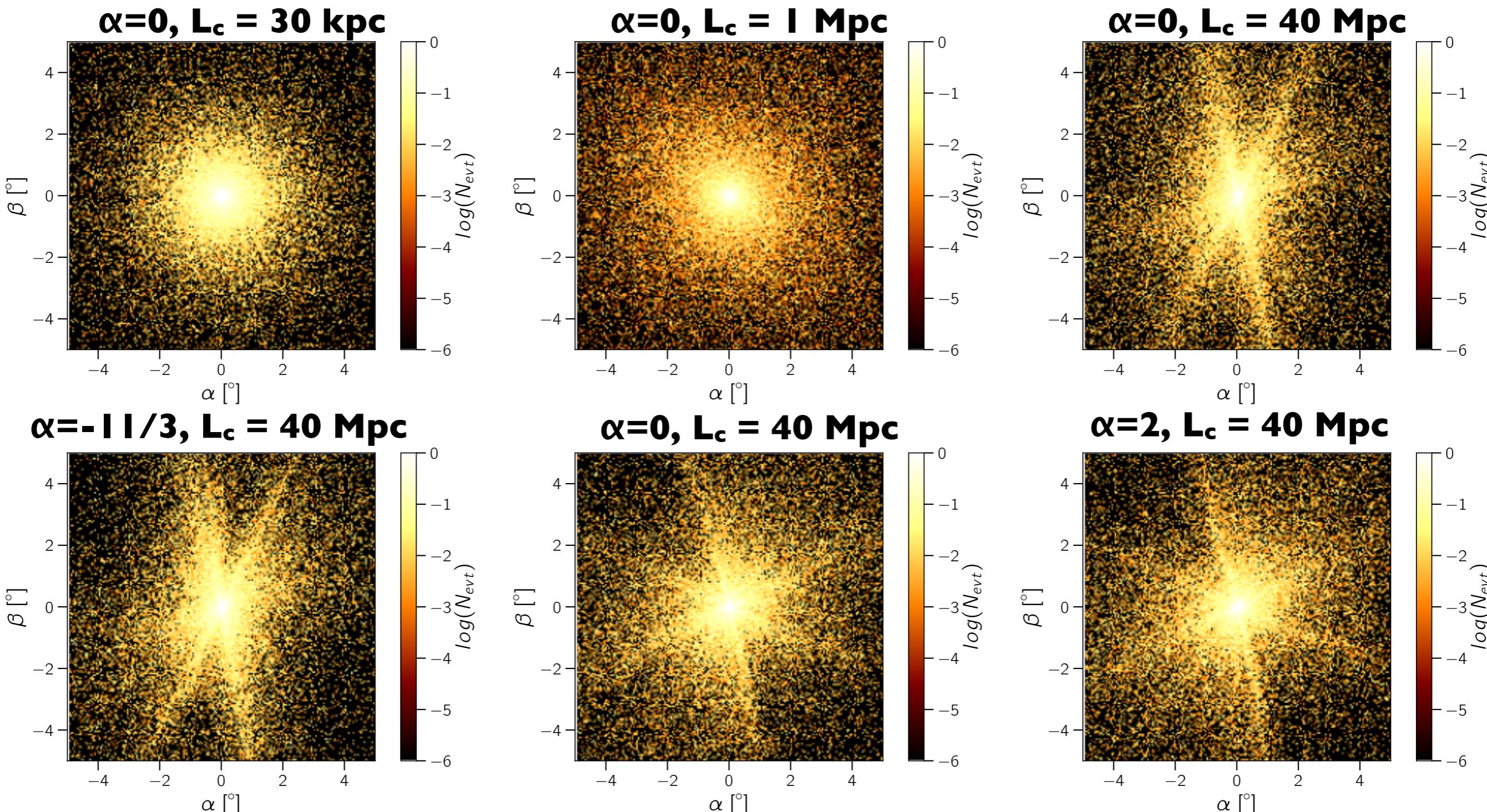


# effects on the spectrum and arrival directions



► effects of the magnetic power spectrum on the gamma-ray spectrum and halo sizes are small

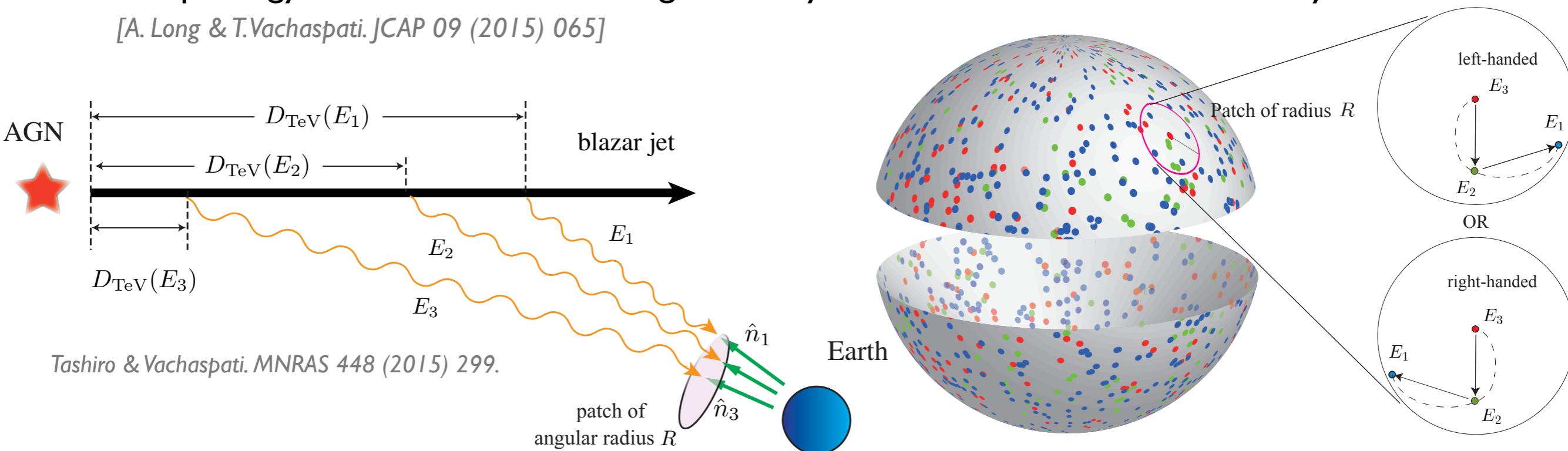
# effects on the spectrum and arrival directions



- coherence length determines the shape of the halo
- magnetic power spectrum changes the appearance of the halo

# helical intergalactic magnetic fields

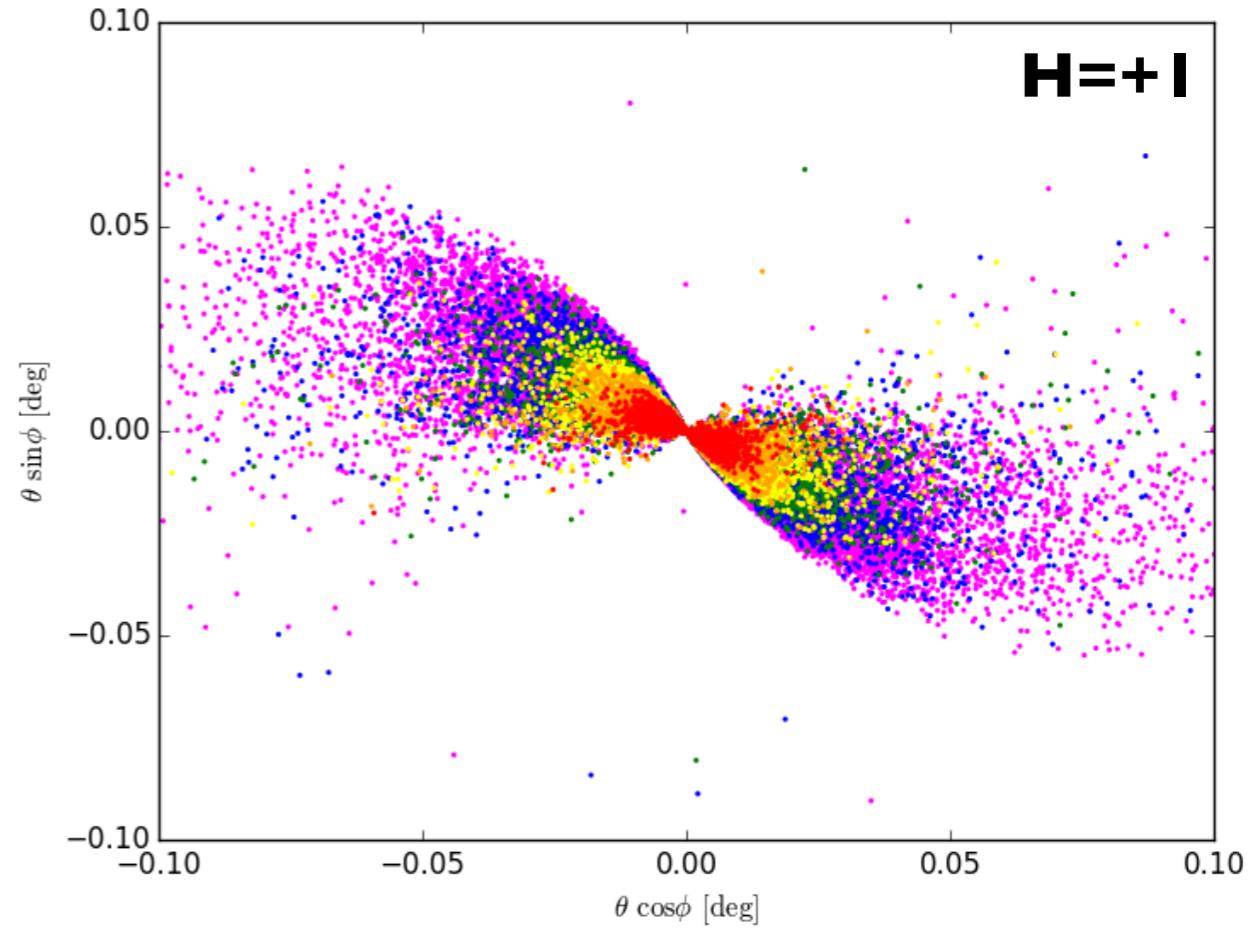
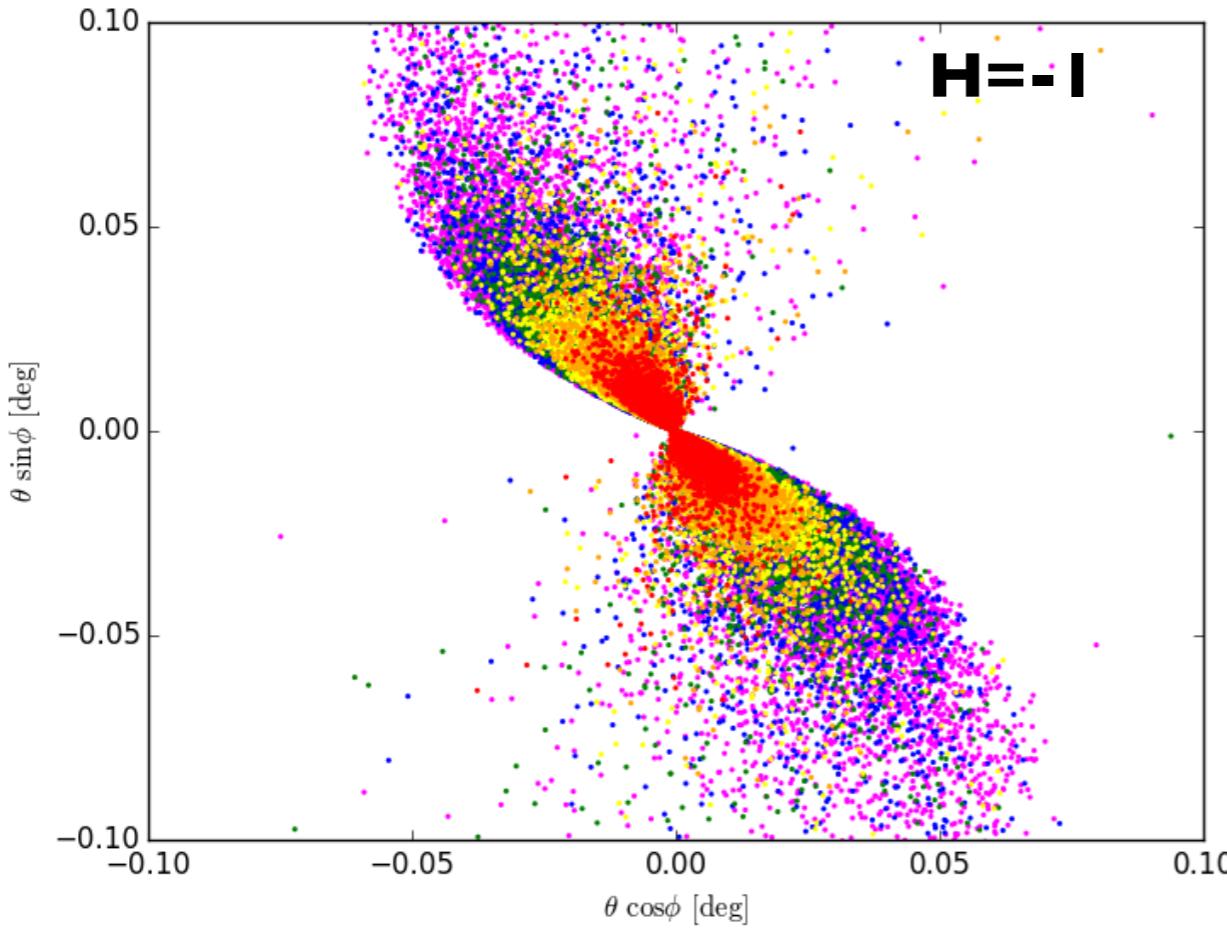
- ▶ helicity  $\mathcal{H} = \frac{1}{V} \int_V d^3r \vec{A} \cdot \vec{B}$
- ▶ helical magnetic fields may be related to baryogenesis via e.g. bubble collisions and linked Z-string creation
- ▶ advantage of helical magnetic fields: they are less likely to dissipate
- ▶ helicity is odd under CP transformation
- ▶ parity-odd correlators give  $B \sim 10 \text{ fG}$  [H.Tashiro & T.Vachaspati. MNRAS 448 (2015) 299]
- ▶ morphology of arrival directions of gamma-rays can be used to infer the helicity of IGMFs  
[A. Long & T.Vachaspati. JCAP 09 (2015) 065]



Chen et al. MNRAS Lett. 445 (2014) L41.

# simulations - part II

RAB,A. Saveliev, G. Sigl, T. Vachaspati. PRD 94 (2016) 083005. arXiv:1607.00320



## setup of simulations

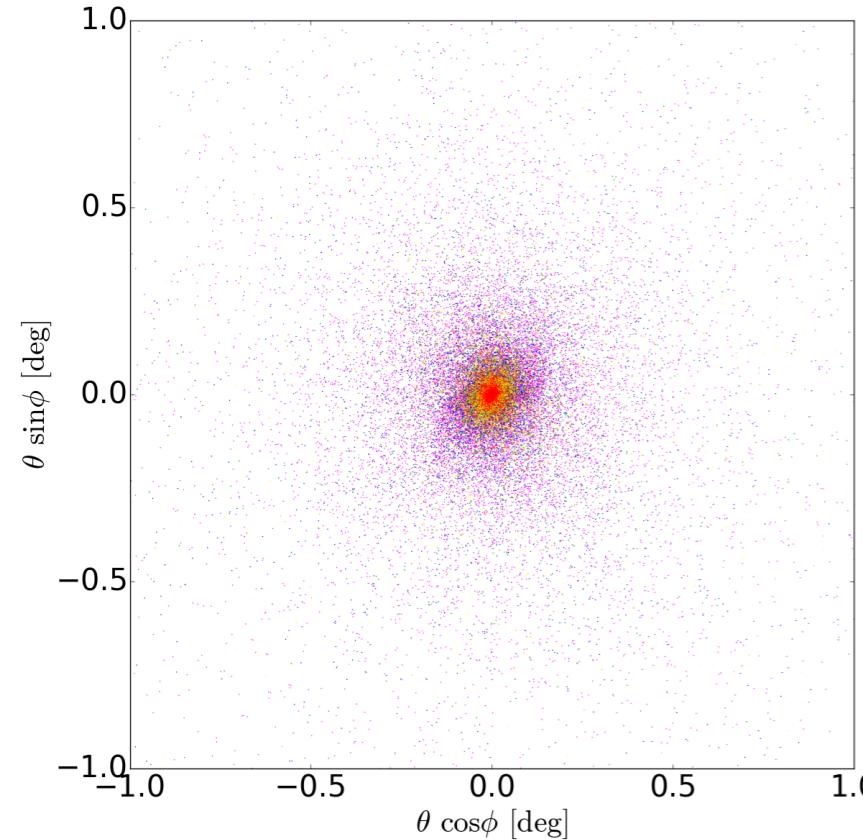
- ▶ source distance: 1 Gpc
- ▶ energy: 10 TeV
- ▶ magnetic field: Bachelor spectrum
- ▶ coherence length: 225 Mpc

magenta:  $E=5-10$  GeV  
blue:  $E=10-15$  GeV  
green:  $E=15-20$  GeV  
yellow:  $E=20-30$  GeV  
orange:  $E=30-50$  GeV  
red:  $E=50-100$  GeV

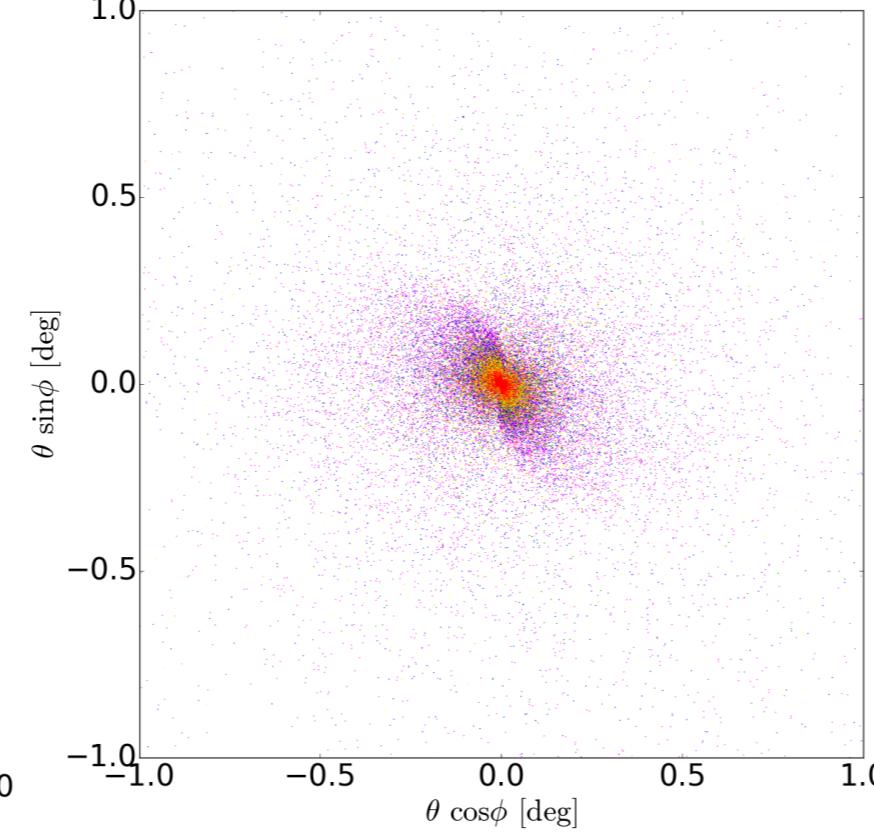
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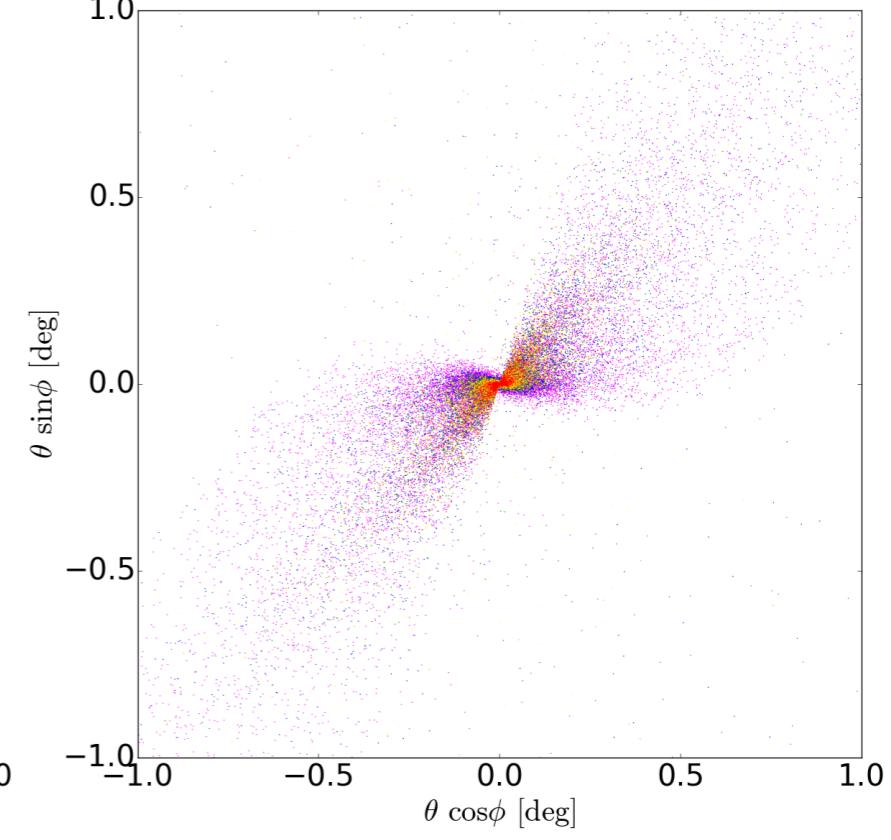
**Lc = 50 Mpc**



**Lc = 150 Mpc**



**Lc = 250 Mpc**



## setup of simulations:

- ▶ source distance: 1 Gpc
- ▶ energy: 10 TeV
- ▶ magnetic field: Bachelor spectrum

magenta: E=5-10 GeV  
blue: E=10-15 GeV  
green: E=15-20 GeV  
yellow: E=20-30 GeV  
orange: E=30-50 GeV  
red: E=50-100 GeV

# conclusions and outlook

- ▶ efficient 3D code for propagation of electromagnetic cascades with weighted sampling for optimal performance
- ▶ lower bound on intergalactic magnetic fields from cascades favours a primordial origin, providing us with a direct window to the early universe
- ▶ pair haloes allow measurements of IGMFs (strength and structure)
- ▶ halo shape depends on the coherence length;  
its size depends on the strength of the field
- ▶ the halo shape is also affected by the structure (power spectrum) of the magnetic field → constraints on magnetogenesis?
- ▶ CTA offers good prospects for observing haloes (see poster by Florian Gaté et al. on behalf of the CTA Collaboration)