# Deriving Constraints on Intergalactic Magnetic Fields

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- Cosmological scenario: Strong seed magnetic fields are generated in the Early Universe, e.g. at a phase transition (QCD, electroweak) [Sigl et al., 1997] or during inflation [Turner and Widrow, 1988], and some of the initial energy content is transfered to larger scales.

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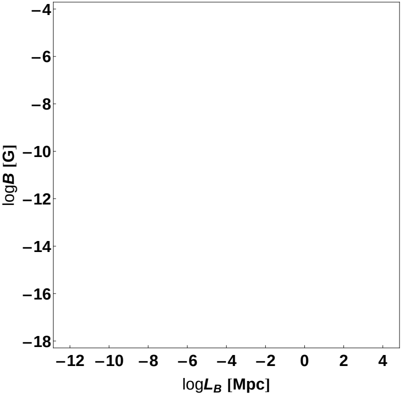
The latter are the so-called Primordial Magnetic Fields and will be (mostly) focused on in the following.

# IGMF - Standard Constraints [Alves Batista and Saveliev, 2021]



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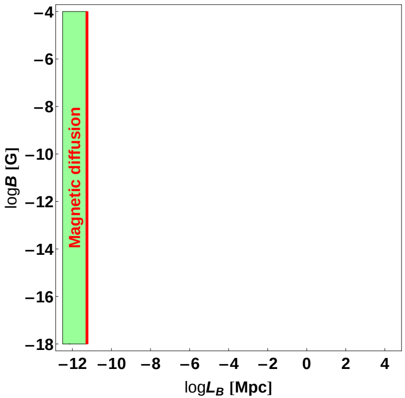


Resistive decay removes short correlation lengths

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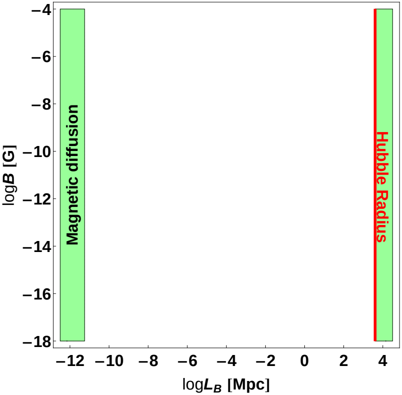


$L_B$ cannot be larger than the Hubble Radius

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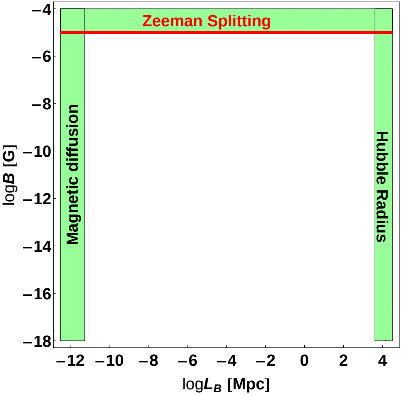


IGMF cannot be stronger than galactic magnetic fields

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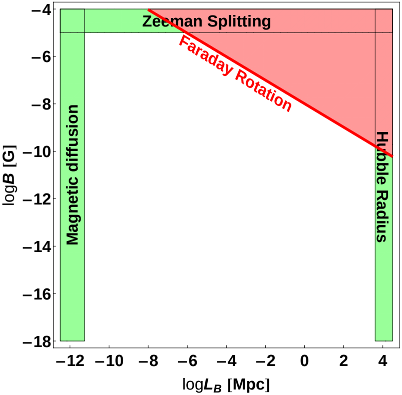


Non-observation of intergalactic FR for radio emisson from Quasars

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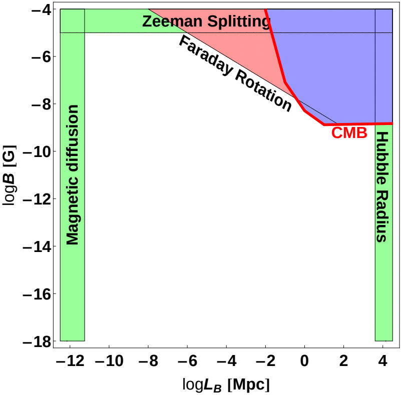


Non-observation of large scale angular anisotropies of the CMB

# IGMF Limits from CMB

There are several previous limits on IGMF from CMB [Jedamzik and Saveliev, 2019]:

| Principal Effect | Upper Limit |
|---|---|
| spectral distortions | $30 - 40\,\mathrm{nG}$ |
| anisotropic expansion | $3.4\,\mathrm{nG}$ |
| CMB temp. anisotropies: | |
| – due to magnetic modes | $1.2 - 6.4\,\mathrm{nG}$ |
| – due to plasma heating | $0.63 - 3\,\mathrm{nG}$ |
| CMB polarization | $1.2\,\mathrm{nG}$ |
| non-Gaussianity bispectrum | $2 - 9\,\mathrm{nG}$ |
| non-Gaussianity trispectrum | $0.7\,\mathrm{nG}$ |
| non-Gaussianity trispectrum with inflationary curvature mode | $0.05\,\mathrm{nG}$ |
| reionization | $0.36\,\mathrm{nG}$ |

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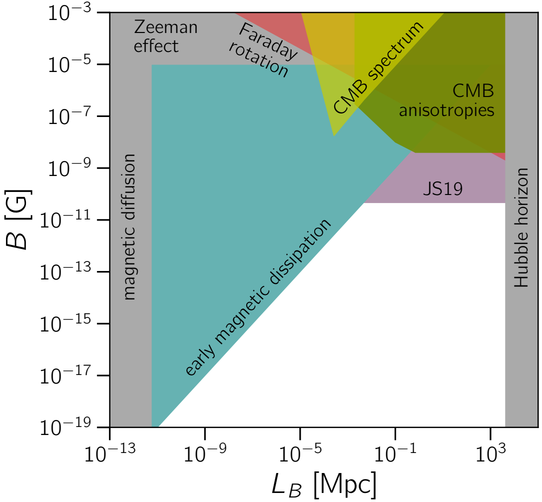
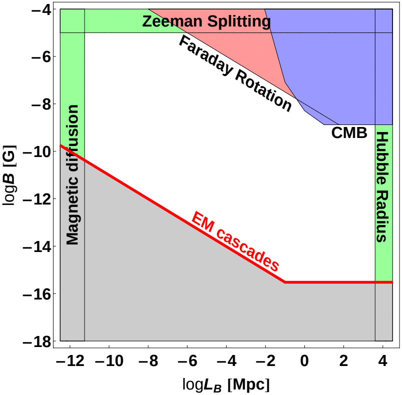
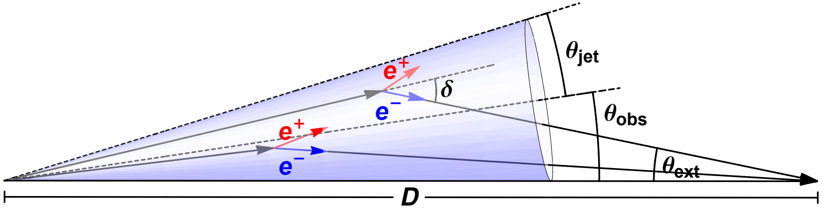


# IGMF – Lower Bound on $B$? [Alves Batista and Saveliev, 2021]



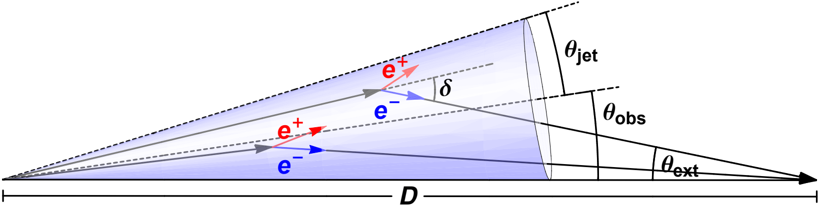

Lower bound on $B$ from gamma ray observations?

# IGMF – Lower Bound on $B$?




Gamma rays emitted from a blazar develop an electromagnetic cascade due to interactions with the Extragalactic Background Light (EBL) via Pair Production and Inverse Compton (IC) scattering. The interaction of this cascade with the IGMF results in several observational features.

# IGMF – Lower Bound on $B$?




Point-like sources appear extensive [Dolag et al., 2009], [Neronov et al., 2010]

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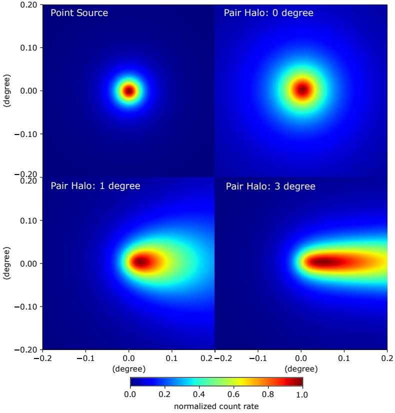


Appearance of a point-like source at the given $\theta_{\text{obs}}$ for magnetic field $B = 10^{-15}$ G [Chen et al., 2018]

- Point-like sources appear extensive [Dolag et al., 2009], [Neronov et al., 2010]

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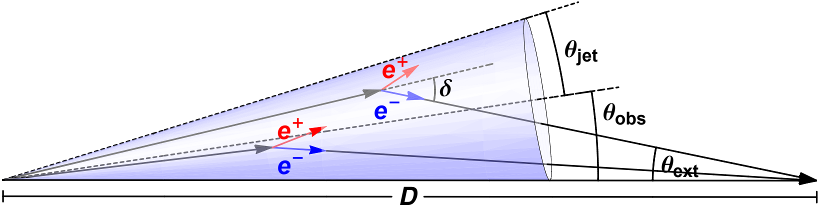


Time-delayed echos of primary gamma rays [Plaga, 1994], [Murase et al., 2008]

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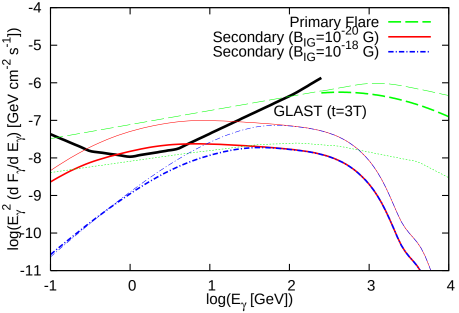


Spectrum of the time-delayed spectrum of the 2005 flare of Mrk 501 for different values of the IGMF after 0.5 days (thin) and 1.5 days (thick) [Murase et al., 2008]

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# Limits on IGMF using Multimessengers

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- A flaring object (flare duration $\Delta t_{\mathrm{flare}}$) which emits gamma rays and neutrinos simultaniously provides a measure for the time delay $\Delta t_{\mathrm{IGMF}}$ of the sec. gamma rays due to IGMF

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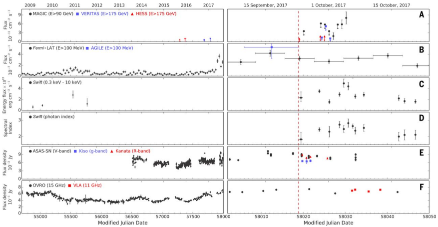
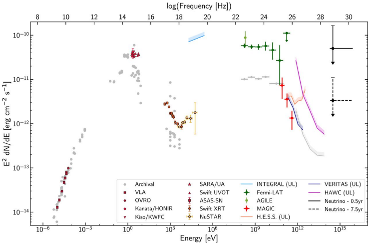
- A flaring object (flare duration $\Delta t_{\rm flare}$) which emits gamma rays and neutrinos simultaniously provides a measure for the time delay $\Delta t_{\rm IGMF}$ of the sec. gamma rays due to IGMF
- Of particular interest is the IceCube neutrino event IC-170922A [IceCube Collaboration, 2018] which is associated with the 2017 flare of the blazar TXS 0506+056 in the electromagn. spectrum [IceCube Collaboration et al., 2018]



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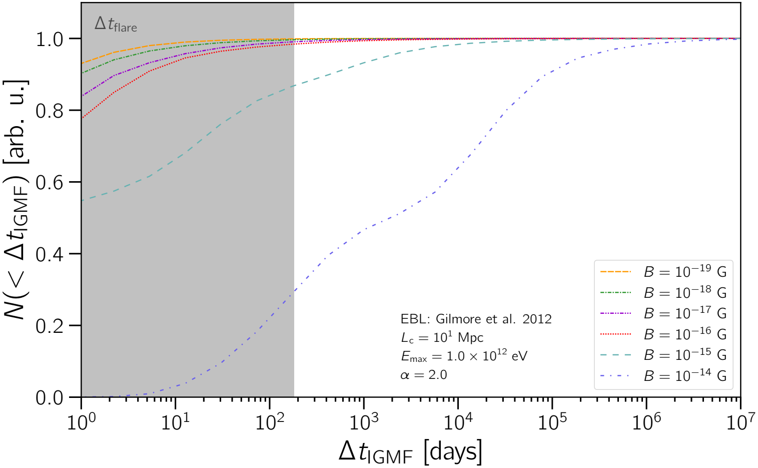


Cumulative distribution of time delays of gamma rays due to IGMF ($\Delta t_{\rm IGMF}$) for TXS 0506+056. The grey shaded region indicate the period of enhanced activity of the object ($\Delta t_{\rm flare}$)

# Limits on IGMF using Multimessengers

- We simulate the emitted flux as

$$\frac{dN}{dE} = J_0 \begin{cases} E^{-\alpha_\mathrm{l}} \exp\left(-\frac{E}{E_{\mathrm{max,l}}}\right) & \text{"low" (non-flaring) state}\,, \\ \eta E^{-\alpha_\mathrm{h}} \exp\left(-\frac{E}{E_{\mathrm{max,h}}}\right) & \text{"high" (flaring) state}\,, \end{cases}$$

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- We use four different EBL models for the simulation of the propagation of the electromagnetic cascade with the CRPropa code [Alves Batista et al., 2016a] and consider large ranges of $B$, $L_{\mathrm{c}}$, $E_{\mathrm{max}}$ and $\alpha$

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- In order to analyze the data, we first determine the best-fit spectral parameters of the low state (i.e. $E_\mathrm{max,l}$ and $\alpha_\mathrm{l}$), and then scan over the remaining parameters ($\eta$, $E_\mathrm{max,h}$, $\alpha_\mathrm{h}$, $B$, $L_\mathrm{c}$)

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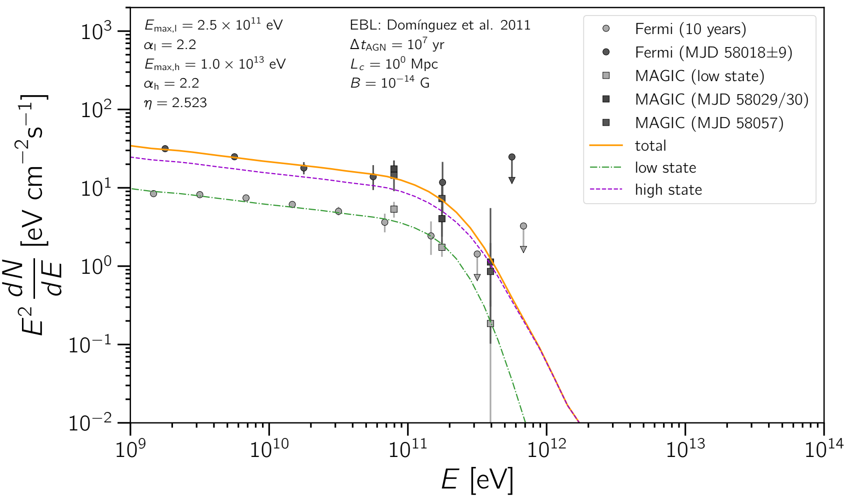

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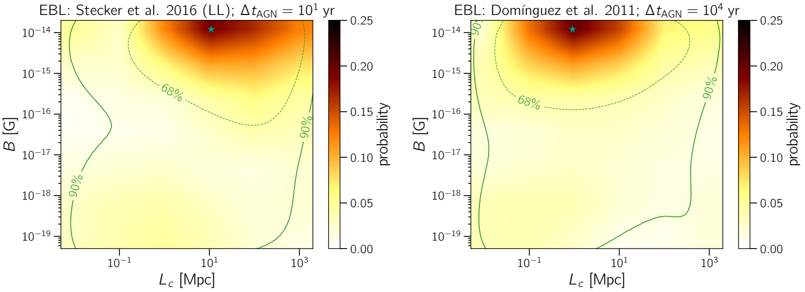


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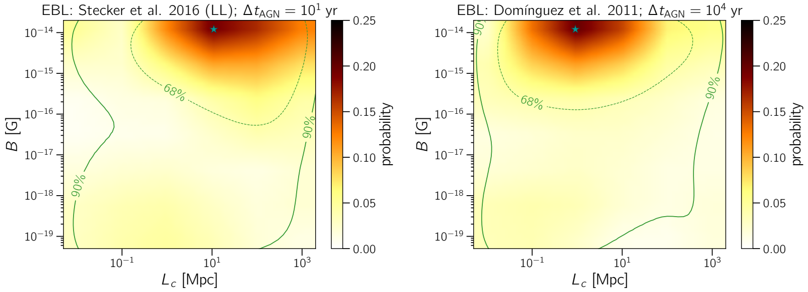


- For two of the EBL models we could reject the $B = 0$ hypothesis
- For these two models it is possible to constrain the magnetic field strength $B$ *and* the correlation length $L_c$ [Alves Batista and Saveliev, 2020]

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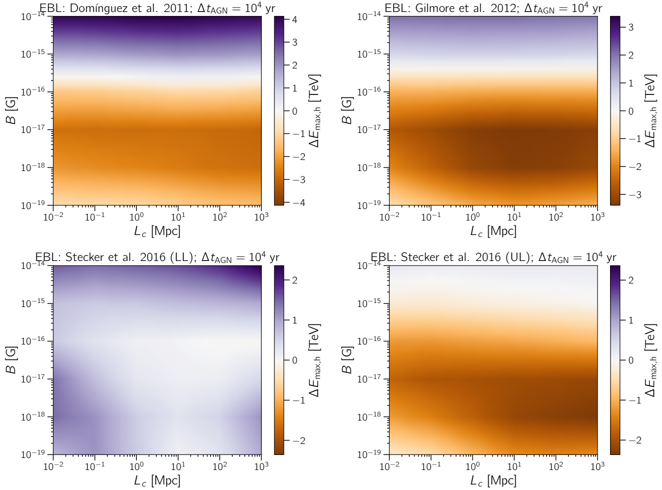
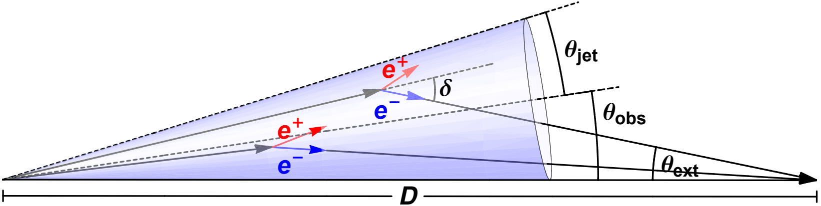



- IGMF have a significant impact on the determination of the intrinsic spectral properties of the source [Saveliev and Alves Batista, 2021]

# IGMF – Lower Bound on $B$?




Suppression of observed photon flux in the GeV region
[d'Avezac et al., 2007], [Neronov and Vovk, 2010],
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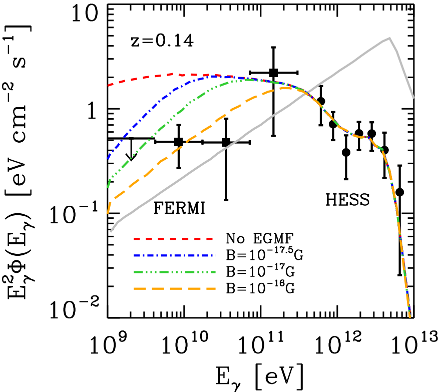


Predicted gamma ray flux of 1ES0229+200 for different magnetic fields with data points of Fermi LAT and HESS [Saveliev et al., 2013a]

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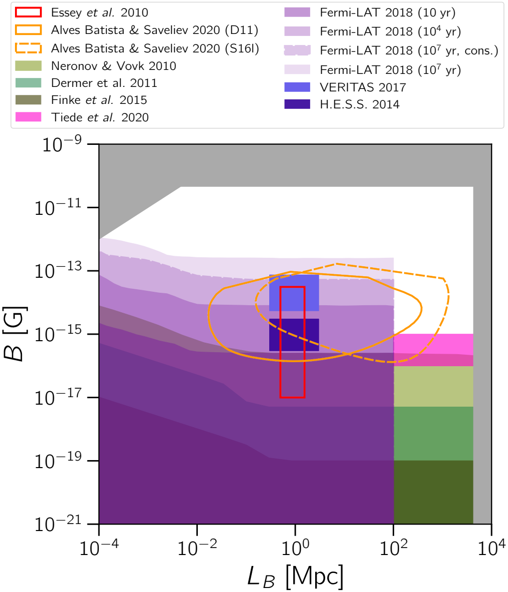
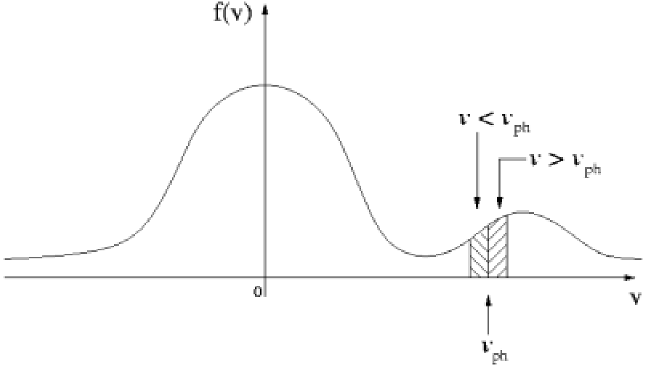


# Relativistic Pair Beams and Plasma Instabilities

However, these results have been criticized: Two-stream-like instabilities might arise [Broderick et al., 2012], [Schlickeiser et al., 2012]



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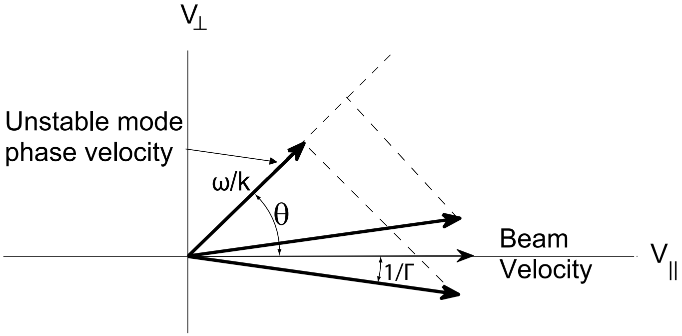
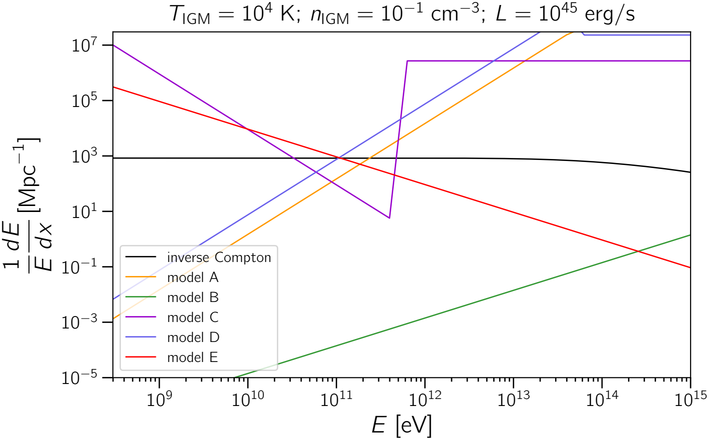



[Nakar et al., 2011]

# Relativistic Pair Beams and Plasma Instabilities

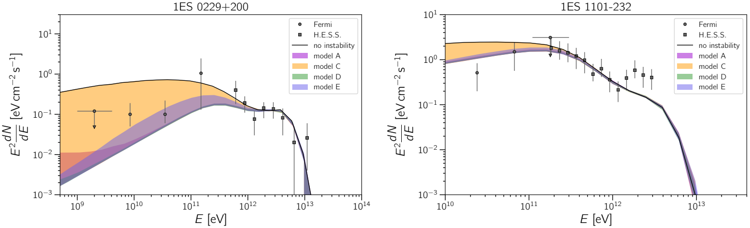
The energy loss time due to these instabilities can be smaller than the mean free path of Inverse Compton Scattering




[Alves Batista et al., 2019b]

# Relativistic Pair Beams and Plasma Instabilities

- Therefore the electromagnetic cascade rapidly loses energy which is a possible reason for the GeV flux suppression as shown by actual MC simulations
  [Alves Batista et al., 2019b]



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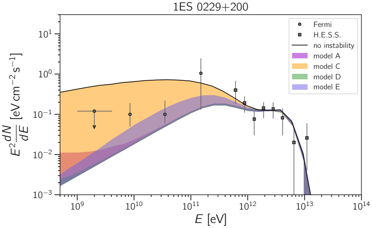


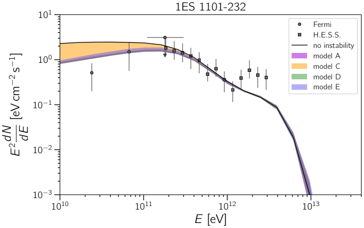


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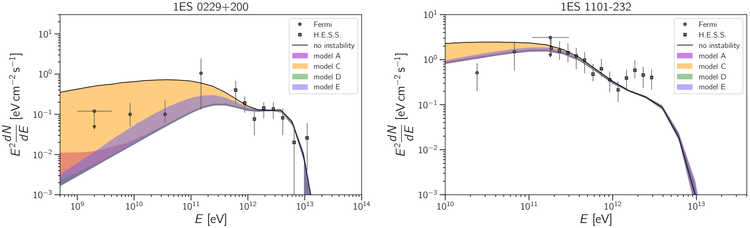


- In the future this might be used to distinguish between the two scenarios for different sources
- However, there is an ongoing debate whether the assumptions are justified (e.g. inhomogeneities)

# Magnetic Helicity

- The magnetic helicity $H$ is defined as $H = \int_V \mathbf{A} \cdot \mathbf{B} \, \mathrm{dV}$, where $\mathbf{A}$ is the vector potential

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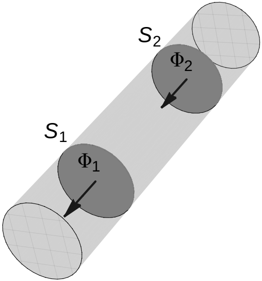
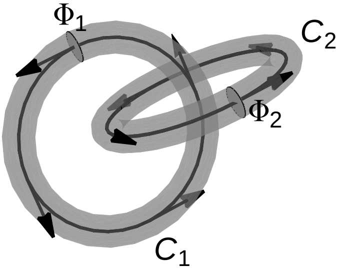
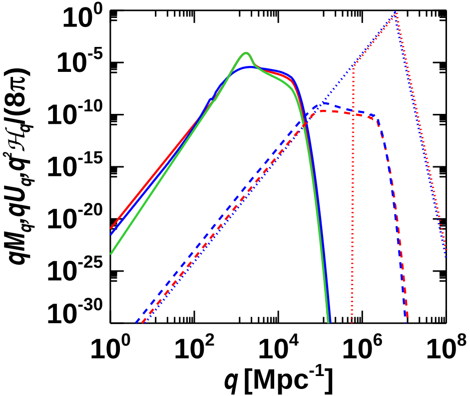
- Next to $B$ and $L_B$ it is an important quantity to characterize a magnetic field as it describes its topology
- It is connected to the linkage numbers of magnetic field lines (infinitisemal magnetic flux tubes)



# Magnetic Helicity




- Important since it is a conserved quantity and hence influences the time evolution of IGMF [Saveliev et al., 2013b]

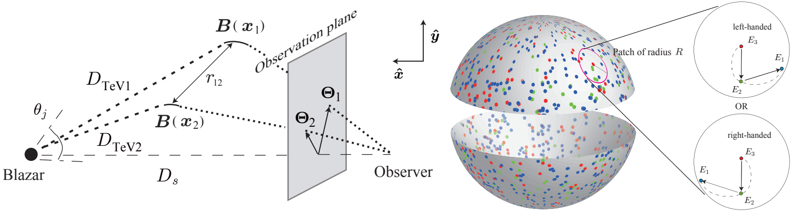
# Measurement of Primordial Magnetic Helicity

It has been shown that [Tashiro and Vachaspati, 2013]

$$G(E_1, E_2) = \left\langle (\Theta_1 \times \Theta_2) \cdot \frac{\mathbf{x}}{|\mathbf{x}|} \right\rangle \propto \frac{1}{2}\mathcal{H}(r_{12})r_{12}$$

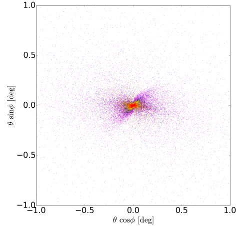
for a known blazar position; otherwise (with $E_3 > E_2 > E_1$)

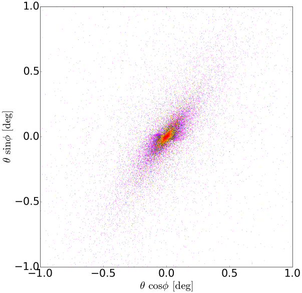
$$G(E_1, E_2, E_3) = \left\langle [(\Theta_1 - \Theta_3) \times (\Theta_2 - \Theta_3)] \cdot \frac{\mathbf{x_3}}{|\mathbf{x_3}|} \right\rangle \propto \frac{1}{2}\mathcal{H}(r_{12})r_{12}$$

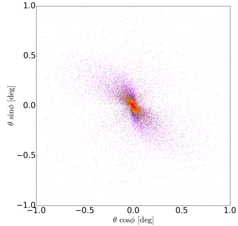



[Tashiro et al., 2014]

# Helicity Analysis – Sky Maps [Alves Batista et al., 2016b]




Sky maps for maximally negative (top left) and positive helicity (bottom left) and zero helicity (top), $B = 10^{-15}\,\mathrm{G}$, $L_B \simeq 120\,\mathrm{Mpc}$.

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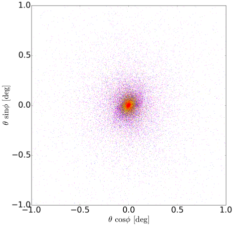
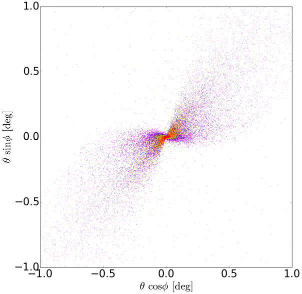
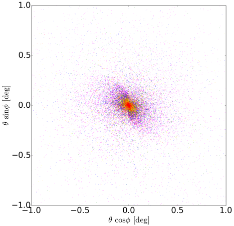


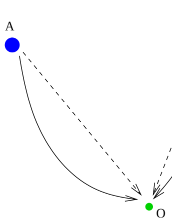




Sky maps for positive helicity with $L_B = 50\,\mathrm{Mpc}$ (top left), $L_B = 150\,\mathrm{Mpc}$ (bottom left) and $L_B = 250\,\mathrm{Mpc}$ (right). The influence of helicity can be seen better with increasing correlation length $L_B$ of the magnetic field.

# IGMF and UHECR

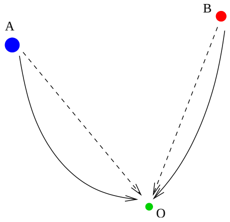
- In a magnetic field UHECR travel on curved trajectories



# IGMF and UHECR

- In a magnetic field UHECR travel on curved trajectories
- Possibility for UHECR astronomy?

Contradicting answers in early works:



# IGMF and UHECR

- In a magnetic field UHECR travel on curved trajectories
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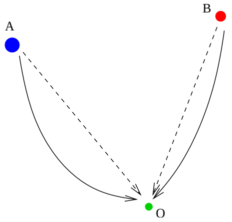


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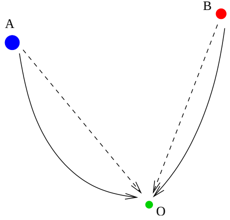


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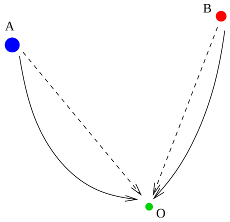


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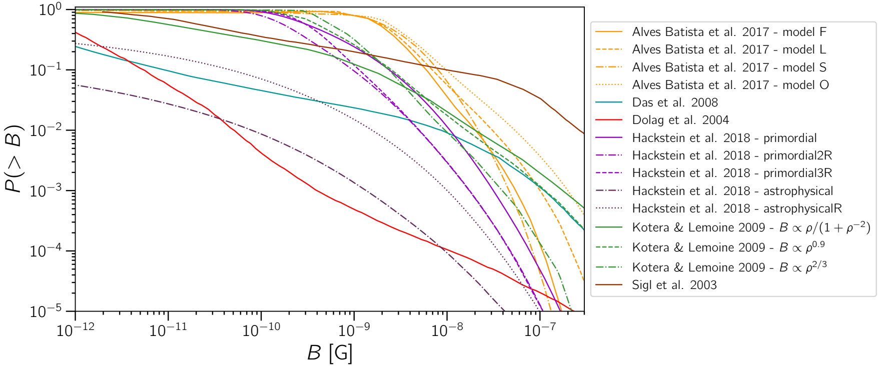


[Alves Batista et al., 2019a]

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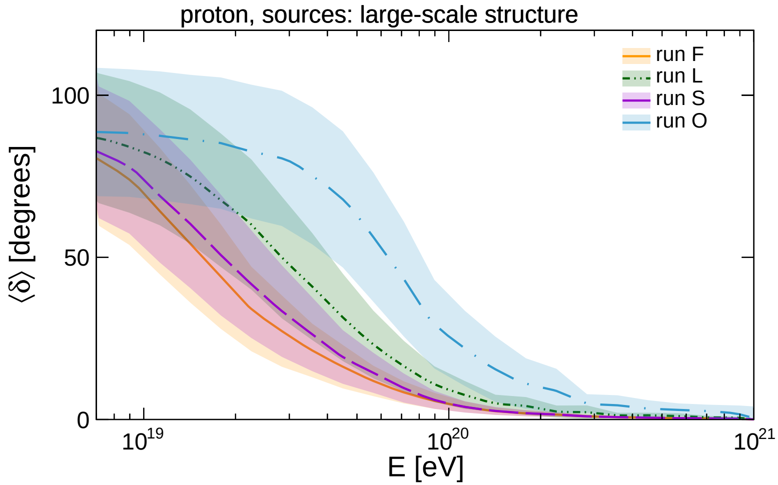


[Alves Batista et al., 2017]

# Measurement of IGMF Helicity Using UHECR

Calculation of correlation between source positions
[Kahniashvili and Vachaspati, 2006]

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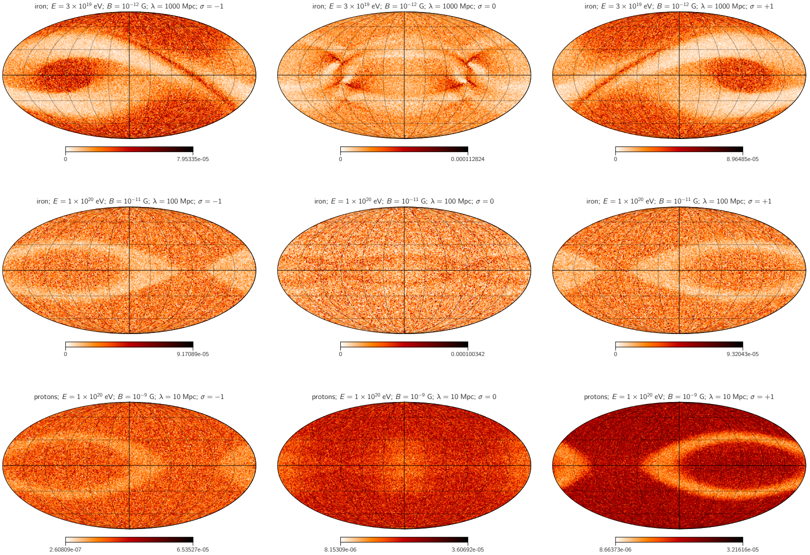

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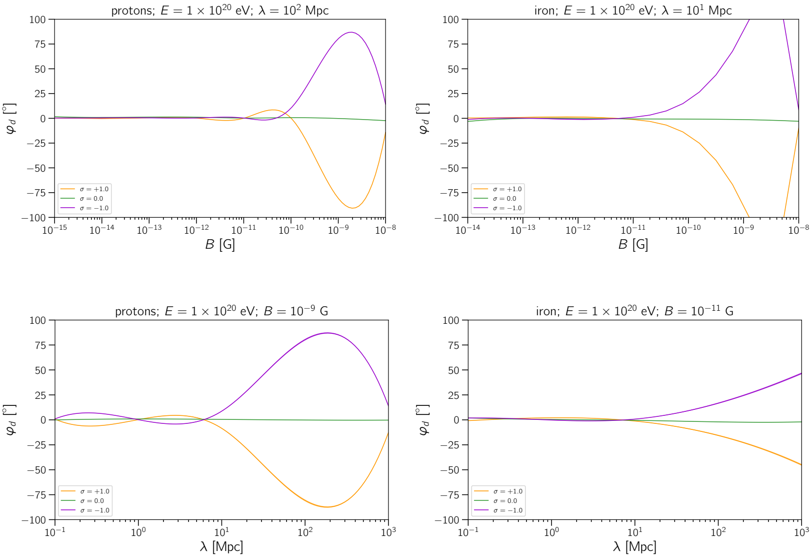

# Conclusions and Outlook

- Actual 3D simulations of gamma-ray propagation have shown that, apart from the field strength, also a statement considering the IGMF correlation length and helicity may be made

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- Actual 3D simulations of gamma-ray propagation have shown that, apart from the field strength, also a statement considering the IGMF correlation length and helicity may be made
- Another possibility is to use UHECR, which, however, is more challenging
- In the future: Extension to more realistic scenarios and combination of the methods, e.g. by using secondaries of UHECR, more realistic magnetic field configurations and plasma instability models, determination of the spectral index of the IGMF distribution, ...

Alves Batista, R., Dundovic, A., Erdmann, M., Kampert, K.-H., Kuempel, D., Müller, G., Sigl, G., van Vliet, A., Walz, D., and Winchen, T. (2016a).
CRPropa 3 - A Public Astrophysical Simulation Framework for Propagating Extraterrestrial Ultra-High Energy Particles.
*J. Cosmol. Astropart. Phys.*, 1605(05):038.

Alves Batista, R. et al. (2019a).
Open Questions in Cosmic-Ray Research at Ultrahigh Energies.
*Front. Astron. Space Sci.*, 6:23.

Alves Batista, R. and Saveliev, A. (2019).
On the Measurement of the Helicity of Intergalactic Magnetic Fields Using Ultra-High-Energy Cosmic Rays.
*J. Cosmol. Astropart. Phys.*, 2019(03):011.

Alves Batista, R. and Saveliev, A. (2020).
Multimessenger Constraints on Intergalactic Magnetic Fields from the Flare of TXS 0506+056.

*Astrophys. J. Lett.*, 902(1):L11.

Alves Batista, R. and Saveliev, A. (2021).
The Gamma-Ray Window to Intergalactic Magnetism.
*Universe*, 7(7):223.

Alves Batista, R., Saveliev, A., and de Gouveia Dal Pino, E. M. (2019b).
The Impact of Plasma Instabilities on the Spectra of TeV Blazars.
*Mon. Not. R. Astron. Soc.*, 489(3):3836–3849.

Alves Batista, R., Saveliev, A., Sigl, G., and Vachaspati, T. (2016b).
Probing Intergalactic Magnetic Fields with Simulations of Electromagnetic Cascades.
*Phys. Rev. D*, 94:083005.

Alves Batista, R., Shin, M.-S., Devriendt, J., Semikoz, D., and Sigl, G. (2017).

Implications of Strong Intergalactic Magnetic Fields for Ultrahigh-Energy Cosmic-Ray Astronomy.
*Phys. Rev. D*, 96(2):023010.

Biermann, L. (1950).
Über den Ursprung der Magnetfelder auf Sternen und im interstellaren Raum (mit einem Anhang von A. Schlüter).
*Zeitschrift f. Naturforschung A*, 5:65.

Broderick, A. E., Chang, P., and Pfrommer, C. (2012).
The Cosmological Impact of Luminous TeV Blazars. I. Implications of Plasma Instabilities for the Intergalactic Magnetic Field and Extragalactic Gamma-Ray Background.
*Astrophys. J.*, 752(1):22.

Chen, W., Errando, M., Buckley, J. H., and Ferrer, F. (2018).
Novel Search for TeV-Initiated Pair Cascades in the Intergalactic Medium.
*arXiv*, 1811.05774.

d'Avezac, P., Dubus, G., and Giebels, B. (2007).

Cascading on Extragalactic Background Light.
*Astron. Astrophys.*, 469:857–860.

Dolag, K., Grasso, D., Springel, V., and Tkachev, I. (2005).
Constrained Simulations of the Magnetic Field in the Local Universe and the Propagation of UHECRs.
*J. Cosmol. Astropart. Phys.*, 0501:009.

Dolag, K., Kachelrieß, M., Ostapchenko, S., and Tomàs, R. (2009).
Blazar Halos as Probe for Extragalactic Magnetic Fields and Maximal Acceleration Energy.
*Astrophys. J.*, 703(1):1078.

IceCube Collaboration (2018).
Neutrino emission from the direction of the blazar txs 0506+056 prior to the icecube-170922a alert.
*Science*, 361(6398):147–151.

IceCube Collaboration, Fermi-LAT Collaboration, MAGIC Collaboration, AGILE Team, ASAS-SN Team, HAWC

Collaboration, H.E.S.S. Collaboration, Abdalla, H., INTEGRAL Team, Kiso and Subaru Observing Teams, Kapteyn Team, Liverpool Telescope Team, Swift/NuSTAR Team, VERITAS Collaboration, and VLA/B Team (2018).
Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A.
*Science*, 361(6398):eaat1378.

Jedamzik, K. and Saveliev, A. (2019).
Stringent Limit on Primordial Magnetic Fields from the Cosmic Microwave Backround Radiation.
*Phys. Rev. Lett.*, 123(2):021301.

Kahniashvili, T. and Vachaspati, T. (2006).
On the Detection of Magnetic Helicity.
*Phys. Rev. D*, 73:063507.

Murase, K., Takahashi, K., Inoue, S., Ichiki, K., and Nagataki, S. (2008).

Probing Intergalactic Magnetic Fields in the GLAST Era through Pair Echo Emission from TeV Blazars.
*Astrophys. J. Lett.*, 686(2):L67.

Nakar, E., Bret, A., and Milosavjevic, M. (2011).
Two-Stream-Like Instability in Dilute Hot Relativistic Beams and Astrophysical Relativistic Shocks.
*Astrophys. J.*, 738:93.

Neronov, A., Semikoz, D., Kachelrieß, M., Ostapchenko, S., and Elyiv, E. (2010).
Degree-Scale GeV "Jets" from Active and Dead TeV Blazars.
*Astrophys. J. Lett.*, 719(2):L130.

Neronov, A. and Semikoz, D. V. (2009).
Sensitivity of $\gamma$-ray Telescopes for Detection of Magnetic Fields in the Intergalactic Medium.
*Phys. Rev. D*, 80:123012.

Neronov, A. and Vovk, I. (2010).

Evidence for Strong Extragalactic Magnetic Fields from Fermi Observations of TeV Blazars.
*Science*, 328(5974):73–75.

Plaga, R. (1994).
Detecting Intergalactic Magnetic Fields Using Time Delays in Pulses of $\gamma$-Rays.
*Nature*, 374:430–432.

Saveliev, A. and Alves Batista, R. (2021).
The Intrinsic Gamma-Ray Spectrum of TXS 0506+056: Intergalactic Propagation Effects.
*Mon. Not. R. Astron. Soc.*, 500(2):2188–2195.

Saveliev, A., Evoli, C., and Sigl, G. (2013a).
The Role of Plasma Instabilities in the Propagation of Gamma-Rays from Distant Blazars.
*arXiv*, page 1311.6752.

Saveliev, A., Jedamzik, K., and Sigl, G. (2013b).

Evolution of Helical Cosmic Magnetic Fields as Predicted by Magnetohydrodynamic Closure Theory.
*Phys. Rev. D*, 87:123001.

Schlickeiser, R., Ibscher, D., and Supsar, M. (2012).
Plasma Effects on Fast Pair Beams in Cosmic Voids.
*Astrophys. J.*, 758(2):102.

Sigl, G., Miniati, F., and Enßlin, T. A. (2004).
Ultrahigh Energy Cosmic Ray Probes of Large Scale Structure and Magnetic Fields.
*Phys. Rev. D*, 70:043007.

Sigl, G., Olinto, A. V., and Jedamzik, K. (1997).
Primordial Magnetic Fields from Cosmological First Order Phase Transitions.
*Phys. Rev. D*, 55:4582–4590.

Tashiro, H., Chen, W., Ferrer, F., and Vachaspati, T. (2014).
Search for CP Violating Signature of Intergalactic Magnetic Helicity in the Gamma Ray Sky.

*Mon. Not. R. Astron. Soc.*, 445:L41–L45.

Tashiro, H. and Vachaspati, T. (2013).
Cosmological Magnetic Field Correlators from Blazar Induced Cascade.
*Phys. Rev. D*, 87:123527.

Turner, M. S. and Widrow, L. M. (1988).
Inflation-Produced, Large-Scale Magnetic Fields.
*Phys. Rev. D*, 37:2743–2754.

Vovk, I., Taylor, A. M., Semikoz, D., and Neronov, A. (2012).
Fermi/LAT Observations of 1ES 0229+200: Implications for Extragalactic Magnetic Fields and Background Light.
*Astrophys. J. Lett.*, 747(1):L14.

Zeldovich, Y. B., Ruzmaikin, D. D., and Sokoloff, D. D. (1980).
*Magnetic Fields in Astrophysics*.
McGraw-Hill.