Blazar Halo Morphology as a Probe of Helical Intergalactic Magnetic Fields

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Kavli Institute
for Cosmological Physics
at The University of Chicago

based on work with Tanmay Vachaspati (1505.07846 & JHEP)

Take-aways

(1) Message from a cosmologist: many of the most compelling models of primordial magnetogenesis predict that the IGMF is helical.

(2) If you simulate EM cascades in the presence of cosmological magnetic fields, then simulate helical B-fields!

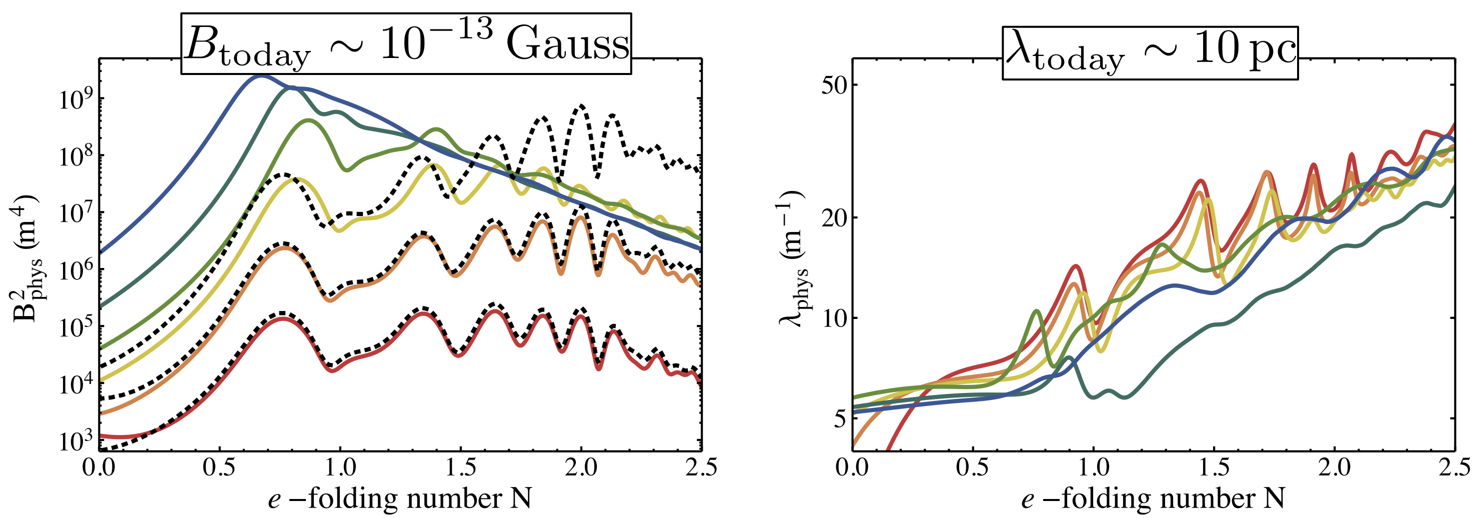
(3) If you make gamma ray measurements to probe the IGMF, then think about ways to probe for helical B-fields … (I'll tell you my idea, but yours might be better!)

Helical B-Field from the Early Universe

Generation via axion inflation

Rolling axion field during inflation leads to the growth of a helical magnetic field.

Garretson, Field, & Carroll (1992); Anber & Sorbo (2006)
Durrer, Hollenstein, Jain (2010)
Barnaby, Moxon, Namba, Peloso, Shiu, & Zhou (2012)
Fujita, Namba, Tada, Takeda, Tashiro (2015)
Anber & Sabancilar (2015)

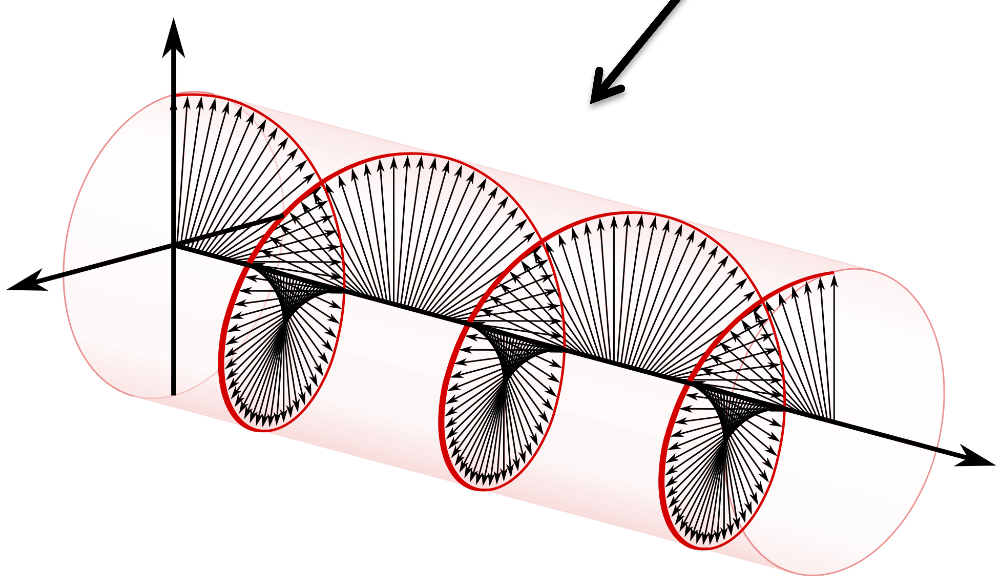


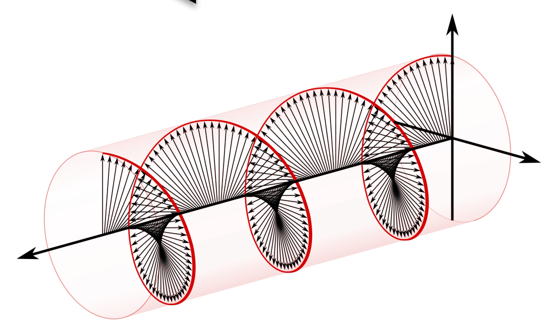
Lattice simulation of B-field growth during preheating after axion inflation
[Adshead, Gilpin, Scully, Sfakianakis (2016)]

What is a helical magnetic field?

More power in left- or right-circular polarization modes.

$$\boldsymbol{B}(\boldsymbol{x},t) = \int \frac{\mathrm{d}^3\boldsymbol{k}}{(2\pi)^3} \left[B_k^+ \, \boldsymbol{e}^+(\boldsymbol{k}) e^{-i\boldsymbol{k}\cdot\boldsymbol{x}} + B_k^- \, \boldsymbol{e}^-(\boldsymbol{k}) e^{-i\boldsymbol{k}\cdot\boldsymbol{x}} \right]$$





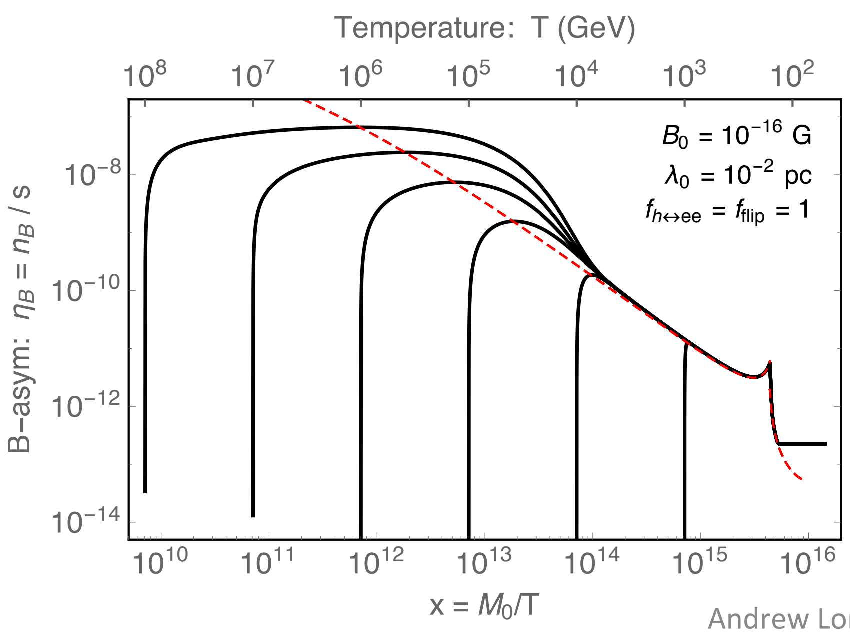
It creates the baryon-asymmetry too!

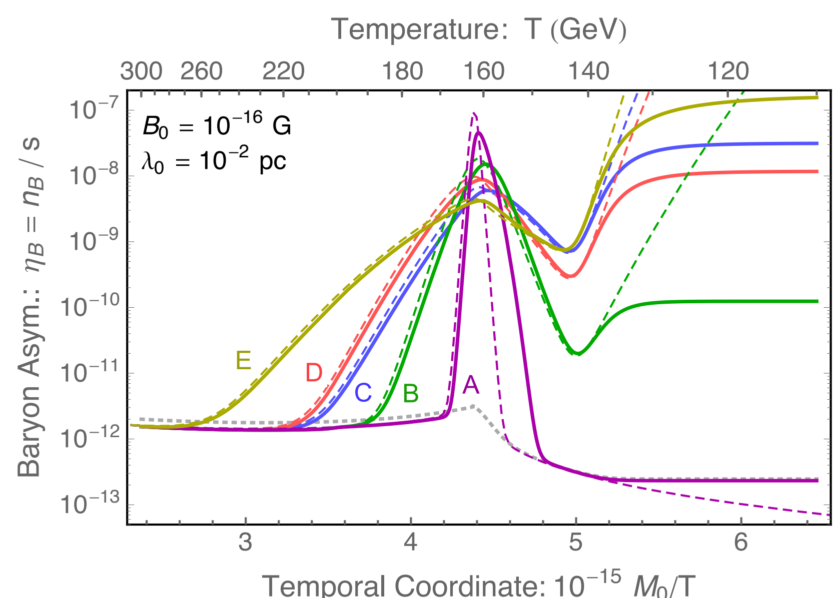
The decaying helicity of the PMF sources baryon-number through Standard Model processes.

Vachaspati (1991, 2001);
Giovannini & Shaposhnikov (1997), Giovannini (1999);
Fujita & Kamada (2016);

Kamada & AL (1606.08891 & 1610.03074)

The discovery of a helical IGMF today could be a hint toward understanding the origin of the matter / antimatter asymmetry of the universe!





How to probe the IGMF today?

Difficult to probe B-field with CMB

The B-field energy density gravitates producing scalar, vector, & tensor metric perturbations … all of the same order:

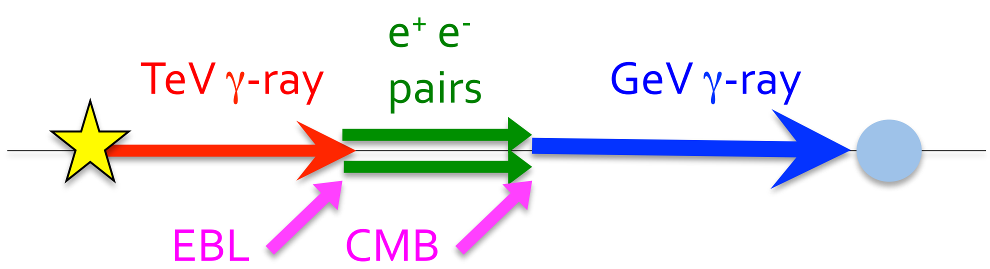
$$\ell^2 C_\ell \propto \left(\frac{\Omega_B}{\Omega_r}\right)^2 \ln^2 \frac{z_{\rm in}}{z_{\rm eq}} \simeq 10^{-11} \left(\frac{B}{10^{-9}\ {\rm Gauss}}\right)^4$$

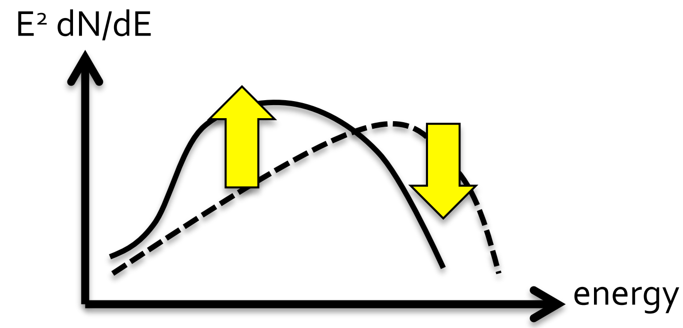
Observations of the TT power spectrum constraint B<~ nG. Limits will not improve much in future (TT is 4$^{\rm th}$ order in B).

Helicity is even harder! The B-field *helicity density* induces parity-odd TB and EB cross-correlations. These are typically set to zero as calibration.

Pogosian, Vachaspati, Winitzki (0112536)
Caprini, Durrer, & Kahniashvilli (0304556)

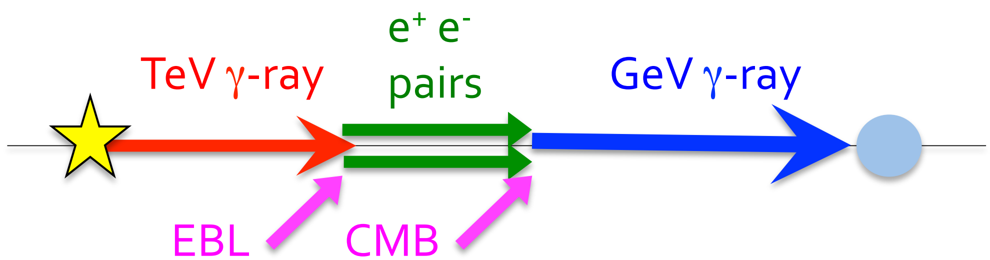
Strategy #1: Blazar Spectra

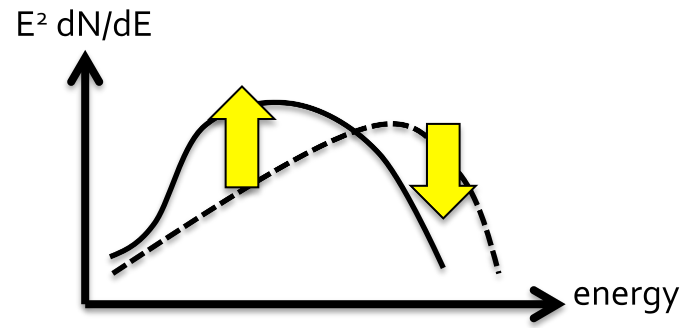




TeV spectrum suppressed,
GeV spectrum enhanced

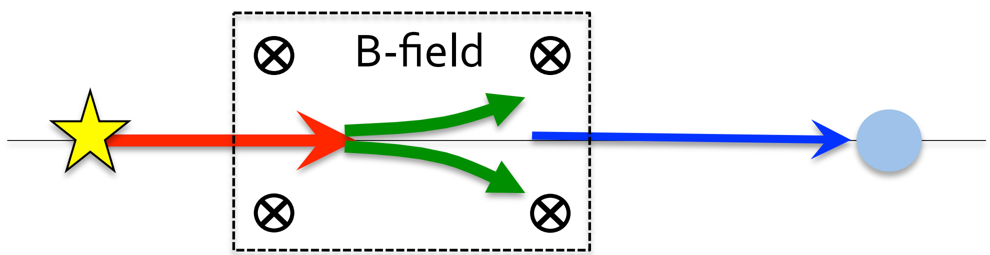
Strategy #1: Blazar Spectra

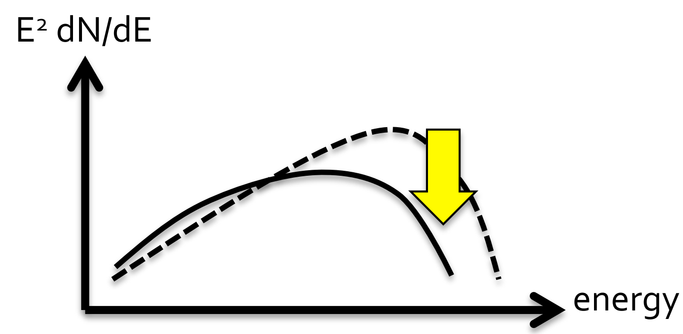




TeV spectrum suppressed,
GeV spectrum enhanced

Cascade deflected by B-field, reducing flux of cascade photons that reach Earth





no GeV enhancement

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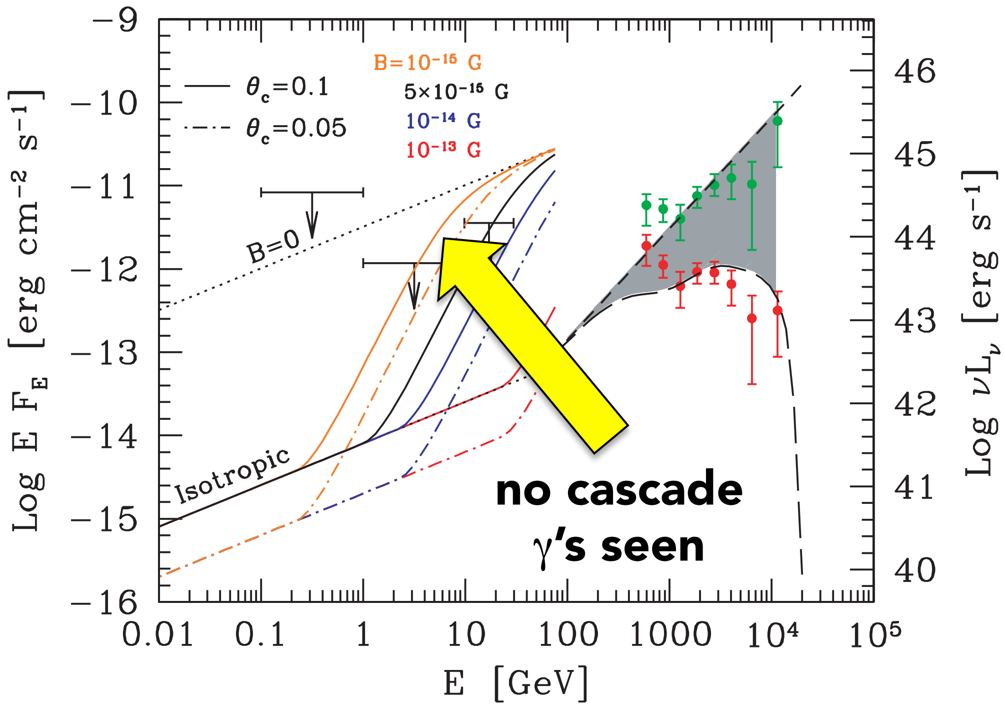


Absence of cascade emission in observations of TeV blazar spectra provide evidence for an IGMF.

Studies in 2010 do not see cascade photons from the TeV blazar 1ES 0229+200 [Neronov & Vovk; Tavecchio et. al.]

Can be interpreted as evidence for an IGMF with field strength

B >~ 10^{-16} … 10^{-14} G

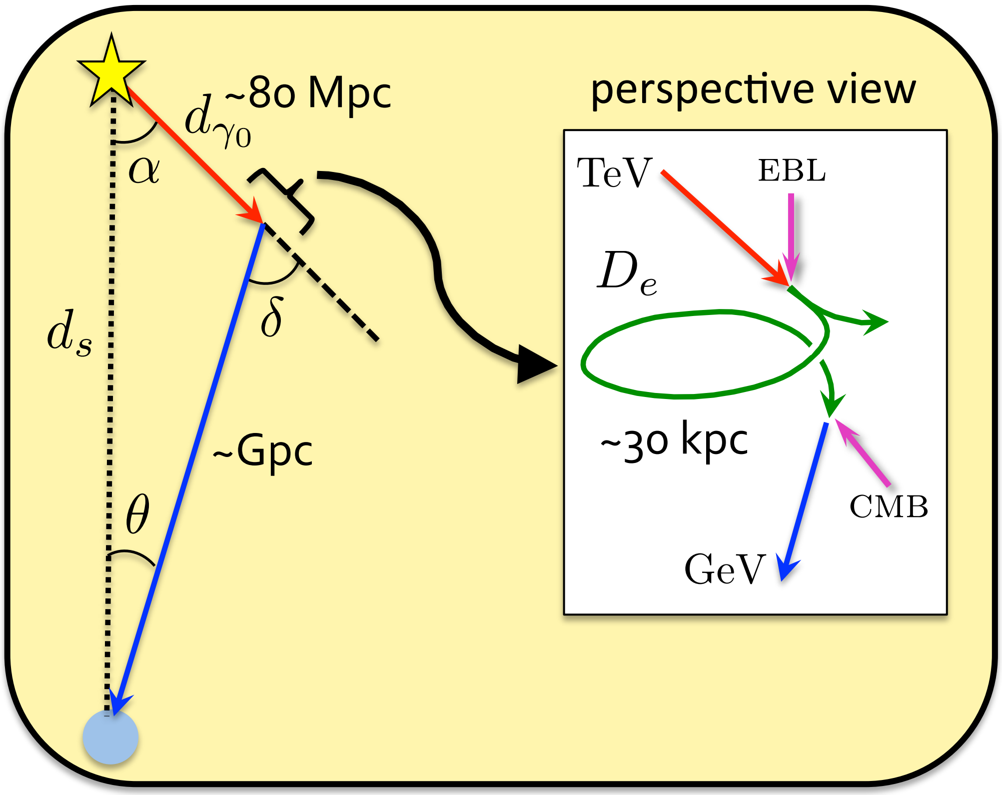
Caveat: assumes O(1) energy goes into EM cascade. It has been argued that most energy is lost into heating the medium via plasma instabilities, and the limits are weakened [Broderick, Chang, Pfrommer, Puchwein] [Menzler & Schlickeiser]

But if some γ's are deflected away, others must be deflected back toward the line of sight

Strategy #2: Blazar Cascade Pair Halo

The cascade gamma rays are also deflected back toward the line of sight creating a halo of GeV gamma rays around the TeV blazar.

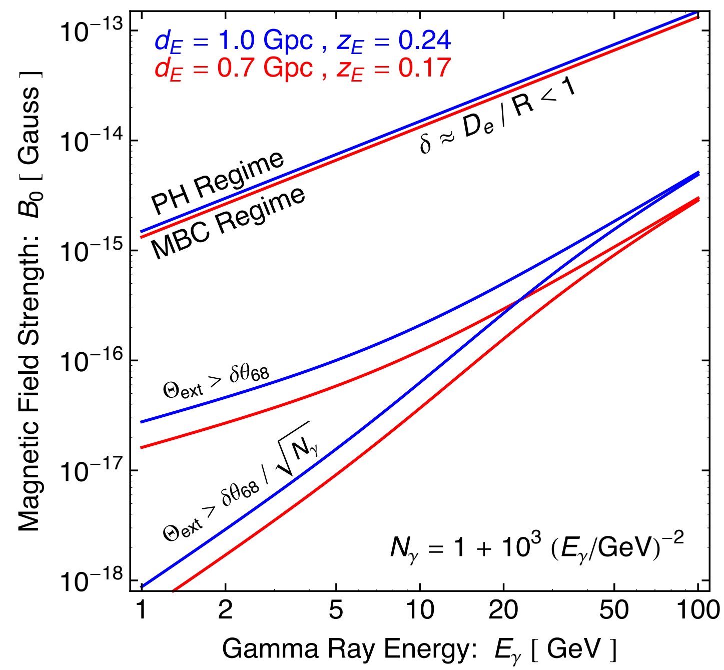
Aharonian, Coppi, & Voelk (1994); Neronov & Semikoz (2006); Elyiv, Neronov, & Semikoz (2009)



$$\Theta_{\rm ext} \simeq (0.68^\circ) \left(\frac{B_0}{10^{-15}\,\rm G}\right) \left(\frac{E_\gamma}{10\,\rm GeV}\right)^{-3/2} \left(\frac{d_s}{1\,\rm Gpc}\right)^{-1}$$

Compare halo diameter Θ_{ext} with PSF of Fermi-LAT $\delta\theta_{68}$.

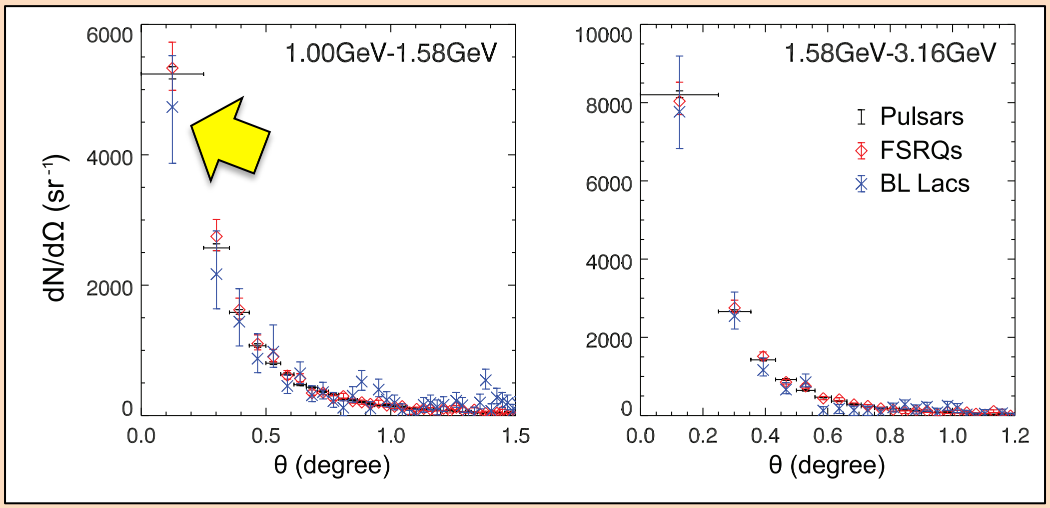
$$\delta\theta_{68} \simeq (0.11^\circ)\sqrt{1 + (E_\gamma/8\ {\rm GeV})^{-1.62}}$$



Strategy #2: Blazar Cascade Pair Halo

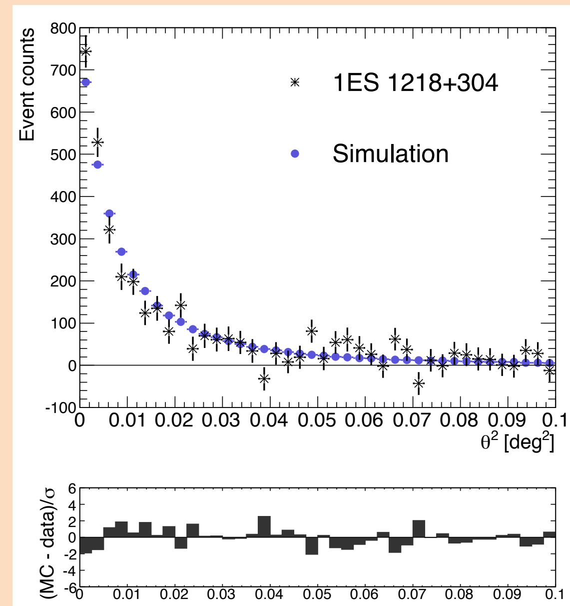
see also talks by F. Oikonomou, M. Meyer, and M. Lorentz (Wednesday)

Evidence for pair halos in stacked blazar analysis



Chen, Buckley, & Ferrer (2015)
-- 24 stacked BL Lacs (z<0.5)
-- evidence for extended emission (over PSF alone)
-- when interpreted as IGMF, implies $B_0 \sim 10^{-17} \ldots 10^{-15}$ G

Limits from γ-ray telescopes (MAGIC, Fermi, HESS, VERITAS)



MAGIC (2010), Fermi-LAT (2013), HESS (2014), & VERITAS (2017) [plot above]
-- no halo observed
-- broadening consistent with PSF

What can blazar halos tell us about helicity?

Blazar Halo Morphology

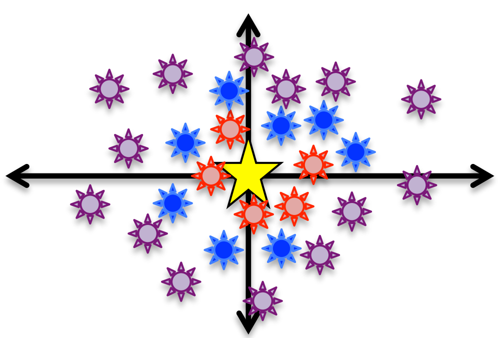
- How does magnetic helicity affect the halo?
  Halo Size ➔ Field Strength
  Halo Shape ➔ Magnetic Helicity

Kahniashvilli & Vachaspati (2006); Tashiro & Vachaspati (2013); Tashiro, Chen, Ferrer, & Vachaspati (2013); Tashiro & Vachaspati (2015);
AL & Vachaspati (2015)

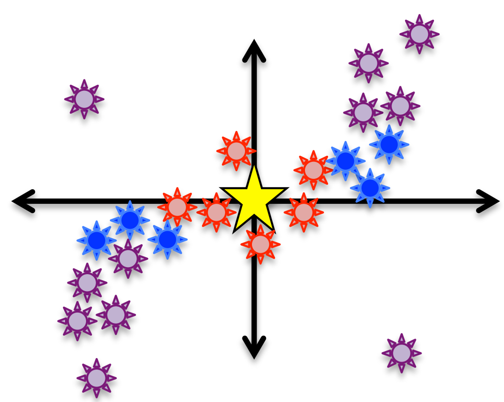
γ-Ray Energy:
RED = high
BLUE = medium
PURPLE = low

- Endows it with parity-violating property: skew

non-helical
deflection ~ $E^{-3/2}$



maximally helical
R-handed



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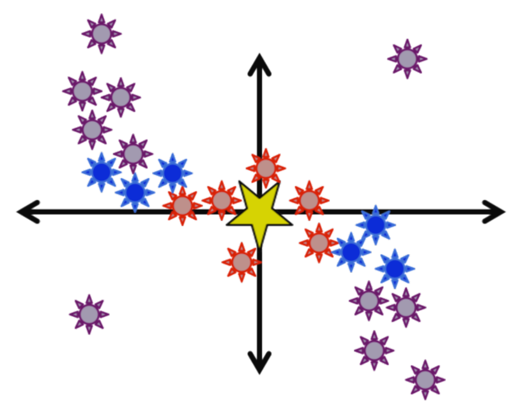
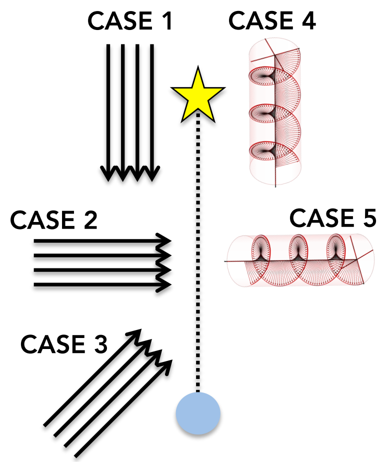


Cascade Evolution "Simulations"



<u>(overly-) Simplifying Assumptions</u>

... Monochromatic blazar spectrum (5 TeV); isotropic emission

... Gamma rays and e^+e^- travel exactly their mean free path

... Single scattering; Minkowski spacetime

... Monochromatic B-field spectrum ($k = 2\pi/\lambda$)

... Simplified models for B-field

➔ Cases 1, 2, & 3 = B-field is homogenous (B_0)

➔ Cases 4 & 5 = B-field is helical (B_0 & λ)

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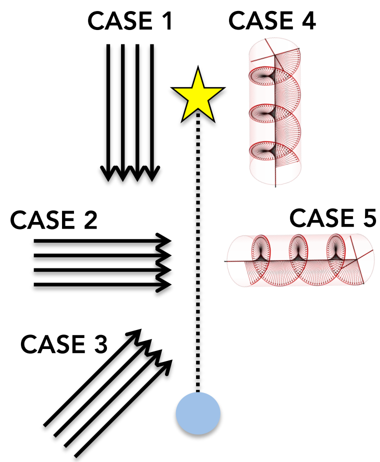

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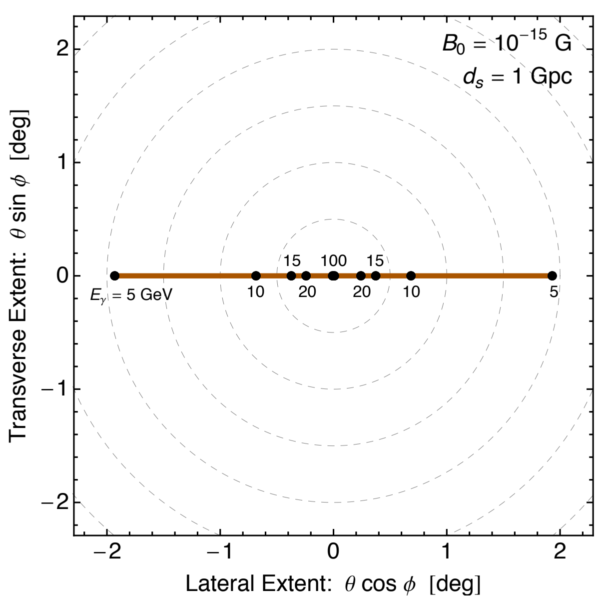
Case 2



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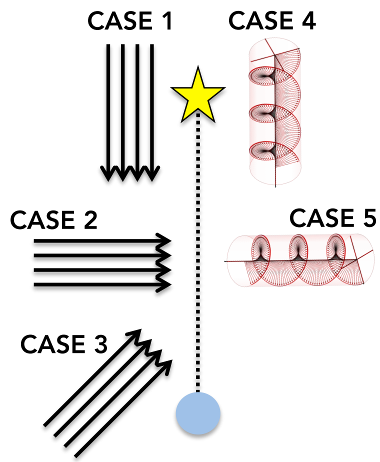

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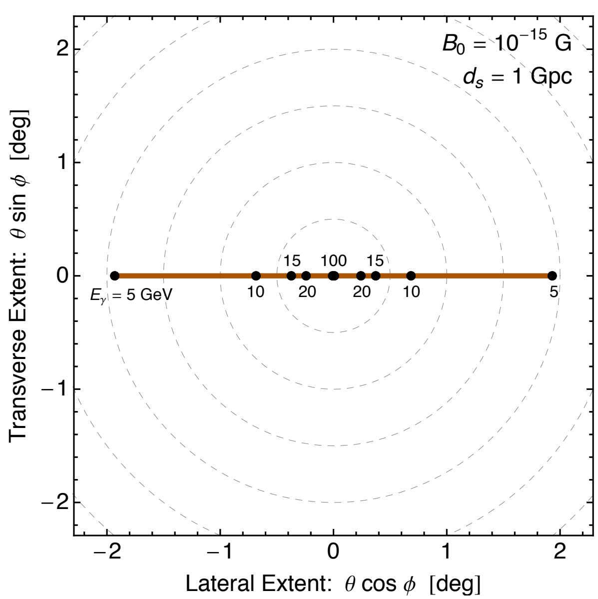
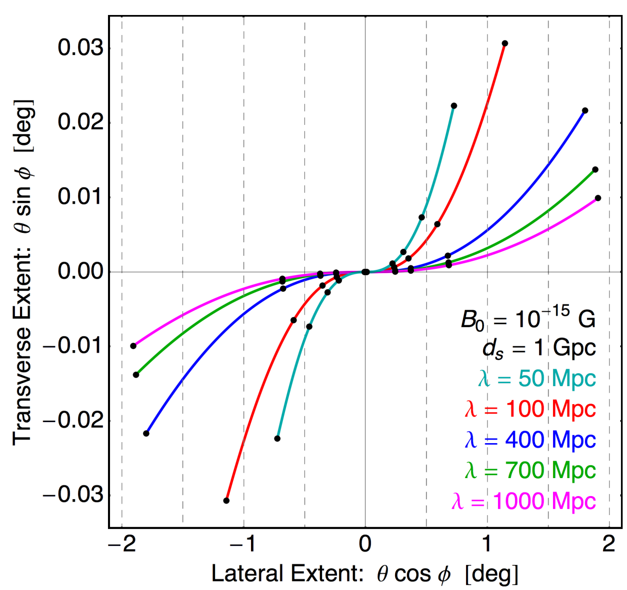
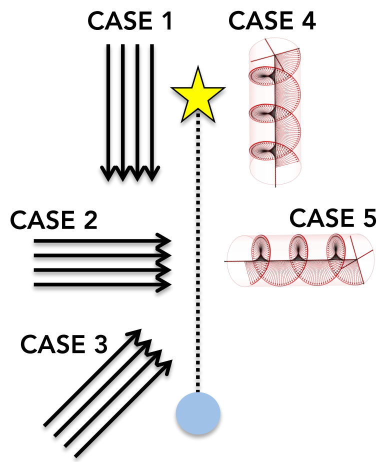


Case 5

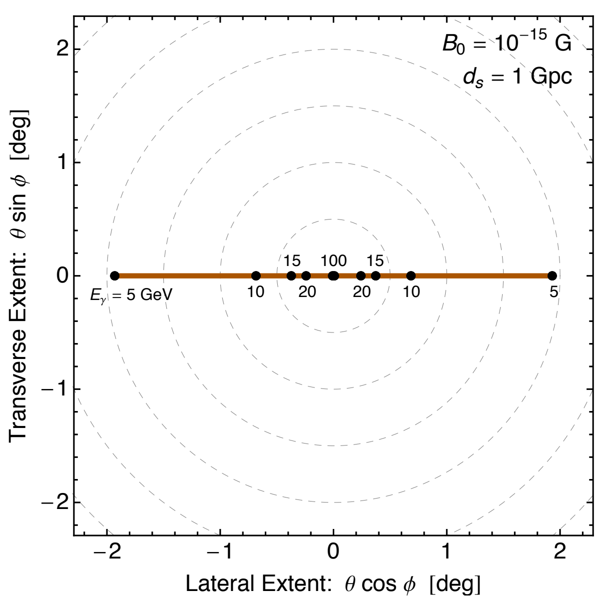


Cascade Evolution "Simulations"

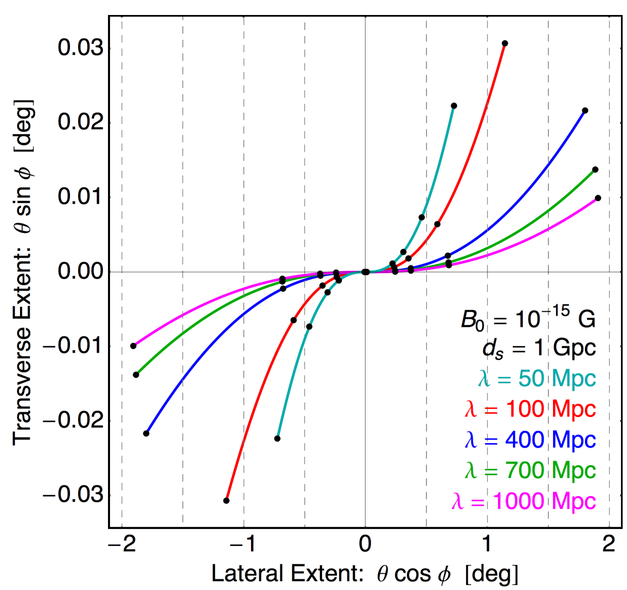


Helicity of the IGMF induces a "twisted" morphology to blazar halo

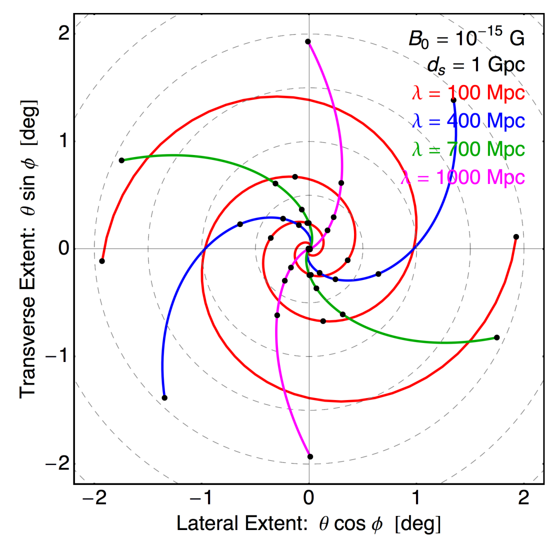
Case 2

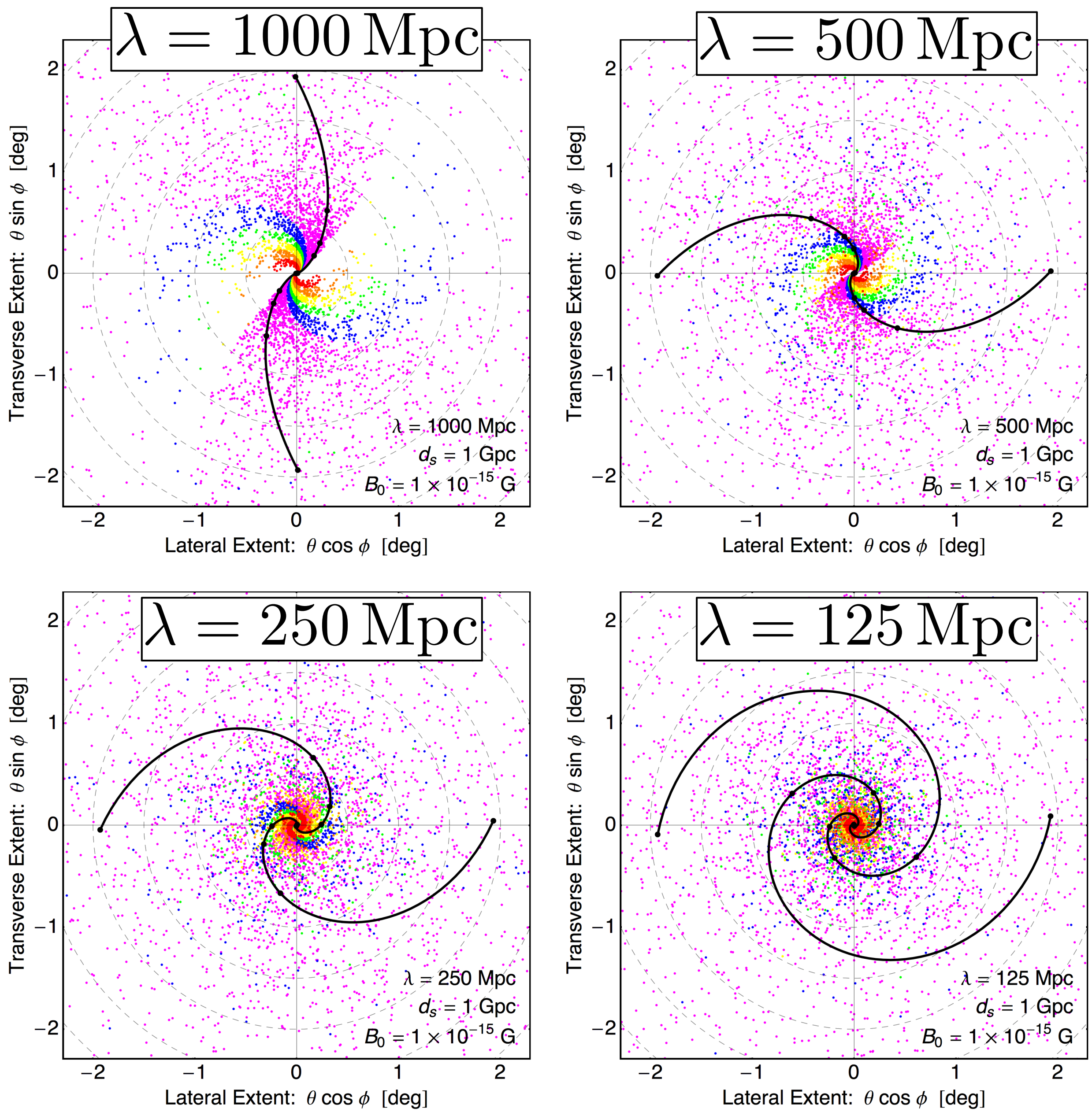


Case 5



Case 4





(now allow exponentially-distributed propagation distances; Case 4)

$$B_0 = 10^{-15}\,\mathrm{G}$$
$$d_s = 1\,\mathrm{Gpc}$$

γ-Ray Energy:
RED = high
BLUE = medium
PURPLE = low

Mag helicity leads to parity-violating halo morphology.

Effect becomes "scrambled" for smaller coherence lengths.

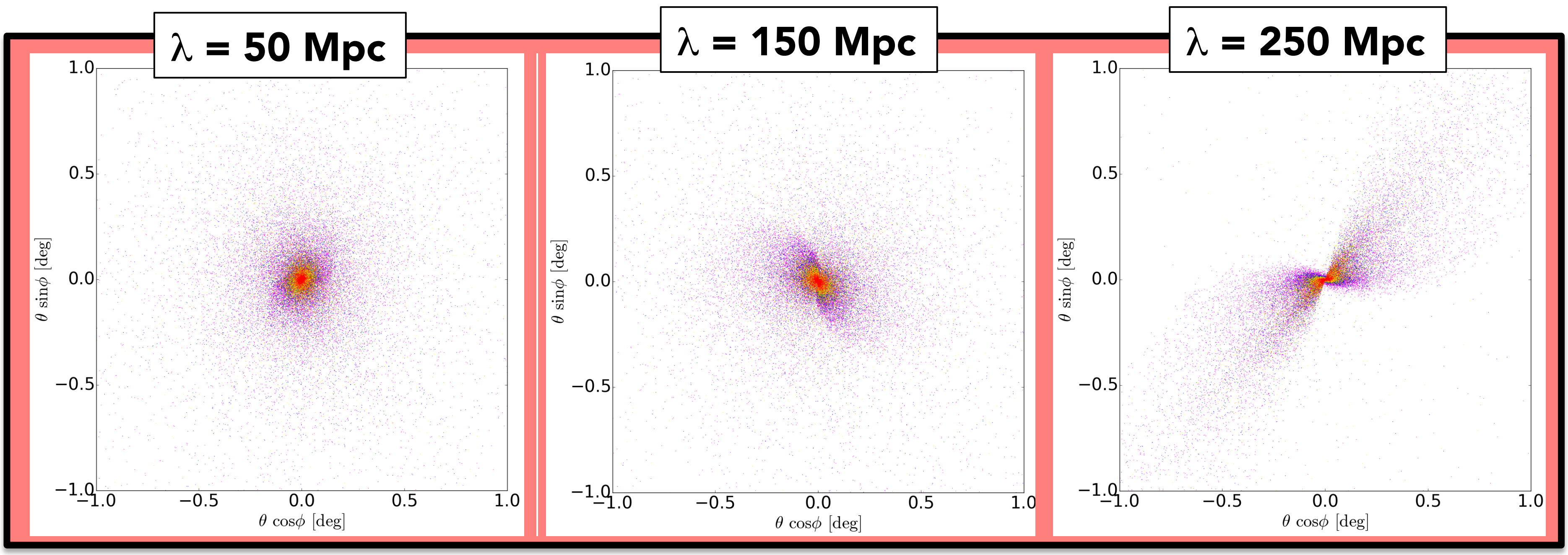
AL & Vachaspati (2015)

Simulations have been refined in subsequent work by other authors

E.g., Batista, Saveliev, Sigl, & Vachaspati (2016) [figures below]
… includes EBL spectrum (Kneiske & Dole), stochastic B-field w/ Batchelor spectrum
other morphology studies: Duplessis & Vachaspati (2017); Tiede et. al. (2017)
see also Fitoussi et. al. (2017) & talk by T. Fitoussi (Friday)

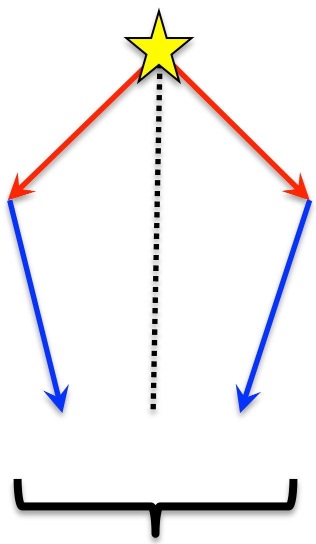
Confirms our results from super-rough "simulation"
… blazar halo acquires skew due to helicity of IGMF
… hard to distinguish helicities for small coherence length.

$$d_s = 1\,\mathrm{Gpc}\,, \quad B_0 = 10^{-15}\,\mathrm{G}\,, \quad E_{\mathrm{blazar}} = 10\ \mathrm{TeV}$$



Why the smearing?

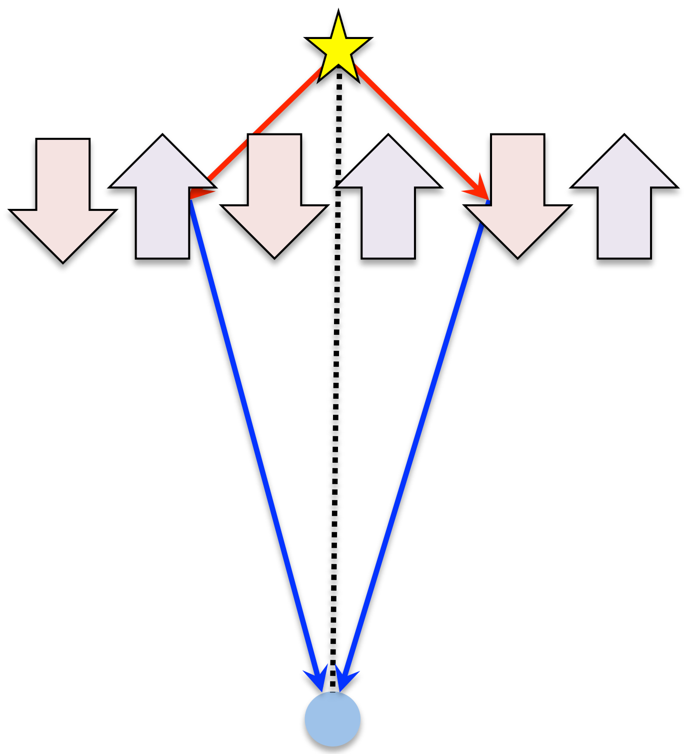
Cascade probes B-field on scales up to ~100 Mpc



$\sim 100\ \mathrm{Mpc}$

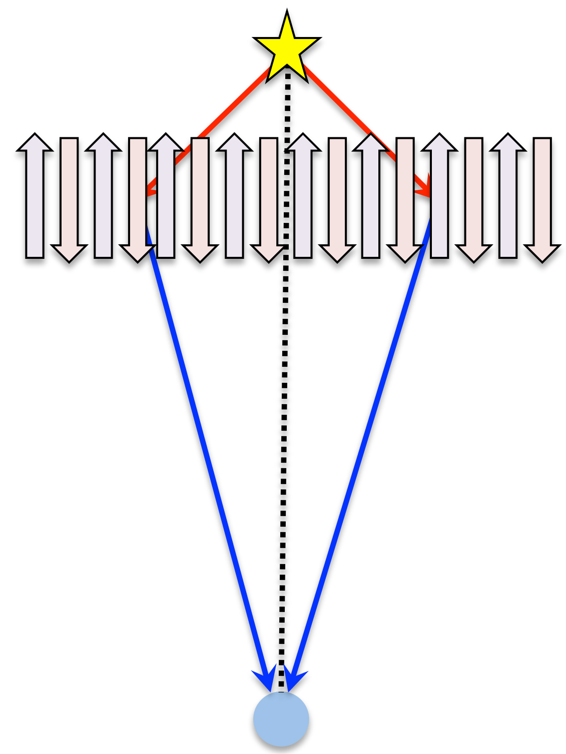
(set by mean free path of TeV gamma ray)

large coherence length >~ 100 Mpc



Results in twisted halo map

small coherence length <~ 100 Mpc



Twist is scrambled

How do we measure it?

How do we get there from here?

(1) The subtle approach: better angular resolution (PSF)

➔ You want good enough resolution to not only see the halo (distinguish from a point source) but also see the "twist."

➔ Predicted twist angle is model-dependent, but typically this requires $\delta\theta_{68} < 0.1^{\circ}$ at $E_{\gamma} \sim$ GeV.

➔ A new telescope?

(2) The brute force approach: more statistics

➔ We don't really need to *see* the halo shape, we just want to know if it has a twist. Define a test statistic that selects out parity-violating shape.

Tashiro & Vachaspati (2013); Tashiro & Vachaspati (2015);
AL & Vachaspati (2015); Batista, Saveliev, Sigl, & Vachaspati (2016)

Parity-Odd Test Statistic

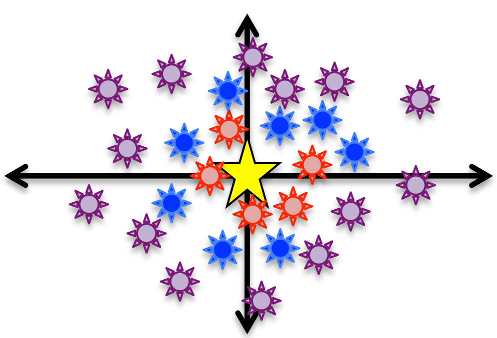
Partition data into three energy bins: high, medium, & low.

$\hat{\boldsymbol{n}}(E) =$ arrival direction of $E_\gamma = E$

test statistic: $Q = \hat{\boldsymbol{n}}_{\rm low} \times \hat{\boldsymbol{n}}_{\rm med} \cdot \hat{\boldsymbol{n}}_{\rm high}$

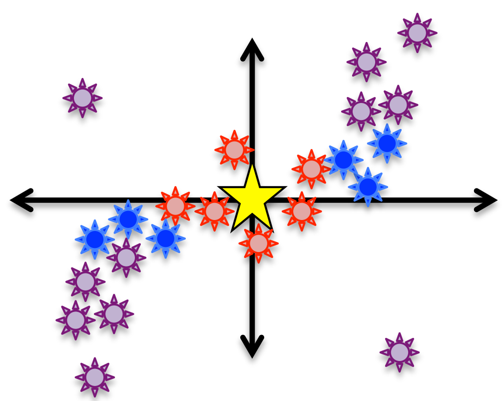
for alternate statistic see also Batista, Saveliev, Sigl, & Vachaspati (2016)

non-helical
deflection ~ $E^{-3/2}$



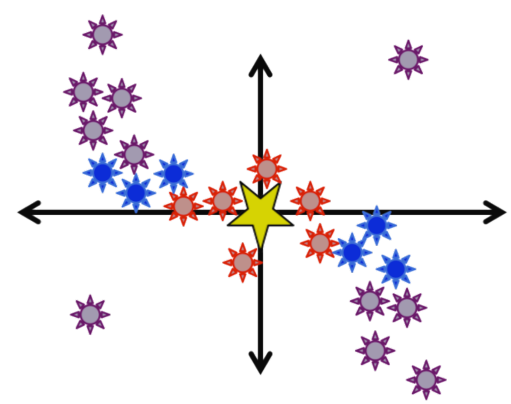
$\langle Q \rangle = 0$

maximally helical
R-handed



$\langle Q \rangle > 0$

maximally helical
L-handed

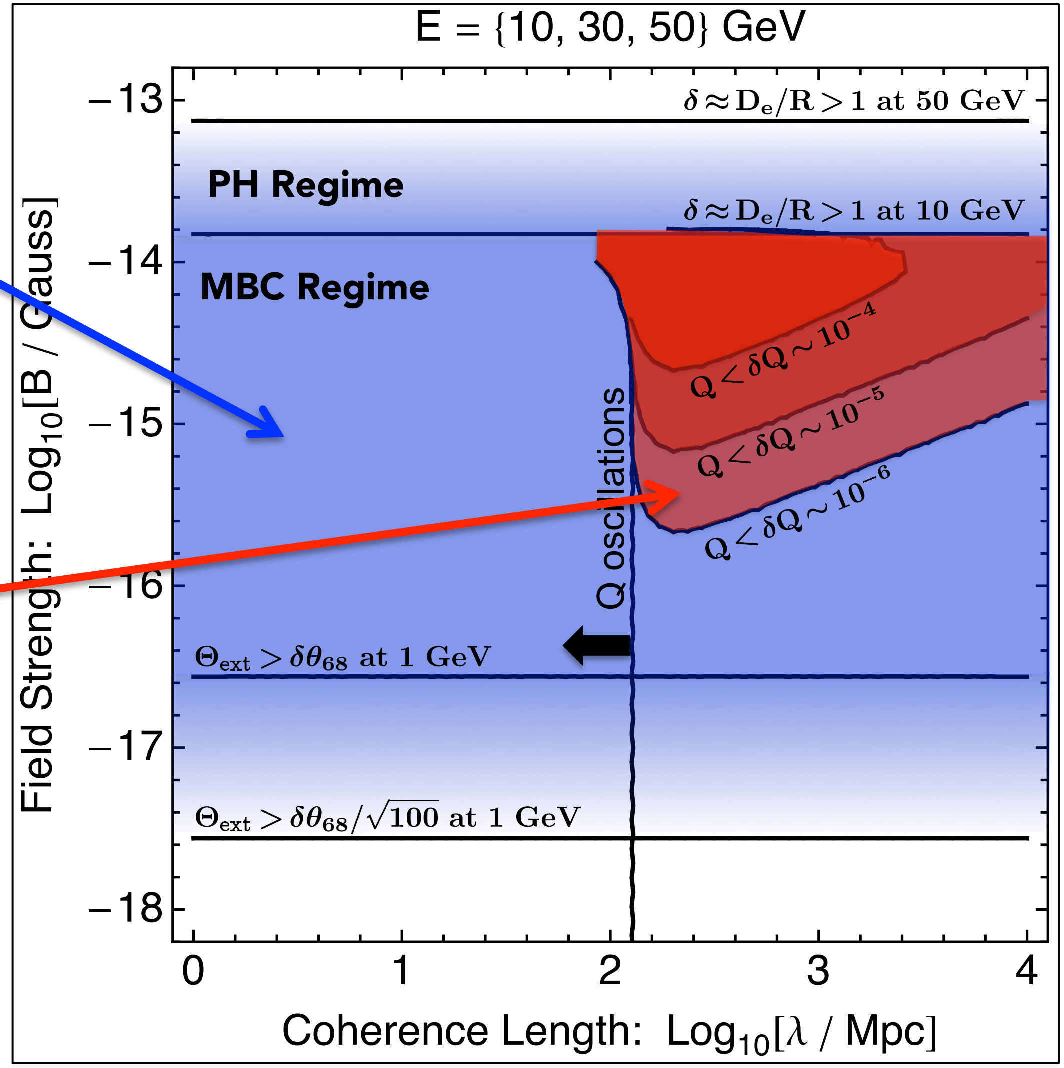


$\langle Q \rangle < 0$

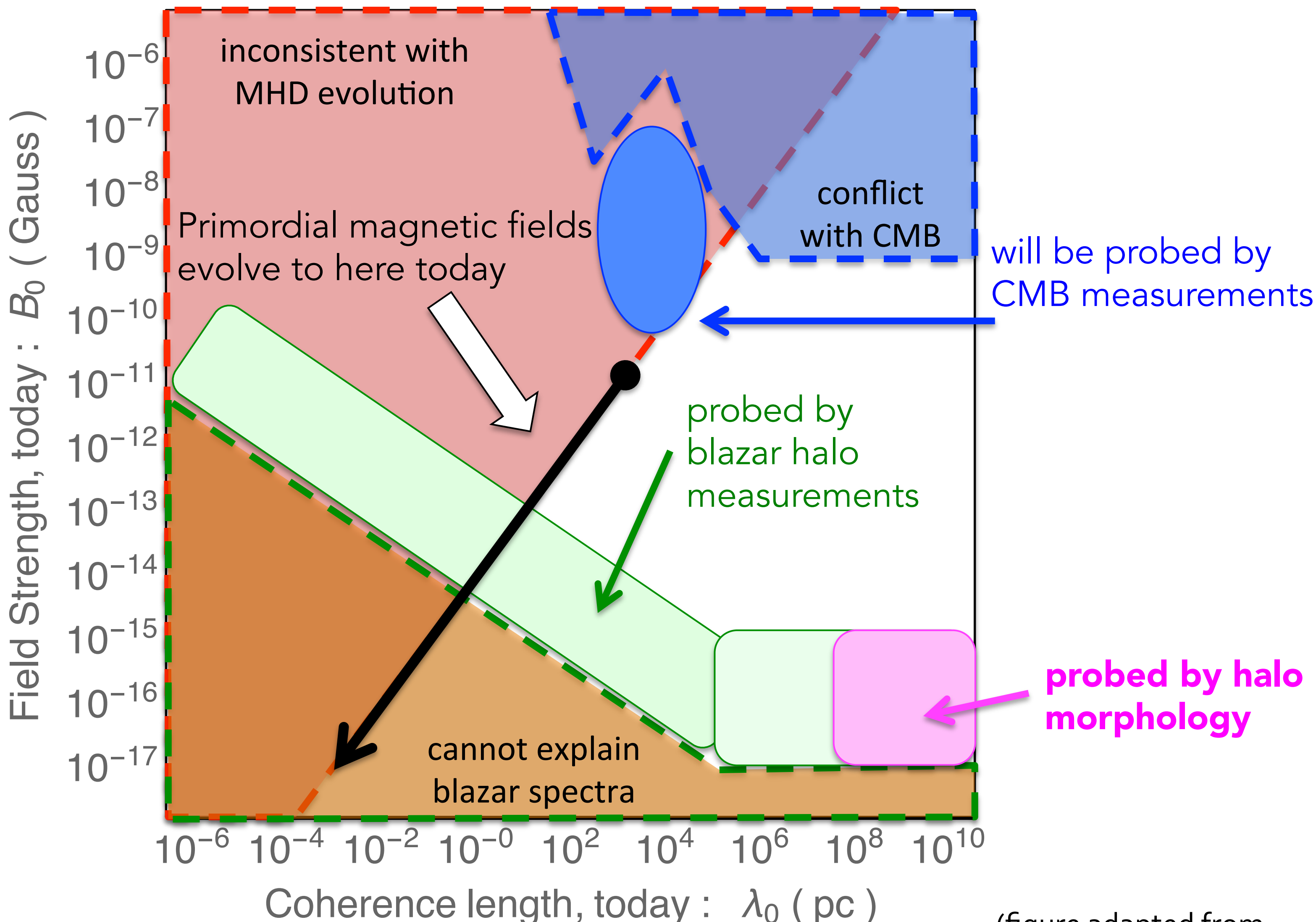
Parity-Odd Test Statistic

BLUE = *halo size* measurements could inform IGMF strength

RED = *halo morphology* measurements could inform IGMF helicity using test statistic



A global perspective



(figure adapted from
Durrer & Neronov, 2013)

Conclusion

The discovery of a **helical intergalactic magnetic field** would have profound implications for our understanding of cosmological inflation, axions, and the matter / antimatter asymmetry.

In this talk, I have discussed how **TeV blazar halos acquire a "twisted" morphology** if the cascade develops in the presence of a helical IGMF.

A **parity-odd test statistic** (like Q) can be used to infer the parity-violating character of the halo.

I'd like to see magnetic helicity included in simulations of cascade development with an eye toward probing helicity of the IGMF with gamma ray observations.