Search for Cosmological CP Violation in the Gamma Ray Sky

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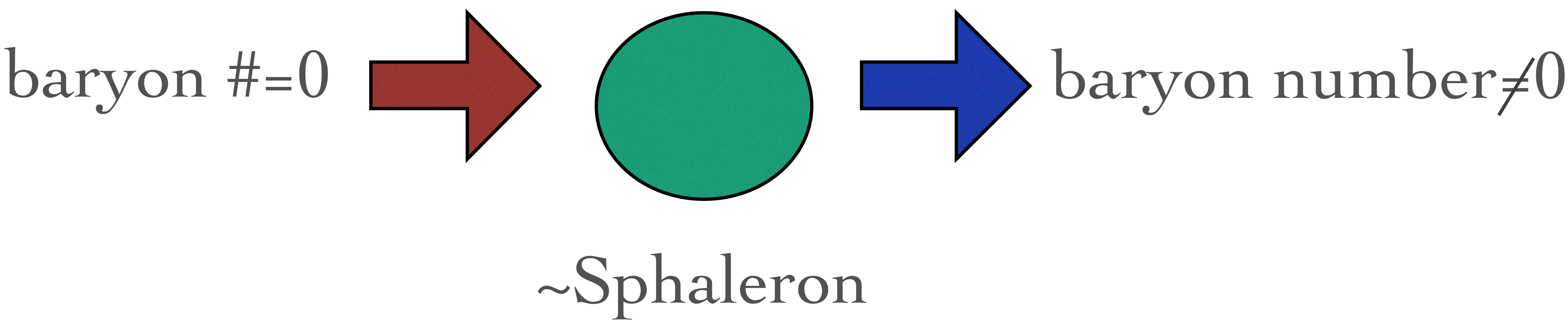
Based on arXiv:1310.4826, Hiroyuki Tashiro, W. Chen, F. Ferrer & T. Vachaspati.
https://sites.physics.wustl.edu/magneticfields/wiki/index.php/Search_for_CP_violation_in_the_gamma-ray_sky

Outline

- Motivation
- Strategy
- Implementation

Matter- & Magneto-genesis

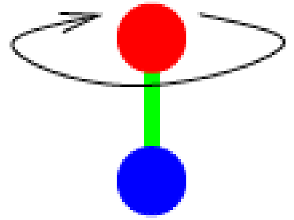
Baryon number violation produces helical magnetic fields.



Sphaleron

Taubes;
Manton;
Manton&Klinkhamer;
TV & Field;
Hindmarsh & James.

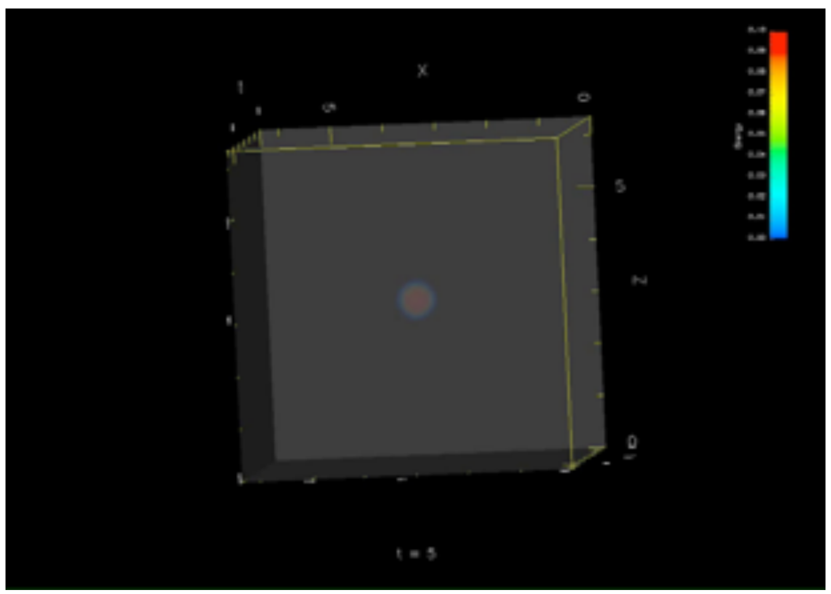
Sphaleron = twisted monopole-antimonopole pair

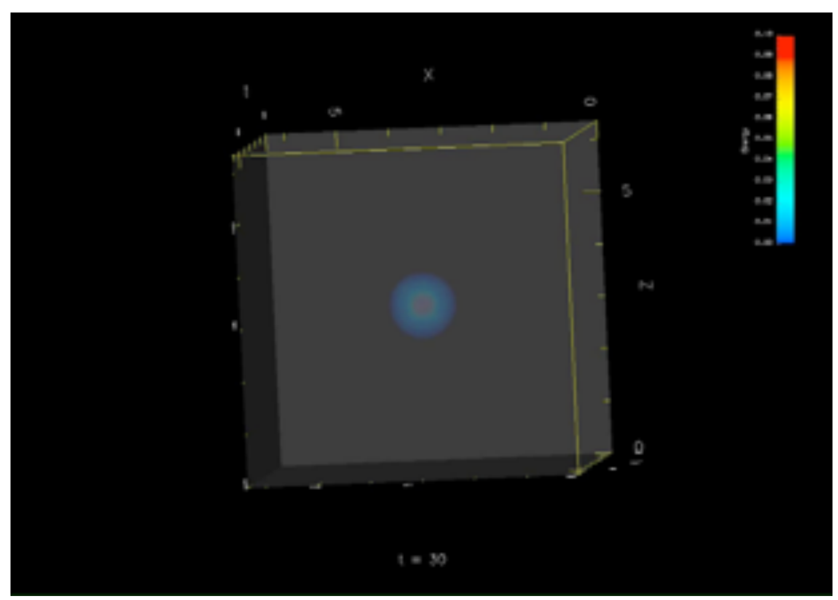


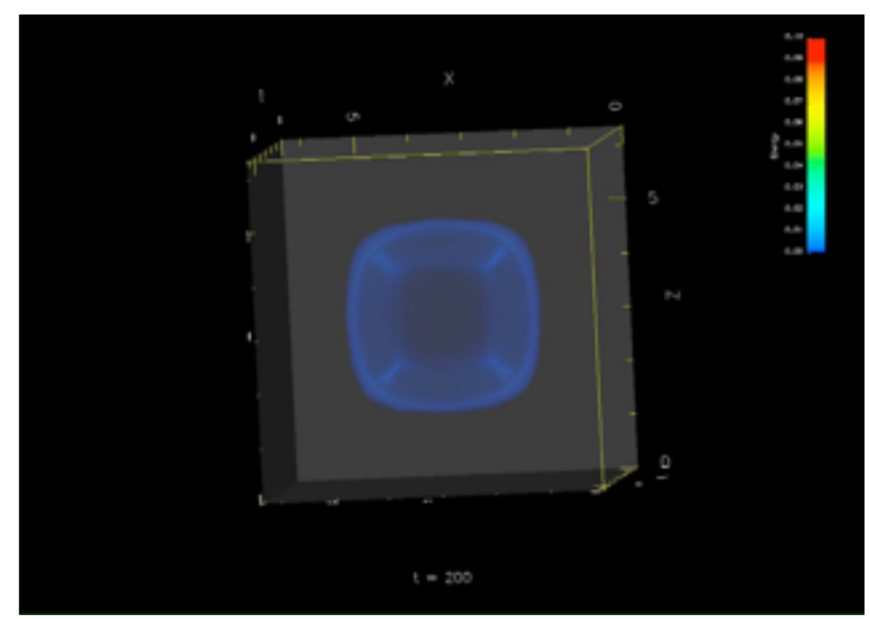
Sphaleron Decay

Copi, Ferrer, TV & Achucarro, 2008

Evolve classical electroweak equations with (perturbed) sphaleron initial conditions.





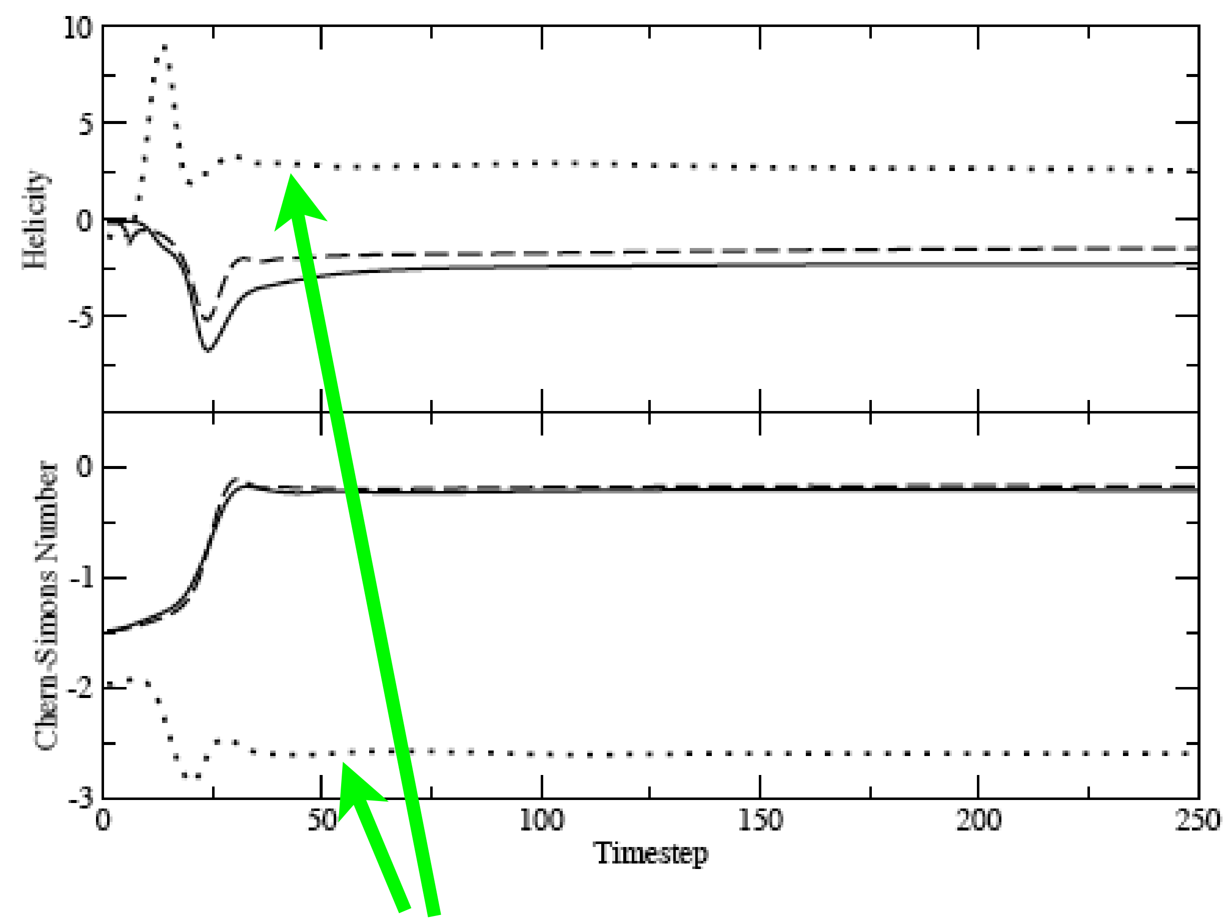


Measure magnetic helicity...

Helicity in sphaleron decay

Copi, Ferrer, TV & Achucarro, 2008
Diaz-Gil, Garcia-Bellido, Perez & Gonzalez-Arroyo, 2008

$$\mathcal{H}(t) = \int d^3x \; \mathbf{A} \cdot \mathbf{B}$$



“inverted decay”

Sphaleron decay II

Y-Z. Chu, J. Dent & TV

A *decay path* for the sphaleron is known. Manton

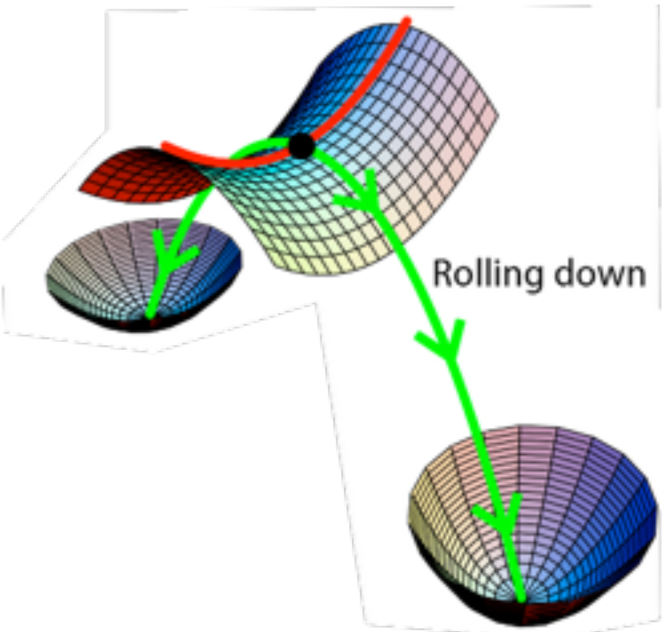


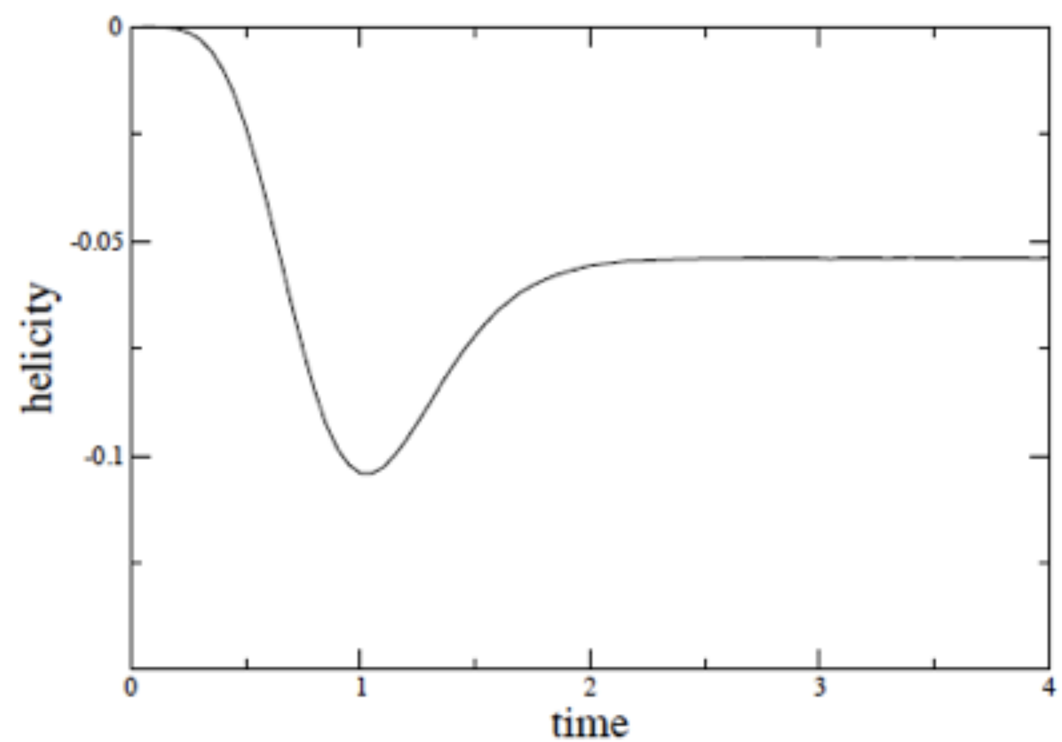
Image- http://spie.org/x31524.xml?ArticleID=x31524

Calculate electric currents along the decay path.
Then solve Maxwell's equation.

$$(\partial_t^2 - \nabla^2)A^\mu = J^\mu$$

Calculate helicity of magnetic field generated along the decay path.

Magnetic helicity



Helicity is conserved at late times. $\mathcal{H}(\infty) \sim -\frac{\sin^2\theta_w}{g^2}$

Baryon production implies left-handed helicity.

Cosmological magnetic helicity

$$\text{Every } \Delta B \implies \Delta\mathcal{H}$$

J. Cornwall
TV

$$\implies \quad \boxed{h \approx -\# \frac{n_b}{\alpha}}$$

Inverse Cascade

Magnetic helicity can cause an "inverse cascade" i.e. transfer power from small to large length scales.

MHD simulations & models in flat spacetime:

Numerical: $\xi \propto t^{1/2}$ — Christensson, Hindmarsh & Brandenburg, 2005

Analytical: $\xi \propto t^{2/3}$ — D. Biskamp, 1993; P. Olesen, 1997; D.T. Son, 1999; Field & Carroll, 2000

Translate these exponents to expanding universe by interpreting t as the conformal time.

$$\xi \propto \tau^{\alpha} \propto t^{\alpha/2} \quad \text{radiation}$$

$$\xi \propto t^{\alpha/3} \quad \text{matter}$$

Also: Kahniashvili, Brandenburg, Tevzadze & Ratra, 2010

Coherence Scale

Length scale grows by Hubble expansion and inverse cascade, in radiation- and matter-dominated epochs.

$$\begin{aligned} \xi_{\rm eq} &= \xi_{\rm inj} \left(\frac{a_{\rm eq}}{a_{\rm inj}}\right)^{1+\alpha} \left(\frac{a_0}{a_{\rm eq}}\right)^{1+\alpha/2} \\ &\lesssim (1\ {\rm cm})\left(\frac{T_{\rm ew}}{1{\rm eV}}\right)^{1+2/3} 10^{4+1} \\ &\sim 10^{20}\ {\rm cm} \\ &\sim 0.1\ {\rm kpc} \end{aligned}$$

$$\xi_0 \sim {\rm Mpc}$$

Field Strength: helicity alone (no chiral effects, no antibaryons)

$$|h| \sim n_b \implies \xi B^2 \sim n_b$$

$$B \sim \sqrt{\frac{n_b}{\xi}}$$

$$B(t_0) \sim 10^{-21}\ \mathrm{G}$$

Better to think of this as:

$$h \sim (10^{-21}\ \mathrm{G})^2 - \mathrm{kpc}$$

Field Strength Re-visited

Sphaleron transitions produce baryons and anti-baryons.
CP violation implies a slight excess of baryons.

The baryons and anti-baryons annihilate but magnetic fields are spread out and cannot annihilate completely.

$$B(t_0) \approx 10^{-21}\mathrm{G} \left(\frac{N_b + N_{\bar{b}}}{N_b - N_{\bar{b}}} \right)^{\gamma}$$

In standard model, CP violation gives -- $\frac{N_b + N_{\bar{b}}}{N_b - N_{\bar{b}}} \approx 10^{20}$

If $\gamma = 1/2:\quad B(t_0) \approx 10^{-11}\ \mathrm{G}$

(In a baryogenesis model that actually works, CP violation would be larger. Then the CP enhancement would be smaller but gamma could compensate.)

Helicity probes early universe

Leptogenesis also leads to helical magnetic fields but the helicity is *right-handed*.

Andrew Long, Eray Sabancilar & TV (2013).

Quite generally: if primordial magnetic fields are produced on sub-horizon scales in the early universe, their survival depends crucially on the presence of magnetic helicity.

How can we probe magnetic helicity?

Probes of helicity?

Faraday Rotation of CMB, Quasars: FR is insensitive to helicity. Milky Way dominates FR except for B > 0.1nG.

Soma De, L. Pogosian & TV

Cosmic rays: Milky Way dominates deflections except for B > 0.01 nG. Need to know CR source locations.

Kahniashvili & TV

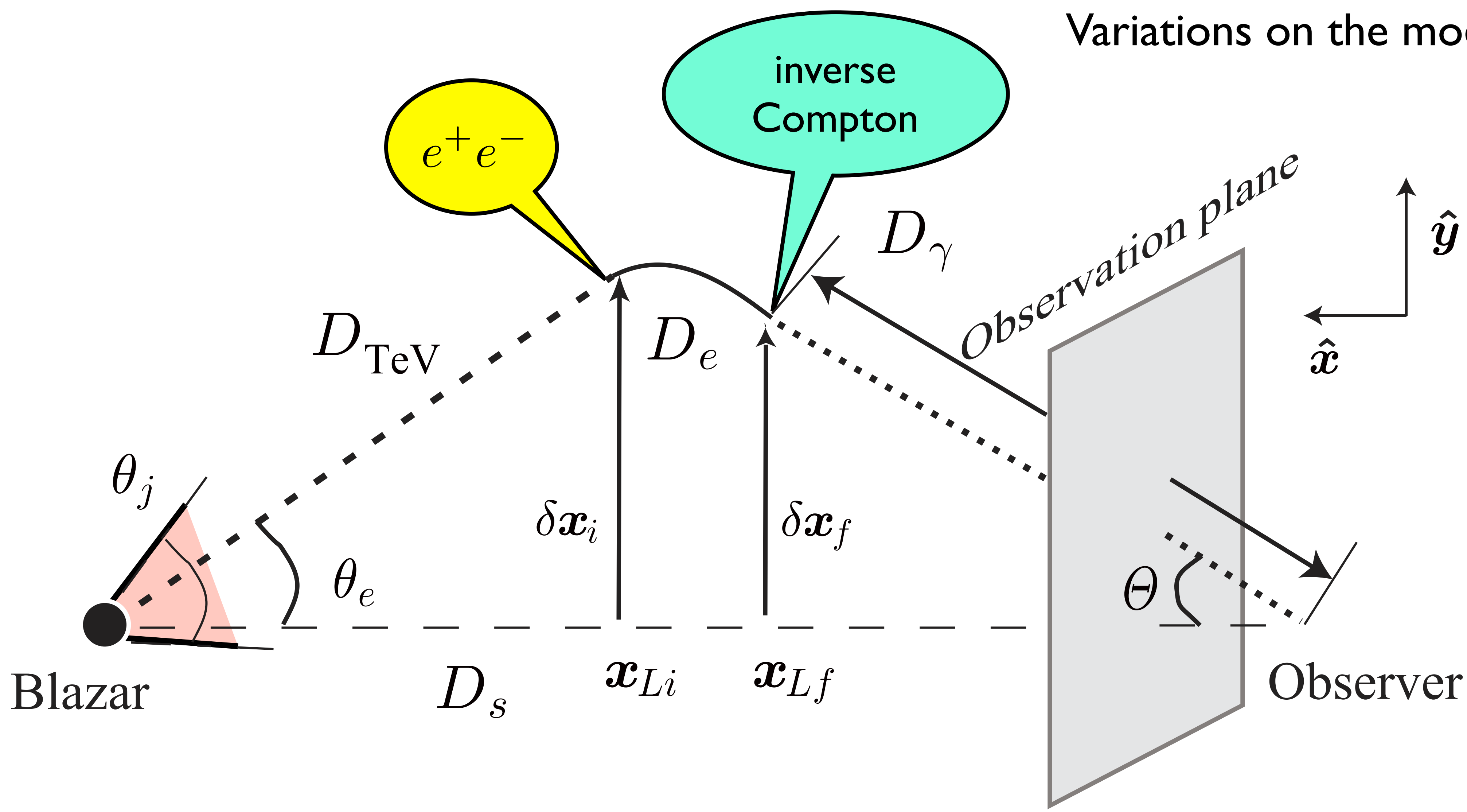
Gamma rays: Sensitive to helicity if produced by charged particles in intergalactic space. Unaffected by Milky Way.

TeV Blazars

Gould & Schreder, 1967; Coppi & Aharonian, 1998; ..... Neronov & Semikoz, 2009

Neronov & Vovk, 2010; Essey, Ando & Kusenko, 2011; Essey & Kusenko, 2010;....

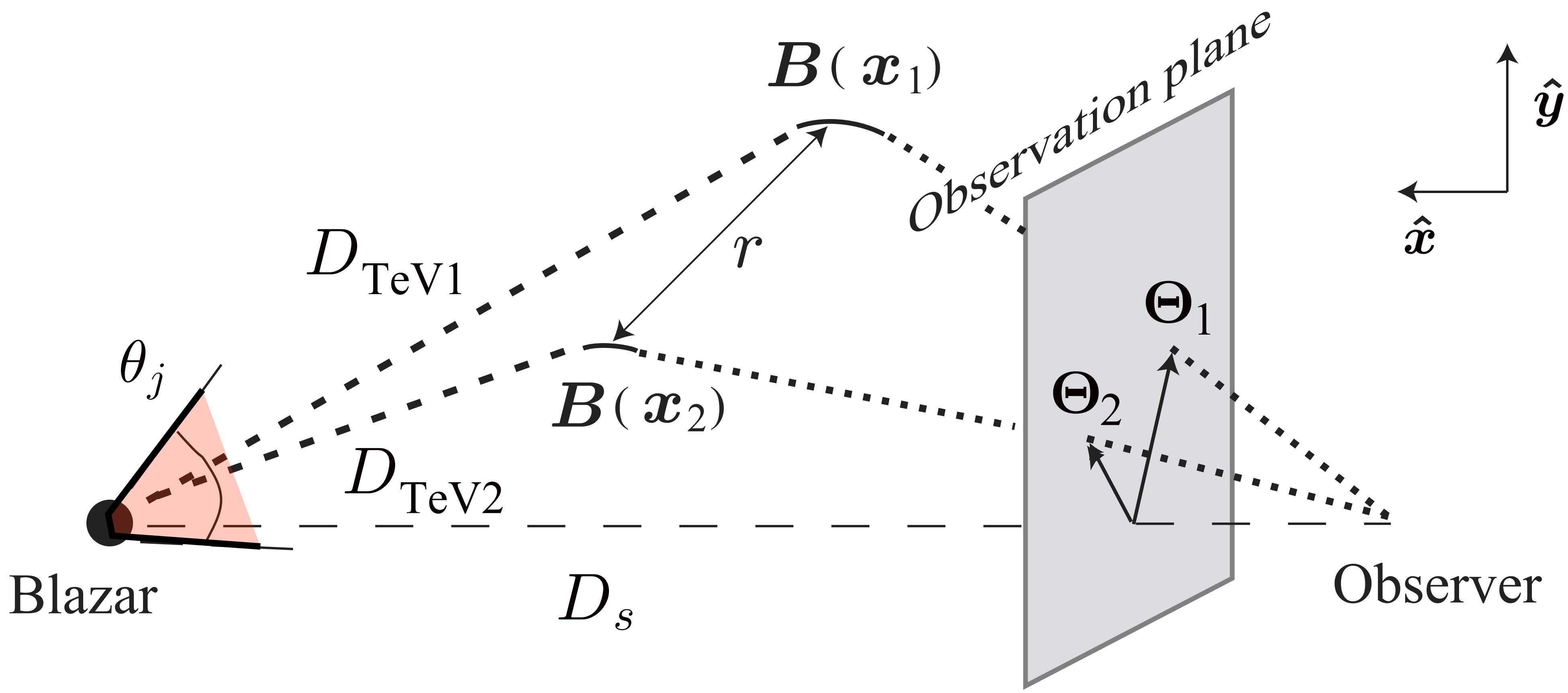
Variations on the model possible.



$$D_{\text{TeV}} \sim 100 \text{ Mpc}, \quad D_e \sim 30 \text{ kpc}, \quad D_\gamma \sim D_s \sim 1 \text{ Gpc}$$

Gamma ray correlators

Tashiro & TV, 2013.



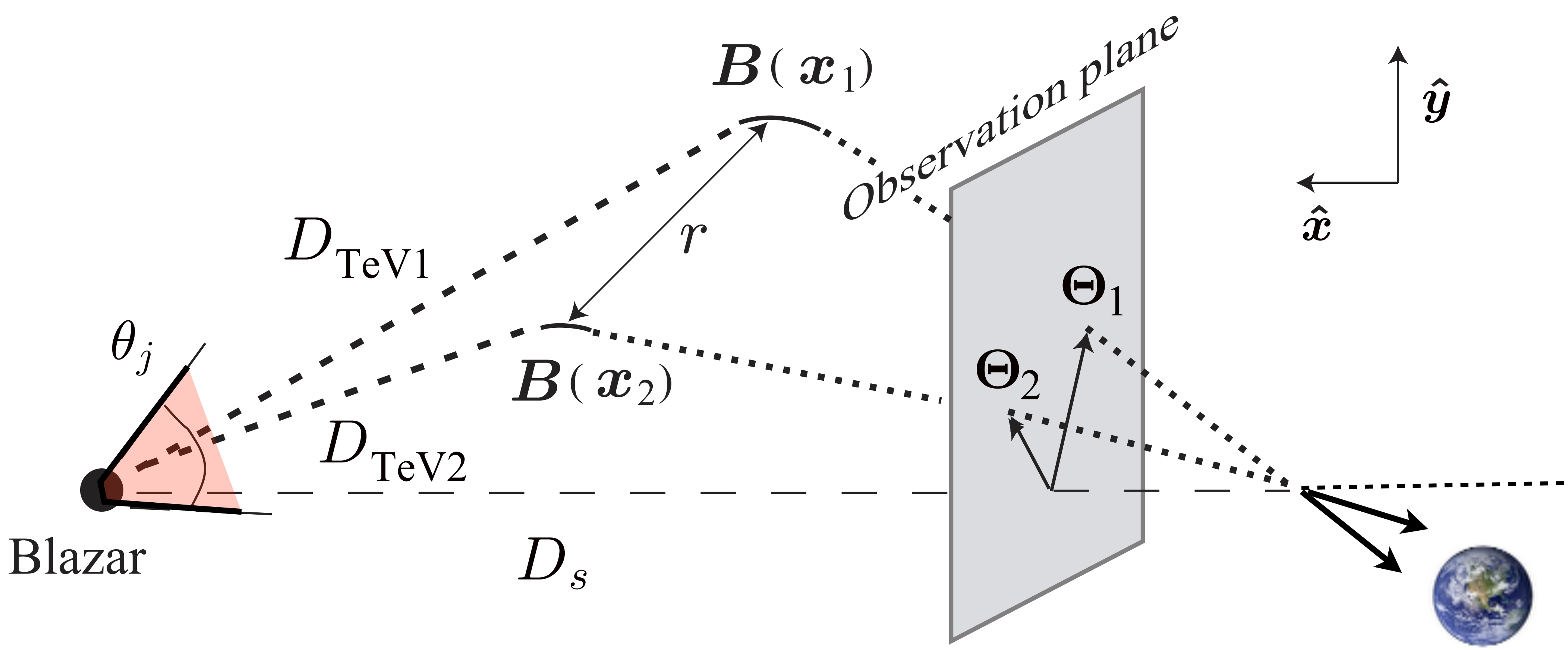
Relate correlators of arriving gamma rays to magnetic field correlators:

$$\langle B_i(\mathbf{x}+\mathbf{r})B_j(\mathbf{x})\rangle = M_N(r)\left[\delta_{ij} - \frac{r_i r_j}{r^2}\right] + M_L(r)\frac{r_i r_j}{r^2} + M_H(r)\epsilon_{ijl}r^l$$

$$G(E_1, E_2) = \langle \boldsymbol{\Theta}(E_1) \times \boldsymbol{\Theta}(E_2) \cdot \hat{\mathbf{x}}\rangle \propto \frac{1}{2} M_H(|r_{12}|)r_{12}$$

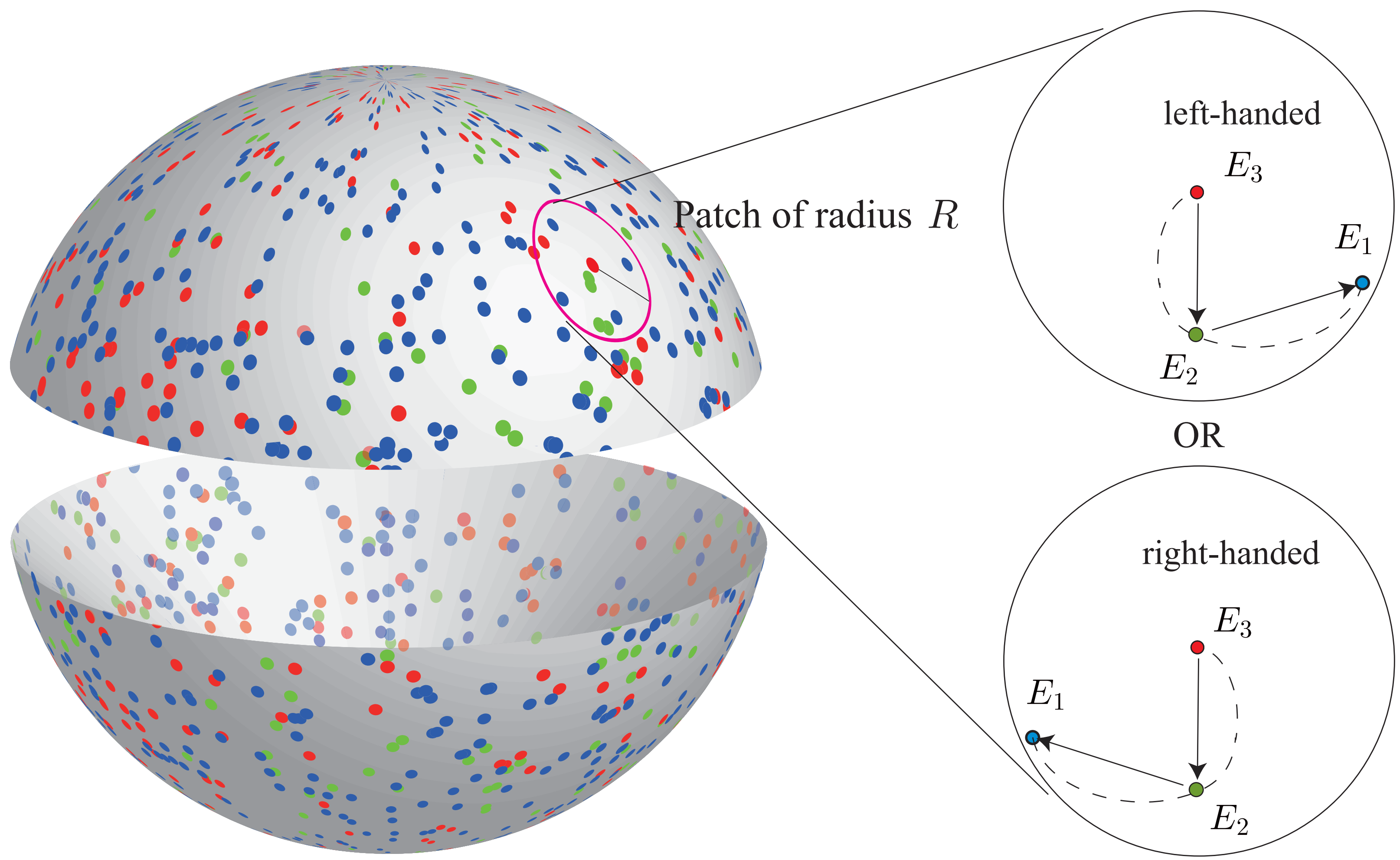
Different energy combinations probe magnetic field on different length scales.

If bending is large, it may be difficult to associate observed GeV gamma rays with their TeV sources.



Use direction of "least bent" (highest energy) gamma ray as an approximation to the source direction.

Unidentified Sources



$$Q(R) = \langle \mathbf{n}_1 \times \mathbf{n}_2 \cdot \mathbf{n}_3 \rangle_R$$

Cascade gamma rays are "signal"; non-cascade gamma rays are "noise".
Remove Milky Way and also 3-degree cones around known gamma ray sources to reduce noise.

Try $Q(R) = \langle \mathbf{n}_1 \times \mathbf{n}_2 \cdot \mathbf{n}_3 \rangle_R$ on existing data . . .

Fermi-LAT CLEAN data

(through mid-September 2013)

	10-20 GeV	20-30 GeV	30-40 GeV	40-50 GeV	50-60 GeV
North($> 60^\circ$)	3098	772	345	168	73
South($> 60^\circ$)	2816	661	281	126	74
Total ($> 60^\circ$)	5914	1433	626	294	147
North($> 70^\circ$)	1322	340	156	79	40
South($> 70^\circ$)	1146	276	120	57	30
Total ($> 70^\circ$)	2468	616	276	136	70
North($> 80^\circ$)	276	74	31	19	9
South($> 80^\circ$)	293	59	20	14	12
Total ($> 80^\circ$)	569	133	51	33	21

TABLE I. Number of photons for each energy bin.

Don’t know which photons are “signal” and which are “noise”.

Fiducial Model

"Diffuse gamma rays are distributed uniformly on the sky."

Allows us to create synthetic data, compute error bars, evaluate statistical significance.

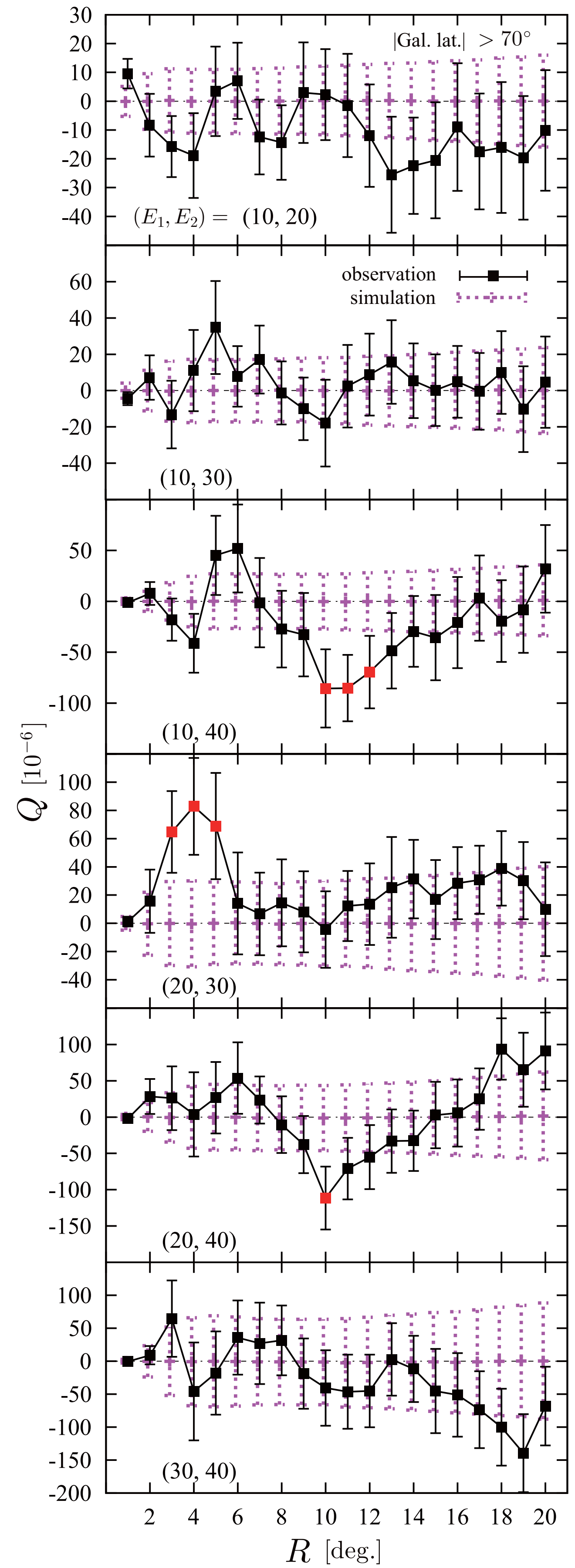
Patch centers with |b| > 70°

$E_3 = 50$ GeV

$$Q(R; E_1, E_2, E_3) = \langle \mathbf{n}_1 \times \mathbf{n}_2 \cdot \mathbf{n}_3 \rangle_R$$

Different energy bins probe magnetic field on different length scales.

("clean" as prescribed in 09/2013)



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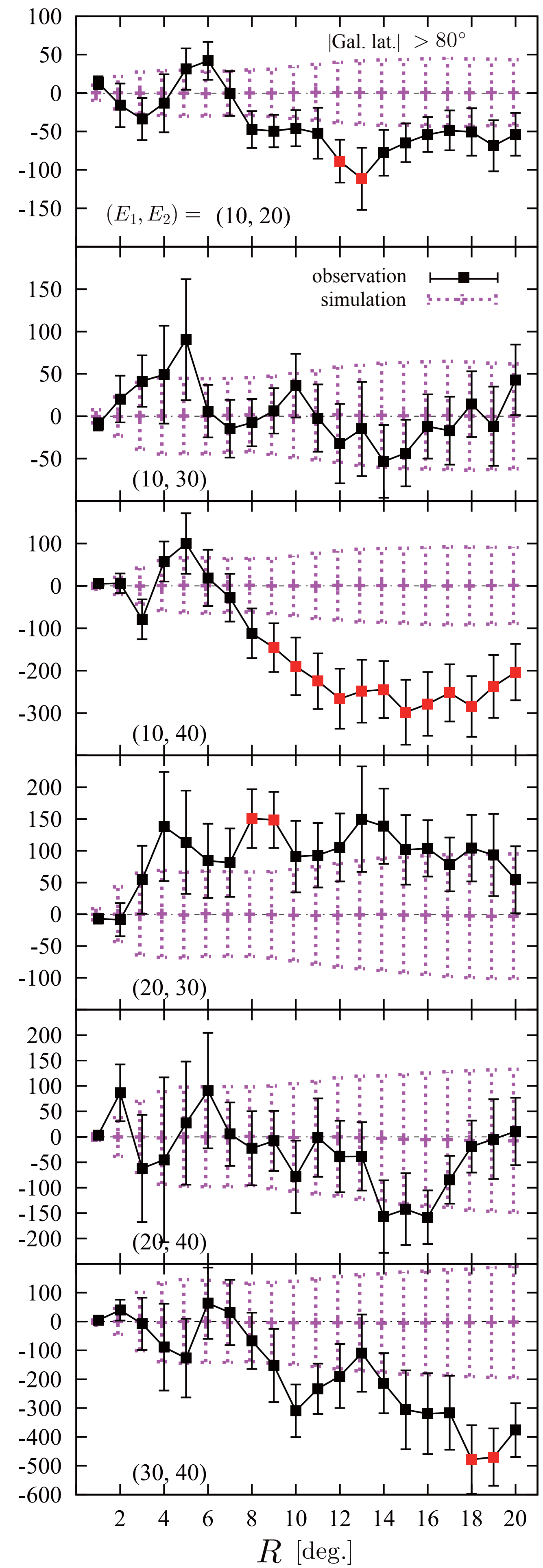
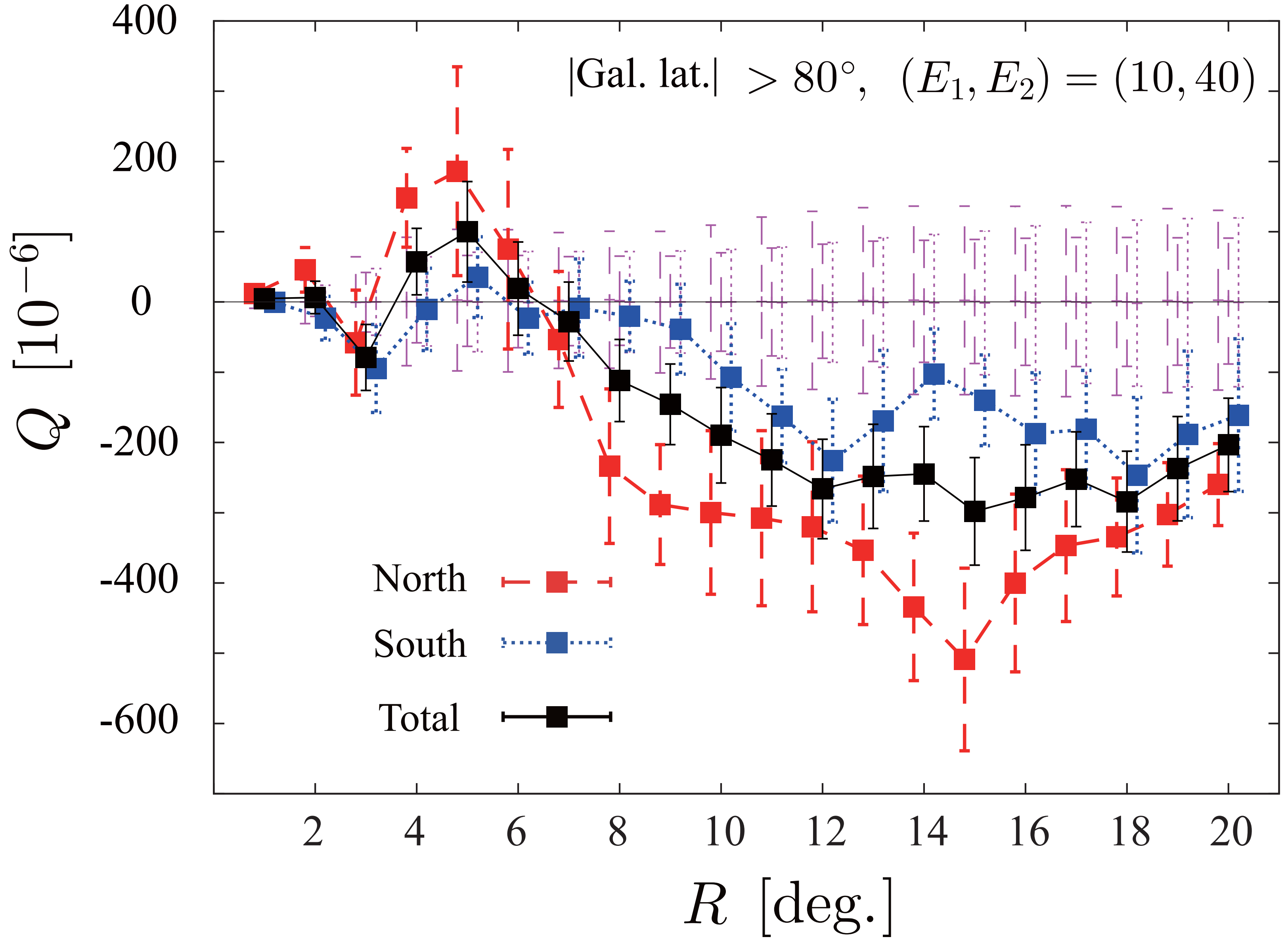


North-South



|Gal. lat.| > 80°, (E_1, E_2) = (10, 40)
400
200
0
-200
-400
-600
Q [10^{-6}]
2
4
6
8
10
12
14
16
18
20
R [deg.]
North
South
Total

Statistical fluctuation?

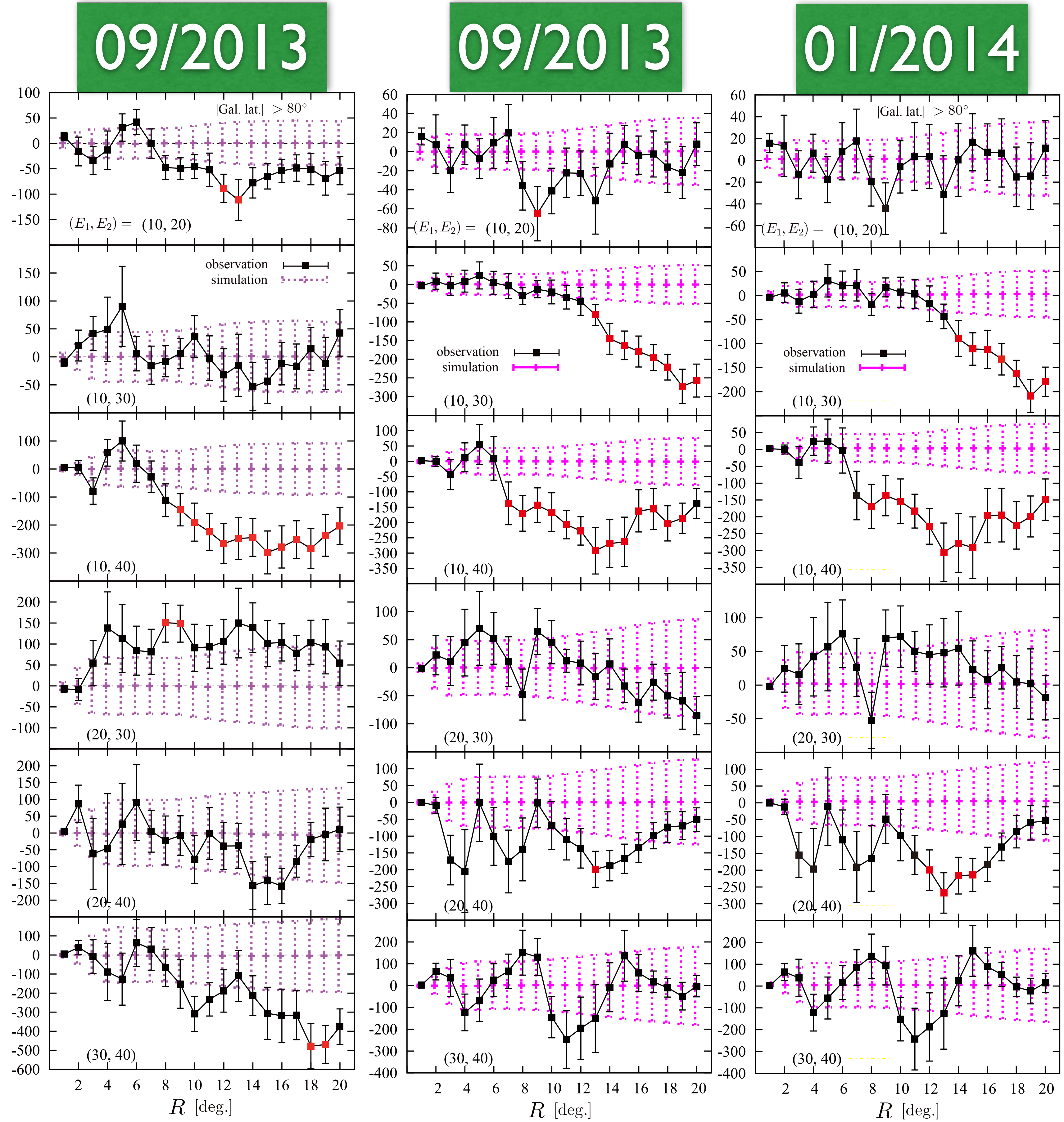
- Statistical chance of similar signal* in synthetic data is ~0.5%.

*Larger than 2-sigma deviation for 12 consecutive R, in any (E1,E2) bin.

Systematics?

- Need a P odd systematic, e.g. rotations of 10 GeV photons around 50 GeV photon directions. Cannot be implemented globally. Tried rotations around poles with no significant change in signal.

From September 2013 to January 2014



“clean” as prescribed 09/2013.

“clean” as prescribed 01/2014.

Analysis Tools at wiki.

Implications for B

Bending angle:

$$\Theta(E_\gamma) \approx 7.3 \times 10^{-5} \left(\frac{B}{10^{-16}\mathrm{G}}\right)\left(\frac{1\mathrm{Gpc}}{D_s}\right)\left(\frac{E_\gamma}{100\mathrm{GeV}}\right)^{-3/2}.$$

$$\Theta \approx 12^\circ,\ E_\gamma \approx 10\ \mathrm{GeV},\ D_s \approx 1\ \mathrm{Gpc}: \quad B \sim 10^{-14}\ \mathrm{G}$$

Energy bins probe length scale: $\xi \sim 10\ \mathrm{Mpc}$

Sign of Q: magnetic field has **left-handed helicity**.

Conclusions

Tantalizing hints* for --

Cosmological CP violation

Cosmological magnetic field

Cosmological matter-genesis

Cosmological phase transition

...

*in order of increasing theoretical input

Coherence Scale

Length scale grows by Hubble expansion and inverse cascade, in radiation- and matter-dominated epochs.

$$
\begin{aligned}
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&\sim 10^{20}\ {\rm cm} \\
&\sim 0.1\ {\rm kpc}
\end{aligned}
$$

Expect