Cosmological Magnetic Fields

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Cosmology Initiative

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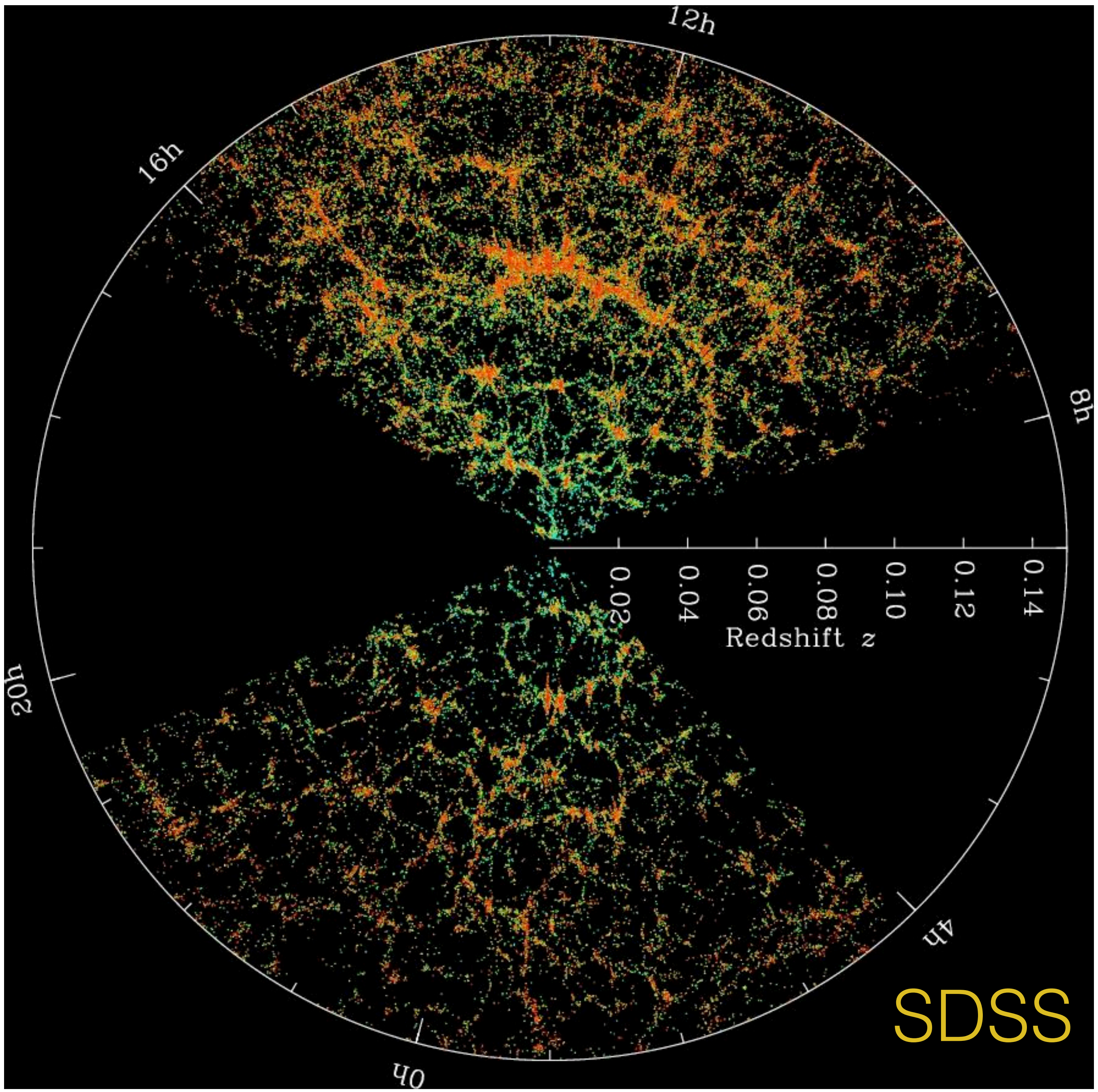
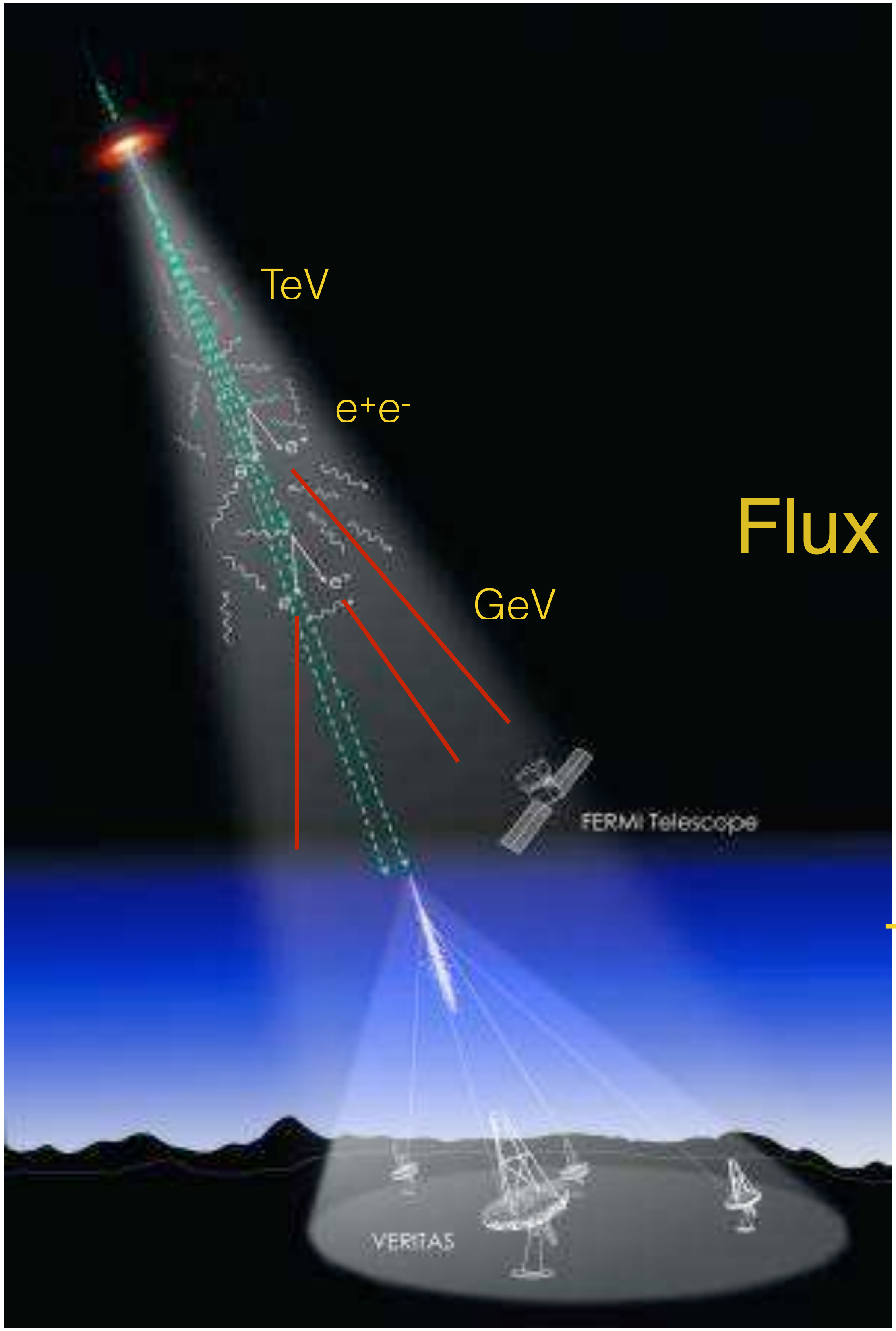
(arXiv:2010.10525)

The Question

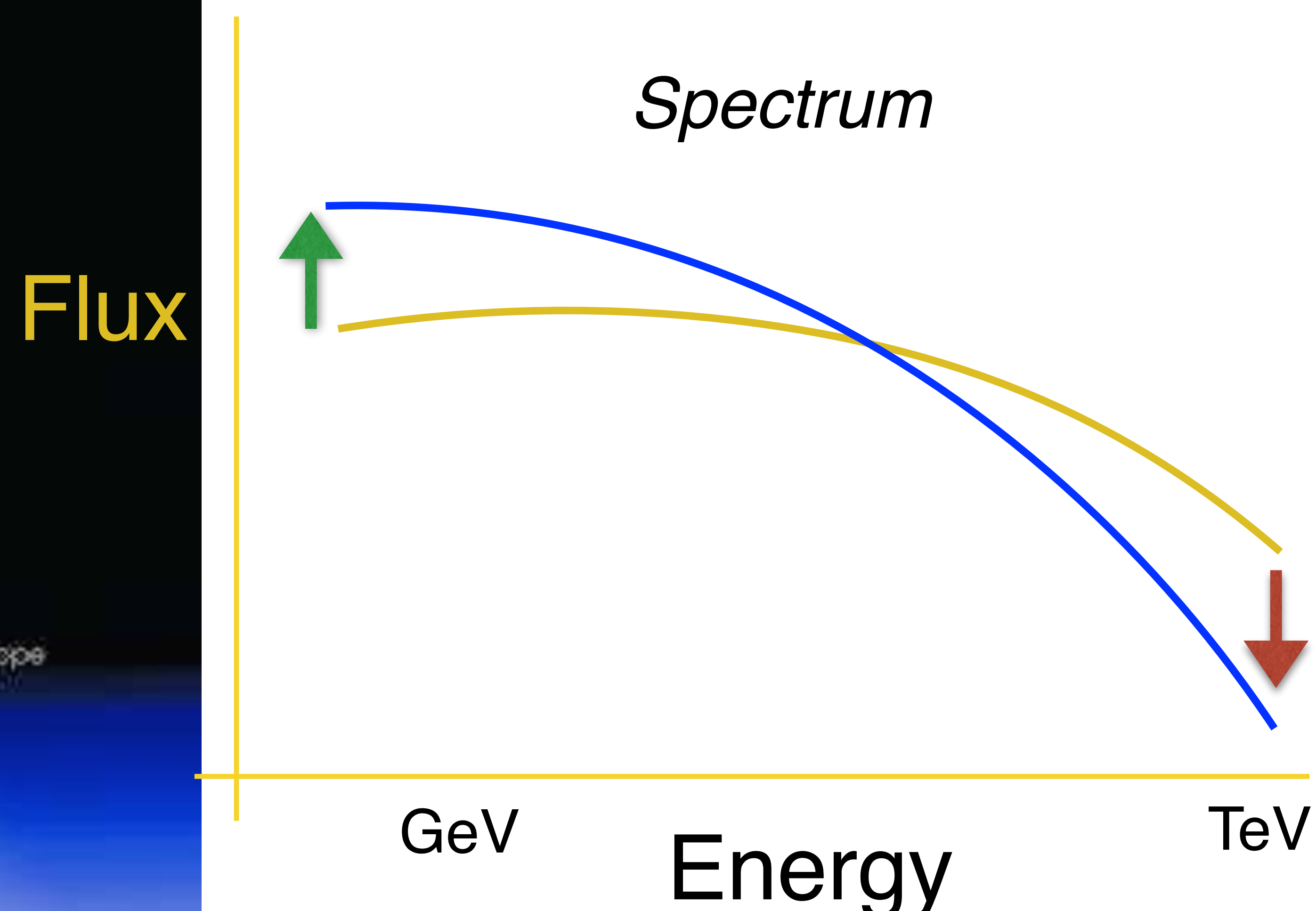


Are voids magnetized?
Voids are ~50 Mpc
in size.

Blazar gamma ray spectrum

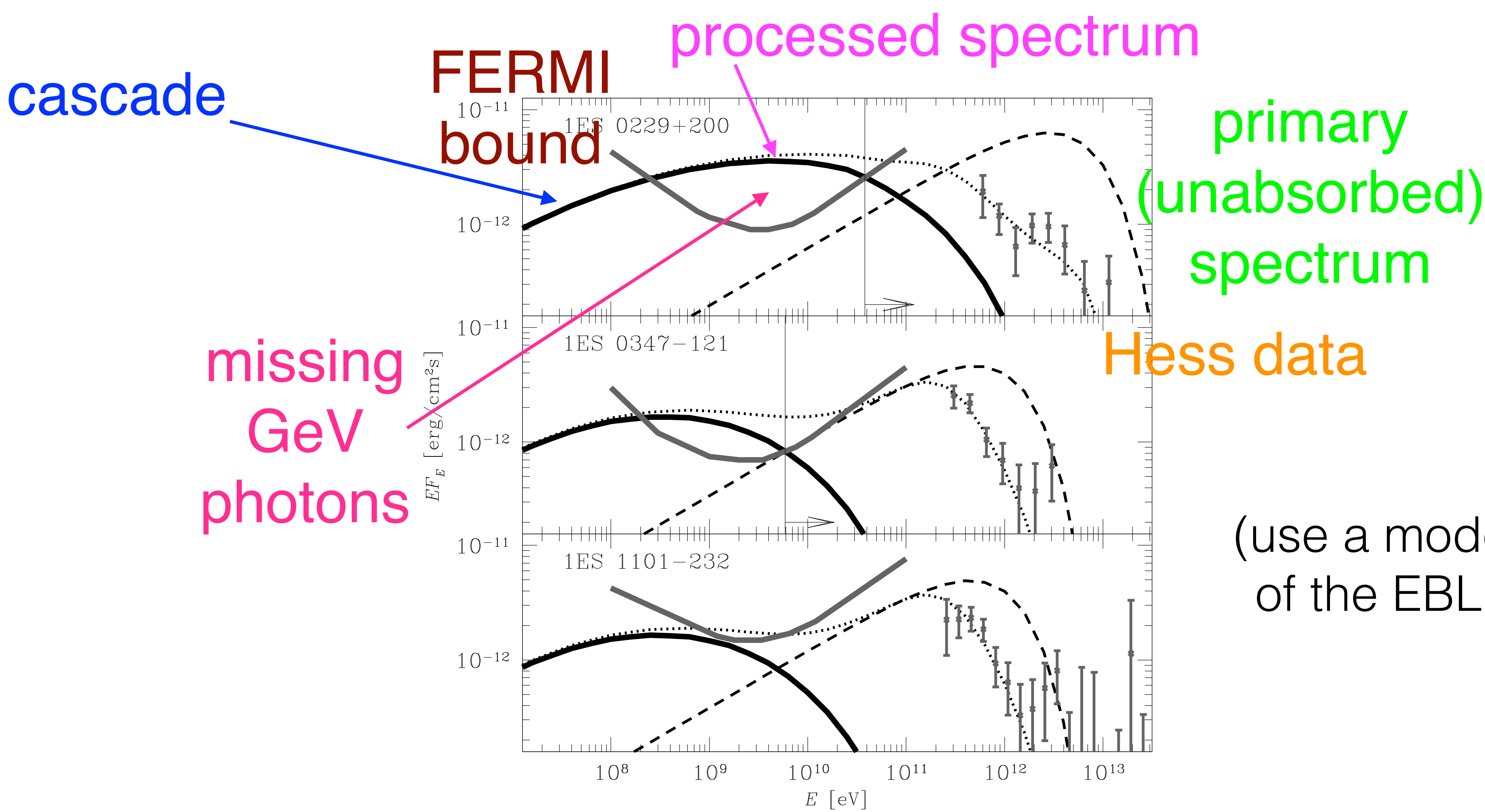


Credit: Nina McCurdy and Joel R. Primack/UC-HiPACC



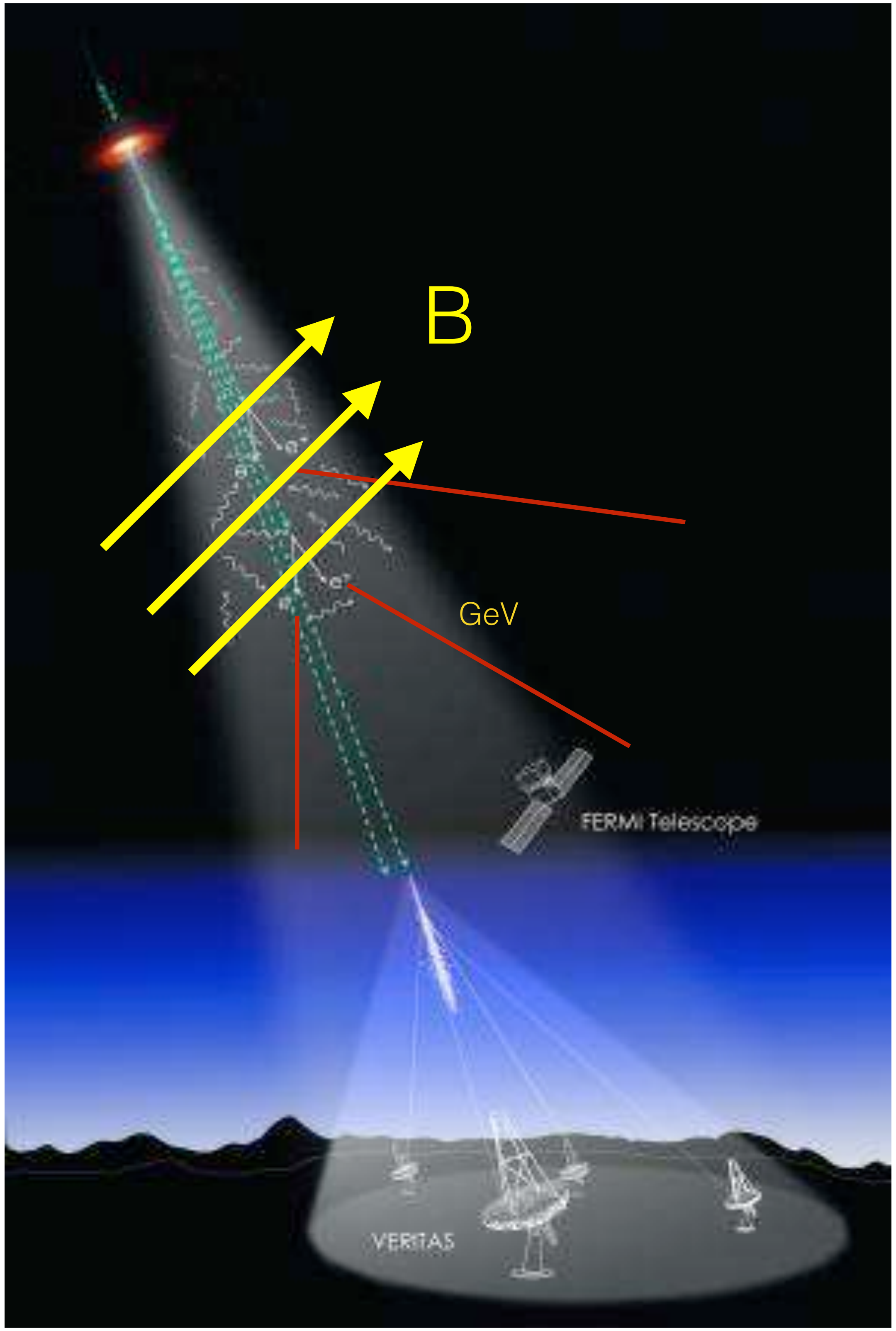
A Lower Bound

Neronov & Vovk, 2010
Essey, Ando & Kusenko 2011
(and several other groups since)



(use a model of the EBL)

Blazar Cascades + **B**



Credit: Nina McCurdy and Joel R. Primack/UC-HiPACC

GeV flux gets spread out by magnetic field and becomes too dilute to distinguish from background for strong enough B.

Missing GeV photons attributed to e.g. B > 10^{-16} Gauss uniform on 1 Mpc

Magnetic field lower bounds:

Neronov & Vovk, 1006.3504
Tavecchio, Ghisellini, Foschini, Bonnoli, Ghirlanda & Coppi, 1004.1329
Dolag, Kachelriess, Ostapenko, Tomas, 1009.1782
Dermer, Cavadini, Razzaque, Finke, Chiang & Lott, 1011.6660
Essey, Ando & Kusenko, 1012.5313
Taylor, Vovk & Neronov, 1101.0932
Huan, Weisberger, Arlen & Wakely, 1106.1218
Takahashi, Mori, Ichiki, Inoue & Takami, 1303.3069
Finke et al, 1510.02485
Ackermannn et al (Fermi-Lat), 1804.08035
Podlesnyi, Dzhatdoev & Galkin, 2204.11110

Plasma instability debate:

Broderick, Chang & Pfrommer, 1106.5494, …
Schlickeiser, Ibscher & Supsar, Ap. J. 758, 102 (2012).
Miniati & Elyiv, 1208.1761
Batista, Saveliev & Dal Pino, 1904.13345

Halo Detection: Stacked Analyses

Ando & Kusenko, 2010

Chen, Buckley & Ferrer, 2015

Detection of cascade photons from (stacked) sources.

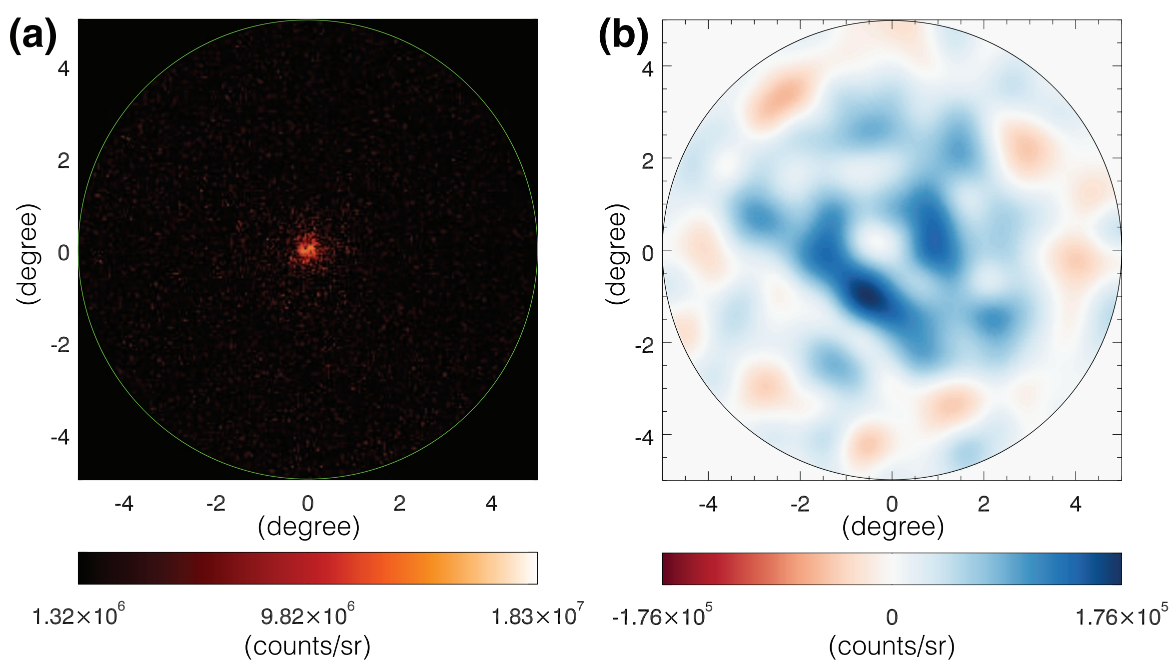
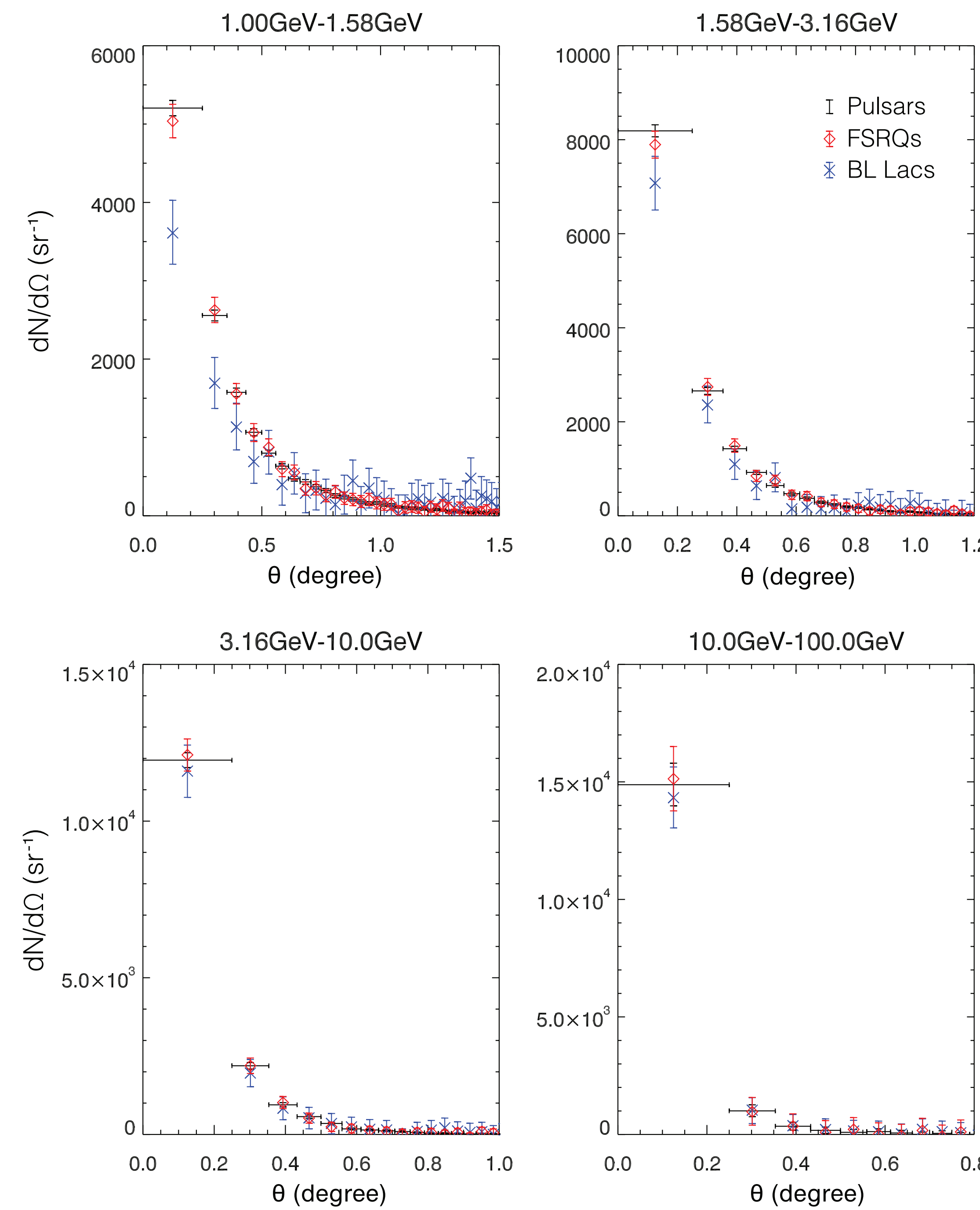


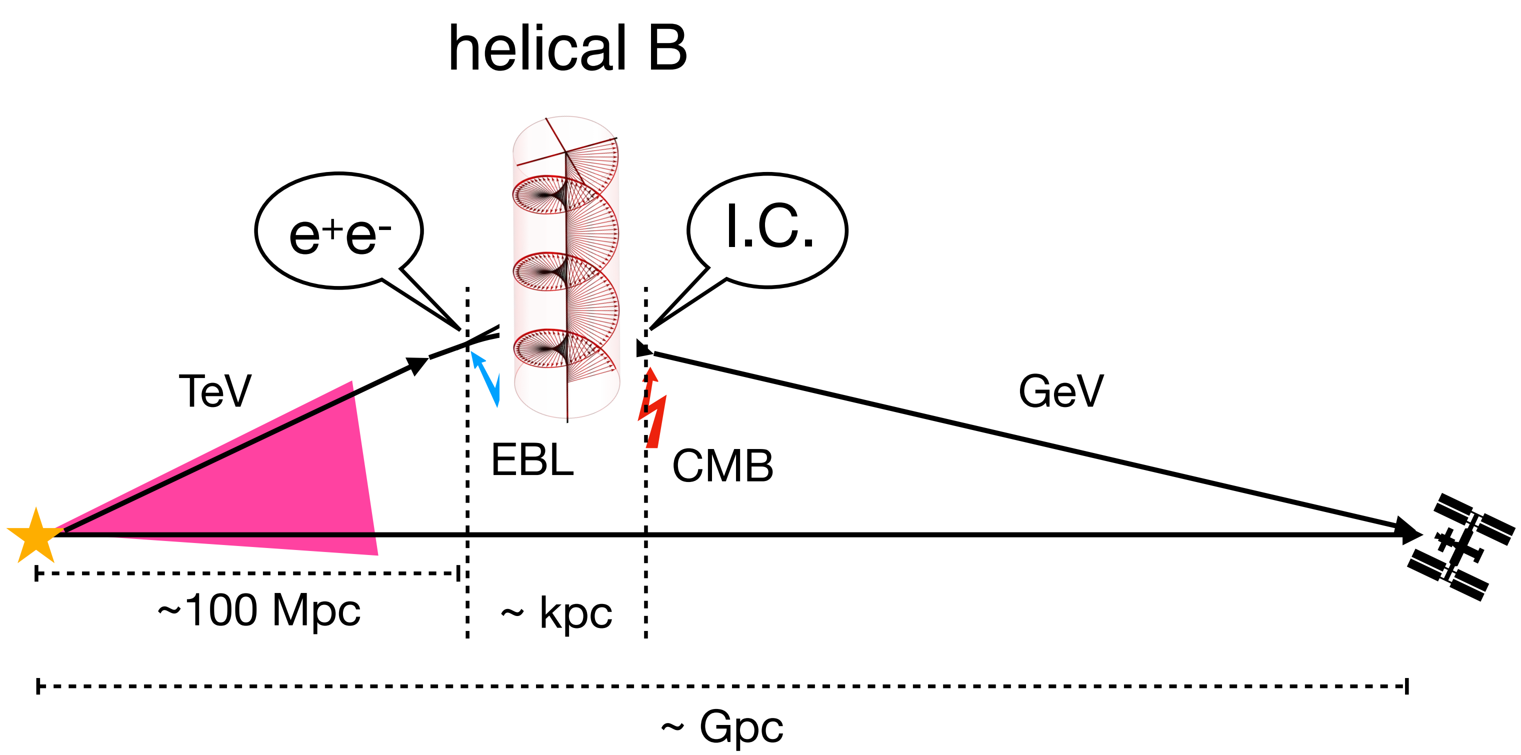
FIG. 1. γ-ray counts maps of the stacked sources in the 1GeV-1.58GeV energy bin. The large circles show the outer edge of the detection region. (a) Counts map of the 24 stacked low-redshift HSP BL Lacs. (b) Smoothed counts difference between the stacked BL Lacs and the center-normalized stacked FSRQs. Positive values indicate the BL Lacs' counts is greater than the FSRQs'.



Halo detected at ~3.5 sigma.

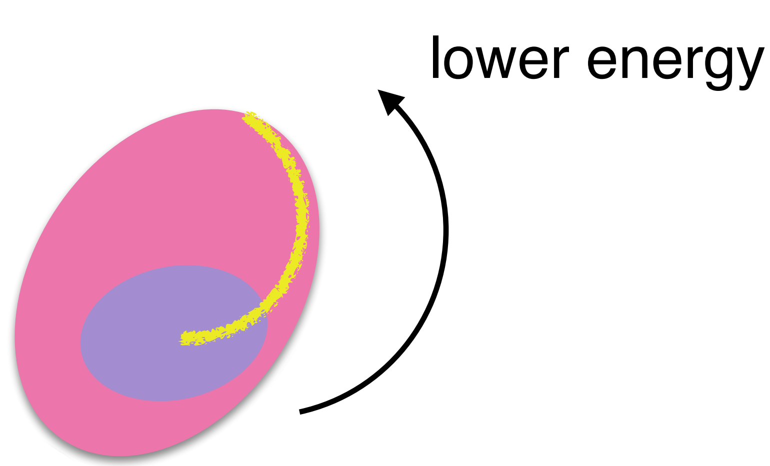
Halo shape and magnetic helicity

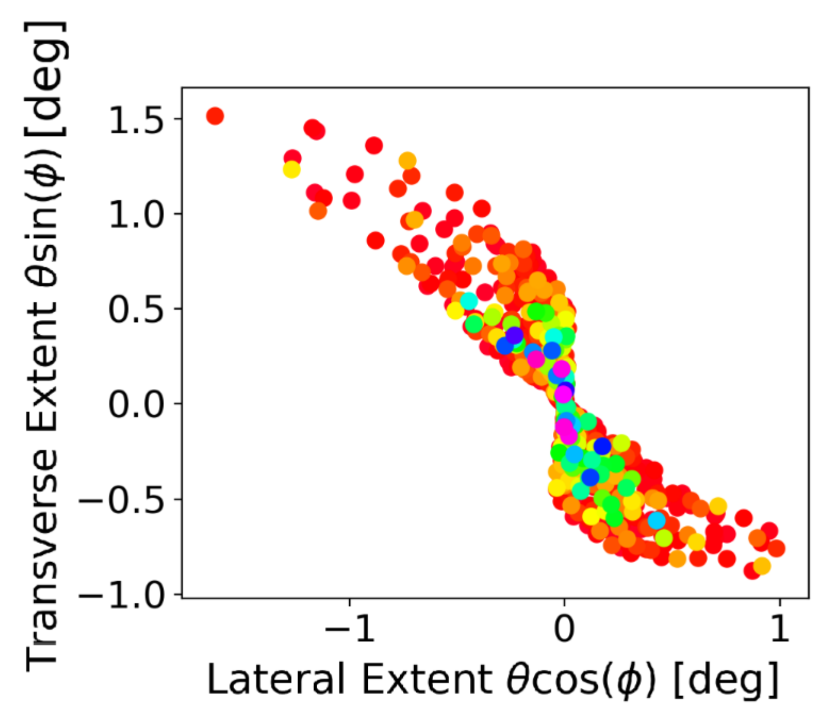
$\text{helicity} \sim \mathbf{B} \cdot \nabla \times \mathbf{B}$



Elyiv, Nerolnov & Semikoz
Tashiro & TV
Duplessis & TV
Long & TV
Batista, Saveliev, Sigl & TV
Broderick et al
Tiede et al
Fitousi et al

Morphology:





Tashiro, Chen, Ferrer & TV
Asplund, Johannesson & Brandenberg
Kachelriess & Martinez

B & CMB

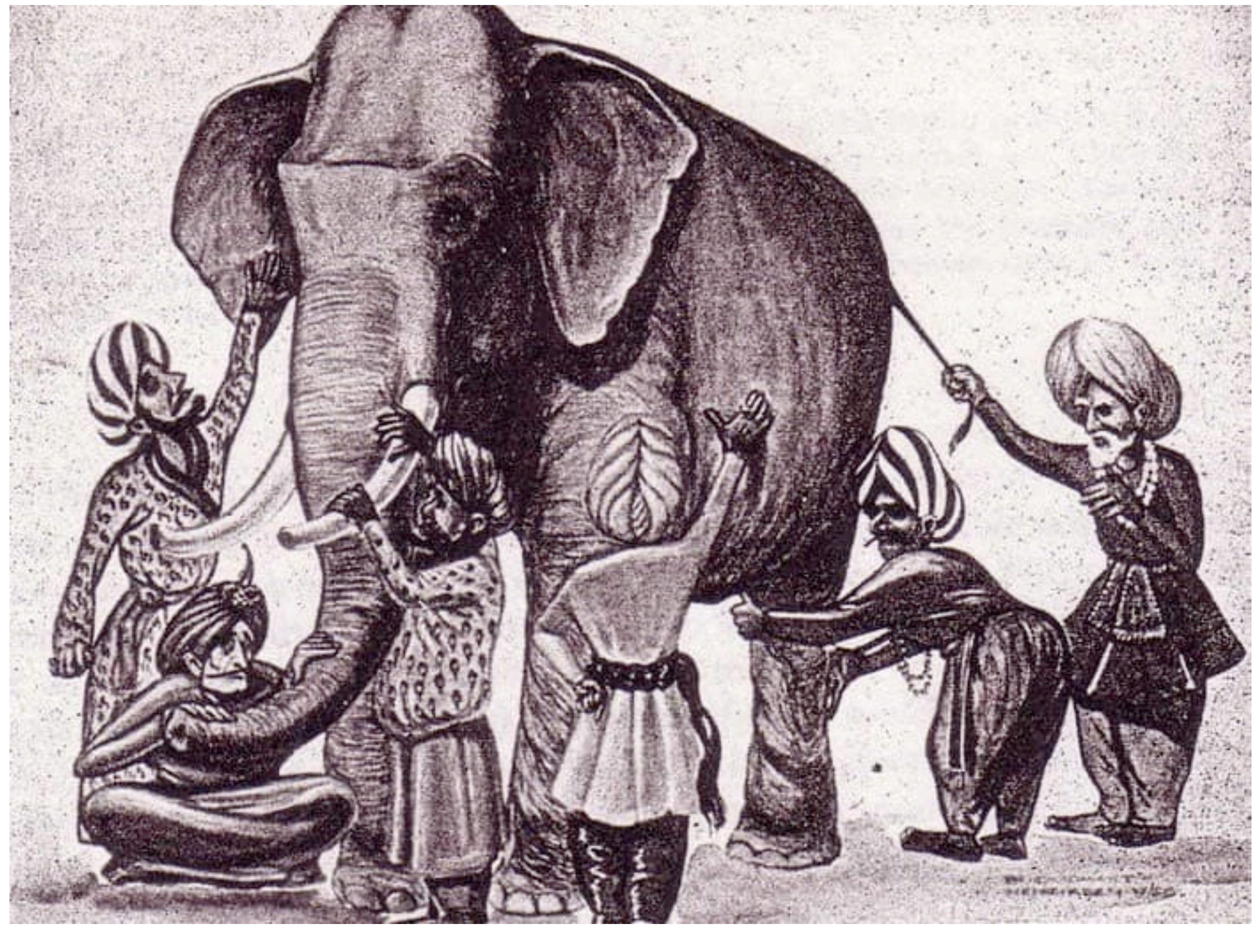
Primordial magnetic fields lead to *inhomogeneous* cosmic recombination.

Jedamzik & Abel, 2013
Jedamzik & Saveliev, 2018

Inhomogeneous cosmic recombination due to magnetic fields can help to at least partially resolve the “Hubble tension”. (Further work ongoing.)

Jedamzik & Pogosian, 2020
Jedamzik, Pogosian & Zhao, 2021
Rashkovetskyi, Munoz, Eisenstein & Dvorkin, 2021
Thien, Gial, Hill, Kosowsky & Spergel, 2021
Galli, Pogosian, Jedamzik & Balkehol, 2022

Time to turn the elephant around….



…and look at it from the particle physics viewpoint.

What could have magnetized the Universe?

Several ideas (using known-unknown physics and with a range of assumptions):

astrophysical outflows;
turbulence at recombination;
axions & QCD;
QCD physics;
cosmic inflation…
electroweak symmetry breaking

Harrison;
Turner & Widrow;
TV;
Kisslinger;
Miniati, Gregori, Reville & Sarkar;
…

Electroweak to Maxwell

Electroweak: W_i^1, W_i^2, W_i^3, Y_i all massless

<Higgs> ↓

at T~100 GeV (10^{15} K), t~1 ns
— electroweak plasma

Weak; E&M: $\{W_i^+, W_i^-, Z_i^0\}, A_i$ photon massless

Claim: EWSB generates magnetic fields.

Electroweak Vacuum Manifold

The electroweak vacuum manifold is a three-sphere (S^3).

$$V(\phi) = \lambda(|\phi|^2 - \eta^2)^2 = \lambda(\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2 - \eta^2)^2$$

Assume that the VEV is homogeneous…

$$V(\phi) = 0 \implies \phi \in S^3$$

$$\pi_1([SU(2)_L \times U(1)_Y / Z_2]/U(1)_Q) = 1$$

S^3 has no incontractable loops or two-spheres. So the electroweak model has no strings or monopoles *by this criterion*.

The Kibble Argument

but the VEV cannot be homogeneous….

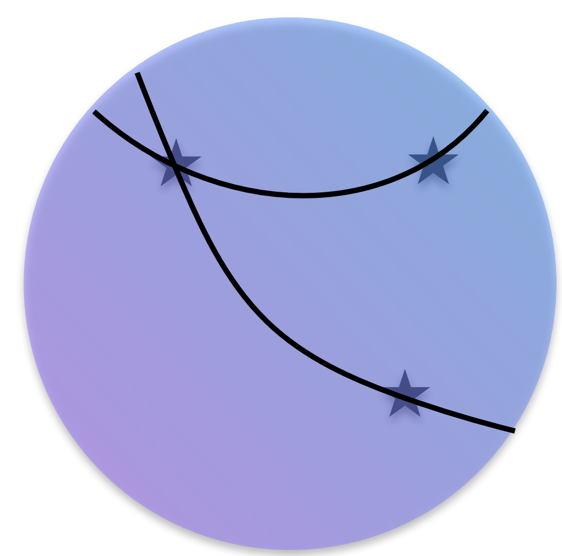
Widely separated domains acquire VEVs independently.

Gradients

Gradient terms must be included for inhomogeneous fields.

The gauge structure defines preferred orbits on the vacuum manifold.
(Like roads in the landscape.)

A point on the vacuum manifold.

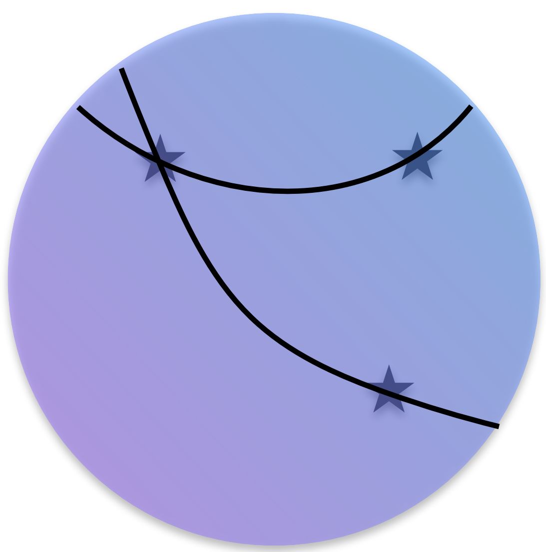


Points on the vacuum manifold
and paths connecting them.

Electroweak Gauge Sector

It is better to think of the electroweak vacuum manifold as the Hopf fibered form of S^3.

This is clearest in the semilocal limit: $g_L=0$.



$U(1)_Y$ gauge orbits are circles on the S^3.

Only pairs of points on these gauge orbits result in vanishing gradient energy.

Similarly, with $g_Y=0$, the gauge orbits are S^2's.

Electroweak Gauge Sector

In the standard model, g_L=0.65 and g_Y=0.34, and there are preferred S^2 and S^1 orbits on the vacuum manifold.

Hopf fibration:

$$S^3 \sim S^2 \times S^1$$

base manifold x fiber

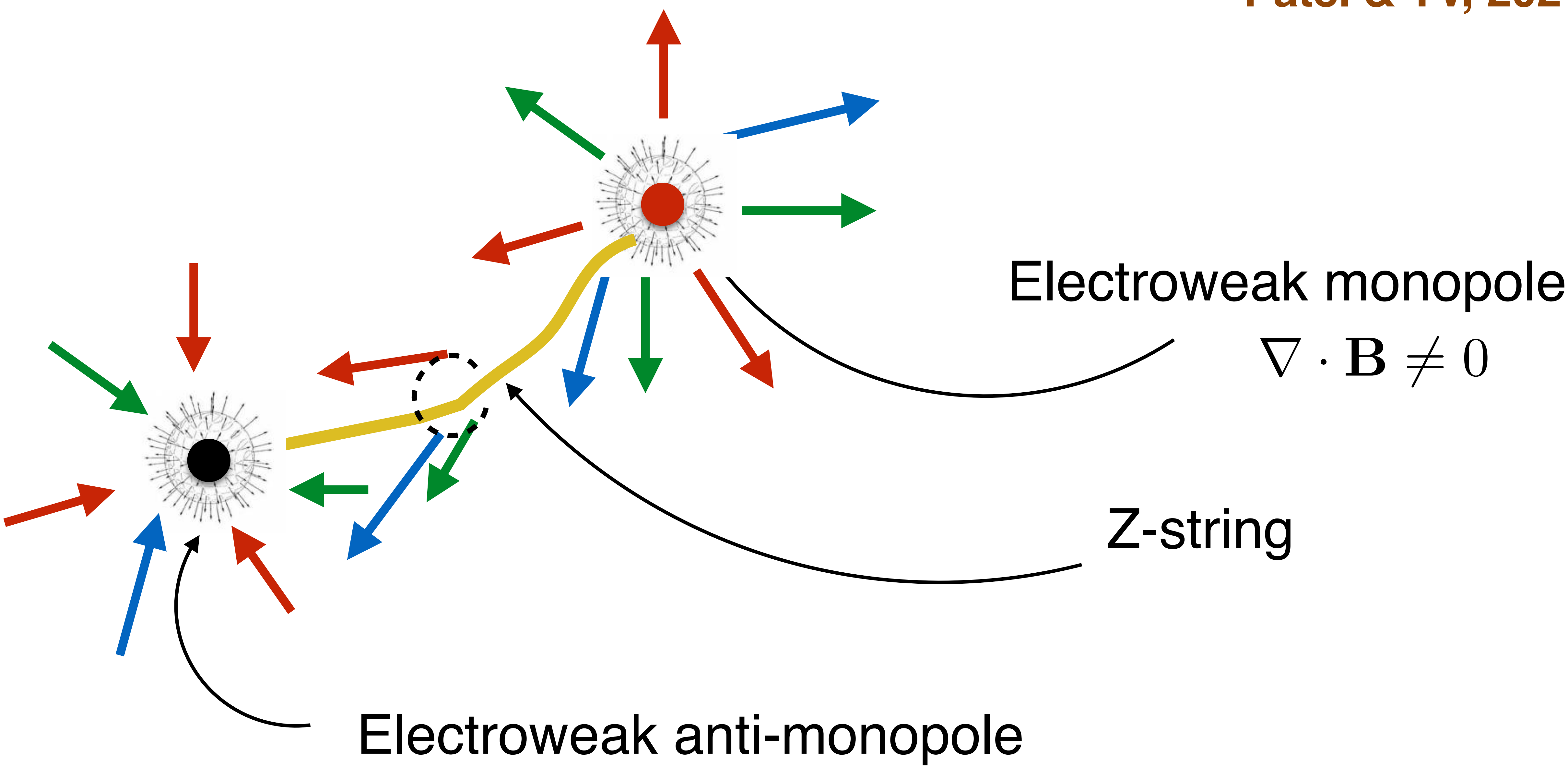
TV & Achucarro, 1991;
Gibbons, Ortiz, Ruiz & Samols, 1992;
Hindmarsh, Holman, Kephart & TV, 1993

Then the electroweak model has *both* magnetic monopoles and strings!

Nambu, 1977; TV, 1992

Electroweak monopoles

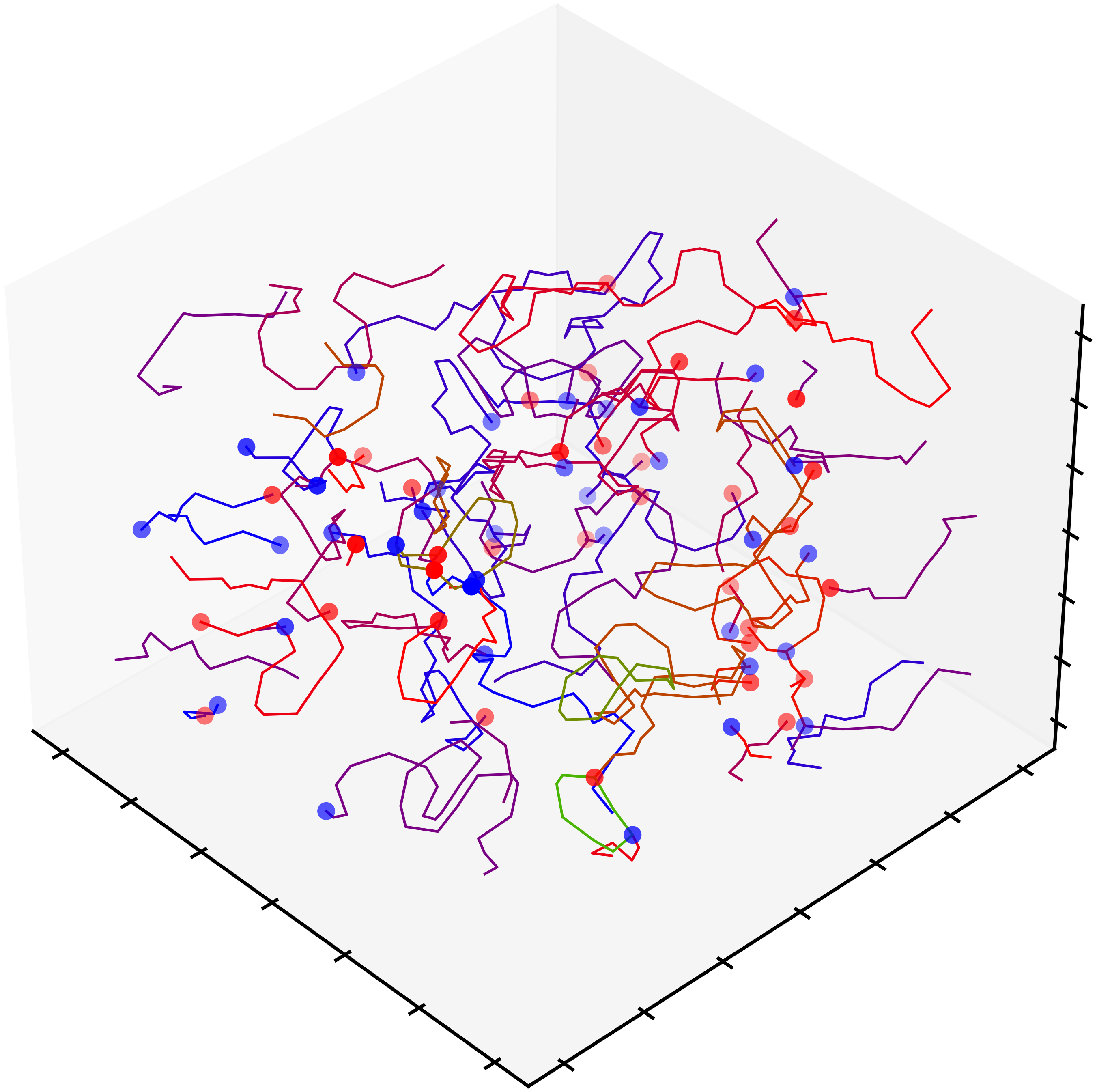
Nambu, 1977
Patel & TV, 2021



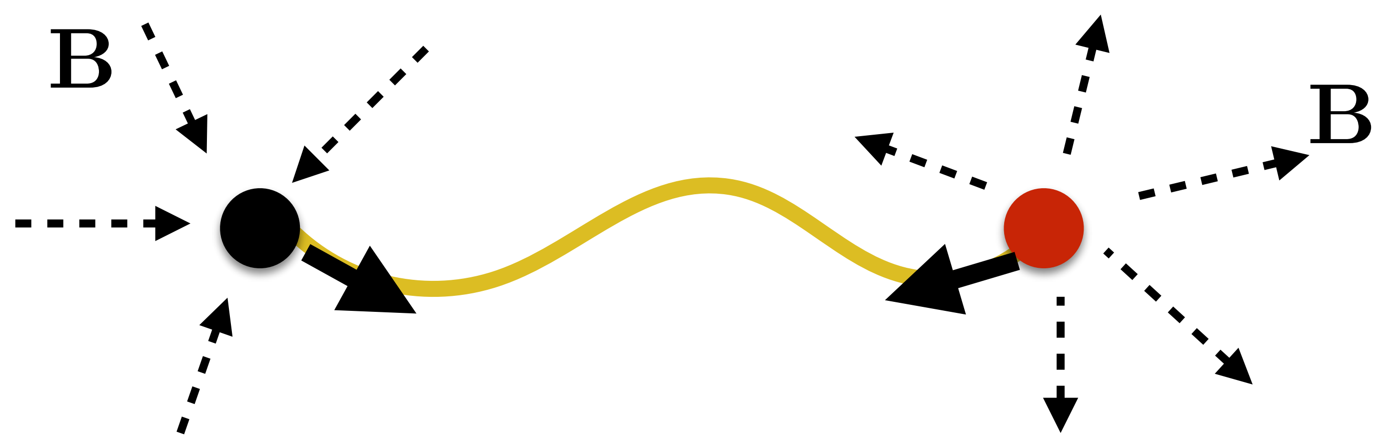
Arrows indicate points on S^2, colors indicate points on S^1.

Monopole-string distribution

Patel & TV, 2021



Fate of monopoles



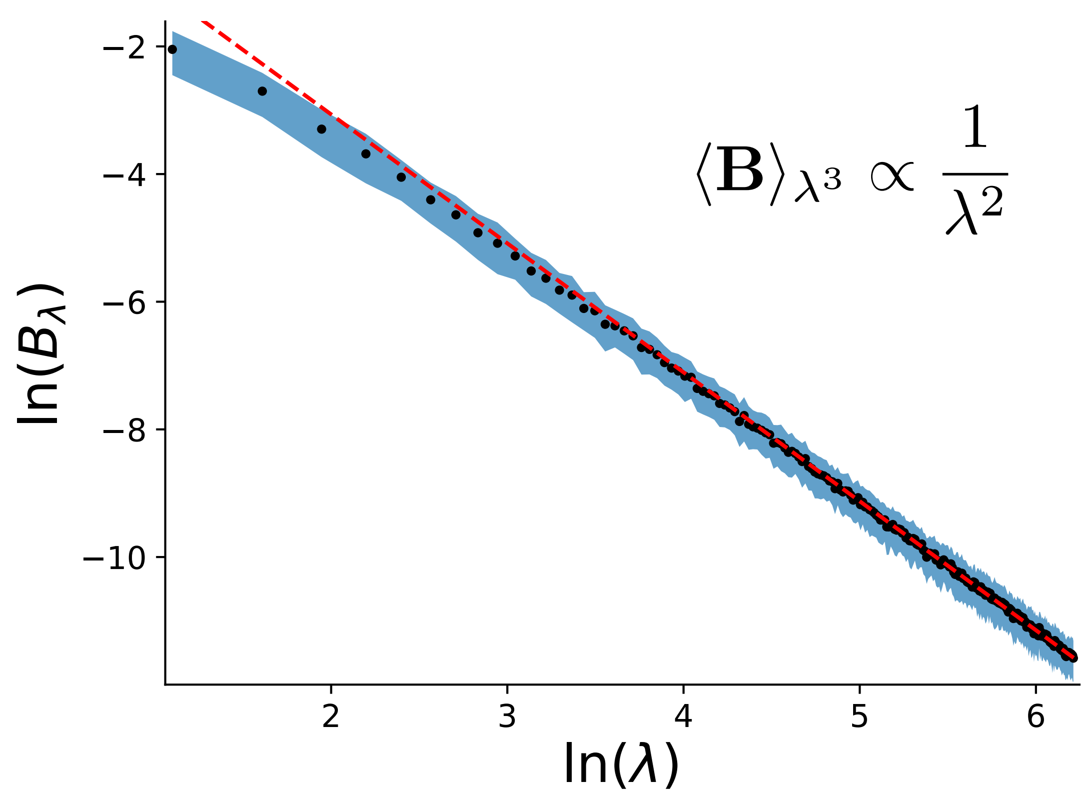
Eventually all the monopoles and anti-monopoles annihilate and leave behind the magnetic field.

$$\mathbf{B} = \nabla \times \mathbf{A} - i\frac{2\sin\theta_w}{g}\nabla\hat{\Phi}^\dagger \times \nabla\hat{\Phi}$$

Fate of the network

Monopole contribution to volume-averaged magnetic field:

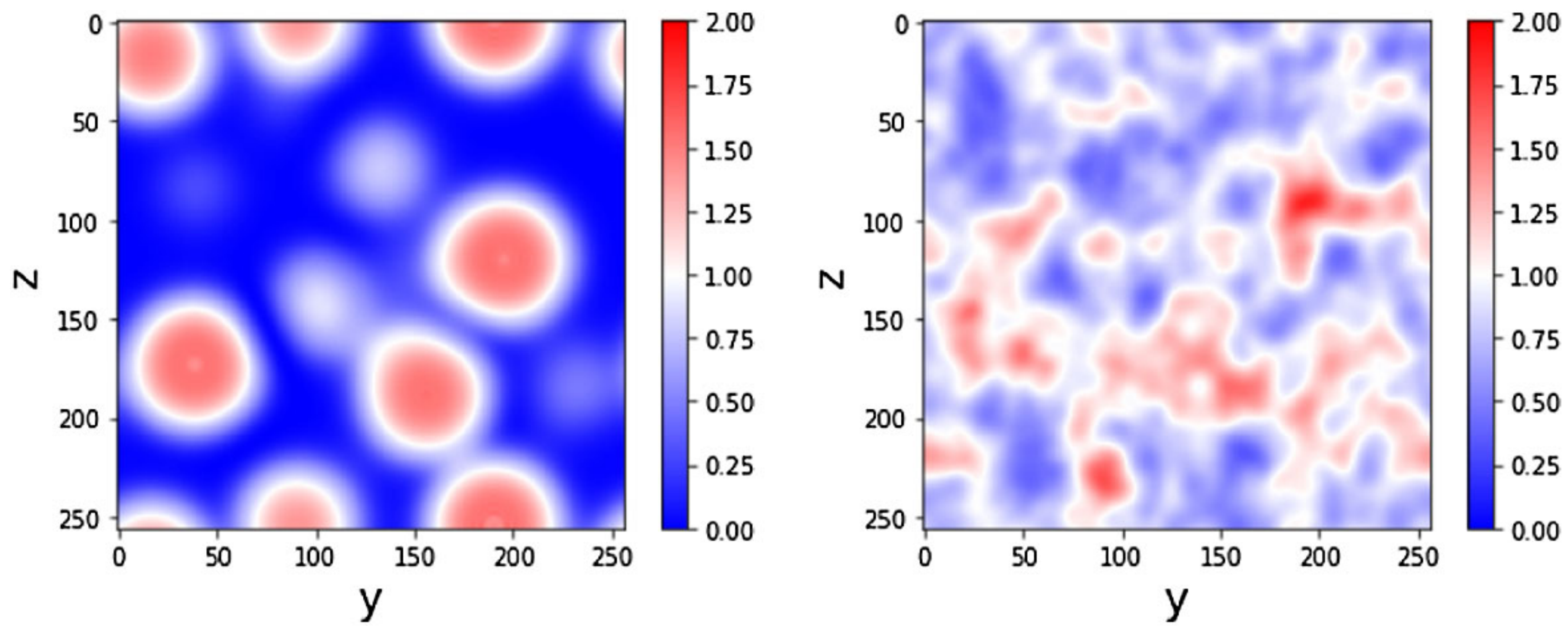
$$\langle \mathbf{B} \rangle_V = \frac{1}{V}\int_V d^3x\,\mathbf{B} = -i\frac{2\sin\theta_w}{gV}\int_{\partial V} d\mathbf{S}\times(\hat{\Phi}^\dagger\nabla\hat{\Phi})$$



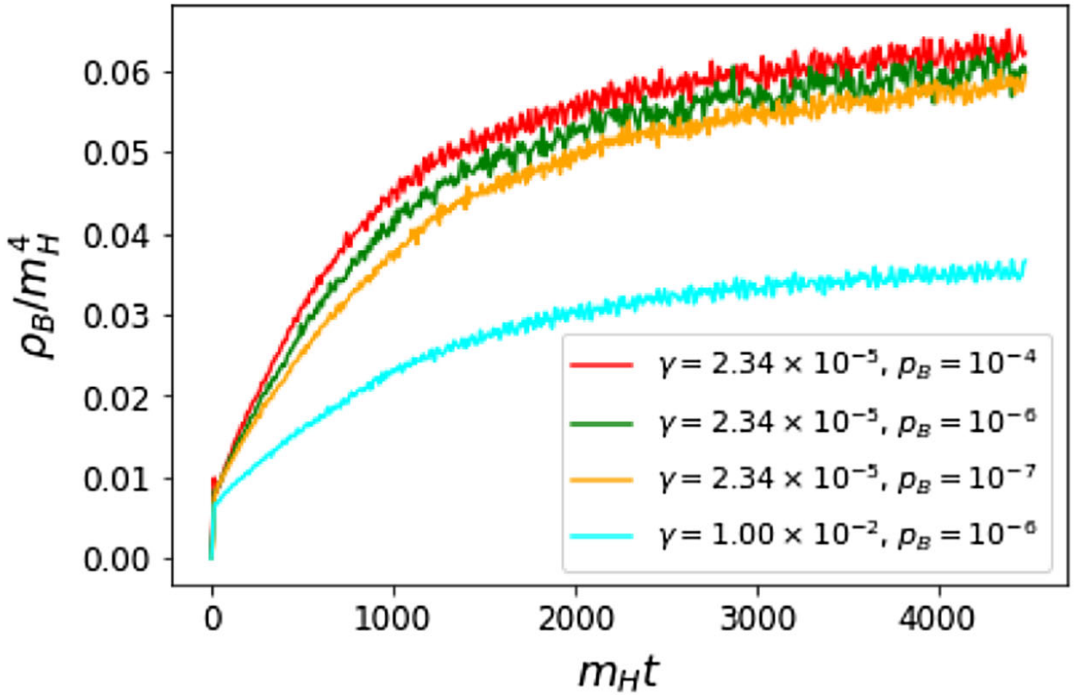
$\langle \mathbf{B} \rangle_{\lambda^3} \propto \frac{1}{\lambda^2}$ or, $\mathbf{B}(k) \propto k^2$

Direct simulations of EWSB

Diaz-Gil, Garcia-Bellido, Perez & Gonzalez-Arroyo
Mou, Saffin & Tranberg



Zhang, Ferrer & TV



Magnetized Universe

Fractional cosmic energy density in magnetic fields:

$$\Omega_B(t_{EW}) \sim 1\%$$

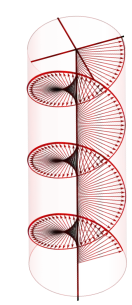
with spectrum: $B_k \propto k^2$

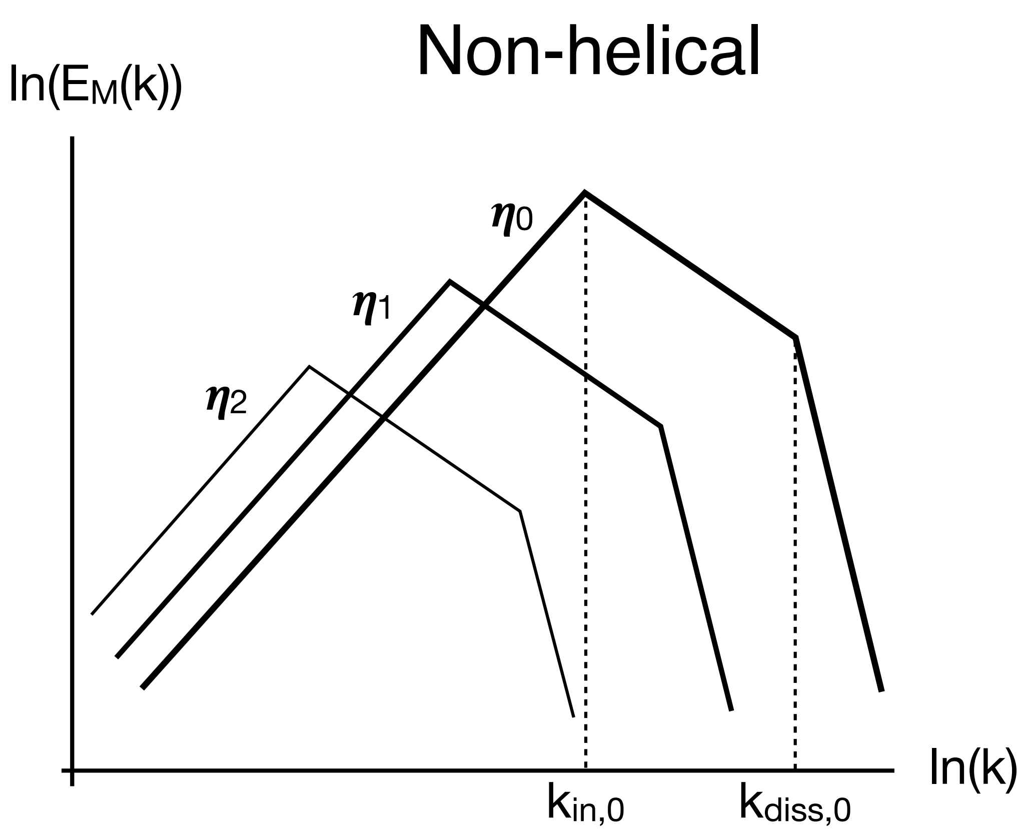
Standard model of particle-cosmology predicts a magnetized Universe.

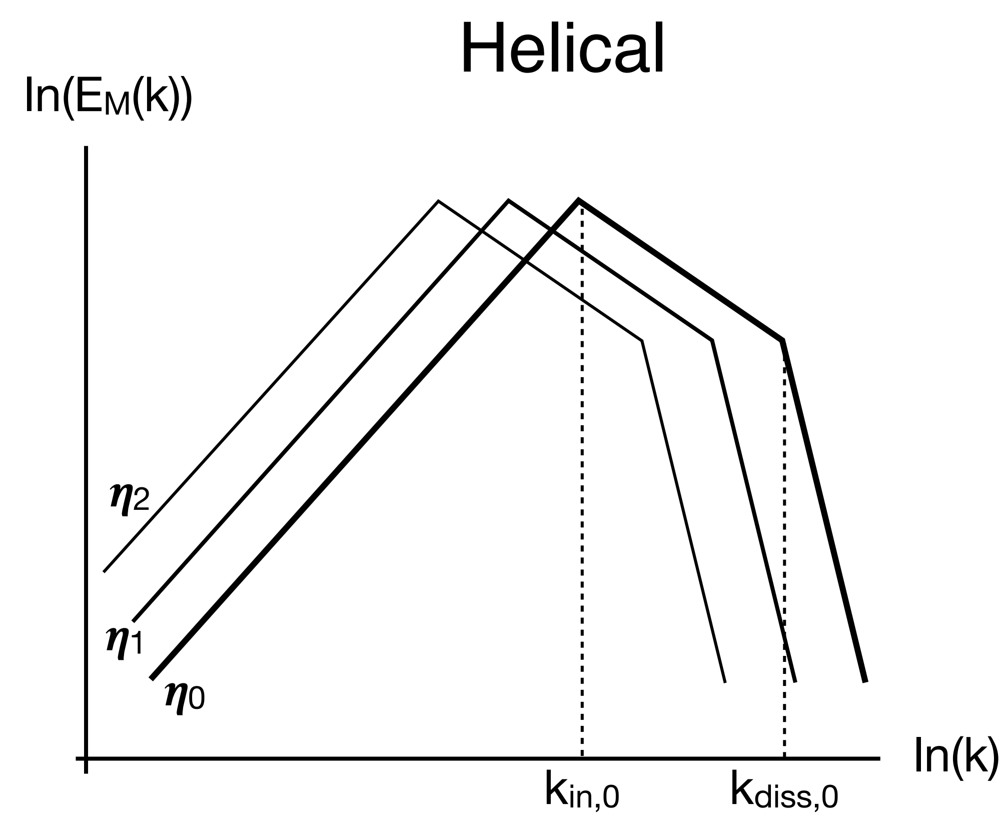
Magnetic field evolution

Banerjee, Barrow, Boyarskyi, Brandenburg, Campanelli, Chirakkara, Christensson, Davis, Dimopoulos, Durrer, Enqvist, Federrath, Frolich, Hindmarsh, Jedamzik, Kahniashvili, Katalinic, Kisslinger, Kleeorin, Neronov, Olesen, Olinto, Pol, Ratra, Reppin, Rogachevskii, Ruchayskiy, Saveliev, Schober, Sigl, Subramanian, Tevzadze, Trivedi, TV, Yin…

$$\text{helicity} \sim \mathbf{B} \cdot \nabla \times \mathbf{B}$$



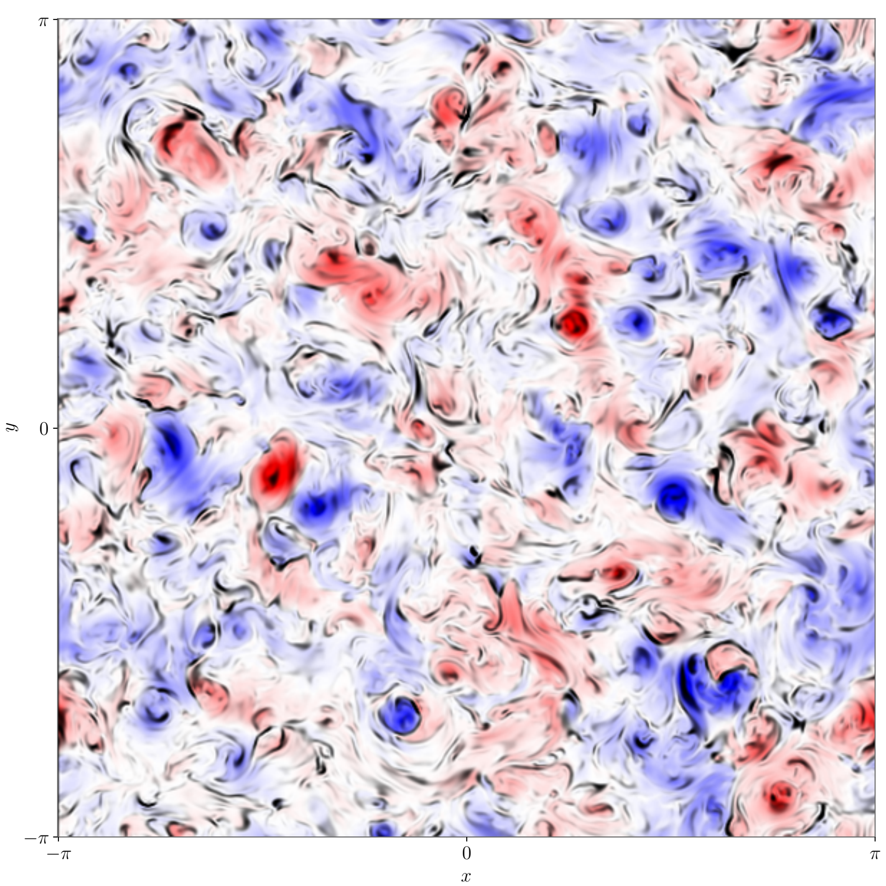


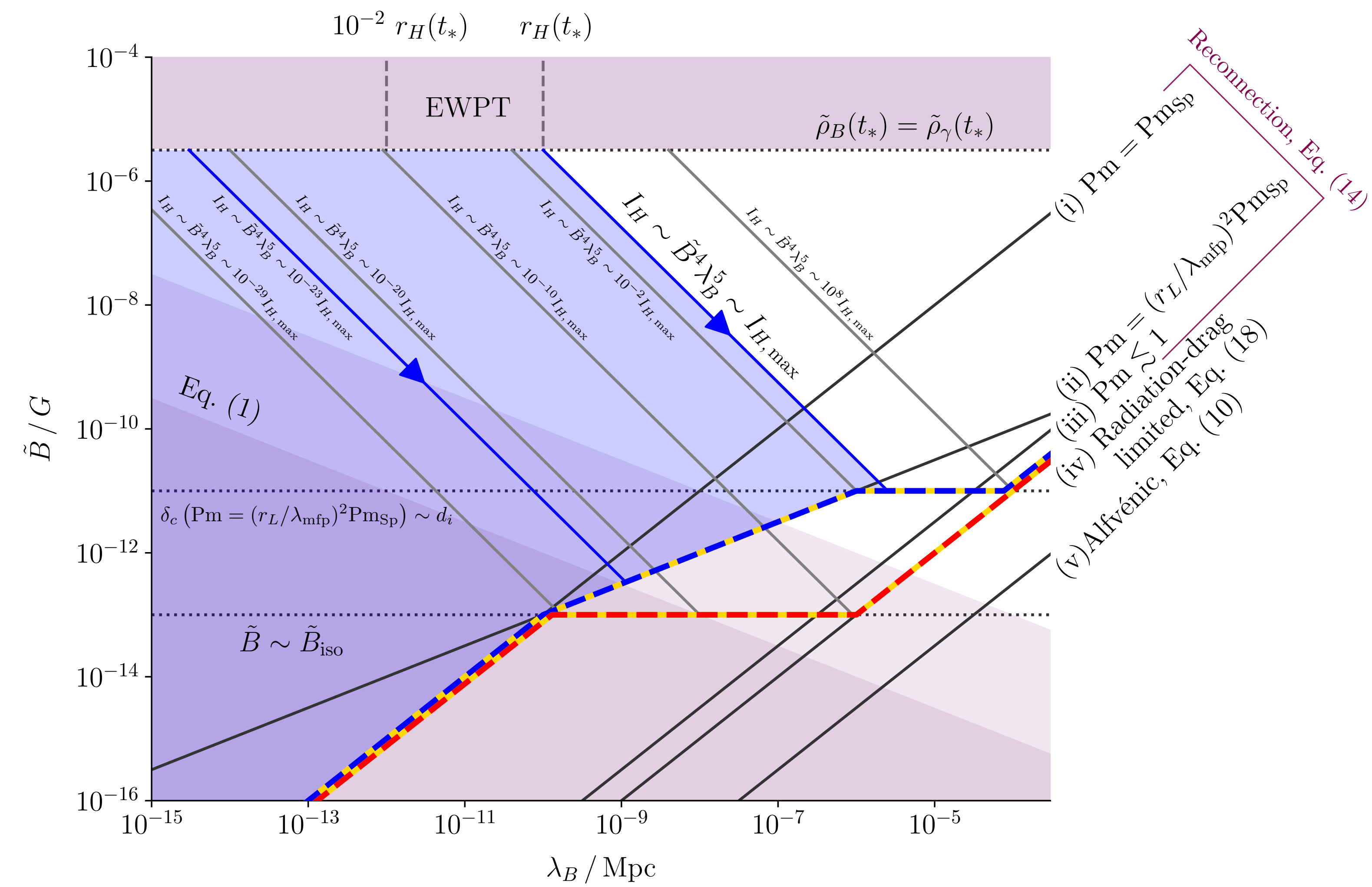


From electroweak epoch to now

Hosking & Schekochihin (2203.03573):

- helicity **fluctuations** are important even for non-helical fields and “helicity Loitsyansky integral” is an invariant. $B^4\lambda^5 \sim$ constant
- field decay on small scales is governed by reconnections.





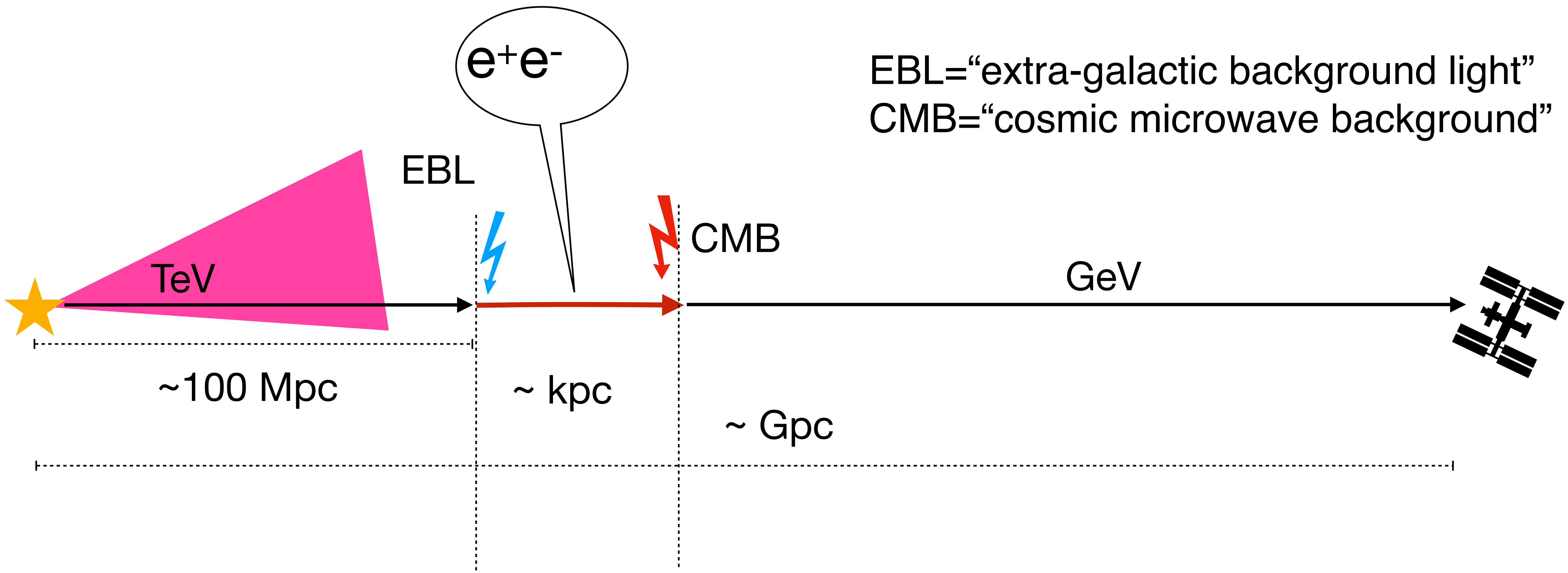
Blazar lower bounds: $B_{1\,\mathrm{Mpc}} \gtrsim 10^{-19} - 10^{-16}\,\mathrm{G}$

Conclusions

- Observations indicate *a magnetized Universe*.
- Standard Model of particle physics predicts a magnetized Universe.
- Evolution of primordial magnetic fields opens up new problems in plasma physics (conservation of helicity fluctuations, chiral phenomena…).
- Primordial magnetic fields imply new astro and cosmological effects (inhomogeneous recombination, blazar halos, magnetic fields in structures,…).

PPC Power!

Blazar Cascades



$$\gamma\gamma_{\mathrm{EBL}} \to e^+e^-$$

pair production (threshold effect)

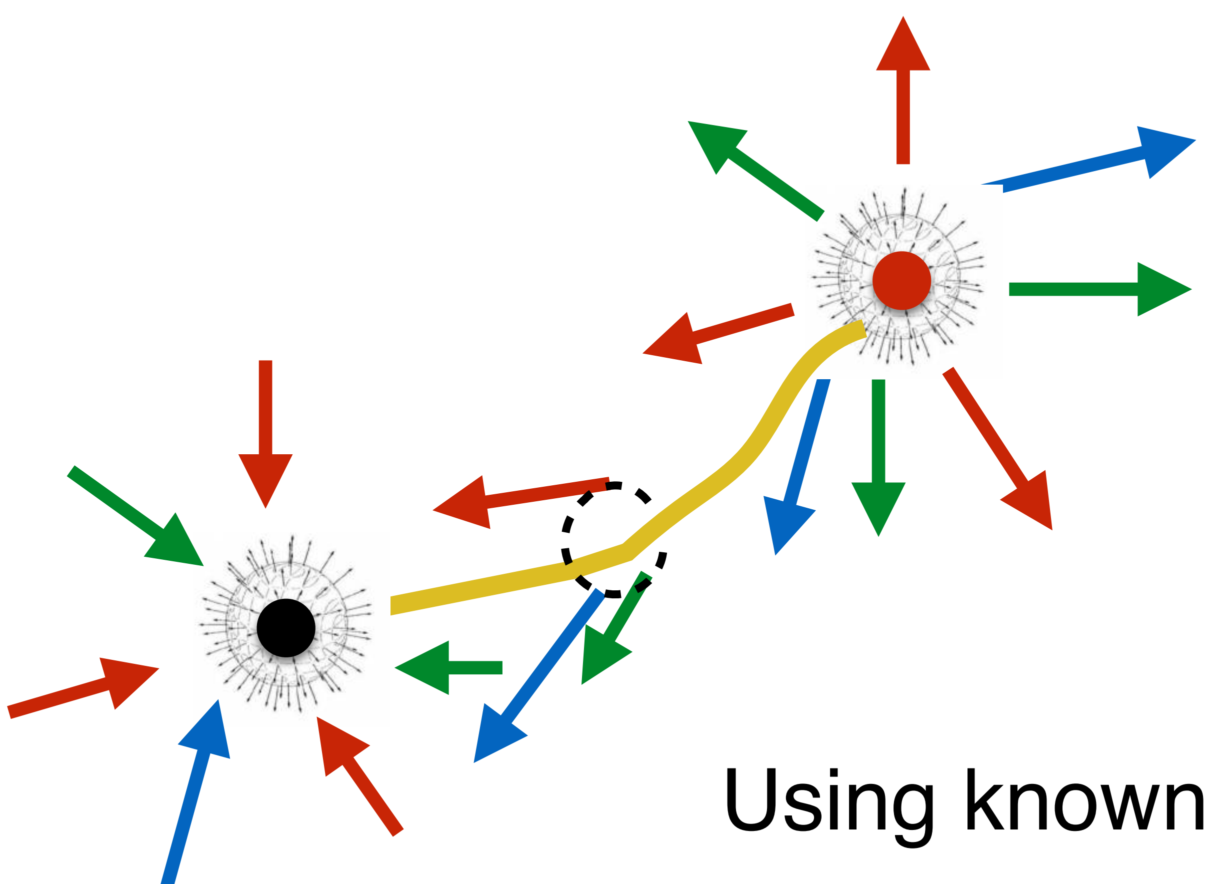
$$e^{\pm}\gamma_{\mathrm{CMB}} \to e^{\pm}\gamma_{\mathrm{GeV}}$$

inverse Compton scattering
(from 10^{-4} eV to 10^{9} eV)

Origin of helicity?

Requires strong Parity (P) & Charge Conjugation+Parity (CP) violation in the early Universe.

(As does the cosmic matter-antimatter asymmetry.)



Twist in the system leads to magnetic helicity and to baryon number when monopoles annihilate.

Using known cosmic baryon number leads to a very small amount of magnetic helicity.