The Magnetized Universe

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Cosmology Initiative

Arizona State University

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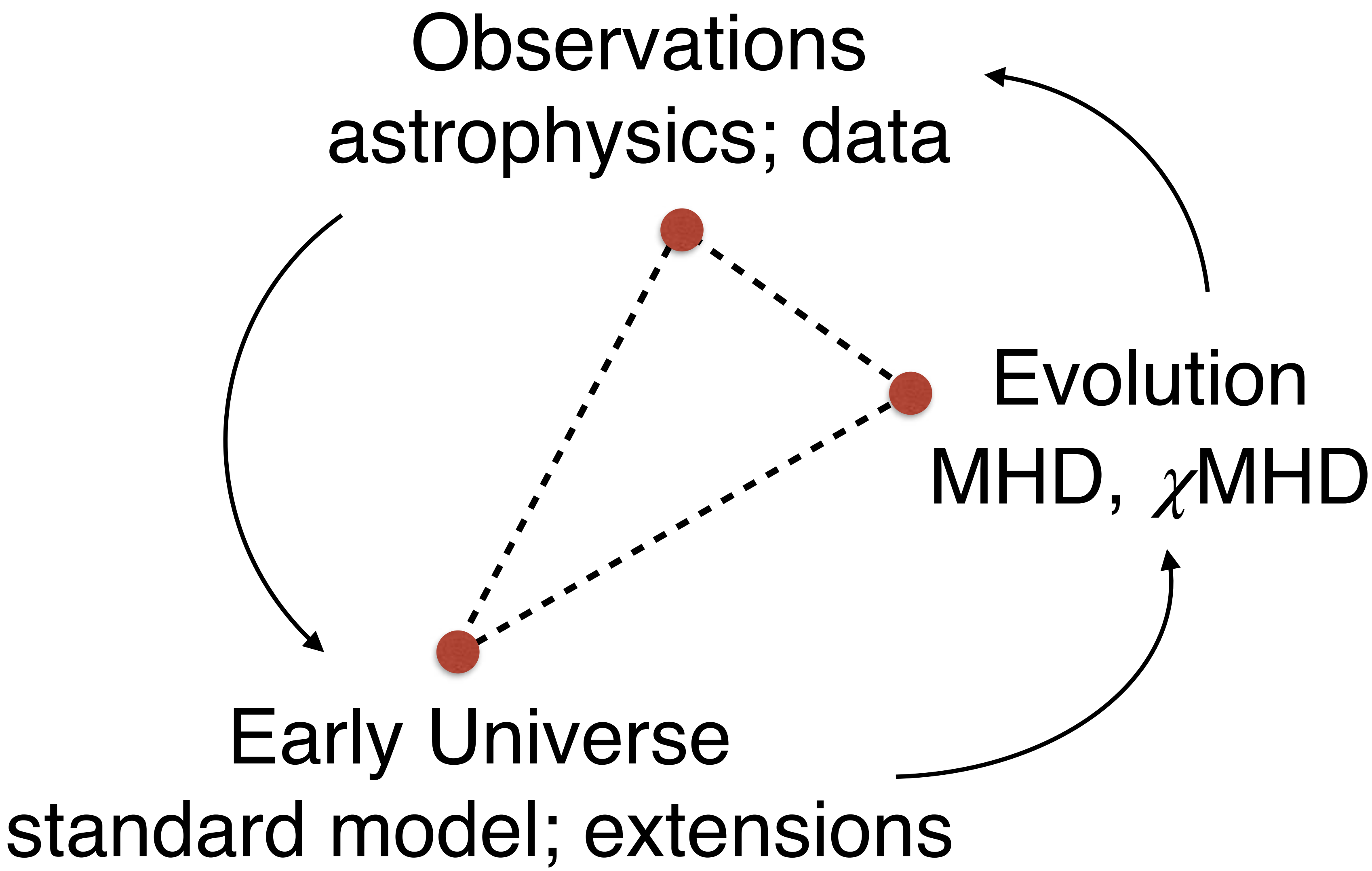
Components


Observations
astrophysics; data
Evolution
MHD, χMHD
Early Universe
standard model; extensions

Observations

[many groups, many decades]

Reviews by Kronberg; Widrow; Durrer & Neronov; Subramanian

Galactic fields: primordial vs. dynamo
(How to explain micro-Gauss fields in galaxies at z > 2?)

Faraday rotation (quasars): *upper bounds of about a nano Gauss on coherent (Gpc) magnetic fields.*

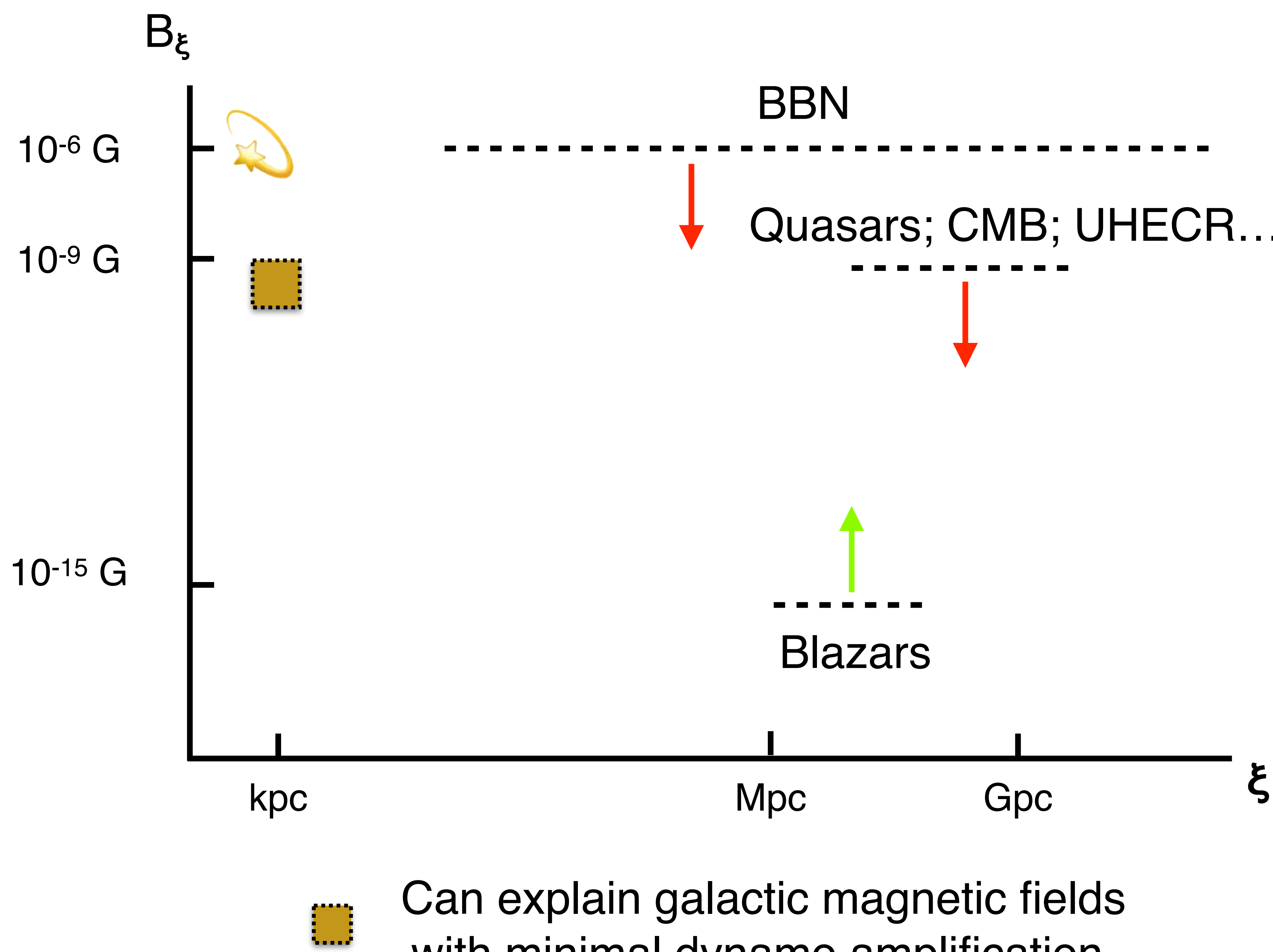
BBN: *Upper bounds at the micro Gauss level on energy density of fields*.

CMB: temperature anisotropies, B-modes.
Upper bounds at the nano Gauss level on coherent fields.

CMB: inhomogeneous recombination. (More later.)

Blazars: *lower bounds* at the 10^{-16} Gauss level on Mpc scales.

Observations: summary plot

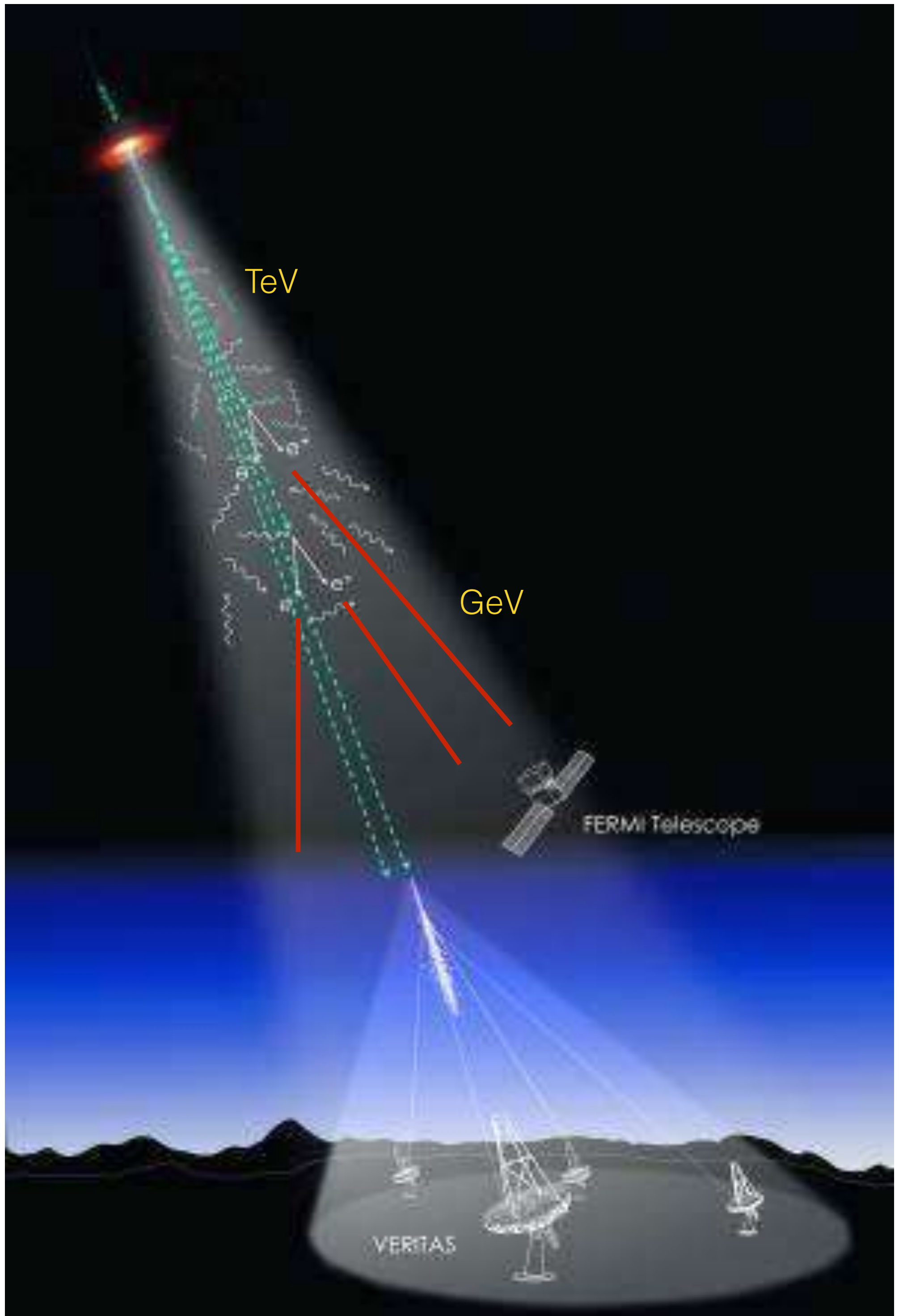


Can explain galactic magnetic fields with minimal dynamo amplification.

Several other constraints, e.g. structure of dwarf galaxies (Sanati et al, 2020).

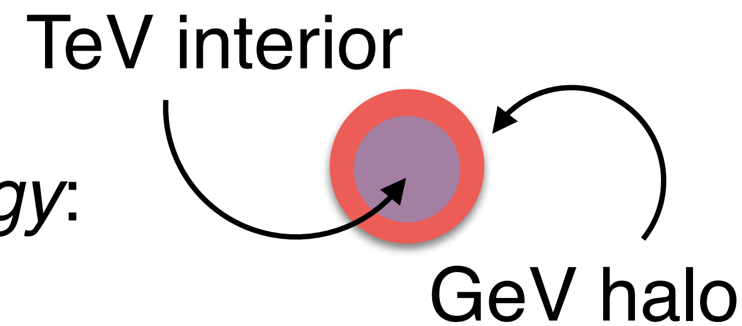
Blazar Cascades

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

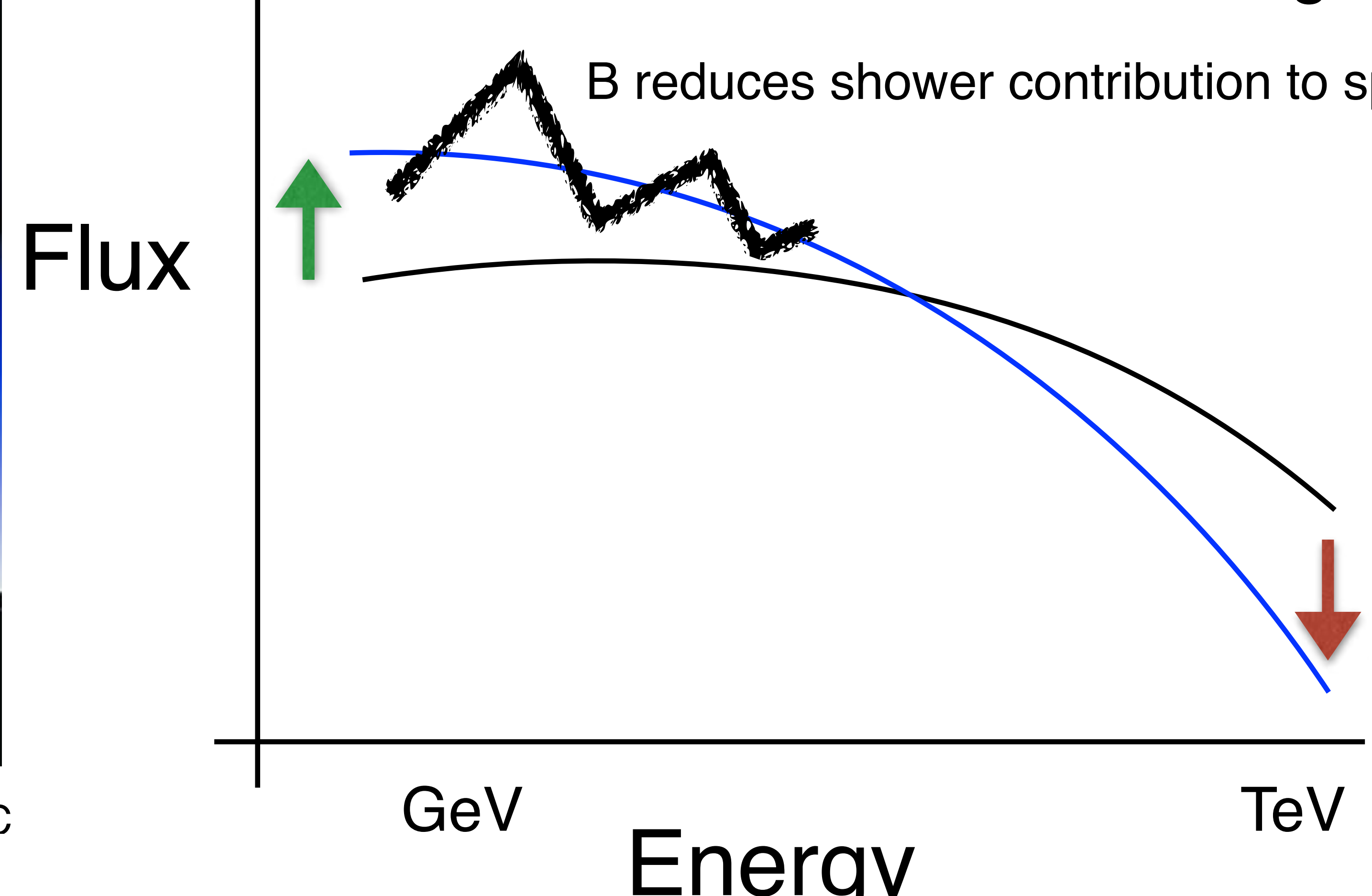


Credit: Nina McCurdy and Joel R. Primack/UC-HiPACC

Morphology:

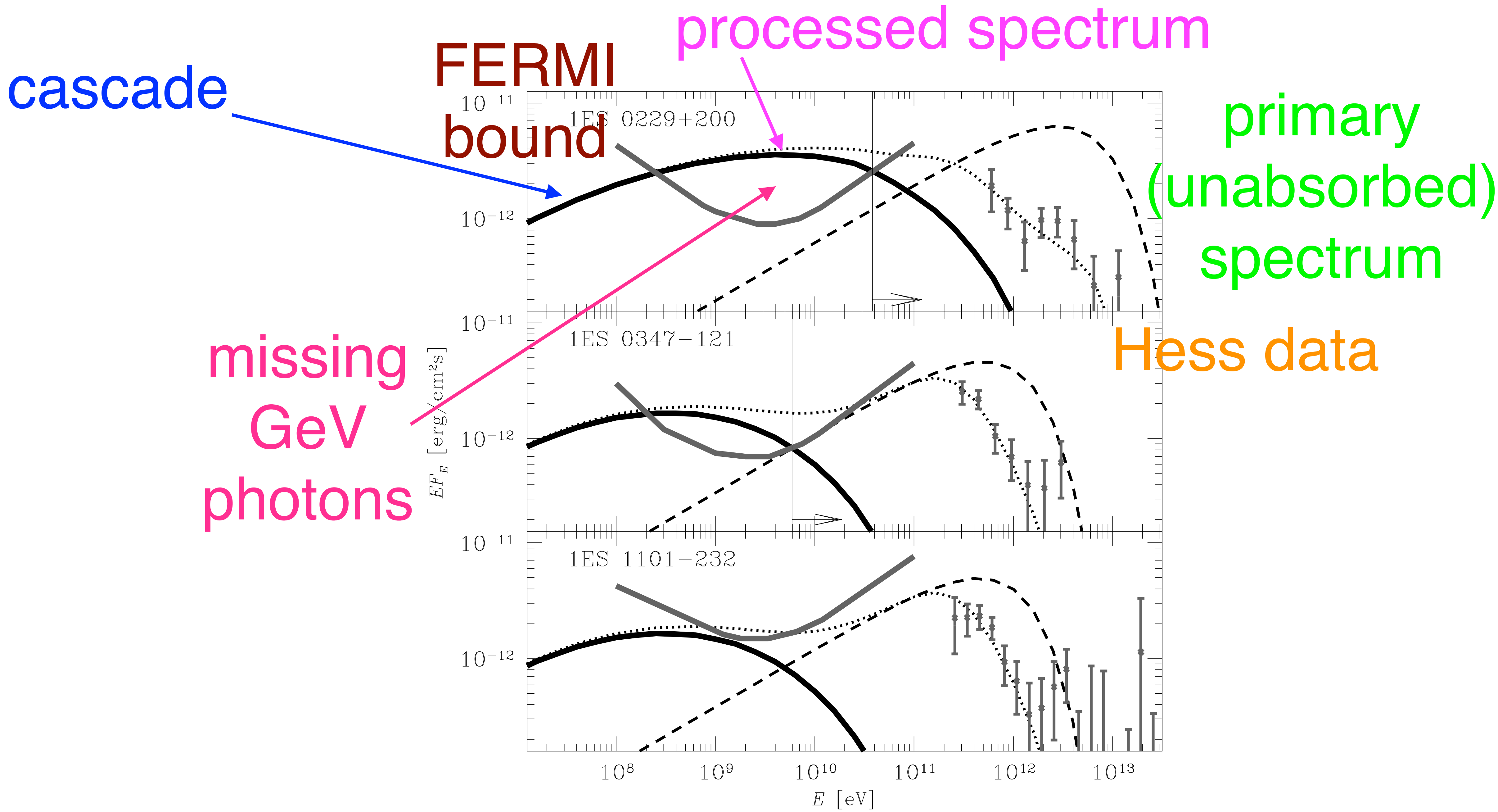


Spectrum: Depletion at TeV energies and excess at GeV energies.

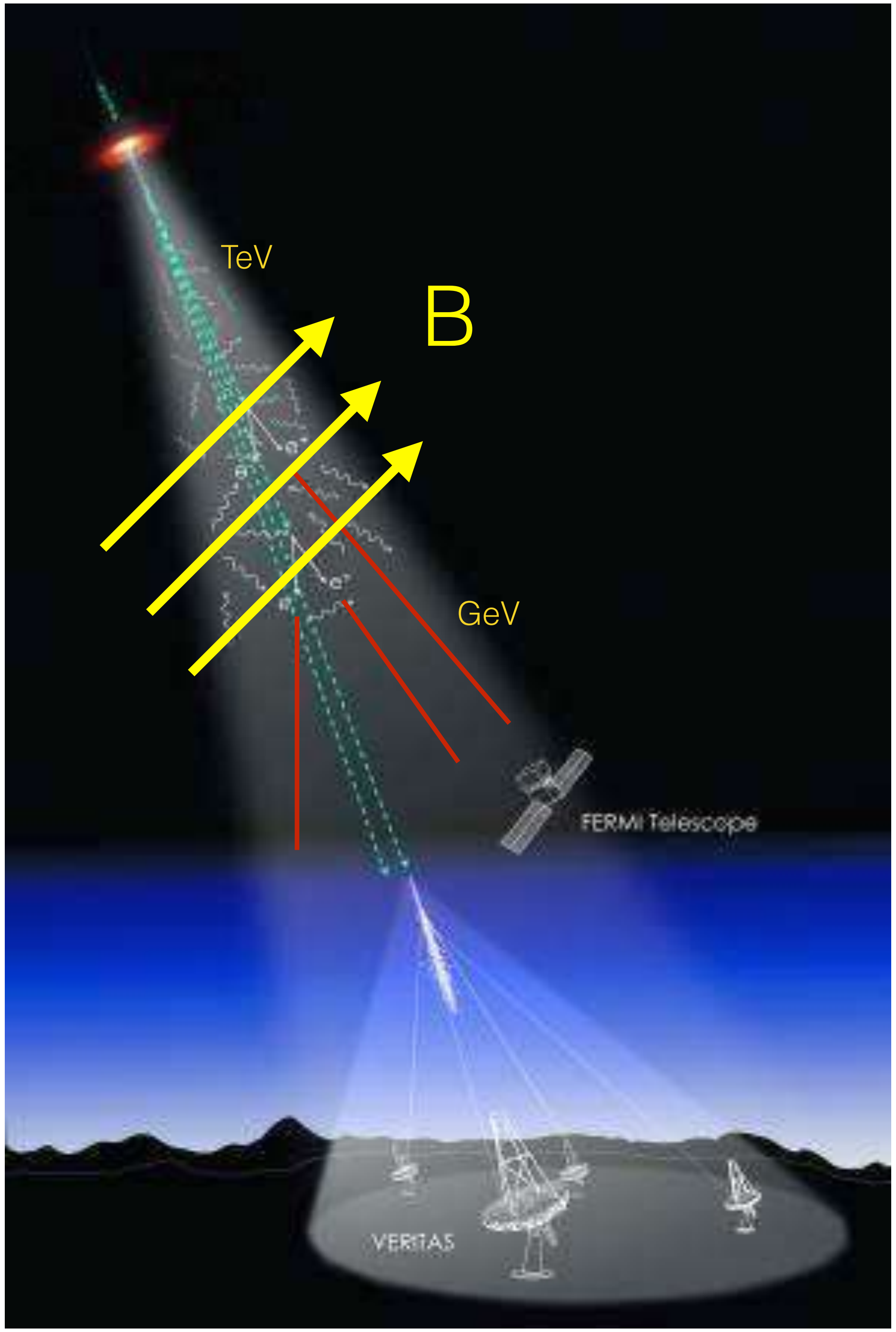


A Lower Bound

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

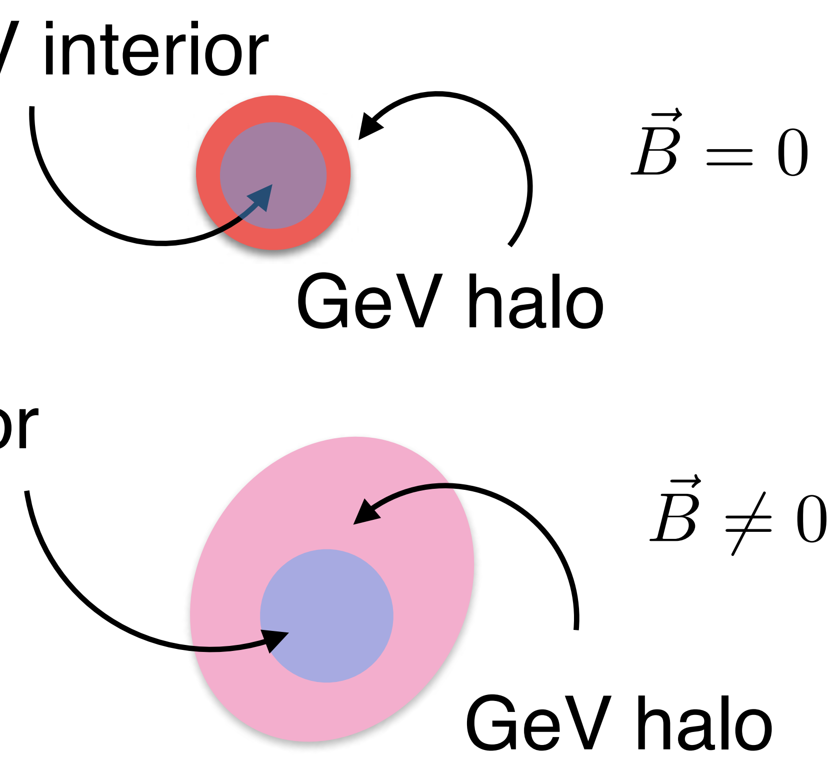


Effect of a magnetic field



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

Morphology:



Missing GeV photons attributed to $B > 10^{-16}$ Gauss

Plasma instabilities?

Broderick, Chang & Pfrommer, 2012

Stacked Analyses

Ando & Kusenko, 2010

Chen, Buckley & Ferrer, 2015

Hints for cascade photons from (stacked) sources.

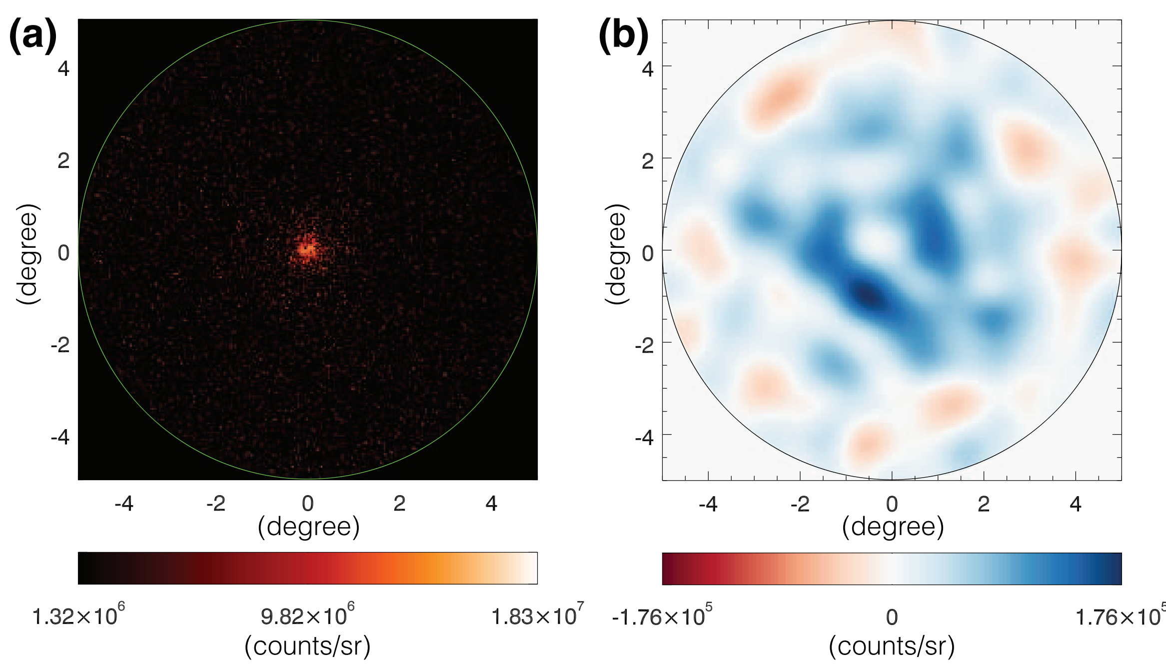
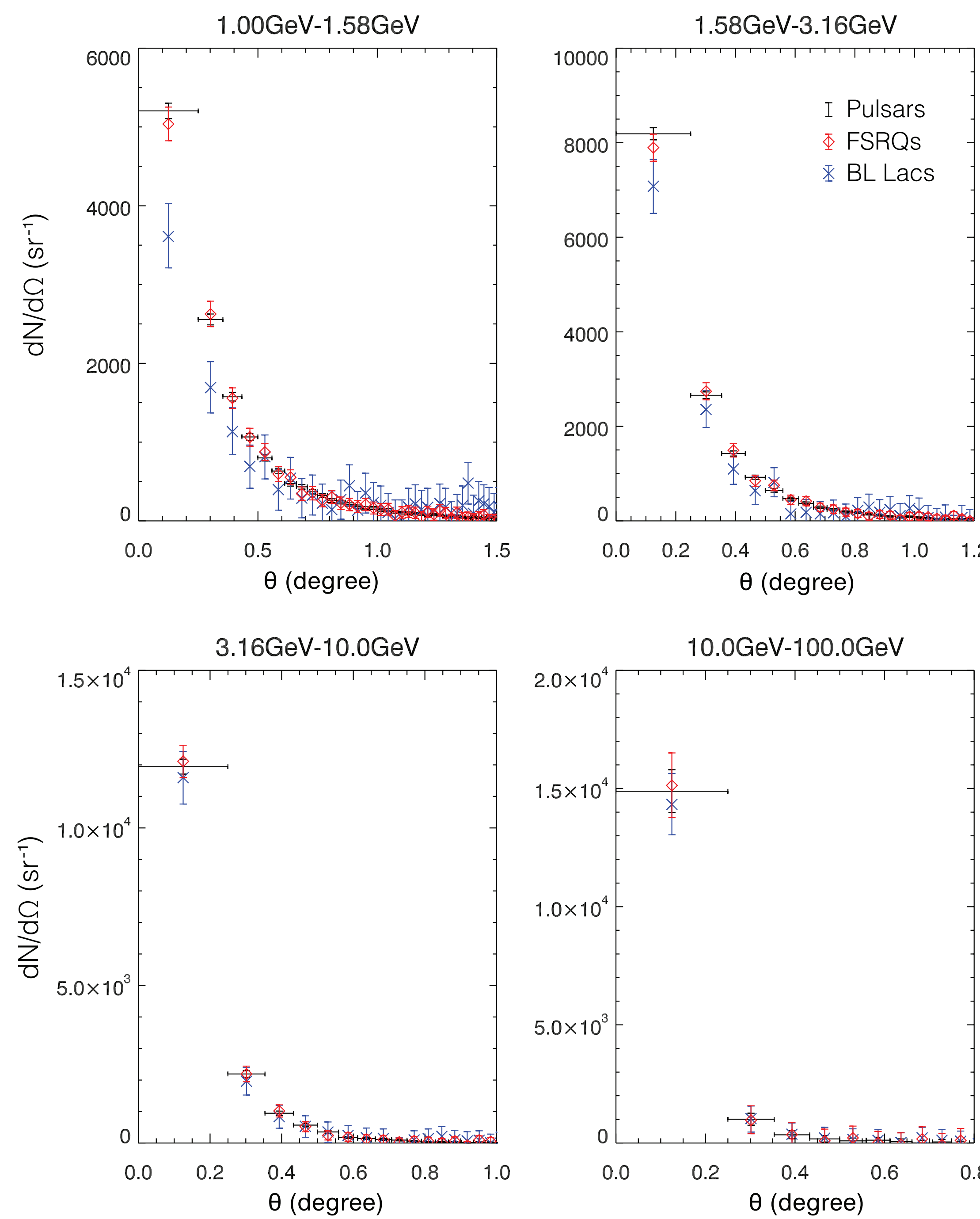


FIG. 1. γ-ray counts maps of the stacked sources in the 1GeV-1.58GeV energy bin. The large circles show the outer edge of the detection region. (a) Counts map of the 24 stacked low-redshift HSP BL Lacs. (b) Smoothed counts difference between the stacked BL Lacs and the center-normalized stacked FSRQs.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

Halo detected at ~3.5 sigma.



Recombination with B

Jedamzik and Abel, 1108.2517
Jedamzik and Saveliev, 1804.06115
Jedamzik and Pogosian, 2004.09487

Magnetic fields at recombination induce inhomogeneities in the baryon density on scales below the photon mean free path.

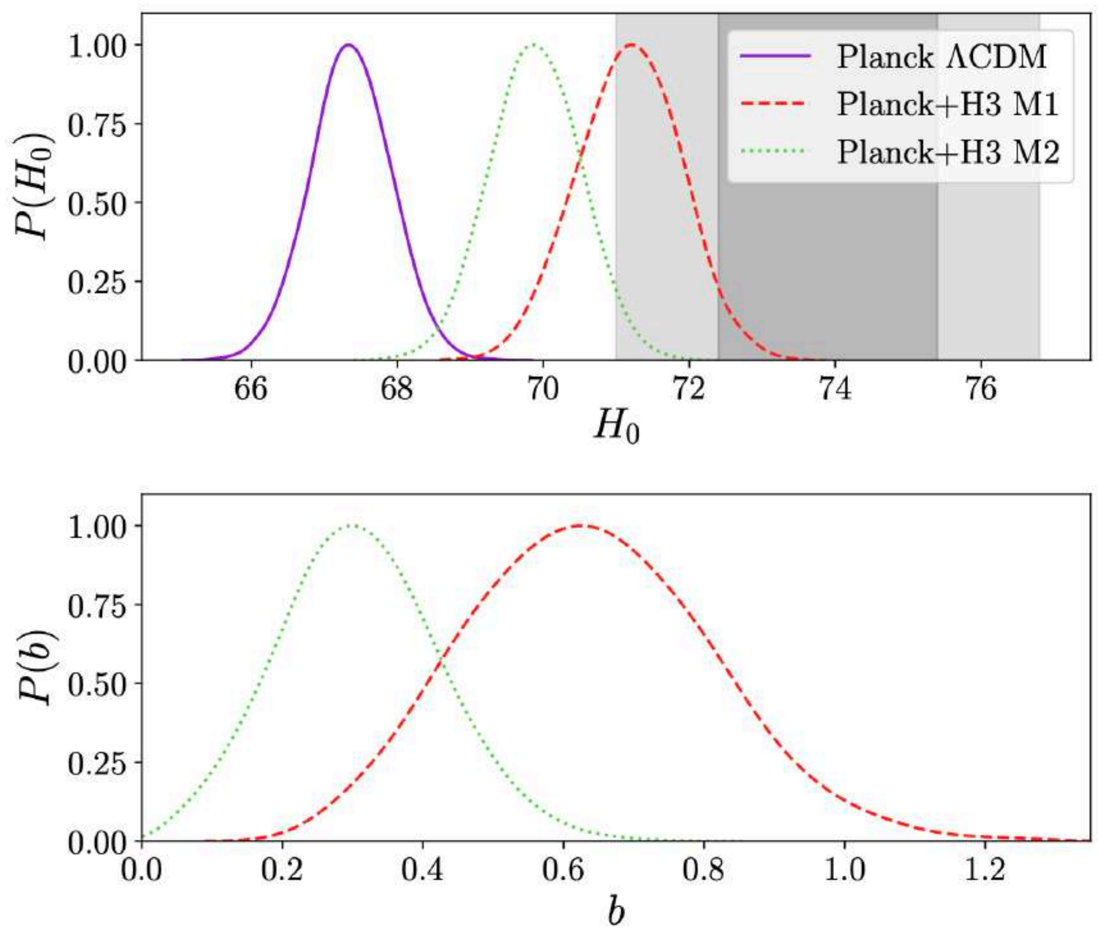
Recombination rate is proportional to $\langle n_e^2 \rangle$ and is larger than $\langle n_e \rangle^2$.

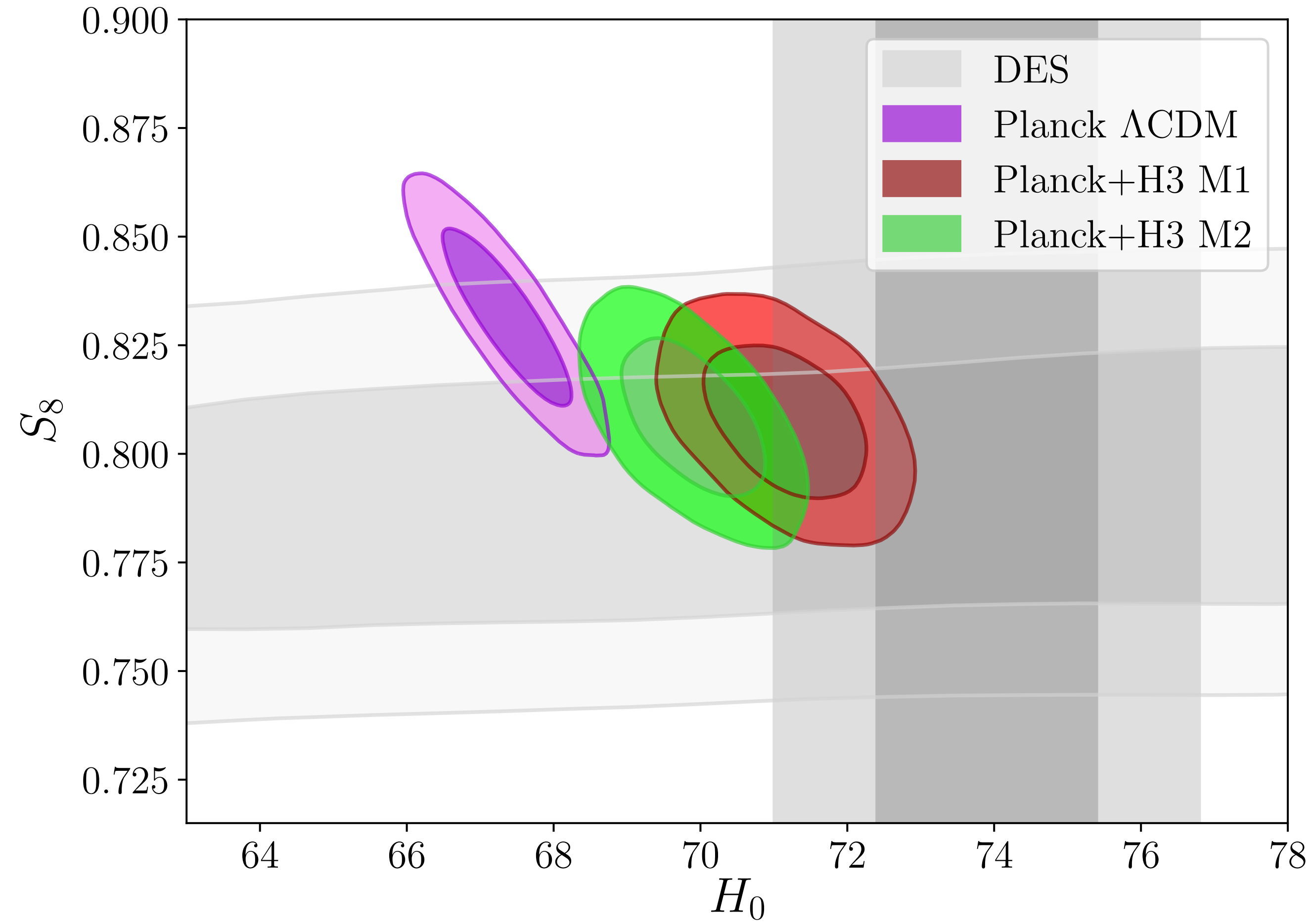
Therefore magnetic fields induce earlier recombination and a reduced sound horizon r_* at recombination.

This would shift the CMB spectral peak positions which are at $l_p \propto r_{ls}/r_*$ unless last scattering surface is closer in, i.e. H_0 is larger.

Resolving the H0 tension with B

(slide provided by Levon Pogosian)





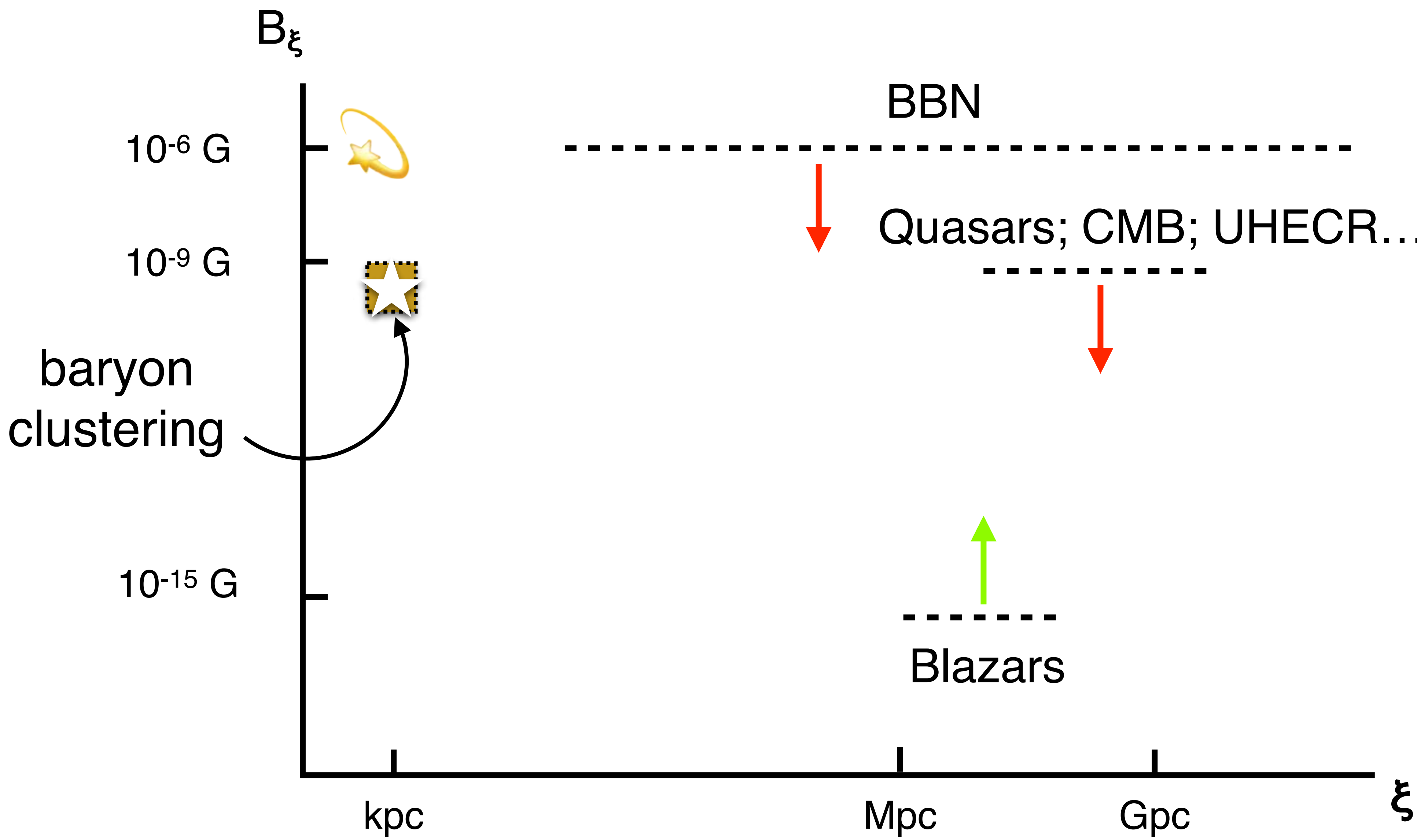
The baryon clumping parameter $b = (\langle n_b^2 \rangle - \langle n_b \rangle^2)/\langle n_b \rangle^2$ detected at ~4σ

Corresponds to magnetic field strengths of ~0.05 nano-Gauss

Also solves the mild tension in S_8 between Planck and DES

K. Jedamzik and L. Pogosian, arXiv:2004.09487

Observations + spectra



Can explain galactic magnetic fields with minimal dynamo amplification.

Origin of cosmological magnetic fields

Several ideas: inflation; electroweak phase transition; QCD epoch; turbulence at recombination; astrophysics.

All scenarios except inflationary magnetogenesis are "causal".

Description of stochastic, isotropic magnetic fields:

Monin & Yaglom

$$\langle b_i(\mathbf{k}) b_j^*(\mathbf{k}') \rangle = \left[\frac{E_M(k)}{4\pi k^2} (\delta_{ij} - \hat{k}_i \hat{k}_j) + i\epsilon_{ijl} k_l \frac{H_M(k)}{8\pi k^2} \right] (2\pi)^6 \delta^{(3)}(\mathbf{k} - \mathbf{k}')$$

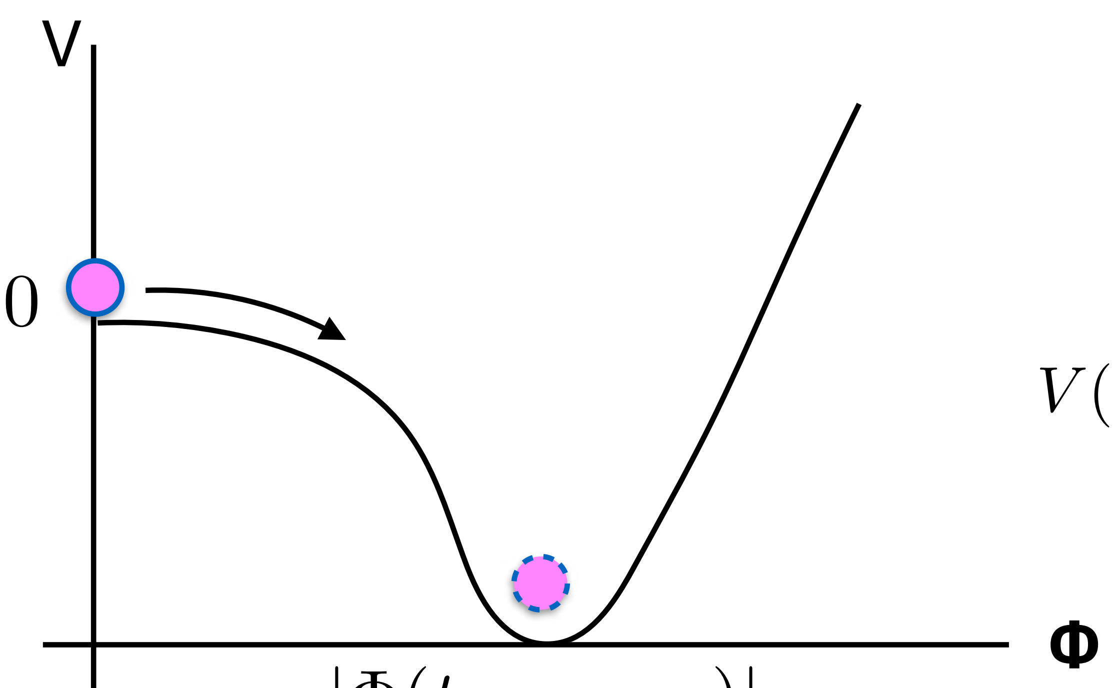
Power spectrum   Helicity spectrum

$\vec{B} \cdot \vec{\nabla} \times \vec{B}$; circular polarization; $\int d^3x \, \vec{A} \cdot \vec{B}$

Magnetic fields from the electroweak epoch

The classical dynamics, as the Higgs acquires a VEV, produces significant magnetic fields.

TV
Baym, Bödekar, McLerran
Diaz-Gil, Garcia-Bellido, Garcia-Perez, Gonzalez-Arroyo
Ferrer, Zhang & TV



$$\Phi(t=0,\mathbf{x})=0$$

$$V(\Phi)=\lambda(|\Phi|^2-\eta^2)^2$$

$$|\Phi(t=\infty,\mathbf{x})|=\eta$$

Simplifying assumptions: zero temperature, only bosonic sector, classical.
(Self-generated plasma.)

Exact form of the potential will not be crucial for us since late time behavior is most interesting.

Triggering the EWPT

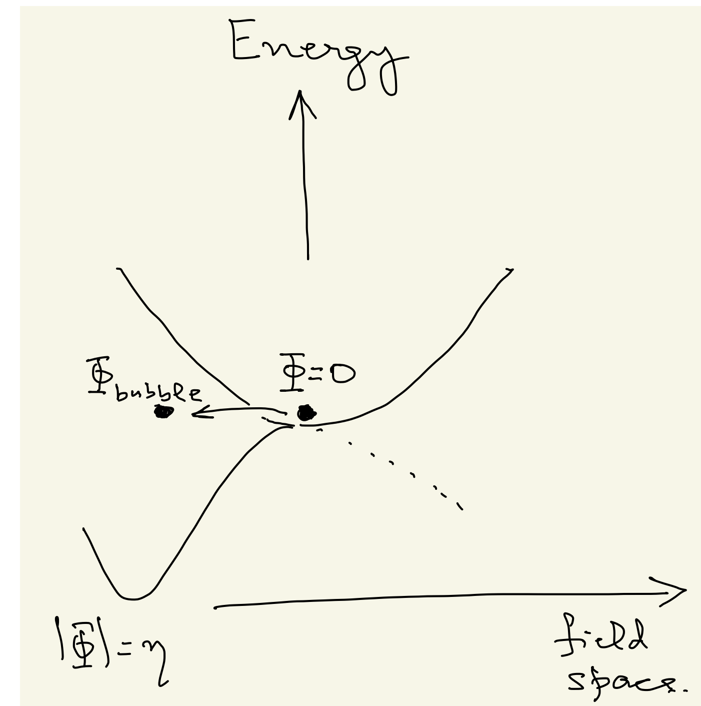
Ferrer, Zhang & TV

A perturbation is required to initiate the phase transition.

Energy with Φ=0 is the same as with:

$$|\Phi| = \eta \frac{2\sqrt{2}Ce^{-m_H r/\sqrt{2}}}{1 + C^2 e^{-\sqrt{2} m_H r}}$$

"trigger bubble" profile



Choose center of bubble to be in true vacuum: $C = \sqrt{2} - 1$

"Direction" of Higgs VEV chosen on 3-sphere: $|\Phi|^2 = \phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2$

Nucleate "trigger bubbles" uniformly in Higgs=0 phase at constant rate.

Evolution

$$\partial_0^2 \Phi = D_i D_i \Phi - 2\lambda(|\Phi|^2 - \eta^2)\Phi - \gamma \Phi\, \partial_0 \ln |\Phi|,$$

$$\partial_0^2 B_i = -\partial_j B_{ij} + g' \,\mathrm{Im}[\Phi^\dagger D_i \Phi],$$

$$\partial_0^2 W_i^a = -\partial_k W_{ik}^a - g\, \epsilon^{abc} W_k^b W_{ik}^c + g\, \mathrm{Im}[\Phi^\dagger \sigma^a D_i \Phi].$$

γ is a damping coefficient for Higgs field oscillations.

We want to damp out radial oscillations but not the angular dynamics because electric charge has to be conserved.

Numerical techniques: (1) lattice inspired, (2) numerically-relativity inspired.

Magnetic Field: Definition

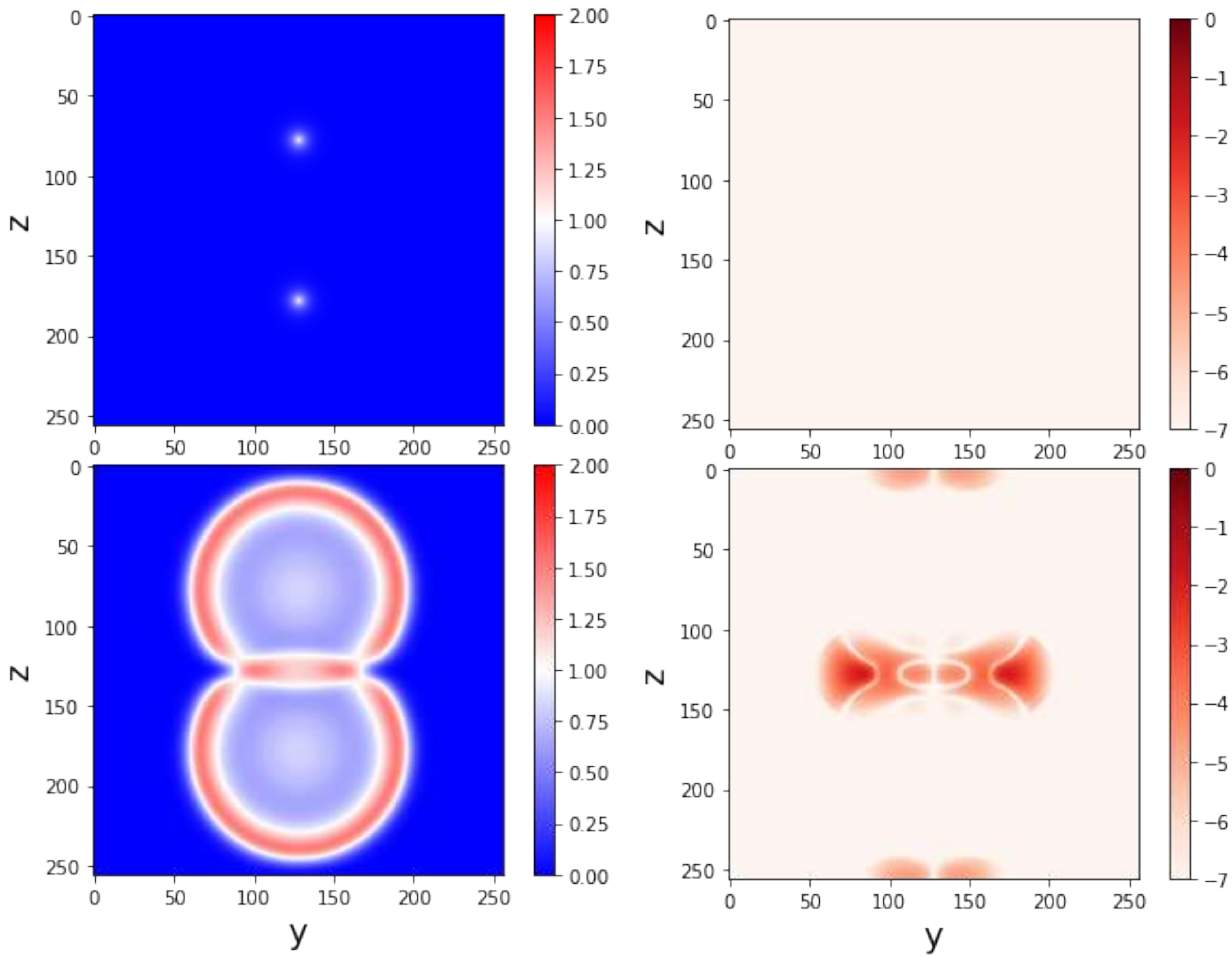
$$A_\mu = \sin\theta_w n^a W^a_\mu + \cos\theta_w B_\mu$$

$$n^a = -\frac{\Phi^\dagger \sigma^a \Phi}{\eta^2}$$

Ambiguities ($|\Phi|^2$ vs. η^2) diminish at late times.

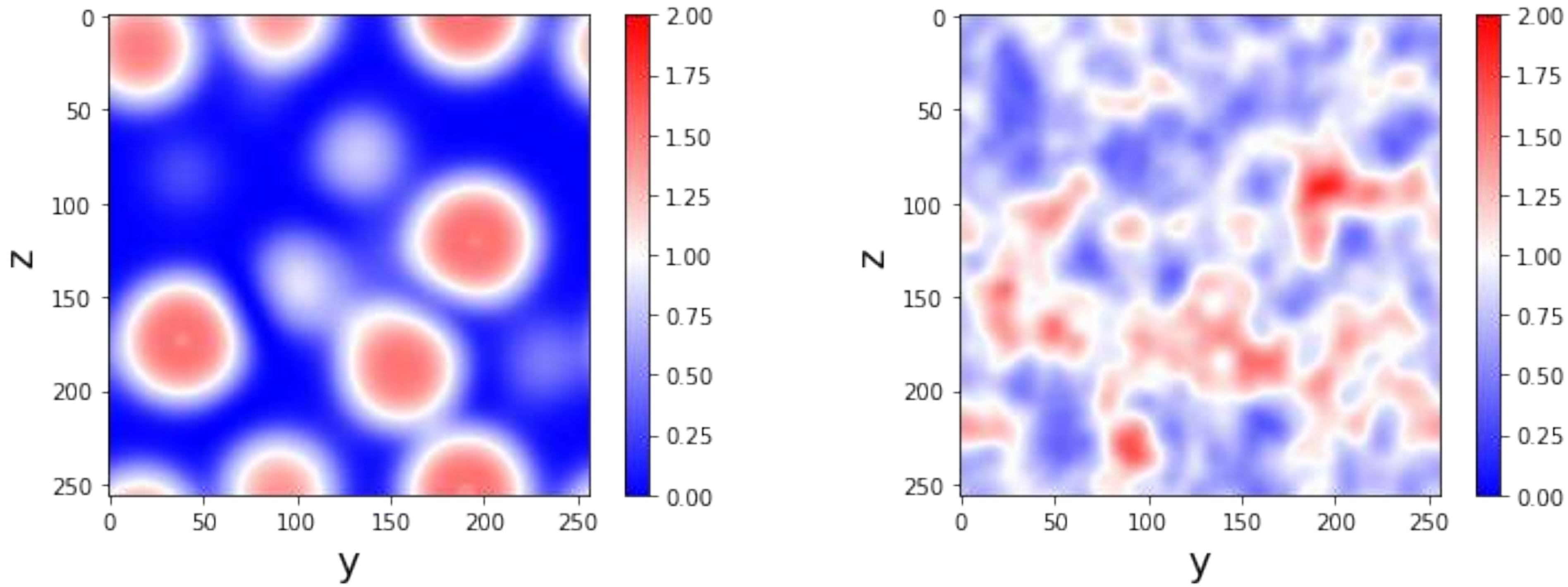
$$A_{\mu\nu} = \sin\theta_w n^a W^a_{\mu\nu} + \cos\theta_w B_{\mu\nu} - i\frac{2}{g\eta^2}\sin\theta_w[(D_\mu\Phi)^\dagger D_\nu\Phi - (D_\nu\Phi)^\dagger D_\mu\Phi]$$

Two bubbles



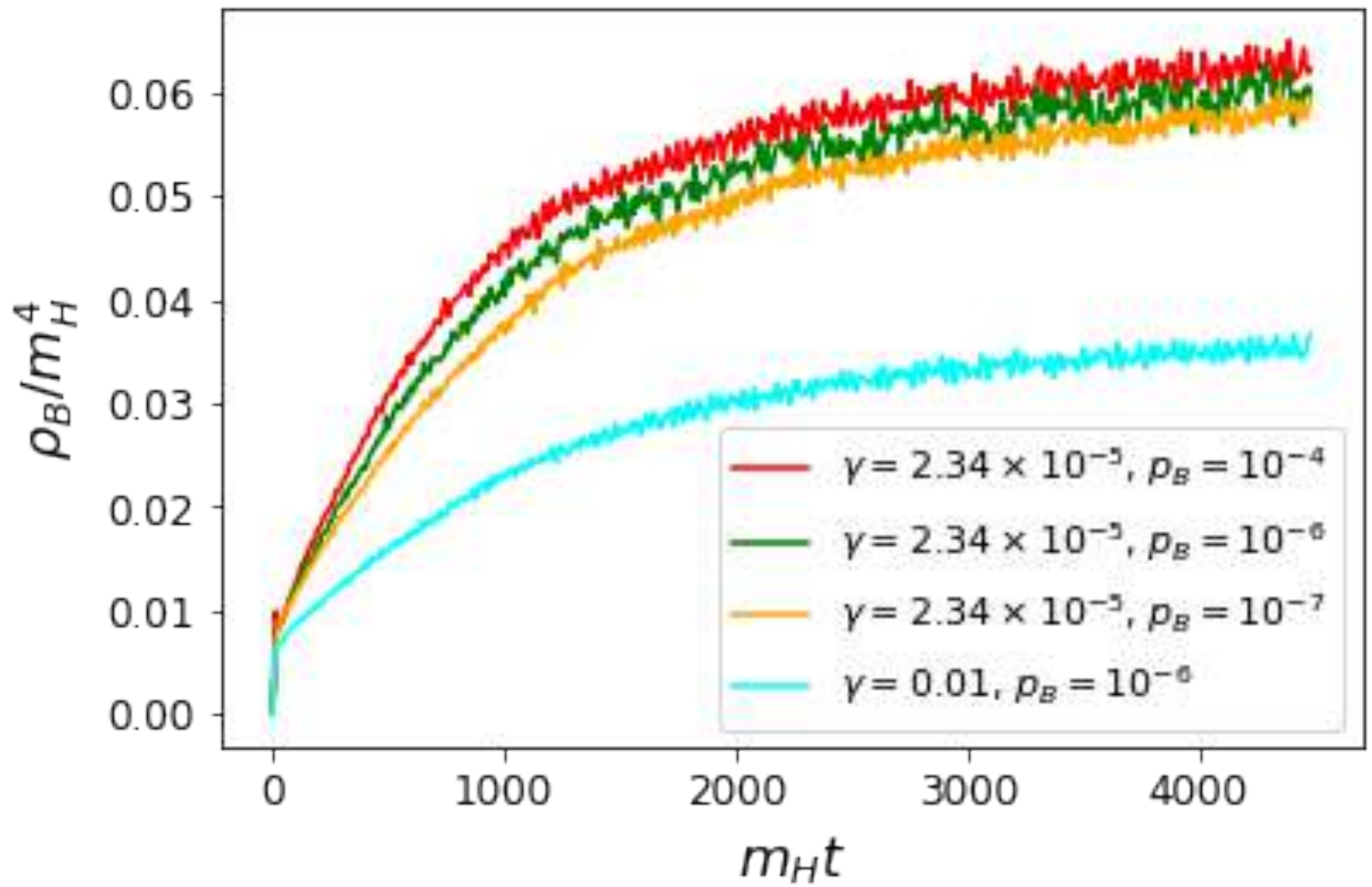
$|\Phi|^2/\eta^2$ $\mathbf{B}^2/2$

Many bubbles



$$|\Phi|^2/\eta^2$$

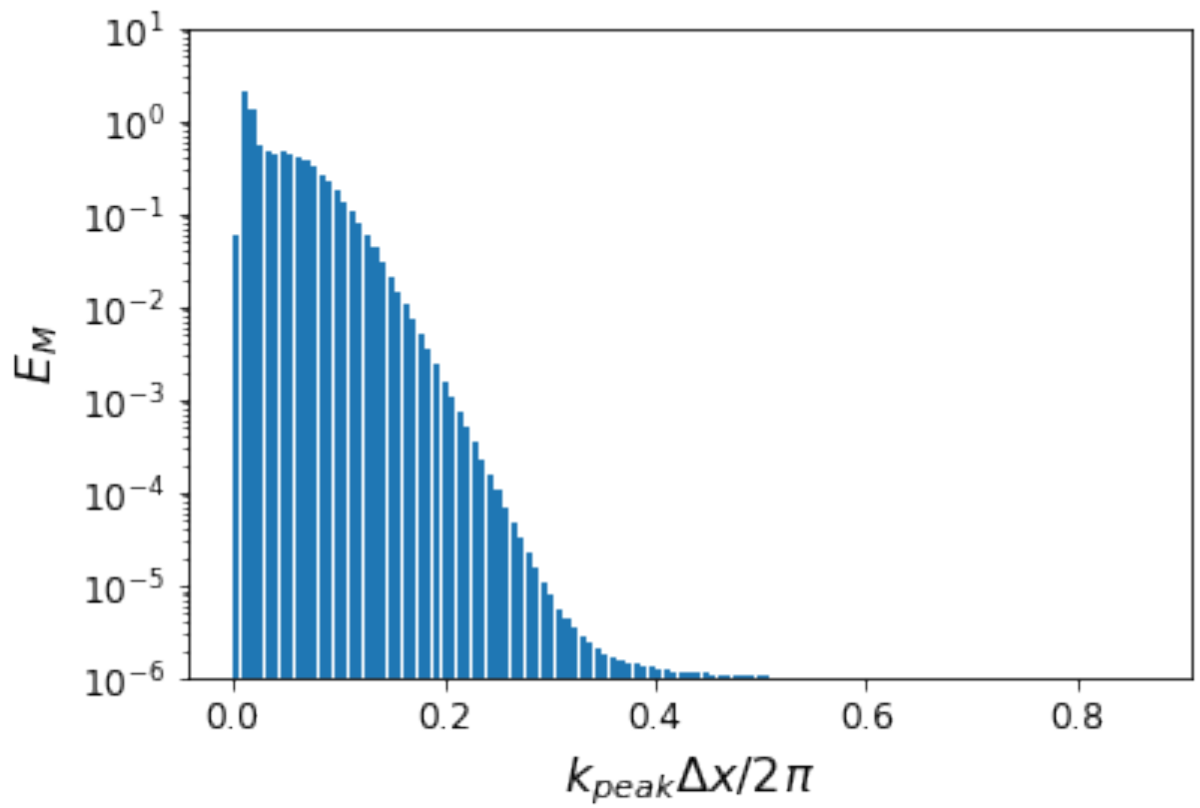
Magnetic Field



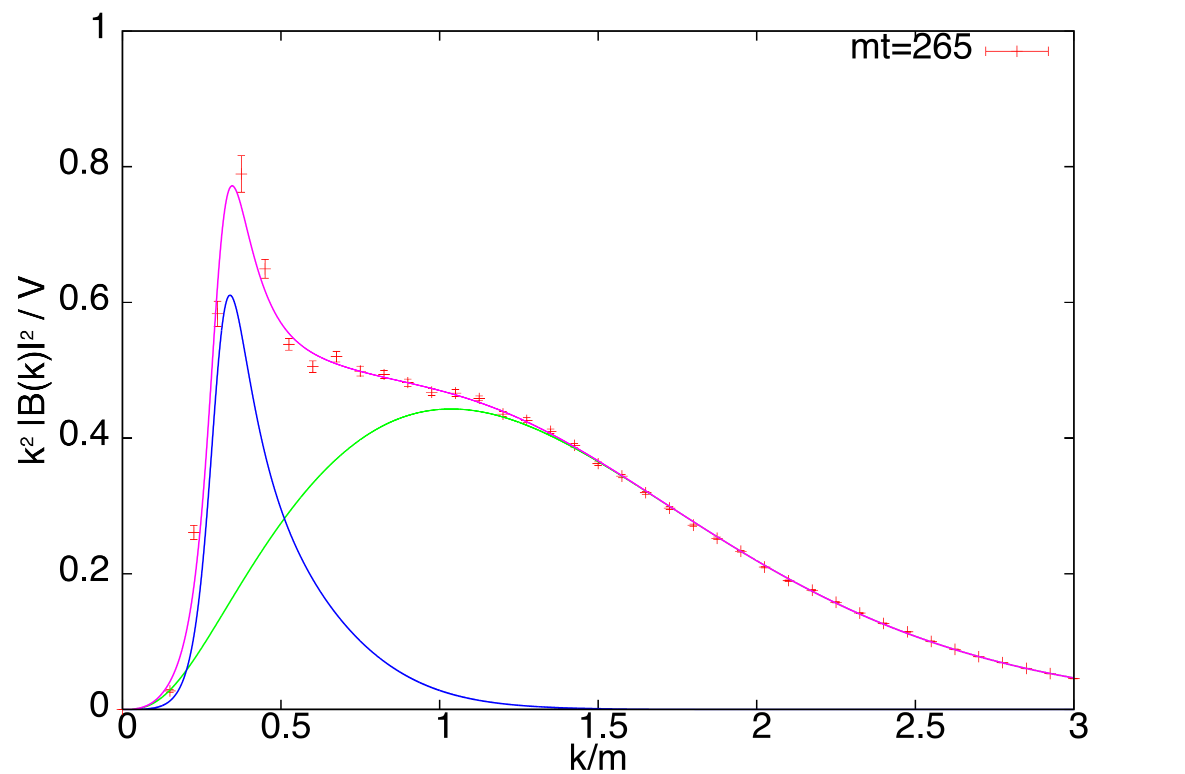
~6% conversion of vacuum energy into magnetic field energy.

Most of the magnetic field energy is produced while the Higgs oscillates around the true vacuum, after bubbles have percolated.

Magnetic Field: Spectral Features



Zhang, Ferrer, TV



Diaz-Gil, Garcia-Bellido, Garcia Perez, Gonzalez-Arroyo
arXiv:0805.4159

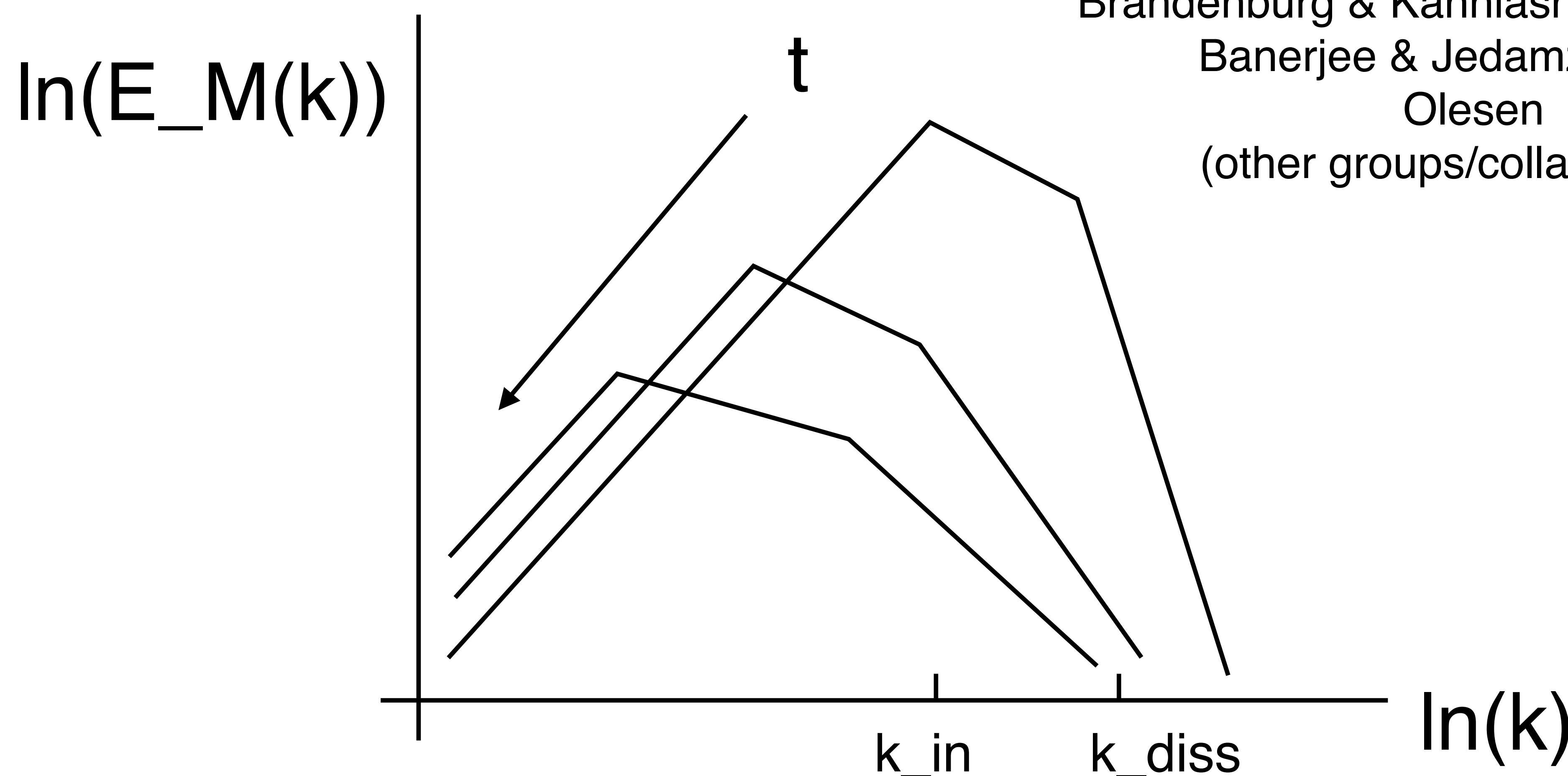
Peak at small k.

Coherence scale = bubble percolation scale?

Evolution of causal cosmological magnetic fields

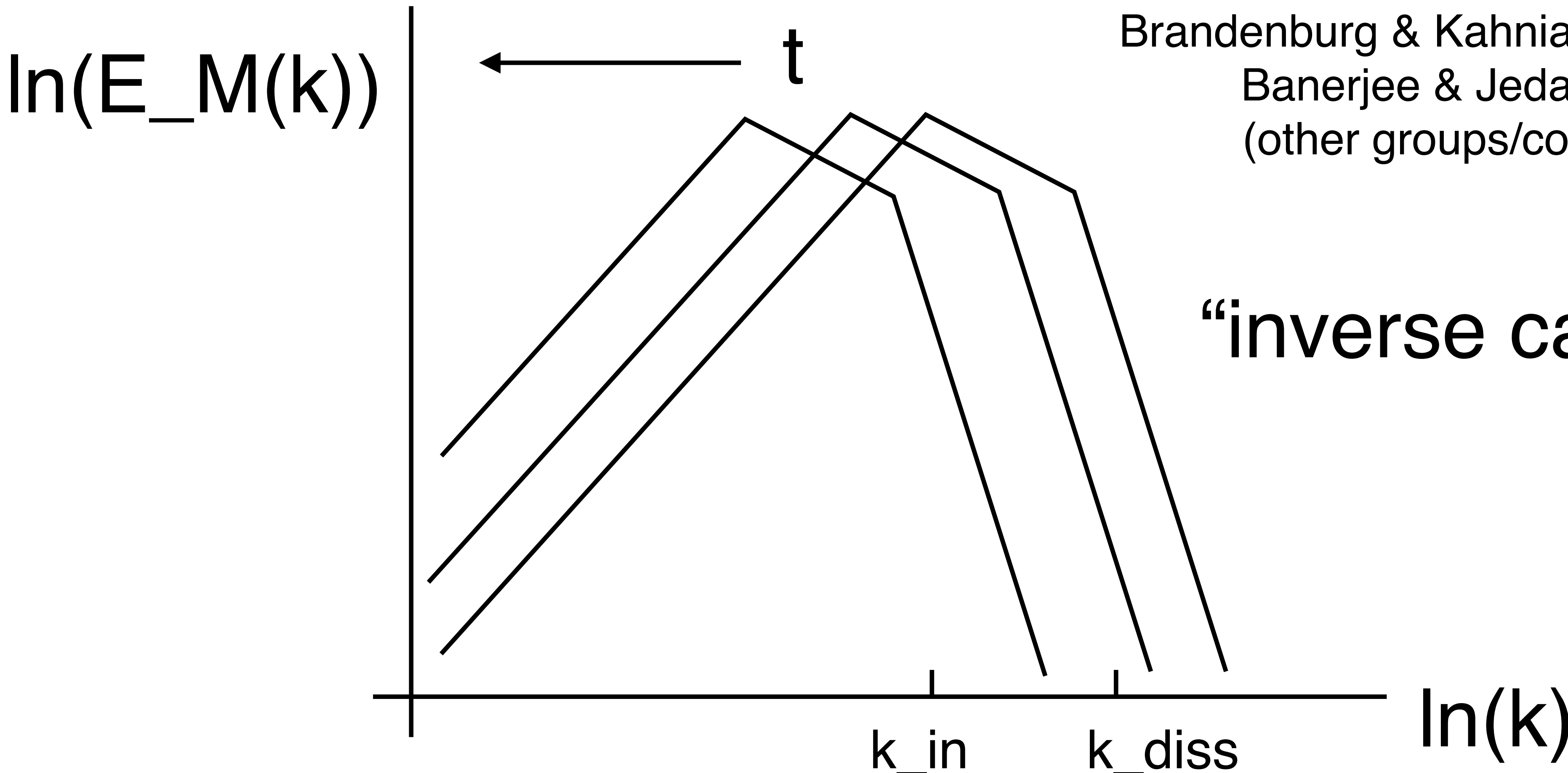
Causal magnetic fields at production have a blue power spectrum, i.e. more energy at small length scales.

Brandenburg & Kahniashvili & Tevzadze
Banerjee & Jedamzik & Sigl
Olesen
(other groups/collaborators)



Power at large length scales (small k) remains small.

Evolution of helical magnetic fields

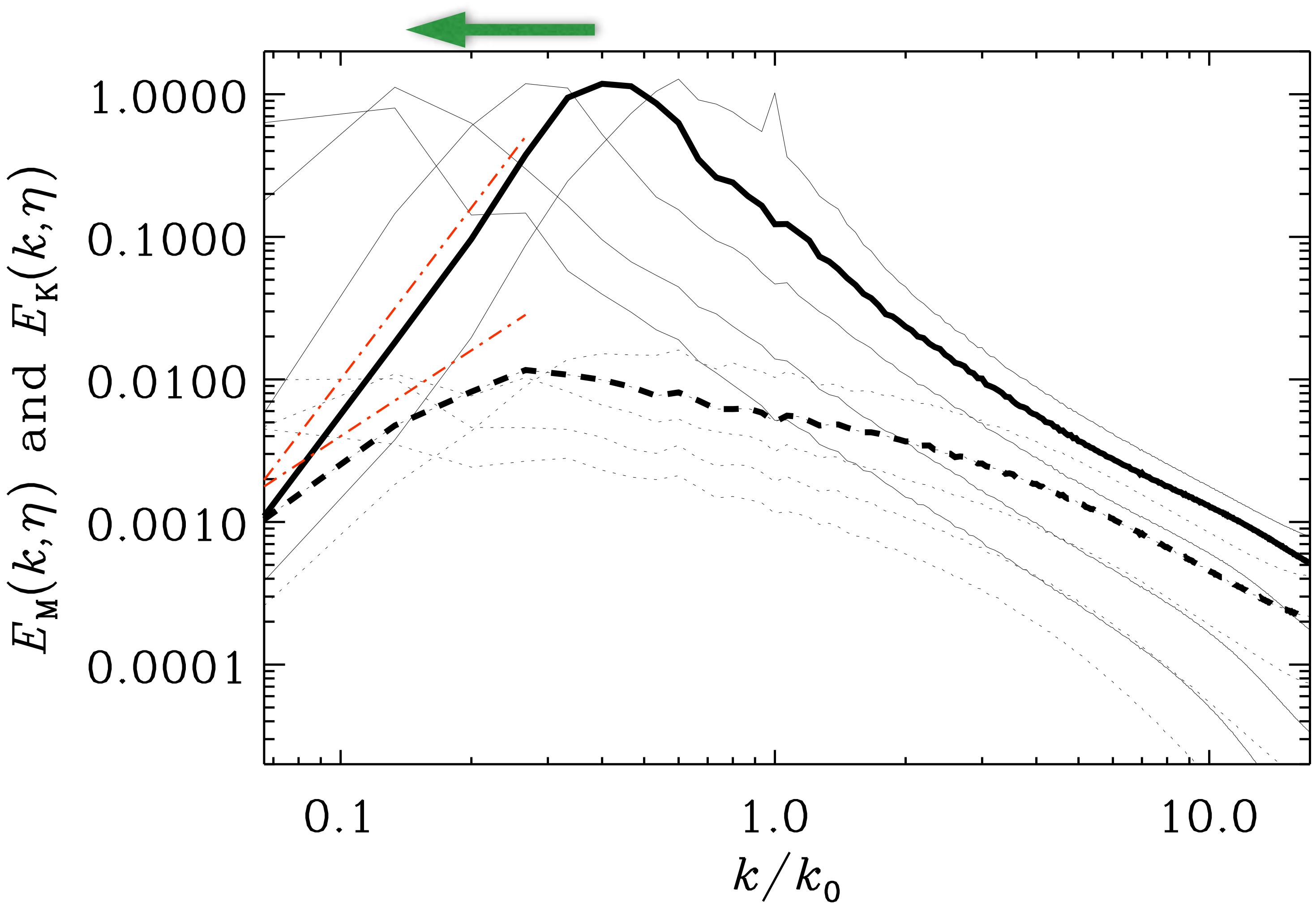


Brandenburg & Kahniashvili & Tevzadze
Banerjee & Jedamzik & Sigl
(other groups/collaborators)

Power at large length scales (small k) grows with time.

Helicity is crucial for the survival of causal fields.

Spectrum: numerical results



Kahniashvili, Tevzadze, Brandenburg & Neronov, 2013

Magnetic field becomes "maximally helical" (only dominant circular polarization survives).

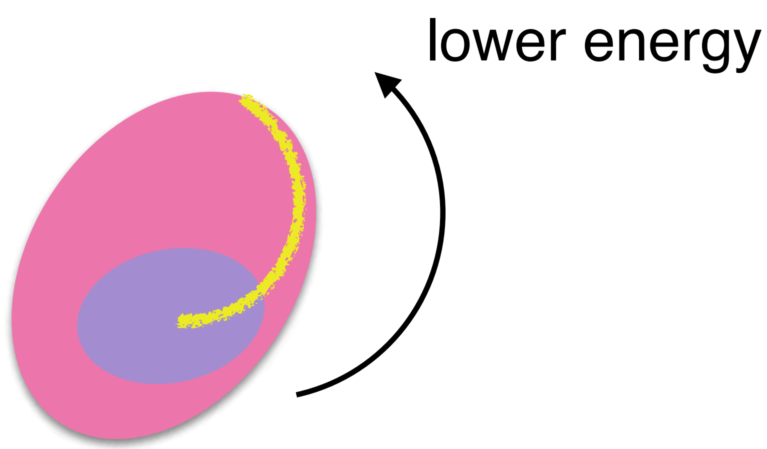
$k_{\rm in} \sim k_{\rm diss}$

$$E_M(k) = \frac{k}{2}|H_M(k)| = \begin{cases} E_0(k/k_d)^4, & 0 \le k \le k_d \\ 0, & k_d < k \end{cases}$$

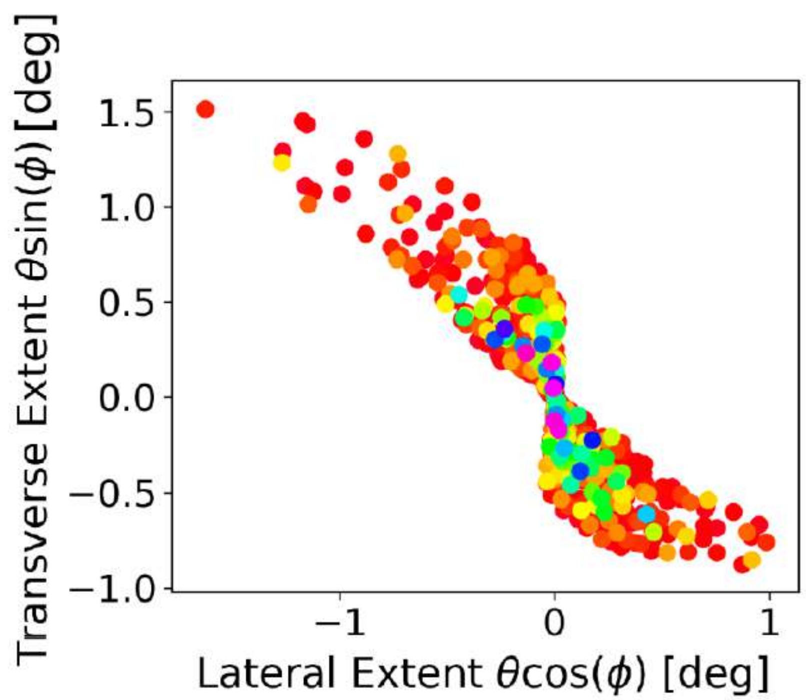
max. hel.

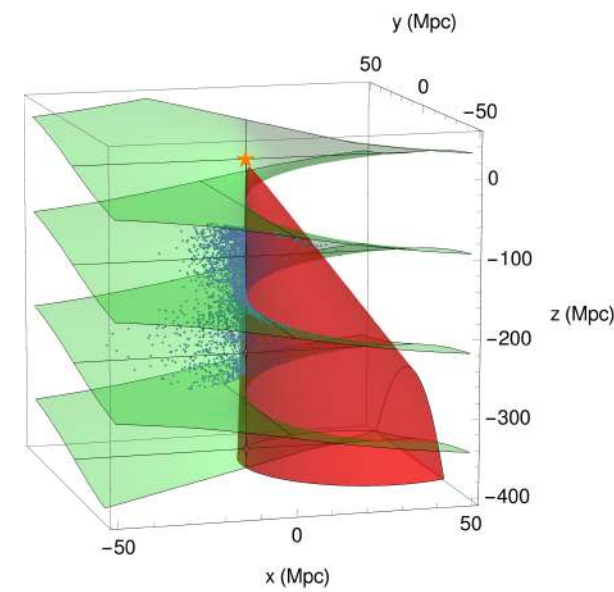
Observation of helicity

Morphology:



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





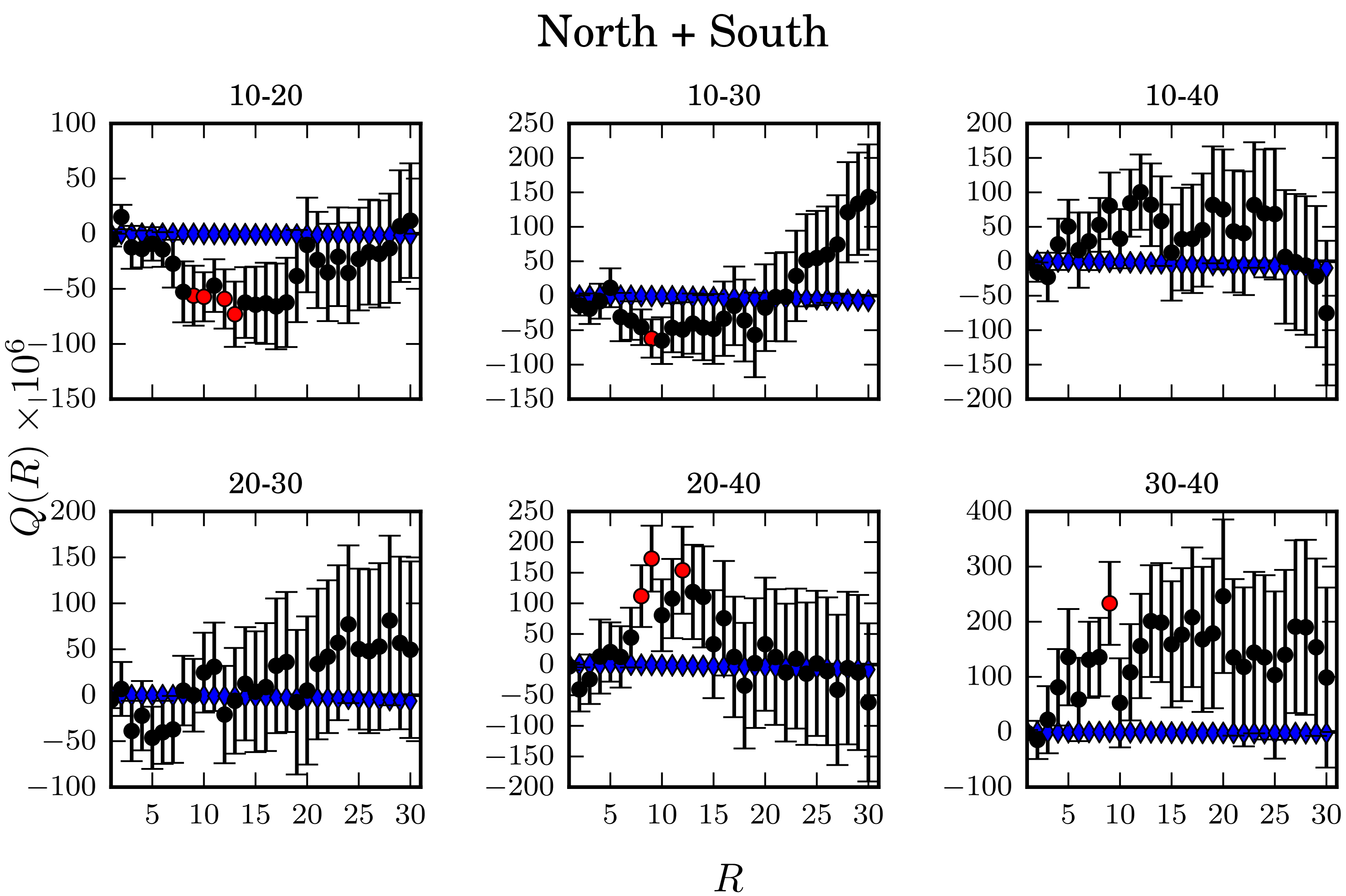
"particle production surface”

Parity-odd statistic:

$$Q(R; E_1 < E_2 < E_3) = \langle \hat{n}_{E_1} \times \hat{n}_{E_2} \cdot \hat{n}_{E_3} \rangle_R$$

(improved statistic in Duplessis & TV)

Observation of helicity



Tashiro, Chen, Ferrer & TV
…
[Asplund, Brandenberger, Guölaugur]

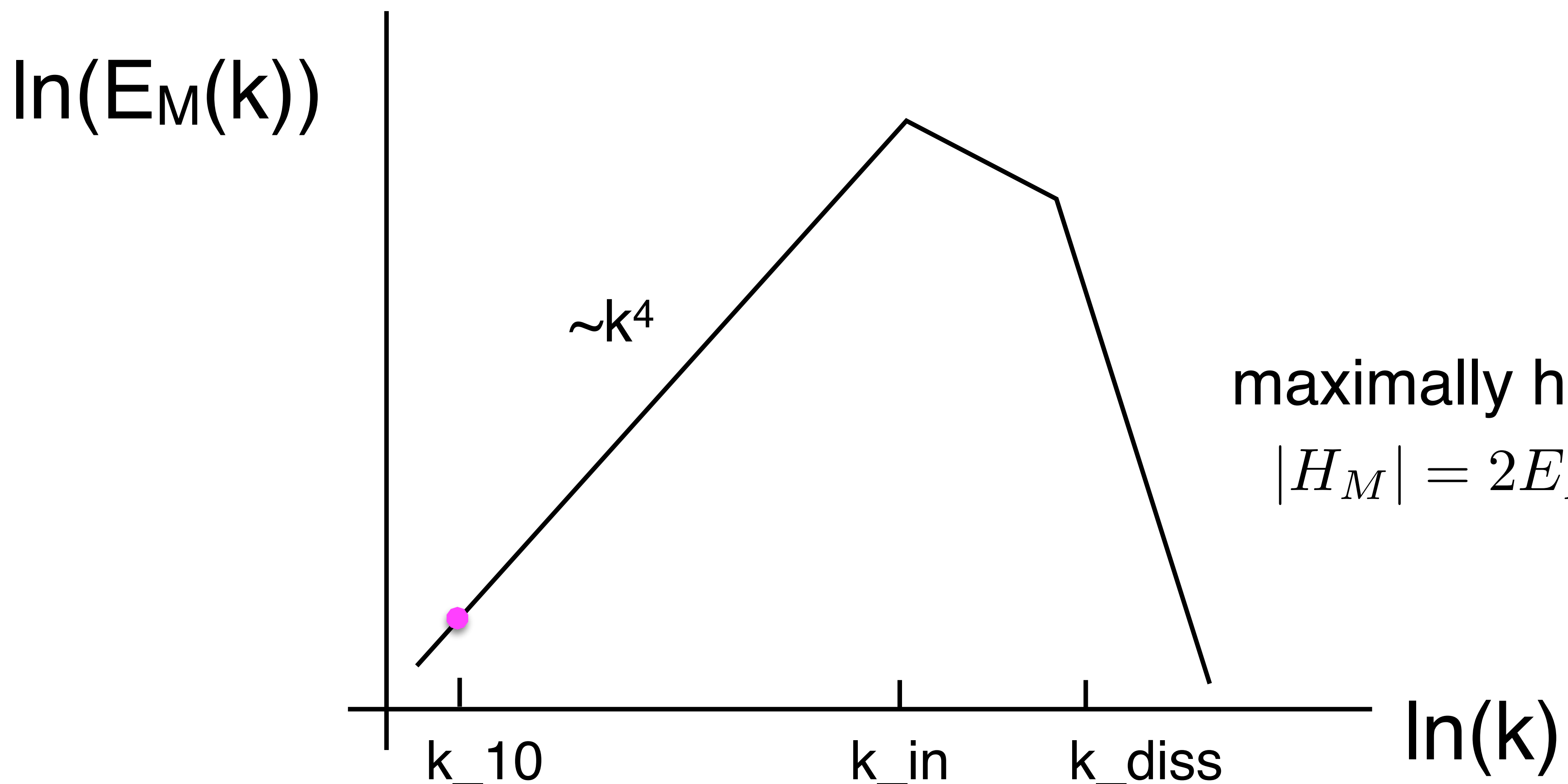
Q is non-zero at about 3 sigma but results may suffer from galactic foreground contamination (even though galaxy is masked out).

Gives B~10^{-14} G on ~10 Mpc.
Technique can be used to determine the magnetic field spectrum.

The Full Spectrum

TV, 2016

$$\langle b_i(\mathbf{k}) b_j^*(\mathbf{k}')\rangle = \left[\frac{E_M(k)}{4\pi k^2} p_{ij} + i\epsilon_{ijl} k_l \frac{H_M(k)}{8\pi k^2}\right] (2\pi)^6 \delta^{(3)}(\mathbf{k} - \mathbf{k}')$$



maximally helical

$$|H_M| = 2E_M/k$$

Dissipation mainly to magnetosonic modes: $l_{d0} \approx 1 \text{ pc} - 1 \text{ kpc}$

Banerjee & Jedamzik, 2003

Estimates

Energy density: $$\mathcal{E}_0 \sim (3 \times 10^{-10}\ \mathrm{G})^2 \left(\frac{1\ \mathrm{kpc}}{l_{d0}}\right)^2$$

Magnetic to photon energy density:

$$\Omega_{B\gamma 0} = \frac{\mathcal{E}_0}{\rho_{\gamma 0}} \sim 10^{-8} \left(\frac{1\ \mathrm{kpc}}{l_{d0}}\right)^2 .$$

Helicity density:

$$H_0 \sim 3 \times 10^{-20}\ \mathrm{G}^2 - \mathrm{kpc} \left(\frac{1\ \mathrm{kpc}}{l_{d0}}\right) \sim 2 \times 10^{17}\ \mathrm{cm}^{-3} \left(\frac{1\ \mathrm{kpc}}{l_{d0}}\right)$$

Sets target parameters for any origin mechanism.
E.g. electroweak can produce sufficient energy density but sufficient helicity will require new physics.

Galactic Magnetic Field

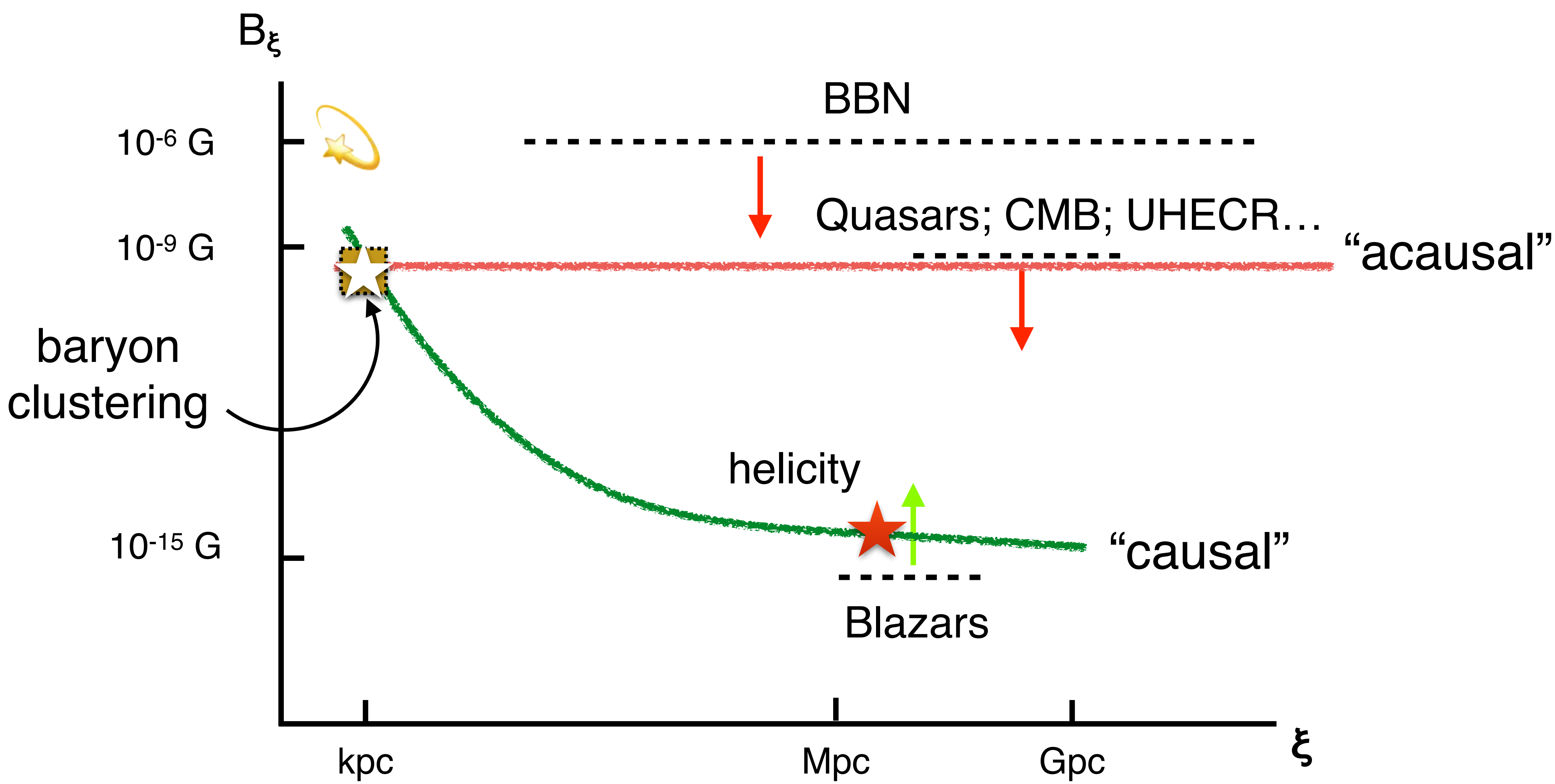
During galaxy formation 3×10^{-10} G on 1 kpc scales gets compressed

by $(\rho_{\rm g}/\rho_{\rm c})^{2/3} \sim 10^5$ to $\sim 3 \times 10^{-5}$ G on 10 pc scales.

Compression of IGMF can *directly* give a relatively large (micro Gauss), random (parsec scale), galactic magnetic field*.

Banerjee & Jedamzik
TV

Observations + spectra



Can explain galactic magnetic fields with minimal dynamo amplification.

Origin of helicity?

Baryogenesis? sphaleron=twisted monopole-antimonopole

$$\text{Every } \Delta B \implies \Delta\mathcal{H} \implies \boxed{h \approx -\# \frac{n_b}{\alpha}}$$

Cornwall, 1997
TV, 2001
Copi et al, 2008
Chu, Dent, TV 2011
Kharzeev, Shuryak, Zahed 2019

Helicity density to baryon number density ratio: $\eta_{Bb} \equiv \dfrac{h}{n_b} \sim 10^2$

$$\eta_{Bb}|_{\rm obs} \equiv 2 \times 10^{24} \left(\frac{1\,{\rm kpc}}{l_d} \right)$$

Large observed helicity needs explanation.
More CP violation; helicity amplification.

Example: chiral effects

Vilenkin, 1980
…

In a magnetized *chiral* plasma

$$\boldsymbol{J}_{\chi B} = \frac{e^2}{2\pi^2}(\mu_L - \mu_R)\boldsymbol{B}$$

compare to Ohm's law

Cosmological-Chiral-MHD:

$$\partial_\eta \boldsymbol{B}_c = \nabla_c \times (\boldsymbol{v}_c \times \boldsymbol{B}_c) + \frac{1}{\sigma_c}\nabla_c^2 \boldsymbol{B}_c + \frac{e\Delta\mu_c^2}{4\pi^2\sigma_c}\nabla_c \times (\nabla_c \times \boldsymbol{v}_c) + \frac{e^2\Delta\mu_c}{2\pi^2\sigma_c}\nabla_c \times \boldsymbol{B}_c$$

conformal time — advection — diffusion — chiral-vorticity — chiral-magnetic term

Joyce & Shaposhnikov, 1997
Boyarsky, Fröhlich & Ruchaiskiy, 2012
Tashiro, TV & Vilenkin, 2012
Rogachevskii, Ruchaiskiy, Boyarsky, Fröhlich, Kleeorin, Brandenburg, Schober 2017
Schober et al 2018
Kharzeev, 2013

Chiral anomaly equation:

$$\frac{d\Delta\mu_c}{d\eta} = -c_\Delta \alpha \partial_\eta h_c - \Gamma_F \Delta\mu_c$$

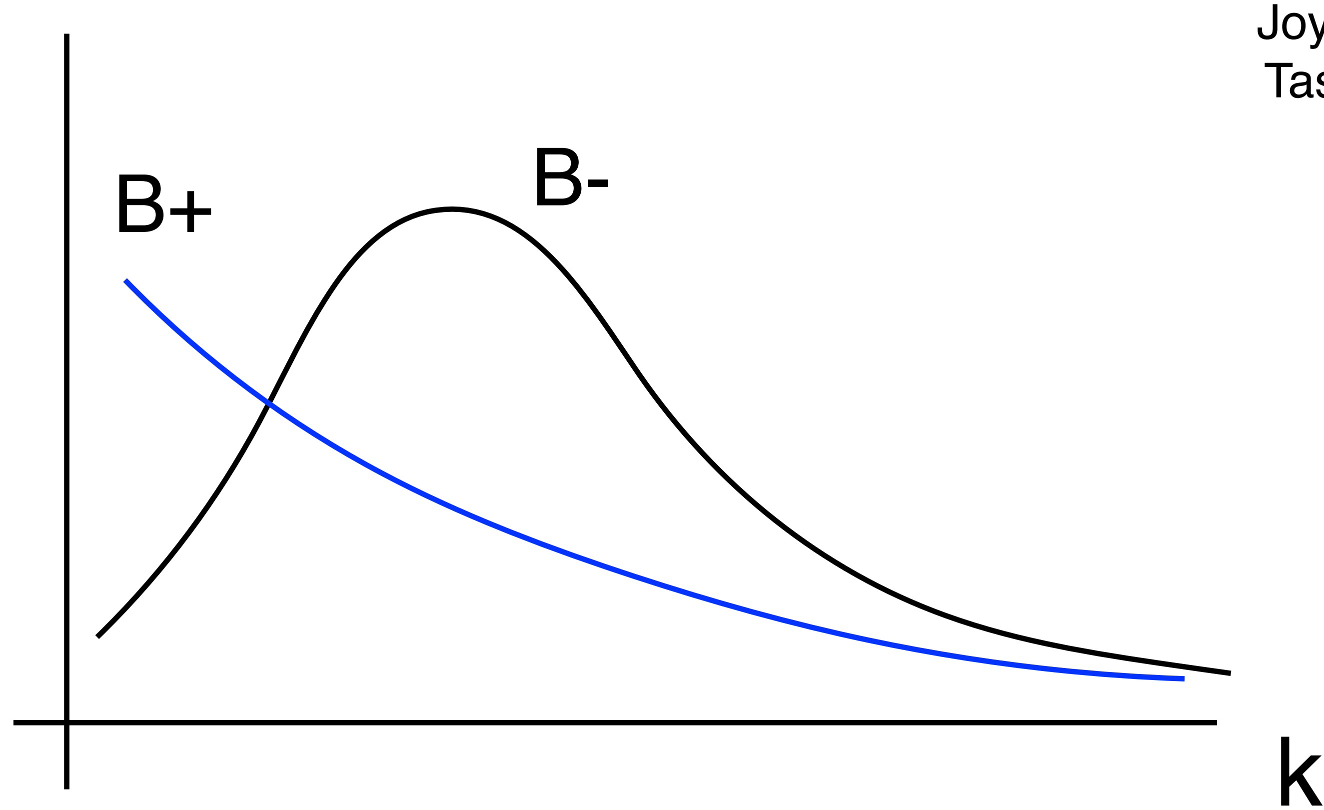
anomaly term — Higgs (mass) term

Solution to the chiral-MHD equations

Decompose magnetic field in left- and right- circular polarization modes.

$$|B^{\pm}(\eta,k)| = |B_0^{\pm}|\exp(K_p^2\eta/\sigma)\exp\left[-(k \mp K_p)^2\eta/\sigma\right]$$

Joyce & Shaposhnikov, 1997
Tashiro, TV & Vilenkin, 2012



Exponential helicity growth: $$h \approx \frac{A}{\sqrt{\eta}} K_p e^{2K_p^2\eta/\sigma}$$

but saturates $$h_* \sim \frac{\Delta\mu(\eta_i)}{\alpha}$$

Chiral-Electroweak Phase Transition?

So far we have been discussing chiral-MHD but we are interested in chiral effects at the electroweak phase transition. Our numerical analysis of magnetic fields generated at the EWPT ignored fermions.

- ★ How can we include fermions in our simulations of the EWPT?
- ★ Could the medium be chiral during the EWPT?
- ★ What is a good description of the chiral electroweak plasma?
- ★ Can there be undiscovered large CP violation?
- ★ Can inclusion of SM chiral fermions suppress/amplify one handedness of the magnetic field?

More questions…

- ★ Can axions play the role of a chiral asymmetry? $\Delta\mu_c \to \dot{a}$
- ★ Leptogenesis. Long, Sabancilar, TV
- ★ (Baryogenesis from magnetic fields.) Fujita & Kamada; Schober, Fujita & Dürrer

Conclusions

- Several observations and lines of reasoning point to maximally helical IGMF of $\sim 10^{-14}$ G on $\sim$10 Mpc scales and sub-nano-Gauss fields at kpc scales. *(But still in need of a "WMAP moment".)*

- Electroweak phase transition can produce magnetic fields with sufficient energy density but large helicity does not seem to fit within the standard model.

- "Large helicity puzzle" requires new particle physics that may be tied to the cosmic baryon asymmetry, *e.g.* large CP violation, chiral magnetic effect, kinetic helicity, ???.