Turbulence and Magnetic fields beyond light years

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Summary

- **The universe is turbulent and magnetized.**
- **Origin: Turbulent dynamos?**
- **Early Universe Generation**
- **Turbulent Evolution**
- **Magnetic signals**

K. Subramanian, The origin, evolution and signatures of primordial magnetic fields, Rep. Prog. Phys. 79, 076901 (2016).

K. Subramanian, "Magnetizing the Universe", PoS proceedings, arXiv:0802.2804

A. Brandenburg & K. Subramanian, Astrophysical magnetic fields and nonlinear dynamo theory, Physics Reports, 417, 1-205 (2005)

The Universe is turbulent & magnetized

- **Galaxies: Turbulent Interstellar medium due to Randomly exploding Supernovae; $B \sim 10\mu G$, ordered on 10 kpc scales + random component**

- **Clusters of Galaxies: Turbulent due to structure formation and mergers; B few μG strengths on ~ 10 kpc scales**

- **First galaxies turbulent due to formation + supernovae? Equally strong B in Young $z \sim 1-2$ galaxies (Bernet et al. 2008)**

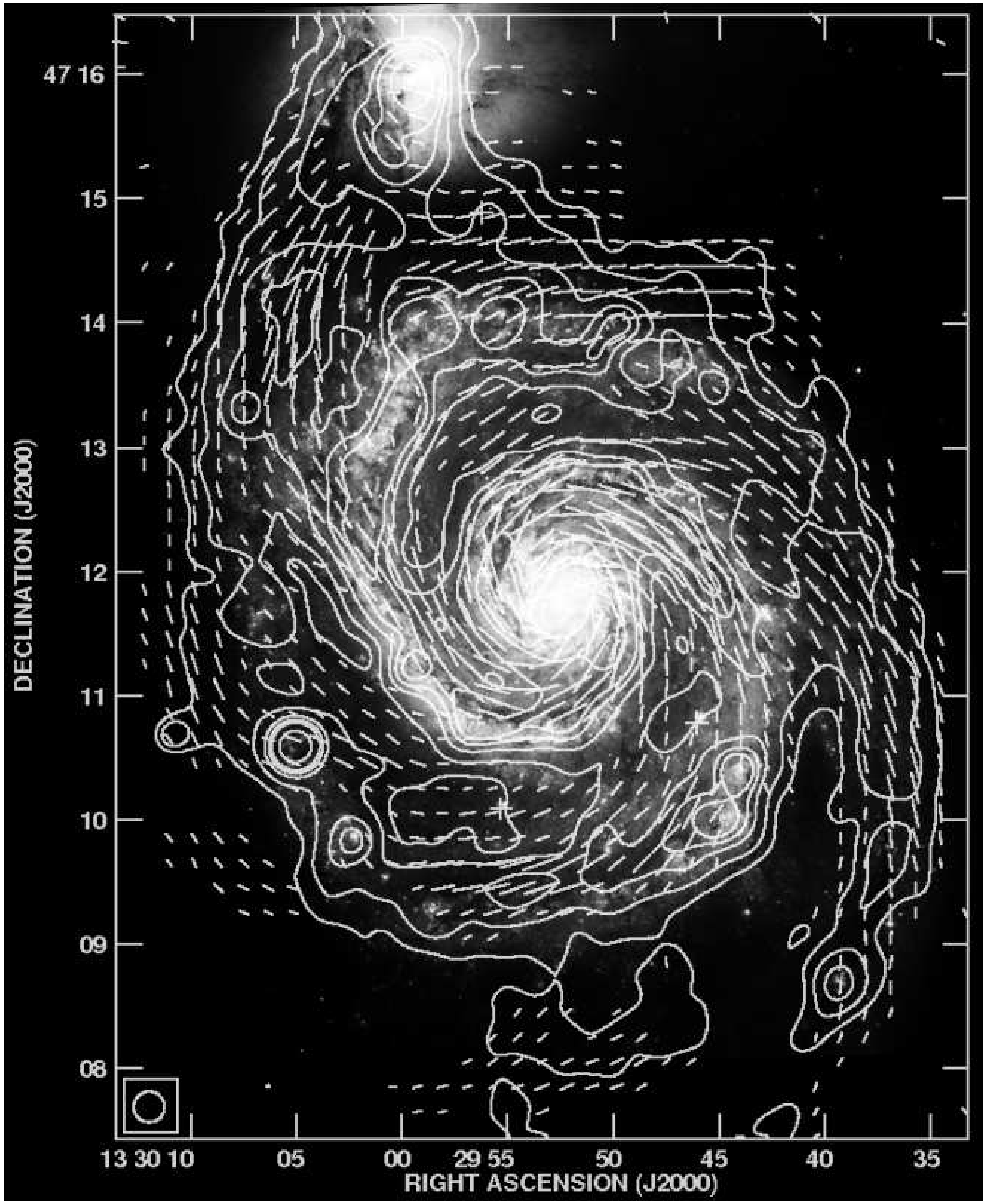
- **Turbulent intergalactic medium? B even in the IGM voids?**
  ($B \geq 3 \times 10^{-16}$ Gauss; Mpc scales)
  (Neronov and Vovk, 2010; BUT Broderick et al., 2011 vs Kempf et al., 2016)

- **Could even be helical with $B \sim 10^{-14} G$ on 10 Mpc scales**
  (Tashiro and Vachaspati, 2014; Chen et al, 2015)

Turbulence generates B fields drive Turbulence! Origin?

IUCAA

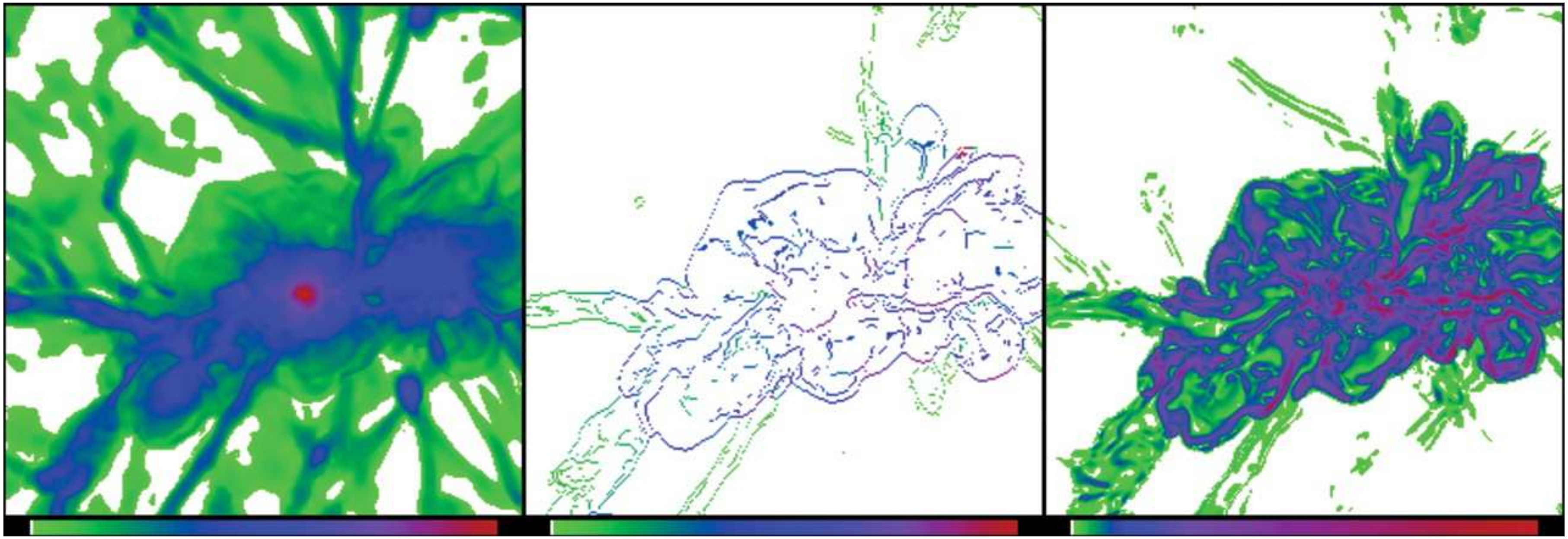
Galactic Magnetic Fields: Observations



- Synchrotron polarization and Faraday rotation probe B fields.
- M51 at 6 cm (Fletcher and Beck)
- Few μG mean Fields coherent on 10 kpc scales
- Correlated with optical spiral
- How do such large scale galactic fields arise?

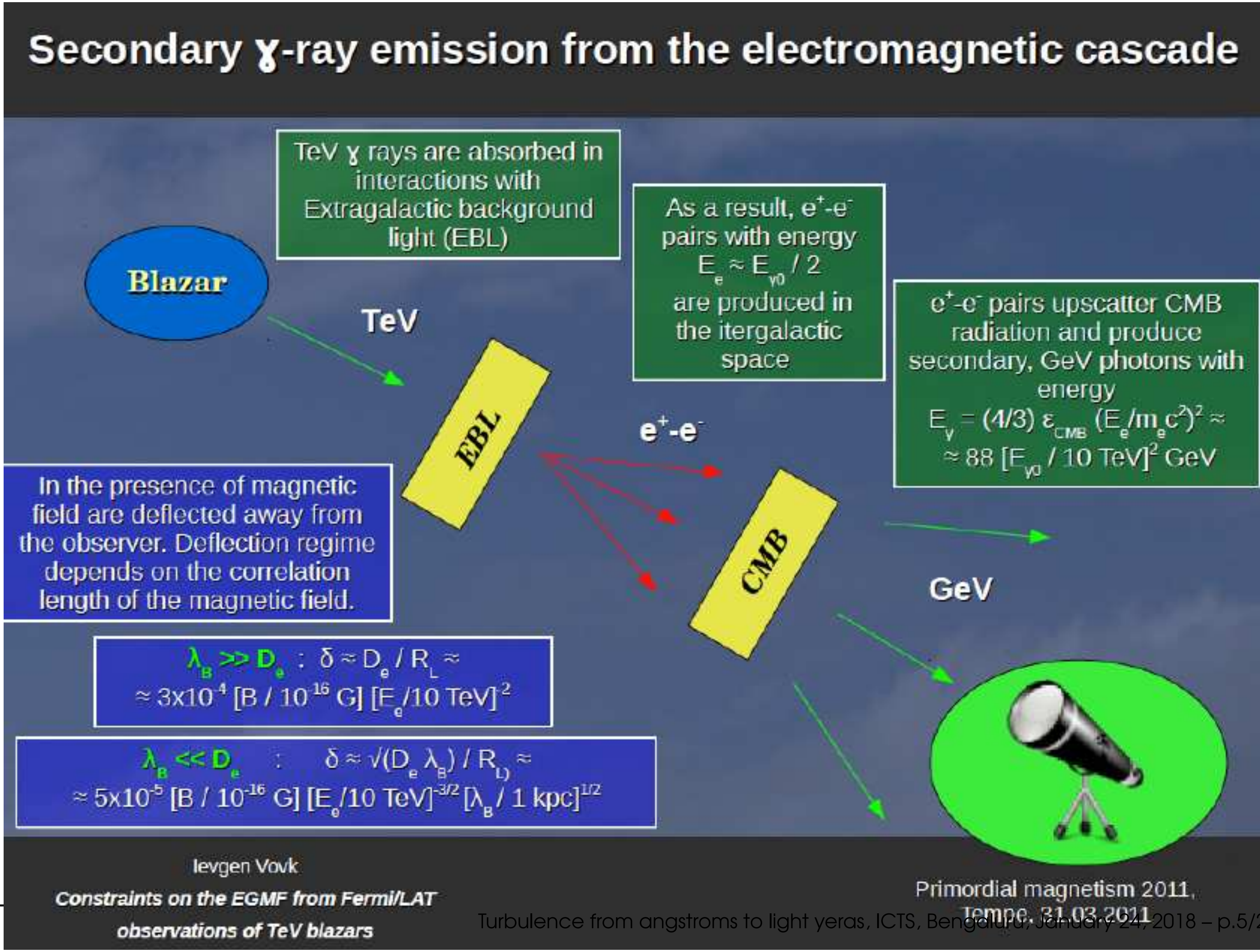
Turbulence in forming galaxy cluster

Ryu et. al., Science, 320, 909, 2008



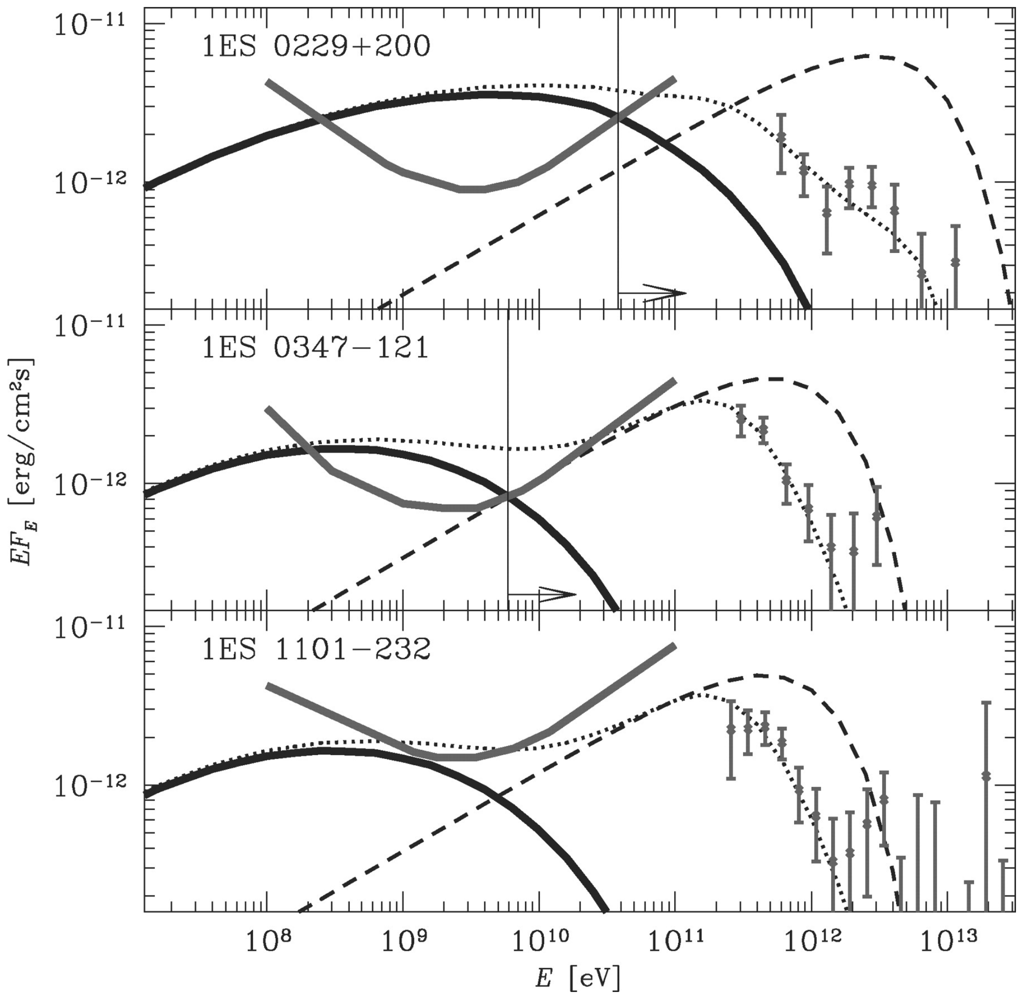
- **Density** **Shocks** **Vorticity**
- $(\rho/\bar{\rho}) = 0.1 - 100$, $v_{shock} = 15 - 1800$ **km s^{-1}**, $\omega t_{age} = 0.5 - 100$
- $25h^{-1}$ Mpc side, $z = 0$
- **Similar turbulence generation in forming galaxies + Supernovae**

Gamma-Ray Constraints on B



Gamma-Ray Constraints on B

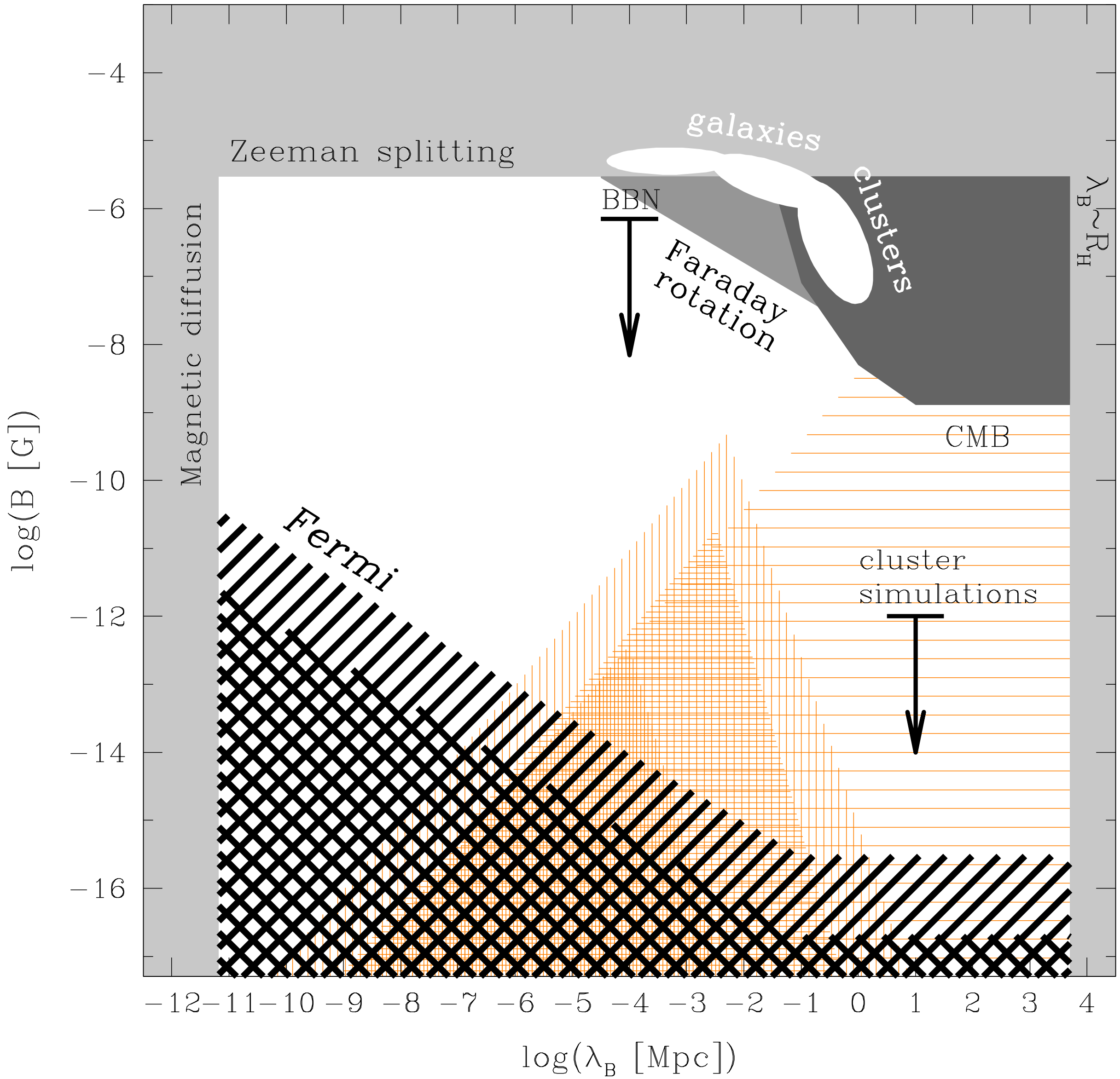
Fig. 1 A comparison of models of cascade emission from TeV blazars (thick solid black curves) with Fermi upper limits (gray curves) and HESS data (gray data points).



Andrii Neronov, and Ievgen Vovk Science 2010;328:73-75

Constraints on B in the universe

Neronov and Vovk, Science, 328, 73 (2010)



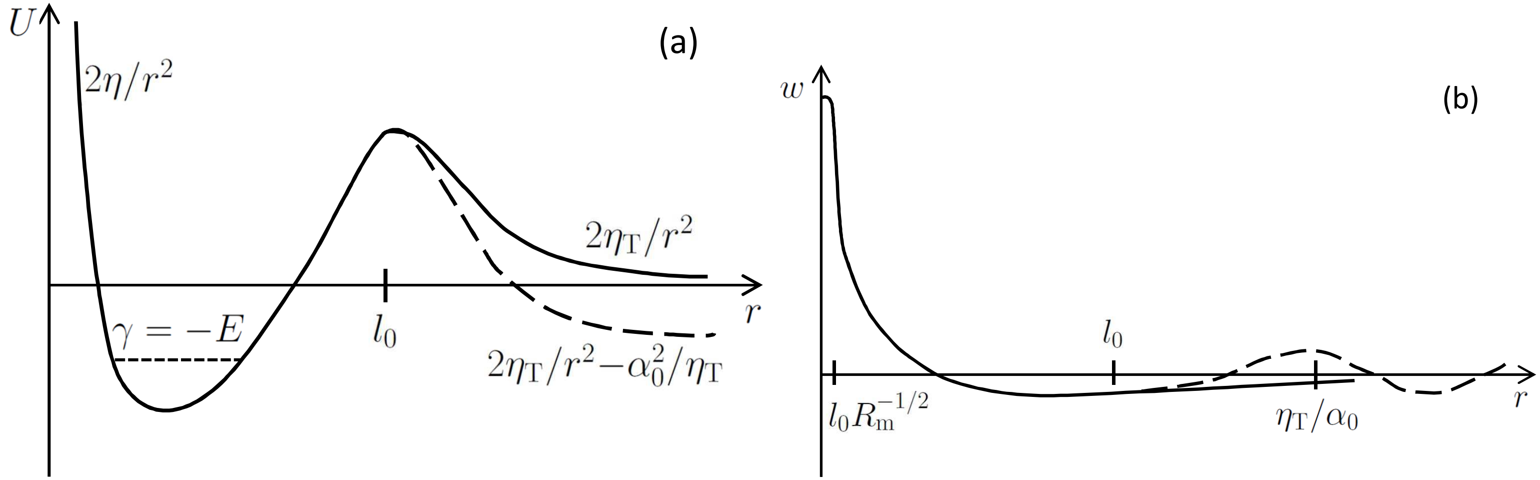
Magnetic field origins: Dynamos

- **EM induction by Motions can maintain magnetic fields**
  $(\partial \mathbf{B}/\partial t) = -c\nabla \times \mathbf{E} = \nabla \times (\mathbf{U} \times \mathbf{B} - \eta \nabla \times \mathbf{B})$

- **Turbulence $\rightarrow$ Random stretching $\rightarrow$ fluctuation dynamo $\rightarrow$ B field growth (FD Bound state problem, Kazantsev1967)**
  $BA =$ **constant and** $\rho AL =$ **constant** $\rightarrow B/\rho \propto L$**, and** $A \propto 1/(\rho L)$

- **Need helicity (parity breaking) to produce "mean" fields**

- **Helicity of turbulence allows 'tunneling' to larger scales than L**
  (Subramanian, PRL, 1999; Brandenburg, Subramanian, A&A Lett, 2000)



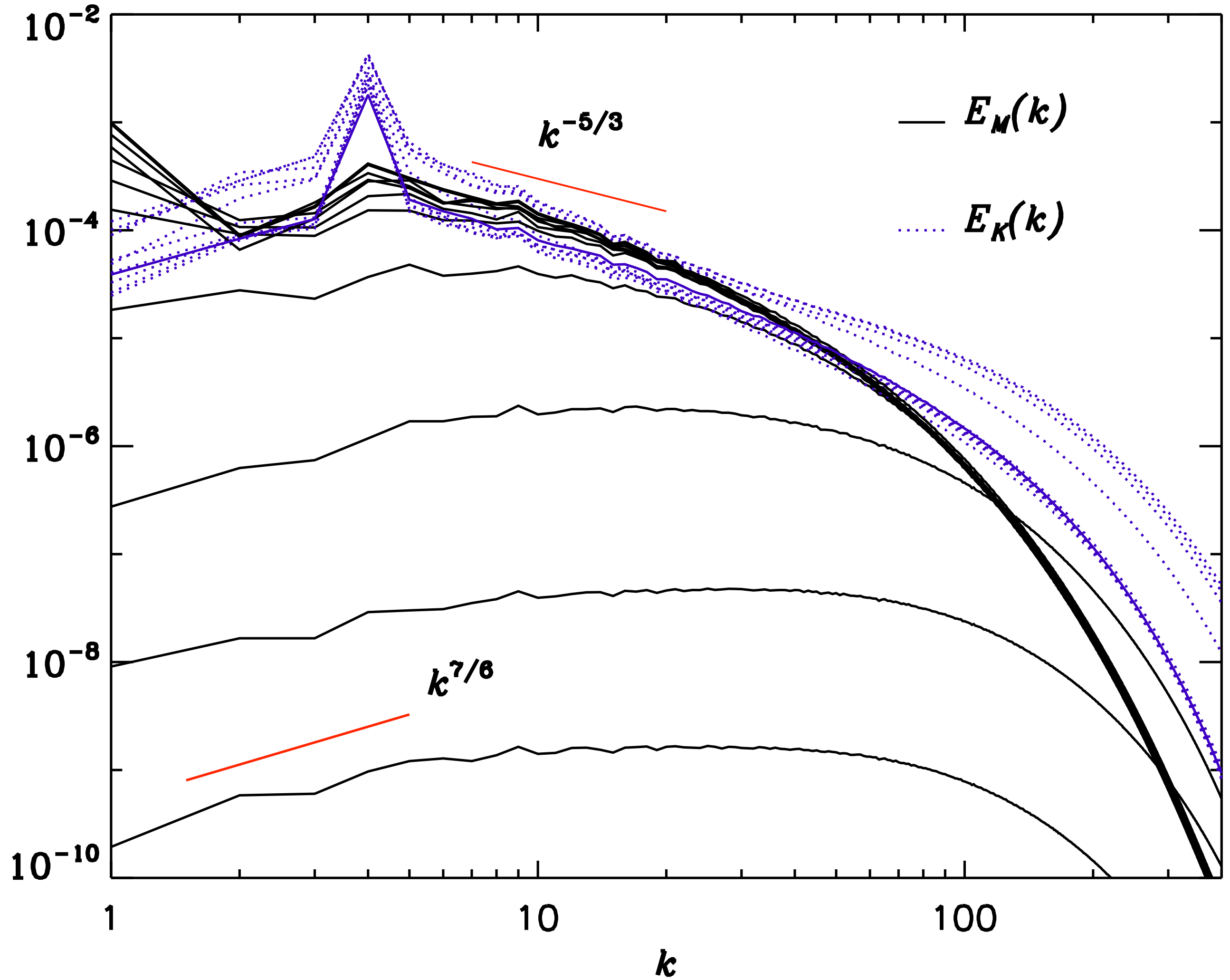
- **At large R_m: Can MFD operate in Presence of FD? Helicity conservation?**

Unified Large/Small scale dynamo?

Pallavi Bhat, Kandaswamy Subramanian, Axel Brandenburg MNRAS, 461, 240, 2016

1024^3, $P_m = 0.1$, $R_m = 330$; **First dog wags tail then tail wags dog!**

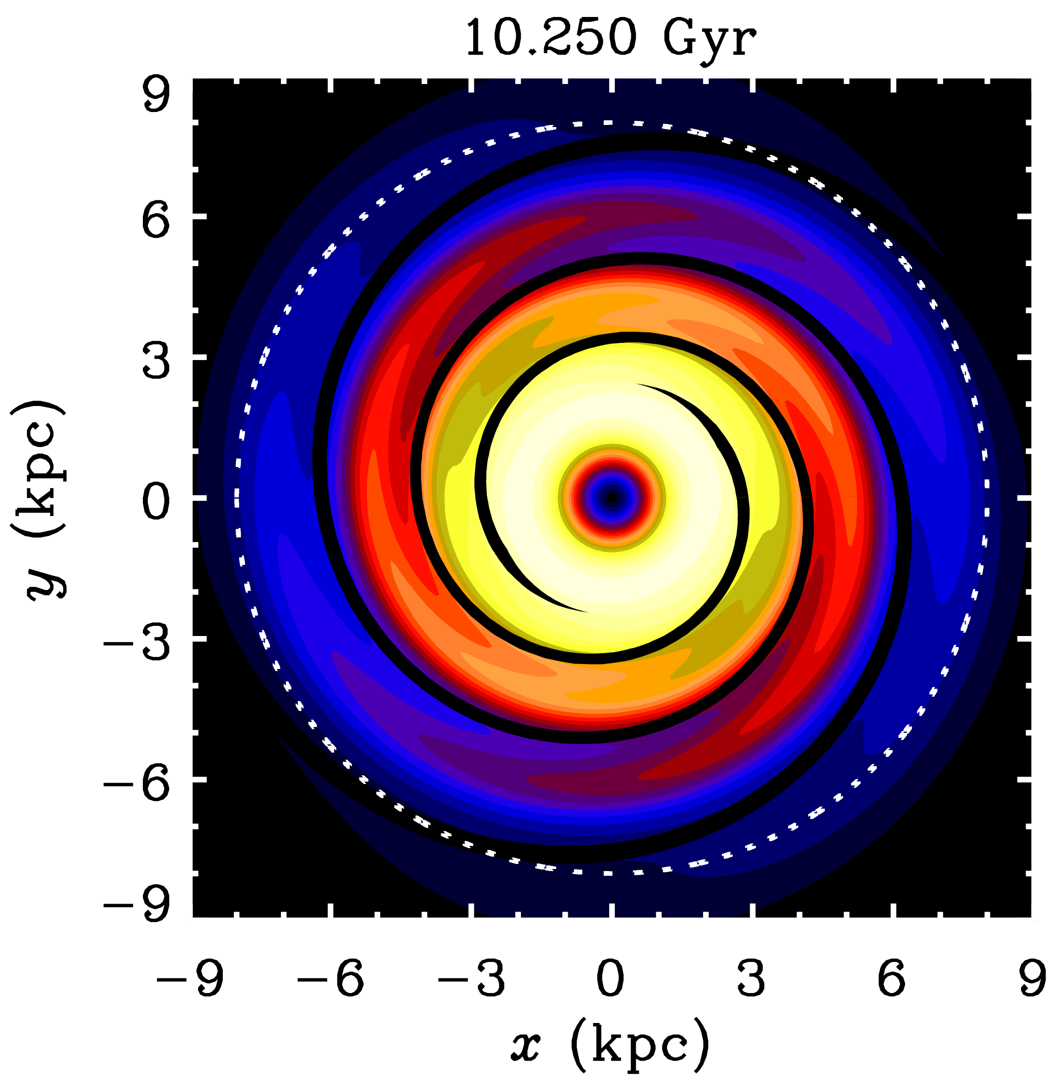
Power shifts to larger scales on saturation:-)



Galactic dynamo and magnetic spirals

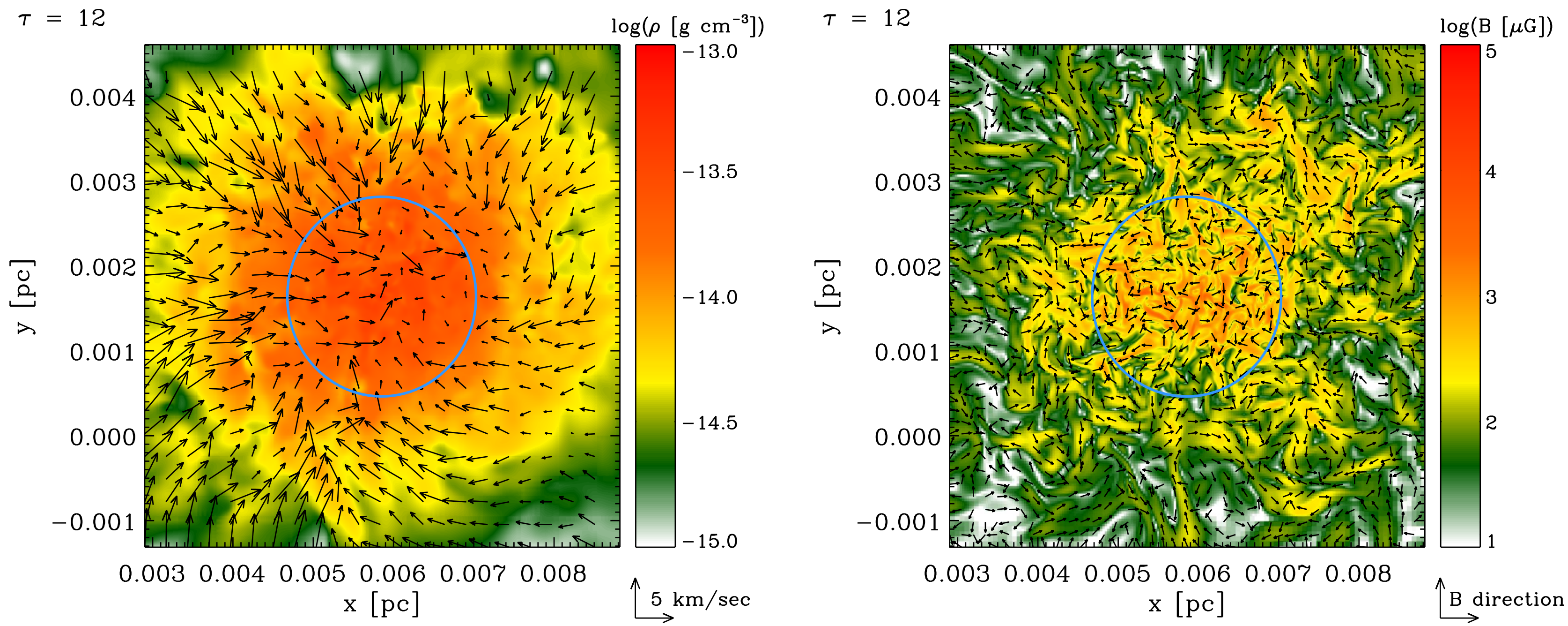
(Luke Chamandy, Shukurov, Subramanian, MN, 2014)

Winding up Spiral + outflow enhanced helicity flux along spiral



Turbulence and Dynamos in first stars

Sharanya Sur et al, ApJL, 721, L134-L138, 2010



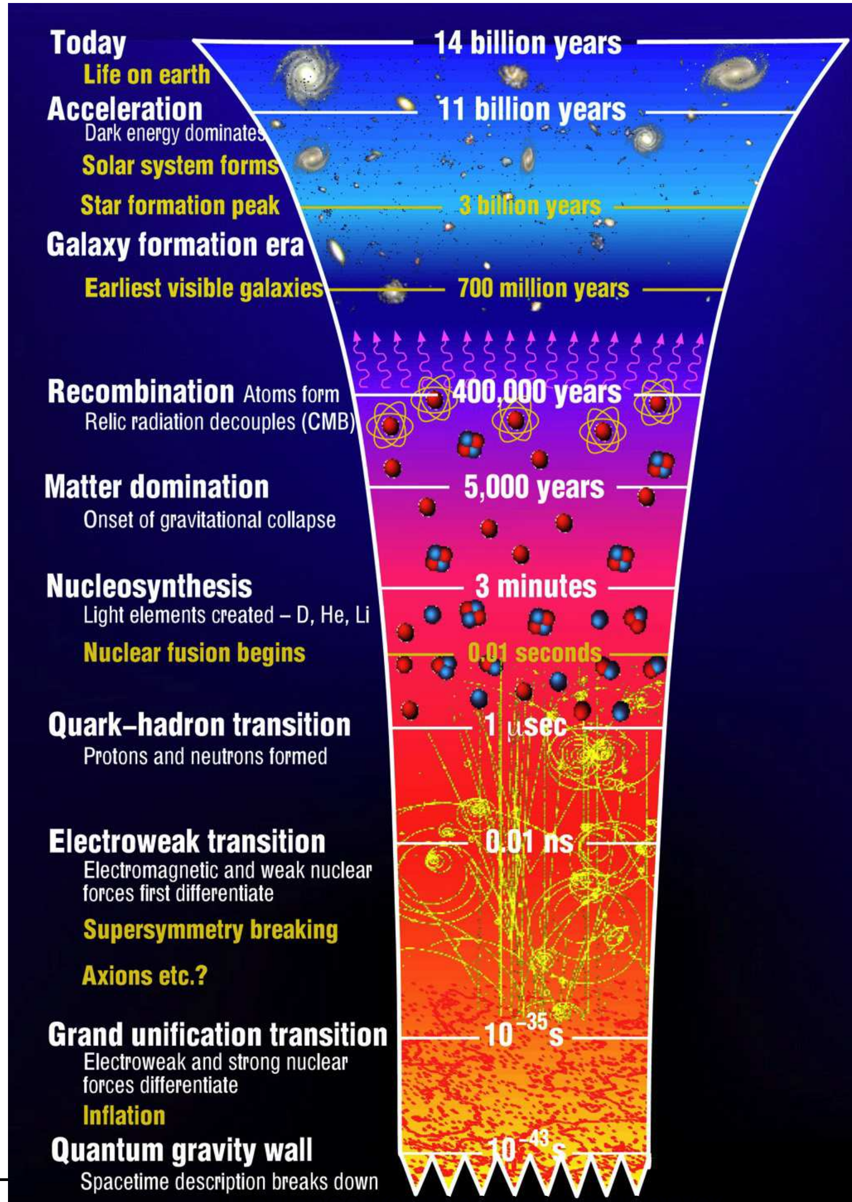
Left: Density/Velocity; Right: Magnetic field

Origin: Primordial?

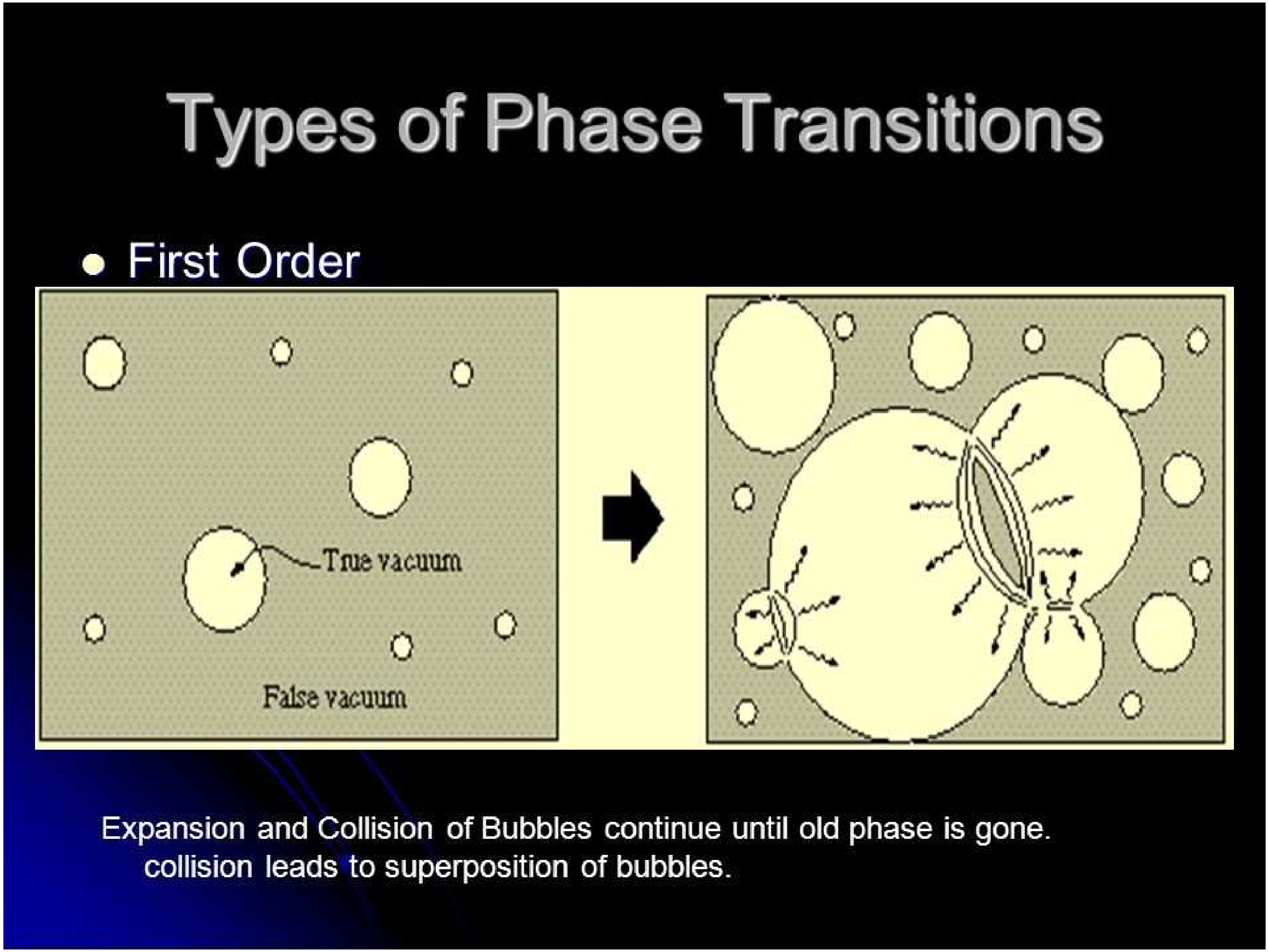
- Primordial magnetic fields: Origin in an early universe phase transition: Inflation, Electroweak, QCD.
  - Natural explanation for field in voids.
  - Provide Seed for dynamo? Help induce coherence?
  - Inflation: Strength? EW/QCD transitions: Scale?
- Flux freezing: On large scales $B(t)a^2(t) =$ constant, So $B(z) = B_0(1+z)^2$
- $\rho_B = \rho_\gamma$ (due to CMB) implies $B_0 \sim 3\mu$G.
- $B_0 \sim 10^{-9}G$ on galactic scales, interesting for Galaxy formation $+$ galaxy/cluster B? ($\rho_B = \rho_\gamma$ implies $B \sim 3\mu$G).
- Detecting relic B fields can probe early universe physics?

Early Universe timeline

http://www.ctc.cam.ac.uk/outreach/origins/



From Electroweak/QCD Phase Transition?



Hubble radius $R_H \sim 2 \times 10^{15}$ **cm (100 GeV);** $R_H \sim 1$ **lt yr (150 MeV)**

Primordial fields origin during Inflation?

(Turner and Widrow, 1988; Ratra 1992; Gasperini et al. 1995, Subramanian 2010/16)

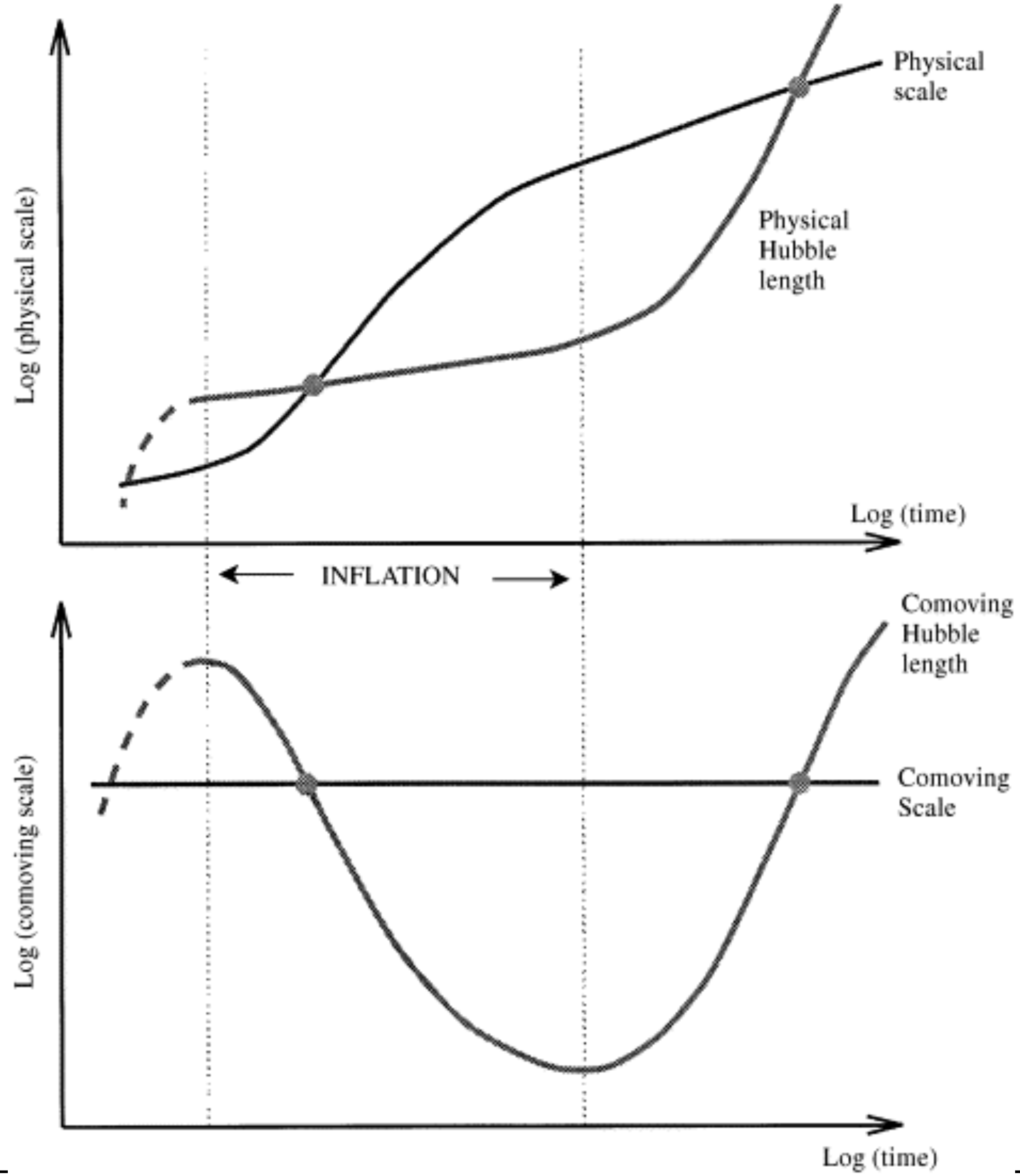
- Rapid expansion $\rightarrow$ vacuum fluctuations amplified and stretched to long wavelength "classical" fluctuations
- Negligible charge density breaks flux freezing.
- BUT Need to break conformal invariance of ED (Couple to inflaton ϕ, higer dimensional scale factor $b(t)$, curvature R, axion θ ...)

$$S = \int \sqrt{-g}\, d^4x\, b(t)[-f^2(\phi)\frac{1}{16\pi}F_{\mu\nu}F^{\mu\nu} - RA^2 + g\theta F_{\mu\nu}\tilde{F}^{\mu\nu}\ ]$$

- The mode function satisfies: $\bar{A}'' + 2\frac{f'}{f}\bar{A}' + k^2\bar{A} = 0$
- EM wave amplified from vacuum fluctuations
- After reheating $\mathbf{E}$ shorted out and $\mathbf{B}$ frozen in.

Inflation and perturbations

A. Linde



Consistent Inflationary Magnetogenesis

Sharma, Sandhya, Seshadri, Subramanian, PRD, 2017; Sharma, Subramanian, Seshadri 2018

- Scale invariant spectrum when $f \propto a^2$ or $f \propto a^{-3}$

$$B_0 \sim 5 \times 10^{-10} \mathrm{G} \left(\frac{H}{10^{-4} M_{pl}} \right)$$

- But 'charge' $e_N = e/f^2$: can become very large/small for $f \propto a^2$. (Demozzi et al, 2009)

- Consider models with matter dominated epoch after inflation before reheating, where f decreases back to 1.

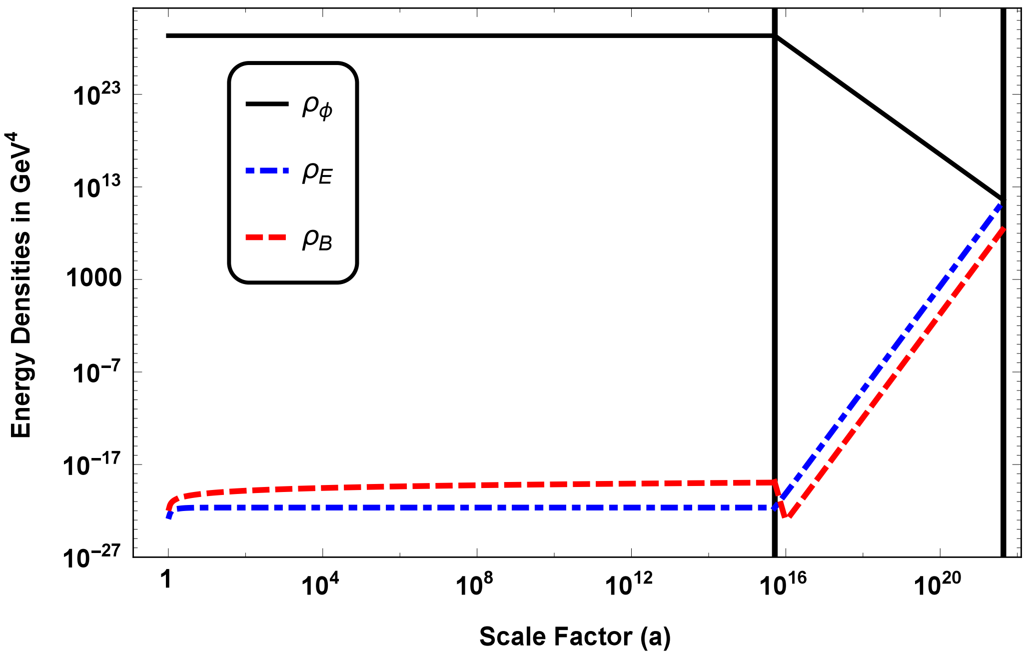
- The mode function satisfies: $\bar{A}'' + 2\frac{f'}{f}\bar{A}' + k^2\bar{A} = 0$

- For $k\eta \ll 1$, $\bar{A} = c_1 + c_2 \int d\tau/f^2$; for growing/decaying f, c_1/c_2 branch is growing mode

- When f transits from growth to decay, the dominant mode transits from c_1 to c_2 branch, spectrum transits to blue: $d\rho_B/d\ln k \propto k^4$

Consistent Inflationary Magnetogenesis

Sharma, SJ, TRS, KS, PRD, 96, 083511, 2017



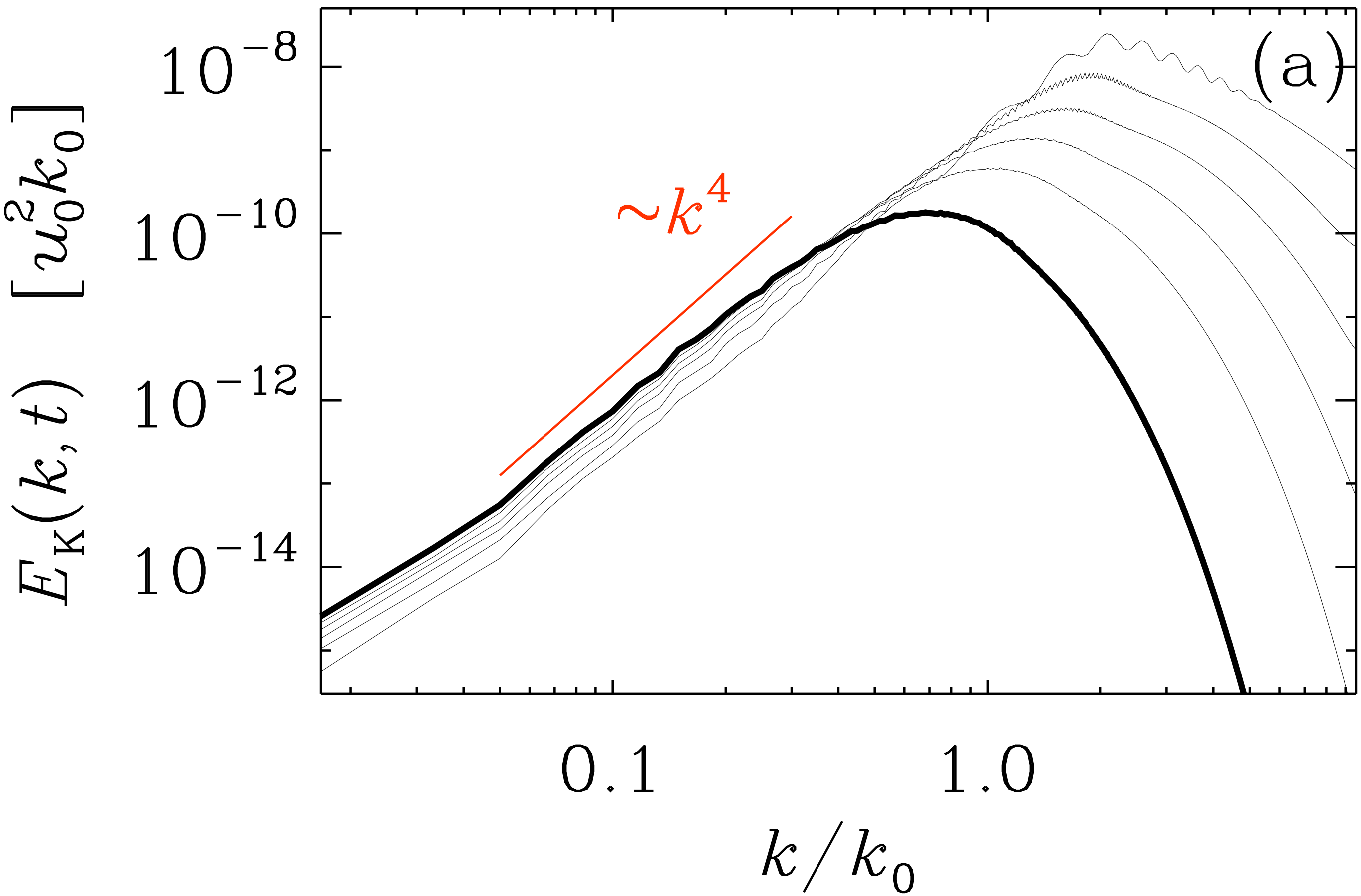
- **Require low scales of inflation and reheating to avoid back reaction**
- **Reheating at** $T = 100$ **GeV (EW), gives initial comoving** $B \sim 6 \times 10^{-7}$**G,** $L_c \sim 3 \times 10^{15} cm$
- **Helical: Initially** $B \sim 3.4 \times 10^{-7}$**G, same** L_c
- **How does it evolve further?**

Evolution in expanding universe

- **Use conformal time $d\tau = dt/a(t)$, co-moving $\mathbf{x} = \mathbf{r}/\mathbf{a}(\mathbf{t})$.** $ds^2 = dt^2 - a^2(t)d\boldsymbol{r}^2 = a^2(\tau)[d\tau^2 - d\boldsymbol{x}^2]$.
- **Conformal invariance of resistive, viscous MHD $\rightarrow$ transform to flat space MHD in scaled variables!** $\boldsymbol{B}^* = a^2\boldsymbol{B}, \boldsymbol{E}^* = a^2\boldsymbol{E}, \rho_q^* = a^3\rho_q, \boldsymbol{J}^* = a^3\boldsymbol{J}, \rho^* = a^4\rho, p^* = a^4 p, \boldsymbol{v}^* = \boldsymbol{v}$.
- $B^2/(8\pi\rho_{rad}) \sim 10^{-7}(B/nG)^2$, $V_A/c \sim 4\times 10^{-4}(B/nG)$
- **Magnetic stress $\Rightarrow$ metric perturbations, including Grav. Waves**
- **Lorentz force $\mathbf{J}\times\mathbf{B}/c \Rightarrow$ almost incompressible motions**
- **Conductivity high, Viscosity important around γ/ν decoupling. Overdamped by radiative viscosity, unlike compressible modes.** (Jedamzik et al, 1998; Subramanian & Barrow 1998)
- **Blue spectra induce decaying MHD turbulence as coherence scales enter the Horizon, and become nonlinear $v_A k\tau = 1$. (Banerjee, Jedamzik, PRD, 2004)**

Hydro Turbulent decay

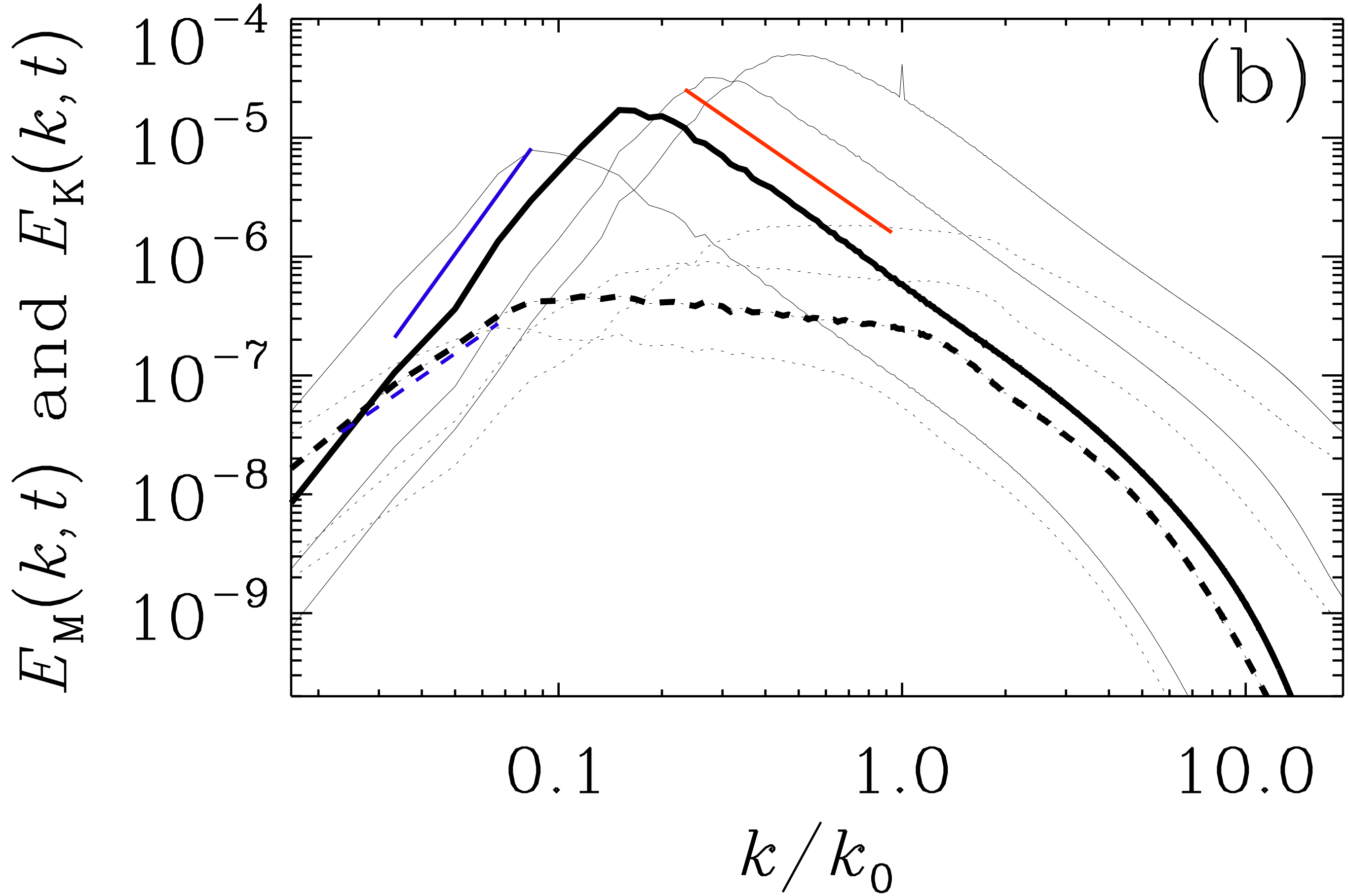
(Brandenburg et. al., PRL, 114, 075001, 2015)



- $B \propto \tau^{-(n+3)/(n+5)}$, $L_c \propto \tau^{2/(n+5)}$
- **We have** $n = 1$**,** $B \sim 7 \times 10^{-15}$ **G,** $L \sim 7$ **pc**

nonhelical MHD Turbulence decay

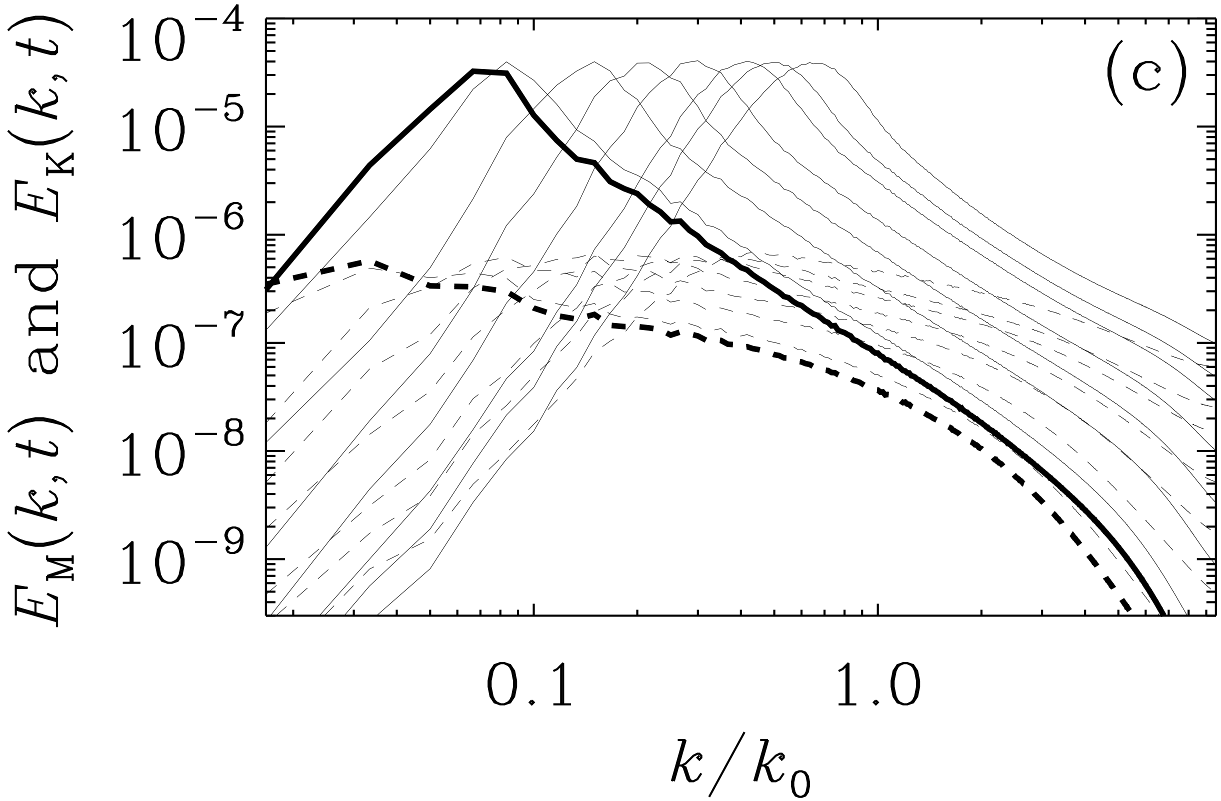
(Brandenburg et. al., PRL, 114, 075001, 2015)



$B \propto \tau^{-0.5}$, $L_c \propto \tau^{0.5}$; $B \sim 7 \times 10^{-13}$G, $L_c \sim 0.2$ kpc

Inverse cascade of helical B

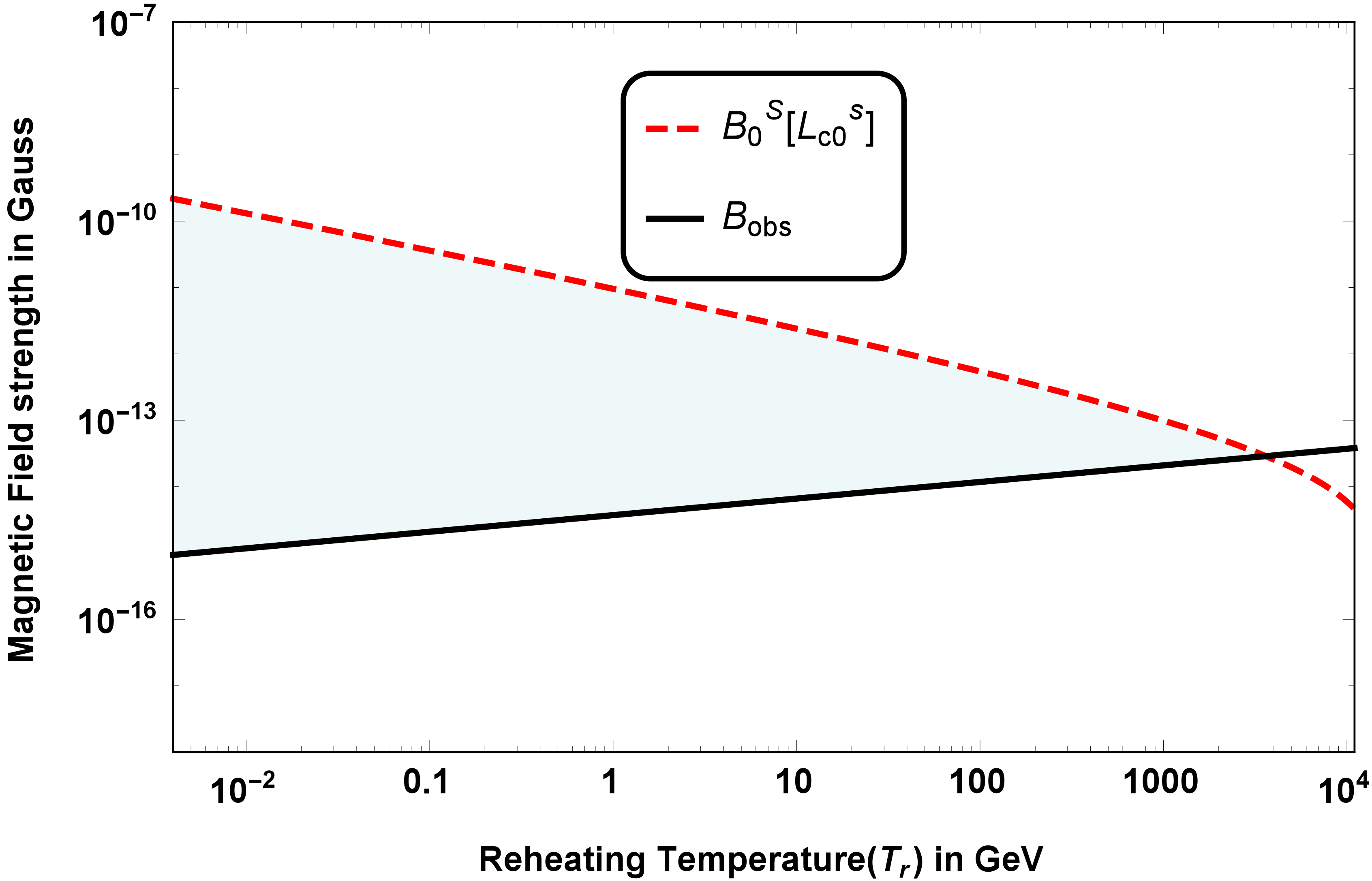
(Christensson, Hindmarsch, Brandenburg, PRE, 2001; Brandenburg et. al. PRL, 2015)



- **Assuming helicity conservation,** $H \sim LB^2 \sim LE \sim$ **constant.**
- **so** $dE/dt \sim E/(L/v) \sim E^{5/2}/H \rightarrow L \propto B^{-2} \propto t^{2/3}$
- $B_0 = 4 \times 10^{-11}\mathrm{G},\ L_c = 70$ kpc

Gamma-ray constraints

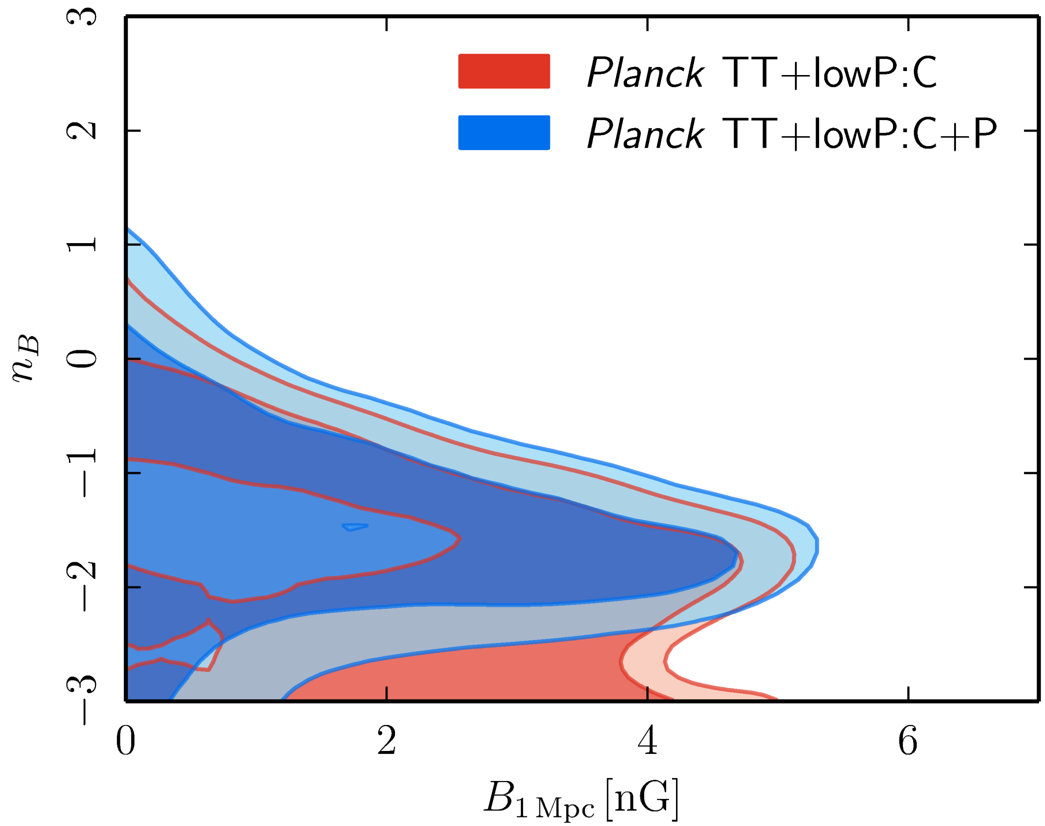
Sharma, SJ, TRS, KS, PRD, 96, 083511, 2017



Planck Constraints on primordial B & n_B

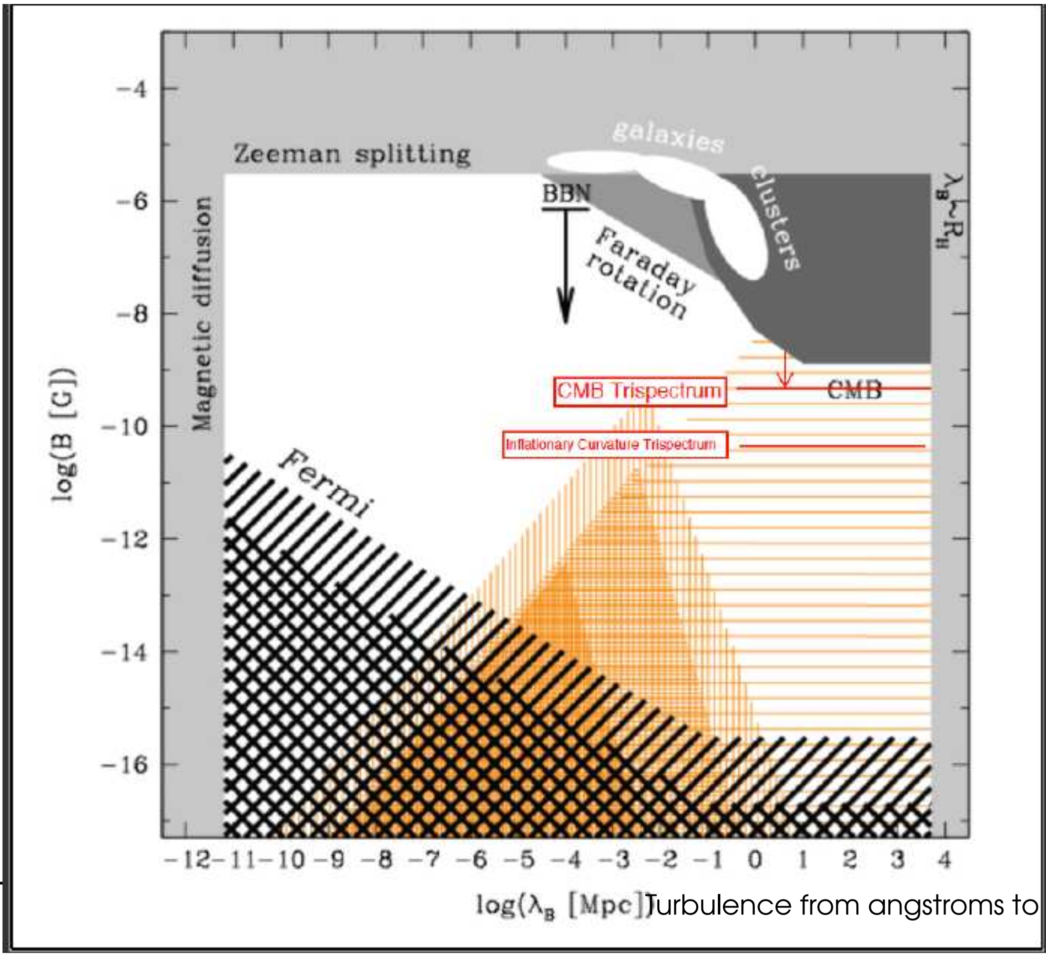
- **CMB signals from metric and velocity perturbations**
  Alfvén waves: (KS,JDB PRL,98; Durrer+98, TRS,KS, PRL, 01)
- **B field Dissipation → Ionization, Heating**
  (Sethi,KS MNRAS, 05,Kunze/Komantsu 15, Chluba+15)

Ade et al. arXiv:1502.01594v1 (Paoletti)



CMB Non Gaussianity from primordial B

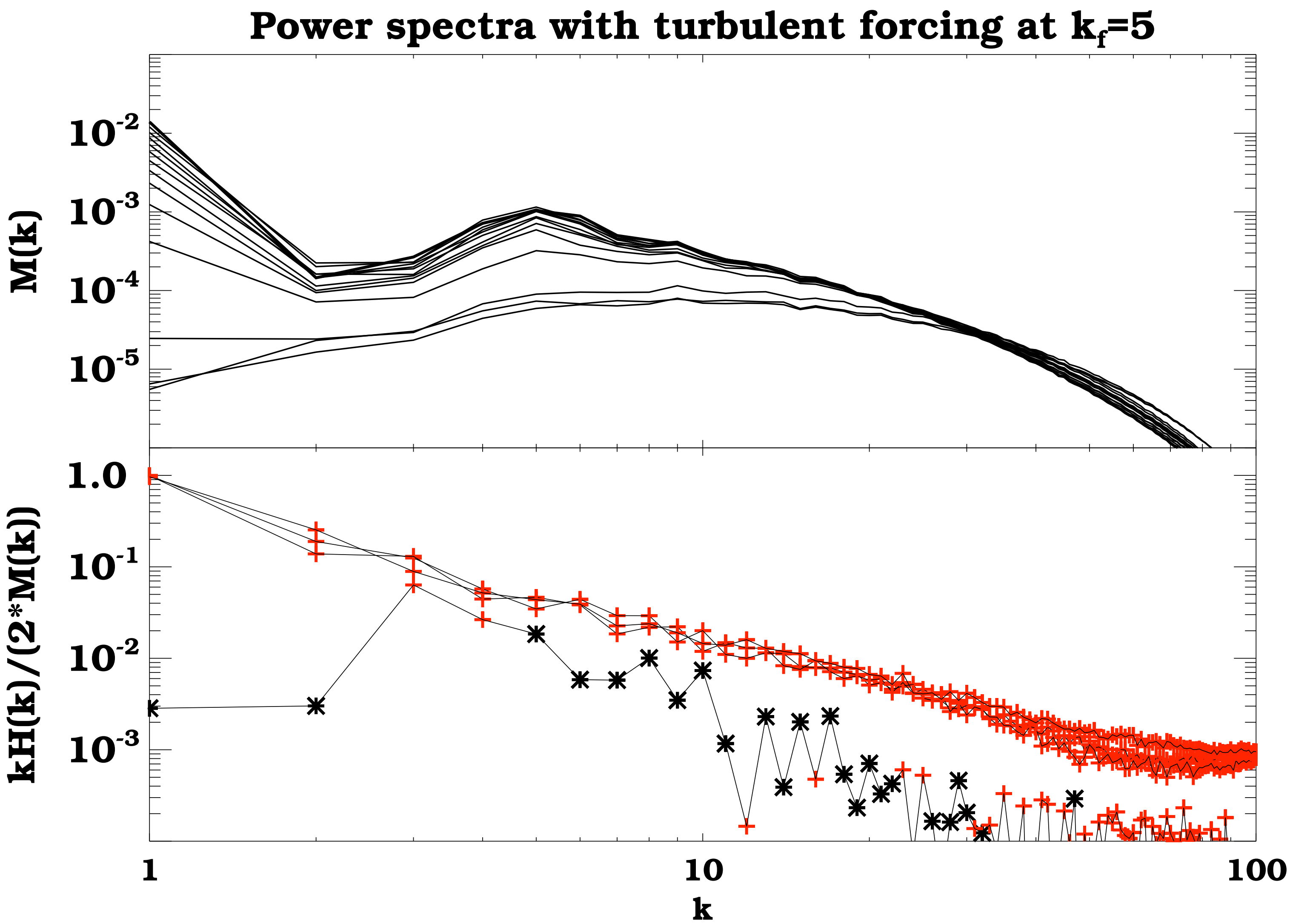
- **Magnetic stresses quadratic in B → Magnetically induced CMB signals non-Gaussian even at lowest order!**
- **Strong sub nano Gauss limit from tripsectrum (TRS, KS, PRL, 2009; Trivedi, TRS, KS, PRL, 2012; Trivedi, KS, TRS, PRD, 2014)**



Helical B resilient to turbulent diffusion

Even sub equipartition Helical fields decay on slow resistive rate

(EB,KS, 2013; Pallavi Bhat, EB, KS, MNRAS, 2014)



Final Thoughts?

- **Universe is turbulent and Magnetized; even B field in voids!**
- **Dynamos needed to maintain fields in collapsed objects BUT how to get fields in voids?**
- **The first fields could be generated from the early universe phase transitions?** Helical magnetic fields particularly interesting.
- **Need Compelling generation mechanism or firm Observations**
- **Primordial fields leave signatures in CMB, Structure formation**
- **Upper limits at sub nano Gauss level for scale invariant spectra**
- **Future probes with Radio RMs (SKA), 21 cm (SKA), High energy CRs and Gamma Rays!**