Challenges in understanding primordial magnetic fields and its evolution.

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Summary

- **The universe is magnetized.**
- **Early Universe Generation**
- **Evolution in 3 Avatars**
- **Magnetic signals**

R. Durrer, A. Neronov,Cosmological Magnetic Fields: Their Generation, Evolution and Observation. A&A Review, 21, 62 (2013).

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

T. Vachaspati, Progress on cosmological magnetic fields, Rep. Prog. Phys. 84, 074901 (2021).

A. Shukurov and K. Subramanian, Astrophysical Magnetic fields: From Galaxies to the Early Universe, CUP, 2021.

The Universe is magnetized

- Cosmic fields from synchrotron emission/polarization and Faraday Rotation, Polarized emission by dust

- Galaxies: $B \sim 10\mu G$, ordered on 10 kpc scales + random component

- $B \sim \mu$G even in Young $z \sim 1-2$ galaxies (Bernet et al. 2008; Malik, Chand, Seshadri 2020.)

- Clusters of Galaxies: few μG strengths on ~ 10 kpc scales. IGM Filaments: ~ 10 nG (Carretti, O'Sullivan + 2023)

- Even in the IGM voids? ($B \geq 10^{-16}$ Gauss; Mpc scales) (Neronov and Vovk, 2010, MAGIC+2022; BUT Broderick et al., 2011)

How do such large scale fields arise?

Seeds from batteries or early universe + Dynamos?

How can One Generate/Detect Primordial B fields?

Galactic Magnetic Fields: Observations

SOFIA Legacy Program, M51: Borlaff, Rodriguez Lopez,....KS+ ApJ (2021)

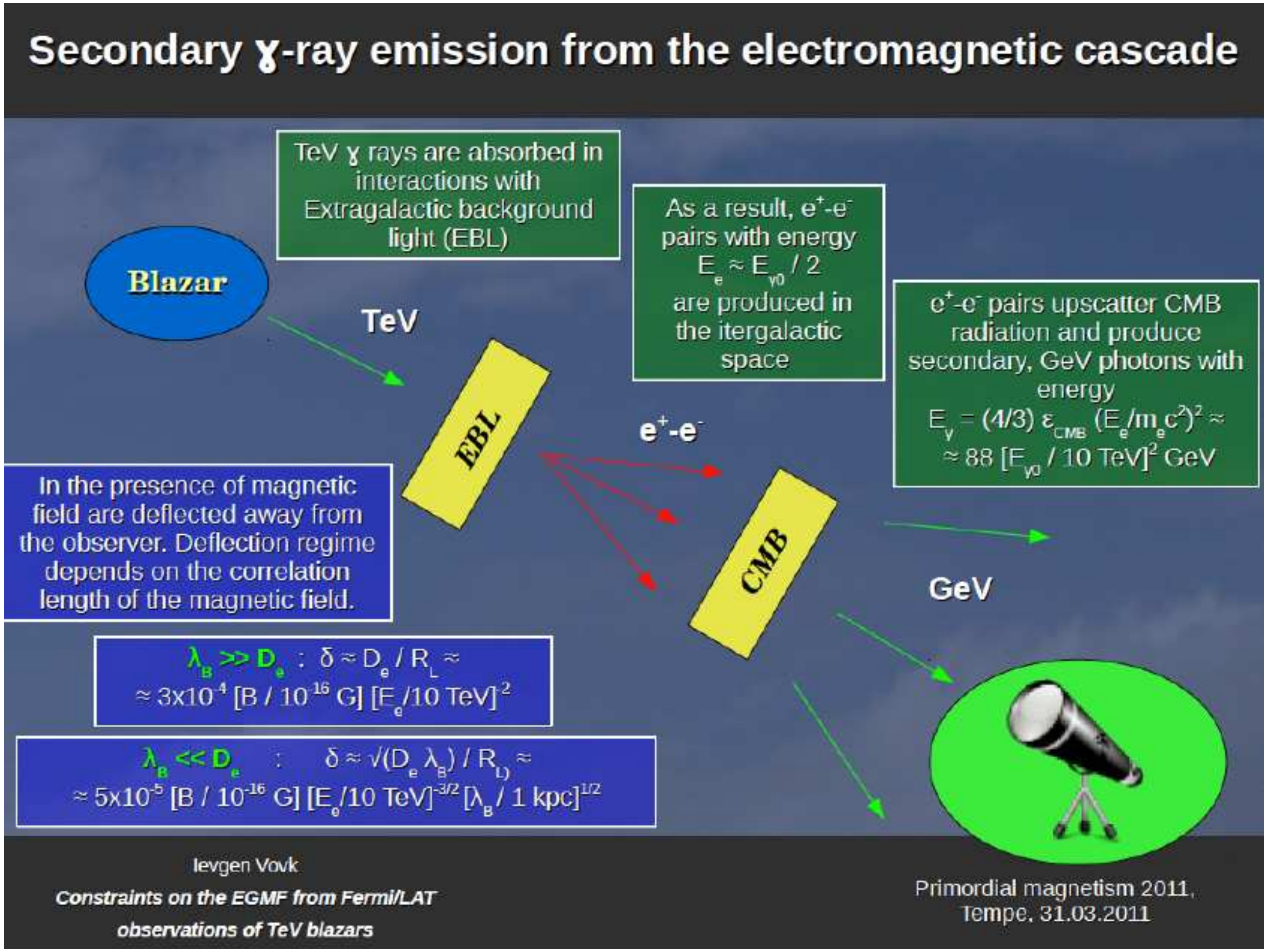
(FIR 145 μm)

(Radio 6 cm Fletcher et. al)

How do such large scale galactic fields arise? Turbulent dynamos?

Gamma-Ray Constraints on B

$l_\gamma = 80\mathrm{Mpc}\,(E_\gamma/10\mathrm{TeV})^{-1}$, $l_{IC} = 30\mathrm{kpc}\,(E_e/10\mathrm{TeV})^{-1}$, $E_{\gamma 2} = (4/3)\gamma_e^2 E_{CMB} = 0.8\mathrm{GeV}\,(E_\gamma/\mathrm{TeV})^2$



B in voids bigger than 10^{-16} Gauss on Mpc scales!

Origin: Primordial?

- Primordial magnetic fields: Origin in the early universe: Inflation (Strength?) Electroweak, QCD PT (Scale?).
  - Naturally explains void fields.
  - Not essential for stars/galaxies/clusters BUT
  - If strong can put dynamo in different regime, influence recombination, first stars/black holes...?
  - Helical fields resist turbulent decay (Kemel,Axel,Ji 11; Bhat,EB,KS, 14)
- Detecting relic B fields can probe early universe physics?
- 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?

Primordial fields origin during Inflation?

(Turner and Widrow, 1988; Ratra 1992; Gasperini et al. 1995,)

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

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

- EM Normal modes satisfy: $\bar{A}'' + 2\frac{f'}{f}\bar{A}' + k^2\bar{A} = 0$

  Scalar curvature perturbations satisfy above with $f = z = a\dot{\phi}/H$.

- After reheating $\mathbf{E}$ shorted out and $\mathbf{B}$ frozen in. Exponentially sensitive to parameters, as need $\rho_B \sim 1/a^\epsilon$
- Scale invariant spectrum for $f \propto a^2$, $f \propto a^{-3}$; $B_0 \sim 0.5\mathrm{nG}(H/10^{-4}M_{pl})$

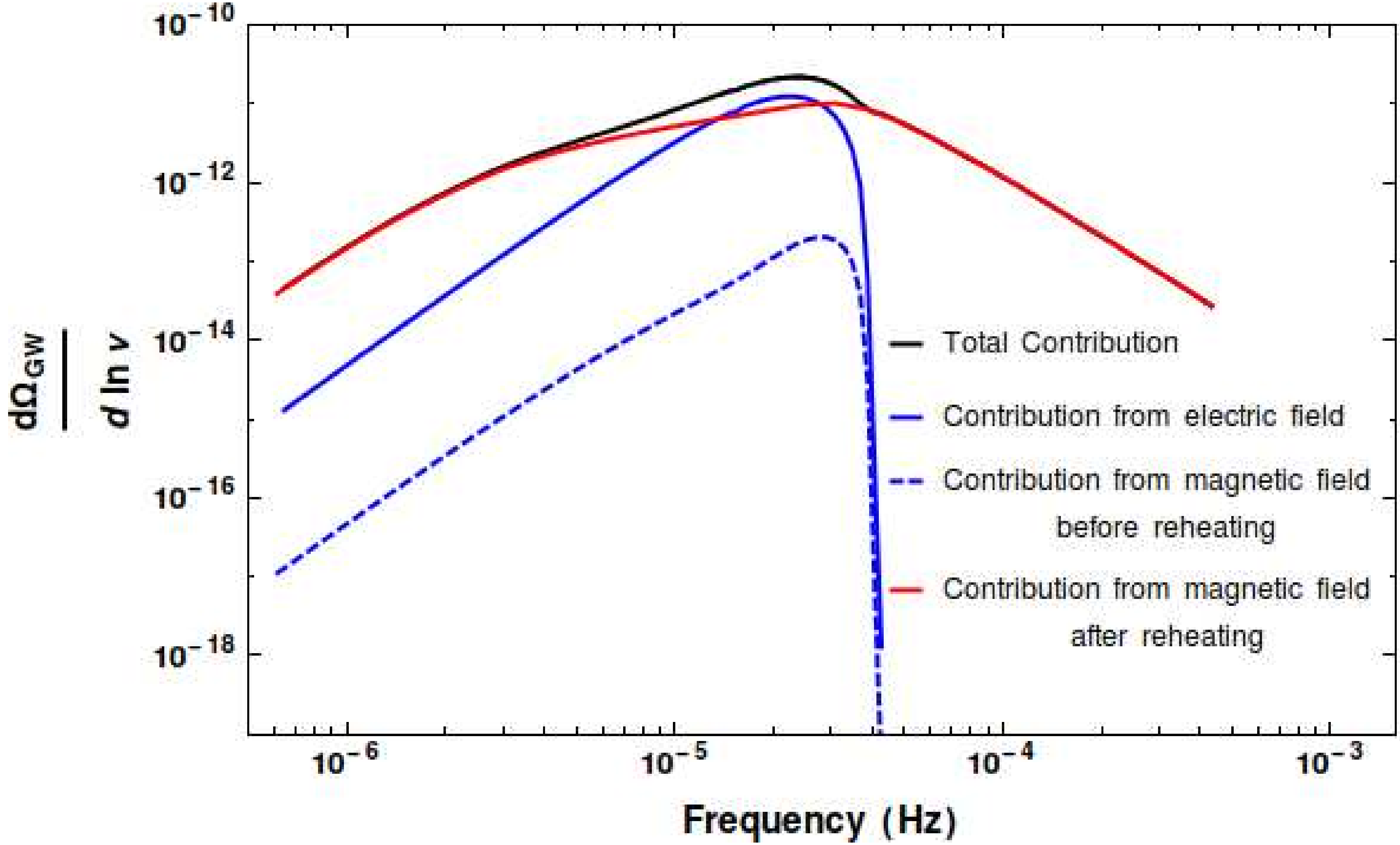
Consistent Inflationary Magnetogenesis?

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

- Strong backreaction for $f \propto a^{-3}$ due to $\mathbf{E}$ field growth. For $f \propto a^2$, 'charge' $e_N = e/f^2$, can become very large/small. (Demozzi et al, 2009)
- Schwinger effect creates charge if electric field is large enough, and freezes $\mathbf{B}$ amplification? Kobayashi, Afshordi, 14
- Consider models with matter dominated epoch after inflation before reheating, where f decreases back to 1.
- 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. As f decays, branch transition $\rightarrow$ blue spectrum
- Require low scales of inflation and reheating to avoid back reaction. Blue Spectrum: $d\rho_B/d\ln k \propto k^4$
- Reheating $T = 100$ GeV (EW), initial $B \sim 0.6\mu$G, $L_c \sim 3 \times 10^{15} cm$. Turbulent decay leads to $B_0 \sim 7 \times 10^{-13}$G, $L_c \sim 0.2$ kpc
- Helical: $B \sim 0.3\mu$G, same L_c. Turbulent decay with inverse cascade gives $B \sim 2.6 \times 10^{-11}$G, $L_c \sim 70$ kpc . How to Probe?

Gravitational Wave Predictions

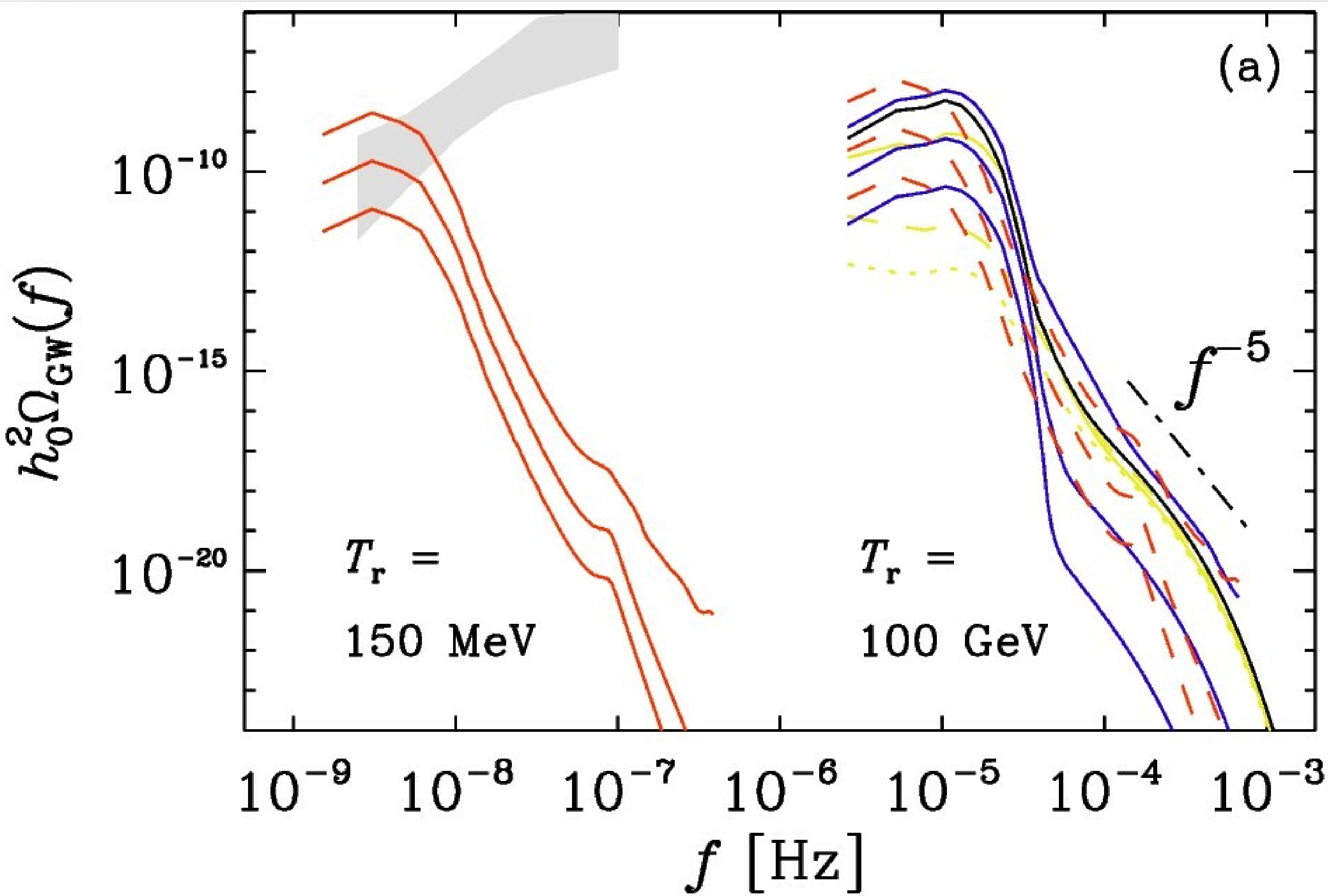
Sharma, KS, TRS, PRD, 101, 103526, 2020



Predictions for 1% in EM energy and $T_R = 100$ GeV

GW predictions from simulations

Brandenburg and Sharma, ApJ, 920, 26, 2021



Sharper fall-off after peak as turbulent cascade takes time to develop

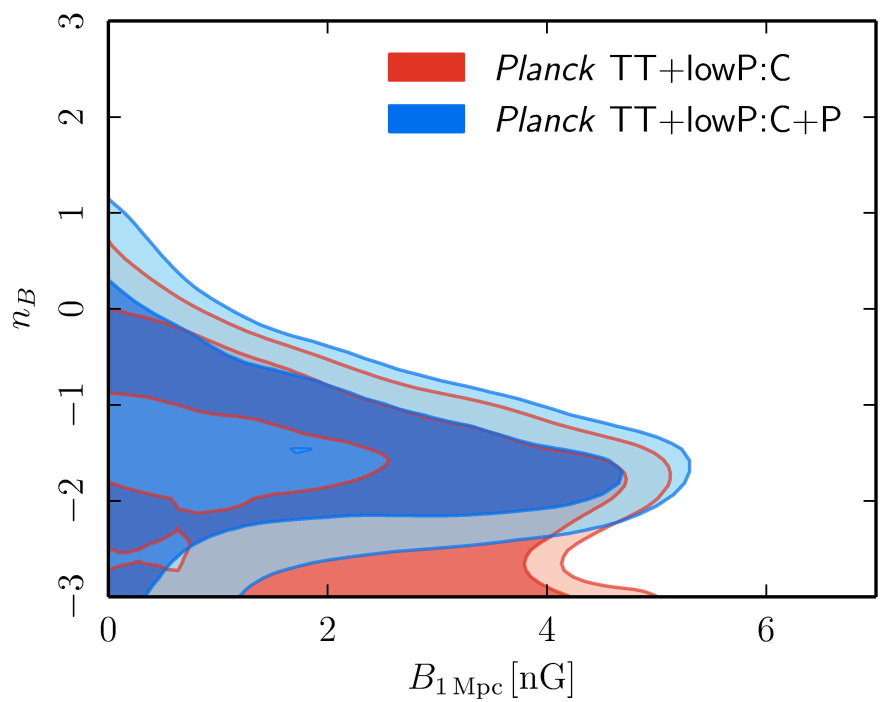
Evolution in expanding universe: I

- $B^2/(8\pi\rho_{rad}) \sim 10^{-7}(B/nG)^2$, $V_A/c \sim 4\times 10^{-4}(B/nG)$
- **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)
- **Survives damping for** $L_A > (V_A/c)L_{Silk} \ll L_{Silk}$
- **CMB signals from metric and velocity perturbations**
- **Post recombination: $n_{rad}/n_b \gg 1 \Rightarrow$ compressible motions $\Rightarrow$ seeds $\delta\rho/\rho \Rightarrow$ First Structures+ inhomogeneous recombination?**
- **B field Dissipation $\rightarrow$ Ionization, Heating, Molecules**

Coherent primordial fields potentially detectable

Planck Constraints on primordial B & n_B

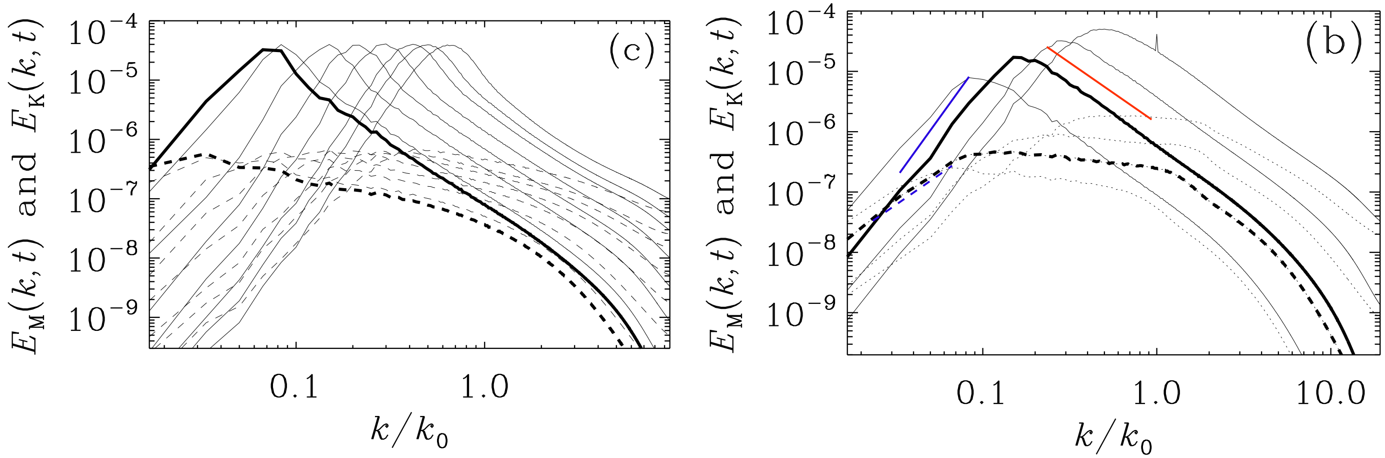
- **CMB signals from metric and velocity perturbations**
  Alfvén waves: (KS,JDB 98; Durrer/Caprini/Kahniashvilli 98, TRS,KS 01)
- **B field Dissipation $\rightarrow$ Ionization, Heating**
  (Sethi,KS 05,Kunze/Komantsu 15, Chluba/Paoletti/Finelli+15/18)
  Ade et al. (Paoletti/Finelli+15)



- **Strong sub nano Gauss upper limit from CMB Non-Gaussianity**
  (TRS/KS, 09; Caprini/Paoletti/Finelli/Riotto 09, Trivedi/TRS/KS 12;14)

Evolution in expanding universe: II

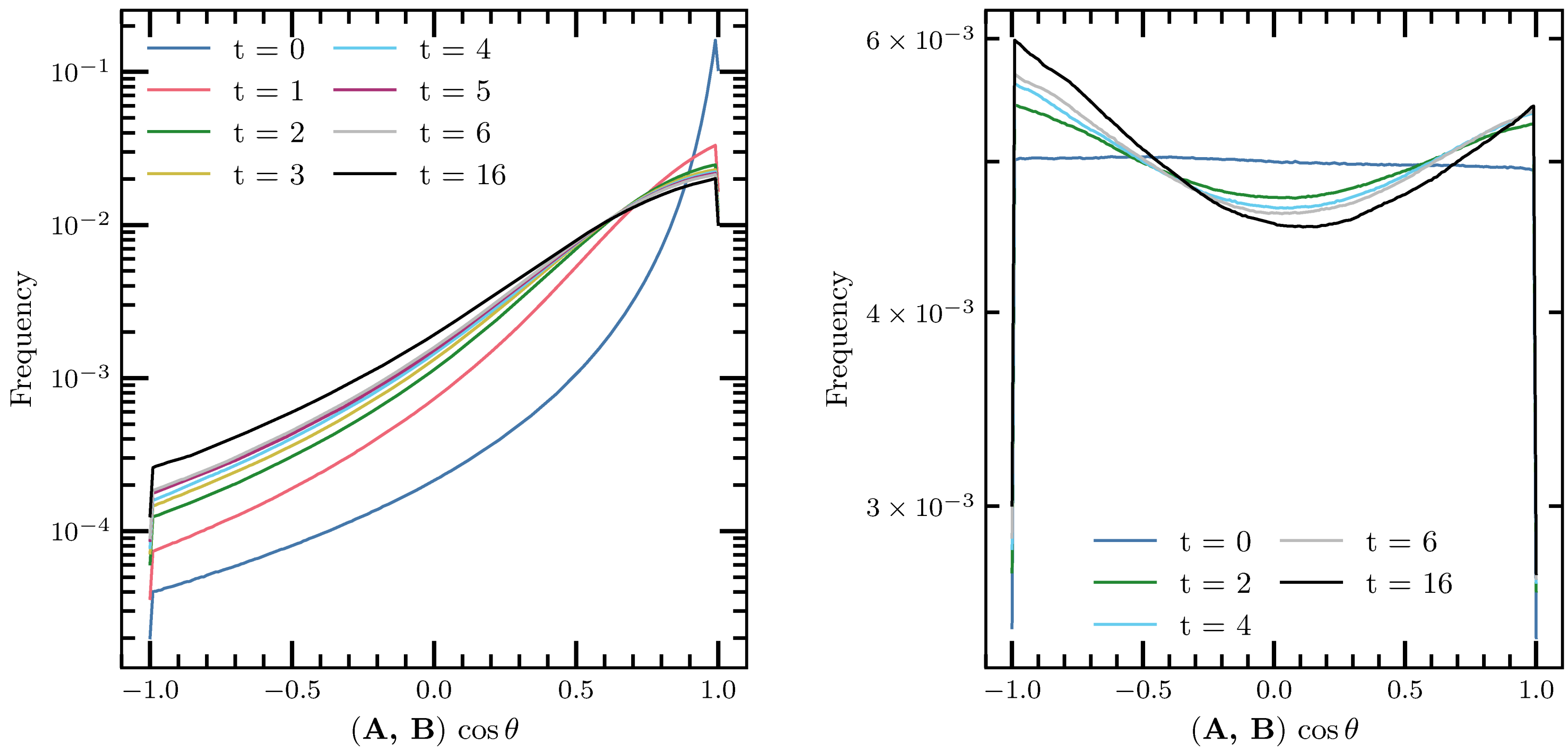
- **Blue spectra induce decaying MHD turbulence as coherence scales enter the Horizon, and $v_A k\tau = 1$ with inverse cascade/transfer. (Banerjee, Jedamzik, 04; Brandenburg+ 15, Zrake 14.....)**



- **Timescale: Alfvenic? Reconnection? (Bhat,Zhou,Louriero, 21; Zhou,Bhat,Louriero, 20; Hosking,Schekhocihin, 21, 23)**
- **Helical: Conservation of helicity B^2L constant; $B \propto \tau^{-1/3}$? $B \propto t^{-2/7}$?**
- **Nonhelical: conservation of Helicity (fluctuations) Saffman invariant: I_H? Anastrophy $< A^2 >$? (HS21, Zhou.H+22 or BZL21, Dwivedi+24)**
- **Partial helical decay completely different from fully helical. What level of helicity fluctuations required? Consistency $\neq$ Causality**

Helicity flutuations

Dwivedi, Anandavijayan, Bhat, 2024



PDF of $\cos\theta$ (θ is angle between A and B).

- **Helical: PDF strongly peaked around $\cos\theta = +1$**
- **Nonhelical: PDF almost uniformly distributedi in $\cos\theta$; no strong peak at $\cos\theta \sim \pm 1$.**

Evolution: III

- **When $\lambda_\gamma > L$: $n_{rad}/n_b \gg 1 \Rightarrow$ compressible motions $\Rightarrow$ seeds $\delta\rho/\rho \Rightarrow$ Inhomogeneous recombination (Hubble tension)? (Jedamzik, Pogosian)**

- **Perturbed density: $\delta_b = -\nabla\cdot\xi$, displacement: $\xi(\boldsymbol{x},t)$, $\boldsymbol{v} = a\partial\xi/\partial t$, $\boldsymbol{B} = \boldsymbol{B}_0 + \boldsymbol{b}$, $\boldsymbol{b} = \nabla\times(\xi\times\boldsymbol{B}_0)$. Then δ_b satisfies (KS, JDB 98)**

$$\frac{\partial^2\delta_b}{\partial t^2} + \left(2H + \frac{4\rho_\gamma}{3\rho_b} n_e\sigma_{\mathsf{T}}\right)\frac{\partial\delta_b}{\partial t} - c_b^2\frac{1}{a^2}\nabla^2\delta_b - 4\pi G\,\rho_m\delta_m = \frac{\nabla\cdot\mathbf{S}_0}{[4\pi\rho_b a^3]a^3},$$

$$\mathbf{S}_0 = [\boldsymbol{B}_0\times(\nabla\times\boldsymbol{B}_0)] + [\boldsymbol{b}\times(\nabla\times\boldsymbol{B}_0)] + [\boldsymbol{B}_0\times(\nabla\times\boldsymbol{b})]$$

- **Uniform B_0, damped MHD waves with $k < k_{max}$. For $B_0 = B_{-9}$ nG at k_{max},**

$$k_{max} = 240\mathrm{Mpc}^{-1}B_{-9}^{-1}f_{\mathsf{b}}^{1/2}\left(\frac{h}{0.7}\right)^{1/4}.$$

- **Random $\boldsymbol{B}_0$ sources δ_b; Be careful re, baryon pressure $B_0 > 50$ pG, spectral index, back reaction due to b, transition in damping nature:**

$$\Delta_b \simeq 3.5\times10^{-5}B_{-9}^2(k/\mathrm{Mpc}^{-1})^2(\Omega_{\mathsf{m}}h^2/0.15)^{-1/2}((1+z)/10^3)^{-5/2}$$

(Talks by Karsten, Pranjal T, Pranjal R, Fabio ...)

- **First Structures when back reaction due magnetic pressure of B_0 smaller than gravity: $k < k_{\mathsf{J}} \simeq 15\mathrm{Mpc}^{-1}B_{-9}^{-1}$. (Sethi, KS 05)**

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 early universe: Inflation/phase transitions? Helical magnetic fields particularly interesting.**
- **Primordial fields leave signatures in CMB, Structure formation, Gamma Rays, Stochastic GW Background**
- **Understanding primordial field origin and evolution still challenging with many interesting open questions**
- **Future probes with Radio RMs (SKA), 21 cm (SKA), High energy CRs, Gamma Rays and Gravitational wave observations!**