Magnetic Sky in an ab-Normal Universe

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AB & Supratik Pal, "Primordial magnetic non-Gaussianity with generic vacua and detection prospects in CMB spectral distortions", *arXiv:2310.10342*

A very brief intro to cosmic magnetic fields…

Growing evidence since the 1950s…

Synchrotron emission from Andromeda galaxy first observed by Brown & Hazard in 1951.

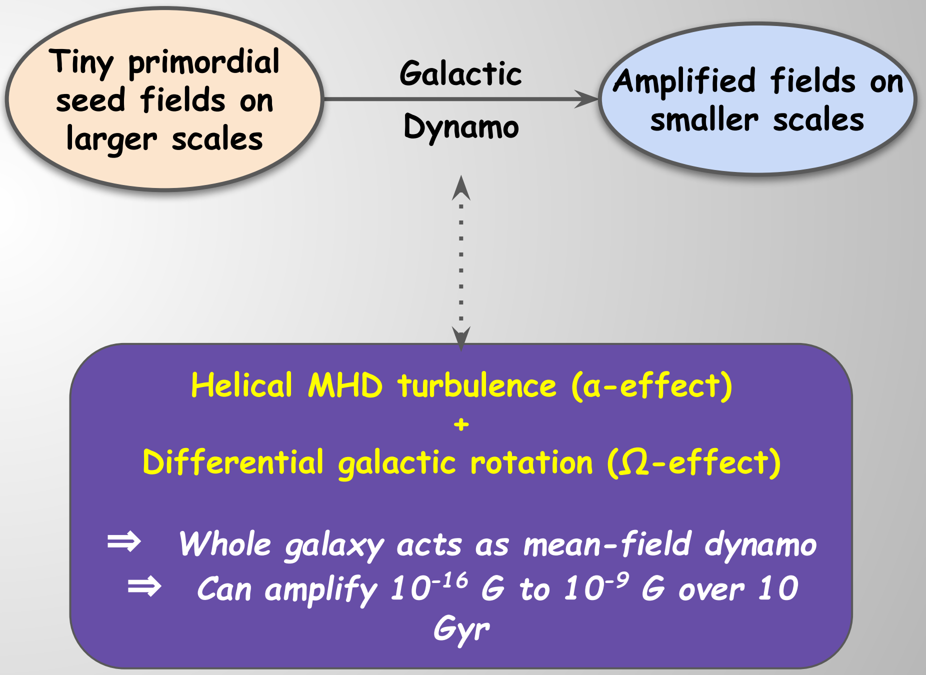
Latest observations of extragalactic polarized emission + Faraday rotation measures:

- Galaxies (~ 10 kpc) ⇒ B_0 ~ 10 nG
- Clusters (10 kpc - 1 Mpc) ⇒ B_0 ~ 1 nG

CMB + TeV blazar observations:

- IGV (≳ 1 Mpc) ⇒ 10^{-16} G ≲ B_0 ≲ 10^{-9} G

Difficult from astrophysical processes alone!



Where did the seed magnetic fields come from?

Inflationary vacuum fluctuations?

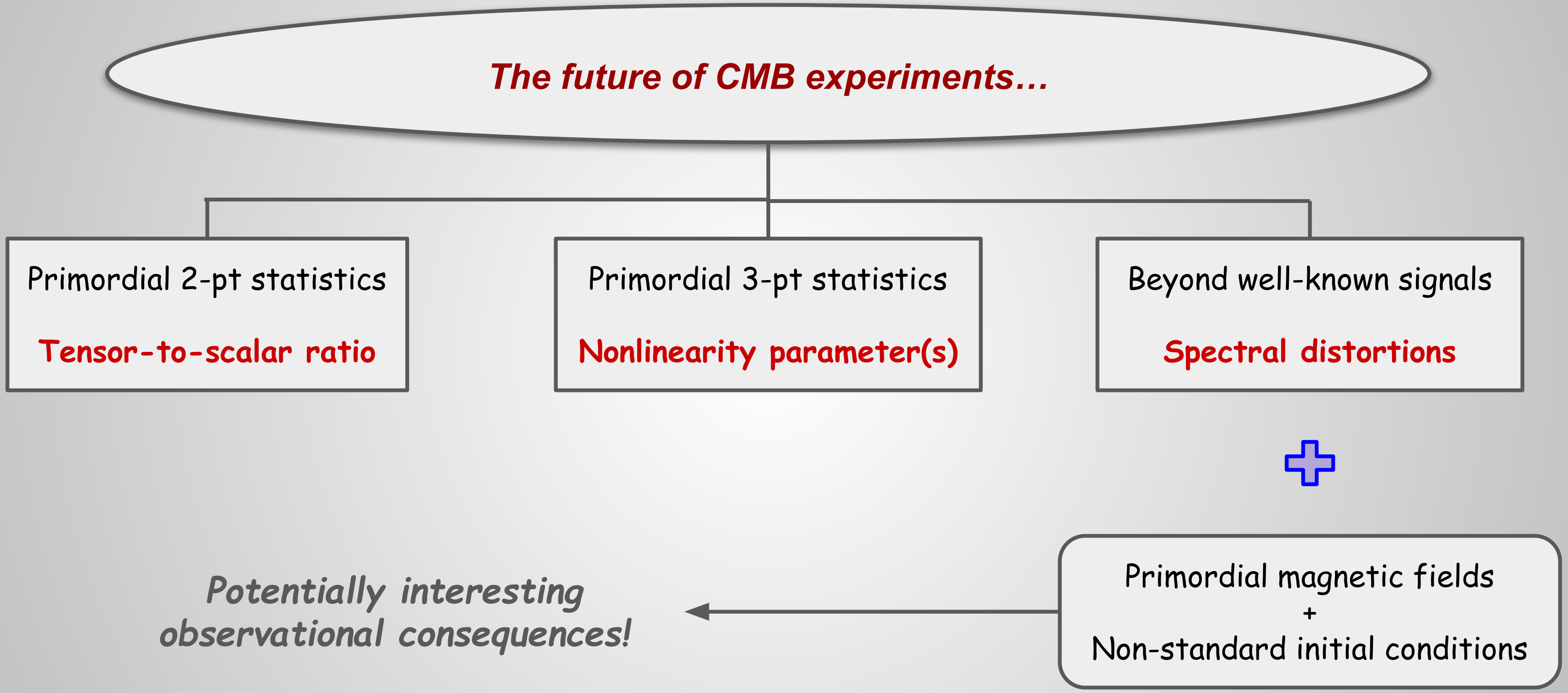
Simplest option (*Ratra '92*) ⇒ Break conformal invariance of Maxwell action!

$$-\frac{1}{4}\int d^4x\sqrt{-g}F_{\mu\nu}F^{\mu\nu} \rightarrow -\frac{1}{4}\int d^4x\sqrt{-g}\,\lambda(\phi)F_{\mu\nu}F^{\mu\nu}$$

Can generate nearly scale-invariant non-helical PMFs of required amplitude…

(High conductivity during reheating ⇒ PMF frozen, PEF shorted)

Only one of many, many proposed theoretical scenarios,
leading to a plethora of possible observational predictions…


The future of CMB experiments…
Primordial 2-pt statistics
Tensor-to-scalar ratio
Primordial 3-pt statistics
Nonlinearity parameter(s)
Beyond well-known signals
Spectral distortions
Primordial magnetic fields
+
Non-standard initial conditions
Potentially interesting observational consequences!

Three-point cross-correlations between inflationary metric perturbation and PMFs

ADM decomposition → Scalar curvature mode + PMF generated from direct kinetic coupling framework

Third-order expansion of background action ⇒ Interaction Hamiltonian → $H_{\zeta AA}(t) = \frac{1}{2}\int d^3x \, \frac{\lambda'(\eta)\zeta}{a(t)^2 H}\left(A_i'^2 - \frac{1}{2}F_{ij}^2\right)$

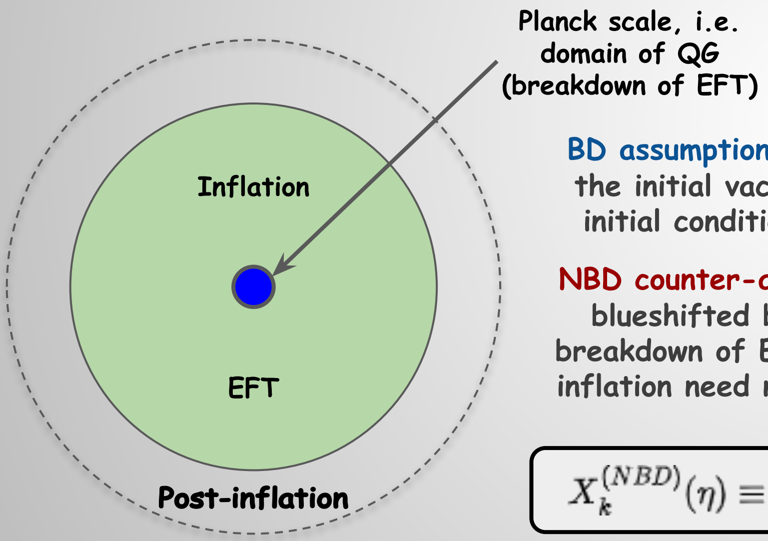
Using the master formula of the in-in formalism…

$$\langle X(\vec{k}_1,\eta_I)A_i(\vec{k}_2,\eta_I)A_j(\vec{k}_3,\eta_I)\rangle = -2\,\mathrm{Im}\int_{-\infty}^{\eta_I} d\eta_1 a(\eta_1)\langle 0|H_{XAA}(\eta_1)X(\vec{k}_1,\eta_I)A_i(\vec{k}_2,\eta_I)A_j(\vec{k}_3,\eta_I)|0\rangle$$

$$\langle X(\vec{k}_1,\eta_I)B_i(\vec{k}_2,\eta_I)B^i(\vec{k}_3,\eta_I)\rangle = -\frac{1}{a(\eta_I)^4}\left(\delta_{ij}\,\vec{k}_2.\,\vec{k}_3 - k_{2j}k_{3i}\right)\langle X(\vec{k}_1,\eta_I)A_i(\vec{k}_2,\eta_I)A_j(\vec{k}_3,\eta_I)\rangle$$

Three-point cross-correlations between inflationary metric perturbation and PMFs

Our aim ⇒ Generalize to generic initial vacua for both curvature perturbation and gauge field.



BD assumption ⇒ Deep inside the horizon, the initial vacuum is Minkowskian and sets initial conditions for the mode functions.

NBD counter-argument ⇒ Modes cannot be blueshifted back to infinite past due to breakdown of EFT, and the initial vacuum of inflation need not be perfectly Minkowskian.

$$X_k^{(NBD)}(\eta) \equiv \alpha_k X_k^{(BD)}(\eta) + \beta_k X_k^{(BD)*}(\eta)$$

The NBD solution is a **Bogolyubov rotation** of the BD solution, where the Bogolyubov coefficients parametrize **our ignorance of pre-inflation physics**.

Only theoretical constraint (from canonical commutation):

$$|\alpha_k|^2 - |\beta_k|^2 = 1$$

Three-point cross-correlations between inflationary metric perturbation and PMFs

We have assumed generic initial vacua for all the modes involved…

$$\zeta_k^{(NBD)}(\eta) = \alpha_k \zeta_k^{(BD)}(\eta) + \beta_k \zeta_k^{(BD)*}(\eta)\,, \qquad |\alpha_k|^2 - |\beta_k|^2 = 1\,,$$
$$h_k^{(NBD)}(\eta) = \rho_k h_k^{(BD)}(\eta) + \sigma_k h_k^{(BD)*}(\eta)\,, \qquad |\rho_k|^2 - |\sigma_k|^2 = 1\,,$$
$$A_k^{(NBD)}(\eta) = \gamma_k A_k^{(BD)}(\eta) + \delta_k A_k^{(BD)*}(\eta)\,. \qquad |\gamma_k|^2 - |\delta_k|^2 = 1\,.$$

…and explicitly computed the three-point correlator $\langle \zeta BB \rangle$ in the kinetic coupling model.

Scalar-magnetic cross-bispectrum:

$$\mathcal{B}(k_1,k_2,k_3;\eta_I) = a(\eta_I)^{-4}\left[2(\vec{k}_2.\vec{k}_3)\mathcal{I}_1 + \left((\vec{k}_2.\vec{k}_3)^2 + k_2^2k_3^2\right)\mathcal{I}_2\right]$$

where

$$\mathcal{I}_1 = (+2n)|\zeta_{k_1^*}|^2 A_{k_2^*} A_{k_3^*} k_2 k_3 \mathcal{J}_1 \quad , \quad \mathcal{I}_2 = (+2n)|\zeta_{k_1^*}|^2 A_{k_2^*} A_{k_3^*} \mathcal{J}_2$$

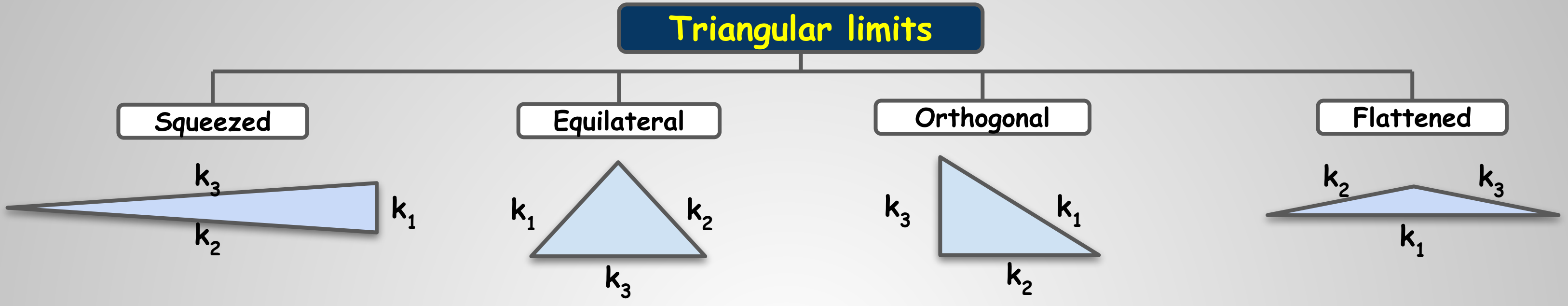
with

$$\mathcal{J}_1 = \frac{\pi^3}{2}\frac{2^{-2n-1}}{\Gamma(n+\frac{1}{2})^2}(-k_2\eta_I)^{n+\frac{1}{2}}(-k_3\eta_I)^{n+\frac{1}{2}}\,\mathrm{Im}\Bigg[\left(\alpha_1(1+ik_1\eta_I)e^{-ik_1\eta_I} + \beta_1(1-ik_1\eta_I)e^{ik_1\eta_I}\right)$$
$$\times\left(\gamma_2 H^{(1)}_{n+\frac{1}{2}}(-k_2\eta_I) - \delta_2 H^{(2)}_{n+\frac{1}{2}}(-k_2\eta_I)\right)\left(\gamma_3 H^{(1)}_{n+\frac{1}{2}}(-k_3\eta_I) - \delta_3 H^{(2)}_{n+\frac{1}{2}}(-k_3\eta_I)\right)$$
$$\times\int_{\eta_0}^{\eta_I} d\eta_1\eta_1\left(\alpha_1^*(1-ik_1\eta_1)e^{ik_1\eta_1} + \beta_1^*(1+ik_1\eta_1)e^{-ik_1\eta_1}\right)$$
$$\left(\gamma_2^* H^{(2)}_{n-\frac{1}{2}}(-k_2\eta_1) - \delta_2^* H^{(1)}_{n-\frac{1}{2}}(-k_2\eta_1)\right)\left(\gamma_3^* H^{(2)}_{n-\frac{1}{2}}(-k_3\eta_1) - \delta_3^* H^{(1)}_{n-\frac{1}{2}}(-k_3\eta_1)\right)\Bigg],$$

$$\mathcal{J}_2 = \frac{\pi^3}{2}\frac{2^{-2n-1}}{\Gamma(n+\frac{1}{2})^2}(-k_2\eta_I)^{n+\frac{1}{2}}(-k_3\eta_I)^{n+\frac{1}{2}}\,\mathrm{Im}\Bigg[\left(\alpha_1(1+ik_1\eta_I)e^{-ik_1\eta_I} + \beta_1(1-ik_1\eta_I)e^{ik_1\eta_I}\right)$$
$$\times\left(\gamma_2 H^{(1)}_{n+\frac{1}{2}}(-k_2\eta_I) - \delta_2 H^{(2)}_{n+\frac{1}{2}}(-k_2\eta_I)\right)\left(\gamma_3 H^{(1)}_{n+\frac{1}{2}}(-k_3\eta_I) - \delta_3 H^{(2)}_{n+\frac{1}{2}}(-k_3\eta_I)\right)$$
$$\times\int_{\eta_0}^{\eta_I} d\eta_1\eta_1\left(\alpha_1^*(1-ik_1\eta_1)e^{ik_1\eta_1} + \beta_1^*(1+ik_1\eta_1)e^{-ik_1\eta_1}\right)$$
$$\left(\gamma_2^* H^{(2)}_{n+\frac{1}{2}}(-k_2\eta_1) - \delta_2^* H^{(1)}_{n+\frac{1}{2}}(-k_2\eta_1)\right)\left(\gamma_3^* H^{(2)}_{n+\frac{1}{2}}(-k_3\eta_1) - \delta_3^* H^{(1)}_{n+\frac{1}{2}}(-k_3\eta_1)\right)\Bigg].$$

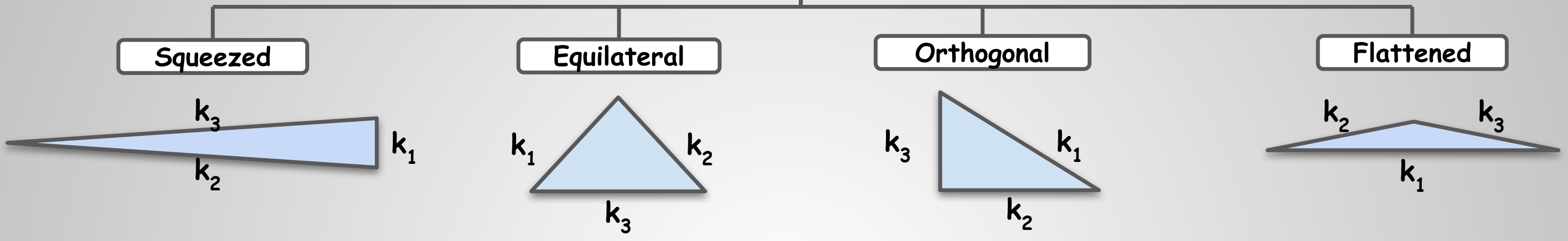
General expressions are extremely cumbersome, but limiting cases show interesting physical features!

Three-point cross-correlations between inflationary metric perturbation and PMFs



Three-point cross-correlations between inflationary metric perturbation and PMFs

Triangular limits



Squeezed ⇒ $\mathcal{B}^{(sq)}(k_1, k_2, k_3; \eta_I) = 4 \times P_\zeta(k_1) P_B(k_2)$ ⇒ **Retains product structure!**

Flattened ⇒ **Apparent divergence of bispectrum is an artifact of assumed infinite past…**

Can be cured by choosing finite past which then acts as regulator!

$$\mathcal{B}^{(fl)}(k_1, k_2, k_3; \eta_I, \eta_0) \approx \mathcal{B}^{(fl)}_{BD}(k_1, k_2, k_3; \eta_I) + \frac{4}{a(\eta_I)^4} |\zeta_{k_1^*}|^2 |A_{k_2^*}|^2 \beta_1^* k_1^2 (k_1 \eta_0)^2$$

…in the limit of weak deviations from BD vacua.

(Further reduction of one order when taking angular average for CMB)

Three-point cross-correlations between inflationary metric perturbation and PMFs

Equilateral

$$
\begin{aligned}
\mathcal{B}^{(eq)}(k_1,k_2,k_3;\eta_I) &= \frac{|\dot{\zeta}_{k^*}|^2|A_{k^*}|^2}{9a(\eta_I)^4}k^2\mathrm{Re}\Bigg[(\gamma+\delta)^2\Big[4(\alpha+\beta)\Big\{\alpha^*\left(17\gamma^{*2}+54\gamma^*\delta^*-27\delta^{*2}\right) \\
&+\beta^*\left(27\gamma^{*2}-54\gamma^*\delta^*-17\delta^{*2}\right)\Big\}+5\Big\{27(\alpha+\beta)\Big(\ln(-3k\eta_I)\left(\beta^*\delta^{*2}-\alpha^*\gamma^{*2}\right) \\
&+\ln(-k\eta_I)(\beta^*\gamma^*(\gamma^*+2\delta^*)-\alpha^*\delta^*(2\gamma^*+\delta^*))\Big)-27\gamma_E(\alpha+\beta)(\alpha^*-\beta^*)(\gamma^*+\delta^*)^2 \\
&+2\gamma^*\Big(\gamma^*(47\alpha\alpha^*+56\alpha^*\beta+9\beta\beta^*)+9\delta^*(4\alpha\alpha^*+5\alpha^*\beta-5\alpha\beta^*-4\beta\beta^*)\Big) \\
&+2\delta^*\Big(9\gamma^*(4\alpha\alpha^*+5\alpha^*\beta-5\alpha\beta^*-4\beta\beta^*)-\delta^*(9\alpha\alpha^*+56\alpha\beta^*+47\beta\beta^*)\Big)\Big\}\Big]\Bigg] \\
&-\frac{15\pi}{2}\frac{|\zeta_{k^*}|^2|A_{k^*}|^2}{a(\eta_I)^4}k^2\mathrm{Im}\Big[(\alpha+\beta)(\gamma+\delta)^2\Big\{\alpha^*(\gamma^{*2}-\delta^{*2}+2\gamma^*\delta^*)+\beta^*\left(-\gamma^{*2}+2\gamma^*\delta^*+\delta^{*2}\right)\Big\}\Big],
\end{aligned}
$$

Orthogonal

$$
\begin{aligned}
\mathcal{B}^{(or)}(k_1,k_2,k_3;\eta_I) &= -\frac{6\sqrt{2}\pi}{a(\eta_I)^4}|\zeta_{k_1^*}|^2|A_{k_2^*}|^2k_1^2\mathrm{Im}\Big[(\alpha_1+\beta_1)(\gamma_2+\delta_2)^2 \\
&\times\Big\{\alpha_1^*\Big(\gamma_2^*(\gamma_2^*+\delta_2^*)+\delta_2^*(\gamma_2^*-\delta_2^*)\Big)+\beta_1^*\Big(\gamma_2^*(\delta_2^*-\gamma_2^*)+\delta_2^*(\gamma_2^*+\delta_2^*)\Big)\Big\}\Big] \\
&-\frac{2}{a(\eta_I)^4}|\zeta_{k_1^*}|^2|A_{k_2^*}|^2k_1^2\mathrm{Re}\Bigg[(\gamma_2+\delta_2)(\gamma_3+\delta_3)\Big[\alpha_1\Big\{\alpha_1^*\Big(\gamma_2^*((6\sqrt{2}\gamma_E-10\sqrt{2}-7 \\
&+6\sqrt{2}\ln(\sqrt{2}+1))\gamma_2^*+2\sqrt{2}(3\gamma_E-5)\delta_2^*)+\delta_2^*(2\sqrt{2}(3\gamma_E-5)\gamma_2^*+\delta_2^*(6\sqrt{2}\gamma_E-10\sqrt{2} \\
&+7+6\sqrt{2}\ln(\sqrt{2}-1)))\Big)+\beta_1^*\Big(\delta_2^*(2\sqrt{2}(7-3\gamma_E)\gamma_2^*+(-6\sqrt{2}\gamma_E+14\sqrt{2}+7 \\
&+3\sqrt{2}\ln(\sqrt{2}-1)-3\sqrt{2}\ln(\sqrt{2}+1))\delta_2^*)-\gamma_2^*((6\sqrt{2}\gamma_E-14\sqrt{2}+7+6\sqrt{2}\ln(\sqrt{2}-1))\gamma_2^* \\
&+2\sqrt{2}(3\gamma_E-7)\delta_2^*)\Big)\Big\}+\beta_1\Big\{\alpha_1^*\Big(\gamma_2^*((6\sqrt{2}\gamma_E-14\sqrt{2}-7+6\sqrt{2}\ln(\sqrt{2}+1))\gamma_2^* \\
&+2\sqrt{2}(3\gamma_E-7)\delta_2^*)+\delta_2^*(2\sqrt{2}(3\gamma_E-7)\gamma_2^*+(6\sqrt{2}\gamma_E-14\sqrt{2}+7+6\sqrt{2}\ln(\sqrt{2}-1))\delta_2^*)\Big) \\
&+\beta_1^*\Big(\delta_2^*(2\sqrt{2}(5-3\gamma_E)\gamma_2^*+(-6\sqrt{2}\gamma_E+10\sqrt{2}+7+3\sqrt{2}\ln(\sqrt{2}-1)-3\sqrt{2}\ln(\sqrt{2}+1))\delta_2^*) \\
&-\gamma_2^*((6\sqrt{2}\gamma_E-10\sqrt{2}+7+6\sqrt{2}\ln(\sqrt{2}-1))\gamma_2^*+2\sqrt{2}(3\gamma_E-5)\delta_2^*)\Big)\Big\} \\
&+6\sqrt{2}(\alpha_1+\beta_1)(\alpha_1^*-\beta_1^*)(\gamma_2^*+\delta_2^*)(\gamma_2^*+\delta_2^*)\ln(-k_1\eta_I)\Big]\Bigg].
\end{aligned}
$$

Presence of additional logarithmic terms even at tree-level, which may dominate at CMB scales for suitable choices of NBD parameters!

Imprints on CMB μT cross-power spectrum

Energy injected into pre-recombination photon-baryon fluid → Deviations of CMB from black-body ⇒

Planckian distribution (zero chemical potential)

↓

Bose-Einstein distribution (non-zero chemical potential)

$$\mu = 1.4 \times \left(\frac{\Delta E}{E}\right)$$

Can be caused by damping of acoustic waves, magnetic fields, etc.

⇒ Pajer & Zaldarriaga (2012), Ganc & Sloth (2014), etc.

Imprints on CMB μT cross-power spectrum

Energy injected into pre-recombination photon-baryon fluid → Deviations of CMB from black-body ⇒ Planckian distribution (zero chemical potential) ↓ Bose-Einstein distribution (non-zero chemical potential)

$$\mu = 1.4 \times \left(\frac{\Delta E}{E}\right)$$

Can be caused by damping of acoustic waves, magnetic fields, etc.

⇒ Pajer & Zaldarriaga (2012), Ganc & Sloth (2014), etc.

Two powers of magnetic field ⇒ μ-distortion multipoles

Scalar curvature perturbation ⇒ T-anisotropy multipoles

→ Scalar-magnetic bispectrum ⇒ μT correlation

$$\langle a^{\mu}_{lm} a^{T}_{l'm'} \rangle \equiv C_l^{\mu T} \delta_{ll'} \delta_{mm'}$$

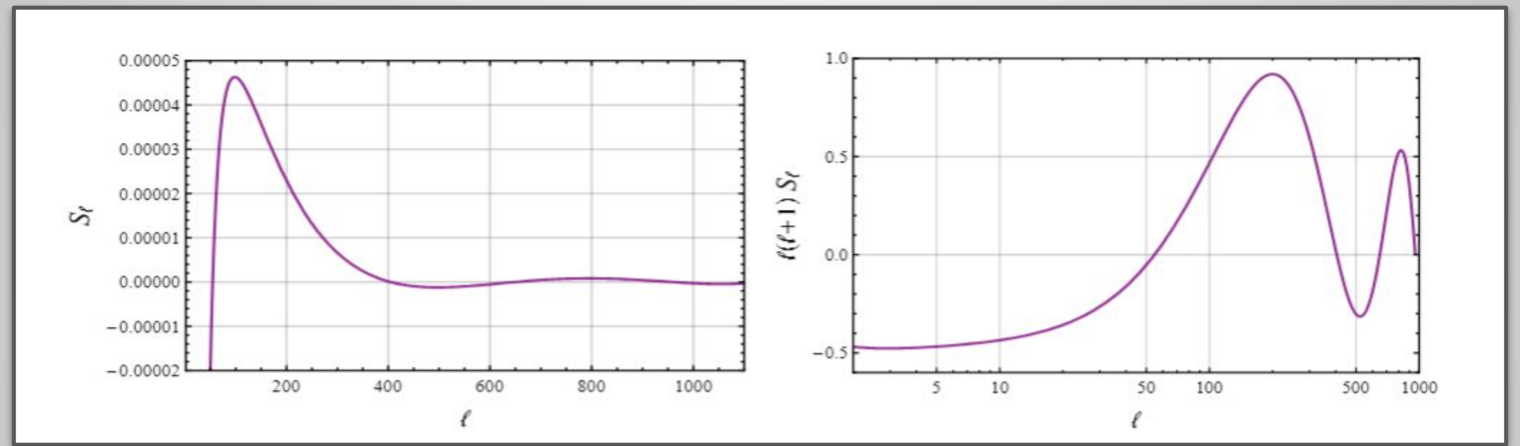
In the squeezed limit which is relevant to the μT correlation:

$$C_l^{\mu T} = 1.4 \times \frac{12}{5(2\pi)^3} \frac{b_{NL}^{(loc)}}{\mu_0 \rho_{\gamma 0}} \int_0^{10k_s} dk k^2 P_\zeta(k) W\left(\frac{k}{k_s}\right) j_l(kr_L) g_{Tl}(k) \int_{\tilde{k}_D^f}^{\tilde{k}_D^i} dk_1 k_1^2 P_B(k_1)$$

- Window function $W(x)=3x^{-3}(\sin x - x\cos x)$
- Scalar radiation transfer function $g_{Tl}(k)$
- Damping limits 2.1×10^4 Mpc^{-1} to 83 Mpc^{-1}
- Smoothing scale $k_s \sim 0.084$ Mpc^{-1}

Imprints on CMB μT cross-power spectrum

Apart from overall normalization, spectral shape governed by ⇒ $$S_l = \int_0^{10k_s} dk_1 k_1^{n_s-3} j_1\left(\frac{k_1}{k_s}\right) j_l(kr_L) g_{Tl}(k)$$



Analytical approximation for $l \lesssim 1200$ ⇒

$$S_l \approx \frac{\bar{A}}{l^3} + \frac{\bar{B}}{l^2} + \bar{C} + \bar{D} l^{3/2} + \bar{E} l^4 + \bar{F} \ln l + \bar{G} J_1\left(\frac{l}{1200}\right),$$

$$\bar{A} = 0.287492\,, \quad \bar{B} = -0.458365\,, \quad \bar{C} = 0.0006464\,,$$

$$\bar{D} = -6.96227 \times 10^{-9}\,, \quad \bar{E} = 2.13935 \times 10^{-17}\,,$$

$$\bar{F} = -0.000130573\,, \quad \bar{G} = 0.00119243\,.$$

Imprints on CMB μT cross-power spectrum

Final form of correlation $\Rightarrow$

$$C_l^{\mu T} \approx (1.34 \times 10^{-7}) \times \theta_B \times S_l$$

$$\theta_B \equiv \left[|\gamma_2 + \delta_2| (H/M_{Pl}) \right]^2$$

Where did the scalar NBD coefficients go??

Imprints on CMB μT cross-power spectrum

Phew!

Where did the scalar NBD coefficients go??

Final form of correlation ⇒

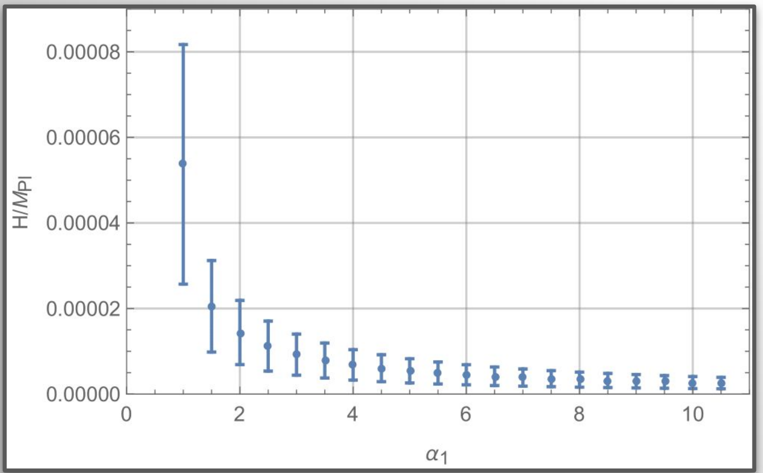
$$C_l^{\mu T} \approx (1.34 \times 10^{-7}) \times \theta_B \times S_l$$

$$\theta_B \equiv \left[|\gamma_2 + \delta_2| (H/M_{Pl}) \right]^2$$

As the scalar power spectrum is accurately constrained, need to keep this constant…

$$|\alpha_1 + \beta_1| \left(\frac{H}{M_{Pl}} \right) = (5.37 \pm 0.28) \times 10^{-5}$$

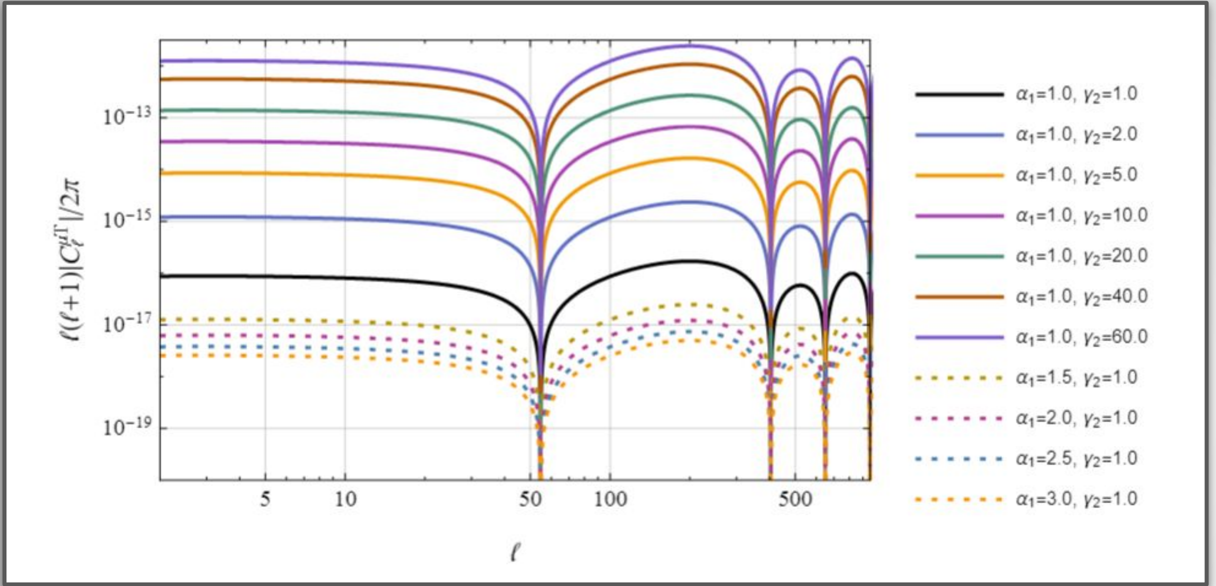
NBD scalar sector entails corresponding tuning of H, which modifies θ_B and affects the amplitude of the correlation!



Variation of H vs α_1 (for positive β_1), error bars scaled x10.

We are now in a position to fully compute the correlation for any choice of NBD parameters…

Imprints on CMB μT cross-power spectrum



Dependence of μT correlation strength on choice of initial vacua (with positive real values of all the NBD parameters). Cannot be enhanced much further while being consistent with the constraint $B_0 \lesssim 27$ nG on μ-distortion scales.

BD scalar + NBD magnetic can enhance the correlation strength by upto $O(10^2)$.

BD scalar + BD magnetic in between, as cross-check for extant results.

NBD scalar + BD magnetic suppresses the correlation strength nearly equally.

Signals potentially detectable by several next-generation CMB missions…

Fisher signal-to-noise ratio for μT spectrum at upcoming missions

$$F_{ij} = \sum_l \sum_{PP',QQ'} \frac{\partial C_l^{PP'}}{\partial \theta_i} \left(\mathrm{Cov}_l^{-1}\right)_{PP',QQ'} \frac{\partial C_l^{QQ'}}{\partial \theta_j}$$

$$(\mathrm{Cov}_l)_{PP',QQ'} = \frac{1}{(2l+1) f_{sky}} \left(C_l^{PQ} C_l^{P'Q'} + C_l^{PQ'} C_l^{P'Q}\right)$$

Fisher signal-to-noise ratio for μT spectrum at upcoming missions

$$F_{ij} = \sum_l \sum_{PP',QQ'} \frac{\partial C_l^{PP'}}{\partial \theta_i} \left(\mathrm{Cov}_l^{-1}\right)_{PP',QQ'} \frac{\partial C_l^{QQ'}}{\partial \theta_j}$$

$$\left(\mathrm{Cov}_l\right)_{PP',QQ'} = \frac{1}{(2l+1) f_{sky}} \left(C_l^{PQ} C_l^{P'Q'} + C_l^{PQ'} C_l^{P'Q}\right)$$

- *PP' = QQ' =* μT in our case
- TT is known precisely
- Noise dominated $\mu\mu$ signal

→ Cramer-Rao bound for maximum SNR

$$\left(\frac{S}{N}\right)_{max} \approx \sqrt{\sum_l (2l+1) f_{sky} \left(C_l^{\mu\mu,N} C_l^{TT,fid}\right)^{-1} \left(C_l^{\mu T}\right)^2}$$

Instrumental noise power spectrum ⇒ $N_\mu \exp\left(l^2/l_{max}^2\right)$

- N_μ is the experimental noise level
- $l_{max} = 8 \ln 2/\theta_b^2$ in terms of FWHM angular beam diameter

E.g.

PIXIE ⇒ $\{N_\mu = 4\pi \times 10^{-16}\,,\ l_{max} = 84\}$

CMBPol ⇒ $\{N_\mu = 2 \times 10^{-18}\,,\ l_{max} = 1000\}$

Fisher signal-to-noise ratio for μT spectrum at upcoming missions

α_1	$\left(\frac{H}{M_{Pl}}\right) \times 10^5$	γ_2	$\widetilde{B}_\mu$ (in nG)	$(S/N)_{PIXIE}$	$(S/N)_{Super\text{-}PIXIE}$	$(S/N)_{CMBPol}$	$(S/N)_{LiteBIRD}$
1.0	5.37	60.0	26.262	4.591	46.693	92.950	83.021
1.0	5.37	40.0	17.506	2.040	20.749	41.303	36.892
1.0	5.37	20.0	8.749	0.510	5.182	10.316	9.214
1.0	5.37	10.0	4.366	0.127	1.291	2.569	2.295
1.0	5.37	5.0	2.167	0.031	0.318	0.633	0.565
1.0	5.37	2.0	0.817	0.004	0.045	0.090	0.080
1.0	5.37	1.0	0.219	3.188×10^{-4}	0.003	0.006	0.006
1.5	2.07	1.0	0.084	4.738×10^{-5}	4.819×10^{-4}	9.593×10^{-4}	8.568×10^{-4}
2.0	1.44	1.0	0.059	2.293×10^{-5}	2.332×10^{-4}	4.642×10^{-4}	4.146×10^{-4}
2.5	1.12	1.0	0.046	1.387×10^{-5}	1.411×10^{-4}	2.802×10^{-4}	2.508×10^{-4}
3.0	0.92	1.0	0.037	9.359×10^{-6}	9.519×10^{-5}	1.895×10^{-4}	1.692×10^{-4}

Signal-to-noise ratio (SNR) at four upcoming CMB missions as a function of the initial vacuum conditions.

Summary of key results

Part 1:

- Assuming generic initial vacua for all the perturbative sectors, we have computed the three-point correlation function of the scalar curvature perturbation with PMFs generated in the gauge-inflaton coupling scheme.

- In the squeezed limit, the correlator reduces to a product between the scalar and the magnetic power spectra. In the flattened limit, NBD enhancement of quadratic order in the finite past appears. In the equilateral & orthogonal limits, NBD logarithmic terms appear that might possibly dominate on CMB scales.

Part 2:

- The squeezed limit scalar-magnetic bispectrum can source CMB μT cross-correlation. The presence of NBD initial conditions can significantly enhance as well as suppress the strength of the cross-power spectrum.

- In cases where it is enhanced, the μT signal should be detectable by several upcoming CMB experiments. This, in turn, could be instrumental in putting constraints on PMFs as well as on non-standard inflationary vacua.

Thank you!

Appendix:

Reserve Slides

"Double, double, toil and trouble…"

Pathologies

- **Back reaction** ⇒ *Magnetic energy density might overshoot inflationary scale…*
- **Strong coupling** ⇒ *Effective electric charge might grow huge at early times…*

$$\lambda(\phi(\eta)) = \lambda_I \left(\frac{\eta_I}{\eta}\right)^{2n}$$

- $n = -3$ ⇒ ***Back reaction w/o strong coupling***
- $n = +2$ ⇒ ***Strong coupling w/o back reaction***

Perturbative framework spoiled

☆ ***Possible way(s) out?***

- Sawtooth coupling
- Broken U(1) symmetry
- Extra dimensions
- Different models altogether (e.g. NLED, DBI, etc.)

What about alternative sources?

$$C^{\mu T}_{l,\, f_{NL}} \approx 1.4 \times \frac{576}{25(2\pi)^3} \times f_{NL} \times \int_0^{10k_s} dk k^2 P_\zeta(k) W\left(\frac{k}{k_s}\right) j_l(kr_L) g_{Tl}(k) \int_{\tilde{k}^f_{D,\rho}}^{\tilde{k}^i_{D,\rho}} dk_1 k_1^2 P_\zeta(k_1)$$

$$C^{\mu T}_{l,\, \zeta_{ev}} \approx -1.4 \times \frac{16\xi}{75(\mu_0 \rho_{\gamma 0})} \times \int_0^{10k_s} dk k^4 W\left(\frac{k}{k_s}\right) j_l(kr_L) g_{Tl}(k) \int_{\tilde{k}^f_D}^{\tilde{k}^i_D} dk_1 P_B(k_1)^2$$

$\Big\}$ $\text{SNR} \ll 1 \Rightarrow$ Not significant as competing signals

Hints of a magnetic Universe…

Cosmic Microwave Background

TT, TE, EE, BB spectra.
Faraday rotation ⇒ BB.

Helical PMFs ⇒ TB, EB.

Non-Gaussian signatures. (CMB bispectra, spectral distortion power spectra.)

May alleviate H_0-tension by sourcing small-scale baryon inhomogeneities in pre-recombination fluid.

Large Scale Structure Formation

Matter power spectrum slightly enhanced on scales $k/h \sim 1\text{-}10\ \mathrm{Mpc}^{-1}$.

Affects distribution of DM halos, star formation rate, secondary CMB anisotropies via thermal SZ effect.

Physics of the Epoch of Reionization

Modified matter power affects 21-cm statistics, potentially detectable by future facilities like SKA.

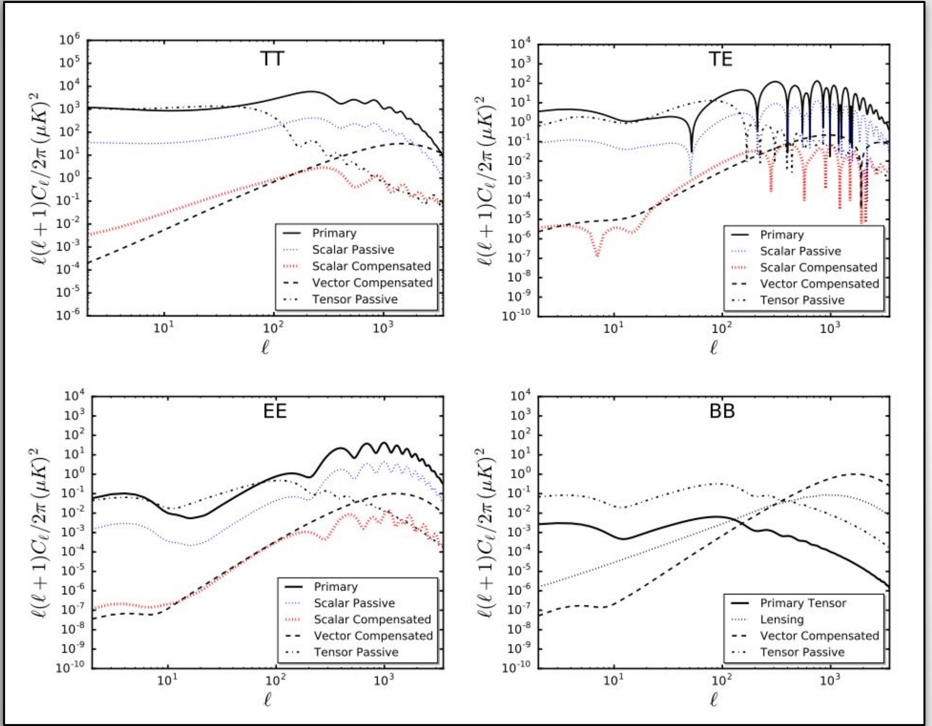
Helical and non-helical PMFs affect heating of the IGM, can help explain the global 21-cm dip in EDGES data.

Gravitational Wave Signatures

Anisotropic stress of PMFs may source secondary stochastic GW background.

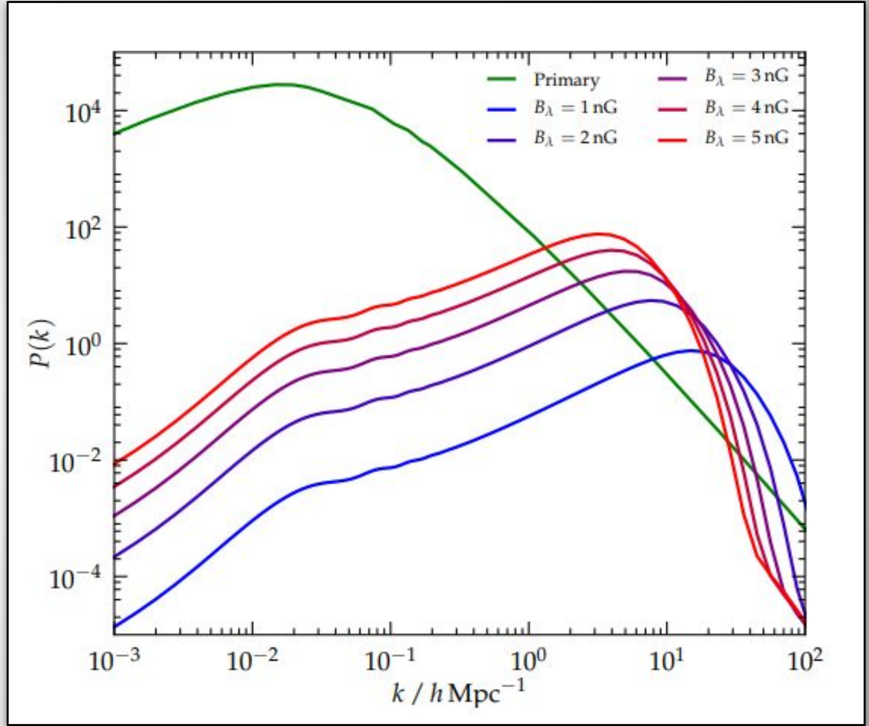
Photon-graviton conversion processes in presence of strong PMFs may also source similar GW spectra.

Hints of a magnetic Universe…



Effects of nearly scale-invariant, non-helical PMFs of amplitude B_0=4.5 nG on CMB temperature and polarization power spectra.

Source: Zucca et al (*PRD*, 2017), 1611.00757



Effects of nearly scale-invariant, non-helical PMFs on matter power spectrum (nonlinear Jeans effect and diffusion damping included).

Source: Shaw & Lewis (*PRD*, 2012), 1006.4242