Finding Evidence of Inflation and Galactic Magnetic Fields with CMB Surveys

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- Scenarios '1' and '2' generate *primordial magnetic fields* (PMFs) – nG scale PMFs at Mpc scales are adiabatically compressed to μG scale fields in galaxies.
- PMFs are an attractive scenario to explain the uniform distribution of magnetic fields in voids.

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- Scale invariant (or nearly) PMF power spectrum.

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- No evidence for any of these models so far.

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- More importantly, it will be a compelling evidence of inflation!!!
- If B_{SI} is constrained below $0.1\,\mathrm{nG}$, inflation isn't the primary source of galactic fields.

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- Birefringence can thus provide a tighter bound on the PMF strength from future surveys.

Realistic PMF Spectrum

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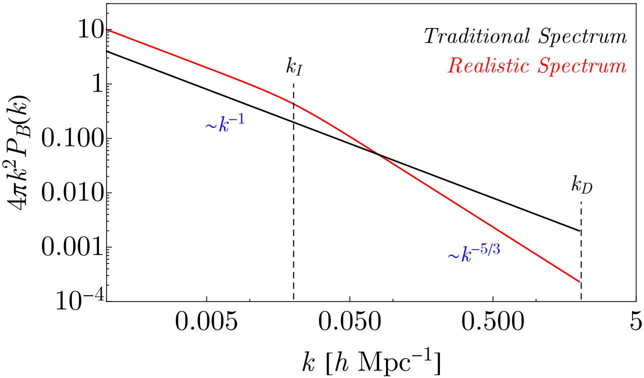

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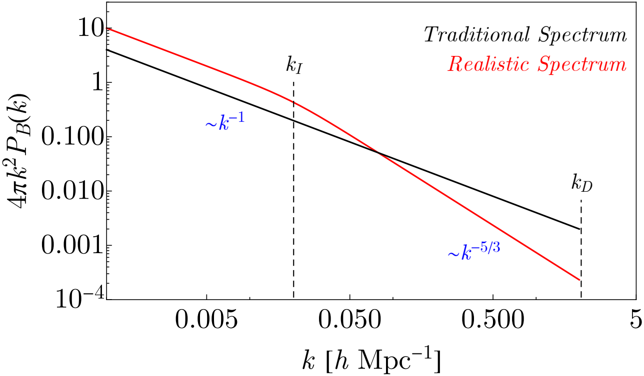

- We use this to theoretically calculate the anisotropic birefringence.

Birefringence Forecasts

- From the rotation angle $\alpha(\hat{\mathbf{n}})$, we get a power spectrum, $\langle\alpha(\hat{\mathbf{n}})\alpha(\hat{\mathbf{n}}')\rangle \equiv \sum_l (2l+1)C_l^{\alpha\alpha}\, P_l(\hat{\mathbf{n}}\cdot\hat{\mathbf{n}}')/4\pi$.

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- CMB-HD will improve the bound on A_α by four orders of magnitude – giving tightest constraints on PMFs.

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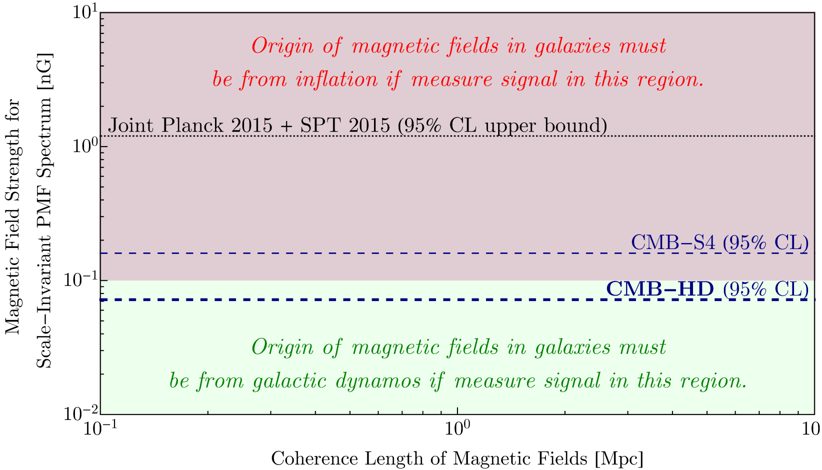
Forecasts on PMFs



Subtracting Milky Way Birefringence

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- Independent MW-induced birefringence obtained from the $\alpha(\hat{\mathbf{n}})$ of 40,000 extragalactic radio sources near the MW (NVSS Catalog).
- $\alpha(\hat{\mathbf{n}})$ is measured at multiple frequencies, giving a precise map of the MW birefringence.

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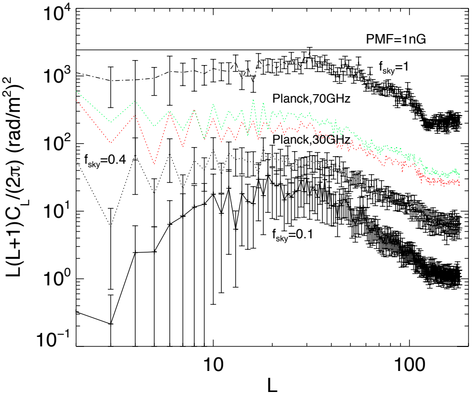

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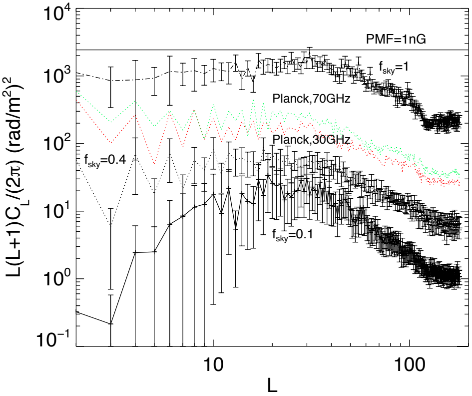

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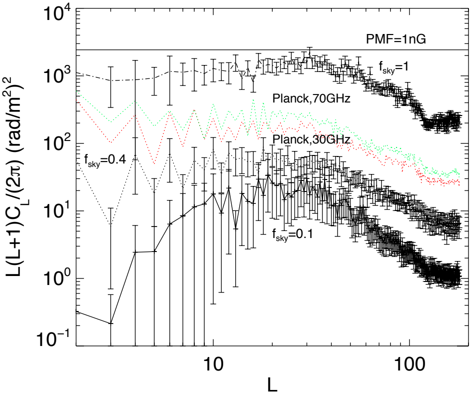

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- We infer the galactic MF to have $\sigma_{B_{\mathrm{SI,G}}} \approx 0.006\,\mathrm{nG}$.
- **The MW birefringence can thus be subtracted from the CMB measurement!!**

	SO	CMB-S4	CMB-HD
$\sigma(B_{\mathrm{SI}})$ (nG)	0.47	0.08	0.036

Discussion

- The current 95% CL upper bound on $B_{\rm SI}$ is $1.2\,{\rm nG}$ – comes from the Planck TT, EE, and TE, and SPT BB data.
- A_α measurements from CMB-S4 and CMB-HD will tighten it to 0.16 nG and 0.072 nG respectively.
- The CMB-HD bound is below the 0.1 nG threshold that distinguishes between purely inflationary and dynamo origins of galactic MFs.
- **Detection** of $B_{\rm SI} < 0.1\,{\rm nG}$ will point to a dynamo origin of galactic MFs.
- **Detection** of $B_{\rm SI} > 0.1\,{\rm nG}$ will be *a compelling evidence* for inflation!
- CMB-HD is capable of detecting inflationary PMFs at 3σ significance.

Thank You!

Supplementary Slides

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- A $\sim 0.1\,\mathrm{nG}$ PMFs before recombination is enough to resolve the Hubble tension.

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Modeling Inflationary PMFs

- The comoving magnetic field $\mathbf{B}$ is a Gaussian random field in three dimensions.
- Information about the energy of PMFs is encapsulated in the power spectrum $P_B(k)$; magnetic helicity does not affect birefringence.
- Traditionally written as

$$P_B(k) = A_B k^{n_B}, \quad k \leq k_D \tag{1}$$

  for some damping scale k_D; For inflationary PMFs $n_B = -3$

- We set k_D to the Silk damping scale $2\,\mathrm{Mpc}^{-1}$; PMFs on scales smaller than these have net rotation.

The Birefringence Spectrum

- From the rotation angle $\alpha(\hat{\mathbf{n}})$, we get a power spectrum, $\langle \alpha(\hat{\mathbf{n}})\alpha(\hat{\mathbf{n}}') \rangle \equiv \sum_l (2l+1) C_l^{\alpha\alpha} P_l(\hat{\mathbf{n}} \cdot \hat{\mathbf{n}}')/4\pi$.

- The amplitude of anisotropic birefringence is

$$A_\alpha \equiv \frac{l(l+1)C_l^{\alpha\alpha}}{2\pi} \propto \frac{B^2}{\nu_0^4} \tag{2}$$

  for frequency ν_0 of observation.

- For a scale-invariant PMFs, A_α is independent of l in the multipole region of interest.

The Birefringence Spectrum (Contd.)

- However, A_α is frequency dependent, and CMB surveys observe at two frequencies.

- Since $A_\alpha \propto \nu_0^{-4}$, we can construct an *effective frequency* for our theoretical prediction,

$$\frac{1}{\nu_{\text{eff}}^4} = \frac{1}{2}\left(\frac{1}{\nu_1^4} + \frac{1}{\nu_2^4}\right). \tag{3}$$

- Equivalent to taking an arithmetic mean of the measurements on the channels – assuming equal noise levels.

- For the channels of 90 and 150 GHz, we find $\nu_{\text{eff}} = 103.8\,\text{GHz}$.

Birefringence Forecasts

Experiment	White noise	Beam	f_{sky}	Delensing Fraction
SO-SAT	$3\,\mu K'$	$17'$	0.1	0.3
CMB-S4	$2\,\mu K'$	$2'$	0.5	0.15
CMH-HD	$0.7\,\mu K'$	$0.4'$	0.5	0.1

The error bars on A_α are computed as:

$$\frac{1}{\sigma^2(A_\alpha)} = \sum_l f_{\text{sky}} \frac{2l+1}{2} \frac{(C_l^{\alpha\alpha,\text{fid}})^2}{(N_l^{\alpha\alpha})^2}, \tag{4}$$

where $C_l^{\alpha\alpha,\text{fid}} = 2\pi/l(l+1)$ and $N_l^{\alpha\alpha}$ is the reconstruction noise spectrum.

Multipole ranges of $100 < l < 5000$ are used for this calculation.

Subtracting Milky Way Birefringence (Contd.)

- At our effective frequency $\nu_{\text{eff}} = 103.8\,\text{GHz}$, we have

$$A_\alpha = 2.363 \times 10^{-7} \left(\frac{A_{\text{RM}}}{1\,\text{rad/m}^2} \right)^2 \text{deg}^2, \tag{5}$$

  where $A^2_{\text{RM},l} \equiv l(l+1)C_l^{\text{RM}}/2\pi \approx A^2_{\text{RM}}$.

- $\sigma_{A^2_{\text{RM},l}}$ comes from both sample variance and measurement uncertainty.

- For the cleanest 40% of the sky, the galactic contribution is $A^2_{\text{RM},l} \approx 70\, l^{-0.17}\,(\text{rad/m}^2)^2$.

- The associated error is $\sigma_{A^2_{\text{RM},l}} \approx 0.7\, A^2_{\text{RM},l}$.

Subtracting Milky Way Birefringence (Contd.)

- $A_{\rm RM}$ is related to $B_{\rm SI}$ as $A_{\rm RM} = 68\,{\rm rad/m^2}\,(B_{\rm SI}/1\,{\rm nG})$.
- The Galactic $A_{RM} \approx \sqrt{70}\,{\rm rad/m^2} \approx 8\,{\rm rad/m^2}$ gives $B_{\rm SI,G} \approx 0.12\,{\rm nG}$ on Mpc scales.
- SNR for detecting MW-induced $A_{\rm RM}$ is

$$\left(\frac{S}{N}\right)^2 = \sum_l \frac{\left(A^2_{{\rm RM},l}\right)^2}{\sigma^2_{A^2_{{\rm RM},l}}} \approx 26^2. \tag{6}$$

- This is likely optimistic – we have ignored covariance between the $\sigma_{A^2_{{\rm RM},l}}$.
- Let's be conservative and take SNR = 10 – this gives $\sigma_{A_{{\rm RM},l}} \approx 0.4\,{\rm rad/m^2}$, and thus $\sigma_{B_{\rm SI,G}} \approx 0.006\,{\rm nG}$.