# Primordial Magnetic Fields and How To Find Them in CMB Polarization

Levon Pogosian

Simon Fraser University
Burnaby, BC, Canada

# Outline

Primordial magnetic fields and their CMB imprints

Current bounds on the PMF

The promise of Faraday Rotation

What can PICO tell us about the PMF?

Based on work with Soma De, Brian Keating, Yun Li, Bess Ng, Meir Shimon, Tanmay Vachaspati, Amit Yadav, Alex Zucca, and the POLARBEAR collaboration

See LP & A. Zucca, 1801.08936, for a related review

# Cosmic Magnetic Fields

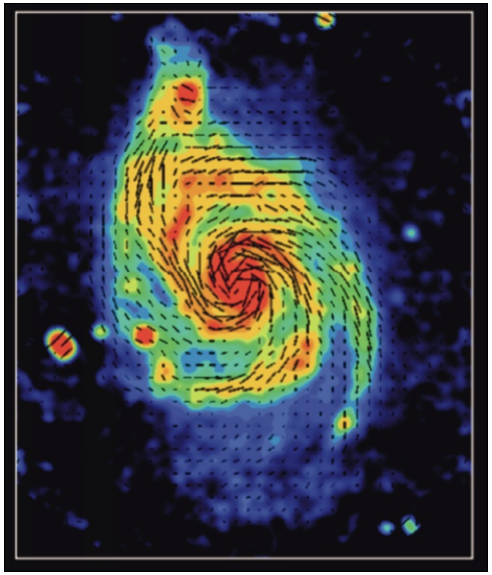


Image courtesy of NRAO/AUI

- Origin of 1-10 $\mu$G fields in galaxies and clusters
  - purely astrophysical? (dynamo, SN, …)
  - purely primordial? (need nG coherent on 1 Mpc)
  - some combination of the two?
- Evidence of magnetic fields in voids
  - missing GeV $\gamma$-ray halos around TeV blazars
- Generated in the early universe – not "if", but "how much"
  - phase transitions
  - inflationary mechanisms
  - a window into the early universe
- A distinct signature in CMB could prove their primordial origin
  - Current upper bounds from CMB are at 1 nG level
  - PICO, S4 can go below 0.1 nG and rule out the purely primordial origin

# Inflationary Magnetogenesis

- The Maxwell action of the electromagnetic field

$$S = -\int \sqrt{-g}\; d^4x\; \frac{1}{16\pi} g^{\mu\alpha} g^{\nu\beta} F_{\mu\nu} F_{\alpha\beta}$$

$$\boxed{\begin{aligned} g^*_{\mu\nu} &= \Omega^2 g_{\mu\nu} \\ S^* &= S \end{aligned}}$$

is conformally invariant, and FRW is conformally flat. Cannot amplify EM wave fluctuations in a FRW universe.

- Introduce couplings that break the conformal invariance:

$$S = \int \sqrt{-g}\; d^4x b(t)[-\frac{f^2(\phi, R)}{16\pi} F_{\mu\nu} F^{\mu\nu} - g_1 R A^2 + g_2 \theta F_{\mu\nu} \tilde{F}^{\mu\nu} - D_\mu \psi (D^\mu \psi)^* \;]$$

e.g. couplings to the inflaton, curvature, axion, extra-D, charged scalars

- See early work by Turner and Widrow (1988) and Ratra (1992), recent review by Subramanian (1504.02311)

# Stochastic Primordial Magnetic Field

- Frozen in to the plasma on large scales, amplitude decays as $B(a)=B_0/a^2$

- Magnetic field power spectrum:

$$\langle b_i(\mathbf{k}) b_j(\mathbf{k}')\rangle = (2\pi)^3 \delta^{(3)}(\mathbf{k}+\mathbf{k}')[(\delta_{ij} - \hat{k}_i \hat{k}_j) S(k) + i\varepsilon_{ijl}\hat{k}_l A(k)]$$

$$S(k) \propto k^n, \quad 0 < k < k_{\rm diss}$$

- Common measures of cosmological magnetic fields:

$$B_\lambda^2 \equiv \int_0^\infty \frac{k^2 dk}{2\pi^2} S(k)\ e^{-\lambda^2 k^2} \qquad B_{\rm eff} \equiv \sqrt{8\pi\epsilon_B}$$

- Fields generated in phase transitions have n=2 on CMB scales
  (Durrer and Caprini, 2003; Jedamzik and Sigl, 2010)

- For scale-invariant PMF, n=-3: $B_\lambda = B_{\rm eff}$
  (Turner & Widrow, 1988; Ratra. 1992)

# Magnetic field effects on CMB

- Gravitational coupling

$$T^0_0 \propto -B^2$$
$$T^i_j \propto B^2\delta^i_j - 2B^iB_j$$

scalar (curvature), vector (vorticity), tensor (gravitational waves) modes

- Electromagnetic coupling

Lorentz force causes vorticity fluctuations in plasma

Magnetic energy dissipates, dumps energy into the plasma

- spectral distortions
- modified ionization history

Faraday Rotation

# Observable CMB signatures of the PMF

- Spatial correlations of anisotropies

- Shift in the time of last scattering

- Departures from the black body spectrum

- Faraday Rotation

    - Frequency dependence
    - Mode-coupling correlations

# Passive (adiabatic) and Active (isocurvature) PMF modes

The way PMF sources CMB fluctuations differs before and after neutrinos decouple

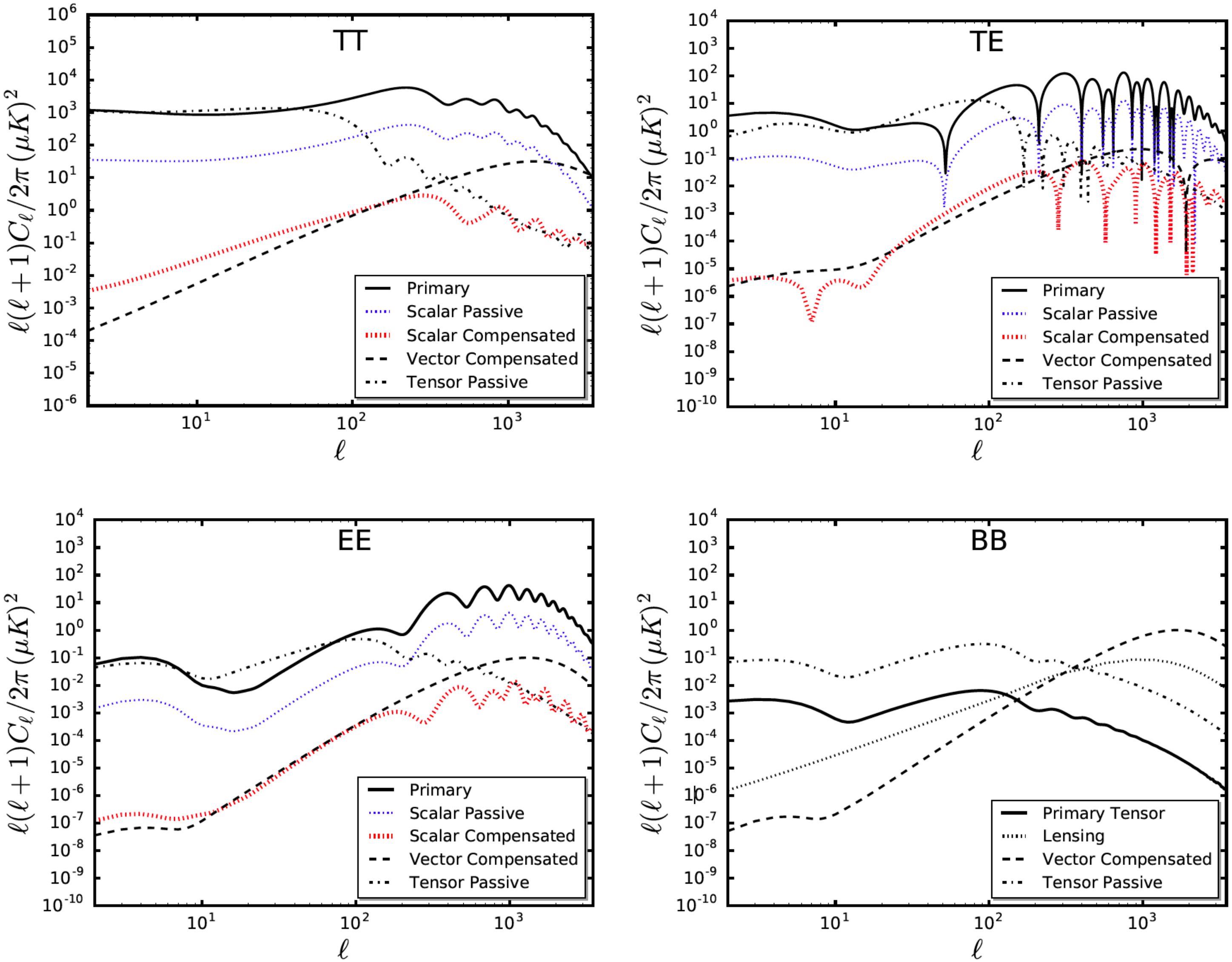
- Before neutrino decoupling: nothing balances the PMF anisotropic stress
  - Added contribution to the scalar adiabatic mode
  - Added contribution to the primordial tensor mode

$$H^{(2)} \approx R_\gamma \Pi_B^{(2)} \left[ \log\left(\tau_\nu/\tau_B\right) + \left( \frac{5}{8R_\nu} - 1 \right) \right]$$

- After neutrino decoupling: the PMF anisotropic stress compensated by neutrinos
  - Actively sourced compensated scalar, vector and tensor modes

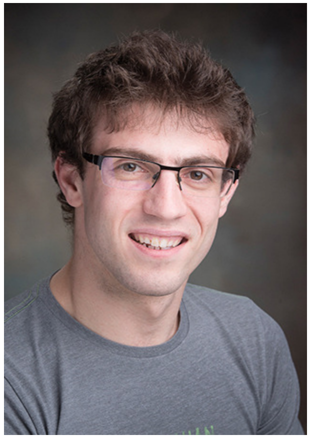
Lewis (2004); Shaw and Lewis, 0911.2714

# PMF contributions to the CMB spectra




A. Zucca, Y. Li, LP, 1611.00757

# MagCAMB and MagCosmoMC



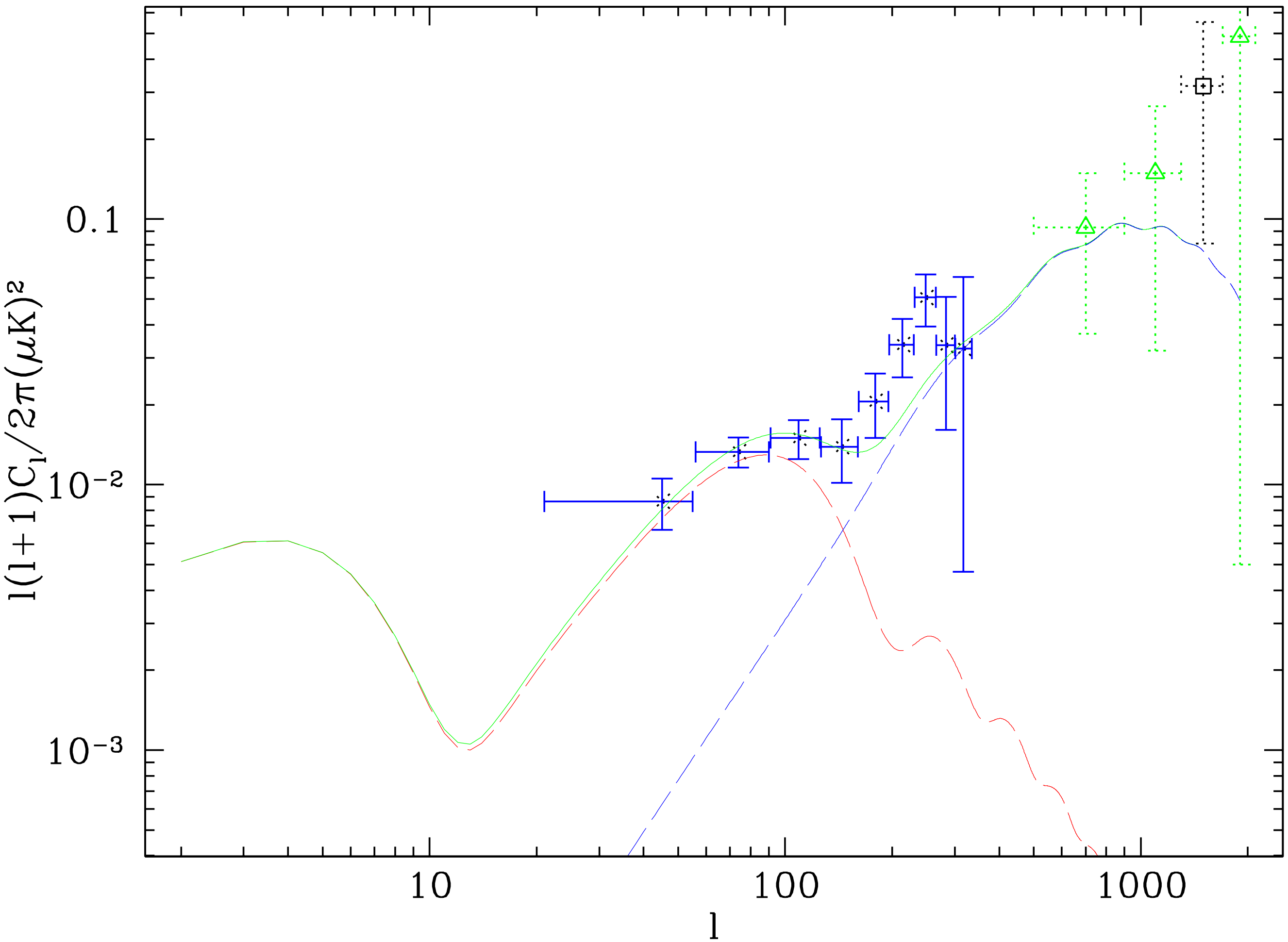
Alex Zucca

- Publicly available patches to CAMB and CosmoMC

  https://alexzucca90.github.io/MagCAMB/
  https://github.com/alexzucca90/MagCosmoMC

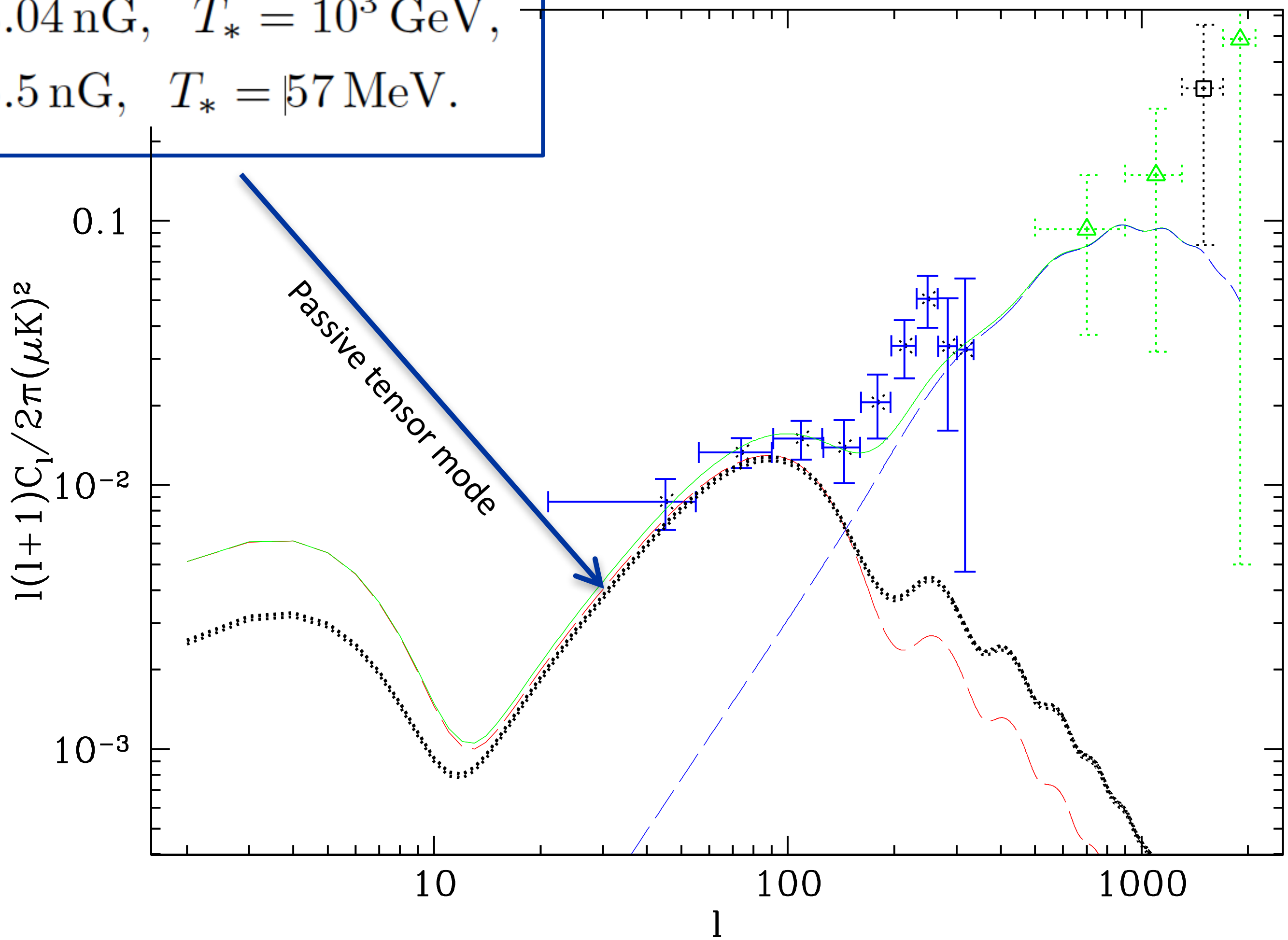
- Developed by A. Zucca (SFU) based on original papers by Lewis (2004) and Shaw & Lewis (0911.2714)

# PMF contributions to the B-mode spectrum



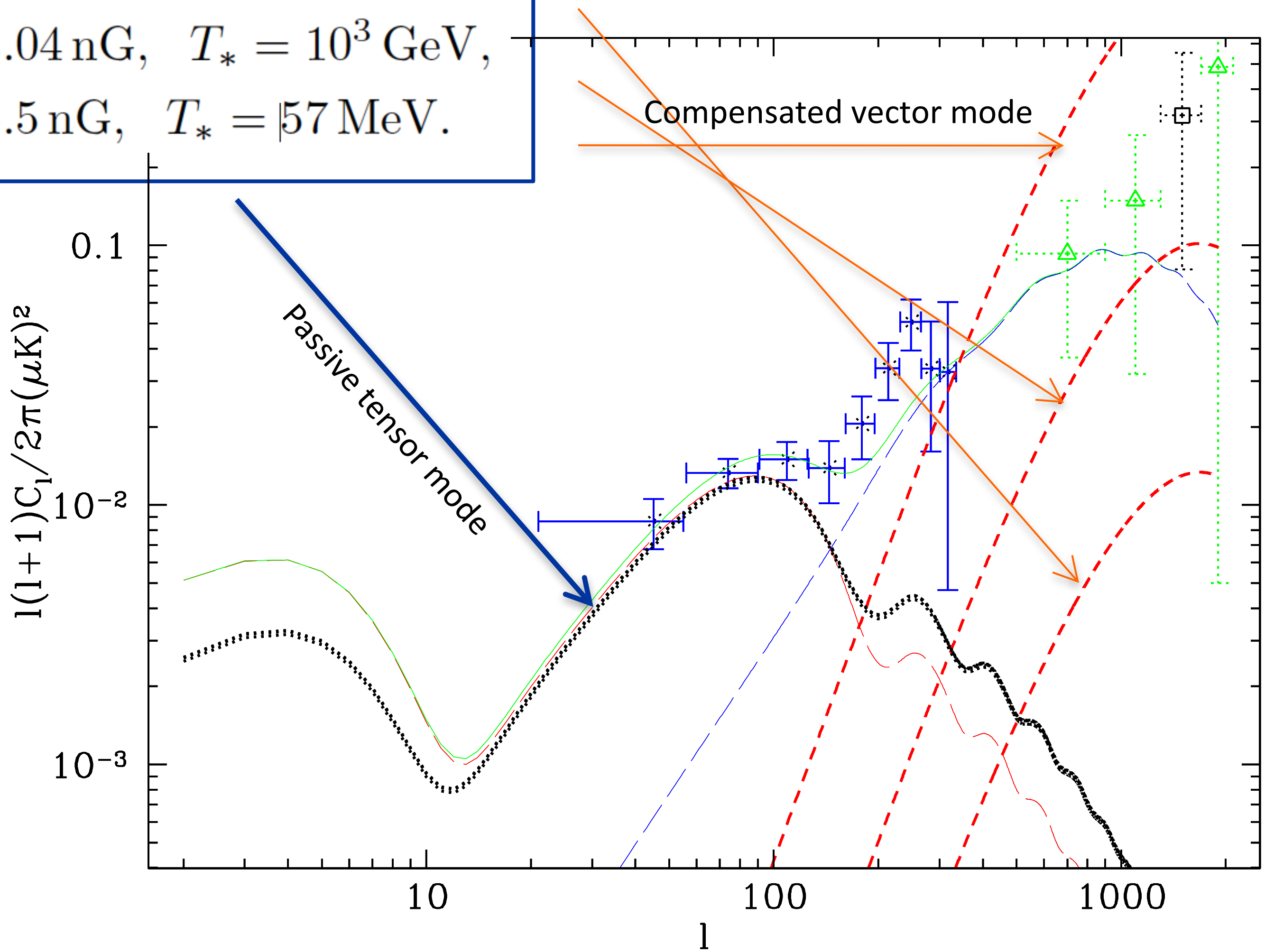
# PMF contributions to the B-mode spectrum

$$B_1 = 1.83\,\mathrm{nG}, \quad T_* = 10^{14}\,\mathrm{GeV},$$
$$B_1 = 3.04\,\mathrm{nG}, \quad T_* = 10^{3}\,\mathrm{GeV},$$
$$B_1 = 5.5\,\mathrm{nG}, \quad T_* = 57\,\mathrm{MeV}.$$



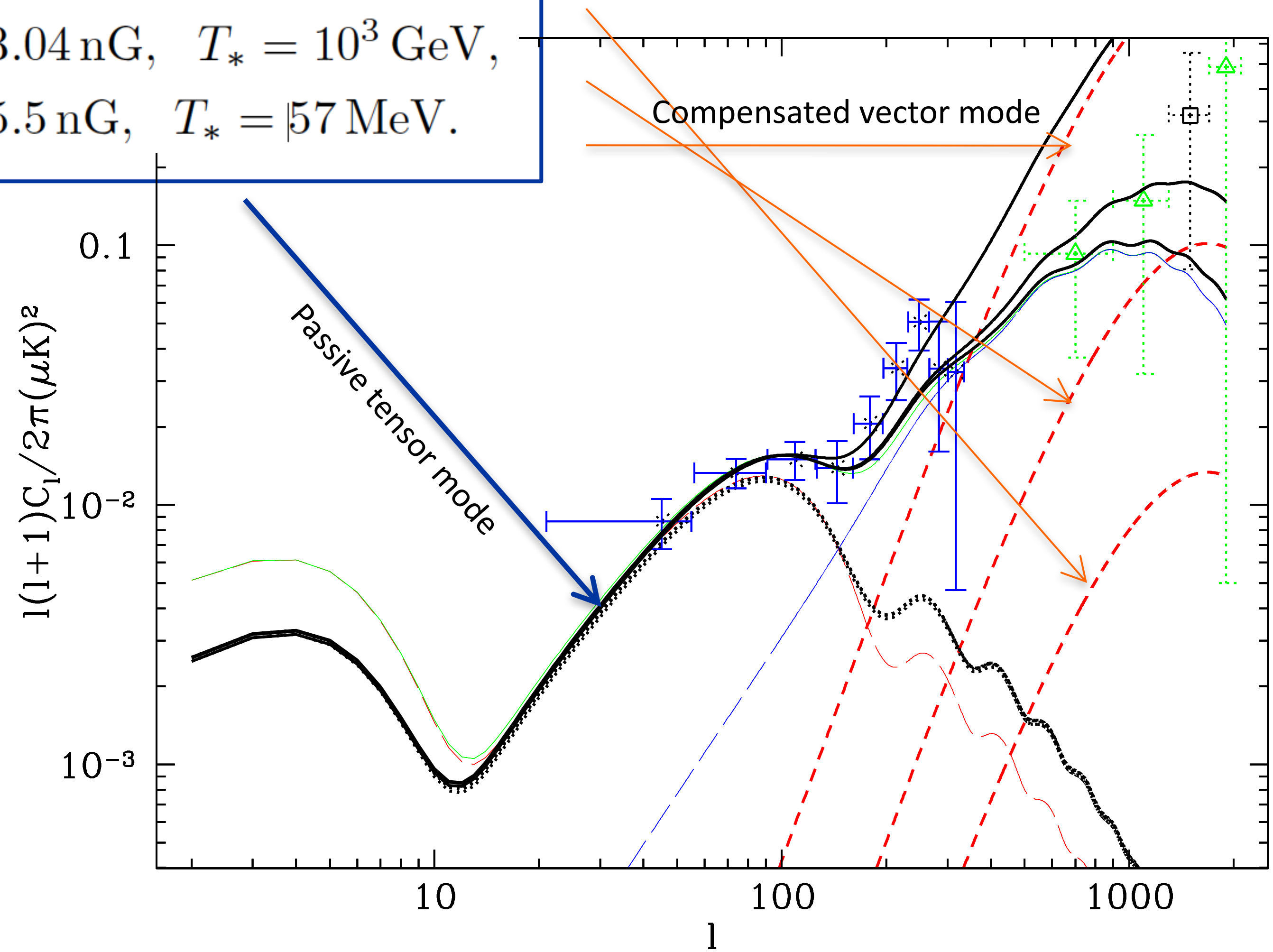
# PMF contributions to the B-mode spectrum

$$B_1 = 1.83\,\mathrm{nG}, \quad T_* = 10^{14}\,\mathrm{GeV},$$
$$B_1 = 3.04\,\mathrm{nG}, \quad T_* = 10^{3}\,\mathrm{GeV},$$
$$B_1 = 5.5\,\mathrm{nG}, \quad T_* = 57\,\mathrm{MeV}.$$

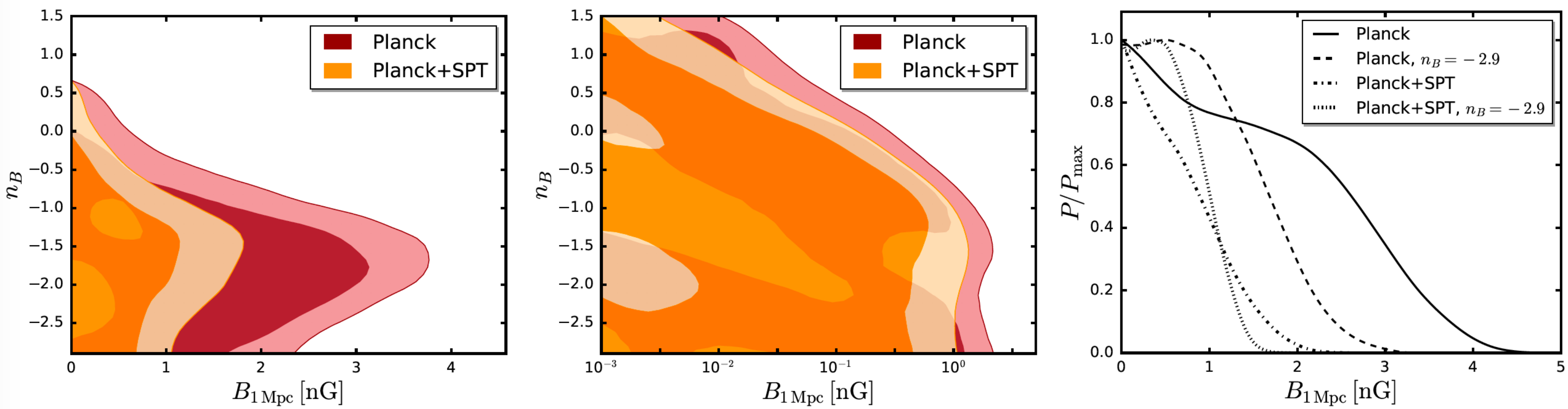


# PMF contributions to the B-mode spectrum

$$B_1 = 1.83\,\mathrm{nG}, \quad T_* = 10^{14}\,\mathrm{GeV},$$
$$B_1 = 3.04\,\mathrm{nG}, \quad T_* = 10^{3}\,\mathrm{GeV},$$
$$B_1 = 5.5\,\mathrm{nG}, \quad T_* = 57\,\mathrm{MeV}.$$



# Bounds from Planck combined with SPT B-modes




- $B_{1Mpc}$< 1.2 nG at 95% CL for a nearly scale-invariant PMF
- Adding SPT BB reduces the Planck bound on $B_{1Mpc}$ by a factor of 2
- using a uniform prior on $B_{1Mpc}$ can lead to fake bounds on $n_B$

A. Zucca, Y. Li, LP, 1611.00757, LP & A. Zucca, 1801.08936

# Crossing the nano-Gauss barrier

- Magnetic stress-energy is quadratic in B

$$
\begin{aligned}
T^0_0 &\propto -B^2 \\
T^i_j &\propto B^2\delta^i_j - 2B^iB_j
\end{aligned}
$$

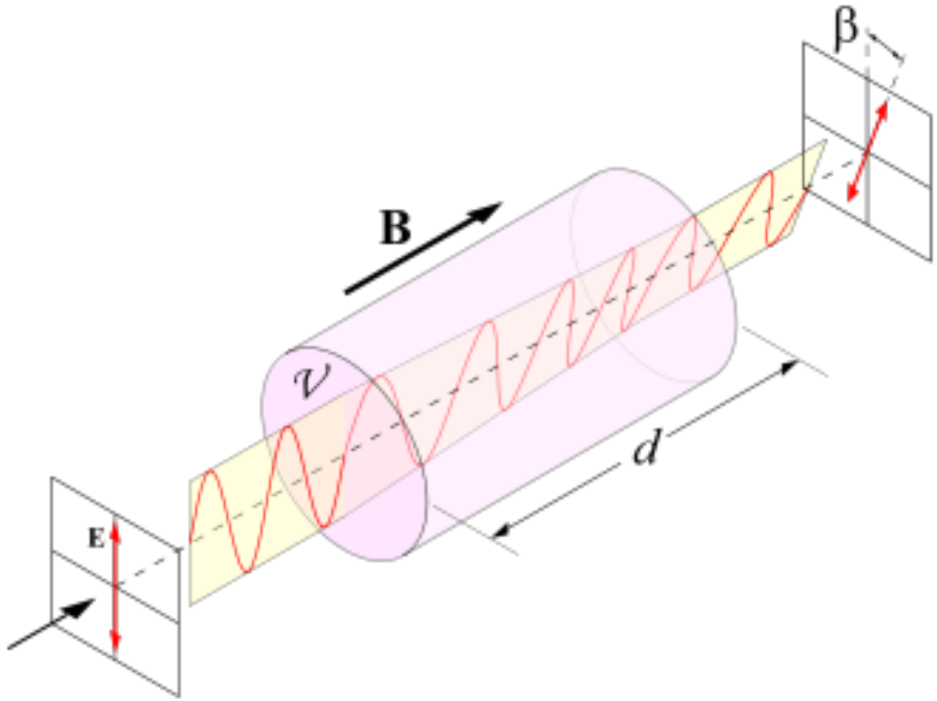
- Thus, $C_L \sim B^4$

- Bounds based on CMB spectra will always remain at O(nG)*

*Potentially very strong bounds from modified recombination history
Jedamzik and Abel (2011, 2013), Jedamzik and Saveliev, 1804.06115

Faraday Rotation is linear in B

# Faraday Rotation




- For CMB: $\alpha(\hat{\mathbf{n}}) = \frac{3c^2\nu_0^{-2}}{16\pi^2 e}\int \dot{\tau}\,\mathbf{B}\cdot d\mathbf{l} = c^2\nu_0^{-2}\,\mathrm{RM}(\hat{\mathbf{n}})$

- Most of the rotation occurs at last scattering (if there is a PMF) and inside our galaxy

# Faraday Rotation converts E-modes into B-modes

$$B_{lm} = 2 \sum_{LM} \sum_{l'm'} \alpha_{LM} E_{l'm'} \xi^{LM}_{lml'm'} H^{L}_{ll'}$$

One can reconstruct the rotation angle from mode-coupling EB correlations
(Kamionkowski, 2009; Glusevic, Kamionkowski, Cooray, 2009)

$$\hat{D}^{LM,\mathrm{map}}_{ll'} = \frac{4\pi}{(2l+1)(2l'+1)} \sum_{mm'} B^{\mathrm{map}}_{lm} E^{\mathrm{map}*}_{l'm'} \xi^{LM}_{lml'm'}$$

$$[\hat{\alpha}_{LM}]_{ll'} = \frac{\hat{D}^{LM,\mathrm{map}}_{ll'}}{2C^{EE}_{l} H^{L}_{ll'}}$$

Generalized to a multiple channel Rotation Measure (RM) estimator
in LP, 1311.2926

# Faraday Rotation converts E-modes into B-modes

$$B_{lm} = 2 \sum \sum \alpha_{LM} E_{l'm'} \xi^{LM}_{lml'm'} H^{L}_{ll'}$$

B = alpha* E

therefore

<EB> = alpha <EE>

then we can find alpha from

alpha = <EB> / <EE>

if <EE> is known

Reconstr … rrelations

(Kamionko

$\hat{D}$ … $^{LM}_{ml'm'}$

Generaliz … estimator

in Pogosi

# What scales are probed?

- Most of the information comes from CMB correlations at $300 < l < 3000$
  - ➢ need low noise high resolution polarization maps
  - ➢ can work with small ($f \sim 0.1$) patches of sky near Galactic poles

- Large scale correlations of the rotation angle are constrained the best
  - ➢ for a sale-invariant rotation spectrum most S/N comes from $2<L<100$

# POLARBEAR Constraints on Cosmic Birefringence and Primordial Magnetic Fields

arXiv:1509.02461, Phys Rev D

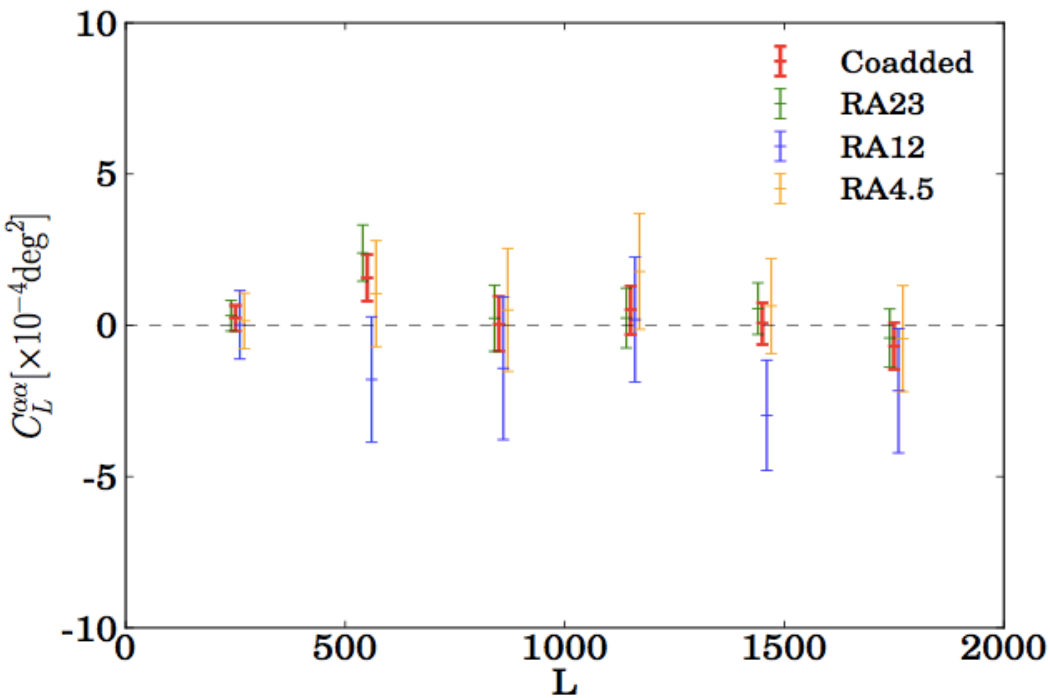



FIG. 2: The anisotropic cosmic rotation power spectra from POLARBEAR 's first-season data in three patches. The spectrum of an individual patch is indicated by the green (RA23), blue (RA12) and orange (RA4.5) colors. The coadded (red) power spectrum is consistent with zero.

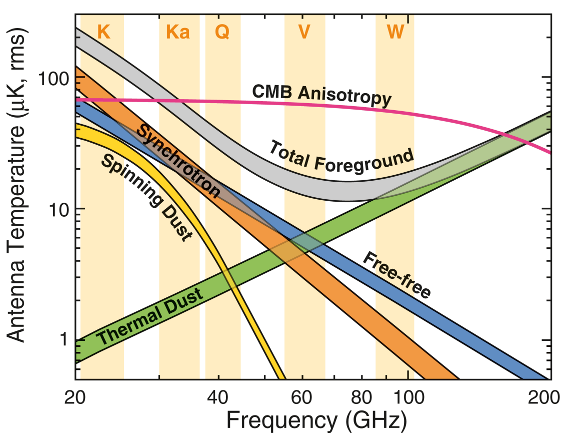
At 148 GHz this implies a bound of 90 nano-Gauss at 95% CL

# What about PICO?

| nu (GHz) | FWHM (arcmin) | PolWeight (uK*arcmin) |
|---|---|---|
| 21 | 38.4 | 16.3 |
| 25 | 32.0 | 11.7 |
| 30 | 28.3 | 7.8 |
| 36.0 | 23.6 | 5.6 |
| 43.2 | 22.2 | 5.4 |
| 51.8 | 18.4 | 4.0 |
| 62.2 | 12.8 | 3.9 |
| 74.6 | 10.7 | 3.2 |
| 89.6 | 9.5 | 2.0 |
| 107.5 | 7.9 | 1.7 |
| 129.0 | 7.4 | 1.6 |
| 154.8 | 6.2 | 1.4 |
| 185.8 | 4.3 | 2.5 |
| 222.9 | 3.6 | 3.1 |
| 267.5 | 3.2 | 2.0 |
| 321.0 | 2.6 | 3.0 |
| 385.2 | 2.5 | 3.3 |
| 462.2 | 2.1 | 7.8 |
| 554.7 | 1.5 | 44.1 |
| 665.6 | 1.3 | 176.9 |
| 798.7 | 1.1 | 1260.7 |

Optimistic range

Conservative Science Frequency Range



# Best case forecast (no systematics)

| | PICO BB | PICO FR (75-150 Ghz) | PICO FR (50-150 GHz) |
|---|---|---|---|
| $1\sigma$ bound on PMF | 0.35 nG | 0.06 nG | 0.05 nG |

## Compared to other CMB experiments

| | Planck +SPT | PB | SPT-3G | Simons Obs. | CMB-S4 | PICO |
|---|---|---|---|---|---|---|
| $1\sigma$ bound from BB, TT, EE, TE | 1 nG | 2.5 nG | 0.8 nG | 0.9 nG | 0.4 nG | 0.35 nG |
| $1\sigma$ bound from FR | n/a | 50 nG | 0.55 nG | 0.4 nG | 0.07 nG | 0.05 nG |

# Systematic Effects

- Weak Lensing contribution to B-modes
- Faraday Rotation in our own galaxy
- Beam Asymmetry
- Galactic foregrounds

# Systematics due to Weak Lensing (WL)

- Mode-coupling due to WL is of opposite parity, does not mix with the FR induced mode-coupling

- WL contributes to the variance of the FR estimator through

$$\tilde{C}_l^{X^i Y^j} \equiv C_l^{XY,\mathrm{prim}} + f_{\mathrm{L}} C_l^{XY,\mathrm{WL}} + \delta_{X^i Y^j} \sigma_{P,i}^2$$

- $0 < f_L < 1$ quantifies how well the WL contribution can be subtracted

  - Perfect WL subtraction ($f_L = 0$) : $B_{PICO} < 0.05$ nG
  - No WL subtraction ($f_L = 1$) : $B_{PICO} < 0.125$ nG

# Galactic Rotation Measure

$$\alpha(\hat{\mathbf{n}}) = \lambda_0^2 \; RM(\hat{\mathbf{n}})$$

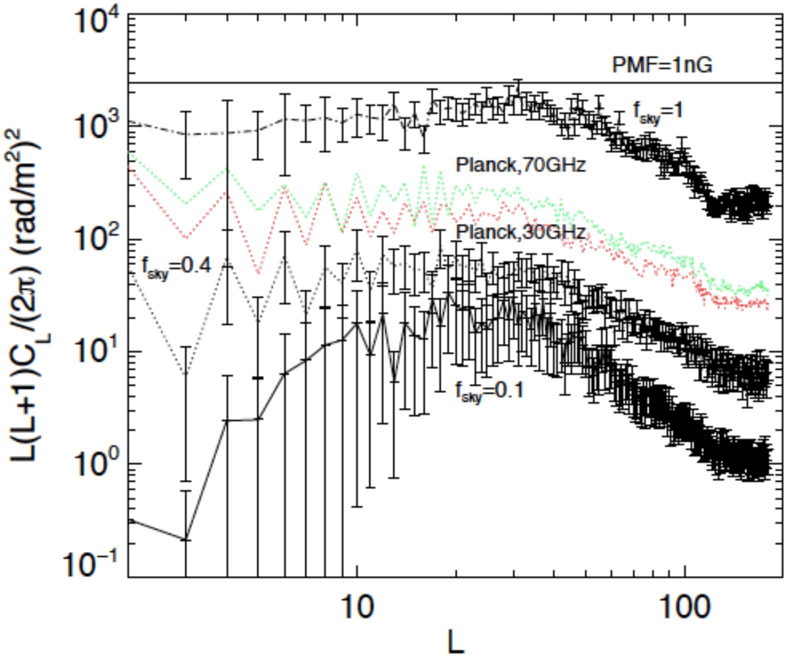
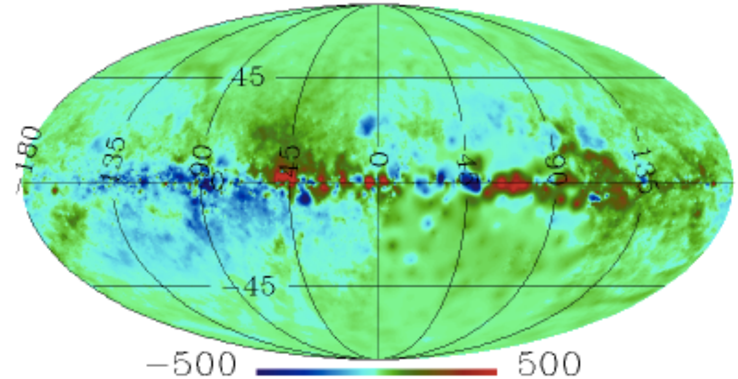
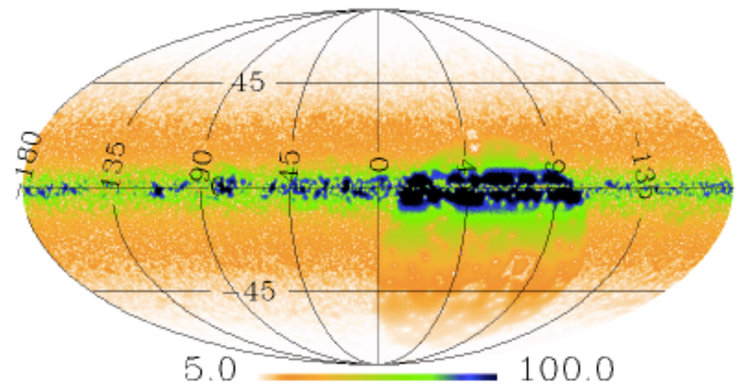



FIG. 3: The RM angular spectra, $L(L+1)C_L^{\rm RM}/2\pi$, obtained from the RM map of Oppermann et al [16] with different cuts. Shown are the RM spectra corresponding to, from top to bottom, a scale-invariant PMF of 1 nG, galaxy with no sky cut, with a mask used by Planck for their 70 GHz map, a Planck mask for the 30 GHz map, and symmetric cuts corresponding to $f_{\rm sky} = 0.4$ and $f_{\rm sky} = 0.1$.

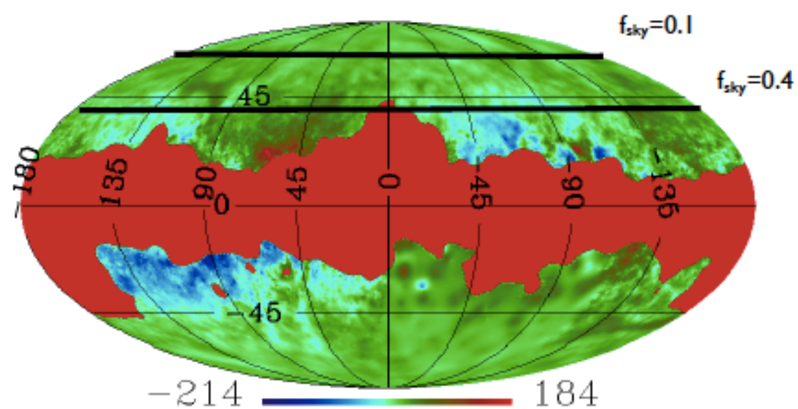
RM in rad/m$^2$




Uncertainty in RM in rad/m$^2$




Galactic RM in rad/m$^2$ with Planck mask at 30GHz




Figures from De, LP, Vachaspati, PRD'13, arXiv:1305.7225
based on the public RM data from Oppermann et al, A&A'12, arXiv:1111.6186

# Systematics due to Galactic FR

- Faraday Rotation inside our galaxy lowers the signal-to-noise of primordial FR

$$\left(\frac{S}{N}\right)^2 = \sum_{L=1}^{L_{max}} \frac{(f_{\rm sky}/2)(2L+1)[C_L^{\rm RM,PMF}]^2}{[C_L^{\rm RM,PMF} + f_{\rm G} C_L^{\rm RM,G} + \sigma^2_{{\rm RM},L}]^2}$$

- $0 < f_G < 1$ quantifies how well Galactic contribution can be subtracted
- Need an independent measurement, such as the Oppermann et al RM map
- Near galactic poles, Galactic FR looks the same as scale-invariant PMF of 0.1 nG

> - Perfect galactic FR subtraction ($f_G = 0$) : $B_{PICO} < 0.05$ nG
> - No galactic FR subtraction ($f_G = 1$) : $B_{PICO} < 0.1$ nG

# Systematics due to Beam Asymmetry

- Beam imperfections induce EE, TE, BB, EB and TB correlations
- Parameterized contributions to CMB spectra for a dual polarized beam experiment derived in Shimon, Keating, Ponthieu, Hivon, 0709.1513
- Our (very) preliminary forecast includes effects of differential pointing, differential ellipticities, and differential rotation
- Asymmetry parameters tuned to achieve target sensitivity to *r*
- For PICO, assumed target sensitivity of $\boldsymbol{\sigma}_r = 5 \times 10^{-5}$

  - No beam systematics : $B_{PICO} < 0.05$ nG
  - With beam systematics: $B_{PICO} < 0.25$ nG

# Other sources of birefringence

- Coupling to a pseudoscalar, axion-like field:

$$\mathcal{L}_{int} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}\partial_\mu a \partial^\mu a + \frac{a}{2f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

- Unlike the PMF, can induce uniform (isotropic) rotation, sourcing $C_L^{EB}$ and $C_L^{TB}$

  - Current bounds on uniform rotation: $\alpha_{iso}$< 30 arcmin
  - PICO (best case) forecast: $\alpha_{iso}$< 0.03 arcmin
  - PICO (with systematics) forecast: $\alpha_{iso}$< 0.2 arcmin

- Stochastic rotation spectrum generated during inflation

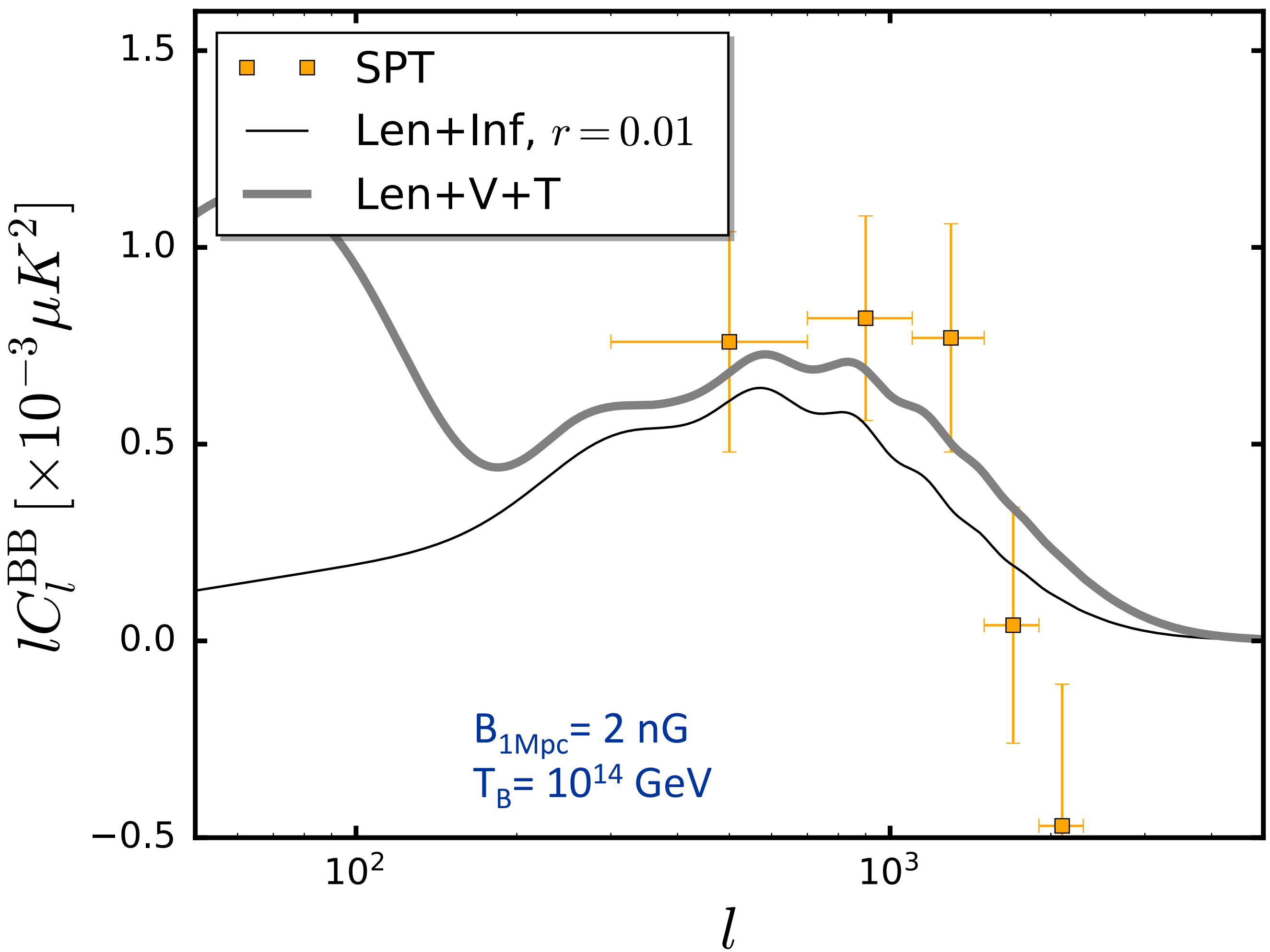
Pospelov, Ritz, Skordis, PRL, 0808.0673

  - Current bound (Planck, PB): $f_a > 10^{15}$ GeV $\frac{H}{10^{14} GeV}$
  - PICO forecast: $f_a > 10^{18}$ GeV $\frac{H}{10^{14} GeV}$
  - Non-trivial bounds on String Theory axions and inflation

# Summary

- Cosmic magnetic fields are real, and maybe primordial in origin
- Mode-coupling correlations induced by Faraday Rotation can reduce the upper bound on PMF from 1 nG to below 0.1 nG
- This would rule out a purely primordial origin of galactic magnetic fields
- Need Q & U with high resolution, low noise at lower frequencies
- Potentially interesting science from cross-correlations of CMB polarization rotation maps with Synchrotron maps and Rotation Measures of radio sources

# PMF contributions to the B-mode spectrum




A. Zucca, Y. Li, LP, 1611.00757, LP & A. Zucca, 1801.08936

*Science* 2 April 2010:
Vol. 328 no. 5974 pp. 73–75
DOI: 10.1126/science.1184192



REPORT

# Evidence for Strong Extragalactic Magnetic Fields from Fermi Observations of TeV Blazars

**Andrii Neronov*, Ievgen Vovk**

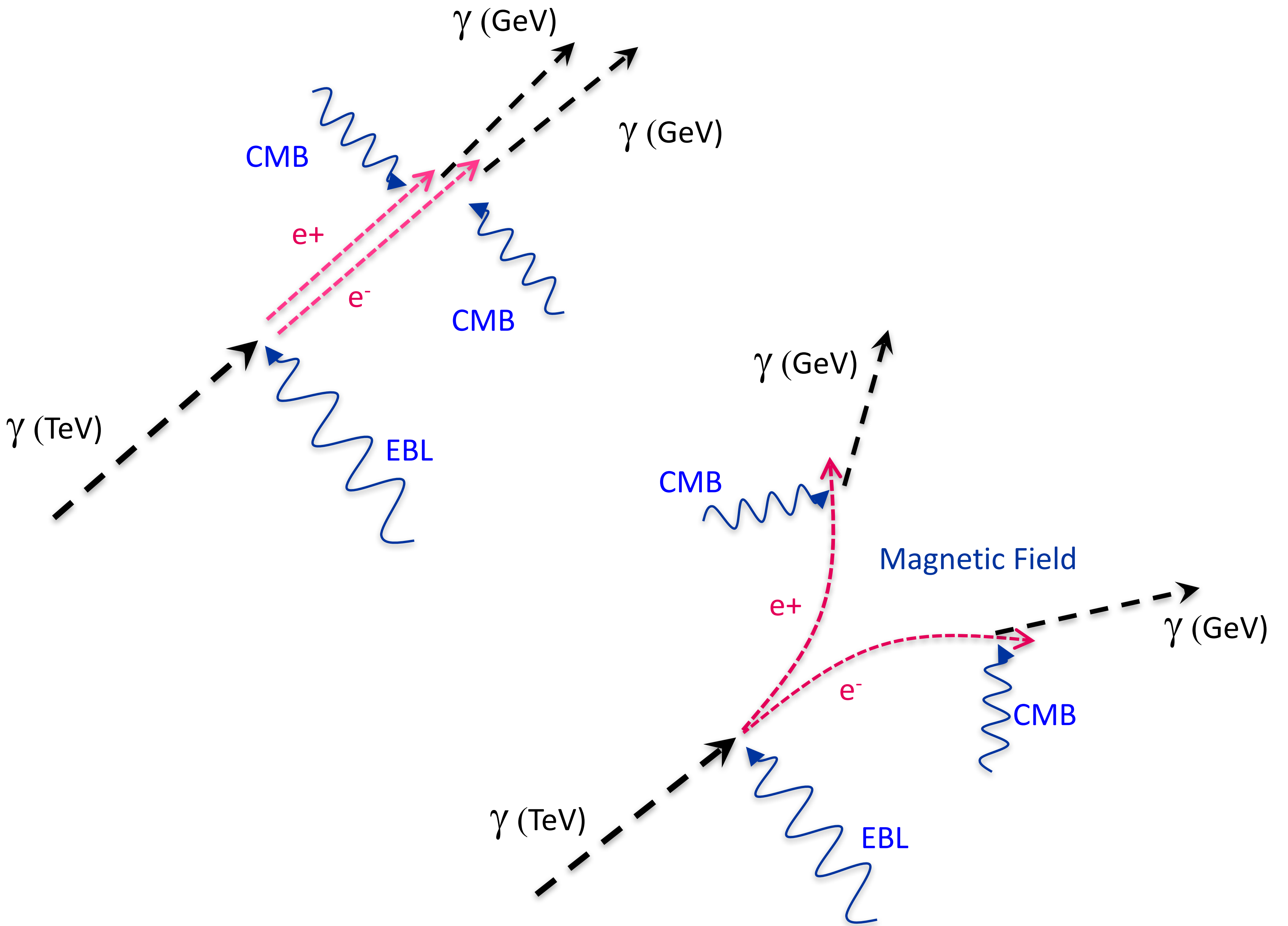
- Author Affiliations

ISDC Data Centre for Astrophysics, Geneva Observatory, Ch. d'Ecogia 16, Versoix 1290, Switzerland.

*To whom correspondence should be addressed. E-mail: Andrii.Neronov@unige.ch

ABSTRACT

**Magnetic fields in galaxies are produced via the amplification of seed magnetic fields of unknown nature. The seed fields, which might exist in their initial form in the intergalactic medium, were never detected. We report a lower bound $B \geq 3 \times 10^{-16}$ gauss on the strength of intergalactic magnetic fields, which stems from the nonobservation of GeV gamma-ray emission from electromagnetic cascade initiated by tera-electron volt gamma rays in intergalactic medium. The bound improves as $\lambda_B^{-1/2}$ if magnetic field correlation length, $\lambda_B$, is much smaller than a megaparsec. This lower bound constrains models for the origin of cosmic magnetic fields.**


γ (GeV)
γ (GeV)
CMB
e+
e-
CMB
γ (TeV)
EBL
γ (GeV)
CMB
Magnetic Field
e+
γ (GeV)
e-
CMB
γ (TeV)
EBL

# Radiative transport with Faraday Rotation

$$\boxed{\begin{aligned} \dot{Q} + i(\vec{k}\cdot\hat{n})Q &= -\dot{\tau}Q + 2\omega_B U + S_+ \\ \dot{U} + i(\vec{k}\cdot\hat{n})U &= -\dot{\tau}U - 2\omega_B Q + S_- \end{aligned}}$$

$$\omega_B = \frac{d\alpha}{d\eta} = \frac{3\lambda_0^2}{2\pi e}\dot{\tau}\mathbf{B}\cdot\hat{n}$$