Cosmic Birefringence and B-modes

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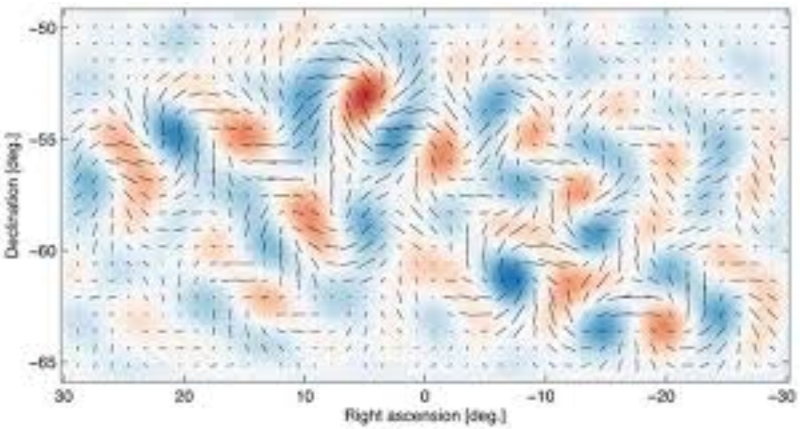
Outline of the talk

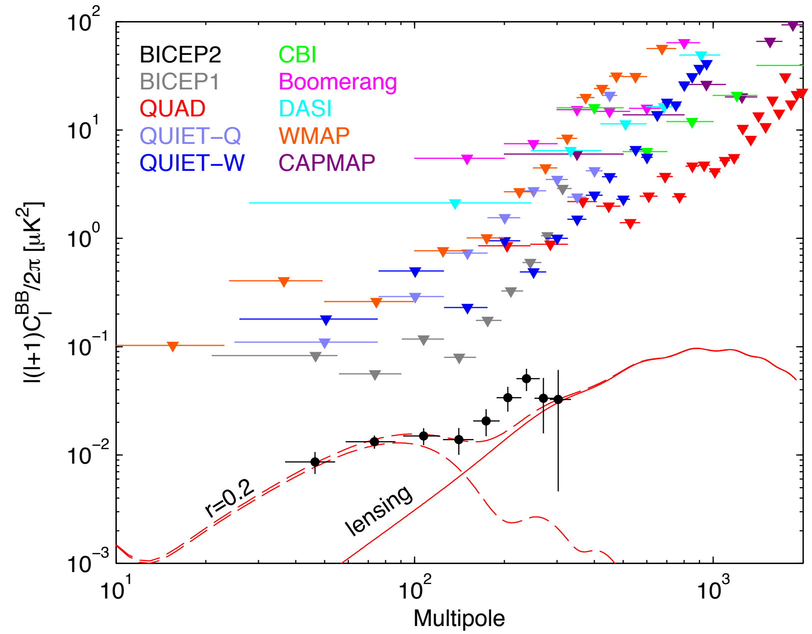
1. Introduction. Search for new IR degrees of freedom with cosmology tools. Necessity to scrutinize the Bicep-2 result, including gravitational wave interpretation of B-modes.
2. Physics of the pseudoscalar boson coupled to spins of particles. Rotation of photon polarization propagating in pseudoscalar background. Polarization of the CMB generated at the surface of last scattering. E and B modes.
3. Pseudoscalar-perturbation-induced rotation of polarization of CMB photons generates <BB> correlation. Details of the calculation.
4. Polarization effects due to possible domain wall structure.
5. Conclusions: constraints on the parameters of the pseudoscalar model. Implications for the gravitational wave signal in B-modes.

Main idea

- *To use CMB physics as a way to search for light degrees of freedom.*
- Inflation generates perturbation of any massless/light field, $\delta\phi \sim H_{infl}$, and H_{infl} can be as large as 10^{14} GeV. This is very large compared to other scales of particle physics we know but very small relative to M_{Planck}.
- Massless pseudoscalar fields of that magnitude can be seen through their couplings to photons, $(\phi/f_a)\, F_{\mu\nu}\, \mathrm{dual}F_{\mu\nu}$.
- This leads to the transfer of power from E-modes (gradient modes) to the B-modes (curl modes) of CMB polarization, and creates <BB> correlation across the sky.
- Precision probes of <BB> correlation in the CMB anisotropy can provide an access to $H/f_a \sim 0.1$ and thus probe the scales of particle physics $f_a \sim 10^{15}$ GeV that are inaccessible in any other way.

1 month ago – Bicep 2 results!!





If interpreted as the signature of primordial tensor perturbations generated by inflation it gives very high Hubble rate during inflation, with $H_{infl} = 10^{14}$ GeV. Well, it poses a lot of questions to anyone who tries to play with some physics that has fundamental scale below 10^{14} GeV. **Profound consequences for theoretical physics!** Gravitational waves generated during inflation is the most economical explanation.

Impact of Bicep-2 results is huge

Finally we come to the early universe. The most solid aspect of early cosmology, namely primordial nucleosynthesis, remains intact in our framework. The reason is simple: The energy per particle during nucleosynthesis is at most a few MeV, too small to significantly excite gravitons. Furthermore, the horizon size is much larger than a mm so that the expansion of the universe is given by the usual 4-dimensional Robertson-Walker equations. Issues concerning very early cosmology, such as inflation and baryogenesis may change. This, however, is not necessary since there may be just enough space to accommodate weak-scale inflation and baryogenesis.

This is from the 1998 classics….

No – unless we find solid alternatives to generation of B-modes than tensor modes, *things will have to change* for all models with low fundamental scales.

<BB> = T or "T-like" modes ?

1. *Every big discovery follows by the period of trying to understand the result.* E.g. excess of events around 125 GeV → Evidence of a new resonance → Higgs-like properties of the resonance → dropping "-like" after lots of tests. In the process you rule out competitors such as KK-graviton, techni-pion, etc [no matter how creepy they are]. Same process will occur with the discovery of B-modes.

2. *The minimal interpretation of B-modes are tensor perturbations*, the remnants of inflation that occurred with $H_{infl}=10^{14}$ GeV. Well, it poses a lot of questions to anyone who tries to play with some physics that has fundamental scale below 10^{14} GeV.

3. One can provide new mechanisms of B-mode generation with a low inflationary scale, e.g. $H_{infl} \sim 10^{10}$ GeV (MP, Ritz, Skordis, 2008). View it as a competitive explanation of Bicep observations, and try to rule it out from data!

Light interacting field

Consider a light field interacting with matter

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) + \bar{\psi}(iD_\mu\gamma^\mu - m)\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$
$$-c_{S\psi}\phi\bar{\psi}\psi - c_{P\psi}\phi\bar{\psi}i\gamma_5\psi - c_{S\gamma}\phi F_{\mu\nu}F^{\mu\nu} - c_{P\gamma}\phi F_{\mu\nu}\tilde{F}^{\mu\nu}.$$

If ϕ is really *really* light (e.g. $m_\phi \sim 10^{-33}$ eV $\sim H_0$) and evolves on the cosmological time scales now, then one has a possibility of probing its presence cosmologically

- $w_{DE} \neq -1$
- Couplings/masses of SM particles may change over cosm time
- New gravitational-type force will appear
- *Birefringence-type phenomena in propagation of polarized particles*
- …

Possible Interactions

Let us call by ϕ, ϕ_1, ϕ_2, … - real scalar fields from "light" sector that interact with SM. Let us represent SM field by an electron, or a nucleon, or a photon.

Interactions can be organized as "*portals*": coeff × $O_{dark}O_{SM}$.

A. $$\frac{\partial_\mu \phi}{f_a} \sum_{\mathrm{SM\ particles}} c_\psi \bar{\psi}\gamma_\mu\gamma_5\psi \quad \text{axionic portal}$$

B. $$\frac{\phi}{M_*} \sum_{\mathrm{SM\ particles}} c_\psi^{(s)} m_\psi \bar{\psi}\psi \quad \text{scalar portal}$$

C. $$\frac{\phi_1^2+\phi_2^2}{M_*^2} \sum_{\mathrm{SM\ particles}} c_\psi^{(2s)} m_\psi \bar{\psi}\psi \quad \text{quadratic scalar portal}$$

D $$\frac{\phi_1 \partial_\mu \phi_2}{M_*^2} \sum_{\mathrm{SM\ particles}} g_\psi \bar{\psi}\gamma_\mu\psi \quad \text{current} - \text{current portal}$$

An atom inside a ϕ-profile will have addt'l contributions to its energy levels

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A. $$\frac{\partial_\mu \phi}{f_a} \sum_{\text{SM particles}} c_\psi \bar{\psi}\gamma_\mu\gamma_5\psi \quad \text{axionic portal}$$ Torque on spin

B. $$\frac{\phi}{M_*} \sum_{\text{SM particles}} c_\psi^{(s)} m_\psi \bar{\psi}\psi \quad \text{scalar portal}$$ Shift of ω + extra gr. force

C. $$\frac{\phi_1^2+\phi_2^2}{M_*^2} \sum_{\text{SM particles}} c_\psi^{(2s)} m_\psi \bar{\psi}\psi \quad \text{quadratic scalar portal}$$ Shift of ω + extra gr. force

D $$\frac{\phi_1 \partial_\mu \phi_2}{M_*^2} \sum_{\text{SM particles}} g_\psi \bar{\psi}\gamma_\mu\psi \quad \text{current} - \text{current portal}$$ extra gr. type force

An atom inside a ϕ-profile will have addt'l contributions to its energy levels

The issue of technical naturalness

Any tree level potential

$V^{tree}(\phi) = c^{tree}{}_0 + c^{tree}{}_1\phi + c^{tree}{}_2\phi^2 + \ldots.$

Would have to have coefficients $c^t{}_i$ very small to keep evolution *slow*. Loops generate *larger* corrections

$V^{loop}(\phi) = c^{loop}{}_0 + c^{loop}{}_1\phi + c^{loop}{}_2\phi^2 + \ldots.$

so that $c^{loop}{}_i >> c^{tree}{}_i$, One has to start with large and opposite tree-vs-loop coefficients $c^{loop}{}_i = - c^{tree}{}_i$ to ensure tight cancellation for several terms in the series… Very unnatural! *Standard problem for scalar portals. (e.g. in the context of changing α)*

Importantly, same pessimistic argument does not apply to interactions protected by shift symmetry, the axionic portal for ex.

(* *But may be the approach idea of having rigid technical naturalness built in a model is not "quite" right, and we would miss out on interesting physics* *)

[Nearly] massless pseudoscalar

$$\mathcal{L}_{everything} = \mathcal{L}_{SM+gravity} + \mathcal{L}_{inflation} + \frac{1}{2}(\partial_\mu a)^2 + \frac{a}{2f_a}F_{\mu\nu}\tilde{F}_{\mu\nu}$$

- The shift symmetry protects V(a) = 0 from being generated (e.g. model is not at all as ugly as "interacting quintessence")
- Large number of possible UV completions via PQ mechanisms
- *a* has commonplace occurrence in models inspired by string theory
- Many phenomenological processes with *a* are well-understood being studied in the axion literature.

Two axion model ("minimal axiverse")

- Two-axion model is like that. One axion becomes a QCD axion, and the other one remains massless,

$$\left(\frac{a_1}{2g_1}+\frac{a_2}{2g_2}\right)G_{\mu\nu}\tilde{G}^{\mu\nu}+\left(\frac{a_1}{2f_1}+\frac{a_2}{2f_2}\right)F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$$\to \mathcal{L}_{\mathrm{QCD}a}+\frac{a}{2f_a}F_{\mu\nu}\tilde{F}^{\mu\nu},$$

- Coupling constant is given by

$$f_a^{-1}=(g_2/f_2-g_1/f_1)/\sqrt{g_1^2+g_2^2}.$$

Photon propagation

- Dispersion for left- and right- handed photons is not the same

$$\omega^2 - \vec{k}^2 \pm \frac{da}{f_a dt}|\vec{k}| = 0$$

$$\Delta\omega_\pm = \pm\frac{da}{f_a dt}$$

- The phase shift after propagating for time T, $\Delta\omega\, T$, is frequency independent. *All CMB frequencies will be affected*.
- Rotation of polarization plane after travelling from point 1 to point 2 is simply (Harrari, Sikivie; Carroll; Lue, Wang, Kamionkowski…)

$$\psi = \frac{a_1 - a_2}{f_a}$$

- Light deflection is suppressed.

Pseudoscalar massless field can interact with photons "stronger" than gravity

- Pseudoscalars coupled to photons can be coupled to photons much stronger than gravity without contradicting other existing constraints.

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

- Other derivative terms, $(\partial_\mu a)\, \psi\, \gamma_\mu \gamma_5 \psi$, are of course also possible but inconsequential for CMB photons
- $(\partial_\mu a)\, \psi\, \gamma_\mu \gamma_5 \psi$ δoes not feed into the photon coupling at the radiative level.

Experimental probes of the model

1. Emission of pseudoscalars from the sun

$e + \gamma \rightarrow e + a$ process creates a flux of E~ 1 keV particles, that can be reconverted to gamma rays in magnetic field.

CAST experiment sets the limit $f_a > 10^{11}$ GeV

2. Stellar constraints. Similar limits, $f_a > 10^{11}$ GeV, can be deduced from the stellar energy loss mechanism.

3. Polarized radio emission from distant galaxies. Any polarized light propagating between points 1 and 2 has its polarization rotated by

$\Delta_{12} a/f_a$. Polarization is usually correlated with galactic axis, and pseudoscalar can destroy this correlation, or rotate it.

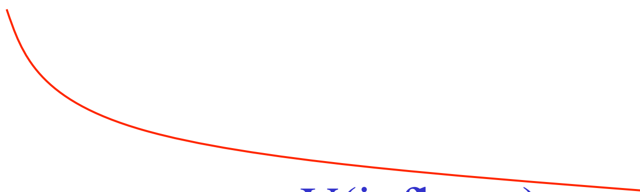
CMB is the oldest polarized source → *pseudoscalar signature in CMB!*

Pre-Bicep dilemma in inflation

Main observational outcome of inflation is density perturbations. Density perturbations are seeded by the fluctuation of the inflaton field:

$\delta\,\phi \sim H_{infl}/(2\,\pi)$. Unfortunately, the measurement of $\Delta\,\rho/\rho$ *does not fix the scale of inflation*:

$(1.93 * 10^{-10})_{COBE,WMAP,PLANCK} \sim G_N\, H_{infl}{}^2/(4\pi\varepsilon)$



V(inflaton)

Slow-roll parameter $\varepsilon = M^2{}_{pl}(V'/V)^2$ can be small…

V(inflaton)

or very very small

Perturbations of light fields

H_{infl} and ε are chosen to satisfy "COBE normalization", and tests of inflationary models come from the measurement of *e.g.* spectral index and other quantities.

Any other massless field (including gravity waves, massless scalars, pseudoscalars) also acquire Gaussian, nearly scale-invariant perturbations. The magnitude depends on *H* during inflation, and after the normalization on COBE, is linearly proportional to the slow-roll parameter ε.

$$\left\langle \xi_\varphi^*\left(\vec{q_1}\right), \xi_\varphi\left(\vec{q_2}\right)\right\rangle = P_\varphi(q)\delta\left(\vec{q_1} - \vec{q_2}\right),$$

$$P_\varphi(q) = \frac{(H/2\pi)^2}{4\pi q^3} q^{n-1}, \quad \text{n is close to 1 for inflation}$$

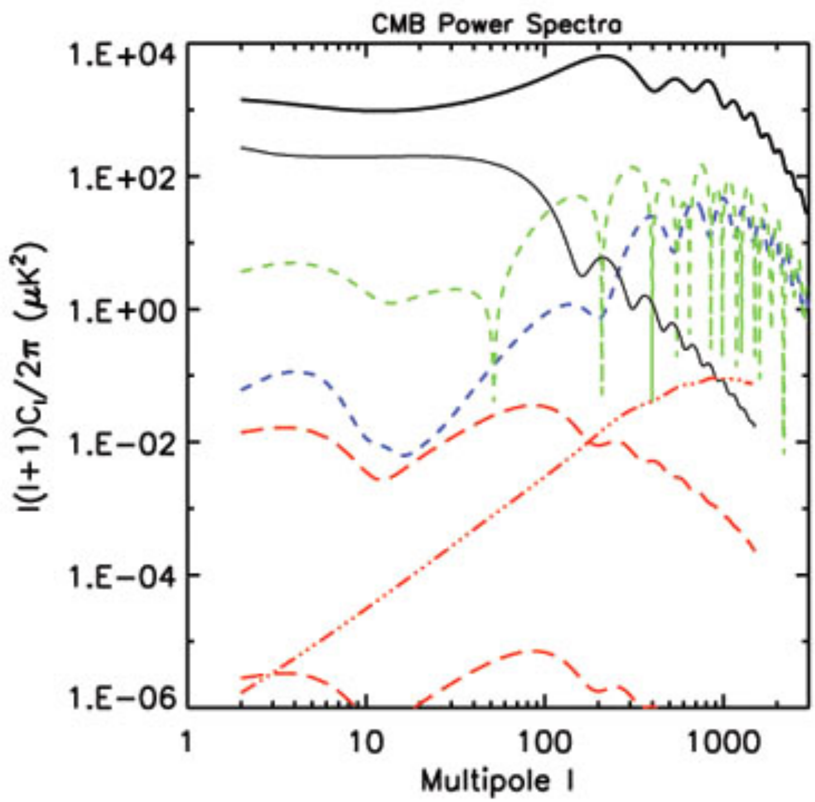
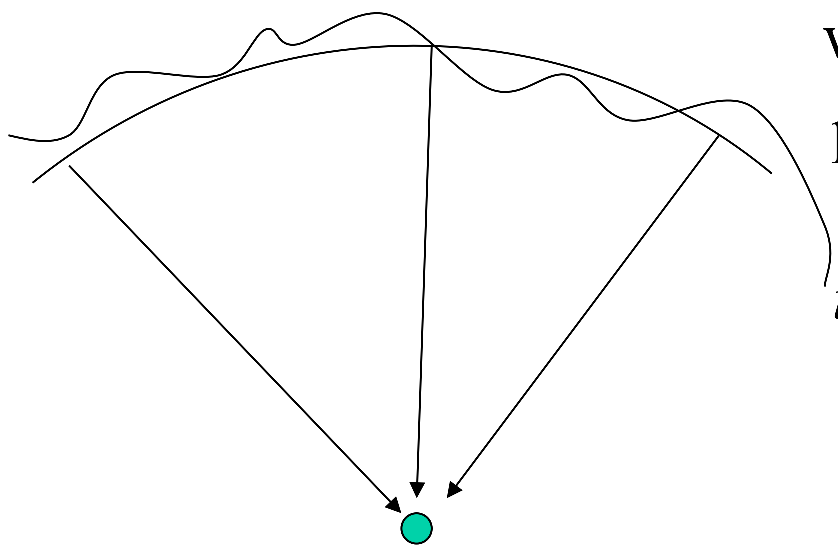


FIG. 2: Angular power spectra. The bold solid black line shows the temperature power spectrum from scalar perturbations in the standard flat model (WMAP 3–year values were adopted: $(\Omega_M h^2, \Omega_B h^2, h, n_s, \tau, \sigma_8) = (0.127, 0.0223, 0.73, 0.951, 0.09, 0.74)$ [15]), while the thin black line gives the temperature perturbations from tensor perturbations when $r = 0.5$. The green (upper) and blue (lower) short dashed curves are, respectively, the scalar *TE* (absolute value shown) and *EE* power spectra for the standard model; the former is well measured on large scales by WMAP [26]. The red long dashed lines indicate the tensor *B*–mode power for $r = 0.5$ (upper) and $r = 10^{-4}$ (lower). Gravitational lensing produces the *B*–mode power shown as the red 3–dot–dashed curve peaking at $l \sim 1000$.

- The progress in measurements of CMB anisotropies has been enormous.
- The <TT>, <TE> and most recently <EE> correlations have been measured with great deal of precision by several groups/instruments
- B-modes are ~~not~~ detected: <BE>, <TB> are zero by parity conservation, and <BB> is often referred to as last frontier, as it can be induced by gravity waves

Propagation of CMB from the LSS



Surface of Last Scattering with chaotic pseudoscalar profile

$t=t_{LSS}$, a_{LSS} *is given by inflation.*

$t=t_{today}$, $a_{today}=0$.

Polarization of arriving to us CMB photons is randomly rotated by
$\Delta\psi(n) = A_{LSS}(n)=a_{LSS}(n)/f_a.$

For convenience, we introduce c_a

$$c_a = \left(\frac{H}{2\pi f_a}\right)^2, \quad |\Delta\psi| \sim \sqrt{c_a}.$$

CMB polarization

Thomson scattering at the surface of last scattering (LSS) combined with guadrupole anisotropy leads to the linearly polarized CMB radiation.

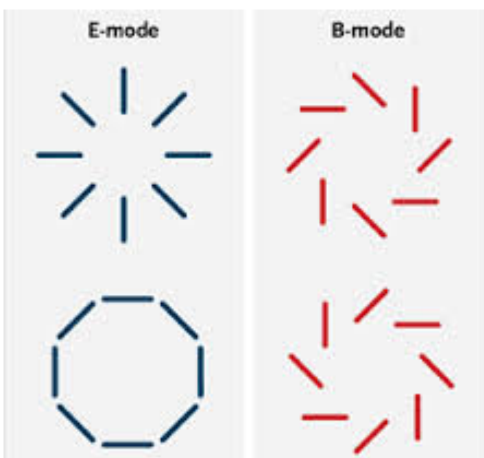
The degree of polarization, and its angular correlations can be directly predicted from the power spectrum of scalar perturbations that can be extracted from <TT>. Current observations are in complete agreement with this prediction.

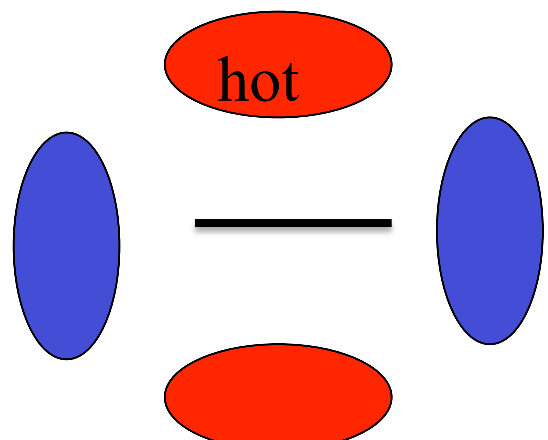
Some background on CMB polarization

(Kamionkowski, Stebbins, Kosowsky; Seljak, Zaldarriaga, 1997…)

$$\vec{P} = \underset{\text{E-mode}}{\nabla S} + \underset{\text{B-mode}}{\mathrm{curl}\ \vec{V}}$$

Polarization is generated by quadrupole temperature anisotropy, and scalar perturbations are capable of generating only the E-modes.





Scalar perturbations [of Newtonian potential] can only generate E-mode but perturbations of the full metric tensor [grav waves] can also give B.

E and B modes

- *Main physics principle:* suppose you have a single mode of scalar (density) perturbation with momentum k || z axis. Suppose you have photons arriving to you from direction *n*. They will be polarized either in the plane formed by *n* and z, or in the perpendicular directions. *These are E-modes*. Or gradient modes. For this fixed geometry (k || z), the following In a fixed frame, Stokes Q parameter is generated, while U=0:

$$Q(k,\hat{n}) = \frac{3}{4}(1-\mu^2)\int_0^{\tau_0} e^{ix\mu} g(\tau)\Pi(k,\tau).$$

Here $x = k(\tau_0 - \tau)$ and $\mu = \hat{k}\cdot\hat{n}$.

- If the perturbation has some additional features (internal polarization, like gravity waves) U-parameter can be generated.

Mechanisms for generating B-modes

An excellent review of CMB polarization can be found in e.g. Seljak, Zaldarriaga, 1996, 1997, Kamionkowski et al 1997 where all the technicalities of standard CMB polarization calculations are dealt with.

- *U*-parameter can be generated by tensor perturbations
- Under the rotation around n by angle Δψ, *Q* parameter transforms to *U*-parameter. Thus, U-parameter can be generated by pseudoscalar perturbation with momentum q, superimposed on the scalar one (*k*||z, *x=(kn), y=(qn)*):

$$U(k,q,\hat{n}) = \frac{3}{2}(1-\mu^2)\int_0^{\tau_0} e^{ix\mu+iy\nu} g(\tau)\Pi(k,\tau)\Delta_A(\tau,q).$$

Technicalities of the calculation

Strategy:

1. Express Stokes parameters $Q(n)$ and $U(n)$ in terms of sources of perturbations, and the so-called *transfer functions*.
2. For a fixed geometry of perturbation modes, form the rotation-invariant combinations of polarization in momentum space by projecting $Q(n)$, $U(n)$ onto the spin 2-weighted spherical functions, $Y_{2,lm}$.

$$a_{Blm} = -\int d\Omega (Y^*_{2,lm} + Y^*_{-2,lm}) U(\hat{n})/2$$

3. Calculate the correlation coefficients by squaring a_{Blm} and employing the scalar [main] and pseudoscalar [auxilary] perturbation spectra.

Technicalities of the calculation

Expression for $a_{\mathrm{B}lm}$:

$$a_{Blm} = \frac{3}{2}\left[\frac{(l-2)!}{(l+2)!}\right]^{1/2}\int d\Omega_n d^3k d^3q Y^*_{0,lm}(\hat{n})$$
$$\times \int_0^{\tau_0} d\tau (m^2 - (1+\partial_x^2)^2 x^2) e^{ix\mu + iy\nu} F(\tau, \vec{k}, \vec{q}).$$

Source function is related to primordial fluctuations $\xi_{\Phi,A}$

$$F(\tau, \vec{k}, \vec{q}) = g(\tau)\Pi(k,\tau)\Delta_A(q,\tau)\xi(\vec{k})\xi_A(\vec{q}).$$

$\xi_{\Phi,A}$ have correlation functions given by inflation:

$$\langle \xi^*(\vec{k}_1)\xi(\vec{k}_2)\rangle = P_\phi(k_1)\delta^{(3)}(\vec{k}_1 - \vec{k}_2),$$
$$\langle \xi_A^*(\vec{q}_1)\xi_A(\vec{q}_2)\rangle = P_A(q_1)\delta^{(3)}(\vec{q}_1 - \vec{q}_2),$$

$$P_A(q) = \frac{c_a}{4\pi q^3} q^{n_a - 1}.$$

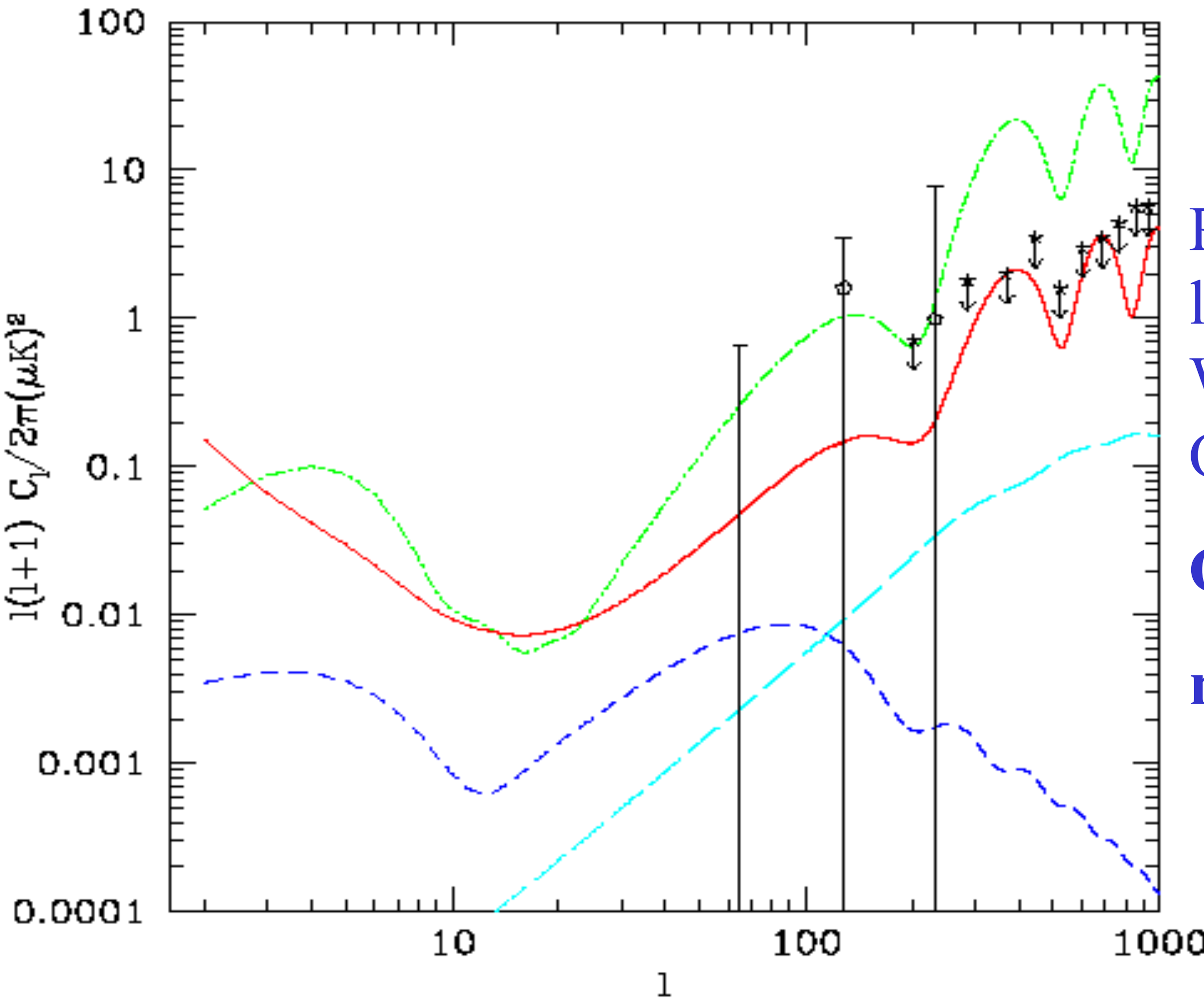
Master formula for <BB> calculation

$$
\begin{aligned}
C_{Bl} \; &= \; \frac{1}{2l+1}\sum_m \langle a^*_{Blm} a_{Blm} \rangle = \frac{4(4\pi)^3}{2l+1}\frac{(l-2)!}{(l+2)!} \\
&\times \sum_{m,l_1,l_2} (2l_1+1)(2l_2+1) \begin{pmatrix} l & l_1 & l_2 \\ 0 & 0 & 0 \end{pmatrix}^2 \\
&\times \int k^2 \underline{P_\Phi} q^2 \underline{\underline{P_A}} dk dq |\Delta_{l_1 l_2 m}(k,q)|^2,
\end{aligned}
$$

with the generalized transfer function,

$$
\begin{aligned}
\Delta_{l_1 l_2 m}(k,q) \; &= \; \frac{3}{4}\int_0^{\tau_0} d\tau g(\tau) j_{l_1}(x) j_{l_2}(y) \\
&\times \left(\frac{(l_1+2)!}{(l_1-2)!}\frac{1}{x^2} - m^2 \right) \Delta_A(\tau,q)\Pi(\tau,k).
\end{aligned}
$$

Numerical Results and comparison with experiment, 2008

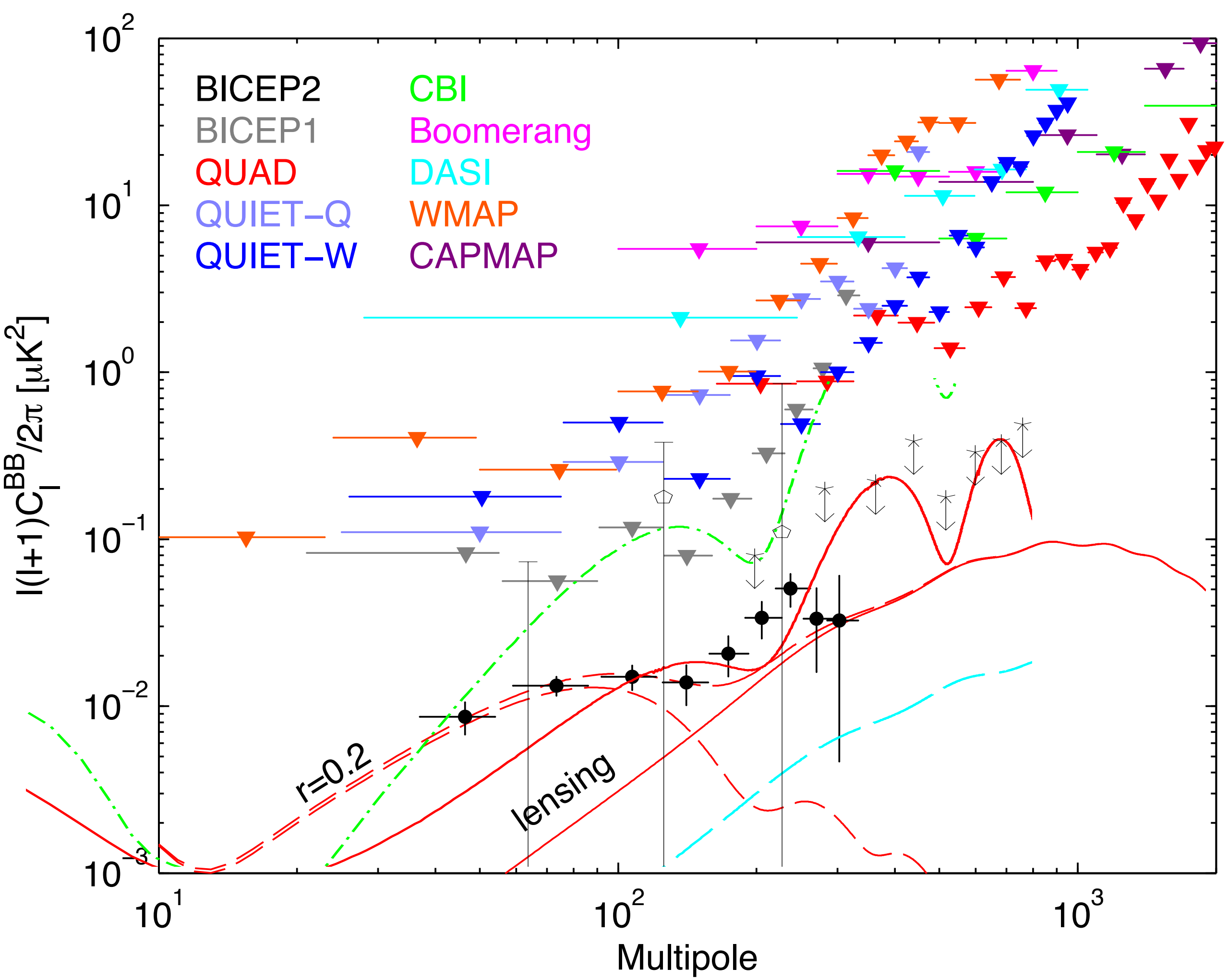


Points: upper limits from WMAP5 and QUaD

One parameter model

Green: EE; Red: BB with c_a =0.004; Dark blue: BB from gravity waves with r=0.14; light blue: BB lensing background

The moment of truth



Inflationary pseudoscalar fluctuations do not give a good fit to Bicep data(too low l<100) !!! So, it more "T-like" and not at all "*a*-like".

Constraints on pseudoscalar model

Results of QUaD collaboration (May 2008) improve the constraints on <BB> correlation (C_{Bl}) and restrict it to be less than 0.1 from <EE> for a wide range of angular momenta.

This sets a constraint on coefficient c_a, and a *conditional constraint* on pseudoscalar coupling f_a in terms of $H_{14} = H_{infl}/10^{14}$ GeV.

If H_{14} is not small, this constraint is superior to any other available constraint.

$$c_a < 4.2 \times 10^{-3} \quad \Longrightarrow \quad f_a > 2.4 \times 10^{14}\ \mathrm{GeV} \times H_{14},$$

After Bicep-2 we have (assuming tensor-like origin of BB),

$$\boldsymbol{f_a > 10^{15}\ \mathrm{GeV}}$$

This is much stronger constraint than direct probes.

Is it possible to separate “rotated” from “genuine, Tensor-like” B-modes??

There is an idea that such separation may be possible observationally (Kamionkowski, October 2008, Yadav, Biswas, Su, Zaldarriaga 2009, Gluscevic, Kamionkowski, Cooray, 2009….)

- Most likely yes, via “statistical de-rotation” akin to the removal of lensed contribution.
- It is true that some strong correlations between C_{El} and C_{Bl} remain. For example, regular polarization (E-mode) is zero in certain direction, so is B-mode.
- Could one use some local correlations of <EB> type? They are zero integrated over the whole sky, but may not be so over small patches of sky.

On-going work

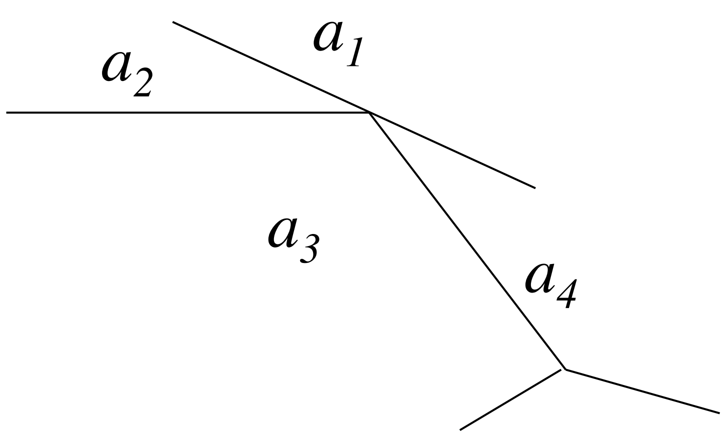
In collaboration with many people (D. Marsh, …) I pursue several tasks:

- Publish an erratum, as the kernel in the 2008 paper is not 100% correctly derived.
- Optimize the numerical part of the calculation (our current version takes too much time to run.)
- Investigate (purely phenomenologically) if it is possible to increase $C_l(BB)$ at $l < 100$, without affecting $C_l(BB)$ at $l \sim 500$ by playing with initial power spectrum of pseudoscalar. (Simple, one parameter predictivity will be lost.) The simplest model does not fit Bicep result, but what about more complicated initial spectra?
- Confront the model with other constraints (from reduction of EE,, from higher-order correlators.)
- See also recent post-Bicep papers by Lee et al.; Li and Zhang;…

Another possibility: domain wall network

A pseudoscalar field *does not have to be strictly massless* to generate interesting effects. Massive field locked into domain walls can generate rotation of polarization of light

Imagine a system of domain walls separating energetically equivalent vacua that have different values of a field. Domains are separated by domain walls, inside which the a field changes.



If domain wall thickness is larger than the wavelength of light, the polarization will rotate in discrete steps $\sim \Delta a = a_{n+1} - a_n$.

After many steps the process will look like the 1D diffusion in the polarization space.

If domain walls are presently abundant are they *directly* detectable??

- If the frustrated network of domain walls forms, there is a non-zero chance for the Solar System – domain wall encounter.
- If the field changing across the domain wall has interaction with spins (electrons, photons, nuclei etc), there might be a chance of directly detecting wall-crossing events.
- There is a group interested atomic experimentalists (D. Budker et al.) that develop techniques for doing this, by creating a global network of correlated magnetometers.

Signal of axion-like domain wall

Consider a very light complex scalar field with Z_N symmetry:

$$\mathcal{L}_\phi = |\partial_\mu \phi|^2 - V(\phi); \quad V(\phi) = \frac{\lambda}{S_0^{2N-4}} \left| 2^{N/2}\phi^N - S_0^N \right|^2$$

Theory admits several distinct vacua, $\phi = 2^{-1/2} S \exp(ia/S_0)$

$$S = S_0; \;\; a = S_0 \times \left\{ 0; \; 2\pi \times \frac{1}{N}; \; 2\pi \times \frac{2}{N}; \dots \; 2\pi \times \frac{N-1}{N} \right\}$$

Reducing to the one variable, we have the Lagrangian

$$\mathcal{L}_a = \frac{1}{2}(\partial_\mu a)^2 - V_0 \sin^2 \left(\frac{Na}{2S_0} \right)$$

that admits domain wall solutions

$$a(z) = \frac{4S_0}{N} \times \arctan\left[\exp(m_a z)\right]; \quad \frac{da}{dz} = \frac{2S_0 m_a}{N \cosh(m_a z)}$$

$$\rho_{\mathrm{DW}} \leq \rho_{\mathrm{DM}} \Longrightarrow \frac{S_0}{N} \leq 0.4 \text{ TeV} \times \left[\frac{L}{10^{-2}\text{ ly}} \times \frac{\text{neV}}{m_a} \right]^{1/2}$$

If on top of that *a*-field has the axion-type couplings, there will be a magnetic-type force on the spin inside the wall, $H_{\text{int}} = \sum_{i=e,n,p} 2 f_i^{-1} \nabla a \cdot \mathbf{s}_i$

Network of Magnetometers

- For alkali magnetometers, the signal is

Exper. Sensitiv.

S ~ below fT/√Hz

MP et al, PRL 2013

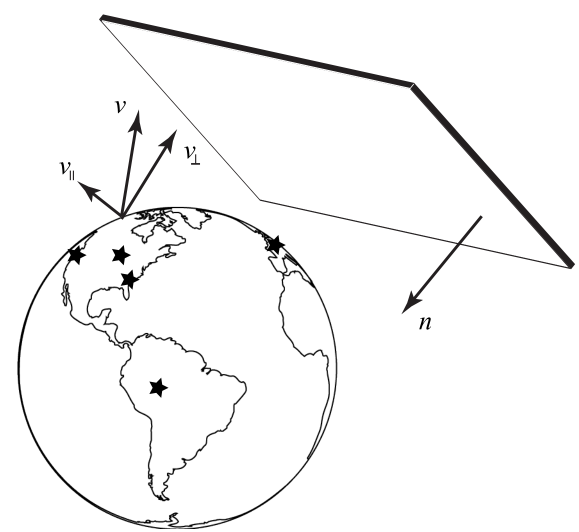
$$\mathcal{S} \simeq \frac{0.4\,\mathrm{pT}}{\sqrt{\mathrm{Hz}}} \times \frac{10^9\,\mathrm{GeV}}{f_{\mathrm{eff}}} \times \frac{S_0/N}{0.4\,\mathrm{TeV}} \times \left[\frac{m_a}{\mathrm{neV}}\frac{10^{-3}}{v_\perp/c}\right]^{1/2}$$

$$\leq \frac{0.4\,\mathrm{pT}}{\sqrt{\mathrm{Hz}}} \times \frac{10^9\,\mathrm{GeV}}{f_{\mathrm{eff}}} \times \left[\frac{L}{10^{-2}\ \mathrm{ly}}\frac{10^{-3}}{v_\perp/c}\right]^{1/2},$$

- For nuclear spin magnetometers, the tipping angle is

$$\Delta\theta = \frac{4\pi S_0}{v_\perp N f_{\mathrm{eff}}} \simeq 5\times 10^{-3}\,\mathrm{rad}\times\frac{10^9\,\mathrm{GeV}}{f_{\mathrm{eff}}}\times\frac{10^{-3}}{v_\perp/c}\times\frac{S_0/N}{0.4\,\mathrm{TeV}}$$

- It is easy to see that one would need >5 stations. 4 events would determine the geometry, and make predictions for the 5th, 6th etc…



* *Nobody has ever attempted this before*

Experimental developments

- First steps towards creating the network of correlated atomic magnetometers have been made with potential nods at Berkeley, Mainz, Cal State East Bay, Krakow… (Budker, Jackson Kimball, Gawlik, Pustelny and others). Some initial NSF funding was secured for this **GNOME** collaboration.
- Atomic clock networks already exist (e.g. GPS, GLONASS etc). However, their sensitivity to a possible transient signal is not quantified properly. Blewitt, Derevianko (UNR) will address that and investigate the best possible clocks for a specialized network.
- A workshop is planned at Perimeter, June 16-19 to further discuss the science topics.

Conclusions

1. **Massless pseudoscalars are natural in many extensions of the SM. Their properties are protected by derivative couplings.**
2. **Perturbations of any massless field are generated during inflation, with an amplitude controlled by H_{infl}.**
3. **Spatially varying pseudoscalar perturbations coupled to photons induce the *chaotic* rotation of polarization of CMB photons, $|\Delta\psi| = a_{LSS}/f_a \sim H_{infl}/f_a$.**
4. **Very preliminary comparison of the shape of predicted $C_l(BB)$ with Bicep-2 does not seem to give a good fit. Some further work is required if more complicated models would work. Alternatively, if Bicep comes from T-modes, then energy scales of 10^{15} GeV for f_a are being probed.**
5. **Domain wall network may also lead to chaotic rotation of polarization, and curiously enough there is a possibility for a direct search of the event of wall crossing.**

Implications for the B-mode searches

- The standard (somewhat pessimistic) approach is that B-modes can be generated at a detectable level *only if* the scale of inflation is large H> 10^{12} GeV. This is assuming that *only* gravity waves are responsible for it. In pseudoscalar models with f_a close to current bounds, even *e.g.* H_{infl} » 10^{10} GeV can lead to B modes. We have a hope/window to see new physics, independently on H_{infl}.
- Future increase in accuracy will likely lead to <BB> detection (BICEP, QUaD, etc). Assuming that the backgrounds can be sorted out, the question arises: Is it possible to tell what caused B-modes, the gravity waves or pseudoscalar waves?
- Also, it is worth noting that <BB> correlation can be induced if there are primordial magnetic fields at the LSS time with » nGs strength.
- Coherent parity violating rotation is limited via <TB> correlation to be less than 5 degrees by WMAP5, QUaD.

Tensor perturbations

In some units the effect of primordial tensor perturbations (gravitational waves) from inflation is *always* proportional to

$\sim (H_{infl}/M_{Planck})^2 \sim \varepsilon$

The smaller parameter $r = 16\,\varepsilon$ is, the more difficult is to see gravitational waves in the CMB. Currently, $r < 0.3$.

This corresponds to a *maximal* inflationary scale,

$H^{max} \sim$ few * 10^{14} GeV.

H_{infl} is a free parameter. This is why detection of gravitational wave signatures in CMB is by no means guaranteed.