Distinctive non-Gaussianity from vector fields coupled to the inflaton

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$\phi \, F \, \tilde{F}$

Barnaby, MP, PRL 106 (2011)

Barnaby, Namba, MP, JCAP 1104 (2011)

$f\,(\phi)\;F^2$

Barnaby, Namba, MP, PRD 85 (2012)

Bartolo, Matarrese, MP, Ricciardone, arXiv:1210.3257

Shift symmetry protects flatness of inflaton potential.

Particularly useful for large $\Delta\phi$, recall $r > 0.01 \Rightarrow \Delta\phi \gtrsim M_p$

E.g. many realizations of axion inflation, characterized by $m \ll f \ll M_p$

Couplings restricted by:

- Shift symmetry
- Parity
- Gauge invariance

$$\mathcal{L}_{\text{int}} = \frac{C}{f}\,\partial_\mu\phi\,\bar{\psi}\,\gamma^\mu\,\gamma_5\,\psi + \frac{\alpha}{f}\,\phi\,F_{\mu\nu}\,\tilde{F}^{\mu\nu}$$

$$\Gamma_{\phi\to\psi\psi} \simeq \frac{C^2}{2\pi f^2}\,m_\phi\,m_\psi^2 \qquad\qquad \Gamma_{\phi\to AA} = \frac{\alpha^2}{64\pi\,f^2}\,m_\phi^3$$

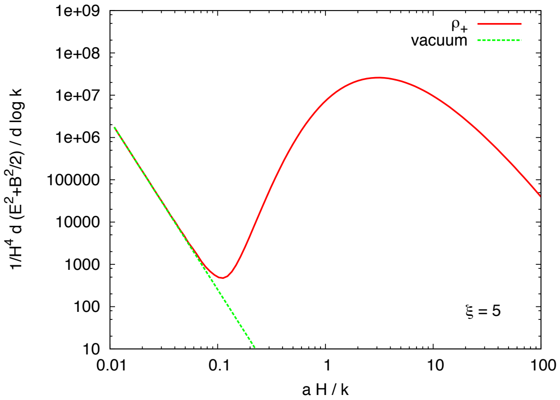
$\mathcal{L} \supset -\frac{1}{4}F^2 - \frac{\alpha}{f}\phi^{(0)}\, F\,\tilde{F}$

Classical motion $\phi^{(0)}(t)$ affects dispersion relations of $\pm$ helicities

$$\Rightarrow \quad \left(\frac{\partial^2}{\partial\tau^2} + k^2 \mp 2\,a\,H\,k\,\xi\right) A_\pm(\tau,\,k) = 0 \qquad \xi \equiv \frac{\alpha\,\dot{\phi}^{(0)}}{2\,f\,H} \simeq \text{const.}$$

One tachyonic helicity at horizon crossing

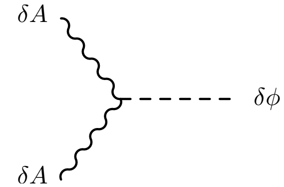
Anber, Sorbo '10



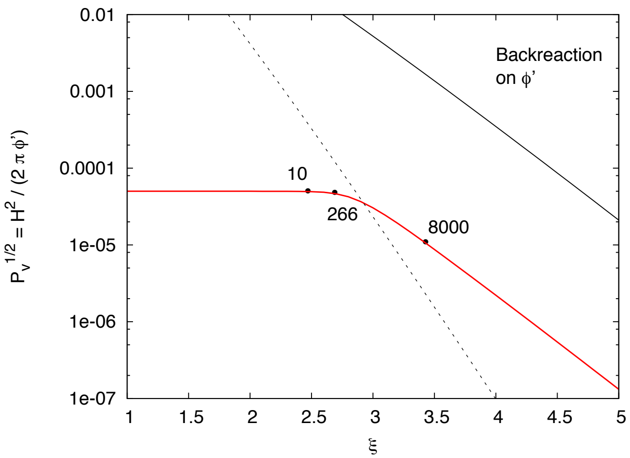
- Growth $A \sim e^{\pi\xi}$ at hor. cross.
- Then diluted away

$\delta\phi = \delta\phi_{\text{vacuum}} + \delta\phi_{\text{inv.decay}}$

Uncorrelated, $\langle \delta\phi^n \rangle = \langle \delta\phi^n_{\text{vac}} \rangle + \langle \delta\phi^n_{\text{inv.dec}} \rangle$



Barnaby, MP '11; Barnaby, Namba, MP '11



At any moment, only δA with $\lambda \sim H^{-1}$ present

cos with equil. = 0.94

cos with orth. = -0.1

- Observable NG for $f/\alpha \lesssim 10^{16}$ GeV , natural in axion inflation !
  (5 orders of magnitude stronger bound than $a_{\rm QCD}\gamma\gamma$ coupling)

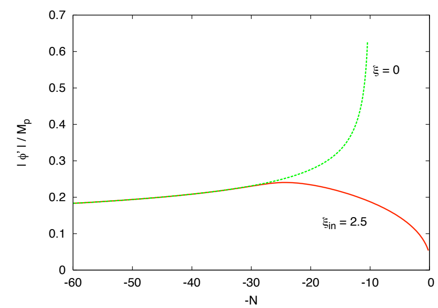
- In principle, $\delta A\, \delta A \to h$ of a given chirality
  However, unobservable due to NG limits

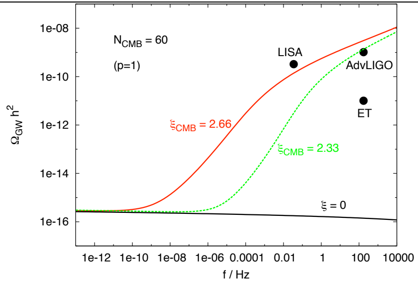
- $\delta A \sim {\rm e}^{\pi\xi}$ and $\xi \propto \dot{\phi}$. Inflaton speeds up during inflation. Possible GW signal at interferometer scales (where weaker limits from ζ)

  Cook, Sorbo'11

- Actually, for interesting ξ
  strong backreaction of δA
  at the end of inflation

  Barnaby, Pajer, MP '12





Barnaby, Pajer, MP '12

Particle production $X \rightarrow$ GW at CMB scales ?

Twofold: (i) $X \rightarrow h$ and (ii) $X \not\rightarrow \zeta$

Barnaby, Moxon, Namba, MP, Shiu, Zhou '12

- No direct $\phi - X$ coupling
- Relativistic X (or suppressed quadrupole moment)

$\psi F\tilde{F} \rightarrow r \gg 16\,\epsilon$ and gaussian ζ

(general discussion; see also Sorbo '11; Senatore, Silverstein, Zaldarriaga '11 Carney, Kovetz, Fischler, Lorshbough, Paban '12)

$f(\phi) F^2$ mechanism

With $\phi F \tilde{F}$, gauge field diluted away after horizon crossing

However, reasons to produce and to keep δA alive

- Magnetogenesis:

  $\vec{B} > \left(10^{-20} - 10^{-14}\right)$ G on extra-galactic scales inferred from γ-rays propagation — Neronov, Vovk '10

- Statistical anisotropy $P_\zeta\left(\vec{k}\right)$:

  No evidence (WMAP systematics) — Hanson, Lewis, A. Challinor '10; Pullen, Hirata '10

  However, Planck will probe anisotropy at $\sim$ % level — Pullen, Kamionkowski '07; Ma, Efstathiou, Challinor '11

What about NG ? (any mark from spin 1 ?)

Seery '08; Barnaby, Namba, MP '12; Bartolo, Matarrese, MP, Ricciardone '12

$P\left(\vec{k}\right)$ from homogeneous $\vec{A}\,(t)$ (anisotropic inflation or curvaton)

"Electric" component. Use em notation also in this case

$$\text{Electric} \leftrightarrow \text{magnetic duality for } \langle f \rangle \leftrightarrow \frac{1}{\langle f \rangle} \qquad \left(f F^2\right)$$

Consider $\langle f \rangle \propto a^n$. Frozen and scale-invariant super-horizon

$$\frac{d\rho_B}{d \ln k} \simeq H^4 \text{ for } n = 4$$

Ratra '92

$$\Rightarrow \quad \rho_B \simeq H^4 \ln \frac{a_{\text{end}}}{a_{\text{in}}} = H^4 \, N_{\text{tot}}$$

Too much energy in IR modes for $|n| > 4$

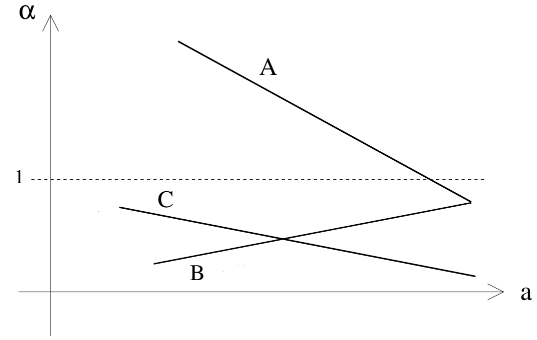
Demozzi, Mukhanov, Rubinstein '09

$$\mathcal{L} \sim -\frac{f}{4} F^2 \quad , \quad f \propto a^n$$

constant $\frac{d\rho_B}{d\ln k}$ for $n = 4$

(ρ_E for $n = -4$)

$$\alpha_{\text{phys}} \propto f^{-1} \propto a^{-n}$$



A) Bad for $n > 0$ and $\alpha_{\text{end}} = \alpha_0$ (magnetogenesis)

Demozzi, Mukhanov, Rubinstein '09

B) No pbm if $n < 0$ (statistical anisotropy)

C) No pbm if $n > 0$ but $\alpha_{\text{end}} \ll \alpha_0$ (NG study for a generic A_μ)

Recent works on $\left\langle \zeta \, \vec{B}^2 \right\rangle$ assume problem somehow solved

Caldwell, Motta, Kamiokowski '11; Kumar, Sloth '12; ....

Functional form $f = f_0 \exp\left[- \int \frac{n \, d\phi}{\sqrt{2\epsilon(\phi)} \, M_p} \right]$, $\langle f \rangle \propto a^n$

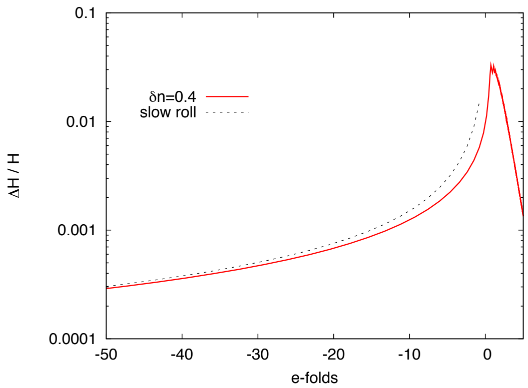
Martin, Yokoyama '07

Anisotropic inflation: Classical background eom solved by $\vec{E}^{(0)}$ with

$$\frac{\Delta H}{H} = \frac{2\rho_{E^{(0)}}}{V(\phi)} \simeq \frac{\delta n \, \epsilon}{4}$$

$$n = -4 - \delta n$$

Watanabe, Kanno, Soda '09



Several models of vector curvaton

Dimopolos, Karciauskas, Lyth, Maeda, Soda, Yamamoto, Yokoyama,...

- Perturbations of anisotropic inflation

Dulaney, Gresham '10;
Gumrukcuoglu, Himmetoglu, MP '10
Watanabe, Kanno, Soda '10

$$P\left(\vec{k}\right) \simeq P\left(k\right)\left[1+g_*\,\cos^2\theta_{\vec{k},\,\vec{E}^{(0)}}\right]$$

$$g_* \simeq -\frac{48}{\epsilon}\,N_{\rm CMB}^2\,\frac{2\rho_{E^{(0)}}}{V\left(\phi\right)}$$

$g_* = 0.1$ for $\frac{\rho_{E^{(0)}}}{V\left(\phi\right)} \simeq 6\cdot 10^{-9}$

$(n = -4 - 10^{-6})$

- In "magnetogenesis" studies $(n=4)$ $\langle A_\mu \rangle = 0$ assumed $\Rightarrow$ $g_* = 0$

- What about electric $\leftrightarrow$ magnetic duality ?
- $g_* = 0.1$ for $\rho_{E^{(0)}} \ll \rho_\phi$. Is this "stable" ?
- $\int \frac{d\rho_B}{dK} \sim H^4\,N_{\rm tot}$. What does this mean ?

After N e – fold of inflation, $\rho = \frac{\langle \vec{V}^2 \rangle}{2} \sim H^4 \, N$

"Random walk" addition of the modes that have left the horizon.

They add up to a classical homogeneous background.

Here, the background is vector that points somewhere in space !

In any realization, CMB modes see a $\vec{V}_{\text{classical}}$ drawn by a statistical distribution of variance $\sim H^4 \, (N_{\text{tot}} - 60)$

Contribution not included, or not associated to a background vector, in previous applications of $f(\phi) \, F^2$

Consequences:

Bartolo, Matarrese, MP, Ricciardone '12

- For any mechanism giving $\vec{V}_k$ on super-horizon scales, expect $\vec{V}_{\rm background}$ with random orientation, and magnitue $\sqrt{\langle \vec{V}^2 \rangle}$

- For $f(\phi)\,F^2$, arranged to produced scale invariant $\vec{B}_k$ or $\vec{E}_k$,

$$|g_*|_{\rm expected} \gtrsim 0.1 \; \frac{N_{\rm tot} - N_{\rm CMB}}{37}$$

(generically, too anisotropic)

- Strict relation between $P_\zeta\left(\vec{k}\right)$ and B_ζ in this mechanism

$$B_\zeta \propto \frac{1 - \cos^2\theta_{\hat{k}_1,\hat{V}} - \cos^2\theta_{\hat{k}_2,\hat{V}} + \cos\theta_{\hat{k}_1,\hat{V}}\cos\theta_{\hat{k}_2,\hat{V}}\cos^2\theta_{\hat{k}_1,\hat{k}_2}}{k_1^3\,k_2^3} \quad , \quad k_1 \ll k_2,\, k_3$$

$$f_{\rm NL}^{\rm eff.local} \simeq 26\,\frac{|g_*|}{0.1}$$

Peaked as local in squeezed limit
nontivial angular dependence

Conclusions

- We are about to detect / improve limits on NG, r, Ω_{GW}, $P\left(\vec{k}\right)$

- Not a guarantee; this motivates theory. Discussed subset of models with $\vec{A}$. Pbm: produce and keep them around

- Natural to use inflaton, $\phi \leftrightarrow F\tilde{F}$, F^2

⇓

- Rich phenomenology from axion inflation; $\sim$ equil. NG; chiral GW

  Gluscevic, Kamionkowski '10;
  Seto, Taruya '07

- NG with nontrivial angular dependence in squeezed limit