Signatures of vector field production during inflation

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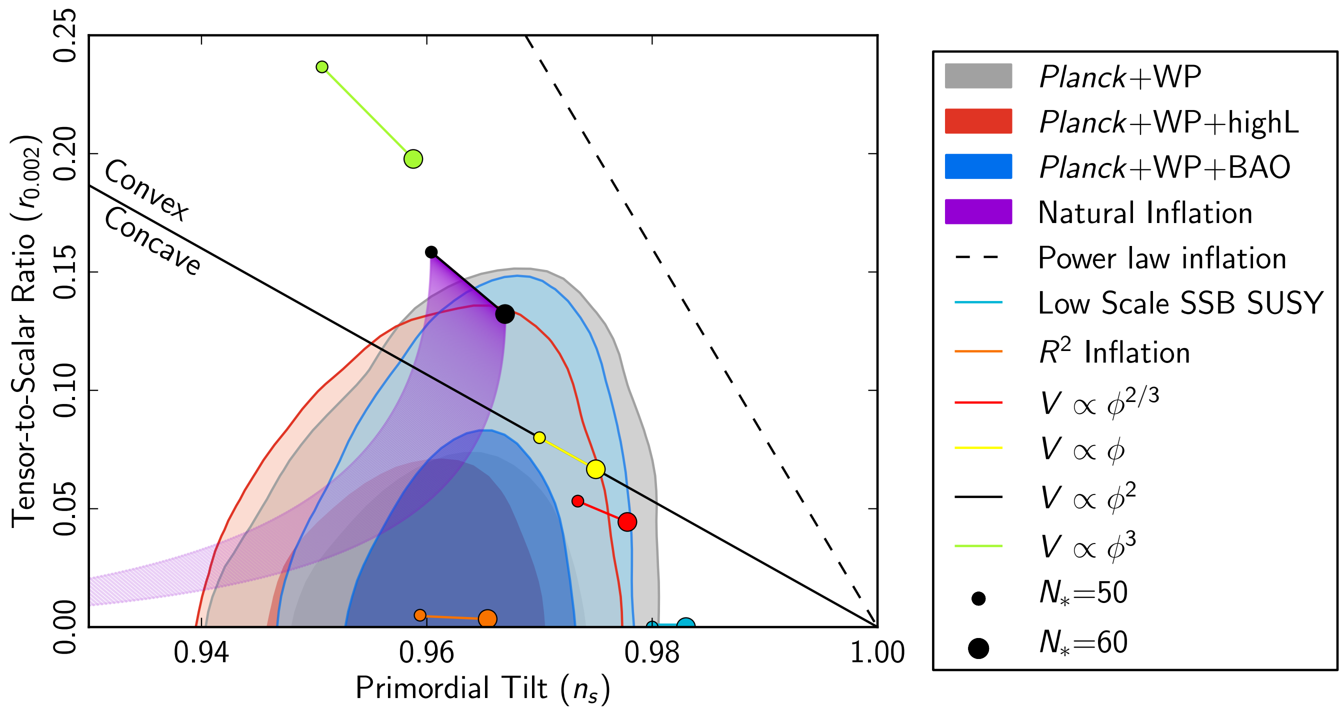
$\phi\, F\, \tilde{F}$	$f\,(\phi)\; F^2$
+ Barnaby, Crowder, Mandic, Moxon, Mukohyama, Namba, Pajer, Shiu, Zhou	+ Barnaby, Bartolo, Komatsu, Matarrese, Namba, Ricciardone, Shiraishi

$\simeq$ scale invariant, adiabatic, $\simeq$ gaussian primordial scalar perturbations;

tensor $\ll$ scalar



Local NG : $\Phi(x) = \Phi_g(x) + f_{\rm NL}^{\rm local}\left[\Phi_g^2(x) - \langle \Phi_g^2 \rangle\right]$

From $\langle T^3 \rangle \neq 0$. Many shapes

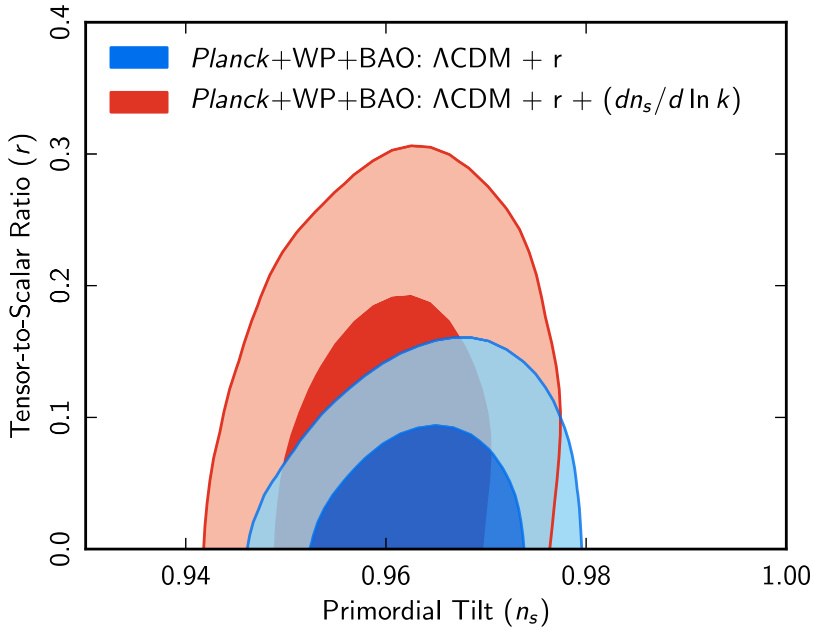
$$f_{\rm NL}^{\rm loc} = 2.7 \pm 5.8$$
$$f_{\rm NL}^{\rm eq} = -42 \pm 75$$
$$f_{\rm NL}^{\rm orth} = -25 \pm 39$$

Agreement with single field slow roll inflation

$$\epsilon \equiv \frac{M_p^2}{2}\left(\frac{V_{,\phi}}{V}\right)^2 \ll 1$$

$$r,\ n_s - 1,\ f_{\rm NL} = O(\epsilon, \eta)$$

$$\eta \equiv M_p^2 \frac{V_{,\phi\phi}}{V} \ll 1$$



Several experiments

with goal $r \lesssim 0.01 - 0.05$:

S: Planck

B: EBEX, PIPER, SPIDER

G: ABS, ACTpol, BICEP2, CLASS
Keck Array, POLAR, PolarBear,
QUBIC, QUIET, QUIJOTE, SPTpol

$$P_\zeta \propto \frac{V}{\epsilon} \quad , \quad P_{\mathrm{GW}} \propto V$$

- Scale of inflation from tensors (GW).

$$V^{1/4} = 10^{16}\,\mathrm{GeV}\left(\frac{r}{0.01}\right)^{1/4}$$

- Larger $r \to$ larger $\epsilon \to$ Inflaton moves more

$$\Delta\phi \gtrsim M_p \left(\frac{r}{0.01}\right)^{1/2}$$

Lyth '96

Flatness is a key requirement

Problem particularly relevant in models that give detectable r.
Flatness must be preserved over the full range $\Delta\phi$ spanned during inflation ($> M_p$ if $r > 0.01$).

For example, $\Delta V = \frac{\lambda}{4}\phi^4 \;\Rightarrow\; \lambda < 10^{-13}$ in large field inflation

$\Rightarrow$ inflaton weakly self coupled (this + weakness of gravitational interactions are the reasons why NG is small)

$\Rightarrow$ In a generic theory, small interactions with other fields to minimize radiative corrections to V

Quantum theory under control through symmetries

Shift symmetry $\phi \to \phi + C$. E.g. axion (natural) inflation

Freese, Frieman, Olinto '90

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi)^2 + V_{\not{\text{shift}}}(\phi) + \frac{C}{f}\,\partial_\mu \phi\, \bar{\psi}\, \gamma^\mu\, \gamma_5\, \psi + \frac{\alpha}{f}\,\phi\, F_{\mu\nu}\, \tilde{F}^{\mu\nu}$$

- Smallness of $V_{\not{\text{shift}}}$ technically natural. $\Delta V \propto V_{\not{\text{shift}}}$
- Constrained couplings to matter (predictivity)

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

$\phi \to AA$ typically controls reheating. Only recently realized that it can play an important role also during inflation.

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

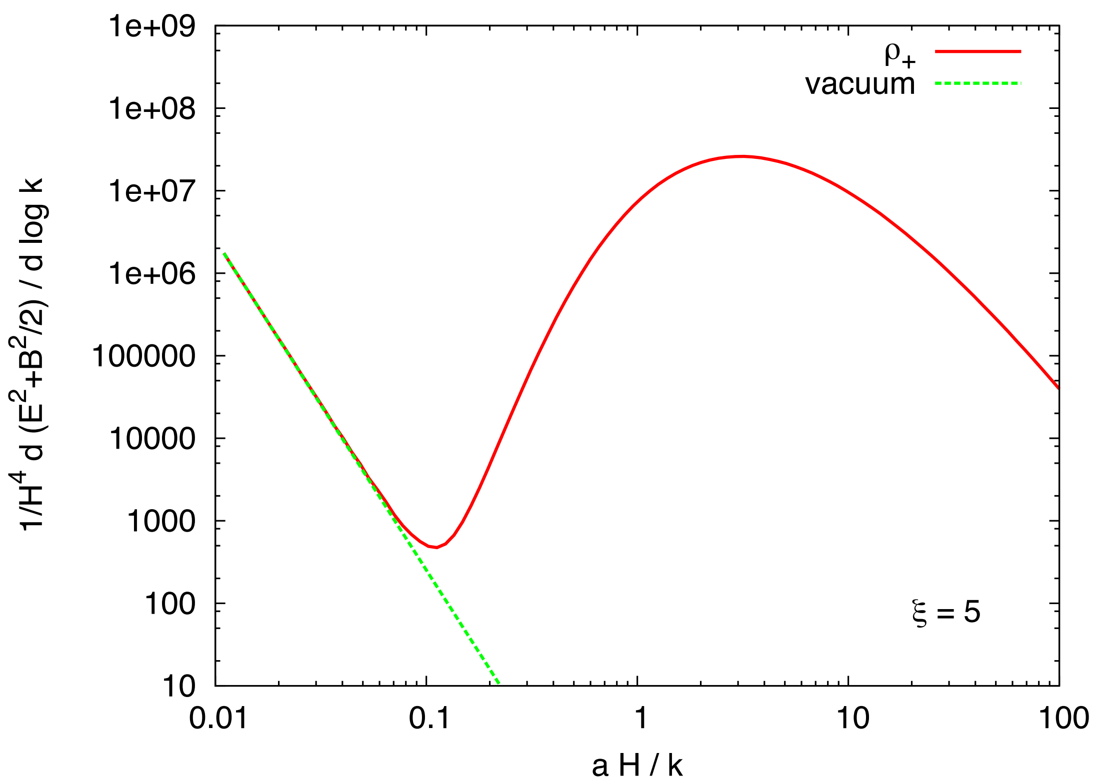
Classical motion $\phi^{(0)}\,(t)$ affects

dispersion relations of $\pm$ helicities

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

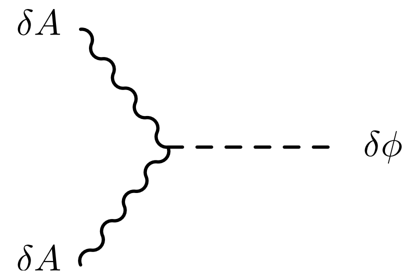
One tachyonic helicity at horizon crossing

Anber, Sorbo '10



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

$$\delta\ddot{\phi} + 3H\delta\dot{\phi} - \frac{\vec{\nabla}^2}{a^2}\delta\phi + m^2\delta\phi = \frac{\alpha}{f}\vec{E}\cdot\vec{B}$$



(Additional interactions due to δg negligible for $\frac{\alpha}{f} \gg \frac{1}{M_p}$)

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

Barnaby, MP '11

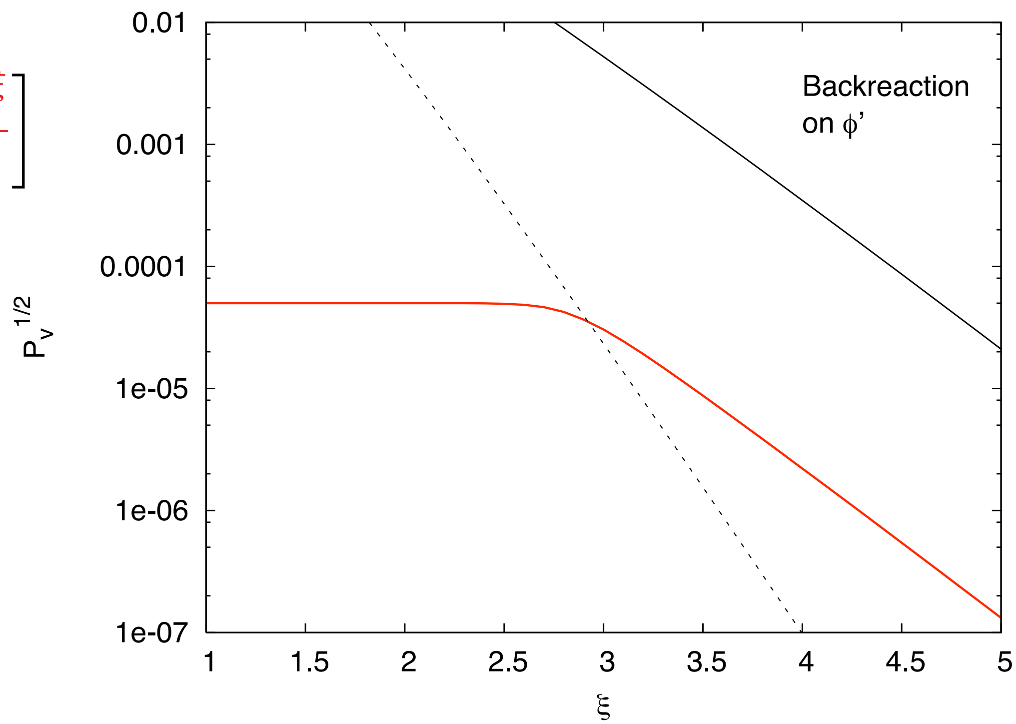
Barnaby, Namba, MP '11

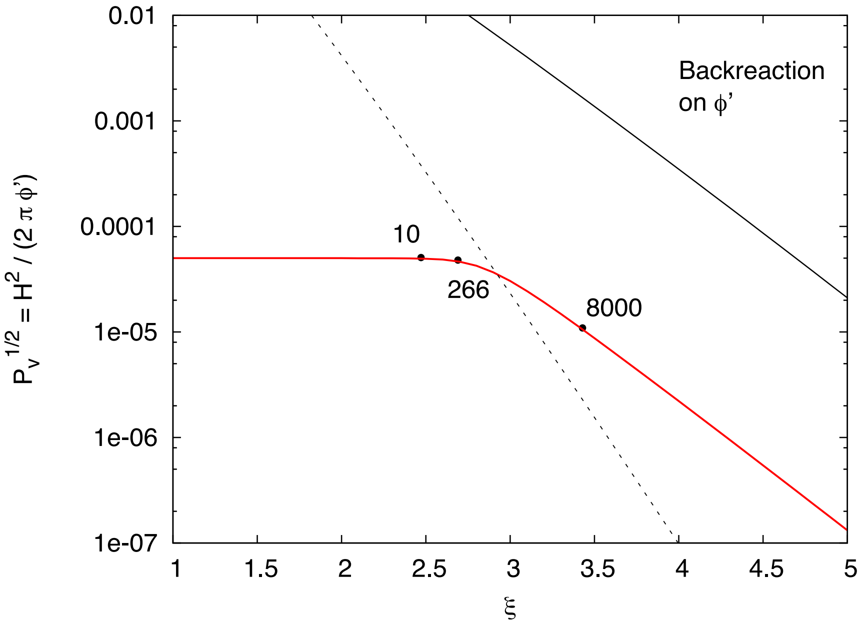
Uncorrelated, $\langle\delta\phi^n\rangle = \langle\delta\phi^n_{\text{vac}}\rangle + \langle\delta\phi^n_{\text{inv.dec}}\rangle$

$$P_\zeta(k) \simeq \mathcal{P}_v \left(\frac{k}{k_0}\right)^{n_s-1}\left[1 + 7.5\cdot 10^{-5}\,\mathcal{P}_v\,\frac{e^{4\pi\xi}}{\xi^6}\right]$$

$$\mathcal{P}_v^{1/2} \equiv \frac{H^2}{2\pi|\dot{\phi}|}$$

$$\xi \equiv \frac{\alpha}{f}\frac{|\dot{\phi}|}{2H}$$





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

⇓

Nearly equilateral NG

$\xi = \mathrm{O}(1)$ for $f/\alpha \lesssim 10^{16}\,\mathrm{GeV}$

- $\delta A \sim \mathrm{e}^{\pi\xi}$ and $\xi \propto \frac{\dot{\phi}}{H}$. Inflaton speeds up during inflation.

$\Rightarrow$ other interesting effects / signatures

For instance, growth of $P_\zeta(k)$

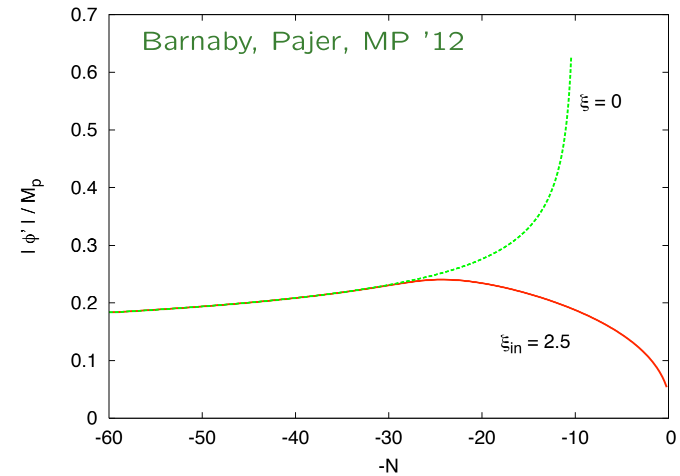
$V \propto \phi^2$	WMAP7 P_ζ	WMAP7 f_{NL}	WMAP7+ACT
flat prior	$\xi_{\mathrm{in}} < 2.66$	$\xi_{\mathrm{in}} < 2.45$	$\xi_{\mathrm{in}} < 2.41$
log prior	$\xi_{\mathrm{in}} < 2.51$	$\xi_{\mathrm{in}} < 2.22$	$\xi_{\mathrm{in}} < 2.15$

Meerburg, Pajer '12

Later stages

(1) Backreaction on background $\phi^{(0)}$

$$\ddot{\phi}^{(0)} + 3\,H\,\dot{\phi}^{(0)} + \frac{dV}{d\phi} = \frac{\alpha}{f}\,\vec{E}\cdot\vec{B}$$

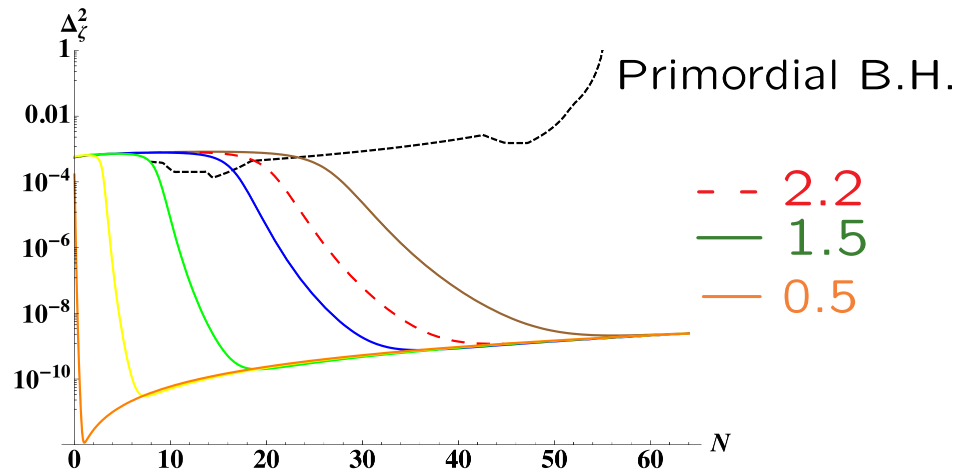


(2) Estimated saturation of P_ζ

Anber, Sorbo '09

Barnaby, Pajer, MP '12

Linde, Mooij, Pajer '12 →



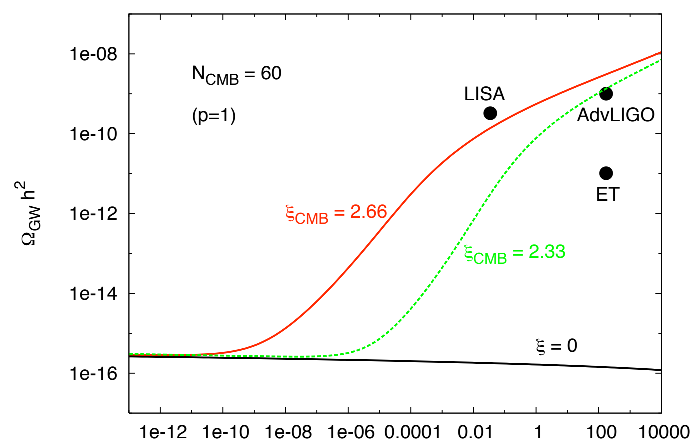
(3) Chiral GW production $A_+ A_+ \to h_L$

Cook, Sorbo '11

Barnaby, Pajer, MP '12

Crowder, Namba, Mandic,

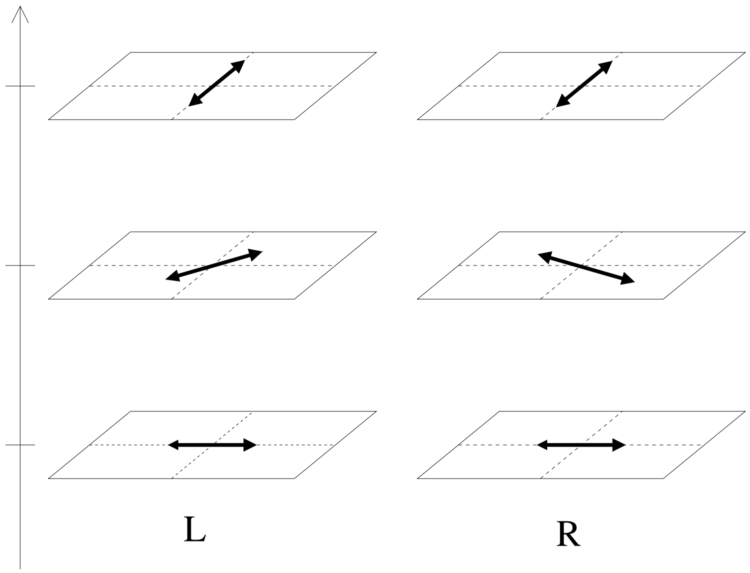
Mukohyama, MP '12



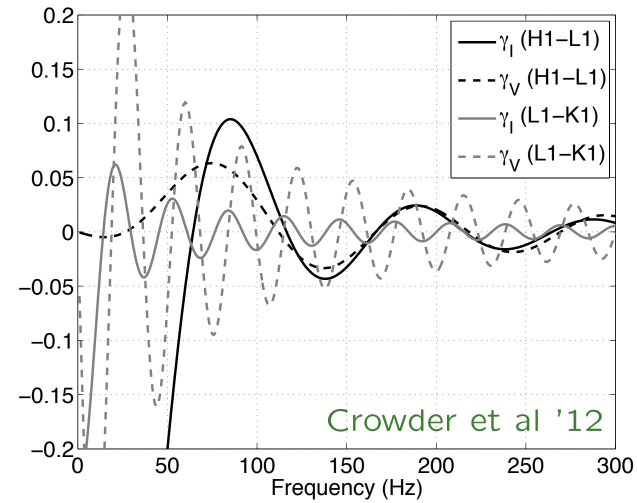
Chiral GW @ interferometers

Seto, Taruya '07

$$\Pi \equiv \frac{P_R - P_L}{P_R + P_L}$$

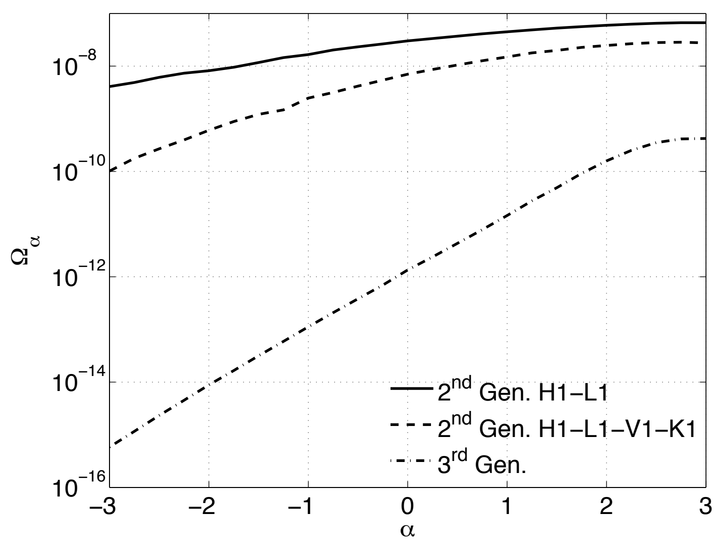


$$\langle s_1 s_2 \rangle \propto \Omega_{GW}(f)\left[\gamma_I(f) + \Pi(f)\,\gamma_\Pi(f)\right]$$



To determine Ω_{GW} and Π need three detectors, or

combine info from $\neq f$ (need to assume $\Pi(f)$)



$$\Omega = \Omega_\alpha \left(\frac{f}{100\,\text{Hz}}\right)^\alpha \;, \quad \Pi = \text{const}$$

Assume $|\Pi| = 1$; forecast to detect GW

and exclude $\Pi = 0$ at 2σ

Axion inflation: $\xi \gtrsim 2$ in 3rd gen.

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

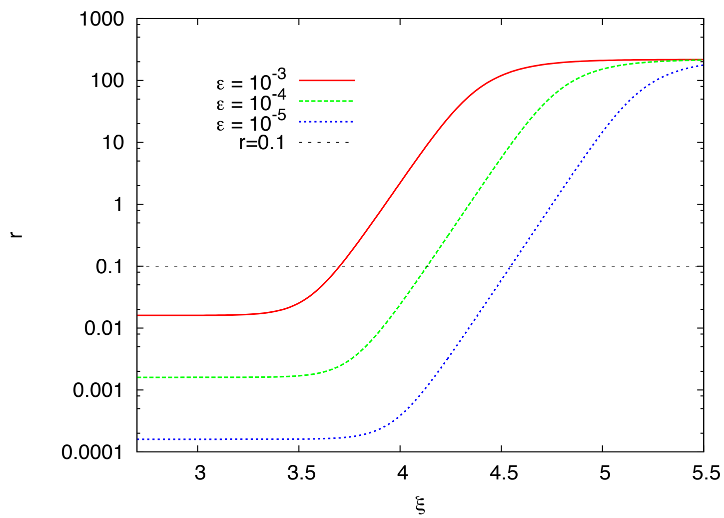
$r \gg 16\epsilon$? See also Sorbo '11; Senatore, Silverstein, Zaldarriaga '11 Carney, Kovetz, Fischler, Lorshbough, Paban '12 Most studied $(\phi - \phi_0)^2 X^2$

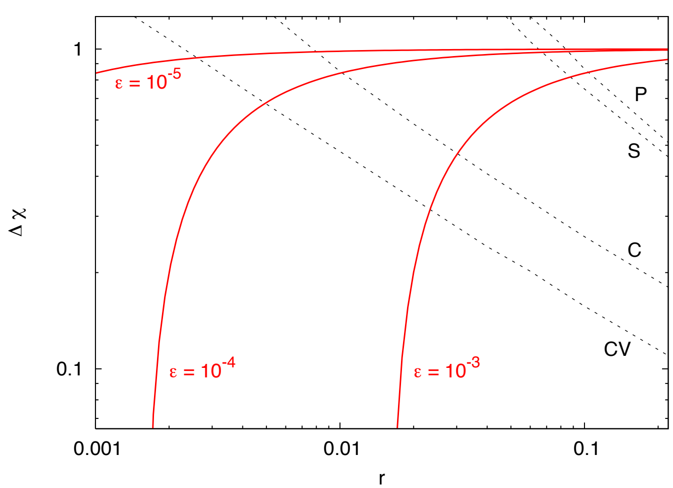
Twofold: (i) $X \to h$ and (ii) $X \not\to \zeta$

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

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

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





1σ forecasts from Gluscevic, Kamionkowski '10

$f(\phi)\,F^2$ 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 $P_\zeta\left(\vec{k}\right) = P(k)\left[1 + g_* \cos^2\theta_{\hat{k}\hat{V}}\right]$:

  $g_* = 0.29 \pm 0.03$ Groeneboom et al '08, 09, but WMAP systematics

  Hanson, Lewis, A. Challinor '10

If primordial, other predictions ? Bispectrum ?

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

In fact, current best bound $|g_*| < 0.05$ from bispectrum

Planck '13

$$-\frac{f}{4}F^2 \quad \Rightarrow$$

scale invariant $\vec{B}$ for $f \propto a^4, a^{-6}$

scale invariant $\vec{E}$ for $f \propto a^{-4}, a^6$

Electric $\leftrightarrow$ magnetic duality

for $\langle f \rangle \leftrightarrow \frac{1}{\langle f \rangle}$

Ratra '92

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

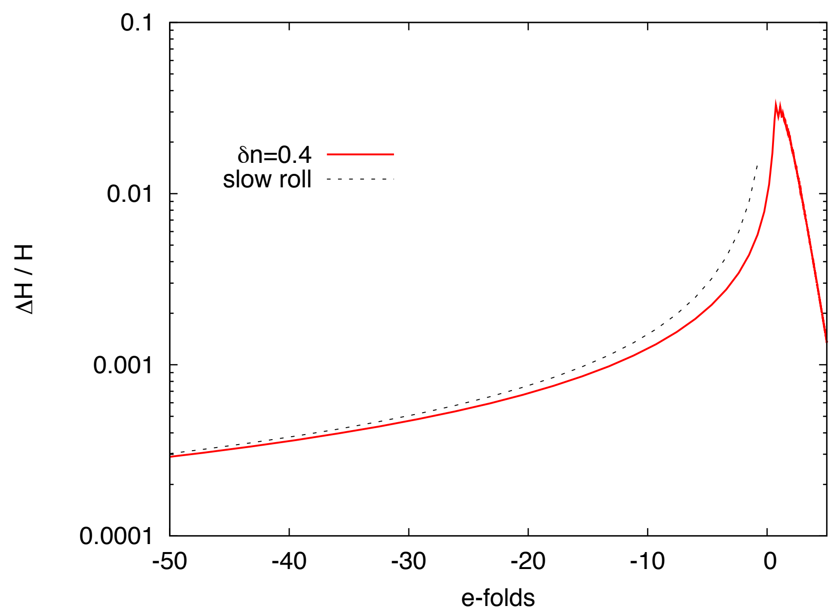
Martin, Yokoyama '07

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,...

$-\frac{f}{4} F^2 \quad \Rightarrow$ scale invariant $\vec{B}$ for $f \propto a^4$, ~~a^{-6}~~

scale invariant $\vec{E}$ for $f \propto a^{-4}$, ~~a^{6}~~

Electric $\leftrightarrow$ magnetic duality

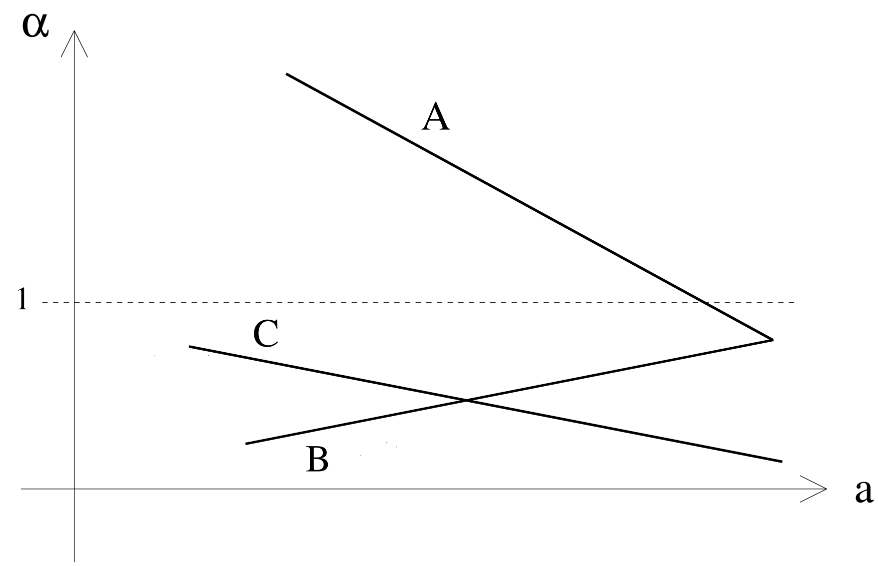
for $\langle f \rangle \; \leftrightarrow \; \frac{1}{\langle f \rangle}$

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

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

Demozzi, Mukhanov, Rubinstein '09

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



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

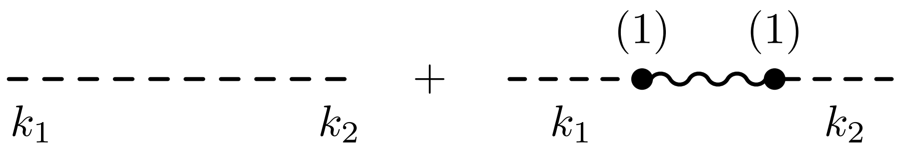
Demozzi et al '09

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

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

Perturbations with $\vec{E}^{(0)} \neq 0$

Expanding $f(\phi)\,F^2$, $\mathcal{L}_{\text{int}} \supset a^4 \left[4\vec{E}^{(0)} \cdot \delta\vec{E}\,\zeta + 2\delta\vec{E} \cdot \delta\vec{E}\,\zeta\right]$



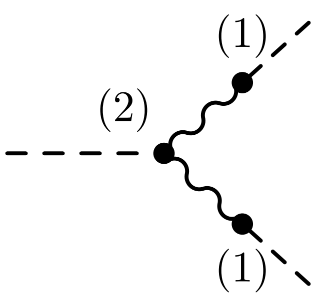
Dulaney, Gresham '10;
Gumrukcuoglu, Himmetoglu, MP '10
Watanabe, Kanno, Soda '10

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

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

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

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



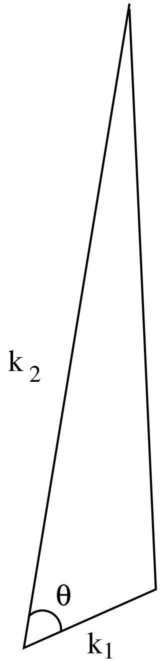
Strict relation between $P_\zeta\left(\vec{k}\right)$ and B_ζ

$$B_\zeta \to \frac{\mathrm{O}(1)}{k_1^3 k_2^3} \quad , \quad k_1 \ll k_2, k_3$$

$$f_{\text{NL}}^{\text{eff.local}} \simeq 24\,\frac{|g_*|}{0.1}$$

Bartolo, Matarrese,
MP, Ricciardone '12

$$B_\zeta \propto \frac{1 - \cos^2\theta_{\hat{k}_1,\,\hat{E}^{(0)}} - \cos^2\theta_{\hat{k}_2,\,\hat{E}^{(0)}} + \cos\theta_{\hat{k}_1,\,\hat{E}^{(0)}}\cos\theta_{\hat{k}_2,\,\hat{E}^{(0)}}\cos^2\theta_{\hat{k}_1,\,\hat{k}_2}}{k_1^3\,k_2^3} \quad , \quad k_1 \ll k_2,\, k_3$$



Peaked as local in squeezed limit

Nontivial angular dependence

$$B_\zeta\Big|_{\text{isotropic measurement}} \propto \frac{1+\cos^2\theta_{\hat{k}_1,\,\hat{k}_2}}{k_1^3\,k_2^3}$$

Motivation for studying

$$B_\zeta(k_1,k_2,k_3) = \sum_L c_L P_L(\hat{\mathbf{k}}_1\cdot\hat{\mathbf{k}}_2) P_\zeta(k_1) P_\zeta(k_2) + (2\text{ perm})$$

Shiraishi, Komatsu, MP, Barnaby, '13

The fF^2 model gives $c_0 = \frac{6}{5} f_{\rm NL} \simeq 32\,\frac{|g_*|}{0.1} \;,\; c_2 = \frac{c_0}{2}$

$$B_\zeta(k_1,k_2,k_3) = \sum_L c_L P_L(\hat{\mathbf{k}}_1 \cdot \hat{\mathbf{k}}_2) P_\zeta(k_1) P_\zeta(k_2) + (2 \text{ perm})$$

$$c_0 = \frac{6}{5} f_{\rm NL}$$

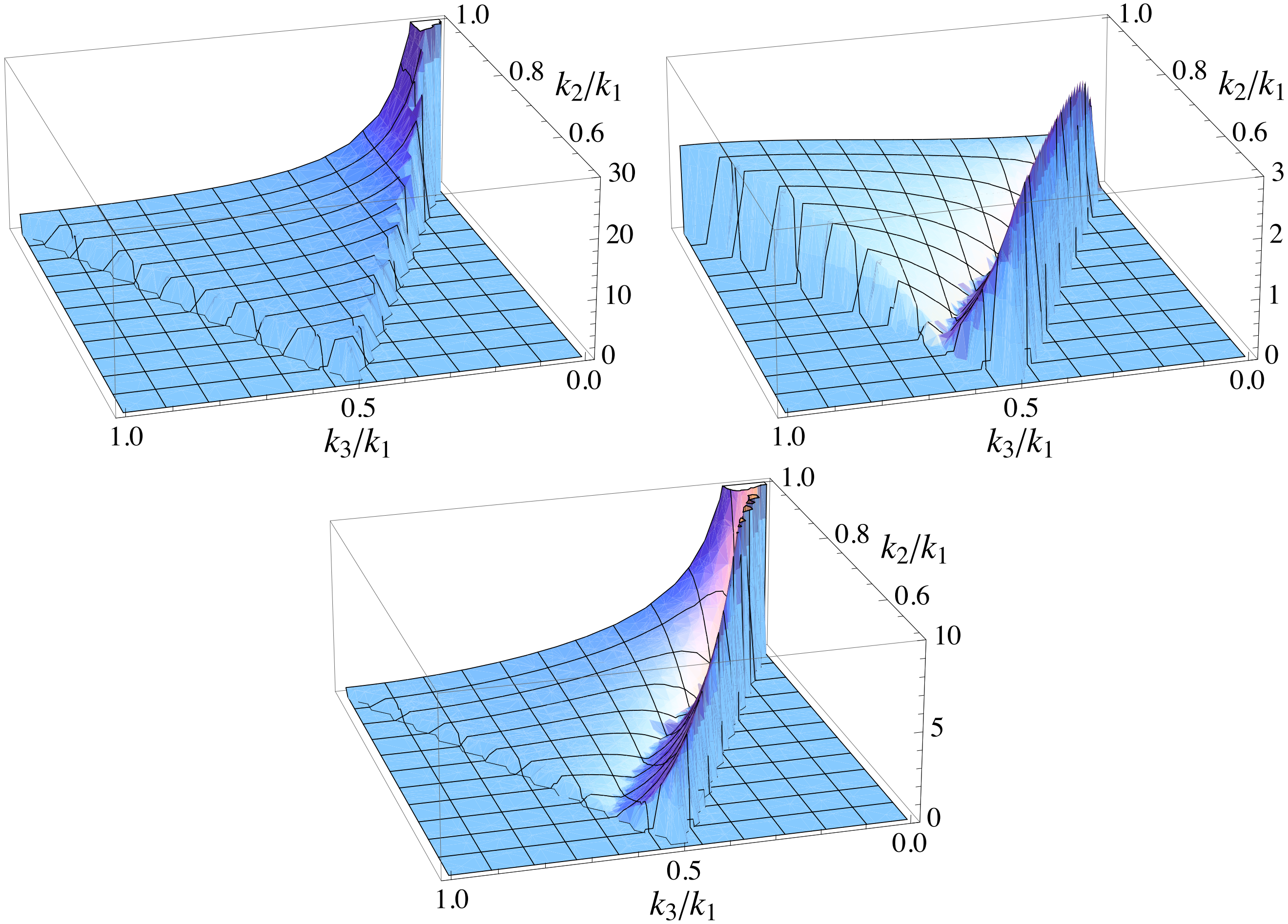


Figure 1. Absolute values of the shape function of $L = 0$, $(k_1k_2k_3)^2 S_0$ (top left panel), that of $L = 1$, $(k_1k_2k_3)^2 S_1$ (top right panel), and that of $L = 2$, $(k_1k_2k_3)^2 S_2$ (bottom panel). We restrict the plot range to $k_3 \le k_2 \le k_1$ and $|k_1 - k_2| \le k_3 \le k_1 + k_2$ for symmetry and the triangular condition. The

Full sky

CV-limited up to $\ell_{\rm max} = 2000$:

$\delta c_0 = 4.4$, $\delta c_1 = 61$,

$\delta c_2 = 13$ (68%CL)

Planck

$c_0 = 3.2 \pm 7$

$c_1 = 11 \pm 113$

$c_2 = 3.8 \pm 27.8$

(68%CL)

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

- However, theoretically expected value, from the addition of the IR modes that left the horizon during the first $N_{\rm tot} - N_{\rm CMB}$ e-folds

$$\rho = \frac{\left\langle \vec{E}^2 \right\rangle}{2} \sim H^4 \left(N_{\rm tot} - 60 \right)$$

The sum is a vector that points somewhere in space, breaking isotropy

$$|g_*|_{\rm expected} \gtrsim 0.1 \; \frac{N_{\rm tot} - N_{\rm CMB}}{37} \qquad \text{(generically, too anisotropic)}$$

- If this model is realized in nature, either $N_{\rm tot} \simeq 60$, or we live in a patch in which $\vec{E}^{(0)}$, or $\vec{B}^{(0)}$, is $\ll$ that the expected value.

Conclusions

- Axion inflation well motivated model (V protected)
- Only recently, seen that $\frac{\alpha}{f}\phi F\tilde{F}$, with $f = \mathrm{O}\left(10^{-2}M_p\right)$ leads to interesting phenomenology:

  $\simeq$ equilateral NG; chiral GW; primordial b.h.

- $f\left(\phi\right)F^2$ for magnetogenesis (difficult) and anisotropic inflation
- Novel NG shape, constrained by Planck
- Typically, (too) large statistical anisotropy