Characteristic Signatures of Vector Fields during Inflation

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N. Barnaby, RN & M. Peloso, Phys. Rev. D **85**, 123523 (2012) [arXiv:1202.1469].
RN, [arXiv:1207.5547].

Outline

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1. Introduction
2. Nearly Local Non-gaussianity from Dilaton-like Kinetic Coupling
3. Statistical Anisotropy from Massive Vector Curvaton
4. Conclusion and Future Prospects

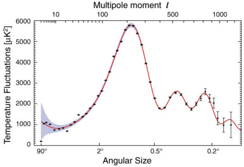
Inflation — era of accelerated expansion in the very early universe

horizon

monopole flatness

$\Updownarrow$

$\phi(t)$



$\Updownarrow$

$\delta\varphi$

- simple realization: single scalar field

$$\mathcal{L} = -\frac{1}{2}(\partial\varphi)^2 - V(\varphi) \;, \quad \epsilon \equiv \frac{M_p^2}{2}\left(\frac{V_\varphi}{V}\right)^2 \ll 1 \;, \quad |\eta| \equiv M_p^2 \left|\frac{V_{\varphi\varphi}}{V}\right| \ll 1$$

$$P_\zeta \cong \mathcal{A}_\zeta \left(k/k_0\right)^{n_s - 1} \gg P_{\rm GW}$$

$$\mathcal{A}_\zeta \cong \frac{V}{24\pi^2 \epsilon M_p^4} \cong 25 \cdot 10^{-10}$$

$$n_s \cong 1 - 6\epsilon + 2\eta \cong 0.963 \pm 0.014$$

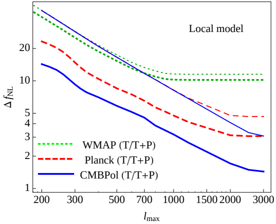
$\Leftrightarrow$

- already consistent with CMB, LSS
- many (nearly) degenerate predictions

- However, large experimental work to search for finer effects
  - *non-gaussianity*, *statistical anisotropy*, gravity waves, . . .

Non-gaussianity ⇔ Interactions

- Claimed: $f_{NL}^{\rm local} = 48 \pm 20 \; (1\sigma)$ Xia, Baccigalupi, Matarrese, Verde & Viel ’11
- Planck forecast – $f_{NL}^{\rm local} \sim 5 - 10$



Liguori, Sefusatti, Fergusson & Shellard ’10

- Simplest models → unobservable NG: $f_{NL}^{\rm local} \sim \mathcal{O}\left(10^{-2}\right)$

Statistical anisotropy ⇔ Broken rotational invariance

- Claimed: $g_* = 0.29 \pm 0.031$ Groeneboom, Ackerman, Wehus & Eriksen ’09
- This apparent broken stat. isotropy is most likely systematic.
- Planck will probe $g_* \sim \mathcal{O}\left(10^{-2}\right)$ Pullen & Kamionkowski ’07

Vector fields can

- source a very distinctive non-gaussianity
- break rotational invariance → give stat. anisotropy

In this talk,

Dilatonic Coupling

$$\mathcal{L}_{\rm int} = -\frac{I^2(\varphi)}{4} F^2$$

- U(1) gauge field
- approximate local NG
- quadrupolar sign. of spin 1 origin

Barnaby , RN & Peloso '12

Massive Vector Curvaton

$$\mathcal{L}_{\rm curv} = -\frac{f(\varphi)}{4} F^2 - \frac{1}{2} m^2(\varphi) A^2$$

- no gauge symmetry
- statistically isotropic spectrum ?
- independent of forms of f & m ?

RN '12

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- Inflaton needs to couple to “matter” to some extent for reheating.
- Indications of large-scale magnetic field
  - Galactic scale ($\sim$ 10 kpc): $\sim 10^{-6}$ G
  - Inter-galactic scale ($\sim$ Mpc): $\gtrsim 10^{-17}$ G   Taylor, Vovk & Neronov ’11
- Standard EM photon *conformally* couples to FRW metric

$$\sqrt{-g}\,\mathcal{L}_{\rm em} = -\frac{1}{4}\sqrt{-g}\,F_{\mu\nu}F^{\mu\nu} \implies \vec{A}'' + k^2\vec{A} = 0$$

  - “Standard” photons are not produced in the expanding universe

$\longrightarrow$ need to break conformal invariance

- Non-minimal coupling: $\mathcal{L} = -\frac{1}{4}F^2 + \frac{\xi}{2}RA^2$ Turner & Widrow ’88
  - $\vec{A}'' + \left(k^2 - 6\xi\frac{a''}{a}\right)\vec{A} = 0 \longrightarrow \vec{B}$ field as large as 10^{-6} G $\sim$ galaxy scale
  - However, the longitudinal mode becomes *ghost* → *theory unstable*

Himmetoglu, Contaldi & Peloso ’08

$\longrightarrow$ better preserve gauge invariance

Break conformal, preserve gauge invariance

$$\mathcal{L} = -\frac{I^2(t)}{4} F^2 \,, \qquad I \propto a^n$$

Ratra '91

- Large-scale $\vec{B}$ field ⇔ scale-inv. $\vec{B}$ spectra preferable $\Longrightarrow$ $n = -3, 2$
- $n = -3$ leads to $\rho_{\text{gauge}} \gg \rho_{\text{inflaton}}$
  - Inflation still continues, but too small $\vec{B}$ field. Kanno, Soda & Watanabe '09
- Let's take $\boxed{n = 2}$

"Magnetic" & "electric" spectra:

$$\frac{d}{d \ln k} \langle \vec{B}^2 \rangle \sim H^4 \quad \gg \quad \frac{d}{d \ln k} \langle \vec{E}^2 \rangle \sim H^4 \left(\frac{k}{aH} \right)^2 \,, \qquad \text{after hor. cross.}$$

In FT,

External function	⇔	Vacuum condensate of field(s)
$I(t)$	⇔	$I\,[\phi(t)]$
		$\hookrightarrow$ inflaton

Model of Dilatonic Coupling

$$S = \int d^4x\sqrt{-g}\left[-\frac{1}{2}\partial_\mu\varphi\partial^\mu\varphi - V(\varphi) - \frac{I^2(\varphi)}{4}F_{\mu\nu}F^{\mu\nu}\right]$$

Effective “charge”: $e_{\rm eff} = e_0 / I\left[\phi(t)\right]$

No vector VEV

Isotropic bckgnd

$\varphi(x) = \phi(t) + \delta\varphi(x)$

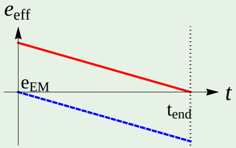
Time dependence dynamically achieved

$$V = \mu^{4-r}\varphi^r \,, \qquad I = I_{\rm end}\exp\left(-\frac{n\,\varphi^2}{2\,r\,M_p^2}\right) \,, \qquad n = 2$$

However . . .

$e_{\rm eff} \propto I^{-1} \propto a^{-2} \Longrightarrow e_{\rm end} \le {\rm e}^{120} e_{\rm in}$

Demozzi, Mukhanov
& Rubinstein ’09



1. $e_{\rm eff} = e_{\rm em}$ at the end ⇒ Strong coupling
2. $e_{\rm eff} \lesssim \mathcal{O}(1)$ initially ⇒ $A_\mu \neq$ photon

- Backreaction limit: $\rho_{\rm inf}^{1/4} \lesssim 2.5 \cdot 10^{-7} M_p \left(\frac{10^{-15}\,G}{B_{\rm obs}}\right)^2$ Fujita & Mukohyama '12
- Give up magnetogenesis application (and take $e_{\rm in} \lesssim 1 \;\Leftrightarrow\; A_\mu \neq$ photon)
- Other signatures ? $\quad\Longrightarrow\quad$ distinctive non-gaussianity !
- Perturbing φ inevitably introduces $\delta\varphi - A_\mu$ direct coupling

$$\begin{tikzcd}
\dot\phi \arrow[r, "\text{continuous production}"'] & A_\mu \arrow[r, "\text{continuous sourcing}"'] & \delta\varphi \arrow[r, "\text{curvature}"'] & \zeta
\end{tikzcd}$$

- Sourcing effect on GW $\sim$ negligible

Gauge Field Production

$$V_\lambda'' + \left(k^2 - \frac{I''}{I}\right) V_\lambda = 0 \,, \qquad A_i = \int \frac{d^3k}{(2\pi)^{3/2}}\, e^{i\vec{k}\cdot\vec{x}} \epsilon_i^\lambda(\hat{k}) \frac{V_\lambda}{I}$$

Outside horizon $\boxed{\rho_{\rm gauge} \simeq \frac{\langle \vec{B}^2 \rangle}{2} \sim H^4 \ln \frac{a}{a_{\rm in}}} \ll \rho_{\rm inflaton}$

Produced gauge quanta source $\delta\varphi$

$$\left[\partial_\tau^2 + 2\frac{a'}{a}\partial_\tau - \nabla^2 + a^2 V_{\varphi\varphi}\right]\delta\varphi = \underbrace{\frac{a^2}{2}\frac{I_\varphi^2}{I^2}\left(\vec{E}^2 - \vec{B}^2\right)}_{\equiv J_\varphi} + \ldots$$

Solution consists of 2 *uncorrelated* parts:

$$\delta\varphi = \underbrace{\delta\varphi_{\rm vac}}_{\text{homogeneous}} + \underbrace{\delta\varphi_{\rm sourced}}_{\text{particular}}$$

- $\delta\varphi_{\rm vac} \sim H/(2\pi) \to$ standard vacuum solution
- $\delta\varphi_{\rm sourced}(\tau, \vec{k}) = \int^\tau d\tau' \underbrace{G_k(\tau, \tau')}_{\substack{\text{constructed}\\ \text{from } \delta\varphi_{\rm vac}}} \underbrace{J_\varphi(\tau', \vec{k})}_{\text{operator}}$ in Fourier space

$\delta\varphi_{\rm sourced} \propto (A_\mu)^2 \implies$ *highly NG !*

- Two-point correlator

$$\left\langle \delta\varphi(\vec{k}_1)\delta\varphi(\vec{k}_2)\right\rangle = \left\langle \delta\varphi_{\rm vac}(\vec{k}_1)\delta\varphi_{\rm vac}(\vec{k}_2)\right\rangle + \left\langle \delta\varphi_{\rm sourced}(\vec{k}_1)\delta\varphi_{\rm sourced}(\vec{k}_2)\right\rangle$$

$$\left\langle \delta\varphi_{\rm sourced}(\vec{k}_1)\delta\varphi_{\rm sourced}(\vec{k}_2)\right\rangle = \int^\tau d\tau_1 d\tau_2\, G_{k_1}(\tau,\tau_1)G_{k_2}(\tau,\tau_2)\langle J_\varphi(\tau_1,\vec{k}_1)J_\varphi(\tau_2,\vec{k}_2)\rangle$$

  - Two pieces are uncorrelated $\langle\delta\varphi_{\rm vac}\delta\varphi_{\rm sourced}\rangle = 0$.
- Three-point correlator

$$\left\langle \delta\varphi(\vec{k}_1)\delta\varphi(\vec{k}_2)\delta\varphi(\vec{k}_3)\right\rangle \simeq \left\langle \delta\varphi_{\rm sourced}(\vec{k}_1)\delta\varphi_{\rm sourced}(\vec{k}_2)\delta\varphi_{\rm sourced}(\vec{k}_3)\right\rangle \sim \left\langle J_\varphi^3\right\rangle$$

  - Contribution from vacuum is undetectable.

$$\boxed{\text{Curvature perturbation : } \quad \zeta = -\frac{H}{\dot\phi}\,\delta\varphi}$$

- Power spectrum: $P_\zeta = P_{\rm vac} + P_{\rm sourced} \sim \left\langle\delta\varphi_{\rm vac}^2\right\rangle + \left\langle\delta\varphi_{\rm sourced}^2\right\rangle$

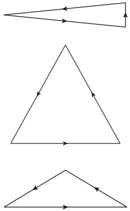
  Vacuum term dominates → $P_{\rm vac} > P_{\rm sourced}$ → $N_{\rm tot} - N_{\rm CMB} < 580\left(\frac{60}{N_{\rm CMB}}\right)^2$

Bispectrum

$$B_\zeta\left(k_1,k_2,k_3\right)\;\delta^{(3)}\left(\vec{k}_1+\vec{k}_2+\vec{k}_3\right)=\left\langle\zeta_{\vec{k}_1}\zeta_{\vec{k}_2}\zeta_{\vec{k}_3}\right\rangle\simeq\left(-\frac{H}{\dot{\phi}}\right)^3\left\langle\delta\varphi^3_{\text{sourced}}\right\rangle$$

$$\vec{k}_1+\vec{k}_2+\vec{k}_3=0\rightarrow\text{forms a triangle}$$

Features in $B_\zeta\left(k_1,k_2,k_3\right)$



1. Shape: relative shape of the triangle
   - squeezed, equilateral, flattened
2. Amplitude: magnitude at a given shape ⇔ $f_{NL}\sim\frac{B_\zeta}{P_\zeta^2}$
3. Running: dependence on the overall size of the triangle

$*$ f_{NL}: deviation from Gaussian statistics

Komatsu & Spergel '00

$$\text{Local ansatz}:\quad\Phi=\Phi_g+f_{NL}\left(\Phi_g^2-\left\langle\Phi_g^2\right\rangle\right)\;,\qquad\zeta\sim\Phi$$

$-10<f_{NL}^{\text{local}}<74$, $-214<f_{NL}^{\text{equil}}<266$, $-410<f_{NL}^{\text{orth}}<6$ 95% CL WMAP7

Results

Bispectrum

$$B_\zeta \propto \frac{1+\cos^2\left(\hat{k}_1,\hat{k}_2\right)}{k_1^3 k_2^3} + (2\text{ permutations}) \quad \Longleftrightarrow \quad \text{nearly local}$$

$$f_{NL}^{\text{equiv. local}} \simeq 0.7 \left(\frac{N_{\text{CMB}}}{60}\right)^3 \left(N_{\text{tot}} - N_{\text{CMB}}\right) \sim \mathcal{O}\left(1-10\right)$$

cosine dependence :

$$1+\cos^2\left(\hat{k}_1,\hat{k}_2\right) \propto \underset{\substack{\nearrow \\ \textit{monopolar}}}{Y_0^0} + \epsilon\, \underset{\substack{\nwarrow \\ \textit{quadrupolar}}}{Y_2^0}\,, \qquad \epsilon \simeq 0.22$$

1. Scalar field case: higher multipole ⇔ gradient
   $\Longrightarrow$ orientation of $\vec{k}_{\text{small}}$ seen by $\vec{k}_{\text{large}}$ when crossing horizon
   $\Longrightarrow$ suppressed higher multipole Lewis '11
2. Gauge field case: angular dependence ⇔ polarization operator
   $\Longrightarrow$ non-vanishing for $k_{\text{small}} \to 0$

Non-vanishing in squeezed limit ($k_1 \ll k_2 \approx k_3$) $\Longrightarrow$ *signature of higher spin !*

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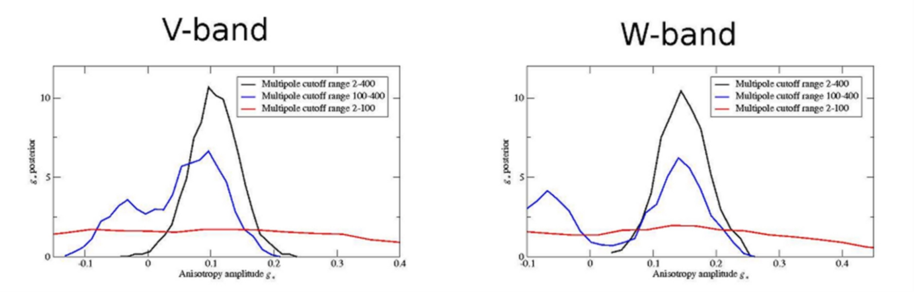
Statistical anisotropy

ACW parametrization : $P_\zeta = P_{\rm iso}\left[1 + g_* \left(\hat{n}\cdot\hat{k}\right)^2\right]$

Assumed: 2D symmetry & parity



$g_* = 0.10 \pm 0.04$

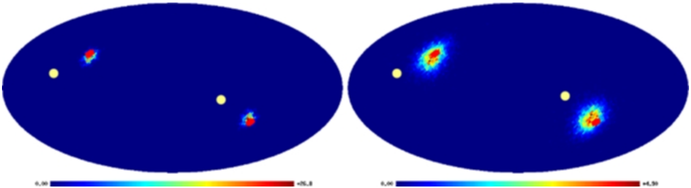
$g_* = 0.15 \pm 0.04$

Groeneboom & Eriksen 2008

Increase of significance with ℓ

Pullen & Kamionkowski 2007

Missing factor corrected by Hanson & Lewis ’09, Groeneboom et al ’09



Band	ℓ range	Mask	Amplitude g_*	Direction (l, b)
W1-4	$2-400$	KQ85	0.29 ± 0.031	$(94^\circ, 26^\circ) \pm 4^\circ$
V1-2	$2-400$	KQ85	0.14 ± 0.034	$(97^\circ, 27^\circ) \pm 9^\circ$
Q1-2	$2-300$	KQ85	-0.18 ± 0.040	$(99^\circ, 28^\circ) \pm 10^\circ$

Groeneboom, Ackerman, Wehus & Eriksen ’09

Note: The values for g_* indicate posterior mean and standard deviation.
The ecliptic poles are located at $\pm(96^\circ, 30^\circ)$.

- g_* cosmological or systematic ? – most likely systematic
  - near alignment with ecliptic poles
  - maybe from asymmetric beams ? Hanson & Lewis ’09
- Planck will probe $g_* \sim \mathcal{O}\left(10^{-2}\right)$

$$\left.\begin{array}{c}\text{Anisotropic inflation}\\ \text{Vector curvaton}\end{array}\right\} \longrightarrow g_*$$

- Rapid isotropization for Bianchi spaces with $\Lambda + T_{\mu\nu}$ satisfying the dominant and strong energy conditions Wald '83
- Counterexamples – breaking the premises of above theorem
  1. Kalb-Ramond axion (Kaloper '91)
  2. higher curvature terms (Barrow & Hervik '05)
  3. Non-minimal vector fields
     - ★ Potential term: $V\left(A^2\right)$ Ford '89
     - ★ Fixed norm: $\lambda\left(A^2 - v^2\right)$ ACW '07
     - ★ Non-minimal coupling: $R\,A^2$ Golovnev, Mukhanov & Vanchurin '08

$\Downarrow$

All these suffer ghost instabilities Himmetoglu, Contaldi & Peloso '08

- Prolonged anisotropy: $f^2\,F^2$ with suitable f Watanabe, Kanno & Soda '09

Vector Curvaton

Vector curvaton: $\mathcal{L} = -\frac{f(t)}{4} F^2 - \frac{1}{2} m^2(t) A^2$ Dimopoulos, Karciauskas & Wagstaff '09

- No ghosts for $f, m^2 > 0$
- Scale-inv. & stat. isotropic spectrum in curvaton mechanism *if*
  - $f \propto a^{-4}$, $m \propto a$
  - Vector is light initially & heavy at the end of inflation
  - Equipartition between initial vector kinetic & potential energy

under the simplifying assumptions of ...

- External functions $f(t)$ & $m(t)$
- Isotropic de Sitter background

However ... RN '12

- Time dependence $\Leftrightarrow$ vacuum condensate of some field
- Min. implementation: $f(t), m(t) \rightarrow f(\varphi), m(\varphi)$
  - φ: inflaton $\leftrightarrow$ physical clock
- f, m nontrivial evolution $\rightarrow$ field cannot be integrated out (i.e. its fluctuations cannot be ignored)

Model of Massive Vector Curvaton

Dimopoulos, Karciauskas & Wagstaff '09
RN '12

$$S = \int d^4x\sqrt{-g}\left[-\frac{1}{2}\partial_\mu\varphi\,\partial^\mu\varphi - V(\varphi) - \frac{f(\varphi)}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}m^2(\varphi)A_\mu A^\mu\right]$$

inflaton sector ↗ ↖ vector curvaton sector

VEV: $A_\mu^{(0)} = (0, A, 0, 0)$ − background orientation
Perturbation: δA_μ − *no gauge freedom*

Only δA_μ in Dimopoulos, Karciauskas & Wagstaff '09, here also $\delta\varphi$ included

1. $\phi(t) \rightarrow$ Expansion mostly driven by $V[\phi(t)]$
2. $A_\mu^{(0)}(t) \rightarrow$ breaks the background isotropy

$$ds^2 = -dt^2 + a^2(t)\,dx^2 + b^2(t)\left(dy^2 + dz^2\right), \quad a = e^{\alpha-2\sigma}, \quad b = e^{\alpha+\sigma}$$

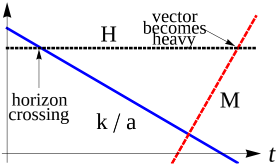
3. Suitable choice dynamically achieves $f \propto a^{-4}$, $m \propto a$ by $\phi(t)$ motion

$$V(\varphi) = \frac{1}{2}m_\varphi^2\varphi^2 \implies f(\varphi) = \exp\left(\frac{c\,\varphi^2}{M_p^2}\right), \quad m(\varphi) = m_0\exp\left(-\frac{c\,\varphi^2}{4M_p^2}\right)$$

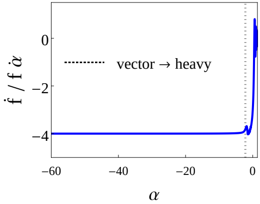
$\longrightarrow$ inevitably introduces $\delta\varphi - \delta A_\mu$ interaction *at linearized level*

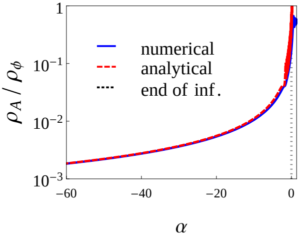
Background Dynamics & Attractor

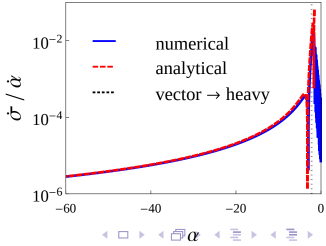
- Three physical scales:
  1. Physical momentum: k/a
  2. “Overall” Hubble parameter: $H \equiv \dot{\alpha}$
  3. “Physical” vector mass: $M \equiv m/\sqrt{f}$



- Attractor solution − valid for $c > 1$
  - achieves the desired $f \propto a^{-4}$ and $m \propto a$
  - fixes $\dot{\phi}$, ρ_A/ρ_ϕ, $\dot{\sigma}/\dot{\alpha} = \Delta H/H$







Perturbations

- Residual 2D symmetry → $\vec{k} = (k_L, k_T, 0)$
- d.o.f: $\delta A_\mu + \delta\varphi + (\text{no } \ \delta g_{\mu\nu}) = \text{total } \ 5 \ \text{ d.o.f}$
- 2D vector: $\delta A_z \quad \longrightarrow$ no contribution to ζ at linearized level

  $\updownarrow$ decoupled

  2D scalar: $\delta A_0 + \boxed{\delta A_x + \delta A_y + \delta\varphi} - (\text{non } \ \text{dynamical } \ \delta A_0) = 3 \ \text{ d.o.f}$

Quantization – in matrix form

1. Diagonalize Hamiltonian: $\hat{\psi}_i = \mathcal{R}_{ij} \, \hat{\delta}_j \, , \quad \hat{\delta}_i = (\delta\varphi, \delta A_x, \delta A_y)_i$

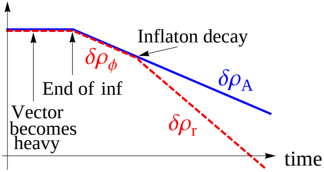
$$H = \frac{1}{2} \int d^3k \left[\hat{\pi}^\dagger \hat{\pi} + \hat{\psi}^\dagger \omega^2 \hat{\psi} \right] \; , \quad \omega^2 : \text{diagonal}$$

2. Quantize:

$$\hat{\psi}_i(t, \vec{k}) = h_{ij}(t, \vec{k}) \, a_j(\vec{k}) + h.c. \; , \quad \hat{\pi}_i(t, \vec{k}) = \tilde{h}_{ij}(t, \vec{k}) \, a_j(\vec{k}) + h.c.$$

3. Bogolyubov: $\quad h = \frac{1}{\sqrt{2\omega}} (\alpha + \beta) \; , \quad \tilde{h} = \frac{-i\,\omega}{\sqrt{2\omega}} (\alpha - \beta)$
4. Adiabatic initial no-particle state $\rightarrow \quad \alpha_{\text{in}} = \text{e}^{-i \int^{t_{\text{in}}} dt \, \omega} \; , \quad \beta_{\text{in}} = 0$

Curvaton Mechanism



1. $\rho_A \sim$ constant during inflation.
2. Inflaton decays into rad. after inflation.
3. Then $\underbrace{\delta\rho_A}_{\propto a^{-3}} \gg \underbrace{\delta\rho_r}_{\propto a^{-4}}$
4. Isocurvature → curvature conversion

$$\zeta = -H\frac{\delta\rho}{\dot\rho} \simeq \frac{r}{\underbrace{4+3r}_{\text{magnitude}}} \frac{\delta\rho_A}{\rho_A} \, , \qquad r \equiv \frac{\rho_A}{\rho_r}$$

Lyth & Wands '02

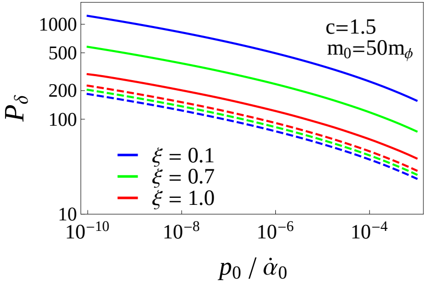
- $*$ r “only” determines the normalization
- $*$ Features (scale dependence, stat. (an)isotropy) in spectrum $\Leftrightarrow \frac{\delta\rho_A}{\rho_A} \equiv \delta$
- $*$ At late times, gradient is negligible

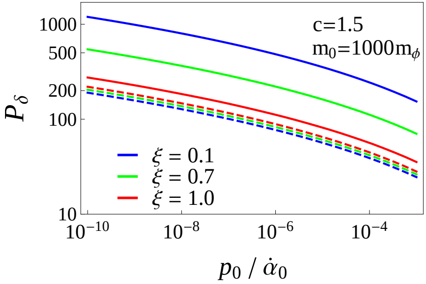
$$\delta\rho_A^{\text{late}} \simeq \frac{f}{a^2}\left[\dot A\,\delta\dot A_x + M^2 A\,\delta A_x\right]$$

Power spec. :$\langle \delta\left(\vec{x}\right)\delta\left(\vec{y}\right)\rangle = \int \frac{dk}{k}\int_0^1 d\xi \, \cos\left(k\,\xi\,r_L\right) J_0\left(k\sqrt{1-\xi^2}\,r_T\right) P_\delta(k,\xi)$

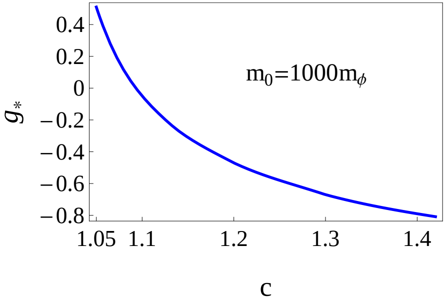
Results

- Freeze-out when coupling terminates $\sim$ a few oscillations after end of inf.
- Near scale invariance is a generic feature.
- The effect from $\delta\varphi - \delta A_\mu$ interaction is significant.
    - $\delta\varphi$ does not produce ζ directly, but *its effect must be taken into account*.
    - artificially removing $\delta\varphi \rightarrow$ gives incorrect result
- Changing m_0 does not affect angular dependence ($\xi \equiv \hat{k} \cdot \hat{n}_A = k_L/k$)





- Instead, changing c makes significant impact (recall: $f, m \sim e^{c\,\varphi^2}$)
  - $g_* = g_*(c)$



∗ Anisotropy is produced & encoded when $\lambda \sim M^{-1}$

∗ $g_* \lesssim 0.1$ can be achieved, but *requires fine-tuning*

∗ The level of stat. anisotropy is a function of the functional forms of f & m, not only on their time dependence.

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Concluding Remarks

Vector fields $\longleftrightarrow$ Distinctive phenomenology

Non-gaussianity

- Model: dilaton-like kinetic coupling $\mathcal{L}_{\rm int} = -\frac{1}{4} I^2 F^2$
- A_μ production $\to$ source $\zeta \sim$ highly NG
- $B_\zeta \propto \frac{1+\cos^2(\hat{k}_1 \cdot \hat{k}_2)}{k_1^3 k_2^3}$, $\quad f_{NL}^{\rm equiv.local} \sim \mathcal{O}(1-10)$
- Difficult realization of primordial magnetogenesis

Statistical anisotropy

- Model: Massive vector curvaton $\mathcal{L}_{\rm curv} = -\frac{1}{4} f\, F^2 - \frac{1}{2} m^2 A^2$
- No ghost instabilities with appropriate kinetic & mass functions
- Anisotropy encoded in the spectrum in the early stage of inflation
- $g_* \lesssim 0.1$ is possible but requires fine-tuning.

Future Prospect

Ongoing work:

- Running non-gaussianity when $I \propto a^n$ in the dilatonic coupling model

$$n = 2 \longrightarrow f_{NL} \propto N_{\rm CMB}^3 \left(N_{\rm tot} - N_{\rm CMB} \right)$$

$$N_{\rm CMB}^3 \to \prod_{i=1}^{3} \left[\frac{(aH/k_i)^{2(n-2)} - 1}{n-2} \right] \ , \quad N_{\rm tot} - N_{\rm CMB} \to \frac{(K/a_{\rm in} H)^{2(n-2)} - 1}{n-2}$$

- Chiral GW at interferometers
  - Axioninc coupling b/w φ & A_μ

$$\mathcal{L}_{\rm int} = -\frac{\alpha}{4f} \varphi F_{\mu\nu} \tilde{F}^{\mu\nu}$$

  - Parity violating $\mathcal{L}_{\rm int}$ → chiral GW, $P_R^{\rm GW} \gg P_L^{\rm GW}$
  - $\Delta\chi \equiv \frac{P_R^{\rm GW} - P_L^{\rm GW}}{P_R^{\rm GW} + P_L^{\rm GW}}$

?? Magnetogenesis from inflation ??