Axion couplings during inflation

MOCa

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Some motivations

Some motivations/concerns and expectations

- Pseudoscalars/axions are suitable candidates for dark matter.
- If present during inflation, DM particles should leave some imprint in the CMB.
- Cosmological observations can be used to constraint DM models (couplings): isocurvature, non-gaussianity, scale dependence, anisotropies, etc.
- Pseudoscalar fields offer a rich phenomenology in inflationary physics.
- Signatures of statistical anisotropies and parity violation in CMB correlators.
- Signatures of anisotropic and parity violating non-Gaussianity.
- Enhancement of gravitation waves. Chiral GW.
- Effects on LSS. Non-Gaussian & anisotropic bias.
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Stable gauge invariant abelian models. Scalar + vector

- General scalar(pseudoscalar) + vector models (allowing for derivative interactions):

$$S = \int d^4x\sqrt{-g}\,[R - \mathcal{L}(\phi, A_\mu)]$$

- Stable and causal gauge invariant ($A_\mu \to A_\mu + \partial_\mu \alpha$) models:

$$S = \int d^4x\sqrt{-g}\left[\mathcal{L}_{gravity} - \mathcal{L}_{\Phi_I}(\Phi_I, \partial\Phi_I) - \frac{1}{4}f_1(\Phi_I)F^{\mu\nu}F_{\mu\nu} - \frac{1}{4}f_2(\Phi_I)F^{\mu\nu}\tilde{F}_{\mu\nu}\right]$$

A saucerful of (scalar-vector-gravity) secrets:

$$\mathcal{L}_{gravity} \Rightarrow R + h(\Phi_I)R$$

$$\mathcal{L}_{\Phi_I}(\Phi_I, \partial\Phi_I) \Rightarrow \mathcal{L}(\phi_{Inf}, \sigma_{DM})$$

$f_1(\phi)F^{\mu\nu}F_{\mu\nu} \Rightarrow$ Non-diluting anisotropic source (“anisotropic hair”).

$f_2(\phi)F^{\mu\nu}\tilde{F}_{\mu\nu} \Rightarrow$ Parity symmetry breaking. Ex. $\frac{\alpha\phi}{4f}F^{\mu\nu}\tilde{F}_{\mu\nu}$

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Consequences of vector fields during inflation

Anisotropic and parity violating correlations in models of the form (some type of) $f_1(\phi)F^2 + f_2(\phi)F\tilde{F}$, Dimopoulos, Karciauskas, Wagstaff, Bartolo, Dimastrogiovanni, Matarrese, Riotto, Liguori, Ricciardone, Peloso, Valenzuela-Toledo, Rodríguez, Lyth, Gumrukcuoglu, Himmetoglu, Shiraishi, Komatsu, Barnaby, Watanabe, Kanno, Soda, Sorbo, Emami, Firouzjahi...

Angle dependent correlations

$$
\begin{aligned}
P_\zeta(k) \quad &\equiv \quad \frac{2\pi^2}{k^3}\mathcal{P}_\zeta\left(\frac{k}{aH}\right)^{n_\zeta - 1} \quad , \quad \mathcal{P}_\zeta \sim (5\times 10^{-5})^2 \\
P_\zeta(k) \quad &\Rightarrow \quad P_\zeta(\vec{k}) = P_\zeta(k)\left[1 + g_\zeta(\hat{k}\cdot\hat{n})^2\right], \\
B_\zeta(k_1,k_2,k_3) \quad &\Rightarrow \quad B_\zeta(\vec{k}_1,\,\vec{k}_2,\,\vec{k}_3) = B_\zeta\left[1 + g_\zeta b_1(\hat{k}_i,\hat{n}) + g_\zeta^2 b_2(\hat{k}_i,\hat{n})\right], \\
&\dots \\
g_\zeta \quad &\sim \quad 0{,}3 \quad \text{(back in 2009)}, \ \hat{n} \to \text{along the ecliptic} \\
-0{,}023 < \quad &g_\zeta \quad < 0{,}036 \quad \underline{\text{Planck 2015.}}
\end{aligned}
$$

1 Inflation with pseudoscalar-vector interactions

2 Particle production

3 Some expectations. NG, GW

4 Final remarks

Particle production. Equations of motion

Background metric

Background metric in conformal time

$$ds^2 = a(\tau)^2(-d\tau^2 + dx_i dx^i),$$

Assume nearly de Sitter geometry $a(\tau) \approx -1/H\tau$ with constant Hubble parameter H,

$$ds^2 = \frac{1}{H^2\tau^2}(-d\tau^2 + dx_i dx^i).$$

Equations of motion

$$S_{\phi A} = -\frac{1}{4}\int d^4x\sqrt{-g}\left[f_1(\phi)F^{\mu\nu}F_{\mu\nu} + f_2(\phi)F^{\mu\nu}\tilde{F}_{\mu\nu}\right]$$

$$\Downarrow$$

$$\nabla_\mu\left(f_1(\phi)F^{\mu\nu} + f_2(\phi)\tilde{F}^{\mu\nu}\right) = 0, \quad \& \quad \nabla_\mu\tilde{F}^{\mu\nu} = 0.$$

Equations of motion

Homogeneous scalar field $\partial_i \phi = 0 \Rightarrow f_1(\phi) = f_1(\phi(\tau)),\ f_2(\phi) = f_2(\phi(\tau))$.
$\Rightarrow \partial_i f_1 = \partial_i f_2 = 0$ Ex. $f_1 = 1/4,\ f_2 = \alpha\phi/4f$.

$$\phi'' + 2aH\phi' + a^2 \frac{dV}{d\phi} = \frac{\alpha}{f} a^2 \langle \vec{E}\cdot\vec{B}\rangle$$

$$A_i'' - \nabla^2 A_i - \frac{\alpha\phi'}{f}\epsilon_{ijk}\partial_j A_k = 0,$$

Polarisation decomposition

$$\vec{\epsilon}_\lambda(\vec{k})\cdot\vec{k} = 0, \qquad \vec{k}\times\vec{\epsilon}_\lambda = -i\lambda|\vec{k}|\vec{\epsilon}_\lambda, \qquad \vec{\epsilon}_\lambda\cdot\vec{\epsilon}_{\lambda'} = \delta_{\lambda,-\lambda'}, \qquad \vec{\epsilon}^{\,*}_\lambda(\hat{k}) = \vec{\epsilon}_{-\lambda}(\hat{k}) = \vec{\epsilon}_\lambda(-\hat{k}).$$

$$\boxed{A_\pm'' + \left(k^2 \pm \frac{2k\xi}{\tau}\right) A_\pm = 0 \quad \text{with} \quad \xi \equiv \frac{\alpha\dot{\phi}_0}{2fH}.}$$

$$\boxed{A_+ \approx \frac{1}{\sqrt{2k}}\left(\frac{k}{2\xi aH}\right)^{1/4} e^{\pi\xi - 2\sqrt{2\xi k/aH}}.}$$

Anber & Sorbo PRD 85 123537 (2012)

Some expectations

Multipolar expansion of the BS

$$B_\zeta = \sum_{L=0} c_L P_L(\hat{\mathbf{k}}_1 \cdot \hat{\mathbf{k}}_2) P(k_1) P(k_2) + perm.$$

c_L	$=$	observable parameters
P_L	$=$	Legendre polynomials

$c_L \rightarrow$ encodes information about statistical anisotropy and parity violation.

$$g = -\frac{48 N^2_{CMB} \rho_{E^{vev}}}{\epsilon \rho_\phi}, \; c_0 = -\frac{4 N_{CMB}}{3\pi} \frac{e^{2\pi\xi}}{\xi^3} g, \; c_1 \neq 0 = -\frac{3c_0}{2}, \; c_2 = \frac{c_0}{2}$$

Bartolo, Matarrese, Peloso, Shiraishi, JCAP07(2015)039

Planck 2015 $\rightarrow -0{,}0225 < g < 0{,}0363, \; -10{,}7 < c_0 < 16{,}7,$
$-89 < c_1 < 324, \; -57 < c_2 < 47$.

Optimal estimator for tracking the parity odd features.

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Gravitational waves production

Equation of motion for the tensor modes (using gauge $h_i{}^i = \partial_j h_{ij} = 0$):

$$\frac{d^2 h_{ij}}{d\tau^2} + 2\frac{a'}{a}\frac{dh_{ij}}{d\tau} - \Delta h_{ij} = \frac{2}{M_p^2}\mathrm{T}_{ij} = \frac{2}{M_p^2}\Pi_{ij}{}^{lm}T_{lm}.$$

Projector operator:

$$\Pi_{ij}{}^{lm} = \Pi_i^l \Pi_j^m - \frac{1}{2}\Pi_{ij}\Pi^{lm}, \quad \Pi_{ij} = \delta_{ij} - \frac{\partial_i\partial_j}{\Delta}.$$

- $\Pi_{ij}{}^{lm}$ projects the spatial energy-momentum tensor T_{ij} in the transverse direction.
- T_{ij} is traceless and divergenceless: $\mathrm{T}_{ii} = \partial_j \mathrm{T}_{ji} = 0$.
- Gravitational waves are only sourced by the transverse components $\tilde{A}_{\pm}$.

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Gravitational waves production

EM tensor for the vector field:

$$T_{\mu\nu} = f_1 \left(\frac{1}{4} g_{\mu\nu} F^2 - F_{\mu\alpha} F_\nu{}^\alpha \right) - m^2 (A_\mu A_\nu - \frac{1}{2} g_{\mu\nu} A^2)$$

Spacial components :

$$T_{ij} = -f_1 F_{i\alpha} F_j{}^\alpha - m^2 A_i A_j + \left(\frac{f_1}{4} F^2 - \frac{m^2}{2} A^2 \right) \delta_{ij} .$$

EM components that source tensor modes equation:

$$\mathrm{T}_{ij} = \Pi_{ij}{}^{lm} \left[-f_1 F_{l\alpha} F_m{}^\alpha - m^2 A_l A_m + (\cdots) \delta_{lm} \right] . \quad (1)$$

$(\cdots)$ terms are projected out by $\Pi_{ij}{}^{lm}$.
Canonical variables $\tilde{h}_{ij} = a h_{ij}$:

$$\frac{d^2 \tilde{h}_{ij}}{d\tau^2} - \frac{a''}{a} \tilde{h}_{ij} - \Delta \tilde{h}_{ij} = \frac{2a}{M_p^2} \mathrm{T}_{ij} = \frac{2a}{M_p^2} \Pi_{ij}{}^{lm} \left[-f_1 F_{l\alpha} F_m{}^\alpha - m^2 A_l A_m \right] . \quad (2)$$

$\Downarrow$Fourier transform

$$\left[\frac{d^2}{d\tau^2} + \left(k^2 - \frac{a''}{a} \right) \right] \tilde{h}_{ij}(\vec{k}) = \frac{2a}{M_p^2} \mathrm{T}_{ij}(\vec{k}).$$

Chiral GW

Enhancement of the + polarisation (Sorbo JCAP06(2011)003, Barnaby, Moxon, Namba, Peloso, Shiu, Zhou PhysRevD.86.103508, Cook & Sorbo JCAP11(2013)047, ...)

$$\mathcal{P}^{+} = \frac{H^2}{\pi^2 M_P^2}(1 + 8{,}6 \times 10^{-7}\frac{H^2}{M_P^2}\frac{e^{4\pi\xi}}{\xi^6})$$

$$\mathcal{P}^{-} = \frac{H^2}{\pi^2 M_P^2}(1 + 1{,}8 \times 10^{-9}\frac{H^2}{M_P^2}\frac{e^{4\pi\xi}}{\xi^6})$$

Non minimal coupling to gravity

Adding non minimal coupling to gravity modify the results for the scalar correlators. In particular, it modifies n_s and r.

$$V(\phi,\sigma) \Rightarrow V_E = \frac{V(\phi,\sigma)}{h(\phi,\sigma)}$$

Slow roll parameters are modified

$$\begin{aligned} \epsilon &= \frac{1}{2} M_{\rm P}^2 \left(\frac{V_E'}{V_E \phi'} \right)^2 \\ \eta &= M_{\rm P}^2 \left(\frac{V_E''}{V_E \phi'^2} - \frac{V_E' \phi''}{V_E \phi'^3} \right) \end{aligned}$$

GW statistics, anisotropic bias and anisotropic IC

Testing the statistics of GW, Shiraishi, Hikage, Namba, Namikawa, Hazumi arXiv:1606.06082. (Scale dependent and sizeable GW due to source fields like axions)

$$\langle B^+ B^+ \rangle$$

Non-gaussianity in B-modes $\langle B^+ B^+ B^+ \rangle$ at 3σ with LiteBIRD

Scale and c_L depending bias

$$P_g = b_1^2 P_m$$

$$P_g = b_1^2(g, c_0, c_1, c_2) P_m + \cdots$$

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Final remarks and hopes

- DM models can be constrained by cosmological observations. Selfcouplings and couplings with the inflaton of the DM sector can be constrained by isocurvature, non-gaussianity, GW, etc.
- Non minimal coupling with gravity is an interesting avenue to explore. This can bring some interesting models such as natural and chaotic inflation inside the allowed n_s, r region.
- Interesting possibilities for the GW production mechanism with a pseudoscalar coupling term. Scale dependent GW.
- Statistical anisotropy, parity violating and scale dependent effect are interesting effects that naturally arise in vector field models.