Pseudoscalar inflation and primordial GWs.

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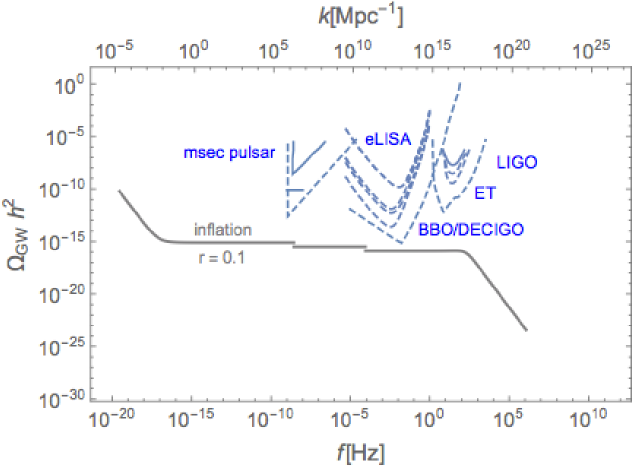
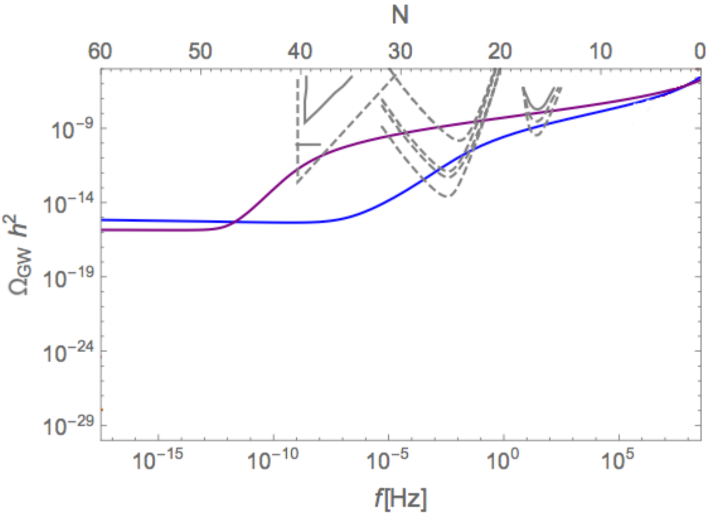
Overview

1. Introduction.
2. GW from pseudoscalar inflation.
   - Inflation in presence of gauge fields.
3. Conclusions and future perspectives.

Primordial GW Vs. direct detection.



A generalized inflationary model.



Standard single field slow roll inflation.

Homogeneus scalar field ϕ in a homogeneous and isotropic universe:

$$S = \int \mathrm{d}^4x \sqrt{-g} \left(\frac{R}{2\kappa^2} + \frac{\dot{\phi}^2}{2} - V(\phi) \right) , \qquad ds^2 = -dt^2 + a^2(t) d\vec{x}^2 \tag{1}$$

Einstein Equations + e.o.m. for ϕ fix the evolution ($\kappa^2 = 1$):

$$\left(\frac{\dot{a}}{a}\right)^2 \equiv H^2 = \frac{\rho}{3}, \qquad -2\dot{H} = p + \rho = \dot{\phi}^2 \qquad \ddot{\phi} + 3H\dot{\phi} + \frac{\partial V}{\partial \phi} = 0 \, . \tag{2}$$

Inflation $\Longleftrightarrow$ H (nearly) constant.

Perturbations over the background: $\begin{cases} \Phi(t, \vec{x}) = \phi(t) + \delta\phi(t, \vec{x}) \\ \mathbf{g}_{\mu\nu}(t, \vec{x}) = g_{\mu\nu}(t) + \delta g_{\mu\nu}(t, \vec{x}) \end{cases}$

Scalar and tensor power spectra:

$$\mathcal{P}_s = \frac{1}{4\pi^2} \left. \frac{H^4}{\dot{\phi}^2} \right|_{k=aH} \qquad \mathcal{P}_t = 8 \left. \left(\frac{H}{2\pi}\right)^2 \right|_{k=aH} . \tag{3}$$

Tensor-to-scalar ratio: $r \equiv \mathcal{P}_t/\mathcal{P}_s|_{k=aH} \lesssim 0.1$ Planck 95%CL.

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Pseudoscalar inflation.

Pseudoscalar inflaton non-minimally coupled to some Abelian gauge fields:

$$\mathcal{L} = \frac{M_p^2}{2} R - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - V(\phi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\alpha}{4\Lambda}\phi F_{\mu\nu}\tilde{F}^{\mu\nu} \quad (4)$$

Turner, Widrow '88,
Garretson, Field, Caroll '92,
Anber, Sorbo '06./'10/'12,
Barnaby, Namba, Peloso '11,
Barnaby, Pajer, Peloso '12 ,
.....

The equations of motion for the fields are:

$$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V}{\partial\phi} = \frac{\alpha}{\Lambda}\langle\vec{E}\cdot\vec{B}\rangle \quad (5)$$

$$\frac{\mathrm{d}^2\,\vec{A}^a(\tau,\vec{k})}{\mathrm{d}\tau^2} - \vec{\nabla}^2\vec{A}^a - \frac{\alpha}{\Lambda}\frac{\mathrm{d}\phi}{\mathrm{d}\tau}\vec{\nabla}\times\vec{A}^a = 0 \quad (6)$$

$$\mathrm{d}t \equiv a\,\mathrm{d}\tau$$

$$N \equiv \int H\mathrm{d}t$$

Friedmann equation reads:

$$3H^2 = \frac{1}{2}\dot{\phi}^2 + V(\phi) + \frac{1}{2}\langle\vec{E}^2 + \vec{B}^2\rangle\,. \quad (7)$$

The equations of motion for the gauge fields in Fourier transform are:

$$\frac{\mathrm{d}^2\,\vec{A}^a(\tau,\vec{k})}{\mathrm{d}\tau^2} - \vec{k}^2\vec{A}^a + i\frac{\alpha}{\Lambda}\frac{\mathrm{d}\phi}{\mathrm{d}\tau}\vec{k}\times\vec{A}^a = 0 \quad (8)$$

Gauge field amplification.

Taking $\vec{k}$ parallel to $\hat{x}$, we use the helicity vectors $\vec{e}_\pm = (\hat{y} \pm i\hat{z})/\sqrt{2}$ to get:

$$\vec{A}^a = \vec{e}_\pm A^a_\pm \qquad \rightarrow \qquad \vec{k} \times \vec{A}^a = A^a_\pm \vec{k} \times \vec{e}_\pm = \mp i A^a_\pm |\vec{k}| \vec{e}_\pm \tag{9}$$

The equations of motion for the Fourier transform of the gauge fields read:

$$\frac{\mathrm{d}^2 A^a_\pm(\tau, \vec{k})}{\mathrm{d}\tau^2} + \left[k^2 \pm 2k\frac{\xi}{\tau}\right] A^a_\pm(\tau, \vec{k}) = 0 \, , \qquad \xi \equiv \frac{\alpha\dot{\phi}}{2H\Lambda} \propto \sqrt{\epsilon_H} \, . \tag{10}$$

If ξ is nearly constant the gauge fields are exponentially growing with ξ.

Substituting $\langle \vec{E} \cdot \vec{B} \rangle \simeq 2.4 \cdot 10^{-4} \mathcal{N} \left(\frac{H}{\xi}\right)^4 e^{2\pi\xi}$, the equation of motion for ϕ is:

$$\ddot{\phi} + 3H\dot{\phi} + \frac{\partial V}{\partial \phi} = \frac{\alpha}{\Lambda}\langle \vec{E} \cdot \vec{B} \rangle \simeq \frac{\alpha}{\Lambda} 2.4 \cdot 10^{-4} \mathcal{N} \left(\frac{H}{\xi}\right)^4 e^{2\pi\xi}, \tag{11}$$

the gauge fields induce a friction term that is exponentially growing with ξ and that dominates the last part of the evolution.

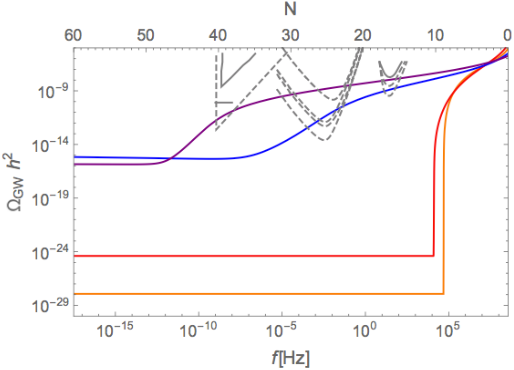
Modified dynamics also affects the scalar and tensor power spectra!

Modified tensor spectrum.

GW spectrum $\longrightarrow$
$$\mathcal{P}_t(k) = \frac{1}{12}\left(\frac{H}{\pi M_p}\right)^2 \left(1 + 4.3 \cdot 10^{-7} \frac{H^2}{M_p^2 \xi^6} e^{4\pi\xi}\right) \quad (12)$$

N-frequency relation $\longrightarrow$
$$N = N_{\text{CMB}} + \ln \frac{k_{\text{CMB}}}{0.002\ \text{Mpc}^{-1}} - 44.9 - \ln \frac{f}{10^2\ \text{Hz}} . \quad (13)$$

- Spectra asymptote to an universal value at small scales
- Low scale models ($p = 3, 4$) have a stronger increase
- Some models produce GW in the observable range of direct GW detectors



$$\epsilon_H \simeq \frac{\mathcal{O}(1)}{N^p}$$

p = 1 (Quadratic)
p = 2 (Starobinsky)
p = 3 (Hilltop)
p = 4 (Hilltop)

V. Domcke, M.P. and P. Binétruy, arXiv:1603.01287 [astro-ph.CO].

Modified scalar spectrum.

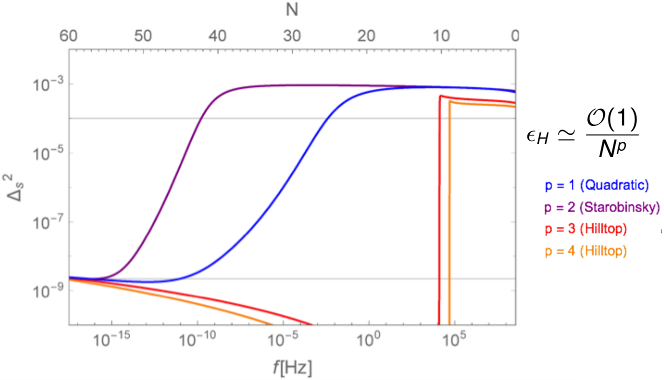
Scalar spectrum $\longrightarrow$

$$\mathcal{P}_s(k) = \left(\frac{H^2}{2\pi\dot{\phi}}\right)^2 + \left(\frac{\alpha\langle\vec{E}\cdot\vec{B}\rangle}{3bH\dot{\phi}}\right)^2 \quad (15)$$

where:

$$b \equiv 1 - 2\pi\xi\frac{\alpha\langle\vec{E}\cdot\vec{B}\rangle}{3\Lambda H\dot{phi}} \quad (16)$$

- COBE normalization fixes V_0
- Nearly universal behavior at large scales
- Stong increase at small scales $\rightarrow$ PBHs
- $\mathcal{P}_s(k) \simeq \frac{1}{\mathcal{N}(2\pi\xi)^2}$ at small scales



V. Domcke, M.P. and P. Binétruy, arXiv:1603.01287 [astro-ph.CO].

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Conclusions and future perspectives.

Main results:

- Possible generation of Primordial GWs in the observable ranges for direct GW detectors.
- If this GW are observed, we get important informations on the microphysics of inflation.
- Models with large n_s may be recovered.

Future perspectives:

- More models.
- Extension to Non-abelian gauge fields.
- Consequences on reheating.
- Generation of PBHs.
- Embedding in a UV complete theory.

The End

Thank you

Models classification.

Classify models using: $\epsilon_H \simeq \frac{\beta}{(1+N)^p}$ V. Mukhanov, [arXiv:1303.3925 [astro-ph.CO]]

The system is specified by four parameters: $\alpha/\Lambda, \beta, p, V_0$.

No gauge fields $\longrightarrow$ $n_s \simeq 1 - \frac{\mathcal{O}(1)}{N}$, $r \simeq 16\epsilon_H \simeq \frac{16\beta}{(1+N)^p}$ (18)

The gauge fields introduce an additional friction term.

- The CMB observables are 'effectively shifted' at a 'later' point N_*:

$$N_* < N_{CMB} \simeq 60 \,, \quad \longrightarrow \quad n_s \simeq 1 - \frac{\mathcal{O}(1)}{N_*} \,, \quad r \propto \epsilon_H \simeq \frac{\mathcal{O}(1)}{(1+N_*)^p} \qquad (19)$$

We get reduced n_s and increased r with respect to the standard case.

- As $\xi \propto \sqrt{\epsilon_H}$, the effects on models with big p will be stronger.

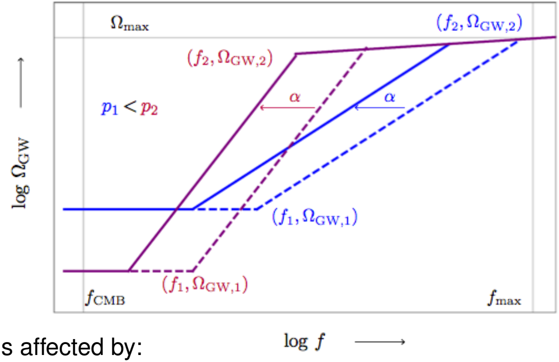
V. Domcke, M.P. and P. Binétruy, arXiv:1603.01287 [astro-ph.CO].

General features of the GW spectrum.

The system is specified by four parameters: $\alpha/\Lambda, \beta, p, V_0$.

Notice that:

- Gauge fields take over at f_1
- Gauge fields' friction dominates at f_2
- Ω_{GW}^{CMB} is fixed by COBE and r.
- Ω_{GW}^{Max} is fixed by $\epsilon_H \leq 1$.



The shape of the spectrum is affected by:

- p : the slope and the vacuum amplitude
- β : vacuum amplitude
- α/Λ : shifts the spectrum horizontally

$$r \propto \epsilon_H \propto \mathcal{O}(1)/N^p$$

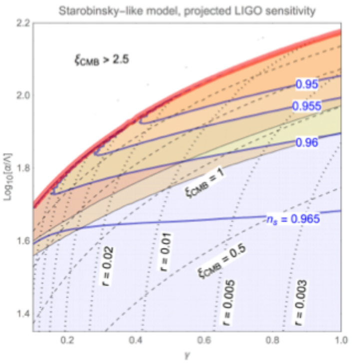
$$\mathcal{L}_{int} = \frac{\alpha}{4\Lambda}\phi F_{\mu\nu}\tilde{F}_{\mu\nu}$$

Starobinsky-like model parameter space.

Choosing:
- $p = 2$
- $\beta = 1/(2\gamma)^2$

leads to:

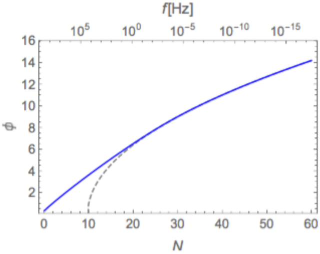
$$V(\phi) \simeq V_0 \left(1 - \exp\{-\gamma\phi\}\right)^2 \quad (20)$$



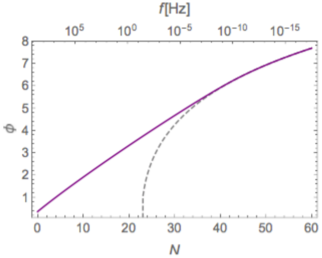
(a) *LIGO plot.* (b) *eLISA plot.*

V. Domcke, M.P. and P. Binétruy, arXiv:1603.01287 [astro-ph.CO].

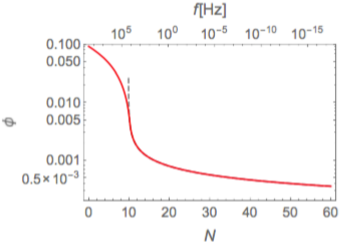
The complementarity between different measures can be used to restrict the parameter space!



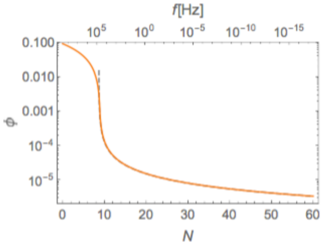
(a) *Quadratic model with* $\alpha/\Lambda = 35$ *and* $V_0 = 1.418 \cdot 10^{-11}$.



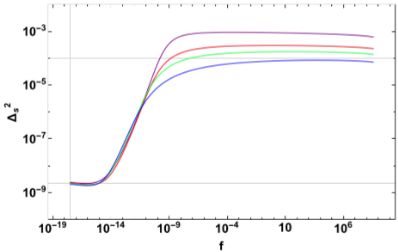
(b) *Starobinsky model with* $\alpha/\Lambda = 75$, $\gamma = 0.3$, $V_0 = 1.17 \cdot 10^{-9}$.



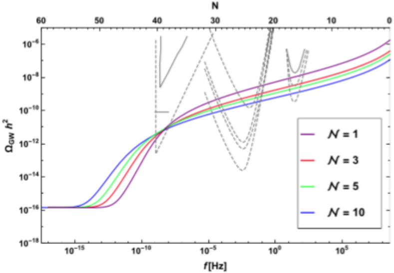
(c) *Hilltop model with* $q = 4$, $\alpha/\Lambda = 2000$, $v = 0.1$ *and* $V_0 = 1.0 \cdot 10^{-21}$.



(d) *Hilltop model with* $q = 3$, $\alpha/\Lambda = 2000$, $v = 0.1$ *and* $V_0 = 3.6 \cdot 10^{-18}$.



(a) *Scalar power spectra.*



(b) *Tensor power spectra.*