Sourced GW from axion inflation

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- Sourced scalar and tensor perturbations
- CMB phenomenology
- Interferometer phenomenology

In collaboration with

Barnaby, Biagetti, Crowder, Dimastrogiovanni, Fasiello, Garcia-Bellido, Kim, Komatsu, Mandic, Mukohyama, Moxon, Namba, Nilles, Pajer, Pearce, Shiu, Shiraishi, Sorbo, Unal, Zhou
• CMB in agreement with simplest models of slow-roll inflation

\[ r \equiv \frac{P_{GW}}{P_\zeta}, \quad n_s - 1 \equiv \frac{d \ln P_\zeta}{d \ln k}, \quad f_{NL} \sim \frac{\langle \zeta^3 \rangle}{\langle \zeta^2 \rangle^2} = \mathcal{O}(\epsilon, \eta) \]

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

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

• Flatness and gaussianity \( \rightarrow \) small inflaton self-couplings

\[ \left( \text{e.g., } \Delta V = \frac{\lambda}{4} \phi^4 \Rightarrow \lambda < 10^{-13} \right) \]

• Shift symmetry on couplings to other fields

\[ \mathcal{L} = \frac{1}{2} (\partial_{\mu} \phi)^2 + V_{\text{shift}}(\phi) + \frac{c_\psi}{f} \partial_{\mu} \phi \overline{\psi} \gamma^\mu \gamma_5 \psi + \frac{\alpha}{f} \phi F_{\mu\nu} \tilde{F}^{\mu\nu} \]

has the advantage that

- Smallness of \( V_{\text{shift}} \) technically natural. \( \Delta V \propto V_{\text{shift}} \)

- Constrained couplings to matter (predictivity)

Freese, Frieman, Olinto '90; . . .

(review Pajer, MP '13)
Classical motion $\phi^{(0)}(t)$ affects dispersion relations of $\pm$ helicities

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

$$\left( \frac{\partial^2}{\partial \tau^2} + k^2 \mp 2aHk \xi \right) A_{\pm}(\tau, k) = 0$$

$$\xi \equiv \frac{\alpha \dot{\phi}^{(0)}}{2fH} \approx \text{const.}$$

One tachyonic helicity at horizon crossing

Anber, Sorbo '06

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

(UV & IR finite)
\[
\delta \ddot{\phi} + 3H \dot{\phi} - \frac{\nabla^2}{a^2} \delta \phi + m^2 \delta \phi = \frac{\alpha}{f} \vec{E} \cdot \vec{B}
\]

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

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

Uncorrelated, \( \langle \delta \phi^n \rangle = \langle \delta \phi_{\text{vac}}^n \rangle + \langle \delta \phi_{\text{inv.decay}}^n \rangle \)

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

($\xi > 1$)

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

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

\[
\text{Backreaction on } \phi'
\]
At any moment, only $\delta A$ with $\lambda \sim H^{-1}$ present

$$f_{\text{NL}}^{\text{equil}} = -4 \pm 43 \quad \text{Planck '15}$$

$\delta A \sim e^{\pi \xi}$ so large variation in a small window of $\xi = \mathcal{O}(1)$

$$\xi = \mathcal{O}(1) \text{ for } f/\alpha = \mathcal{O}(10^{16} \text{ GeV})$$

More production $\rightarrow$ smaller $r$

(sourced GW $\ll$ sourced $\delta \phi$)
- $f \gtrsim 7 M_p$ needed in $V = \Lambda^4 \left[ 1 + \cos \left( \frac{\phi}{f} \right) \right]$. Values $f \approx 10^{-2} M_p$ relevant for models with sub-Planckian axion scale, but effective $\Delta \phi > M_p$

E.g., Monodromy, N-flation, **Aligned Natural Inflation**

$$V = \Lambda_1^4 \left[ 1 - \cos \left( \frac{\theta}{f_1} + \frac{\rho}{g_1} \right) \right] + \Lambda_2^4 \left[ 1 - \cos \left( \frac{\theta}{f_2} + \frac{\rho}{g_2} \right) \right]$$

$$f_{\text{eff}} \gg f_i, g_i \quad \text{if} \quad \frac{f_1}{g_1} \sim \frac{f_2}{g_2}$$

(gravitational instanton corrections may still be a problem if $f_{\text{eff}} > M_p$)

$$\alpha \equiv \frac{f_1 g_2 - f_2 g_1}{f_1 g_2 + f_2 g_1} \ll 1 \quad \text{alignment parameter}$$

$\psi \equiv \text{heavy combination}$

Effective scale: $f_\psi = \mathcal{O}(f_i, g_i)$

$\phi \equiv \text{light combination}$

Effective scale: $f_\phi = \mathcal{O} \left( \frac{f_i}{\alpha}, \frac{g_i}{\alpha} \right)$

Fields rescaled

- curvature
  - in 2 directions

$\psi$ much heavier

Inflation along

valleys $\frac{\partial V}{\partial \psi} = 0$
Stable valleys, \( \frac{\partial V}{\partial \psi} = 0 \), \( \frac{\partial^2 V}{\partial \psi^2} > 0 \) → inflationary trajectories

Unstable crests, \( \frac{\partial V}{\partial \psi} = 0 \), \( \frac{\partial^2 V}{\partial \psi^2} < 0 \)

For some parameters inflationary trajectories ending because

1. reach a minimum or
2. become unstable in heavy direction

Connected to minima

Disconnected

Trajectories (2) have a flatter potential \( \equiv \) smaller \( \epsilon \propto \frac{V'}{V^2} \)
and so smaller GW (recall \( r = 16 \epsilon \))

All above natural inflation!
GW at CMB scales

- With latest Keck Array: $r < 0.07$

- Strong experimental program, from ground, balloon, and (proposed) satellite

**Ground Based**

- **Chile**
  - ABS
  - ACTPol/AdvACT
  - POLARBEAR
  - CLASS
  - Have data
  - Current or planned freqs
    - 145 GHz
    - 30, 40, 90, 150, 230 GHz
    - 90, 150 GHz
    - 40, 90, 150 GHz

- **Antarctica**
  - BICEP/KECK
  - SPTPol
  - QUBIC-Bolo int.
  - 2016
  - 90, 150, 220 GHz
  - 90, 150 GHz
  - 90, 150, 220 GHz

- **Elsewhere (for now)**
  - B-Machine–WMRS
  - GroundBIRD, LiteBIRD
  - GLP–Greenland
  - MuSE-Multimoded
  - QUIJOTE–Canaries, HEM
  - 40 GHz
  - 2016
  - 150 GHz
  - TBD
  - TBD
  - 11-20, 30 GHz

**Balloons**

- **Have data**
- **Current or planned freqs**
  - EBEX
  - LPSE
  - PIPER
  - SPIDER
  - 150, 250, 210 GHz
  - TBD
  - 5 chan 40-250 GHz
  - 2015
  - 200, 270, 350, 600 GHz
  - 90, 150, 280 GHz


- Multi-frequency is key, to eliminate dust
2.6.3 Distinguishing vacuum fluctuations from other particle physics sources of B modes

- Vacuum modes: \( V^{1/4} = 10^{16} \text{ GeV} \left( \frac{r}{0.01} \right)^{1/4} \). \( \Delta \phi \gtrsim M_p \left( \frac{r}{0.01} \right)^{1/2} \)

**How robust?**

\( \mathcal{L} = (\phi - \phi_*)^2 \chi^2 \)

Cook, Sorbo '11

\( \mathcal{L} = \sigma F \tilde{F} \)

Senatore, Silverstein, Zaldarriaga '11

\( \mathcal{L} = \frac{1}{2} \left( \delta \sigma^2 - c_s^2 (\nabla \delta \sigma)^2 \right) \), \( c_s \ll 1 \)

Biagetti, Fasiello, Riotto '13

Biagetti, Dimastrogiovanni, Fasiello, MP '14

A field \( X \) produced during inflation, and \( X \rightarrow h_{\text{sourced}} \gg h_{\text{vacuum}} \)

**Models I worked on**

(standard GR and QM)

- Alternative mechanism in chromonatural inflation
  - Maleknejad; Obata, Soda; Dimastrogiovanni, Fastello; Fujita; Adshead, Martinec, Sfakianakis, Wyman '16

- Whatever sources GW is also at least gravitationally coupled to \( \zeta \)

Barnaby, MP '10; Barnaby et al' 12;

Mirbabayi, Senatore, Silverstein, Zaldarriaga '14; Namba et al '15
Burst of particle production

\[ V = V(\phi) + \frac{g^2}{2} (\phi - \phi_*)^2 \chi^2 \]

Number. Value reached by the inflaton during inflation

- For most of the evolution, \( m_\chi \sim g\phi, g\phi_* \gg H \), no effect
- At \( \phi = \phi_* \), nonadiabatic \( m_\chi \) variation

\[ \Rightarrow n_\chi(t_*) = \exp \left( -\frac{\pi k^2}{g \dot{\phi}} \right) \]

Produced \( \chi \) sources \( \delta\phi \) (later). Also, source of GW

Analogously for \( V(\phi) + \frac{g^2}{2} (\phi - \phi_*)^2 A_\mu A^\mu \)  

For the following slide, keep in mind that quanta of \( \chi, A_\mu \) produced when massless, but - due to motion of \( \phi \) - quickly become non-relativistic.
Few GW in simplest implementation (more possibilities Senatore et al ’11)

**How to increase \( h_{\text{sourced}} \) vs. \( \zeta_{\text{sourced}} \)?**

**Rule 1:** Source of GW in a sector gravitationally coupled to inflaton

**E.g.**  
\[ V(\phi) + V(\sigma) + \frac{g^2}{2} (\sigma - \sigma_*)^2 A_\mu A^\mu \]

Canonical inflaton / GW mode satisfy  
\[ \left( \partial_\tau^2 - \frac{a''}{a} + k^2 \right) Q_i \simeq J_i \]

with

\[ J_\phi \simeq \frac{\dot{\phi}}{2M_p^2 H a} \int \frac{d^3p}{(2\pi)^{3/2}} \left[ \hat{k}_i \hat{k}_j \left( M^2 - \partial_\tau^{(1)} \partial_\tau^{(2)} \right) - M^2 \delta_{ij} \right] A_i(\vec{p}) A_j(\vec{k} - \vec{p}) \]

\[ J_\lambda = \frac{\Pi_{mn,\lambda}^*(k)}{aM_p} \int \frac{d^3p}{(2\pi)^{3/2}} \left[ \delta_{mi} \delta_{nj} \left( -\partial_\tau^{(1)} \partial_\tau^{(2)} + M^2 \right) + \epsilon_{mai} \epsilon_{njb} p_a (k - p)_b \right] A_i(\vec{p}) A_j(\vec{k} - \vec{p}) \]

Recall \( \partial_\tau \simeq M \gg p \). Big cancellation on tensor source

Non-relativistic quanta have suppressed quadrupole moment

**Rule 2:** Source of GW should be relativistic
Both rules satisfied by \[ V_\phi (\phi) + V_\sigma (\sigma) + \frac{\sigma}{f} F \tilde{F} \]

- \( A_+ \) produced by rolling \( \sigma (t) \), different from inflaton \( \phi \)
- Due to helicity, \( A + A \to h \) stronger than \( A + A \to \delta \phi \) (both gravitational)
- However, large \( \delta \sigma \) production. As long as \( \sigma \) is rolling, linearly coupled (again, gravitational effect) to \( \delta \phi \). Significant \( A + A \to \delta \sigma \to \delta \phi \)

Ferreira, Sloth '14

\begin{center}
Rule 3: Source effective only for limited time
\end{center}

Namba, MP, Shiraishi, Sorbo, Unal '15

- Less time for \( \delta \text{source} \to \delta \phi \)
- Can produce modes at \( \ell \lesssim 100 \) (good for GW, looser limits from NG)

Bump in \( \delta_{\text{sourced}}, h_{\text{sourced}} \) on scales that left horizon while source effective
Simplest potential for a pseudoscalar: \[ V(\sigma) = \frac{\Lambda^4}{2} \left[ \cos\left(\frac{\sigma}{f}\right) + 1 \right] \]

Slow roll sol. \[ \dot{\sigma} = \frac{fH\delta}{\cosh[\delta H(t-t_*)]} \], where \[ \delta \equiv \frac{\Lambda^4}{6H^2f^2} = \frac{m^2}{3H^2} \]

\[ \dot{\sigma}_{\text{max}} \text{ at } t = t_*, \text{ when } \sigma = \frac{\pi f}{2}, \quad \dot{\sigma} \neq 0 \quad \text{for} \quad \Delta N \sim \frac{1}{\delta} \]

Three examples with \( \epsilon_\phi = 10^{-5} \) (so that \( r_{\text{vacuum}} = 16 \epsilon \) is unobservable):

- Can be distinguished from vacuum by tensor running and BBB
  - (in principle also TB, but we found small S/N)
• Vacuum mechanism for GW very robust

• Under specific conditions, can produce visible $r$ at arbitrarily small $r_{\text{vacuum}} / \text{scale of inflation}$

• Computations under perturbative control
  Ferreira, Ganc, Noreña, Sloth ’15
  MP, Sorbo, Unal ’16

• At small $\epsilon_\phi$, we have $\dot{H}$ controlled by $\dot{\sigma} > \dot{\phi}$ at the bump.

  Not a problem: In this model $n_s$ controlled by $\eta_\phi \sim 10^{-2} \gg \epsilon_\phi, \epsilon_\sigma$
GW at interferometers

Back to $\frac{\phi}{f} F \tilde{F}$

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

$\Rightarrow$ other interesting effects / signatures

- For instance, growth of $P_\xi(k)$

\[
P_\xi \sim P_v \left[1 + 7.5 \cdot 10^{-5} P_v \frac{e^{4\pi \xi}}{\xi^6} \right] \rightarrow P_\ast \left(\frac{k}{k_\ast}\right)^{n_s-1} \left[1 + P_\ast \left(\frac{k}{k_\ast}\right)^{n_s-1} f_2(\xi(k)) e^{4\pi \xi} \left(\frac{k}{k_\ast}\right)^{2\pi \xi \eta_\ast}\right]
\]

$\xi_\ast = \xi$ when Planck pivot scale left horizon

NG : $\xi_\ast \leq 2.5$ (95% CL)

Planck '15

PS : $0.1 \leq \xi_\ast \leq 2.3$ (95% CL)

\[
V = M^3 \phi \Rightarrow \frac{f}{\alpha} \gtrsim 0.021 M_p \\
V = \frac{m^2}{2} \phi^2 \Rightarrow \frac{f}{\alpha} \gtrsim 0.029 M_p
\]
• $\dot{\phi}$ keeps increasing. Unique opportunity to explore later stages of inflation.

• As $\xi$ grows, $\delta A$ grows, and additional interactions with $\delta \phi$ relevant. Since $\dot{\phi} \rightarrow \xi \rightarrow \delta A$, first interaction estimated to be

$$\delta \ddot{\phi} + 3 \left[ 1 - \frac{2\pi \xi \alpha}{3H\dot{\phi}f} \vec{E} \cdot \vec{B} \right] H\delta \dot{\phi} - \frac{\vec{V}^2}{a^2} \delta \phi + m^2 \delta \phi = \frac{\alpha}{f} \vec{E} \cdot \vec{B}$$

Anber, Sorbo ’09

Scalar perturbations may grow to above primordial black hole bound

Linde, Mooij, Pajer ’13

Fraction in PBH

- Non-gaussian statistics of $\zeta_{\text{sourced}}$ enhances PBH fraction

- Large uncertainty, related to validity of the above equation
- Chiral GW production $A_+A_+ \rightarrow h_L$
at interferometer scales

- New window on inflation; CMB / LSS for $10^{-4} \lesssim k/{\text{Mpc}}^{-1} \lesssim 10^{-1}$;CMB distortions down to $10^4$. This is 18 e-folds, say from 42 to 60

- LISA peaks at $N \sim 25$; AdvLIGO at $N \sim 15$

- In chaotic inflation, PBH bound (if accurate) prevents GW from being observable.
- PBH at $N \sim 10$. GW (particularly LISA) probe ≠ scales

- Due to $\propto e^{\phi}$, significant differences from a minor change of $V$

- If $N$ gauge fields (eg. non-abelian), more backreaction, and $\frac{P_{GW}}{P_{\z}} \propto N^2$

- GW signal is non-gaussian, $k^6 \langle h_L^3 \rangle_{\text{equil}} \sim 23 P_{GW}^{3/2}$ and chiral
Chiral GW @ interferometers

\[ \langle s_1 s_2 \rangle \propto \Omega_{GW}(f) [\gamma_I(f) + \Pi(f) \gamma_R(f)] \]

\[ \Pi \equiv \frac{P_R - P_L}{P_R + P_L} \]

\( \gamma \) depend on orientations of the detectors and on the GW frequency

- Need three detectors To determine \( \Omega_{GW} \) and \( \Pi \)

Assume \( |\Pi| = 1 \). How large does signal need to be to detect GW and exclude \( \Pi = 0 \) at 2\( \sigma \) ?

\[ \Omega = \Omega_\alpha \left( \frac{f}{100 \text{Hz}} \right)^\alpha \]

Axion inflation \( V \propto \phi^p \)

<table>
<thead>
<tr>
<th>Detector Network</th>
<th>p</th>
<th>( \xi ) (sensitivity)</th>
<th>( \xi ) (exclude ( \Pi = 0 ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>2\text{nd} Gen H1-L1-V1-K1</td>
<td>1</td>
<td>2.3</td>
<td>2.8</td>
</tr>
<tr>
<td>2\text{nd} Gen H1-L1-V1-K1</td>
<td>2</td>
<td>2.2</td>
<td>2.6</td>
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<td>3\text{rd} Gen</td>
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<td>1.8</td>
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</tr>
<tr>
<td>3\text{rd} Gen</td>
<td>2</td>
<td>1.9</td>
<td>2.0</td>
</tr>
</tbody>
</table>
Conclusions

- Simplest model for axion inflaton starts to be in tension with CMB. Not so for multi-fields. \( f/\alpha \gtrsim 10^{-2} M_p \) for coupling to any gauge field.

- \( r = 16 \epsilon \) very robust. Possible to violate this (existence proof) but hard to source GW without disturbing \( \zeta \). Distinctive properties (running tensor tilt, non-gaussianity, chirality)

- Increase of signal at smaller scales naturally opens potential observational window on \( N \sim 15 - 25 \). Again, fight against \( P_\zeta \rightarrow PBH \)

  Not a no-go (uncertainty, \( \neq \) scales). Distinctive properties can help discriminate against astrophysical background