Phenomenology of Axion Inflation

based on

Flauger & E.P. 1002.0833

Flauger, McAllister, E.P., Westphal & Xu 0907.2916

Barnaby, EP & Peloso to appear

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Outline

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Tensor modes and the Lyth bound

- Assuming slow-roll inflation and N_{CMB} e-foldings

$$\frac{d\phi}{M_{pl}} = dN\sqrt{2\epsilon} \simeq dN\sqrt{\frac{r}{8}}$$
$$\frac{\Delta\phi}{M_{pl}} > \sqrt{\frac{r}{0.01}}\frac{N_{CMB}}{30}$$

- Measuring tensor modes puts a lower bound on the range of variation of the inflaton [Lyth 98]
- In a fundamental theory a flat potential over a superplanckian distance is hard to control, e.g. η-problem.
- This is the main motivation to consider axion inflation

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Schematically

Tensor modes $\Rightarrow$ High scale $\Rightarrow$ Large field $\Rightarrow$ more UV-sensitive

UV-sensitivity

- EFT approach: learn about higher scales studying UV-sensitive observables.
- Inflation is a UV-sensitive mechanism. Schematically

$$V(\phi) = \frac{1}{2}m^2\phi^2 + \sum_n \lambda_n \frac{\phi^n}{M_{pl}^{n-4}}$$

- Within string theory and supergravity many models suffer from an η-problem.
- Invoke a shift symmetry to protect flatness
- Study all the couplings allowed by the symmetry
- Find a UV embedding in which the symmetry is realized

Axion Inflation

Many realizations:

- Shift symmetry protects the flatness of the potential. E.g. Natural Inflation with non-perturbative effects [Freese et al 90]
- Superplanckian axion decay constants f are elusive. [Banks et al. 03]
- Multiple axions can avoid this problem: [Peloso et al 04] , Dante's Inferno [Berg et al 09] , N-flation [Dimopoulos et al 05]
- Axion mixing with a 4-form [Kaloper & Sorbo 08]
- Axion monodromy from controlled explicit shift-symmetry breaking [Silverstein & Westphal (1+McAllister)]

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Logic

Tensor modes $\Rightarrow$ Large field $\Rightarrow$ Shift symmetry $\Rightarrow$ Shift-symmetric couplings

The effective potential

Inflaton action has more than just the slow-roll potential as *consequence of the shift-symmetry*

$$L = -\frac{1}{2}\partial\phi^2 - V_{sr}(\phi) - \frac{1}{4}F^2 - \Lambda^4 \cos\left(\frac{\phi}{f}\right) - \frac{\alpha\phi}{4f}F\tilde{F}$$

- Oscillating (but monotonic) potential
- $f \ll M_{pl}$ many short ripples, stronger coupling
- $\alpha \sim \mathcal{O}(1)$ in generic EFT (we will compute it in string theory)
- Any shift-symmetric model (large field) should come with these couplings
- Tensor modes correlate with other observables

Outline

Correlated Observables

Observable tensor modes ($r \geq .01$) naturally correlate with

1. Non-perturbative oscillatoric contribution leading to
    - Oscillations in the two point function
    - Detectably large and oscillatoric three point function (resonant non-Gaussianity)
2. Coupling to gauge fields leading to
    - Additional efoldings close to the end of inflation due to the strong backreaction
    - Additional contribution to scalar and tensor power spectra with strong running
    - Scale dependent equilateral non-Gaussianity from inverse decay
    - Gravitational waves detectable at interferometers such as LIGO/VIRGO

Background equations

Extra terms from the tachyonic gauge fields

$$\ddot{\phi} + 3H\dot{\phi} + V' = \frac{\alpha}{f}\langle \vec{E}\cdot\vec{B}\rangle$$

$$3H^2 = \frac{1}{M_p^2}\left[\frac{1}{2}\dot{\phi}^2 + V + \frac{1}{2}\langle \vec{E}^2 + \vec{B}^2\rangle\right]$$

Gauge fields sources grow [Anber & Sorbo 08, Barnaby & Peloso 10]

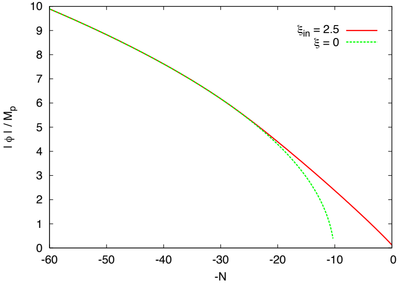
$$\langle \vec{E}\cdot\vec{B}\rangle \simeq -2.4\cdot 10^{-4}\,\frac{H^4}{\xi^4}\,\mathrm{e}^{2\pi\xi}$$

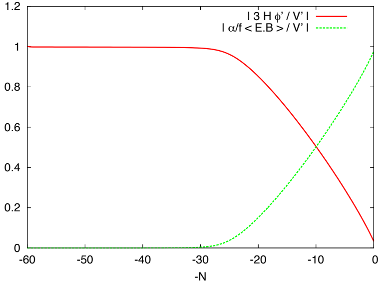
$$\langle \frac{\vec{E}^2 + \vec{B}^2}{2}\rangle \simeq 1.4\cdot 10^{-4}\frac{H^4}{\xi^3}\mathrm{e}^{2\pi\xi}$$

since $\xi \equiv \frac{\alpha\dot{\phi}}{2fH}$

Numerical background evolution

Inflation lasts longer due to extra friction





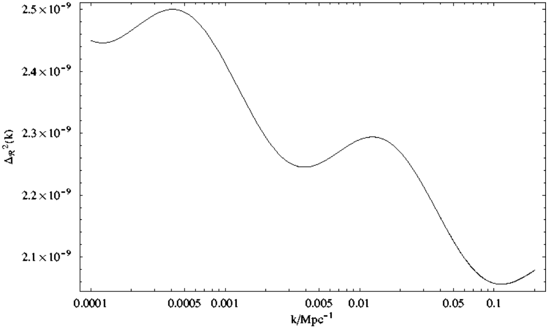
Additional $\mathcal{O}(10)$ efoldings have important consequences.

CMB Phenomenology

The scalar power spectrum is (for $\phi \gg M_{pl} \gg f$ and $\Lambda^4/(V'f) \ll 1$)

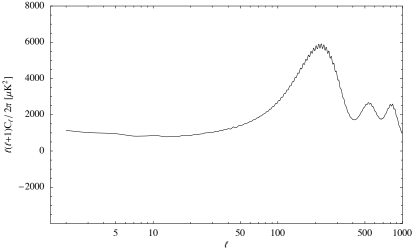
$$P_s(k) = A_s \left(\frac{k}{k_*}\right)^{n_s-1} \left[1 + \delta n_s \cos\left(\frac{\phi_k}{f}\right)\right]$$

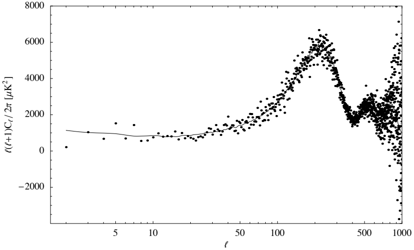
$$\delta n_s \simeq 3\frac{\Lambda^4}{V'f}\sqrt{\frac{2\pi f}{\sqrt{2\epsilon}}}$$



Observational constraints on the spectrum

- The best fit next to the unbinned WMAP5 data looks like



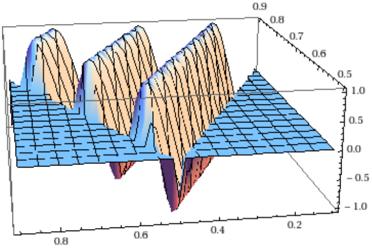


- The improvement of the fit is not statistically significant.
- The bound of WMAP5 data on the parameters of the model is roughly $\Lambda^4/(V' M_{pl}) < 10^{-4}$

Resonant non-Gaussianity

Large non-Gaussianity from modulations

Modulations on the potential violate slow roll and can induce large non-Gaussianity.



- Resonant non-Gaussianity [Chen et al. 08] .
- They are very large and are not scale invariant.
- Resonant non-Gaussianity is orthogonal to any other known shape. No constraints on it yet.

Resonant of non-Gaussianity

Direct analytical computation [Flauger & Pajer 10]

$$\langle \zeta_{\mathbf{k_1}} \zeta_{\mathbf{k_2}} \zeta_{\mathbf{k_3}} \rangle = (2\pi)^7 \Delta_\zeta^4 \frac{\delta^3(\mathbf{k_1}+\mathbf{k_2}+\mathbf{k_3})}{k_1^2 k_2^2 k_3^2} f^{res} \times \left[\sin\left(\frac{\sqrt{2\epsilon}}{f} \log K/k_* \right) + \frac{f}{\sqrt{2\epsilon}} \sum_{i,j} \frac{k_i}{k_j} \cos\left(\frac{\sqrt{2\epsilon}}{f} \log K/k_* \right) \right]$$

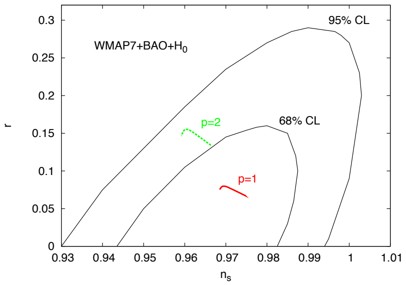
$$f^{res} \equiv \frac{3\sqrt{2\pi}\Lambda^4}{8V' f} \left(\frac{\sqrt{2\epsilon}}{f} \right)^{3/2} .$$

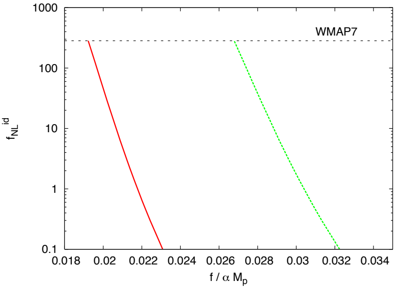
Large resonant non-Gaussianity

- Liner in Λ^4 as for the spectrum
- Spectrum and bispectrum are correlated and observable.
- Non-scale-invariant due to the sinusoidal oscillation

Inverse Decay in Axion Monodromy

- Inverse decay $A^2 \to \delta\phi$ generates running of the spectral tilt and non-Gaussianity
- All effects are controlled by $\xi \equiv \frac{\dot{\phi}\alpha}{2Hf}$
- Current bound $\xi < 2.6$ from non-Gaussianity.





What is the coupling in string theory?

- Axion inflation in string theory with a monodromy from an NS5-brane [McAllister, Silverstein & Westphal 08] .
- The DBI action after S-duality gives

$$S = \int d^4x\sqrt{-g}\left[-\frac{B}{4}F^{\mu\nu}F_{\mu\nu} - \frac{C}{4}F^{\mu\nu}\tilde{F}_{\mu\nu}\right],$$

$$B \equiv \frac{1}{|\tau|^2(2\pi)^3 g_s}\sqrt{g_2 g_s|\tau|^2 + (2\pi\phi/f)^2}, \quad C \equiv \frac{C_0 g_s^2\phi}{(2\pi)^2 f},$$

- Two regimes

$$C_0 g_s \ll 1 \to \xi \simeq \frac{M_{pl}^2}{2\phi^2}C_0 g_s \sim C_0 g_s 10^{-2} \ll 10^{-2}$$

$$C_0 g_s \gg 1 \to \xi \simeq \frac{M_{pl}^2}{2\phi^2}\left(C_0 g_s\right)^3 \sim \left(C_0 g_s\right)^3 10^{-2},$$

Observable only for $C_0 g_s \gtrsim 7$

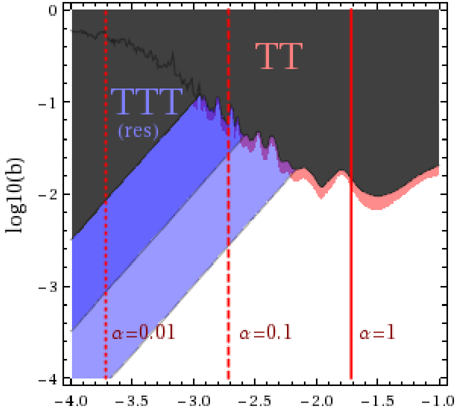
- In a toy IIB flux compactification this happens .5% of the time

Summary of Scalar Observables

- Remarkably, the coupling to a D5-brane would be

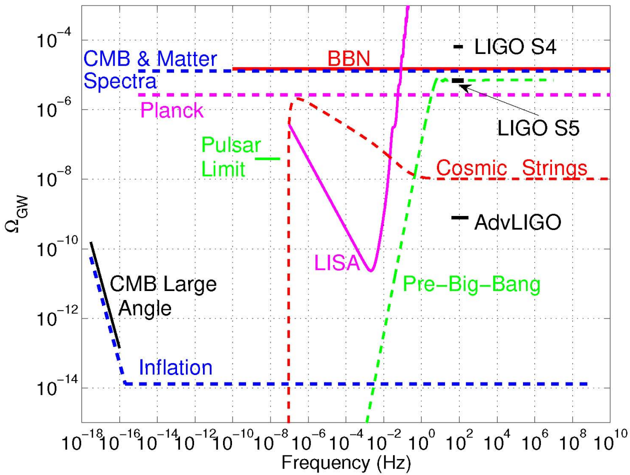
$$\alpha \equiv \frac{2\pi g_s}{v_2^s} \simeq .06$$

- Summarizing, all signals are competitive



Outline

It looks vary hard. . .



The standard vacuum contribution from inflation is quite small

But is it theoretically possible?

- Conservatively, consider Advanced LIGO's sensitivity around 10^2Hz

$$\Omega_{GW} \sim \frac{\Omega_{R,0}}{12\pi^2}|h_0|^2 > 6 \cdot 10^{-10}$$

- Not to stop inflation requires

$$M_{pl}^2 \dot{h}^2 \ll 3 M_{pl}^2 H^2 \quad \rightarrow \quad h \ll 1$$

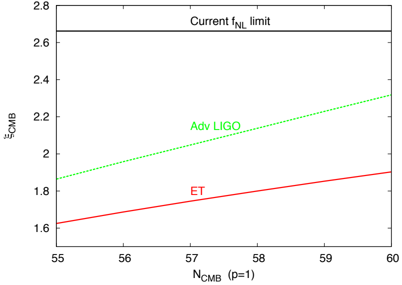
- There is a viable window!

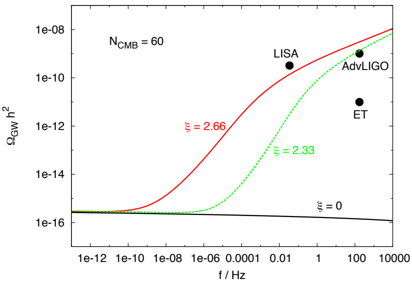
$$10^{-3} < h^2 \ll 1$$

- LISA/ELISA and Einstein Telescope will broaden this window

Numerical Results

Axion inflation with $\frac{\alpha}{f}\phi F\tilde{f}$ is the existence proof.





- Signal at LIGO/VIRGO correlated with non-Gaussianity in CMB
- Visible for $N \simeq 60$

What about the Scalars?

- Perturbation theory requires $\zeta^2 \ll 1$
- In the weak backreaction regime

$$P_\zeta \simeq P_T \epsilon^{-2}$$

- In the strong backreaction regime again $P_\zeta \simeq P_T \epsilon^{-2}$.
- One ϵ from $\delta\phi = \zeta\sqrt{2\epsilon}$. The other?
- Close to the end of inflation $\epsilon \sim .1$, so perturbation theory is OK (but close).
- Also tensors from particle production scale the same. There should be a reason …

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Observable tensor modes, through symmetry arguments, correlate with

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