Can you hear the shape of an axion potential?

Observing axion potentials through gravitational waves

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25 June, 2019
String **Phenomenology** Conference

based on:

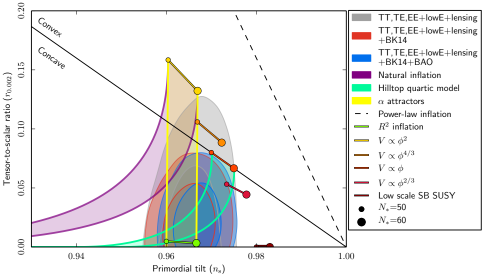
- JCAP **1905**, no. 05, 057 (2019), with T. Fujita, M. Shiraishi

related work:

- JHEP **1612**, 137 (2016), with P. Adshead, E .Martinec, M. Wyman
- JHEP **1708**, 130 (2017), with P. Adshead

(Simple) Single field inflation:

- Solves horizon, flatness, monopole problems
- Explains fluctuations as stretched quantum mechanical perturbations
- Predicts a **nearly scale invariant** spectrum (of tunable amplitude)
- Predicts **Gaussian** perturbations



- Spectral index is 5σ **away from flat**
- Spectral index running is small
- $|f_{NL}| \lesssim \mathcal{O}(1)$

$$n_T \lesseqgtr 0$$

$$r \leftrightarrow H$$

Axions & Natural Inflation

- A **pseudo-scalar** (axion) field obeys a **shift symmetry** that protects the potential from UV sensitive terms (η problem)
  Freese, Frieman, & Olinto 1990

- A field with a shift symmetry can only couple **derivatively** to other degrees of freedom

$$\mathcal{L}_{\rm int} \subset \boxed{\frac{\alpha}{f}\phi\epsilon^{\mu\nu\alpha\beta}F_{\mu\nu}F_{\alpha\beta}} + \frac{C}{f}\partial_\mu\phi\bar{\psi}\gamma_5\gamma^\mu\psi$$

- Fermions: not efficiently produced (Pauli blocking) and quickly diluted & redshifted. However there is interesting phenomenology, e.g. leptogenesis
  Adshead, EIS 2015 (JCAP & PRL)
  Adshead, Pearce, Peloso, Roberts, Sorbo 2018 & 2019

- $U(1)$ gauge fields with a Chern-Simons coupling grow **tachyonically** towards the end of inflation.
  Adshead, Giblin, Scully, EIS 2015 & 2016

Spectator Chromo-Natural Inflation

$$\mathcal{S} = \int d^4x\sqrt{-g}\ \Big\{ \frac{M_{\rm Pl}^2}{2}R - \frac{1}{2}(\partial\phi)^2 - V(\phi) - \frac{1}{2}(\partial\chi)^2 - U(\chi) - \frac{1}{2}Tr[F^2] - \frac{\lambda}{4f}\chi\, Tr[F\tilde{F}] \Big\}$$

Dimastrogiovanni, Fasiello, Fujita 2016

- The $SU(2)$ fields in the configuration

$$A_0^\alpha = 0\ ,\ \ A_i^\alpha = a(t)Q(t)\delta_i^\alpha$$

  exhibit a **scalar degree of freedom** $Q(t)$

  - Rotations: $A_i^\alpha \to R_{ij}\left(\vec{\theta}\right)A_j^\alpha = (\delta_{ij} + \epsilon_{ijk}\theta^k)A_j^\alpha$
  - Gauge tr.: $A_i^\alpha \to U(\lambda)A_iU^{-1}(\lambda))^\alpha = (\delta_b^a + \epsilon_{bc}^a\lambda^c)A_j^b$

- Is this configuration stable? **YES!**

Maleknejad & Sheikh-Jabbari 2011

Background evolution

$$\ddot{\chi} + 3H\dot{\chi} + U'(\chi) = -\frac{3g\lambda}{f} HQ^3 - \frac{3g\lambda}{f} Q^2 \dot{Q}$$

$$\ddot{Q} + 3H\dot{Q} + \dot{H}Q + 2H^2Q + 2g^2Q^3 = \frac{g\lambda}{f} Q^2 \dot{\chi}$$

for $\Lambda \equiv \frac{\lambda Q}{f} \gg 1$ and $m_Q \equiv \frac{gQ}{H} \gtrsim 1$

Introducing $\boxed{\xi \equiv \frac{\lambda \dot{\chi}}{2fH}}$

- $\xi \simeq m_Q + {m_Q}^{-1}$ and
- $Q \simeq \left(\frac{-f\,U'}{3\lambda g H}\right)^{1/3}$, $m_Q \simeq \left(\frac{-g^2 f\,U'}{3\lambda H^4}\right)^{1/3}$

The inflaton ϕ is responsible for the scalar modes and defines n_s.
The tensor modes in the metric (GW's) are

$$ds^2 = -dt^2 + a^2 e^{\gamma_{ij}} dx^i dx^j$$

In this case the **gauge sector has a tensor mode** too

$$A_\mu = (0, a(t)Q(t)\delta_i^\alpha + t_i^\alpha(t,x))\,\frac{\sigma_\alpha}{2}$$

Tensor fluctuations

$$\Box h_{ij} = -16\pi G \pi_{ij}$$

- Usually we consider the homogenous solution, which is a manifestation of quantum gravity
- The inhomogenous solution is given by sources of gravitational waves.

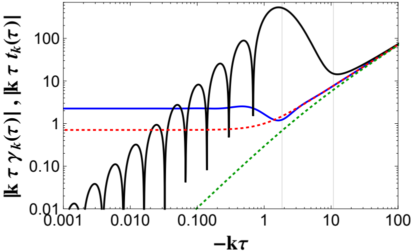
$$\partial_\tau^2 \gamma^\pm + \left(k^2 - \frac{2}{\tau^2}\right)\gamma^\pm = \mathcal{O}(\sqrt{\epsilon})t^\pm$$

$$\partial_\tau^2 t^\pm + \left(k^2 + \frac{2m_Q\xi}{\tau^2}\right)t^\pm \pm \frac{k}{\tau}(m_Q+\xi)\,t^\pm = \mathcal{O}(\sqrt{\epsilon})\gamma^\pm$$

Parity violation in $t^\pm$

unstable for $m_Q + \xi - \sqrt{m_Q^2+\xi^2} < -k\tau < m_Q + \xi + \sqrt{m_Q^2+\xi^2}$

Potential types & GW templates



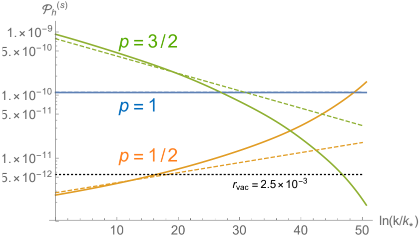
The GW's are given by

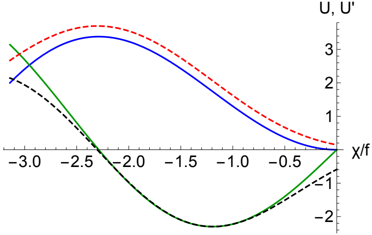
$$\mathcal{P}_h^{(s)} \simeq \frac{m_Q^4 H^4}{\pi^2 g^2 M_{\rm Pl}^4} \exp[2\alpha m_Q]$$

controlled by $m_Q \simeq \left(\frac{-g^2 f\, U'}{3\lambda H^4}\right)^{1/3}$

potential type	sample potential	GW template
I: convex / concave	$U(\chi) \propto \chi^p$	$\mathcal{P}_h^{(s)}(k) \propto \left(\frac{k}{k_*}\right)^{n_T}$
II: one inflection point	$\left[1 - \cos\left(\frac{\chi}{f}\right)\right]^{\frac{p}{2}}$	$\mathcal{P}_h^{(s)} \propto \exp\left[-\frac{\ln^2(k/k_*)}{2\sigma_h^2}\right]$
III: axion monodromy (modulated)	$\chi^p + \delta\cos(\nu\chi)$	$1 + A\sin\left[C\ln(\frac{k}{k_*}) + \theta\right]$ for $p = 1$ & $A \ll 1$

$$U \propto \chi^p \Rightarrow n_T = (p-1)\frac{2\alpha m_* + 4}{\Delta N}$$



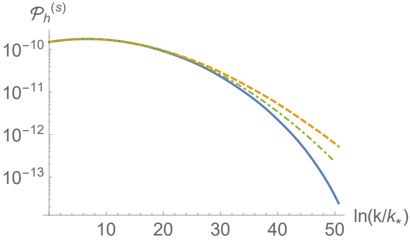


Kobayashi, Oikawa & Otsuka 2016

$$U \propto [1 - \cos(\chi/f)]^{\frac{p}{2}}$$

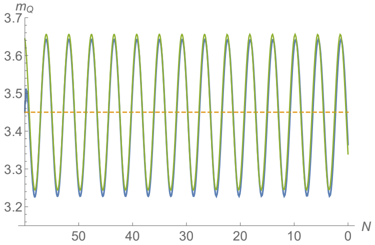
Around the **inflection point** the GW spectrum has a Gaussian shape

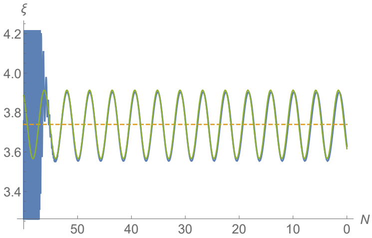
$$\mathcal{P}_h^{(s)} \simeq A_h \exp\left[-\frac{\ln^2(k/k_*)}{2\sigma_h^2}\right]$$



Consider a **modulated** potential $$U(\chi) = \mu^4 \left[\left| \frac{\chi}{f} \right|^p + \delta \cos\left(\frac{\kappa \chi}{\delta f} \right) \right]$$

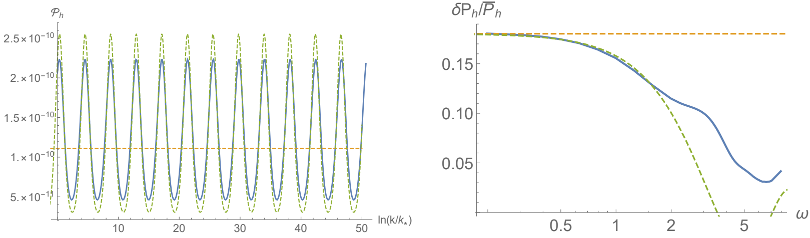
- Decompose the background quantities $\chi, Q, \ldots$ to extract the oscillatory part $\chi = \chi_0 + \chi_{\rm osc}$, $Q = Q_0 + Q_{\rm osc}$ etc.





Monodromy 2/2

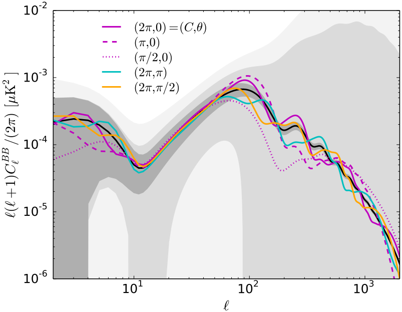
- Use the **oscillatory background functions** to compute the power spectrum.

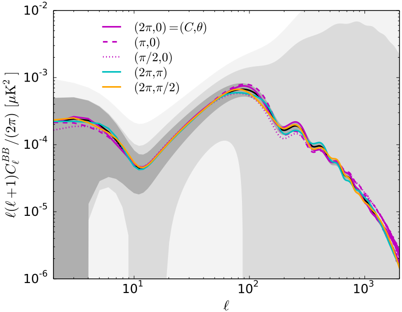


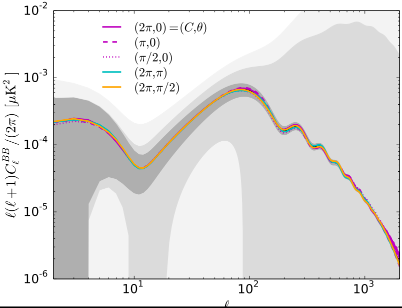
- We **analytically** capture the **period** and the **modulation amplitude** of GW's for small / intermediate values of the modulation frequency $\omega = \frac{2\kappa}{\delta\lambda}\xi_0$.

$$\mathcal{P}_h^{(s)}(k) \simeq \frac{H^4 m_0^4}{\pi^2 g^2 M_{\rm Pl}^4}\left[1 + 2(\alpha m_0 + 2)\Delta \cdot \sin(\omega H t)\right] e^{2\alpha m_0}$$

Anticipating LiteBIRD







$$\mathcal{P}_h^{(s)}(k) = \mathcal{P}_h^{(0)}\left[1 + A\sin\left(C\ln\frac{k}{k_*} + \theta\right)\right]$$

with $A = 0.9, 0.3, 0.1$

In principle **detectable modulation** for $A \gtrsim 0.3$

Is a blue tensor tilt a smoking gun for String Cosmology ?

Tensor Modes from a Primordial Hagedorn Phase of String Cosmology

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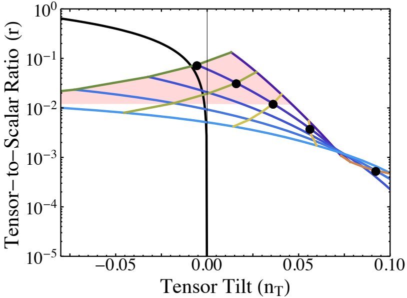
2) Jefferson Physical Laboratory, Harvard University, Cambridge, MA 02138, U.S.A.

(Dated: February 1, 2008)

SU(2) fields can lead to blue-tilted tensor modes!

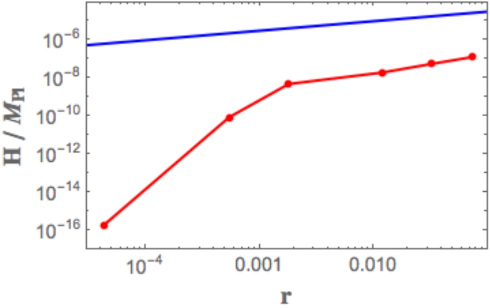
We did **not** ask for $n_T > 0$, it just happened . . .

We need better ballistics!



Holy Grail

<u>Standard Assumption:</u>
A detection of tensor modes reveals the **energy scale** of inflation



Observable gravity waves can be produced at a (much)
lower inflationary scale
than naively estimated

Experimental roadmap

First of all:

Discover **tensor modes** & make sure they're truly **primordial**

1. Measure the **tensor spectrum**: scale-invariant, red or blue?
2. Measure TE, TB correlators: test **parity-violating** modes.
3. Measure tensor **non-Gaussianity**

If:

1. scale-invariant
2. non-chiral
3. Gaussian

$\Rightarrow$ vacuum modes

If:

1. scale-invariant or not
2. parity-violating
3. non-Gaussian

$\Rightarrow$ sourced primordial GW's

If in addition we detect **modulated** B-modes
$\Rightarrow$ String **Phenomenology** takes off

Thank you . . .

This work is supported by the
Netherlands Organisation for Scientific Research (NWO).