Probing axion-like particles using gravitational waves

Theory Seminar
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Overview

- The early Universe and new physics
- Gravitational waves as windows into the early Universe
  - Axions, strong CP problem, and dark matter
- Probing axions with GWs
We want to find new physics!

- To explain/understand
  - Dark Matter
  - Baryon asymmetry
  - Naturalness, flavour, neutrino masses, strong CP...
We want to find new physics!

- To explain/understand
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- Our best evidence for new physics comes from astrophysics and cosmology
  - Can hope to learn something about new physics by studying and observing the early universe
What do we know about the early Universe?
 Thermal History

- Afterglow Light Pattern 380,000 yrs.
- Dark Ages
- Development of Galaxies, Planets, etc.
- Dark Energy Accelerated Expansion
- Inflation
- Quantum Fluctuations
- 1st Stars about 400 million yrs.

Big Bang Expansion
13.7 billion years
Gravitational Waves?

- First direct observation in 2016
- New window into early universe

- Electroweak symmetry breaking
- Baryogenesis
- Dark matter production
GWs & early Universe

- CMB encodes information about the state of the universe at the time of its emission
  - Densities of matter, radiation, dark matter
  - Fluctuations (seeds for galaxy formation)
  - Hubble rate (interesting discrepancy!)
- GWs could do the same
  - For earlier (and different) times
  - Need a strong source (CMB photons are just there!)
Primordial sources of GWs

- First order phase transitions (symmetry breaking)
- Inflation/Reheating
- Cosmic strings
- and now... Axions!

from Hindmarsh et al

Pedro Schwaller — Astro/Particle Theory
- Characteristic for source, e.g.
- Phase transition, peak location depends on $T_{\text{nuc}}$
- Cosmic strings
Frequency ranges

**FIG. 2.** Noise curves (left) and PLI sensitivity curves (right) for various gravitational wave observatories. Dashed black lines in the left-hand plot indicate the expected magnitude of several important backgrounds, in particular super-massive black hole binaries (SMBHB)\(^5\)\(^5\),\(^5\)\(^6\), and galactic\(^5\)\(^7\),\(^5\)\(^8\), as well as extra-galactic\(^5\)\(^9\),\(^5\)\(^10\) compact binaries (CB). In determining the power-law integrated sensitivity curves (as well as in the toy model analyses presented in Section 11), we assume that the SMBHB background will eventually be resolvable, while the CB background will remain unresolved. In the right-hand plot, we also show example spectra generated by a phase transition at \(T_{nuc} = 10\) GeV and with \(\phi = 0\).\(^1\),\(^1\)/\(H = 10\) for both runaway and non-runaway bubbles. The parameter choices made for forthcoming experiments are given in Appendix B, and the data underlying our noise curves and PLI sensitivity curves can be found in the ancillary material.

A stochastic gravitational wave background is detectable if the signal-to-noise ratio (SNR) is greater than a certain threshold value \(\chi_{\text{thr}}\), which is either given by the experimental collaborations or extracted from existing data as described in Appendix B.\(^6\),\(^6\),\(^6\).\(^1\)

The optimal-filter cross-correlated signal-to-noise is \[^4\]

\[
\frac{\chi^2_{\text{GW}}(f)}{\chi^2_{\text{EE}}(f)} = 2, \quad t_{\text{obs}} f_{\text{max}} = \int_{f_{\text{min}}}^{f_{\text{max}}} h^2 \Delta f \equiv h^2 \Delta f \int_{f_{\text{min}}}^{f_{\text{max}}} f^b \Delta f
\]

where \(t_{\text{obs}}\) is the duration of the observation, \((f_{\text{min}}, f_{\text{max}})\) is the detector frequency band, and \(h^2 \Delta f\) is the gravitational wave energy density at the arbitrarily chosen reference frequency \(\bar{f}\). According to Eq. (27), such a power-law signal is detectable if \(h^2 \Delta f > h^2 \Delta f_{\text{thr}}\) (29).

For the case of a single-detector auto-correlated analysis, the factor 2 in Eq. (27) has to be dropped.

Space based

Ground based

Pulsar timing arrays
Data already available
Axions?
Axions & ALPs

- Strong CP problem
  \[ \mathcal{L}_{\text{QCD}} \supset \theta \frac{g_s^2}{32\pi^2} G \tilde{G} \]
  with \( \Theta \sim 1 \)

- Neutron EDM:
  \[ |d_n| \lesssim 10^{-26} \text{e cm} \implies \theta < 10^{-10} \]

- Axion is dynamical solution
  \[ \mathcal{L}_{\text{QCD}} \supset \left( \theta + \frac{a}{f_a} \right) \frac{g_s^2}{32\pi^2} G \tilde{G} \]

- Ground state has \( \Theta \sim 0 \)

symmetry breaking scale, suppresses couplings to SM
Axion misalignment and DM

- Axion EOM

\[ \phi'' + 2aH \phi' + a^2 m_\phi^2 \phi = 0 \]

- Starts rolling when \( H \sim m_\phi \)

- Redshifts with \( a^{-3} \), i.e. like non-relativistic matter

- Candidate for non-particle dark matter
Relic abundance

- Energy density
  \[ \rho_\phi = \frac{1}{2} m_\phi^2 \theta^2 f^2 \]

- Hubble
  \[ m_\phi \sim H_{osc} \sim \frac{T_{osc}^2}{M_P} \]

- Energy fraction
  \[ \frac{\rho_\phi}{\rho_{rad}} \sim \frac{m_\phi^2 \theta^2 f^2}{T_{osc}^4} \sim \frac{\theta^2 f^2}{M_P^2} \]

- Increases due to redshift
  \[ \frac{a_{osc}}{a_{eq}} \sim \sqrt{\frac{m_\phi M_P}{eV}} \]
Relic abundance II

\[ \Omega_{\text{today}} \sim \theta^2 f^2 \frac{m_\phi^{1/2}}{M_P^{3/2} \text{eV}} \]

\[ \Omega_{\text{observed}} \approx 0.12 \]

\[ \text{Log}[\text{GeV}/f] \]

\[ \text{Log}[m_\phi/\text{GeV}] \]

OK

overproduction
The Audible Axion

- We consider the following effective field theory consisting of an axion-like particle (ALP) $\phi$ and a massless dark photon $X_{\mu}$

$$S = \int d^4 x \sqrt{-g} \left[ \frac{1}{2} \partial_\mu \phi \partial^\mu \phi - V(\phi) - \frac{1}{4} X_{\mu\nu} X^{\mu\nu} - \frac{\alpha}{4 f^2} \phi X_{\mu\nu} \tilde{X}^{\mu\nu} \right]$$

- We assume some explicit breaking of the global symmetry at the scale $\Lambda = \sqrt{m_f}$, which generates a mass for the ALP

$$V(\phi) = m^2 f^2 \left[ 1 - \cos \left( \frac{\phi}{f} \right) \right]$$

$$\phi_i = \theta f , \quad \phi'_i \approx 0 , \quad \theta \sim \mathcal{O}(1)$$
• Since the ALP has no reason to be near the minimum of the potential when it tilts, we generically expect initial conditions of the form

\[ \phi_i = \theta f, \quad \phi_i' \approx 0, \quad \theta \sim \mathcal{O}(1) \]
Rolling

• The ALP begins to oscillate when the Hubble rate drops below the ALP mass

\[ H_{\text{osc}} \sim m, \quad \rho_{\phi}^{\text{osc}} \sim \frac{1}{2} m^2 \phi_i^2 \]

\[ \Omega_{\phi}^{\text{osc}} = \frac{\rho_{\phi}^{\text{osc}}}{\rho_{\text{tot}}^{\text{osc}}} \approx \frac{m^2 \theta^2 f^2 / 2}{3M_P^2 H_{\text{osc}}^2} \approx \left( \frac{\theta f}{M_P} \right)^2 \]

• Dark Photon EOM

\[
\left( \frac{\partial^2}{\partial \tau^2} - \nabla^2 \right) \vec{X} = \alpha \frac{\phi'}{f} \vec{\nabla} \times \vec{X}, \quad \vec{\nabla} \cdot \vec{X} = 0. 
\]

Source for dark photons (while ALP rolls)
We quantize the dark photon field as

$$\hat{X}^i(x, \tau) = \sum_{\lambda=\pm} \int \frac{d^3k}{(2\pi)^3} v_\lambda(k, \tau) \varepsilon^i_\lambda(k) \hat{a}_\lambda(k) e^{ik \cdot x} + h.c.$$ 

which leads to the following equation for the mode functions

$$v''_{\pm} + \omega^2_{\pm}(\tau) v_{\pm} = 0, \quad \omega^2_{\pm}(\tau) = k^2 \mp k \frac{\alpha}{f} \phi'$$

As the ALP rolls, there exist momenta for which $\omega^2_{\pm}$ is negative. The corresponding modes are tachyonic and grow exponentially:

$$v_{\pm}(k, \tau) \sim e^{\pm |\omega_{\pm}| \tau}$$

Circular pols. $(k \times \varepsilon_{\pm} = \mp ik\varepsilon_{\pm})$
- Initial condition violates parity (field rolls to the left or to the right)
- One dark photon helicity dominates
- A certain range of modes undergoes tachyonic growth

\[ 0 < k < \frac{\alpha \phi'}{f}, \quad \frac{k}{m} \lesssim \alpha \theta \]
Relic abundance

- Tachyonic dark photon production
- + parametric resonance
- Efficient energy transfer away from axion
- $N_{\text{eff}}$ constraint on dark photon abundance
GW production

Dark photon modes in the range $0 < k < \theta \alpha m$ which were initially in vacuum grow exponentially when the axion begins to oscillate

$$v_{\pm}(k, \tau \ll \tau_{osc}) = \frac{1}{\sqrt{2k}} e^{-ik\tau} \quad \omega^2_{\pm} < 0 \quad v_{\pm}(k, \tau) \sim e^{\omega_{\pm}|\tau|}$$

These rapidly growing modes amplify quantum fluctuations of the dark photon into a time-varying, anisotropic classical energy distribution which sources gravitational waves

$$h_{ij}''(k, \tau) + k^2 h_{ij}(k, \tau) = \frac{2}{M_P^2} \Pi_{ij}(k, \tau),$$

$$\Pi_{ij}(k, \tau) = \frac{\Lambda_{ij}^{kl}}{a^2} \int \frac{d^3 q}{(2\pi)^3} \left[ \hat{E}_k(q, \tau) \hat{E}_l(k - q, \tau) + \hat{B}_k(q, \tau) \hat{B}_l(k - q, \tau) \right].$$
GW production II

Energy Density of Dark Photon

Anisotropic Stress
$k_{\text{peak}} \approx (\alpha \theta)^{2/3} m$,

$\Omega_{GW}(k_{\text{peak}}) \approx \left( \frac{f}{M_P} \right)^4 \left( \frac{\theta^2}{\alpha} \right)^{\frac{4}{3}}$
\[ f_0 \approx m \left( \frac{T_0}{T_*} \right) (\alpha \theta)^{2/3} = \sqrt{\frac{m}{M_P}} T_0 (\alpha \theta)^{2/3}, \quad \Omega_{GW}^0 \approx \Omega_\gamma^0 \left( \frac{f}{M_P} \right)^4 \left( \frac{\theta^2}{\alpha} \right)^{4/3} \]
Signals

Also strongly polarized since one dark photon chirality is dominantly produced

\[ f_0 \approx m \left( \frac{T_0}{T^*} \right) (\alpha \theta)^{2/3} = \sqrt{\frac{m}{M_P}} T_0 (\alpha \theta)^{2/3}, \]

\[ \Omega_{GW}^0 \approx \Omega_{\gamma}^0 \left( \frac{f}{M_P} \right)^4 \left( \frac{\theta^2}{\alpha} \right)^{4/3} \]
Constraints on ALP plane

Machado, Ratzinger, PS, Stefanek, 1912.01007
- Green: Dark Photon DM produced by tachyonic instability

- See models by Dror, Harigaya, Narayan; Co, Pierce, Zhang, Zhao; Bastero-Gil, Santiago, Ubaldi, Vega-Morales; Agrawal, Kitajima, Reece, Sekiguchi, Takahashi

Machado, Ratzinger, PS, Stefanek, 1912.01007
Probes of dark photon DM

- Large suppression of axion relic abundance required
- Could be spoiled by backscattering of dark photons into axions

Machado, Ratzinger, PS, Stefanek, 1912.01007
Lattice

\[ \phi'' + 2aH\phi' + a^2 \frac{\partial V}{\partial \phi} = \frac{\alpha}{f} a^2 \vec{E} \cdot \vec{B}, \]

- So far we solved this equation for the zero mode (vacuum expectation value) of the axion field, taking the expectation value of \( \vec{E} \cdot \vec{B} \)
- Dark photons will scatter back into axions, producing quanta (= inhomogeneities)
- To include this, add back \( \nabla \phi \) terms in EOM, and solve coupled EOMs on the lattice
  (in position space... )
Preliminary results

- Dark photon backscattering induces inhomogeneities in the axion field—destroys the coherently oscillating condensate.

- Lose parametric resonance, so can only suppress by $10^2 - 10^3$

ongoing work, with Wolfram Ratzinger and Ben Stefanek
- GWs mainly produced during initial tachyonic phase
  - expect that signal remains similar

- ... yes, but peak is broadened from contribution of axion inhomogeneities to GW spectrum

ongoing work, with Wolfram Ratzinger and Ben Stefanek
- Performing lattice study of axion-dark photon system
  - important for relic abundance estimate
  - GW shape and polarisation

- Solving relic abundance requires additional model building outside of SKA region
  - Monodromy
  - Witten effect
  - ...

\[ T_{\text{osc}} \text{ (GeV)} \]

\[ \frac{1}{f} \text{ (GeV}^{-1}) \]

\[ m \text{ (eV)} \]
Summary

- Gravitational waves offer unique window into the early universe
- Can hope to observe GWs from a strong EWPT
- Could be first (or only) way to obtain signals from a strongly coupled hidden sector
- New way to probe axions/ALPs
- Tachyonic particle production frequently used in model building (inflation, relaxion, reheating)
  - More precise numerical studies under way
Cosmic strings

- Topological defects or stretched superstrings
- Formed after inflation or in PTs
- Interact and form loops
- Loops loose energy by GW radiation
We have seen DM in the sky:

Maybe DM is just part of a larger dark sector

- Example: Proton is massive, stable, composite state
- DM self interactions solve structure formation problems
- New signals, new search strategies!

But no direct observation
DM Motivation

• New mechanisms for relic density, extend mass range:
  ‣ Asymmetric DM - GeV-TeV scale
  ‣ Strong Annihilation - 100 TeV scale
  ‣ SIMP - MeV scale
  Hochberg, Kuflik, Volansky, Wacker, 2014; + Murayama, 2015

• Advantages of Composite
  ‣ DM mass scale and stability
  ‣ Fast annihilation for ADM
  ‣ Self-interactions for structure formation
GW spectra

• Lot of work on GW from 1st order PT
  • Still difficult to simulate or model

• Here in addition:
  • Transition is non-perturbative
  • Parameters not known - take an optimistic guess

\[
\frac{\beta}{H_*} = 1 - 100
\]

\[
\nu = 1
\]

\[
\frac{\kappa \alpha}{1 + \alpha} = 0.1
\]

See talks by Hindmarsh, Weir for more details
SU(N) - PT 2

- One more parameter: $\Theta$ angle
- Effect on PT not well studied
- $N_d, n_f$ dependence of PT strength?
  - QCD FOPT?
    - QCD FOPT? [Schwarz, Stuke, 2009]
  - GW signal:
    - GW signal: [Caprini, Durrer, Siemens, 2009]

Finite density/chemical potentials?

- Finite density/chemical potentials?
  - Finite density/chemical potentials? [Panero, 2009]

\[ H^2 \Omega(f) \]

Current NANOGrav sensitivity

PTA 2020

LISA

Current NANOGrav sensitivity

PTA 2020

LISA
Electroweak Baryogenesis

• Baryogenesis requires departure from thermal equilibrium

• EWPT also provides B and CP violation, but no first order transition

• Strong motivation to study BSM scenarios with a strong EWPT. Examples:
  ‣ Modified Higgs self-coupling
  ‣ Extended scalar sectors
  ‣ Radion in warped extra dimensions

For more details, see talks by Geraldine, Michael, Jeremy
Example: Radion in RS

Konstandin, Nardini, Quiros, 2010
Example: Strong EWPT

\[
T_* = 100 \text{ GeV}
\]