Gravitational waves from a dilaton-induced, first-order QCD phase transition

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Motivation

- Pulsar Timing Array (PTA) collaborations have reported evidence for a stochastic nanohertz GW background.
- Cosmological first-order phase transitions are a compelling source of stochastic GWs.
- This paper shows how a QCD-sector *dilaton can make the QCD transition first-order and produce a PTA-scale GW signal.*

QCD dilaton: basic idea

- Quantum gravity is expected to have no free parameters or true constants.
- Introduce a scalar 'dilaton' field ϕ that the dynamical QCD coupling constant 'secretly' depend on.
- μ the energy scale, $\beta_0 = 11 - 2N_f/3$, g_3 coupling constant. $f(\phi)$ sets the coupling.

$$\Lambda_{\mathrm{QCD}} = \mu \exp\left[-\frac{8\pi^2}{\beta_0 g_3^2(\mu)}\right]$$

$$\mathcal{L} = -\frac{1}{2}\mathfrak{f}(\phi)\mathrm{tr}\left(G_{\mu\nu}G^{\mu\nu}\right) + \sum_i \bar{q}_i \left(i\not{D} - m_i\right) q_i + \frac{1}{2}(\partial\phi)^2 - V_0(\phi)\,,$$

Scenario

- The zero-temperature dilaton potential $V_0(\phi)$ has two minima with $V_0(\phi_{FV}) > V_0(\phi_{TV})$, and, importantly, $f(\phi_{FV}) > f(\phi_{TV})$.
- This **assumption** means that QCD is more weakly coupled in the false vacuum than in the true vacuum.
- Possible realisations: modulus field from string theory, holomorphic gauge kinetic function of supergravity...
- For $\Delta f \sim O(1)$, QCD with ϕ_{FV} remains weakly coupled well below the critical temperature.
- Experiments: $\alpha_s(m_Z) = 0.1180 \pm 0.0009$

$$\mathfrak{f}_{\rm TV} \equiv \mathfrak{f}\left(\phi_{\rm TV}\right) = \frac{\beta_0}{8\pi^2} \ln\left(\frac{\Lambda_{\rm UV}}{m_Z}\right) + \frac{1}{4\pi\alpha_s(m_Z)}$$

$$\Lambda_{\rm QCD}^{\rm FV} = \Lambda_{\rm QCD}^{\rm TV} \exp\left(-\frac{8\pi^2 \Delta\mathfrak{f}}{\beta_0}\right)$$

Potential

- V_0 zero-temperature potential, V_T thermal one loop correction, J_B thermal bosonic function, $m_\phi \sim 10$ TeV, V_P thermal QCD correction, $\alpha_s = 1/(4\pi f)$

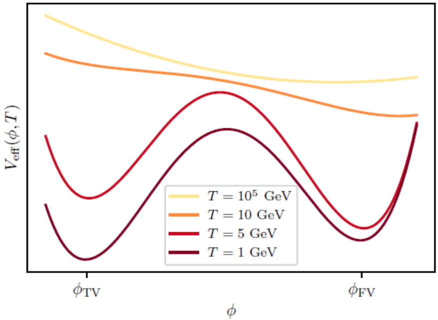
$$V_{\rm eff}(\phi) = V_0(\phi) + V_{\rm T}(\phi) + V_{\mathcal{P}}(\phi)$$

$$V_{\rm T}(\phi) = \frac{T^4}{2\pi^2} J_{\rm B}\left(\frac{m_\phi^2(\phi)}{T^2}\right)$$

$$V_{\mathcal{P}}(\phi) = -\frac{8\pi^2 T^4}{45}\left(\frac{17}{3} - \frac{235}{16}\alpha_s(\phi) + \mathcal{O}(\alpha_s^{3/2})\right)$$

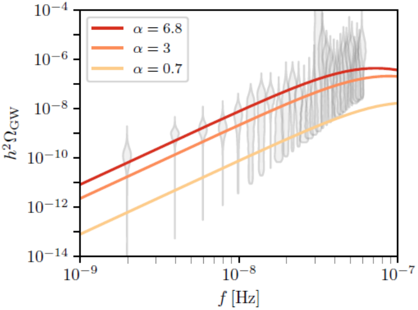
Phase Transition

- **Outside** the bubble, ϕ is at false vacuum, QCD coupling is weak and quark matter remains.
- **Inside** the bubble, ϕ is at true vacuum, QCD coupling is strong and the crossover rapidly realizes the hadronisation.
- This scenario effectively turns the QCD phase transition first order.
- Supercooled: β/H is small.



GW sources and spectrum

- Peak frequency falls in the PTA band (nano-Hz) for QCD-scale transitions with the model's parameters.
- $\beta/H = 3 \sim 8$



Conclusions

- A QCD dilaton can turn the QCD phase transition first-order and produce a stochastic GW background.
- Dilation and false vacuum scenario is applicable ?