Chiral Primordial GWs due to the produ ction of non-Abelian gauge field

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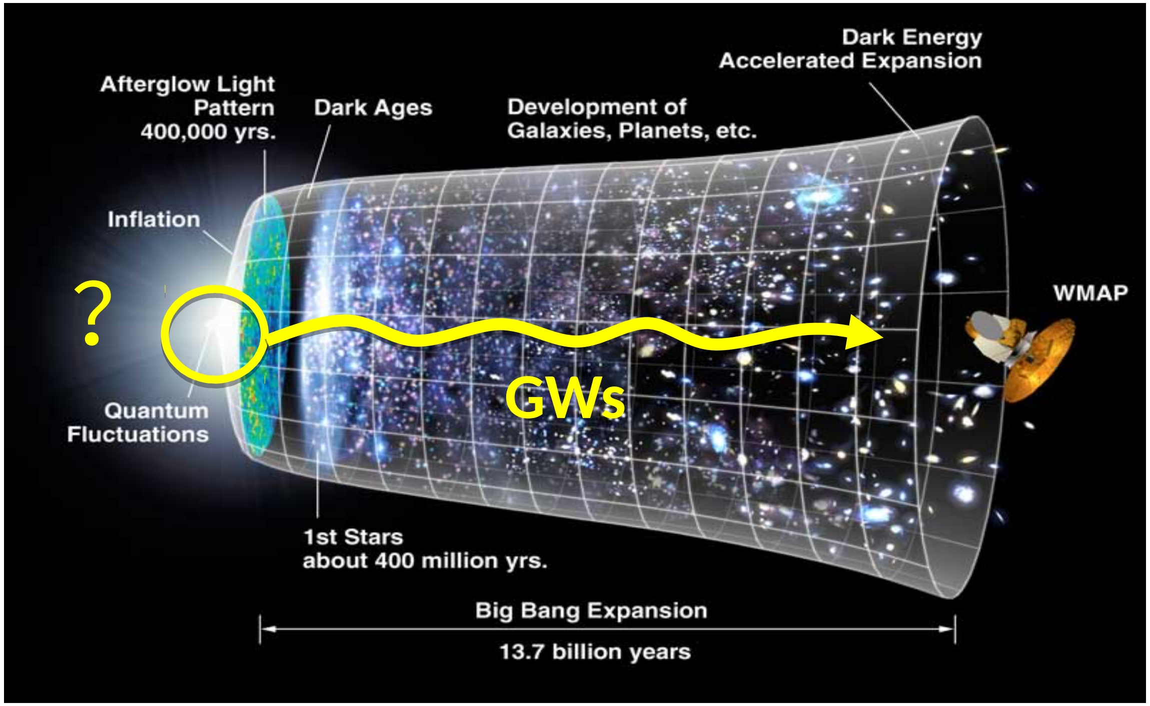
Introduction

Primordial GWs from an early Universe



Inflationary energy scale (single field)

$$\Lambda \simeq 10^{16}\text{GeV}\left(\frac{r}{0.01}\right)^{1/4}$$

← **High energy physics?**

How are GWs generated?

Simple scenario (inflaton + graviton)

$$(ah_{ij})'' + \left(k^2 - \frac{a''}{a}\right)(ah_{ij}) = 0$$ (vacuum fluctuations)

↕

High energy physics (many scalar fields + gauge fields)

$$(ah_{ij})'' + \left(k^2 - \frac{a''}{a}\right)(ah_{ij}) = \underline{S_{ij}}$$

⟶ $$h_{ij} = (h_{ij})_{\mathrm{vacuum}} + \boxed{(h_{ij})_{\mathrm{source}}}$$

Today's talk...

Primordial GWs souced by gauge field coupled to axion

(Abelian case)

$$\delta A_i \times \delta A_j \to h_{ij}$$ (provide GWs at non-linear level)

(non-Abelian (SU(2)) case)

$$\delta A_i^a \to h_{ij}$$ (provide GWs at linear level !)

Axion-gauge interaction

$$\boxed{\frac{\varphi}{f} F\tilde{F}} \supset \pm k \frac{\bar{\varphi}'}{f} \delta A_k^{\pm} \delta A_k^{\pm}$$

$$|\delta A_k^+| \neq |\delta A_k^-| \longrightarrow |\delta g_k^+| \neq |\delta g_k^-|$$

Parity-violated GWs !

Today's talk…

Primordial GWs souced by gauge field coupled to axion

- ✓ We focus on the mechanism of providing chiral tensor spectrum sourced by non-Abelian gauge field coupled to axion.

- ✓ We construct the model which generates testable chiral GWs with space-based GW experiments and pulsar timing array, which satisfy CMB constraints.

Background of our study

Axionic inflation with SU(2) gauge field

Chromo-natural inflation

P.Adshead & M. Wyman 2012

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g\epsilon^{abc} A^b_\mu A^c_\nu$$

$$S = S_{\rm EH} + S_{\rm axion} + S_{\rm gauge} + S_{\rm CS}$$
$$= \int d^4x \left[\frac{1}{2}R - \frac{1}{2}(\partial_\mu\varphi)^2 - V(\varphi) - \frac{1}{4}F^{a\mu\nu}F^a_{\mu\nu} - \frac{1}{4}\lambda\frac{\varphi}{f}\tilde{F}^{a\mu\nu}F^a_{\mu\nu}\right]$$

inflaton + SU(2) gauge field

$$\lambda \gg 1$$

$$\varphi = \bar{\varphi}(t) + \delta\varphi \qquad A^a_i = a(t)Q(t)\delta^a_i + \delta A^a_i$$

Slow-roll equation

$$\ddot{\varphi} + 3H\dot{\varphi} + V_\varphi = -3\frac{\lambda}{f}gQ^2\frac{\dot{(aQ)}}{a}$$

Friction term

$$Q(t) \simeq Q_{\rm min} \equiv -\left(\frac{V_{\tilde{\varphi}}}{3\lambda g H}\right)^{1/3}$$

$$\tilde{\varphi} \equiv \frac{\varphi}{f}$$

Axionic inflation with SU(2) gauge field

Considering perturbaitons...

$$\varphi = \bar{\varphi}(t) + \delta\varphi \quad A_i^a = a(t)Q(t)\delta_i^a + \delta A_i^a$$

$$(\delta A_i^a)^{\mathrm{TT}} \leftrightarrow \delta g_{\mu\nu}$$

couples through $Q(t)$

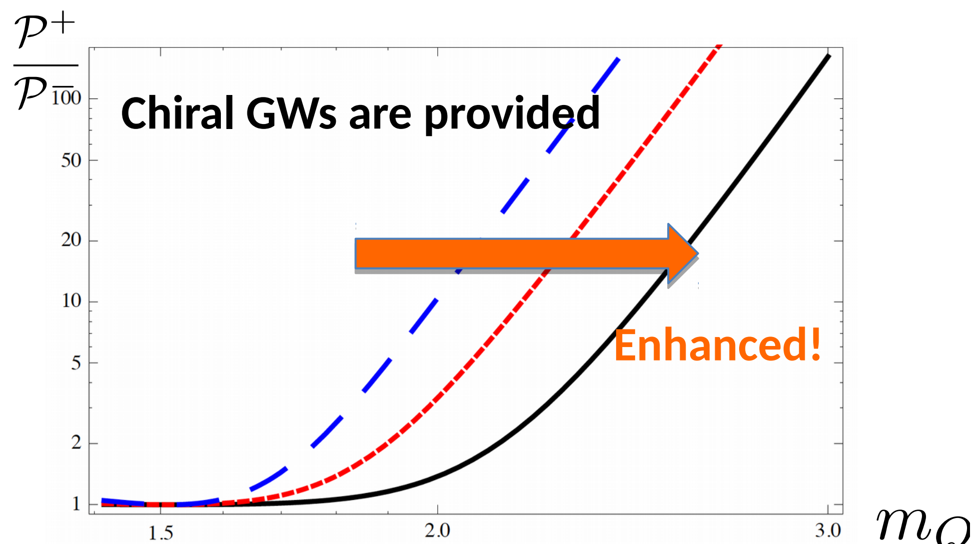
EOM for free gauge particle (tensor modes) (x : dimensionless time variable)

$$\frac{d^2 t_k^{\pm}}{dx^2} + \left(1 + \frac{A}{x^2} \mp \frac{2B}{x}\right) t_k^{\pm} \simeq 0$$

$$\supset \frac{\varphi}{f} F\tilde{F}$$

$$A = 2(m_Q^2 + 1) > 0$$
$$B = 2m_Q + m_Q^{-1} > 0$$

$$m_Q \equiv \frac{gQ}{H}$$



P.Adshead, E. Martinec & M. Wyman 2013

One hericity mode is enhanced

Axionic inflation with SU(2) gauge field

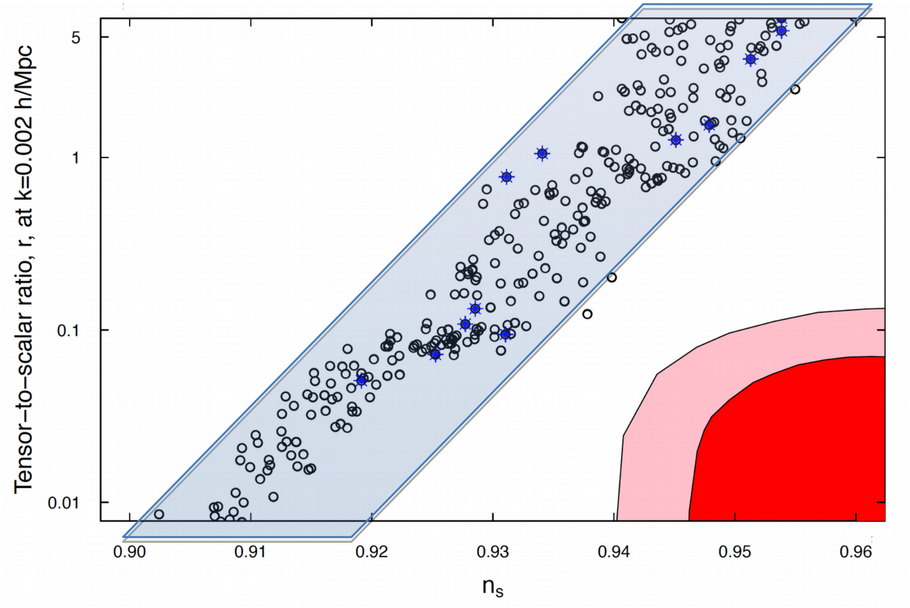
Observational constraint on CMB

Gauge field also produces scalar part.

$$\delta A + \bar{A} \longrightarrow \delta\varphi \ (\zeta)$$

affect

n_s , r (CMB observation)



P.Adshead, E. Martinec & M. Wyman 2013

In conflict with CMB observation…

Our study

Reconsidering conventional model…

Chromo-natural inflation

$$\mathcal{L} = -\frac{1}{2}(\partial_\mu \varphi)^2 - V(\varphi) - \frac{1}{4}FF - \frac{\lambda}{4}\frac{\varphi}{f}F\tilde{F}$$

✕ **CMB observation**

(large amount of chiral GWs)

Considering from the point of high energy physics…

$$FF \to I(t)^2 FF \quad \left(\lambda \to \frac{\lambda}{I(t)^2} \equiv \lambda_{\rm eff}(t) : \text{dynamical} \right)$$

A gauge-kinetic function of scalar field "dilaton"

Chiral GWs generation should depend on time!

Dilaton and Axion with SU(2) fields

Model building

IO and J. Soda 2016

Action

$$S = S_{\rm EH} + S_{\rm dilaton} + S_{\rm axion} + S_{\rm gauge} + S_{\rm CS}$$
$$= \int dx^4 \sqrt{-g}\left[\frac{1}{2}R - \frac{1}{2}(\partial_\mu \varphi)^2 - V(\varphi) - \frac{1}{2}(\partial_\mu \sigma)^2 - W(\sigma) - \frac{1}{4}I(\varphi)^2 F^{a\mu\nu}F^a_{\mu\nu} - \frac{1}{4}\lambda\frac{\sigma}{f}\tilde{F}^{a\mu\nu}F^a_{\mu\nu}\right]$$

The scalar fields and SU(2) gauge field

$\varphi(t)$: dilaton

$Q(t)$: VEV of the gauge fields $\quad A^a_i = A(t)\delta^a_i = a(t)Q(t)\delta^a_i$

$\sigma(t)$: axion

Dilaton and Axion with SU(2) fields

Friedmann equation and EOM for a(t)

$$3H^2 = \frac{1}{2}\dot{\varphi}^2 + V + \frac{1}{2}\dot{\sigma}^2 + W + \rho_E + \rho_B$$

$$\dot{H} = -\left(\frac{1}{2}\dot{\varphi}^2 + \frac{1}{2}\dot{\sigma}^2 + \frac{2}{3}(\rho_E + \rho_B)\right)$$

$$\rho_E \equiv \frac{3}{2}I^2 E^2 = \frac{3}{2}I^2 \frac{\dot{A}^2}{a^2}$$

$$\rho_B \equiv \frac{3}{2}I^2 B^2 = \frac{3}{2}I^2 \frac{g^2 A^4}{a^4}$$

EOMs for φ(t), σ(t) and A(t)

$$\ddot{\varphi} + 3H\dot{\varphi} + V_\varphi = 2\frac{I_\varphi}{I}(\rho_E - \rho_B)$$

$$\ddot{\sigma} + 3H\dot{\sigma} + W_\sigma = -3\frac{\lambda}{f}EB$$

$$\ddot{A} + \left(H + 2\frac{\dot{I}}{I}\right)\dot{A} + 2g^2\frac{A^3}{a^2} = \frac{\lambda}{f}\dot{\sigma}g\frac{A^2}{aI^2}$$

$$I(\varphi) = I_0 \exp[-n\int_0 \frac{V}{V_\varphi}d\varphi]$$

Dilaton and Axion with SU(2) fields

Initial conditions of the background motion

- dilaton is energy dominant (playing a role of an inflaton) :

$$3H^2 \simeq V \quad (\varphi(t) : \text{inflaton})$$

→ Producing CMB fluctuations!

- weak gauge kinetic coupling function :

$$I(\varphi) \propto a(t)^n \ , \ n \leq -2 \quad \left(\frac{\lambda}{I(\varphi_i)^2} \ll 1 \right)$$

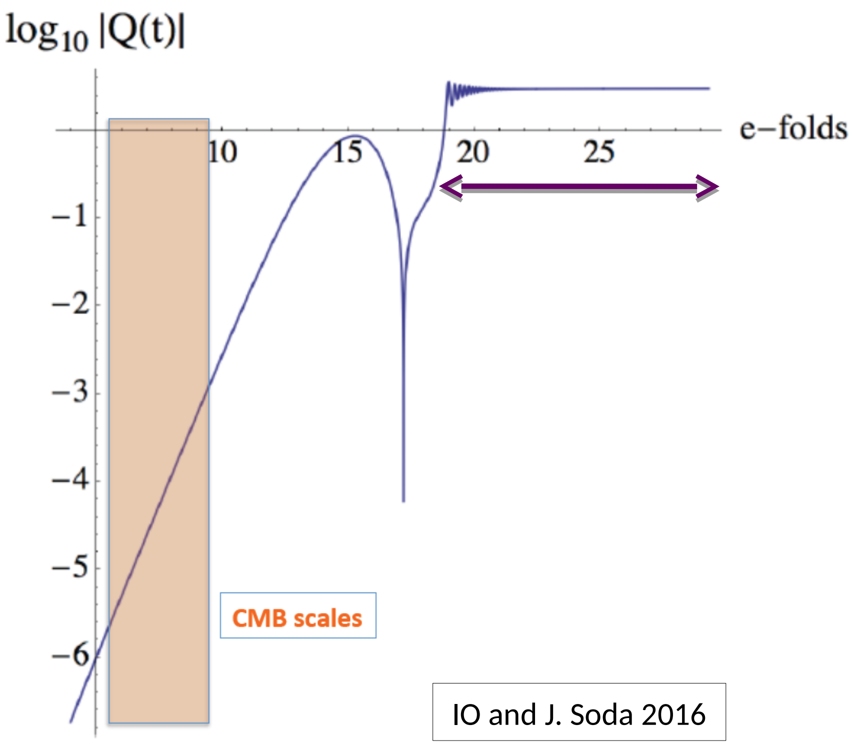
(Suppressing axion-gauge interactions)

- The vev of gauge field is near the origin of its effective potential:

$$U_{\rm eff}(Q) = \left(1 + \frac{\dot{I}}{HI}\right) H^2 Q^2 - \frac{1}{3}\frac{\lambda}{f}\dot{\sigma}\frac{gQ^3}{I^2} + \frac{1}{2}g^2 Q^4$$

Dilaton and Axion with SU(2) fields

The dynamics of the vev of gauge field



$$(\Lambda_\varphi,\ \Lambda_\sigma,\ r,\ n,\ g,\ \lambda,\ f) = (10^{-2},\ 2\times10^{-3},\ 1,\ -2.01,\ 10^{-6},\ 10^{-1},\ 10)$$

$$V(\varphi) = \Lambda_1^4 \exp[r\varphi] \qquad W(\sigma) = \Lambda_2^4\left(1-\cos\left(\frac{\sigma}{f}\right)\right)$$

Slow-roll solutions of ⟷

$$3H^2 \simeq W$$

$$Q \simeq Q_{\rm min} = -\left(\frac{fW_\sigma}{3\lambda g H}\right)^{1/3} \quad \text{(const.)}$$

$$\frac{1}{2}\frac{\lambda}{I^2}\frac{\dot\sigma}{fH} \simeq m_Q + \frac{1}{m_Q}\left(1+\frac{\dot I}{HI}\right)$$

Chromo-natural inflation

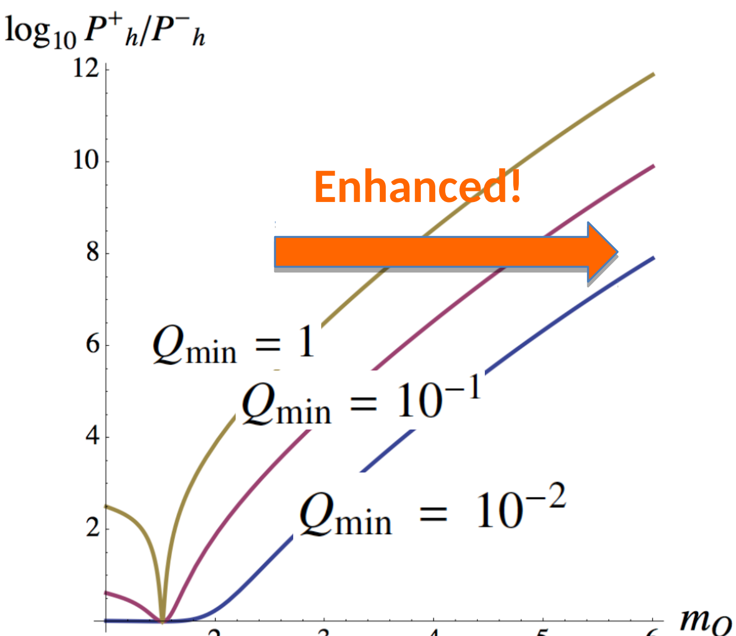
(Providing chiral GWs!) (>nHz)

Our results

Power spectrum of chiral GWs in late time periods (f>nHz) :

$$\mathcal{P}_h^-(k) \simeq \frac{2H^2}{k^3}$$

$$\mathcal{P}_h^+(k) \simeq \frac{2H^2}{k^3}\left[1 + 8Q_{\rm min}^2\left|\mathcal{I}_0(m_{\bar{Q}}) - m_{\bar{Q}}\mathcal{I}_1(m_{\bar{Q}}) + (-2 + m_{\bar{Q}}^2)\mathcal{I}_2(m_{\bar{Q}})\right|^2\right]$$



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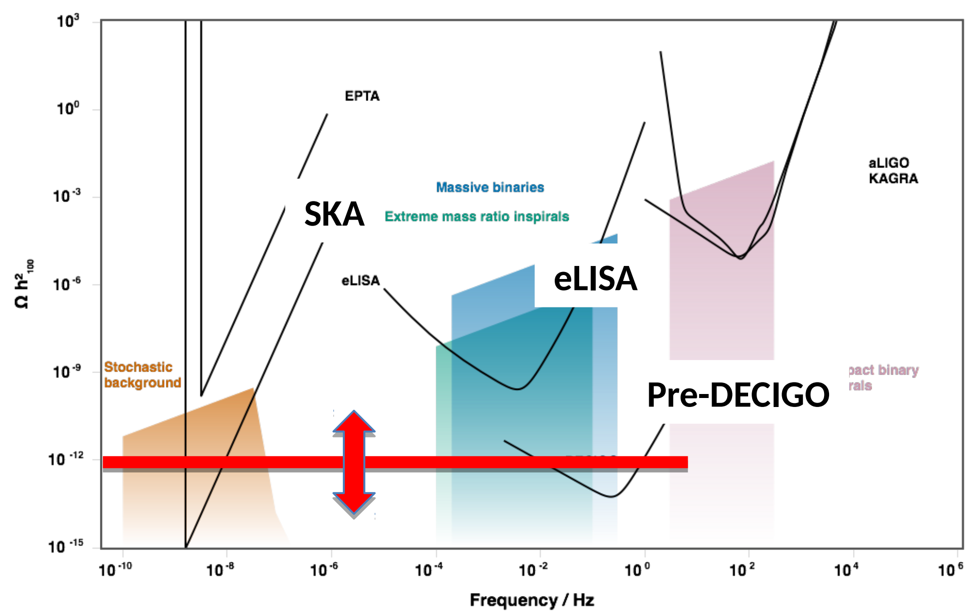

Summary & Outlook

- We study the mechanism of generating chiral primordial gravitational waves from particle production of SU(2) gauge field, which are consistent with CMB observations.

- We introduce a dilatonic field in the conventional model , chromo-natural inflation, and generalize an axion-gauge interaction dynamically based on the fundamental theory.

- We discover the parameter region where chiral GWs consistent with CMB data are produced, which might be detectable in future GW experiments (DECIGO, eLISA, SKA…).

- We must check the reheating age in this model and consider the dynamics of anisotropic background.