Blue Tensor Spectra
(with slightly parity-violated)
from axion-gauge couplings

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(in preparation)

29_Nov_CosPA2016

Primordial GWs from the inflation

Tensor power spectrum (vacuum fluctuations):

$$\Delta_h^{\pm} = \left. \frac{H^2}{\pi^2 M_p^2} \right|_{k=aH} = A_t \left(\frac{k}{k_0} \right)^{n_t < 0}$$

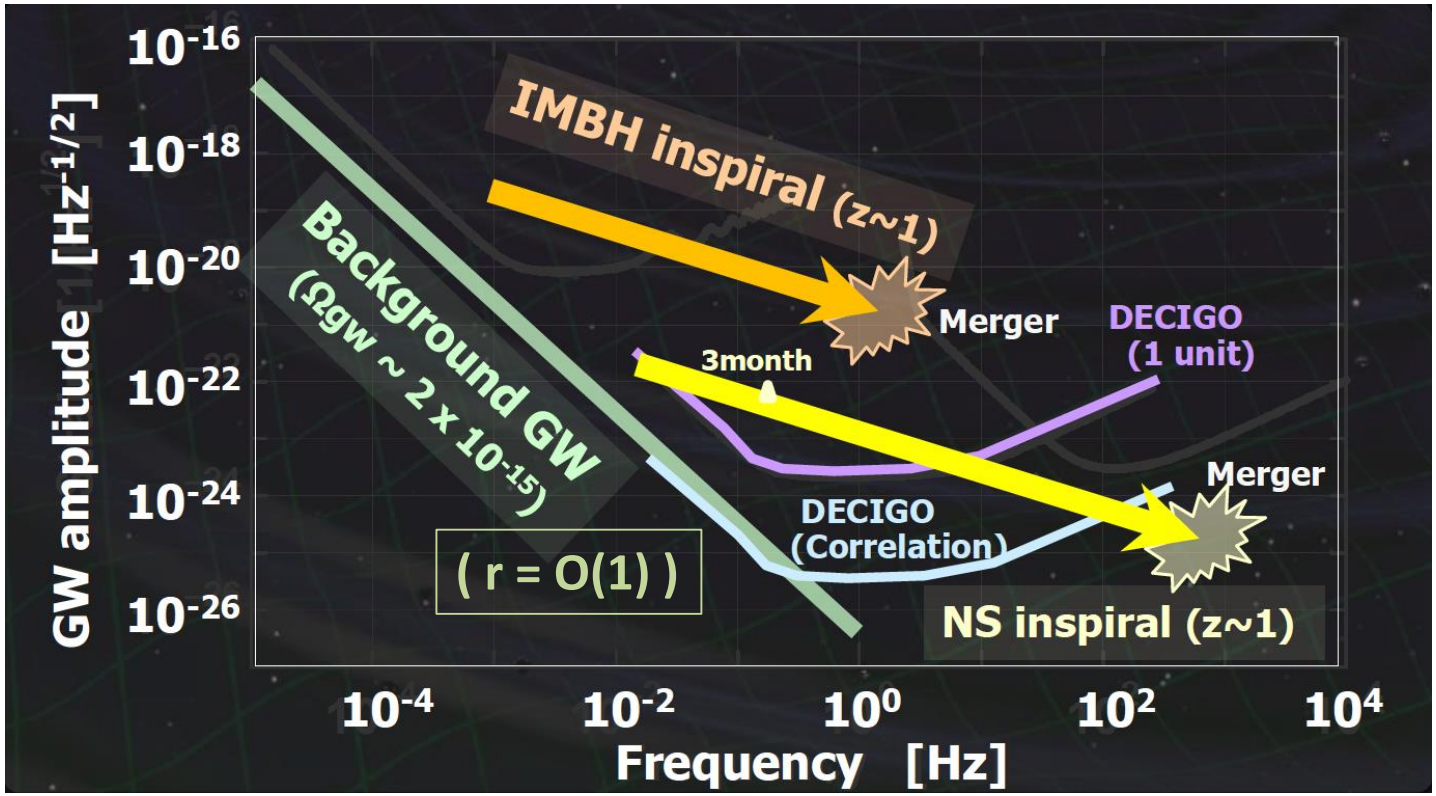
info

- Energy scale of early Universe
- Red-tilted.
- Parity-symmetric.
- Tiny amplitude.

$r < 0.07$ BICEP2/Keck Array (2016)

Is it detectable directly?

Sensitivity curves of DECIGO: Ando (2013, DECIGO workshop)



challenging for $r < \mathcal{O}(0.01)$!

if the source of GWs is vacuum fluctuations

Additional sources of GWs

Sorbo (2011), Barnaby et al. (2011), …

(inflationary axion-gauge coupling)

$$\mathcal{L} = -\frac{1}{2}(\partial\varphi)^2 - V(\varphi) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}\frac{\varphi}{f}F_{\mu\nu}\tilde{F}^{\mu\nu}$$

$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$

EOM for gauge field:

$$\frac{d^2 A_k^{\pm}}{d\tau^2} + \left(k^2 \pm \frac{2k\xi}{\tau}\right) A_k^{\pm} = 0$$

$$\xi \equiv \frac{\dot{\bar{\varphi}}}{2fH} > 0\ ,\ \tau = -(Ha)^{-1} < 0$$

$A_k^+ \nearrow e^{\pi\xi}$ (One helicity mode enhancement!)

→Additional sources for scalar and tensor perturbations!

Testable chiral blue tensor spectrum

Valerie *et al*. 2016

Tensor spectrum:

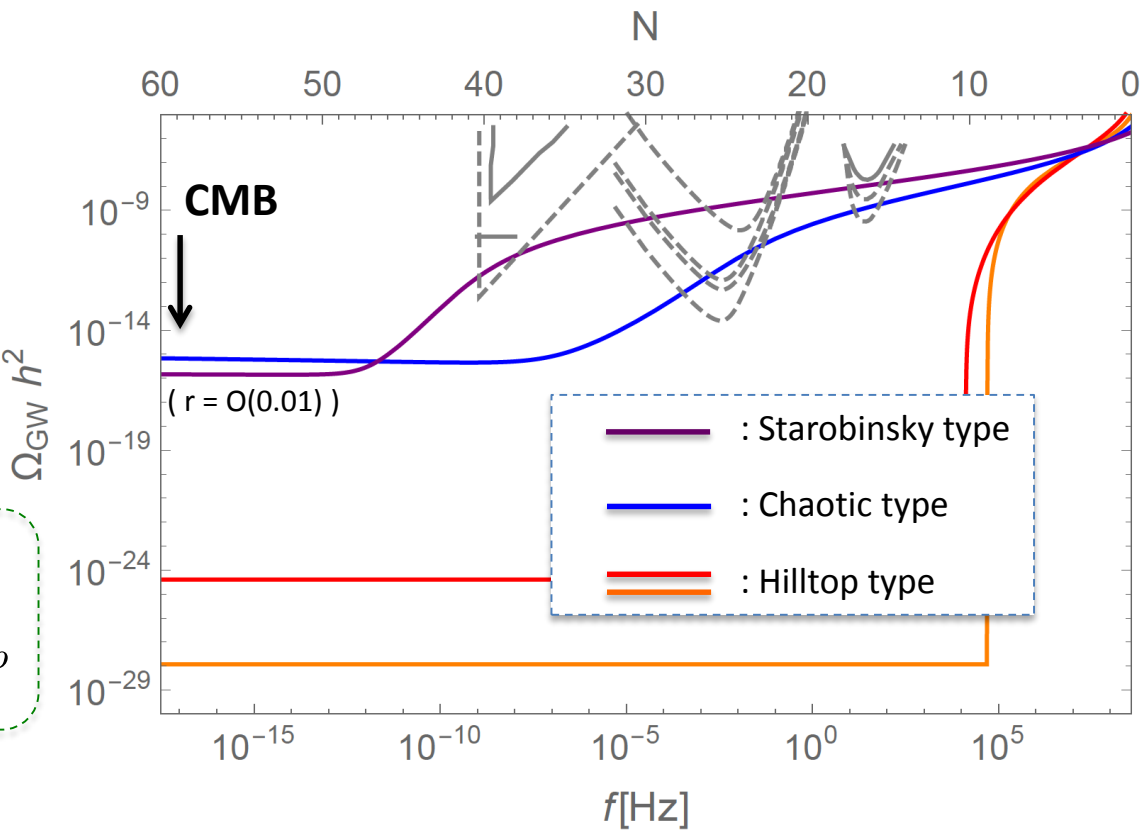
$$\simeq \Delta_h^V + \Delta_{h+}^S$$

$$= \Delta_h^V \left[1 + 10^{-6} \frac{H^2}{M_p^2 \xi^6} e^{4\pi\xi}\right]$$

$$\xi(t) \propto \dot{\varphi}(t) : \text{increasing in time}$$

Preferable parameter region

$$\xi \sim \frac{\sqrt{\epsilon_\varphi}}{f} \gtrsim \mathcal{O}(1) \leftrightarrow f \lesssim 10^{-2} M_p$$



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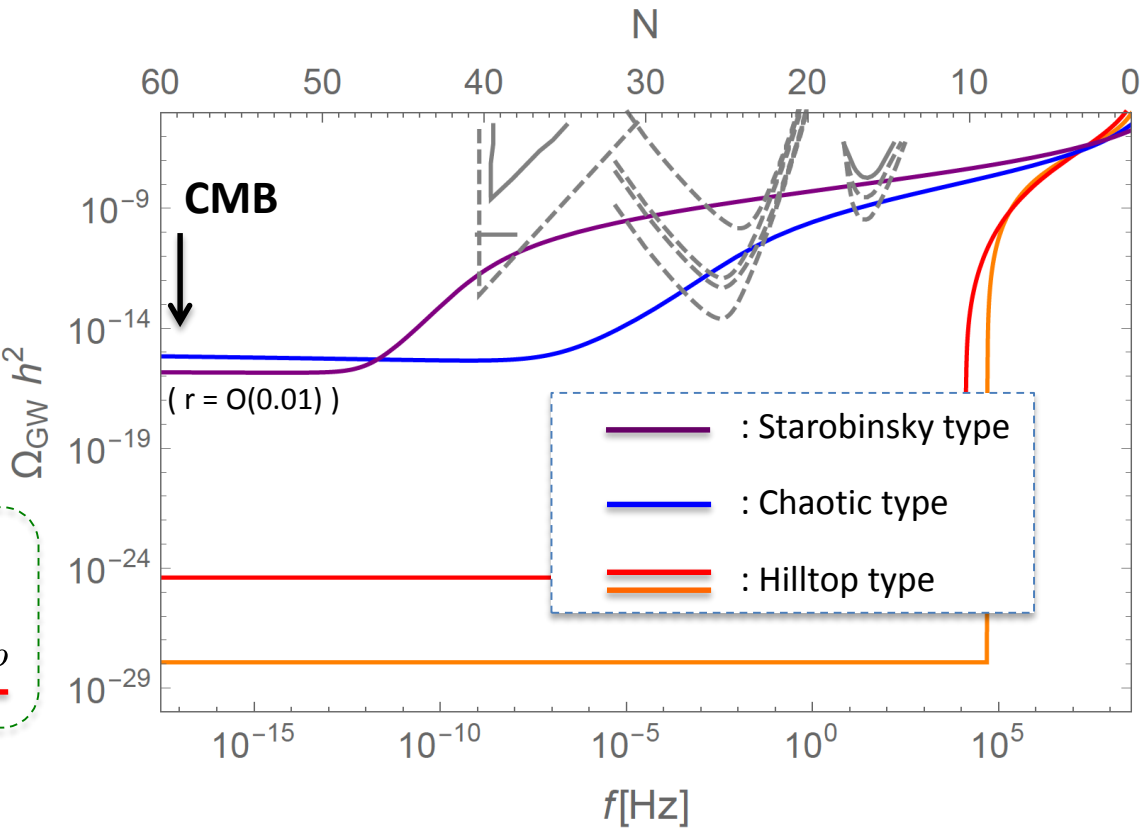

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Natural scale predicted by the heterotic superstring!

Svrcek & Witten (2005)

$$(f \sim \frac{\alpha_G}{2\pi} M_p,\ \alpha_G : \text{GUT gauge coupling})$$

Our question and study

Question…

? : Testable blue tensor spectrum $\leftrightarrow$ EFT of the heterotic string theory

In this work…

- ✓ We explore the concrete model building based on the heterotic string theory and reconsider the form of axion-gauge couplings.
- ✓ We found that rich varieties of blue tensor spectra could be provided sourced by gauge fields coupled to two types of axions.

Axions from the heterotic superstring

$\mathrm{E}_8 \times \mathrm{E}_8$

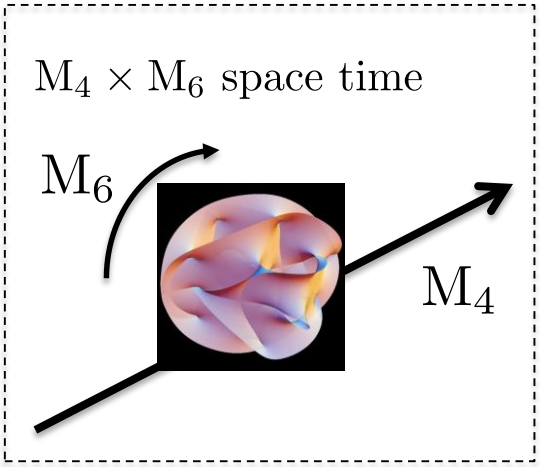
Choi &Kim (1985), …

Axions arise from the B field:

$$B = B_{MN} dx^M \wedge dx^N \quad (M, N = 0 \sim 9)$$

$$H = dB - \omega_Y + \omega_L$$: its field strength

$$(d\omega_Y = \mathrm{Tr} F^2, d\omega_L = \mathrm{Tr} R^2)$$



Two types of axion

"Model-independent" type $H_{\mu\nu\rho} = M_1 \epsilon_{\mu\nu\rho\alpha} \partial^\alpha \varphi_1 \quad (\mu, \nu, \ldots = 0 \sim 3)$

"Model-dependent" type $H_{\mu mn} = M_2 \epsilon_{mn} \partial_\mu \varphi_2 \quad (m, n, \ldots = 4 \sim 9)$

compactification

Axions from the heterotic superstring

$\mathrm{E}_8 \times \mathrm{E}_8$

Choi &Kim (1985), …

Origin of axion-gauge couplings:

Bianchi identity: $dH = -\mathrm{Tr}F^2 + \mathrm{Tr}R^2 \qquad (F^2 \equiv F \wedge F, R^2 \equiv R \wedge R)$

$(= f_1 \Box \varphi_1)$

Anomaly cancellation term: $S_{\mathrm{GS}} = \dfrac{1}{48(2\pi)^5} \displaystyle\int_{\mathrm{M}_4} \mathrm{Tr}F^2 \int_{\mathrm{M}_6} B \left[\mathrm{Tr}F^2 - \frac{1}{2}\mathrm{Tr}R^2 + \ldots \right]$

$\mathrm{Tr}F^2 = \mathrm{Tr}F_1^2 + \mathrm{Tr}F_2^2$

$\mathrm{E}_8 \times \mathrm{E}_8$

4-dim. reduced axion-gauge coupling

Model-independent axion: $-\dfrac{1}{4}\dfrac{\varphi_1}{f_1}\left(F_1\tilde{F}_1 + F_2\tilde{F}_2\right)$

Model-dependent axion: $-\dfrac{1}{4}\dfrac{\varphi_2}{f_2}\left(F_1\tilde{F}_1 - F_2\tilde{F}_2\right)$

(omitting Lorentz indices)

Source of GWs from superstring

Model example (1):

$$\mathcal{L} \supset -\frac{1}{4}\frac{\varphi_2}{f_2}\left(F_1\tilde{F}_1 - F_2\tilde{F}_2\right) - V(\varphi_2)$$

$F_{1,2}$: Abelian gauge field (for simplicity)

$$\frac{d^2A_{1k}^{\pm}}{d\tau^2} + \left(k^2 \pm \frac{2k\xi}{\tau}\right)A_{1k}^{\pm} = 0 \longrightarrow A_{1k}^{+} \nearrow e^{\pi\xi} \longrightarrow h^{+}$$

$$\frac{d^2A_{2k}^{\pm}}{d\tau^2} + \left(k^2 \mp \frac{2k\xi}{\tau}\right)A_{2k}^{\pm} = 0 \longrightarrow A_{2k}^{-} \nearrow e^{\pi\xi} \longrightarrow h^{-}$$

→ **parity-symmetric blue tensor spectra!**

Source of GWs from superstring

Model example (2):

$$\mathcal{L} \supset -\frac{1}{4}\left(\frac{\varphi_1}{f_1}+\frac{\varphi_2}{f_2}\right)F_1\tilde{F}_1 - \frac{1}{4}\left(\frac{\varphi_1}{f_1}-\frac{\varphi_2}{f_2}\right)F_2\tilde{F}_2 - V(\varphi_1,\varphi_2)$$

$F_{1,2}$: Abelian gauge field (for simplicity)

diagonalising $\varphi \equiv \frac{f_2}{\sqrt{f_1^2+f_2}}\varphi_1 - \frac{f_1}{\sqrt{f_1^2+f_2^2}}\varphi_2$, $\tilde{\varphi} \equiv \frac{f_1}{\sqrt{f_1^2+f_2^2}}\varphi_1 + \frac{f_2}{\sqrt{f_1^2+f_2^2}}\varphi_2$

$$\to -\frac{1}{4}\frac{\varphi}{f}\left(F_2\tilde{F}_2 + \frac{f_2^2-f_1^2}{f_1^2+f_2^2}F_1\tilde{F}_1\right) - \frac{1}{4}\frac{\tilde{\varphi}}{\tilde{f}}F_1\tilde{F}_1 - V(\varphi,\tilde{\varphi})$$

if $\tilde{\varphi}$ has been stabilized and $f_1 \gg f_2$...

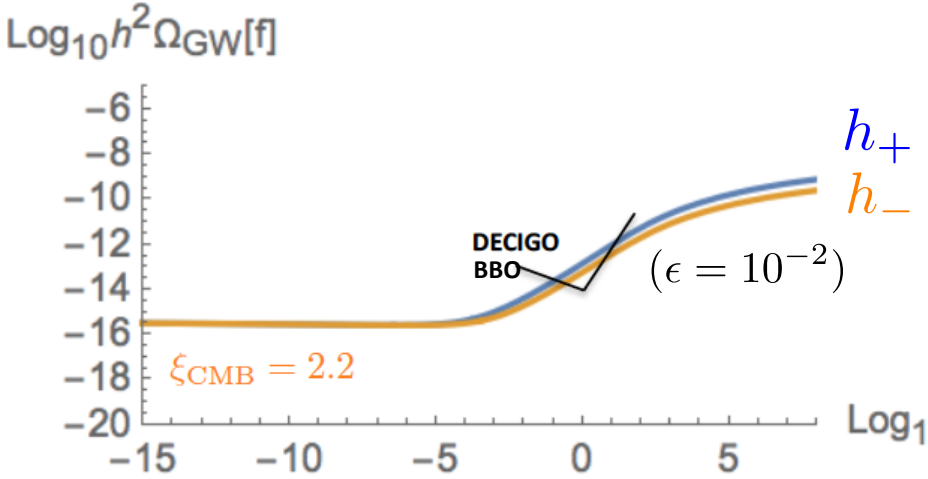
$$\to -\frac{1}{4}\frac{\varphi}{f}\left(F_2\tilde{F}_2 - (1-2\epsilon)F_1\tilde{F}_1\right)$$

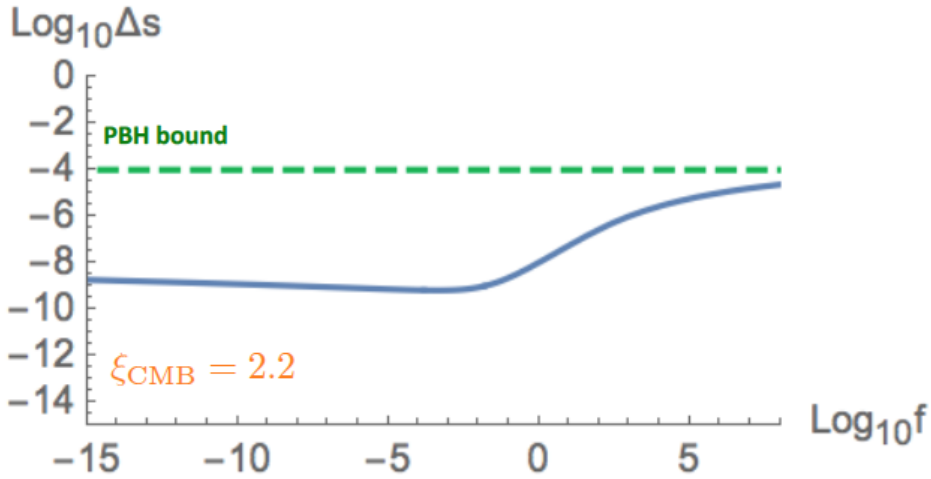
$$\epsilon \equiv f_2^2/f_1^2 \ll 1$$

→ **slightly parity-violated blue tensor spectra!**

Main Results

ex: $V(\varphi) = V_0\left[1 - \cos\left(\frac{\varphi}{h}\right)\right]$





- ✓ Bule-tilted and slightly parity violated spectra.
- ✓ Testable by future gravitational wave interferometers (DECIGO, BBO).
- ✓ Avoiding the overproduction of scalar modes.

Summary & Outlook

- ✓ We explore the concrete model building based on the heterotic string theory and reconsider the form of axion-gauge couplings.
- ✓ We found that rich varieties of blue tensor spectra sourced by gauge fields coupled to the model-(in)dependent axion could be provided.

? Possible potential forms of axion, the non-Abelian gauge interaction, …

Working in progress!