Primordial Chiral Gravitational Waves from the Axiverse

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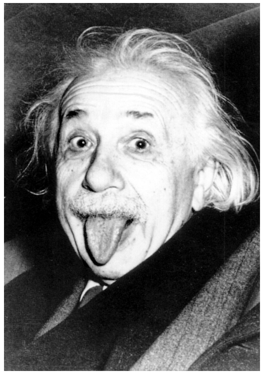
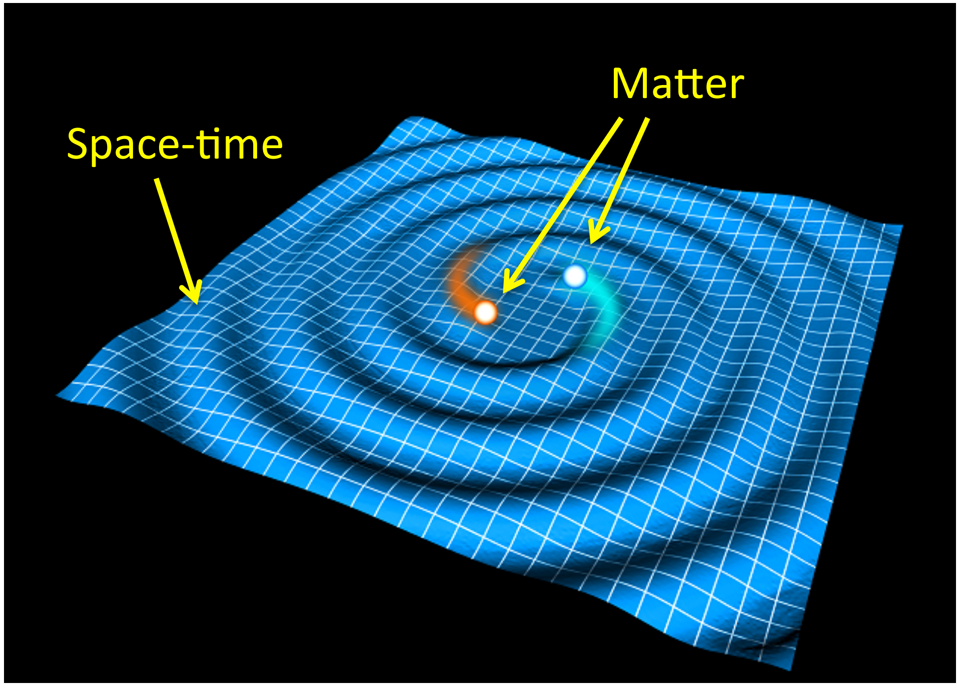
26 June @Zaragoza

The gravitational waves (GWs) physics

The gravitational waves are…

The ripples of space-time propagating as a wave!





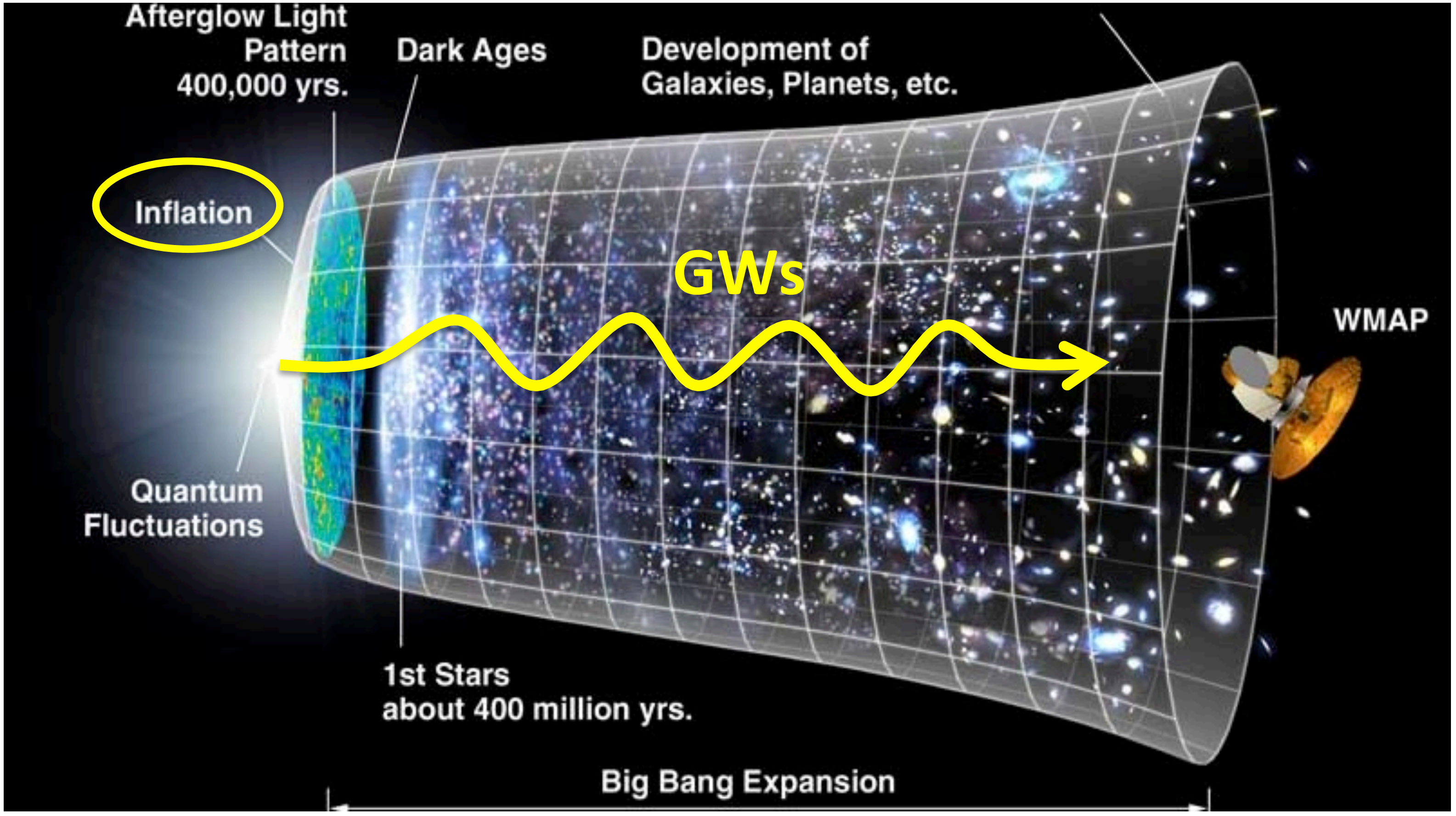
The source of GWs

- Binary star systems
- Black hole dynamics
- **The physics in the early Universe**

etc.

The gravitational waves (GWs) physics

Primordial GWs from an early universe



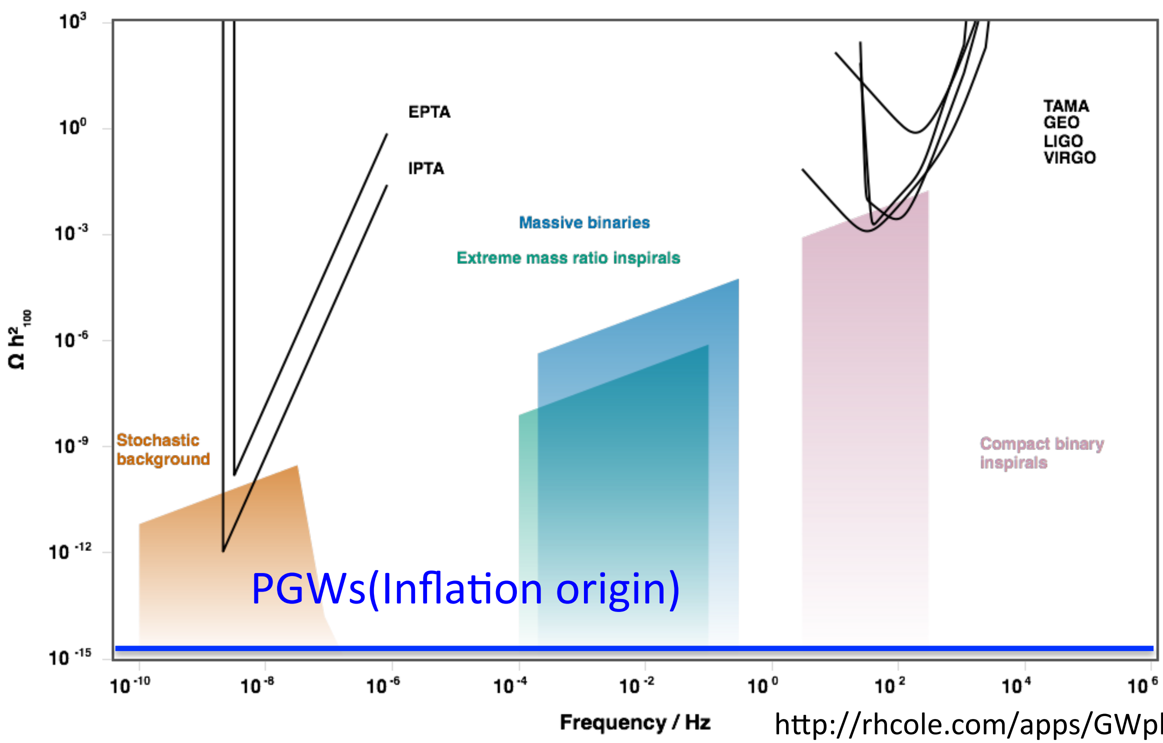
The gravitational waves (GWs) physics

✧ What is amount of PGWs from an ordinary inflation?

Maggiore 2000 [9909001]

Characterizing GWs signal by the energy intensity of GWs: $\Omega_{\rm gw}(f) = \frac{1}{\rho_c}\frac{d\rho_{\rm gw}}{d\log f}$

<u>Sensitivity Curve of GWs</u>



http://rhcole.com/apps/GWplotter/

The GWs' energy intensity from an inflation is

$$h_0^2\Omega_{\rm gw}(f) \sim 10^{-13}\left(\frac{H}{10^{-4}M_p}\right)^2$$

$(f > 10^{-16}{\rm Hz})$

$$< 10^{-13}\ ({\rm COBE\ bound})$$

Very small signal!

Our motivation is…

To research axion physics by using PGWs!

Plan of this talk

- ✓ Axion is a favorable candidate for inflaton.
- ✓ Axion can produce parity-violating GWs(chiral GWs) by the strong coupling of gauge fields.
- ✓ (**our work**) We might detect such a signal in future experiments! arXiv: 1412.7620

Axion can be inflaton

Axion can be inflaton

String Axiverse

Arvanitaki, Dimopoulos, Dubovsky, Kaloper & March-Russell 2010

String theory suggests the presence of a plentitude of axions.

✓ Axions are produced through the flux compactification of two-form:

$$B = \frac{1}{2\pi}\sum_{i}^{N} a_i(x)\omega_i(y) + \ldots, \quad \int_{C_j} \omega_i = \delta_{ij}$$

N : number of compactification

$N \gg 1$

✓ The effective 4-dim. axion Lagrangian is written as

$$\mathcal{L} = \sum_{i}^{N}\left[\frac{f_i^2}{2}(\partial_\mu a_i)^2 - \Lambda_i^4 U_i(a_i)\right] \qquad \Lambda_i^4 = M_i^4 e^{-S_i}, \; m_i \sim \Lambda_i^2/f_i$$

$$\supset \Lambda^4/M_p^2 \sim H_{inf}^2$$

Axion can affect an inflation!

Axion can be inflaton

Natural Inflation

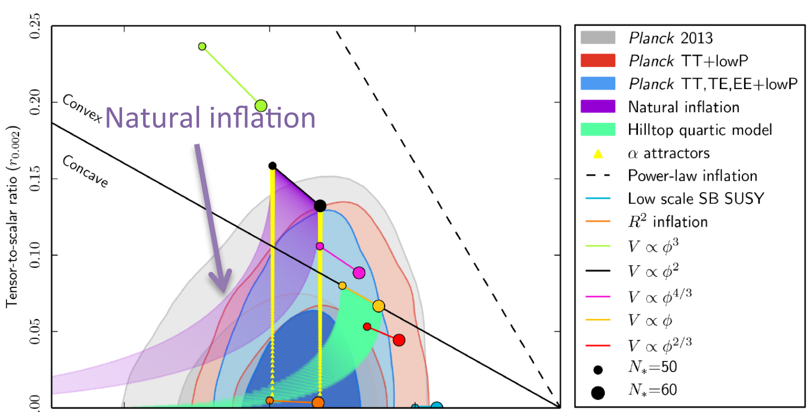
Freese, Frieman and Olinto 1990

✓ Axion can naturally explain the flatness of the potential by using its shift symmetry!

$$\varphi \longrightarrow \varphi + \text{const.}$$

✓ Axion gets a cosine potential due to instanton effects.

$$V(\varphi) = \Lambda^4[1 + \cos(\varphi/f)]$$ →inflation occurs



Planck collaboration 2015

For successful inflation,

$$f \gtrsim M_p \text{ and } \Lambda \sim \Lambda_{\rm GUT}$$

Not UV complete…

Banks, Dine, Fox & Gorbatov 2003

Freese & Kinney 2004

Axion can be inflaton

In order to realize UV complete theory…

Generalizing multi-field axionic inflation

Multiple scalar(axion) fields

- ☐ Aligned natural inflation — Kim Nilles & Peloso 2005
- ☐ Monodromy inflation — Silverstein & Westphal 2008
- ☐ N-flation — Dimopoulos, Kachru, McGreevy & Wacker 2008

Axion + vector fields

- ☐ Natural inflation with abelian gauge field — Anber & Sorbo 2010
- ☐ Natural inflation with SU(2) gauge field — Adshead & Wyman 2012

Chiral GWs from an axionic inflation

Chiral GWs from an axionic inflation

Chromo-Natural Inflation

Adshead & Wyman 2012

Axionic inflation with SU(2) gauge field:

$$S = \int d^4x\sqrt{-g}\left[\frac{M_p^2}{2}R - \frac{1}{2}\partial^\alpha\varphi\partial_\alpha\varphi - V(\varphi) - \frac{1}{4}F^{a\alpha\beta}F^a_{\alpha\beta} - \lambda\frac{\varphi}{4f}\tilde{F}^{a\alpha\beta}F^a_{\alpha\beta}\right]$$

$\lambda \gg 1$

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

$$A^a{}_0 = 0,\ \ A^a{}_i = a(t)\phi(t)\delta^a{}_i : \mathrm{SU(2)\ gauge\ field}$$

$$V(\varphi) = \Lambda^4[1+\cos(\varphi/f)]$$

f : the decay constant of axion

Λ : the energy scale of axion

g : the coupling constant of SU(2) gauge field

λ : the coupling constant of axion to gauge field

Slow-roll parameters:

$$\epsilon \approx \frac{f}{\lambda}\frac{1+m_\phi^2}{m_\phi}\frac{V_\varphi}{V} \qquad \eta \approx \frac{f}{\lambda}\frac{1+m_\phi^2}{m_\phi}\left(\frac{2V_\varphi}{V} - \frac{V_{\varphi\varphi}}{V_\varphi}\right)$$

$$m_\phi \equiv \frac{g|\phi|}{H}$$

⟶ We can make $f \ll M_{pl}$ by $\lambda \gg 1$

Chiral GWs from an axionic inflation

Considering tensor fluctuations...

$$ds^2 = a(\tau)^2[-d\tau^2 + (\delta_{ij} + h_{ij})dx^i dx^j] \quad A_i^a = a\phi\delta_i^a + t_i^a$$

$$\psi_{ij} = a(\tau)h_{ij}$$

interacts metric perturbation

EOM of tensor perturbations in Fourier space $x \equiv -k\tau$

$$\frac{d^2\psi_{\boldsymbol{k}}^{\pm}}{dx^2} + \left(1 - \frac{2}{x^2} - \frac{2}{x^2}(1 - m_\phi^2)\phi^2\right)\psi_{\boldsymbol{k}}^{\pm} \approx 2\frac{\phi}{x}\frac{dt_{\boldsymbol{k}}^{\pm}}{dx} + 2m_\phi(m_\phi \pm x)\frac{\phi}{x^2}t_{\boldsymbol{k}}^{\pm}, \quad m_\phi \equiv \frac{g|\phi|}{H}$$

$$m \equiv 2(1 + m_\phi^2),$$

$$\frac{d^2t_{\boldsymbol{k}}^{\pm}}{dx^2} + \left(1 + \frac{m}{x^2} \pm \frac{m_t}{x}\right)t_{\boldsymbol{k}}^{\pm} \approx -2\phi\frac{d}{dx}\left(\frac{\psi_{\boldsymbol{k}}^{\pm}}{x}\right) + 2m_\phi(m_\phi \pm x)\frac{\phi}{x^2}\psi_{\boldsymbol{k}}^{\pm} \quad m_t \equiv 2\left(2m_\phi + \frac{1}{m_\phi}\right)$$

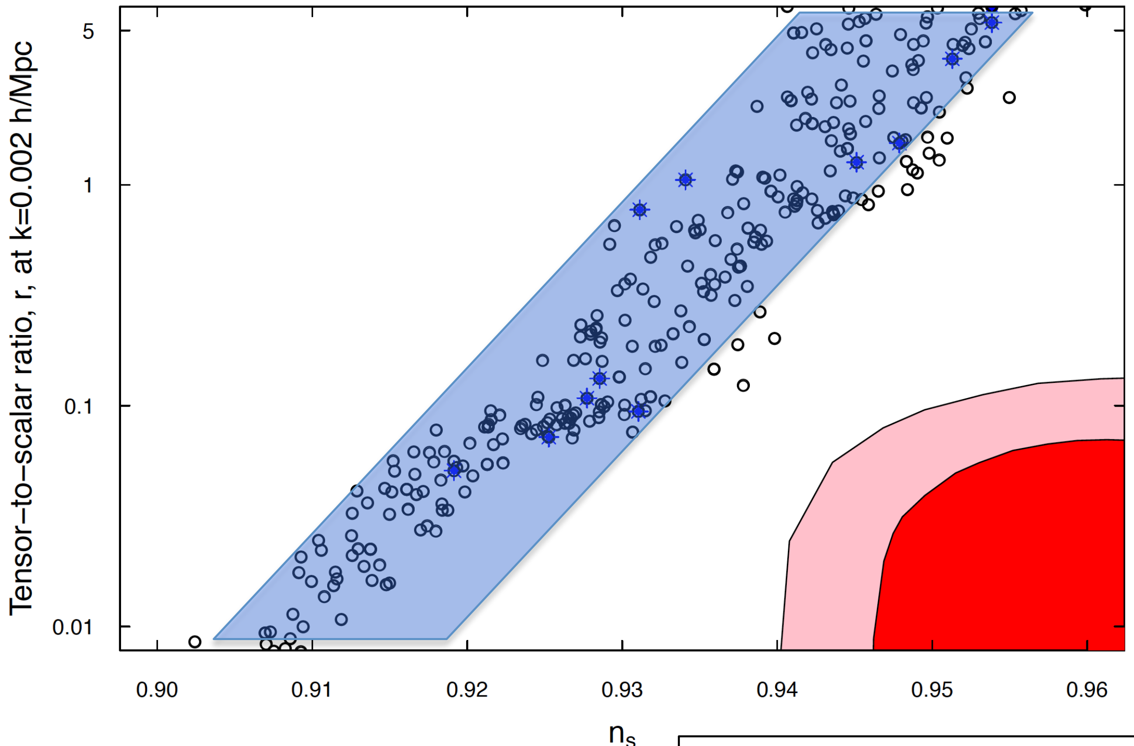
minus mode: tachyonic instability appears during $\frac{1}{2}(m_t - \sqrt{m_t^2 - 4m}) < x < \frac{1}{2}(m_t + \sqrt{m_t^2 - 4m})$

→One helicity mode of metric fluctuations is enhanced!

Chiral GWs from an axionic inflation

However…

The CMB constraint on chromo-natural inflation



Adshead, Martinec & Wyman 2013

Parameters of this model

$$f \ll M_{pl}$$
$$10^{-4} M_{pl} \lesssim \Lambda \lesssim 10^{-2} M_{pl}$$
$$10^{-6} \lesssim g \lesssim 10^{-4}$$
$$\lambda \gtrsim 10^{2}$$

Chromo-natural inflation predicts too much chiral enhancement of GWs

Chromo-natural inflation from the axiverse

Obata, Miura & Soda 2014

Chromo-natural inflation from the axiverse

Chromo-natural inflation with two axions

$$S = \int dx^4 \sqrt{-g}\left[\frac{1}{2}R - \frac{1}{2}(\partial_\mu \chi)^2 - \frac{1}{2}(\partial_\mu \omega)^2 - \frac{1}{4}F^{a\mu\nu}F^a_{\mu\nu} - \frac{1}{4}\left(\lambda_\chi \frac{\chi}{f} + \lambda_\omega \frac{\omega}{h}\right)\tilde{F}^{a\mu\nu}F^a_{\mu\nu} - V(\chi,\omega)\right]$$

Parameters of this model

- μ : the energy scale of axion
- $f,\ h$: the decay constants of two axions
- g : the coupling constant of SU(2) gauge field
- $\lambda_\chi, \lambda_\omega$: the coupling constants of two axions to gauge field

$$V(\chi,\omega) = \mu_1^4\left[1 - \cos\left(\frac{\chi}{f}\right)\right] + \mu_2^4\left[1 - \cos\left(\frac{\omega}{h}\right)\right]$$

$$\equiv U(\chi) + W(\omega)\ .$$

$$\mu_1 = \mu_2 \equiv \mu$$

$$\lambda_\chi \ll 1, \lambda_\omega \gg 1$$

χ : weak coupling $\rightarrow$ Natural inflation ✕ (chirally-enhanced GWs)

ω : strong coupling $\rightarrow$ Chromo-natural inflation ○ (chirally-enhanced GWs)

We can expect to avoid the CMB constraint on chromo-natural inflation
If natural inflation gives CMB initial conditions

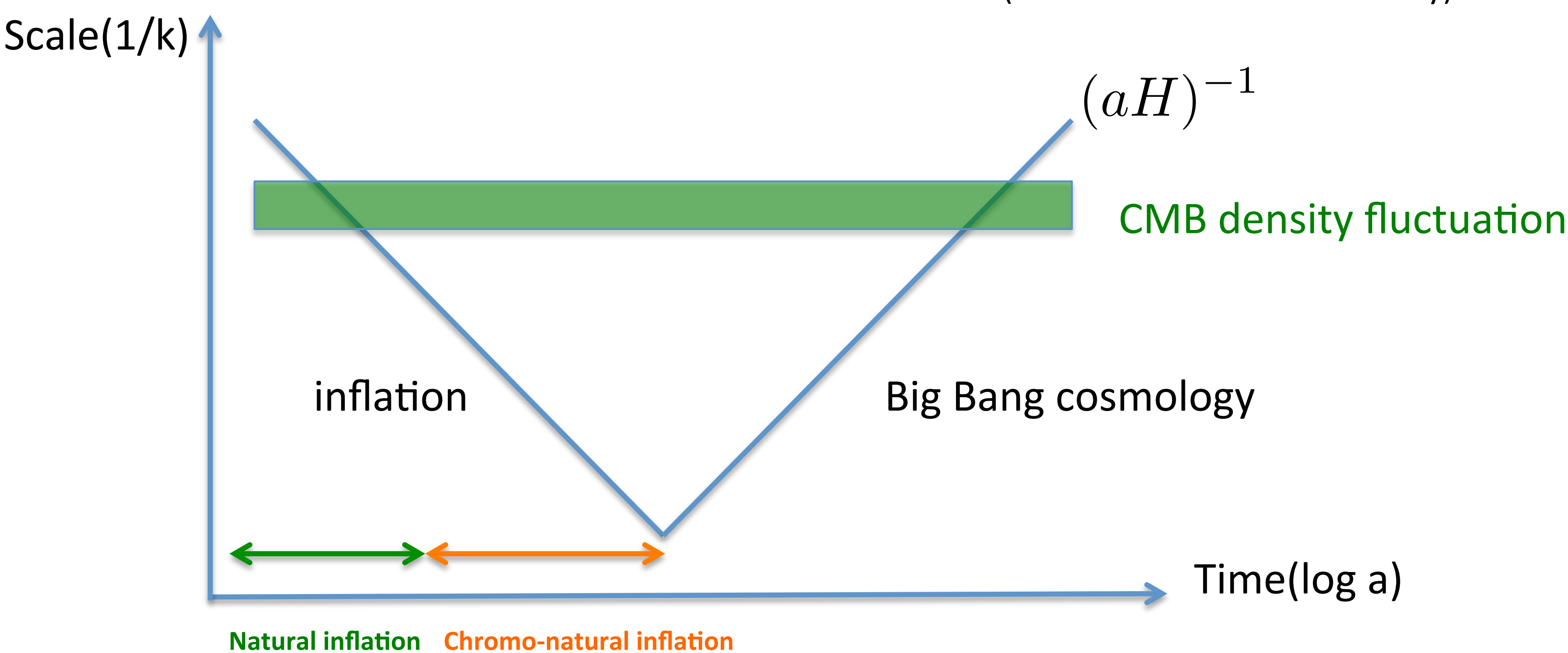
Chromo-natural inflation from the axiverse

Slow-roll equations

$$3H\dot{\chi} + U_\chi \approx 0 \qquad \frac{\lambda_\omega}{h}\dot{\omega} \approx 2g\phi + \frac{2H^2}{g\phi}$$

$$\left|\frac{\dot{\omega}}{\dot{\chi}}\right| \approx 2\frac{V}{U_\chi}\frac{h}{\lambda_\omega}\frac{1+m_\phi^2}{m_\phi} \ll 1 \qquad m_\phi \equiv \frac{g|\phi|}{H}$$

(Natural inflation occurs firstly)

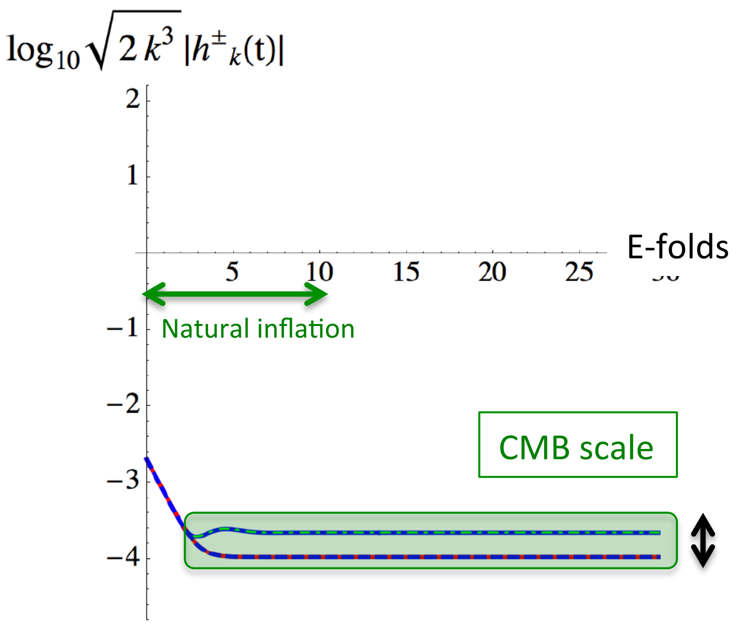


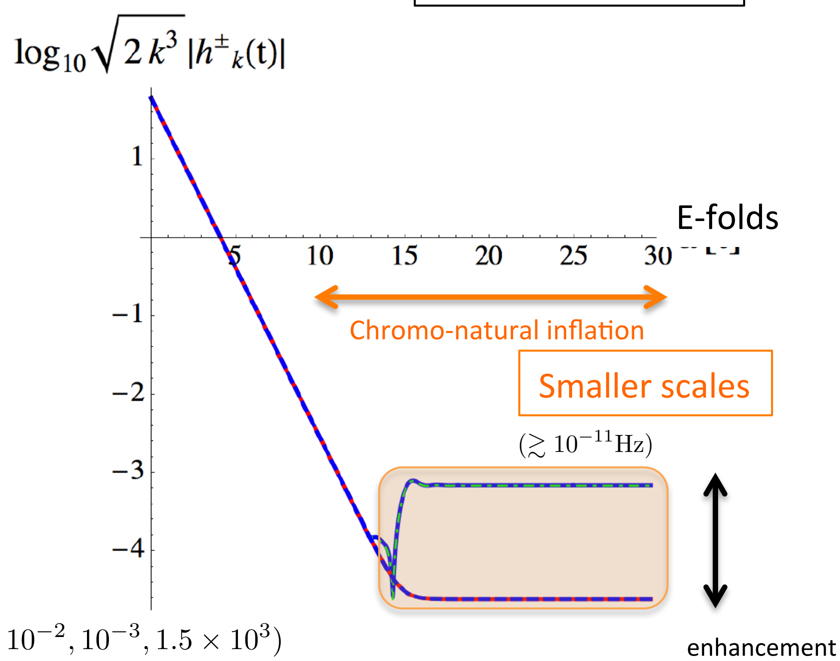
Chromo-natural inflation from the axiverse

Metric fluctuations

$$ds^2 = a(\tau)^2[-d\tau^2 + (\delta_{ij} + h_{ij})dx^i dx^j]$$

Obata, Miura & Soda 2014





$(f, h, \mu, g, \lambda_\omega) = (3.5, 3.5 \times 10^{-4}, 10^{-2}, 10^{-3}, 1.5 \times 10^3)$

energy intensity of chiral GW

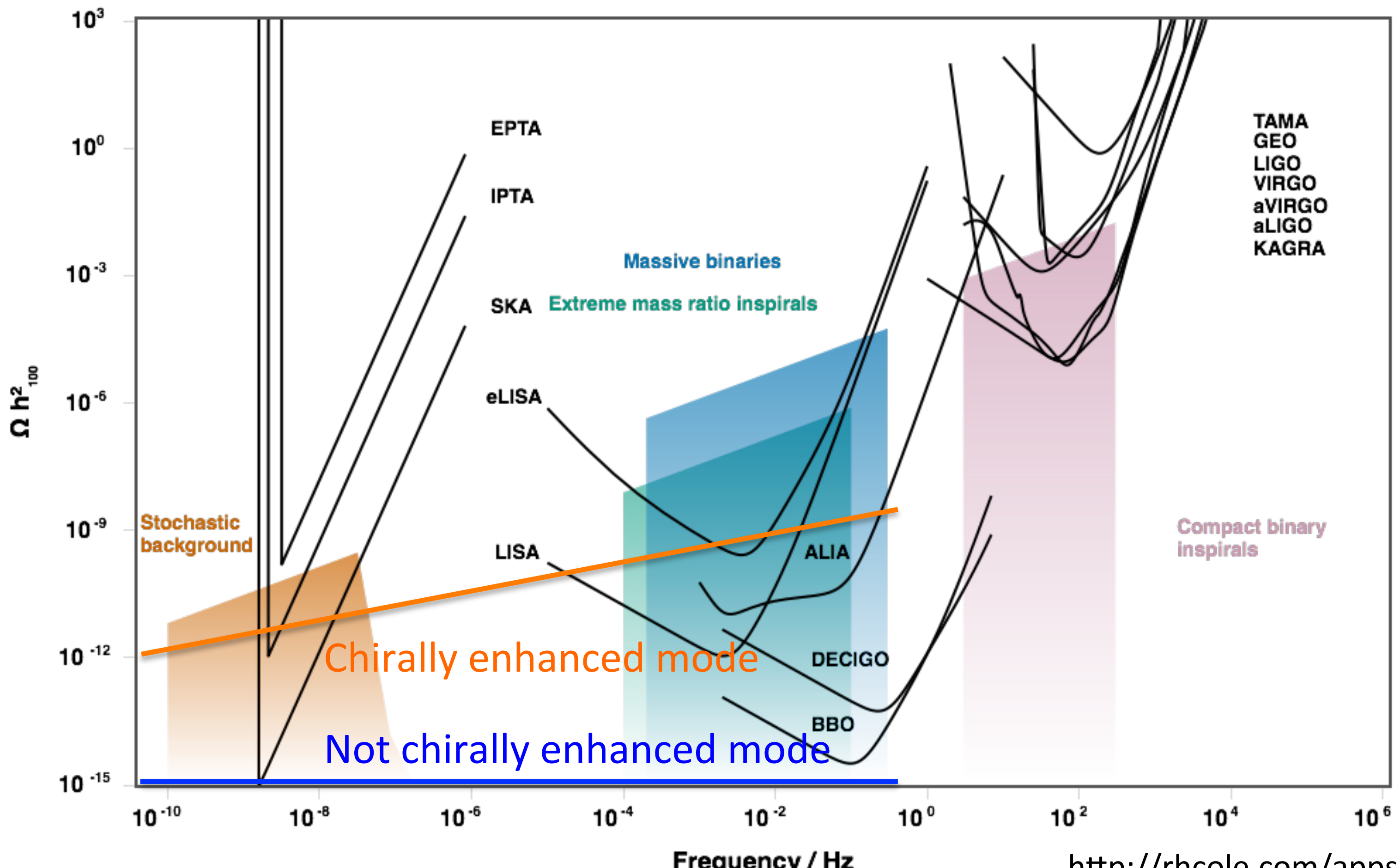
$$h_0^2\Omega_{\rm CMB} \sim 10^{-15}$$

energy intensity of chiral GW

$$h_0^2\Omega_{\rm small} \sim 10^{-12}$$

Chromo-natural inflation from the axiverse

Sensitivity Curve of GWs



http://rhcole.com/apps/GWplotter/

Summary and outlook

- ✓ Axion is a favorable candidate for inflaton. Moreover, it can produce the chirally enhanced GWs due to the strong coupling to the gauge fields.
- ✓ If there exist multiple axions, we might make the model which suppresses the overproduction of chiral GWs and the predictions might be in agreement with observations on CMB scales.
- ✓ Moreover, chirally GWs might be enhanced in higher frequency regions, so we expect that it might be detectable in future GWs observations.
- ✓ We need to analyze the spectrum of chiral GWs in detail to compare the predictions with observations. We should also study scalar perturbations and explicitly check stability of natural inflation with two axions.