PRESENTATION

Primordial GWs from the axion-SU(2) gauge fields during inflation

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Mainly based on arXiv:1608.04216
w/ Dimastrogiovanni(UNSW) & Fasiello(ICG)

CERN Zooming in on Axions in the Early Universe

26th Jun 2020 @CERN(Virtual)

Outline of talk

① Introduction

② Model

③ Consistency

④ Predictions

⑤ Future Prospects

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Model

[Dimastrogiovanni, Fasiello & TF (2017)]

Theoretically well motivated, Rich phenomenology

$$\mathcal{L} = \boxed{\mathcal{L}_{\text{inflaton}}}$$

Inflaton sector

$$\boxed{\begin{aligned} &+\frac{1}{2}(\partial\chi)^2 - U(\chi) \\ &-\frac{1}{4}F^aF^a - \frac{\lambda}{4f}\chi F^a\tilde{F}^a \end{aligned}}$$

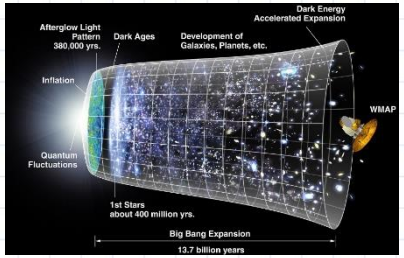
Axion- SU(2) gauge spectator sector

Additional Primordial GW

cf. Ira & Leila's talk on the same model

Dani, Benedict, Kyohei's on U(1) model

Why Primordial GW?



© WMAP collaboration

- Universal prediction of inflation

  Vacuum GW: $r_{\mathrm{vac}} \approx 10^{-3} \left(\frac{H_{\mathrm{inf}}}{10^{13}\mathrm{GeV}}\right)^2$

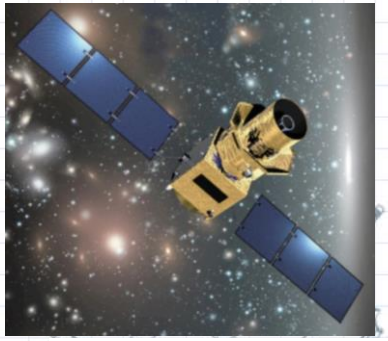
- Unique probe of the highest energy scale

  $\rho_{\mathrm{inf}} \approx 10^{16}\mathrm{GeV} \ggg \rho_{\mathrm{LHC}} \approx 10^{4}\mathrm{GeV}$ New physics?

ATLAS@CERN

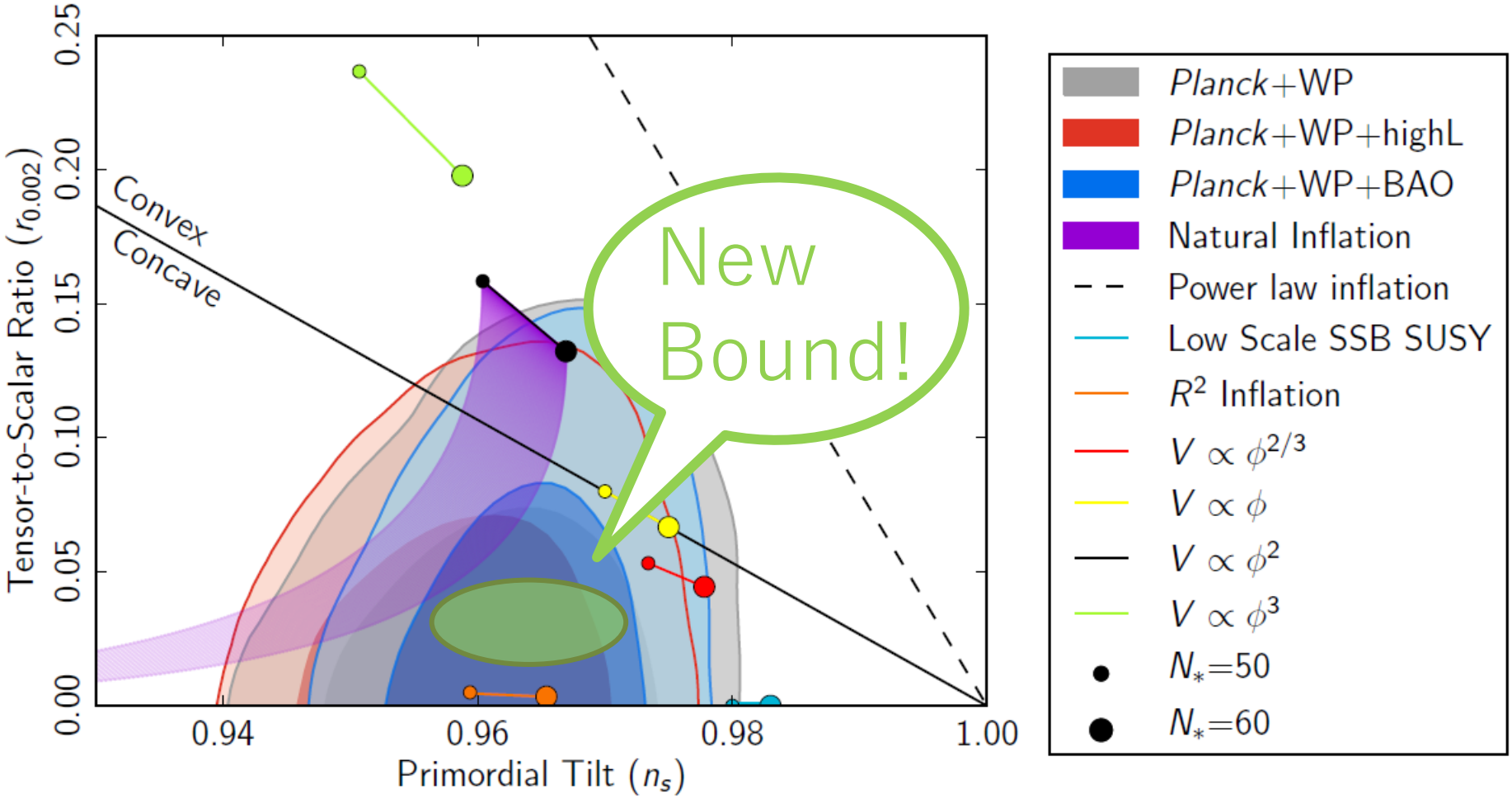
- Upcoming observations before 2030

  LiteBIRD, CMB-S4 will reach $r_{\mathrm{obs}} \approx 10^{-3}$



LiteBIRD satellite © JAXA

What if r is detected?



Are You Sure??

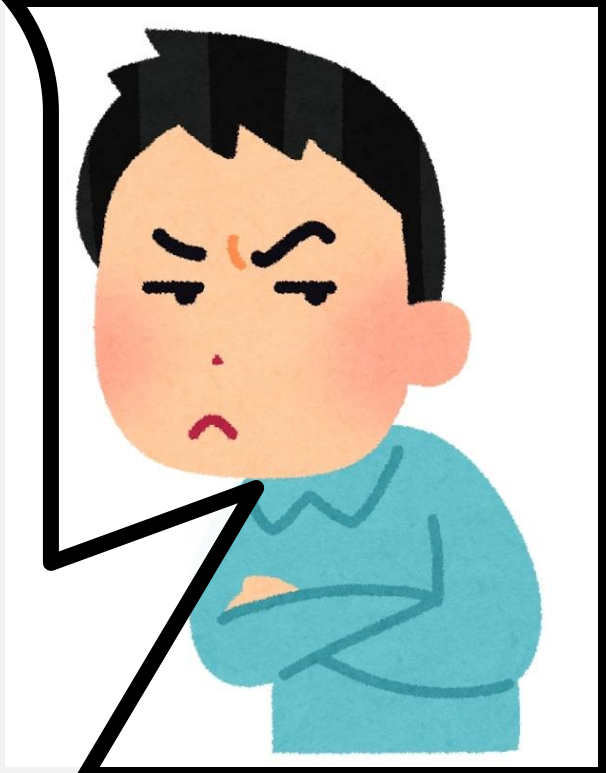
If we detect

$r \approx 0.05$,

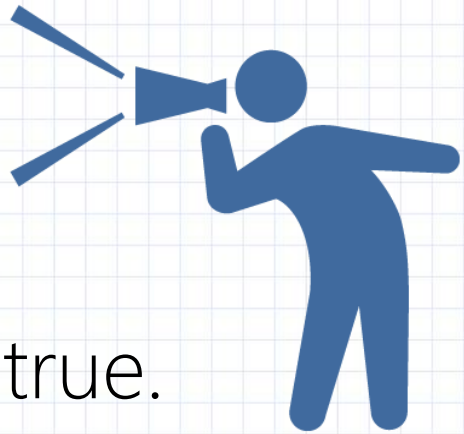
is it 100% OK

to report

$H_{\mathrm{inf}} \approx 6 \times 10^{13}\,\mathrm{GeV}$?



No!



That's not necessarily true.

The Golden Rule

$$H_{\rm inf} \approx 10^{13}\,{\rm GeV}\left(\frac{r_{\rm obs}}{0.001}\right)^{1/2}$$

can be broken.

Another GW source

- Larger GW than h^{vac} can be produced

$$r_{obs} = r_{\mathrm{vac}} + r_{\mathrm{src}}$$

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Another GW source

- Larger GW than h^{vac} can be produced

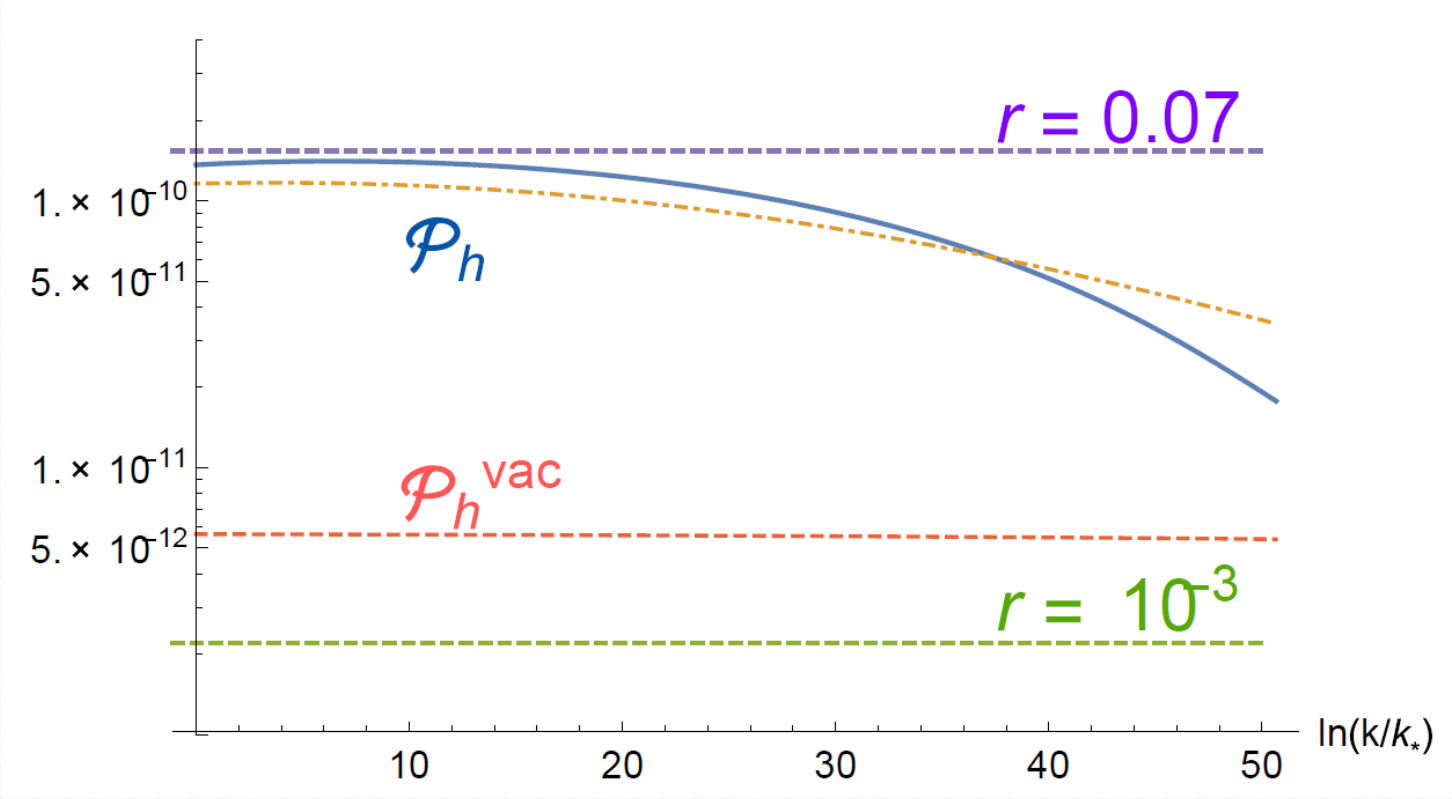
$$r_{obs} = r_{\mathrm{vac}} + r_{\mathrm{src}}$$

$$r_{obs} \cancel{=} r_{\mathrm{src}} \approx 10^{-3} \left(\frac{H_{\mathrm{inf}}}{10^{13}\mathrm{GeV}}\right)^2$$

Example

○ $H_{\rm inf} \approx 1 \times 10^{13}\,{\rm GeV}$

× $H_{\rm inf} \approx 6 \times 10^{13}\,{\rm GeV}$



Dimastrogiovanni, Fasiello & TF (2017)

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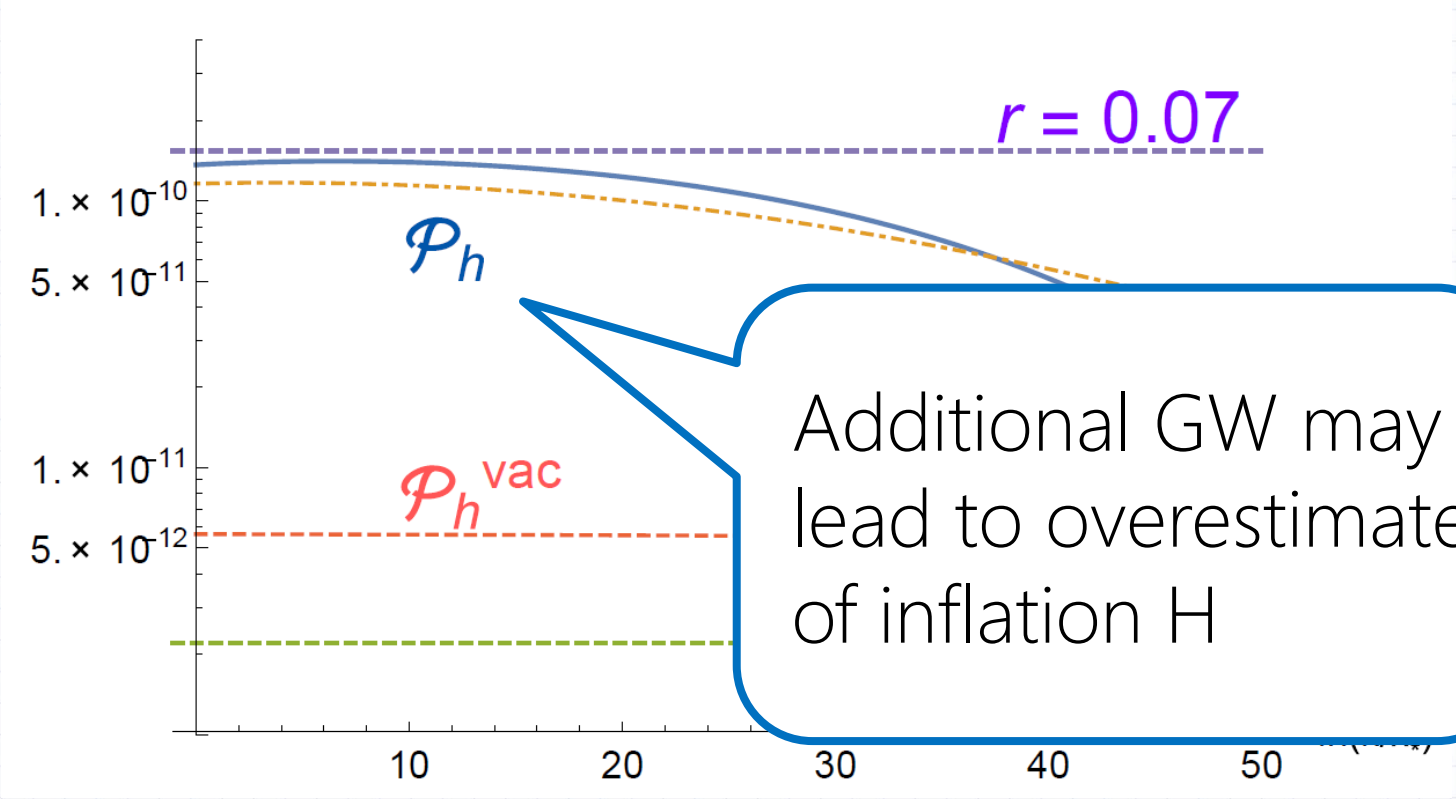

Additional GW may lead to overestimate of inflation H

Dimastrogiovanni, Fasiello & TF (2017)

Axion-SU(2) model

- Larger GW than h^{vac} can be produced

$$r_{obs} = r_{\mathrm{vac}} + r_{\mathrm{src}}$$

- Distinguishable with
  - Non-Gaussianity $\langle hhh \rangle$
  - Polarization $h_R \neq h_L$
  - Tensor tilt n_t

- We can learn more than ρ_{inf} from PGW!

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[Enqvist&Sloth(2002),
Lyth&Wands(2002),
Moroi&Takahashi(2002)]

Basic idea

[Biagetti, Fasiello & Riotto(2013)]
[TF, Yokoyama & Yokoyama(2013)]

GW version of Curvaton mechanism

$$\mathcal{L}_{\rm inflaton} + \mathcal{L}_{\rm spectator}$$

$$\rho_{\rm inf} \gg \rho_{\rm spec}$$

$H_{\rm inf}$ ↓ ↓ Source

$$\mathcal{P}_{\rm GW}^{\rm vac} \lesssim \mathcal{P}_{\rm GW}^{\rm spec}$$

$\mathcal{L}_{\rm inf}$ is arbitrary and responsible for ζ generation.

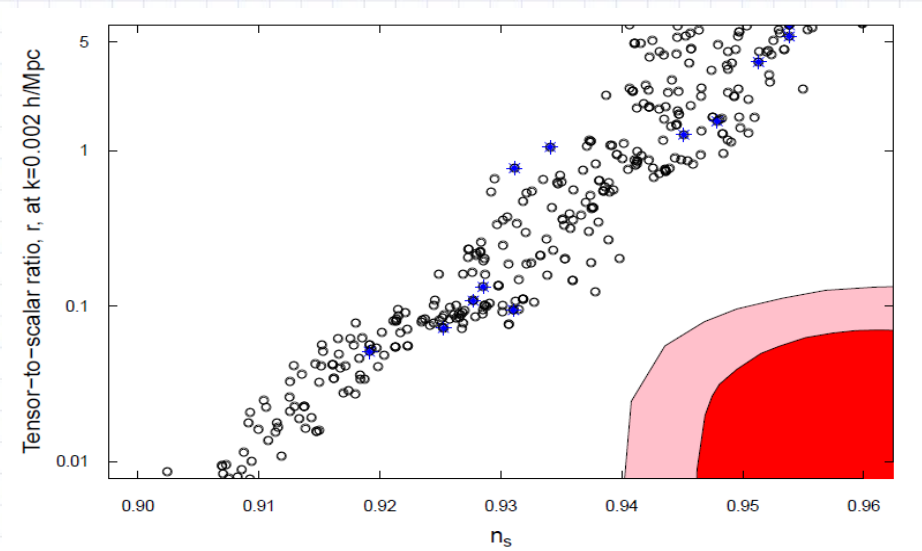
$\mathcal{L}_{\rm spec}$ is added just to produce GW during inf.

Chromo-natural

[Adshead&Wyman(2012)]
[Maleknejad&Sheikh-Jabbari(2011,2013)]

Inflaton coupled to SU(2) gauge fields

$$\mathcal{L} = +\frac{1}{2}(\partial\phi)^2 - \mu^4\left(\cos\frac{\phi}{f}+1\right) - \frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} - \frac{\lambda}{4f}\phi F^a_{\mu\nu}\tilde{F}^{a\mu\nu}$$



Excluded by CMB due to too much GW production

See, however, [Adshead et al.(2016)]

[Adshead, Martinec&Wyman(2013)]

Our model

[Dimastrogiovanni, Fasiello & TF (2017)]

Adding axion-SU(2) gauge spectator sector to the inflaton inspired by the Chromo-natural inflation

$$\mathcal{L} = \mathcal{L}_{\text{inflaton}} + \frac{1}{2}(\partial\chi)^2 - U(\chi) - \frac{1}{4}FF - \frac{\lambda}{4f}\chi F\tilde{F}$$

Inflaton sector → $\mathcal{P}_\zeta$

Decoupled

Axion- SU(2) gauge spectator sector → $\mathcal{P}_{\text{GW}}^{\text{spec}}$

Why SU(2)?

SVT Decomposition Theorem:

At the 1st order cosmological perturbation, scalar, vector and tensor are decoupled.

$$\delta S, \delta V_i \xrightarrow[\text{Source}]{\cancel{\quad}} \delta T_{ij}$$

Why SU(2)?

Using the 2nd order pert., GW can be sourced.
But it's hard to generate $\mathcal{P}_{\mathrm{GW}}^{\mathrm{src}} \gg \mathcal{P}_{\mathrm{GW}}^{\mathrm{vac}}$.

$$\partial_i \delta S \partial_j \delta S,\ \delta V_i \delta V_j \xrightarrow[\text{Source}]{} \delta T_{ij}$$

[Biagetti et al.(2013), Mukohyama et al.(2014), TF et al.(2015), Ferreira et al.(2015), Choi et al.(2015), Namba et al.(2016).]

Way Out

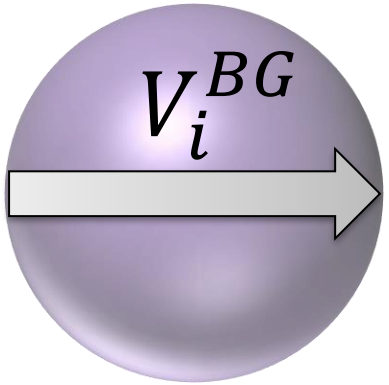
Background vector field V_i^{BG} helps.

$$V_i^{BG}\delta V_j \xrightarrow[\text{Source}]{} \delta T_{ij}$$

CMB says the universe is isotropic.

U(1) gauge ⇨ Anisotropic BG

Isotropy is violated



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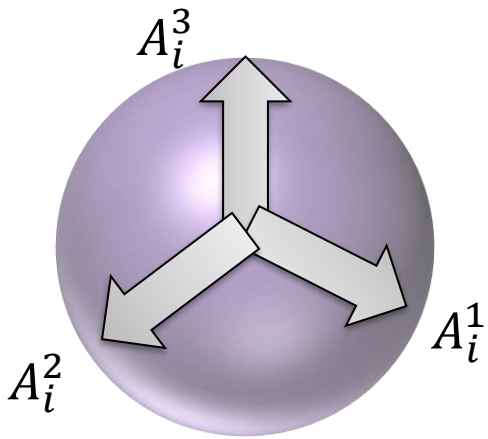
CMB says the universe is isotropic.

U(1) gauge ⇨ Anisotropic BG

SU(2) gauge ⇨ Isotropic BG is Attractor.

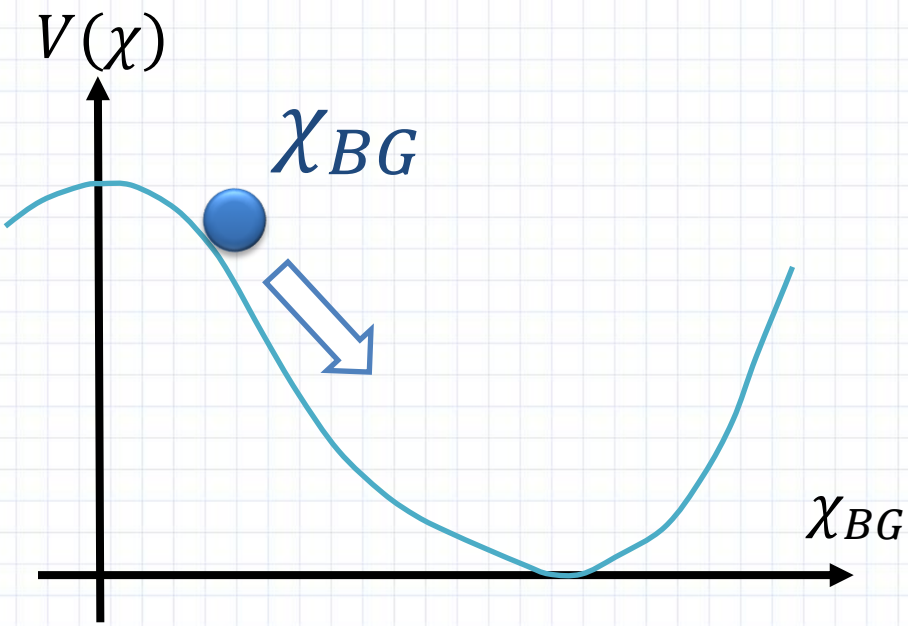
Isotropy is respected



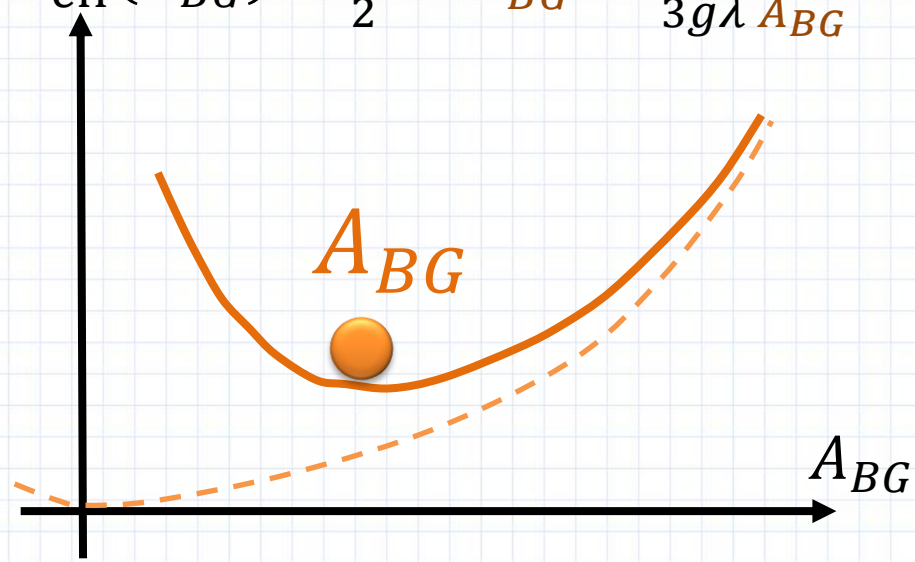
$$A_i^a = aA_{BG}(t)\delta_i^a$$

[Maleknejad&Erfani(2014)] [Domcke,Mares,Muia,Pieroni(2019)] [Wolfson,Maleknejad,Komatsu(2020)]

BG dynamics



$$V_{\text{eff}}(A_{BG}) \simeq \frac{1}{2} H^2 A_{BG}^2 + \frac{\mu^4 \sin\left(\frac{\chi}{f}\right)}{3g\lambda\, A_{BG}}$$



SU(2) gauge field has non-zero vev while χ is slowly rolling down its potential.

$$\Lambda \equiv \frac{\lambda Q}{f} \gg \sqrt{2},$$

$$\Lambda m_Q \gg \sqrt{3},$$

Flow of dynamics

BG: Axion χ_{BG} → Vector A_i^{BG}

Pert: $t_{ij} = \delta A_j^i$ → GW $h_{ij}^{(s)}$

Instability of Chiral Tensor

"T.T. component" of $\delta A_j^a = t_{aj}$ linearly coupled to GW

EoM:

$$h''_{R,L} + \left(1 - \frac{2}{x^2}\right) h_{R,L} = \mathcal{O}\left(\Omega_A^{1/2}\right) t_{R,L}$$

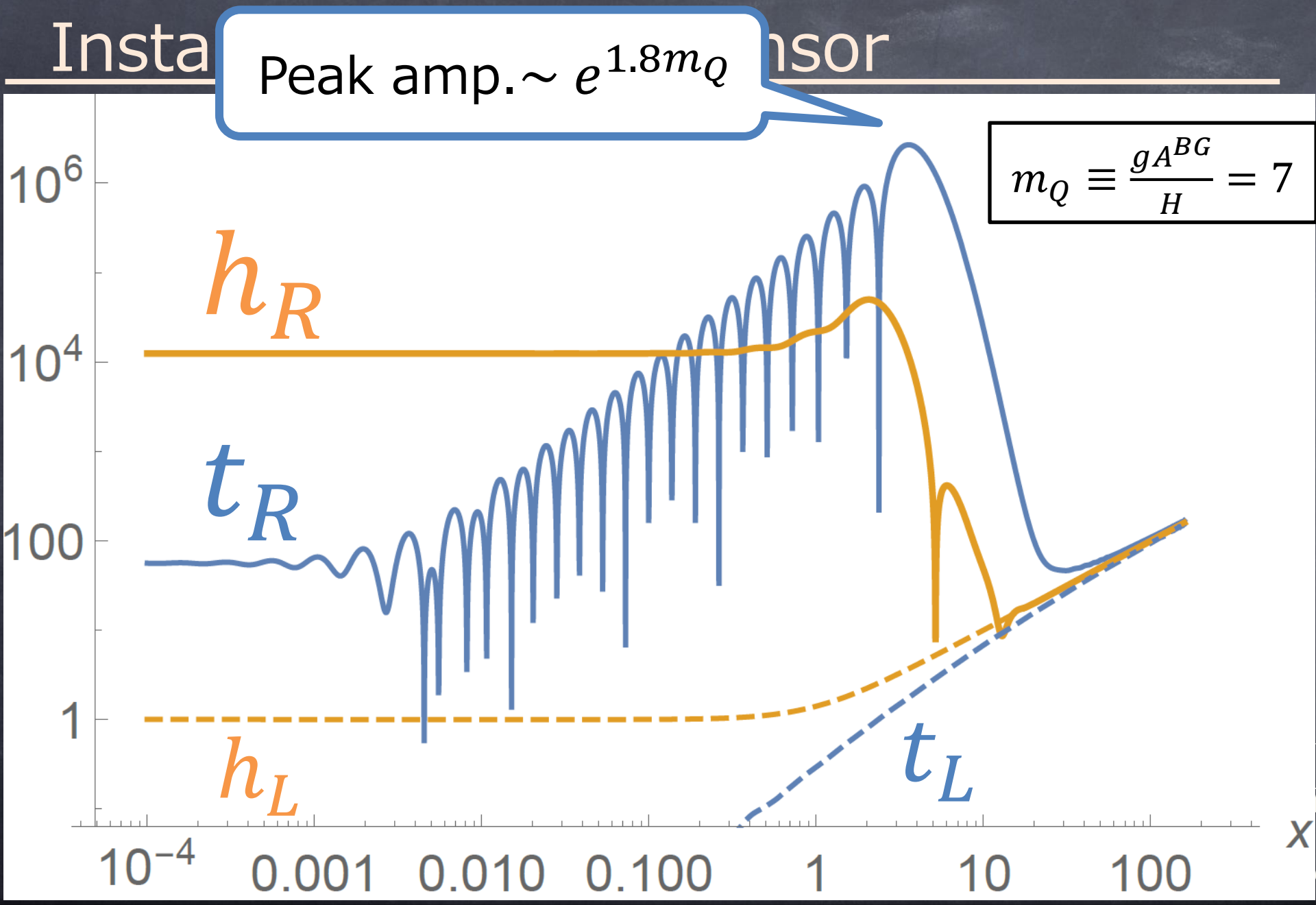
$$t''_{R,L} + \left(1 + \frac{2m_Q\xi}{x^2} \mp \frac{2}{x}\left(m_Q + \xi\right)\right) t_{R,L} = \mathcal{O}\left(\Omega_A^{1/2}\right) h_{R,L}$$

Only t_R undergoes tachyonic instability for $\dot{\chi} > 0$.

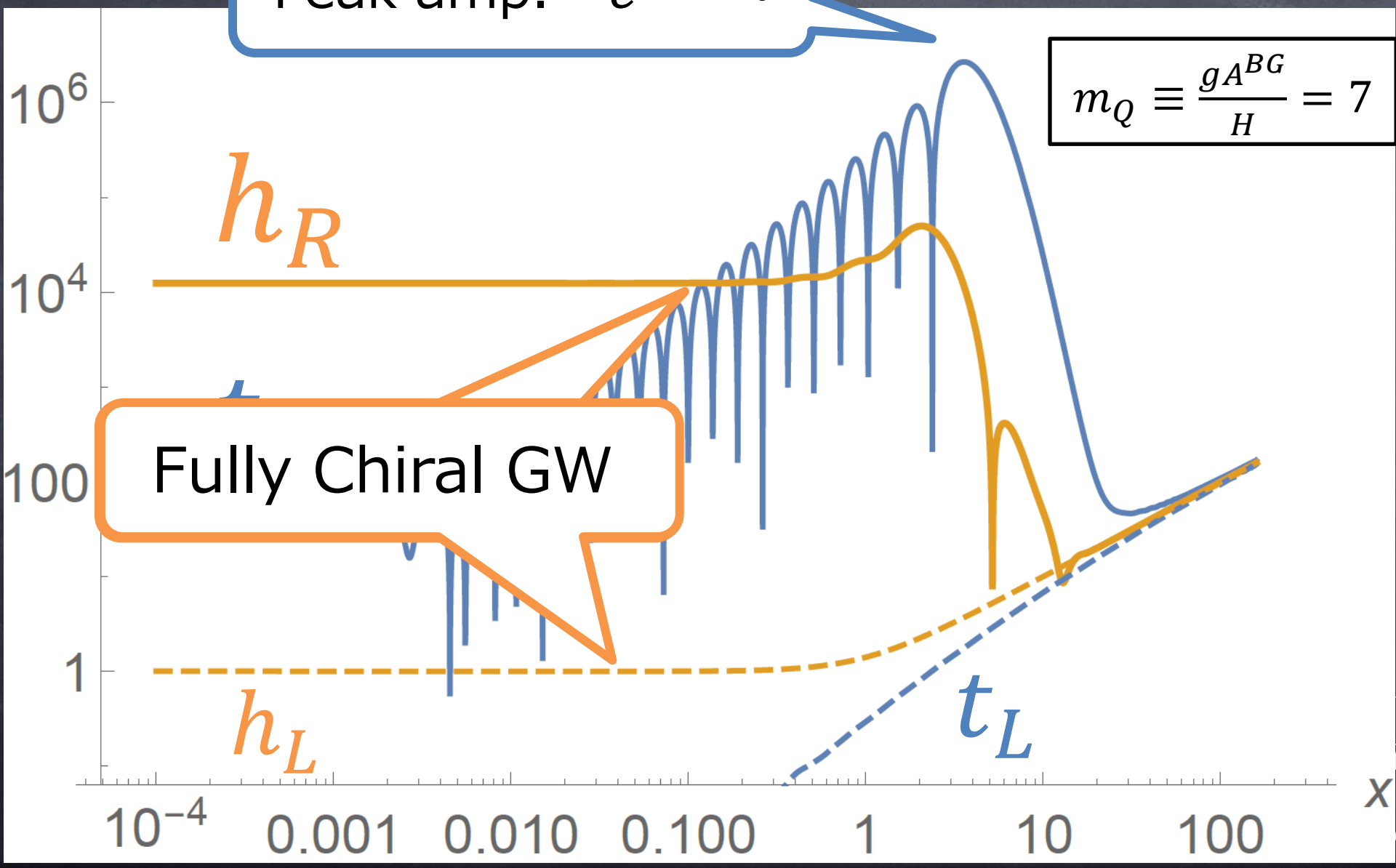
$\Rightarrow$ $h_R \gg h_L$: **Chiral GW is generated!**

$$x \equiv -k\eta$$
$$m_Q \equiv gA^{BG}/H$$
$$\xi \equiv \lambda\dot{\chi}/2fH$$
$$A_i^a \equiv a\delta_i^a A^{BG}$$

Insta nsor


Peak amp.~ $e^{1.8m_Q}$
$m_Q \equiv \frac{gA^{BG}}{H} = 7$
h_R
t_R
h_L
t_L
10^6
10^4
100
1
10^{-4}
0.001
0.010
0.100
1
10
100
x

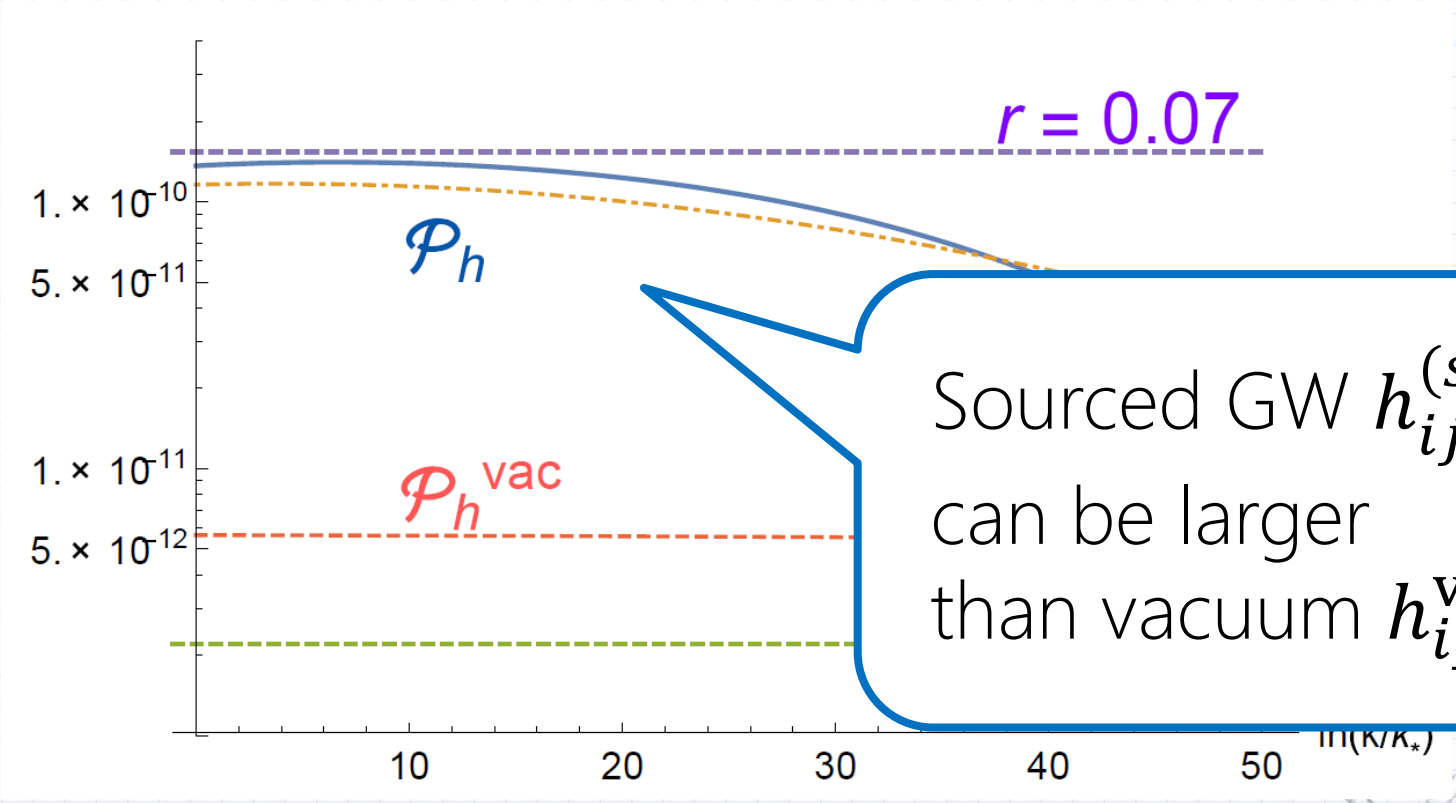
Insta nsor


Peak amp.~ $e^{1.8m_Q}$
$m_Q \equiv \frac{gA^{BG}}{H} = 7$
h_R
Fully Chiral GW
h_L
t_L
10^6
10^4
100
1
10^{-4}
0.001
0.010
0.100
1
10
100
x

Amplitude

○ $H_{\rm inf} \approx 1 \times 10^{13}\,{\rm GeV}$

× $H_{\rm inf} \approx 6 \times 10^{13}\,{\rm GeV}$



Sourced GW $h_{ij}^{(s)}$ can be larger than vacuum $h_{ij}^{\rm vac}$

Obs. properties of PGW

	Vacuum	SU(2)
①Amplitude	$\left(\frac{H_{\rm inf}}{M_{\rm Pl}}\right)^2$	$\left(\frac{H_{\rm inf}}{M_{\rm Pl}}\right)^2 \Omega_A e^{3.6 m_Q}$
②Tensor tilt n_t	Small	Can be large
③Polarization	None	Circular
④Non-Gaussianity	Small	Large

Obs. properties of PGW

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①Amplitude	$\left(\frac{H_{\rm inf}}{M_{\rm Pl}}\right)^2$	$\left(\frac{H_{\rm inf}}{M_{\rm Pl}}\right)^2 \Omega_A e^{3.6 m_Q}$
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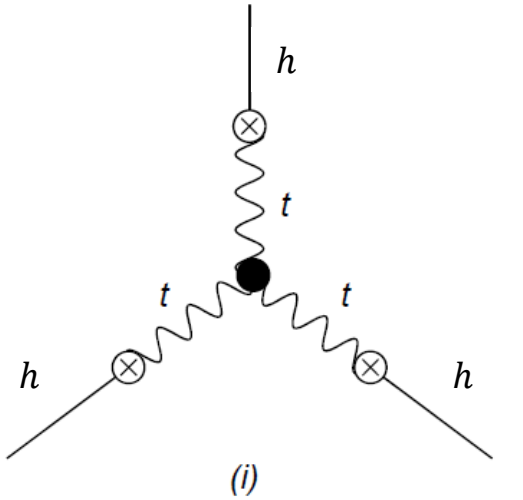
Non-Gaussianity

Large $\langle h_R h_R h_R \rangle$ $\xleftarrow{\text{linear}}$ Large $\langle t_R t_R t_R \rangle$

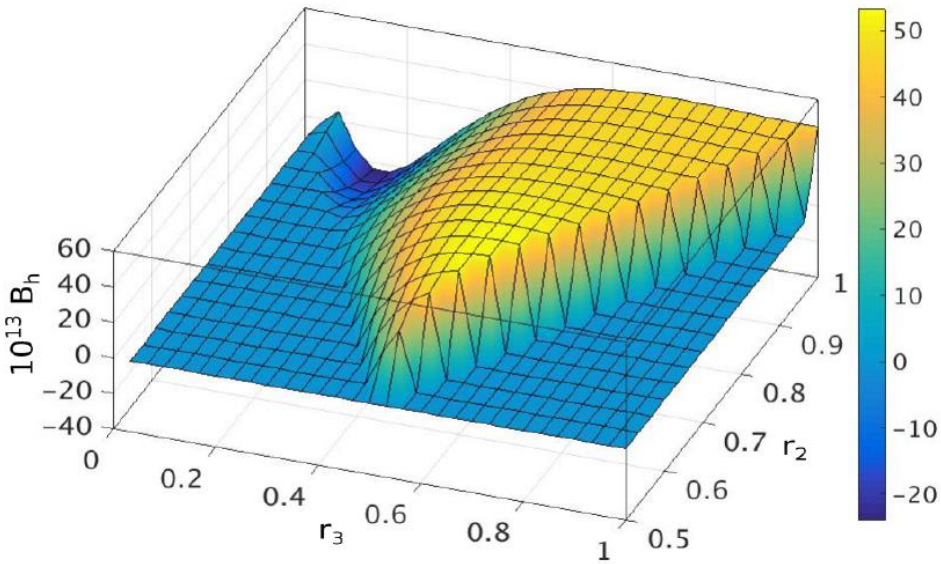
The self-interaction of SU(2) gives the non-linear dynamics (3p vertex)!

$$L_3^{(i)} = c^{(i)} \left[\epsilon^{abc} t_{ai} t_{bj} \left(\partial_i t_{cj} - \frac{m_Q^2 + 1}{3 m_Q \tau} \epsilon^{ijk} t_{ck} \right) - \frac{m_Q}{\tau} t_{ij} t_{jl} t_{li} \right],$$



[Agrawal,TF,Komatsu (2017)]

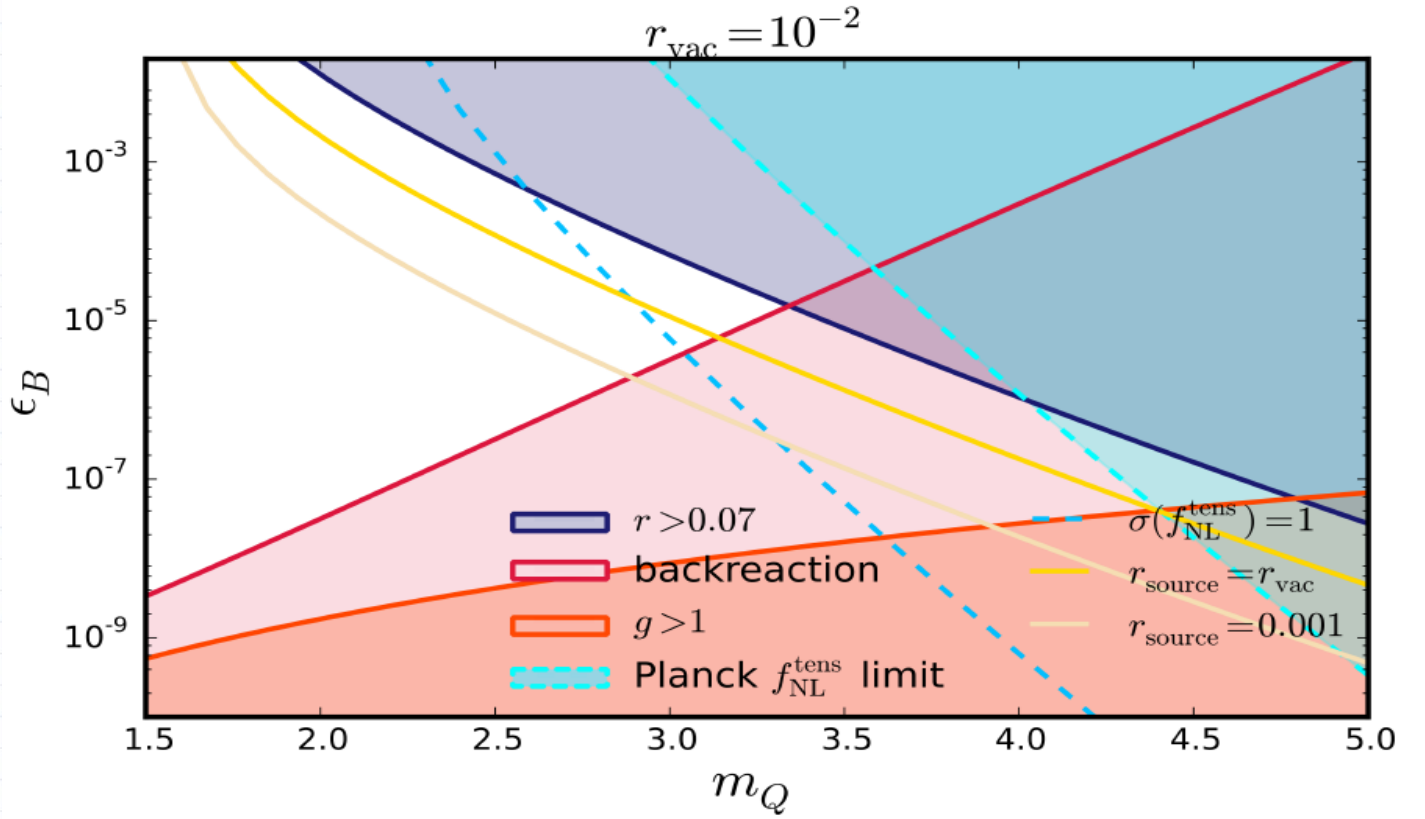
Non-Gaussian shape



The NG shape is almost equilateral ($\cos\theta \approx 0.9$)

Detectability

[Agrawal,TF,Komatsu (2018)]

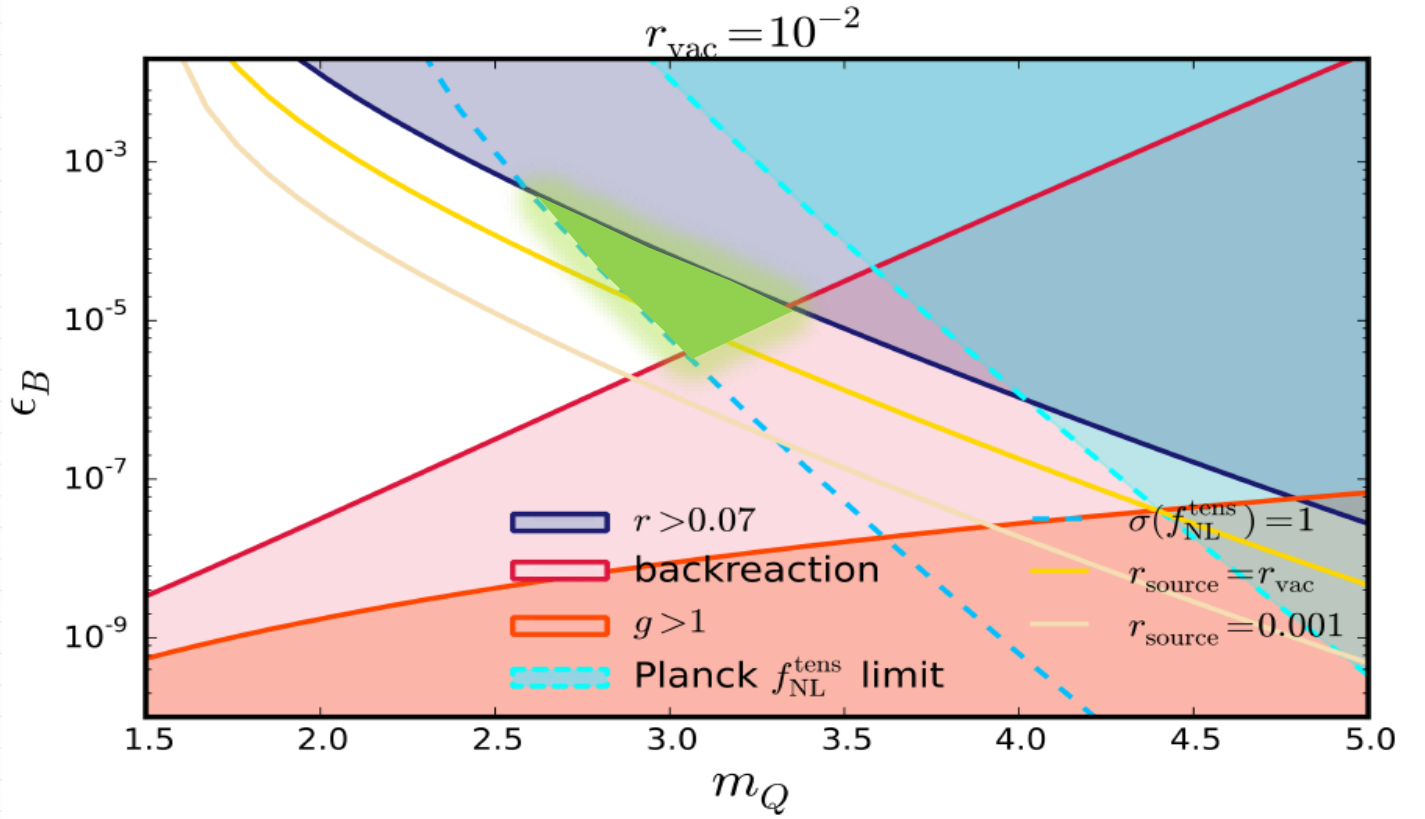


$m_Q \equiv gA^{BG}/H$

$\epsilon_B \simeq 2\Omega_A$

[Agrawal,TF,Komatsu (2018)]

Detectability



LiteBIRD can detect NG tensor mode!!

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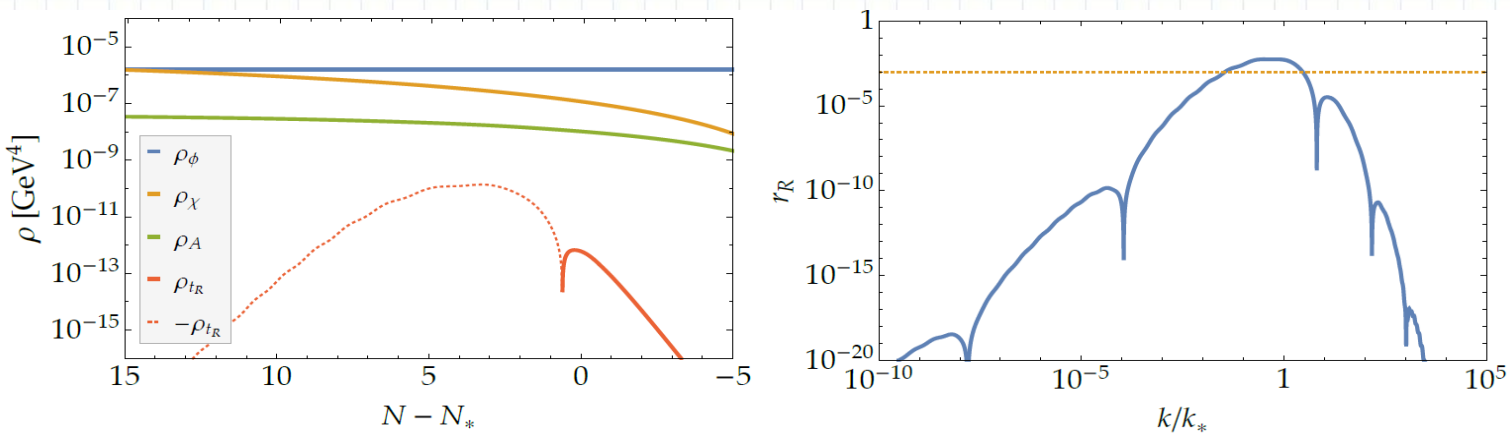
[TF,Namba,Tada (2017)]

Lowest $\rho_{\rm inf}$ for $r \geq 10^{-3}$

How much can we boost r by axion-SU(2)??

Once I said… $r_{\rm vac} \sim 10^{-80}$,

Even $\rho_{\rm inf}^{1/4} = 30{\rm MeV}$, $r \geq 10^{-3}$ is possible



$H_{\rm inf} = 3 \times 10^{-22}\,{\rm GeV}$, $\mu = 0.055\,{\rm GeV}$, $f = 1.5 \times 10^{17}\,{\rm GeV}$, $\lambda = 3000$, $g = 1.9 \times 10^{-36}$

Consistency

[TF,Namba,Tada (2017)]

Lowest $\rho_{\rm inf}$ for $r \geq 10^{-3}$

How much c[illegible]e boost r by a[illegible]SU(2)??

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$r_{\rm vac}$

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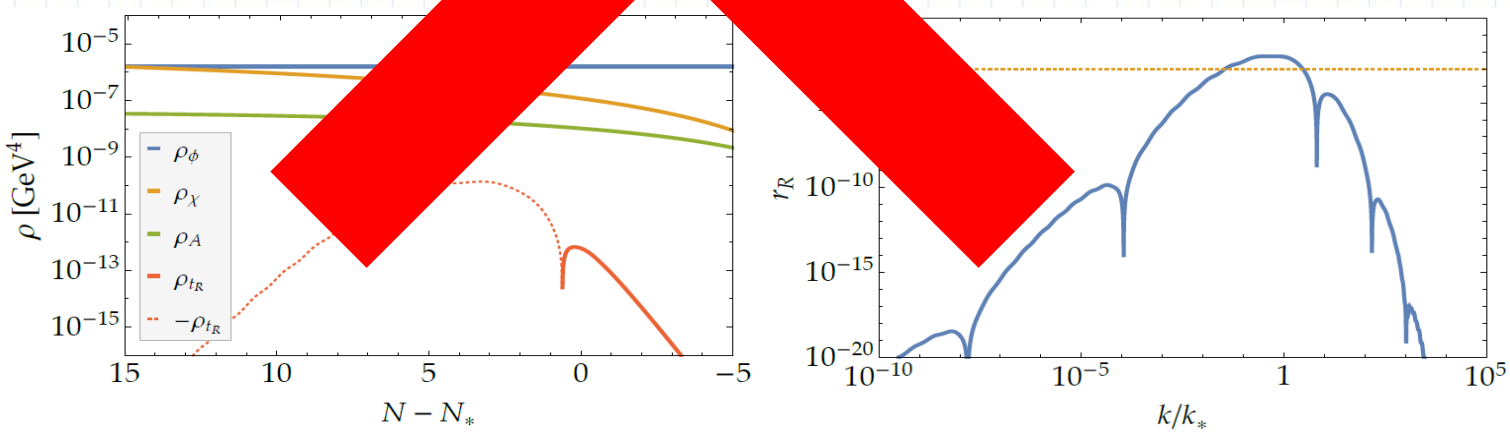
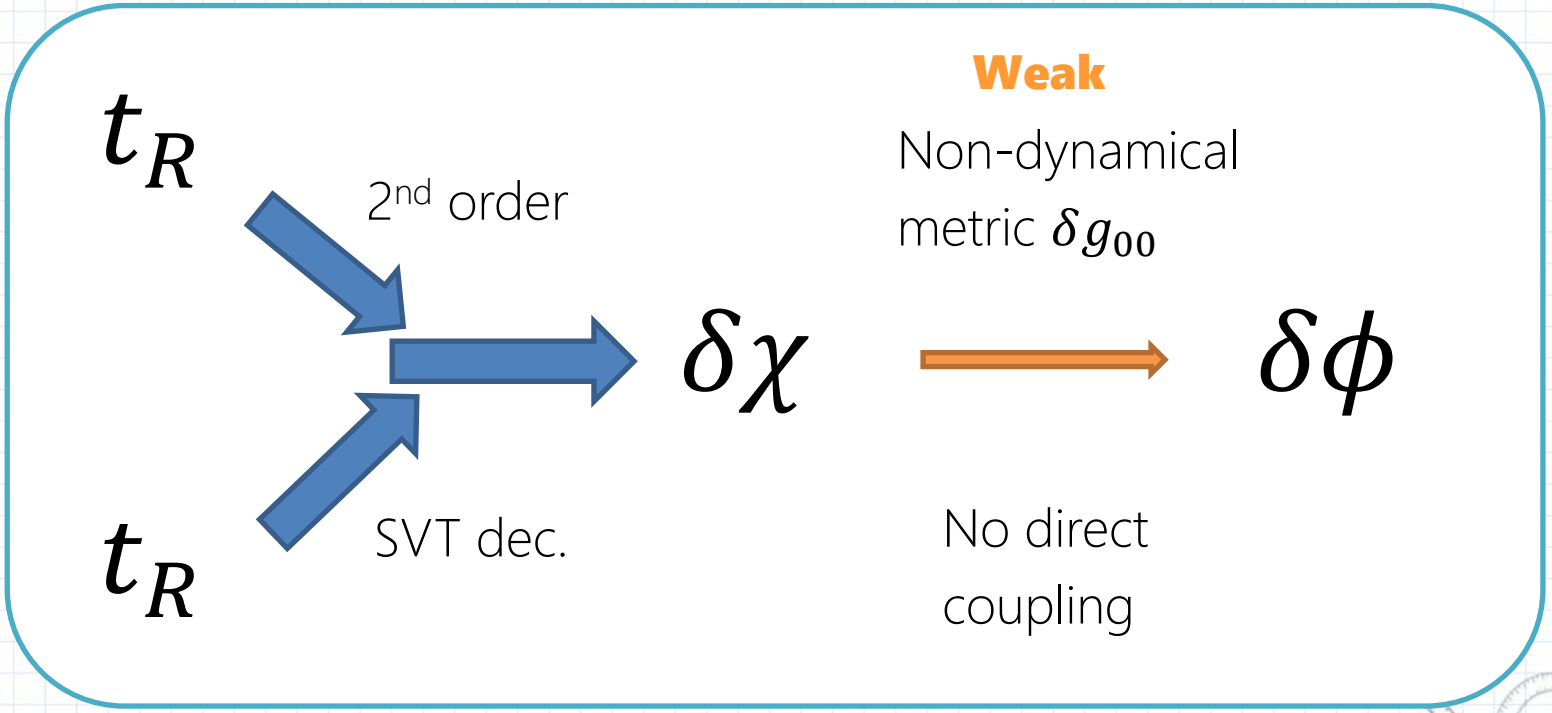


$H_{\rm inf} = 3 \times 10^{-22}\,{\rm GeV}, \quad \mu = 0.055\,{\rm GeV}, \quad f = 1.5 \times 10^{17}\,{\rm GeV}, \quad \lambda = 3000, \quad g = 1.9 \times 10^{-36}$

Stringent constraint

[Papageorgiou,Peloso,Unal(2019)]

t_R induces the inflaton perturbation $\delta\phi \propto \zeta$ at 2nd order and leads to highly NG curvature pert, $\zeta_{\mathrm{src}} \sim \zeta_\phi$



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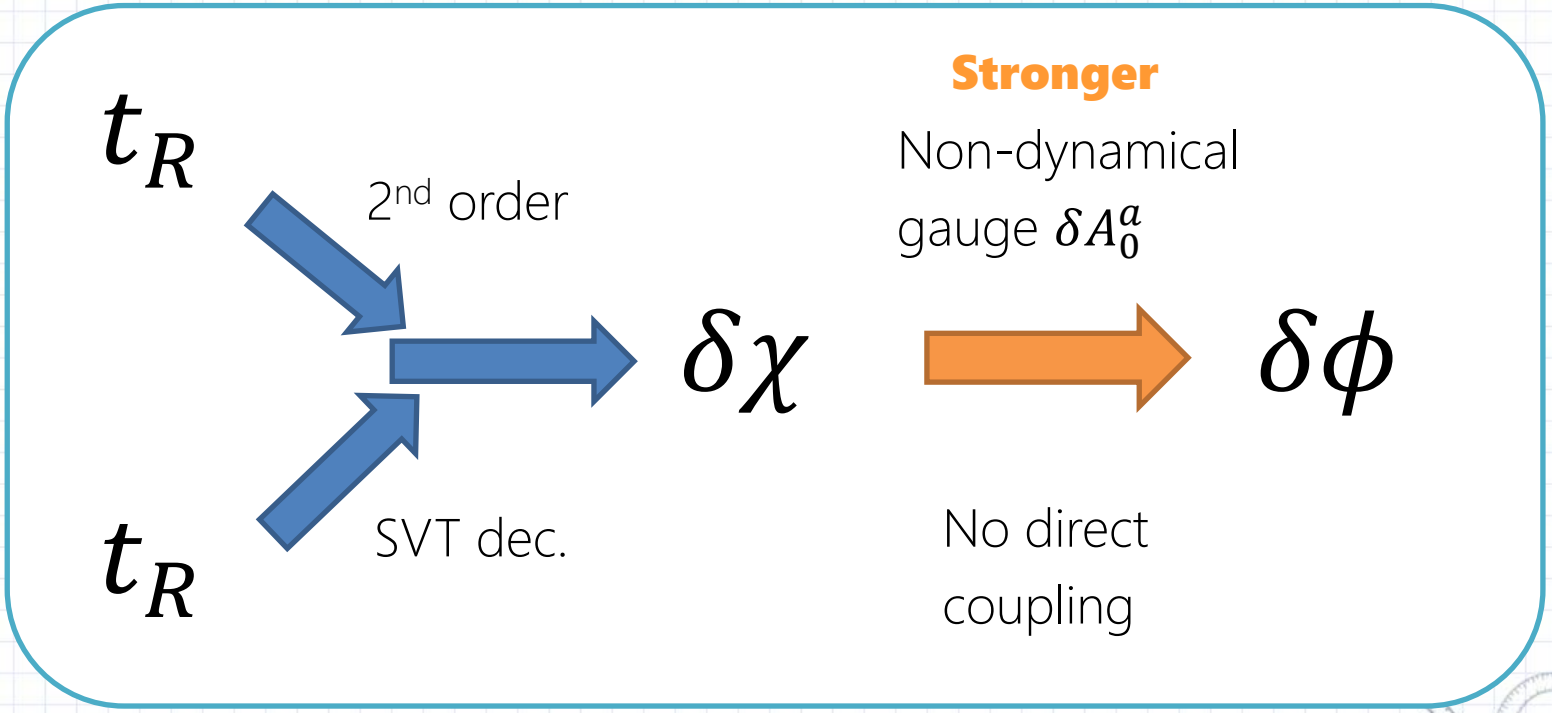

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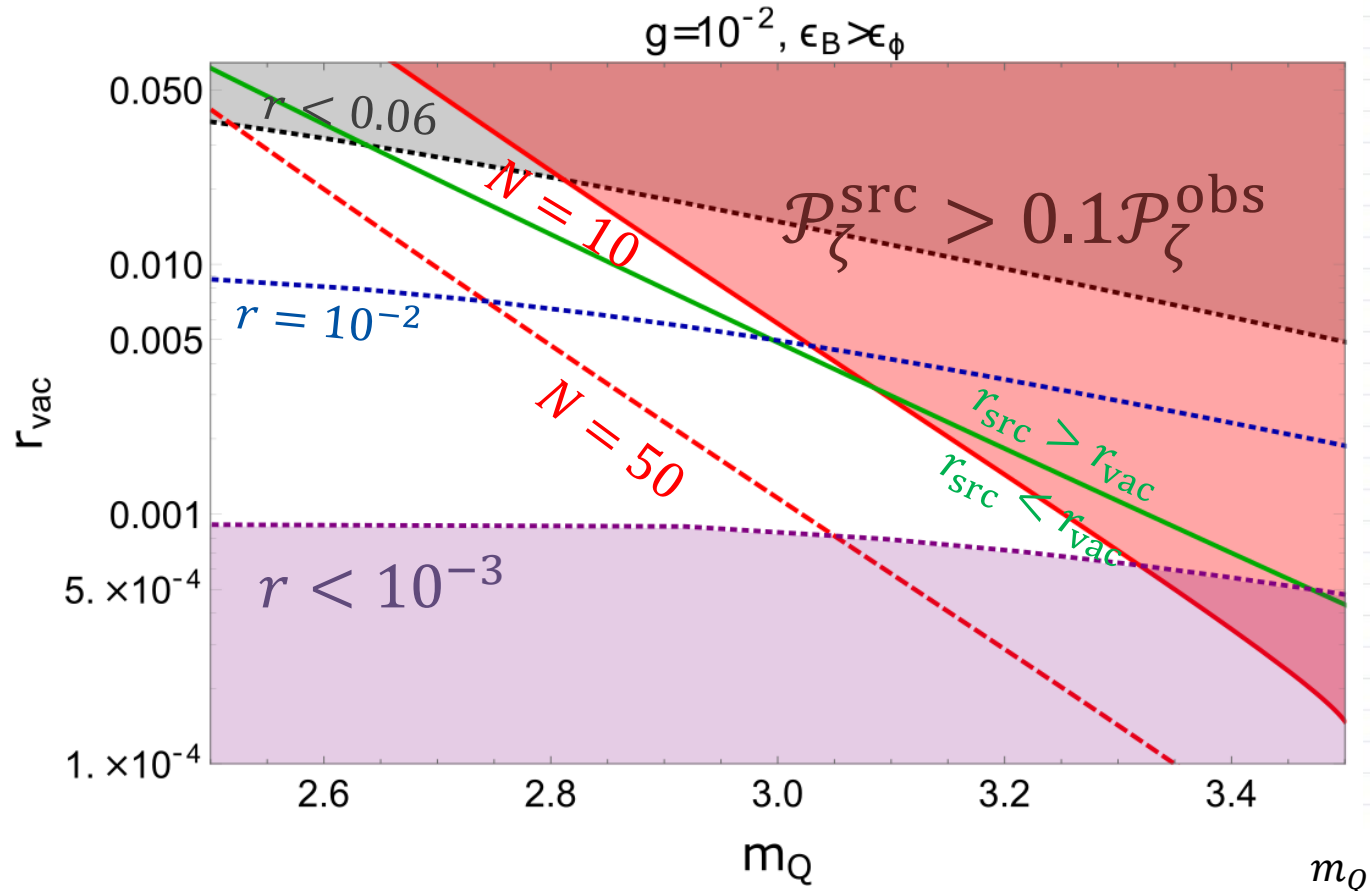
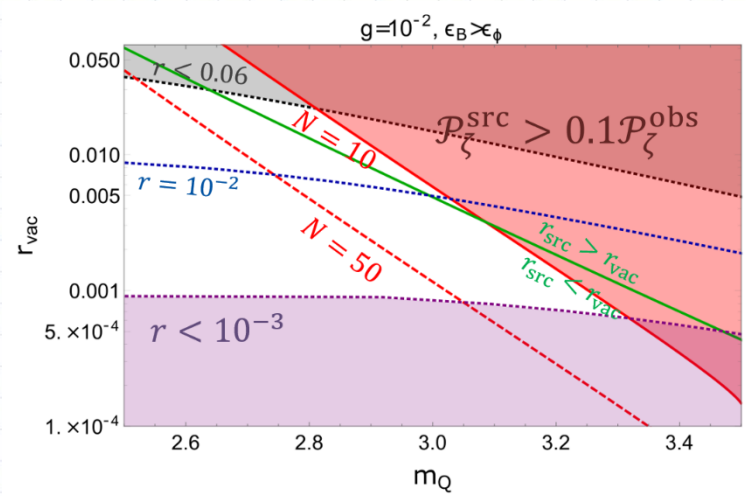


$m_Q \equiv gA^{BG}/H$

$r_{\rm src} \gg r_{\rm vac}$ is not allowed on the CMB scale

[Papageorgiou,Peloso,Unal(2019)]

Lessons



$r_{\mathrm{src}} \gg r_{\mathrm{vac}}$ is impossible on the CMB scale

Analysis with $m = const.$ is allowed only for $N < 10$

Prediction with varying m is favored

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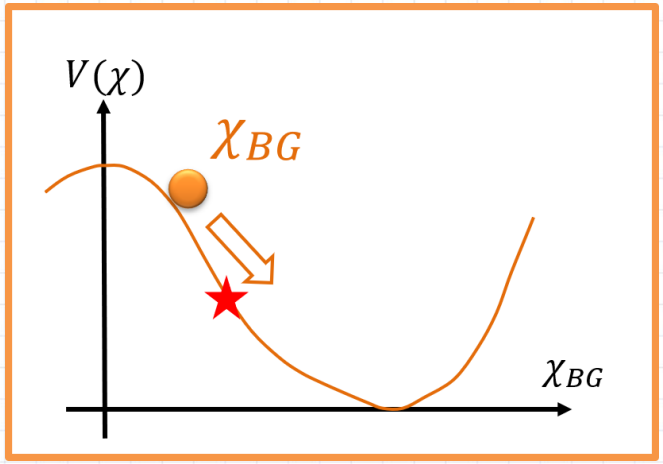
Varying m_Q case

$m_Q \equiv gA^{BG}/H$

GW production ($\propto e^{3.6m_Q}$) is most efficient when the axion velocity $\dot{\chi}$ reaches a maximum at inflection



$$\dot{\chi}_{\max} \Leftrightarrow V'_{\max}(\chi)$$

$$\chi(t) \simeq \frac{\pi}{2} f + \dot{\chi}_*(t - t_*)$$

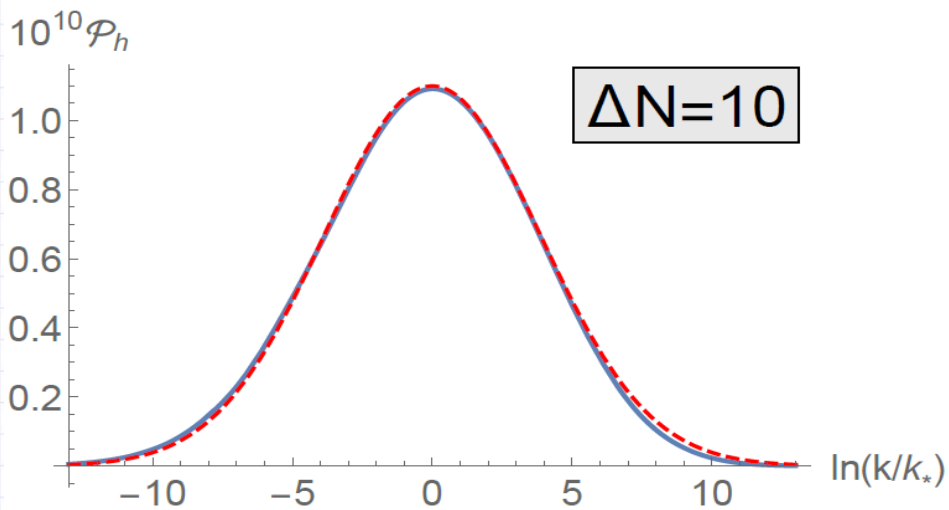
$$m_Q(t) \simeq m_* \left[1 - \frac{1}{6}\left(\frac{H_{\inf}(t - t_*)}{\Delta N}\right)^2\right]$$

Expand the analytic expression for $m_Q = const.$ around the inflection point

Excellent Template

Derived template matches the numerical result.

$V(\chi) \propto \left(\cos\frac{\phi}{f} + 1\right)$ → $\mathcal{P}_h^{(s)}$ = Gaussian shape.



$$\mathcal{P}_h(k) \simeq \mathcal{A}^2(m_*, \epsilon_{B*}) \exp\left[-\frac{1}{2\sigma^2(\Delta N)} \ln^2(k/k_p)\right]$$

$$\mathcal{A}(m_*, \epsilon_{B*}) \equiv \frac{\sqrt{\epsilon_{B*}} H}{\pi M_{\rm Pl}} \mathcal{F}(m_*)$$

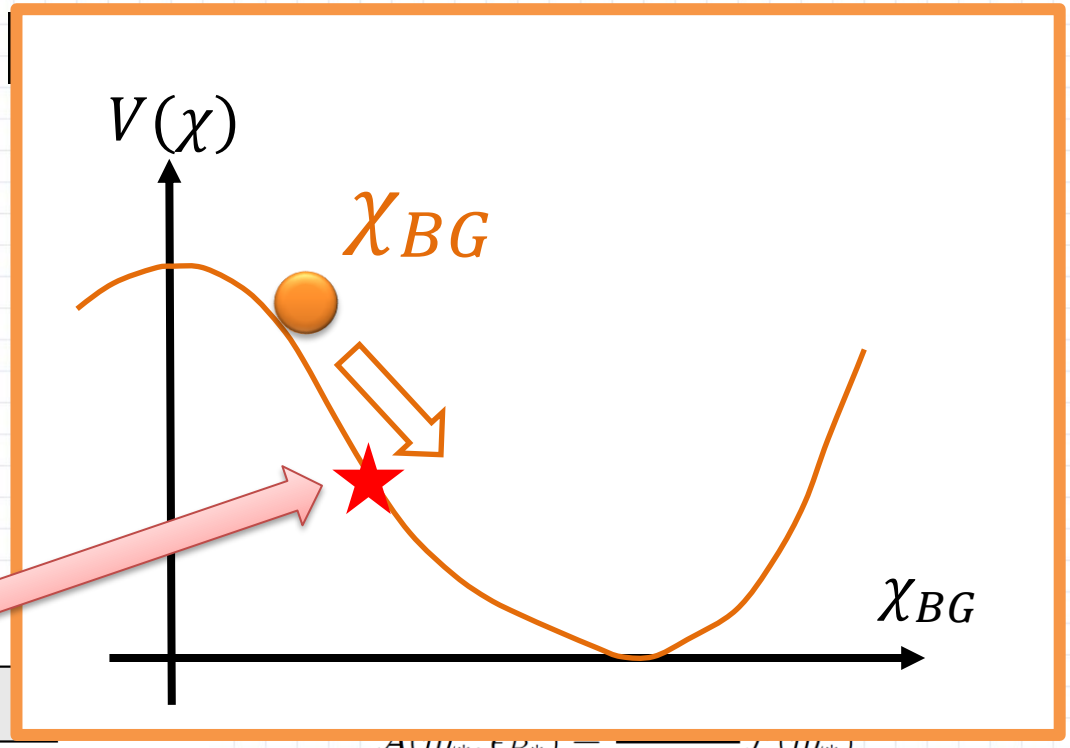
$\sigma = \Delta N / \mathcal{G}(m_*)$,

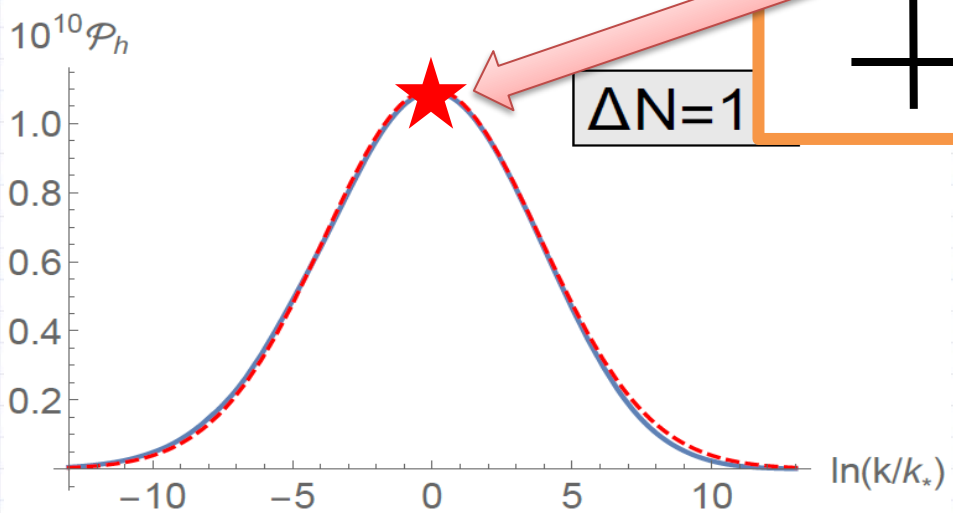
k_p = arbitrary

Excellent Temp

Derived template matches

$$V(\chi) \propto \left(\cos\frac{\phi}{f} + 1\right)$$





$$\sigma = \Delta N / \mathcal{G}(m_*),$$

$$k_p = \text{arbitrary}$$

Obs. properties of PGW

	Vacuum	SU(2)
①Amplitude	$\left(\frac{H_{\rm inf}}{M_{\rm Pl}}\right)^2$	$\left(\frac{H_{\rm inf}}{M_{\rm Pl}}\right)^2 \Omega_A e^{3.6 m_Q}$
②Tensor tilt n_t	Small	Can be large
③Polarization	None	Circular
④Non-Gaussianity	Small	Large

TB,EB probe parity

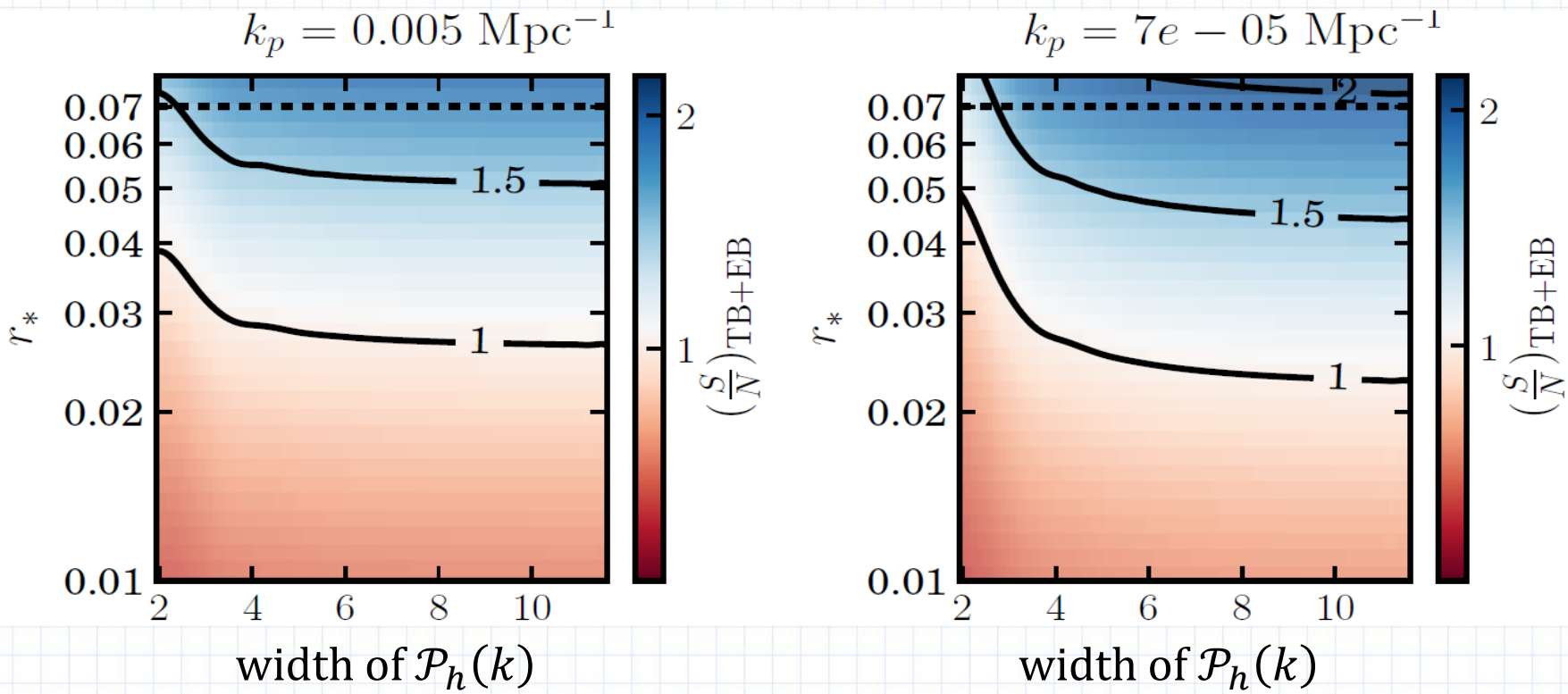
Chiral GW induces TB & EB cross correlations

$$\langle TT\rangle, \langle TE\rangle, \langle EE\rangle, \langle BB\rangle \propto \langle h_R h_R\rangle + \langle h_L h_L\rangle$$

$$\langle TB\rangle, \langle EB\rangle \propto \langle h_R h_R\rangle - \langle h_L h_L\rangle$$

By detecting TB & EB correlations, we can distinguish $\boldsymbol{h}_{\mathbf{src}}$ from $\boldsymbol{h}_{\mathbf{vac}}$

Detectability of Pol.



Parity violation in PGW can be detected for $r_* \gtrsim 0.03$

[Thone, TF, Hazumi + (2018)]

$V(\chi) - P_h(k)$ correspondence

[T.F. Sfakianakis, Shiraishi(2019)]

We find axion potentials are categorized into 3 types, according to the GW power spectrum.

	potential type	sample potential	GW template
Type I	convex / concave	$U(\chi) \propto \chi^p$	$\mathcal{P}_h^{(s)}(k) \propto \left(\frac{k}{k_*}\right)^{n_T}$
Type II	one inflection point	$U(\chi) \propto \left[1 + \cos\left(\frac{\chi}{f}\right)\right]^{\frac{p}{2}}$	$\mathcal{P}_h^{(s)} \propto \exp\left[\frac{\ln^2(k/k_*)}{2\sigma_h^2}\right]$
Type III	axion monodromy (modulated)	$U(\chi) \propto \chi^p + A\cos(C\chi)$	$\mathcal{P}_h^{(s)} \propto 1 + \mathcal{A}\sin(\omega \ln(\frac{k}{k_*}) + \theta)$ for $p = 1$ & $\mathcal{A} \ll 1$

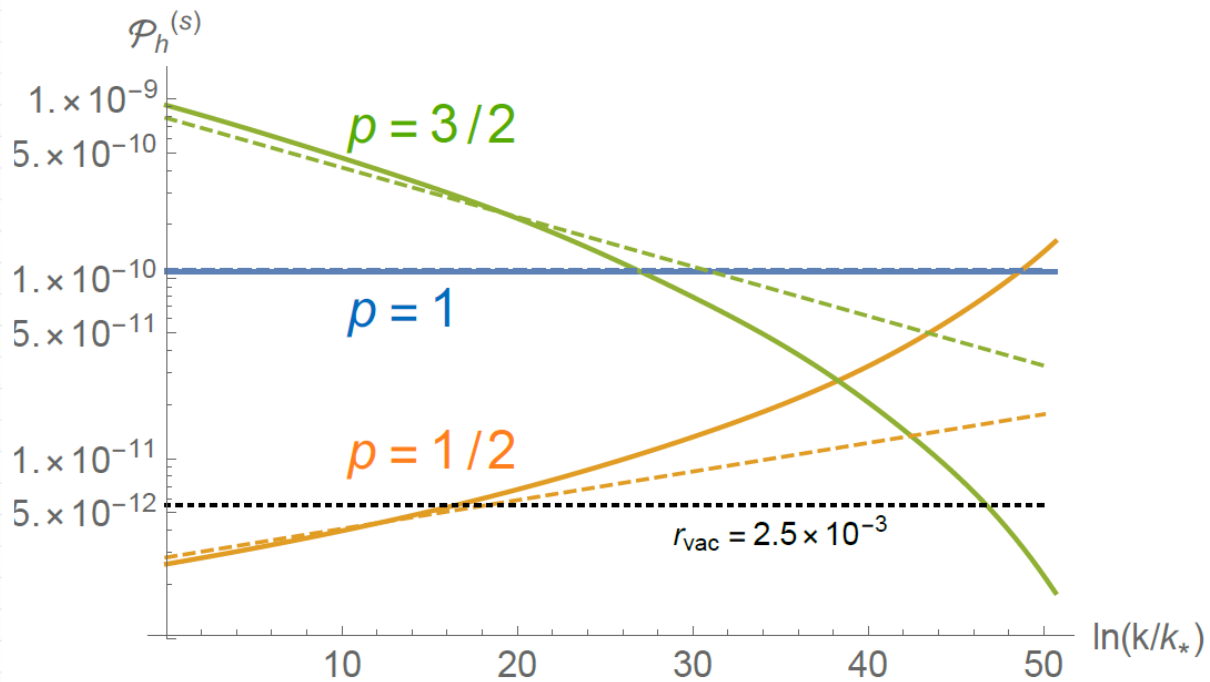
Type I: $V(\chi) \propto \chi^p$

[T.F. Sfakianakis, Shiraishi(2019)]

	potential type	sample potential	GW template
Type I	convex / concave	$U(\chi) \propto \chi^p$	$\mathcal{P}_h^{(s)}(k) \propto \left(\frac{k}{k_*}\right)^{n_T}$

Power-law $V(\chi)$ leads to power-law PGW power spectrum

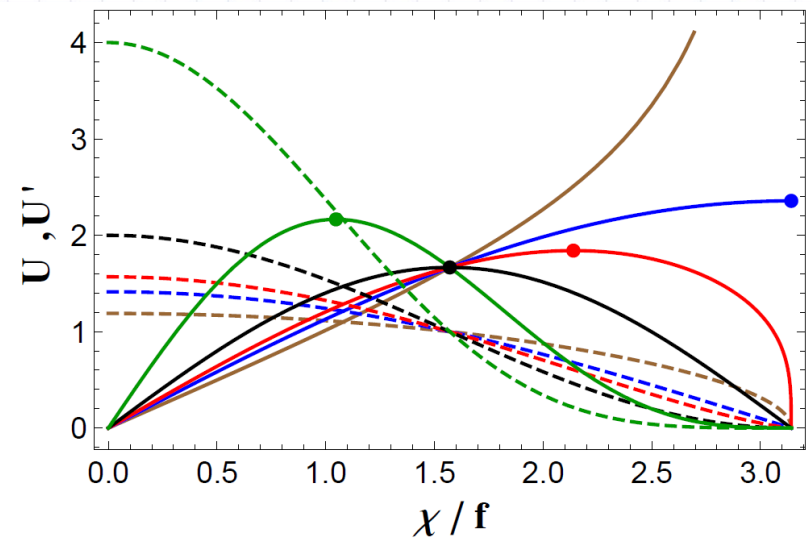
From the tilt of $\mathcal{P}_h(k)$, you can know about the potential index p.

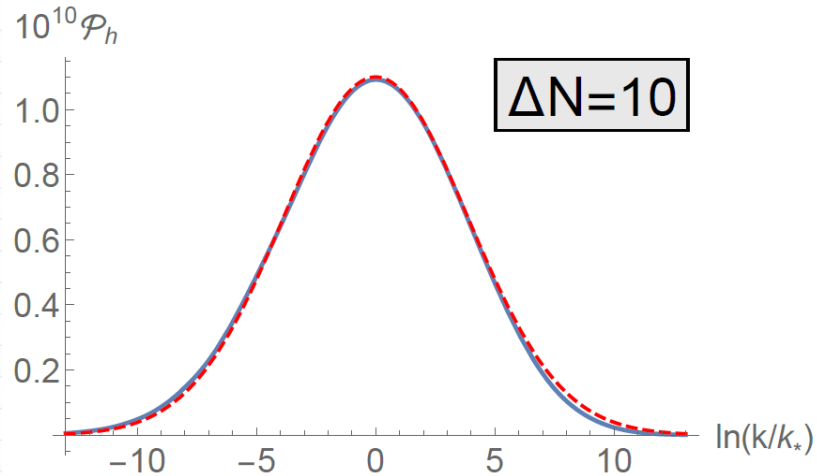


Model

Type II: $V(\chi) \propto (1+\cos\chi/f)^{p/2}$

Type II	one inflection point	$U(\chi) \propto \left[1+\cos\left(\frac{\chi}{f}\right)\right]^{\frac{p}{2}}$	$\mathcal{P}_h^{(s)} \propto \exp\left[\frac{\ln^2(k/k_*)}{2\sigma_h^2}\right]$

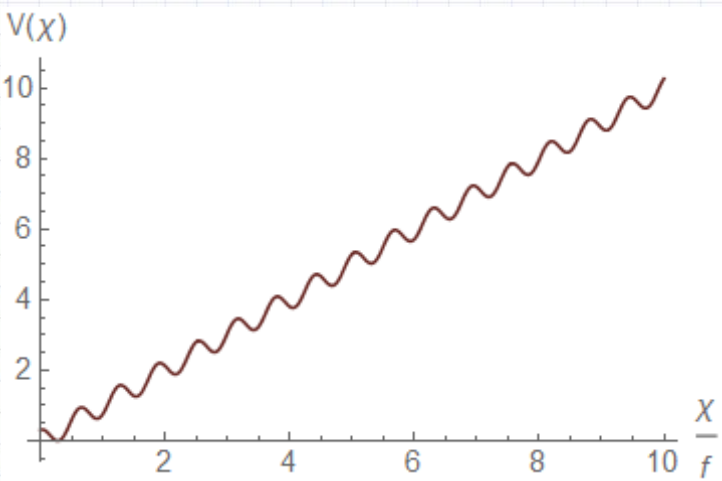


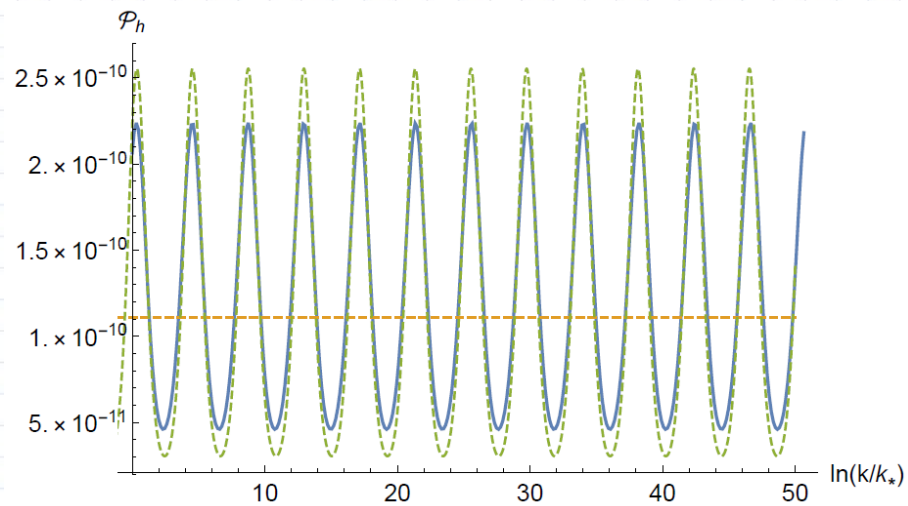


Potential with an inflection point universally produces a gaussian shape $\mathcal{P}_h(k)$

Type III: monodromy $V(\chi)$

Type III	axion monodromy (modulated)	$U(\chi) \propto \chi^p + A\cos(C\chi)$	$\mathcal{P}_h^{(s)} \propto 1 + \mathcal{A}\sin(\omega \ln(\frac{k}{k_*}) + \theta)$ for $p = 1$ & $\mathcal{A} \ll 1$





Oscillating potential leads to oscillating $\mathcal{P}_h(k)$

PGW observation may reveal UV theories.

[Silverstein&Westphal(2008)]

Outline of talk

① Introduction

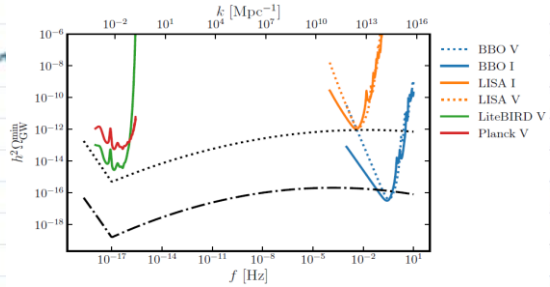
② Model

③ Consistency

④ Predictions

⑤ Future Prospects

Future Prospects

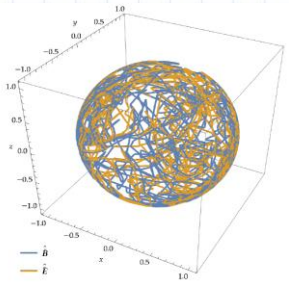


- PGW from axion-SU(2) for **LISA**

  Why axion passes the inflection point around LISA band?

- How the attractor solution begins? [TF, Mukaida, Tada(in prep)]

  Stochastic formalism can take into account the perturbation



- Higher and Mixed correlators

  $\langle hhhh \rangle, \langle hh\zeta \rangle, \langle h\zeta\zeta \rangle$ [Dimastrogiovanni+(2018)][TF, Namba, Obata(2018)]

- Extend the model

  Yuki's poster, Leila's talk, Ashead's higgsed model,... [Watanabe, Komatsu(2020)]

- Chiral anomaly

  Ask Valerie and Kyohei... [Domcke,Mukaida(2018)]

Thank you!