PRESENTATION

Gravitational wave production during inflation revisited

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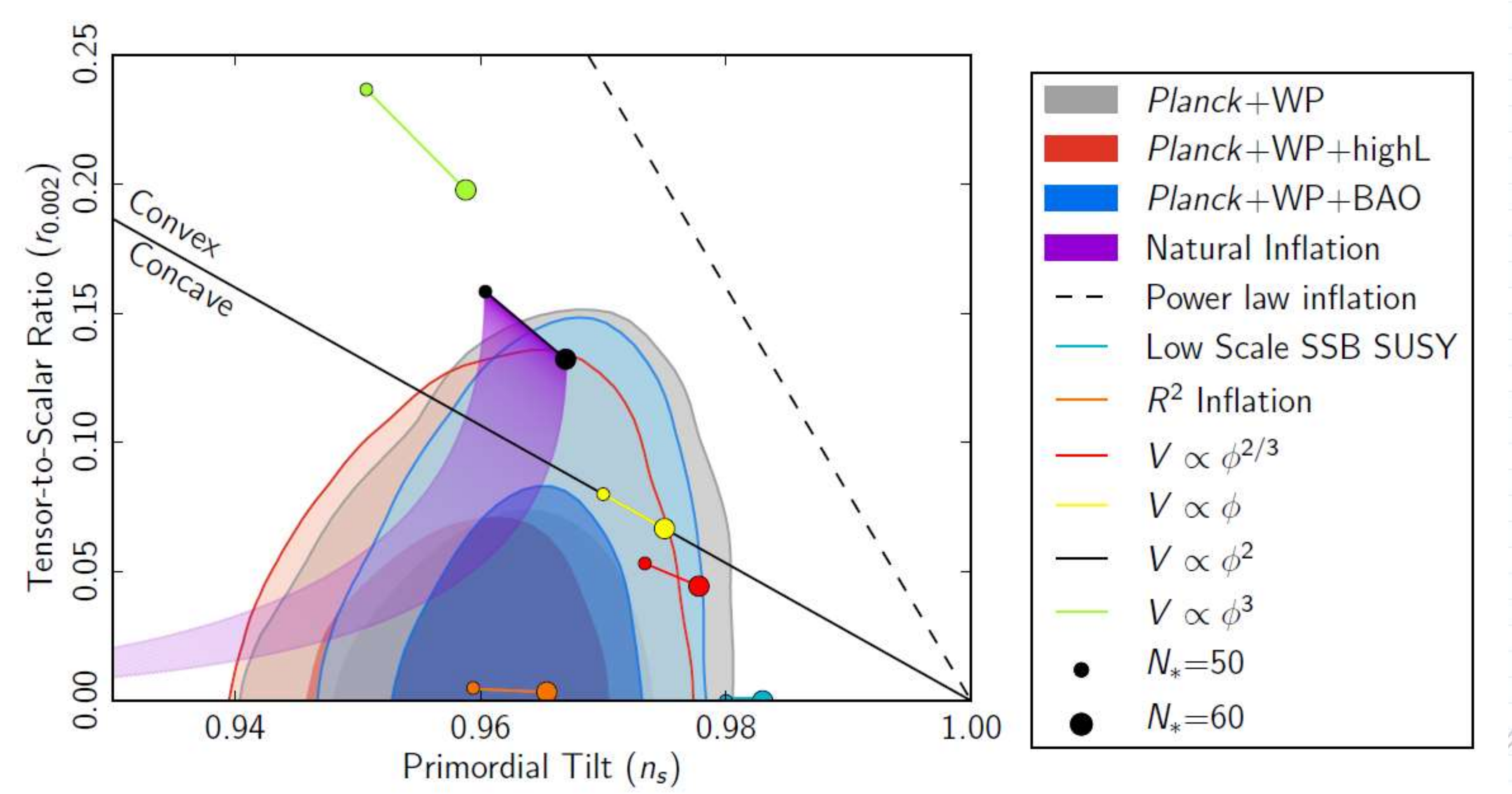
arXiv:1608.04216, 1705.01533, 1707.03023, 1707.03240
w/ Dimastrogiovanni(CWRU) & Fasiello(Stanford);
w/Namba(McGill)&Tada(IAP)
w/Komatsu&Agrawal(MPA);
w/Thone(Oxford),Hazumi(KEK),Katayama(IPMU)
Komatsu(MPA)&Shiraishi(Kagawa)

30th/Aug/2017 @COSMO17

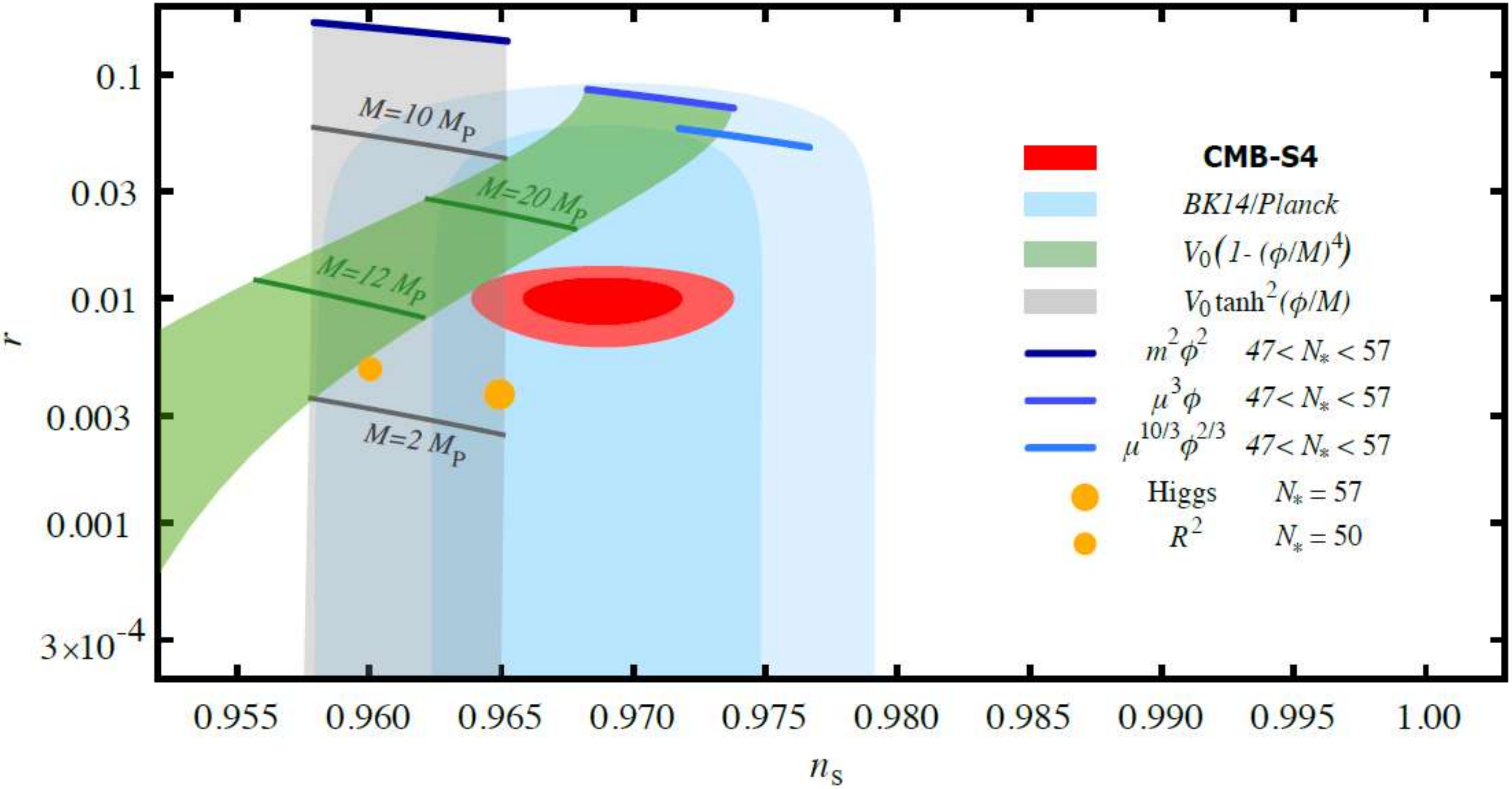
introduction

PRESENTATION

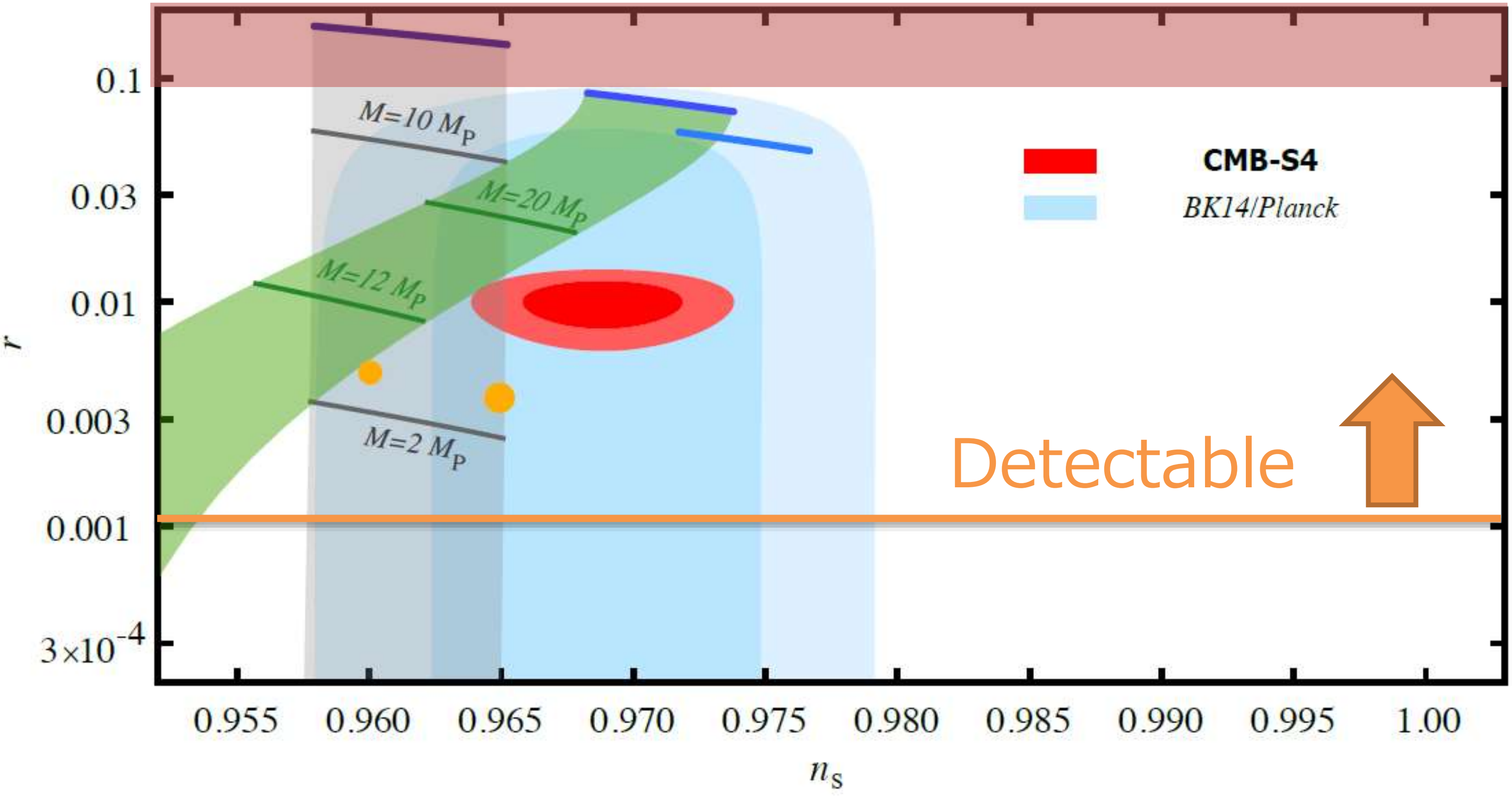


introduction

PRESENTATION

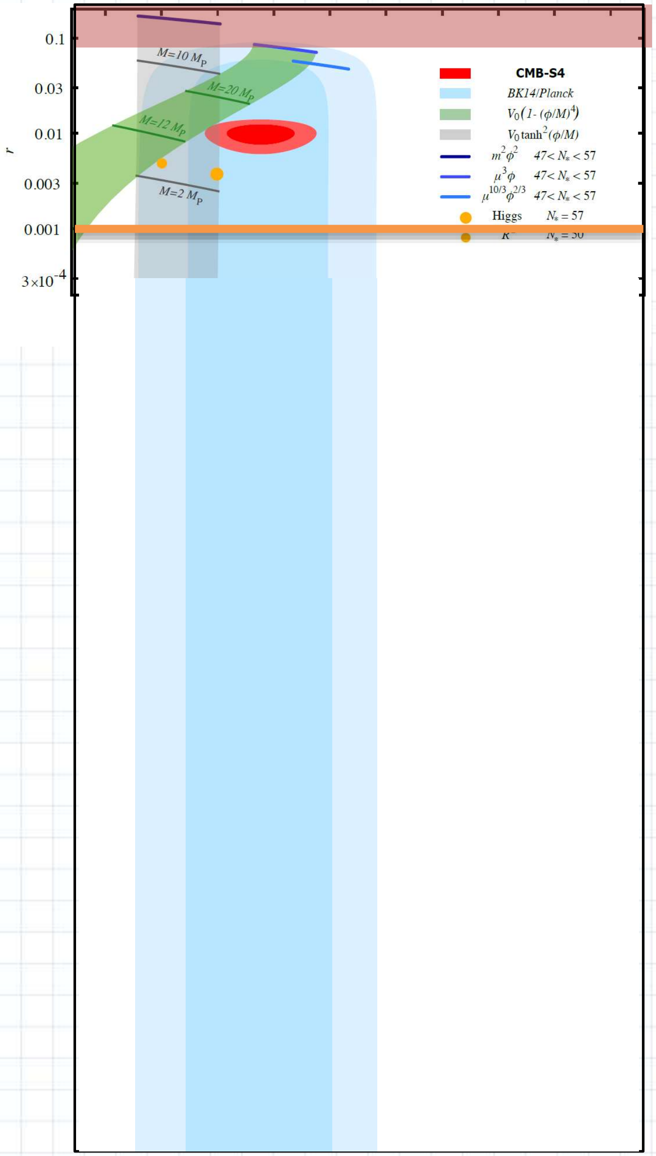


Upper bound: $r < 0.07$



What about the lower bound?

introduction



Upper bound:

$r < 7 \times 10^{-2}$

Detectable

introduction

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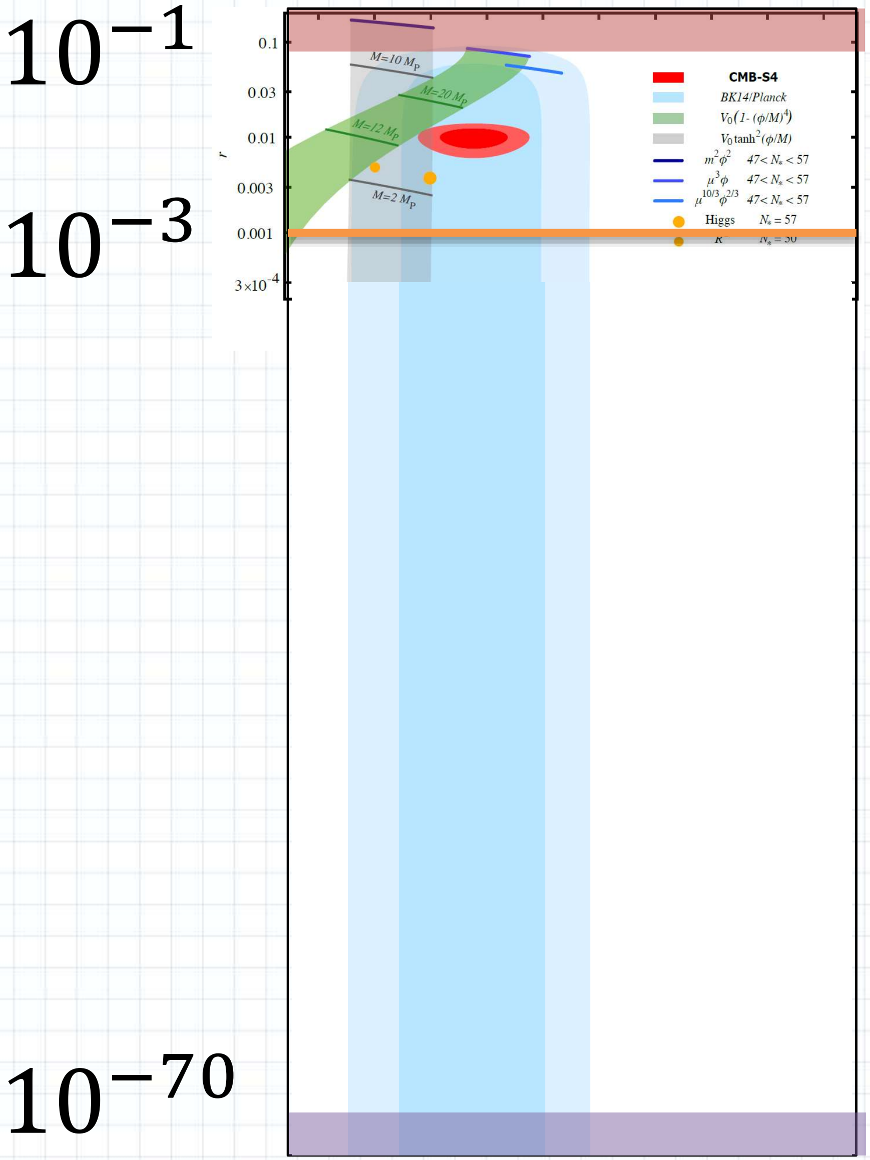

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Detectable

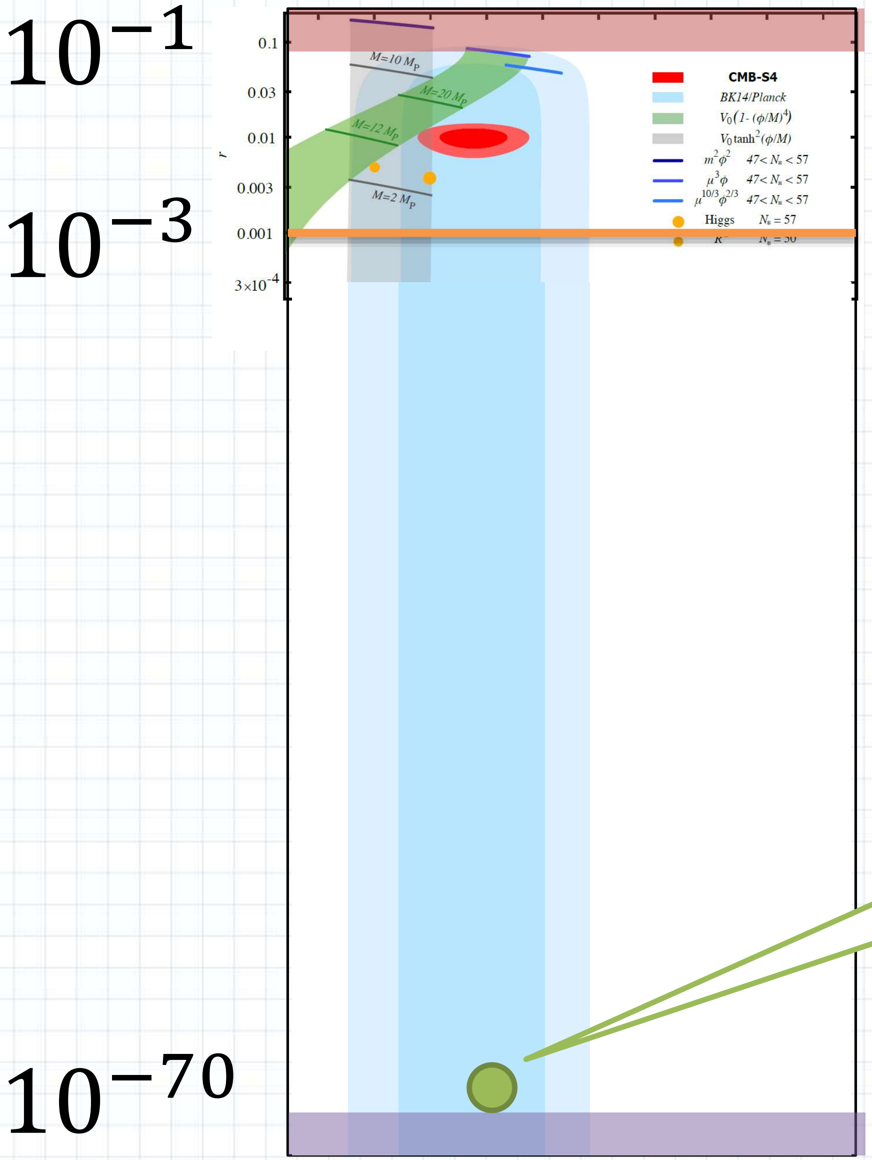
BBN bound:

$$\rho_{\inf}^{1/4} \gtrsim 0.1\mathrm{GeV}$$

Lower bound:

$$r \gtrsim 10^{-70}$$

introduction



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Extremely low energy inflation model

Lower bound:

$r \gtrsim 10^{-70}$

introduction

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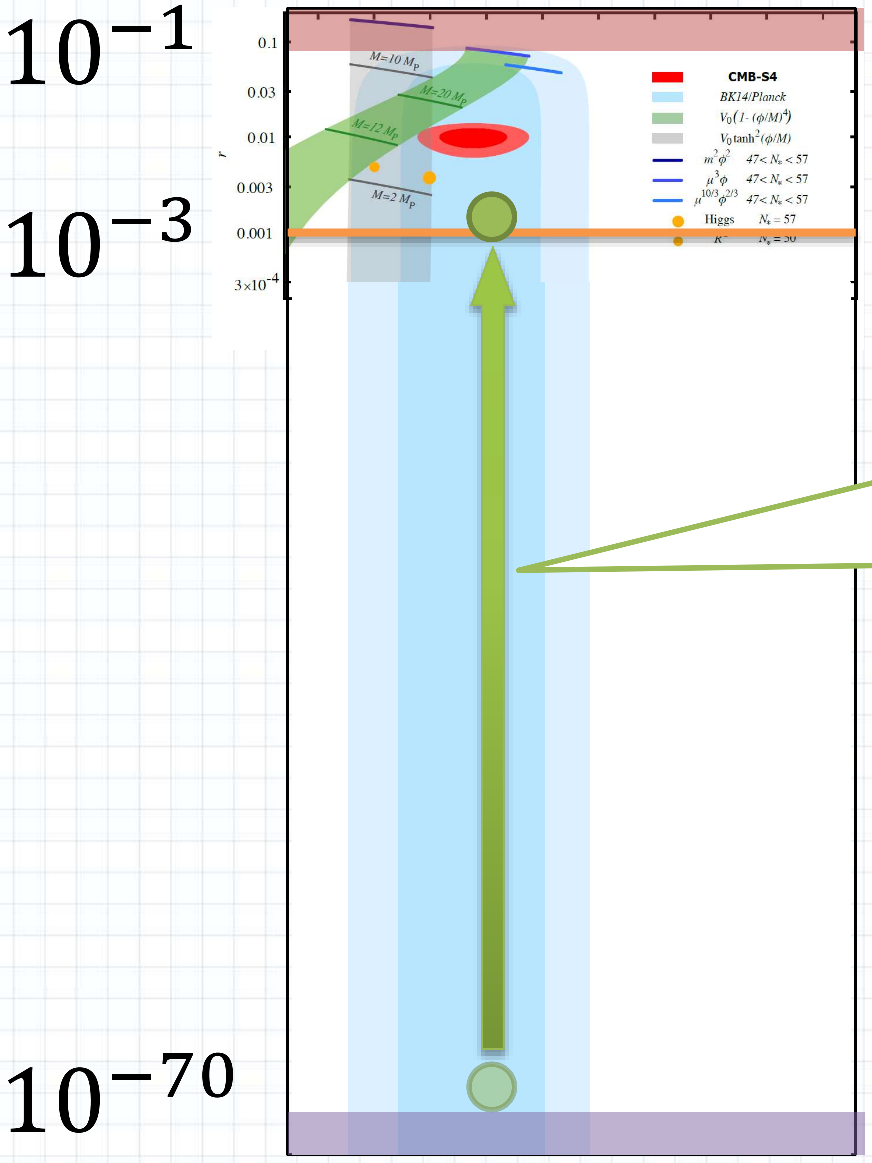

Upper bound:

$r < 7 \times 10^{-2}$

Detectable

With our new GW production mechanism, even low energy models can have detectable GW

Lower bound:

$r \gtrsim 10^{-70}$

How come!?

$$\mathcal{P}_{\mathrm{GW}} = \mathcal{P}_{\mathrm{GW}}^{\mathrm{vac}} + \mathcal{P}_{\mathrm{GW}}^{\mathrm{sourced}}$$

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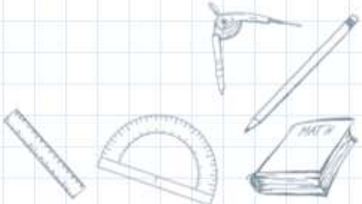
Additional contribution to GW can be much larger than the conventional vacuum fluctuation of tensor mode.



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- Change predictions of models
- Non-trivial to fix ρ_{inf} from obs

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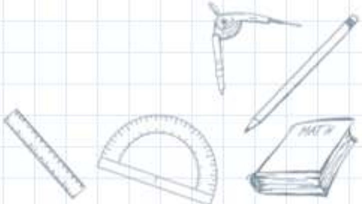
$$r \approx 0.01 \left(\frac{\rho_{\mathrm{inf}}^{1/4}}{10^{16}\mathrm{GeV}} \right)^4$$

- Change predictions of mode
- Non-trivial to fix ρ_{inf} from obs



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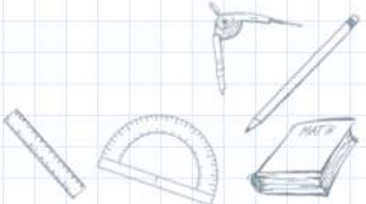


Our scenario

GW version of Curvaton mechanism

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

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

$$\begin{tikzcd}
\rho_{\mathrm{inf}} \arrow[d, "H_{\mathrm{inf}}"'] & \gg & \rho_{\mathrm{spec}} \arrow[d, "\text{Source}"] \\
\mathcal{P}_{\mathrm{GW}}^{\mathrm{vac}} & \ll & \mathcal{P}_{\mathrm{GW}}^{\mathrm{spec}}
\end{tikzcd}$$

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

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

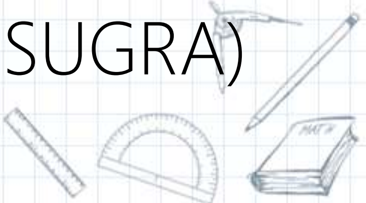
How's it work?

Adding axion-SU(2) gauge spectator sector

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

Very well motivated terms in HEP (e.g. String, SUGRA)

[cf. Chromo-natural inflation: Adshead&Wyman(2012)]



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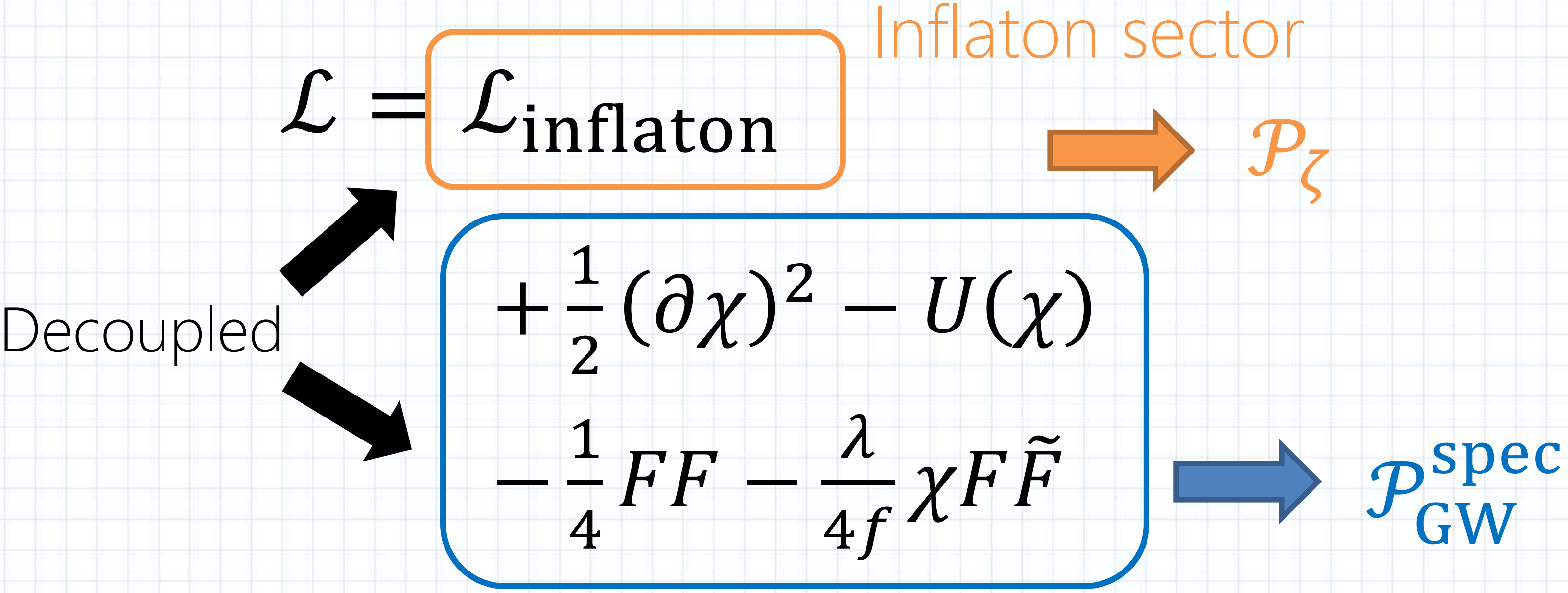

Inflaton sector

$$\mathcal{L} = \boxed{\mathcal{L}_{\text{inflaton}}} \Rightarrow \mathcal{P}_\zeta$$

Decoupled

$$\boxed{\begin{array}{l} +\frac{1}{2}(\partial\chi)^2 - U(\chi) \\ -\frac{1}{4}FF - \frac{\lambda}{4f}\chi F\tilde{F} \end{array}} \Rightarrow \mathcal{P}_{\text{GW}}^{\text{spec}}$$

Axion- SU(2) gauge spectator sector

2 Key Points

① Background SU(2) field

⟹ Source GW at 1st order pert.

- $\bar{\chi}$ rolling down $V(\chi)$ ⟹ Attractor $\bar{A}_i^a = \delta_i^a a\, A_{BG}(t)$

  [Maleknejad&Erfani(2014)]

-

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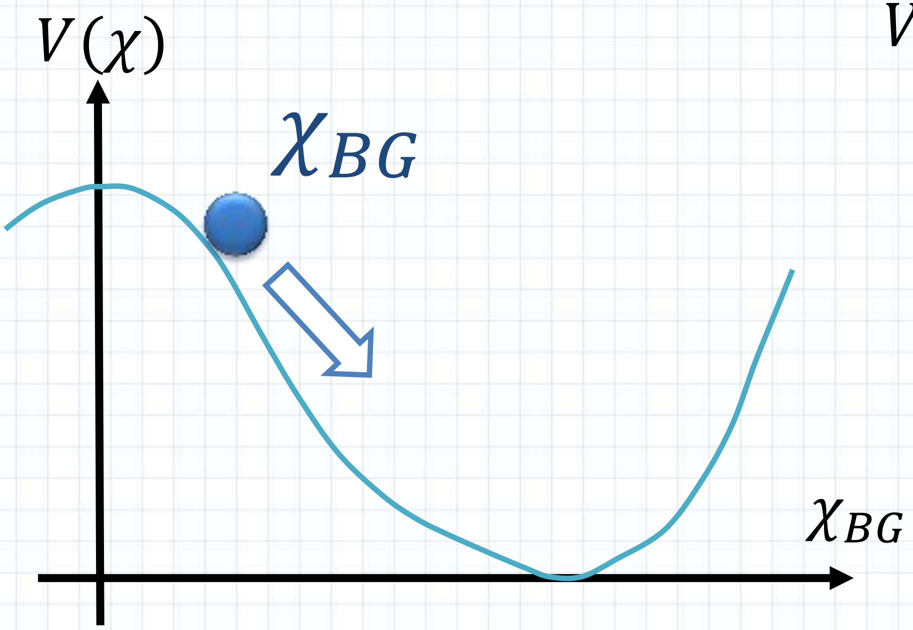
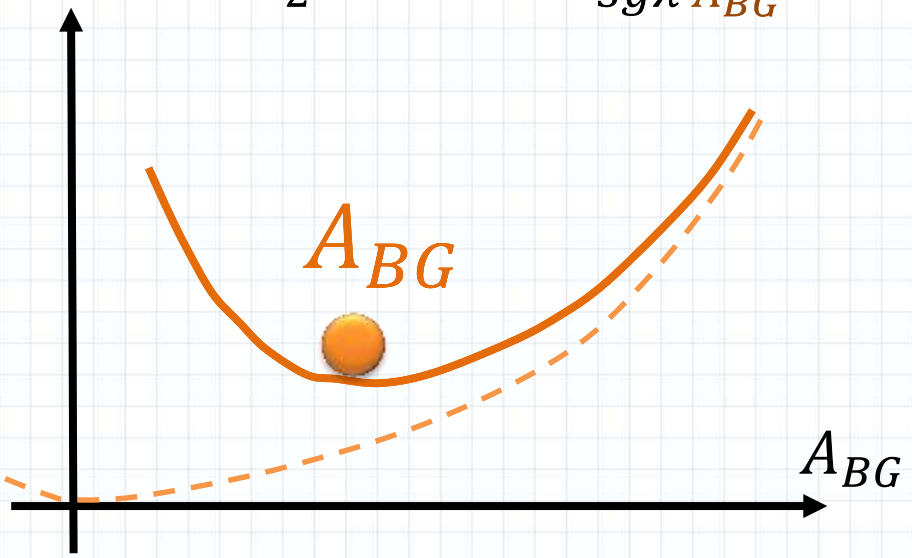
BG dynamics



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



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

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

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

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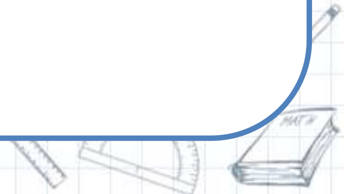
- EMT of $\bar{A}_i^a$ is isotropic → FRW universe
-



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- EMT of $\bar{A}_i^a$ is isotropic → FRW universe
- 1st order EMT has $\bar{A}_i^a \delta A_j^a$ → $h_{ij}^{\mathrm{sourced}}$ at linear

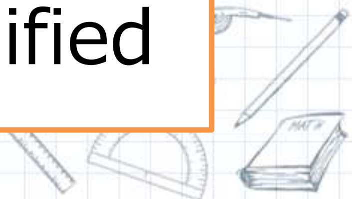
2 Key Points

② Huge amplification only for tensor not scalar

$$\delta A_j^a = 2\ \text{scalar} + 2\ \text{vector} + \underset{\underset{t_R + t_L}{\shortparallel}}{\underline{2\ \text{tensor}}}$$

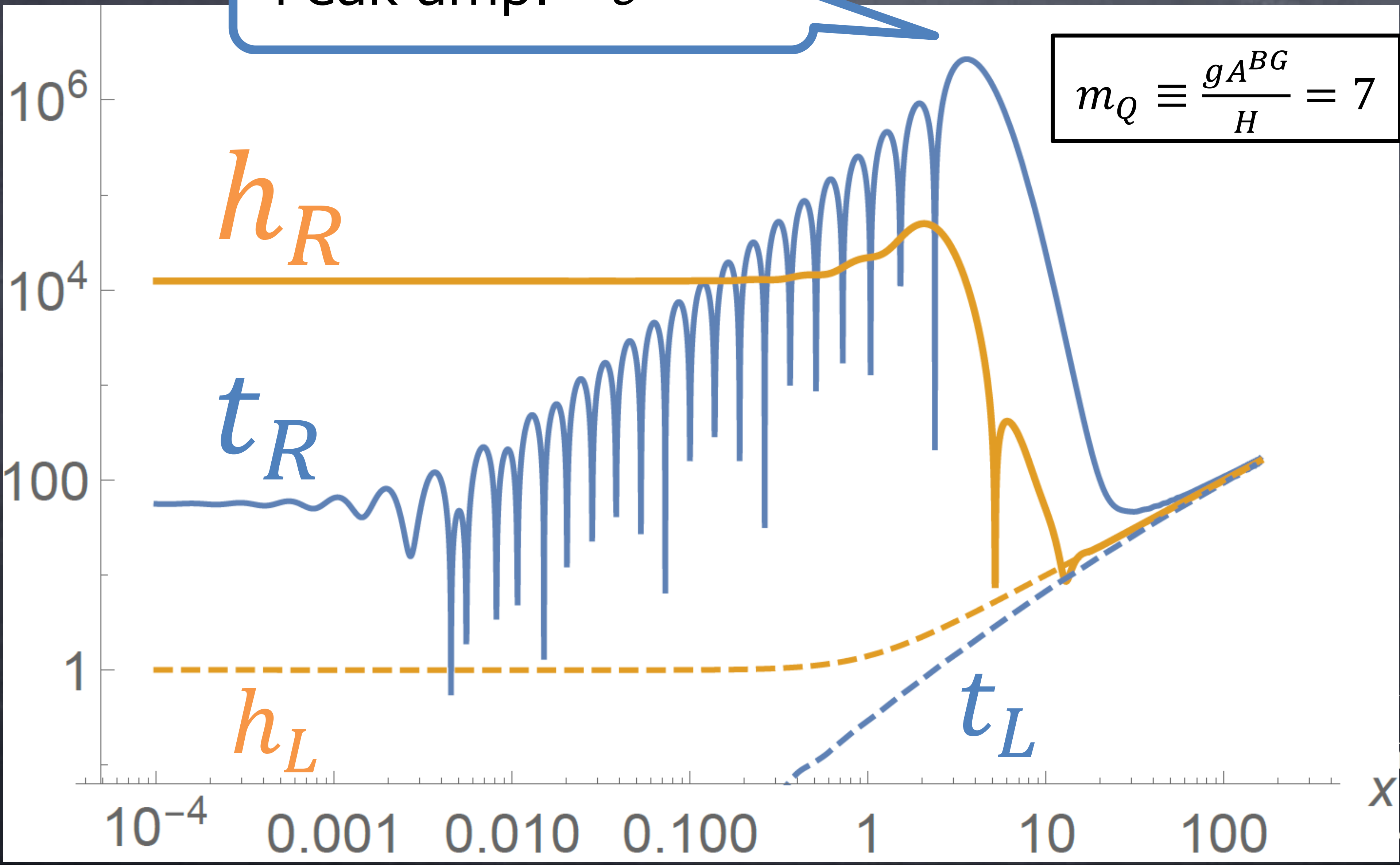
No instability

Either of them gets amplified



Insta nsor

Peak amp.$\sim e^{1.8 m_Q}$



$$m_Q \equiv \frac{gA^{BG}}{H} = 7$$

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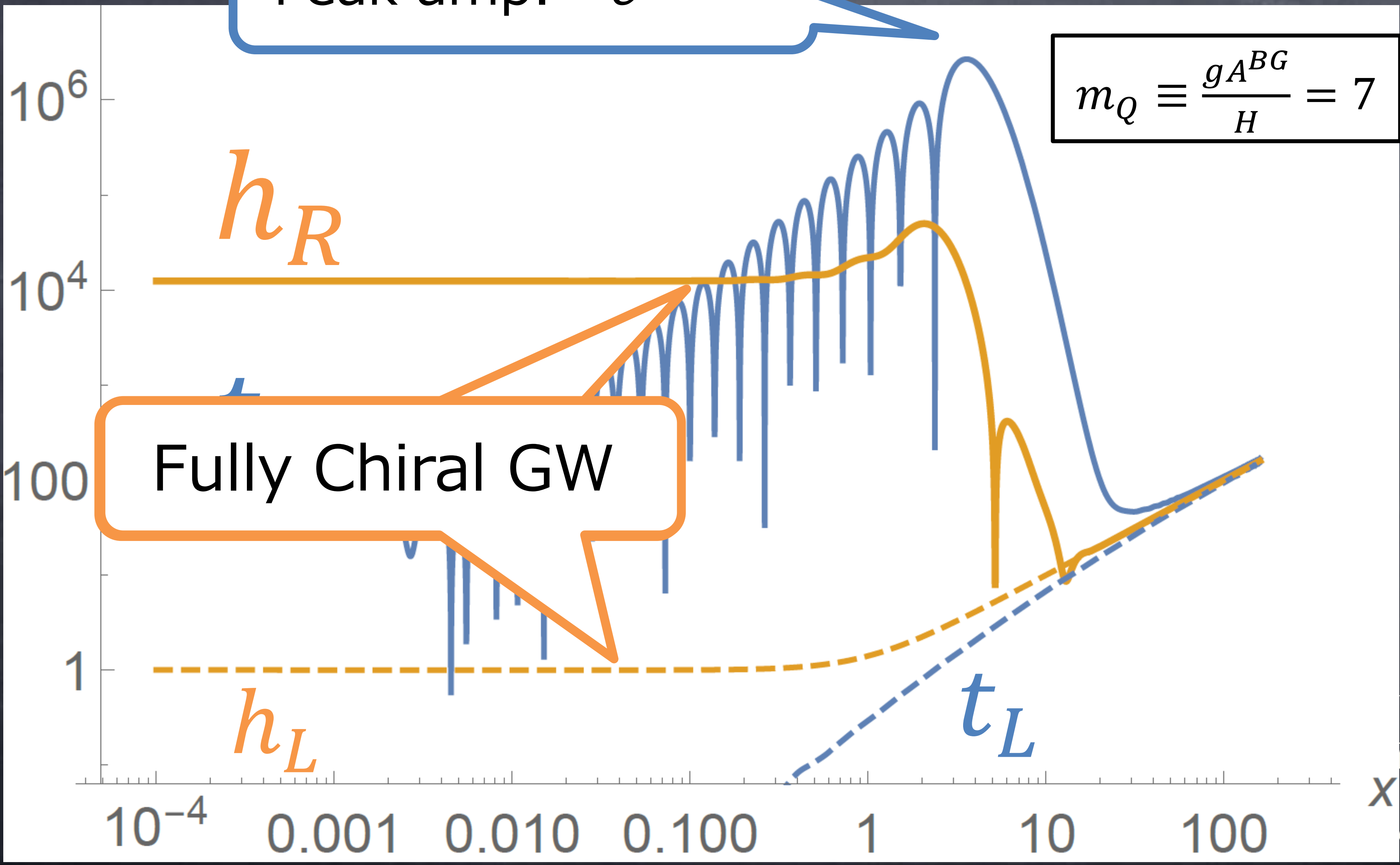
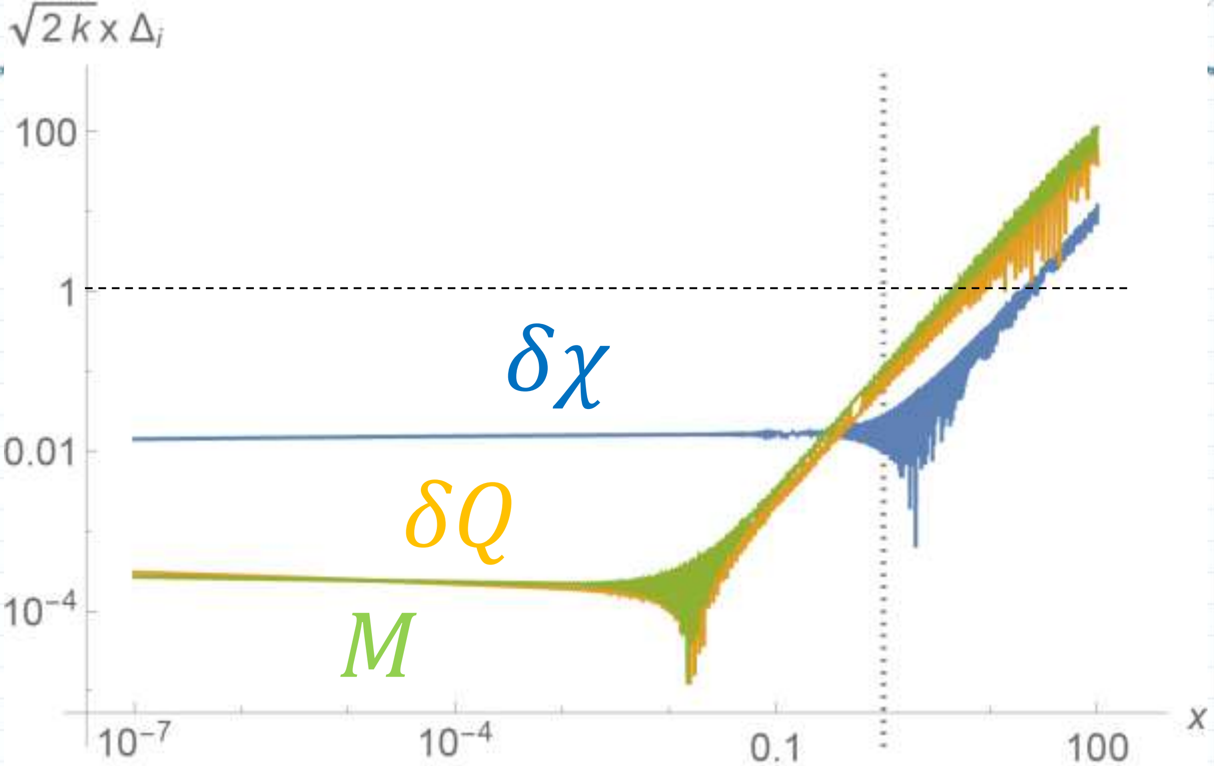


Fully Chiral GW

SU(2) Scalar pert.



- Smaller than normal case. No instability for $gA_{BG} > \sqrt{2}H$
- They don't contribute to ζ unless χ becomes Curvaton.

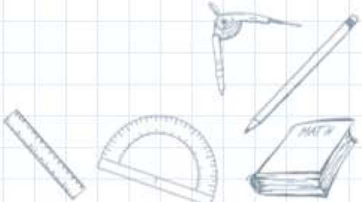
2 Key Points

① Background SU(2) field

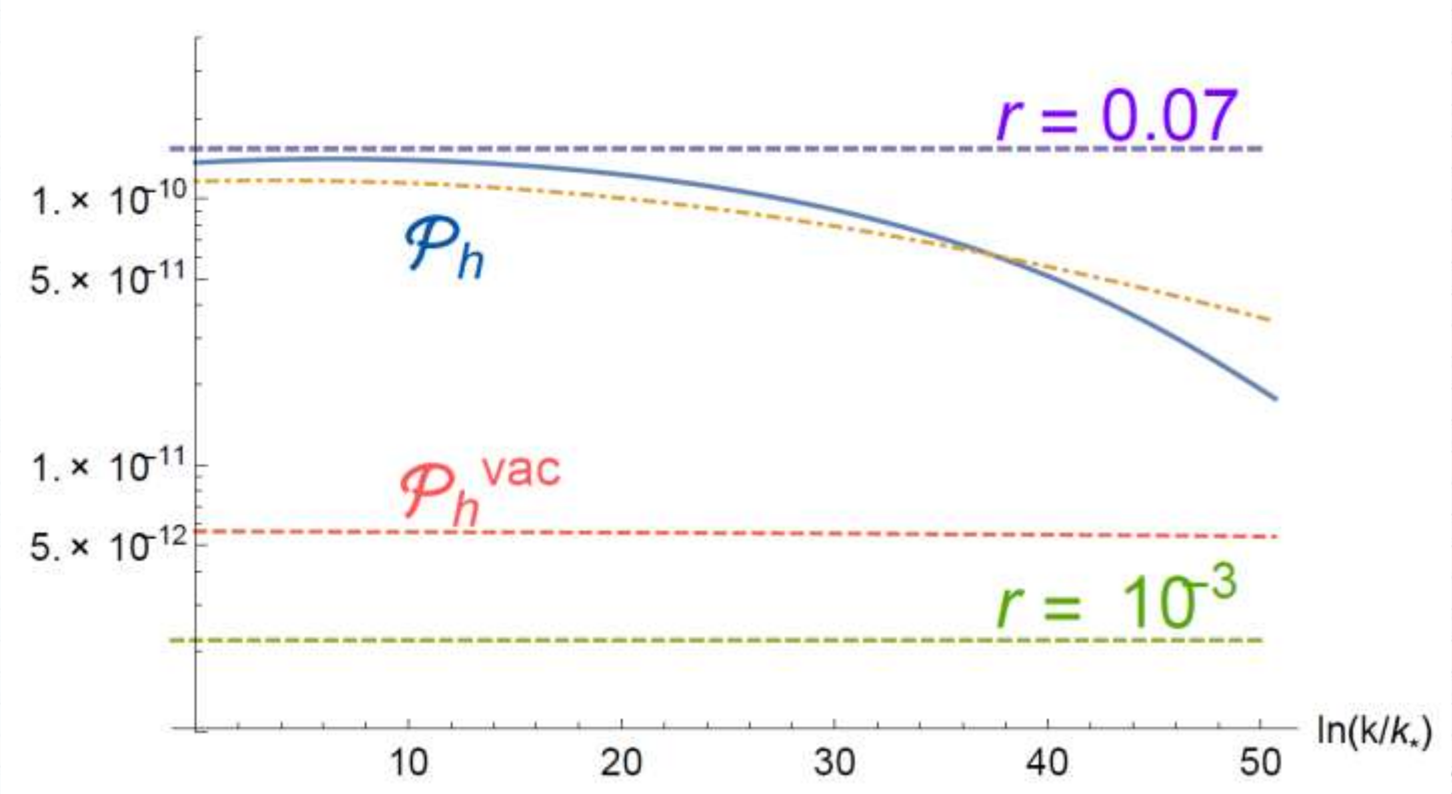
→ Source GW at 1st order pert.

② Huge amplification only for tensor not scalar

→ Enhance r without boosting $\mathcal{P}_\zeta$



Result (mild case)



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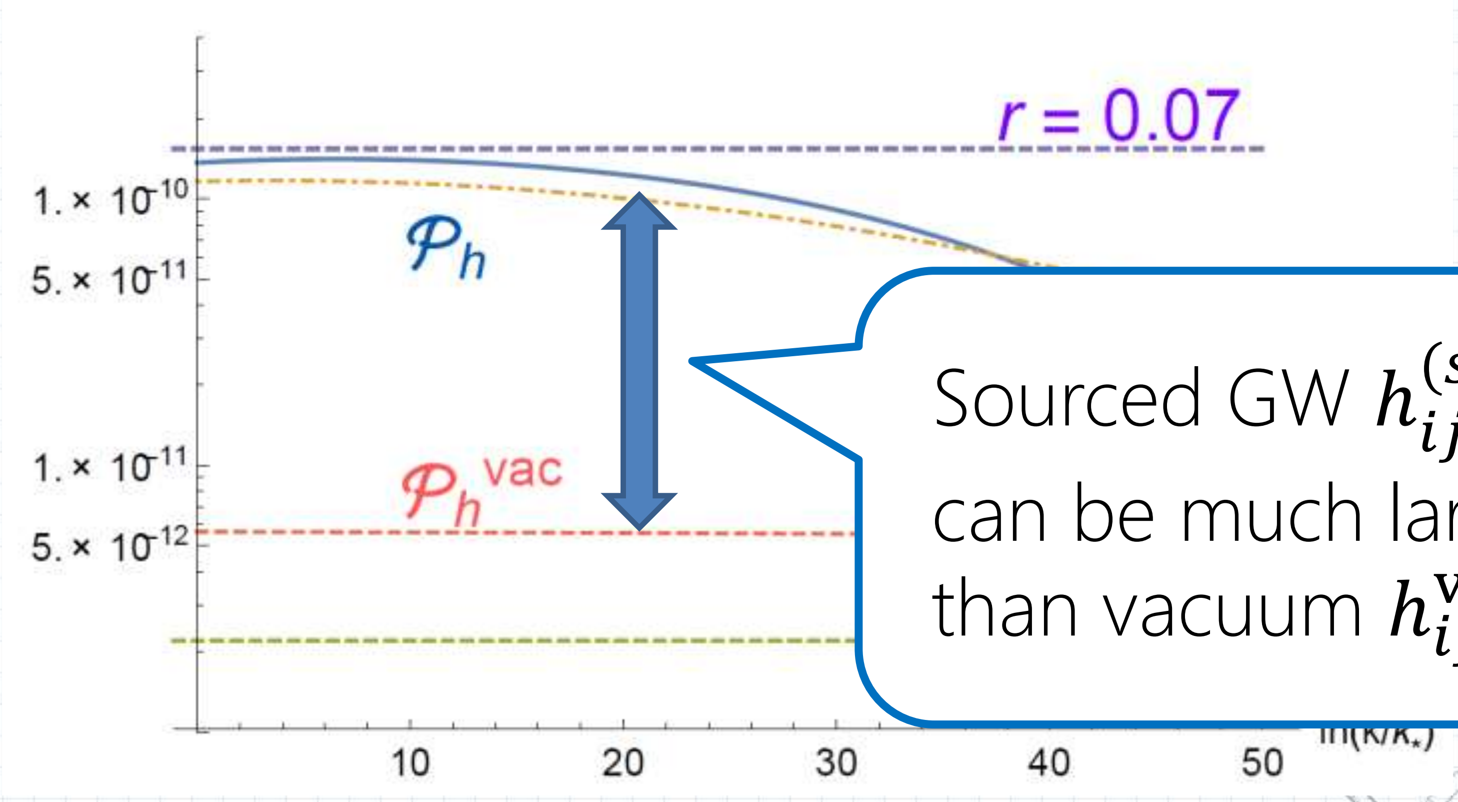

Sourced GW $h_{ij}^{(s)}$ can be much larger than vacuum h_{ij}^{vac}

Model

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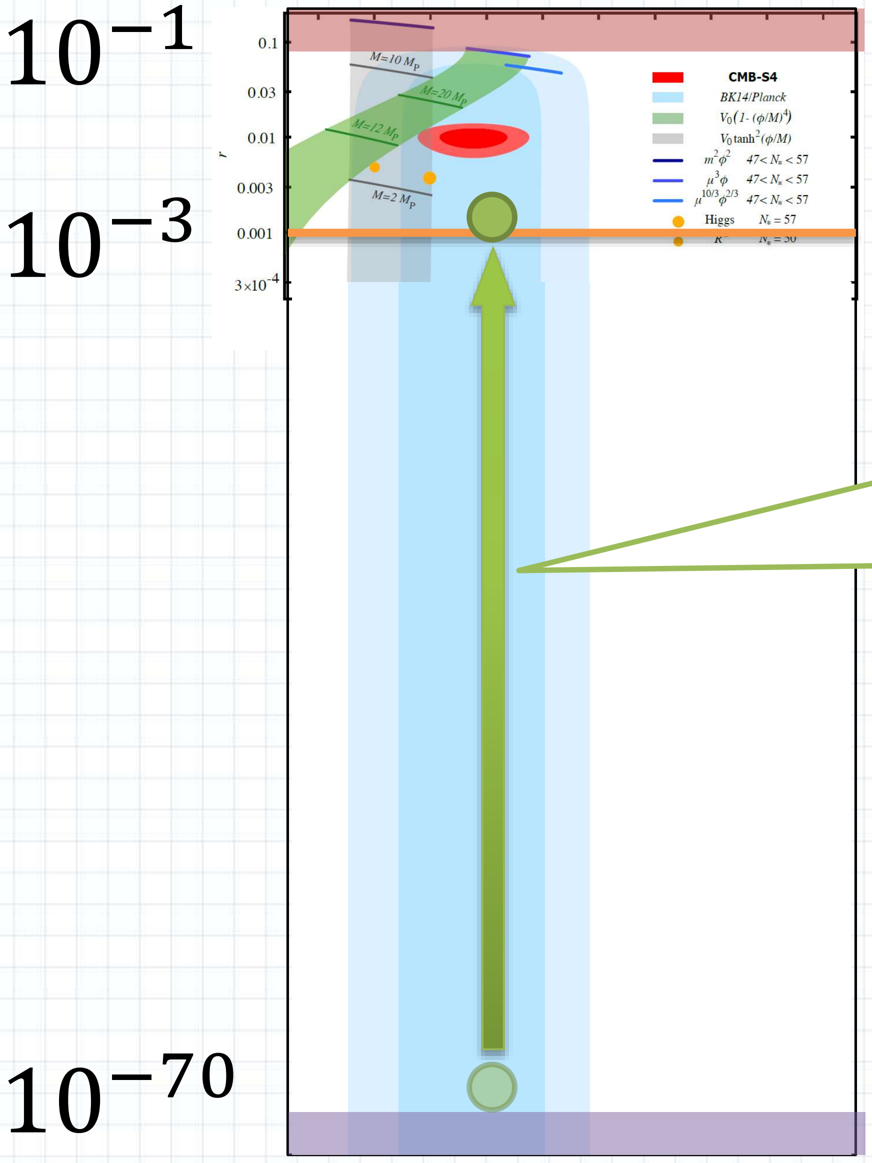

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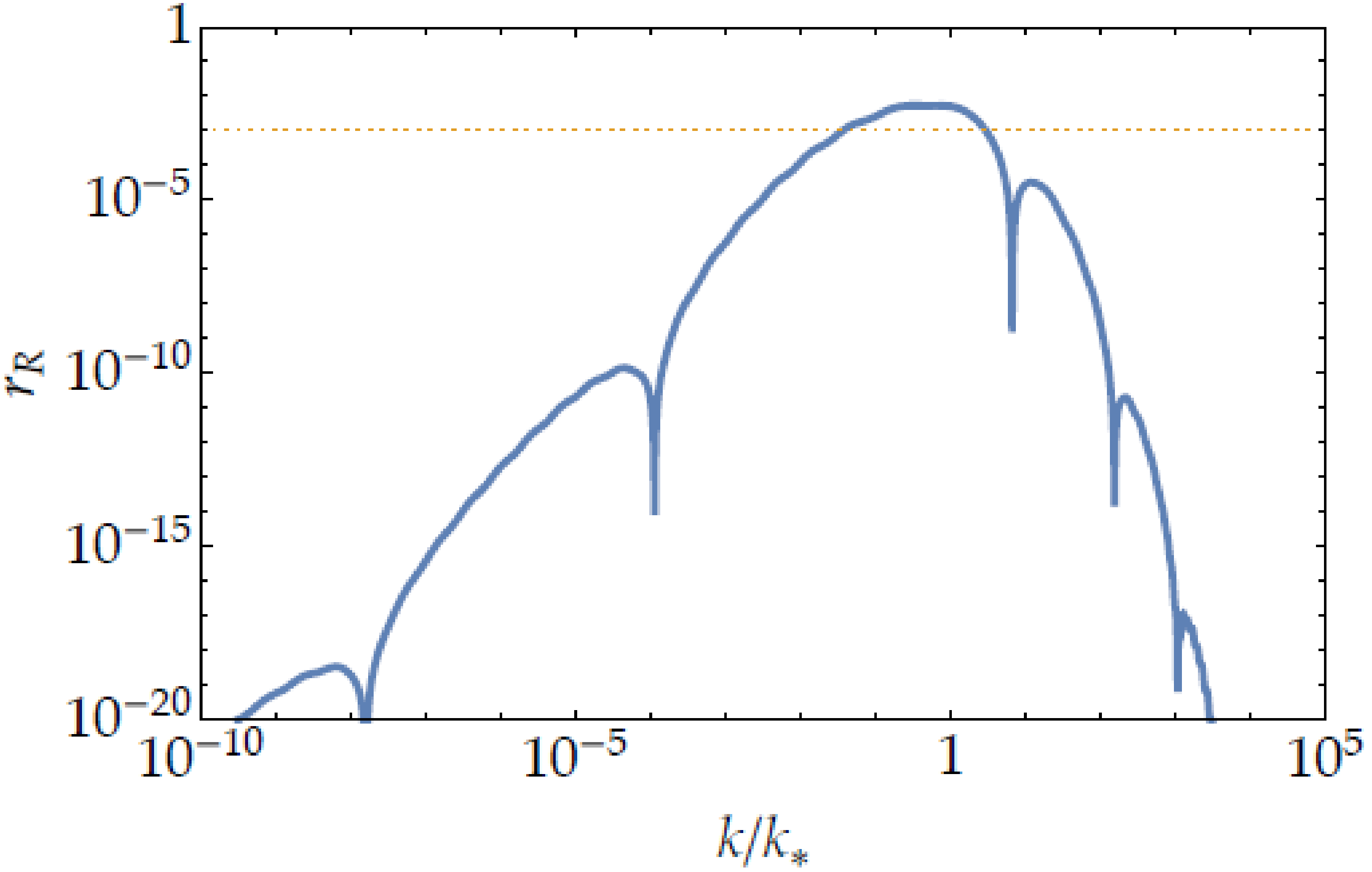
Result $(\rho_{\rm inf}^{1/4} = 0.03{\rm GeV})$

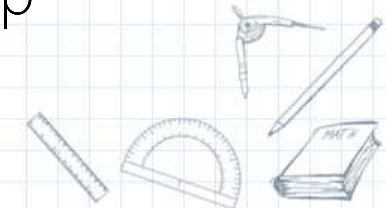


Full numerical result w/ back reaction

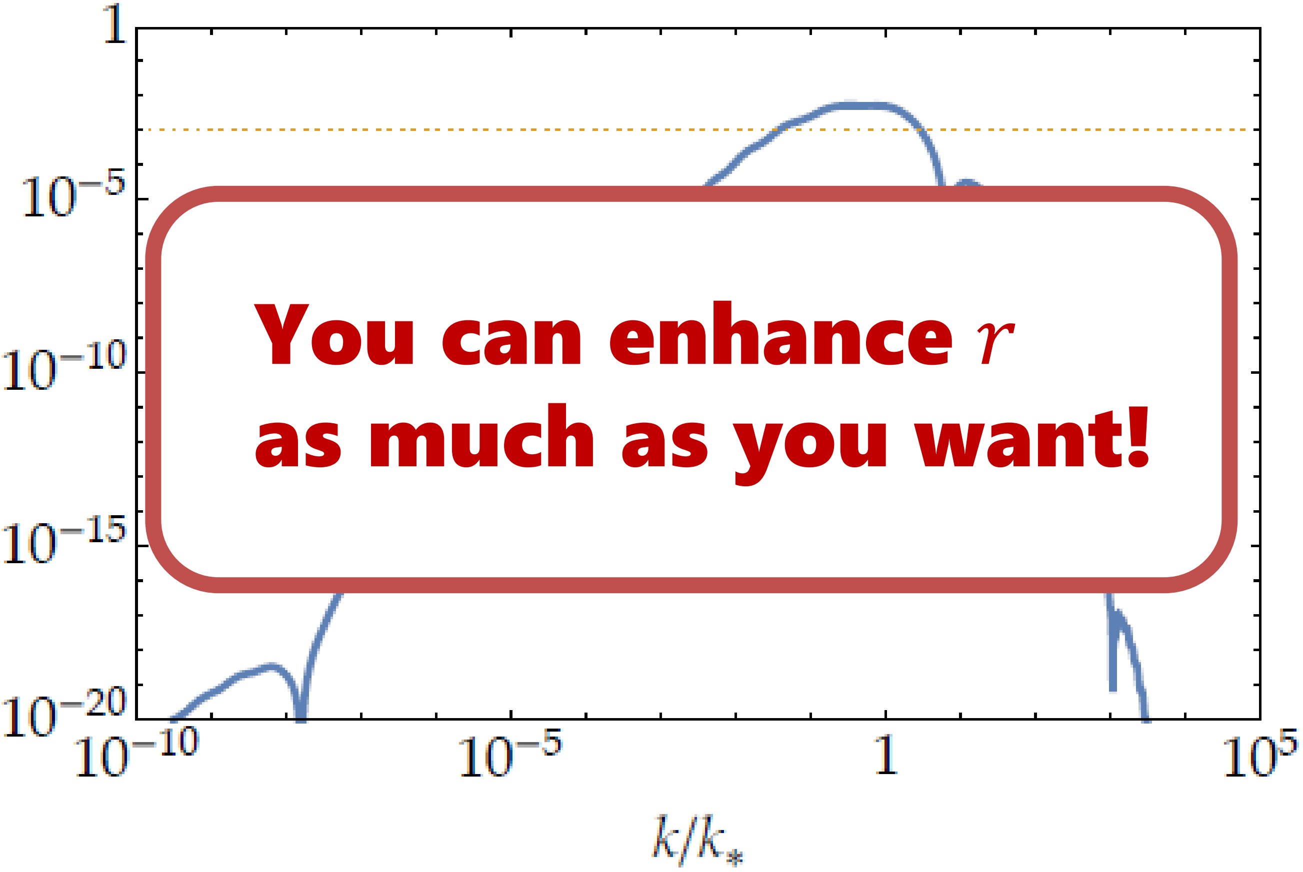
Possible obstacles

- ✓ ① Scalar perturbations: $\delta\chi, \delta Q, M \to \zeta$
- ✓ ② Spectral index: $\rho_A \to \dot{H} \to \phi\ \mathrm{EoM} \to\ n_s$
- ✓ ③ Energy hierarchy: $\rho_\chi > \rho_A > \rho_{t_R}$
- ✓ ④ Backreaction: $\langle t_R t_R \rangle \to \mathrm{EoM\ of}\ \chi, A_{\mathrm{BG}}$
- ✓ ⑤ Perturbativity: $\langle t_R t_R \rangle$ Tree > 1loop

[TF, Namba & Tada, 1707.03023]



Result $(\rho_{\text{inf}}^{1/4} = 0.03\text{GeV})$



You can enhance r as much as you want!

Full numerical result w/ back reaction

Bad news for observationalists

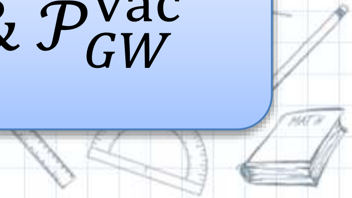
Without $\mathcal{P}_{\mathrm{GW}}^{\mathrm{source}}$, we believed

$$\rho_{\mathrm{inf}}^{1/4} \approx 10^{16}\mathrm{GeV}\left(\frac{r}{0.001}\right)^{1/4}$$

However, the correct energy scale might be

$$\rho_{\mathrm{inf}}^{1/4} \approx 10^{-1}\mathrm{GeV} \qquad \text{if} \quad \mathcal{P}_{GW}^{s} \gg \mathcal{P}_{GW}^{\mathrm{vac}}$$

Other observables to distinguish $\mathcal{P}_{GW}^{s}$ & $\mathcal{P}_{GW}^{\mathrm{vac}}$



3 Unique signatures

- $\cancel{P}$ Polarization $h_R \neq h_L$ $\Longrightarrow$ TB&EB correlation
- Tensor Non-Gaussianity $\langle hhh \rangle$ $\Longrightarrow$ large B_h^{equil}
- Tensor tilt n_t $\Longrightarrow$ $n_t \xcancel{=} -r/8$

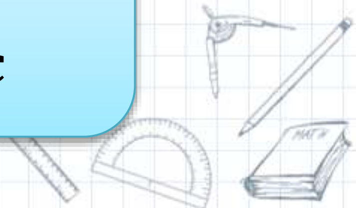
TB, EB correlation

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 $h^{(s)}$ from h_{vac}

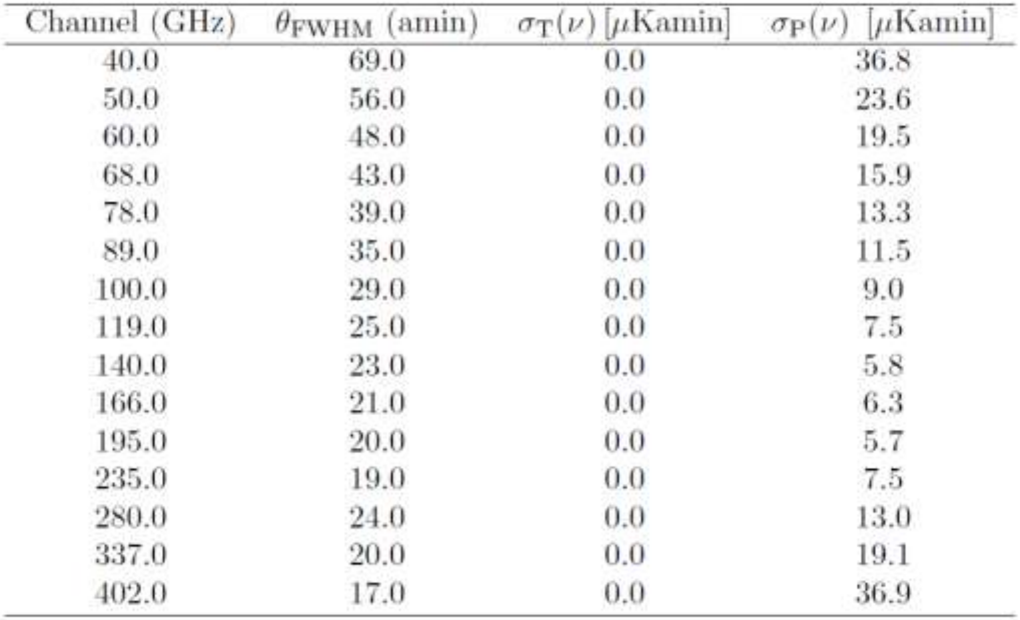


Observation

PRESENTATION

LiteBIRD

- CMB satellite mission
- Will be launched in 2020s
- Aims to detect $r \geq 10^{-3}$



Channel (GHz)	θ_{FWHM} (amin)	$\sigma_{\mathrm{T}}(\nu)$ [μKamin]	$\sigma_{\mathrm{P}}(\nu)$ [μKamin]
40.0	69.0	0.0	36.8
50.0	56.0	0.0	23.6
60.0	48.0	0.0	19.5
68.0	43.0	0.0	15.9
78.0	39.0	0.0	13.3
89.0	35.0	0.0	11.5
100.0	29.0	0.0	9.0
119.0	25.0	0.0	7.5
140.0	23.0	0.0	5.8
166.0	21.0	0.0	6.3
195.0	20.0	0.0	5.7
235.0	19.0	0.0	7.5
280.0	24.0	0.0	13.0
337.0	20.0	0.0	19.1
402.0	17.0	0.0	36.9

Table 3: Summary of the LiteBIRD specifications. And $f_{\mathrm{sky}} = 0.5$

S/N for TB+EB

- w/ lensing effect (no delensing)
- LiteBIRD instrumental noise
- 2% foreground contamination

S/N ratio for TB+EB with noises

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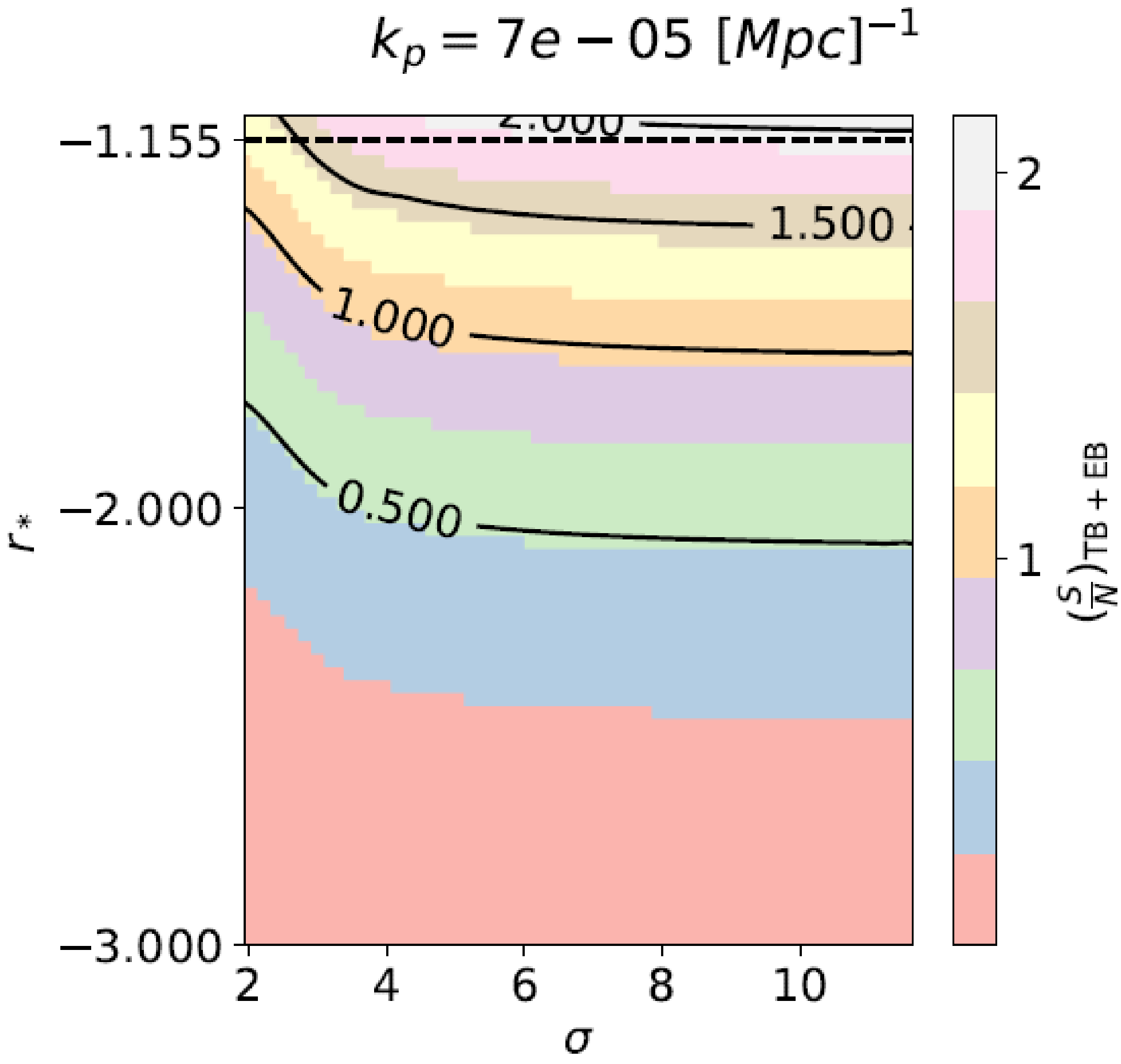

Cosmic Variance limited case

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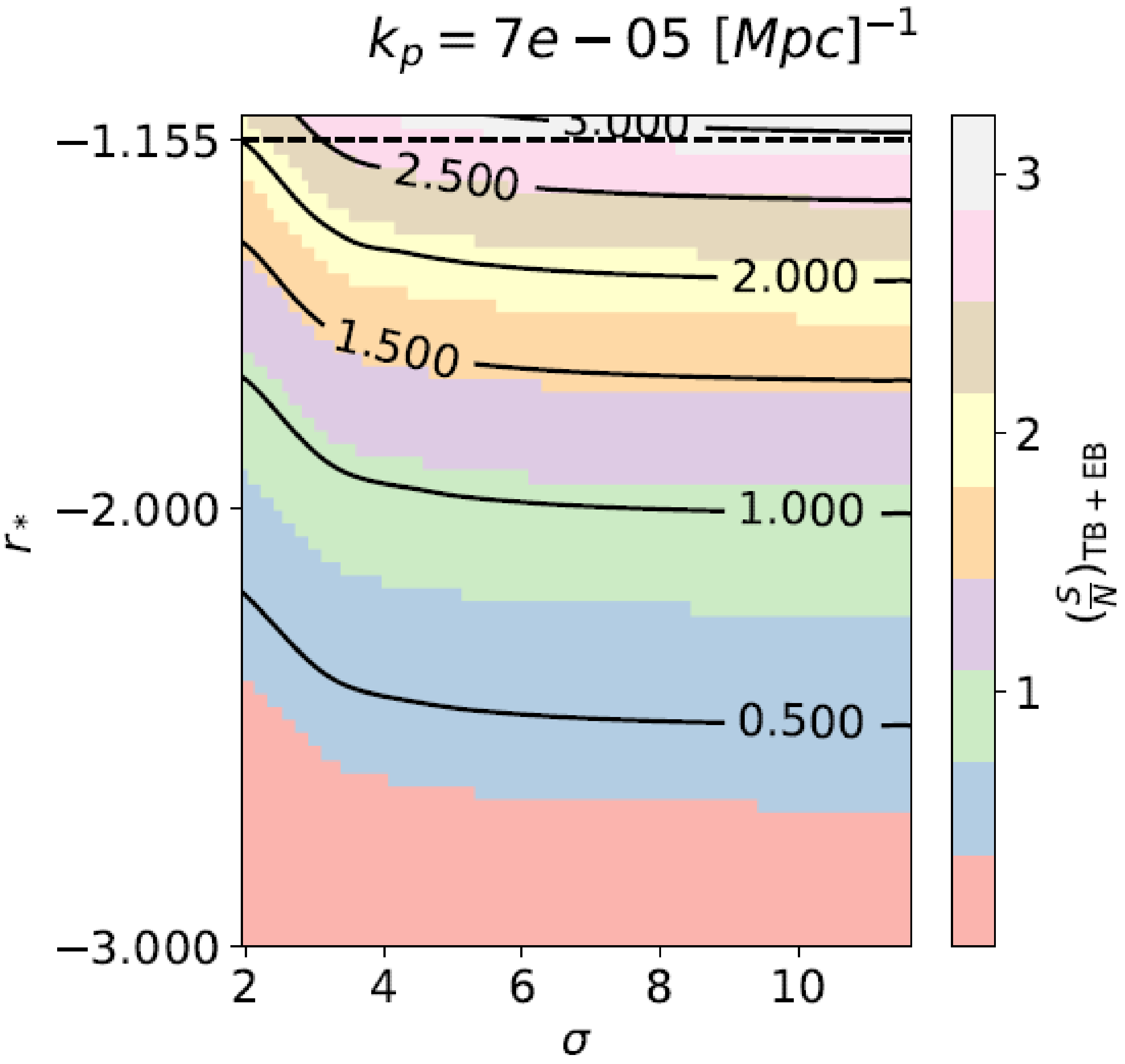


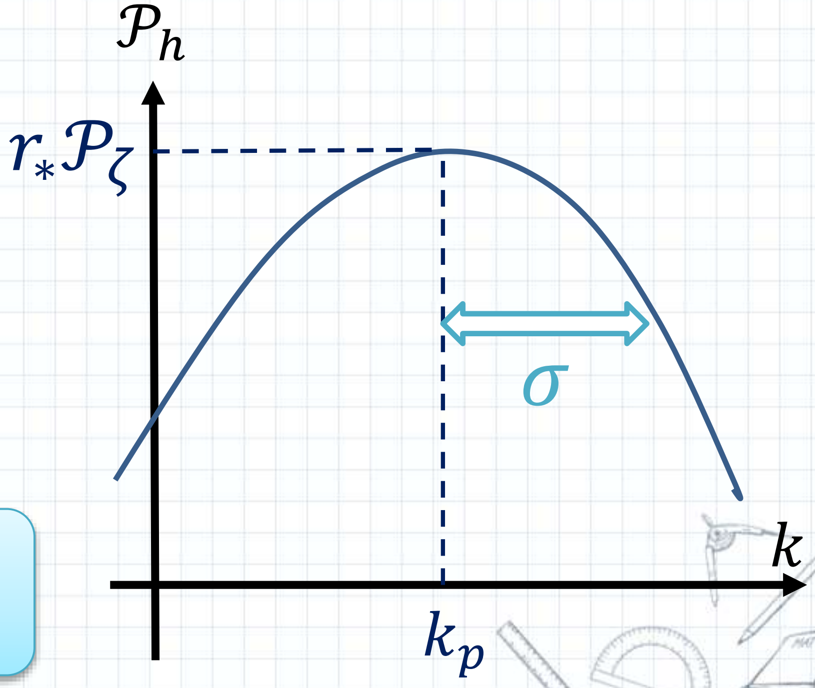
Excellent Template

$$\mathcal{P}_h^{\mathrm{L,\ Sourced}}(k) = r_*\mathcal{P}_\zeta \exp\left[-\frac{1}{2\sigma^2}\ln^2\left(\frac{k}{k_p}\right)\right]$$

$$\sigma^2 = \frac{\Delta N^2}{2\mathcal{G}(m_*)}. \quad \Delta N \equiv \frac{\lambda}{2\xi_*}.$$

$k_p =$ arbitrary (depend on χ_i)

$\mathcal{P}_h^{(s)}$ takes Gaussian shape.



S/N for TB+EB

- w/ lensing effect (no delensing)
- LiteBIRD instrumental noise
- 2% foreground contamination

TB + EB can be detected by LiteBIRD for $r > 0.03$.

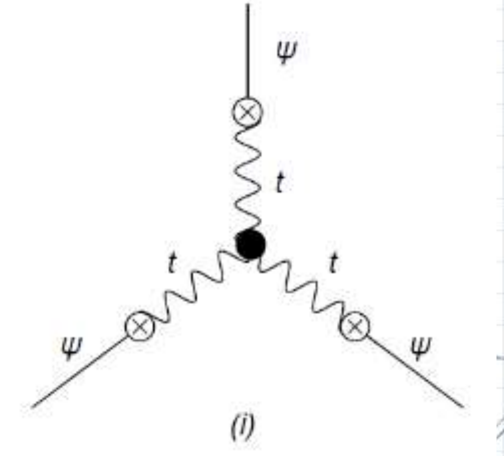
Non-Gaussianity

Large $\langle h_R h_R h_R \rangle$ ← Large $\langle t_R t_R t_R \rangle$

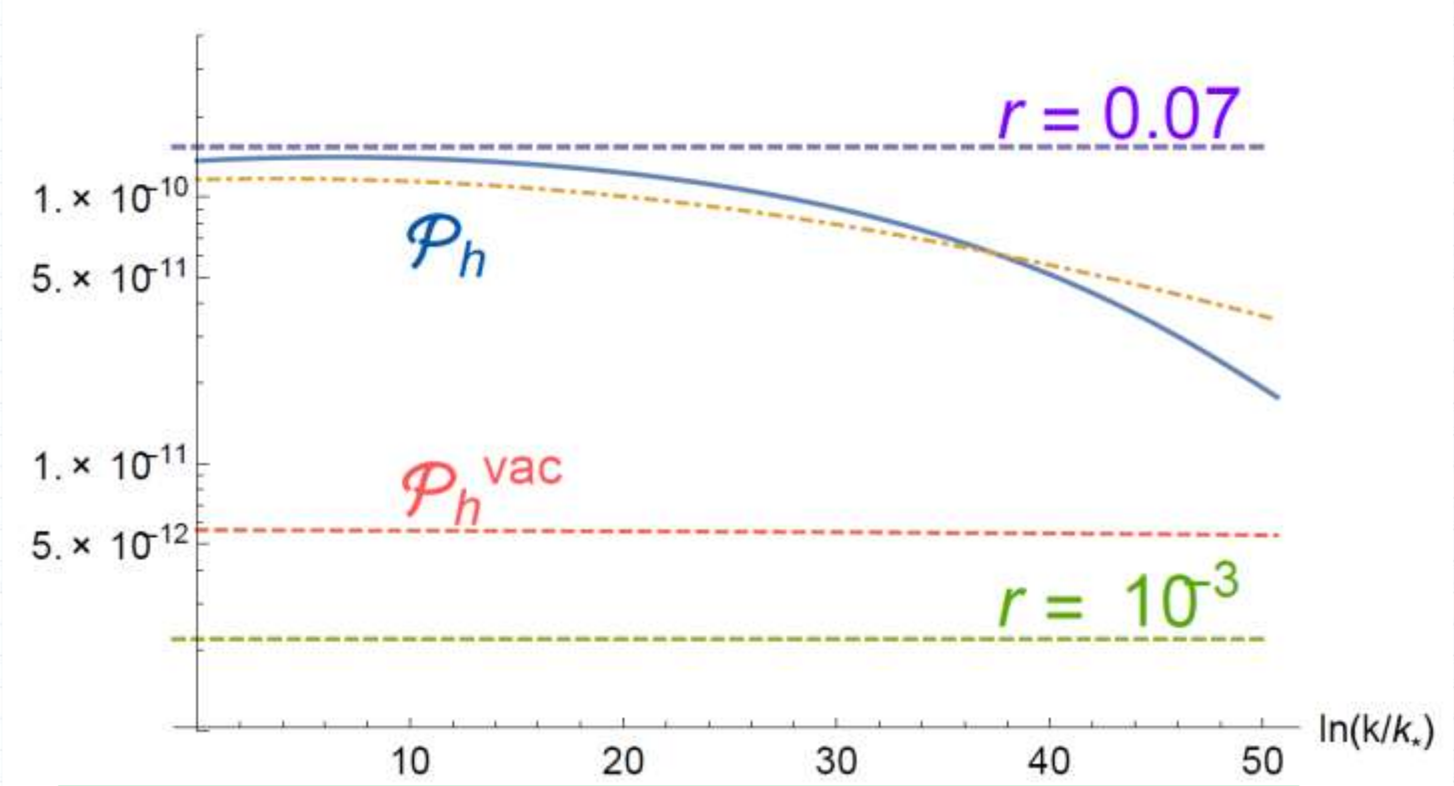
The EoM for SU(2) gauge field is non-linear

$$\delta A_i^a = t_{ai} + \cdots \,, \quad t_{ii} = \partial_a t_{ai} = \partial_i t_{ai} = 0,$$

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



Result



$$g = 1.11\times 10^{-2},\quad \lambda = 500,\quad \chi_* = \frac{\pi}{2}f = 6.28\times 10^{16}\mathrm{GeV},$$

$$H_* = 1.28\times 10^{13}\mathrm{GeV},\quad \mu = 1.92\times 10^{15}\mathrm{GeV},$$

Non-Gaussianity

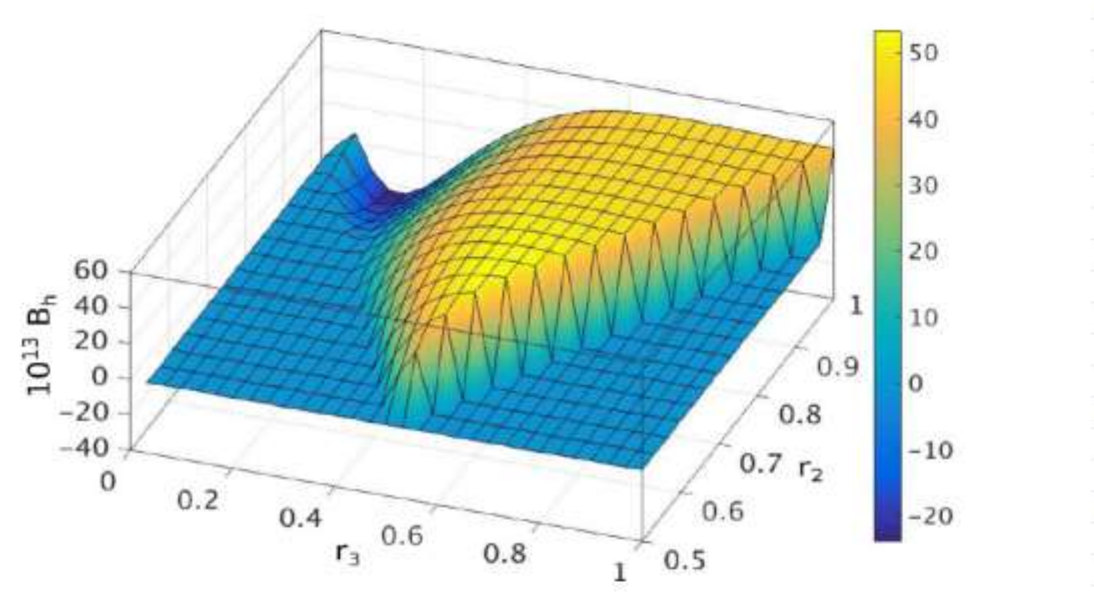


FIG. 2. The 3D plot of the numerical result of $10^{13}(k_1k_2k_3)^2(B_h^{(i)} + B_h^{(ii)})$. Only $r_3 \leq r_2$ is shown. The bispectrum vanishes for $r_2 + r_3 < 1$ by the triangle condition.

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

Non-Gaussianity

Relationship btw NG and energy fraction of A_{BG}

$$f_{\mathrm{NL}}^{\mathrm{tens}} \approx \frac{125}{18\sqrt{2}} \frac{r^2}{\epsilon_B} \approx 2.5 \frac{r^2}{\Omega_A}$$

The current observational bound from Planck is

$$f_{\mathrm{NL}}^{\mathrm{tens}} = 400 \pm 1500$$

It may be observed in next CMB observations!

Summary

Axion-SU(2) model

PRESENTATION

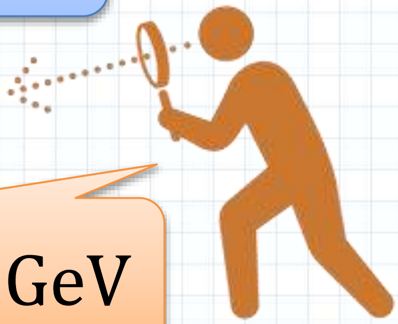
- Larger GW than h^{vac} can be produced

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

r_{obs} doesn't fix ρ_{inf}

- Lowest ρ_{inf} can have $r = 10^{-3}$
  - $r \propto H^2 \exp[3.6 m_Q]$

$\rho_{\mathrm{inf}}^{1/4} \geq 0.1\mathrm{GeV}$



- Distinguishable w/
  - Polarization $h_R \neq h_L$ ⇨ TB&EB correlation
  - Non-Gaussianity $\langle hhh \rangle$ ⇨ large B_h^{equil}
  - Tensor tilt n_t ⇨ $n_T \cancel{=} -r/8$

LiteBIRD will detect!

THE THEME
OF CHAPTER IS...

Thank you !