PRESENTATION

Does the detection of primordial gravitational waves exclude low energy inflation?

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Based on arXiv:1608.04216, 1705.01533
w/ Dimastrogiovanni(CWRU) & Fasiello(Stanford);
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In prep w/Komatsu&Agrawal(MPA);
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Komatsu&Shiraishi(Kagawa)

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京都大学
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Era of PGW

- GW exists!

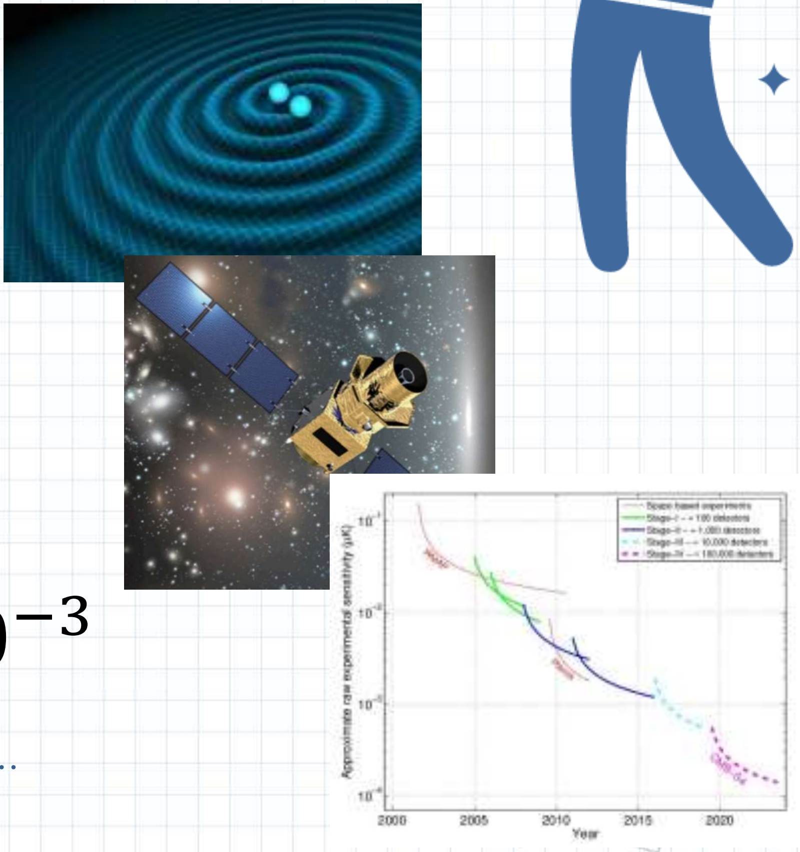
  aLIGO detected GW from BH binary

- Primordial GW soon?

  PGW observed by the CMB B-mode

- New Obs aiming $r \geq 10^{-3}$

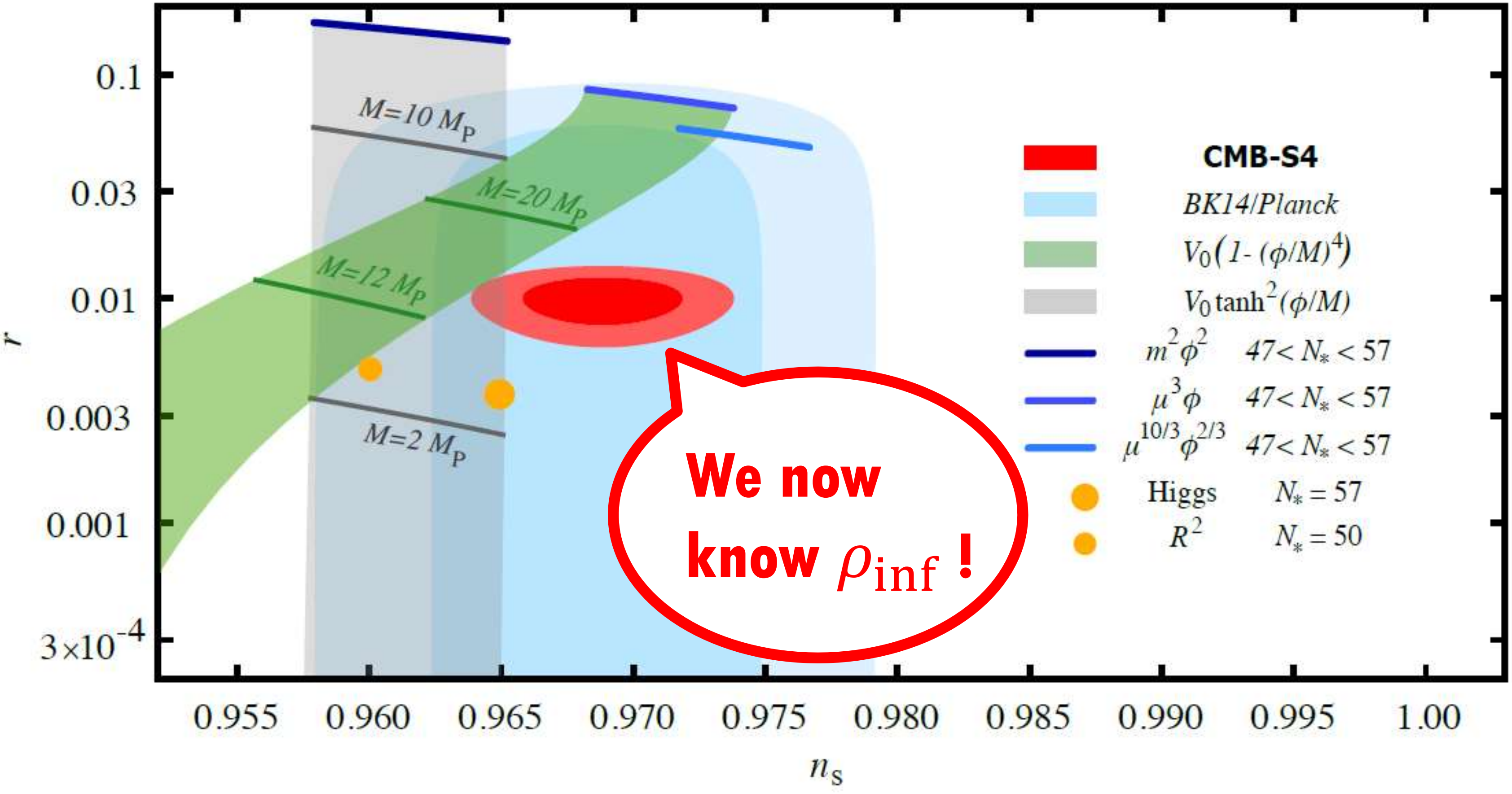
  e.g. CMB-S4(US), LiteBIRD (Japan), etc..



Simple relationship

$$\rho_{\text{inf}}^{1/4} \approx 6 \times 10^{15}\,\text{GeV}\left(\frac{r}{0.001}\right)^{1/4}$$

What if r is detected?

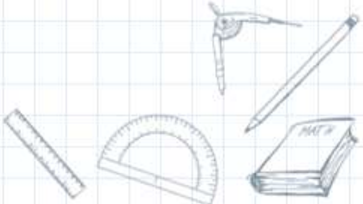


We now know ρ_{inf} !

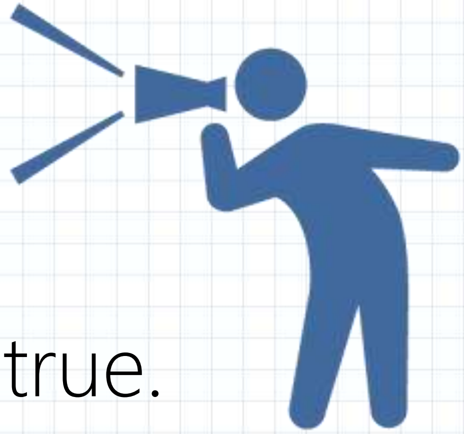
Simple relationship

$$\rho_{\mathrm{inf}}^{1/4} \approx 6 \times 10^{15}\mathrm{GeV}\left(\frac{r}{0.001}\right)^{1/4}$$

- Is this relation robust?
- Detection of B-mode kills low energy inflation models?



No!



That's not necessarily true.

This simple relationship

$$\rho_{\mathrm{inf}}^{1/4} \approx 6 \times 10^{15}\mathrm{GeV}\left(\frac{r_{\mathrm{obs}}}{0.001}\right)^{1/4}$$

is derived under

2 Assumptions

introduction

2 assumptions

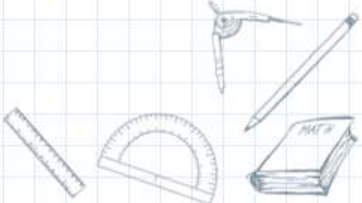
[Creminelli et al.(2014) PRL113,231301;
T.F., X.Gao & J.Yokoyama. JCAP1602.014]

① GW is described by GR

2nd order tensor Lagrangian is same as GR.

② No dominant source effect

Inhomogeneous solution of EoM is insignificant.



introduction

2 assumptions

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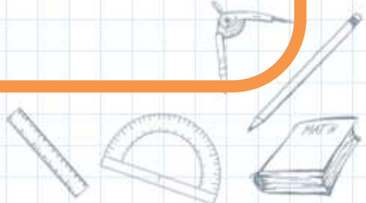


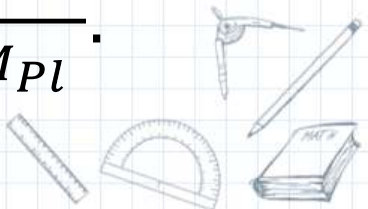
2nd assumptions

② No dominant source effect

Inhomogeneous solution of EoM is insignificant.

We use the homogeneous solution

$$\left[\partial_\tau^2 + k^2 - \frac{2}{\tau^2}\right] a h_k = 0, \qquad a h_k = \frac{2}{\sqrt{2k}} \frac{e^{-ik\tau}}{M_{Pl}}.$$



2nd assumptions

② No dominant source effect

Inhomogeneous solution of EoM is insignificant.

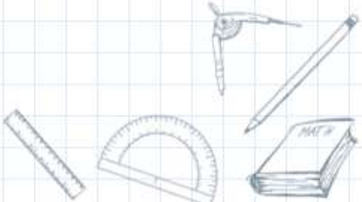
What if we have a significant source term??

$$\left[\partial_\tau^2 + k^2 - \frac{2}{\tau^2}\right] a h_k = S_k, \qquad a h_k = \frac{2}{\sqrt{2k}} \frac{e^{-ik\tau}}{M_{Pl}}.$$

Axion-SU(2) model

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

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



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Axion-SU(2) model

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

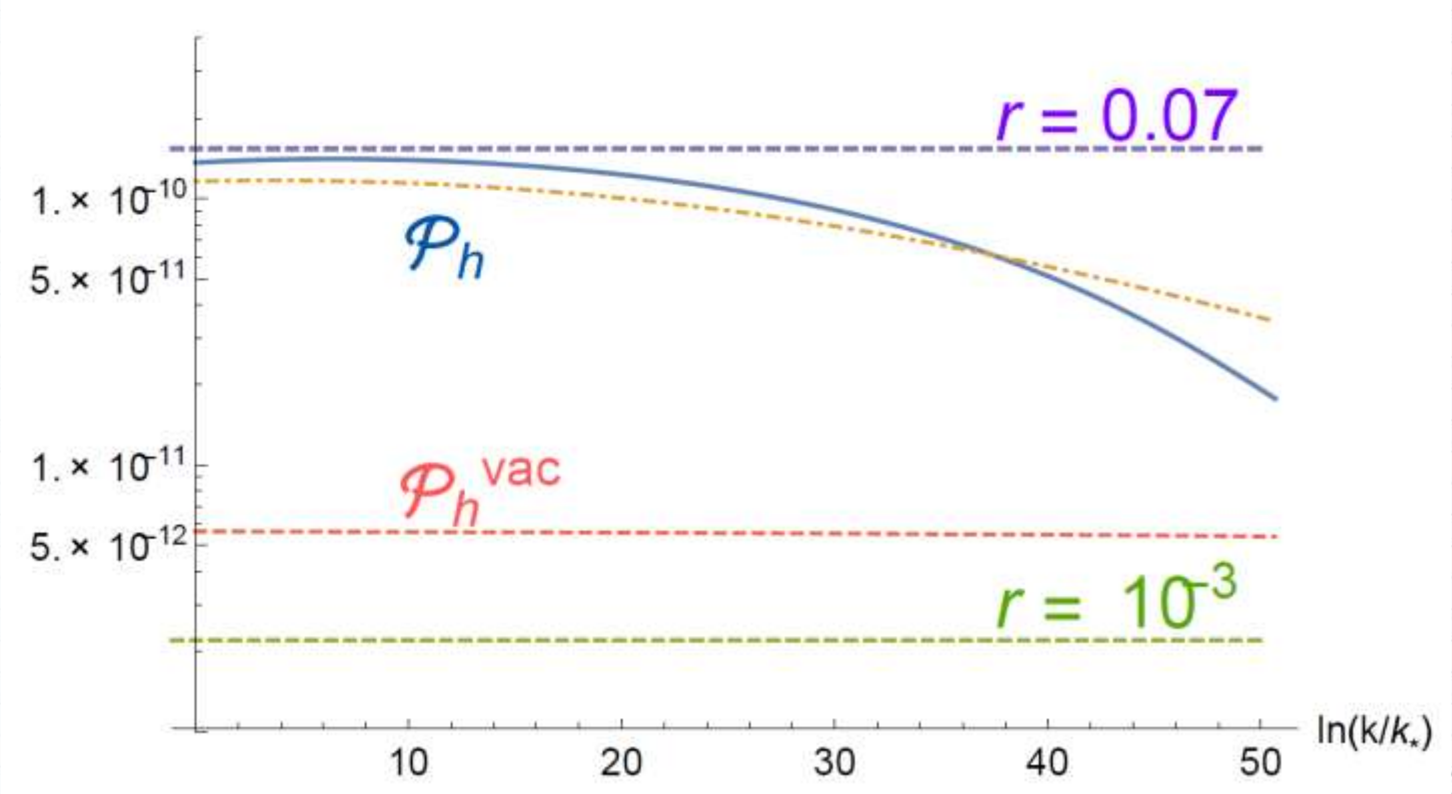
$$r_{obs} = r_{\mathrm{vac}} + r_{\mathrm{add}}$$

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

Result

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

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



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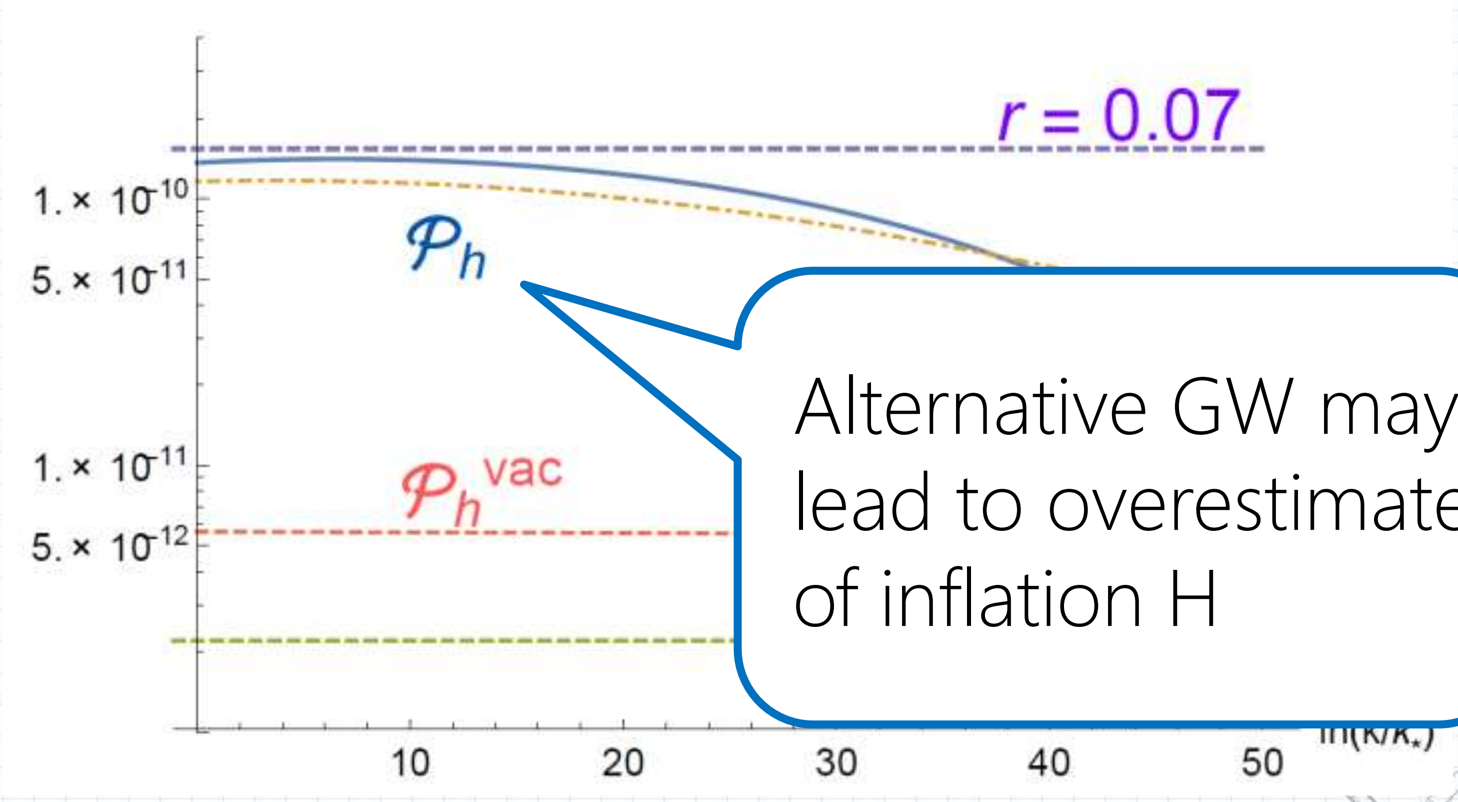
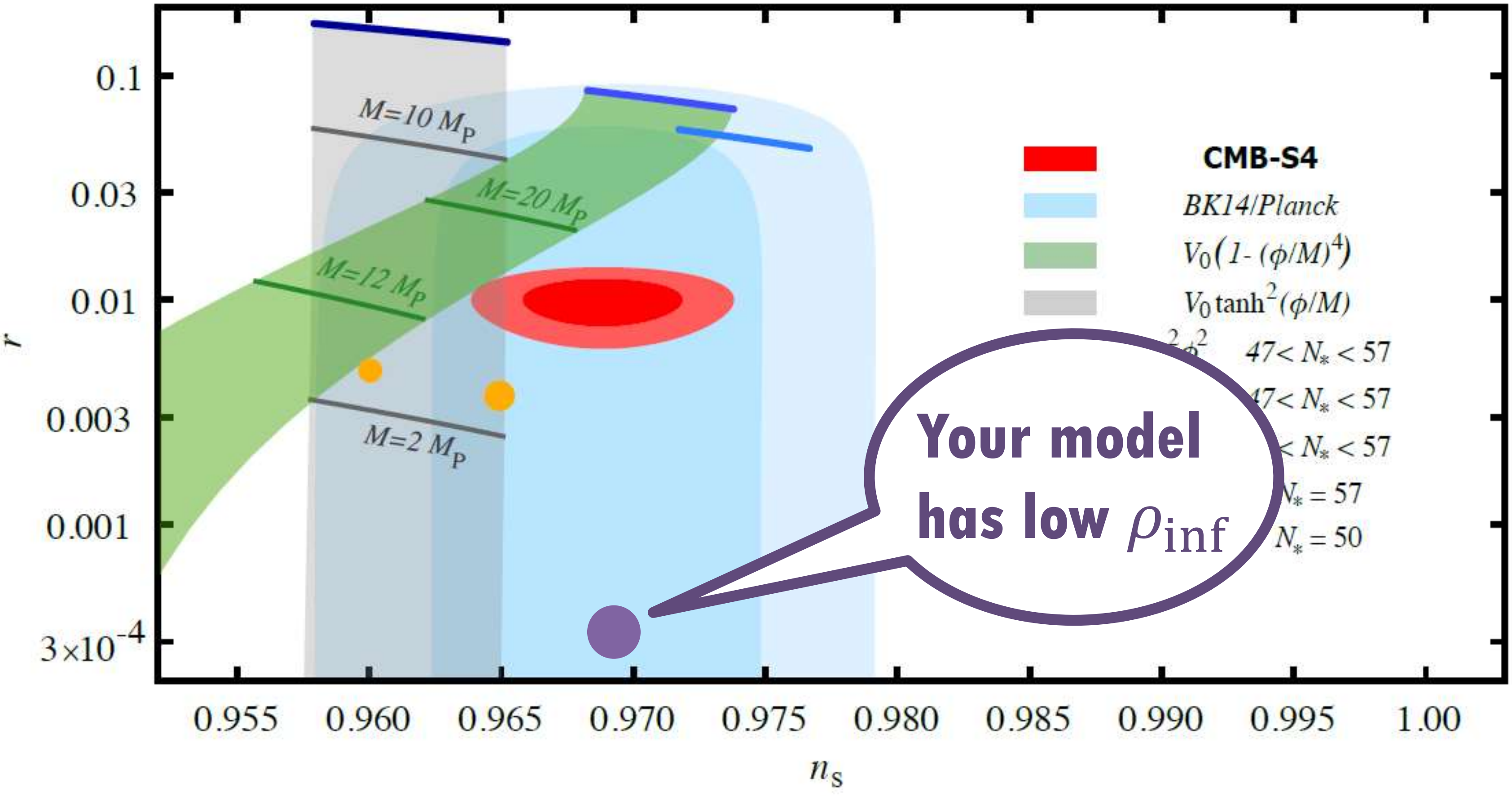


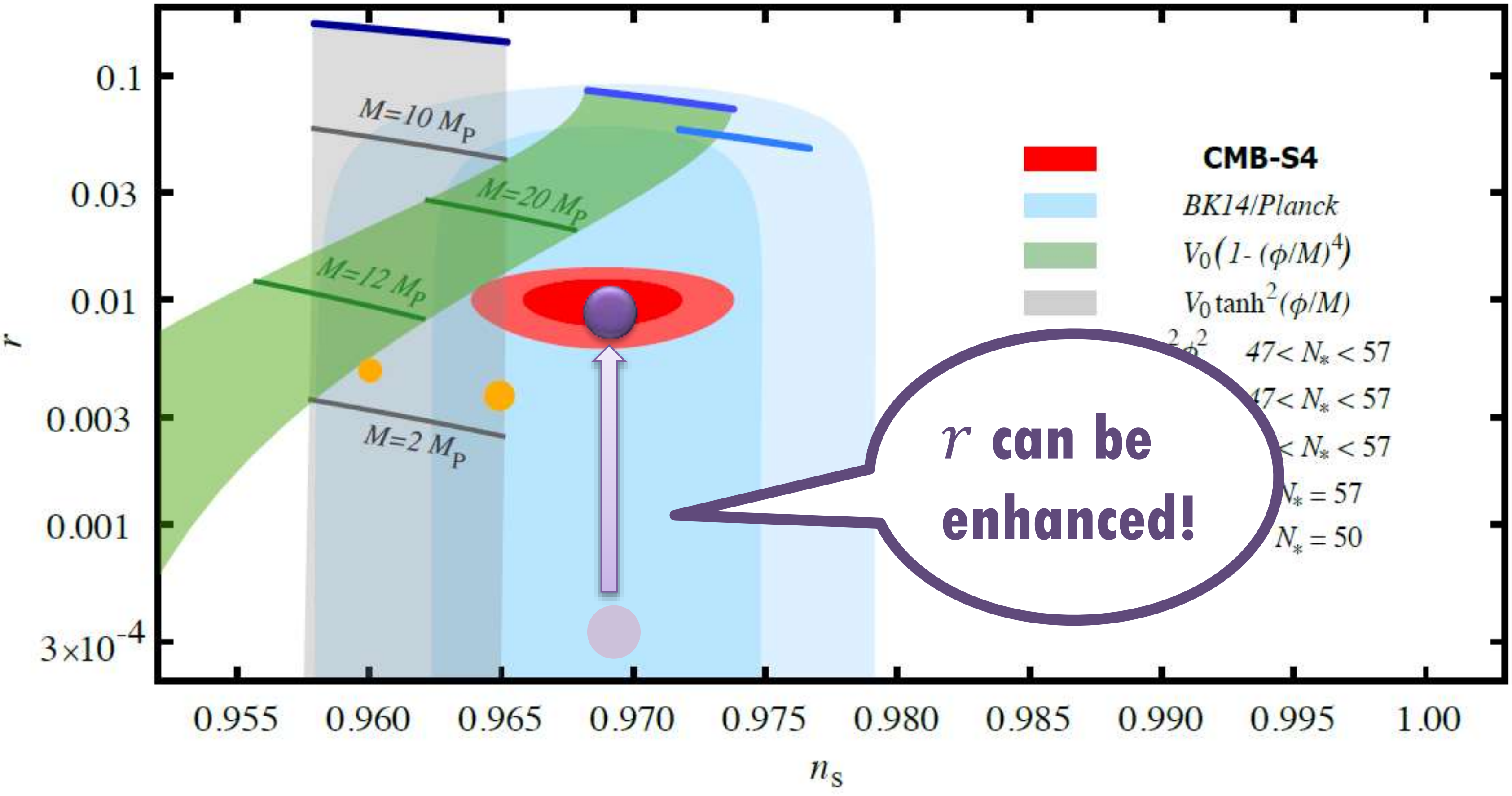
Alternative GW may lead to overestimate of inflation H

Low ρ_{inf} model can be rescued!



Your model has low ρ_{inf}

Low ρ_{inf} model can be rescued!



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

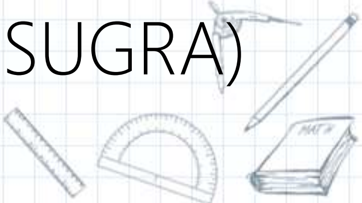
$$\mathcal{L} = \mathcal{L}_{\mathrm{inflaton}}$$

$$+\frac{1}{2}(\partial\chi)^2 - \mu^4\left(\cos\frac{\chi}{f} + 1\right)$$

$$-\frac{1}{4}F^a_{\mu\nu}F^{a\mu\nu} - \frac{\lambda}{4f}\chi F^a_{\mu\nu}\tilde{F}^{a\mu\nu}$$

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

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



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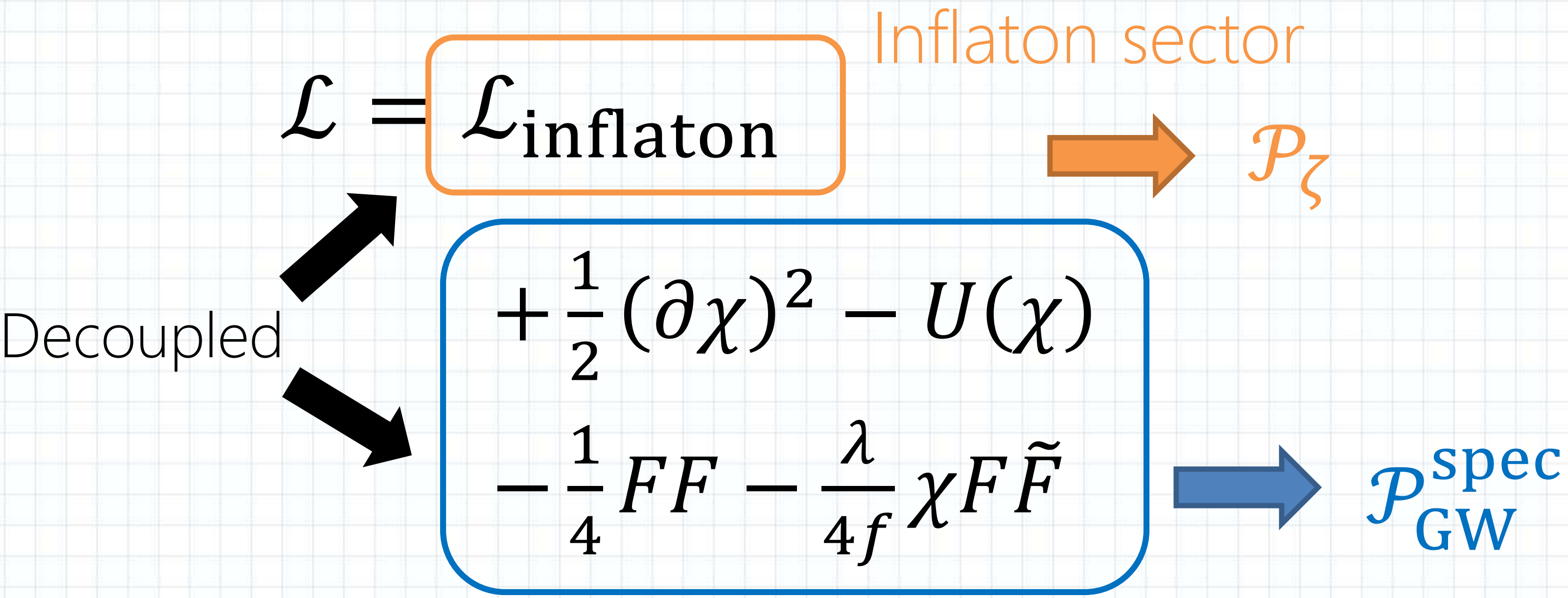

Inflaton sector

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

Decoupled

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

Axion- SU(2) gauge spectator sector

Why SU(2)?

SVT Decomposition Theorem:

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

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

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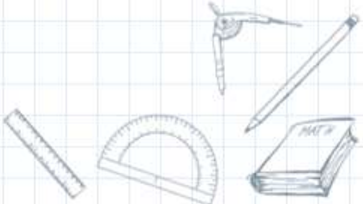


Why SU(2)?

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

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

[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.

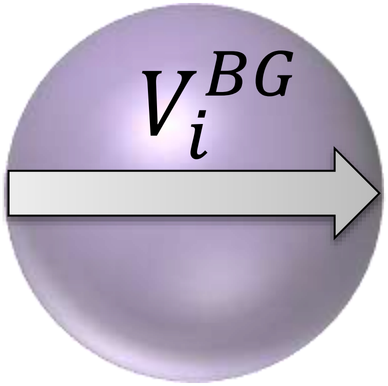
$$V_i^{BG}\delta V_j \xrightarrow[\text{Source}]{} \delta T_{ij}$$

CMB says the universe is isotropic.

U(1) gauge → Anisotropic BG

SU(2) gauge → Isotropic BG is Attractor.

Isotropy is violated



[Maleknejad&Erfani(2014)]

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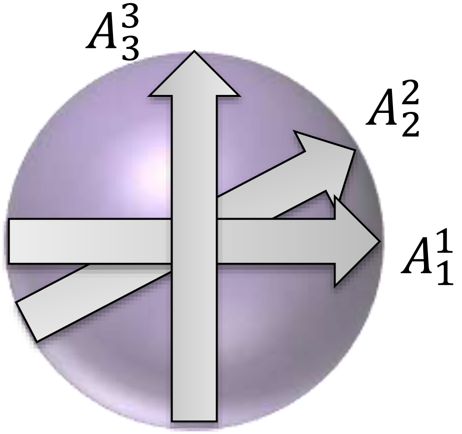
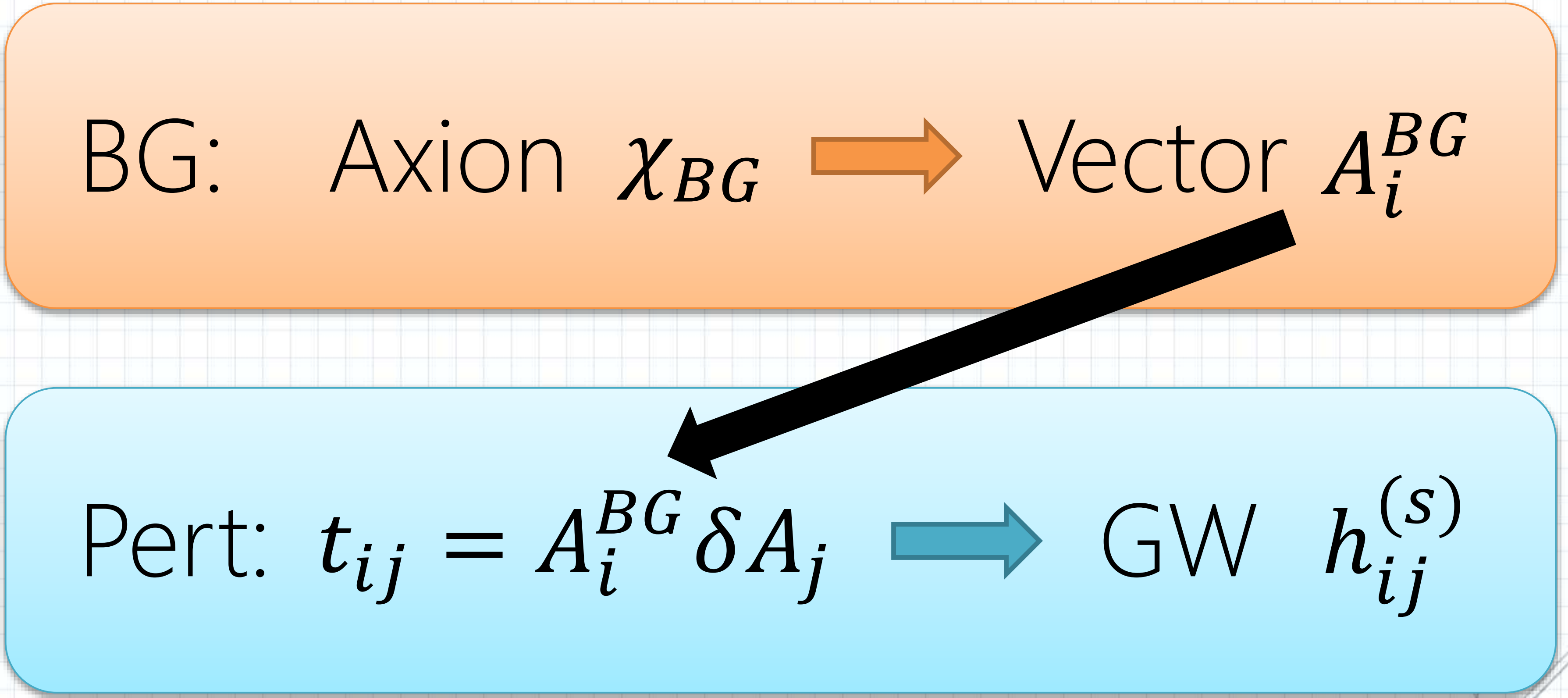
Isotropy is conserved



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

[Maleknejad&Erfani(2014)]

Flow of dynamics

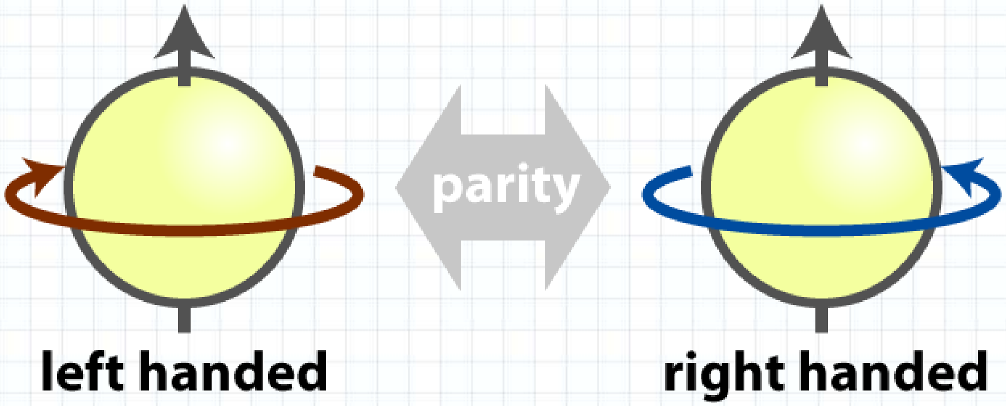


BG: Axion χ_{BG} → Vector A_i^{BG}

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

Parity-breaking

Parity symmetry is spontaneously broken while χ is rolling



Either one of two circular polarization of GW is amplified

Instability of Chiral Tensor

The EoMs for tensor perturbations are

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

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

$$FF \supset g\epsilon^{ijk} A^i A^j \partial A^k, \qquad \chi F\tilde{F} \supset \dot{\chi}\epsilon_{ijk} A_i \partial_j A_k$$

where we have used $\epsilon_{ijk} k_i e_{jl}^{R,L}(\hat{\boldsymbol{k}}) = \mp k e_{kl}^{R,L}(\hat{\boldsymbol{k}})$.

ϵ_{ijk} **terms make t_R instable (but not t_L)**

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

$x \equiv -k\eta$

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

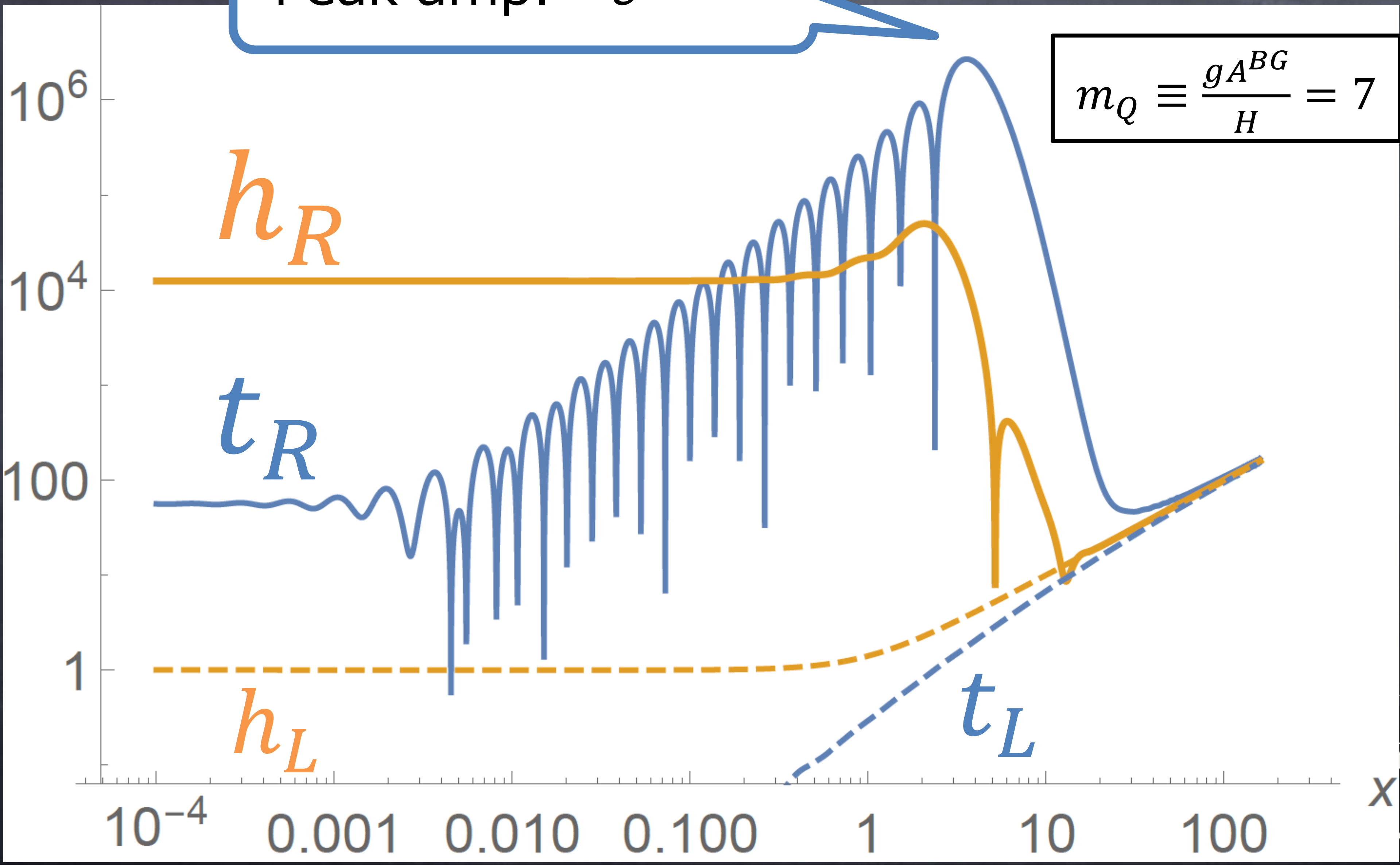
$\xi \equiv \lambda\dot{\chi}/2fH$

$A_i^a \equiv a\delta_i^a A^{BG}$

Insta nsor

Peak amp.∼ $e^{1.8 m_Q}$

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



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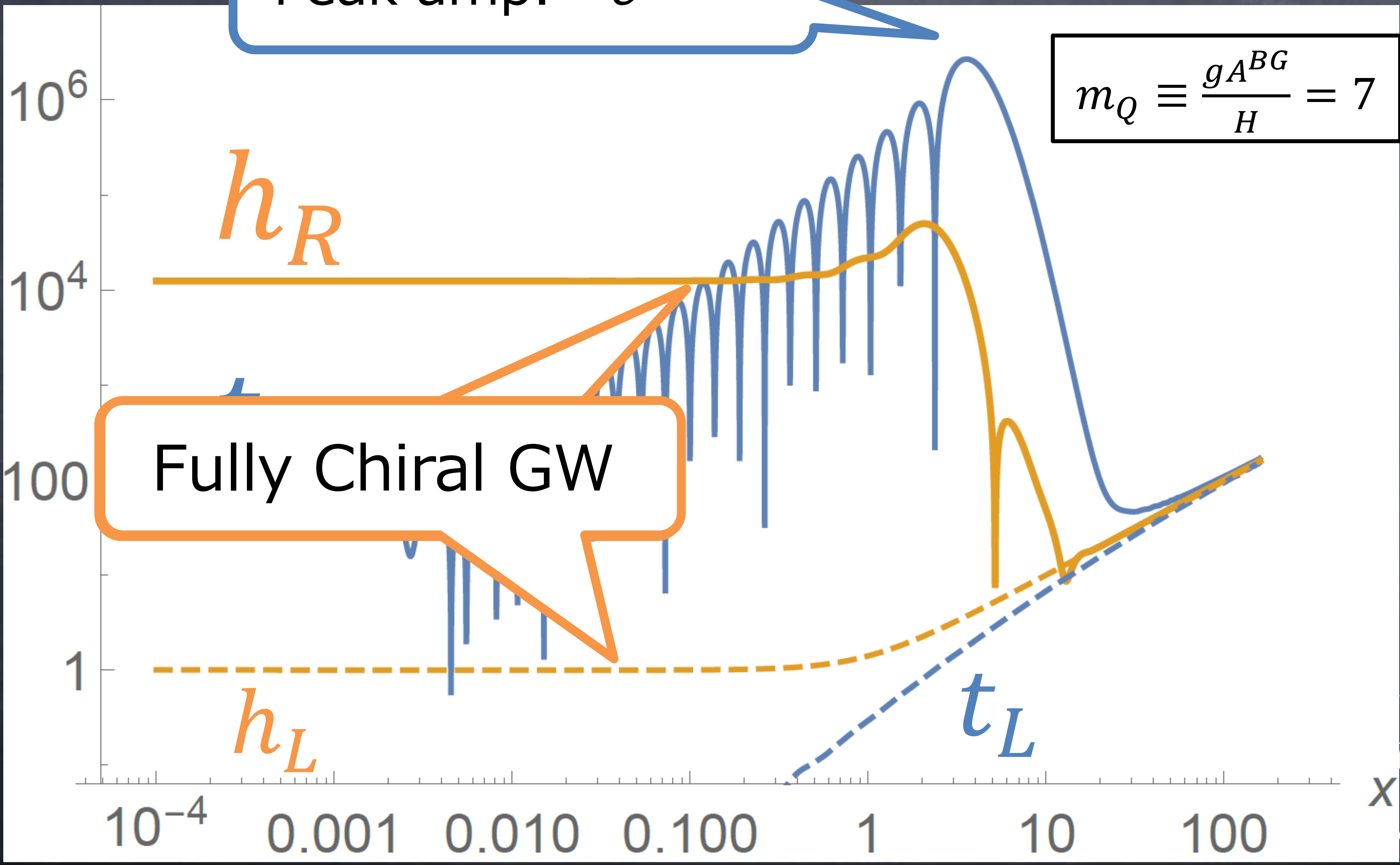


Peak amp.$\sim e^{1.8m_Q}$

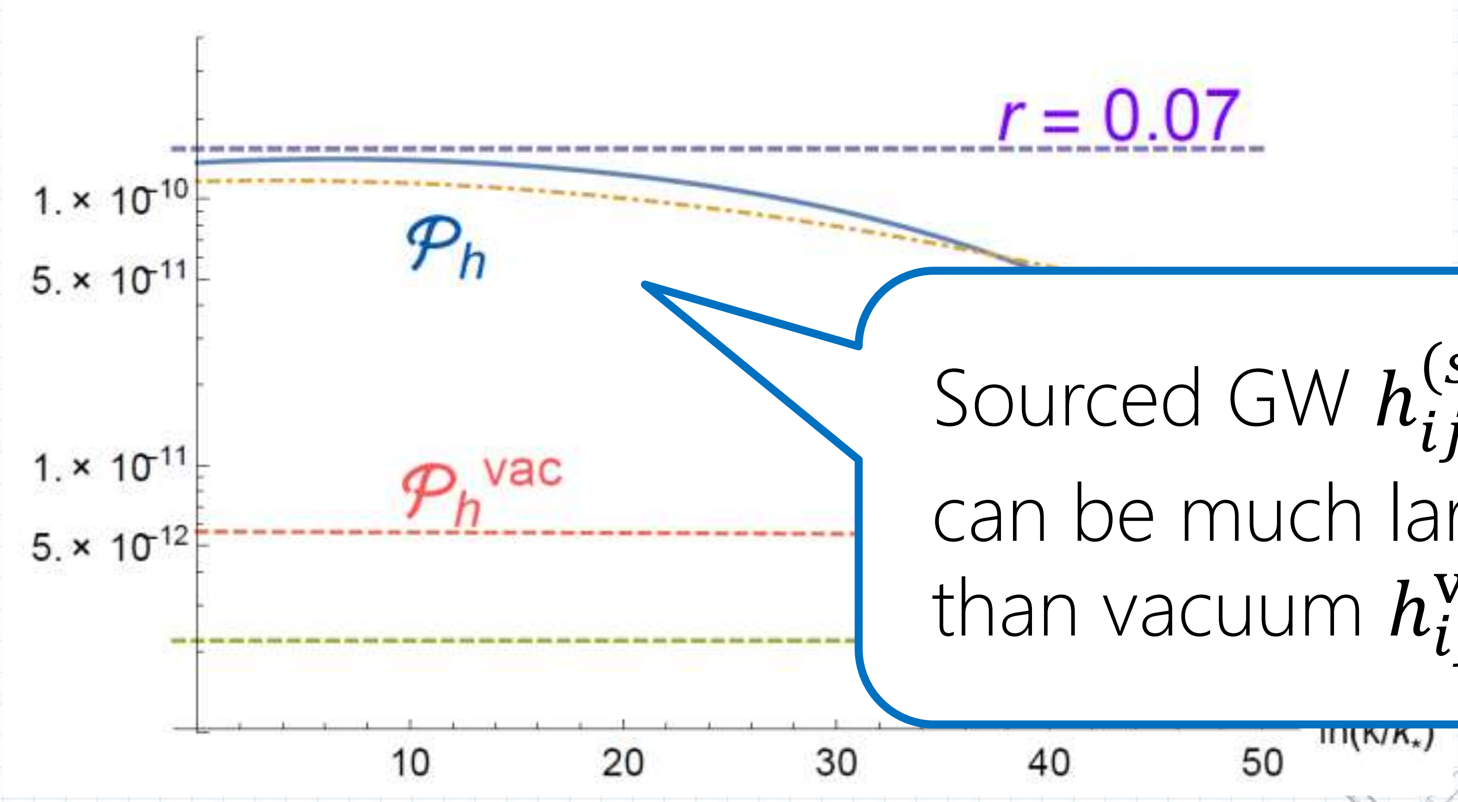
$m_Q \equiv \frac{gA^{BG}}{H} = 7$

Fully Chiral GW

Result

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

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



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

Short summary of the model

① It naturally realizes $r_{\mathrm{add}} > r_{\mathrm{vac}}$

② GW can be sourced at linear order with $\mathbf{SU(2)}$ gauge field

③ SSB of the parity symmetry leads to the Chiral GW

Axion-SU(2) model

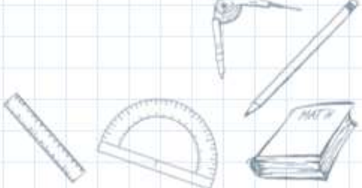
- Larger GW than h^{vac} can be produced

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

r_{obs} doesn't fix H_{inf}

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

Let's observe the signature



TB, EB correlation

Chiral GW induces TB & EB cross correlations

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

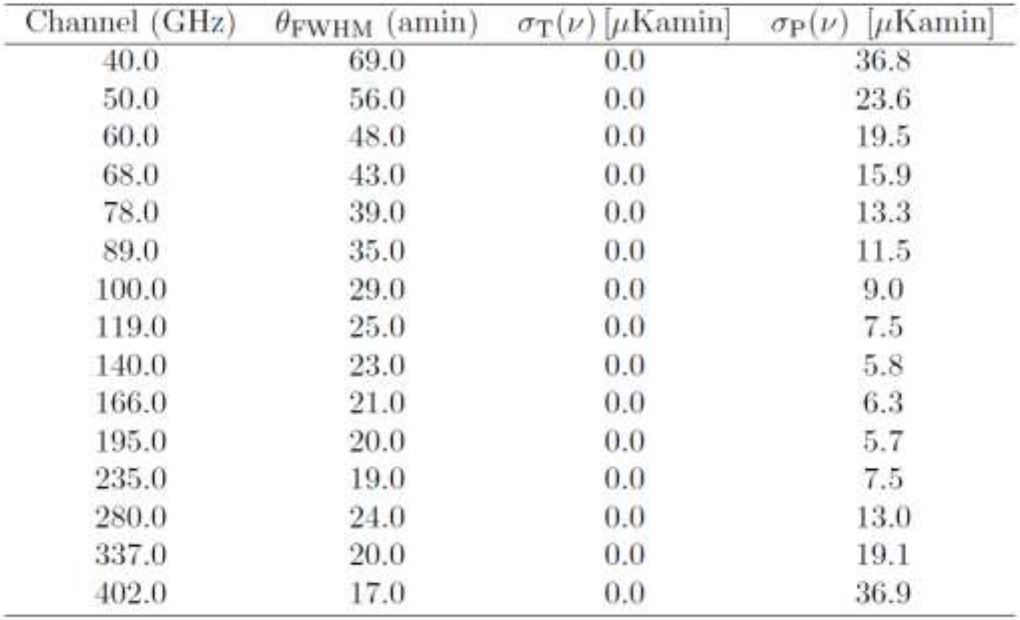
$$\langle TB\rangle, \langle EB\rangle \propto \langle h_R h_R\rangle - \langle h_L h_L\rangle$$

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

introduction

LiteBIRD

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



Channel (GHz)	θ_{FWHM} (amin)	$\sigma_{\text{T}}(\nu)$ [μKamin]	$\sigma_{\text{P}}(\nu)$ [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 $f_{\text{sky}} = 0.5$

Model prediction

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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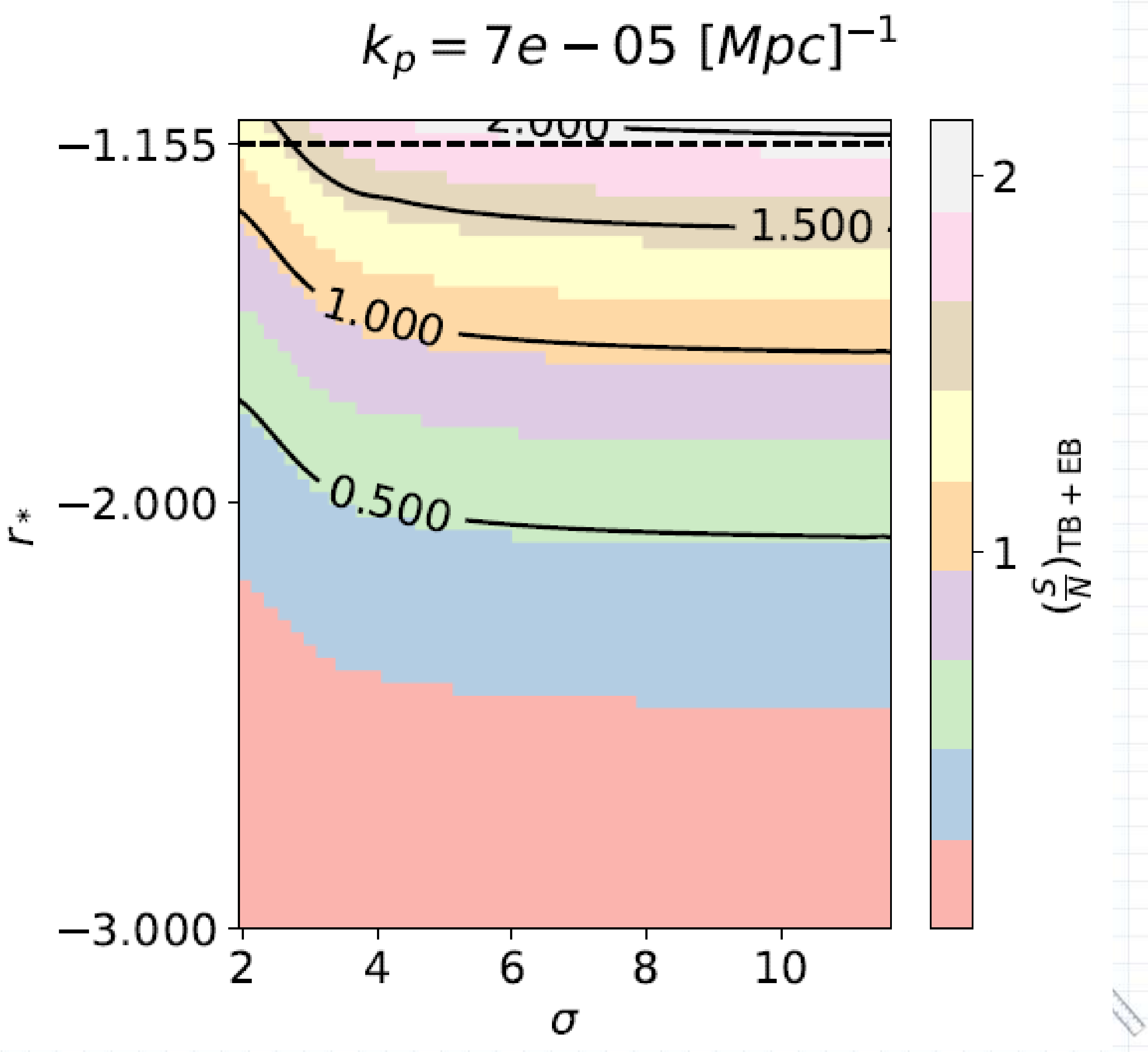

Cosmic Variance limited case

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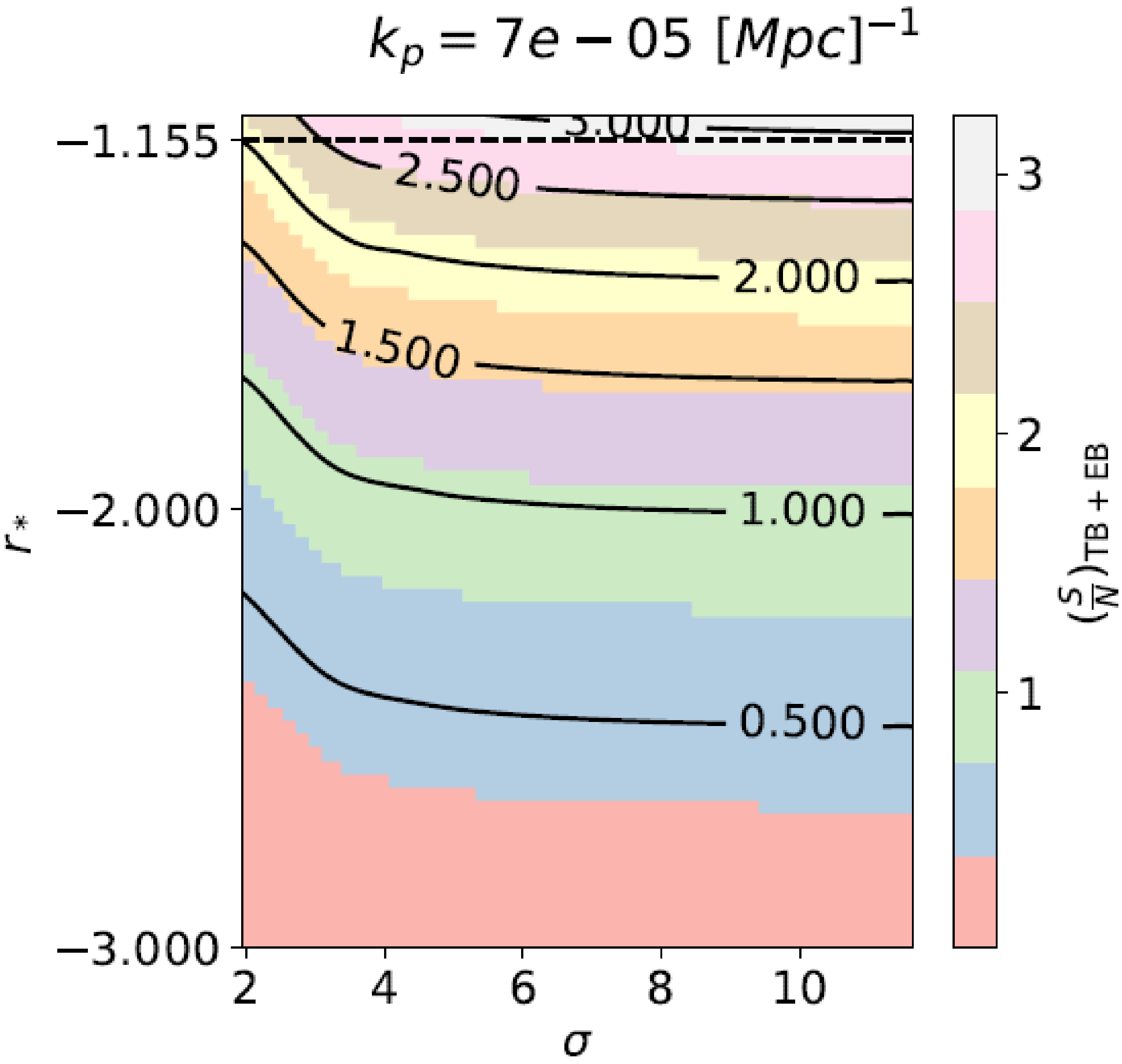


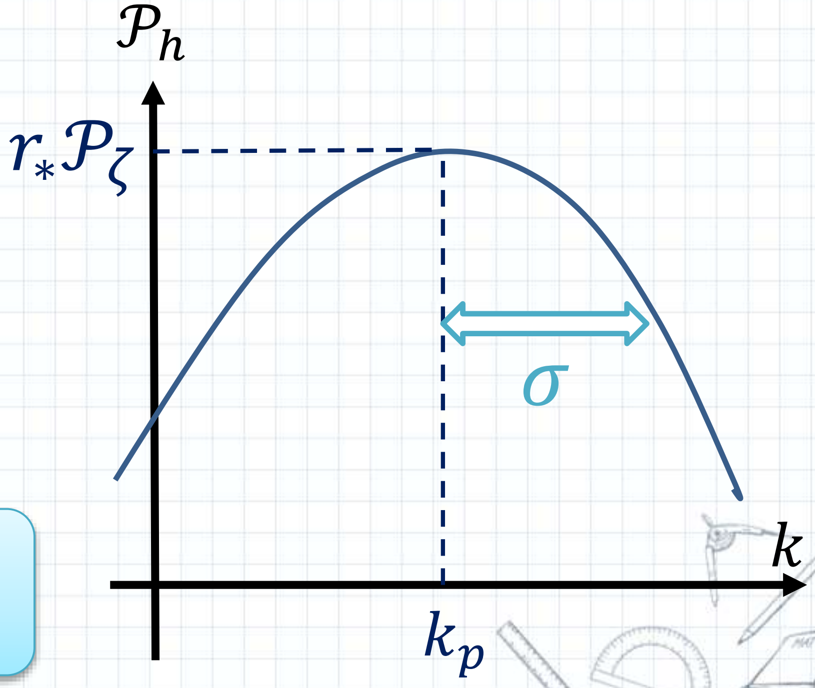
Model prediction

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

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

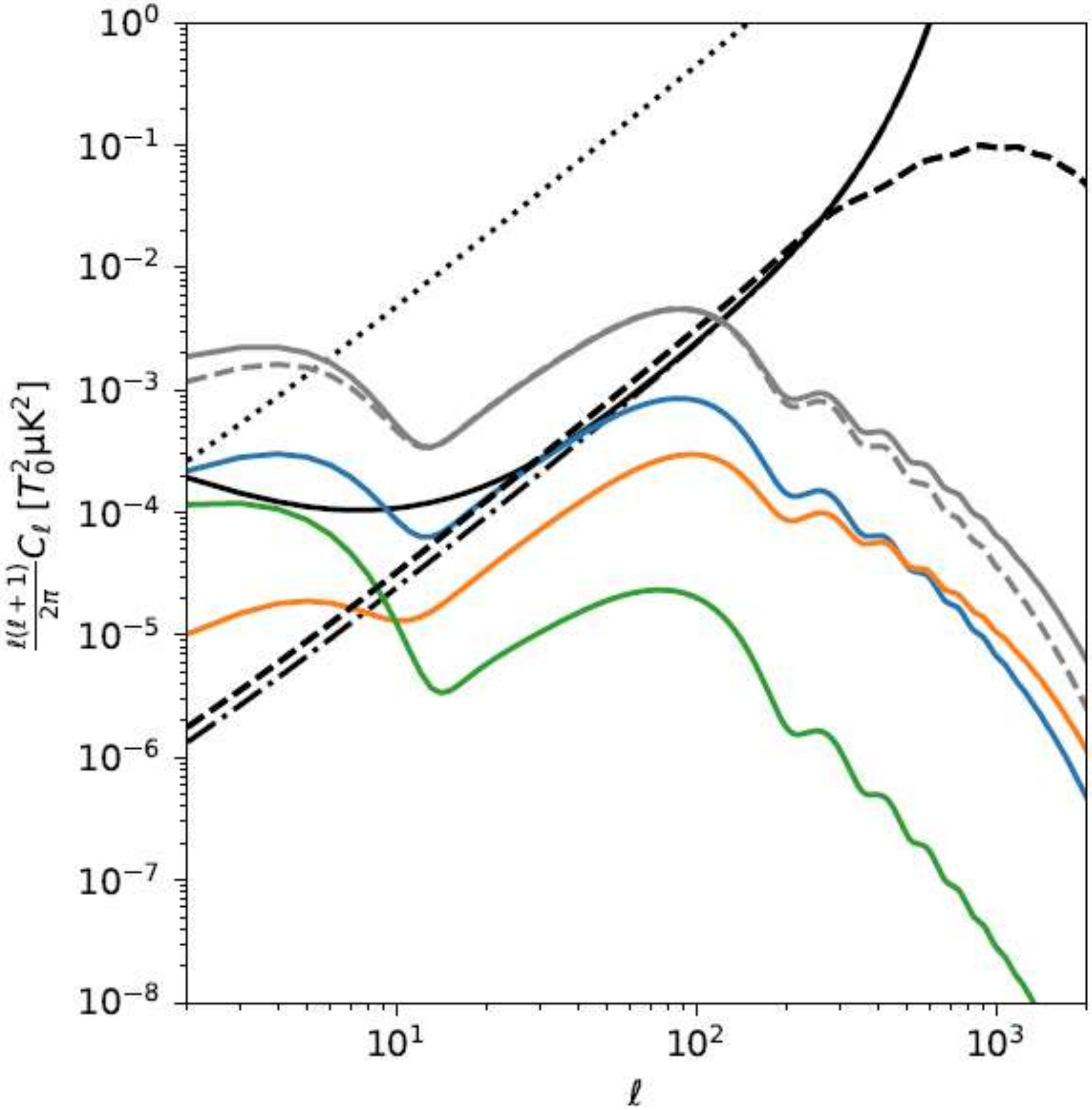
$k_p =$ arbitrary (depend on χ_i)

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



C_ℓ for BB and sensitivity curves

PRESENTATION



Model prediction

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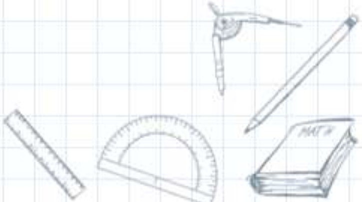
TB + EB can be detected by LiteBIRD for $r > 0.03$.



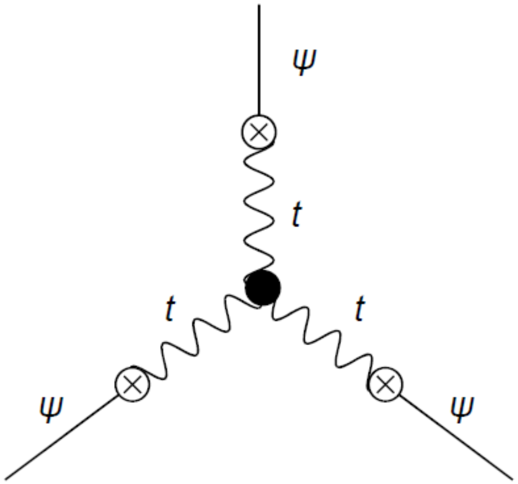
Non-Gaussianity

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

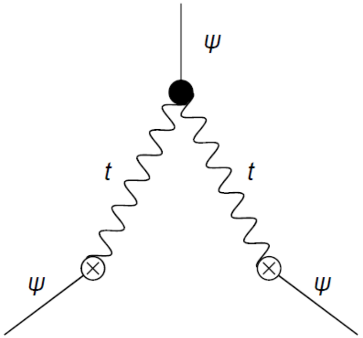
The EoM for SU(2) gauge field is non-linear

$$\partial_\tau^2 t_R(\tau, \boldsymbol{k}) + \left(k^2 + \frac{2m_Q\xi}{\tau^2} + 2\frac{m_Q+\xi}{\tau}k \right) t_R(\tau, \boldsymbol{k}) \\ = g\left[e_{ij}^R(\hat{\boldsymbol{k}})\right]^{-1} \iint \frac{\mathrm{d}^3p\mathrm{d}^3q}{(2\pi)^3}\,\delta(\boldsymbol{p}+\boldsymbol{q}-\boldsymbol{k})Q_{ij}(\boldsymbol{p},\boldsymbol{q},\tau)t_R(\tau,\boldsymbol{p})t_R(\tau,\boldsymbol{q})$$

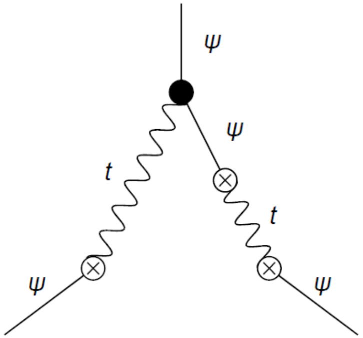
Non-Gaussianity



(i)



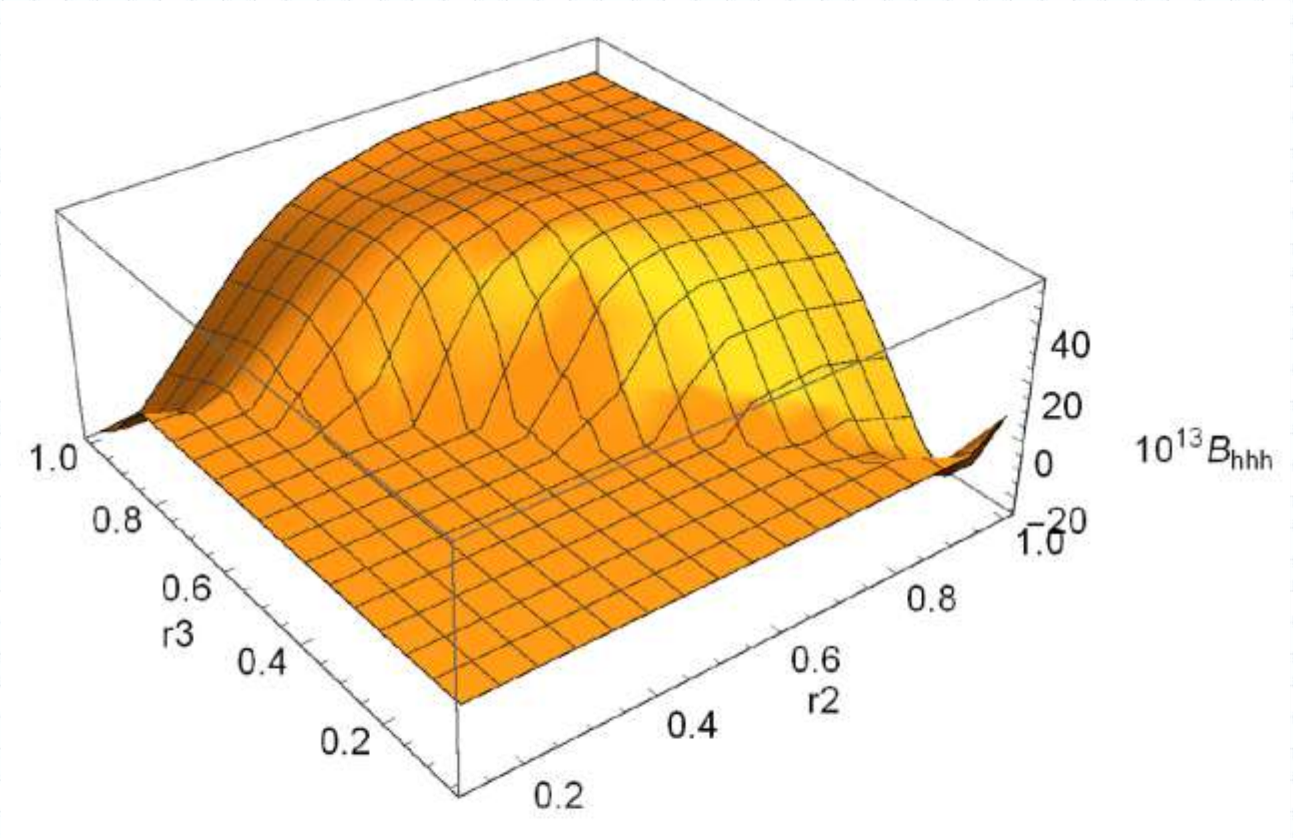
(ii)



(iii)

$\langle h_R h_R h_R \rangle$ is produced at Tree level

Non-Gaussianity



$\langle h_R h_R h_R \rangle$ has an interesting shape

Non-Gaussianity

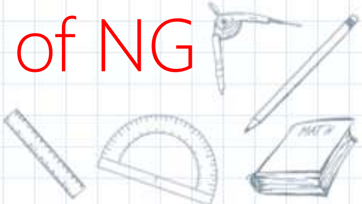
Model prediction (preliminary):

$$(k_1^2k_2^2k_3^2)B_h^{\text{equil}} \sim -10^{-12}$$

Planck 2015 XVII constraint on $\langle h_R h_R h_R \rangle$

$$(k_1^2k_2^2k_3^2)B_h^{\text{equil}} = (3.5 \pm 13.2) \times 10^{-12}$$

Note: Planck analysis assumes different shape of NG



Non-Gaussianity

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GW NG may be detected soon?

Planck 2015 XVII constraint:

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

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

r_{obs} doesn't fix H_{inf}

- Distinguishable w/

Let's observe it!

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

- Lowest ρ_{inf} for $r = 10^{-3}$
  - $r \propto \Omega_{GW}(k) \propto \Omega_{\mathrm{source}}(k)$

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

Fin

Thank you !