# Implications of Inflationary Interaction on Gravitational-wave Detection

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Fujita, **RN** & Tada, arXiv: 1707.05820

Shiraishi, Hikage, **RN**, Namikawa & Hazumi, PRD 94(2016)043506, arXiv: 1606.06082

**RN**, Peloso, Shiraishi, Sorbo & Unal, JCAP 1601(2016)041, arXiv: 1509.07521

Barnaby, **RN** & Peloso, JCAP 1104(2011)009, arXiv: 1102.4333

# Standard Prediction

## Standard prediction for GWs from inflation

$$P_{\rm GW}(k) = \left.\frac{2H^2}{\pi^2 M_p^2}\right|_{k=aH}, \qquad E_{\rm inflation} \cong 5 \cdot 10^{15}\,\text{GeV}\left(\frac{P_{\rm GW}}{10^{-12}}\right)^{1/4}$$

**Standard lore**

**Detectable GW** $P_{\rm GW} \gtrsim \mathcal{O}(10^{-12}) \iff$ **Large** $E_{\rm inflation} \gtrsim \mathcal{O}(10^{16})$ **GeV**

- Considered as direct probe of inflationary energy scale
- Slightly red-tilted $\sim$ decreasing $H$

?

# General arguments

**Heuristically,**

$$P_{\rm GW} \sim \frac{1}{\rho_{\rm total}} \frac{d}{d\ln k}\rho_{\rm GW} = \frac{d}{d\ln k}\Omega_{\rm GW}$$

$\rho_{\rm total} \nearrow 3M_{\rm Pl}^2 H^2$

$\rho_{\rm GW} \nwarrow \sim M_{\rm Pl}^2 \langle(\partial_t \delta g_{ij}^{TT})^2\rangle \sim M_{\rm Pl}^2 H^2 \langle(\delta g_{ij}^{TT})^2\rangle$

GW power spectrum $\sim$ Spectrum of GW energy fraction $\Omega_{\rm GW}$

- **The standard single-field slow-roll case:**

**Crucial assumptions**

Source of GWs = **vacuum fluctuations** of graviton

Evolution driven only by **expansion** of the universe

- *(continued...)* **The standard single-field slow-roll case:**

**Initial Vacuum State**

**Initial**

$\Downarrow$

deep inside the horizon

$\Downarrow$

$k \gg aH$

**Vacuum**

$\Downarrow$

no particle state

$\Downarrow$

$n_\lambda = 0$

$\Downarrow$

Classical evolution — governed by **expansion** $\sim H$

$\Downarrow$

$$\rho_{\rm GW} \sim H^4 \quad , \quad P_{\rm GW}(k) = \left.\frac{2H^2}{\pi^2 M_p^2}\right|_{k=aH}$$

◇ (Quasi) de Sitter: symmetry under $t \to t + \Delta t$, $\vec{x} \to e^{-H\Delta t}\vec{x}$ enforces (approximate) scale-invariance of $P_{\rm GW}$

- **More general cases:** There can occur **particle production** during infl.

  Focus on $\mathcal{L}_{\rm int} = \chi F\tilde{F}$

  ▷ **Inflationary interaction can induce copious production of quanta**

  ▷ **Additional sources for GW can lead to $\rho_{\rm GW} \not\propto H^4$**

**Detectable GW $\neq$ Large $E_{\rm inflation}$**

This is an simple argument...

Why has such a simple argument not been considered extensively?

## Decomposition theorem (in cosmology)

On homogeneous and isotropic background,

scalar, vector & tensor modes are decoupled

at the 1st-order cosmological perturbations

$$\delta_1 S \,, \quad \delta_1 V_i \qquad \not\Rightarrow \qquad h_{ij}$$

What to come:

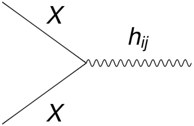
1. **CASE I:** Sources for GW are only scalar or vector fields
   1. **EXAMPLE I:** Inflaton + $U(1)$ gauge field (Axion inflation)
   2. **EXAMPLE II: Spectator axion** + $U(1)$ gauge field

2. **CASE II:** Sources for GW are an additional “tensor” modes
   1. **EXAMPLE III:** Inflaton + $SU(2)$ gauge field (Chromo-natural inflation)
   2. **EXAMPLE IV: Spectator axion** + $SU(2)$ gauge field

- **CASE I:** “tensor” modes only from the metric perturbations $\delta g_{\mu\nu}$

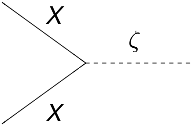
— Scalar/vector sources need to be 2nd order

$$\partial_i \delta S \, \partial_j \delta S \, , \quad \delta V_i \, \delta V_j \qquad \Longrightarrow \qquad h_{ij}$$




— However, they also source **curvature (scalar) perturbations**

$$(\delta S)^2 \, , \quad (\delta V_i)^2 \qquad \Longrightarrow \qquad \zeta$$




— We need to ensure the following two results:

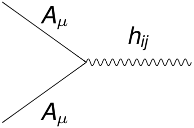
1. To respect constraints on scalar perturbations ($n_s$, $f_{\rm NL}$)
2. To have sourced $h_{ij}$ be dominant over the vacuum fluctuations

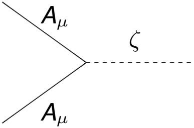
# **CASE I:** GWs from 2nd order effects

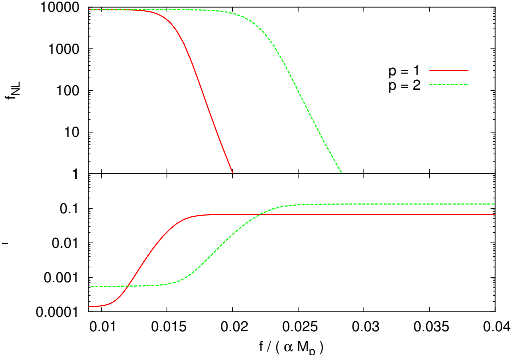
**EXAMPLE I:** Inflaton + $\boldsymbol{U(1)}$ **gauge field**

$$\mathcal{L}_{\rm int} = -\frac{\alpha}{4f}\,\varphi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

inflaton  $U(1)$ gauge field




$\boldsymbol{r \propto \epsilon^2}$

when sourcing effects dominate

Barnaby & Peloso '10; Barnaby, RN & Peloso. '11

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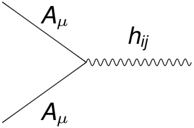
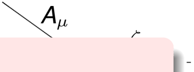
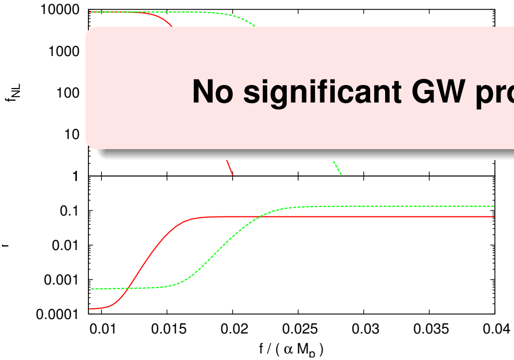



**No significant GW production**

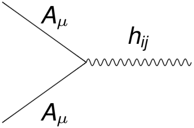
$\boldsymbol{r \propto \epsilon^2}$

when sourcing effects dominate

Barnaby & Peloso '10; Barnaby, RN & Peloso. '11

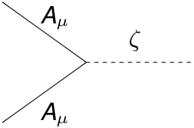
# **CASE I:** GWs from 2nd order effects

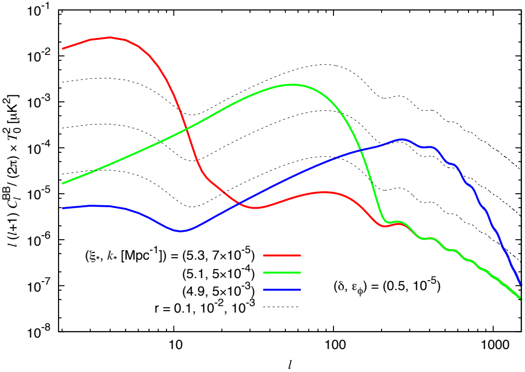
**EXAMPLE II:** Spectator axion + $\boldsymbol{U(1)}$ **gauge field**

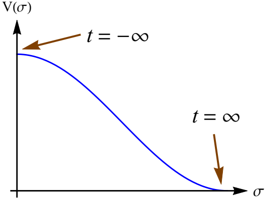



$$\mathcal{L}_{\rm int} = -\frac{\alpha}{4f}\,\sigma F_{\mu\nu}\tilde{F}^{\mu\nu}$$

pseudo-scalar ($\sigma$) — $U(1)$ gauge field ($F_{\mu\nu}\tilde{F}^{\mu\nu}$)




Barnaby et al. '12; Mukohyama et al. '14; RN et al. '15; Shiraishi et al. '16

# **CASE I:** GWs from 2nd order effects

**EXAMPLE II:** Spectator axion + $\boldsymbol{U(1)}$ **gauge field**

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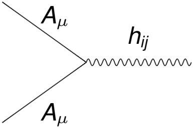
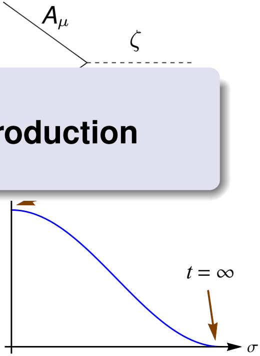
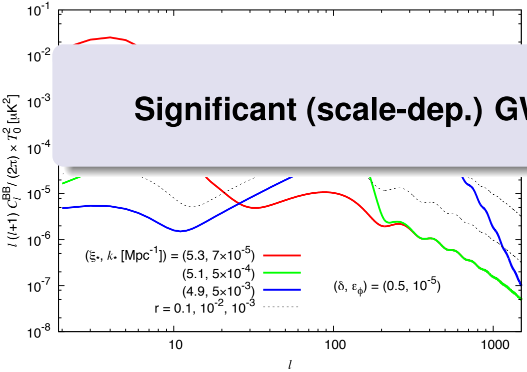



**Significant (scale-dep.) GW production**

Barnaby et al. '12; Mukohyama et al. '14; RN et al. '15; Shiraishi et al. '16

## CASE I

**Decomposition theorem**

$\Downarrow$

**No 1st-order sourcing for GWs**

$\Downarrow$

**2nd-order sourcing is necessary**

Cook & Sorbo '11; Senatore et al. '11; Cook & Sorbo '13; Ferreira & Sloth '14; Biagetti et al. '14; Mirbabayi et al. '14; Choi et al. '15; Ferreira et al. '15; Peloso et al. '16

## CASE I

**Decomposition theorem**

$\Downarrow$

**ANY EXCEPTIONS ?**

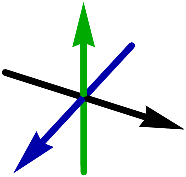
Cook & Sorbo '11; Senatore et al. '11; Cook & Sorbo '13; Ferreira & Sloth '14; Biagetti et al. '14; Mirbabayi et al. '14; Choi et al. '15; Ferreira et al. '15; Peloso et al. '16

- **CASE II: Exceptions to standard decomposition**

  **— requires additional "tensor"**

— **Introduce an $SU(2)$ gauge field with a vev**

$$\langle A_\mu^a \rangle = A(t)\, \delta_\mu^a$$



▷ Isotropic ($SO(3)$ invariant) configuration for background

▷ Perturbations $\delta A_\mu^a$ contain **"tensor" modes**

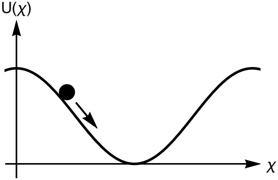
Maleknejad & Sheikh-Jabbari '11

$\delta A_i^a \supset t_i^a \quad \longrightarrow \quad$ couled to GW modes **at linear order**

# **CASE II:** GWs from 1st order effects

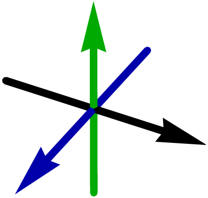
Pseudo-scalar $+$ $\boldsymbol{SU(2)}$ **gauge field**

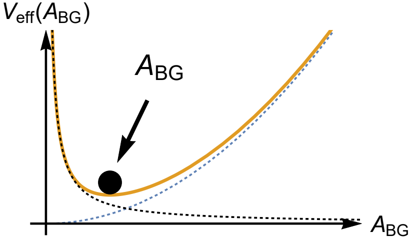
$$\mathcal{L} = -\frac{1}{2}(\partial\chi)^2 - U(\chi)$$
$$-\frac{1}{4}F^a_{\mu\nu}F^{a,\,\mu\nu} + \frac{\boldsymbol{\lambda}}{\boldsymbol{4f}}\,\chi\boldsymbol{F^a_{\mu\nu}\tilde{F}^{a,\,\mu\nu}}$$




**Isotropic configuration**

$$\langle \boldsymbol{A_0^a}\rangle = \boldsymbol{0}\,, \quad \langle \boldsymbol{A_i^a}\rangle = \boldsymbol{a\,A_{\rm BG}\,\delta_i^a}$$





# **CASE II:** GWs from 1st order effects

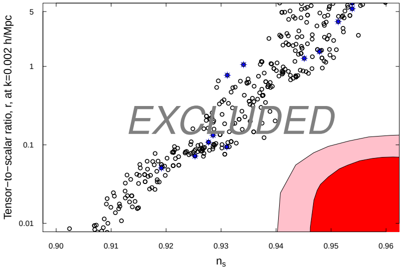
**EXAMPLE III:** Chromo-natural inflation **($\chi =$ inflaton)** Adshead & Wyman '12

$$\mathcal{L}_{\rm int} = -\frac{\alpha}{4f}\,\chi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

inflaton ($\chi$)    $SU(2)$ gauge field ($F_{\mu\nu}\tilde{F}^{\mu\nu}$)

- **Observationally excluded** — too much GW production for a given $n_s$

Dimastrogiovanni & Peloso '12; Adshead, Martinec & Wyman '13




- Modification: **Higgsed Chromo-natural Inflation** Adshead et al.'16

# **CASE II:** GWs from 1st order effects

**EXAMPLE IV:** $\chi$ **= spectator axion** + ***SU*(2) gauge field**

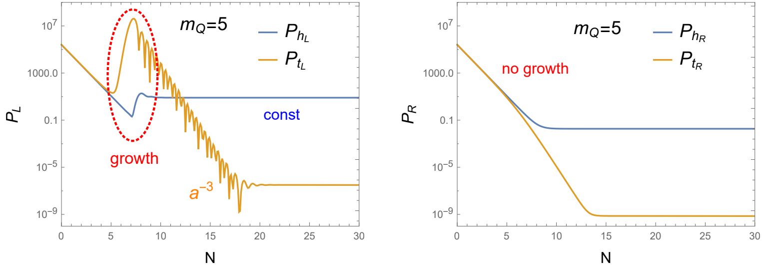
Dimastrogiovanni, Fujita & Fasiello '16

$$\mathcal{L}_{\text{int}} = -\frac{\alpha}{4f}\chi F_{\mu\nu}\tilde{F}^{\mu\nu}$$

spectator ($\chi$) $SU(2)$ gauge field ($F_{\mu\nu}\tilde{F}^{\mu\nu}$)

▷ **Parity-violating production**

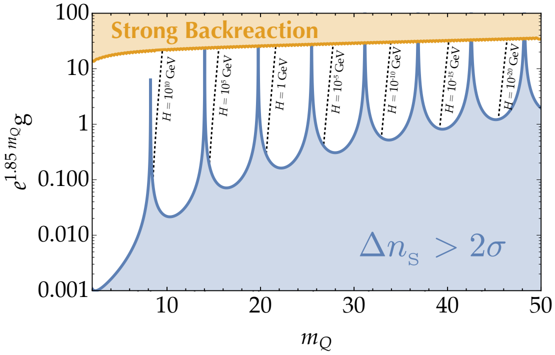
— Transient exponential production of only one helicity



▷ Observationally viable

— Available parameter space

Fujita, RN & Tada '17




$\boldsymbol{m_Q \equiv g A_{BG}/H}$

— Other signatures: Tensor non-Gaussianity, TB/EB correlations

Agrawal, Fujita & Komatsu '17; Thorne et al. '17

# Summary and Discussion

- **Future observations aim for $\sigma(r) = \mathcal{O}\left(10^{-3}\right)$**
- Generally GW power spectrum relates to

$$P_{\rm GW} \sim \frac{1}{\rho_{\rm total}} \frac{d\rho_{\rm GW}}{d\ln k}$$

  - ▷ Standard single-field case: $\rho_{\rm GW} \sim H^4$ — detection implies high $H_{\rm inflation}$
- **Inflationary interaction induce production of particles**
  - ▷ Additional source for GWs $\Longrightarrow$ $\rho_{\rm GW} \not\sim H^4$
- **Copious production:** $\mathcal{L}_{\rm int} = \chi\,{\rm Tr}\left[\boldsymbol{F}\tilde{\boldsymbol{F}}\right]$

1. [EXAMPLE I] Inflaton $+$ $\boldsymbol{U(1)}$ (axion inflation) $\Longrightarrow$ Not enough production
2. [EXAMPLE II] **Spectator axion** $+$ $\boldsymbol{U(1)}$ $\Longrightarrow$ Scale-dependent spectrum
3. [EXAMPLE III] Inflaton $+$ $\boldsymbol{SU(2)}$ (chromo-natural) $\Longrightarrow$ Observ. excluded
4. [EXAMPLE IV] **Spectator axion** $+$ $\boldsymbol{SU(2)}$ $\Longrightarrow$ Wide parameter range