Particle Production & Gravitational Waves with SU(2) Gauge Fields in Inflation

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Max Planck Institute for Astrophysics

YITP Accelerating Universe in the Dark March 2019

Motivation

- Inflation: Universe at highest observable energy!

- Gauge field theories, Abelian or non-Abelian, are the widely accepted framework for particle physics beyond SM.

- The Primordial gauge fields in the physics of inflation compatible with the FRW symmetries?

Energy

$E \lesssim 10^{14} GeV$

$(\frac{E_{LHC}}{\mathrm{E}} \gtrsim 10^{-11})$

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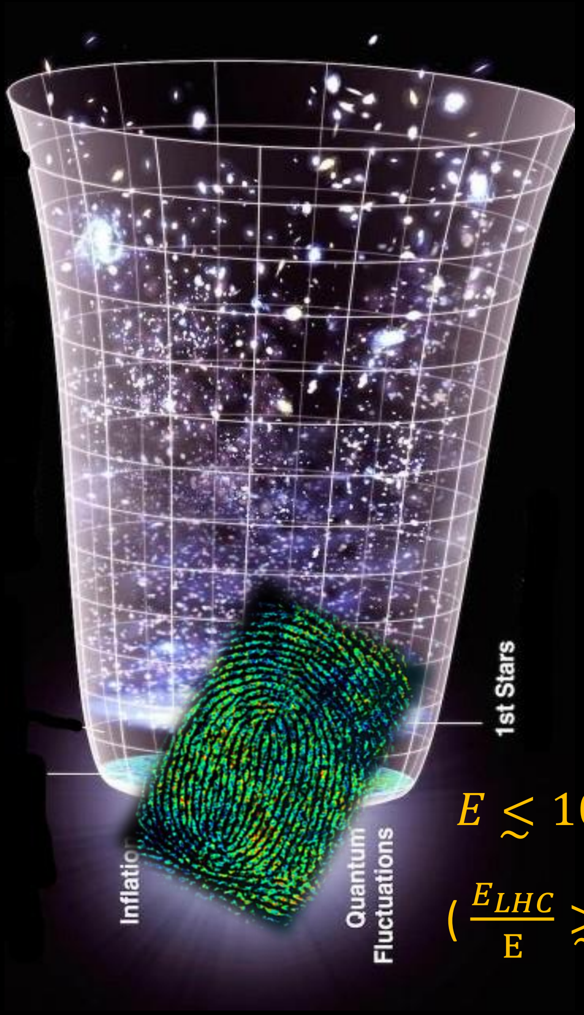

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Non-Abelian Gauge fields in Inflation?

The story started in 2011

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- Breaking the conformal symmetry
- Respecting gauge symmetry

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- Spatial isotropy and homogeneity ✓
- Breaking the conformal symmetry ✓
- Respecting gauge symmetry ✓

Isotropic
SU(2) Gauge field
Background

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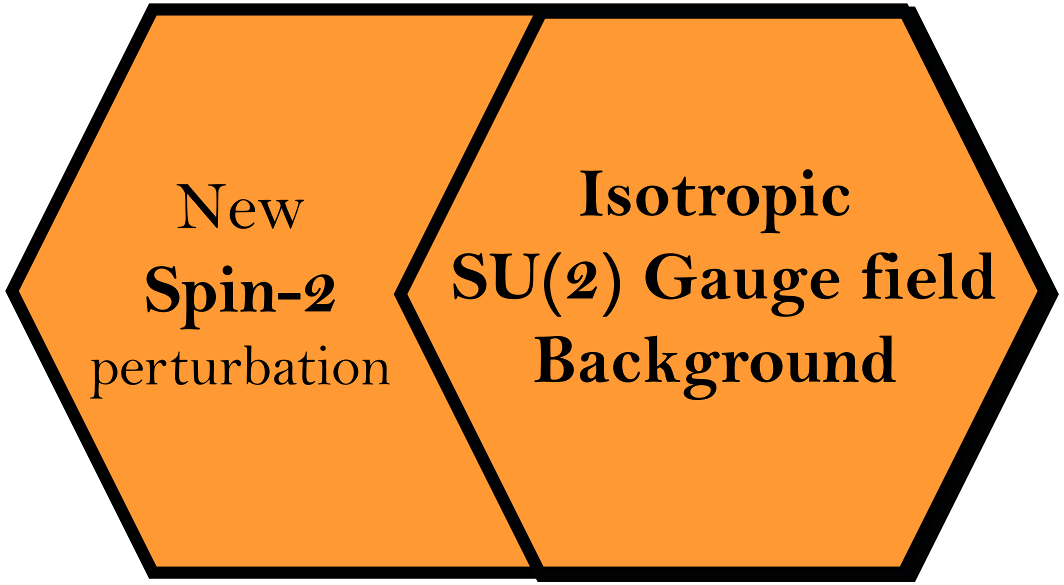

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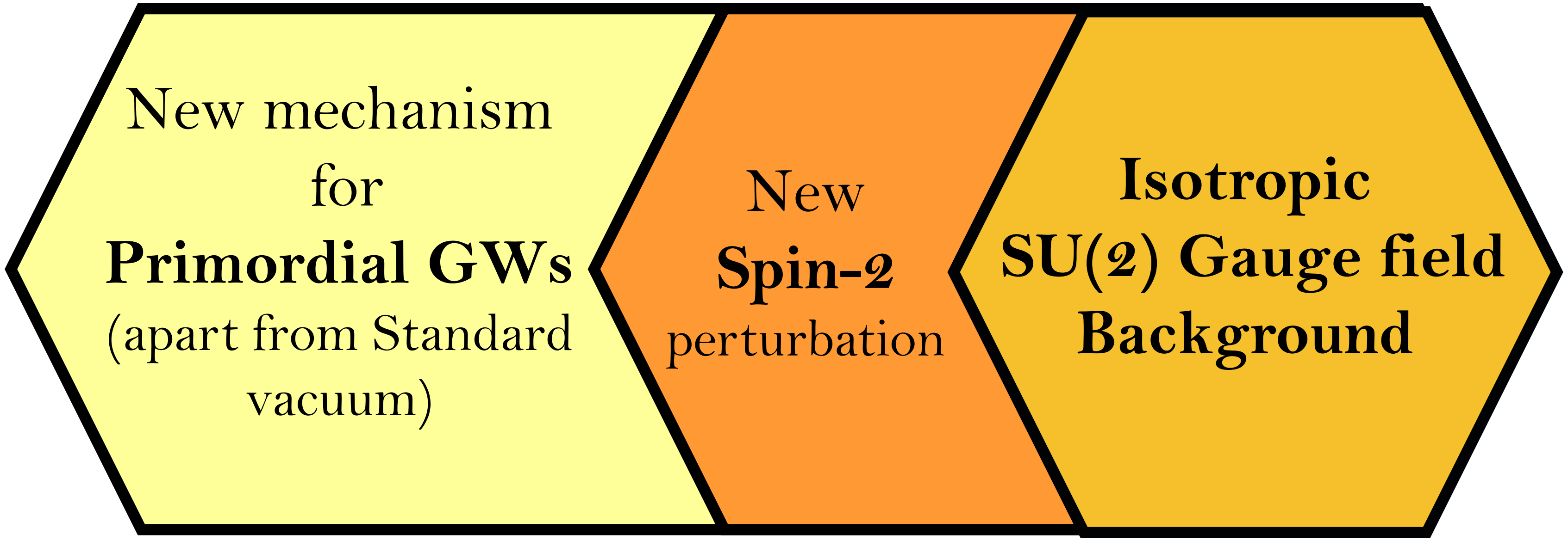

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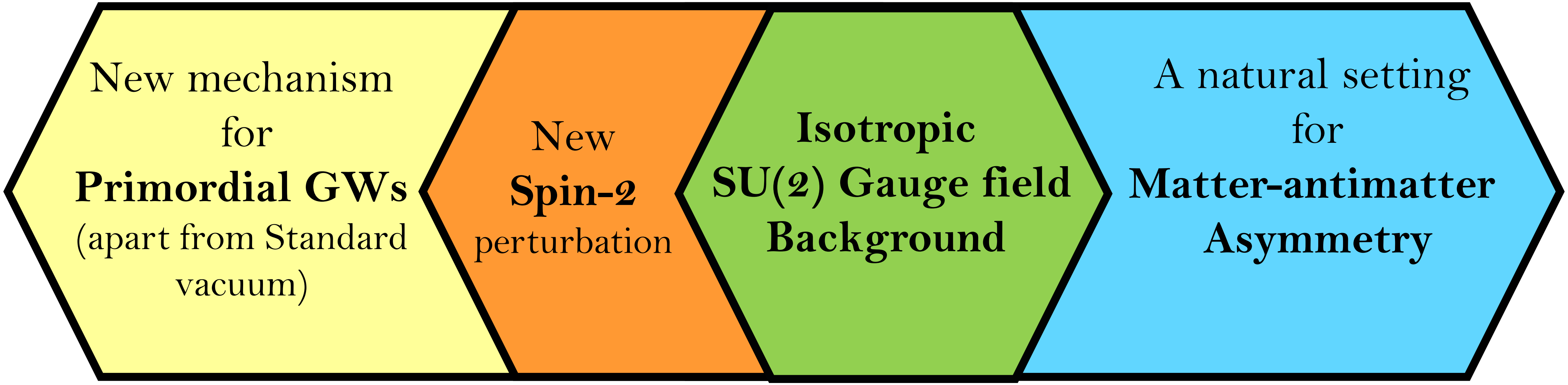

Turns out that my setup is much Smarter than me!

Since 2011, many aspects and different realization of non-Abelian gauge fields in inflation have been studied.

Here is an incomplete list of colleagues and friends that contribute to the better understanding of this setup.

A.M., P. Adshead, M. Wyman, M. Peloso, M.M. Sheikh-Jabbari, J. Soda, E. Dimastrogiovanni, E. Komatsu, A. Agrawal, T. Fujita, E. Sfakianakis, M. Noorbala, R. Caldwell, K. Lozanov, B. Thorne, M. Hazumi, N. Katayama, M. Shiraishi, J. Bielefeld, C. Devulder, N. A. Maksimova, R. Namba, I. Obata, V. Domcke, Y. Ema, K. Mukaida, R. Sato and ...

SU(2) Gauge fields and Inflation

- Gauge-flation

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$$S_{Gf} = \int d^4x \sqrt{-g}\left(-\frac{R}{2} - \frac{1}{4}F^2 + \frac{\kappa}{384}(F\tilde{F})^2\right)$$

- Chromo-natural

P. Adshead, M. Wyman, Phys. Rev. Lett.(2012) [*arXiv:1202.2366*]

$$S_{Cn} = \int d^4x \sqrt{-g}\left(-\frac{R}{2} - \frac{1}{4}F^2 - \frac{1}{2}\left(\partial_\mu\chi\right)^2 - \mu^4\left(1 + \cos(\frac{\chi}{f}\right)\right) - \frac{\lambda}{8f}\chi F\tilde{F}\right)$$

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- Inspired by them, several different models with SU(2) fields have been proposed and studied.

An incomplete list of models with SU(2) gauge field:	α_H	α_s
1. A. M. and M. M. Sheikh-Jabbari, Phys. Lett. B723 (2013) [*arXiv:1102.1513*]	0	0
2. P. Adshead, M. Wyman, Phys. Rev. Lett.(2012) [*arXiv:1202.2366*]	0	0
3. A. M. JHEP 07 (2016) 104 [arXiv:1604.03327]	0	0
4. C. M. Nieto and Y. Rodriguez Mod. Phys. Lett. A31 (2016) [arXiv:1602.07197]	1	0
5. E. Dimastrogiovanni, M. Fasiello, and T. Fujita JCAP 1701 (2017) [arXiv:1608.04216]	0	1
6. P. Adshead, E. Martinec, E. I. Sfakianakis, and M. Wyman JHEP 12 (2016) 137 [arXiv:1609.04025]	1	0
7. P. Adshead and E. I. Sfakianakis JHEP 08 (2017) 130 [arXiv:1705.03024]	1	0
8. R. R. Caldwell and C. Devulder Phys. Rev. D97 (2018) [arXiv:1706.03765]	0	0
-	1	1

- These models can be represented in the unified form

$$S = \alpha_H \underbrace{S_H(A_\mu, H)}_{\text{Higgs sector (mass for gauge field)}} + \underbrace{\alpha_s S_s(\chi)}_{\text{Scalar inflaton (spectator SU(2))}} + S_A(A_\mu, \varphi)$$

S_A is either S_{Gf} (Gauge-flation) or S_{Cn} (Chromo-natural with an arbitrary potential)

$$\alpha_H = \begin{cases} 0 & \\ 1 & \text{Higgsed (massive SU(2))} \end{cases}$$

$$\alpha_s = \begin{cases} 0 & \\ 1 & \text{Spectator SU(2)} \end{cases}$$

A. M. and E. Komatsu, [arXiv:1808.09076]

- The unified action for the inflation models with an SU(2) gauge field

$$S = \alpha_H \underbrace{S_H(A_\mu, H)}_{} + \alpha_s \underbrace{S_s(\chi)}_{} + S_A(A_\mu, \varphi)$$

Higgs sector (mass for gauge field)

Scalar inflaton (spectator SU(2))

S_A is either S_{Gf} (Gauge-flation) or S_{Cn} (Chromo-natural with an arbitrary potential)

- Due to the SU(2) gauge field with a non-zero VEV, they all share these features

I. The FRW friendly VEV solution $A^a_\mu(t) = \begin{cases} 0 & \mu = 0 \\ a(t)\psi(t)\delta^a_i & \mu = i \end{cases}$

II. New Spin-2 field $\delta A^a_i(t, \vec{x}) = B_{ij}\,\delta^a_i$ + scalar & vector fields

SU(2) Gauge fields and Inflation

- It starts in 2011 $A_\mu = A^a_\mu T_a$ $[T_b , T_c] = i \epsilon_{abc} T_a$

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ii) Breaking conformal symmetry & respecting the gauge symmetry

Background

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Perturbation

iii) Extra spin-2 degrees of freedom:

$$\delta A^a_i(t,\vec{x}) = \underbrace{\delta S^a_i}_{\text{Scalar and vector d.o.f}} + \overbrace{B_{ij}}^{\text{Spin-2 field}}\,\delta^a_i$$

iv) Spin-2 field breaks Parity & coupled linearly with gravity waves

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→ Chiral primordial Gravitational waves

Spin-2 Particle Production & Chiral Gravity waves

- Spin-2 field $\delta A_i^a(t,\vec{x}) = B_{ij}(t,\vec{x})\delta_i^a$ is governed by (δ_C and $\frac{m^2}{H^2}$ are two positive, order 10, given by BG fields)

$$B_\pm'' + \underbrace{[k^2 \mp \delta_C k\mathcal{H} + \frac{m^2}{H^2}\mathcal{H}^2 - \frac{a''}{a}]}_{\omega_\sigma^2(\tau,k)\ \text{effective frequency}} B_\pm \approx 0$$

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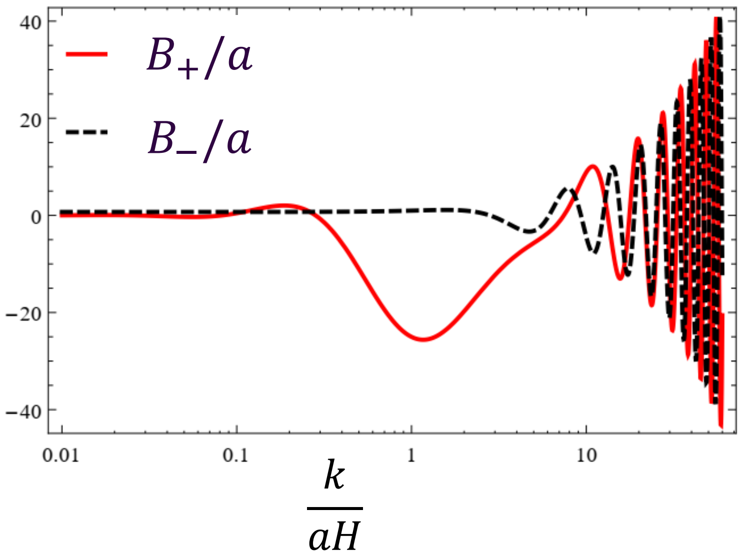
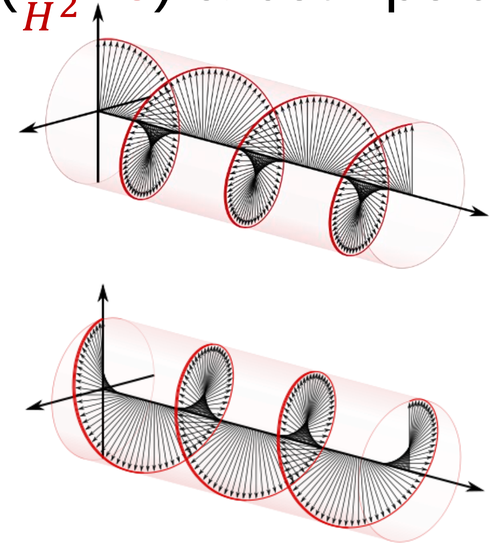
- Polarization B_+ has a short time of particle production before horizon crossing.
- Polarization B_- is (almost) always very close to its vacuum state, negligible pair production.
- The $B_\pm$ fields are massive ($\frac{m^2}{H^2}$>8) & both polarizations decay after horizon crossing.





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- due to the derivative interaction, $\omega_\sigma^2(\tau,k)$ is
- 1) chiral
- 2) violates adiabaticity condictiones for

a short period before horizon exit.

$$\left(\frac{\partial_\tau\, \omega_+(\tau,k)}{\omega_+^2(\tau,k)}\right)^2 \ll 1 \text{ and } \frac{\partial_\tau^2\omega_+(\tau,k)}{\omega_+^3(\tau,k)} \ll 1$$

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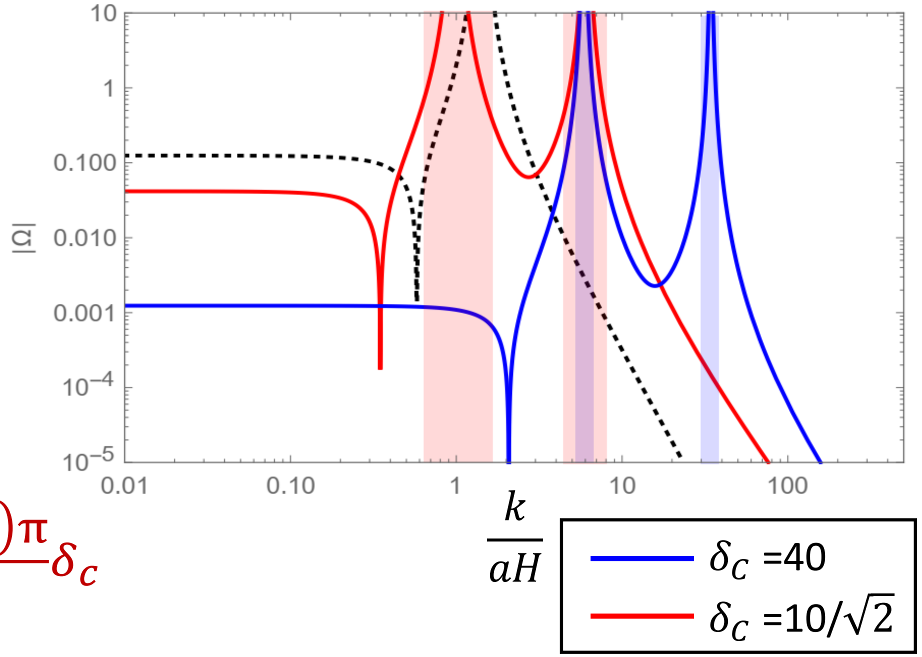
Deviation from adiabaticity



Chiral particle production $n_B \sim \frac{H^3}{6\pi^2}\delta_c^3\, e^{\frac{(2-\sqrt{2})\pi}{2}\delta_c}$

A. M. and E. Komatsu, [arXiv:1808.09076]

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- That sourced the Gravity waves $\delta g_{ij}(t,\vec{x}) = a\, h_{ij}\,(t,\vec{x})$ as $(h_{ij} \equiv a\,\gamma_{ij})$

$$h''_\pm + [k^2 - \frac{a''}{a}]\, h_\pm \approx \underbrace{\frac{2\psi}{M_{Pl}}\mathcal{H}^2\, \Pi_\pm[B_\pm]}$$

Anisotropic stress
Linear in $B_\pm$

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The efficiency of the coupling of $B_\pm$ to GWs is proportional to the VEV of the SU(2) gauge field.

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- Gravitational waves have two uncorrelated terms

$$h_\pm = \underbrace{h_\pm^{vac}}$$

Vacuum
GWs
unpolarized
$h_+^{vac} = h_-^{vac}$

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Sourced by $B_\pm$ Polarized $h_+^s \neq h_-^s$

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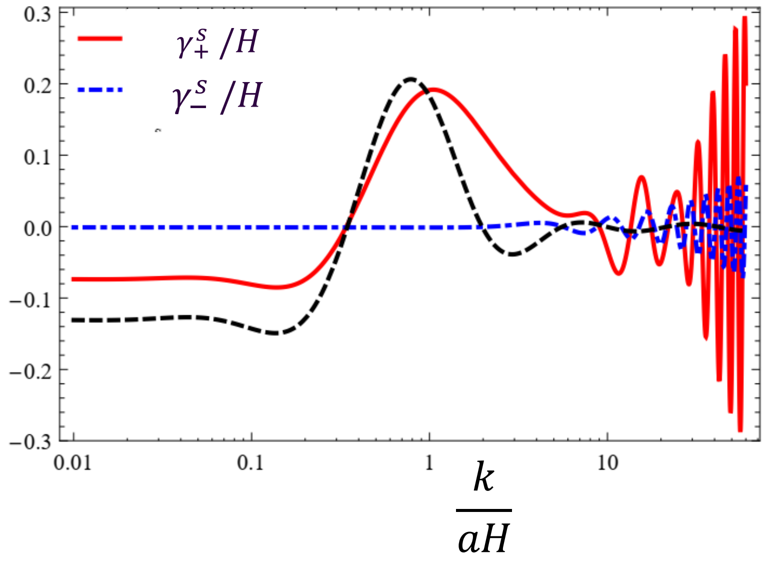

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- Gravitational waves have two uncorrelated terms

$$h_{\pm} = h_{\pm}^{vac} + h_{\pm}^{s}$$

The ratio of the power spectra of sourced to vacuum gravitational waves is

$$\frac{P_T^s}{P_T^{vac}} = \frac{\langle\gamma_+^s\gamma_+^s\rangle}{\langle\gamma_+^{vac}\gamma_+^{vac}\rangle}\Big|_{-k\tau\ll 1} \simeq \left(\frac{\psi}{M_{Pl}}\right)^2 \left(\frac{n_B}{H^3}\right) \frac{3\pi^3|\mathcal{A}_+|^2|\kappa|}{(|\kappa| + \sqrt{|\kappa|^2 - |\mu|^2})^3}$$

A. M. and E. Komatsu, [arXiv:1808.09076]

Spin-2 Particle Production & Chiral Gravity waves

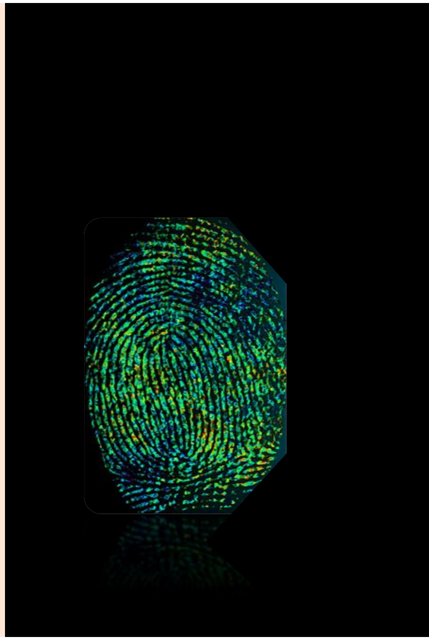
In the presence of the primordial SU(2) gauge fields

i) The tensor power spectrum is not entirely specified by the scale of inflation!

ii) Sizable tensor to scalar ratio without large field = violation of Lyth bound!

iii) The tensor power spectrum is partially chiral and parity odd correlations

$\langle TB \rangle$ and $\langle EB \rangle$ are non-zero!



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Schwinger Particle Production

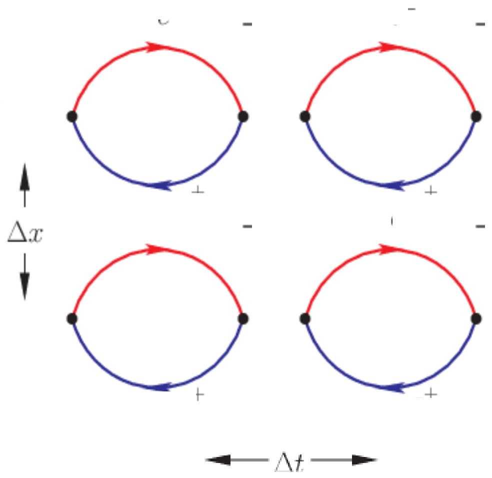
- Charged scalar fields coupled to the

SU(2) gauge field BG

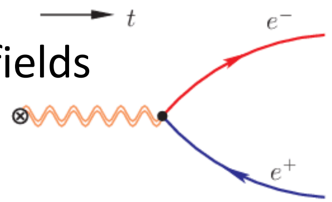
$$S_{\text{matter}} = \int d^4x\sqrt{-g}\left[(\mathbf{D}_\mu\varphi)^\dagger\,\mathbf{D}^\mu\varphi - m^2\varphi^\dagger\varphi\right]$$

$$\mathbf{D}_\mu\varphi = \left(\mathbf{I}_{2\times2}\nabla_\mu + ig_A\mathbf{A}_\mu\right)\varphi$$

Virtual particles



BG fields



pair production

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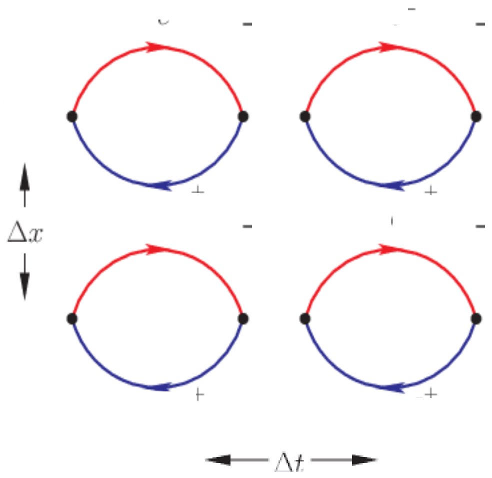
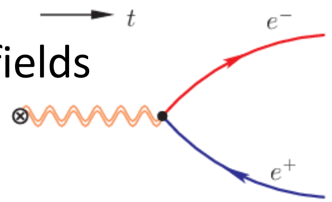
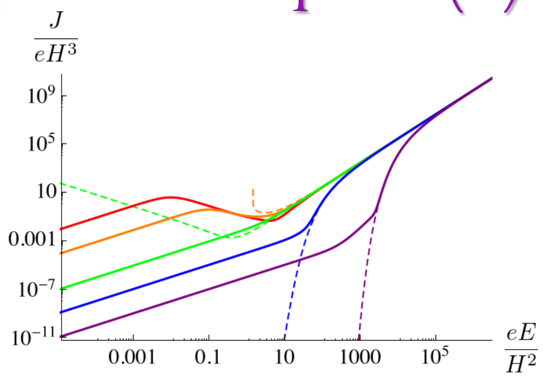


BG fields



pair production

Anisotropic U(1)



(a) current

Schwinger Particle Production

- Charged scalar fields coupled to the

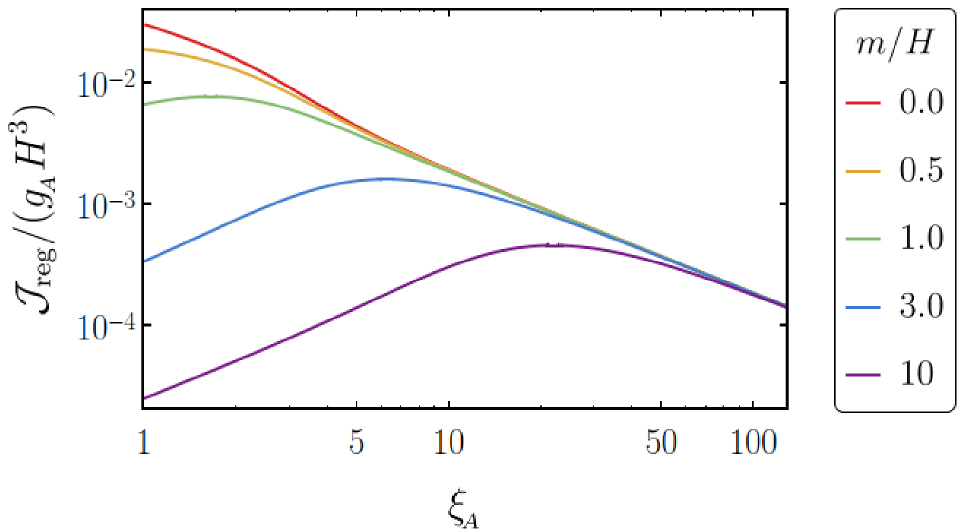
SU(2) gauge field BG

$$S_{\mathrm{matter}} = \int \mathrm{d}^4x\sqrt{-g}\left[(\mathbf{D}_\mu\boldsymbol{\varphi})^\dagger\,\mathbf{D}^\mu\boldsymbol{\varphi} - m^2\boldsymbol{\varphi}^\dagger\boldsymbol{\varphi}\right]$$

$$\mathbf{D}_\mu\boldsymbol{\varphi} = \left(\mathbf{I}_{2\times2}\nabla_\mu + ig_A\mathbf{A}_\mu\right)\boldsymbol{\varphi}$$

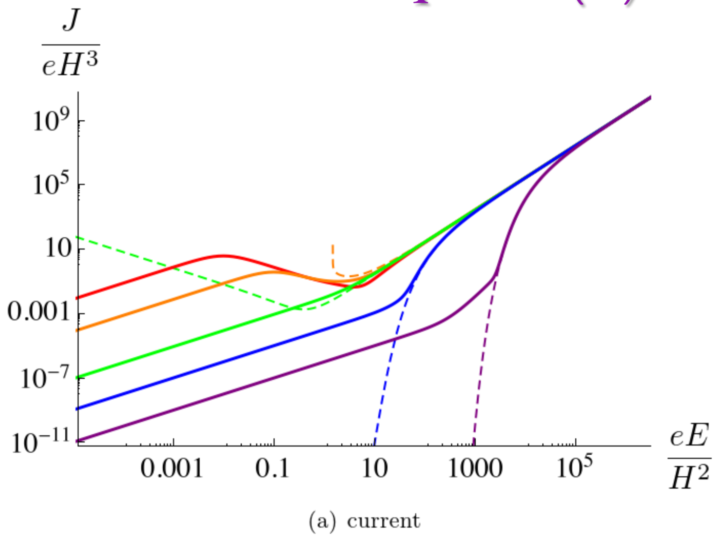
The induced current

Isotropic SU(2)



Kaloian D. Lozanov, A. M., Eiichiro Komatsu JHEP 1902 (2019) 041

Anisotropic U(1)



Takeshi Kobayashi, Niayesh Afshordi, JHEP10(2014)166

Schwinger Particle Production

- Charged scalar fields coupled to the

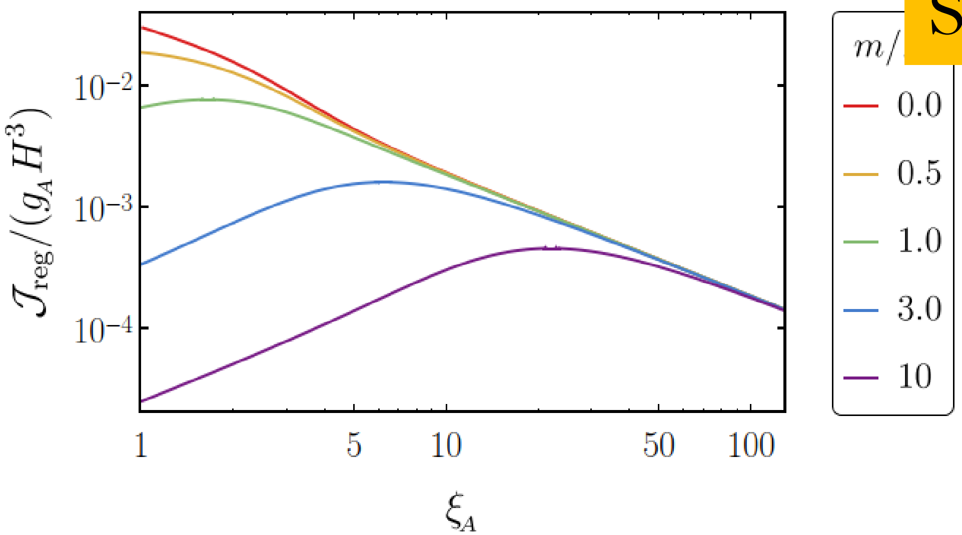
SU(2) gauge field BG

$$S_{\rm matter} = \int d^4x \sqrt{-g} \left[(\mathbf{D}_\mu \boldsymbol{\varphi})^\dagger \mathbf{D}^\mu \boldsymbol{\varphi} - m^2 \boldsymbol{\varphi}^\dagger \boldsymbol{\varphi} \right]$$

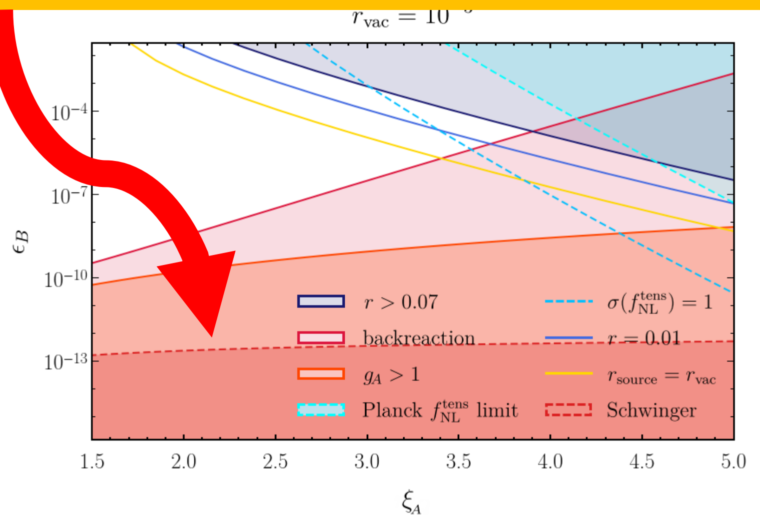
$$\mathbf{D}_\mu \boldsymbol{\varphi} = \left(\mathbf{I}_{2\times 2} \nabla_\mu + i g_A \mathbf{A}_\mu \right) \boldsymbol{\varphi}$$

The induced current

Isotropic SU(2)

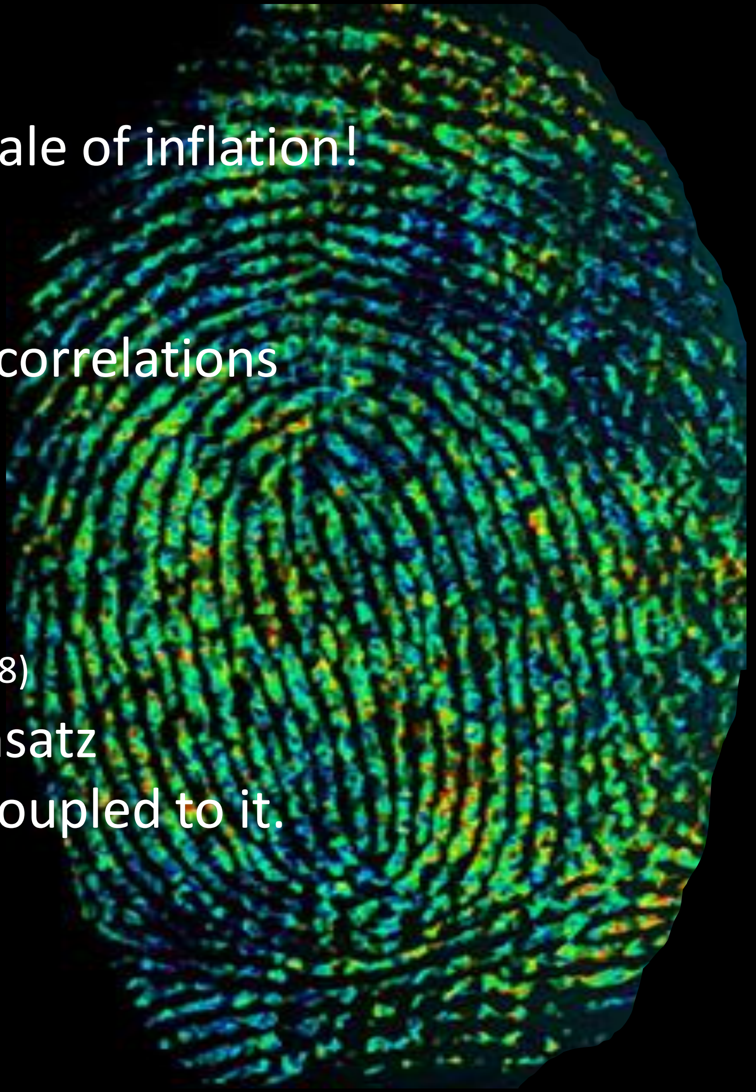


Unlike U(1) case! Negligible Schwinger effect for Iso. SU(2)



Kaloian D. Lozanov, A. M., Eiichiro Komatsu JHEP 1902 (2019)

In the presence of the primordial SU(2) gauge fields



i) The tensor power spectrum is not entirely specified by the scale of inflation!

ii) Sizable tensor to scalar ratio without large field.

iii) The tensor power spectrum is partially chiral and parity odd correlations

$\langle TB \rangle$ and $\langle EB \rangle$ are non-zero!

iv) Possible large tensor non-Gaussianity.

Aniket Agrawal, Tomohiro Fujita, Eiichiro Komatsu, JCAP 1806 (2018) & Phys.Rev. D97 (2018)

v) Unlike U(1) gauge fields, the SU(2) field in the FRW friendly ansatz does not receive any sizable backreaction from charged fields coupled to it.

vi) Naturally explains the matter asymmetry in our Universe!

A. M. Phys. Rev. D (2014) & JCAP 1612 (2016)


おしん
総集編
Thank You!