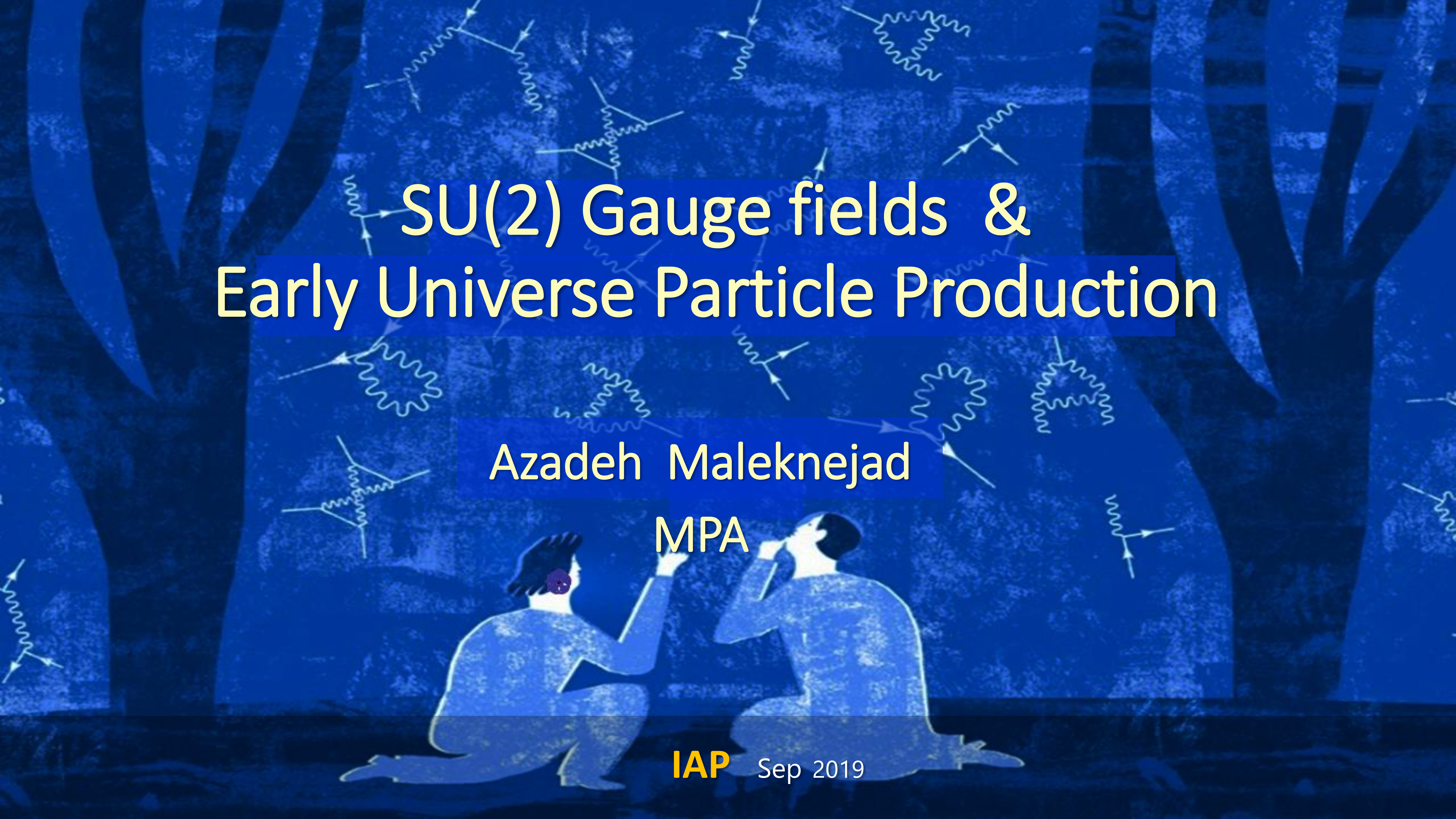


SU(2) Gauge fields &
Early Universe Particle Production

Azadeh Maleknejad
MPA

IAP Sep 2019

Gauge fields and Inflation?!

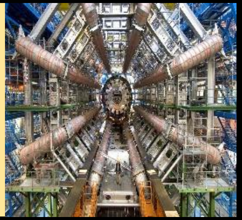
- Inflation: Universe at highest observable energy!

Energy

$E \lesssim 10^{14} GeV$

Comparing to LHC

$\frac{\boldsymbol{E}}{\boldsymbol{E_{LHC}}} \lesssim \mathbf{10^{11}}$!!!!



Gauge fields and Inflation?!

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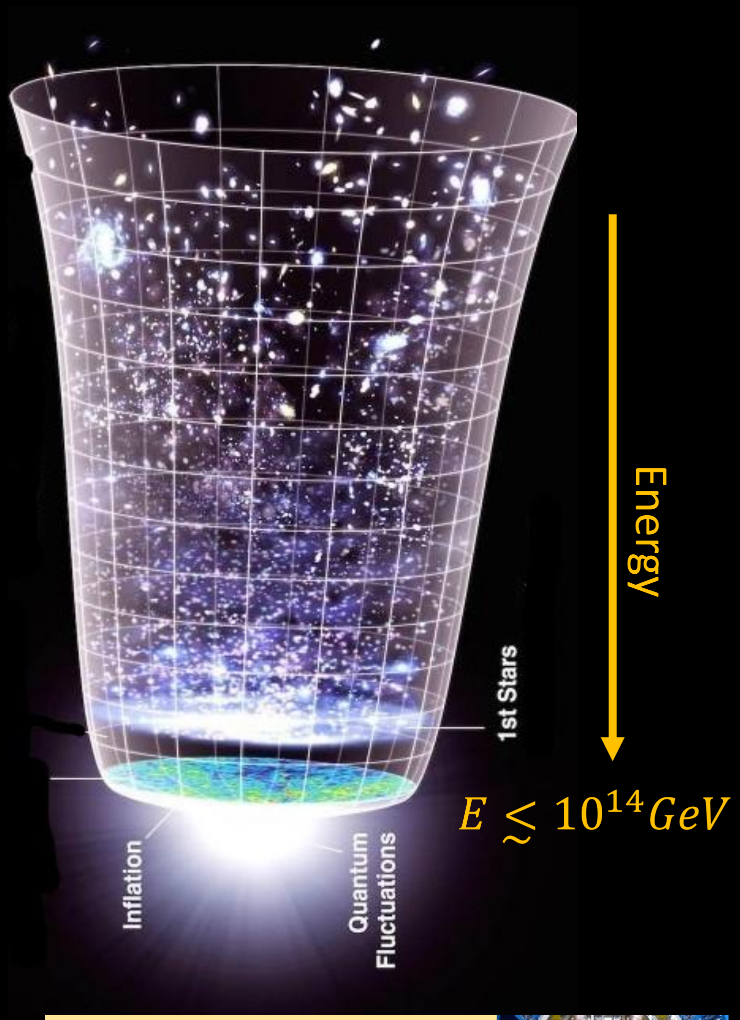
Free & powerful particle
accelerator in the Sky to catch
Physics Beyond SM

impossible for experiments on Earth
either because they are
too *heavy* or
too *weakly coupled!*



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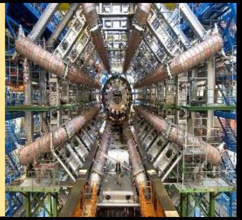
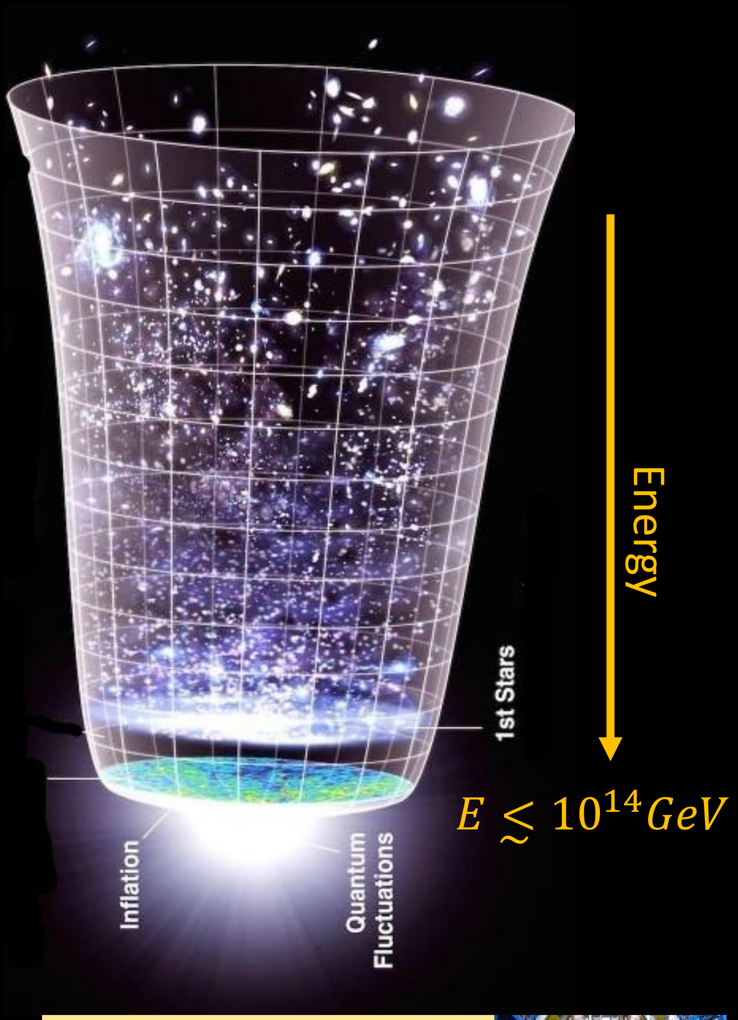


Gauge fields and Inflation?!

- Inflation: Universe at highest observable energy!

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



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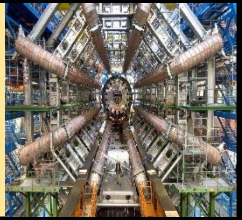

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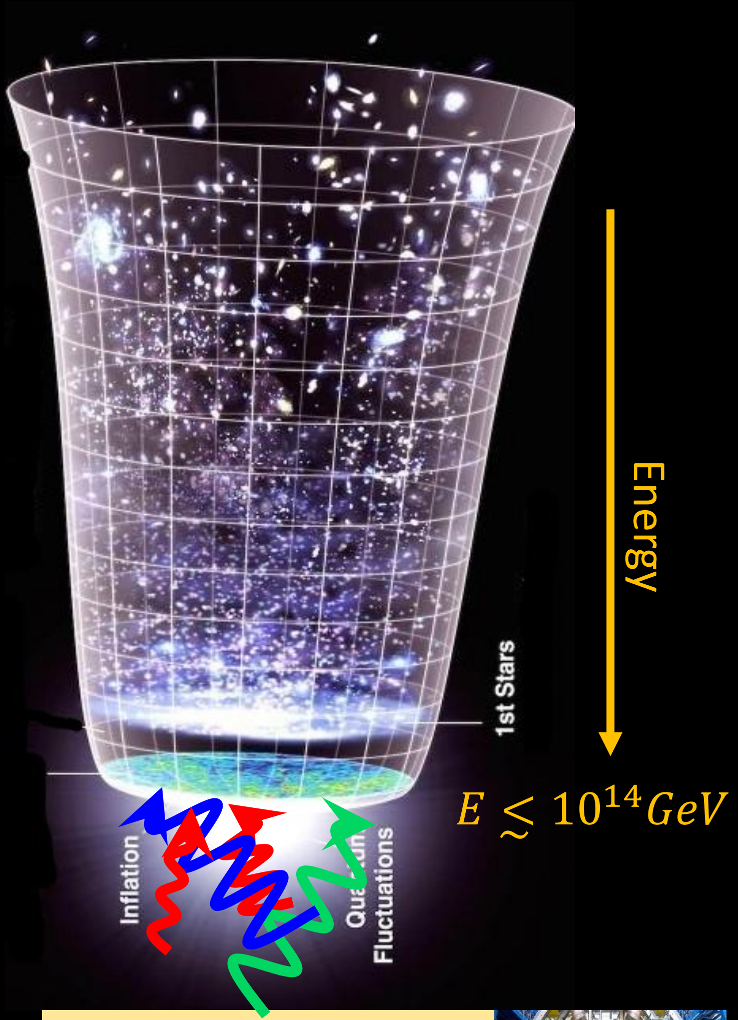

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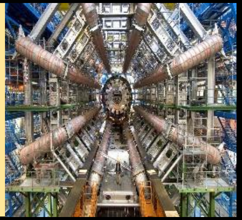

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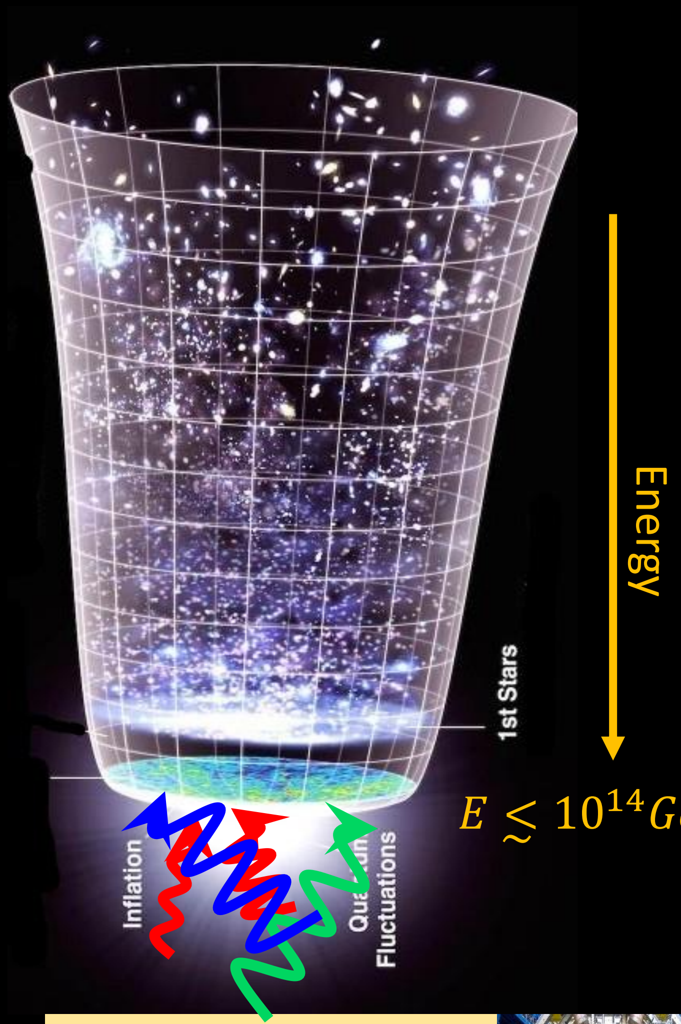
Challenges:

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



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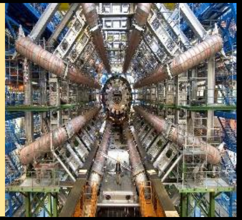

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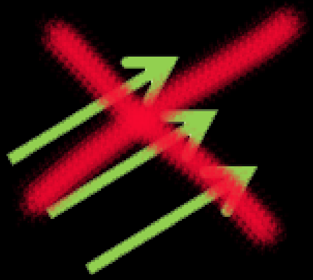

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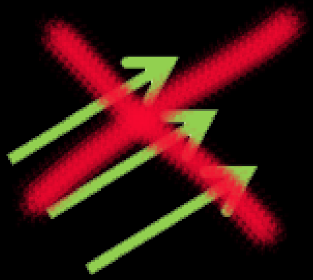

SU(2) Field Instead!

A.M. and M. M. Sheikh-Jabbari, 2011

$$A_\mu = A_\mu^a\, T_a \qquad [T_b\, , T_c\,] = \mathrm{i}\, \epsilon_{abc} T_a$$

$$A_\mu^a(t) = \begin{cases} 0 & \mu = 0 \\ \psi(t) e_i^a & \mu = i \end{cases}$$

Isomorphy of so(3) and su(2) algebras

Gauge fields & Physics of Inflation?!

- Can gauge fields contribute to the physics of inflation & be compatible with its symmetries?
  - Breaking the conformal symmetry ✓
  - Spatial isotropy and homogeneity ✓
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Yes!

A. M. and M. M. Sheikh-Jabbari, Phys. Rev. D 84 (2011) [*arXiv:1102.1932*]
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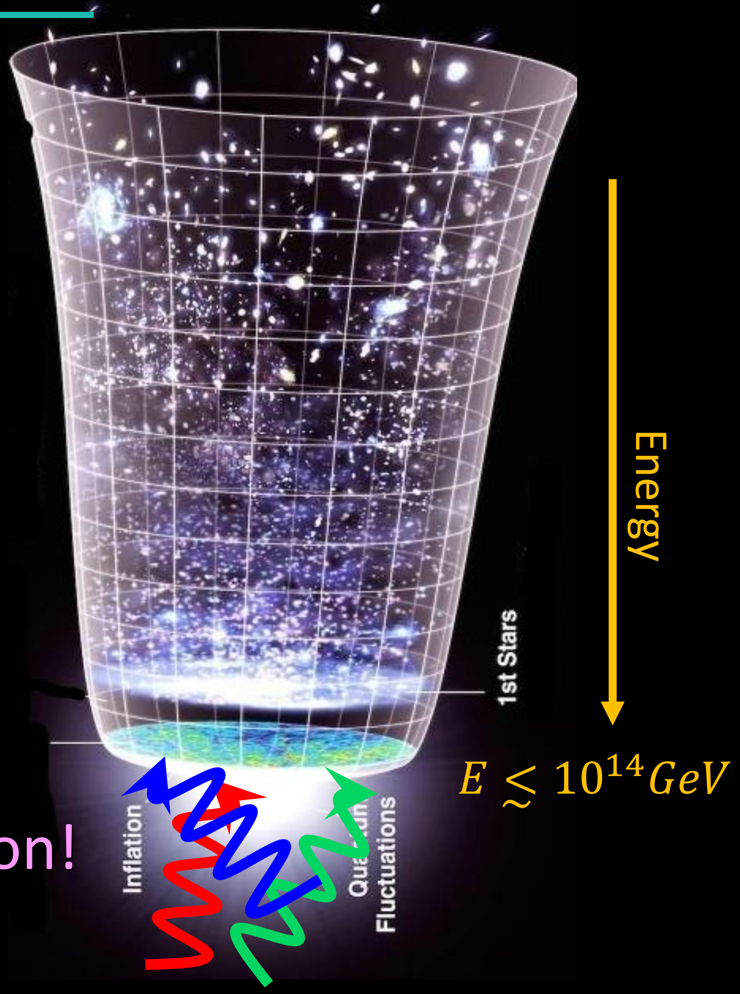

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a new class of consistent models for
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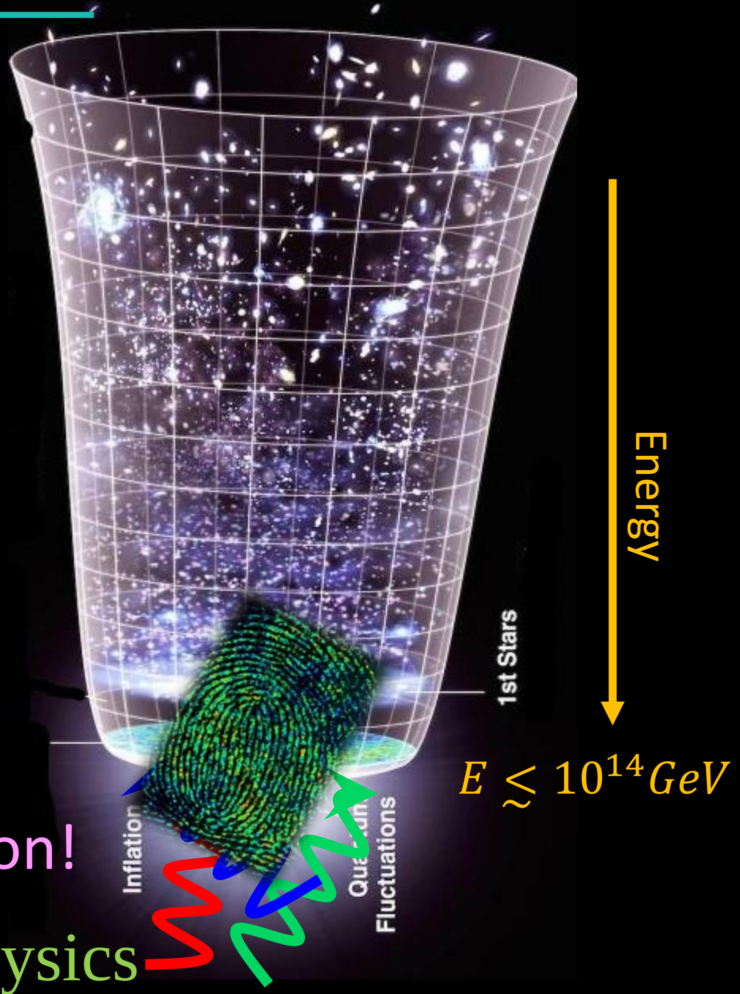

a new class of consistent models for
non-Abelian gauge fields that contribute to inflation!

It opens a new window on an unexplored direction in physics
of the early Universe and particle cosmology!

Since 2011, many aspects and different realization of non-Abelian and SU(2) gauge fields in inflation have been studied

My collaborators at MPA are Eiichiro Komatsu, Kaloian Lozanov, Leila Mirzagholi, and Ira Wolfson.

Here is an incomplete list of colleagues that contribute to the better understanding of the rich phenomenology of this setup:

M.M. Sheikh-Jabbari, P. Adshead, M. Wyman, E. Martinec, M. Peloso, J. Soda, E. Dimastrogiovanni, A. Agrawal, T. Fujita, E. Sfakianakis, C. Unal, M. Fasiello, M. Noorbala, R. Caldwell, B. Thorne, E. McDonough, D. Spergel, S. Alexander, A. Liu, M. Hazumi, N. Katayama, M. Shiraishi, J. Bielefeld, C. Devulder, N. A. Maksimova, R. Namba, I. Obata, V. Domcke, Y. Ema, K. Mukaida, Y. Watanabe, R. Sato, and ...

A new Window to Particle Cosmology

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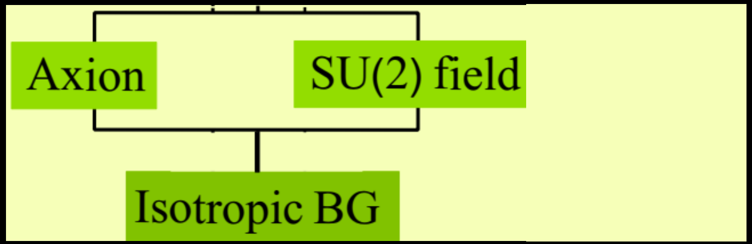
A. M. and M. M. Sheikh-Jabbari, 2011
P. Adshead, M. Wyman, 2012

SU(2)-axion models acquire an isotropic and homogenous vacuum with a slow-varying energy density during inflation.



Axion

SU(2) field

Isotropic BG

A New Window to Particle Cosmology

SU(2)-axion models acquire an isotropic and homogenous vacuum with a slow-varying energy density during inflation.

This vacuum **violates** both **P** & **CP**!

Particles with spin, e.g. Fermions & Spin-2 fields are sensitive to this **non-trivial Vacuum during inflation**!

Pre-Hot Big Bang Particle Production!
(during inflation)

A. M. and M. M. Sheikh-Jabbari, 2011
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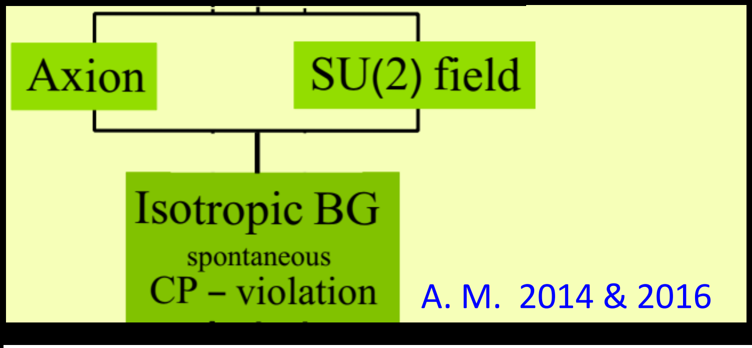
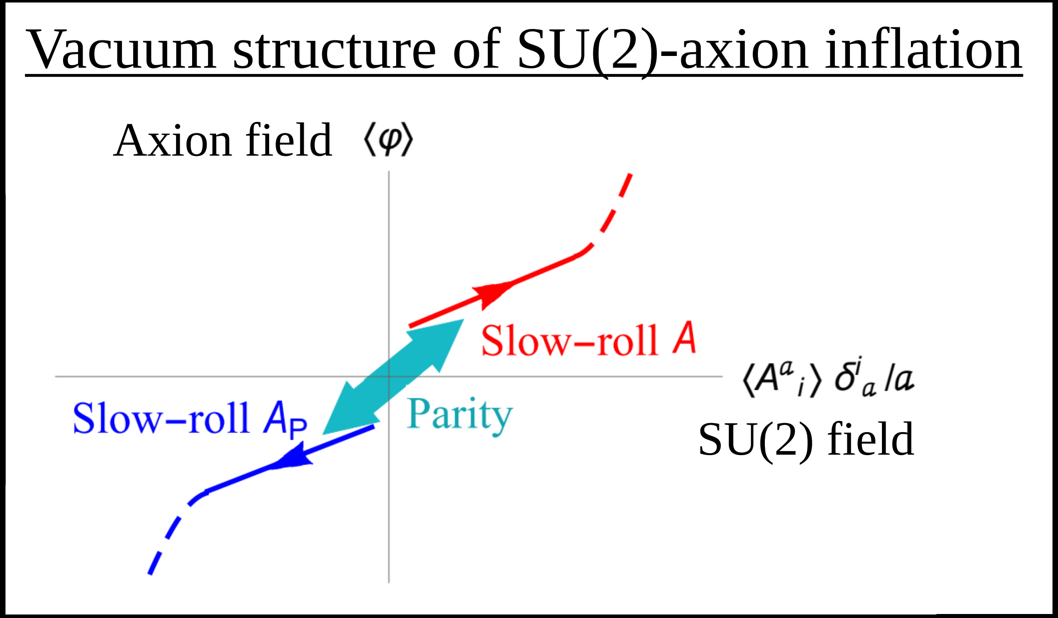


A. M. 2014 & 2016


Vacuum structure of SU(2)-axion inflation

A.M., 2019

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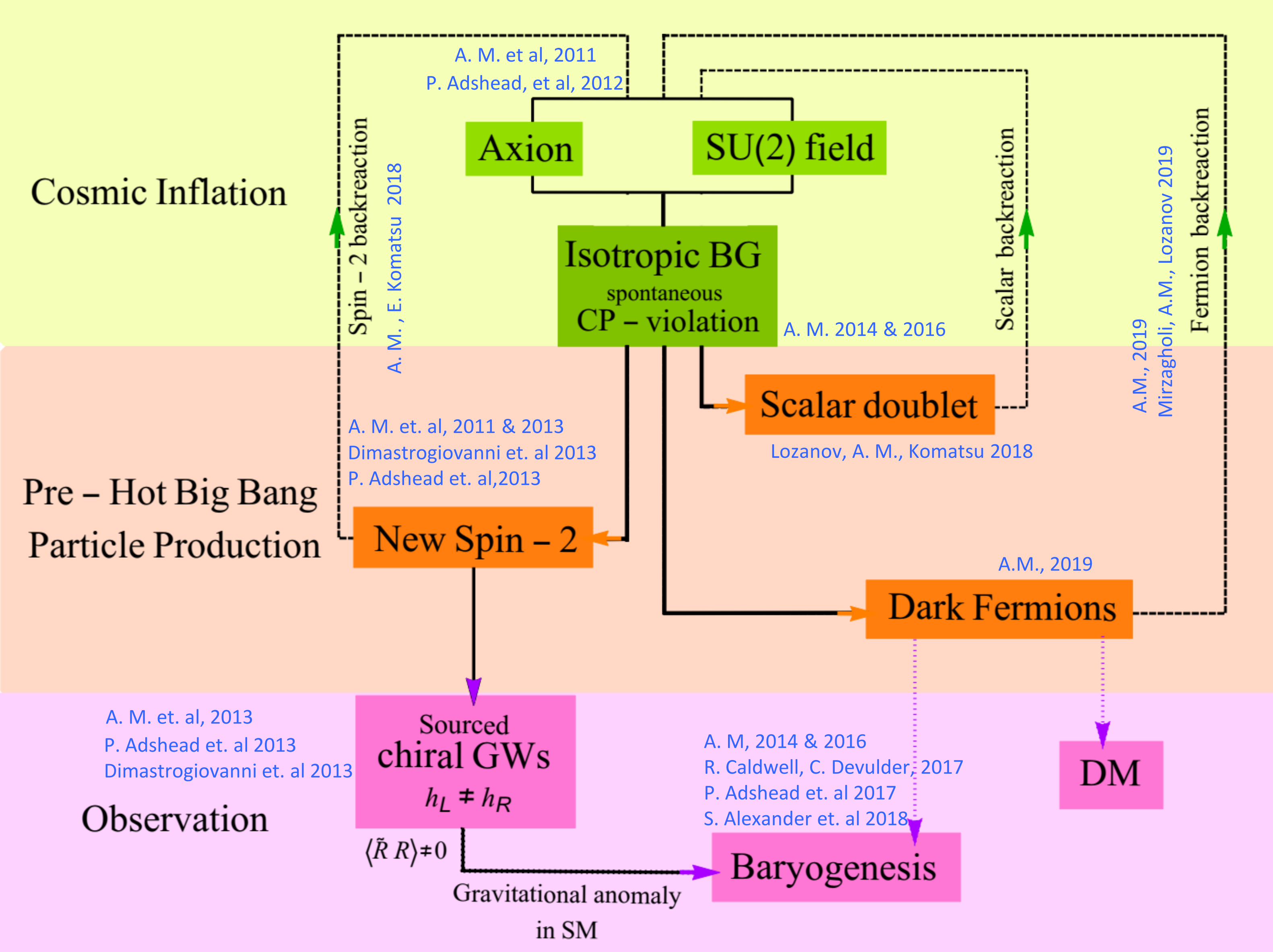

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A.M., 2019

Dark Fermions

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Sourced
chiral GWs
$h_L \neq h_R$

$\langle \tilde{R} R \rangle \neq 0$

Gravitational anomaly
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Baryogenesis

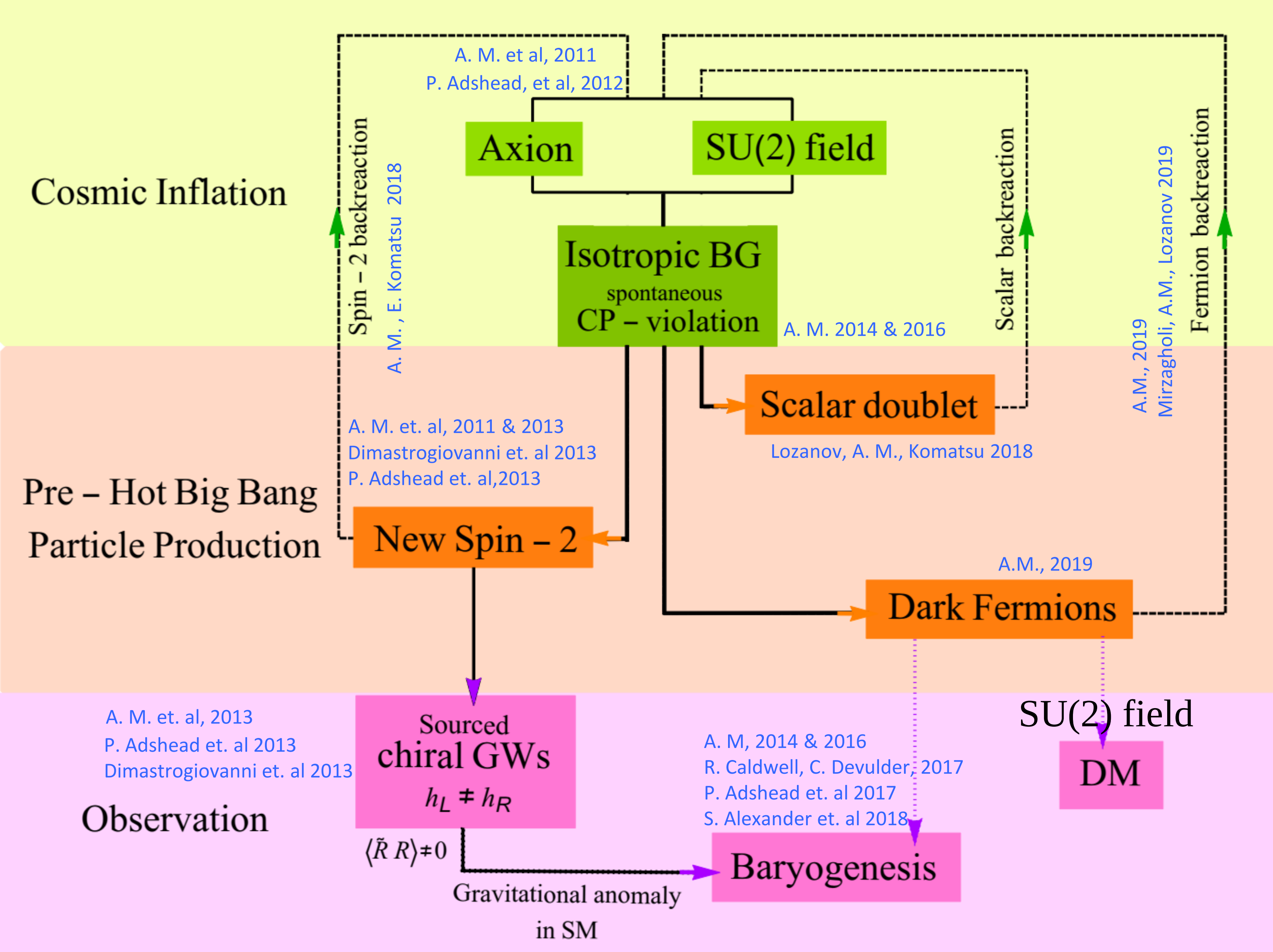
DM

A New Window to Particle Cosmology

New Spin – 2

Belongs to perturbed
SU(2) field $\delta A_i^a \ni B_{ij}\delta_i^a$

Is Chiral $B_R \neq B_L$
and linearly coupled to GWs.



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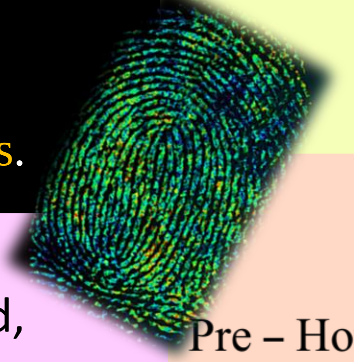

i) Violation of the Lyth bound,
ii) parity odd CMB correlations $\langle TB\rangle$ and $\langle EB\rangle$
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B. Thorn et. al 2017
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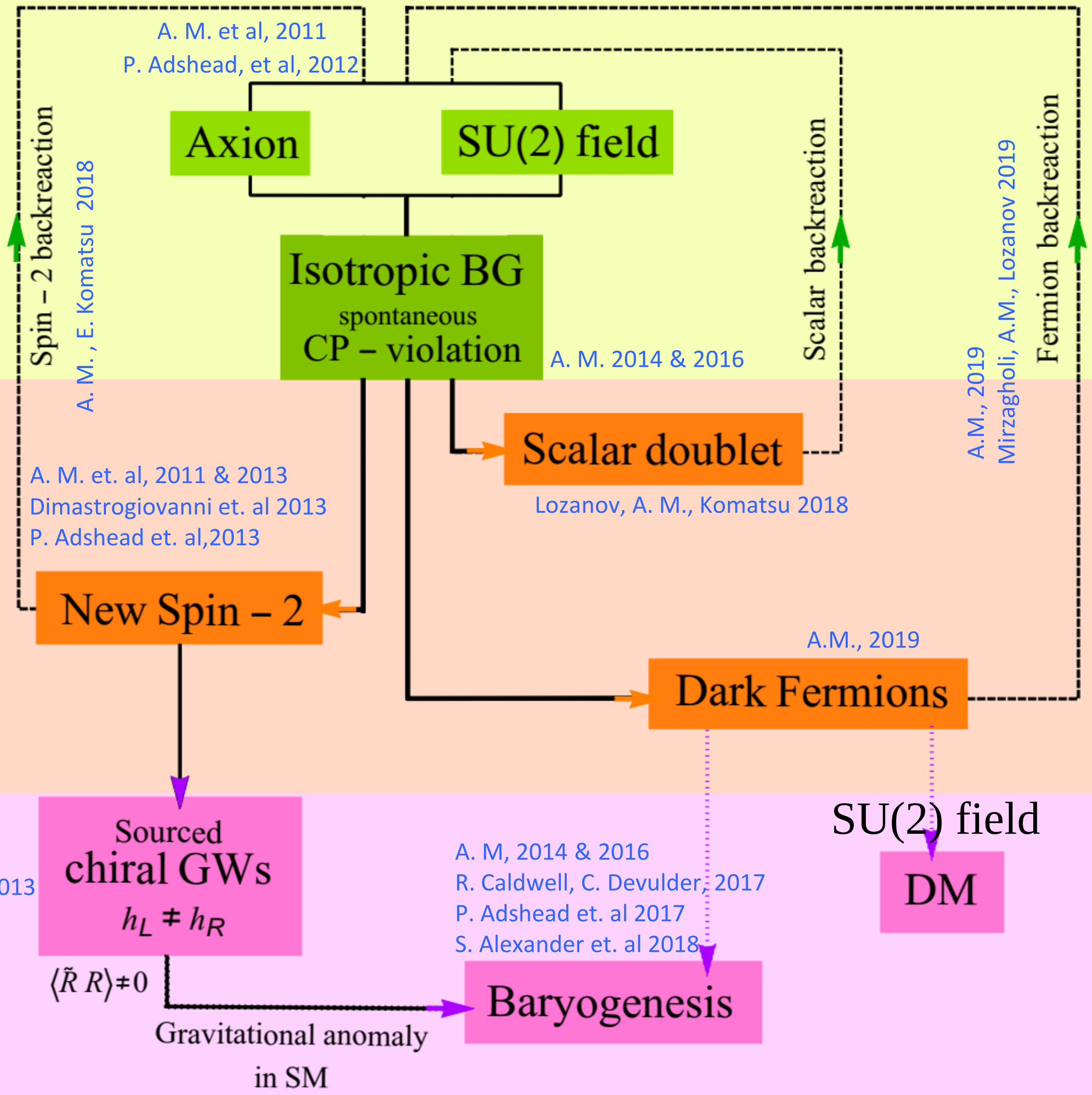

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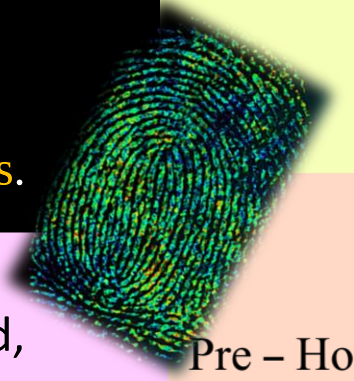

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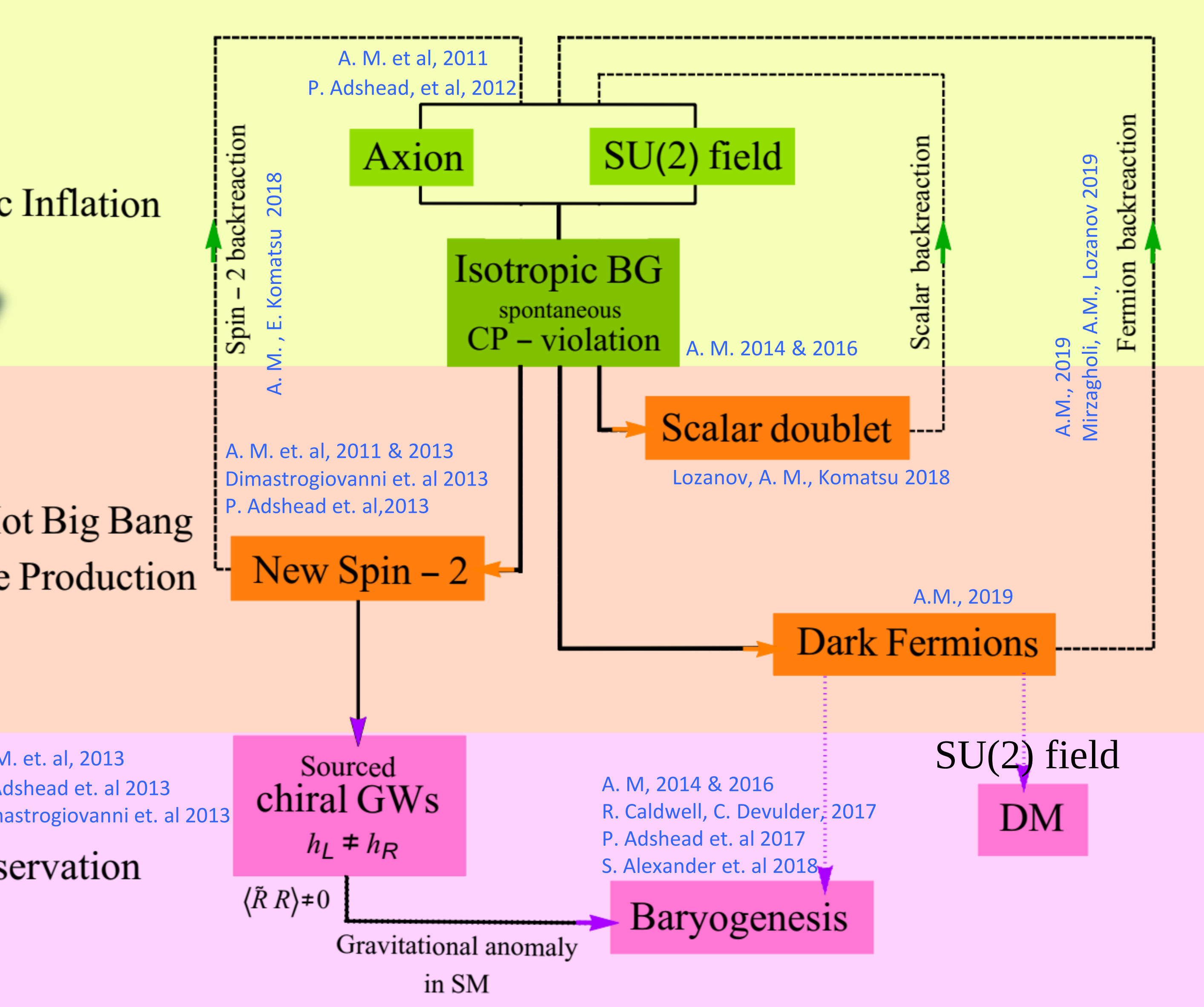
LiteBIRD would nail it!
(2020)



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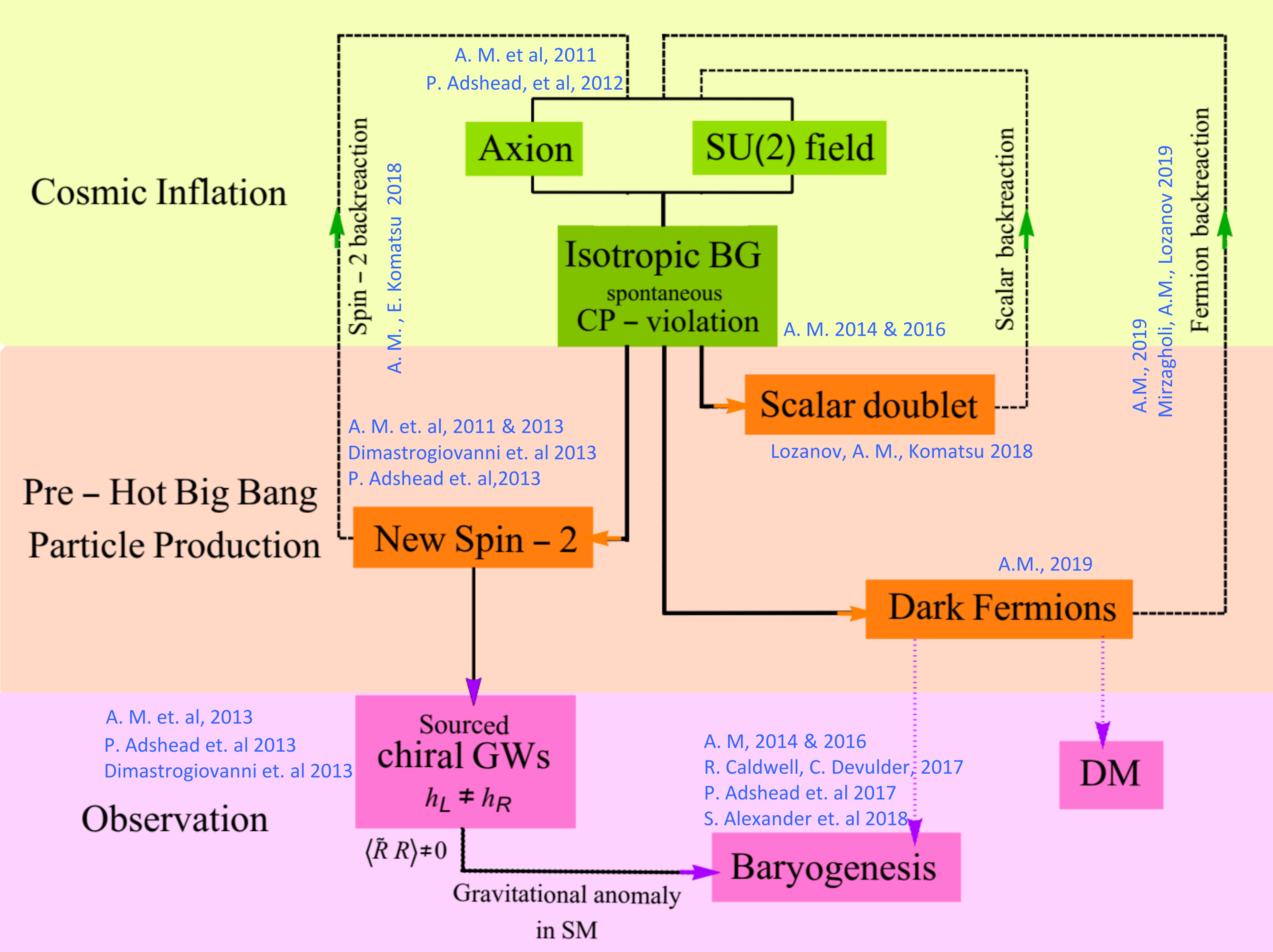

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SU(2)-axion Inflation is a Complete Setup

Among challenges of modern
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I) Particle Physics of Inflation,

II) Observed matter asymmetry, &

III) Particle nature of DM

IV) Primordial GWs the only
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SU(2)-axion inflation
Spontaneously breaks P and CP
and relates all of these seemingly unrelated Phenomena in early and late cosmology!

Part II

SU(2)-axion Model building

SU(2) Gauge fields and Inflation

- Gauge-flation

A. M. and M. M. Sheikh-Jabbari, Phys. Rev. D 84 (2011) [*arXiv:1102.1932*]
A. M. and M. M. Sheikh-Jabbari, Phys. Lett. B723 (2013) [*arXiv:1102.1513*]

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

- Chromo-natural

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

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

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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

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

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

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

A. M. and E. Komatsu, JHEP 05 (2019) 174

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

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

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

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

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

Background

i) SU(2) gauge fields are FRW friendly: (respect isotropy & homogeneity)

$$A^a_\mu(t) = \begin{cases} 0 & \mu = 0 \\ \psi(t) a(t) \delta^a_i & \mu = i \end{cases}$$

$e^a_i = a(t)\delta^a_i$

spatial part of tetrads

ii) Breaking conformal symmetry & respecting the gauge symmetry

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 is chiral & coupled linearly with gravity waves

→ Chiral primordial Gravitational waves

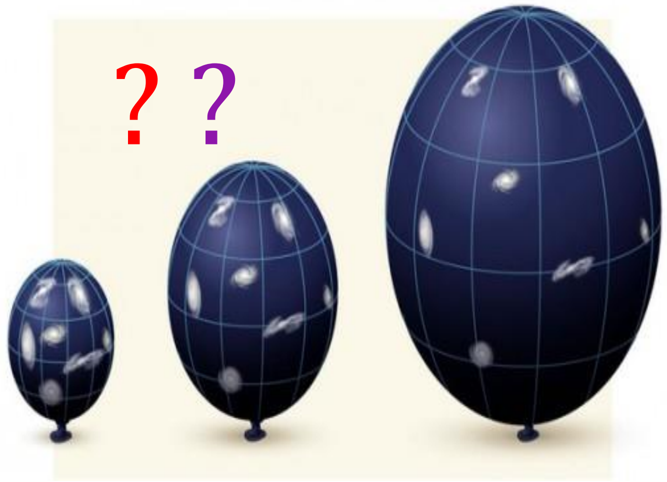
SU(2) Gauge fields and Stochastical Anisotropies

SU(2) gauge fields are FRW friendly: (respect isotropy & homogeneity)

$$A^a_\mu(t) = \begin{cases} 0 & \mu = 0 \\ a(t)\psi(t)\delta^a_i & \mu = i \end{cases}$$

Isotropic
Background

How stable is the isotropic ansatz against initial stochastical anisotropies, i.e. Bianchi geometry?



Anisotropic
Background??

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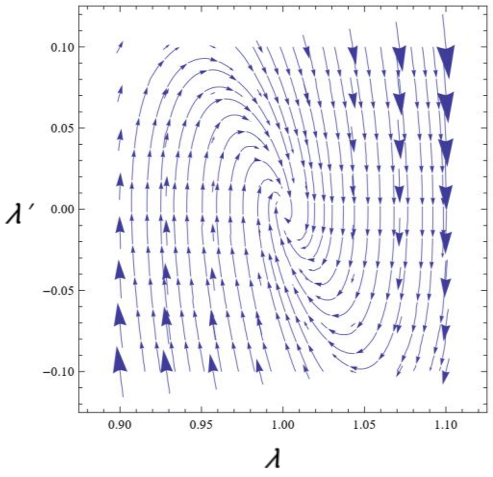
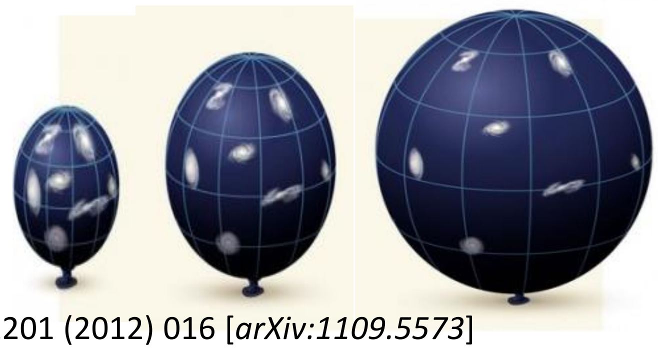


$\lambda(t)$ Parametrizes the amount of anisotropy in the gauge field

Isotropic solution is the attractor!

$$(2+\lambda^6)(\frac{\lambda''}{\lambda}+3\frac{\lambda'}{\lambda})-6\frac{\lambda'^2}{\lambda^2}+(\lambda^6-1)(2+\lambda^2\gamma)\simeq 0\,;$$



An pic
Bac nd??

A. M. and M.M. Sheikh-Jabbari, J. Soda, JCAP 1201 (2012) 016 [*arXiv:1109.5573*]
A. M. and E. Erfani, JCAP03 (2014) 016 [*arXiv:1311.3361*]

SU(2) Gauge fields and Stochastical Anisotropies

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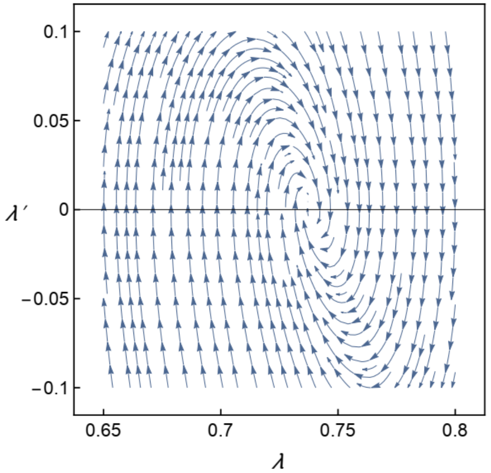
$$A^a_\mu(t) = \begin{cases} 0 & \mu = 0 \\ a(t)\psi(t)\delta^a_i & \mu = i \end{cases}$$

Isotropic Background

How stable is the isotropic ansatz against initial stochastical anisotropies, i.e. Bianchi geometry?



$\lambda(t)$ Parametrizes the amount of anisotropy in the gauge field

The only exception is with massive SU(2) models when different colors of the SU(2) field has different masses!

$$(2+\lambda^6)(\lambda\lambda''+3\lambda\lambda') - 6\lambda'^2 + \lambda^2(\lambda^6-1)(2+\lambda^2\gamma) - \lambda^2(M_1^2 - M_2^2\lambda^6) \simeq 0$$

Peter Adshead, Aike Liu, JCAP 07 (2018)

Anisotropic Background??

Part III

Pre-Hot Big Bang Particle Production

Spin-2 fields production

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, given by BG)

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

Spin-2 Particle Production & Chiral Gravity waves

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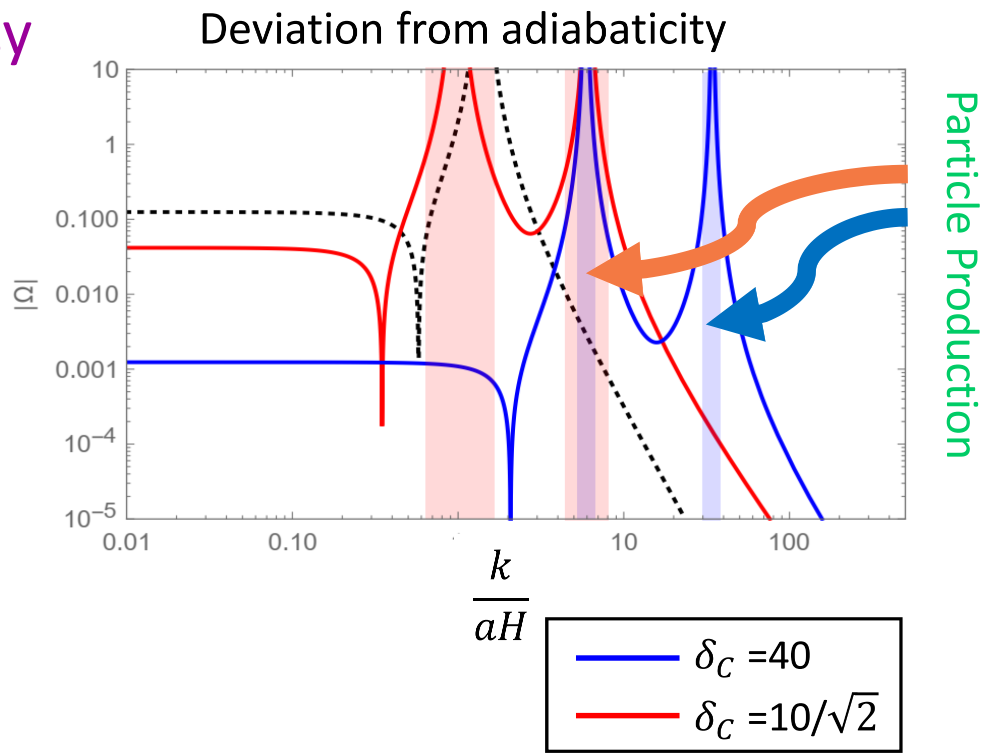
- due to the derivative interaction, $\omega_\sigma^2(\tau,k)$ is
- 1) chiral
- 2) violates adiabaticity conditions

for a short period before horizon exit



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, given by BG)

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

$\omega_\sigma^2(\tau,k)$ effective frequency

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

for a short period before horizon exit

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, 2018

Deviation from adiabaticity

- 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, given by BG)

- due to the derivative interaction, $\omega_\sigma^2(\tau,k)$ is
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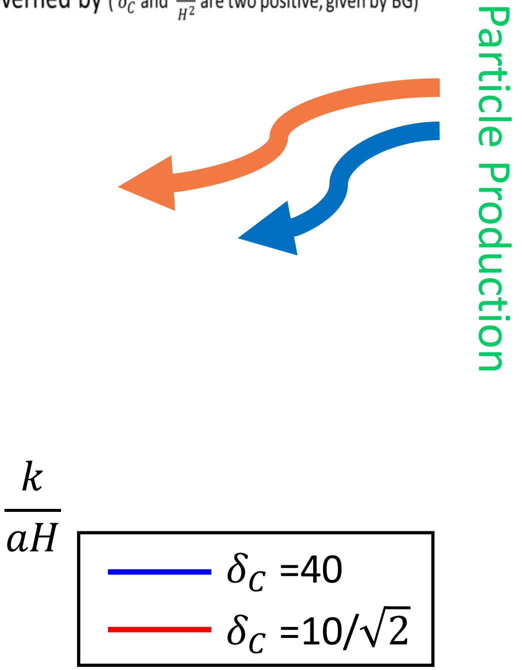
Particle Production

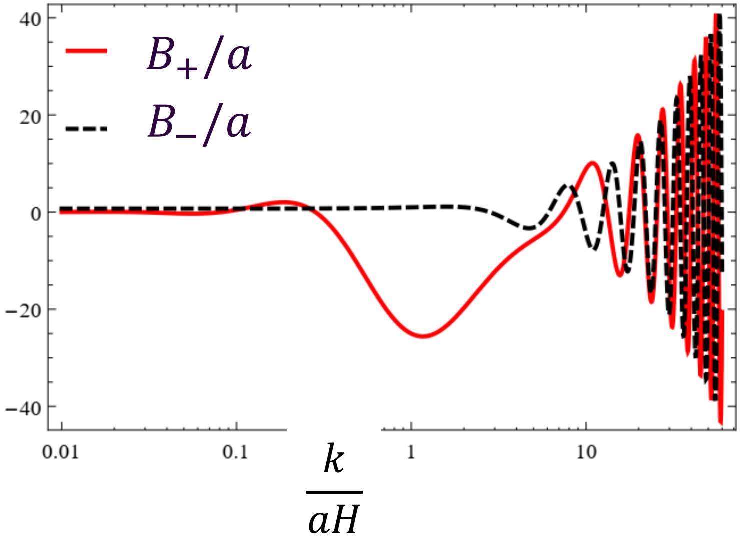


Spin-2 Particle Production & Chiral Gravity waves

- 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, given by BG)

$$B''_{\pm} + [k^2 \mp \delta_C k\mathcal{H} + \frac{m^2}{H^2}\mathcal{H}^2 - \frac{a''}{a}]\, B_{\pm} \approx 0$$

- 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) & decay after horizon crossing.



A. M. and E. Komatsu, 2018

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

Backreaction of the spin-2 field can be very important:

$$BR \approx g_A n_B \sim \delta_c^3\, e^{\frac{(2-\sqrt{2})\pi}{2}\delta_c}$$

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

$$B''_\pm + [k^2 \mp \delta_C k\mathcal{H} + \frac{m^2}{H^2}\mathcal{H}^2 - \frac{a''}{a}]\, B_\pm \approx 0$$

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

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

- Gravitational waves have two uncorrelated terms

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

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

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

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

$$B_\pm'' + [k^2 \mp \delta_C k\mathcal{H} + \frac{m^2}{H^2}\mathcal{H}^2 - \frac{a''}{a}]\, B_\pm \approx 0$$

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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 <u>sourced</u> to <u>vacuum</u> gravitational waves is

$$\frac{P_T^s}{P_T^{vac}} \approx (\frac{\psi}{M_{Pl}})^2 \times (\frac{n_B}{H^3})$$

A. M. and E. Komatsu, 2018

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

Spin-2 Particle Production & Chiral Gravity waves

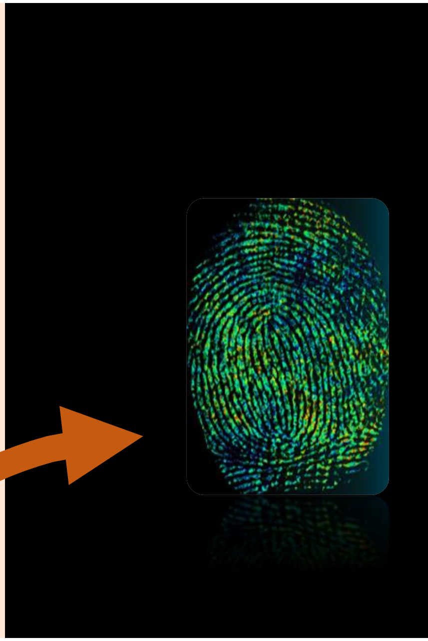
In the presence of the primordial SU(2) gauge fields

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!



- Gravitational waves have two uncorrelated terms

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A. M. and E. Komatsu, 2018

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

Spin-2 backreaction puts constraints on ratio of the power spectra of sourced to vacuum gravitational waves $\frac{P_T^S}{P_T^{vac}} \sim O(1)$

A. M. and E. Komatsu, 2018

$$\frac{P_T^S}{P_T^{vac}} \approx \left(\frac{\psi}{M_{Pl}}\right)^2 \times \left(\frac{n_B}{H^3}\right)$$

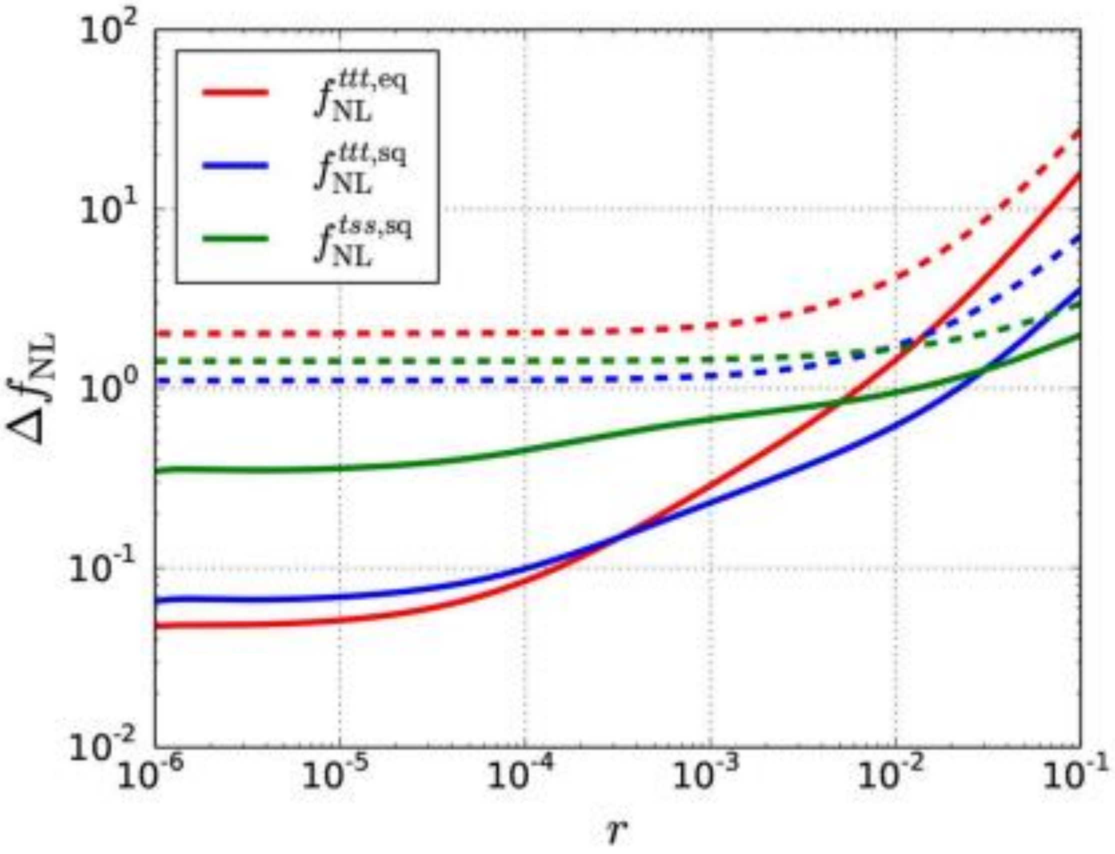
$$n_B \sim \frac{H^3}{6\pi^2}\delta_c^3\, e^{\frac{(2-\sqrt{2})\pi}{2}\delta_c}$$

Observation!

The sourced tensor modes is
Highly non-Gaussian.

Agrawal, Fujita, Komatsu 2018

That can be probe with future CMB missions., e.g. *Litebird*!

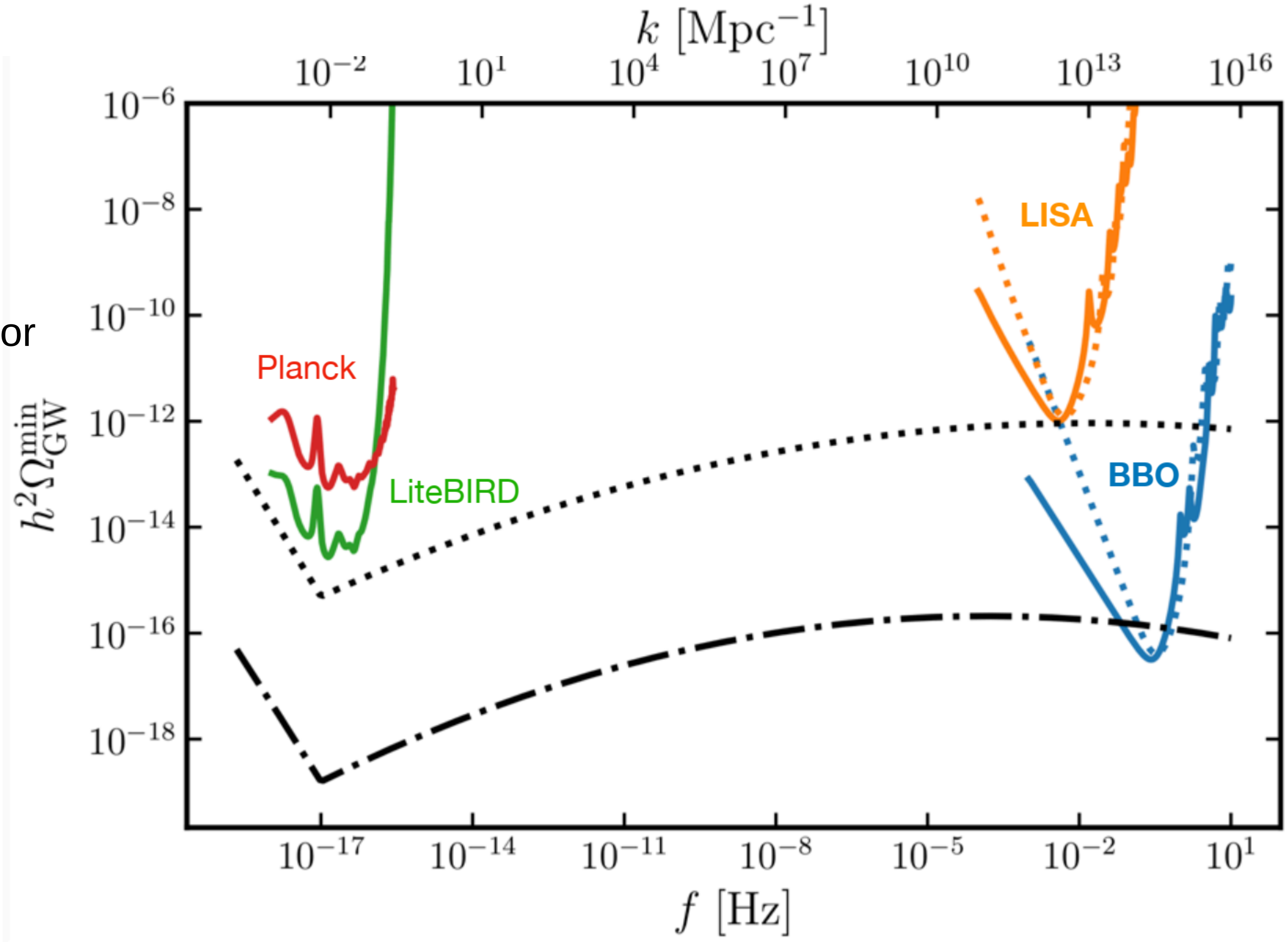


Maresuke Shiraishi, Front. Astron. Space Sci. 2019

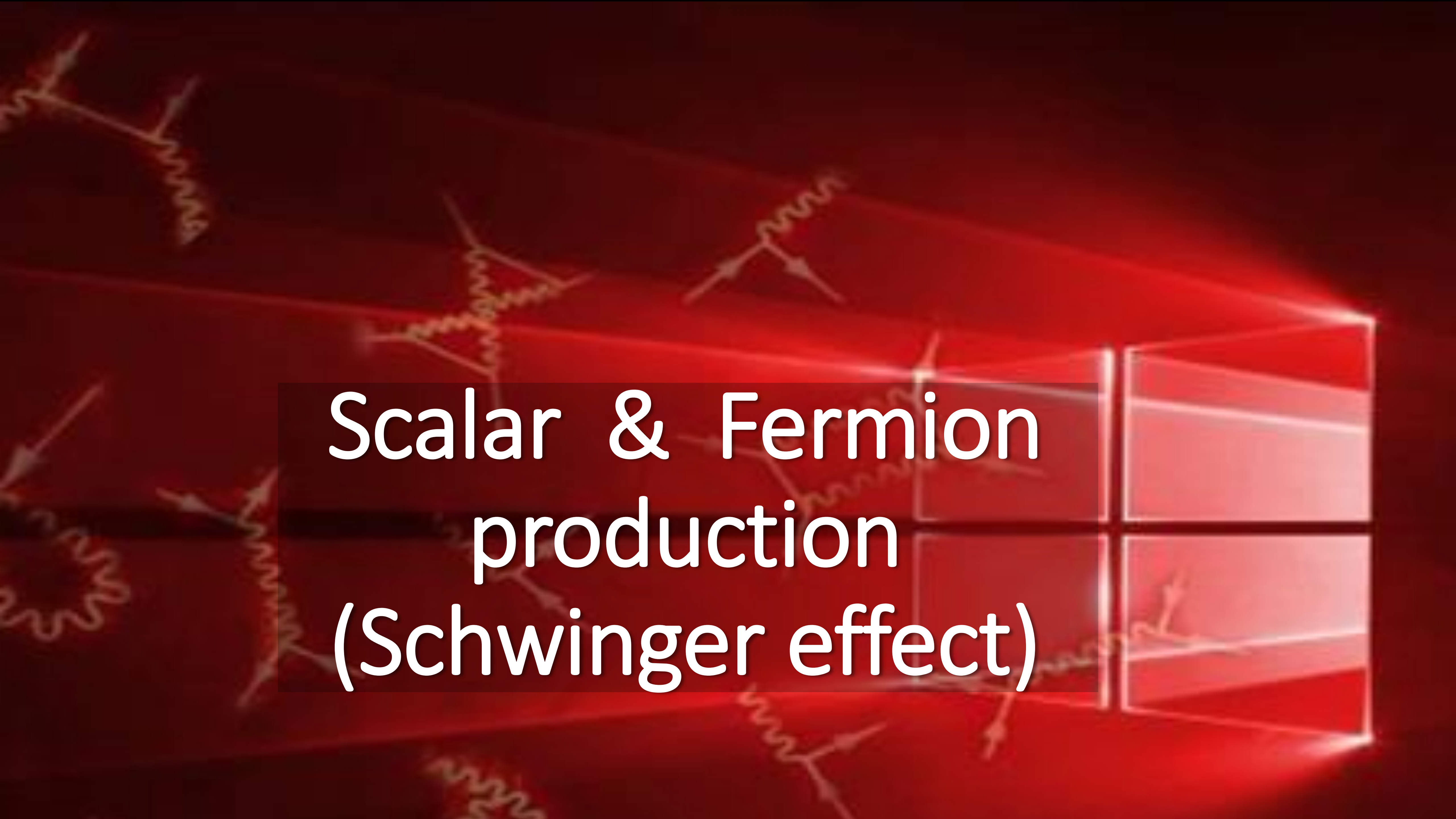
Observation!

More than just CMB!

Comparison of the sensitivity curves for LiteBIRD, Planck, LISA, and .



Thorne, Fujita, Hazumi, Katayama, Komatsu & Shiraishi, 2018



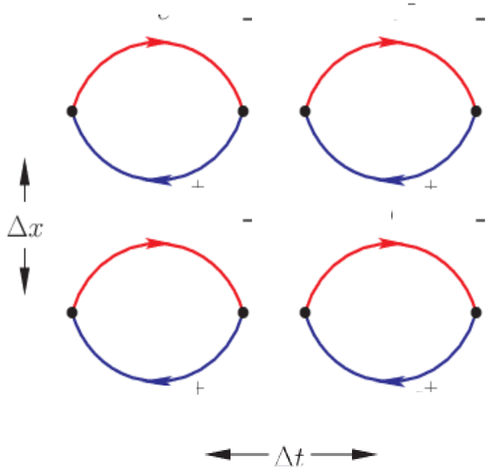
Scalar & Fermion production (Schwinger effect)

Particle Production

Vacuum is much more than just nothingness!

It is a vast ocean of virtual particles which are creating and annihilating very quickly.

Virtual particles



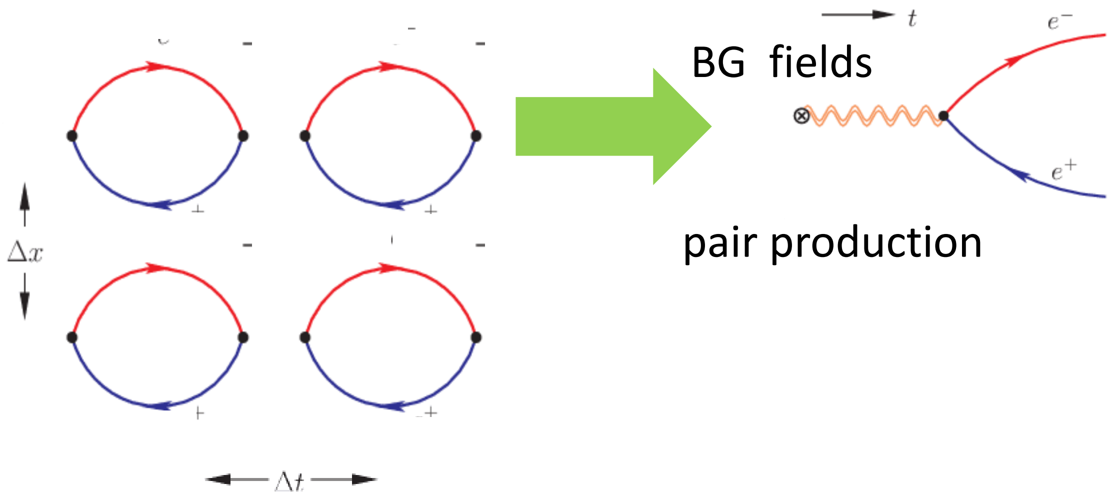
Particle Production

Vacuum is much more than just nothingness!

It is a vast ocean of virtual particles which are creating and annihilating very quickly.

In the presence of background fields, i.e. Electric, or Gravitational background fields this virtual particles can be physical!

Virtual particles



BG fields

pair production

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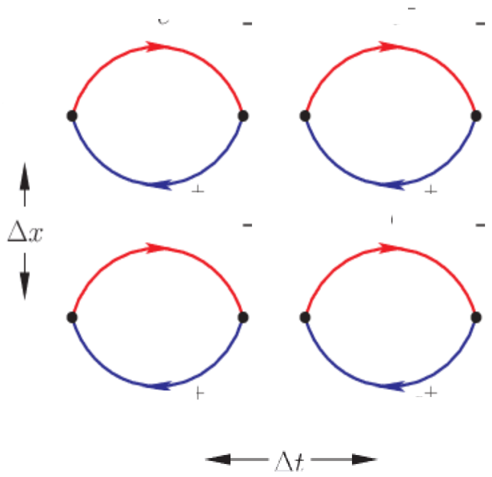

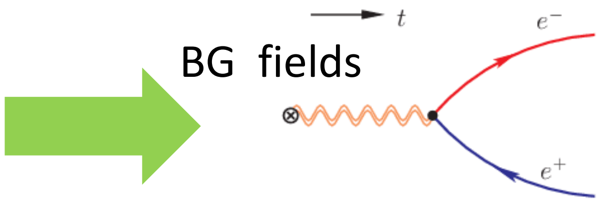

BG fields

pair production

Two source of Particle Production:

I) Expanding universe

II) Background Gauge field

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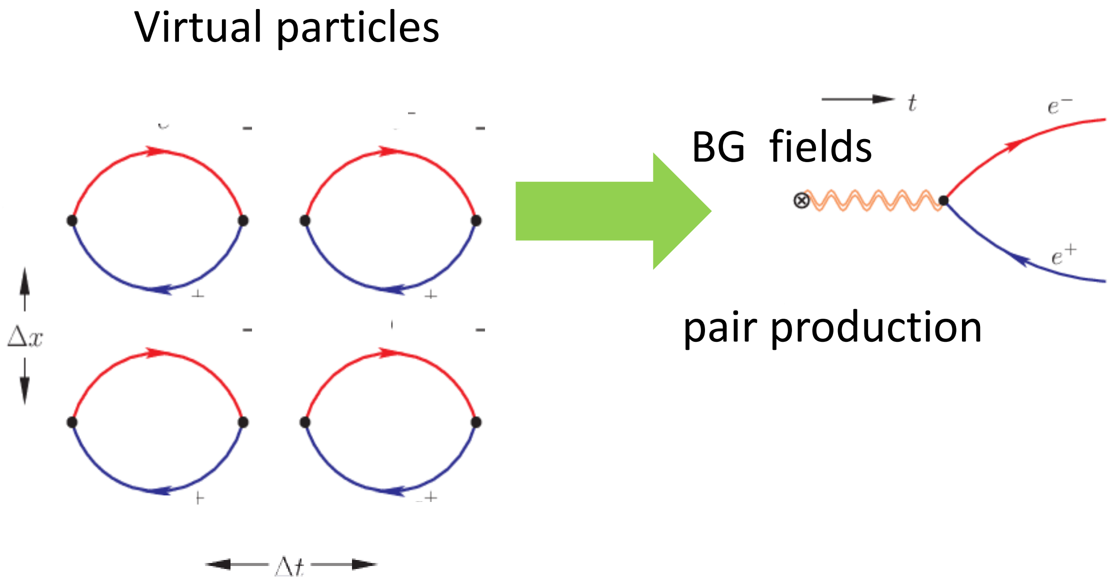

Two source of Particle Production:

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(produces ζ and γ_{ij} by inflation)

II) Background Gauge field
(Schwinger effect)

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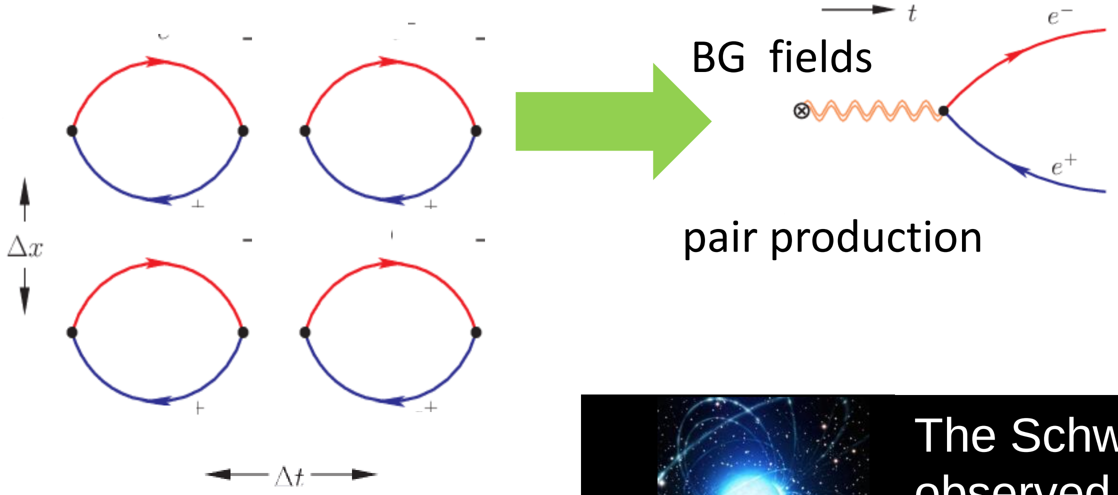


Virtual particles

BG fields

pair production

Two source of Particle Production:

I) Expanding universe
(produces ζ and γ_{ij} by inflation)
II) Background Gauge field
(Schwinger effect)

The Schwinger effect on flat space has never been observed due to the extremely strong electric-field strengths required, i.e. $10^{18} V/m$.

Schwinger Particle Production

- Charged scalar fields coupled to the SU(2) gauge field BG

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

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

- (Dark) massive fermion doublet

$$S_{\mathrm{fermion}} = \int \mathrm{d}^4x\sqrt{-g}\left[i\underbrace{\bar{\bar{\Psi}}\,\not{D}\,\bar{\Psi}}_{} - m\bar{\bar{\Psi}}\bar{\Psi} + \beta\frac{\lambda\chi}{f}\nabla_\mu J_5^\mu\right]$$

$$\not{D} \equiv D_\mu \otimes \gamma^\mu = \left[\mathbf{I}_2\nabla_\mu - ig_A A_\mu^a\mathbf{T}_a\right] \otimes \gamma^\mu$$

Schwinger Particle Production-scalar

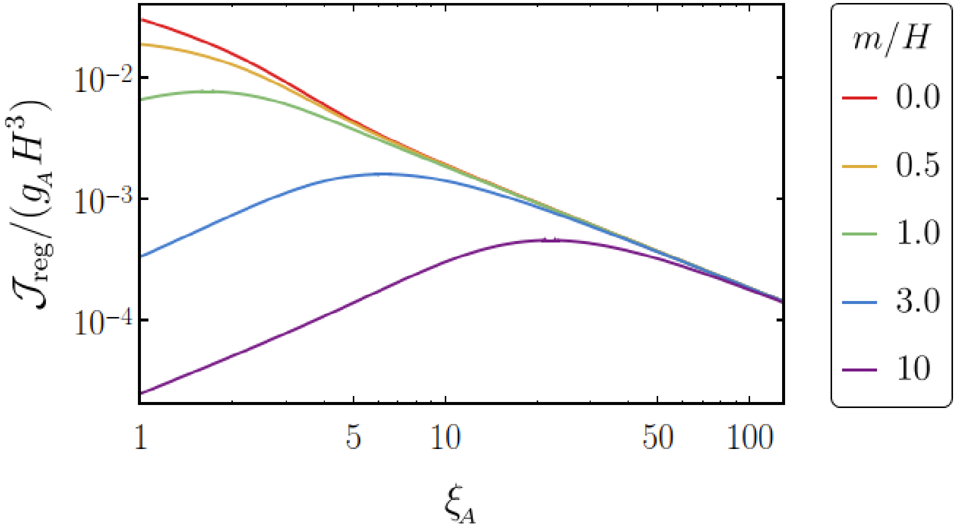
- Charged scalar fields coupled to the SU(2) gauge field BG

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

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

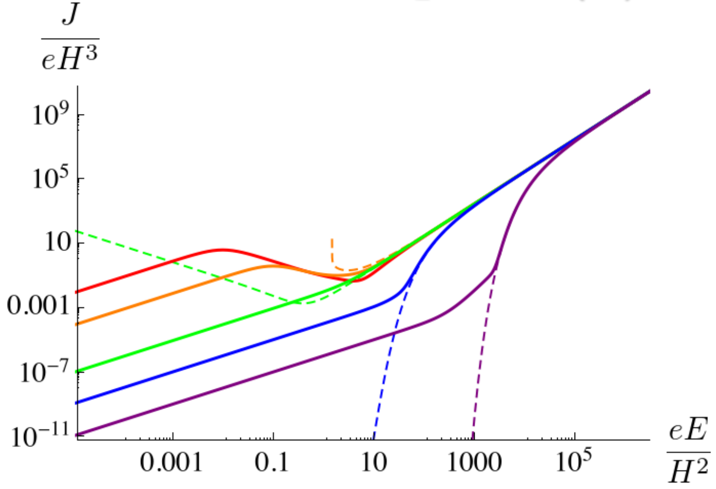
The induced current

Isotropic SU(2)



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

Anisotropic U(1)



(a) current

Takeshi Kobayashi, Niayesh Afshordi, JHEP10(2014)166

Schwinger Particle Production-scalar

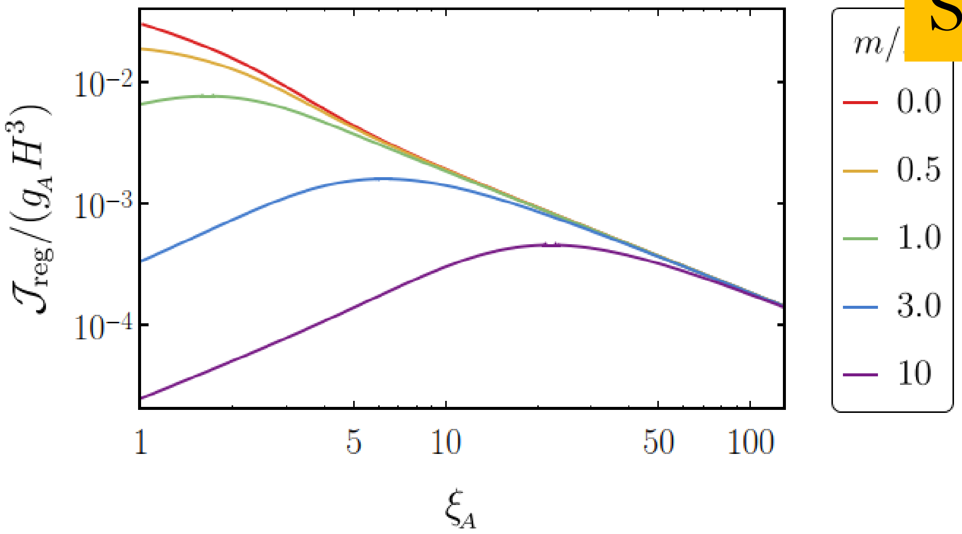
- Charged scalar fields coupled to the SU(2) gauge field BG

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

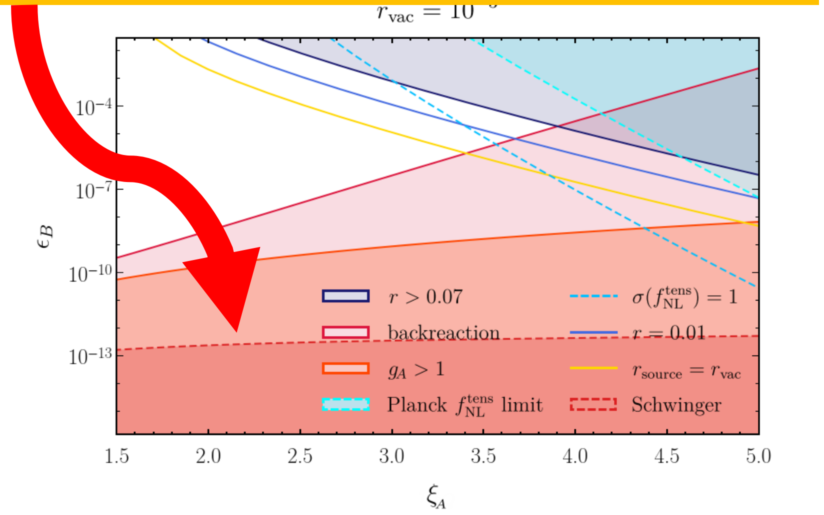
$$\mathbf{D}_\mu\varphi = \left(\mathbf{I}_{2\times2}\nabla_\mu + ig_A\mathbf{A}_\mu\right)\varphi$$

The induced current

Isotropic SU(2)



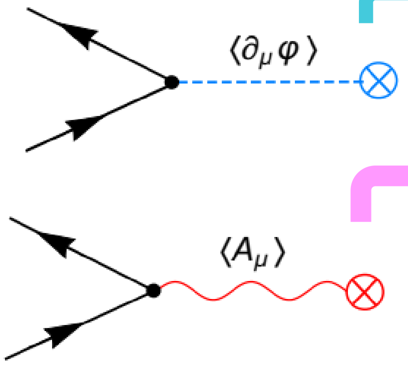
Unlike U(1) case! Negligible Schwinger effect for Iso. SU(2)



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

Schwinger Particle Production-fermions

Axion BG field



$$S_{\text{fermion}} = \int \mathrm{d}^4 x \sqrt{-g} \left[i \bar{\tilde{\Psi}} \underbrace{\not{D}}_{} \tilde{\Psi} - m \bar{\tilde{\Psi}} \tilde{\Psi} + \beta \frac{\lambda \varphi}{f} \nabla_\mu J_5^\mu \right]$$

$$\not{D} \equiv D_\mu \otimes \gamma^\mu = \left[\mathbf{I}_2 \nabla_\mu - i g_A A_\mu^a \mathbf{T}_a \right] \otimes \gamma^\mu$$

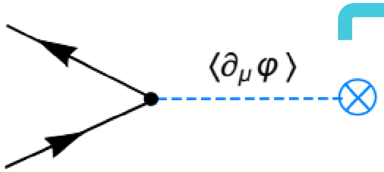
SU(2) gauge field BG

L. Mirzagholi, A.M. D. Lozanov , arXiv:1905.09258

A. M arXiv:1909.11545

Schwinger Particle Production-fermions

Axion BG field



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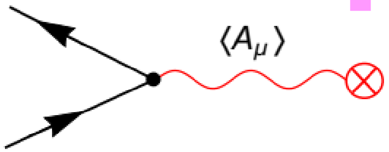


$$\not{D} \equiv D_\mu \otimes \gamma^\mu = \left[\mathbf{I}_2\nabla_\mu - ig_A A_\mu^a \mathbf{T}_a\right] \otimes \gamma^\mu$$

SU(2) gauge field BG

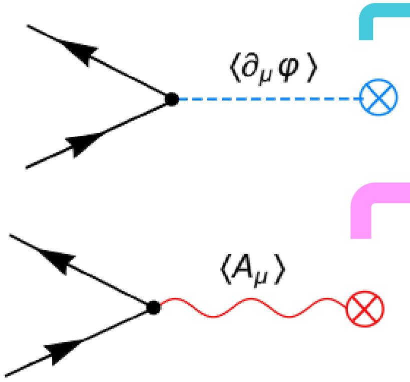
This vacuum **violates** both **P** & **CP**!

L. Mirzagholi, A.M. D. Lozanov , arXiv:1905.09258

A. M arXiv:1909.11545

Schwinger Particle Production-fermions

Axion BG field



SU(2) gauge field BG

$$S_{\rm fermion} = \int \mathrm{d}^4x\sqrt{-g}\left[i\underbrace{\bar{\tilde{\Psi}}\not{D}\tilde{\Psi}}_{} - m\bar{\tilde{\Psi}}\tilde{\Psi} + \beta\frac{\lambda\varphi}{f}\nabla_\mu J_5^\mu\right]$$

$$\not{D} \equiv D_\mu \otimes \gamma^\mu = \left[\mathbf{I}_2\nabla_\mu - ig_A A_\mu^a \mathbf{T}_a\right] \otimes \gamma^\mu$$

This vacuum **violates** both **P** & **CP**!

Massive Dirac fermions generate during inflation.

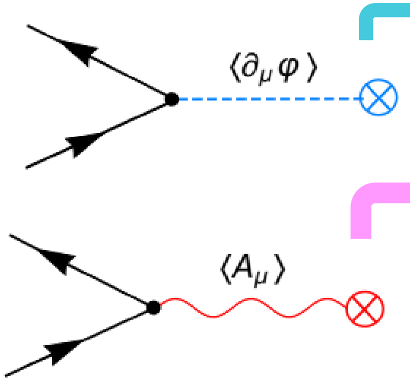
$$\nabla_\mu J_5^\mu = -\frac{2im}{a^3}\bar{\tilde{\Psi}}\gamma_5\tilde{\Psi} + \frac{2g_A^2}{16\pi^2}F_{\mu\nu}^a\tilde{F}_{a\mu\nu}$$

The efficiency of the process is proportional to the source of the CP breaking!

A. M arXiv:1909.11545

Schwinger Particle Production-fermions

Axion BG field



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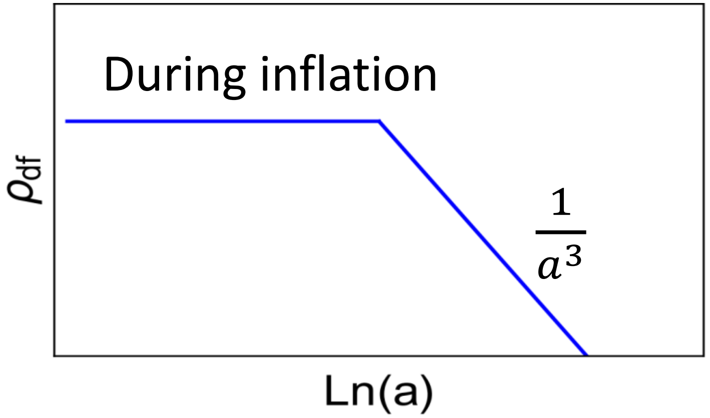

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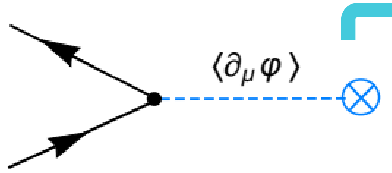

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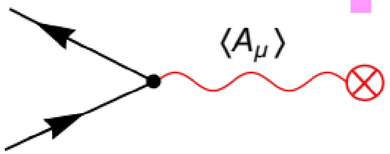

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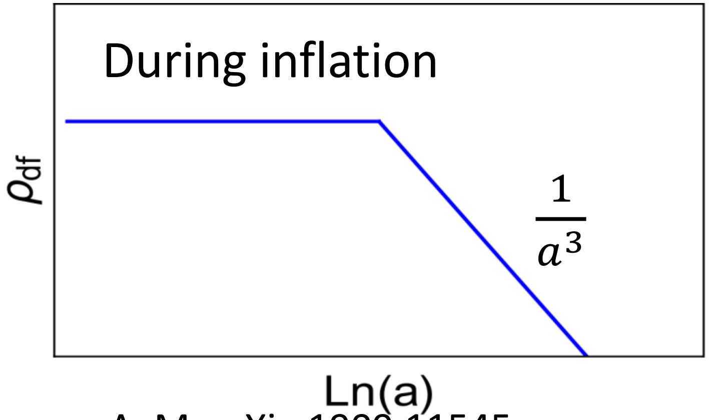

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Schwinger Particle Production-fermions

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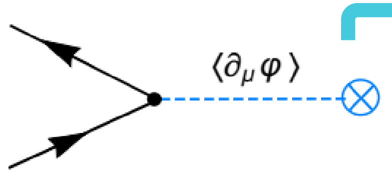

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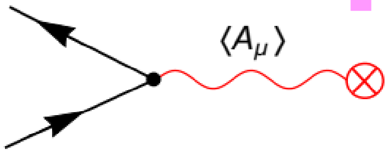

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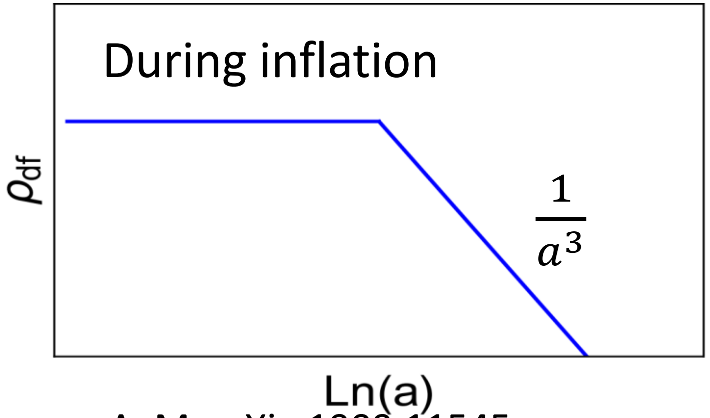
Massiv

A new non-thermal mechanism for generating massive (Dark) fermions!



A. M arXiv:1909.11545

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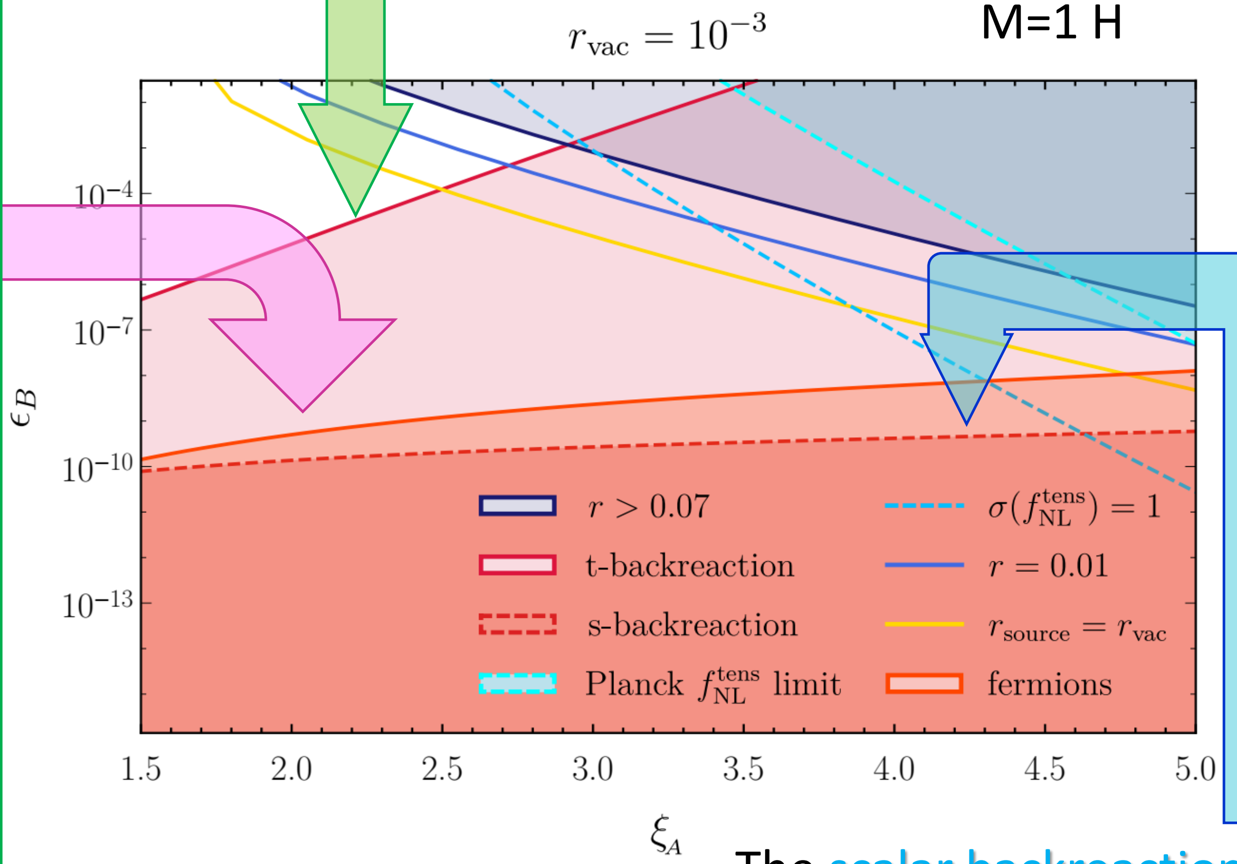
Schwinger Particle Production-fermions

The fermion backreaction is negligible for M<100 H!

A. M, to appear soon

M=1 H



The Dirac fermion backreaction for fermions with mass M=1 H.

L. Mirzagholi, A.M. D. Lozanov , arXiv:1905.09258

The spin-2 backreaction constraint.

A.M. and Komatsu, 2018

The scalar backreaction constraint.

D. Lozanov, A.M., and Komatsu 2018

Summary and Outlook

The presence of the primordial SU(2) gauge fields with a VEV in Inflation

* Spontaneous P violation leads to a rich phenomenology for the particles with spin coupled to it.

- Spin-2 particles: 1) gauge field includes an extra spin-2 field which is chiral, linearly coupled to GWs

2) Partially chiral GWs, with parity odd correlations $\langle TB\rangle$ and $\langle EB\rangle$!

3) The size of the spin-2 backreaction puts an upper bound on $\frac{P_T^s}{P_T^{vac}} \sim O(1)$

4) With a non-trivial topology $\langle R\tilde{R}\rangle \neq 0$ by SM gravitational anomaly provides a natural leptogenesis.

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Thank You!