Title: Primordial SU(2), a new paradigm for Particle Cosmology

Speakers: Azadeh Maleknejad

Series: Cosmology & Gravitation

Date: January 14, 2020 - 11:00 AM

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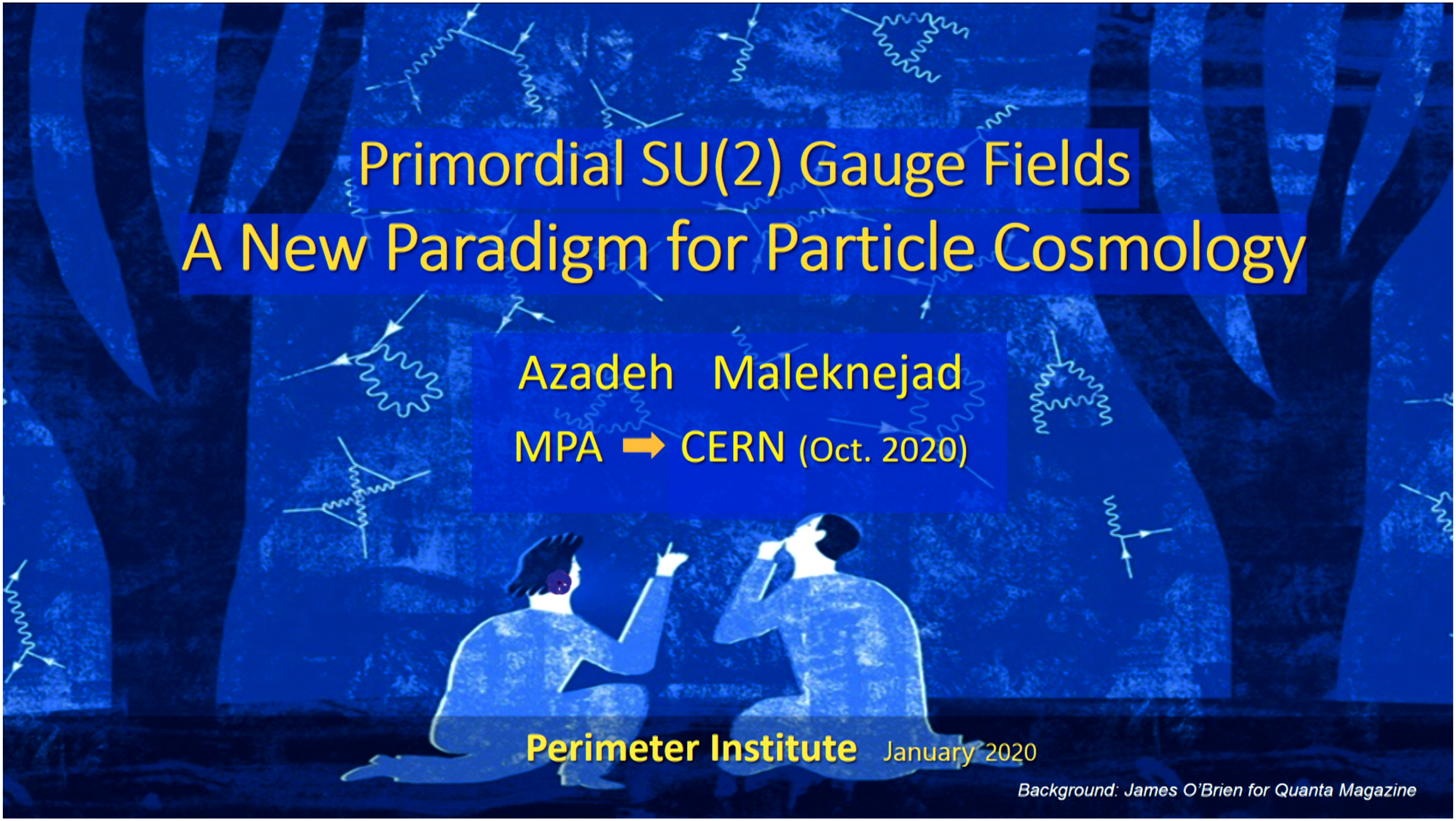
Abstract: Primordial SU(2) gauge fields and axions can contribute to the physics of inflation. In this class of models, both the gauge field and axion acquire a VEV, which is P and CP breaking and enriches the phenomenology of particles with spin. Their multifaceted phenomenology and unique observational signatures, e.g., chiral primordial gravitational waves and gravitational leptogenesis, turned this class of models to a hot topic of research in the past nine years. In this talk, first, I will briefly review the different realizations of this setup. Next, I will tell you about the three different types of particles produced by the SU(2) gauge field, i.e., scalar, fermion, and spin-2 particles and their observable signatures. In particular, the new spin-2 field produces chiral gravitational waves, which can be detected with LiteBIRD, CMB-S4, adv LISA, and BBO. Last but not least, I will tell you about the fermion generation during inflation, dark and visible, as yet another generous opportunity offered by the primordial SU(2)!

Primordial SU(2) Gauge Fields
A New Paradigm for Particle Cosmology

Azadeh Maleknejad

MPA ➡ CERN (Oct. 2020)

Perimeter Institute January 2020



Background: James O'Brien for Quanta Magazine

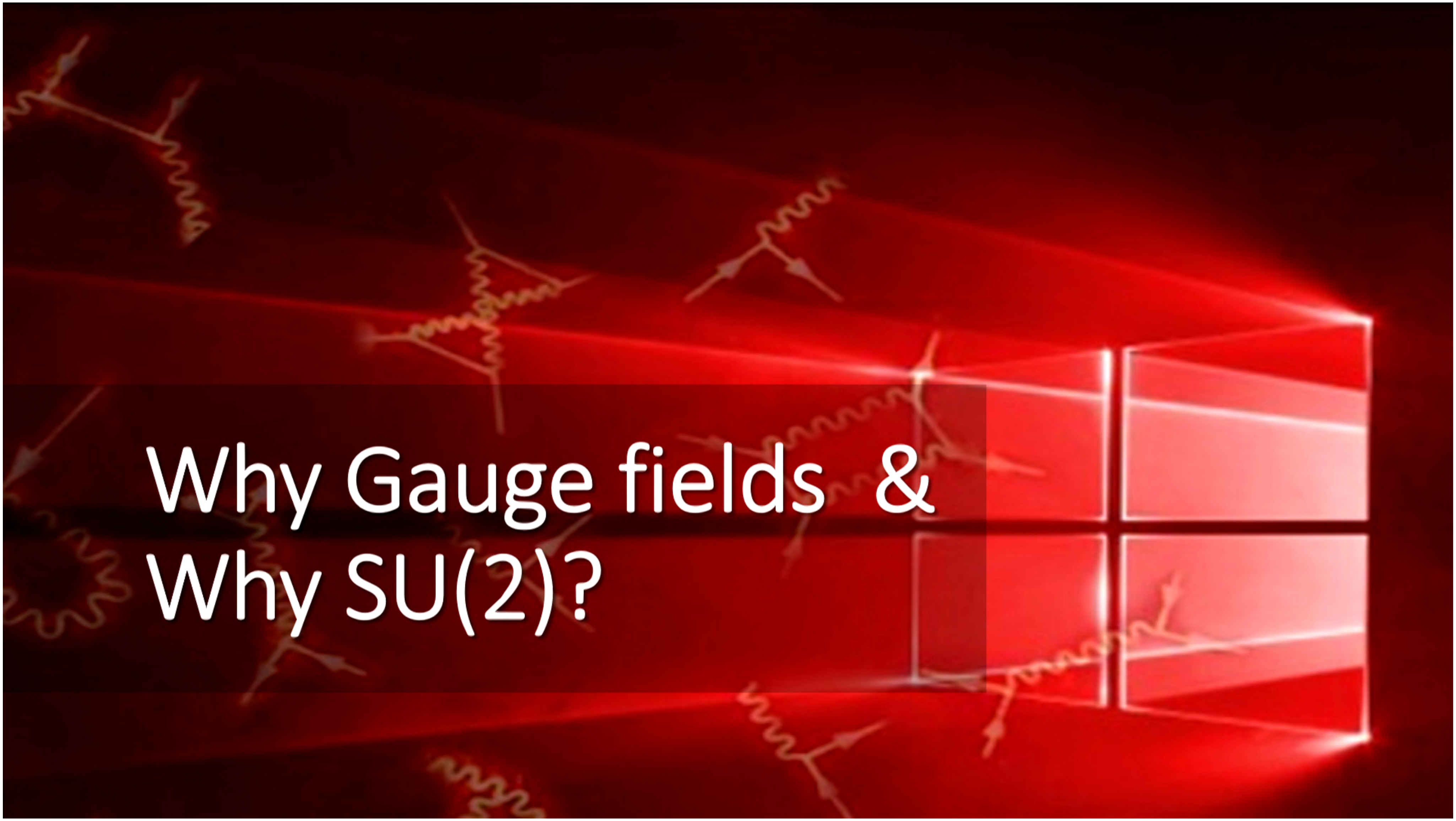
PART ONE

- Why Gauge Fields, why SU(2) in Inflation?
- Novel Window to Particle Cosmology

PART TWO

- SU(2)-Axion Model Building
- Particle Production in Inflation

Summary & Outlook


Why Gauge fields &
Why SU(2)?

Why Gauge Fields during Inflation?!

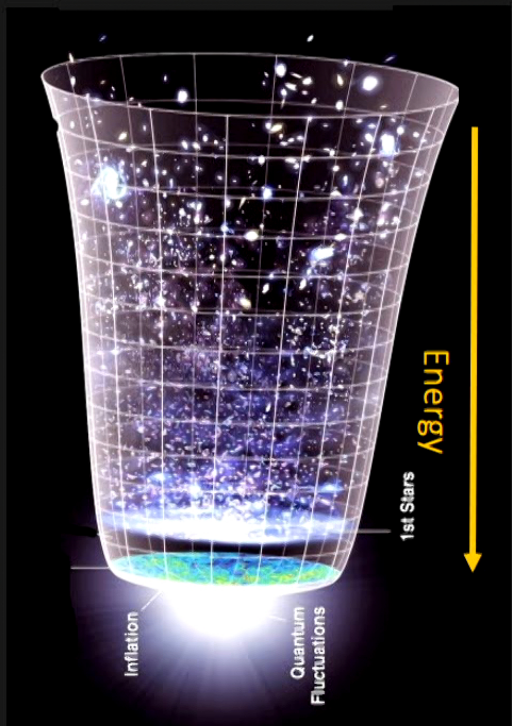
- Why not?

I. Inflation happened at highest energy scales observable!

II. Gauge fields are ubiquitous in physics & building blocks of standard model (SM) and beyond.

- What do they do in inflation?

Mission Impossible?!



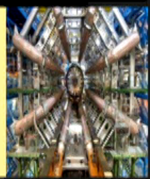
$E_{Inf} \lesssim 10^{14} GeV$

Challenges:

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

Comparing to LHC

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



Challenges:

1) Conformal symmetry of Yang-Mills

   gauge field decays like $A_\mu \sim 1/a$

2) Respecting gauge symmetry

   Not to break gauge symmetry explicitly

3) Spatial isotropy & homogeneity

   U(1) vacuum A_μ

$$A_i = Q(t)\delta_i^3$$

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

Adding new terms
to the gauge theory

$$\frac{\kappa}{384}(F\tilde{F})^2$$

or

$$\frac{\lambda}{8f} F\tilde{F}\,\varphi$$

Axion

SU(2) vacuum $A_\mu = A_\mu^a T_a$

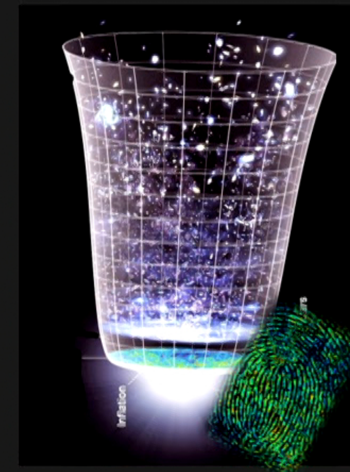
$[T_a, T_b] = i\,\varepsilon^{abc}\,T_c$

Spatially isotropic

$$A_i^a = Q(t)\delta_i^a$$

so(3) & su(2) are isomorphic

Why Gauge Fields during Inflation?!



Non-Abelian Gauge fields can contribute to inflation &

respect spatial isotropy!

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

A new class of inflation models with SU(2) gauge fields & axions,

SU(2)-axion models!

It opens a Novel Window to Particle Cosmology:

Novel Observable Signatures
e.g. Chiral, non-Gaussian GWs!


A Novel Window to
Particle Cosmology

SU(2)-axion Inflation: a Complete Setup

SM of Particle Physics, the most rigorous theory of physics cannot explain Cosmology!

Big Questions of modern Cosmology & Particle Physics:

I) Origin of matter asymmetry,

II) Particle nature of DM,

III) Primordial GWs
(only missing prediction of inflation)

Fundamental discrete Symmetries and their violation played a key role in understanding SM, e.g. C & P violation in weak interactions, CP violation to explain matter asymmetry.

Yet, it is mostly assumed that physics of inflation is P and CP symmetric.

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

SU(2) Gauge fields and Inflation: Two examples

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

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

- Chromo-natural P. Adshead, M. Wyman, 2012

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

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

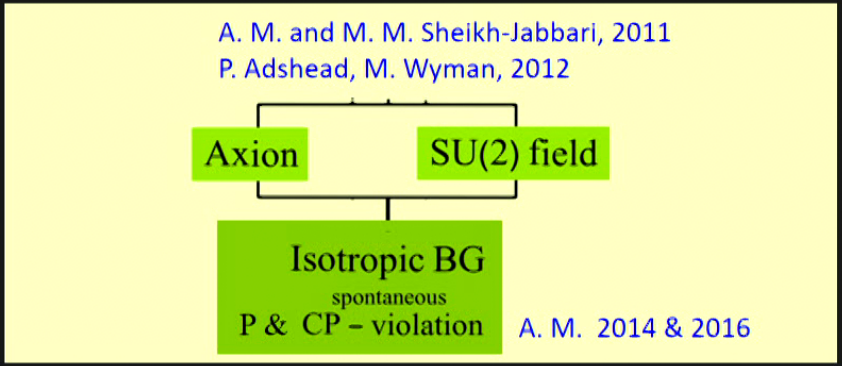
A New Window to Particle Cosmology

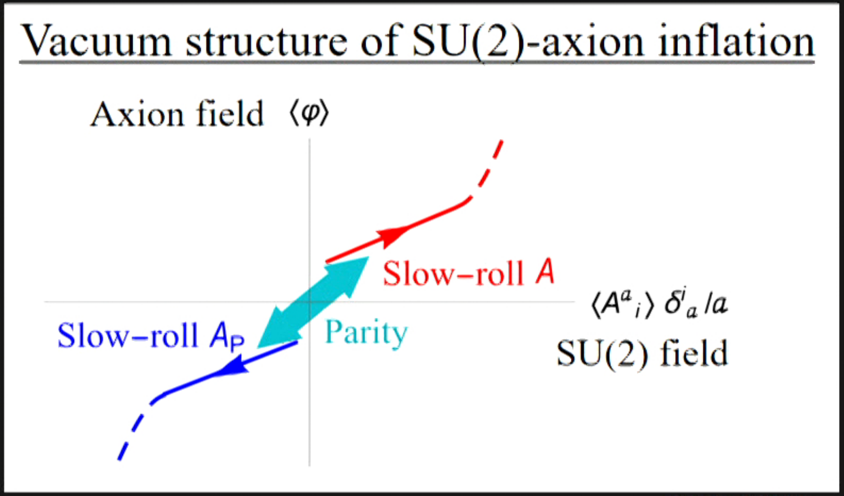
- SU(2)-axion models acquire a vacuum during inflation.

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., 2019

Particle Production

- Vacuum is a vast ocean of virtual particles &

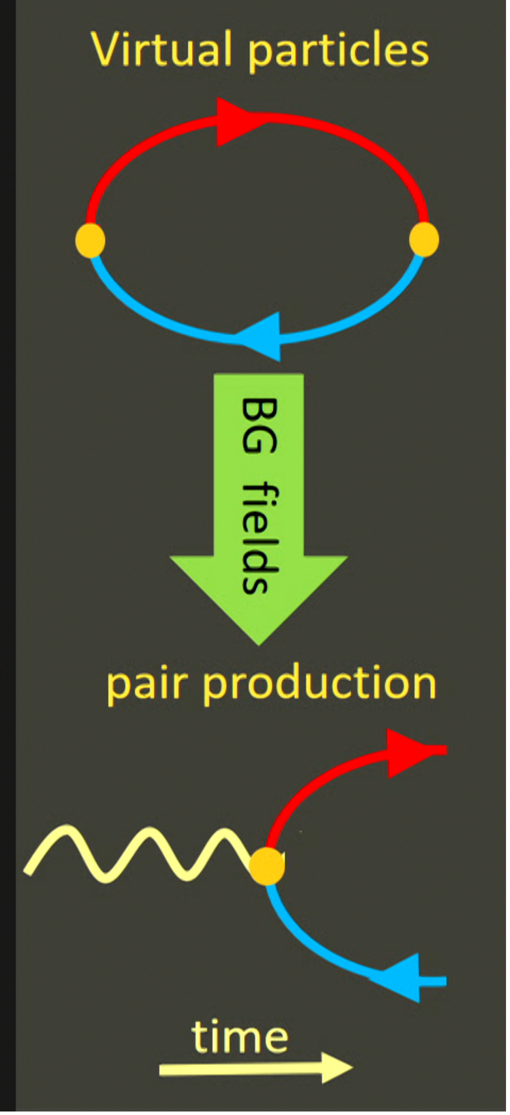
- Background field upgrades it to actual particles!

  Background Gauge field
  (Schwinger effect)

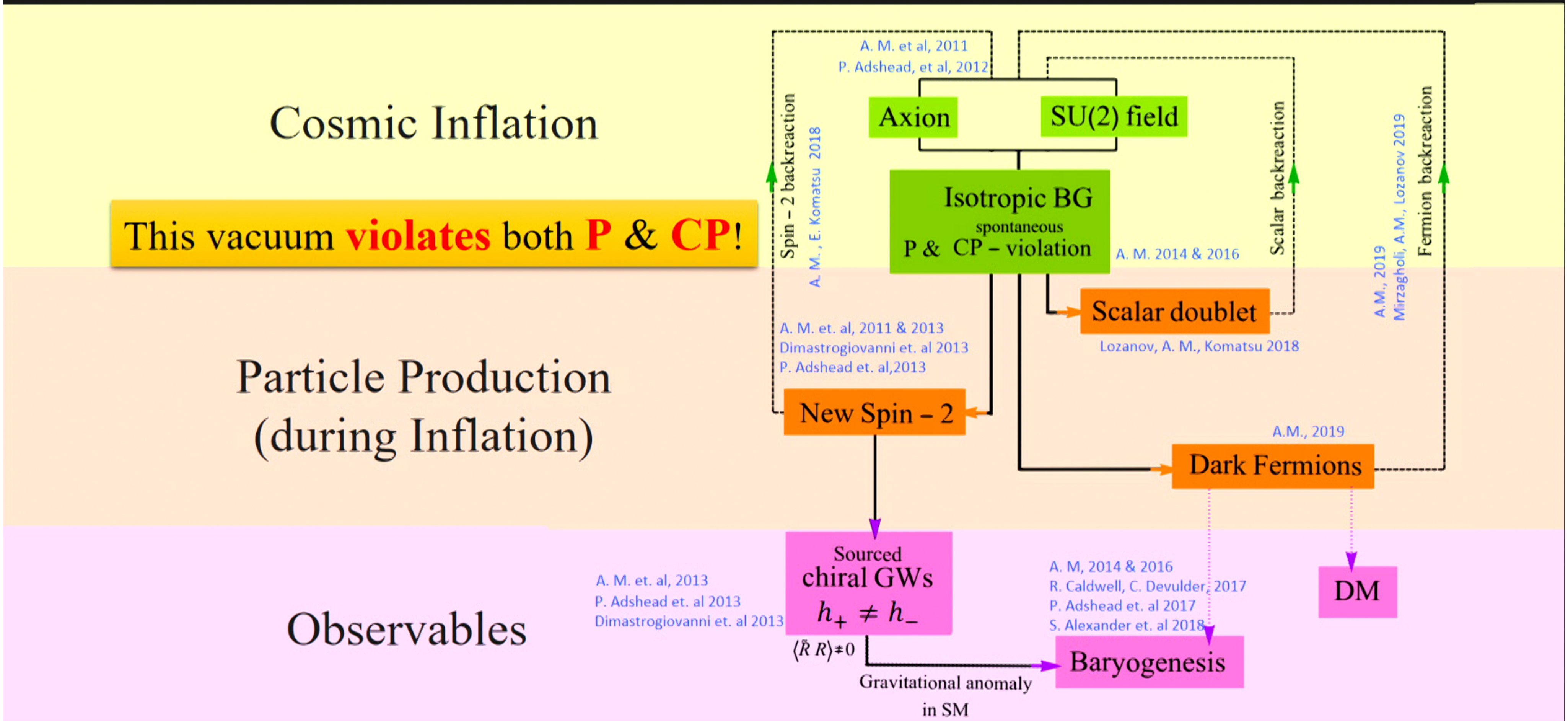
- In flat space, it has never been observed, $E > 10^{18} V/m$.
- Schwinger particle production is important

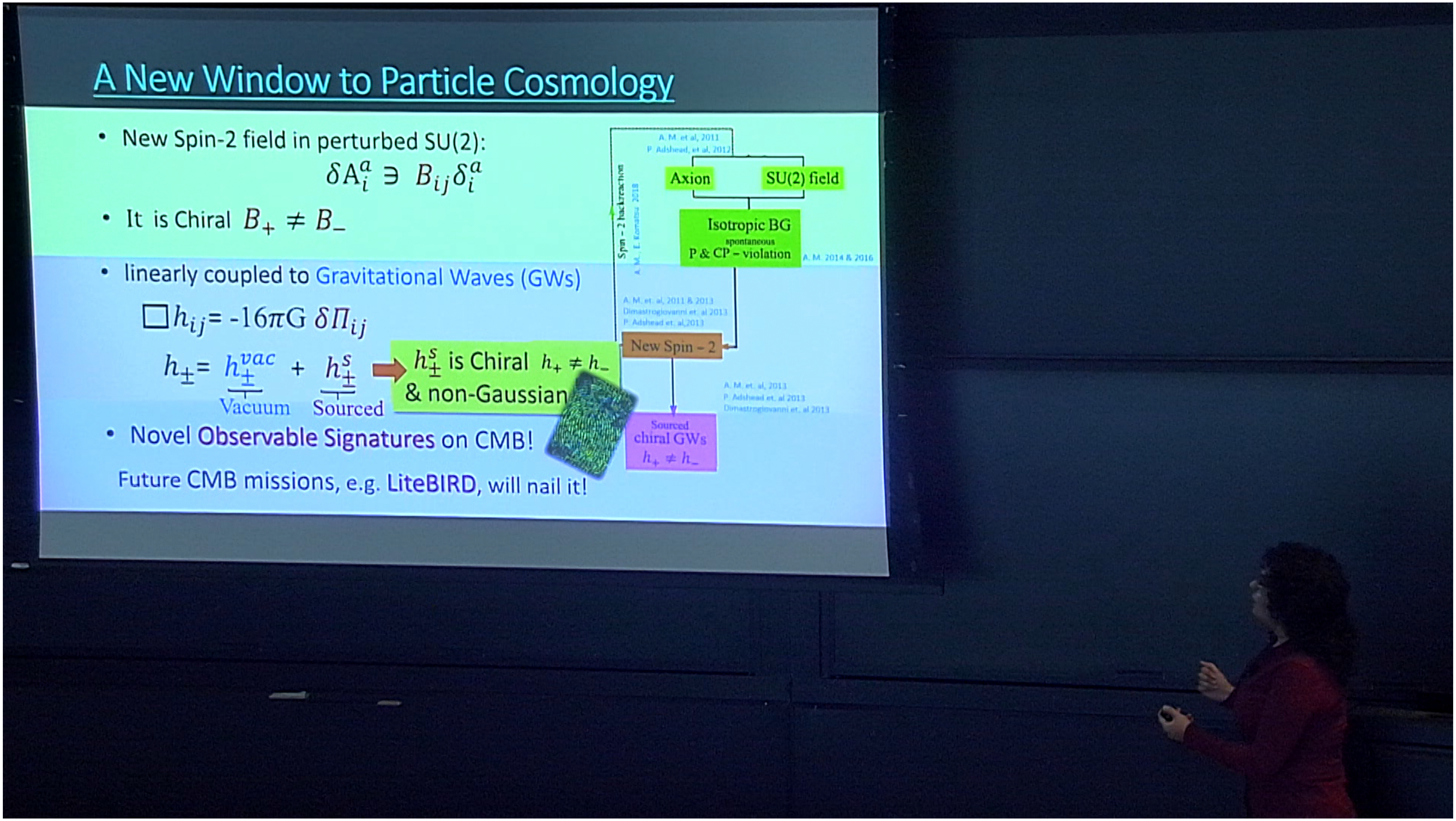
in Physics of Inflation:

Particle Production during Inflation!



A New Window to Particle Cosmology




A New Window to Particle Cosmology
New Spin-2 field in perturbed SU(2):
$\delta A_i^a \ni B_{ij}\delta_i^a$
It is Chiral $B_+ \neq B_-$
linearly coupled to Gravitational Waves (GWs)
$\Box h_{ij} = -16\pi G\, \delta\Pi_{ij}$
$h_\pm = h_\pm^{vac} + h_\pm^{s}$
Vacuum
Sourced
$h_\pm^s$ is Chiral $h_+ \neq h_-$
& non-Gaussian
Novel Observable Signatures on CMB!
Future CMB missions, e.g. LiteBIRD, will nail it!
A. M. et al, 2011
P. Adshead, et al, 2012
Axion
SU(2) field
Isotropic BG
spontaneous
P & CP – violation
A. M. 2014 & 2016
Spin – 2 backreaction
A. M., E. Komatsu 2018
A. M. et. al, 2011 & 2013
Dimastrogiovanni et. al 2013
P. Adshead et. al, 2013
New Spin – 2
A. M. et. al, 2013
P. Adshead et. al 2013
Dimastrogiovanni et. al 2013
Sourced
chiral GWs
$h_+ \neq h_-$

A New Window to Particle Cosmology

- New Spin-2 field in perturbed SU(2):

$$\delta A_i^a \ni B_{ij}\delta_i^a$$

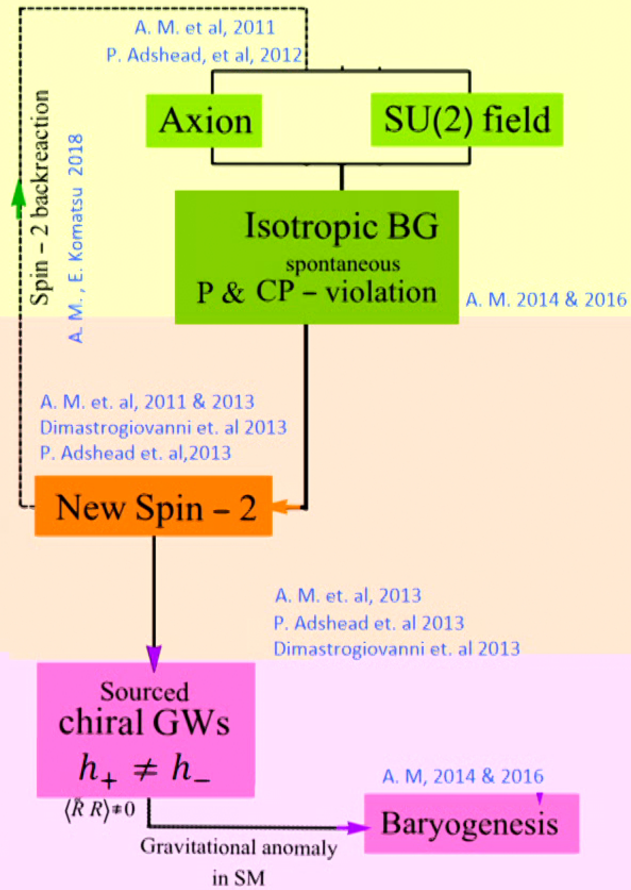
- It is Chiral $B_R \neq B_L$
- linearly coupled to Gravitational Waves

$$\Box h_{ij} = -16\pi G\, \delta\Pi_{ij}$$

$$h_{\pm} = \underbrace{h_{\pm}^{vac}}_{\text{Vacuum}} + \underbrace{h_{\pm}^{s}}_{\text{Sourced}} \Rightarrow$$

$h_{\pm}^{s}$ is Chiral & non-Gaussian

- Inflationary Leptogenesis naturally arises to explain the matter asymmetry!



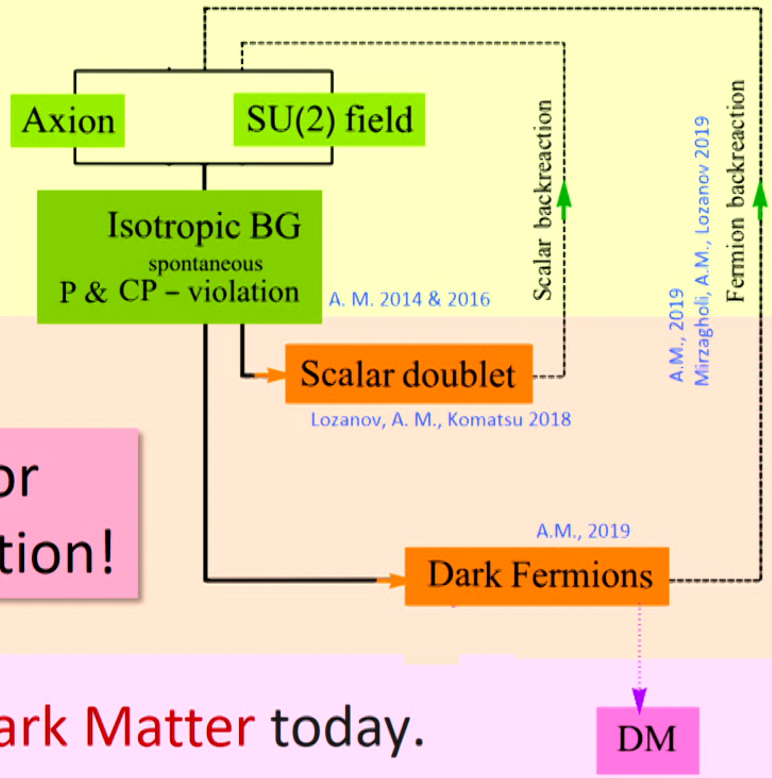
A New Window to Particle Cosmology

- Scalar doublet, and Dark Fermions charged under the Primordial SU(2) will be created by it!

- They will backreact to it as well.

- A new non-thermal mechanism for generating Dark Fermions during Inflation!

- This Dark fermions can be part of Dark Matter today.



PART TWO:

- SU(2)-Axion Model Building
- Particle Production in Inflation

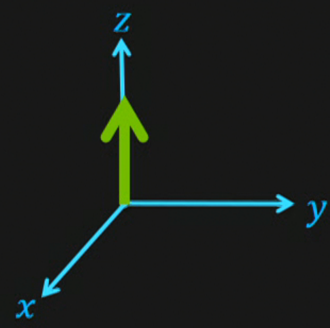

SU(2)-Axion
Model Building

How su(2) algebra restores the spatial isotropy?

Let us work in temporal gague, $A_0 = 0$.

U(1) vacuum A_μ

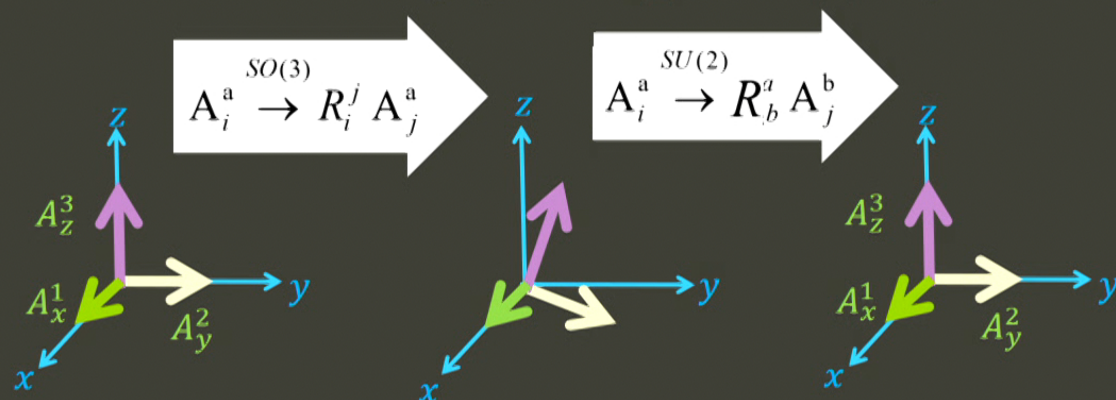
$$\mathrm{A}_i = Q(t)\delta_i^3$$



SU(2) VEV, $A_\mu = A_\mu^a\, T_a$

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

$$\mathrm{A}_i^a = Q(t)\delta_i^a$$



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

SU(2)-Axion Model Building

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

- 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

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

$S_s(\chi)$: Scalar inflaton (spectator SU(2))

$S_H(A_\mu, H)$: Higgs sector (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

- SU(2)-Axion Inflation models :

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

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

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

All share these features:

Background

i) **SU(2) gauge field VEV:** (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) **P and CP violating** in inflation background.

Perturbation

iii) **New spin-2** degrees of freedom:

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

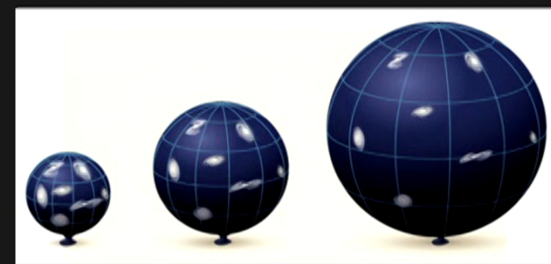
iv) Spin-2 field is **chiral** & **linearly coupled to GWs**

→ **Chiral, non-Gaussian primordial GWs!**

SU(2) Gauge fields and Initial Anisotropies

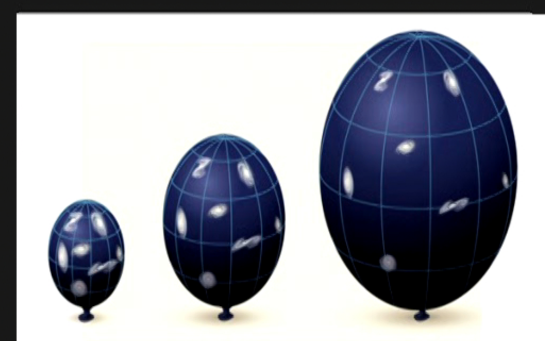
- SU(2) gauge fields are FRW friendly: (respect isotropy & homogeneity)

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



Isotropic Background

- How stable is the isotropic ansatz against initial anisotropies, i.e. Bianchi

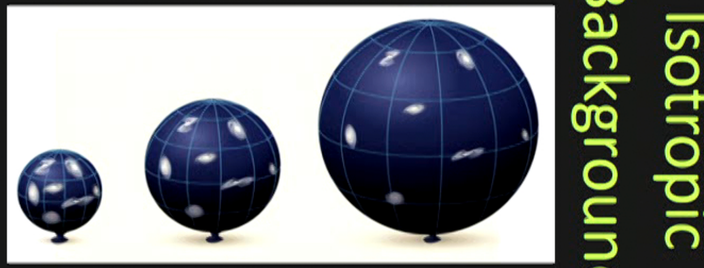


Anisotropic Background??

SU(2) Gauge fields and Initial Anisotropies

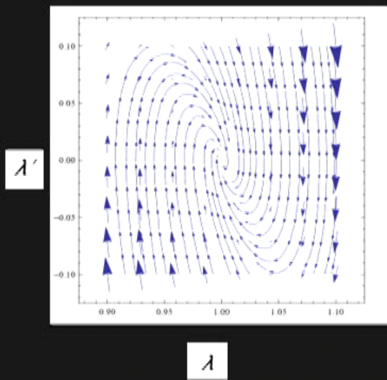
- SU(2) gauge fields are FRW friendly: (respect isotropy & homogeneity)

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



- How stable is the isotropic ansatz against initial anisotropies, i.e. Bianchi

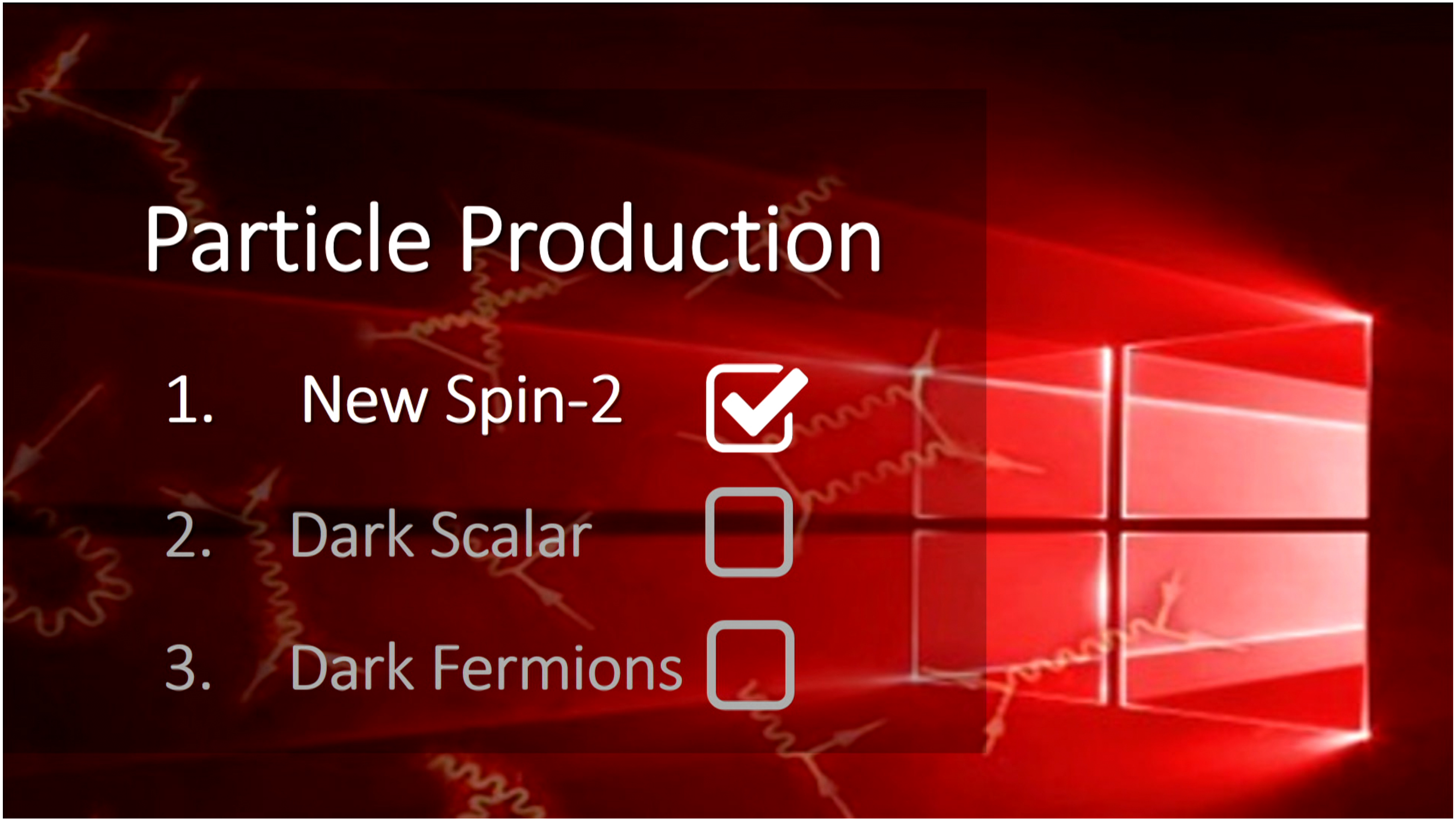
$\lambda(t)$ Parametrizes the amount of anisotropy in the gauge field



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

Isotropic Solution is the Attractor!

A. M. and M.M. Sheikh-Jabbari, J. Soda, 2012
A. M. and E. Erfani, 2013


Particle Production
1. New Spin-2
2. Dark Scalar
3. Dark Fermions

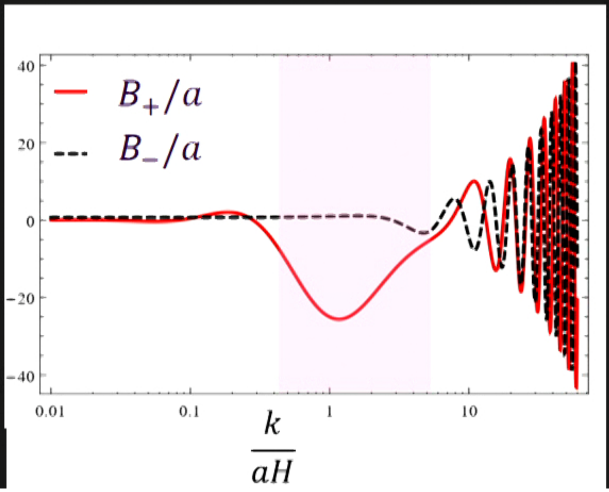
New Spin-2 & Chiral GWs

- New spin-2 field $\delta A_i^a(t,\vec{x}) = B_{ij}(t,\vec{x})\,\delta_i^a$ is governed by

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

(δ_C and $\frac{m^2}{H^2}$ are positive, given by BG)

- The B_+ has a short phase of particle production before horizon exit.



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

- Backreaction of the spin-2 field is important: $BR \approx g_A n_B \sim \delta_c^3\, e^{\frac{(2-\sqrt{2})\pi}{2}\delta_c}$

A. M. and E. Komatsu, 2018

New Spin-2 & Chiral GWs

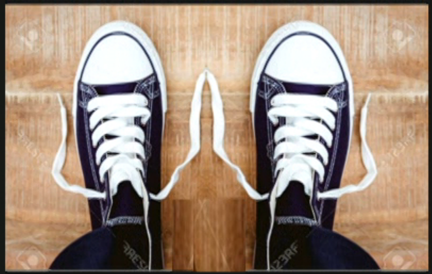
- New spin-2 field $\delta A_i^a(t,\vec{x}) = B_{ij}(t,\vec{x})\,\delta_i^a$ is governed by

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

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

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

- Gravitational waves have two uncorrelated terms



$$h_\pm = \underbrace{h_\pm^{vac}}_{\text{Vacuum GWs}} + \underbrace{h_\pm^{s}}_{\text{Sourced by } B_\pm}$$

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

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

New Spin-2 & Chiral GWs

- New spin-2 field $\delta A_i^a(t,\vec{x}) = B_{ij}(t,\vec{x})\,\delta_i^a$ is governed by

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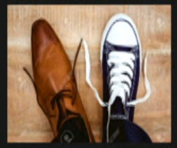
- Gravitational waves have two uncorrelated terms: $h_\pm = \underbrace{h_\pm^{vac}}_{\text{Vacuum}} + \underbrace{h_\pm^{s}}_{\text{Sourced by } B_\pm}$



- The ratio of the power spectra of sourced to vacuum 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

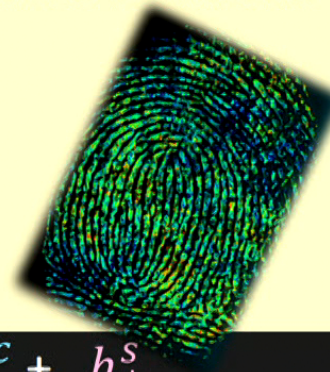
i) Tensor power spectrum is not entirely specified by the scale of inflation,

ii) Sizable tensor to scalar ratio without large field,

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

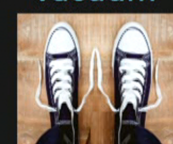
$\langle TB \rangle$ and $\langle EB \rangle$ are non-zero, &

iv) Non-Gaussian Primordial GWs!



- Gravitational waves have two un ated terms: $h_{\pm} = h_{\pm}^{vac} + h_{\pm}^{S}$

Vacuum



Sourced by $B_{\pm}$

- The ratio of the power spec of sourced to vacuum is

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

A. M. and E. Komatsu, 2018

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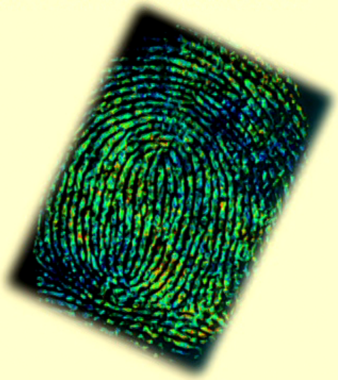
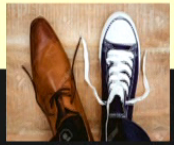


Backreaction of New Spin-2 puts constraints on ratio of the power spectra of sourced to vacuum gravitational waves

A. M. and E. Komatsu, 2018



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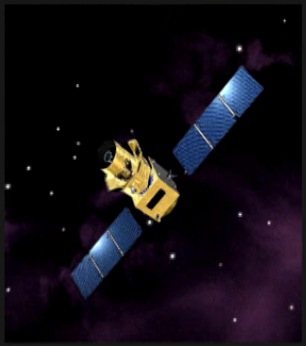
A. M. and E. Komatsu, 2018

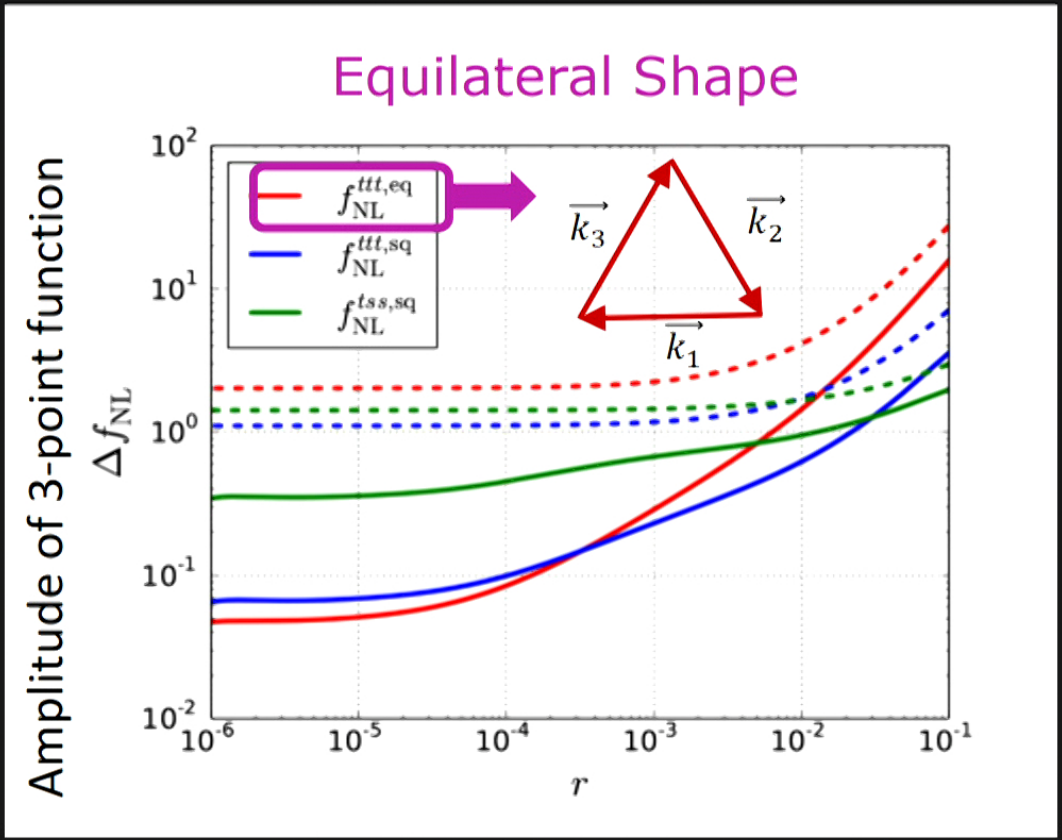
Novel Observable Signature: CMB

- The sourced tensor modes is Highly non-Gaussian.

Agrawal, Fujita, Komatsu 2018

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

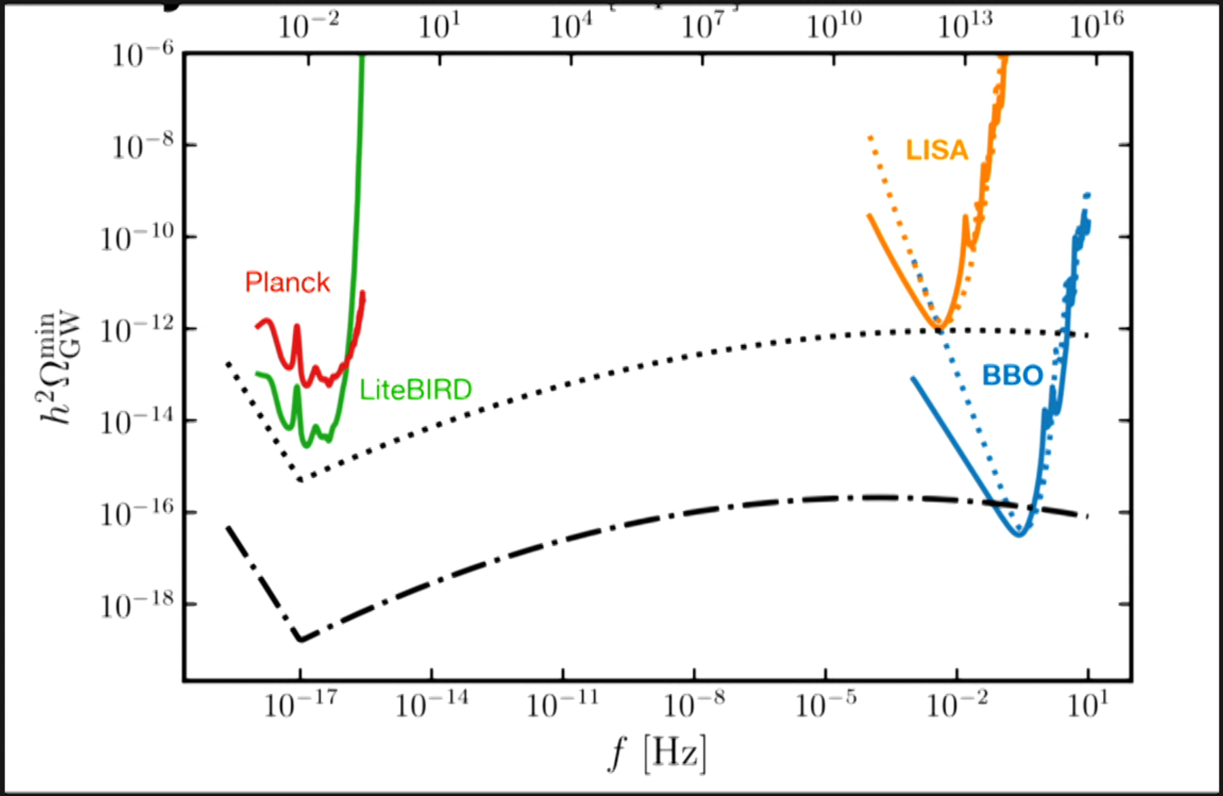




Maresuke Shiraishi, Front. Astron. Space Sci. 2019

Novel Observable Signature: Beyond CMB

- Comparison of the sensitivity curves for LiteBIRD, Planck, LISA & BBO.



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

Particle Production

1. New Spin-2 ☑
2. Dark Scalar ☑
3. Dark Fermions ☑

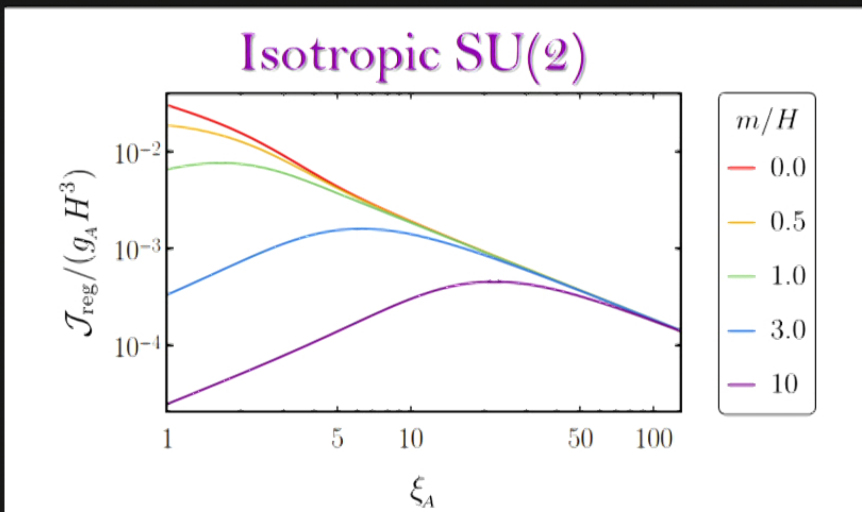
Particle Production-scalar

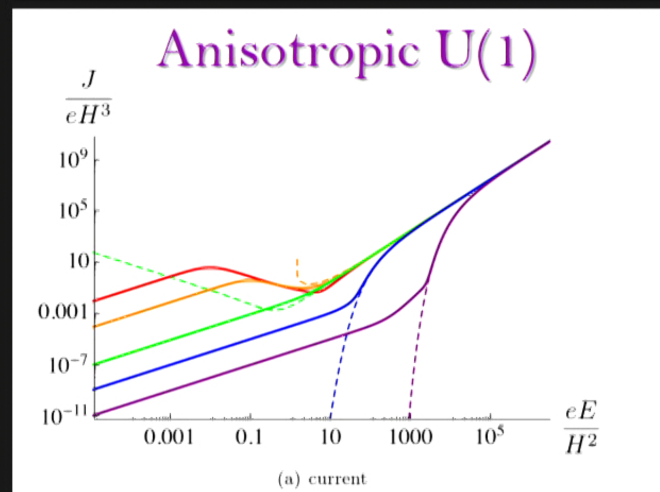
- Charged scalar fields coupled to the SU(2) gauge field BG

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

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

- The scalar field's induced current:

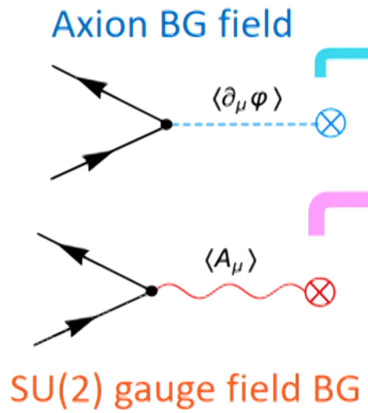




Kaloian D. Lozanov, A. M., Eiichiro Komatsu JHEP 1902 (2019) 041

Takeshi Kobayashi, Niayesh Afshordi, JHEP10(2014)166

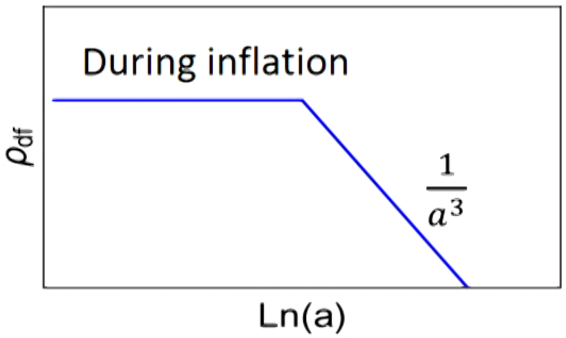
Particle Production-Dark Fermion



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

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

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



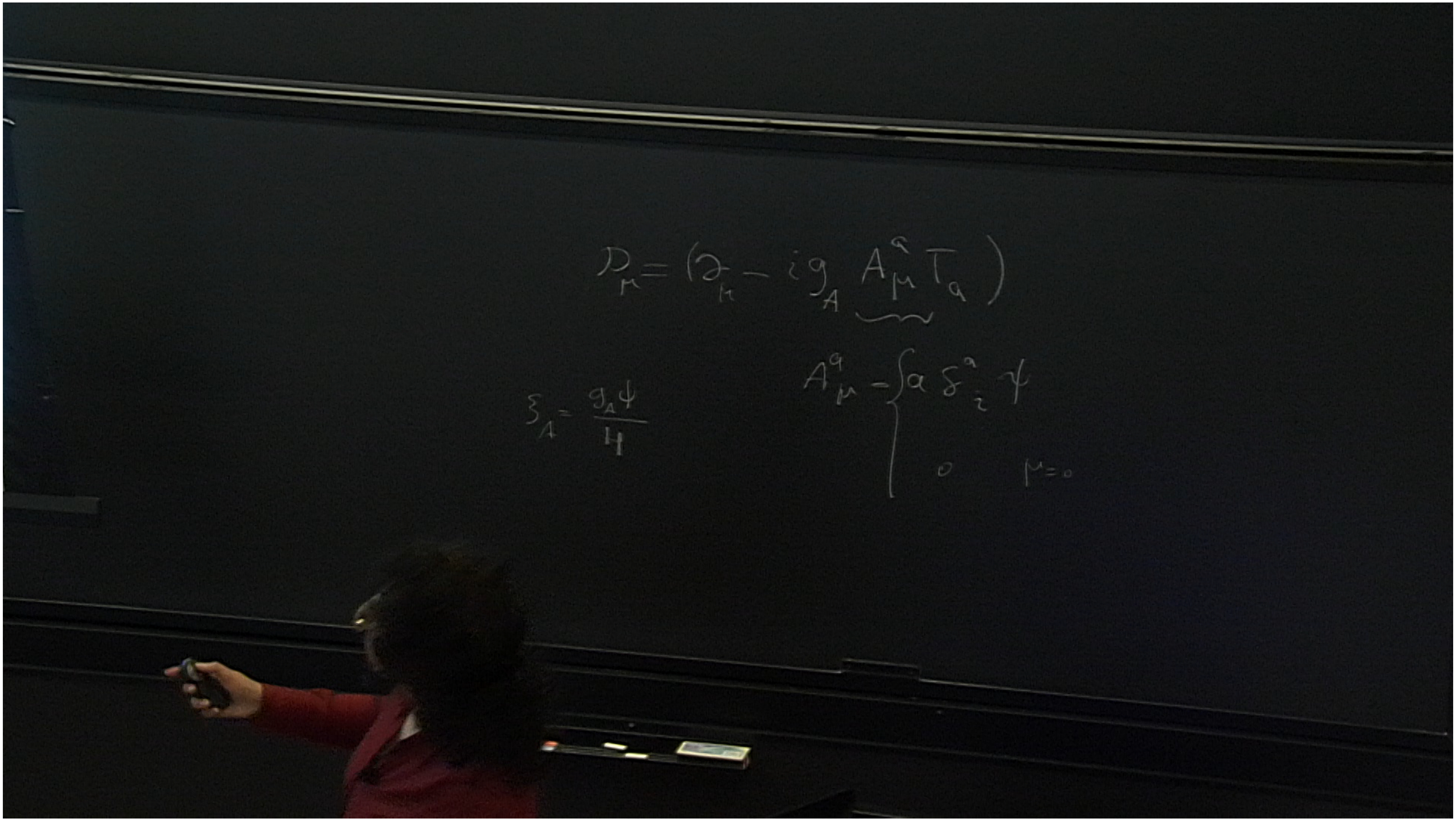
A. M arXiv:1909.11545

Massive Dirac fermions are generated during inflation.

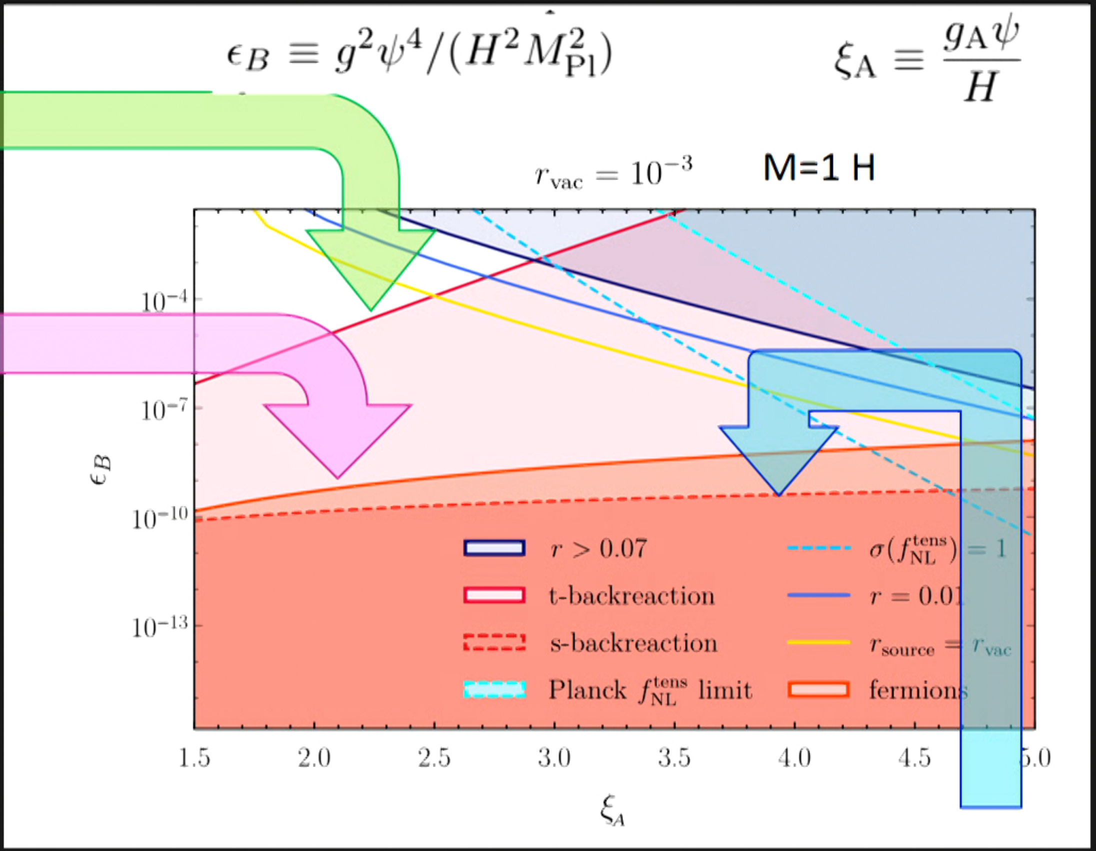
$$\nabla_\mu J_5^\mu = -\frac{2im}{a^3} \bar{\tilde{\Psi}} \gamma_5 \tilde{\Psi} + \frac{2g_A^2}{16\pi^2} F_{\mu\nu}^a \tilde{F}_{a\mu\nu}$$

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

These fermions can be as massive as M<10 TeV!


D_μ = (∂_μ − i g_A A^a_μ T_a)
ξ_A = g_A ψ / 4
A^a_μ − α δ^a_i ψ
0   μ=0

Particle Production & Backreaction



The spin-2 backreaction constraint.

A.M. and Komatsu, 2018

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

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

The scalar field backreaction constraint.

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

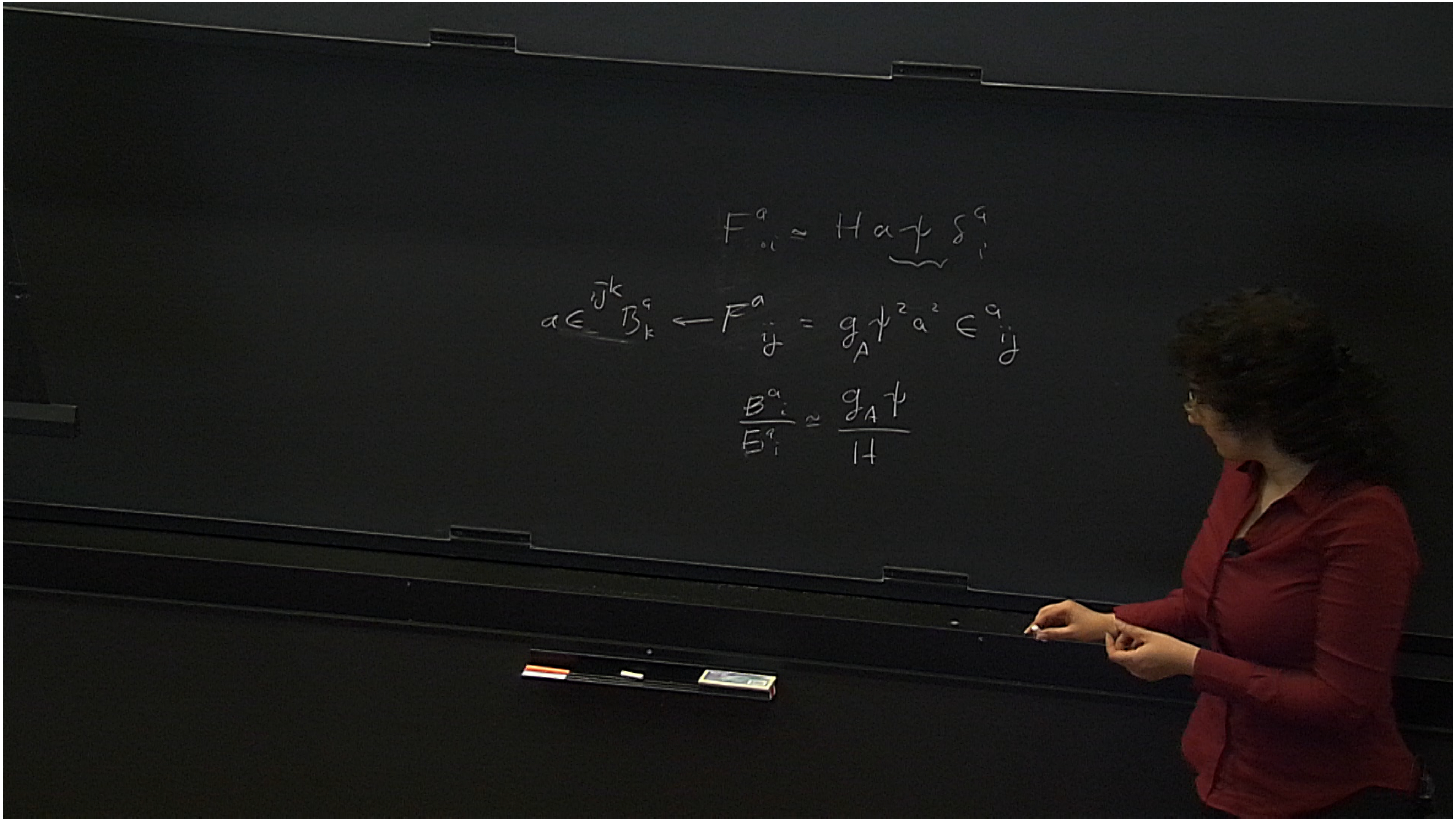
- SU(2)-axion models of inflation enriches the Particle Cosmology.
- Spontaneous P & CP violation in Inflation.

- Spin-2 particles: (The smoking gun for Primordial SU(2)!)

1) Gauge field includes a New spin-2 field which is chiral
2) It produces partially chiral and non-Gaussian GWs

- Spin-1/2 particles:

a new non-thermal mechanism for generating massive (Dark) fermions.


$F^a_{0i} \simeq H a \psi \delta^a_i$
$a \epsilon^{ijk} B^a_k \leftarrow F^a_{ij} = g_A \psi^2 a^2 \epsilon^a_{ij}$
$\frac{B^a_i}{E^a_i} \simeq \frac{g_A \psi}{H}$