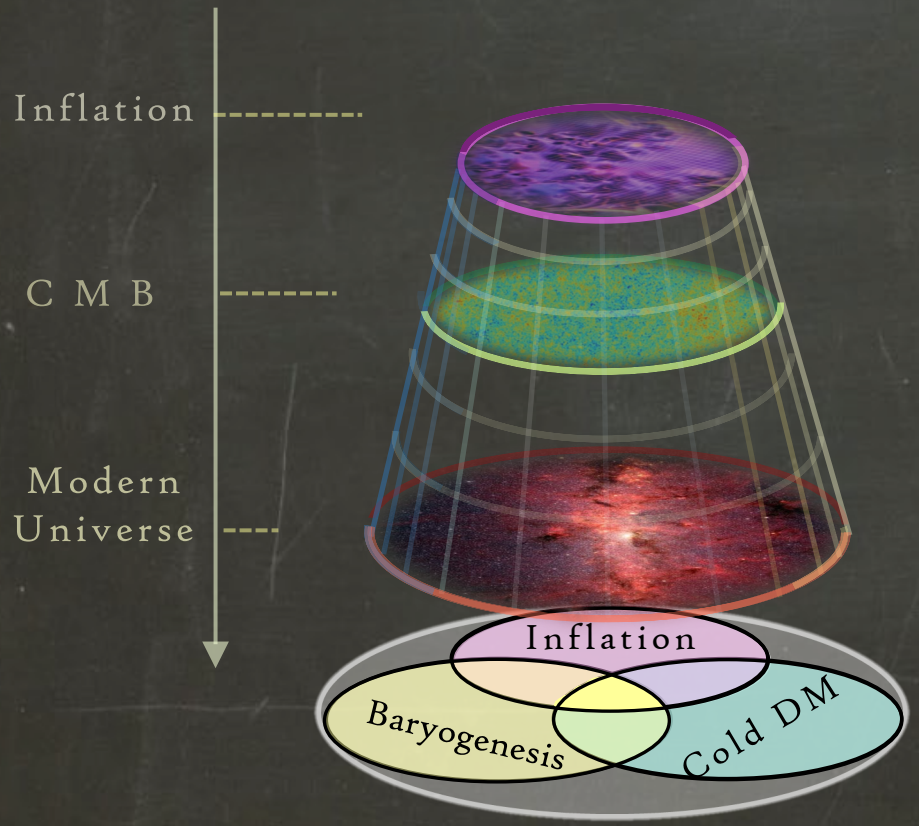
(Non-Abelian) Gauge Fields in the Sky?



Azadeh Malek-Nejad
CERN

My Research

Early Universe

- Cosmic Inflation Model Building
- QFT in (quasi) de Sitter
- Origin of Matter Asymmetry

A Theorem in GR

- Inflation anisotropic hair

Late Universe

- Dark Matter Model Building (Composite DM)
- Dark Energy & Large-Scale Structure

My Research

Early Universe

- **Cosmic Inflation Model Building**
  Introduced a new class of inflation models based on Non-Abelian gauge theories
- **QFT in (quasi) de Sitter**
  Particle production in inflation
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  Global gravitational and chiral anomaly in inflation

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My Research

Early Universe

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  Disproving Hawking's cosmic no-hair conjecture!

Late Universe

- Dark Matter Model Building (Composite DM)
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My Research

Early Universe

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A Theorem in GR

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Late Universe

- Dark Matter Model Building (Composite DM)
  Admixture of light pions & heavy baryons
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My Research

Early Universe

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Introduced a new class of inflation models based on Non-Abelian gauge theories

QFT in (quasi) de Sitter

Particle production in inflation

Origin of Matter Asymmetry

Global gravitational and chiral anomaly in inflation

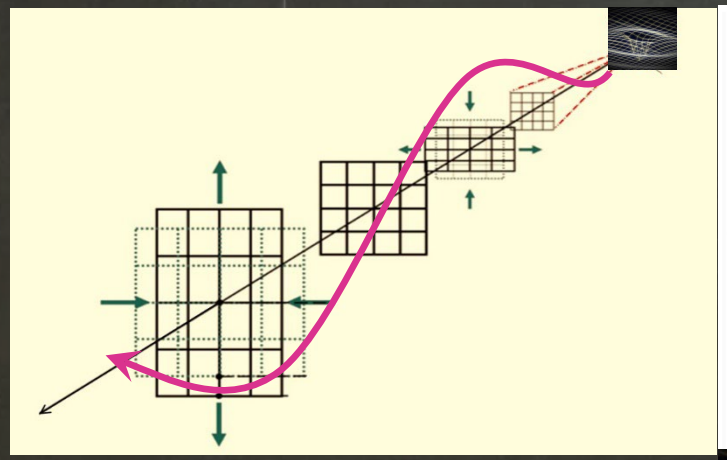
The Story of (Non-Abelian) Gauge Fields in the Sky!

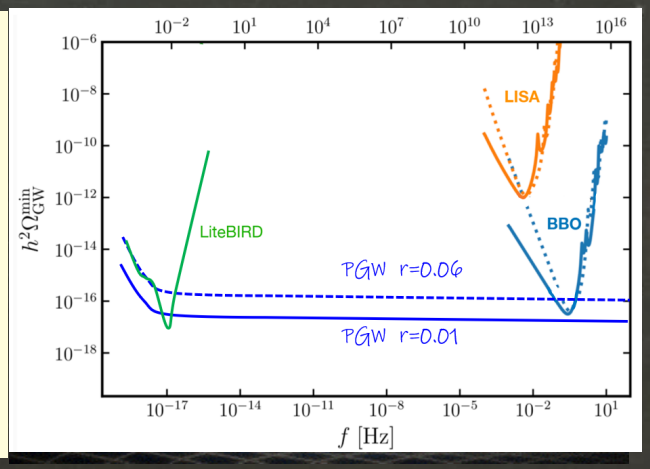
As Yet

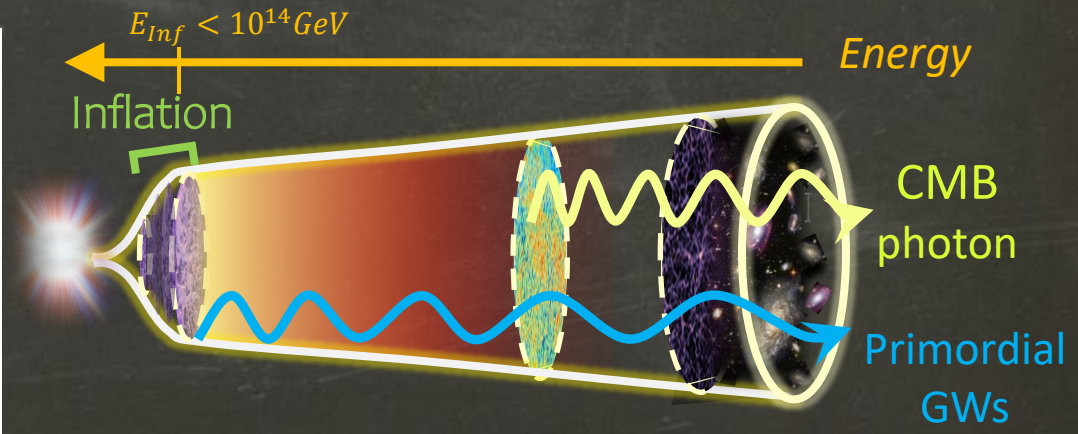
- Observations are in perfect agreement with Inflation.
- The Particle Physics of Inflation is still unknown.
- The Standard models of inflation are based on Scalars.

  Inflation Particle Physics: a scalar field beyond the SM.
- Primordial Gravitational Waves (PGW):

  Vacuum fluctuations: unpolarized, red-tilted, and nearly Gaussian.







As Yet

- Observations are in perfect agreement with Inflation.
- The Particle Physics of Inflation is still unknown.
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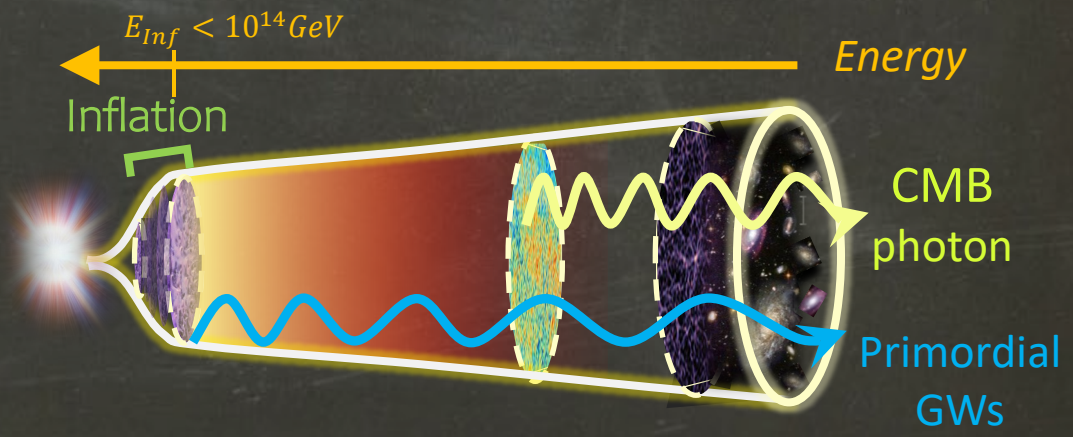
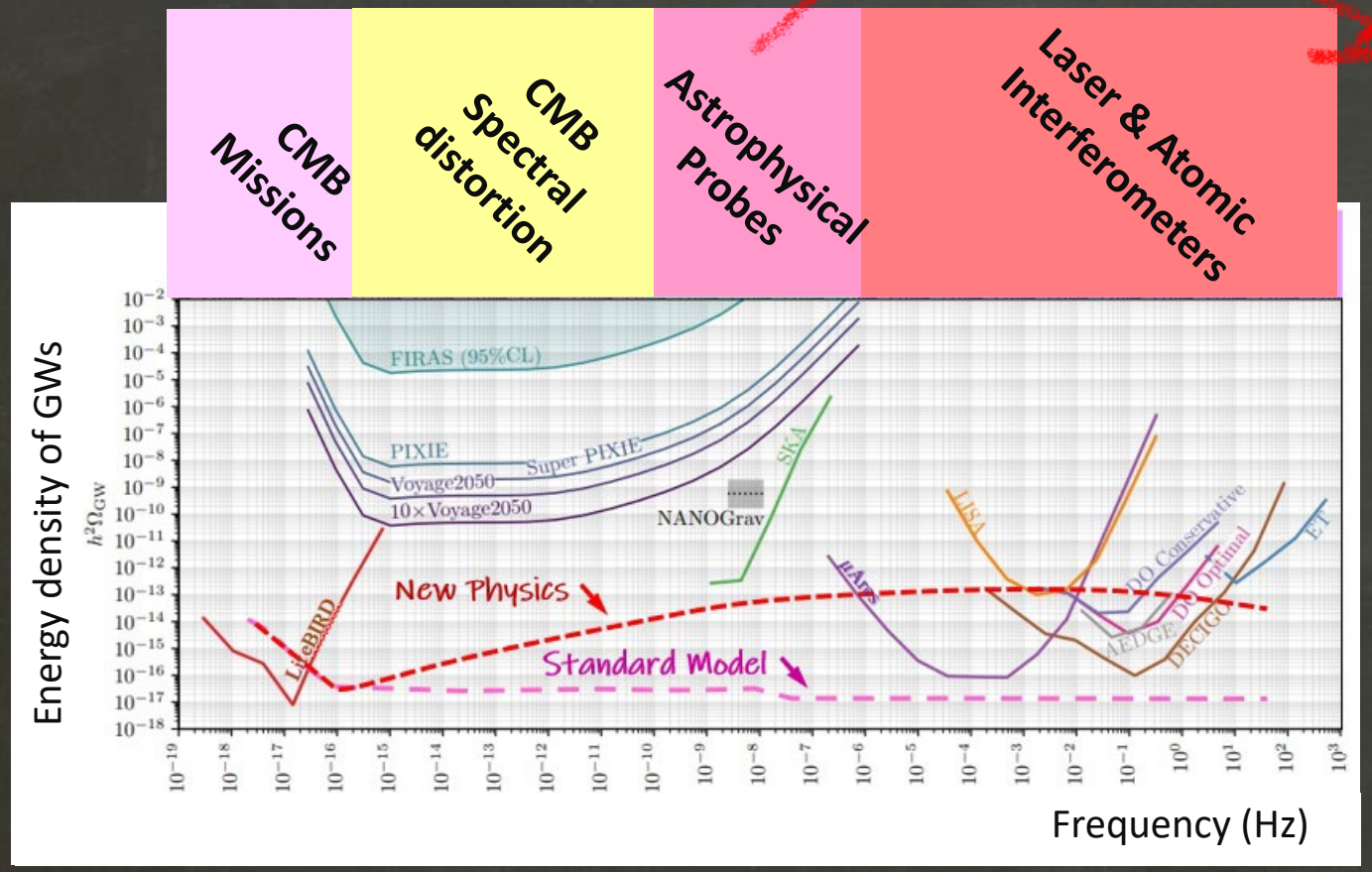
What about Gauge Fields?!

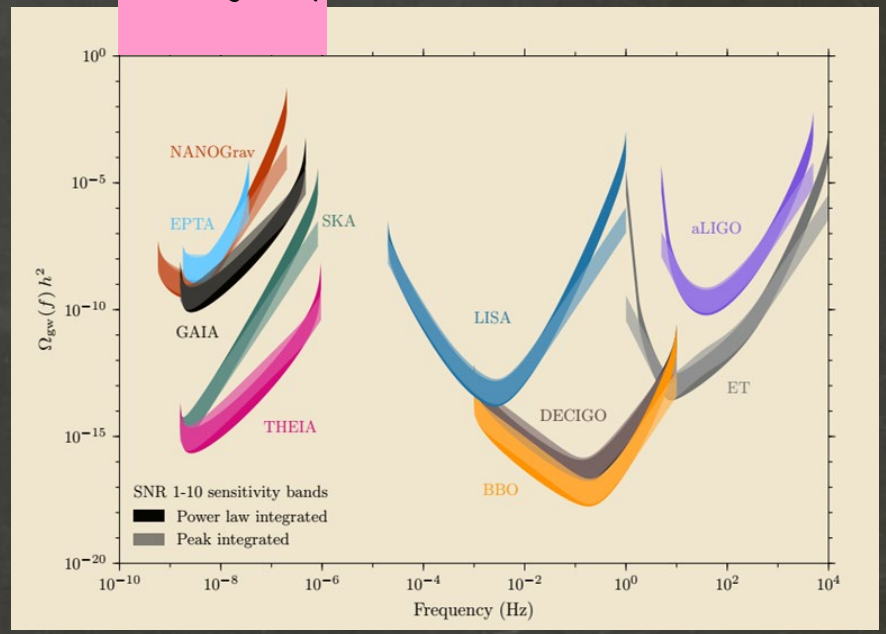
- Inflation happened at highest energy scales observable!
- They are building blocks of particle physics, SM & beyond.
- What do they do in inflation?!



Sensitivity curves on energy density of GWs



P. Campeti, E. Komatsu, D. Poletti, C. Baccigalupi 2021



J. Garcia-Bellido, H. Murayama, and G. White 2021

Challenges:

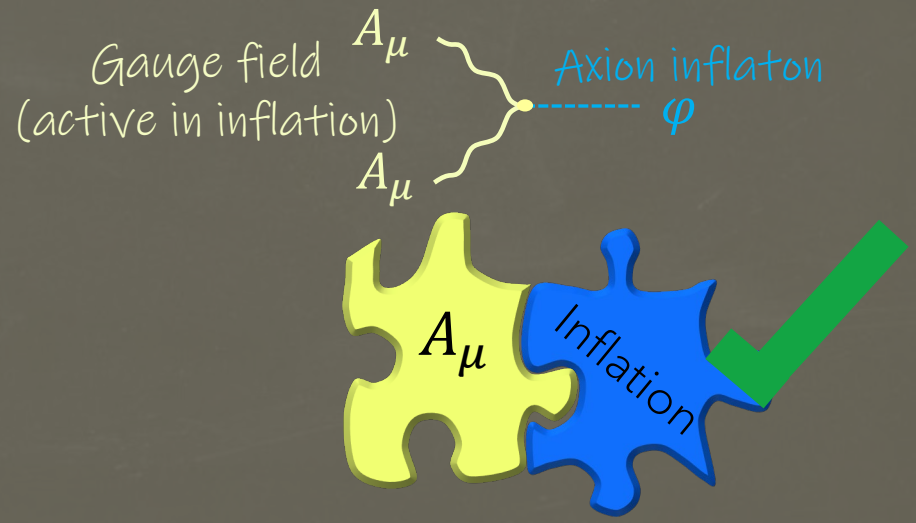
Gauge fields given by Yang-Mills

dilutes like radiation $A_\mu \sim 1/a$

Gauge fields coupled to inflaton are generated in inflation.

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

(Axion fields are naturally coupled to gauge fields.)



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Spatial isotropy & homogeneity

U(1) vacuum $\boldsymbol{A_\mu}$

$$\boldsymbol{A_i = Q(t)\delta_i^3}$$

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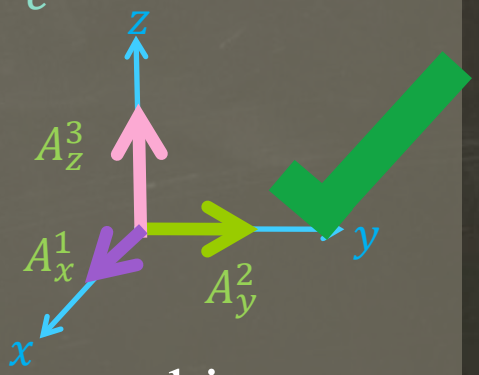
A.M. & Sheikh-Jabbari, 2011

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

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

Spatially isotropic

$$\boldsymbol{A_i^a = Q(t)\delta_i^a}$$



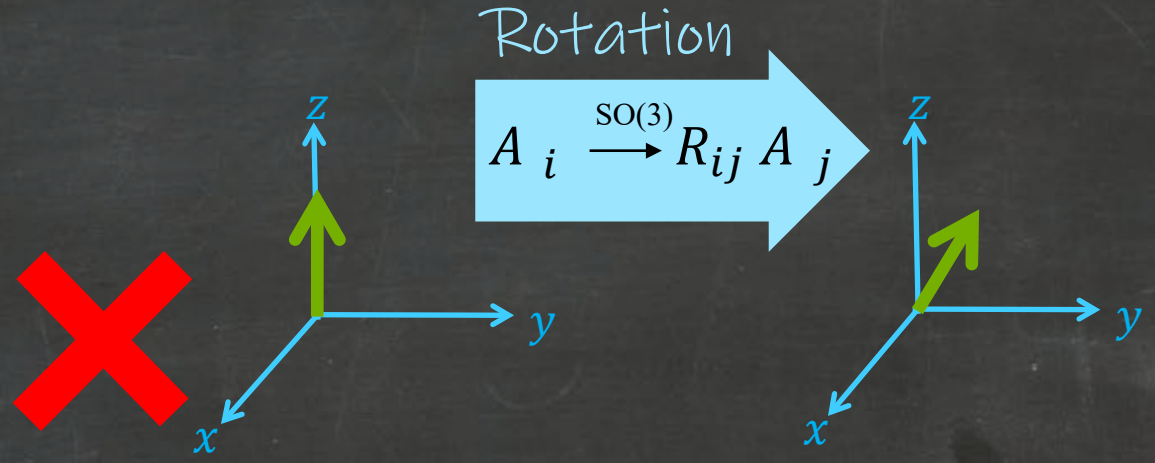
so(3) & su(2) are isomorphic

How SU(2) restores isotropy?

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

U(1) vacuum A_μ

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



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

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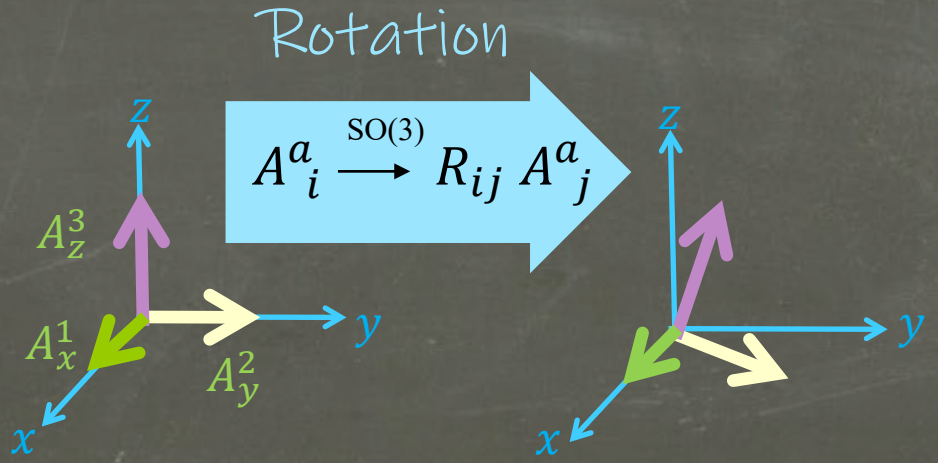

A.M. and M. M. Sheikh-Jabbari, 2011

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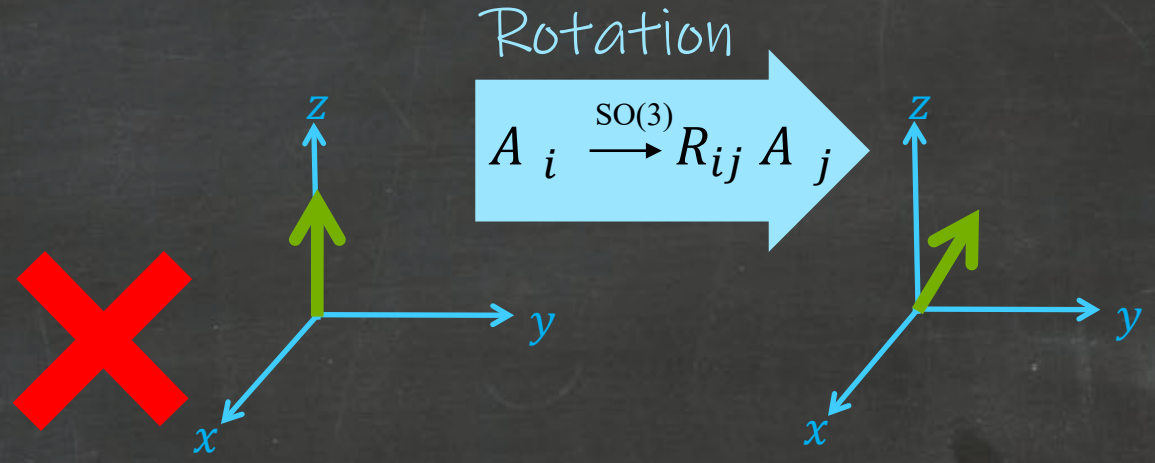

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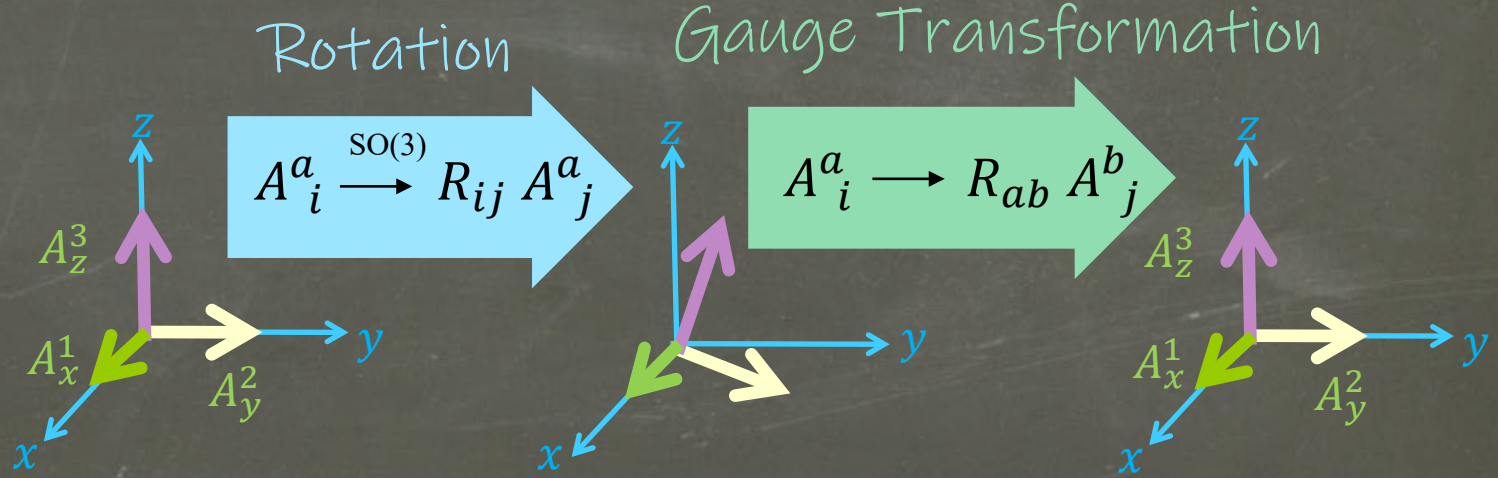


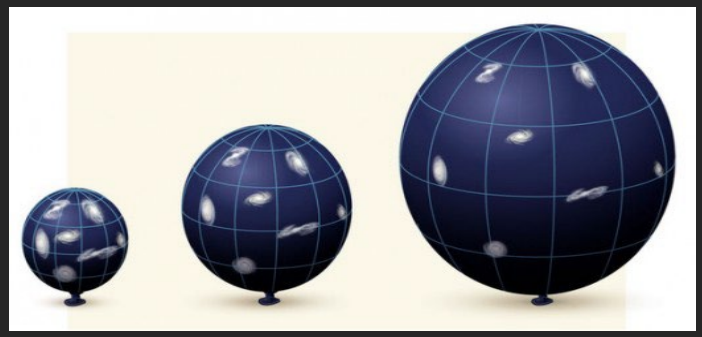
A.M. and M. M. Sheikh-Jabbari, 2011

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

SU(2) Gauge fields and Initial Anisotropies

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

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

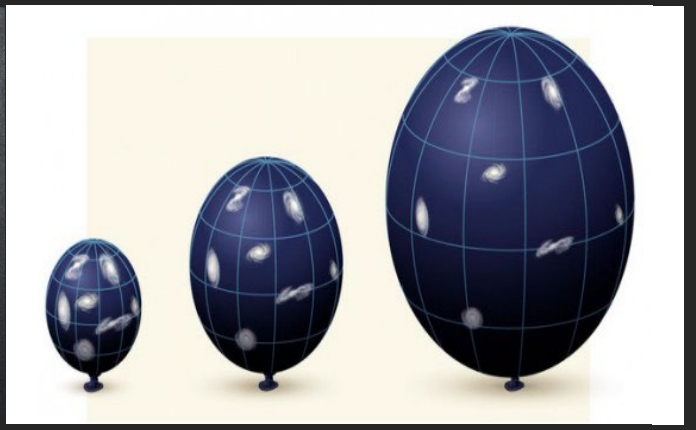


Isotropic Background

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

$$A^a_\mu(t) = \begin{cases} 0 & \mu = 0 \\ Q(t)a(t)\delta^a_j \, e^{\lambda_{ij}(t)} & \mu = i \end{cases}$$

Anisotropies in gauge field $Tr[\lambda_{ij}(t)] = 0$



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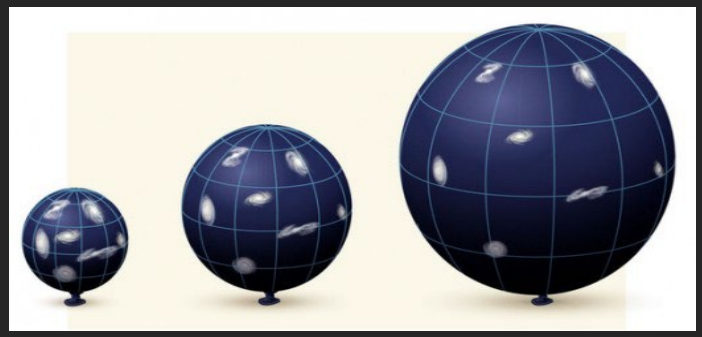

Isotropic Background

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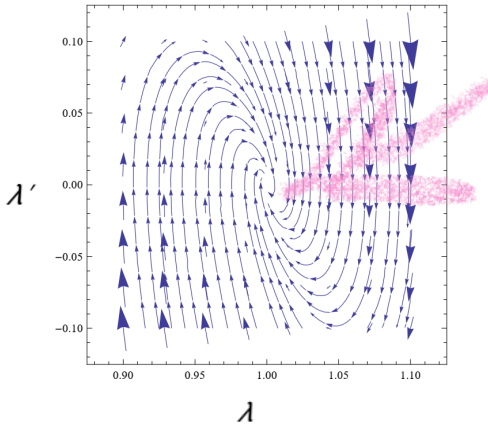
I. Wolfson, A. M., T. Murata, E. Komatsu, T. Kobayashi arXiv:2105.06259

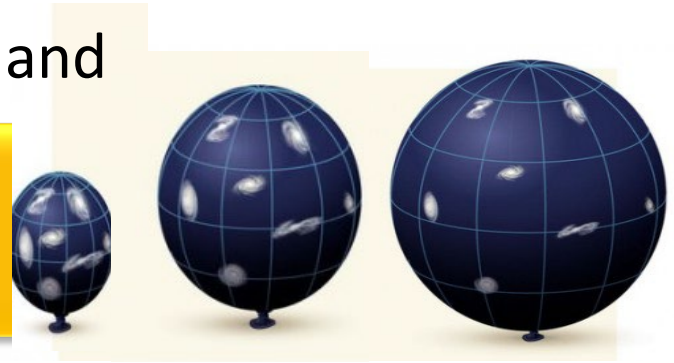
Axion is only coupled to the isotropic part of the gauge field,

Anisotropic part decays like radiation and



Isotropic Solution is the Attractor!

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



Anisotropic Background

An incomplete list of Different Realizations of the SU(2)-Axion Inflation:

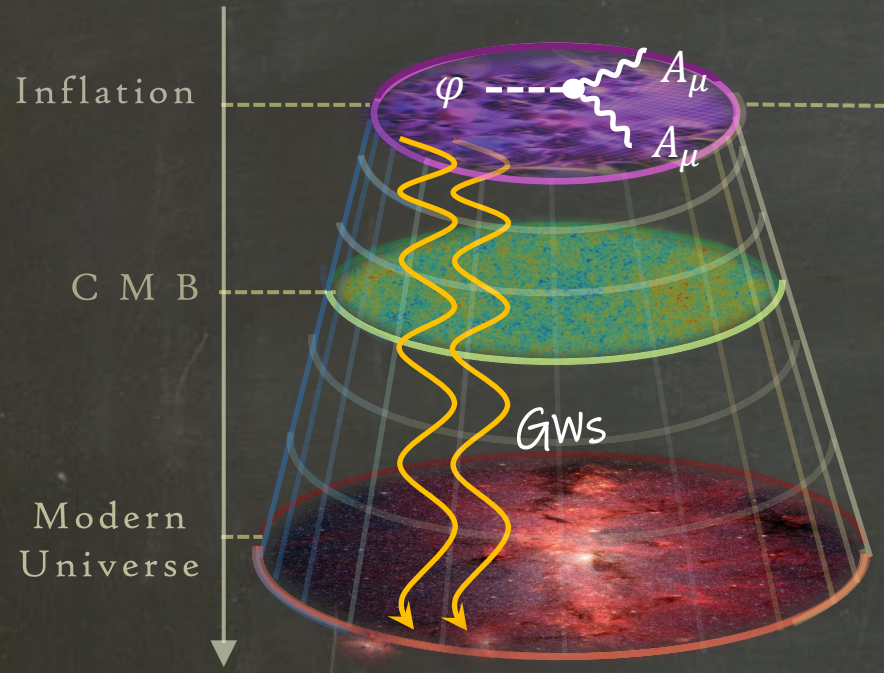
1. **A. M.** and M. M. Sheikh-Jabbari, Phys. Rev. D 84:043515, 2011 [*arXiv:1102.1513*]
2. P. Adshead, M. Wyman, Phys. Rev. Lett.(2012) [*arXiv:1202.2366*]
3. **A. M.** JHEP 07 (2016) 104 [arXiv:1604.03327]
4. C. M. Nieto and Y. Rodriguez Mod. Phys. Lett. A31 (2016) [arXiv:1602.07197]
5. E. Dimastrogiovanni, M. Fasiello, and T. Fujita JCAP 1701 (2017) [arXiv:1608.04216]
6. P. Adshead, E. Martinec, E. I. Sfakianakis, and M. Wyman JHEP 12 (2016) 137 [arXiv:1609.04025]
7. P. Adshead and E. I. Sfakianakis JHEP 08 (2017) 130 [arXiv:1705.03024]
8. R. R. Caldwell and C. Devulder Phys. Rev. D97 (2018) [arXiv:1706.03765]
9. E. McDonough, S. Alexander, JCAP11 (2018) 030 [arXiv:1806.05684]
10. L. Mirzagholi, E. Komatsu, K. D. Lozanov, and Y. Watanabe, [arXiv:2003.04350]
11. Y. Watanabe, E. Komatsu, [arXiv:2004.04350]
12. J. Holland, I. Zavala, G. Tasinato, [arXiv:2009.00653]
13. A. M. **SU(2)R –axion inflation** [arXiv:2012.11516]
14. Oksana Iarygina, Evangelos I. Sfakianakis, [arXiv:2105.06972]
15. T. Fujita, Nakatsuka, K. Mukaida, & K. Murai [arXiv:2110.03228]

A New Class of Inflation Models

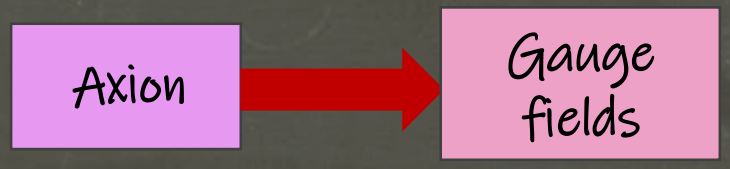
(closer to Particle Physics)

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

Axion-inflation and gauge fields (non-Abelian)



Particle Production
In Axion-Inflation



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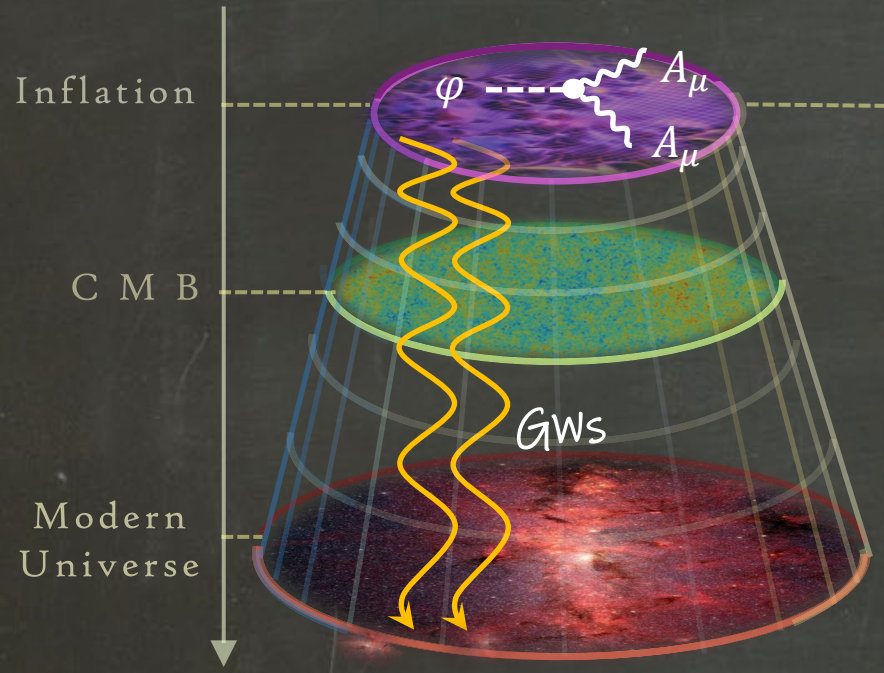

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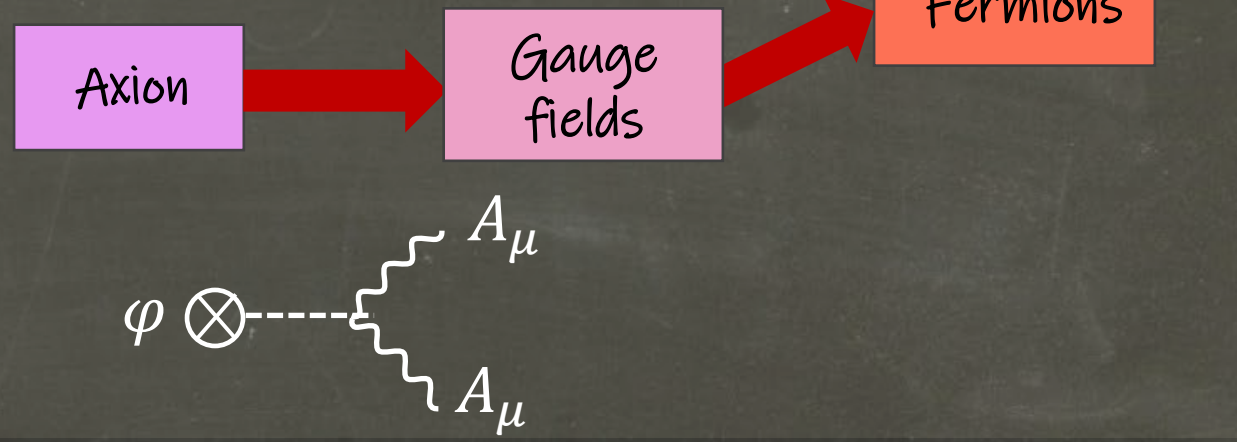

A.M., 2019
Mirzagholi, A.M., Lozanov 2019

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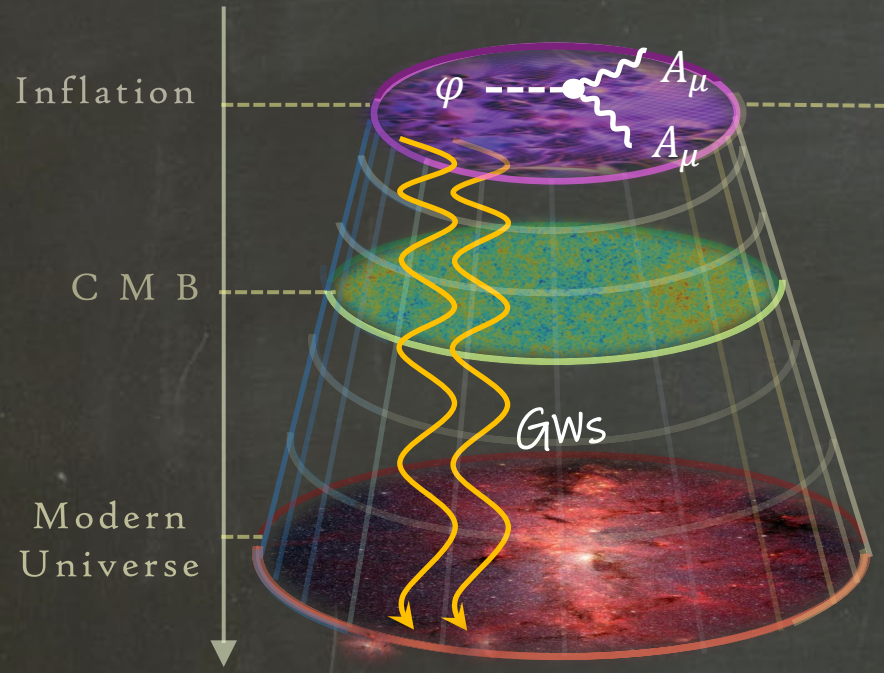

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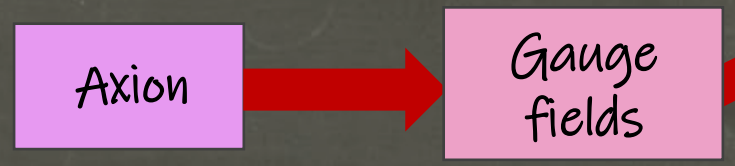

Fermions

A new mechanism
for Fermion Production in
Inflation!

A.M., 2019
Mirzagholi, A.M., Lozanov 2019

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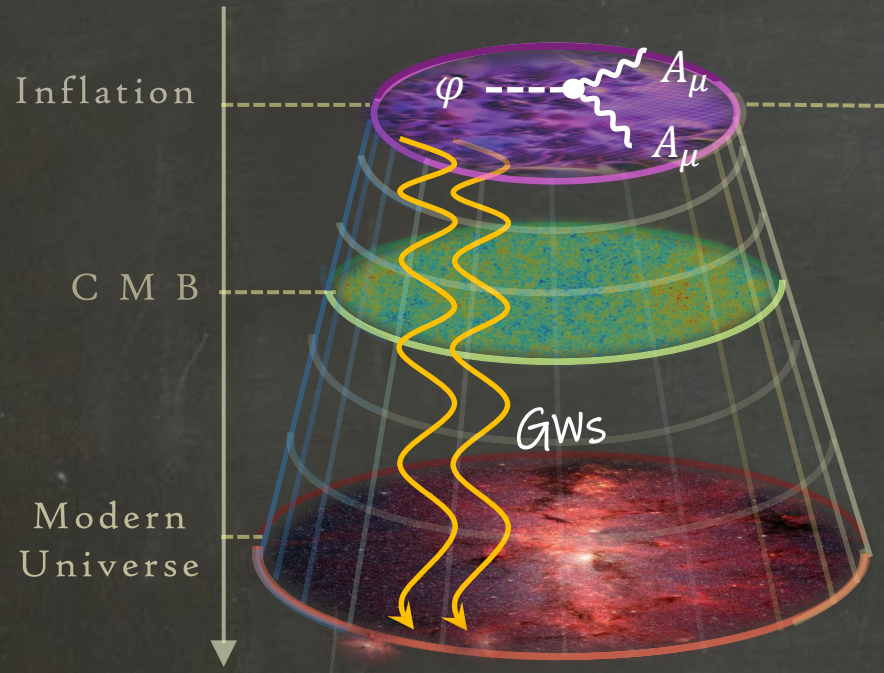
(closer to Particle Physics)



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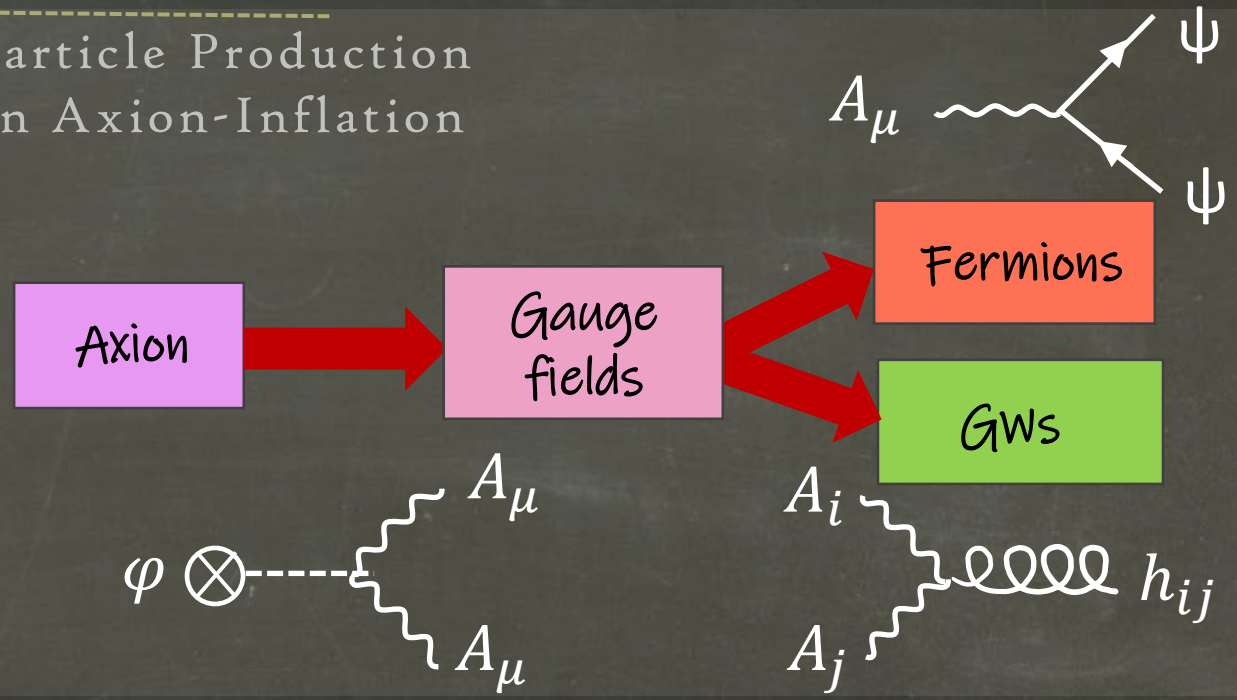

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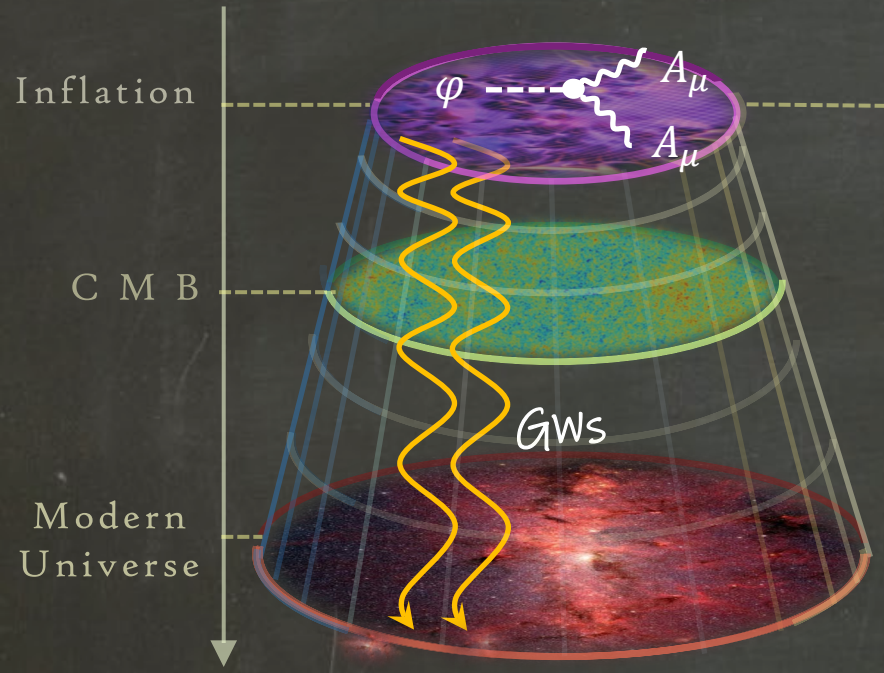

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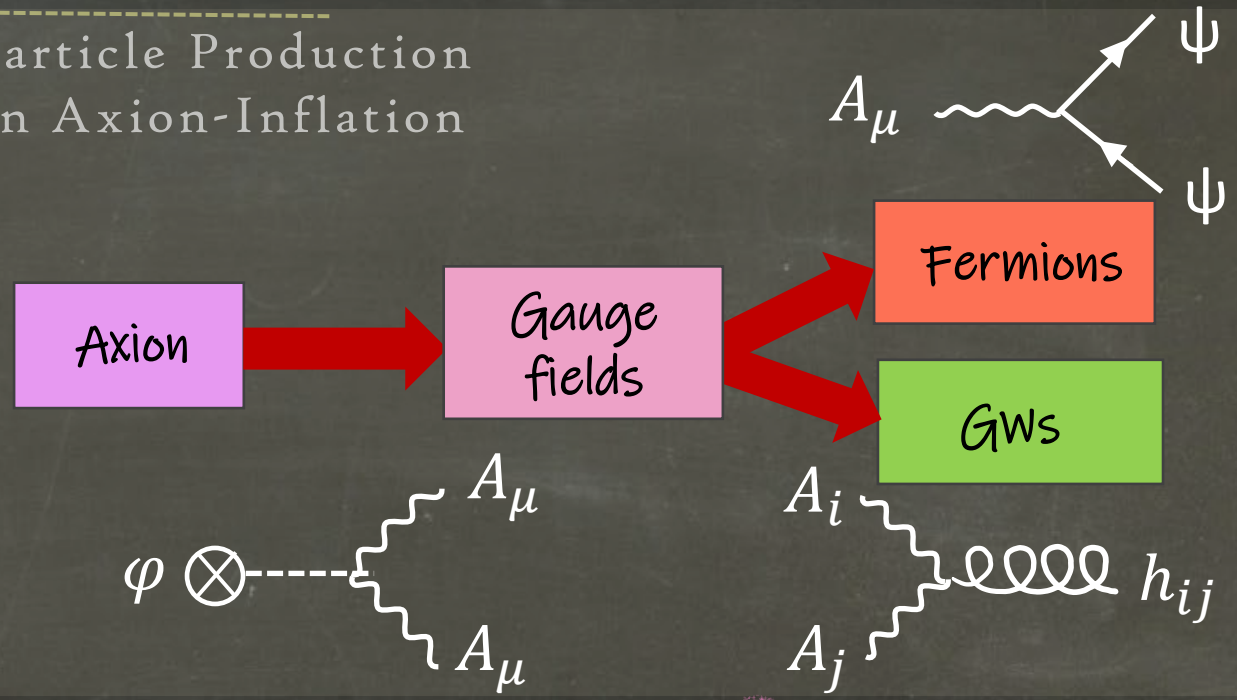

Sourced GWs:
Chiral & non-Gaussian

A.M., 2019
Mirzagholi, A.M., Lozanov 2019
A. M. et. al, 2011 & 2013
Dimastrogiovanni et. al 2013
P. Adshead et. al,2013

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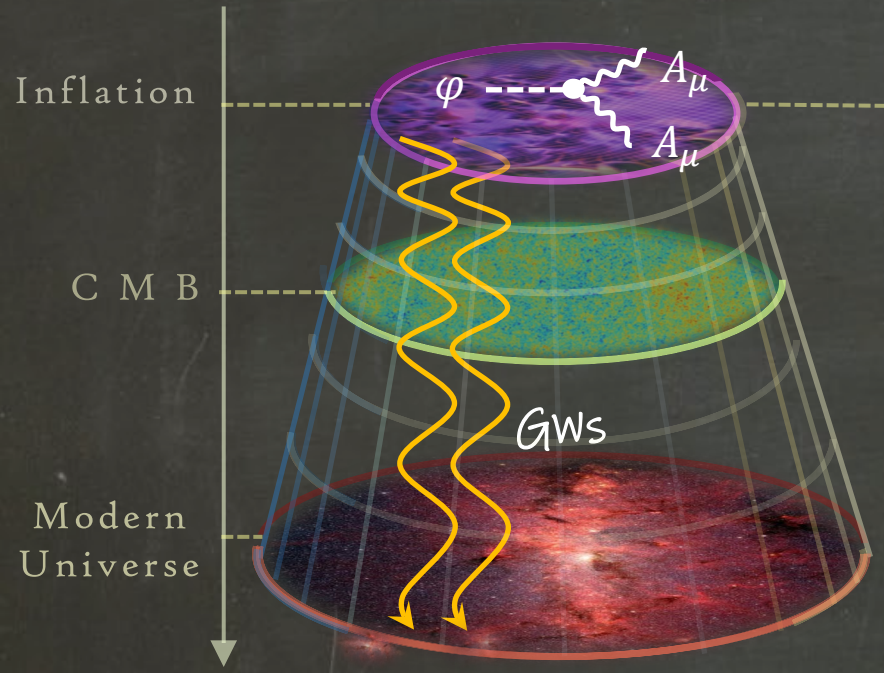

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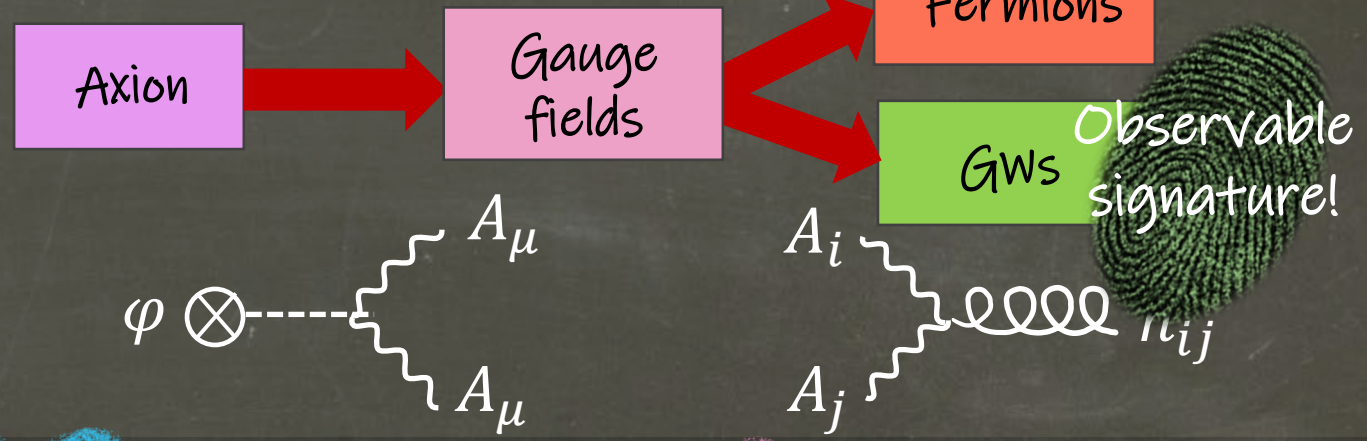

Vacuum GWs:
Unpolarized & Gaussian

Sourced GWs:
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A.M., 2019
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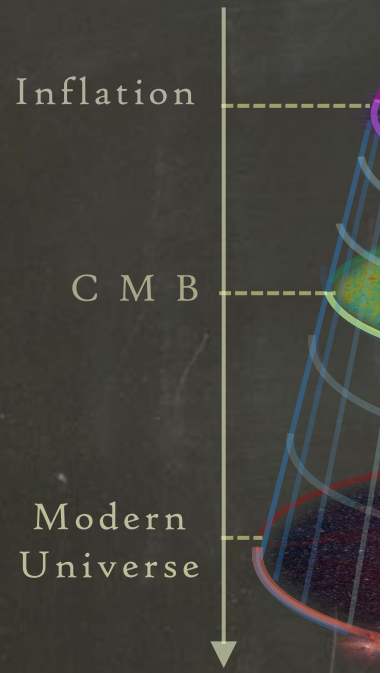

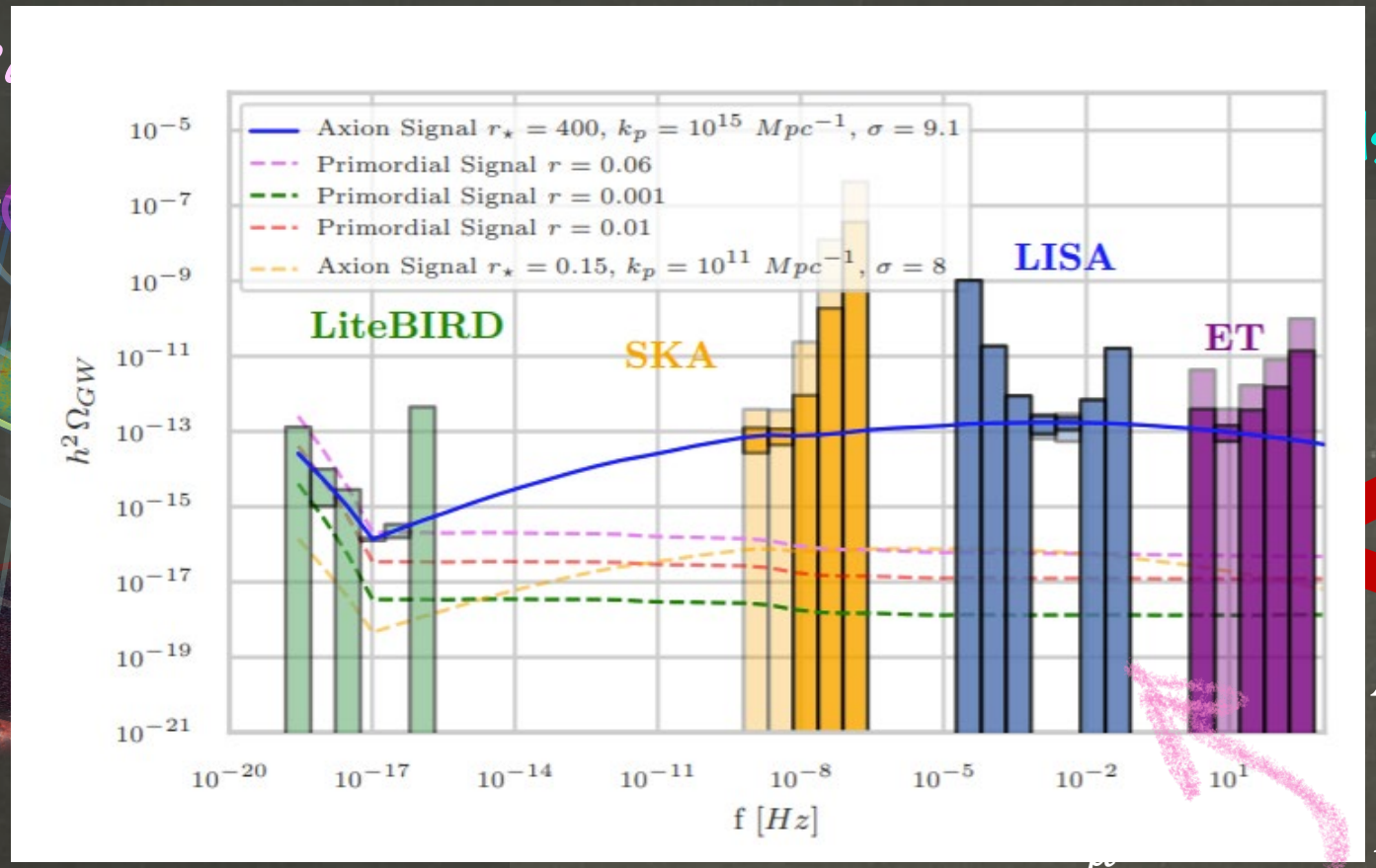

P. Campeti, E. Komatsu, D. Poletti, C. Baccigalupi 2020

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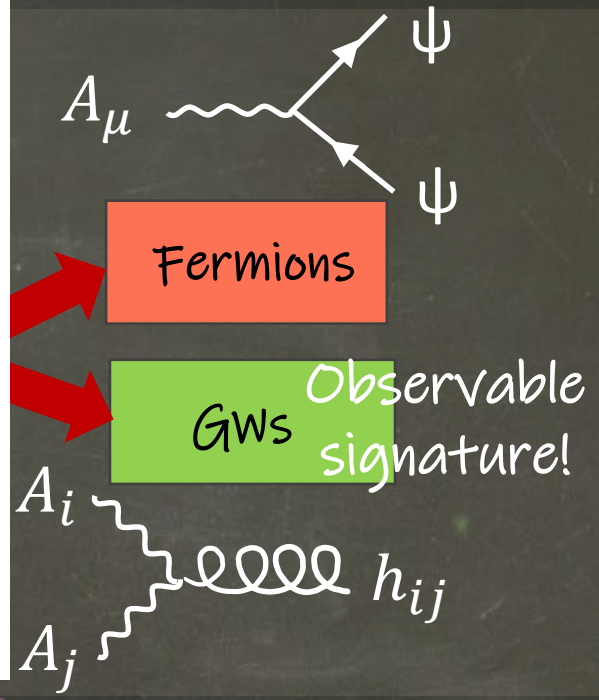

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Vacuum GWs:
Unpolarized & Gaussian

Sourced GWs:
Chiral & non-Gaussian

Novel Observable Signature: CMB

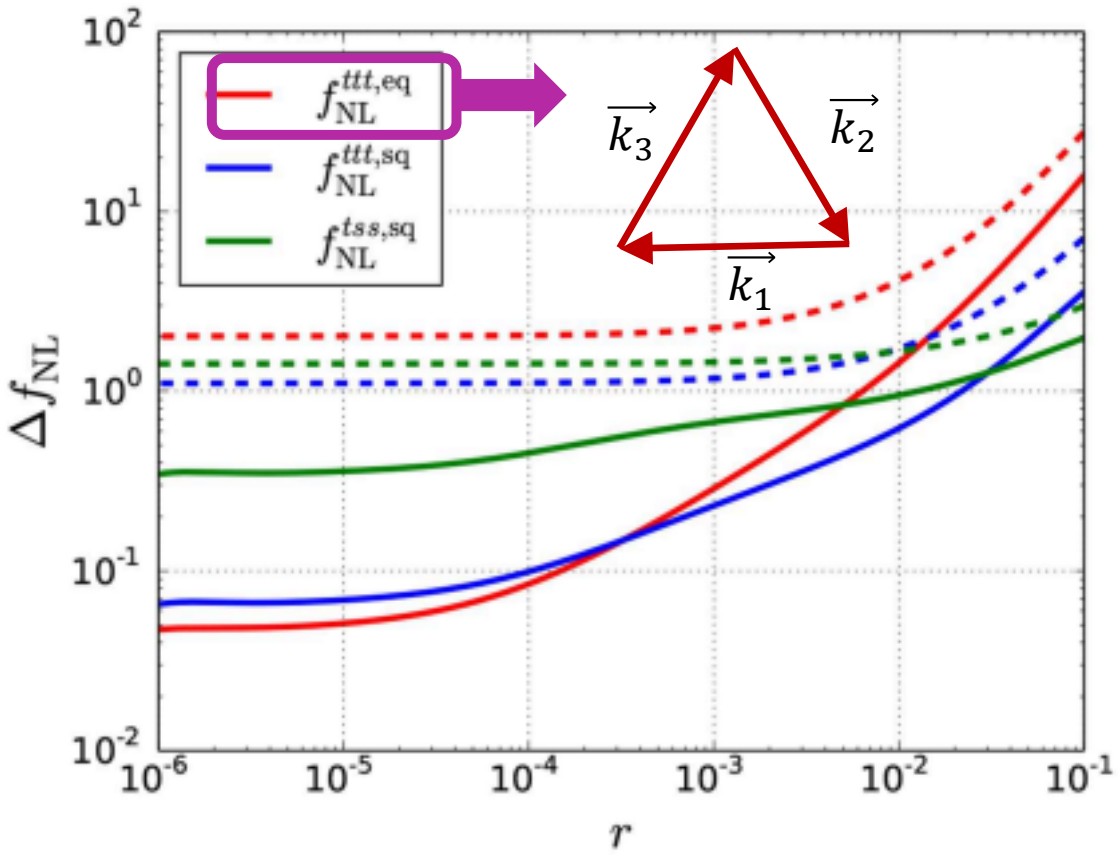
- The sourced tensor modes is Highly non-Gaussian.

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu - \underbrace{ig\,[A_\mu, A_\nu]}_{\text{Self-interaction}}$$

Agrawal, Fujita, Komatsu 2018

- That can be probe with future CMB missions., e.g. *Litebird* and *CMB-S4*!

Equilateral Shape

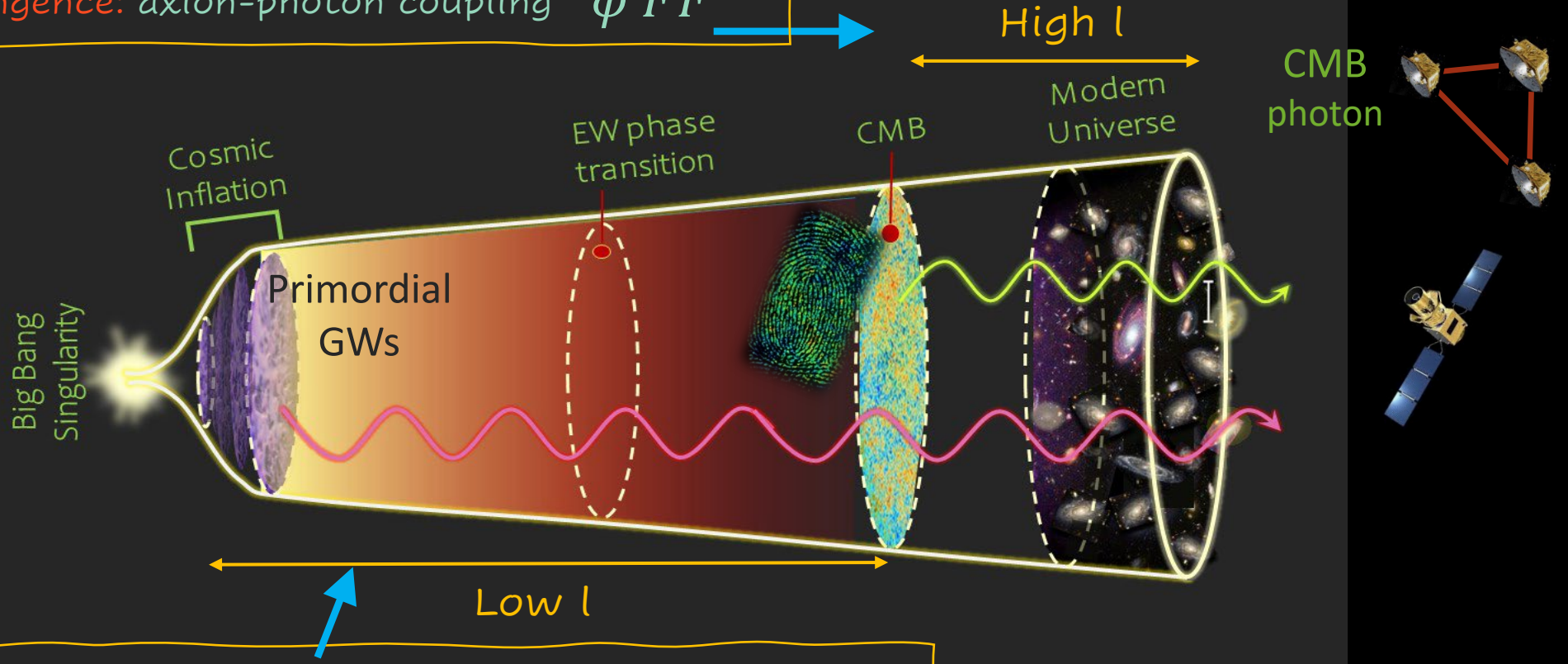


Maresuke Shiraishi, Front. Astron. Space Sci. 2019

Parity Odd CMB Correlations: TB & EB ≠ 0

Sources of Parity violation on CMB:

- Cosmic Birefringence: axion-photon coupling $\varphi F\tilde{F}$



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B. Thorne et. al.2018

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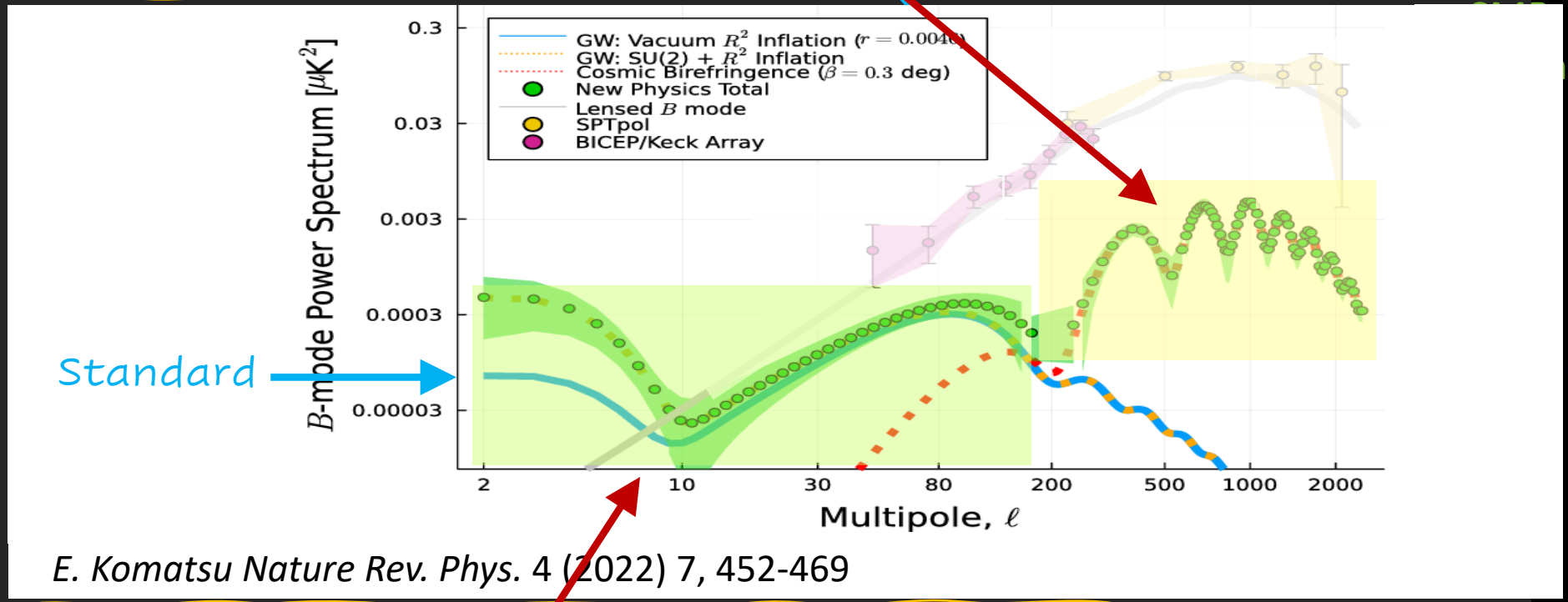

Standard

E. Komatsu Nature Rev. Phys. 4 (2022) 7, 452-469

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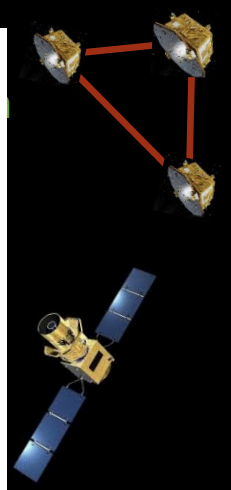
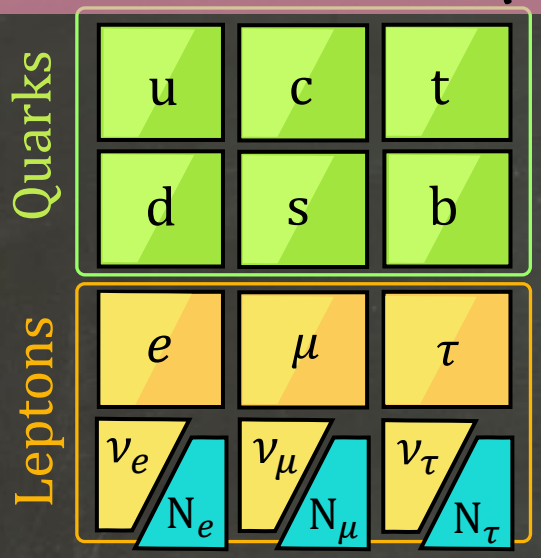
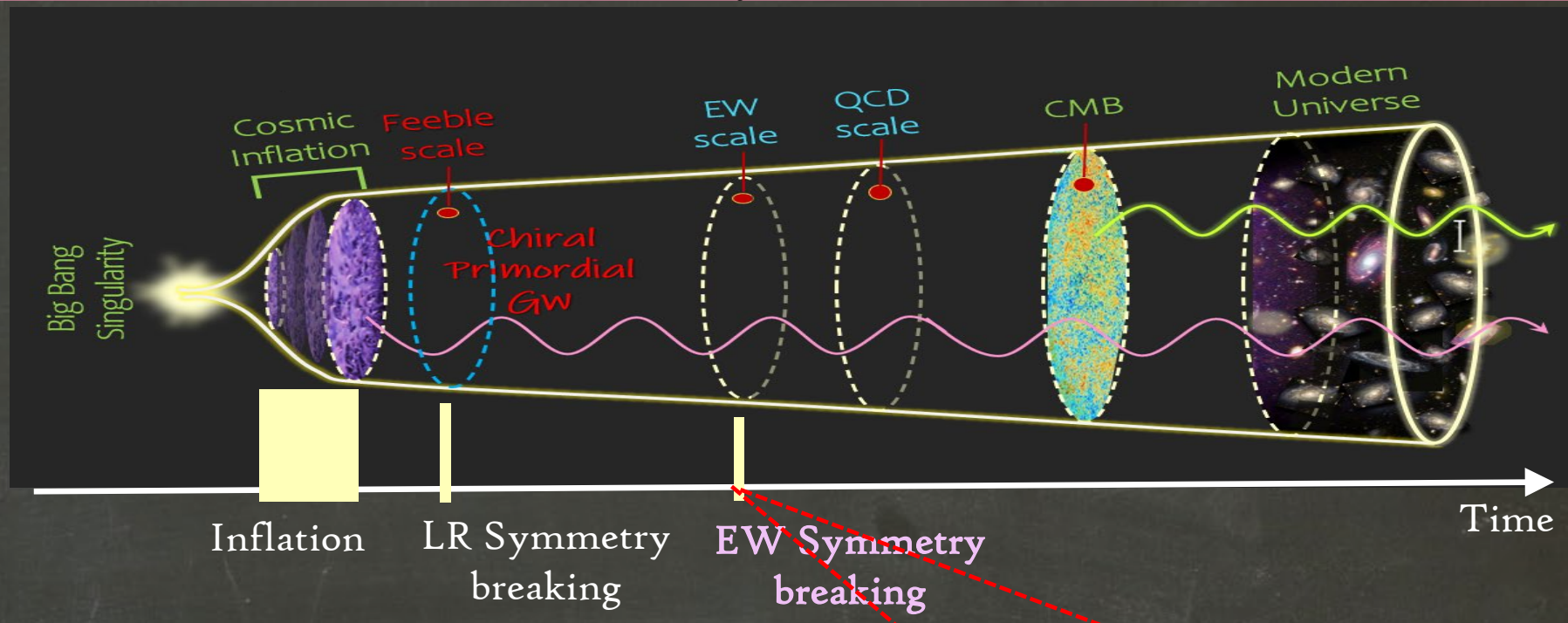
- Gravitational Chern-Simons: axion-graviton coupling $\varphi R\tilde{R}$

B. Thorne et. al.2018

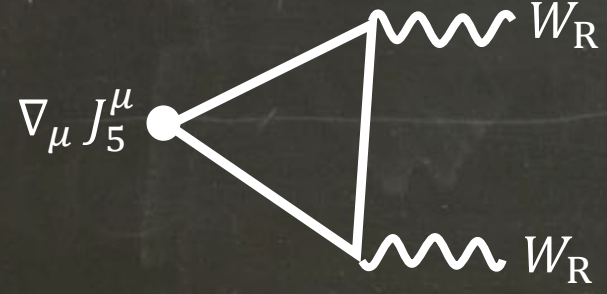


Summary of the Inflationary Baryogenesis mechanism:

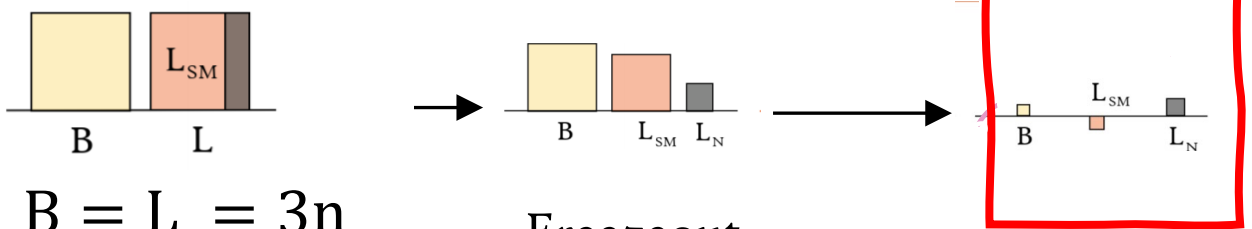




Chiral anomaly of SU(2)R
In inflation



A. M. 2021

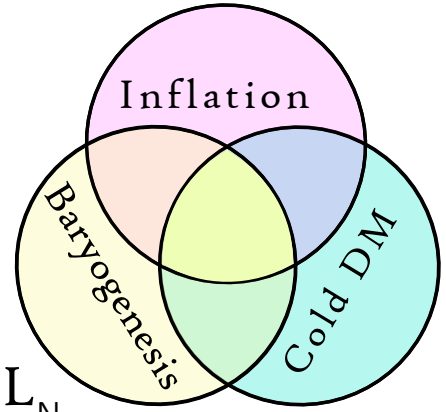


$B = L = 3n_{CS}$

$B - L_{SM} \neq 0$

Freezeout of W_R

Spectator effects reshuffle B, L_{SM} & L_N



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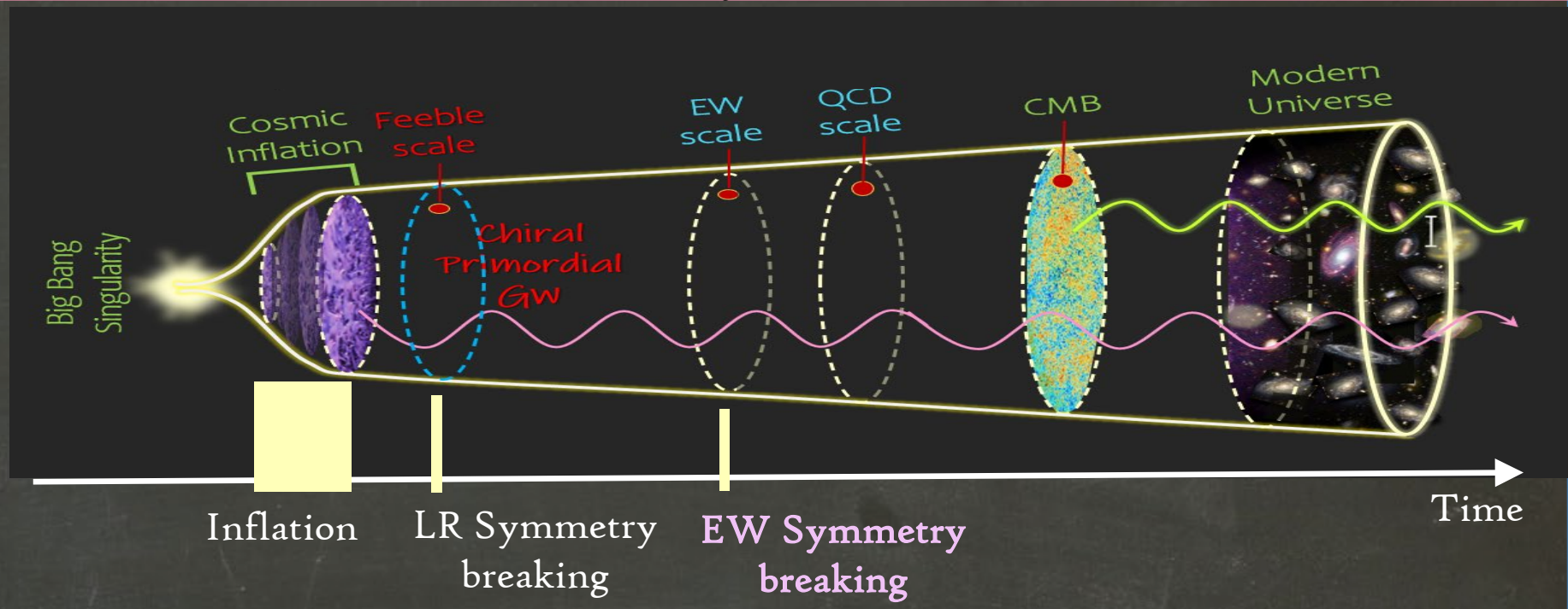
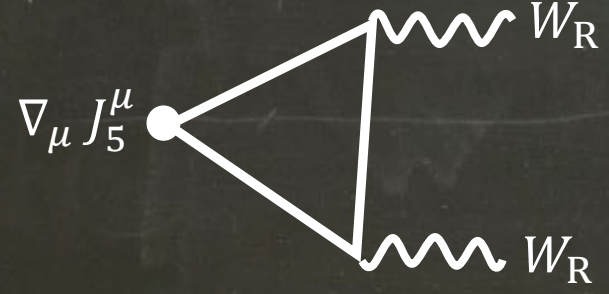
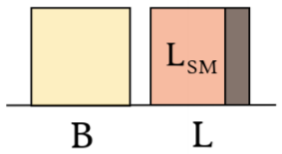


Chiral anomaly of SU(2)R
In inflation

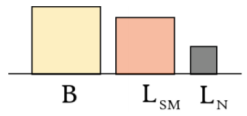


A. M. 2021

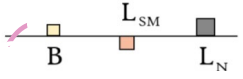


$$B = L = 3n_{CS}$$

$$B - L_{SM} \neq 0$$



Freezeout of W_R



DM

$$\Omega_{N_1} \approx 2.8 \frac{m_{N_1}}{m_p} \Omega_B$$

$$m_{N_1} \simeq 1.8\, m_p = 1.7\ GeV.$$

Baryogenesis

$$\eta_B^0 \approx 3 \left(\frac{g_{eff}}{100}\right)^{\frac{3}{4}} \frac{\alpha_{inf}(\xi)}{(\delta_{reh})^{\frac{3}{4}}} \left(\frac{H}{M_{Pl}}\right)^{\frac{3}{2}}$$

Gauge fields are expected to contribute in physics of axion inflation.

Compelling Consequences:

This Set-up is a complete BSM that can solve I-IV:

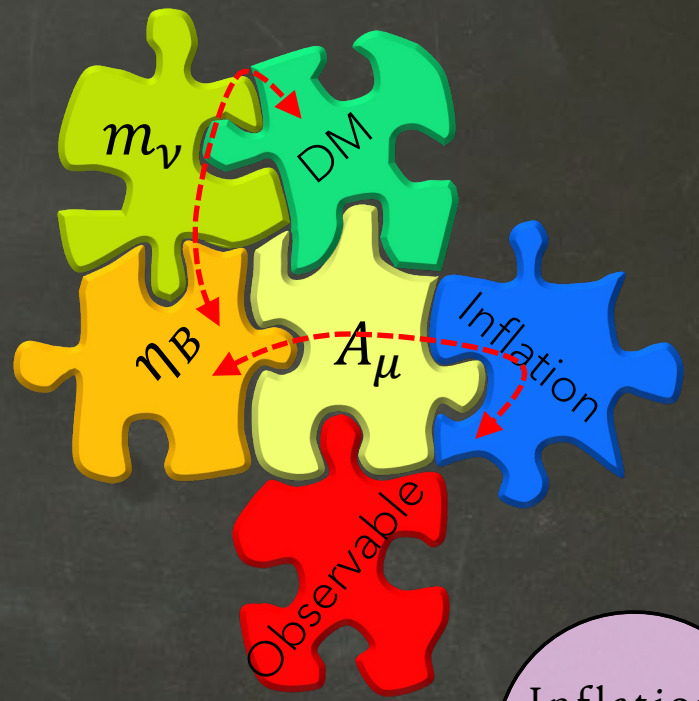
Puzzles of Particle Cosmology

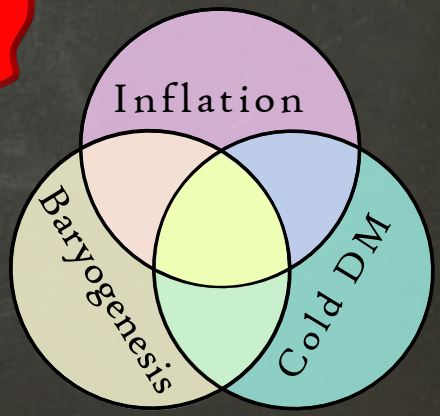
I) Particle physics of Inflation

II) Origin of matter asymmetry

III) Origin of Neutrino mass

IV) Particle nature of DM





It provides a deep connection between inflation, baryogenesis & DM,

So naturally explains cosmological coincidences $\eta_B \simeq 0.3\, P_\zeta$ and $\Omega_{DM} \simeq 5\Omega_B$!

It comes with a cosmological smoking gun on Primordial GWs.