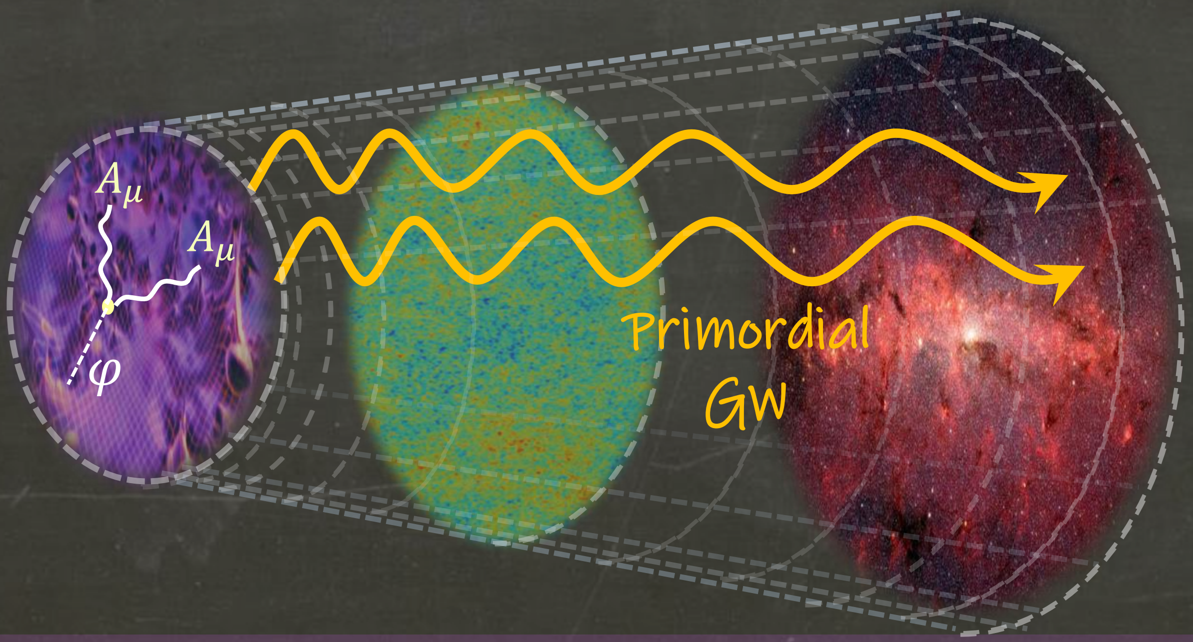
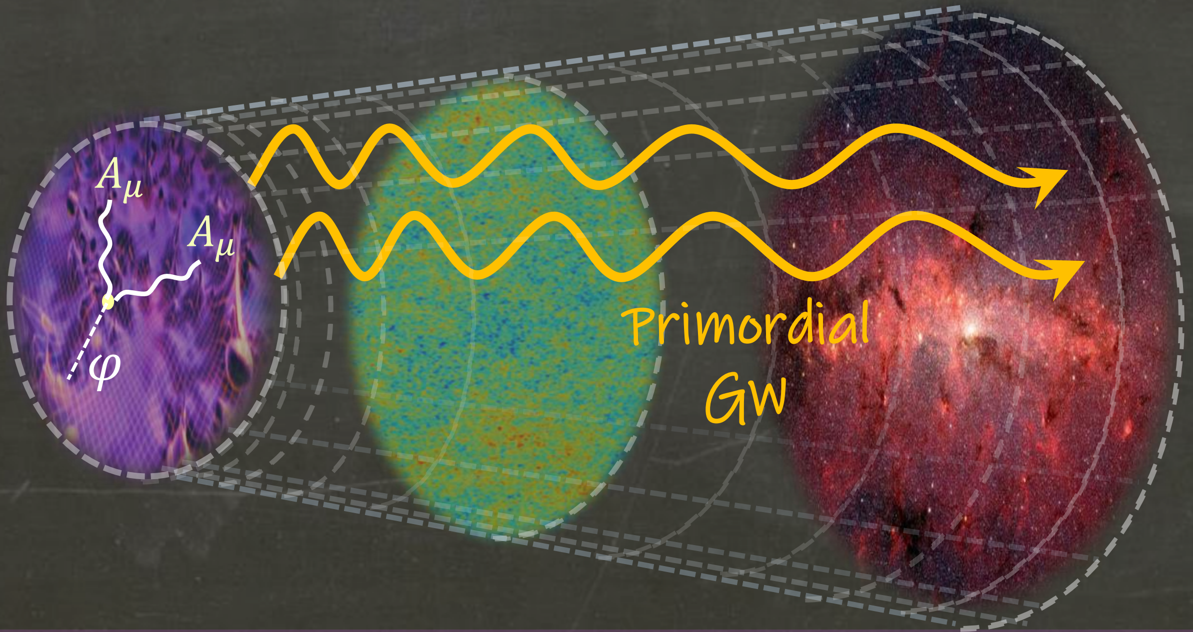
Gauge Fields in Inflation, Origin of Matter, and Gravitational Waves

Azadeh Malek-Nejad
CERN



Setup

1. What We Already Know about Early Universe.
2. Gauge Fields in Inflation: Why & How?
3. Primordial GWs & Gauge Fields



Setup

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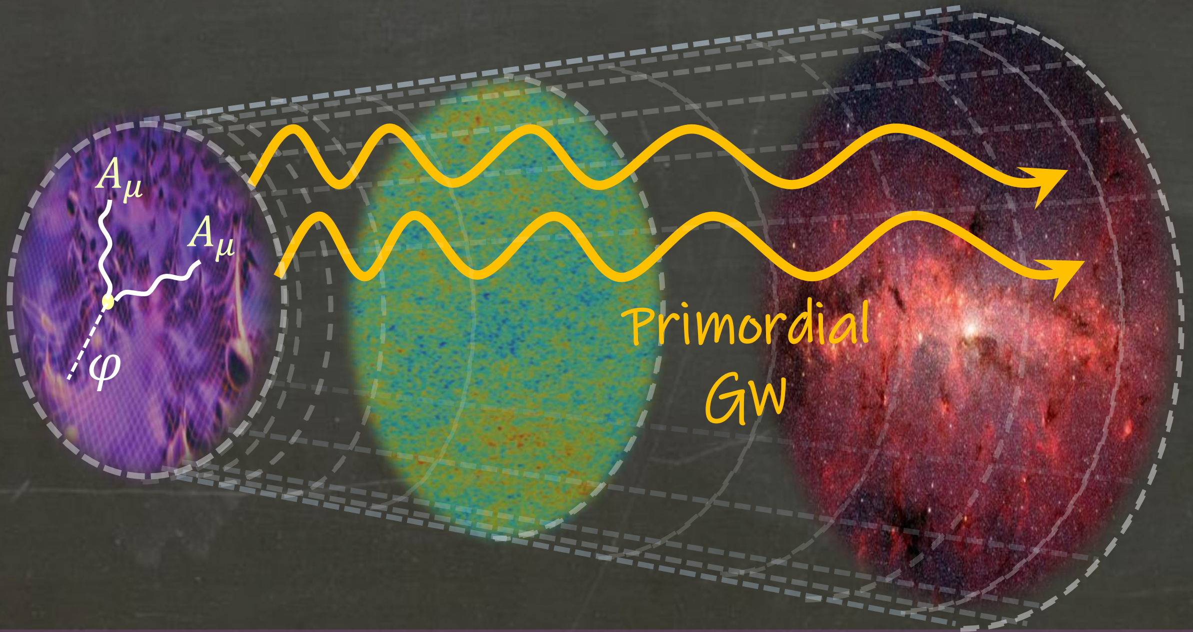
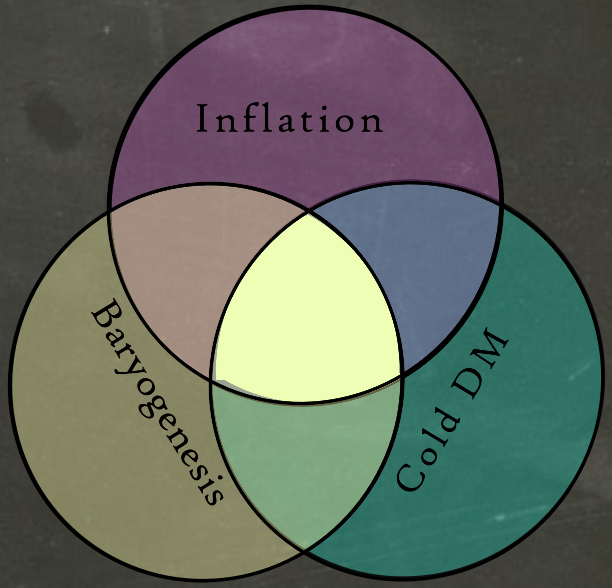
2. Gauge Fields in Inflation: Why & How?
3. Primordial GWs & Gauge Fields
4. Let's Embed axion-inflation in Left-Right Symmetric models





Puzzles of SM & Cosmology

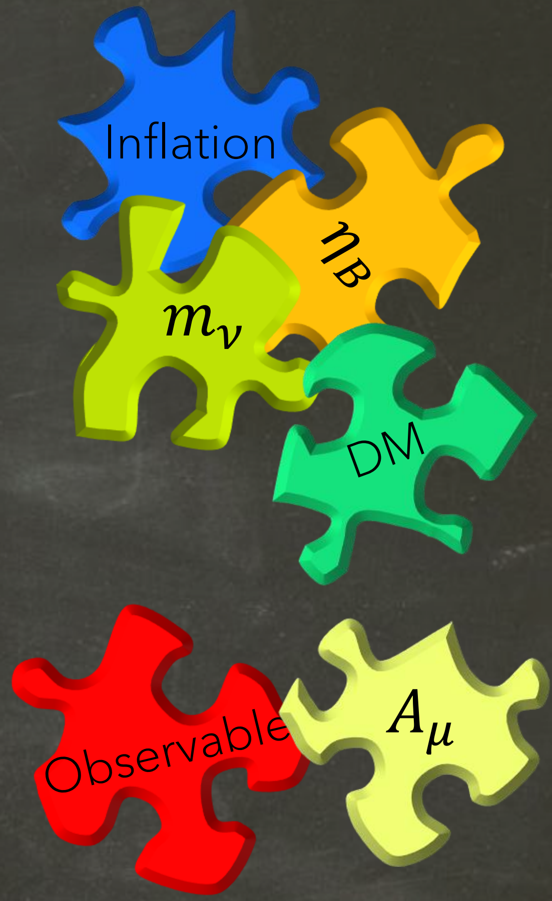
I) Particle physics of Inflation

II) Origin of matter asymmetry

III) Origin of Neutrino mass

IV) Particle nature of DM

Puzzles of
Standard Model of Particle Physics (SM)
& Cosmology which need
Physics Beyond SM



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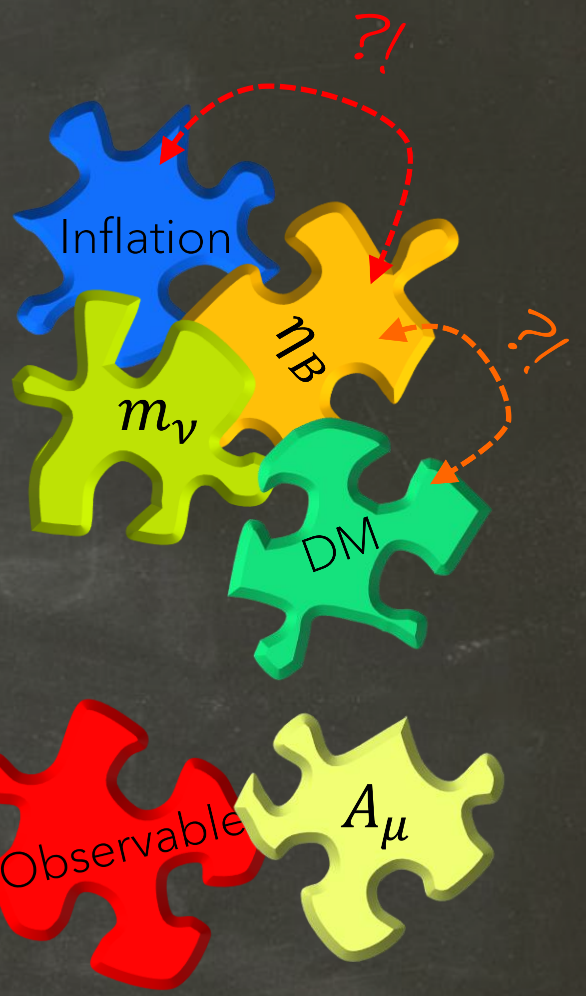

- Curious cosmological coincidences $\eta_B \simeq 0.3\, \mathrm{P}_\zeta$ and $\Omega_{DM} \simeq 5\Omega_B$!

$$\eta_B = \frac{\mathrm{n}_B - \mathrm{n}_{\bar{B}}}{\mathrm{n}_\gamma} \approx 6 \times 10^{-10}$$

Baryon to Photon Ratio Today

$$\mathrm{P}_\zeta = \frac{1}{2\epsilon}\left(\frac{1}{2\pi}\frac{H}{\mathrm{M}_{pl}}\right)^2 \approx 2 \times 10^{-9}$$

Curvature Power Spectrum in Inflation

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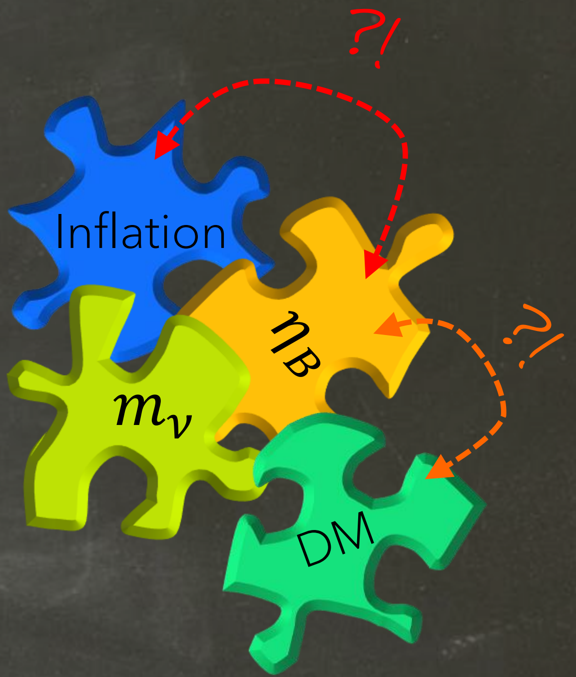

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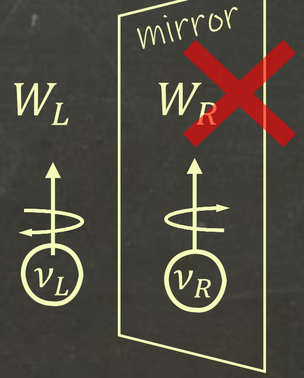
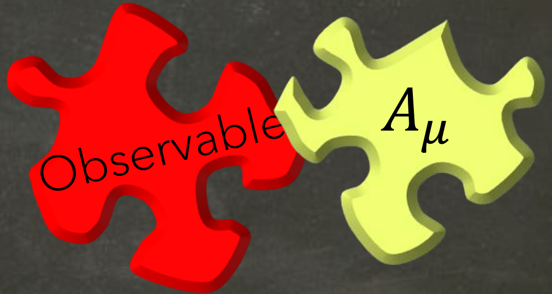
1. Ad hoc parity violation
2. Accidental B-L global symmetry
3. Vacuum Stability problem
4. Strong CP problem

SM as a particle physics model
also faces some **conceptual issues**



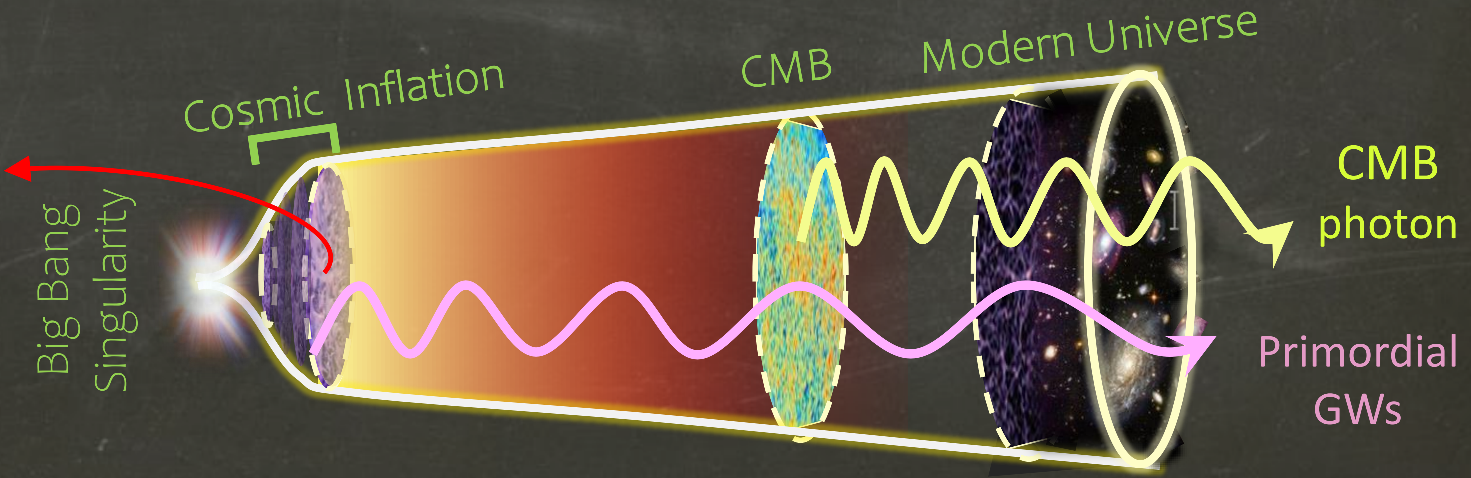


As Yet

- 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 singlet BSM

-Unpolarized, Gaussian GW



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What about Gauge Fields?!

Inflation Particle Physics:

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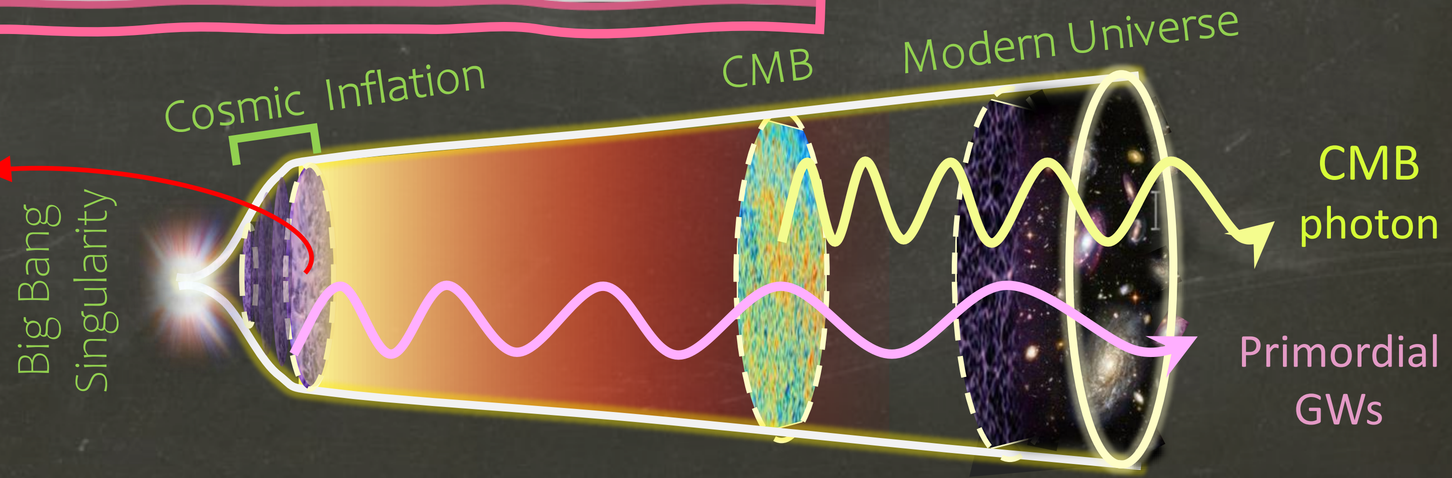
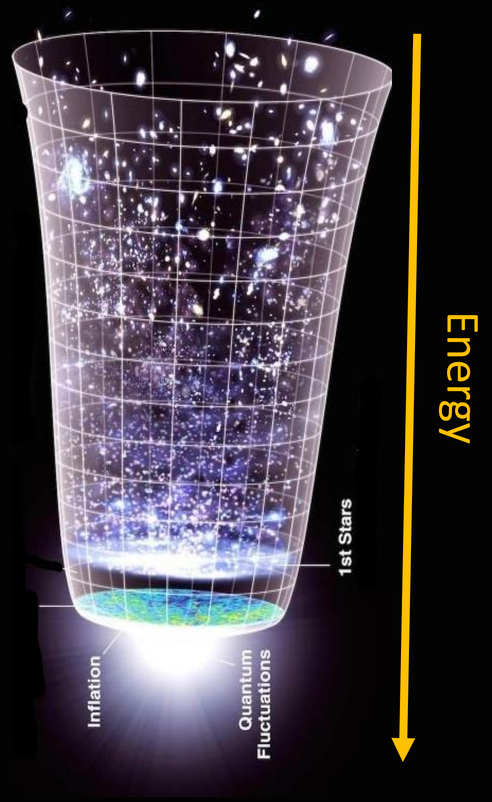


Gauge Fields & Inflation

Why Gauge Fields in Inflation?!

- Why not?
  - Inflation happened at highest energy scales observable!
  - Electromagnetic, Strong, and Weak forces shaped our Universe.
  - We are surrounded by Gauge fields. They are building blocks of nature.
- What do they do in inflation?



$E_{Inf} < 10^{14} GeV$

Comparing to LHC

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

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I. Can Gauge Fields Contribute to Physics of Inflation?
   Yes!

II. Do they leave an observable signature?
   Yes! Robust prediction for GW background.

III. How much they can change the cosmic history?
   A lot! Novel mechanisms for Baryo- and Dark-genesis.

$E_{Inf} < 10^{14} GeV$

Comparing to LHC

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

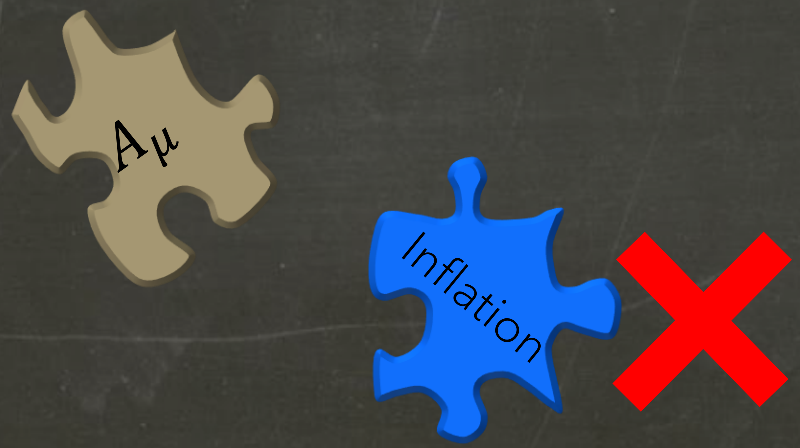
Challenges:

1) Conformal symmetry of Yang-Mills

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

2) Respecting gauge symmetry

   Not to break gauge symmetry explicitly



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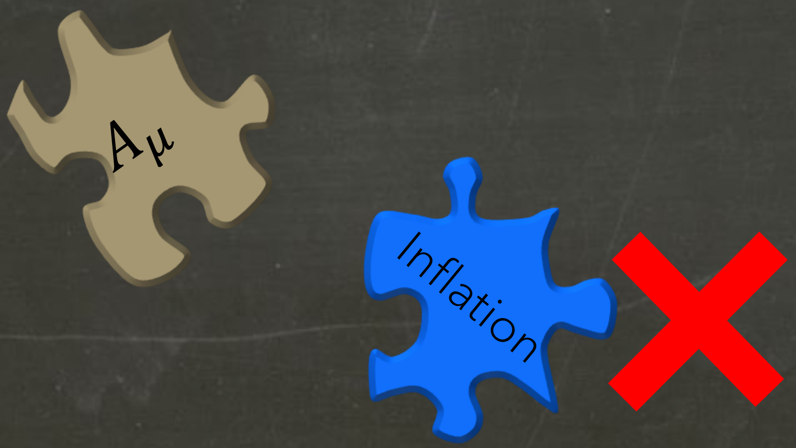


Adding new terms to the gauge theory

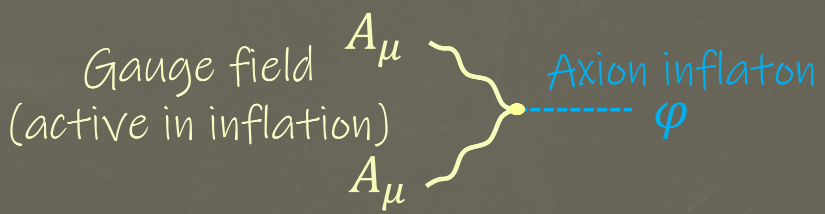
$$\frac{\kappa}{384}(F\tilde{F})^2$$

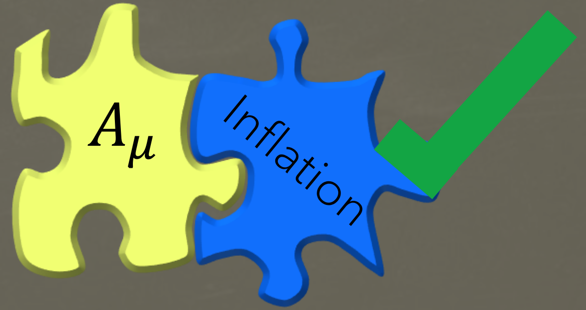
or

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

Axion

A.M. & Sheikh-Jabbari, 2011





Challenges:

1) Conformal symmetry of Yang-Mills

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

2) Respecting gauge symmetry

Not to break gauge symmetry explicitly

3) Spatial isotropy & homogeneity

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

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

A.M. & Sheikh-Jabbari, 2011

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Axion

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

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

Spatially isotropic

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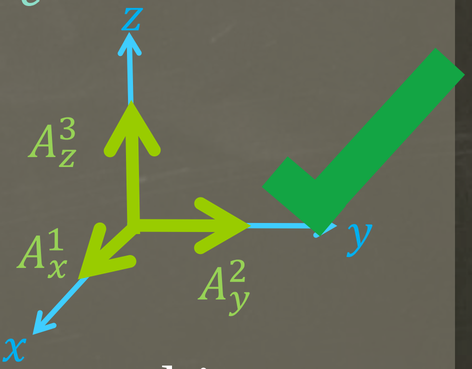


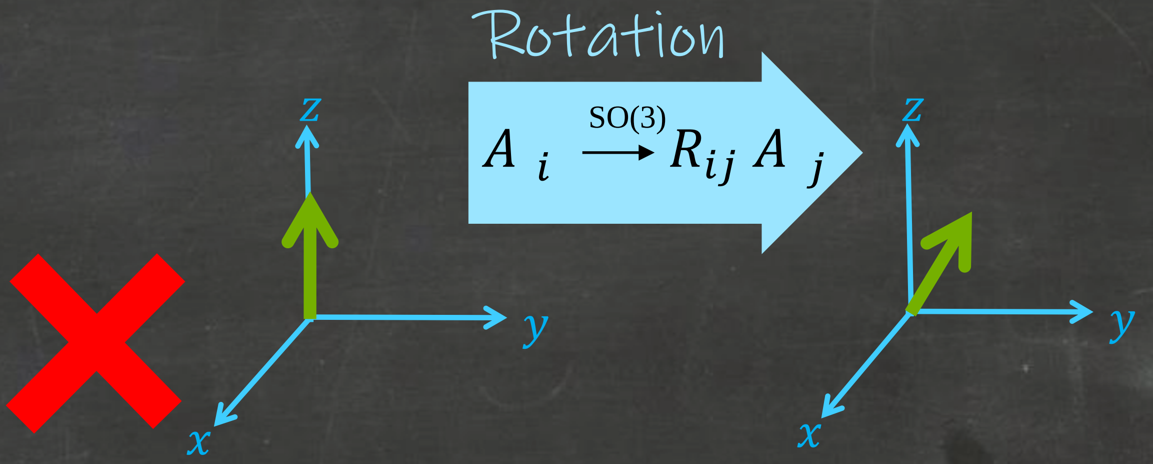
so(3) & su(2) are isomorphic

How SU(2) restores isotropy?

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

U(1) vacuum A_μ

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



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

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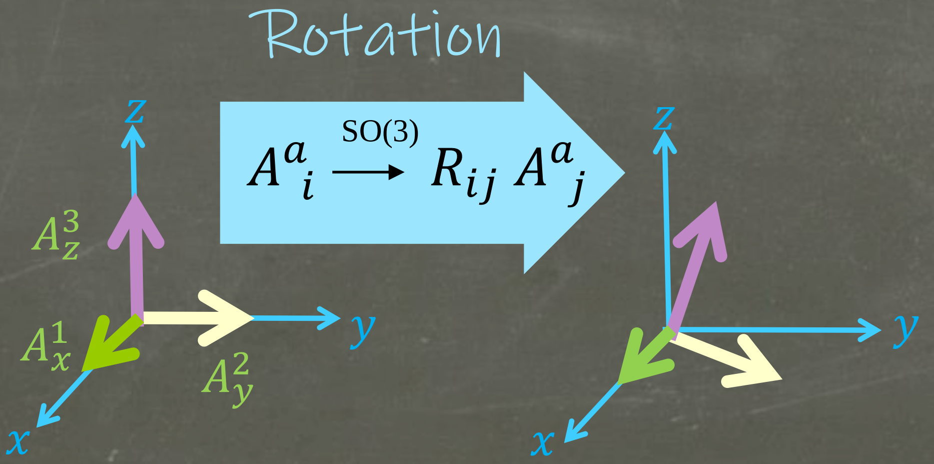

A.M. and M. M. Sheikh-Jabbari, 2011

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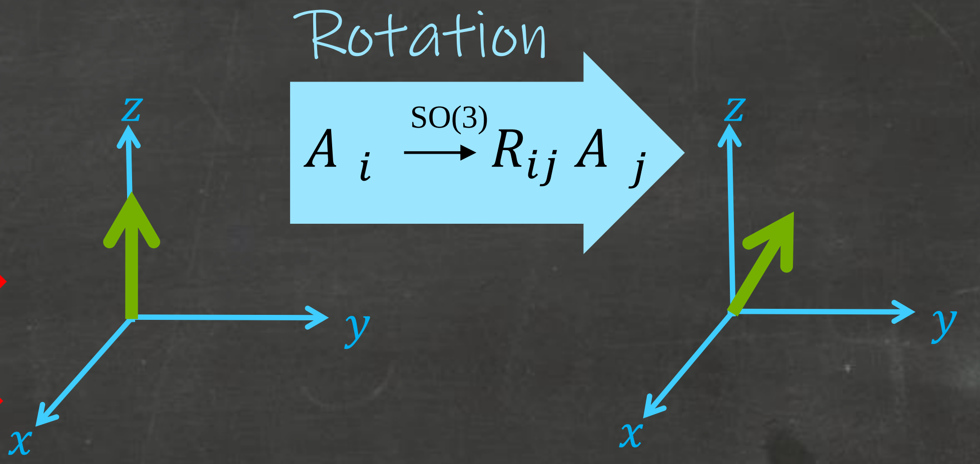

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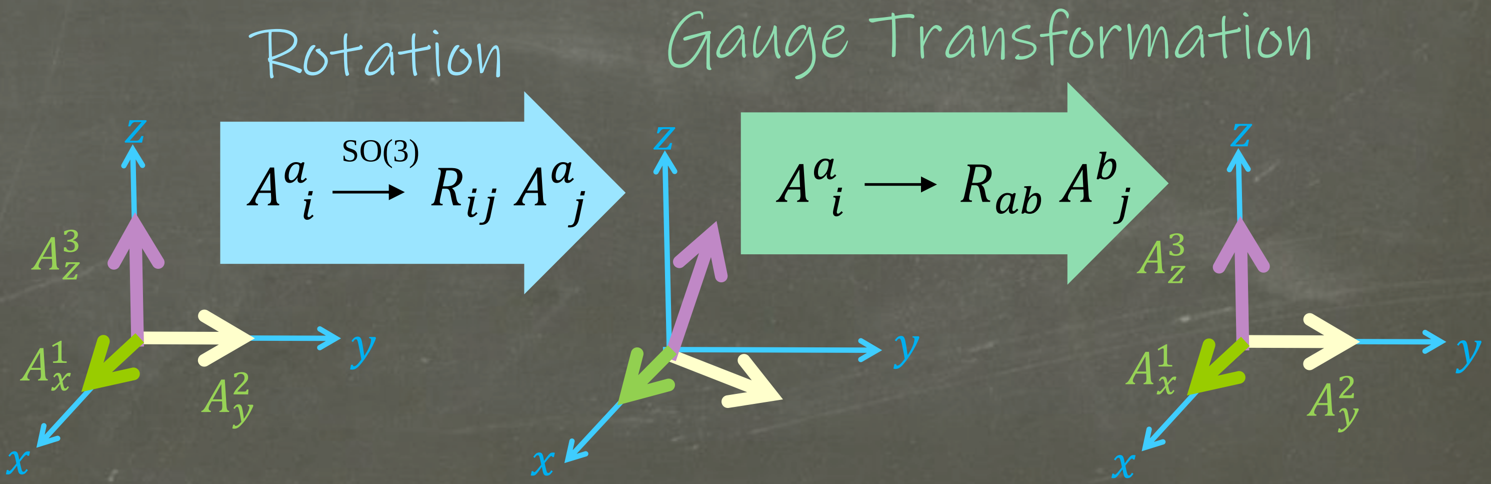

A.M. and M. M. Sheikh-Jabbari, 2011

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

Why SU(N) and not U(1)?

- Spatial isotropic field configuration.

A.M. & Sheikh-Jabbari, 2011

- Any SU(N) gauge field in its SU(2) subsector can have an isotropic & homogeneous solution.

U(1) vacuum A_μ

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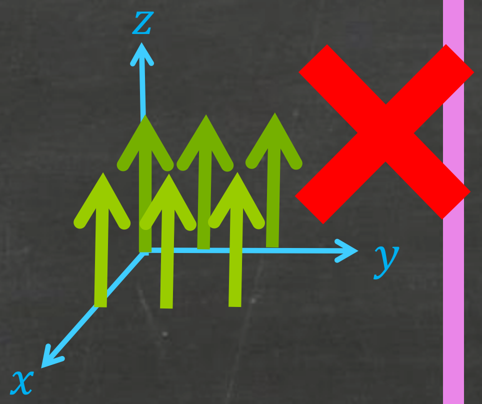

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Spatially isotropic

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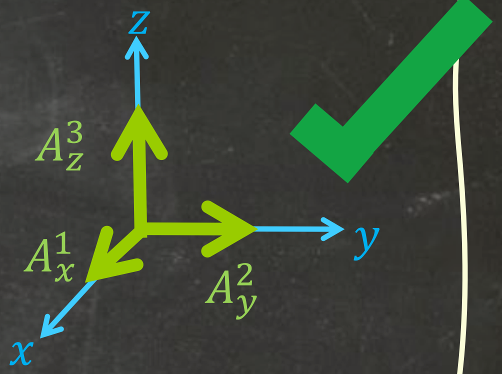

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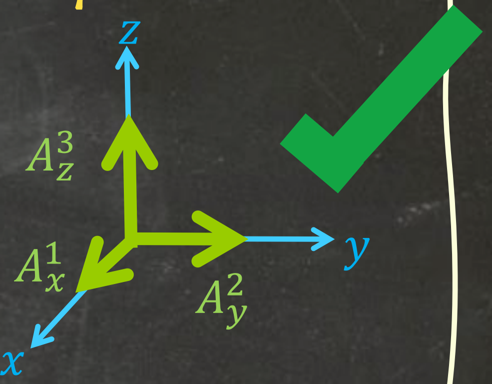

- Non-Abelian gauge fields have self-interactions:

field strength tensor

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu - ig\left[A_\mu, A_\nu\right]$$

Self-interaction

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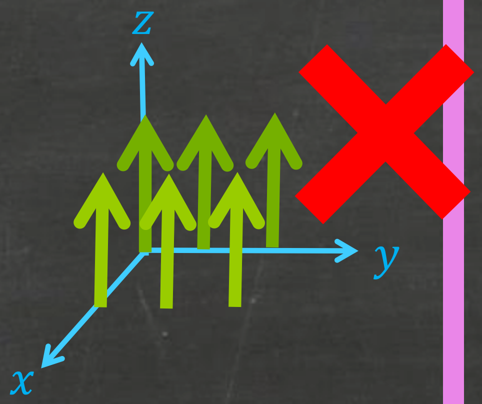

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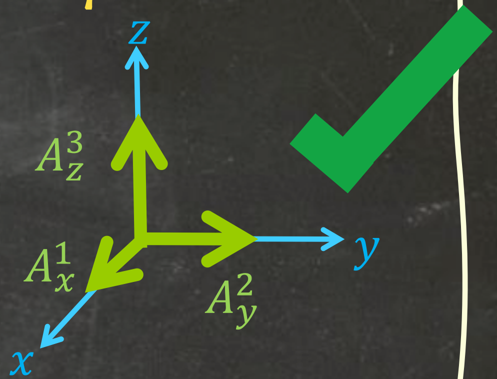

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Self-interaction

- Chern-Simons term can be non-zero at BG level: $\langle F\tilde{F}\rangle \neq 0$

SU(2) Gauge fields and Initial Anisotropies

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

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

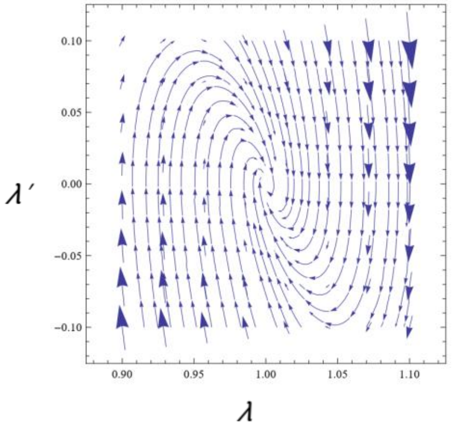
Isotropic Background

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

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!

Anisotropic Background

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

SU(2)-Axion Model Building

- Gauge-flation **A. 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

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

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$\rho = -P$

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Natural inflation

Friction

K. Freese, J. A. Frieman and A. V. Olinto 1990

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Ruled-out by the data

R. Namba, E. Dimastrogiovanni, M. Peloso 2013

P. Adshead, E. Martinec, M. Wyman 2013

+ Theoretical issue:

Very large $\lambda \sim 100$!

D. Baumann & L. McAllister 2014

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

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]
	Oksana Iarygina, Evangelos I. Sfakianakis, [arXiv:2105.06972]

Appeared Today!

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SU(2)-Axion inflation has a very rich phenomenology:

- A new mechanism for generation of Primordial Gravitational Waves
  P. Adshead et. al 2013
  Dimastrogiovanni et. al 2013
  A. M. et. al, 2013
- All Sakharov conditions are satisfied in inflation: a new baryogenesis mechanism
  A. M. 2014 & A.M. 2016
  R. Caldwell et. al 2017
- Particle Production in inflation by Schwinger effect and chiral anomaly
  K. Lozanov, **A. M**, E. Komatsu **2017,**
  L. Mirzagholi, **A. M**, K. Lozanov **2019**
  A.M. 2019

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- Minimal Scenario of SU(2)-axion inflation **A. M.**, 2016 f<0.1 Mpl & λ<0.1

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

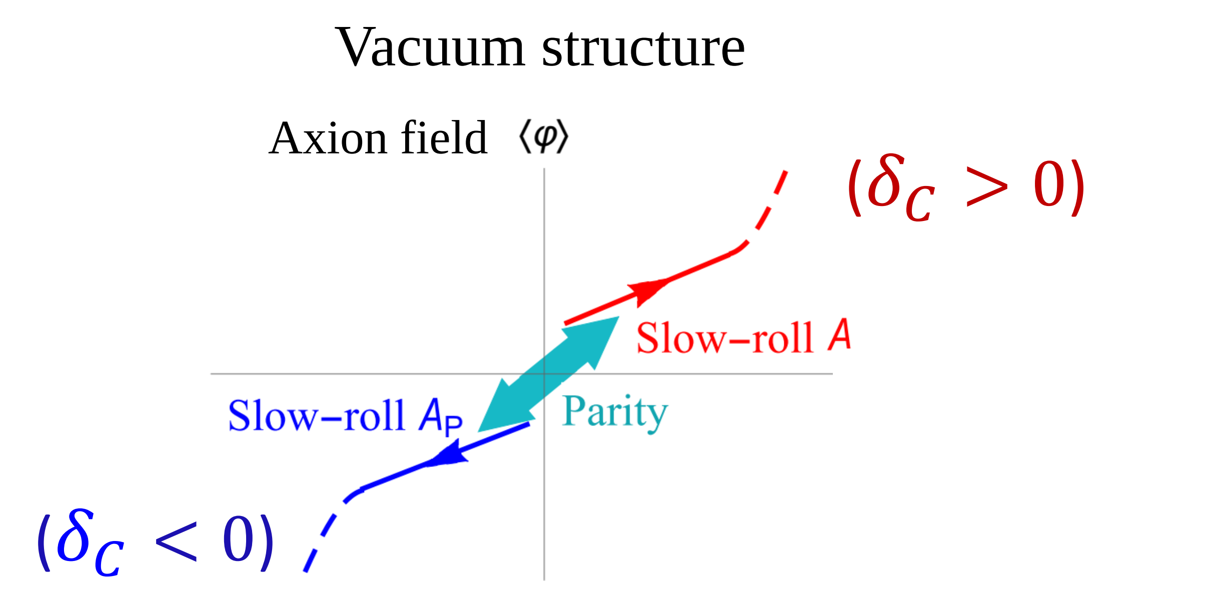
Axion Monodromy or any mechanism that gives a flat potential

New Tensorial mode in SU(2) Gauge Field

- $\delta A_i^a = \left(B_+(t,k)e_{ij}^+(\vec{k}) + B_-(t,k)e_{ij}^-(\vec{k})\right)\delta_j^a$

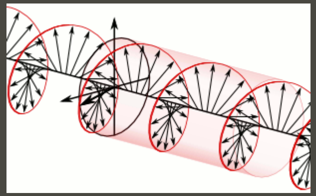
$$B_\pm'' + [\underbrace{k^2 \mp \delta_C k\mathcal{H} + \frac{m^2}{H^2}\mathcal{H}^2 - \frac{a''}{a}}_{\text{effective frequency}}] B_\pm \approx 0$$

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



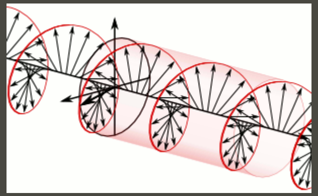
Circular polarizations

Right-handed



B_+

Left-handed



B_-

$B_\pm$ is a new tensorial mode in the perturbed SU(2) gauge field!

A.M. & Sheikh-Jabbari, 2011

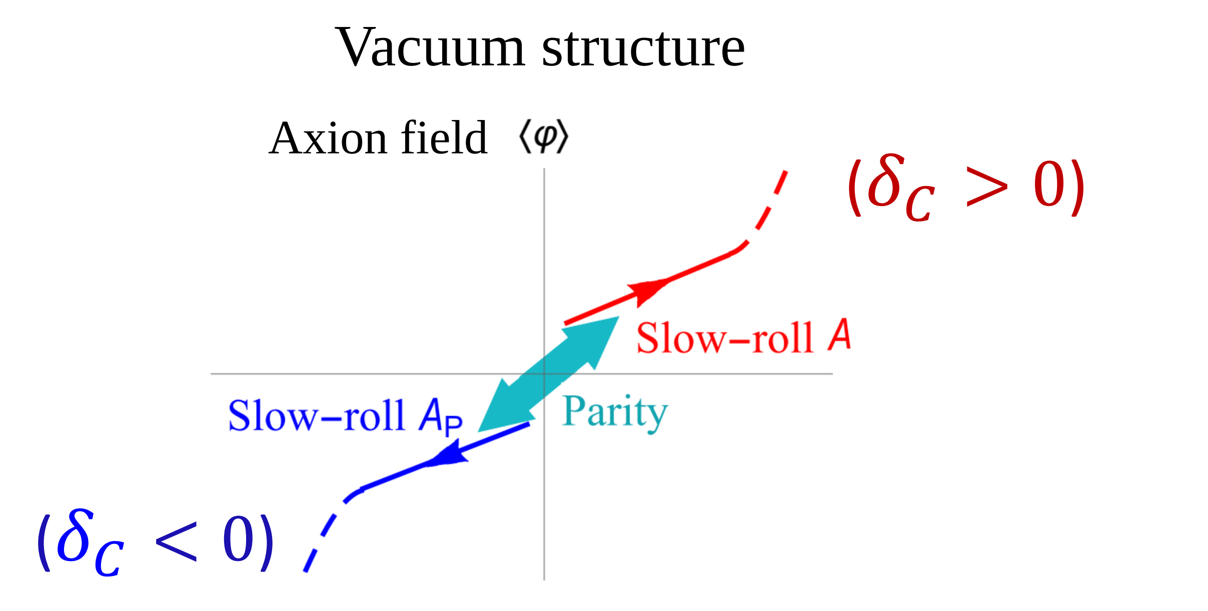
New Tensorial mode in SU(2) Gauge Field

- $\delta A_i^a = \left(B_+(t,k)e_{ij}^+(\vec{k}) + B_-(t,k)e_{ij}^-(\vec{k})\right)\delta_j^a$

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

effective frequency

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



For $\delta_c > 0$

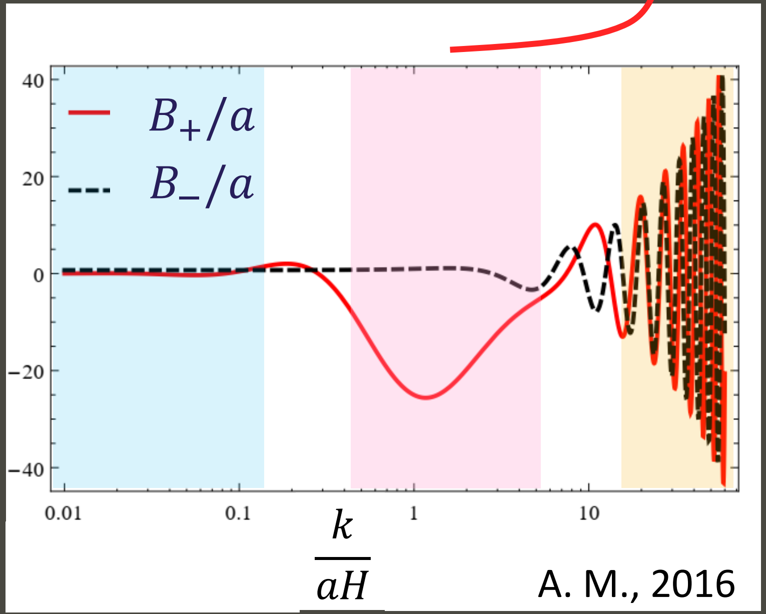
Short tachyonic growth of B_+

Chiral Field

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

Particle Production

A. M. and E. Komatsu, 2018

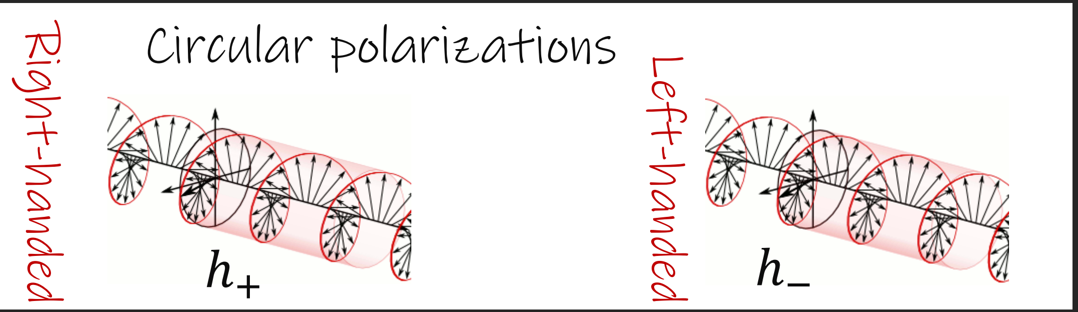


Gauge Field sources Primordial GWs

- $\delta A_i^a = \left(B_+(t,k)e_{ij}^+(\vec{k}) + B_-(t,k)e_{ij}^-(\vec{k})\right)\delta_j^a$
- The field equation: $B_\pm'' + [k^2 \mp \delta_C k\mathcal{H} + \frac{m^2}{H^2}\mathcal{H}^2 - \frac{a''}{a}]\, B_\pm \approx 0$

- That sourced the GWs

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

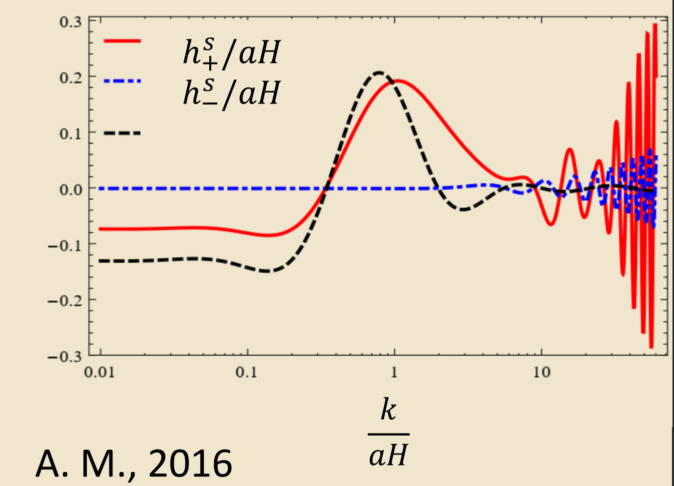


- Gravitational waves have two uncorrelated terms

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

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

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



A. M., 2016

Novel Observable Signature: CMB

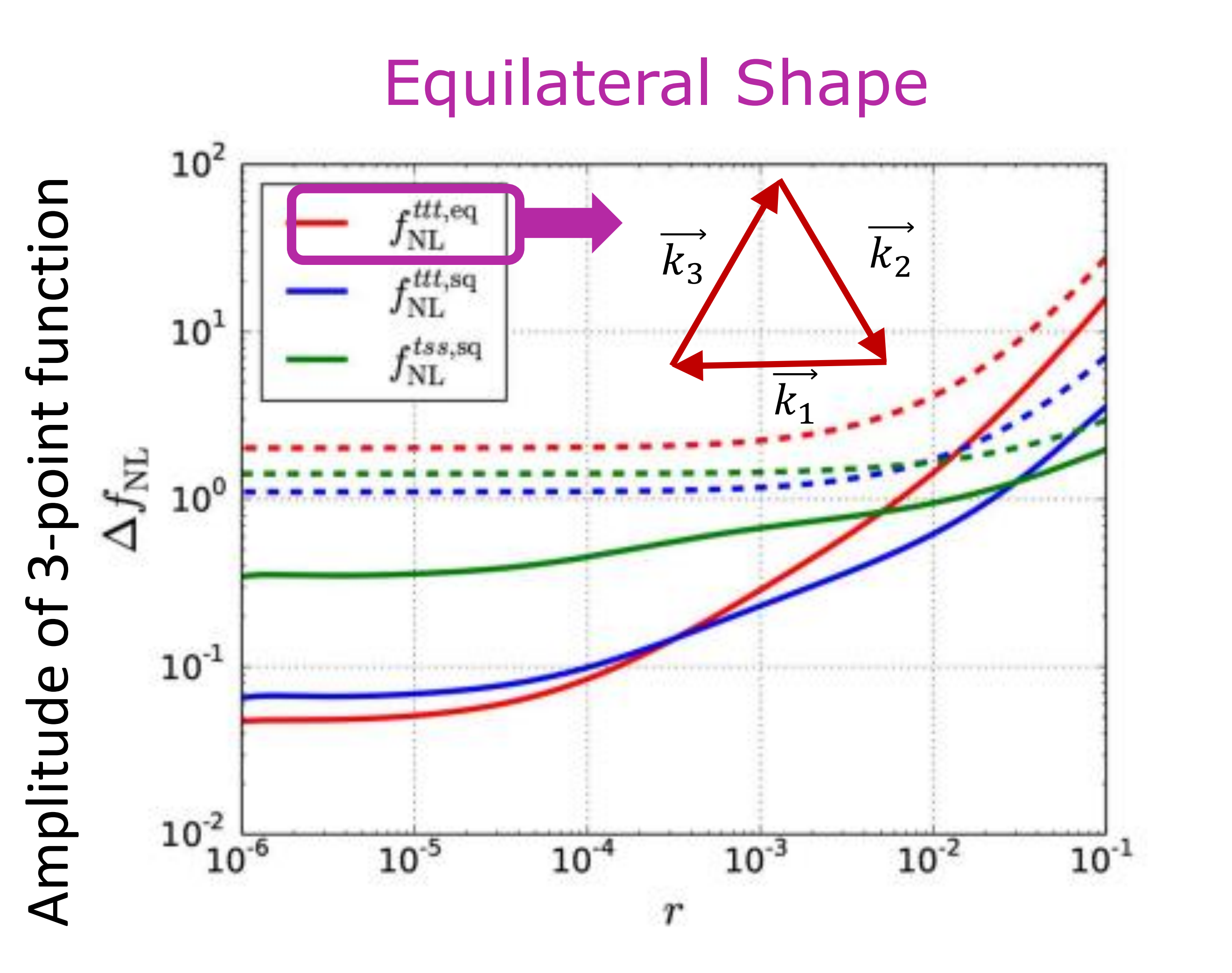
- The sourced tensor modes is Highly non-Gaussian.

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu - ig\,[A_\mu, A_\nu]$$

Self-interaction

Agrawal, Fujita, Komatsu 2018

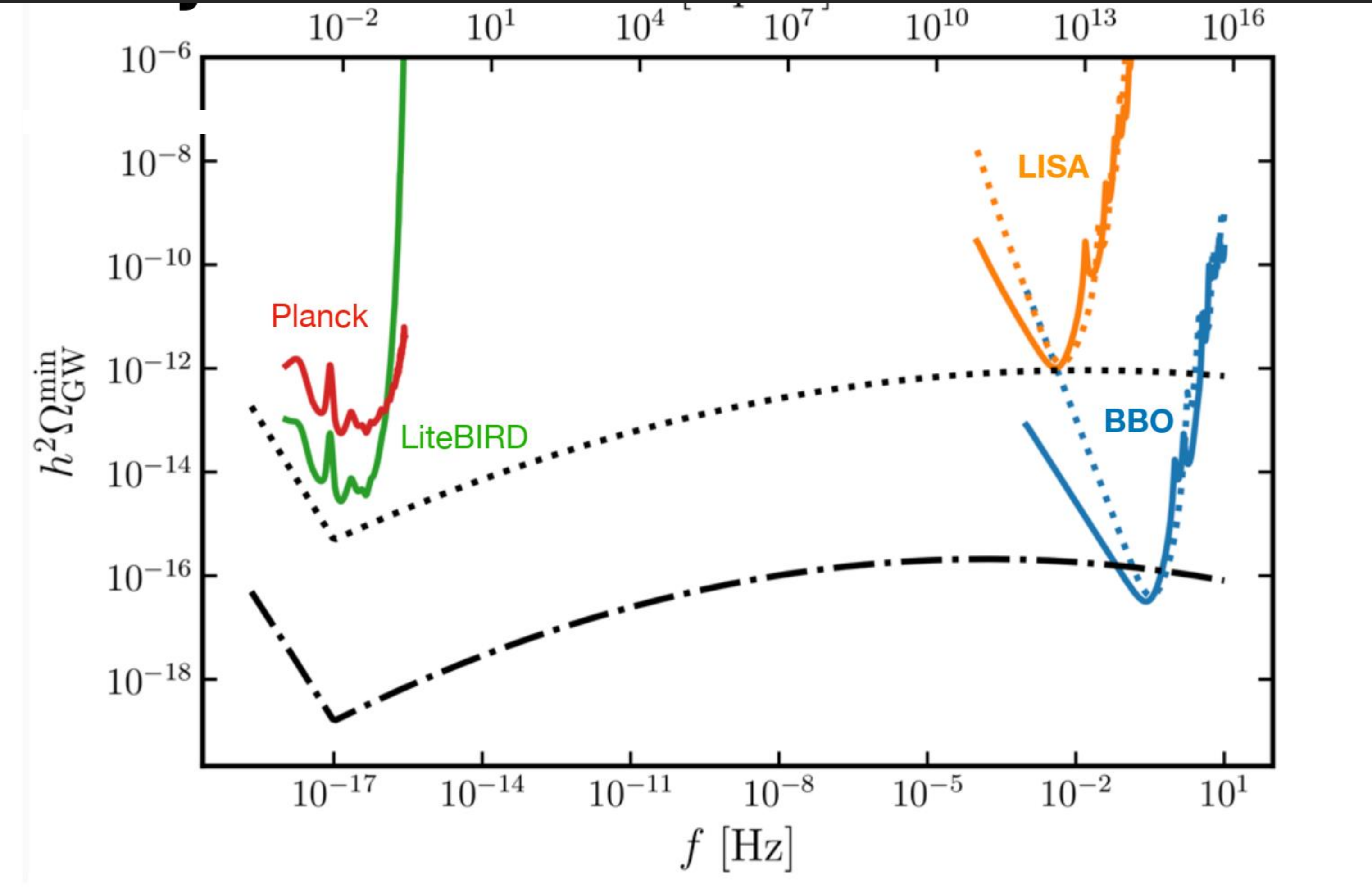
- That can be probe with future CMB missions., e.g. *Litebird* *and CMB-S4*!



Maresuke Shiraishi, Front. Astron. Space Sci. 2019

Novel Observable Signature: Beyond CMB

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

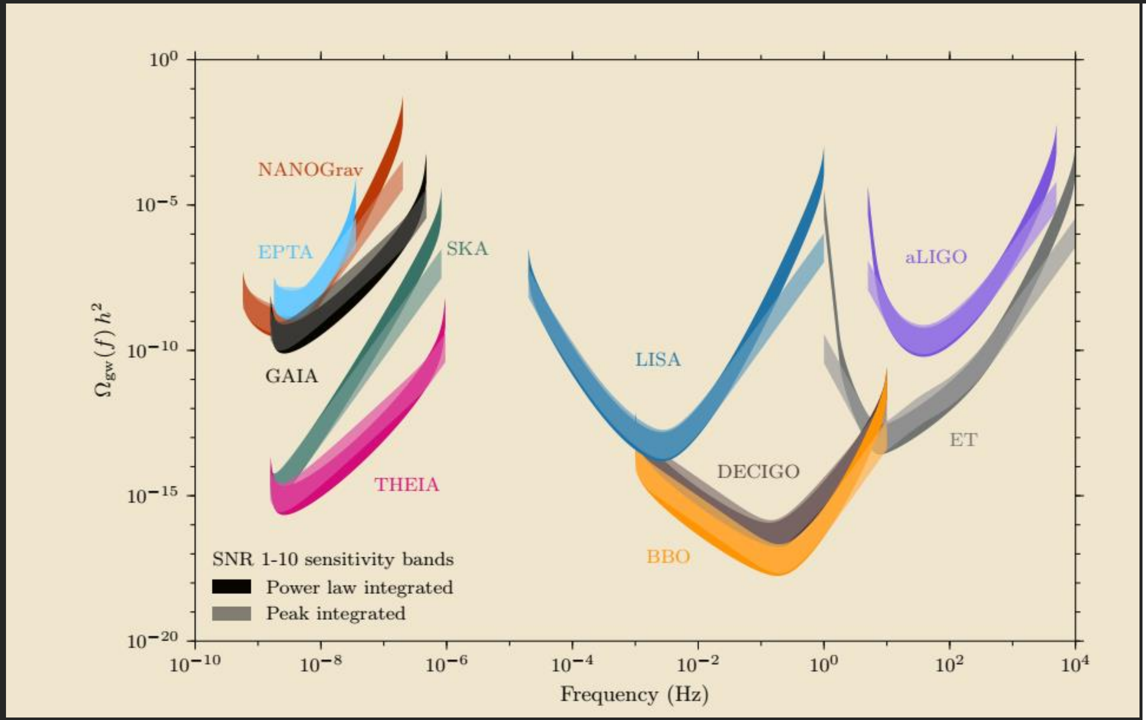


Detection of this background is an excellent target for all GW experiments across at least 21 decades in frequencies.

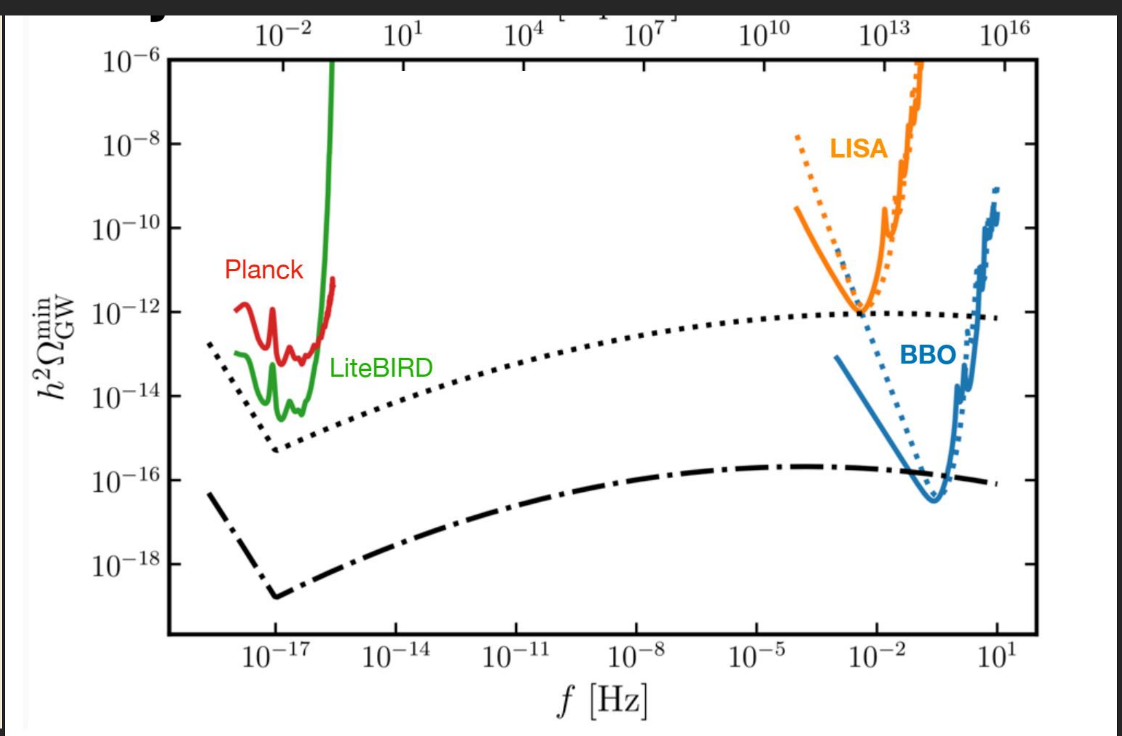
P. Campeti, E. Komatsu, D. Poletti, C. Baccigalupi 2020

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

Novel Observable Signature: Beyond CMB



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

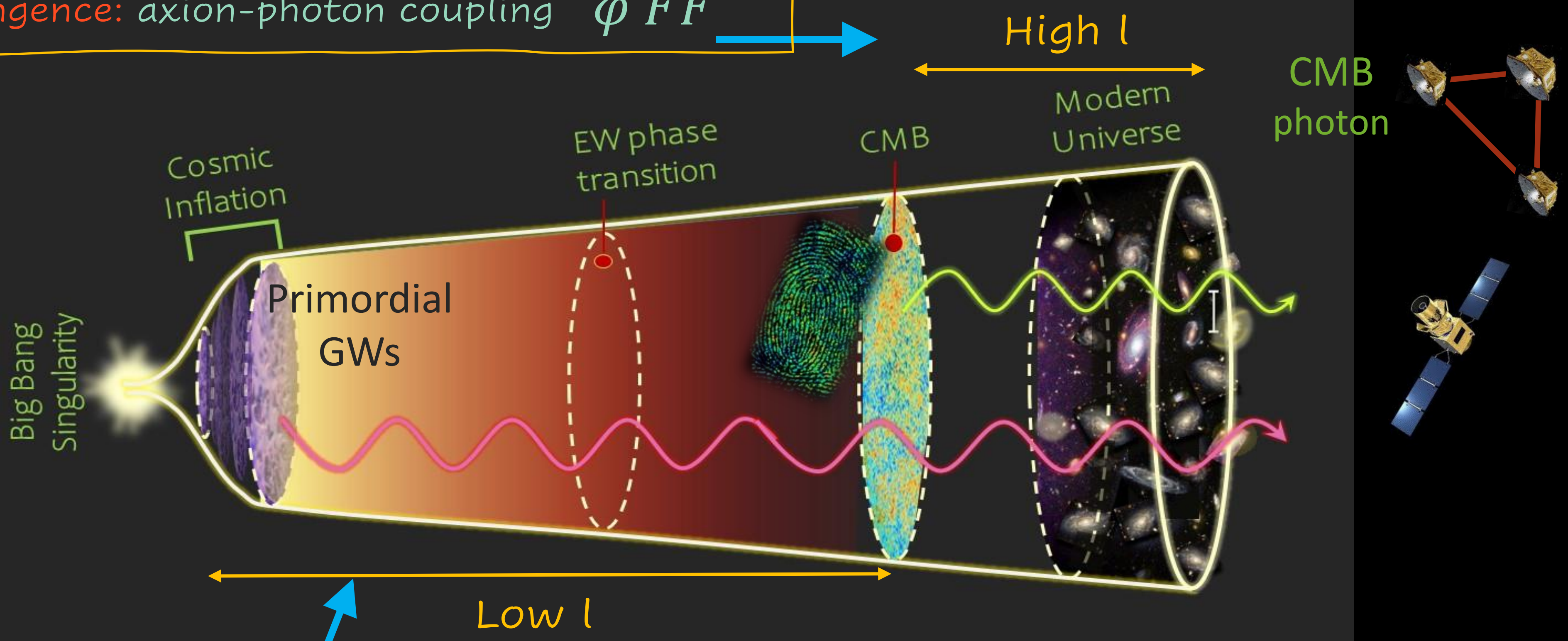


Thorne, Fujita, Hazumi, Katayama, Komatsu & Shiraishi, 2018

Parity Odd CMB Correlations: TB & EB $\neq 0$

Sources of Parity violation on CMB:

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



- SU(2)-axion Inflation: SU(2) field-Graviton coupling
- Gravitational Chern-Simons: axion-graviton coupling $\varphi R\tilde{R}$

B. Thorne et. al.2018

How to Connect Inflaton to SM?

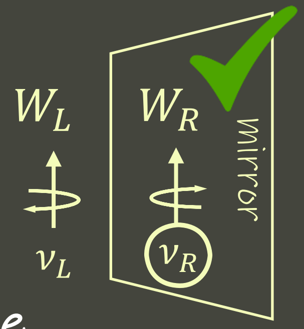
How to Connect it to the SM?

Let us Extend SM Gauge Symmetry by an $SU(2)_R$ and couple it to Axion Inflaton!

- Left-Right Symmetric Model + axion!

$SU(2)_R \times SU(2)_L \times U(1)_{B-L} \longrightarrow SU(2)_L \times U(1)_Y$

Left-Right Symmetric — SM Left-handed Weak force



- Minimal Scenario of SU(2)-axion inflation **A. M.**, 2016 f<0.1 Mpl & λ<0.1

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

Axion Monodromy or any mechanism that gives a flat potential

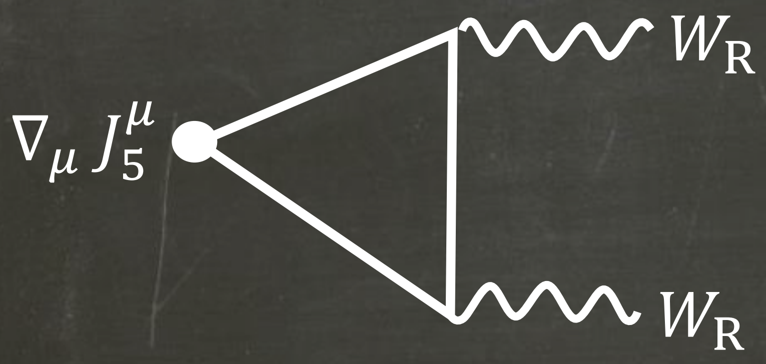
Gauge field is $SU(2)_R$

A. M. arXiv: 2012.11516
A.M. arXiv:2103.14611

Lepton & quark Production in Inflation

- Left-handed fermions are diluted by inflation, BUT
- Right-handed fermions are generated by $SU(2)_R$ gauge field:

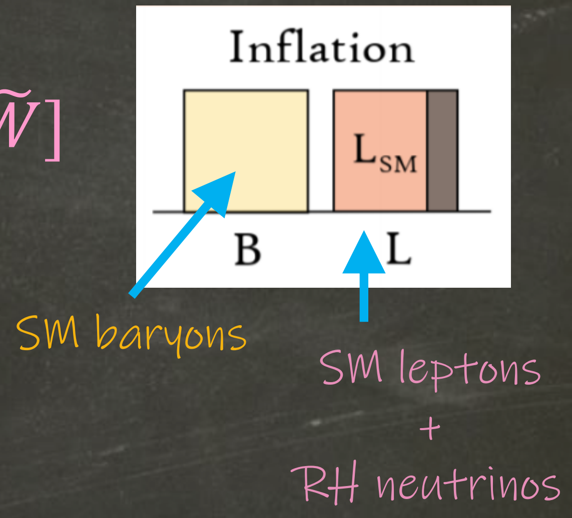
The key ingredient is the Chiral anomaly of $SU(2)_R$ in inflation:



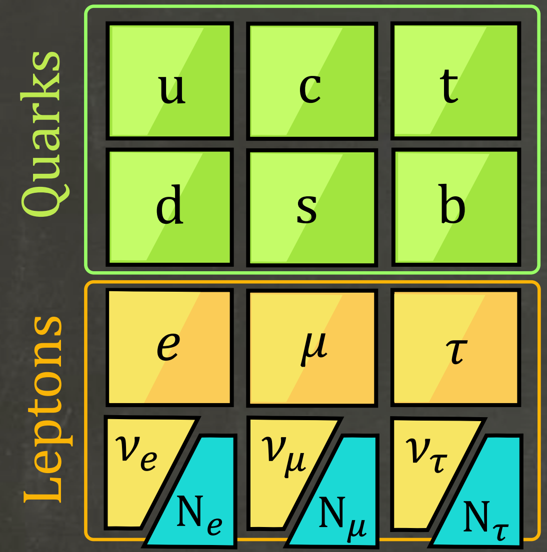
$$\nabla_\mu J_B^\mu = \nabla_\mu J_L^\mu = \frac{g^2}{16\pi^2} tr[W\tilde{W}]$$

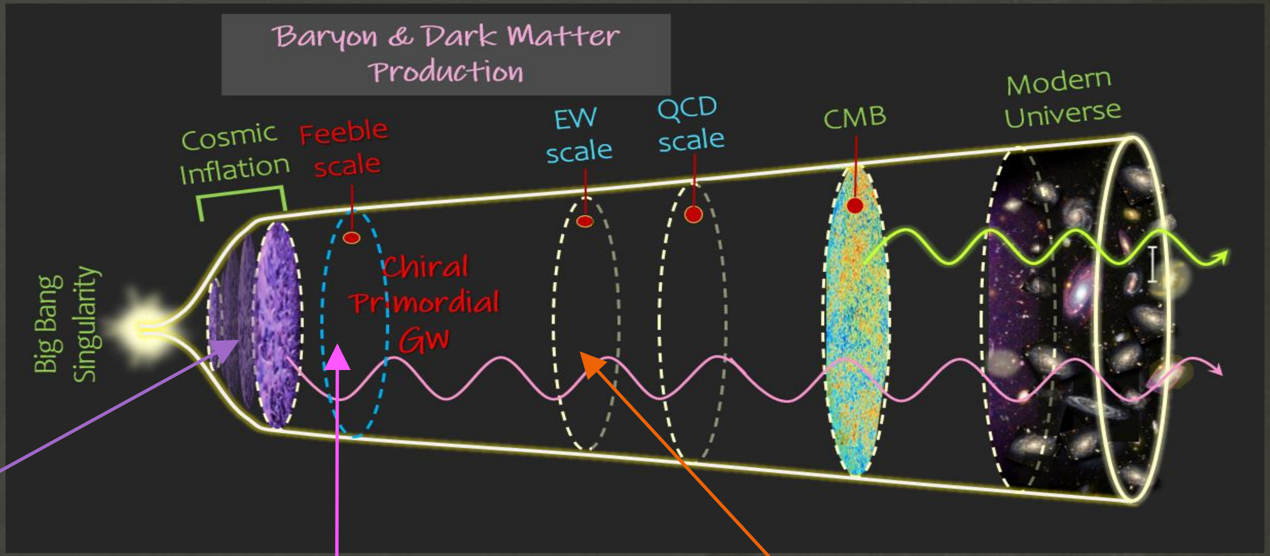
$$n_B = n_L = \alpha_{inf}(\xi) H^3$$

$$\alpha_{inf}(\xi) \sim \frac{g^2}{(2\pi)^4} e^{2\pi\xi}$$



Summary of the mechanism:

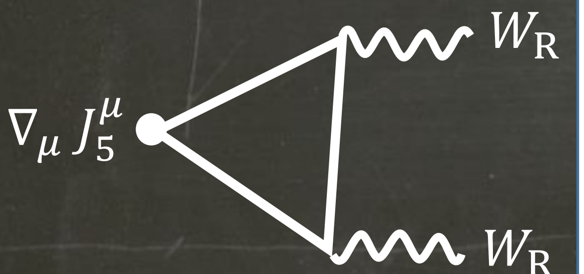


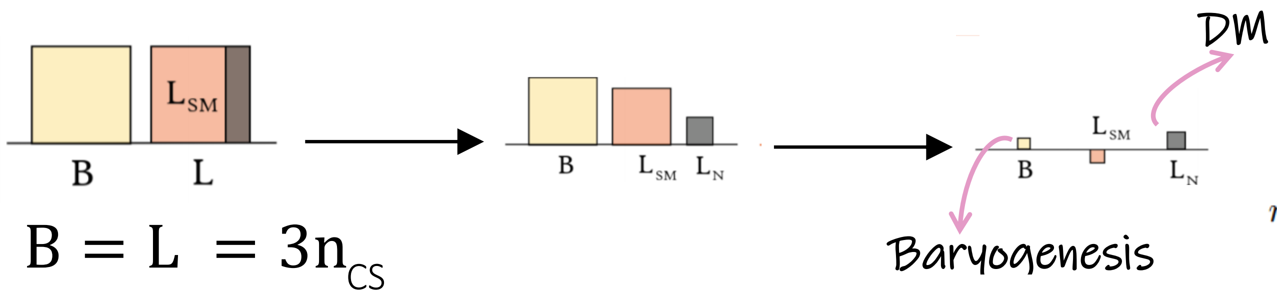


Chiral anomaly of SU(2)R in inflation

Freezeout of Ni

EW scale





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

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

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

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

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

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

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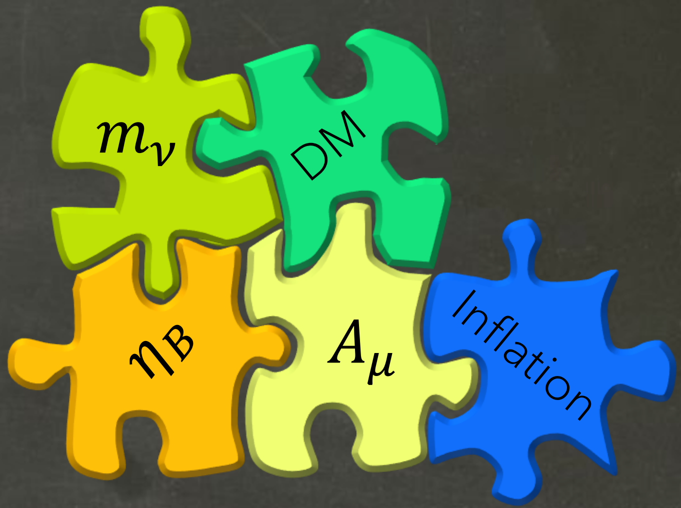
Compelling Consequences:

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

- I) Particle physics of Inflation
- II) Origin of matter asymmetry
- III) Origin of Neutrino mass
- IV) Particle nature of DM



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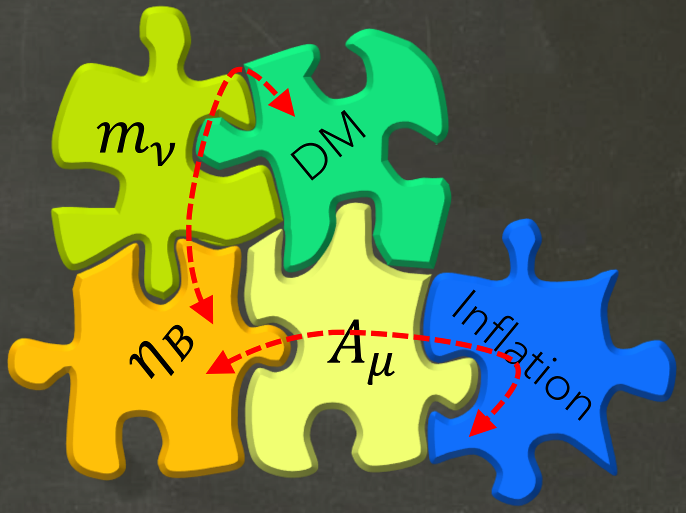
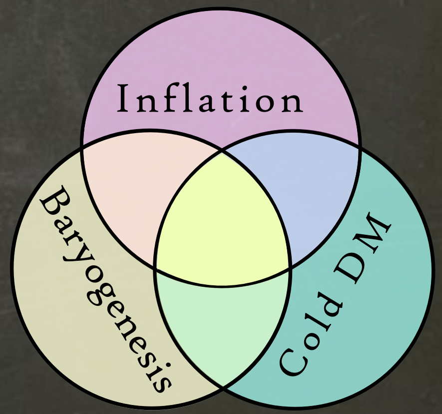


It provides a deep connection between inflation, baryogenesis & DM,

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



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Puzzles of Particle Cosmology

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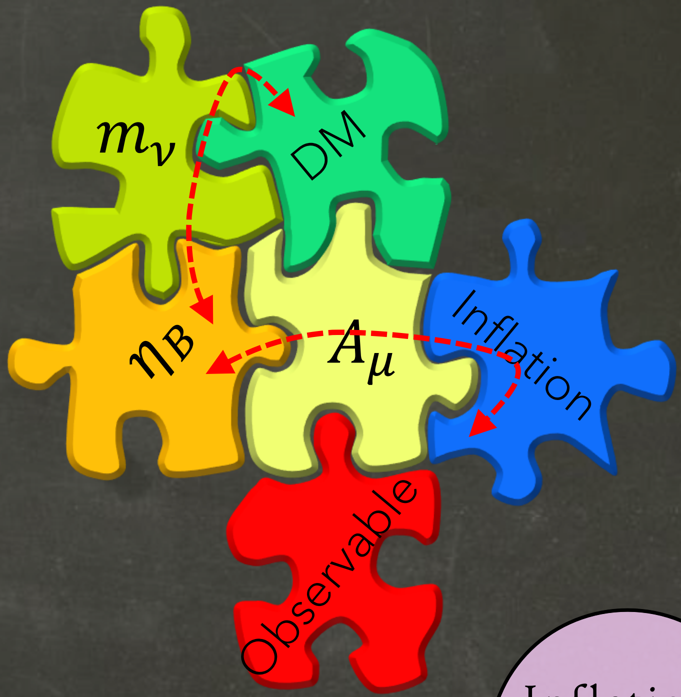

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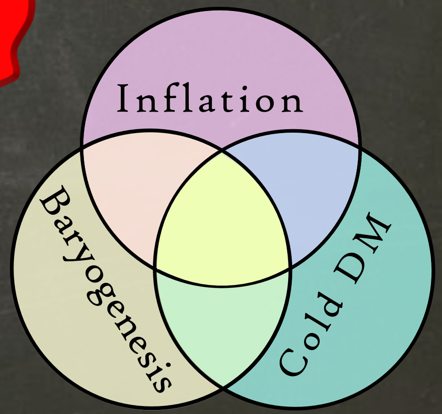

It comes with a cosmological smoking gun on Primordial GW.

Questions?!