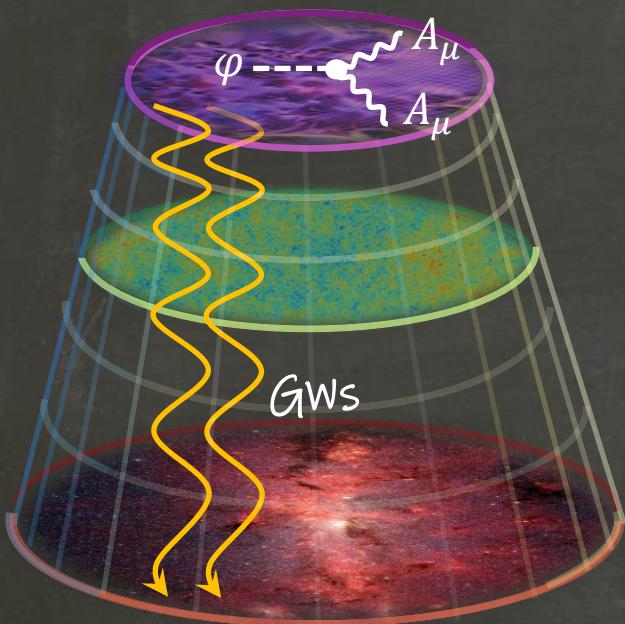


# Gauge fields in Inflation & Origin of Matter in the Universe

Based on  
arXiv:2012.11516 & arXiv:2103.14611

Azadeh Malek-Nejad  
CERN

# Setup:



## I) Axion-inflation and gauge fields (non-Abelian)

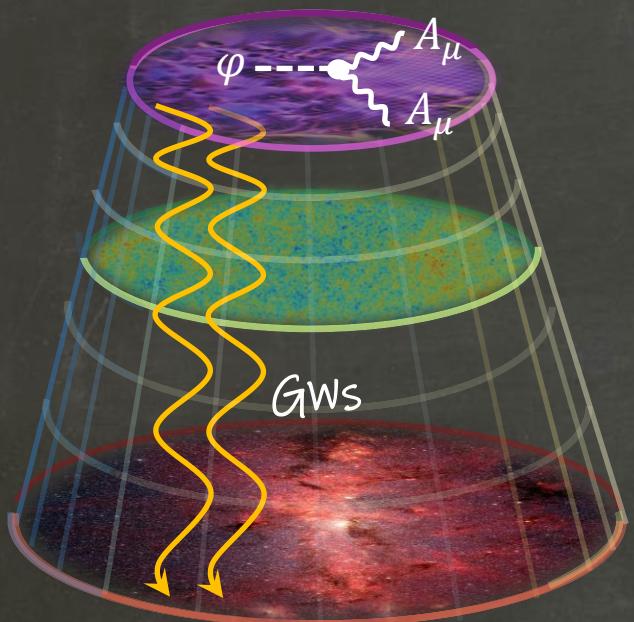
Collaborators:

E. Komatsu, K. Lozanov, L. Mirzagholi , I. Wolfson,  
M. Sheikh-Jabbari, J. Soda

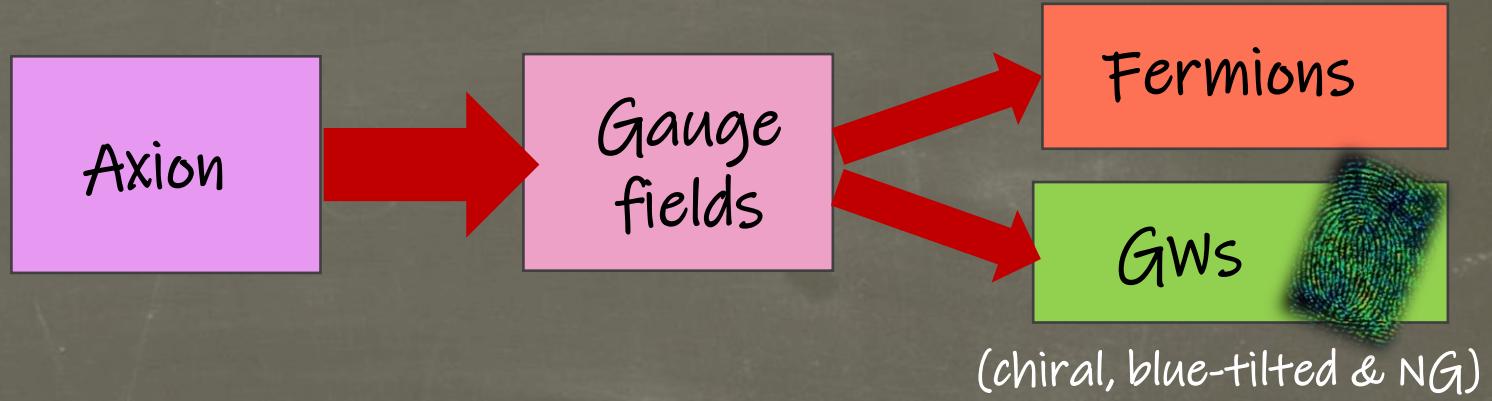
Colleagues:

P. Adshead, E. Martinec, M. Peloso, E. Dimastrogiovanni, T. Fajita, M. Wyman, E. Sfakianakis, M. Fasiello, R. Caldwell, C. Devulder, Y. Watanabe, V. Domcke, ...

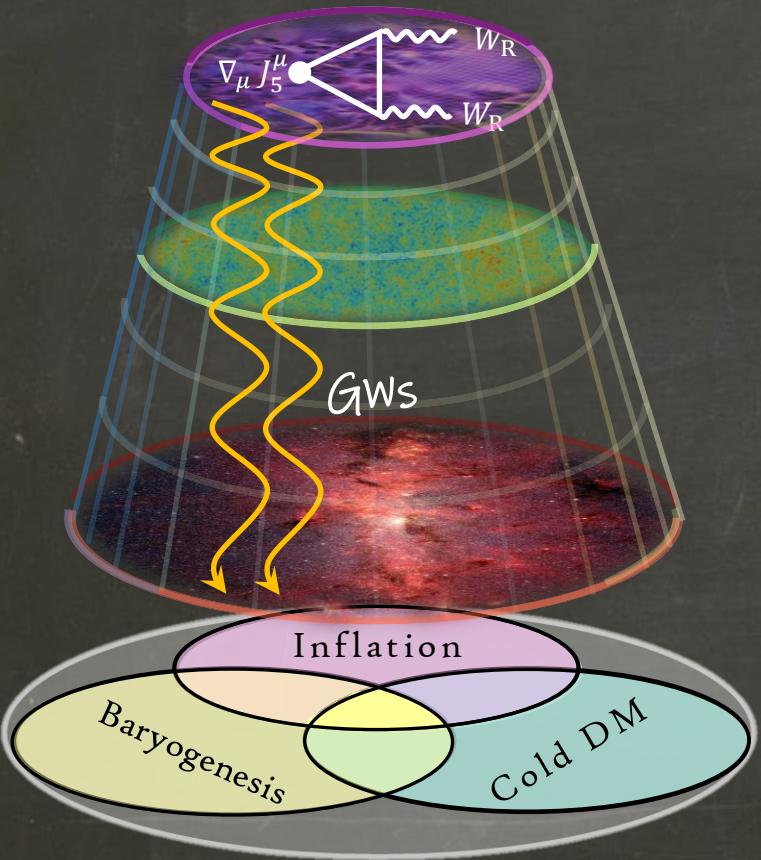
# Setup:



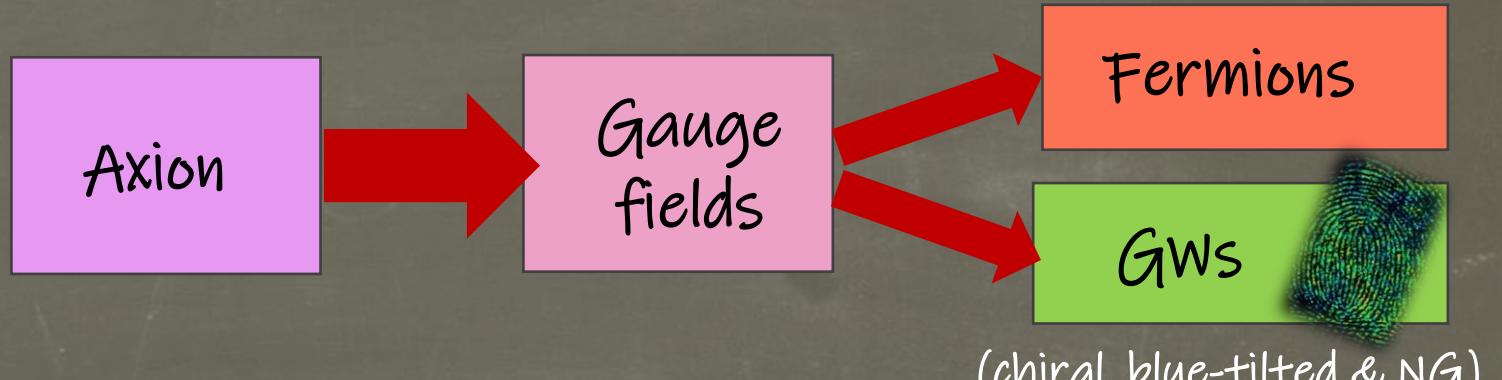
## I) Axion-inflation and gauge fields



# Setup:



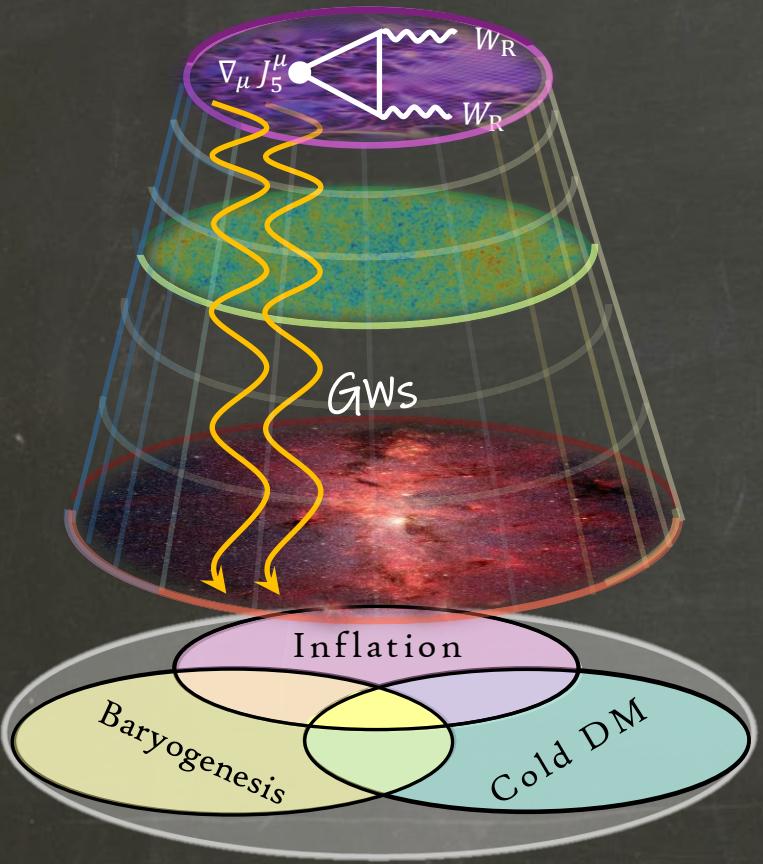
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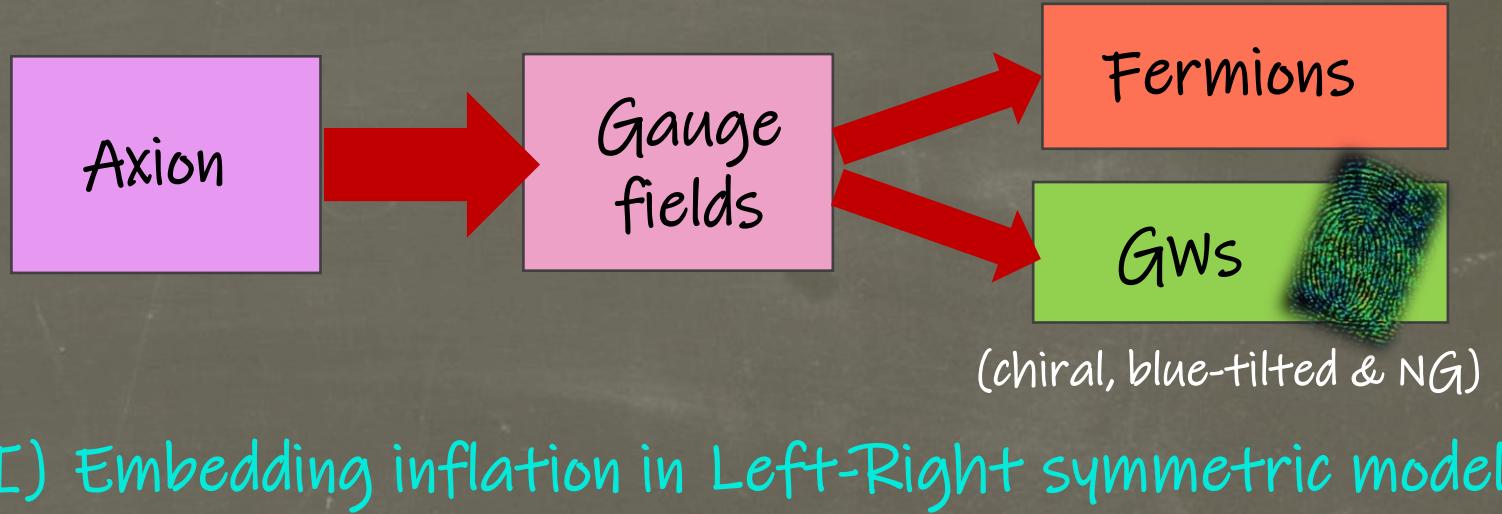
## II) Embedding inflation in Left-Right symmetric model

Based on  
arXiv:2012.11516 & arXiv:2103.14611

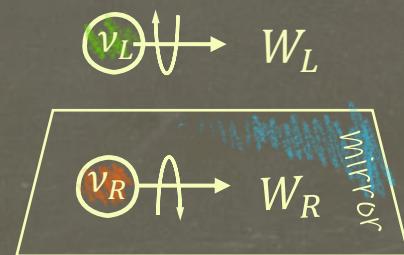
# Setup:



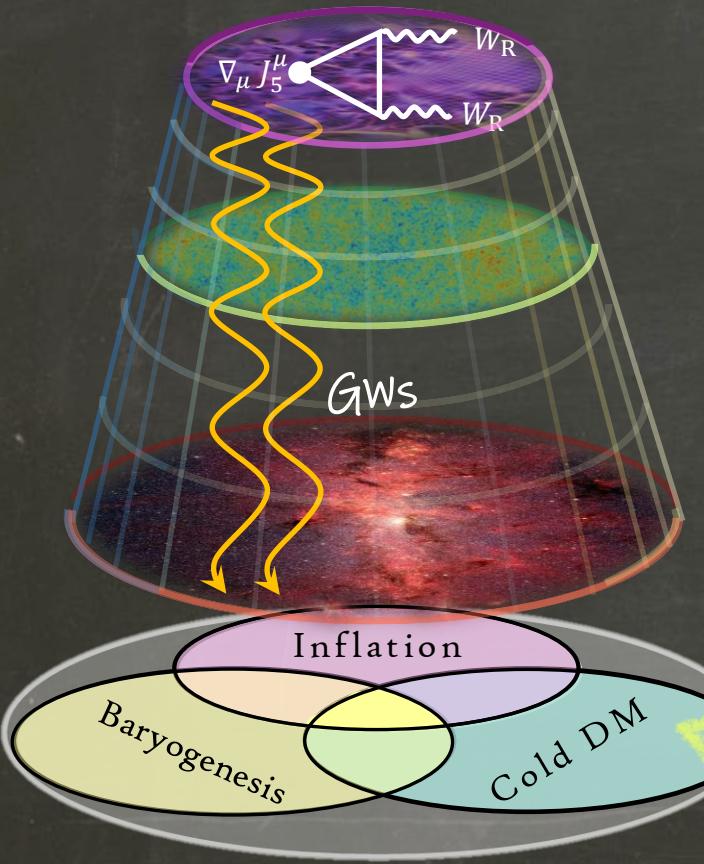
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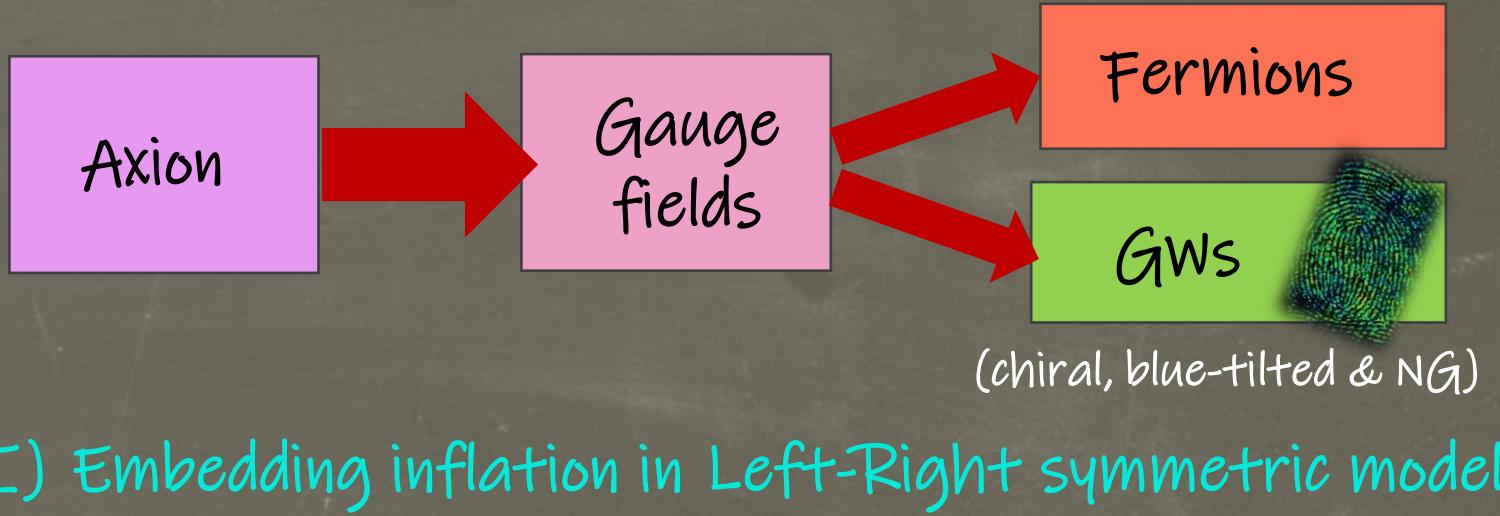
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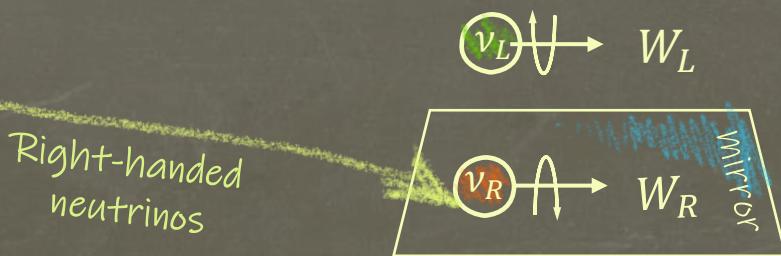
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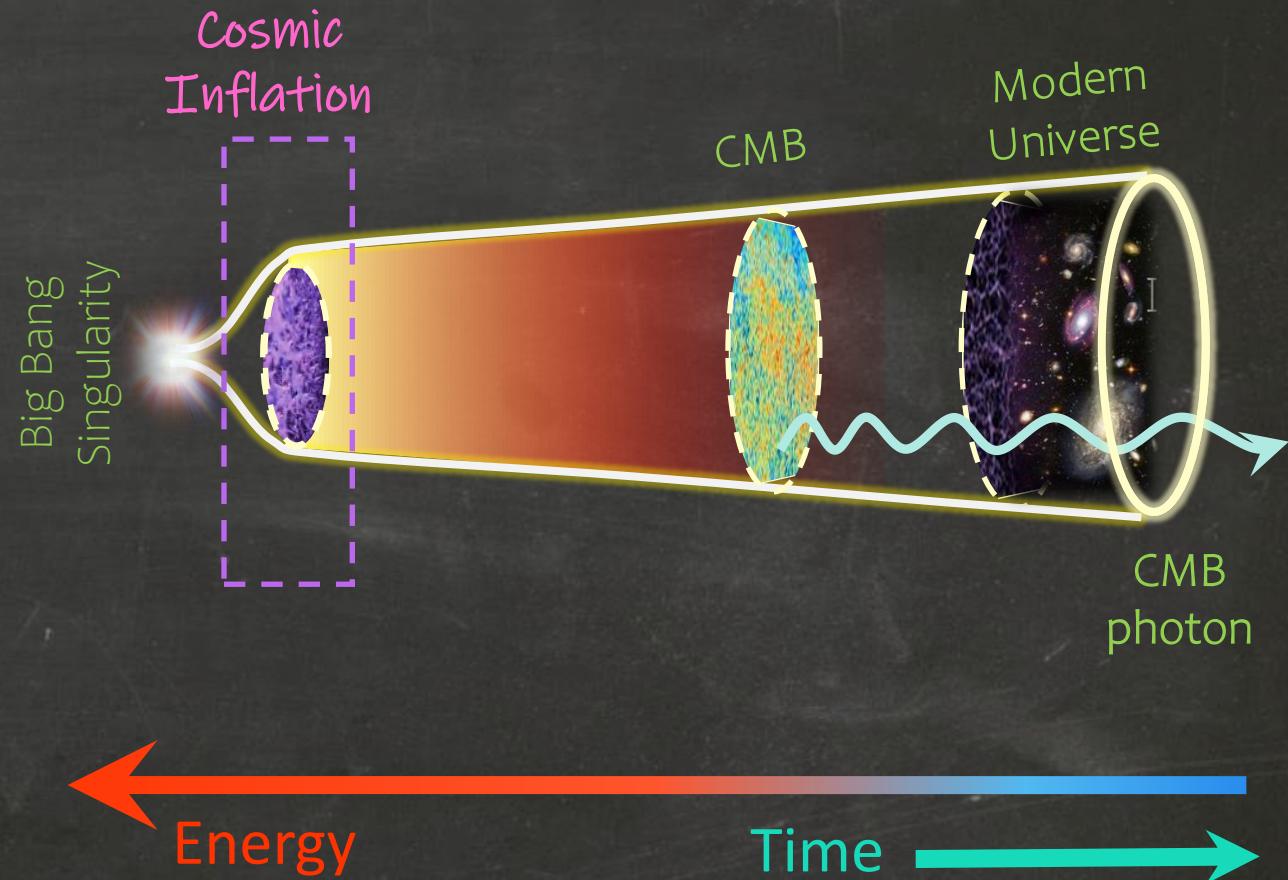
# Cosmic Inflation

A period of exponential expansion of space shortly after the Big Bang



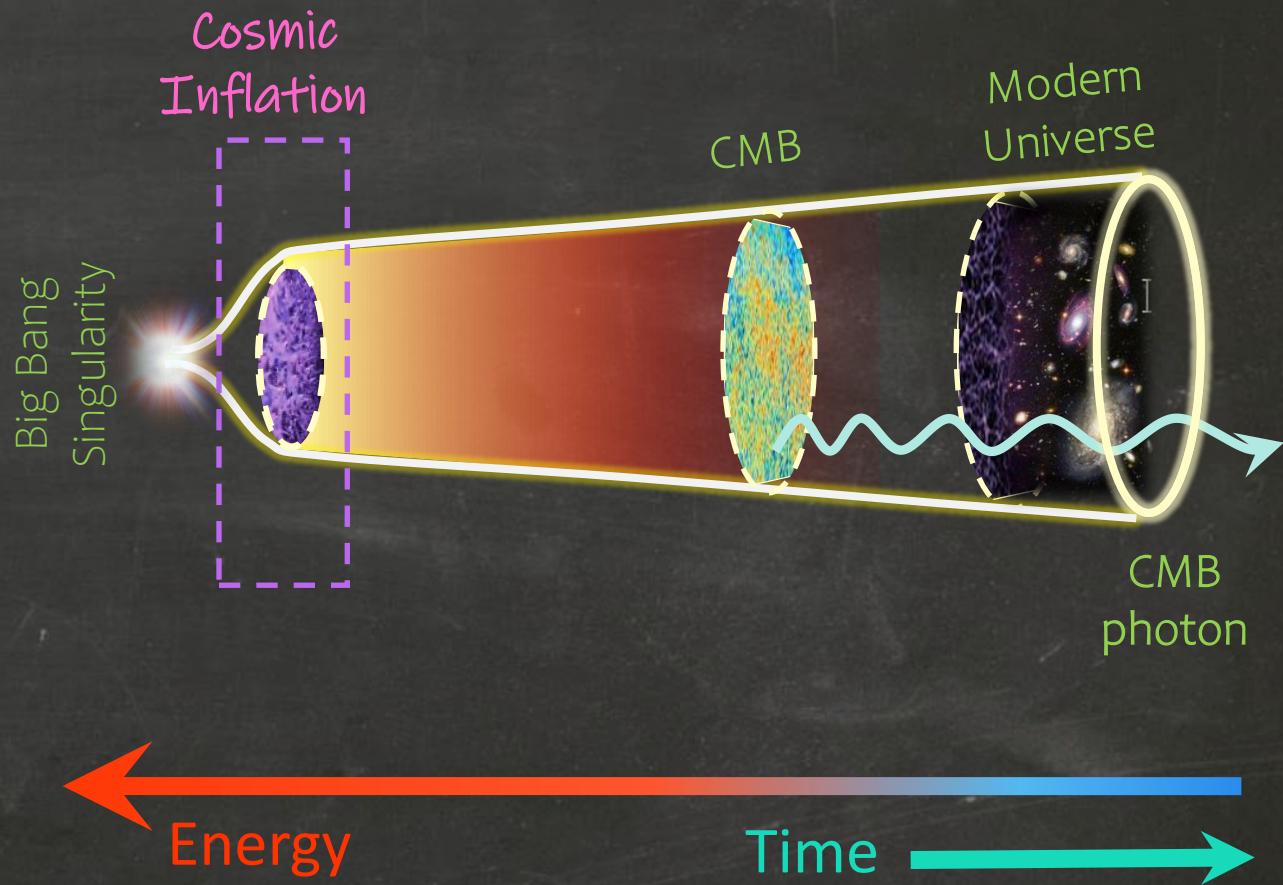
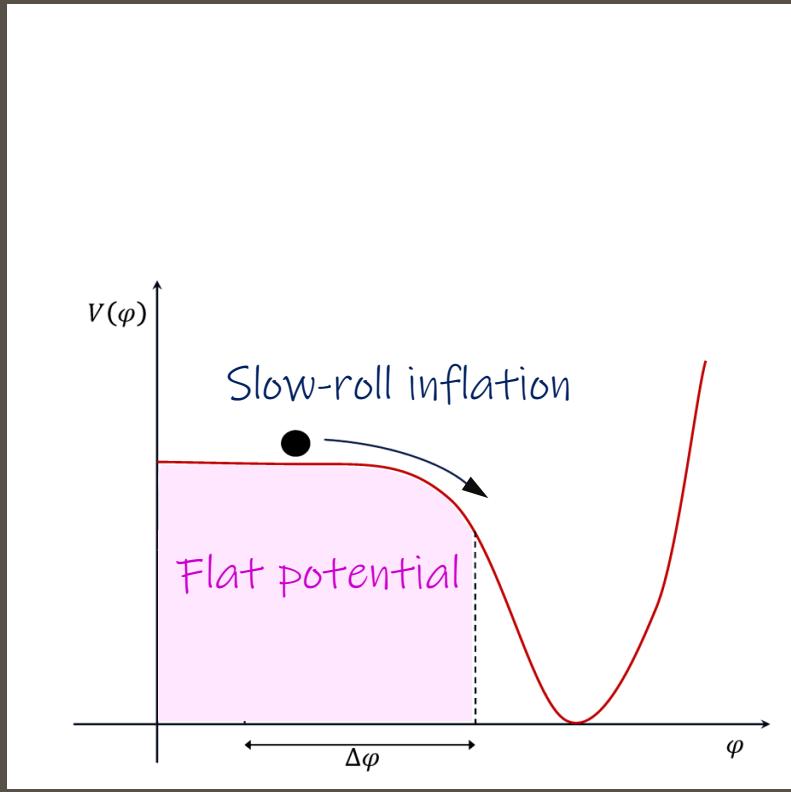
$$\frac{a_f}{a_i} = e^{60} \approx 10^{26}!$$

Guth Phys. Rev. D23 (1981)  
Linde Phys. Lett. B 108 (1982)



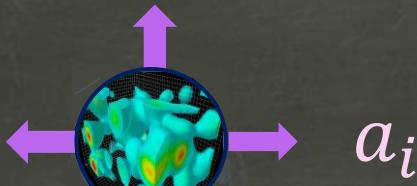
# What caused inflation?

A scalar field “slow-rolling” toward its true vacuum provides a simple model for inflation.



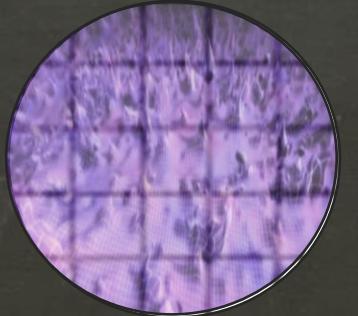
# Cosmic Perturbations

Cosmic inflation turns initial quantum vacuum fluctuations

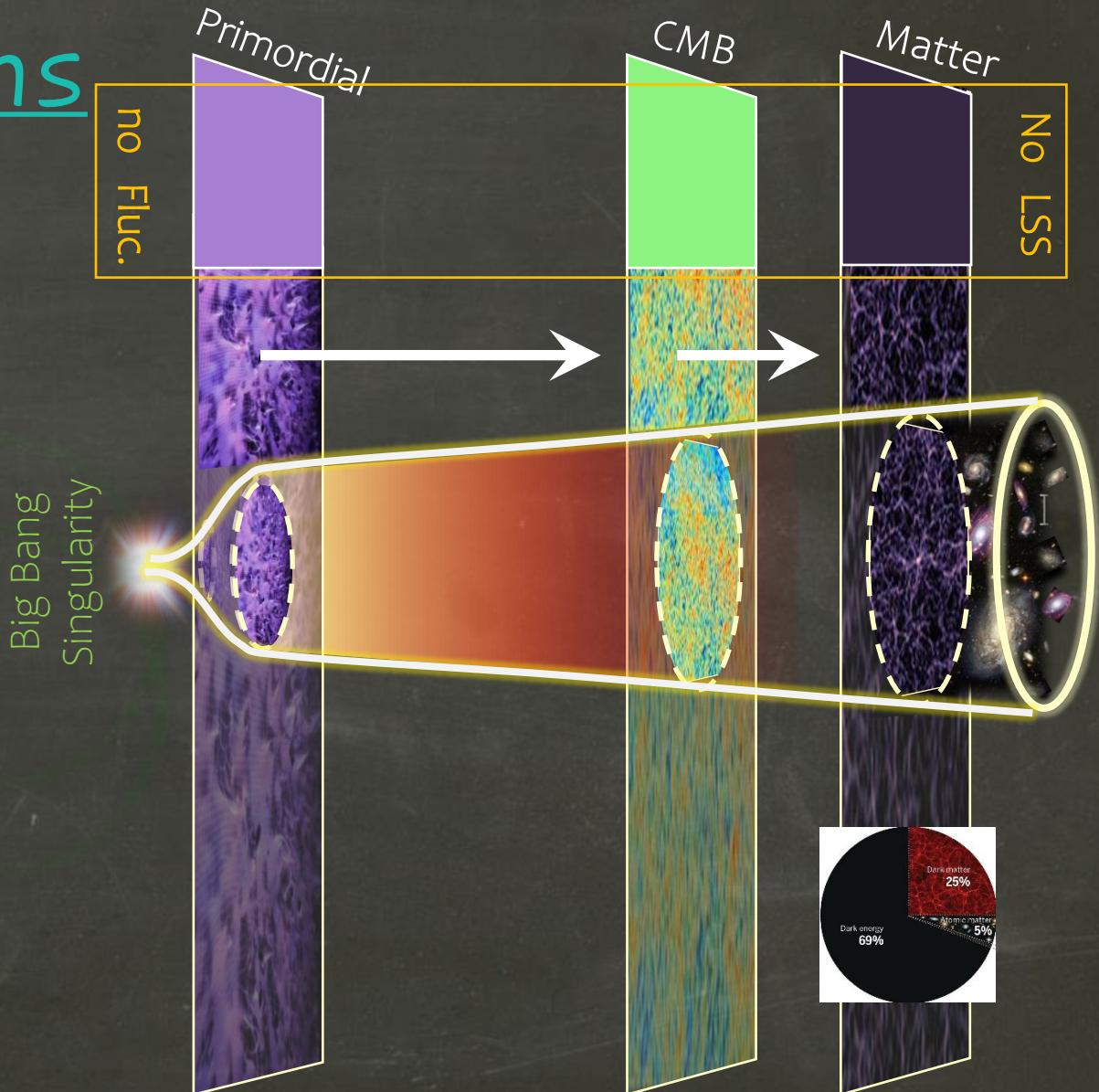


$a_i$

into actual cosmic perturbations.



$a_f$

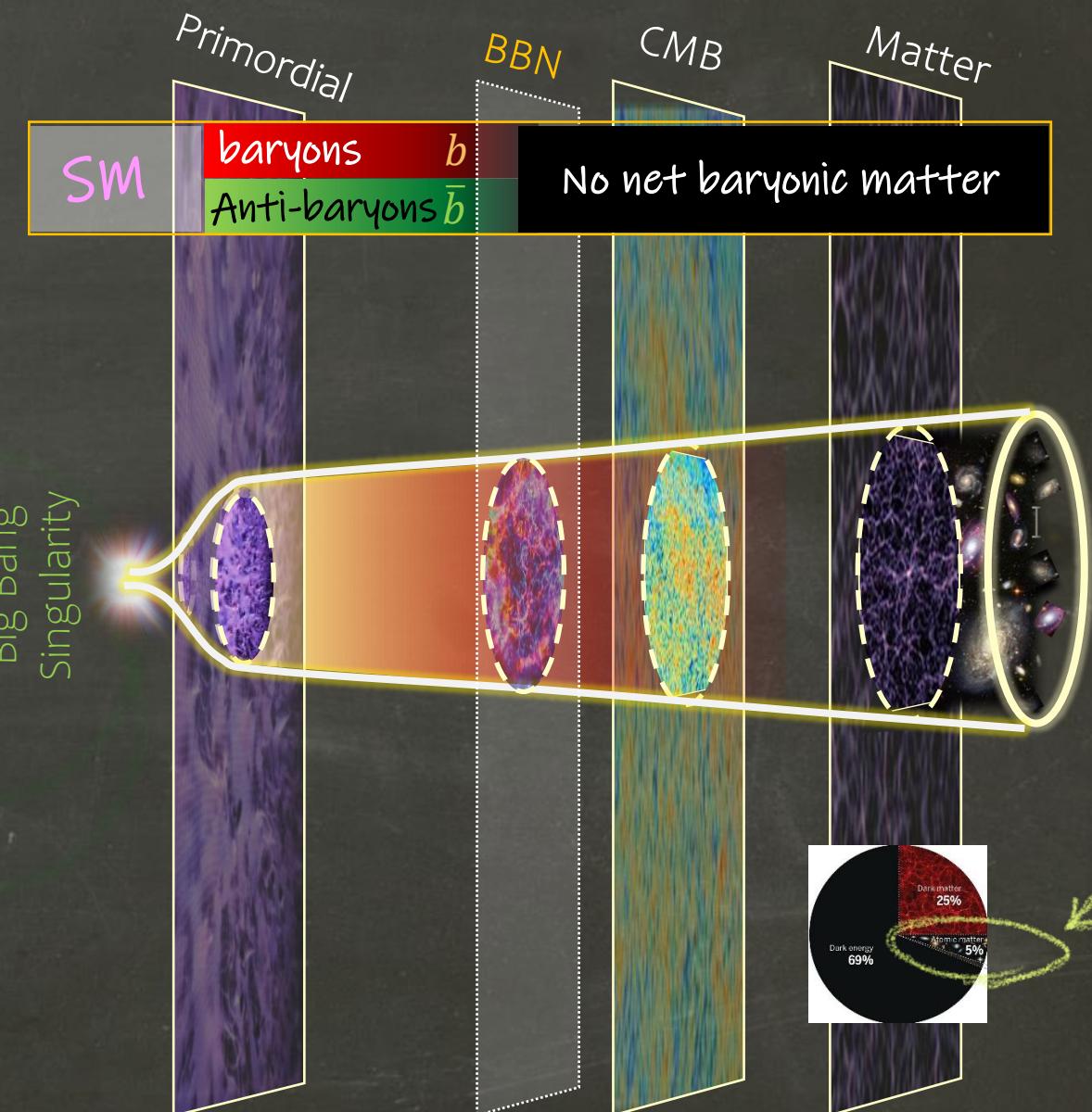


# Baryon Asymmetry

Standard Model predicts (almost) equal baryons & antibaryons:  $\frac{n_b}{n_\gamma} \approx \frac{n_{\bar{b}}}{n_\gamma} \approx 10^{-20} !!$

(assuming equal initial baryon & antibaryons)

CP is mildly broken in SM.



# Baryon Asymmetry

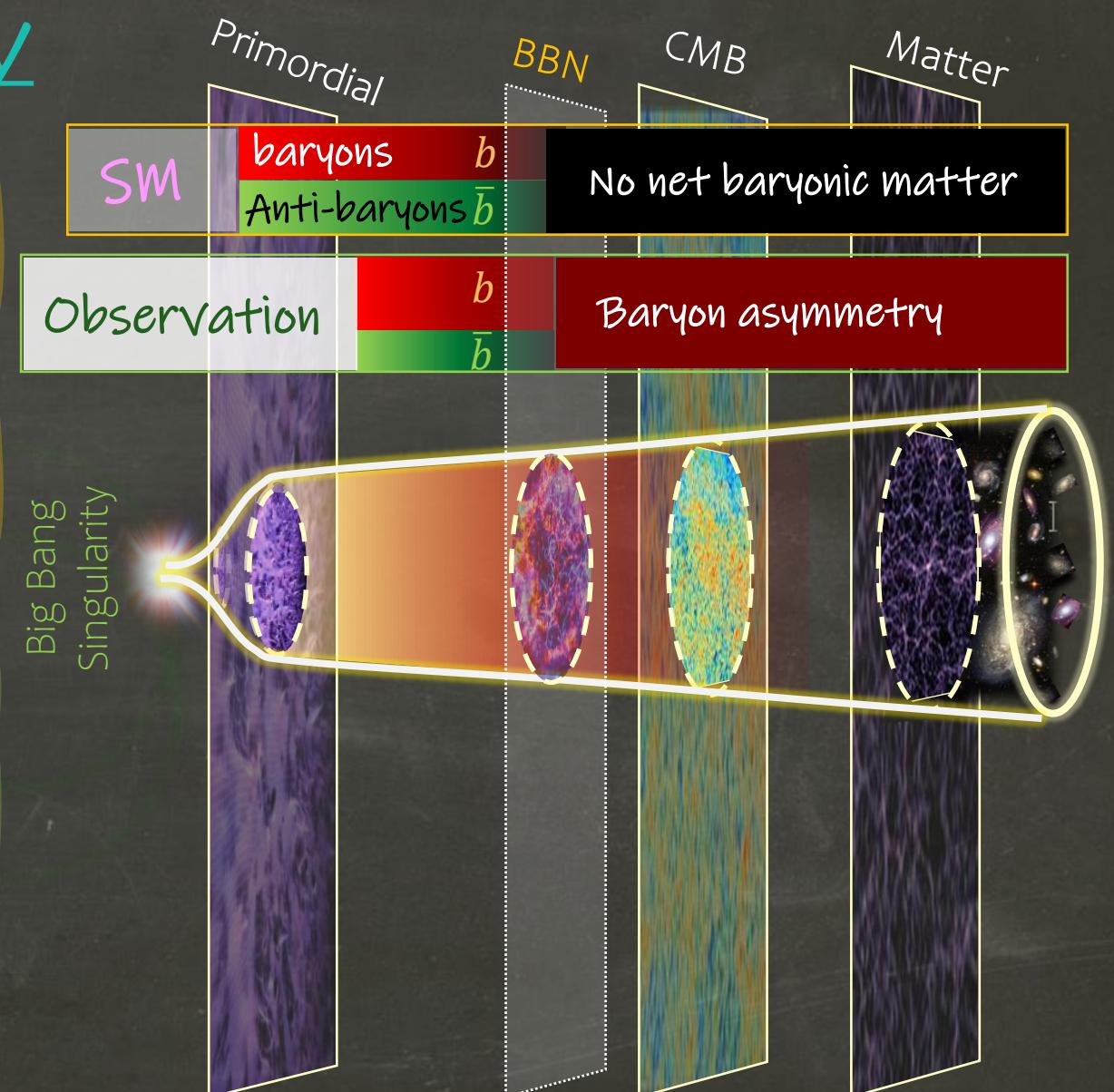
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$$\frac{n_b - n_{\bar{b}}}{n_\gamma} \approx 6 \times 10^{-10}$$



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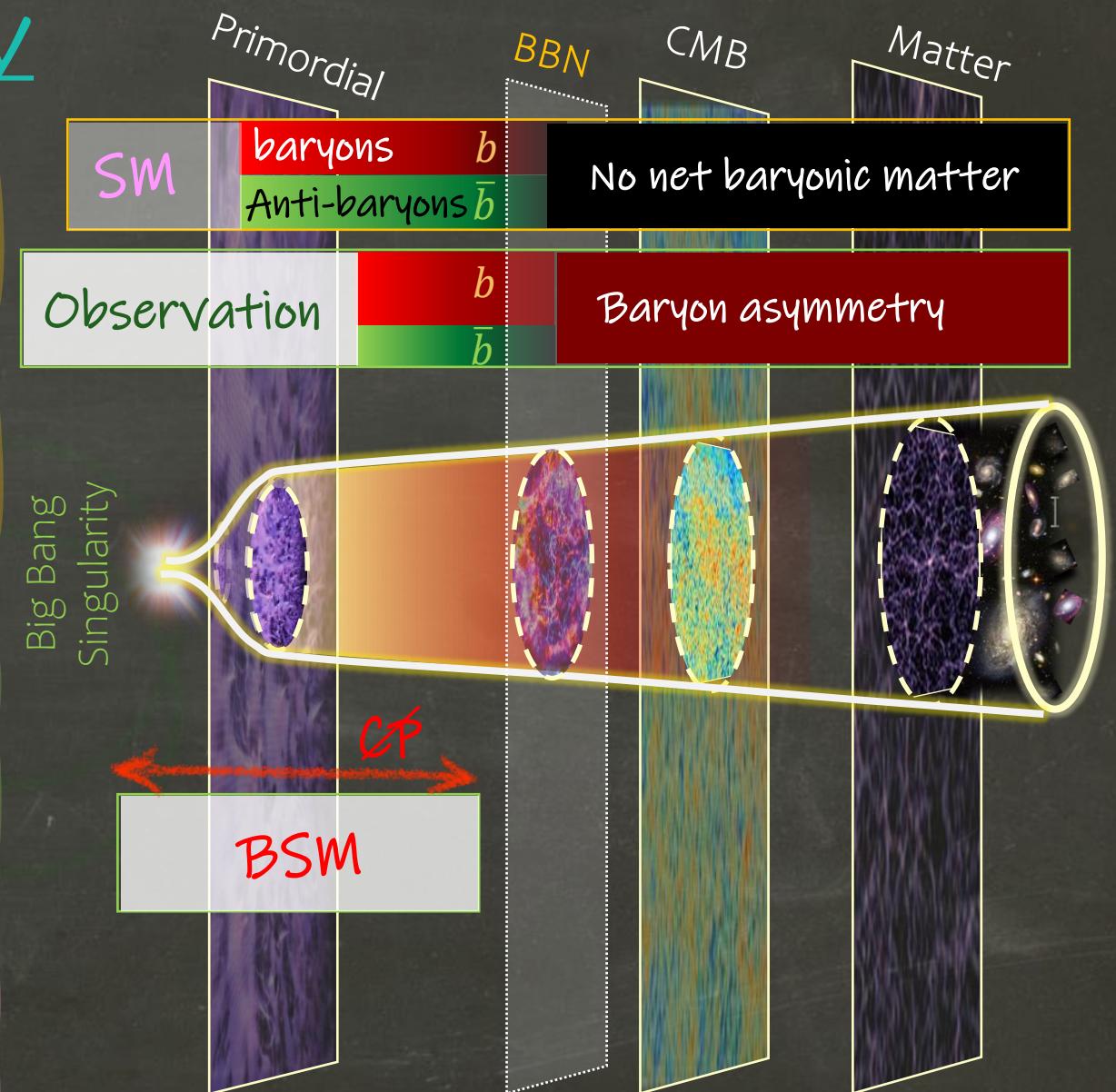
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Observation shows our Universe is highly matter dominated:

$$\frac{n_b - n_{\bar{b}}}{n_\gamma} \approx 6 \times 10^{-10}$$

Beyond the Standard Model physics with sufficient CP violation to produce a net baryonic matter out of thermal equilibrium.

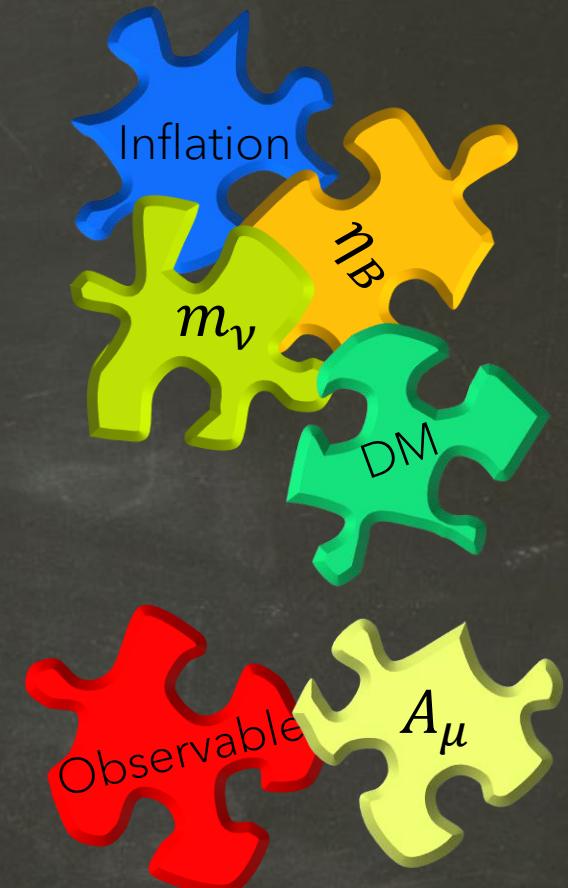


# Puzzles of SM & Cosmology

- 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



# Puzzles of SM & Cosmology

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

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

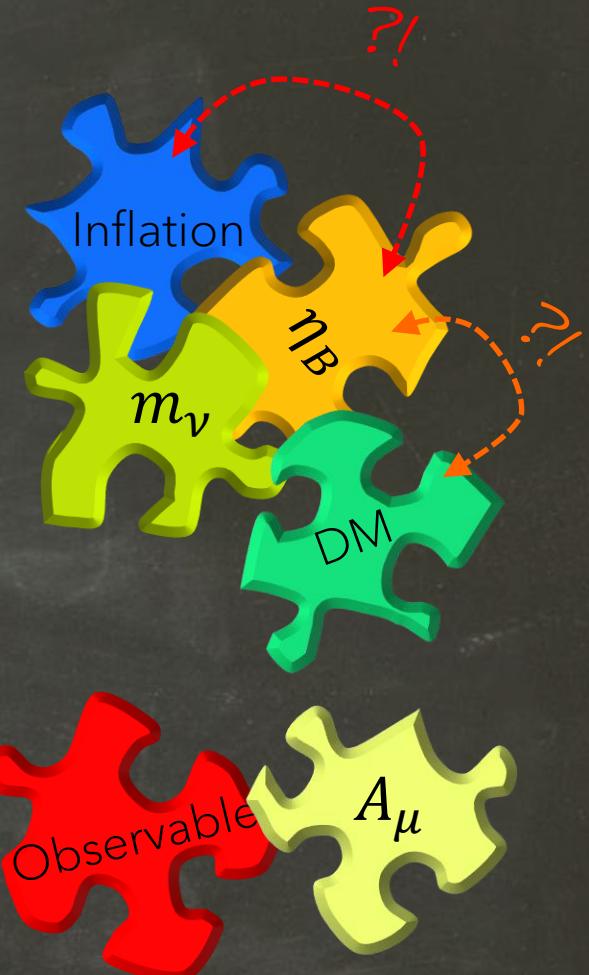
$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} \approx 6 \times 10^{-10}$$

Baryon to Photon Ratio  
Today

$$P_\zeta = \frac{1}{2\epsilon} \left( \frac{1}{2\pi M_{pl}} H \right)^2 \approx 2 \times 10^{-9}$$

Curvature Power Spectrum in  
Inflation

Puzzles of  
Standard Model of Particle Physics (SM)  
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Physics Beyond SM



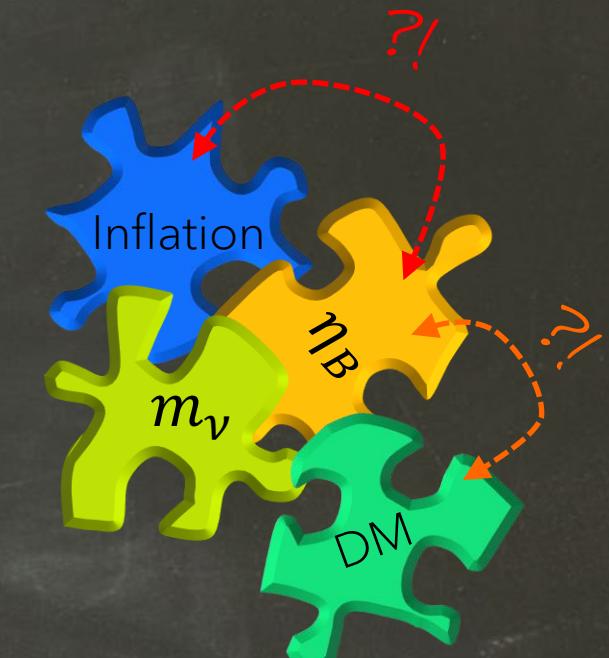
# Puzzles of SM & Cosmology

- I) Particle physics of Inflation
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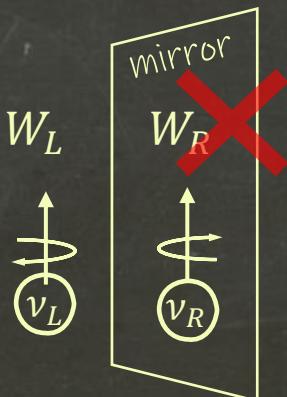
◆ Curious cosmological coincidences  $\eta_B \simeq 0.3 P_\zeta$  and  $\Omega_{DM} \simeq 5\Omega_B$ !

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

Puzzles of  
Standard Model of Particle Physics (SM)  
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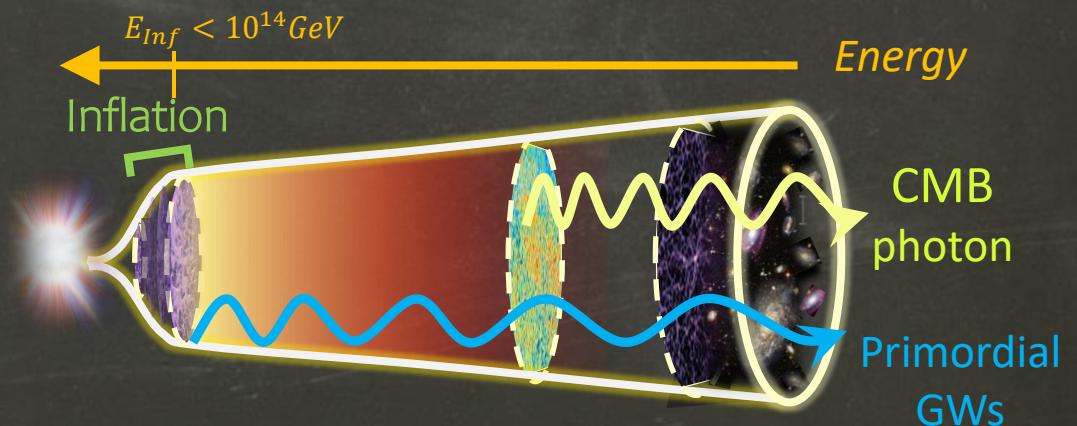
SM as a particle physics model  
also faces some **conceptual issues**



# 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.

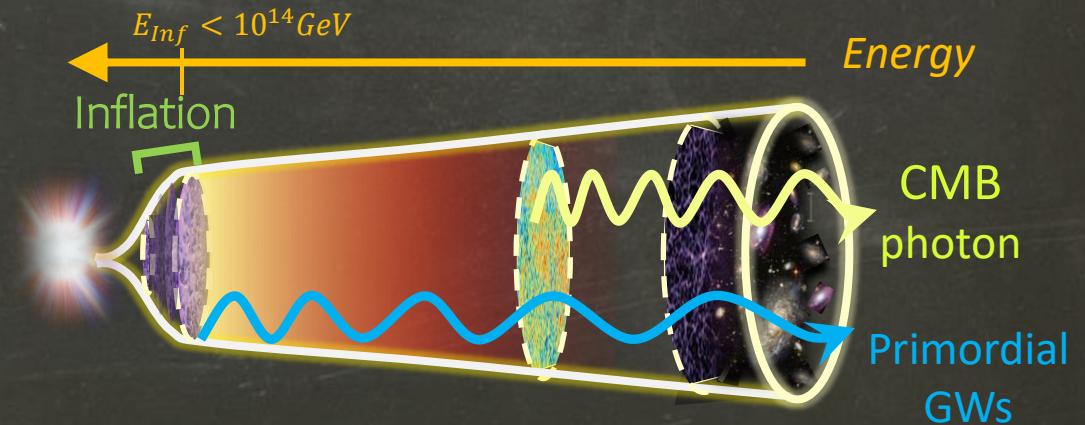
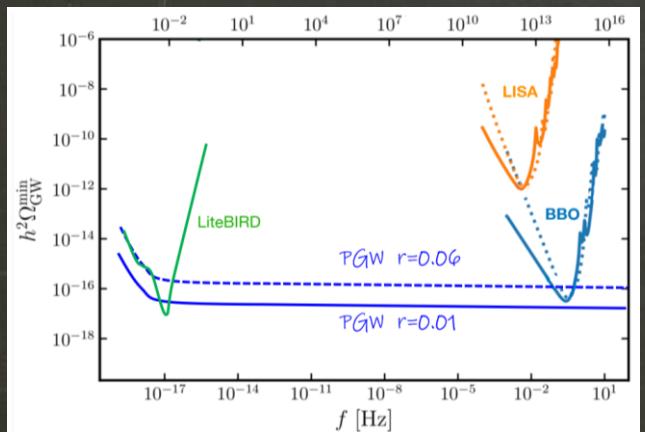
Inflation Particle Physics: a scalar field beyond the SM.



# As Yet

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

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

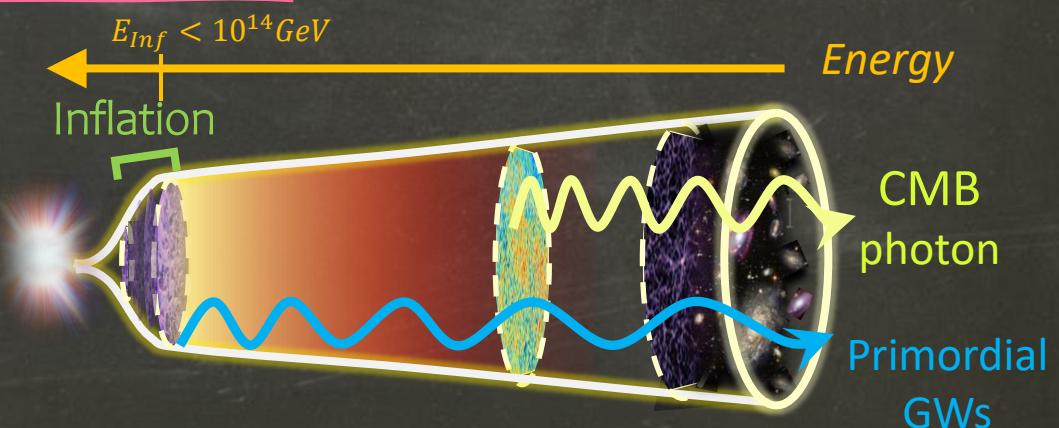


# As Yet

- Observations are in perfect agreement with Inflation.
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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?!



# I) Axion-inflation & gauge fields (non-Abelian)



# Challenges:

Gauge fields given by Yang-Mills

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



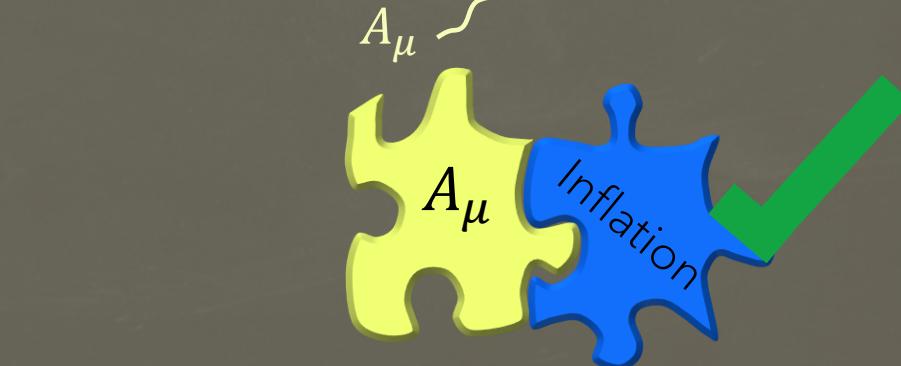
Gauge fields coupled to inflaton  
are generated in inflation.

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

Axion

(Axion fields are naturally  
coupled to gauge fields.)

Gauge field  $A_\mu$   
(active in inflation)



# Challenges:

Gauge fields given by Yang-Mills

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

Spatial isotropy & homogeneity

U(1) vacuum  $A_\mu$

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



Gauge fields coupled to inflaton  
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Axion

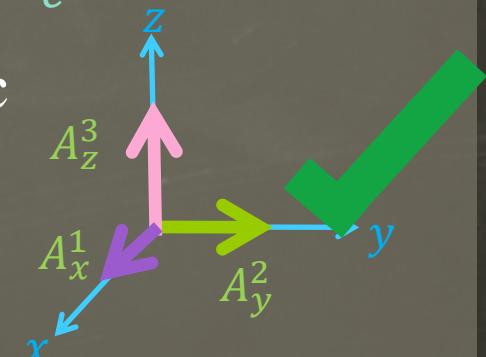
(Axion fields are naturally  
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A.M. & Sheikh-Jabbari, 2011

$$\text{SU}(2) \text{ vacuum } A_\mu = A_\mu^a T_a$$
$$[T_a, T_b] = i \epsilon^{abc} T_c$$

Spatially isotropic

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



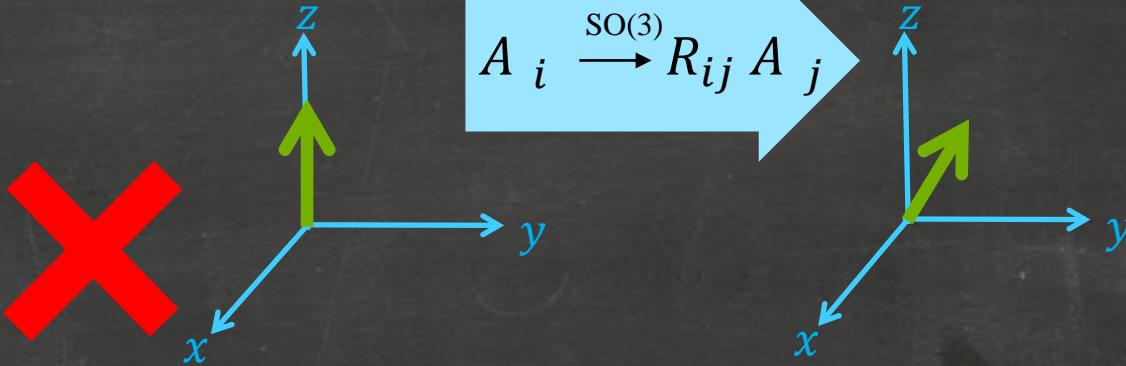
so(3) & su(2) are isomorphic

# How $SU(2)$ restores isotropy?

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

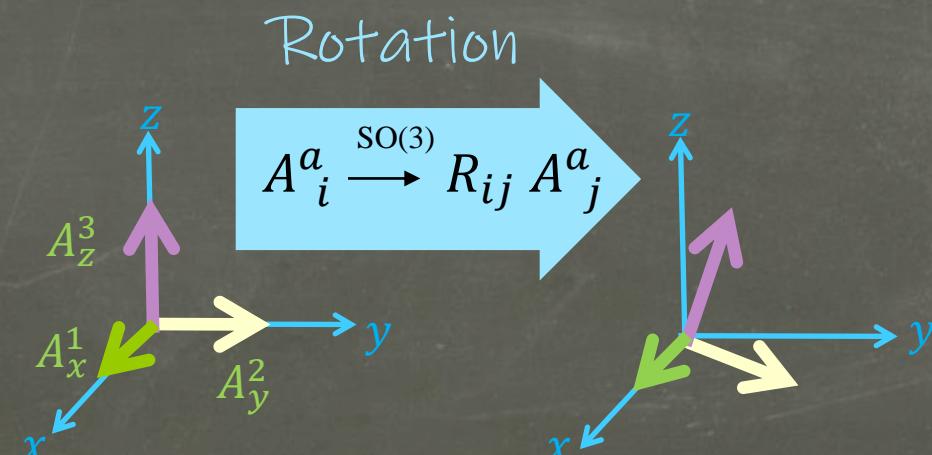
$U(1)$  vacuum  $A_\mu$

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



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

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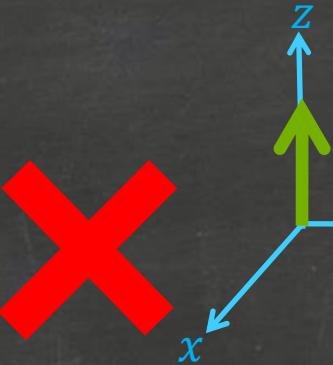


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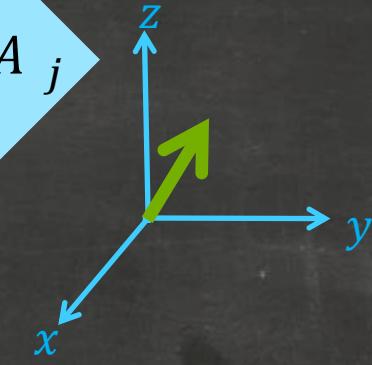
U(1) vacuum  $A_\mu$

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Rotation

$$A_i \xrightarrow{\text{SO}(3)} R_{ij} A_j$$



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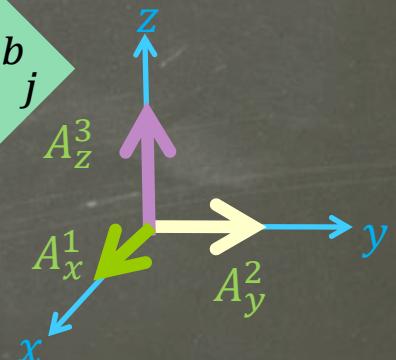


Rotation

$$A_i^a \xrightarrow{\text{SO}(3)} R_{ij} A_j^a$$

Gauge Transformation

$$A_i^a \rightarrow R_{ab} A_j^b$$



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

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

A.M. & Sheikh-Jabbari, 2011

$U(1)$  vacuum  $A_\mu$

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A.M. & Sheikh-Jabbari, 2011



- Non-Abelian gauge fields have self-interactions:

field strength tensor

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

Self-interaction

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A.M. & Sheikh-Jabbari, 2011

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field strength tensor

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

- Chern-Simons term can be non-zero at BG level:

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

Self-interaction

# SU(2) Gauge fields and Initial Anisotropies

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

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



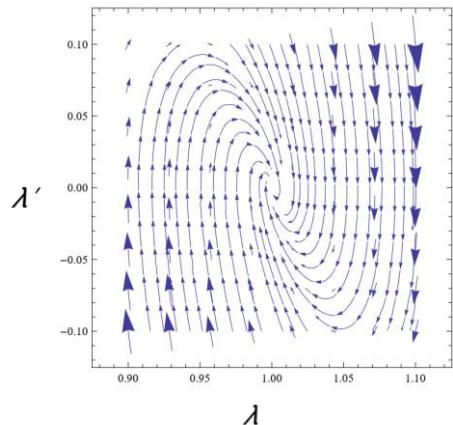
- How stable is the isotropic ansatz against **initial anisotropies**, i.e. Bianchi

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!



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



Background  
Isotropic

Background  
Anisotropic

# 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

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

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$\xi = -\mathcal{P}$

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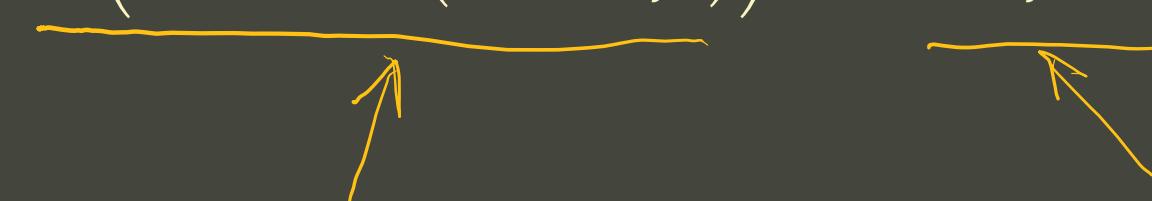
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Natural inflation

Friction

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

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A. M., & Sheikh-Jabbari, 2011

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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)<sub>R</sub> –axion inflation [arXiv:2012.11516]**
- Oksana Iarygina, Evangelos I. Sfakianakis, [[arXiv:2105.06972](#)]

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D. Baumann & L. McAllister 2014

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

- A new mechanism for generation of Primordial Gravitational Waves
- All Sakharov conditions are satisfied in inflation: a new baryogenesis mechanism
- Particle Production in inflation by Schwinger effect and chiral anomaly

P. Adshead et. al 2013  
Dimastrogiovanni et. al 2013  
A. M. et. al, 2013

**A. M. 2014 & A.M. 2016**  
R. Caldwell et. al 2017

K. Lozanov, **A. M.**, E. Komatsu 2017,  
L. Mirzagholi, **A. M.**, K. Lozanov 2019,  
Domcke et al 2019, **A.M. 2019**

# 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

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

- Minimal Scenario of SU(2)-axion inflation      A. M., 2016       $f < 0.1 \text{ M}_{\text{Pl}}$  &  $\lambda < 0.1$

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

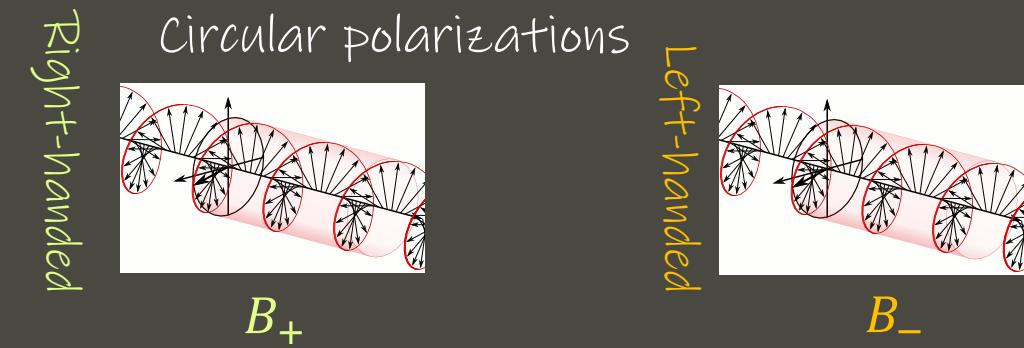
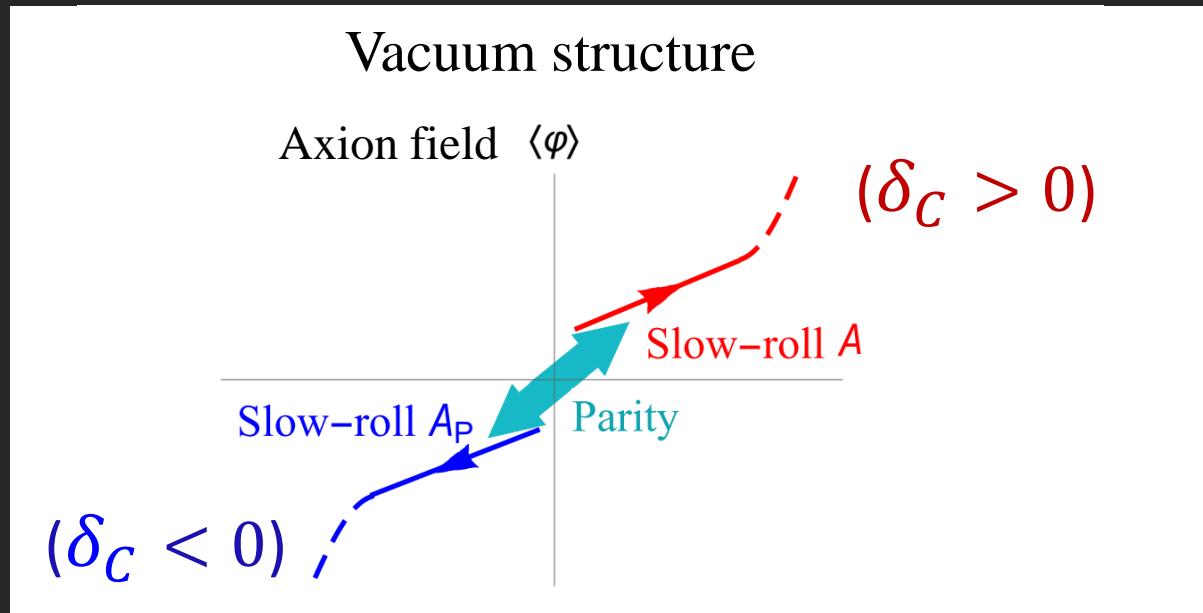
Axion Monodromy or any mechanism that gives a flat potential

# New Tensorial mode in $SU(2)$ Gauge Field

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

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

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



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

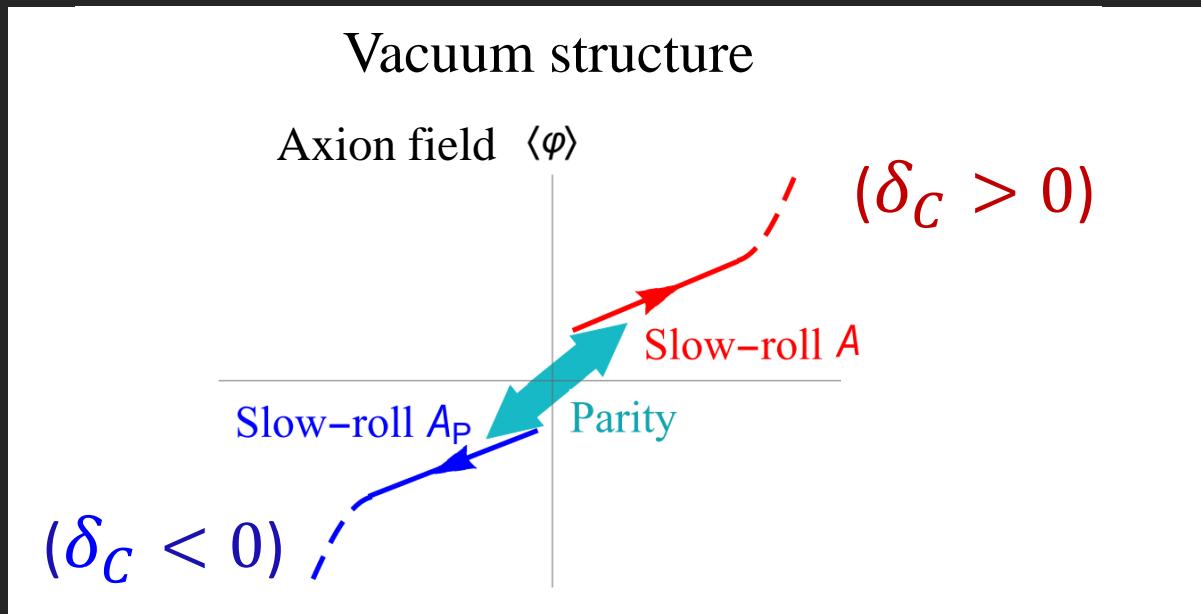
A.M. & Sheikh-Jabbari, 2011

# New Tensorial mode in $SU(2)$ Gauge Field

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

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

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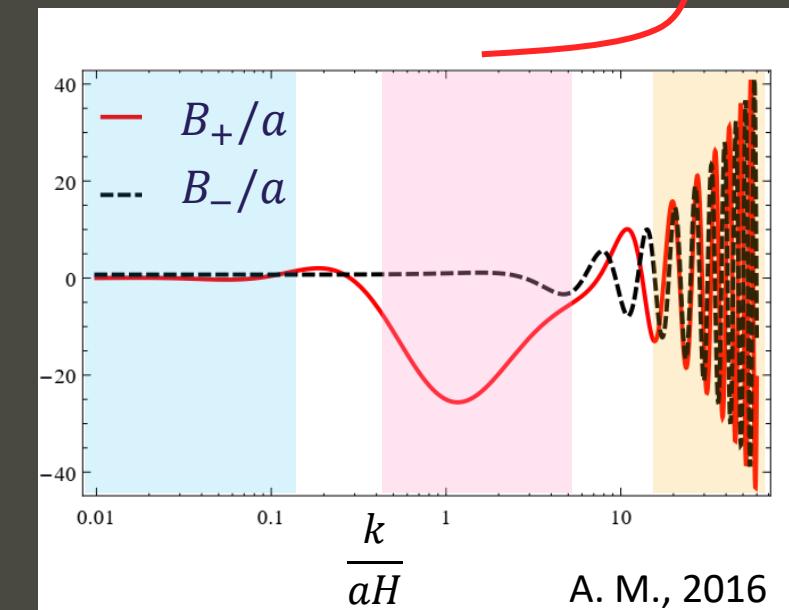
For  $\delta_C > 0$   
Short tachyonic growth of  $B_+$



Chiral Field

Particle Production

A. M. and E. Komatsu, 2018



# Gauge Field sources Primordial GWs

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

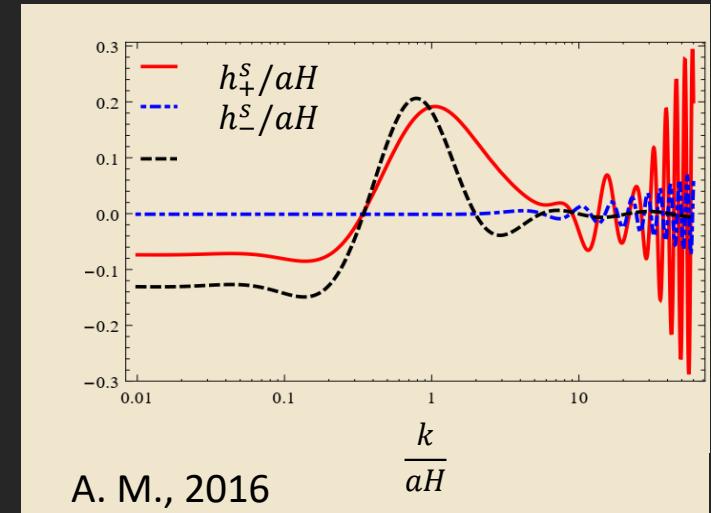
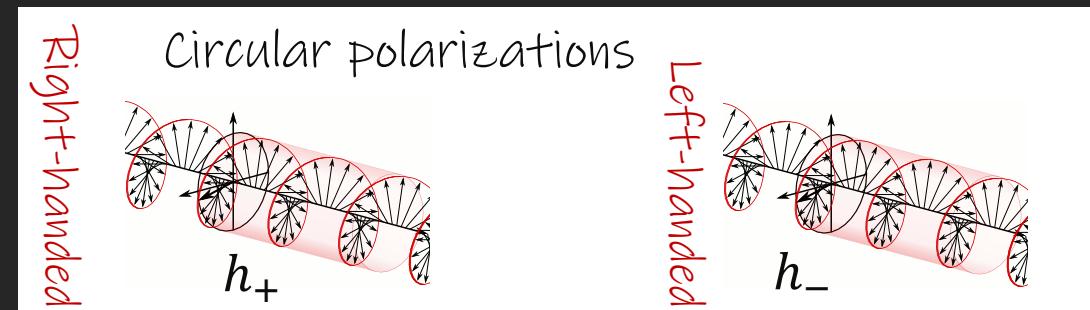
$$h_\pm'' + [k^2 - \frac{a''}{a}] h_\pm = \mathcal{H}^2 \Pi_\pm[B_\pm]$$

- Gravitational waves have two uncorrelated terms



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

$h_+^{vac} = h_-^{vac}$        $h_+^S \neq h_-^S$



# Novel Observable Signature: CMB

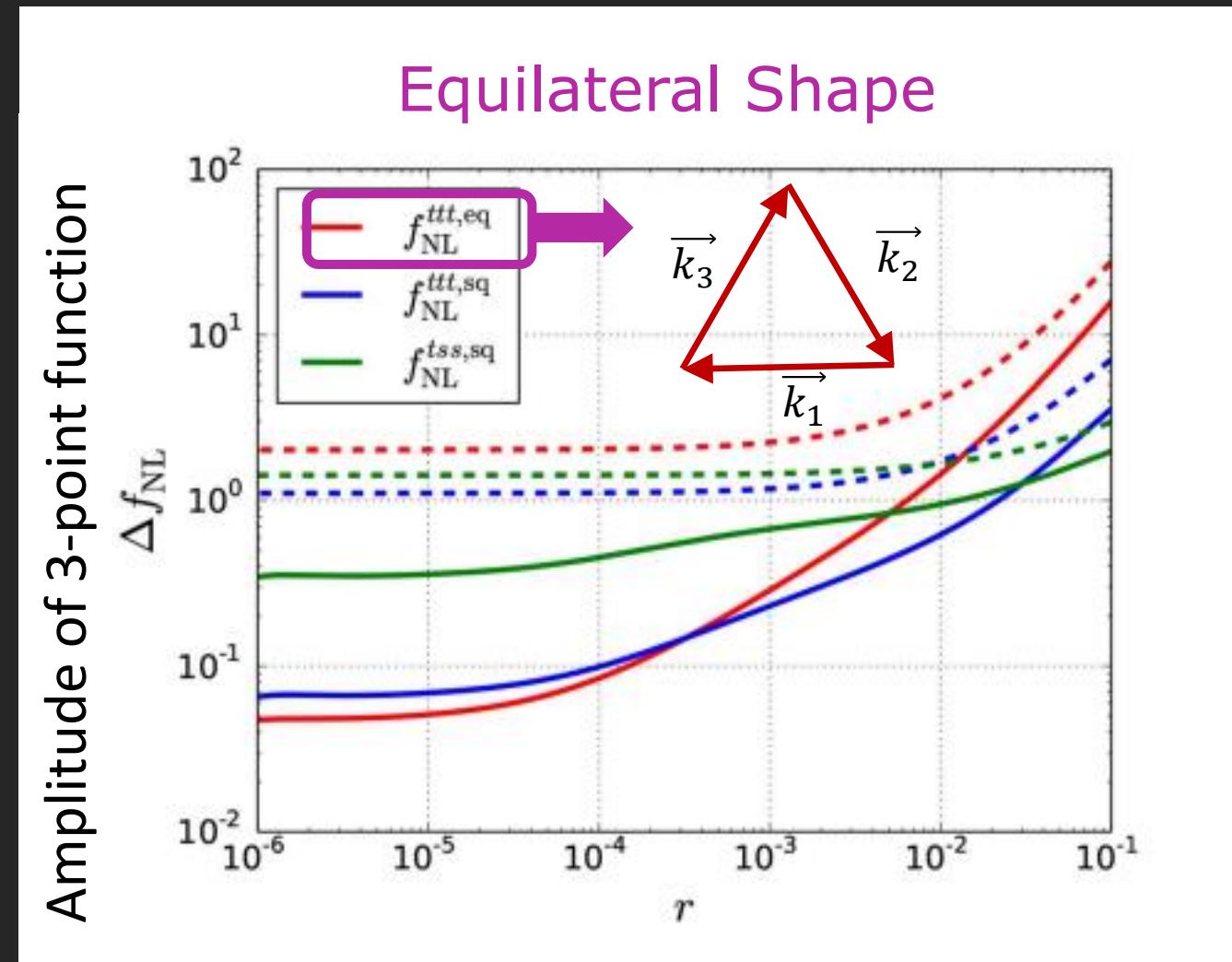
- The sourced tensor modes is Highly non-Gaussian.

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

Self-interaction

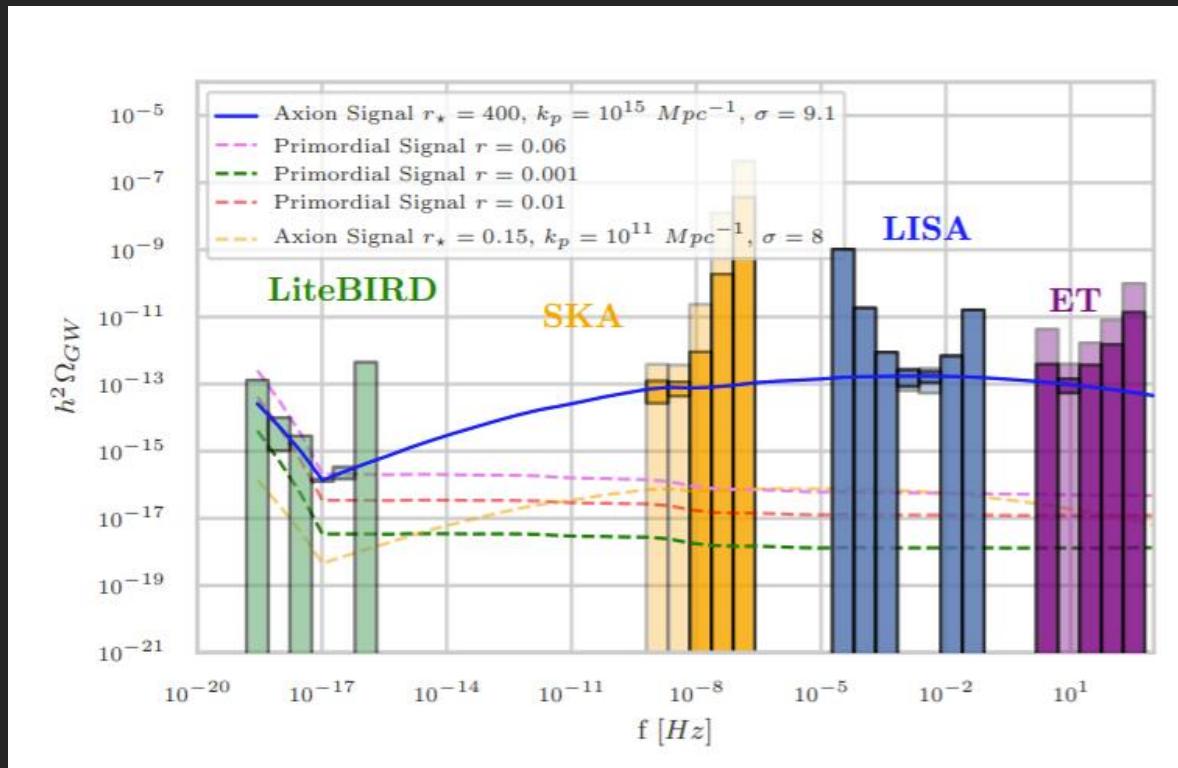
Agrawal, Fujita, Komatsu 2018

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



# Novel Observable Signature: Beyond CMB

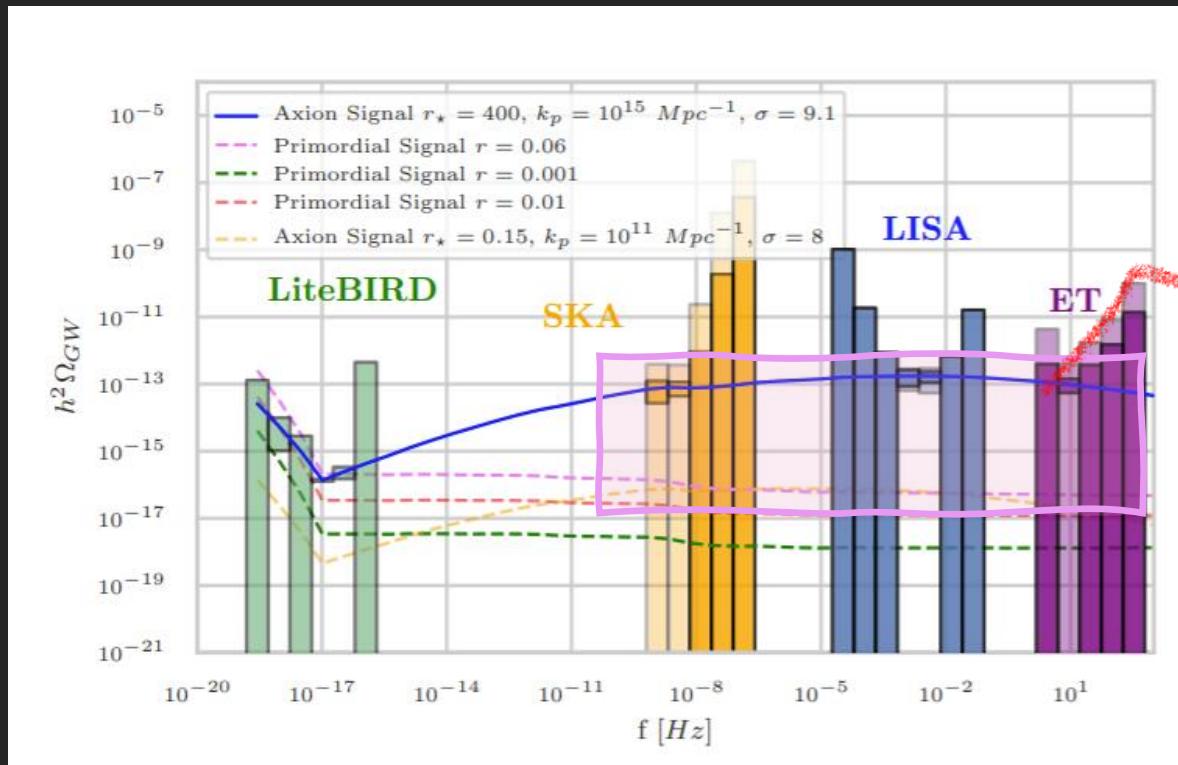
Detection of this background is an excellent target for all GW experiments across at least 21 decades in frequencies.



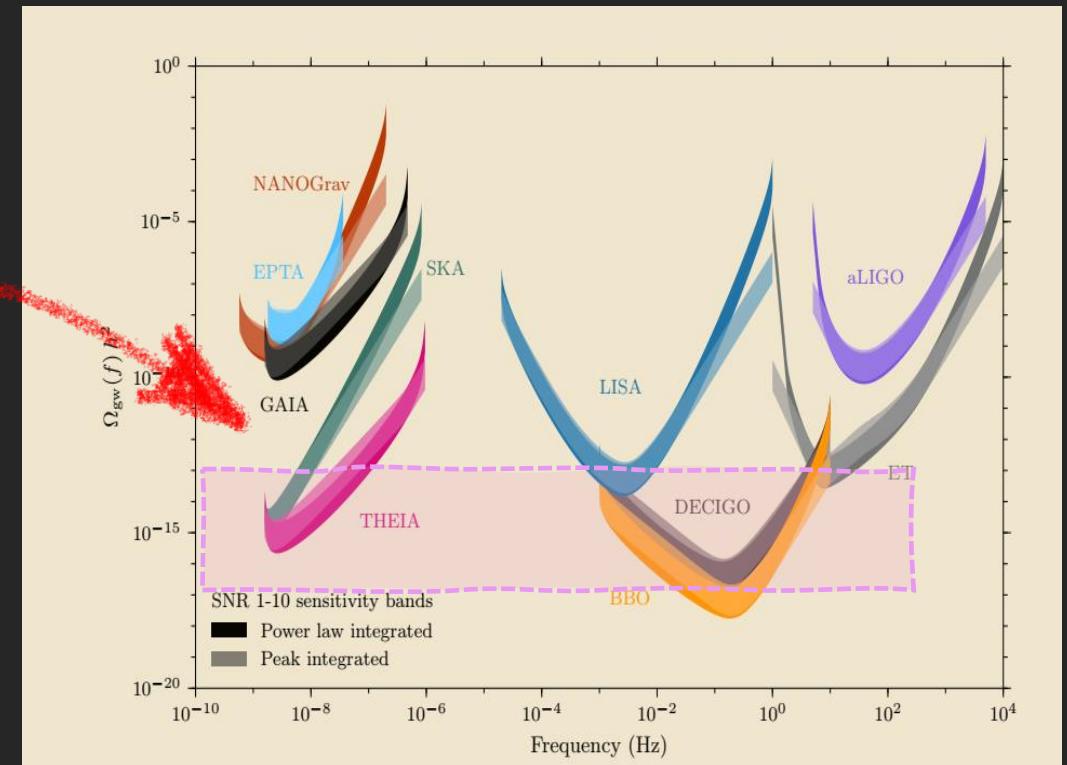
P. Campeti, E. Komatsu, D. Poletti, C. Baccigalupi 2020

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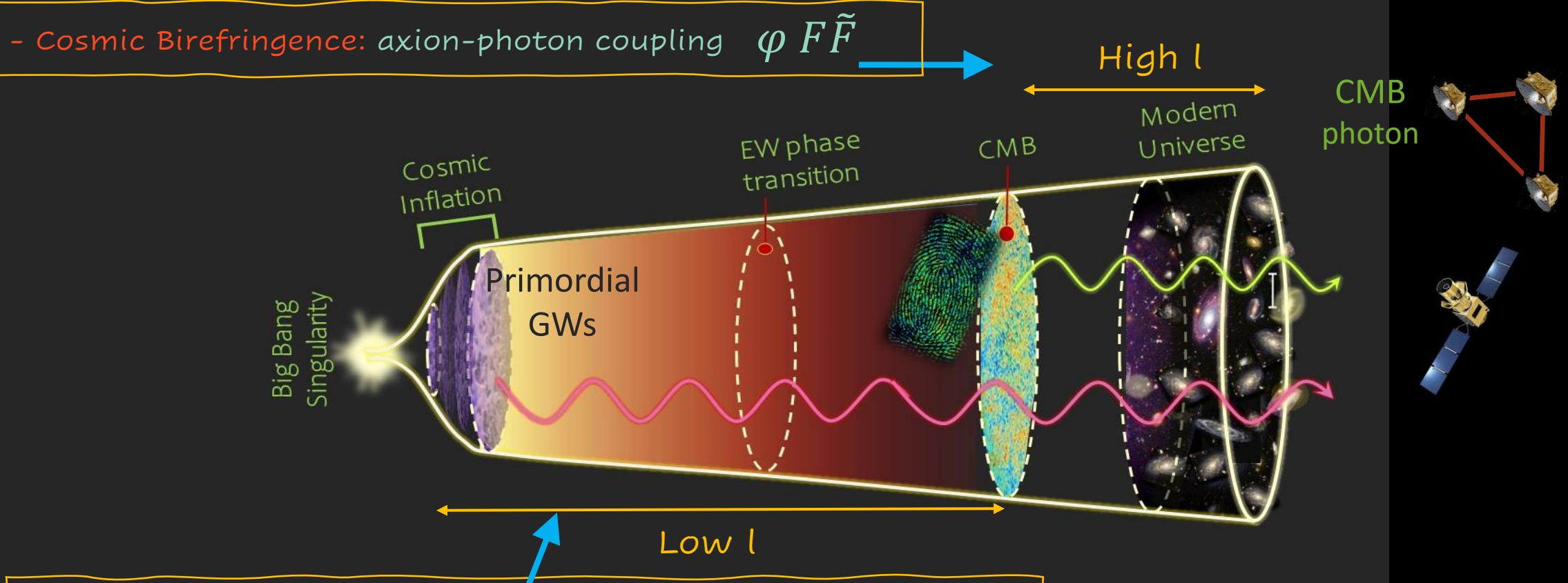
P. Campeti, E. Komatsu, D. Poletti, C. Baccigalupi 2020



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

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

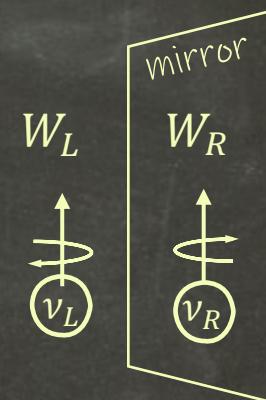
Sources of Parity violation on CMB:



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

## II) Embedding axion-inflation in Left-Right Symmetric Models

(How to Connect Inflaton to SM?)



# How to Connect it to the SM?

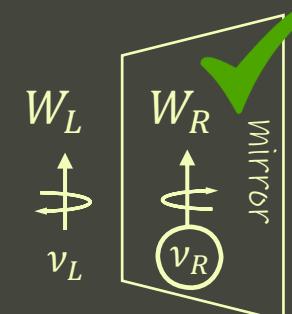
Let us Extend SM Gauge Symmetry by an  $SU(2)_R$  and couple it to Axion Inflaton!

- 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



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Axion Monodromy or any mechanism that gives a flat potential

Gauge field is  $SU(2)_R$

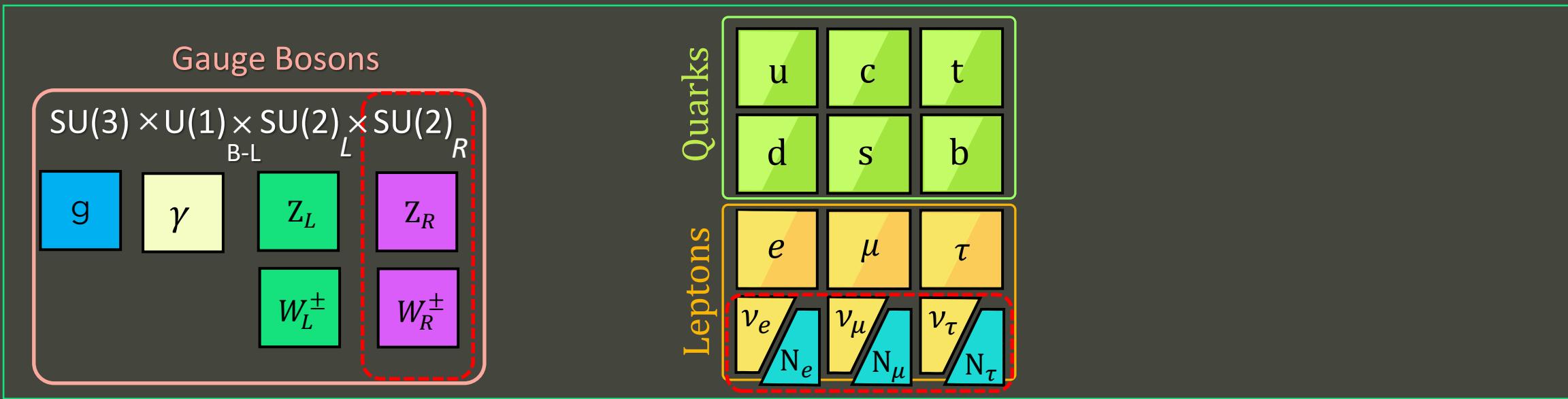
A. M. arXiv: 2012.11516

A. M. arXiv: 2103.14611

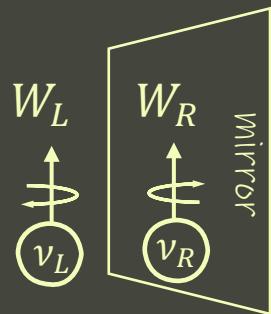
# Left-Right Symmetric Model

- An  $SU(2)$ -gauge extension of SM with 3 Right-handed Neutrinos coupled to it.

Minimal Left-Right Symmetric model



J. C. Pati and A. Salam, Phys. Rev. D 10, 275-289 (1974) R. N. Mohapatra and J. C. Pati, Phys. Rev. D 11, 2558 (1975) G. Senjanovic and R. N. Mohapatra, Phys. Rev. D 12, 1502 (1975)

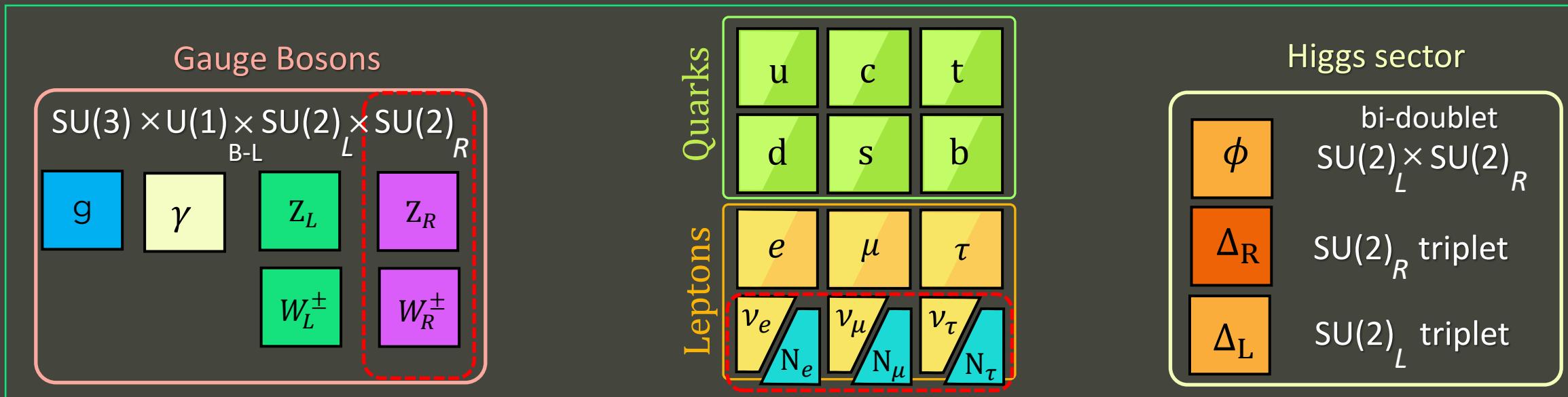


$SU(2)_L \times SU(2)_R \times U(1)_{B-L}$   
Spontaneous  
Symmetry Breaking  
 $SU(2)_L \times U(1)_Y$

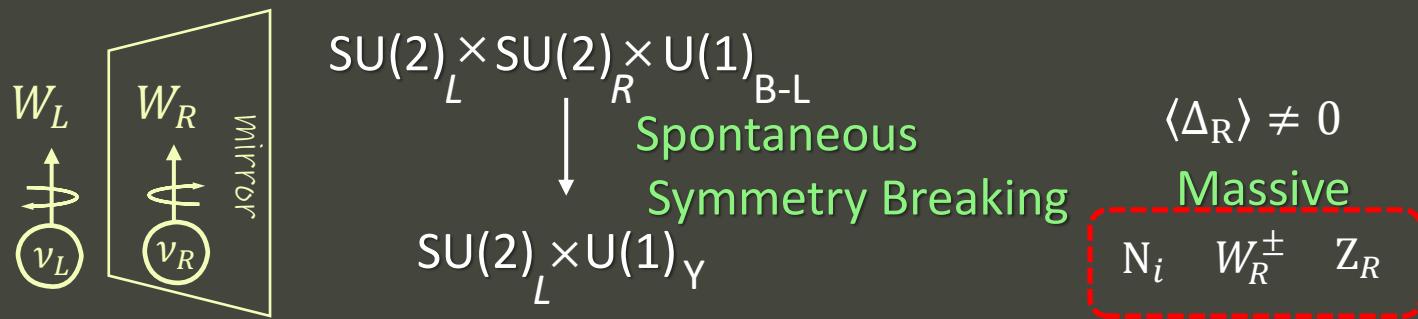
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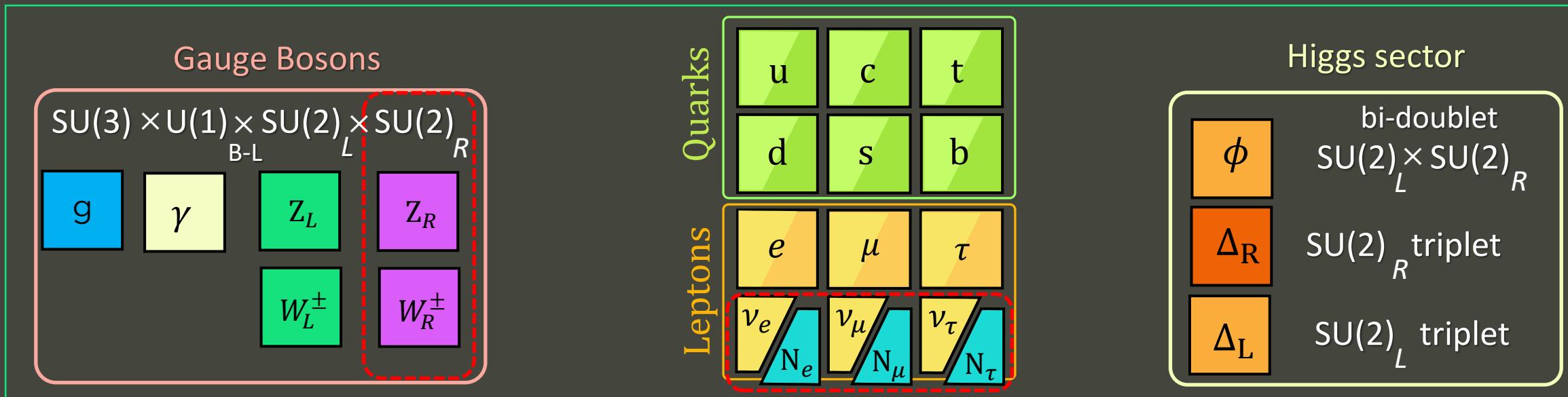
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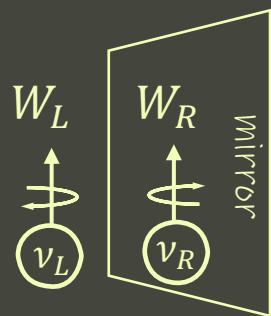
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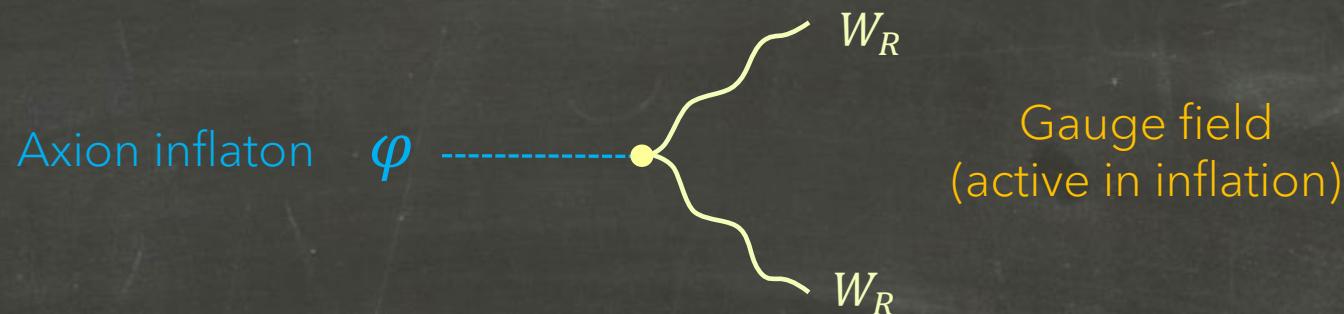
$SU(2)_L \times SU(2)_R \times U(1)^{B-L}$   
 $\downarrow$   
**Spontaneous Symmetry Breaking**  
 $SU(2)_L \times U(1)_Y$

$\langle \Delta_R \rangle \neq 0$   
**Massive**  
 $N_i \quad W_R^\pm \quad Z_R$

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

# Gauge field Production in Inflation

- SM Gauge fields are diluted by inflation & unimportant , BUT  $SU(2)_R$ :



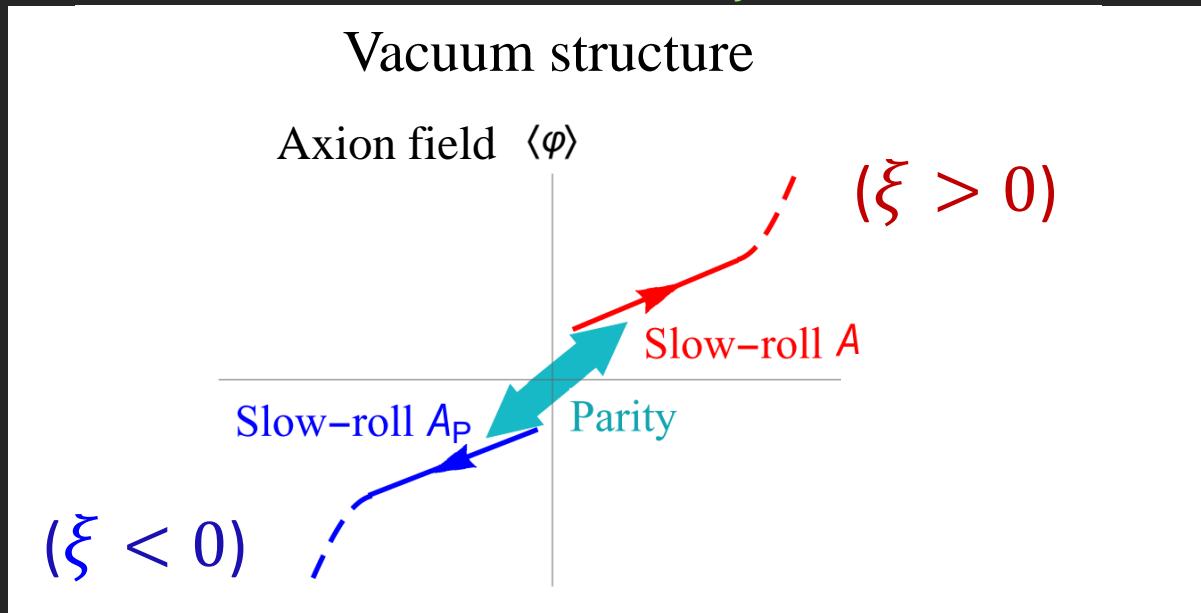
# $SU(2)_{\mathbb{R}}$ Gauge Field

- $\delta A_i^a = B_+^a(t, k) e_i^+(\vec{k}) + B_-^a(t, k) e_i^-(\vec{k})$

$$B''_{\pm} + [k^2 \mp \xi k \mathcal{H}] B_{\pm} \approx 0$$

effective frequency

Given by the BG ( $\xi = \frac{2\lambda \partial_t \varphi}{f_H}$ )



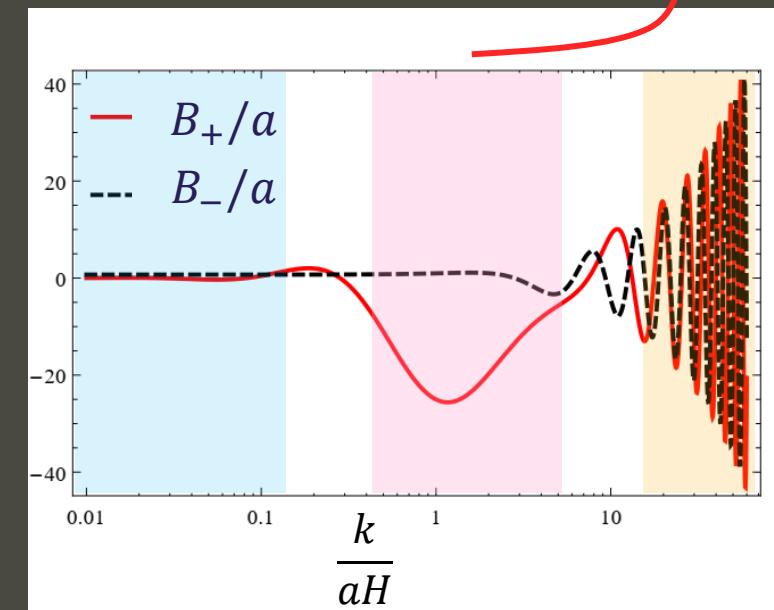
For  $\xi > 0$   
Short tachyonic growth of  $B_+$



Chiral Field

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

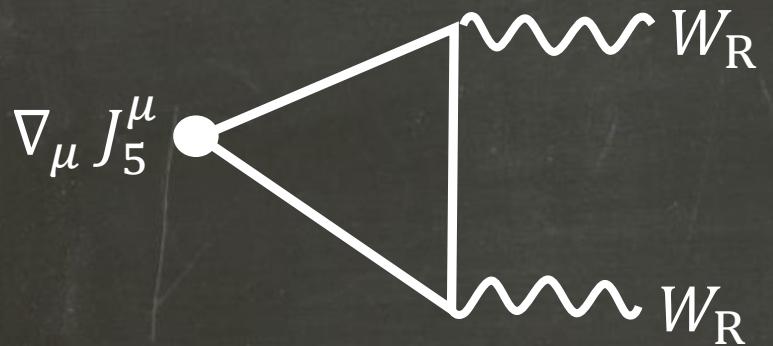
Particle Production



# Lepton & quark Production in Inflation

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

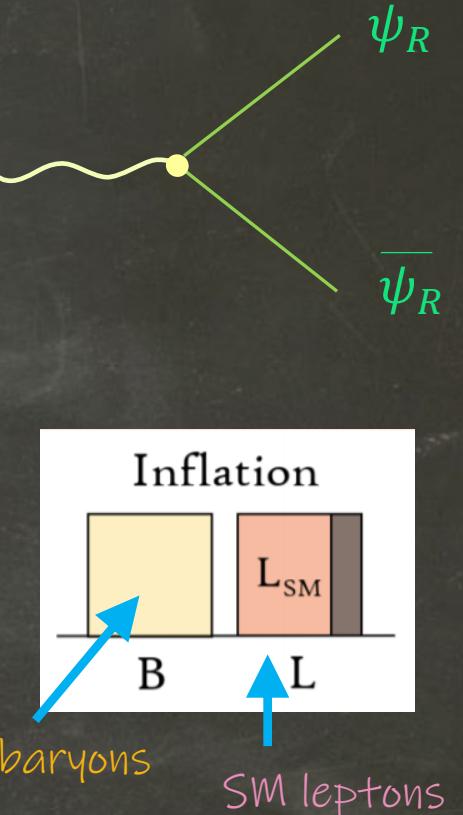
The key ingredient is the Chiral anomaly of  $SU(2)_R$  in inflation:



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

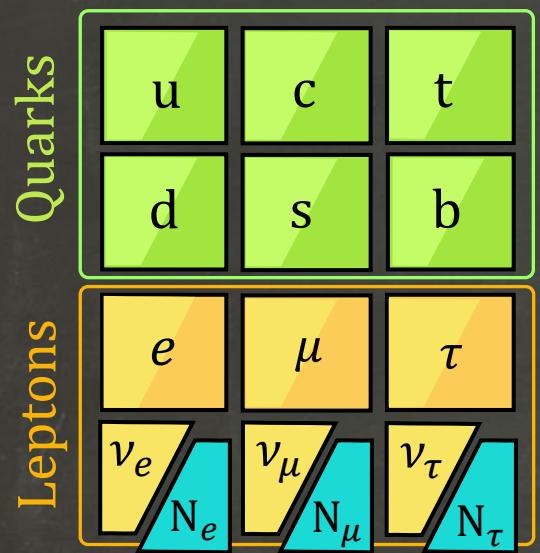
$$n_B = n_L = \alpha_{inf}(\xi) H^3$$

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

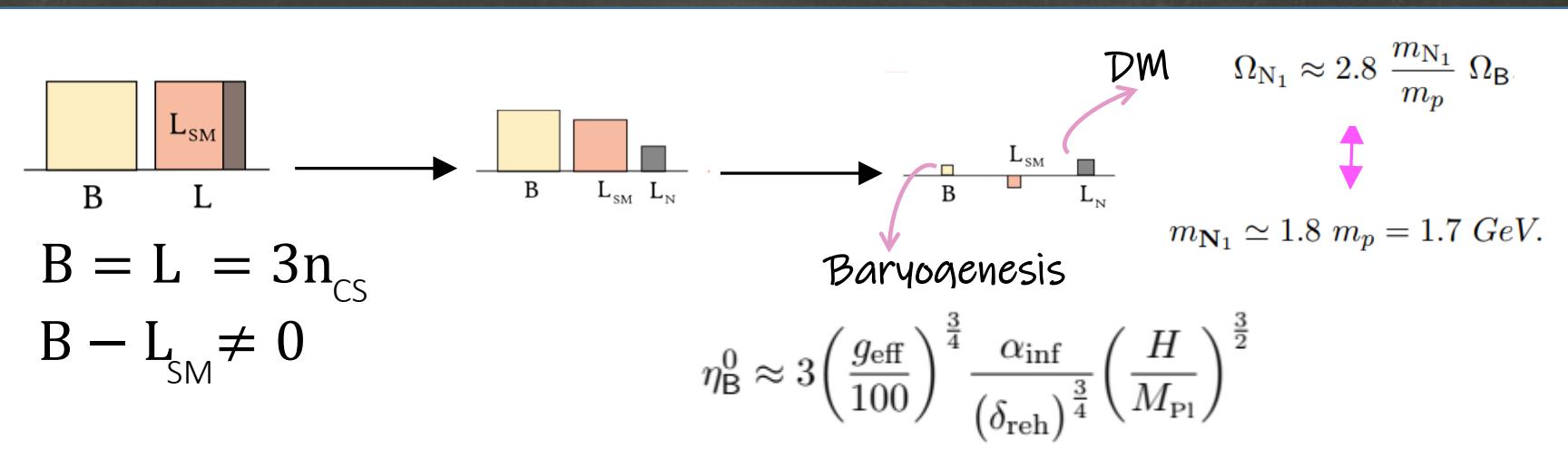
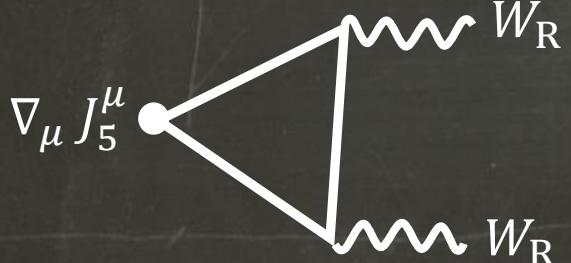


$\text{SM leptons}$   
+  
 $\text{RH neutrinos}$

# Summary of the mechanism:



Chiral anomaly of  $SU(2)_R$  in inflation



# Summary & Conclusions



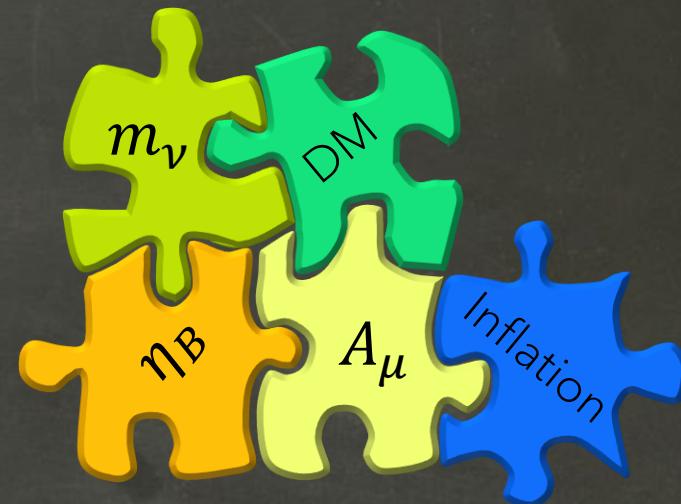
Gauge fields are expected to contribute in physics of axion-inflation.

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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



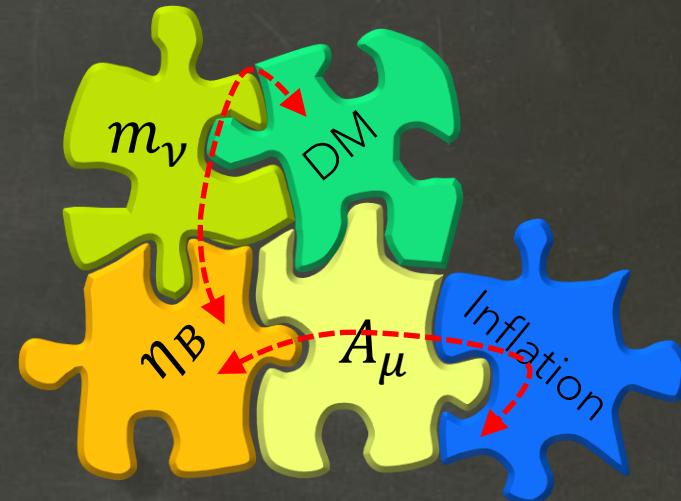
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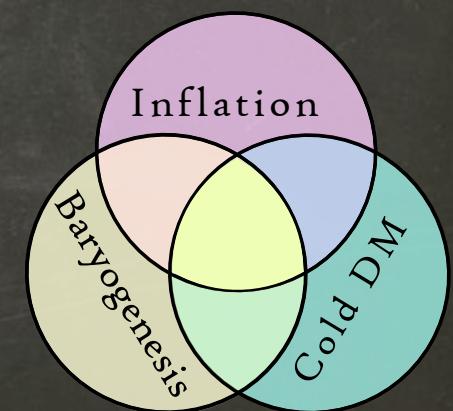
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It provides a deep connection between **inflation**, **baryogenesis** & **DM**,

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



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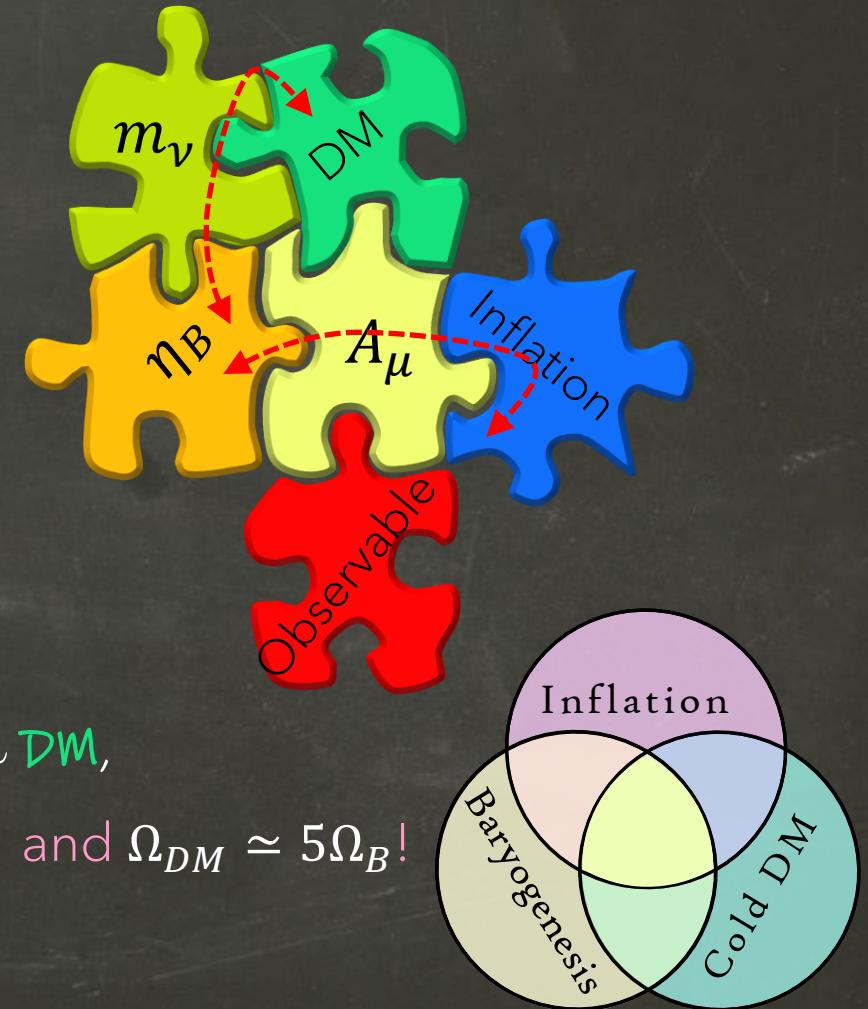
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It comes with a cosmological smoking gun on **Primordial Gw**.



Questions?!

