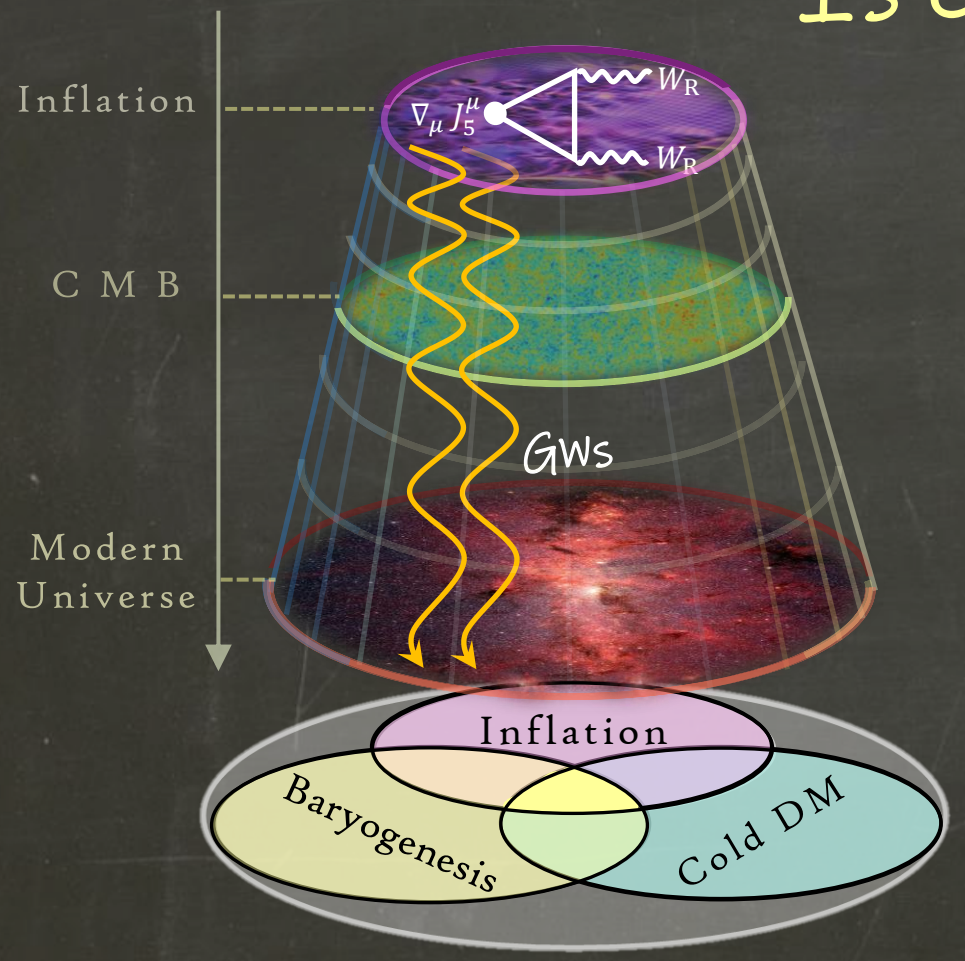
Is Our Universe the Remnant of Chiral Anomaly in Axion-Inflation?!



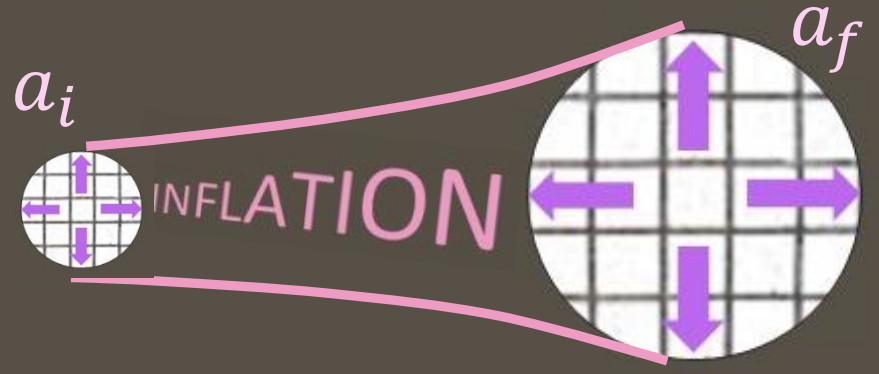
Azadeh Malek-Nejad
CERN

Cosmic Inflation

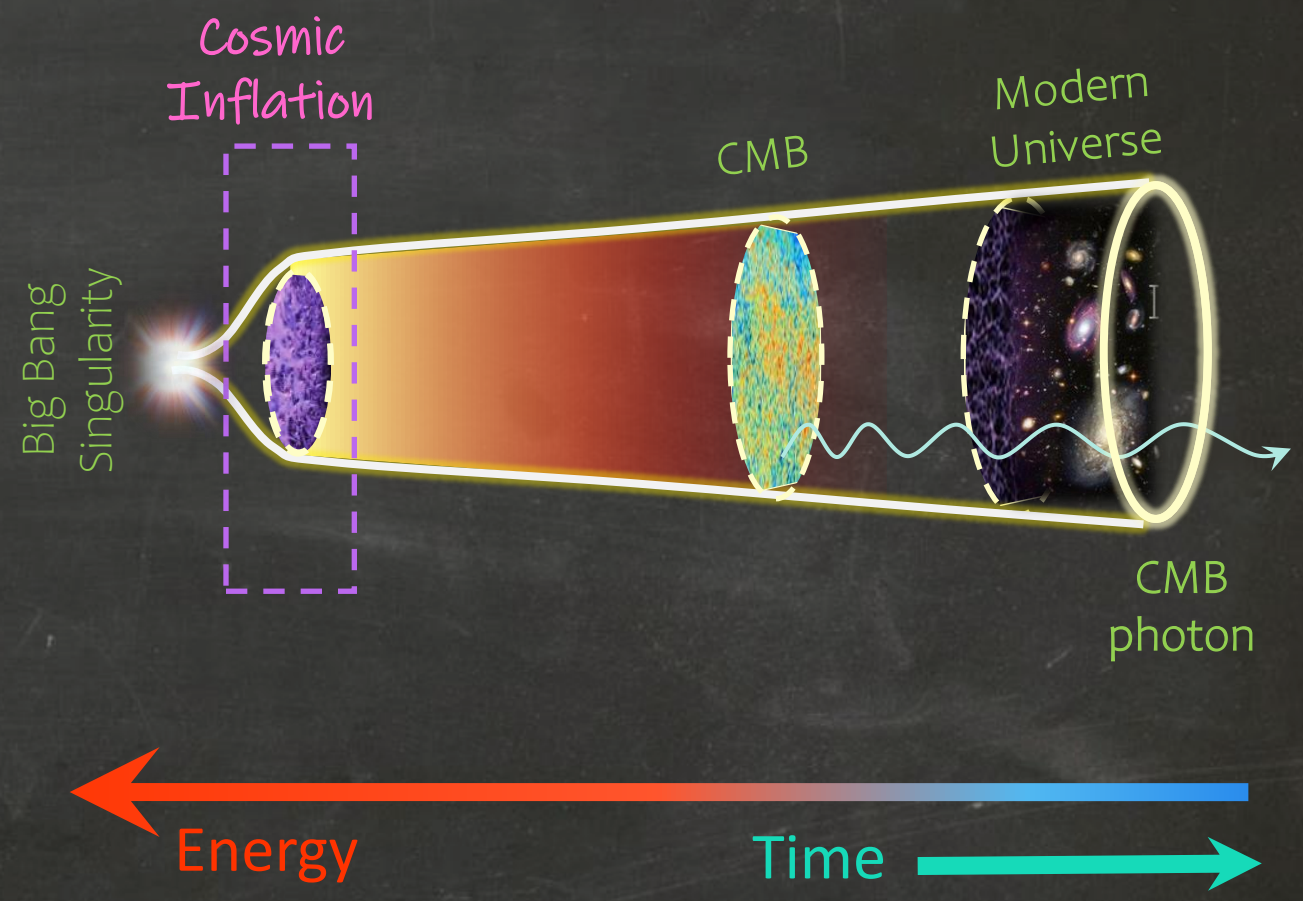
Guth Phys. Rev. D23 (1981)

Linde Phys. Lett. B 108 (1982)

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

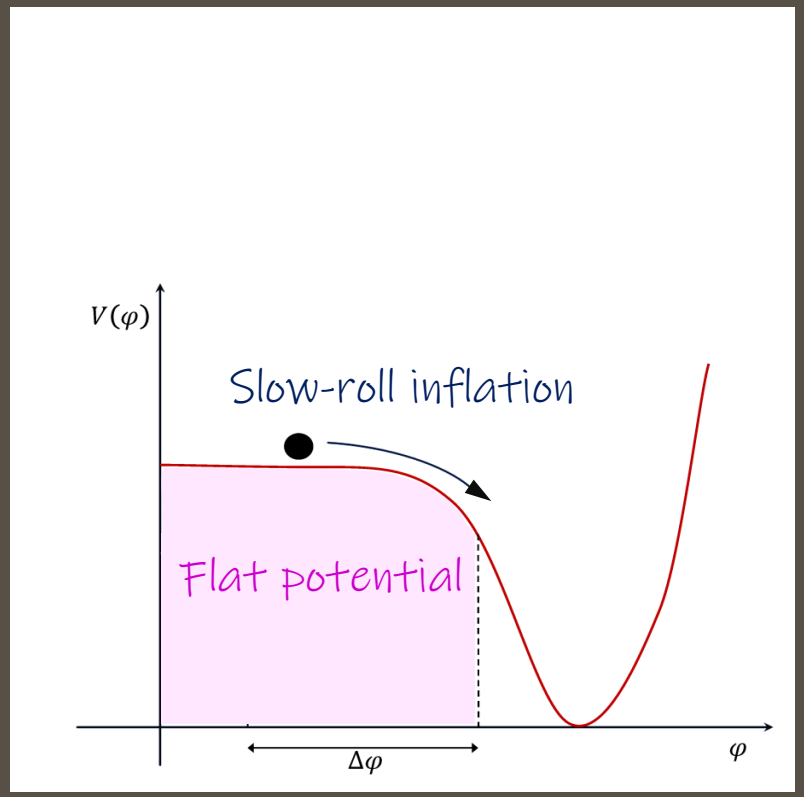


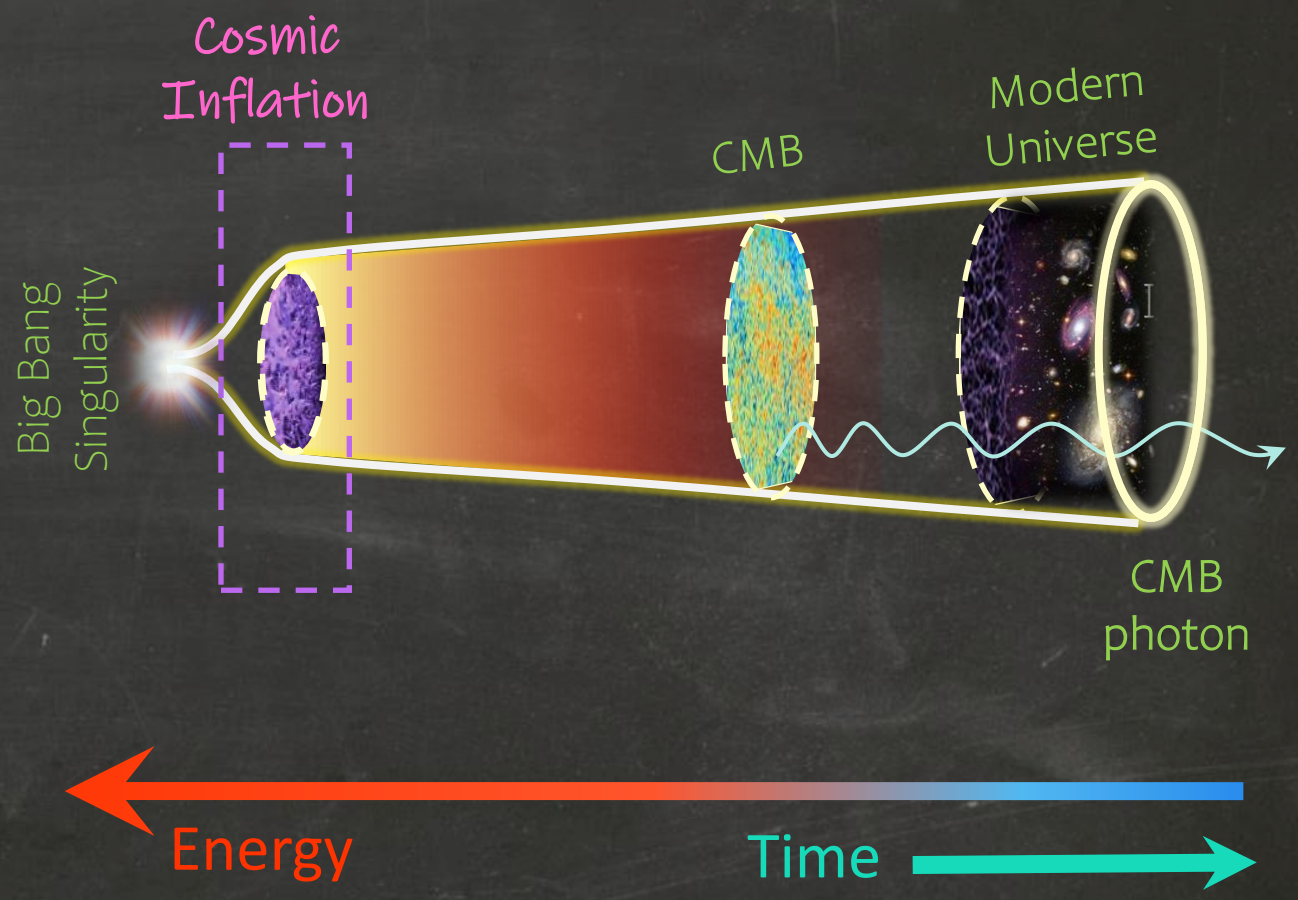
$$\frac{a_f}{a_i} = e^{60} \approx 10^{26}!$$



What caused inflation?

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





Puzzles of SM & Cosmology

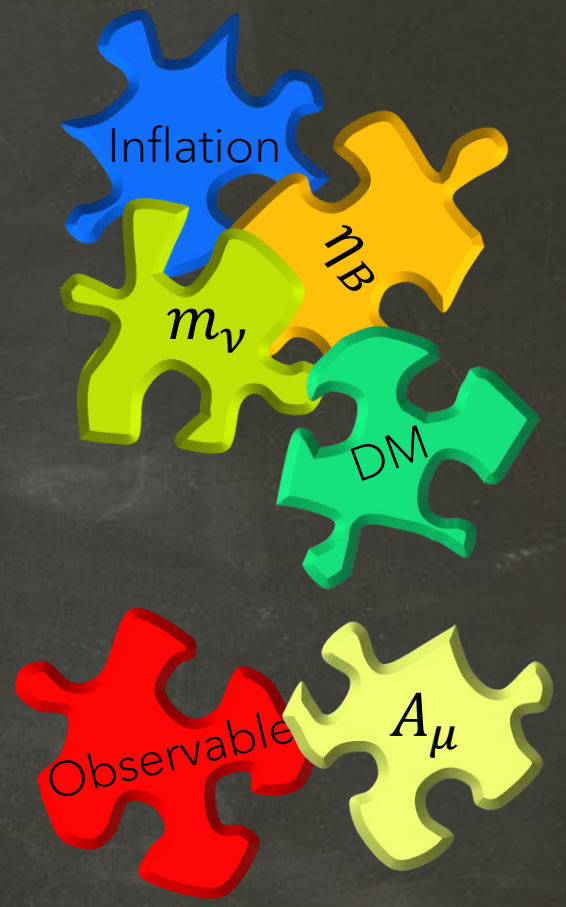
I) Particle physics of Inflation

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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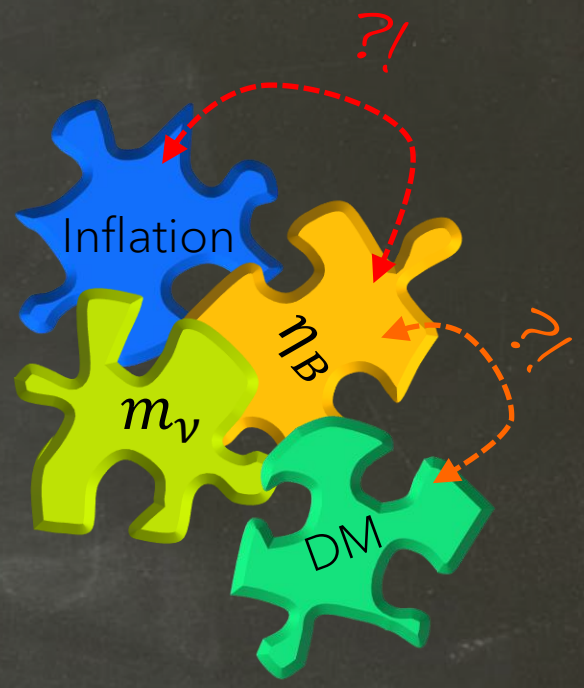


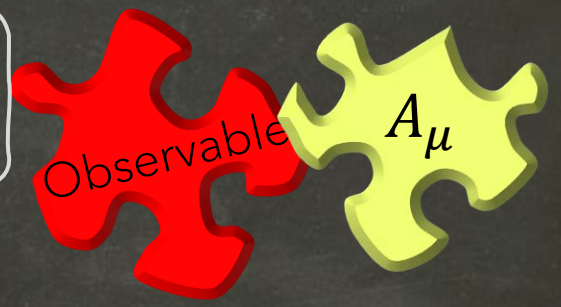
- Curious cosmological coincidences $\eta_B \simeq 0.3\, \mathrm{P}_\zeta$ and $\Omega_{DM} \simeq 5\Omega_B$!

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

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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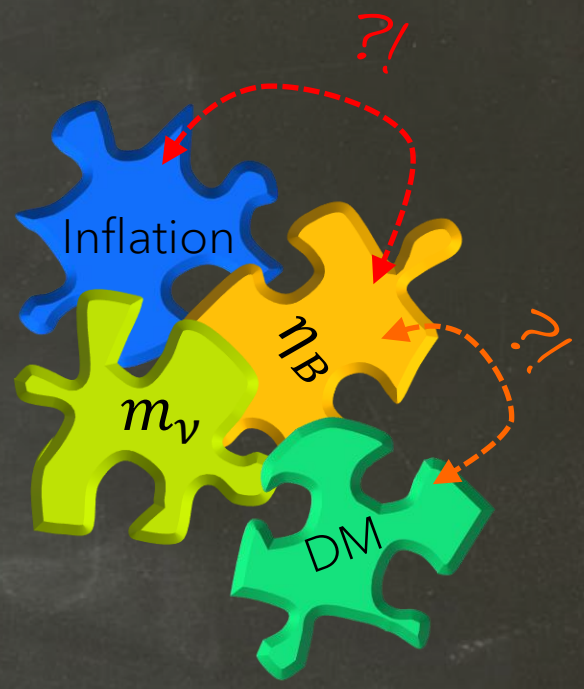
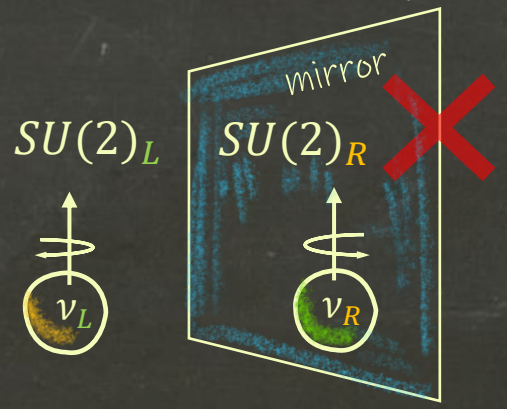
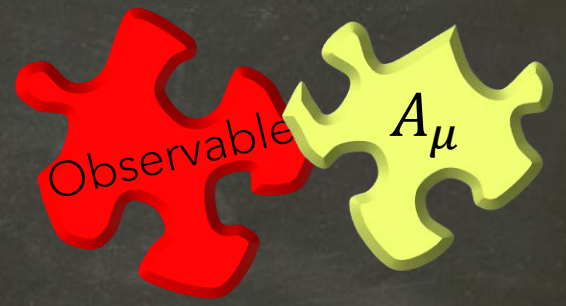


- Curious cosmological coincidences $\eta_B \simeq 0.3\, \mathrm{P}_\zeta$ and $\Omega_{DM} \simeq 5\Omega_B$!

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

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

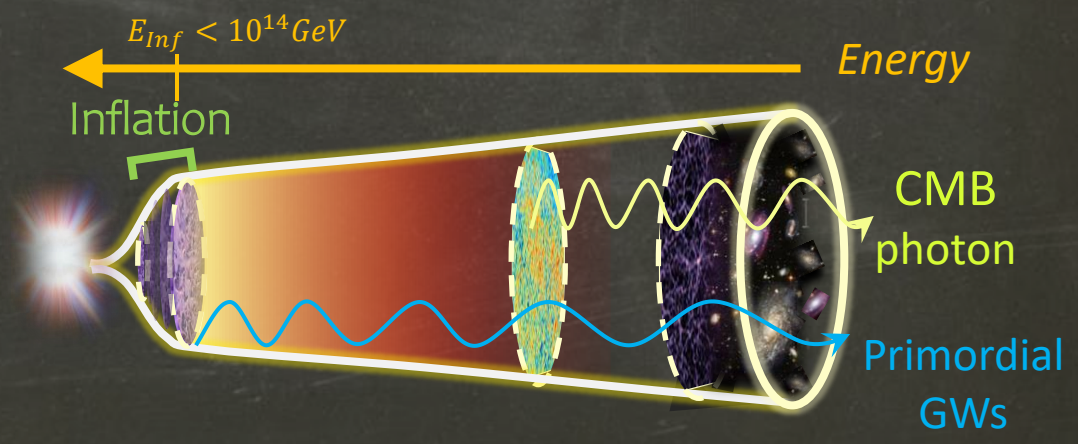




As Yet

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

Inflaton: a scalar field beyond the SM. A well-motivated candidate: Axion!



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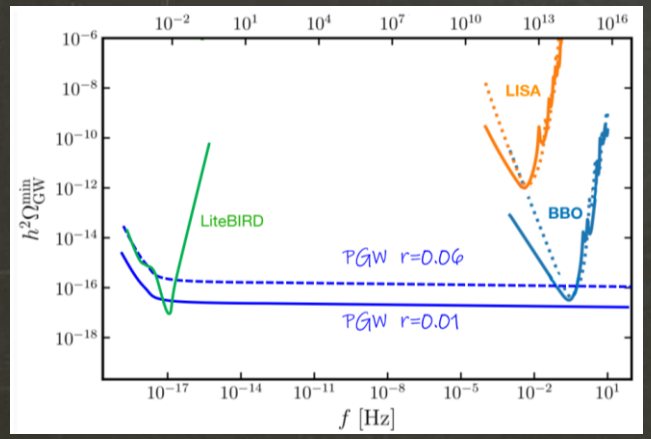
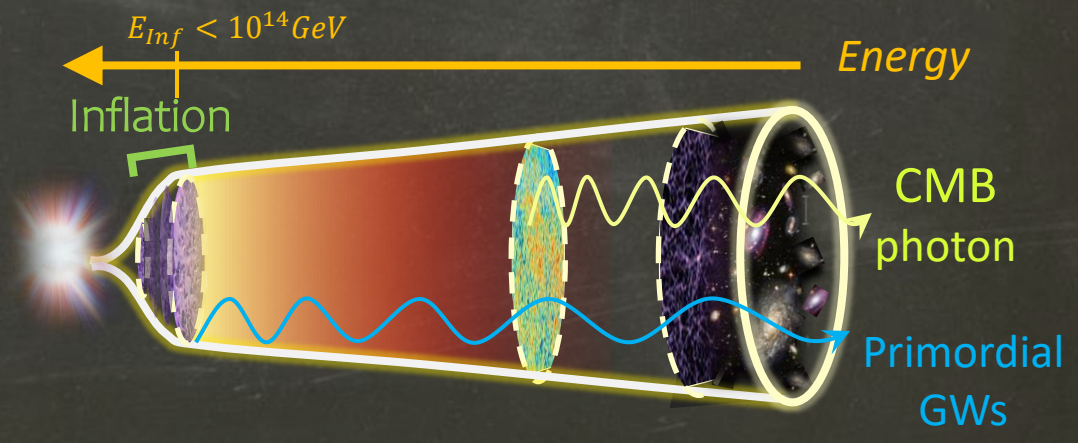
  Inflaton: a scalar field beyond the SM. A well-motivated candidate: Axion!
- Primordial Gravitational Waves (PGW):

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





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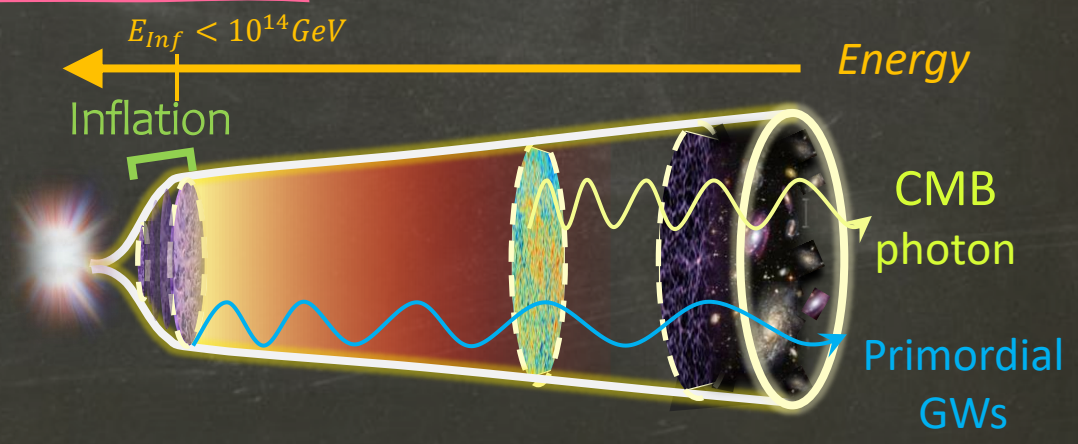
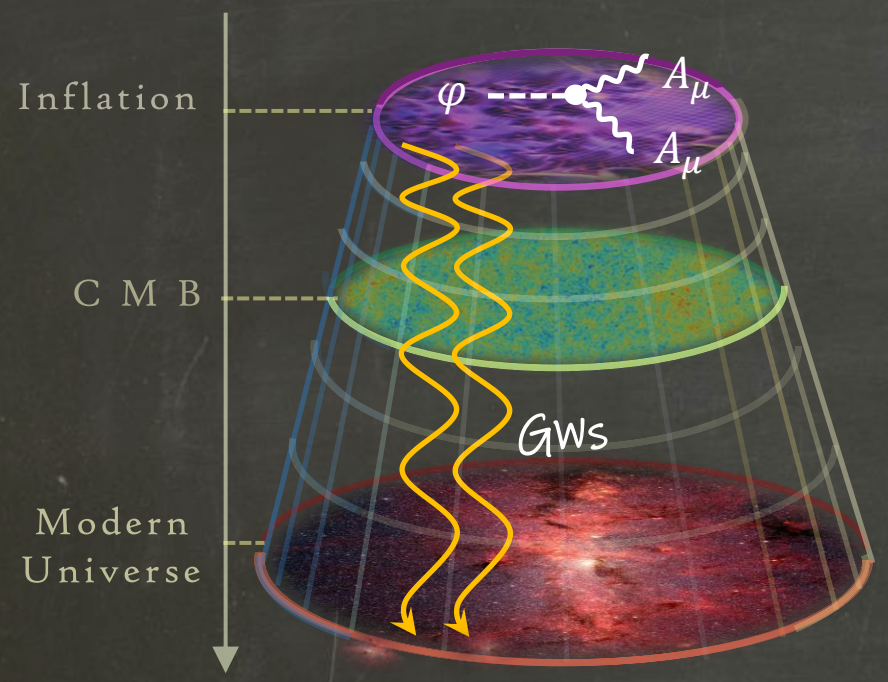
What about Gauge Fields?!

- They are building blocks of particle physics, SM & beyond.
- They are naturally coupled with axion like particles.
- What do they do in Axion-inflation?!



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, …

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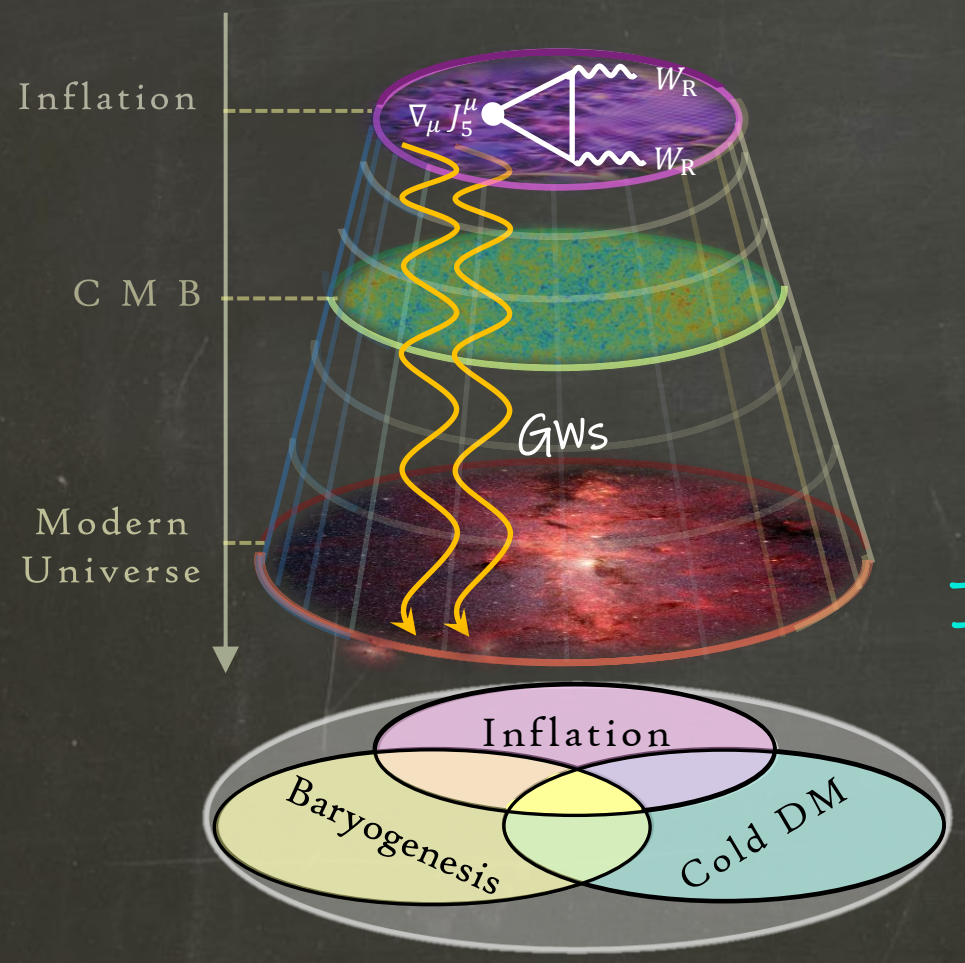

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II) Embedding Axion-inflation in LR symmetric model

A.M. JHEP 2021, 113 (2021)

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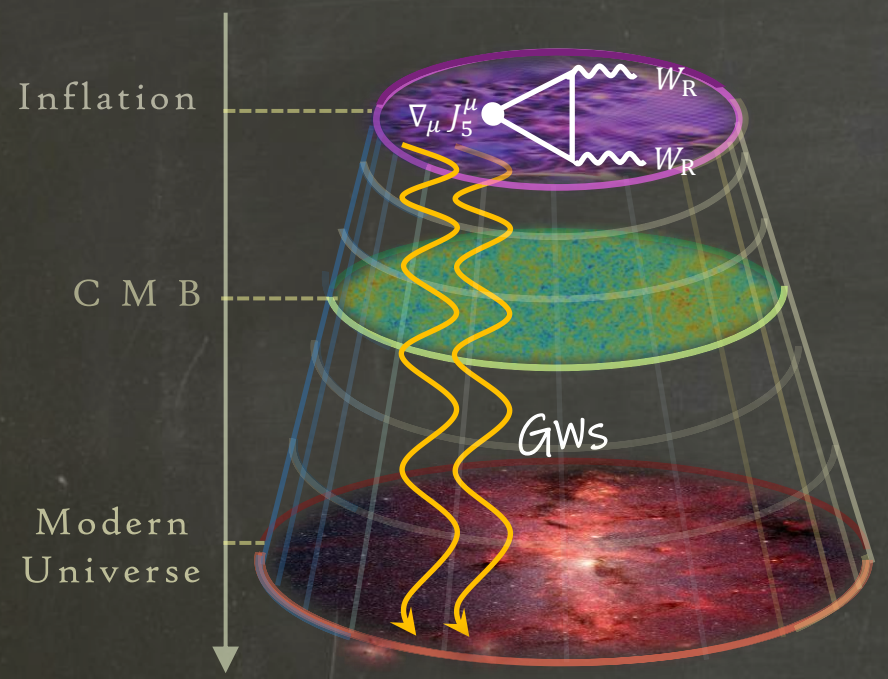

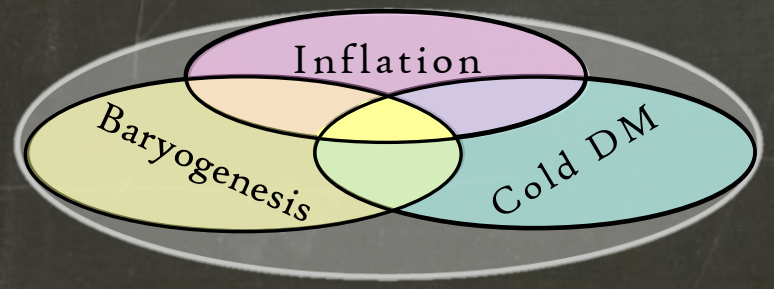

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A Common Origin for Inflation, Baryogenesis & Dark Matter

Setup:

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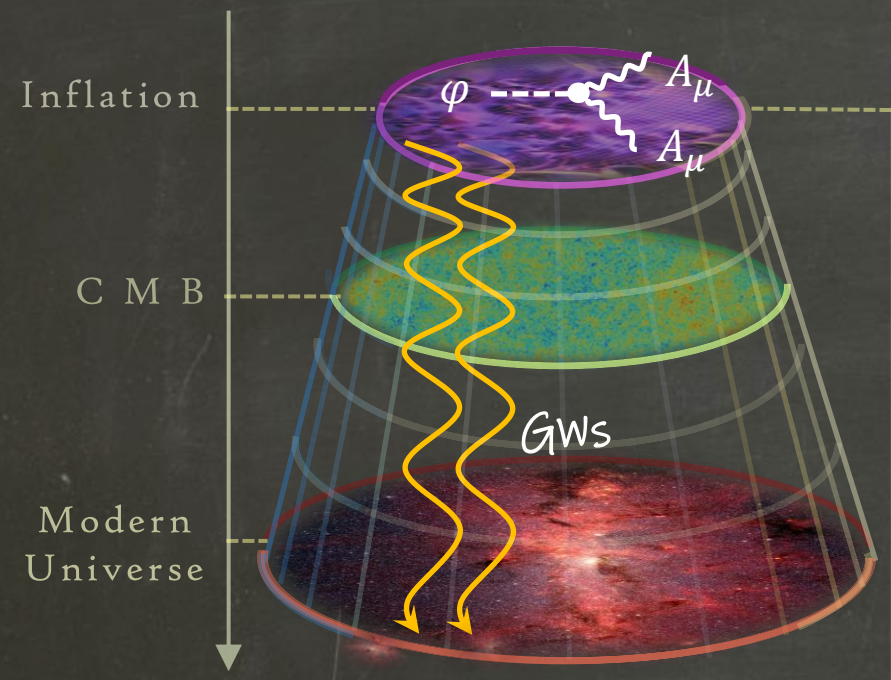
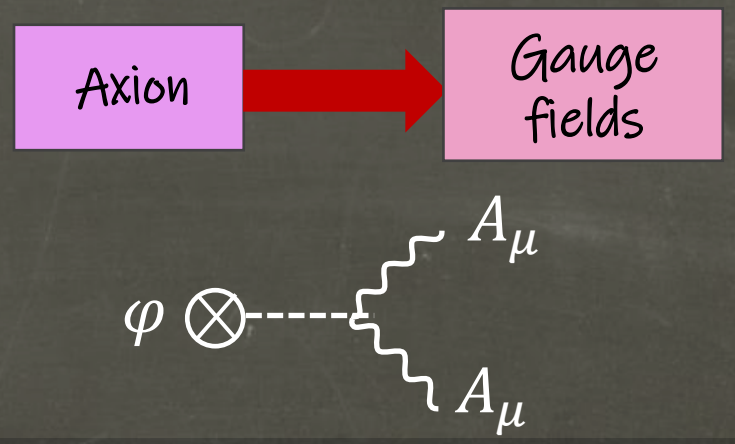


Particle Production
In Axion-Inflation



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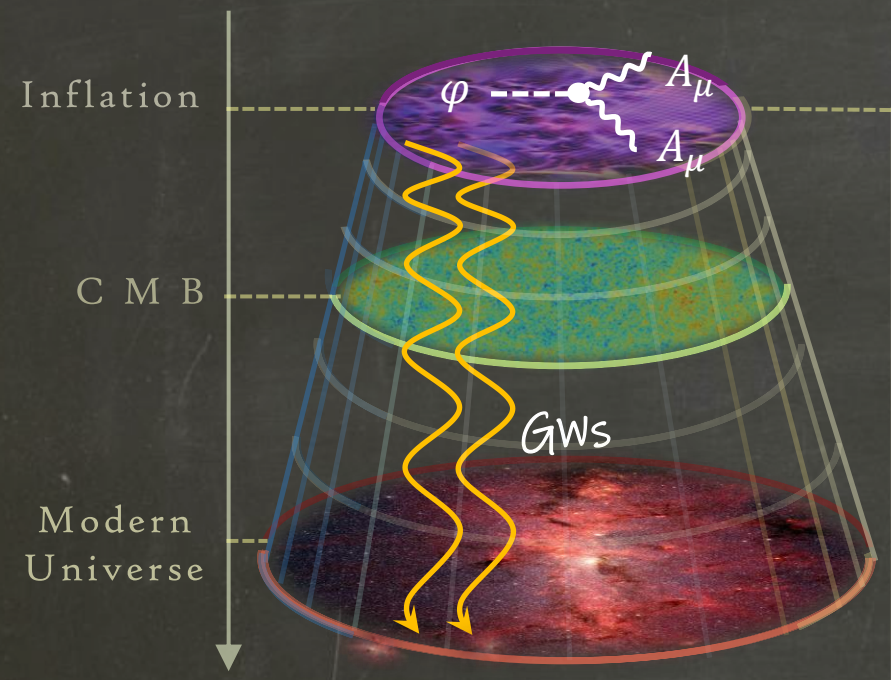

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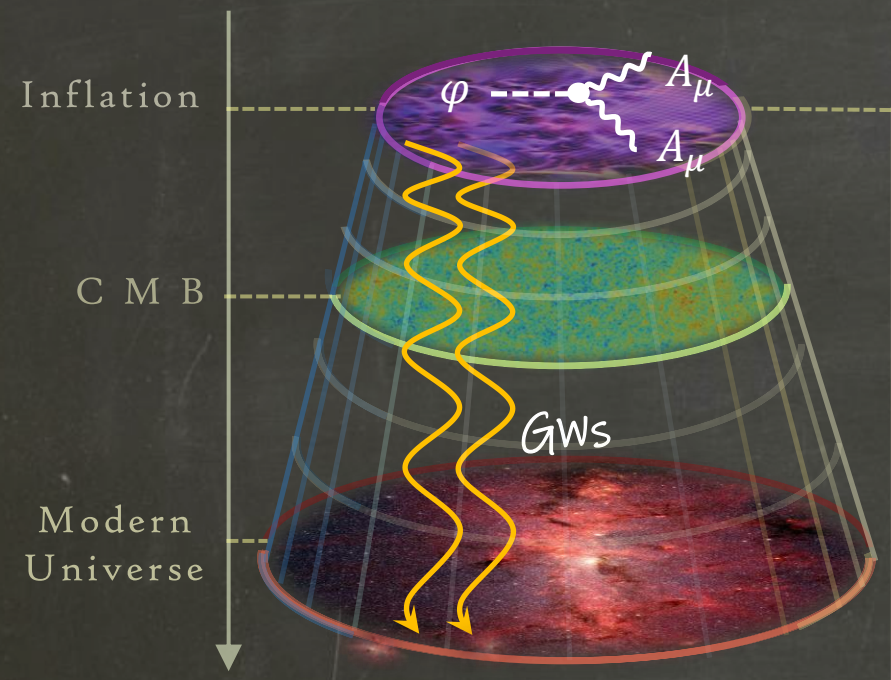

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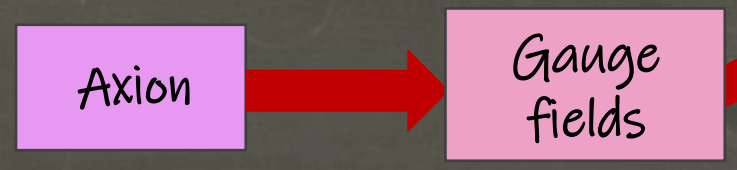

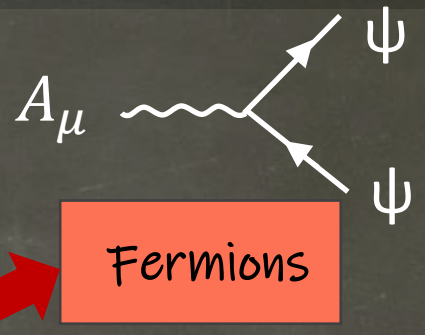

A new mechanism for Fermiogenesis in Inflation!

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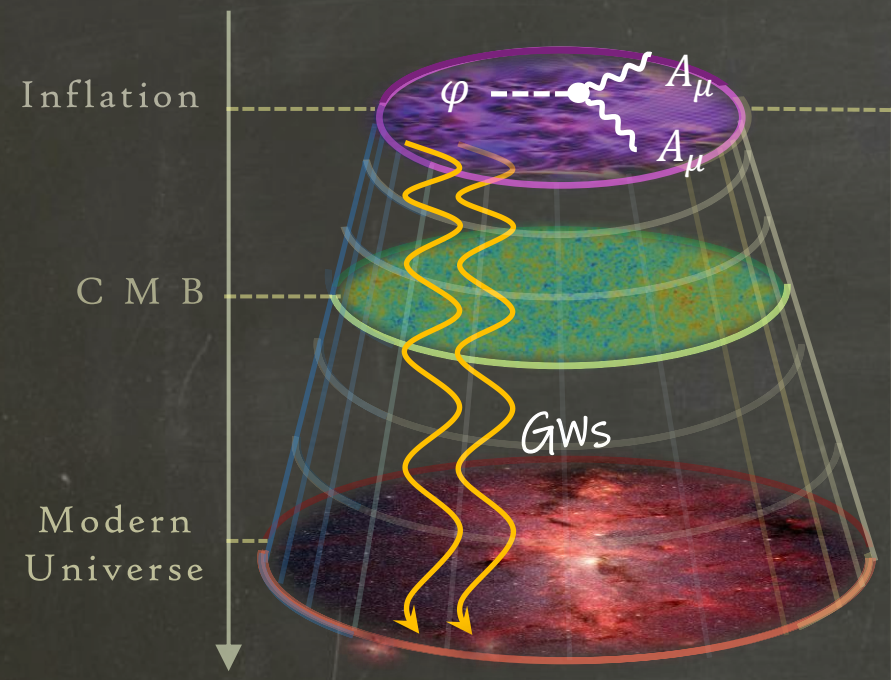

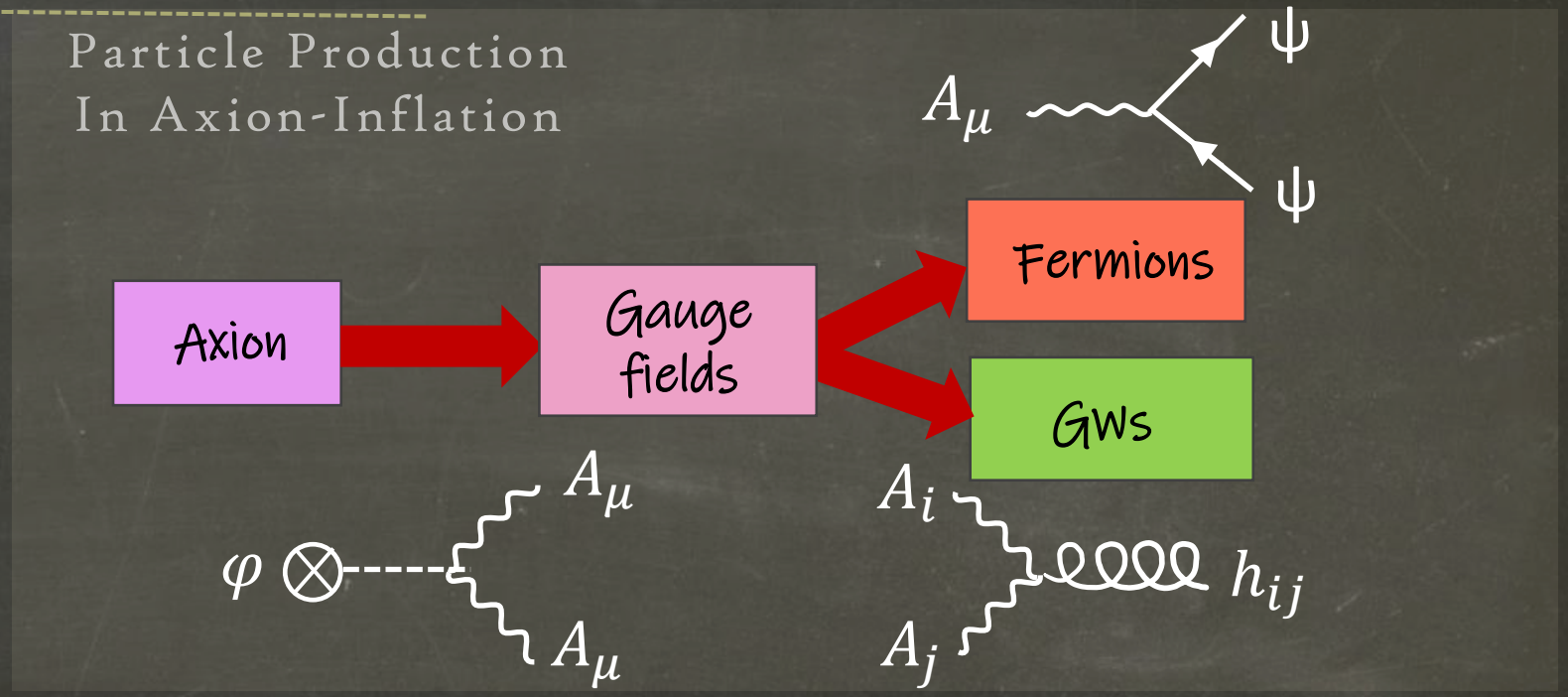

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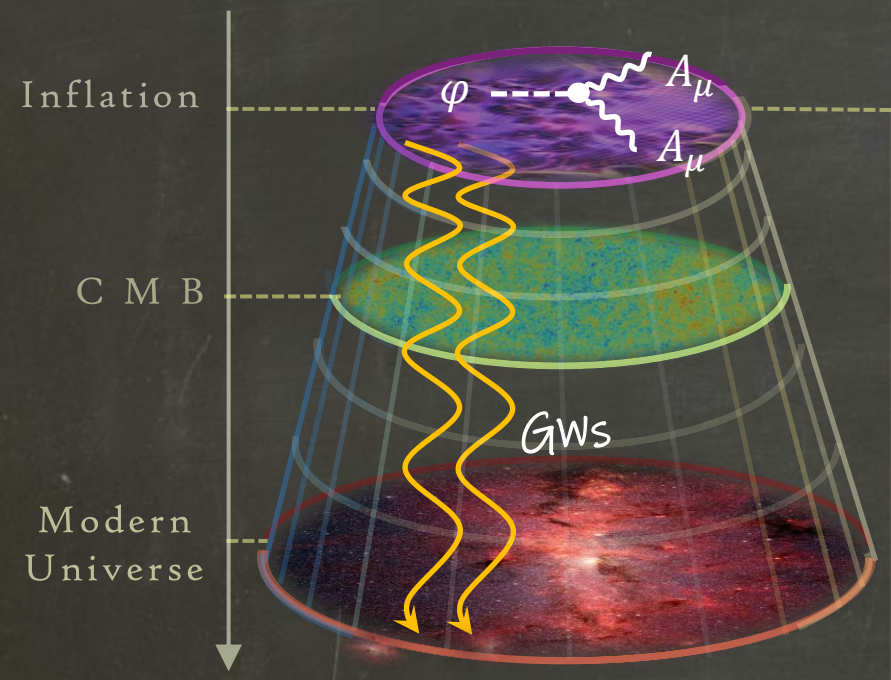

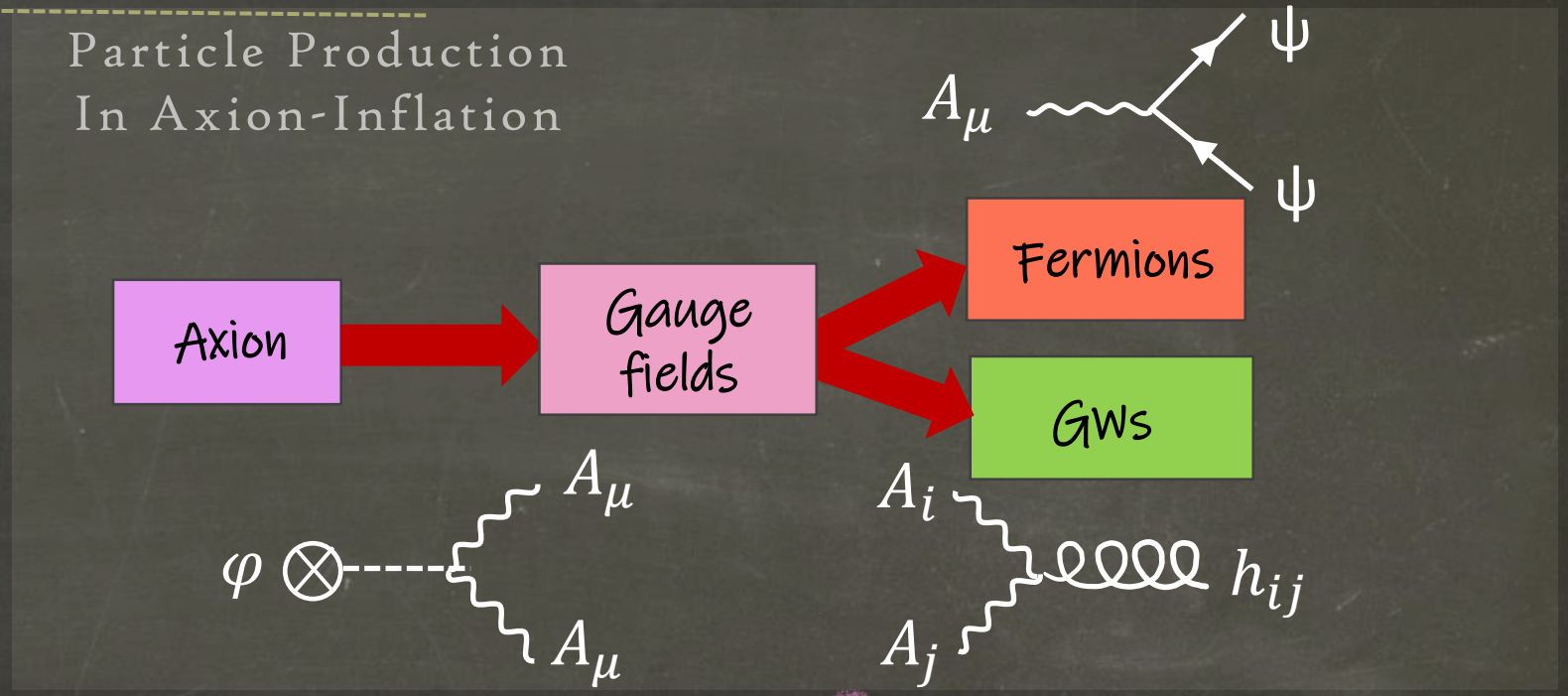

Sourced GWs:
Chiral & non-Gaussian

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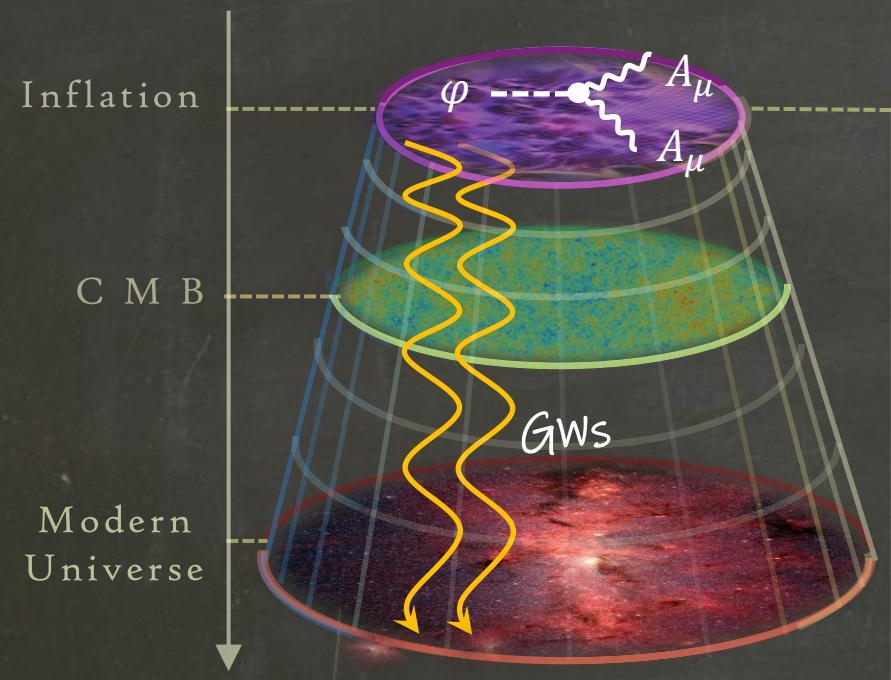
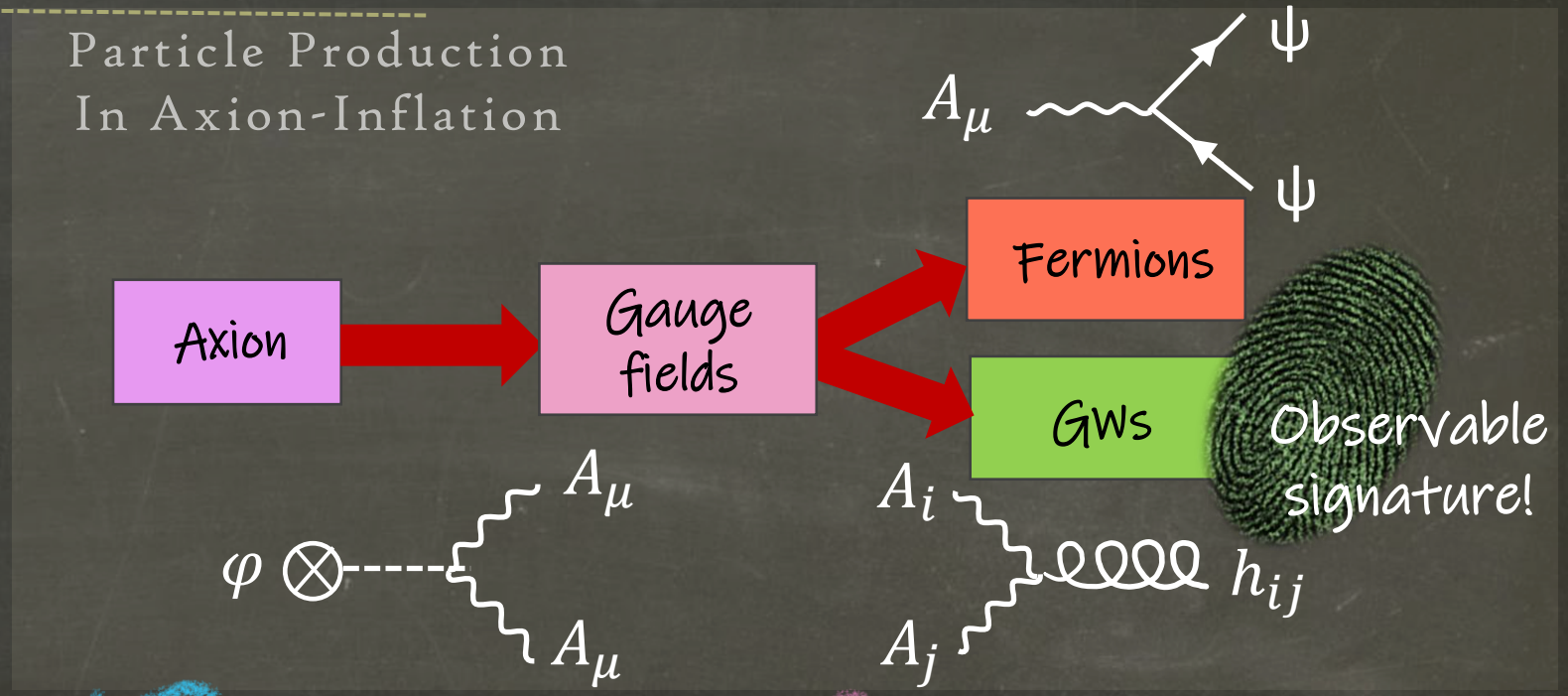




Vacuum GWs:
Unpolarized & Gaussian

Sourced GWs:
Chiral & non-Gaussian

I) Axion-inflation & gauge fields

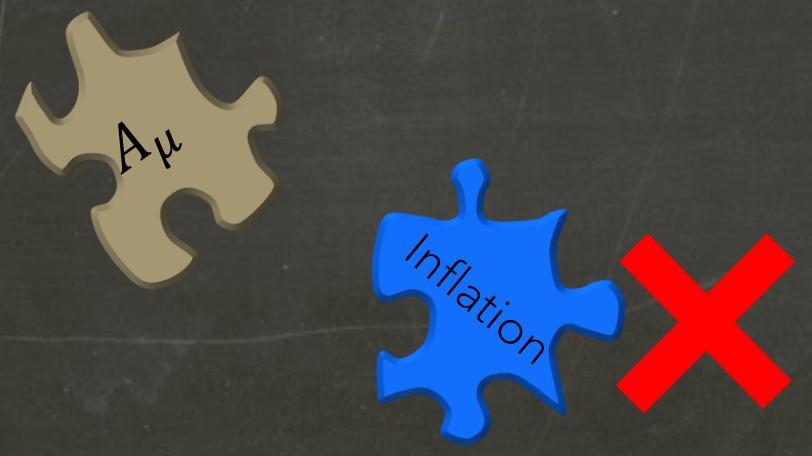
(non-Abelian)

Challenges:

Gauge fields given by Yang-Mills

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

$$\dot{\rho}_A + 4H\rho_A = 0$$



(Axion fields are naturally coupled to gauge fields.)

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

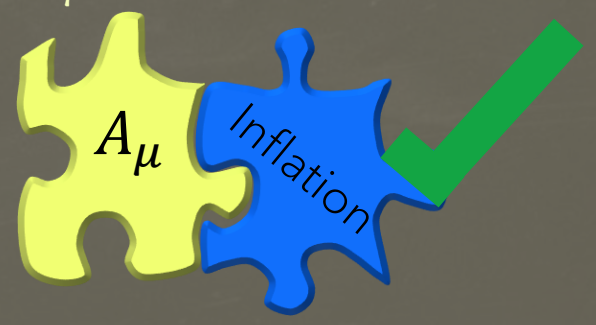
Axion

$$\dot{\rho}_A + 4H\rho_A = \frac{\lambda}{f}\dot{\varphi}\,\mathrm{E.B}$$

(Axion generates gauge fields!

Gauge field A_μ
(active in inflation) A_μ

Axion inflaton φ



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Spatial isotropy & homogeneity

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

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

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.)

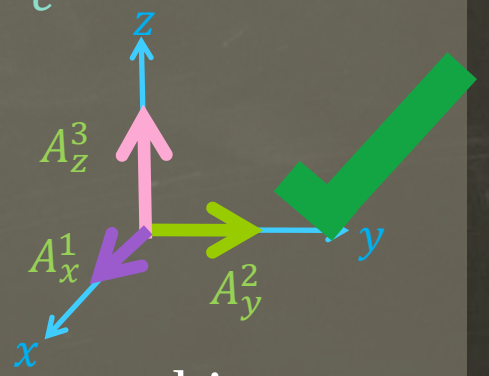
A.M. & Sheikh-Jabbari, 2011

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

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



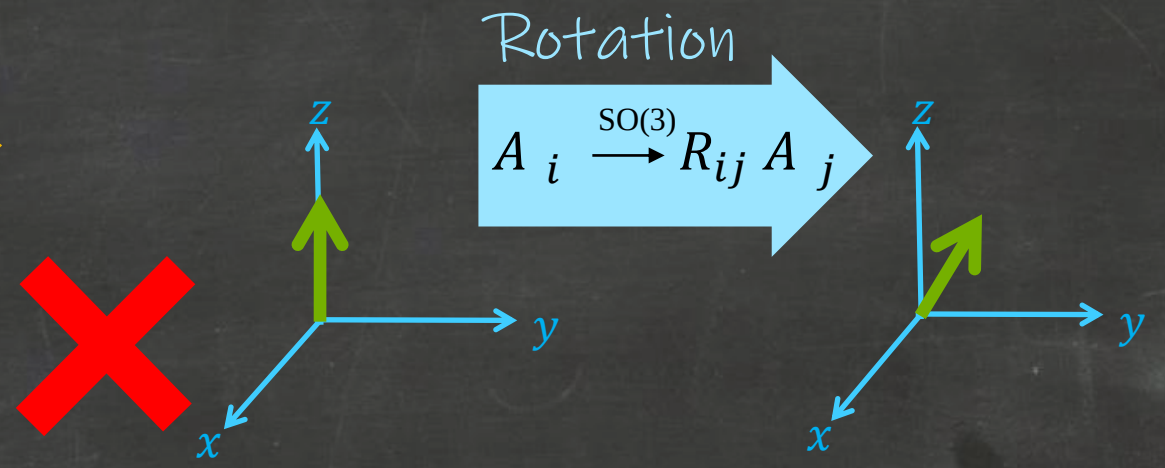
so(3) & su(2) are isomorphic

How SU(2) restores isotropy?

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

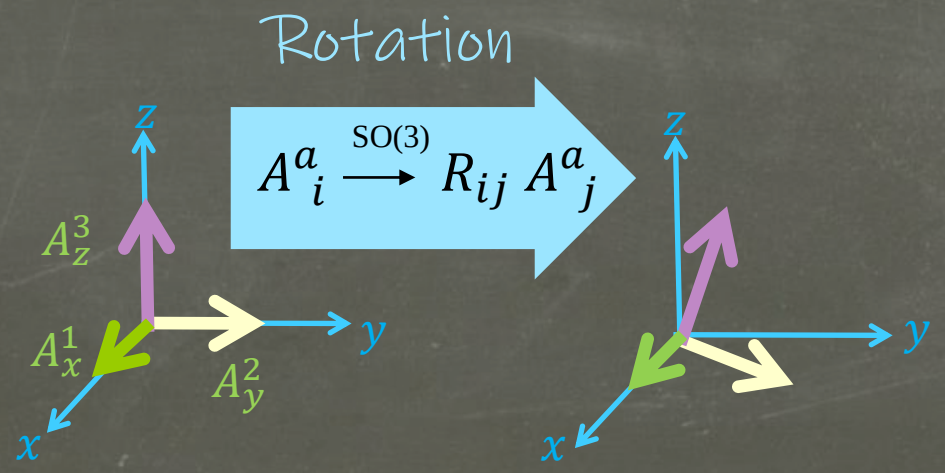
U(1) vacuum A_μ

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



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

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



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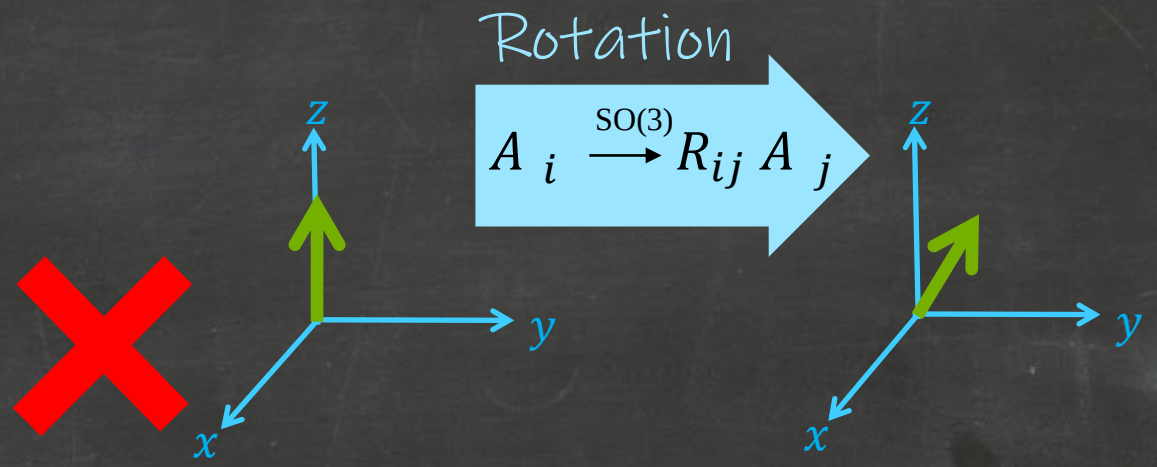

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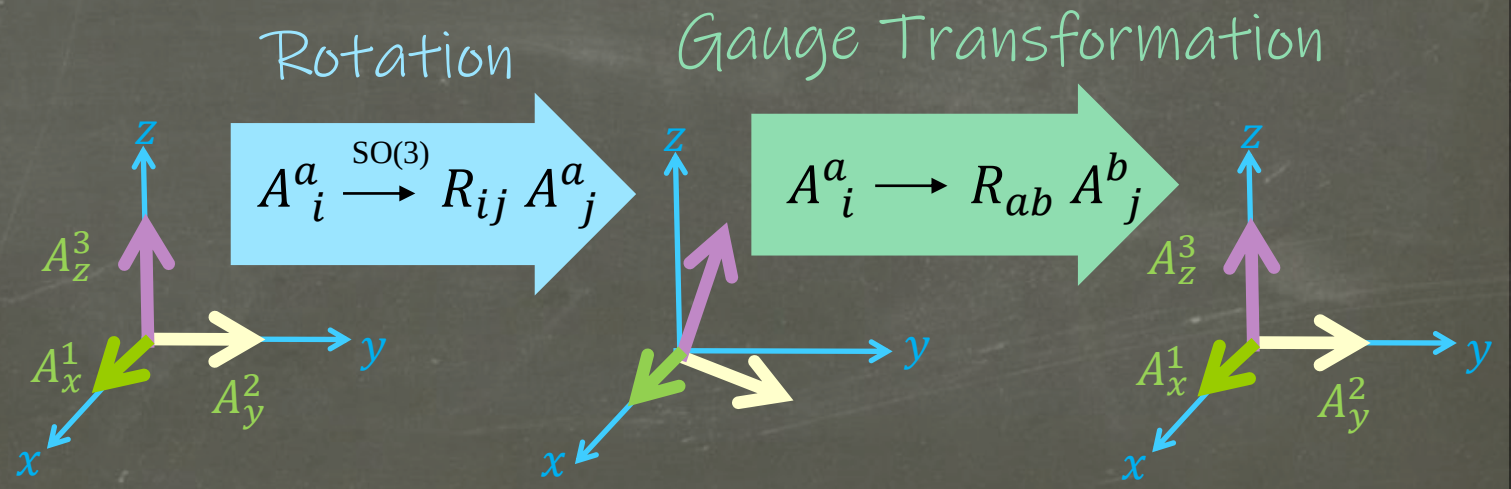

A.M. and M. M. Sheikh-Jabbari, 2011

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

SU(2)-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

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

SU(2)-Axion Model Building

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$\xi = -P$

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

SU(2)-Axion Model Building

- Gauge-flation **A. M.**, & Sheikh-Jabbari, **2011**

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

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

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

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

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]

SU(2)-Axion Model Building

- Gauge-flation **A. M.**, & Sheikh-Jabbari, **2011**

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

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

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

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

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,**
Domcke et al 2019, **A.M. 2019**

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

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

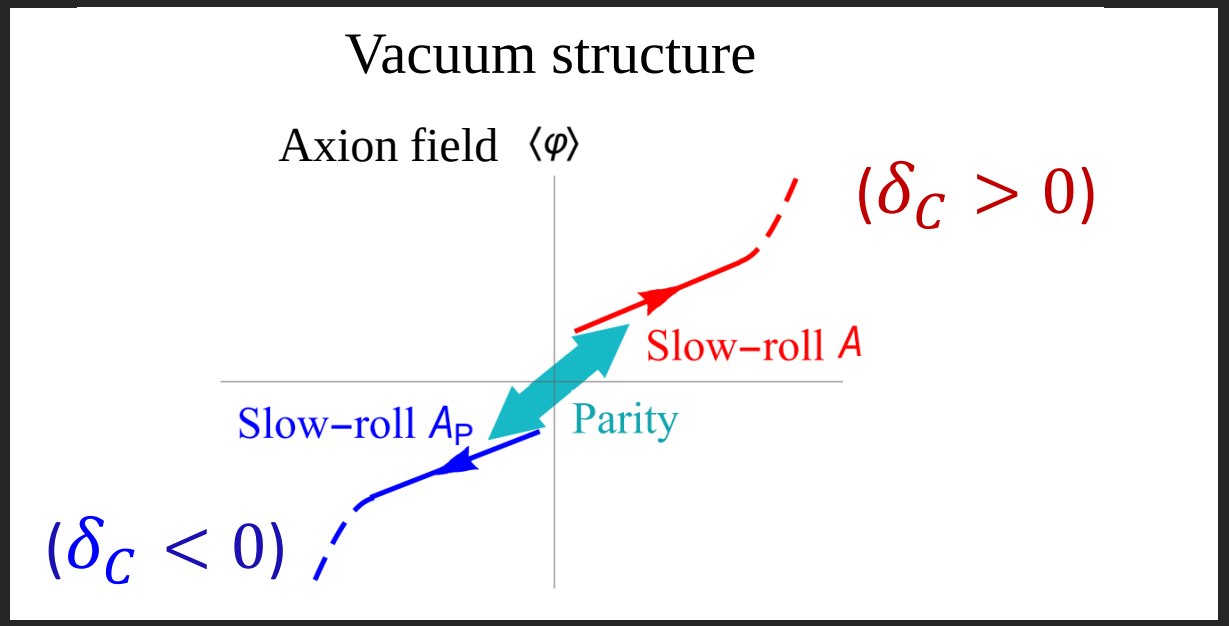
Axion Monodromy or any mechanism that gives a flat potential

New Tensorial mode in SU(2) Gauge Field

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

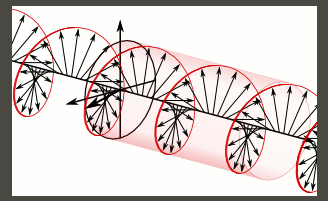
$$B_\pm'' + \underbrace{\left[k^2 \mp \delta_C k\mathcal{H} + \frac{m^2}{H^2}\mathcal{H}^2 - \frac{a''}{a}\right]}_{\text{effective frequency}} B_\pm \approx 0$$

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



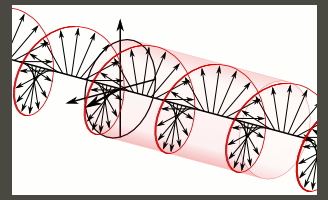
Circular polarizations

Right-handed



B_+

Left-handed



B_-

$\boldsymbol{B}_\pm$ 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

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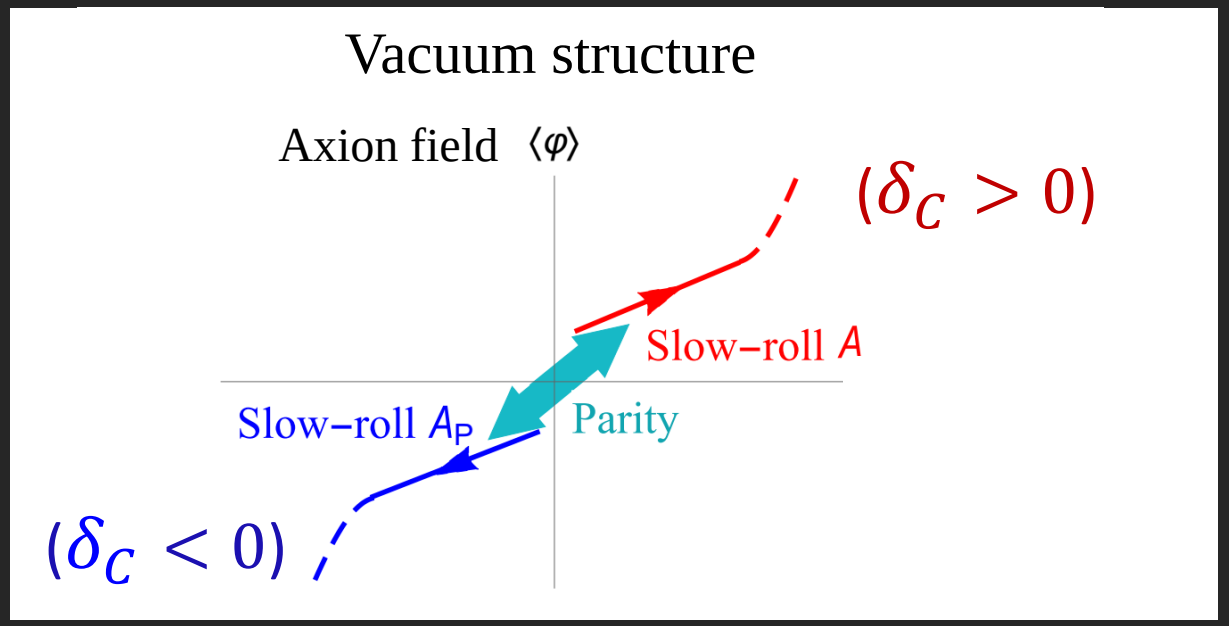


For $\delta_C > 0$

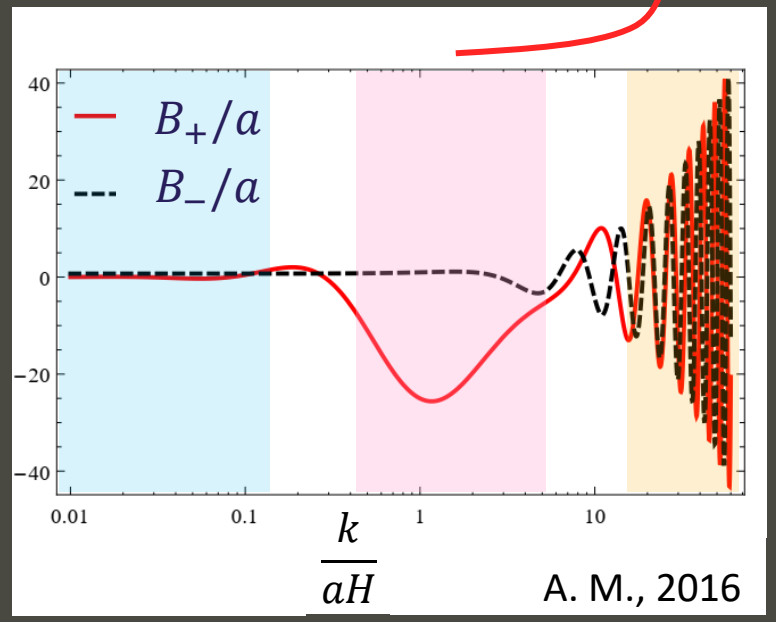
Short tachyonic growth of B_+

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



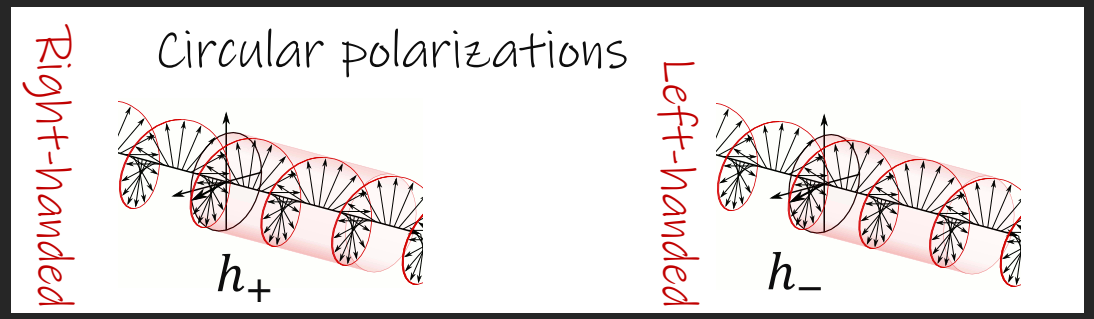
A. M., 2016

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

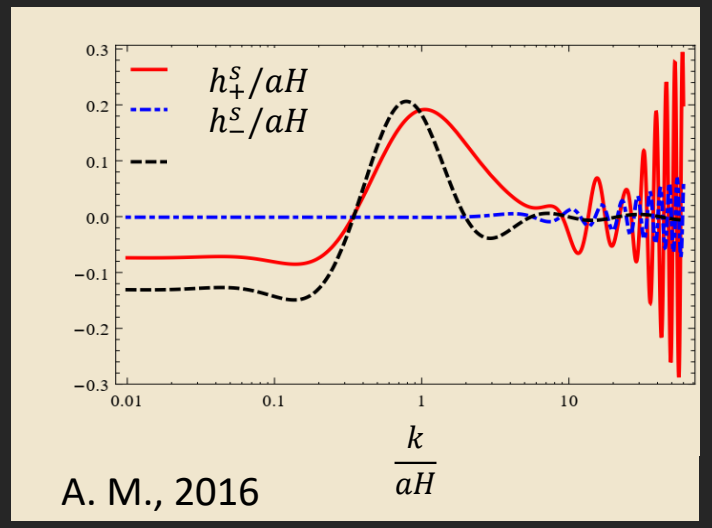
- That sourced the GWs

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



- Gravitational waves have two uncorrelated terms

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



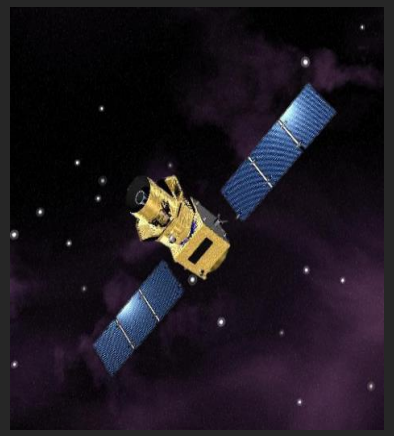
Novel Observable Signature: CMB

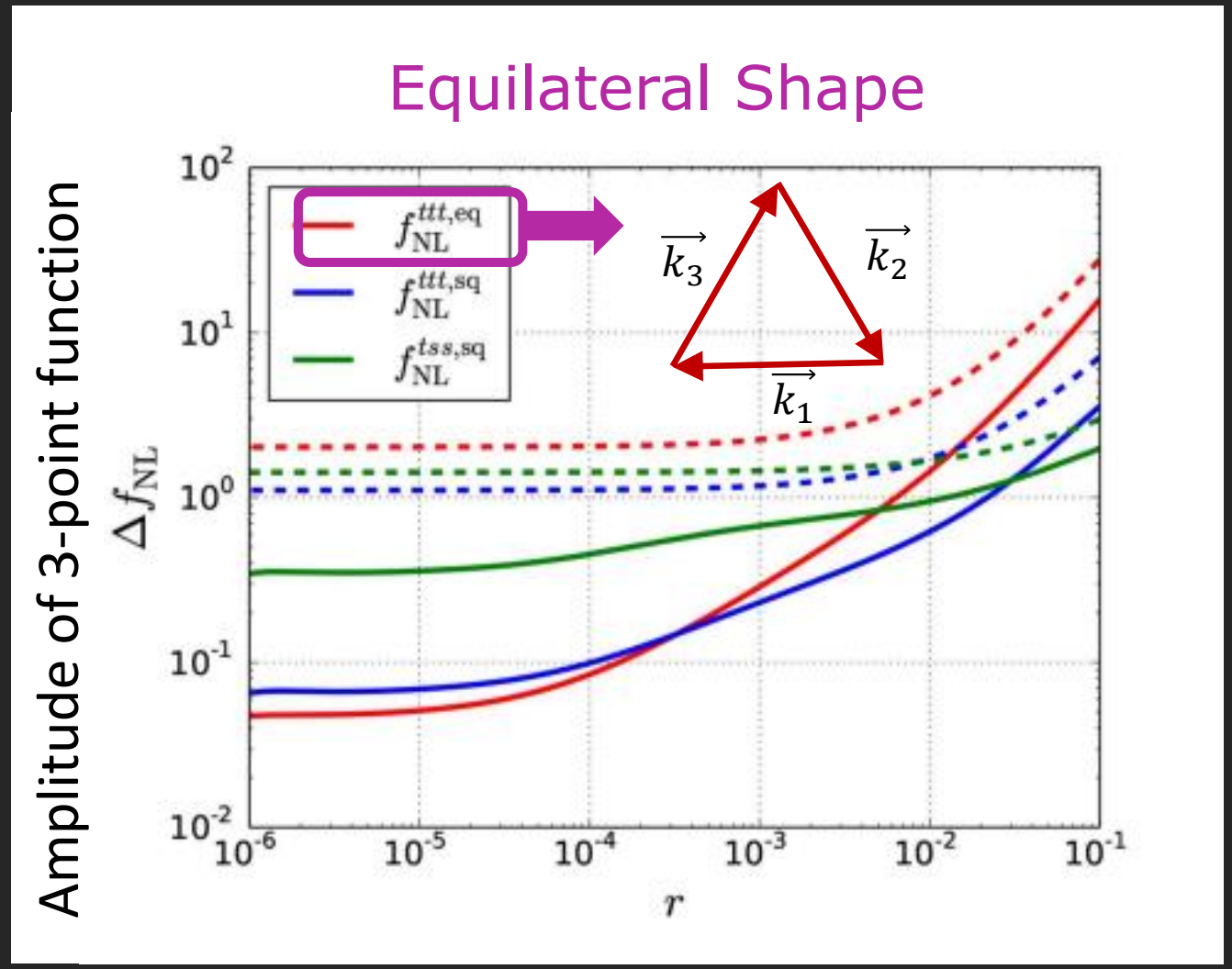
- The sourced tensor modes is Highly non-Gaussian.

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

Agrawal, Fujita, Komatsu 2018

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

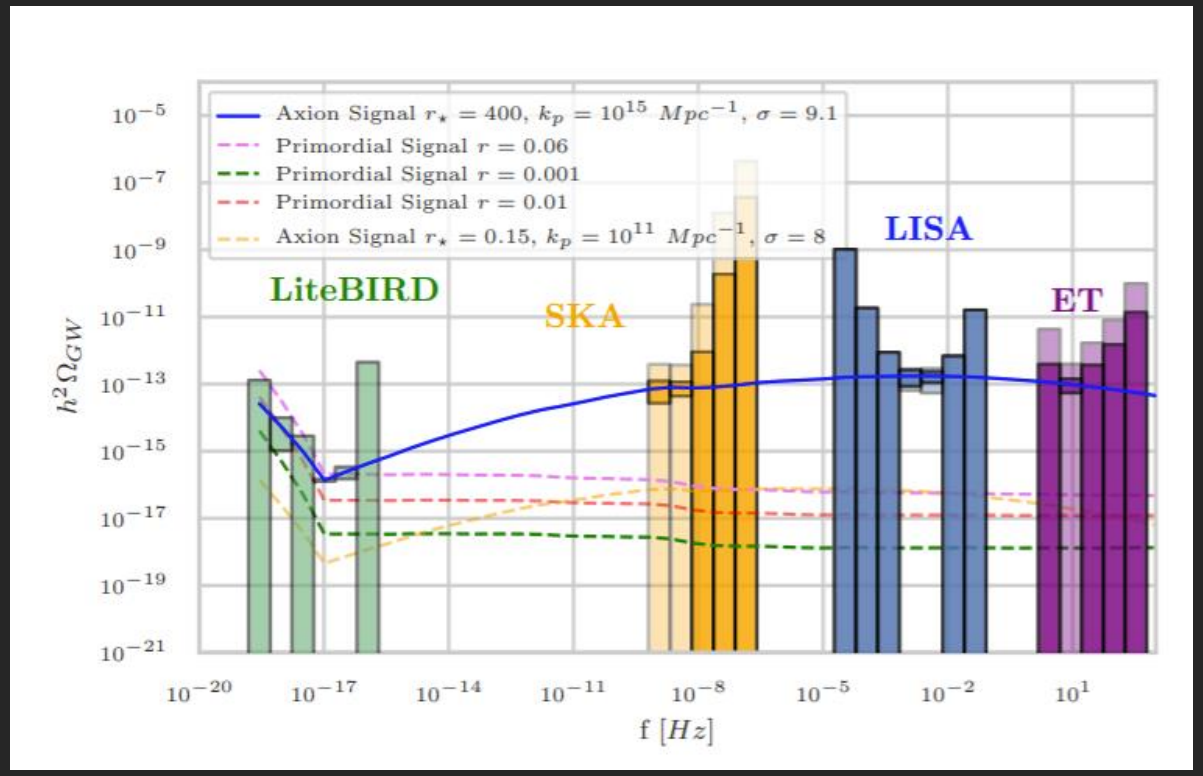




Maresuke Shiraishi, Front. Astron. Space Sci. 2019

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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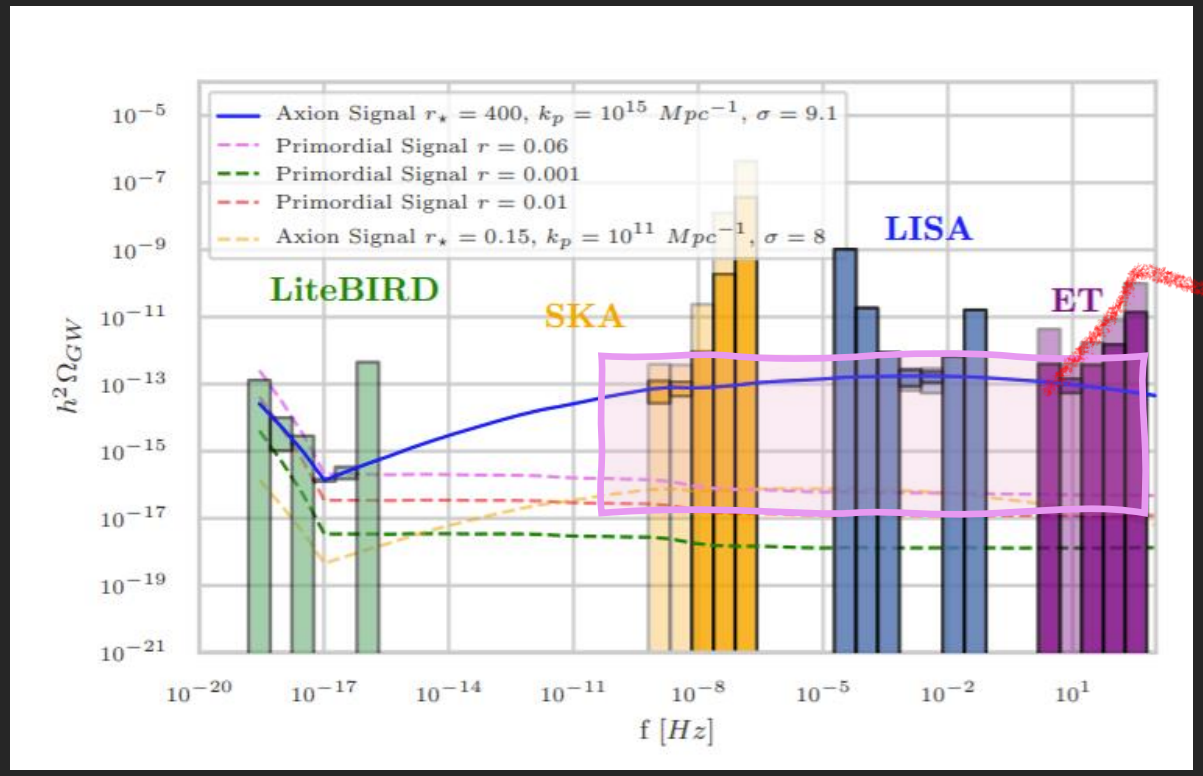
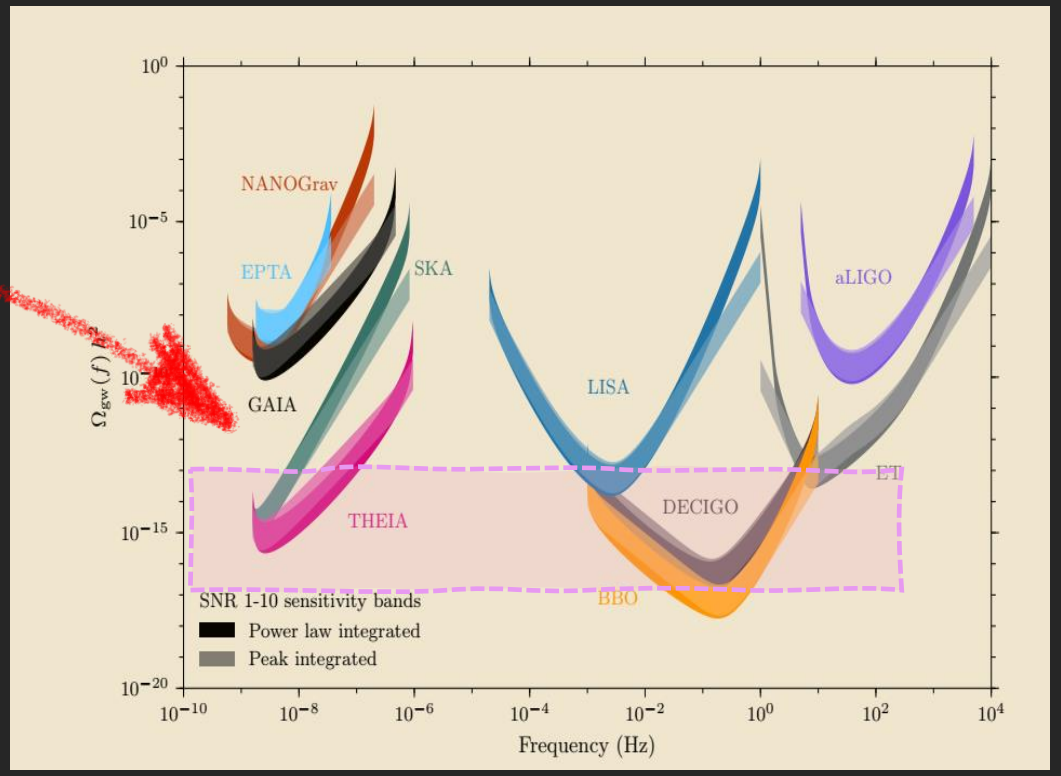


P. Campeti, E. Komatsu, D. Poletti, C. Baccigalupi 2020

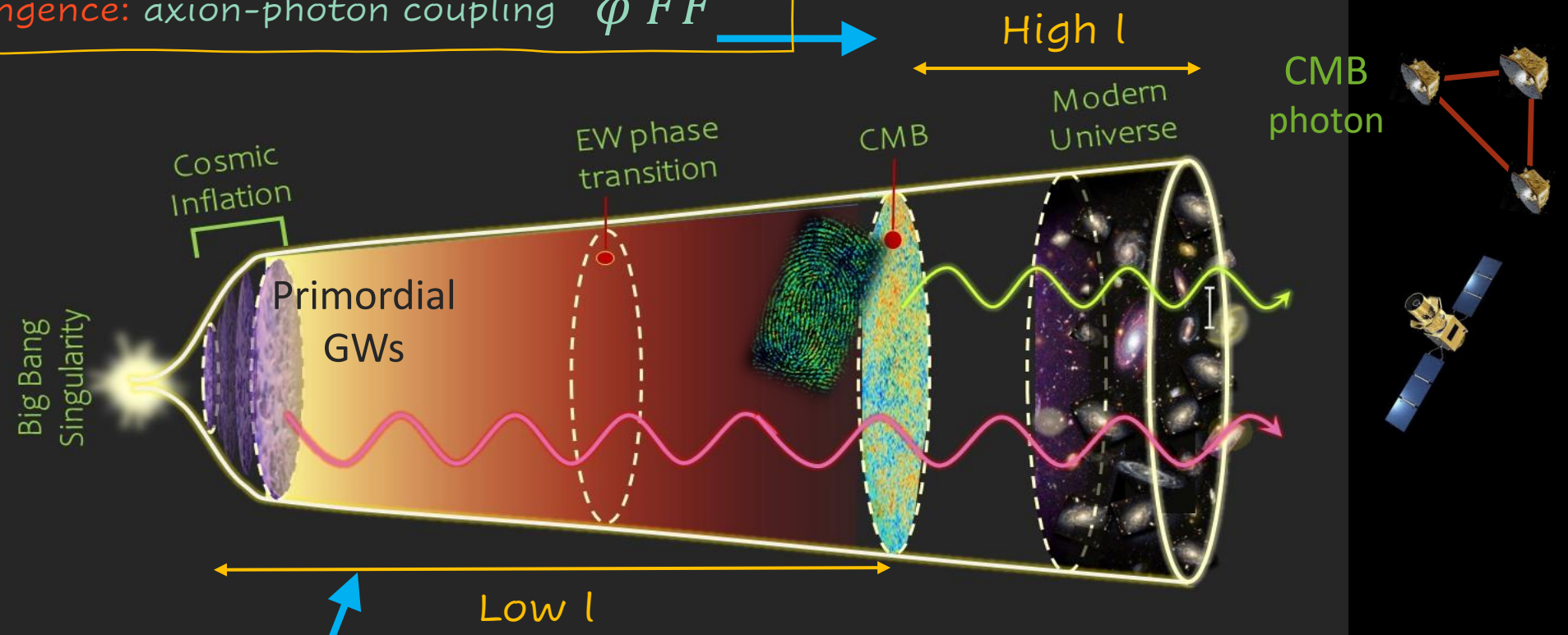


J. Garcia-Bellido, H. Murayama, and G. White 2021

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

Sources of Parity violation on CMB:

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



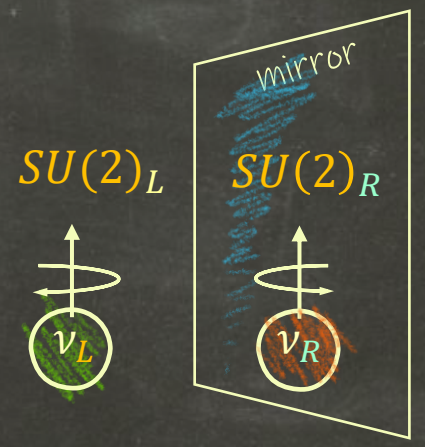
- SU(2)-axion Inflation: SU(2) field-Graviton coupling
- Gravitational Chern-Simons: axion-graviton coupling $\varphi R\tilde{R}$

B. Thorne et. al.2018

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

(How to Connect Inflaton to BSM?)

Axion-Inflation + Left-Right Symmetric Model (LRSM)

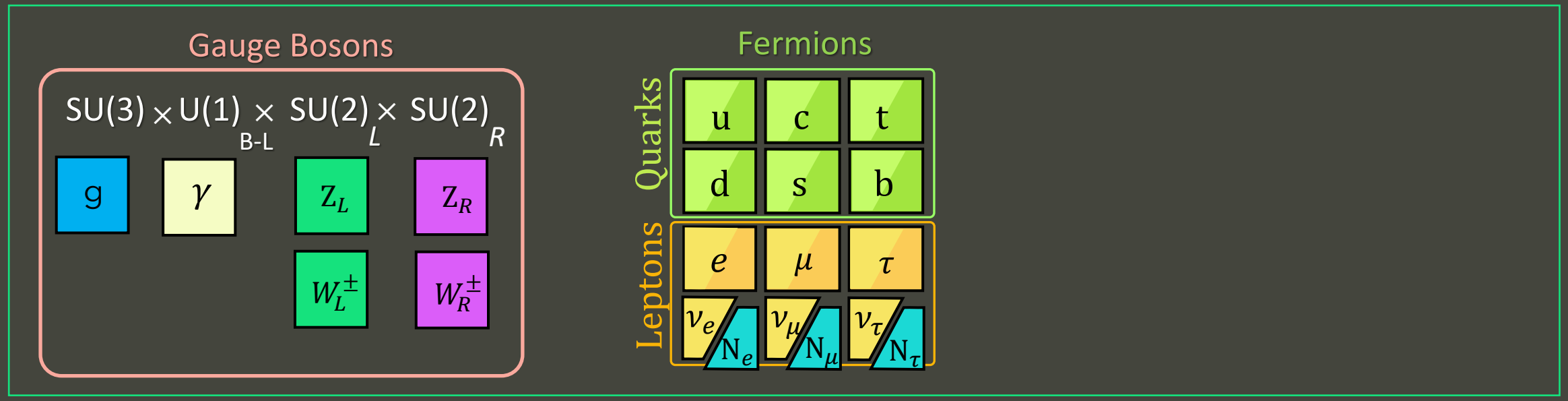


A.M. JHEP 2021, 113 (2021)

Left-Right Symmetric Model

Minimal Left-Right Symmetric model

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



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)

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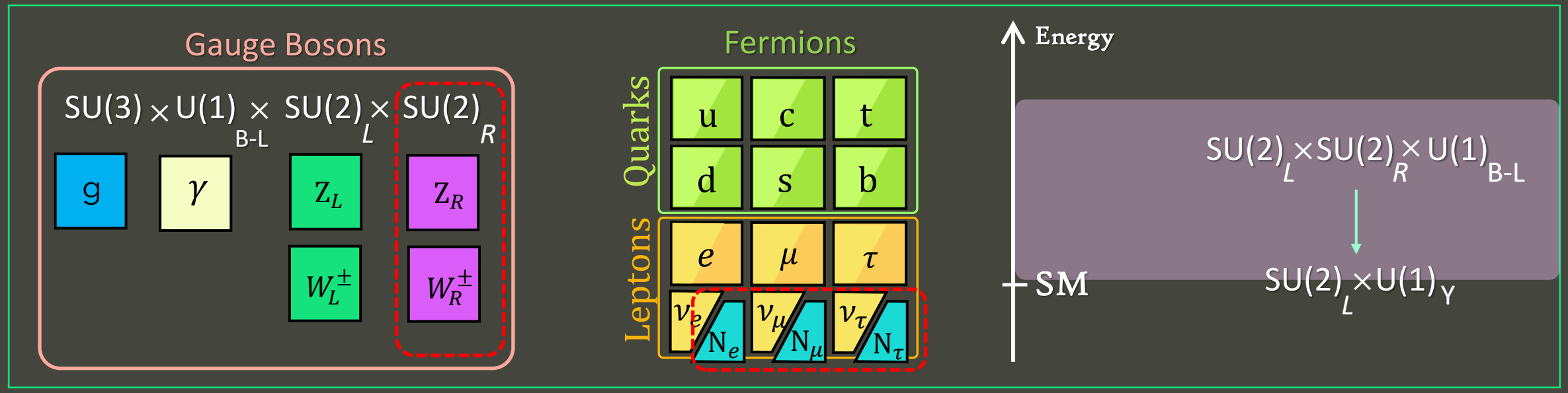

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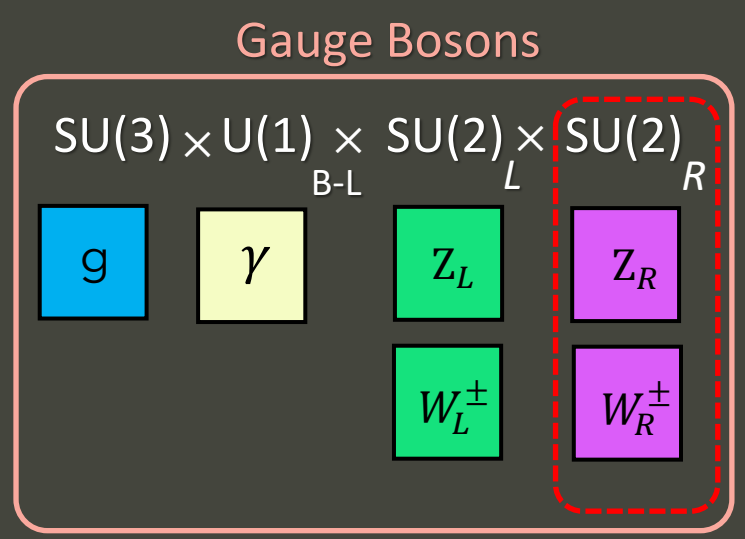

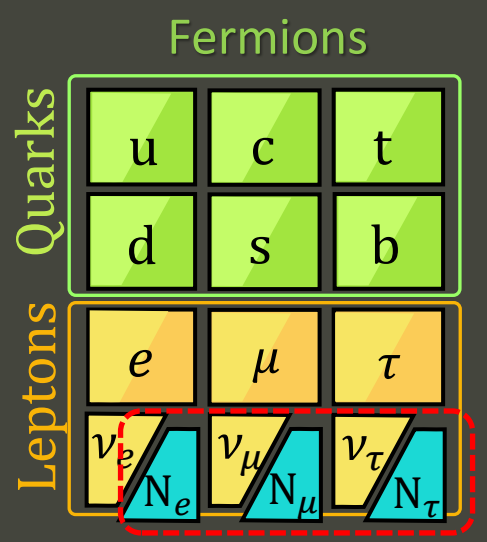

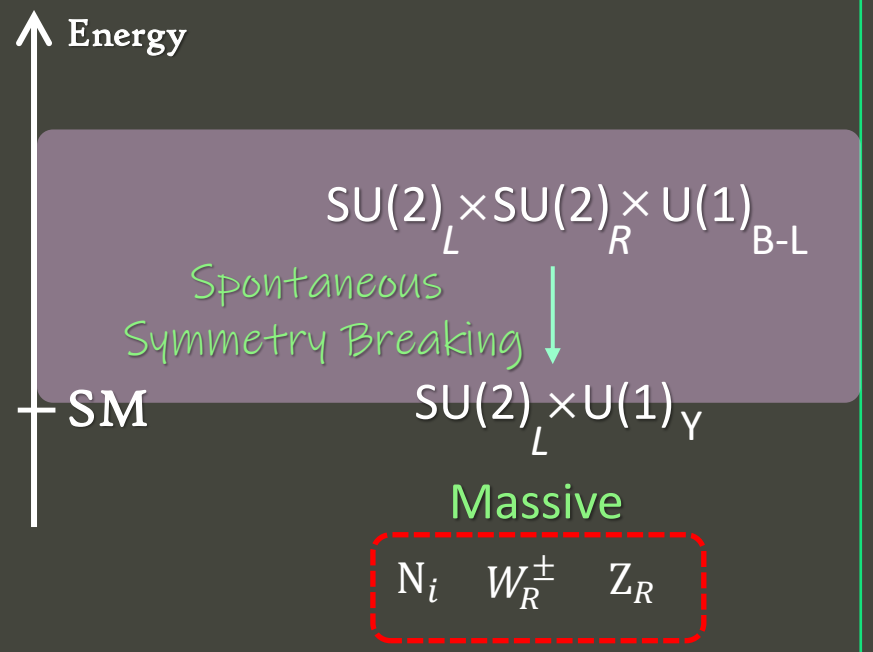

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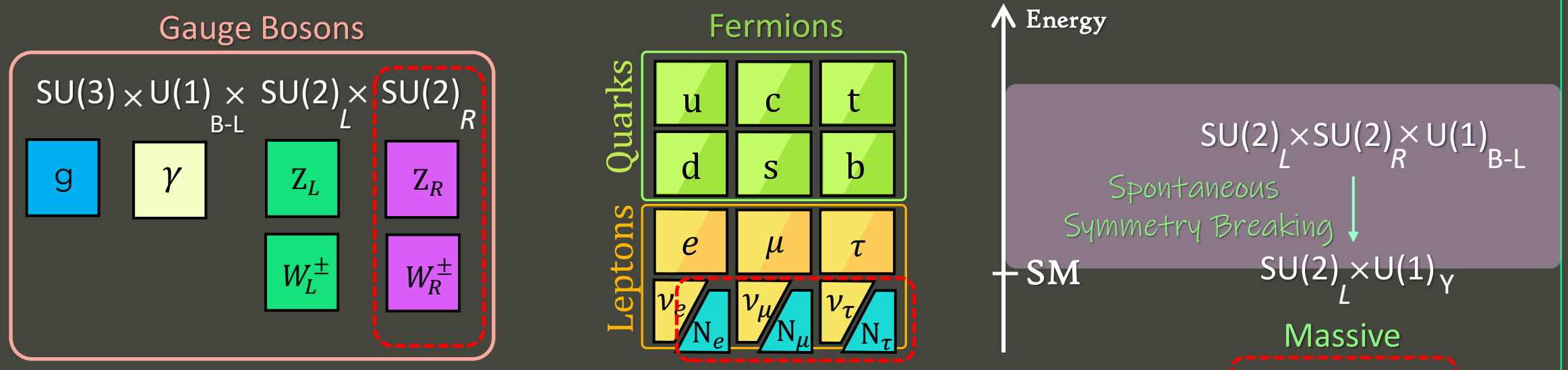

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Interesting features of LRSM:

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

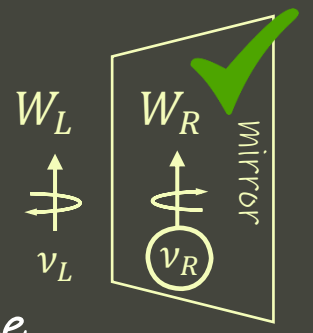
How to Connect it to the SM?

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

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

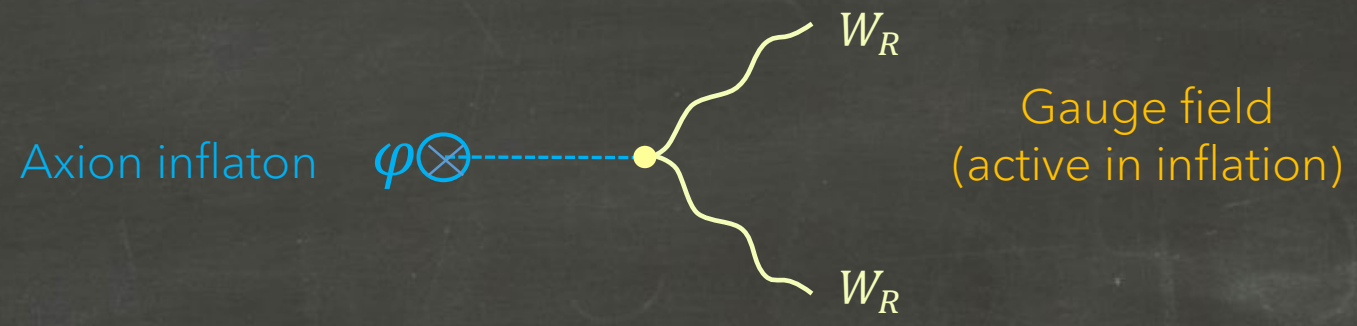
Axion Monodromy or any mechanism that gives a flat potential

Gauge field is $su(2)_R$

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

Gauge field Production in Axion-Inflation

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



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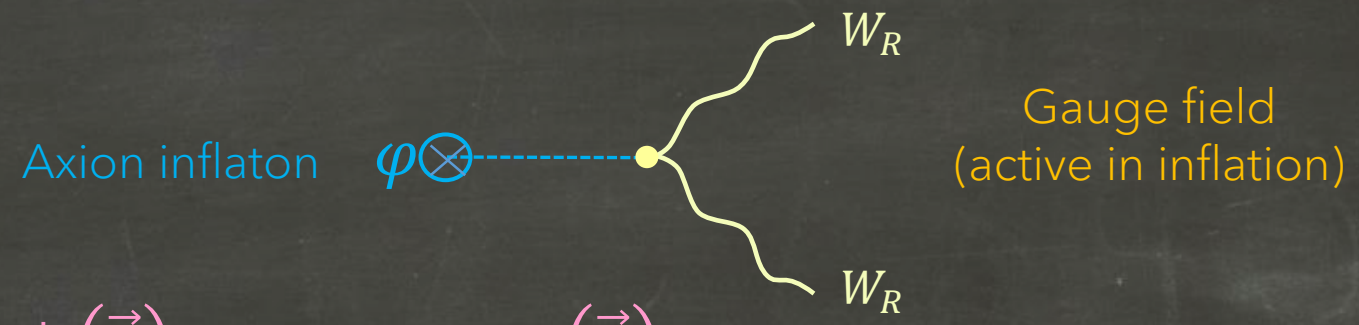

- $W_R^i = B_+(t,k)e_i^+\left(\vec{k}\right) + B_-(t,k)e_i^-\left(\vec{k}\right)$

Field Eq. $\quad B_\pm'' + \underline{[k^2 \mp \xi\, k\mathcal{H}]}\, B_\pm \approx 0$

$\left(\xi = \frac{2\lambda\partial_t\varphi}{fH}\right)$ effective frequency

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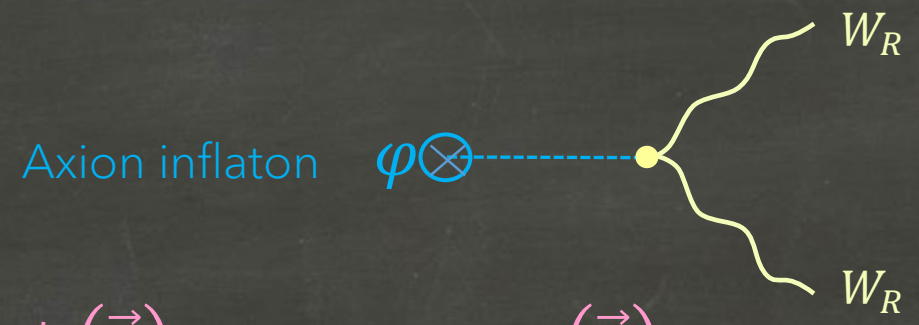

$$n_{WR} \sim \frac{H^3}{6\pi^2}\xi^3\, e^{\frac{(2-\sqrt{2})\pi}{2}\xi}$$

Particle Production

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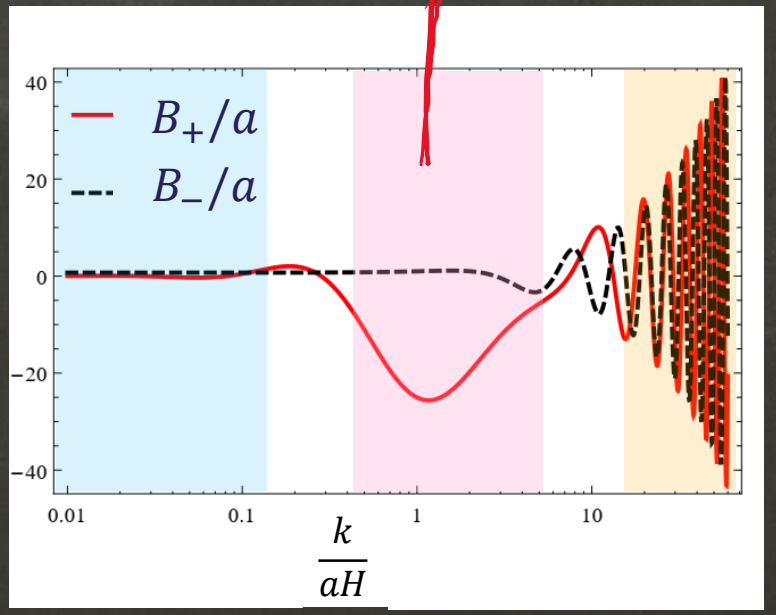

Lepton & Baryon Production in Inflation

- Left-handed fermions are diluted by inflation, BUT

Axion → W_R Gauge fields → Right-handed Leptons & Baryons

- Right-handed fermions are generated by $\mathrm{SU(2)_R}$ gauge field:

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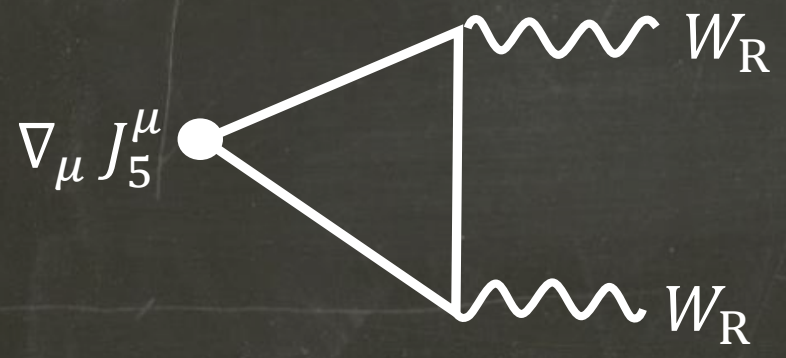
The key ingredient is the **Chiral anomaly** of $\mathrm{SU(2)_R}$ in inflation:



$$\frac{g^2}{16\pi^2} tr[W\widetilde{W}] = \nabla_\mu J^\mu_{\mathrm{B}} = \nabla_\mu J^\mu_{\mathrm{L}}$$

R-Baryons R-Leptons

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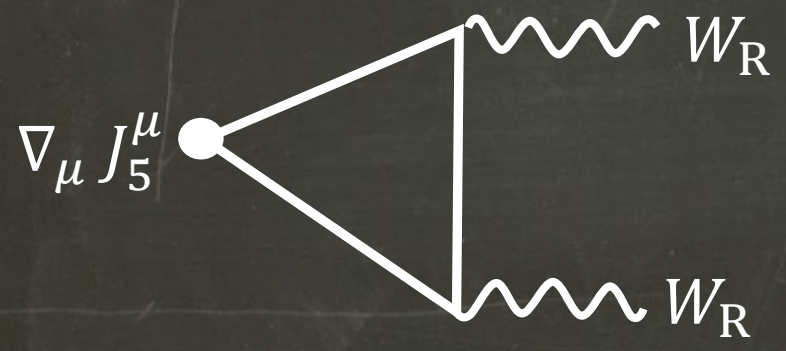


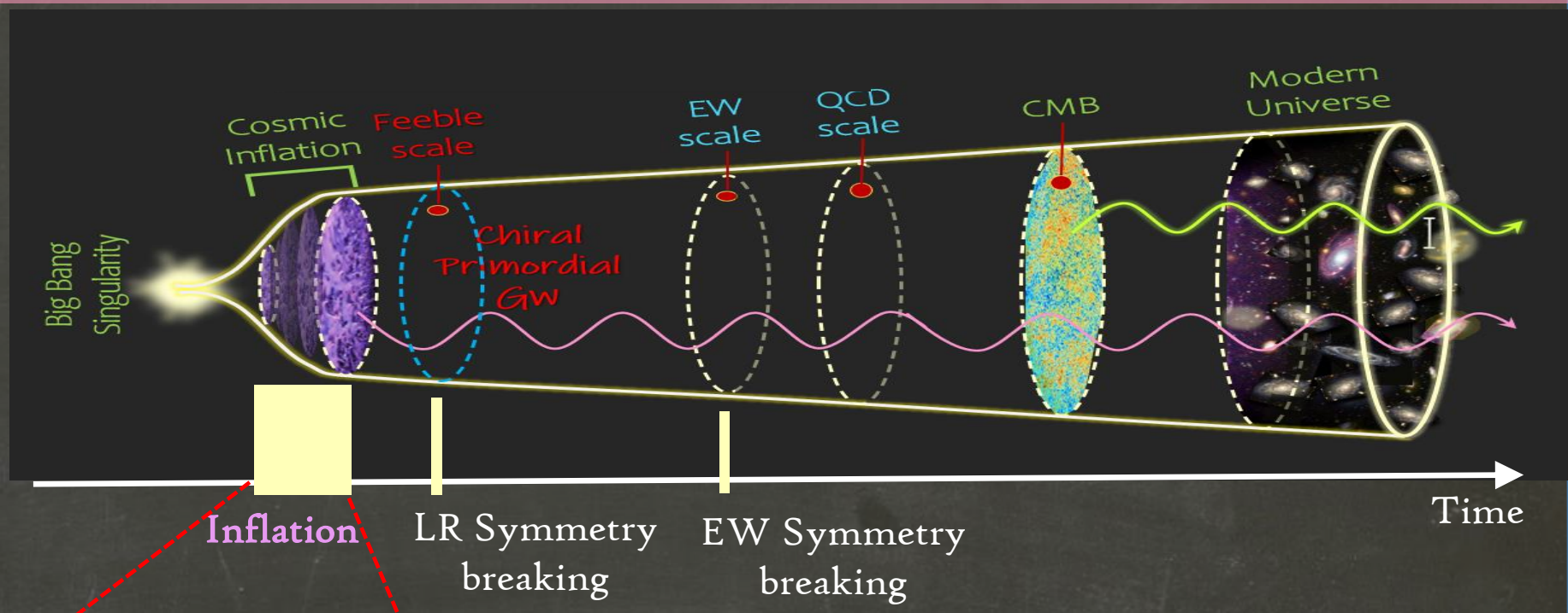
$$\frac{g^2}{16\pi^2} tr[W\tilde{W}] = \nabla_\mu J^\mu_{\mathrm{B}} = \nabla_\mu J^\mu_{\mathrm{L}}$$

R-Baryons R-Leptons

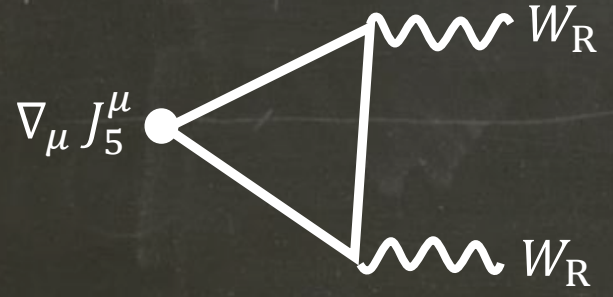
$$\mathrm{n_B} = \mathrm{n_L} = \alpha_{inf}(\xi) H^3 \sim \frac{g^2}{(2\pi)^2} H^3 \left(\frac{n_{WR}}{H^3}\right)^2$$

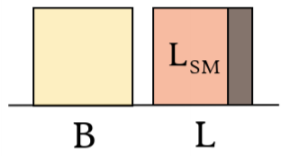
$$\alpha_{inf}(\xi) \sim \frac{g^2}{(2\pi)^4} \mathrm{e}^{2\pi\xi}$$

Summary of the mechanism:



Chiral anomaly of SU(2)R
In inflation





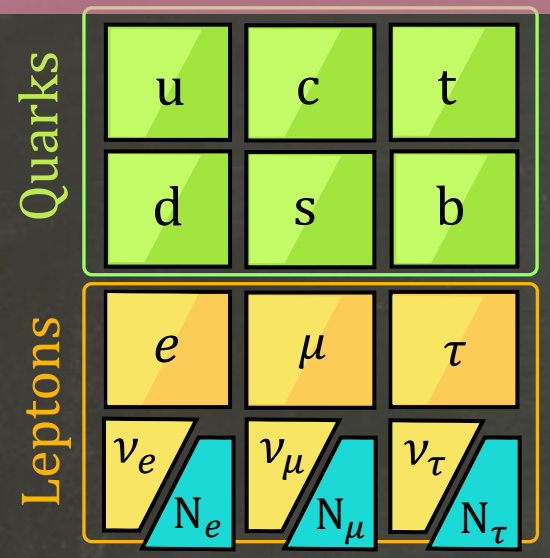
$$B = L = 3n_{CS}$$

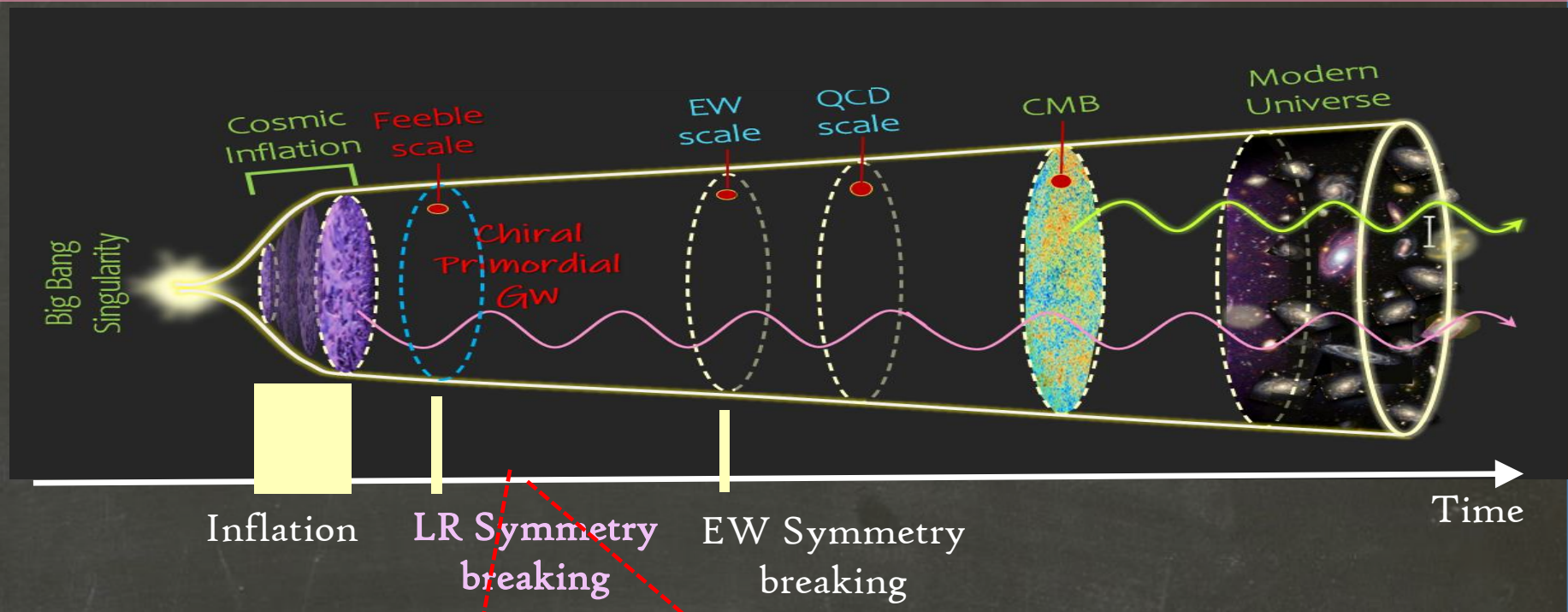
$$B - L_{SM} \neq 0$$

B= SM baryons

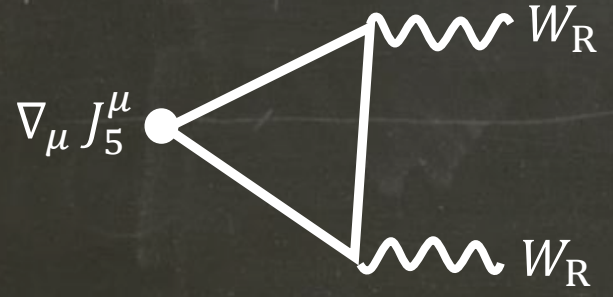
L= SM leptons + RH neutrinos

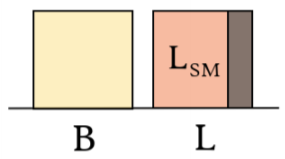
Summary of the mechanism:





Chiral anomaly of SU(2)R
In inflation





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

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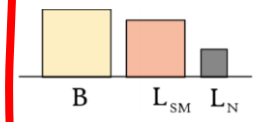

Freezeout of W_R

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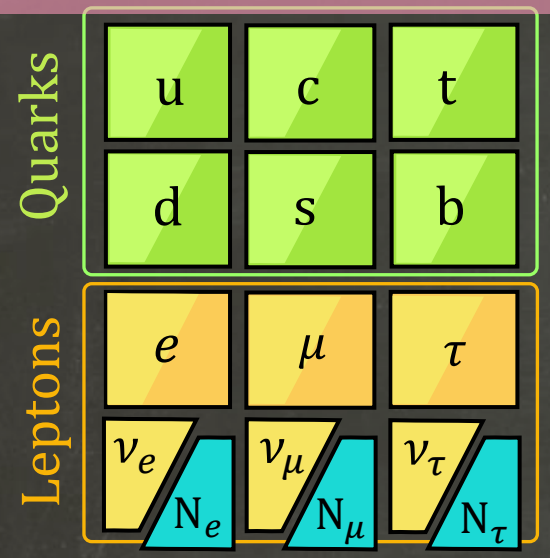

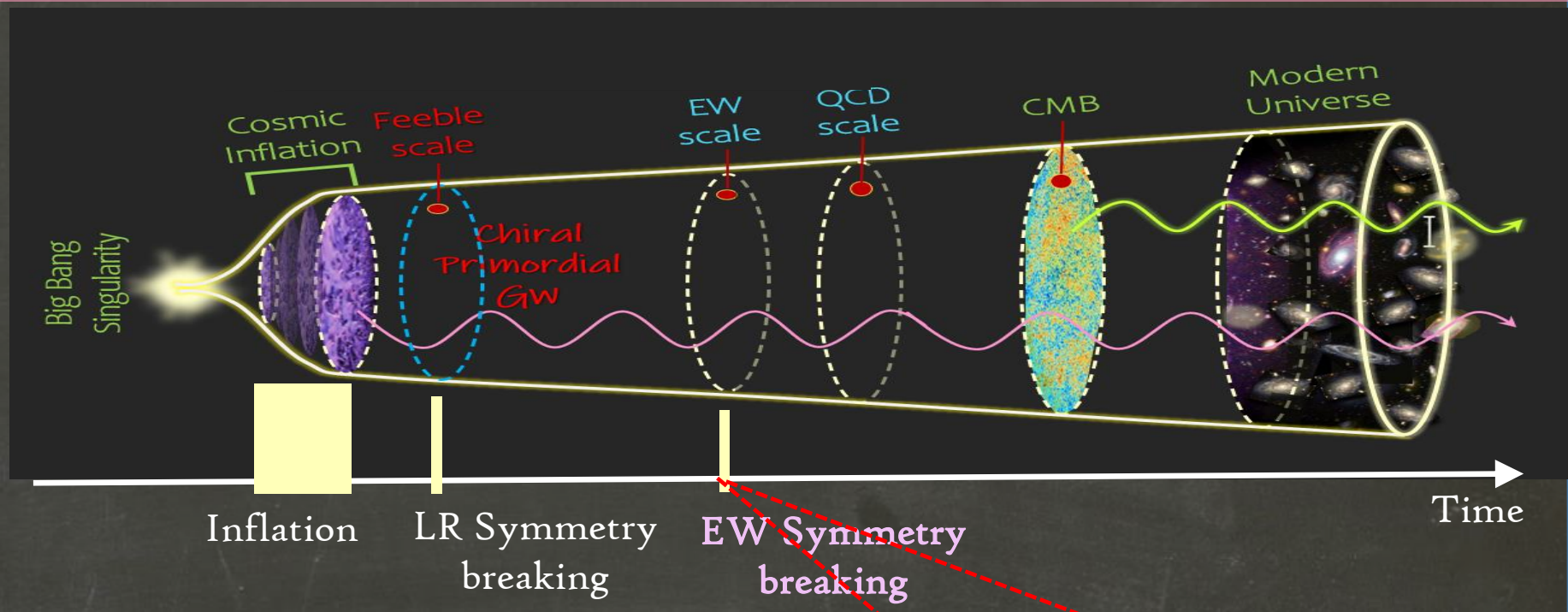

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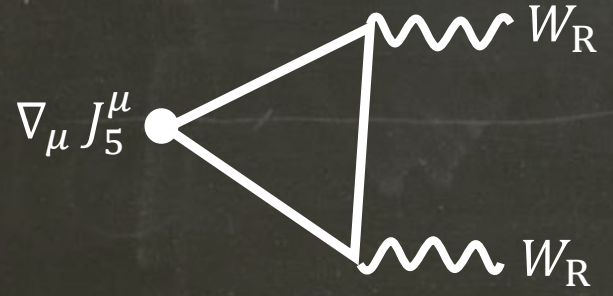

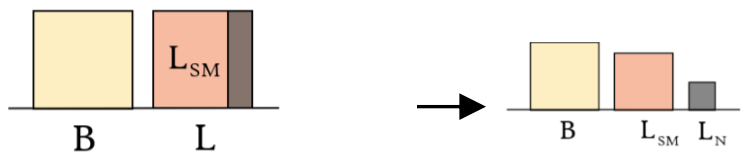

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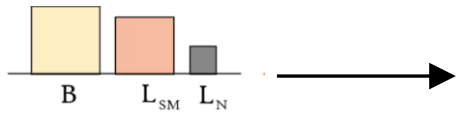

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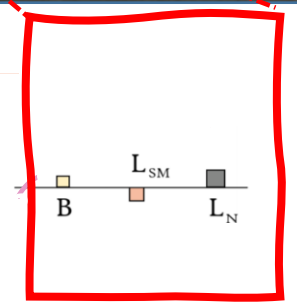

Spectator effects reshuffle B, L_{SM} & L_N

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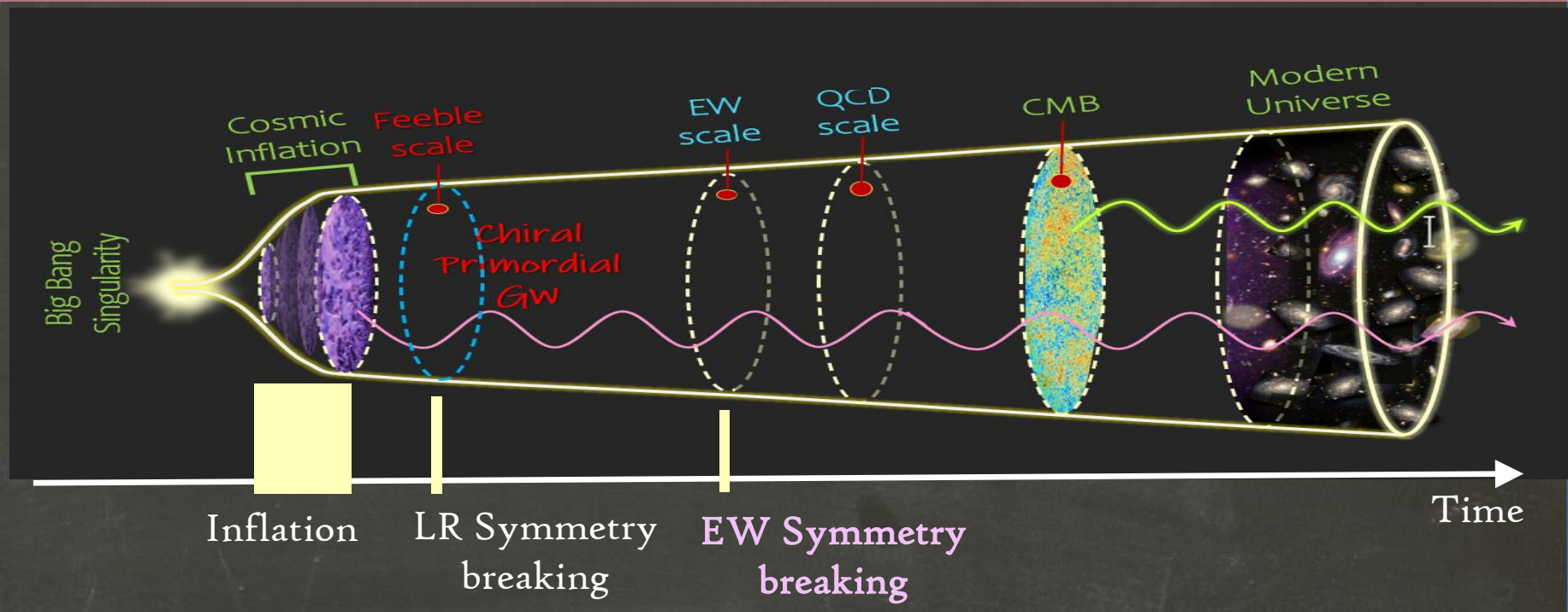

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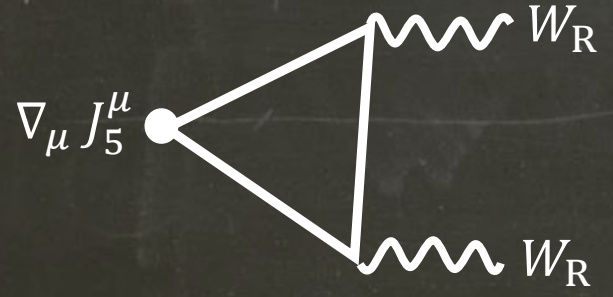

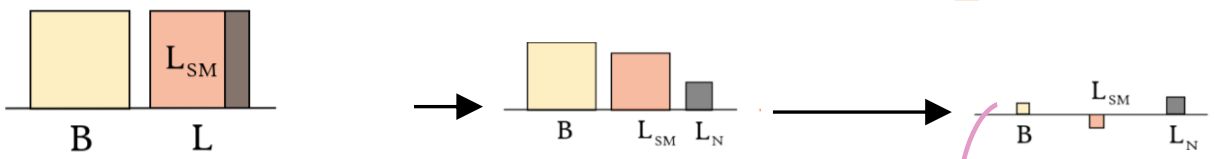

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Freezeout of W_R

Baryogenesis

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

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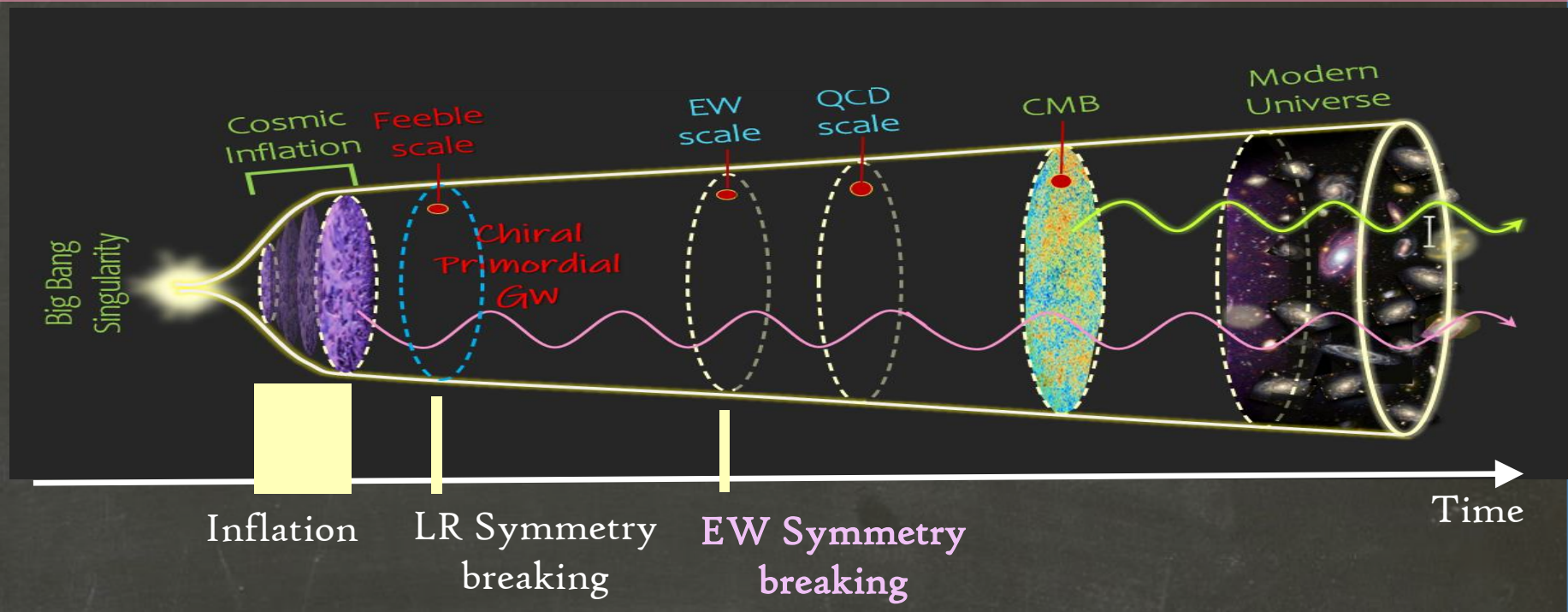

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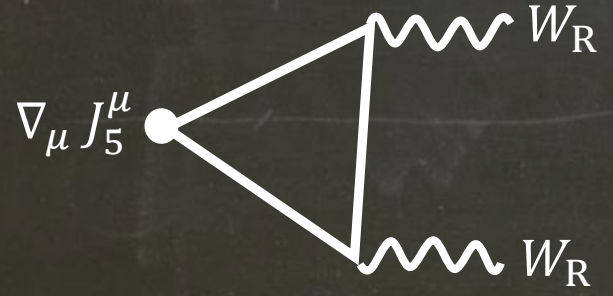

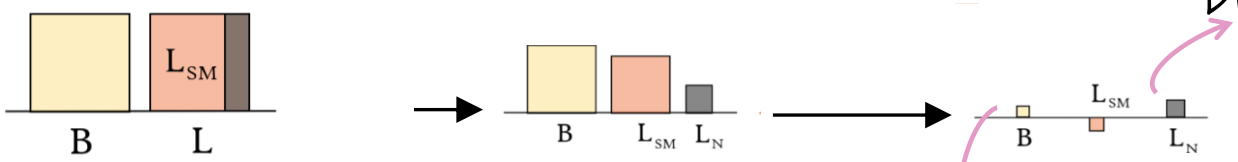

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Freezeout of W_R

Baryogenesis

DM

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

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

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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:

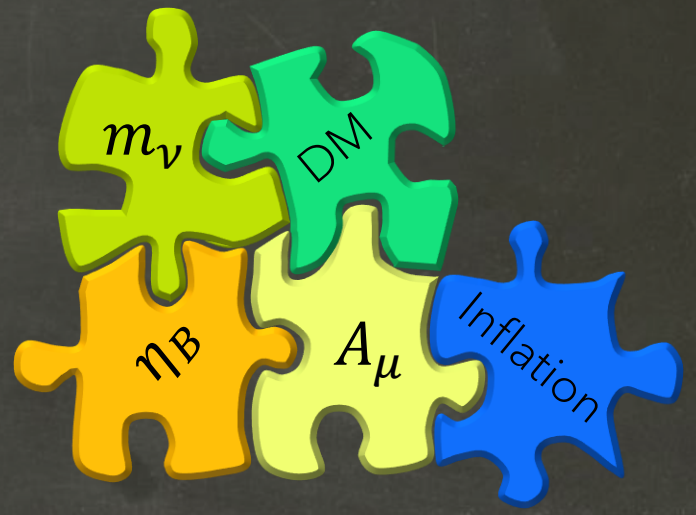
Puzzles of Particle Cosmology

I) Particle physics of Inflation

II) Origin of matter asymmetry

III) Origin of Neutrino mass

IV) Particle nature of DM



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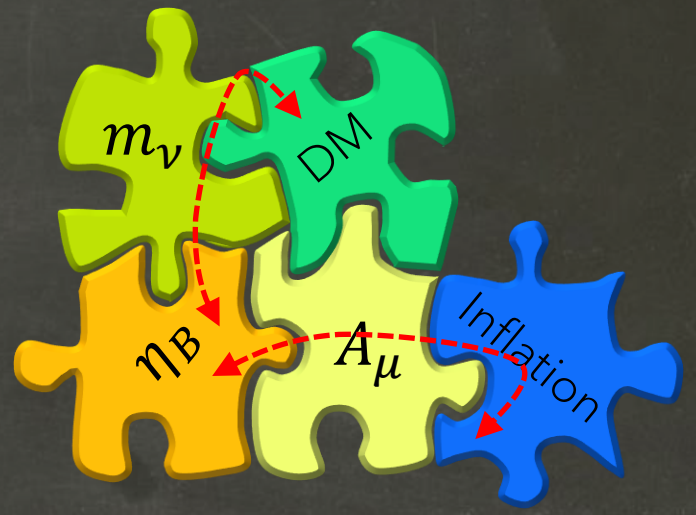

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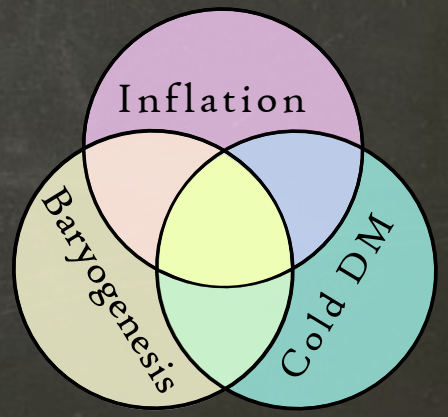

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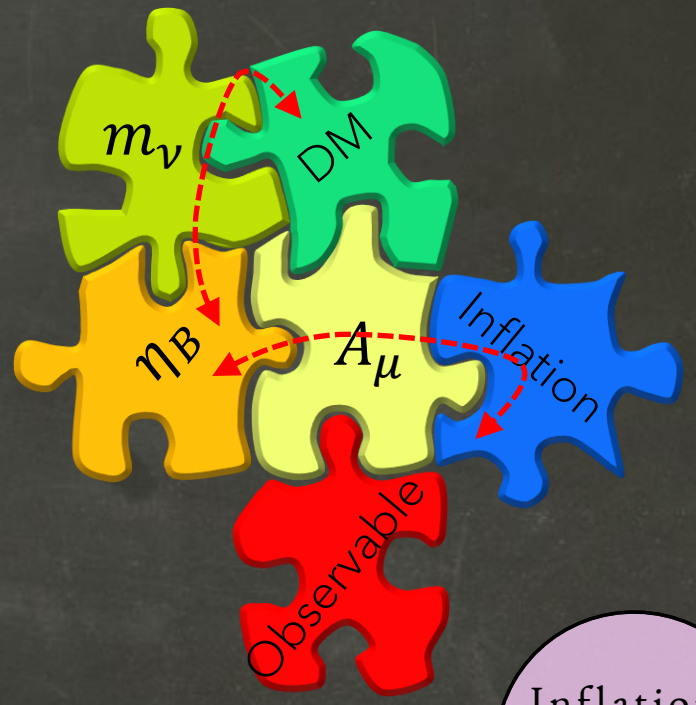

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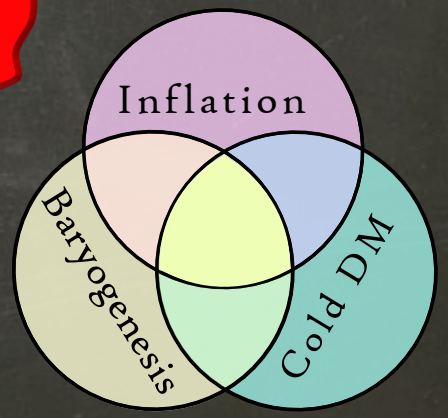

It comes with a cosmological smoking gun on Primordial GW.


Questions?!