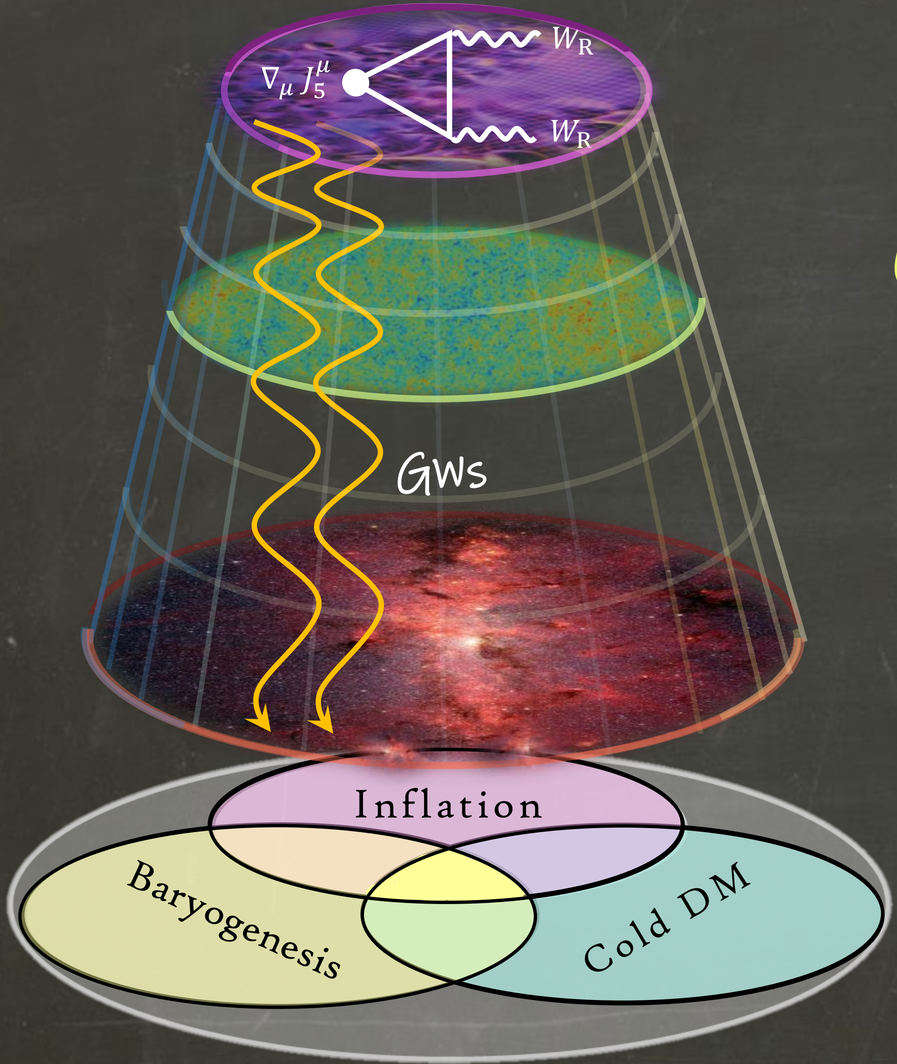
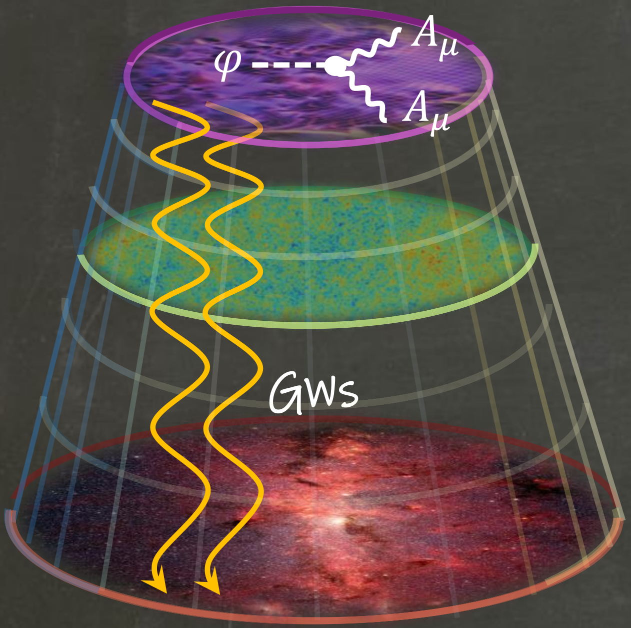


Is our Universe Remnant of Chiral Anomaly in Inflation?

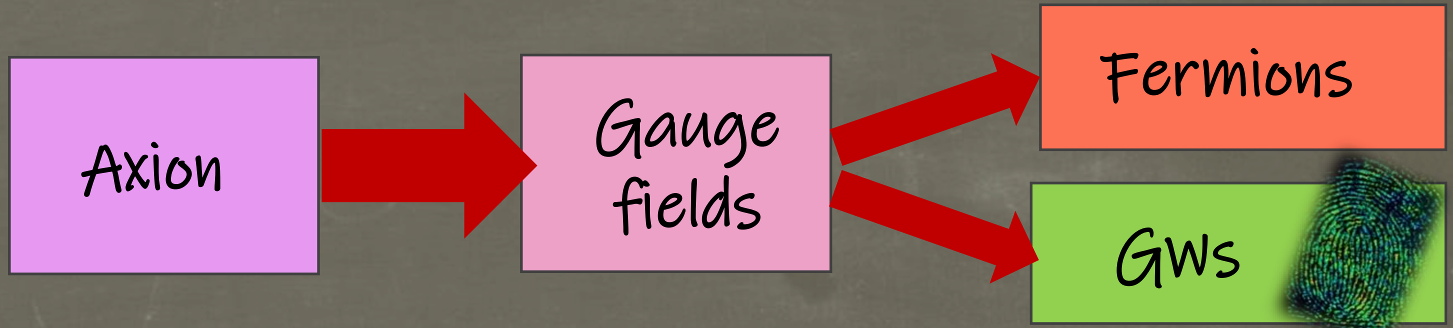
Based on
arXiv:2012.11516 & arXiv:2103.14611

Azadeh Malek-Nejad
CERN

Setup:

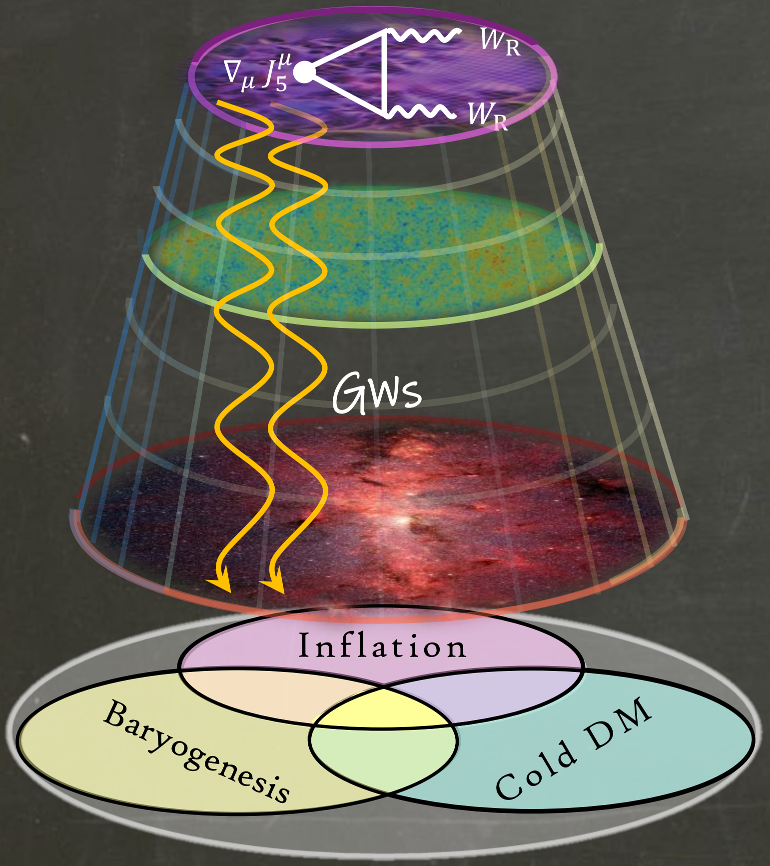


I) Axion-inflation and gauge fields



(chiral, blue-tilted & NG)

Setup:



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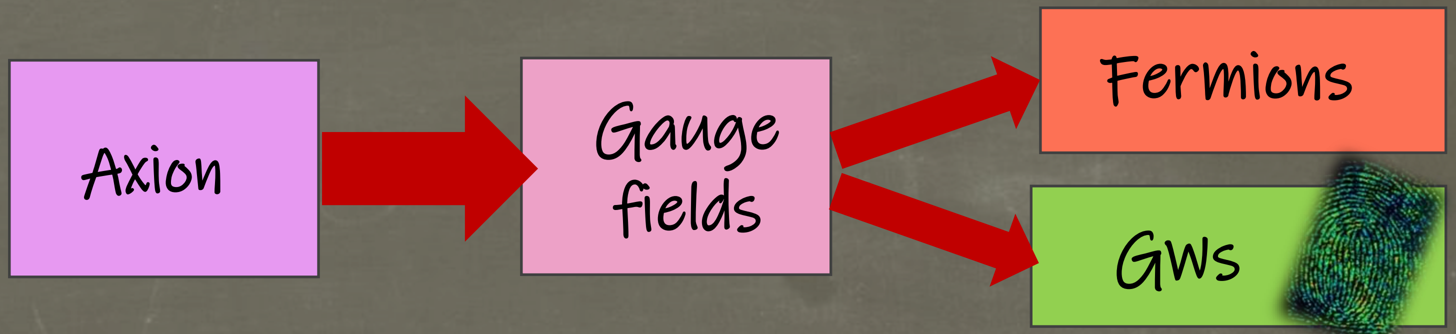
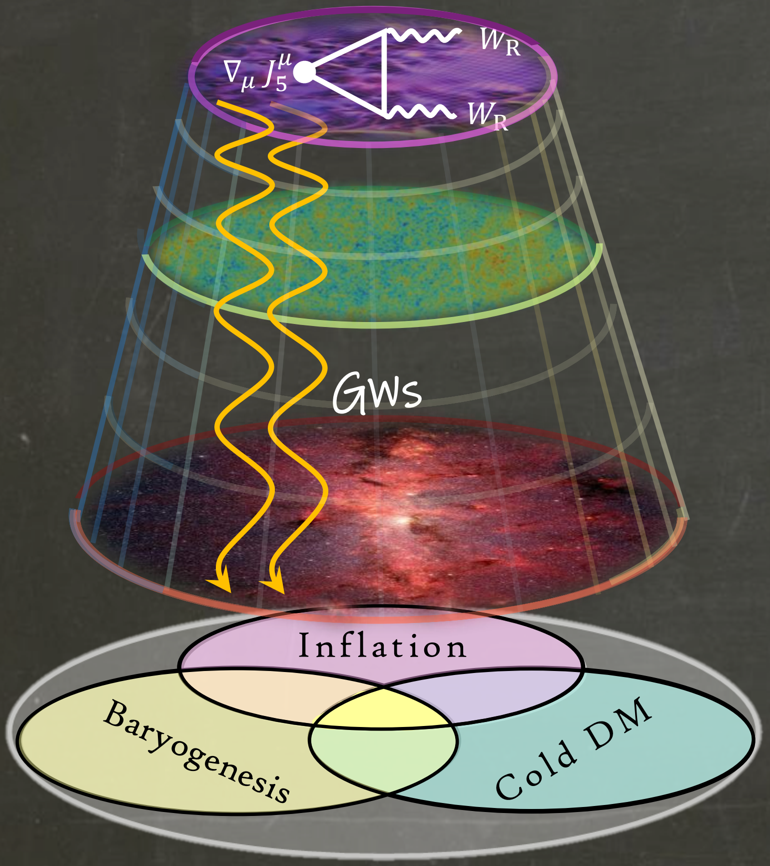


(chiral, blue-tilted & NG)

II) Embedding inflation in Left-Right symmetric model

Based on
arXiv:2012.11516 & arXiv:2103.14611

Setup:



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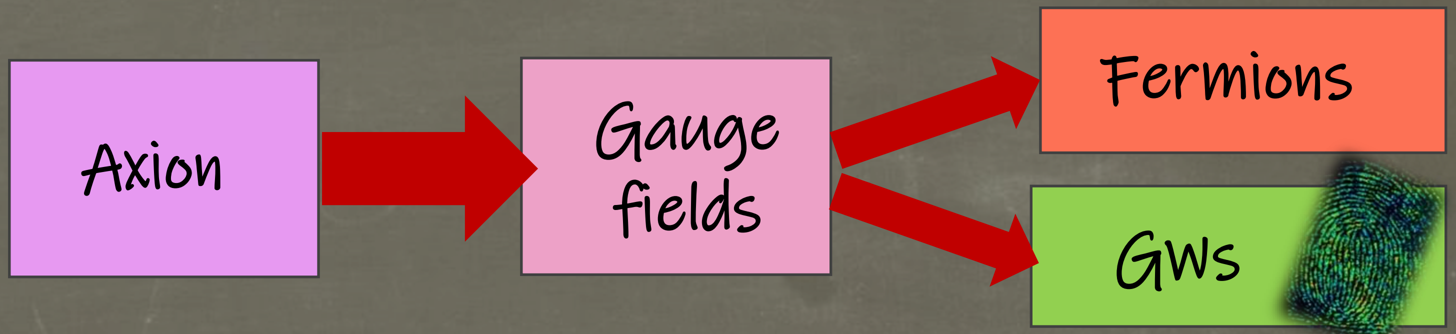

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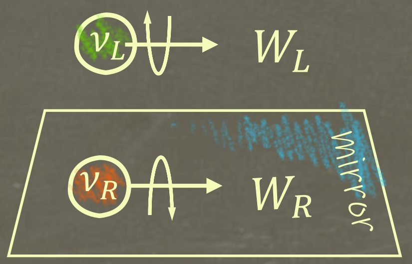

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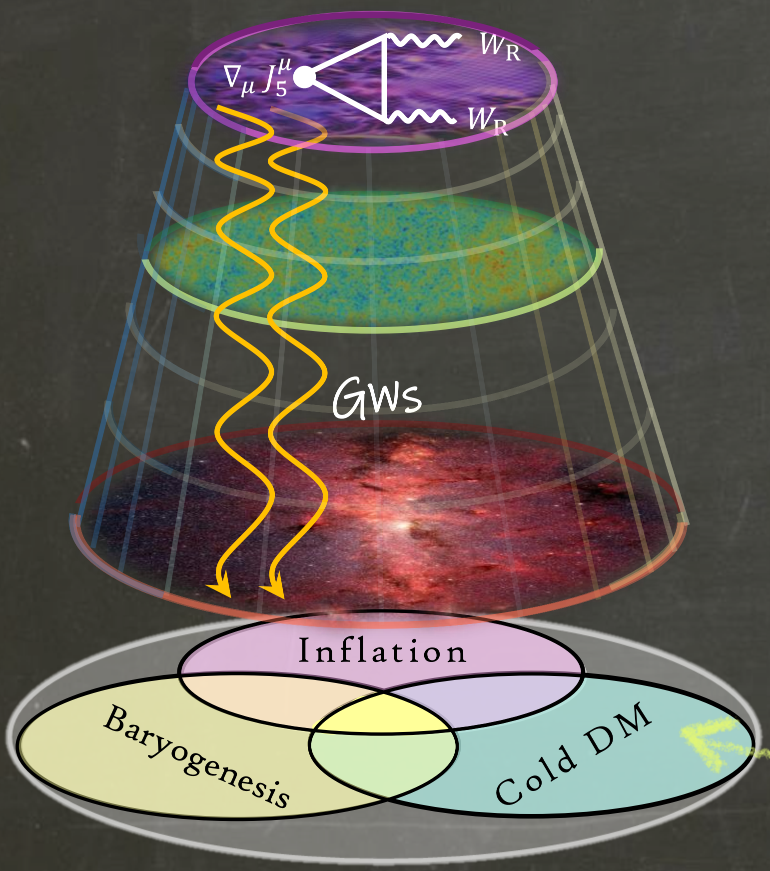

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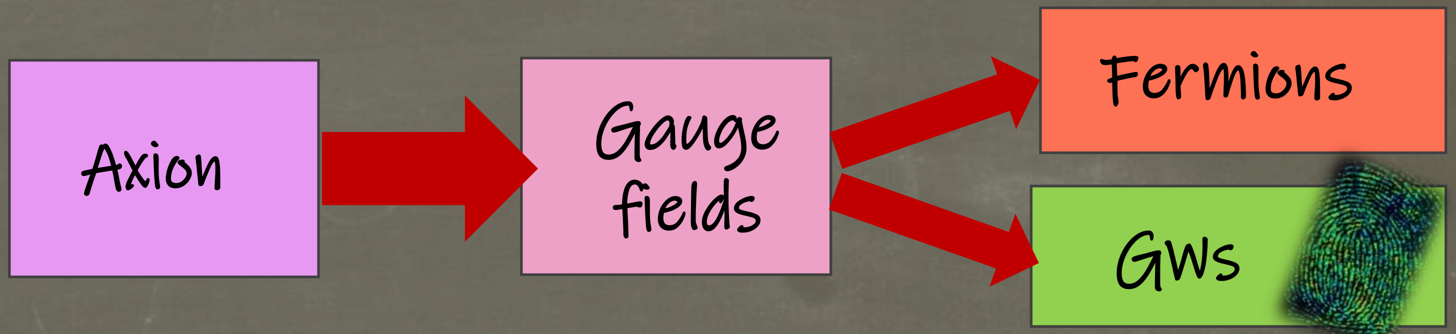

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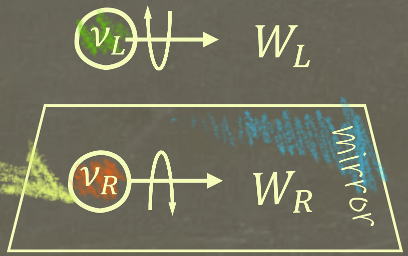


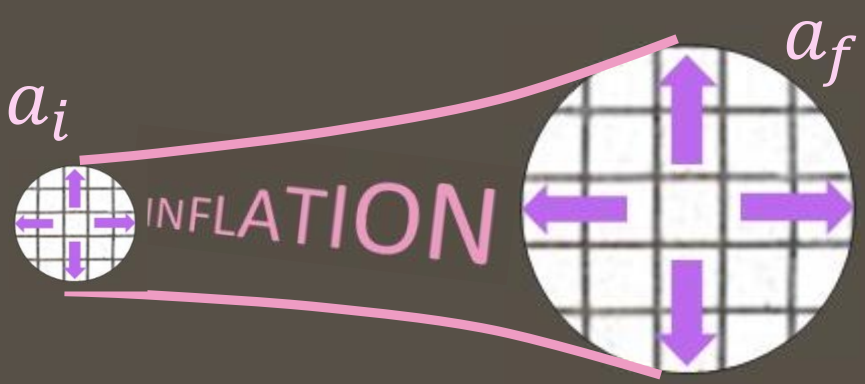
Right-handed neutrinos

Cosmic Inflation

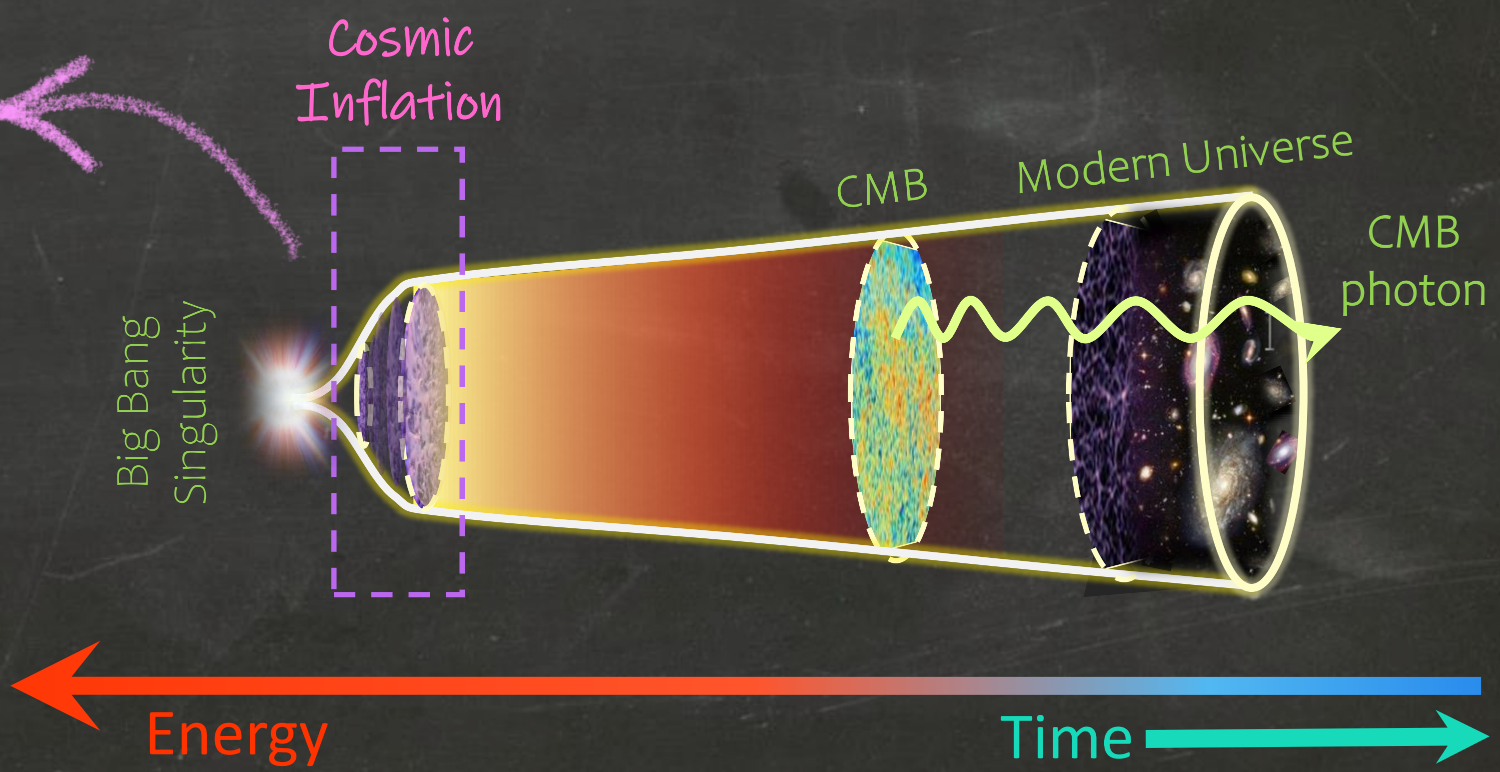
Guth Phys. Rev. D23 (1981)

Linde Phys. Lett. B 108 (1982)

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

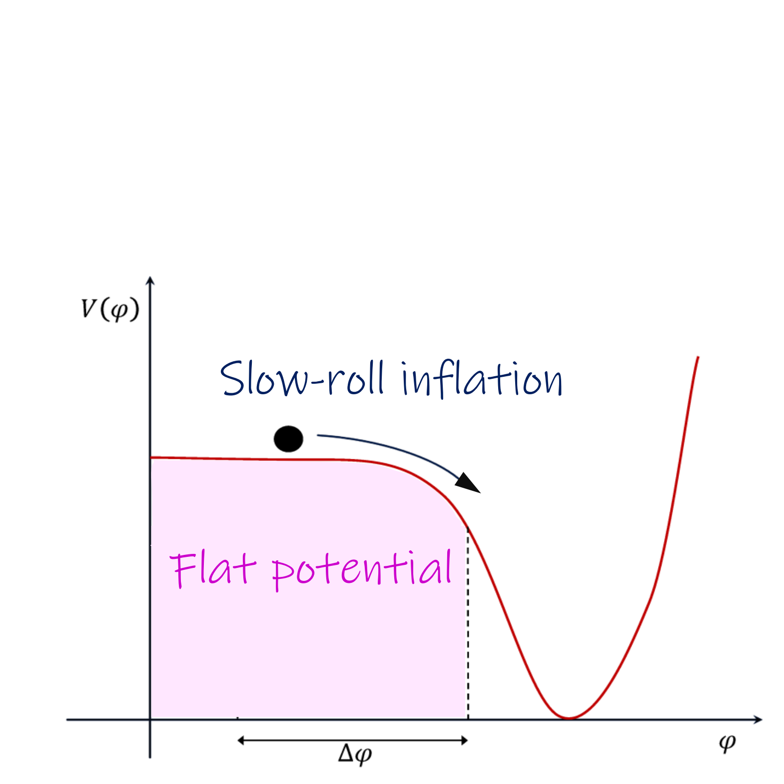


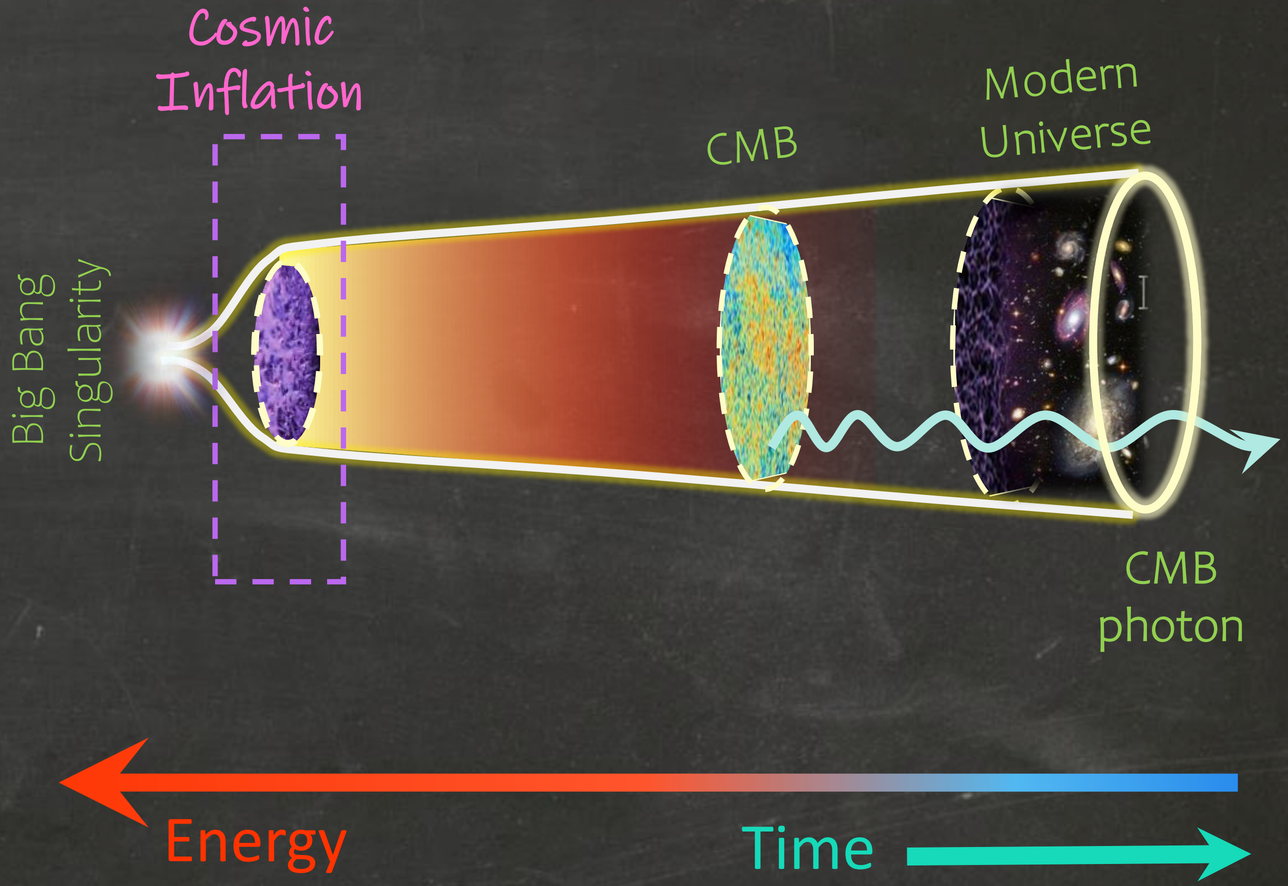
$$\frac{a_f}{a_i} = e^{60} \approx 10^{26}!$$



What caused inflation?

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





Puzzles of SM & Cosmology

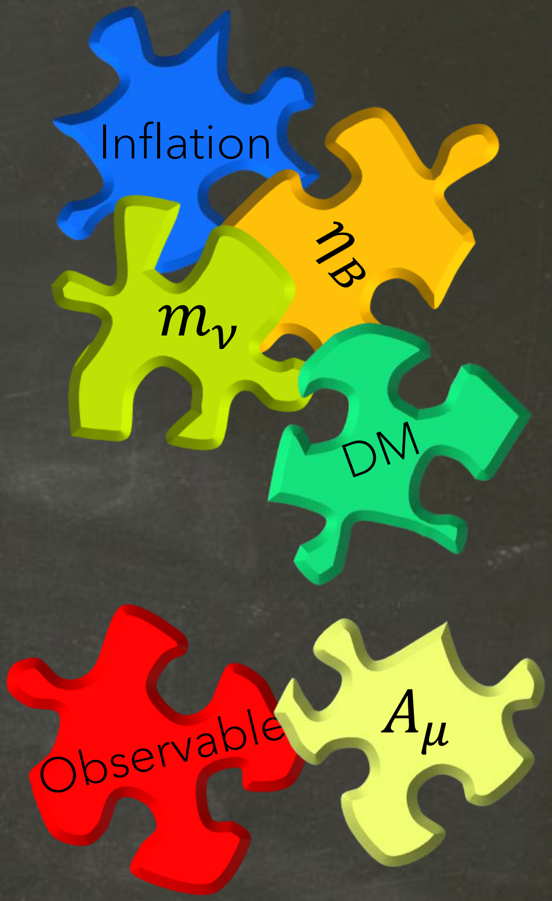
I) Particle physics of Inflation

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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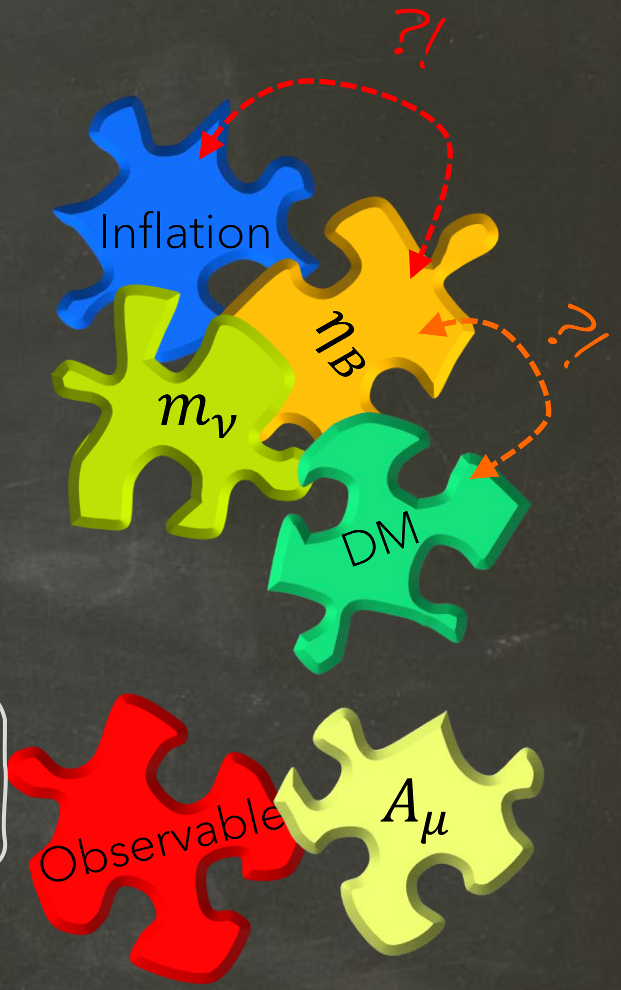

- Curious cosmological coincidences $\eta_B \simeq 0.3\, \mathrm{P}_\zeta$ and $\Omega_{DM} \simeq 5\Omega_B$!

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

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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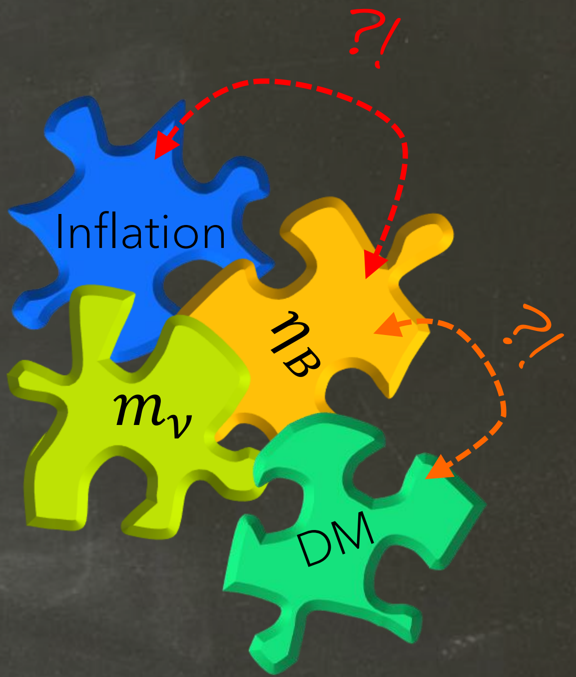

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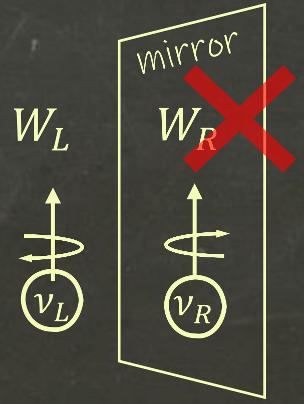
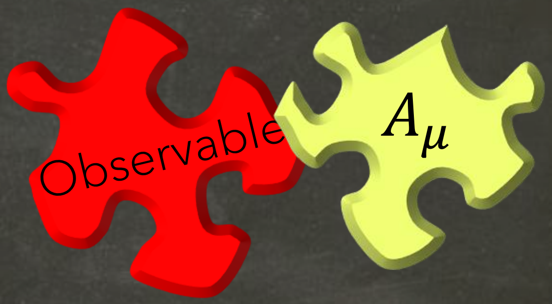
1. Ad hoc parity violation
2. Accidental B-L global symmetry
3. Vacuum Stability problem

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

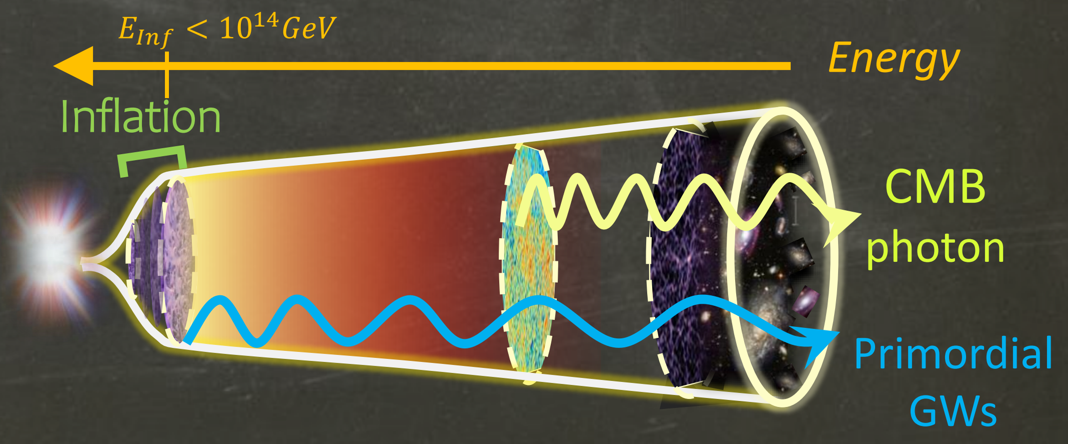




As Yet

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

Inflation Particle Physics: a scalar field beyond the SM.



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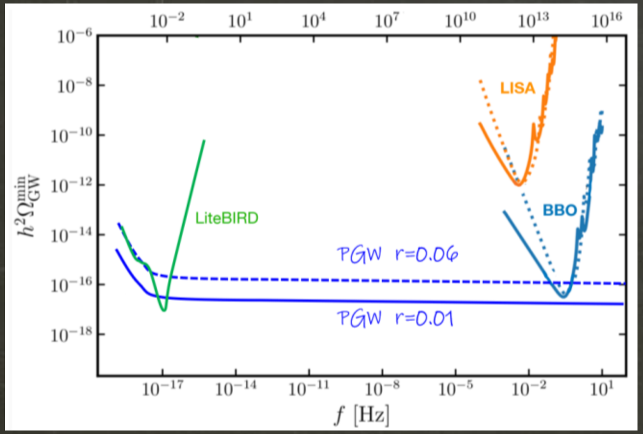
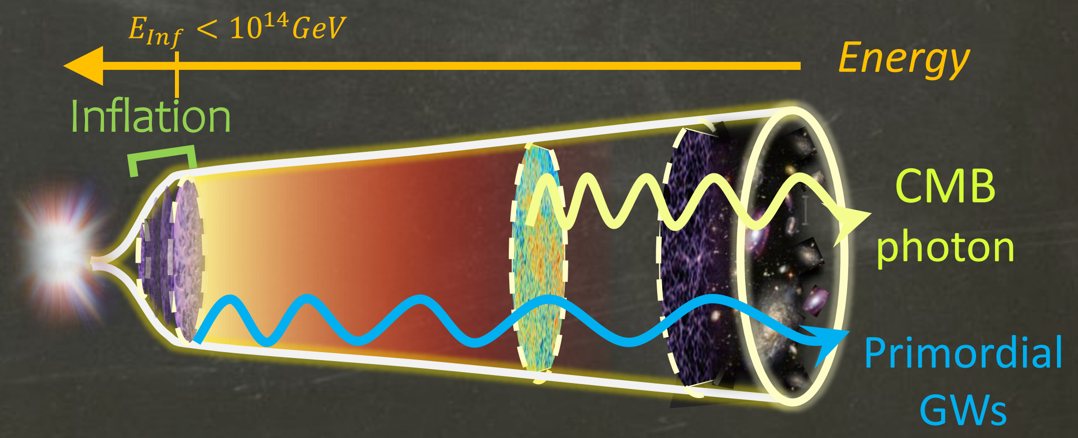
  Inflation Particle Physics: a scalar field beyond the SM.

- Primordial Gravitational Waves (PGW):

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





As Yet

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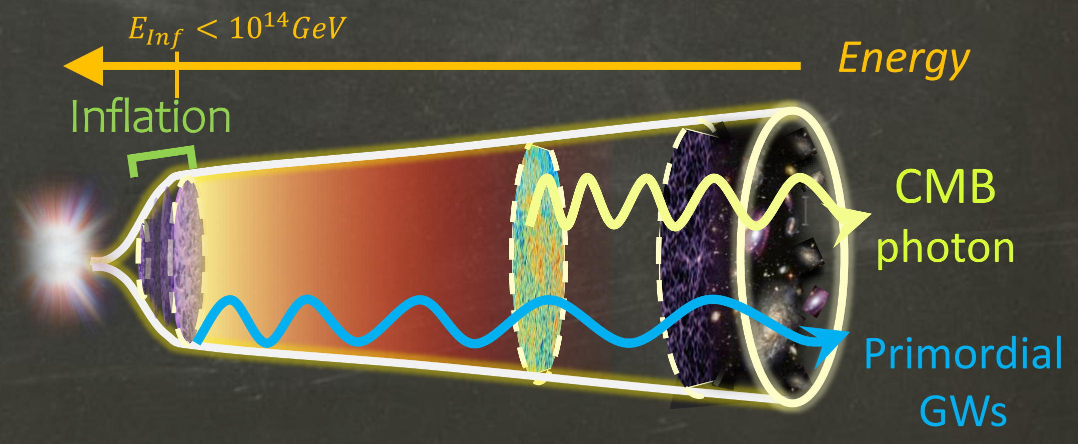
What about Gauge Fields?!

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

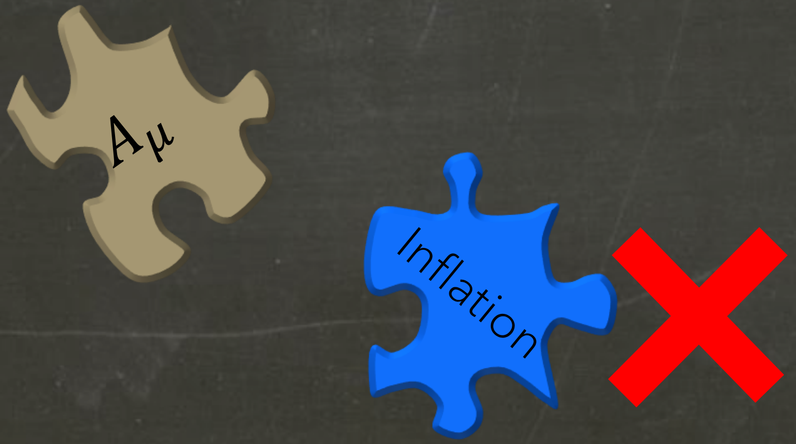


Gauge Fields & Inflation

Challenges:

Gauge fields given by Yang-Mills

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

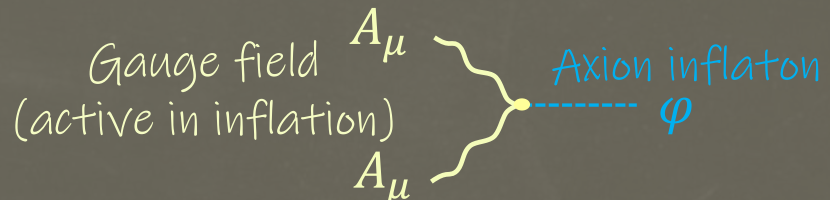


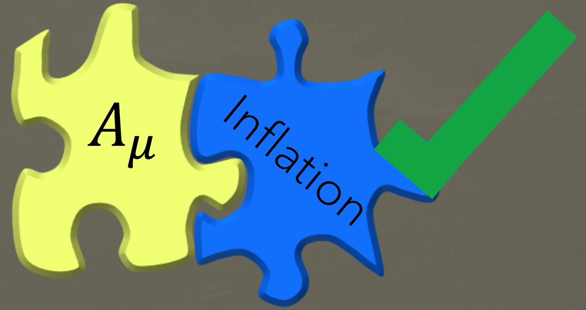
Gauge fields coupled to inflaton are generated in inflation.

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

Axion

(Axion fields are naturally coupled to gauge fields.)





Challenges:

Gauge fields given by Yang-Mills

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

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.)

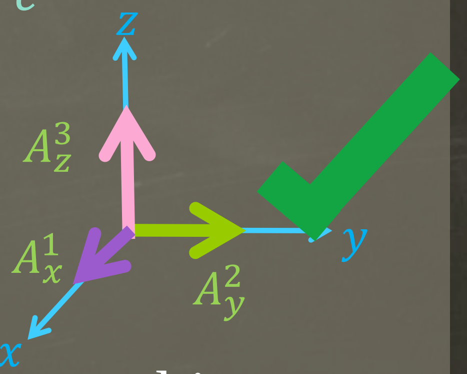
A.M. & Sheikh-Jabbari, 2011

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

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

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

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]

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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,** Domcke et al 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

SU(2)-Axion Model Building

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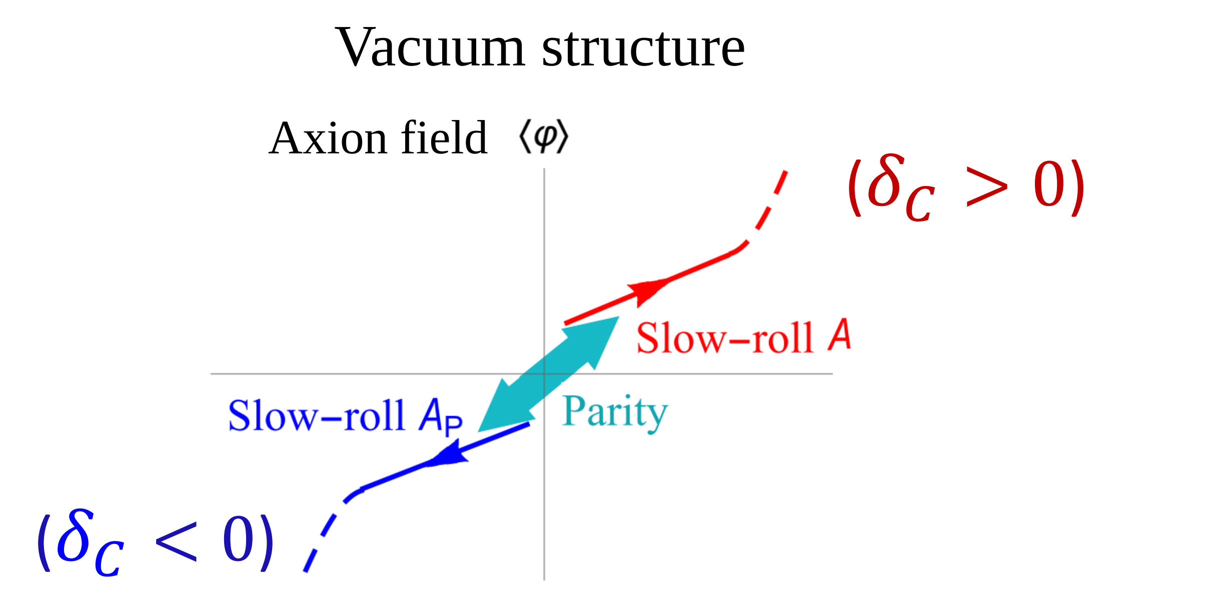
Axion Monodromy or any mechanism that gives a flat potential

New Tensorial mode in SU(2) Gauge Field

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

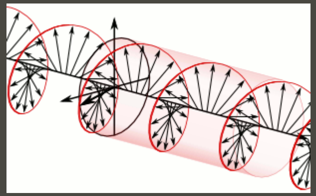
$$B_\pm'' + \underbrace{\left[k^2 \mp \delta_C k\mathcal{H} + \frac{m^2}{H^2}\mathcal{H}^2 - \frac{a''}{a}\right]}_{\text{effective frequency}} B_\pm \approx 0$$

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



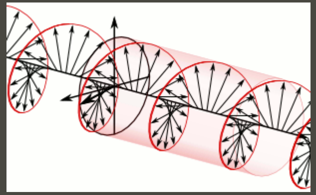
Circular polarizations

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

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

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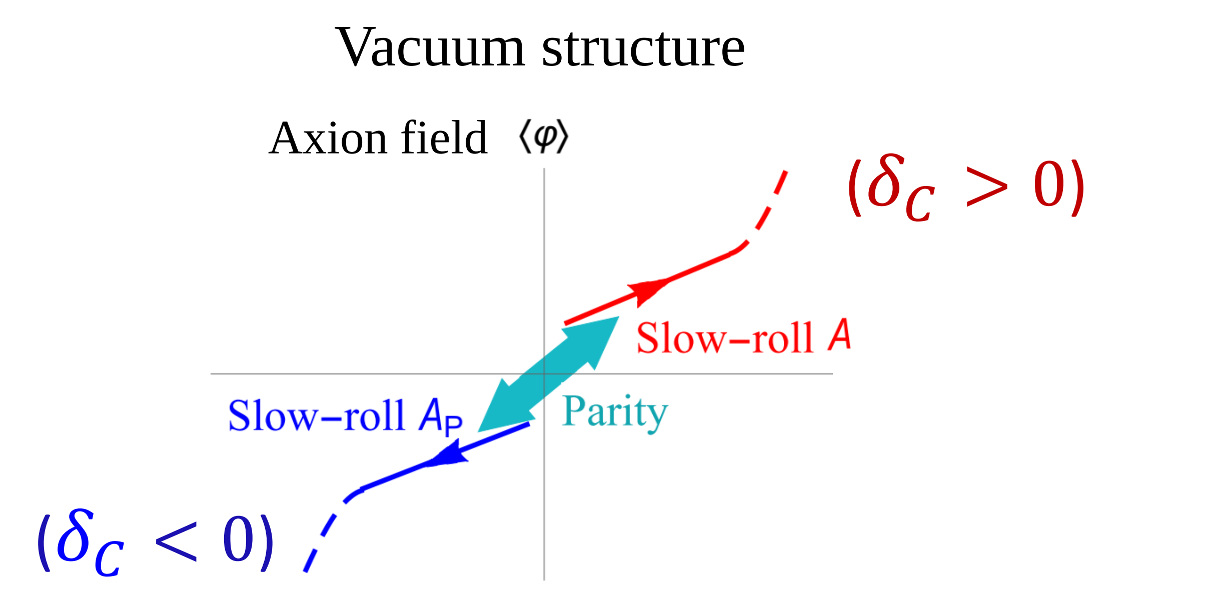


For $\delta_C > 0$

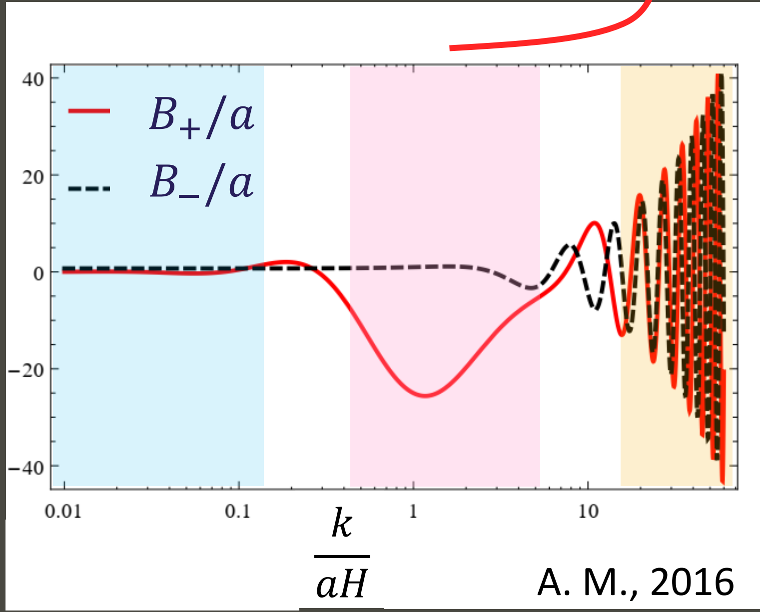
Short tachyonic growth of B_+

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



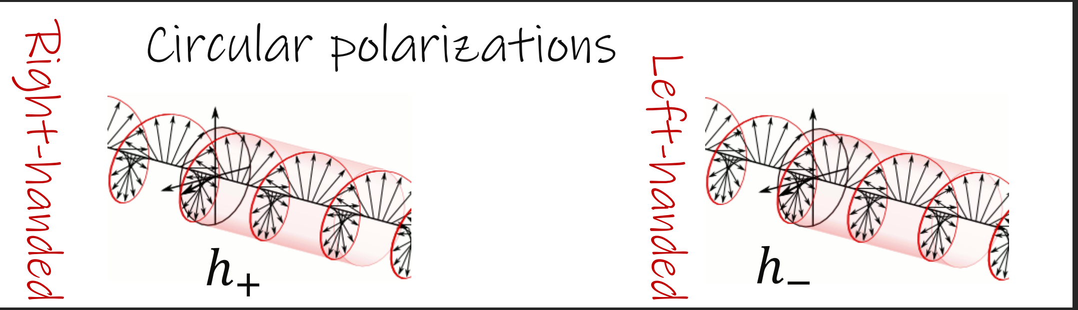
A. M., 2016

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

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

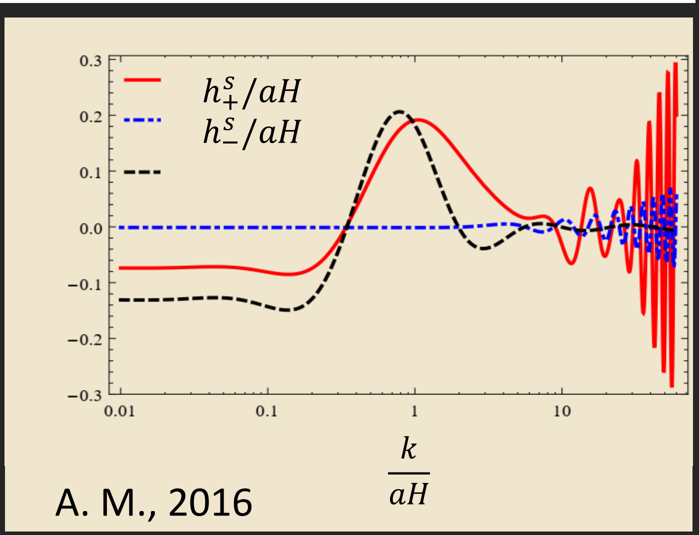


- Gravitational waves have two uncorrelated terms

$$h_\pm = \underbrace{h_\pm^{vac}}_{} + \underbrace{h_\pm^{s}}_{}$$

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

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



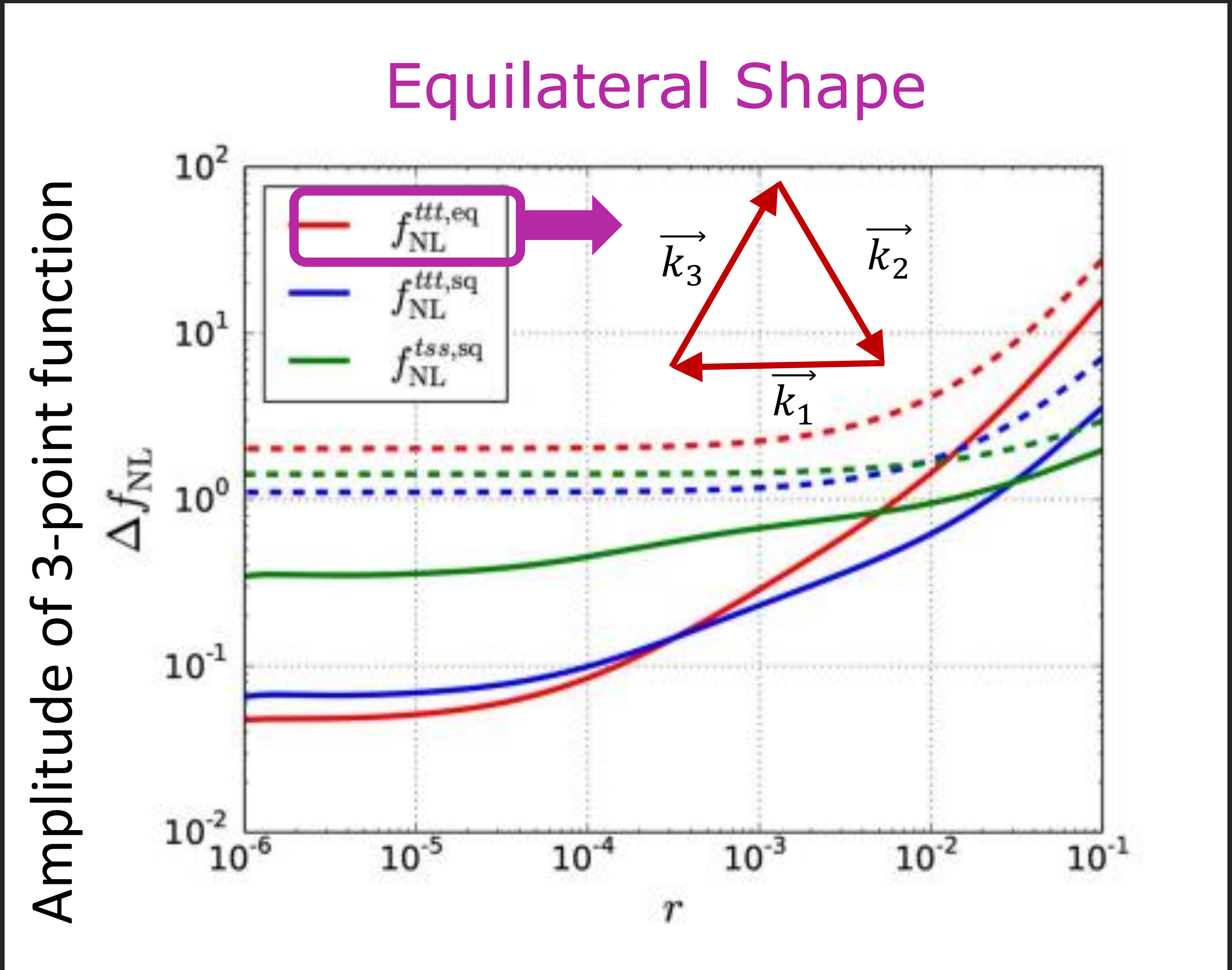
Novel Observable Signature: CMB

- The sourced tensor modes is Highly non-Gaussian.

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

Agrawal, Fujita, Komatsu 2018

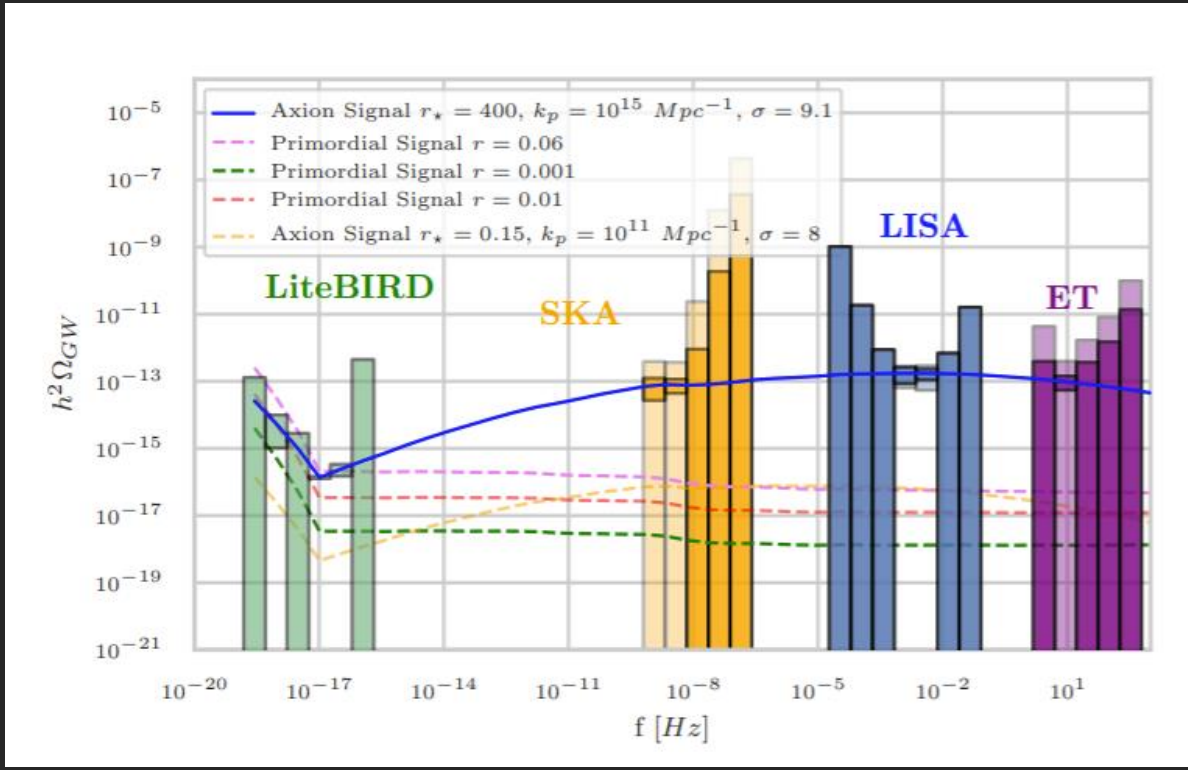
- That can be probe with future CMB missions., e.g. *Litebird* and *CMB-S4*!



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

How to Connect Inflaton to SM?

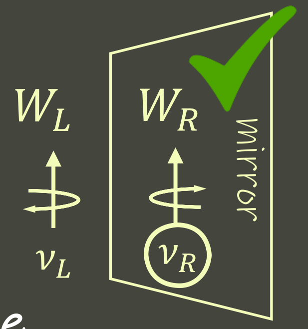
How to Connect it to the SM?

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

- Left-Right Symmetric Model + axion!

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

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 $SU(2)_R$

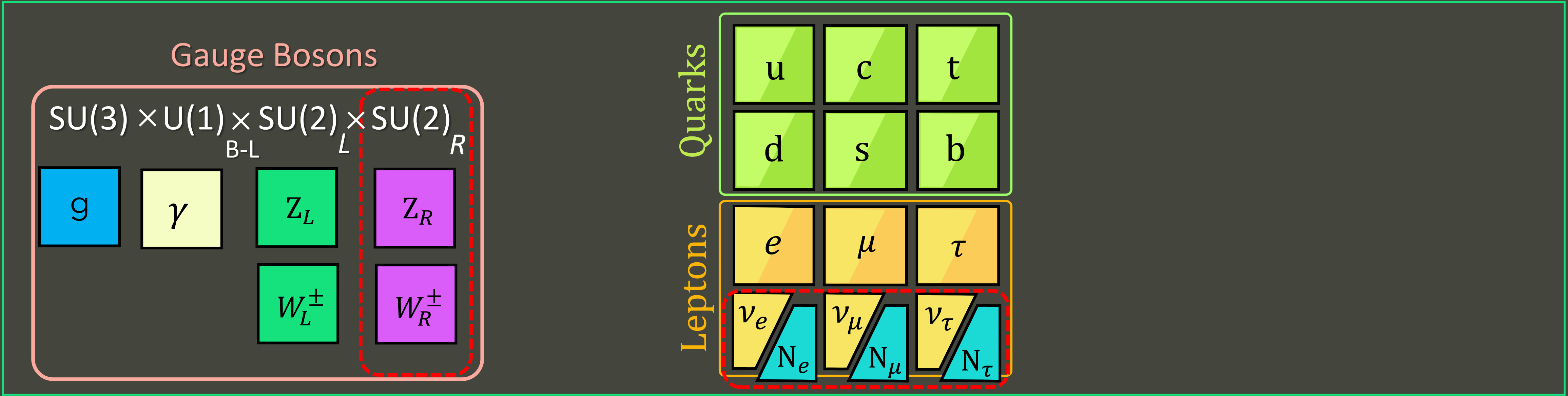
A. M. arXiv: 2012.11516

A.M. arXiv:2103.14611

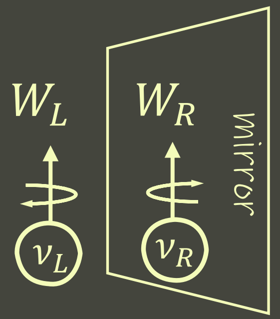
Left-Right Symmetric Model

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)



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

$\downarrow$ Spontaneous Symmetry Breaking

$$SU(2)_L \times U(1)_Y$$

Minimal Left-Right Symmetric model

Left-Right Symmetric Model

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

Gauge Bosons

$SU(3) \times U(1)_{B\text{-}L} \times SU(2)_L \times SU(2)_R$

g γ Z_L Z_R

$W_L^{\pm}$ $W_R^{\pm}$

Quarks

u c t

d s b

Leptons

e μ τ

ν_e N_e ν_μ N_μ ν_τ N_τ

Higgs sector

ϕ bi-doublet $SU(2)_L \times SU(2)_R$

Δ_R $SU(2)_R$ triplet

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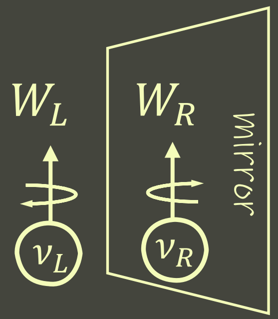

$SU(2)_L \times SU(2)_R \times U(1)_{B\text{-}L}$

$\downarrow$ Spontaneous Symmetry Breaking

$SU(2)_L \times U(1)_Y$

$\langle \Delta_R \rangle \neq 0$

Massive

N_i $W_R^{\pm}$ Z_R

Left-Right Symmetric Model

Minimal Left-Right Symmetric model

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

Gauge Bosons

$SU(3) \times U(1)_{B\text{-}L} \times SU(2)_L \times SU(2)_R$

g, γ, Z_L, $W_L^{\pm}$, Z_R, $W_R^{\pm}$

Quarks

u, c, t

d, s, b

Leptons

e, μ, τ

ν_e N_e, ν_μ N_μ, ν_τ N_τ

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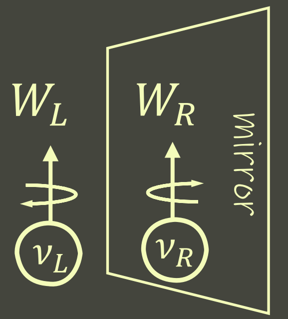

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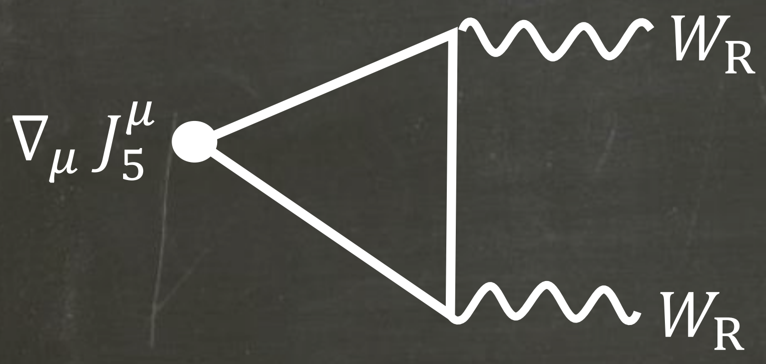
1. Ad hoc parity violation
2. Accidental B-L global symmetry
3. Vacuum Stability problem

Lepton & quark Production in Inflation

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

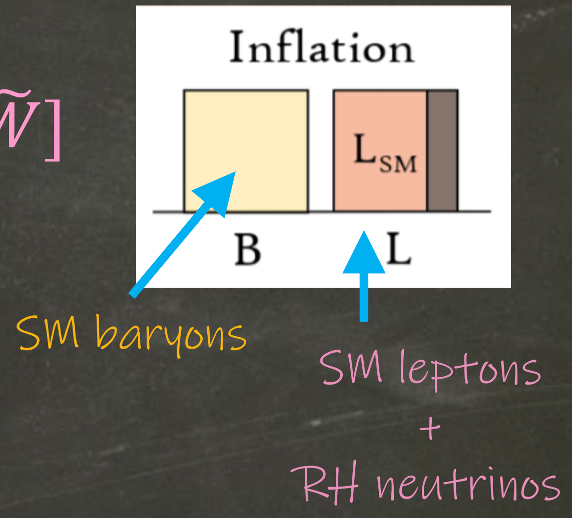
The key ingredient is the Chiral anomaly of $\mathrm{SU(2)_R}$ in inflation:



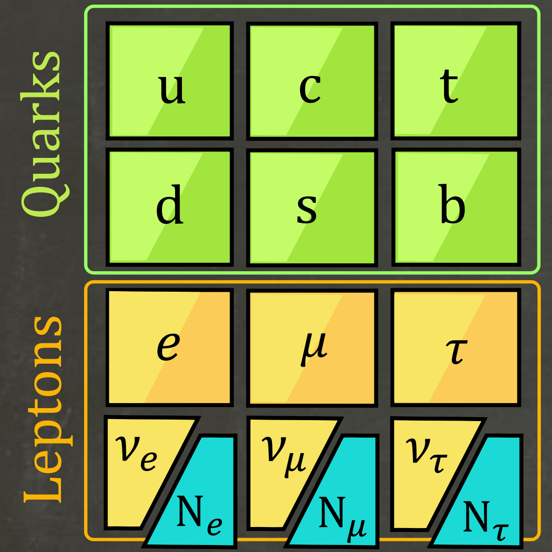
$$\nabla_\mu J^\mu_\mathrm{B} = \nabla_\mu J^\mu_\mathrm{L} = \frac{g^2}{16\pi^2} tr[W\widetilde{W}]$$

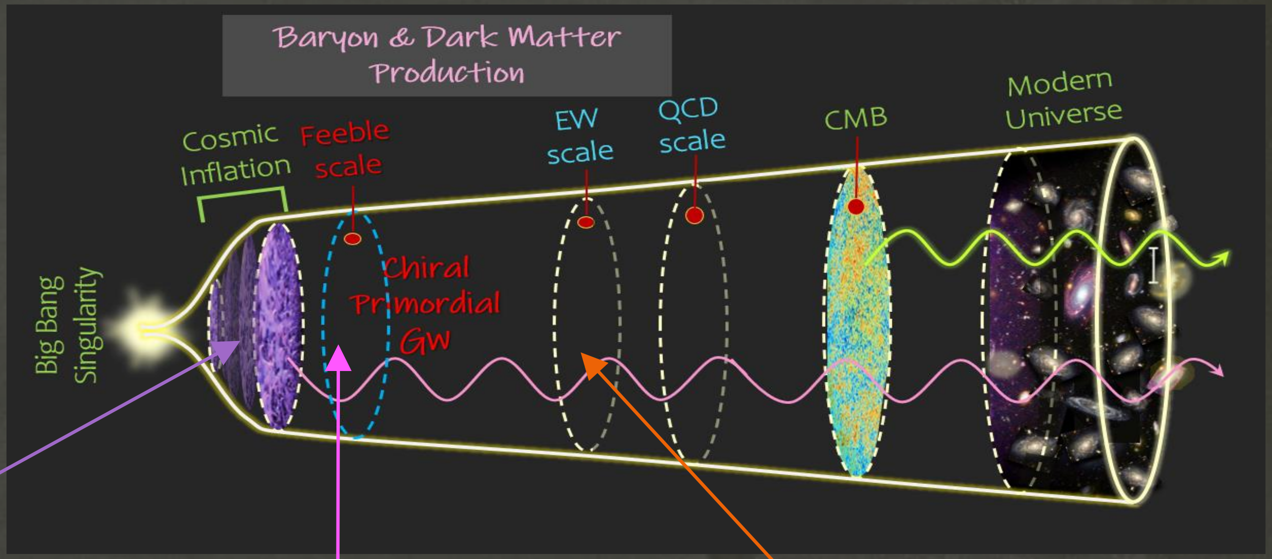
$$\mathrm{n_B} = \mathrm{n_L} = \alpha_{inf}(\xi) H^3$$

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



Summary of the mechanism:

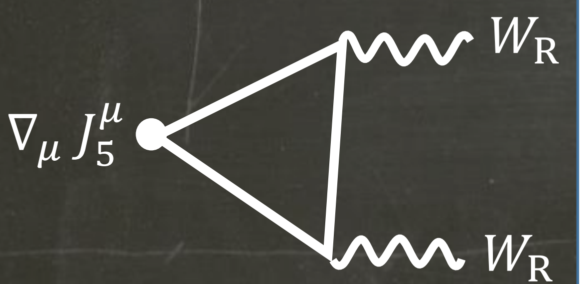


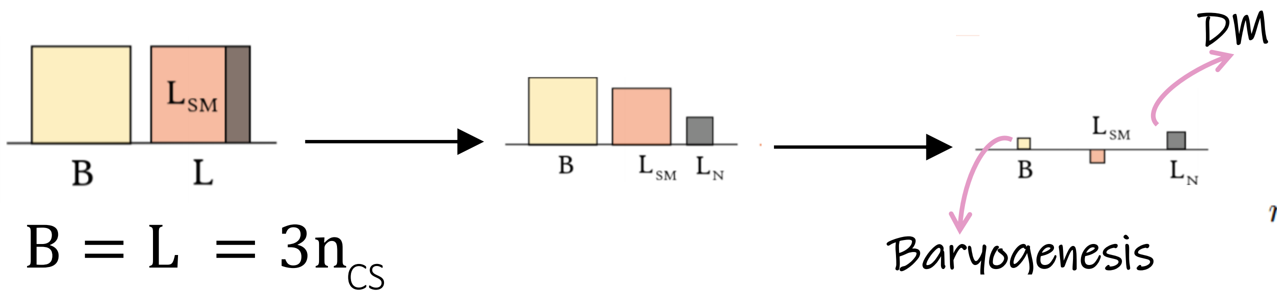


Chiral anomaly of SU(2)R in inflation

Freezeout of Ni

EW scale





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

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

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

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

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

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

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Compelling Consequences:

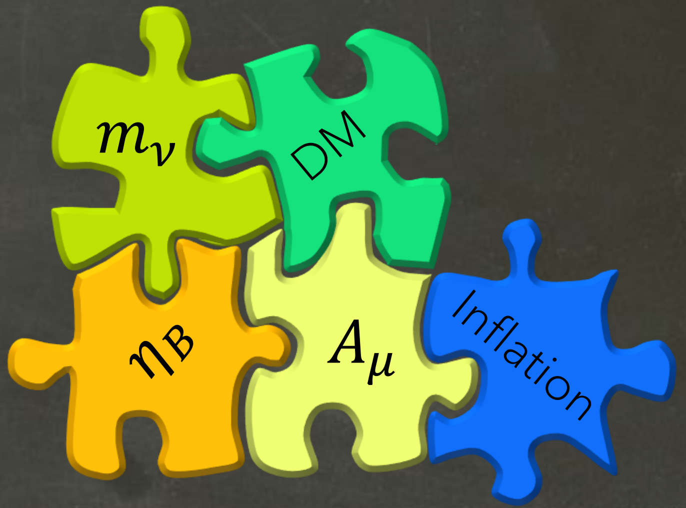
This Set-up is a complete BSM that can solve I-IV:

I) Particle physics of Inflation

II) Origin of matter asymmetry

III) Origin of Neutrino mass

IV) Particle nature of DM



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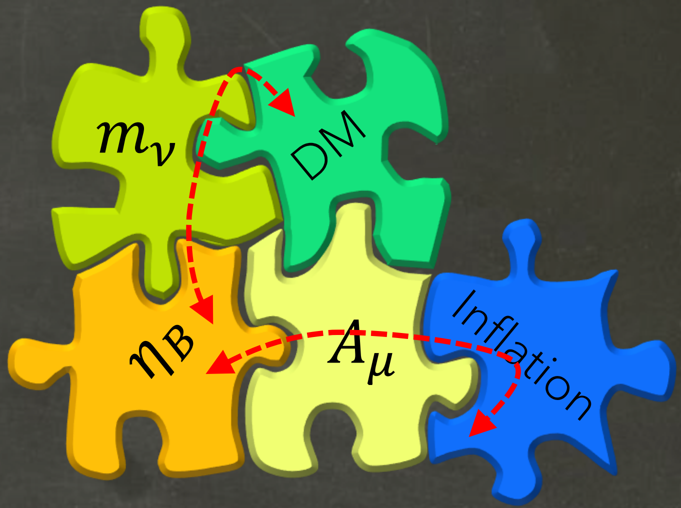
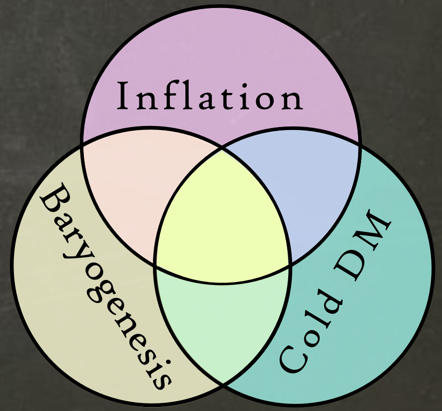
Puzzles of Particle Cosmology



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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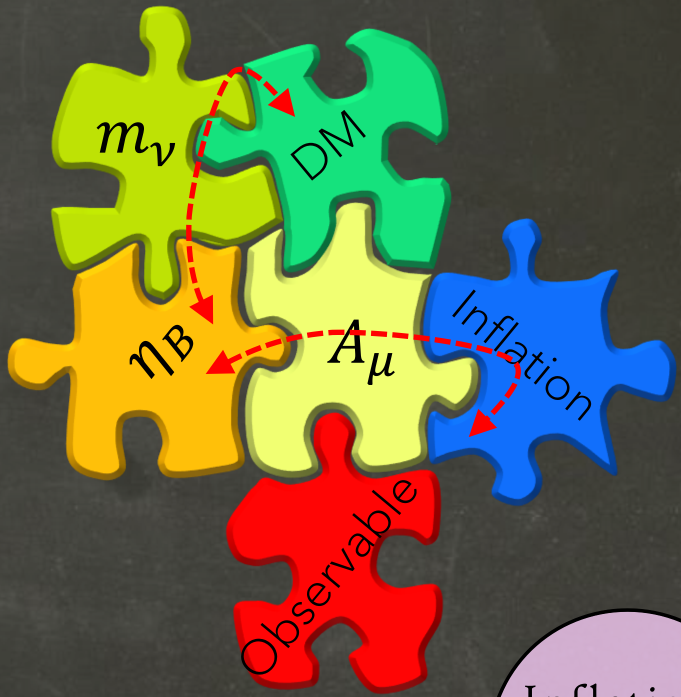

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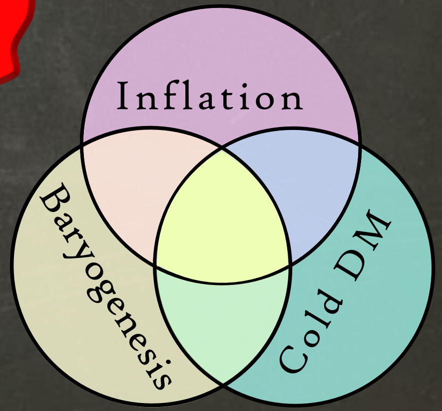

It comes with a cosmological smoking gun on Primordial GW.


Questions?!