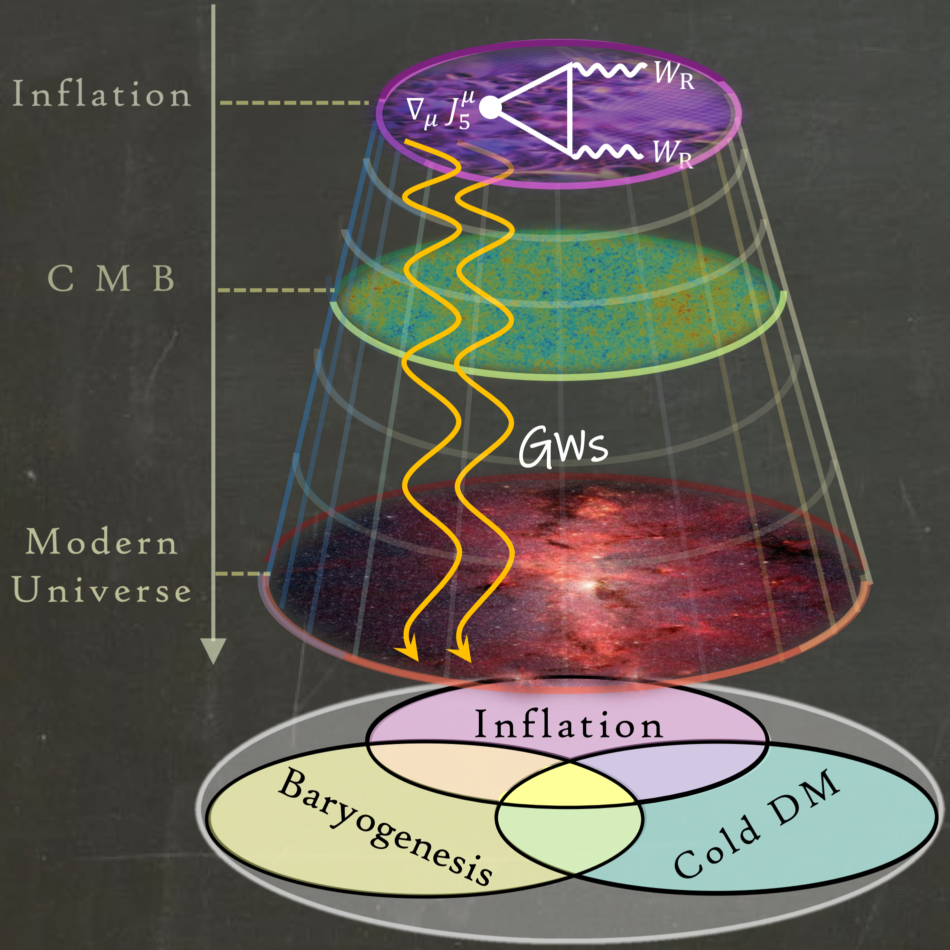


Cosmic Inflation, Origin of Matter & Gravitational Waves

Azadeh Malek-Nejad
CERN

- **Particle Physics of Inflation**
  Based on Axion-Inflation with Gauge Fields

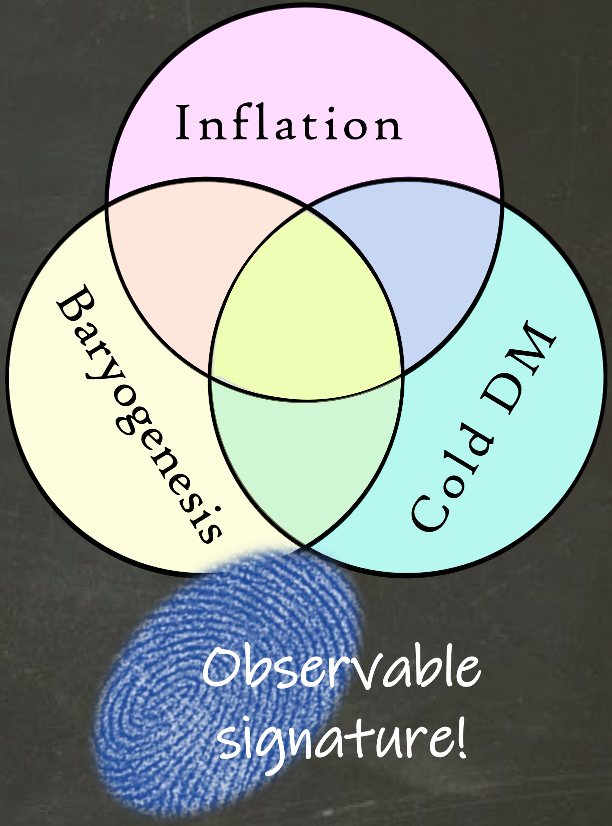
- **Fermions & QFT Anomalies**

$$\nabla_\mu J^\mu_5 = \frac{g^2}{16\pi^2} W\widetilde{W} + \frac{N_L - N_R}{24(16\pi^2)} R\tilde{R}$$

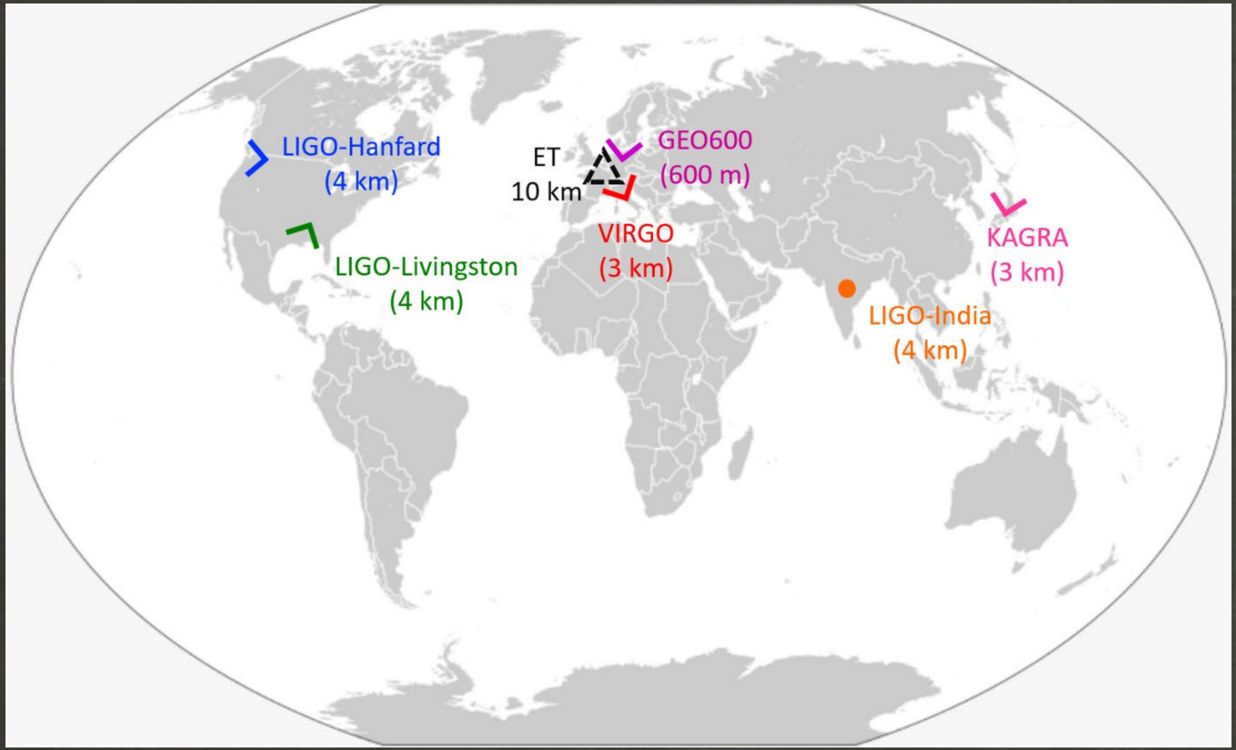
Adler–Bell–Jackiw anomaly

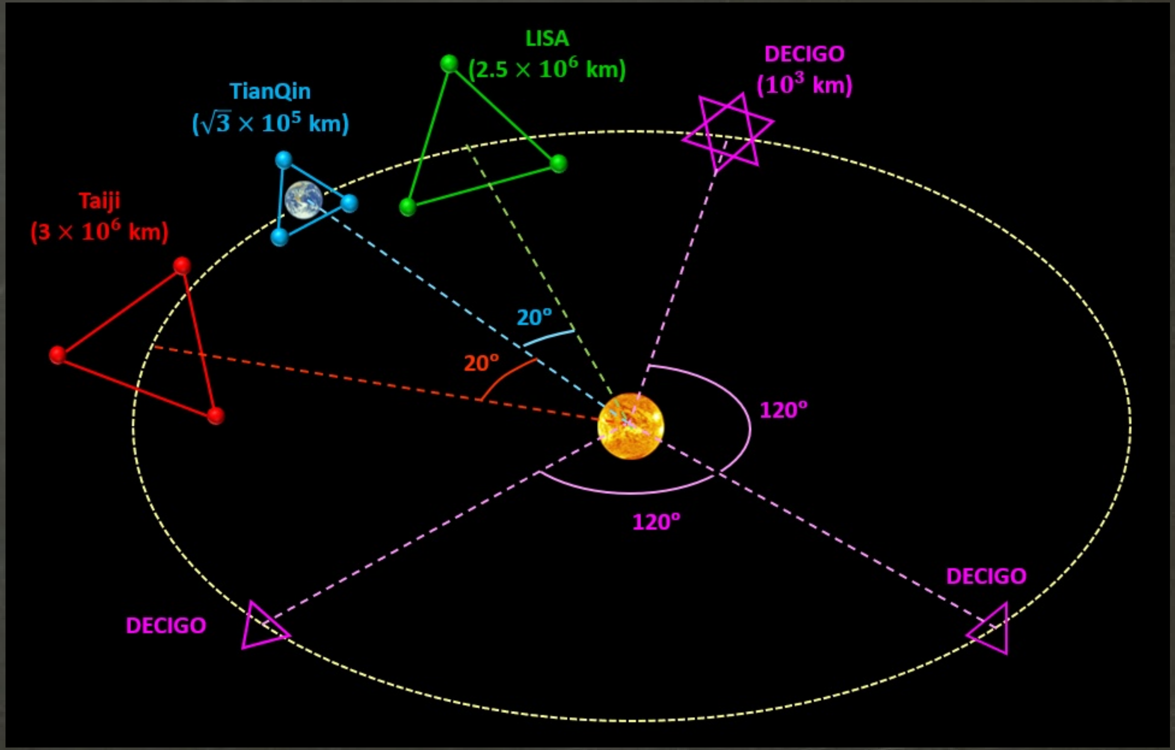
(Global) Gravitational anomaly

- **Gravitational Waves Signature**



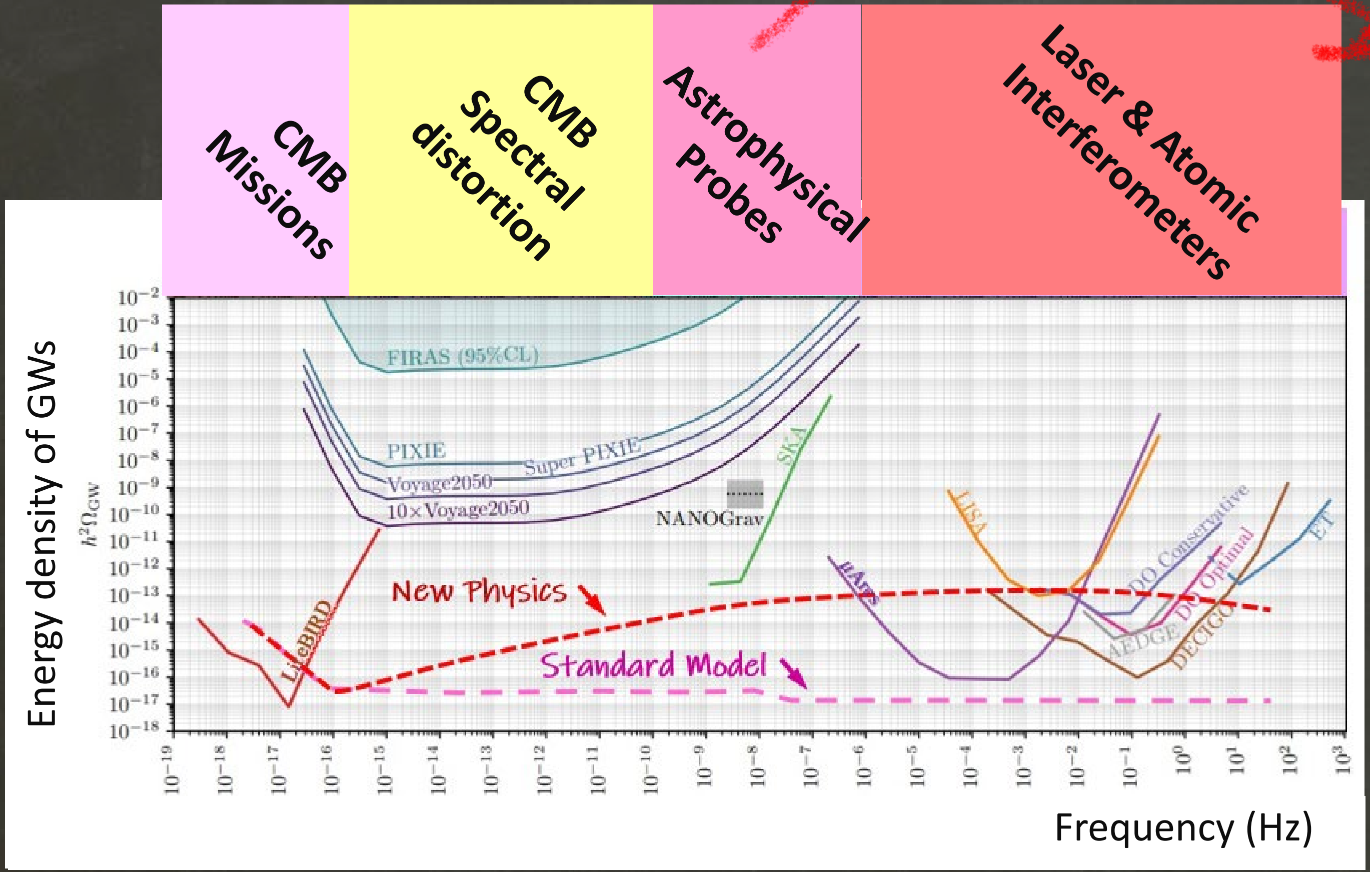
Networks of GWs Detectors



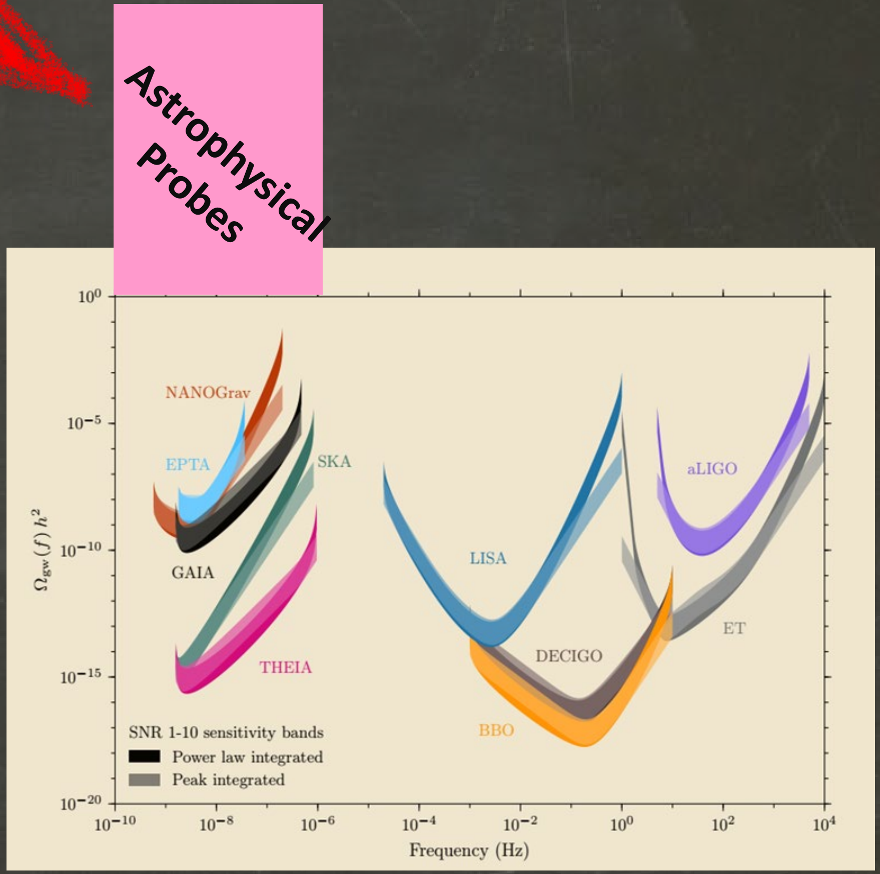


Network of laser interferometer detectors of GWs on Earth (left) & in the sky (right)

Sensitivity curves on energy density of GWs



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



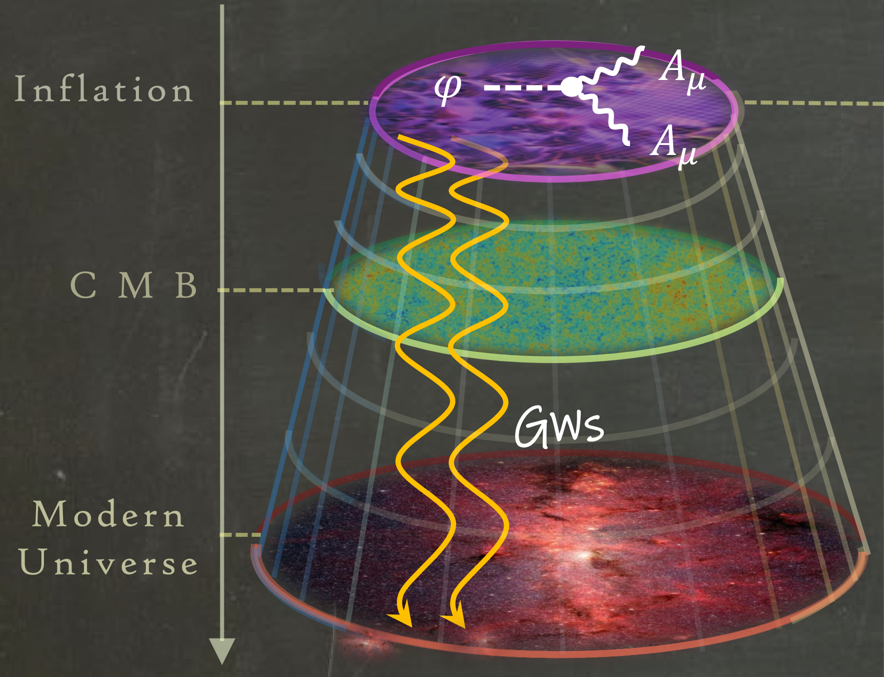
J. Garcia-Bellido, H. Murayama, and G. White 2021

A New Class of Inflation Models

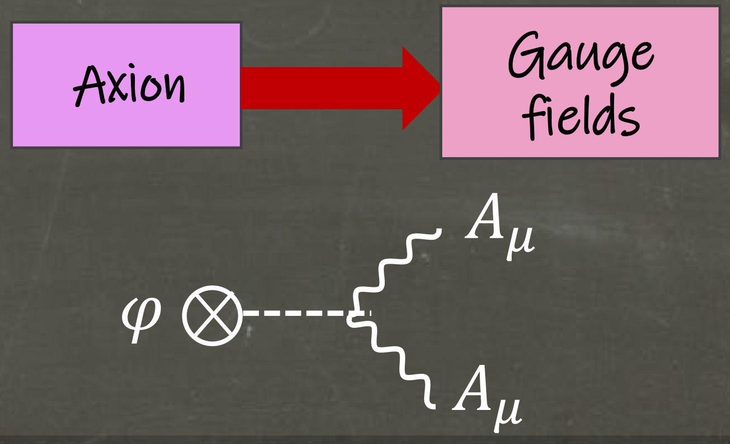
(closer to Particle Physics)

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

Axion-inflation and gauge fields (non-Abelian)



Particle Production
In Axion-Inflation



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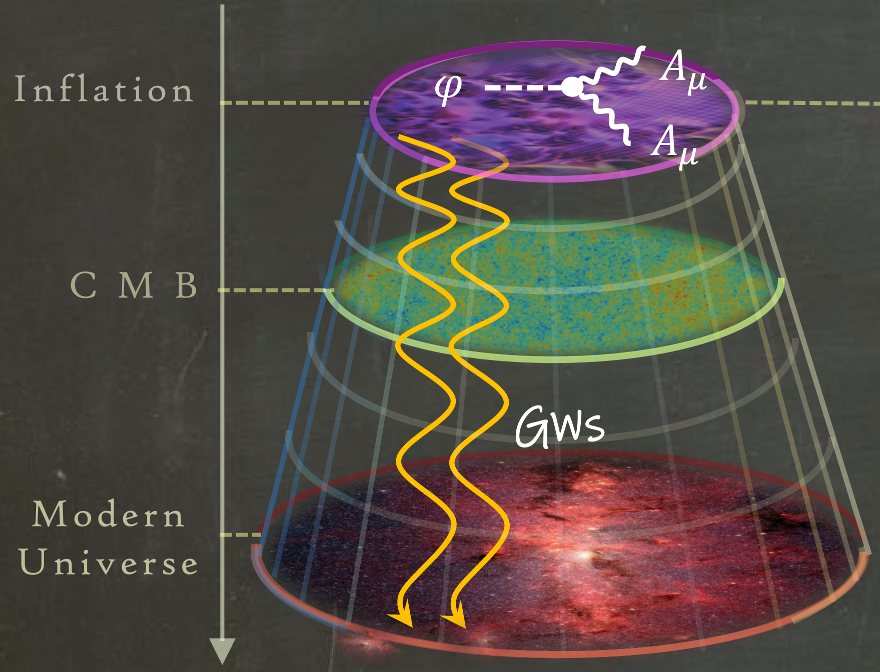

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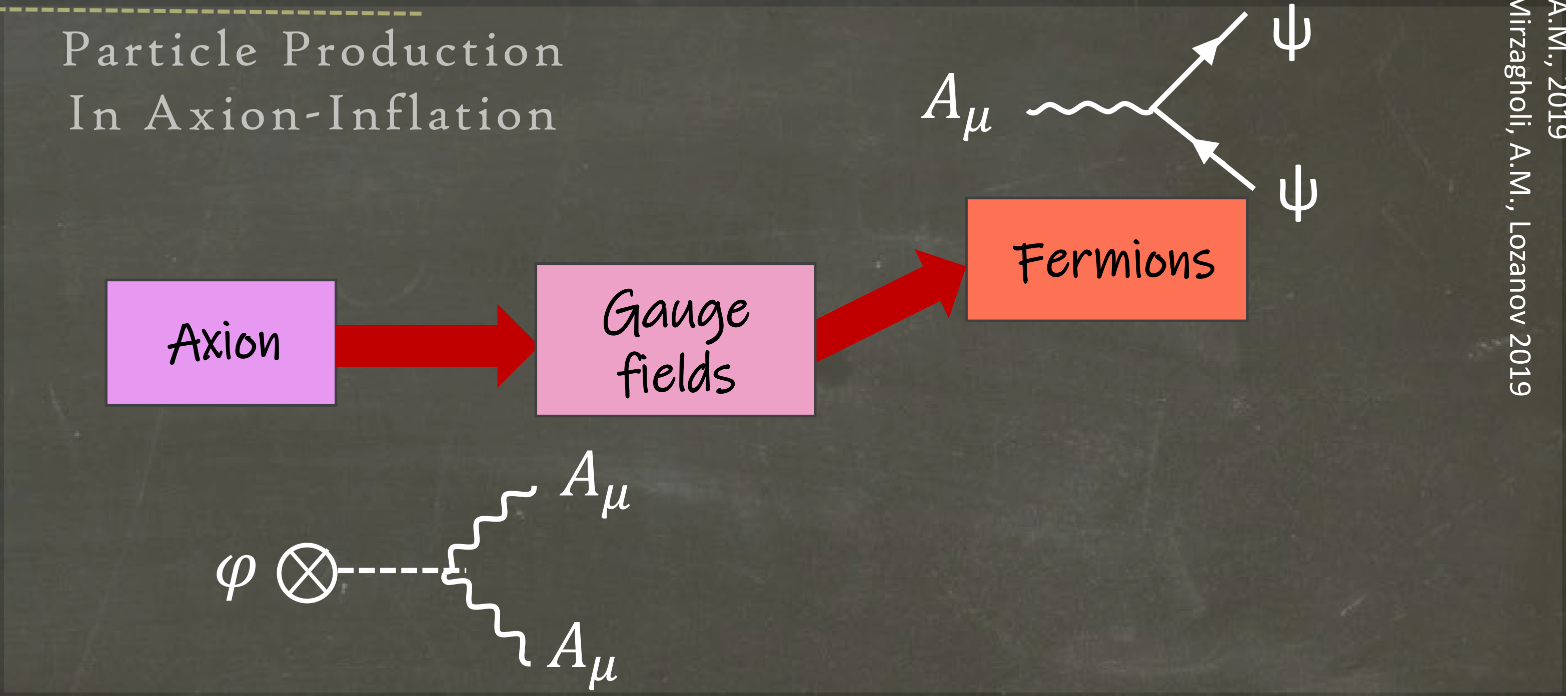

A.M., 2019
Mirzagholi, A.M., Lozanov 2019

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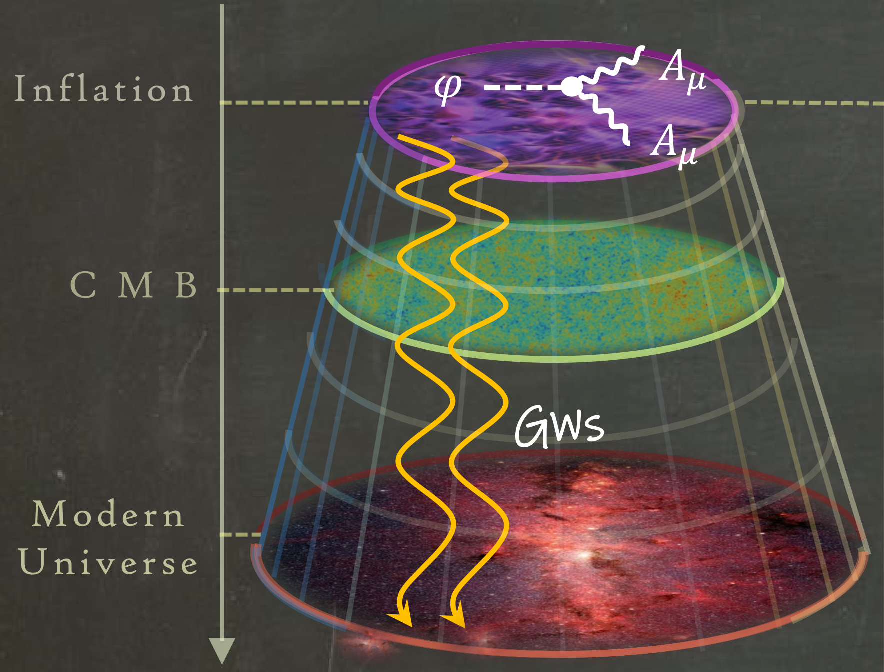

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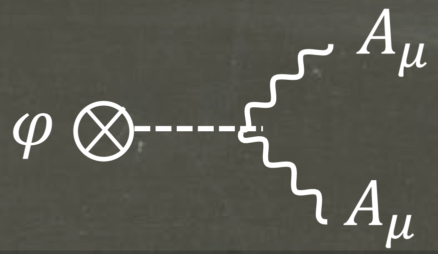

A new mechanism for Fermion Production in Inflation!

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

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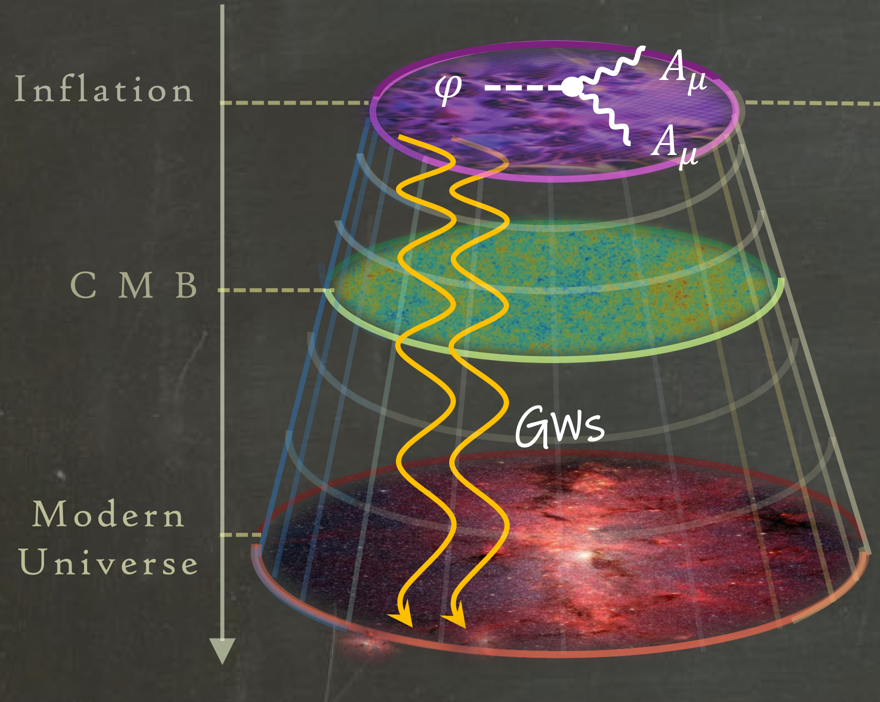

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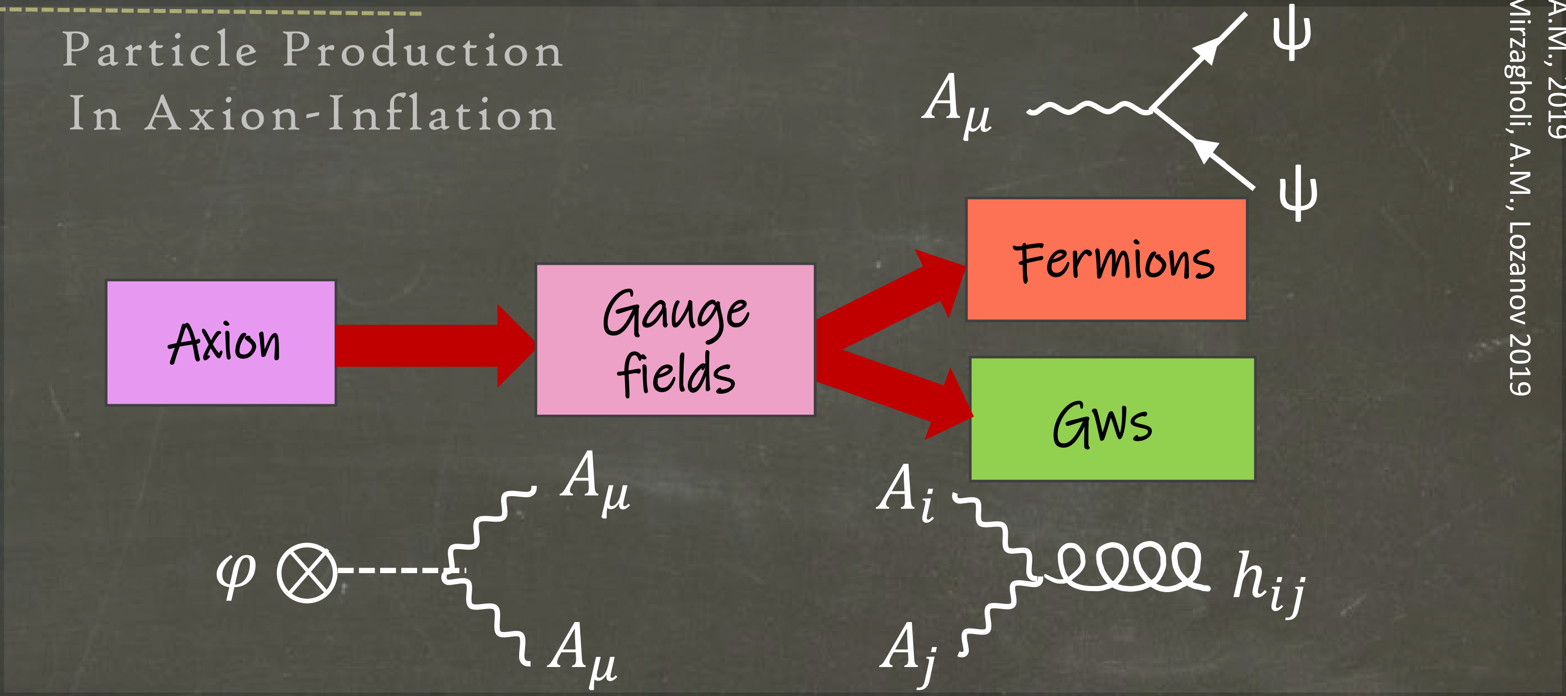

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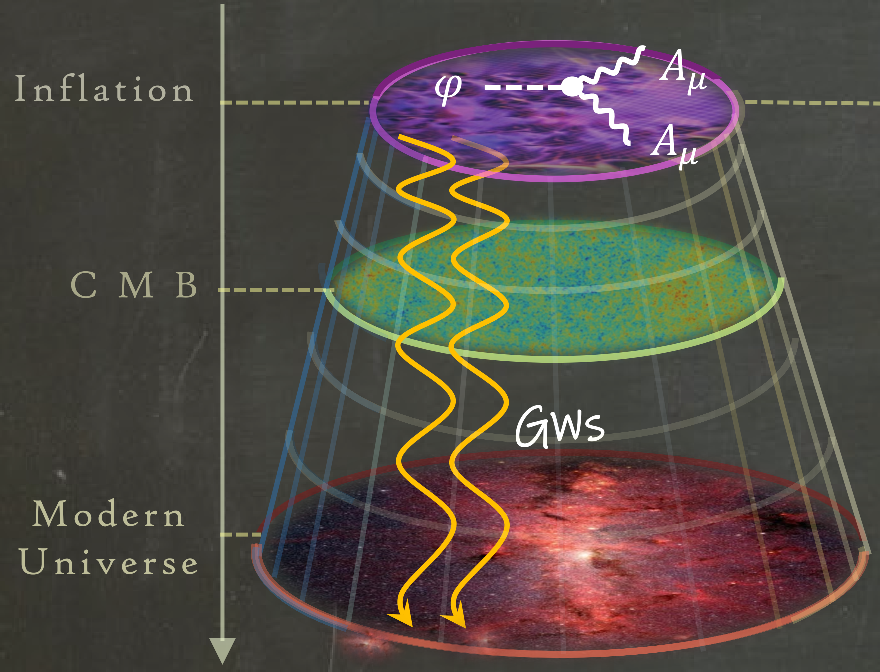

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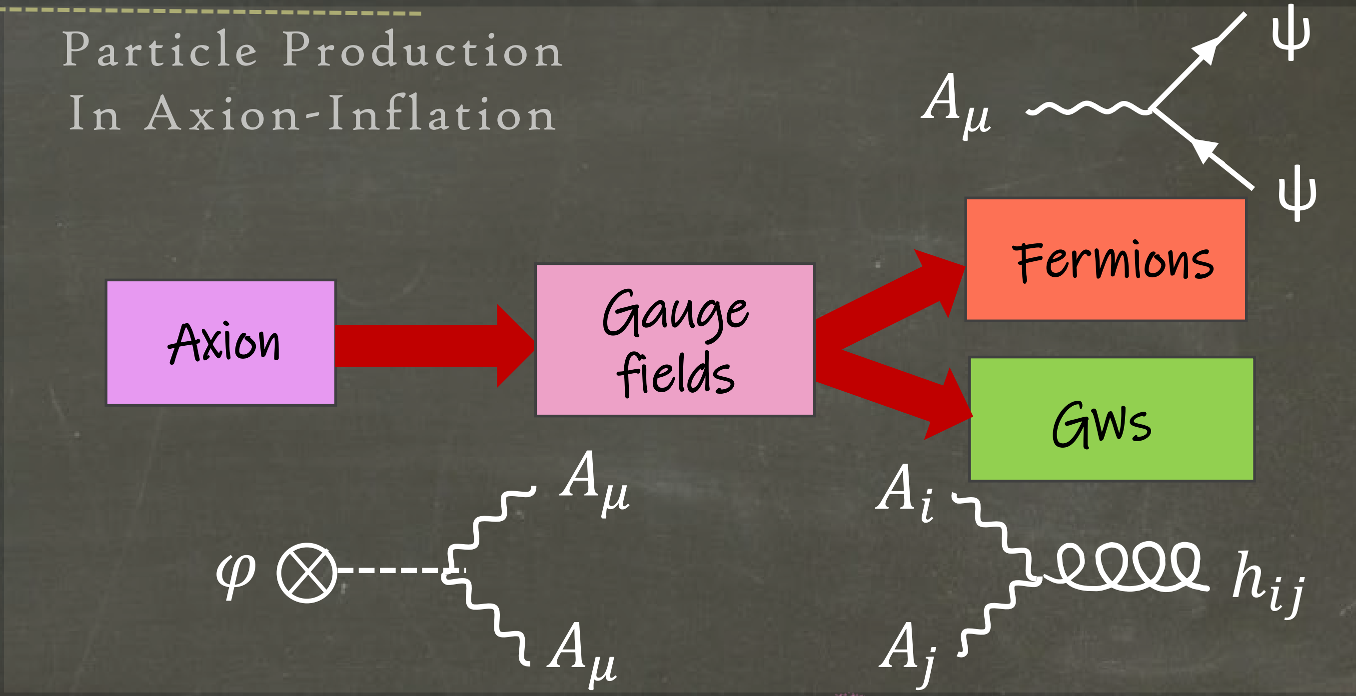

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Sourced GWs:
Chiral & non-Gaussian

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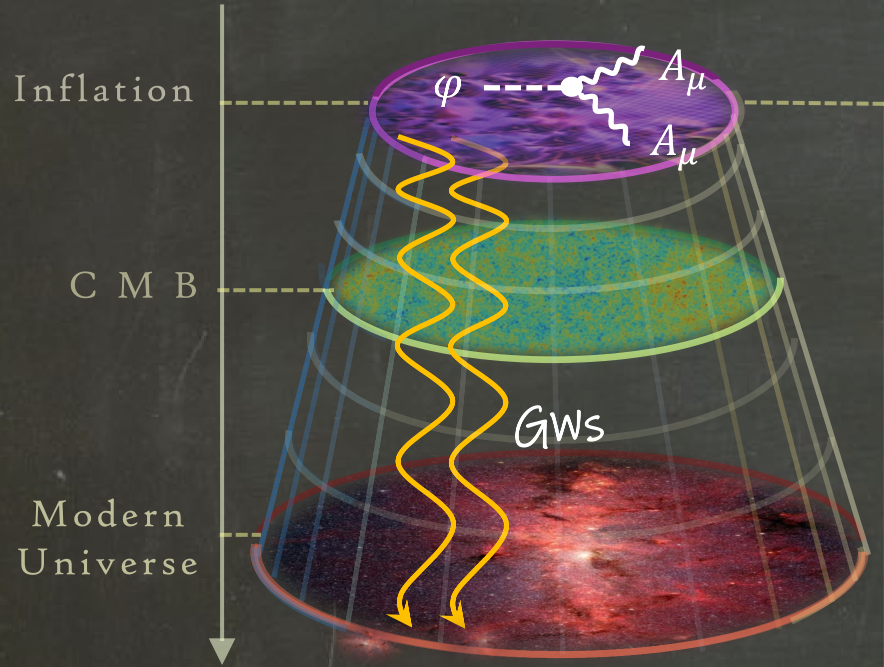

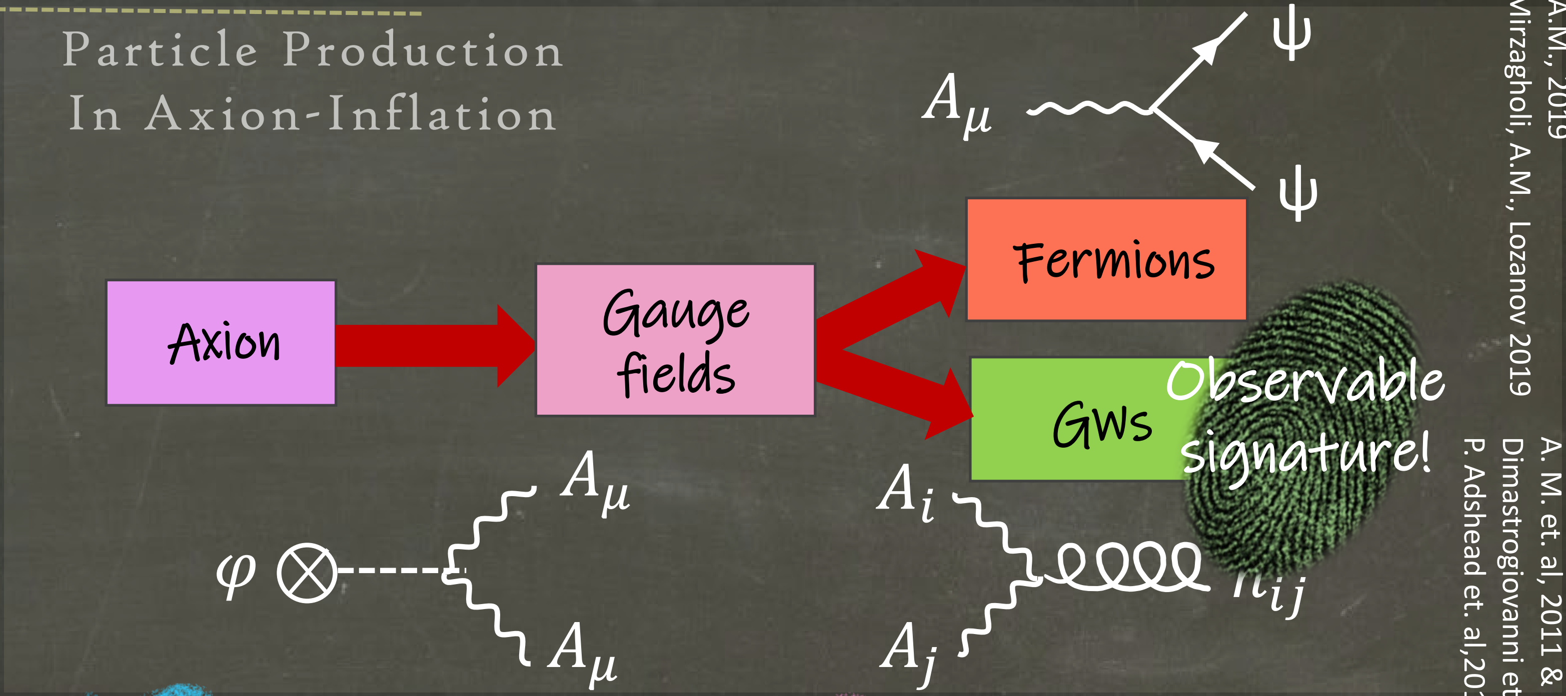

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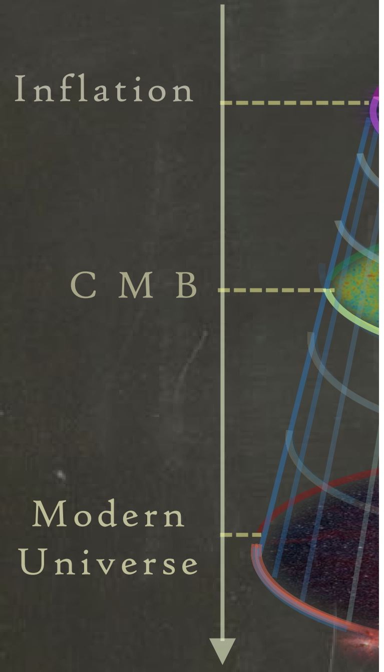
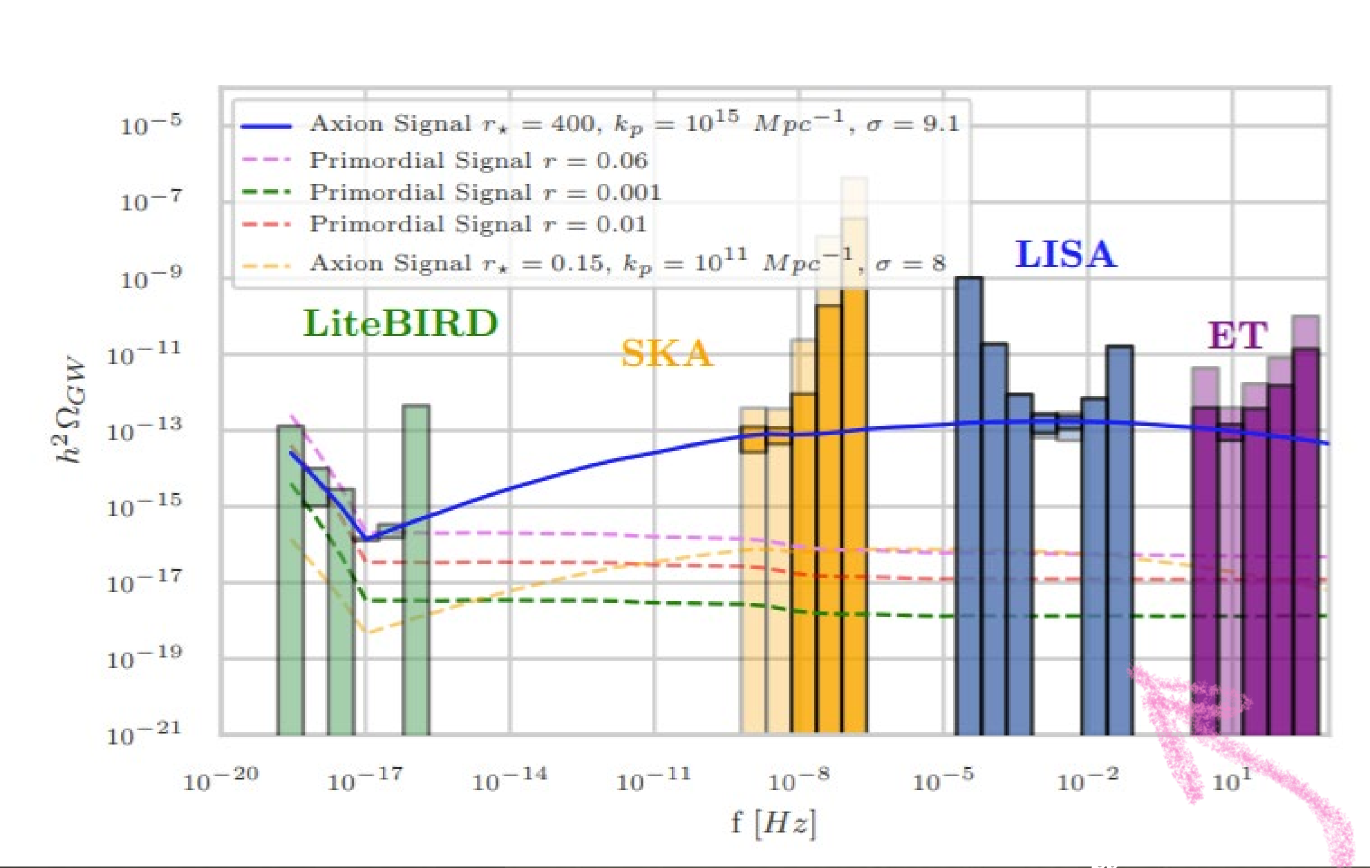
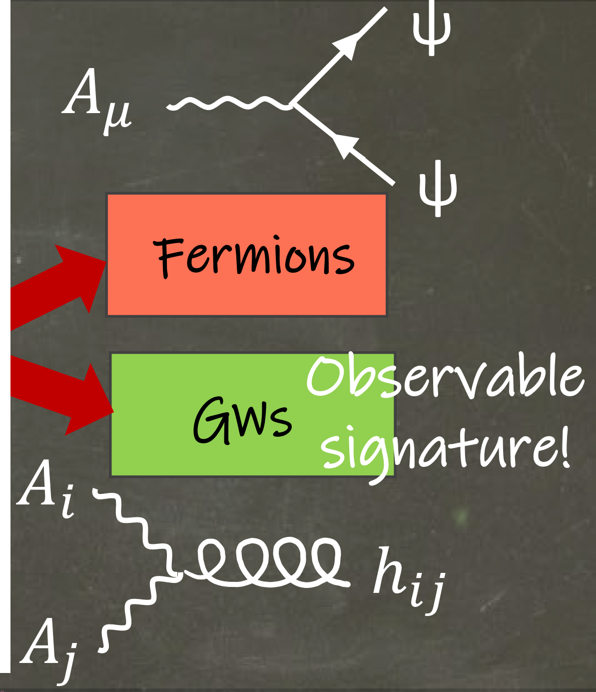




P. Campeti, E. Komatsu, D. Poletti, C. Baccigalupi 2020



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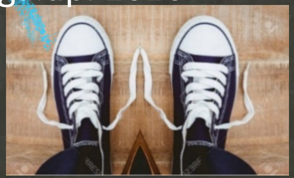

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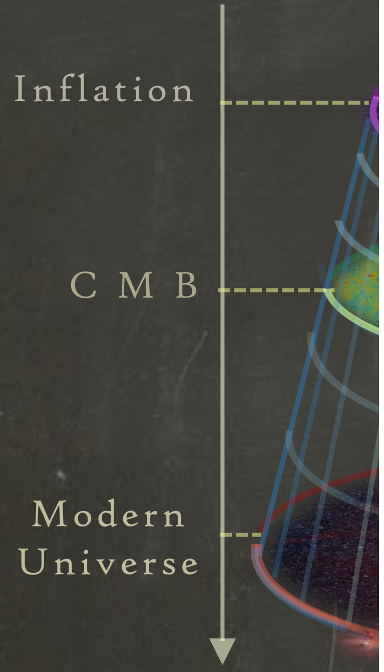

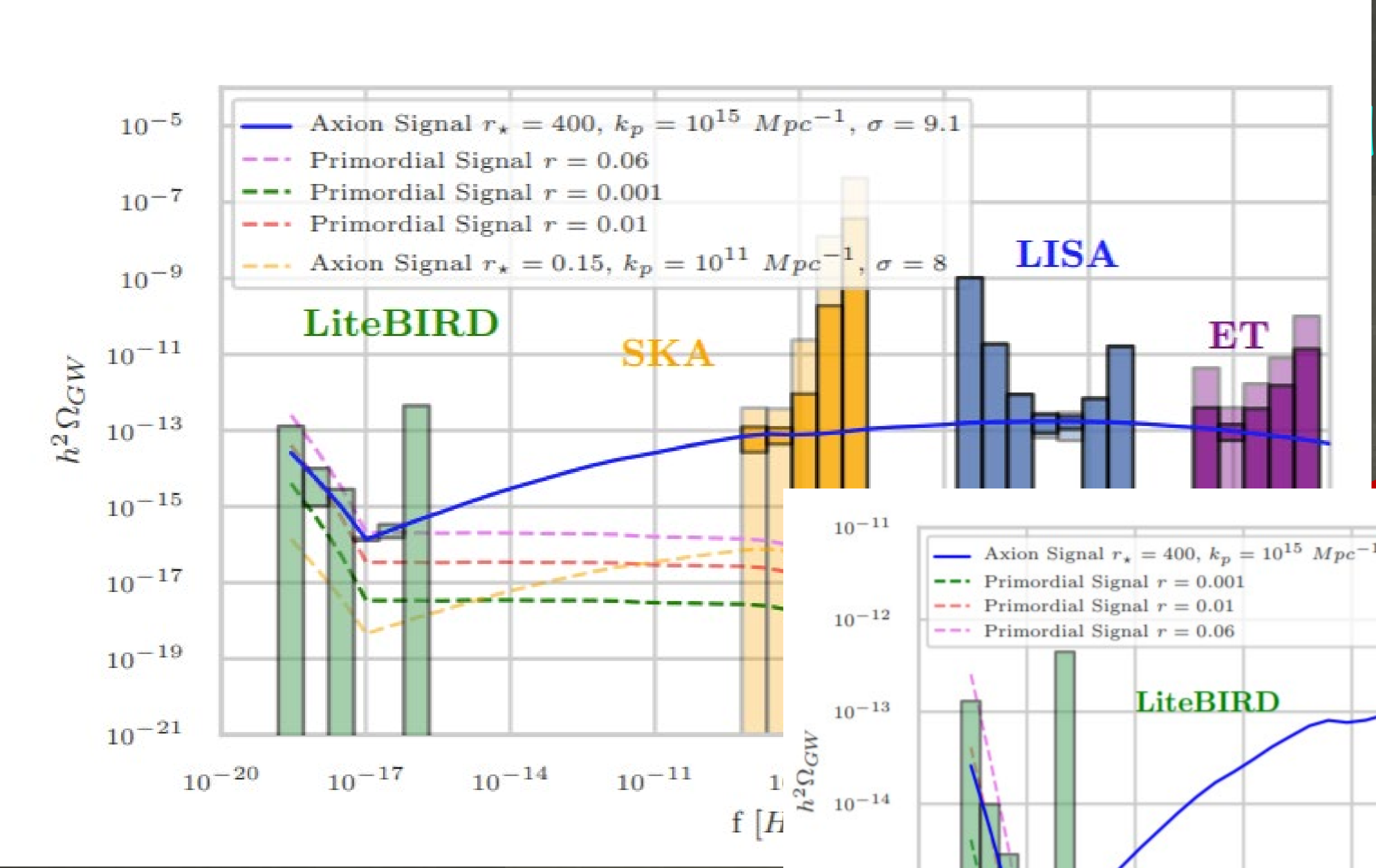

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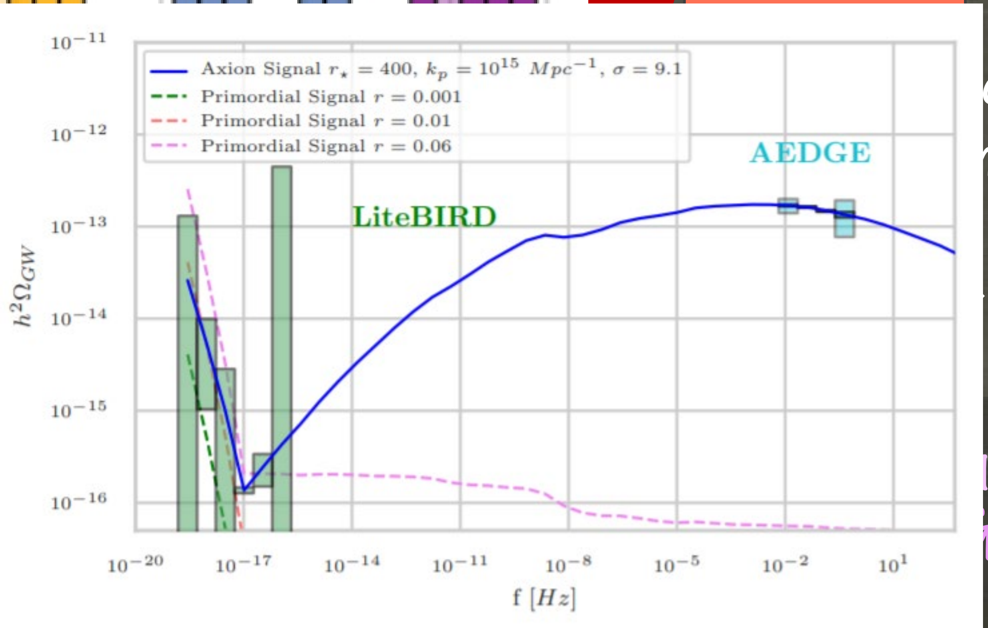
Fermions

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

ervable
nature!

ij



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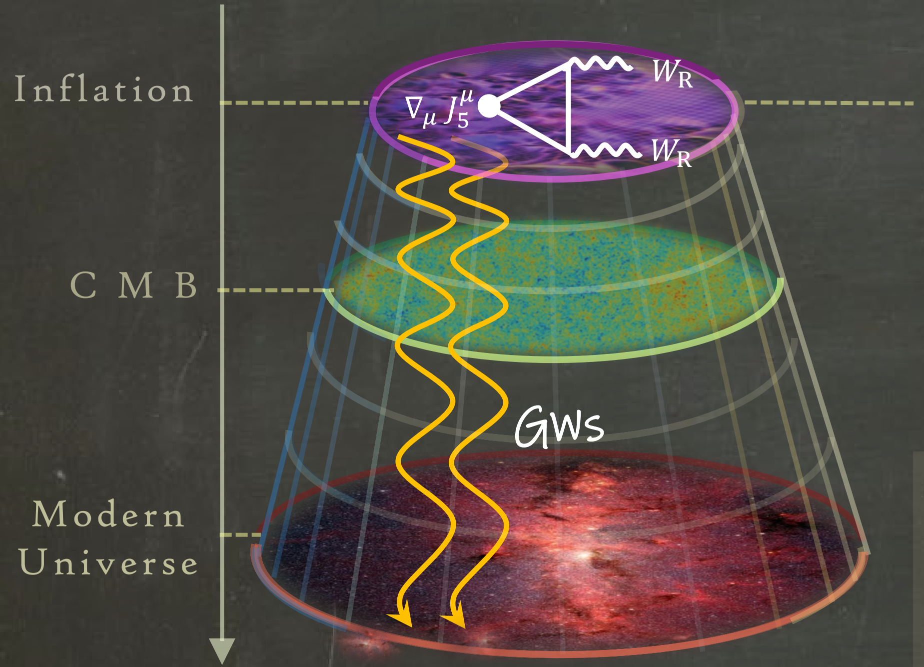


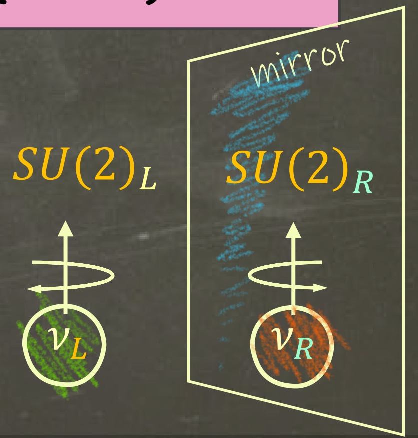
I) Axion-inflation and gauge fields (non-Abelian)

A New Class of Inflation Models

II) Embedding Axion-inflation in LR symmetric model

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

LRSM: the minimal beyond SM
with
SU(2)_R Gauge Symmetry
& Right-handed Neutrinos



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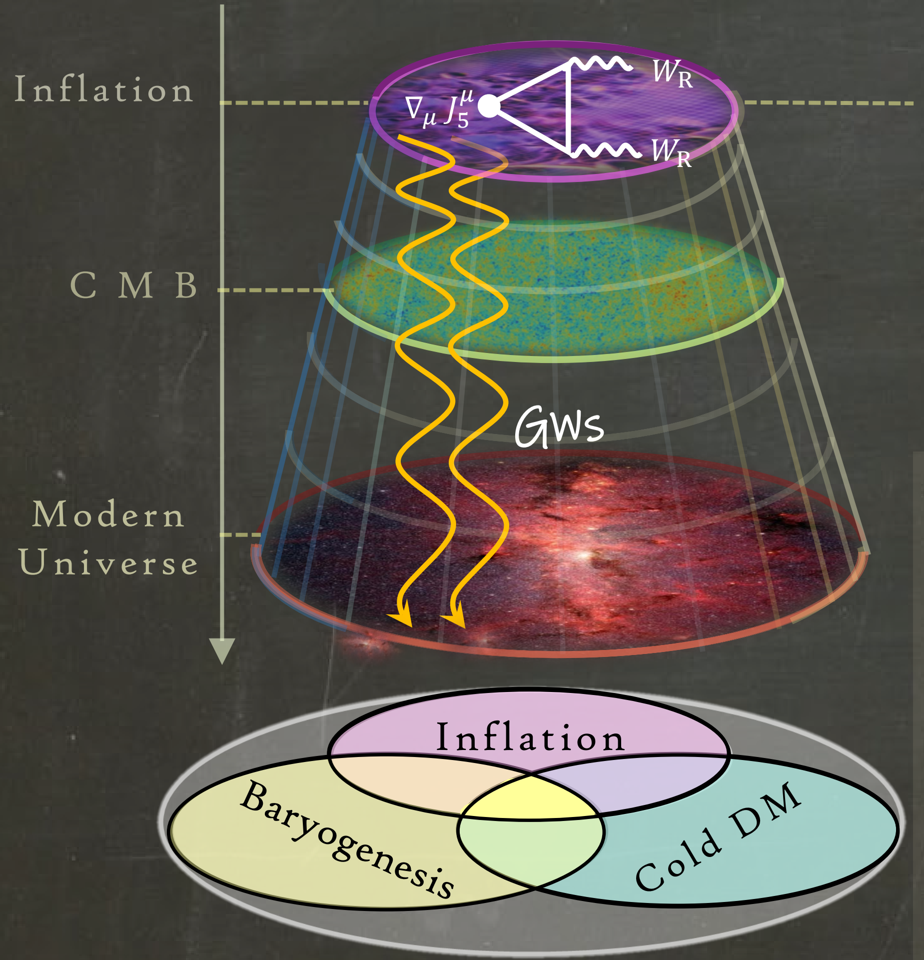

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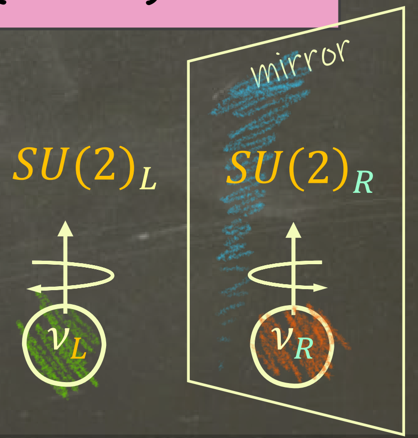
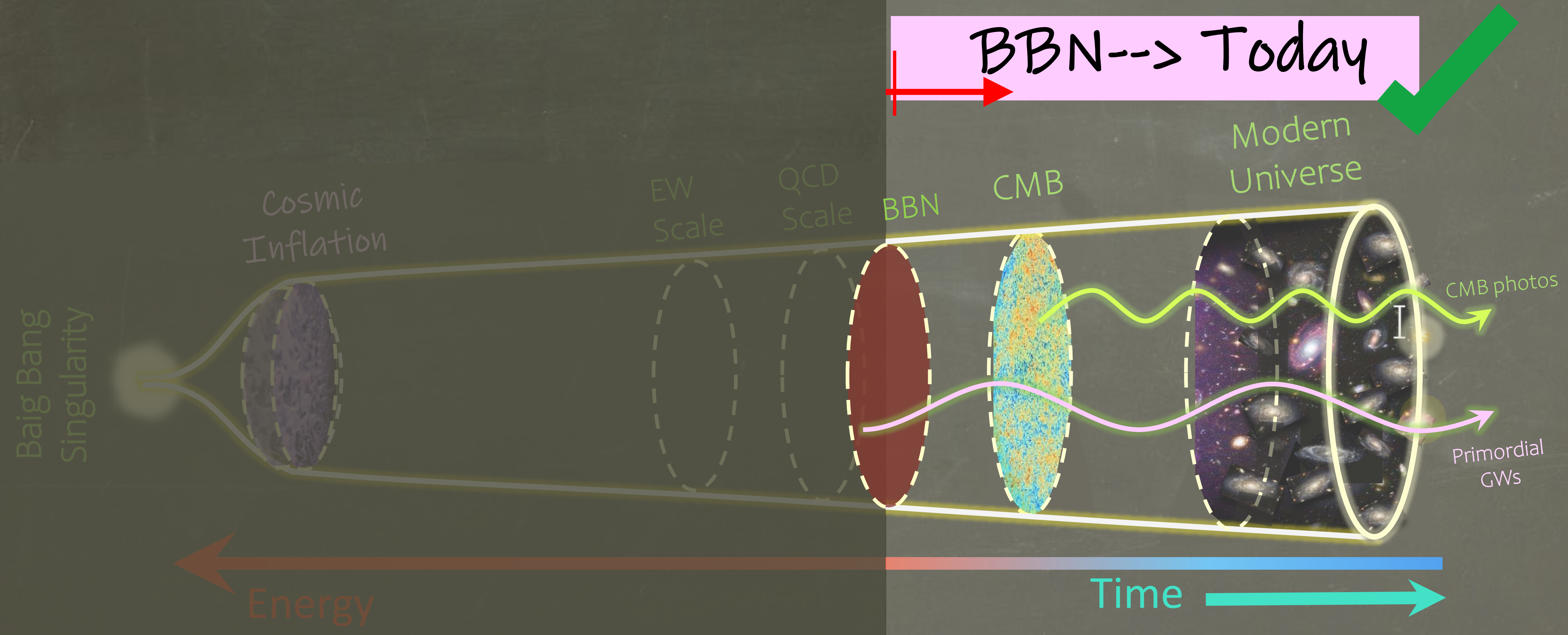


A.M. JHEP 2021, 113 (2021)
A. M. Phys. Rev. D 104, 083518 (2021)

Early Universe Physics

Modern cosmology remarkably successful from **BBN until today!**
But the physics before BBN is still much less certain!



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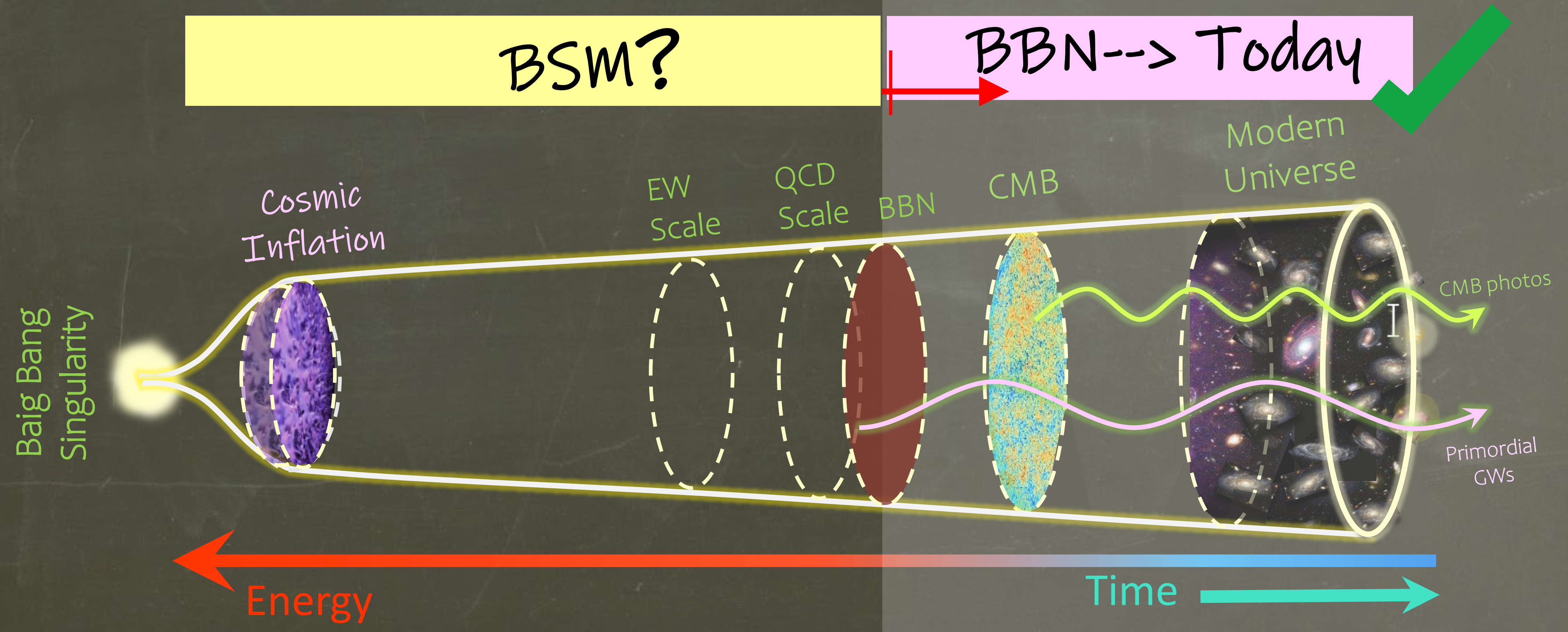
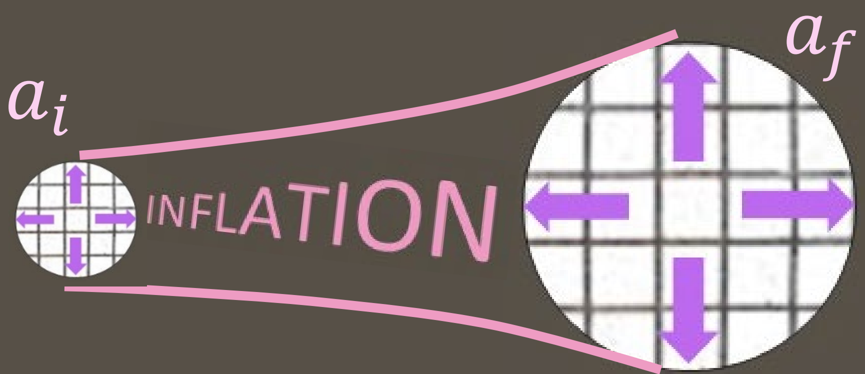


Cosmic Inflation

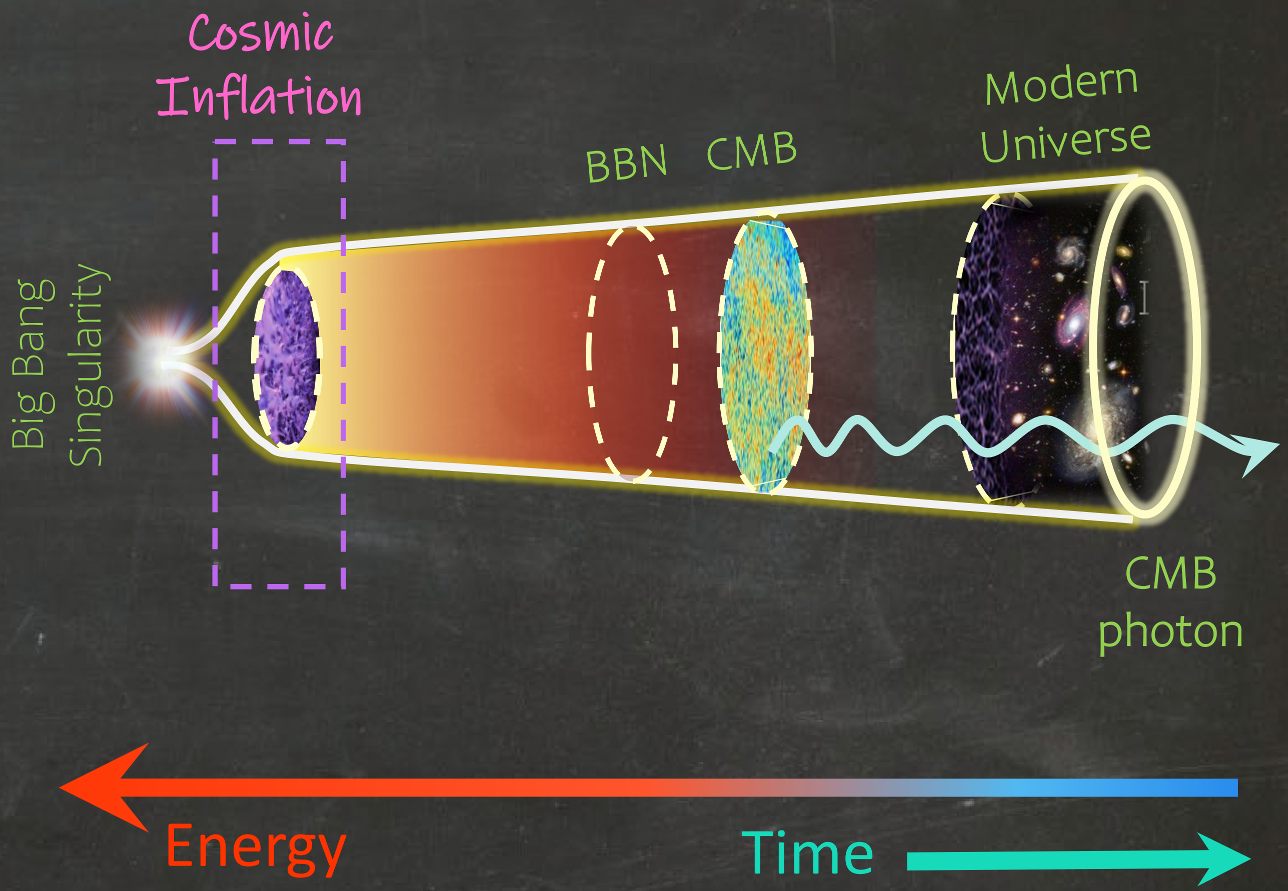
Guth Phys. Rev. D23 (1981)

Linde Phys. Lett. B 108 (1982)

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



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



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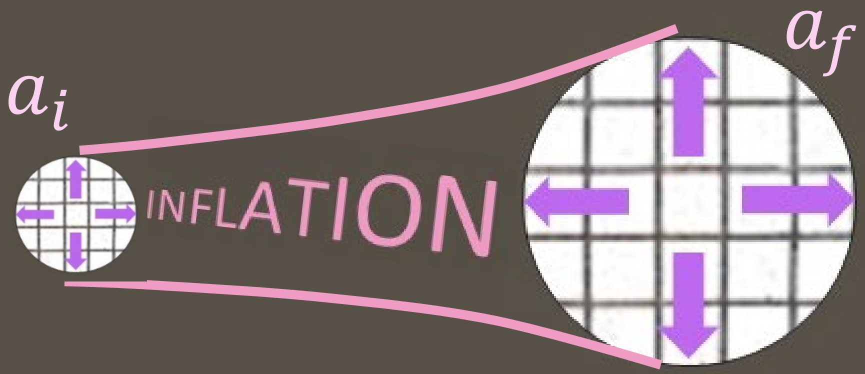

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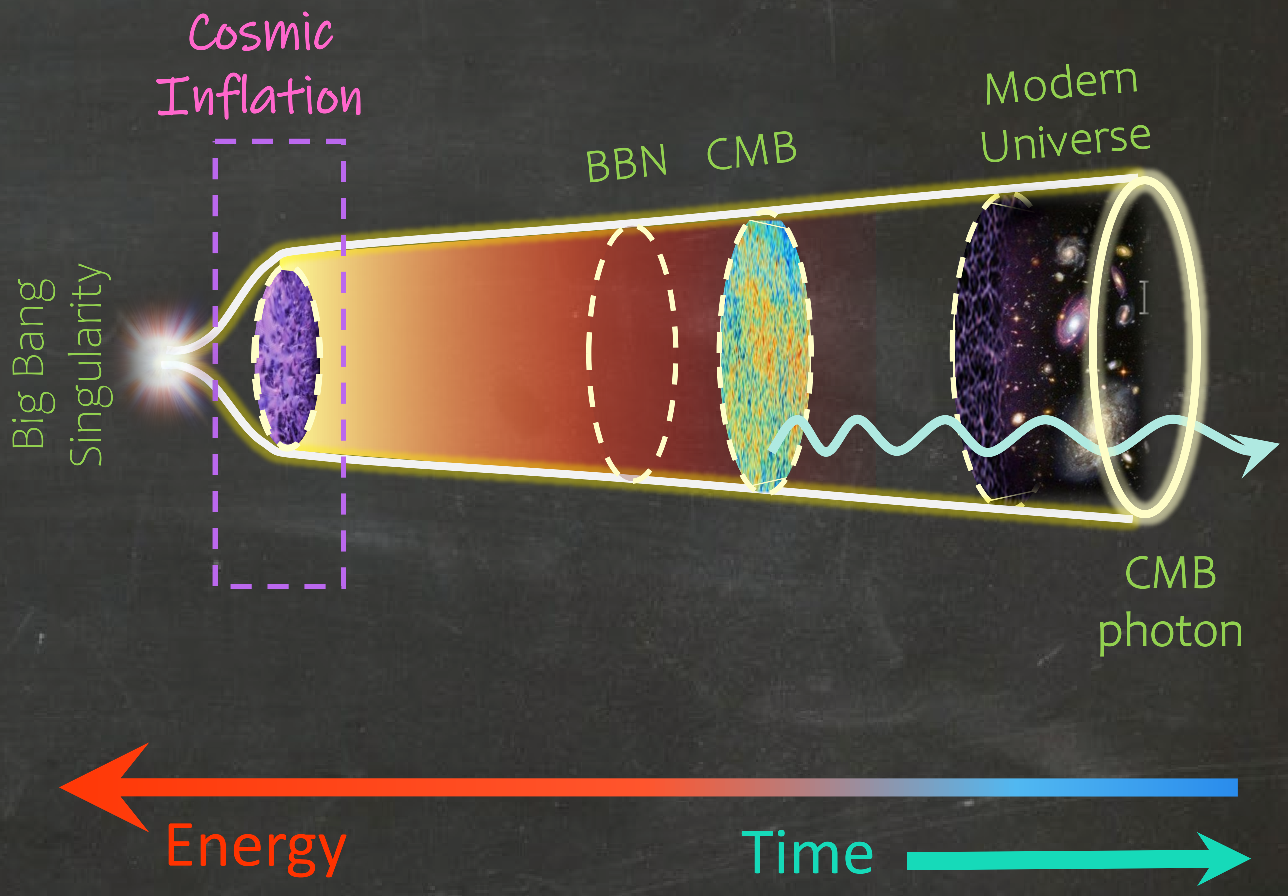
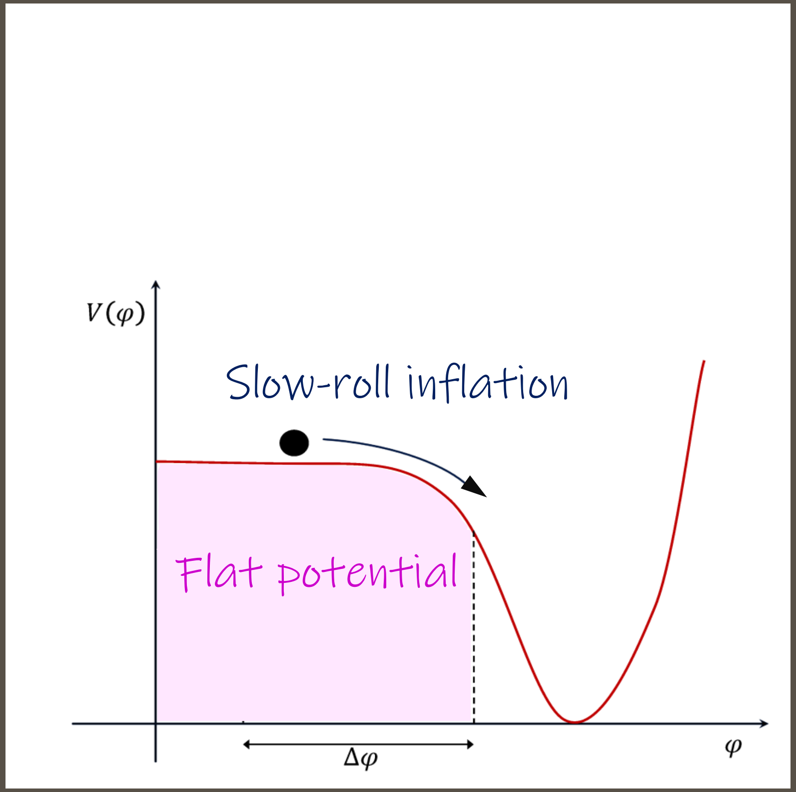
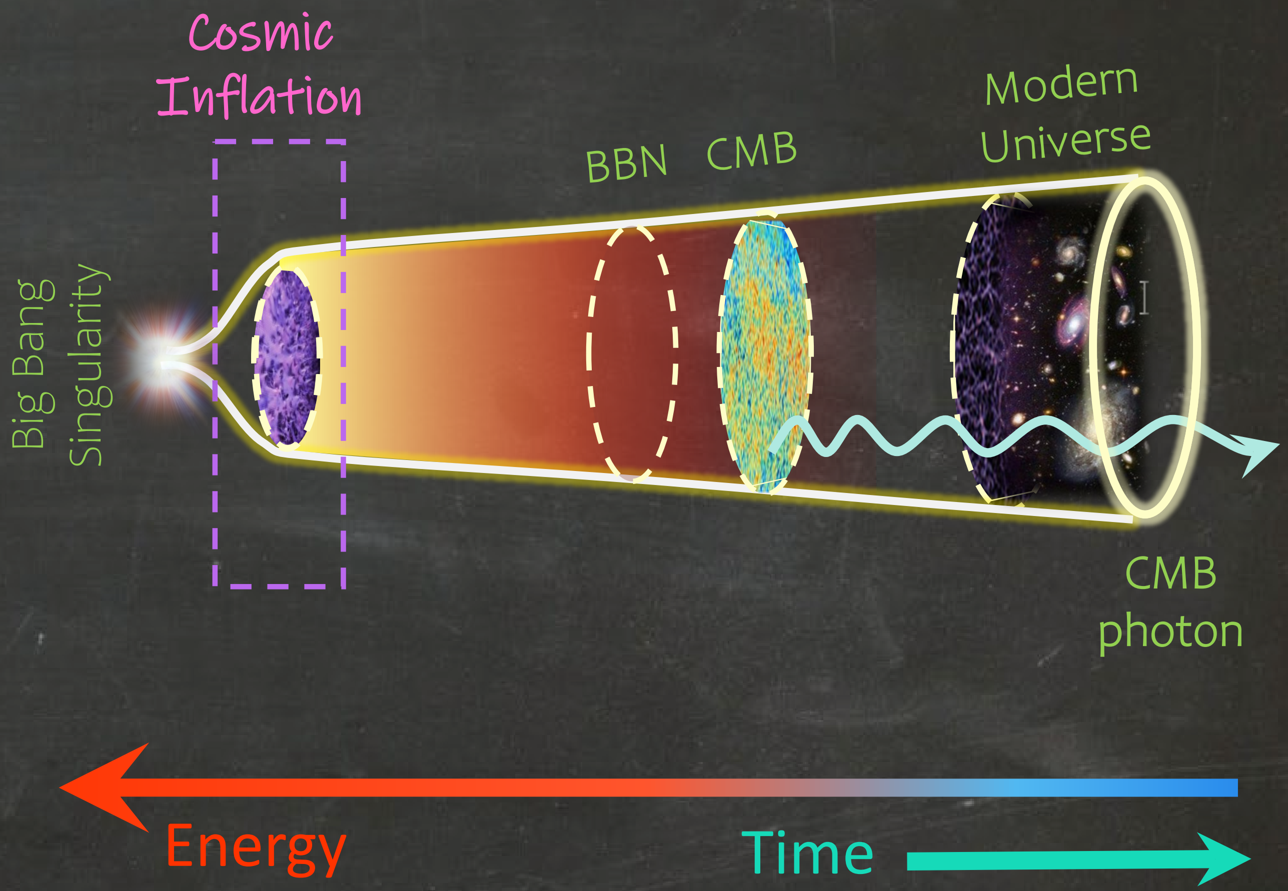


What caused inflation?

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





Puzzles of SM & Cosmology

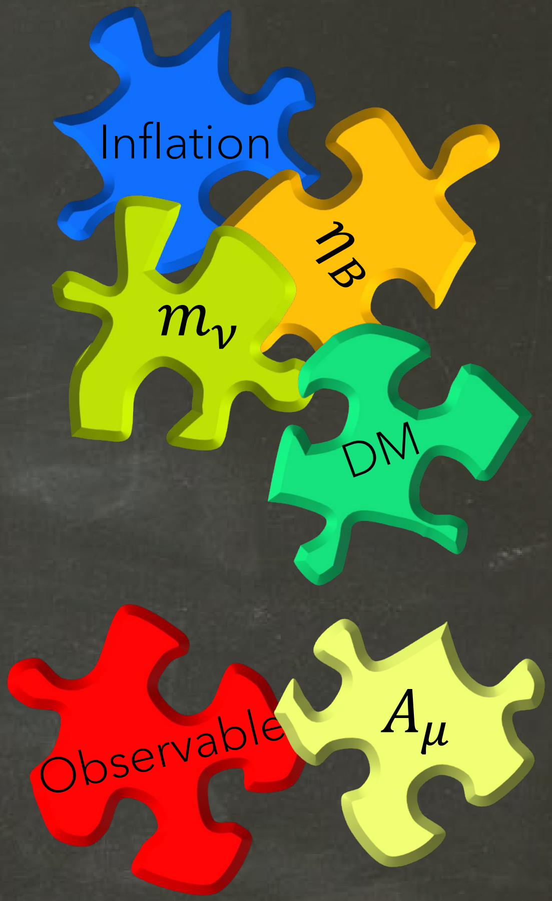
I) Particle physics of Inflation

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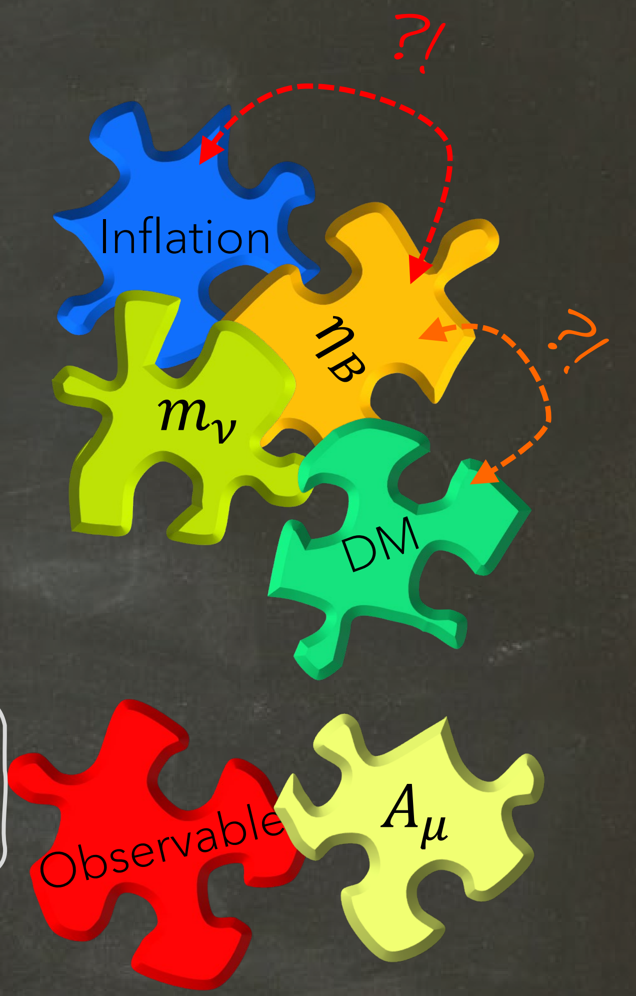
Puzzles of Standard Model of Particle Physics (SM) & Cosmology which need **Physics Beyond SM**



- 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

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

Curvature Power Spectrum in Inflation

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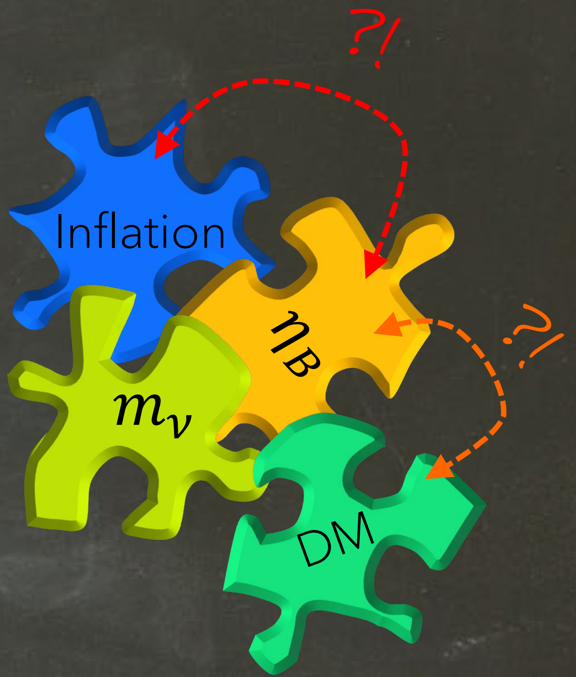

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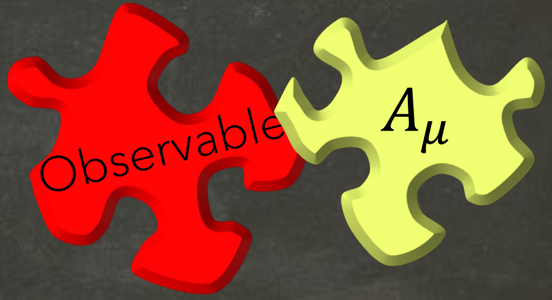
1. Ad hoc parity violation
2. Accidental B-L global symmetry
3. Vacuum Stability problem

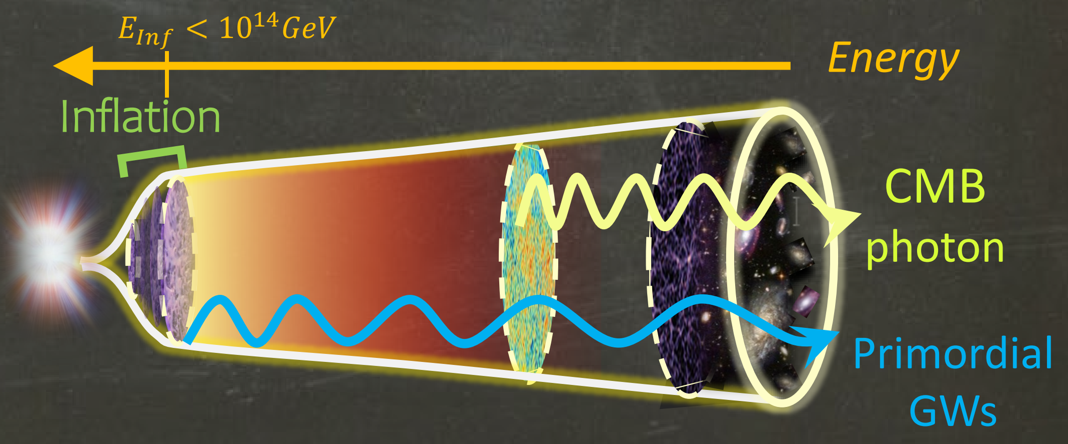
SM as a particle physics model
also faces some **conceptual issues**



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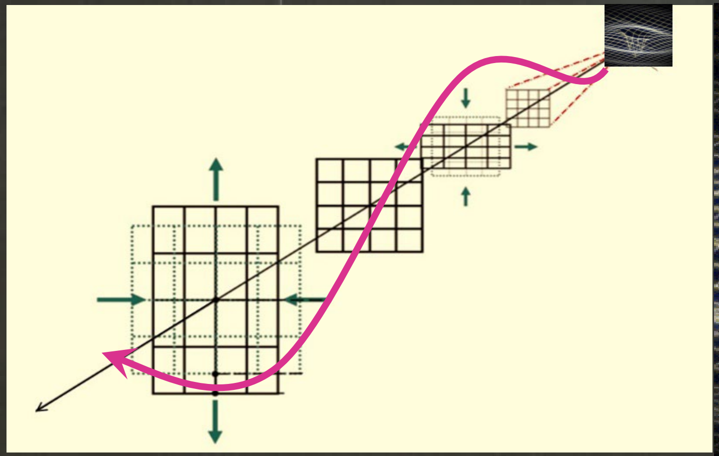
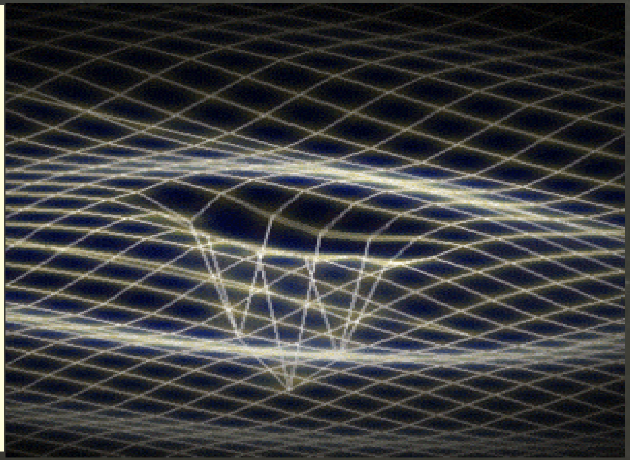
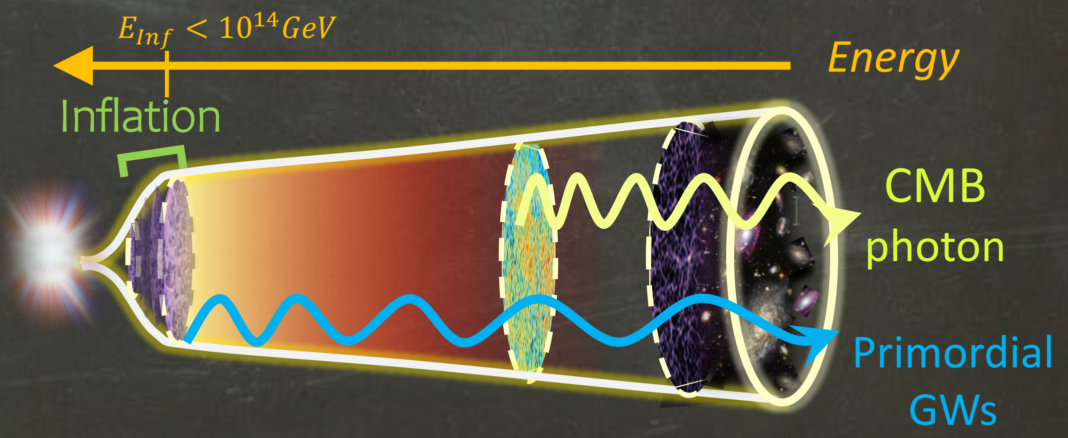
  Vacuum fluctuations: unpolarized, red-tilted, and nearly Gaussian.







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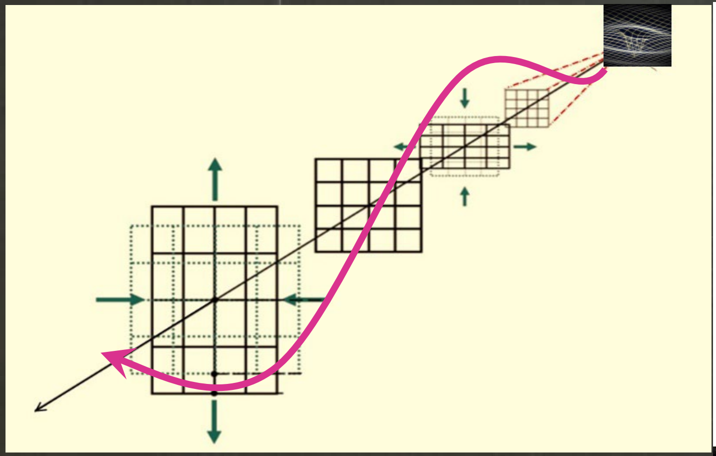

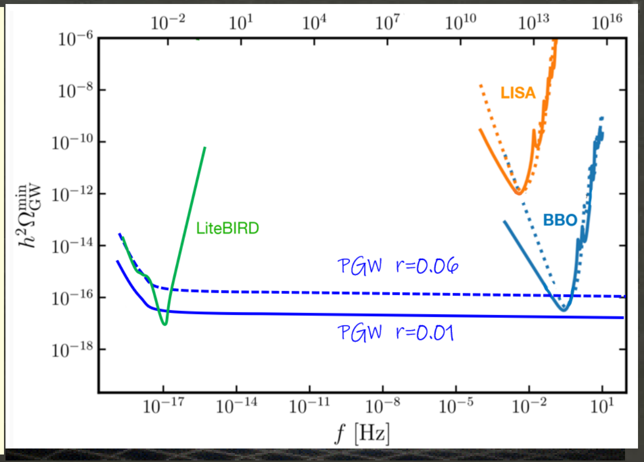

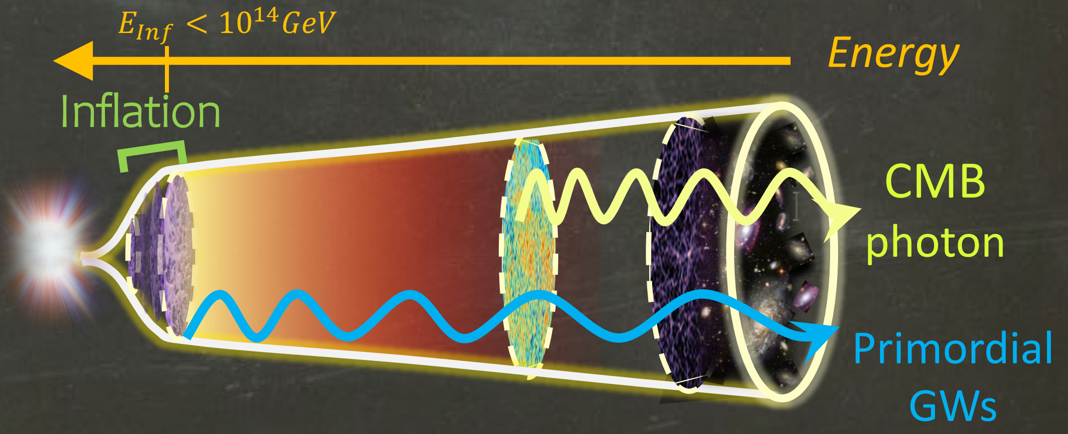

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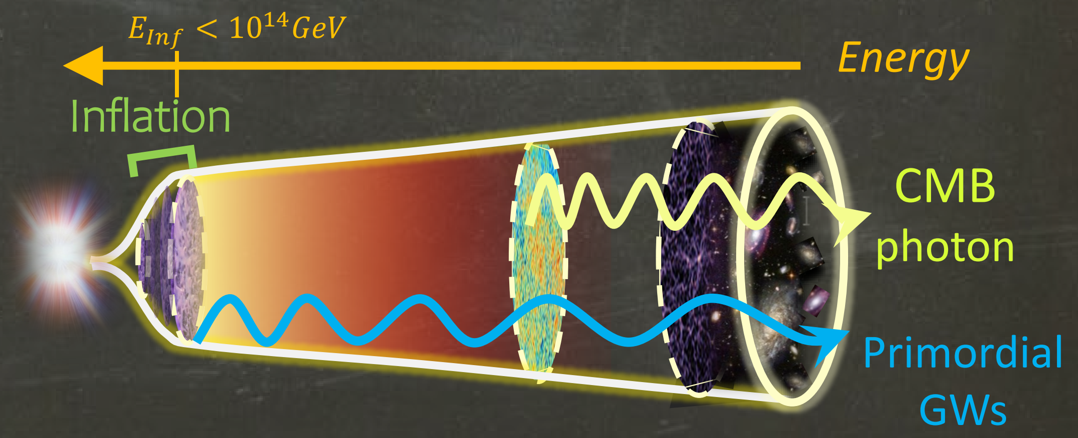
What about Gauge Fields?!

- Inflation happened at highest energy scales observable!
- They are building blocks of particle physics, SM & beyond.



- What do they do in inflation?!

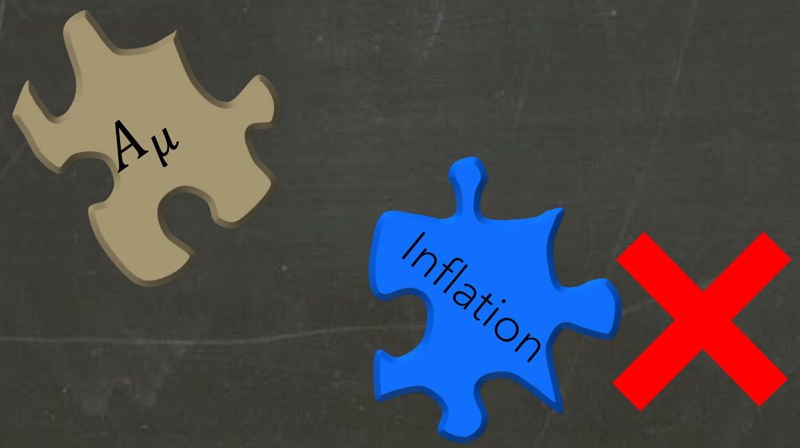
I) Axion-inflation & gauge fields

(non-Abelian)

Challenges:

Gauge fields given by Yang-Mills

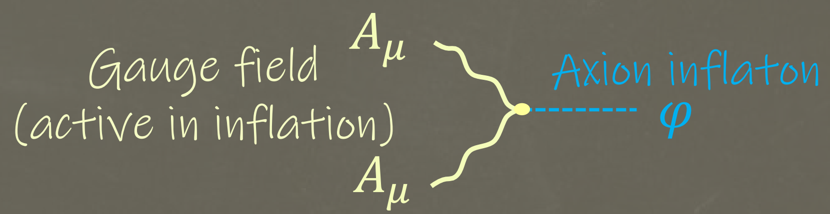
dilutes like radiation $A_\mu \sim 1/a$

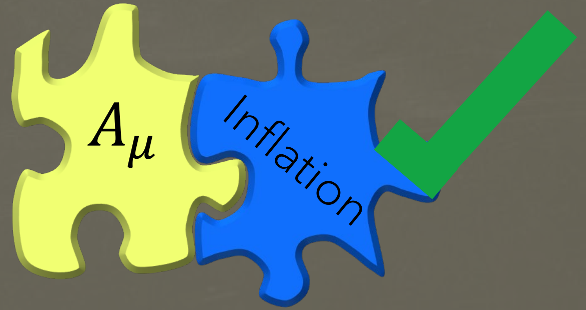


Gauge fields coupled to inflaton are generated in inflation.

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

(Axion fields are naturally coupled to gauge fields.)





Challenges:

Gauge fields given by Yang-Mills

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Spatial isotropy & homogeneity

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

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

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

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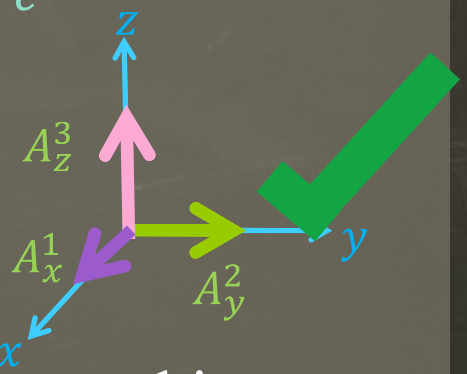
A.M. & Sheikh-Jabbari, 2011

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

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

Spatially isotropic

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



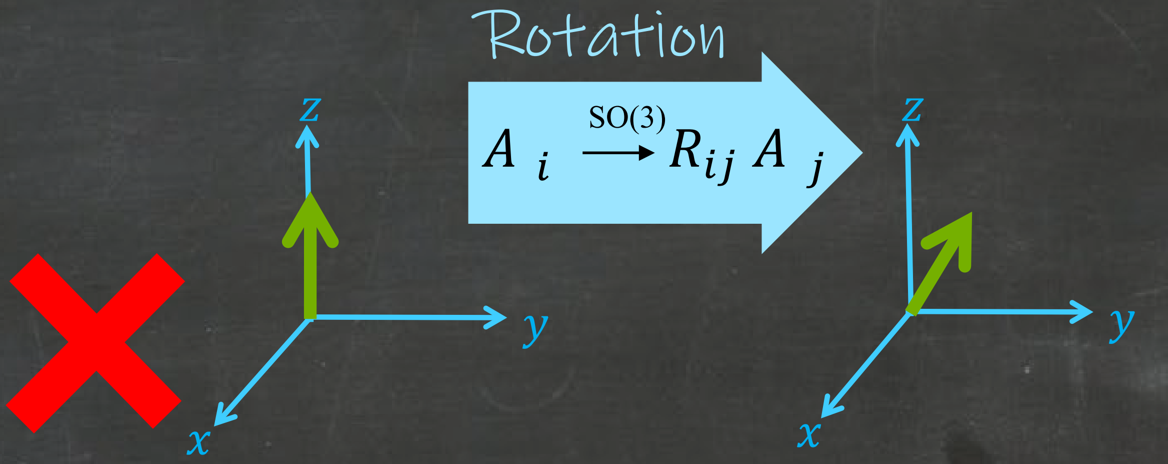
so(3) & su(2) are isomorphic

How SU(2) restores isotropy?

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

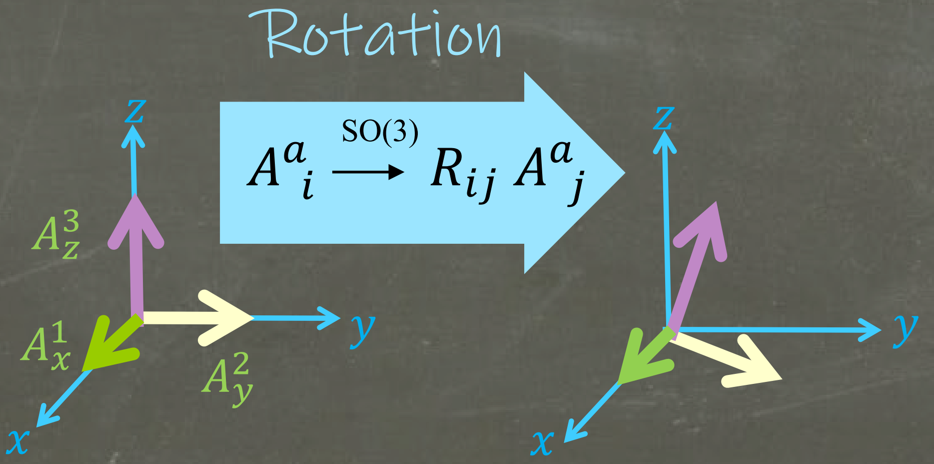
U(1) vacuum A_μ

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



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

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



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

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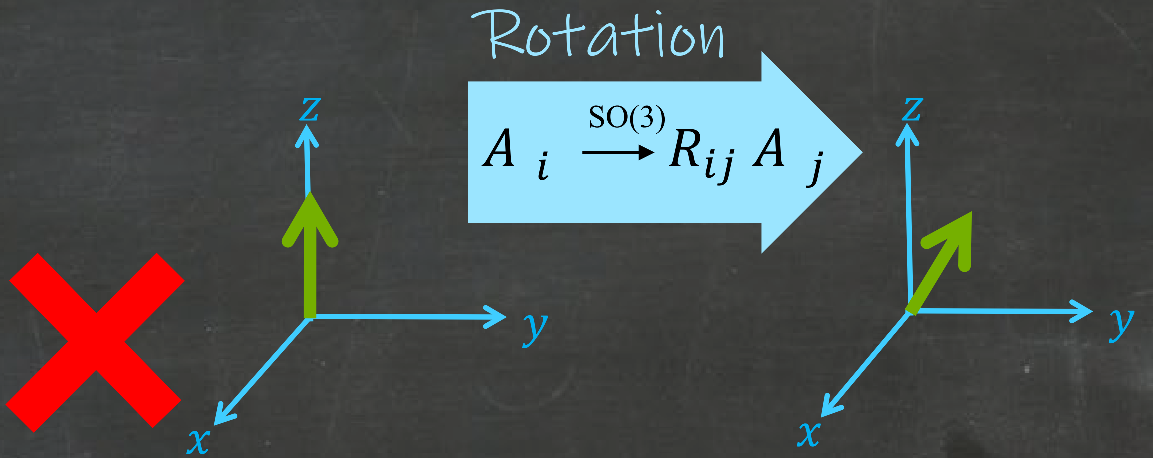

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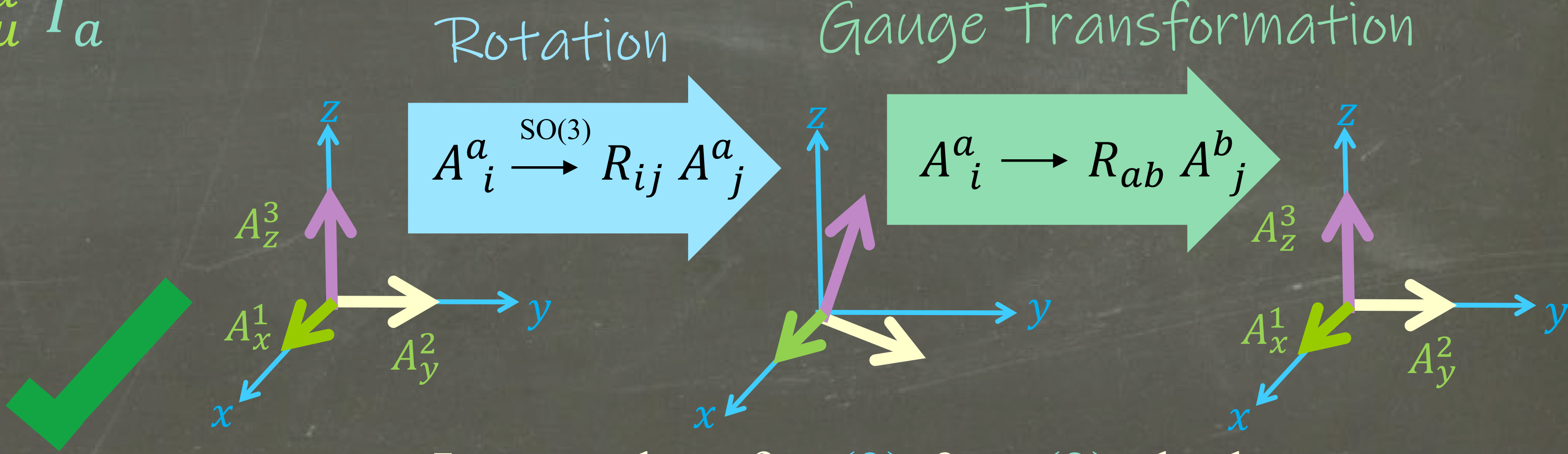


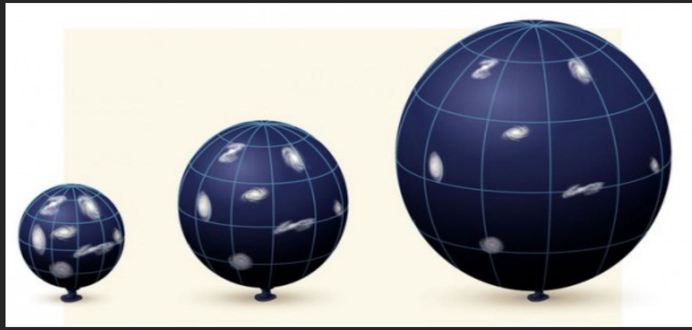
A.M. and M. M. Sheikh-Jabbari, 2011

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

SU(2) Gauge fields and Initial Anisotropies

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

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

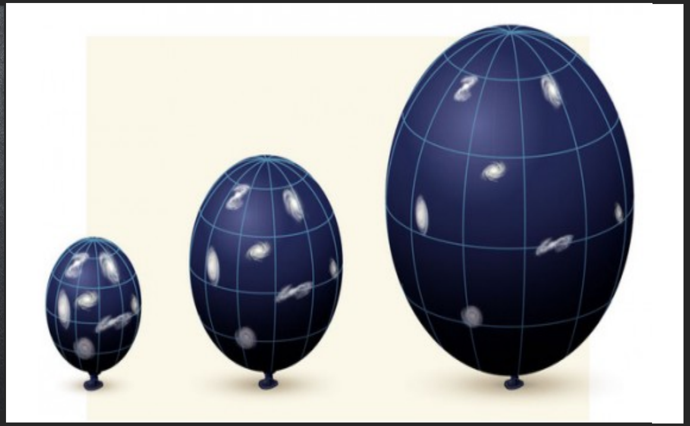


Isotropic Background

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

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

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



Anisotropic Background

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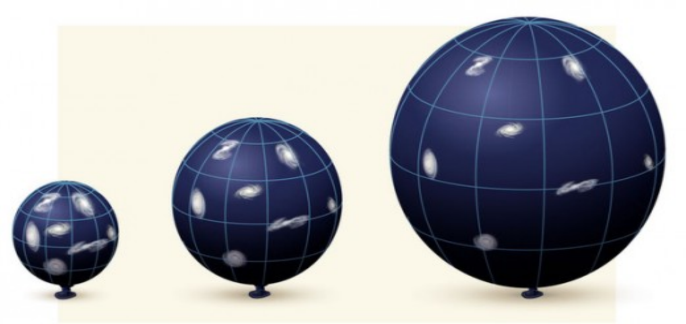


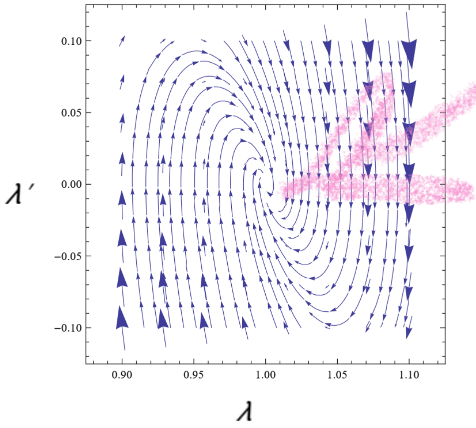
Isotropic Background

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

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

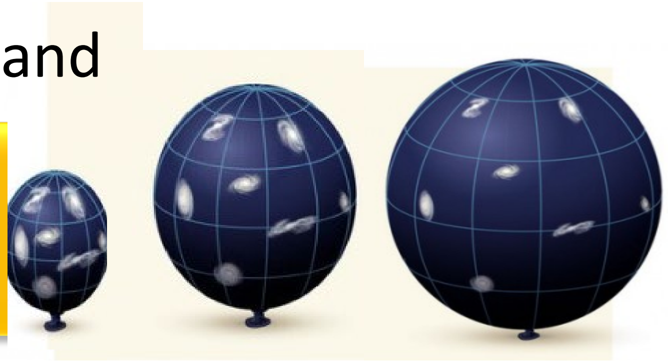
Axion is only coupled to the isotropic part of the gauge field,

Anisotropic part decays like radiation and



Isotropic Solution is the Attractor!

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



Isotropic Background

SU(2)-Axion Model Building

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

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

$\rho = -P$

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

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

Natural inflation

Friction

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

SU(2)-Axion Model Building

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Ruled-out by the data

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

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

+ Theoretical issue: Very large $\lambda \sim 100$!

D. Baumann & L. McAllister 2014

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

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

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

SU(2)-Axion Model Building

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

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

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

- A new mechanism for generation of Primordial Gravitational Waves

A. M. 2014 & **A.M. 2016**
R. Caldwell et. al 2017
A. M. 2021

- All Sakharov conditions are satisfied in inflation: a new baryogenesis mechanism

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

- Particle Production in inflation by Schwinger effect and chiral anomaly

SU(2)-Axion Model Building

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

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Axion Monodromy or any mechanism that gives a flat potential

New Tensorial mode in SU(2) Gauge Field

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

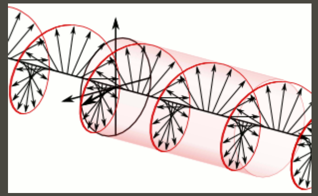
$$B_\pm'' + [k^2 \mp \delta_C k\mathcal{H} + \frac{m^2}{H^2}\mathcal{H}^2 - \frac{a''}{a}] B_\pm \approx 0$$

effective frequency

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

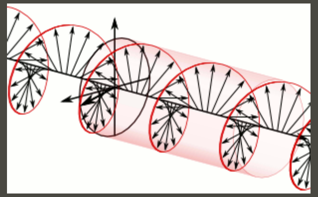
Circular polarizations

Right-handed



B_+

Left-handed



B_-

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

A.M. & Sheikh-Jabbari, 2011

New Tensorial mode in SU(2) Gauge Field

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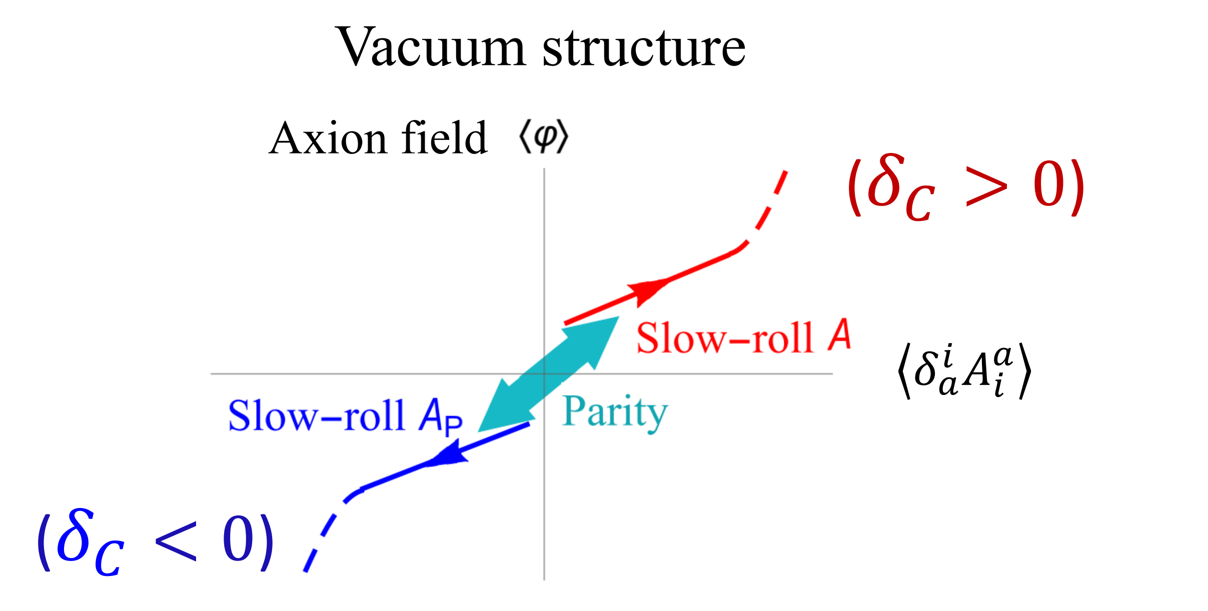

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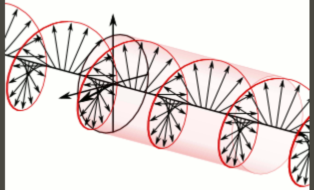

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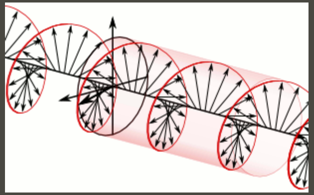
Left-handed



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effective frequency

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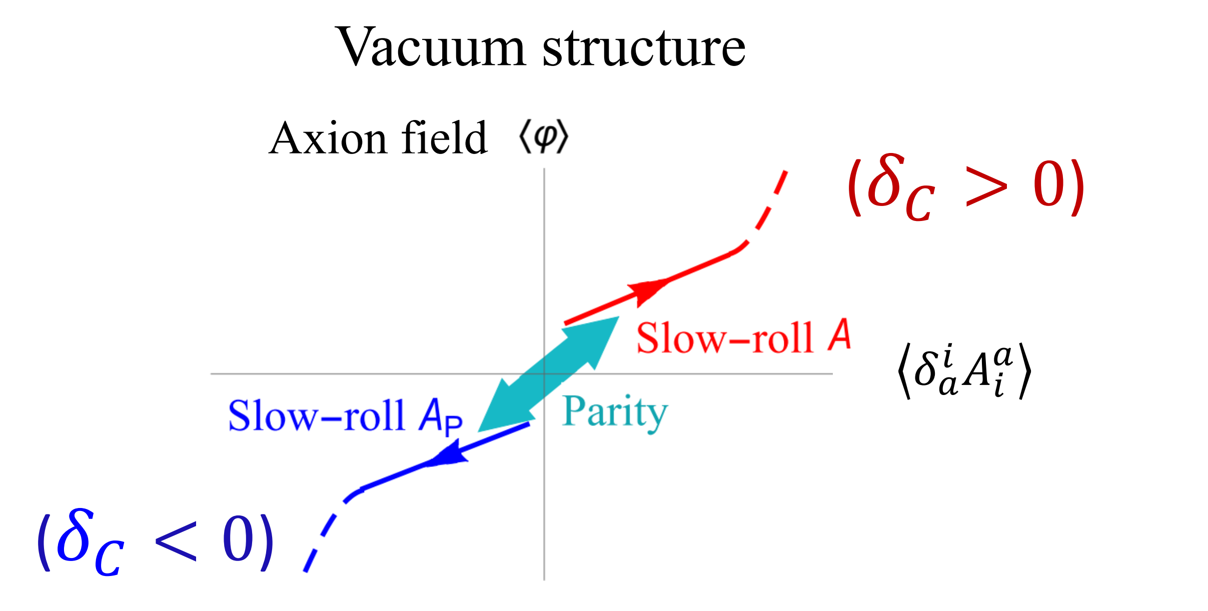


For $\delta_C > 0$

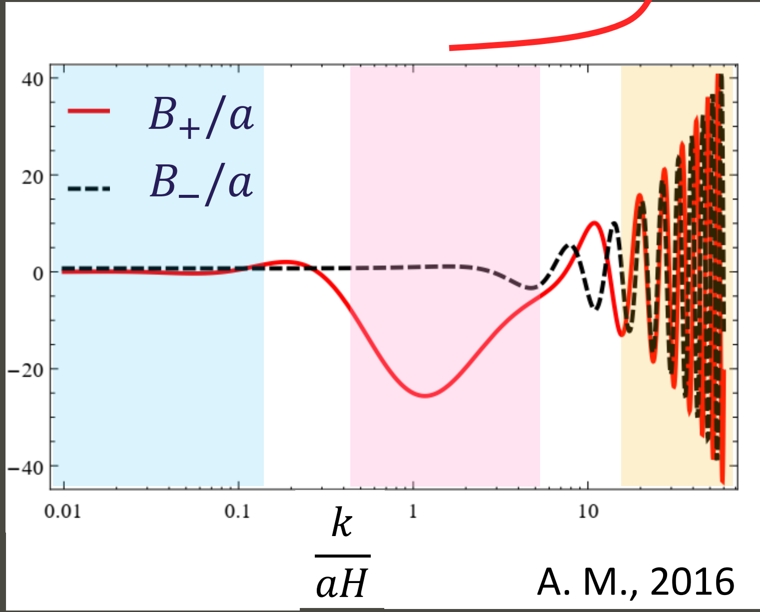
Short tachyonic growth of B_+

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



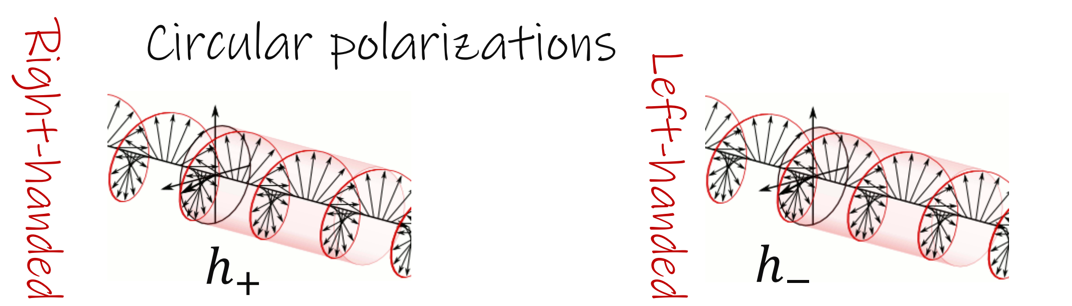
A. M., 2016

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

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

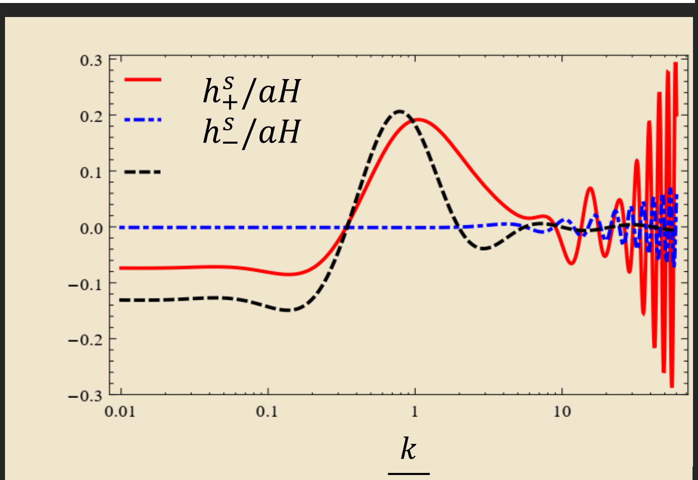


- Gravitational waves have two uncorrelated terms

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

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

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



A. M., 2016

Novel Observable Signature: CMB

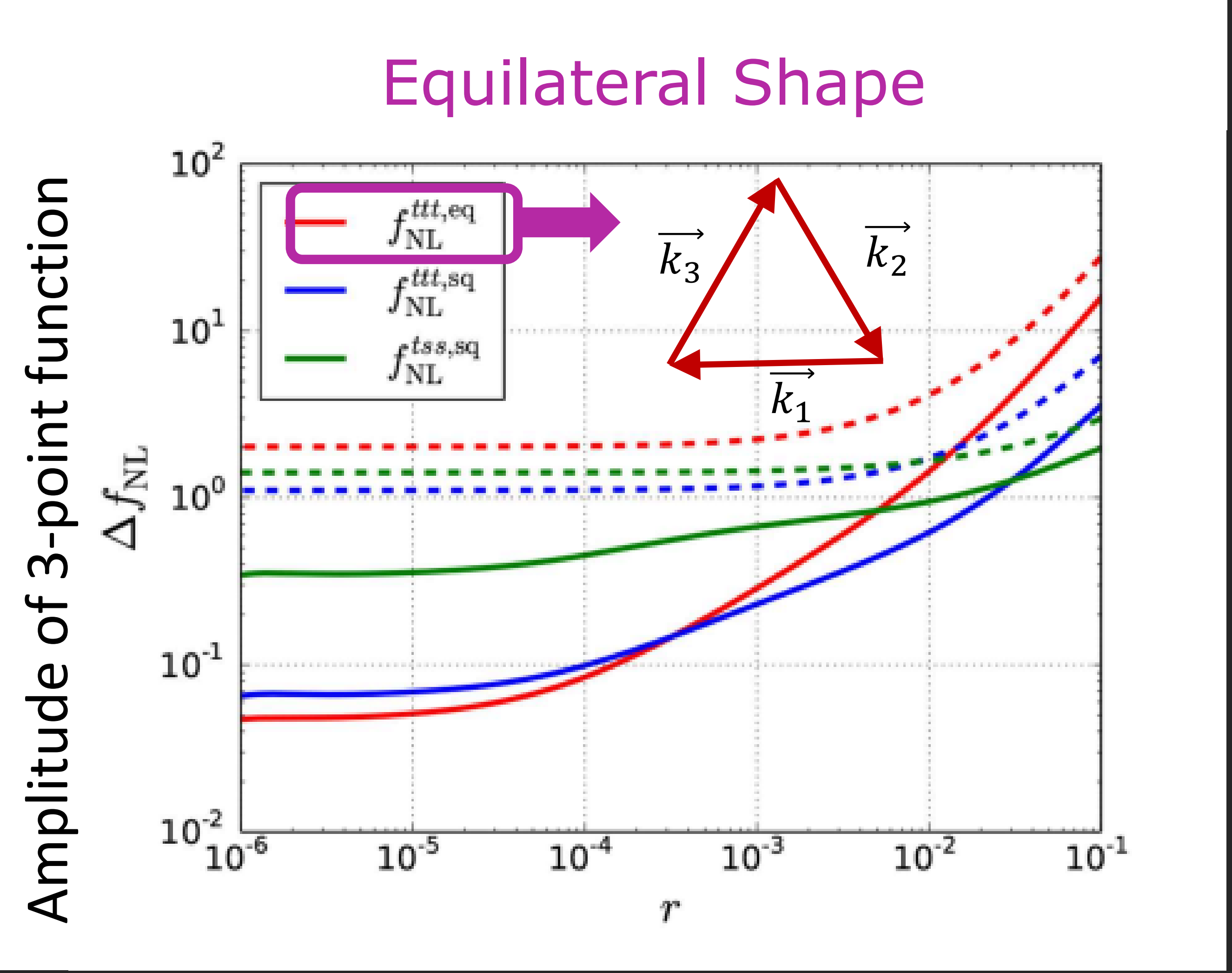
- The sourced tensor modes is Highly non-Gaussian.

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

Self-interaction

Agrawal, Fujita, Komatsu 2018

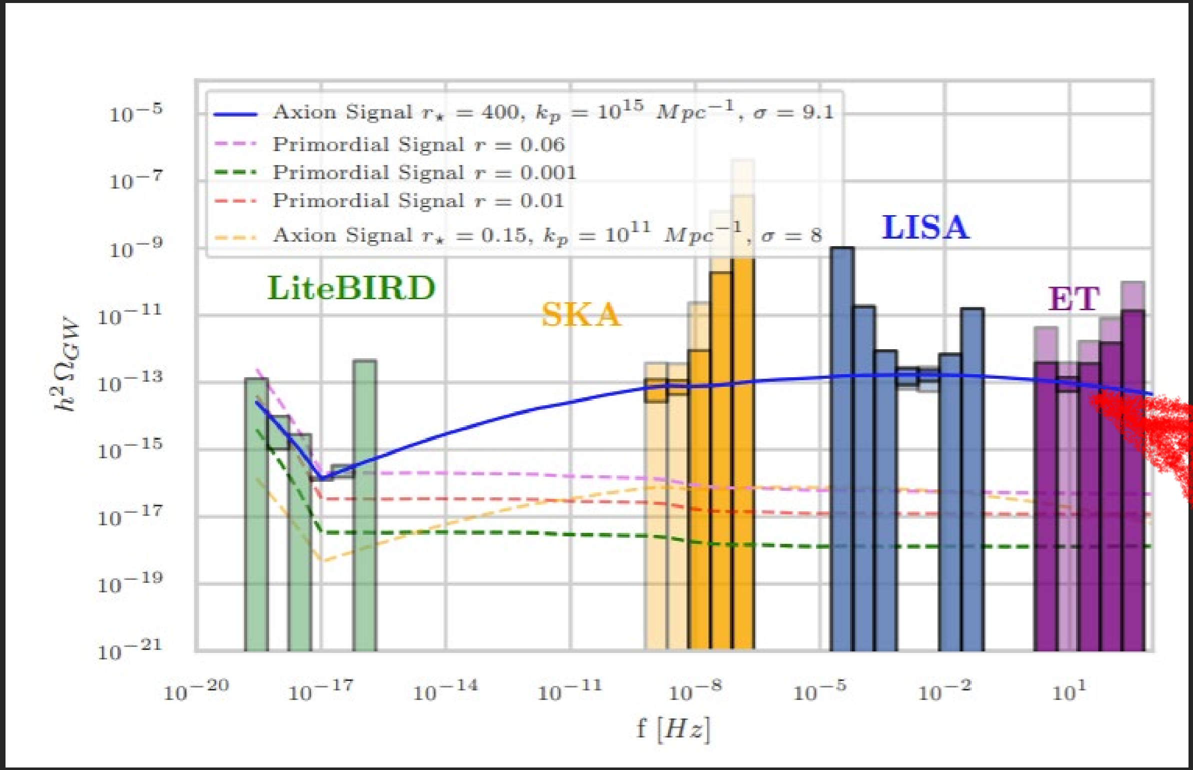
- That can be probe with future CMB missions., e.g. *Litebird* and *CMB-S4*!



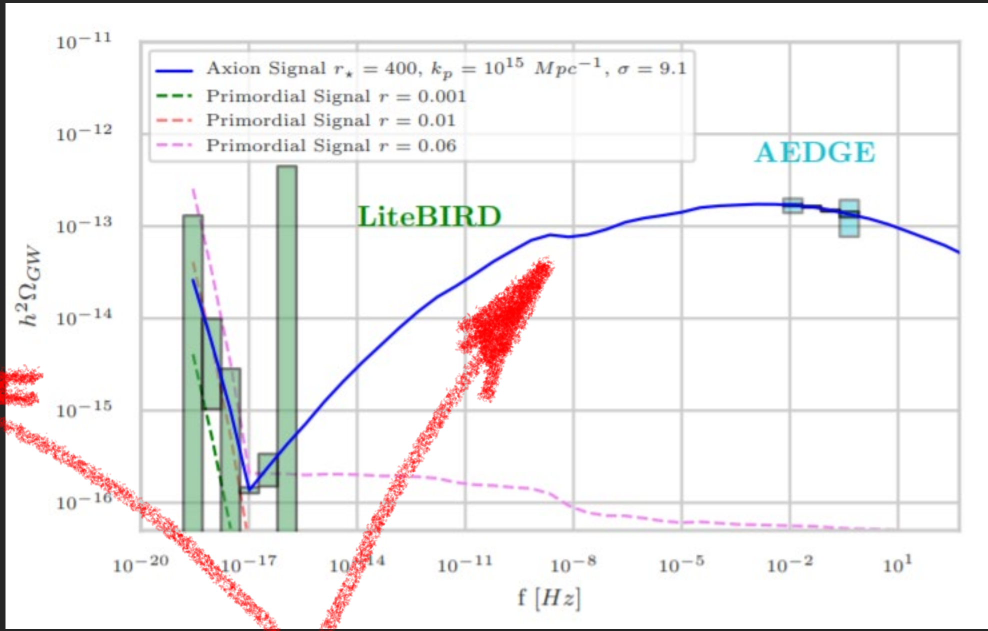
Maresuke Shiraishi, Front. Astron. Space Sci. 2019

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



New Physics

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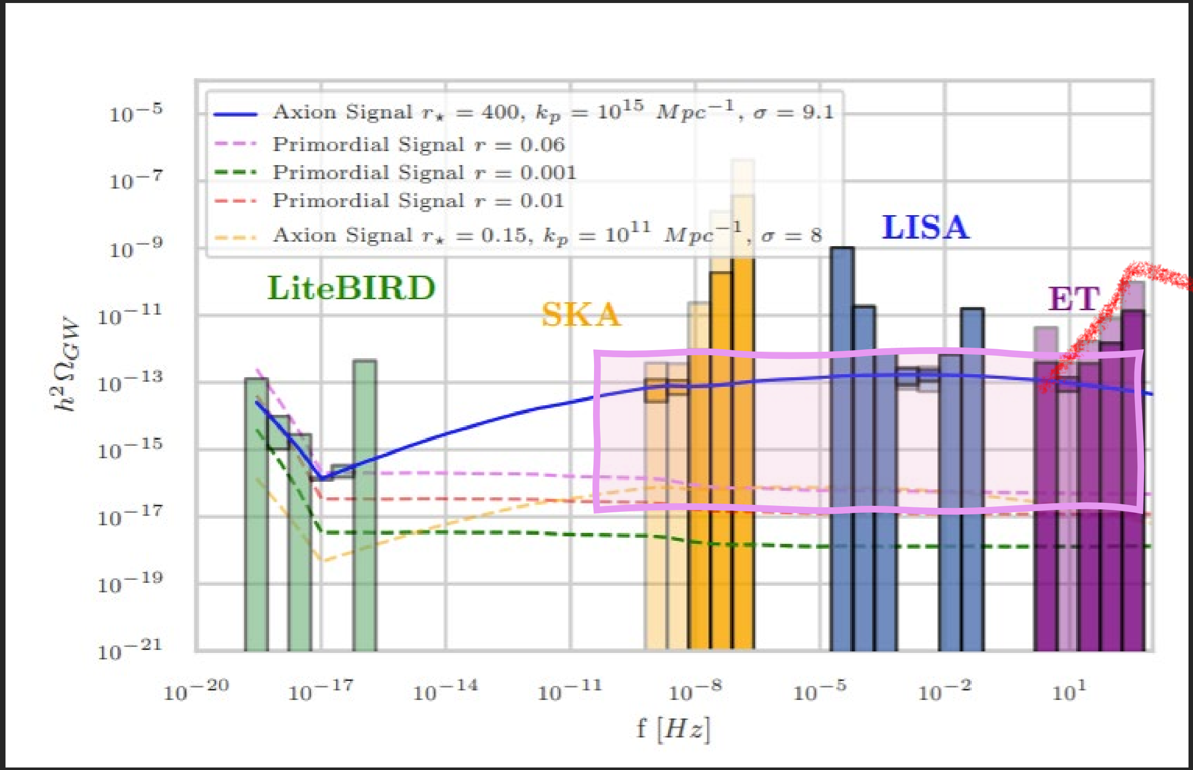
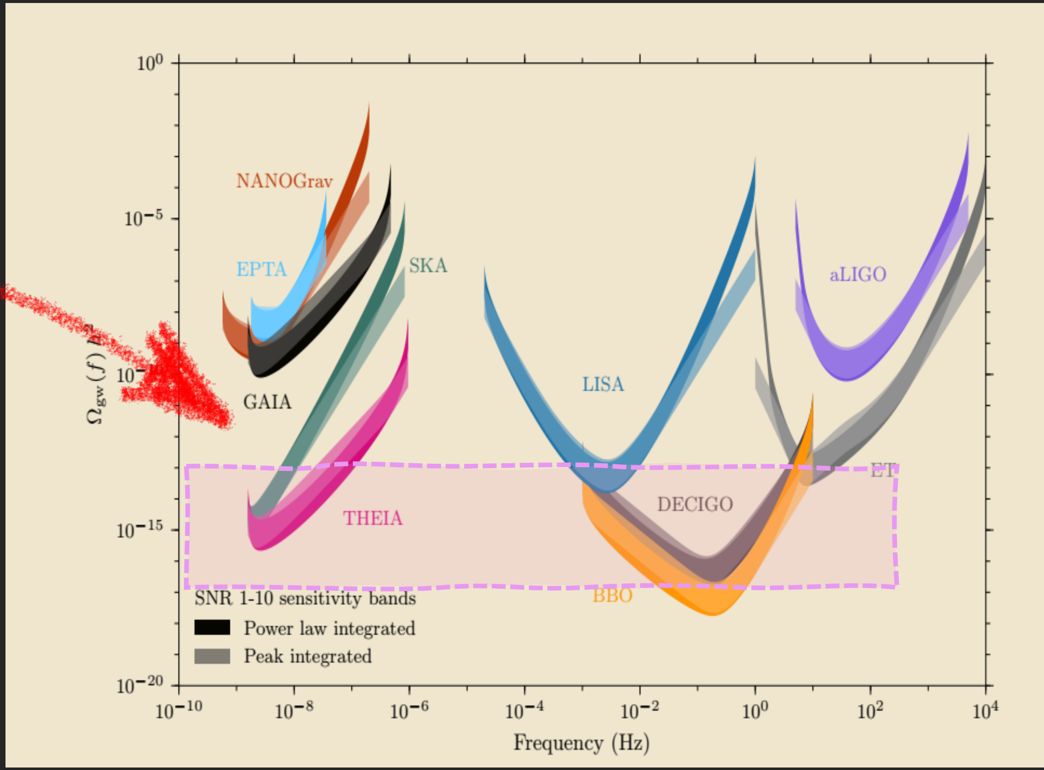


P. Campeti, E. Komatsu, D. Poletti, C. Baccigalupi 2020

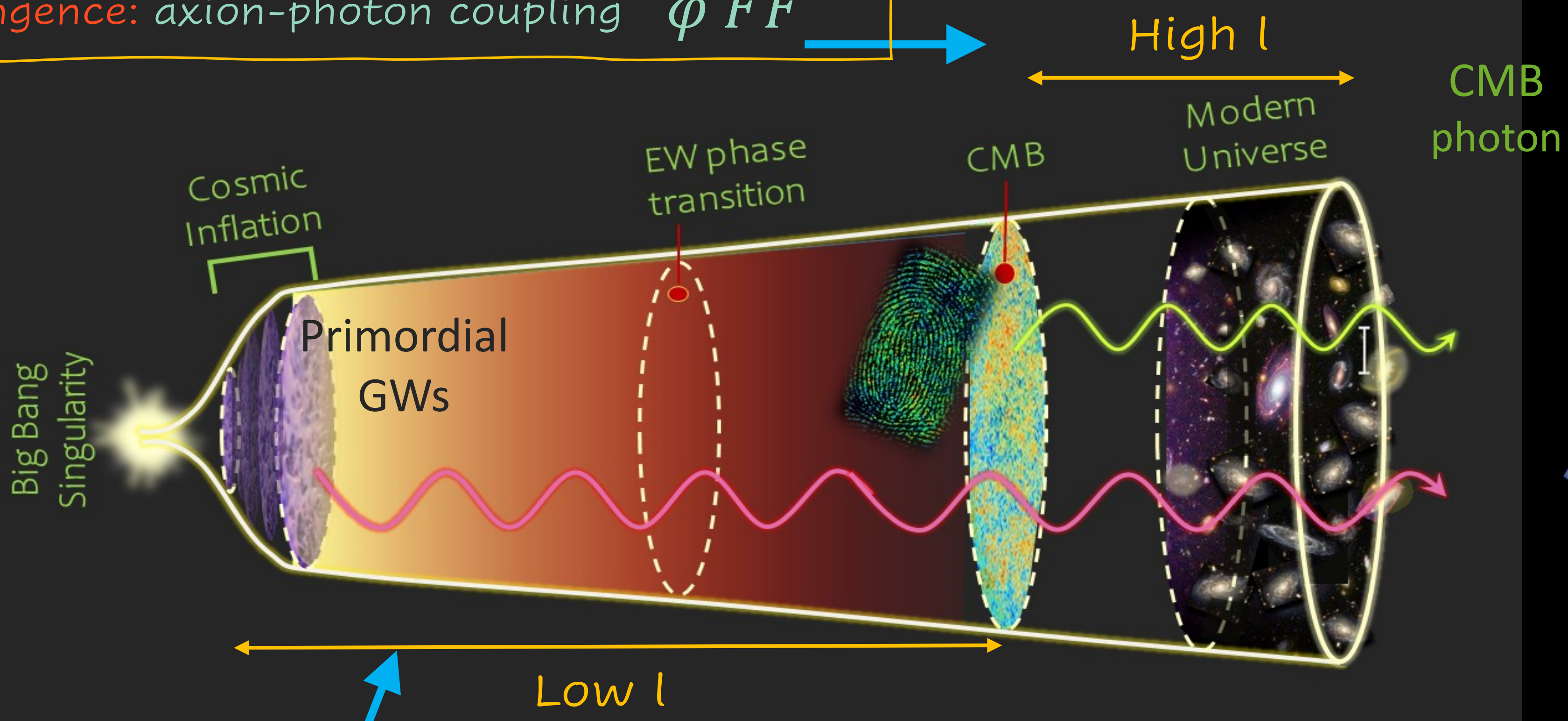


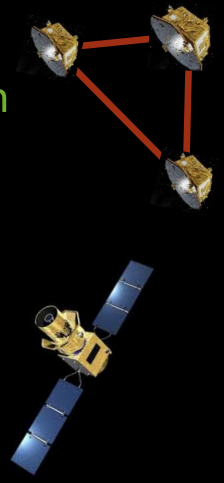
J. Garcia-Bellido, H. Murayama, and G. White 2021

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

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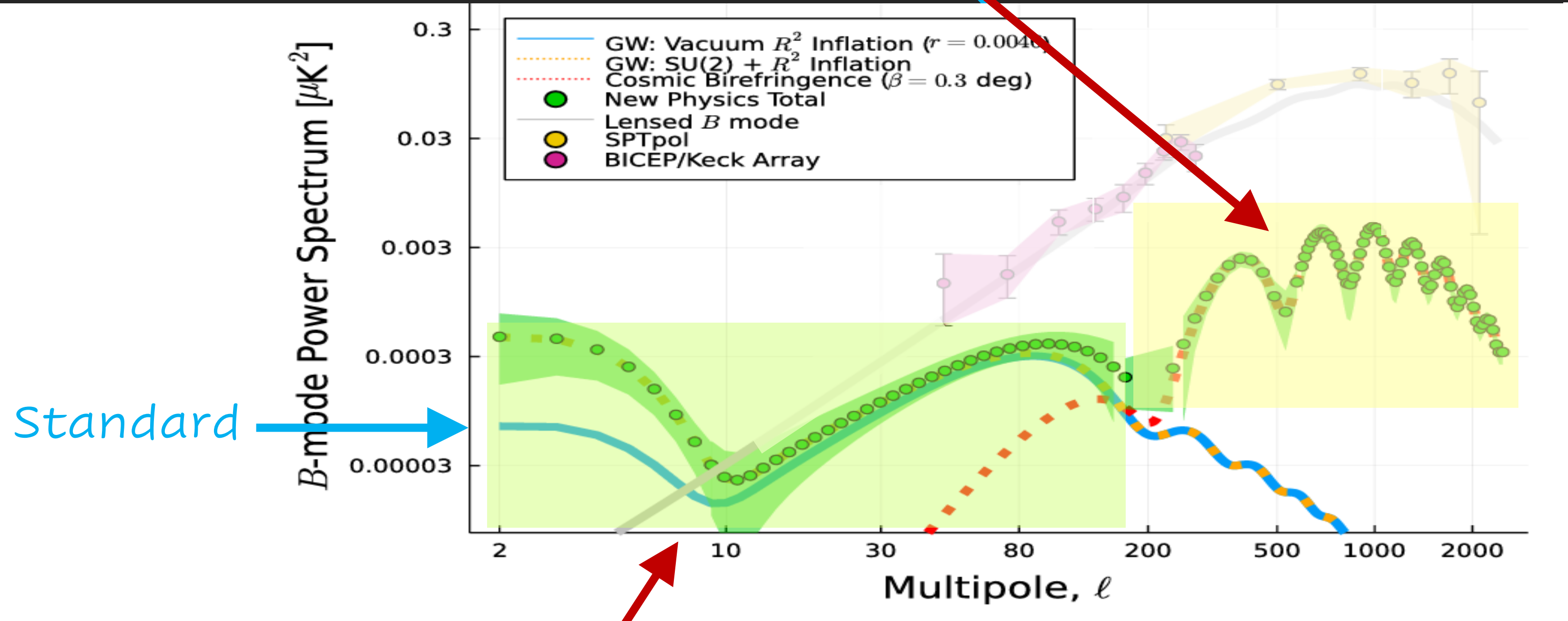
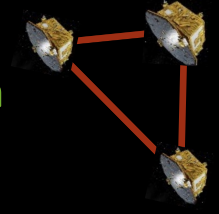


E. Komatsu Nature Rev. Phys. 4 (2022) 7, 452-469



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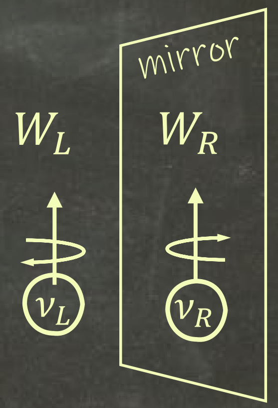
B. Thorne et. al.2018

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

(How to Connect Inflaton to SM?)



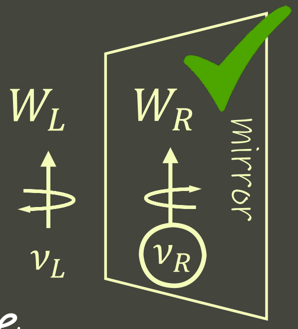
How to Connect it to the SM?

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

- Left-Right Symmetric Model + axion!

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

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

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Axion Monodromy or any mechanism that gives a flat potential

Gauge field is $SU(2)_R$

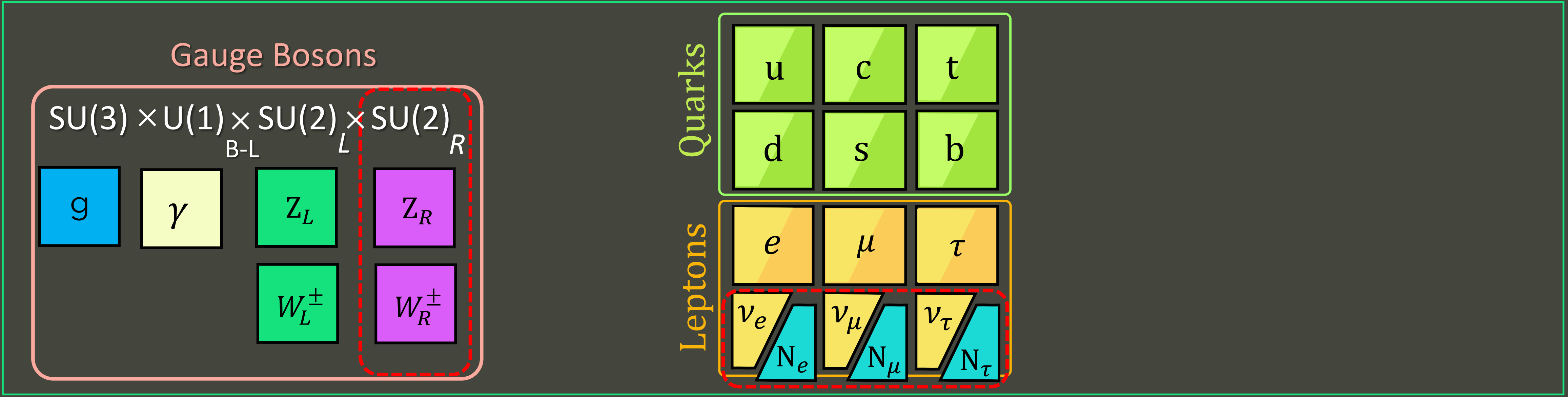
A. M. arXiv: 2012.11516

A.M. arXiv:2103.14611

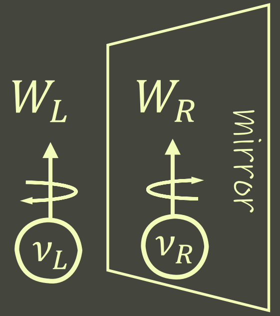
Minimal Left-Right Symmetric model

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)



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

↓ 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

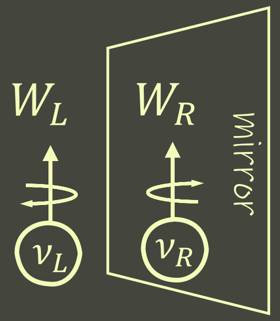
Higgs sector

ϕ bi-doublet $SU(2)_L \times SU(2)_R$

Δ_R $SU(2)_R$ triplet

Δ_L $SU(2)_L$ triplet

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)



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

↓ 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

Higgs sector

ϕ bi-doublet $SU(2)_L \times SU(2)_R$

Δ_R $SU(2)_R$ triplet

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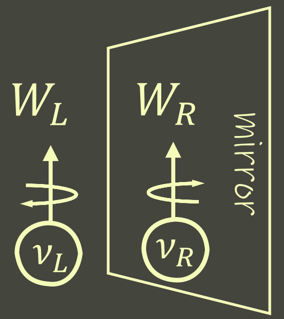

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$\langle \Delta_R \rangle \neq 0$

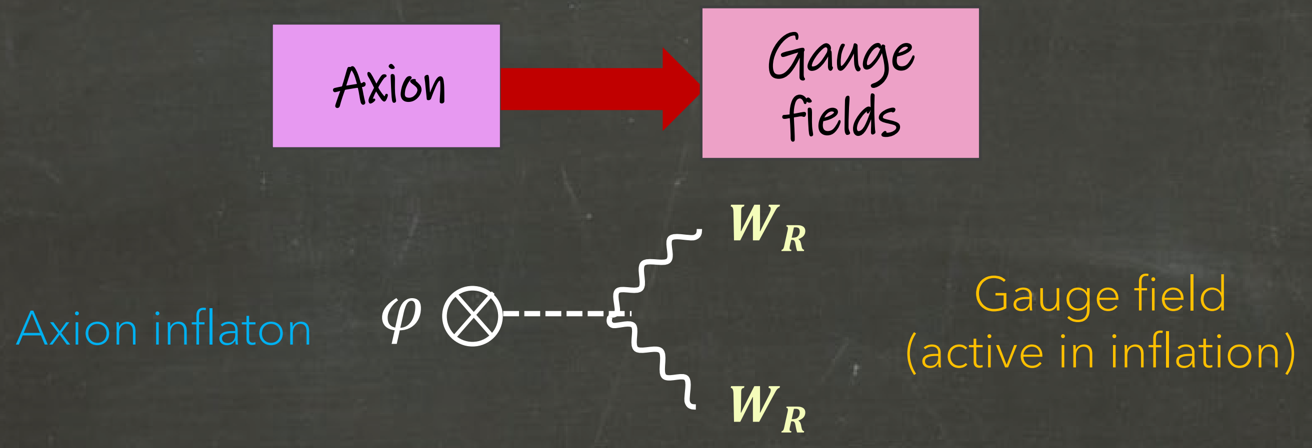
Massive

N_i $W_R^{\pm}$ 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 $SU(2)_R$:



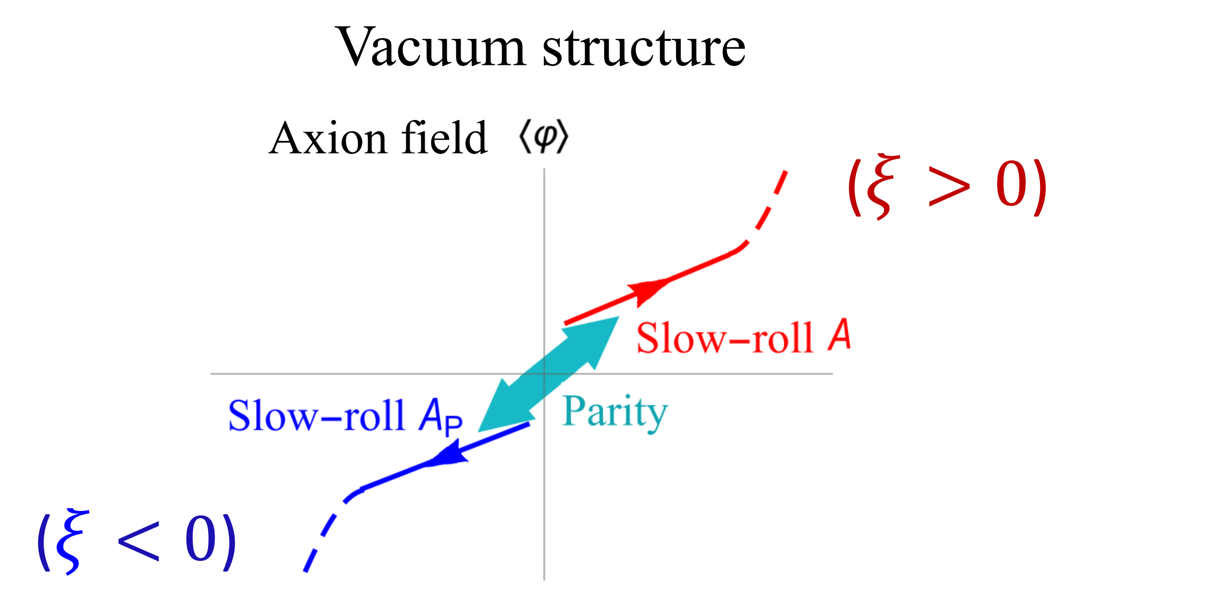
$SU(2)_R$ Gauge Field

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

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

effective frequency

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

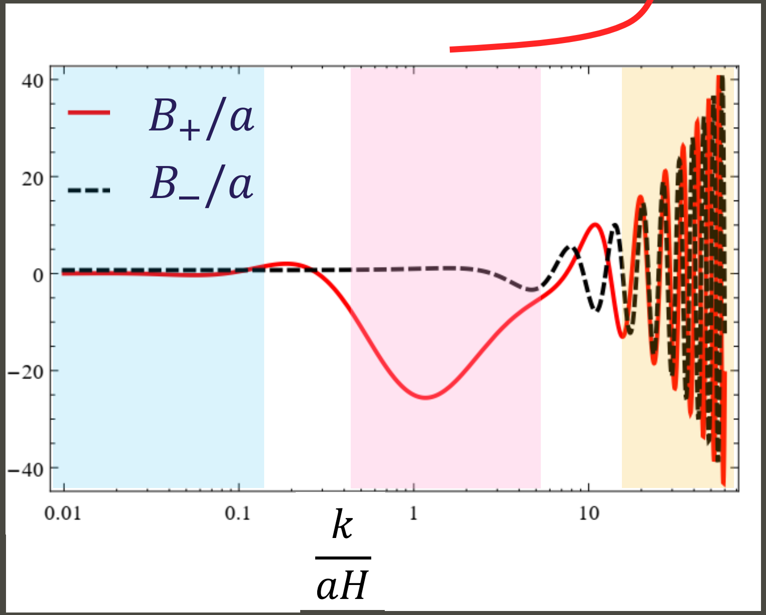


For $\xi > 0$
Short tachyonic growth of B_+

Chiral Field

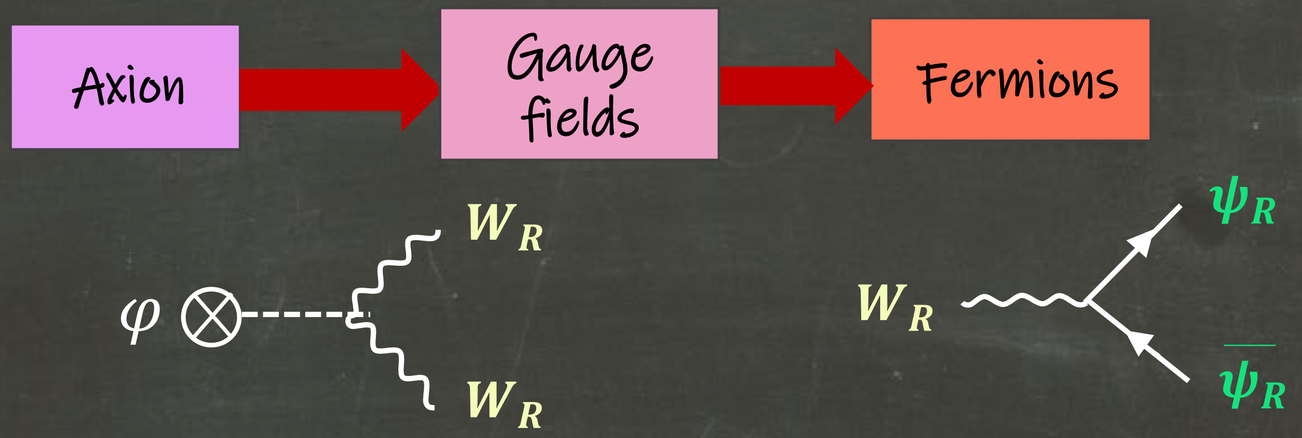
$$n_B \sim \frac{H^3}{6\pi^2}\xi^3\, e^{\frac{(2-\sqrt{2})\pi}{2}\xi}$$

Particle Production



Lepton & quark Production in Inflation

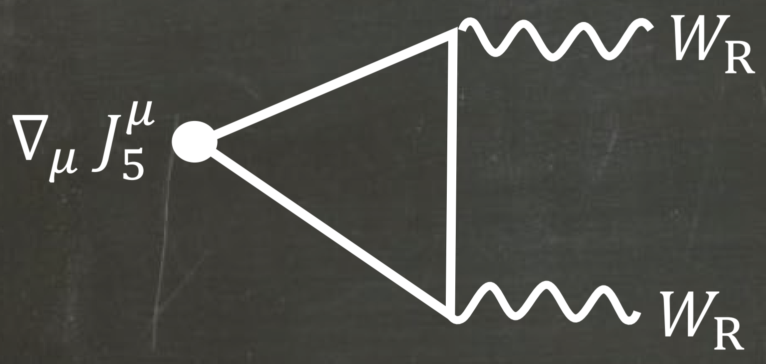
- Left-handed fermions are diluted by inflation, BUT
- Right-handed fermions are generated by $\mathrm{SU(2)_R}$ gauge field:



Lepton & quark Production in Inflation

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

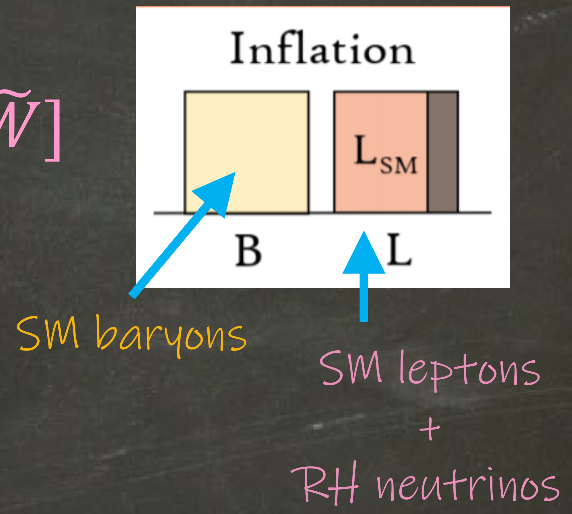
The key ingredient is the Chiral anomaly of $SU(2)_R$ in inflation:



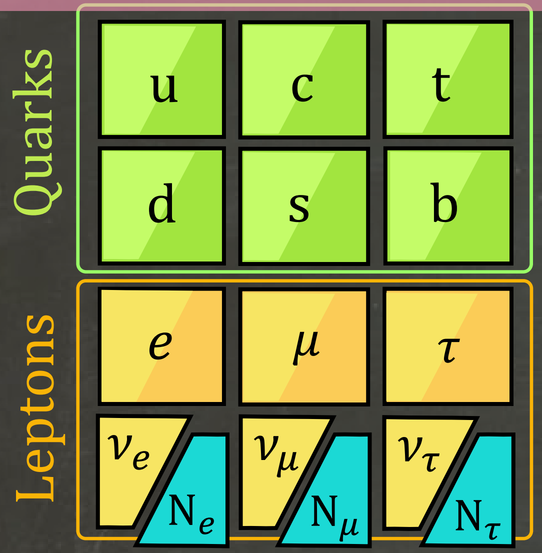
$$\nabla_\mu J_B^\mu = \nabla_\mu J_L^\mu = \frac{g^2}{16\pi^2} tr[W\widetilde{W}]$$

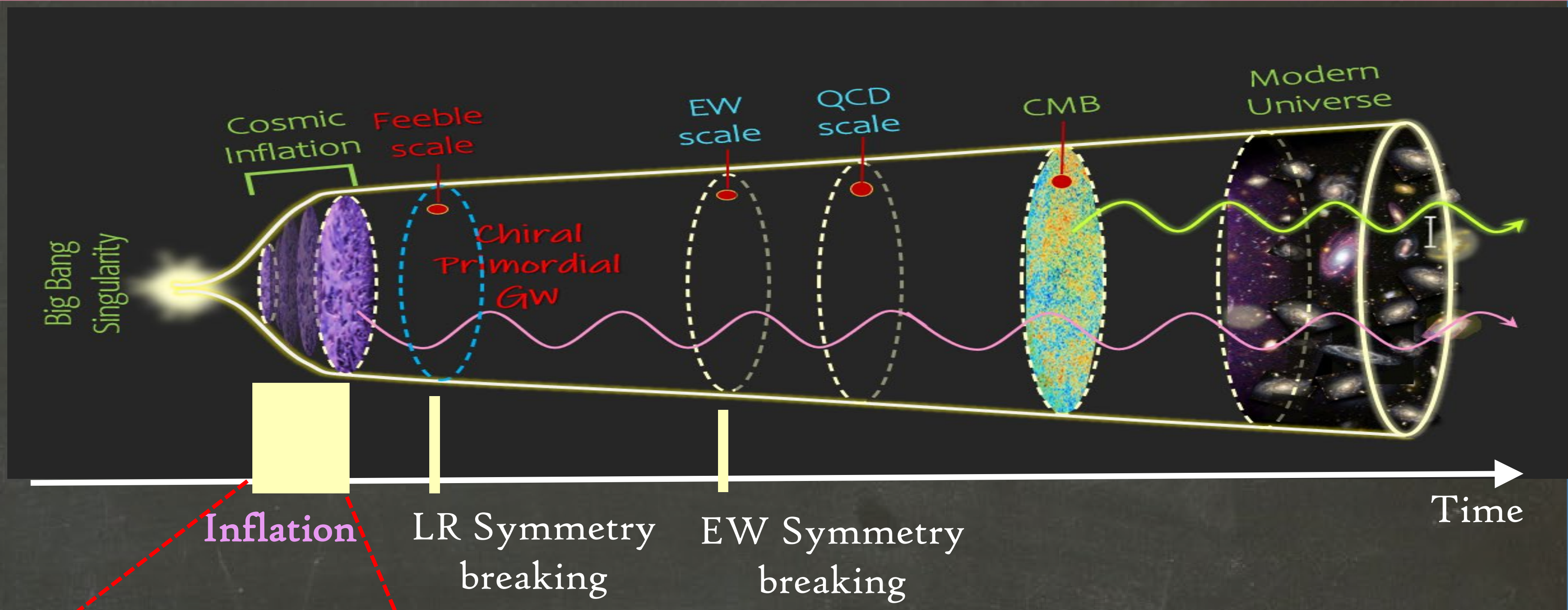
$$n_B = n_L = \alpha_{inf}(\xi) H^3$$

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

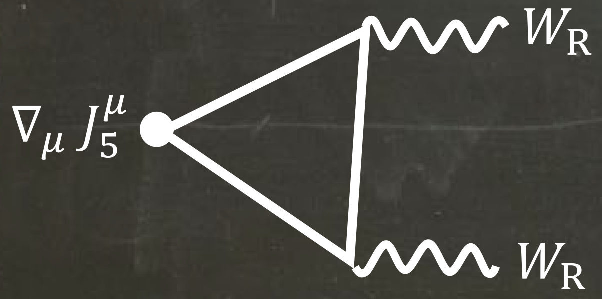


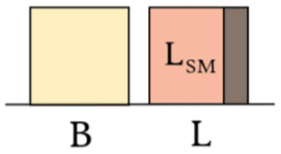
Summary of the mechanism:





Chiral anomaly of SU(2)R
In inflation





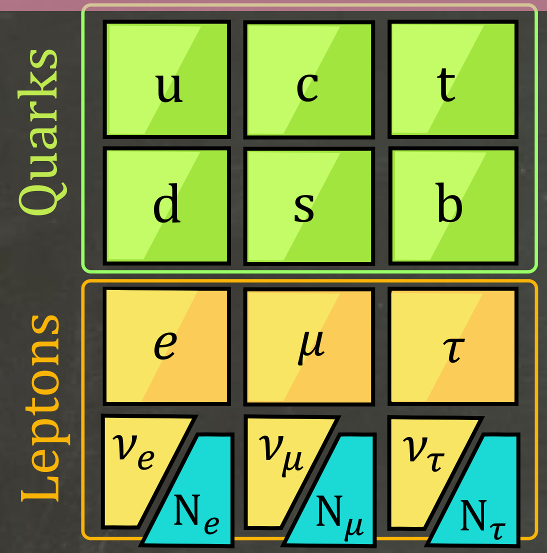
$$B = L = 3n_{CS}$$

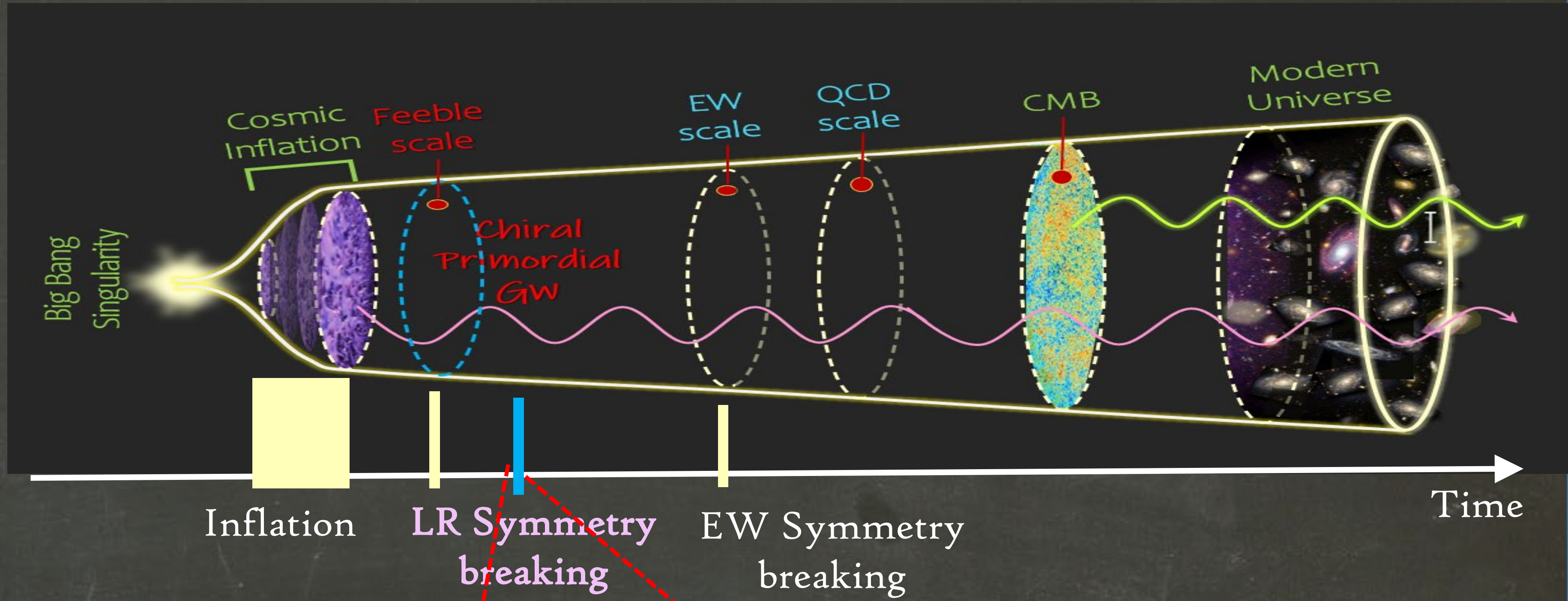
$$B - L_{SM} \neq 0$$

B= SM baryons

L= SM leptons + RH neutrinos

Summary of the mechanism:





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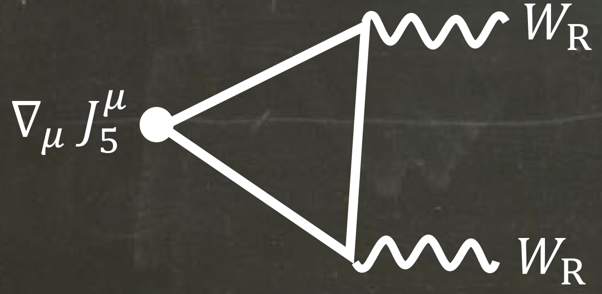

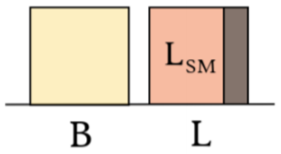

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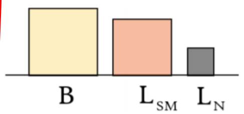
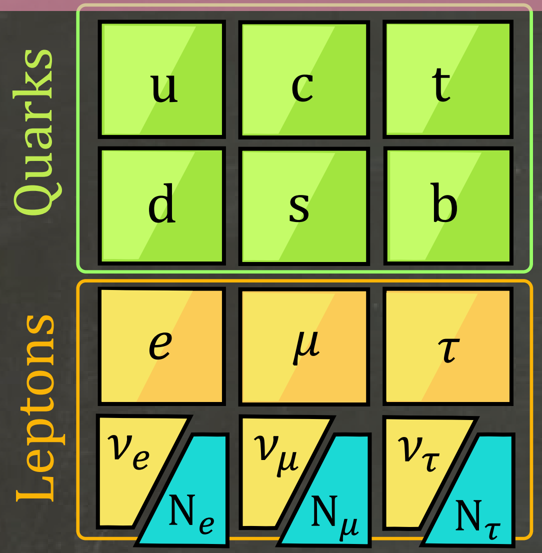
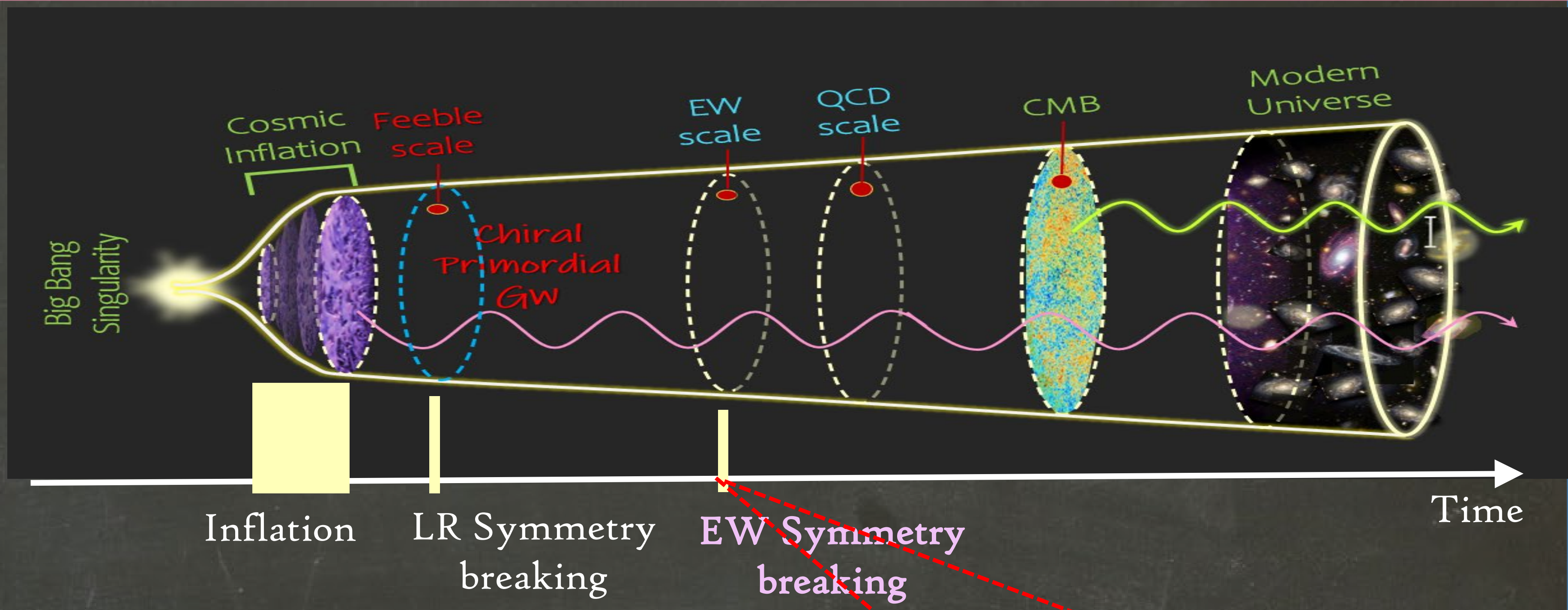
→



Freezeout of W_R

Summary of the mechanism:





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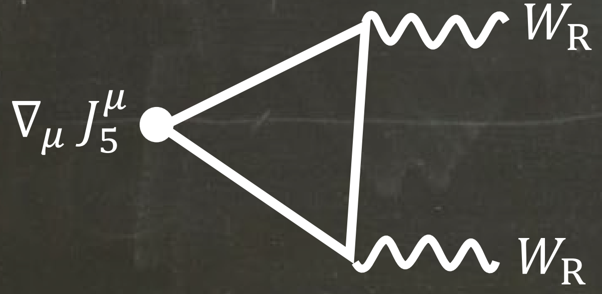

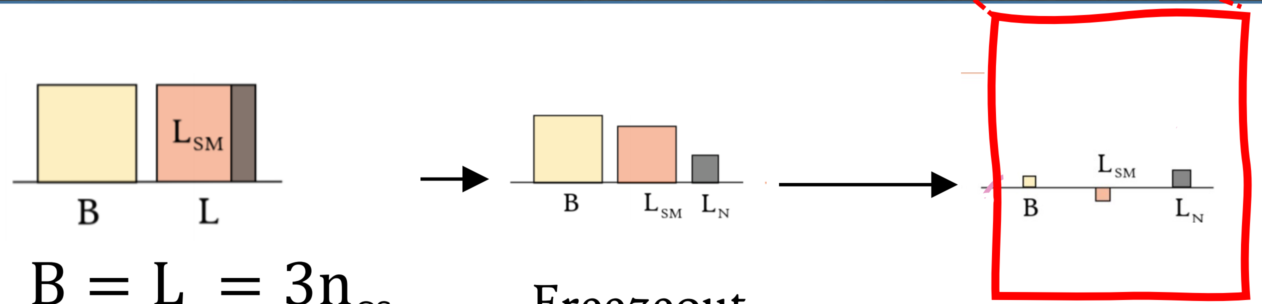

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Freezeout of W_R

Spectator effects reshuffle B, L_{SM} & L_N

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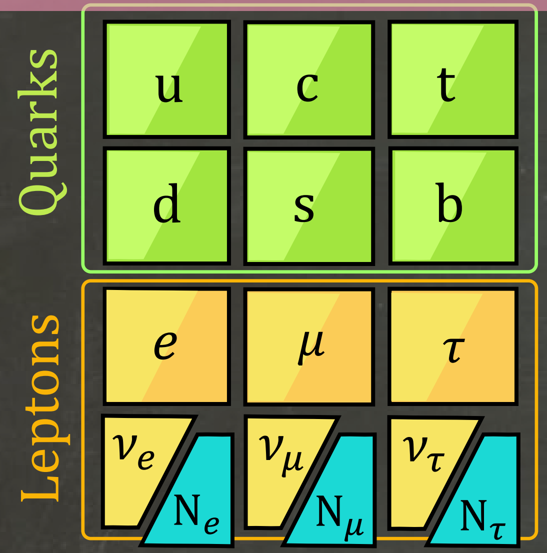

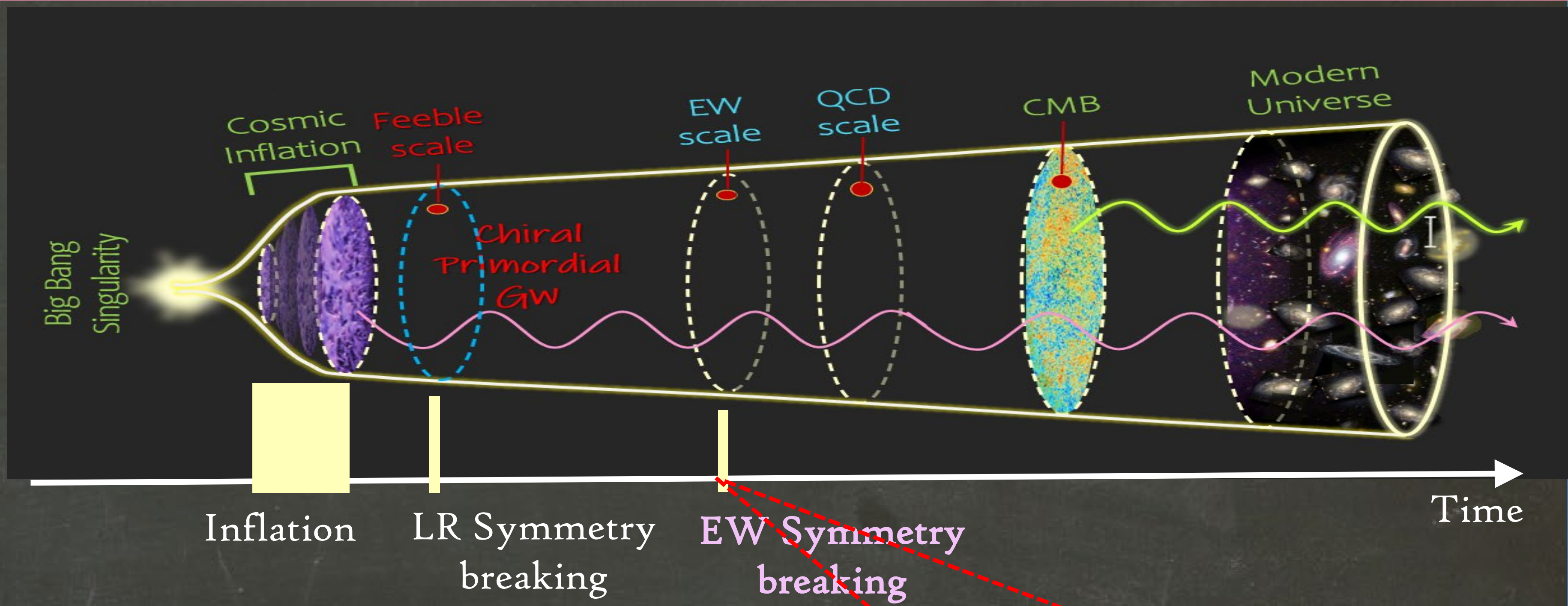

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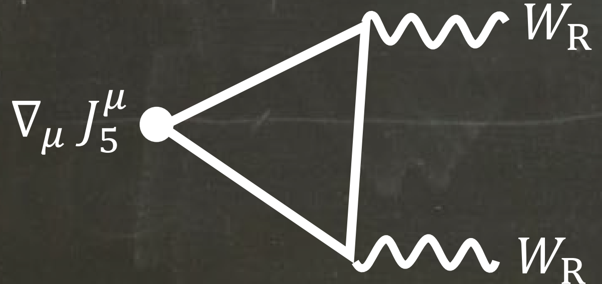

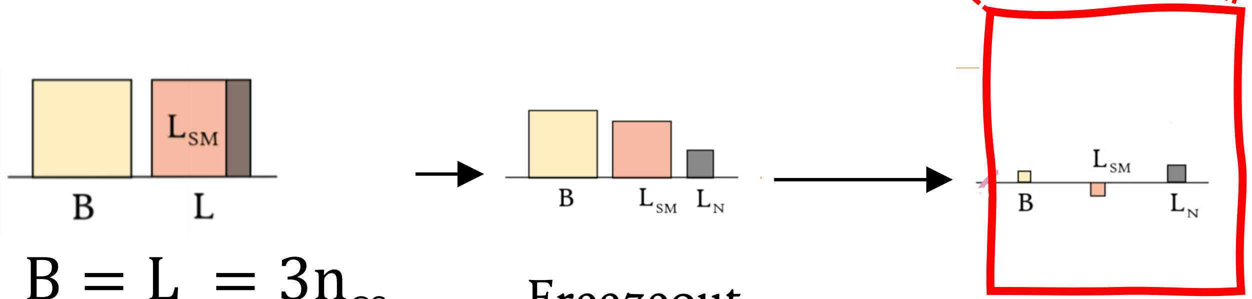

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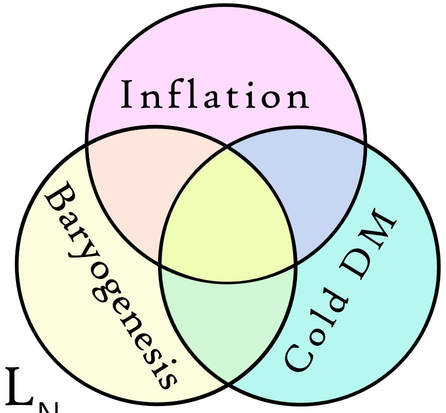

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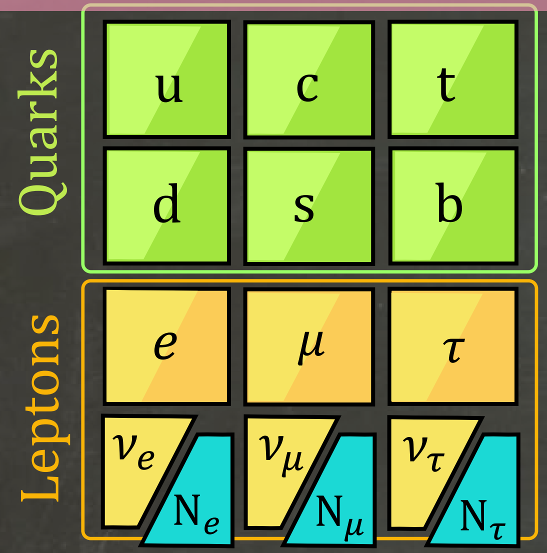

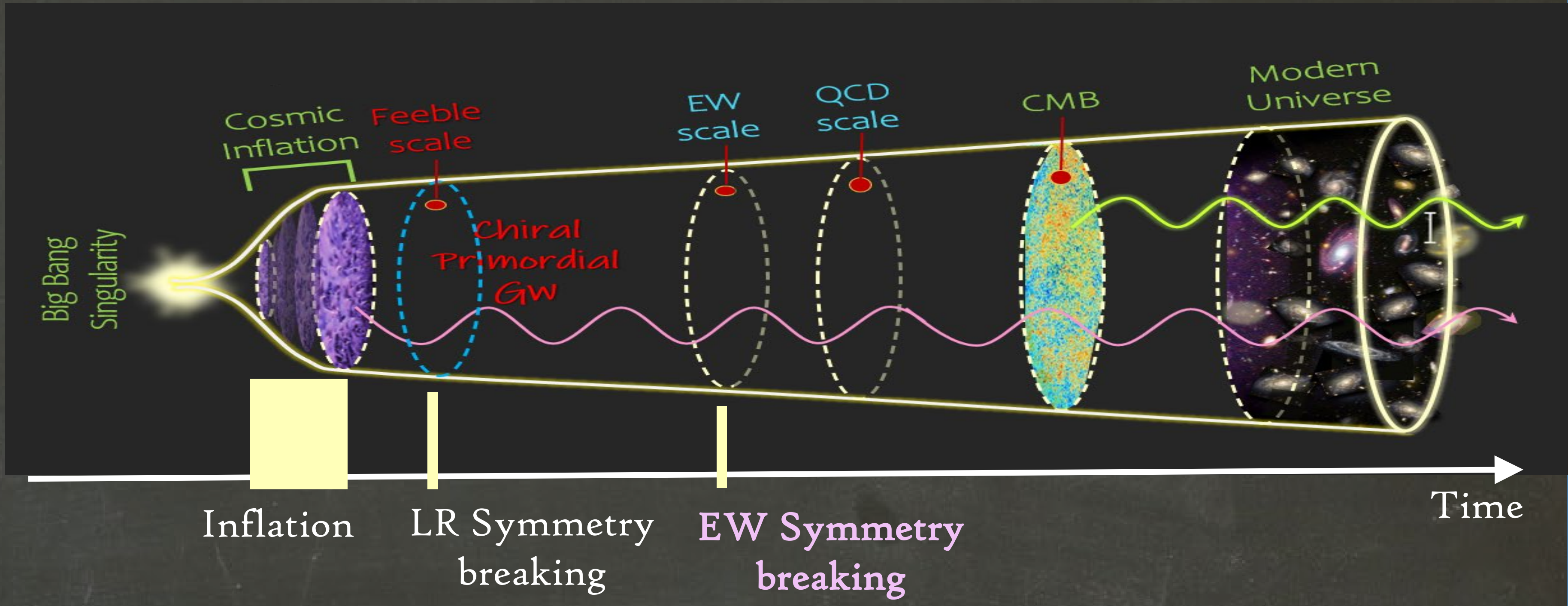

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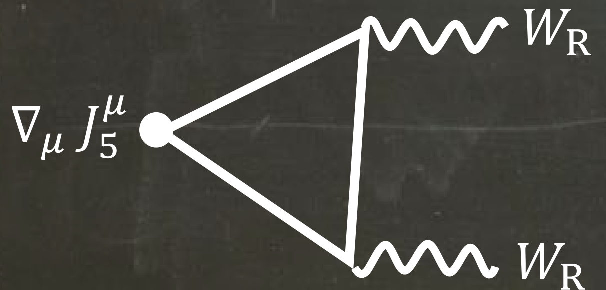

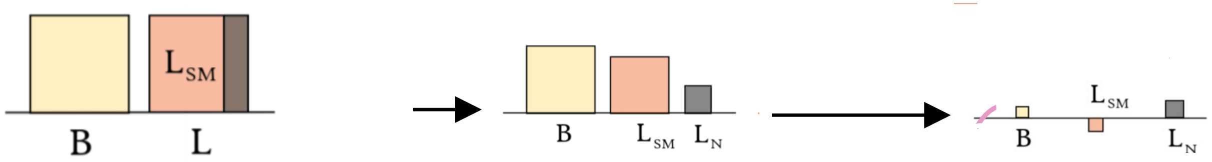

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Freezeout of W_R

DM

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

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

Baryogenesis

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

Summary & Conclusions

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

Compelling Consequences:

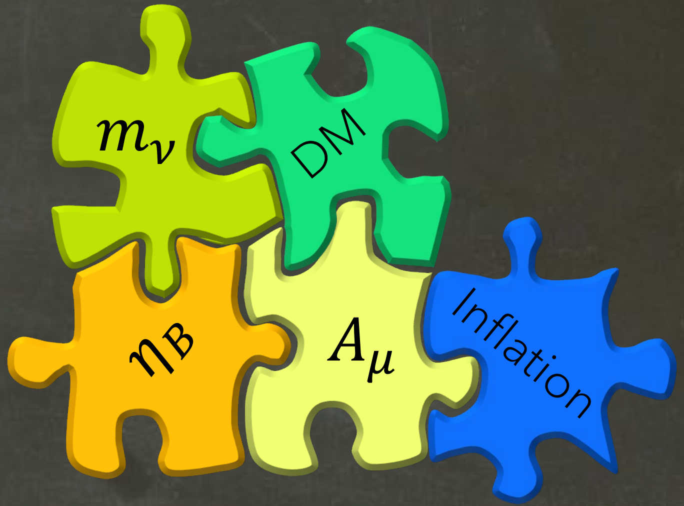
This Set-up is a complete BSM that can solve I-IV:

I) Particle physics of Inflation

II) Origin of matter asymmetry

III) Origin of Neutrino mass

IV) Particle nature of DM



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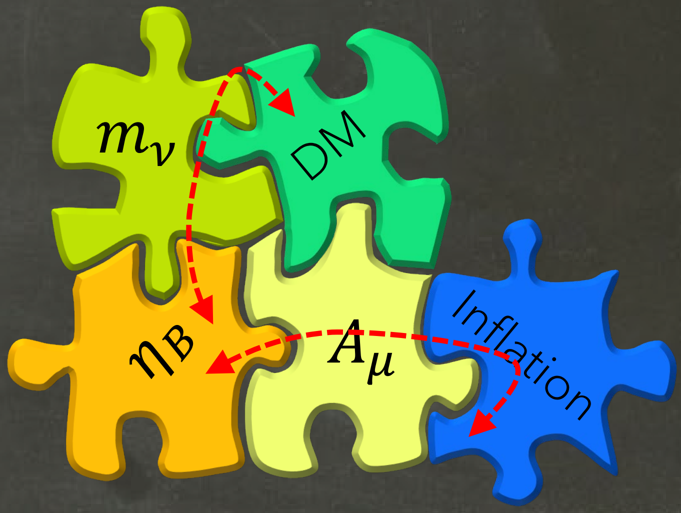

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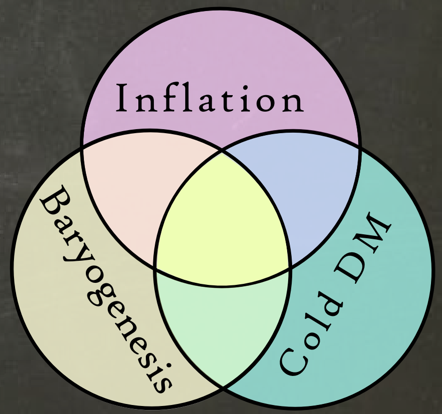
It provides a deep connection between inflation, baryogenesis & DM,

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



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Puzzles of Particle Cosmology

I) Particle physics of Inflation

II) Origin of matter asymmetry

III) Origin of Neutrino mass

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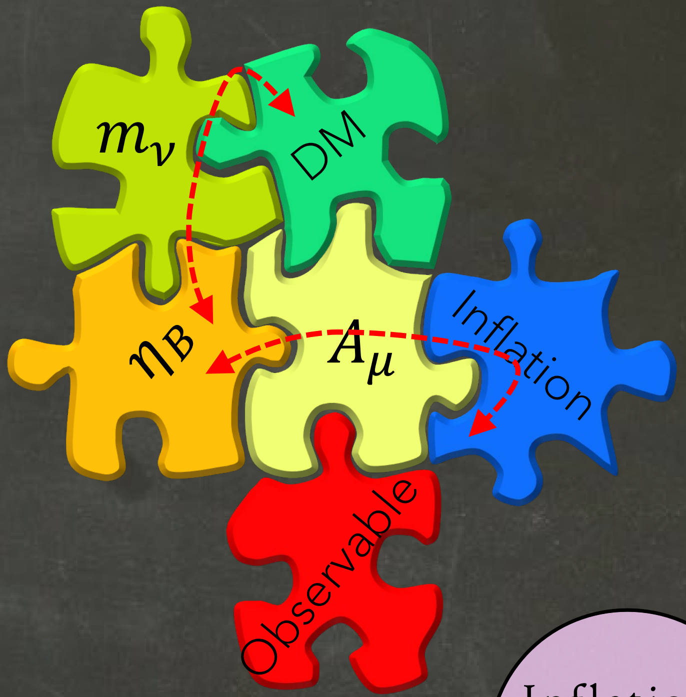

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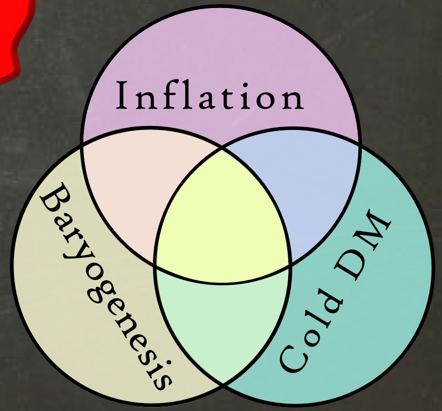
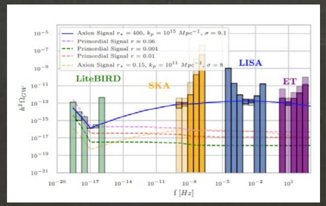
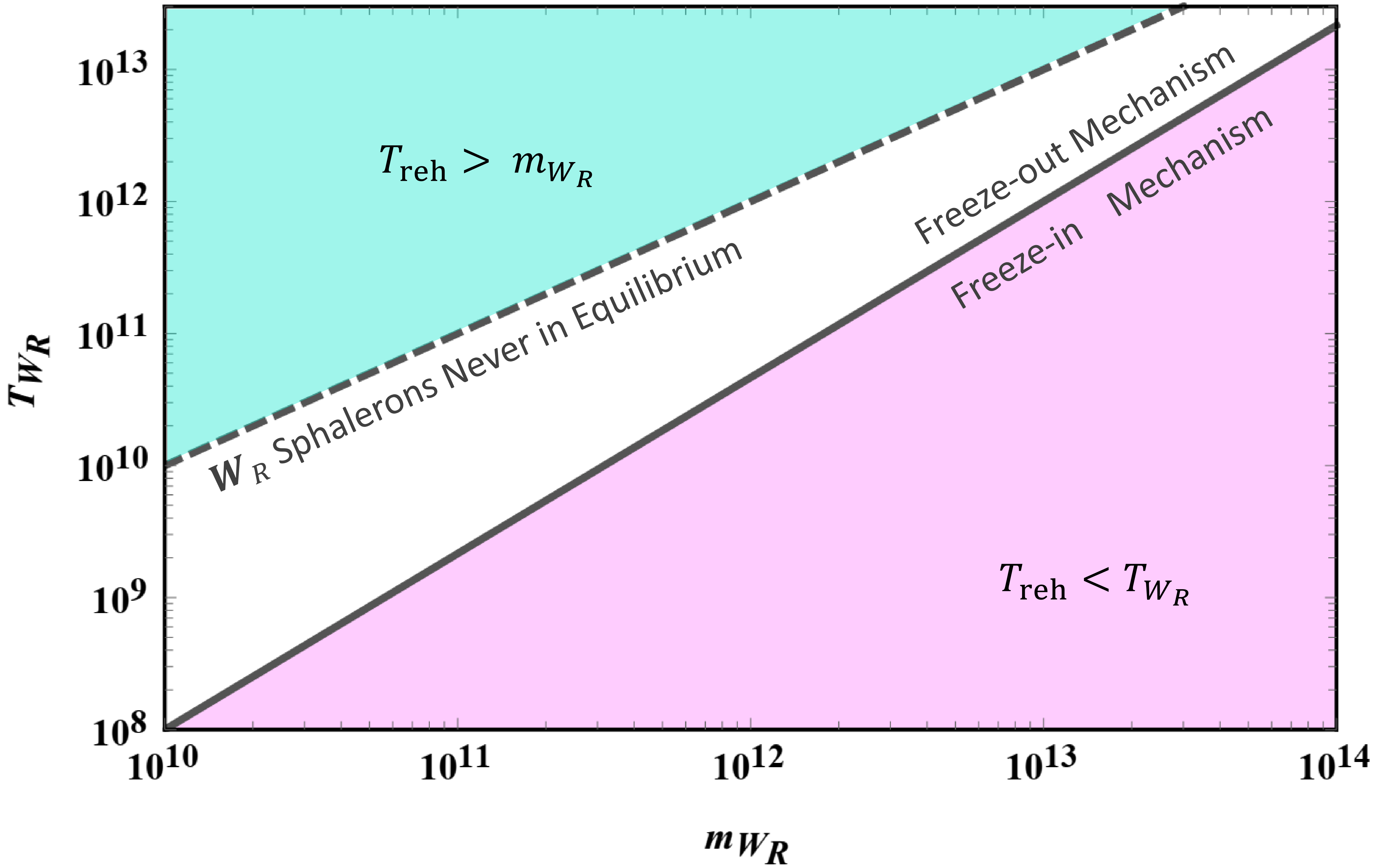


It comes with a cosmological smoking gun on Primordial GWs.




Questions?!



$T_{\rm reh} > m_{W_R}$
W_R Sphalerons Never in Equilibrium
Freeze-out Mechanism
Freeze-in Mechanism
$T_{\rm reh} < T_{W_R}$
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
10^{13}
T_{W_R}
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}
m_{W_R}

This setup prefers Left-Right symmetry breaking scales above $m_{W_R} = 10^{10}$ GeV !

(same as scales suggested by the non-SUSY SO(10) GUT models with intermediate LR symmetry scale.)