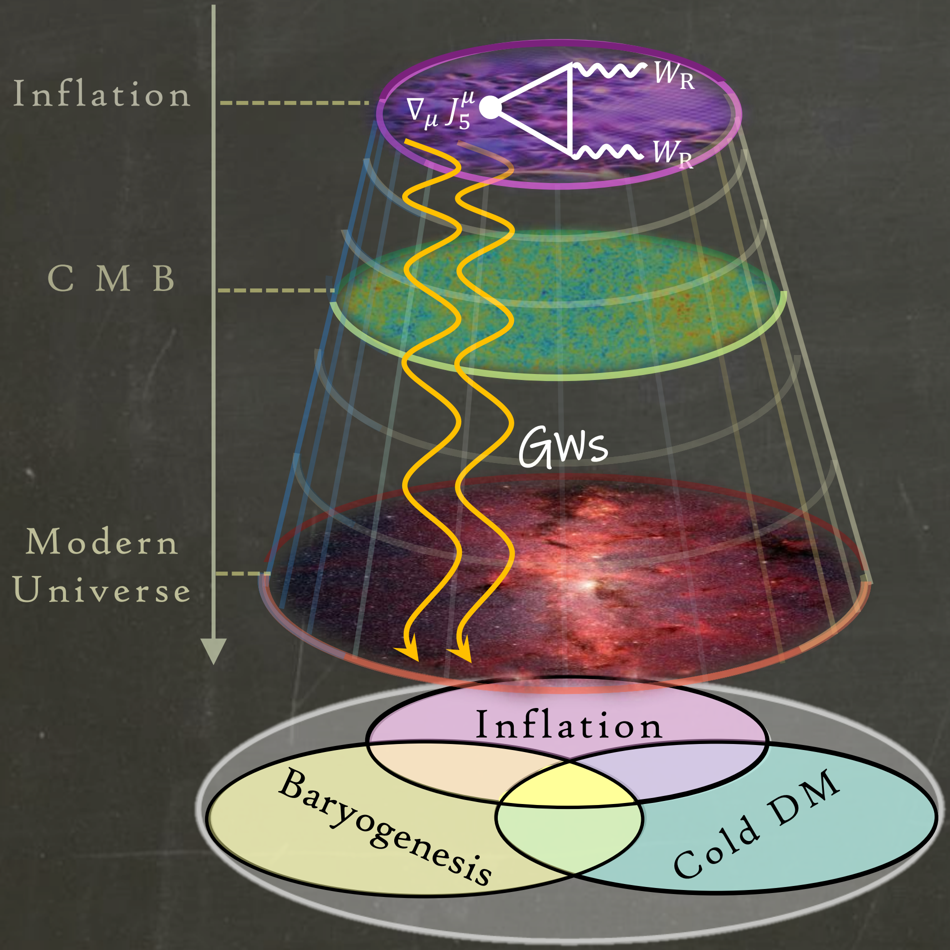
THE ROYAL SOCIETY

Gauge fields in the early Universe and their remnants in the Sky



Azadeh Malek-Nejad

King's College London

- Particle Physics of Inflation

  Based on Axion-Inflation with Gauge Fields

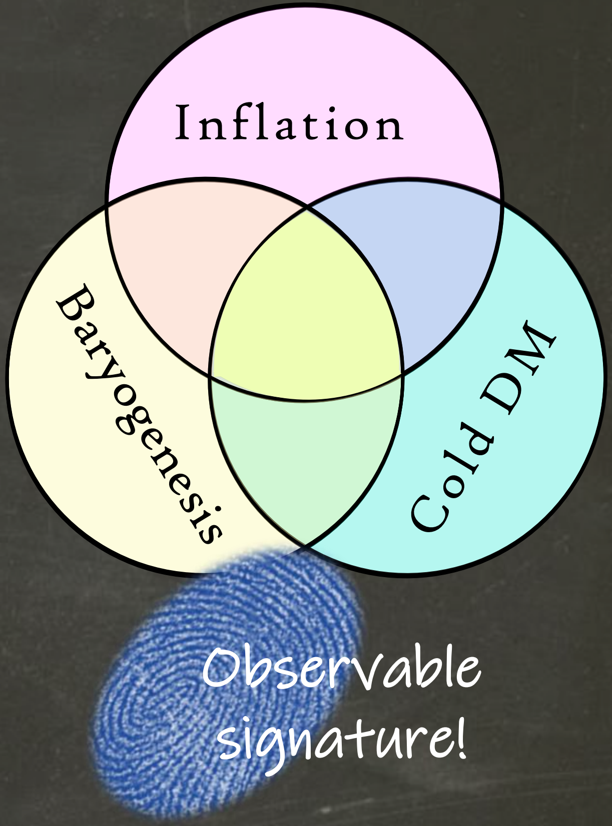
- Fermions & QFT Anomalies

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

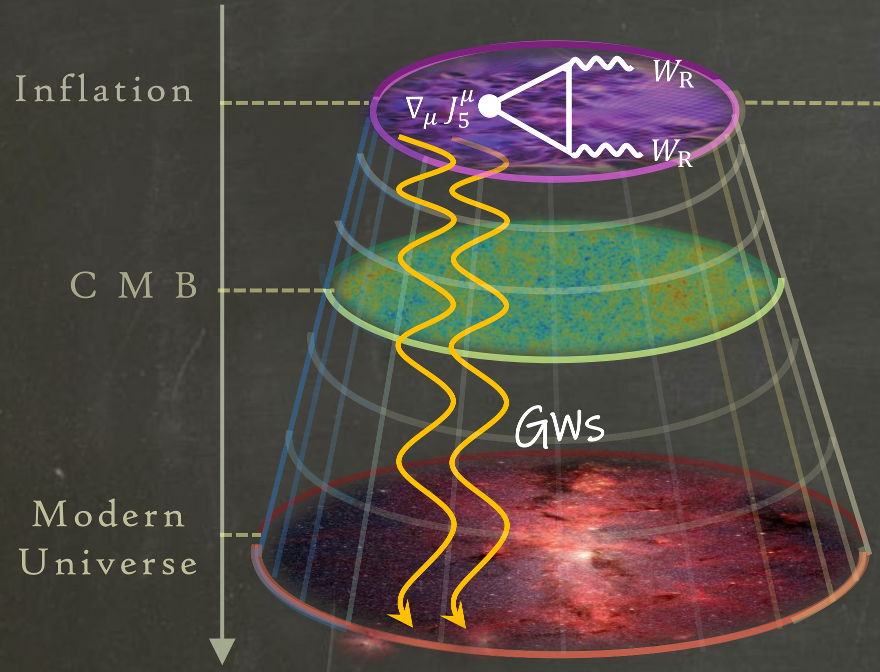
Adler–Bell–Jackiw anomaly

(Global) Gravitational anomaly

- Gravitational Waves Signature



Setup:



I) Recap on Early Universe

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

III) inflation & Particle Physics

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

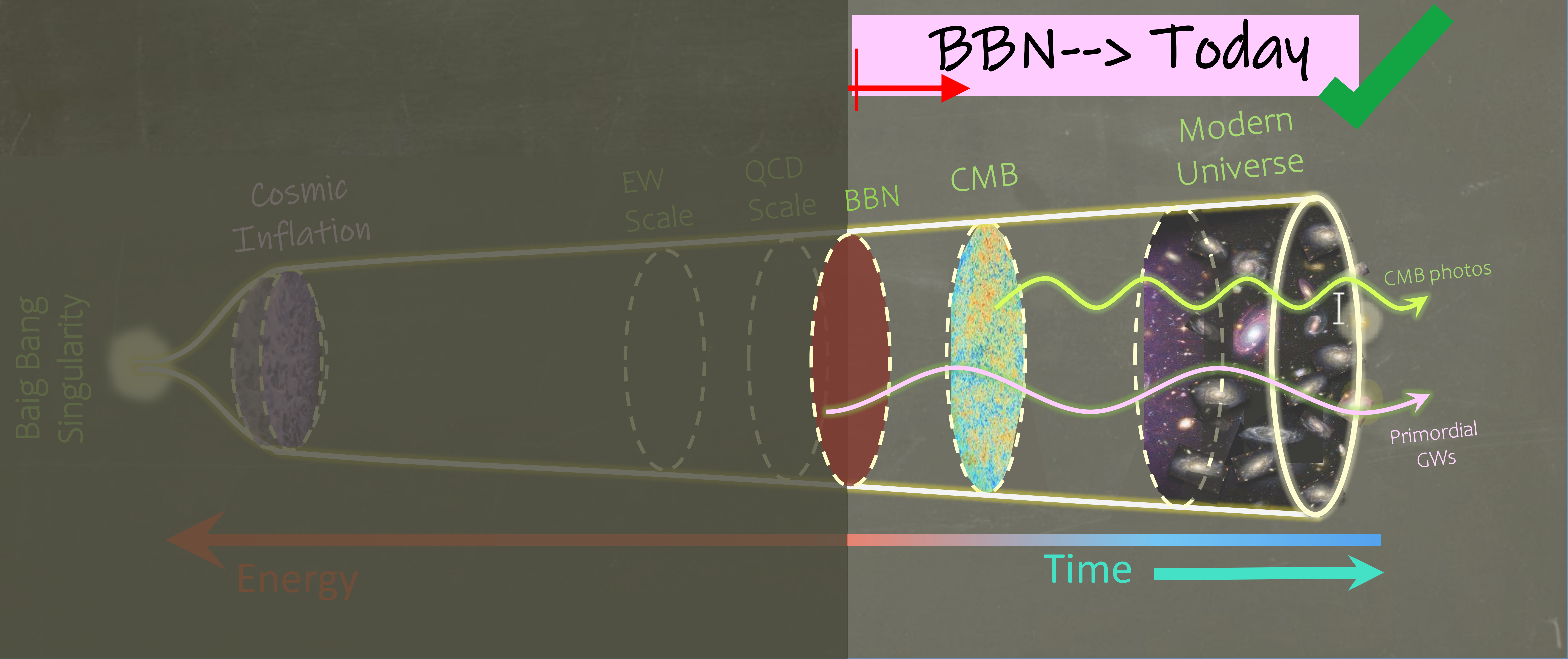
IV) Open Questions and Future Directions

I) Early Universe

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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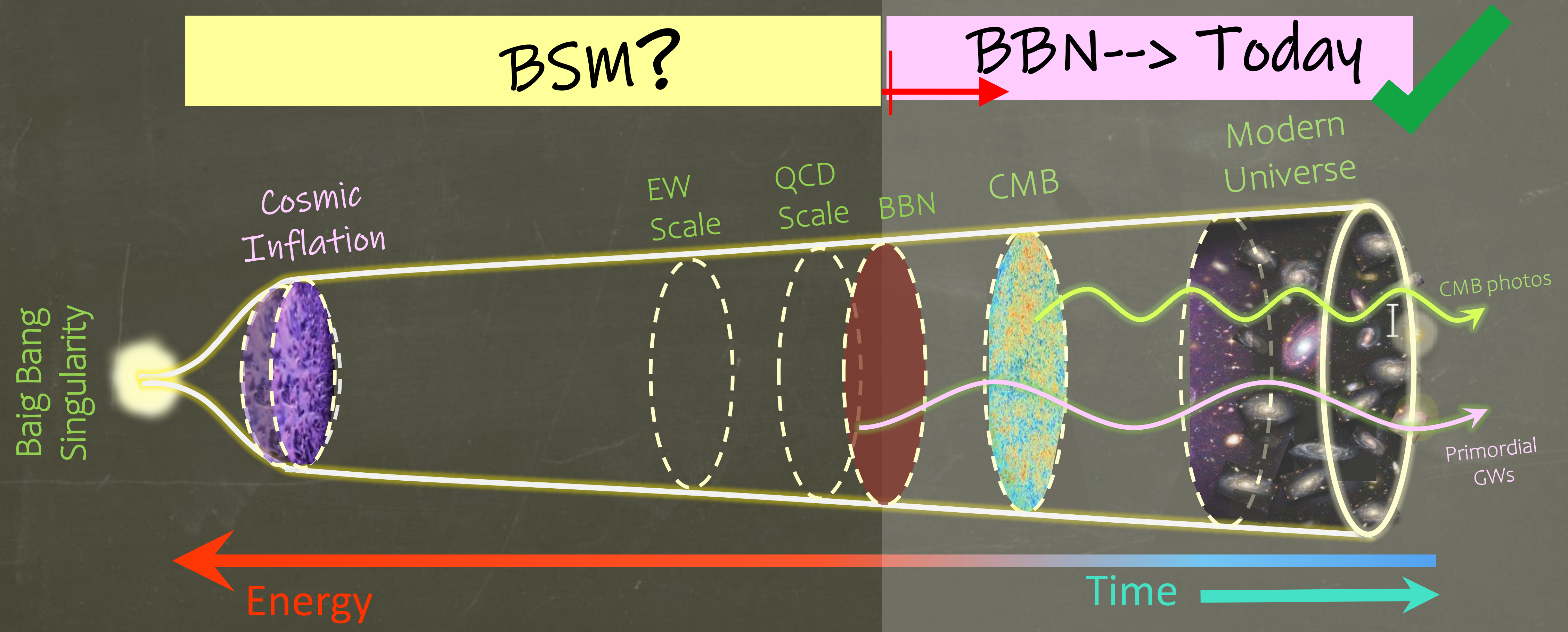
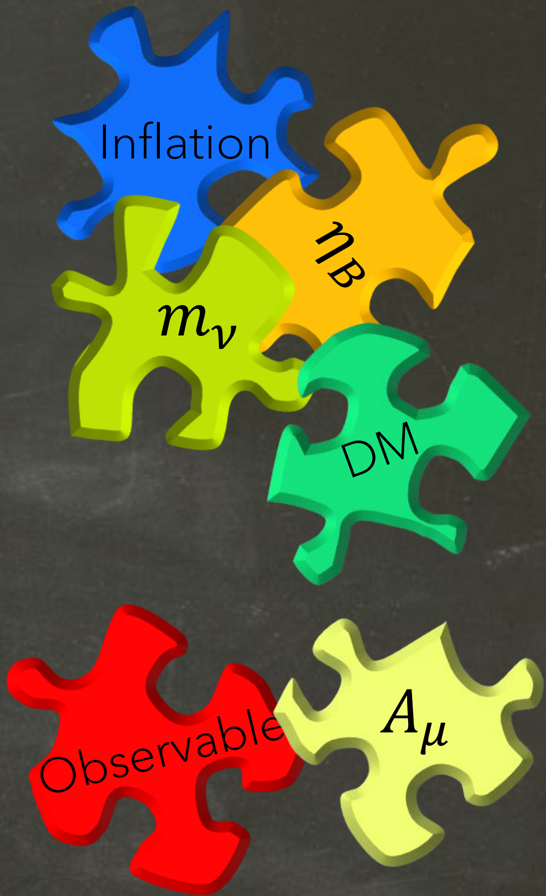
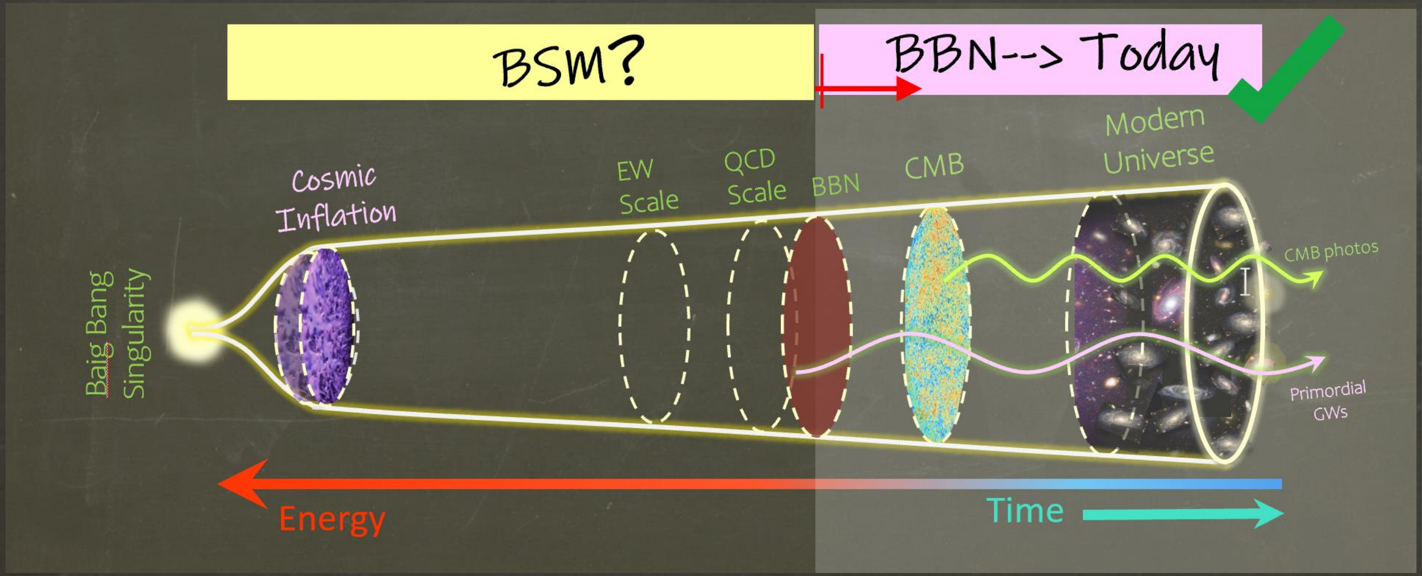


Puzzles of SM & Cosmology

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





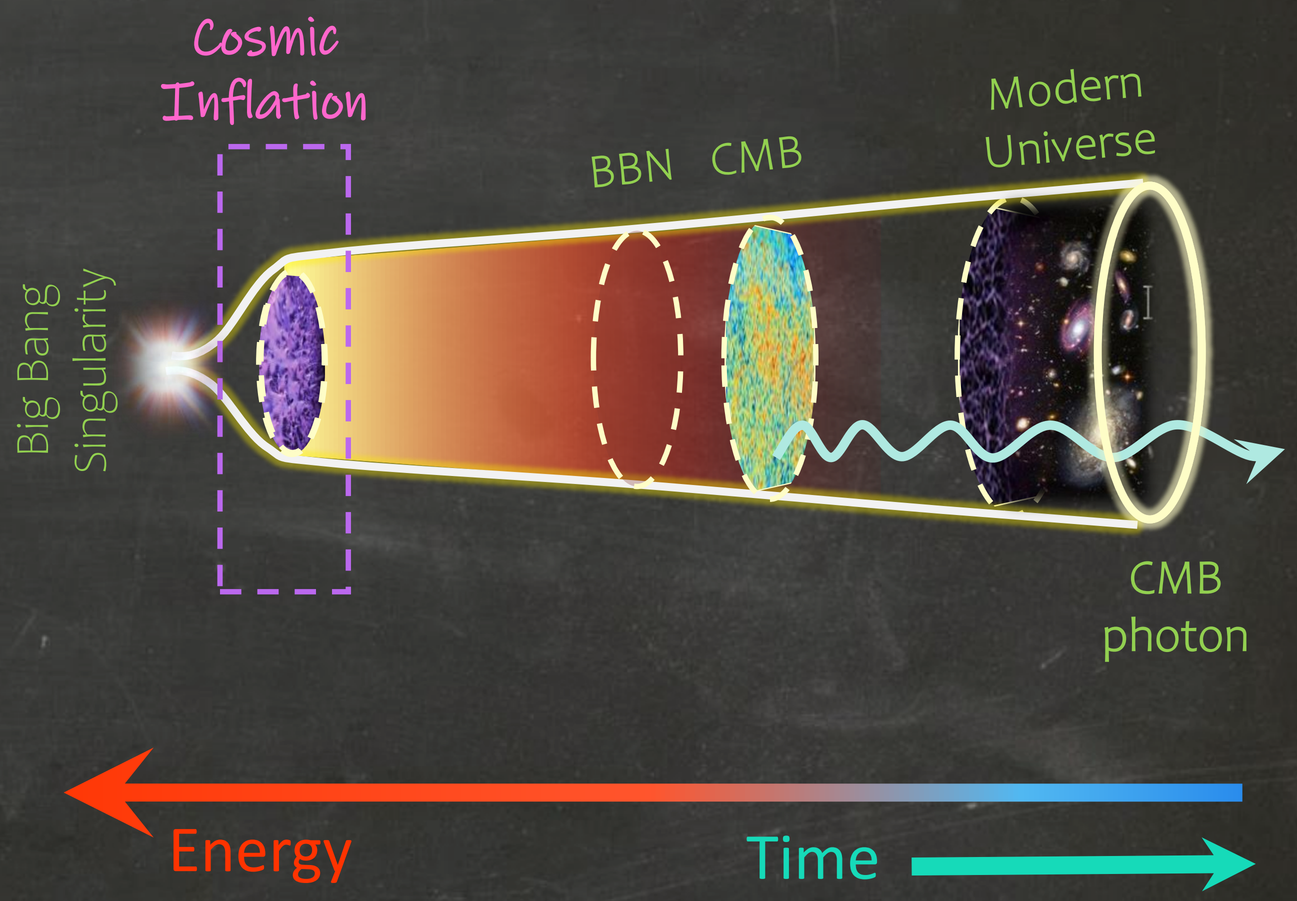
Cosmic Inflation

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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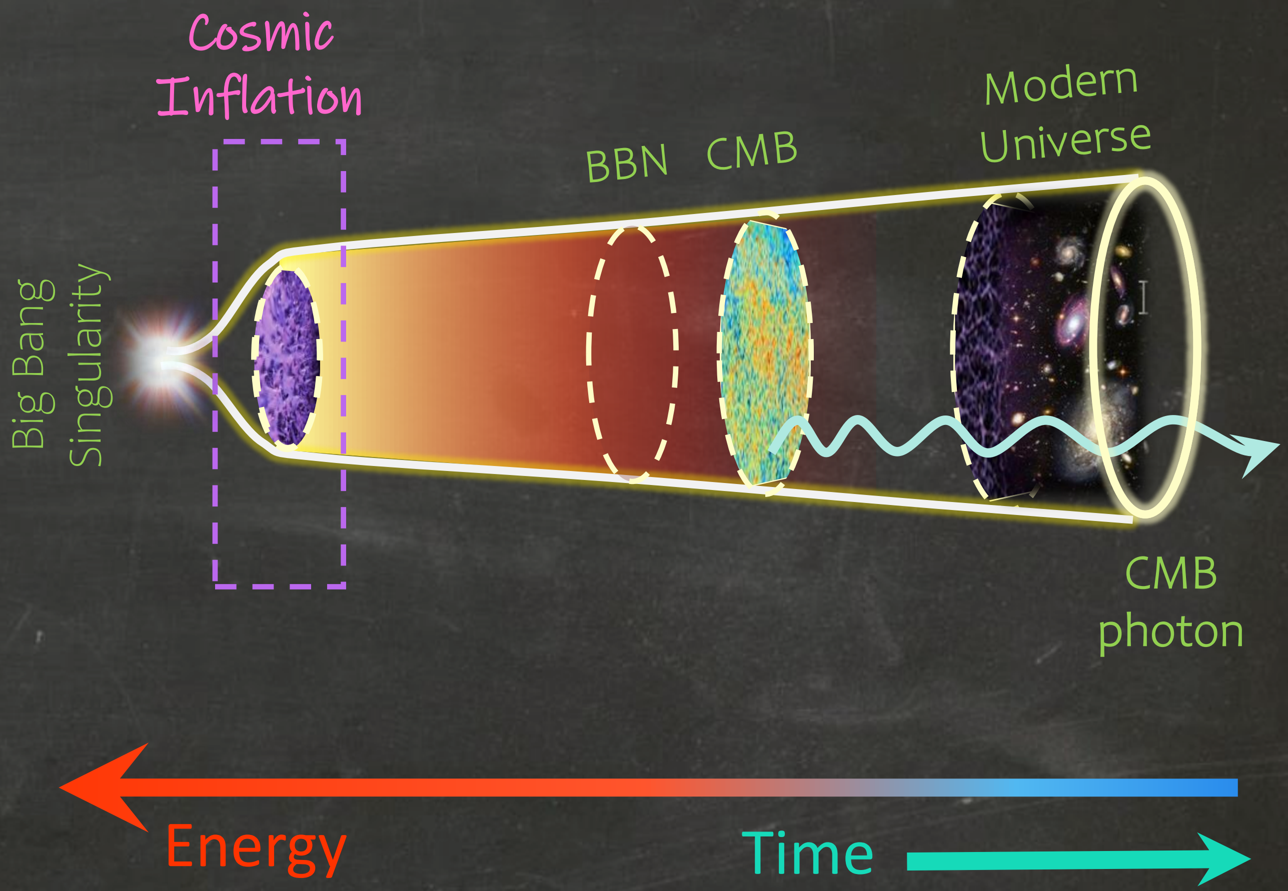
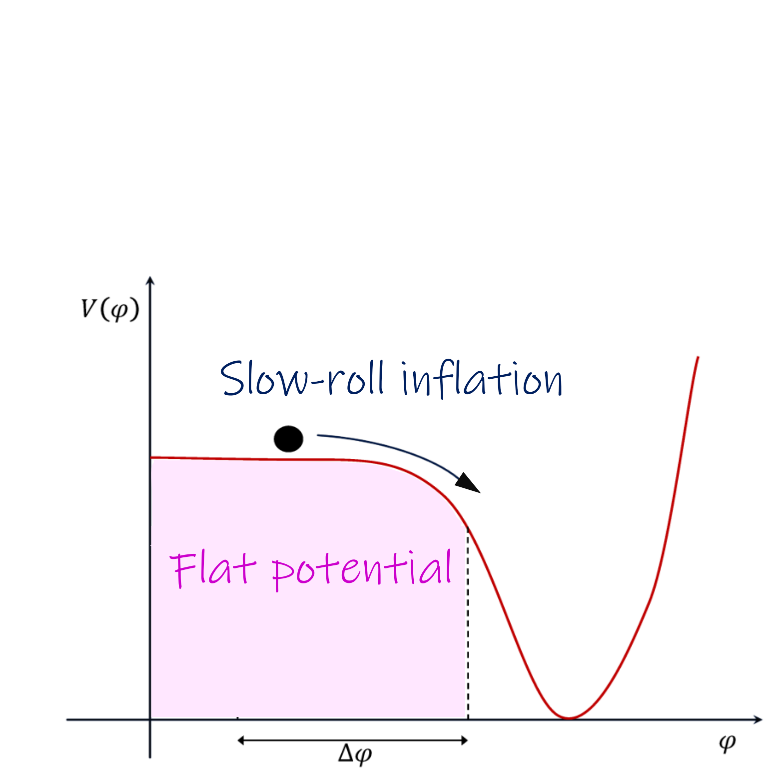
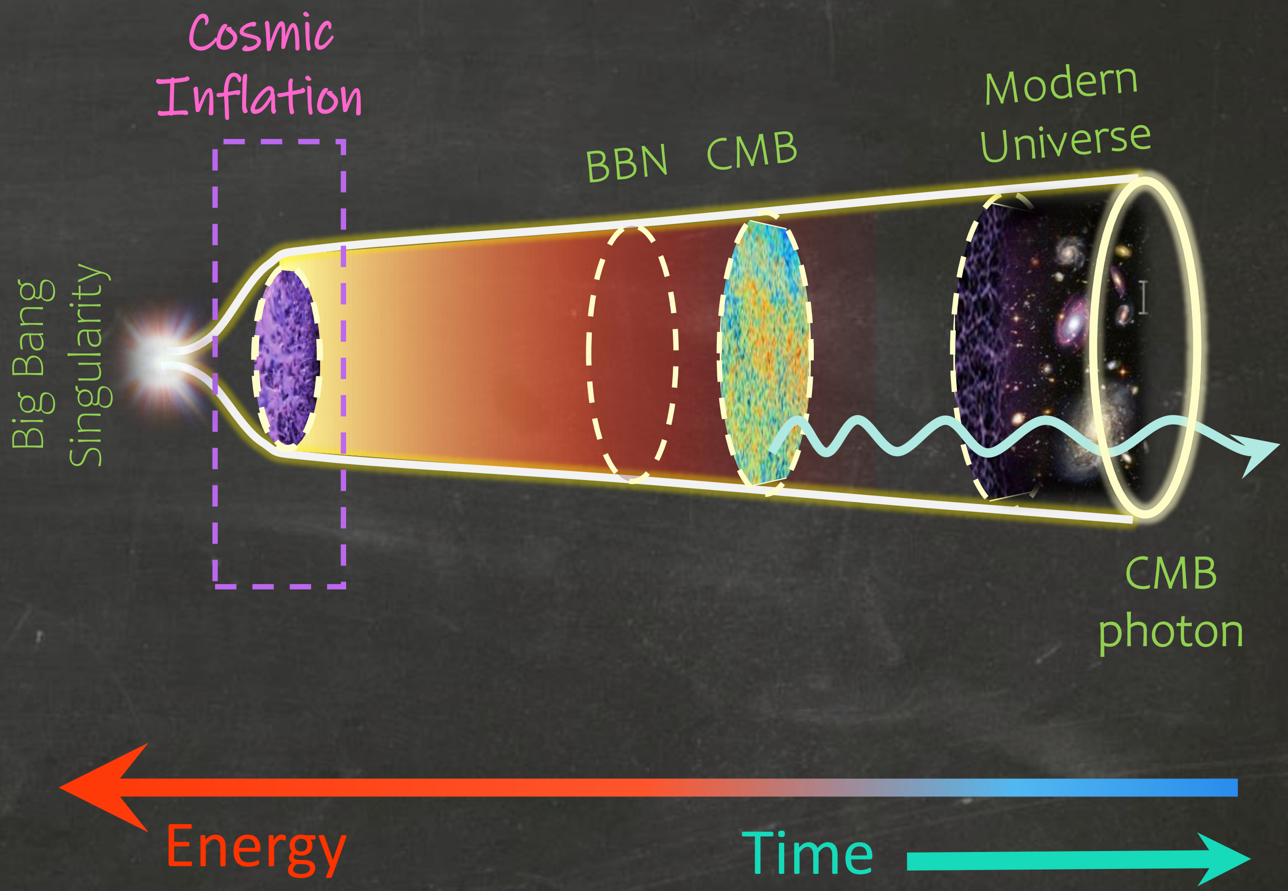


What caused inflation?

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





Quantum Fluctuations in Cosmology

$$\hbar \neq 0$$

Quantum Vacuum $\hbar \neq 0$

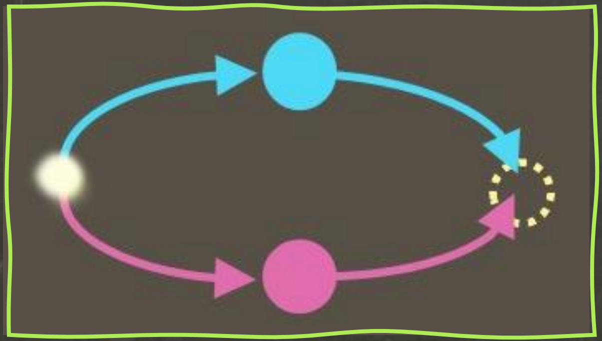
Due to Uncertainty Principle

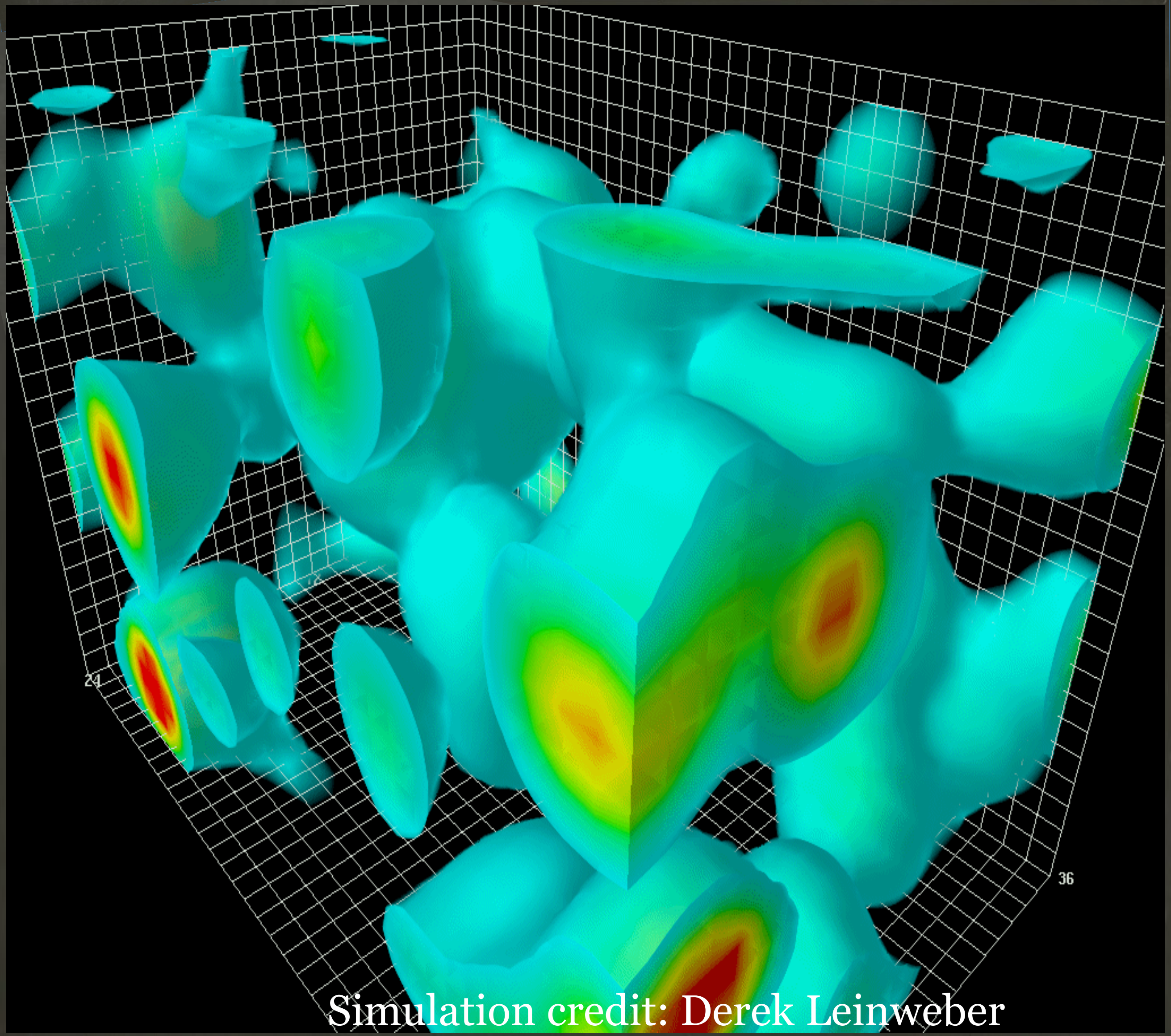
$$\Delta x\, \Delta p \geq \hbar/2$$

quantum vacuum is NOT nothing!

But, a vast ocean made of

Virtual particles

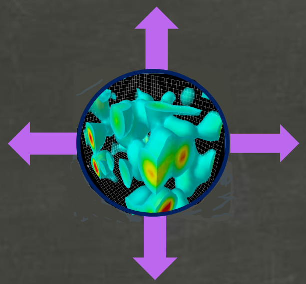
vacuum  vacuum



Simulation credit: Derek Leinweber

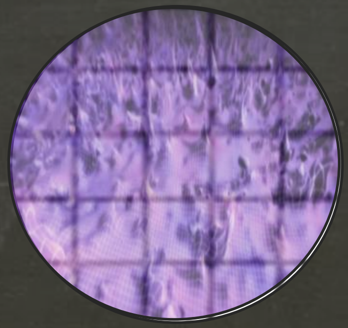
Cosmic Perturbations

Cosmic inflation turns initial quantum vacuum fluctuations



a_i

into actual cosmic perturbations.



a_f

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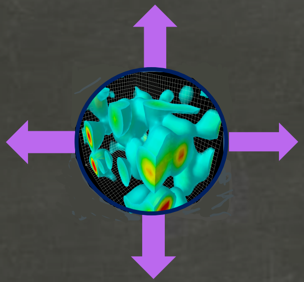

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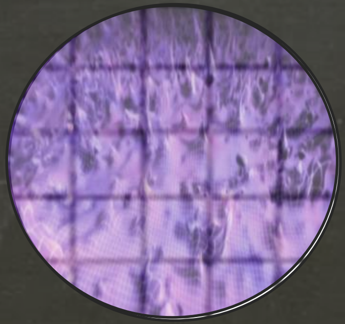
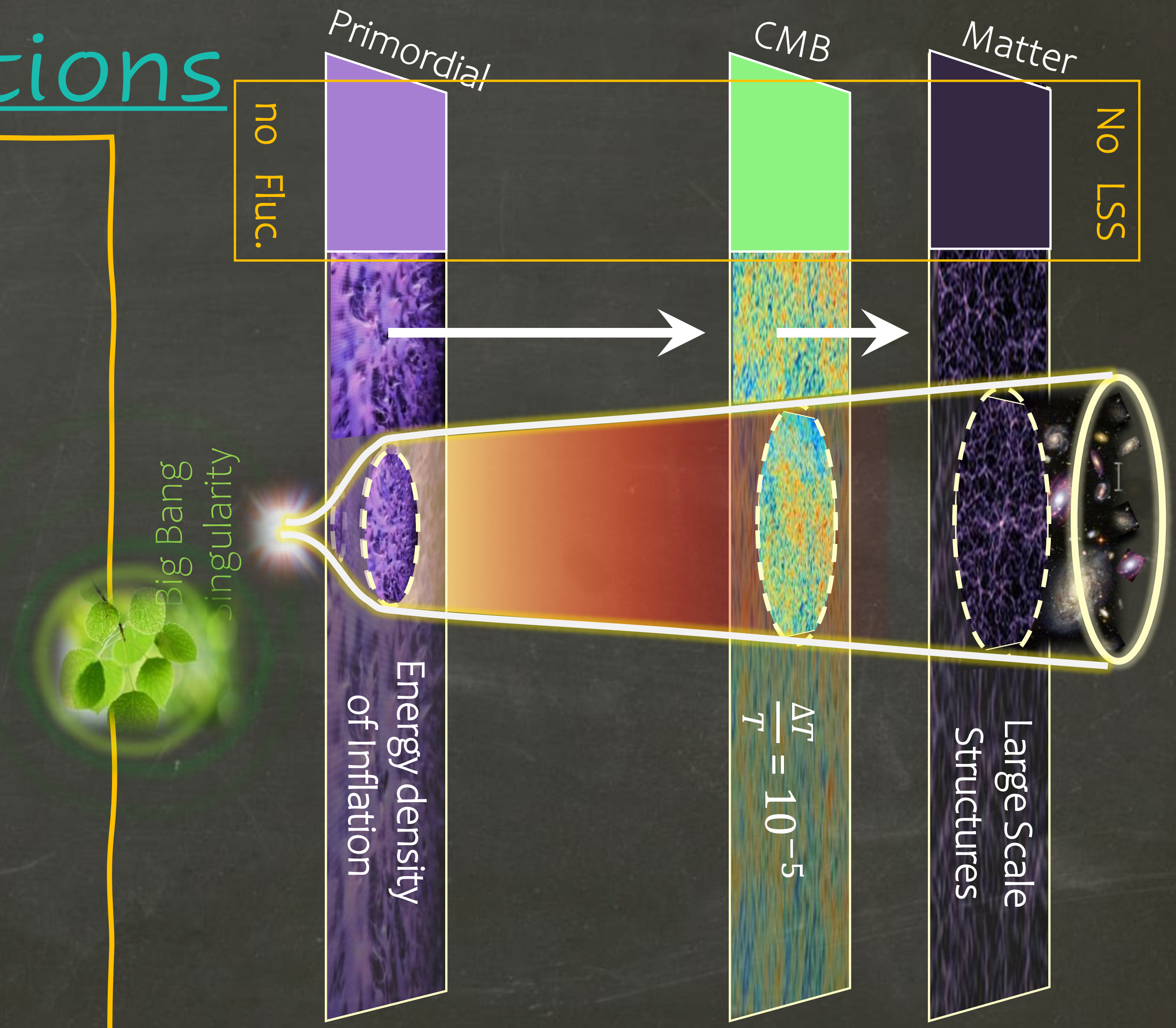
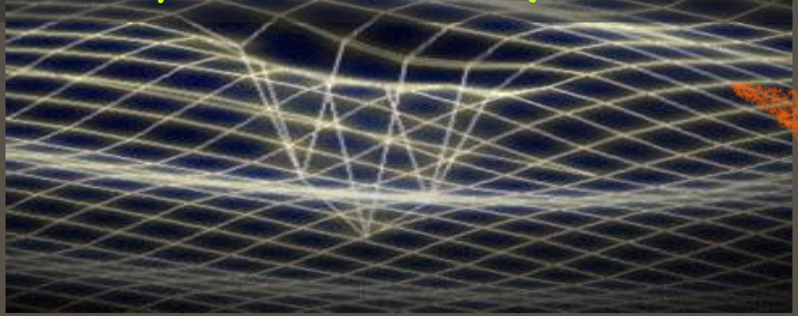


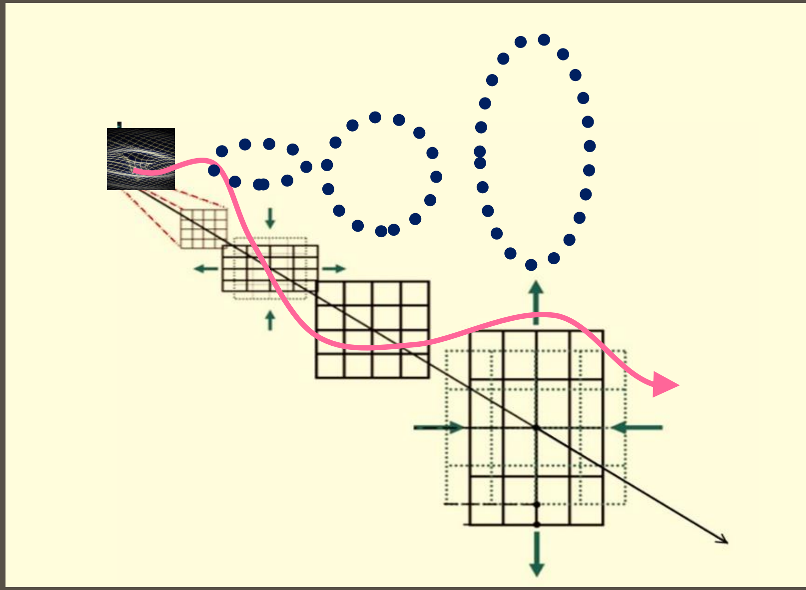
a_f



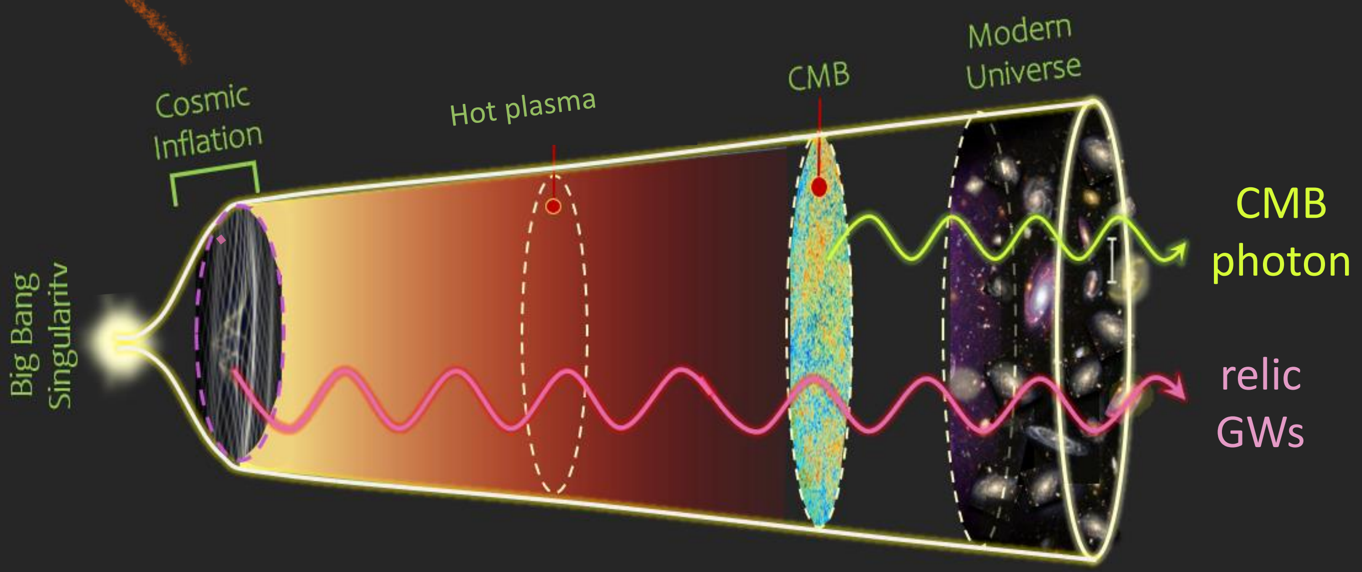
Primordial Gravitational Waves

Inflation also predicts **primordial GWs:**





Primordial GWs: tiny waves in the fabrics of the space-time that squeeze and stretch anything in their path as they pass by.



Primordial Gravitational Waves

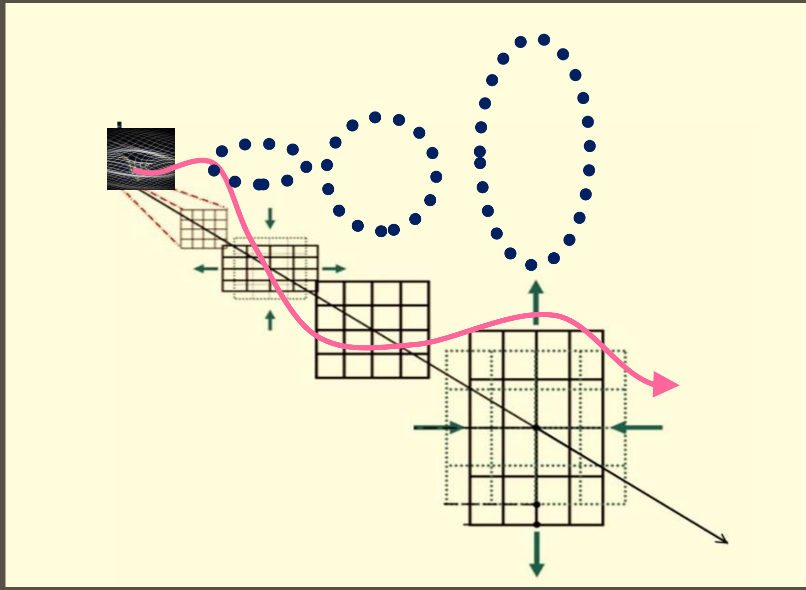
- Vacuum GWs

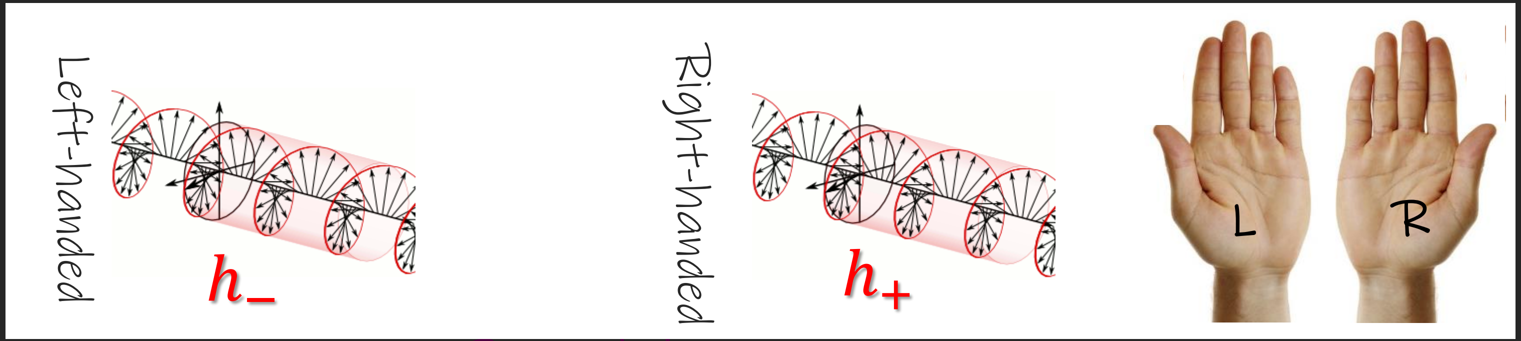
$$\Box h_{ij} = 0 \rightarrow h_{\pm} = h_{\pm}^{vac}$$

- Unpolarizaed

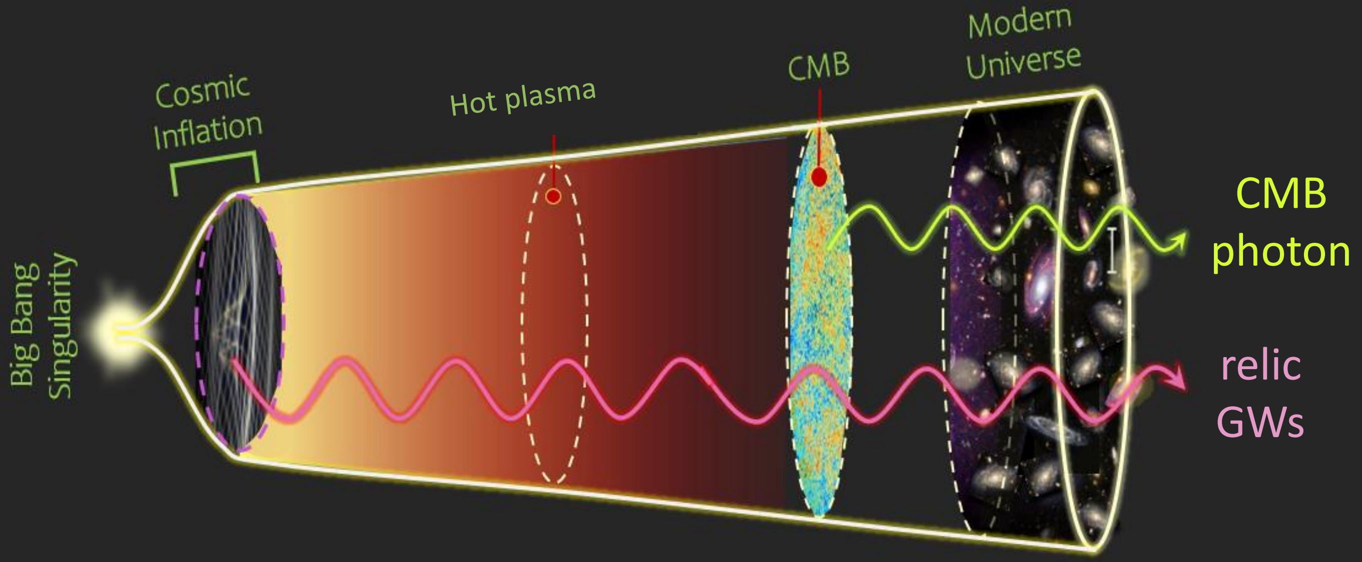
$$<|h_{+}^{vac}|^2> = <|h_{-}^{vac}|^2>$$

- Nearly Gaussian





Circular polarizations



Cosmic Perturbations-Gravitational Waves

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  - Unpolarizaed

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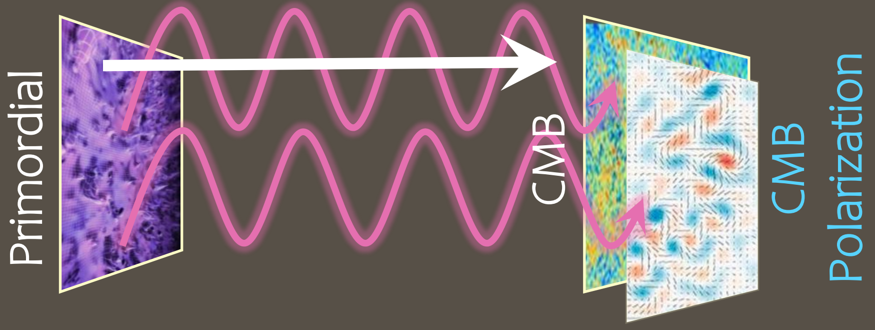
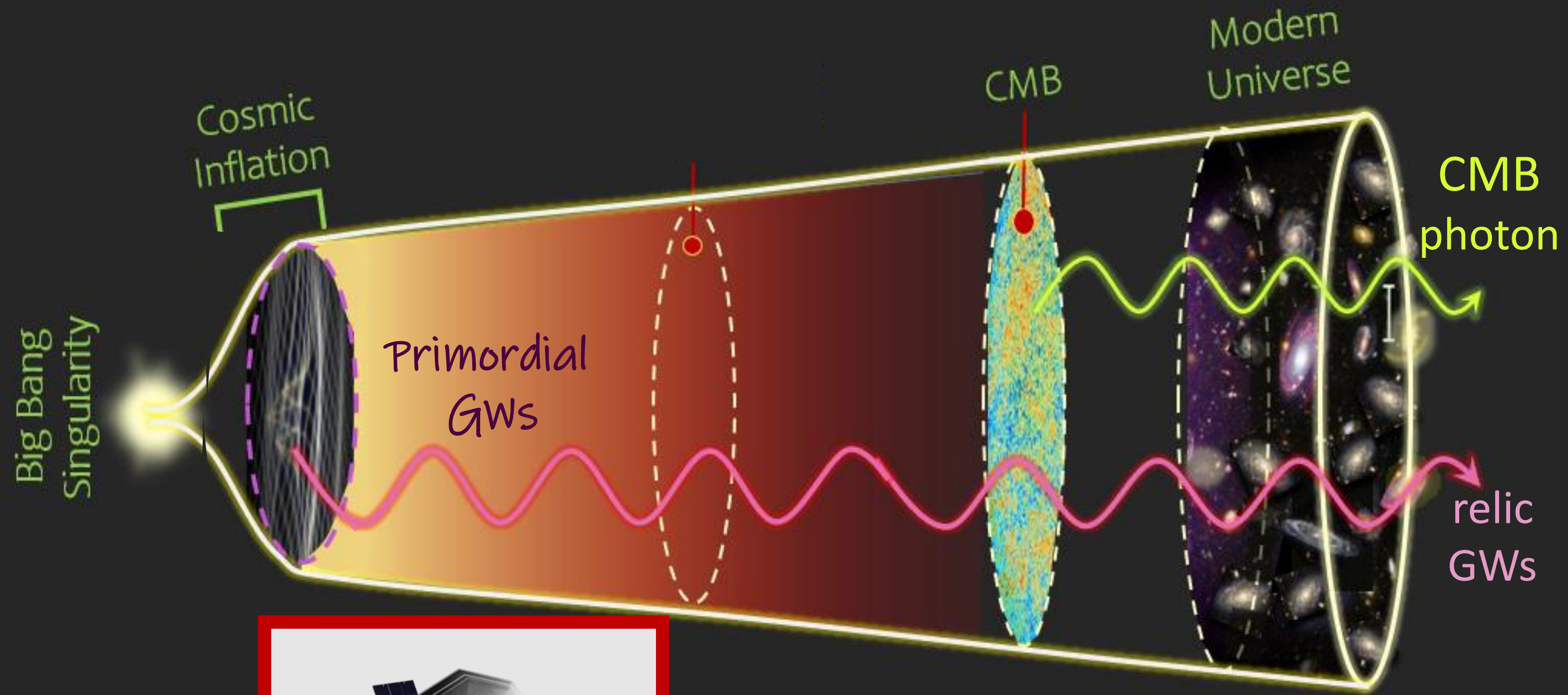
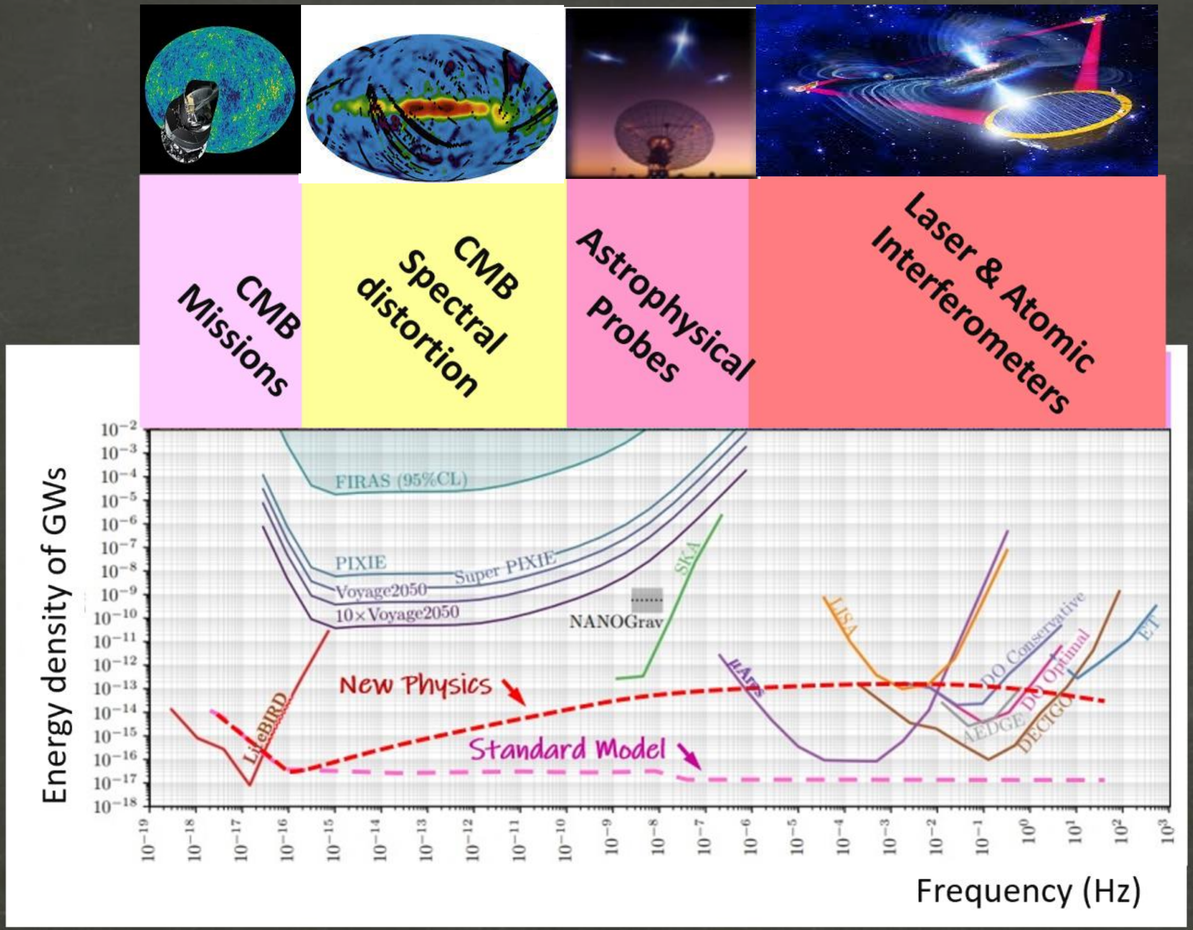
  - Nearly Gaussian
  - CMB polarization





CMB-S4
Next Generation CMB Experiment

Sensitivity curves on energy density of GWs



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

Networks of GWs Detectors

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

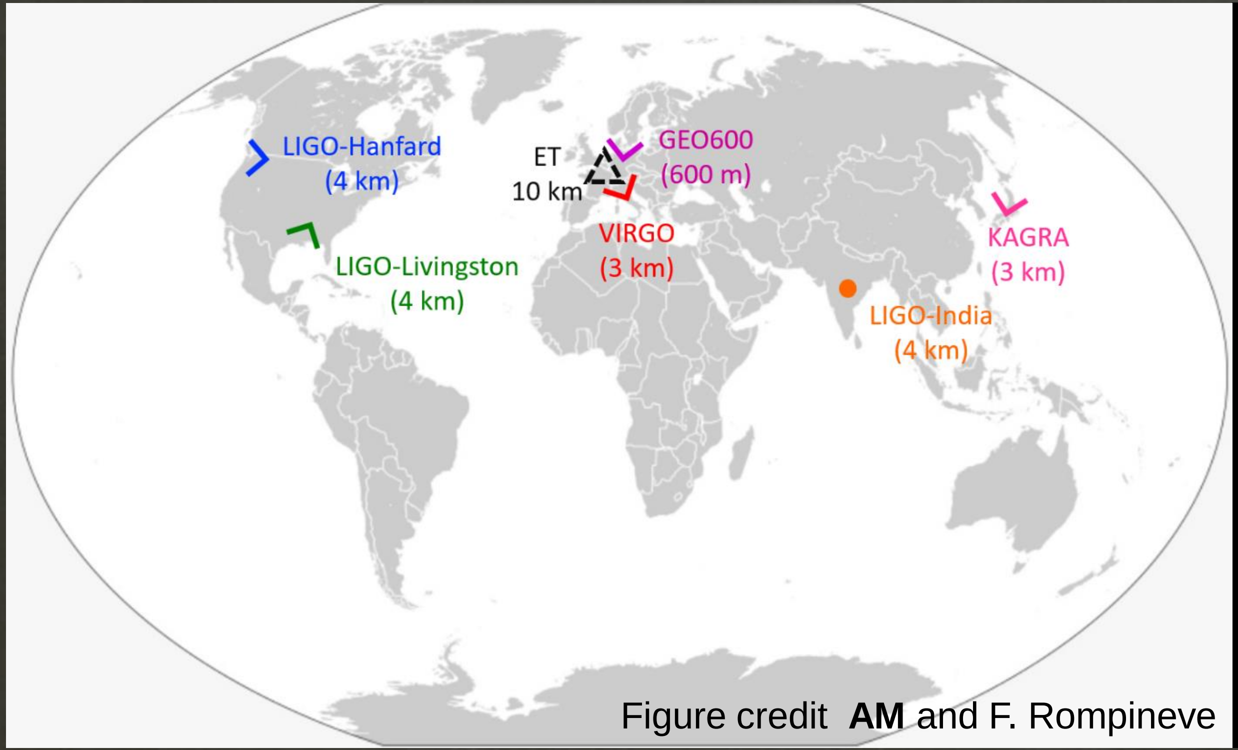
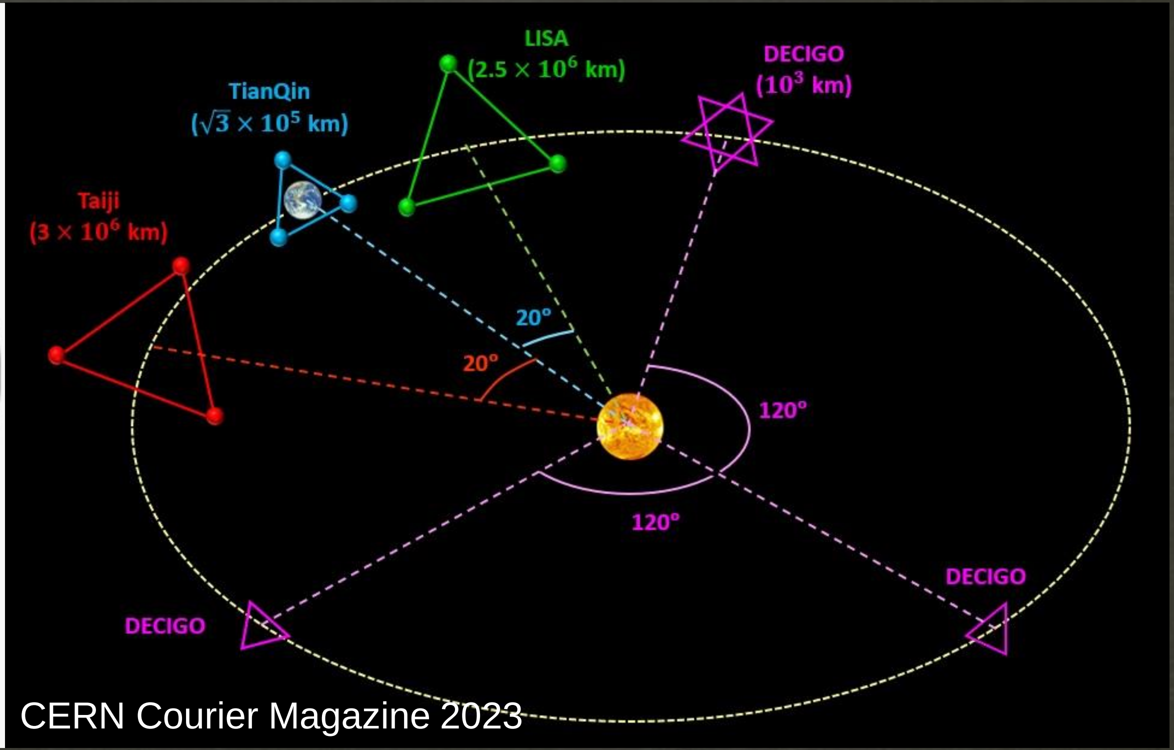


Figure credit **AM** and F. Rompineve

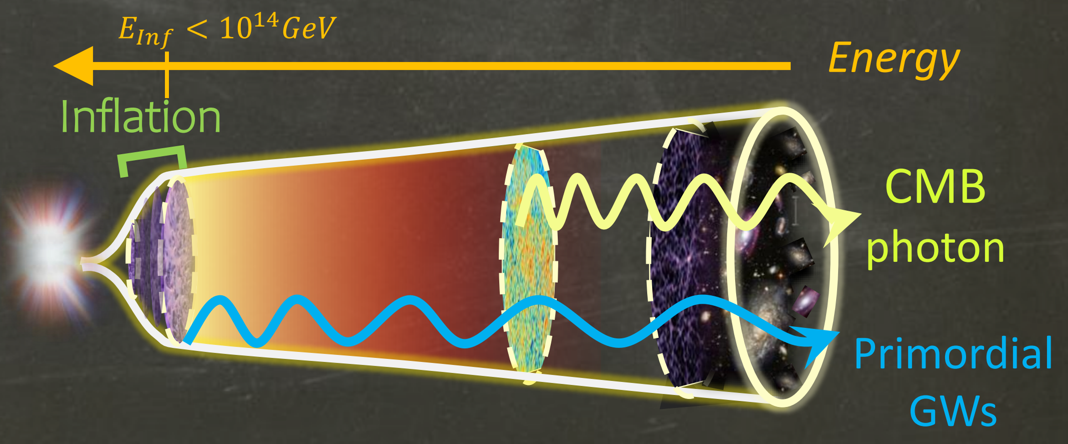


CERN Courier Magazine 2023

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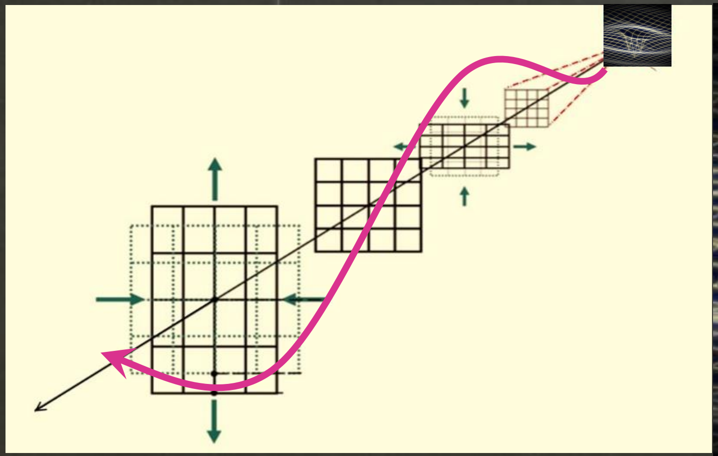
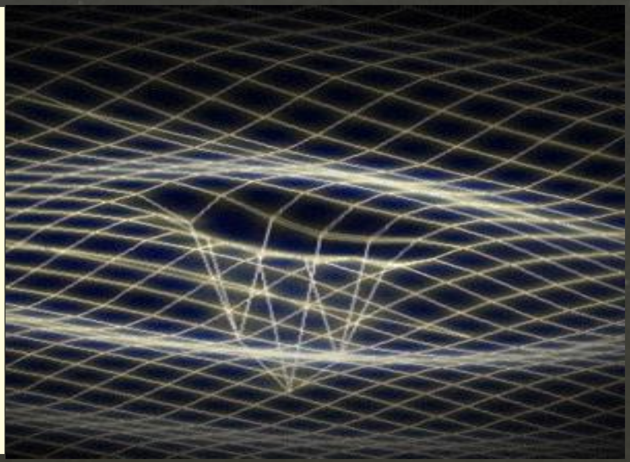
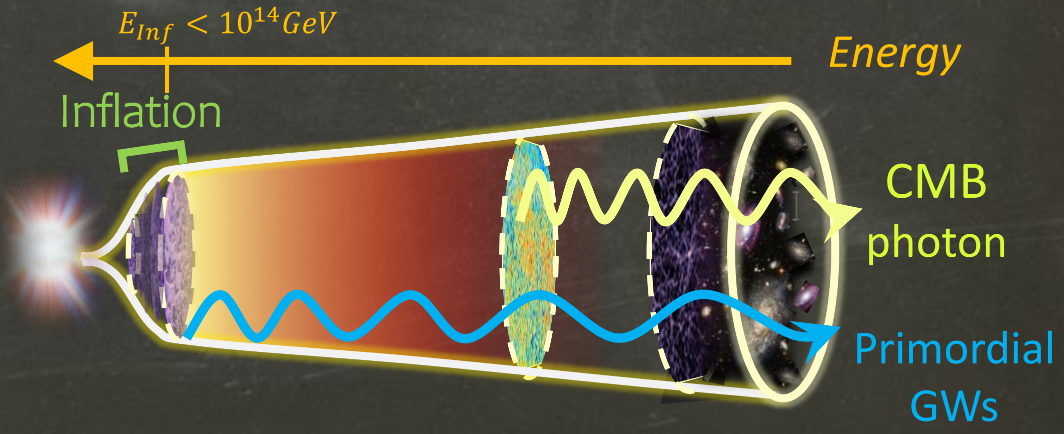
  Vacuum fluctuations: unpolarized, red-tilted, and nearly Gaussian.







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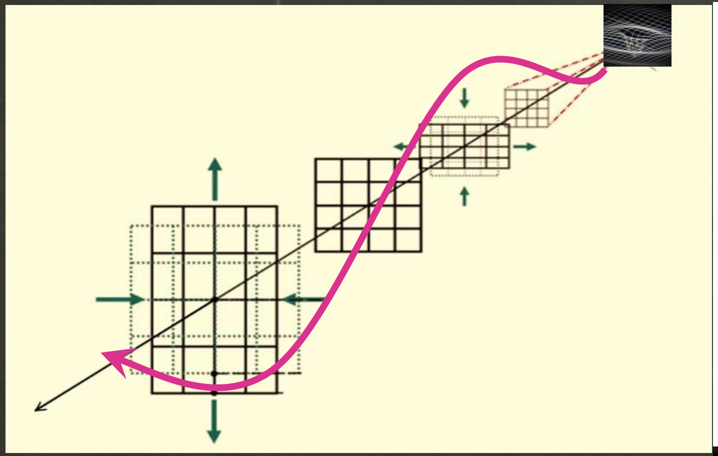
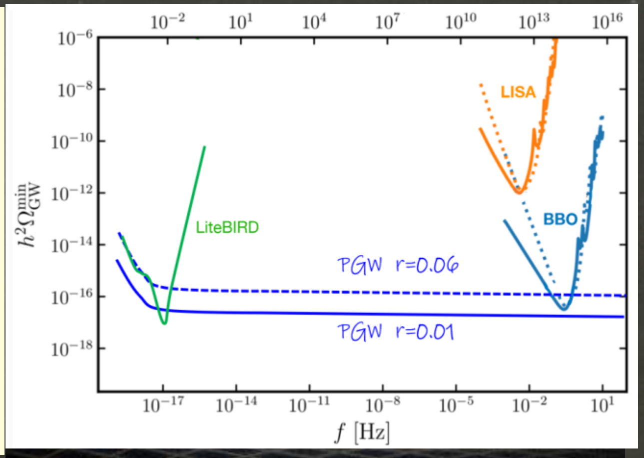
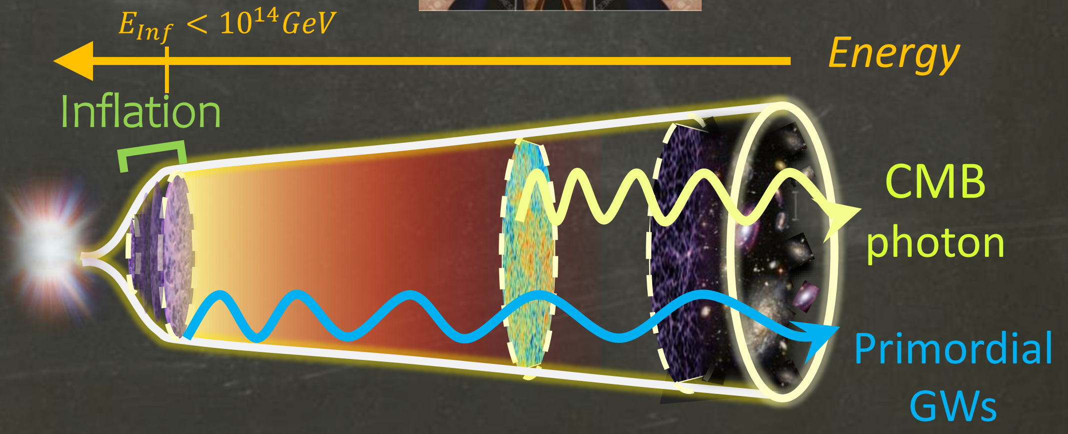
Parity is the symmetry







As Yet

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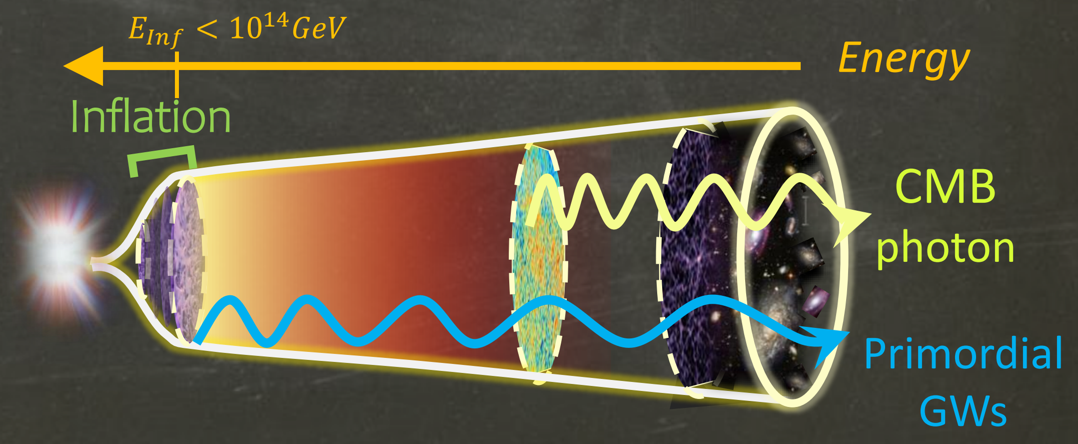
What about Gauge Fields?!

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



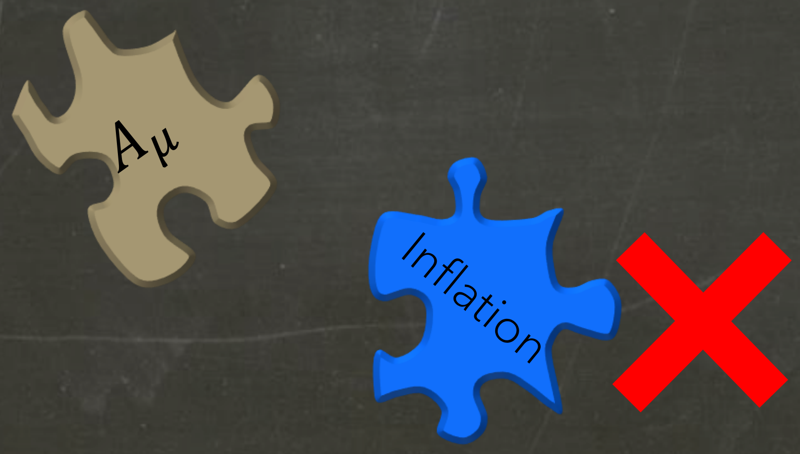
II) Axion-inflation & gauge fields

(non-Abelian)

Challenges:

Gauge fields given by Yang-Mills

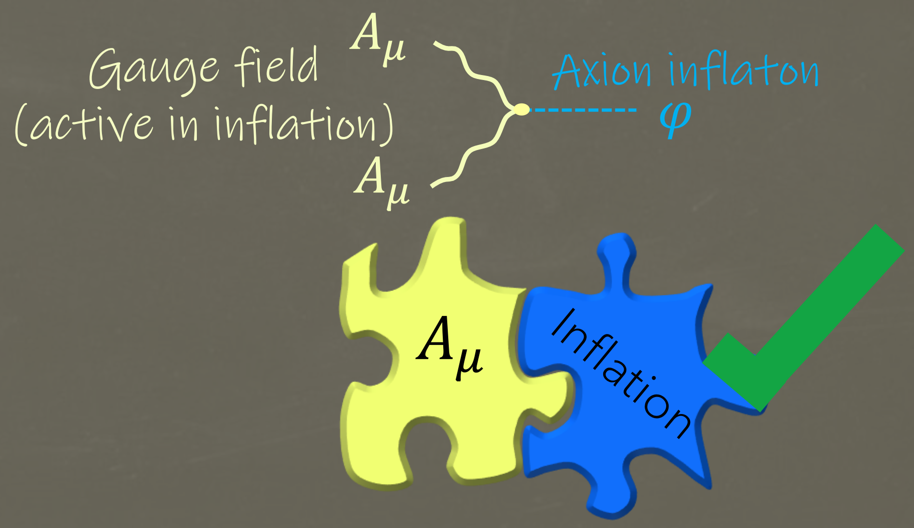
dilutes like radiation $A_\mu \sim 1/a$



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.)



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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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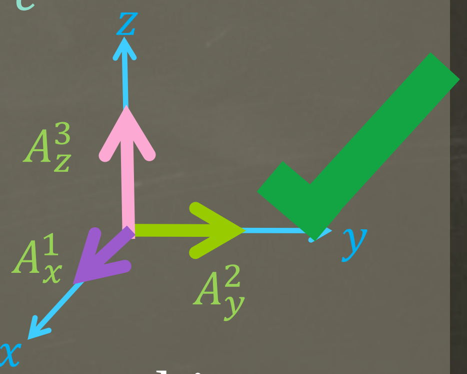
A.M. & Sheikh-Jabbari, 2011

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

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



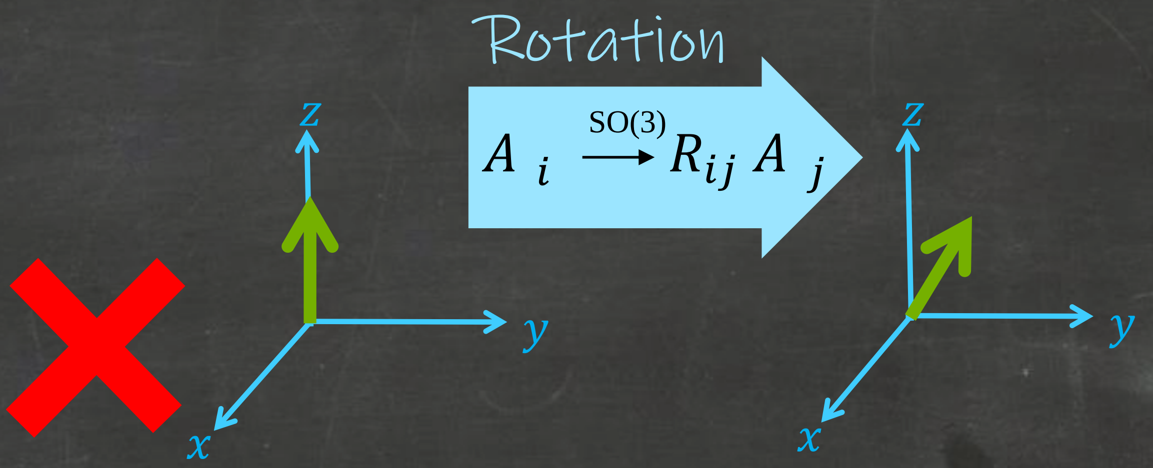
so(3) & su(2) are isomorphic

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, $A_\mu = A_\mu^a T_a$

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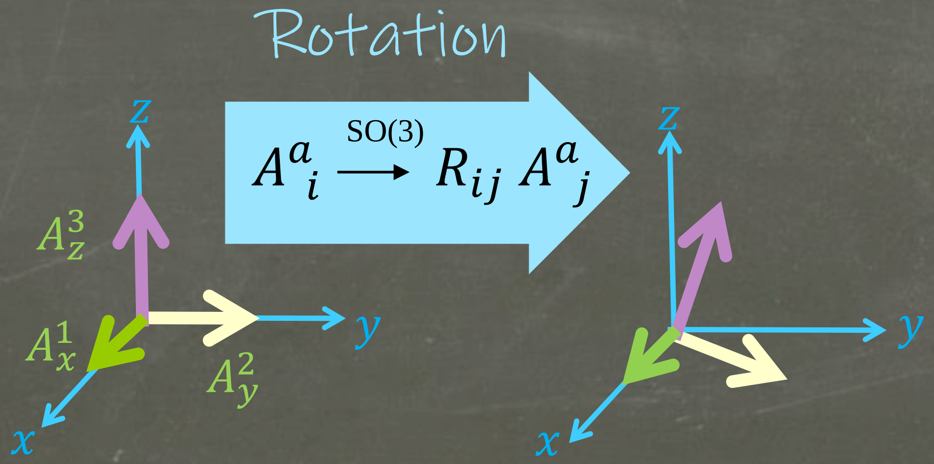

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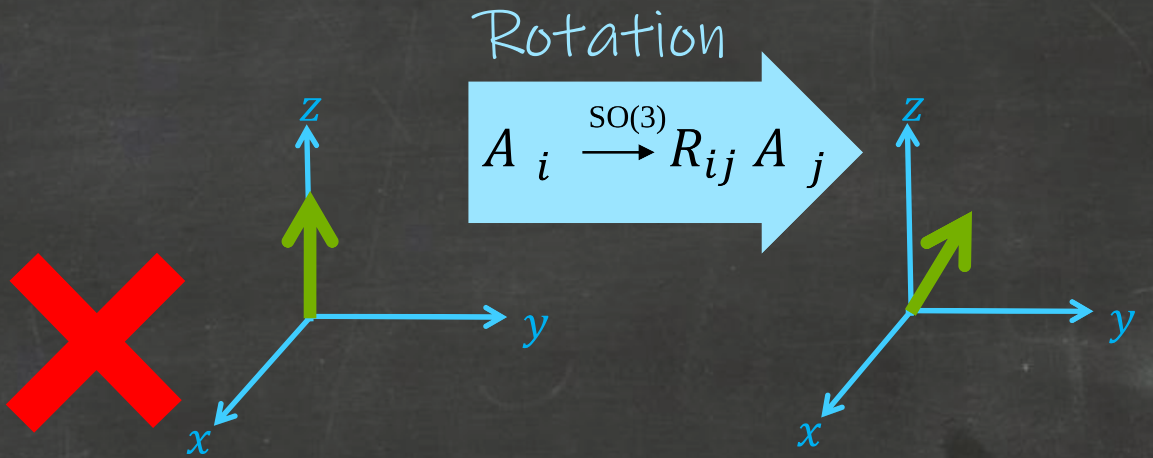

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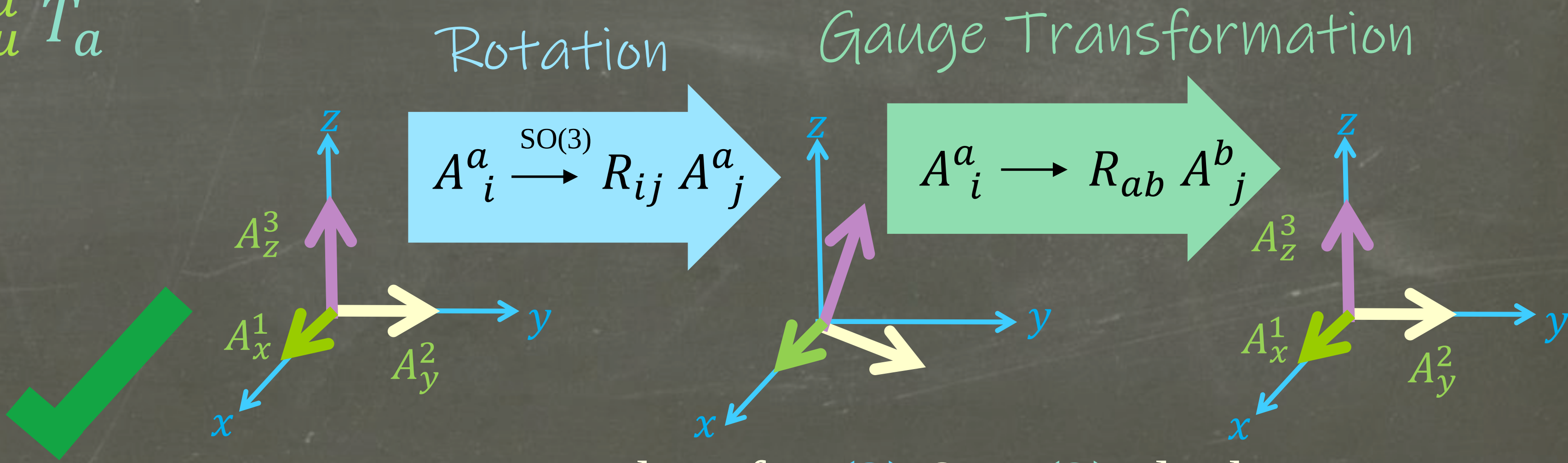


A.M. and M. M. Sheikh-Jabbari, 2011

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

SU(2) Gauge fields and Initial Anisotropies

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

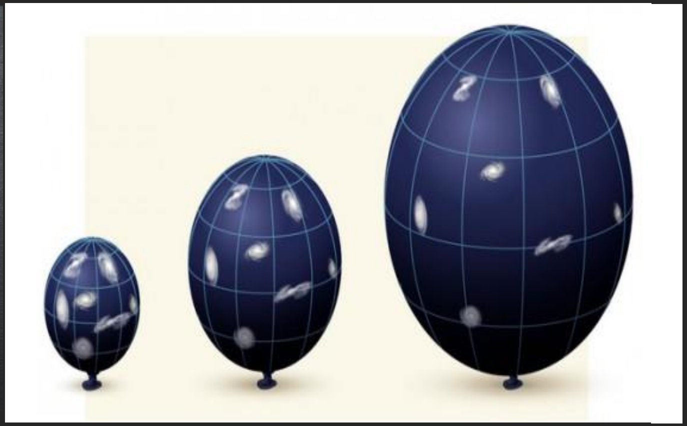
$$A^a_\mu(t) = \begin{cases} 0 & \mu = 0 \\ Q(t)a(t)\delta^a_i & \mu = i \end{cases}$$

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 $Tr[\lambda_{ij}(t)] = 0$



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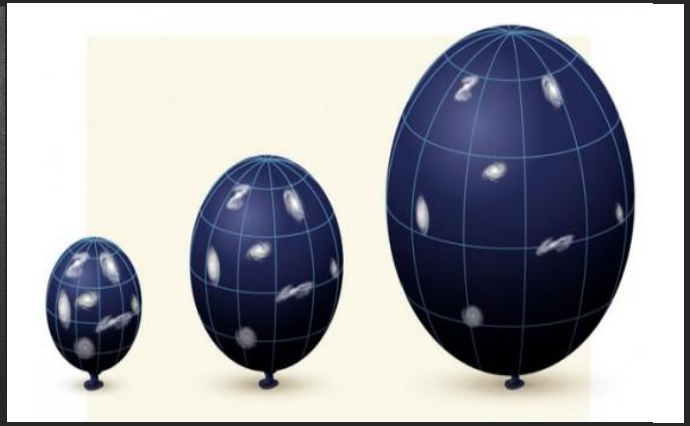
$$(2+\lambda^6)(\frac{\lambda''}{\lambda} + 3\frac{\lambda'}{\lambda}) - 6\frac{\lambda'^2}{\lambda^2} + (\lambda^6 - 1)(2 + \lambda^2\gamma) \simeq 0\,,$$

$\lambda = \pm 1$ Is the attractor solution!

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



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Isotropic Background

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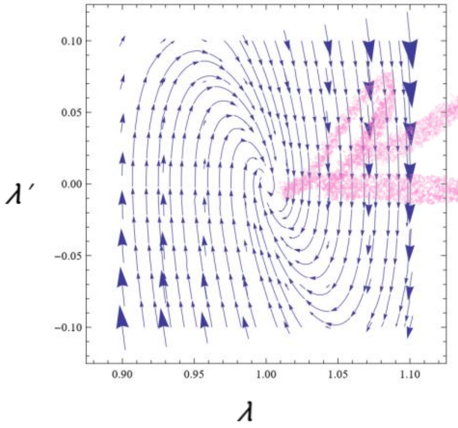
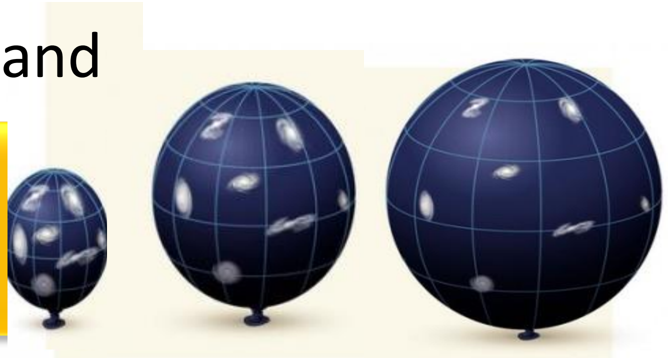
I. Wolfson, A. M., T. Murata, E. Komatsu, T. Kobayashi arXiv:2105.06259

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

Anisotropic part decays like radiation and



Isotropic Solution is the Attractor!



Anisotropic Background

A. M. and M.M. Sheikh-Jabbari, J. Soda, 2012

A. M. and E. Erfani, 2013

SU(2)-Axion Model Building

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

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

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

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

- 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

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]
16. A. Brandenburg, O. Iarygina, E. Sfakianakis, R. Sharma [arXiv:2408.17413]

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]

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

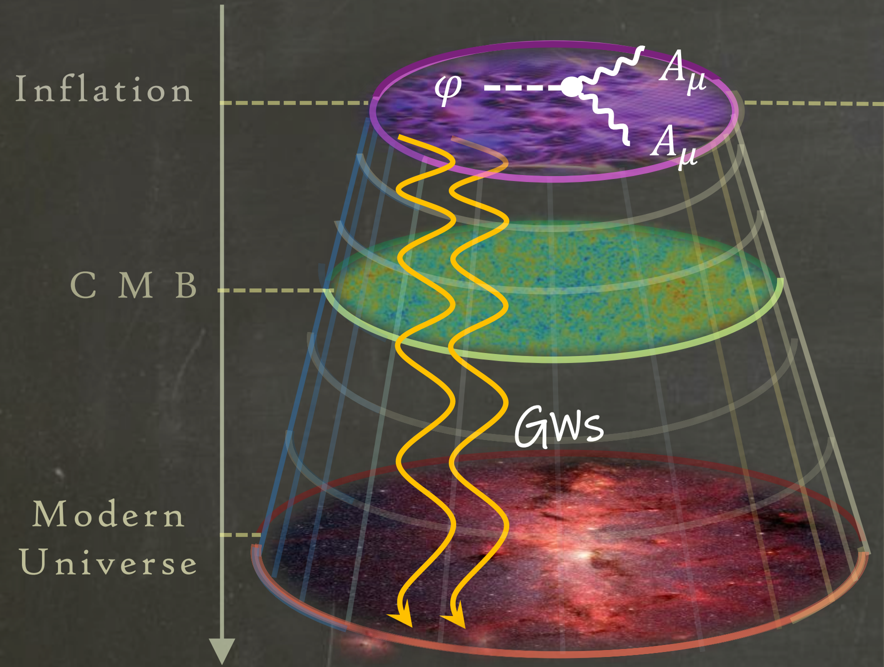
- A new mechanism for generation of Primordial Gravitational Waves
- All Sakharov conditions are satisfied in inflation: a new baryogenesis mechanism
- Particle Production in inflation by Schwinger effect and chiral anomaly
- Primordial Magnetic Fields…

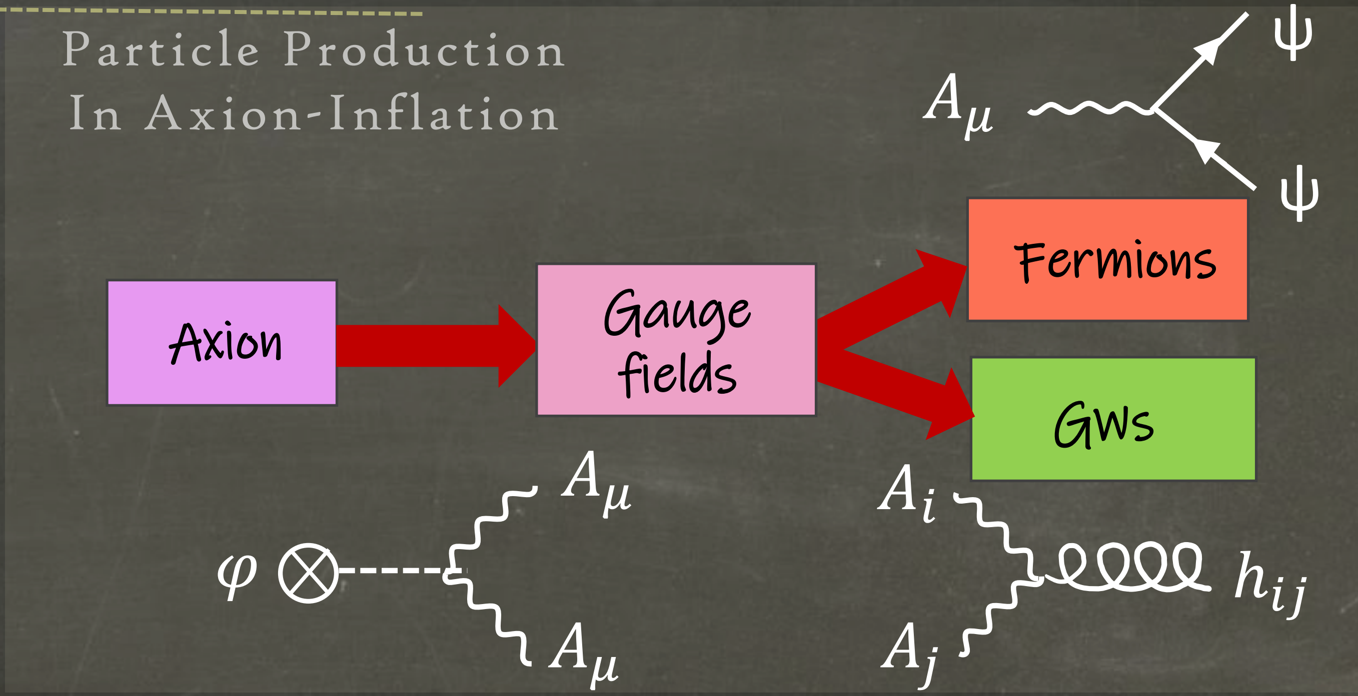
14. Oksana Iarygina, Evangelos I. Sfakianakis, [arXiv:2105.06972]
15. T. Fujita, Nakatsuka, K. Mukaida, & K. Murai [arXiv:2110.03228]
16. A. Brandenburg, O. Iarygina, E. Sfakianakis, R. Sharma [arXiv:2408.17413]

Inflation Particle Physics

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

Axion-inflation and gauge fields (non-Abelian)





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

A. M. et. al, 2011 & 2013
Dimastrogiovanni et. al 2013
P. Adshead et. al, 2013

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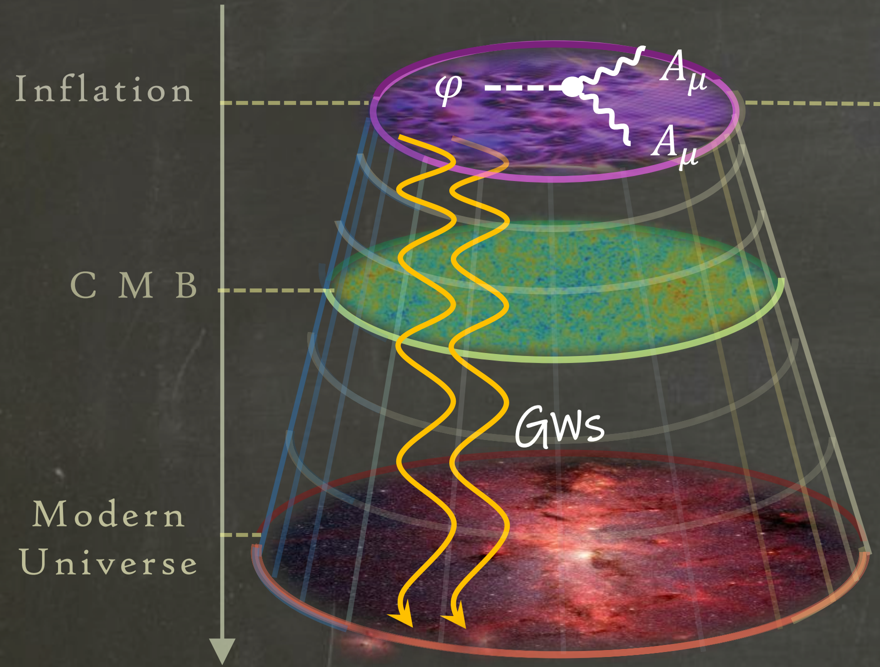
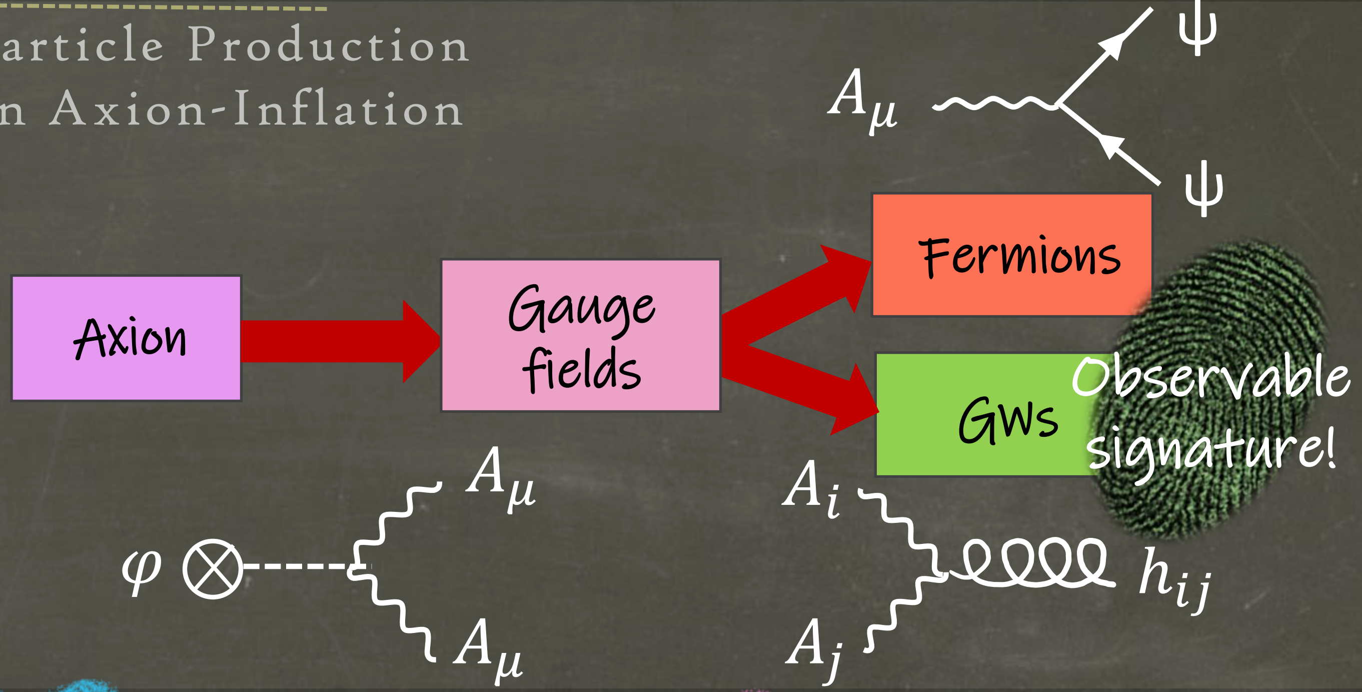


Particle Production
In Axion-Inflation



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

A. M. et. al, 2011 & 2013
Dimastrogiovanni et. al 2013
P. Adshead et. al,2013

Vacuum GWs:
Unpolarized & Gaussian

Sourced GWs:
Chiral & non-Gaussian

New Tensorial mode in SU(2) Gauge Field

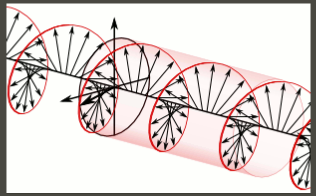
- $\delta A_i^a = \left(B_+(t,k)e^+_{ij}(\vec{k}) + B_-(t,k)e^-_{ij}(\vec{k})\right)\delta_j^a$

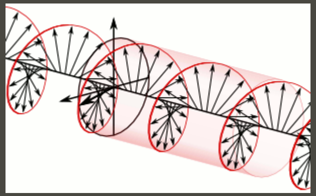
$$B''_\pm + \left[k^2 \mp \delta_C k\mathcal{H} + \frac{m^2}{H^2}\mathcal{H}^2 - \frac{a''}{a}\right] B_\pm \approx 0$$

effective frequency

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

Circular polarizations





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

A.M. & Sheikh-Jabbari, 2011

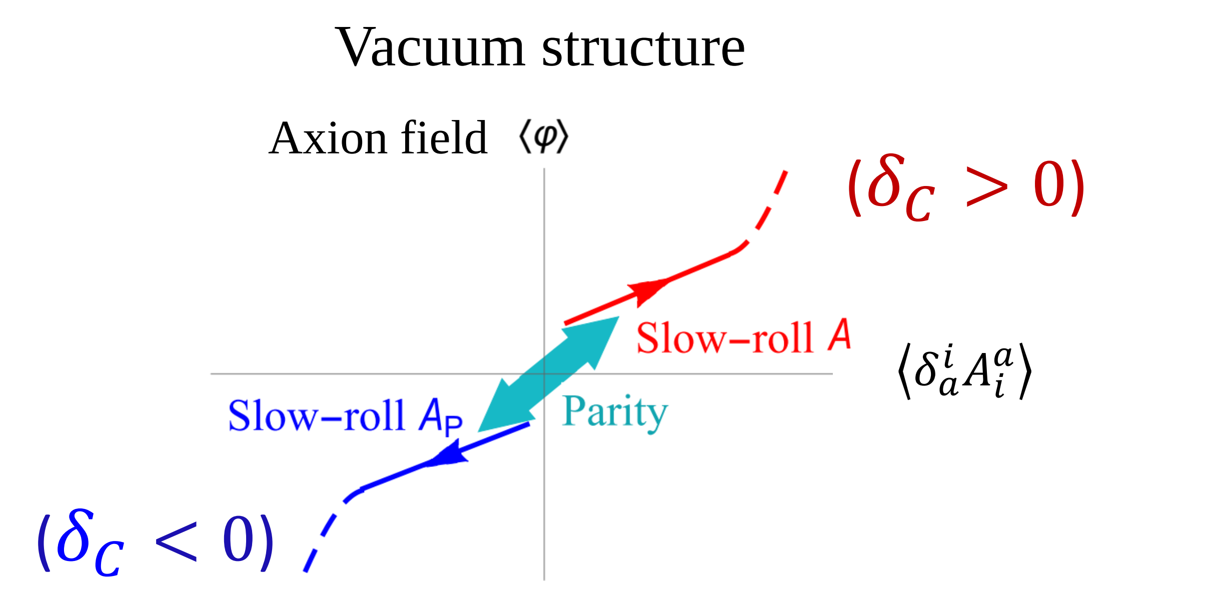
New Tensorial mode in SU(2) Gauge Field

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

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

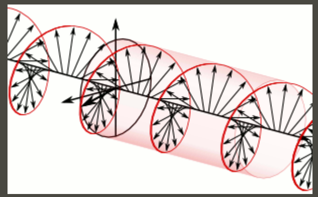
effective frequency

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



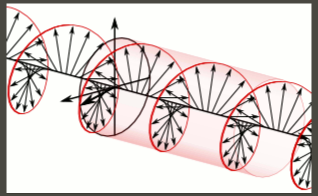
Circular polarizations

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

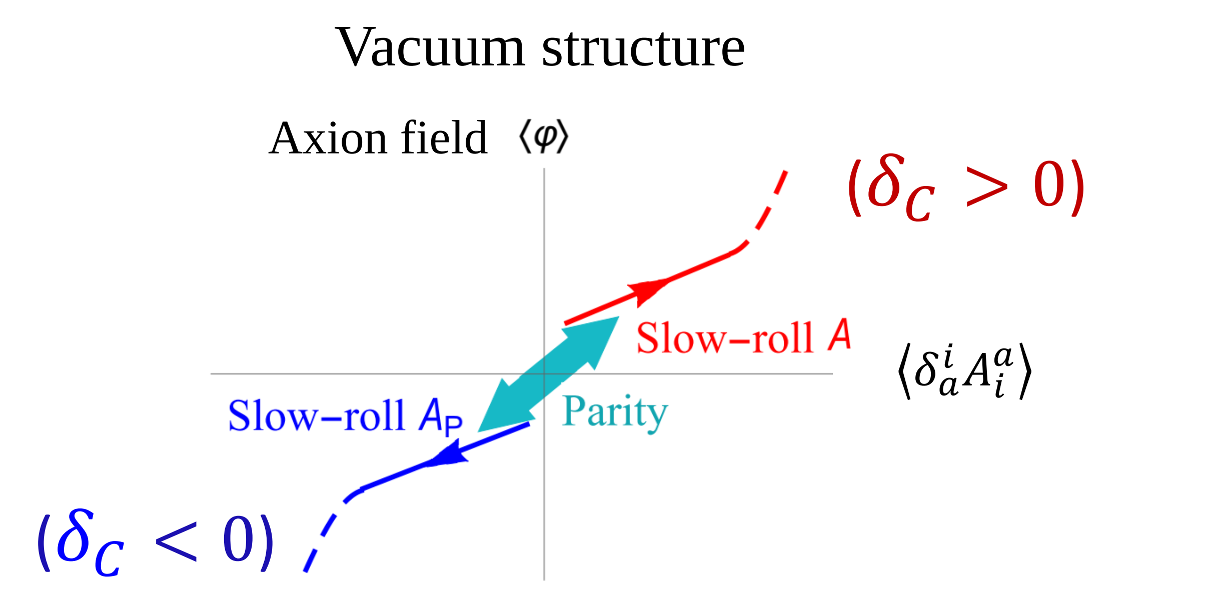
New Tensorial mode in SU(2) Gauge Field

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

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

effective frequency

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



For $\delta_C > 0$

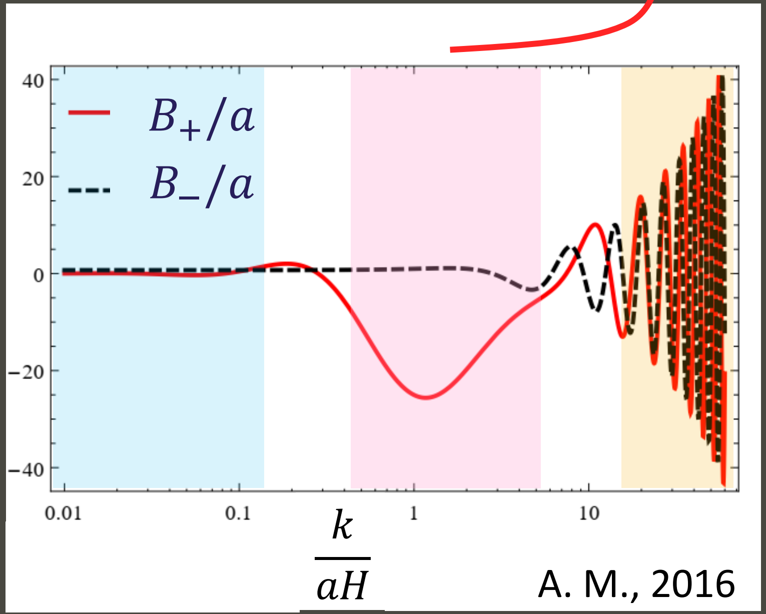
Short tachyonic growth of B_+

Chiral Field

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

Particle Production

A. M. and E. Komatsu, 2018

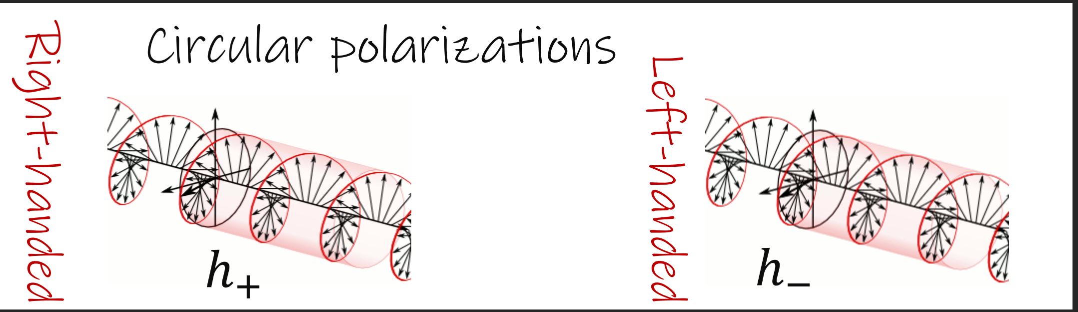


Gauge Field sources Primordial GWs

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

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

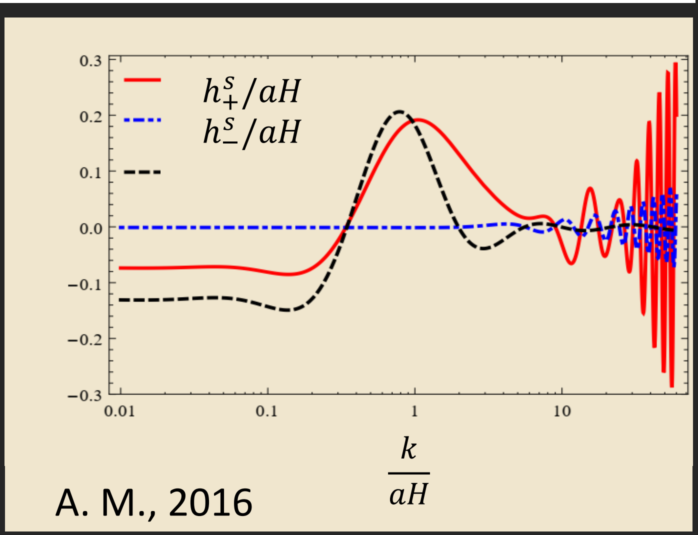


- Gravitational waves have two uncorrelated terms

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

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

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



Novel Observable Signature: CMB

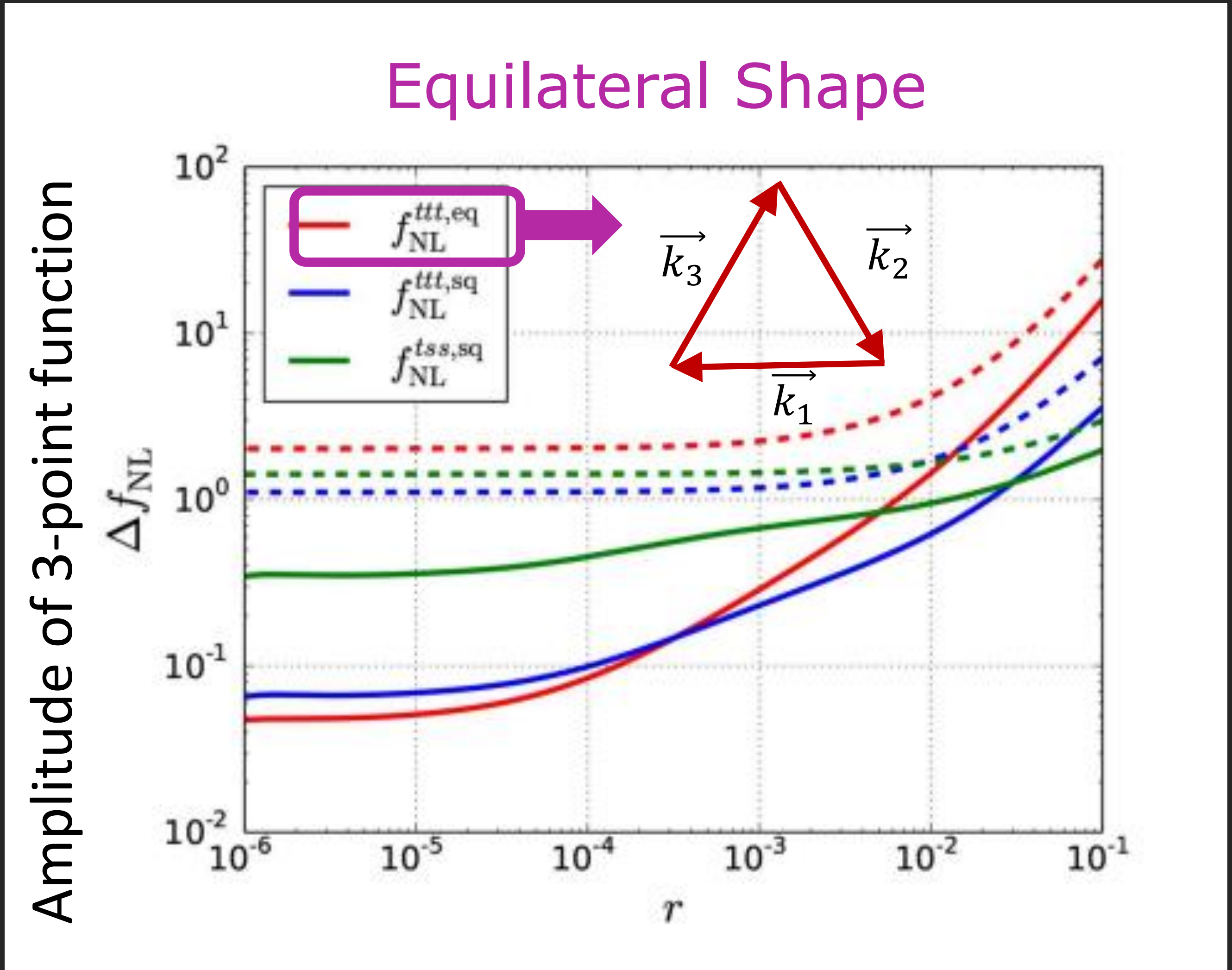
- The sourced tensor modes is Highly non-Gaussian.

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

Self-interaction

Agrawal, Fujita, Komatsu 2018

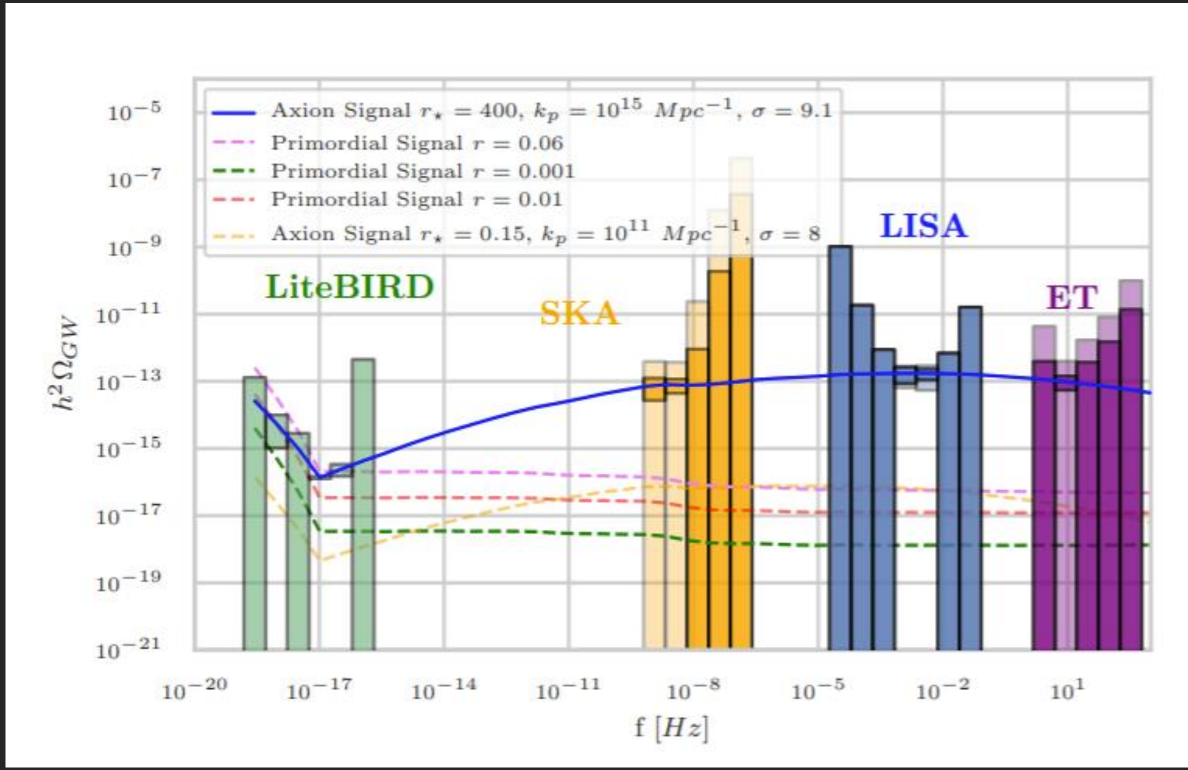
- That can be probe with future CMB missions., e.g. *Litebird* and *CMB-S4*!

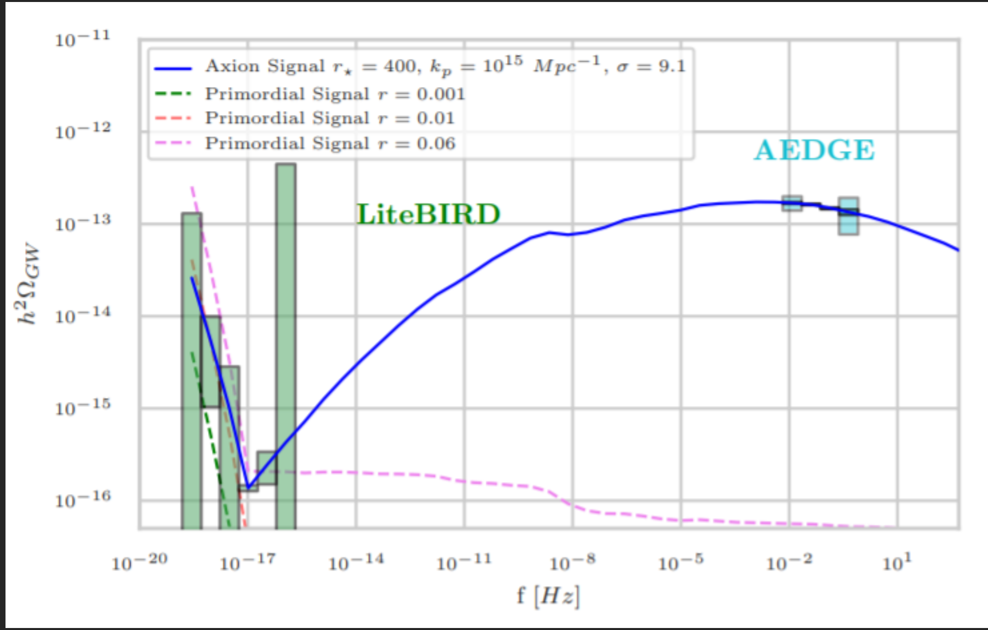


Maresuke Shiraishi, Front. Astron. Space Sci. 2019

Novel Observable Signature: Beyond CMB

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

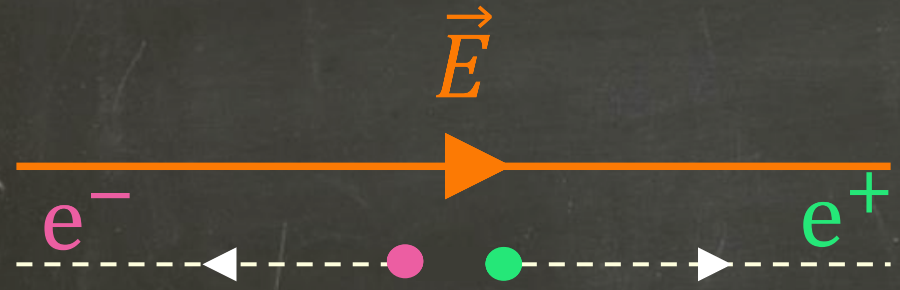




P. Campeti, E. Komatsu, D. Poletti, C. Baccigalupi 2020

What about
Schwinger Effect in Early Universe?

Electric Field *Schwinger effect*

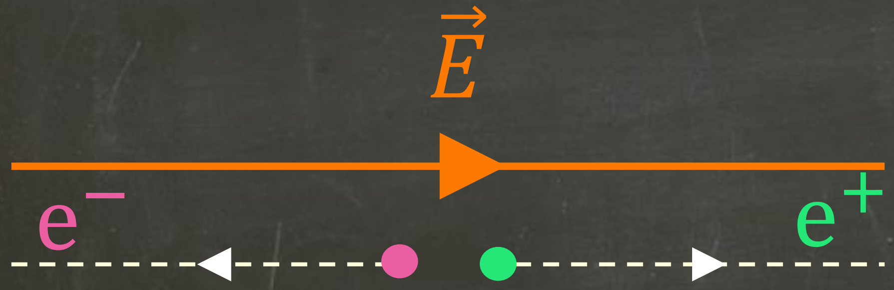


Schwinger effect in scalar QED in 4d de Sitter

- T. Kobayashi, N. Afshordi 2014

What about
Schwinger Effect in Early Universe?

Electric Field *Schwinger effect*



Schwinger effect in axion-inflation

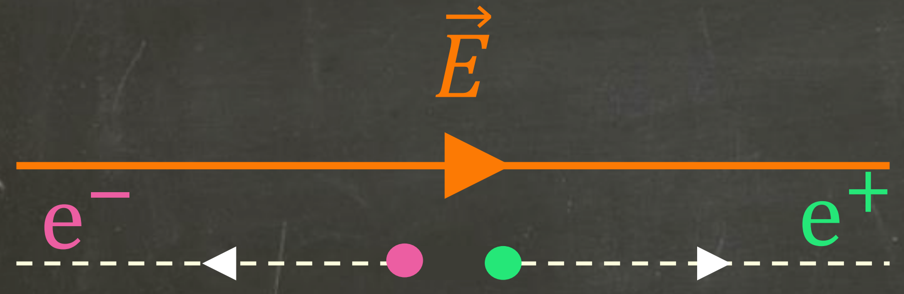
K. Lozanov

E. Komatsu

- K. Lozanov, **A. M.**, E. Komatsu **2018**
- V. Domcke, K. Mukaida 2018
- **A. M.**, E. Komatsu **2018**
- V. Domcke, Y. Ema, K. Mukaida, R. Sato 2018
- L. Mirzagholi, **A. M.**, K. Lozanov **2019**
- Many many more…

What about
Schwinger Effect in Early Universe?

Electric Field *Schwinger effect*



Schwinger effect in axion-inflation

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- L. Mirzagholi, **A. M.**, K. Lozanov **2019**
- E. Komatsu **2022**

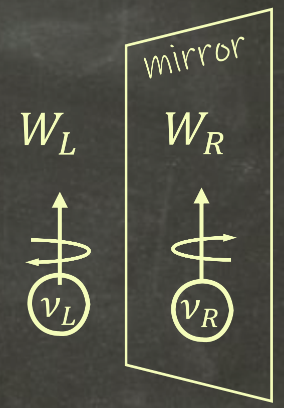
nature reviews physics

New physics from the polarized light of the cosmic microwave background

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

(How to Connect Inflaton to SM?)

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



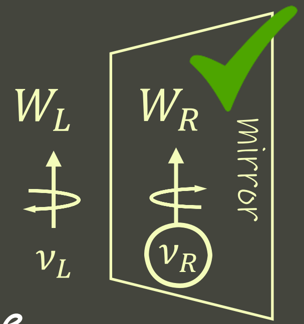
How to Connect it to the SM?

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

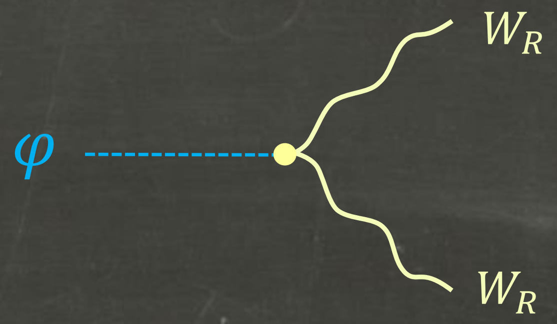
A.M. arXiv:2103.14611

Gauge field Production in Inflation

Let us set the VEV of the Gauge field to zero $\langle W_R \rangle = 0$

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

Axion inflaton



Gauge field
(active in inflation)

W_R Gauge Field Perturbation $\delta W_i^a = B_+^a(t,k)e_i^+\left(\vec{k}\right) + B_-^a(t,k)e_i^-\left(\vec{k}\right)$

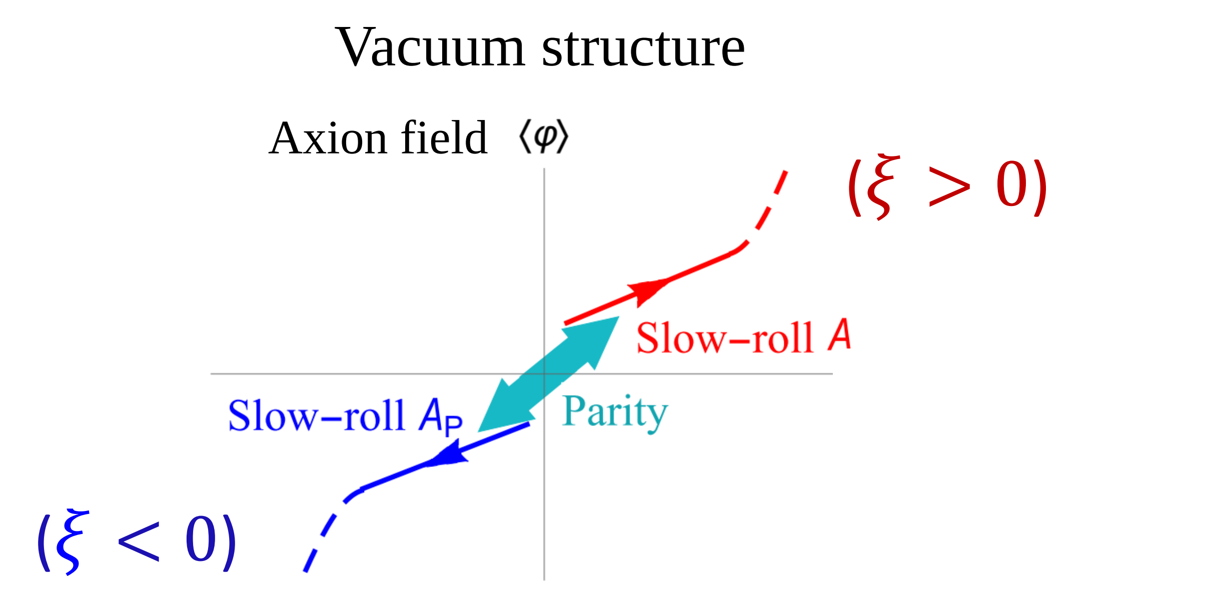
$SU(2)_{\mathbb{R}}$ Gauge Field

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

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

effective frequency

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



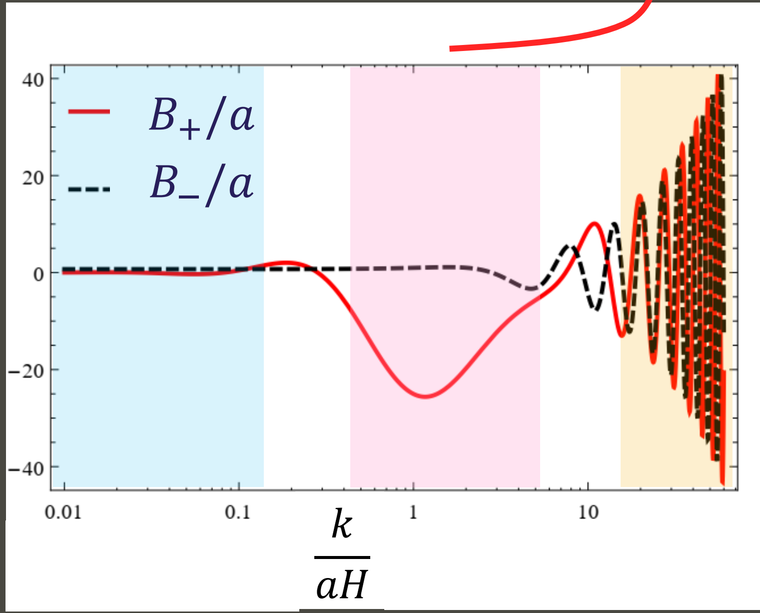
For $\xi > 0$

Short tachyonic growth of B_+

Chiral Field

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

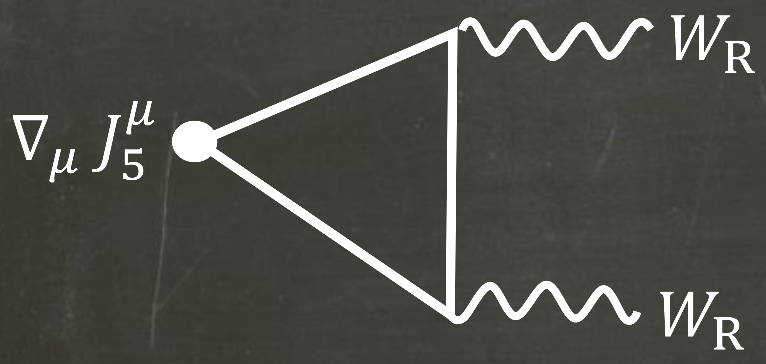
Particle Production



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:

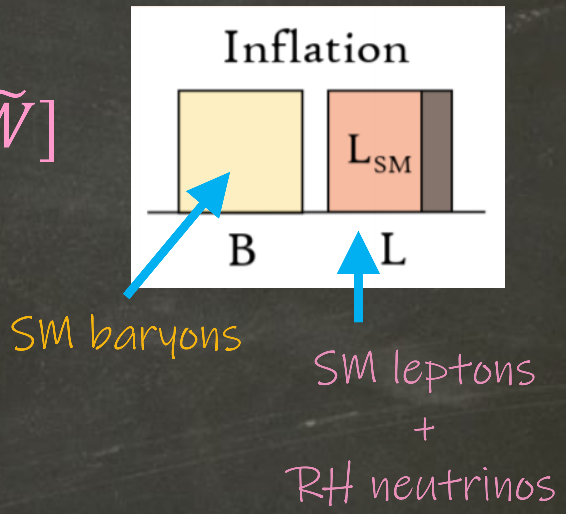
The key ingredient is the Chiral anomaly of $\mathrm{SU(2)_R}$ in inflation:



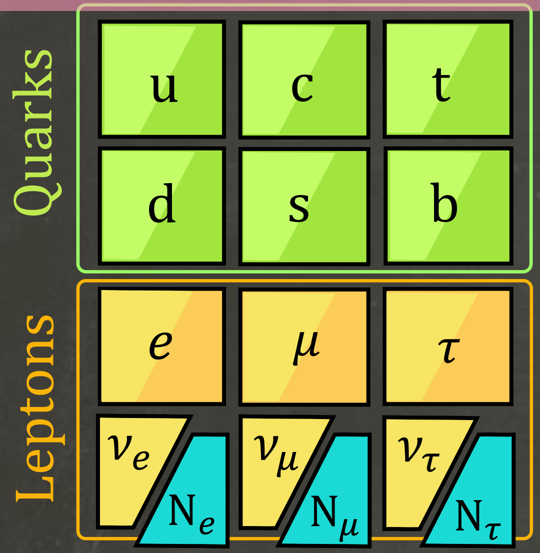
$$\nabla_\mu J_\mathrm{B}^\mu = \nabla_\mu J_\mathrm{L}^\mu = \frac{g^2}{16\pi^2} tr[W\widetilde{W}]$$

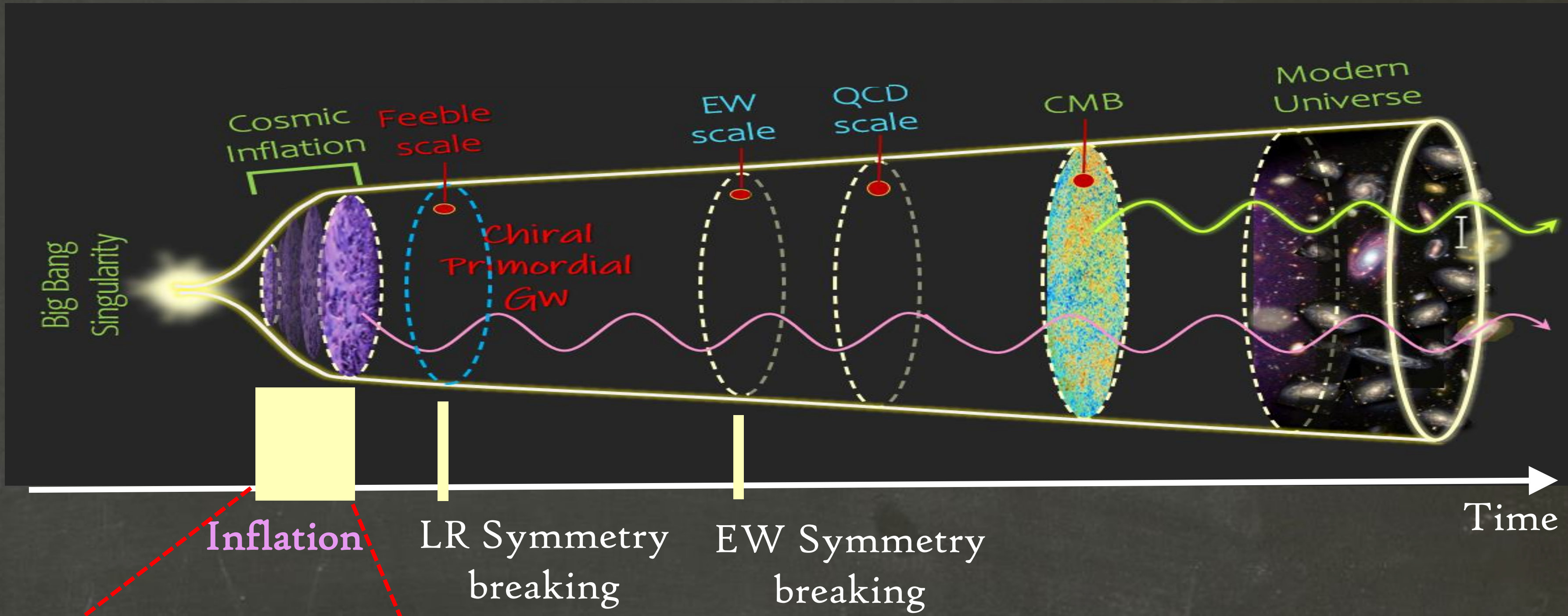
$$\mathrm{n_B} = \mathrm{n_L} = \alpha_{inf}(\xi) H^3$$

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

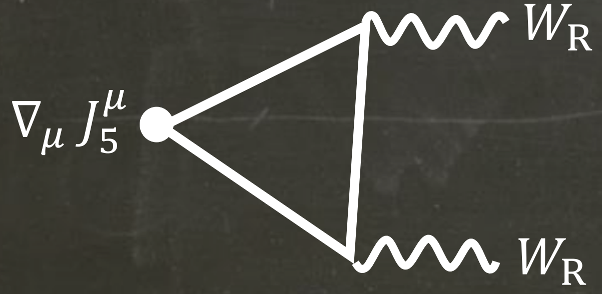


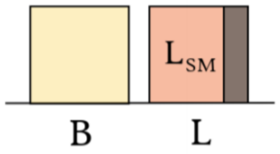
Summary of the mechanism:





Chiral anomaly of SU(2)R
In inflation





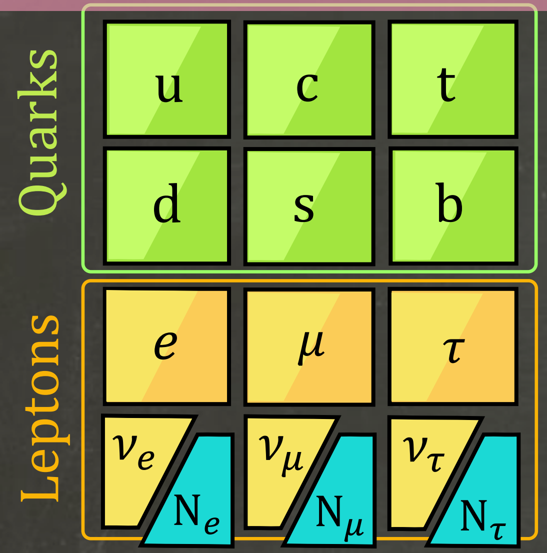
$$B = L = 3n_{CS}$$

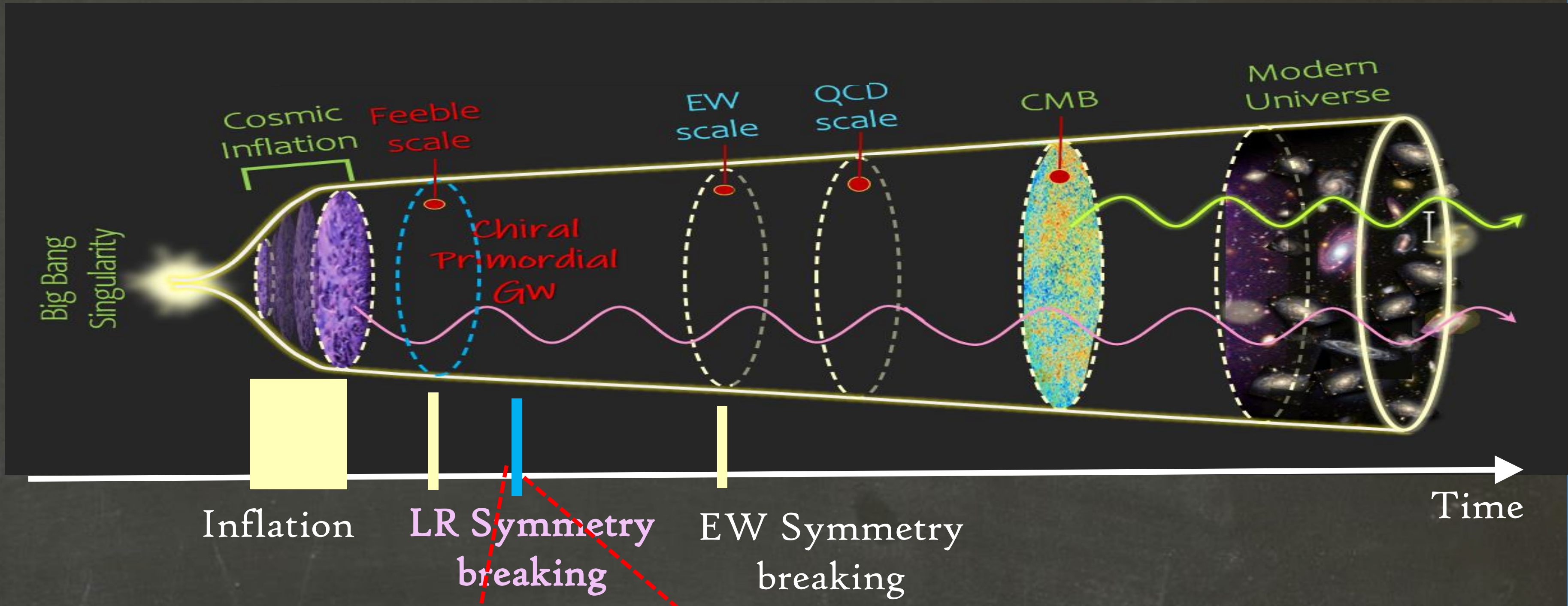
$$B - L_{SM} \neq 0$$

B= SM baryons

L= SM leptons + RH neutrinos

Summary of the mechanism:





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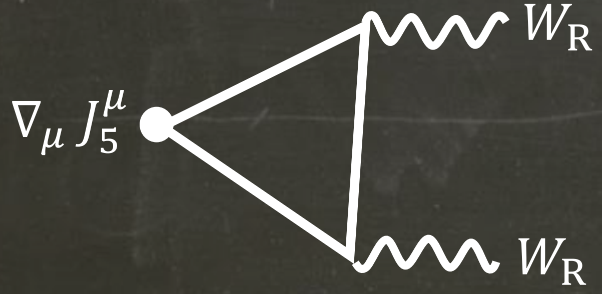
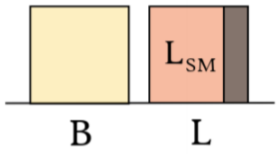
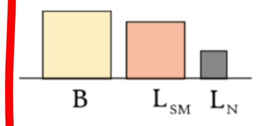




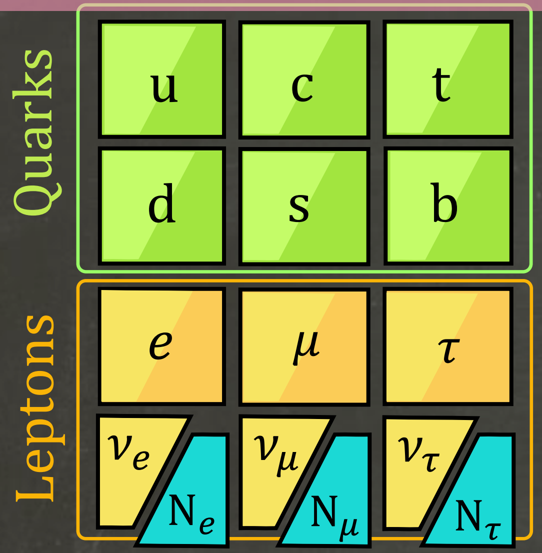
$$B = L = 3n_{CS}$$
$$B - L_{SM} \neq 0$$

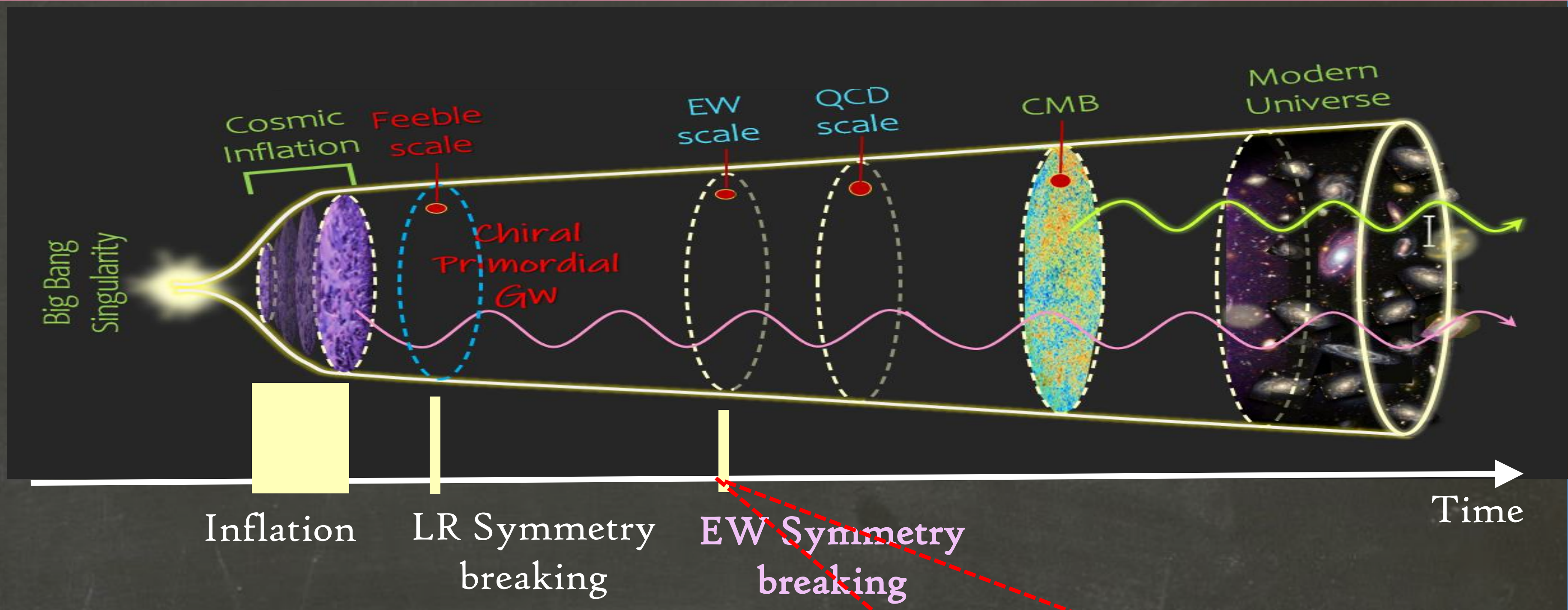
→



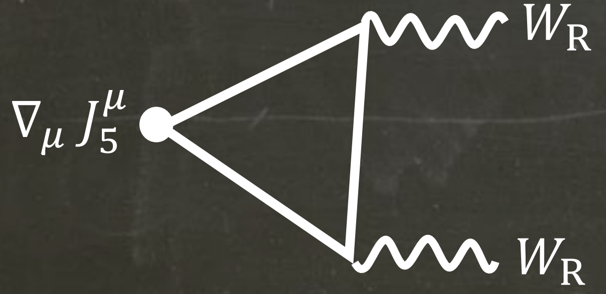
Freezeout of W_R

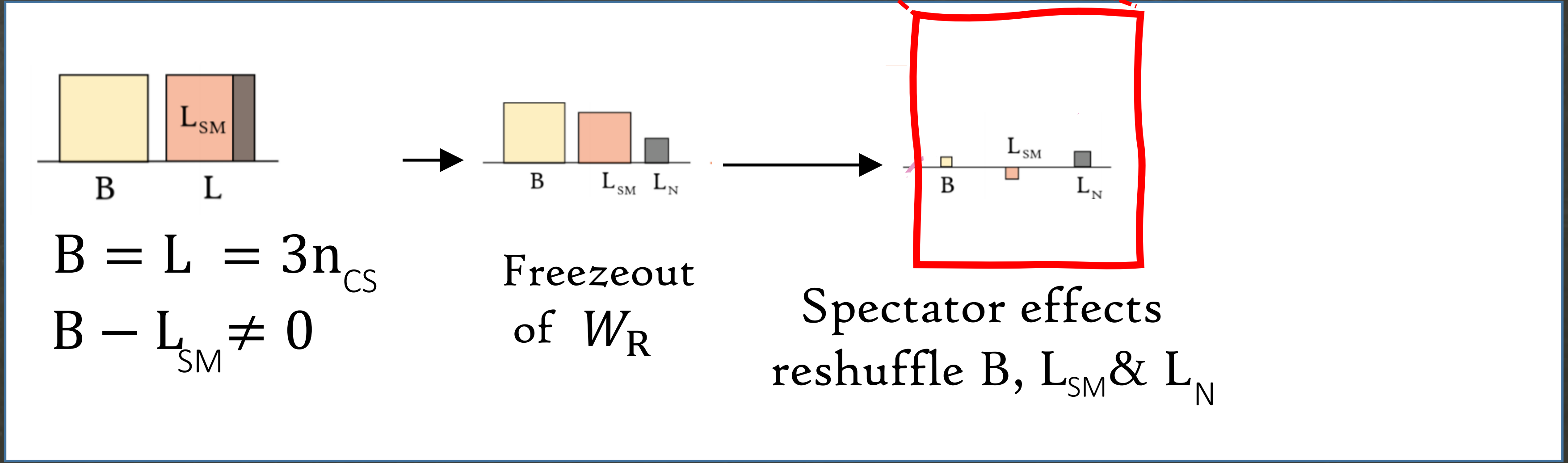
Summary of the mechanism:



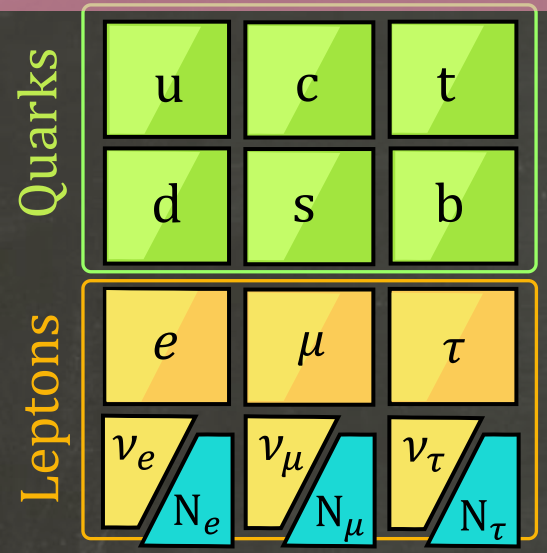


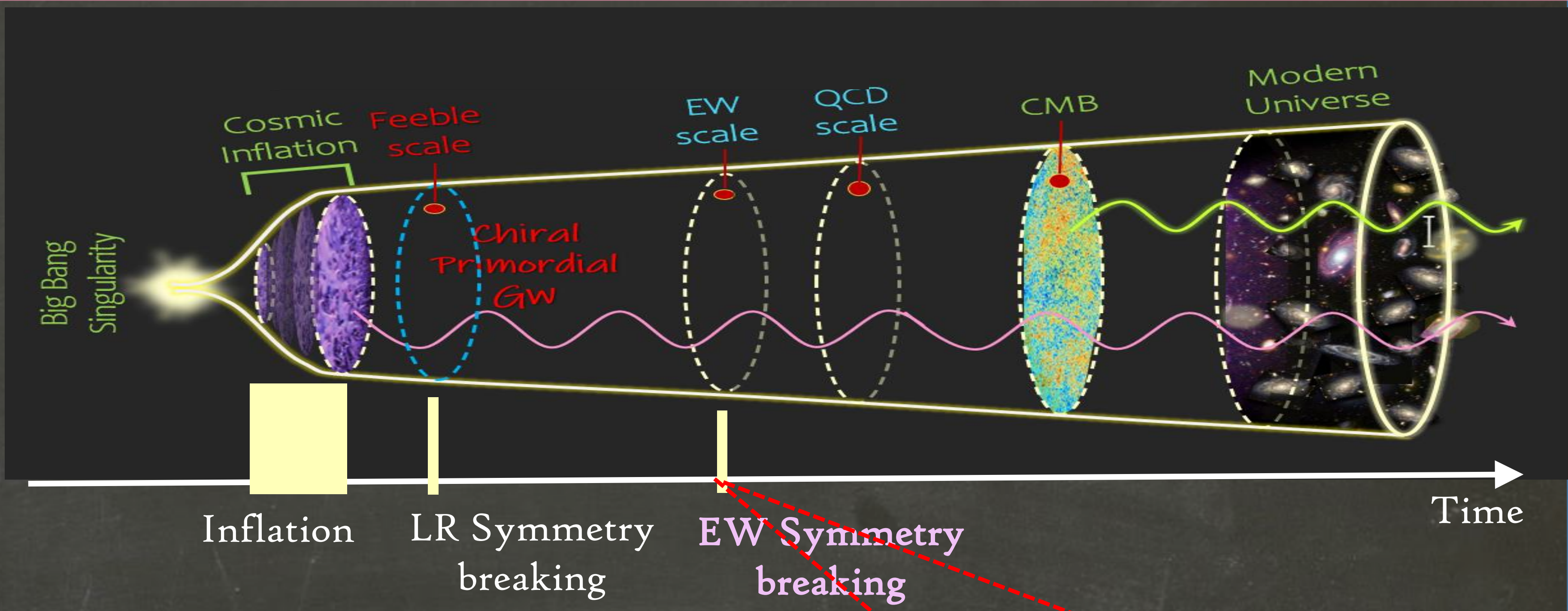
Chiral anomaly of SU(2)R
In inflation



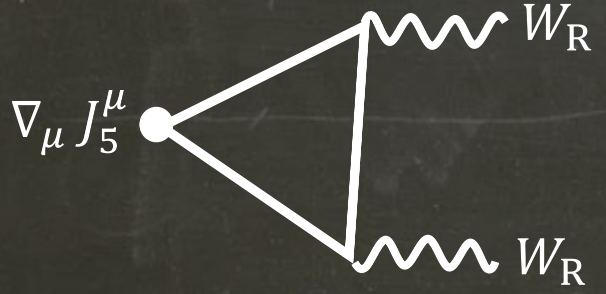


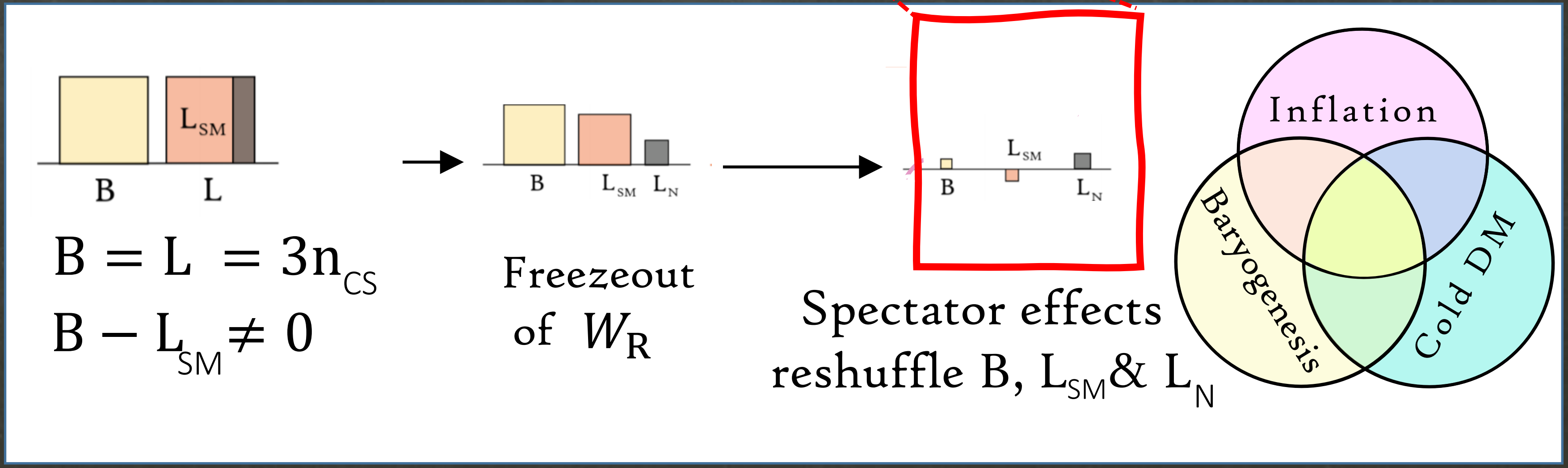
Summary of the mechanism:



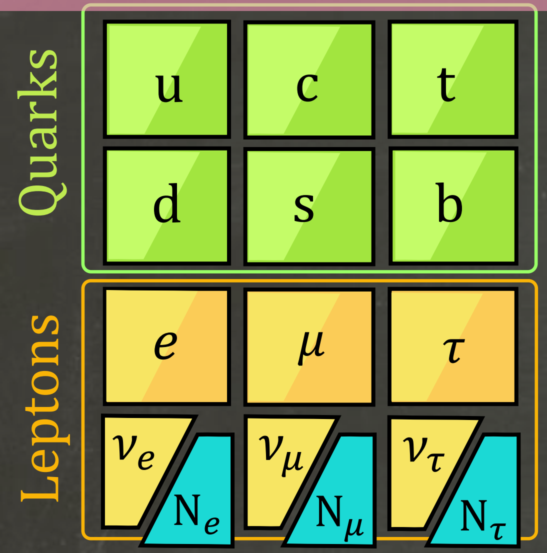


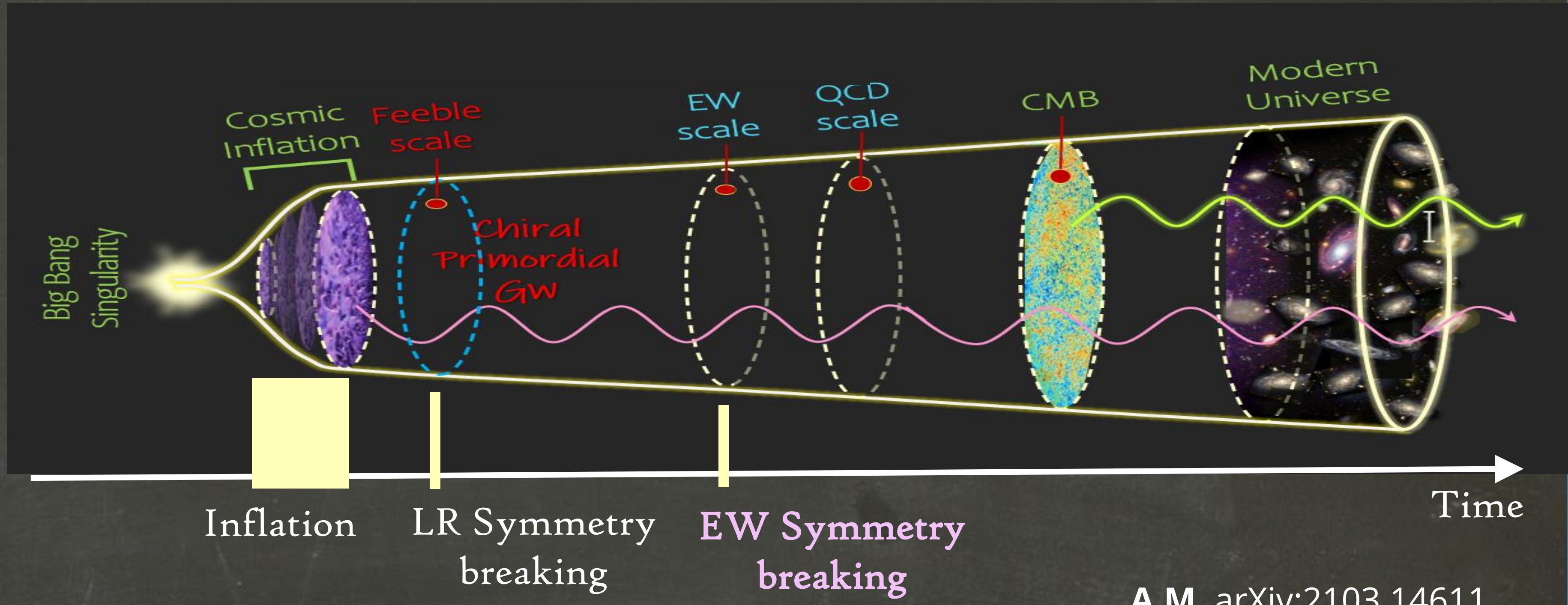
Chiral anomaly of SU(2)R
In inflation





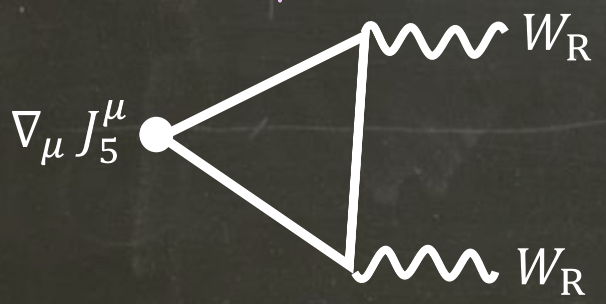
Summary of the mechanism:

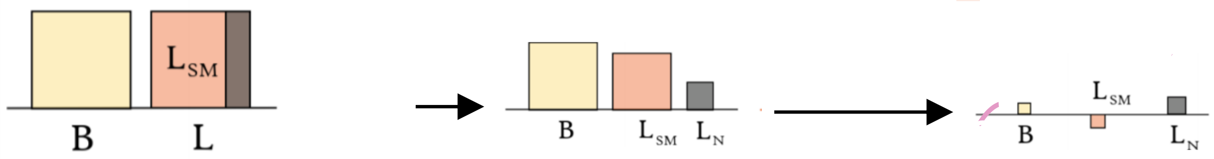




A.M. arXiv:2103.14611

Chiral anomaly of SU(2)R
In inflation





$B = L = 3n_{CS}$

$B - L_{SM} \neq 0$

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

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

Summary & Conclusions

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

Compelling Consequences:

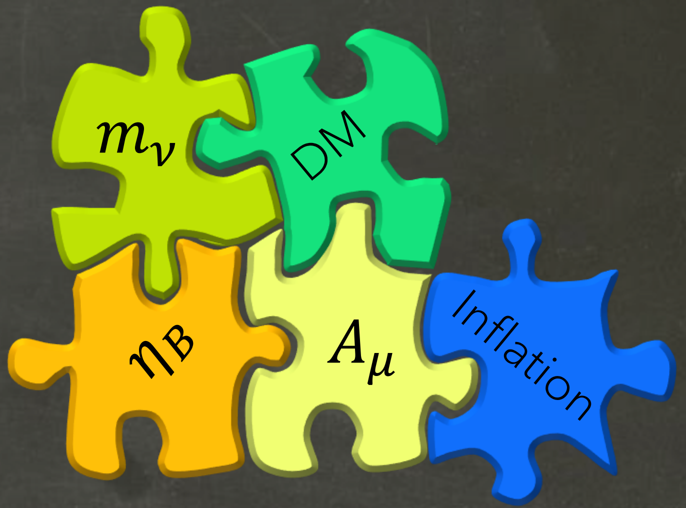
This Set-up is a **complete BSM** that can solve I-IV:

I) Particle physics of Inflation

II) Origin of matter asymmetry

III) Origin of Neutrino mass

IV) Particle nature of DM



Puzzles of Particle Cosmology

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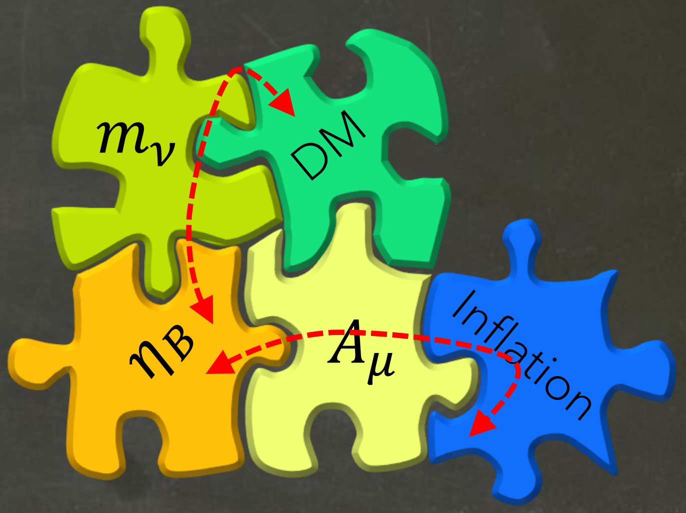

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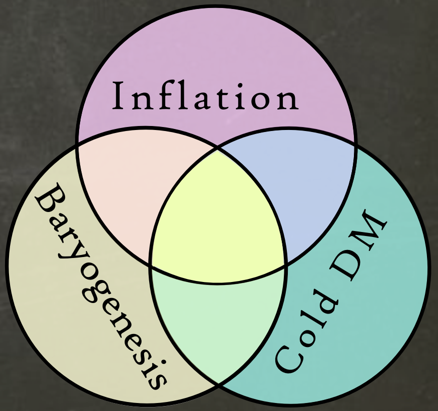
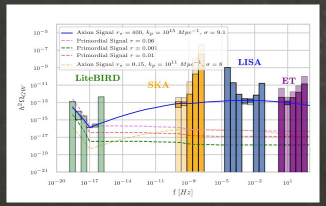


It provides a deep connection between inflation, baryogenesis & DM

It comes with a cosmological smoking gun on Primordial GWs.



Open Questions & Future Directions

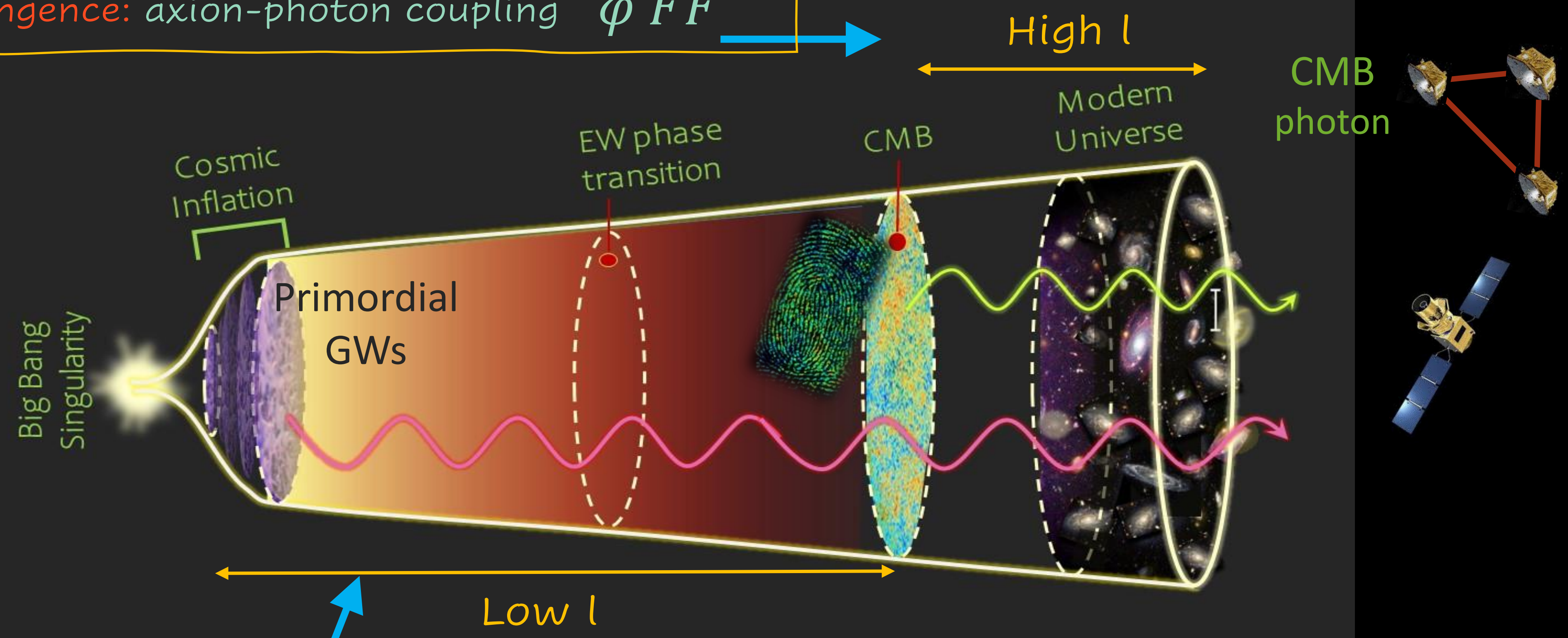
- Thermal Effects in inflation and Warm Inflation
- Strong Backreaction Regime
- Primordial Magnetic Fields
- Connection to the Standard Model


Questions?!

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

Sources of Parity violation on CMB:

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



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- Gravitational Chern-Simons: axion-graviton coupling $\varphi R\tilde{R}$

B. Thorne et. al.2018

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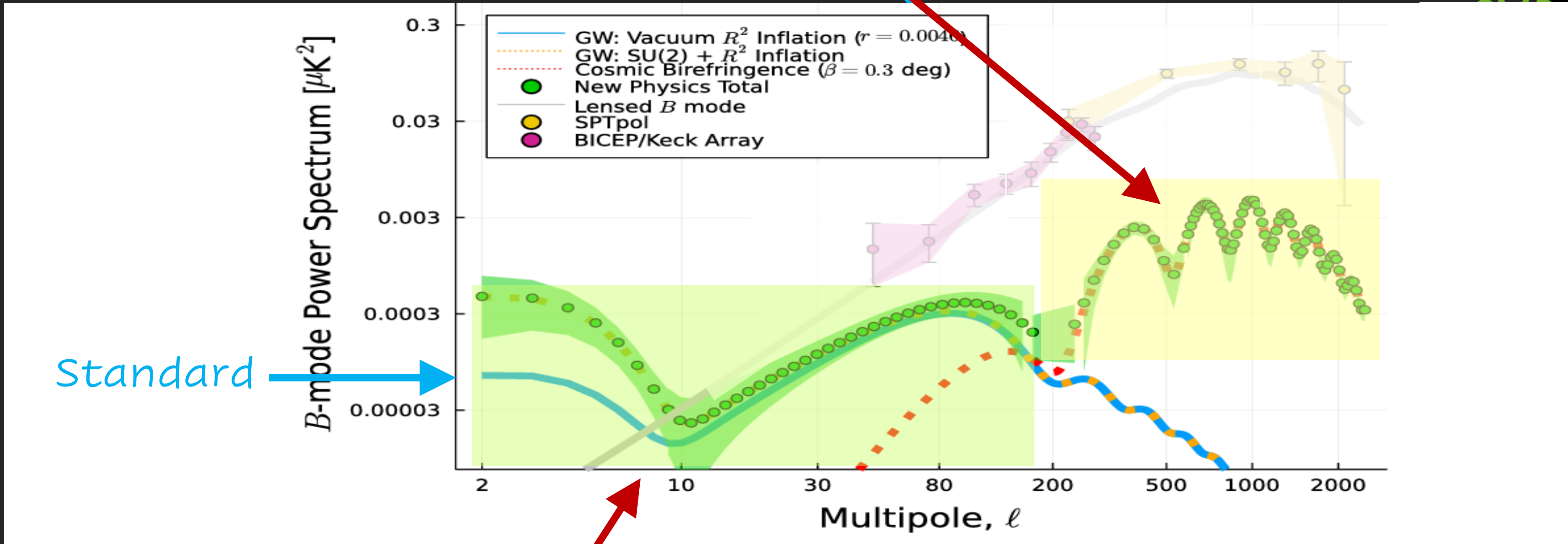

E. Komatsu *Nature Rev. Phys.* 4 (2022) 7, 452-469

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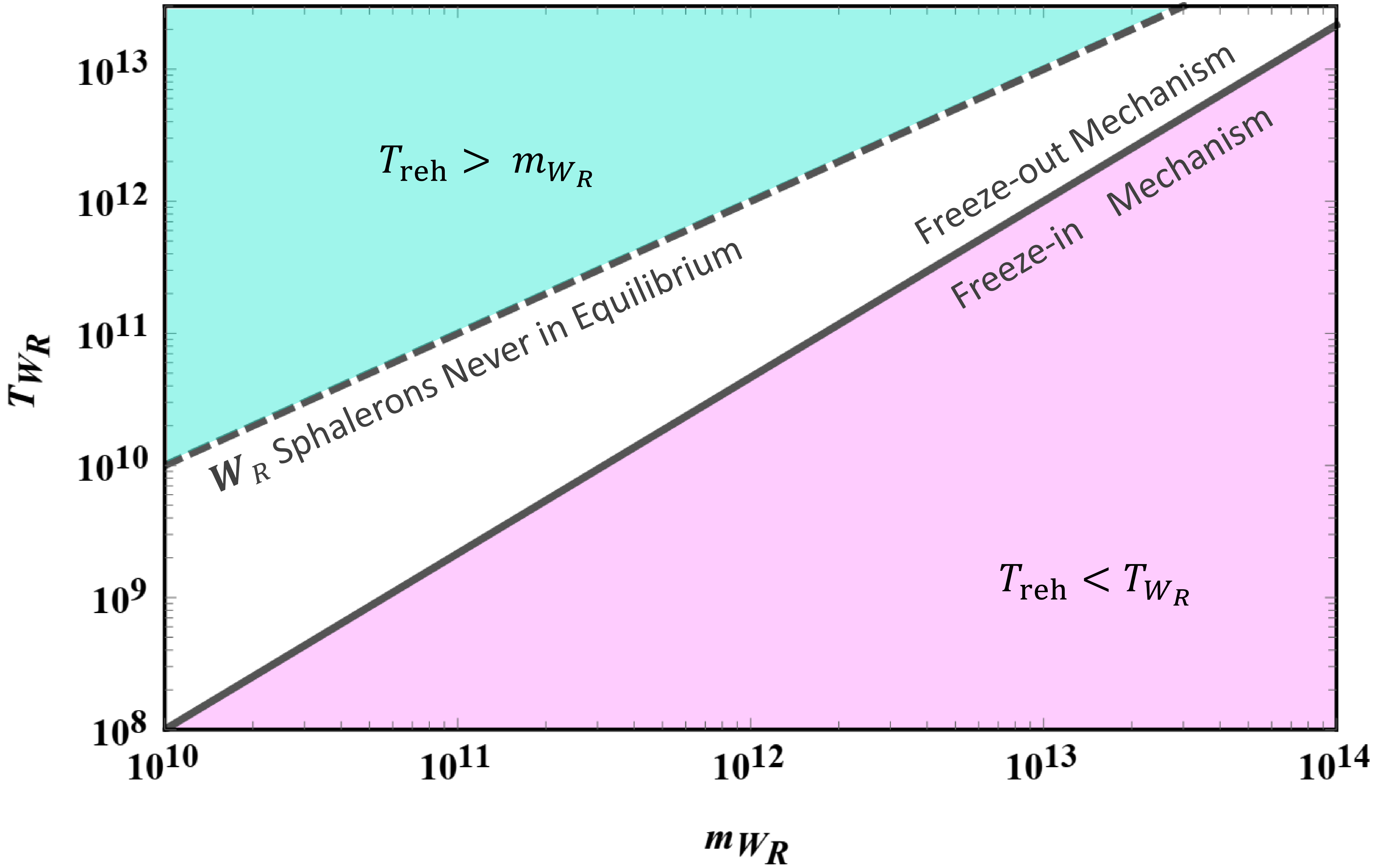

$T_{\rm reh} > m_{W_R}$
W_R Sphalerons Never in Equilibrium
Freeze-out Mechanism
Freeze-in Mechanism
$T_{\rm reh} < T_{W_R}$
T_{W_R}
m_{W_R}
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
10^{13}
10^{10}
10^{11}
10^{12}
10^{13}
10^{14}

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.)