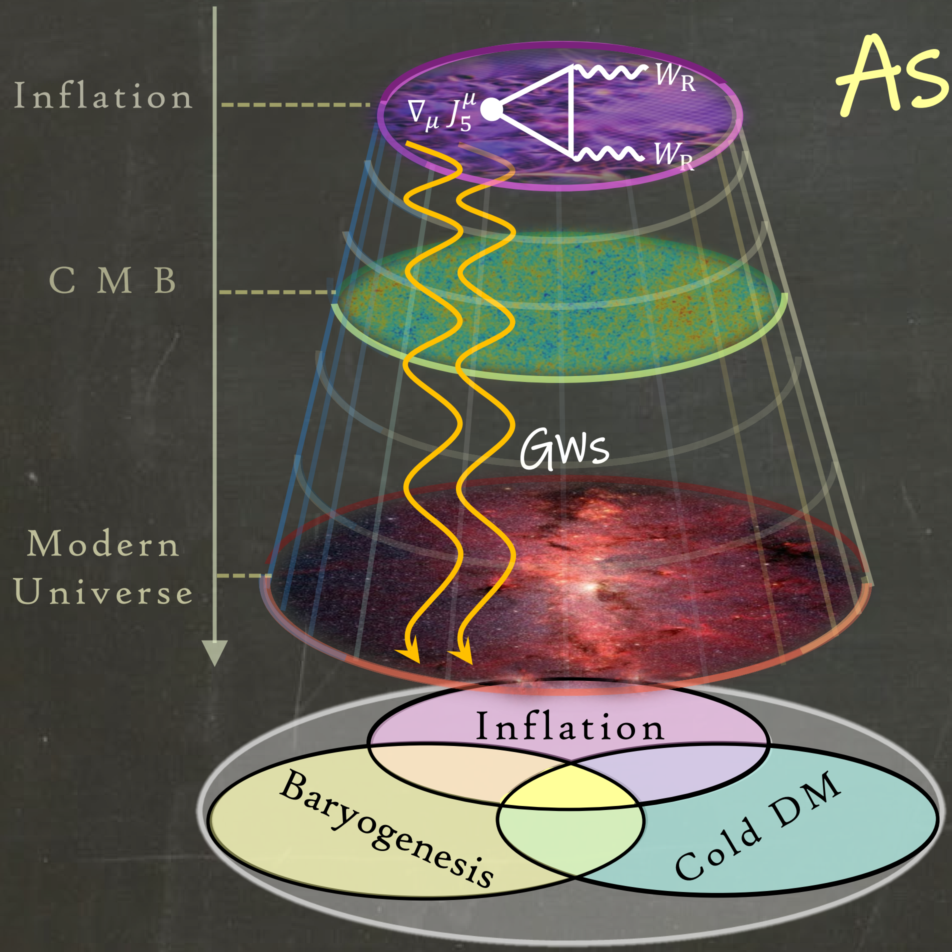
Inflation, Origin of Matter Asymmetry, and GW Background



Azadeh Malek-Nejad
CERN

Copernicus Webinar

Nov 2022

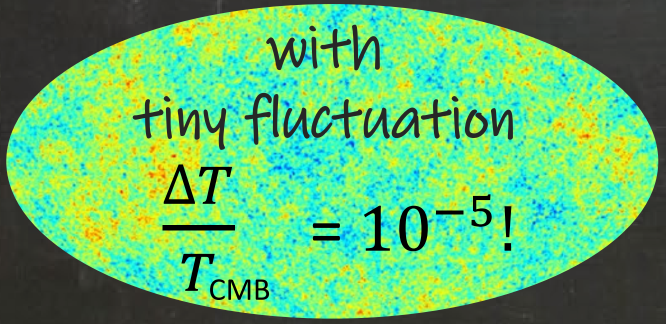
Cosmic History

Cosmic History

Our Universe is too simple, too symmetric at very large scales!

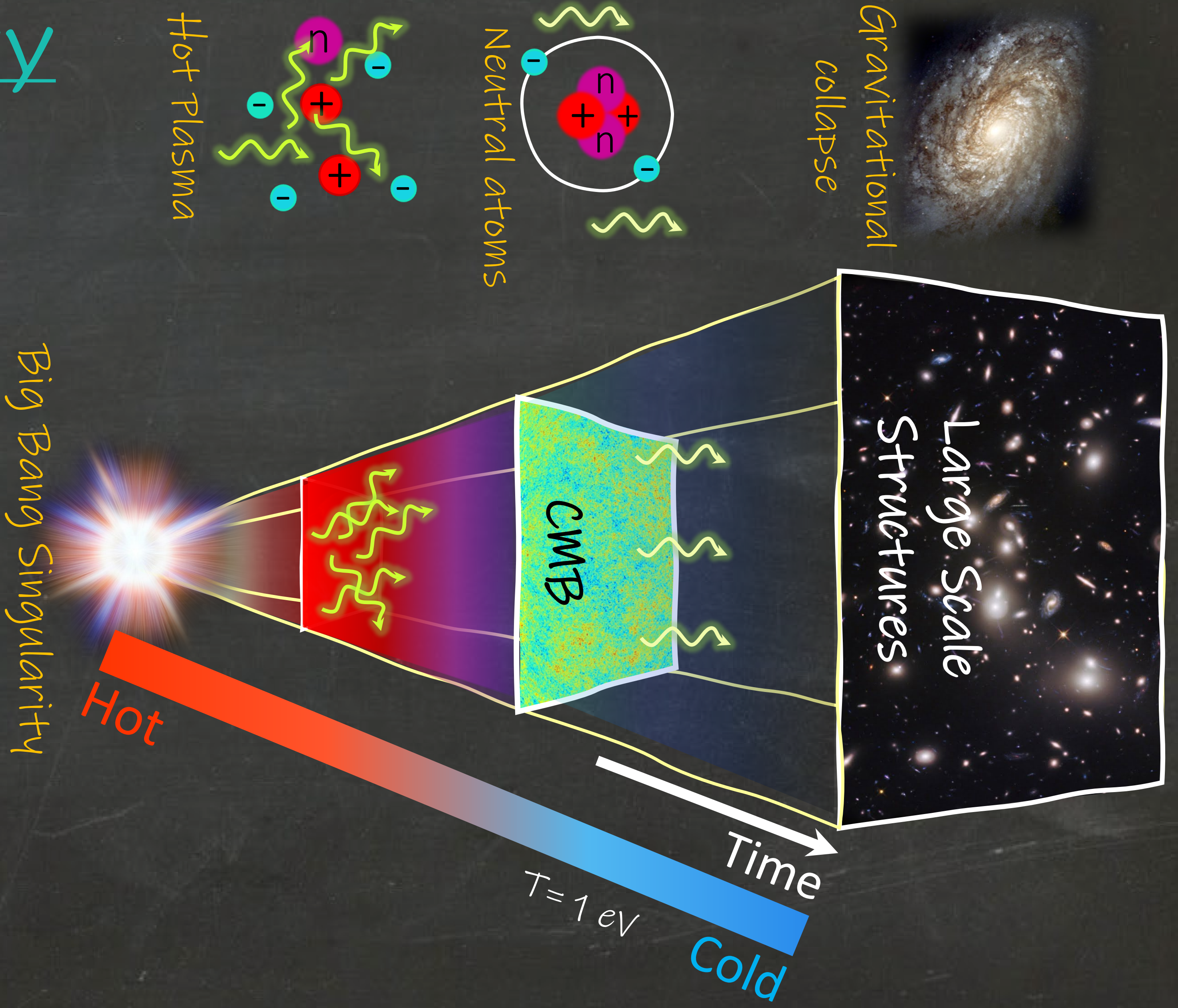
CMB is nearly homogenous & isotropic!

$T_{\text{CMB}} = 2.7$ K



with tiny fluctuation

$$\frac{\Delta T}{T_{\text{CMB}}} = 10^{-5}!$$

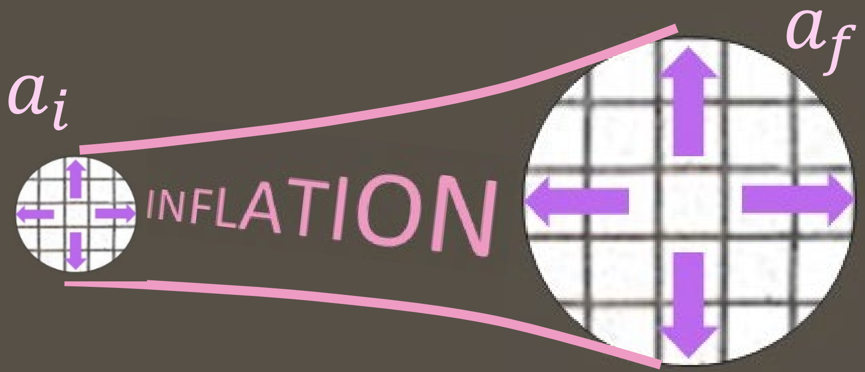


Cosmic Inflation

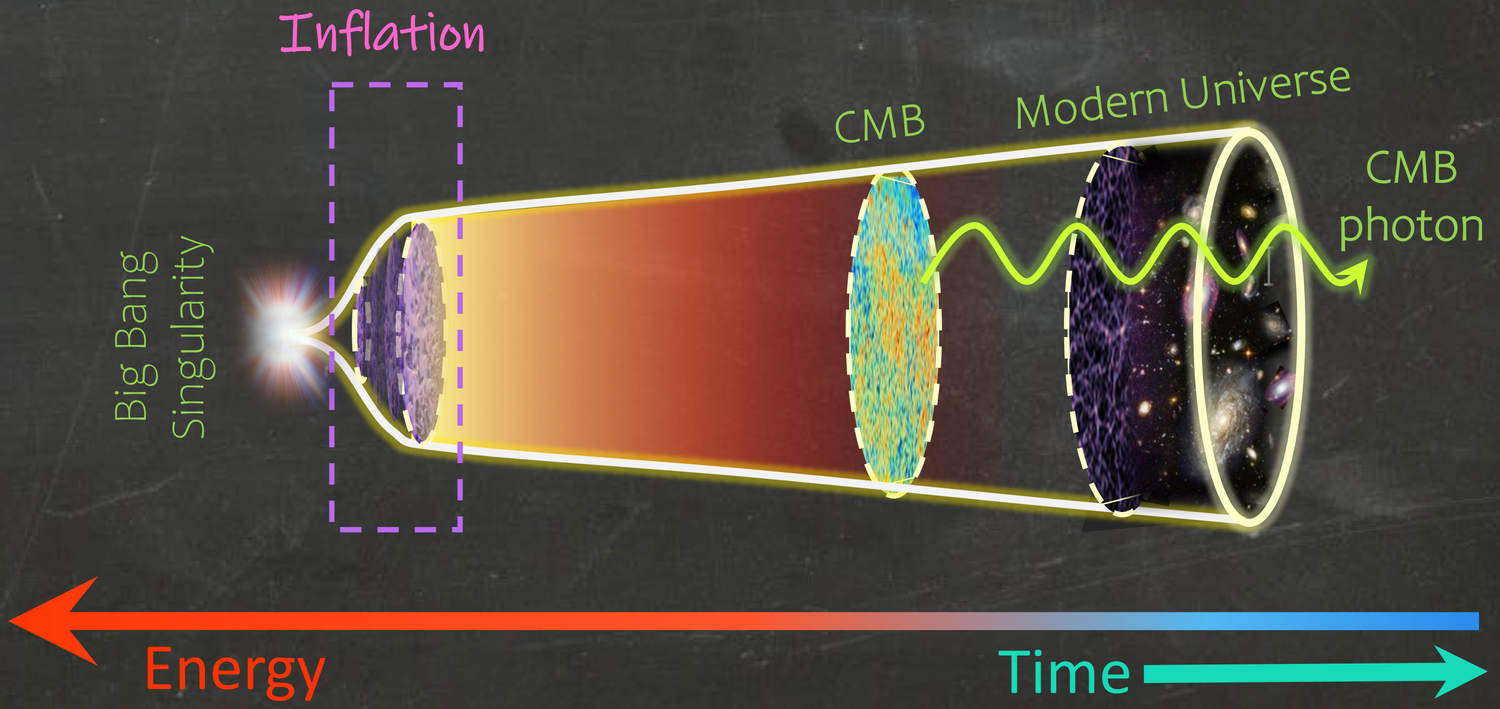
Guth Phys. Rev. D23 (1981)

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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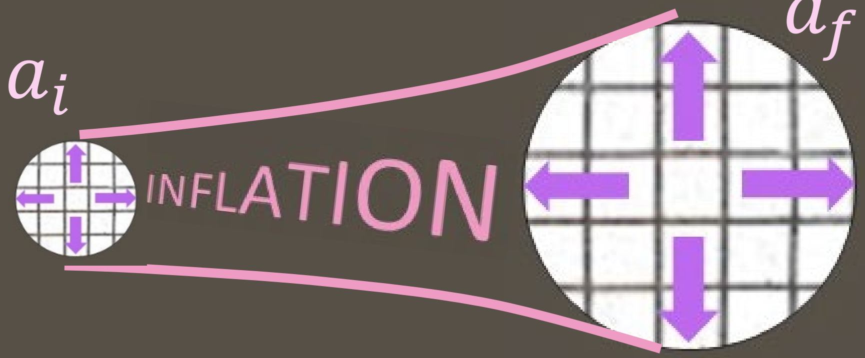

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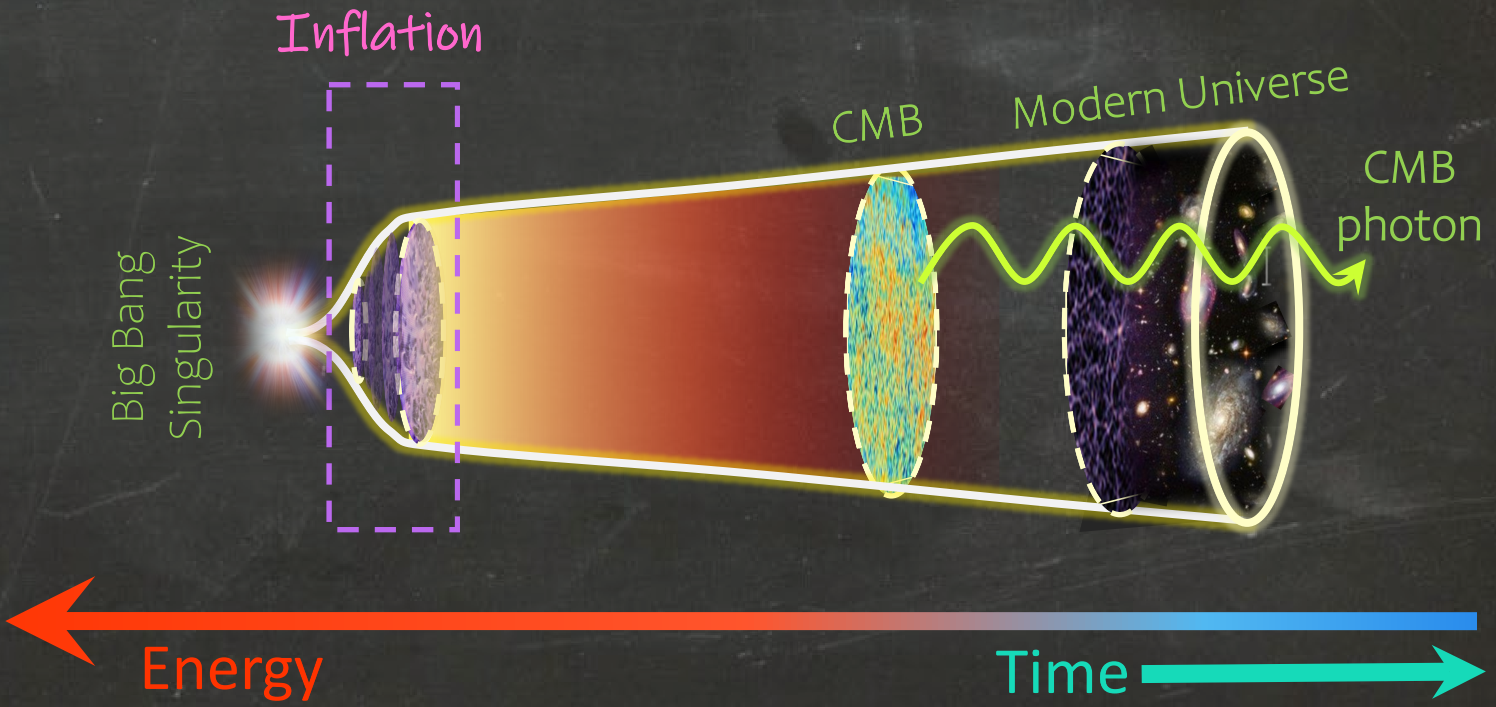
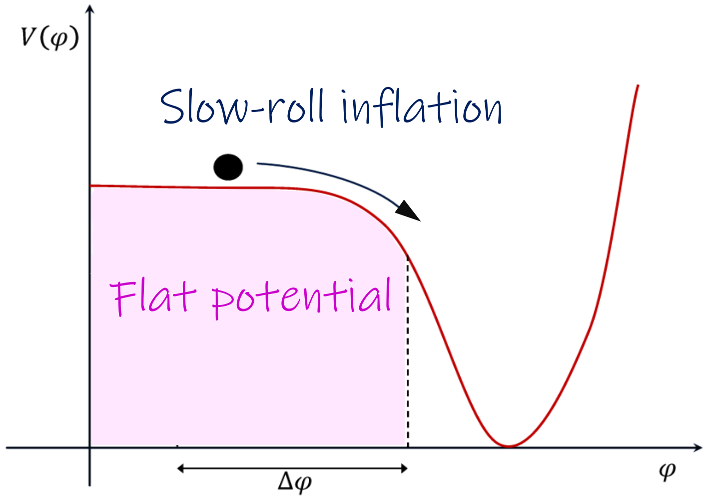


What caused inflation?

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

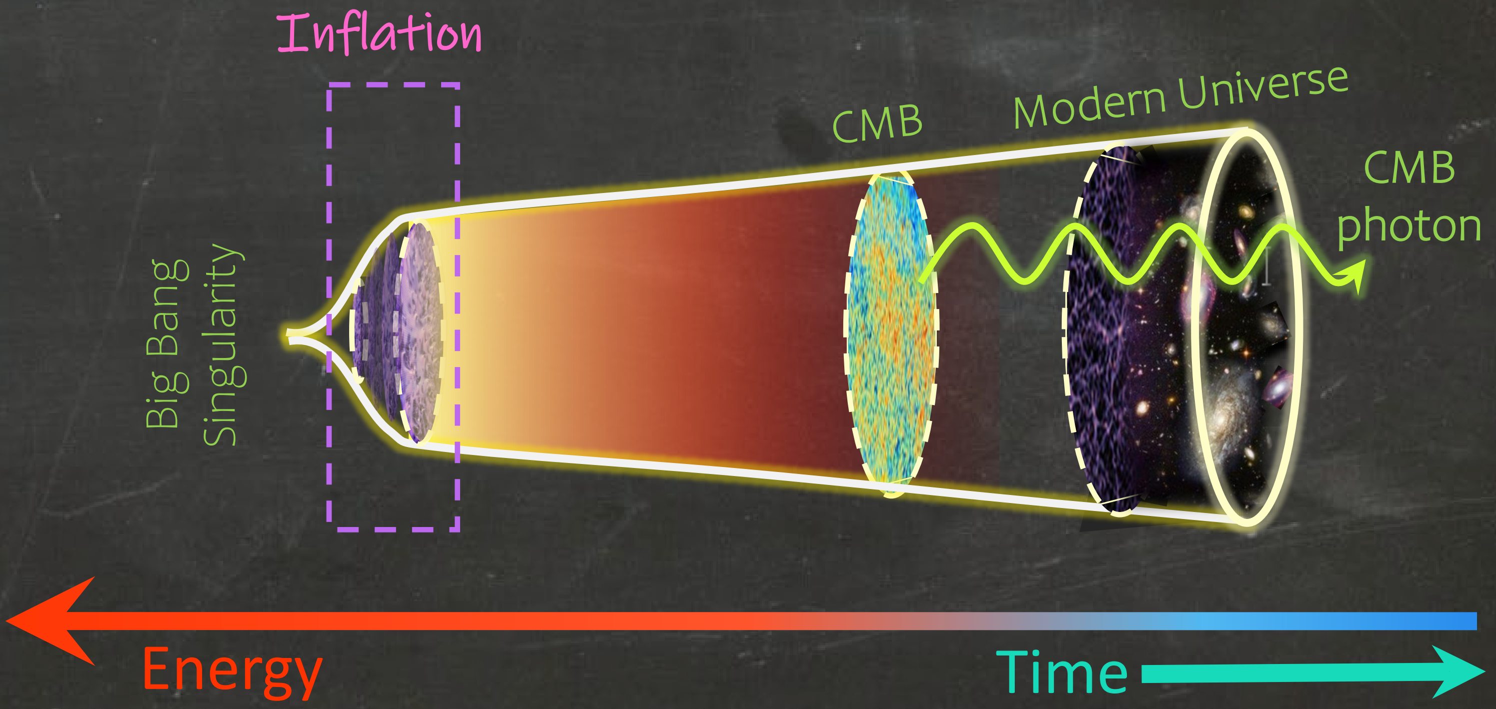
$$\rho = \frac{1}{2}\dot{\phi}^2 + V(\phi)$$

$$\mathrm{P} = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$



It is assumed that the cosmos was filled with a homogenous scalar field beyond the SM in inflation

$$\phi(\mathrm{t}, \vec{x}) = \phi(\mathrm{t})$$



Quantum Fluctuations

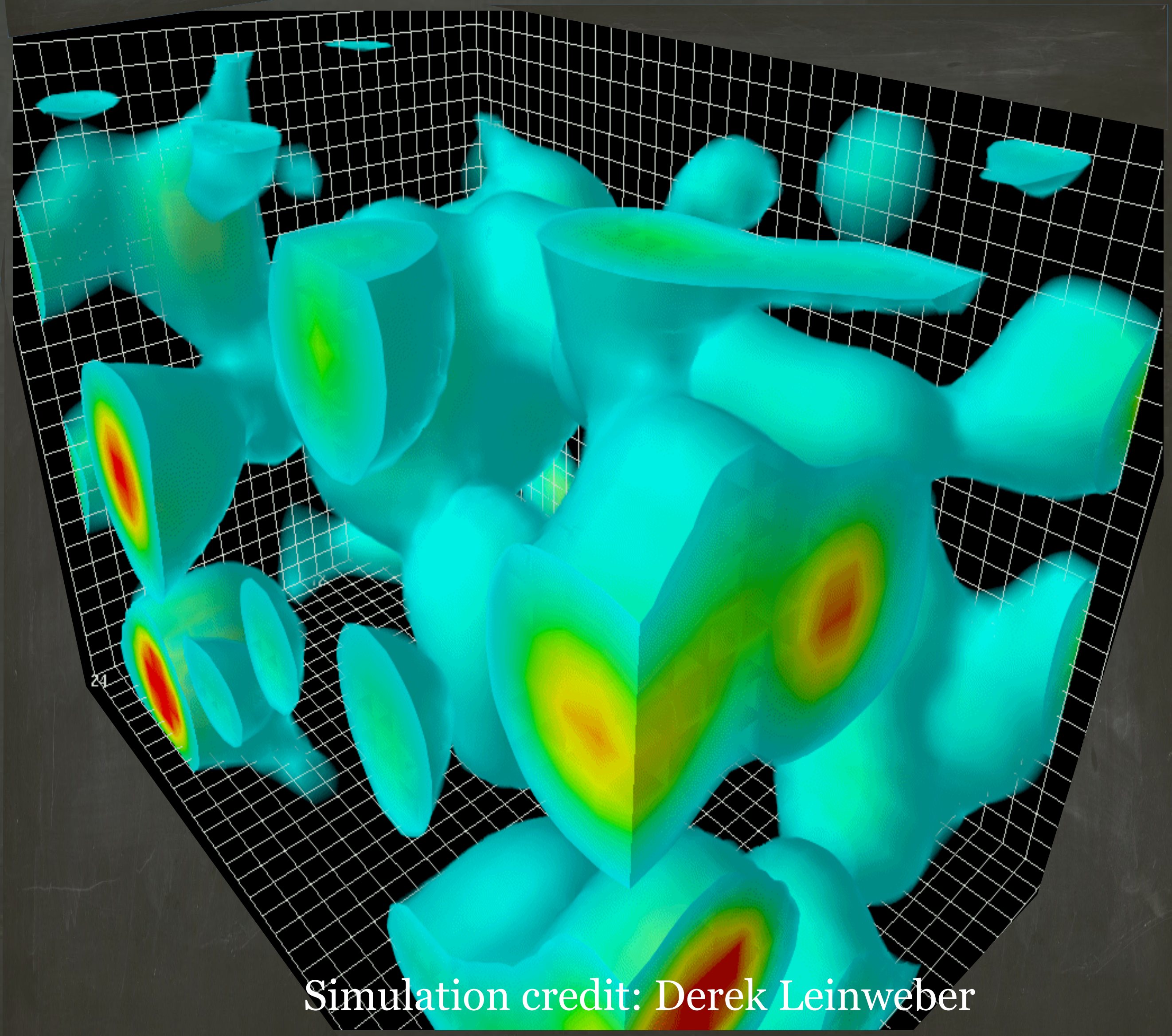
$$\hbar \neq 0$$

Quantum Vacuum $\hbar \neq 0$

Due to Uncertainty Principle

$$\Delta x \, \Delta p \geq {}^{\hbar}/_{2}$$

quantum vacuum is NOT nothing!



Simulation credit: Derek Leinweber

Quantum Vacuum $\hbar \neq 0$

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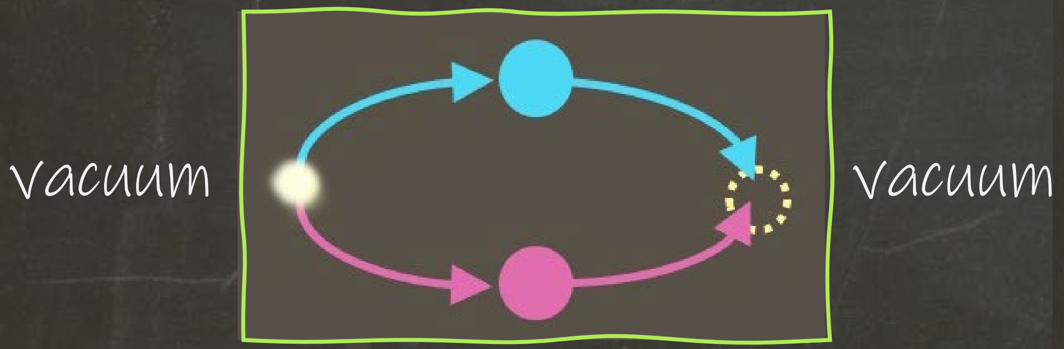
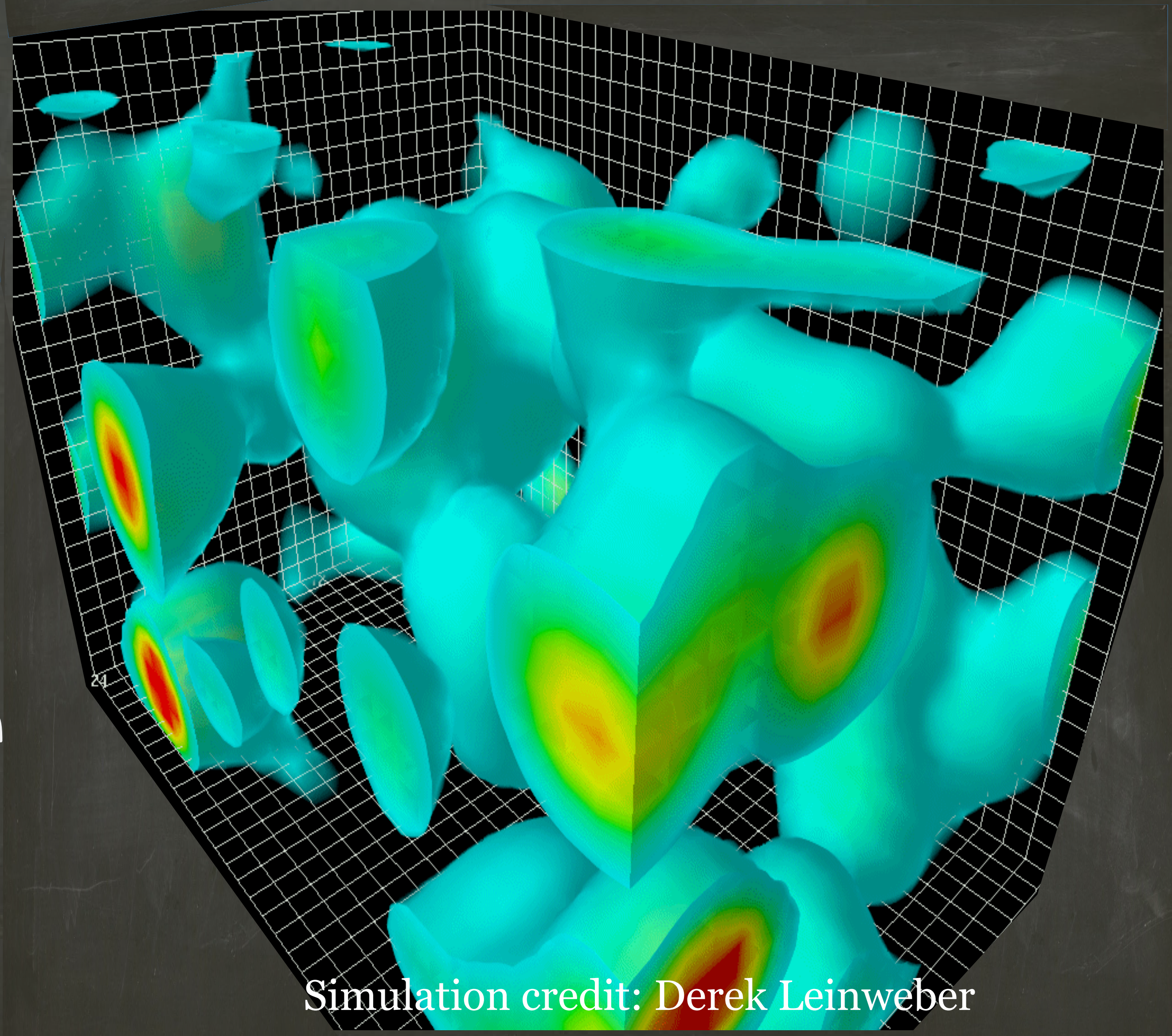
But, a vast ocean made of

Virtual particles




Simulation credit: Derek Leinweber

Quantum Vacuum

Due to Uncertainty Principle

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

the quantum vacuum is
NOT nothing!

But, a vast ocean made of

Particle Production

Background field can upgrade them into **actual particles**!

Examples of such BG fields:

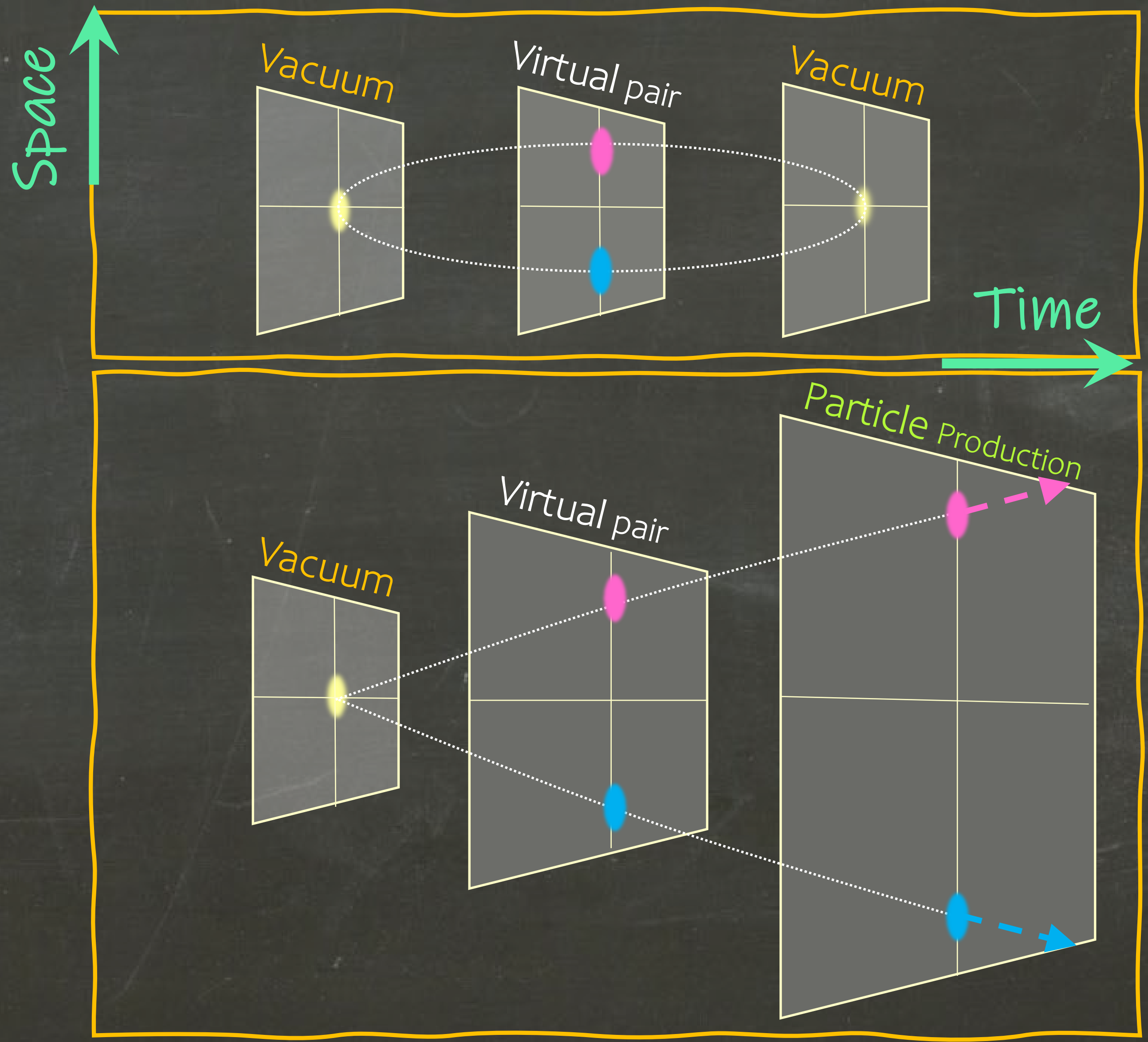
1) Electric *(Schwinger effect)*
2) Gravitational *(Gravitational production)*

Virtual particles

BG field

Actual particles

Inflation Produces Particles!



Flat Space:

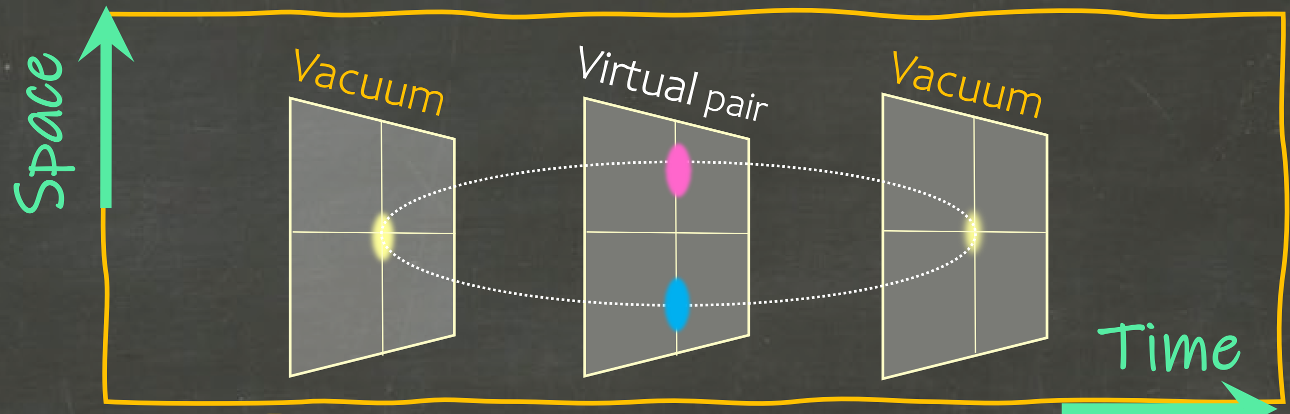
Vacuum

Expanding space:

Particle Production

Inflation Produces Particles!

Flat Space:

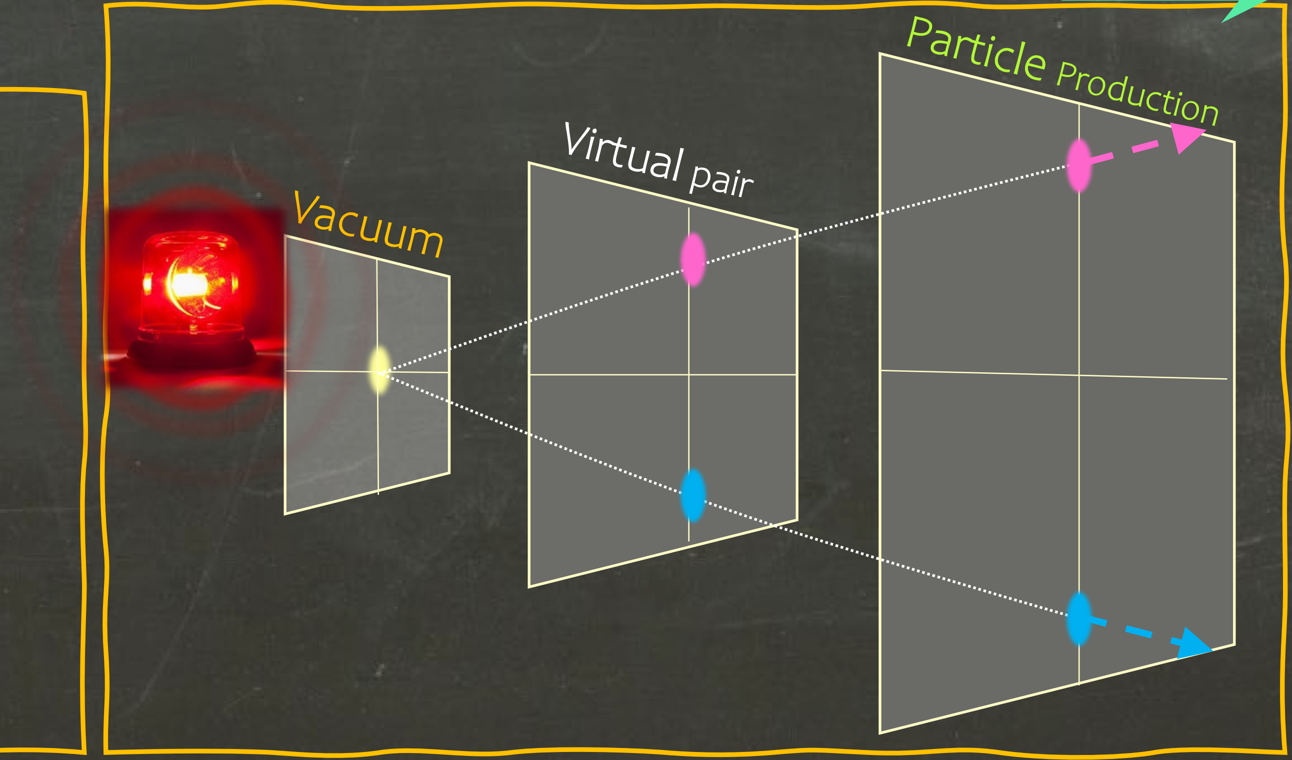


Vacuum

Expanding space:

Edwin Schrödinger
(1939)

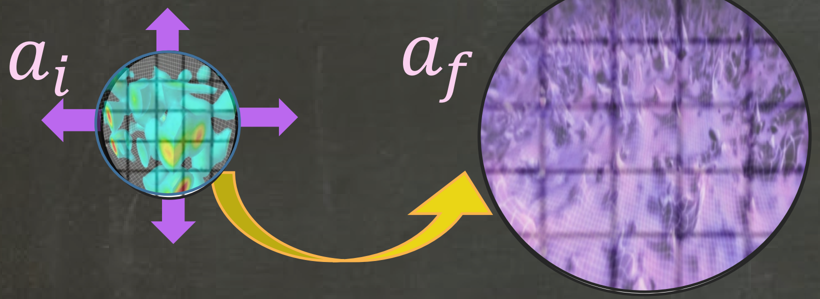
Shocked by his discovery,
Schrödinger found it
an alarming phenomenon!



Particle
Production

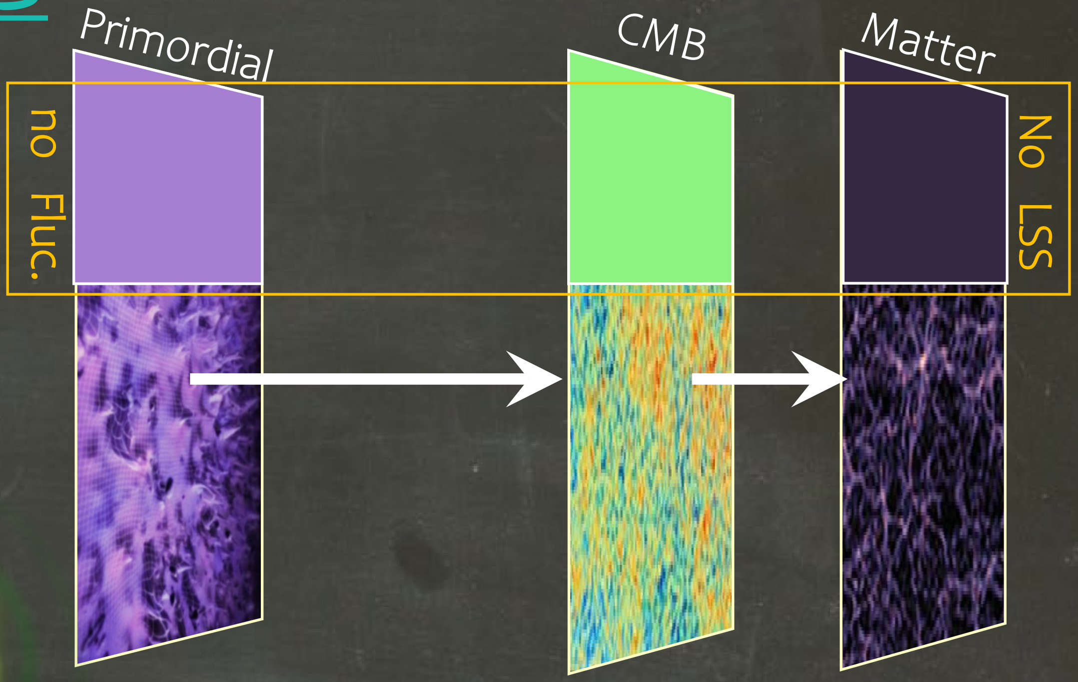
Cosmic Perturbations

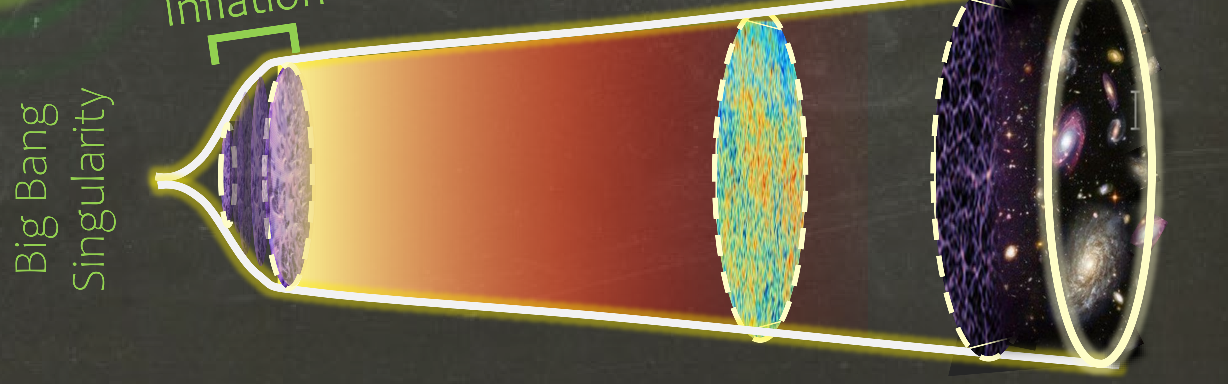
Exponential expansion turns initial quantum vacuum fluctuations into



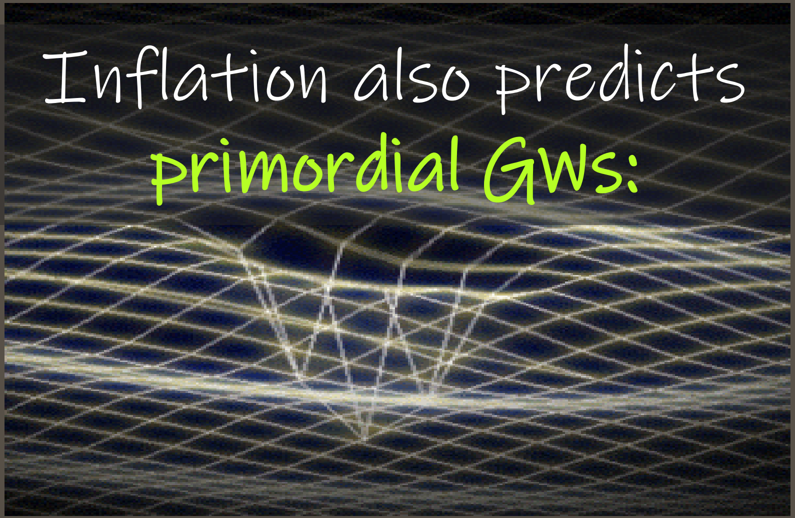
actual cosmic perturbations!

> We are the product of quantum fluctuations in the very early universe!
>
> (Stephen Hawking)

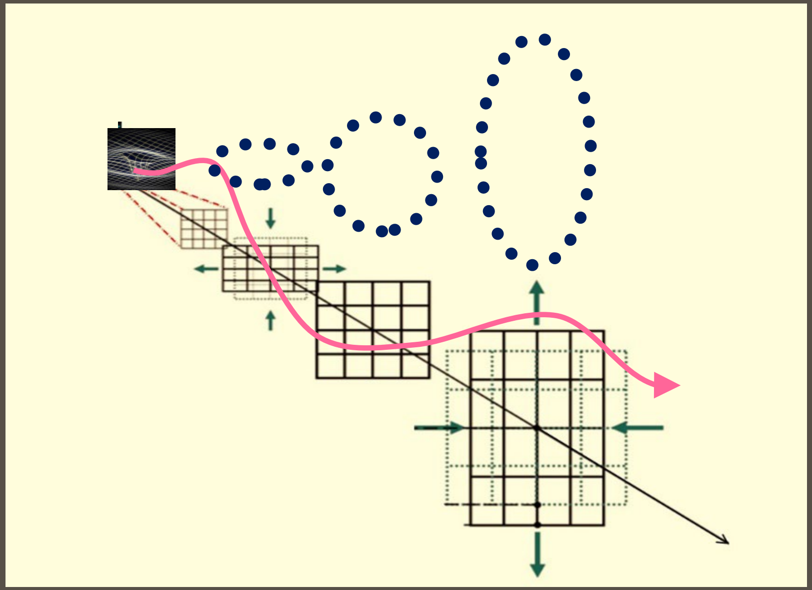




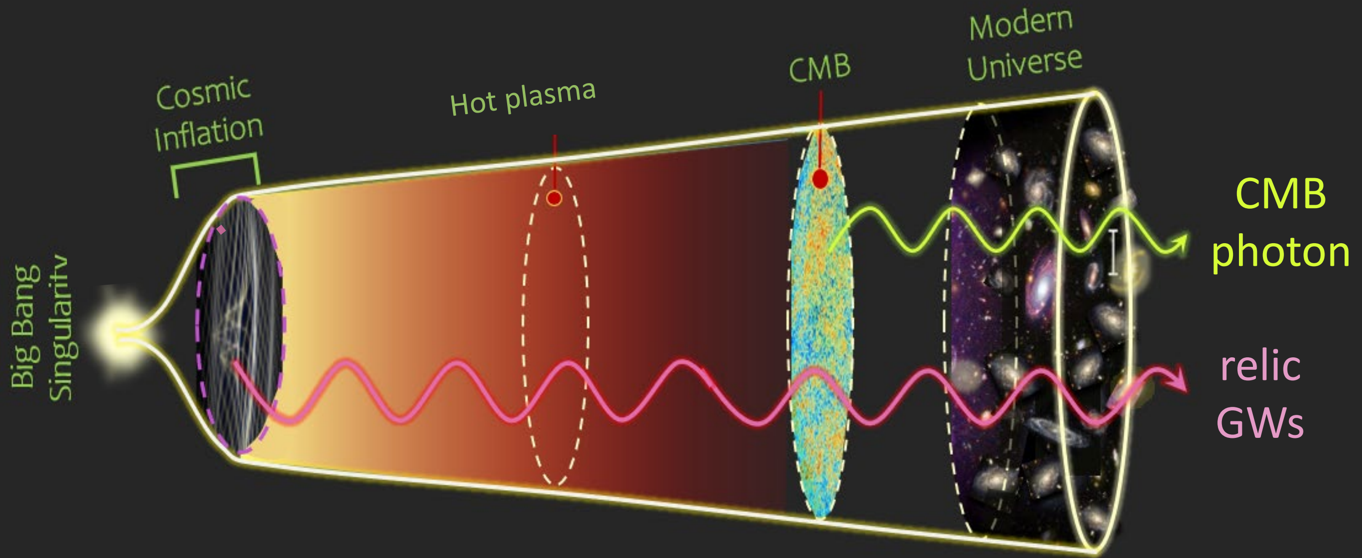
Primordial Gravitational Waves



Inflation also predicts **primordial GWs:**



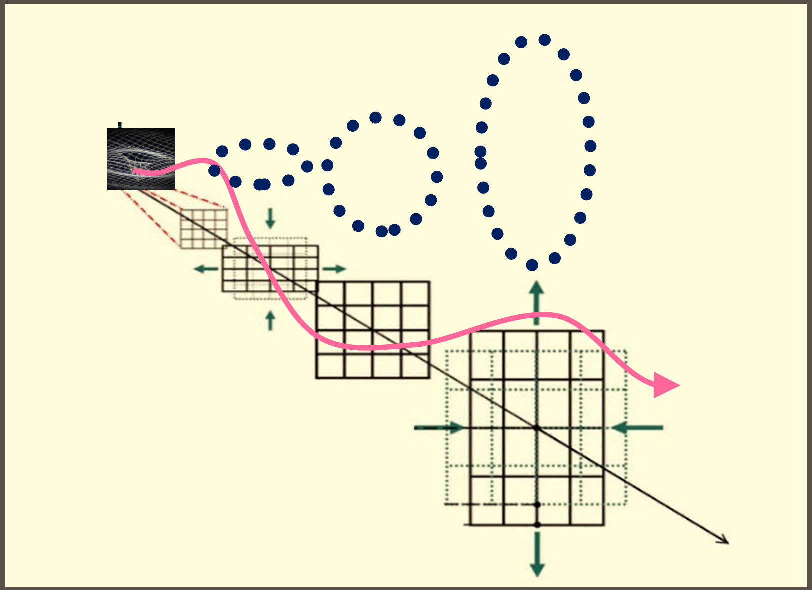
Primordial GWs: tiny waves in the fabrics of the space-time that squeeze and stretch anything in their path as they pass by.

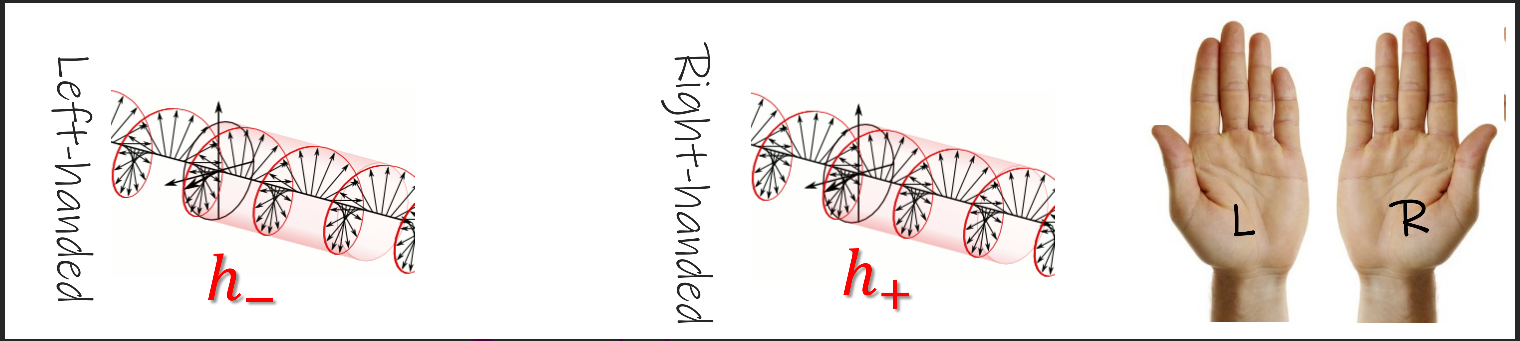


Primordial Gravitational Waves

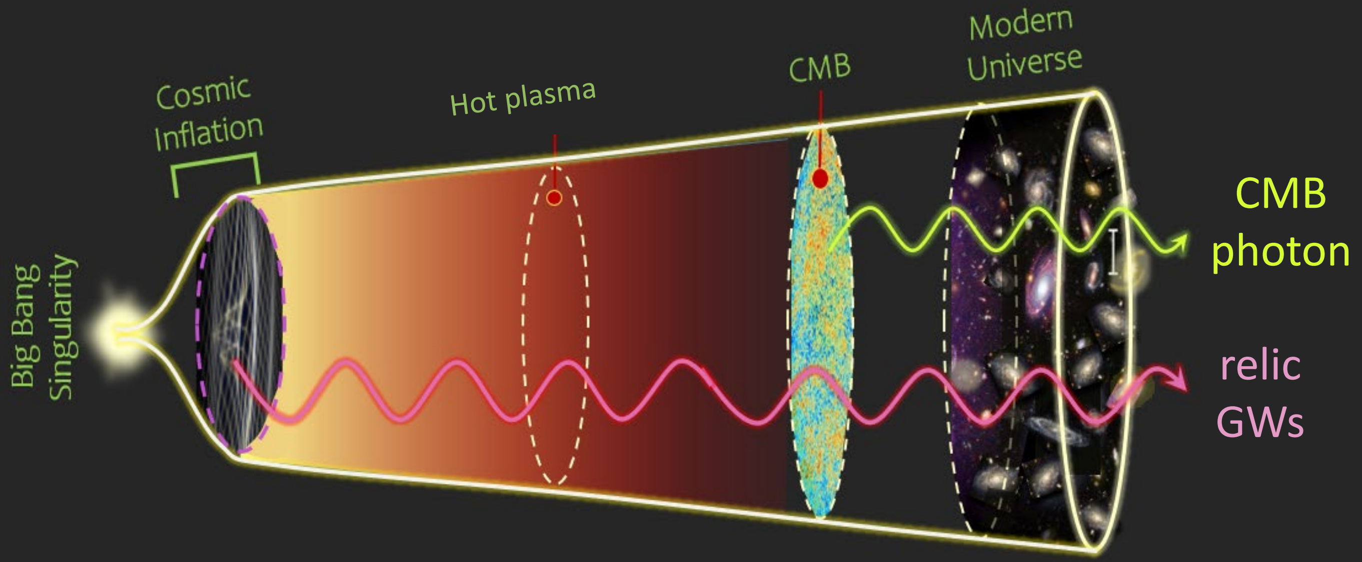
- ○ Vacuum GWs

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





Circular polarizations



Primordial Gravitational Waves

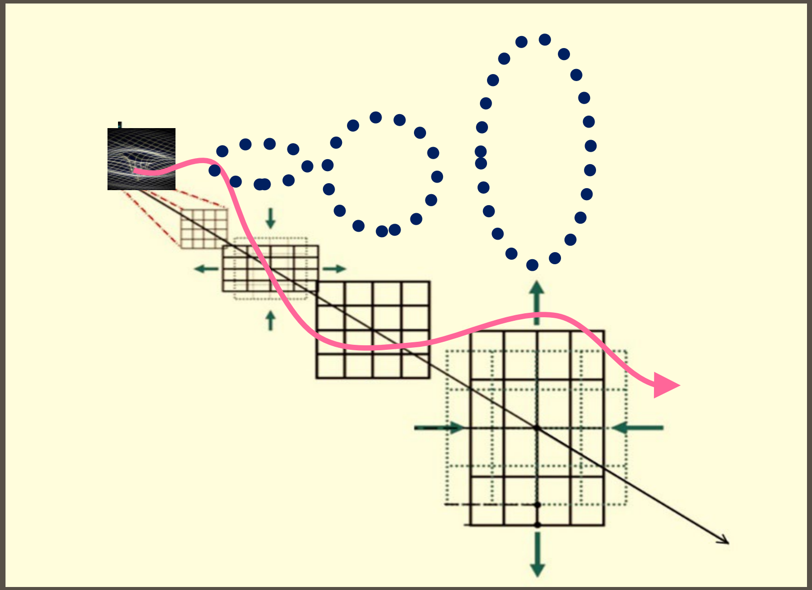
○ Vacuum GWs

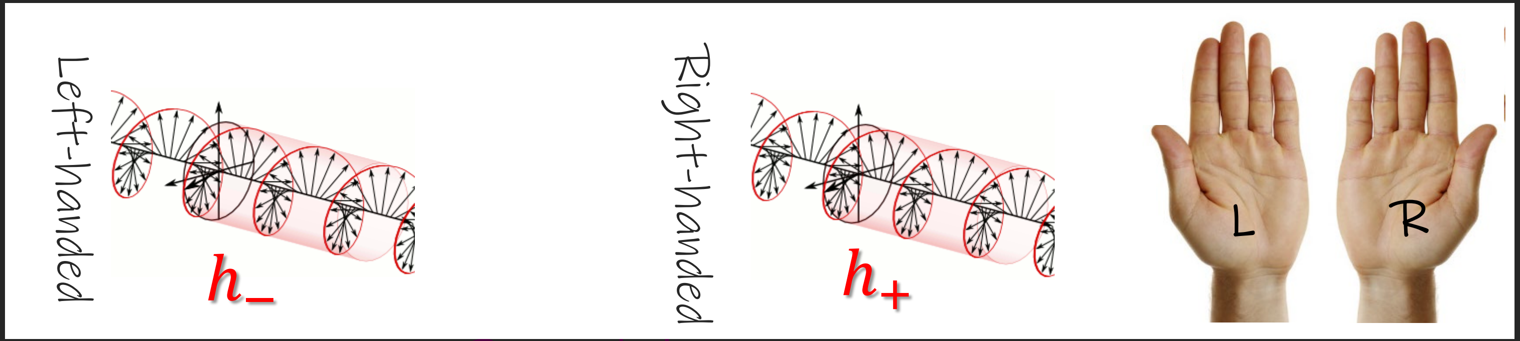
$\Box h_{ij}=0 \rightarrow h_{\pm}= h_{\pm}^{vac}$

○ Unpolarizaed

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

○ Nearly Gaussian





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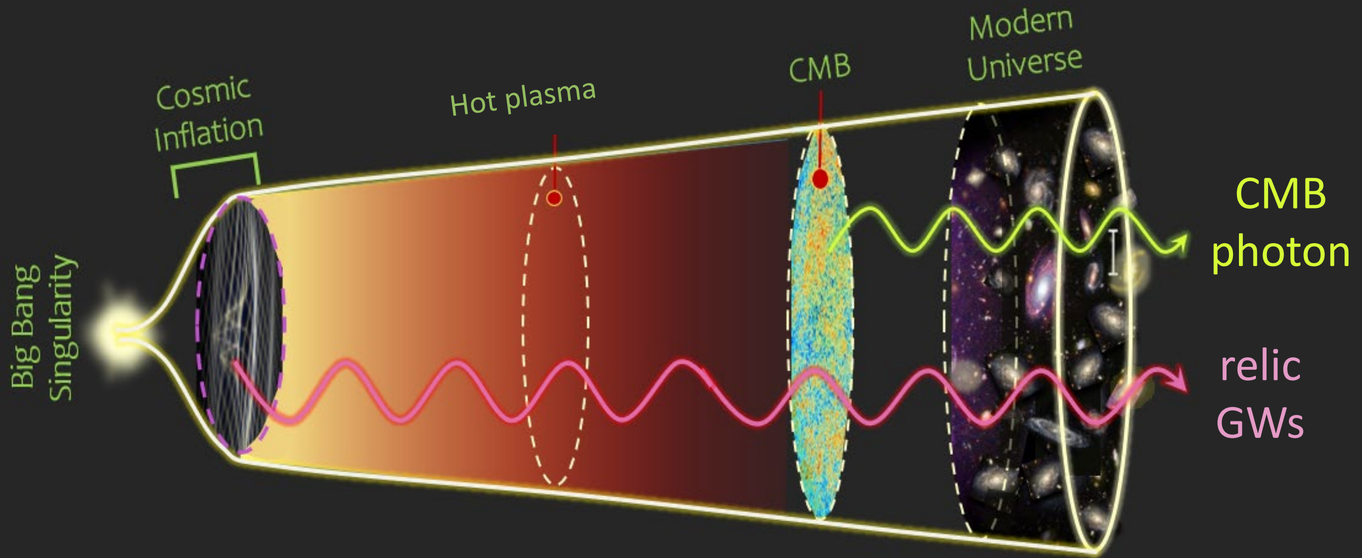


Cosmic Perturbations-Gravitational Waves

○ Inflation also redicts primordial GWs:

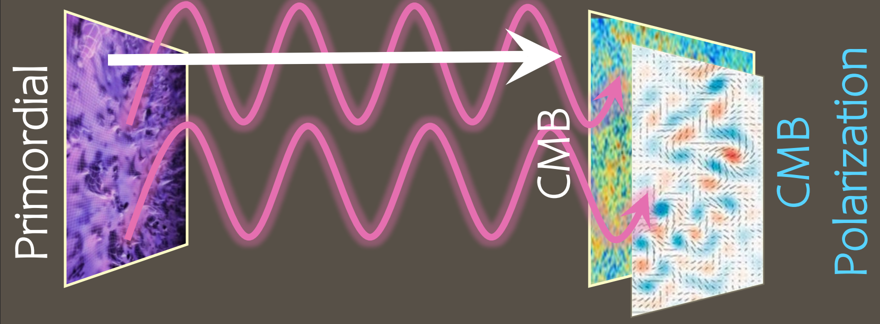
$$\Box h_{ij}=0 \rightarrow h_{\pm} = h_{\pm}^{vac}$$

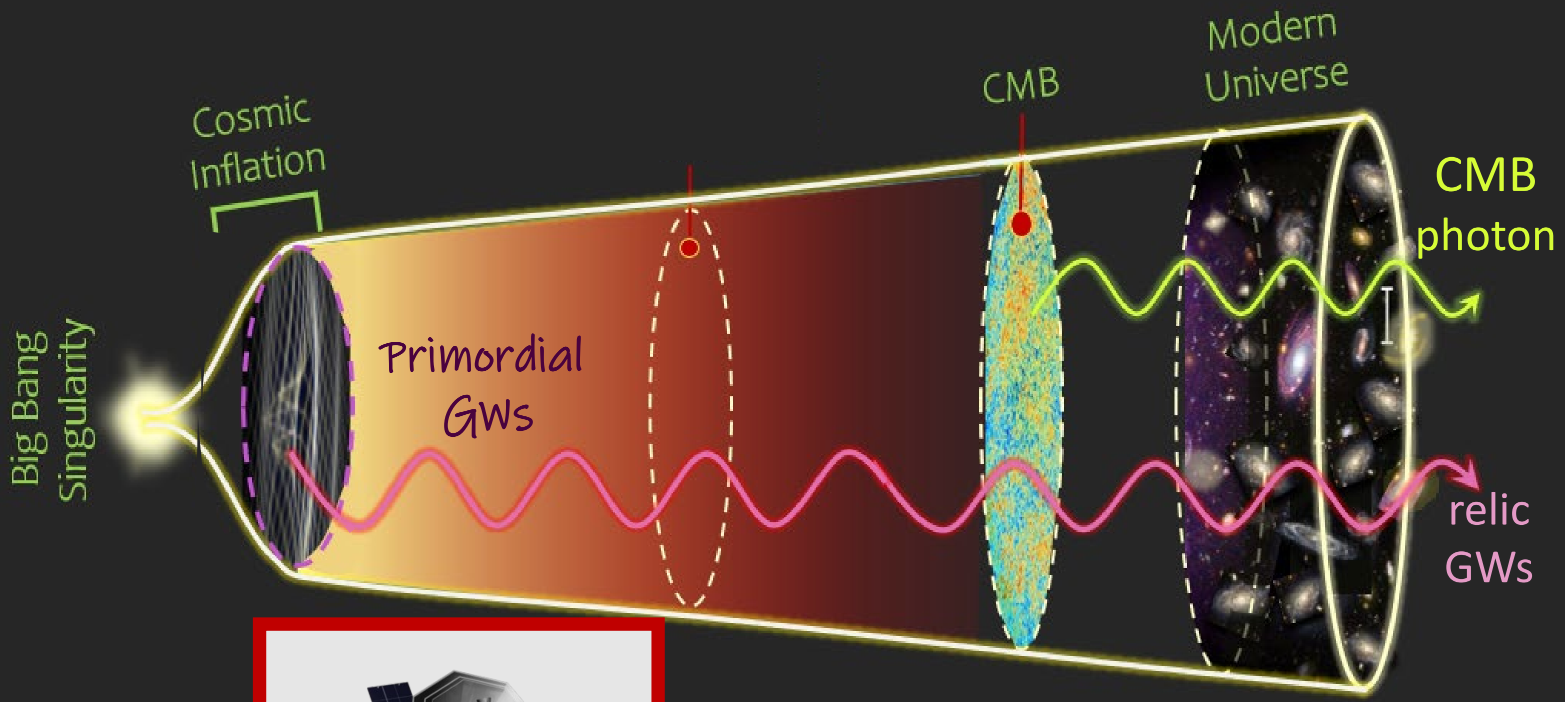
○ Unpolarizaed

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

○ Nearly Gaussian

○ CMB polarization



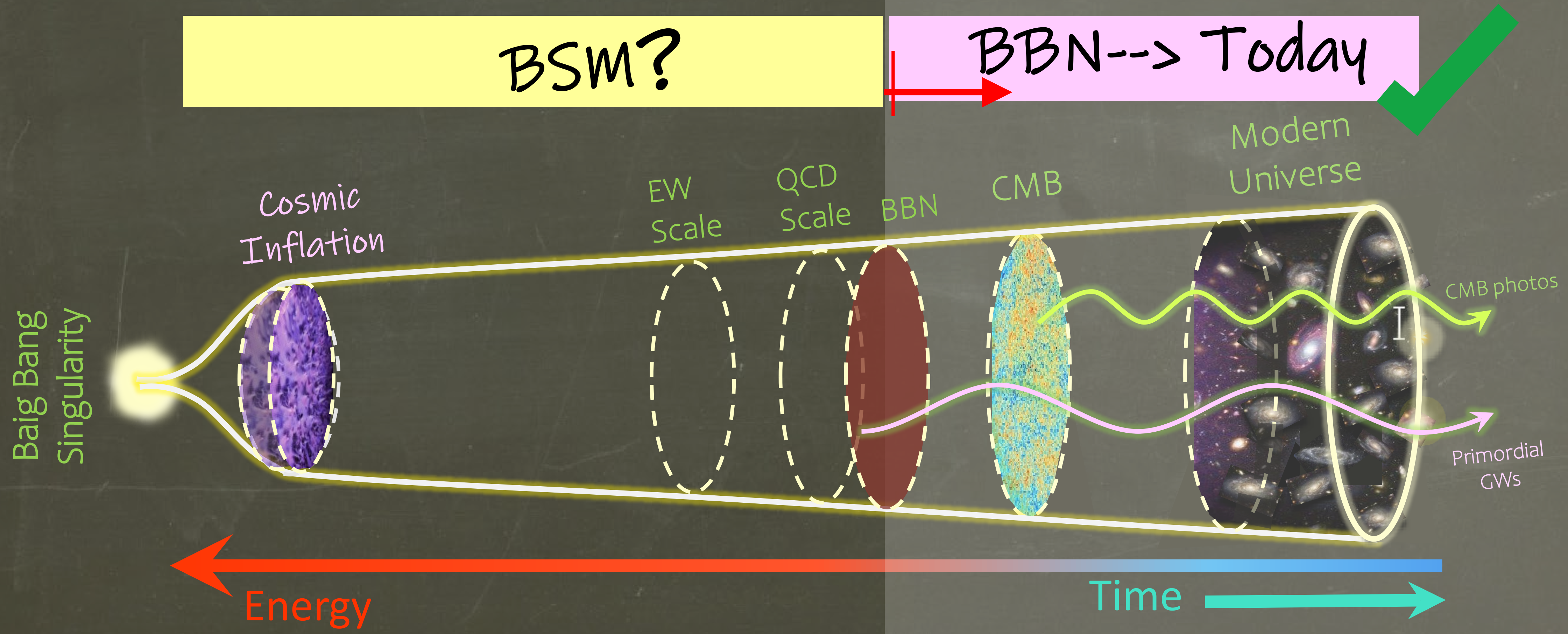


CMB-S4
Next Generation CMB Experiment

Puzzles of SM & Cosmology

Modern cosmology remarkably successful from **BBN until today!**

But the physics before BBN is still much less certain!



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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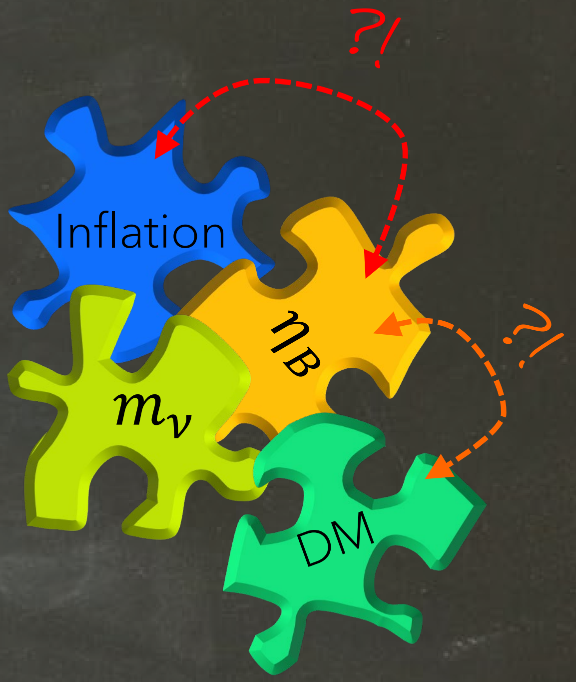


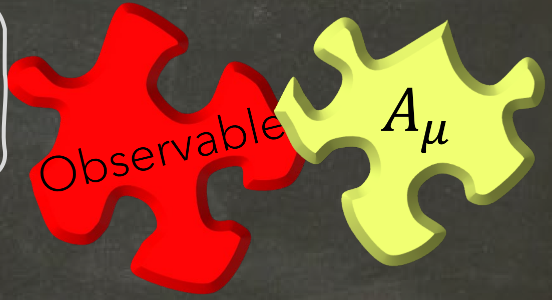
- Curious cosmological coincidences $\eta_B \simeq 0.3\, P_\zeta$ and $\Omega_{DM} \simeq 5\Omega_B$!

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

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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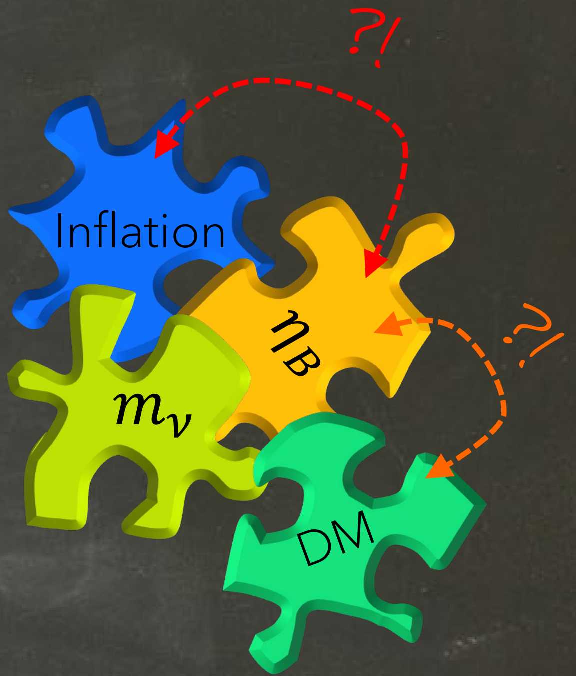
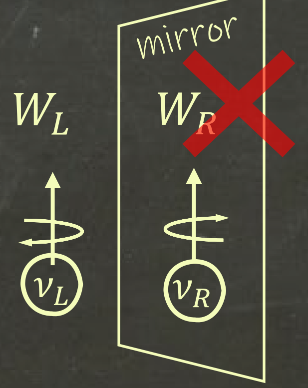
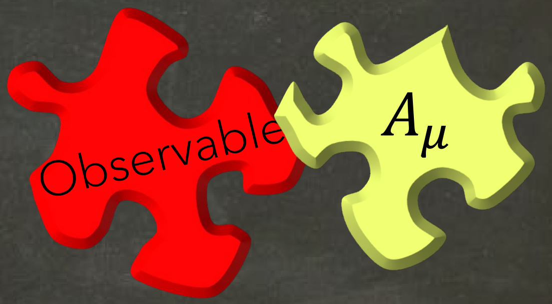


⬟ Curious cosmological coincidences $\eta_B \simeq 0.3\,\mathrm{P}_\zeta$ and $\Omega_{DM} \simeq 5\Omega_B$!

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

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



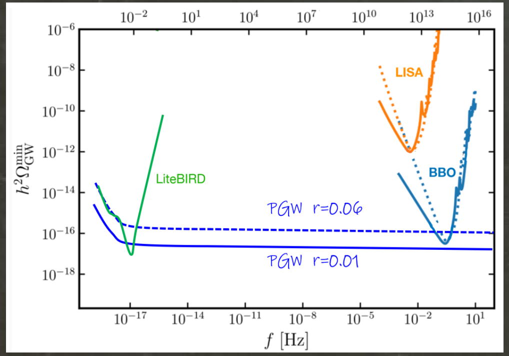


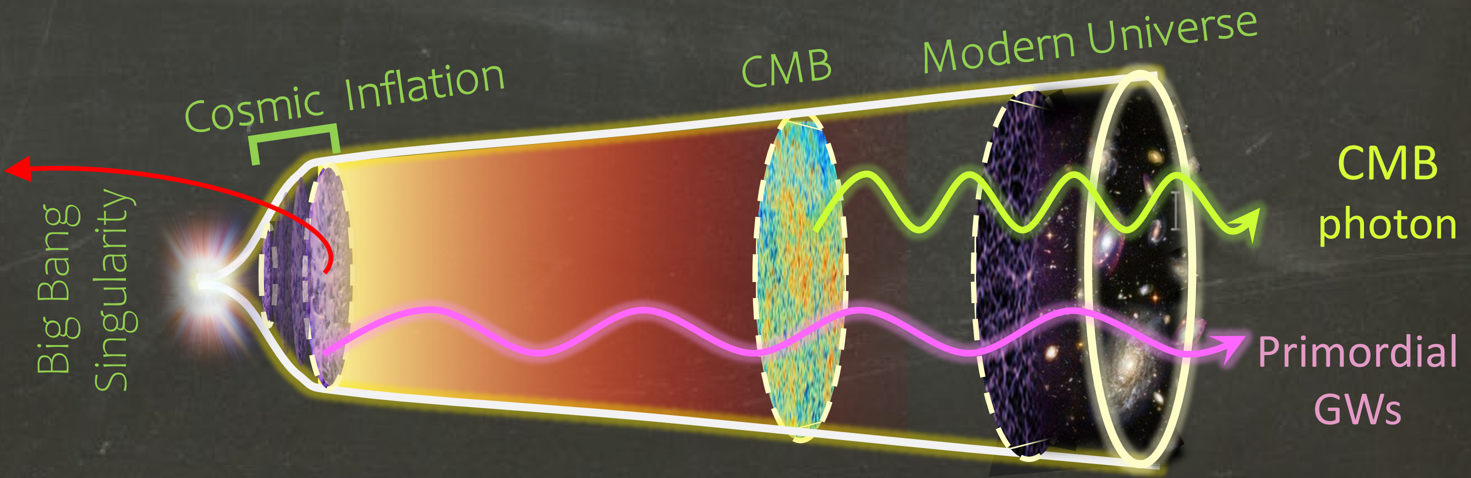
As Yet

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

  Inflation Particle Physics: a **scalar** singlet BSM
- ○ Primordial Gravitational Waves

  Unpolarized, Gaussian





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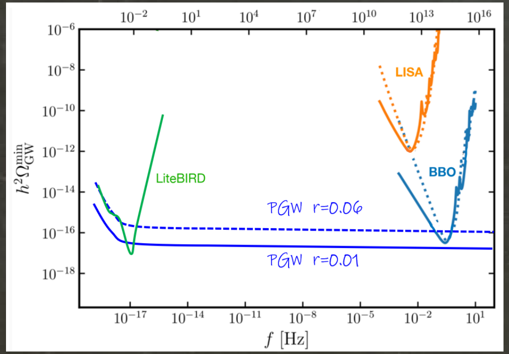
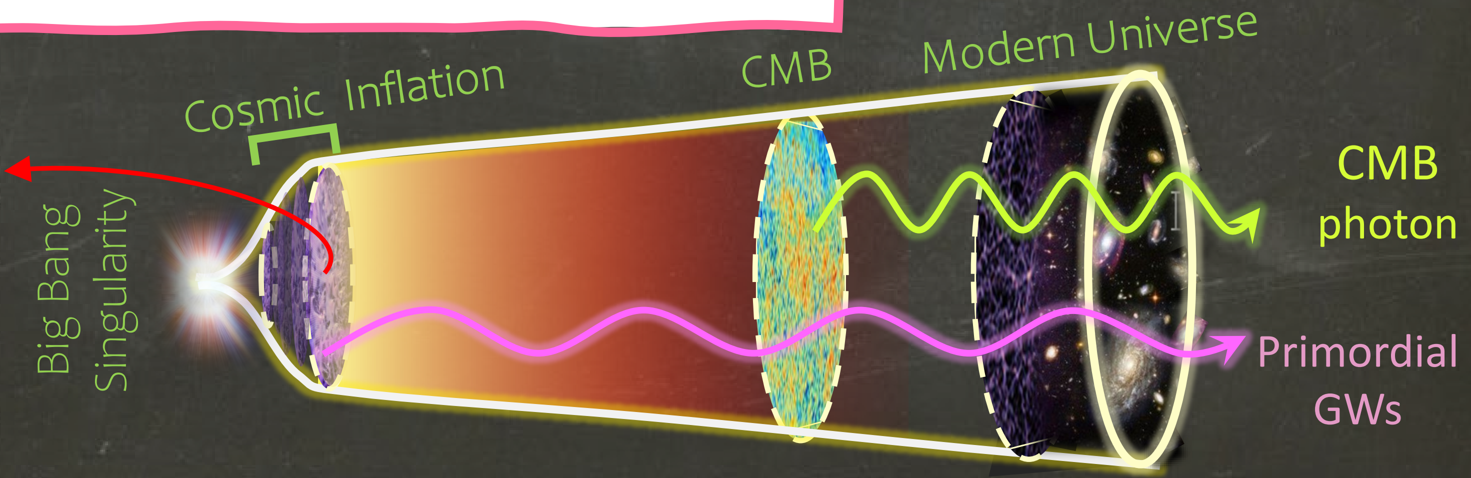
What about Gauge Fields?!





Modern Universe

CMB

Cosmic Inflation

Big Bang Singularity

CMB photon

Primordial GWs

Why Gauge Fields in Inflation?!

- Why not?
  - ○ Inflation happened at highest energy scales observable!
  - ○ Gauge fields are ubiquitous, building blocks of SM & beyond.
- What do they do in inflation?

$E_{Inf} < 10^{14} GeV$

Comparing to LHC

$\frac{E_{Inf}}{E_{LHC}} \lesssim \mathbf{10^{11}}$!!!!

Why Gauge Fields in Inflation?!

- Why not?
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  - ○ Gauge fields are ubiquitous, building blocks of SM & beyond.
- What do they do in inflation?

I. Can Gauge Fields Contribute to Physics of Inflation?
   Yes!

II. Do they leave an observable signature?
   Yes! Robust prediction for GW background.

III. How much they can change the cosmic history?
   A lot! Novel mechanisms for Baryo- and Dark-genesis.

$E_{Inf} < 10^{14} GeV$

Comparing to LHC

$\frac{E_{Inf}}{E_{LHC}} \lesssim 10^{11}$!!!!

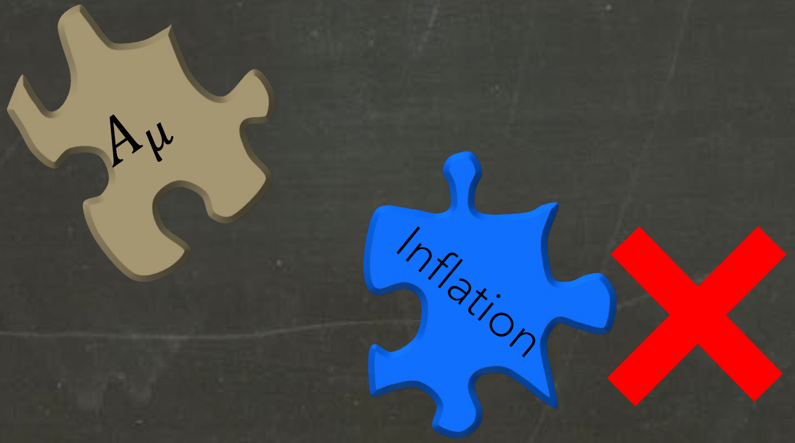
I) Axion-inflation & gauge fields

(non-Abelian)

Challenges:

Gauge fields given by Yang-Mills

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

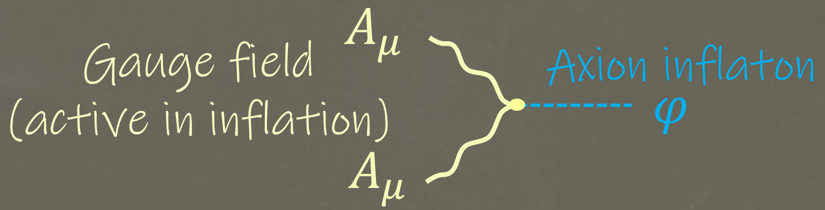


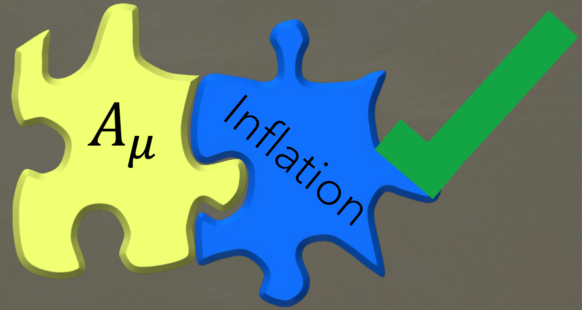
Gauge fields coupled to inflaton are generated in inflation.

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

Axion

(**Axion fields** are naturally coupled to **gauge fields**.)





Challenges:

Gauge fields given by Yang-Mills

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.)

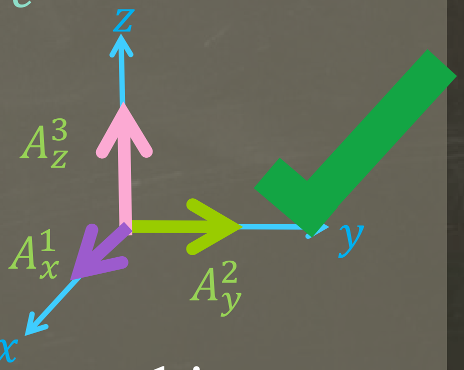
A.M. & Sheikh-Jabbari, 2011

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

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

Spatially isotropic

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



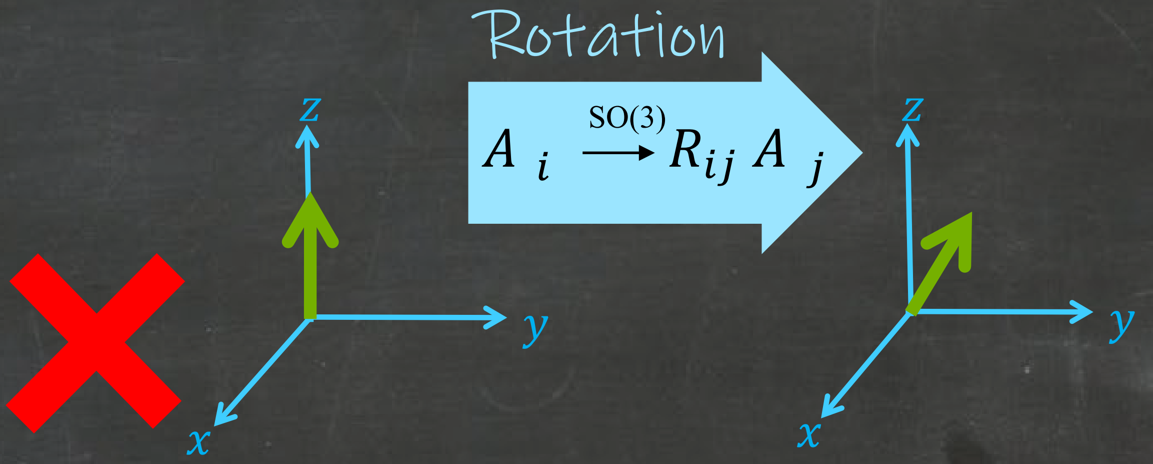
so(3) & su(2) are isomorphic

How SU(2) restores isotropy?

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

U(1) vacuum A_μ

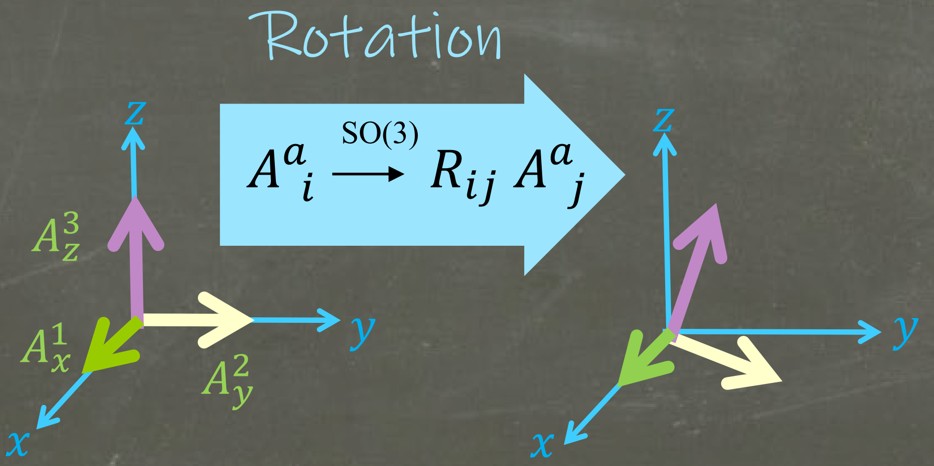
$$A_i = Q(t)\delta_i^3$$



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

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

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



$$A^a_i \xrightarrow{\text{SO(3)}} R_{ij} A^a_j$$

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

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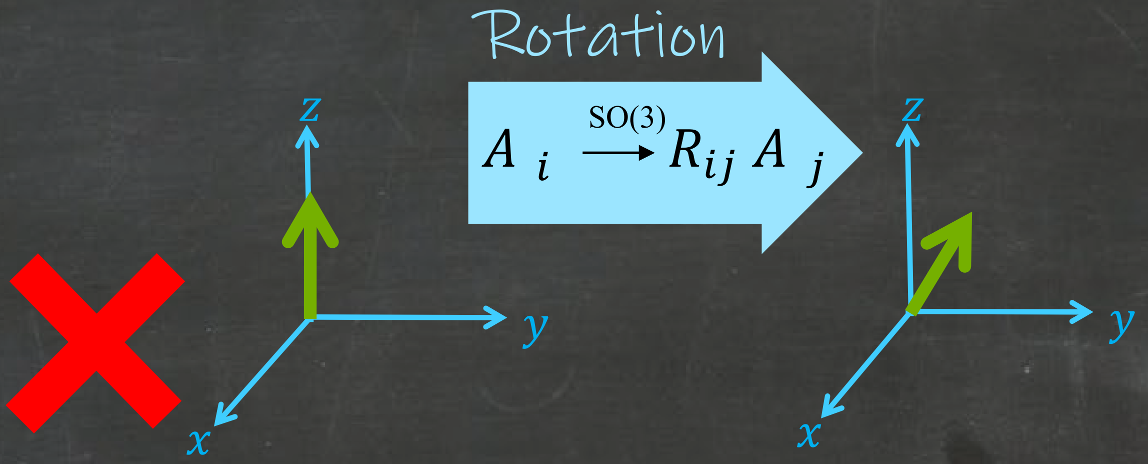

Rotation

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

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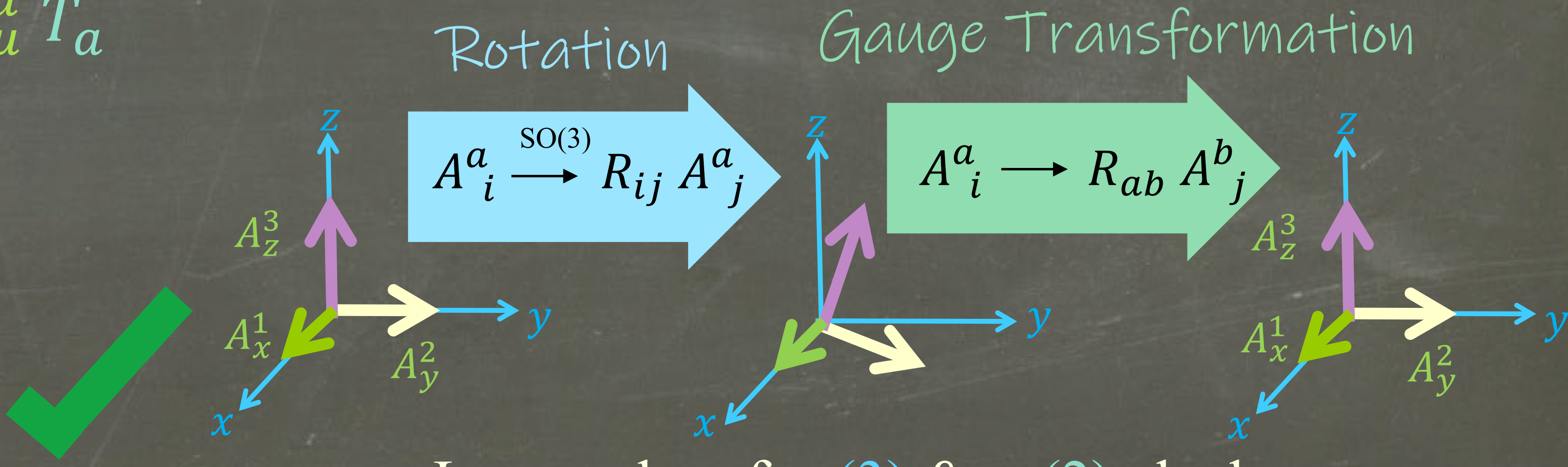


Rotation

$$A^a{}_i \xrightarrow{\mathrm{SO(3)}} R_{ij} A^a{}_j$$

Gauge Transformation

$$A^a{}_i \longrightarrow R_{ab} A^b{}_j$$

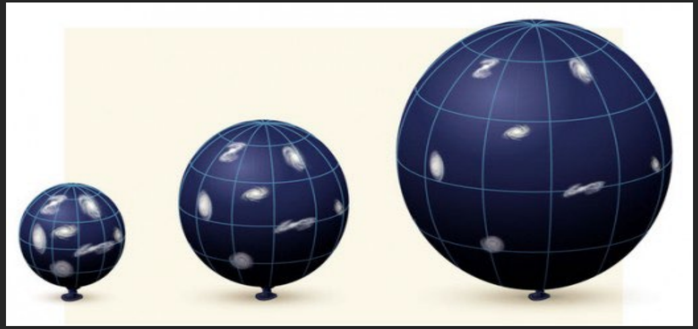
A.M. and M. M. Sheikh-Jabbari, 2011

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

SU(2) Gauge fields and Initial Anisotropies

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

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

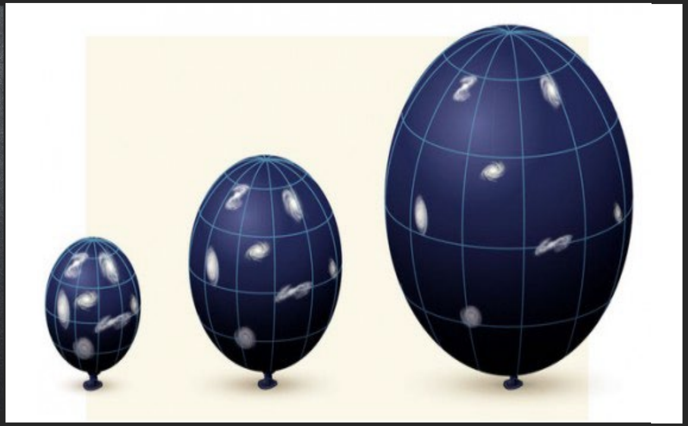


Isotropic Background

- 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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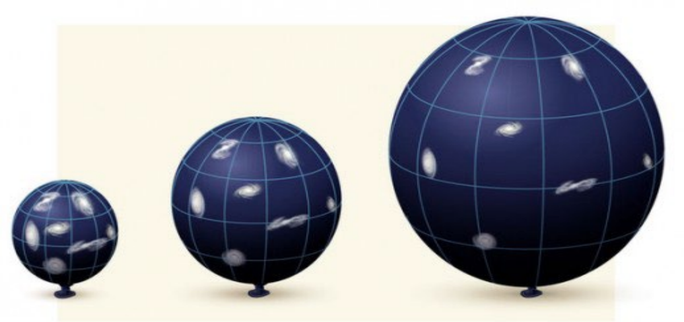
SU(2) Gauge fields and Initial Anisotropies

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

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



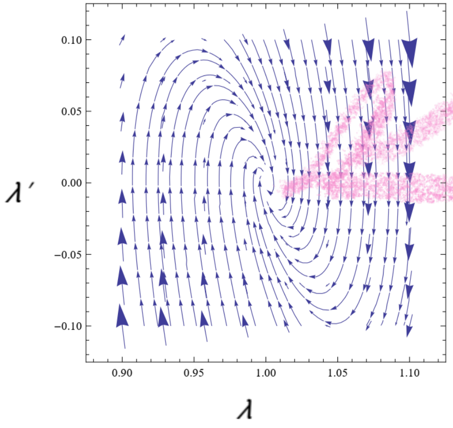
Isotropic Background

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

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

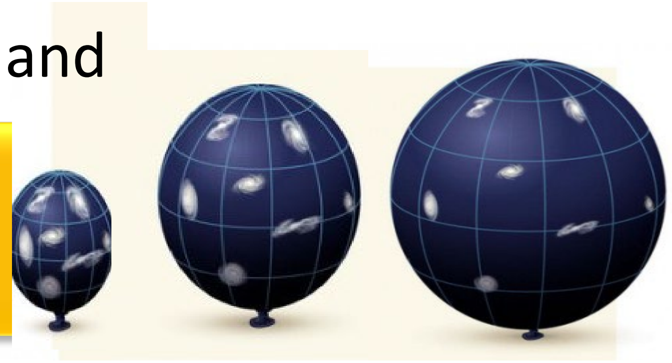
Axion is only coupled to the isotropic part of the gauge field,

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



Anisotropic Background

SU(2)-Axion Model Building

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

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

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

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

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

SU(2)-Axion Model Building

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

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

Ruled-out by the data

R. Namba, E. Dimastrogiovanni, M. Peloso 2013
P. Adshead, E. Martinec, M. Wyman 2013

+ Theoretical issue:

Very large $\lambda \sim 100$!

D. Baumann & L. McAllister 2014

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

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

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

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

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

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

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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; **A. M. 2021**
- 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**
- Common Origin for inflation, Baryogenesis & CDM production **A.M. 2021**

SU(2)-Axion Model Building

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

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

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

Axion Monodromy or any mechanism that gives a flat potential

II) Cosmic Perturbations

Axion field perturbations $\delta\varphi$

Metric perturbations $\delta g_{\mu\nu}$

Decomposition of fluctuation

Scalar
Vector
Tensor

The only tensorial modes are in the metric, i.e, GWs! $\Box h_{ij}=0$

Primordial GWs are sourceless

II) Cosmic Perturbations

Axion field perturbations $\delta\varphi$

Metric perturbations $\delta g_{\mu\nu}$

+

Gauge field perturbations δA_i^a

Decomposition of fluctuation

Scalar
Vector
Tensor

$\Box h_{ij} = S_{ij}$

The perturbed gauge field has a tensorial which sources GWs!

New Tensorial mode in SU(2) Gauge Field

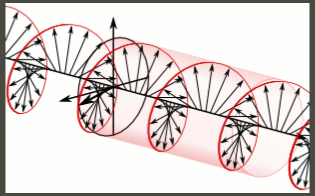
- $\delta A_i^a = \left(B_+(t,k)e^{+}_{ij}(\vec{k}) + B_-(t,k)e^{-}_{ij}(\vec{k})\right)\delta^a_j$

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

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

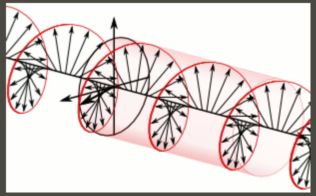
Circular polarizations

Right-handed



B_+

Left-handed



B_-

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

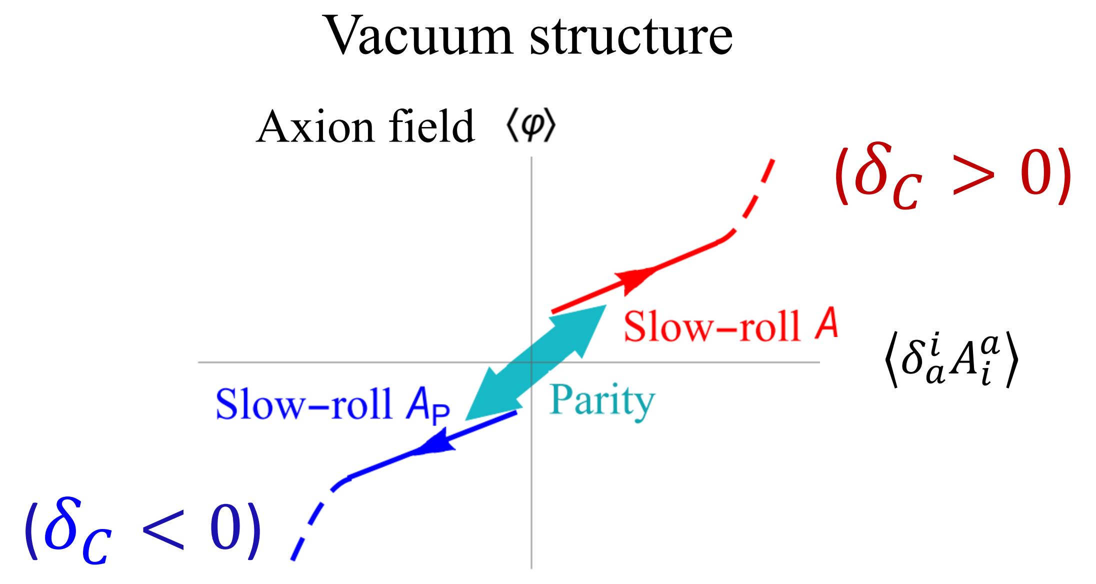
A.M. & Sheikh-Jabbari, 2011

New Tensorial mode in SU(2) Gauge Field

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

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

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



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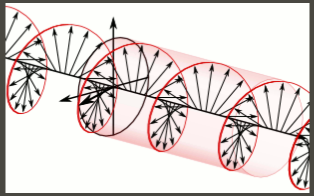

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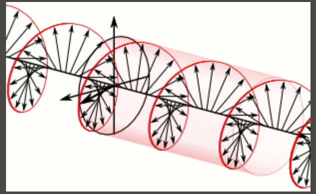
Left-handed



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

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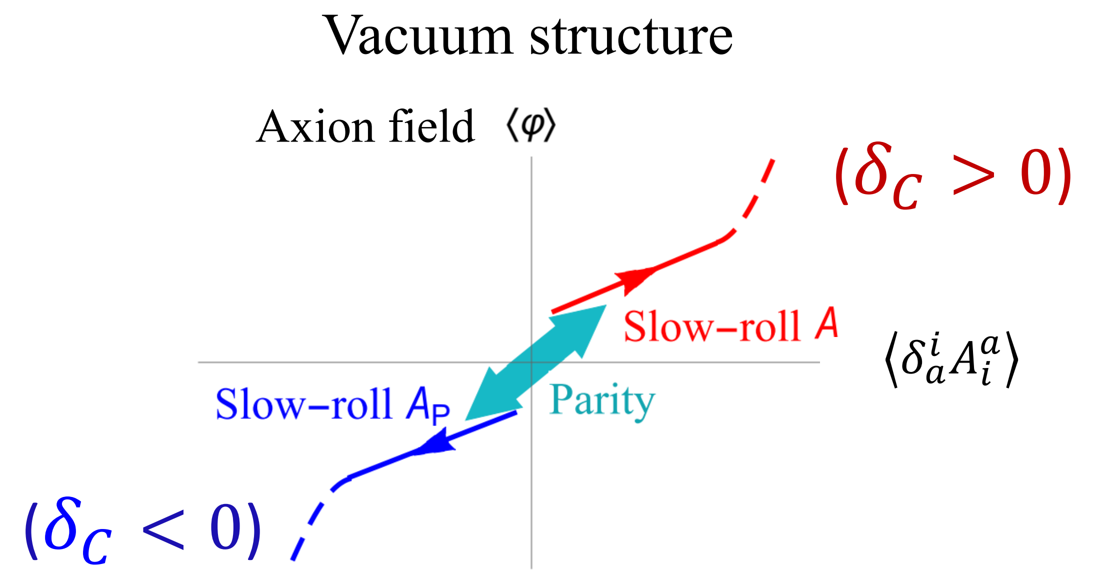


For $\delta_C > 0$

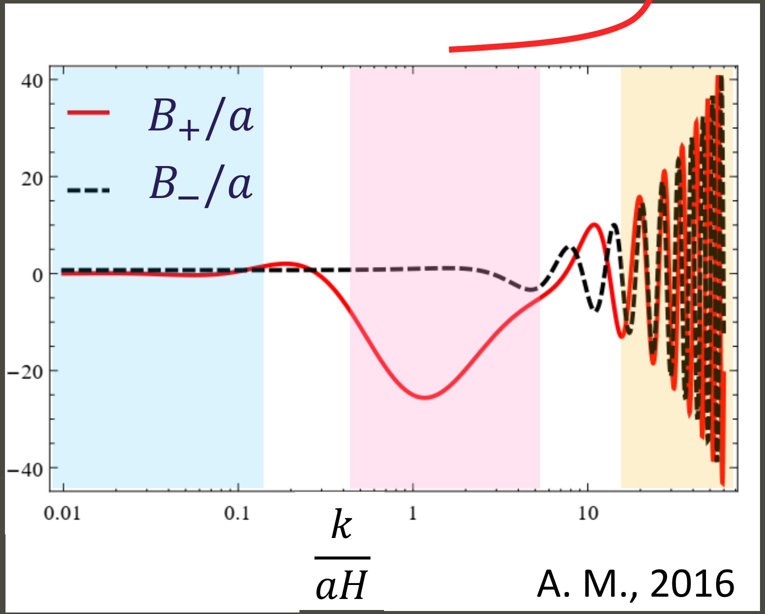
Short tachyonic growth of B_+

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



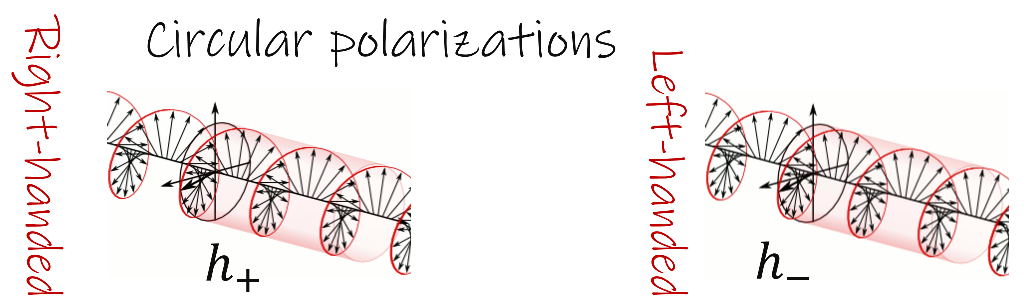
A. M., 2016

Gauge Field sources Primordial GWs

- $\delta A^a_i = (B_+(t,k)\, e^+_{ij}(\vec{k}) + B_-(t,k)\, e^-_{ij}(\vec{k}))\, \delta^a_j$
- 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

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

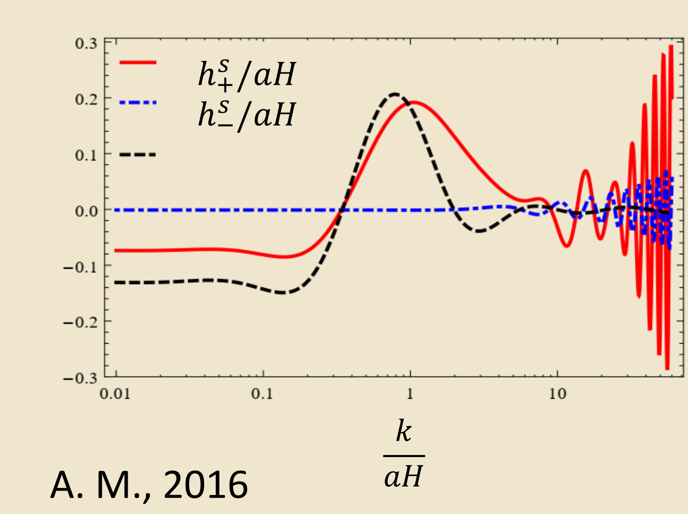


- Gravitational waves have two uncorrelated terms

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

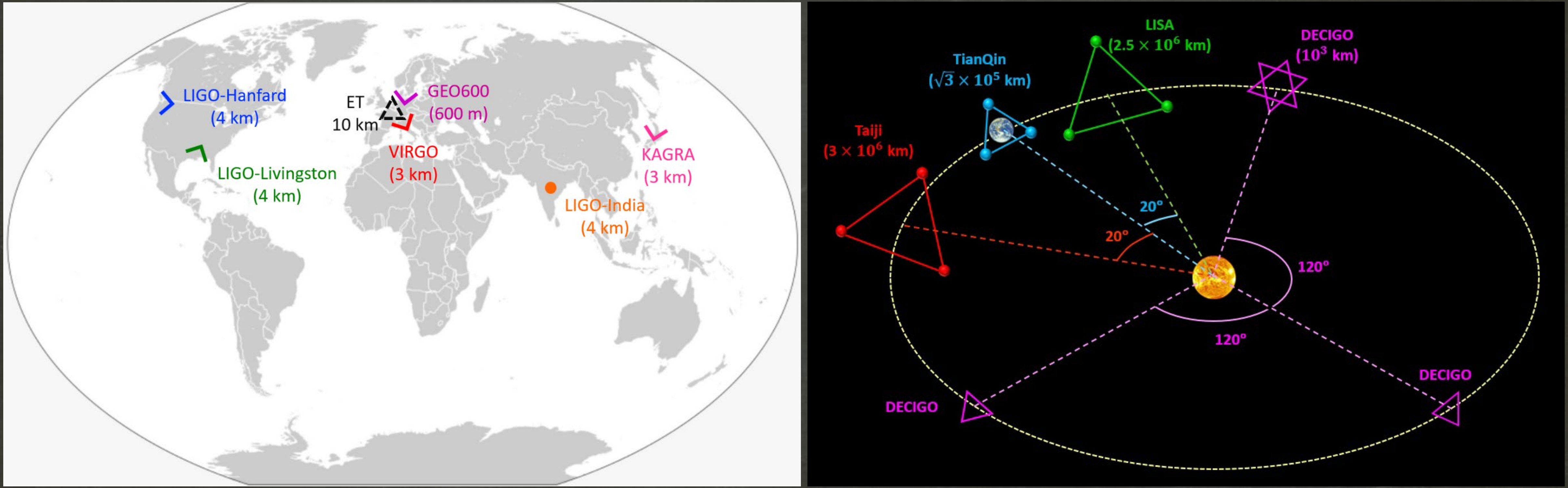
Vacuum GWs unpolarized $h^{vac}_+ = h^{vac}_-$

Sourced by $B_\pm$ Polarized $h^s_+ \neq h^s_-$



A. M., 2016

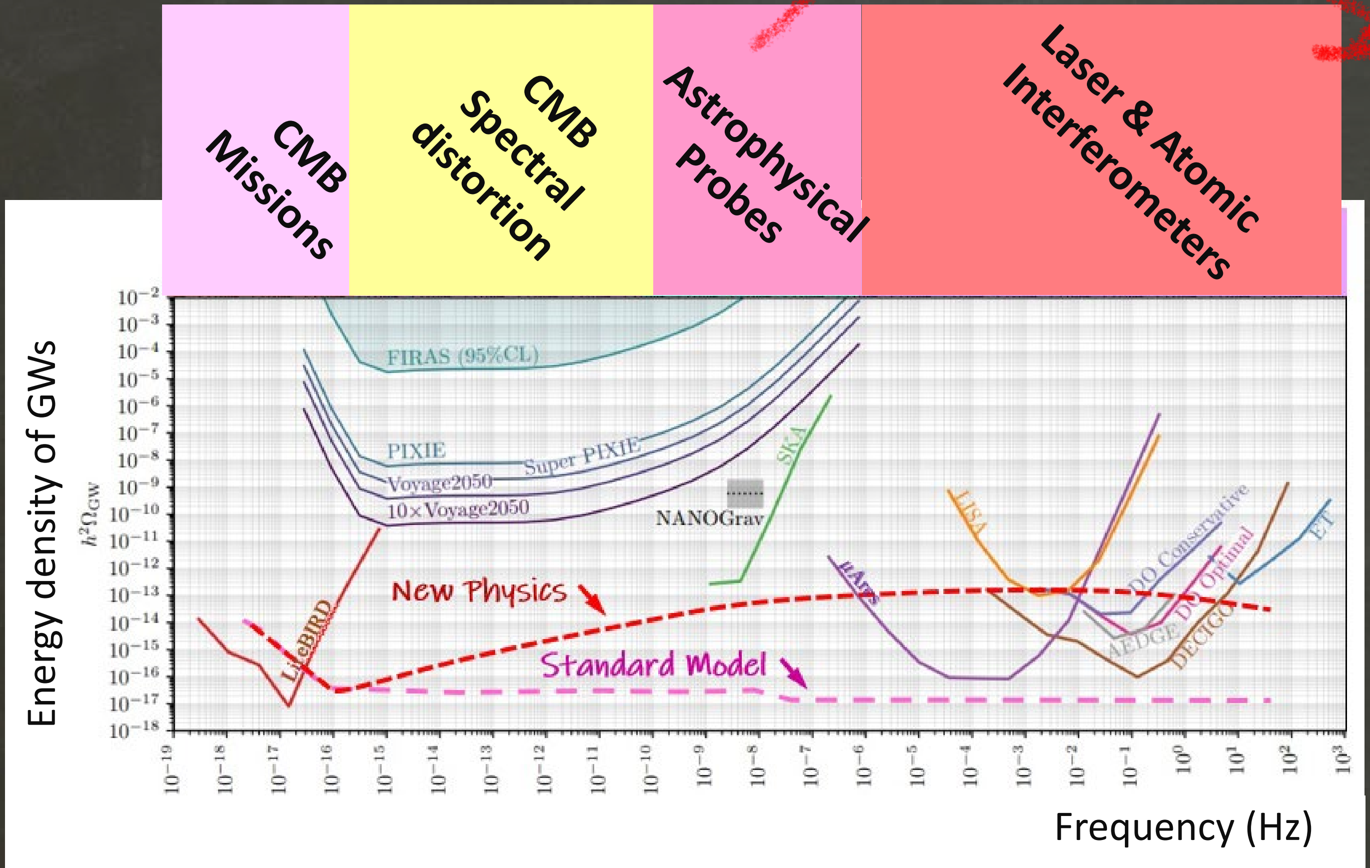
Networks of GWs Detectors



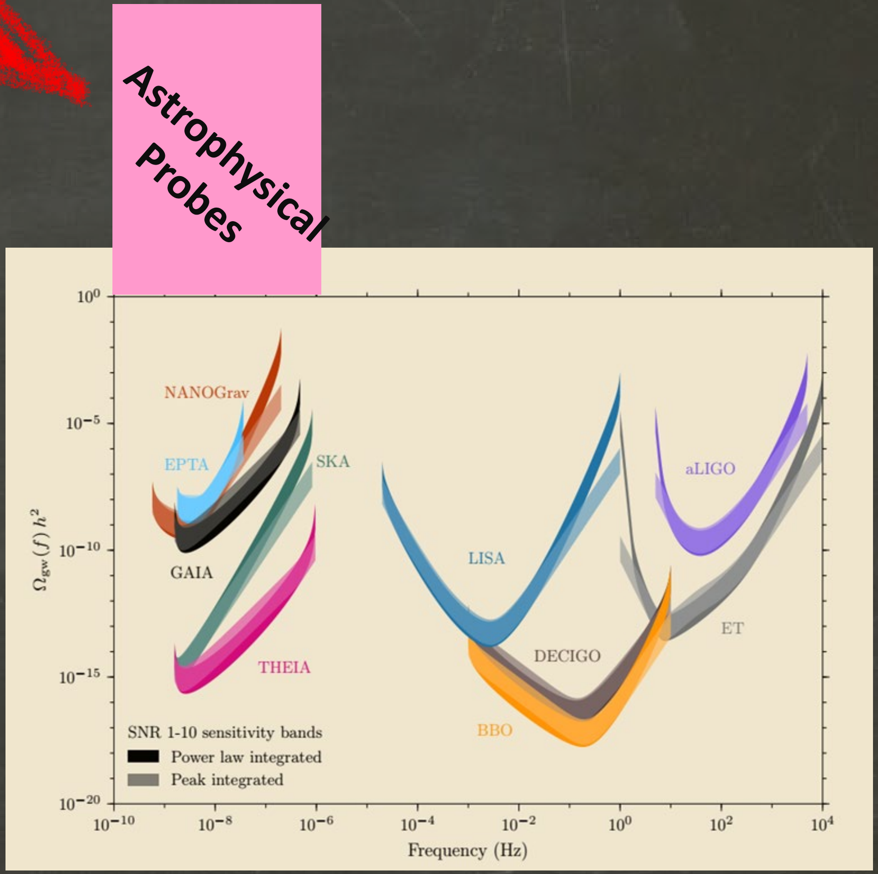
Network of laser interferometer detectors of GWs on Earth (left) & in the sky (right)

Sensitivity curves on energy density of GWs

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 2021



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

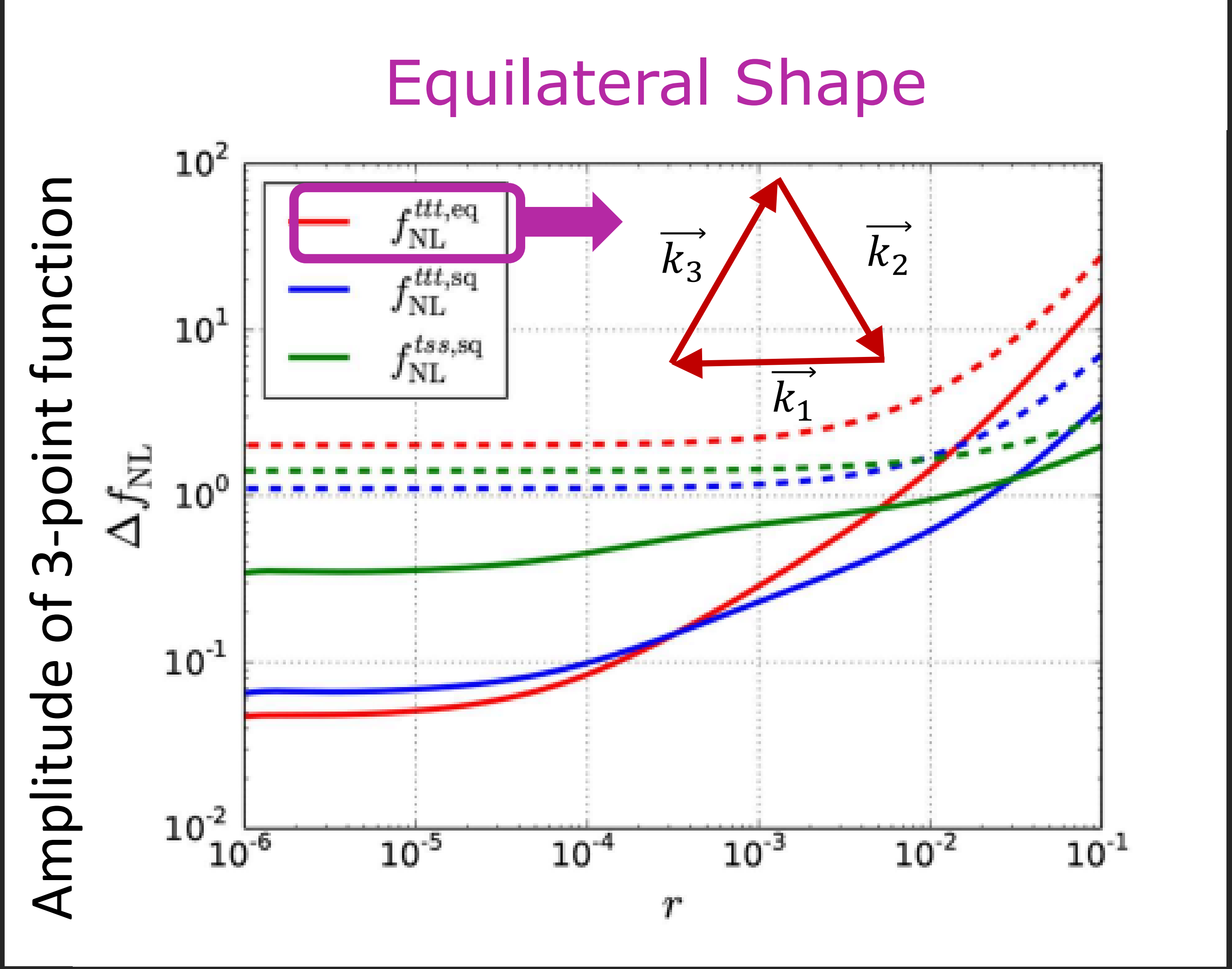
Novel Observable Signature: CMB

- 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*!

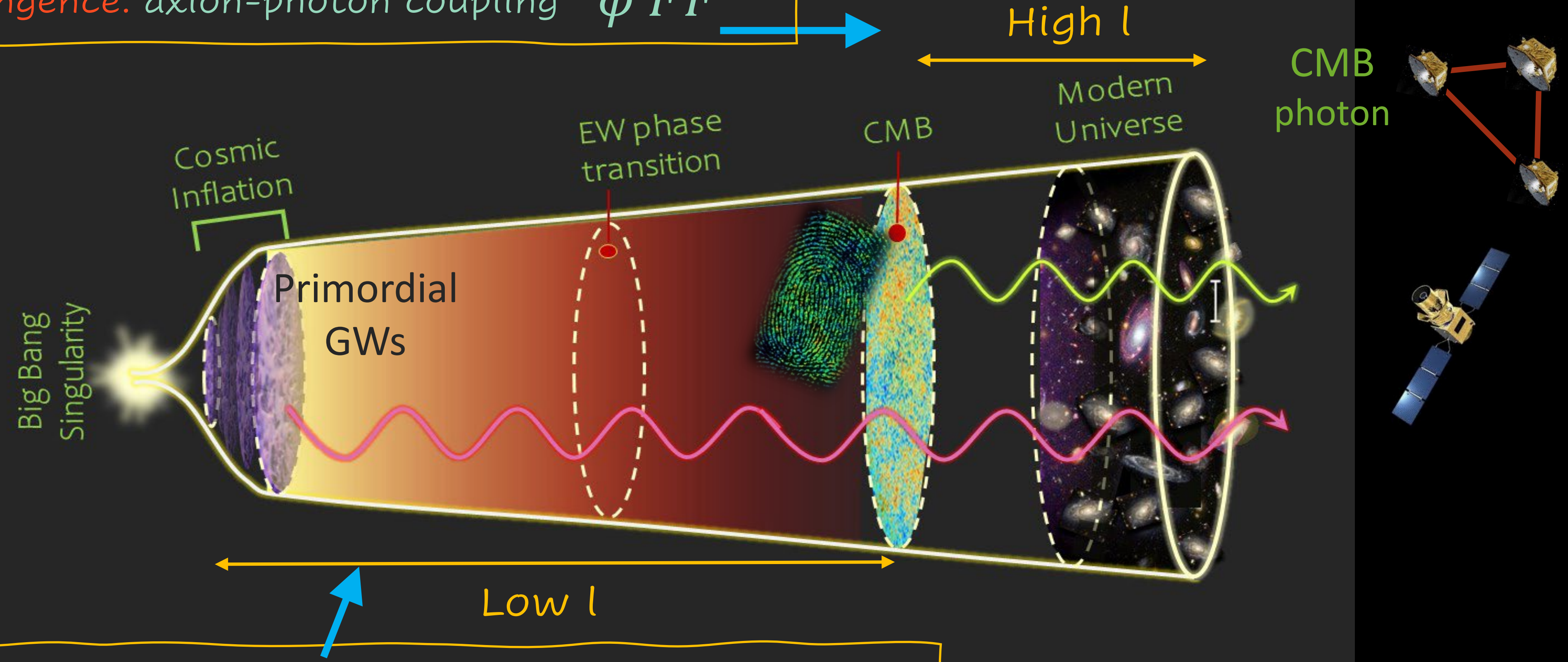


Maresuke Shiraishi, Front. Astron. Space Sci. 2019

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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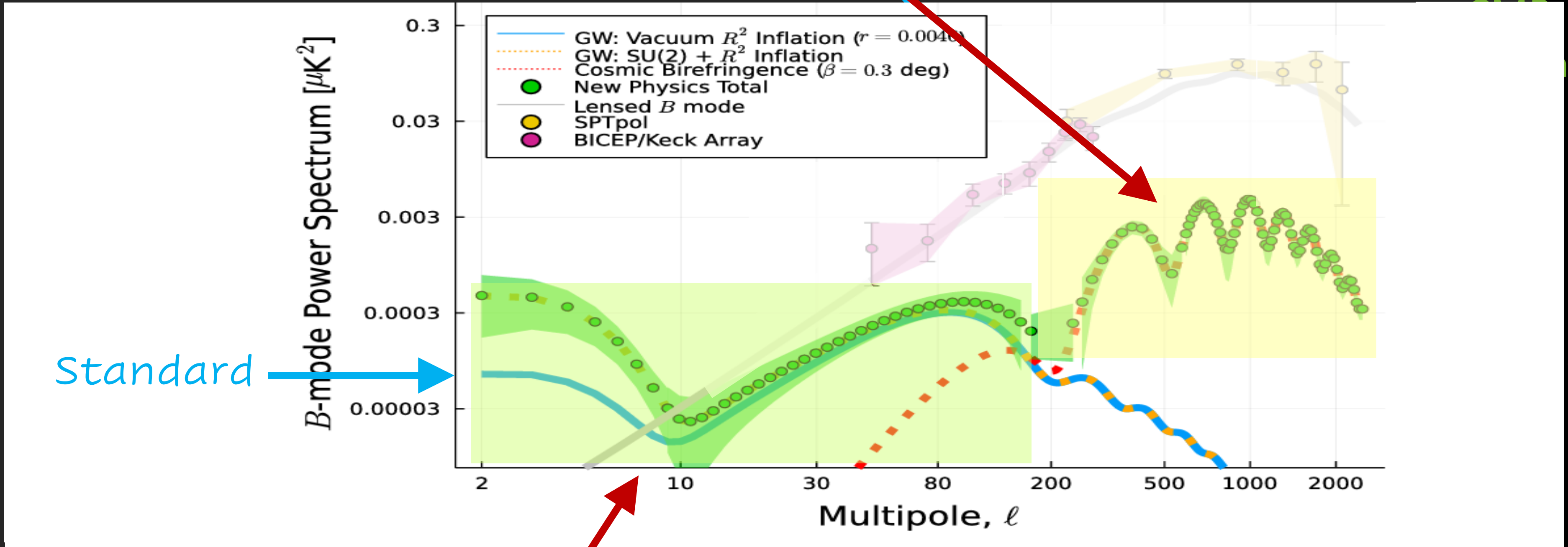
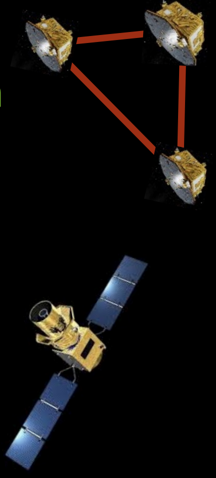


E. Komatsu Nature Rev. Phys. 4 (2022) 7, 452-469



- SU(2)-axion Inflation: SU(2) field -Graviton coupling
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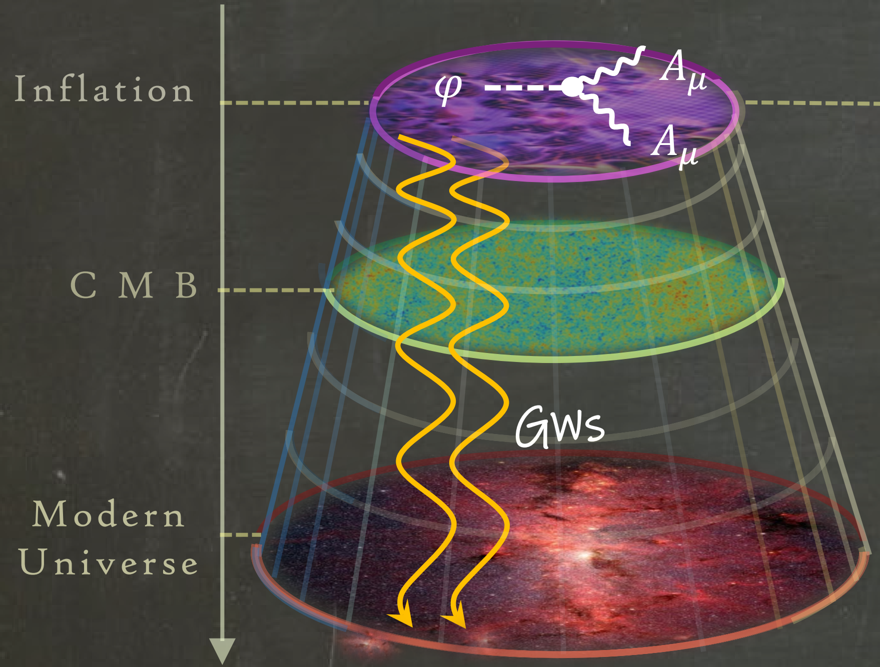
B. Thorne et. al.2018

III) Particle Production in Inflation

A New Class of Inflation Models

(closer to Particle Physics)

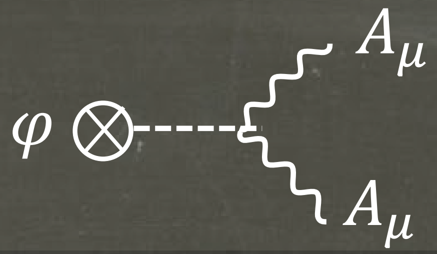
A. M., & Sheikh-Jabbari, **2011**
P. Adshead, M. Wyman, 2012



Axion-inflation and gauge fields (non-Abelian)

Particle Production
In Axion-Inflation

Axion → Gauge fields



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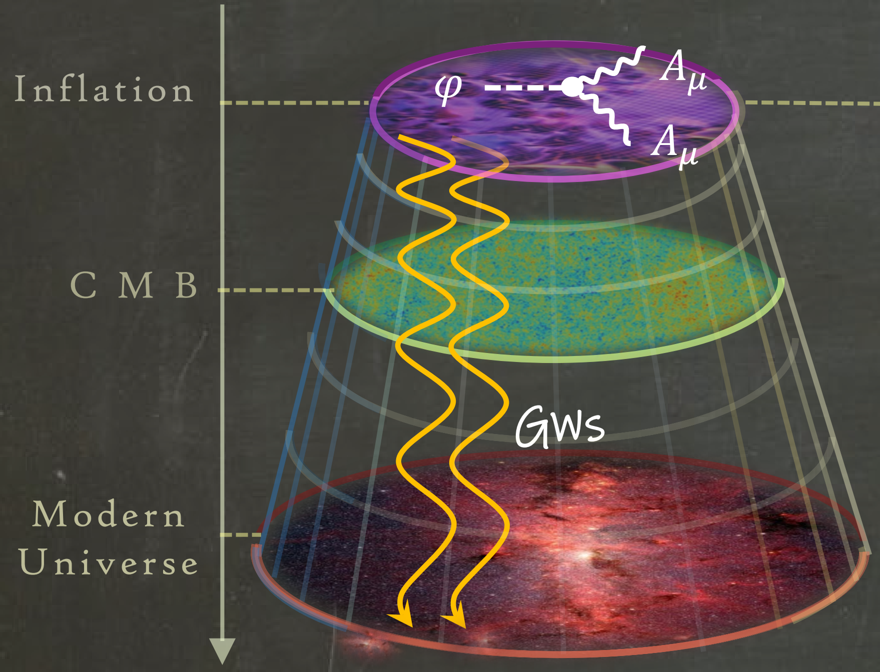

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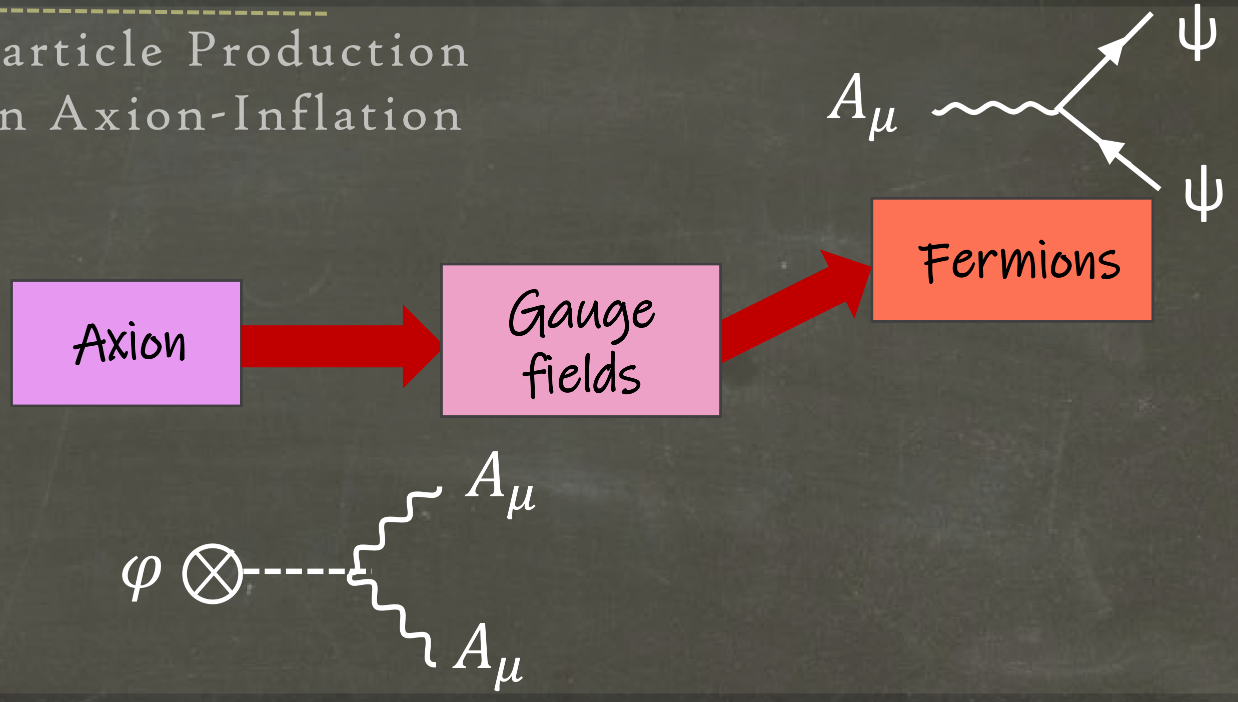

Axion → Gauge fields → Fermions

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

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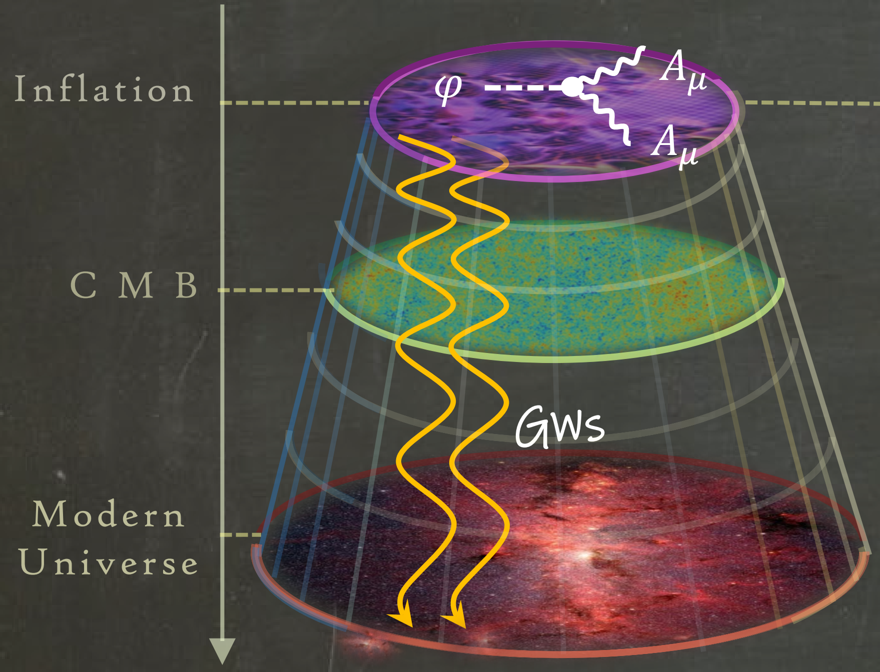

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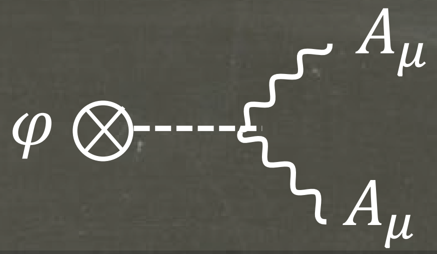
Axion-inflation and gauge fields (non-Abelian)

Particle Production In Axion-Inflation

Axion → Gauge fields → Fermions

A new mechanism for Fermion Production in Inflation!



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

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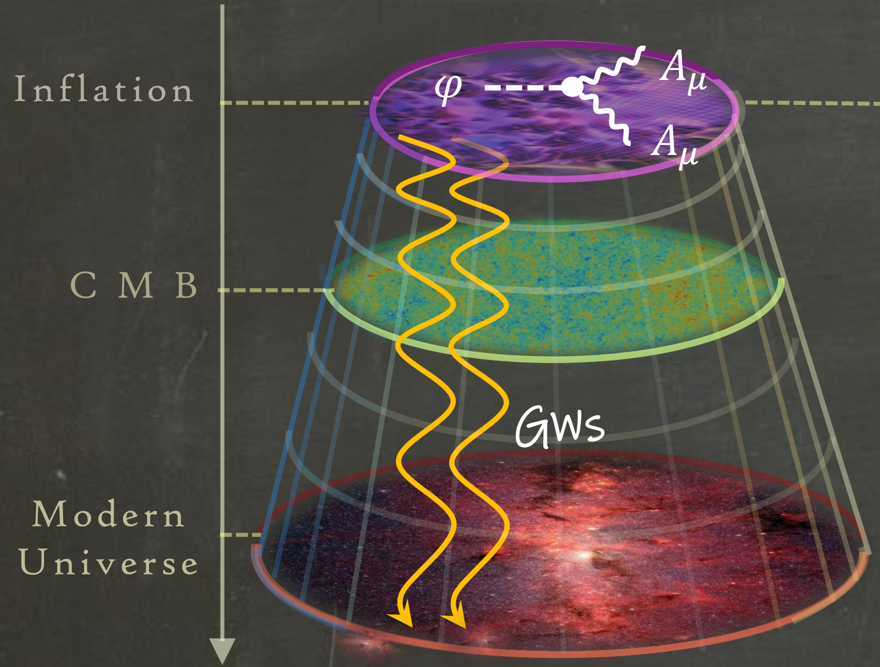

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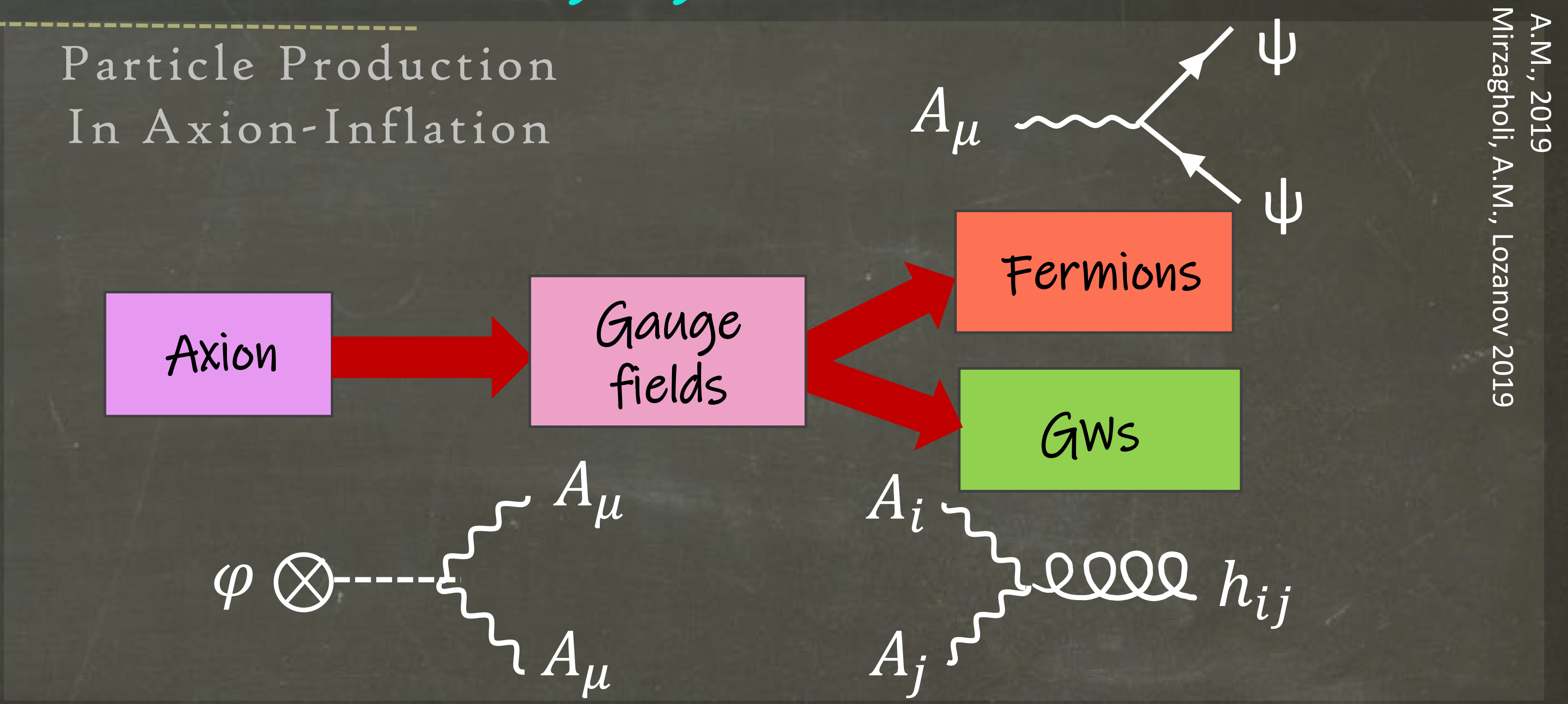

A.M., 2019
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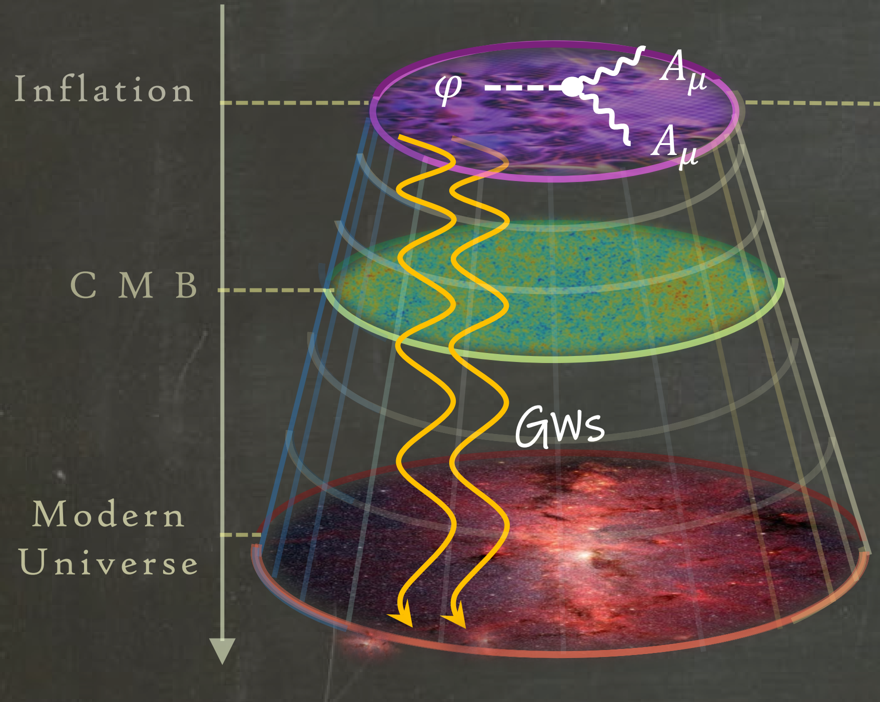

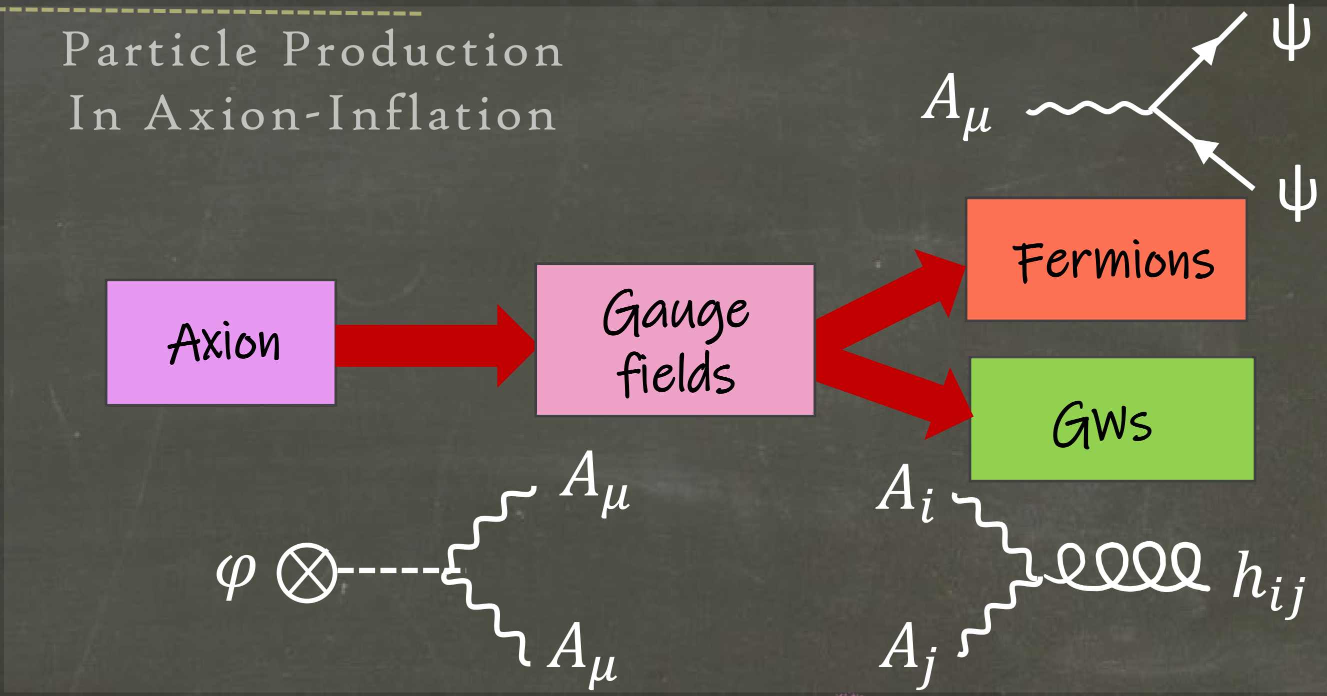
Particle Production In Axion-Inflation

Axion → Gauge fields → Fermions, GWs

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

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

Sourced GWs:
Chiral & non-Gaussian

A New Class of Inflation Models

(closer to Particle Physics)

A. M., & Sheikh-Jabbari, **2011**
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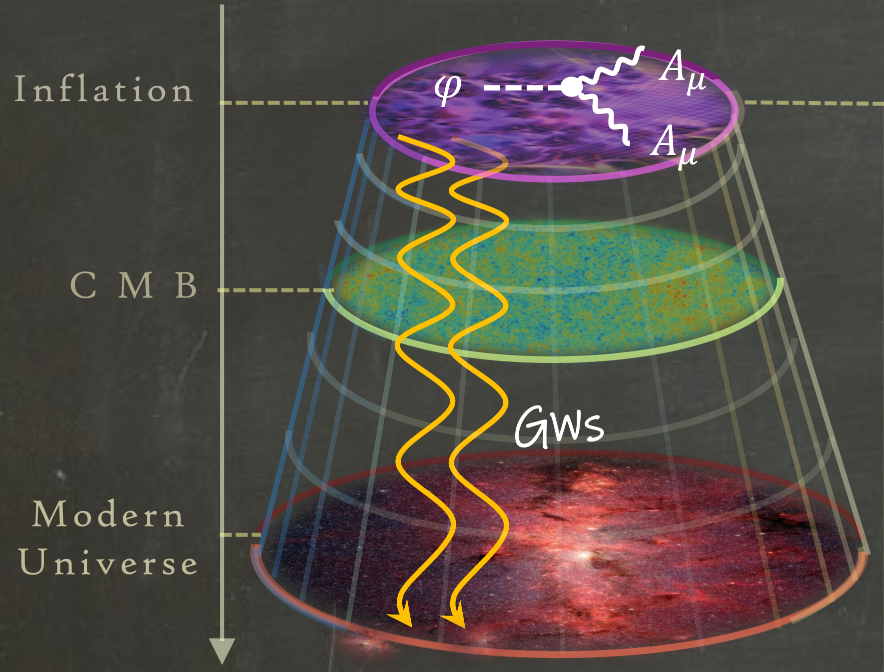
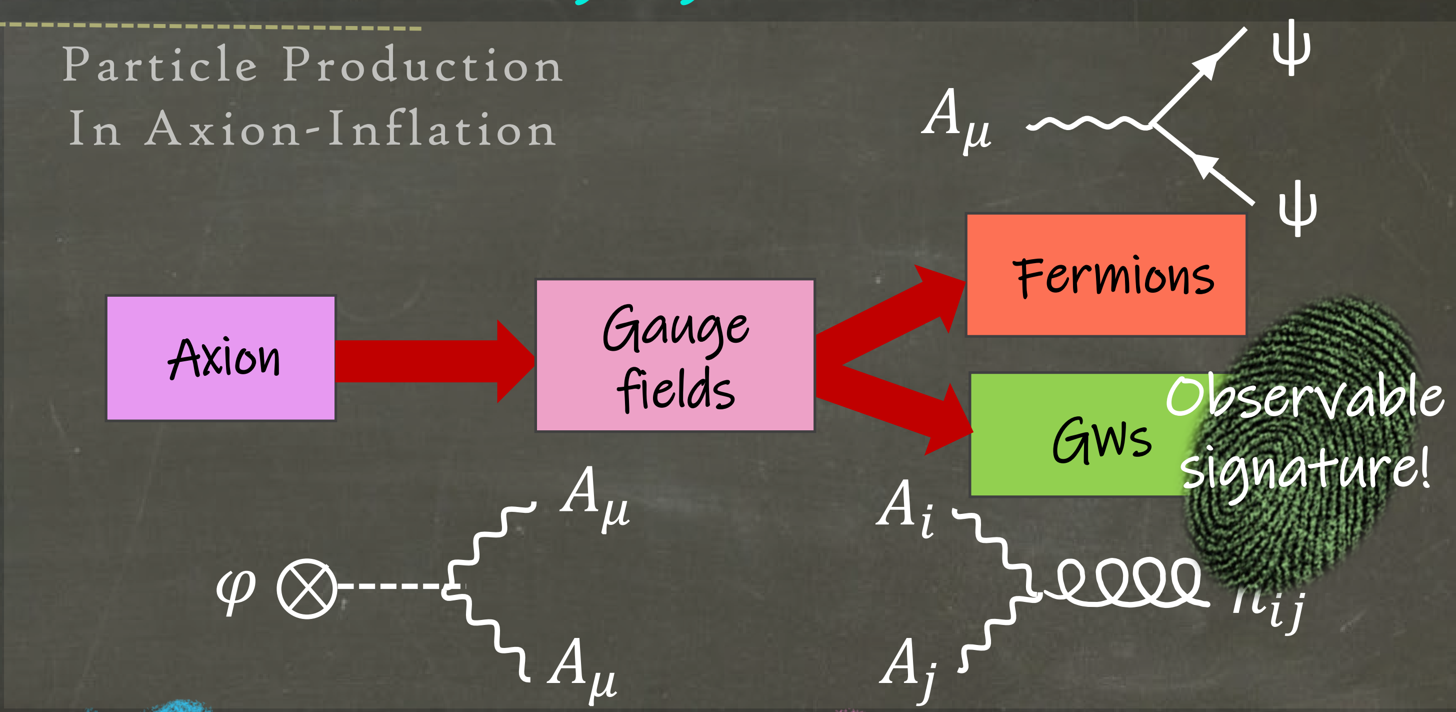
Axion-inflation and gauge fields (non-Abelian)





Particle Production In Axion-Inflation

Axion → Gauge fields → Fermions

Gauge fields → GWs

Observable signature!

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

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

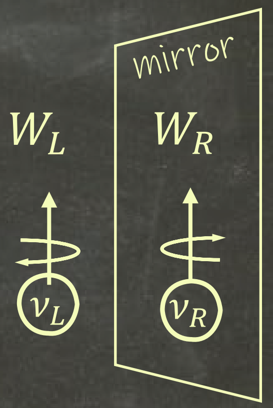
Vacuum GWs:
Unpolarized & Gaussian

Sourced GWs:
Chiral & non-Gaussian

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

(How to Connect Inflaton to SM?)

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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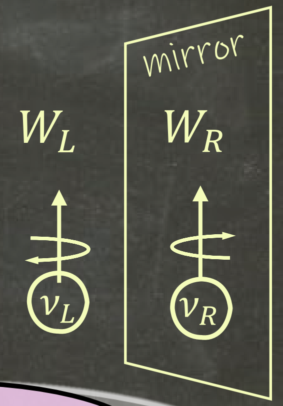
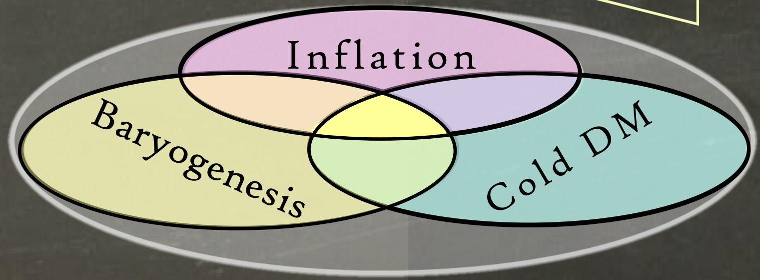
(How to Connect Inflaton to SM?)

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



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



A.M. 2021

How to Connect it to the SM?

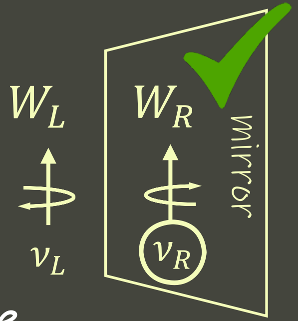
Let us Extend SM Gauge Symmetry by an $SU(2)_R$ and couple it to Axion Inflaton!

○ 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 $SU(2)_R$

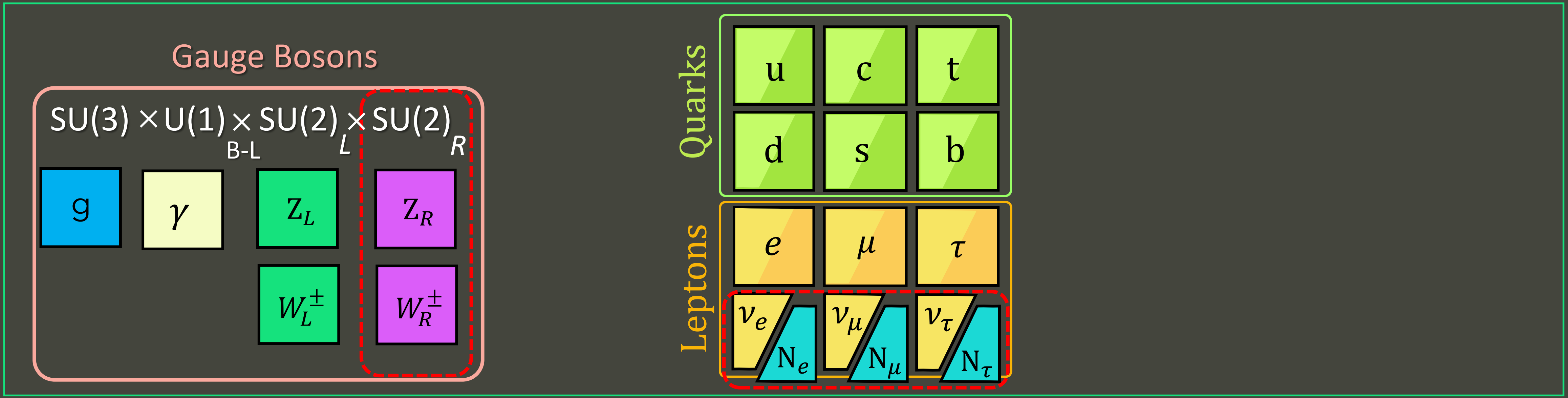
A. M. arXiv: 2012.11516

A.M. arXiv:2103.14611

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

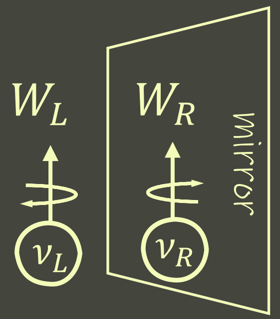
d s b

Leptons

e μ τ

ν_e N_e ν_μ N_μ ν_τ N_τ

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)



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

$$\Big\downarrow \ \text{Spontaneous Symmetry Breaking}$$

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

Left-Right Symmetric Model

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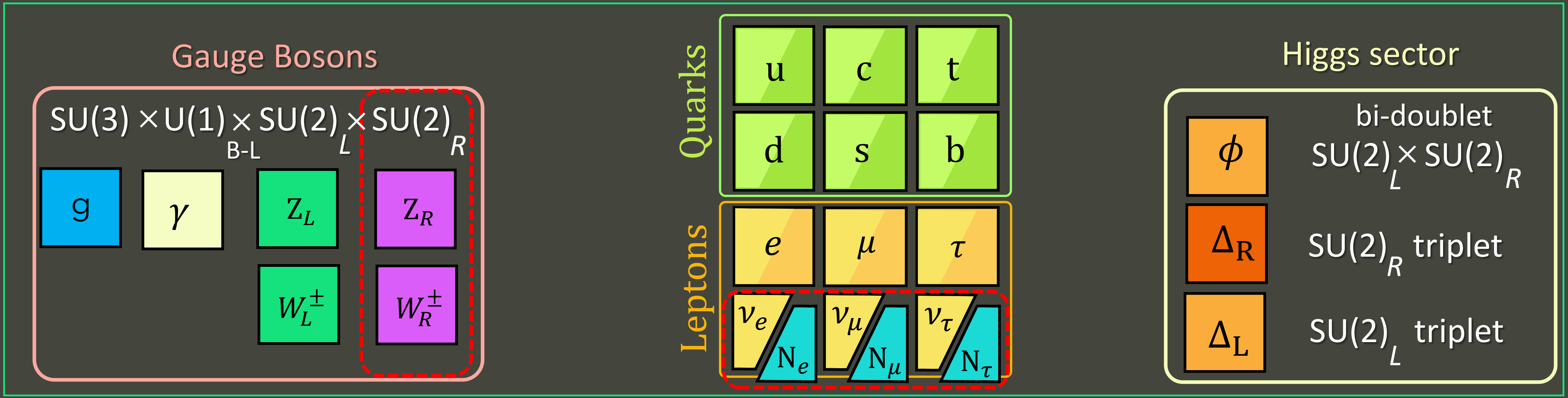

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g γ Z_L Z_R

$W_L^\pm$ $W_R^\pm$

Quarks

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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

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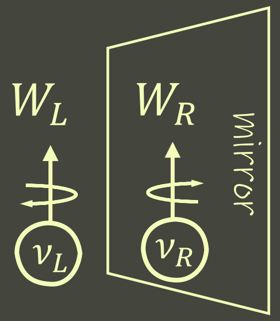

$$SU(2)_L \times SU(2)_R \times U(1)_{B-L} \xrightarrow{\text{Spontaneous Symmetry Breaking}} SU(2)_L \times U(1)_Y$$

$\langle \Delta_R \rangle \neq 0$

Massive

N_i $W_R^\pm$ Z_R

Minimal Left-Right Symmetric model

Left-Right Symmetric Model

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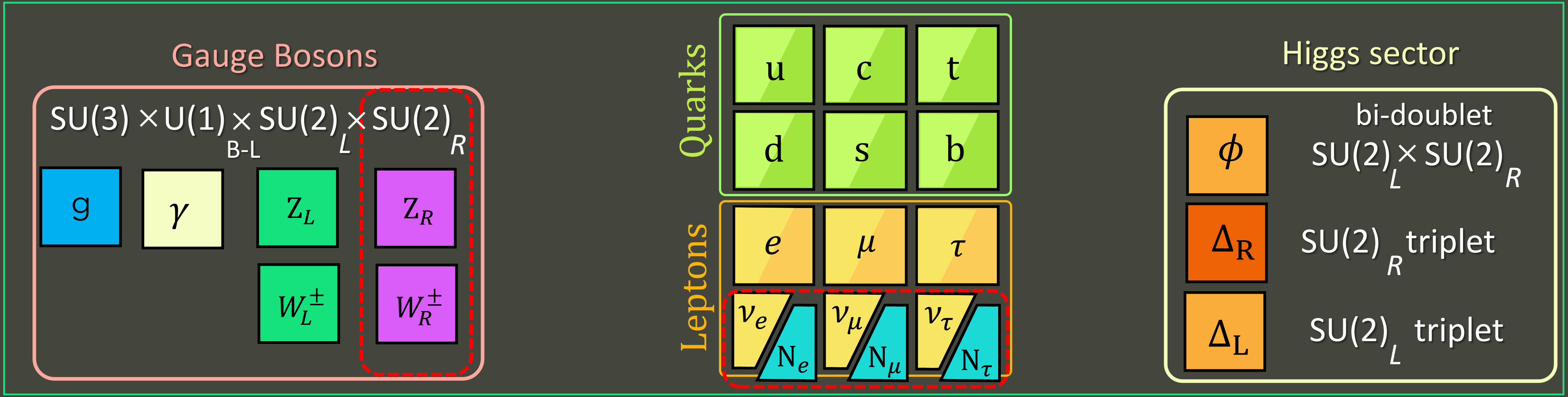

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$SU(3) \times U(1)_{B\text{-}L} \times SU(2)_L \times SU(2)_R$

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

Quarks

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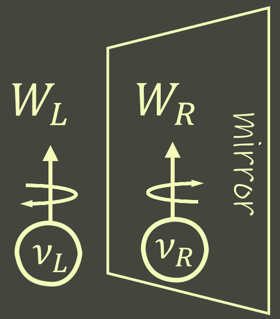


$$SU(2)_L \times SU(2)_R \times U(1)_{B\text{-}L} \Big\downarrow SU(2)_L \times U(1)_Y$$

Spontaneous Symmetry Breaking

$\langle \Delta_R \rangle \neq 0$

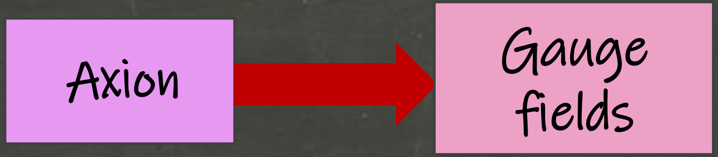
Massive

N_i $W_R^{\pm}$ Z_R

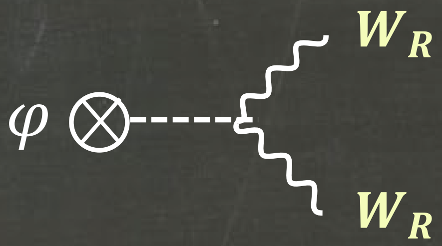
1. Ad hoc parity violation
2. Accidental B-L global symmetry
3. Vacuum Stability problem

Gauge field Production in Inflation

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



Axion inflaton



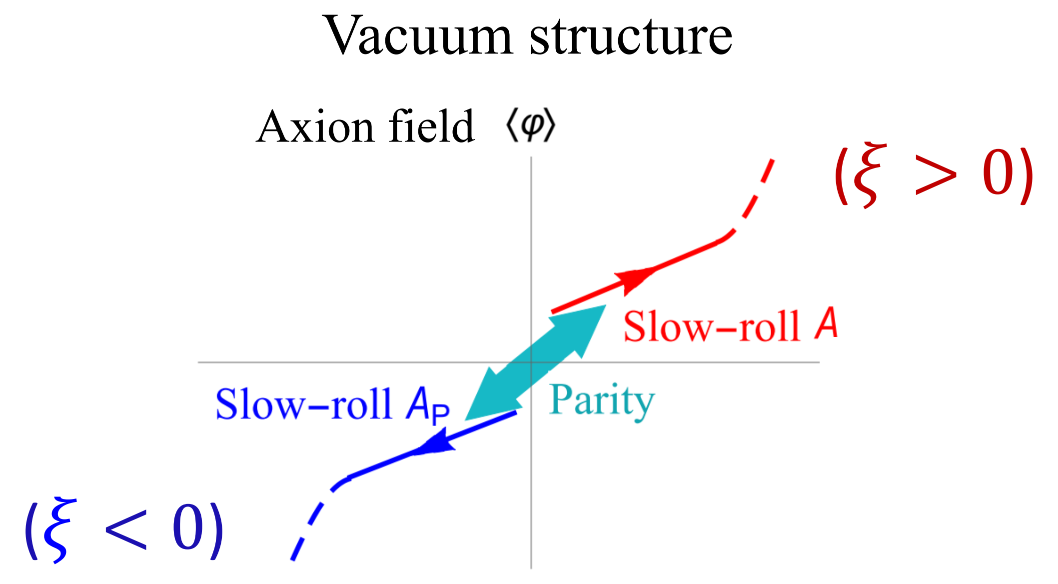
Gauge field
(active in inflation)

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

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

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

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



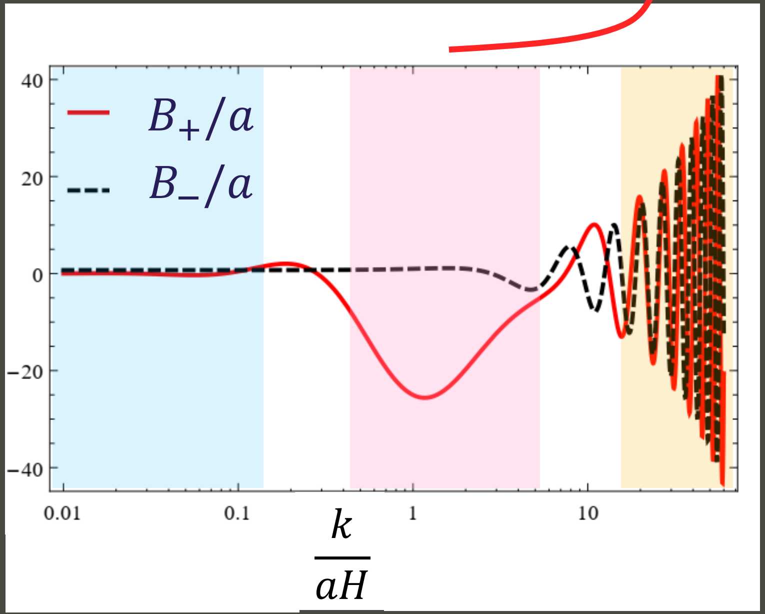
For $\xi > 0$

Short tachyonic growth of B_+

Chiral Field

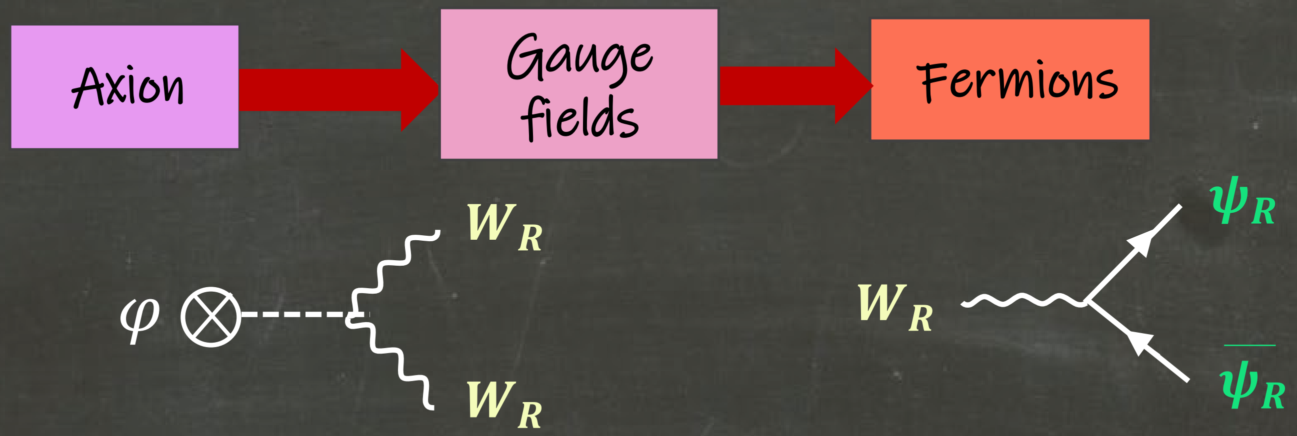
$$n_B \sim \frac{H^3}{6\pi^2}\xi^3\, e^{\frac{(2-\sqrt{2})\pi}{2}\xi}$$

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

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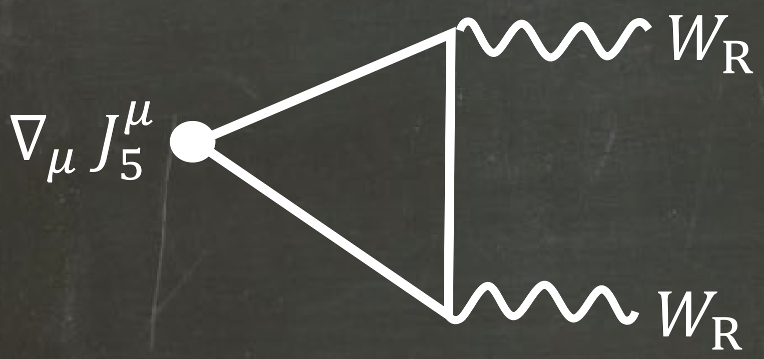
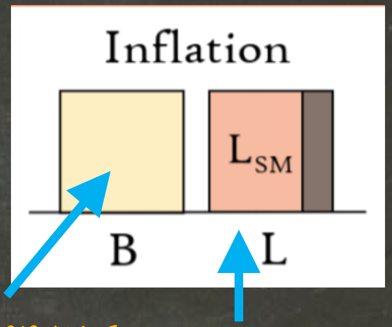
The key ingredient is the Chiral anomaly of $\mathrm{SU(2)_R}$ in inflation:



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

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

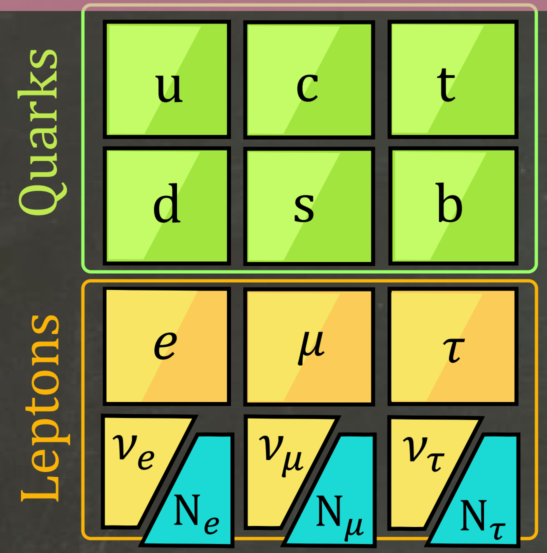
$$\alpha_{inf}(\xi) \sim \frac{g^2}{(2\pi)^4} \mathrm{e}^{2\pi\xi}$$

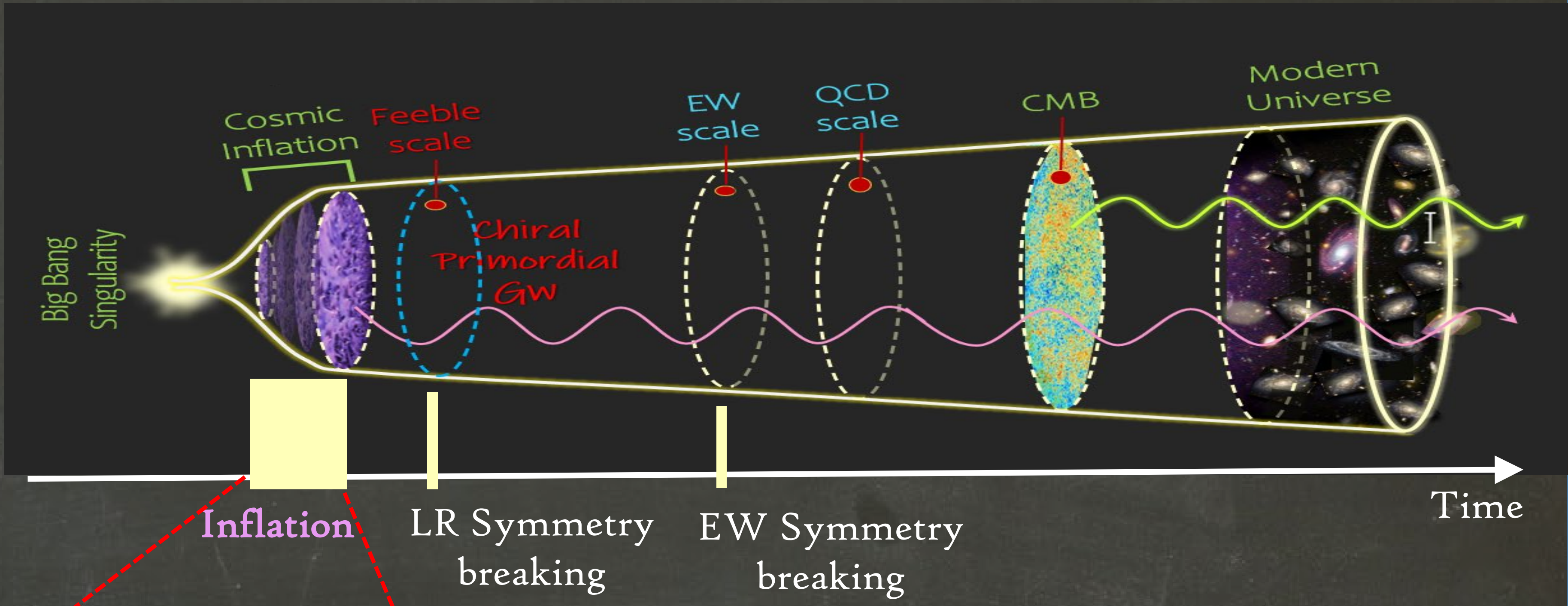


SM baryons

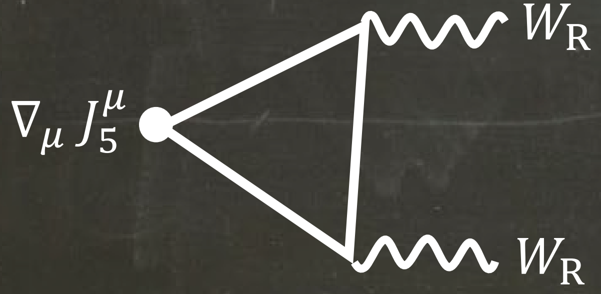
SM leptons
+
RH neutrinos

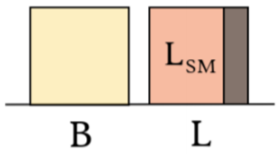
Summary of the mechanism:





Chiral anomaly of SU(2)R
In inflation





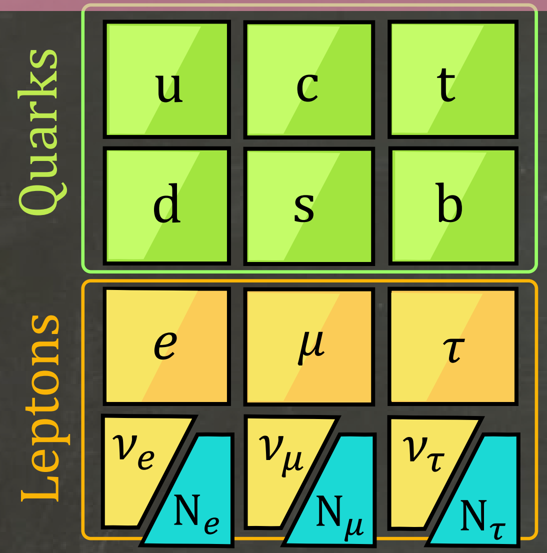
$$B = L = 3n_{CS}$$

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

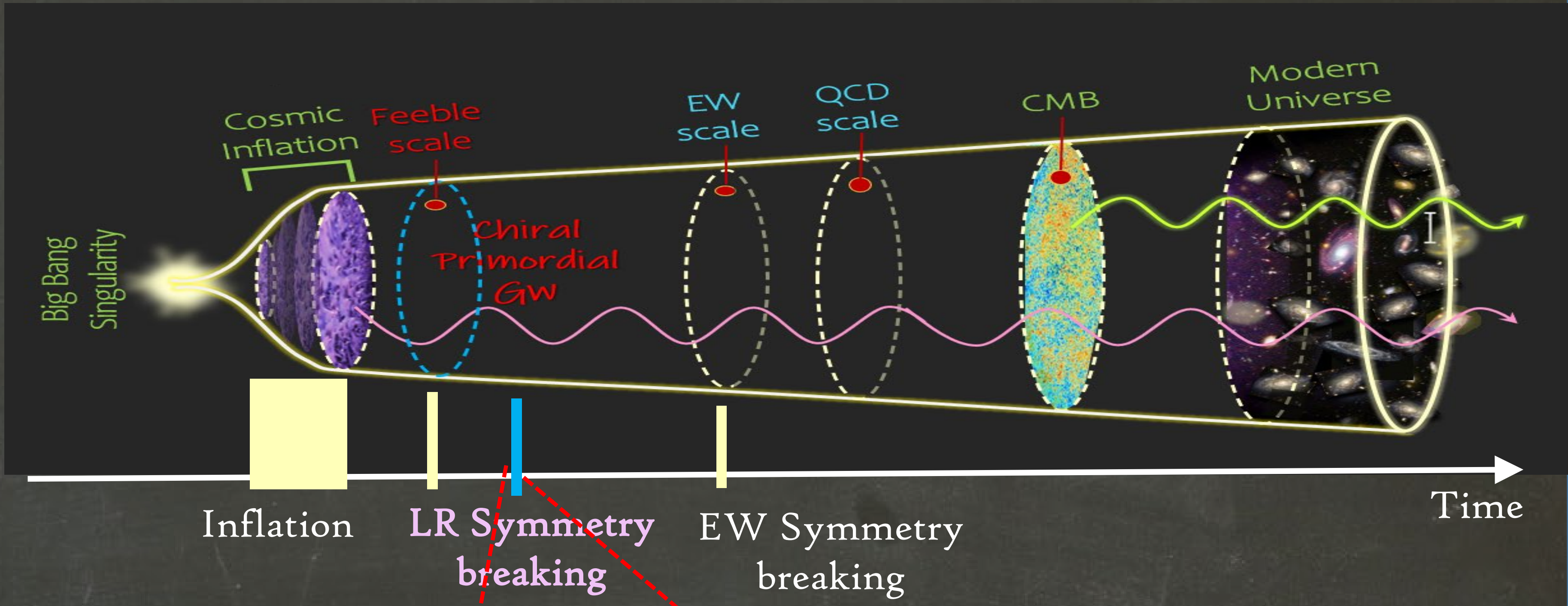
B= SM baryons

L= SM leptons + RH neutrinos

Summary of the mechanism:



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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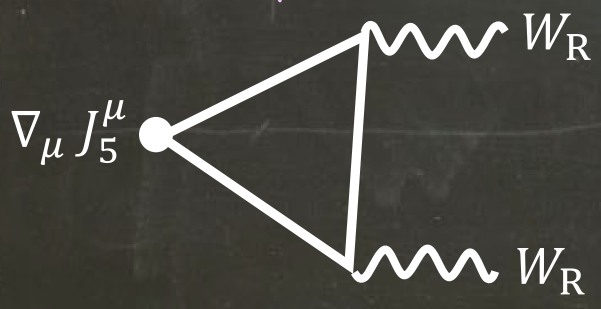

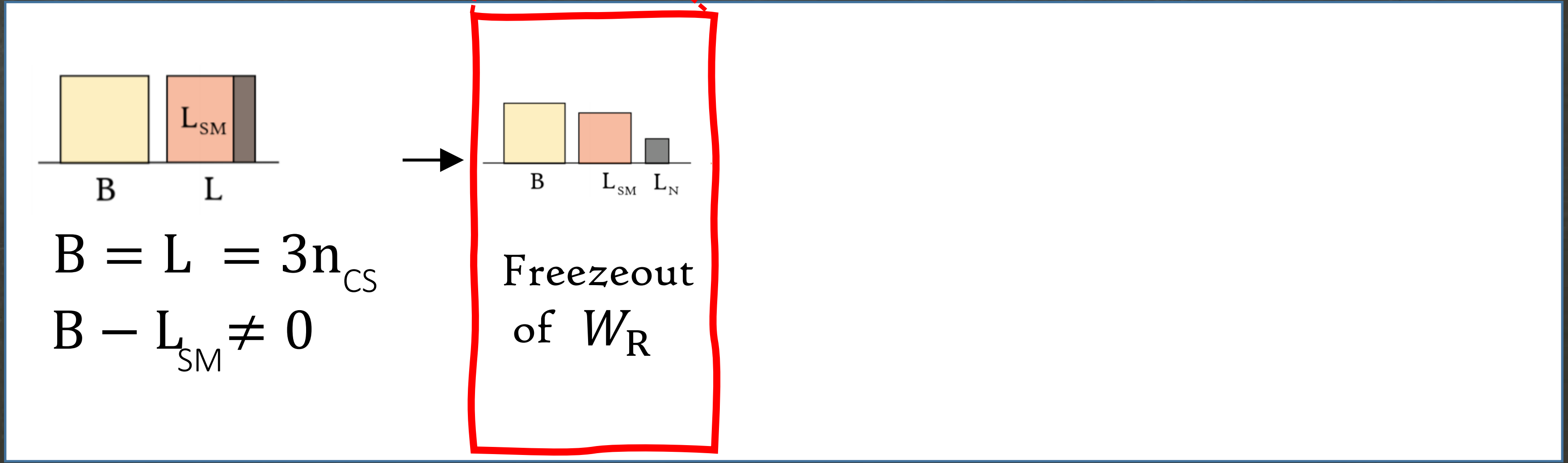

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Freezeout of W_R

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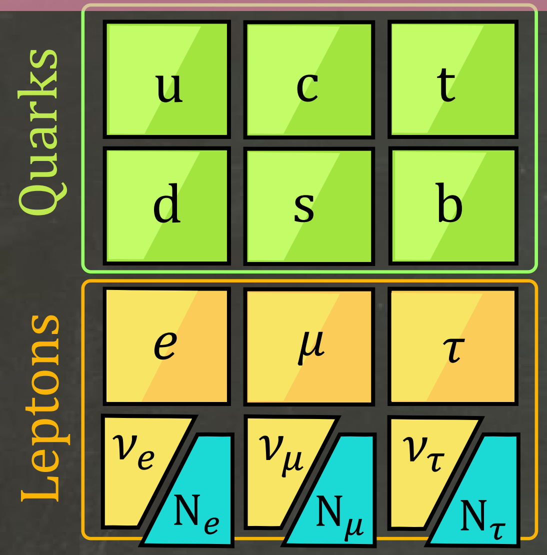
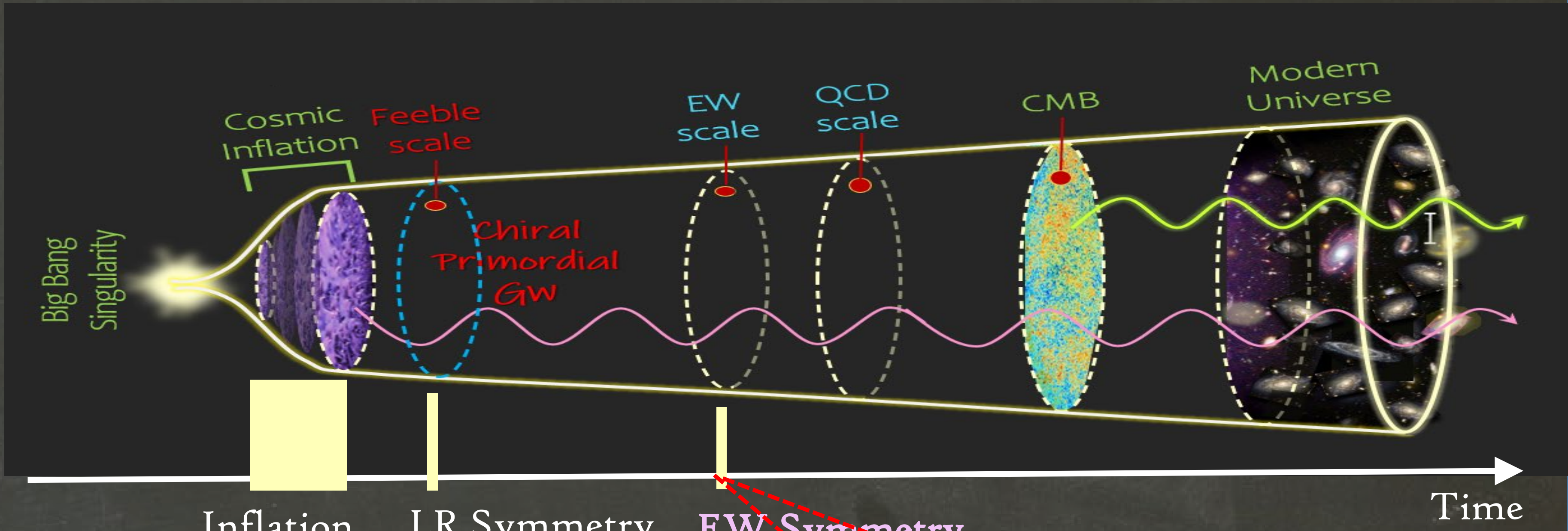


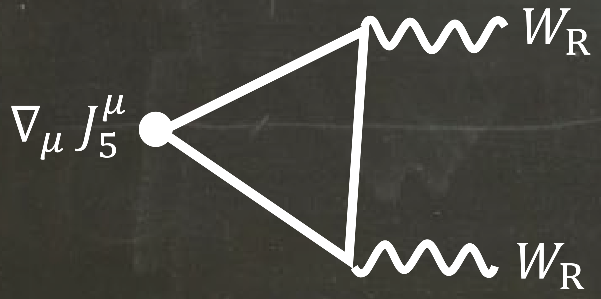


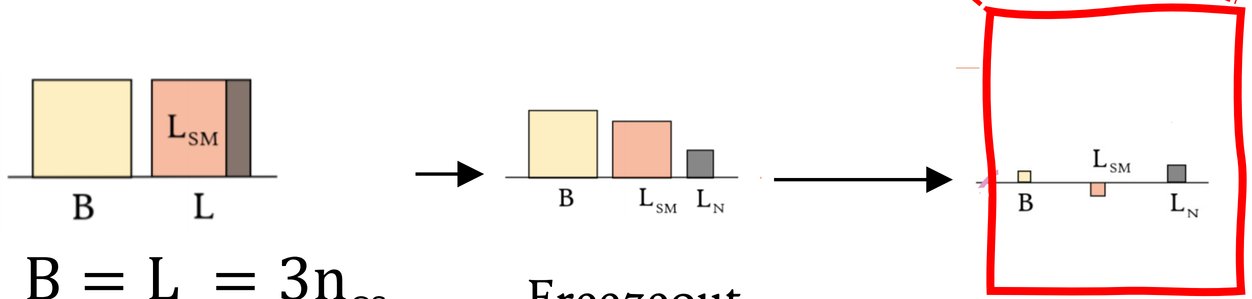
Inflation

LR Symmetry breaking

EW Symmetry breaking

Chiral anomaly of SU(2)R In inflation





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Freezeout of W_R

Spectator effects reshuffle B, L_{SM} & L_N

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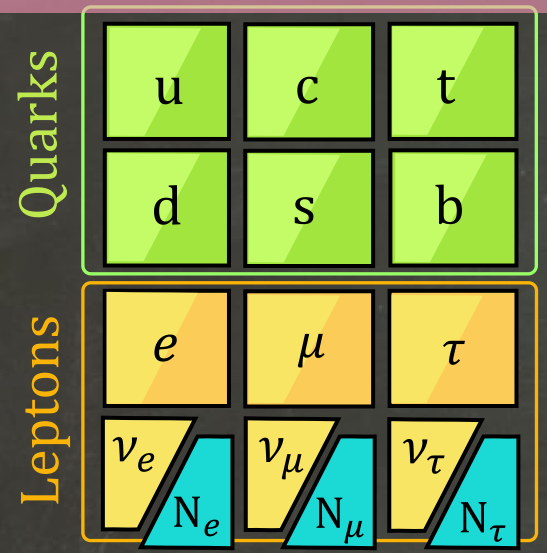

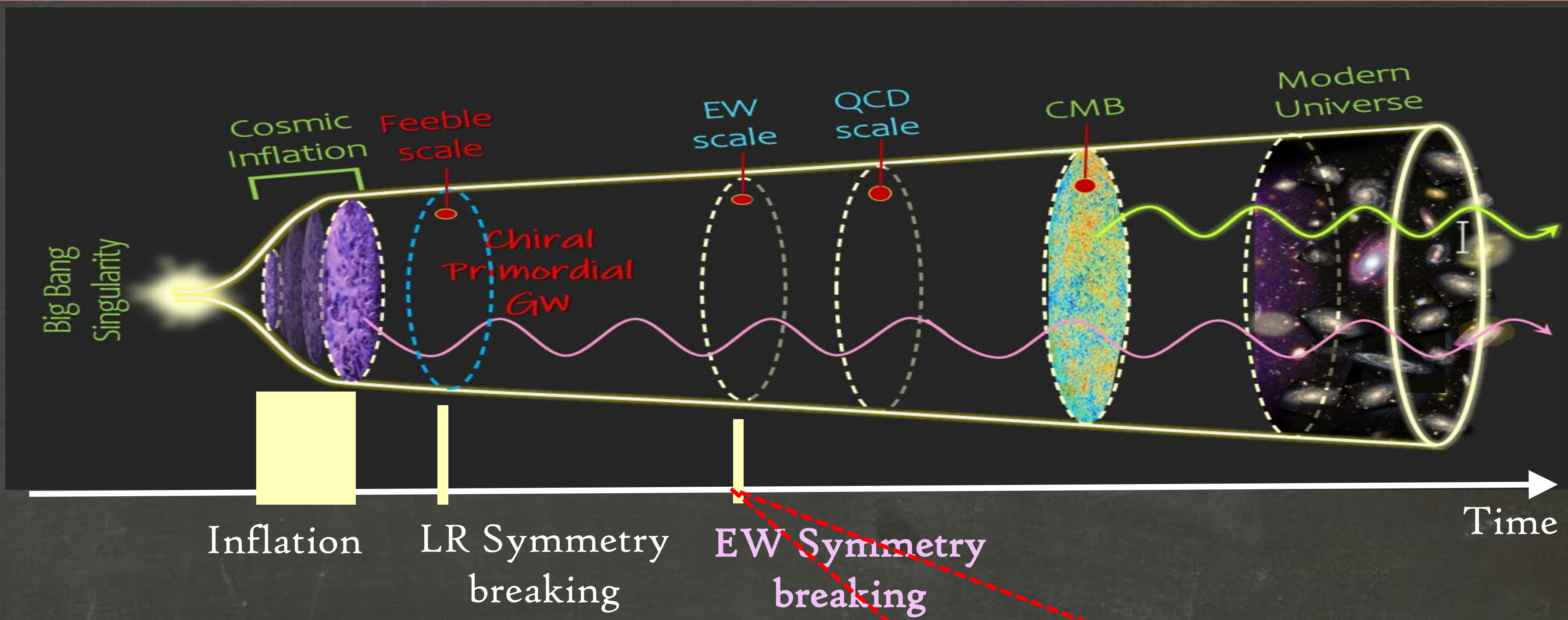

Inflation

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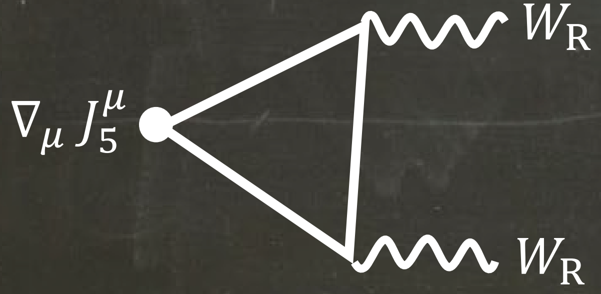

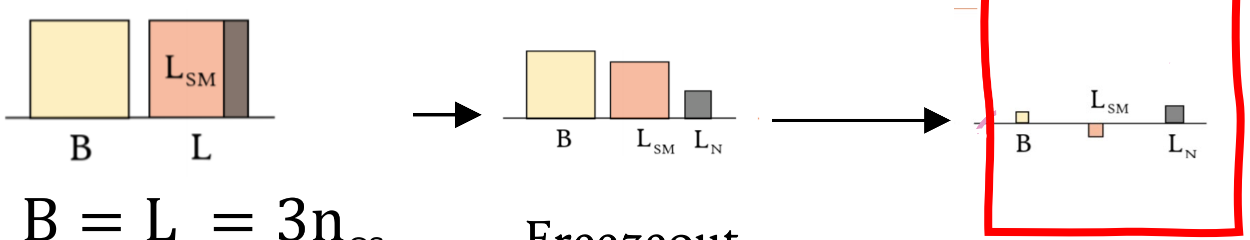

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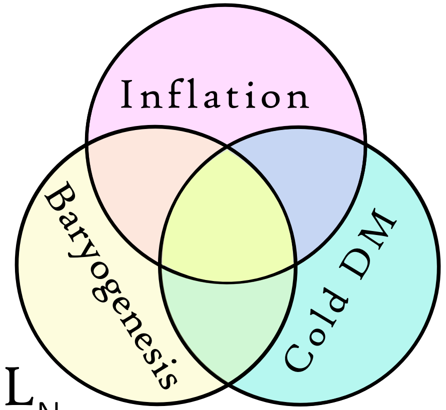

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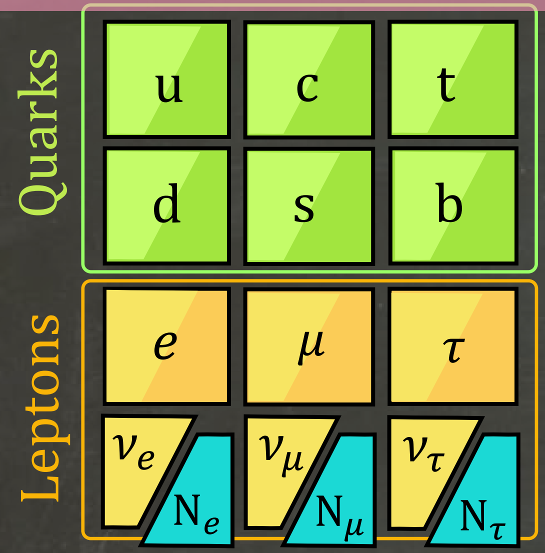

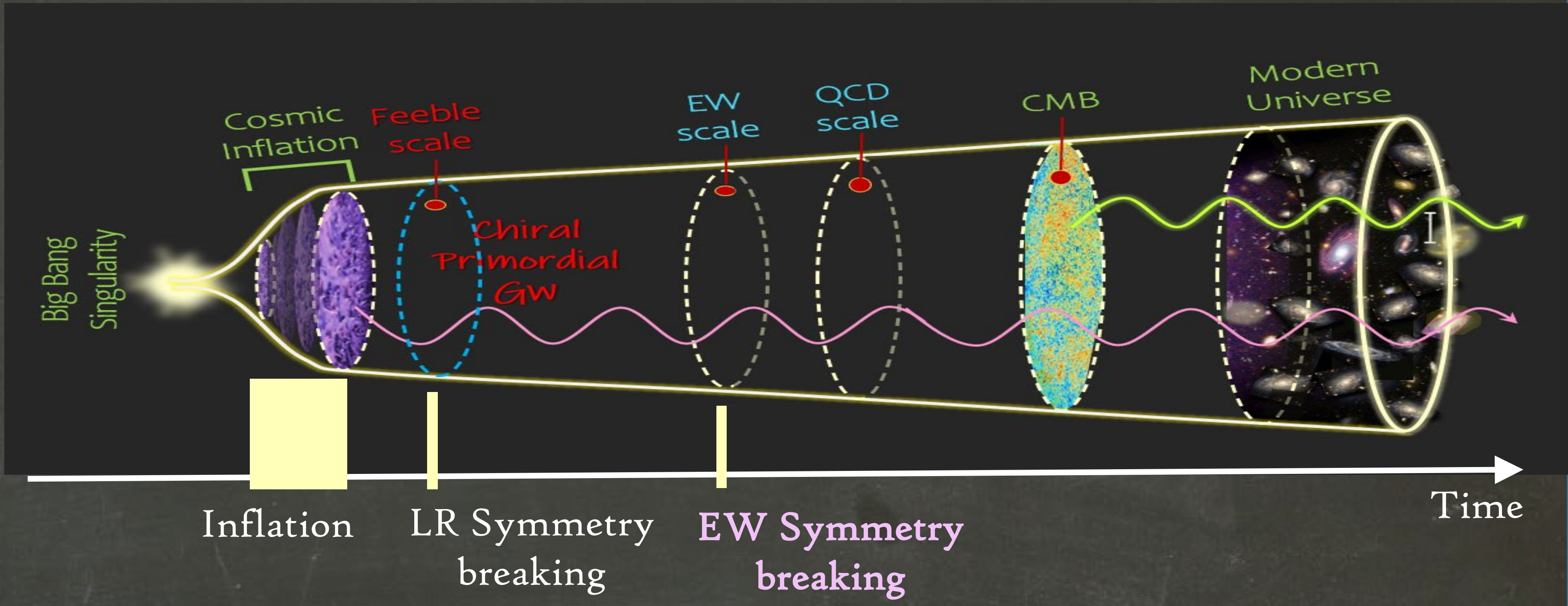

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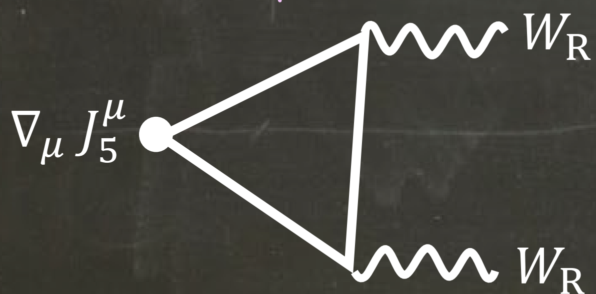

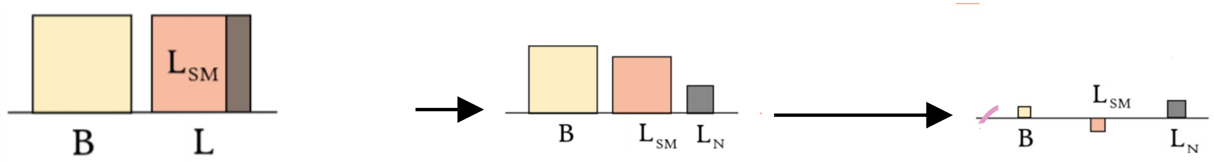

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Freezeout of W_R

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

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

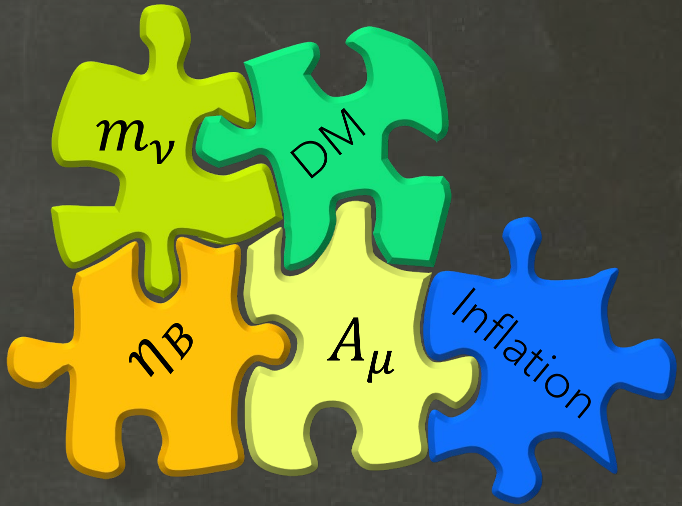
Summary & Conclusions

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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Puzzles of Particle Cosmology

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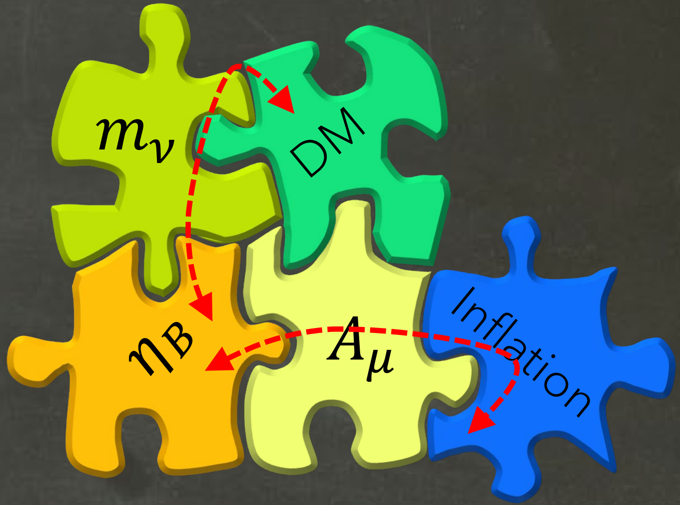
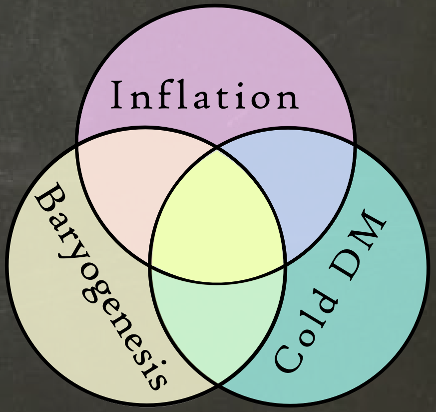


It provides a deep connection between inflation, baryogenesis & DM,

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



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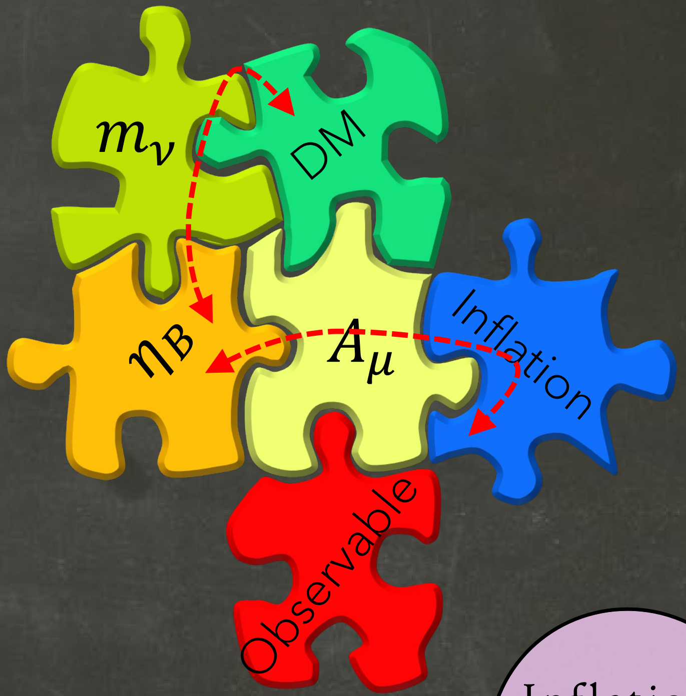

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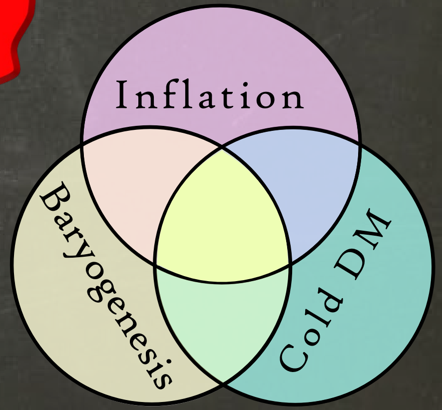
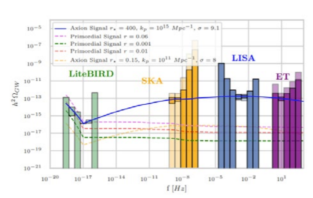
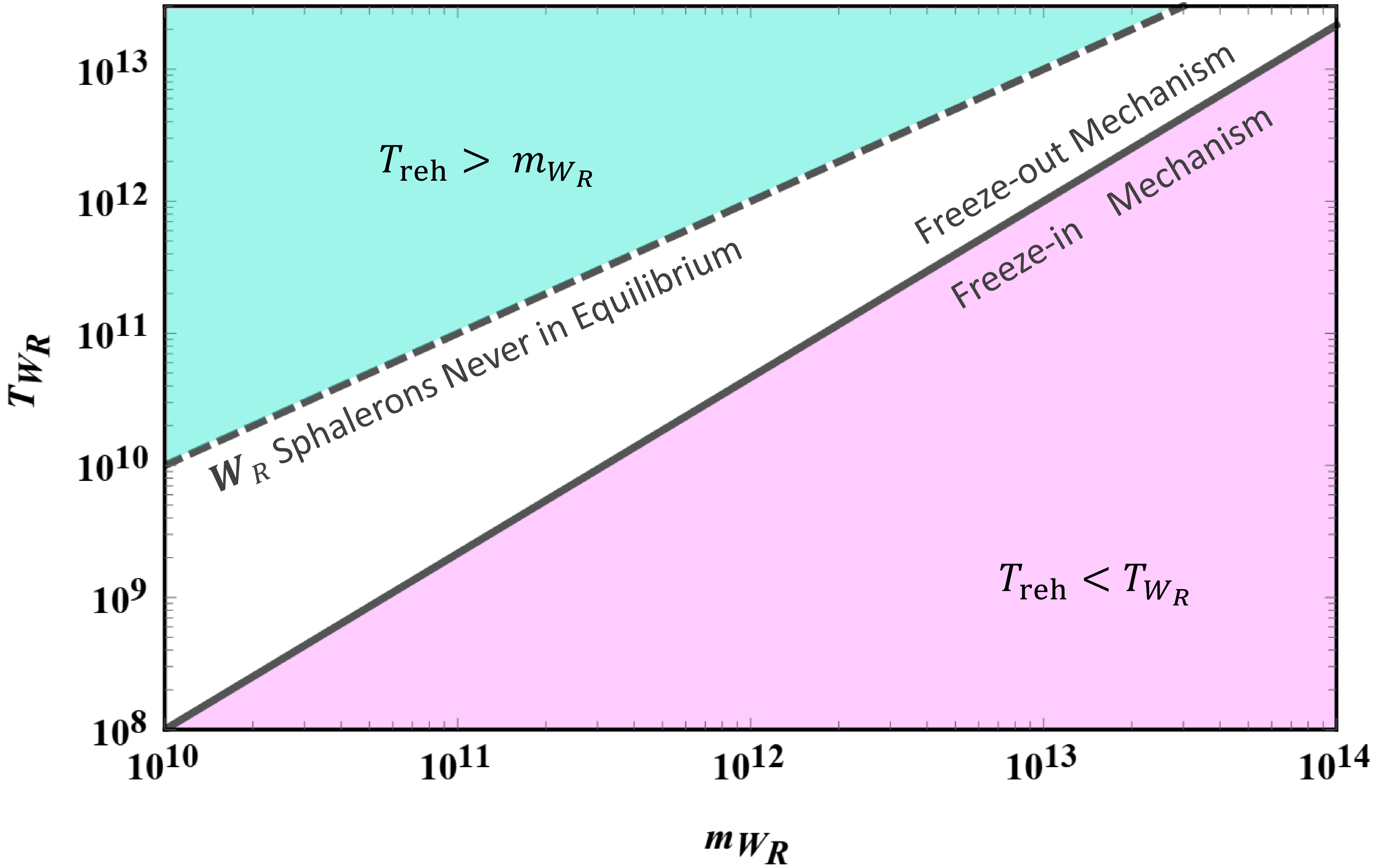


It comes with a cosmological smoking gun on Primordial GWs.

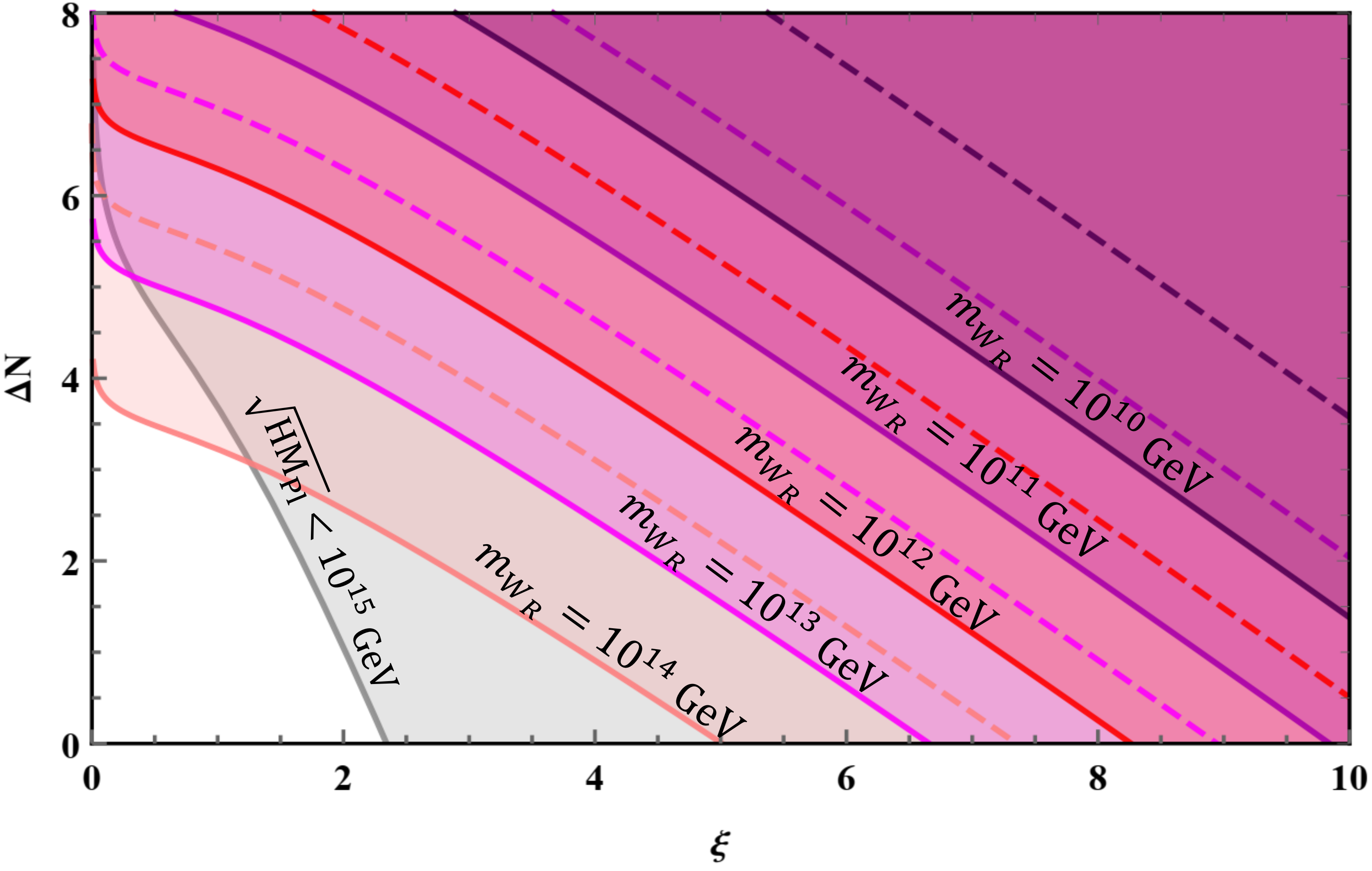


Questions?!


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

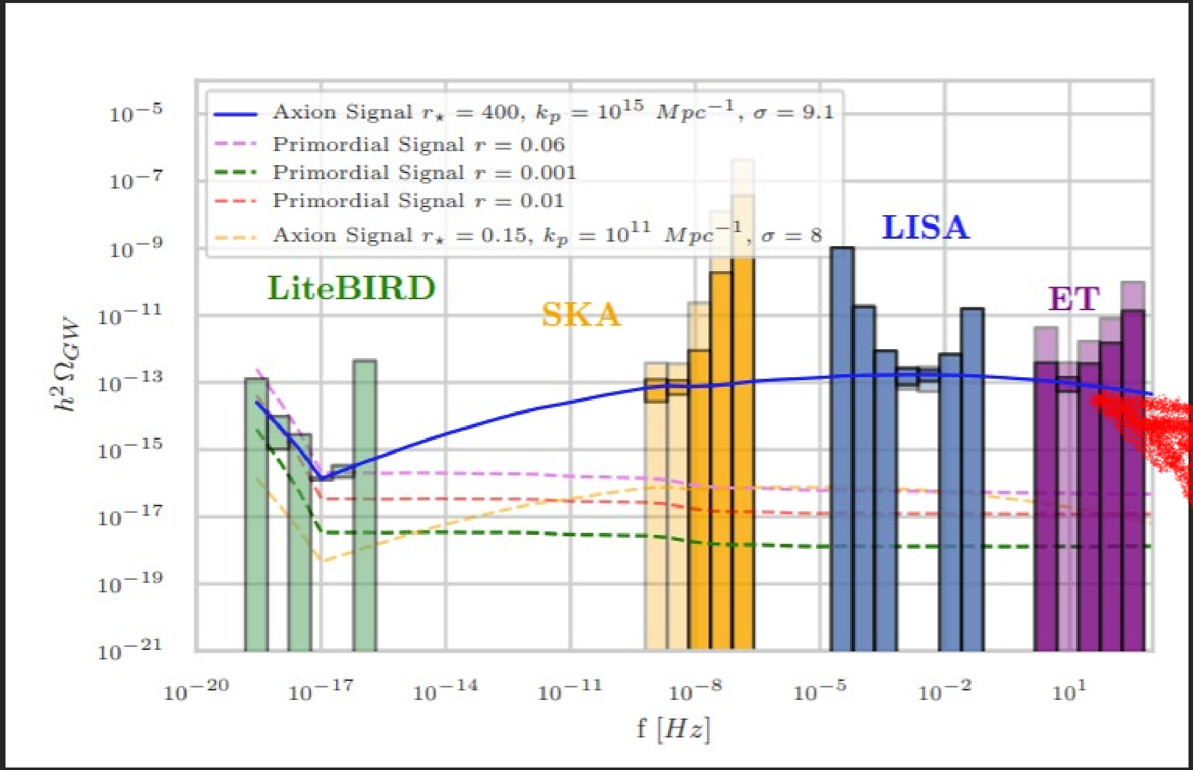
This setup prefers Left-Right symmetry breaking scales above $m_{W_R} = 10^{10}$ GeV !

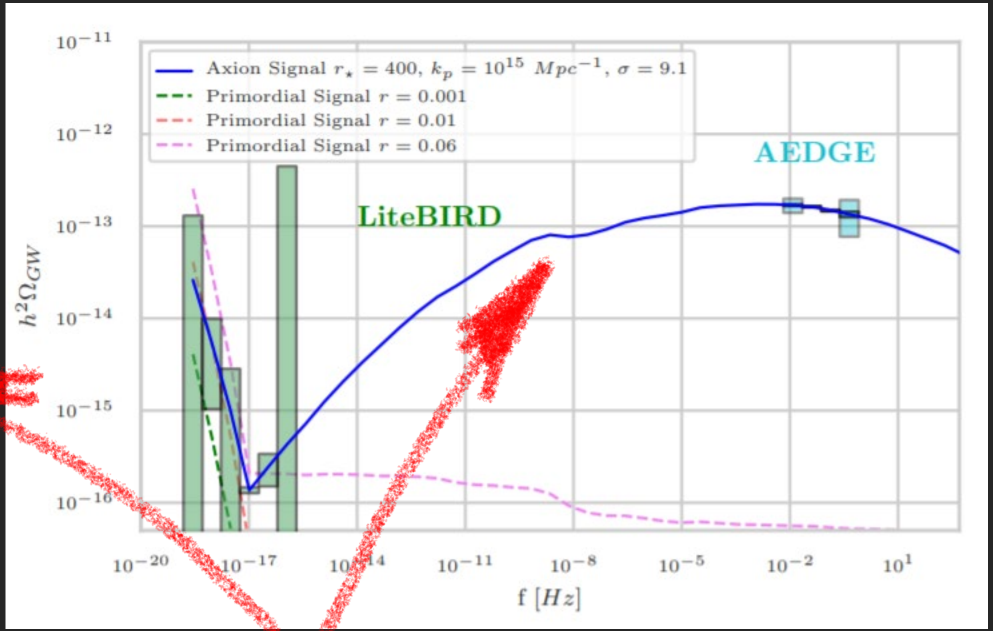
(same as scales suggested by the non-SUSY SO(10) GUT models with intermediate LR symmetry scale.)



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