The Particle Physics of Axion Inflation

From Theory to Observation

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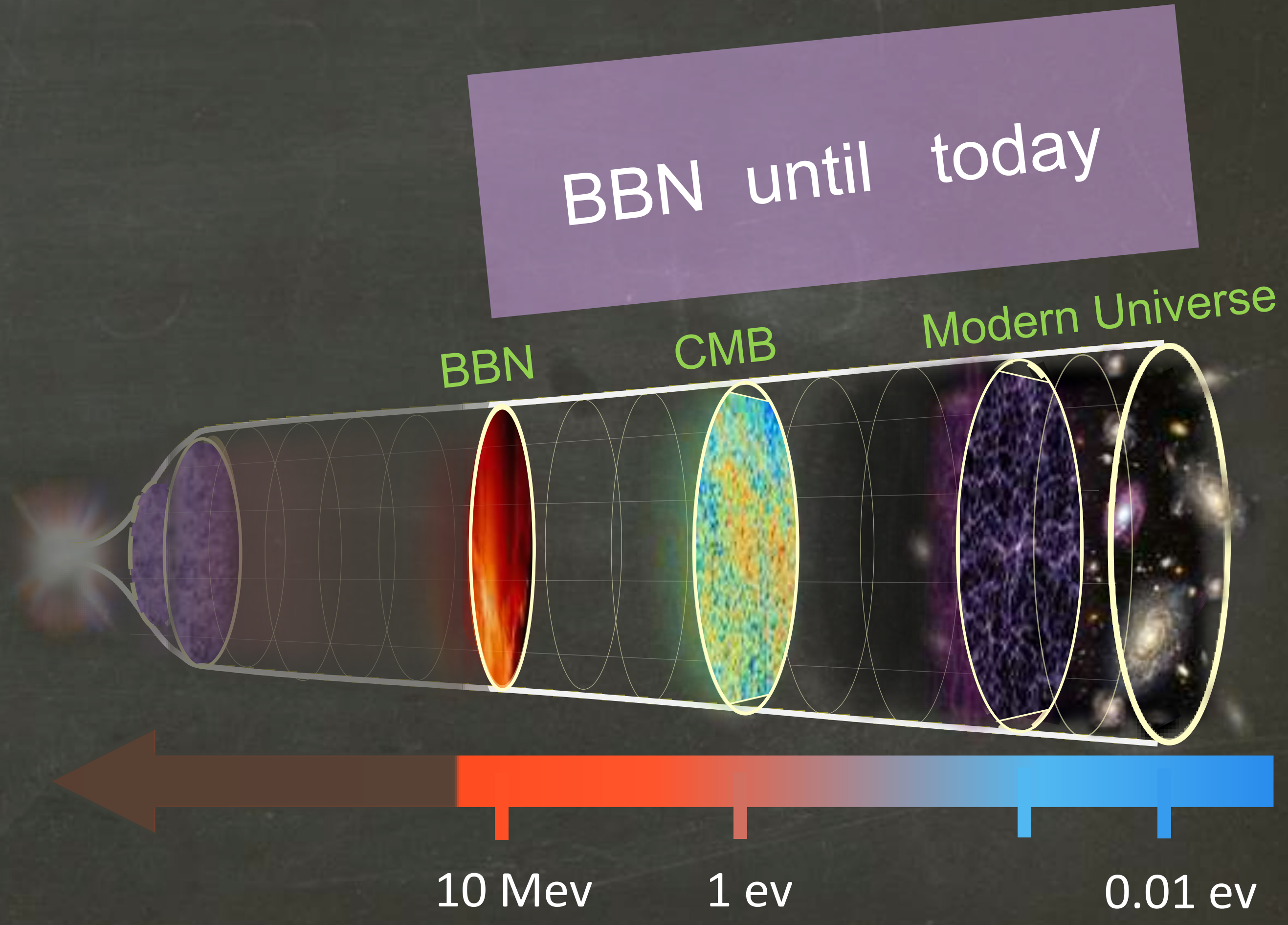
Swansea University

THE ROYAL SOCIETY

Cosmic History

What we know so far?

Particle cosmology is successful in explaining our universe from BBN onward.



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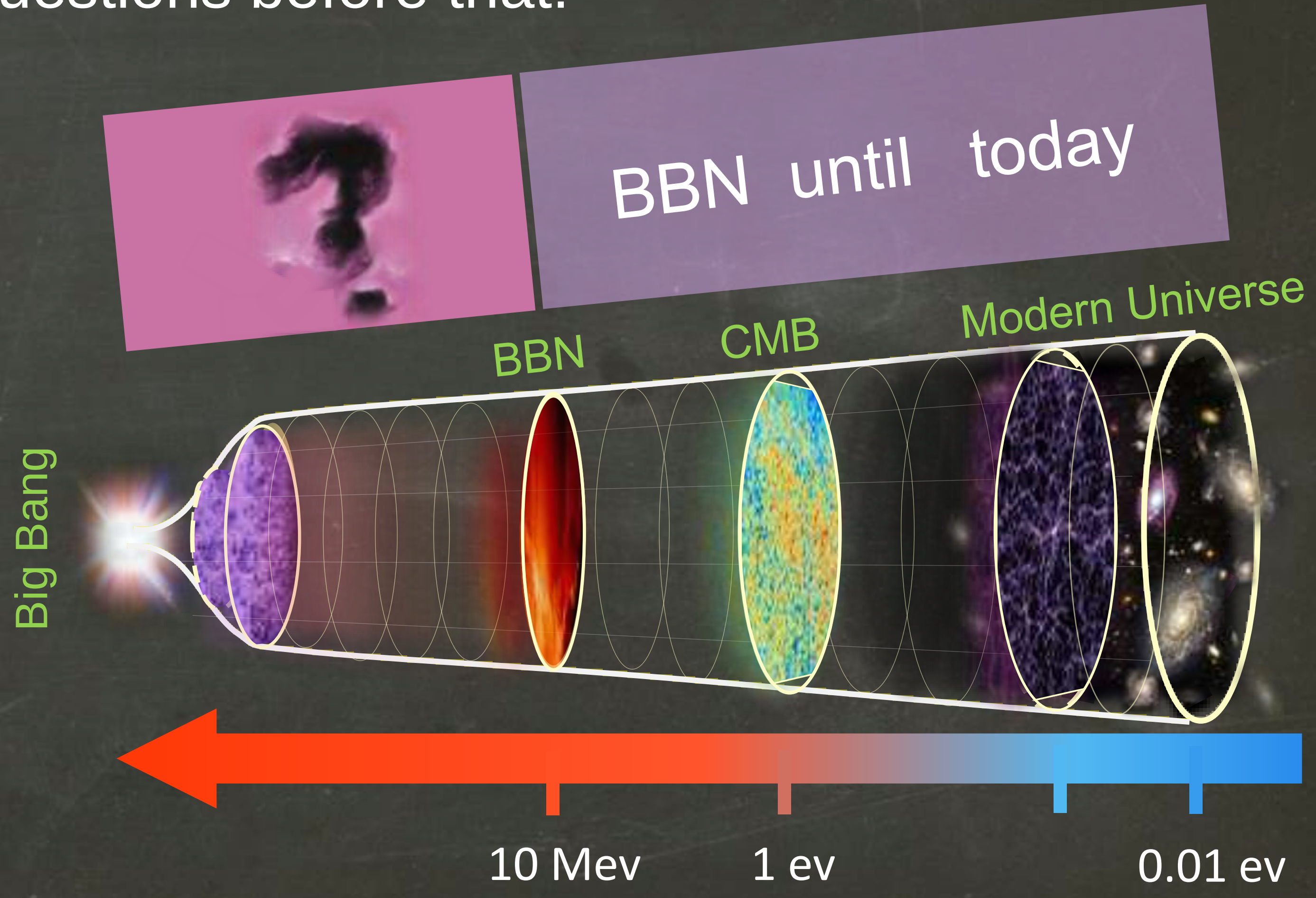
But there are still major open questions before that!



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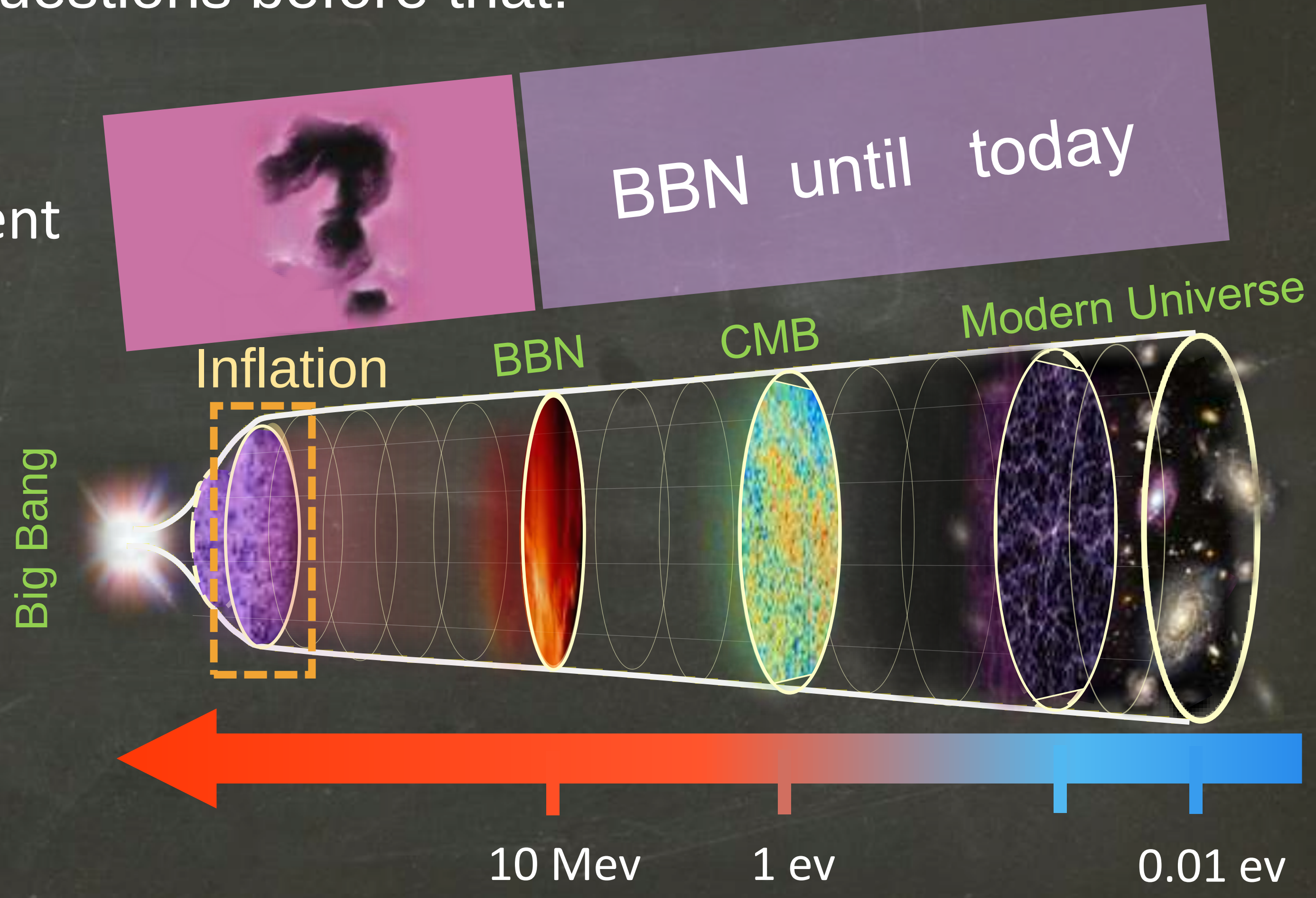
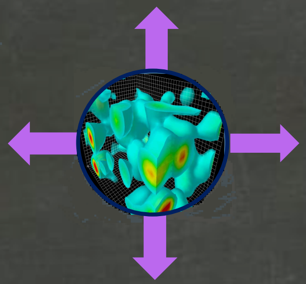
Current observations are in agreement with the paradigm of inflation.



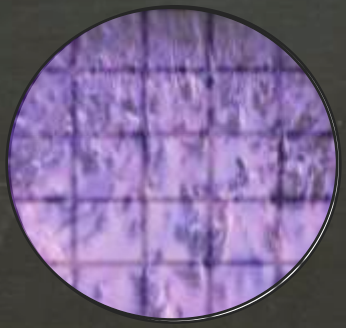
Density Perturbations

Cosmic inflation turns initial quantum vacuum fluctuations

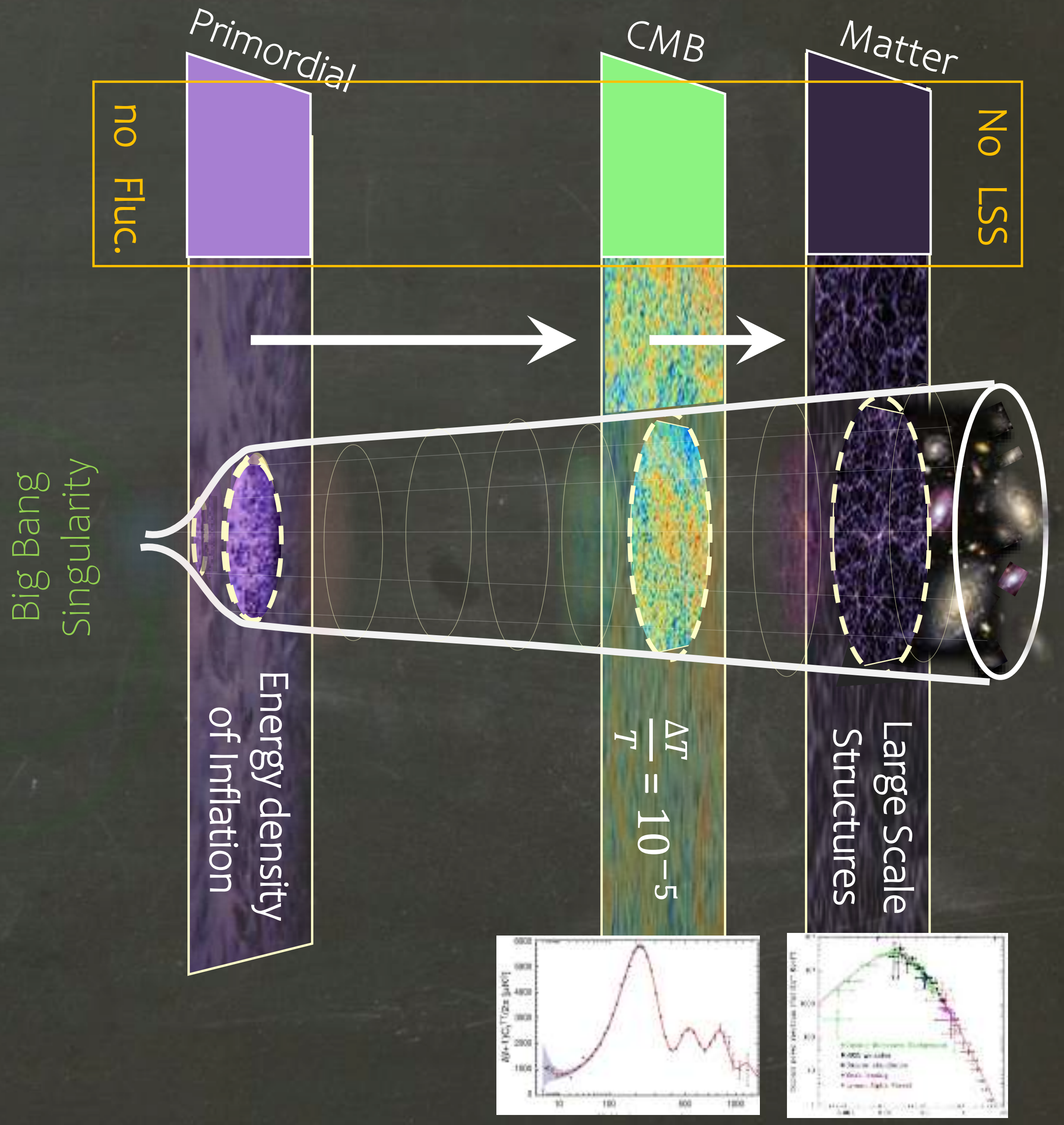


a_i

into actual cosmic perturbations.

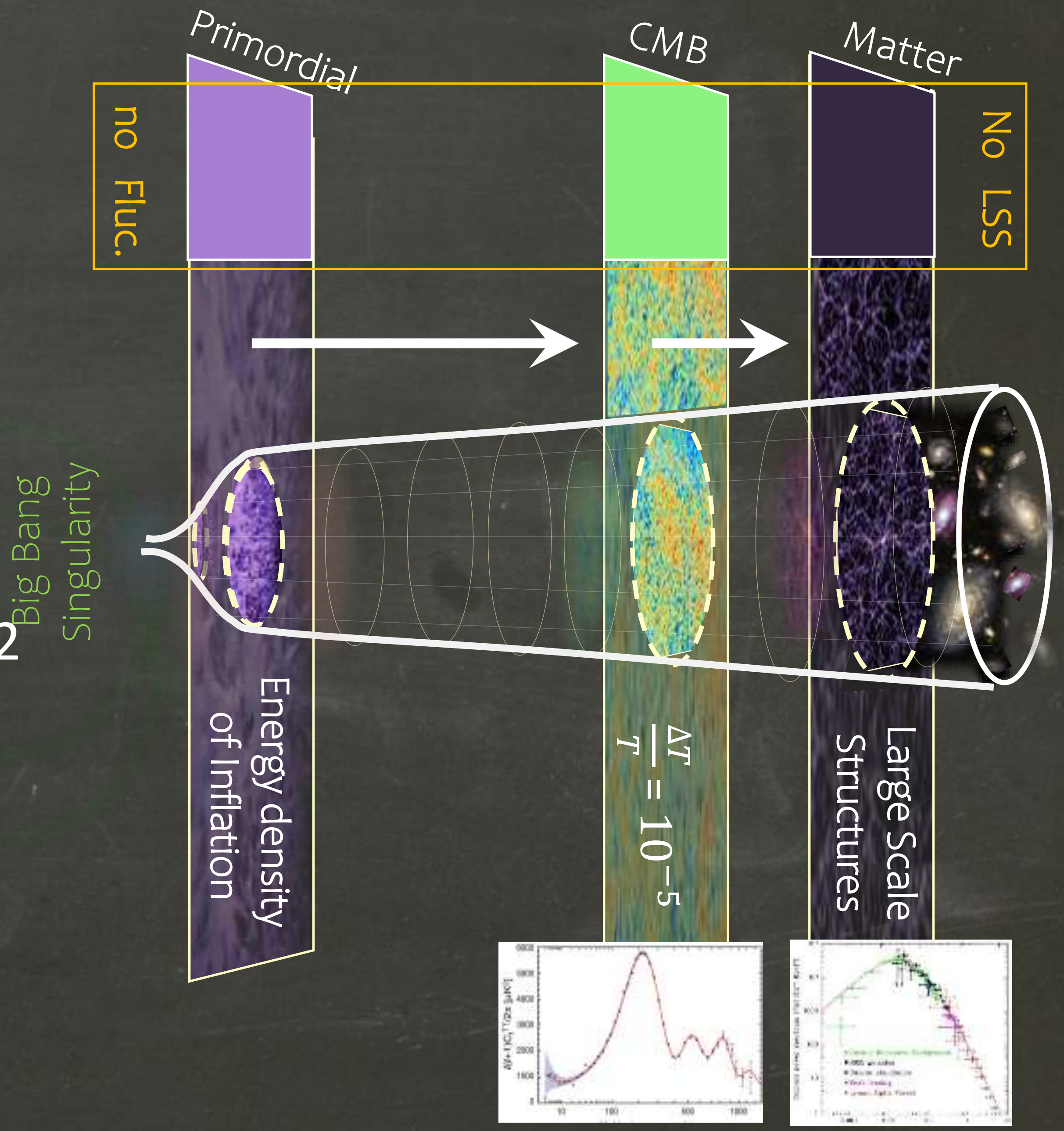


a_f



Density Perturbations

- ✓ red-tilted adiabatic spectrum
- ✓ Gaussianity,
- ✓ spatial flatness $\Omega_K = 0.001 \pm 0.002$
- ✓ no isocurvature $\beta_{\rm iso} \lesssim 10^{-2}$



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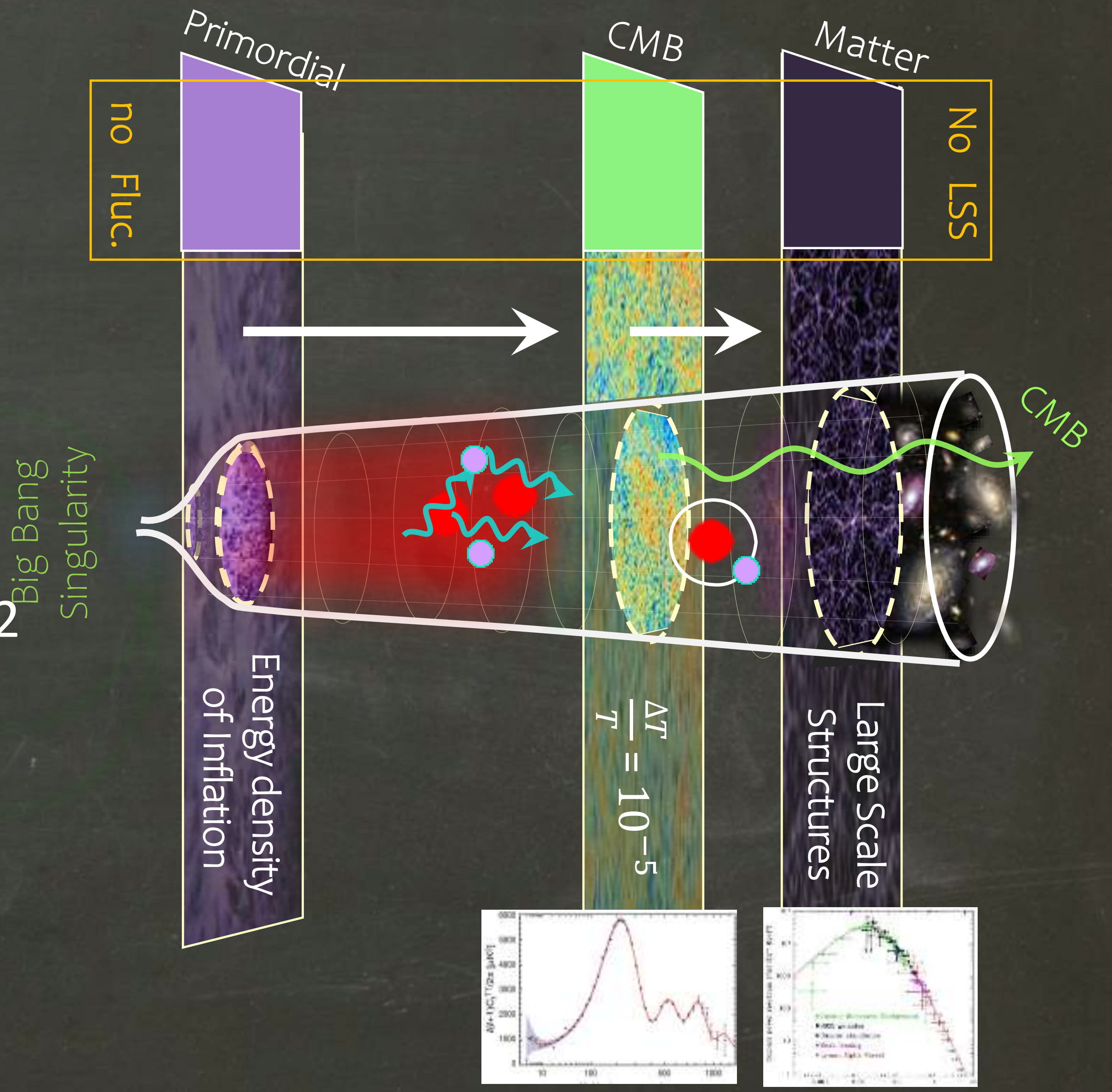

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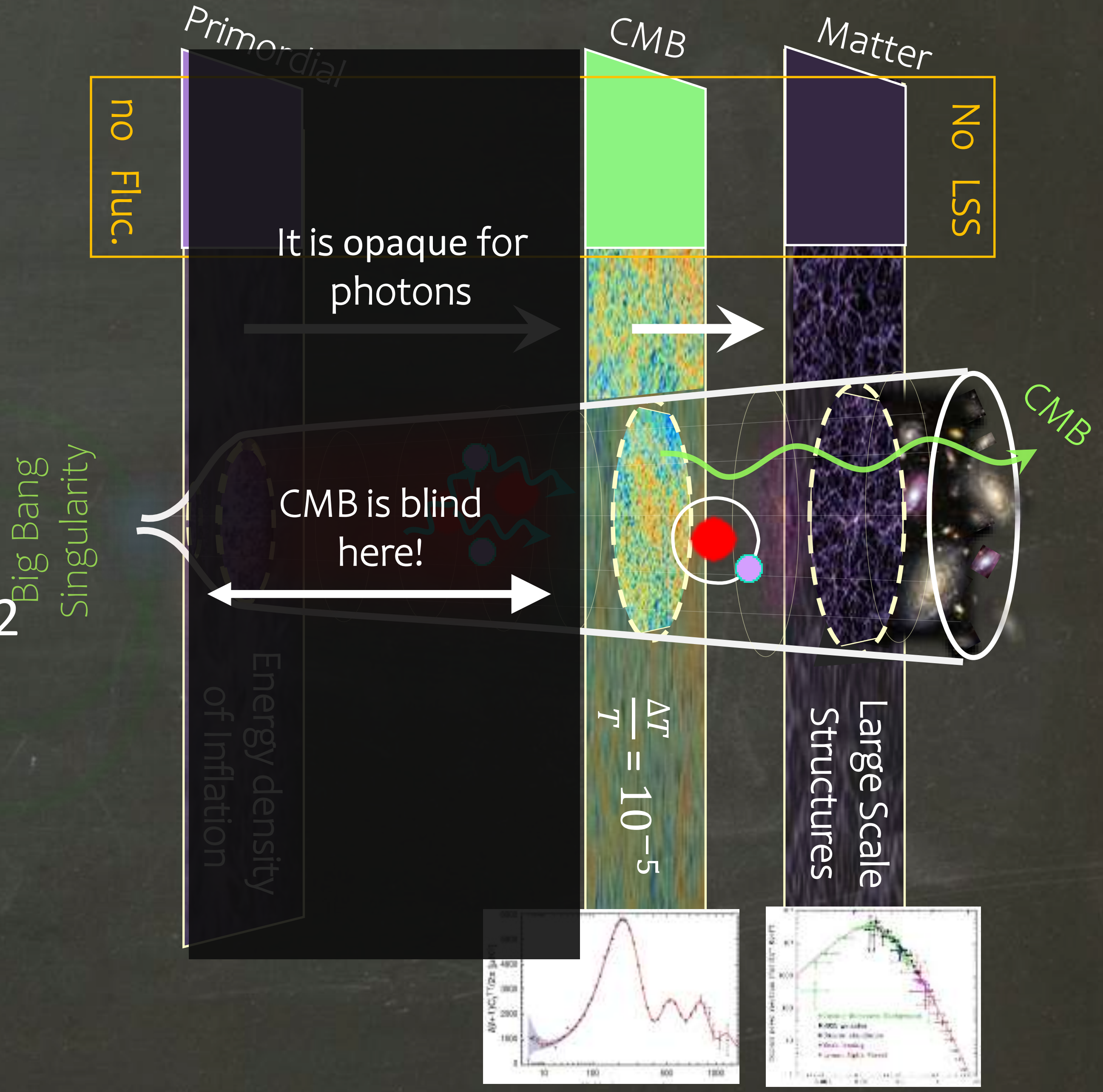
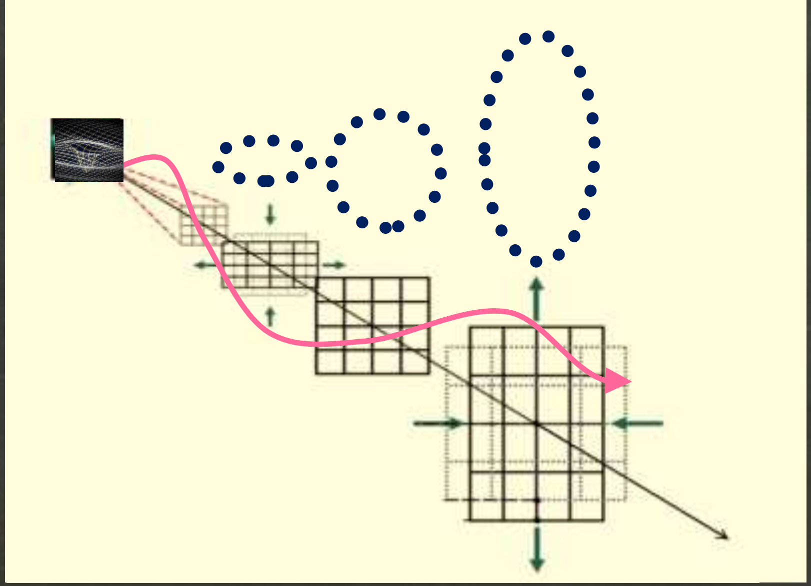
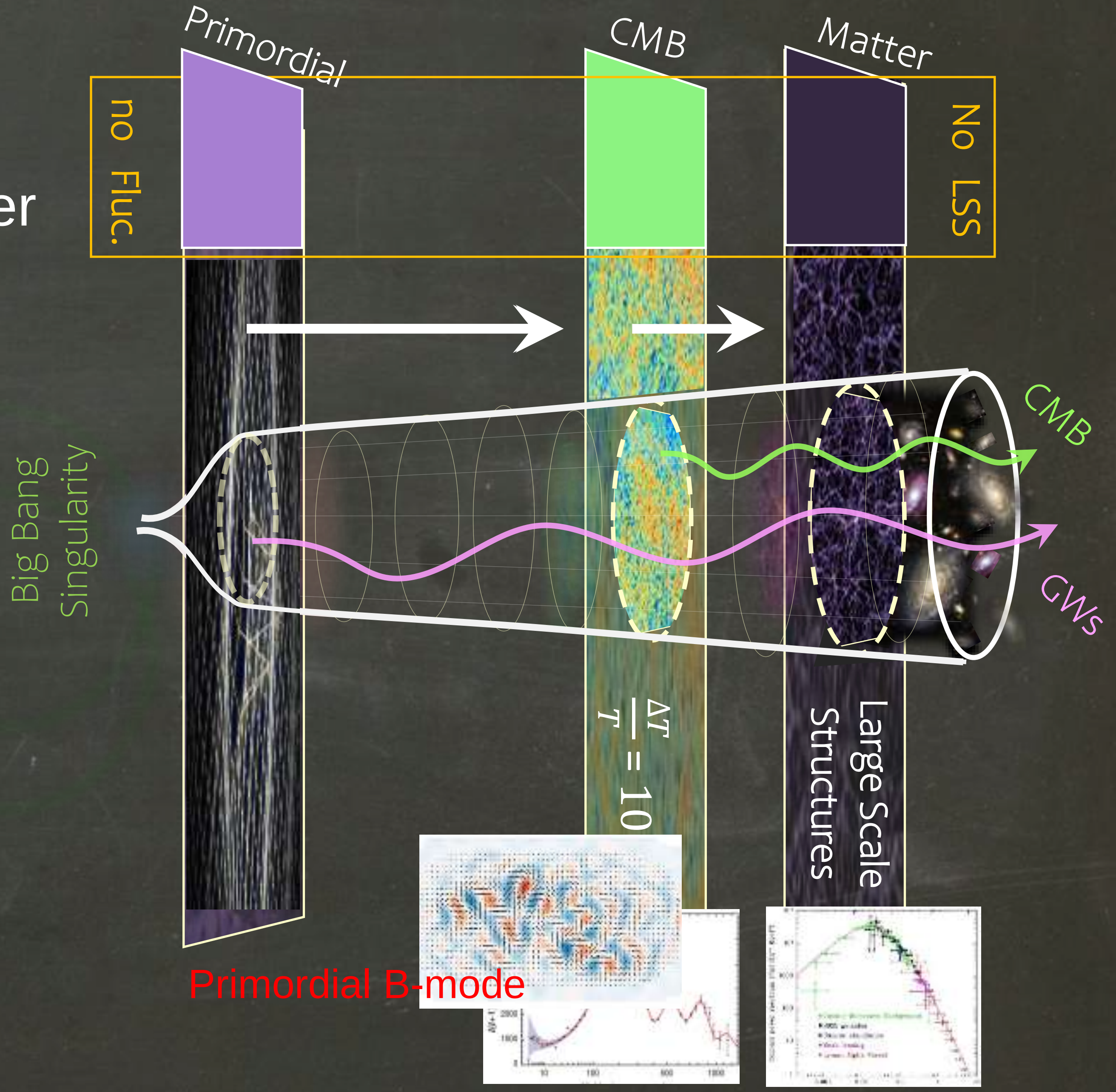


Tensor Perturbations

Nature generously gave us yet another observable: Primordial GWs

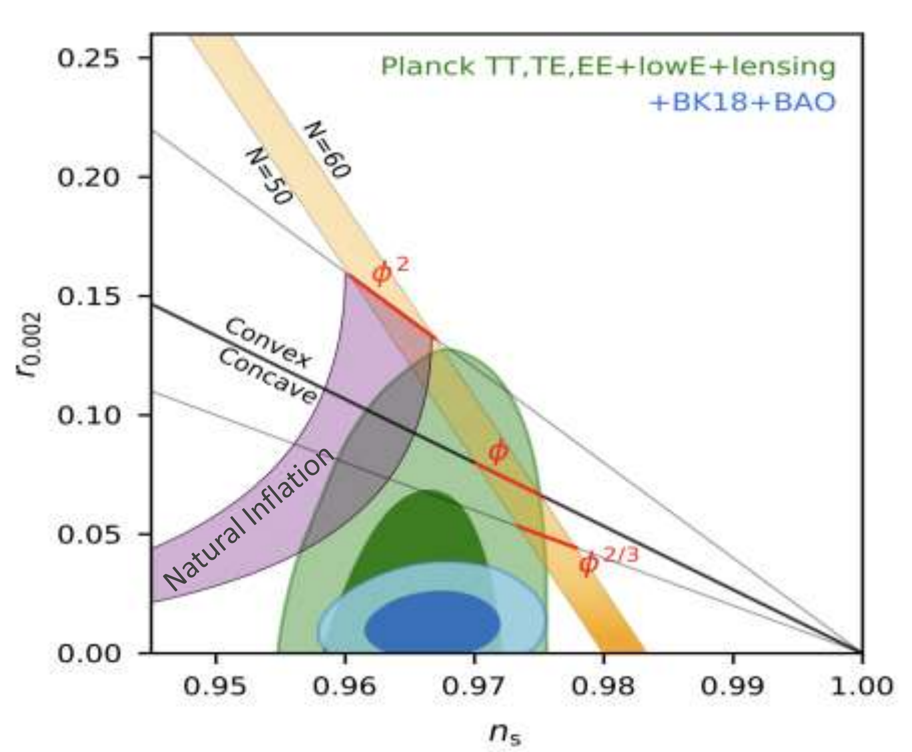




n_s- r plane

$r_{0.05} < 0.036$ (95% CL)

ns = 0.9649±0.0042 (95% CL)



Planck 2018 + lensing

w\ BICEP2/Keck Array (BK18) & BAO data

BICEP and Keck Collaborations PRL 127 (2021) 15, 151301

n_s - r plane

$r_{0.05} < 0.036$ (95% CL)

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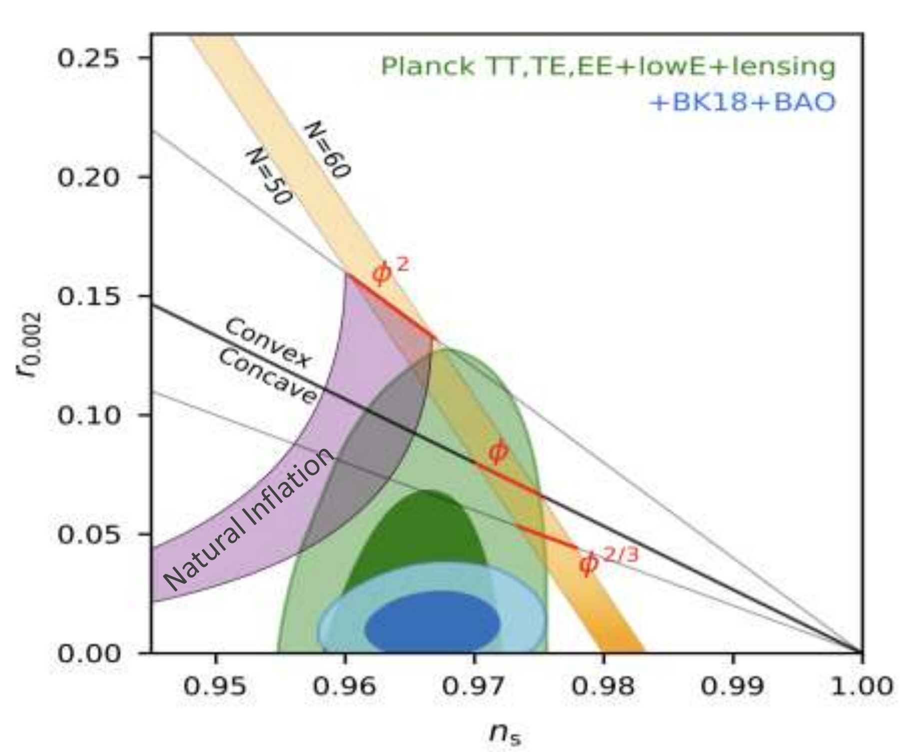
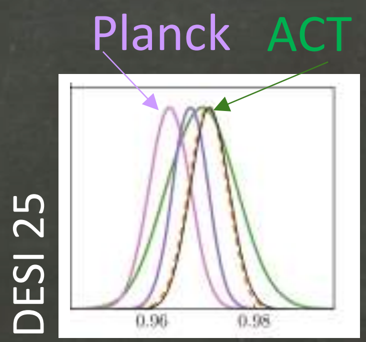
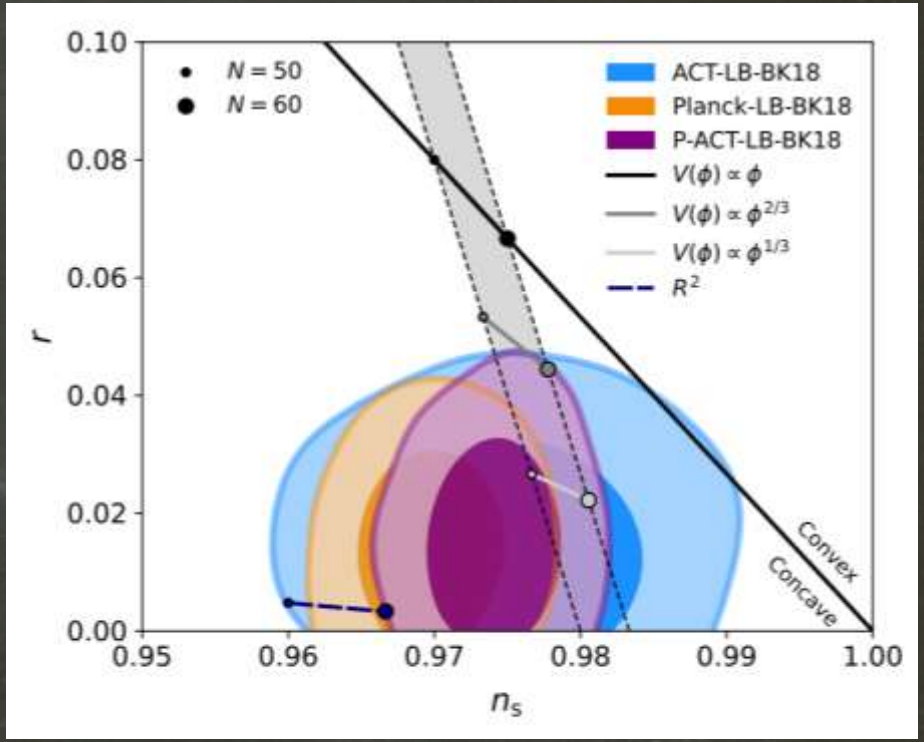
ACT shifted ns!

ns = 0.9743 ± 0.0034 (95% CL)







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Planck + lensing + BK18 + BAO data

w/ ACT

BICEP and Keck Collaborations PRL 127 (2021) 15, 151301

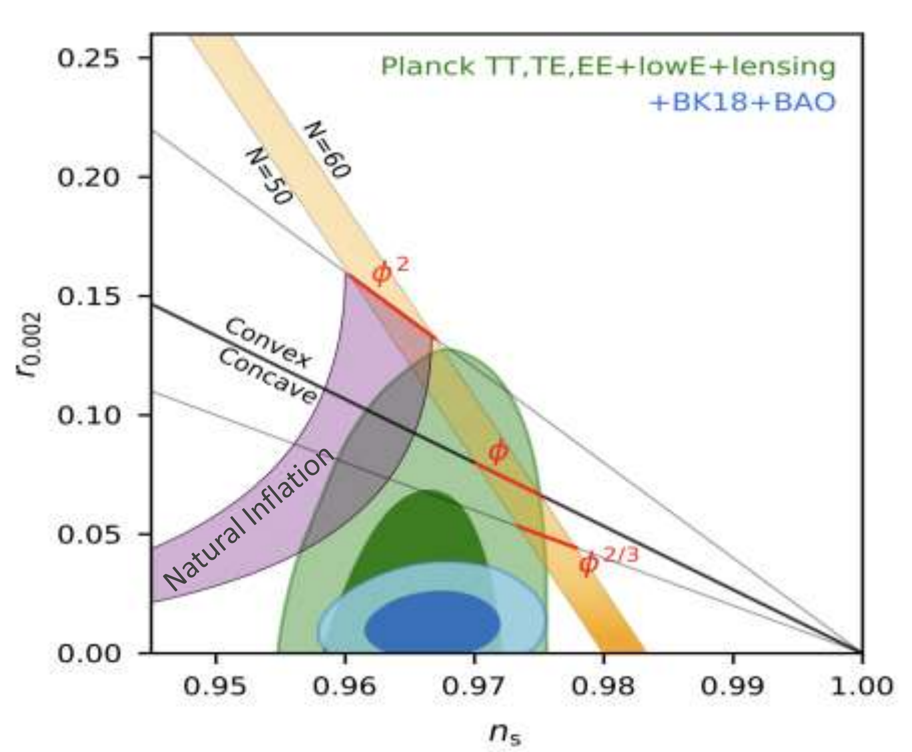
ACT Collaboration 25

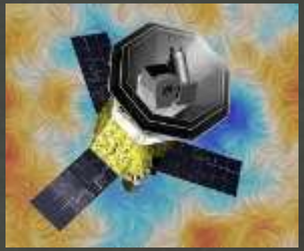
A big goal remains! Primordial B-modes

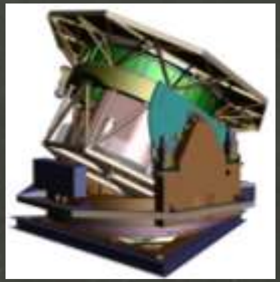
$r_{0.05} < 0.036$ (95% CL)

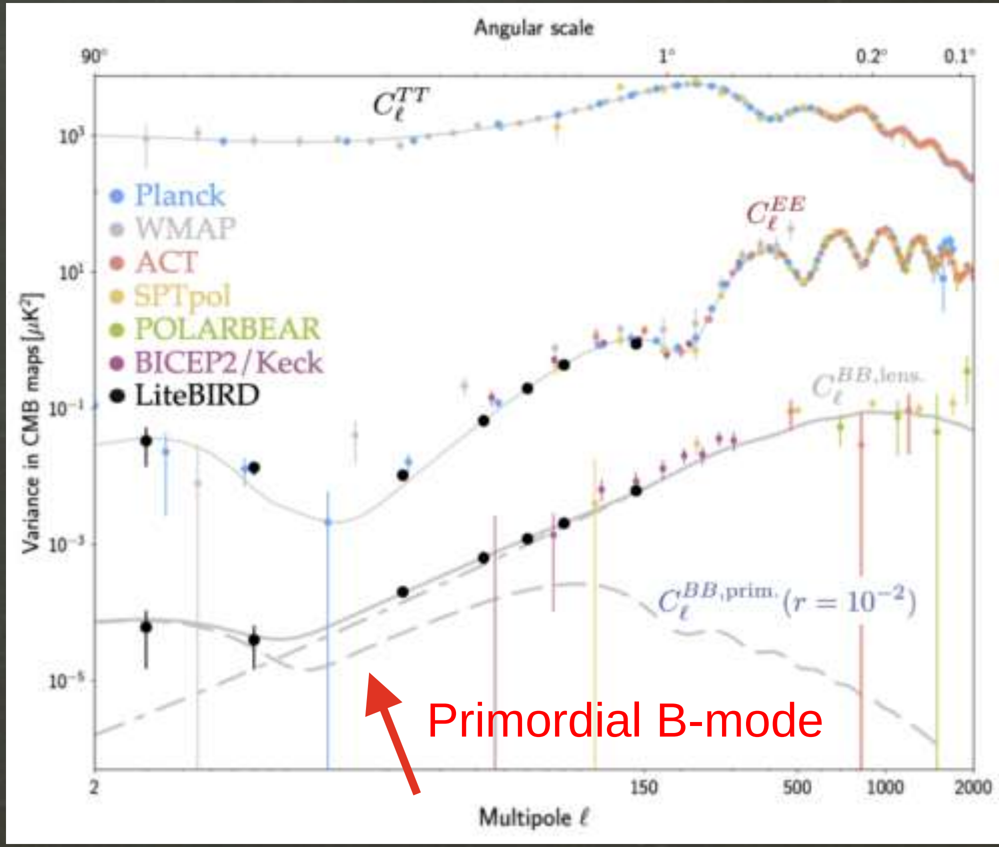
ns = 0.9649±0.0042 (95% CL)

CMB-S4 & LiteBird expected to reach $r < 10^{-3}$









Planck 2018 + lensing

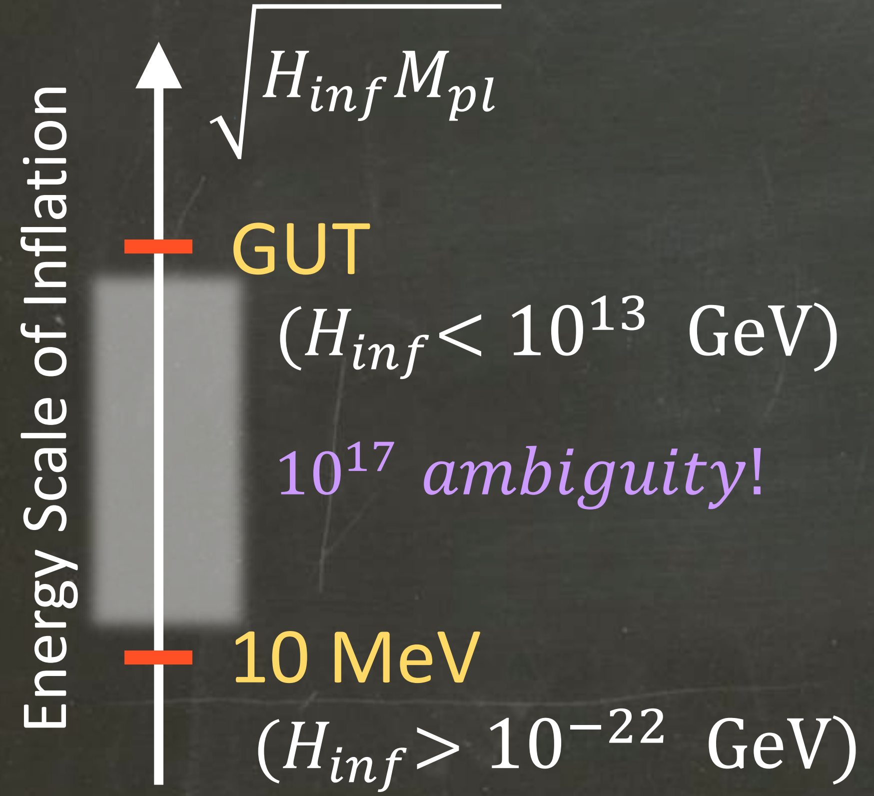
w\ BICEP2/Keck Array (BK18) & BAO data

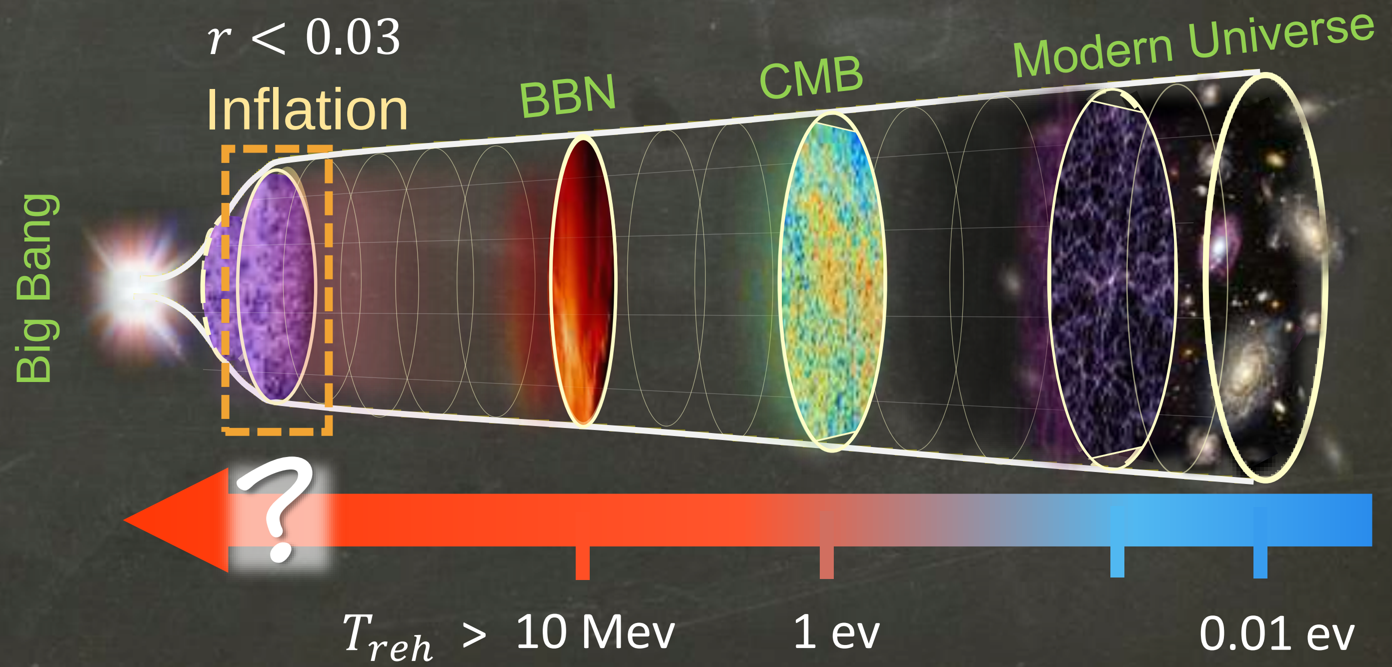
BICEP and Keck Collaborations PRL 127 (2021) 15, 151301

LiteBIRD mission

What is the scale of Inflation? From MeV to GUT

A 17-Order Window of Ignorance Still Surrounds the Inflationary Energy Scale!





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
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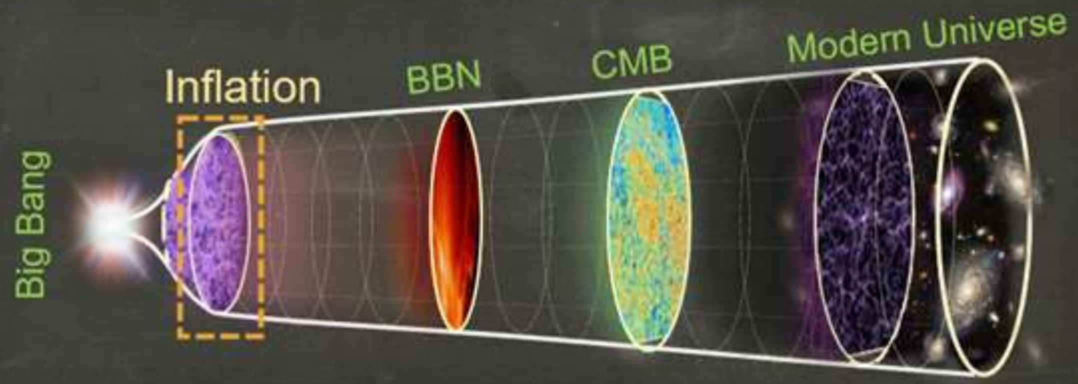

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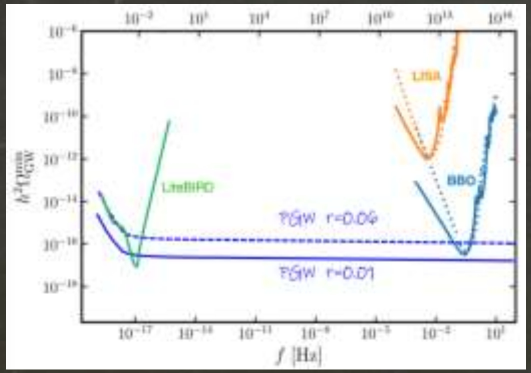
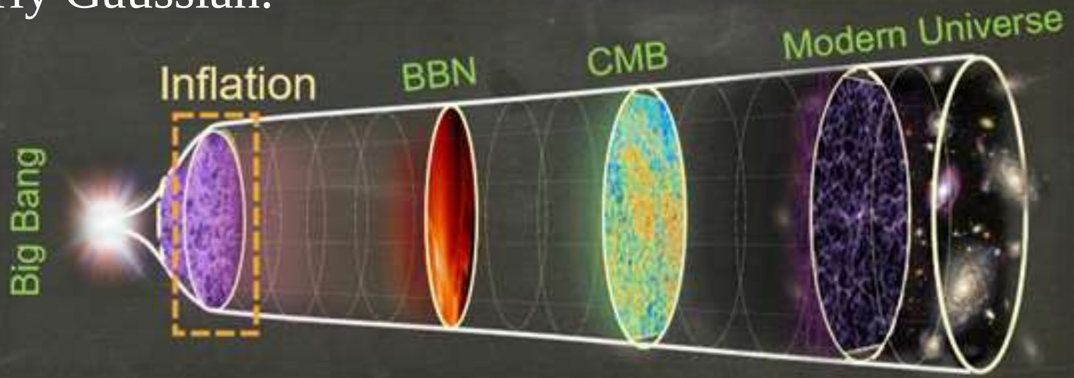
  Parity is a symmetry in inflation

- Primordial Gravitational Waves (PGW):

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

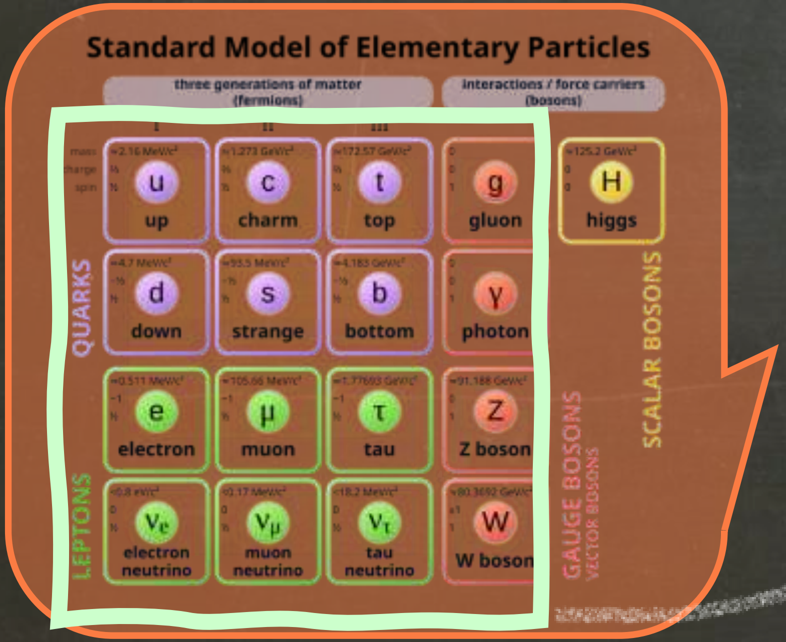




But wait!

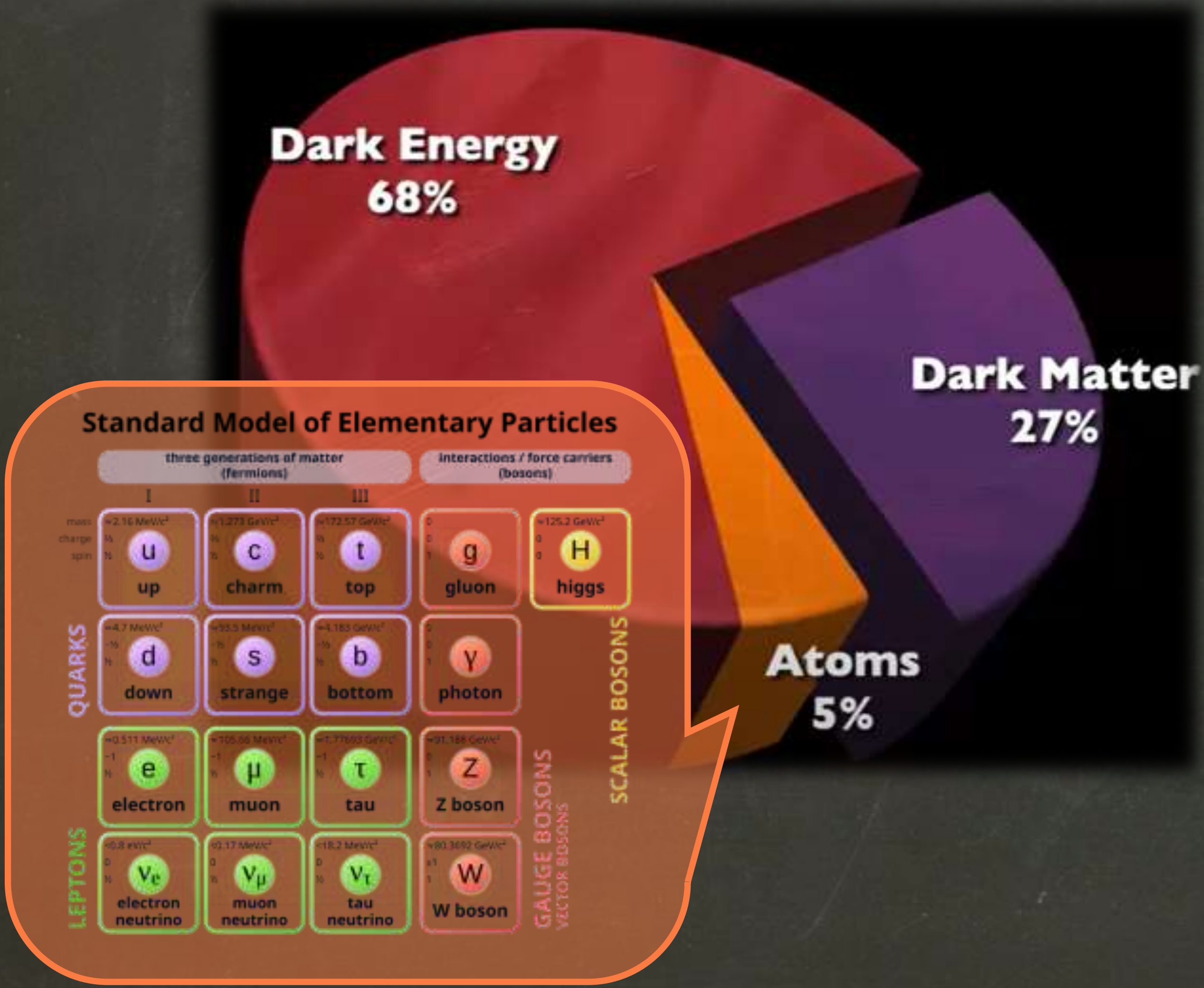
What about all other matter fields in the Universe?

Gauge fields are the carries of fundamental forces, and
Fermions are the matter fields.



Spinning fields

The Matter content of Universee today!



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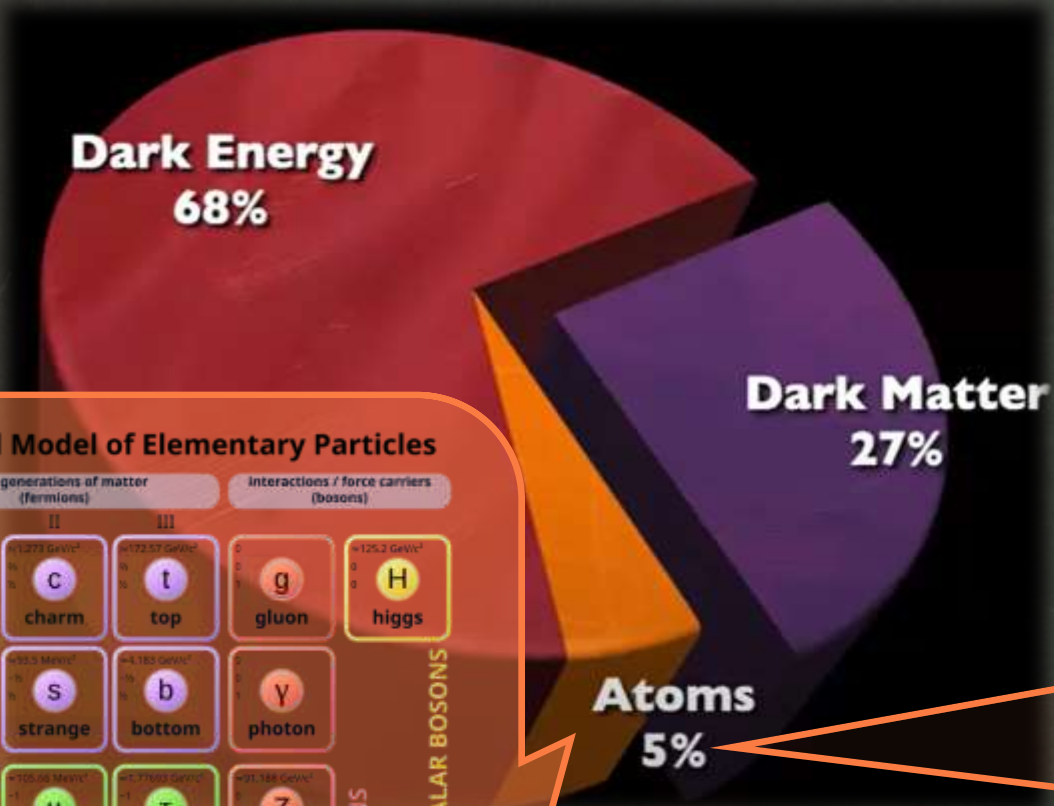
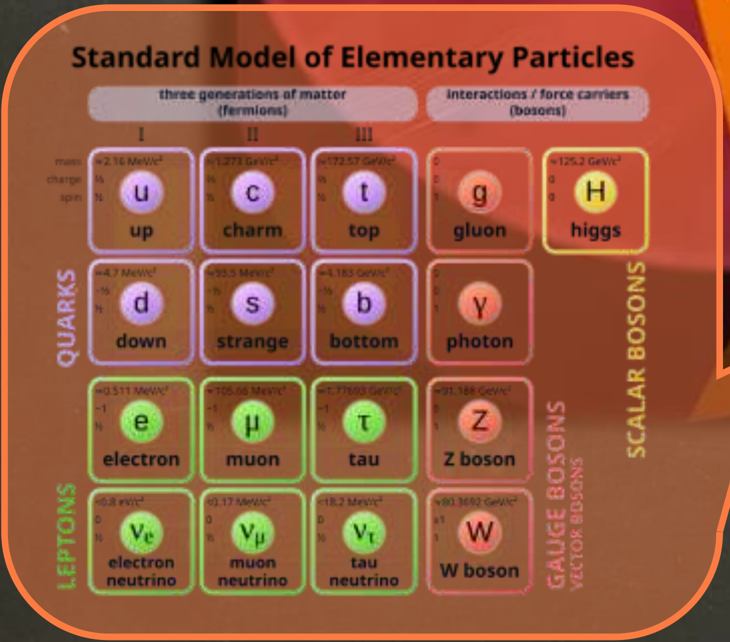
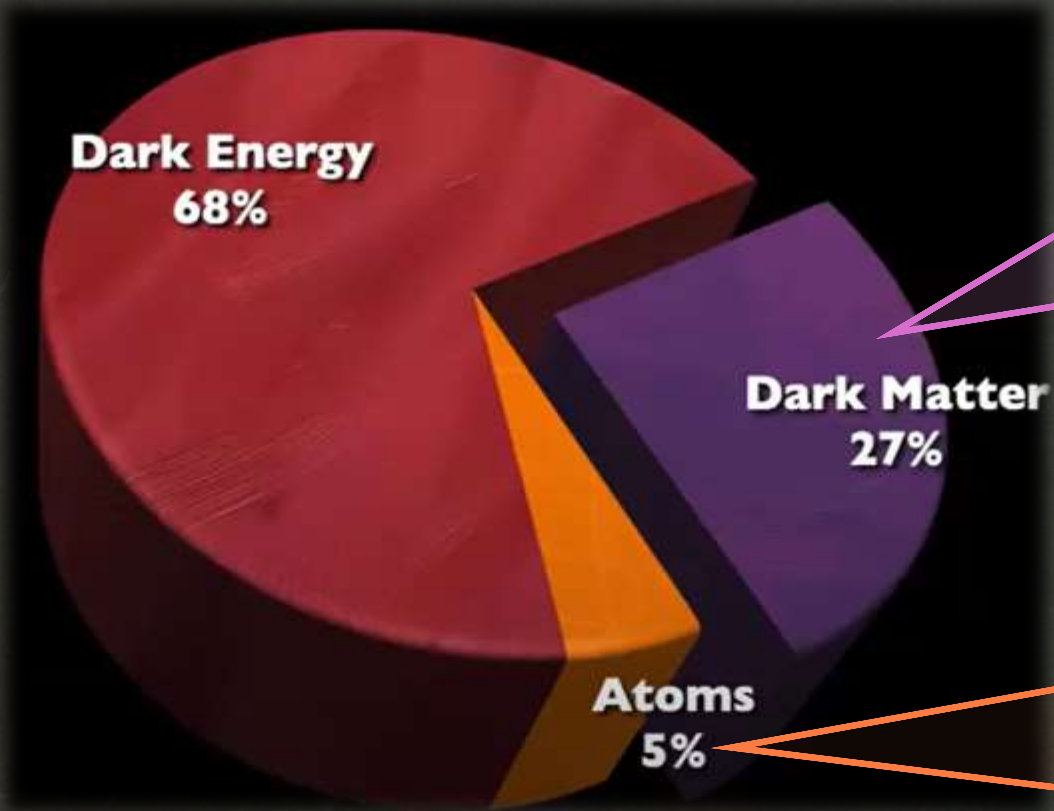




Requires

Matter – antimatter Asymmetry!

The Matter content of Universee today!



Open questions

i) Particle Nature of DM

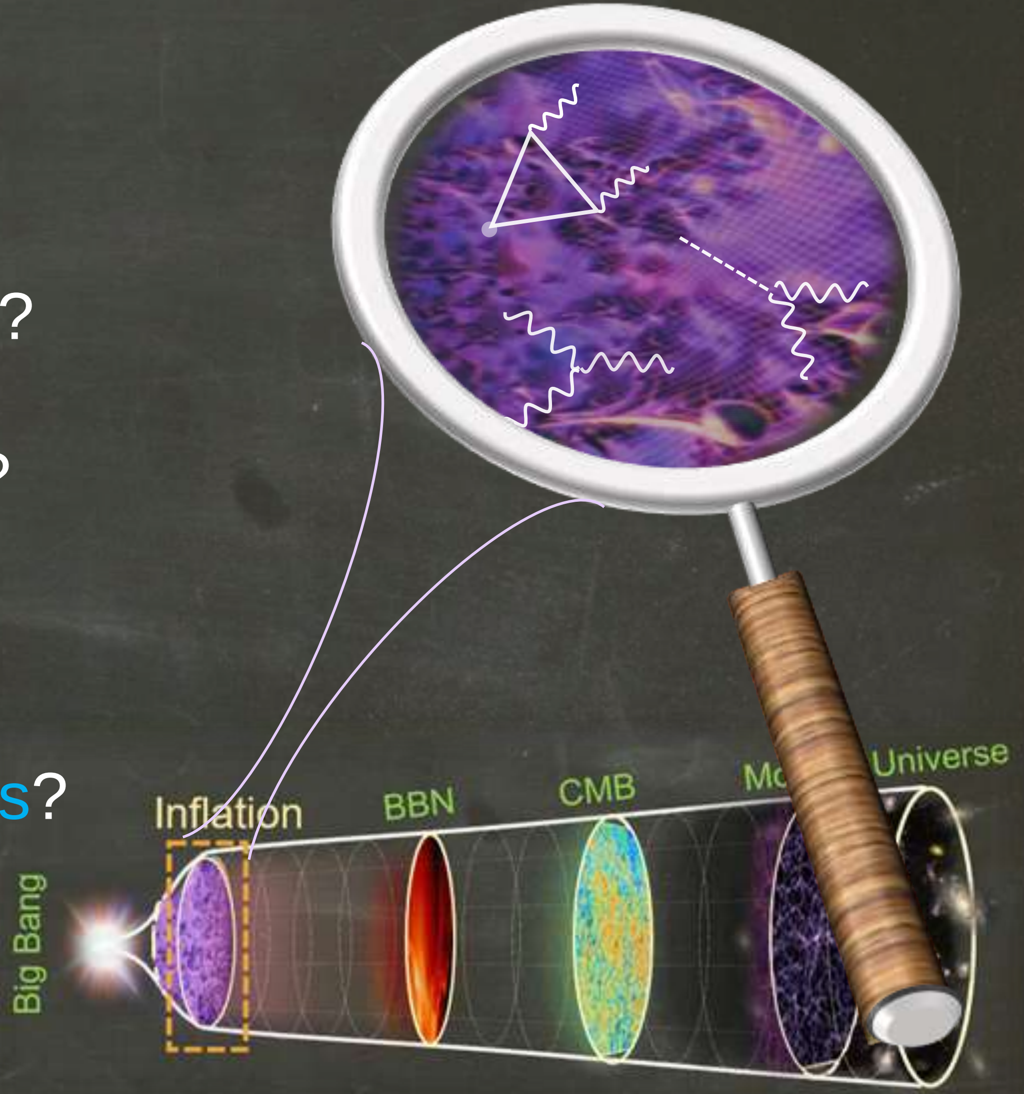
ii) Its Production mechanism

Requires

Matter – antimatter Asymmetry!

Particle Physics of Inflation?

- Gauge fields in inflation: what do they do?
- Could inflation create the matter asymmetry?
- Which model-building frameworks realize it?
- When did the Universe actually thermalize?
- How can we confront them with observations?



Axion Inflation

Toward a Particle Physics for Inflation

Setup

1- Theory and Model building

- Axion-gauge field models
- Thermalization

2- Phenomenology & Observation

- Gauge field & matter production
- Baryogensis in axion inflation
- Schwinger effect
- GWs

Gauge Fields in Inflation

Gauge fields given by Yang-Mills

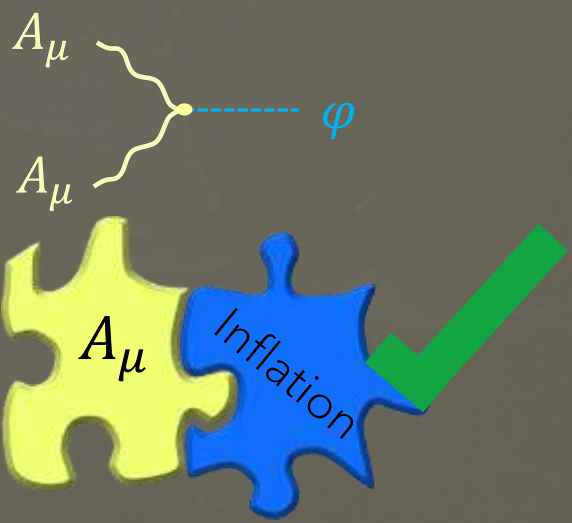
dilutes like radiation $A_\mu \sim 1/a$

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.)

Kaloper & Sorbo 2009



Gauge Fields in Inflation

Gauge fields given by Yang-Mills

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Spatial isotropy & homogeneity

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

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

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.)

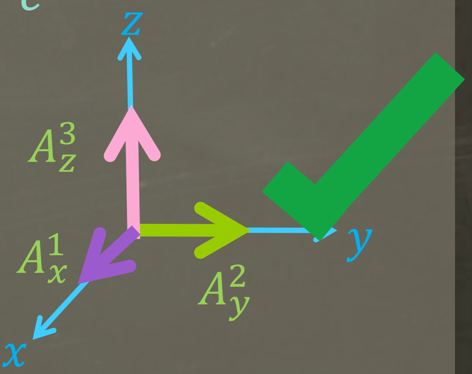
so(3) & su(2) are isomorphic

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

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



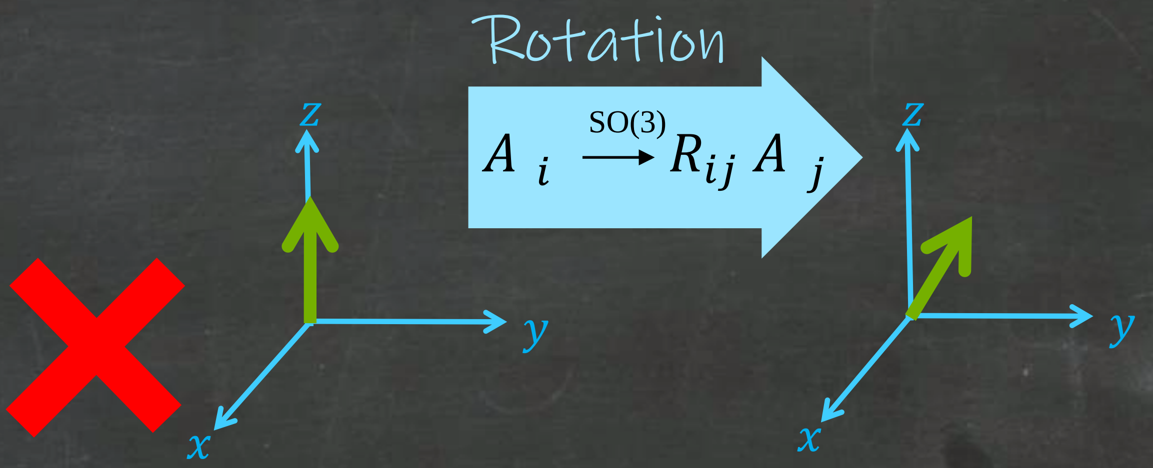
A.M. & Sheikh-Jabbari, 2011

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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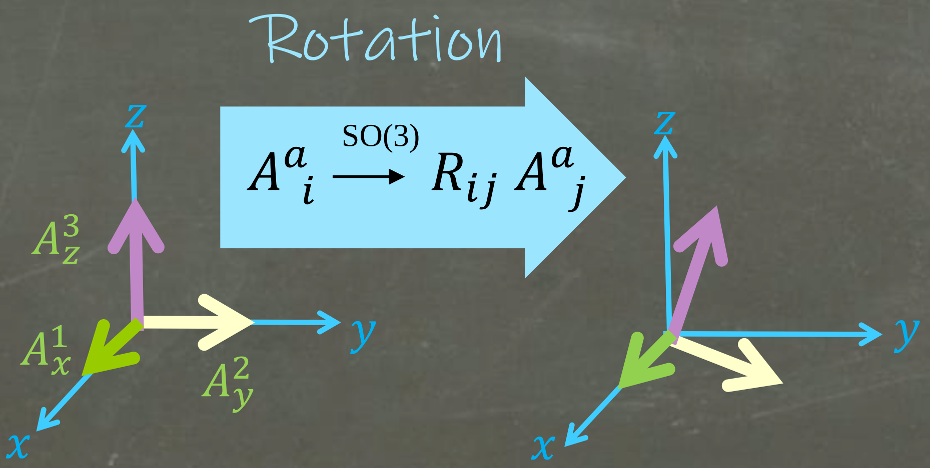

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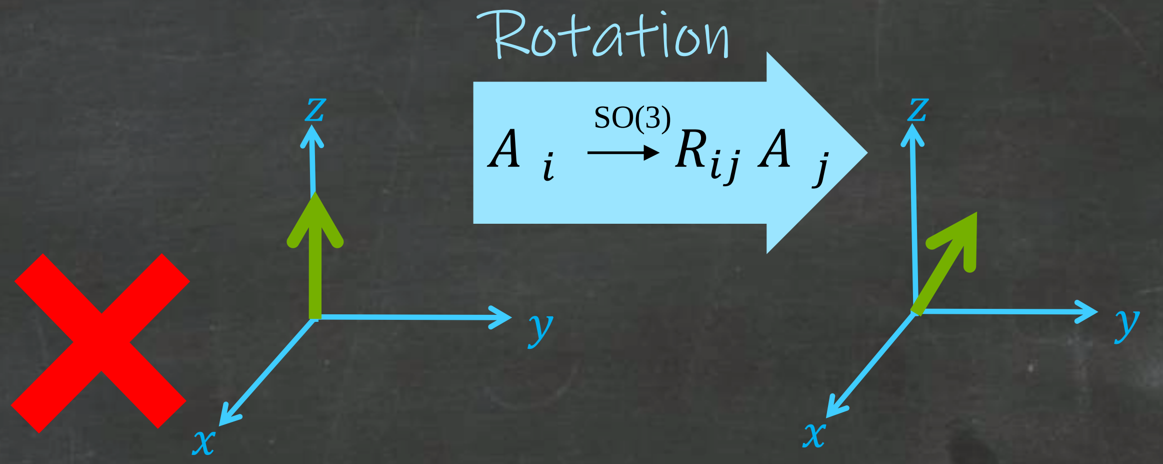

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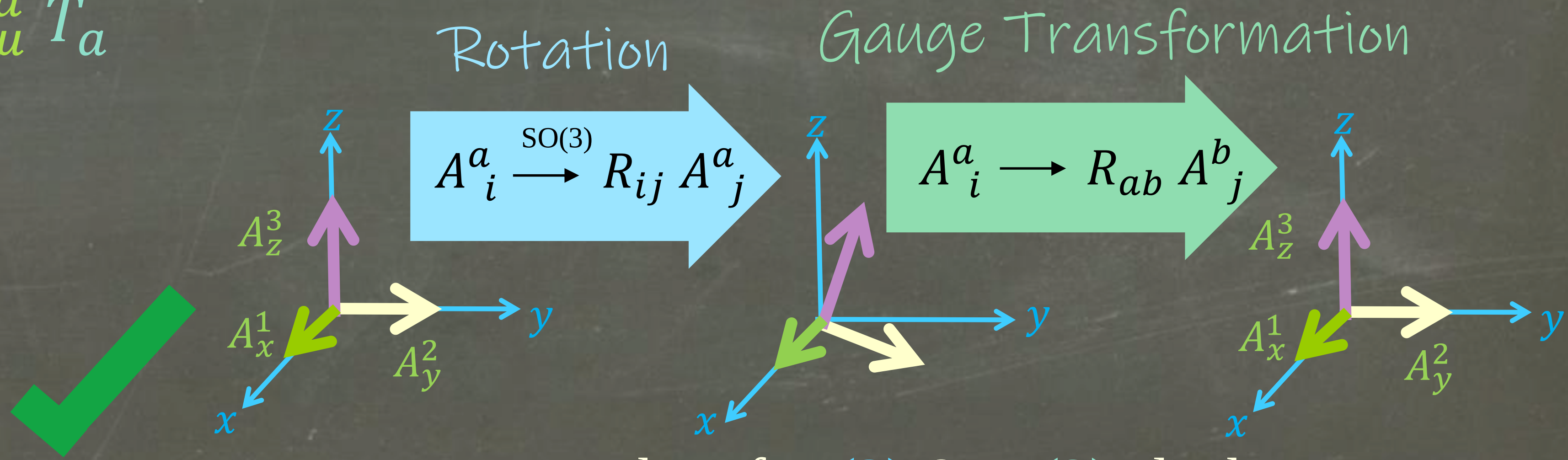

A.M. and M. M. Sheikh-Jabbari, 2011

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

Gauge Fields in Inflation

Given the spatial isotropy of the Universe

Gauge fields in inflation must satisfy:

	Abelian	Non-Abelian
Background	$\boldsymbol{A_i = 0}$	$\boldsymbol{A_i^a = Q(t)\delta_i^a}$
Fluctuations	$\langle \boldsymbol{A_\mu A_\nu} \rangle \neq 0$	$\langle \boldsymbol{A_\mu^a A_\upsilon^a} \rangle \neq 0$

SU(2)-Axion Model Building

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

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

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

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

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$\rho = -P$

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Natural inflation

Friction

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

SU(2)-Axion Model Building

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

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

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

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

SU(2)-Axion Model Building

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- Minimal Scenario of SU(2)-axion inflation   **A. M.**, 2016

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

$f<0.1$ Mpl & $\lambda<0.1$

Axion Monodromy or any mechanism that gives a flat potential

SU(2)-Axion Model Building

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

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f<0.1 Mpl & λ<0.1

Axion Monodromy or any mechanism that gives a flat potential

Dimastrogiovanni, Fasiello, Papageorgiou, Zenteno Gatica 2025 (Pure Chromo-natural)

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]

SU(2)-Axion Model Building

Chromo-Natural Inflation	Natural Inflation+ SU(2)
Minimal Axion-SU(2) **MA** 2016	Axion inflation with flat potential+ SU(2)
Spectator Chromo-natural Dimastrogiovanni, Fasiello, Fujita, 2016	Inflation + Axion-SU(2) with Cos potential
Higgsed Chromo-natural Adshead, Martinec, Sfakianakis, Wyman 2016	Chromo-natural + Higgs

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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

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*]
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- Primordial Magnetic Fields...

Brandenburg, Iarygina, Sfakianakis, Sharma 2024

14. Oksana Iarygina, Evangelos I. Sfakianakis, [arXiv:2105.06972]
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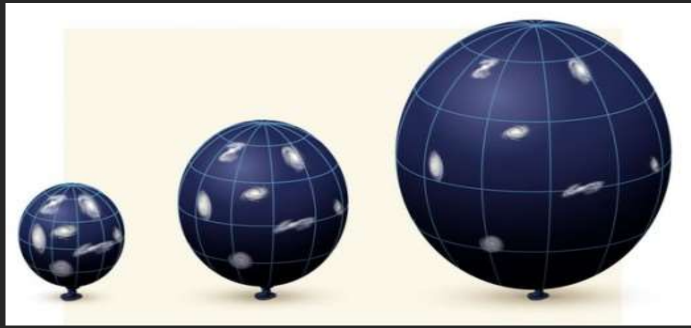
SU(2) Gauge fields and Initial Anisotropies

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

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

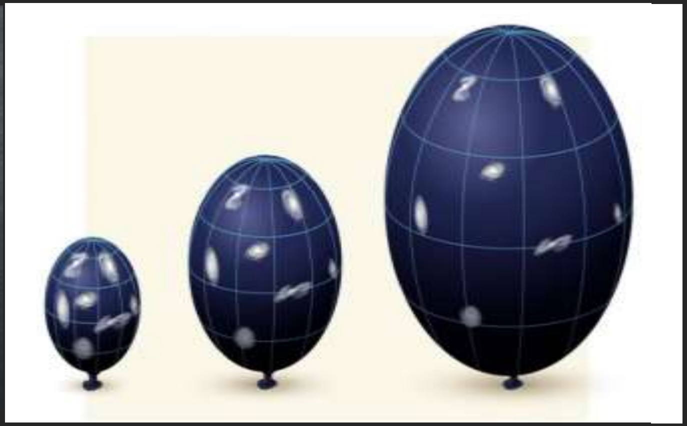


Isotropic Background

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

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

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



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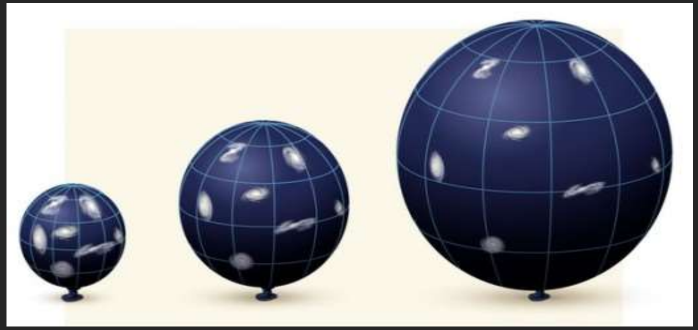

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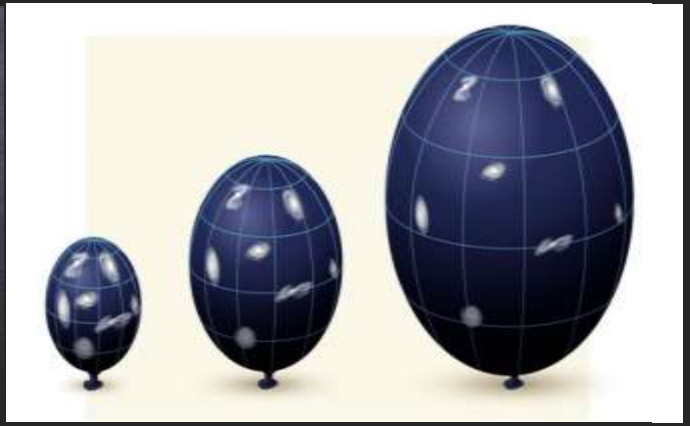
$$(2+\lambda^6)\left(\frac{\lambda''}{\lambda}+3\frac{\lambda'}{\lambda}\right)-6\frac{\lambda'^2}{\lambda^2}+(\lambda^6-1)(2+\lambda^2\gamma)\simeq 0\,,$$

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



Anisotropic Background

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

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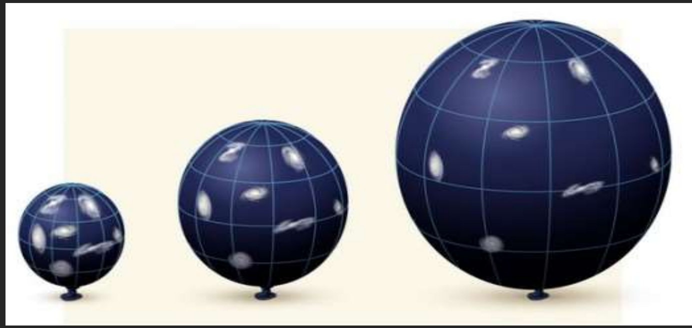


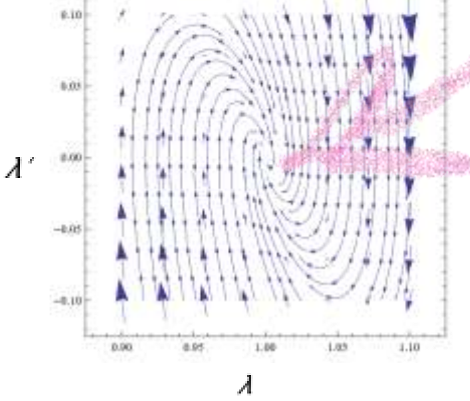
Isotropic Background

- 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
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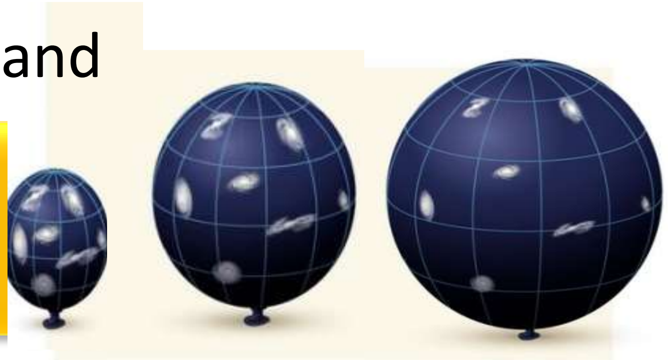

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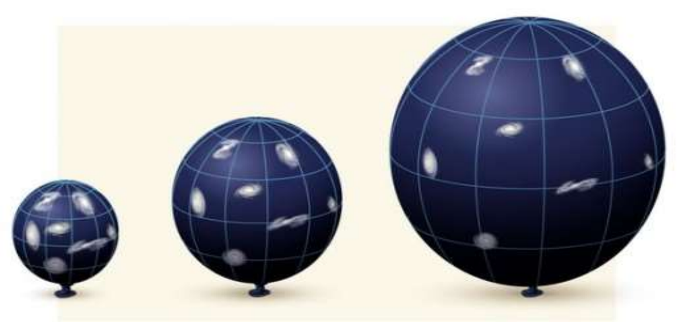
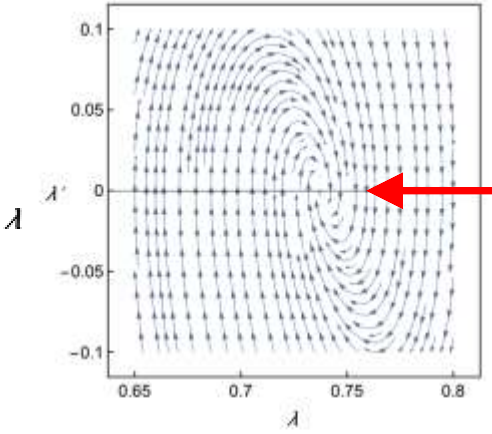


Isotropic Background

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

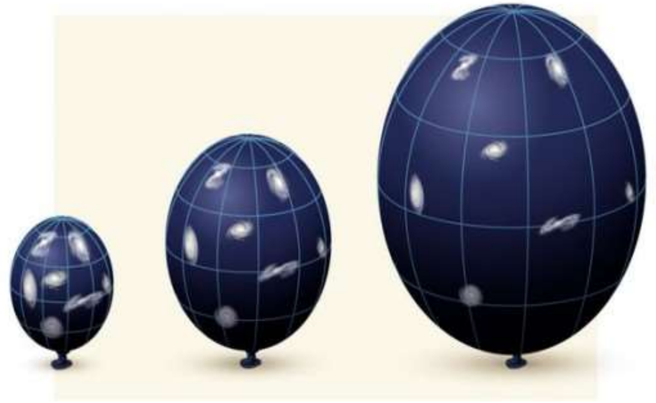
Adshead & Liu 1803.07168

Higgsed axion-SU(2) with different masses for 2 colors $M_1 \neq M_2$



attractor $\neq$ 1

Anisotropic Solution is Attractor!



isotropic Background

Warm Inflation

Warm Inflation

The effective description of warm inflation   Berera, 1995

$$\ddot{\phi} + (3H + \Upsilon)\dot{\phi} + V' = 0,$$

dissipation

$$\dot{\rho}_R + 4H\rho_R = \Upsilon\dot{\phi}^2.$$

The axion inflation with SU(N) gauge field backreaction

$$\ddot{\phi} + 3H\dot{\phi} + V' = -\frac{\alpha_s}{8\pi f}\langle G^a_{\mu\nu}\tilde{G}^{a\mu\nu}\rangle .$$

$$\frac{\alpha_s}{8\pi f}\langle G^a_{\mu\nu}\tilde{G}^{a\mu\nu}\rangle \equiv \Upsilon_{\rm sph}\dot{\phi} = \frac{\Gamma_{\rm sph}}{2Tf}\frac{\dot{\phi}}{f}$$

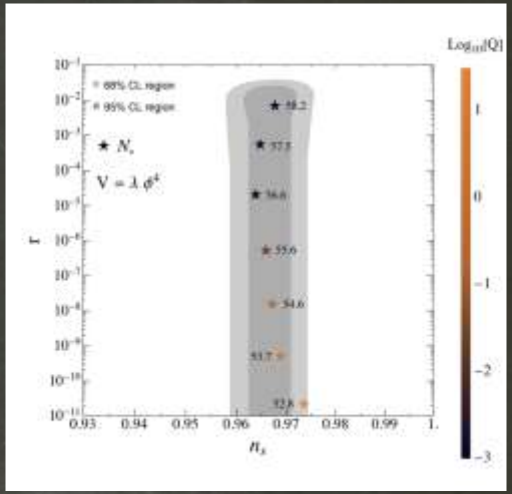
$$\Upsilon_{\rm sph} \simeq (\alpha_s N_c)^5 \frac{T^3}{2f^2}$$

Berghaus, Graham & Kaplan 2020

Sphaleron rate

Warm Inflation

SM+axion



Berghaus , Drewes , & Zell 25

The effective description of warm inflation   Berera, 1995

$$
\begin{aligned}
\ddot{\phi} + (3H + \Upsilon)\dot{\phi} + V' &= 0\,, \\
\dot{\rho}_R + 4H\rho_R &= \Upsilon\dot{\phi}^2\,.
\end{aligned}
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dissipation

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$$
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$$

Berghaus, Graham & Kaplan 2020

Sphaleron rate

2- Phenomenology & Observation

Quantum Vacuum $\hbar \neq 0$

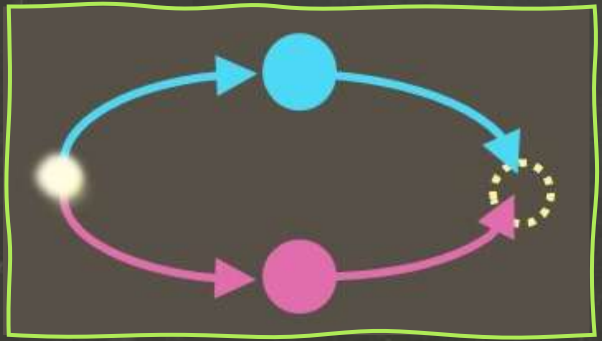
Due to Uncertainty Principle

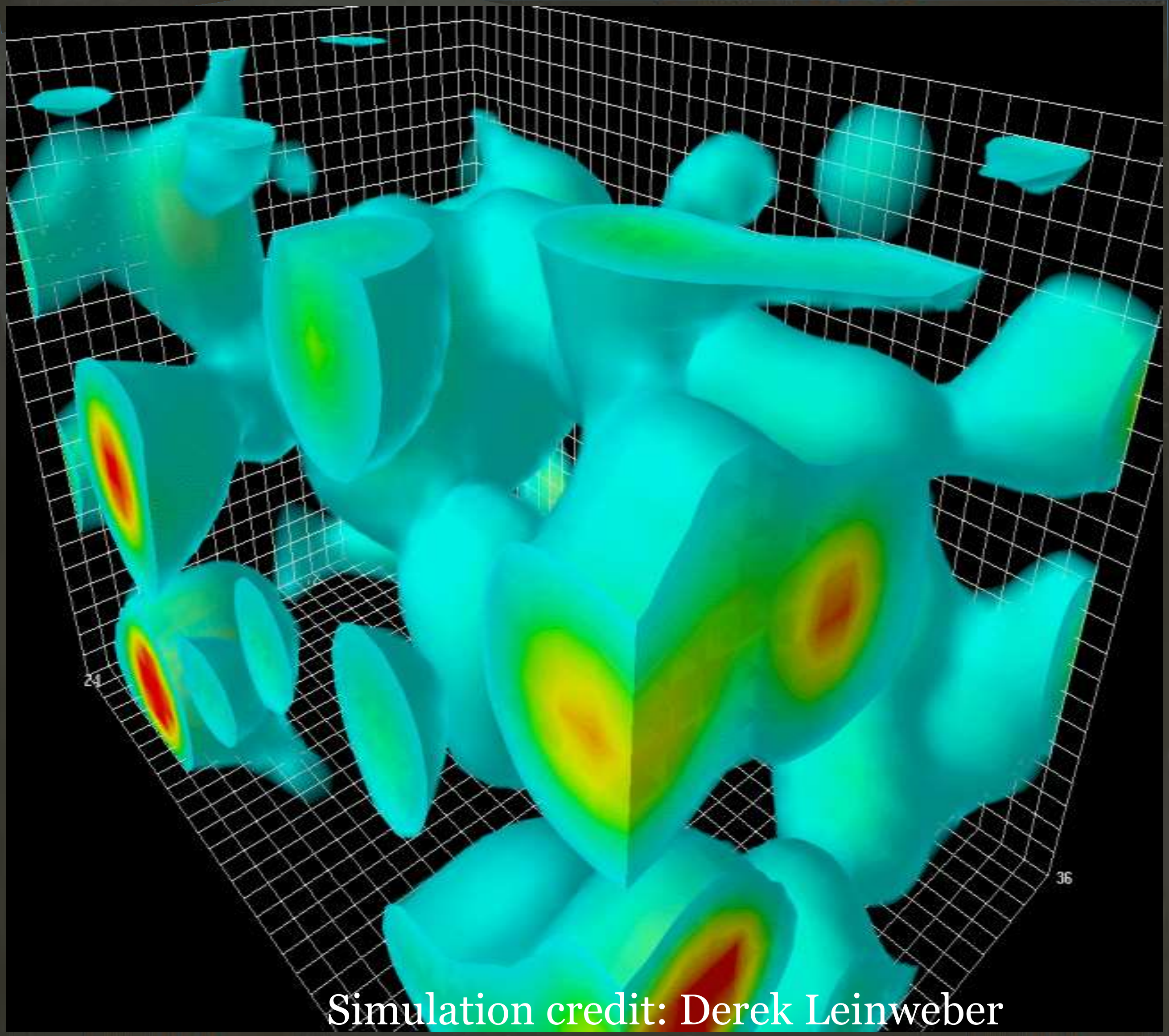
$$\Delta x \, \Delta p \geq \hbar/2$$

quantum vacuum is NOT nothing!

But, a vast ocean made of

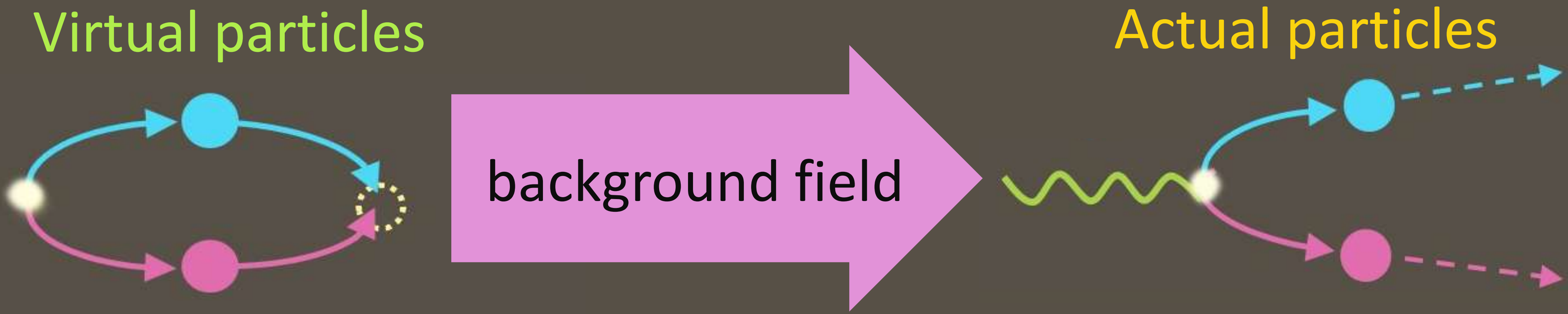
Virtual particles

vacuum  vacuum



Quantum Vacuum

Particle Production



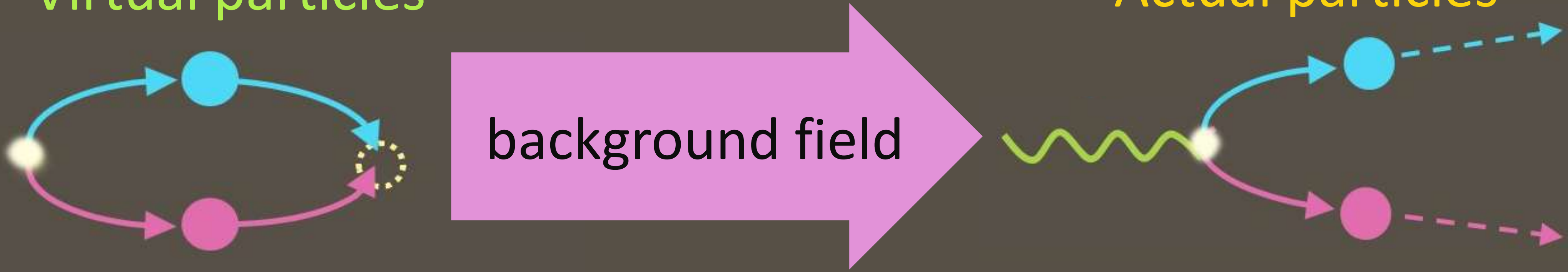
Background field can upgrade them into actual particles!

$\langle J \rangle = 0$

$\langle J \rangle \neq 0$

Quantum Vacuum — Particle Production

Virtual particles — Actual particles



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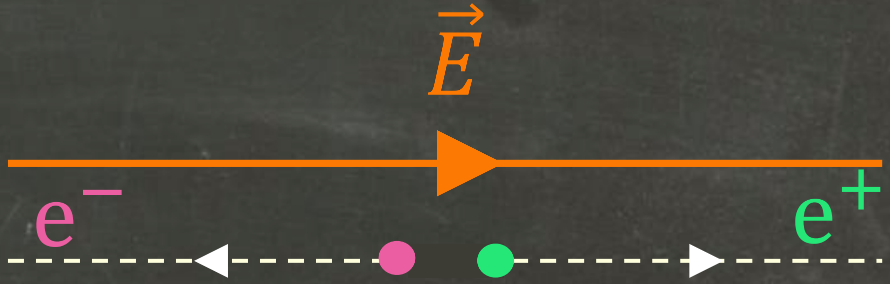
Examples of such BG fields:

1) Electric Field *Schwinger effect*



Work of the Lorentz force over Comptom wavelength

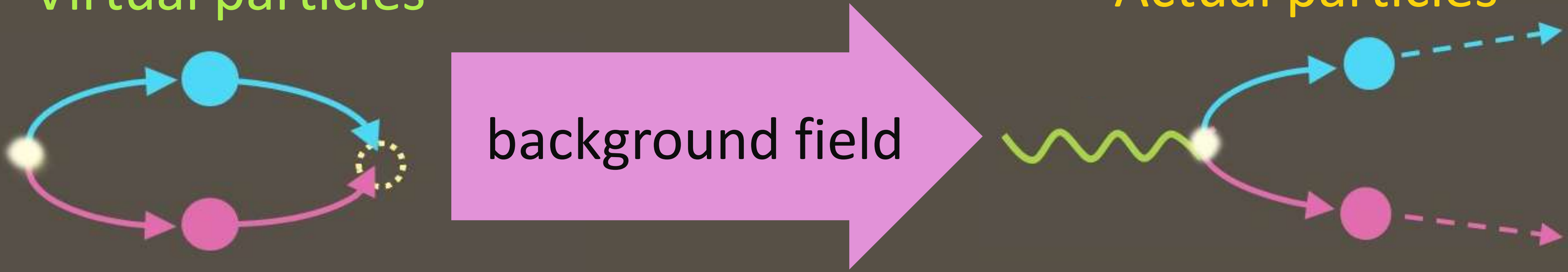
$$eE\,\lambda_{comp} = mc^2$$

Rest energy of charged particle

J. Schwinger (1951)

Quantum Vacuum — Particle Production

Virtual particles — Actual particles



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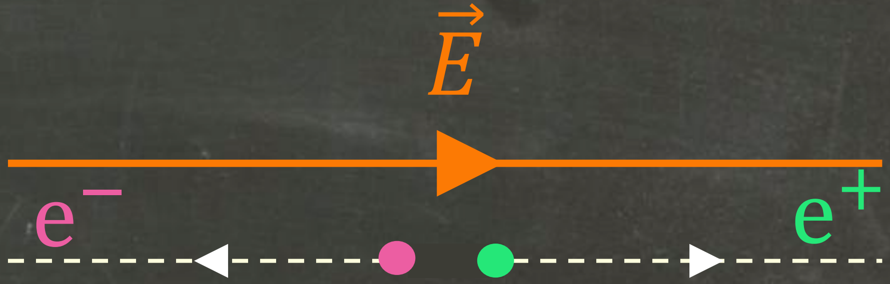

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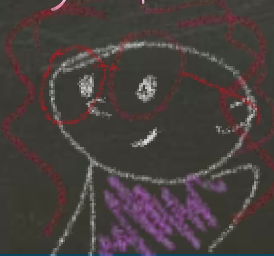
The Electric field that can create electron pairs $E = \frac{m_e^2 c^3}{e\hbar} = 10^{18}\ V/m$



What about

Schwinger Effect in Early Universe?

Schwinger effect in scalar QED in 4d de Sitter

- T. Kobayashi, N. Afshordi 2014

It requires assuming an ad hoc constant Electric Field

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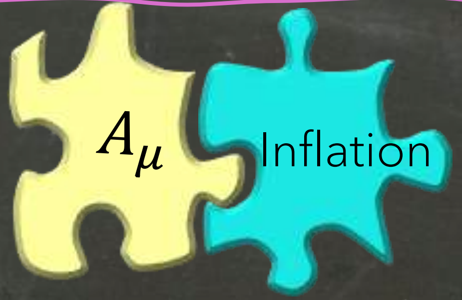
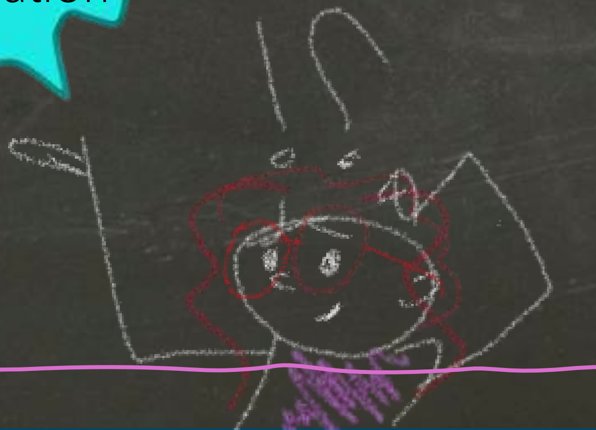
How about Axion-inflation (quasi-de Sitter)?!

i) a natural candidate for the inflaton field

ii) Naturally coupled to gauge fields



It naturally generates a constant Electric Field



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Schwinger effect in axion-inflation


K. Lozanov


E. Komatsu

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

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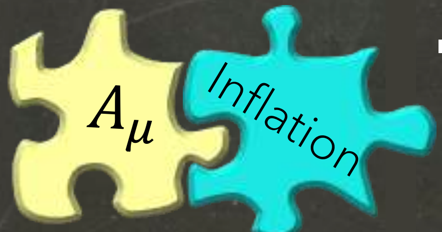

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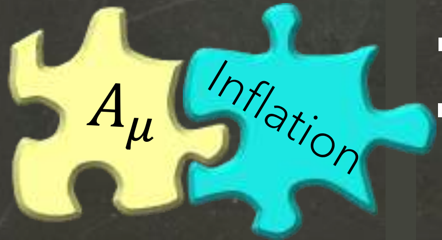

Schwinger effect in axion-inflation


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- K. Lozanov, **A. M.**, E. Komatsu **2018**
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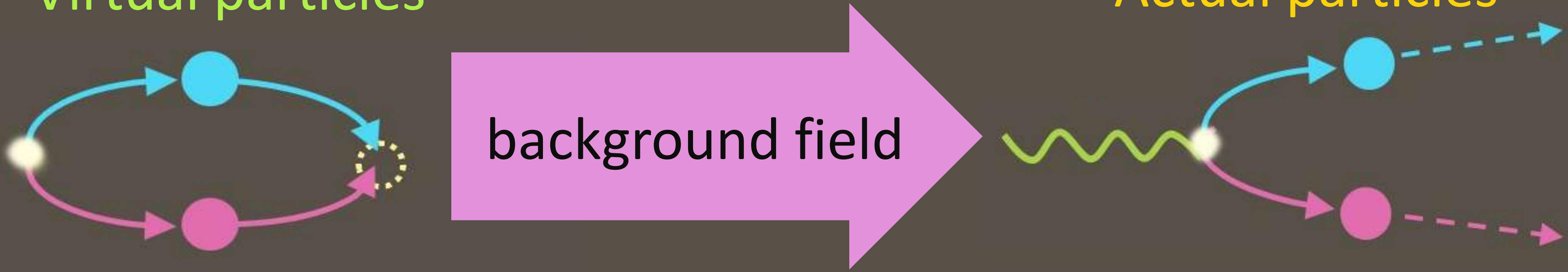
- ....
- E. Komatsu **2022** **nature reviews** physics

  New physics from the polarized light of the cosmic microwave background

Quantum Vacuum — Particle Production

Virtual particles

Actual particles



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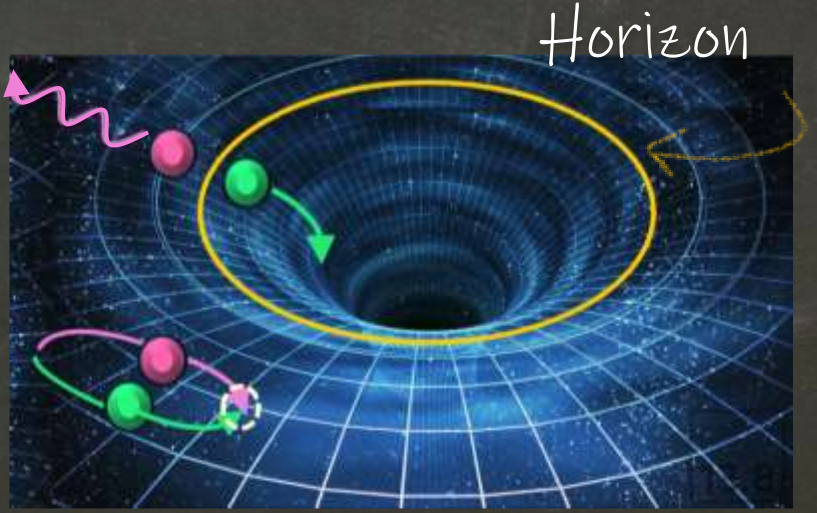
Examples of such BG fields:

2) Gravitational

Hawking radiation



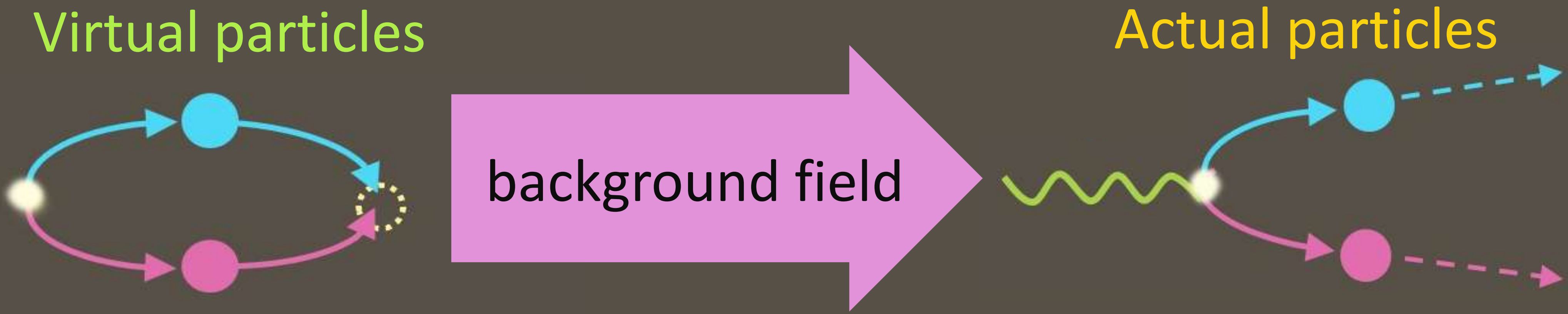
one particle fall into the BH, while the other escapes…

Power BH emitted is

$$P = \frac{\pi c^3 M_{pl}^4}{240} \frac{1}{M^2}$$

S. Hawking (1974)

Quantum Vacuum — Particle Production



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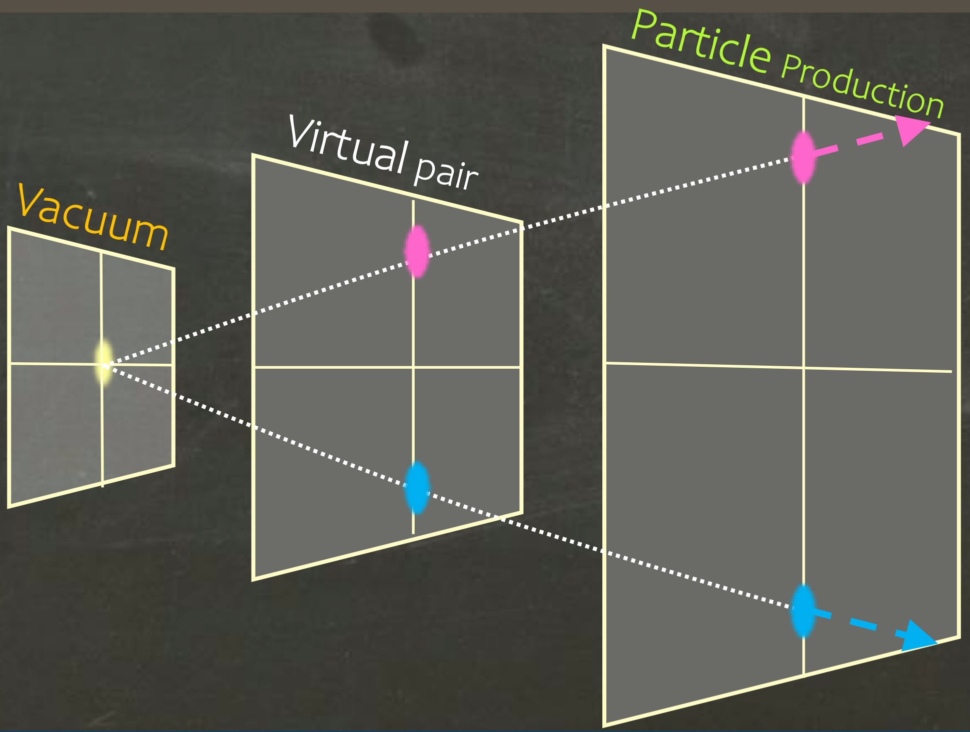
Examples of such BG fields:

1) Electric Field — *Schwinger effect*

2) Gravitational

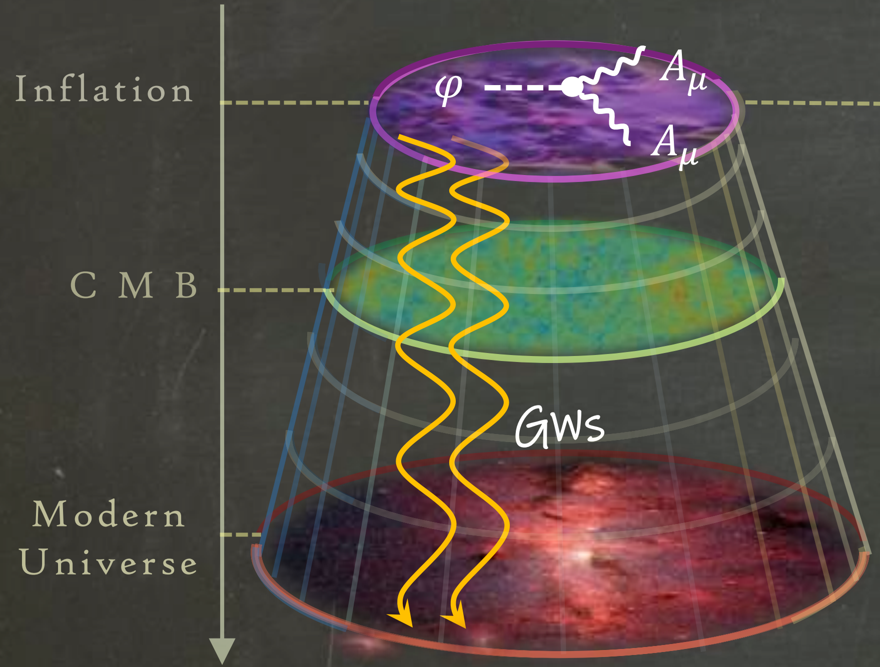
- i) *Hawking radiation*
- ii) *expansion of the Universe!*

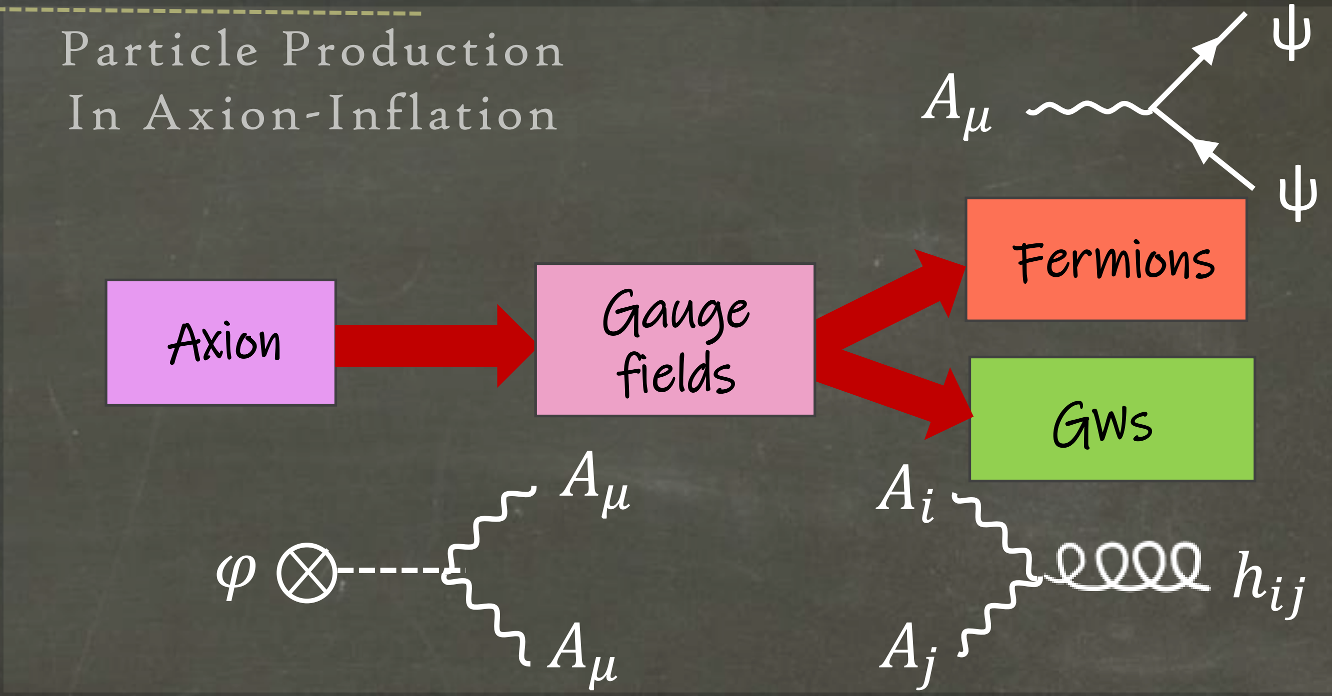


Inflation Particle Physics

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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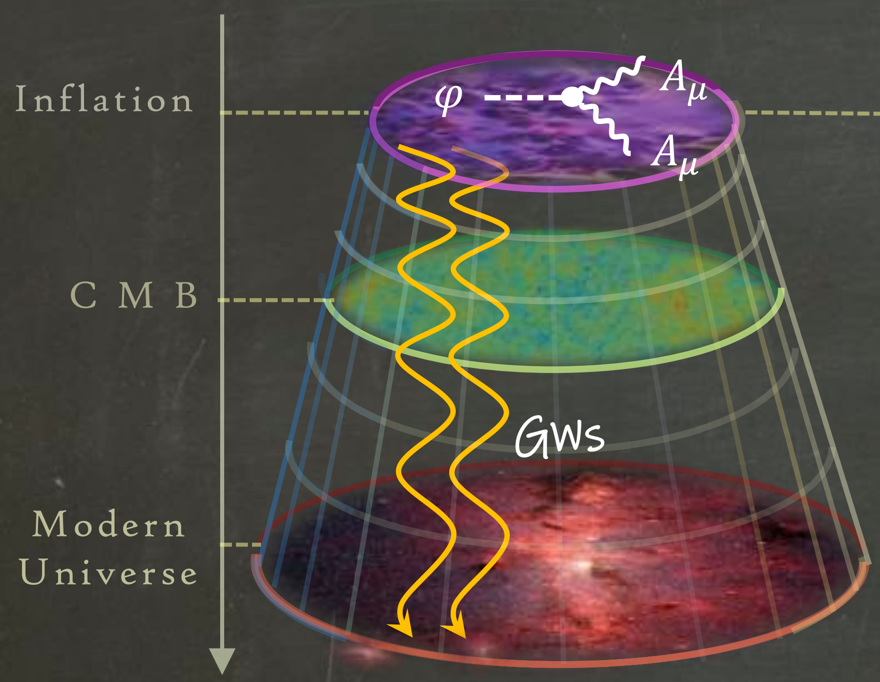
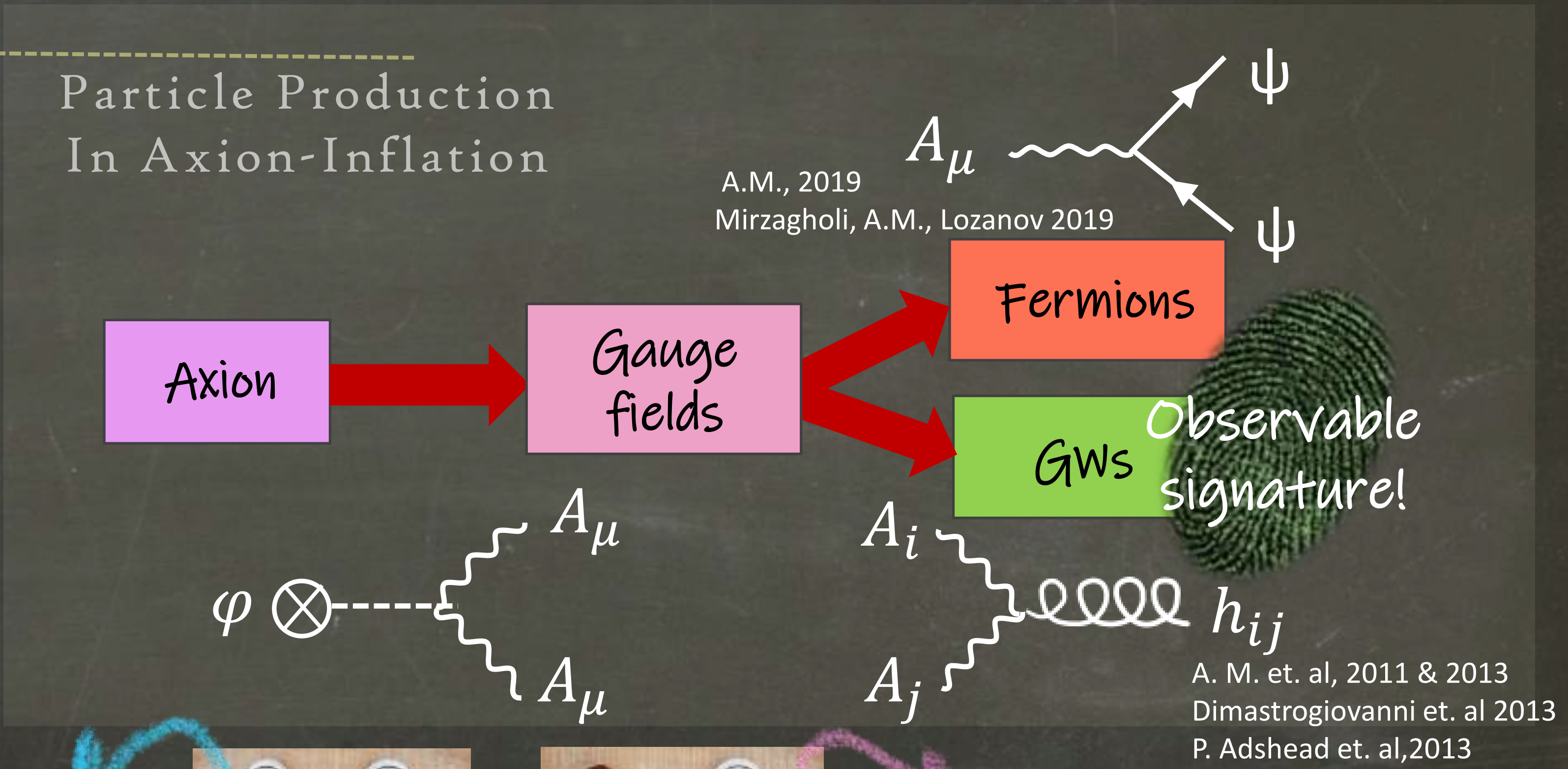




Vacuum GWs:
Unpolarized & Gaussian

Sourced GWs:
Chiral & non-Gaussian

New Tensorial mode in SU(2) Gauge Field

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

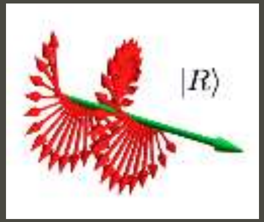
$$B_\pm'' + [k^2 \mp \delta_C k\mathcal{H} + \frac{m^2}{H^2}\mathcal{H}^2 - \frac{a''}{a}]\,B_\pm \approx 0$$

effective frequency

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

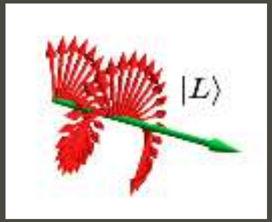
Circular polarizations

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

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

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

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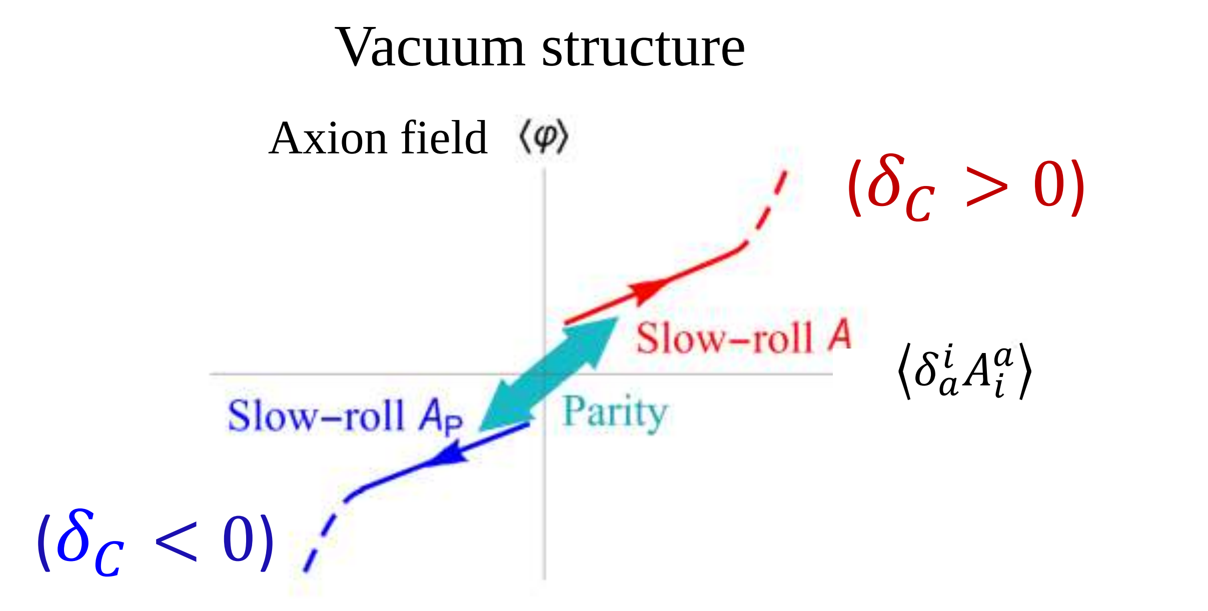

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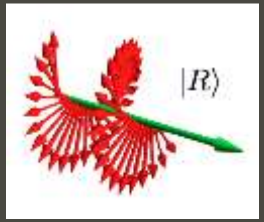

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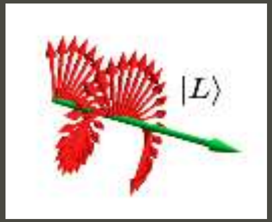

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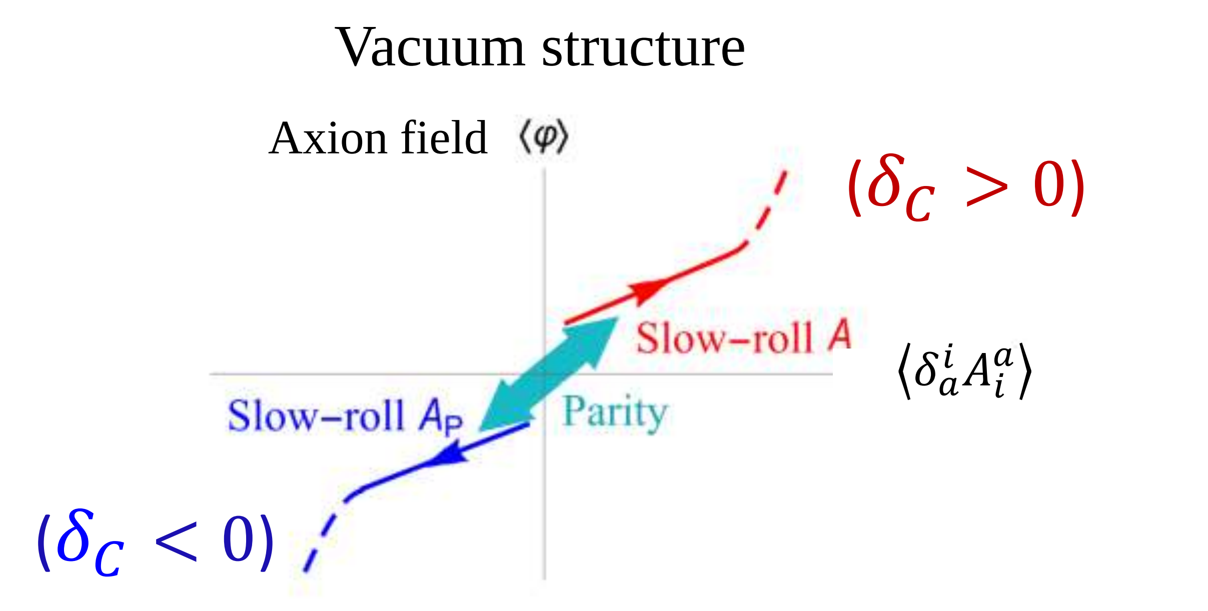
$$B_\pm'' + \underbrace{\left[k^2 \mp \delta_C k\mathcal{H} + \frac{m^2}{H^2}\mathcal{H}^2 - \frac{a''}{a}\right]}_{\text{effective frequency}} B_\pm \approx 0$$

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



For $\delta_C > 0$

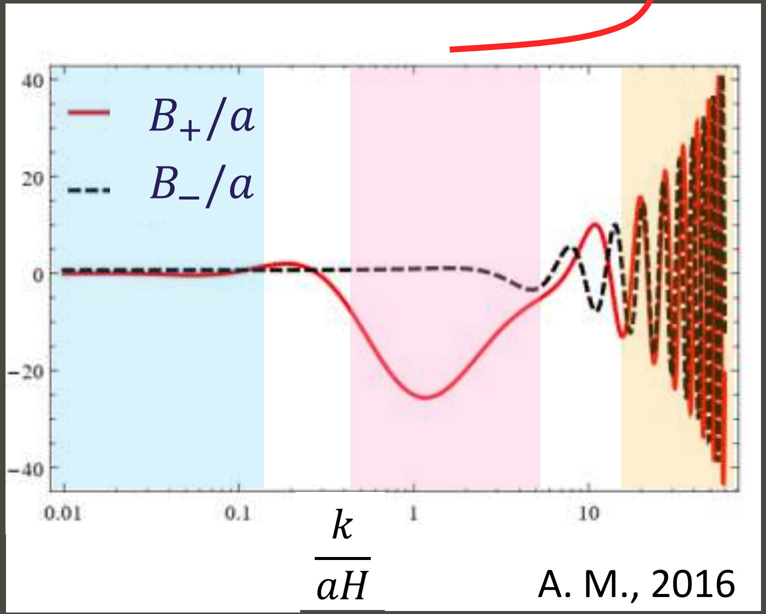
Short tachyonic growth of B_+

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

Chiral Field

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

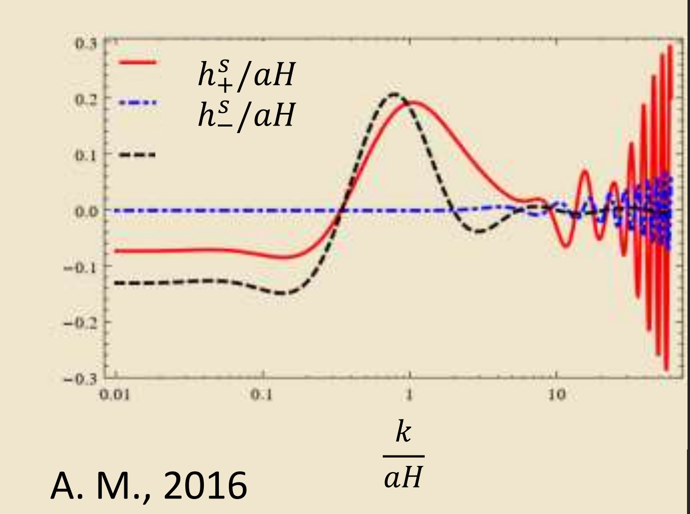
$$h_\pm'' + [k^2 - \frac{a''}{a}]\,h_\pm = \mathcal{H}^2\,\Pi_\pm[B_\pm]$$

- 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

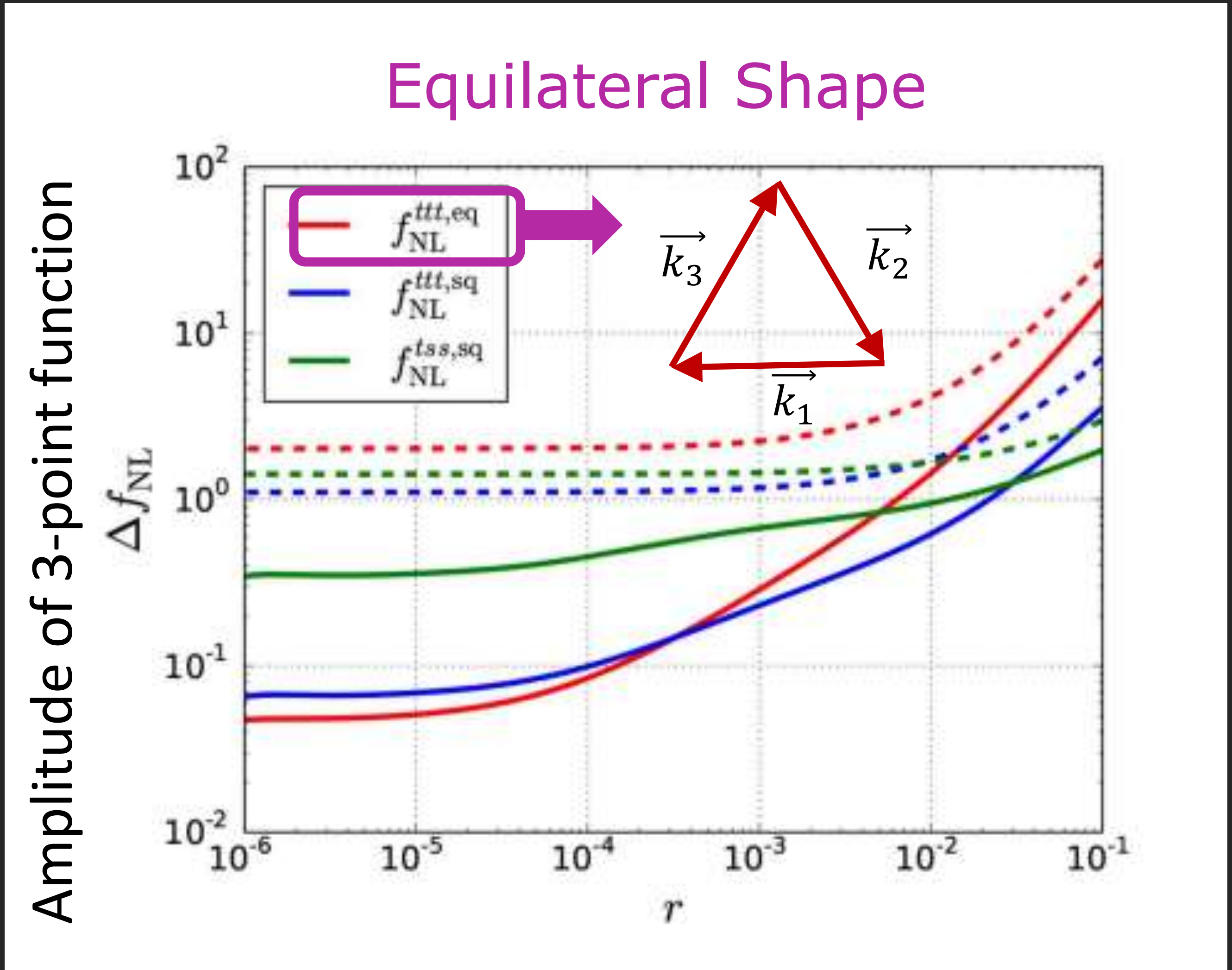
- The sourced tensor modes is Highly non-Gaussian.

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

Self-interaction

Agrawal, Fujita, Komatsu 2018

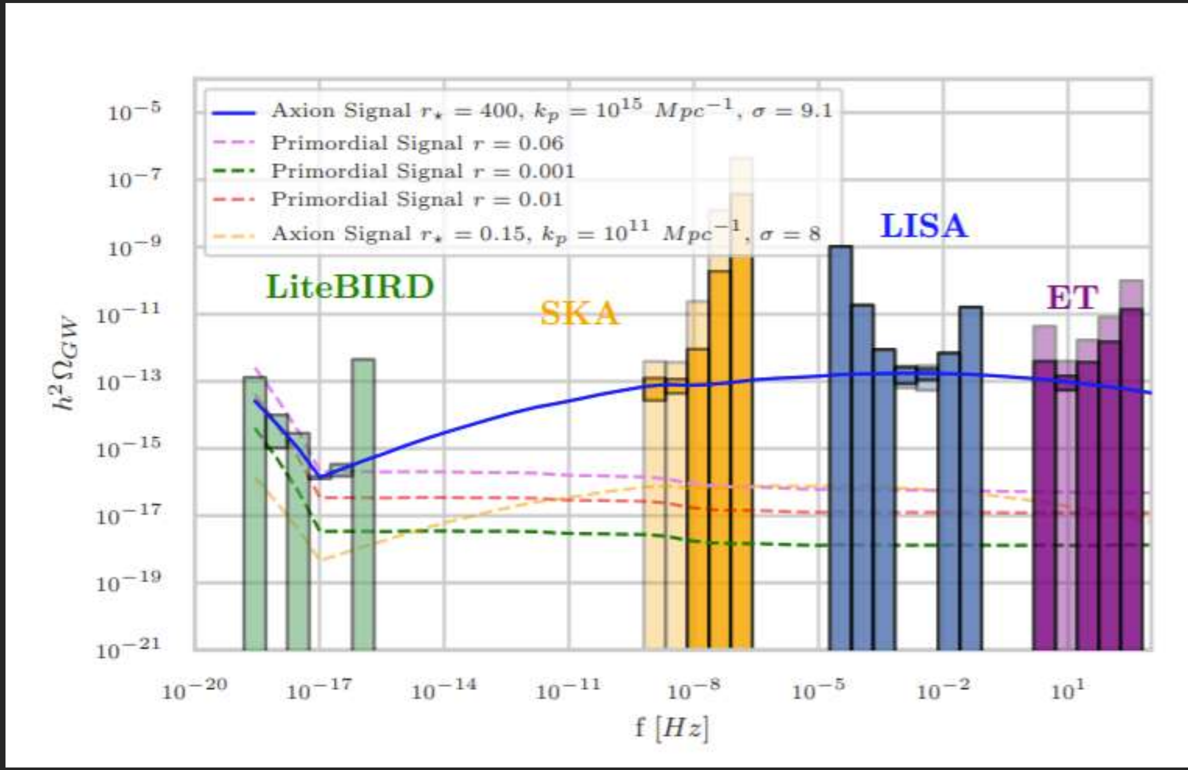
- That can be probe with future CMB missions., e.g. *Litebird* and *CMB-S4*!

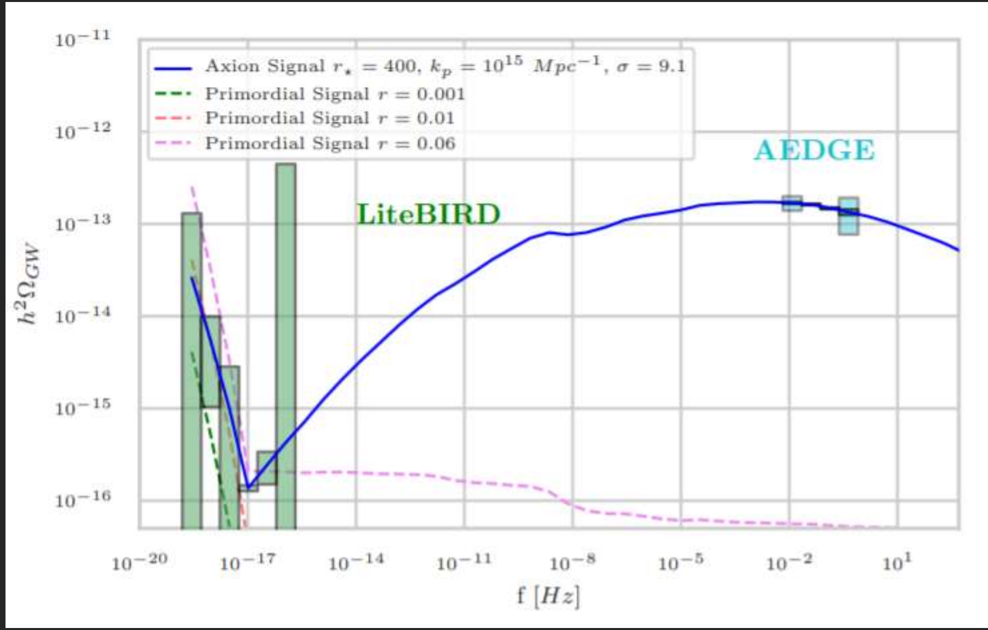


Maresuke Shiraishi, Front. Astron. Space Sci. 2019

Novel Observable Signature: Beyond CMB

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



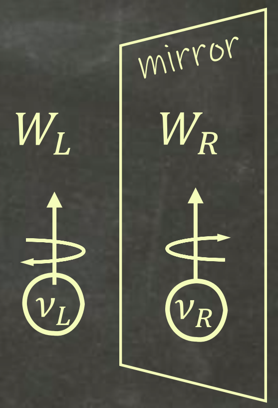


P. Campeti, E. Komatsu, D. Poletti, C. Baccigalupi 2020

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

(How to Connect Inflaton to SM?)

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



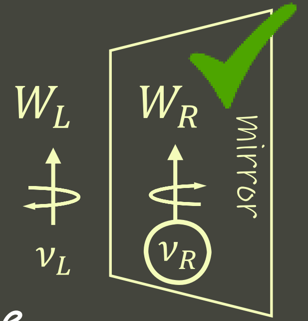
How to Connect it to the SM?

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

- Left-Right Symmetric Model + axion!

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

Left-Right Symmetric — SM Left-handed Weak force



- Minimal Scenario of SU(2)-axion inflation **A. M.**, 2016 f<0.1 Mpl & λ<0.1

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

Axion Monodromy or any mechanism that gives a flat potential

Gauge field is $SU(2)_R$

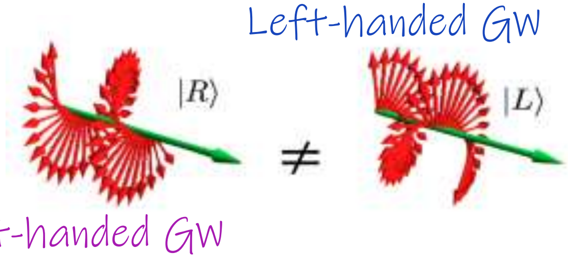
A. M. arXiv: 2012.11516

A.M. arXiv:2103.14611

Gravitational Leptogenesis: $\langle R\tilde{R}\rangle \neq 0!$

What makes Chiral Gravitational Waves?

To generate circularly polarized GWs, we need Parity violation in inflation.
Two possible models are



1) Chern-Simons Gravity $\mathcal{L}_{eff} = \frac{1}{\Lambda}\varphi R\tilde{R}$

Alexander, Peskin, Sheikh-Jabbari 2006

2) Non-Abelian Gauge fields in axion-inflation $\mathcal{L}_{eff} = \frac{1}{\Lambda}\varphi F\tilde{F}$ (Chiral Gauge Field ⟶ Chiral GWs)

A.M., Noorbala, Sheikh-Jabbari 2012
A.M. 2014 & 2016
Caldwell, Devulder 2017
Adshead, Long, Sfakianakis 2017
Alexander, McDonough, Spergel 2018
Kamada, Kume, Yamada, Yokoyama 2019

Axion-inflation is a generic setting for leptogenesis
(All the Sakharov conditions are satisfied)
A.M. 2014

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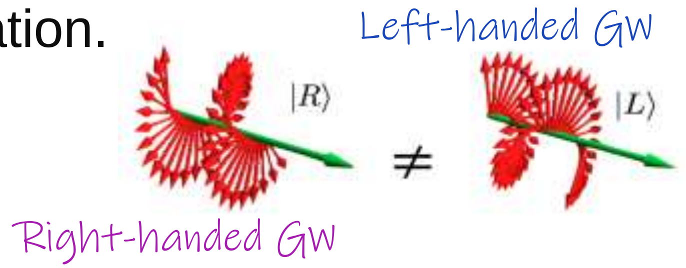

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A.M. 2014

~~3) U(1) Gauge fields in axion-inflation~~

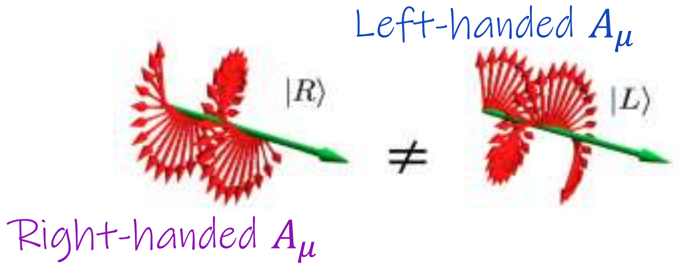
Papageorgiou, Peloso 2017

Matter Asymmetrey by Chiral Anomaly: $\langle F\tilde{F}\rangle \neq 0!$

Axion-inflation is a generic setting for lepto/Baryogenesis
(All the Sakharov conditions are satisfied)

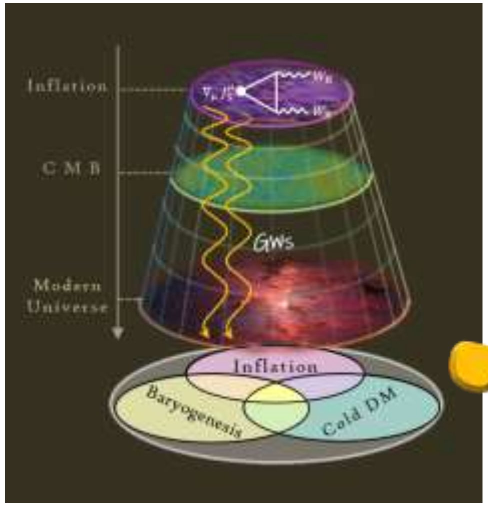
1) U(1) Gauge fields in axion-inflation

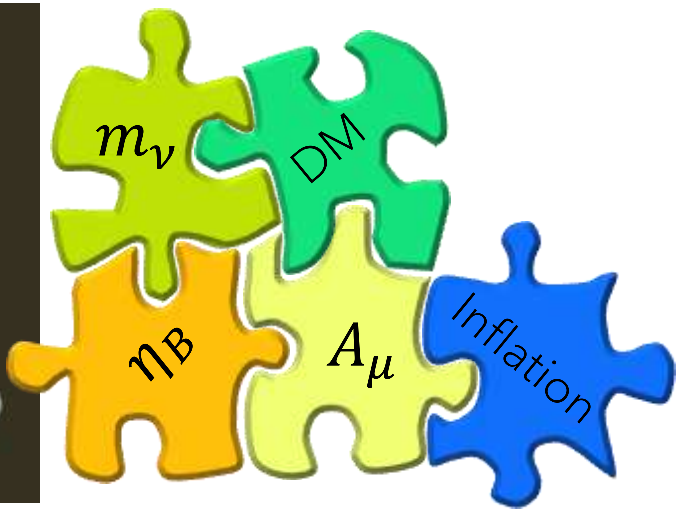
Domcke, Harling, Morgante, Mukaida 2019
Domcke, Kamada, Mukaida, Schmitz, Yamada 2020



2) Non-Abelian Gauge fields in axion-inflation

A.M. 2019
A.M. 2020, 2021

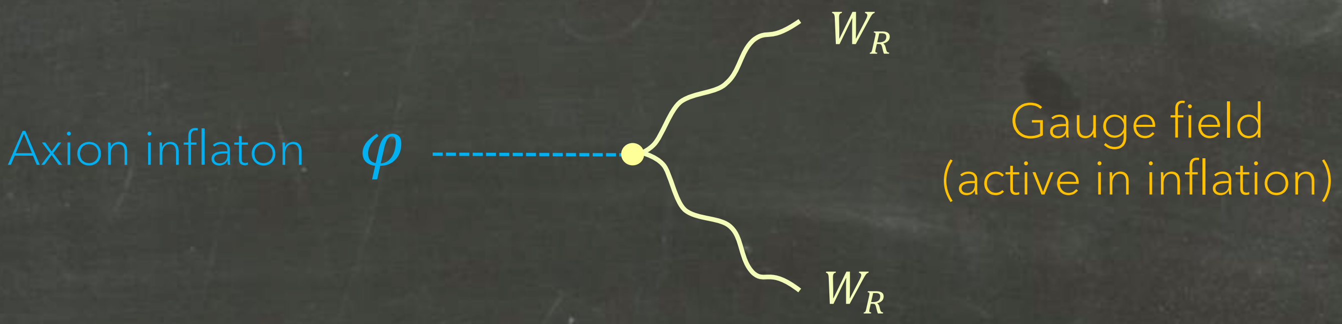




Gauge field Production in Inflation

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 $SU(2)_R$:



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

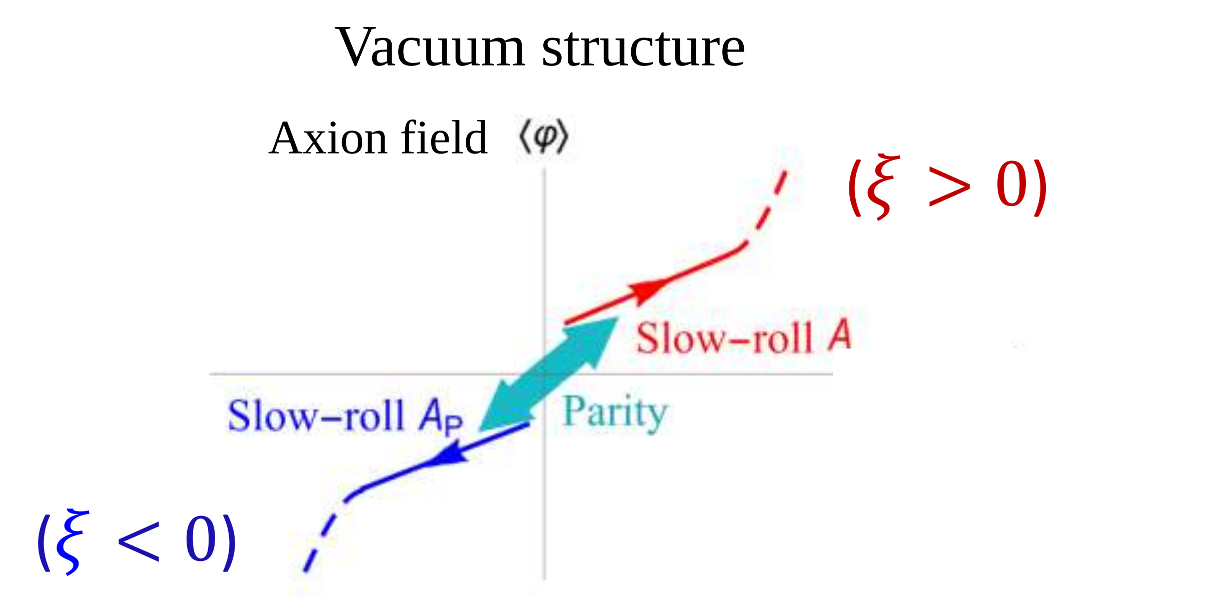
$SU(2)_R$ Gauge Field

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

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

effective frequency

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



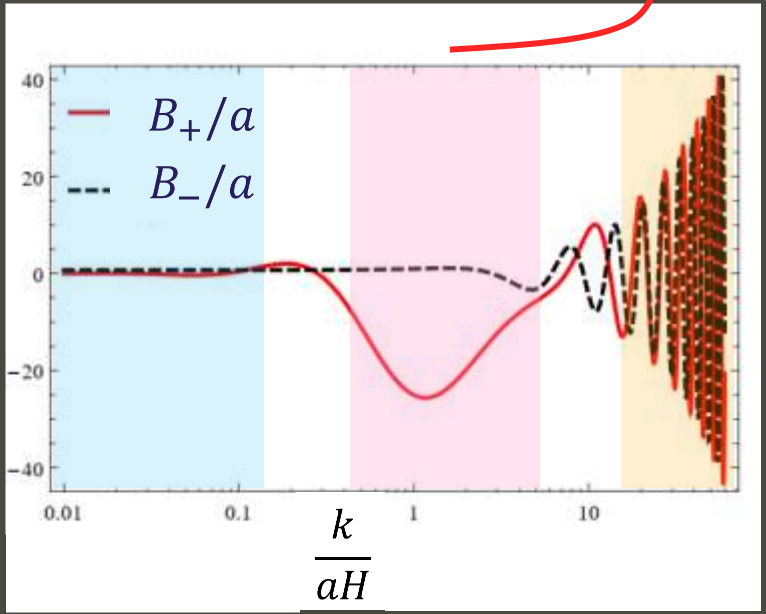
For $\xi > 0$

Short tachyonic growth of B_+

Chiral Field

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

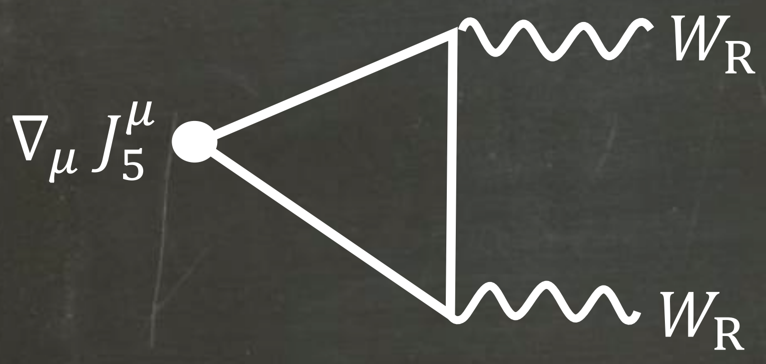
Particle Production



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:

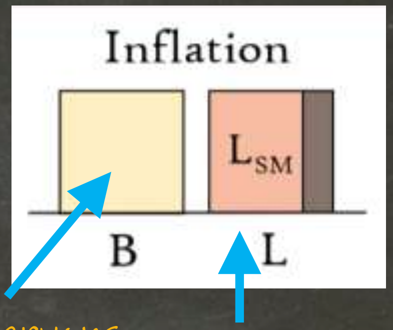
The key ingredient is the Chiral anomaly of $\mathrm{SU(2)_R}$ in inflation:



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

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

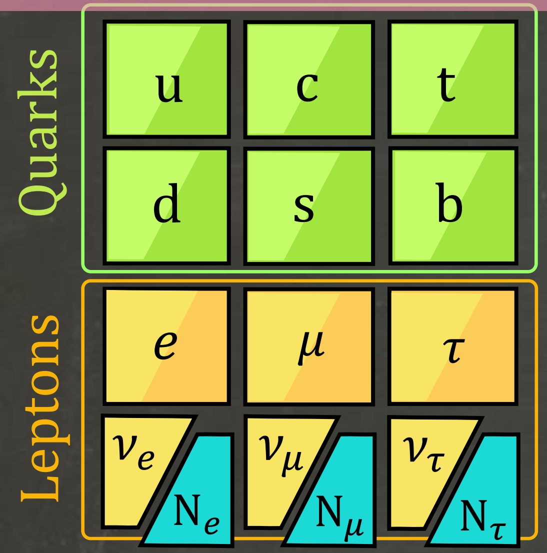
$$\alpha_{inf}(\xi) \sim \frac{g^2}{(2\pi)^4} \mathrm{e}^{2\pi\xi}$$

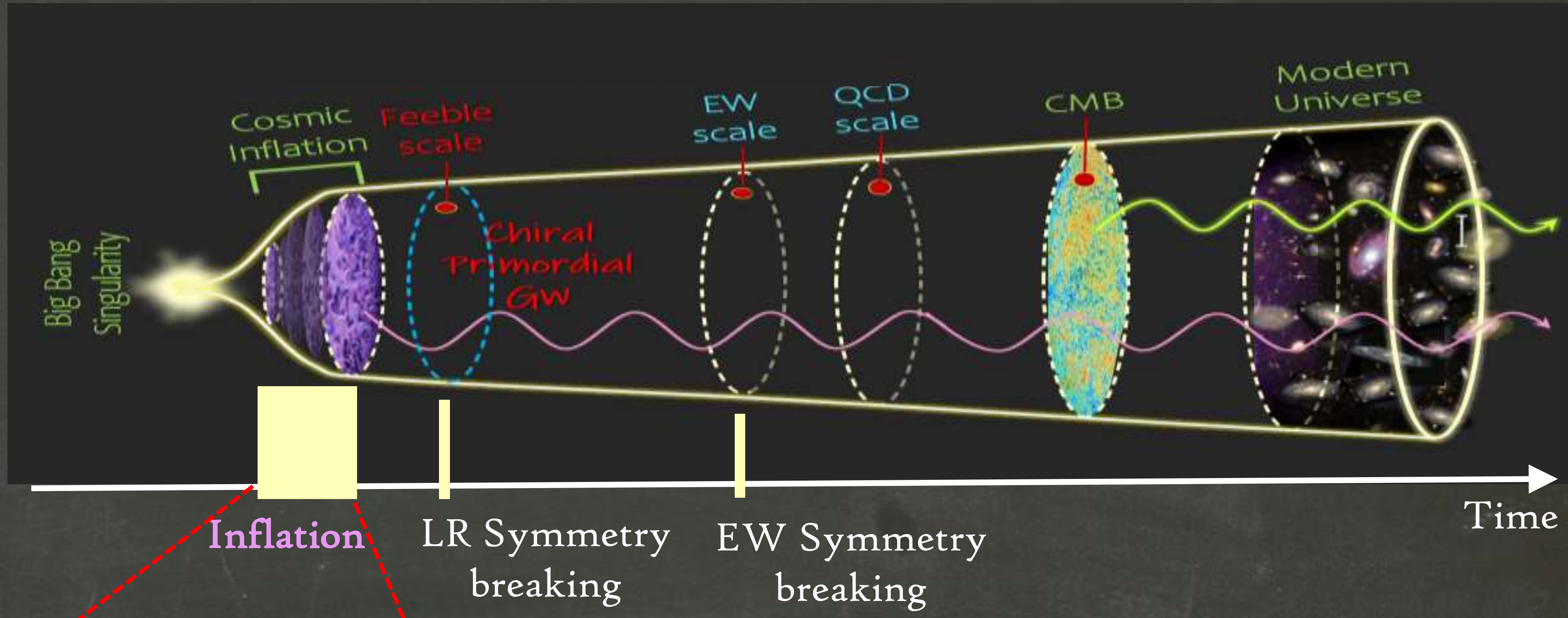


SM baryons

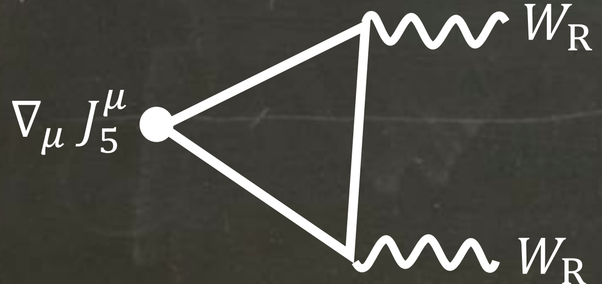
SM leptons
+
RH neutrinos

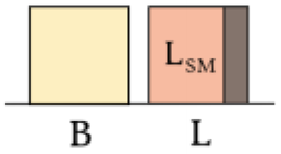
Summary of the mechanism:





Chiral anomaly of SU(2)R
In inflation





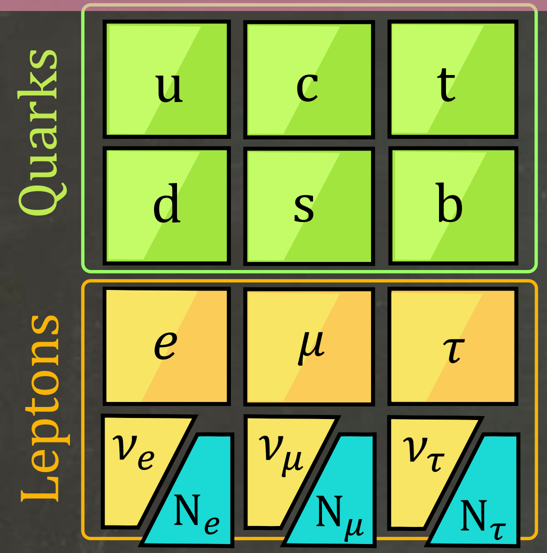
$B = L = 3n_{CS}$

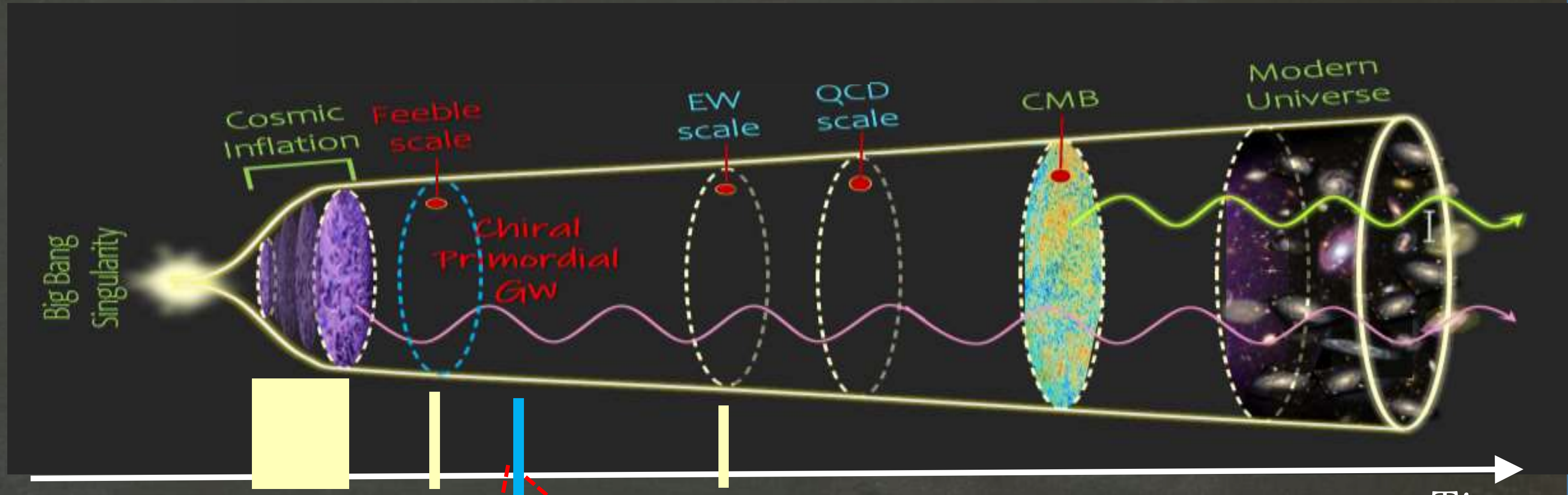
$B - L_{SM} \neq 0$

B= SM baryons

L= SM leptons + RH neutrinos

Summary of the mechanism:





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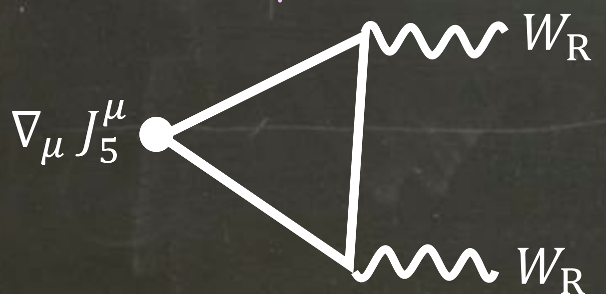

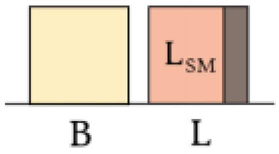

$B = L = 3n_{CS}$

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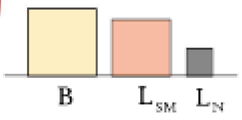
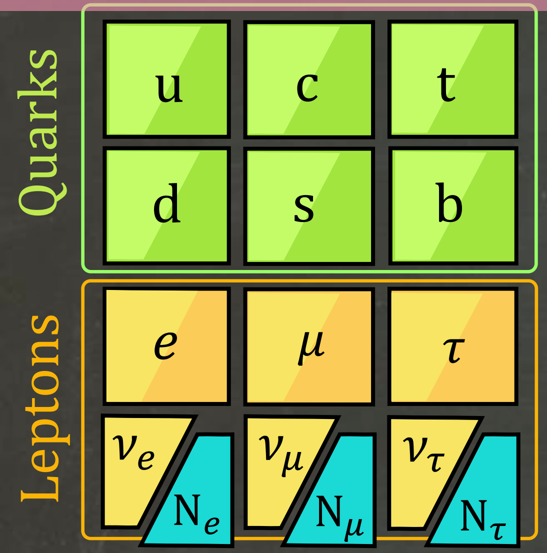
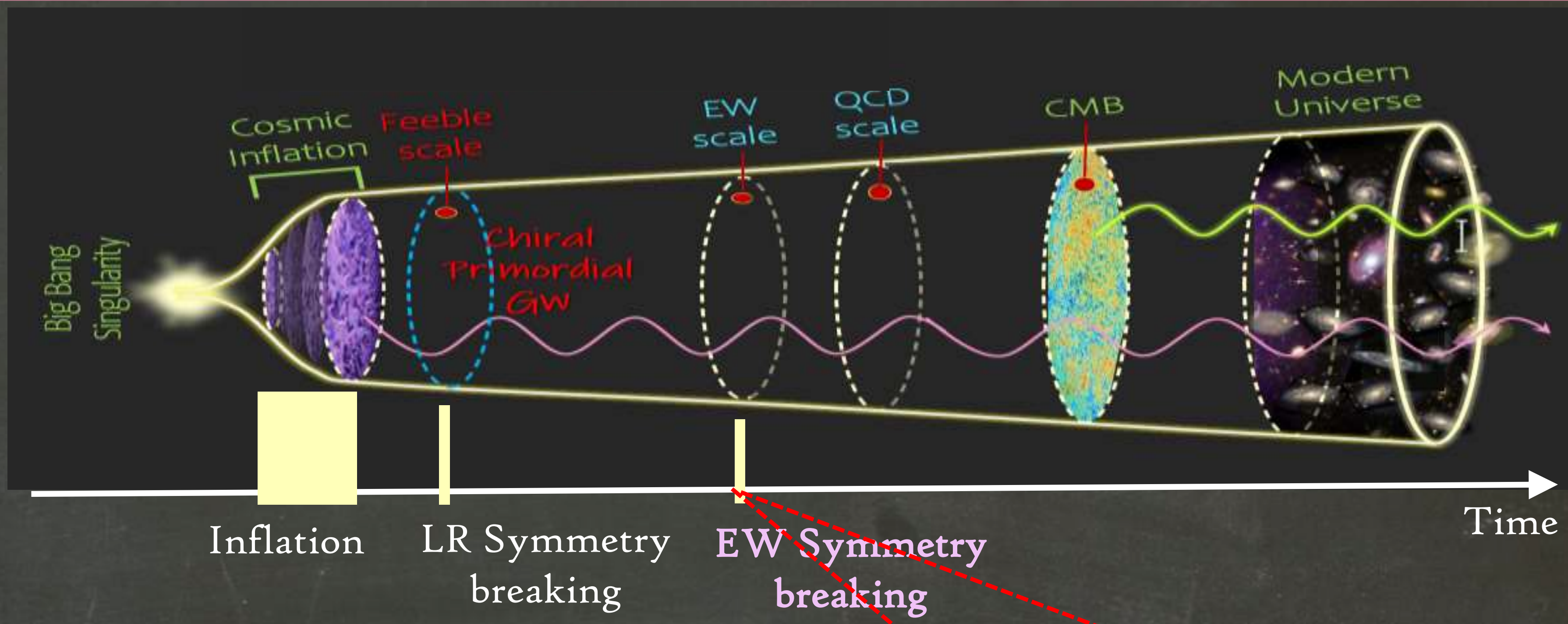
→



Freezeout of W_R

Summary of the mechanism:





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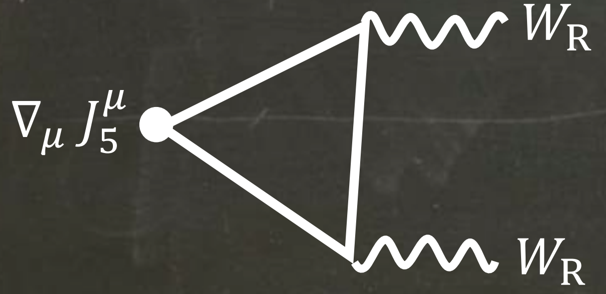

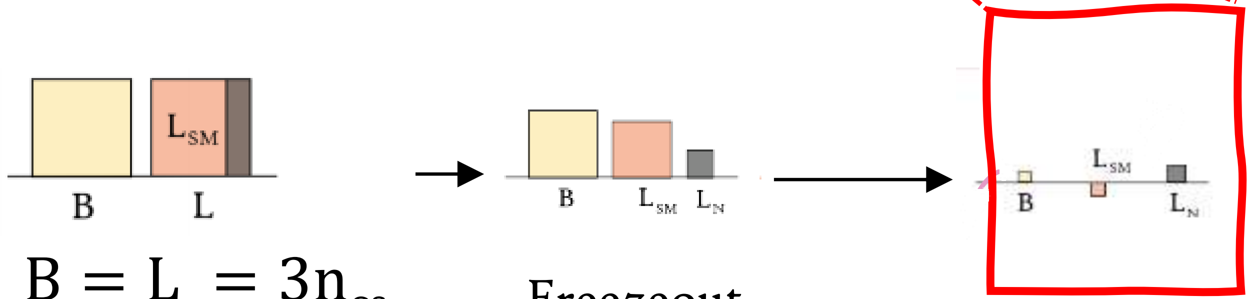

$B = L = 3n_{CS}$

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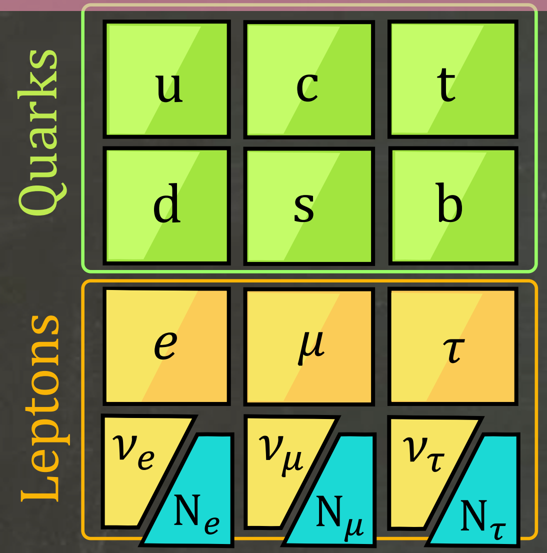
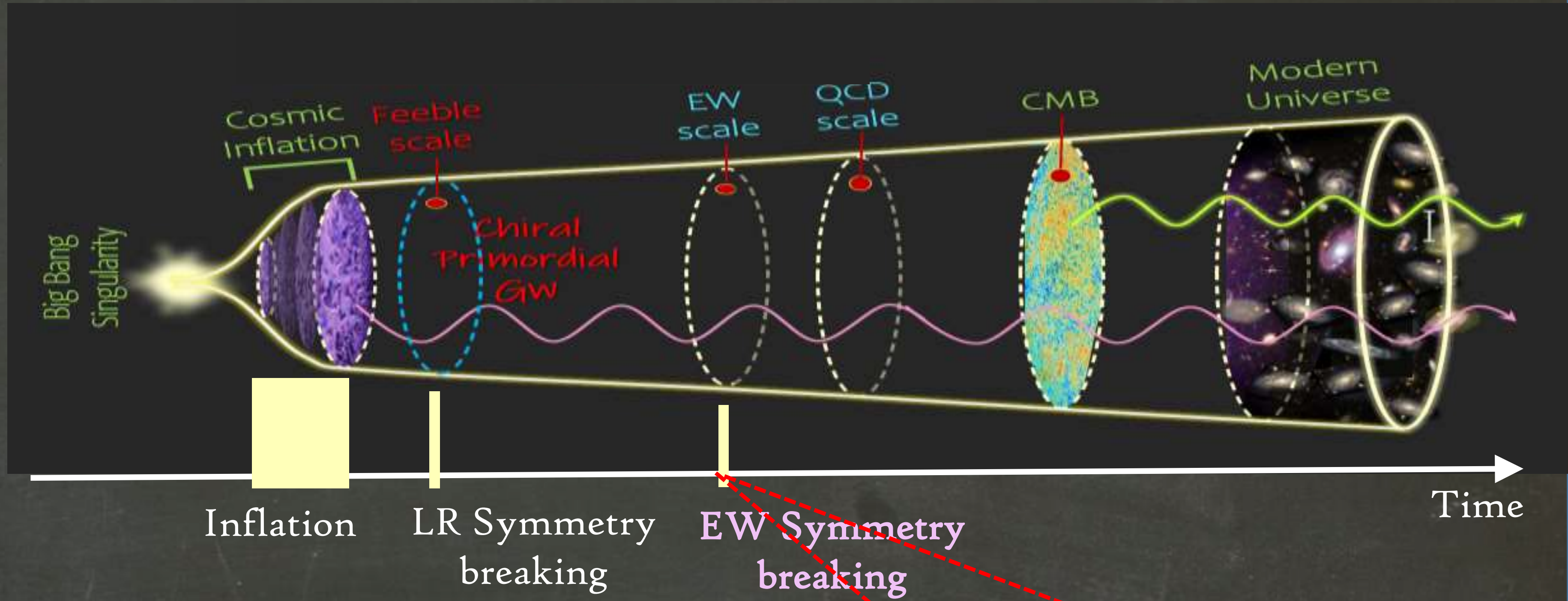
Freezeout of W_R

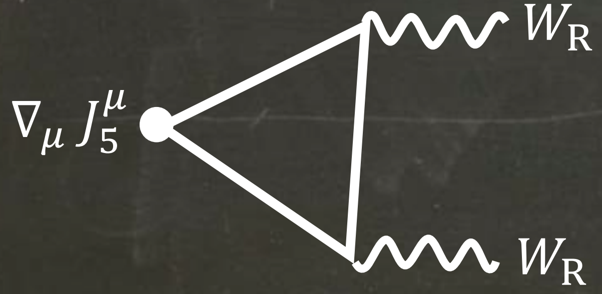
Spectator effects reshuffle B, L_{SM} & L_N

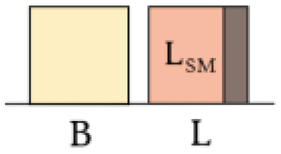
Summary of the mechanism:





Chiral anomaly of SU(2)R
In inflation





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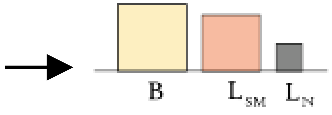

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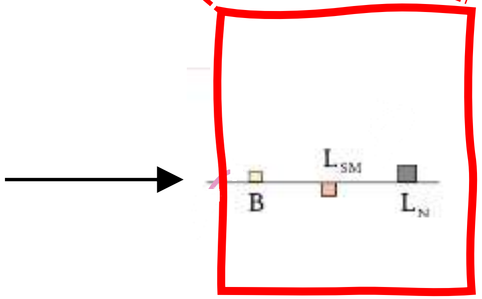

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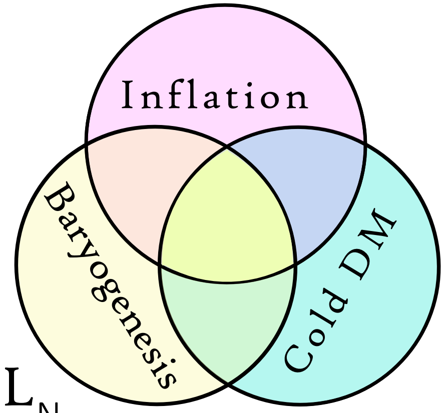

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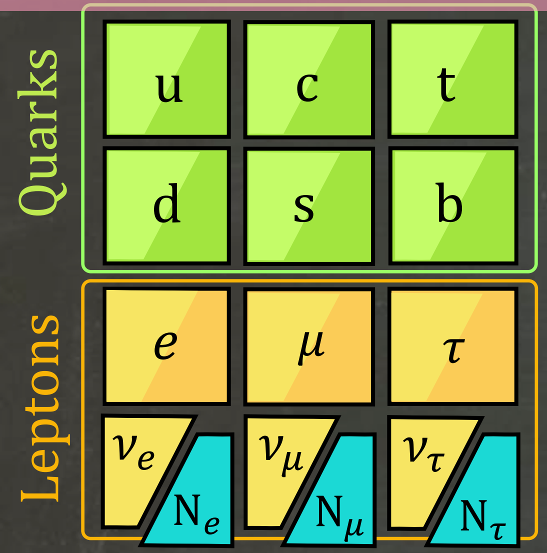

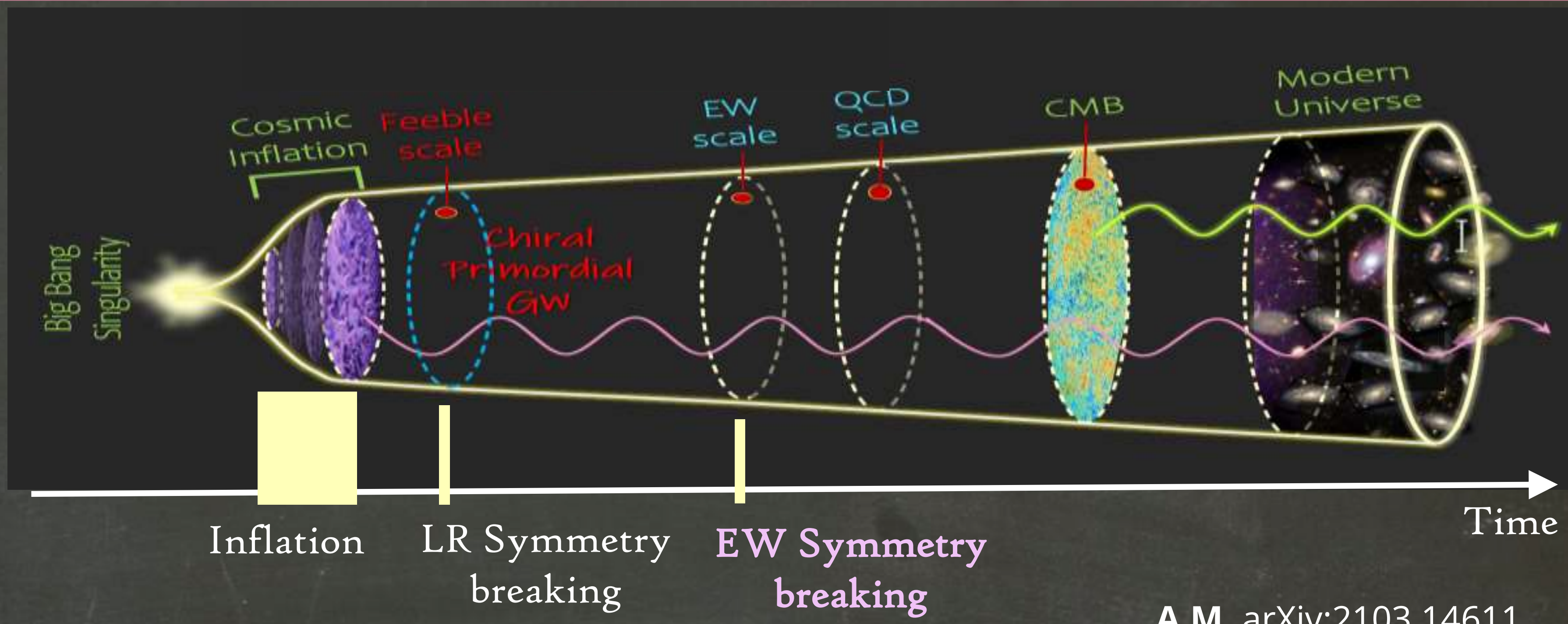

A.M. arXiv:2103.14611

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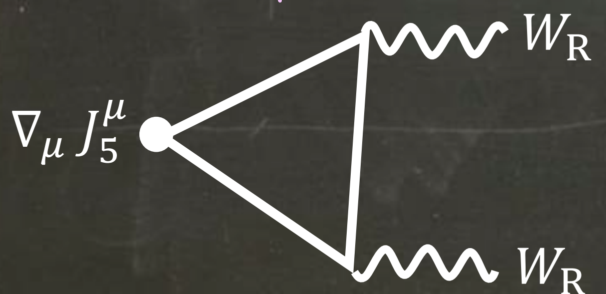

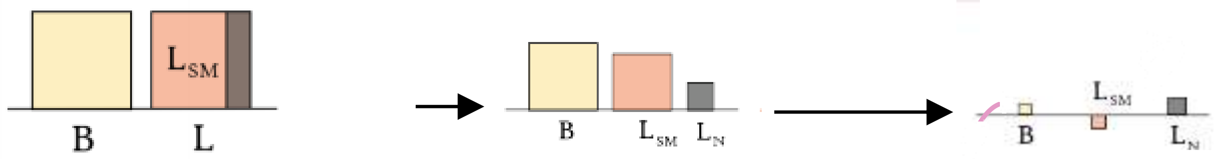

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Freezeout of W_R

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

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

Summary & Conclusions

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

Compelling Consequences:

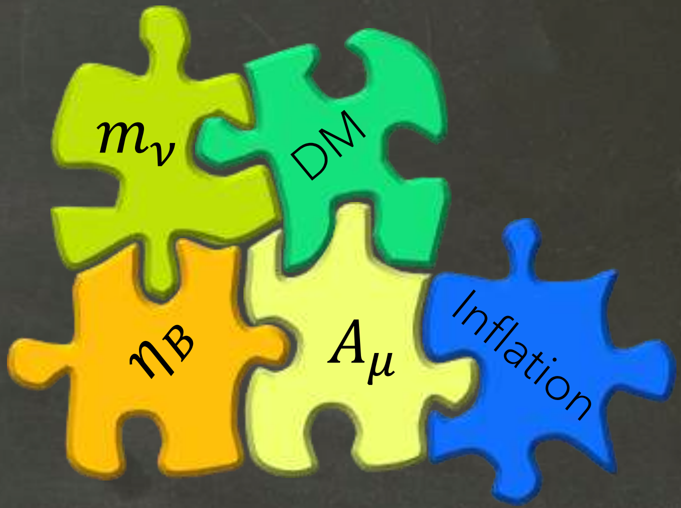
This Set-up is a complete BSM that can solve I-IV:

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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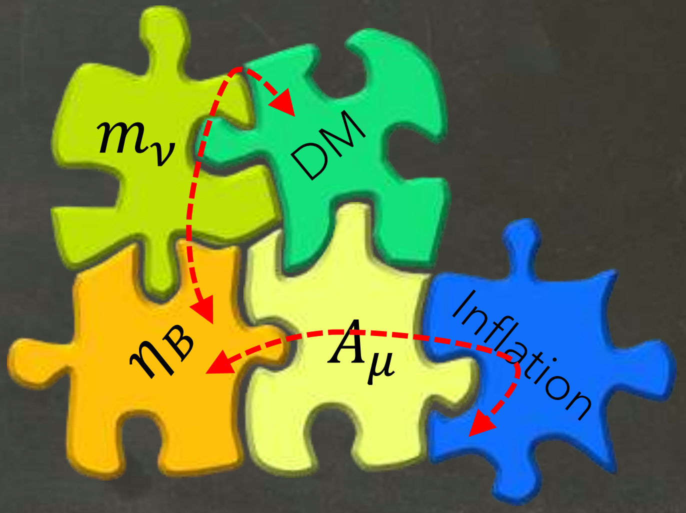
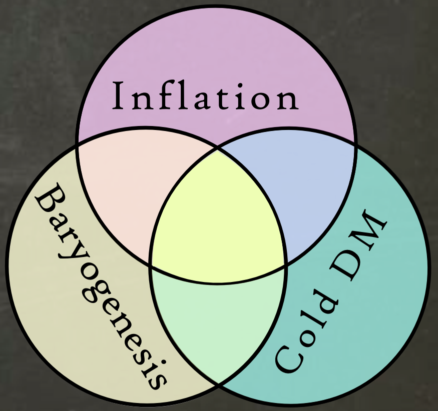
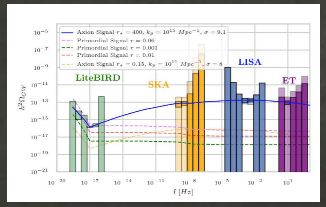


It provides a deep connection between inflation, baryogenesis & DM



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

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Swansea University
Prifysgol Abertawe