A New Paradigm for Particle Cosmology

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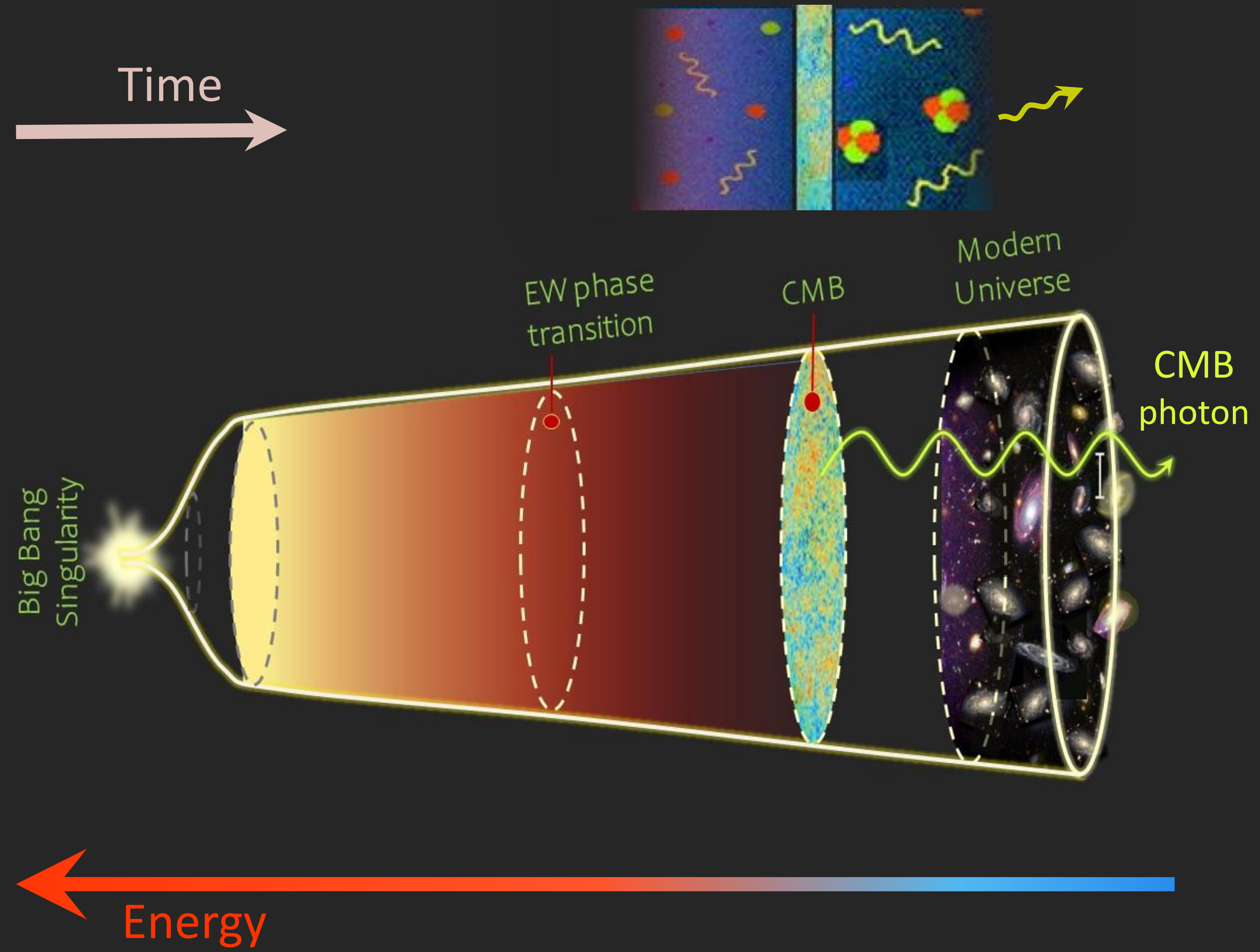
Virtual HET @ Brookhaven National Lab

Background: Discover magazine

PART ONE Motivation & Big Picture

PART TWO All of the Exciting Details!

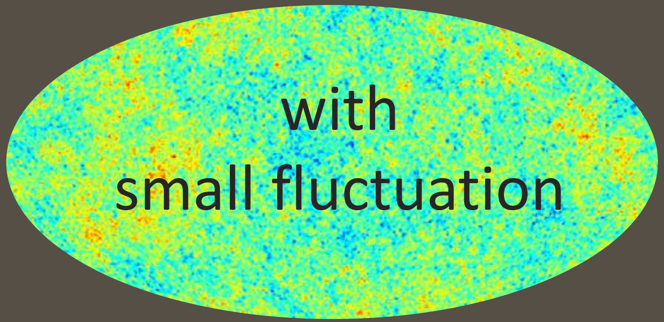
Cosmic History



Cosmic History

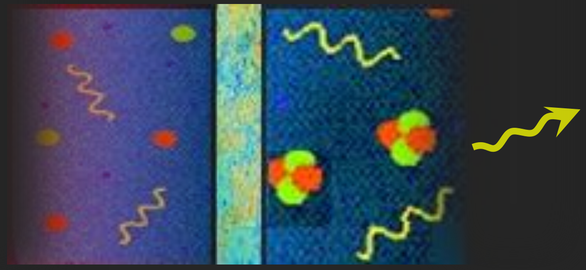
CMB is nearly homogenous & isotropic!

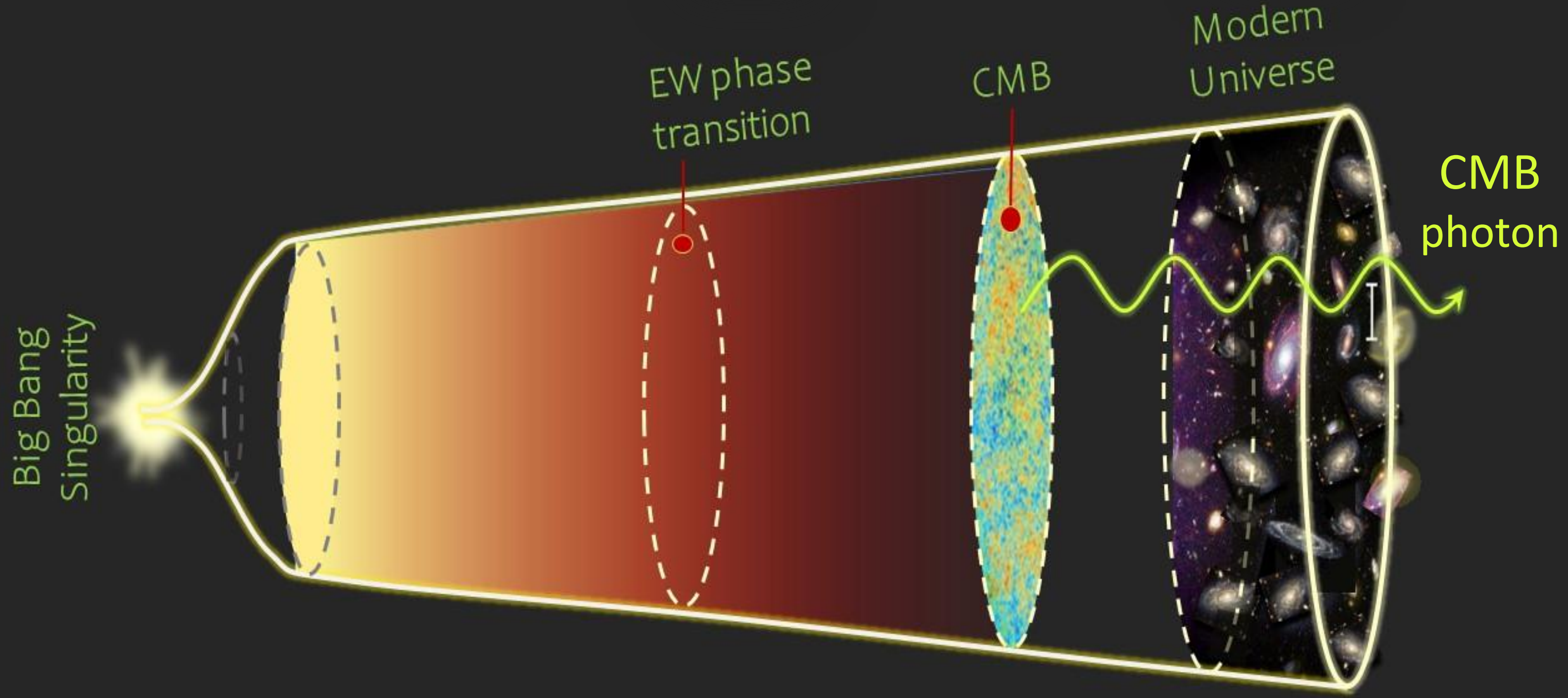
T_{CMB} =2.7 K



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

Time



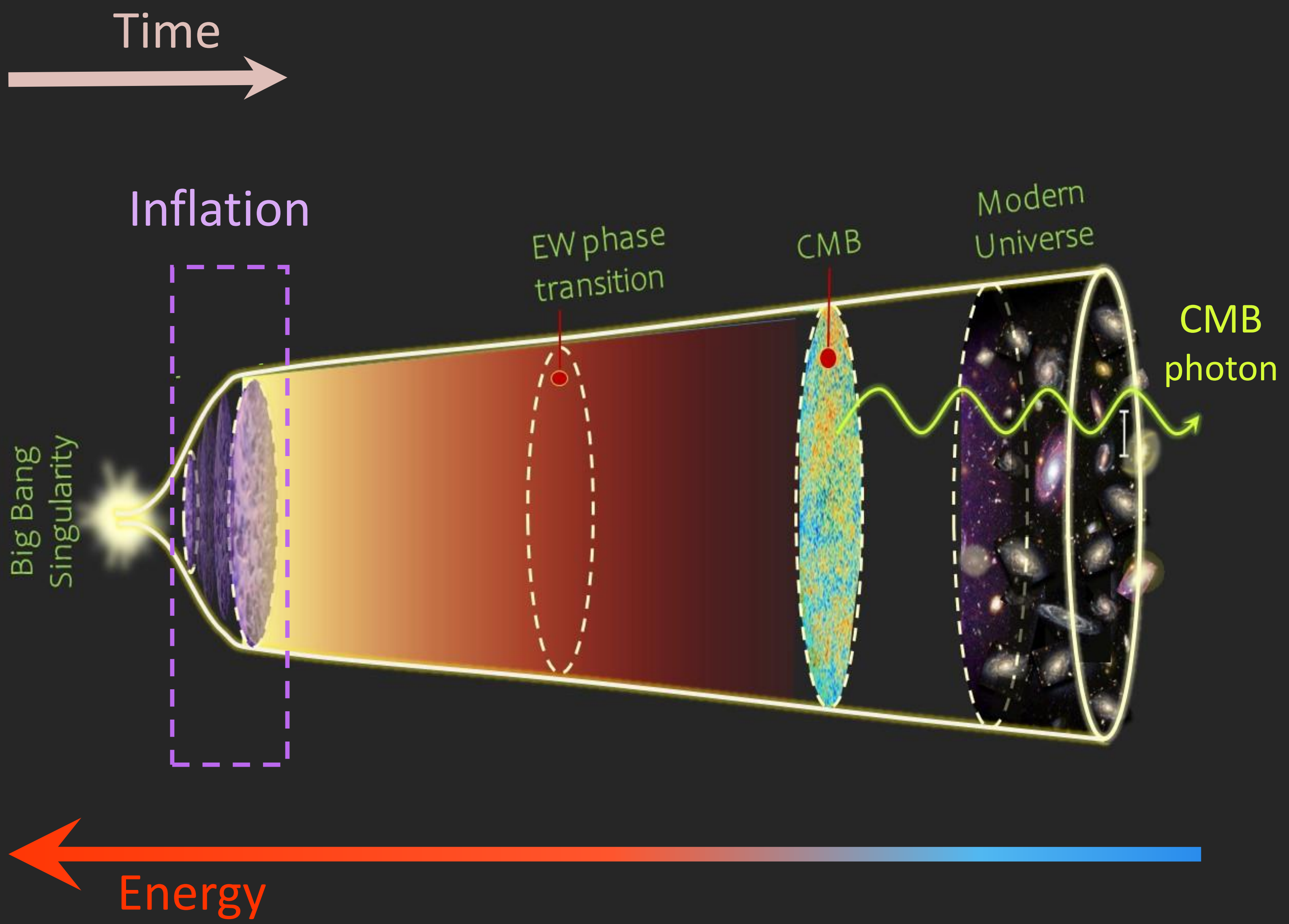


Energy

Cosmic Inflation

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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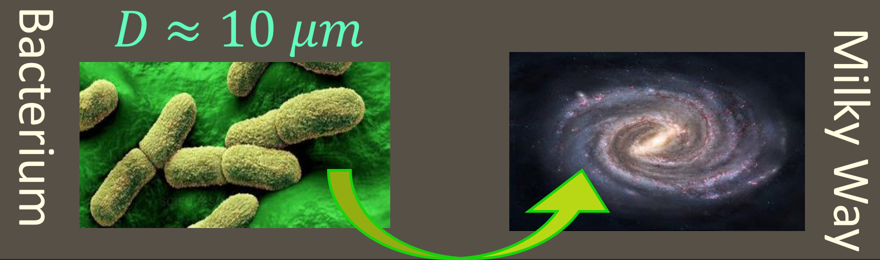
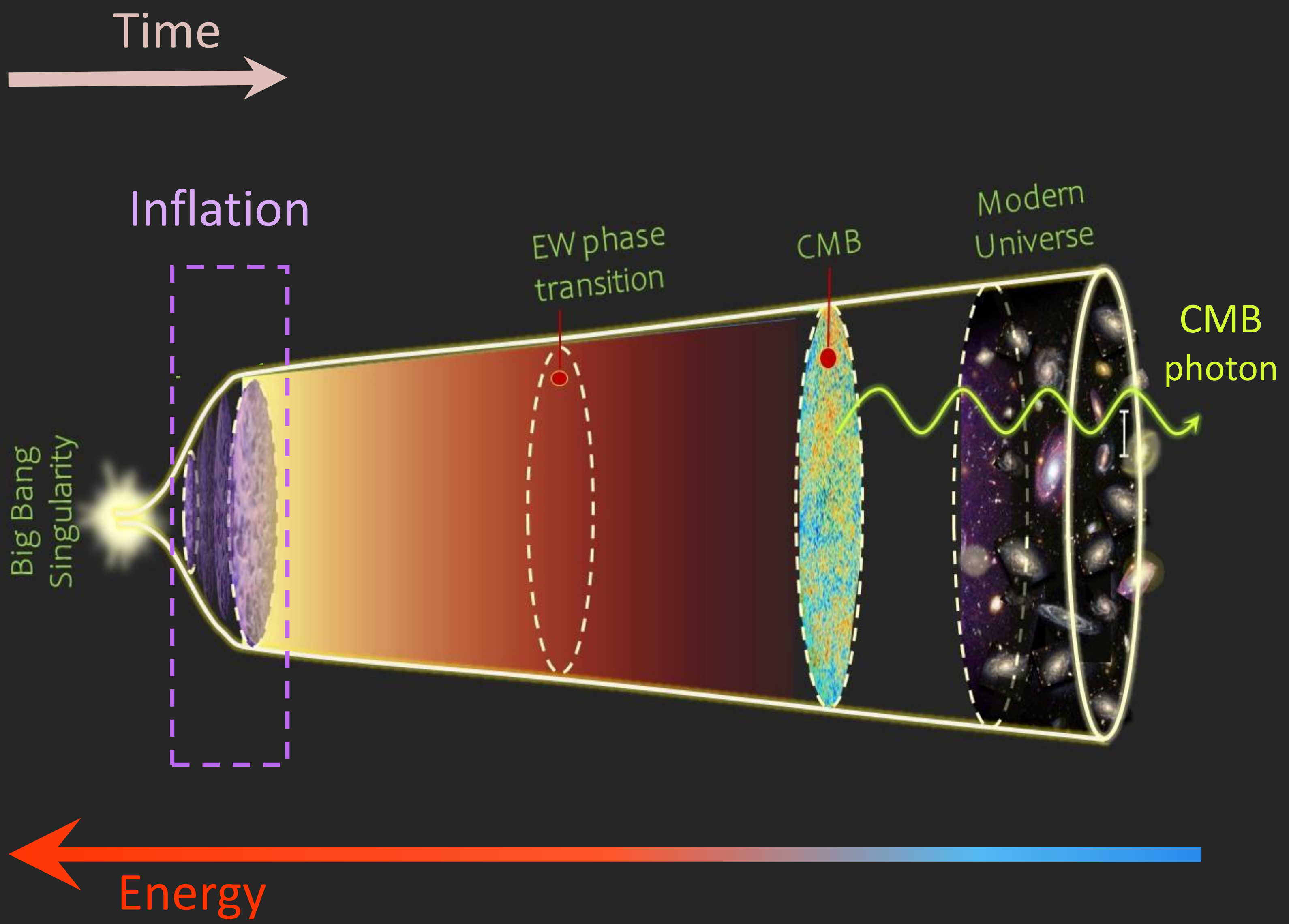
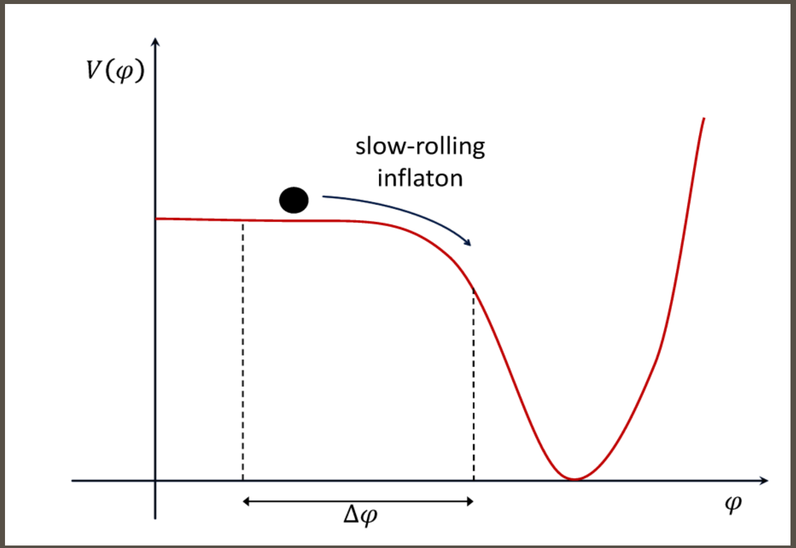


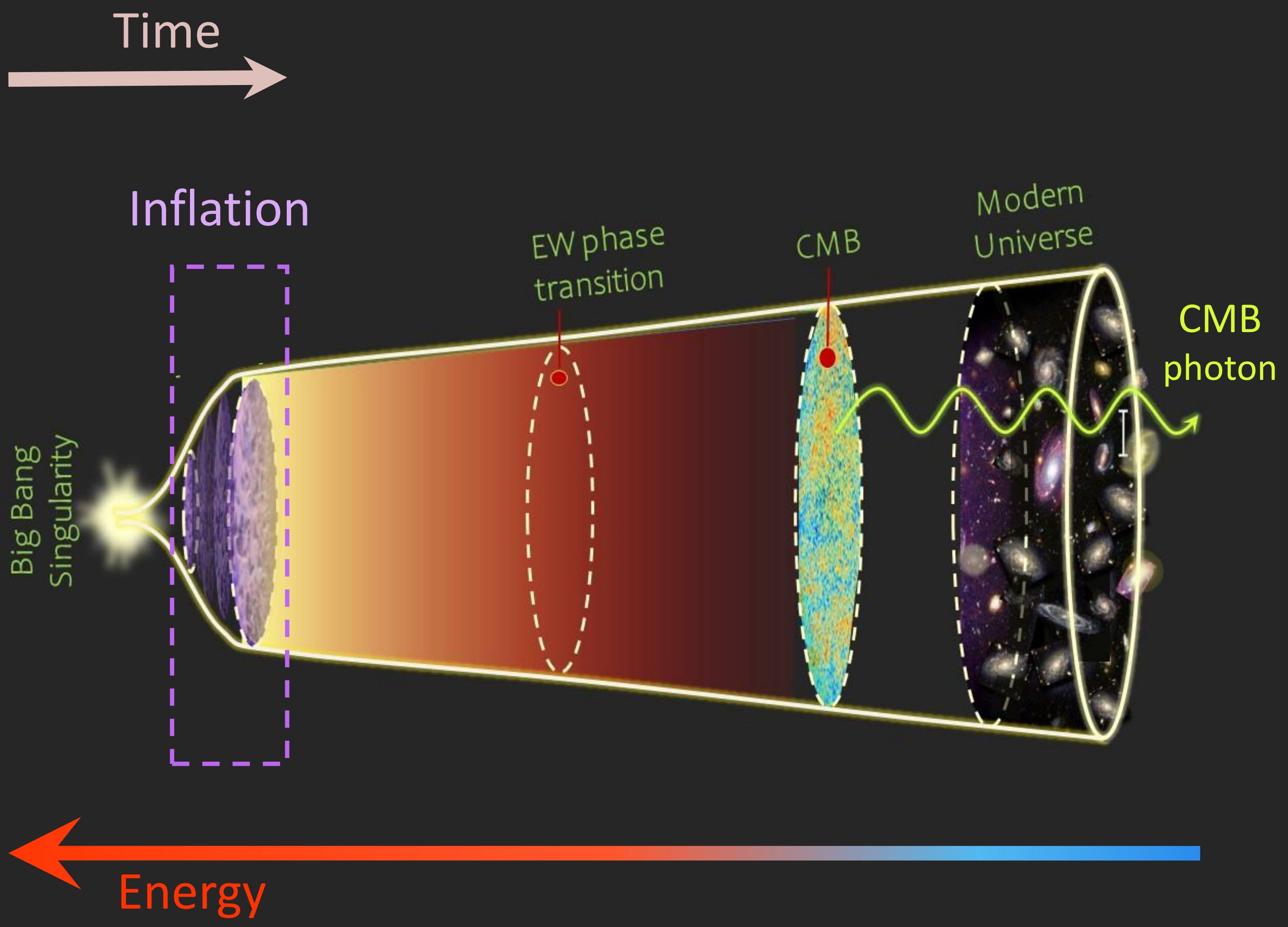


Cosmic Inflation

What caused inflation?

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





Quantum Vacuum

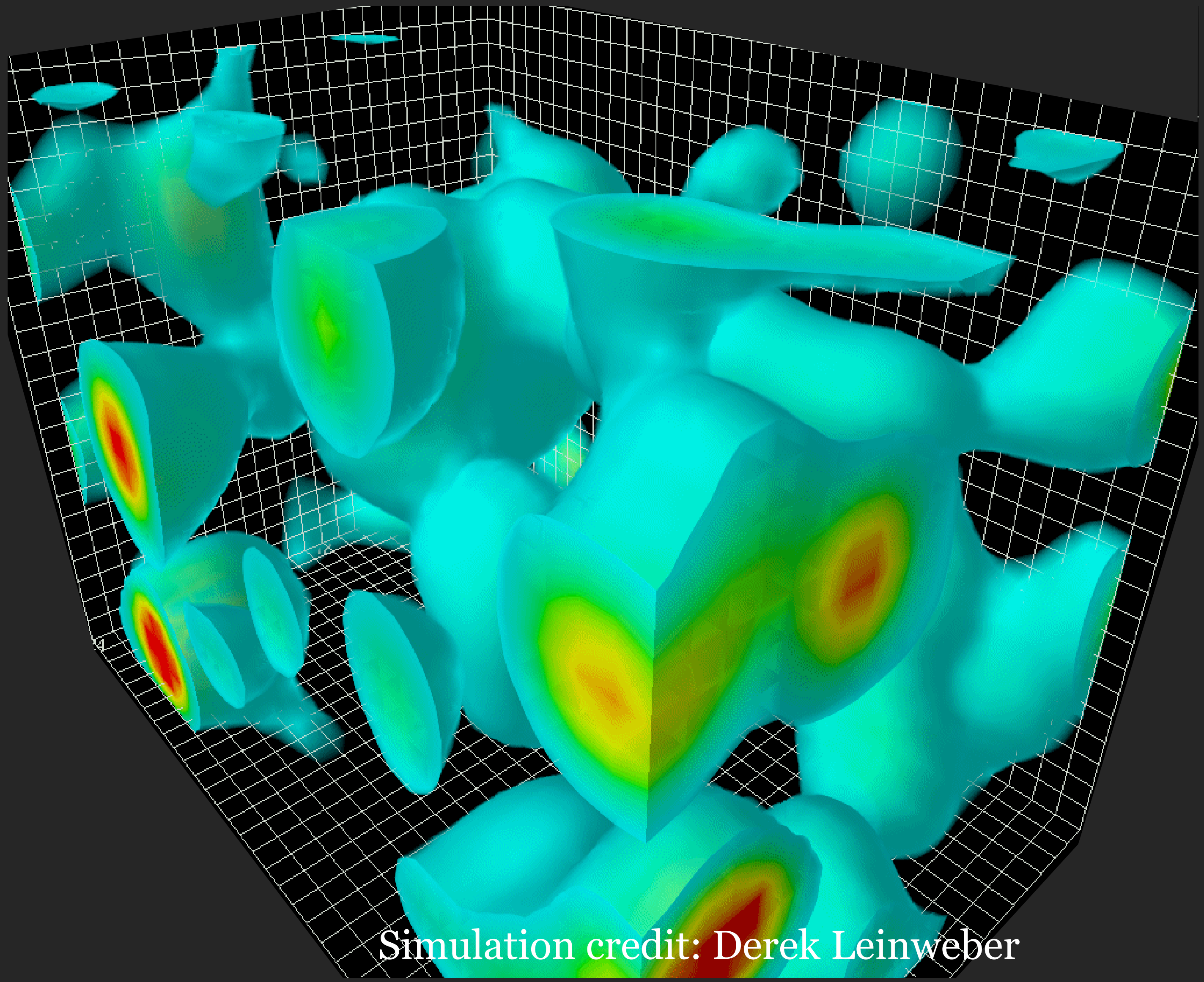
$\hbar \neq \mathbf{0}$

Due to Uncertainty Principle

$$\Delta x \, \Delta p \geq \hbar/_2$$

the quantum vacuum is

NOT nothing!



Quantum Vacuum

$$\hbar \neq \mathbf{0}$$

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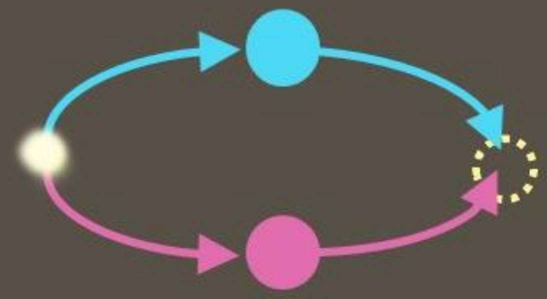
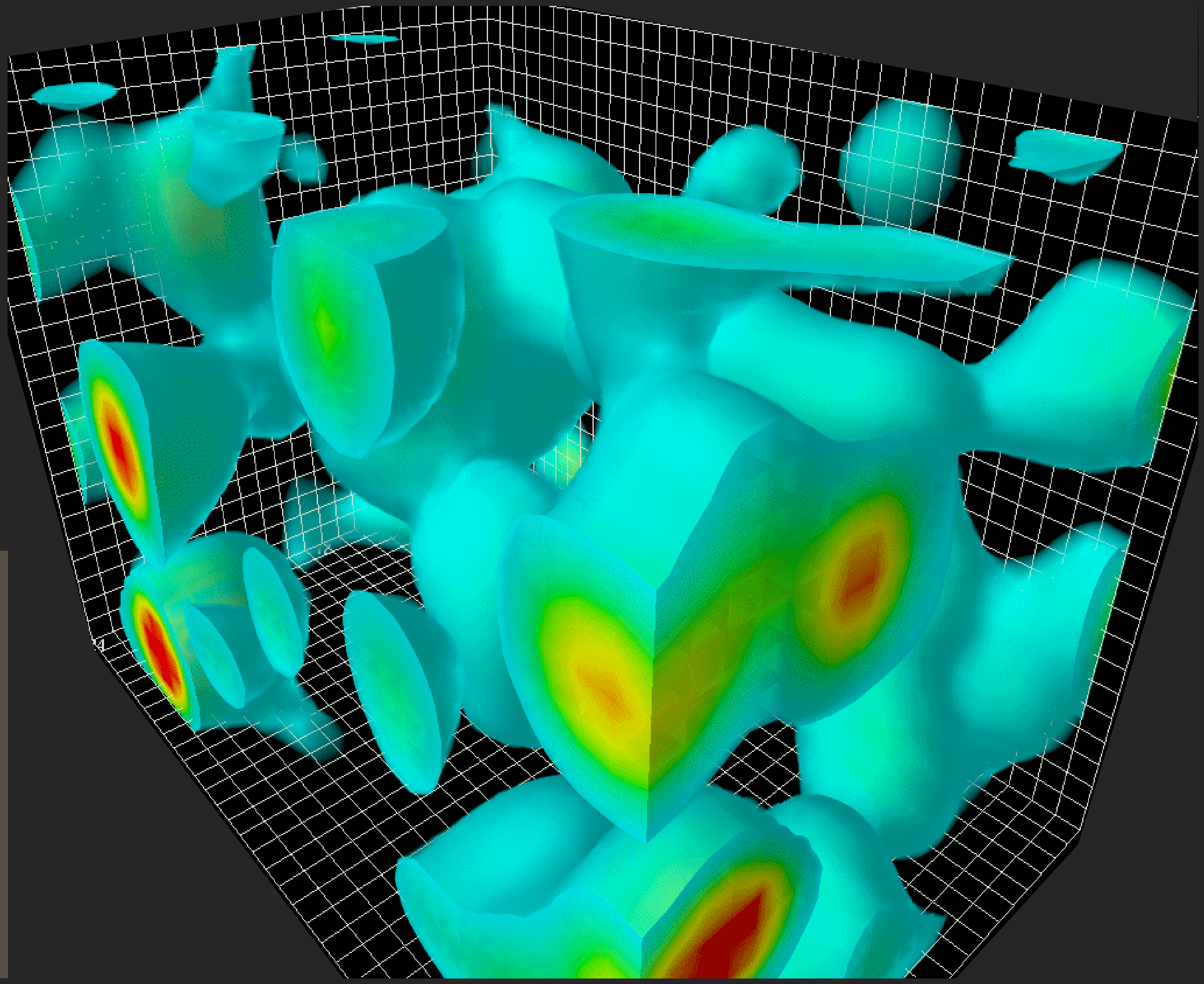
But, a vast ocean made of

Virtual particles





Quantum Vacuum → Particle Production

Due to Uncertainty Principle

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

the quantum vacuum is

NOT nothing!

But, a vast ocean made of

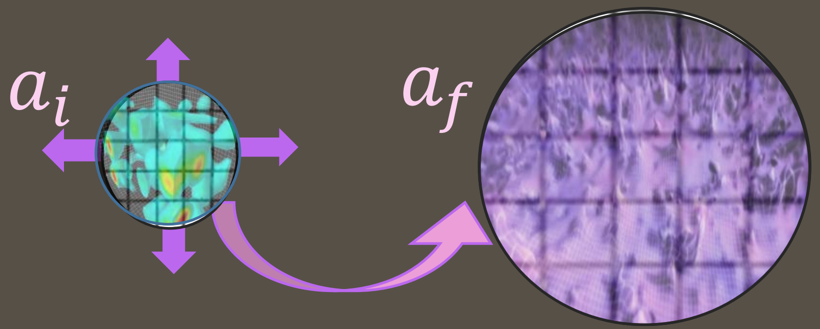
Background field can upgrade them into actual particles!

Examples of such BG fields:

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

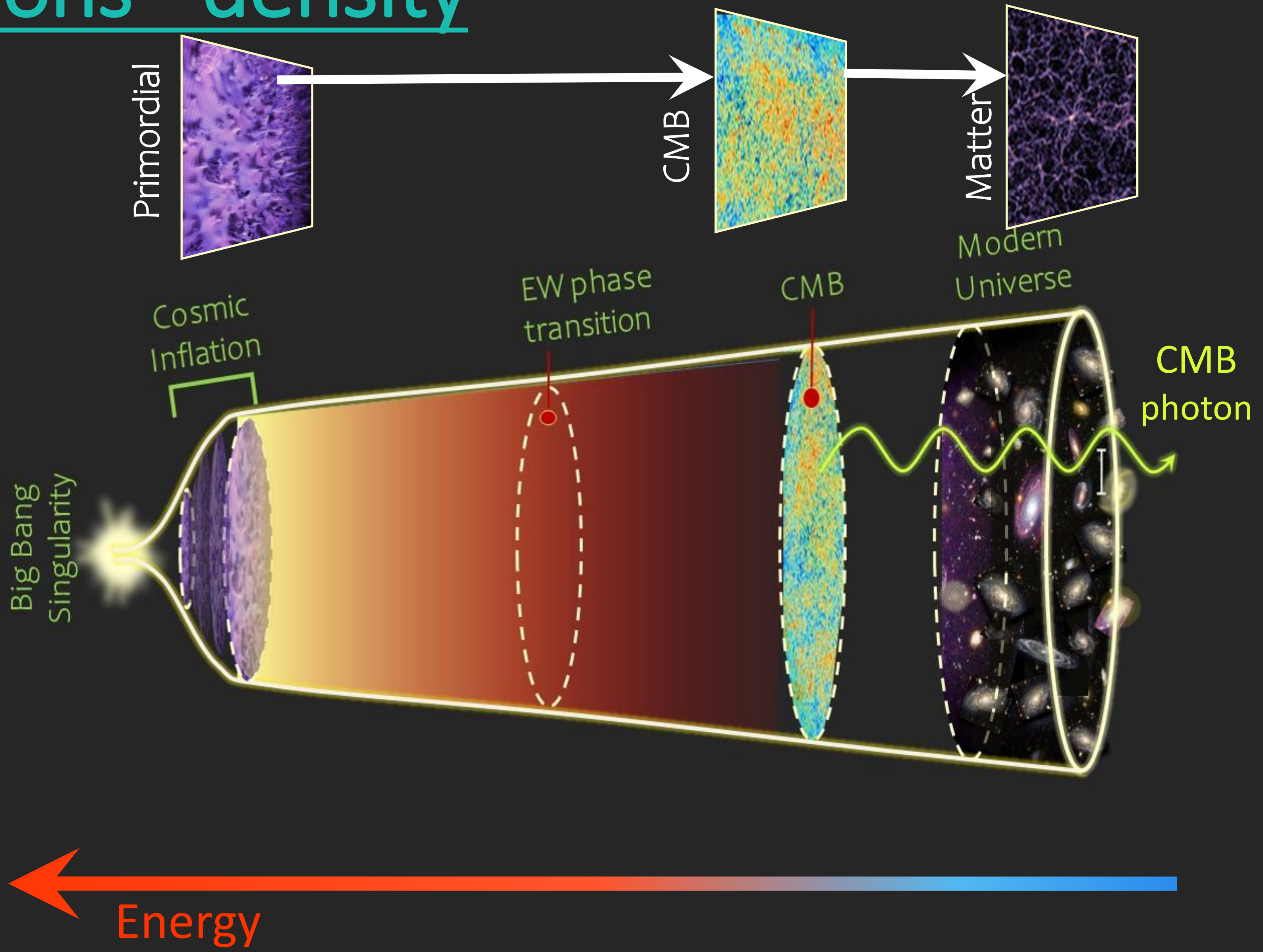
Cosmic Perturbations - density

Exponential expansion turns initial quantum vacuum into



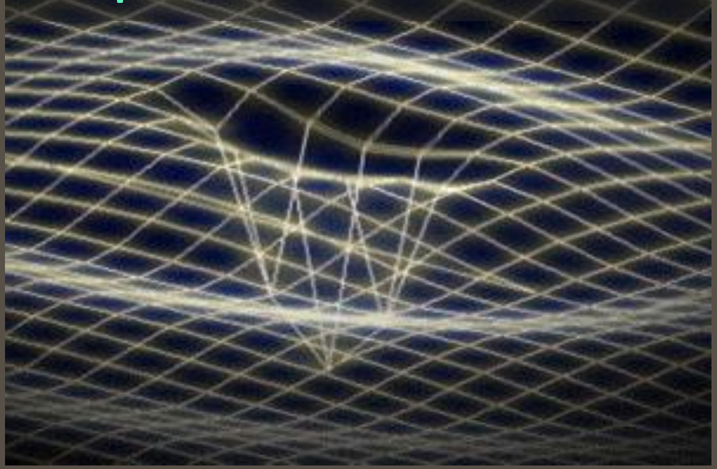
actual cosmic perturbations!

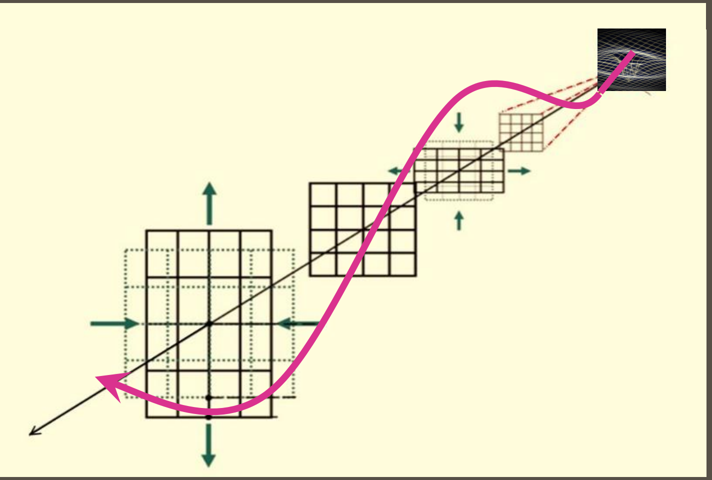
We all came ultimately from quantum fluctuations!

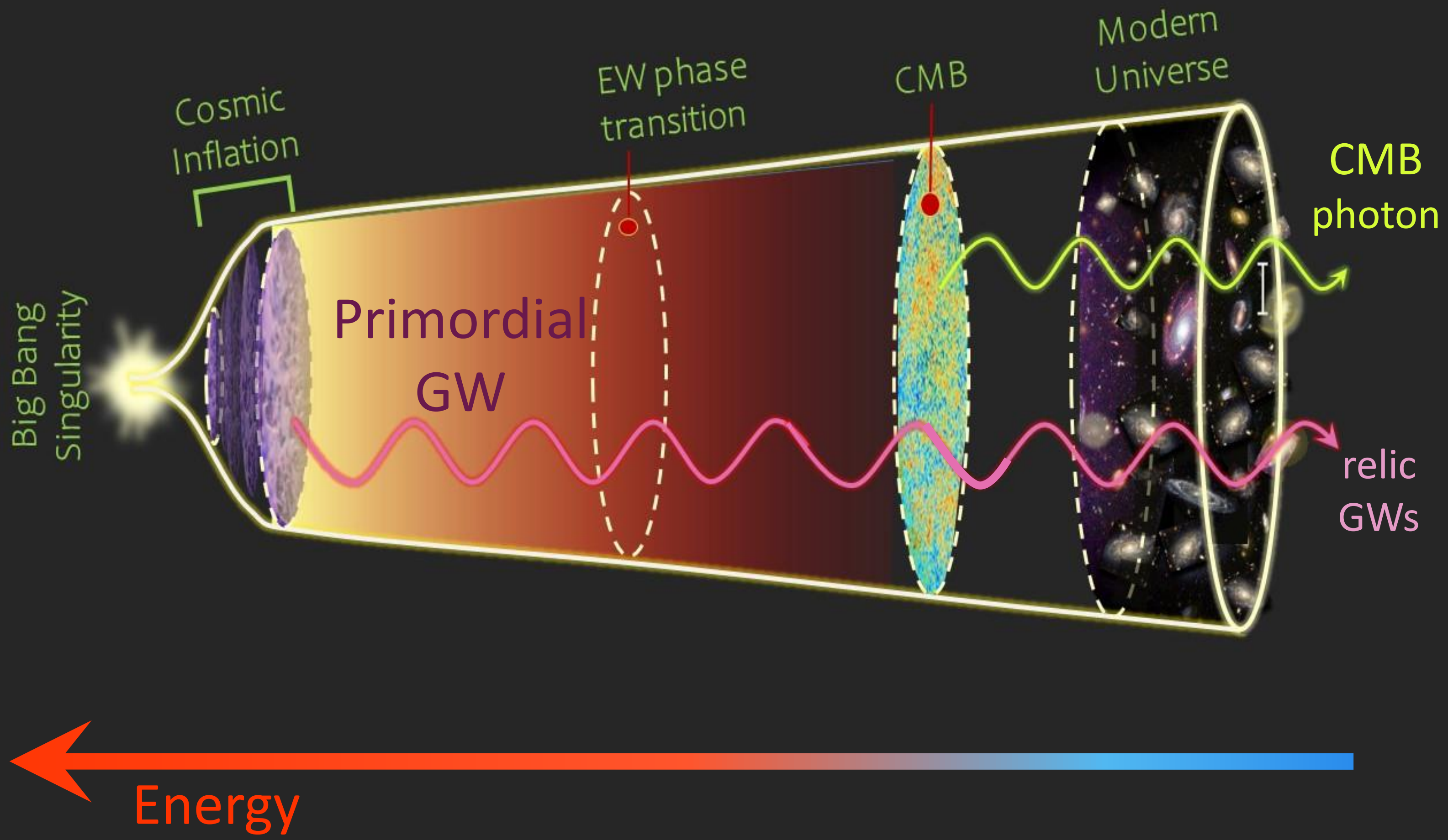


Cosmic Perturbations – Gravitational Waves

Inflation also predicts primordial GWs:







Cosmic Perturbations – Gravitational Waves

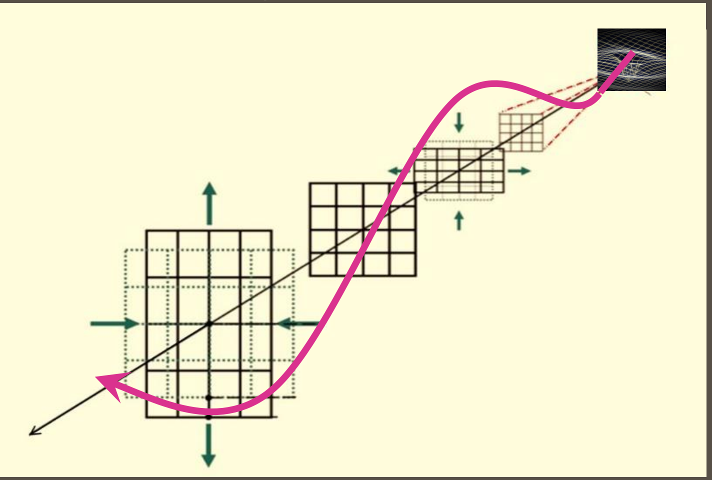
- Inflation also predicts primordial GWs:

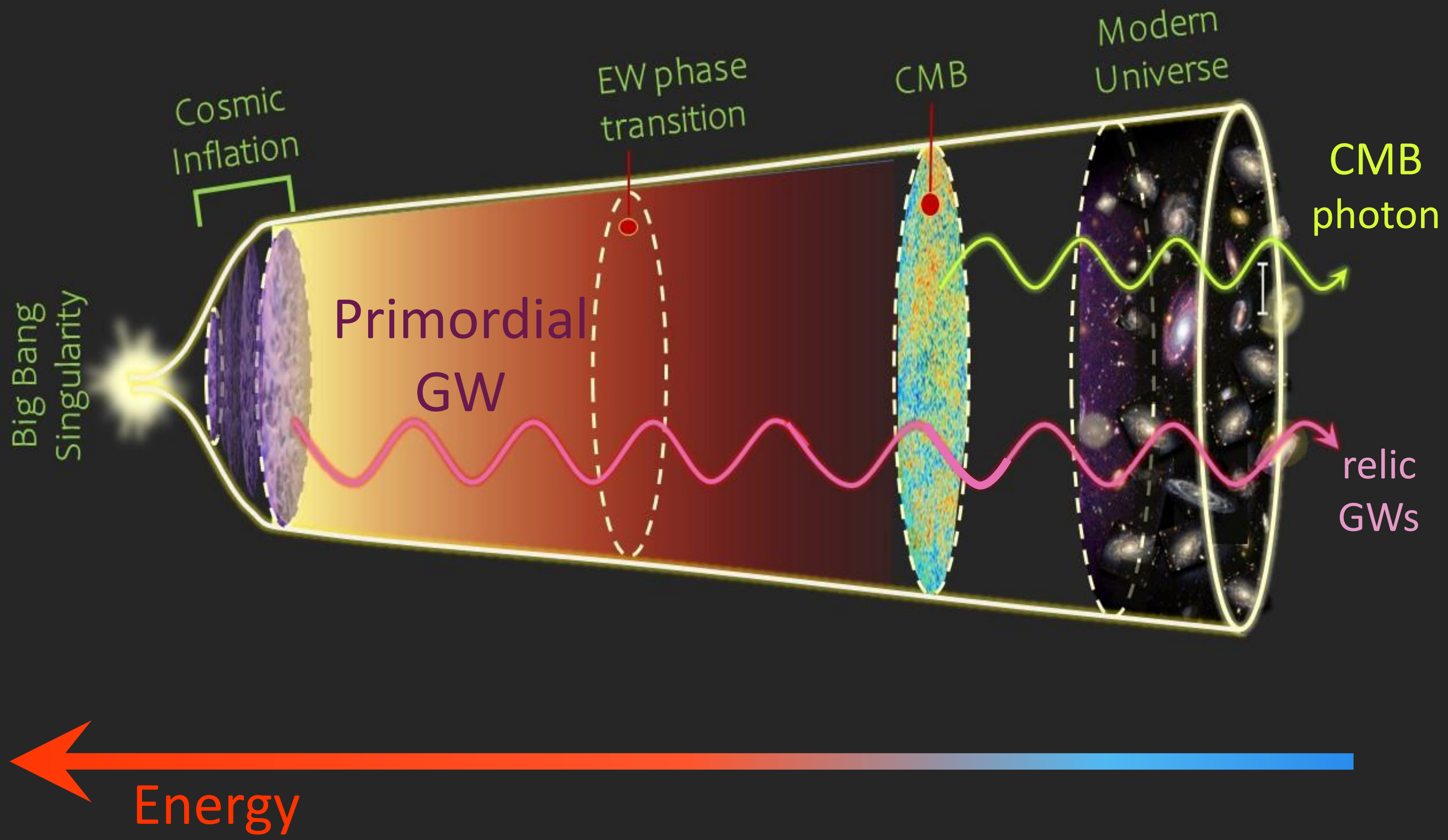
$\Box h_{ij}=0 \rightarrow h_{\pm} = h_{\pm}^{vac}$

- Unpolarizaed

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

- Nearly Gaussian





Cosmic Perturbations – Gravitational Waves

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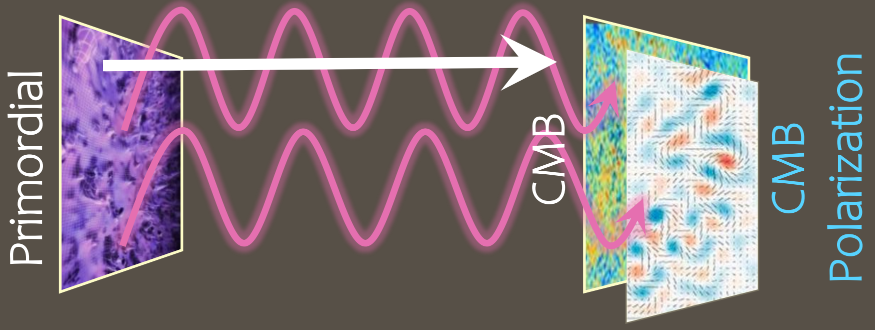
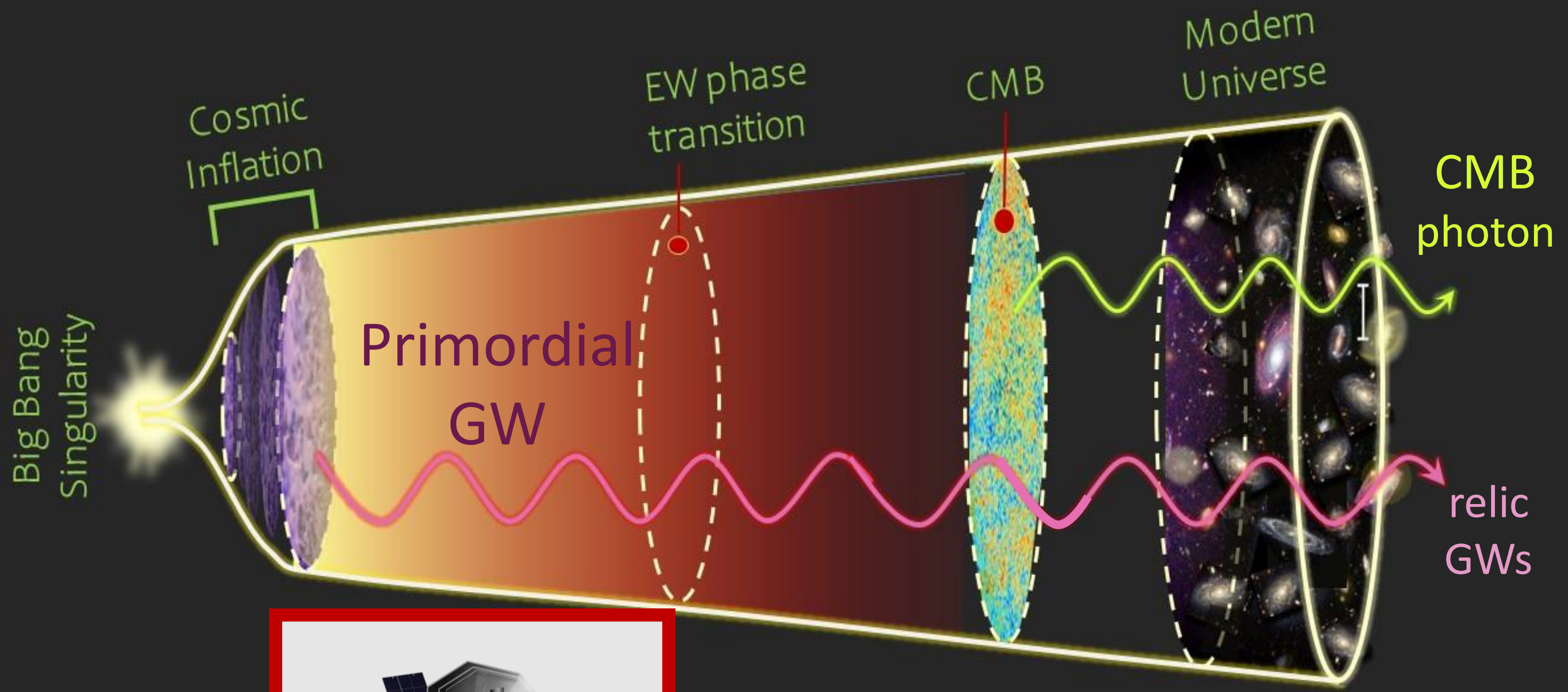
- Nearly Gaussian
- CMB polarization





CMB-S4

Next Generation CMB Experiment

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.

What about Gauge Fields?

Why Gauge Fields during Inflation?!

- ***Why not?***

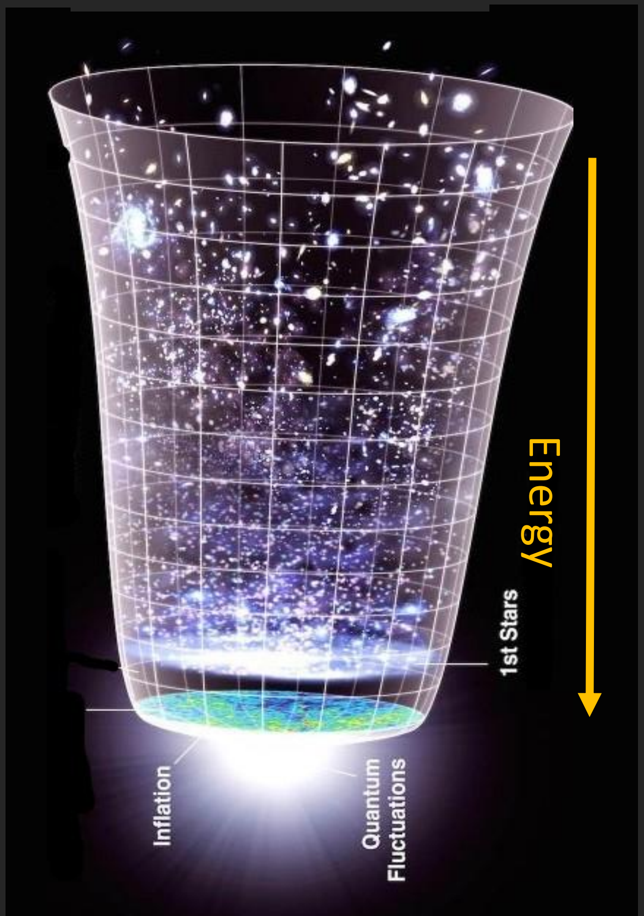
I. Inflation happened at highest energy scales observable!

II. Gauge fields are ubiquitous in physics &
building blocks of standard model (SM) and beyond.

- ***What do they do in inflation?***

Can Gauge Fields Contribute to Physics of Inflation &
leave an observable signature?

Mission Impossible?!



$E_{Inf} \lesssim 10^{14} GeV$

Comparing to LHC

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

Challenges:

1) Conformal symmetry of Yang-Mills

gauge field decays like $A_\mu \sim 1/a$

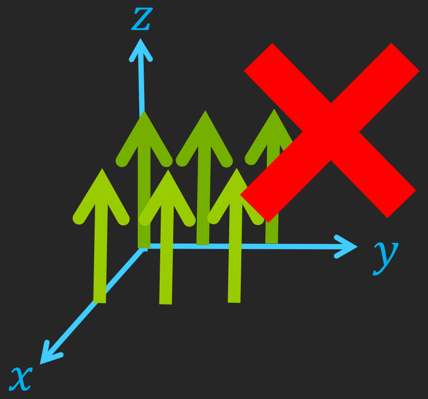
2) Respecting gauge symmetry

Not to break gauge symmetry explicitly

3) Spatial isotropy & homogeneity

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

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



Adding new terms
to the gauge theory

$$\frac{\kappa}{384}(F\tilde{F})^2$$

or

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

Axion

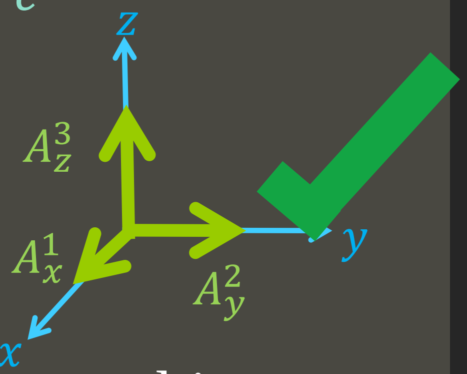
A.M. & Sheikh-Jabbari, 2011

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

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

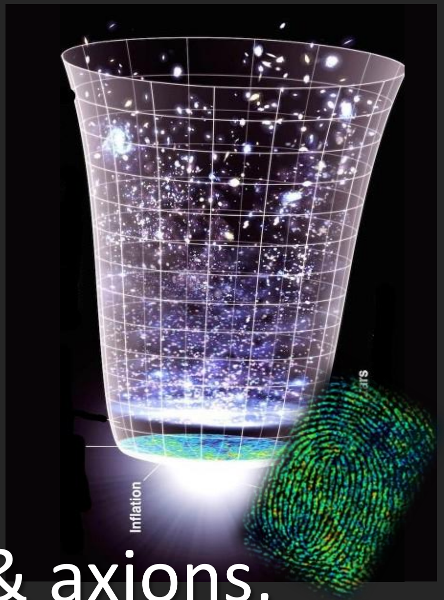
Spatially isotropic

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



so(3) & su(2) are isomorphic

Why Gauge Fields during Inflation?!



Non-Abelian Gauge fields can contribute to inflation &

respect spatial isotropy!

A new class of inflation models with SU(2) gauge fields & axions,

SU(2)-axion models!

It opens a New Window to Particle Cosmology:

A.M. & Sheikh-Jabbari, 2011

Novel Observable Signatures
e.g. Chiral, non-Gaussian GWs!

SU(2)-axion Inflation: a Complete Setup

SM of Particle Physics, the most rigorous theory of physics cannot explain Cosmology!

Big Questions of modern Cosmology & Particle Physics:

I)) Particle physics of Inflation,

II) Origin of matter asymmetry,

III) Particle nature of DM,

IV) Primordial GWs

(only missing prediction of inflation)

Fundamental discrete Symmetries and their violation played a key role in understanding SM, e.g. C & P violation in weak interactions, CP violation to explain matter asymmetry.

Yet, it is mostly assumed that physics of inflation is P and CP symmetric.

SU(2)-axion inflation
Spontaneously breaks P and CP
and relates all of these seemingly unrelated Phenomena in early and late cosmology!

SU(2) Gauge fields and Inflation: Two examples

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

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

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

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

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

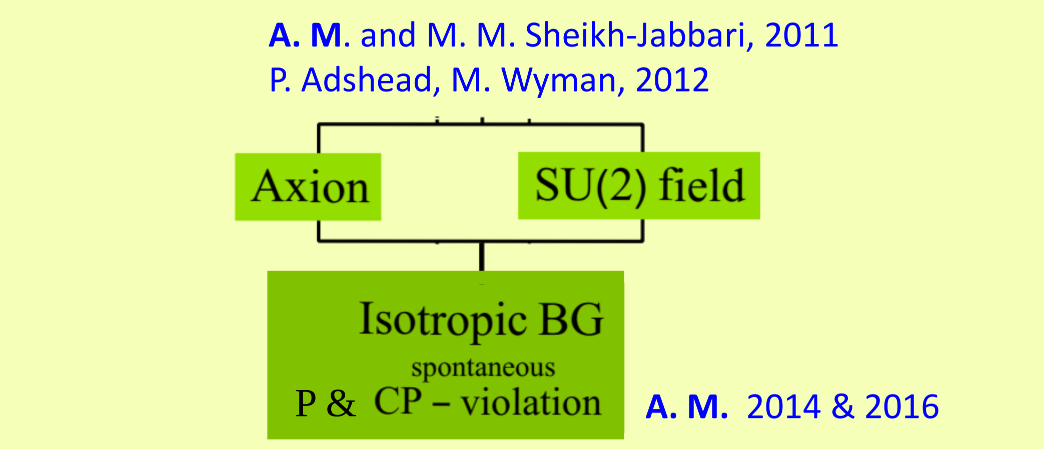
A New Window to Particle Cosmology

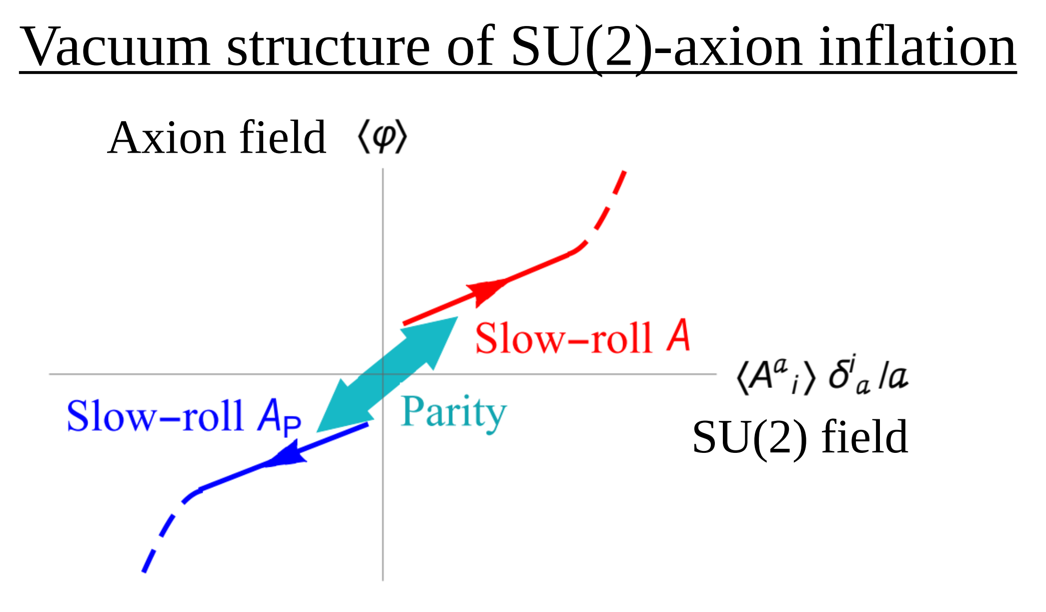
- SU(2)-axion models acquire a vacuum during inflation.

This vacuum violates Parity!

- Particles with spin, e.g. Fermions & Spin-2 fields are sensitive to this **non-trivial Vacuum during inflation**!

- Pre-Hot Big Bang Particle Production! (during inflation)





A.M. 2019

Particle Production

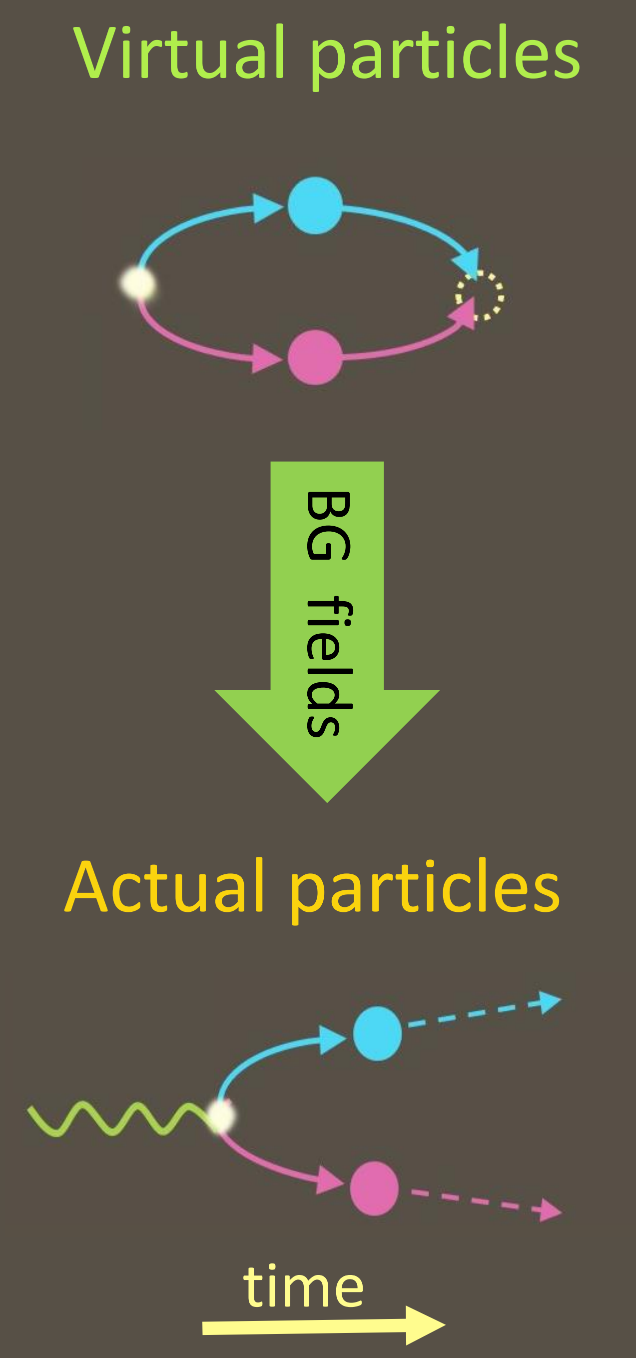
- Vacuum is a vast ocean of virtual particles &
- Background field upgrades it to actual particles!

  Background Gauge field
  (Schwinger effect)

- In flat space, it has never been observed, $E > 10^{18} V/m$.
- Schwinger particle production is important

in Physics of Inflation:

Particle Production during Inflation!



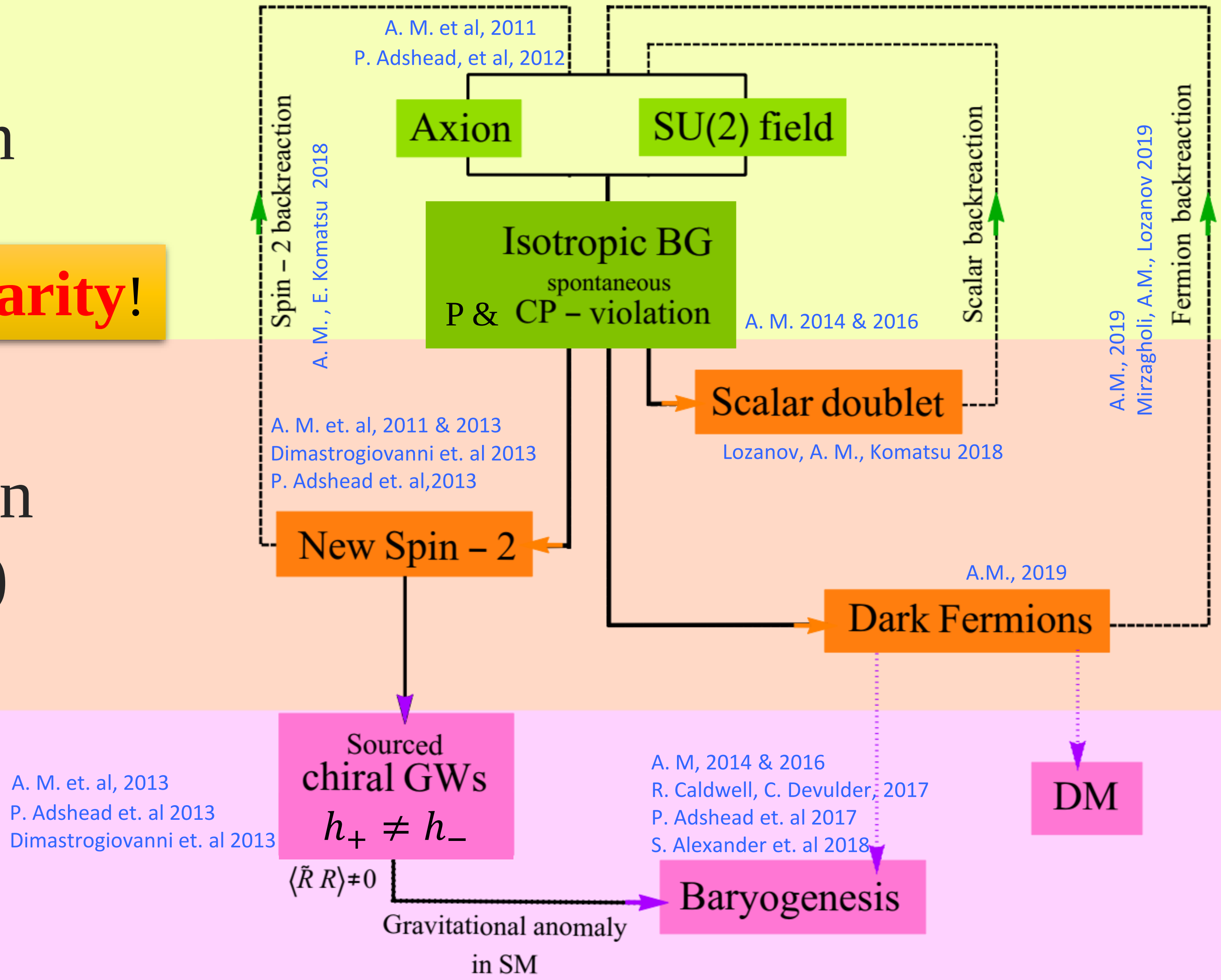
A New Window to Particle Cosmology

Cosmic Inflation

This vacuum violates Parity!

Particle Production
(during Inflation)

Observables



A New Window to Particle Cosmology

- New tensorial field in perturbed SU(2):

$$\delta A^a_i \ni B_{ij}\delta^a_i$$

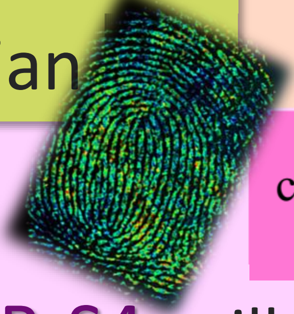
- It is Chiral $<|B_+|^2> \neq <|B_-|^2>$

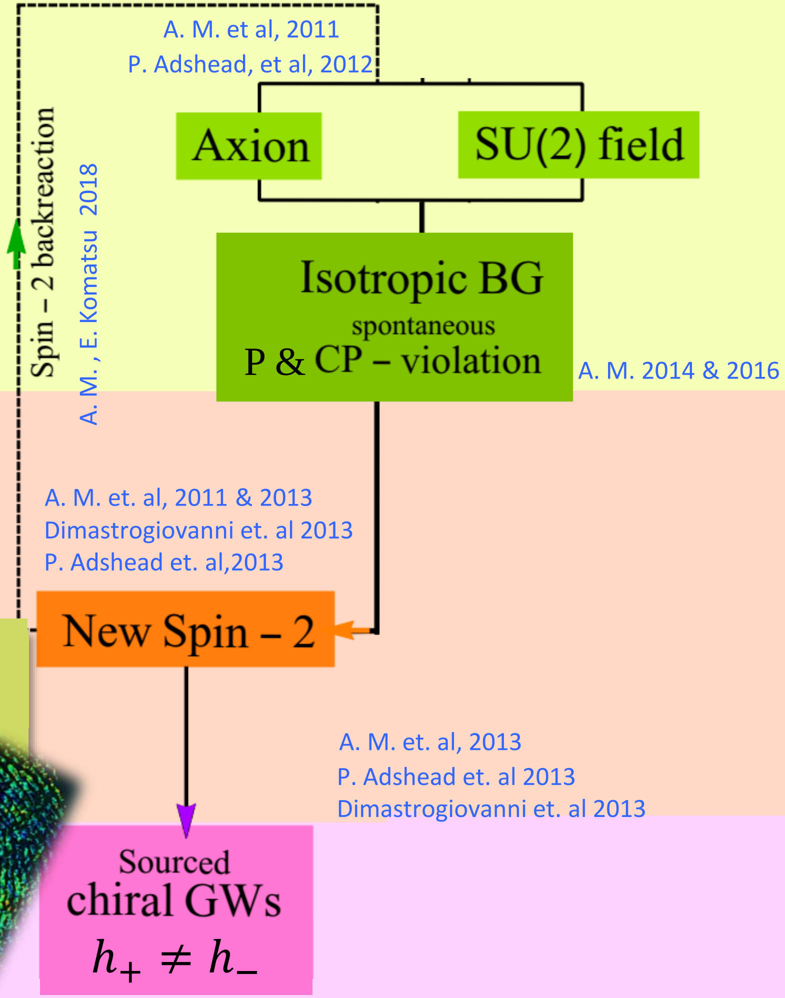
- linearly coupled to Gravitational Waves (GWs)

$$\Box h_{ij} = -16\pi G\, \delta\Pi_{ij}$$

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

$h^s_\pm$ is Chiral $h_+ \neq h_-$ & non-Gaussian





- Novel Observable Signatures on CMB!

Future CMB missions, e.g. LiteBIRD & CMB-S4, will nail it!

A New Window to Particle Cosmology

- New Spin-2 field in perturbed SU(2):

$$\delta A_i^a \ni B_{ij}\delta_i^a$$

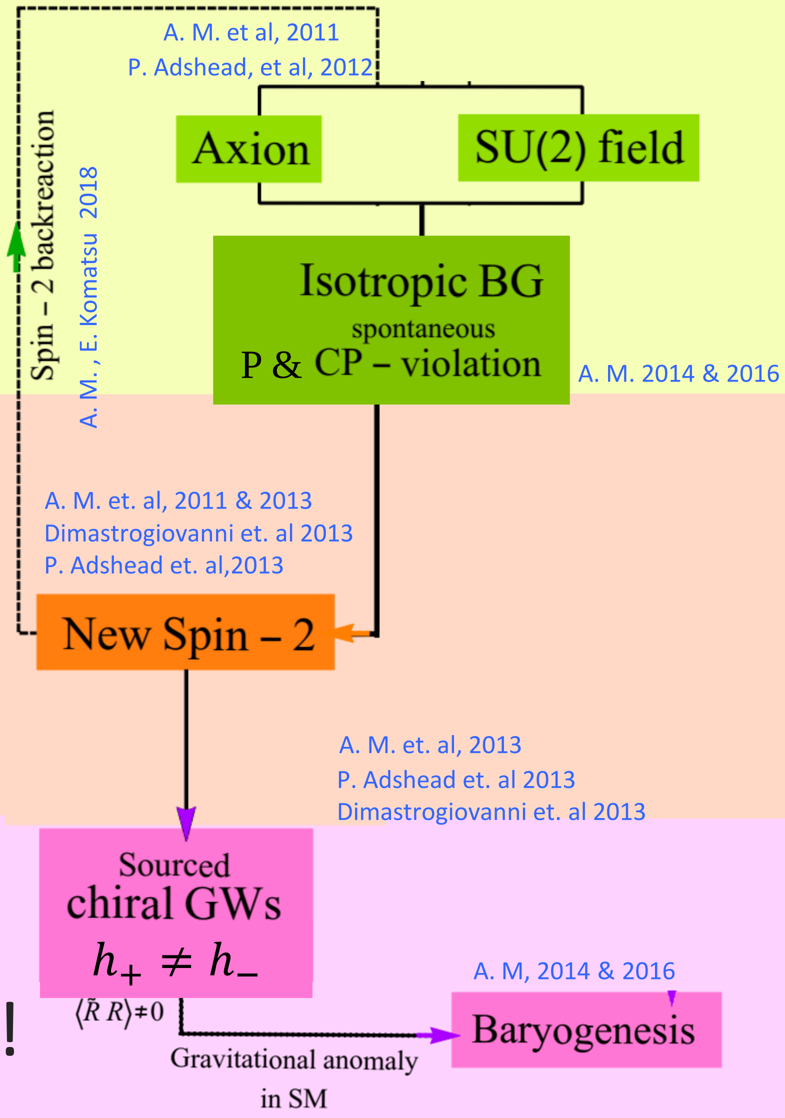
- It is Chiral $B_R \neq B_L$

- linearly coupled to Gravitational Waves

$$\Box h_{ij} = -16\pi G\, \delta\Pi_{ij}$$

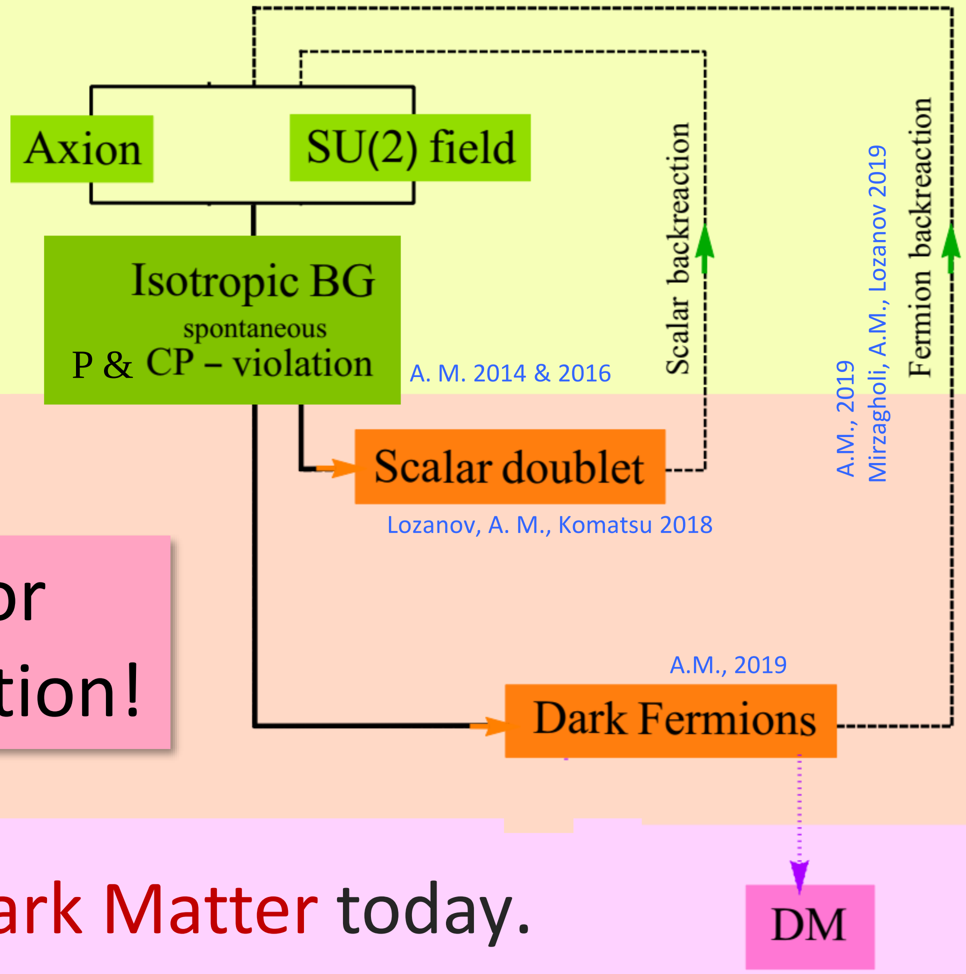
$$h_\pm = h_\pm^{vac} + h_\pm^{s}$$

- $\not{CP}$ in inflation so it is a natural setting for leptogenesis to explain the matter asymmetry!

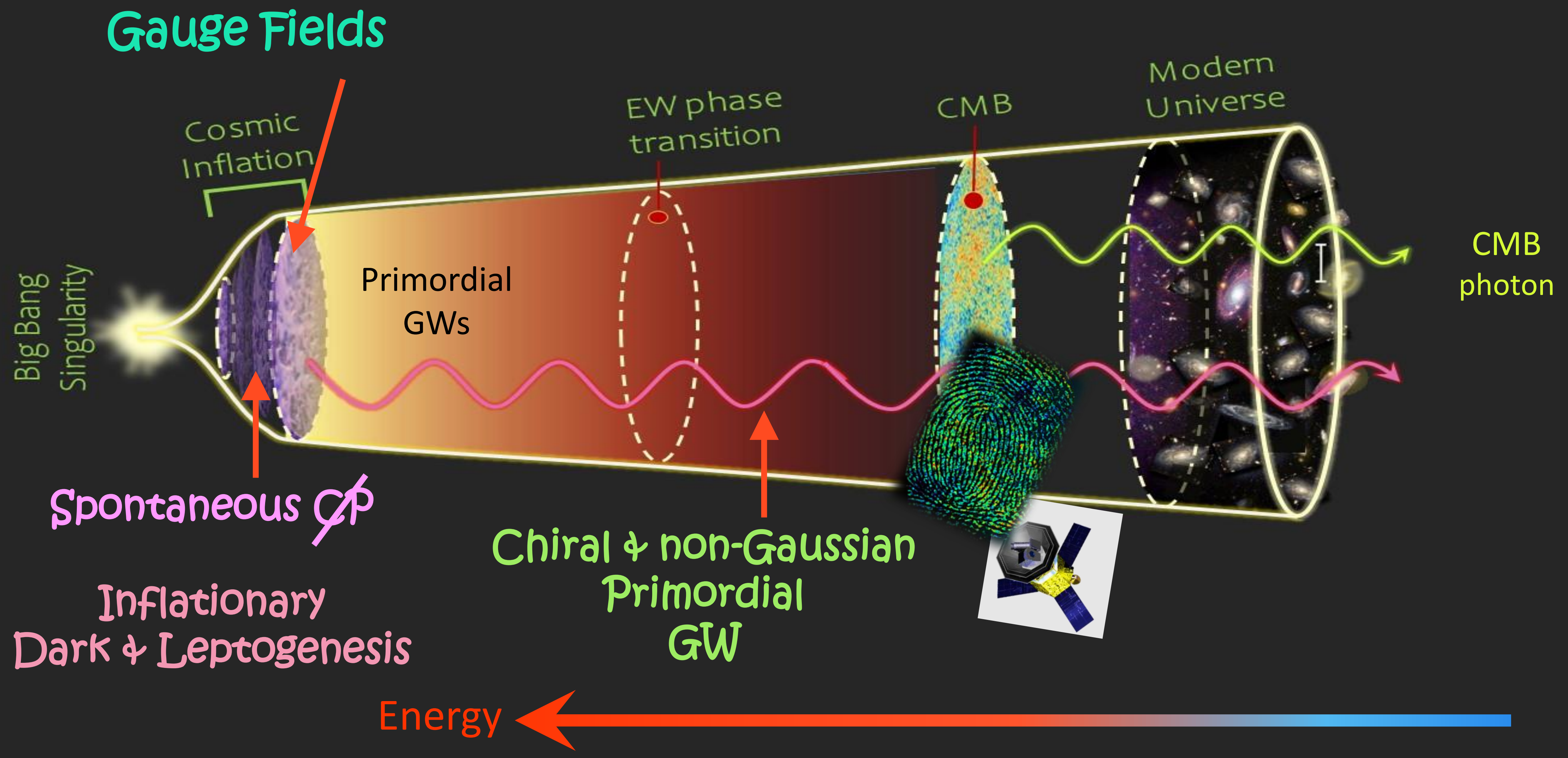


A New Window to Particle Cosmology

- Scalar doublet, and Dark Fermions charged under the Primordial SU(2) will be created by it!
- They will backreact to it as well.
- A new non-thermal mechanism for generating Dark Fermions during Inflation!
- This Dark fermions can be part of Dark Matter today.



Gauge Fields in Inflation



PART TWO: (the exciting details)

- SU(2)-Axion Model Building
- Particle Production in Inflation

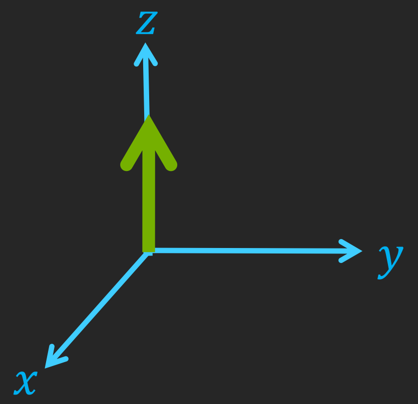
SU(2)-Axion Model Building

How su(2) algebra restores the spatial isotropy?

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

U(1) vacuum A_μ

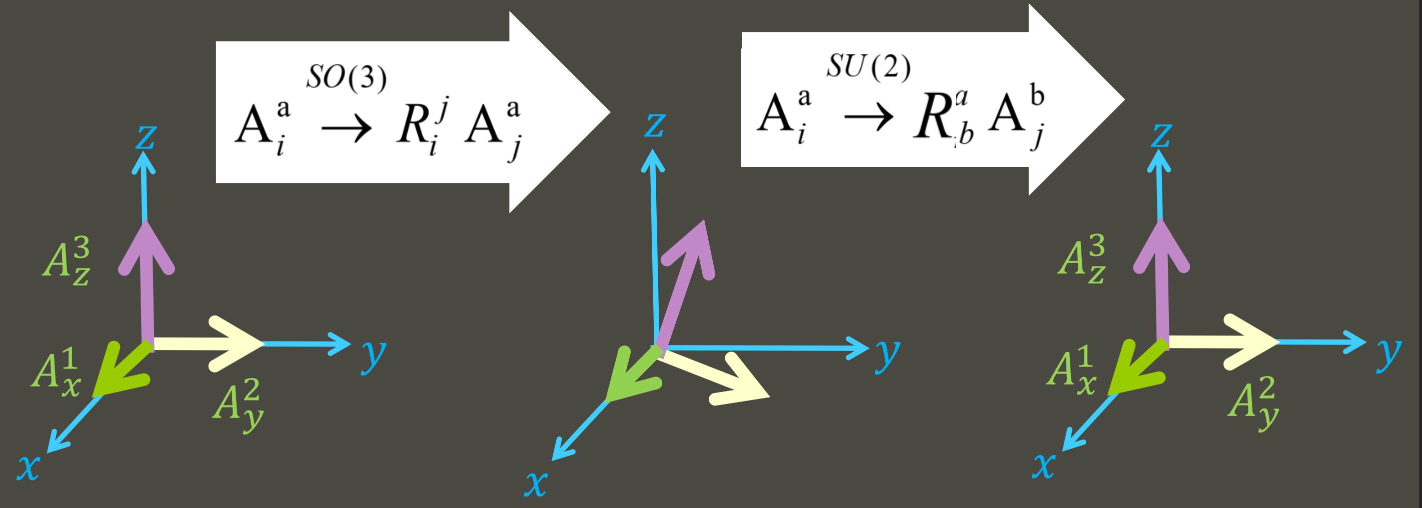
$$\mathrm{A}_i = Q(t)\delta_i^3$$



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

$$\mathrm{A}_i^a = Q(t)\delta_i^a$$

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



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

SU(2)-Axion Model Building

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

An incomplete list of Different Realizations of the Setup:

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]
	….

- SU(2)-Axion Inflation models :

$$S = S_A(A_\mu , \varphi) + \alpha_s\, S_s(\chi) + \alpha_H\, S_H(A_\mu , H)$$

$$\alpha_H = \begin{cases} 0 & \\ 1 & \text{massive SU(2)} \end{cases}$$

$$\alpha_s = \begin{cases} 0 & \\ 1 & \text{Spectator SU(2)} \end{cases}$$

All share these features:

Background

i) **SU(2) gauge field background**: (respect isotropy & homogeneity)

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

$e^a_i = a(t)\delta^a_i$ spatial part of tetrads

ii) **P and CP violating** in inflation background.

Perturbation

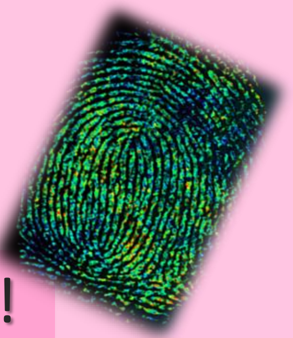
iii) **New spin-2** degrees of freedom:

$$\delta A^a_i(t,\vec{x}) = \underbrace{\delta S^a_i}_{\text{Scalar and vector d.o.f}} + \overbrace{B_{ij}}^{\text{Spin-2 field}}\, \delta^a_i$$

iv) Spin-2 field is **chiral** & linearly **coupled to GWs**

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

Chiral, non-Gaussian primordial GWs!



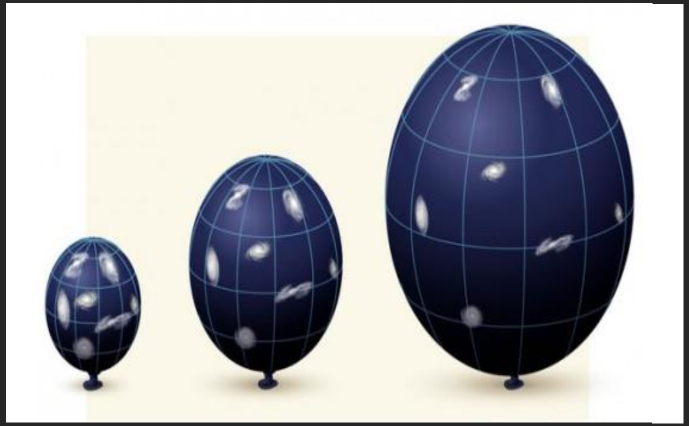
SU(2) Gauge fields and Initial Anisotropies

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

$$A_\mu^a(t) = \begin{cases} 0 & \mu = 0 \\ Q(t)a(t)\delta_i^a & \mu = i \end{cases}$$

Isotropic Background

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



Anisotropic Background??

SU(2) Gauge fields and Initial Anisotropies

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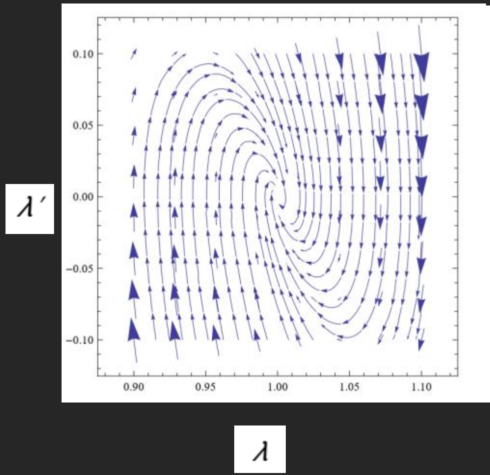
Isotropic Background

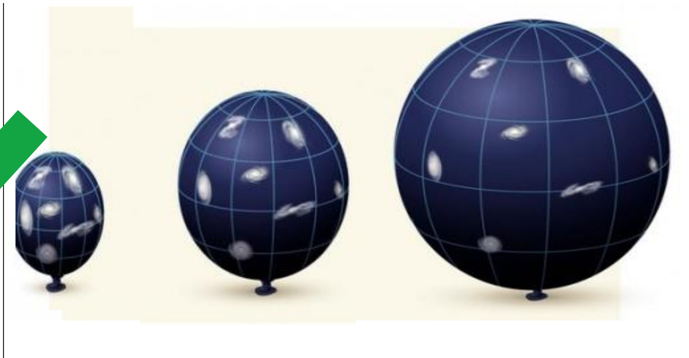
- How stable is the isotropic ansatz against initial anisotropies, i.e. Bianchi

$\lambda(t)$ Parametrizes the amount of anisotropy in the gauge field



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

Isotropic Solution is the Attractor!



isotropic Background

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

Particle Production

1. Tensor modes ☑
2. Dark Scalar ☐
3. Dark Fermions ☐

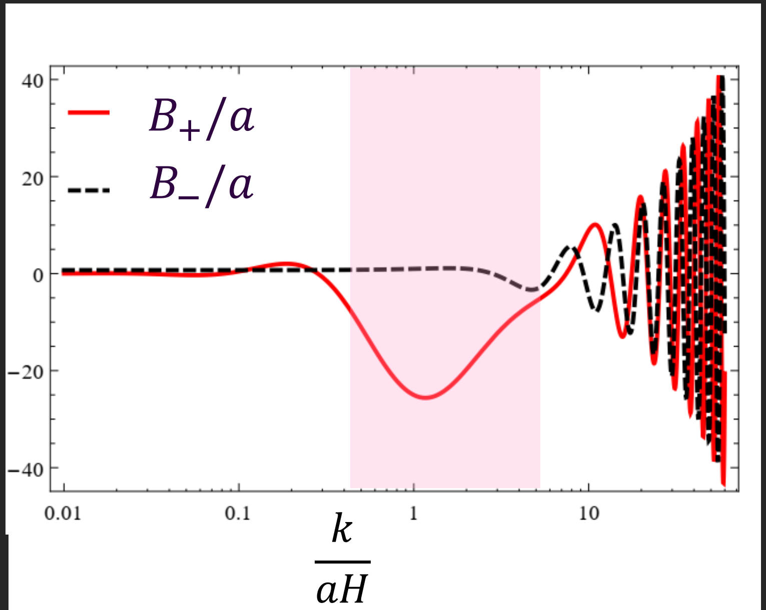
New Tensorial mode & Chiral GWs

- New spin-2 field $\delta A_i^a(t,\vec{x}) = B_{ij}(t,\vec{x})\,\delta_i^a$ is governed by

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

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

- The B_+ has a short phase of particle production before horizon exit.



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

- Backreaction of the spin-2 field is important: $BR \approx g_A n_B \sim \delta_c^3\, e^{\frac{(2-\sqrt{2})\pi}{2}\delta_c}$

A. M. and E. Komatsu, 2018

New Tensorial & Chiral GWs

- New spin-2 field $\delta A_i^a(t,\vec{x}) = B_{ij}(t,\vec{x})\,\delta_i^a$ is governed by

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

- That sourced the GWs $\delta g_{ij}(t,\vec{x}) = a\,h_{ij}\,(t,\vec{x})$ as $(h_{ij} \equiv a\,\gamma_{ij})$

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

- 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 $h_+^{s} \neq h_-^{s}$

i) Tensor power spectrum is not entirely specified by the scale of inflation,

ii) The tensor power spectrum is partially chiral and parity odd correlations $\langle TB \rangle$ and $\langle EB \rangle$ are non-zero, &

iii) Non-Gaussian Primordial GWs!

- Gravitational waves have two unc… ated terms: $h_{\pm} = \underbrace{h_{\pm}^{vac}}_{\text{Vacuum}} + \underbrace{h_{\pm}^{s}}_{\text{Sourced by } B_{\pm}}$

Vacuum

Sourced by $B_{\pm}$

- The ratio of the power spec… of sourced to vacuum is

$$\frac{P_T^S}{P_T^{vac}} \approx \left(\frac{Q}{M_{Pl}}\right)^2 \times \left(\frac{n_B}{H^3}\right)$$

A. M. and E. Komatsu, 2018

i) Tensor power spectrum is not entirely specified by the scale of inflation,

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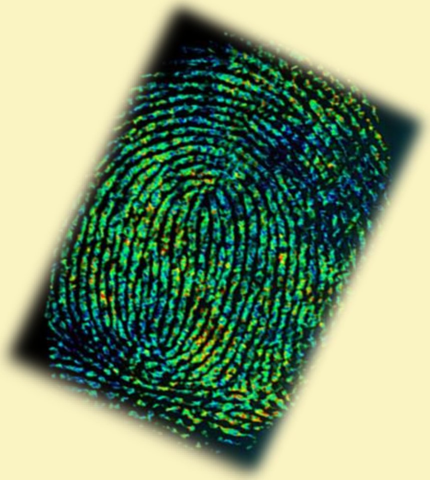


Backreaction of New Spin-2 puts constraints on ratio of the power spectra of sourced to vacuum gravitational waves

A. M. and E. Komatsu, 2018

$$\frac{P_T^S}{P_T^{vac}} \approx \left(\frac{Q}{M_{Pl}}\right)^2 \times \left(\frac{n_B}{H^3}\right)$$

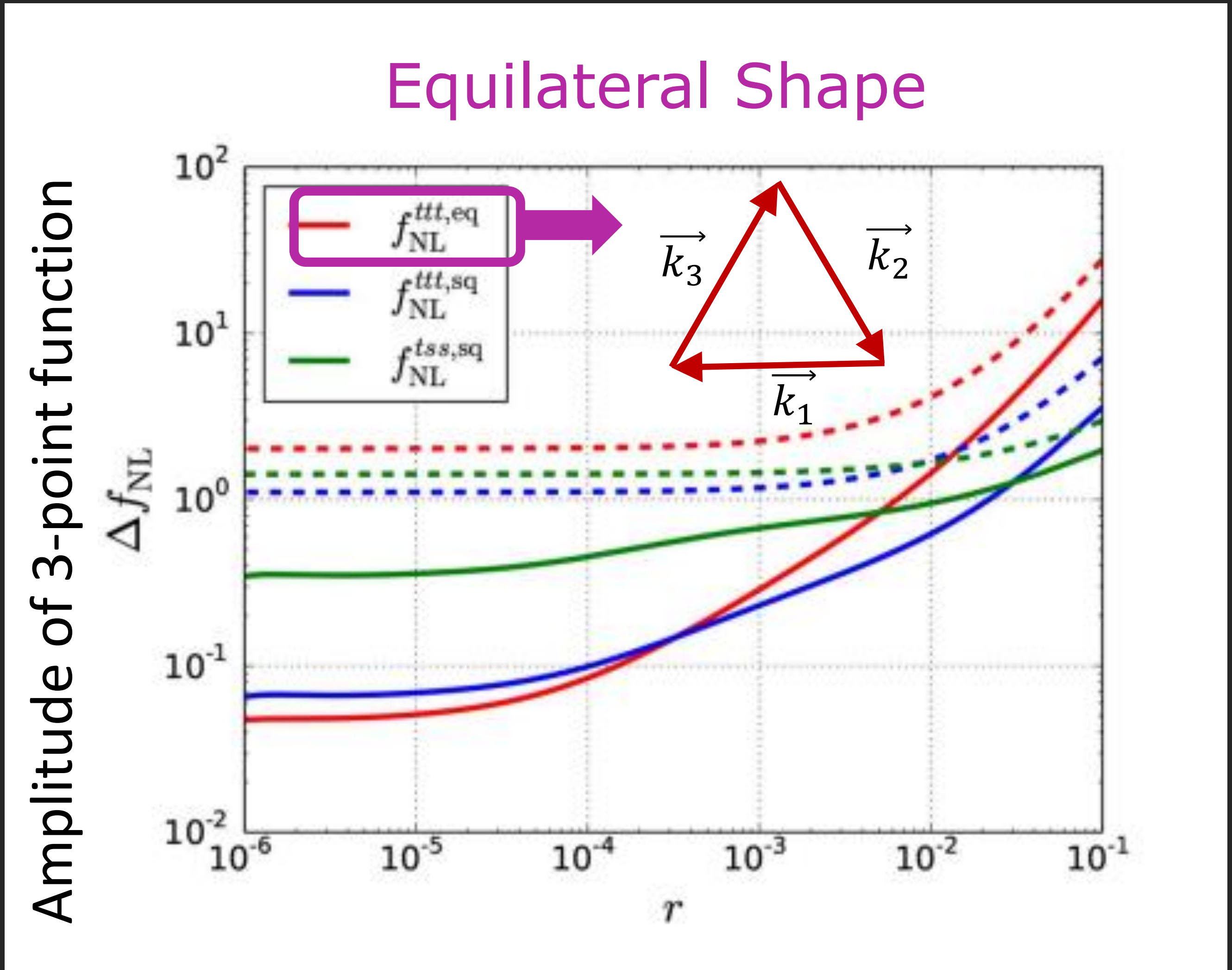
A. M. and E. Komatsu, 2018

Novel Observable Signature: CMB

- The sourced tensor modes is Highly non-Gaussian.

Agrawal, Fujita, Komatsu 2018

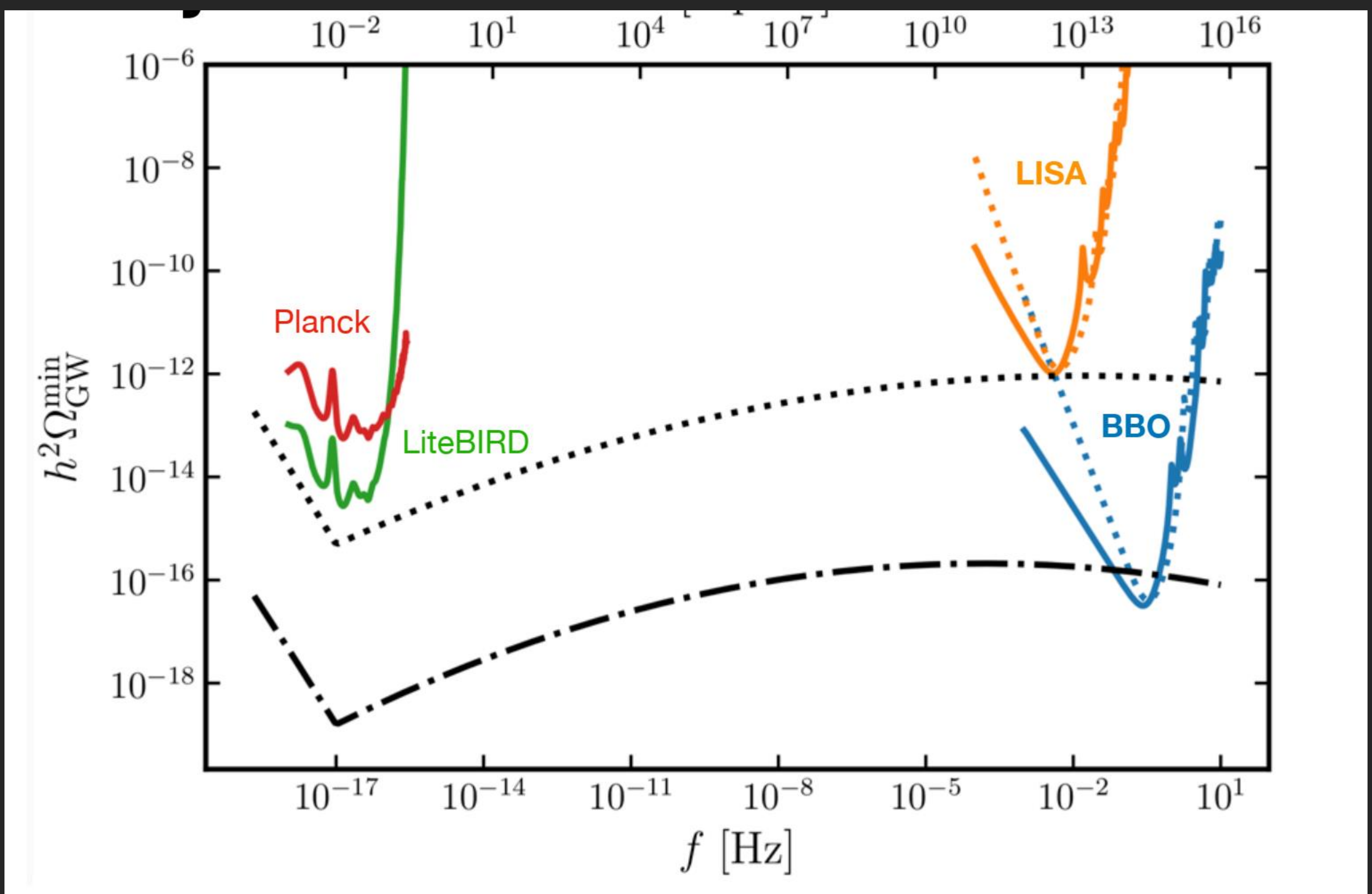
- That can be probe with future CMB missions., e.g. *Litebird* and *CMB-S4*!



Maresuke Shiraishi, Front. Astron. Space Sci. 2019

Novel Observable Signature: Beyond CMB

- Comparison of the sensitivity curves for LiteBIRD, Planck, LISA & BBO.



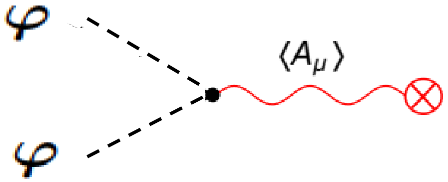
Thorne, Fujita, Hazumi, Katayama, Komatsu & Shiraishi, 2018

Particle Production

1. Tensor Models ☑
2. Dark Scalar ☑
3. Dark Fermions ☑

Particle Production-scalar

- **Charged scalar fields** coupled to the SU(2) gauge field BG

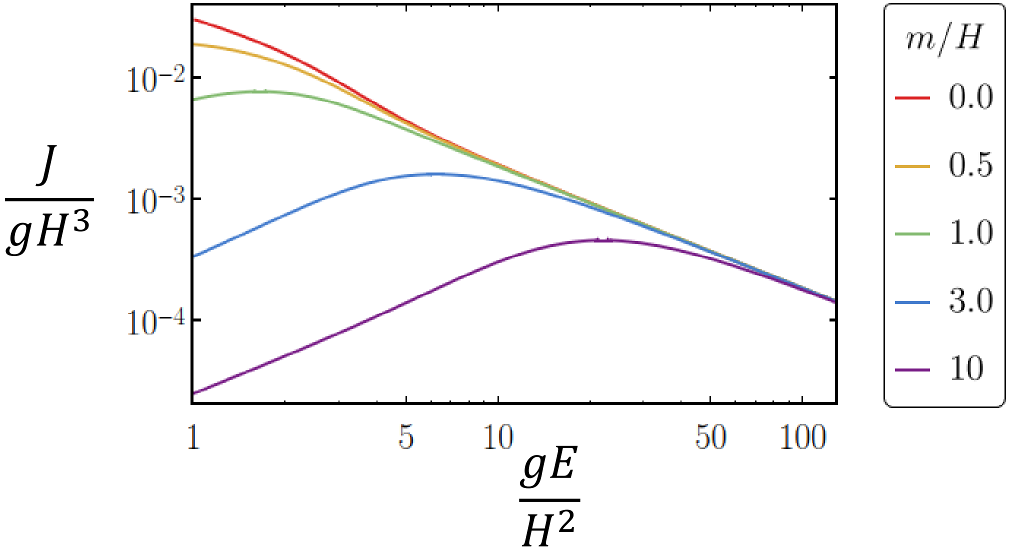


$$S_{\rm matter} = \int d^4x \sqrt{-g} \left[(\mathbf{D}_\mu \varphi)^\dagger \mathbf{D}^\mu \varphi - m^2 \varphi^\dagger \varphi \right]$$

$$\mathbf{D}_\mu \varphi = (\nabla_\mu + i g_A \mathbf{A}_\mu)\, \varphi$$

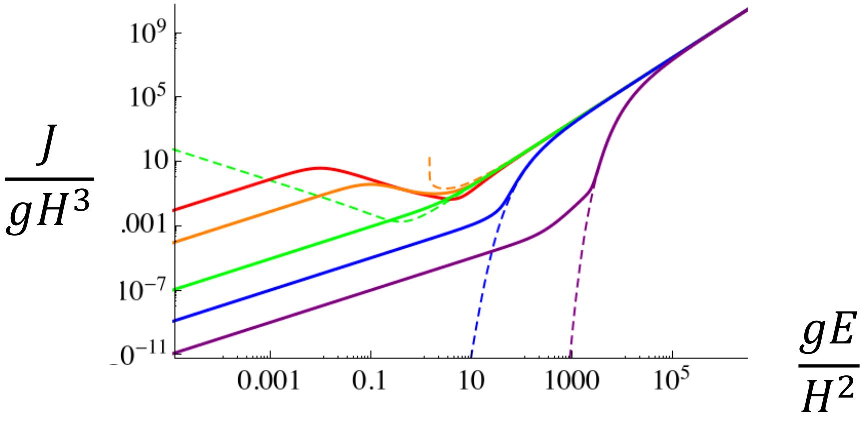
- The scalar field's induced current:

Isotropic SU(2)



Kaloian D. Lozanov, A. M., Eiichiro Komatsu JHEP 1902 (2019) 041

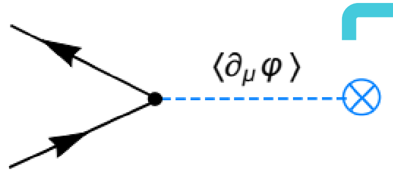
Anisotropic U(1)

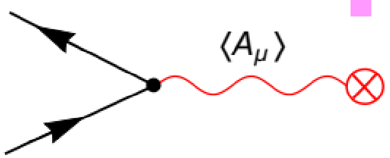


Takeshi Kobayashi, Niayesh Afshordi, JHEP10(2014)166

Particle Production-Dark Fermion

Axion BG field



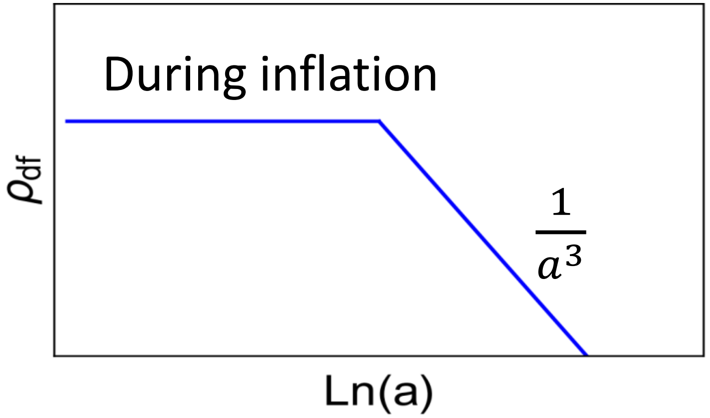


SU(2) gauge field BG

$$S_{\rm fermion} = \int d^4x\sqrt{-g}\left[i\bar{\tilde{\Psi}}\not{D}\tilde{\Psi} - m\bar{\tilde{\Psi}}\tilde{\Psi} + \beta\frac{\lambda\varphi}{f}\nabla_\mu J^\mu_5\right]$$

$$\not{D} \equiv D_\mu \otimes \gamma^\mu = \left[\mathbf{I}_2\nabla_\mu - ig_A A^a_\mu \mathbf{T}_a\right] \otimes \gamma^\mu$$

This vacuum violates both P & CP!



A. M JHEP 2020

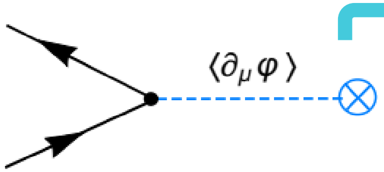
Fermions (massive and massless) are generated during inflation.

$$\nabla_\mu J^\mu_5 = -\frac{2im}{a^3}\bar{\tilde{\Psi}}\gamma_5\tilde{\Psi} + \frac{2g_A^2}{16\pi^2}F^a_{\mu\nu}\tilde{F}_{a\mu\nu}$$

The efficiency of the process is proportional to the source of the CP breaking!

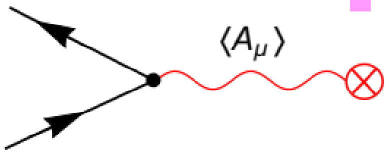
Particle Production-Dark Fermion

Axion BG field



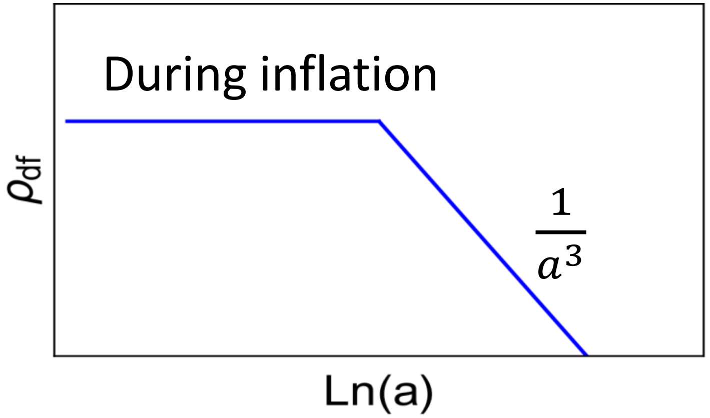
$$S_{\rm fermion} = \int d^4x \sqrt{-g} \left[i\bar{\tilde{\Psi}} \not{D} \tilde{\Psi} - m \bar{\tilde{\Psi}} \tilde{\Psi} + \beta \frac{\lambda\varphi}{f} \nabla_\mu J_5^\mu \right]$$

$$\not{D} \equiv D_\mu \otimes \gamma^\mu = \left[\mathbf{I}_2 \nabla_\mu - i g_A A_\mu^a \mathbf{T}_a \right] \otimes \gamma^\mu$$



SU(2) gauge field BG

This vacuum **violates** both **P** & **CP**!

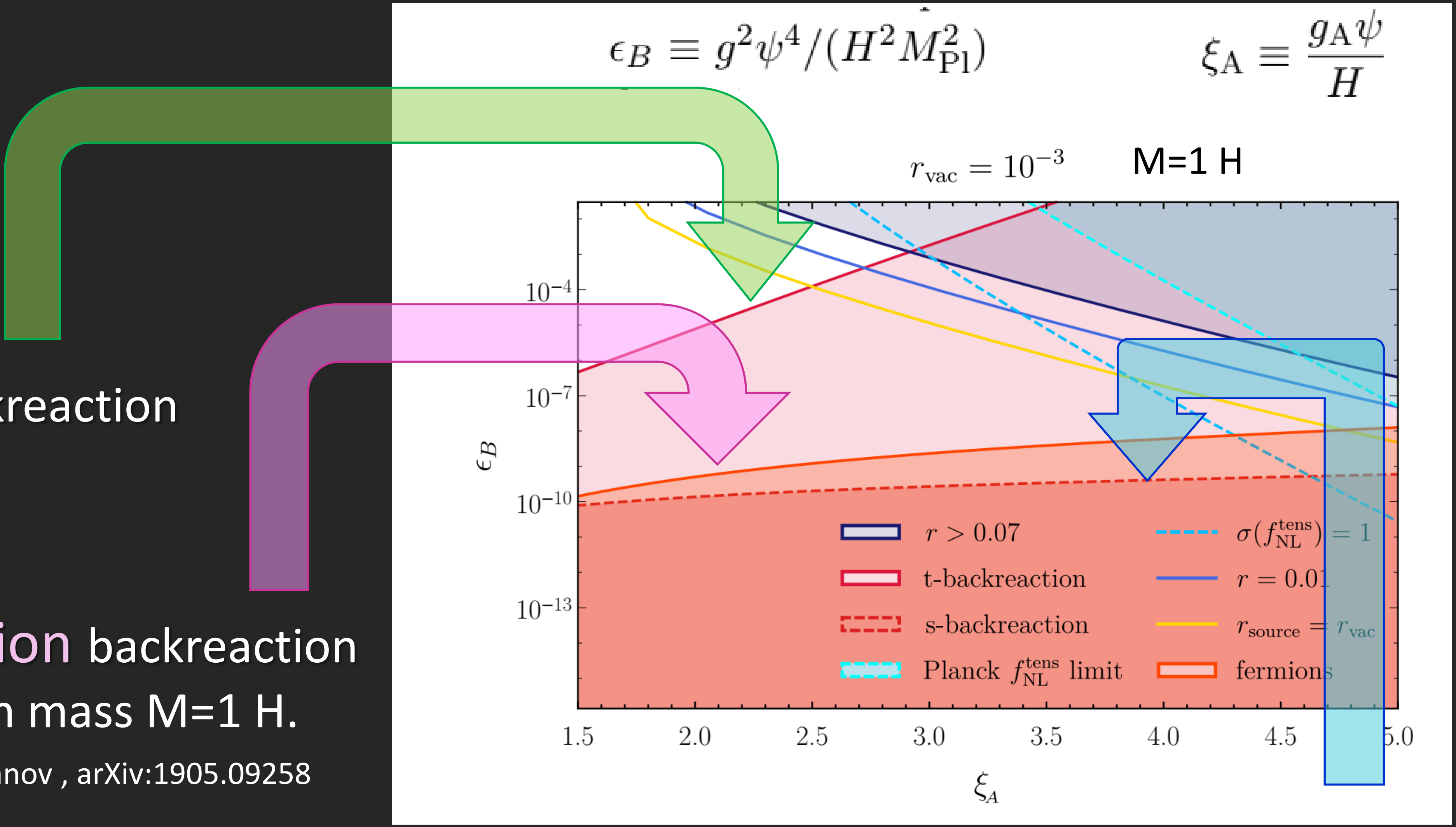


A. M arXiv:1909.11545

Massive Dirac fermions are generated during inflation.

A new non-thermal mechanism for generating massive (Dark) fermions!

Particle Production & Backreaction



The spin-2 backreaction constraint

A.M. and Komatsu, 2018

The Dirac fermion backreaction for fermions with mass M=1 H.

L. Mirzagholi, A.M. D. Lozanov , arXiv:1905.09258

The scalar field backreaction constraint.

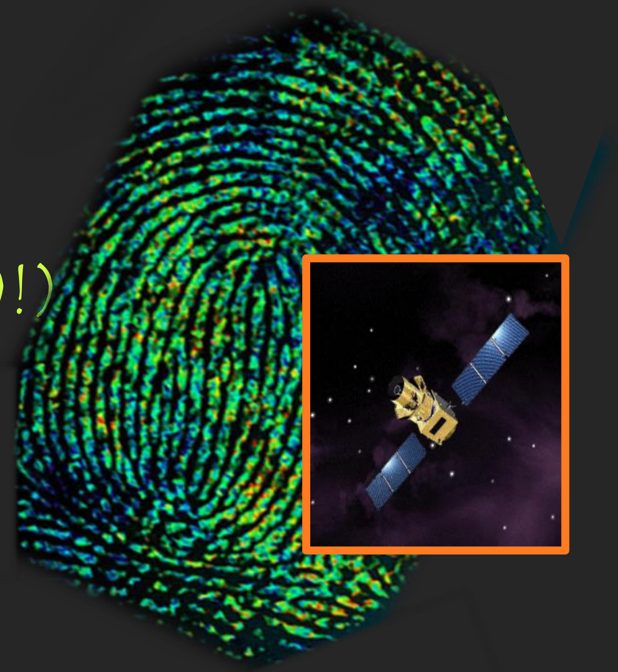
D. Lozanov, A.M., and Komatsu 2018

Summary and Outlook

- SU(2)-axion models of inflation enriches the Particle Cosmology.
- Spontaneous P & CP violation in Inflation.

- Spin-2 particles: (The smoking gun for Primordial SU(2)!)

1) Gauge field includes a New chiral tensorial field
2) It produces partially chiral and non-Gaussian GWs



- Spin-1/2 particles:

a new non-thermal mechanism for generating massive (Dark) fermions.


Questions?!