Is our Universe Remnant of Chiral Anomaly in Inflation?

Based on

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CERN

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Cosmic History
Cosmic History

Our Universe is expanding.

For many it was filled with a hot plasma.

As it expands it becomes colder and colder.
Cosmic History

Our Universe is expanding. For many it was filled with a hot plasma.

As it expands it becomes colder and colder. When temperature got below 1 eV, neutral atoms & Cosmic Microwave Background (CMB) is formed.
Cosmic History

Our Universe is expanding. For many it was filled with a hot plasma. As it expands it becomes colder and colder. When temperature got below 1 eV, neutral atoms & Cosmic Microwave Background (CMB) is formed. Those initially hot atoms slowly assembled & cooled into Large Scale Structures.
Cosmic History

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

CMB is nearly homogenous & isotropic!

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

with tiny fluctuation

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

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

\[ \frac{a_f}{a_i} = e^{60} \approx 10^{26}! \]
Cosmic Inflation

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Energy

Time

What caused inflation?

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

Flat potential

Slow-roll inflation

Energy

Time
What caused inflation?

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

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

$$\phi(t, \tilde{x}) = \phi(t)$$

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

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

$$\nu(\varphi)$$

Slow-roll inflation

Flat potential

Energy

Time

Big Bang Singularity

CMB

Modern Universe

CMB photon
Quantum Fluctuations

\( \hbar \neq 0 \)
Quantum Vacuum $\hbar \neq 0$

Due to Uncertainty Principle

$\Delta x \Delta p \geq \frac{\hbar}{2}$

quantum vacuum is NOT nothing!
Quantum Vacuum $\hbar \neq 0$

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quantum vacuum is NOT nothing!

But, a vast ocean made of

Virtual particles
Quantum Vacuum

Due to Uncertainty Principle

$$\Delta x \Delta p \geq \frac{\hbar}{2}$$

the quantum vacuum is NOT nothing!

But, a vast ocean made of

Virtual particles

Particle Production

Background field can upgrade them into actual particles!

Examples of such BG fields:

1) Electric (Schwinger effect)
2) Gravitational (Gravitational production)
Inflation Produces Particles!

Flat Space:

Expanding space:
Inflation Produces Particles!

Flat Space:

Vacuum → Virtual pair → Vacuum

Expanding space:

Vacuum → Virtual pair → Vacuum

Particle Production

Edwin Schrödinger (1939)

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

\[a_i \rightarrow a_f\]
**Primordial Gravitational Waves**

Inflation also predicts primordial GWs:

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

- Vacuum GWs

\[
\begin{align*}
    h_{ij} &= 0 \quad \Rightarrow \quad h_{\pm} &= h_{\pm}^{\text{vac}}
\end{align*}
\]

Circular polarizations

Left-handed

Right-handed

Vacuum GWs

Circular polarizations

Relic GWs

CMB photon
Primordial Gravitational Waves

- Vacuum GWs
  \[ h_{ij} = 0 \rightarrow h_{\pm} = h_{\pm}^{\text{vac}} \]
- Unpolarized
  \[ \langle | h_{\text{vac}}^{+} |^2 \rangle = \langle | h_{\text{vac}}^{-} |^2 \rangle \]
- Nearly Gaussian

Circular polarizations

- Left-handed
  \[ h_{-} \]
- Right-handed
  \[ h_{+} \]
Cosmic Perturbations - Gravitational Waves

- Inflation also predicts primordial GWs:
  - $h_{ij}=0 \Rightarrow h_\pm = h_{\pm}^{\text{vac}}$
  - Unpolarized
  - $|h_{\pm}^{\text{vac}}|^2 = |h_{\mp}^{\text{vac}}|^2$
  - Nearly Gaussian
  - CMB polarization

---

LiteBIRD

Next Generation CMB Experiment

CMB-S4
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
- Unpolarized, Gaussian GW

Cosmic Inflation
CMB
Modern Universe

Big Bang Singularity
CMB photon
Primordial GWs
As Yet

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What about Gauge Fields?!

Inflation Particle Physics:
- a scalar singlet BSM
- Unpolarized, Gaussian GW
Puzzles of SM & Cosmology

I) Particle physics of Inflation
II) Origin of matter asymmetry
III) Origin of Neutrino mass
IV) Particle nature of DM
Matter asymmetric

Universe is highly matter asymmetric

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

- Statistical fluctuations \( \times \) (Too small)
- Initial condition \( \times \) (due to inflation)

Must be produced dynamically, i.e. Baryogenesis by

- Baryon number violation,
- C and CP violation,
- Out of thermal equilibrium

Sakharov Conditions:

Physics Beyond the Standard Model!

SM Has All, But Too Tiny!
Baryogenesis via Leptogenesis

Lepton asymmetry $\Delta L$ \rightarrow EW sphalerons \rightarrow Baryon asymmetry $\Delta B$

Leptogenesis
Baryogenesis via Leptogenesis

Lepton asymmetry $\Delta L$ $\rightarrow$ EW sphalerons $\rightarrow$ Baryon asymmetry $\Delta B$

Sphaleron transitions: Conserve $B-L$

Leptogenesis

$\bar{l}$ $\rightarrow$ $l$ via $B - L = \text{const}$
Baryogenesis via Leptogenesis

Lepton asymmetry $\Delta L$ → EW sphalerons $\rightarrow$ Baryon asymmetry $\Delta B$

Sphaleron transitions:
- Conserve $B-L$
- Wash out $B+L!$ \( \rightarrow \) $B+L=0$

Leptogenesis

$\bar{l} \leftrightarrow l$

$B + L = 0$

$B - L = \text{const}$
Baryogenesis via Leptogenesis

Lepton asymmetry $\Delta L$ \hspace{1cm} EW sphalerons \hspace{1cm} Baryon asymmetry $\Delta B$

Sphaleron transitions:
- Conserve $B$-$L$
- Wash out $B+L$! \hspace{1cm} $\rightarrow$ \hspace{1cm} $B+L=0$

Leptogenesis

Baryogenesis
**Puzzles of SM & Cosmology**

I) Particle physics of Inflation
II) Origin of matter asymmetry
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IV) Particle nature of DM

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

**Curios cosomological coincidences**

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

Baryon to Photon Ratio Today

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

Curvature Power Spectrum in Inflation

\[ \Omega_B = 7.5 \times 10^{-10} \]

\[ \Omega_{DM} = 0.02 \]

\[ \Omega_{DM} = \frac{1}{4} \eta_B \]

\[ \eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} \]

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

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Puzzles of SM & Cosmology

I) Particle physics of Inflation
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Curious cosmological coincidences $\eta_B \simeq 0.3\, P_\zeta$ and $\Omega_{DM} \simeq 5\Omega_B$!

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

SM as a particle physics model also faces some conceptual issues
Gauge Fields & Inflation
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?
**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?**
  1. Can Gauge Fields Contribute to Physics of Inflation? **Yes!**
  2. Do they leave an observable signature? **Yes!** Robust prediction for GW background.
  3. How much they can change the cosmic history? **A lot!** Novel mechanisms for Baryo- and Dark-genesis.

\[
E_{\text{Inf}} < 10^{14} \text{GeV}
\]

Comparing to LHC
\[
\frac{E_{\text{Inf}}}{E_{\text{LHC}}} < 10^{11} \text{ !!!}
\]
**Challenges:**

1) Conformal symmetry of Yang-Mills
gauge field dilutes like $A_\mu \sim 1/\alpha$

2) Respecting gauge symmetry
Not to break gauge symmetry explicitly

Adding new terms to the gauge theory

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

or

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

Axion

Gauge field (active in inflation)

Axion inflaton

$A_\mu$
**Challenges:**

1) Conformal symmetry of Yang-Mills gauge field dilutes like $A_\mu \sim 1/\alpha$

2) Respecting gauge symmetry
   Not to break gauge symmetry explicitly

3) Spatial isotropy & homogeneity
   
   - $U(1)$ vacuum $A_\mu$
   - $SU(2)$ vacuum $A_\mu = A^a_\mu T_a$

   Adding new terms to the gauge theory
   
   $$\frac{\kappa}{384} (F \tilde{F})^2$$
   or
   $$\frac{\lambda}{8f} F \tilde{F} \varphi$$

   Axion

   Spatially isotropic
   
   $A^a_i = Q(t) \delta^a_i$

   so(3) & su(2) are isomorphic
\[ S_{Gf} = \int d^4 x \sqrt{-g} \left( -\frac{R}{2} - \frac{1}{4} F^2 + \frac{\kappa}{384} (F\widetilde{F})^2 \right) \]

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

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

- **Chromo-natural**  
  P. Adshead, M. Wyman, 2012
SU(2)-Axion Model Building

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  P. Adshead, M. Wyman, 2012

Ruled-out by the data
R. Namba, E. Dimastrogiovanni, M. Peloso 2013
P. Adshead, E. Martinec, M. Wyman 2013
+ Theoretical issue: Very large \( \lambda \sim 100 \! \rightarrow \)
D. Baumann & L. McAllister 2014

Inspired by them, several different models with SU(2) fields have been proposed and studied.
An incomplete list of Different Realizations of the SU(2)-Axion Inflation:

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SU(2)-Axion Model Building

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  *P. Adshead, M. Wyman, 2012*

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

*R. Namba, E. Dimastrogiovanni, M. Peloso 2013*  
*P. Adshead, E. Martinec, M. Wyman 2013*  
*D. Baumann & L. McAllister 2014*  
*Very large \( \lambda \sim 100! \)*

*P. Adshead et. al 2013*  
*Dimastrogiovanni et. al 2013*  
*A. M. et. al, 2013*  
*A. M. 2014 & A.M. 2016*  
*R. Caldwell et. al 2017*  
*A. M. et. al 2017 & 2018*  
*A.M. 2019*
**SU(2)-Axion Model Building**

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

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- **Minimal Scenario of SU(2)-axion inflation**  
  A. M., 2016  
  \[ f < 0.1 \text{ Mpl} \text{ & } \lambda < 0.1 \]

  *Axion Monodromy*

---

Ruled-out by the data  
+ Theoretical issue: Very large $\lambda \sim 100!$
How to Connect them with the SM?

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

- **Left-Right Symmetric Model + axion!**

- **Minimal Scenario of $SU(2)$-axion inflation**

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

  Axion Monodromy

  **A. M., 2016**  \( f < 0.1 \) MPl & \( \lambda < 0.1 \)

**Gauge field is $SU(2)_R$**

**A. M. arXiv: 2012.11516**
Left-Right Symmetric Model

- An SU(2) gauge extension of SM with 3 Right-handed Neutrinos coupled to it.

Gauge Bosons

- SU(3) × U(1) × SU(2) × SU(2)
- SU(2) × SU(2) × U(1)
- Spontaneous Symmetry Breaking

Quarks

- u, c, t
- d, s, b

Leptons

- e, μ, τ
- νₑ, ν₁, ν₉
- Nₑ, N₃, N₉

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

\[ SU(3) \times U(1) \times SU(2) \times SU(2) \]

- SU(3) x U(1) x SU(2) x SU(2)
- B-L

\[ g, \gamma, Z_L, Z_R, W^\pm_L, W^\pm_R \]

Quarks

\[ u, c, t, d, s, b \]

Leptons

\[ e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau, N_e, N_\mu, N_\tau \]

Higgs sector

\[ \phi, \Delta_R, \Delta_L \]

\[ SU(2)_L \times SU(2)_R, SU(2)_R \text{ triplet}, SU(2)_L \text{ triplet} \]

Minimal Left-Right Symmetric model

\[ SU(2)_L \times SU(2)_R \times U(1)_Y \]

Spontaneous Symmetry Breaking

\[ \langle \Delta_R \rangle \neq 0 \]

Massive

\[ N_i, W^\pm_R, Z_R \]

References:

Left-Right Symmetric Model

- An SU(2) gauge extension of SM with 3 Right-handed Neutrinos coupled to it.


1. Ad hoc parity violation
2. Accidental B-L global symmetry
3. Vacuum Stability problem
4. Strong CP problem
**Left-Right Symmetric Model**

- **An SU(2)** gauge extension of SM with 3 Right-handed Neutrinos coupled to it.

### Gauge Bosons

- SU(3) × U(1) × SU(2) × SU(2)
  - g
  - γ
  - Z_L
  - Z_R
  - W_L^±
  - W_R^±

### Quarks

- u
- c
- t
- d
- s
- b

### Leptons

- e
- μ
- τ
- ν_e
- ν_μ
- ν_τ

### Higgs sector

- φ
- Δ_R
- Δ_L

- Axion is the inflaton which is coupled to SU(2)_R

SU(2)\textsubscript{R} -axion Inflation

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

Axion inflaton $\varphi$  ___________  Gauge field (active in inflation)
SU(2)\textsubscript{R} Gauge Field

\[ \delta A^a_i = B^a_\pm(t, k)e^\pm_i(k) \]

\[ B''_\pm + [k^2 \mp \xi kH] B_\pm \approx 0 \]

**effective frequency**

Given by the BG \( \xi = \frac{2\lambda\partial t\phi}{fH} \)

**Vacuum structure**

- Axion field \( \langle \phi \rangle \)
- Slow-roll Axion
- Slow-roll \( A \)
- Parity

\( (\xi > 0) \)

\( (\xi < 0) \)
\[ \delta A^a_i = B^a_{\pm}(t, k)e^\pm_i(\vec{k}) \]
\[ B''_{\pm} + [k^2 \mp \xi kH] B_{\pm} \approx 0 \]

**Effective Frequency**

Given by the BG \((\xi = \frac{2\lambda \partial_t \phi}{f_H})\)

**Vacuum Structure**

Axion field \(\langle \varphi \rangle\)

(\(\xi > 0\))

Slow-roll \(A\)

Parity

(\(\xi < 0\))

**For \(\xi > 0\)**

Short tachyonic growth of \(B_+\)

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

**Chiral Field**

Particle Production

**SU(2)\(_R\)** Gauge Field
Gauge Field sources Primordial GWs

\[ \delta A_i^a \left( t, k \right) = B_i^a(t, k)e_i^\pm \left( k \right) \]

is governed by

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

That sourced the GWs

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

Gravitational waves have two uncorrelated terms

\[ h_\pm = h_{\pm}^{\text{vac}} + h_{\pm}^{\text{s}} \]

Vacuum GWs unpolarized

\[ h_+^{\text{vac}} = h_-^{\text{vac}} \]

Sourced by \( B_\pm \)

Polarized

\[ h_+ \neq h_- \]
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!
Novel Observable Signature: Beyond CMB

• Comparison of sensitivity curves for LiteBIRD, Planck, LISA & BBO.
Sources of Parity violation on CMB:

- **Cosmic Birefringence**: axion-photon coupling $\varphi F \tilde{F}$
- **Gravitational Chern-Simons**: axion-graviton coupling $\varphi R \tilde{R}$
- **SU(2)-axion Inflation**: SU(2) field-Graviton coupling

B. Thorne et. al. 2018
Lepton & quark Production by $SU(2)_R$
Lepton & quark Production in Inflation

- Left-handed fermions are diluted by inflation, BUT
- Right-handed fermions are generated by $SU(2)_R$ gauge field:
Lepton & quark Production in Inflation

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

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

\[ \nabla_\mu J_5^\mu = \nabla_\mu J_5^\mu = \frac{g^2}{16\pi^2} tr[W\tilde{W}] \]

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

\[ \alpha_{inf}(\xi) \sim \frac{g^2}{(2\pi)^4} e^{2\pi \xi} \]
Chiral anomaly of $W_R$ in inflation produces $B=L$

Energy

$\left(\frac{M_{Pl}}{H}\right)^{\frac{1}{2}}$

$\Lambda_F = \frac{m_{W_R}}{g_R}$

$T_{W_R}$

$T_{reh}$

$\Lambda_{EW} = 246$ GeV

Quantum Effects in Inflation: common origin for Baryogenesis & Cold DM

Inflation
\[ T_{\text{reh}} > m_{W_R} \]

- \( W_R \) Sphalerons Never in Equilibrium
- \( T_{\text{reh}} < T_{W_R} \)
- Freeze-out Mechanism
- Freeze-in Mechanism
Summary of the mechanism:

Chiral anomaly of SU(2)R in inflation

Freezeout of Ni

EW scale

B = L = 3n_{CS}

B - L_{SM} ≠ 0

Baryogenesis

\[ n_B^0 \approx 3 \left( \frac{g_{\text{eff}}}{100} \right)^{\frac{3}{4}} \frac{\alpha_{\text{inf}}}{(\delta_{\text{reh}})^{\frac{3}{4}}} \left( \frac{H}{M_{\text{Pl}}} \right)^{\frac{3}{2}} \]

\[ \Omega_{N_1} \approx 2.8 \frac{m_{N_1}}{m_p} \Omega_B \]

m_{N_1} ≈ 1.8 m_p = 1.7 \text{ GeV.}
This setup prefers Left-Right symmetry breaking scales above $m_{WR} = 10^{10}$ GeV!
(same as scales suggested by the non-SUSY SO(10) GUT models with intermediate LR symmetry scale.)
Compelling Consequences:

I) Particle physics of Inflation
II) Origin of matter asymmetry
III) Origin of Neutrino mass
IV) Particle nature of DM

Curious cosmological coincidences $\eta_B \approx 0.3 \, \rho_\zeta$ and $\Omega_{DM} \approx 5 \Omega_B$!

Questions

- What do Gauge Fields do in Inflation? May be coupled to axion inflaton
- Does it come with a cosmological signature? Yes! Chiral, non-Gaussian GWs.
- How Inflaton & its Gauge Field are connected to the SM? Left-Right Symmetric Model + axion!
- (Is there a simple, elementary & minimal set-up that can solve all the above issues? Yes!)
  This Set-up is a complete beyond SM that can solve I-IV & explain !
Minimal Set-up:
- Inflation Particle Physics: a scalar singlet BSM
- Unpolarized, Gaussian GWs
- Baryon asymmetry (BAU):
  - CP violating phases in neutrino sector
- Sterile neutrino DM: \( m_{N_1} = O(10) \text{keV} \) & x-ray radiation!

SU(2)\(_R\) – Axion Inflation:
- Inflation Particle Physics (BSM):
  - Axion & its SU(2) Gauge Field
  - Chiral, non-Gaussian GWs
  - BAU: Spontaneous CP violation in inflation
  - Right neutrino DM: \( m_{N_1} = O(1) \text{GeV} \) & gamma-ray radiation!
  - Simultaneous Baryon & DM production in inflation
  - Explains coincidences among cosmological parameters \( \eta_B \sim P_R \) & \( \Omega_{DM} \approx 5 \Omega_B \)
Questions?!