Affleck-Dine Leptogenesis with One Loop Neutrino Mass and a solution to Strong CP problem

Nobuchika Okada

University of Alabama

Based on

Rabindra N. Mohapatra (U of Maryland) & NO,
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1. Five Questions that the Standard Model cannot answer

(5 Major Problems of the SM)

Five Questions that the Standard Model cannot answer

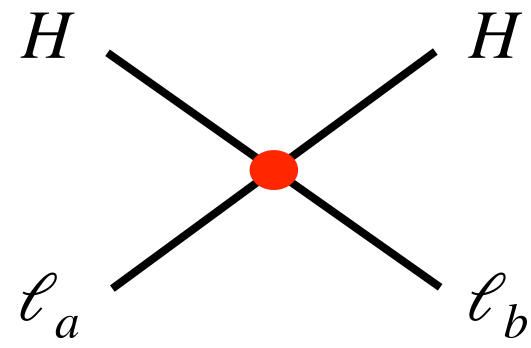
1. Why are Neutrino Masses are non-zero and so tiny?
2. What is the nature of Dark Matter?
3. Why is CP-violation in QCD so negligible?
4. What drives Cosmic Inflation before Big Bang?
5. What is the origin of Matter-Antimatter asymmetry in the Universe?

2. Possible solution to each problem

1. Effective Theory for Neutrino Mass Generation

Dim. 5 operators (Weinberg operator) consistent with the SM gauge symmetry

$$\mathscr{L}_5 = -\frac{c_{ab}}{\Lambda}\ell_a \ell_b HH$$

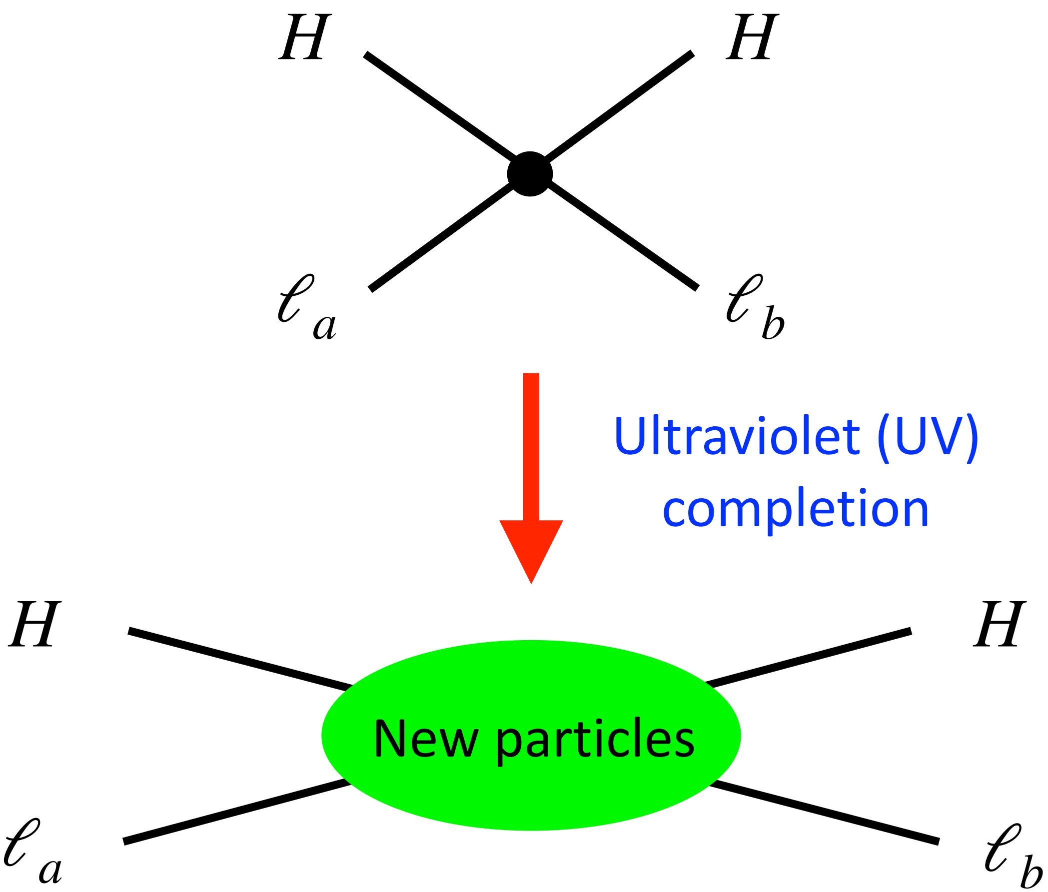


After the electroweak (EW) symmetry breaking,

$$\langle H \rangle = \frac{1}{\sqrt{2}}\begin{bmatrix} 0 \\ v_{EW} \end{bmatrix}, \quad \mathscr{L}_5 \to -m_\nu^{ab}\nu_a \nu_b$$

Majorana mass: $m_\nu^{ab} = c_{ab} v_{EW} \times \frac{v_{EW}}{\Lambda} \ll v_{EW}$, for $v_{EW} \ll \Lambda / c_{ab}$

For Ultraviolet (UV) completion, the dim-5 operators from integrating out heavy states (at tree-level/loop-levels)



Seesaw mechanism at tree/loop level

2. Dark Matter as a new particle

DM candidate: Massive Particle/Oscillating scalar field

$Q_X = 0, \tau_X \gg \tau_U$ & Presser-less Equation of State (w=0)

The observed DM density measured by Planck 2018:

$$\Omega_{DM} h^2 = 0.12$$

This must be reproduced by some physics processes

3. QCD axion model for solving the strong CP problem

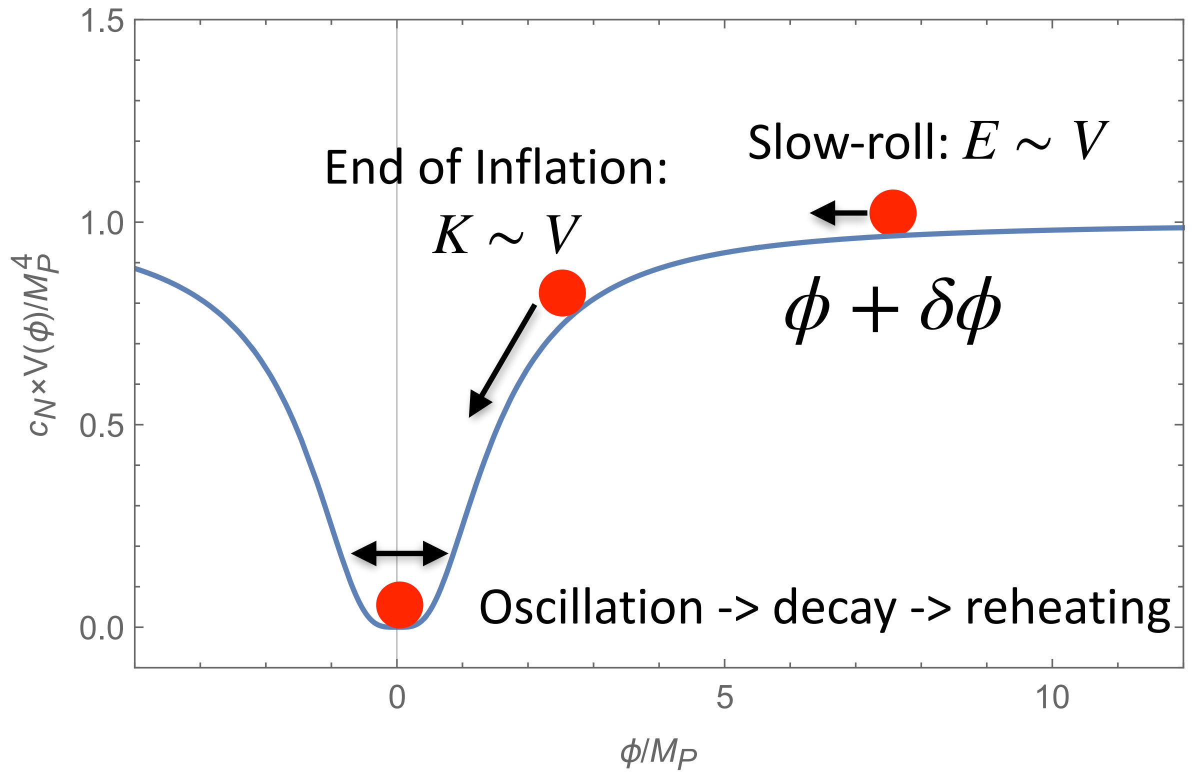
A solution proposed by Peccei & Quinn (1977)

- Extend the SM to incorporate a global PQ symmetry and a complex scalar to spontaneously break at f_a
- Nambu-Goldstone boson (axion ``a”) arises and has a coupling:

$$\mathscr{L} \supset \frac{g_s^2}{32\pi^2} \frac{a}{f_a} \sum_{c=1}^{8} G^c_{\mu\nu} \tilde{G}^{c\mu\nu}$$

- The CP-violating parameter θ is replaced by the field axion
- $\langle a \rangle = 0$ is realized at the axion potential minimum
- Bonus: axion is a good candidate of DM for $f_a \sim 10^{12}$ GeV!

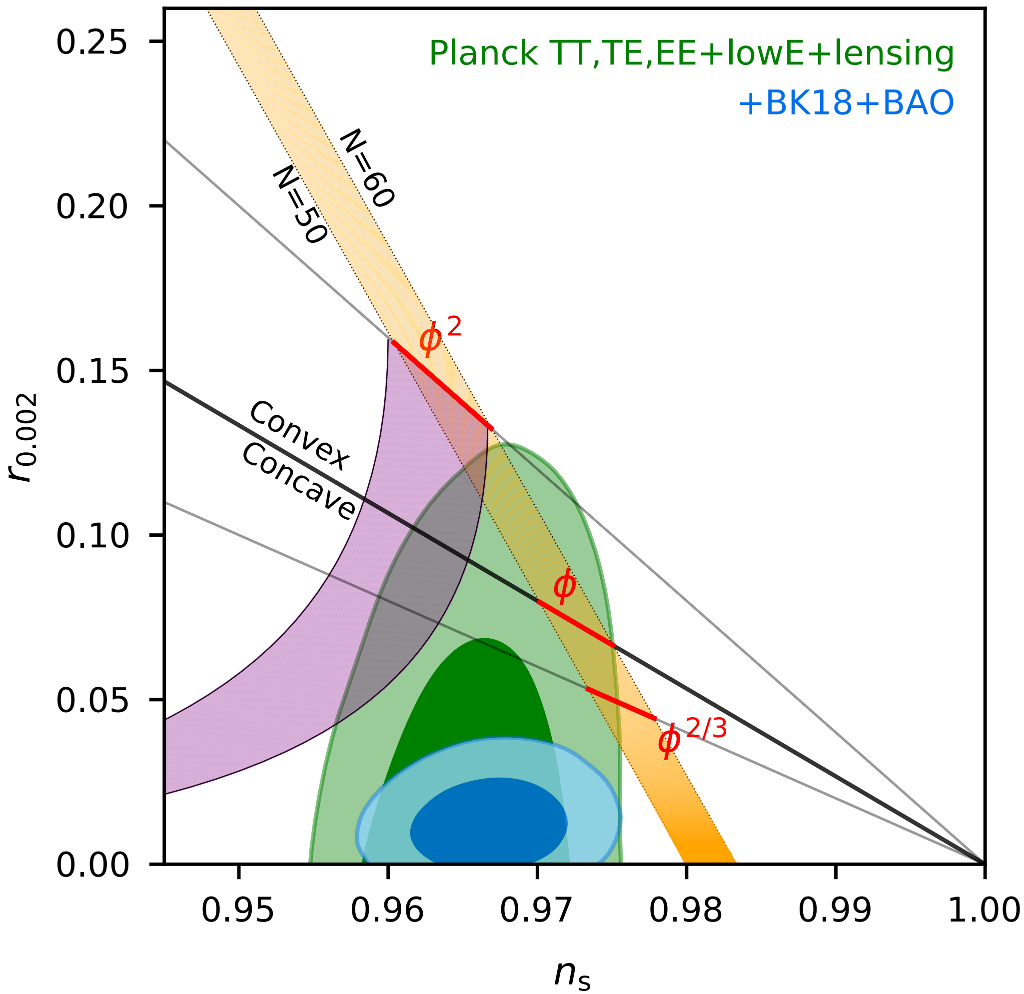
4. Slow-roll inflation to drive the cosmic inflation



- Inflation takes place during slow-roll: $a(t) \propto e^{H_{inf}t}$
- Quantum fluctuation $\delta\phi$ is magnified to a macroscopic scale —> primordial density fluctuation

Constraints on inflation scenario from CMB observations

BICEP/Keck 2018
PRL 127 (2021) 151301



Power spectrum of scalar perturbation:

$$P_S(k_0) = 2.099 \times 10^{-9}$$

$$k_0 = 0.05\ \mathrm{Mpc}^{-1}$$

Spectral index:

$$n_s = 1 + \frac{d \ln P_S}{d \ln k} \simeq 0.965$$

Tensor-to-scalar ratio:

$$\frac{P_T}{P_S} = r \leq 0.036\ (95\%)$$

A successful inflation scenario: non-minimal $\lambda\phi^4$ inflation

Action in the Jordan frame:

See, for example,
NO, Rehman & Shafi, PRD 82 (2010) 04352

$$\mathcal{S}_J = \int d^4x\sqrt{-g}\left[-\frac{1}{2}f(\phi)\mathcal{R} + \frac{1}{2}g^{\mu\nu}\left(\partial_\mu\phi\right)\left(\partial_\nu\phi\right) - V_J(\phi)\right]$$

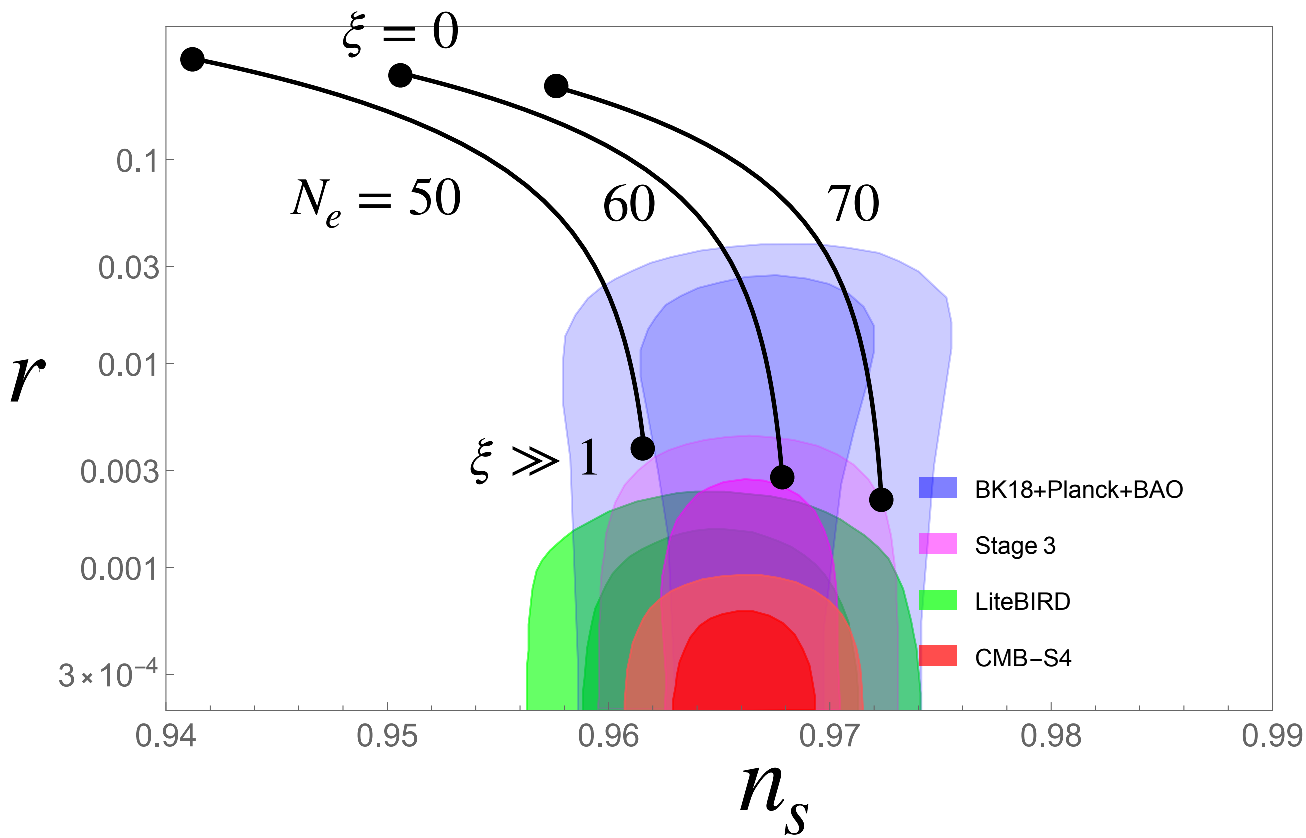
- Non-minimal gravitational coupling

$$f(\phi) = M_P^2 + \xi\phi^2$$ with a real parameter $\xi > 0$

- Quartic coupling dominates during inflation

$$V_J(\phi) = \frac{1}{4}\lambda\phi^4$$

Inflationary Predictions VS Planck+BK18+BAO results



- Once N_e is fixed, only 1 free parameter (ξ) determines the predictions
- Predicted GWs are $r \gtrsim 0.003$

Future experiments (CMB-S4, LiteBIRD) will cover the region!

Non-minimal $\lambda\phi^4$ inflation

- Simple 1-field inflation with the introduction of $\xi|\phi|^2 R$
- Consistent with Planck + others with a suitable choice of quartic coupling $\lambda|\phi|^4$
- Potentially, any scalar can play the role of inflaton

5. Affleck-Dine (AD) Baryogenesis (Affleck-Dine, 1985)

- A complex scalar field carries B/L number

$$\Phi = \frac{1}{\sqrt{2}} \left(\phi_1 + i\phi_2 \right)$$

- AD field potential includes B/L violating term(s)

$$\mathscr{L} \supset \partial_\mu \Phi^\dagger \partial^\mu \Phi - V \quad \text{with } V = V_{sym}(\Phi^\dagger \Phi) + \left(V_{asym}(\Phi, \Phi^\dagger) + h.c. \right)$$

- A suitable initial condition of the AD field away from the potential minimum

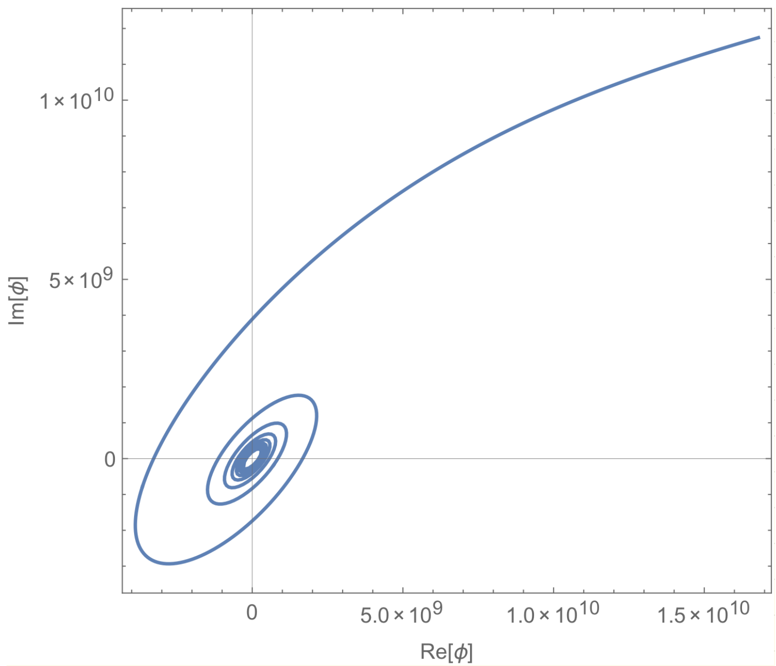
- During the evolution of the AD field, the B/L number is generated

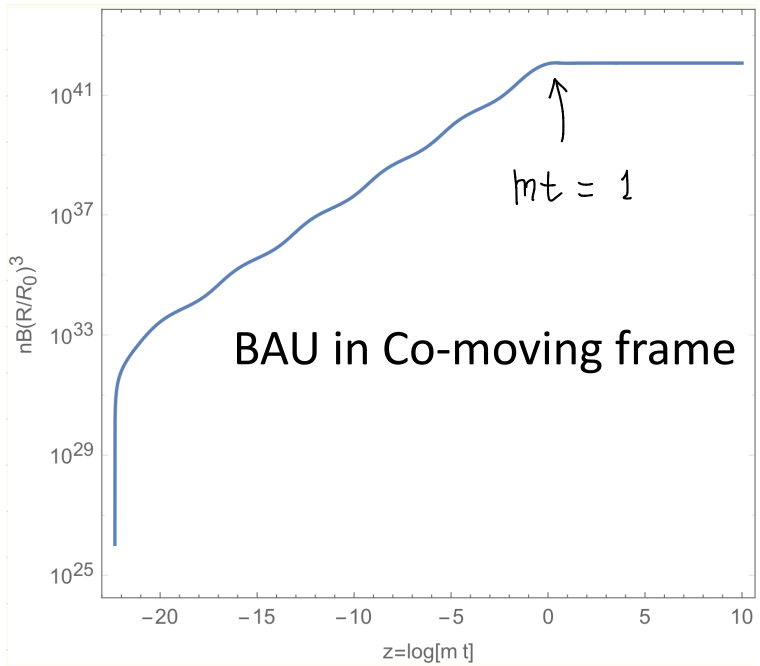
$$n_B(t) = Q_\Phi (\dot{\phi}_1 \phi_2 - \dot{\phi}_2 \phi_1)$$

$$\dot{n}_B + 3H n_B = 2Q_\Phi \mathrm{Im} \left(\frac{\partial V}{\partial \Phi^\dagger} \Phi^\dagger \right)$$

Sample: AD field evolution & baryon number generation

Illustration purpose (not a realistic value)





- Generated B/L asymmetry is transferred the SM thermal plasma by the AD field decay with B/L conserving interactions: $\mathscr{L}_{int} \sim \Phi\mathcal{O}_{SM}$ or $\Phi\mathcal{O}_{BSM}$

It would be interesting to ask the following questions:

AD field = Inflaton?

Recently, the models in which the AD field is identified with inflaton have been proposed several groups:

Chang, Lee, Leung & Ng (2009);
Hertzberg & Karouby (2014);
Takeda (2015);
Babichev, Gorbunov & Ramazanov (2019);
Cline, Puel & Toma (2020);
Lloyd-Stubbs & McDonald (2021);
Kawasaki & Ueda (2021);
Barrie, Han & Murayama (2021)

A simple idea: Introduce non-minimal gravitational coupling to the AD field:

$$\mathcal{S} = \int d^4x \sqrt{-g} \left[-\frac{1}{2} M_P^2 f R + \partial_\mu \Phi^\dagger \partial^\mu \Phi - V(\Phi) \right]$$

where $f = 1 + 2\xi \frac{\Phi^\dagger \Phi}{M_P^2}$

Identify the AD field with the inflaton in the non-minimal $\lambda\phi^4$ inflation scenario

- During the inflation, the inflation potential is dominated by $V \sim \lambda_\Phi (\Phi^\dagger \Phi)^2$
- The AD baryogengesis takes place after inflation

We follow a simple AD=Inflaton scenario by Lloyd-Stubbs & McDonald (2021): AD=Inflaton carries B/L number

$$V(\Phi) = m_\Phi^2 \Phi^\dagger \Phi + \boxed{\epsilon m_\Phi^2 (\Phi^2 + \Phi^{\dagger 2})} + \lambda (\Phi^\dagger \Phi)^2$$

Explicit B/L violating term: $0 < \epsilon \ll 1$

Simple expression for the resultant B/L asymmetry:

$$\boxed{\frac{n_B}{s} \simeq \frac{3}{8} \sqrt{\frac{\pi^2}{90} g_*} \frac{Q_\Phi}{\epsilon} \frac{T_R^3}{m_\Phi^2 M_P} \sin(2\theta)}$$

for $\Gamma_\Phi / m_\Phi \ll \epsilon \ll 1$

Suitable choice of the model parameters, the successful inflation and the observed baryon asymmetry can be achieved!

3. A unified Model

``Partially unified'' pictures

2. Dark Matter

3. Strong CP problem

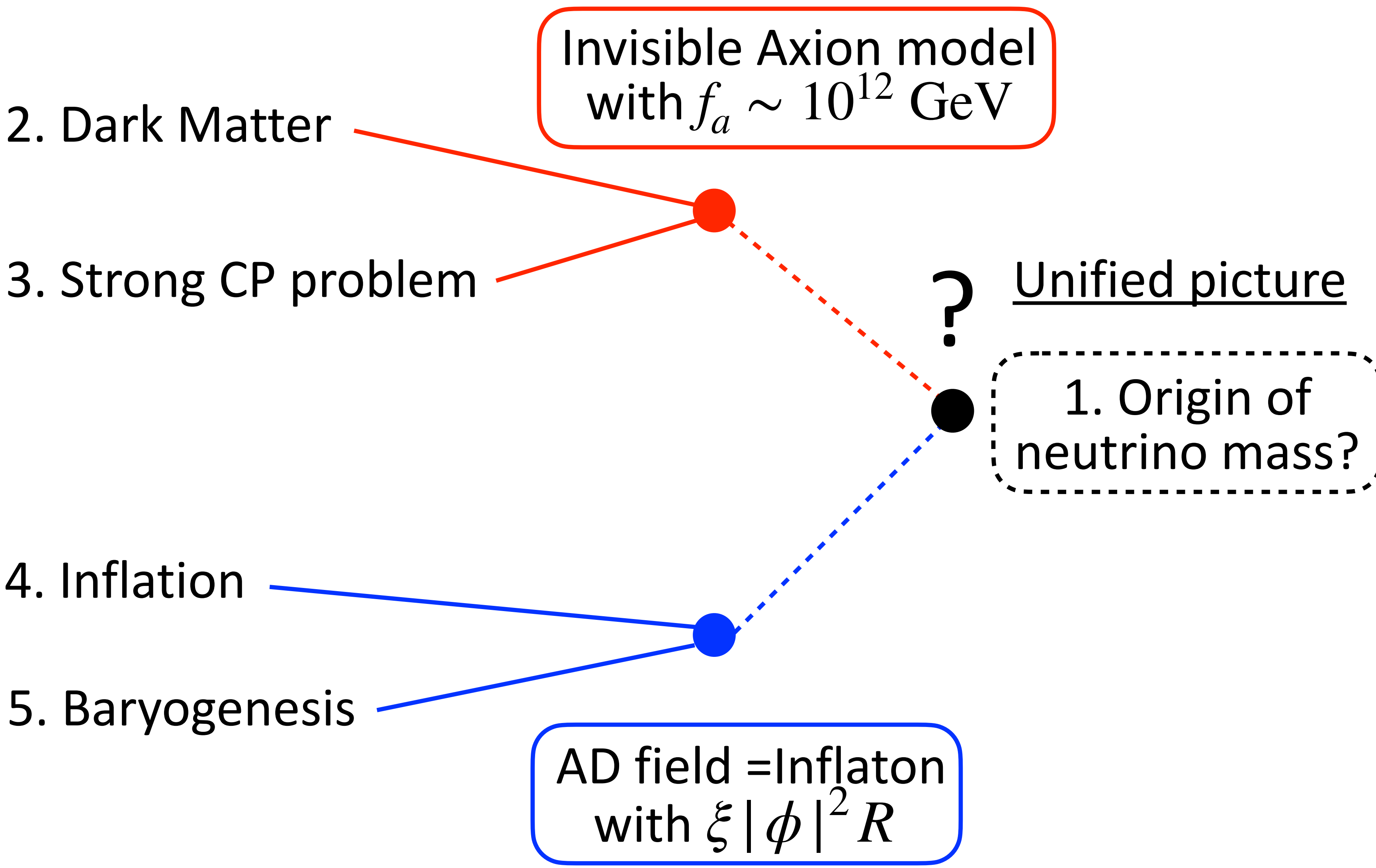
Invisible Axion model with $f_a \sim 10^{12}$ GeV

4. Inflation

5. Baryogenesis

AD field = Inflaton with $\xi |\phi|^2 R$

``Partially unified'' pictures



Particle content

Field	$U(1)_{PQ}$	SM quantum number	L
Fermion			
ℓ_a	$+1$	$(\mathbf{1}, \mathbf{2}, -1)$	$+1$
e_a^c	-1	$(\mathbf{1}, \mathbf{1}, +2)$	-1
q	$+1$	$(\mathbf{3}, \mathbf{2}, +1/3)$	0
u^c	-1	$(\mathbf{3}^*, \mathbf{1}, -4/3)$	0
d^c	-1	$(\mathbf{3}^*, \mathbf{1}, +2/3)$	0
Q	-1	$(\mathbf{3}, \mathbf{1}, -2/3)$	$+1/2$
Q^c	$+2$	$(\mathbf{1}, \mathbf{3}^*, \mathbf{1}, +2/3)$	$+1/2$
χ_i	0	$(\mathbf{1}, \mathbf{1}, 0)$	0
Scalars			
σ	-1	$(\mathbf{1}, \mathbf{2}, +1)$	-1
H	0	$(\mathbf{1}, \mathbf{2}, +1)$	0
Φ	$+1$	$(\mathbf{1}, \mathbf{1}, 0)$	$+1$
Δ	-1	$(\mathbf{1}, \mathbf{1}, 0)$	-1

Vector-like exotic quarks

3 new singlet fermions $\neq$ RHNs

inert Higgs doublet like scalar

AD field = Inflaton

PQ scalar field

A unified framework for solving 5 major SM puzzles

I. Inflation driven by Inflaton/AD field

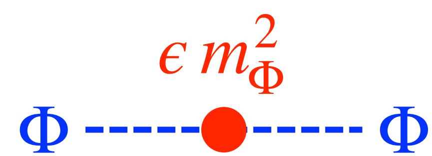
II. PQ sim. breaking by $\langle \Delta \rangle = f_a \sim 10^{12}$ GeV

KSVZ-type axion model: $Y_Q \Delta Q Q^c \rightarrow m_Q Q Q^c$

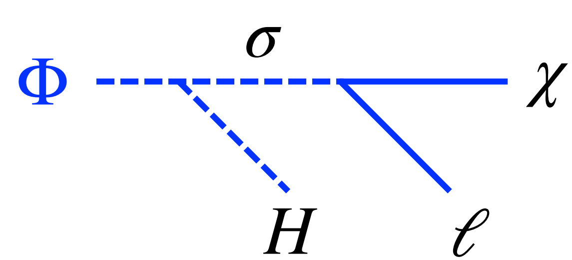
Lepton number violating term generation:

$$\lambda' \Delta^2 \Phi^2 \rightarrow \epsilon m_\Phi^2 \Phi^2$$

III. Lepton asymmetry generation during oscillation after inflation

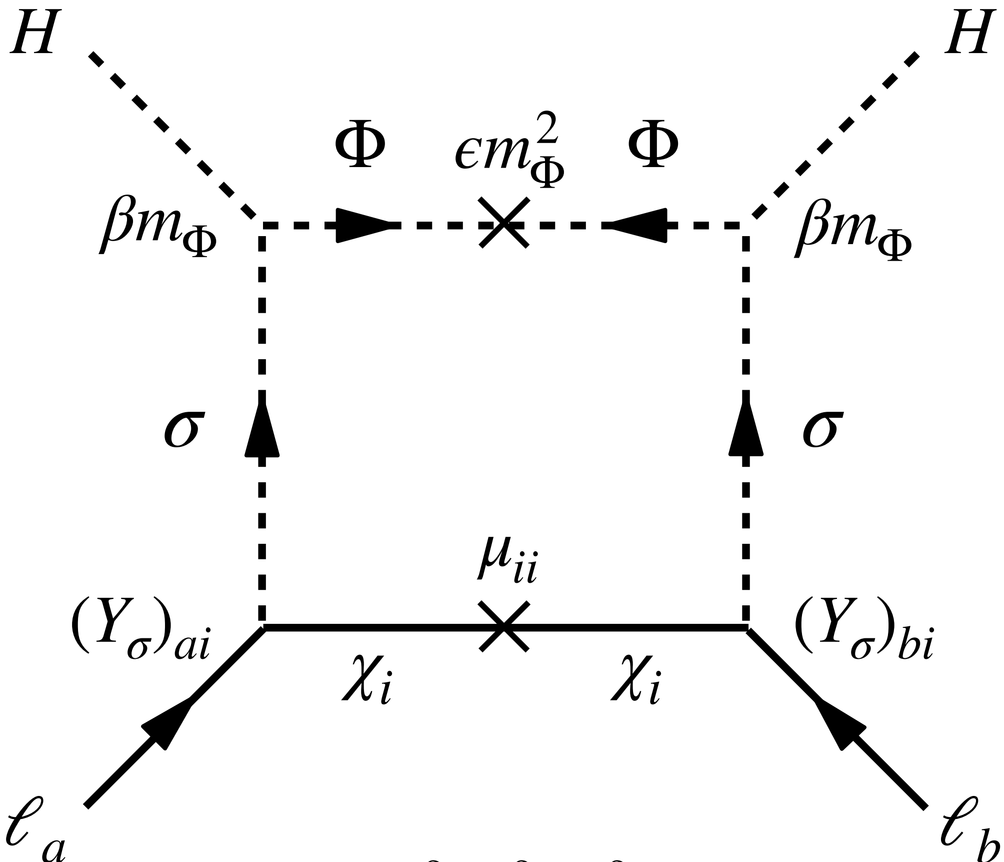


IV. Reheating & Lepton asymmetry transmission to the SM sector by inflaton/AD decay



V. Combining all diagrams

Radiative seesaw mechanism



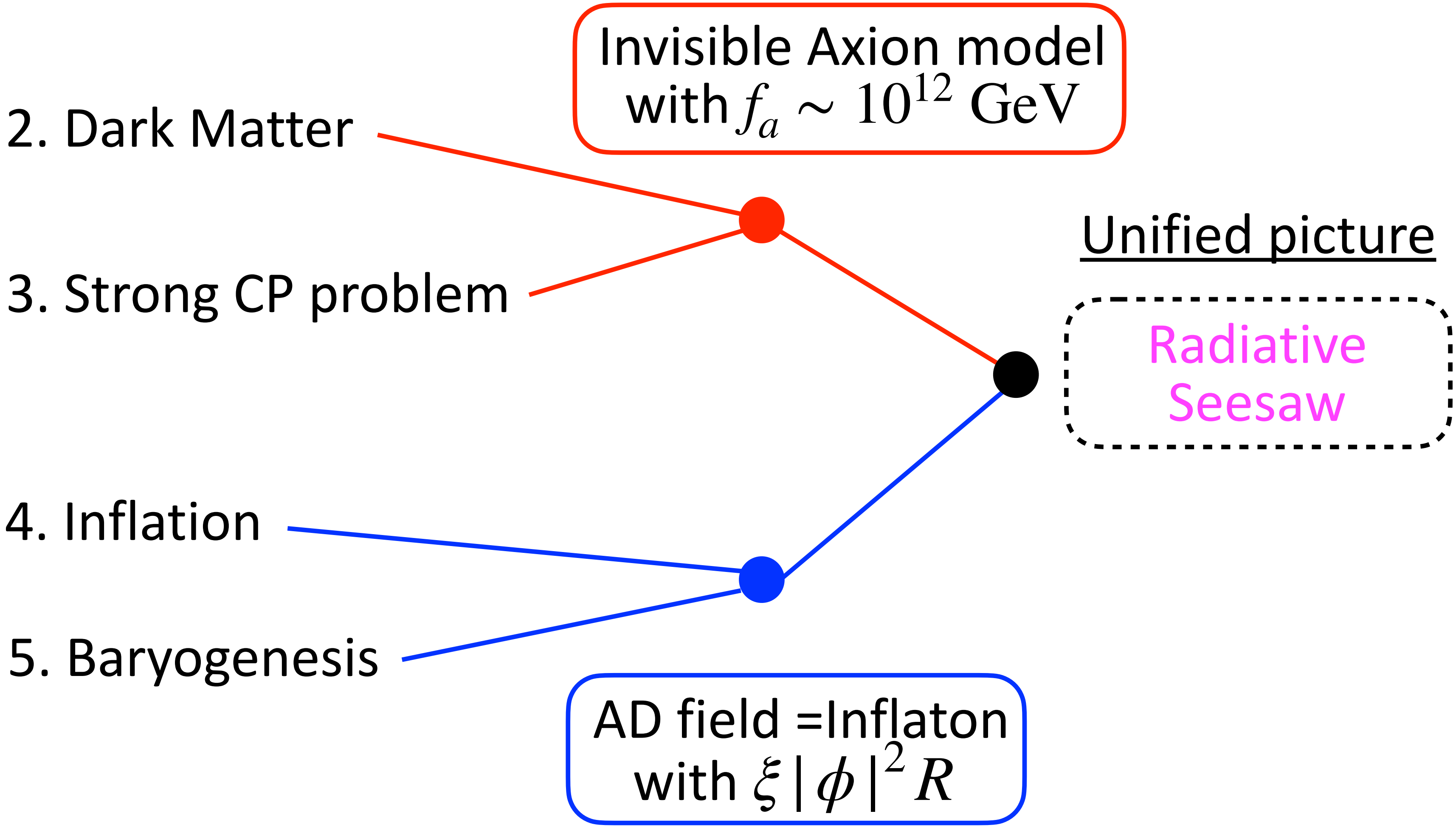
$$m_\nu = \frac{v_{wk}^2 \beta^2 \epsilon m_\Phi^2}{16\pi^2 m_\sigma^4} Y_\sigma \mu Y_\sigma^T$$

Phenomenologically viable Benchmarks

parameter	value(set 1)	value(set 2)
ϵ	10^{-5}	10^{-3}
T_R/m_Φ	0.1	0.1
m_Φ	10^6 GeV	10^8 GeV
$m_\sigma \sim \mu_{22,33}$	$10^{6.5}$ GeV	$10^{8.5}$ GeV
β	~ 1	~ 1
m_{χ_1}	≤ 1 eV	≤ 1 eV
m_{ν_1}	~ 0 eV	~ 0 eV

4. Summary

We have proposed a unified framework for solving 5 major puzzles of the Standard Model



Thank you

for your attention!