Recent Work with Rabi: A unified model for solving big problems of the Standard Model

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Based on

Rabindra N. Mohapatra & NO,
PRD 105, 035024 (2022) [arXiv: 2112.02069];
JHEP 03 (2022) 092 [arXiv: 2201.06151];
arXiv: 2207.10619

Rabi-Fest 2022 @ University of Maryland
Oct. 20-21, 2022

1. Five Questions that the SM cannot answer

Five Questions that the Standard Model cannot answer

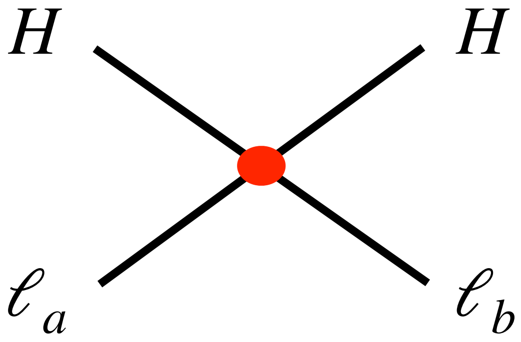
1. Why are Neutrino Masses are non-zero and so tiny?
2. What is the nature of Dark Matter?
3. Why is CP-violation in QCD so negligible?
4. What drives Cosmic Inflation before Big Bang?
5. What is the origin of Matter-Antimatter asymmetry in the Universe?

2. Possible solution to each problem

1. Effective Theory for Neutrino Mass Generation

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

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

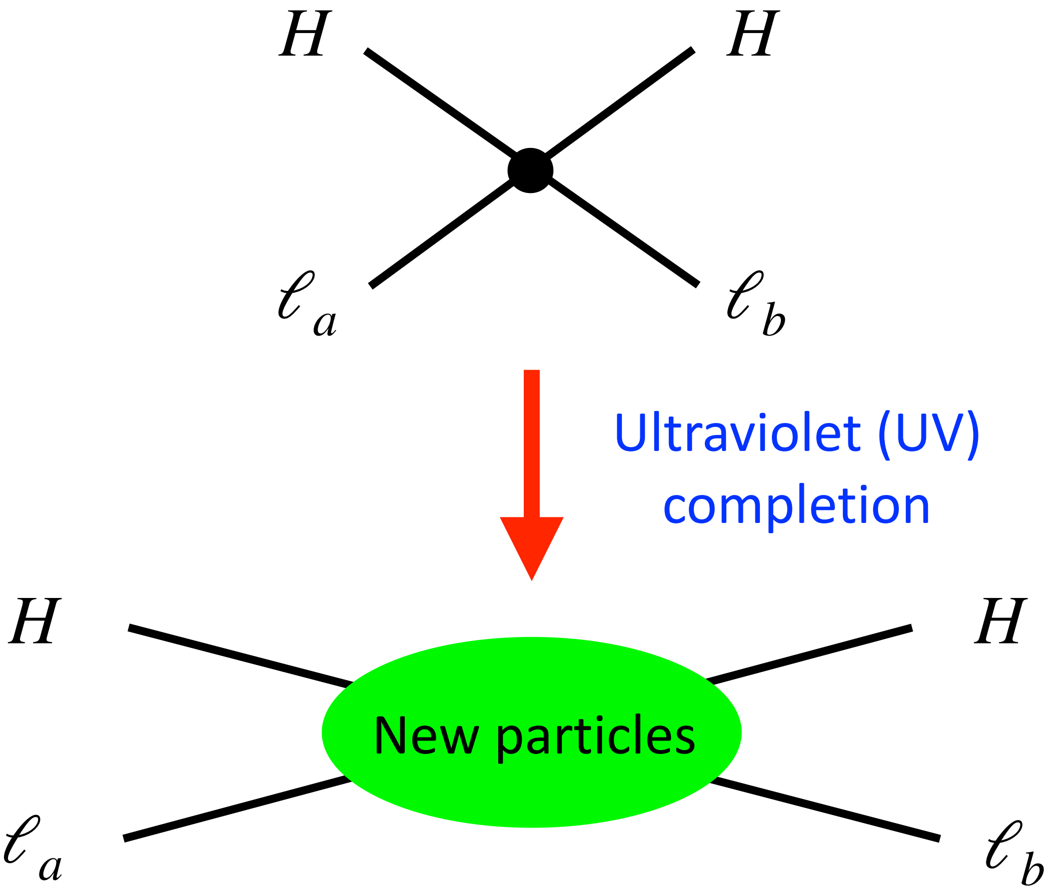


After the electroweak (EW) symmetry breaking,

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

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:

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

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)

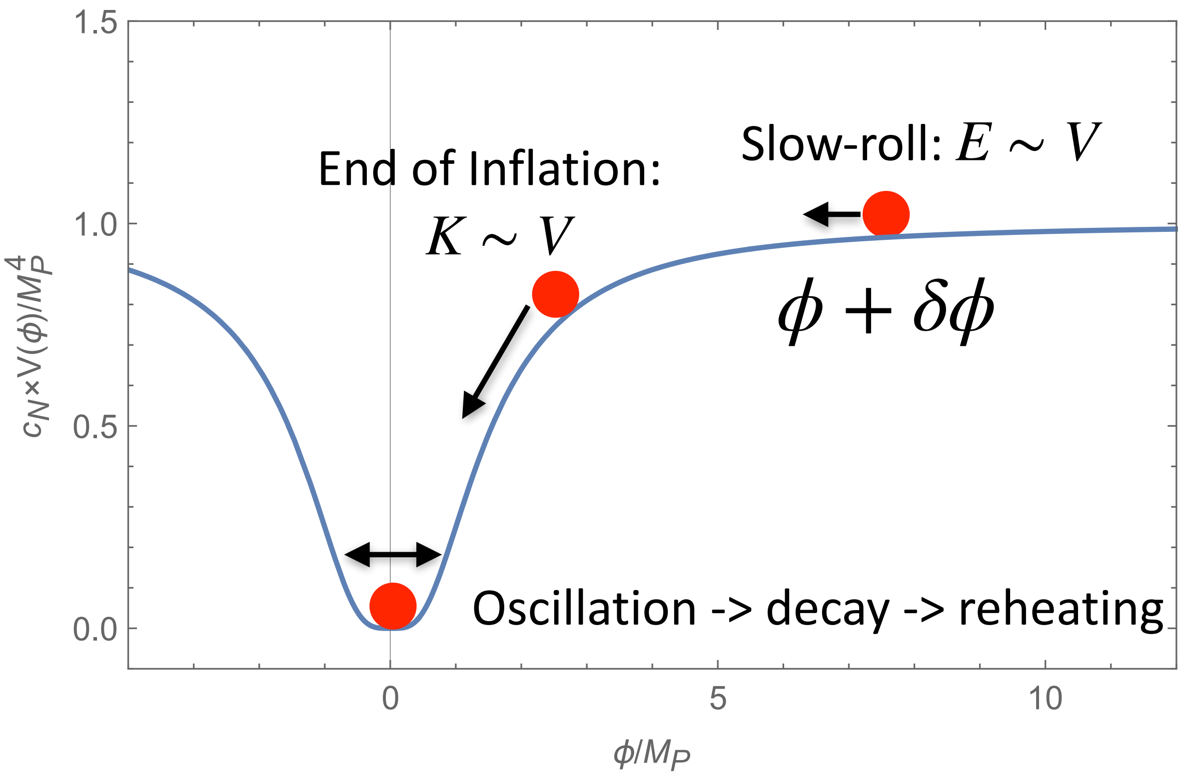
- Extend the SM to incorporate a global PQ symmetry and a complex scalar to spontaneously break at f_a
- Nambu-Goldstone boson (axion ``a") arises and has a coupling:

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

⬇

- 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 $f_a \sim 10^{12}\ \mathrm{GeV}!$

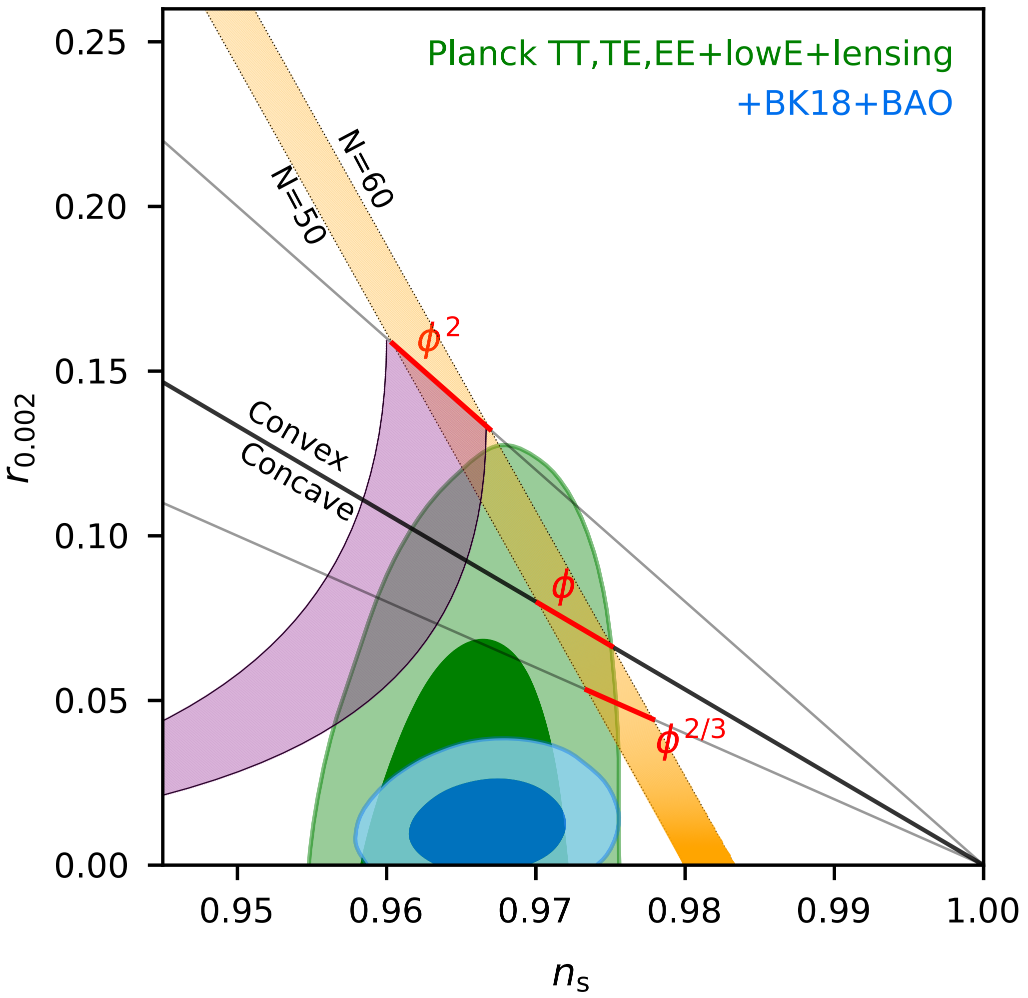
4. Slow-roll inflation to drive the cosmic inflation



- 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:

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

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

Spectral index:

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

Tensor-to-scalar ratio:

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

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

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

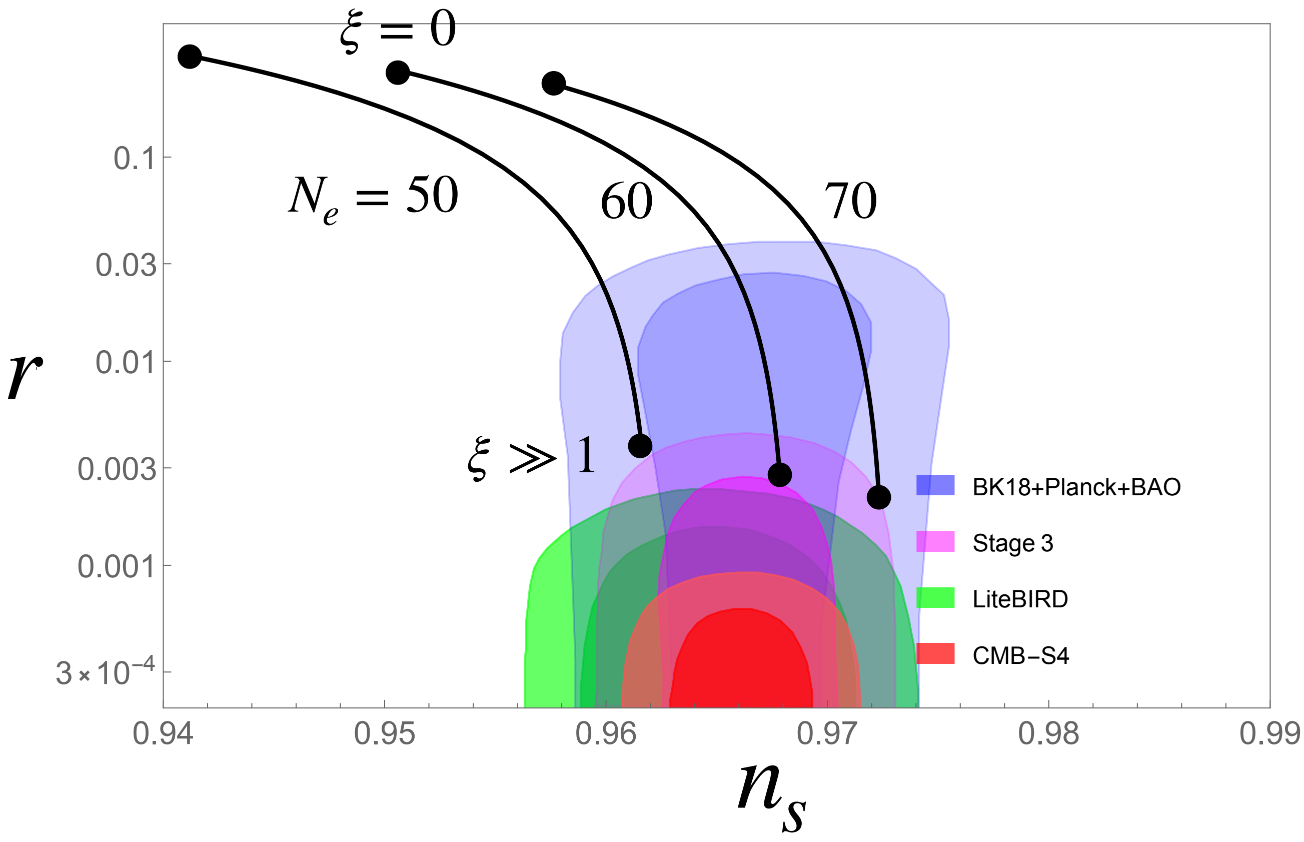
- Non-minimal gravitational coupling

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

- Quartic coupling dominates during inflation

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

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

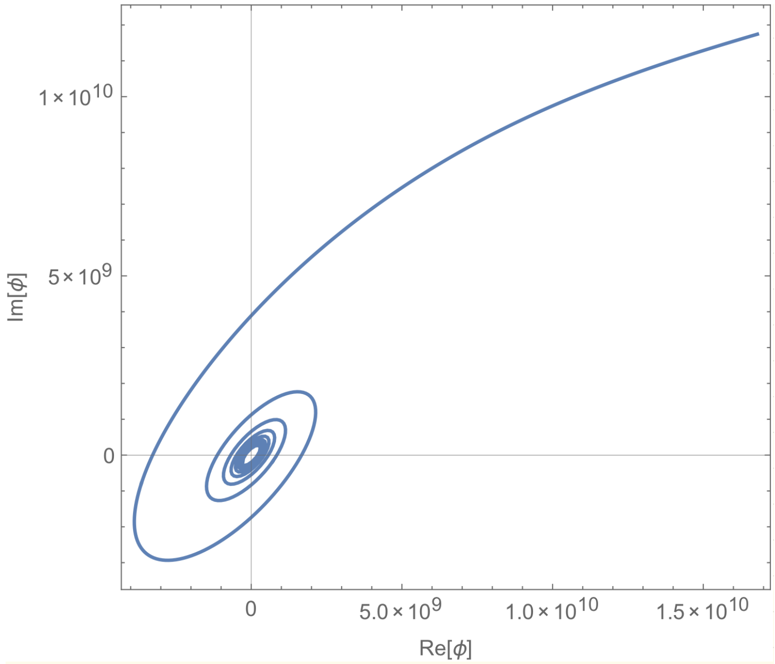
- During the evolution of the AD field, the B/L number is generated

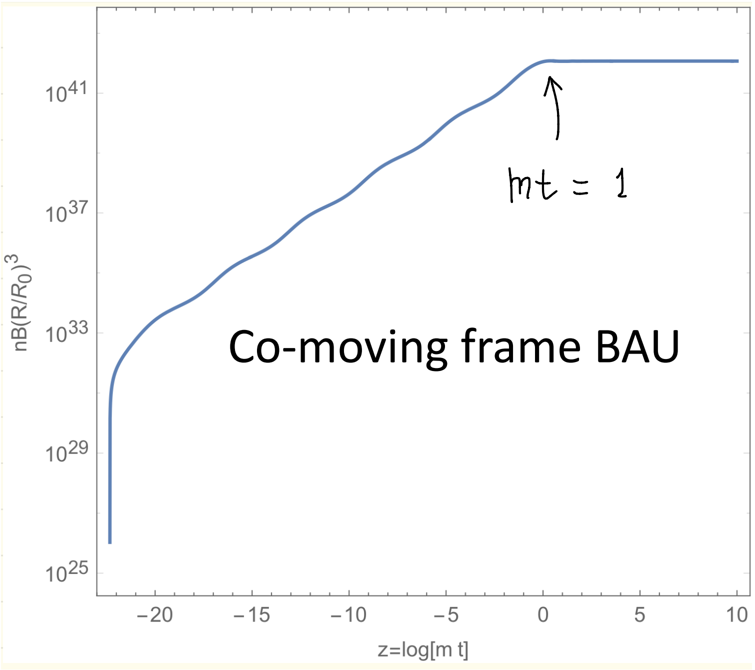
$$n_B(t) = Q_\Phi(\dot{\phi}_1\phi_2 - \dot{\phi}_2\phi_1)$$

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

Sample: AD field evolution & baryon number generation

Illustration purpose (not a realistic value)





mt = 1

Co-moving frame BAU

- Generated B/L asymmetry is transferred the SM thermal plasma by the AD field decay with B/L conserving interactions:

$$\mathscr{L}_{int} \sim \Phi\mathcal{O}_{SM} \text{ or } \Phi\mathcal{O}_{BSM}$$

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:

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

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

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: $0 < \epsilon \ll 1$

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

$$\boxed{\begin{aligned} \ddot{\phi}_1 + 3H\dot{\phi}_1 &= -m_1^2\phi_1 - \lambda(\phi_1^2 + \phi_2^2)\phi_1, \\ \ddot{\phi}_2 + 3H\dot{\phi}_2 &= -m_2^2\phi_2 - \lambda(\phi_1^2 + \phi_2^2)\phi_2, \end{aligned}}$$

where $m_1^2 = (1-2\epsilon)m_\Phi^2$, and $m_2^2 = (1+2\epsilon)m_\Phi^2$

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

AD=Inflaton field evolution in the early Universe

Step 1: non-minimal $V(\Phi) \sim \lambda(\Phi^\dagger\Phi)^2$ inflation

$$\phi_1 = \phi_{inf}\cos\theta \;\&\; \phi_2 = \phi_{inf}\sin\theta$$

Step 2: End of inflation & oscillation with $V(\Phi) \sim \lambda(\Phi^\dagger\Phi)^2$

$$\phi_{1,2} \propto \frac{1}{a(t)}, \;\; \theta(t) \simeq \text{const}$$

Step 3: Damped harmonic oscillation for $\boxed{\phi_i \lesssim m_\Phi/\sqrt{\lambda}}$ with

$$V(\Phi) \sim m_\Phi^2(\Phi^\dagger\Phi) + \epsilon m_\Phi^2(\Phi^2 + \Phi^{\dagger 2})$$

Asymmetric oscillations: $\boxed{\phi_i \propto a(t)^{-3/2}\,\cos(m_i(t - t_*))}$

—> Generation of B/L asymmetry

Step 4: Created B/L asymmetry is transferred to the SM sector by the inflaton/AD field decay at the reheating

Simple expression for the resultant B/L asymmetry:

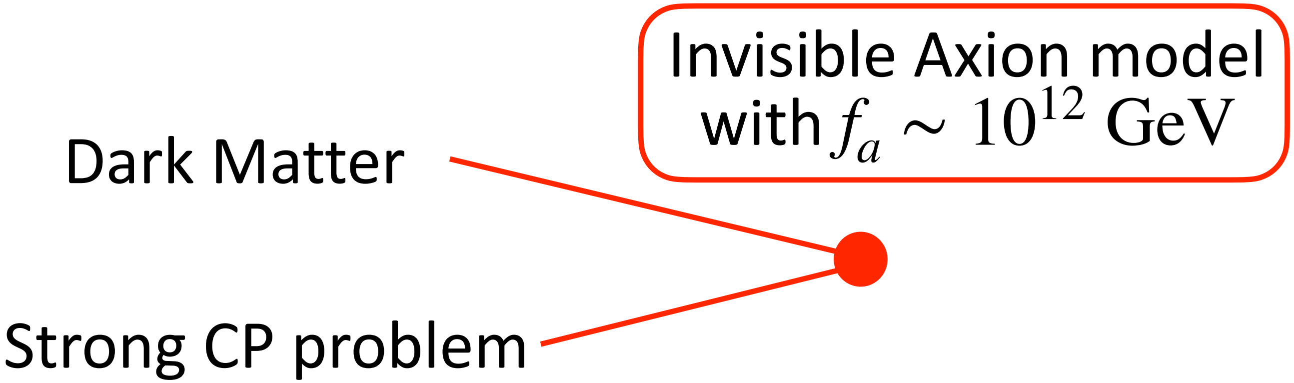
$$\boxed{\frac{n_B}{s} \simeq \frac{3}{8}\sqrt{\frac{\pi^2}{90}g_*}\,\frac{Q_\Phi}{\epsilon}\,\frac{T_R^3}{m_\Phi^2 M_P}\,\sin(2\theta)}$$

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

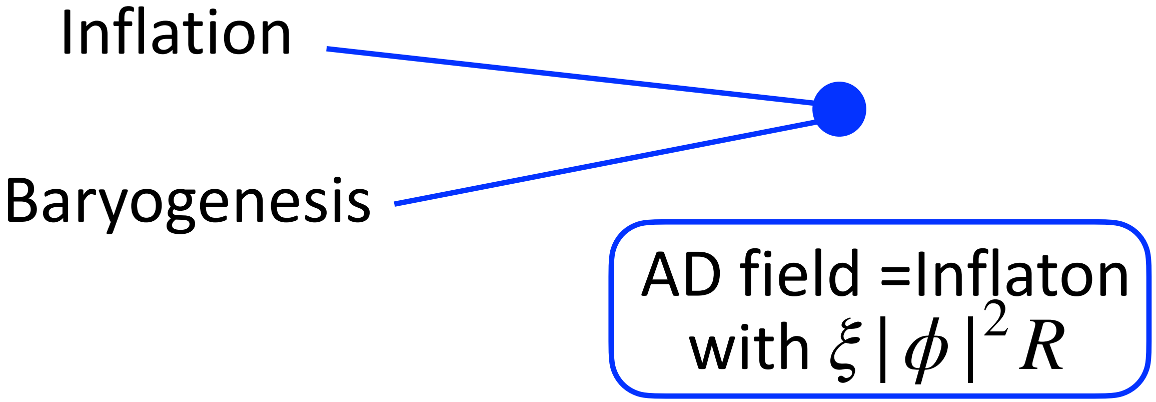
``Partially unified'' pictures



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

Dark Matter

Strong CP problem

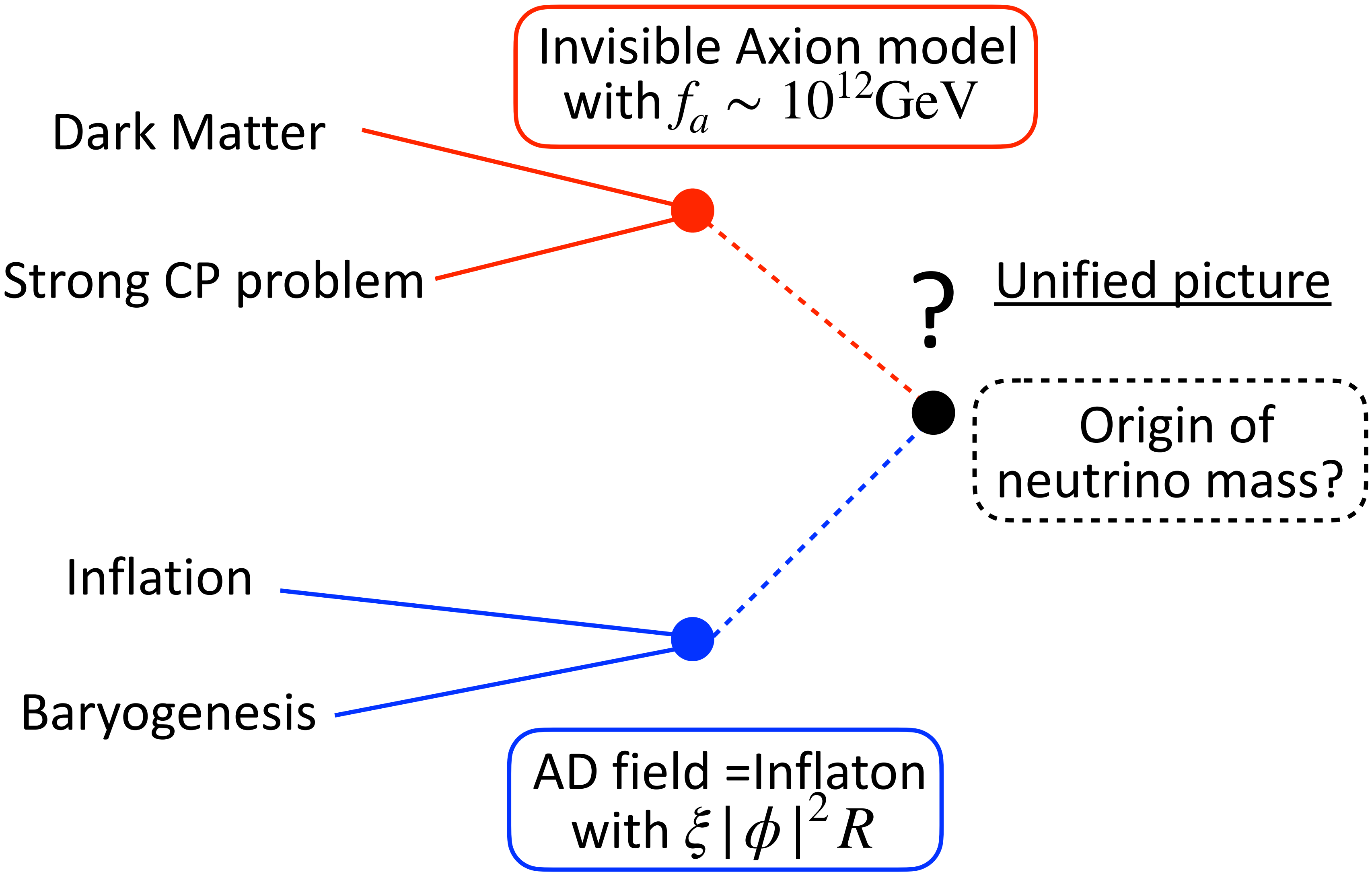


Inflation

Baryogenesis

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

``Partially unified’’ pictures



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

Dark Matter

Strong CP problem

?

Unified picture

Origin of neutrino mass?

Inflation

Baryogenesis

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

Particle content

Field	$U(1)_{PQ}$	SM quantum number	L
Fermion			
ℓ_a	$+1$	$(\mathbf{1}, \mathbf{2}, -1)$	$+1$
e^c_a	-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

AD field = Inflaton

PQ scalar field

A unified framework for solving 5 major SM puzzles

1. Inflation driven by Inflaton/AD field

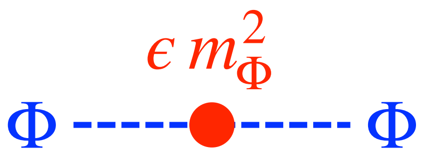
2. PQ sim. breaking by $\langle \Delta \rangle = f_a \sim 10^{12}\ \mathrm{GeV}$

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

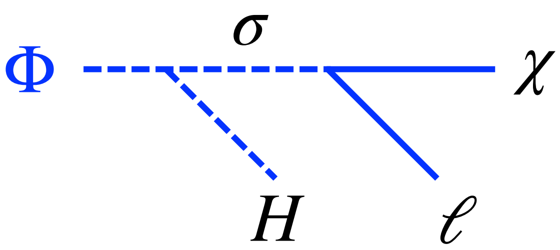
   Lepton number violating term generation:

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

3. Lepton asymmetry generation during oscillation after inflation

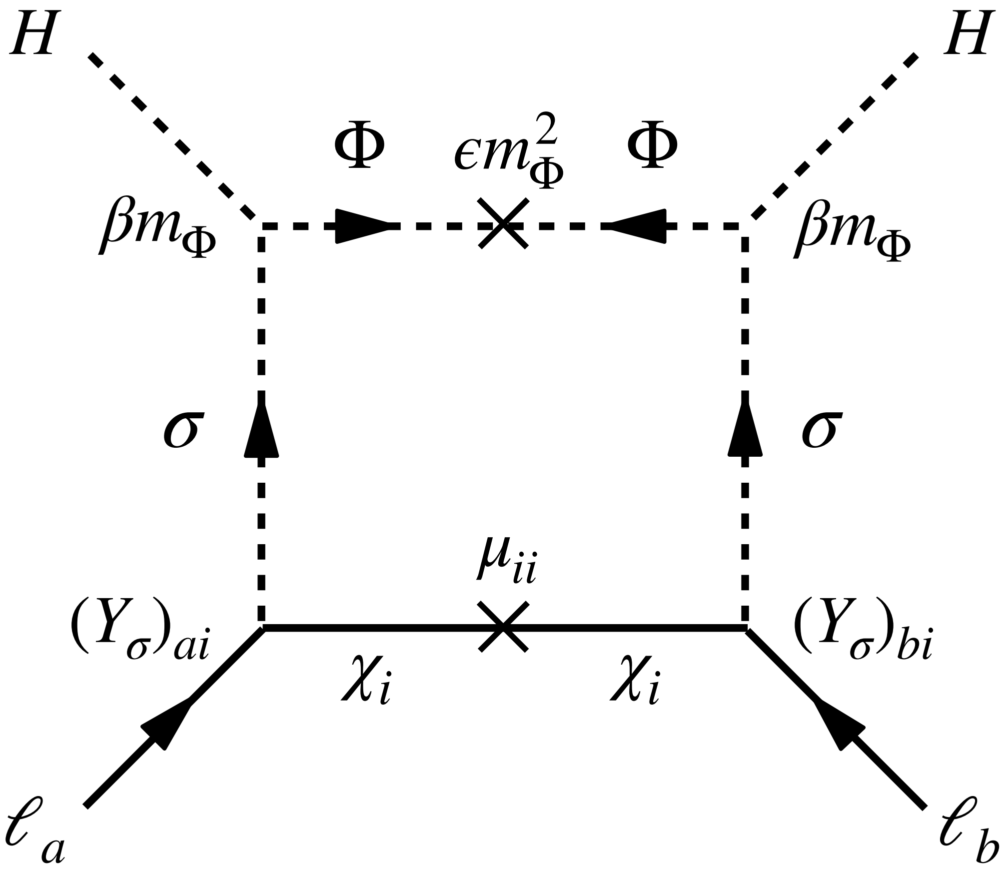


4. Reheating & Lepton asymmetry transmission to the SM sector by inflaton/AD decay



5. Combining all diagrams

Radiative seesaw mechanism



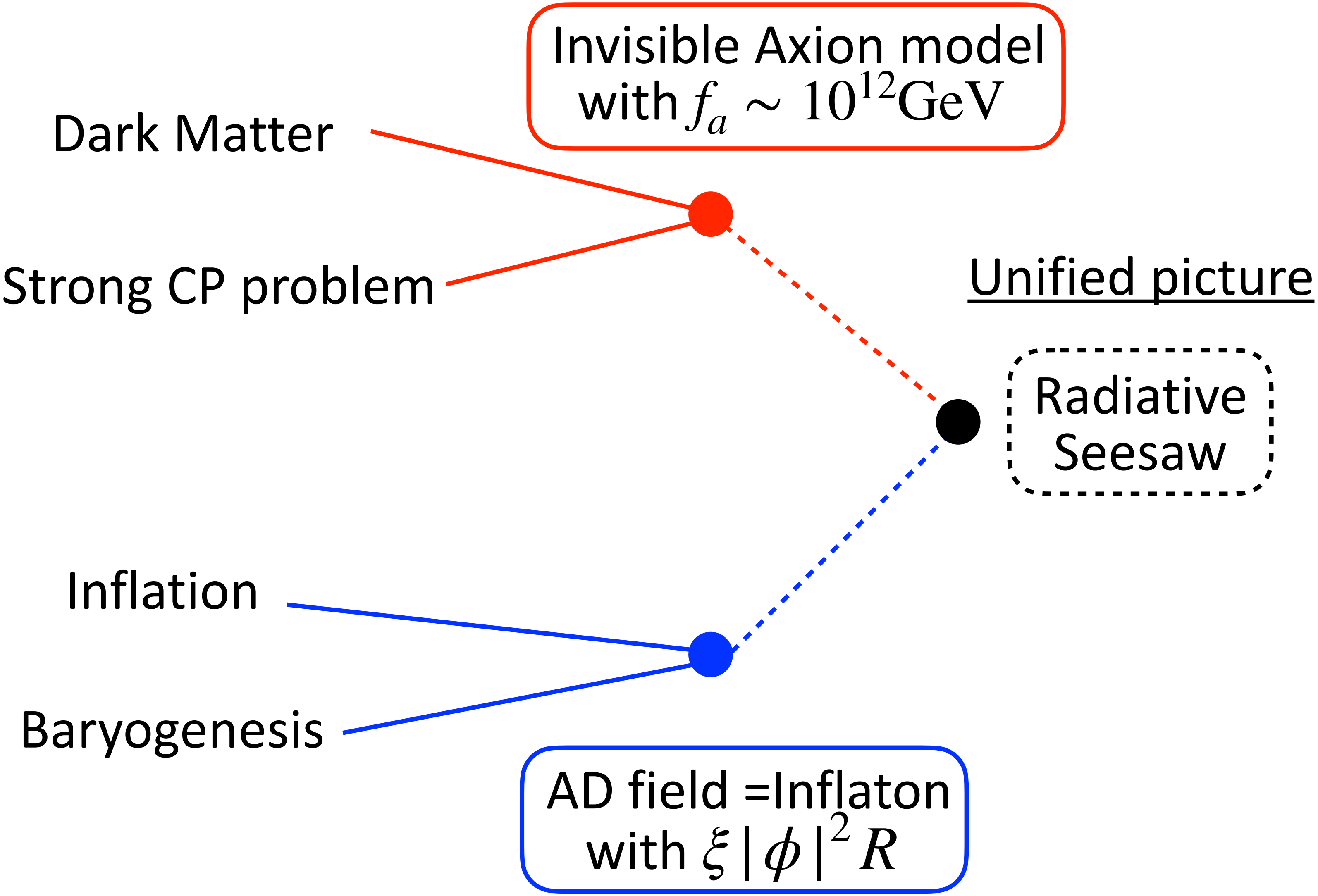
$$m_\nu = \frac{v_{wk}^2 \beta^2 \epsilon m_\Phi^2}{16\pi^2 m_\sigma^4} Y_\sigma \mu Y_\sigma^T$$

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_σ	$10^{6.5}$ 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



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

Dark Matter

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Unified picture

Radiative Seesaw

Inflation

Baryogenesis

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

My message to Rabi

First met when I joined UMD as a postdoc in 2001

I left UMD in 2002 to fill a tenured professor position at KEK, Japan

My first paper with Rabi (and Haibo): 2007
Since then, 11 publication with Rabi

I came back in the US (U. of Alabama) in 2009. Thank you very much for your great supports for my US job hunting.

Collaborations/discussion with Rabi are extremely enjoyable and inspiring! Thank you so much for collaborations!
Let us continue working together!

Congratulations on your great achievement in Particle Physics!

Enjoy your retirement!

Finally…..

Finally, I want to share with people here the words Rabi said in our collaboration meetings……

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Oh, that’s very interesting!

Let’s cook up the model!

Thank you

for your attention!