A unified model for solving big problems of the Standard Model

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Based on collaboration with
Rabi Mohapatra (University of Maryland)

Ref: Rabindra N. Mohapatra & NO,
PRD 105, 035024 (2022) [arXiv: 2112.02069]];
JHEP 03 (2022) 092 [arXiv: 2201.06151 [hep-ph]];
In Preparation

SUSY 2022 @ Ioannina, Greece, June 28, 2022

1. Introduction & Motivation

Problems in the Standard Model

The Standard Model (SM) is the best theory in describing the nature of elementary particle physics, which is in excellent agreement with almost of all current experimental results (including LHC Run-2 results) as of TODAY

However,

New Physics beyond SM is strongly suggested by both experimental & theoretical points of view

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We have many supporting messages to SUSY in the plenary and parallel sessions!

Five Questions that the Standard Model cannot answer

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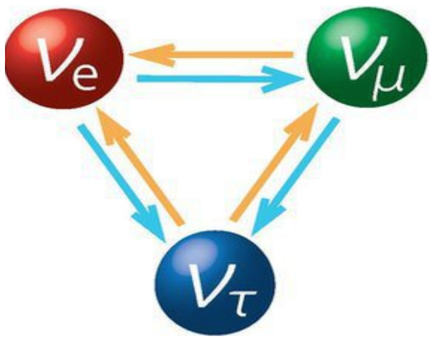
1. Why are Neutrino Masses are non-zero and so tiny?

Neutrino Mass problem

Neutrino Oscillation Phenomena



$$\Delta m^2_{21} = (7.53 \pm 0.18) \times 10^{-5}\ \mathrm{eV}^2$$

$$\Delta m^2_{32} = (2.44 \pm 0.06) \times 10^{-3}\ \mathrm{eV}^2$$

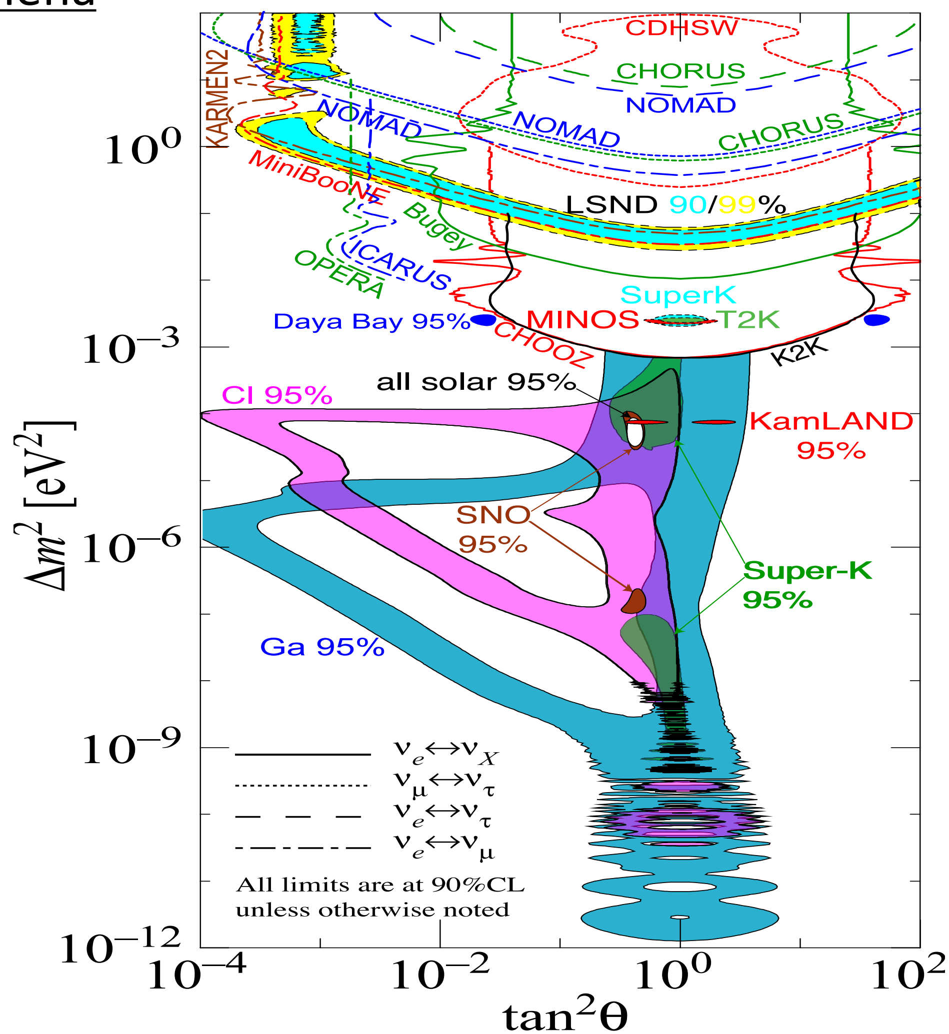
$$\sin^2(2\theta_{12}) = 0.846 \pm 0.021$$

$$\sin^2(2\theta_{23}) = 0.999^{+0.001}_{-0.018}$$

$$\sin^2(2\theta_{13}) = (9.3 \pm 0.8) \times 10^{-2}$$

Neutrinos are massless in the Standard Model

Particle Data Group



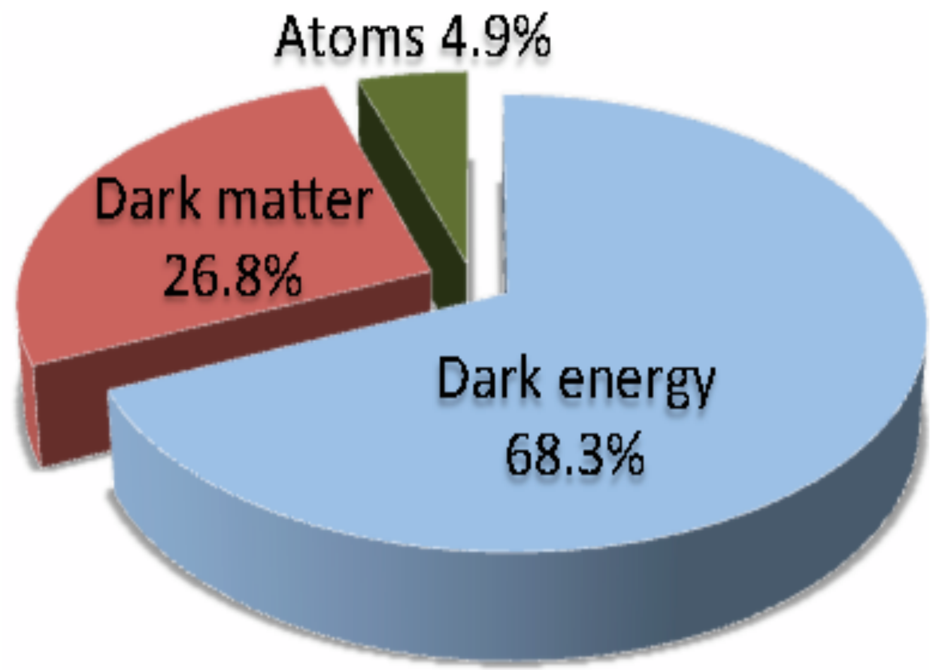
Five Questions that the Standard Model cannot answer

1. Why are Neutrino Masses are non-zero and so tiny?
2. What is the nature of Dark Matter?

Dark Matter Problem

Existence of Dark Matter has been established!

Energy budget of the Universe is precisely determined by recent CMB anisotropy observations (WMAP & Planck)



Dark Matter particle: non-baryonic
electric charge neutral
(quasi) stable $\tau_{DM} > t_U$

No suitable DM candidate in the Standard Model

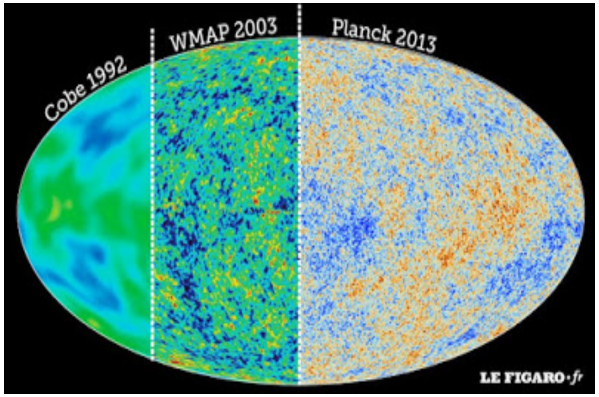
Five Questions that the Standard Model cannot answer

1. Why are Neutrino Masses are non-zero and so tiny?
2. What is the nature of Dark Matter?
3. What drives Cosmic Inflation before Big Bang?

Cosmic Infaltion

The problems of Big-Bang Cosmology

- Flatness problem
- Horizon problem
- Need to dilute unwanted topological defects
- Origin of the primordial density fluctuations



$$\boxed{\frac{\delta T}{T} \simeq 10^{-5}}$$

Seeds of the large scale structure

Solution: Cosmic Inflation before Big-Bang cosmology,
driven by a scalar field (inflaton) which has a very flat potential

No suitable inflaton candidate in 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. What drives Cosmic Inflation before Big Bang?
4. What is the origin of Matter-Antimatter asymmetry in the Universe?

What is the origin of Matter-Antimatter Asymmetry?

Observations: (1) Big asymmetry $\boxed{n_B \gg n_{\bar{B}}}$

(2) Small ratio to entropy

$$\boxed{\frac{n_B}{s} \simeq \frac{n_B - n_{\bar{B}}}{s} \simeq 10^{-10} \ll 1}$$

What is the origin?

*Baryogenesis in the SM context: Electroweak Baryogenesis
Unfortunately, <u>it doesn't work with the 125 GeV Higgs mass</u>

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. What drives Cosmic Inflation before Big Bang?
4. What is the origin of Matter-Antimatter asymmetry in the Universe?
5. Why is CP-violation in QCD so negligible?

Strong CP problem

The SM gauge symmetry allows us to add a CP violating term:

$$\mathcal{L}_{\rm SM} \supset \theta \sum_{a=1}^{8} \epsilon^{\mu\nu\rho\sigma} G^a_{\mu\nu} G^a_{\rho\sigma}$$

Gluon Field Strength: $G^a_{\mu\nu}$

This term generates Neutron EDM at quantum level,

$$|d_n| \sim |\theta| \times 10^{-13}\ e\,{\rm cm}$$

while the experimental upper bound is

$$|d_n| < 10^{-26}\ e\,{\rm cm}$$

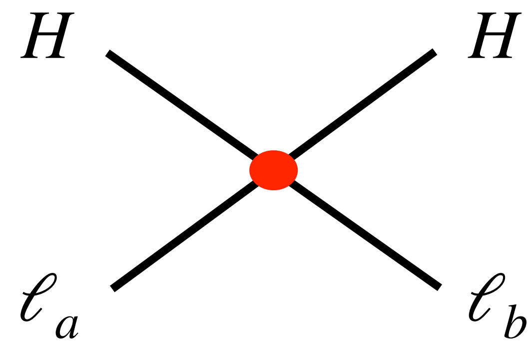
Why is θ turned to be extremely small?

2. Possible solution to each problem

1. Effective Theory for Neutrino Mass Generation

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

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

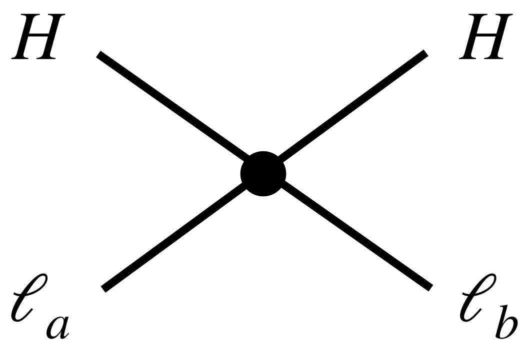


After the electroweak (EW) symmetry breaking,

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

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)



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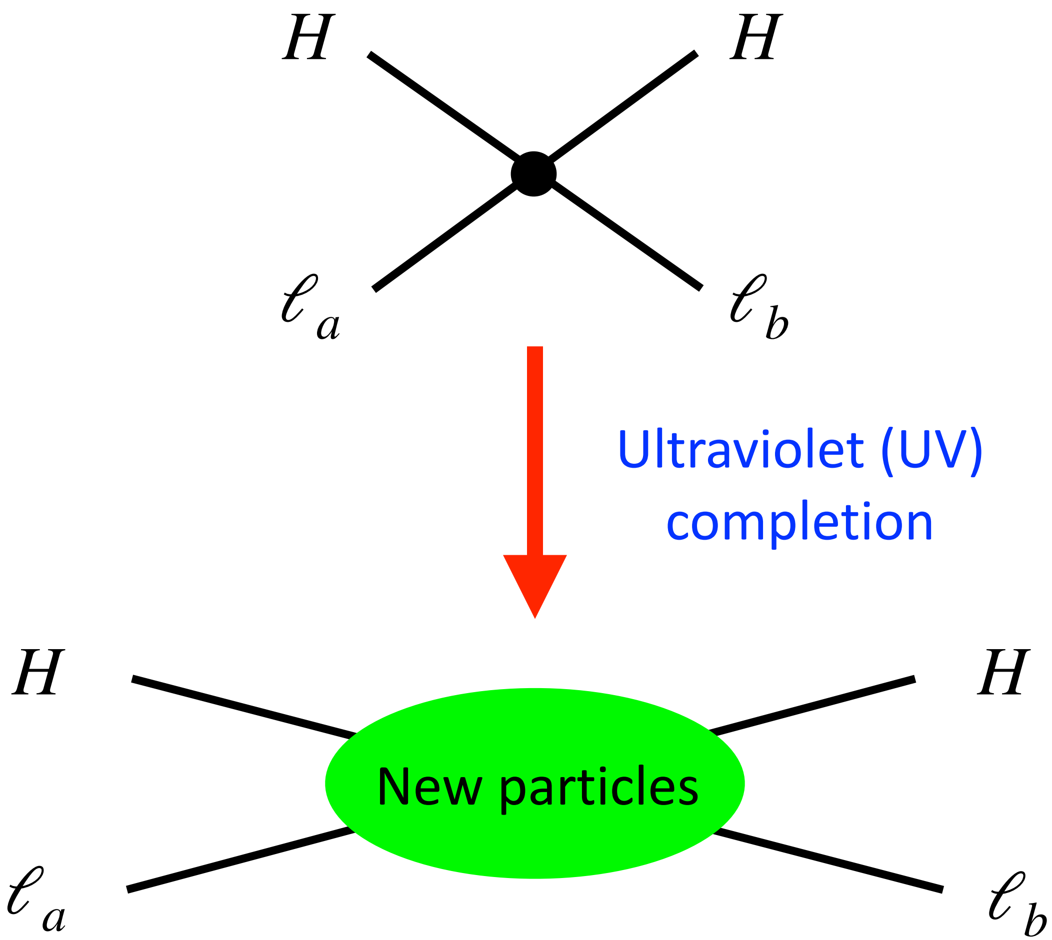


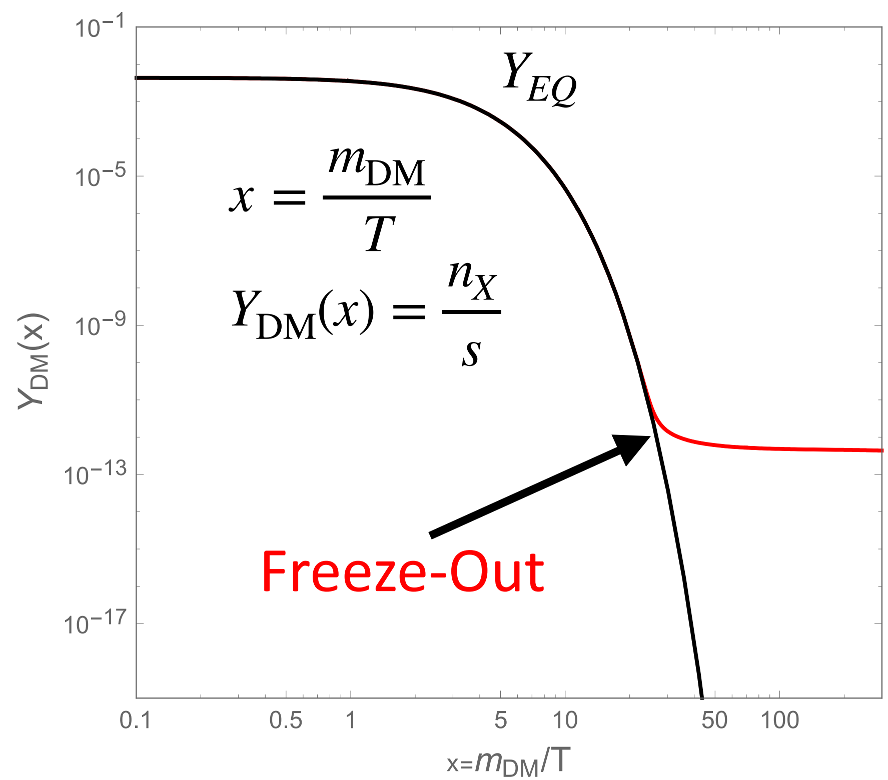
2. WIMP scenario for Dark Matter Problem

DM candidate: Weakly Interacting Massive Particle (WIMP) with $Q_X = 0$ and $\tau_X \gg \tau_U$

Decoupling from the SM thermal plasma:

Boltzmann equation

$$\frac{dn_X}{dt} + 3Hn_X = -\langle \sigma_{X\bar{X}} v_{rel} \rangle \left(n_X^2 - \left(n_X^{EQ} \right)^2 \right)$$



The DM relic density: $$\boxed{\Omega_{DM}h^2 = \frac{m_\chi s_0 Y(\infty)}{\rho_c/h^2},}$$

$$\text{where } s_0 = 2890 \text{ cm}^{-3}$$

$$\rho_c/h^2 = 1.05 \times 10^{-5} \text{ GeV/cm}^3$$

This should reproduce the observed DM density measured by Planck 2018

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

``WIMP DM Miracle”

With a given annihilation cross section, the Boltzmann equation is easily solved, and we can find a good proximation formula to derive the observed DM density:

$\Omega_{DM}h^2 \sim 0.1$ is obtained if $\langle \sigma v_{rel} \rangle \sim 1\,\mathrm{pb}$

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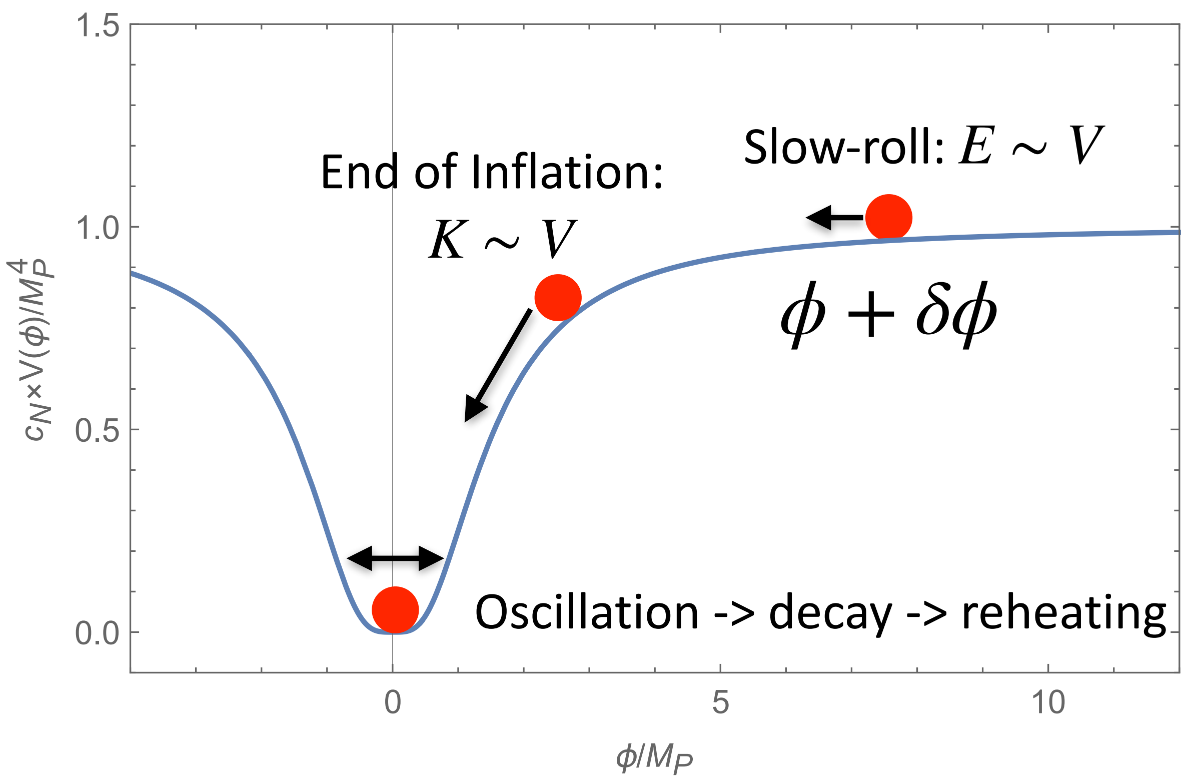
We may parametrize $\boxed{\langle \sigma v_{rel} \rangle = \frac{g_2^4}{4\pi}\frac{1}{m_\chi^2}}$

For the SU(2) gauge coupling, we find

$m_\chi \sim 1\,\mathrm{TeV}$ leads to $\langle \sigma v_{rel} \rangle \sim 1\,\mathrm{pb}$

The mass (physics) scale of WIMP to be around 1 TeV is suggested by the observation!

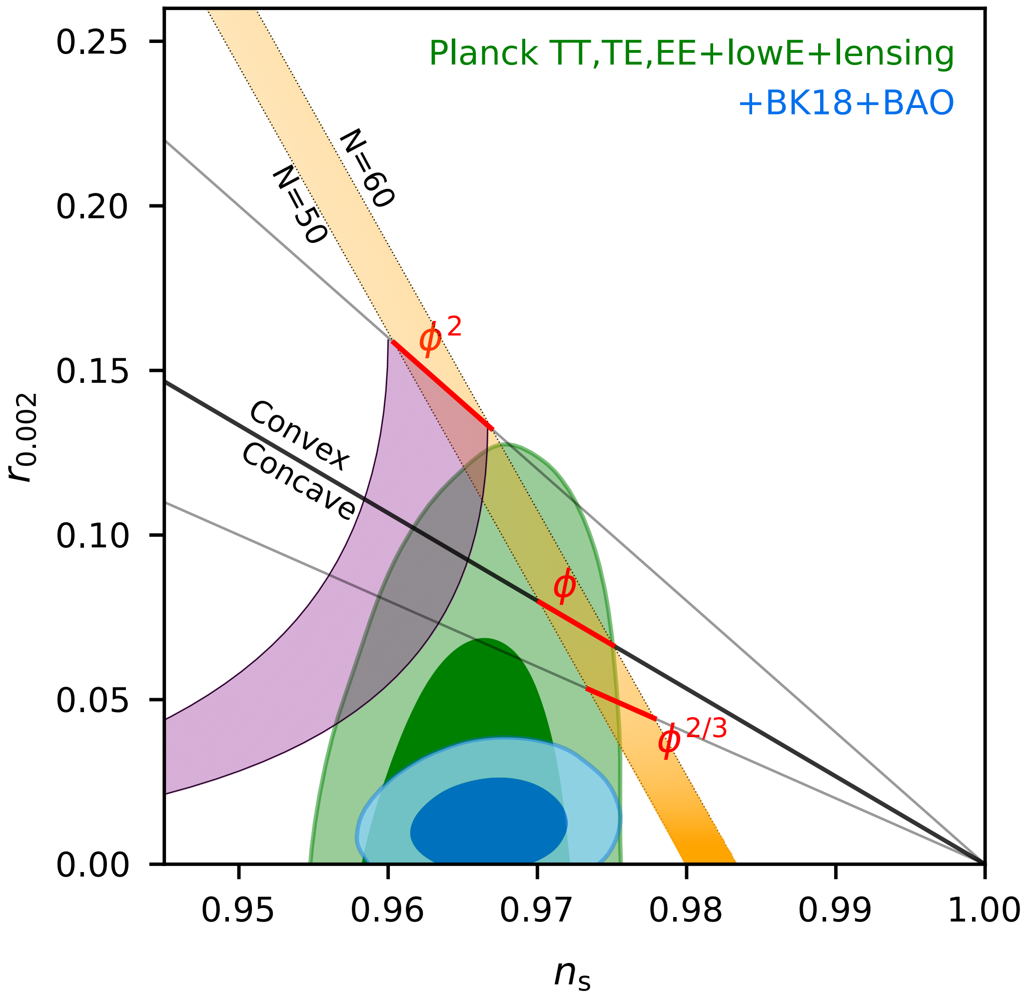
3. Slow-roll inflation to drive the cosmic inflation



- 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:

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

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

Spectral index:

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

Tensor-to-scalar ratio:

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

Inflationary predictions of a slow-roll inflation

$$\mathcal{L}_{inf} = \frac{1}{2}\eta^{\mu\nu}(\partial_\mu\phi)(\partial_\nu\phi) - \boxed{V(\phi)}$$

Defining the slow-roll parameters (in Planck units $M_P = 1$)

$$\epsilon = \frac{1}{2}\left(\frac{V'}{V}\right)^2, \quad \eta = \frac{V''}{V}$$

the spectral index & tensor-to-scalar ratio:

$$n_s = 1 - 6\epsilon + 2\eta\,, \quad r = 16\epsilon$$

The power spectrum of scalar perturbation: $P_S = \frac{1}{12\pi^2}\frac{V^3}{(V')^2}$

The number of e-folds: $N_e = \int_{\phi_e}^{\phi_0} d\phi \frac{V}{V'}$

Here, $\phi = \phi_0$ at the horizon exit & the end of inflation $\epsilon(\phi_e) = 1$

Inflationary predictions of a slow-roll inflation

The power spectrum of scalar perturbation:

$$P_S = \frac{1}{12\pi^2}\frac{V^3}{(V')^2} \to 2.099 \times 10^{-9}$$

The number of e-folds: $N_e = \int_{\phi_e}^{\phi_0} d\phi \frac{V}{V'} \to$ Fix (say, 50-60)

$\xrightarrow[\text{predictions}]{}$ n_s & r

Ex) 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

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

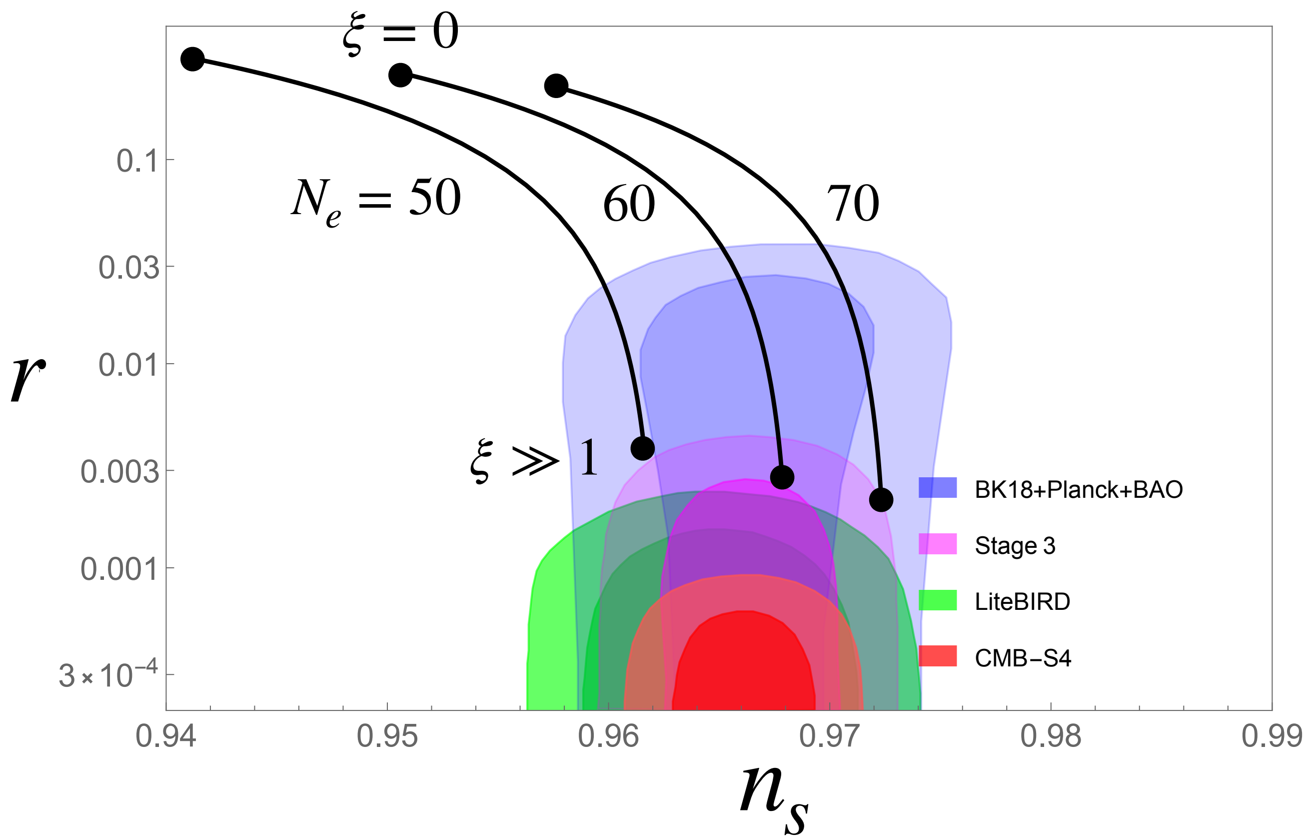
- Non-minimal gravitational coupling

$\boxed{f(\phi) = (1+\xi\phi^2)}$ 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

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

- A complex scalar field carries B/L number

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

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

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

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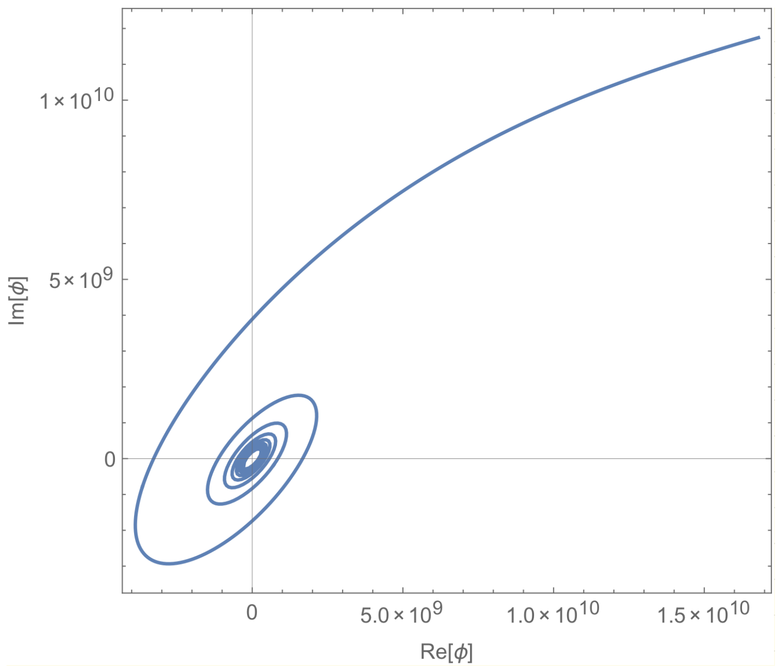
- During the evolution of the AD field, the B/L number is generated

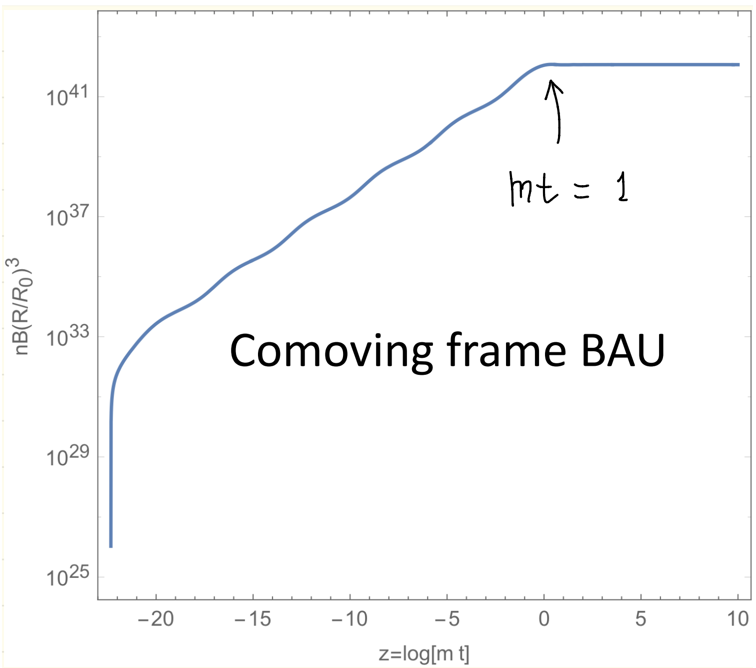
$$n_B(t) = Q_\Phi(\dot{\phi}_1\phi_2 - \dot{\phi}_2\phi_1)$$

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

Sample: AD field evolution & baryon number generation

Illustration purpose (not a realistic value)





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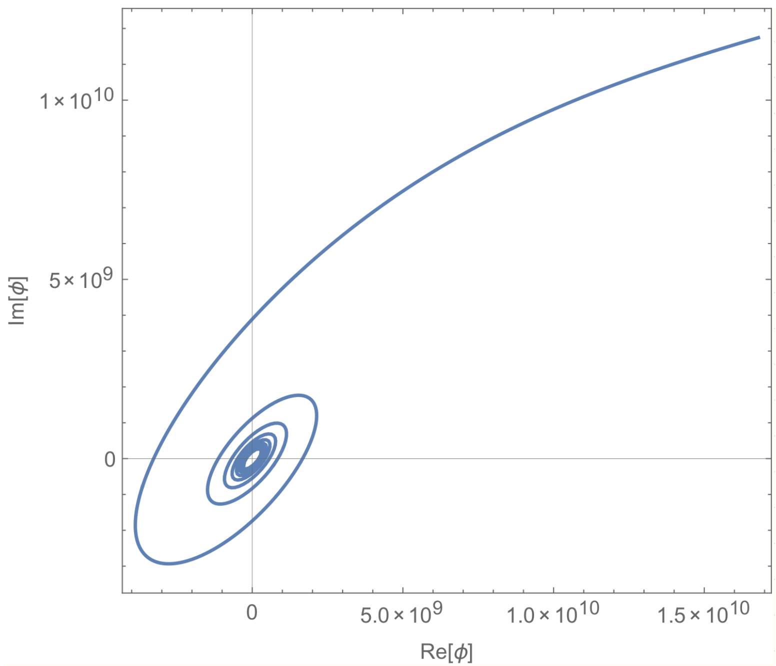

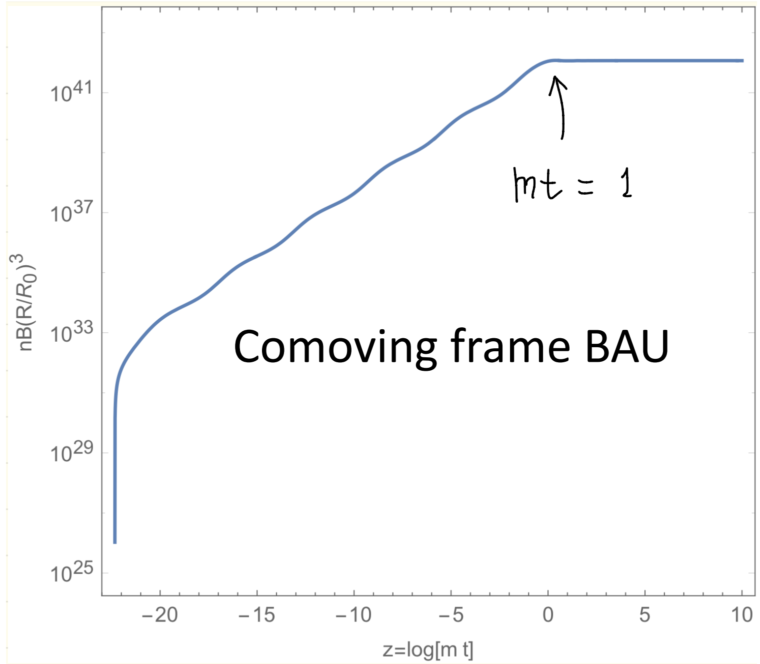

- Generated B/L asymmetry is transferred the SM thermal plasma by the AD field decay with B/L conserving interactions: $\mathscr{L}_{int} \sim \Phi\mathcal{O}_{SM}$ or $\Phi\mathcal{O}_{BSM}$

It is interesting to ask the following questions:

Can AD field play another important role in particle physics?

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

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

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: $0 < \epsilon \ll 1$

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

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

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

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

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

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

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

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

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

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

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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!

5. 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, which is spontaneously broken at f_a
- Nambu-Goldstone boson (axion ``a”) arises and has a coupling:

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

$$\Downarrow$$

- The CP-violating parameter θ is replaced by the field axion
- $\langle a \rangle = 0$ is realized at the axion potential minimum

3. A unified Model

Particle content (only relevant fields)

$\mathrm{U}(1)_L$: lepton number

Field	$\mathrm{U}(1)_L$	SM quantum number	Z_2'
Fermion			
ℓ_a	$+1$	$(\mathbf{2}, -1)$	$+$
e_a^c	-1	$(\mathbf{1}, +2)$	$+$
D_i	0	$(\mathbf{2}, -1)$	$-$
$\bar{D}_i$	0	$(\mathbf{2}, +1)$	$-$
χ_i	0	$(\mathbf{1}, 0)$	$-$
Scalar			
H	0	$(\mathbf{2}, +1)$	$+$
Φ	-1	$(\mathbf{1}, 0)$	$-$

$a, i = 1, 2, 3.$

New fermions

AD=Inflaton

* Z_2' is guaranteed by the lepton number (not by hand)

Lagrangian of the model

$$\mathscr{L} - \mathscr{L}_{\rm SM} = \mathscr{L}_{\rm inf} + \mathscr{L}_{\rm AD} + \mathscr{L}_{\rm Y} + \mathscr{L}_{fm}$$

- Non-minimal gravitational coupling for inflation

$$\mathscr{L}_{\rm inf} = -\frac{1}{2}(M_P^2 + 2\xi\,|\,\Phi\,|^2)R$$

- Suitable potential for the AD/Inflation field

$$\mathscr{L}_{\rm AD} = (\partial_\mu \Phi)^\dagger (\partial^\mu \Phi) - \left(m_\Phi^2\,|\,\Phi\,|^2 + \lambda\,|\,\Phi\,|^4 + \epsilon m_\Phi^2 (\Phi^2 + \Phi^{\dagger 2}) \right)$$

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- Yukawa couplings with Φ and H

$$\mathscr{L}_{\mathrm{Y}} = -(Y_\Phi)_{ai}\ell_a \bar{D}_i \Phi - (Y_D)_{ij} D_i \chi_j H - (Y_{\bar{D}})_{ij} \bar{D}_i \chi_j \tilde{H} + h.c.$$

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$$\mathscr{L}_{\rm inf} = -\frac{1}{2}(M_P^2 + 2\xi\,|\,\Phi\,|^2)R$$

- Suitable potential for the AD/Inflation field

$$\mathscr{L}_{\rm AD} = (\partial_\mu \Phi)^\dagger (\partial^\mu \Phi) - \left(m_\Phi^2 \,|\,\Phi\,|^2 + \lambda\,|\,\Phi\,|^4 + \epsilon m_\Phi^2 (\Phi^2 + \Phi^{\dagger 2}) \right)$$

- Yukawa couplings with Φ and H

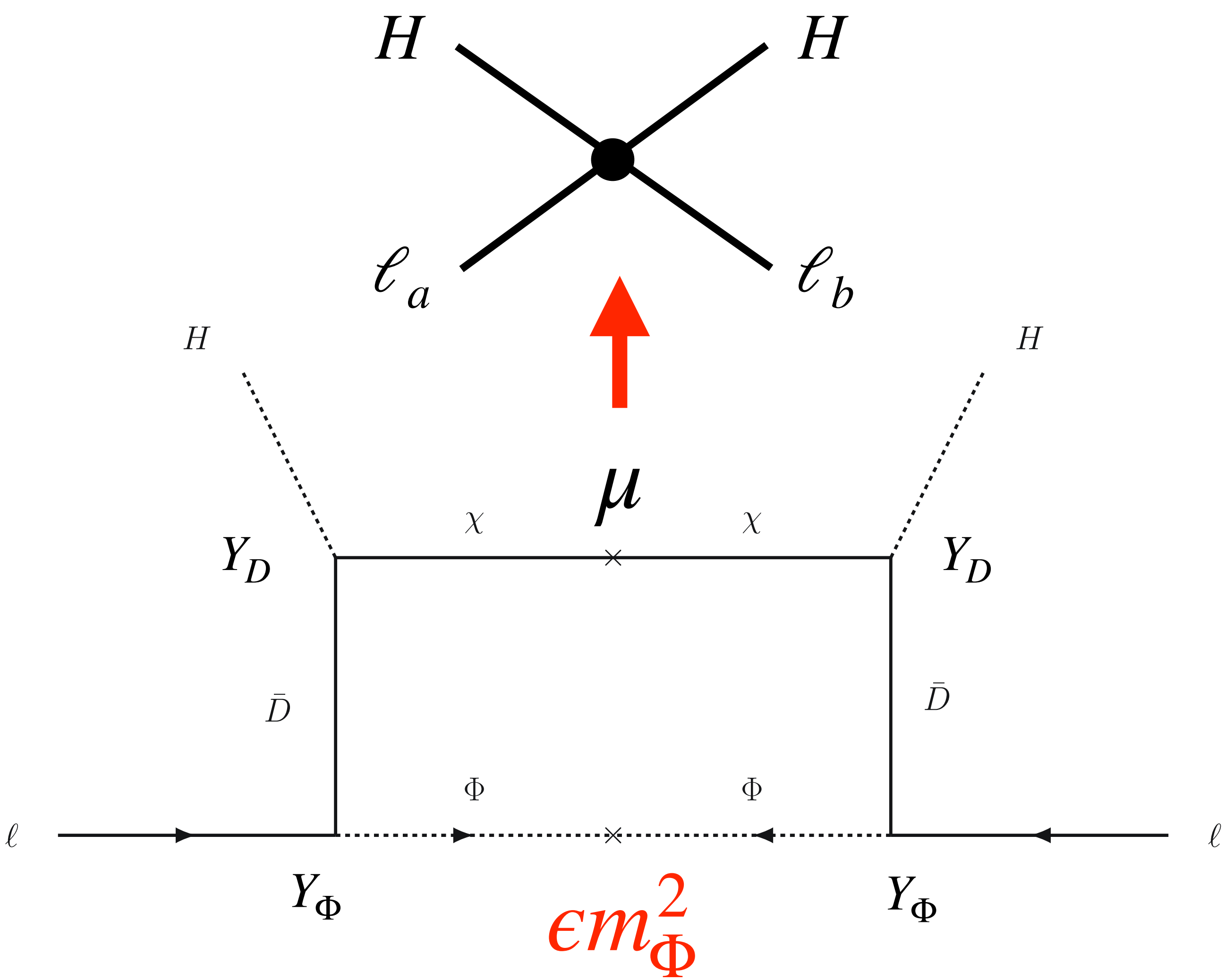
$$\mathscr{L}_{\rm Y} = -(Y_\Phi)_{ai} \ell_a \bar{D}_i \Phi - (Y_D)_{ij} D_i \chi_j H - (Y_{\bar{D}})_{ij} \bar{D}_i \chi_j \tilde{H} + h.c.$$

- New fermion mass terms

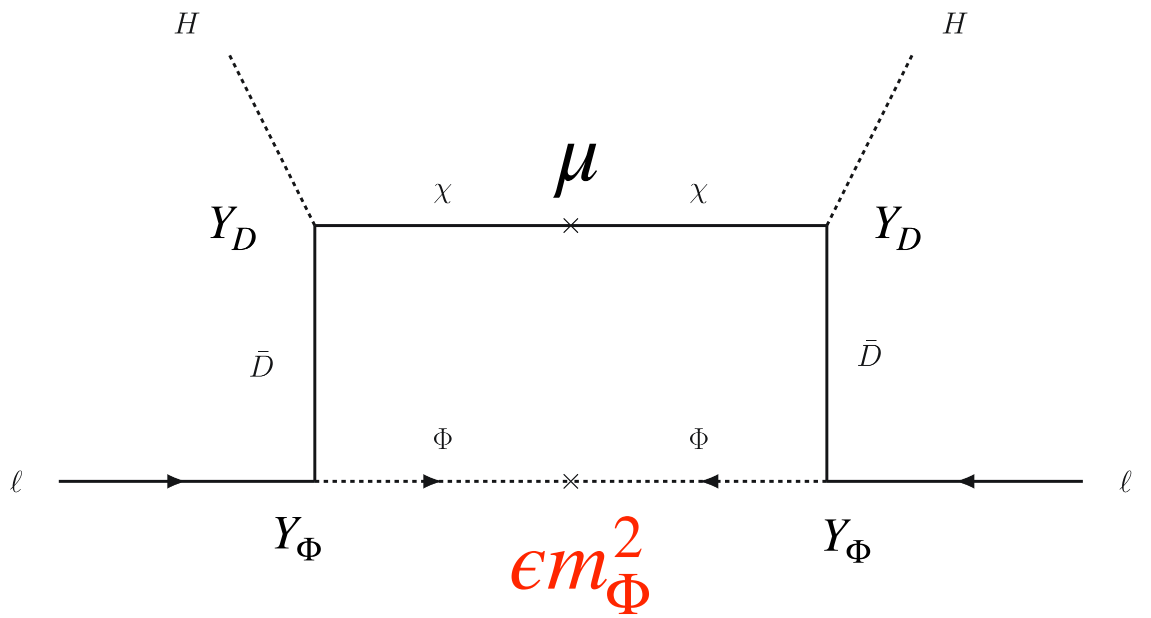
$$\mathscr{L}_{fm} = -\mu_i \chi_i \chi_i - (m_D)_i D_i \bar{D}_i + h.c.$$

1. Neutrino Mass Generation

- With the particle contents, no tree-level neutrino mass
- Neutrino mass at 1-loop level (radiative seesaw)



Radiative seesaw mechanism



$$\boxed{(m_\nu)_{ab} \simeq \frac{\epsilon\, v_{wk}^2}{16\pi^2 m_\Phi} (Y_\Phi Y_\Phi^T)_{ab}\, Y_D^2}$$

- For simplicity, $\mu_{ij} = m_\Phi \delta_{ij}$ and $(Y_D)_{ij} = Y_D \delta_{ij}$
- ϵm_Φ^2 insertion is crucial, which is also crucial for the AD mechanism

One Benchmark parameter set

parameter	value
ϵ	10^{-5}
m_Φ T_R	10^6 GeV 10^5 GeV
m_{D_1} $m_{D_{2,3}}$	10^3 GeV 3×10^6 GeV
$(Y_\Phi)_{a1}$ $(a = 1, 2, 3)$ $(Y_\Phi)_{ai}$ $(a = 1, 2, 3;\ i \neq 1)$	$\sim 10^{-6.5}$ $\sim 10^{-0.5}$

For our benchmarks, we find the light neutrino mass eigenvalues:

$$m_1 \ll m_2 \sim m_3 \sim 0.1 \text{ eV}$$

The neutrino oscillation data can be reproduced.

2. WIMP DM

- The lightest Z_2'-odd particle is stable
- In our benchmarks, a mixture of fermions is the DM candidate (singlet-doublet fermion DM scenario)

$$M = \begin{pmatrix} D_1^0 & \bar{D}_1^0 & \chi \end{pmatrix} \begin{pmatrix} 0 & m_{D_1} & Y_D v_{wk} \\ m_{D_1} & 0 & Y_D v_{wk} \\ Y_D v_{wk} & Y_D v_{wk} & \mu \end{pmatrix} \begin{pmatrix} D_1^0 \\ \bar{D}_1^0 \\ \chi \end{pmatrix}$$

For our benchmarks,

$$\boxed{\psi_{DM} \simeq \frac{1}{\sqrt{2}} D_1^0 + \frac{1}{\sqrt{2}} \bar{D}_1^0 + \frac{v_{EW}}{\mu} \chi}$$

The DM particle is a Majorana fermion from mostly the SU(2) doublet components: similar to Higgsino-like DM in the MSSM: $m_{DM} \simeq 1\ \mathrm{TeV}$ for $\Omega_{DM} h^2 = 0.12$

3 & 4. AD/Inflaton

$$\mathscr{L} - \mathscr{L}_{\rm SM} \supset \mathscr{L}_{\rm inf} + \mathscr{L}_{\rm AD}$$

- Non-minimal gravitational coupling for inflation

$$\mathscr{L}_{\rm inf} = -\frac{1}{2}(M_P^2 + \xi|\Phi|^2)R$$

- AD/Inflation field

$$\mathscr{L}_{\rm AD} = (\partial_\mu \Phi)^\dagger(\partial^\mu \Phi) - \left(m_\Phi^2|\Phi|^2 + \lambda|\Phi|^4 + \epsilon m_\Phi^2(\Phi^2 + \Phi^{\dagger 2})\right)$$

For our benchmark,

$$\boxed{\frac{n_B}{s} \sim \frac{n_L}{s} \simeq \frac{T_R^3}{\epsilon\, m_\Phi^2 M_P} \simeq 10^{-10}}$$

4. Summary

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

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1. Inflation driven by Inflaton/AD field Φ --------

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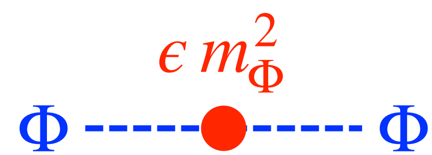
2. Lepton asymmetry generation during oscillation after inflation



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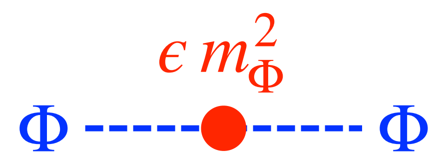
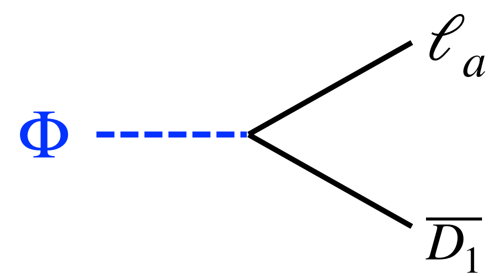


3. Reheating & Lepton asymmetry transmission to the SM sector by inflaton/AD decay



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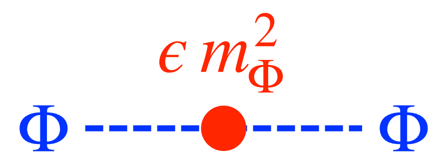

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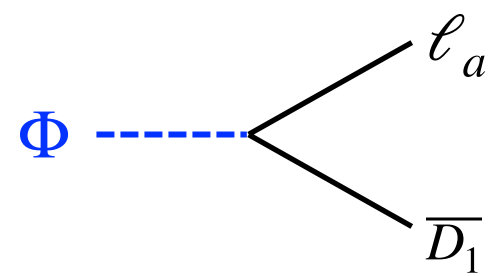
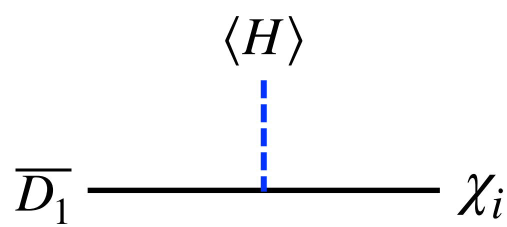
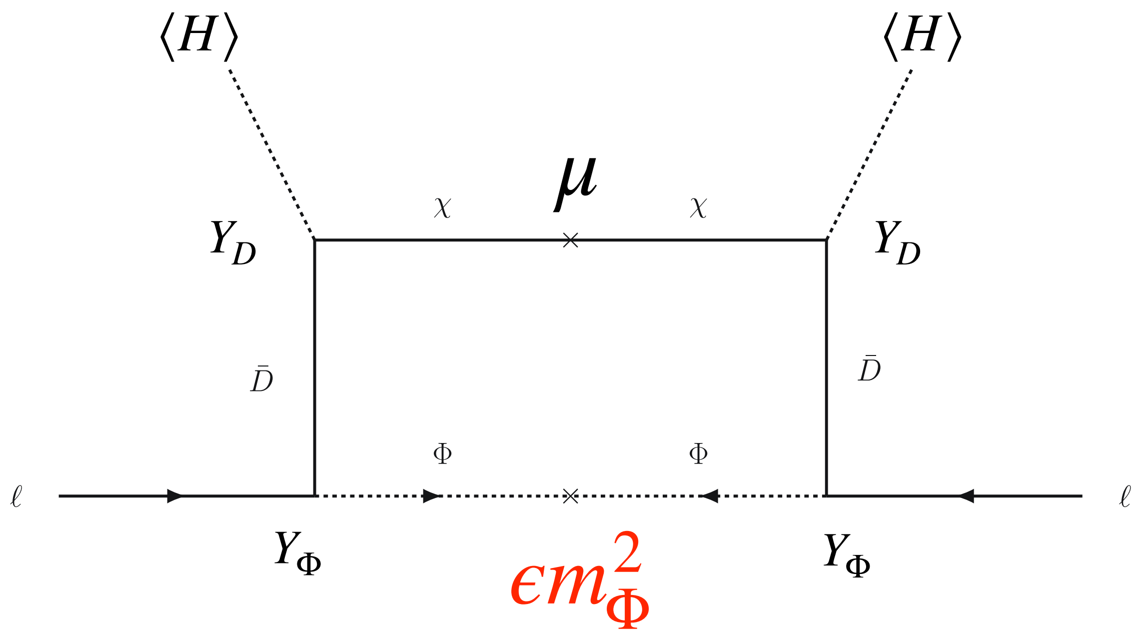


4. Doublet-singlet fermion DM



5. Combining all diagrams

Radiative seesaw mechanism



$$\boxed{(m_\nu)_{ab} \simeq \frac{\epsilon\, v_{wk}^2}{16\pi^2 m_\Phi} (Y_\Phi Y_\Phi^T)_{ab}\, Y_D^2}$$

New paper in preparation (Mohapatra & NO)

Towards a solution to the Strong CP problem

A way to implement Axion model

$$\mathscr{L} - \mathscr{L}_{\mathrm{SM}} \supset \mathscr{L}_{\mathrm{AD}}$$

- AD/Inflation field

$$\mathscr{L}_{\mathrm{AD}} = (\partial_\mu \Phi)^\dagger (\partial^\mu \Phi) - \left(m_\Phi^2 |\Phi|^2 + \lambda |\Phi|^4 + \epsilon m_\Phi^2 (\Phi^2 + \Phi^{\dagger 2}) \right)$$

- Identification of $\mathrm{U}(1)_L$ with $\mathrm{U}(1)_{PQ}$
- $\epsilon m_\phi^2 = M\langle \varphi \rangle$
- A complex scalar φ in the invisible axion models

Thank you

for your attention!

Back up slides

Reheating after inflation and AD mechanism

- Yukawa coupling from the radiative seesaw formula

$$(Y_\Phi)_{ai} = \frac{1}{\sqrt{X}}(U^* \sqrt{D_\nu})_{ai},$$

$$\text{where } X = \frac{\epsilon v_{wk}^2}{16\pi^2 m_\Phi} Y_D^2, \text{ and } D_\nu = \text{diag}(m_1, m_2, m_3).$$

- Reheating by the AD/Inflaton decay

$$\Gamma_\Phi = \sum_a \Gamma_{\Phi \to \ell_a D_1} = (Y_\Phi^\dagger Y_\Phi)_{11} \frac{m_\Phi}{4\pi} = \frac{m_\Phi}{4\pi X} m_1$$

$$T_R \simeq K m_\Phi = \sqrt{\Gamma_\Phi M_P}$$

$$\longrightarrow \quad m_1(\text{eV}) \simeq 10^{-6} \times Y_D^2 \, \epsilon \, K^2$$

Thus, the lightest neutrino mass should be very small,

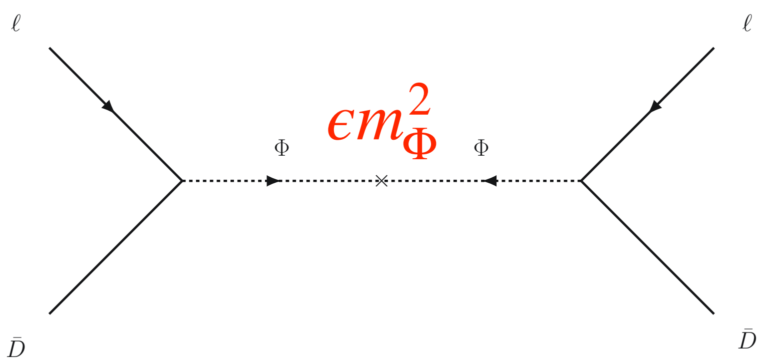
$$m_1(\text{eV}) \ll 10^{-6}$$

Phenomenological viability/consistency checks

- $n_B/s \sim 10^{-10}$ and $m_\nu \sim 0.1\,\mathrm{eV}$ are closely related, and the perturbativity of the Yukawa couplings leads to

$$K \equiv \frac{T_R}{m_\Phi} \gtrsim 0.046$$

- No washout: the following washing-out process must be out-of-equilibrium



$$m_\Phi \gtrsim \frac{10^{-8}\epsilon^2}{4\pi K^3} M_P$$

Combining with $n_B/s \sim 10^{-10}$, $\epsilon \lesssim 4\pi \times 10^{-2}$

Our benchmarks salsify all conditions