Froggatt-Nielsen模型の宇宙論的影響に関する強化学習を用いた統計的分析 [arXiv:2409.xxxxx]

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1. Abstract

- In our previous work, we focused on the flavor structures of quarks & leptons, and applied **reinforcement learning (RL)**, that is one method of machine learning (ML).
- Now, we discuss **cosmological topics** using RL. (QCD axion / Dark Matter / Inflation)
- We searched parameters of Froggatt-Nielsen model with renormalized masses, and discuss efficiency of RL.
- We showed that solutions reproducing renormalized masses tend to be at certain energy scales.
- We evaluated a coupling of QCD axion based on realistic models by RL, and it will be tested by future experiments.

2. Methods | one of flavor models & cosmological topics

2.1. Froggatt-Nielsen Model

Yukawa lagrangian has additional $U(1)$ flavor symmetry.

$$L_{\text{Yuk}} = y^u_{ij}\left(\frac{\phi}{M}\right)^{n^u_{ij}} \bar{Q}^i H^c u^j + y^d_{ij}\left(\frac{\phi}{M}\right)^{n^d_{ij}} Q^i H d^j$$
$$+ y^\nu_{ij}\left(\frac{\phi}{M}\right)^{n^\nu_{ij}} \bar{L}^i H^c N^j + y^l_{ij}\left(\frac{\phi}{M}\right)^{n^l_{ij}} L^i H l^j$$
$$+ \frac{1}{2} y^N_{ij}\left(\frac{\phi}{M}\right)^{n^N_{ij}} M \bar{N}^{ci} N^j + \text{h.c.}$$

Yukawa couplings y are $O(1)$ real parameters.

L_{Yuk} is $U(1)$ invariant ↔ sums of $U(1)$ charges are zero
ex. $q(\phi) n^u_{ij} - q(Q^i) - q(H) + q(u^j) = 0$

When complex scalar field ϕ develops an expectation value $\langle\phi\rangle$, Froggatt-Nielsen (FN) charges will lead to a **hierarchical** structure of physical Yukawa couplings (ex., $Y^u_{ij} = y^u_{ij}\langle\phi\rangle^{n^u_{ij}}$).

2.2. Pseudo-Scalar as QCD axion

Expanding the scalar field as $\phi = \langle\phi\rangle + (s + ia)/\sqrt{2}$, the interaction of pseudo-scalar field is described by

$$L_{\text{Yuk}} = \frac{g_s^2}{32\pi^2}\frac{a}{f_a} G^a_{\mu\nu}\tilde{G}^{\mu\nu a} \quad \left(f_a = \frac{\sqrt{2}\langle\phi\rangle}{N_{\text{DW}}} \text{ is a decay const.} \right)$$

a is called an axion and studied to solve strong CP problem.

Comparing with the current experimental bound,
$$\text{Br}(K^+ \to \pi^+ a) \lesssim 7.3 \times 10^{-11}$$
the lower bound on f_a is determined.

Moreover, based on constraint from cosmology, we can discuss excluding sets of parameters.

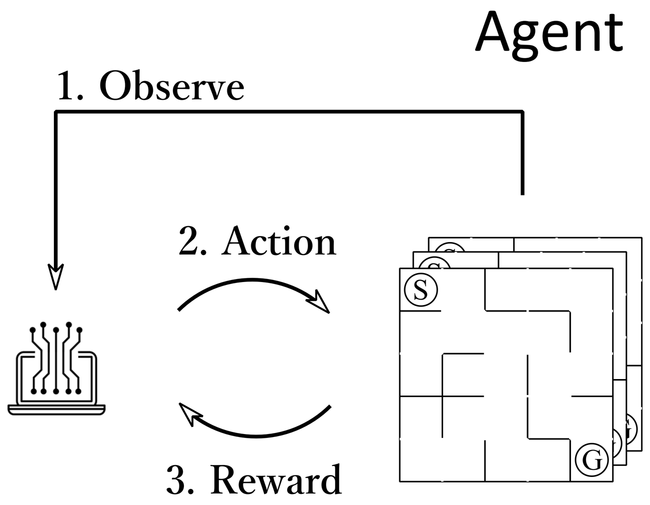
Our previous work proposed that RL is useful to analyze the flavor structures of quarks & leptons.
J. High Energ. Phys. 2023, 21 (2023) [arXiv:2304.14176]

In this work, we develop that analyzing method to cosmological physics considering renormalized masses.

2.3. Reinforcement Learning

Reinforcement Learning (RL) is a method of ML.

Agent
1. observes the environment
2. chooses actions
3. gets rewards



The agent autonomously find the principle of action that maximizes the total reward.

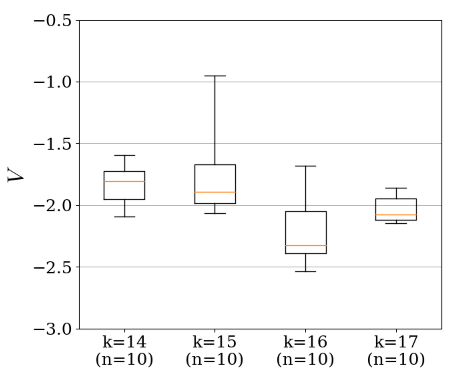
Agent : increasing or decreasing any FN charge of matters by ±1 (in 32 steps × 100,000 episodes)

20 agents in each of 4 energy scales search the FN charges reproducing renormalized masses & experimental mixing.

We found 156 solutions reproducing quark masses for various energy scales more than 9 times faster than traditional optimization methods.

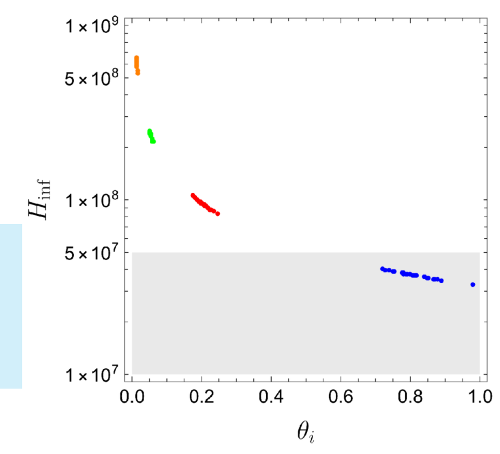
3. Result | the solutions can be tested in experiments

The boxplot shows top 10 models with high accuracy for each energy scale.



$M = 10^{14}, 10^{15}$ GeV is good to reproduce renomalized masses of quark sector.

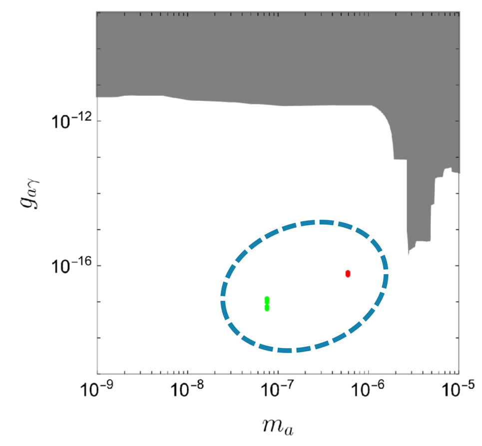
The graph shows constraints from dark matter, isocurvature perturbation and inflation as the gray region.



$M = 10^{14}$ GeV is excluded from inflationary scales and alignment angles.

We also search the FN charges of leptons relating to benchmark points of quarks, and calculate axion-photon couplings $g_{a\gamma}$. **These will be observed in the future.** (ex : DMRadio-m^3, Phys. Rev. D 106, 103008)

x-axis : axion masses m_a, y-axis : $g_{a\gamma}$



4. Conclusions | RL is applicable for cosmological topics

1. We developed RL-based search strategy, and discussed QCD axion with the cosmological topics as an application.
2. We showed the efficiency of RL concretely, and it makes **statistically analyzes** can be done.
3. We found some benchmark points which will be checked in the future experiments. Thus, RL is applicable to search for realistic models based on cosmology.

5. Future Works

1. Adding another flavon is promising to make CP violation. One of the two axions is taken as the QCD axion, and mass generation for another axion should be discussed.
2. Complex Yukawa is also promising. If a model is not found, it is also important to estimate how much of the parameter space has been explored by the agent.
3. "Generalization" of RL makes further reduction of calc. time.