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ASYMMETRIC DARK MATTER IN FLUFFY STANDARD MODEL

Based on K.O. and H.Suzuki, PTEP 2016 123B07 (arXiv:1608.02217)
K.O. and H.Suzuki, work in progress

Introduction

- There is no compelling evidence of new physics at LHC…
- Expectation relying on "the hierarchy problem" could be wrong. (SUSY, extra-dim, composite etc.)
- But we have several phenomena cannot fit into the SM. （baryon # asymmetry, dark matter, …） So work on them.
- We can introduce new freedoms/interactions as we like to "explain" them. However, we really want a new guiding principle based on the "physics". (eg. axion)
- In this talk, we focus on the fact that the SM is a chiral gauge theory. We discuss a possibility that a mirror fermion called "fluff" in the new lattice formulation of chiral gauge theory could be the dark matter.

Lattice Chiral Gauge Theory

The SM is a chiral gauge theory. However, surprisingly, we don't know its non-perturbative DEFINITION by lattice gauge theory yet.

(c.f. H.Fukaya, T.Onogi, S.Yamamoto, and R.Yamamura 2016)

Lattice gauge theory＝Numerical integration **No direct fermion treatment**

$$\int D\psi D\bar{\psi} \exp\left(-S_{YM} - \bar{\psi} \not{D} \psi\right) \Rightarrow \mathrm{Det}(\not{D}) \exp\left(-S_{YM}\right)$$

$$\mathrm{Det}\left(\not{D}\right) = \prod_{\alpha} \lambda_{\alpha}$$

Product of eigenvalues

We can not properly define the eigenvalue problem in chiral gauge theory.

$$\begin{pmatrix} 0 & D_\mu \sigma^\mu \\ 0 & 0 \end{pmatrix} \begin{pmatrix} 0 \\ \bar{\psi}_L \end{pmatrix} = \lambda \begin{pmatrix} \chi_R \\ 0 \end{pmatrix}$$

$$\not{D}\not{D} = 0$$

We can define $\not{D}^\dagger \not{D}$, But we can not define the phase of $\mathrm{Det}(\not{D})$.

(Following discussion by D.B.Kaplan @ Lattice 2016)

Grabowska-Kaplan Formulation

D.M.Grabowska and D.B.Kaplan 2015

Naïve solution： Introduce a dummy mirror fermion and make a Dirac pair.

$$\begin{pmatrix} 0 & D_\mu \sigma^\mu \\ \partial_\mu \overline{\sigma}^\mu & 0 \end{pmatrix} \begin{pmatrix} \psi_R \\ \bar{\psi}_L \end{pmatrix} = \lambda \begin{pmatrix} \psi_R \\ \bar{\psi}_L \end{pmatrix}$$

No exact chiral symmetry on the lattice（Nilsen-Ninomiya）.
（or Should break to reproduce the chiral anomaly. ）

↓

We can not separate the mirror fermion from gauge symmetry.

$$\begin{pmatrix} \epsilon & D_\mu \sigma^\mu \\ D^*_\mu \overline{\sigma}^\mu & \epsilon \end{pmatrix} \begin{pmatrix} \psi_R \\ \bar{\psi}_L \end{pmatrix} = \lambda \begin{pmatrix} \psi_R \\ \bar{\psi}_L \end{pmatrix}$$

Couple the gauge field infinitely diffused by the "gradient flow".
(No propagating degree of freedom)

Gradient Flow

R. Narayanan and H. Neuberger 2006, M. Lüscher 2010

Flow the configuration of gauge field by the diffusion eq.

t: flow time

$$-\frac{\delta S_{YM}}{\delta A_\mu}$$ **EOM**

$$B_\mu(x,0) = A_\mu(x)$$

$$\frac{\partial}{\partial t} B_\mu(x,t) = D_\nu G_{\nu\mu}(x,t)$$

$$D_\mu = \partial_\mu + [B_\mu,]$$

$$G_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu + [B_\mu, B_\nu]$$

Local fluctuation is smeared along the flow.

(No new divergence in the correlation fn. or composite op. of flowed fields)

(Various applications in lattice)

Infinite flow limit

$$A^*_\mu(x) = B_\mu(x,\infty)$$

$$D_\nu G^*_{\nu,\mu} = 0$$

Converge to classical solution

Fermion Number Anomaly

Does mirror fermion (fluff) decouple from the original fermion ?

The classical solutions include topologically non-trivial configurations like instantons and fluff couples with them. It might contribute to anomaly.

Fermion and fluff form a Dirac pair and the total anomaly must cancel.

The sum of # fermion and # fluff conserve

Selection rule by gauge anomaly ?

On the lattice

Gradient flow+
Domain wall fermion

→

Chiral Overlap Operator

(D.M.Grabowska and D.B.Kaplan 2016)

We proved that chiral overlap operator satisfies this nature.

K.O and H.Suzuki 2016

Divergence of the fermion number current

H.Makino and O.Morikawa 2016

Fluff as Asymmetric Dark Matter

It is phenomenologically interesting if the GK formulation is consistent and the fluff is not an artifact of a particular lattice formulation.

In the SM, B+L is broken by anomaly, however, if we introduce fluffs (Fluffy SM) the total B+L including fluffs is conserved.

If the baryon number is produced in the early universe, the fluffs are also produced via anomaly and become the dark matter if they couple with gravity.

If the symmetric part of the fluffs is not produced or efficiently annihilates, the DM/baryon ratio in the energy density of the universe could be explained.

"Asymmetric Dark Matter" Scenario

D.E.Kaplan, M.A.Luty, and K.M.Zurek 2009

J.A.Harvey and M.S.Turner 1990

S. Weinberg

Thermal Equilibrium

Treat the fluffs as radiation and assume thermal equiliburium with the SM. Express all the charge densities with those of the 4 conserved charge Y, $B-L$, $B+L+(B+L)_{\text{fluff}}$, $(B-L)_{\text{fluff}}$.

$$n_B = \frac{21}{52} n_{B-L} + \frac{1}{4} n_{B+L+(B+L)_{\text{fluff}}} + \frac{5}{52} n_{(B-L)_{\text{fluff}}},$$

$$n_L = -\frac{31}{52} n_{B-L} + \frac{1}{4} n_{B+L+(B+L)_{\text{fluff}}} + \frac{5}{52} n_{(B-L)_{\text{fluff}}},$$

$$n_{B_{\text{fluff}}} = \frac{5}{52} n_{B-L} + \frac{1}{4} n_{B+L+(B+L)_{\text{fluff}}} + \frac{21}{52} n_{(B-L)_{\text{fluff}}},$$

$$n_{L_{\text{fluff}}} = \frac{5}{52} n_{B-L} + \frac{1}{4} n_{B+L+(B+L)_{\text{fluff}}} - \frac{31}{52} n_{(B-L)_{\text{fluff}}}.$$

Interestingly, independent of n_Y, # Higgs bosons and # generations.

Note that $B+L$ is not washed out. SU(5) GUT baryogenesys is possible.

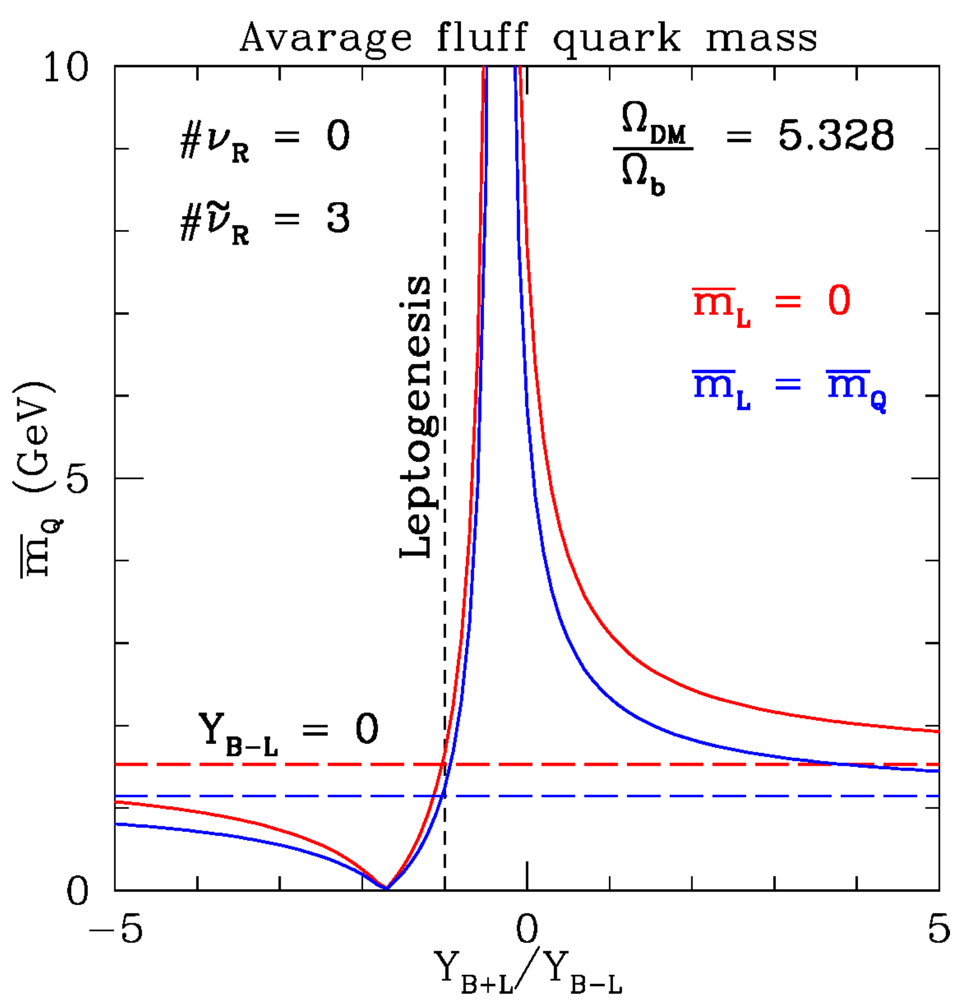
Required Fluff Mass

Calculate fluff mass reproducing the DM/baryon ratio.

If we assume leptogenesis（L) and GUT baryogenesis（B+L), the mass becomes １－１．５GeV averaged over 6 flavors.

The mass is sensitive to the B+L/B-L ratio due to cancellation

If only B-L is produced, the fluff mass can be as heavy as top quark.



Conclusion and Discussion

- New formulation of the lattice chiral gauge theory by Grabowska-Kaplan includes mirror fermions called “fluff”.
- Chiral overlap operator constructed based on the GK formulation conserves the sum of fermion and fluff numbers.
- If these are universal nature of the chiral gauge theory, the fluff provides a good candidate of the DM.
- The average fluff mass explaining the amount of DM is about 1 GeV, however, depends on the mechanism of the baryogenesis.
- Phenomenology heavily depends on the mechanism giving the mass to the fluff and eliminating the symmetric component.
- Still the consistency of the formulation is controversial and detailed phenomenology is premature. However, interesting enough to pursue this new direction.

BACKUP

Gradient Flow

Formal Solution

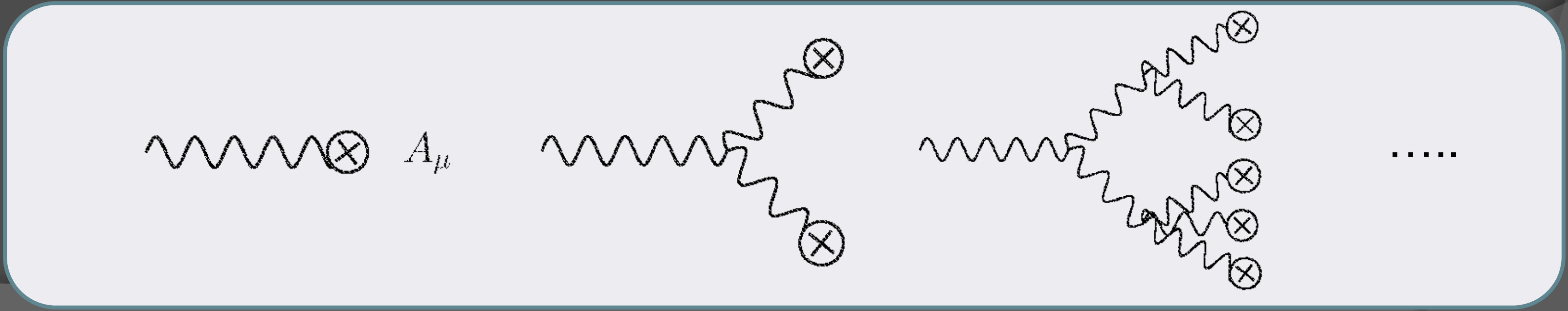
$$B_\mu(t,x) = \int d^D y \left[K_t(x-y)_{\mu\nu} A_\nu(y) + \int_0^t ds K_{t-s}(x-y)_{\mu\nu} R_\nu(s,y) \right]$$

Heat Kernel

$$K_t(x)_{\mu\nu} \equiv \int_p \frac{e^{ipx}}{p^2} \left[(\delta_{\mu\nu} p^2 - p_\mu p_\nu)\, e^{-t\, p^2} + p_\nu p_\nu \right]$$

Interactions

$$R_\mu = 2[B_\nu, \partial_\nu B_\mu] - [B_\nu, \partial_\mu B_\nu] - [B_\mu, \partial_\nu B_\nu] + [B_\nu, [B_\nu, B_\mu]]$$



J.A.Harvey and M.S.Turner 1990

S. Weinberg

Thermal Equiliburium

Relativistic ideal gas $$n_i = \frac{4\pi^3}{3}\frac{(k_B T)^2}{(2\pi\hbar)^3}\tilde{g}_i\,\mu_i \equiv f(T)\,\tilde{g}_i\,\mu_i$$

Thermal Eq. : $\sum_i \mu_i \Delta n_i = 0$ Conserved charge : $\sum_i Q_i^a \Delta n_i = 0$

Feedom = # conserved charge → Indep.var. : $n_a = \sum_i Q_i^a n_i$ a: kind of charge

$$\sum_i (\mu_i - \sum_a \mu_a Q_i^a)\Delta n_i = 0 \quad \Rightarrow \quad \mu_i = \sum_a \mu_a Q_i^a$$

Lagrange multiplyer

$$n_a = f(T)\sum_i Q_i^a \tilde{g}_i \mu_i = f(T)\sum_i Q_i^a \tilde{g}_i \left(\sum_b \mu_b Q_i^b\right) = f(T)\sum_b M_{ab}\,\mu_b$$

Solve about μa : $\mu_a = f^{-1}(T)\sum_b M_{ab}^{-1} n_b$ → $n_i = \tilde{g}_i \sum_{a,b} Q_i^a M_{ab}^{-1} n_b$