What will be the next paradigm?

Tsutomu Yanagida (TDLI)

Multi-Boson Interactions (MBI) 2022 at TDLI

The Golden Time Started

Discovery of neutral currents at CERN ---1973

v_bar + e → v_bar + e --- 3 events

A sharped-eye's graduate student found them from 100,000 pictures scanned in Gargamelle heavy-liquid bubble chamber

The new paradigm based on gauge theories started after this NC discovery

In the beginning of my graduate student period

What is the next physics ?

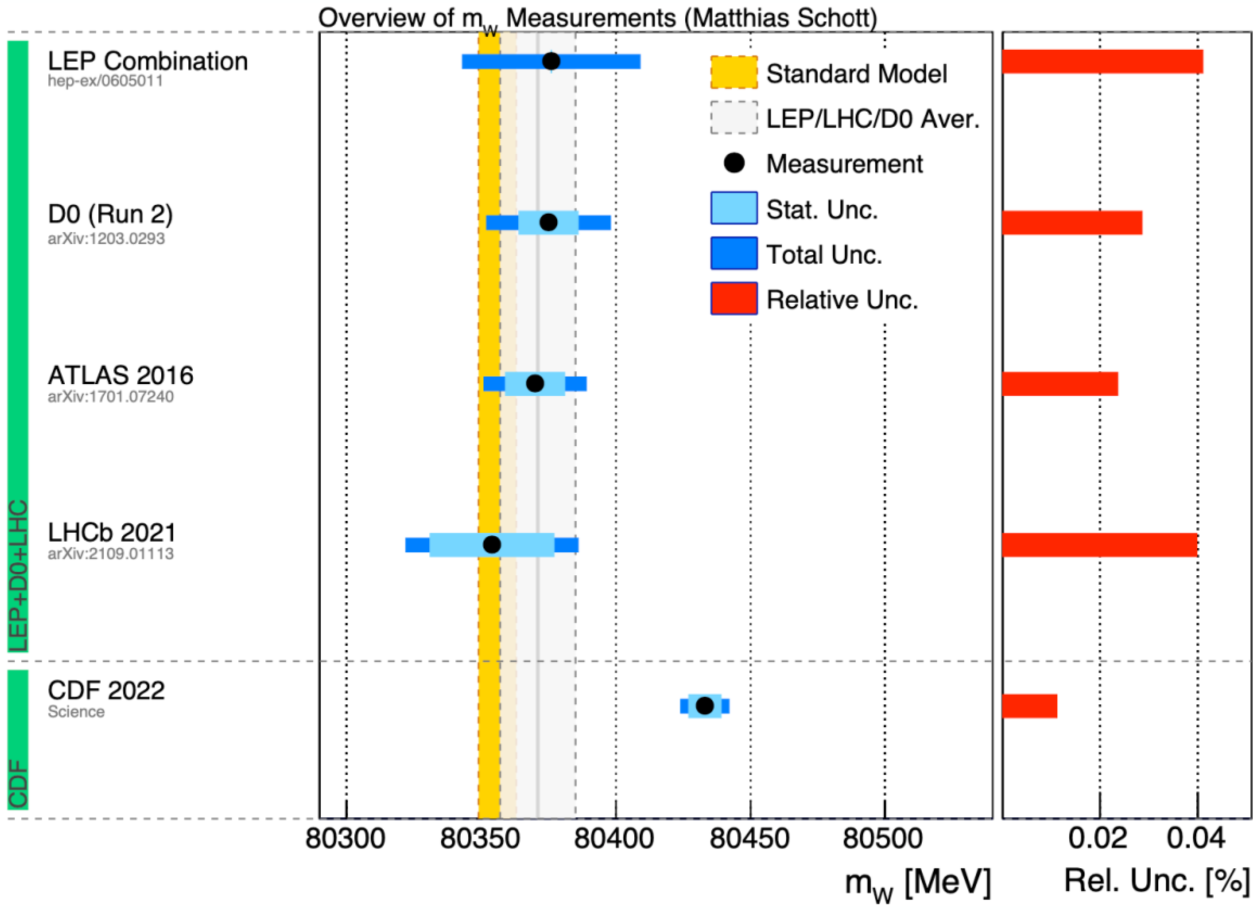
I spent the golden time in particle physics when I was young

- We now have confirmed the standard model in about 50 years after the neutral current discovery!!!

What are new discoveries and anomalies?

- **Cosmic Birefringence**   3.6 sigma (2022) Komatsu …
- **Shift of the W Mass**   >5 sigma (2022) CDF II
- Muon g-2   Theories **???**

W-boson mass anomaly



$$(M_W)_{\text{exp}} = (80.4133 \pm 0.0080)\,\text{GeV}$$

$$(M_W)_{\text{SM}} = (80.3500 \pm 0.0056)\,\text{GeV}$$

$$\delta M_W \sim 50\,\text{MeV}$$

[2204.04204]

W boson mass shift from radiative corrections by new particles

N. Yokozaki

$$\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha}{2M_W^2 s_W^2}(1+\Delta r)$$

Δr : radiative correction $\quad s_W^2 = 1 - \frac{M_W^2}{M_Z^2}$

$$M_W \approx (M_W)_{\rm SM}\left(1 + \frac{1}{2}\frac{c_W^2}{c_W^2 - s_W^2}(\Delta\rho)_{\rm NP}\right)$$

$$(\Delta\rho)_{\rm NP} \sim \frac{g_2^2}{(16\pi^2)}\frac{M_W^2}{m_{\rm NP}^2} \Rightarrow m_{\rm NP} \sim 200\,{\rm GeV}$$

Those new particles carry the non-trivial SU(2) charges ← Excluded by LHC

Mass shift at the tree level may be required

- If a **SU(2) triplet Higgs** has a vev, it is easy to shift the W mass

- But the vev must be sufficiently small, otherwise it is excluded by many precision measurements

vev < a few GeV

W-boson mass shift and triplet Higgs

- SU(2) triplet with zero hyper-charge

$$\mathcal{L} \ni 2\,\mathrm{Tr}\big[(D_\mu \Sigma_3)^\dagger D^\mu \Sigma_3\big] \qquad \Sigma_3 = \Sigma^a \frac{\tau^a}{2} = \frac{1}{2}\begin{pmatrix} H_T & \sqrt{2} H_1^+ \\ \sqrt{2} H_2^- & -H_T \end{pmatrix}$$

$$D_\mu \Sigma_3 = \partial_\mu \Sigma_3 - i g_2 [W_\mu, \Sigma_3] \qquad [W_\mu, \langle \Sigma_3 \rangle] = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & -\langle H_T \rangle W_\mu^+ \\ \langle H_T \rangle W_\mu^- & 0 \end{pmatrix}$$

⇓

At the tree-level the W-boson mass is shifted $\delta M_W^2 = 2 g_2^2 \langle H_T^2 \rangle$

W-boson mass shift and triplet Higgs

$$M_W \approx (M_W)_{\rm SM}\left(1+\frac{1}{2}\frac{c_W^2}{c_W^2-s_W^2}\frac{4\left\langle H_T\right\rangle^2}{v^2}\right) \quad \langle H_T\rangle \sim 3\,\mathrm{GeV} \quad \Rightarrow \quad \delta M_W \sim 60\,\mathrm{MeV}$$

Scalar Potential

Norimi Yokozaki

Introduce a complex SU(2) triplet Higgs in the Standard model

$$V(H,\Sigma_3) = -\mu_H^2|H|^2 + \lambda_H|H|^4 + A_{3H}H^\dagger\Sigma_3 H + h.c. + 2\mu_3^2\mathrm{Tr}(\Sigma_3^\dagger\Sigma_3),$$

$$\langle H\rangle = (0,v)^T, \quad \langle\Sigma_3\rangle = \frac{1}{2}\begin{pmatrix} v_T & 0 \\ 0 & -v_T \end{pmatrix}$$

$$v^2 = (\mu_H^2 + A_{3H}v_T)/(2\lambda_H), \quad v_T = \frac{A_{3H}v^2}{2\mu_3^2}.$$
$$\approx (174\,\mathrm{GeV})^2$$

例

$A_{3H} = 200\,\mathrm{GeV}$

$\mu_3 = 1\,\mathrm{TeV}$

We have **6 new bosons** $H,\ A,\ H_a^\pm,\ H_b^\pm \quad \mathrm{mass} \approx |\mu_3|$

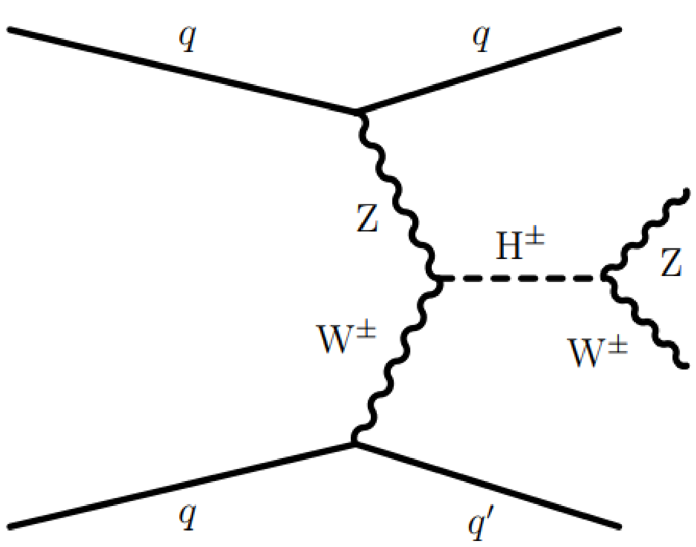
We have **6 new bosons**, H, A, H^pm and H’^pm

Masses are O(1) TeV

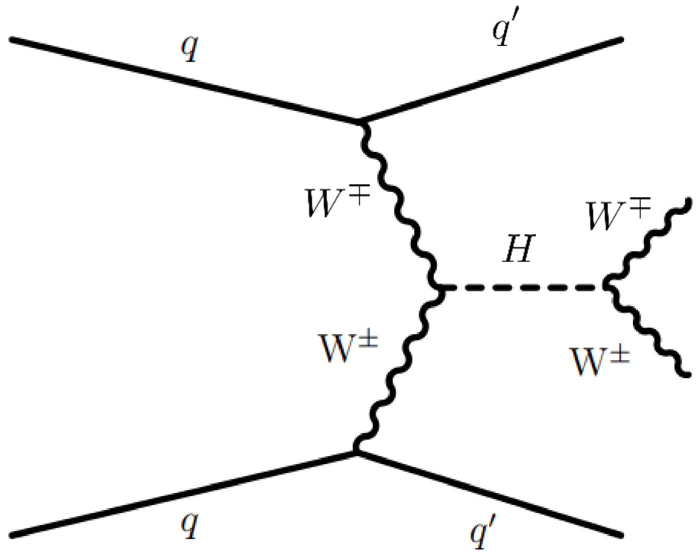
Discovery of them at LHC is crucial !!!

Searches for additional Higgs bosons

Charged Higgs



CP-even Heavy Higgs



The present bound of their masses are roughly 2 TeV

Notice the coupling of Higgs-vector-vector is proportional to v_T and hence the production cross section is small

- SU(2) Triplet Higgs(with zero-hypercharge) give a mass only to $W^{\pm}$ and hence we can shift only W-boson mass
- VEV ~ 3 GeV of the Triplets Higgs enough to explain the observed shift
- It is consistent with all experimental constraints

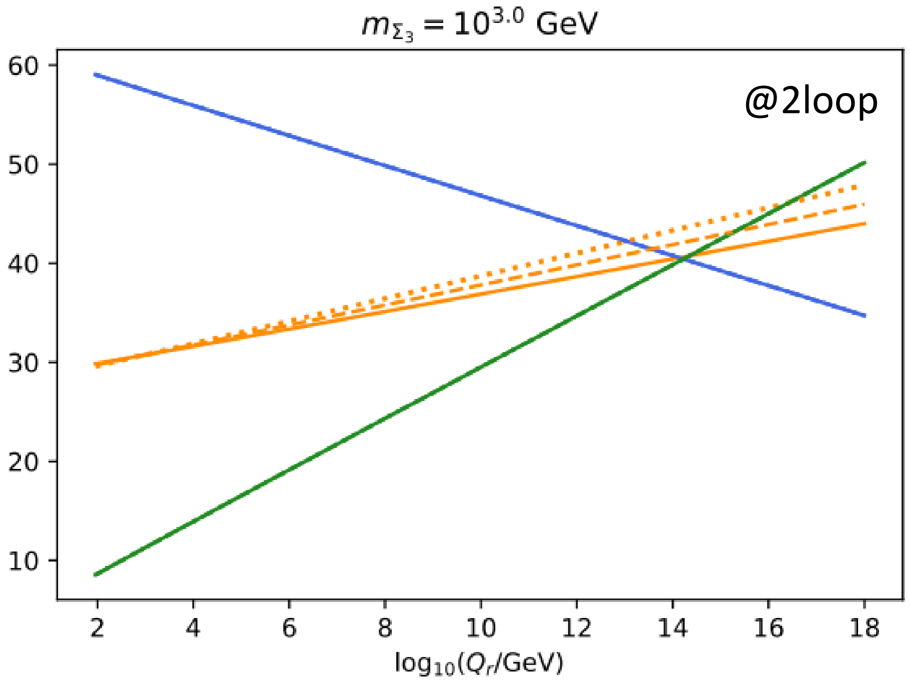
But who ordered such a Triplet ?

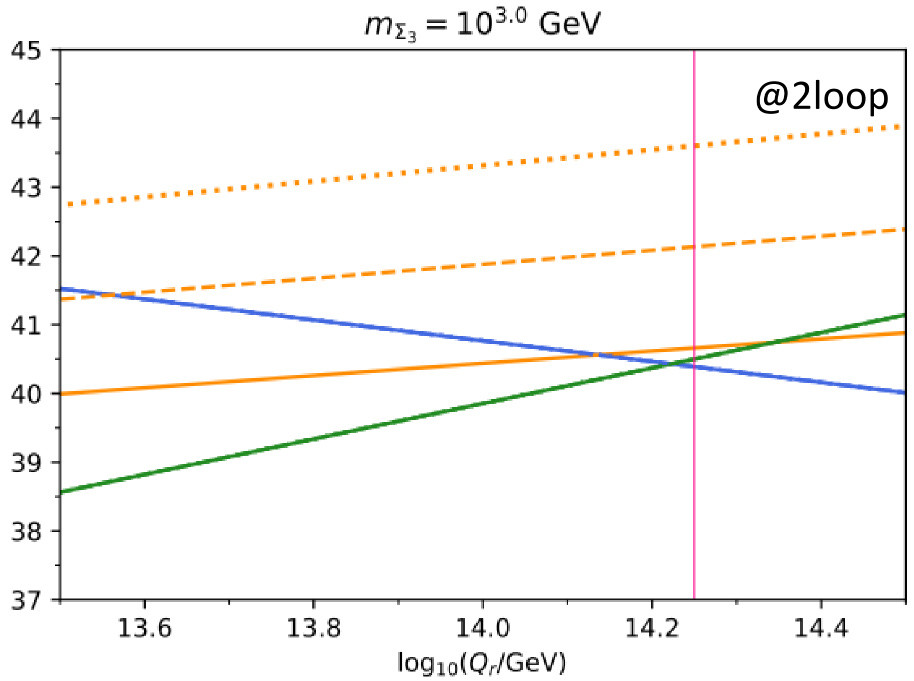
↓

Grand Unification SU(5) **Evans, Yanagida, Yokozaki (2022)**

$$\Sigma_{24} \ni \Sigma_3 = (\mathbf{1}, \mathbf{3}, 0) \ (SU(3)_c \times SU(2)_L \times U(1)_Y)$$

Gauge coupling unification with triplet Higgs





Dotted: SM
Dashed: Real SU(2) triplet
Solid: Complex SU(2) triplet

$$\Delta b_2 = \frac{2}{3}$$ for complex SU(2) triplet

Gauge coupling unification is very good

A few x 10^{14} GeV is the unification scale

（The **proton decay** should be discussed below）

Minimal SU(5) Grand Unified Theory

- Standard Model gauge group → SU(5) (rank=4)
- Quarks and Leptons belong to 10+5*
- The charge quantization can be easily explained
- The doublet Higgs belongs to 5 together with a colored Higgs

$$\bar{\mathbf{5}}_i = (\bar{D}, L)_i \quad \mathbf{10}_i = (Q, \bar{U}, \bar{E})_i$$

$H_5 = (H_C, H)$ $\quad H_C$: colored Higgs

$$A^a_\mu T^a = \begin{pmatrix} G_\mu & X_\mu/\sqrt{2} \\ X^\dagger_\mu/\sqrt{2} & W_\mu \end{pmatrix} - \frac{1}{2\sqrt{15}} \begin{pmatrix} 2B_\mu & \\ & -3B_\mu \end{pmatrix}$$

$X_\mu(\mathbf{3}, \mathbf{2}, -5/6)$ causes the proton decays

Light SU(2) triplet from SU(5) adjoint scalar

Σ_{24}Contains a SU(2) triplet

$$\Sigma_{24} = \begin{pmatrix} \Sigma_3 & X_1/\sqrt{2} \\ X_2^\dagger/\sqrt{2} & \Sigma_8 \end{pmatrix}$$ + gauge singlet

$$\Sigma_3 : (\mathbf{1}, \mathbf{3}, 0) \quad \Sigma_8 : (\mathbf{8}, \mathbf{1}, 0) \quad X_1,\ X_2 : \left(\mathbf{3}, \mathbf{2}, -\frac{5}{6}\right)$$

We assume a global U(1) for simplicity $\Sigma_{24} \to e^{i\alpha}\Sigma_{24}$

($H_5^\dagger \Sigma_{24} H_5 \ni H^\dagger \Sigma_3 H$ breaks the U(1) softly)

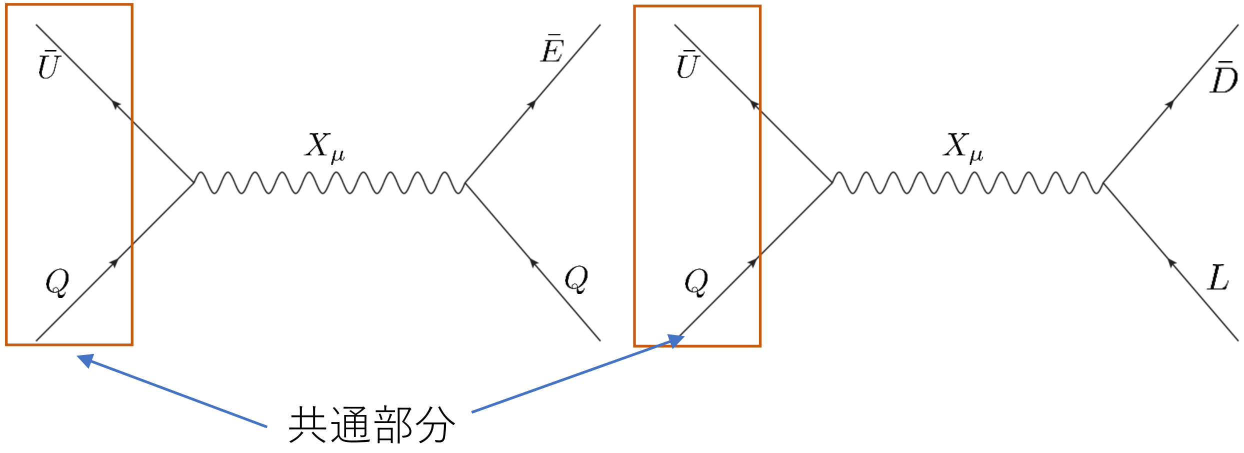
$$\begin{aligned} V \ \ni\ & 2\mu_{24}^2 \mathrm{Tr}(\Sigma_{24}^\dagger \Sigma_{24}) + 2A_1 \mathrm{Tr}(\Sigma_{24H}\Sigma_{24}^\dagger \Sigma_{24}) + 2A_2 \mathrm{Tr}(\Sigma_{24}^\dagger \Sigma_{24H}\Sigma_{24}) \\ +\ & \lambda_1 \mathrm{Tr}(\Sigma_{24H}^2)\mathrm{Tr}(\Sigma_{24}^\dagger \Sigma_{24}) + 2\lambda_2 \mathrm{Tr}(\Sigma_{24H}^2 \Sigma_{24}^\dagger \Sigma_{24}) + 2\lambda_3 \mathrm{Tr}(\Sigma_{24H}\Sigma_{24}^\dagger \Sigma_{24H}\Sigma_{24}) \end{aligned}$$

We can make all bosons beside Σ_3 super heavy at ~GUT scale

Proton decay

X gauge boson exchanges

$p \to e^+\pi^0$



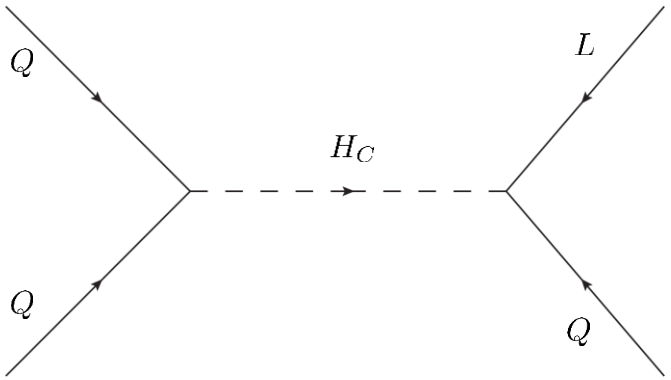
$$\tau_p = \frac{1}{\Gamma_p} \sim \frac{M_X^4}{\alpha_{\rm GUT}^2 m_p^5} = 2.4\times 10^{34}{\rm yrs}\left(\frac{\frac{1}{40}}{\alpha_{\rm GUT}}\right)^2\left(\frac{M_X}{5.3\times 10^{15}{\rm GeV}}\right)^4$$

$$M_X \approx 5.3\times 10^{15}\ {\rm GeV}$$

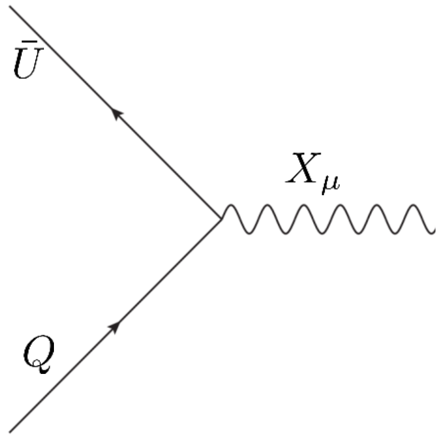
$M_X \sim 10^{14}\ {\rm GeV}$ gives a too short life time

Colored Higgs exchanges

$p \to K^+\bar{\nu}$



Suppression of proton decay



We should suppress this vertex

Vector-like matter $\psi_{\mathbf{10}} = (\psi_Q, \psi_{\bar{U}}, \psi_{\bar{E}})$ $\psi_{\overline{\mathbf{10}}}$

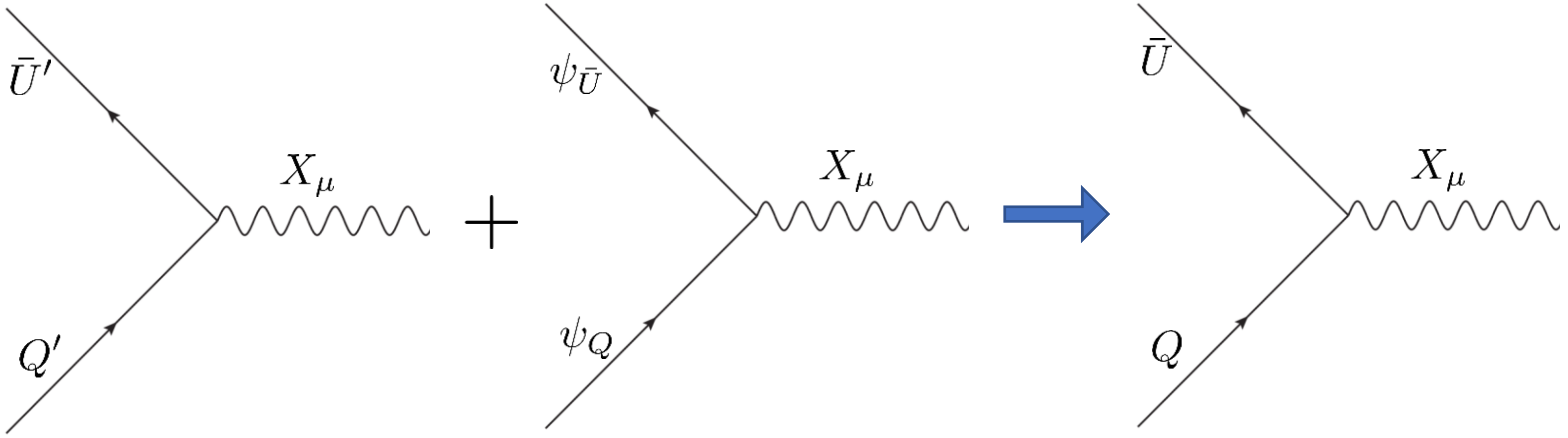
is introduced to mix the SM 10

Only the mixing of the first family is sufficienet

massless

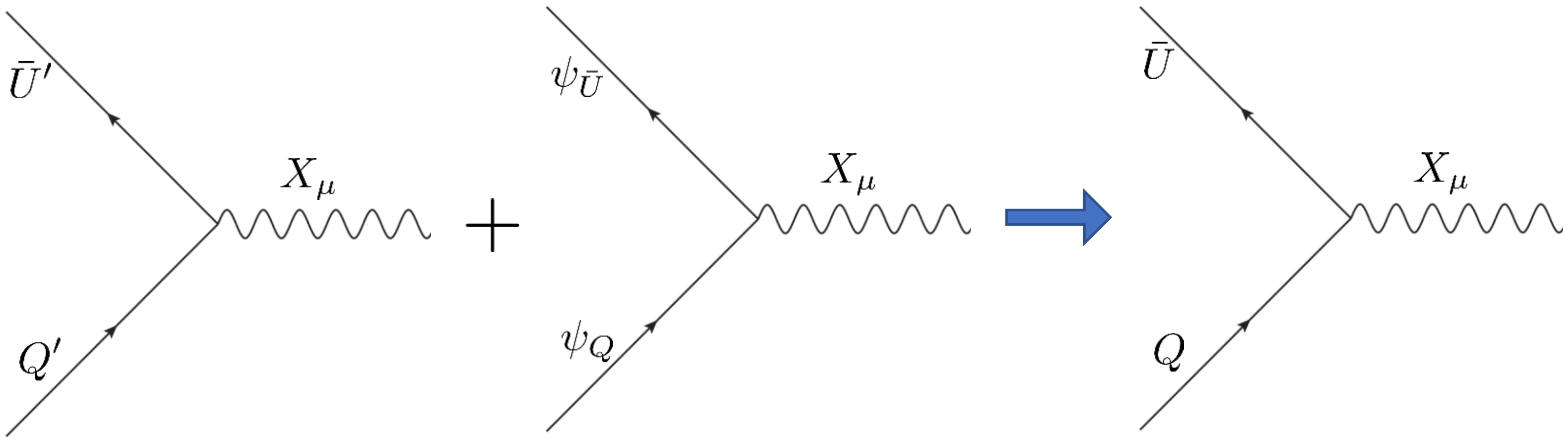
$$\begin{pmatrix} \mathbf{10}' \\ \psi_{\mathbf{10}} \end{pmatrix} = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} \mathbf{10}_{\mathrm{SM}} \\ \psi_{\mathbf{10},\mathrm{heavy}} \end{pmatrix}$$

But it does not give us any suppression



$\propto \cos^2\theta + \sin^2\theta = 1$

Suppression of proton decay



$Q,\ \bar{U}$ Only are mixed with heavy vector-like multiplets It can be done by using the GUT breaking VEV

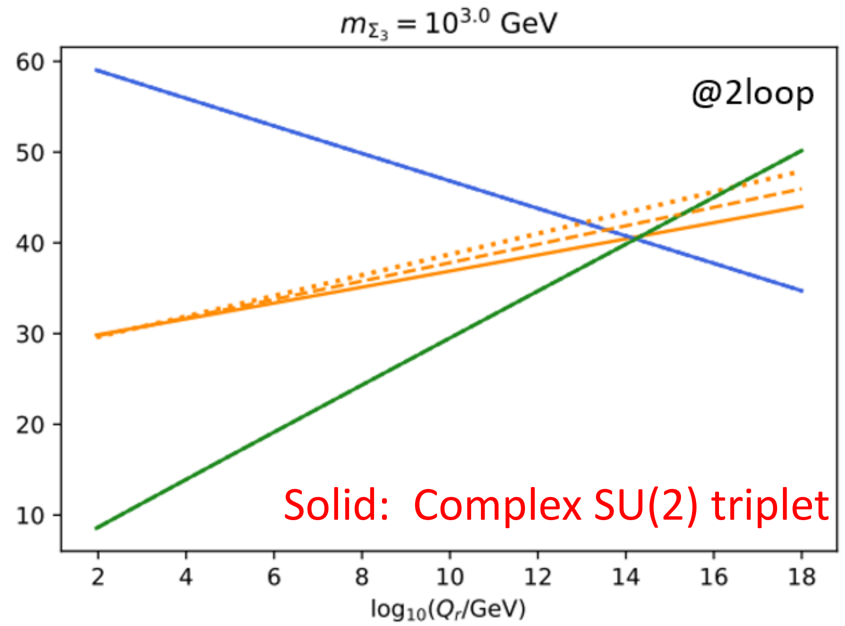
$$\begin{pmatrix} Q' \\ \psi_Q \end{pmatrix} = \begin{pmatrix} \cos\theta_Q & \sin\theta_Q \\ -\sin\theta_Q & \cos\theta_Q \end{pmatrix} \begin{pmatrix} Q \\ \psi_{Q,\mathrm{heavy}} \end{pmatrix}$$

$$\begin{pmatrix} \bar{U}' \\ \psi_{\bar{U}} \end{pmatrix} = \begin{pmatrix} \cos\theta_U & \sin\theta_U \\ -\sin\theta_U & \cos\theta_U \end{pmatrix} \begin{pmatrix} \bar{U} \\ \psi_{\bar{U},\mathrm{heavy}} \end{pmatrix}$$

vertex $\propto \cos\theta_Q \cos\theta_U + \sin\theta_Q \sin\theta_U$

Summary

- SU(2) triplet Higgs with zero hyper-charge can explain the shift of the W-boson mass
- One complex SU(2) triplet is very much consistent with the non-SUSY GUT
- We can suppress the proton decay by using the GUT breaking VEV



Evans, Yanagida, Yokozaki (2022)

Search for the 6 new bosons at LHC!!!

Cosmological Constant 1 9 9 8

CC =O(a few meV)^4 is 10^{-120} smaller than the naïve expectation M_pl^4

Why is it extremely small ?

Why is it nonzero ?

- This looks a surprising discovery
- But we have already expectation of such a cosmological constant
- In fact, we predicted it even 4 years before the discovery

Yukawa Institute Kyoto

YITP/K-1098
February 1994

Model for the Cosmological Constant

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Significant progress achieved recently has been resolving the notoriously controversial problem of the Hubble constant [1-3]. The controversy had arisen from the difficulty in determining the distance to galaxies, in particular, to those in the Virgo cluster. A number of qualified distance indicators have been studied over the last five years to determine the distance to the Virgo cluster. Now, with the exception of the work with type Ia supernovae, all qualified distance indicators point towards a so-called short distance to the Virgo cluster, and most importantly, this is strongly corroborated by recent observations of Cepheids in Virgo galaxies [4]. Contrary to the distance to the Virgo cluster, little dispute has been made on the relative distance between the Virgo galaxies and those in distant clusters that are well on the Hubble flow. The result is a high value of the Hubble constant $H_0 = 75 - 85\text{km s}^{-1}\ \text{Mpc}^{-1}$. This means that the age of the Universe is at longest 11.5 Gyr, which is significantly shorter than the age inferred from the stellar evolution. Should the stellar age be correct, we would then be forced to introduce a finite cosmological constant in excess of matter density, the observationally relevant value $\Delta V = (3 \pm 1\text{meV})^4$ in terms of the vacuum energy. The cosmological constant, however, is an anathema to most physicists, the most important reason being that the required value of the cosmological constant is extraordinarily small by a factor of 10^{-120} compared to the gravity scale. It is still smaller by many orders of magnitude than any vacuum energy that appears in particle physics [5]; it has been considered that it is not easy to conceive a mechanism that leads to such a minuscule vacuum energy [5].

Discovery of Cosmological constant

1998

$$\Lambda_{\cos}^{4} \simeq (2 \times 10^{-3}\ \mathrm{eV})^{4}$$

2011

Why is CC extremely small ?

Symmetries, Dynamics or Modified GR ?

Symmetry;

de Sitter space ← → Anti- de Sitter space

't Hooft

→ CC=0 is the symmetric space

But we need a **complex extension of the space-time?**

- **Wheeler-DeWitt equation of the wavefunction of the universe**

With the Hartle-Hawking no-boundary condition we find the solution of the equation which has a sharp peak at CC=0 point

$$P \simeq e^{-2S_{\rm E}}, \qquad S_{\rm E} \simeq -\frac{12\pi^2}{V(\phi)}$$

We get **dynamically CC=0** universe

But it is extremely **difficult** to have the inflationary expanding universe

- **Unimodular gravity**

Einstein(1916)

$$\sqrt{g} = 1$$

The classical unimodular gravity is physically the same as Einstein gravity since it has **a symmetry** the volume-preserving diffeomorphisms

The cosmological constant CC is an integration constant !!!

We can choose CC=0 without the miracle cancellation of vacuum energy at the quantum level

But there is no reason to choose CC~0 ???

- **Anthropic principle** Weinberg

The cosmological constant must be smaller than the critical value (CC)_c so that galaxies can be formed for us to live

But the observed value of the cosmological constant is two orders magnitude smaller than the critical value of (CC)_c ???

No theory for CC was found

- If we want to explain the observed value of the cosmological constant we need to assume the vanishing cosmological constant CC=0

We assume a new cosmological principle

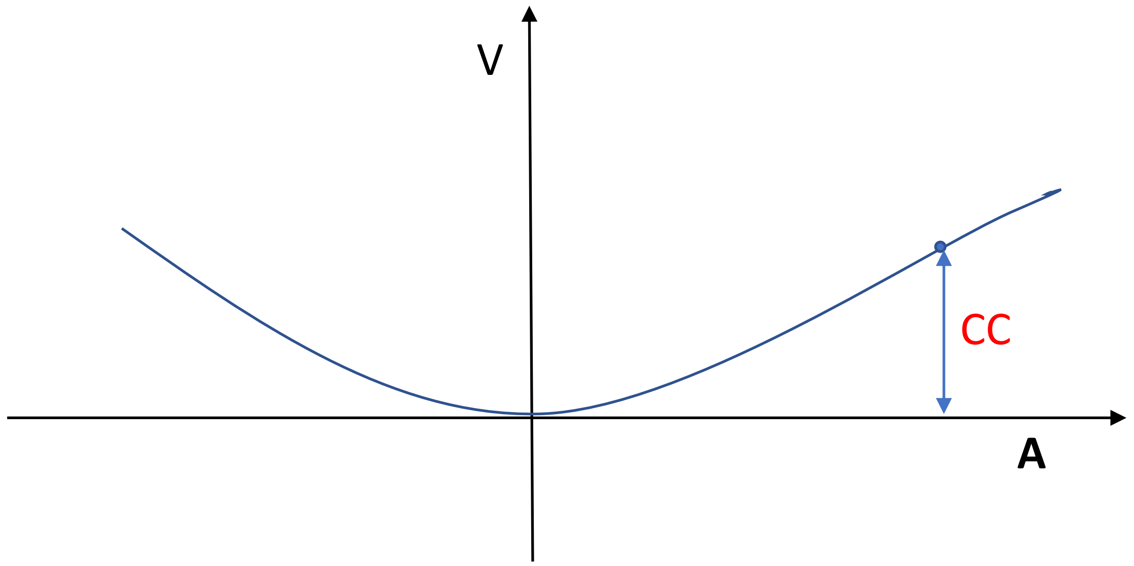
--- Asymptotic Flatness---

Why nonzero?

Calculate the small CC assuming a non-asymptotic stage of the present universe

How to explain non vanishing CC?

- Quintessence Dark Energy



→The boson **A** should be **extremely light**

m ~ 10^{-33} eV !!! **Why so small?→NG boson**

Quintessence Axion Dark Energy

- Q-axion potential

$$V= K(1- \cos(A/F))$$

At the potential minimum A=0, V=0 (CC=0)

At the asymptotic true vacuum the cosmological constant is vanishing

But A~F we have a non vanishing vacuum energy

$$V \sim K$$

If the present value of A is around F we have an effective cosmological constant CC~ K

How to calculate the vacuum energy K?

- **Electroweak instanton;**

We assume the Q axion A couples to SU(2) gauge bosons through the anomaly term A/F WW~

Fukugita Yanagida (1994)

The **electroweak instantons** give us the Q axion potential

$$V=K(1- \cos(A/F))$$

- **We obtain**

$$K \simeq e^{-\frac{2\pi}{\alpha_2(M_{\rm pl})}} c\,\epsilon^{10} m_{\rm SUSY}^3 M_{\rm pl}$$
$$\simeq c\left(\frac{\epsilon}{1/17}\right)^{10} (1\times 10^{-3}\ {\rm eV})^4$$

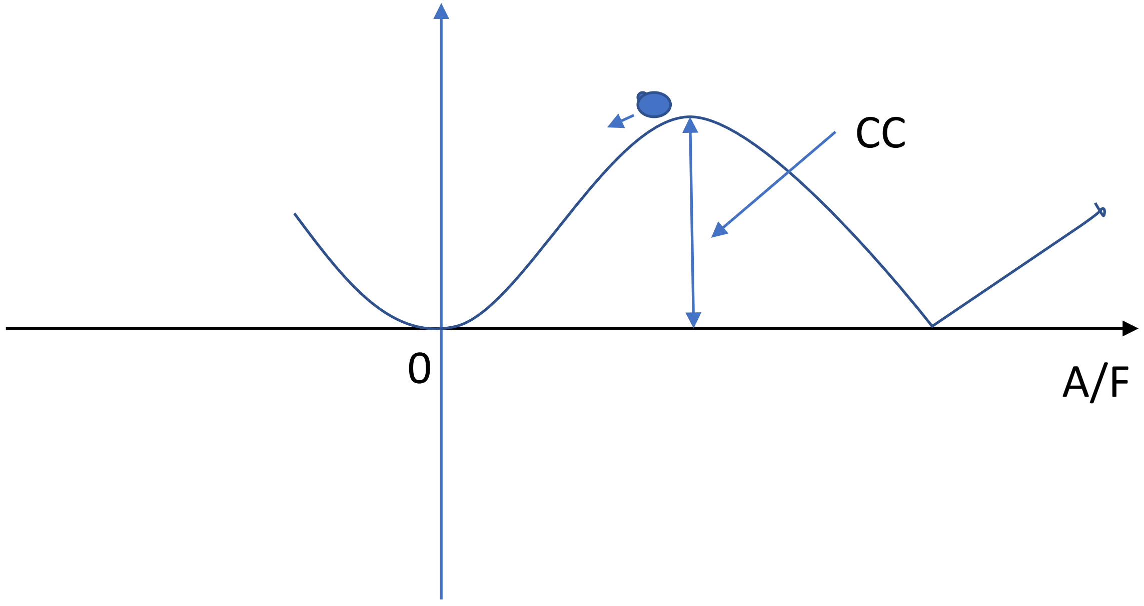
For m_SUSY =1 TeV

Nomura, Watari ,Yanagida (2000)

The observation is

$$\Lambda_{\rm cos}^4 \simeq (2\times 10^{-3}\ {\rm eV})^4$$

SUSY is crucial for the result!!!



$$V_A = \frac{\Lambda_A^4}{2}\left(1 - \cos(A/F_A)\right)$$

How to test the Q-axion model

The Q axion A has a two photon coupling

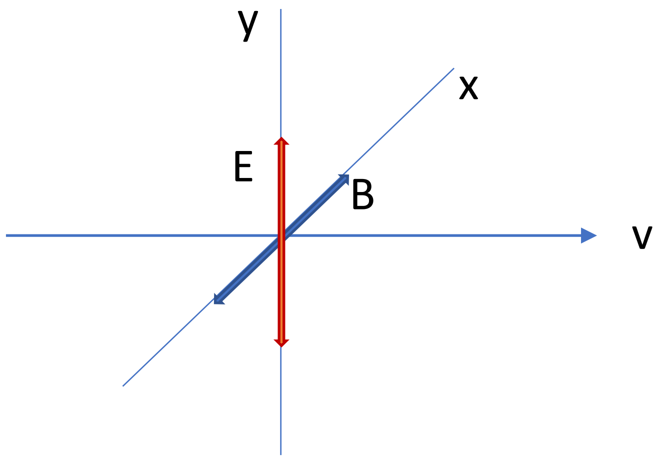
$$-c_\gamma \frac{g_{\rm em}^2}{16\pi^2}\frac{A}{F_A}F^{\mu\nu}\tilde{F}_{\mu\nu}$$

This is EB coupling

Parity Violation

Cosmic birefringence

- The CMB photon is **linearly polarized** by the Thomson scattering at the recombination time



The polarization does not change
The electric field is oscillating, but the direction does not change

- **What happens if A couples to EB?**

D=E+A(t)B field is oscillating, but the direction does not change!!! ←Maxwell's equation coupled to the A(t) field

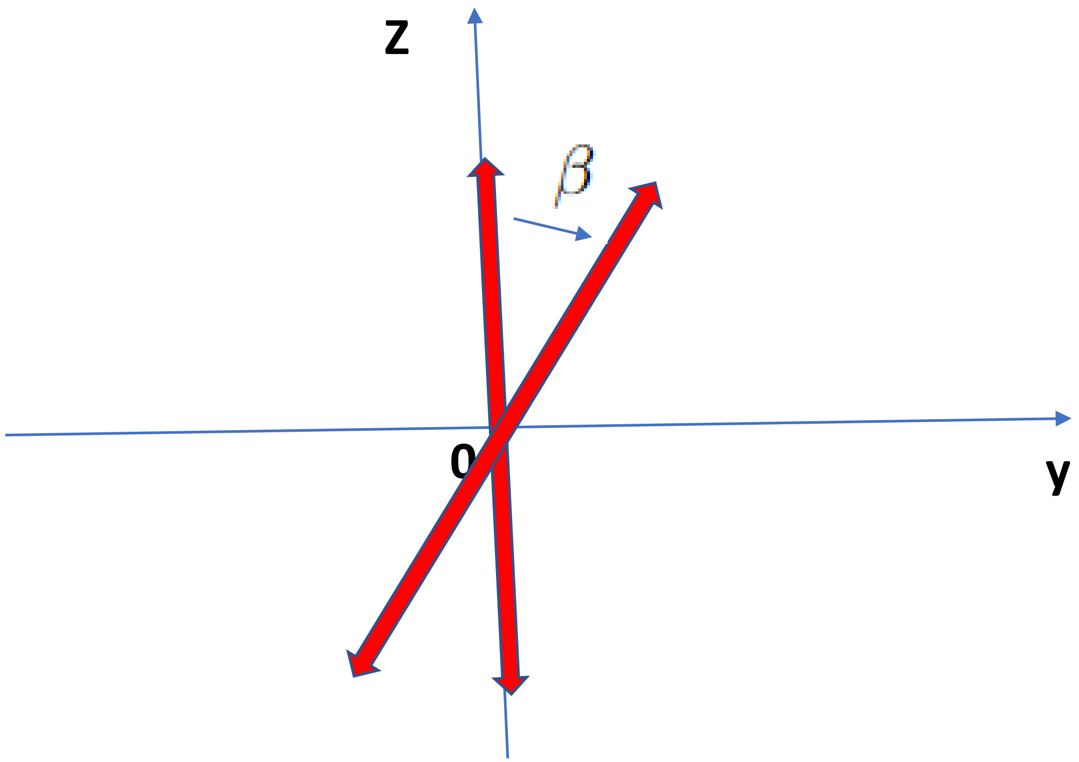
If the Q axion A(t) changed its value from the recombination time to the present, the E direction changed; **The polarization changed** !!!

The cosmic birefringence angle is given by

$$\beta = 0.42\,\mathrm{deg} \times c_\gamma \times \frac{\Delta A}{2\pi F_A}$$

Carroll, Field , Jackiw (1990)

- **The CMB photon's polalization changes**



$$\beta = 0.42\,\mathrm{deg} \times c_\gamma \times \frac{\Delta A}{2\pi F_A}$$

Discovery of the cosmic birefringence

Komatsu/Planck (2020)

- This is a parity violating phenomenon
- In fact, the interaction A(t)EB violates the parity
- The E mode polarization is parity even and the B mode polarization is parity odd
- Komatsu etal found a nonvanishing correlation between the E and B modes;

<E mode,B mode>=non vanishing !!!

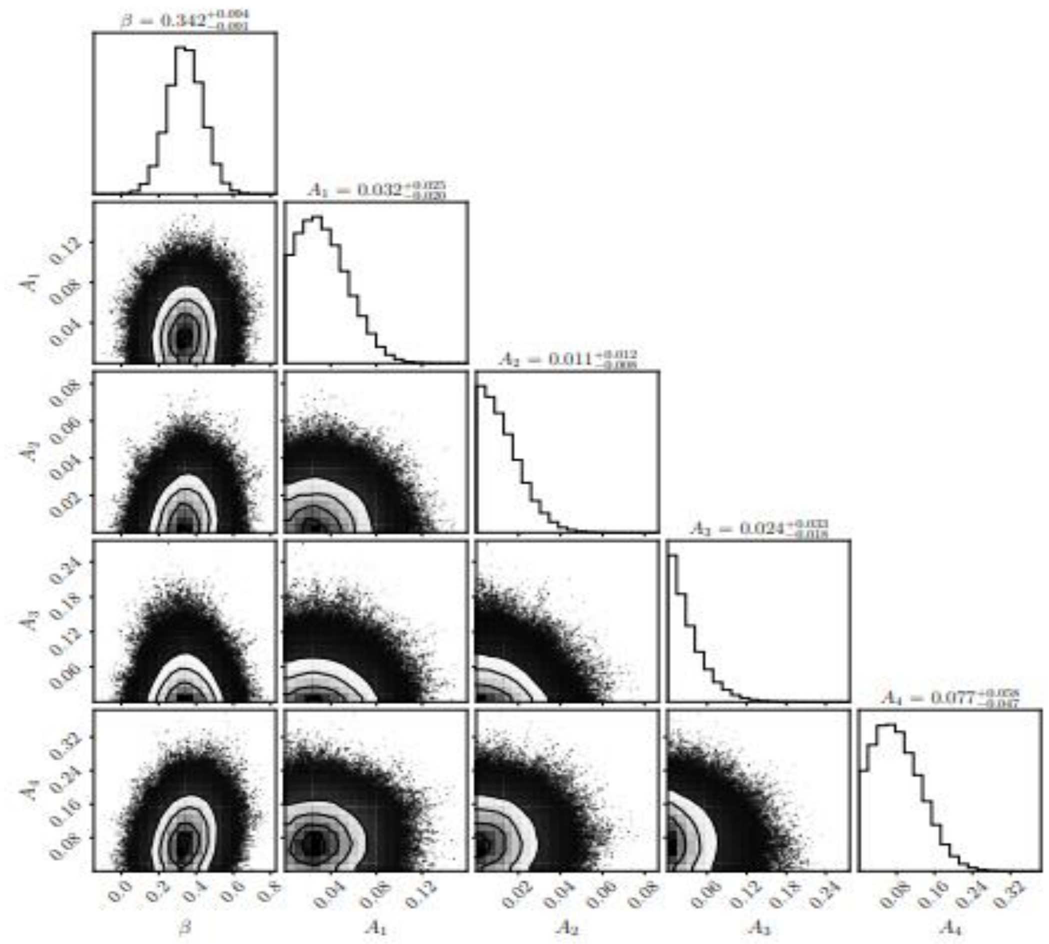


FIG. 1. Posterior distributions of the cosmic birefringence angle, β, and the dust EB amplitude, A_ℓ [Eq. (10)], in 4 bins for nearly full-sky data ($f_{\rm sky} = 0.92$; the 5th row in Table I). The miscalibration angles, α_i, are jointly sampled with β and A_ℓ but not shown here. See Fig. 3 for the 1-d marginalized posterior distribution of α_i.

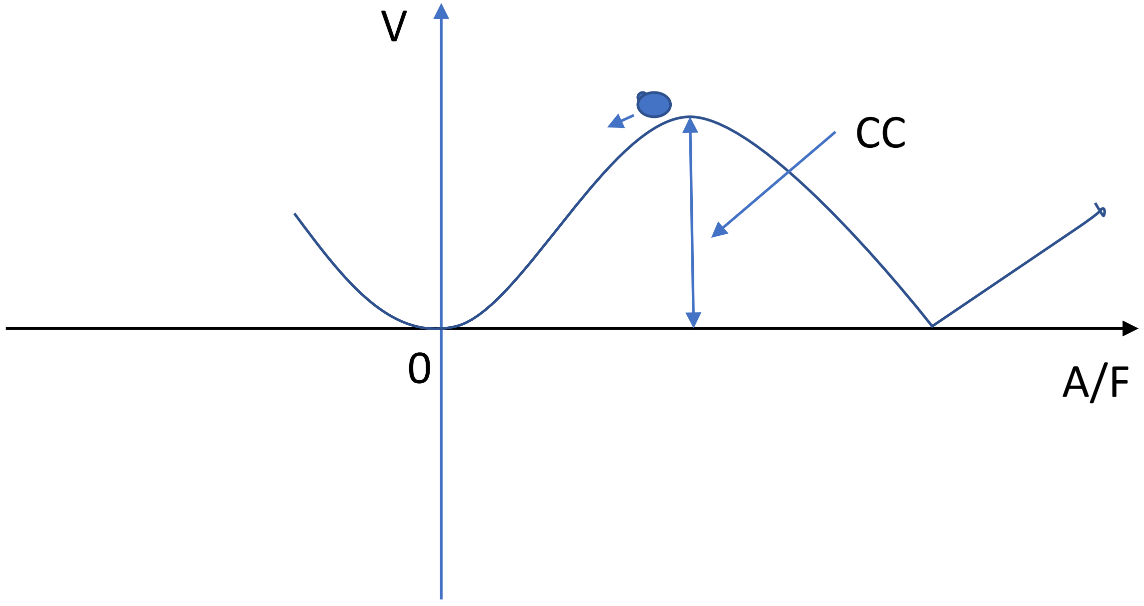
$$\beta = 0.342^\circ {}^{+0.094^\circ}_{-0.091^\circ}$$

Eskilt,Komatsu (2022)

The most recent data; 3.6 sigma

$$\beta = 0.342^\circ {}^{+0.094^\circ}_{-0.091^\circ}$$

Eskilt,Komatsu (2022)



$$V_A = \frac{\Lambda_A^4}{2}\left(1 - \cos(A/F_A)\right)$$

The quintessence axion A can explain the observed dark energy

Nomura, Watari, Yanagida (2000)

Our quintessence axion A can explain the observed cosmic birefringence !!!

Choi, Lin, Visinelli, Yanagida (2021)

SUSY is a key point

m_SUSY ~ 1-100 TeV

Summary

- The mass shift of the W $\delta M_W \sim 60\,\mathrm{MeV}$

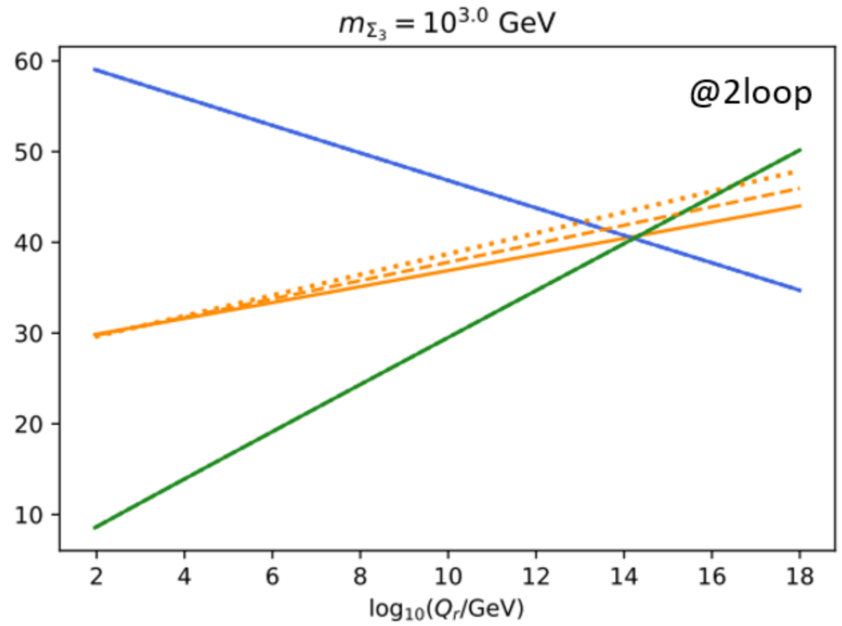
It is easily explained by a triplet higgs vev ~ 3 GeV → O(1) TeV new bosons

A complex Triplets bosons at O(1) TeV make a GUT unification very good!!!

The SU(5) GUT ordered the Triplet boson at O(1) TeV

Discovery of 6 new bosons may open

a new paradigm in this century!!!



- The non-zero cosmological constant

It can be explained by the vacuum energy of the electroweak axion

If the axion slowly moves recently it causes the cosmic birefringence

It was recently discovered at the 3.6 sigma level

$$\beta = 0.342^\circ \,{}^{+0.094^\circ}_{-0.091^\circ}$$

The model needs SUSY ~1-100 TeV

If the discovery is correct

it will open a new paradigm in this century!!!