
Corfu
Athens
Greece
Workshop on Testing Fundamental Physics Principles
Corfu, 22-27 September 2017

We are players in the set-up theater

Workshop on Testing Fundamental Physics Principles
Corfu, 22-27 September 2017

Anomalous gauge U(1), ’t Hooft mechanism, and “invisible” axion from string

Jihn E. Kim

Kyung Hee University,
Seoul National Univ.

Coufu, Greece, 27 September 2017

1. ’t Hooft mechanism

't Hooft mechanism:

If a gauge symmetry and a global symmetry are broken by one complex scalar by the BEHGHK mechanism, then the gauge symmetry is broken and a global symmetry remains unbroken.

Q_{gauge}	Q_{global}
1	1

Unbroken $X = Q_{global} - Q_{gauge}$

$$\phi \to e^{i\alpha(x)Q_{\text{gauge}}} e^{i\beta Q_{\text{global}}} \phi$$

the α direction becomes the longitudinal mode of heavy gauge boson. The above transformation can be rewritten as

$$\phi \to e^{i(\alpha(x)+\beta)Q_{\text{gauge}}} e^{i\beta(Q_{\text{global}}-Q_{\text{gauge}})} \phi$$

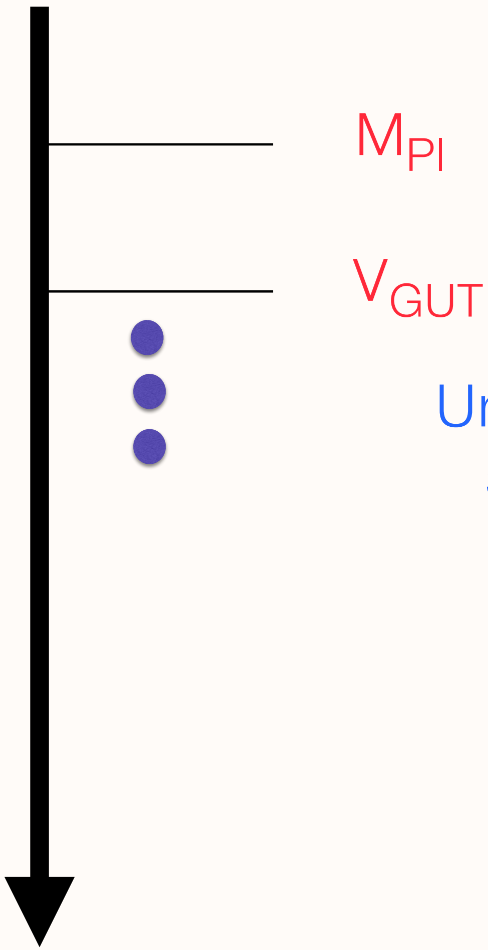
Redefining the local direction as $\alpha'(x) = \alpha(x) + \beta$, we obtain the transformation

$$\phi \to e^{i\alpha'(x)Q_{\text{gauge}}} e^{i\beta(Q_{\text{global}}-Q_{\text{gauge}})} \phi.$$

$$|D_\mu \phi|^2 = |(\partial_\mu - igQ_a A_\mu)\phi|^2_{\rho=0} = \frac{1}{2}(\partial_\mu a_\phi)^2 - gQ_a A_\mu \partial^\mu a_\phi + \frac{g^2}{2} Q_a^2 v^2 A_\mu^2$$
$$= \frac{g^2}{2} Q_a^2 v^2 (A_\mu - \frac{1}{gQ_a v}\partial^\mu a_\phi)^2$$

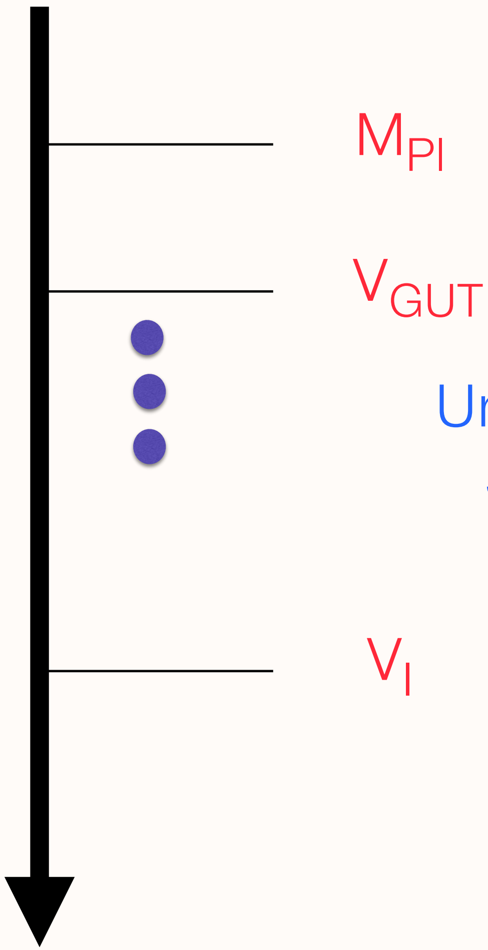
So, the gauge boson becomes heavy and there remains the x-independent transformation parameter beta. The corresponding charge is a combination: $X = Q_{\text{global}} - Q_{\text{gauge}}$

This process can be worked out at any step. When one global symmetry survives below a high energy scale, we consider another gauged U(1) and one more complex scalar to break two U(1)'s. Then, one global symmetry survives.



One complex scalar for one gauge symmetry breaking

Until all wanted U(1) gauge symmetries are broken.



One complex scalar for one gauge symmetry breaking

Until all wanted U(1) gauge symmetries are broken.

At the next step, a global symmetry is broken

Even if we consider the FI term with a non-vanishing \xi and there is no hierarchy between the comp scale and the GUT scale, a global symmetry can be derived:

$$\frac{1}{2}\partial^\mu a_{\rm MI}\partial_\mu a_{\rm MI} + M_{\rm MI} A_\mu \partial^\mu a_{\rm MI} + \left| -\xi + e\sum_a \phi_a^* Q_a \phi_a \right|^2 + \left[|(\partial_\mu - ieA_\mu)\phi_1|^2 + \cdots \right]$$
$$= (M_{\rm MI}\partial^\mu a_{\rm MI} - eV_1 \partial^\mu a_1)A_\mu + \cdots ,$$

Assume: one phi_a is carrying the anomalous charge.

ϕ_1 develops a VEV, V_1, by minimizing the FI term.

a_1 [= the phase of ϕ_1 (= $(V_1+\rho_1)e^{ia_1/V_1})/\sqrt{2}$] are considered and only one Goldstone boson

$$\sqrt{M_{\rm MI}^2+e^2V_1^2}\,(\cos\theta_G\, a_{\rm MI}-\sin\theta_G\, a_1)$$

re $\tan\theta_G = eV_1/M_{\rm MI}$. The orthogonal Goldestone boson direction

$$a'=\cos\theta_G\, a_1+\sin\theta_G\, a_{\rm MI}$$

a global direction below the scale $\sqrt{M_{\rm MI}^2+e^2V_1^2}$

This process can be worked out further below the GUT scale as far as U(1) gauge symmetries (to be broken above the EW scale) are present. Then, one global symmetry survives down to the intermediate scale.

At the intermediate scale a scalar field carrying no gauge charge, i.e. with Y=0, breaks the PQ symmetry, and we obtain the needed “invisible” axion, originating from string. Actually, source of everything is the anomalous U(1) gauge symmetry.

$$a = \cos\theta\, a_\phi + \sin\theta\, a_{\rm MI}, \quad \text{with } \sin\theta = \frac{gQ_a v}{\sqrt{M_{\rm MI}^2 + g^2 Q_a^2 v^2}}$$

At the intermediate scale a scalar field carrying no gauge charge, i.e. with Y=0, breaks the PQ symmetry, and we obtain the needed “invisible” axion, originating from string. Actually, source of everything is the anomalous U(1) gauge symmetry.

$$a = \cos\theta\, a_\phi + \sin\theta\, a_{\rm MI}, \quad \text{with } \sin\theta = \frac{gQ_a v}{\sqrt{\quad_{\rm I} + g^2 Q_a^2 v^2}}$$

V_1^2

2. Model-independent axion in string theory

Green-Schwarz mechanism:

The gravity anomaly in 10D requires 496 spin-1/2 fields. Possible non-Abelian gauge groups are rank 16 groups SO(32) and E8xE8'. The anti-symmetric field B_{MN} has field strength (in diff notation), $H = dB + w_{3Y}^{0} - w_{3L}^{0}$:SO(32). Three indices matched.

$$-\frac{3\kappa^2}{2g^4\,\varphi^2} H_{MNP}H^{MNP}, \text{ with } M,N,P=\{1,2,\cdots,10\}$$

H_{MNP} is the field strength of B_{MN} : This is called the MI-axion.

$$H = dB + \omega_{3Y}^0 - \omega_{3L}^0$$

$$H = dB + \frac{1}{30}\omega_{3Y_1}^0 + \frac{1}{30}\omega_{3Y_2}^0 - \omega_{3L}^0$$

$$H = dB + \frac{1}{30}\omega_{3Y_1}^0 + \frac{1}{30}\omega_{3Y_2}^0 - \omega_{3L}^0$$

$$\omega_{3Y}^0 = \mathrm{tr}(AF - \frac{1}{3}A^3)$$

$$d\omega_{3Y}^0 = \mathrm{tr}F^2$$

The dual of H is the so-called MI-axion [Witten (1984)]

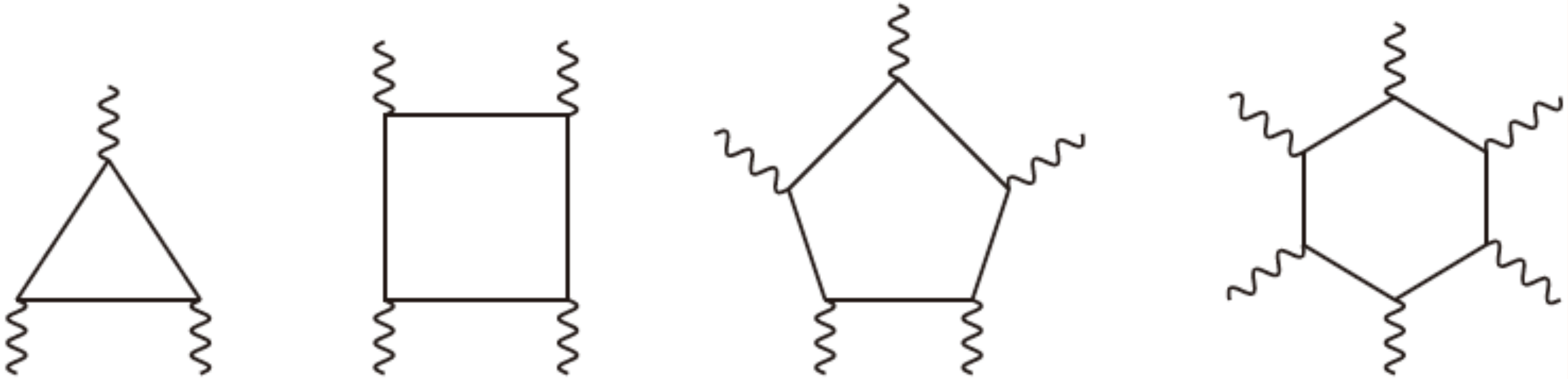
$$H_{\mu\nu\rho} = M_{\rm MI}\,\epsilon_{\mu\nu\rho\sigma}\,\partial^\sigma a_{\rm MI}$$

Counter term is introduced to cancel the anomalies: $E_8 \times E_8'$

$$S_1' = \frac{c}{108\,000}\int \{30B\,[(\mathrm{tr}_1 F^2)^2 + (\mathrm{tr}_2 F^2)^2 - \mathrm{tr}_1 F^2\,\mathrm{tr}_2 F^2] + \cdots\}$$

One needs a term (GS-term) to cancel the gauge and gravitational anomalies.

Anomalies: even dimensions



$D = 4$ $D = 6$ $D = 8$ $D = 10$

In 10D, the hexagon anomaly. It is cancelled by the previous GS term.

One may look this in the following way.

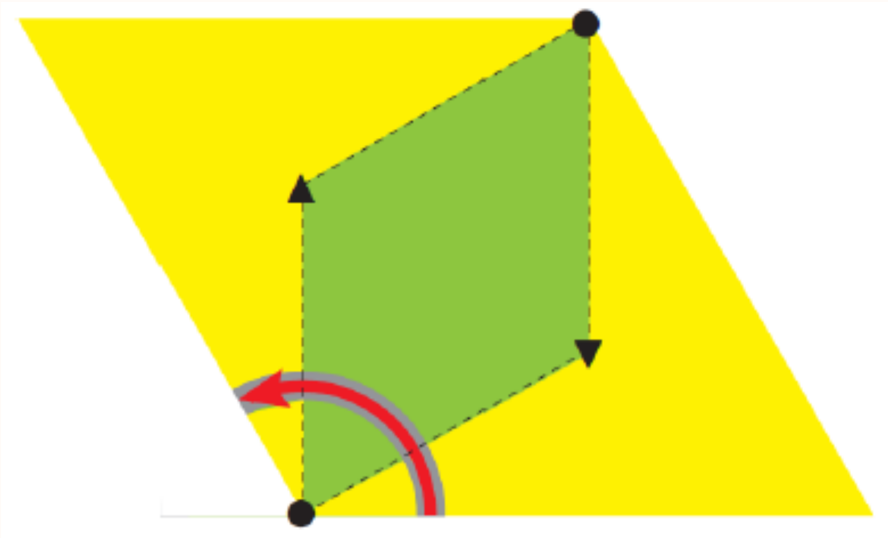
The10 supergravity quantum field theory with SO(32) and E8xE8' gauge groups has gauge and gravity anomalies. Let us believe that string theory is consistent, effectively removing all divergences, i.e. removing all anomalies. The point particle limit of 10D string theory should not allow any anomalies. There must be some term in the string theory removing all these anomalies. It is the Green-Schwarz term. One may remember the Wess-Zumino term removing anomalies by some term involving pseudoscalar fields.

For the GS term, already there is the field B_{MN} needed for the anomaly cancellation.

In the orbifold compactification, e.g. at a Z_3 torus, there are 3 fixed points. Here, we interpret that the flux is located at the fixed points. We take the limit of string loop almost sitting at the fixed points.

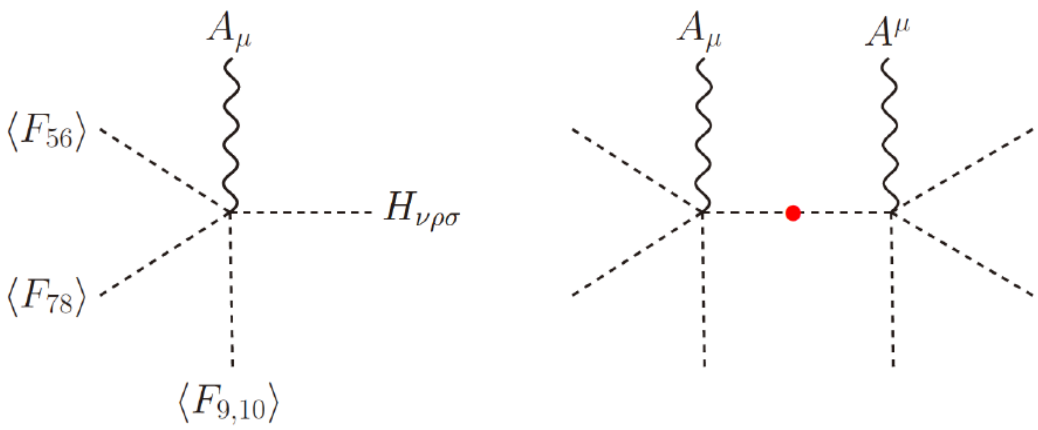
It involves 2nd rank antisymmetric field B_{MN}.

$$S_1' \propto -\frac{c}{10800}\left\{H_{\mu\nu\rho}A_\sigma\,\epsilon^{\mu\nu\rho\sigma}\epsilon^{ijklmn}\langle F_{ij}\rangle\langle F_{kl}\rangle\langle F_{mn}\rangle+\cdots\right\}\to\frac{1}{3!}\epsilon_{\mu\nu\rho\sigma}H^{\mu\nu\rho}A^\sigma$$



$$S_1' \propto -\frac{c}{10800}\left\{H_{\mu\nu\rho}A_\sigma\,\epsilon^{\mu\nu\rho\sigma}\epsilon^{ijklmn}\langle F_{ij}\rangle\langle F_{kl}\rangle\langle F_{mn}\rangle + \cdots\right\} \to \frac{1}{3!}\epsilon_{\mu\nu\rho\sigma}H^{\mu\nu\rho}A^\sigma$$

$$\frac{1}{2\cdot 3!M_{MI}^2}H_{\mu\nu\rho}H^{\mu\nu\rho},\ \text{with } \mu,\nu,\rho=\{1,2,3,4\}.$$



(a) (b)

$$M_{MI} A_\mu \partial^\mu a_{MI}$$

$$\frac{1}{2} M_{MI}^2 A_\mu A^\mu$$

$$\frac{1}{2} M_{MI}^2 (A_\mu + \frac{1}{M_{MI}} \partial_\mu a_{MI})^2$$

This gives with $$H_{\mu\nu\rho} = M_{MI}\epsilon_{\mu\nu\rho\sigma}\partial^\sigma a_{MI}.$$

$$\frac{1}{2}\partial^\mu a_{MI}\partial_\mu a_{MI} + M_{MI}A_\mu\partial^\mu a_{MI}.$$

This is the Higgs mechanism, i.e. a_{MI} becomes the longitudinal mode of the gauge boson. The previous two terms from the GS counter term gives

$$\frac{1}{2}(\partial_\mu a_{MI})^2 + M_{MI}A_\mu\partial^\mu a_{MI} + \frac{1}{2\cdot 3!}A_\mu A^\mu \to \frac{1}{2}M_{MI}^2(A_\mu + \frac{1}{M_{MI}}\partial_\mu a_{MI})^2.$$

It is the 't Hooft mechanism working in the string theory. So, the continuous direction a_{MI} –> a_{MI} + (constant) survives as a global symmetry at low energy. "Invisible" axion!!!!!

$$|D_\mu\phi|^2 = |(\partial_\mu - igQ_aA_\mu)\phi|^2_{\rho=0} = \frac{1}{2}(\partial_\mu a_\phi)^2 - gQ_aA_\mu\partial^\mu a_\phi + \frac{g^2}{2}Q_a^2v^2A_\mu^2$$

$$= \frac{g^2}{2}Q_a^2v^2(A_\mu - \frac{1}{gQ_av}\partial^\mu a_\phi)^2$$

$$\boxed{\frac{1}{2}\left(M_{MI}^2 + g^2Q_a^2v^2\right)(A_\mu)^2 + A_\mu(M_{MI}\partial^\mu a_{MI} - gQ_av\partial^\mu a_\phi) + \frac{1}{2}\left[(\partial_\mu a_{MI})^2 + (\partial^\mu a_\phi)^2\right]}$$

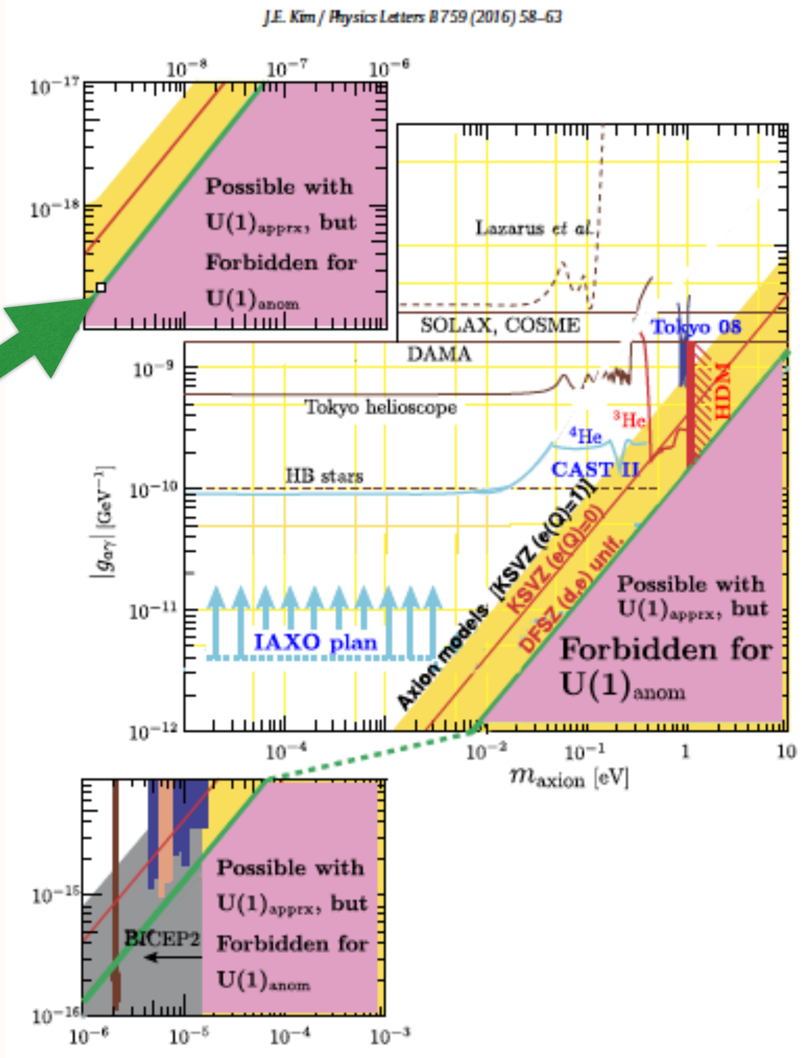
$$a = \cos\theta\, a_\phi + \sin\theta\, a_{MI}$$

$$\sin\theta = \frac{gQ_av}{\sqrt{M_{MI}^2 + g^2Q_a^2v^2}}.$$

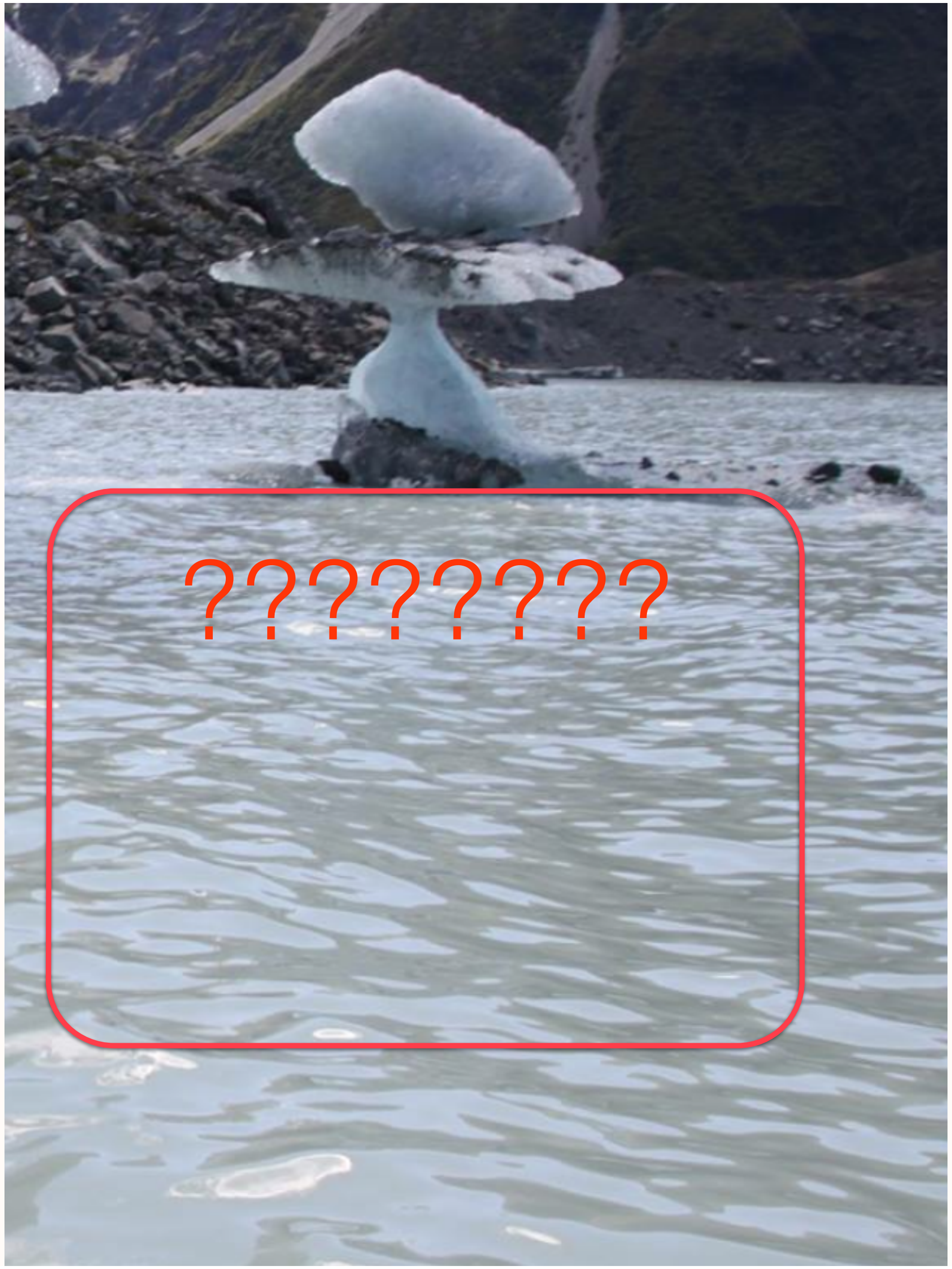
$$\partial^2 a = \frac{1}{32\pi^2 M_{\rm MI}} F^a_{\mu\nu}\tilde{F}^{a\,\mu\nu}$$

$$\to \frac{1}{2}(\partial^\mu a_{\rm MI})^2 + \frac{1}{32\pi^2 M_{\rm MI}} F^a_{\mu\nu}\tilde{F}^{a\,\mu\nu}$$

It is an axion.



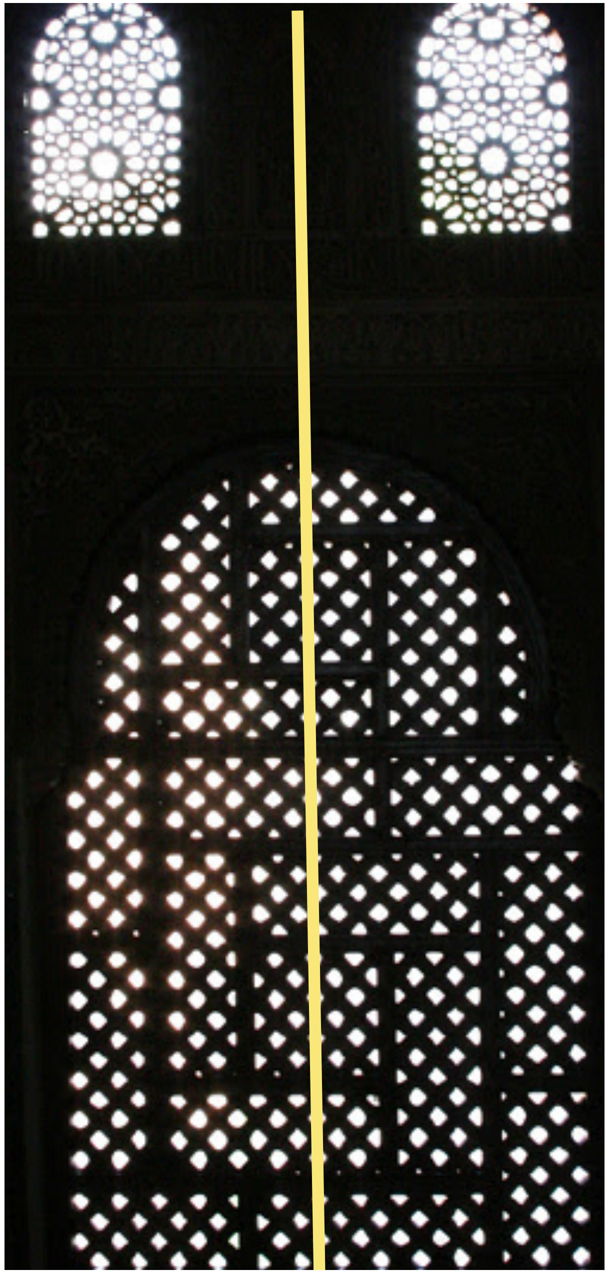
3. Approximate global symmetry




Search has begun with symmetry principles

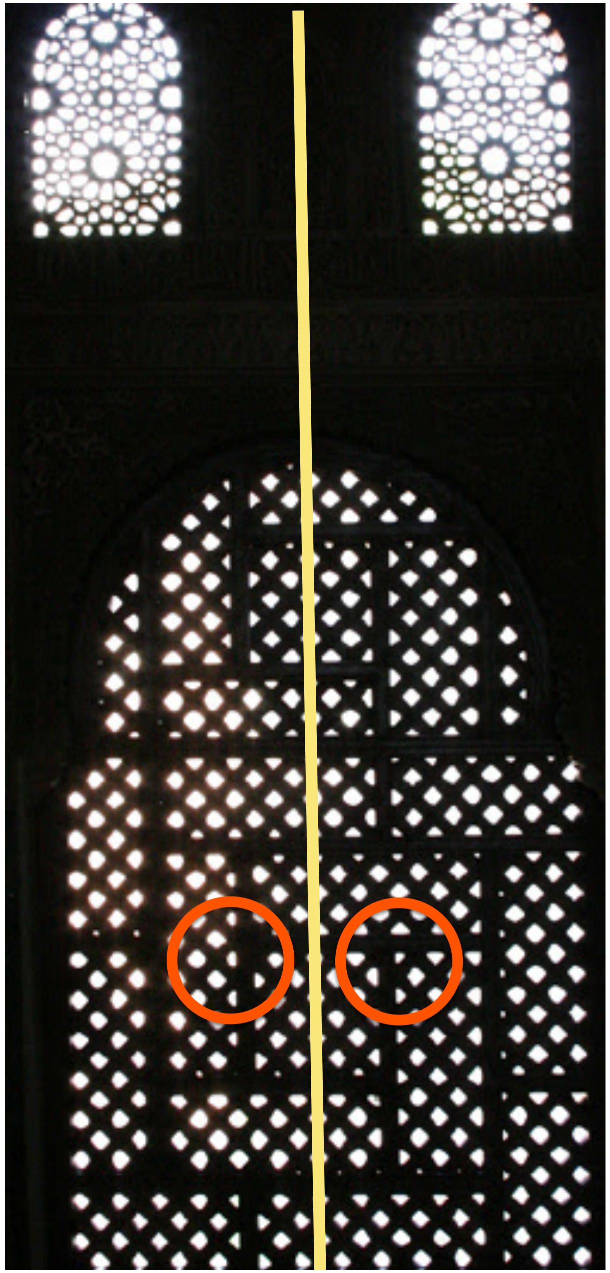
Symmetry is beautiful: a framework, beginning with Gross' grand design.

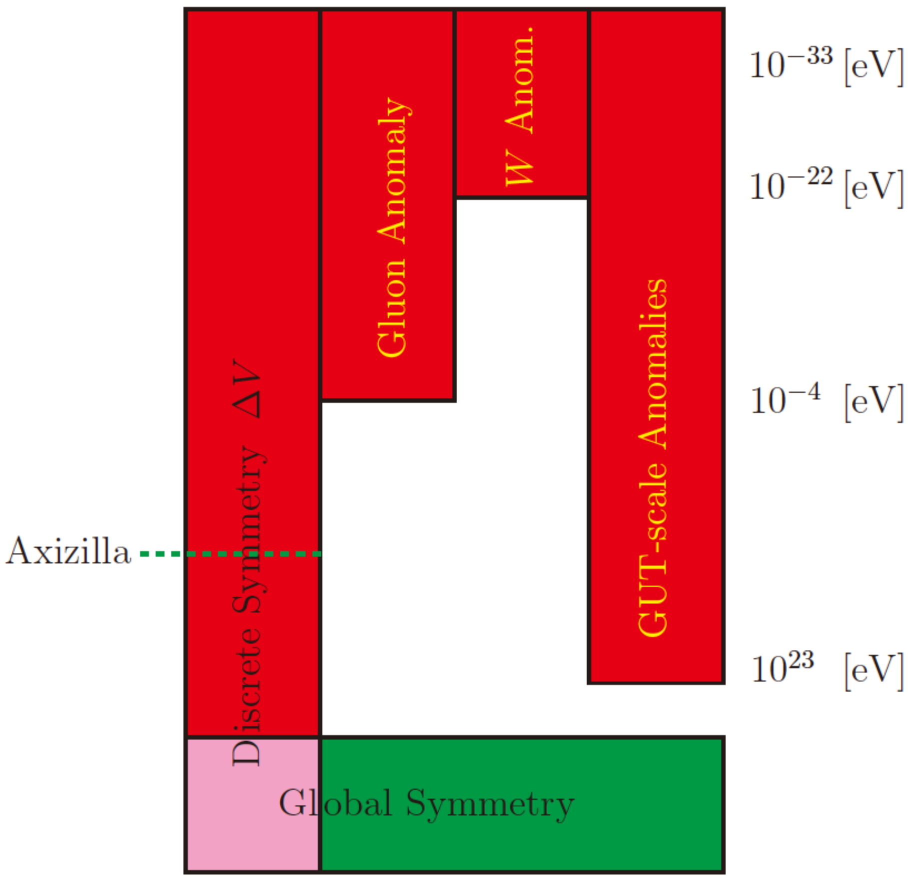
Parity:



Symmetry is beautiful: a framework, beginning with Gross' grand design.

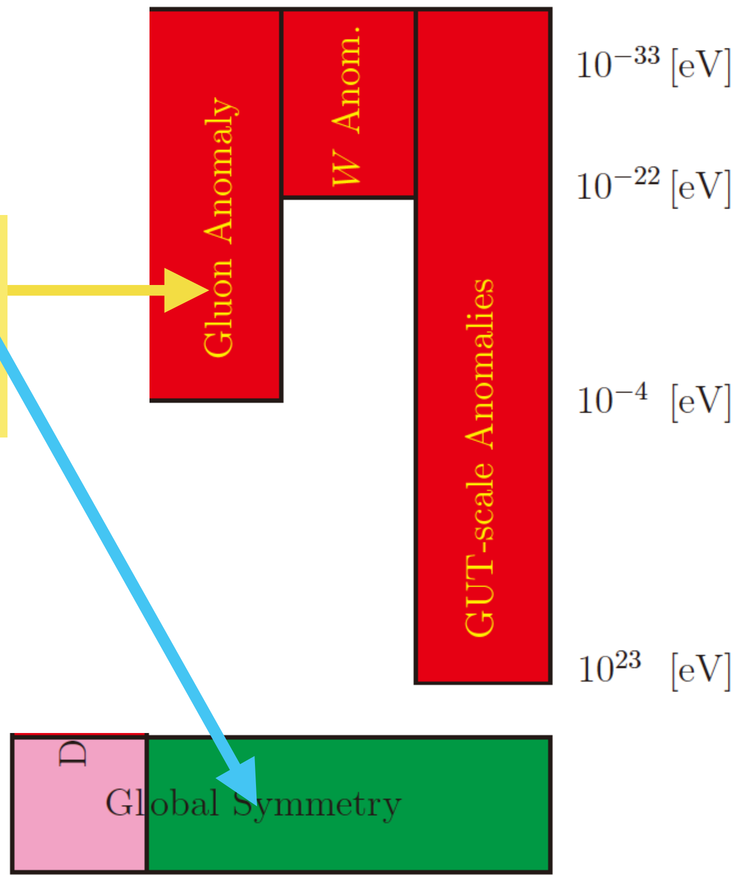
Parity: Slightly broken!




Discrete Symmetry ΔV
Gluon Anomaly
W Anom.
GUT-scale Anomalies
10^{-33} [eV]
10^{-22} [eV]
10^{-4} [eV]
10^{23} [eV]
Axizilla
Global Symmetry

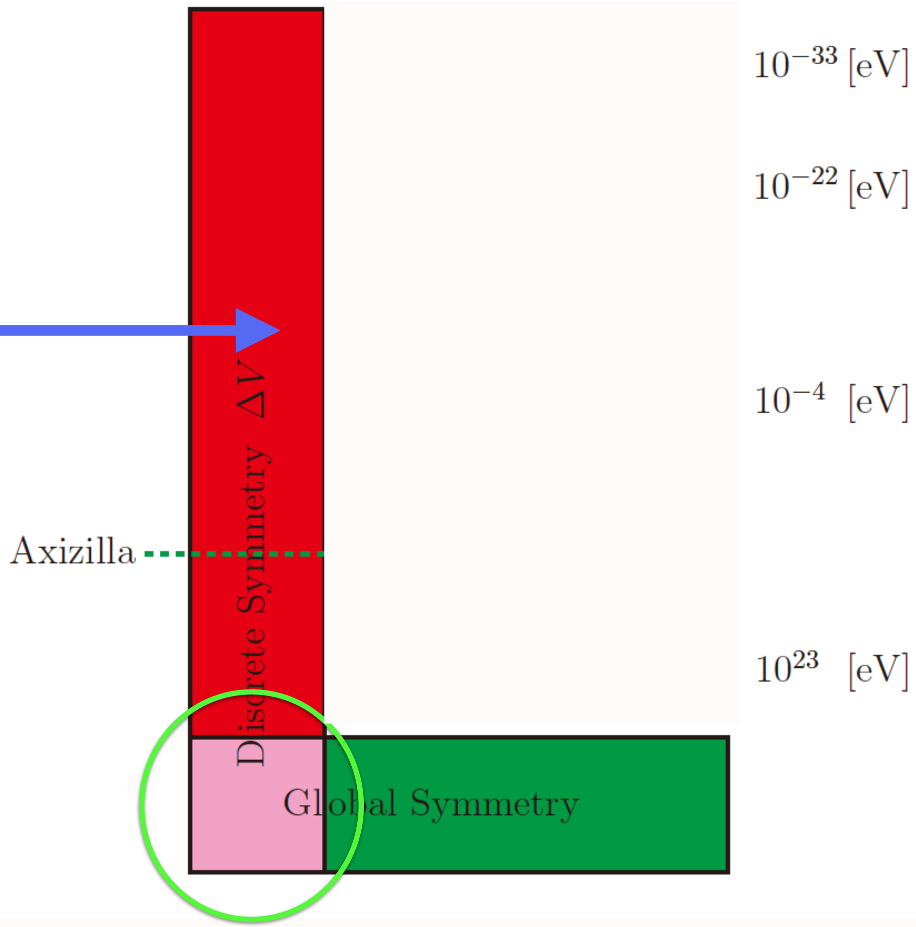
From the exact global symmetry.

This anomaly breaks the PQ symmetry.



VEV of scalar phi gives the f_a scale.

Except the anomalous U(1), any global symmetry does not have anomalies from string theory. So, this V is present.

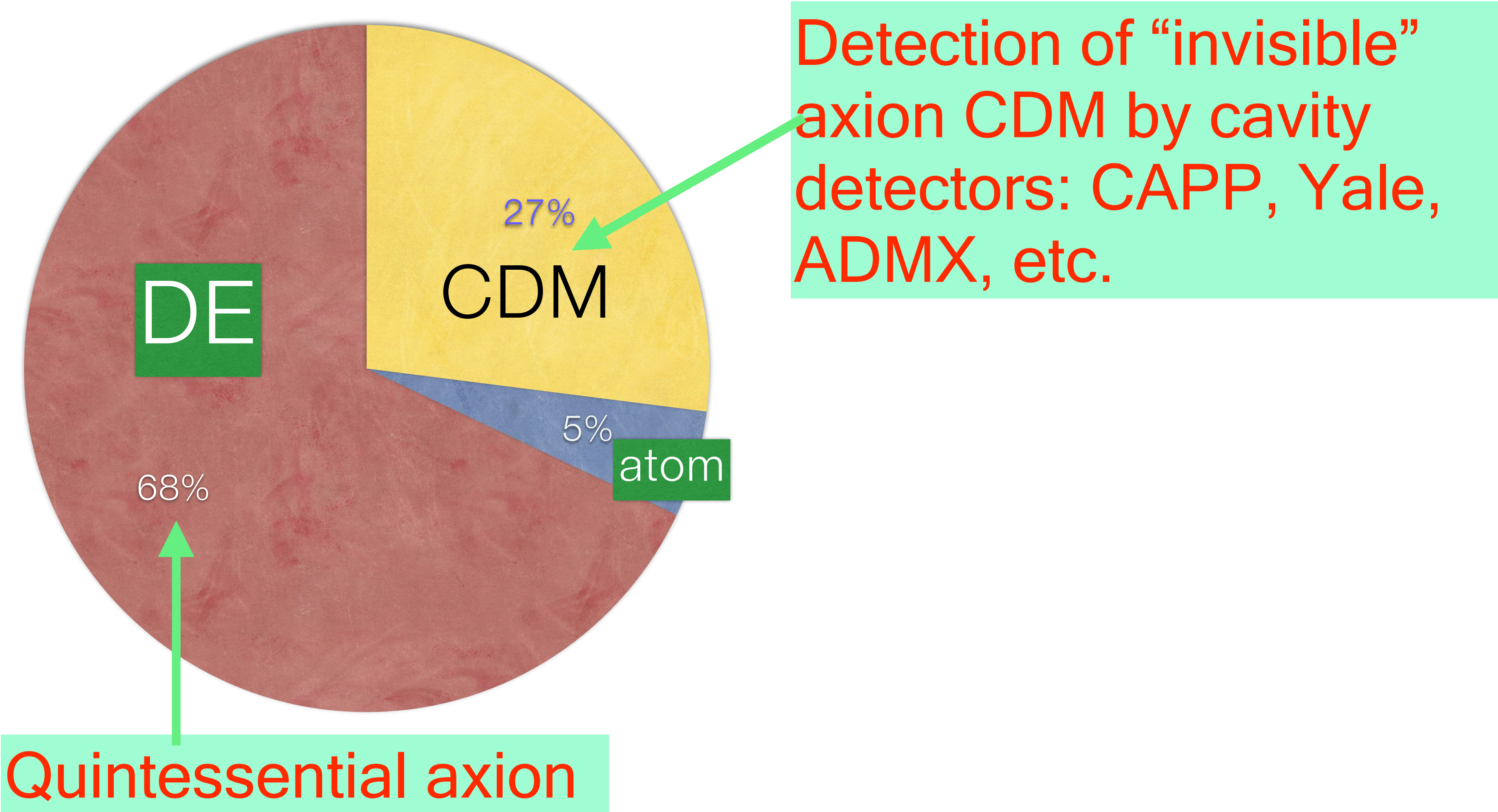


Quintessential axion

ULA

ALPs

Still the question is at what level? If one allows the discrete symmetry from string.


Detection of “invisible” axion CDM by cavity detectors: CAPP, Yale, ADMX, etc.
27%
CDM
DE
5%
atom
68%
Quintessential axion

4. Conclusion

In the compactification, if an anomalous gauge U(1) is created, then
the ’t Hooft mechanism works and a global PQ symmetry comes down to the low energy scale.

1. ’t Hooft mechanism.

2. MI-axion.

3. Approximate global symmetries

Strings 2018,
25-29 June 2018,
OIST, Okinawa