CP-conservation in QCD and why only ``invisible” axions work

Jihn E. Kim

CAPP, Kyung Hee University,
Seoul National Univ.

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From a fundamental point of view, presumably the most fundamental parameters are given at a defining scale. In this sense,

Natural mass scales are the Planck mass and/or some scales suppressed by small coupling times that, i.e. GUT scale.

All smaller mass scales are better to come from symmetry arguments. Fermions by chiral symmetry and scalars by the Goldstone theorem.

Among Goldstone bosons,
“Invisible” axion is the most interesting one.

1. Strong CP problem

- Because of instanton solutions of QCD, there exists an effective interaction term G G-dual. It is the flavor singlet and the source solving the U(1) problem of QCD: ’t Hooft, Phys. Rep. (1986).

- This term is physical, but leads to

- The strong CP problem, “Why is the nEDM so small?”

- The remaining ‘natural solution’ is “invisible” axion as given in my title.

- The gluon interaction.

$$\mathcal{L} = \bar{\theta}\{G\tilde{G}\} \equiv \frac{\bar{\theta}}{64\pi^2}\epsilon^{\mu\nu\rho\sigma}G^a_{\mu\nu}G^a_{\rho\sigma},$$

- The neutron mass term.

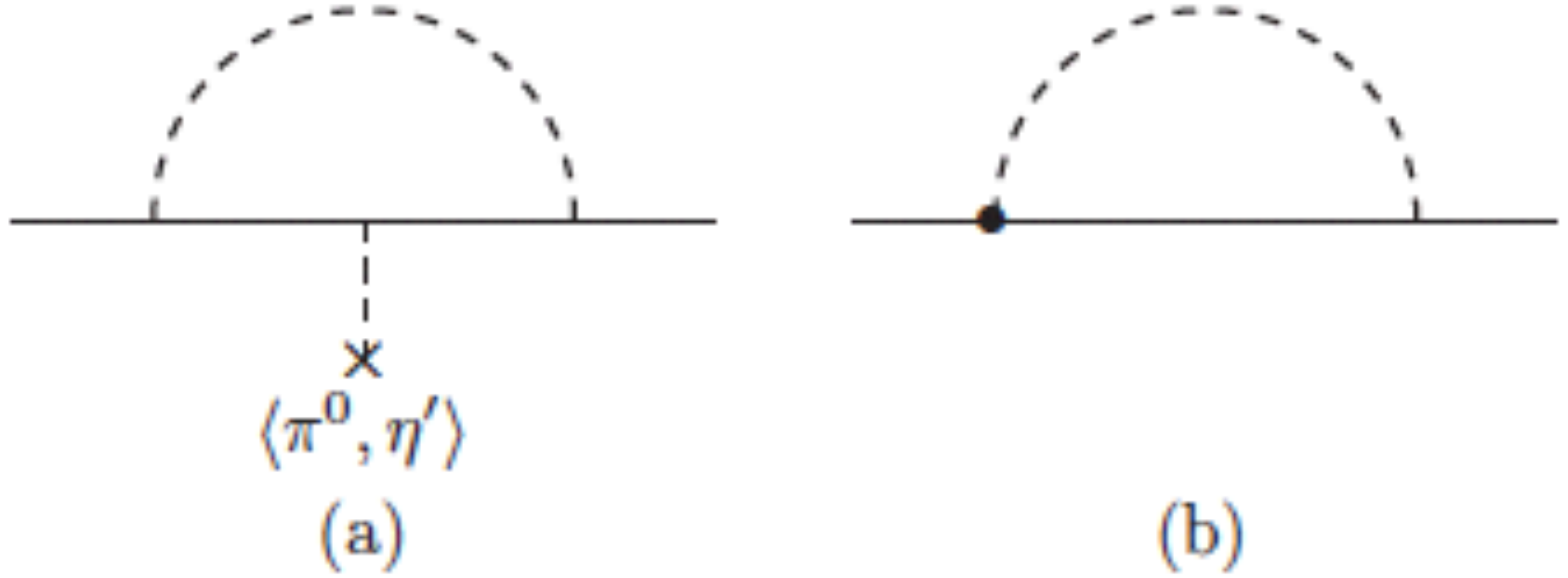


FIG. 4. Loop corrections for $\bar{n}n$-meson coupling. Insertion of the CP violation effect by VEVs of π^0 and η' in (a). They can be transferred to one vertex shown as a bullet in (b). With this bullet, CP violation is present because of a mismatch between the CP-conserving RHS vertex and CP-violating LHS vertex.

- The neutron EDM term.

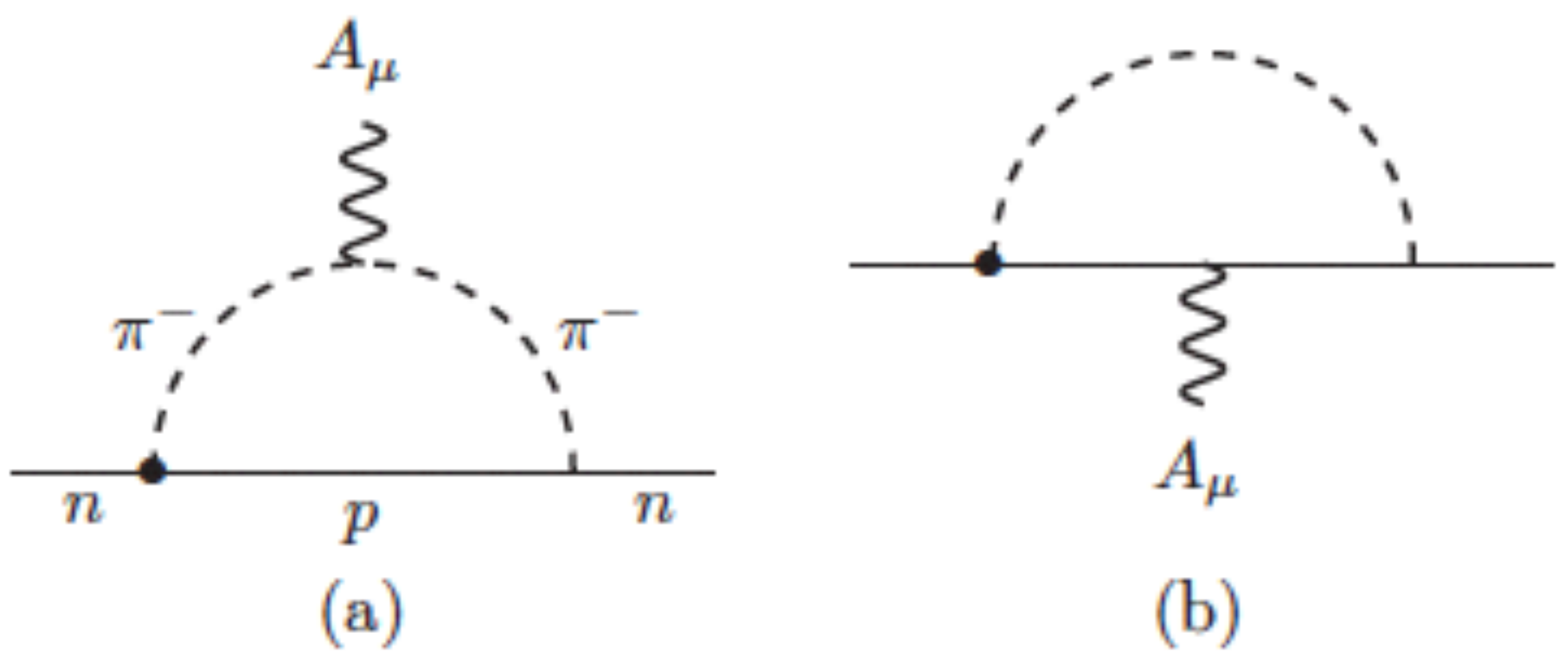


FIG. 5. Diagrams contributing to the NEDM with the bullet representing the *CP* violation effect. (a) is the physically observable contribution.

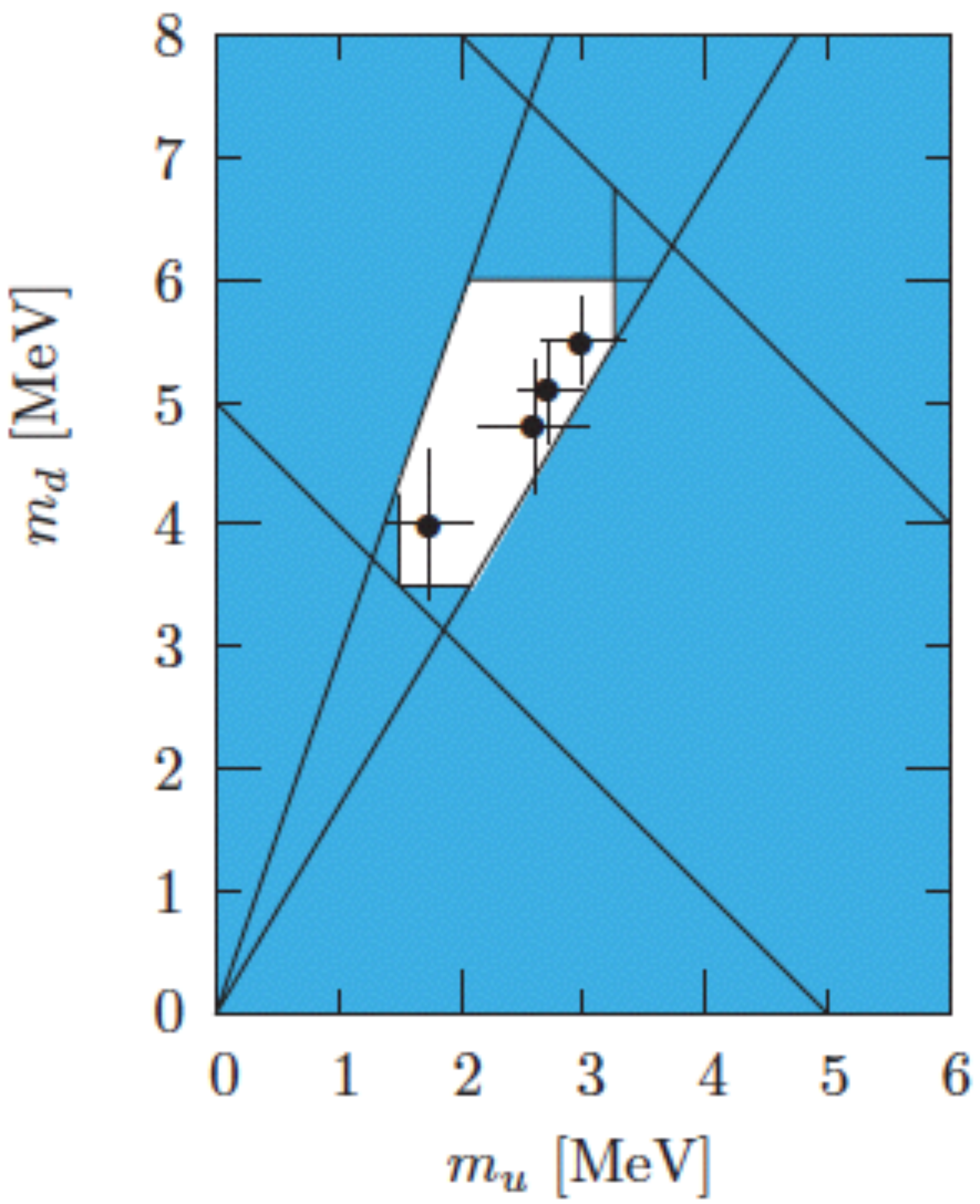
$$\frac{d_n}{e} = \frac{g_{\pi NN}\overline{g_{\pi NN}}}{4\pi^2 m_N}\ln\left(\frac{m_N}{m_\pi}\right),$$

Pion VEV (CP violating) in the meson L can give

$$\overline{g_{\pi NN}} = -\bar{\theta}\frac{Z}{(1+Z)} \simeq -\frac{\bar{\theta}}{3}.$$

Massles up quark:

PDG book,
Manohar-Sachrajda

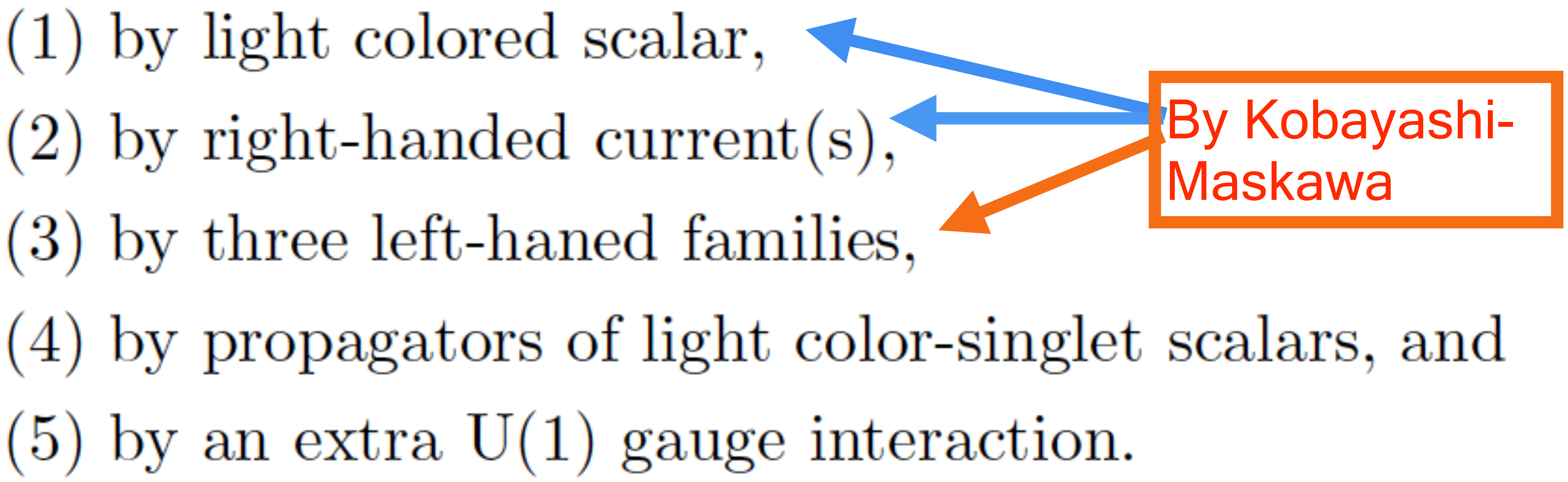


Symmetry solution (natural solution, calculable solution):

Beg-Tsao, Georgi, MS, ⋯, Nelson, Barr:
But no compelling model with very small theta-bar

2. PQ symmetry

After Cronin et al paper, “Need for a theory of weak CP violation”: KM+…



(1) by light colored scalar,

(2) by right-handed current(s),

(3) by three left-haned families,

(4) by propagators of light color-singlet scalars, and

(5) by an extra U(1) gauge interaction.

By Kobayashi-Maskawa

CP violation by many Higgs doublets

At the time when the third quark family was not discovered, Weinberg tried to introduce the weak CP violation in the Higgs potential. Due to the GW theorem, he introduced two Higgs doublets, one coupling to the up quarks and the other coupling to the down quarks. His Higgs potential with multi Higgs fields is

$$V=\frac{1}{2}\sum_{I} m_I^2\phi_I^\dagger\phi_I+\frac{1}{4}\sum_{IJ}\left\{a_{IJ}\phi_I^\dagger\phi_I\phi_J^\dagger\phi_J+b_{IJ}\phi_I^\dagger\phi_J\phi_J^\dagger\phi_I+(c_{IJ}\cancel{\phi_I^\dagger\phi_J}\phi_I^\dagger\phi_J+\mathrm{H.c.})\right\}$$

Removed by Peccei-Quinn

CP violation by Weinberg, including Yukawa of H_u and H_d couplings.

A ha, then there appears a U(1) global symmetry. The Peccei-Quinn symmetry.

1. PQWW axion reported by Weinberg and Wilczek at Ben Lee Memorial, Oct 1977
2. Calculable models(no axion), 1978
3. Invisible axion, 1979
4. Invisible axion as CDM, 1983
5. Axion detection, 1983 [2013]
6. Model-Ind. axion, 1985
7. Anomalous U(1) gauge symmetry, 1986
8. Axion-photon coupling from string compactification, 1988, 2014, 2016

Fine-tuning problem in invisible axion

KSVZ: $f\,\overline{Q}_R\,Q_L\,\sigma + \mathrm{H.c.}$

VEV of sigma is f_a. No fine-tuning problem.

DFSZ:

$$-\mu_1^2 H_u^* H_u - \mu_2^2 H_d^* H_d + \lambda_1 (H_u^* H_u)^2 + \lambda_2 (H_d^* H_d)^2 + \cdots$$
$$(+M H_u H_d \sigma') + \lambda_{h\sigma} H_u H_d \sigma^2 + \mathrm{H.c.}$$

VEV of sigma for f_a and electroweak scale v needs some fine-tuning.

(Mixing term)/lambda$_{(1,2)}$ needs a fine-tuning of order 10^{-18}.

A similar issue for WarmDM axino was studied at Bonn: Dreiner-Staub-Ubaldi, 1402-5977 [hep-ph]

Supersymmetry

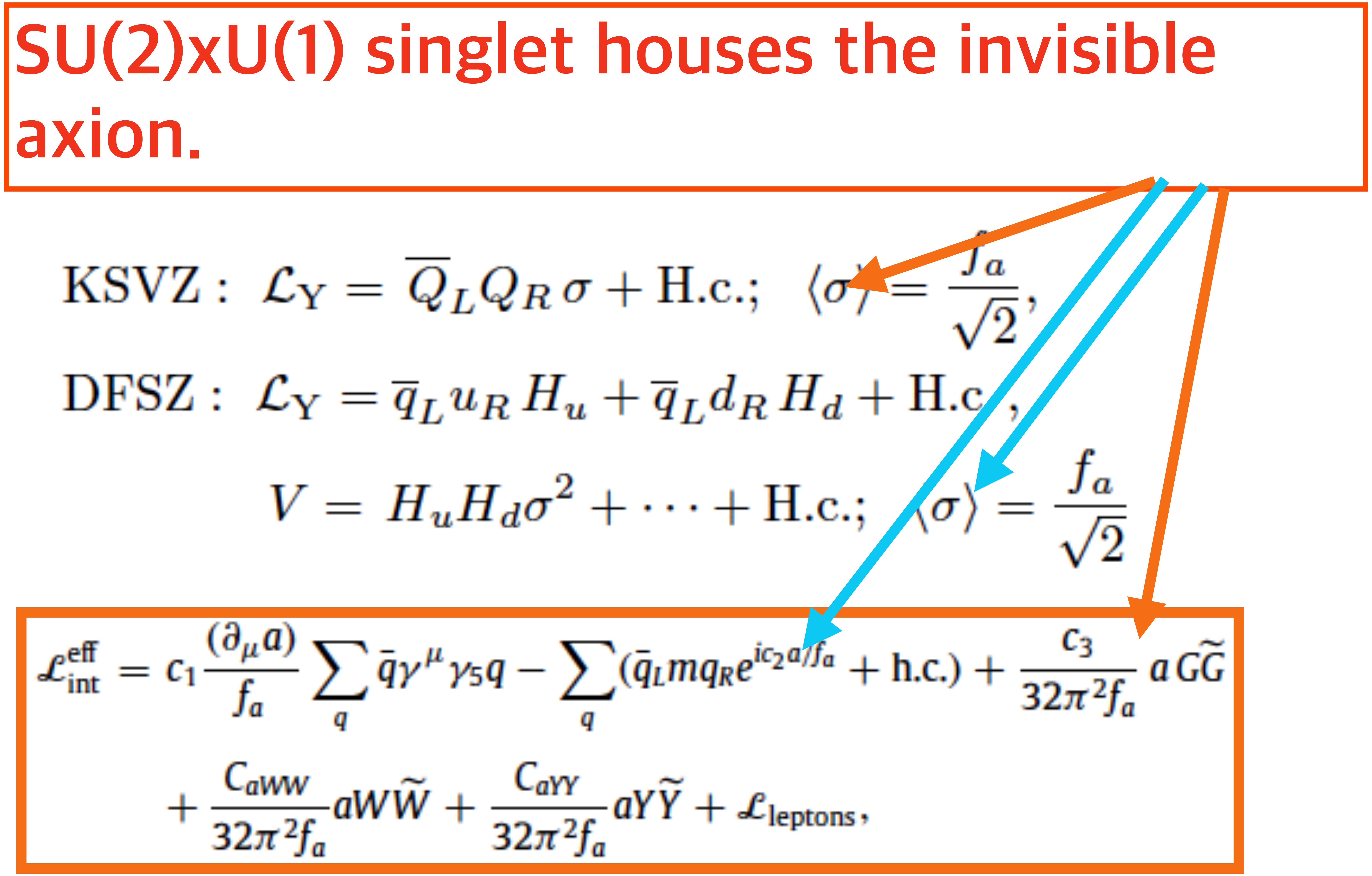
KN term: $$\frac{1}{M} H_u H_d \sigma^2$$

M is determined from the theory.

This term is the definition of the PQ symmetry.

2. “Invisible” axions

SU(2)xU(1) singlet houses the invisible axion.



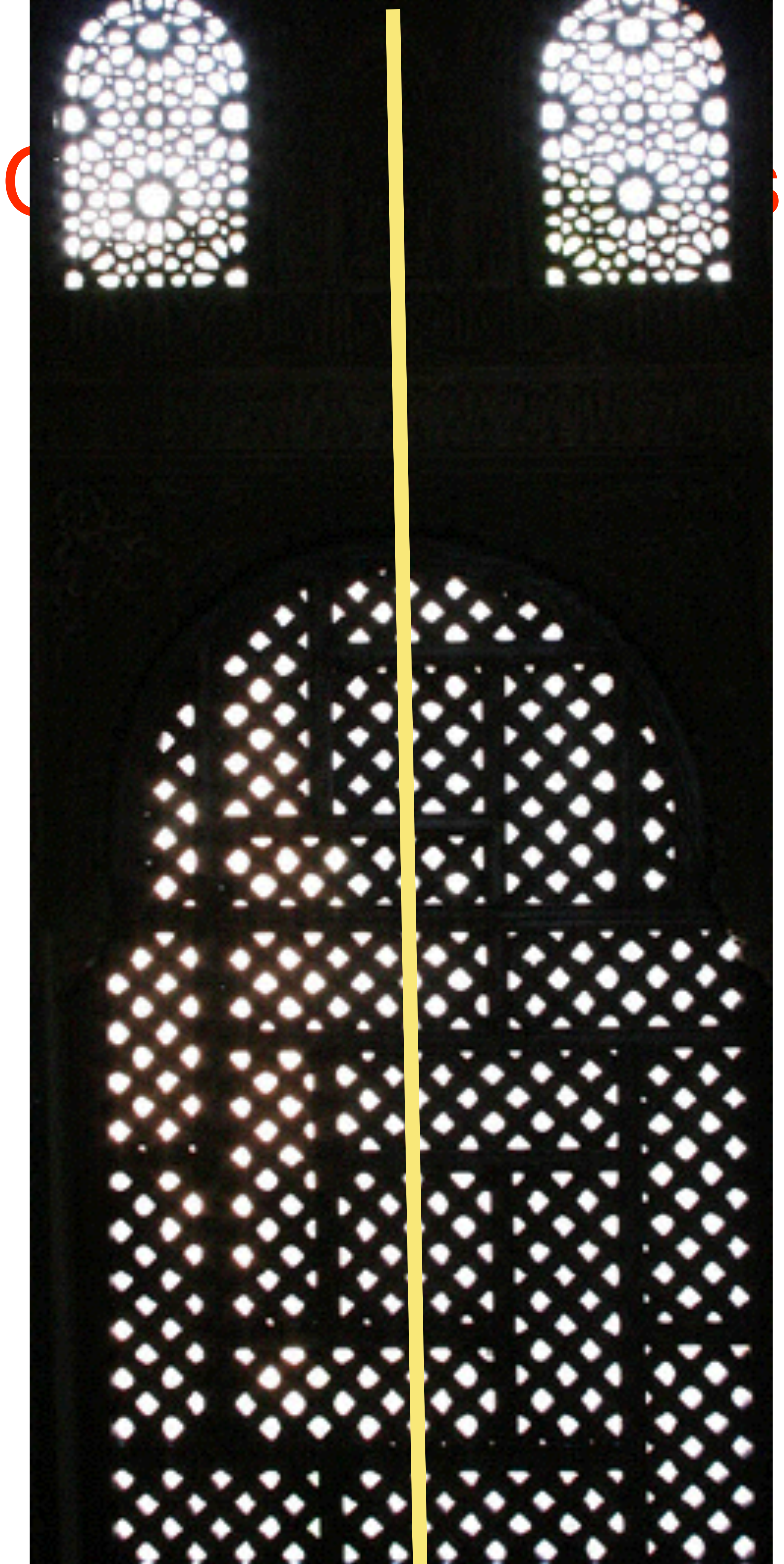
$$\text{KSVZ}: \quad \mathcal{L}_Y = \overline{Q}_L Q_R\, \sigma + \text{H.c.}; \quad \langle\sigma\rangle = \frac{f_a}{\sqrt{2}},$$

$$\text{DFSZ}: \quad \mathcal{L}_Y = \bar{q}_L u_R H_u + \bar{q}_L d_R H_d + \text{H.c.},$$

$$V = H_u H_d \sigma^2 + \cdots + \text{H.c.}; \quad \langle\sigma\rangle = \frac{f_a}{\sqrt{2}}$$

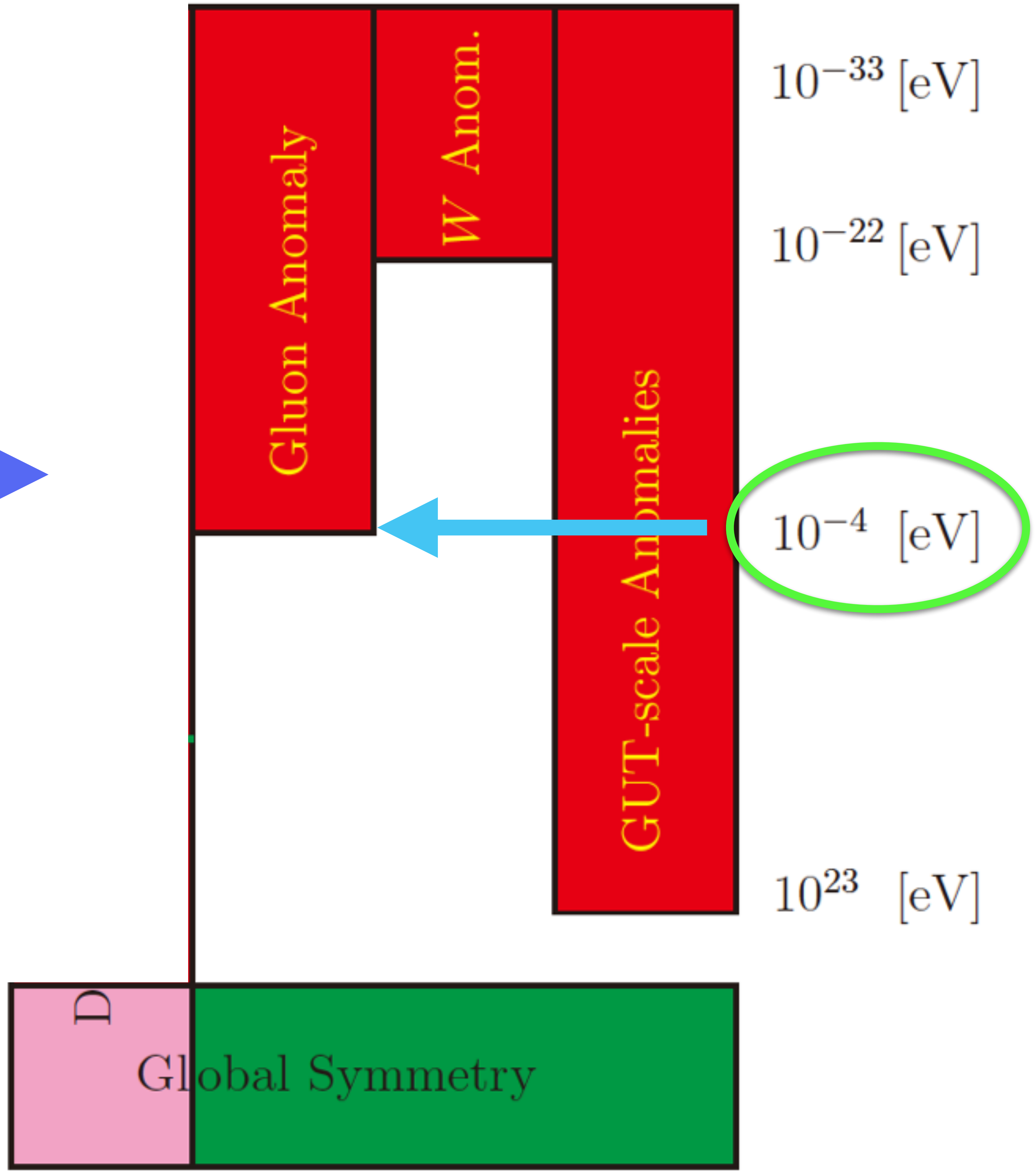
$$\mathcal{L}_{\text{int}}^{\text{eff}} = c_1 \frac{(\partial_\mu a)}{f_a} \sum_q \bar{q}\gamma^\mu \gamma_5 q - \sum_q \left(\bar{q}_L m q_R e^{ic_2 a/f_a} + \text{h.c.}\right) + \frac{c_3}{32\pi^2 f_a} a G\widetilde{G} + \frac{C_{aWW}}{32\pi^2 f_a} a W\widetilde{W} + \frac{C_{aYY}}{32\pi^2 f_a} a Y\widetilde{Y} + \mathcal{L}_{\text{leptons}},$$

Light bosons are pseudo-



Pseudoscalars fit to this scheme. Somehow discrete symmetries (P) seem to work as the messengers to low and high energy scales. Mainly from the string compactification examples.

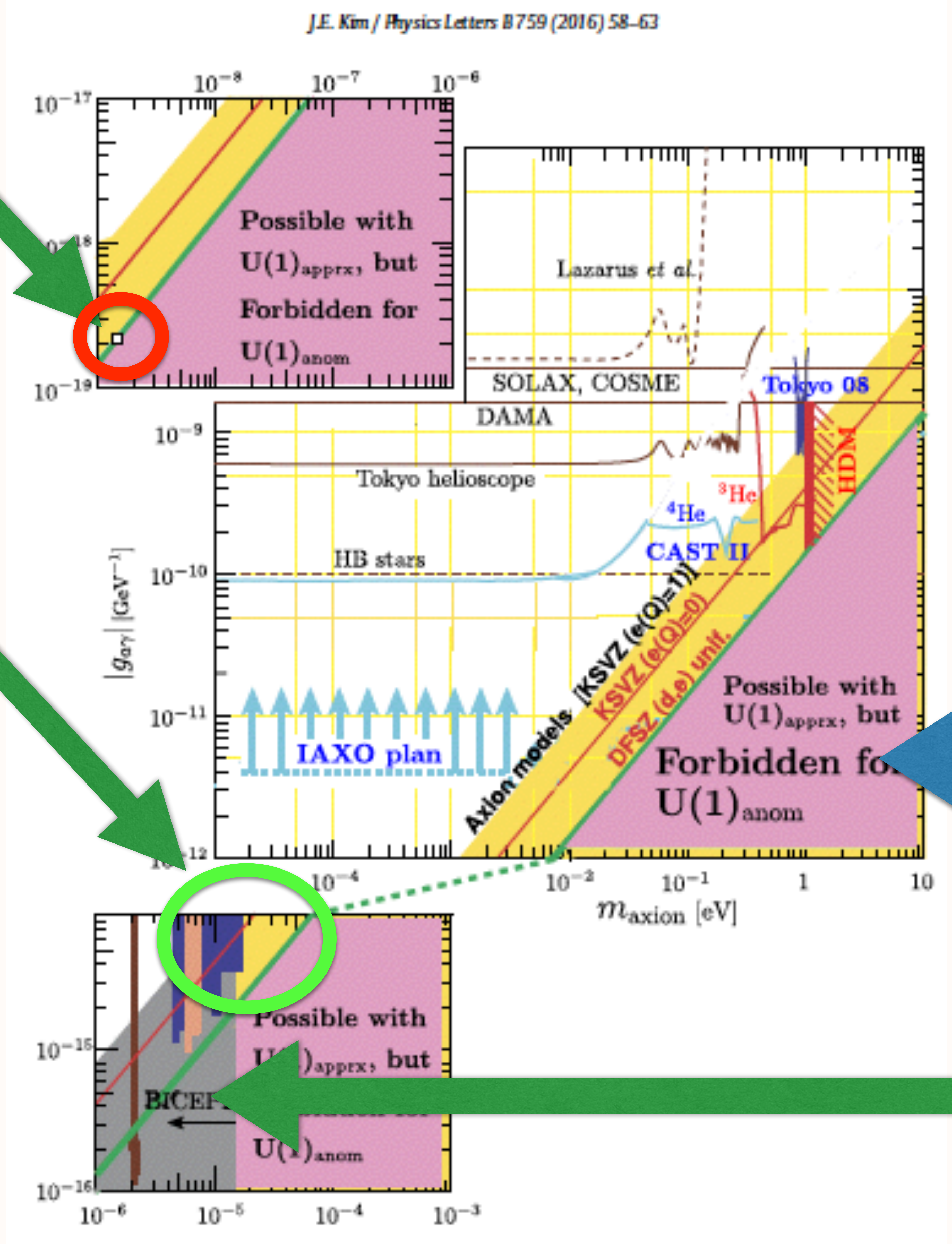
If this is absent, it is called axion. And theta=0 is the minimum.



Still some term in V is present with discrete symmetry, then theta=0 is not guaranteed to be the minimum.

MI axion

A small allowed region by $U(1)_{anom}$



$g_{a\gamma}(= 1.57 \times 10^{-10} c_{a\gamma\gamma})$ vs. m_a plot

Kim-Semertzidis-Tsujikawa, Front. Phys. 2 (2014) 60

Kim-Nam, 1603.02145[hep-ph]

$U(1)_{anom}$ forbidden

If H_I is greater than f_a, there is the isocurvature constraint.

In SUSY, without extra small parameters, the following dim-4 W is the minimum example.

Summarized by

Weinberg operator:

[13.08.1979, Received]

$$\frac{1}{M}\overset{L=2}{\ell\ell}\,\overset{L=-2}{H_uH_u}$$

gives ν mass

Realized in seesaw:

Minkowski [13.04.1977, Published],
Yanagida [13-14 Feb 79, Conf. talk]

……

$$\ell_L H_u N_R$$

Kim-Nilles SUSY operator:

[24.11.1983, Received]

$$\frac{1}{M}\overset{Q=2}{S_1S_2}\,\overset{Q=-2}{H_uH_d}$$

gives TeV scale μ term

We neglected SH_uH_d since the VEV of S at intermediate scale is too large for SU(2) breaking.

Realized in string comp.:
Many papers,⋯.

$$S_1\underset{-1}{H_u}X_{\rm doublet},\ S_2\underset{-1}{H_d}X'_{\rm doublet},\ \overbrace{\bar{Q}_L Q_R}^{-1/2}\overset{+1}{S_1},\cdots$$

The Peccei-Quinn symmetry at low energy with SUSY is introduced in this way. Breaking the PQ symmetry in SUGRA is

$$W = Z\left(S_1 S_2 - \frac{f^2}{2}\right)$$

Kim, PLB136 (1984) 378.

Most SUGRA models, breaking a global symmetry use this superpotential. Sometimes used in hybrid inflation also.

But it is not a minimal model for “invisible” axion.

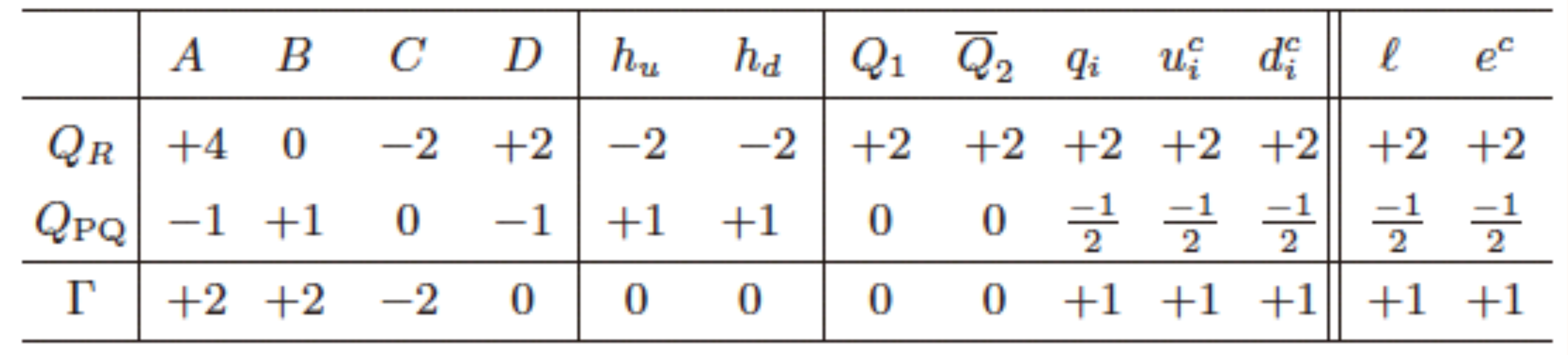
The minimal “invisible” axion model :

$$W_1 = \lambda\, ABC + mBD + \frac{1}{M} ADh_u h_d,$$ Kim-Kyae-Nam-Nilles, 2016.

$$W_2 = f_Q\, CQ_1\overline{Q}_2 + f_u^{ij}\, q_i u_j^c h_u + f_d^{ij}\, q_i d_j^c h_d,$$

This minimal model has a far reaching consequences:

$$\Gamma = Q_{\rm R} + 2Q_{\rm PQ}$$



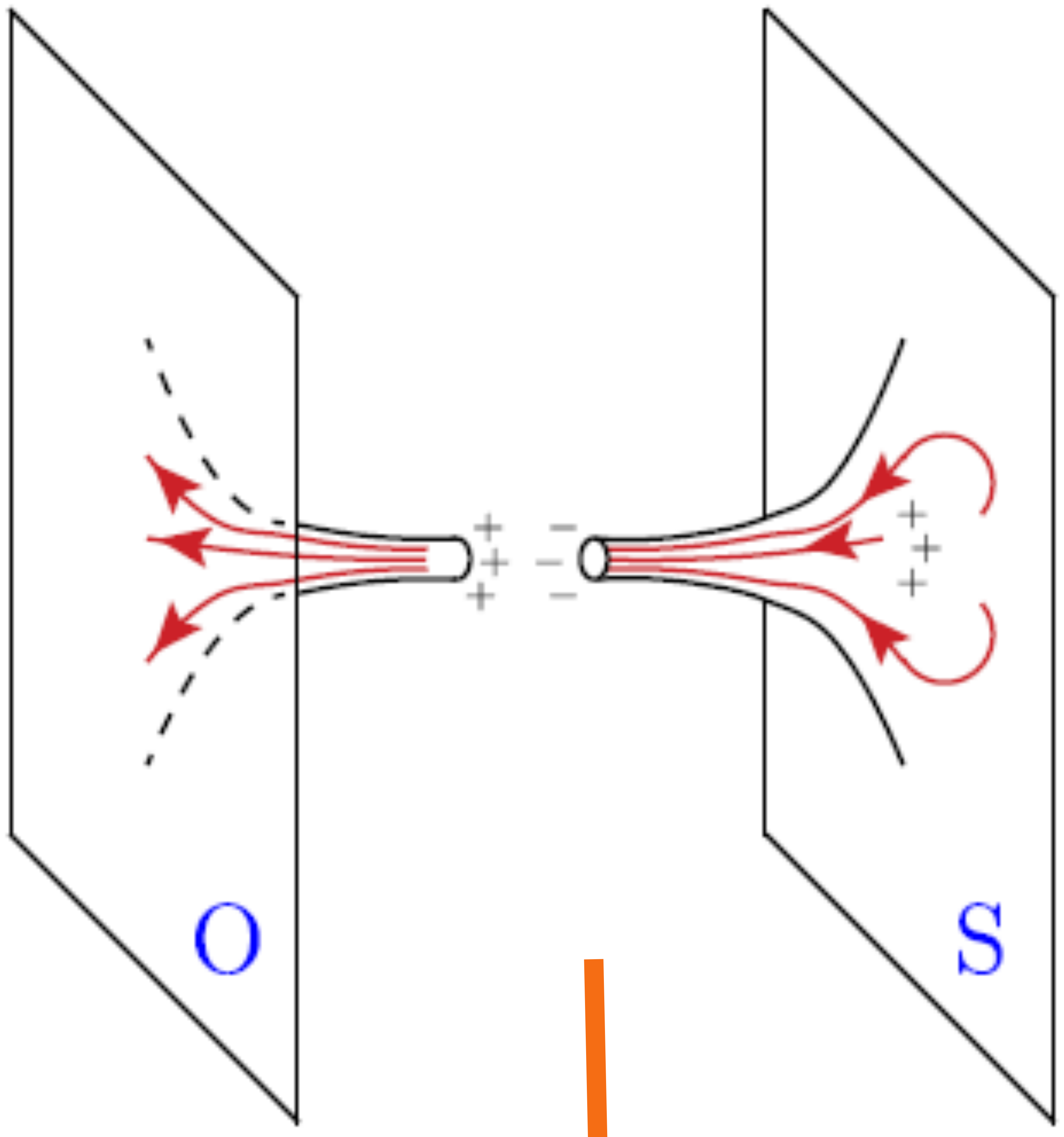
	A	B	C	D	h_u	h_d	Q_1	$\overline{Q}_2$	q_i	u_i^c	d_i^c	ℓ	e^c
Q_R	$+4$	0	-2	$+2$	-2	-2	$+2$	$+2$	$+2$	$+2$	$+2$	$+2$	$+2$
$Q_{\rm PQ}$	-1	$+1$	0	-1	$+1$	$+1$	0	0	$\frac{-1}{2}$	$\frac{-1}{2}$	$\frac{-1}{2}$	$\frac{-1}{2}$	$\frac{-1}{2}$
Γ	$+2$	$+2$	-2	0	0	0	0	0	$+1$	$+1$	$+1$	$+1$	$+1$

This minimal ABCD model has a far reaching consequences:

(1) Heavy axino: Choi-Kim-Lee-Seto, 0801.0491; Kim-Huh, 0908.0152.

(2) Inflation, to appear.

(3) Correct SUGRA phenomenology, to appear.



Wormholes:
Gidding-Strominger,
Coleman, Cline

Exact global symmetries?

Kamionkowski-MarchRussel,
Holdom et al.
Exclude terms up to dim 8.

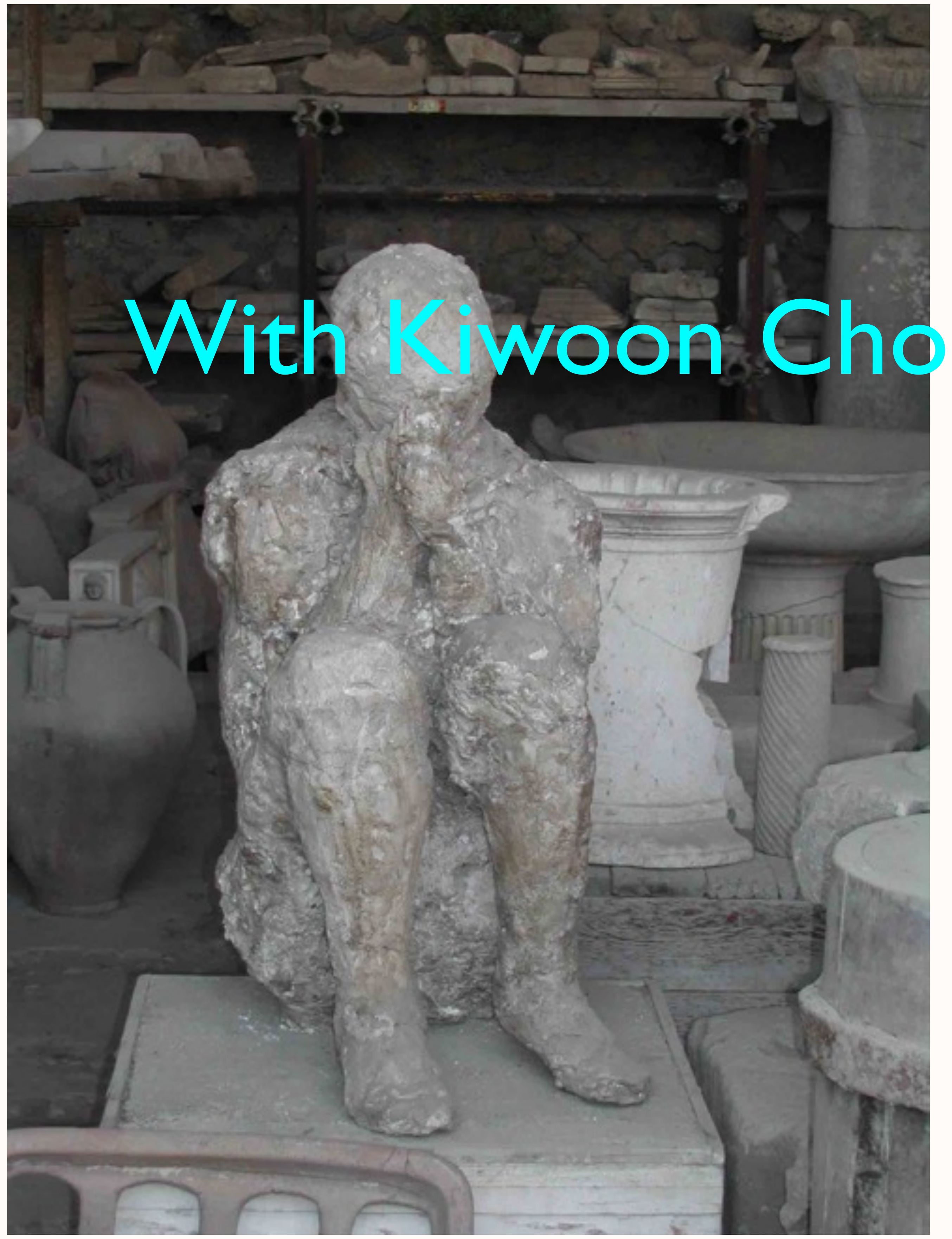
The example of acc symm.

Discrete gauge symmetry:
Krauss-Wilczek

After many years,
Model-independent axion (Green-Schwarz, Witten) strikes back

With the anomalous U(1) gauge symmetry in string compactification

JEK, 1604.00716 [hep-ph]



With Kiwoon Choi

Antisymmetric tensor fields: B_{MN}

They are gauge fields in 10D. Their couplings to matter fields are from compactification process, including the Green-Schwarz term. If some of them give color anomaly coupling without anomalous U(1), they must be necessarily the hadronic axion-type. Anyway, their decay constants are above the GUT scale. Without fine tuning, it is expected that f_a near the string scale.

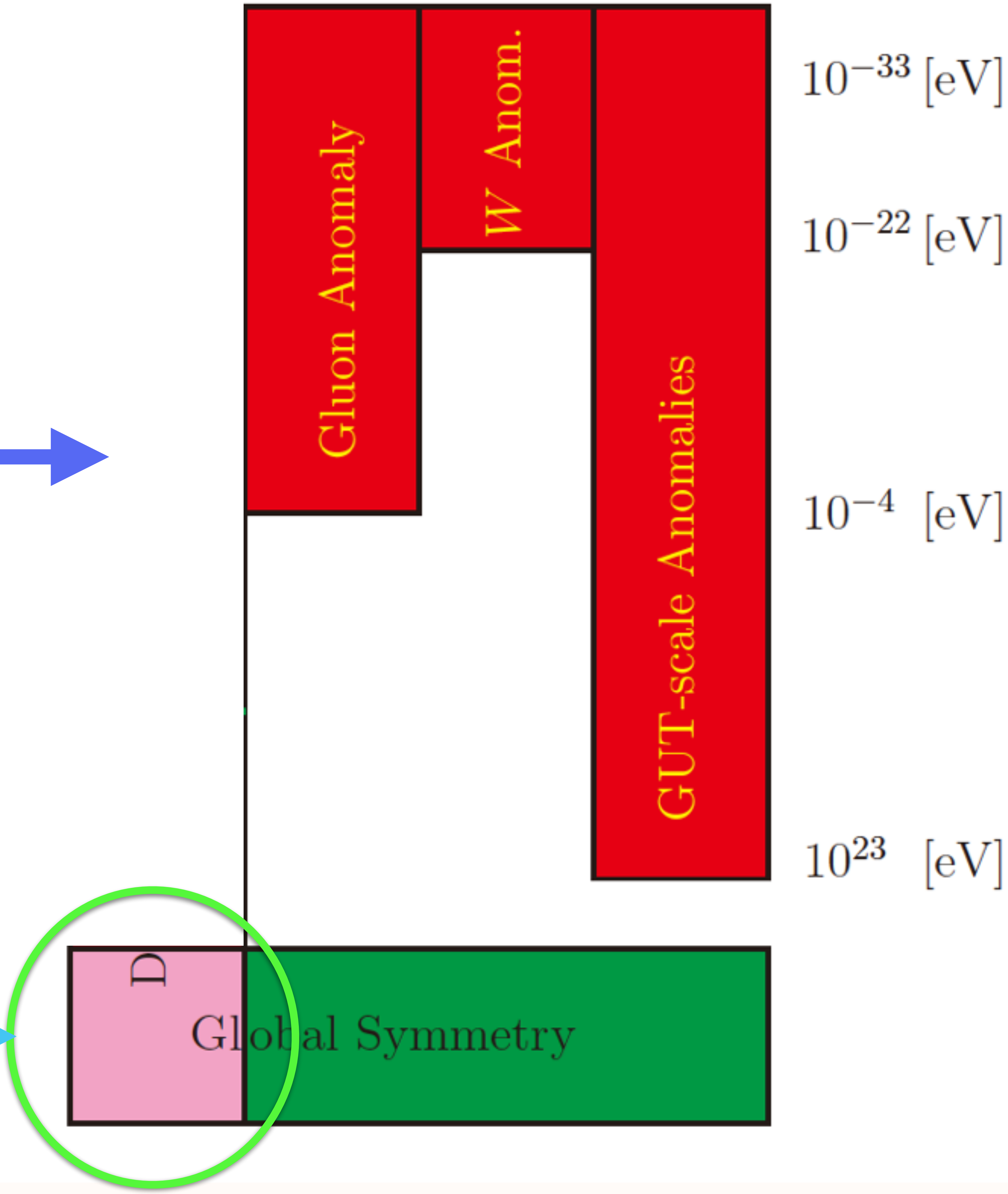
MI axion: Choi-K, PLB 154 (1985) 393;
MD axion: Svrcek-Witten, JHEP 06 (2006) 051.

Gauge symmetry origin, but from compactification:

Anomalous U(1) gauge symmetry in string compactification:

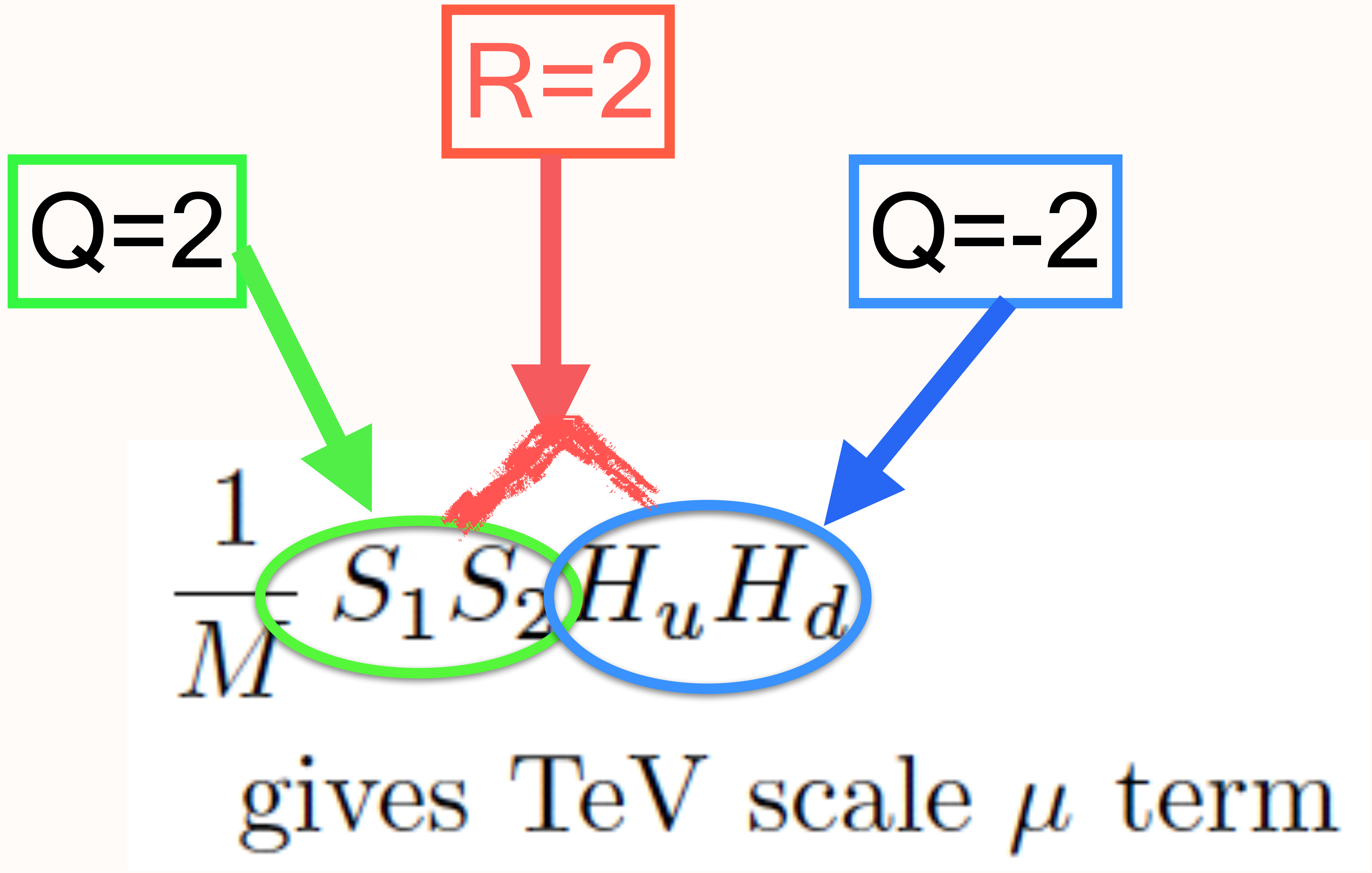
becomes PQ global symmetry below 10^{15} GeV.

There can be terms in W, but the PQ symm breaking terms are absent. This can be achieved in compactification, with anomalous U(1).



The KN term is the leading one here.

We have seen the KN SUSY operator:



$$\frac{1}{M} S_1 S_2 H_u H_d$$

gives TeV scale μ term

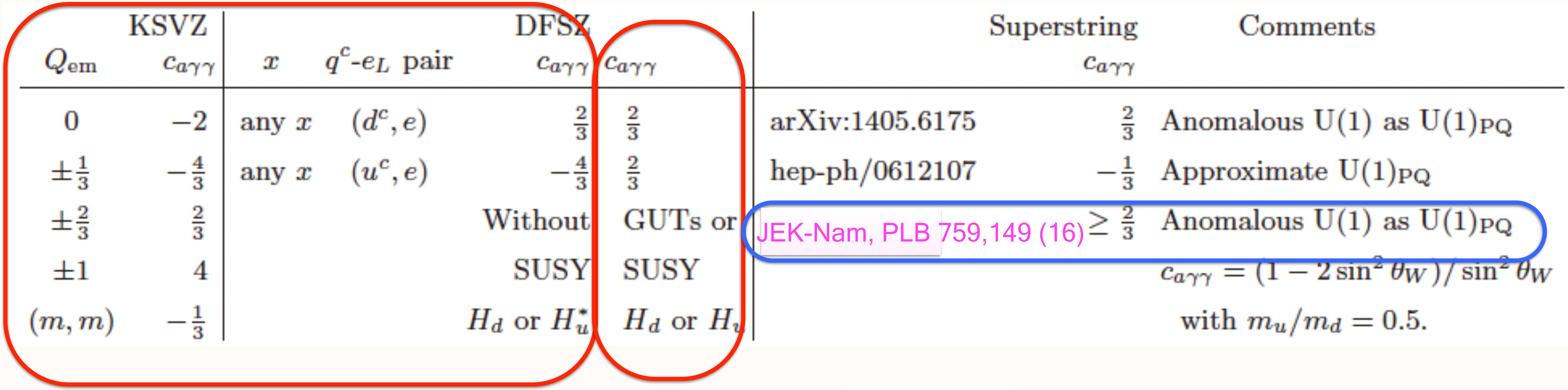
It can be realized in string compactification. In the QCD axion coupling to photons, one has to work within a complete phenomenologically working model, taking into account all fermion spectra. Axion-photon-photon coupling:

JEK, PLB 207 (1988) 434;
JEK, PLB 735 (2014) 95, 741 (2014) 317;
JEK-Nam, PLB 759 (2016) 149; coupl.
JEK, PLB 759 (2016) 58. DW No.=1

The minimal model (Kim-Kyae-Nam-Nilles) satisfies both R and PQ global symmetries.

Here, DW number can be made 1 as in the non-SUSY KSVZ model.

But QCD axion and photon couplings are given phenomenologically in the BSM field theory.



KSVZ		DFSZ					Superstring	Comments
$Q_{\rm em}$	$c_{a\gamma\gamma}$	x	q^c-e_L pair	$c_{a\gamma\gamma}$	$c_{a\gamma\gamma}$		$c_{a\gamma\gamma}$	
0	-2	any x	(d^c, e)	$\frac{2}{3}$	$\frac{2}{3}$	arXiv:1405.6175	$\frac{2}{3}$	Anomalous U(1) as $\text{U(1)}_{\rm PQ}$
$\pm\frac{1}{3}$	$-\frac{4}{3}$	any x	(u^c, e)	$-\frac{4}{3}$	$\frac{2}{3}$	hep-ph/0612107	$-\frac{1}{3}$	Approximate $\text{U(1)}_{\rm PQ}$
$\pm\frac{2}{3}$	$\frac{2}{3}$			Without	GUTs or	JEK-Nam, PLB 759,149 (16)	$\geq \frac{2}{3}$	Anomalous U(1) as $\text{U(1)}_{\rm PQ}$
± 1	4			SUSY	SUSY			$c_{a\gamma\gamma} = (1-2\sin^2\theta_W)/\sin^2\theta_W$
(m, m)	$-\frac{1}{3}$			H_d or H_u^*	H_d or H_u			with $m_u/m_d = 0.5$.

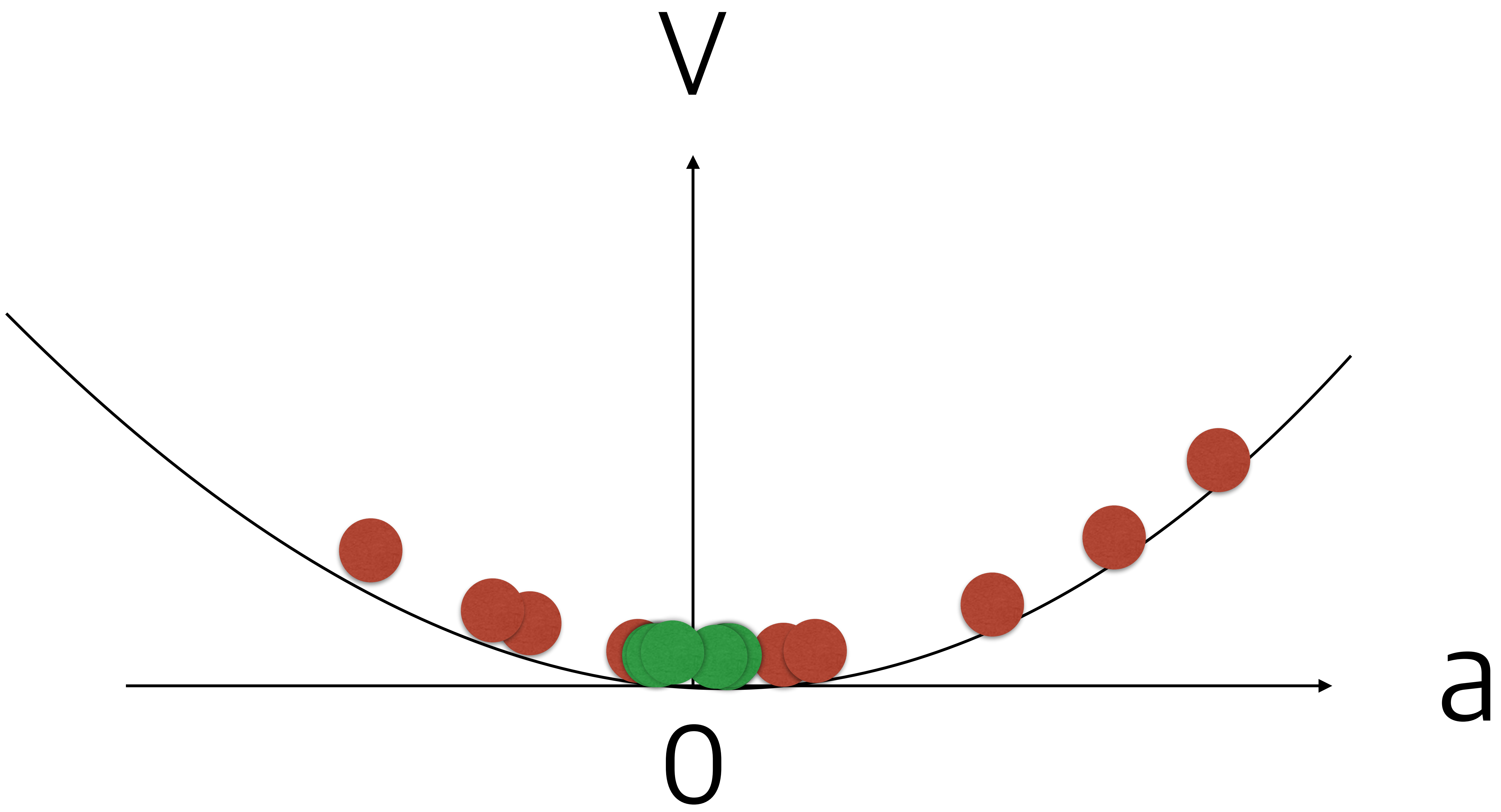
Given in JEK, PRD 58 (1998) 055006;
K-Carosi, RMP 82 (2010) 557.

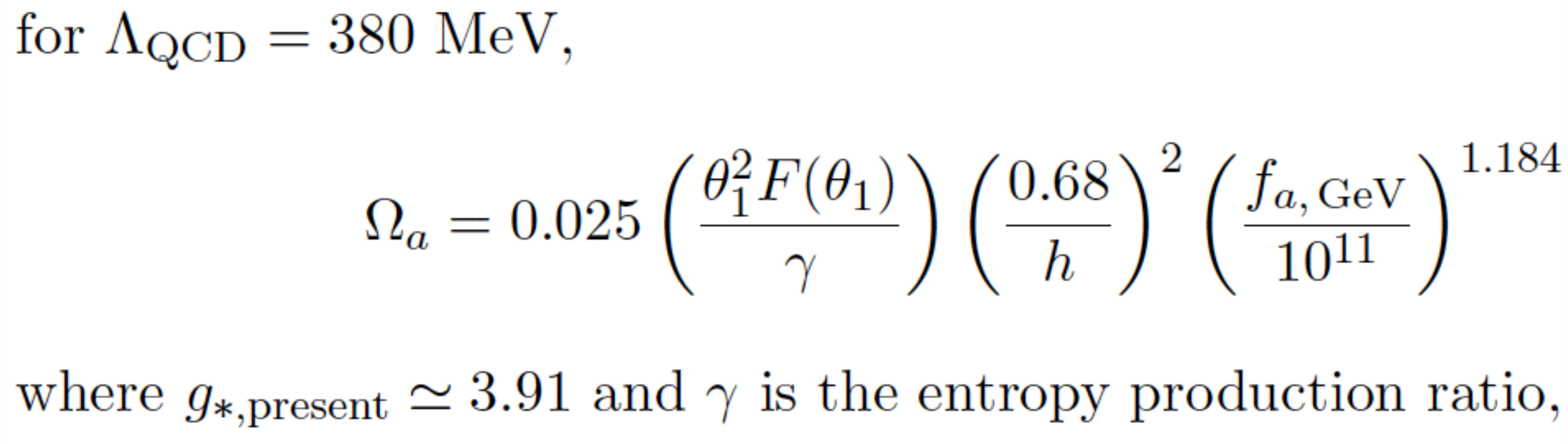
$$\frac{1-2\sin^2\theta_W}{\sin^2\theta_W} \geq 2/3$$

3. QCD axion in cosmology

Axion energy density

Axion solution = cosmological solution





for $\Lambda_{\mathrm{QCD}} = 380$ MeV,

$$\Omega_a = 0.025 \left(\frac{\theta_1^2 F(\theta_1)}{\gamma} \right) \left(\frac{0.68}{h} \right)^2 \left(\frac{f_{a,\,\mathrm{GeV}}}{10^{11}} \right)^{1.184}$$

where $g_{*,\mathrm{present}} \simeq 3.91$ and γ is the entropy production ratio,

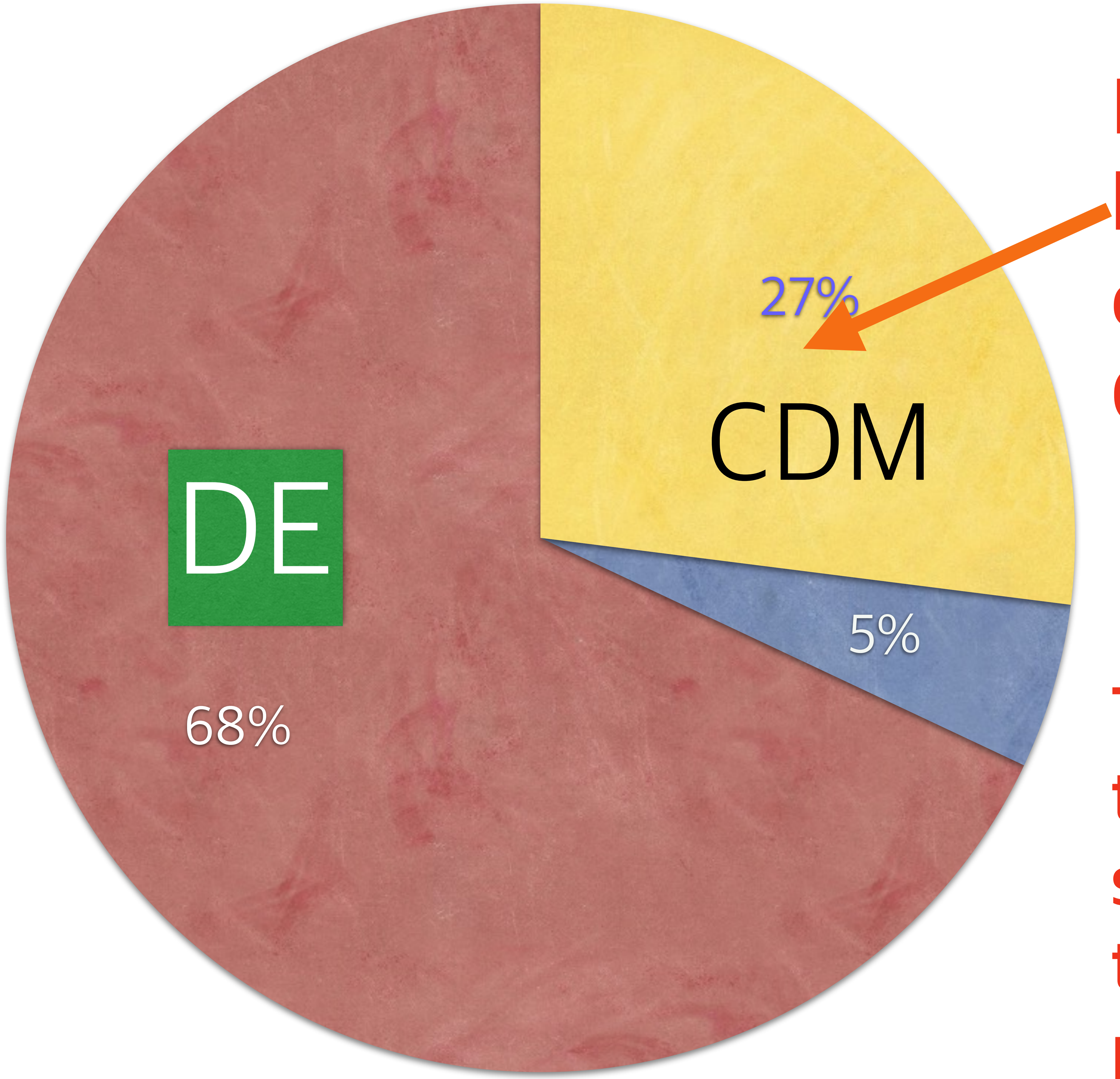
Kim-Semertzidis-Tsujikawa, Front. Phys. 2, 60 (2014): Bosonic coherent motion review

[Review in research topic BCM,
New one: Frontiers in Physics,
HE & astroparticle physics]

BCM initiated by three groups in 83.
(Preskill et al, Dine et al, Abbott et al.)

BCM:
- BCM1 → Axion
- BCM2 → Inflaton

CCtmp: → Dark energy

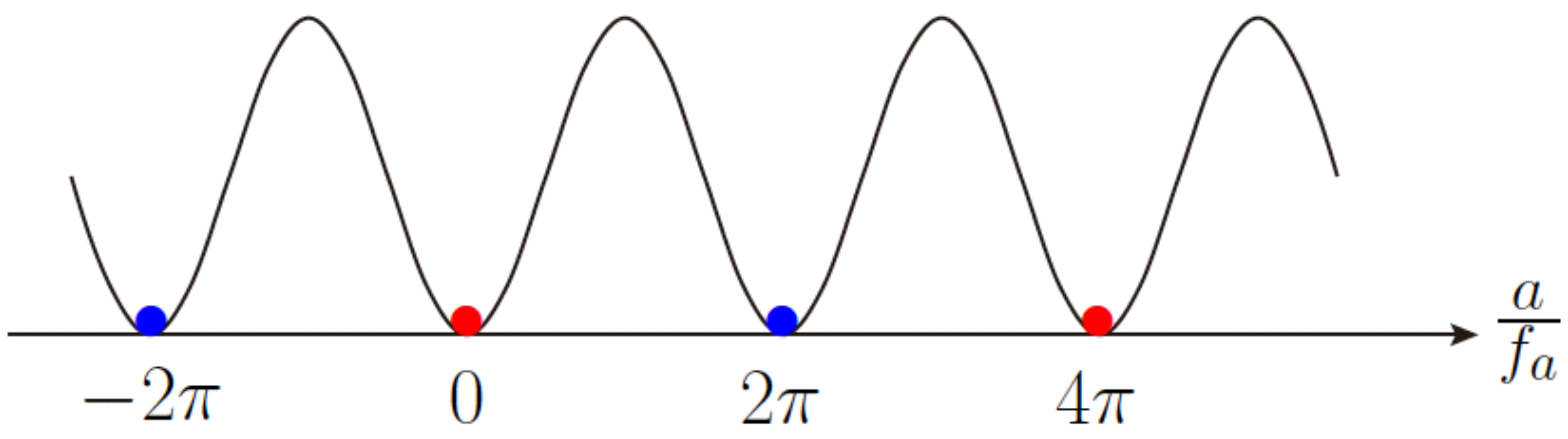


For the invisible axion here, the present axion detection experiments on CDM axions are going on.

The QCD axion is studied for this region of parameter space. Any constraints are talked about with this CDM possibility.

Axionic domain walls

$$S = -\frac{\bar{\theta}}{32\pi^2}\int d^4x\, G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu} .$$



But other matter fields can give

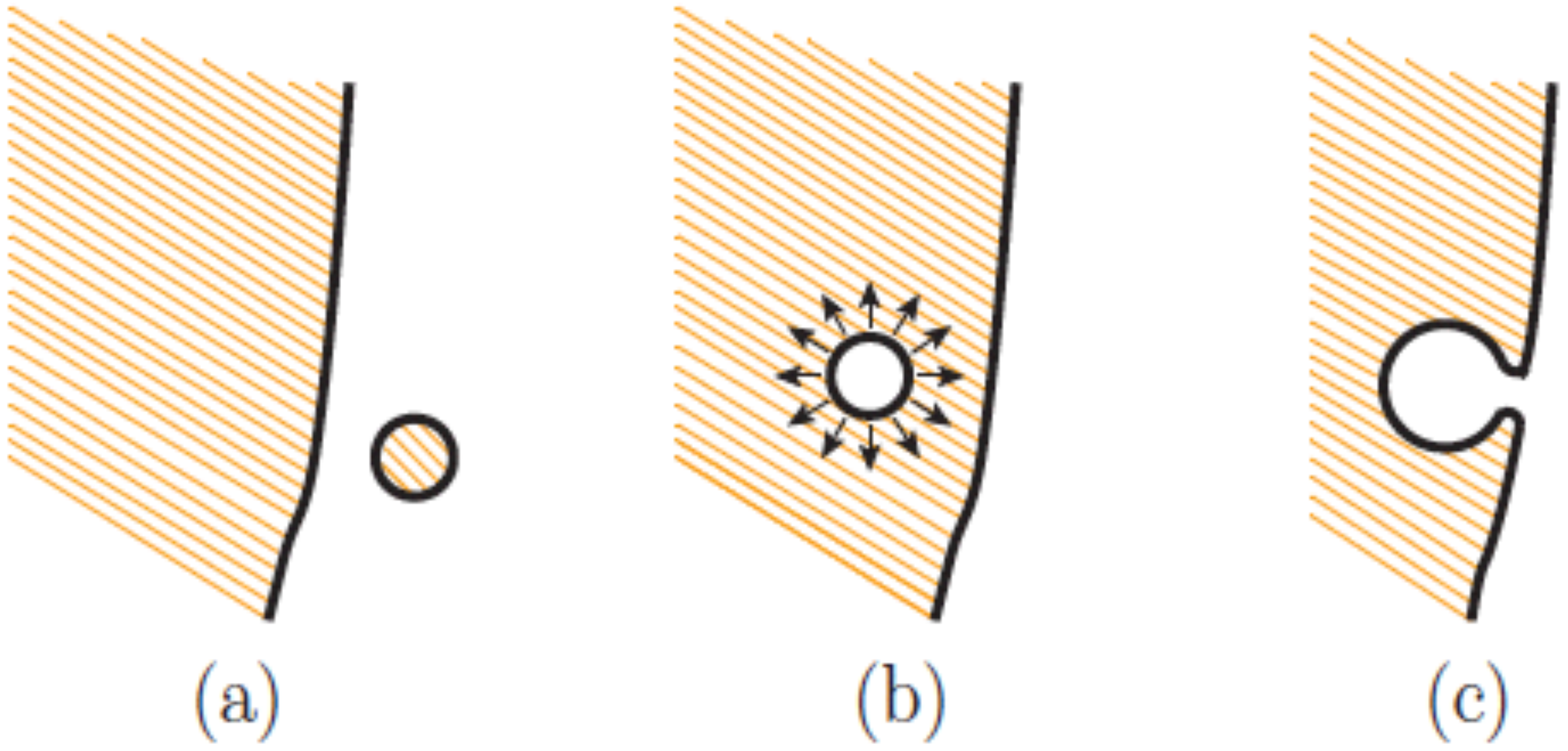
$$\Phi \to e^{i\theta/N}\,\Phi, \quad \theta = \frac{a}{f_a}$$

Phi returns to its original value after
a —> a+ 2 pi N fa. N is the domain-wall number.
[Sikivie (1982)]

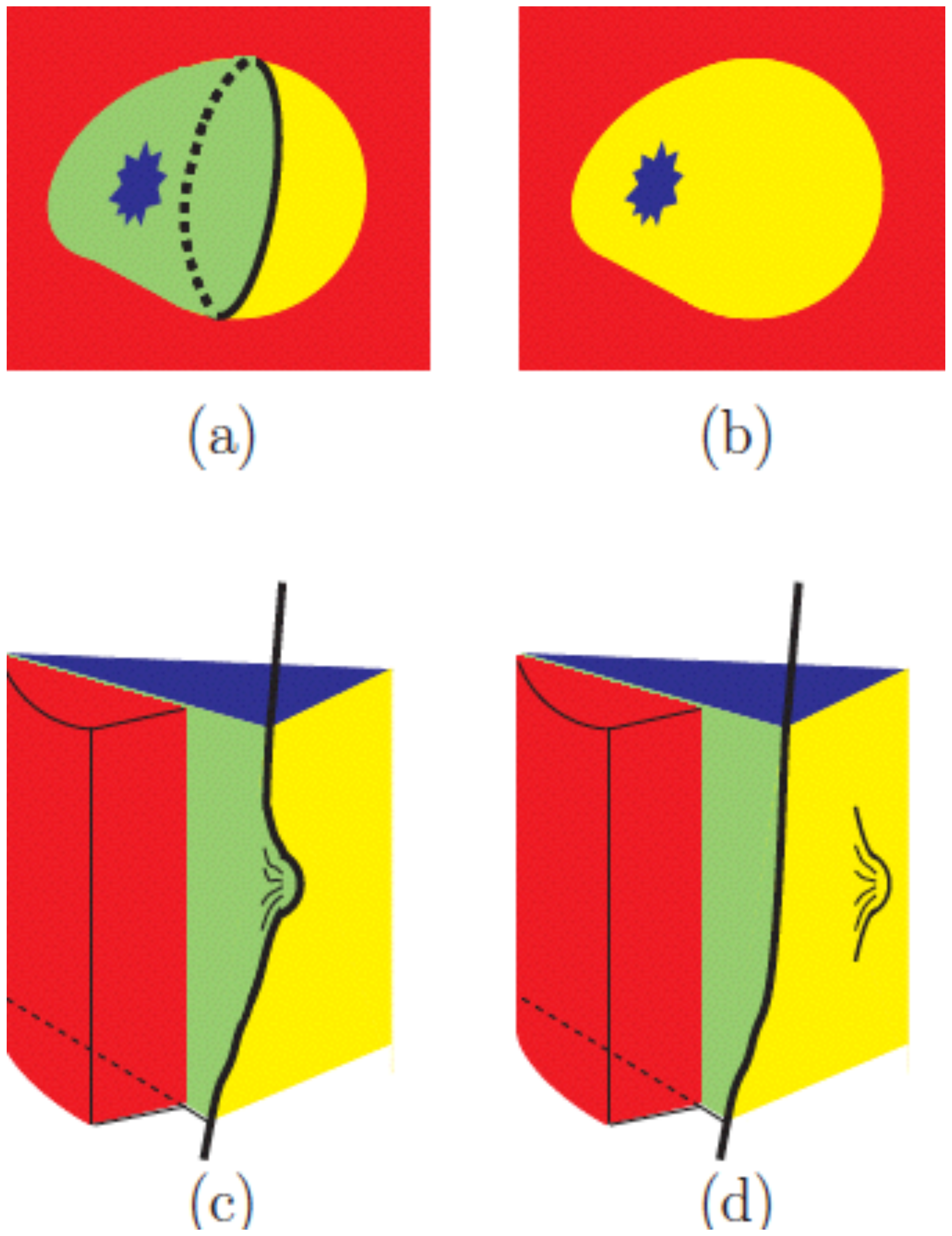
Small string-DW are not problematic.

The horizon scale string-DW system is problematic.

Barr-Kim, PRL 113 (2014) 241301.



Vilenkin-Everett (1982);
Barr-Choi-Kim (1987)



Sikivie (1982)

Top-down approach, using string compactification

1. Anomalous U(1) gauge symmetry.
2. Anomalous U(1) becomes global U(1) below the GUT scale.
3. The global U(1) is broken at the axion window.
4. DW number here. By giving a VEV to NPQ=1 field, we obtain NDW=1.
5. Choi-Kim mechanism: with hidden sector force.

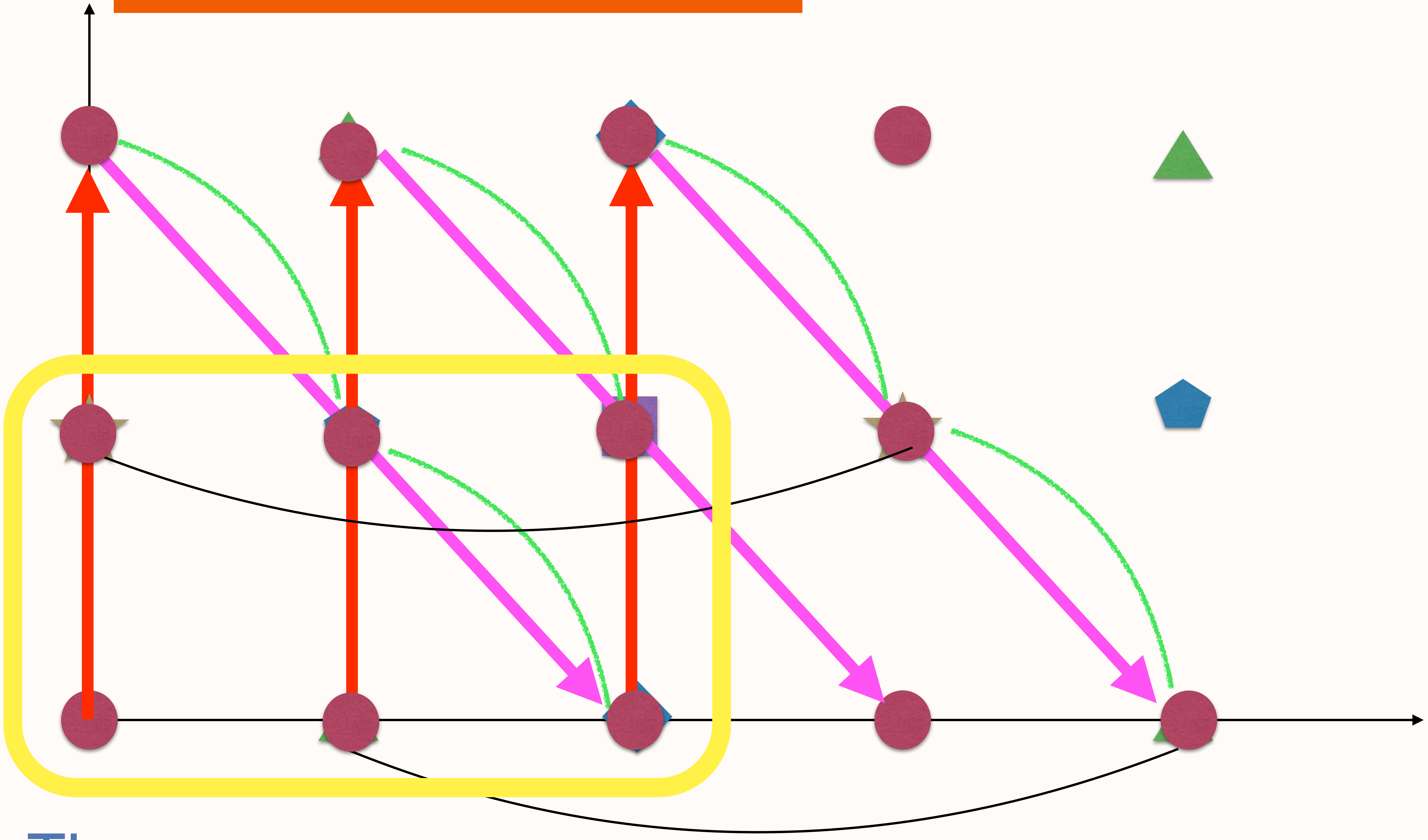
Better way: we need a Goldstone boson direction

Choi-Kim, PRL55 (1985) 2637

with two confining forces

For the center of GUT group, Lazarides-Shafi (1982).
But, the following ideas are more widely applicable.

Goldstone boson direction



The same vacuum

Torus identification

Goldstone boson directions are in principle discussed here:

JEK, PLB 207 (1988) 434;
JEK, PLB 735 (2014) 95, 741 (2014) 317;
JEK-Nam, PLB 759 (2016) 149; coupl.
JEK, PLB 759 (2016) 58. DW No.=1

Axionic string contribution: It is important if strings are created after PQ symmetry breaking. With a high scale inflation, this string contribution has been considered.

Probably, this is the most significant implication of BICEP2 result on axion physics, with DW number 1:

Vissineli-Gondolo, 1403.4594.
Marsh et al, 1403.4216. 71 micro-eV???

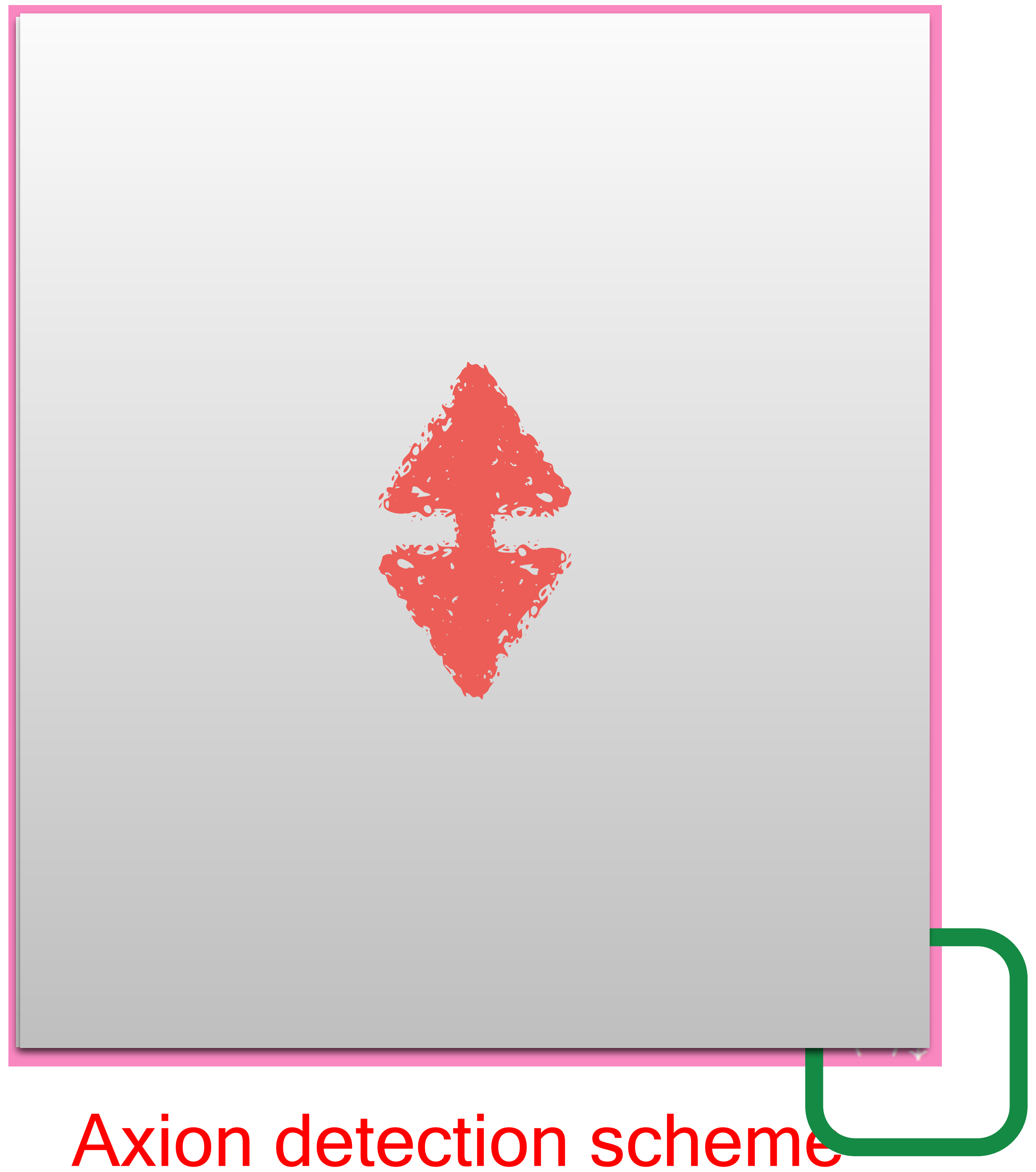
But, it depends a calculation of axions from the system of string-domain walls.

1. Kamionkowski-March-Russel(1982)

2. Numerical estimates

Florida group: 1
Cambridge group: O(100-1000)
Tokyo group: 25 ← This number is used

4. Axion detection

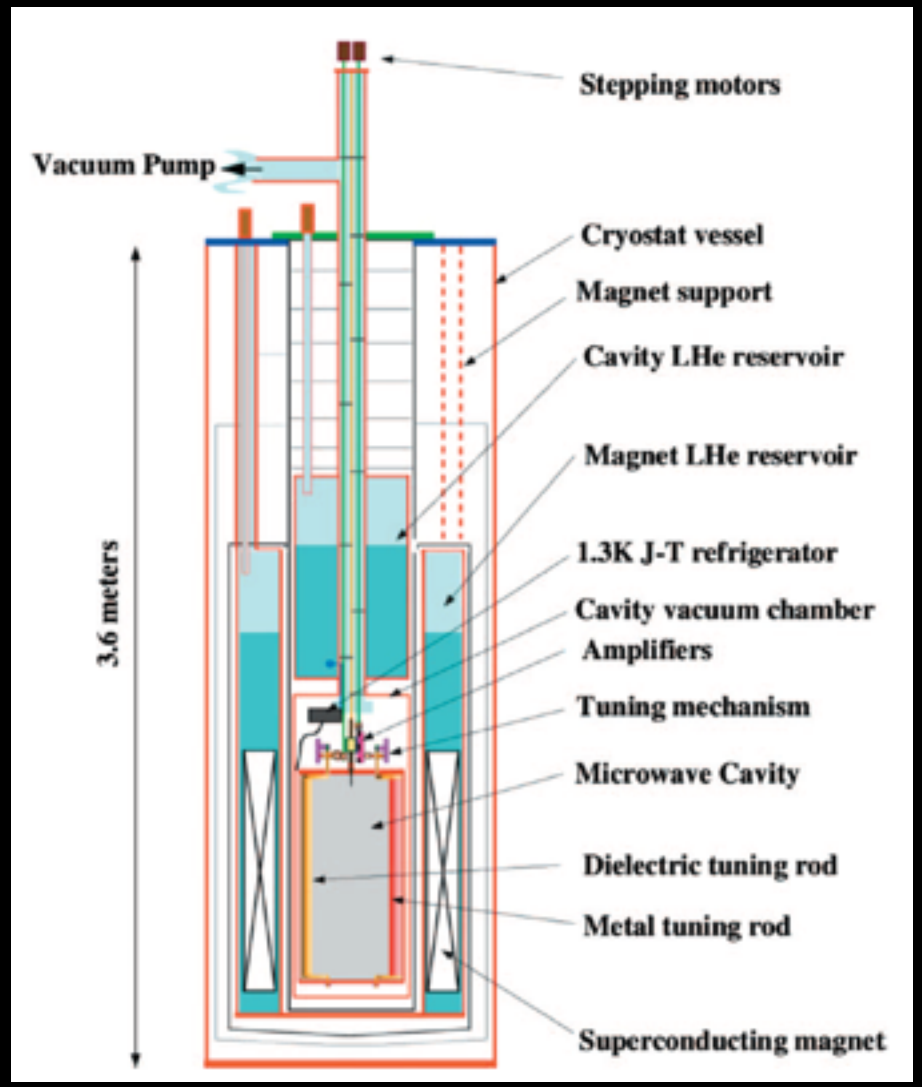


Axion detection scheme

Constant B field

E field follows the axion oscillation

Very light axion : 1979
CDM candidate

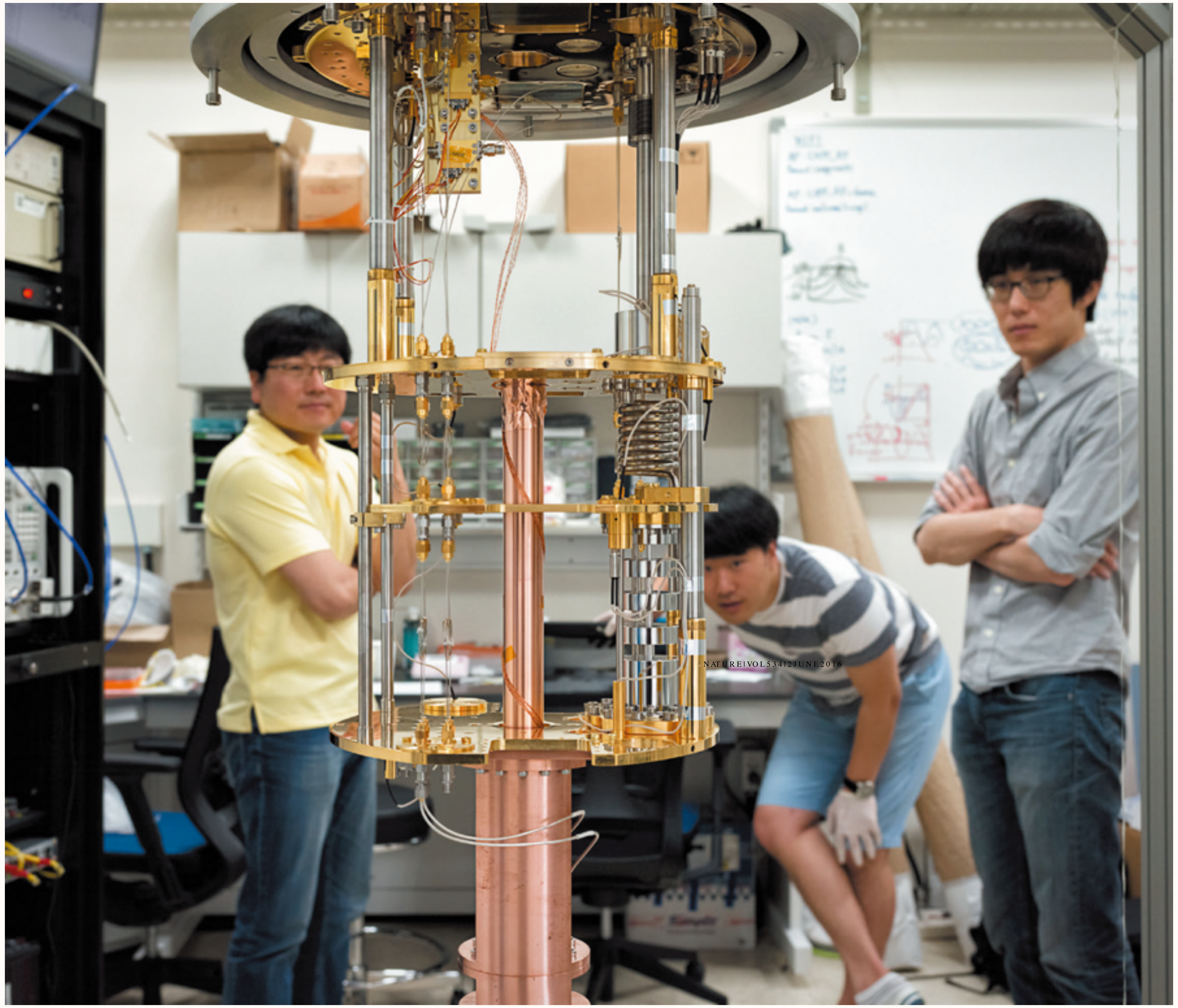


ADMX

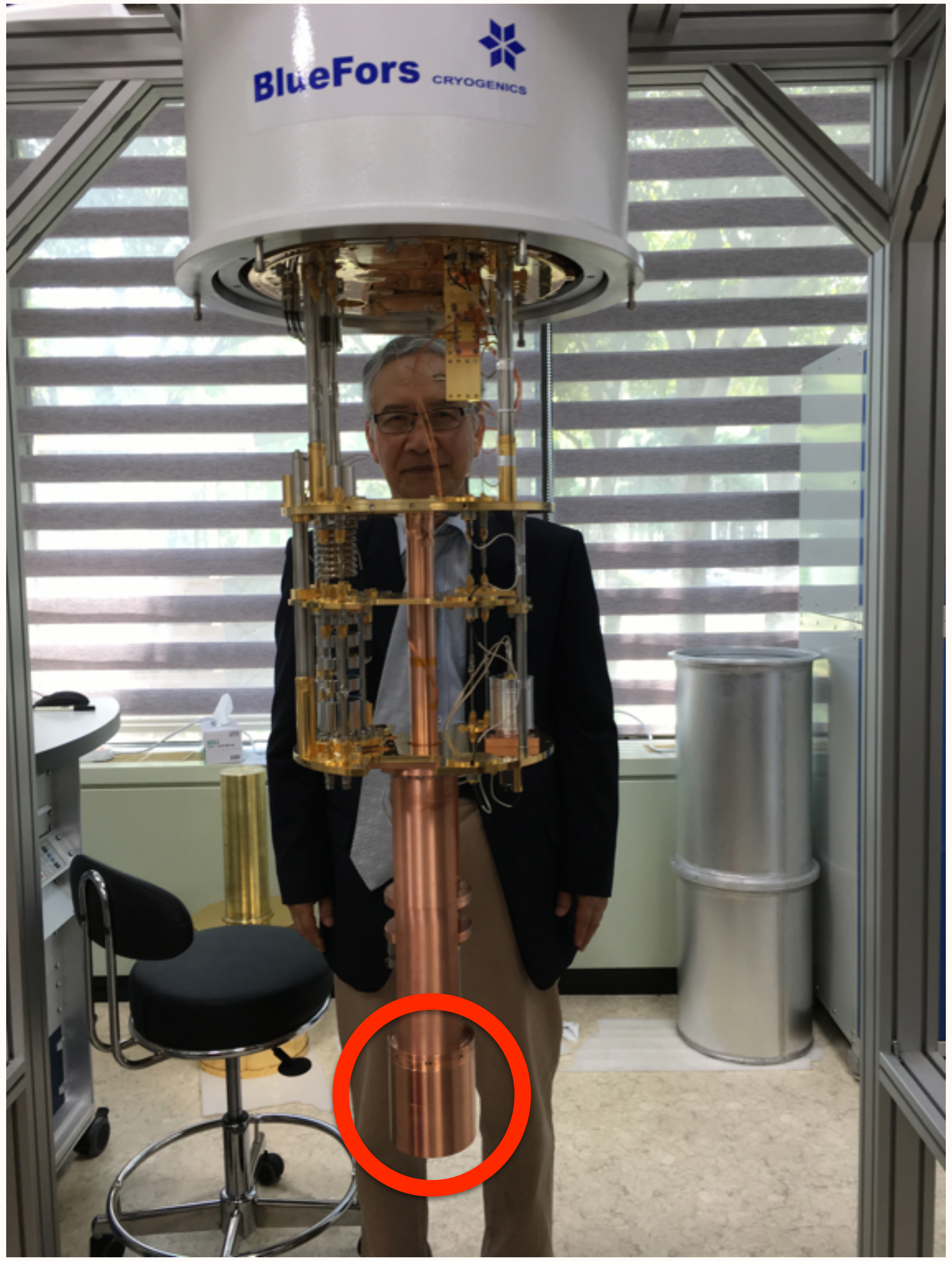
CAPP: ???

Detection suggested : 1983
CAPP started : 2013

Sikivie's cavity detector



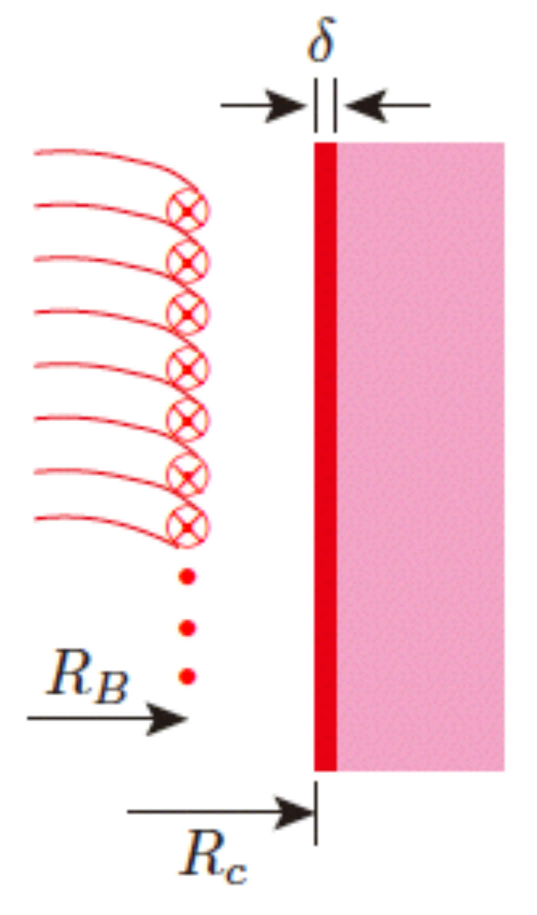
Nature Vol. 534 (June 2, 2016)



May 18, 2016

The design requires the solution in axio-electrodynamics, given in Hong-K-Semetrtzidis, 1403.1576 [hep-ph]: The record exists.

$$
\begin{aligned}
&\nabla \cdot \mathbf{E} = \rho + g\nabla a \cdot \mathbf{B},\\
&\nabla \times \mathbf{B} - \partial_t \mathbf{E} = \mathbf{j} - g\mathbf{B}\partial_t a - g\nabla a \times \mathbf{E},\\
&\nabla \cdot \mathbf{B} = 0,\\
&\nabla \times \mathbf{E} + \partial_t \mathbf{B} = 0,\\
&(\partial_t^2 - \nabla^2)a = -V'(a) - g\mathbf{E}\cdot\mathbf{B} + \rho_a.
\end{aligned}
$$



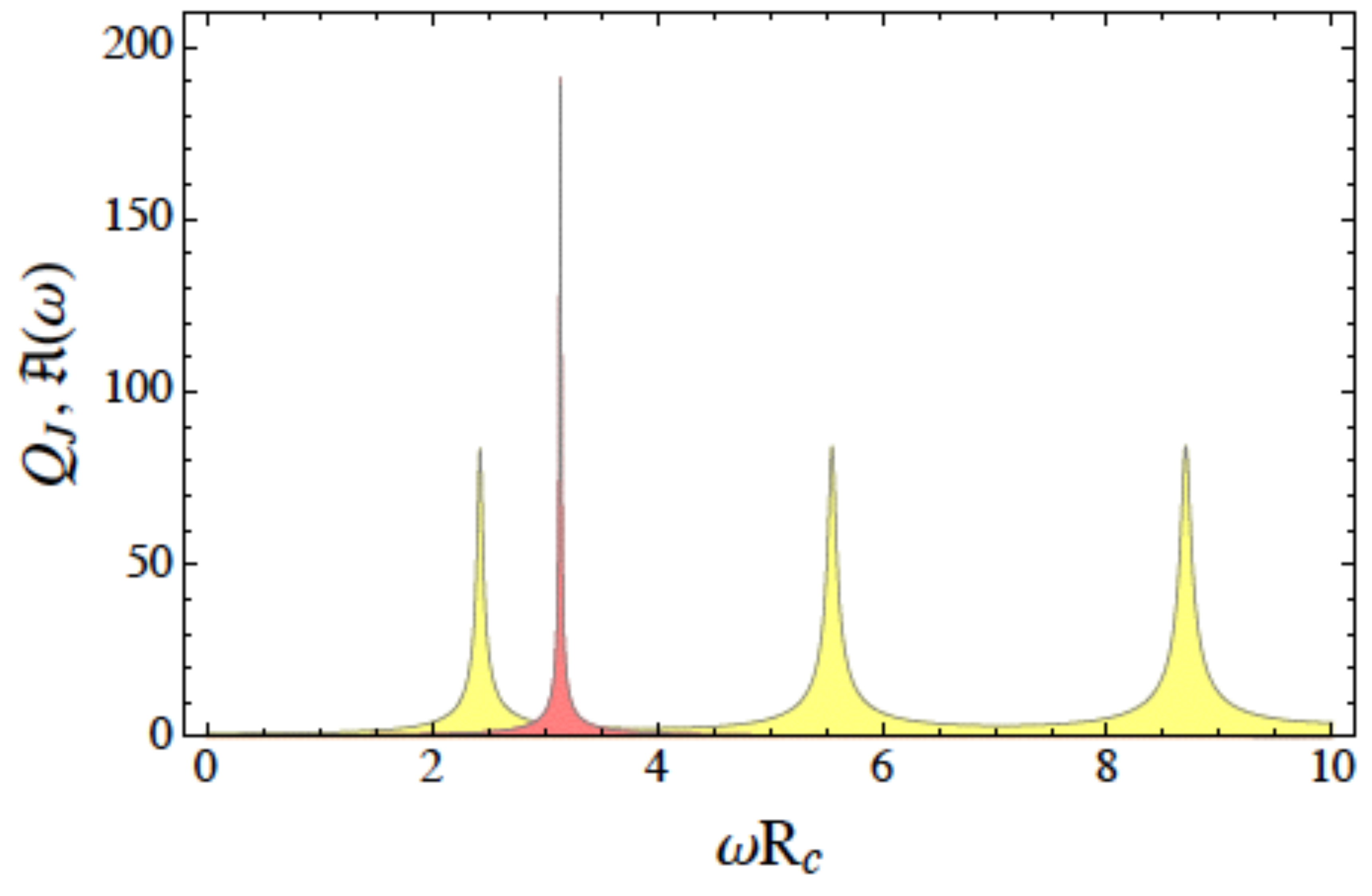
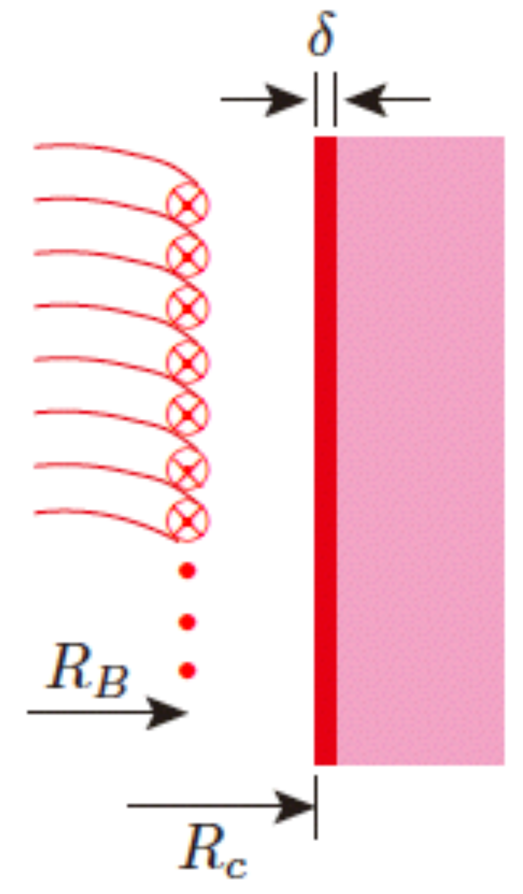


FIG. 2: An illustration of axion-tube resonance($Q_l \sim 100$, $Q_a \sim 300$, $m_a \sim 1.3\omega_1$). The yellow curve is Q_J as a function of ωR_c and the reddish one is $|\mathcal{A}(\omega)|$ peaked at $m_a R_c$. A resonance occurs when the center of $|\mathcal{A}(\omega)|$ coincides with one of the peaks of Q_J, *i.e.* $\omega_l \simeq m_a$. The actual resonance curves would be much sharper.

$$
\begin{aligned}
&\nabla\cdot\mathbf{E}=\rho+g\nabla a\cdot\mathbf{B},\\
&\nabla\times\mathbf{B}-\partial_t\mathbf{E}=\mathbf{j}-g\mathbf{B}\partial_t a-g\nabla a\times\mathbf{E},\\
&\nabla\cdot\mathbf{B}=0,\\
&\nabla\times\mathbf{E}+\partial_t\mathbf{B}=0,\\
&(\partial_t^2-\nabla^2)a=-V'(a)-g\mathbf{E}\cdot\mathbf{B}+\rho_a.
\end{aligned}
$$



Cavity detectors:

Axion detection is going on at
- ADMX: Seattle, USA
- CAPP: Daejeon, Korea

(Haloscope: cosmic axions, f_a nea 10^{11} GeV)

Planned at
- IAXO: Spain

(Helioscope: Solar axions, f_a near 10^{9} GeV)

5. Conclusion

1. The need: a solution of strong CP problem.
2. "Invisible" axions.
3. Prospective models from an ultra-violet completion, and presented couplings.
4. Commented on its implications in cosmology and possible detection.