CP’s and Type-II Leptogenesis

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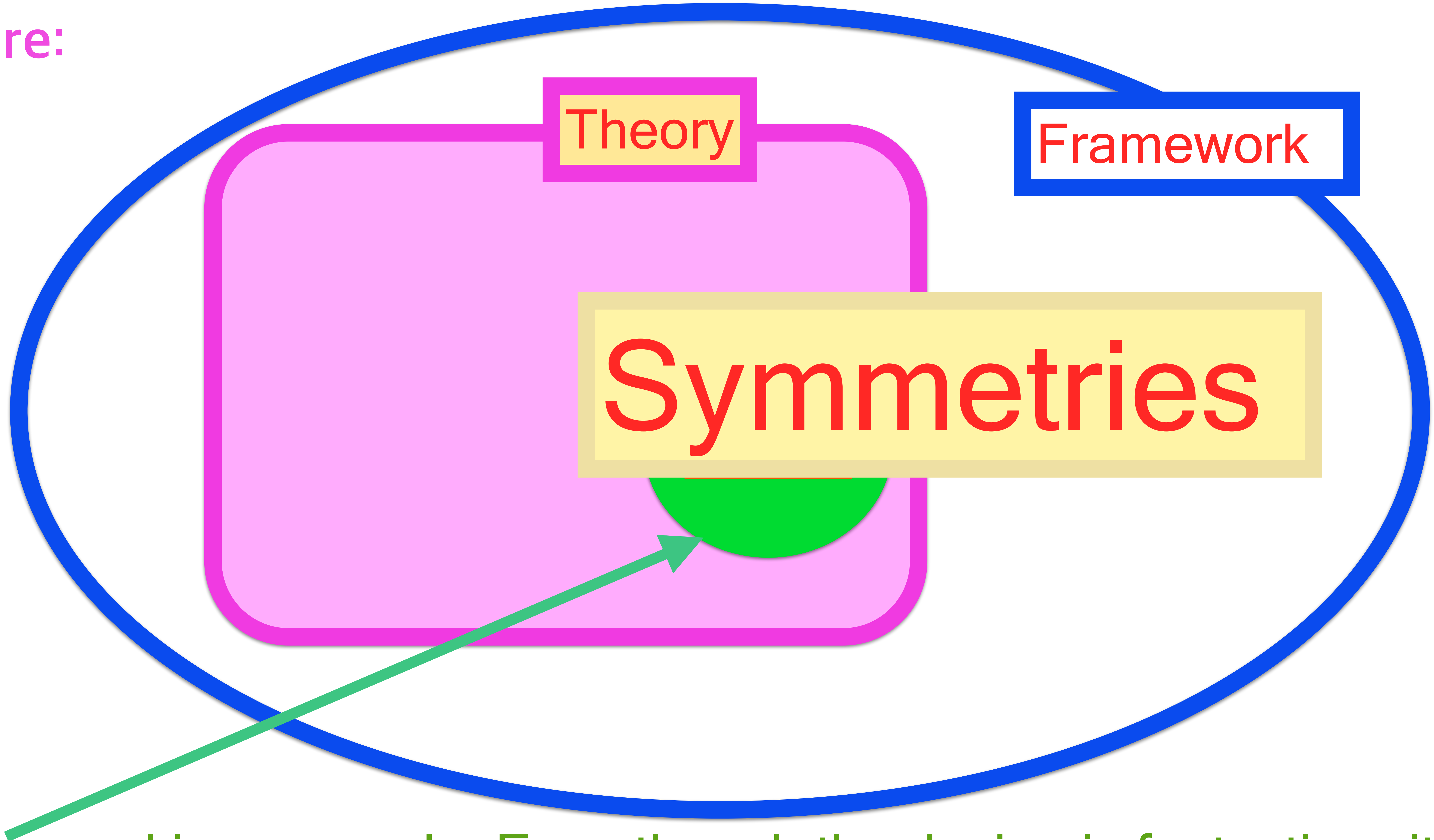
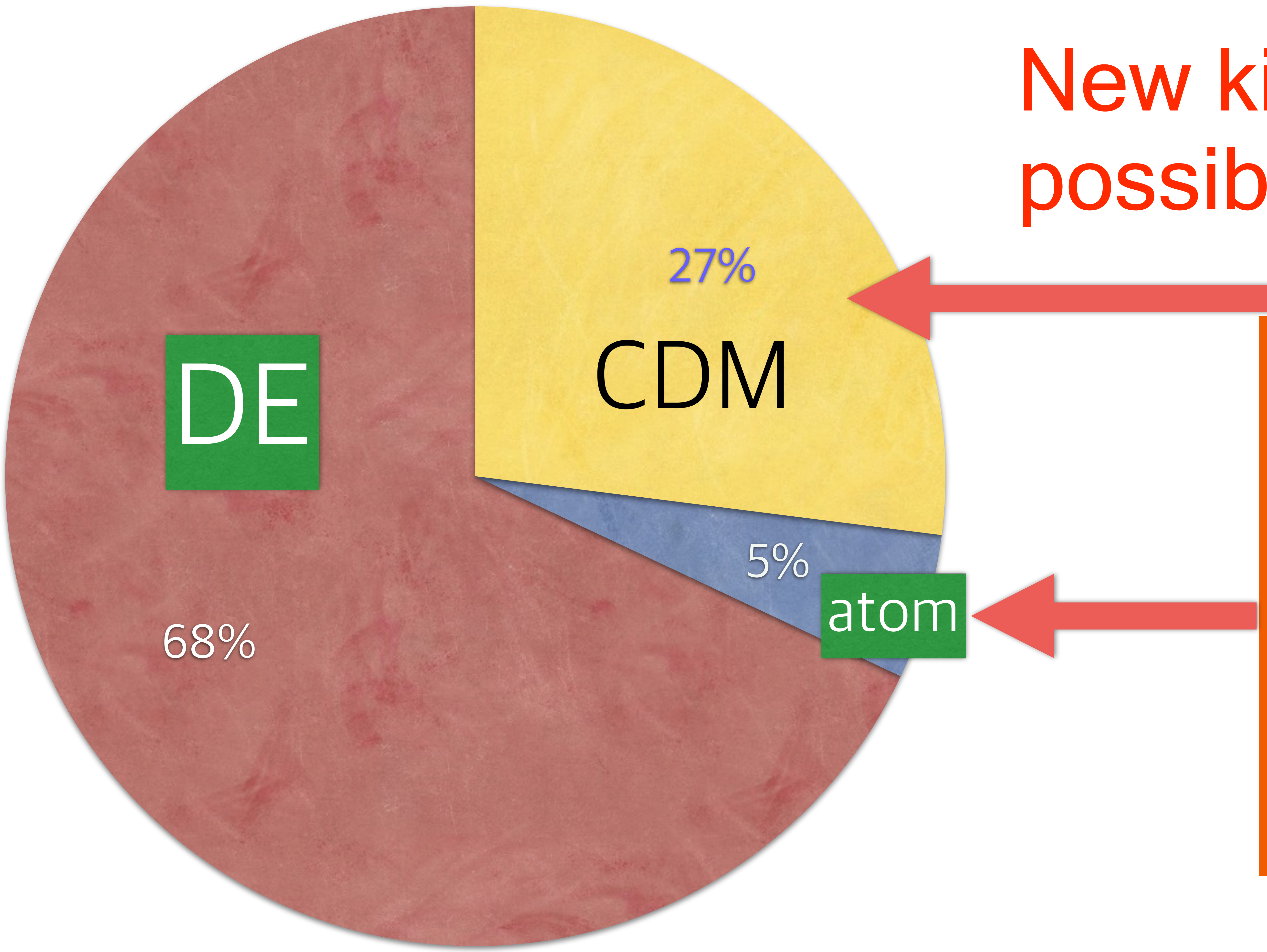
NCTS Annual Theory Meeting 2016
— Particle, Cosmology, String —

Gross's picture:



"Model" is a working example. Even though the design is fantastic, without a model example some will say that it is a religion.
Efforts to find a working model is our job toward THEORY/FRAMEWORK.



CP violation by J

New kind leptogenesis possible with PMNS phase

BCM such as axions
(from global symmetery)
WIMP(from discrete symm)

Chiral fields at GUT scale
SU(5), SU(7) GUTs

UGUTF:
Kim, PRL 45, 1916 (1980);
arXiv:1503.03104;
JEK, D.Y.Mo, S. Nam,
JKPS 66, 894 (2015) [arXiv: 1402.2978]

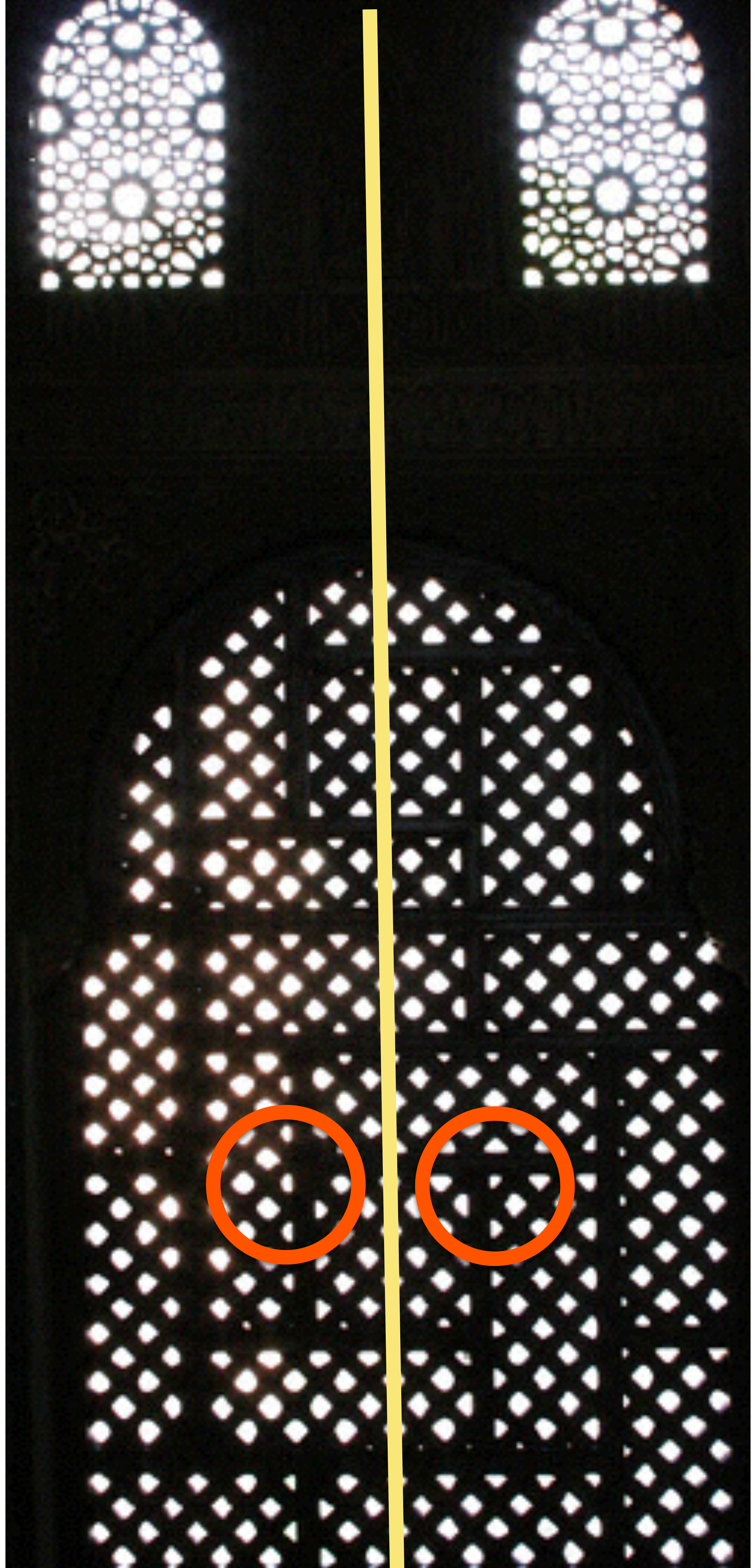
1. CPs
2. Weak CP violation
3. Strong CP problem
4. PQ symmetry
5. “Invisible axion”
6. Cosmology with CP violation
7. Type-II leptogenesis

1. CPs

Symmetry is beautiful: Gross' framework.

Parity:

Slightly broken!



If there exists a possibility of

$$(\mathbf{CP})\mathcal{L}(\mathbf{CP})^{-1} = \mathcal{L}$$

Then, the CP symmetry is preserved.

The first thing to do is to define fields with CP quantum numbers. Next, find out terms breaking CP.

So, CP violation is an interference phenomenon:

Neutral K mesons are a unique physical system which appears to be created by nature to demonstrate, in the most impressive manner, a number of spectacular phenomena.
....
If the K mesons did not exist, they should have been invented "on purpose" in order to teach students the principles of quantum mechanics. [talk, A. De Domenico, 1 Sep.]

Lev B. Okun

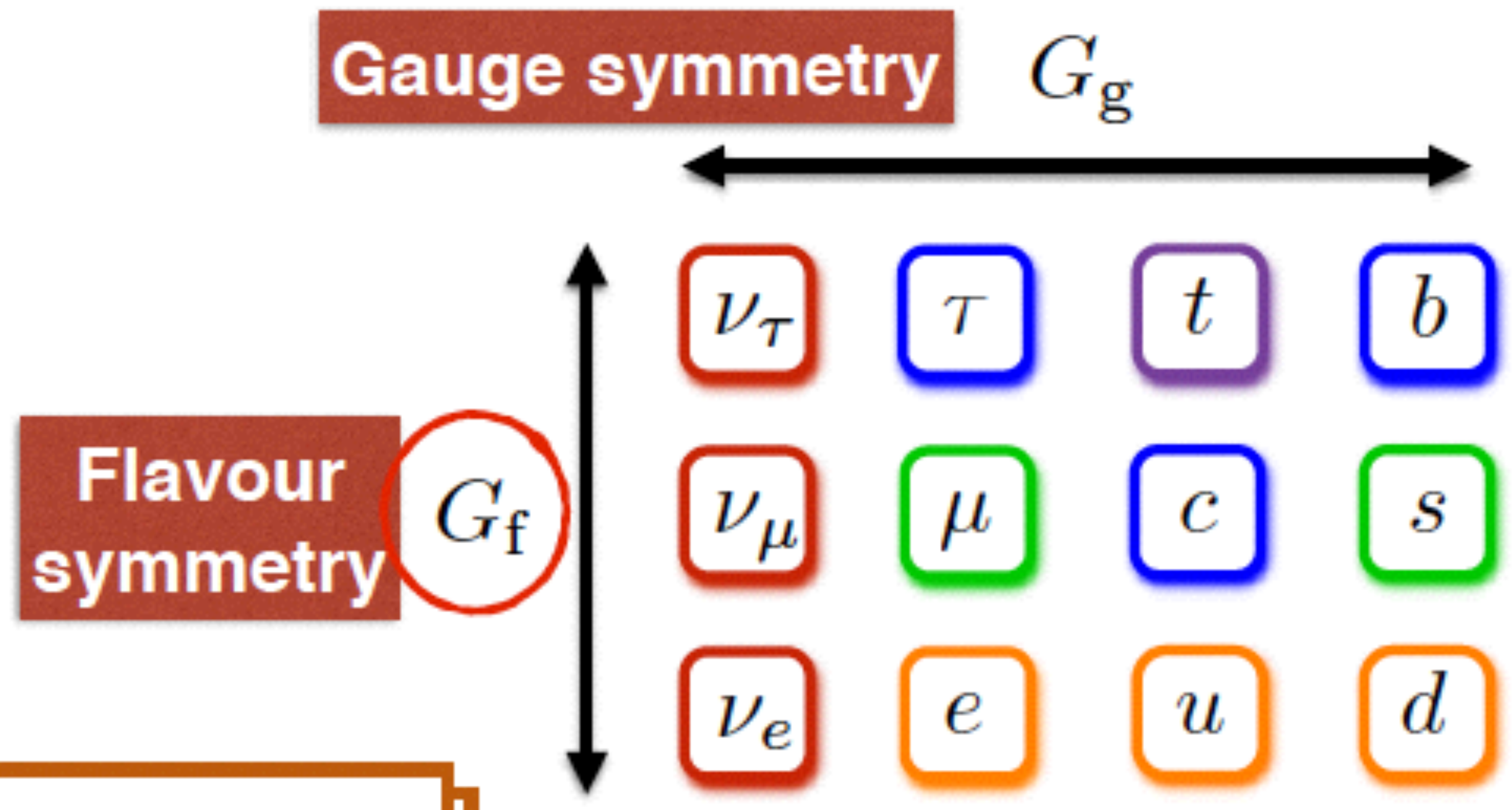
and most importantly,

5. Weak CP violation in the SM.

2. Weak CP violation

Flavour symmetry

Y-L Zhou, 4 Aug 2016



Useful for CP phase calculation.

Anarchy

	Continuous	Discrete
Abelian	U(1)	Z_n
Non-Abelian	SU(3), SO(3),…	A_4, S_4, A_5, $\Delta(48)$, …

(i) SM x (Family symmetry)
(ii) GUT x (Family symmetry)
(iii) Unification of GUT families in a simple gauge group!!!

One CP phase is given. Froggatt-Nielsen form, with non-trivial entries with (iii):

$$\tilde{M}^{(u)} = \left(\begin{array}{c|ccc} & u_R(+5) & c_R(+4) & t_R(+2) \\ \hline \bar{q}_1(+1) & cX^{u6}_{-1} & -cX^{u5}_{-1} & \kappa_t X^{u3}_{-1} \\ \bar{q}_2(0) & -cX^{u5}_{-1} & cX^{u4}_{-1} & -\kappa_t X^{u2}_{-1} \\ \bar{q}_3(-2) & \kappa_t X^{u3}_{-1} & -\kappa_t X^{u2}_{-1} & 1 \end{array}\right) v_u, \qquad \tilde{M}^{(d)} = \left(\begin{array}{c|ccc} & d_R(-5) & s_R(0) & b_R(+2) \\ \hline \bar{q}_1(+1) & dX^{d4}_{+1} & 0 & 0 \\ \bar{q}_2(0) & 0 & sX^{d}_{+1}X^{d}_{-1} & \kappa_b X^{d2}_{-1} \\ \bar{q}_3(-2) & 0 & \kappa_b X^{d2}_{+1} & 1 \end{array}\right) v_d$$

Entries must have different phases

These are real, for example

CKM and PMNS matrices

CP violation by Jarlskog determinant J

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

The CKM or PMNS matrix is, with the 1st row real,

$$\begin{pmatrix} c_1, & s_1 c_3, & s_1 s_3 \\ -c_2 s_1, & e^{-i\delta} s_2 s_3 + c_1 c_2 c_3, & -e^{-i\delta} s_2 c_3 + c_1 c_2 s_3 \\ -e^{i\delta} s_1 s_2, & -c_2 s_3 + c_1 s_2 c_3 e^{i\delta}, & c_2 c_3 + c_1 s_2 s_3 e^{i\delta} \end{pmatrix}$$

The individual element of determinant is

$$\begin{aligned}
V_{11}V_{22}V_{33} &= c_1^2 c_2^2 c_3^2 + c_1^2 s_2^2 s_3^2 + 2c_1 c_2 c_3 s_2 s_3 \cos\delta \\
&\quad - c_1 c_2 c_3 s_1^2 s_2 s_3 e^{i\delta}, \\
-V_{11}V_{23}V_{32} &= c_1^2 c_2^2 s_3^2 + c_1^2 s_2^2 c_3^2 - 2c_1 c_2 c_3 s_2 s_3 \cos\delta \\
&\quad + c_1 c_2 c_3 s_1^2 s_2 s_3 e^{i\delta}, \\
V_{12}V_{23}V_{31} &= s_1^2 s_2^2 c_3^2 - c_1 c_2 c_3 s_1^2 s_2 s_3 e^{i\delta}, \\
-V_{12}V_{21}V_{33} &= s_1^2 c_2^2 c_3^2 + c_1 c_2 c_3 s_1^2 s_2 s_3 e^{i\delta}, \\
V_{13}V_{21}V_{32} &= s_1^2 c_2^2 s_3^2 - c_1 c_2 c_3 s_1^2 s_2 s_3 e^{i\delta}, \\
-V_{13}V_{22}V_{31} &= s_1^2 s_2^2 s_3^2 + c_1 c_2 c_3 s_1^2 s_2 s_3 e^{i\delta}.
\end{aligned}$$

Is Im(V_{11} V_{22} V_{33}) the Jarlskog determinant?

With the usual definition on J:
J=|Im V_{11} V_{33} $V_{13}^*V_{31}^*$|. Then, on 1=Det V

$$V_{13}^* V_{22}^* V_{31}^* = |V_{22}|^2 V_{11} V_{33} V_{13}^* V_{31}^* - V_{11} V_{23} V_{32} V_{13}^* V_{31}^* V_{22}^* + |V_{31}|^2 V_{12} V_{23} V_{13}^* V_{22}^* - V_{12} V_{21} V_{33} V_{13}^* V_{31}^* V_{22}^* + |V_{13}|^2 V_{21} V_{32} V_{31}^* V_{22}^* - |V_{13} V_{22} V_{31}|^2.$$

unitarity of V

imaginary part of this is J

$$V_{13}^* V_{22}^* V_{31}^* = (1 - |V_{21}|^2) V_{11} V_{33} V_{13}^* V_{31}^* + V_{11} V_{23} V_{13}^* V_{21}^* |V_{31}|^2 + (1 - |V_{11}|^2) V_{12} V_{23} V_{13}^* V_{22}^* + |V_{13}|^2 (V_{12} V_{21} V_{11}^* V_{22}^* + V_{21} V_{32} V_{31}^* V_{22}^*) - |V_{13} V_{22} V_{31}|^2.$$

Similar considerations for other elements give the imaginary part as [(1-$|V_{21}|^2$) -$|V_{31}|^2$ +(1-$|V_{11}|$)^2]J=J

$$\begin{pmatrix} c_1, & s_1 c_3, & s_1 s_3 \\ -c_2 s_1, & e^{-i\delta} s_2 s_3 + c_1 c_2 c_3, & -e^{-i\delta} s_2 c_3 + c_1 c_2 s_3 \\ -e^{i\delta} s_1 s_2, & -c_2 s_3 + c_1 s_2 c_3 e^{i\delta}, & c_2 c_3 + c_1 s_2 s_3 e^{i\delta} \end{pmatrix}$$

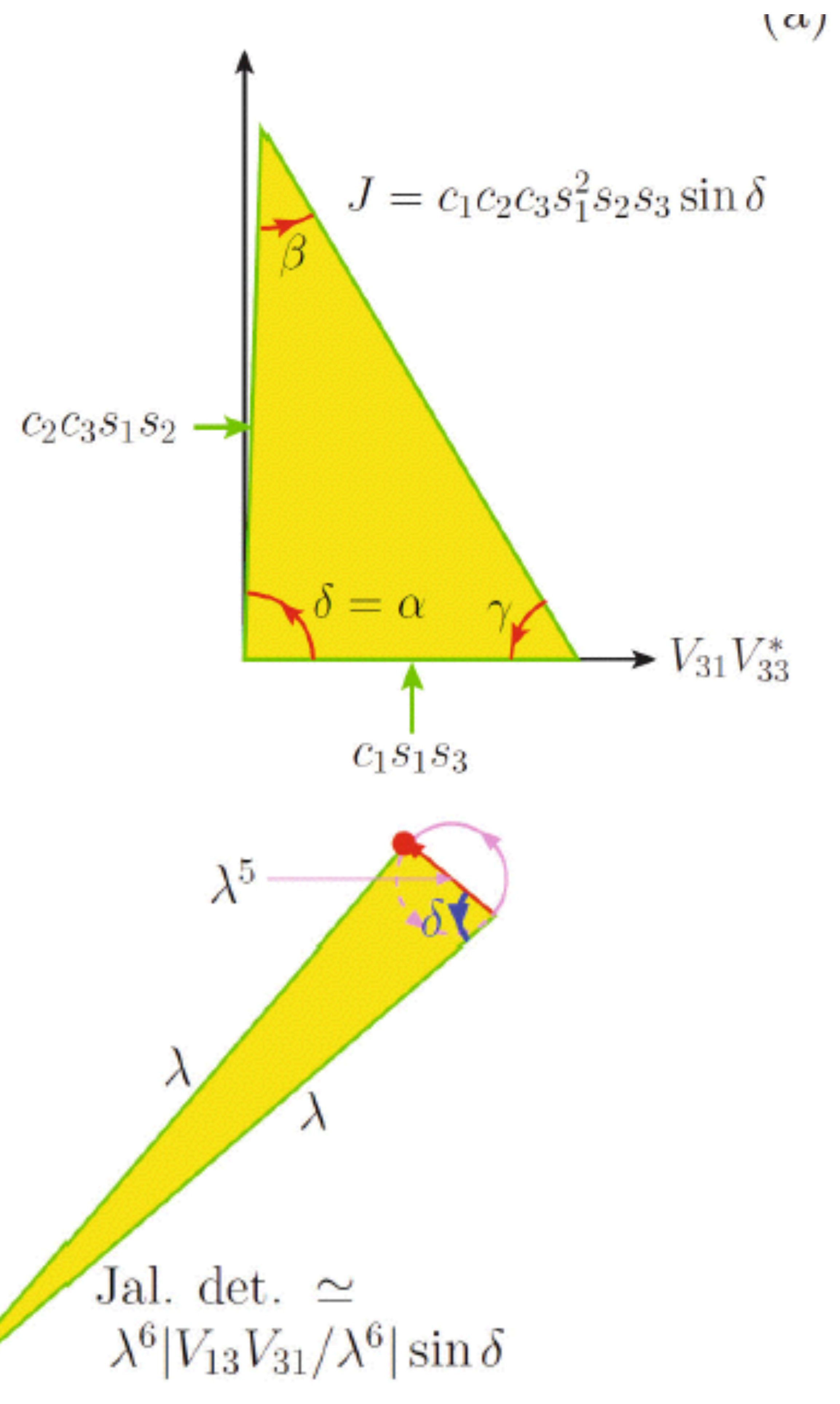
$$J = |c_1 c_2 c_3 s_1^2 s_2 s_3 \sin(\mathrm{delta})|$$

All three families participate.
And also u-type quark masses must be different, and d-type quark masses different.

There are 6 Jarlskog triangles. One of them corresponds to B-meson decay to K. PDG gives alpha or our delta almost 90 degrees.

We can consider another J: B decaying to pi meson. This has two long sides.

So, delta=90 degrees is a maximal CP violation! in KS parametrization. In other parametrizations too.



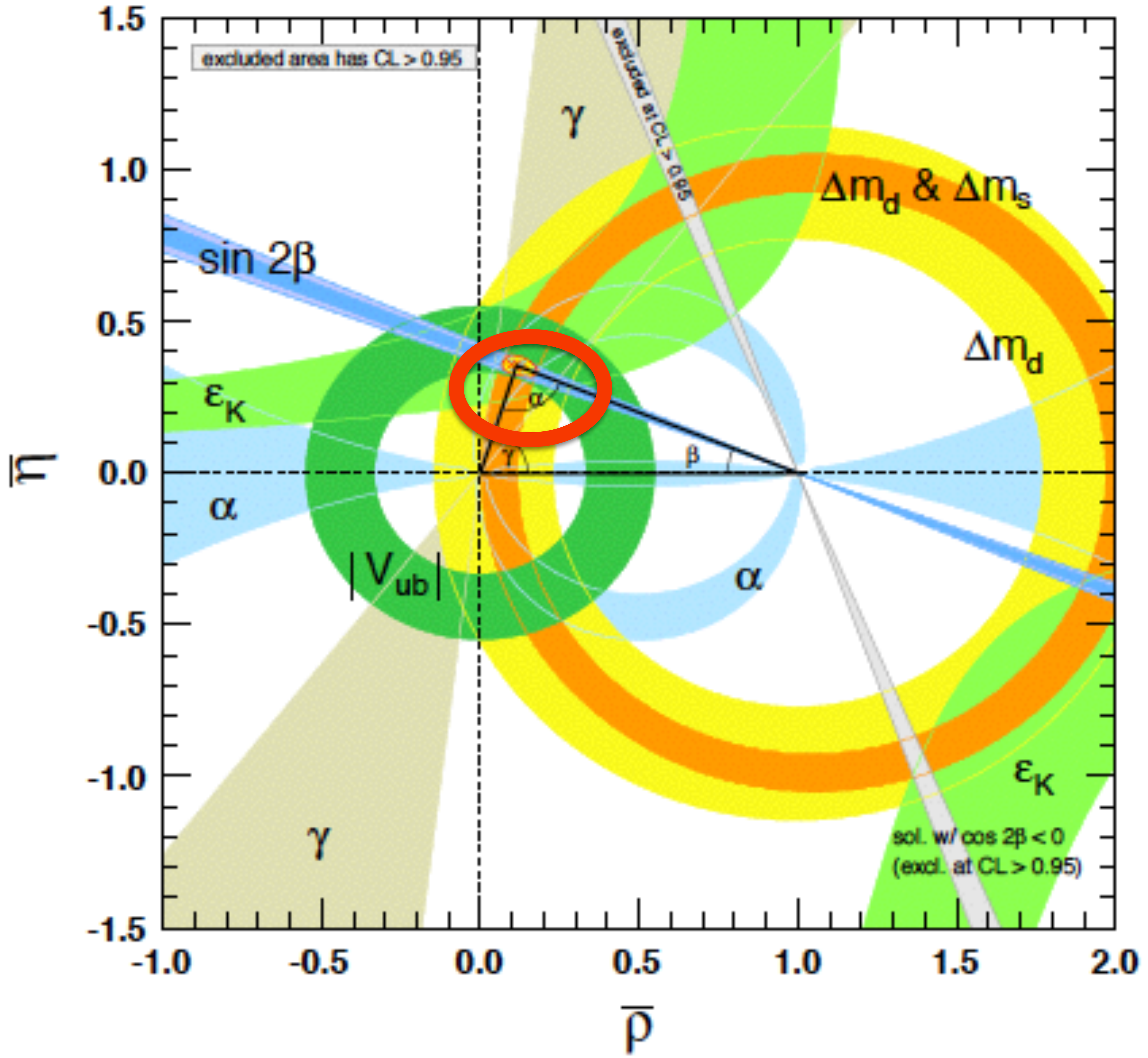


Figure 12.2: Constraints on the $\bar{\rho}, \bar{\eta}$ plane. The shaded areas have 95% CL.

and the Jarlskog invariant is $J = (3.06^{+0.21}_{-0.20}) \times 10^{-5}$.

This is PDG compilation.

α is our δ .

PDG determines

Combining the $B \to \pi\pi$, $\rho\pi$, and $\rho\rho$ decay modes [105], α is constrained as

$$\alpha = (85.4^{+3.9}_{-3.8})^{\circ}.$$

U_{fit} determines

alpha= (88.6+-3.3)^{o}

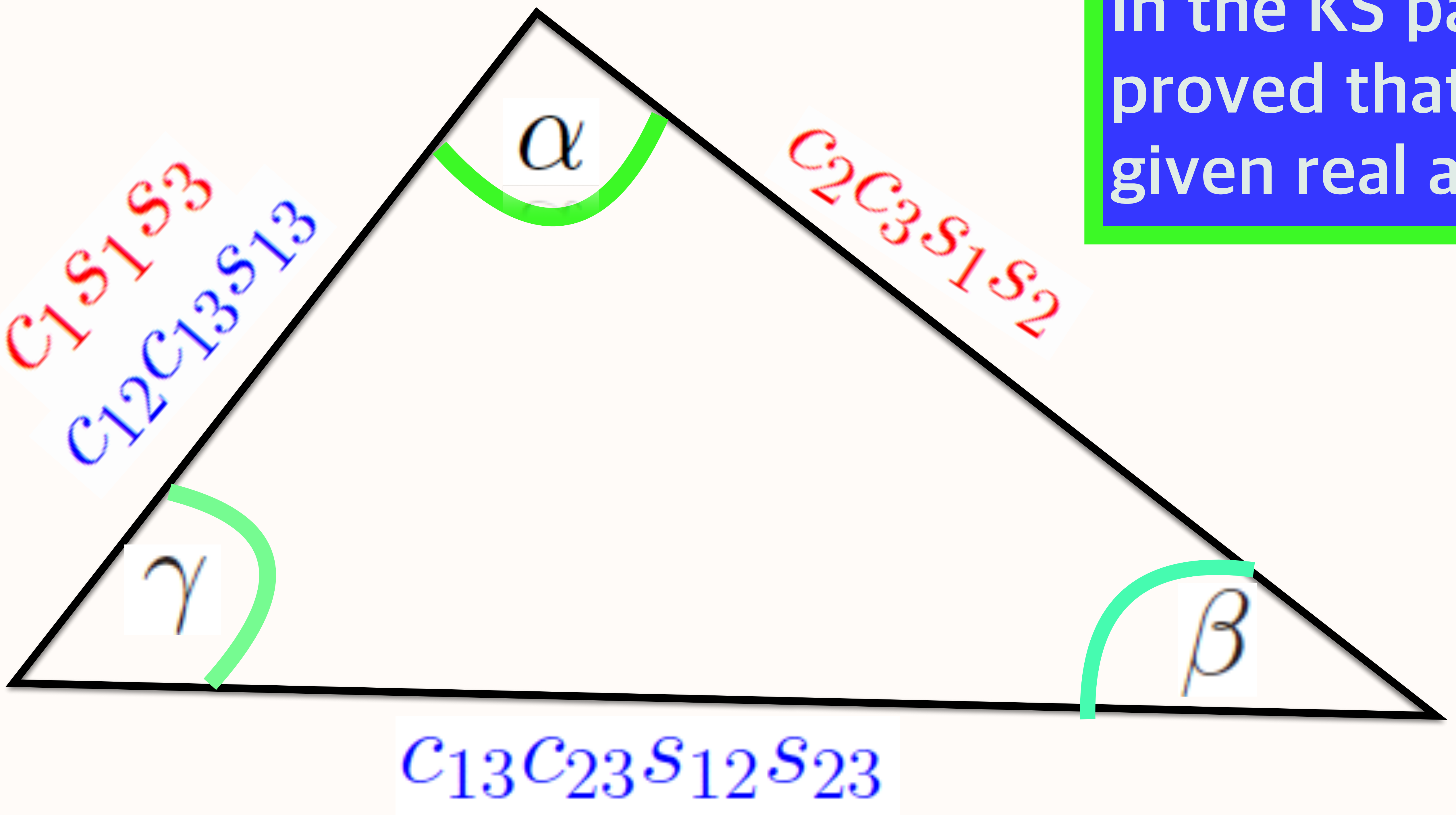
CKM_{fit} determines

alpha= $(90.6^{+3.9}_{-1.1})^{o}$

This implies that the weak CP violation in the quark sector is almost maximal with some forms of CKM matrix.

KS parametrization: $J = |c_1 c_2 c_3 s_1^2 s_2 s_3 \sin\alpha|$

In the KS parametrization, we proved that it is maximal with given real angles.



CKM parametrization: $J = |c_{12} c_{13}^2 c_{23} s_{12} s_{13} s_{23} \sin\gamma|$

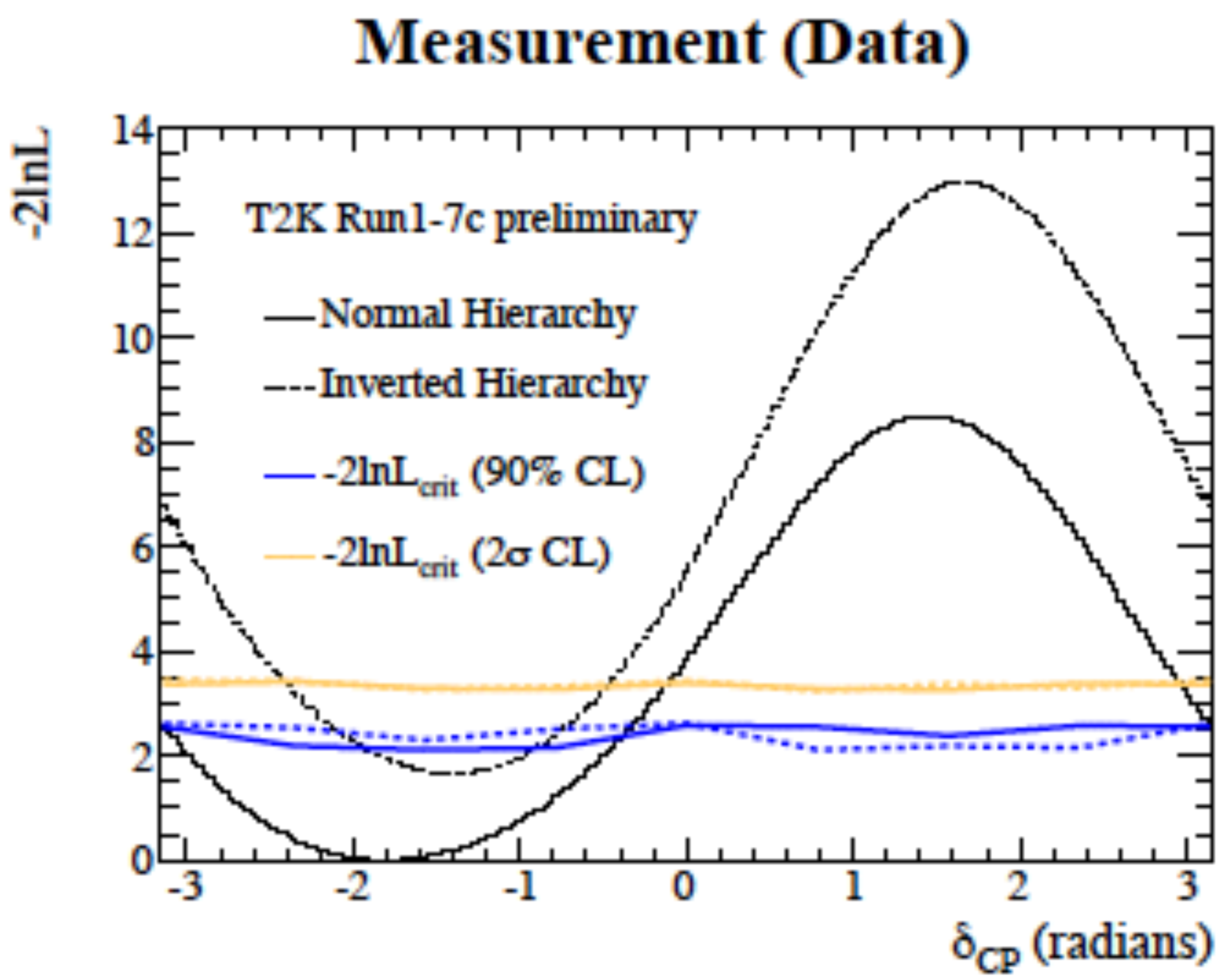
Any parametrization gives the same area.

See: Spinrath: Talk on Dec. 6, here.

Maximal CP violation in lepton sector?

T2K experiment [S.V. Cao at PASCOS 2016; K. Iwamoto at ICHEP2016], slightly favors $\delta_{\rm PMNS}$ near -90 degrees.

Determination of $\delta_{\rm PMNS}$ may choose $\delta_{\rm CKM}$ in certain models.



$$\delta_{cp} = [-3.13, -0.39](NH), [-2.09, -0.74]\ (IH) \text{ at } 90\% \text{ CL}$$

Is $\delta_{\rm PMNS} = \pm\delta_{\rm CKM}$?

JEK + S. Nam, arXiv:1506.08491
JEK + D. Y. Mo + M-S. Seo, arXiv:1506.08984

3. 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.

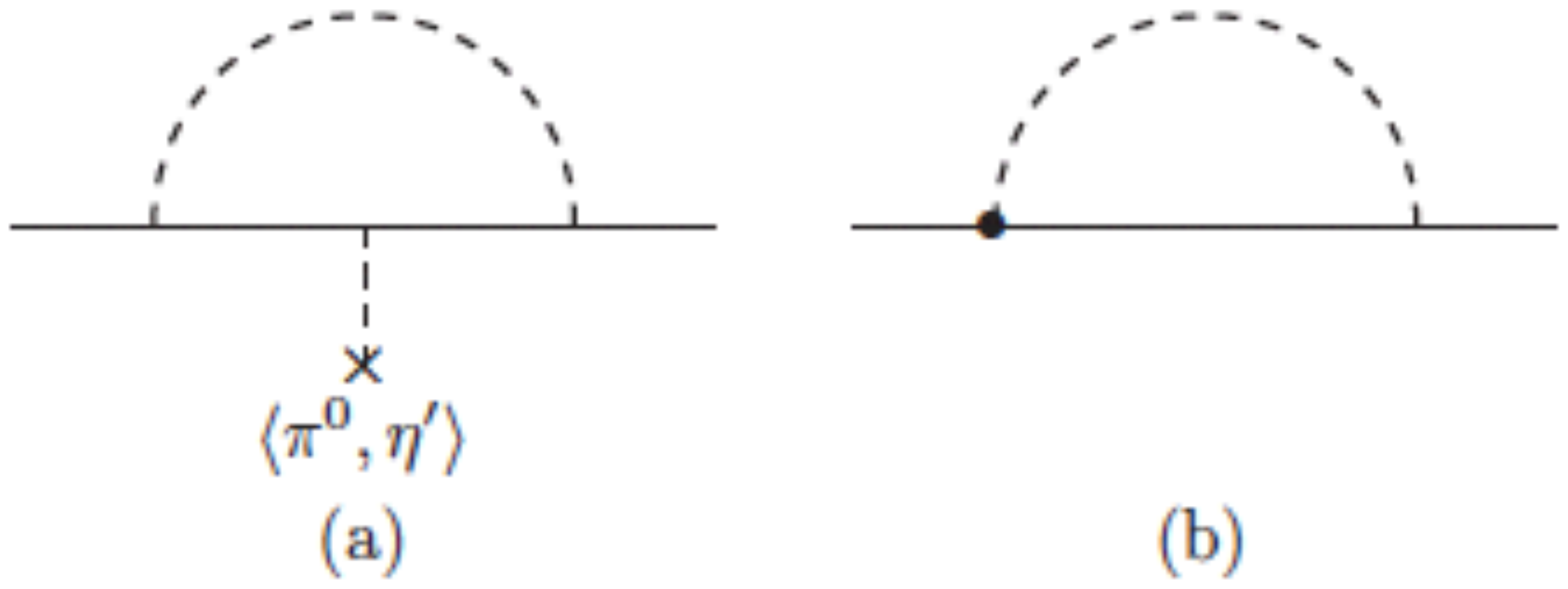
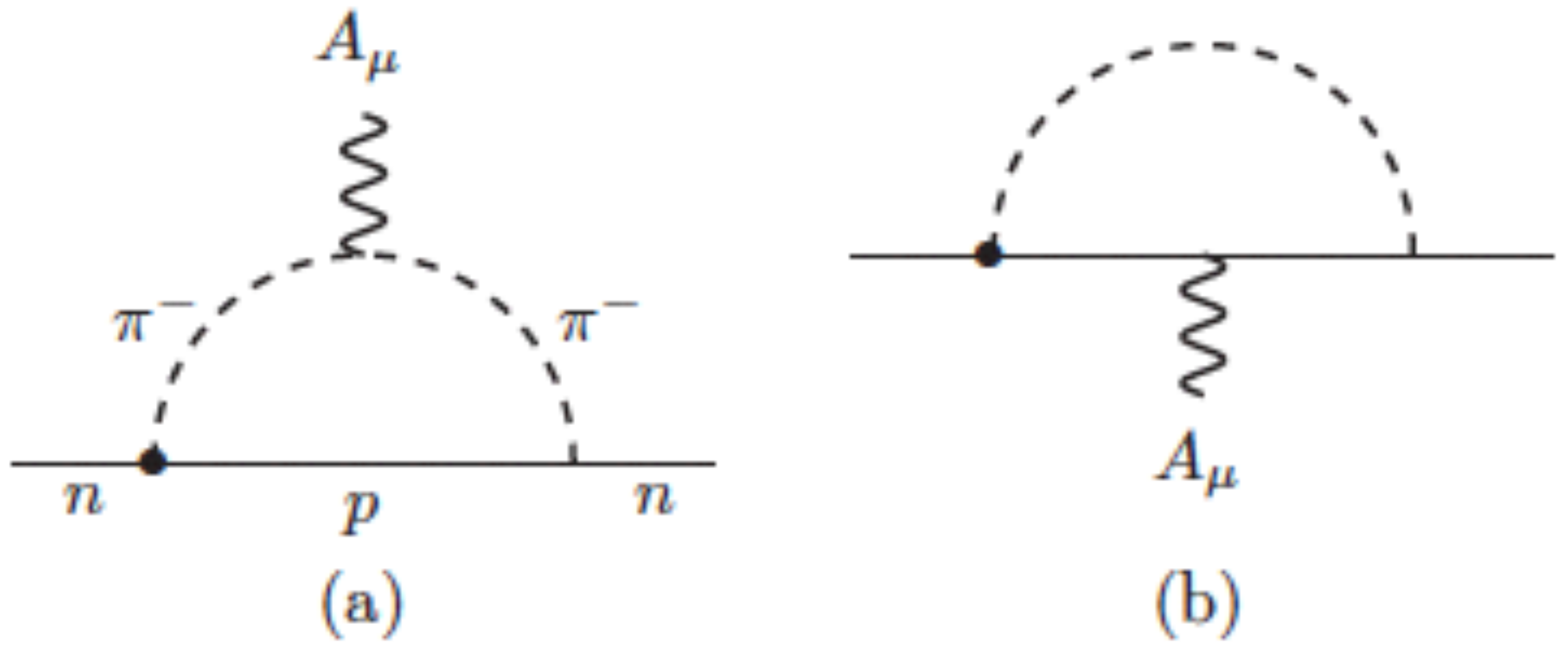


FIG. 4. Loop corrections for $\bar{n}n$-meson coupling. Insertion of the CP violation effect by VEVs of π^0 and η' in (a). They can be transferred to one vertex shown as a bullet in (b). With this bullet, CP violation is present because of a mismatch between the CP-conserving RHS vertex and CP-violating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

- The neutron EDM term.



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

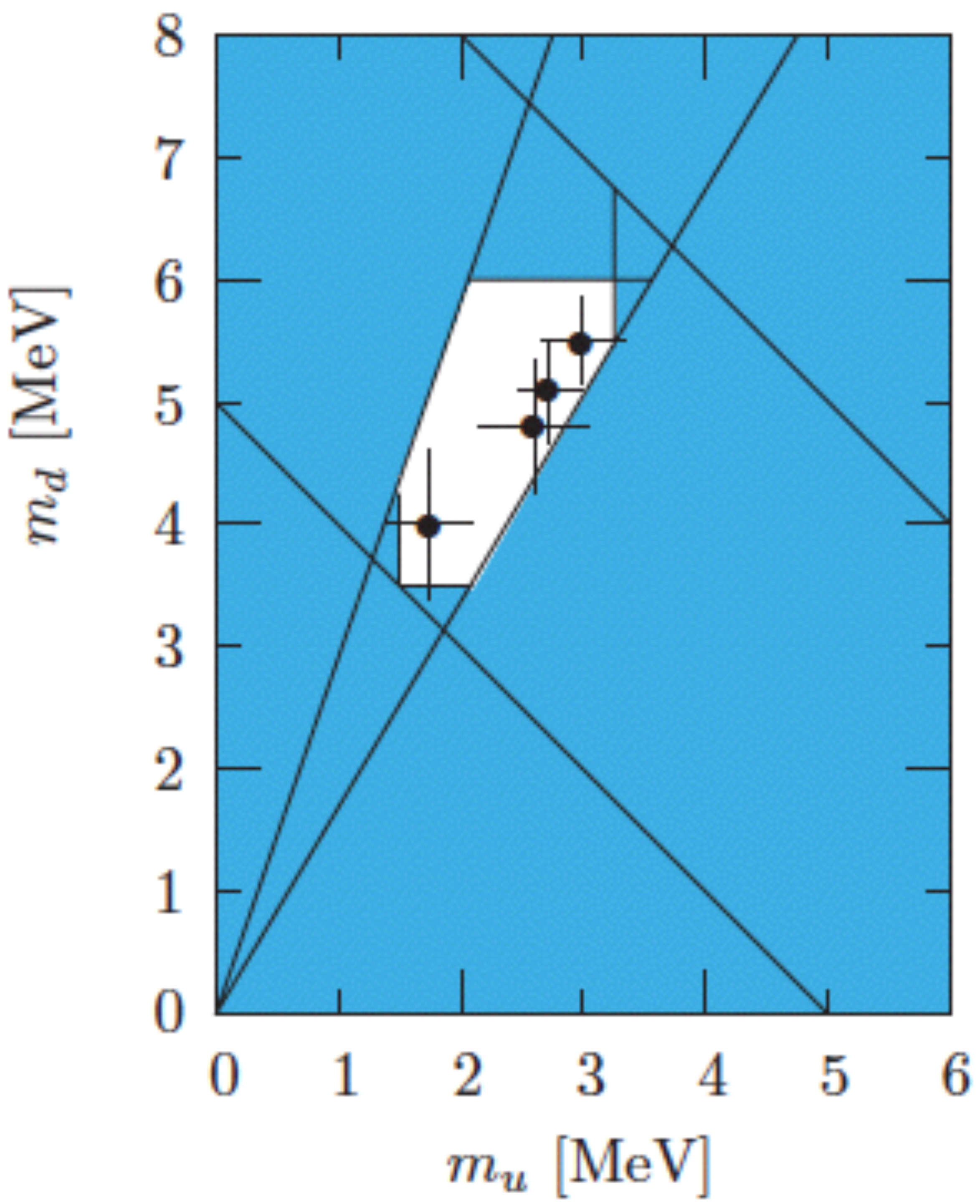
FIG. 5. Diagrams contributing to the NEDM with the bullet representing the *CP* violation effect. (a) is the physically observable contribution.

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

4. PQ symmetry

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

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

Removed by Peccei-Quinn

$$\boxed{\text{CP violation by Weinberg, including Yukawa of } H_u \text{ and } H_d \text{ couplings.}}$$

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.

5. “Invisible” axions

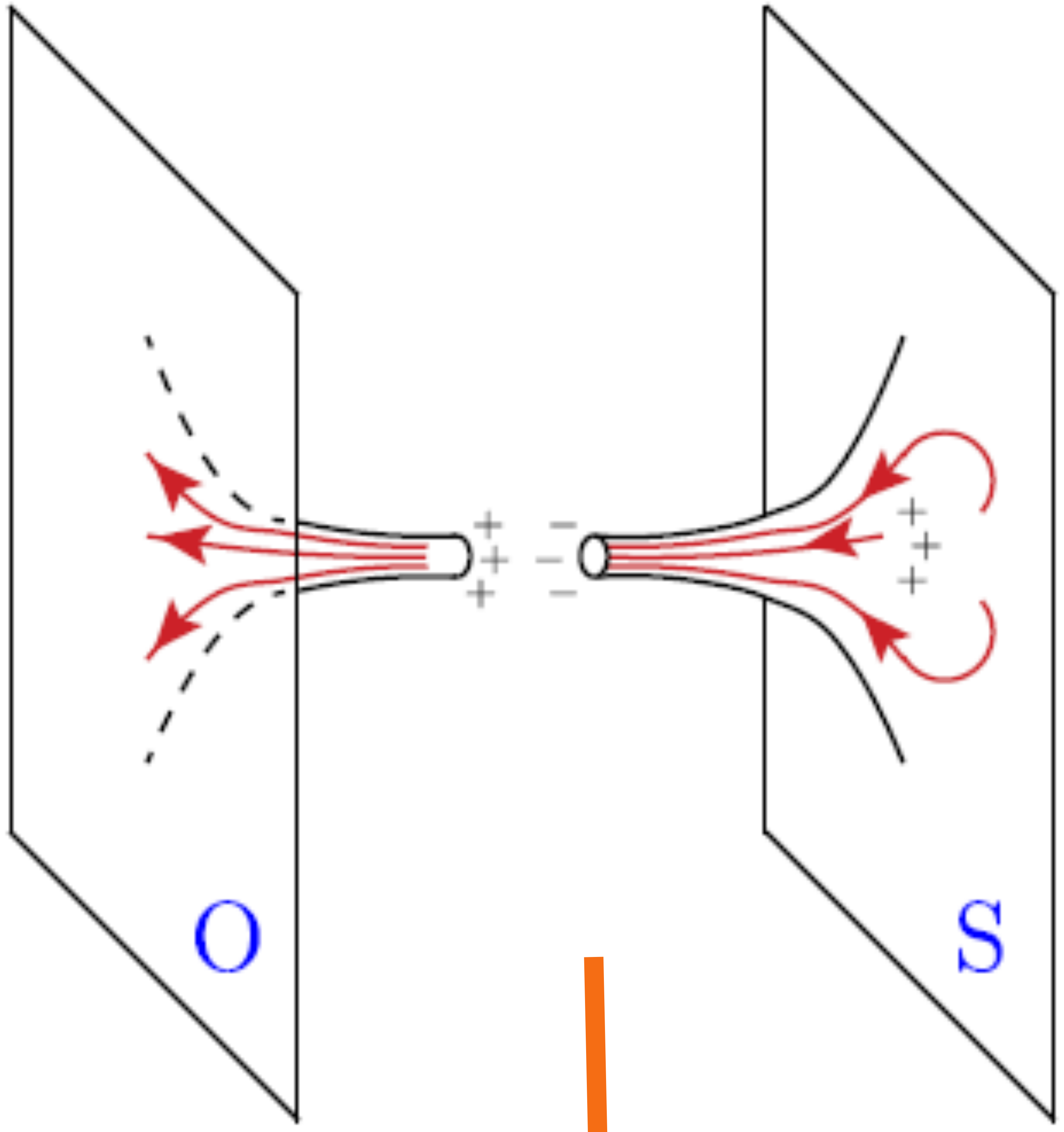
SU(2)xU(1) singlet houses the invisible axion.

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

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

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

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



Wormholes:
Gidding-Strominger,
Coleman, Cline

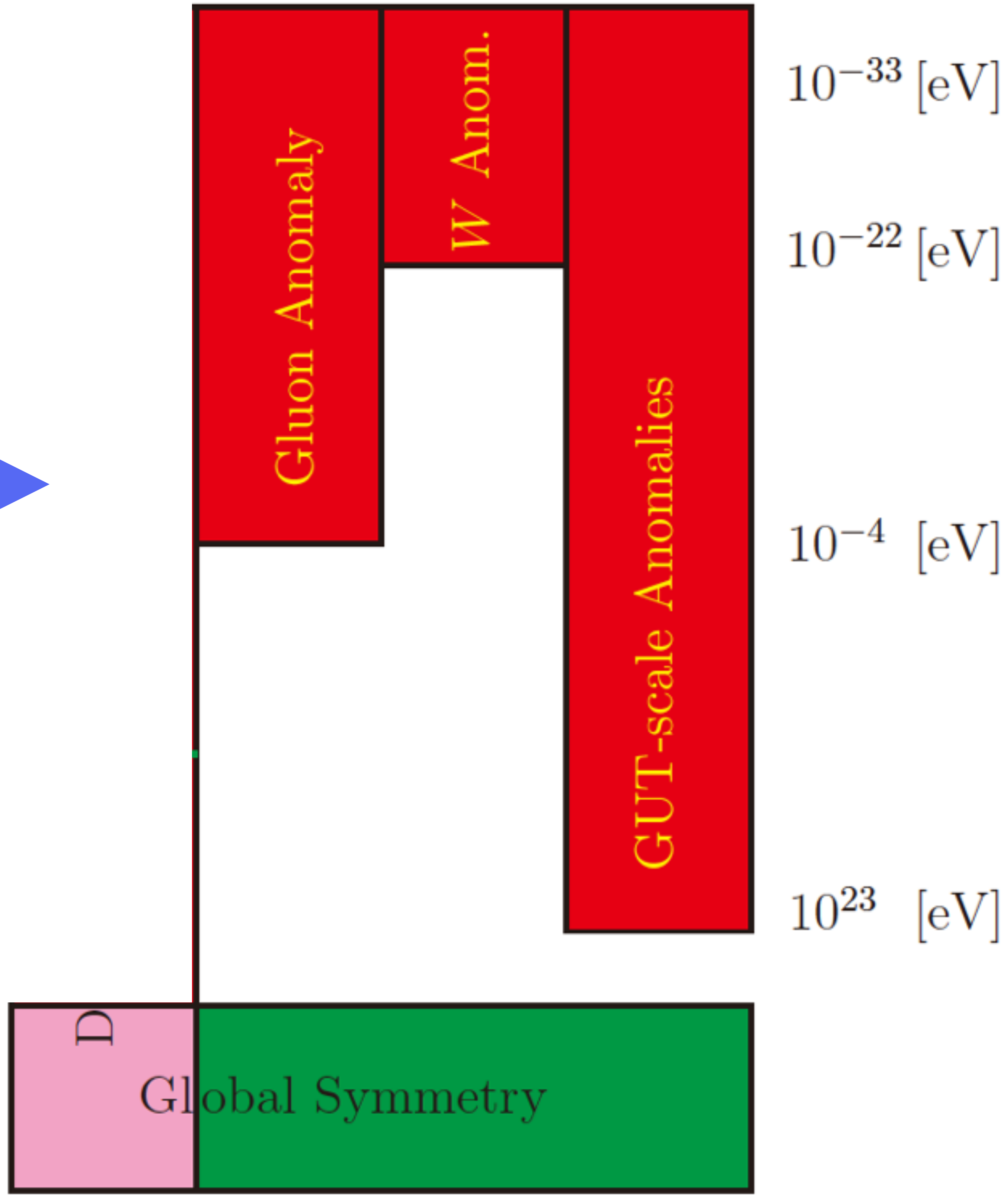
Exact global symmetries?

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

The example of acc symm.

Discrete gauge symmetry:
Krauss-Wilczek;
Ibanez-Ross

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.

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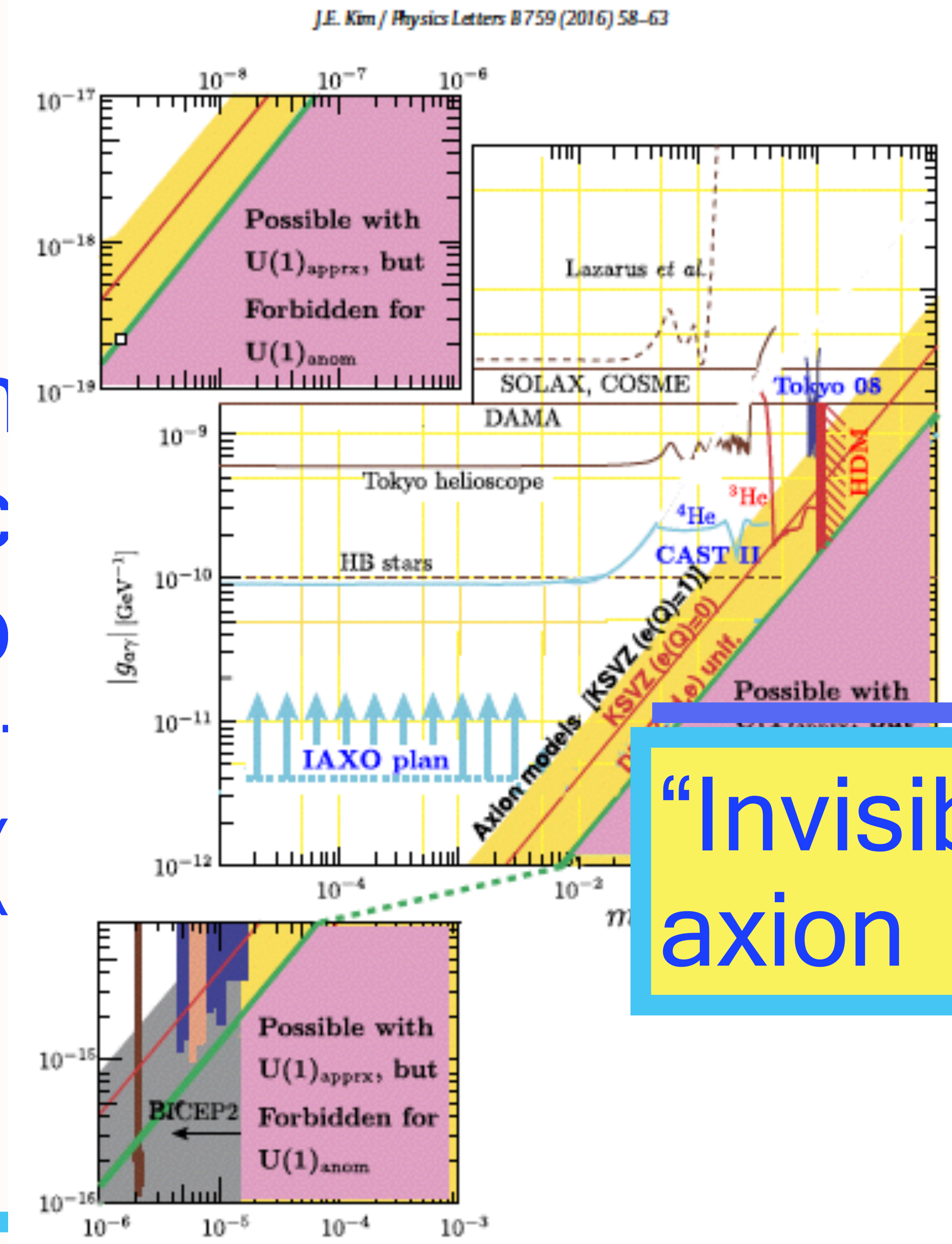
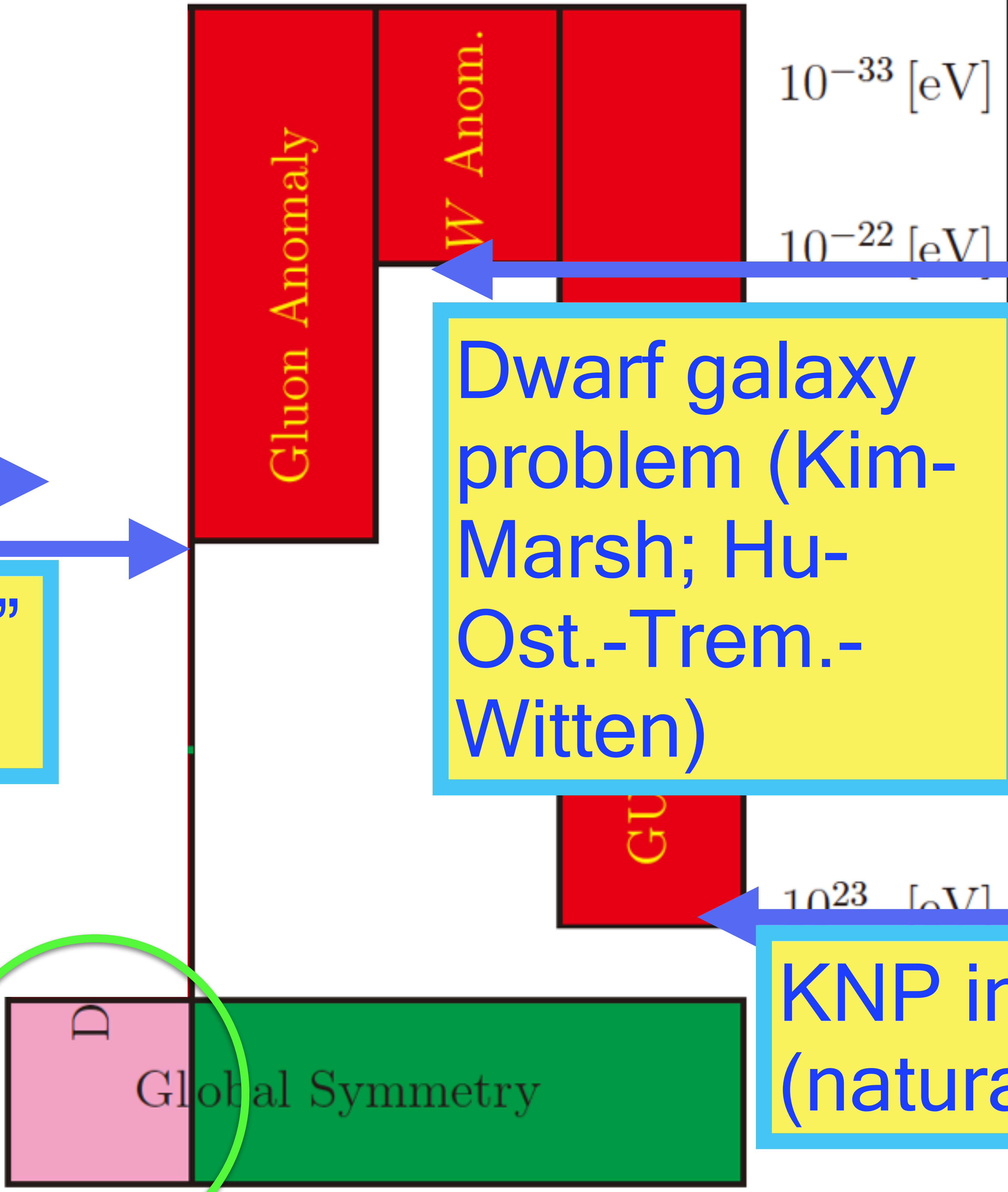
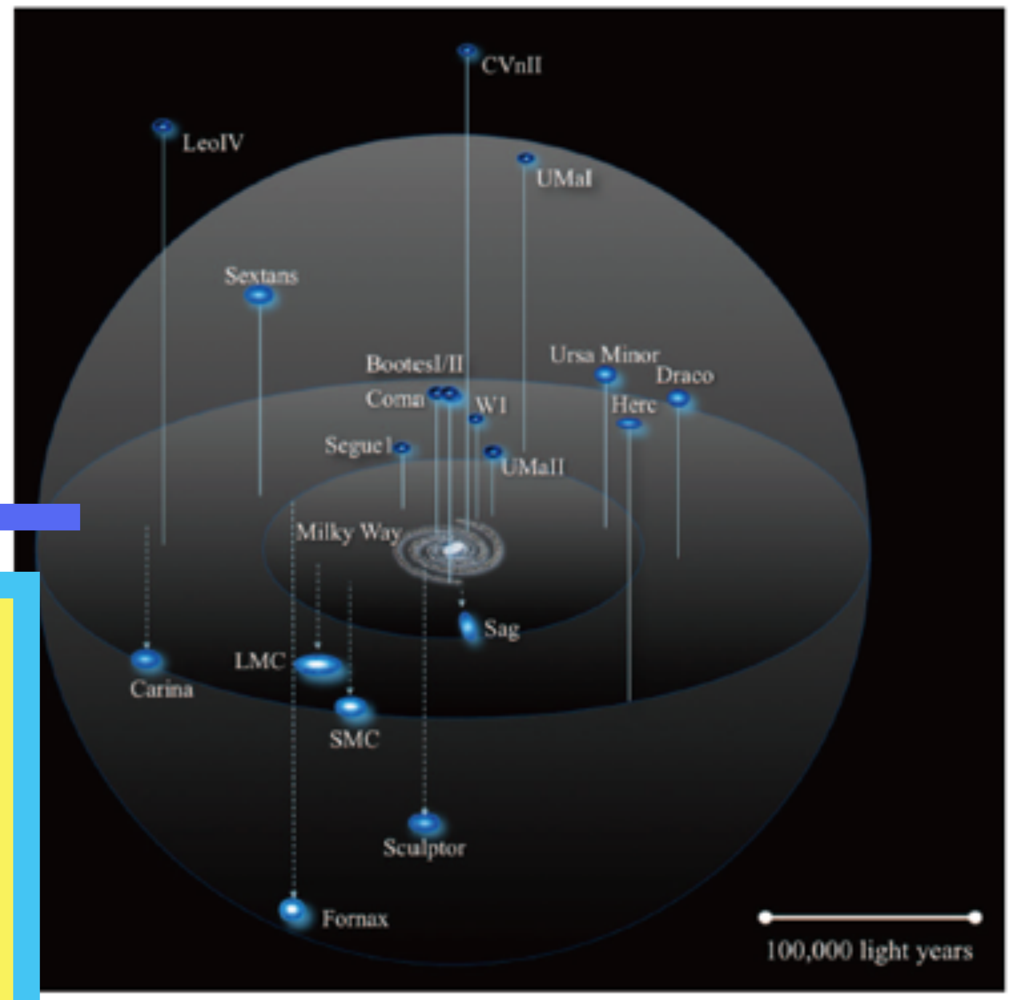


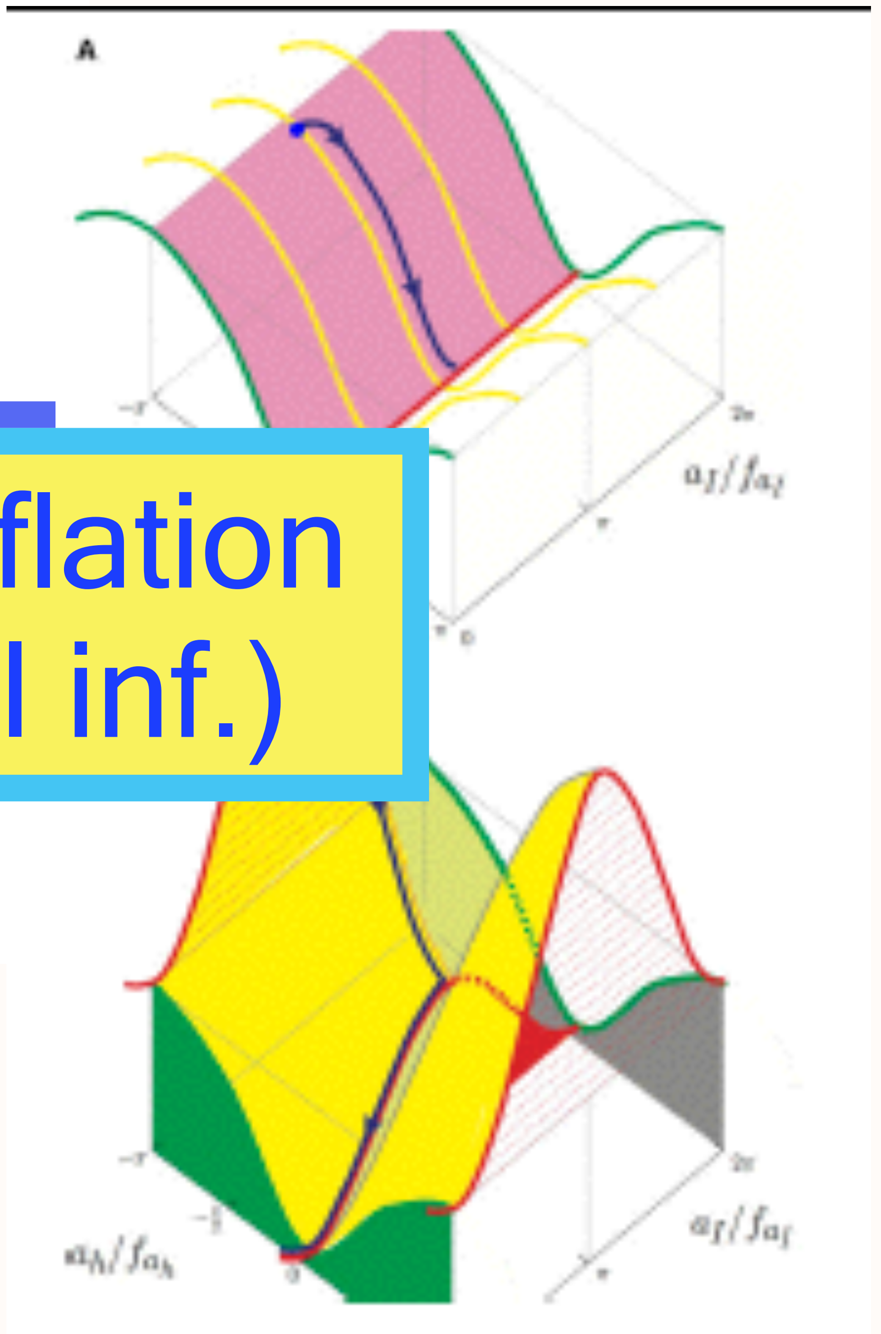
“Invisible” axion



Dwarf galaxy problem (Kim-Marsh; Hu-Ost.-Trem.-Witten)



e 2.12: An artists(J.S. Bullock, M. Geha and R. Powell) view of dw



KNP inflation (natural inf.)

The KN term is the leading one here.

Summarized by

Weinberg operator:

[13.08.1979, Received]

$$\frac{1}{M}\overbrace{\ell\ell}^{L=2}\overbrace{H_uH_u}^{L=-2}$$

gives ν mass

Kim-Nilles SUSY operator:

[24.11.1983, Received]

$$\frac{1}{M}\overbrace{S_1S_2}^{Q=2}\overbrace{H_uH_d}^{Q=-2}$$

gives TeV scale μ term

Realized in seesaw:

Minkowski [13.04.1977, Published],

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

......

$$\ell_L H_u N_R$$

Realized in string comp.:

Many papers,⋯.

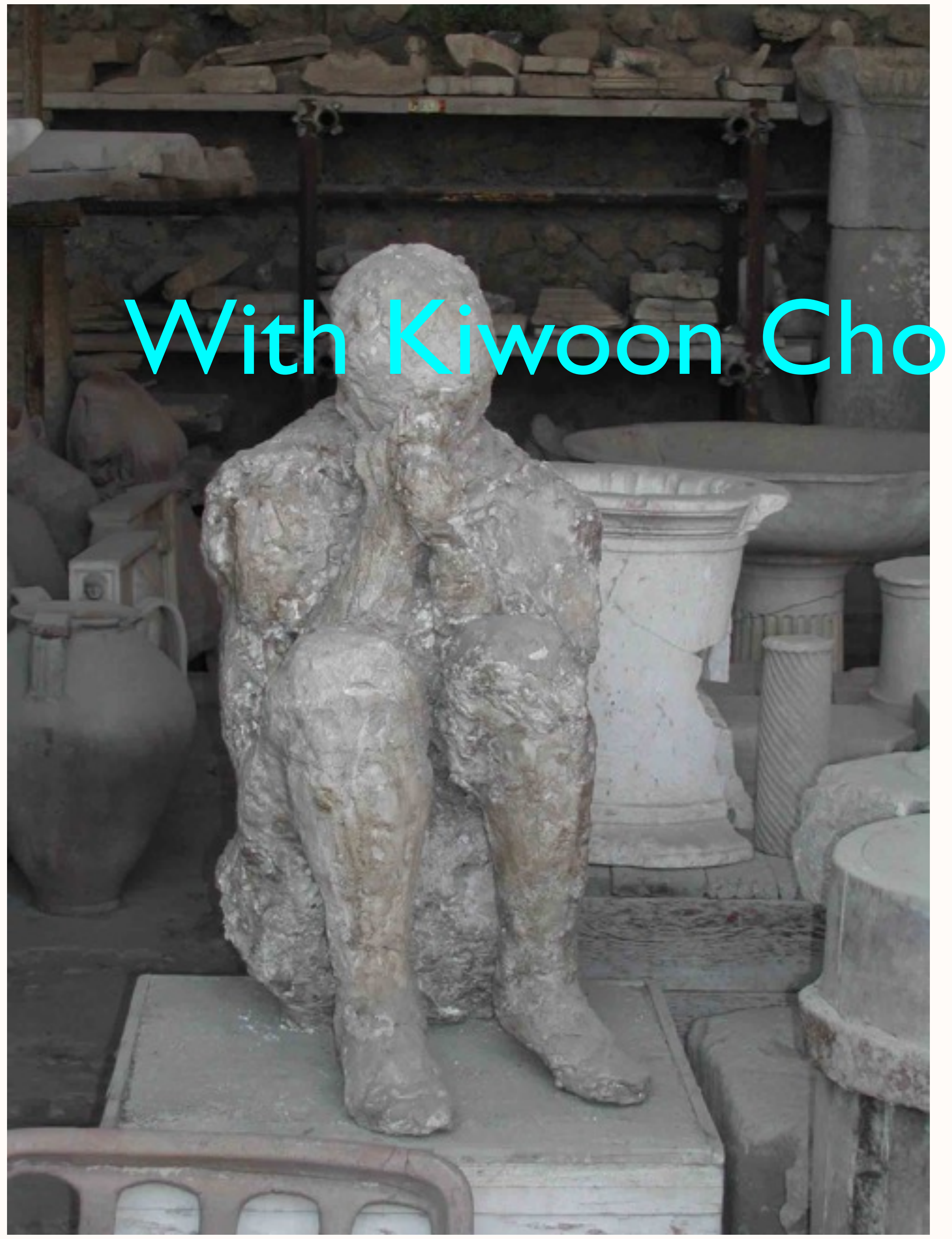
$$S_1\underset{-1}{H_u}X_{\rm doublet},\;\; S_2\underset{-1}{H_d}X'_{\rm doublet},\;\; \overset{-1/2}{\bar{Q}_L}\overset{-1/2}{Q_R}\overset{+1}{S_1},\cdots$$

After many years,

Model-independent axion (Green-Schwarz, Witten)

strikes back

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



With Kiwoon Choi

JEK, 1604.00716 [hep-ph]

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

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.

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

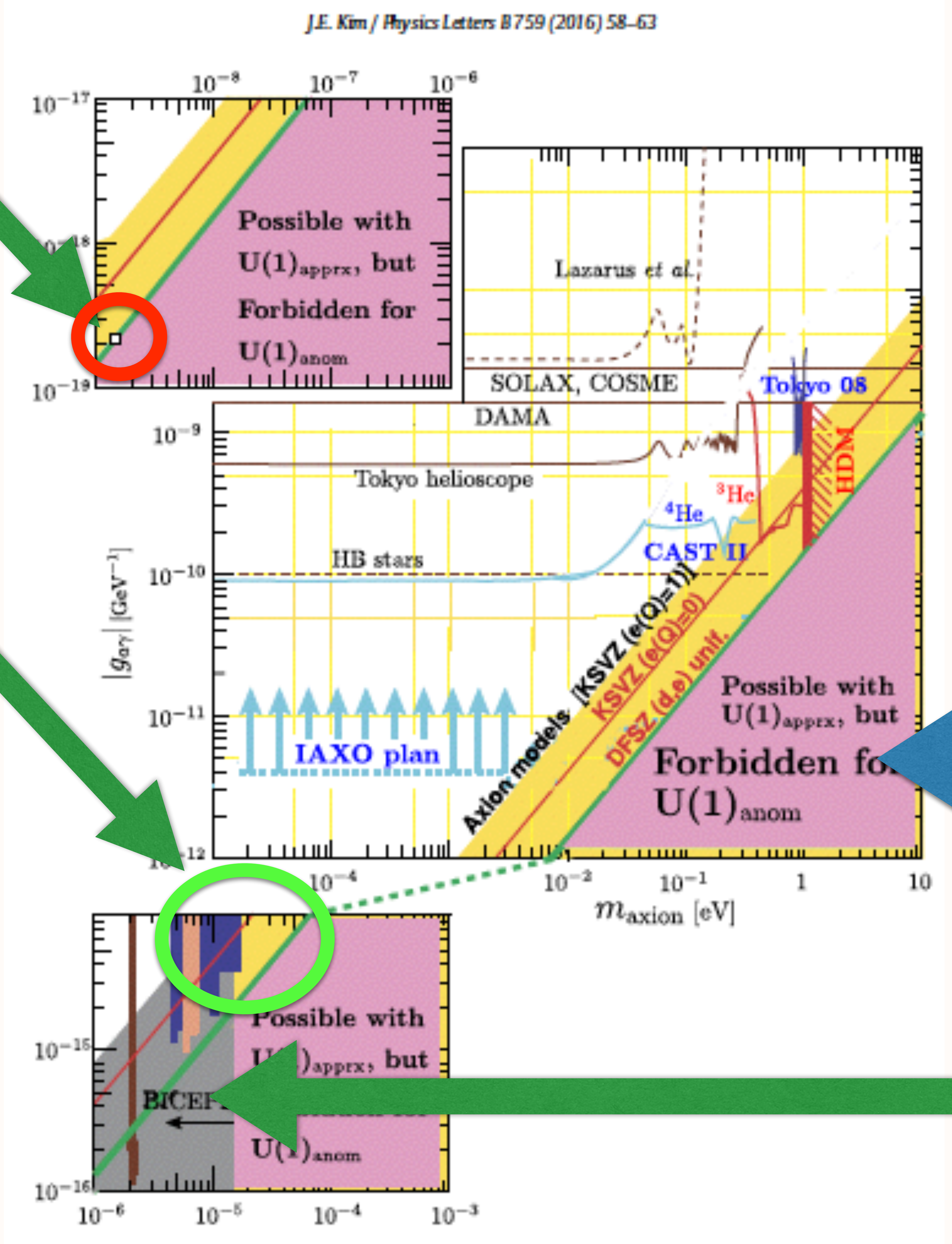
KSVZ $Q_{\rm em}$	KSVZ $c_{a\gamma\gamma}$	DFSZ x	DFSZ q^c-e_L pair	DFSZ $c_{a\gamma\gamma}$	$c_{a\gamma\gamma}$	Superstring	Superstring $c_{a\gamma\gamma}$	Comments
0	-2	any x	(d^c, e)	$\frac{2}{3}$	$\frac{2}{3}$	arXiv:1405.6175	$\frac{2}{3}$	Anomalous U(1) as $\rm U(1)_{PQ}$
$\pm\frac{1}{3}$	$-\frac{4}{3}$	any x	(u^c, e)	$-\frac{4}{3}$	$\frac{2}{3}$	hep-ph/0612107	$-\frac{1}{3}$	Approximate $\rm U(1)_{PQ}$
$\pm\frac{2}{3}$	$\frac{2}{3}$			Without	GUTs or	JEK-Nam, PLB 759,149 (16)	$\ge \frac{2}{3}$	Anomalous U(1) as $\rm U(1)_{PQ}$
± 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.

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

MI axion

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



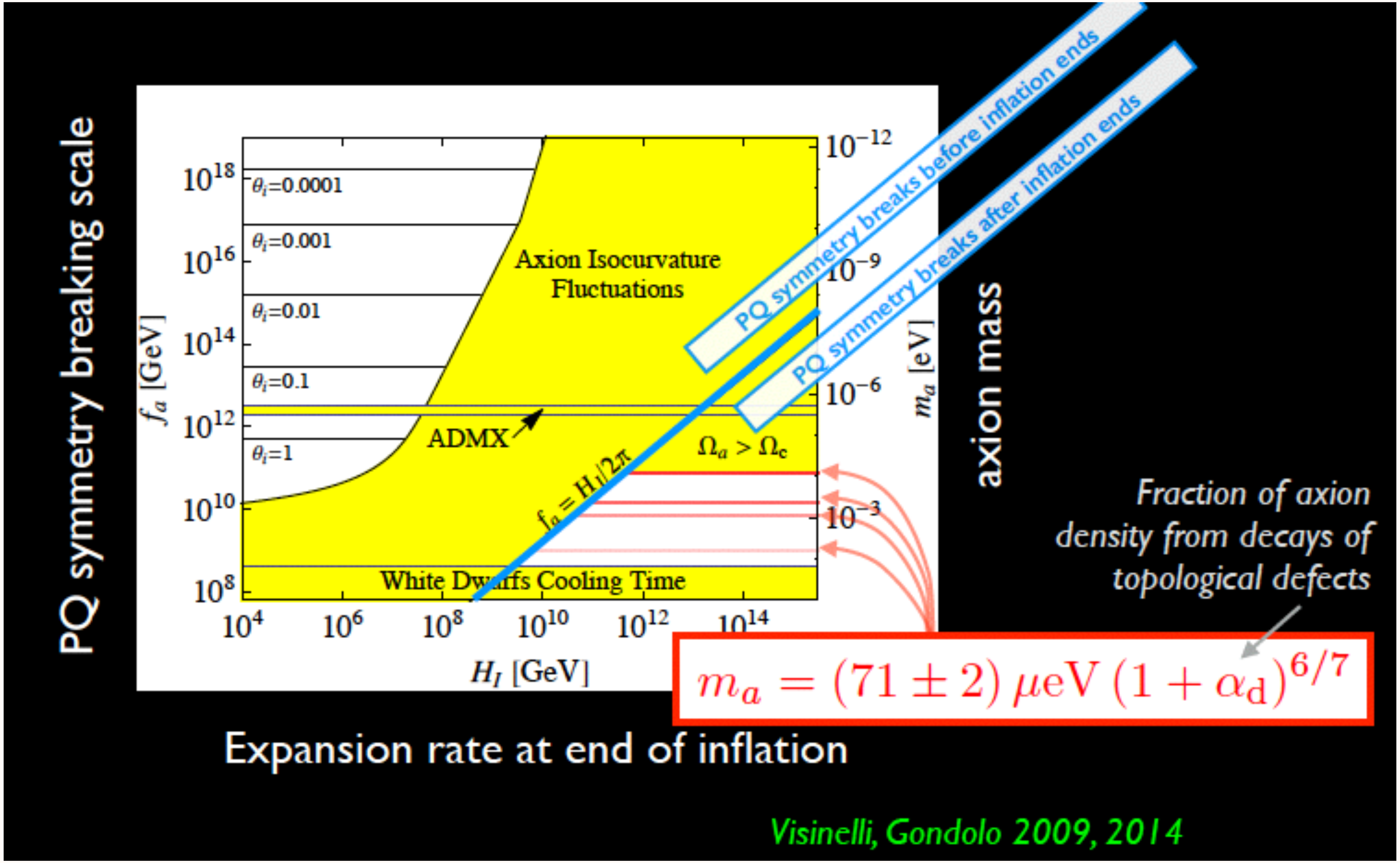
$g_{a\gamma}(= 1.57\times 10^{-10}\, c_{a\gamma\gamma})$ vs. m_a plot

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

Kim-Nam, 1603.02145[hep-ph]

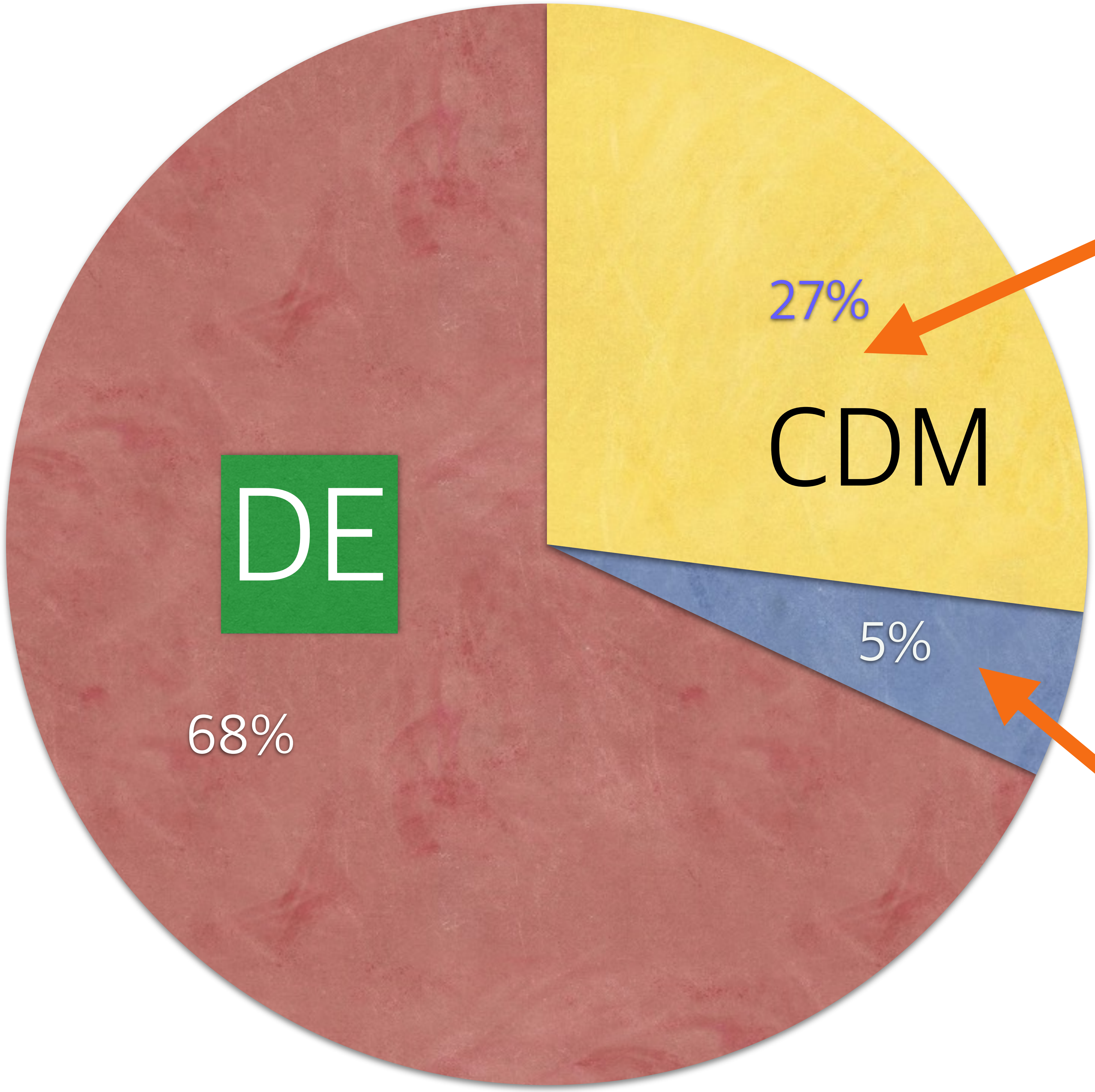
$U(1)_{anom}$ forbidden

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



PQ symmetry breaking scale
f_a [GeV]
10^{18}
10^{16}
10^{14}
10^{12}
10^{10}
10^{8}
θ_i=0.0001
θ_i=0.001
θ_i=0.01
θ_i=0.1
θ_i=1
Axion Isocurvature Fluctuations
ADMX
$f_a = H_I/2\pi$
$\Omega_a > \Omega_c$
White Dwarfs Cooling Time
10^4 10^6 10^8 10^{10} 10^{12} 10^{14}
H_I [GeV]
10^{-12}
10^{-9}
10^{-6}
10^{-3}
m_a [eV]
axion mass
PQ symmetry breaks before inflation ends
PQ symmetry breaks after inflation ends
Fraction of axion density from decays of topological defects
$m_a = (71 \pm 2)\,\mu\text{eV}\,(1 + \alpha_\text{d})^{6/7}$
Expansion rate at end of inflation
Visinelli, Gondolo 2009, 2014

6. CP and cosmology

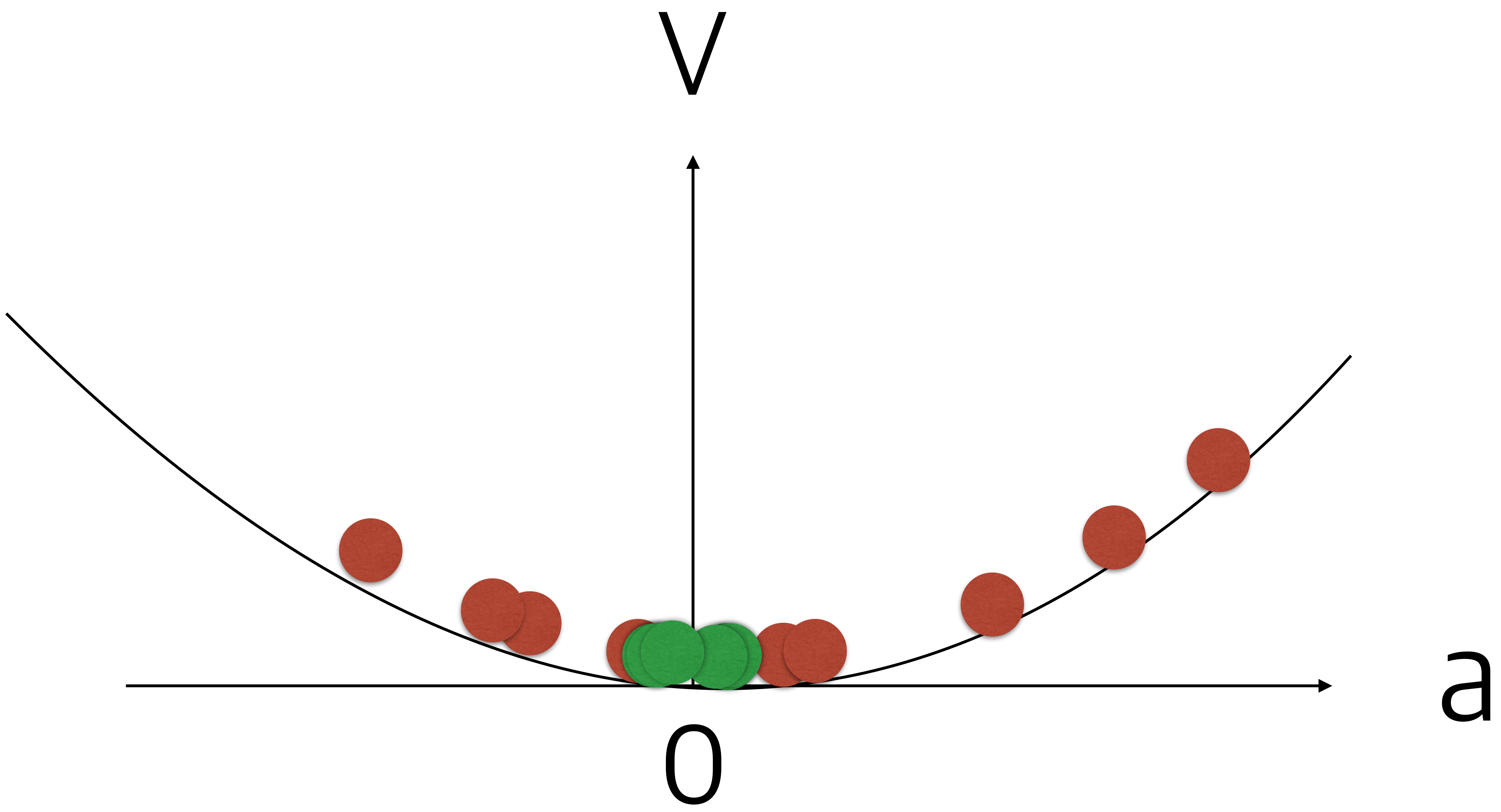


Oscillating CDM axions are oscillate around CP violating phases.

CP violation in weak interactions.

Axion energy in the Universe

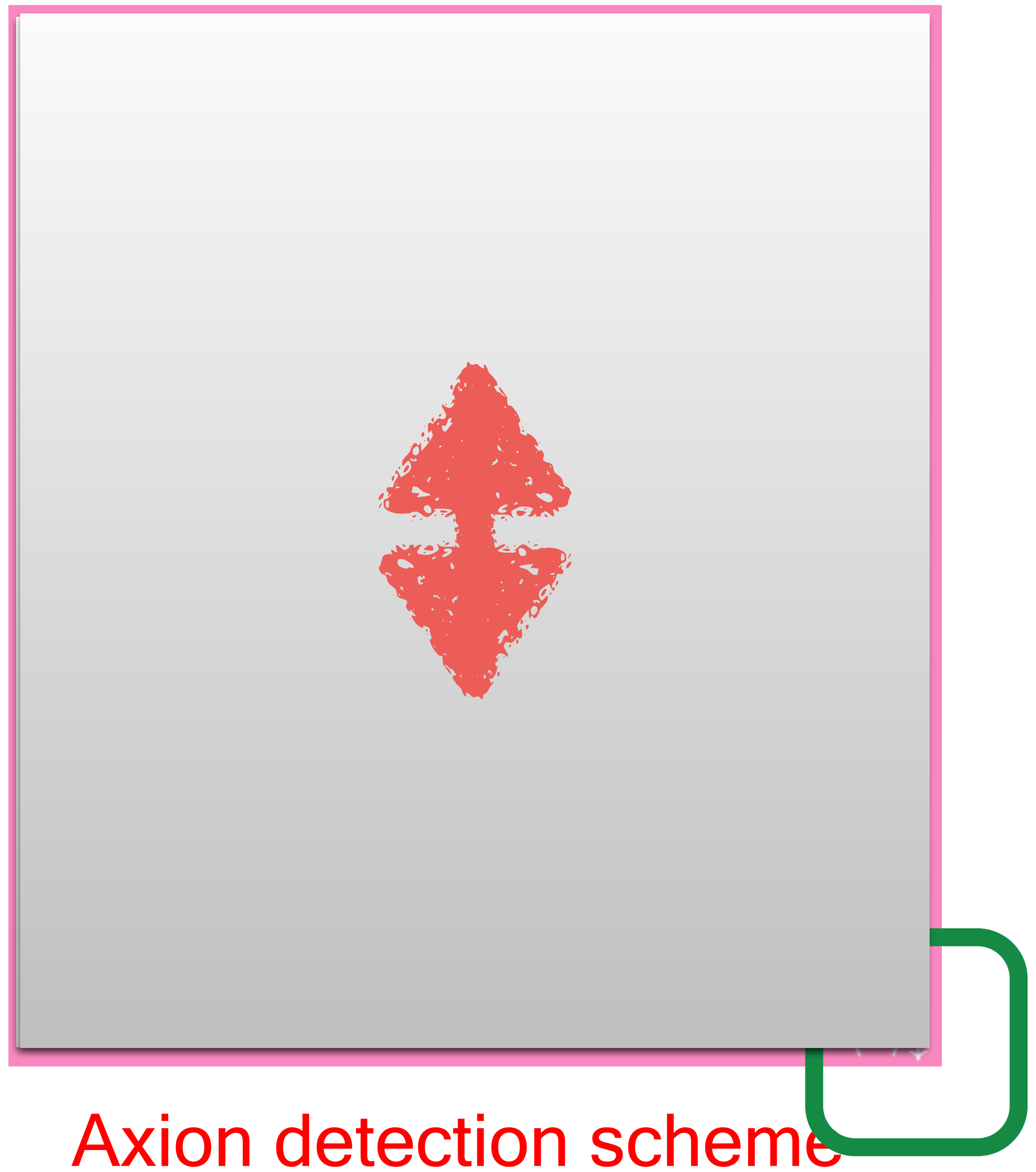
Axion solution = cosmological solution



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

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

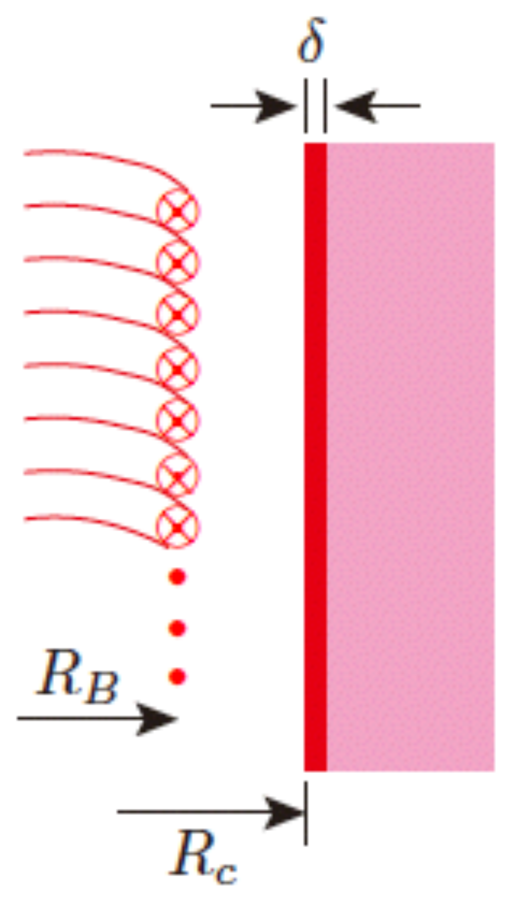
where $g_{*,\rm present} \simeq 3.91$ and γ is the entropy production ratio,



Axion detection scheme

Constant B field
E field follows the axion oscillation

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



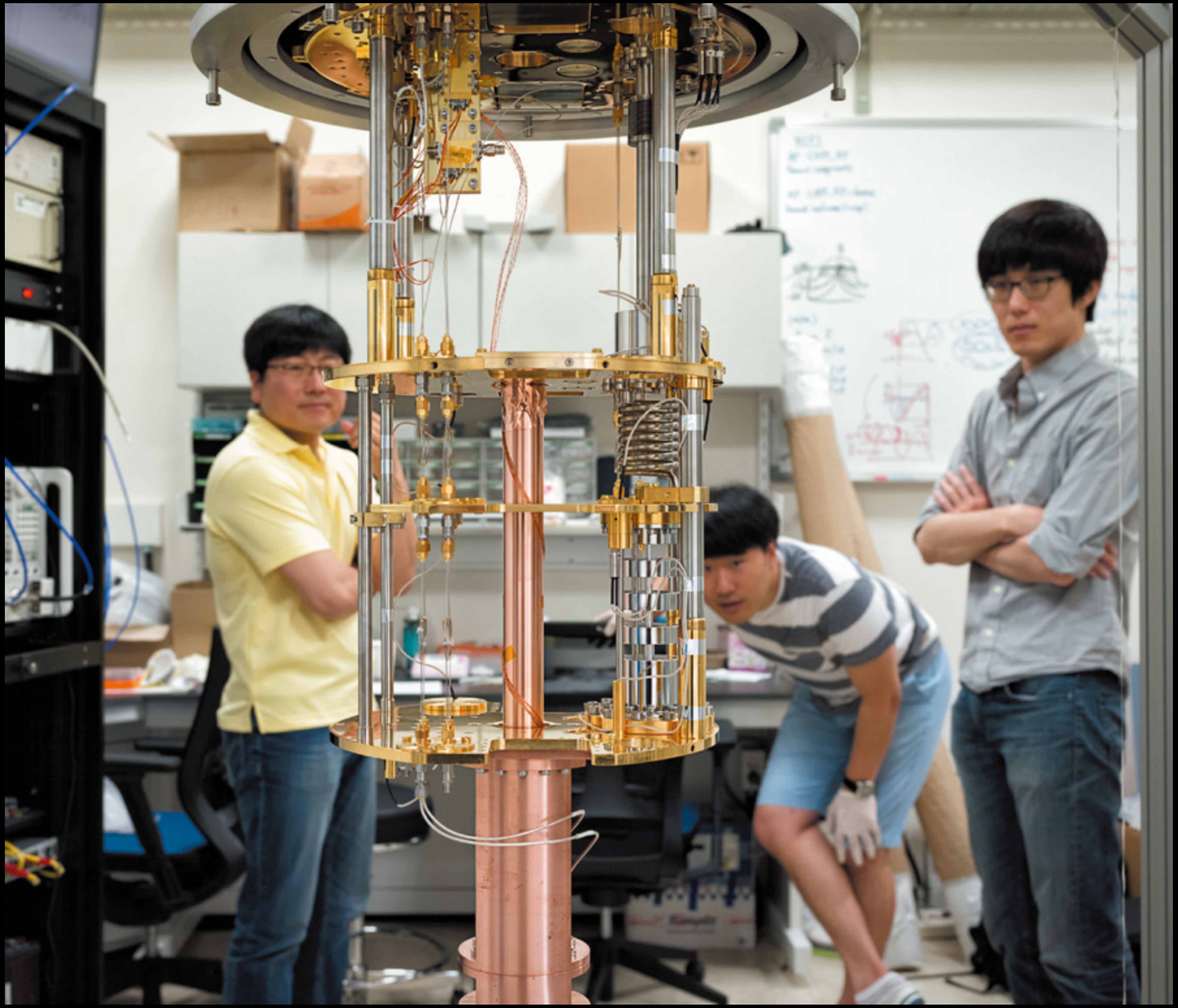
Cavity detectors:

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)



CAPP started : 2013

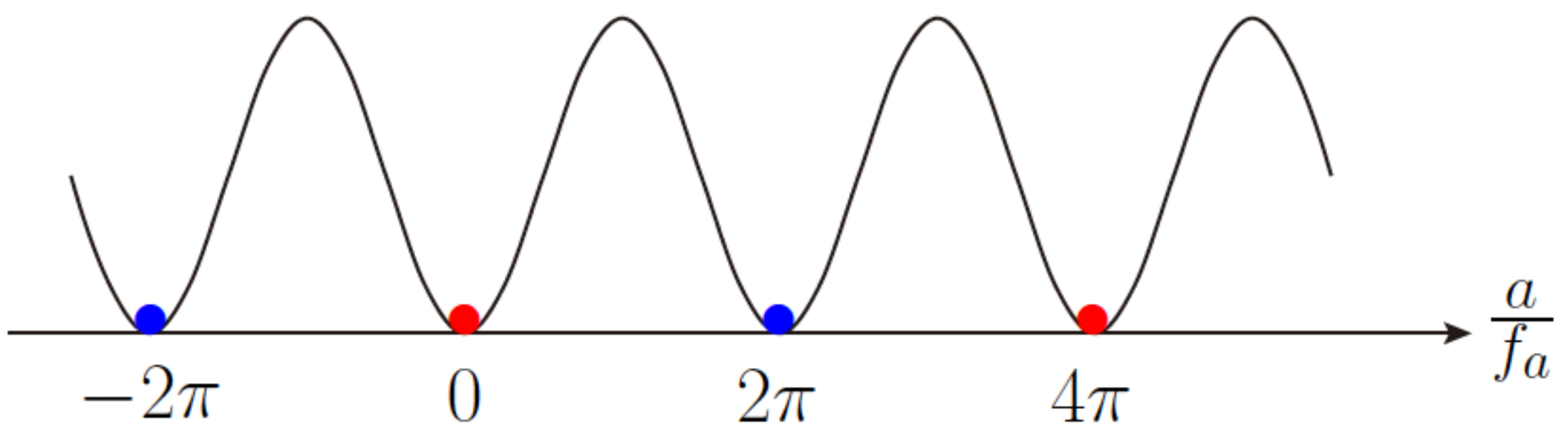
Nature Vol. 534 (June 2, 2016)

ADMX

CAPP: ???

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

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

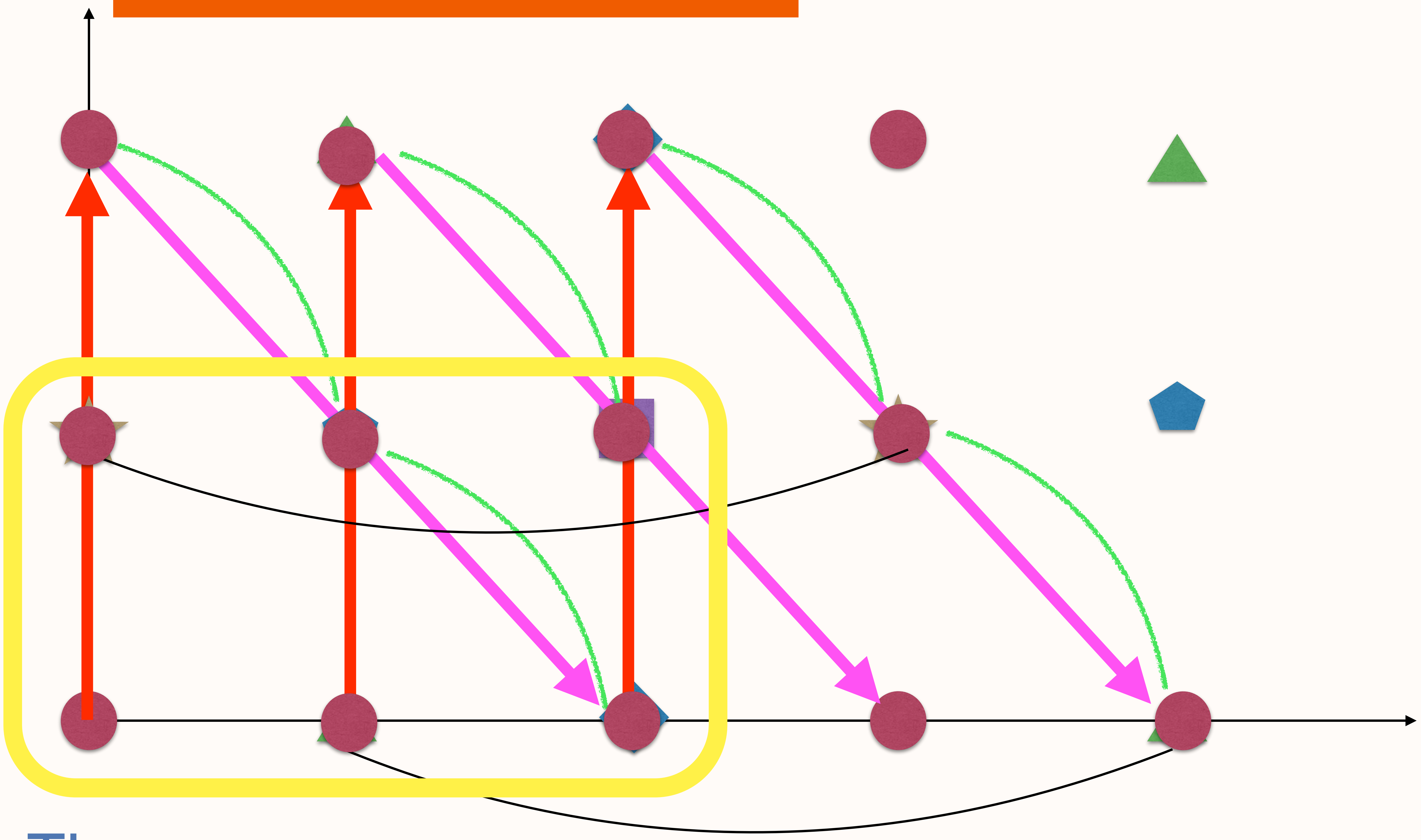
Phi returns to its original value after
a —> a+ 2 pi N fa. N is the domain-wall number.
[Sikivie (1982)]

Choi-Kim, PRL55 (1985) 2637

with two confining forces

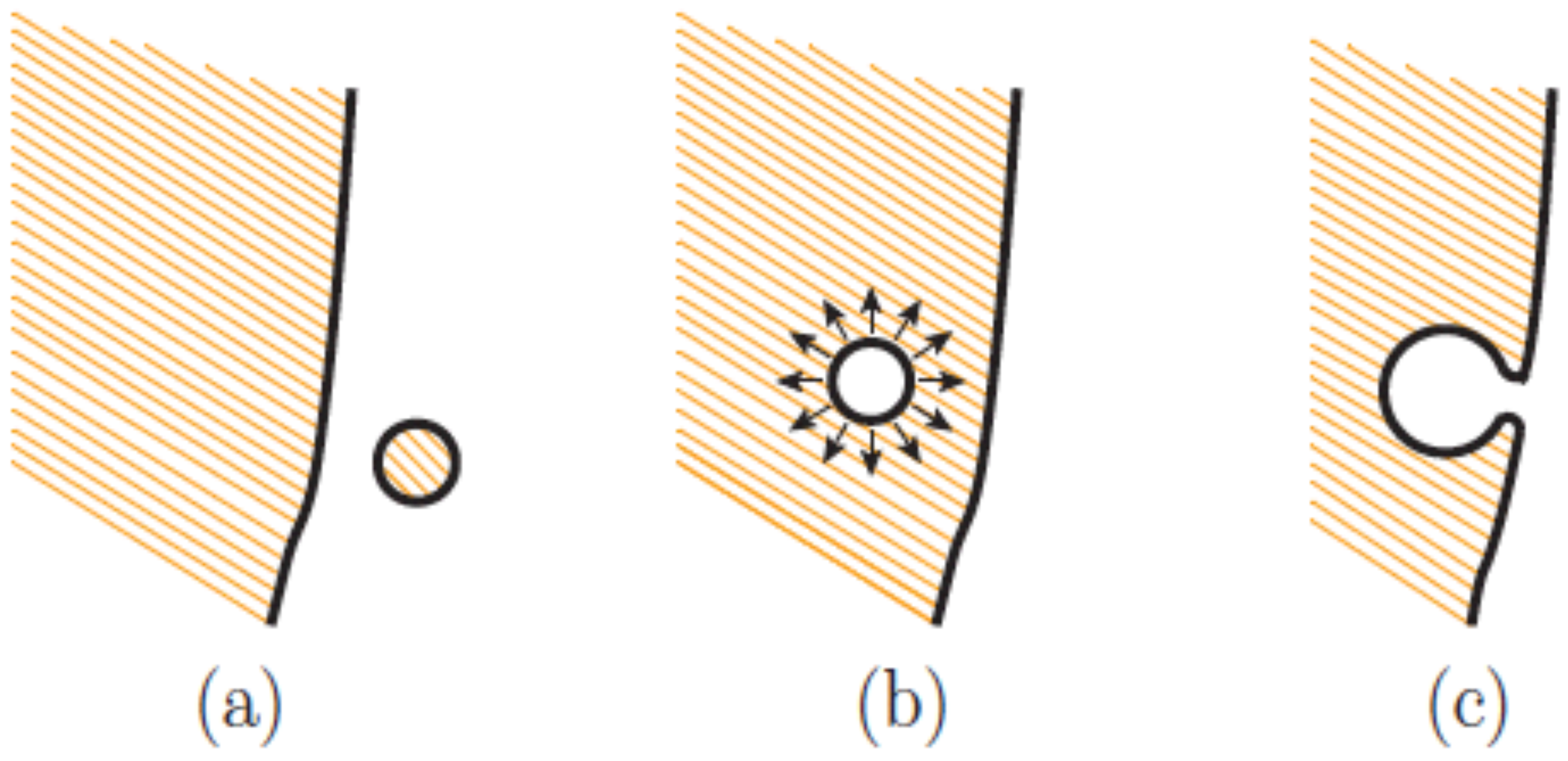
For the center of GUT group, Lazarides-Shafi (1982).
But, the following ideas are more widely applicable.

Goldstone boson direction

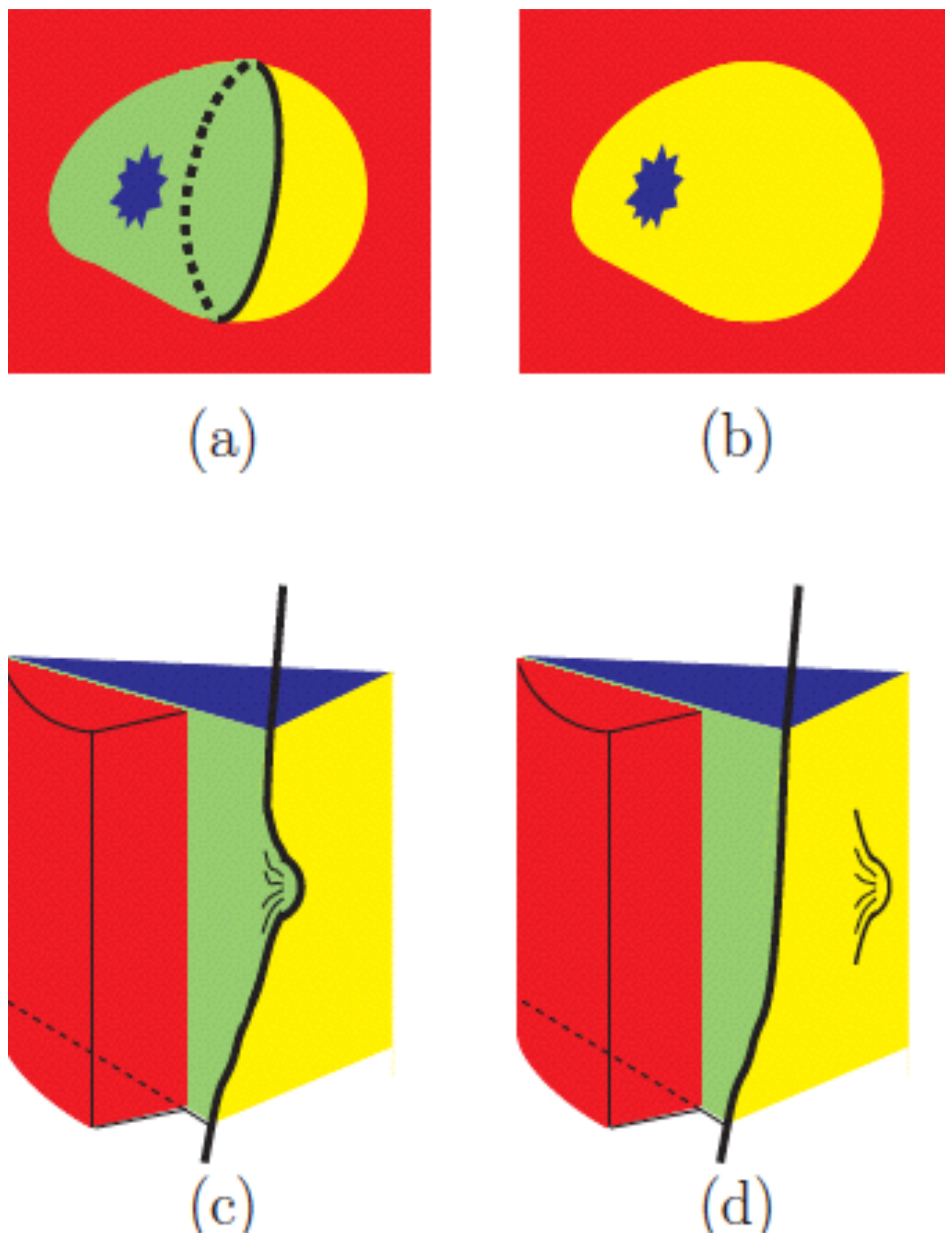


The same vacuum

Torus identification



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



Sikivie (1982)

Small string-DW are not problematic.

The horizon scale string-DW system is problematic.

Barr-Kim, PRL 113 (2014) 241301.

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 2012 number was used before

Axion abundance

when $U(1)_{PQ}$ is restored during or after inflation

Three sources:

- Strings (before DW-domination)

$$[\Omega_{\rm axion}h^2]_{\rm strings} = (1.7 \pm 0.9) \times \left(\frac{f_a}{10^{12}\mathrm{GeV}}\right)^{1.2}$$

- String-DW (after DW-domination)

$$[\Omega_{\rm axion}h^2]_{\rm DWs} = (0.9 \pm 0.3) \times \left(\frac{f_a}{10^{12}\mathrm{GeV}}\right)^{1.2}$$

- Coherent oscillation

$$[\Omega_{\rm axion}h^2]_{\rm osc} = 1.1 \times \left(\frac{f_a}{10^{12}\mathrm{GeV}}\right)^{1.2}$$

→ **Contributions of defects are dominant**

Constraint on axion decay constant: $f_a \lesssim (4.6 - 7.2) \times 10^{10}\mathrm{GeV}$

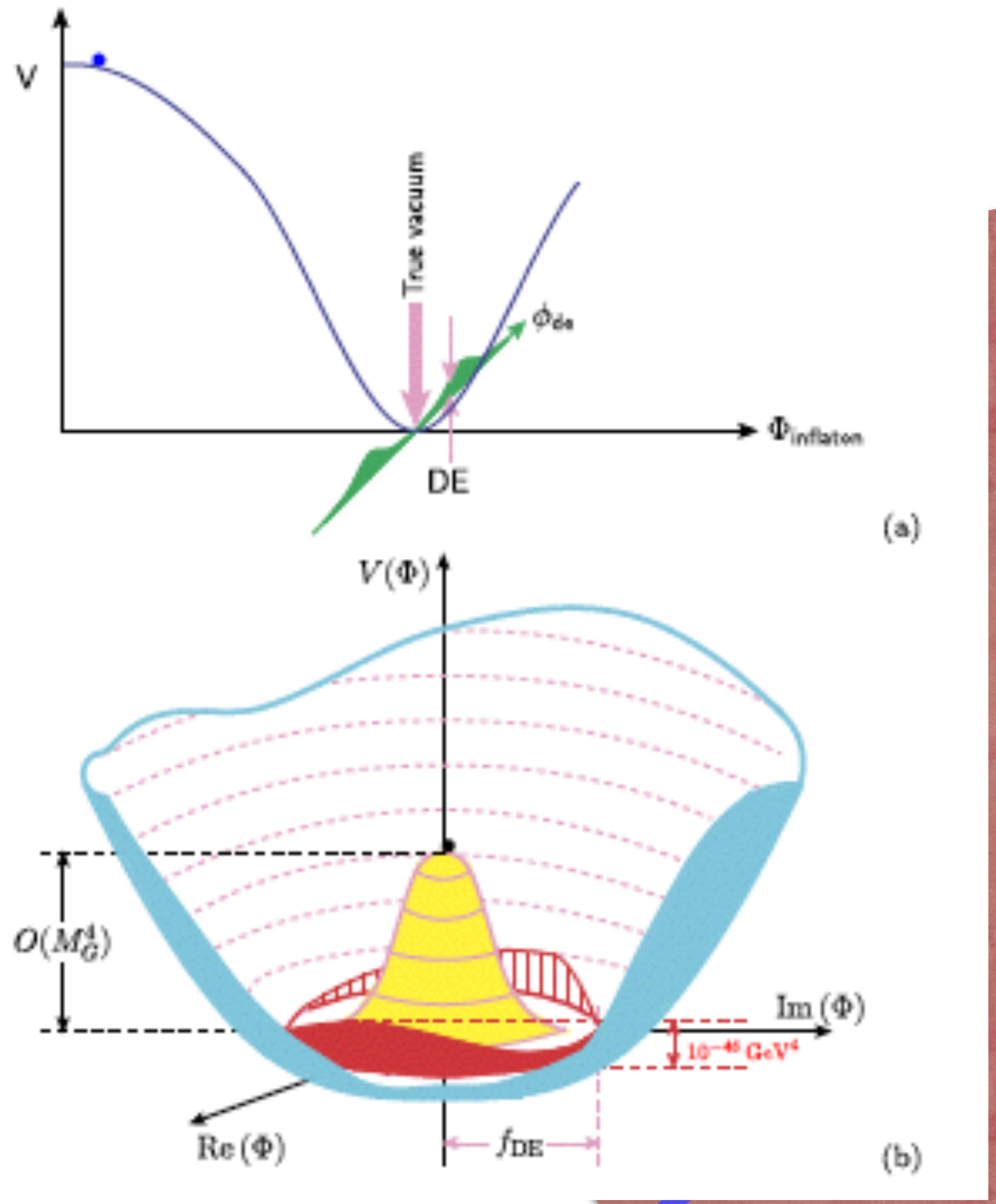
T. Sekiguchi et al, talk presented at CosPA 2016, Sydney

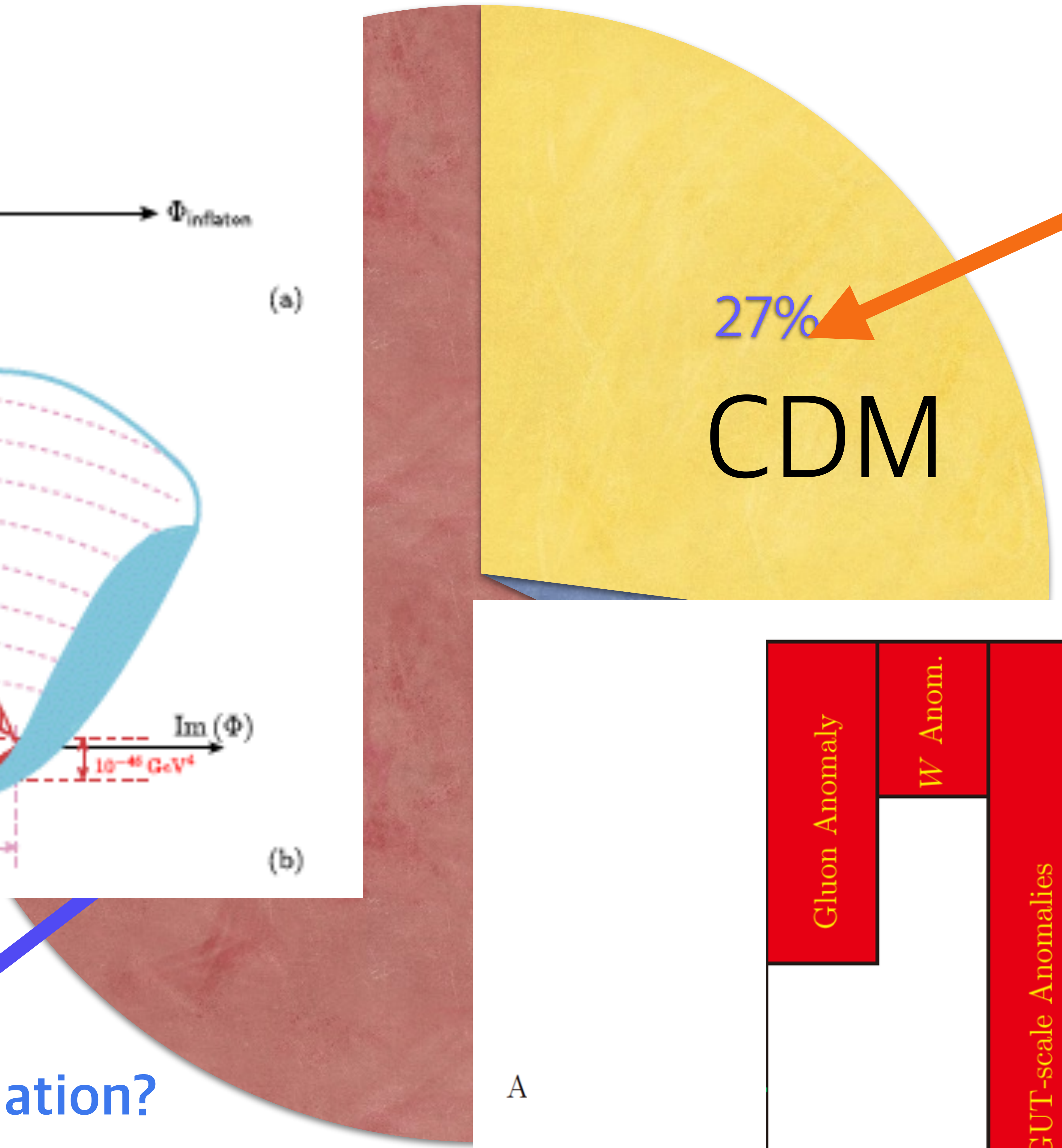
Closer to the Florida estimate

$m_a \sim 10^{-4\text{-}5}$ eV

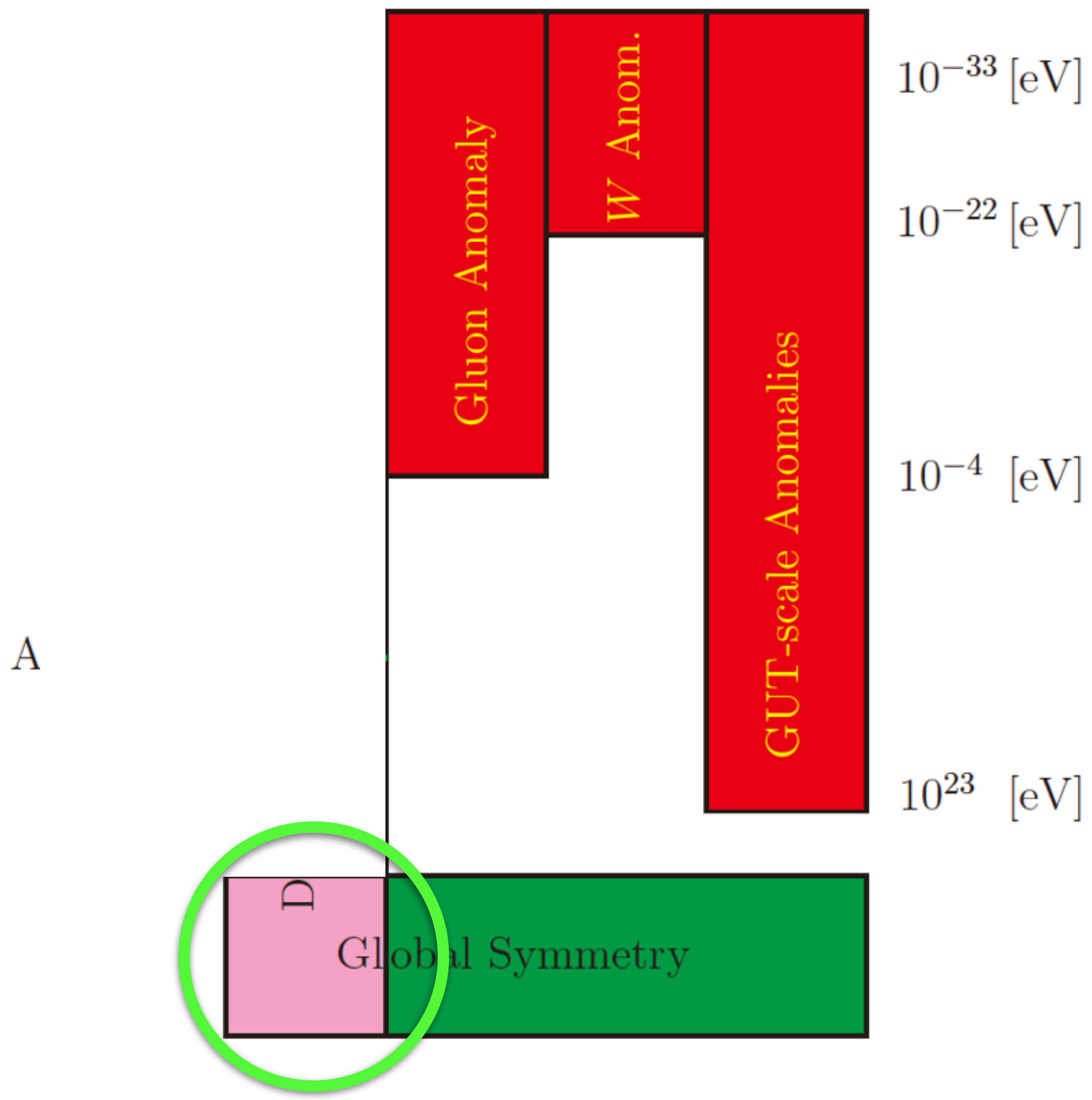
7. Type-II leptogenesis

Covi, Kim, Kyae, Nam:
1601.00411v3





Oscillating CDM axions are oscillate around CP violating phases.



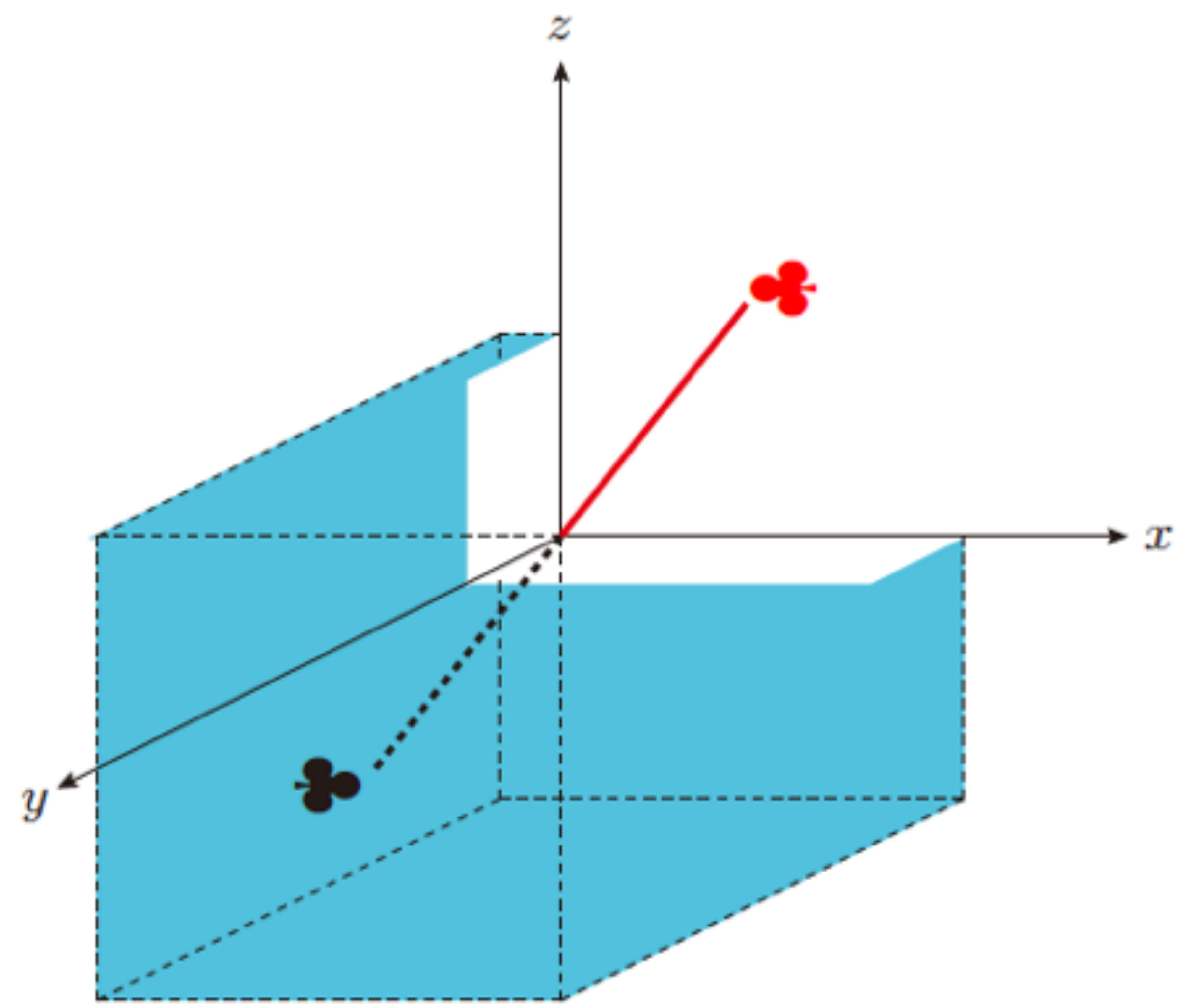
iolation in weak
ractions.

Is DE also
related to CP violation?

Quintessential axion: Kim-Nilles,
[hep-ph/0210402],
[arXiv:1311.0012[hep-ph]]

Sakharov conditions for B generation:

1. B number violation
2. CP and C violation
3. Out of thermal equilibrium



For 3, we just make sure that the process proceeds in non-equilibrium conditions. If it is a decay, almost surely the condition 3 is satisfied.

Sphaleron processes at electroweak scale changes B and L numbers but no change of (B-L).

If generation of B at GUT scale accompanies L such that creation of (B-L)=0, then we end up most probably B=0 after the effective sphaleron processes. B and L generation processes at high temperature must occur through processes which generate nonzero (B-L).

SU(5) is not working.

GUT: Use (B-L) breaking interaction in SO(10) for B and L generation processes.

SU(3)xSU(2)xU(1): Just use N at high energy scale.

Type-I leptogenesis:

Neutrino mass summarized by **Weinberg operator:**

L=2

L=-2

$$\frac{1}{M}\ell\ell H_u H_u$$

gives ν mass

Realized in seesaw with renormalizable terms:

Minkowski, Yanagida……

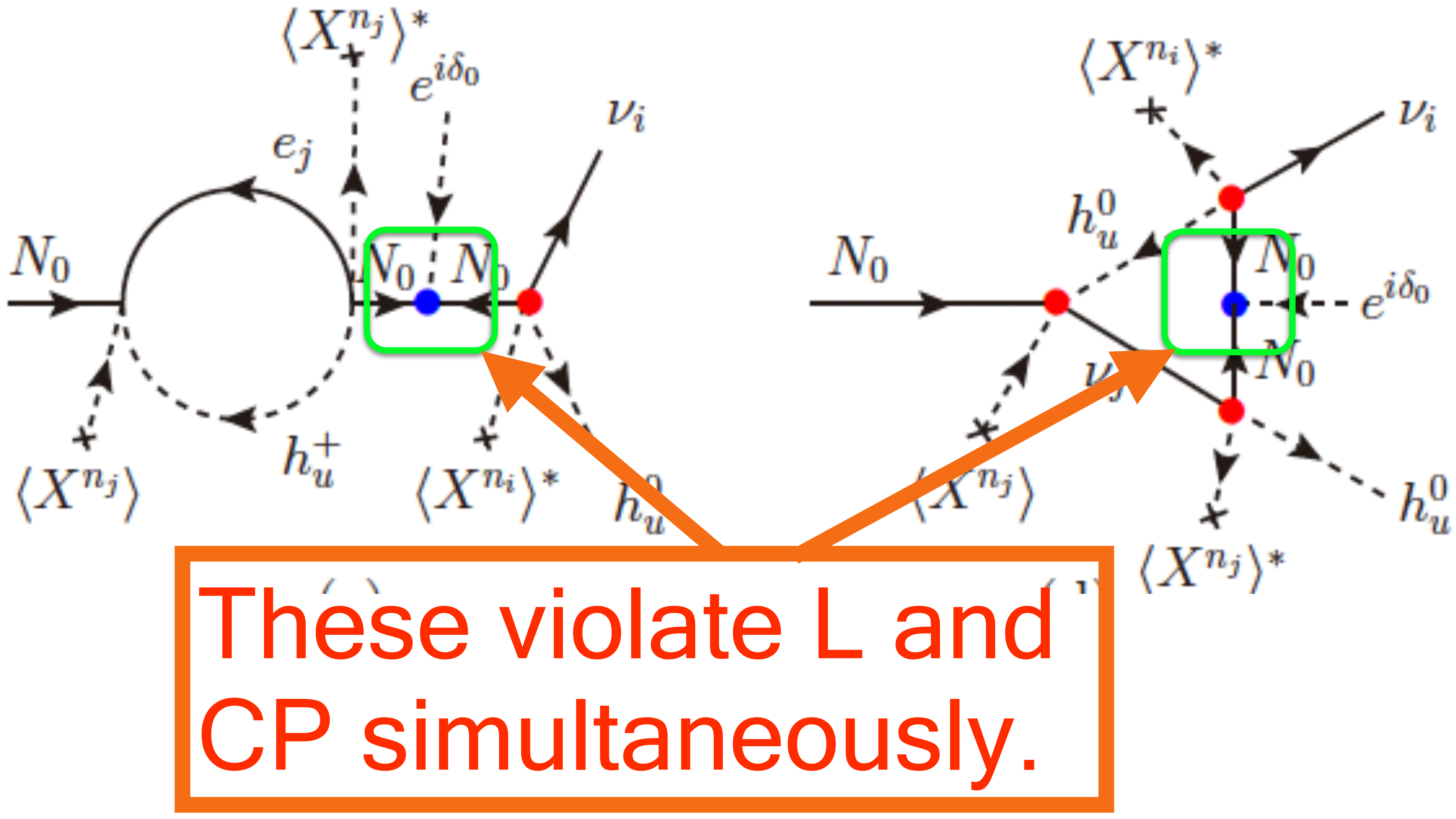
L=+1 L=0 L=-1

$$\ell_L H_u N_R$$

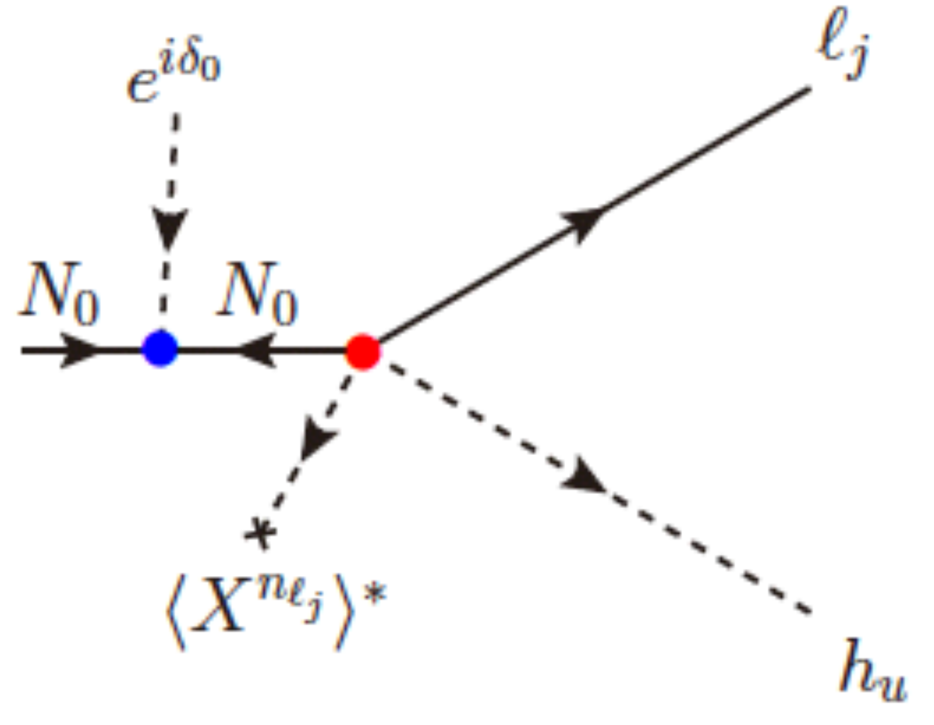
L=+1 L=-1 L=0

Who cares about renormalizable terms very importantly at low energy?

In cosmology, however, it is important. Not to worry about L number of Higgs doublets, we choose the first one. It is a first guess. It leads to the Type-I leptogenesis.



With only one N, phase can be zero. At least two heavy neutrinos are needed.



Definition of lepton numbers:

H_u	L=-2
H_d	L=+2
N	L=-1
$\mathcal{N}$	L=+1
h_u	L=0

L=+1 L=+1

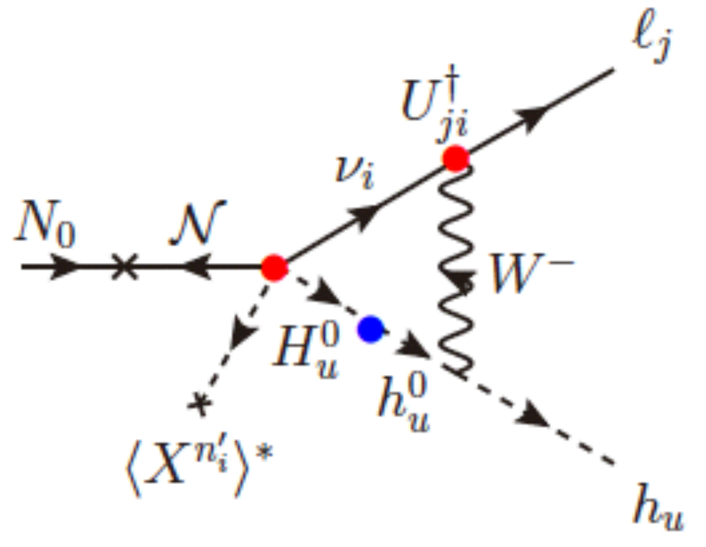
$$f N_1 h_u \ell_L , \qquad \tilde{f} \mathcal{N}_1 H_u \ell_L$$

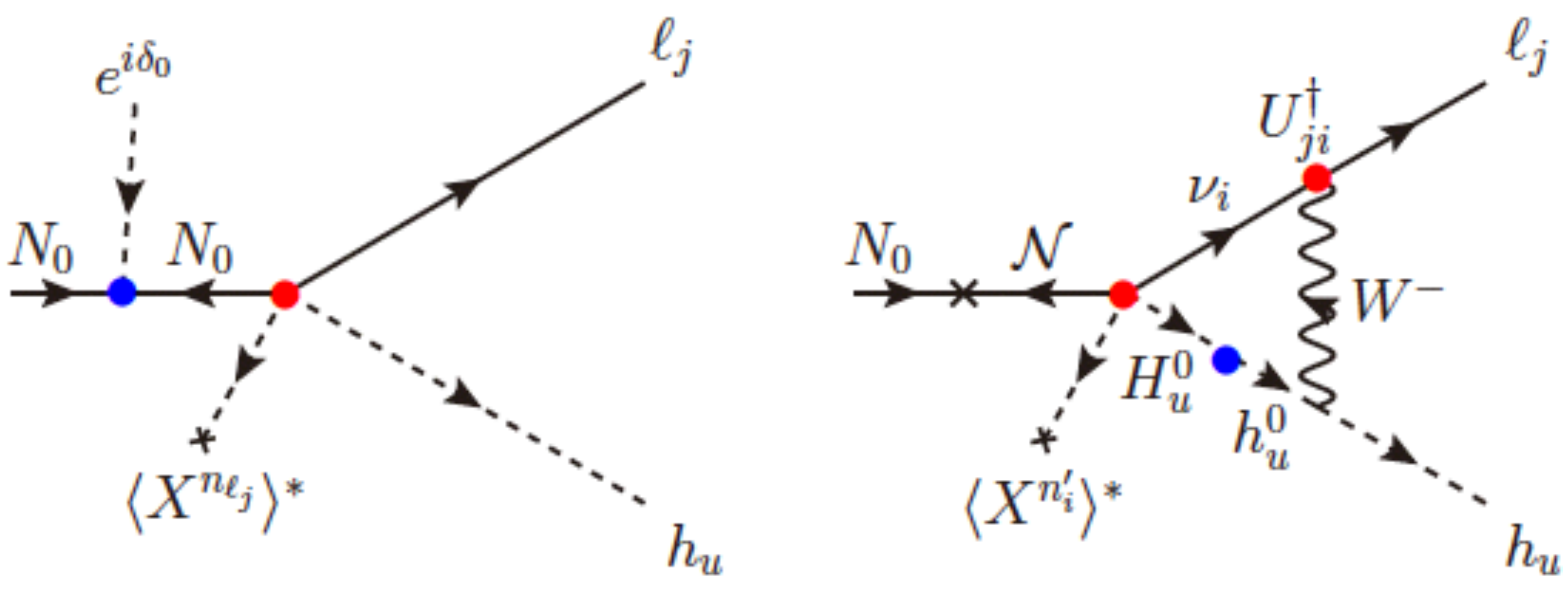
$$\Delta m_0\, N_1 \mathcal{N}_1 + \mu_H^2 H_u H_d + \text{H.c.}$$

These conserve L.

$$\Delta\mathcal{L} \ni \mu'^2 h_u^* H_u + m_0'\, N_1 N_1 + m_0''\, \mathcal{N}_1 \mathcal{N}_1 + \text{h.c.}$$

This violate L .





Different Higgs doublets needed. Anyway, these are the fields at high energy scale.

In models with SU(2)xU(1) breaking at high temperature, this kind of leptogenesis is present.
[Mohapatra-Senjanovic in non-SUSY models; also in SUSY models]

Sphaleron processes might enter into equilibrium for [D'Onofrio+, 1404.3565]

$$\Gamma_{\rm sph}^{\rm broken} = \kappa\alpha_W^4 T^4 \left(\frac{4\pi v}{g_W T}\right)^7 e^{-\frac{E_{\rm sph}}{T}}$$

E_{sph}=1.524 v / g_W. So, until T is lowered to T*=131.7 GeV,

$$\frac{\Gamma_{\rm sph}^{\rm broken}}{T^3 H(T)} = \kappa\alpha_W^4 \left(\frac{4\pi k}{g_W}\right)^7 e^{-1.52k\frac{4\pi}{g_W}} \sqrt{\frac{90}{\pi^2 g_*}}\frac{M_P}{T} \geq 1$$

$$U = \begin{pmatrix} c_1 & s_1 c_3 & s_1 s_3 \\ -c_2 s_1 & e^{-i\delta_{\text{PMNS}}} s_2 s_3 + c_1 c_2 c_3 & -e^{-i\delta_{\text{PMNS}}} s_2 c_3 + c_1 c_2 s_3 \\ -e^{i\delta_{\text{PMNS}}} s_1 s_2 & -c_2 s_3 + c_1 s_2 c_3 e^{i\delta_{\text{PMNS}}} & c_2 c_3 + c_1 s_2 s_3 e^{i\delta_{\text{PMNS}}} \end{pmatrix}_{\text{KS}} \begin{pmatrix} e^{i\delta_a} & 0 & 0 \\ 0 & e^{i\delta_b} & 0 \\ 0 & 0 & e^{i\delta_c} \end{pmatrix}_{\text{Maj}}$$

$$\epsilon_{\text{L}}^{N_0}(W) \approx \frac{\alpha_{\text{em}}}{2\sqrt{2}\sin^2\theta_W} \frac{\Delta m_h^2}{m_0^2} \sum_{i,j} \mathcal{A}_{ij} \sin[(\pm n_P + n' - n_i + n_j)\delta_{\text{X}}]$$

$$\delta_{\text{PMNS}} = n_P \delta_{\text{X}} \text{ and } \delta_a = n_a \delta_{\text{X}},$$

$$\sin[\delta_{\text{PMNS}} + \delta_a - (n_1 - n_3)\delta_{\text{X}}].$$

For $\epsilon_L \simeq 6 \times 10^{-6}$

we need [1601.00411]:

$$c_2 c_3 \sin\delta_c + c_1 s_2 s_3 \sin(\delta_c + \delta_{PMNS}) \simeq 2.4 \times 10^{-2}$$

Conclusion

1. CP violation may influence at all stages of the Universe evolution.
2. J is given in a simple form.
3. ”Invisible” axions.
4. Type-II leptogenesis: $\text{delta}_{\text{PMNS}}$ is related to the leptogenesis phase. Need certain CP violation models with SU(2)xU(1) breaking at high temperature.

$$U = \begin{pmatrix} c_1 & s_1 c_3 & s_1 s_3 \\ -c_2 s_1 & e^{-i\delta_{\mathrm{PMNS}}} s_2 s_3 + c_1 c_2 c_3 & -e^{-i\delta_{\mathrm{PMNS}}} s_2 c_3 + c_1 c_2 s_3 \\ -e^{i\delta_{\mathrm{PMNS}}} s_1 s_2 & -c_2 s_3 + c_1 s_2 c_3 e^{i\delta_{\mathrm{PMNS}}} & c_2 c_3 + c_1 s_2 s_3 e^{i\delta_{\mathrm{PMNS}}} \end{pmatrix}_{\mathrm{KS}} \begin{pmatrix} e^{i\delta_a} & 0 & 0 \\ 0 & e^{i\delta_b} & 0 \\ 0 & 0 & e^{i\delta_c} \end{pmatrix}_{\mathrm{Maj}}$$

$$\epsilon_{\mathrm{L}}^{N_0}(W) \approx \frac{\alpha_{\mathrm{em}}}{2\sqrt{2}\sin^2\theta_W} \frac{\Delta m_h^2}{m_0^2} \sum_{i,j} \mathcal{A}_{ij} \sin[(\pm n_P + n' - n_i + n_j)\delta_{\mathrm{X}}]$$

one FN phase

$$\delta_{\mathrm{PMNS}} = n_P \delta_{\mathrm{X}} \text{ and } \delta_a = n_a \delta_{\mathrm{X}},$$

$$\sin[\delta_{\mathrm{PMNS}} + \delta_a - (n_1 - n_3)\delta_{\mathrm{X}}].$$

family indices