Dark Energy from New Confining Force

Jihn E. Kim

Kyung Hee University

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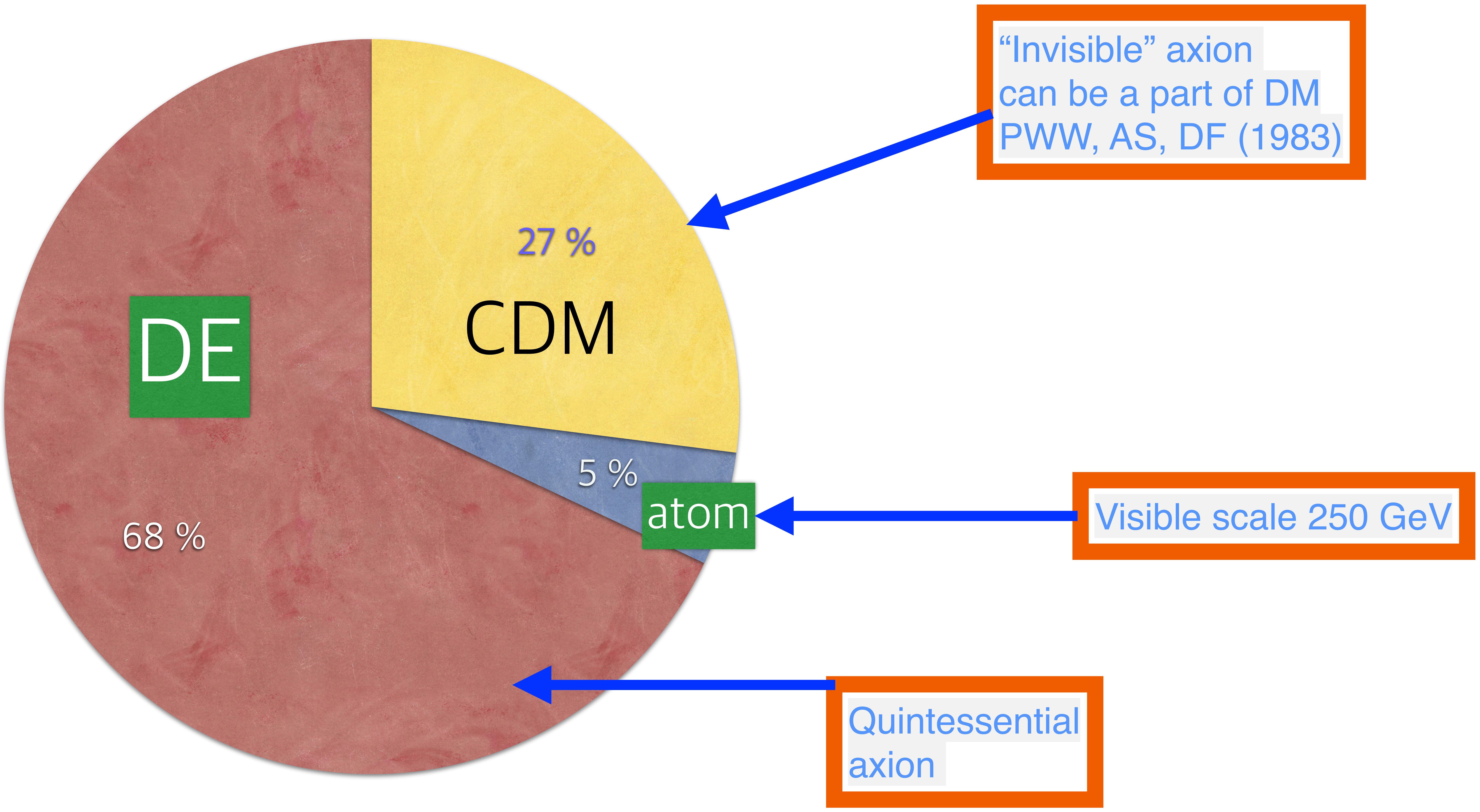
Jihn E. Kim
김 진 의

Seoul National University,
Kyung Hee University

Bonn, 10 Oct. 2022



27 %
CDM
DE
5 %
atom
68 %
“Invisible” axion
can be a part of DM
PWW, AS, DF (1983)
Visible scale 250 GeV
Quintessential
axion

Dark Energy in the Universe

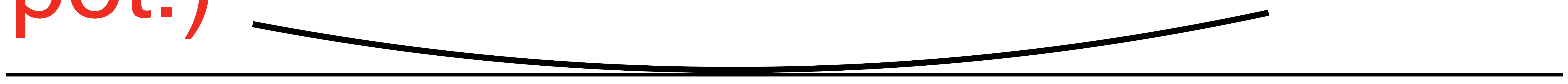
$$c.c=(3\times10^{-3}\ \mathrm{eV})^4$$

Why is c.c. taking this value?

Even anthropic principle is added!!

“Axion” starts from a global symmetry.
Global symmetry has a flat direction.

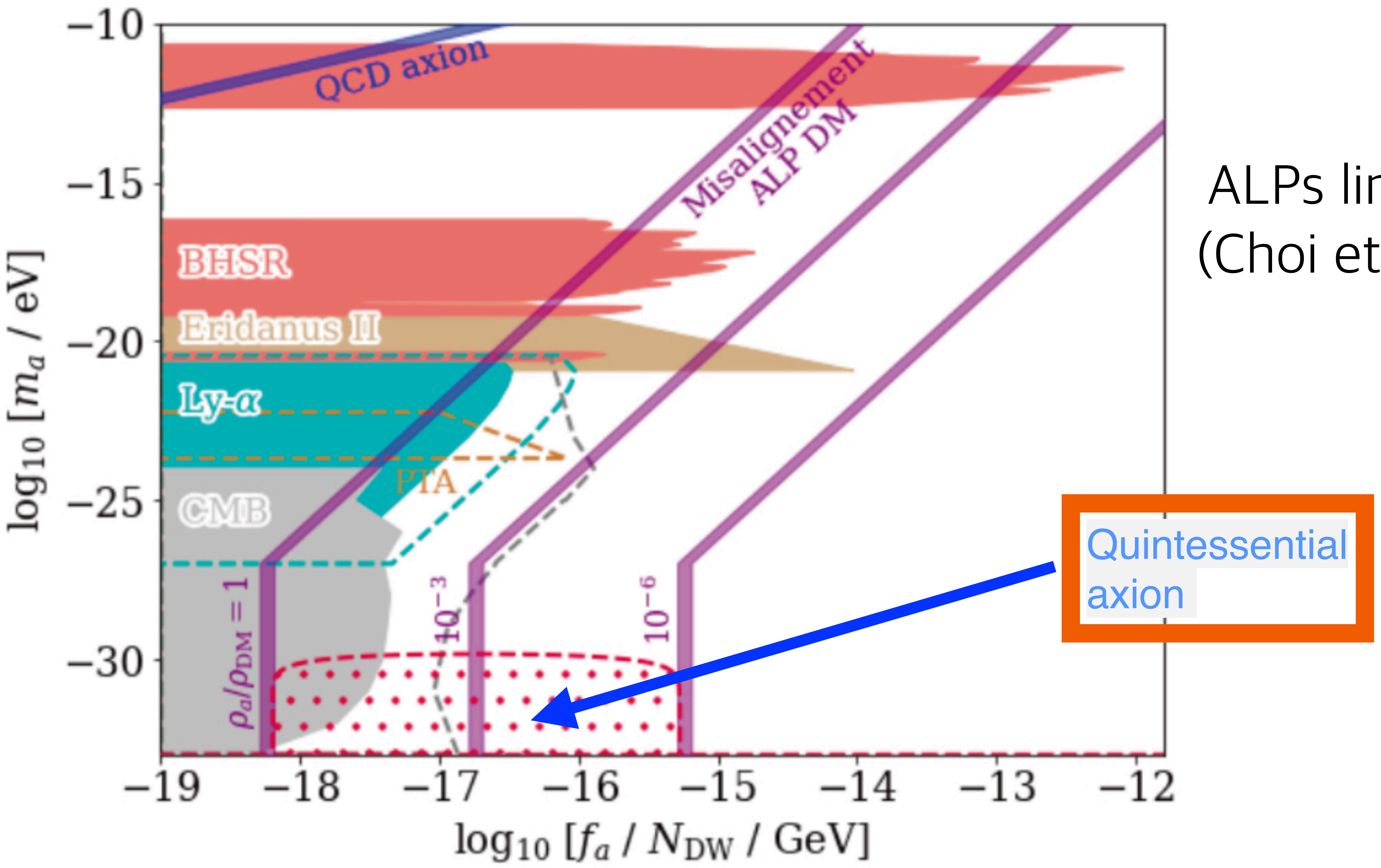
An explicit breaking of the flat direction introduces a curvature or mass. (gauge, pot.)



Quintessential axions require

- The decay constant is near the Planck scale
- QA mass is near 10^{-32} eV (needs a negligible explicit breaking term)

90 degrees rotated from Choi et al.



ALPs limit (Choi et al)

FIG. 5: A summary of the axion scale f_a/N_{DW} versus axion mass from gravitational probes [18]. The shaded regions are excluded by the existing constraints, while the dashed lines show the sensitivities of future experiments. f_a/N_{DW} is identified as the field VEV $\langle a \rangle$ for ALP DM or DE.

Another parameter to mention is the confining force for SUSY breaking around

$$\Lambda = 10^{13}\ \text{GeV}$$

Quark condensates from confining force

$$\langle \overline{Q}_L T^{a\,i}_{j} Q_L \rangle = \Lambda^3 e^{i\Pi^{a\,i}_{j}/f}$$

confining scale

Goldstone boson

Decay constant near confining scale

Mesons from light quarks in QCD

pi/K mesons and eta’

Octet
+singlet

f=250 MeV

We concentrate on SUSY. When we talk about MSSM or SUSY GUTs, we must introduce a TeV(> 5 TeV) scale super partner masses.

With super-fields, fermion condensates were used to introduce SUSY breaking source.

Scalar:

No SUSY breaking

$$M_I = \sqrt{M_{\rm P}{\rm TeV}} \sim 5 \times 10^{10}\,{\rm GeV}$$

Fermion condensate:

$$\mathrm{TeV} = \frac{M_I^3}{M_{\mathrm{P}}^2} \quad \rightarrow \quad M_I = (\,\mathrm{TeV} \cdot M_{\mathrm{P}}^2)^{1/3} \sim 10^{13}\,\mathrm{GeV}$$

Price or prediction:
New confining force?

Quintessential axion as a pseudoscalar first mentioned in

JEK+Nilles, PLB 553, 1 (2003):

A quintessential axion

It was meant to explain DE.

New Confining Force Example

H. P. Nilles, Phys. Lett. B115, 193 (1982):
Dynamically Broken Supergravity and the Hierarchy Problem

S. Ferrara, L. Girardello, H. P. Nilles, Phys. Lett. B125, 457 (1982):
Breakdown of Local Supersymmetry Through Gauge Fermion Condensates

$$\Lambda = 10^{13}\ \mathrm{GeV}$$

Mesons from the new confining force with extremely small masses are the source of DE. So, the explicit breaking term must be very small.Then the mesons are the DE source.

In this case, the key is introducing a new confining force.

U(1)_global has anomaly with non-abelian gauge groups: We need global U(1) to have a pseudoscalar particle.

PQ symmetry is an example: Breaking Scale Lambda-QCD.

U(1)-SU(2)-SU(2):

We want to use this anomaly for breaking the DE global symmetry U(1).

What is the scale for DE SU(2)?

SU(2) gauge coupling by running the value at the electroweak scale already given.

With \alpha_2=29.600 +-0.010 at M_Z, SUSY

[1508.04176]

Threshold correction [%]	M_{SUSY}[GeV],	Mg[GeV],	$1/\alpha_{GUT}$	χ^2
$+1$	$10^{3.96\pm0.10}$	$10^{15.85\pm0.03}$	26.74 ± 0.17	8.2%
±0	$10^{3.45\pm0.09}$	$10^{16.02\pm0.03}$	25.83 ± 0.16	8.2%
-1	$10^{3.02\pm0.08}$	$10^{16.16\pm0.03}$	25.07 ± 0.15	9.5%
-2	$10^{2.78\pm0.07}$	$10^{16.25\pm0.02}$	24.63 ± 0.13	25.1%
-3	$10^{2.60\pm0.06}$	$10^{16.31\pm0.02}$	24.28 ± 0.10	68.1%
-4	$10^{2.42\pm0.05}$	$10^{16.38\pm0.02}$	23.95 ± 0.09	138.3%
-5	$10^{2.26\pm0.05}$	$10^{16.44\pm0.02}$	23.66 ± 0.09	235.7%

2-loop beta function :

$$\beta = -(\frac{\alpha_s}{4\pi})^2 \left(\frac{11}{3} C_2(G) - \frac{2}{3} \sum_R T(R) - \frac{\alpha_s}{4\pi} \Big(\frac{10}{3} \sum_R C_2(G) T(R) + 2 \sum_R \mathrm{Cashimir}_2(\mathrm{SU}(N)) T(R) - \frac{34}{3} (C_2(G))^2 \Big) \right)$$

where

$$C_2(\mathrm{SU}(N)) = N,\ \mathrm{Cashimir}_2(\mathrm{SU}(N)) = \frac{N^2-1}{2N},\ T(R) = \ell(R), \ell(\mathbf{N}) = \frac{1}{2}.$$

Table I was obtained with the following input parameters,

$$\text{At } M_Z = 91.19 \text{ GeV} : \begin{cases} \sin^2\theta_W \Big|_{\overline{\mathrm{MS}}} = 0.23126 \pm 0.00005, \\ \alpha_s = 0.1185 \pm 0.0006, \end{cases} .$$

We obtain

The number of SU(2)-left-handed doublets is [3(colored)+1]x3=12. If counted as left+right, it corresponds to 6.
So, 3Nc-Nf=0. So, this value is not changing.

$$\text{MSSM}: \quad \left[\begin{array}{l} e^{-2\pi/\alpha_2}\Big|_{M_{\rm GUT}} = 1.69 \times 10^{-81}, \\ \\ \left\{ \begin{array}{l} M_{\rm SUSY} = 2820 + 670 - 540 \ \ \text{GeV}, \\ M_{\rm GUT} = (1.065 \pm 0.06) \times 10^{16}\,\text{GeV}. \end{array} \right. \end{array} \right.$$

$$\text{SM}: \quad \left[\begin{array}{l} e^{-2\pi/\alpha_2}\Big|_{M_{\rm GUT}} = 1.69 \times 10^{-131}, \\ M_{\rm GUT} = (1.096 \pm 0.06) \times 10^{15}\,\text{GeV}. \end{array} \right.$$

If SU(2) gauge force is responsible for DE,

$$\mathrm{MSSM}: \ 1.69 \times 10^{-81} \Lambda^4 = (0.003 \text{ eV})^4 \to \Lambda \sim 1.48 \times 10^8 \text{ GeV},$$
$$\mathrm{SM}: \ 1.065 \times 10^{-131} \Lambda^4 = (0.003 \text{ eV})^4 \to \Lambda \sim 5.25 \times 10^{20} \text{ GeV}.$$

So, only the MSSM or SSM has a possibility.

There is a more complicated theory introducing a DE axion.

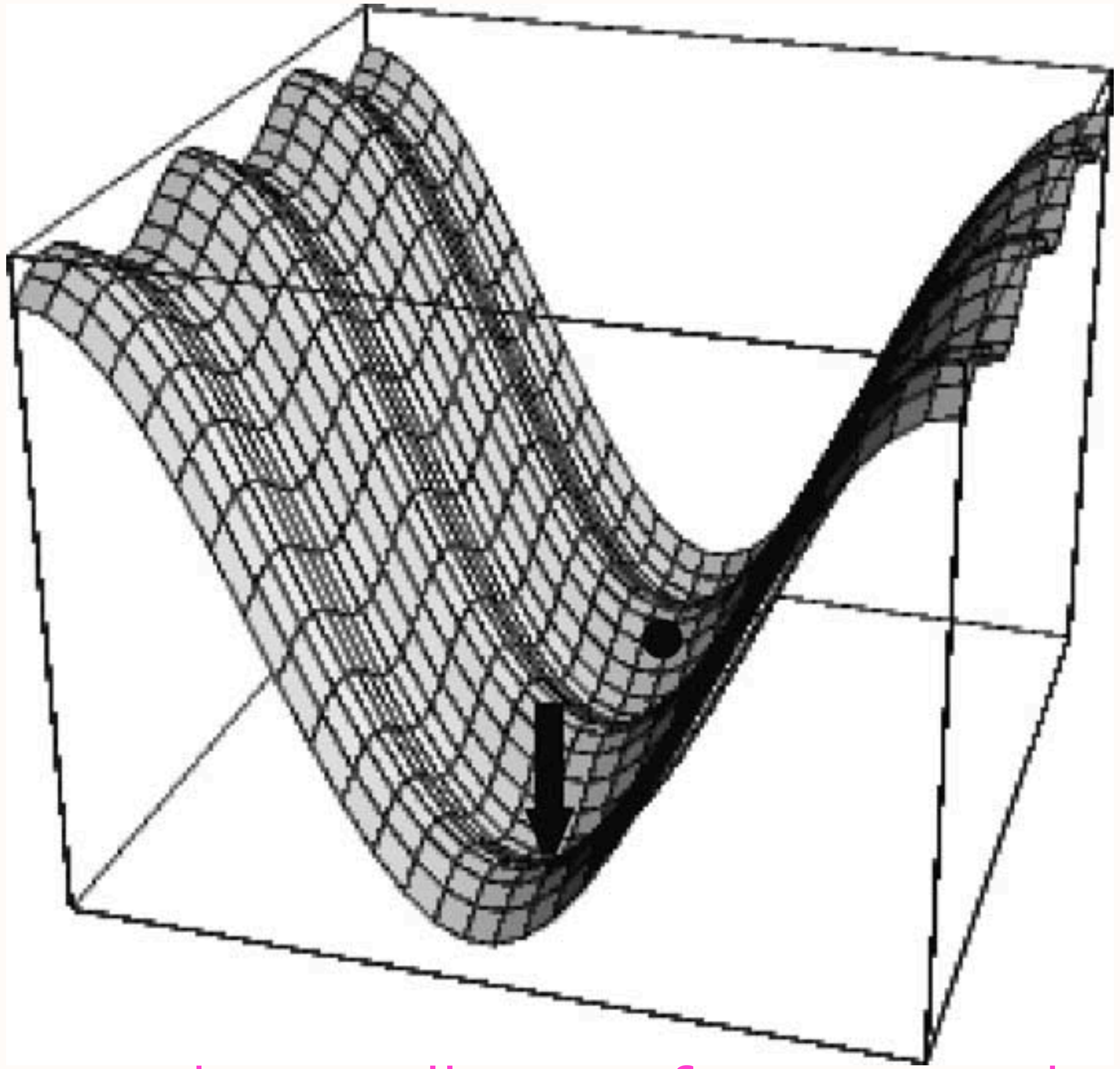
Since we already has the example of the QCD axion, providing DM of the universe, it is tempting to explain both DE and DM by axions.

Word axion = from non-abelian force.

From divergence of axial vector current

Two U(1) global symmetries.

One for the QCD axion and the other for the quintessential axion (with extremely small explicit breaking term)



By the smallness of extra quark mass and many powers of n. Many powers of n hints some discrete symmetry.

JEK+Nilles, PLB 553, 1 (2003)

$$\lambda_h^4 \equiv m_Q^n m_{\tilde{G}}^N \Lambda_h^{4-n-N}, \tag{4}$$

where $\Lambda_h \simeq 10^{13}$ GeV is the hidden sector scale and $m_{\tilde{G}}$ is the hidden sector gaugino mass.

Let us now discuss some illustrative examples for the conditions between m_Q, n and N needed to account for the $(0.003\ \text{eV})^4$ dark energy, assuming $m_{\tilde{G}} \simeq 1$ TeV,

$$\left(\frac{m_Q}{\Lambda_h}\right)^n \sim \begin{cases} 10^{-68}, & \text{for } SU(3)_h, \\ 10^{-58}, & \text{for } SU(4)_h, \\ 10^{-48}, & \text{for } SU(5)_h. \end{cases} \tag{5}$$

For $N = 4$, we obtain $m_Q \simeq 10^{-45}$ GeV, 10^{-16} GeV, and 10^{-7} GeV, respectively, for $n = 1, 2$, and 3.

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B. Ratra, P.J.E. Peebles, Phys. Rev. D 37 (1988) 3406;
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A. Masiero, M. Pietroni, F. Rosati, Phys. Rev. D 61 (2000) 023504;
M.C. Bento, O. Bertolami, Gen. Relativ. Gravit. 31 (1999) 1461;
F. Perrotta, C. Baccigalupi, S. Matarrase, Phys. Rev. D 61 (2000) 023507;
A. Arbey, J. Lesgourgues, P. Salati, Phys. Rev. D 65 (2002) 083514.

Here, we do not try to explain by ex-quark mass, but by the confining scale itself. Then, we have another reasons for introducing a new confining force. We mentioned it already.

Mesons have the adjoint representation of $SU(N)_A$

$$\mathrm{SU}(N)_A \subset \mathrm{SU}(N)\times\mathrm{SU}(N)$$

Condensate is parametrized by Π and f,

$$\langle \overline{Q}_L T_j^{a\,i} Q_L \rangle = \Lambda^3 e^{i\Pi_j^{a\,i}/f}$$

Example, non-susy

	Representation under $\mathcal{G} \equiv \mathrm{SU}(\mathcal{N})$	$\mathrm{SU}(N)_L$	$\mathbf{Z}_{12}$
Q_L	$\mathcal{N}$	$\mathbf{N}$	$+1$
$\overline{Q}_L$	$\overline{\mathcal{N}}$	$\overline{\mathbf{N}}$	$+1$
σ	$\mathbf{1}$	$\mathbf{1}$	$+7$

$$\frac{1}{M^9}\overline{Q}_L \mathcal{C}^{-1} Q_L \sigma^{10},$$

Sigma is of order the Planck mass

$$\Lambda \simeq 2.9 \times 10^6\,\mathrm{GeV}$$

With SUSY

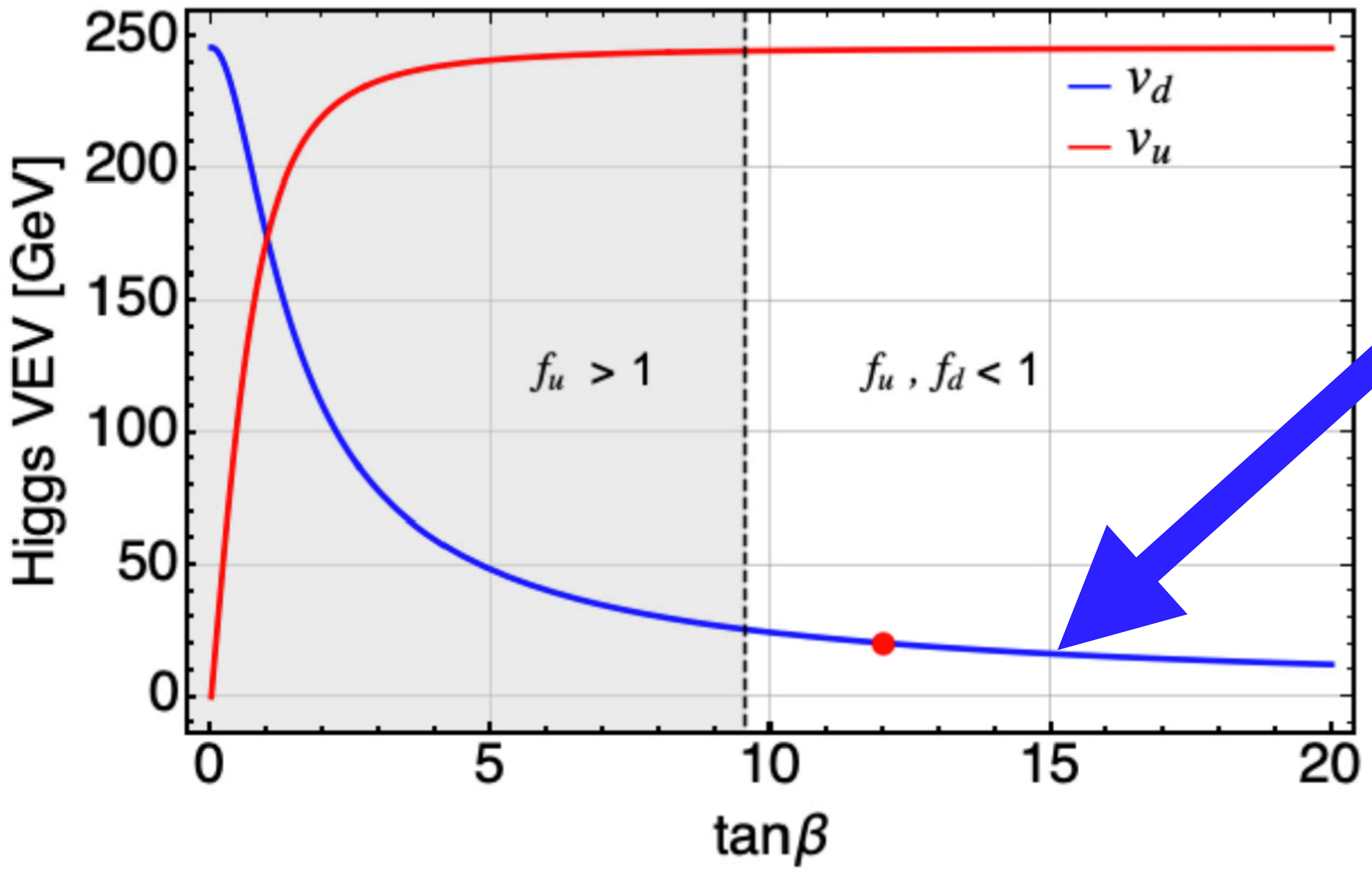
$$\Delta W = \frac{1}{M^{n+3}} \overline{Q}_L Q_L \left(H_u H_d\right)^2 \sigma^n.$$

An example

Then, condensation of the hidden sector quark Q leads to the following VEVs

$$\frac{1}{M^{n+3}} \Lambda^3 (v_u v_d)^2 V^n = \frac{1}{M^{n+3}} \Lambda^3 \frac{v_d^4}{\cos\beta^4} V^n \simeq (0.003\,\mathrm{eV})^4$$

We can fit Lambda and V by this.
Then, the curve shows the one satisfying the DE.



ΔV =(0.003eV)^4

FIG. 1: Potential generated by Yukawa terms breaking $U(1)_{DE}$. At the intersection of the blue curve and the $f_u = 1$ line, v_d is 25.6 GeV.

Model

	Representation under $\mathcal{G} \equiv$SU($\mathcal{N}$)	SU(2)$_W \times$U(1)$_Y$	$\mathbf{Z}_{6R}$
Q_L	$\mathcal{N}$	$\mathbf{1}$	$+1$
$\overline{Q}_L$	$\overline{\mathcal{N}}$	$\mathbf{1}$	-1
H_u	$\mathbf{1}$	$\mathbf{2}_{+1/2}$	$+3$
H_d	$\mathbf{1}$	$\mathbf{2}_{-1/2}$	$+2$
σ	$\mathbf{1}$	$\mathbf{1}$	$+4$
S	$\mathbf{1}$	$\mathbf{1}$	$+5$

TABLE II: $\mathbf{Z}_{6R}$ quantum numbers of relevant chiral superfileds appearing

Here, we write W terms having $U(1)_R$ quantum number 2 modulo 6. SUSY conditions are

$$W = -\alpha\sigma S^2 + \frac{\varepsilon}{M} S^4 - \frac{x}{M^2}\sigma S^2 Q_L \overline{Q}_L + \cdots$$

$$\frac{\partial W}{\partial \sigma} :\to Q_L\overline{Q}_L = -\frac{\alpha M^2}{x}$$

$$\frac{\partial W}{\partial S} :\to (x\frac{Q_L\overline{Q}_L}{M^2} + \alpha)\sigma = \frac{2\varepsilon}{M}S^2.$$

No acceptable solution.

So we add SUSY breaking effects parametrized by deltas. Then minima occur at

$$-\alpha S^2 - \frac{x}{M^2} S^2 Q_L \overline{Q}_L + \delta_1 \Lambda^2 = 0,$$

$$-\alpha S\sigma - \frac{x}{M^2} S Q_L \overline{Q}_L \sigma + \delta_1 \Lambda^2 \sigma / S = 0,$$

$$2\alpha\sigma S^2 + 2\frac{\varepsilon}{M} S^4 + (\frac{\delta_2 S - 2\delta_1 \sigma}{2})\Lambda^2 = 0.$$

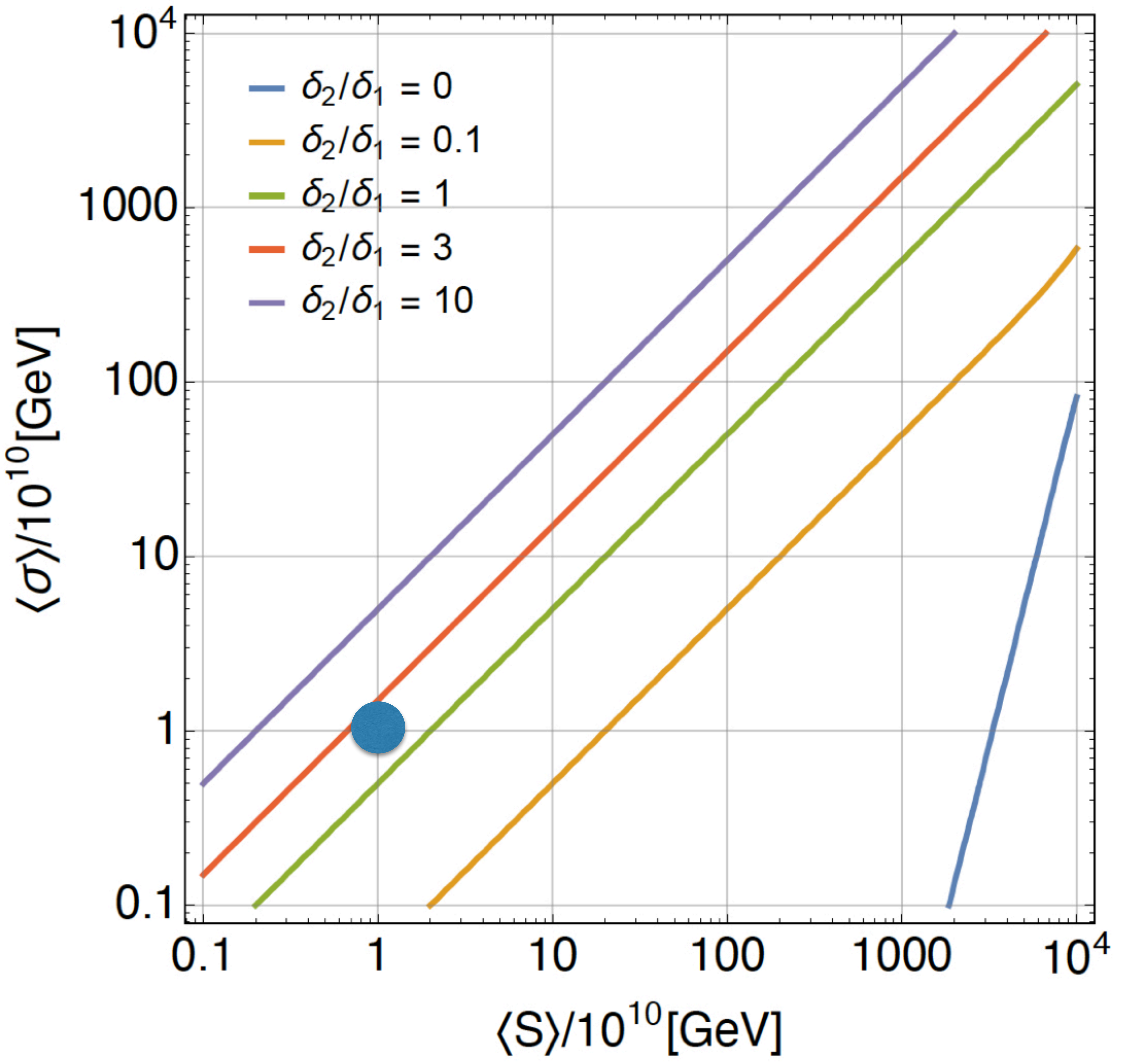


FIG. 2: Solutions of σ and S satisfying Eq. (2).

Two singlets have VEVs around 10^{10} GeV.

But f quintessential axion is near the Planck scale. Not at the confining scale.

In SUSY, condensation of scalar ex-quarks do not break SUSY. So, this squark condensation scale can be nearer to the Planck scale.

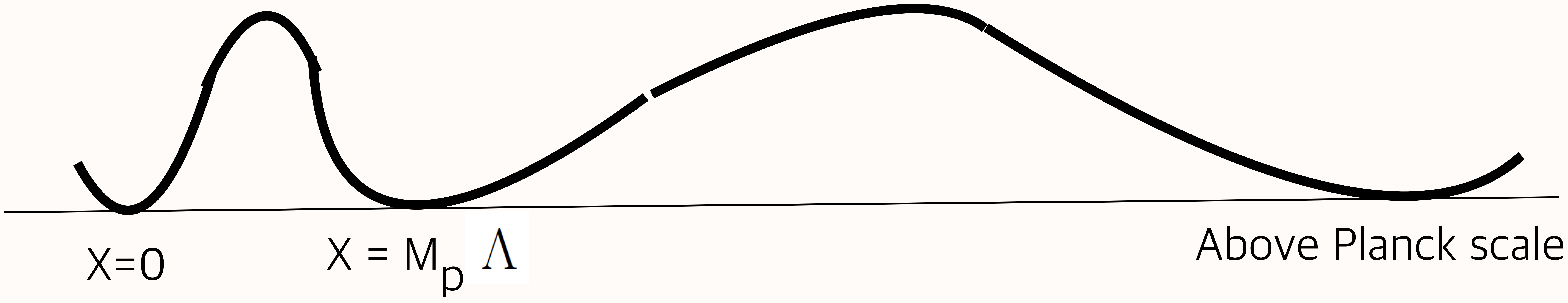
$$\overline{Q}_L Q_L \equiv X.$$

Nonzero X does not break supersymmetry. If we consider a potential in terms of X,

$$W = \Lambda X - \frac{1}{2M_{\mathrm{P}}} X^2 + \cdots .$$

$$V = \left(\Lambda - \frac{1}{M_{\mathrm{P}}} X\right)^2 + \cdots .$$

So, $f = \sqrt{X}$ is expected at a median of Λ and M_{P}.



For SUSY breaking effects to the SM superpartners, we need the mu term

$$W_\mu = \frac{(10^{10}\ \mathrm{GeV})^2}{M} H_u H_d$$

J. E. Kim and H. P. Nilles, The   problem and the strong CP problem, Phys. Lett.B 138 (1984) 150 [doi:10.1016/0370-2693(84)91890-2].

But, there should be no HuHd and HuHdS terms.

$$W_\mu = \frac{\sigma\, S}{M} H_u H_d$$

With <sigma> and <S> VEVs around 10^{10} GeV, we have a needed mu term.

Conclusion

I reviewed the quintessential axion.

Thanks for attention