Flaxion

a minimal extension to solve puzzles in the standard model

Koichi Hamaguchi (University of Tokyo)

@Moriond EW 2018, Mar. 13, 2018

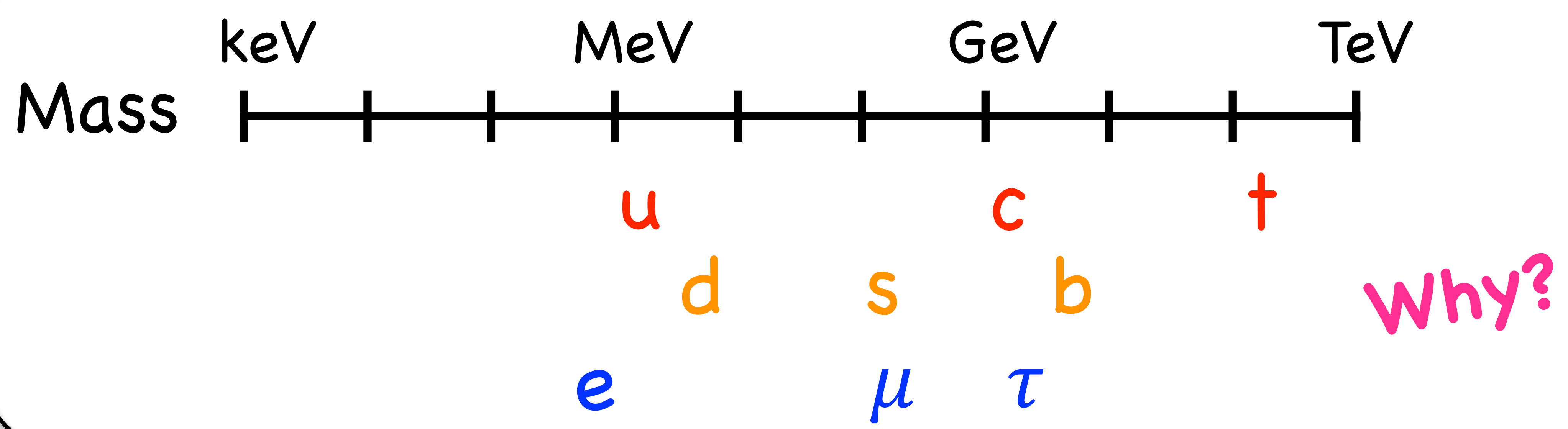
Based on
Y. Ema, KH, T. Moroi, K. Nakayama, arXiv:1612.05492 [JHEP 1701 (2017) 096],
Y. Ema, D. Hagihara, KH, T. Moroi, K. Nakayama, arXiv:1802.07739.

Summary:

$$U(1)_{FN} = U(1)_{PQ}$$

Summary:

We proposed a new model (scenario) that explains the hierarchical flavor structure of quarks/leptons,



and solves the strong CP problem,

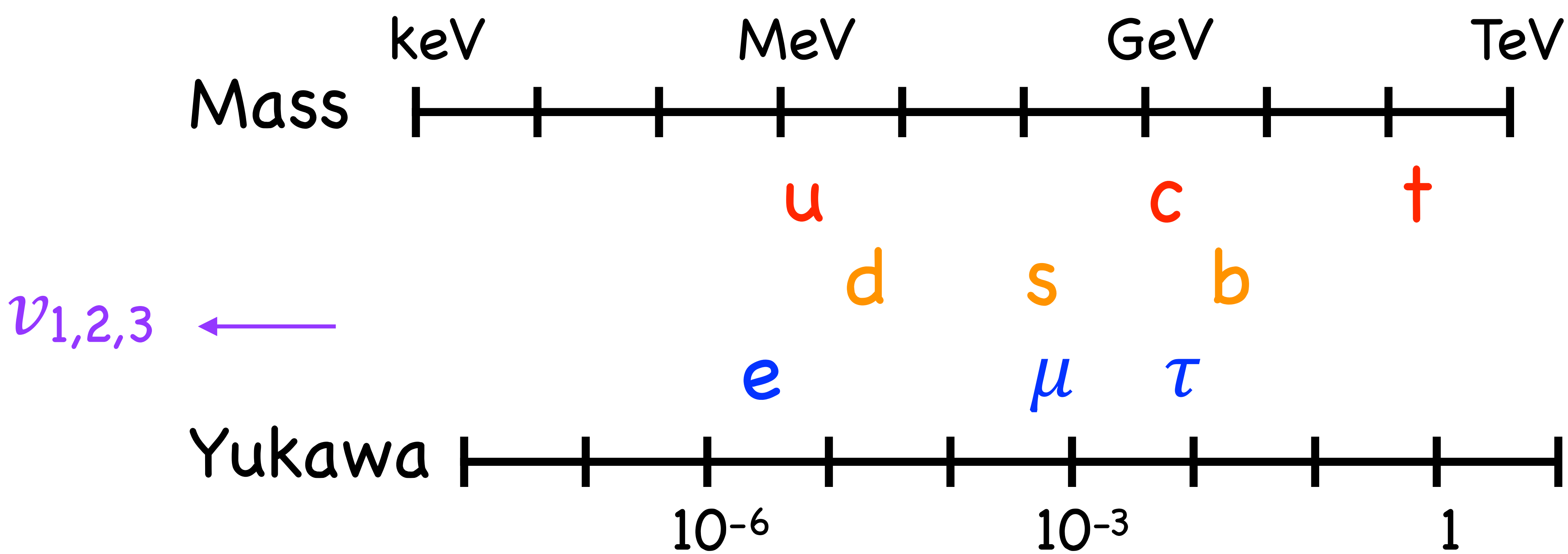
$$\mathcal{L}_\theta = \frac{\alpha_s}{8\pi}\theta\, F_a^{\mu\nu}\widetilde{F}_{a\mu\nu}, \quad \bar{\theta} = \theta + \arg\det m_q$$

$\underline{|\bar{\theta}| \lesssim 10^{-10}}$ <u>from neutron EDM</u> Why?

and includes DM, Leptogenesis, and Inflation.

Q: What's the origin of the quark and lepton mass hierarchy and mixings ??

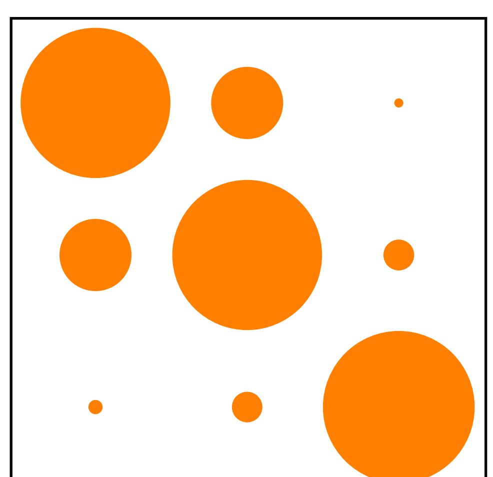
cf. Talks by
R. Alonso
J. Fuentes-Martín
on Sunday.



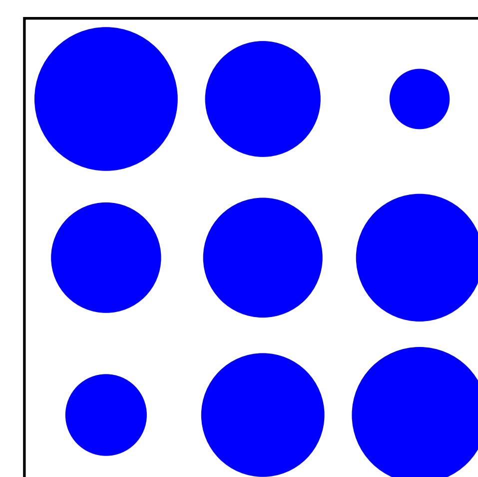
$\hat{y}^u_{ij}\ \overline{Q_i} H u_{Rj}$

large hierarchy

quark mixing



neutrino mixing



A simple possibility:

a spontaneously broken global U(1) symmetry. [Froggatt-Nielsen,'79]

$$\hat{y}^u_{ij}\,\overline{Q_i}Hu_{Rj}$$

up-type quark
Yukawa couplings
in the Standard Model

A simple possibility:
a spontaneously broken global U(1) symmetry. [Froggatt-Nielsen,'79]

	Q_i	u_{R_j}	H	ϕ
U(1) charge	q_{Q_i}	q_{u_j}	0	$+1$

New complex scalar:
Flavon

$$\cancel{\hat{y}^u_{ij}\, \overline{Q}_i H u_{Rj}} \quad \longrightarrow \quad y^u_{ij} \left(\frac{\phi}{M}\right)^{q_{Q_i} - q_{u_j}} \overline{Q}_i H u_{Rj}$$

up-type quark
Yukawa couplings
in the Standard Model

cutoff scale

288 C.D. Froggatt, H.B. Nielsen / Hierarchy of quark masses

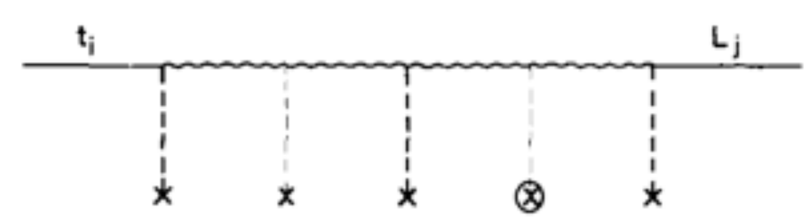


Fig. 1. Feynman diagram which generates the quark mass matrix element $M_{t,ij}$. Full lines represent quarks and wavy lines represent super heavy fermions. The dashed lines represent Higgs tadpoles as follows: ---× $\langle\phi_1\rangle$, and ---⊗ $\langle\phi_2\rangle$.

A simple possibility:

a spontaneously broken global U(1) symmetry. [Froggatt-Nielsen,'79]

	Q_i	u_{R_j}	H	ϕ
U(1) charge	q_{Q_i}	q_{u_j}	0	+1

$\leftarrow$ New complex scalar: **Flavon**

$$\cancel{\hat{y}^u_{ij}\,\overline{Q}_i H u_{Rj}} \quad \longrightarrow \quad y^u_{ij}\left(\frac{\langle\phi\rangle}{M}\right)^{q_{Q_i}-q_{u_j}}\overline{Q}_i H u_{Rj}$$

→ After U(1) breaking by $\langle\phi\rangle \neq 0$,

$$m^u_{ij} = \underbrace{y^u_{ij}}_{O(1)}\,\underbrace{\epsilon^{q_{Q_i}-q_{u_j}}}_{\text{Mass hierarchy and mixings}}\langle H\rangle$$

O(1)

Mass hierarchy and mixings

where $\dfrac{\langle\phi\rangle}{M} \equiv \epsilon < 1$

Example:

$q_Q = \{3,2,0\},\, q_u = \{-5,-1,0\}$

$$\to m^u \sim \begin{pmatrix} \epsilon^8 & \epsilon^4 & \epsilon^3 \\ \epsilon^7 & \epsilon^3 & \epsilon^2 \\ \epsilon^5 & \epsilon & 1 \end{pmatrix}$$

up charm top

A simple possibility:

a spontaneously broken global U(1) symmetry. [Froggatt-Nielsen,'79]

Our setup:

$$\mathcal{L} = y^d_{ij}\left(\frac{\phi}{M}\right)^{n^d_{ij}} \overline{Q}_i H d_{Rj} + y^u_{ij}\left(\frac{\phi}{M}\right)^{n^u_{ij}} \overline{Q}_i \widetilde{H} u_{Rj}$$
$$+ y^l_{ij}\left(\frac{\phi}{M}\right)^{n^l_{ij}} \overline{L}_i H l_{Rj} + y^\nu_{i\alpha}\left(\frac{\phi}{M}\right)^{n^\nu_{i\alpha}} \overline{L}_i \widetilde{H} N_{R\alpha}$$
$$+ \frac{1}{2} y^N_{\alpha\beta}\left(\frac{\phi}{M}\right)^{n^N_{\alpha\beta}} M \overline{N^c_{R\alpha}} N_{R\beta} + \text{h.c.}$$

We also introduce
2 or 3 right-handed neutrinos.

where $\dfrac{\langle\phi\rangle}{M} \equiv \epsilon \simeq 0.2$

$$\begin{cases} n^u_{ij} = q_{Q_i} - q_{u_j}\,, \\ n^d_{ij} = q_{Q_i} - q_{d_j}\,, \\ n^l_{ij} = q_{L_i} - q_{l_j}\,, \\ n^\nu_{i\alpha} = q_{L_i} - q_{N_\alpha} \\ n^N_{\alpha\beta} = -q_{N_\alpha} - q_{N_\beta}\,. \end{cases}$$

A simple possibility:
a spontaneously broken global U(1) symmetry. [Froggatt-Nielsen,'79]

Then, **Quark** mass hierarchy as well as **CKM** angles are naturally explained as e.g.,

$$\begin{cases} q_Q = \{3,2,0\}, \\ q_u = \{-5,-1,0\}, \\ q_d = \{-4,-3,-3\} \end{cases} \to \begin{cases} m^u_{ij} \sim \begin{pmatrix} \epsilon^8 & \epsilon^4 & \epsilon^3 \\ \epsilon^7 & \epsilon^3 & \epsilon^2 \\ \epsilon^5 & \epsilon & 1 \end{pmatrix} \langle H \rangle, \\ \\ m^d_{ij} \sim \begin{pmatrix} \epsilon^7 & \epsilon^6 & \epsilon^6 \\ \epsilon^6 & \epsilon^5 & \epsilon^5 \\ \epsilon^4 & \epsilon^3 & \epsilon^3 \end{pmatrix} \langle H \rangle, \end{cases} \to \begin{cases} \mathrm{diag}(m_u) \sim (\epsilon^8, \epsilon^3, 1)\langle H \rangle, & \text{u,c,t} \\ \\ \mathrm{diag}(m_d) \sim (\epsilon^7, \epsilon^5, \epsilon^3)\langle H \rangle, & \text{d,s,b} \\ \\ V_{\mathrm{CKM}} \sim \begin{pmatrix} 1 & \epsilon & \epsilon^3 \\ \epsilon & 1 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix} \end{cases}$$

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Lepton masses and **MNS** angles are also explained as

$$\begin{cases} q_L = \{1,0,0\}, \\ q_e = \{-8,-5,-3\}, \\ q_N = \{q_{N_1}, q_{N_2}, (q_{N_3})\} \end{cases} \to \begin{cases} m^\ell_{ij} \sim \begin{pmatrix} \epsilon^9 & \epsilon^6 & \epsilon^4 \\ \epsilon^8 & \epsilon^5 & \epsilon^3 \\ \epsilon^8 & \epsilon^5 & \epsilon^3 \end{pmatrix} \langle H \rangle, \\ \\ m^\nu_{ij} \sim \begin{pmatrix} \epsilon^2 & \epsilon & \epsilon \\ \epsilon & 1 & 1 \\ \epsilon & 1 & 1 \end{pmatrix} \dfrac{\langle H \rangle^2}{M}, \end{cases} \to \begin{cases} \mathrm{diag}(m_e) \sim (\epsilon^9, \epsilon^5, \epsilon^3)\langle H \rangle, & e,\mu,\tau \\ \mathrm{diag}(m_\nu) \sim (\epsilon^2, 1, 1)\dfrac{\langle H \rangle^2}{M}, \\ V_{\mathrm{MNS}} \sim \begin{pmatrix} 1 & \epsilon & \epsilon \\ \epsilon & 1 & 1 \\ \epsilon & 1 & 1 \end{pmatrix} \end{cases}$$

q_N-dependence cancels because of the **seesaw** formula.

large 2-3 mixing

[cf. Sato-Yanagida,'98, Ramond,'98]

Quark and lepton mass hierarchy and mixings.

Neutrino masses and mixings.

Standard Model

Quark and lepton mass hierarchy and mixings.

Neutrino masses and mixings.

seesaw

Standard Model

+ one complex scalar with $U(1)_F$

ϕ : **flavon**

+ 2 (or 3) right-handed neutrinos.

Our setup: $$\mathcal{L} = y^d_{ij}\left(\frac{\phi}{M}\right)^{n^d_{ij}}\overline{Q}_i H d_{Rj} + y^u_{ij}\left(\frac{\phi}{M}\right)^{n^u_{ij}}\overline{Q}_i \widetilde{H} u_{Rj}$$
$$+ y^l_{ij}\left(\frac{\phi}{M}\right)^{n^l_{ij}}\overline{L}_i H l_{Rj} + y^\nu_{i\alpha}\left(\frac{\phi}{M}\right)^{n^\nu_{i\alpha}}\overline{L}_i \widetilde{H} N_{R\alpha}$$
$$+ \frac{1}{2} y^N_{\alpha\beta}\left(\frac{\phi}{M}\right)^{n^N_{\alpha\beta}} M\overline{N^c_{R\alpha}} N_{R\beta} + \text{h.c.}$$

can explain the quark and lepton mass hierarchy and mixings.

OK, but……… **What's new?**

Froggatt-Nielsen paper was in 1979……

Our setup:

$$\mathcal{L} = y_{ij}^d \left(\frac{\phi}{M}\right)^{n_{ij}^d} \overline{Q}_i H d_{Rj} + y_{ij}^u \left(\frac{\phi}{M}\right)^{n_{ij}^u} \overline{Q}_i \widetilde{H} u_{Rj}$$
$$+ y_{ij}^l \left(\frac{\phi}{M}\right)^{n_{ij}^l} \overline{L}_i H l_{Rj} + y_{i\alpha}^\nu \left(\frac{\phi}{M}\right)^{n_{i\alpha}^\nu} \overline{L}_i \widetilde{H} N_{R\alpha}$$
$$+ \frac{1}{2} y_{\alpha\beta}^N \left(\frac{\phi}{M}\right)^{n_{\alpha\beta}^N} M \overline{N_{R\alpha}^c} N_{R\beta} + \text{h.c.}$$

POINT: The global, spontaneously broken U(1) flavor symmetry is **anomalous** under SU(3)$_C$, which means… **the Peccei-Quinn mechanism (to solve the strong CP problem) is automatically included:**

U(1)$_F$ = U(1)$_{PQ}$!! "Flaxion"

* As far as we know, this simple realization has not been studied explicitly before.

cf. related earlier works, **Wilczek,'82,** Geng-Ng,'89, Berezhiani-Khlopov,'91, Babu-Barr,'92, Albrecht et.al.,'10, Fong-Nardi,'13, Ahn,'14,'16, Celis et.al.,'14,…..

arXiv:1612.05492 [pdf, ps, other]

Flaxion: a minimal extension to solve puzzles in the standard model

Yohei Ema, Koichi Hamaguchi, Takeo Moroi, Kazunori Nakayama

Comments: 23 pages, 1 figure; v2: version published in JHEP

Subjects: **High Energy Physics - Phenomenology (hep-ph)**

arXiv:1612.08040 [pdf, other]

The Axiflavon

Lorenzo Calibbi, Florian Goertz, Diego Redigolo, Robert Ziegler, Jure Zupan

Comments: 6 pages, typos corrected, references added

Subjects: **High Energy Physics - Phenomenology (hep-ph)**

Flaxion

$$\boxed{\phi = \frac{1}{\sqrt{2}}\left(\varphi + i a\right)}$$

flavon

axion

Flaxion

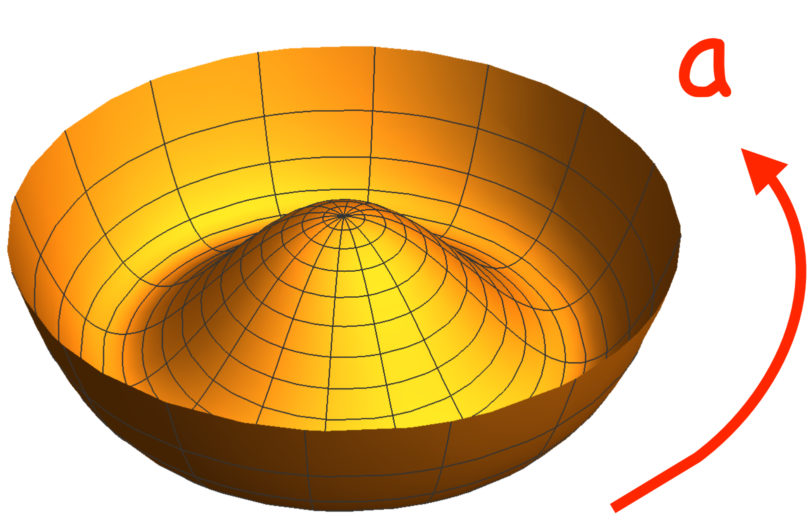
$$\boxed{\underset{\text{flavon}}{\phi} = \frac{1}{\sqrt{2}}\left(\varphi + i\underset{\text{axion}}{a}\right)}$$

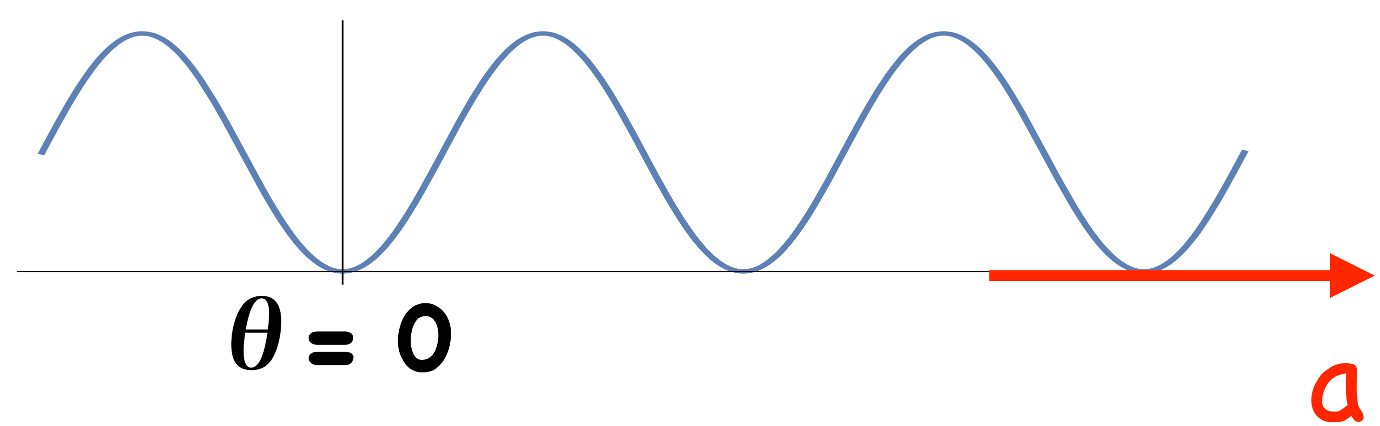
(1) Strong CP problem is solved by the PQ mechanism.

[Peccei-Quinn,'77]

$$\mathcal{L} = \frac{g_s^2}{32\pi^2}\frac{a}{f_a}G^a_{\mu\nu}\widetilde{G}^{a\mu\nu} \quad \text{where} \quad f_a = \frac{\sqrt{2}\langle\phi\rangle}{N_{\rm DW}}, \quad N_{\rm DW} = \sum_i (2q_{Q_i} - q_{u_i} - q_{d_i})$$

(In the example before, N_{DW} = 26.)





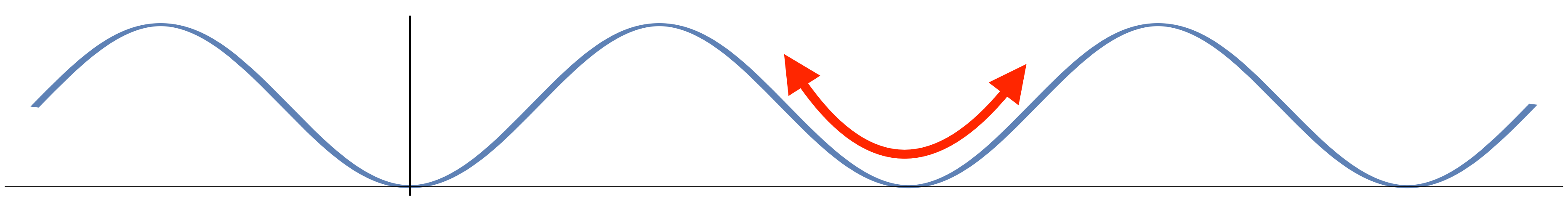
Flaxion

$$\boxed{\phi = \frac{1}{\sqrt{2}}\left(\varphi + i a\right)}$$

flavon axion

(1) **Strong CP problem is solved** by the PQ mechanism.

(2) The axion can be **the dark matter.**



$$\Omega_a h^2 = 0.18\,\theta_i^2 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{1.19} .$$

[Turner,'86]

Flaxion

$$\boxed{\underset{\text{flavon}}{\phi} = \frac{1}{\sqrt{2}}\left(\varphi + i\underset{\text{axion}}{a}\right)}$$

(1) **Strong CP problem is solved** by the PQ mechanism.

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Any new prediction?

Flaxion

$$\boxed{\phi = \frac{1}{\sqrt{2}}(\varphi + ia)}$$

flavon axion

(1) Strong CP problem is solved by the PQ mechanism.

(2) The axion can be the dark matter.

Any new prediction?

......Yes!

(3) Characteristic flavor-changing signals are predicted.

[cf. Wilczek,'82]

(3) Characteristic flavor-changing signals.

$$\mathcal{L} = y^d_{ij}\left(\frac{\phi}{M}\right)^{n^d_{ij}} \overline{Q}_i H d_{Rj} + y^u_{ij}\left(\frac{\phi}{M}\right)^{n^u_{ij}} \overline{Q}_i \widetilde{H} u_{Rj}$$
$$+ y^l_{ij}\left(\frac{\phi}{M}\right)^{n^l_{ij}} \overline{L}_i H l_{Rj} + y^\nu_{i\alpha}\left(\frac{\phi}{M}\right)^{n^\nu_{i\alpha}} \overline{L}_i \widetilde{H} N_{R\alpha}$$
$$+ \frac{1}{2} y^N_{\alpha\beta}\left(\frac{\phi}{M}\right)^{n^N_{\alpha\beta}} M \overline{N^c_{R\alpha}} N_{R\beta} + \text{h.c.}$$

$$\longrightarrow \quad -\mathcal{L} = \sum_{f=u,d,l}\left[m^f_{ij}\left(1+\frac{h}{\sqrt{2}\langle H\rangle}\right) + \frac{m^f_{ij} n^f_{ij}(s+ia)}{\sqrt{2}\langle\phi\rangle}\right]\overline{f_{Li}} f_{Rj} + \text{h.c.}$$

They are not simultaneously diagonalized.

-> **flavor changing processes.**

The most stringent bound comes from K+ -> π^+ a.

$$\text{Br}(K^+ \to \pi^+ a) \simeq 3\times 10^{-10}\left(\frac{10^{10}\,\text{GeV}}{f_a}\right)^2 \underbrace{\left(\frac{26}{N_{\text{DW}}}\right)^2 \left|\frac{(\kappa^d_{\text{AH}})_{12}}{m_s - m_d}\right|^2}_{O(1)} < 7.3\times 10^{-11}$$

[BNL-E787, E949]

$$\rightarrow \quad f_a \gtrsim 2\times 10^{10}\text{GeV}$$

CERN **NA62 experiment** can improve the sensitivity !!

Flaxion Scenario

Quark and lepton
mass hierarchy
and mixings.

Standard Model

+ one complex scalar
with $U(1)_F = U(1)_{PQ}$

$$\phi = \frac{1}{\sqrt{2}}(\varphi + ia)$$

flavon

Strong CP
problem.

Dark
Matter.

Neutrino
masses
and mixings.

seesaw

+ 2 (or 3)
right-handed
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characteristic signal:

K $\rightarrow$ π a

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characteristic signal:
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What about the real part?

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flavon

inflaton

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Inflation !

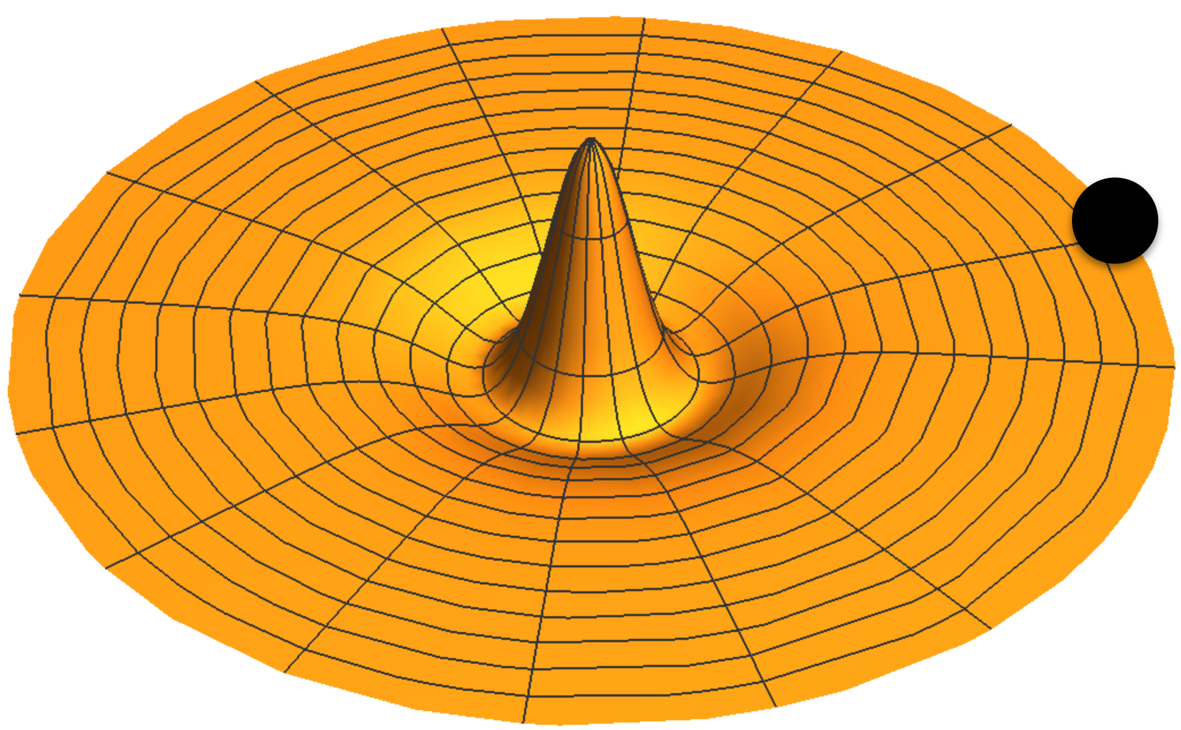
Flaxion Inflation:

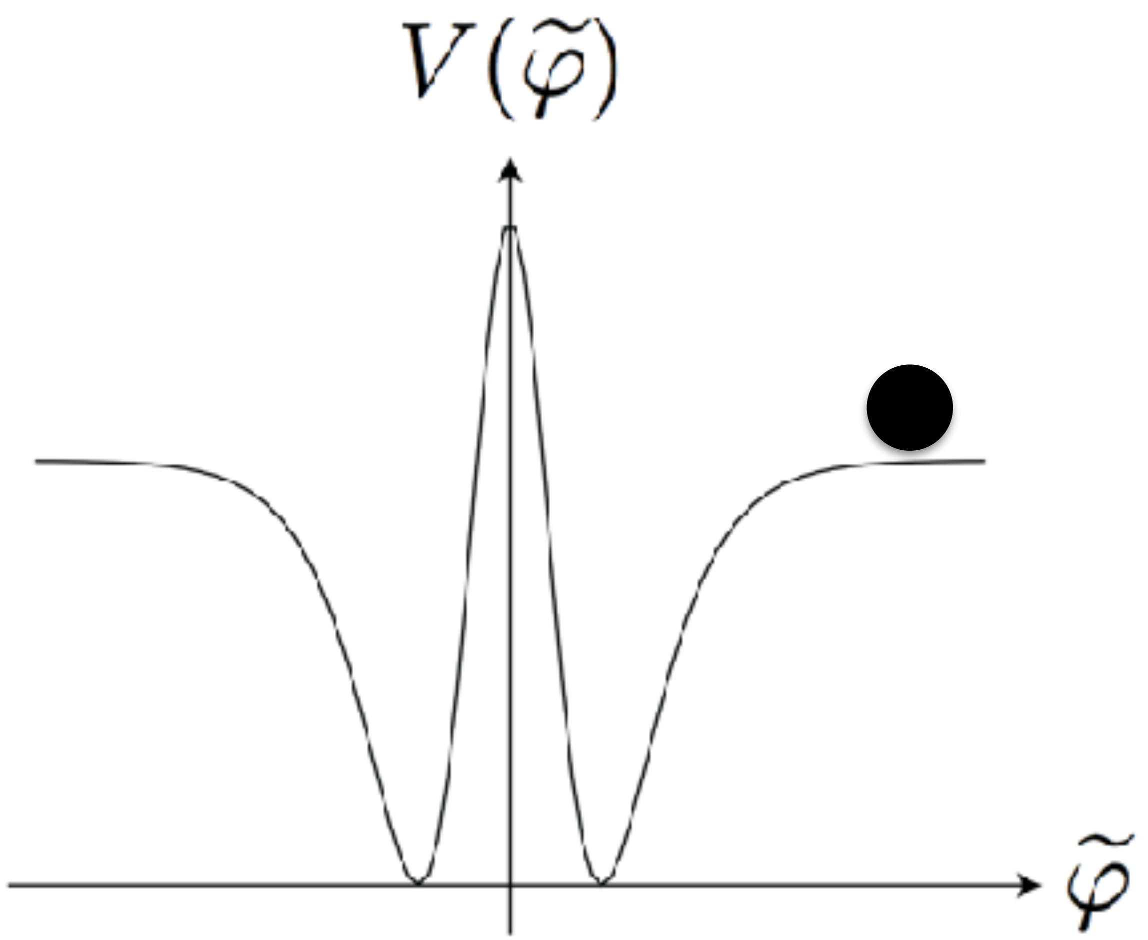
$$\mathcal{L} = -\frac{|\partial\phi|^2}{\left(1 - |\phi|^2/\Lambda^2\right)^2} - \lambda_\phi \left(|\phi|^2 - v_\phi^2\right)^2$$

$$v_\phi < \Lambda < \sqrt{2} v_\phi$$

canonical field $\widetilde{\varphi}$:

$$\frac{\varphi}{\sqrt{2}\Lambda} \equiv \tanh\left(\frac{\widetilde{\varphi}}{\sqrt{2}\Lambda}\right)$$





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canonical field $\widetilde{\varphi}$:

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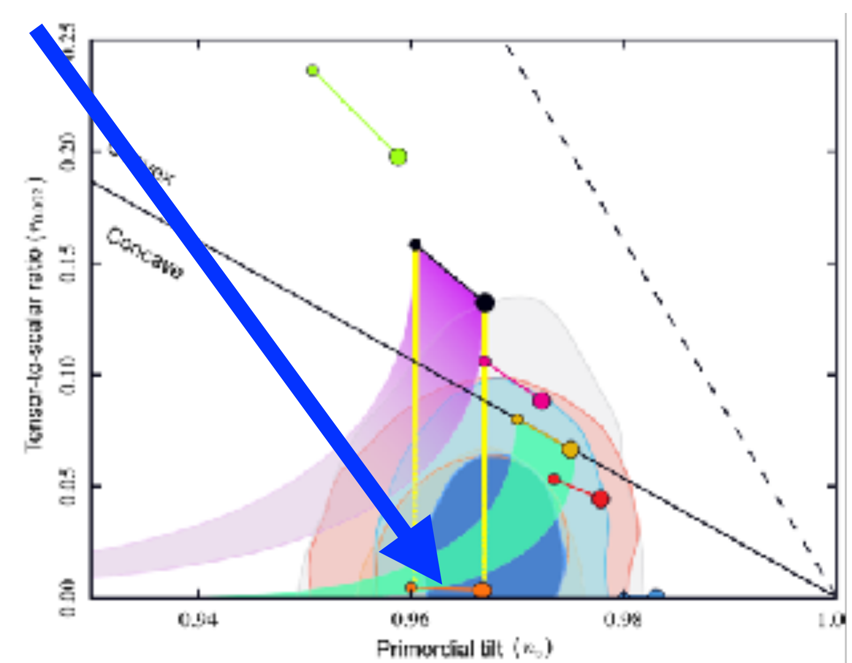
☑ Curvature fluctuation:

$P_\xi = 2.2 \times 10^{-9}$ [Planck,'15] is reproduced

for $\lambda_\phi \lesssim 1$ and $\Lambda \gtrsim 10^{13}\mathrm{GeV}$, which is consistent with the scale for flaxion DM.

☑ (n_s, r) is in the Planck best-fit region.

$$n_s \simeq 1 - \frac{2}{N_e}, \quad r \simeq \frac{4}{N_e^2}\left(\frac{\Lambda}{M_P}\right)^2.$$



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- ☑ (n_s, r) is in the Planck best-fit region.
- ☑ The U(1) symmetry is never restored -> No Domain wall.
- ☑ Isocurvature fluctuation is suppressed.
- ☑ Reheating temperature is high enough for Leptgenesis.

($T_R \simeq 10^{12}$ - 10^{14} GeV) ("strong washout")

Flaxion Inflation:

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See Backup slides for details.

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☑ Isocurvature fluctuation is suppressed.

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($T_R \simeq 10^{12}$ - 10^{14} GeV) ("strong washout")

Flaxion Scenario

characteristic signal:
$K \to \pi\ a$

Standard Model

+ one complex scalar
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$$\phi = \frac{1}{\sqrt{2}}(\varphi + ia)$$

flavon

inflaton

axion

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seesaw

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Dark Matter.

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flavon   inflaton   axion

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P_ξ & (n_s, r) in the Planck best-fit region

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flavon

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Quark and lepton

mass hierarchy

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Neutrino

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seesaw

Strong CP

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Dark

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solves DW and

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problems

P_ξ & (n_s, r)

in the Planck

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flavon

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Quark and lepton mass hierarchy and mixings.

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seesaw

Leptogenesis

Baryon asymmetry of the Universe.

Strong CP problem.

Dark Matter.

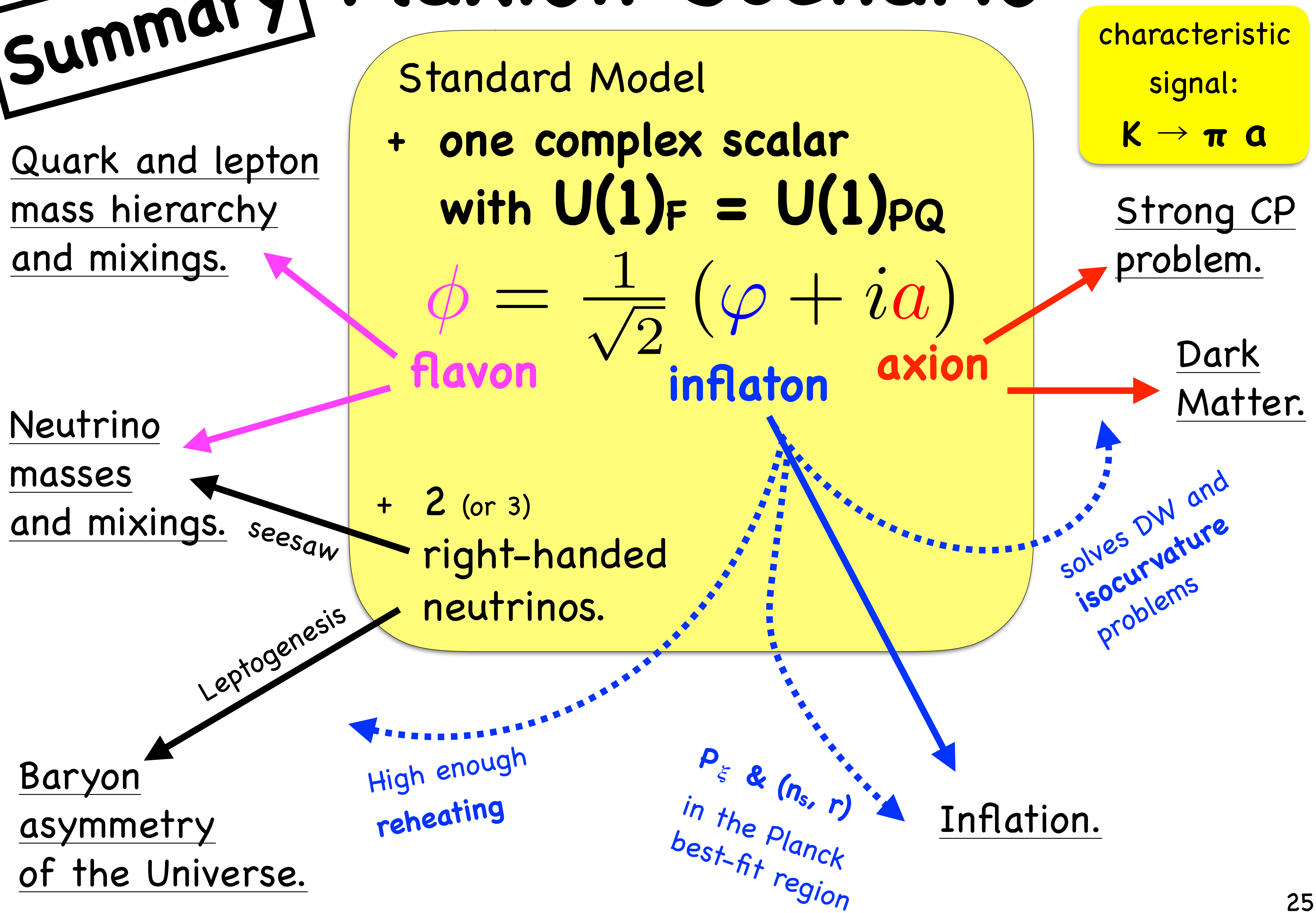
solves DW and **isocurvature** problems

High enough **reheating**

P_ξ & (n_s, r) in the Planck best-fit region

Inflation.

Summary Flaxion Scenario



Backup

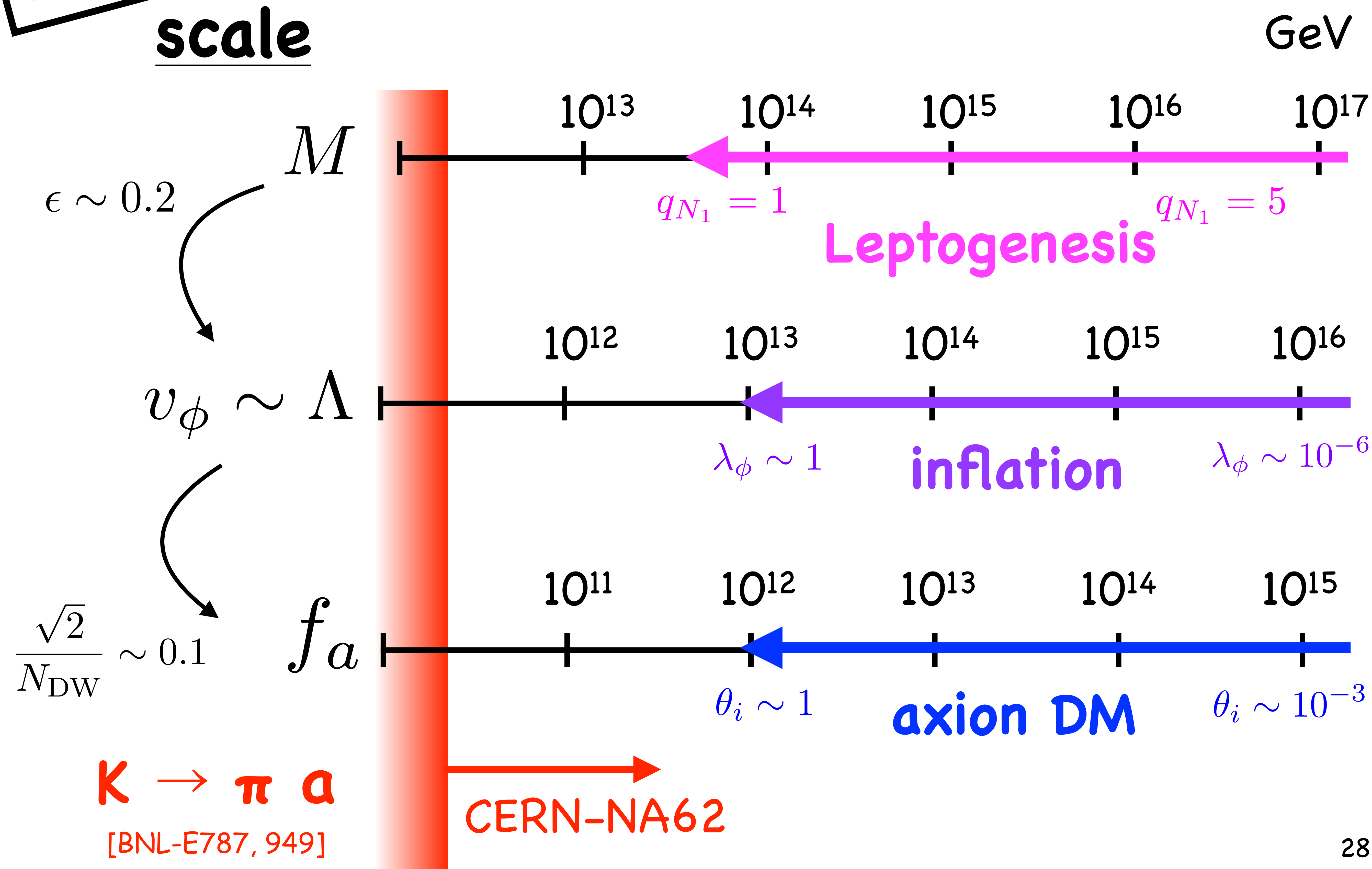
Summary

Flaxion Scenario

Lagrangian

$$\mathcal{L} = -\frac{|\partial\phi|^2}{\left(1-|\phi|^2/\Lambda^2\right)^2} - \lambda_\phi \left(|\phi|^2 - v_\phi^2\right)^2$$
$$+ y_{ij}^d \left(\frac{\phi}{M}\right)^{n_{ij}^d} \overline{Q}_i H d_{Rj} + y_{ij}^u \left(\frac{\phi}{M}\right)^{n_{ij}^u} \overline{Q}_i \widetilde{H} u_{Rj}$$
$$+ y_{ij}^l \left(\frac{\phi}{M}\right)^{n_{ij}^l} \overline{L}_i H l_{Rj} + y_{i\alpha}^\nu \left(\frac{\phi}{M}\right)^{n_{i\alpha}^\nu} \overline{L}_i \widetilde{H} N_{R\alpha}$$
$$+ \frac{1}{2} y_{\alpha\beta}^N \left(\frac{\phi}{M}\right)^{n_{\alpha\beta}^N} M \overline{N_{R\alpha}^c} N_{R\beta} + \text{h.c.}$$

Summary Flaxion Scenario



Supersymmetric flaxion ?

$$W = \lambda X(\phi\bar{\phi} - v_\phi^2)$$

- Cosmology becomes nontrivial; **gravitino, sflaxion**,...
- SUSY flavor/CP,
- R-parity violation,
- Inflation model,...

Y. Ema, D. Hagihara, KH, T. Moroi, K. Nakayama, arXiv:1802.07739.

Other constraints?

$$\left(\kappa^f_{\rm H}\right)_{ij} = \frac{1}{2}\left(V^{f\dagger}\widehat{q}_Q V^f - U^{f\dagger}\widehat{q}_f U^f\right)_{ij}(m^f_j + m^f_i),$$
$$\left(\kappa^f_{\rm AH}\right)_{ij} = \frac{1}{2}\left(V^{f\dagger}\widehat{q}_Q V^f + U^{f\dagger}\widehat{q}_f U^f\right)_{ij}(m^f_j - m^f_i).$$

- $K^+ \to \pi^+ a$

$$f_a \gtrsim 2\times 10^{10}\,\mathrm{GeV}\left(\frac{26}{N_{\rm DW}}\right)\left|\frac{(\kappa^d_{\rm AH})_{12}}{m_s}\right|$$

$$\mathrm{Br}(K^+ \to \pi^+ a) \lesssim 7.3\times 10^{-11}$$

$$\Gamma(K^+ \to \pi^+ a) = \frac{m_K^3}{32\pi v_\phi^2}\left(1-\frac{m_\pi^2}{m_K^2}\right)^3\left|\frac{(\kappa^d_{\rm AH})_{12}}{m_s - m_d}\right|^2$$

- $\mu \to e\, a\, \gamma$

$$f_a \gtrsim 1\times 10^{8}\,\mathrm{GeV}\left(\frac{26}{N_{\rm DW}}\right)\left|\frac{(\kappa^l_{\rm AH})_{12}}{m_\mu}\right|$$

$$\mathrm{Br}(\mu \to e a\gamma) \lesssim 1.1\times 10^{-9},$$

- SN1987A

$$\frac{f_a}{|C_N|} \gtrsim 1\times 10^9\,\mathrm{GeV}$$

$$\mathcal{L} = \sum_{N=p,n}\frac{C_N m_N}{f_a} ia\overline{N}\gamma_5 N$$

$C_p \simeq -0.4$ and $|C_n| \ll |C_p|$ for $N_{\rm DW} \gg 1$.

- cooling of the white dwarf stars. (g_{aee})

$$f_a \gtrsim 7\times 10^{7}\,\mathrm{GeV}\left(\frac{26}{N_{\rm DW}}\right)\left|\frac{(\kappa^l_{\rm H})_{11}}{m_e}\right|$$

Decay	Physics	Present limit	NA62
$\pi^+\mu^+e^-$	LFV	$1.3 \cdot 10^{-11}$	$0.7 \cdot 10^{-12}$
$\pi^+\mu^-e^+$	LFV	$5.2 \cdot 10^{-10}$	$0.7 \cdot 10^{-12}$
$\pi^-\mu^+e^+$	LNV	$5.0 \cdot 10^{-10}$	$0.7 \cdot 10^{-12}$
$\pi^-e^+e^+$	LNV	$6.4 \cdot 10^{-10}$	$2.0 \cdot 10^{-12}$
$\pi^-\mu^+e^+$	LNV	$1.1 \cdot 10^{-9}$	$0.4 \cdot 10^{-12}$
$\mu^-\nu e^+e^+$	LFV/LNV	$2 \cdot 10^{-8}$	$4.0 \cdot 10^{-12}$
$e^-\nu\mu^+\mu^+$	LNV	No data	$1.0 \cdot 10^{-12}$
$\pi^+\chi^0$	New particle	$5.9 \cdot 10^{-11}$, $M\chi = 0$	$1.0 \cdot 10^{-12}$
$\pi^+\chi\chi$	New particle	No data	$1.0 \cdot 10^{-12}$
$\pi^+\pi^+e^-\nu$	$\Delta S \neq \Delta Q$	$1.2 \cdot 10^{-8}$	$1.0 \cdot 10^{-11}$
$\pi^+\pi^+\mu^-\nu$	$\Delta S \neq \Delta Q$	$3.0 \cdot 10^{-6}$	$1.0 \cdot 10^{-11}$
$\pi^+\gamma$	Angular momentum	$2.3 \cdot 10^{-9}$	$1.0 \cdot 10^{-11}$
$\mu^+\nu_h, \nu_h \to \nu\gamma$	Heavy neutrino	Limits up to $M\nu_h = 350MeV/c^2$	$1.0 \cdot 10^{-12}$
R_K	LU	$(2.488 \pm 0.010) \cdot 10^{-5}$	2x better
$\pi^+\gamma\gamma$	ChPT	< 500 events	10^5 events
$\pi^0\pi^0e^+\nu$	ChPT	66000 events	$O(10^6)$ events
$\pi^0\pi^0\mu^+\nu$	ChPT		$O(10^5)$ events

Table 2: NA62 sensitivities for other rare decay channels

[arXiv:1407.8213]

The NA62 experiment at CERN: status and perspectives

NA62 Collaboration

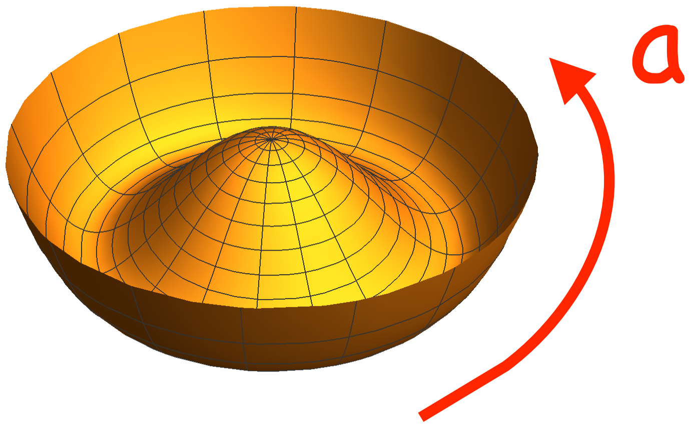
$B^+ \rightarrow K^+ \, a$??

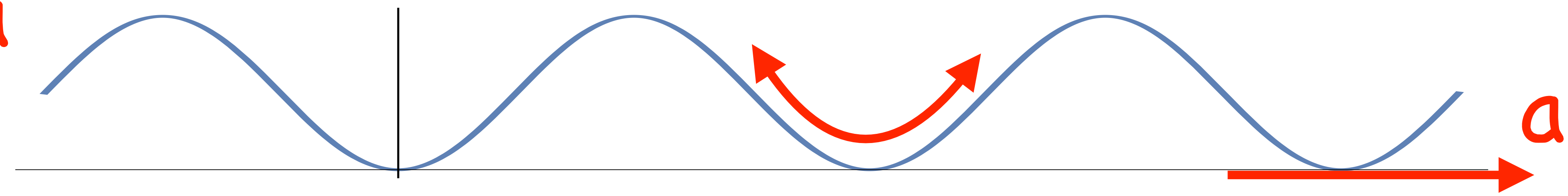
[arXiv:1612.08040] Phys.Rev. **D95** (2017) 095009
The Axiflavon
L. Calibbi, F. Goertz, D. Redigolo, R. Ziegler, J. Zupan

$$\mathrm{BR}(B^+ \to K^+ a) \simeq 1.4 \cdot 10^{-12} \Big(\underbrace{\frac{m_a}{0.1\,\mathrm{meV}}}_{\simeq \left(\frac{6\times 10^9\ \mathrm{GeV}}{f_a}\right)} \times \frac{\kappa_{bs}}{N} \Big)^2$$

$\kappa_{bs}/N \sim \mathcal{O}(1)$

Flaxion Dark Matter:



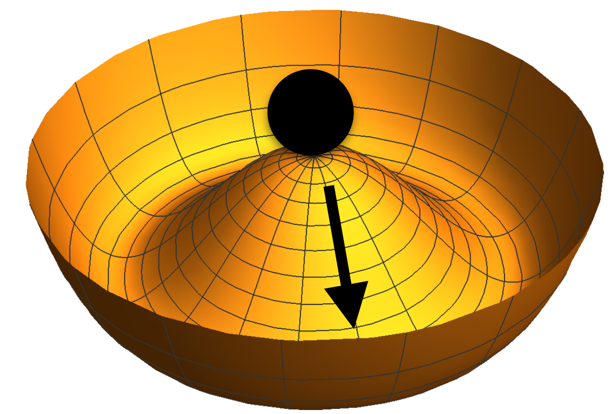


Case 1: U(1) is broken after inflation.

-> **Domain Wall !**

In the flaxion scenario, typically $N_{DW} \neq 1$,

and this possibility is **excluded**.



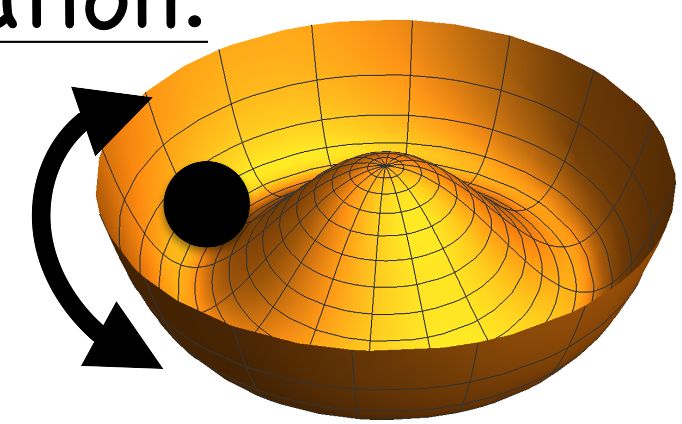
Case 2: U(1) was already broken during inflation.

Quantum fluctuation during inflation

leads to **DM isocurvature** perturbation,

which is severely constrained [Planck,'15].

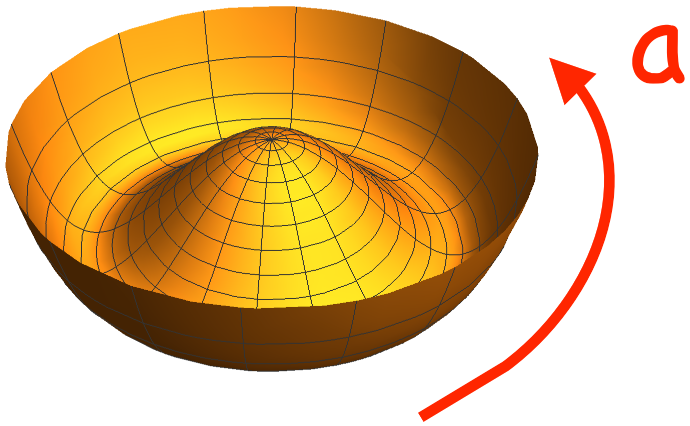
-> Strong bound on inflation scale.

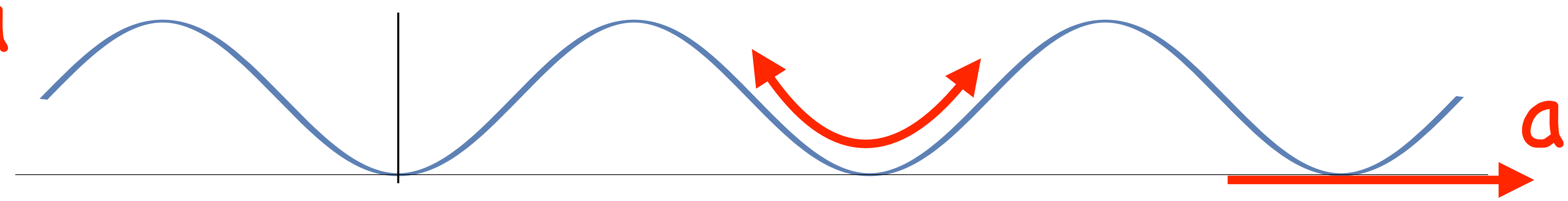


$\delta a \sim H_{\rm inf}$

$$H_{\rm inf} \lesssim 3 \times 10^7\,{\rm GeV}\,\theta_i^{-1} \left(\frac{10^{12}\,{\rm GeV}}{f_a}\right)^{0.19} .$$

Flaxion Dark Matter:





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$$\delta a \sim H_{\rm inf}$$

Case 2: U

Quantum flu

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which is seve

-> **Strong bo ... ion scale.**

$$H_{\rm inf} \lesssim 3 \times 10^7\,{\rm GeV}\,\theta_i^{-1} \left(\frac{10^{12}\,{\rm GeV}}{f_a}\right)^{0.19}.$$

No problem in "flaxion-inflation" scenario !

Flaxion Inflation:

$$\mathcal{L} = -\frac{|\partial\phi|^2}{(1-|\phi|^2/\Lambda^2)^2} - \lambda_\phi \left(|\phi|^2 - v_\phi^2\right)^2$$

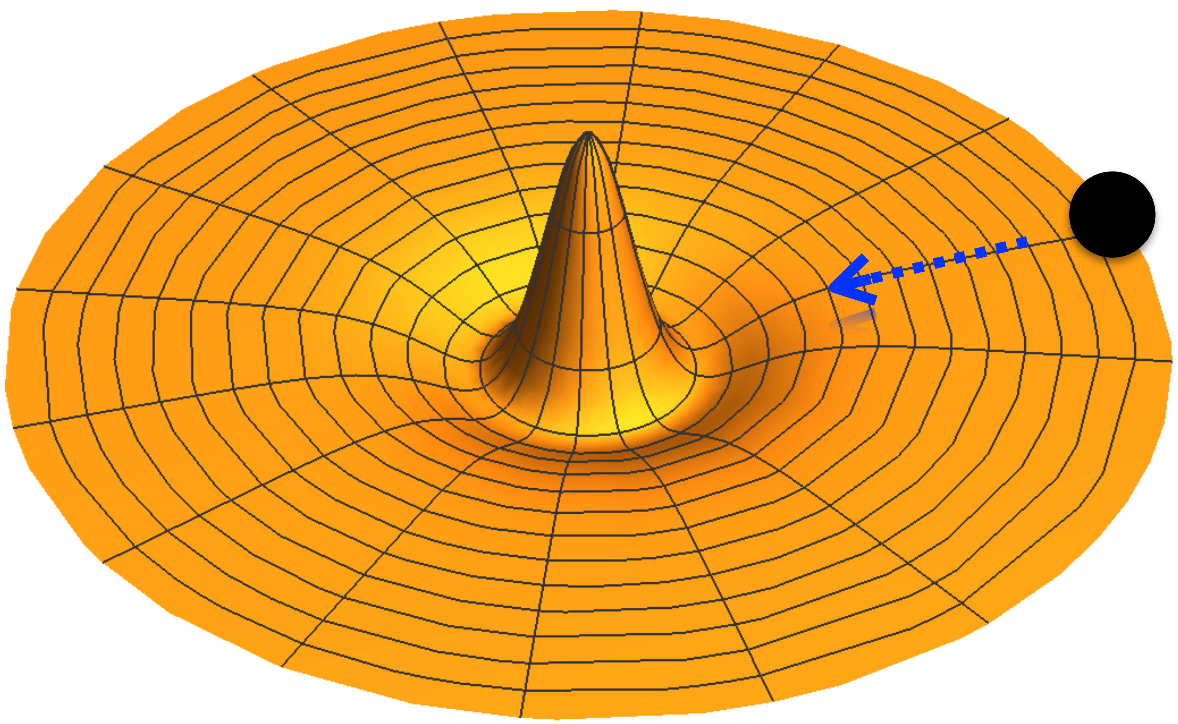
$$v_\phi < \Lambda < \sqrt{2} v_\phi$$

canonical field $\widetilde{\varphi}$:

$$\frac{\varphi}{\sqrt{2}\Lambda} \equiv \tanh\left(\frac{\widetilde{\varphi}}{\sqrt{2}\Lambda}\right)$$

- The U(1) symmetry is never restored

-> No Domain wall.



Flaxion Inflation:

$$v_\phi < \Lambda < \sqrt{2} v_\phi$$

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canonical field $\widetilde{\varphi}$:

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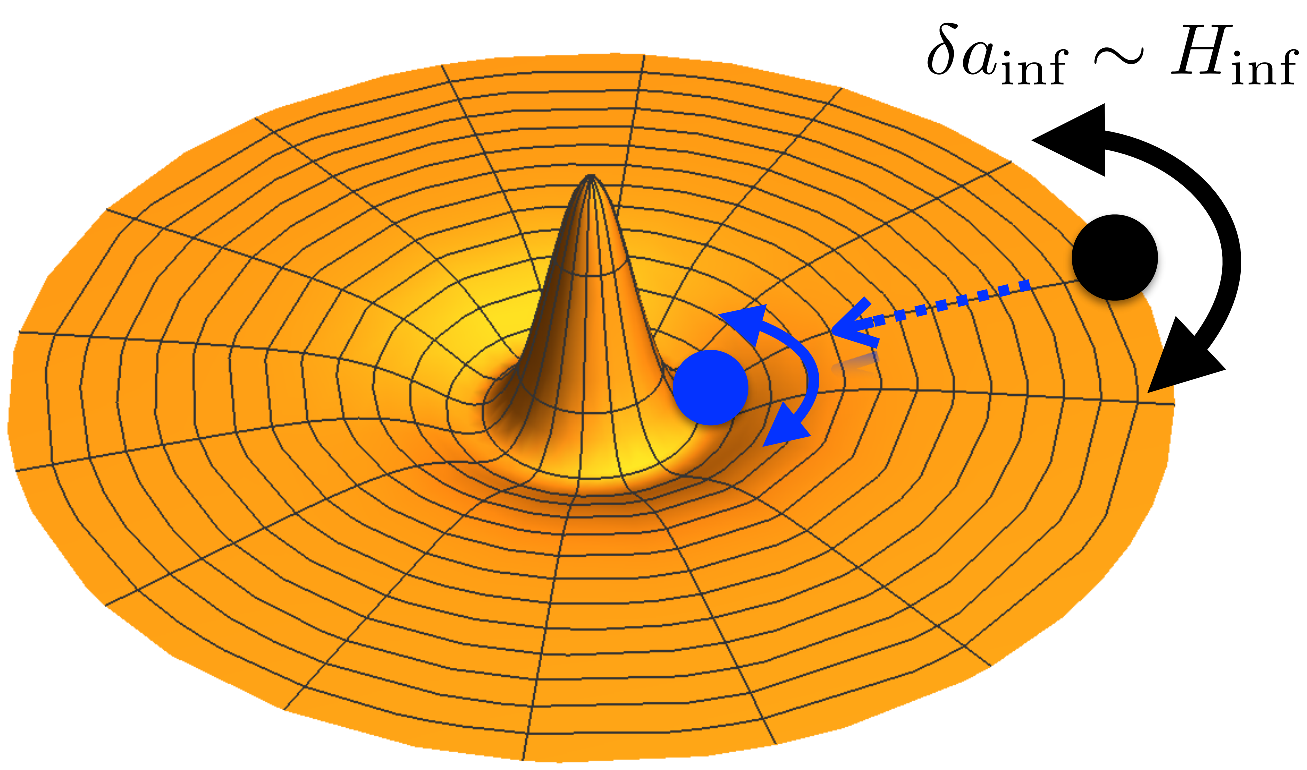
- The U(1) symmetry is never restored

  -> No Domain wall.

- Isocurvature fluctuation is suppressed.



Flaxion Inflation: Reheating and Leptogenesis

Inflaton partial decay rate into RHNs,

$$\Gamma(\widetilde{\varphi} \to N_R N_R) \simeq \sum_{\alpha\beta} \frac{|y^N_{\alpha\beta} n^N_{\alpha\beta} \epsilon^{n^N_{\alpha\beta}-1}|^2}{32\pi} \Delta^2 m_\varphi$$

$$\Delta \equiv 1 - v_\phi^2/\Lambda^2$$

$$m_\varphi \sim 3 \times 10^{13}\,\mathrm{GeV}(v_\phi/\Lambda)$$

$$\gg$$

$$H_{\rm inf} \simeq 5 \times 10^8\,\mathrm{GeV}\left(\frac{\Lambda}{10^{14}\,\mathrm{GeV}}\right).$$

Reheating is completed almost instantaneously.

Reheating temperature

$$T_R \sim 10^{12} - 10^{14}\mathrm{GeV}.$$

Flaxion Inflation: Reheating and Leptogenesis

... and **thermal leptogenesis** [Fukugita-Yanagida,'86]

can work successfully for $m_{N1} \simeq O(10^{12})$ GeV !

In more details,...

Final baryon asymmetry: $\frac{n_B}{s} \simeq \epsilon_1 \kappa_f \frac{28}{79} \left(\frac{n_{N_1}}{s}\right)_{\rm th} \simeq 1.3 \times 10^{-3} \epsilon_1 \kappa_f$,

Asymmetry parameter: $\epsilon_1 = \frac{3}{16\pi} \frac{m_{N_1} m_{\nu_3}}{v_{\rm EW}^2} \delta_{\rm eff} \simeq 1 \times 10^{-4} \left(\frac{m_{N_1}}{10^{12}\,{\rm GeV}}\right) \left(\frac{m_{\nu 3}}{0.05\,{\rm eV}}\right) \delta_{\rm eff}$

Effective neutrino mass: $\widetilde{m}_{\nu 1} \equiv \sum_k |\epsilon^{n^\nu_{k1}} y^\nu_{k1}|^2 v_{\rm EW}^2 / m_{N_1} \sim m_{\nu_3}$

-> Efficiency factor $\kappa_f \sim 3 \times 10^{-3}$ (strong washout region)

Altogether, observed asymmetry $n_B/s \simeq 0.9 \times 10^{-10}$ can be obtained for $m_{N1} \simeq O(10^{12})$ GeV, corresponding to

$q_{N_1} = 1 - 5$ for $M \sim O(10^{14}\text{–}10^{17})$ GeV

Proton decay ?

$$\mathcal{L} \sim \frac{QQQL}{M^2}, \quad \frac{uude}{M^2}, \quad \frac{QQue}{M^2}, \quad \frac{QLud}{M^2}$$

—> In the case of example charge assignments, the most dangerous one is the last one.
With O(1) coefficients,

$$M > 5 \times 10^{14} \text{ GeV}$$

is sufficient to suppress it.