

Flaxion

a minimal extension to solve puzzles in the standard model

Koichi Hamaguchi (University of Tokyo)

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Based on

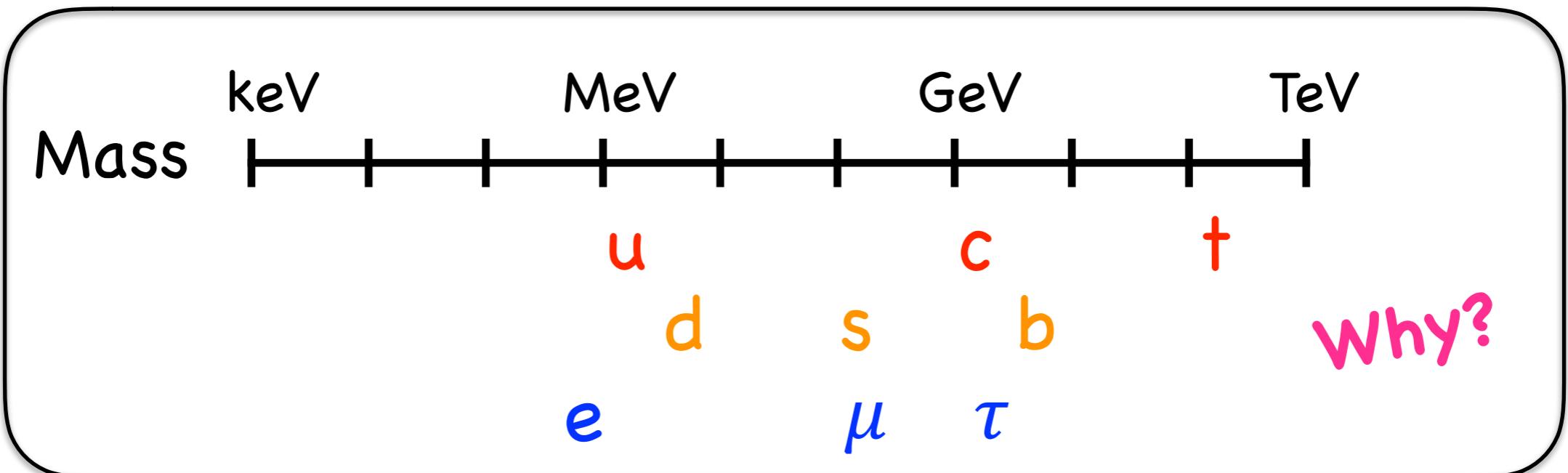
Y. Ema, KH, T. Moroi, K. Nakayama, arXiv:1612.05492 [JHEP 1701 (2017) 096],
Y. Ema, D. Hagihara, KH, T. Moroi, K. Nakayama, in preparation.

Summary:

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

Summary (2):

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



and solves the strong CP problem.

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

$|\bar{\theta}| \lesssim 10^{-10}$ from neutron EDM Why?

Summary (3):

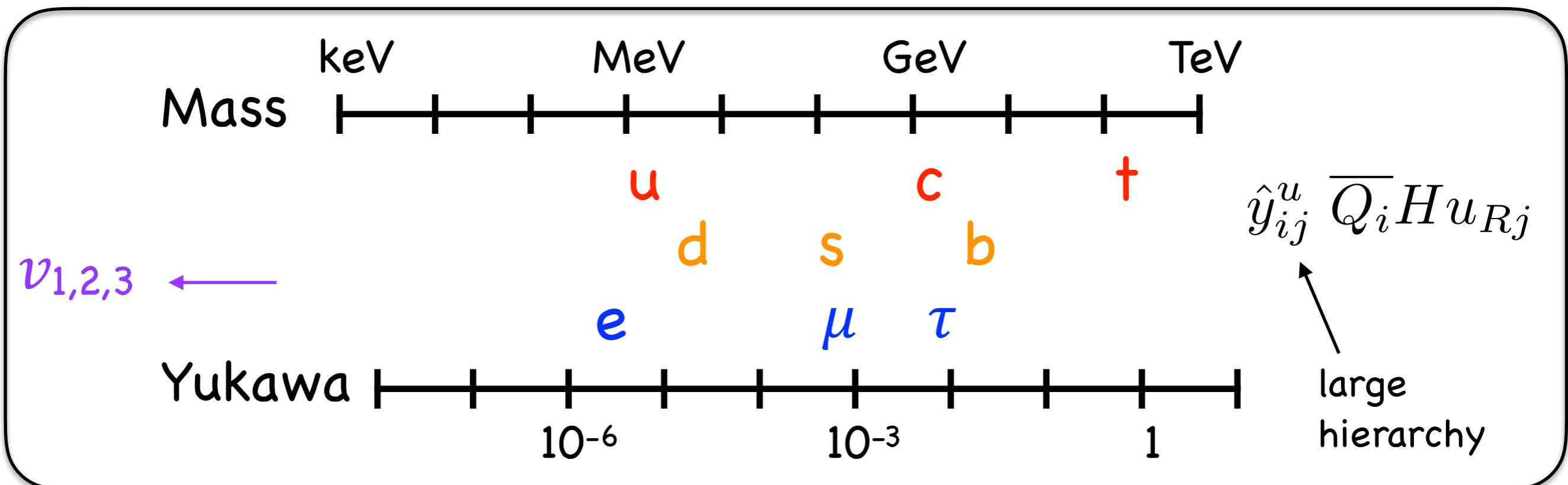
Flavon



Axion

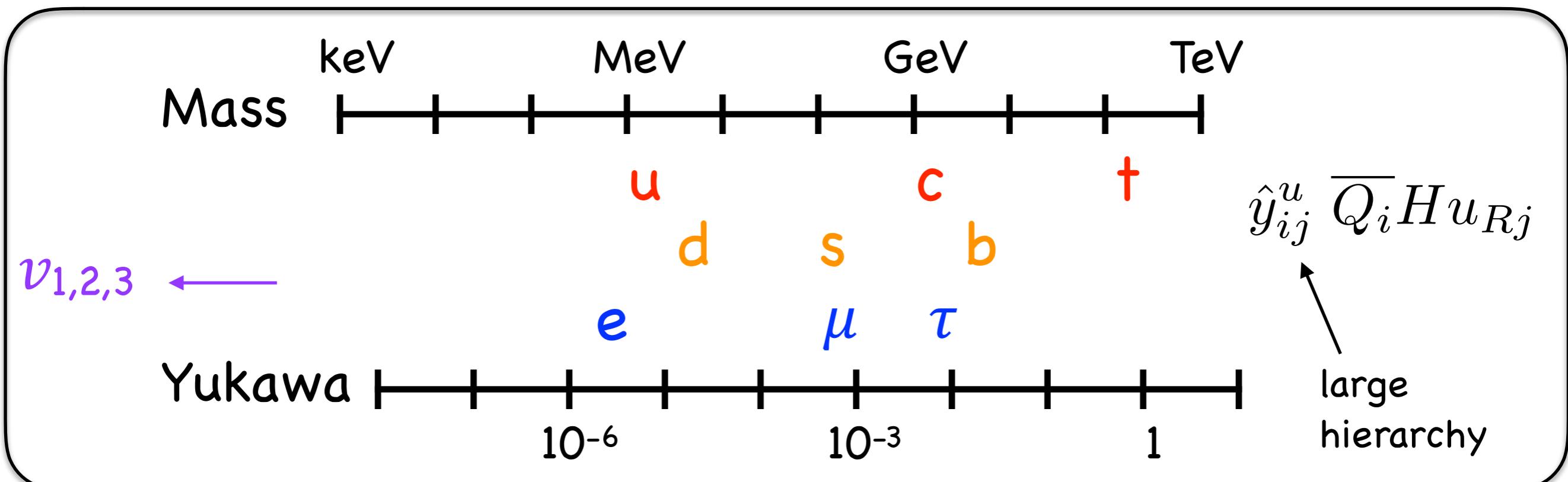


Q: What's the origin of
the quark and lepton mass hierarchy and mixings ??

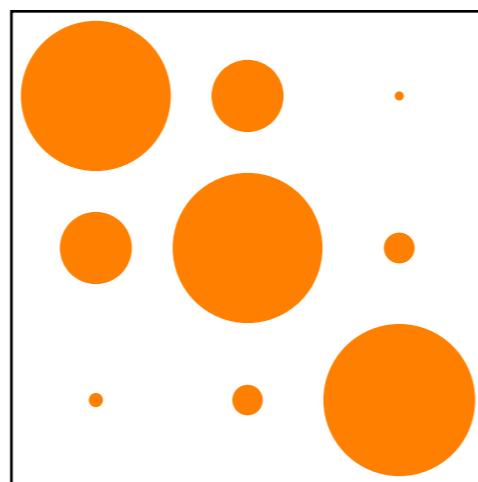


$$(\text{Mass}) = (\text{Yukawa}) \times (\text{Higgs VEV } \langle H \rangle = 174 \text{ GeV})$$

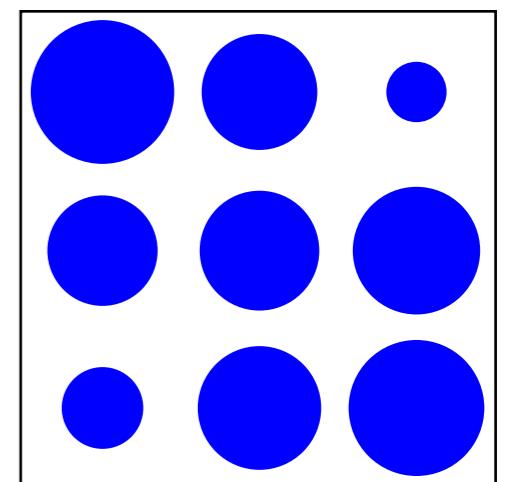
Q: What's the origin of
the quark and lepton mass hierarchy and mixings ??



quark mixing



neutrino mixing



A simple possibility:

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

$$\hat{y}_{ij}^u \overline{Q}_i H u_{Rj}$$



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	$\phi \leftarrow$	New complex scalar:
U(1) charge	q_{Q_i}	q_{u_j}	0	+1	Flavon

$$\hat{y}_{ij}^u \bar{Q}_i H u_{Rj}$$



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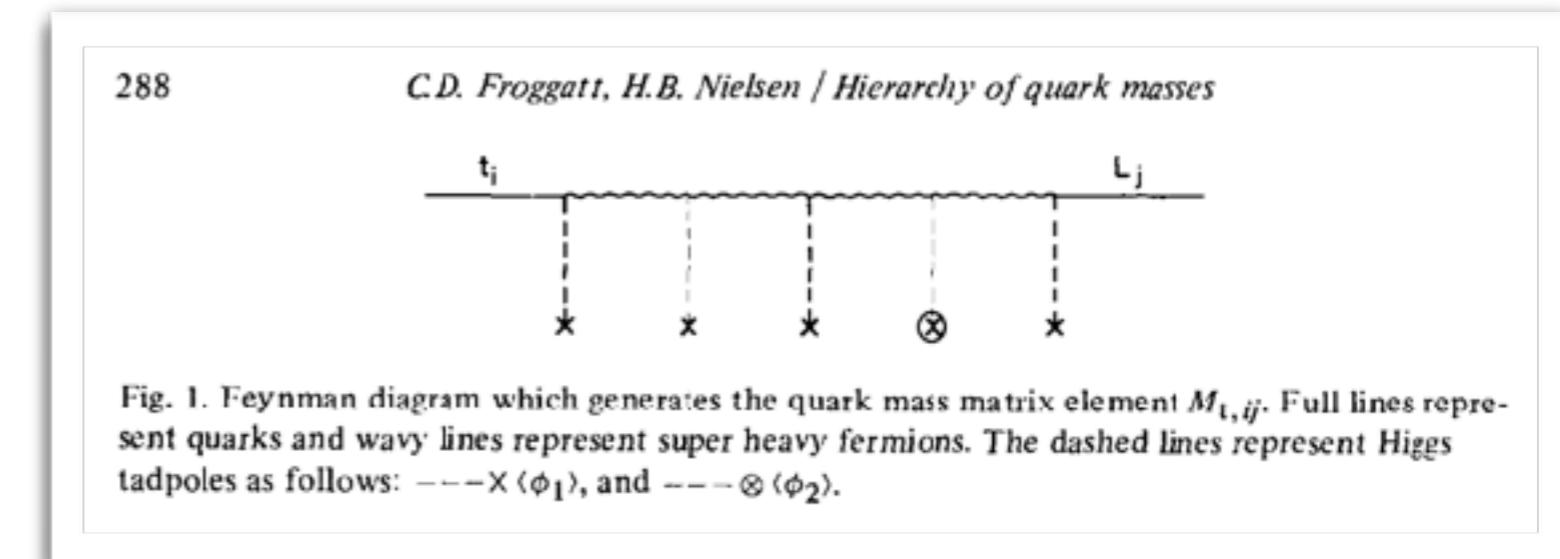
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	Q_i	u_{R_j}	H	ϕ	New complex scalar: Flavon
U(1) charge	qQ_i	q_{u_j}	0	+1	

$$\cancel{\hat{y}_{ij}^u \bar{Q}_i H u_{Rj}} \rightarrow y_{ij}^u \left(\frac{\phi}{M}\right)^{qQ_i - q_{u_j}} \bar{Q}_i H u_{Rj}$$

cutoff scale

up-type quark
Yukawa couplings
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→ After U(1) breaking by $\langle\phi\rangle \neq 0$,

$$m_{ij}^u = y_{ij}^u \underbrace{\epsilon^{q_{Q_i} - q_{u_j}}}_{O(1)} \langle H \rangle$$

Mass hierarchy
and mixings

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

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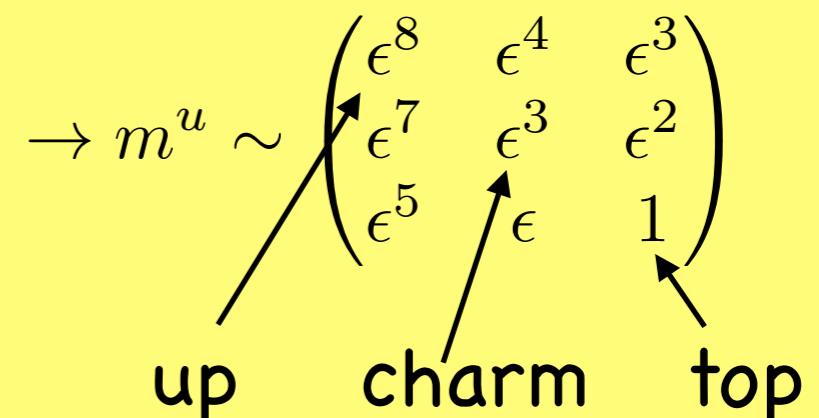
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Mass hierarchy
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where $\frac{\langle\phi\rangle}{M} \equiv \epsilon < 1$

Example:

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



A simple possibility:

a spontaneously broken global U(1) symmetry.

[Froggatt-Nielsen,'79]

$$\mathcal{L} = y_{ij}^d \left(\frac{\phi}{M} \right)^{n_{ij}^d} \bar{Q}_i H d_{Rj} + y_{ij}^u \left(\frac{\phi}{M} \right)^{n_{ij}^u} \bar{Q}_i \tilde{H} u_{Rj}$$

Our setup:

$$+ y_{ij}^l \left(\frac{\phi}{M} \right)^{n_{ij}^l} \bar{L}_i H l_{Rj} + y_{i\alpha}^\nu \left(\frac{\phi}{M} \right)^{n_{i\alpha}^\nu} \bar{L}_i \tilde{H} N_{R\alpha}$$
$$+ \frac{1}{2} y_{\alpha\beta}^N \left(\frac{\phi}{M} \right)^{n_{\alpha\beta}^N} M \overline{N_{R\alpha}^c} N_{R\beta} + \text{h.c.}$$

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

$$\begin{cases} n_{ij}^u = q_{Q_i} - q_{u_j}, \\ n_{ij}^d = q_{Q_i} - q_{d_j}, \\ n_{ij}^l = q_{L_i} - q_{l_j}, \\ n_{i\alpha}^\nu = q_{L_i} - q_{N_\alpha} \\ n_{\alpha\beta}^N = -q_{N_\alpha} - q_{N_\beta}. \end{cases}$$

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

We have also introduced
(2 or 3) right-handed neutrinos.

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

$$\left\{ \begin{array}{l} q_Q = \{3, 2, 0\}, \\ q_u = \{-5, -1, 0\}, \\ q_d = \{-4, -3, -3\} \end{array} \right. \rightarrow \left\{ \begin{array}{l} m_{ij}^u \sim \begin{pmatrix} \epsilon^8 & \epsilon^4 & \epsilon^3 \\ \epsilon^7 & \epsilon^3 & \epsilon^2 \\ \epsilon^5 & \epsilon & 1 \end{pmatrix} \langle H \rangle, \\ m_{ij}^d \sim \begin{pmatrix} \epsilon^7 & \epsilon^6 & \epsilon^6 \\ \epsilon^6 & \epsilon^5 & \epsilon^5 \\ \epsilon^4 & \epsilon^3 & \epsilon^3 \end{pmatrix} \langle H \rangle, \end{array} \right. \rightarrow \left\{ \begin{array}{l} \text{diag}(m_u) \sim (\epsilon^8, \epsilon^3, 1) \langle H \rangle, \quad u, c, t \\ \text{diag}(m_d) \sim (\epsilon^7, \epsilon^5, \epsilon^3) \langle H \rangle, \quad d, s, b \\ V_{\text{CKM}} \sim \begin{pmatrix} 1 & \epsilon & \epsilon^3 \\ \epsilon & 1 & \epsilon^2 \\ \epsilon^3 & \epsilon^2 & 1 \end{pmatrix} \end{array} \right.$$

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

$$\left\{ \begin{array}{l} q_L = \{1, 0, 0\}, \\ q_e = \{-8, -5, -3\}, \\ q_N = \{q_{N_1}, q_{N_2}, (q_{N_3})\} \end{array} \right. \rightarrow \left\{ \begin{array}{l} m_{ij}^\ell \sim \begin{pmatrix} \epsilon^9 & \epsilon^6 & \epsilon^4 \\ \epsilon^8 & \epsilon^5 & \epsilon^3 \\ \epsilon^8 & \epsilon^5 & \epsilon^3 \end{pmatrix} \langle H \rangle, \\ m_{ij}^\nu \sim \begin{pmatrix} \epsilon^2 & \epsilon & \epsilon \\ \epsilon & 1 & 1 \\ \epsilon & 1 & 1 \end{pmatrix} \frac{\langle H \rangle^2}{M}, \end{array} \right. \rightarrow \left\{ \begin{array}{l} \text{diag}(m_e) \sim (\epsilon^9, \epsilon^5, \epsilon^3) \langle H \rangle, \quad e, \mu, \tau \\ \text{diag}(m_\nu) \sim (\epsilon^2, 1, 1) \frac{\langle H \rangle^2}{M}, \\ V_{\text{MNS}} \sim \begin{pmatrix} 1 & \epsilon & \epsilon \\ \epsilon & 1 & 1 \\ \epsilon & 1 & 1 \end{pmatrix} \end{array} \right.$$

q_N-dependence cancels
 because of the **seesaw formula**. large 2-3 mixing

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

Standard Model

Quark and lepton
mass hierarchy
and mixings.

Neutrino
masses
and mixings.

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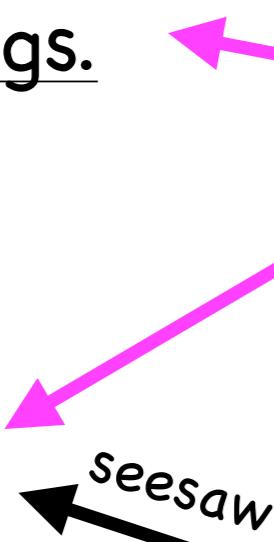
Neutrino
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Standard Model

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

ϕ : **flavon**

- + 2 (or 3)
right-handed
neutrinos.



Our setup: $\mathcal{L} = y_{ij}^d \left(\frac{\phi}{M} \right)^{n_{ij}^d} \bar{Q}_i H d_{Rj} + y_{ij}^u \left(\frac{\phi}{M} \right)^{n_{ij}^u} \bar{Q}_i \tilde{H} u_{Rj}$

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can explain the quark and lepton mass hierarchy and mixings.

OK, but..... **What's new?**

Froggatt-Nielsen paper was in 1979.....

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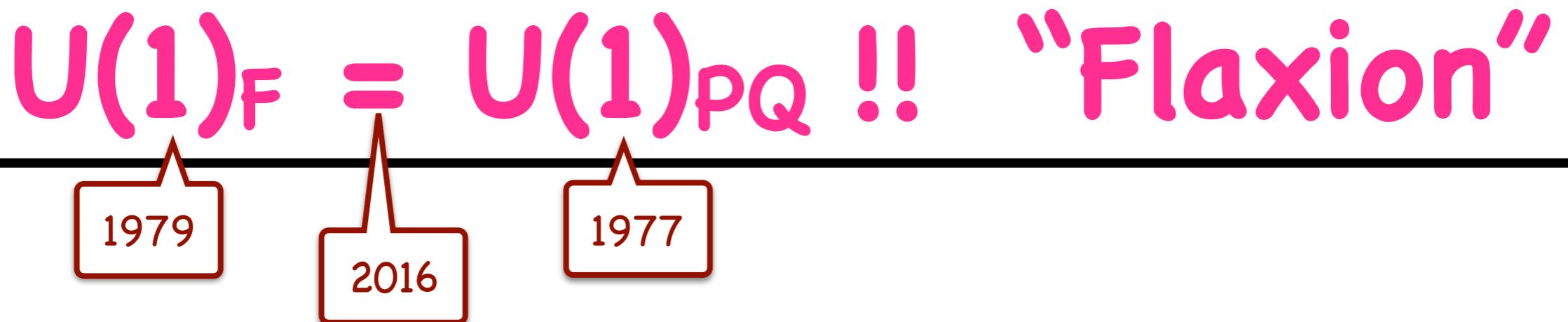
POINT: The global, spontaneously broken U(1) flavor symmetry is **anomalous** under SU(3)_C, which means... the Peccei-Quinn mechanism (to solve the strong CP problem) is automatically included:

U(1)_F = U(1)_{PQ} !! “Flaxion”

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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:



* 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 Axiflavor

[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

$$\phi_{\text{flavon}} = \frac{1}{\sqrt{2}} (\varphi + ia_{\text{axion}})$$

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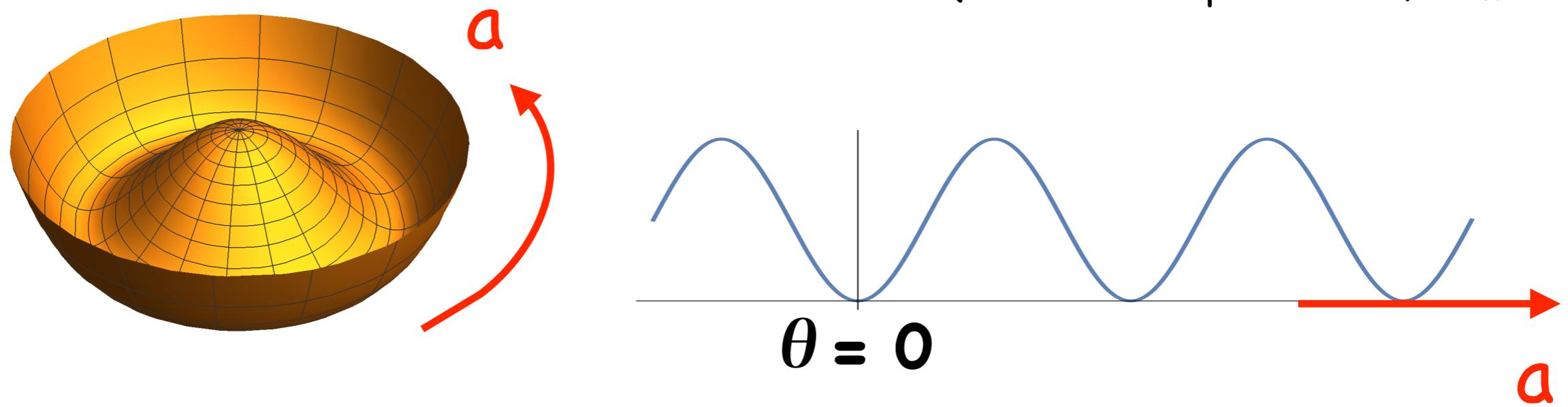
flavonaxion

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

[Peccei-Quinn,'77]

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

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

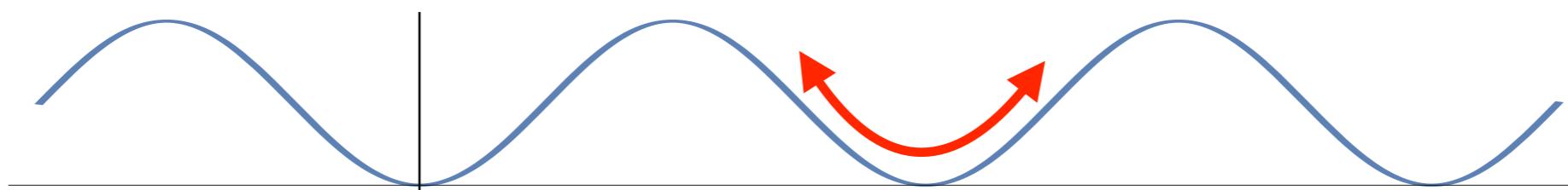


Flaxion

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

flavon axion

- (1) Strong CP problem is solved by the PQ mechanism.
- (2) The axion can be the dark matter.



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

[Turner, '86]

Flaxion

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Any new prediction?

Flaxion

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flavon axion

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Any new prediction?
.....Yes!

- (3) Characteristic flavor-changing signals are predicted.

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

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

*They are not simultaneously diagonalized.
→ flavor changing processes.*

The most stringent bound comes from $K^+ \rightarrow \pi^+ a$.

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

[BNL-E787, E949]

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

CERN-NA62 experiment will improve the sensitivity soon !!

Flaxion Scenario

Quark and lepton mass hierarchy and mixings.

Neutrino masses and mixings. seesaw

Standard Model

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

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

flavon

- + 2 (or 3) right-handed neutrinos.

Strong CP problem.

Dark Matter.

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characteristic signal:
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What about
the real part?

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flavon **inflaton** **axion**

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Inflation !

Flaxion Inflation:

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

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

canonical field $\tilde{\varphi}$:

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

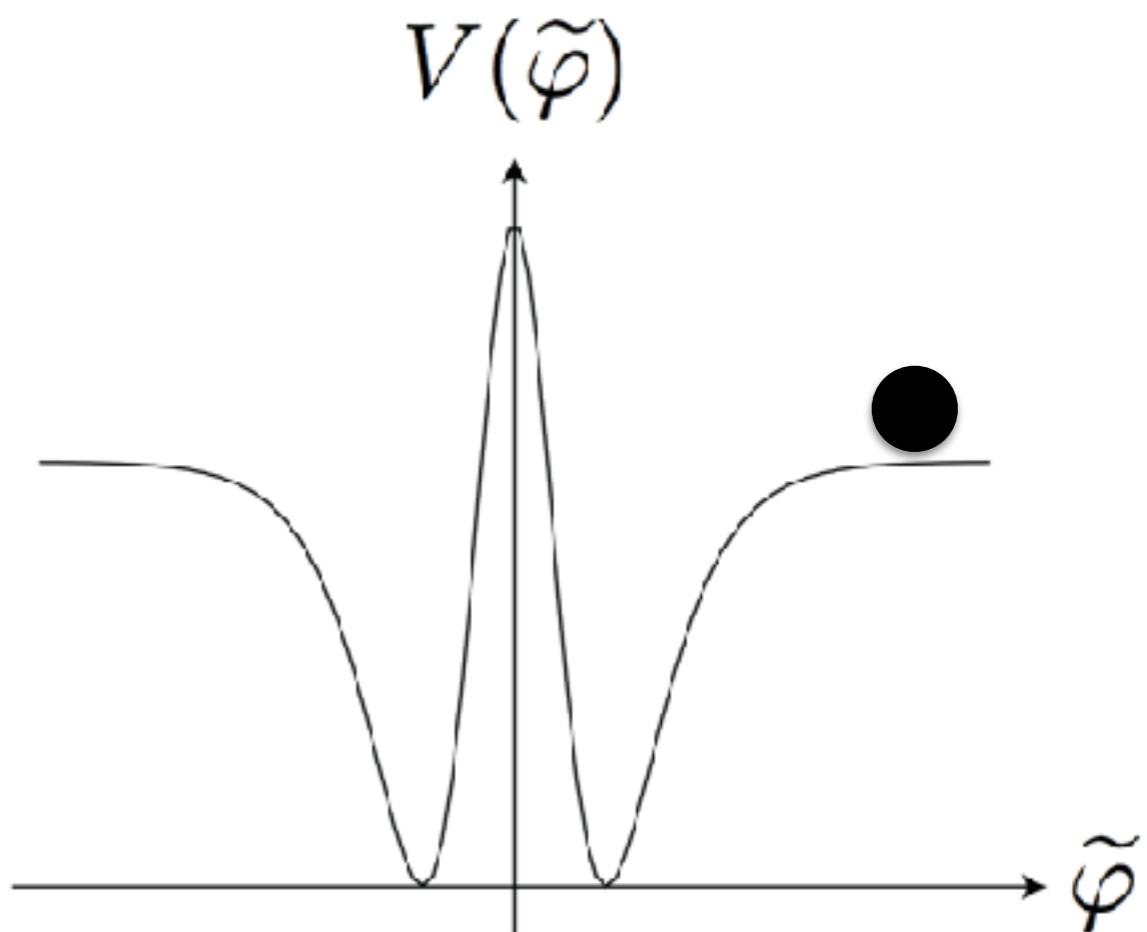
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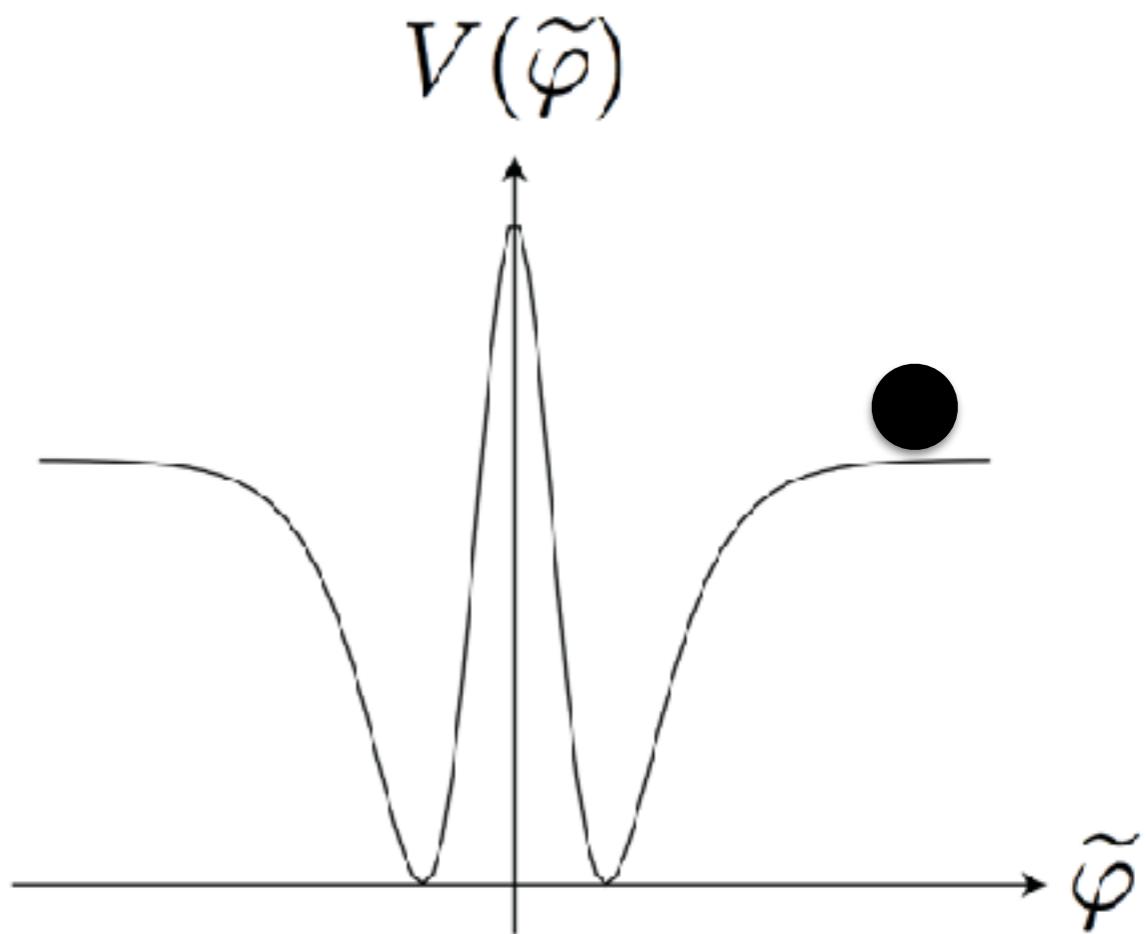
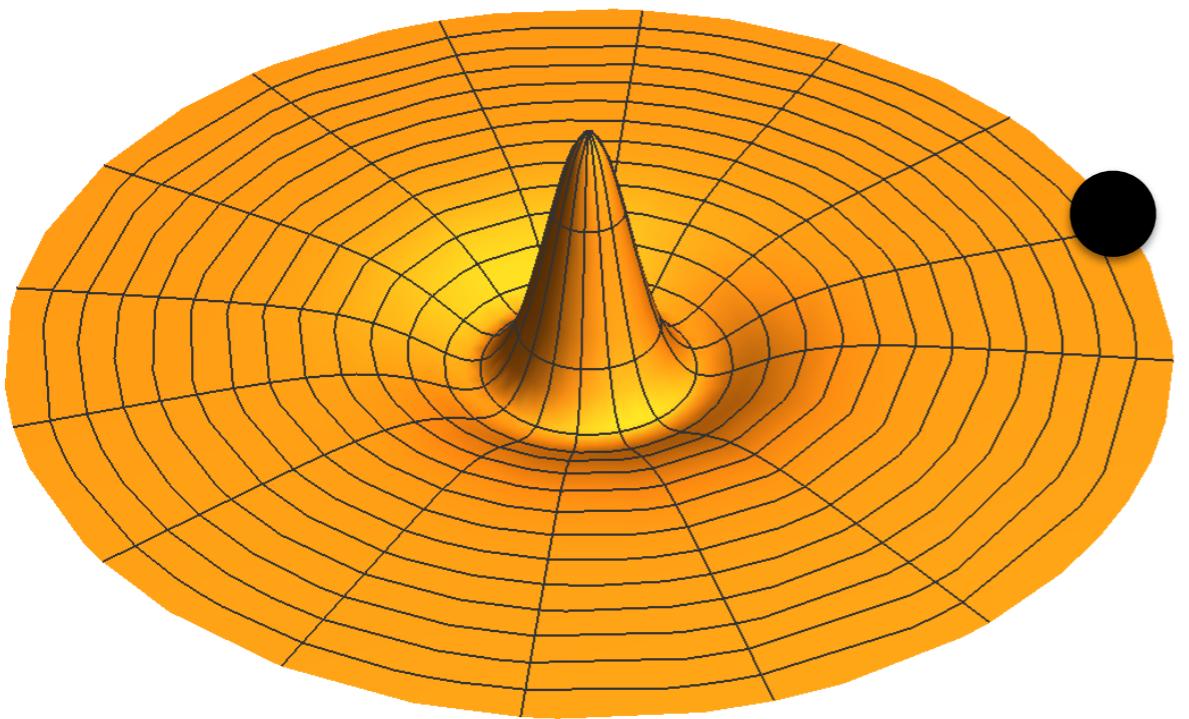
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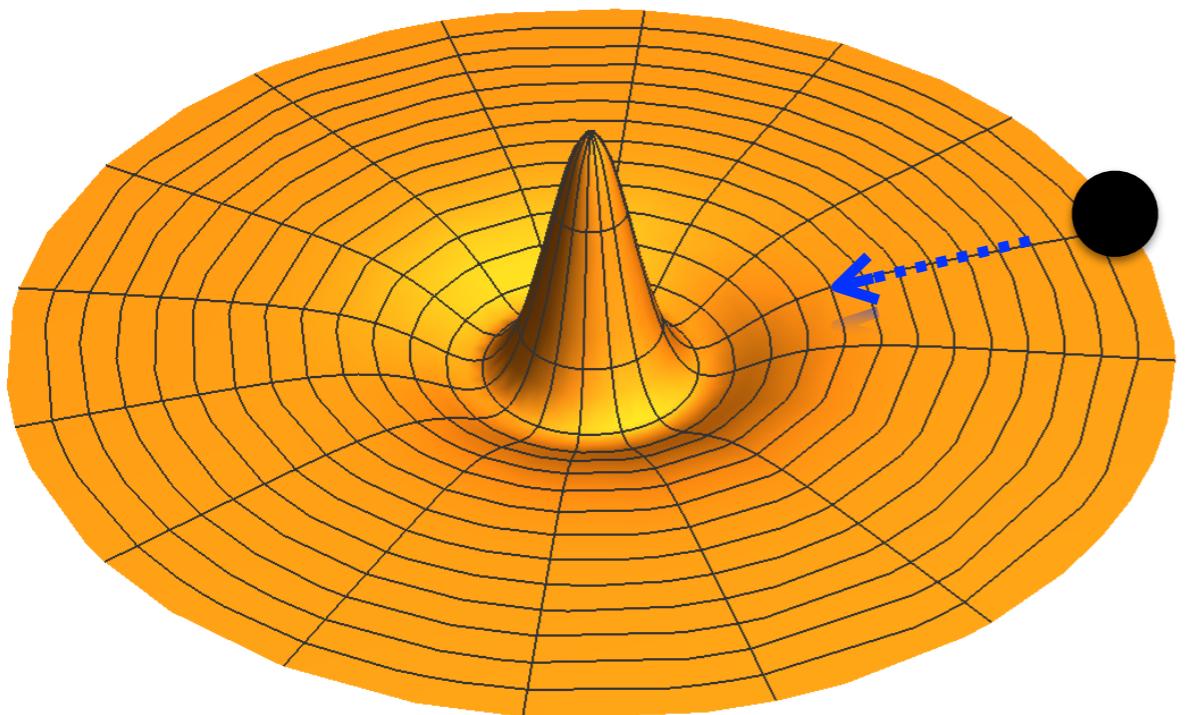
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(1) The U(1) symmetry is never restored

-> No Domain wall.



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

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

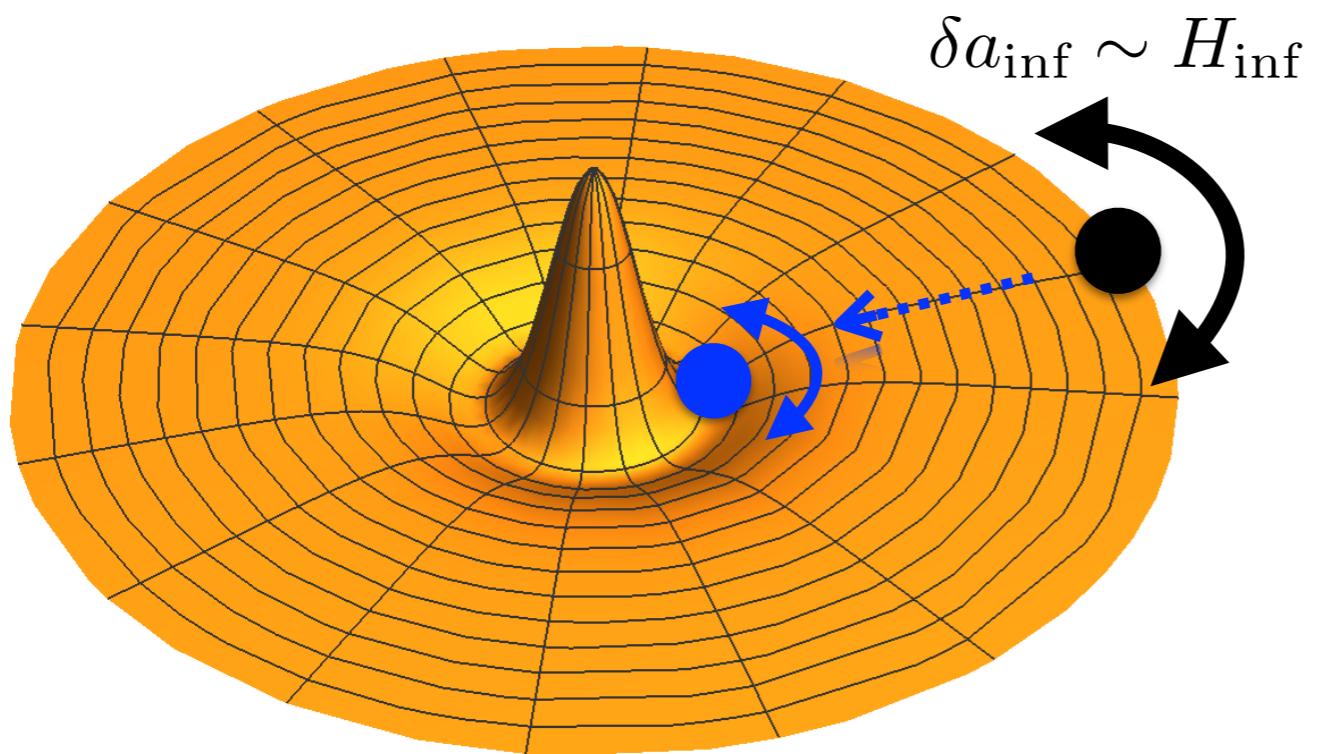
canonical field $\tilde{\varphi}$:

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

(1) The U(1) symmetry is never restored

-> No Domain wall.

(2) Isocurvature fluctuation is suppressed.



Flaxion Inflation:

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

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(3) Observed curvature fluctuation, $P_\xi = 2.2 \times 10^{-9}$ [Planck,'15]

is reproduced for $\lambda_\phi \lesssim 1$ and $\Lambda \gtrsim 10^{13} \text{ GeV}$,

which is consistent with the scale for flaxion DM.

$$f_a \sim v_\phi/N_{\text{DW}} \sim \Lambda/N_{\text{DW}} \gtrsim 10^{12} \text{ GeV}.$$

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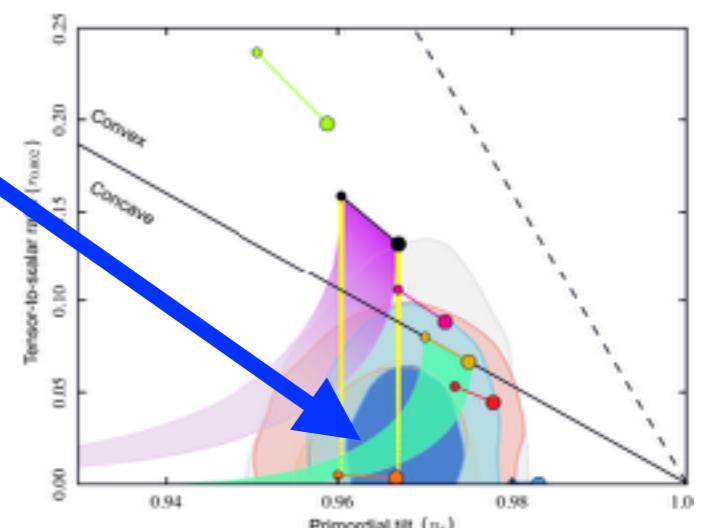
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(4) (n_s, r) is in the Planck best-fit region.

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



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

(5) Reheating temperature is high enough for Leptogenesis.

More on this next

Flaxion Scenario

Quark and lepton mass hierarchy and mixings.

Neutrino masses and mixings.

seesaw



Standard Model

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

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

flavon
 inflaton
 axion

+ 2 (or 3)
right-handed
neutrinos.

characteristic
signal:
 $K \rightarrow \pi^+ \pi^-$

Strong CP

Dark Matter.

Inflation.

Flaxion Scenario

Quark and lepton mass hierarchy and mixings.

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seesaw



A pink arrow points from the top right towards the word 'Neutrino'. A black arrow points from the bottom right towards the same word.

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

Flaxion Inflation: Reheating and Leptogenesis

Inflaton partial decay rate into RHNs,

$$\Gamma(\tilde{\varphi} \rightarrow N_R N_R) \simeq \sum_{\alpha\beta} \frac{|y_{\alpha\beta}^N n_{\alpha\beta}^N \epsilon^{n_{\alpha\beta}^N - 1}|^2}{32\pi} \Delta^2 m_\varphi$$

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

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



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

Reheating is completed almost instantaneously.

Reheating temperature

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

Flaxion Inflation: Reheating and Leptogenesis

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

can work successfully for $m_{N_1} \simeq O(10^{12}) \text{ GeV}$!

In more details,...

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

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

Effective neutrino mass: $\tilde{m}_{\nu_1} \equiv \sum_k |\epsilon^{n_{k_1}^\nu} y_{k1}^\nu|^2 v_{\text{EW}}^2 / m_{N_1} \sim m_{\nu_3}$

-> 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 $m_{N_1} \simeq O(10^{12}) \text{ GeV}$, corresponding to

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

Flaxion Scenario

Quark and lepton mass hierarchy and mixings.

Neutrino masses and mixings. seesaw

Baryon asymmetry of the Universe.

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flavon **inflaton** **axion**

+ 2 (or 3) right-handed neutrinos.

characteristic signal:
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Strong CP problem.

Dark Matter.

solves DW and isocurvature problems

P_ξ & (n_s, r)
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Inflation.

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

Inflation.

High enough reheating

Leptogenesis

seesaw

Summary Flaxion Scenario

Lagrangian

Summary

Flaxion Scenario

Lagrangian

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

Summary

Flaxion Scenario

Quark and lepton mass hierarchy and mixings.

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P_ξ & (n_s, r)
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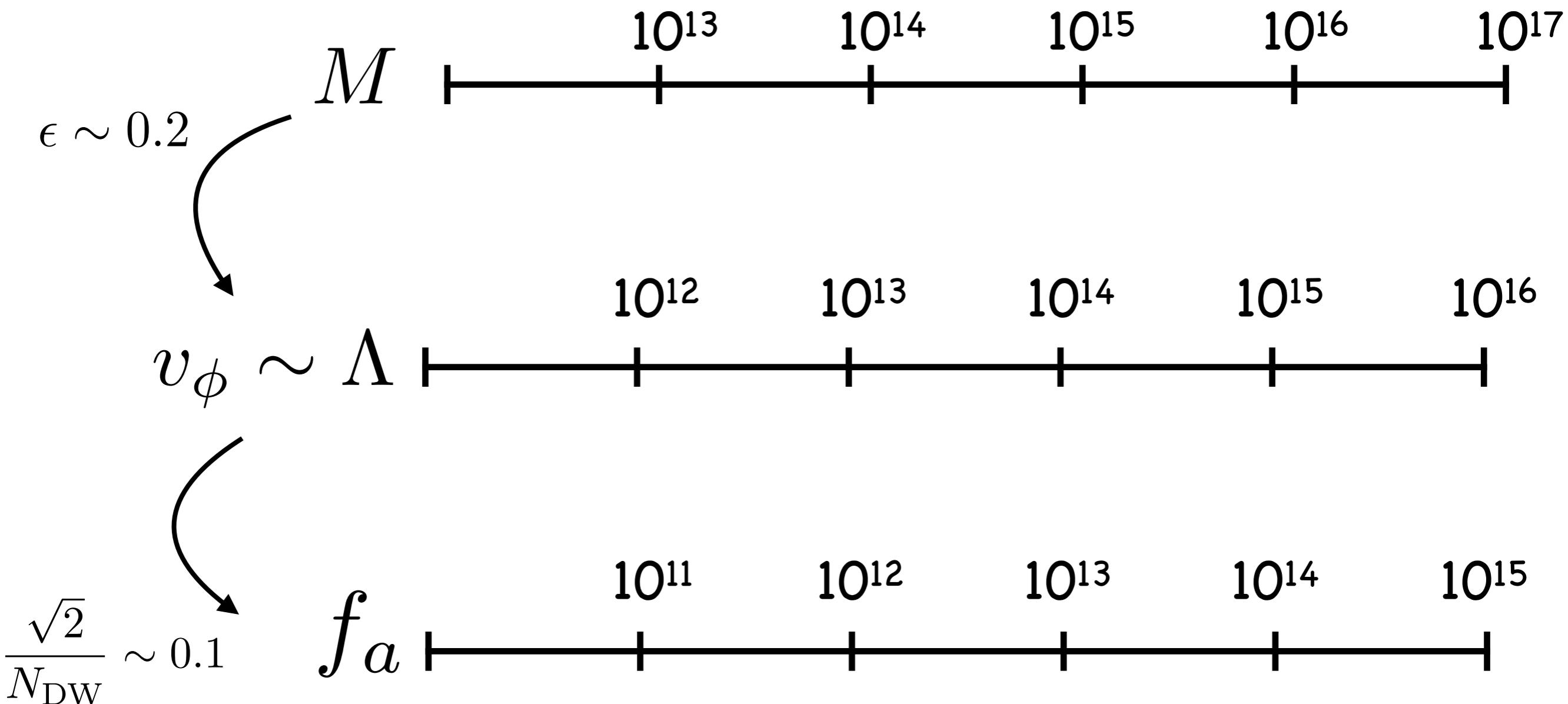
Inflation.

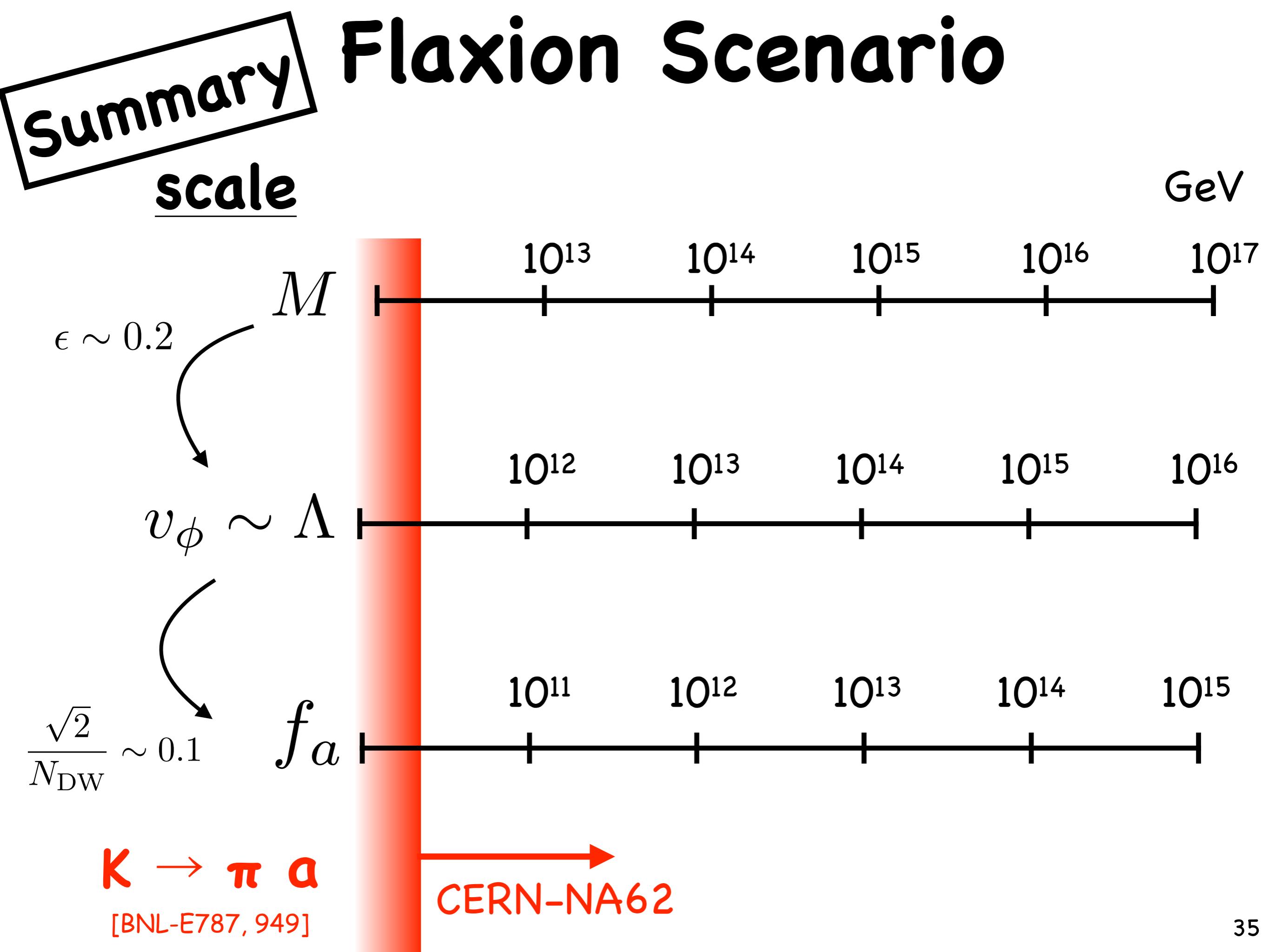
High enough reheating

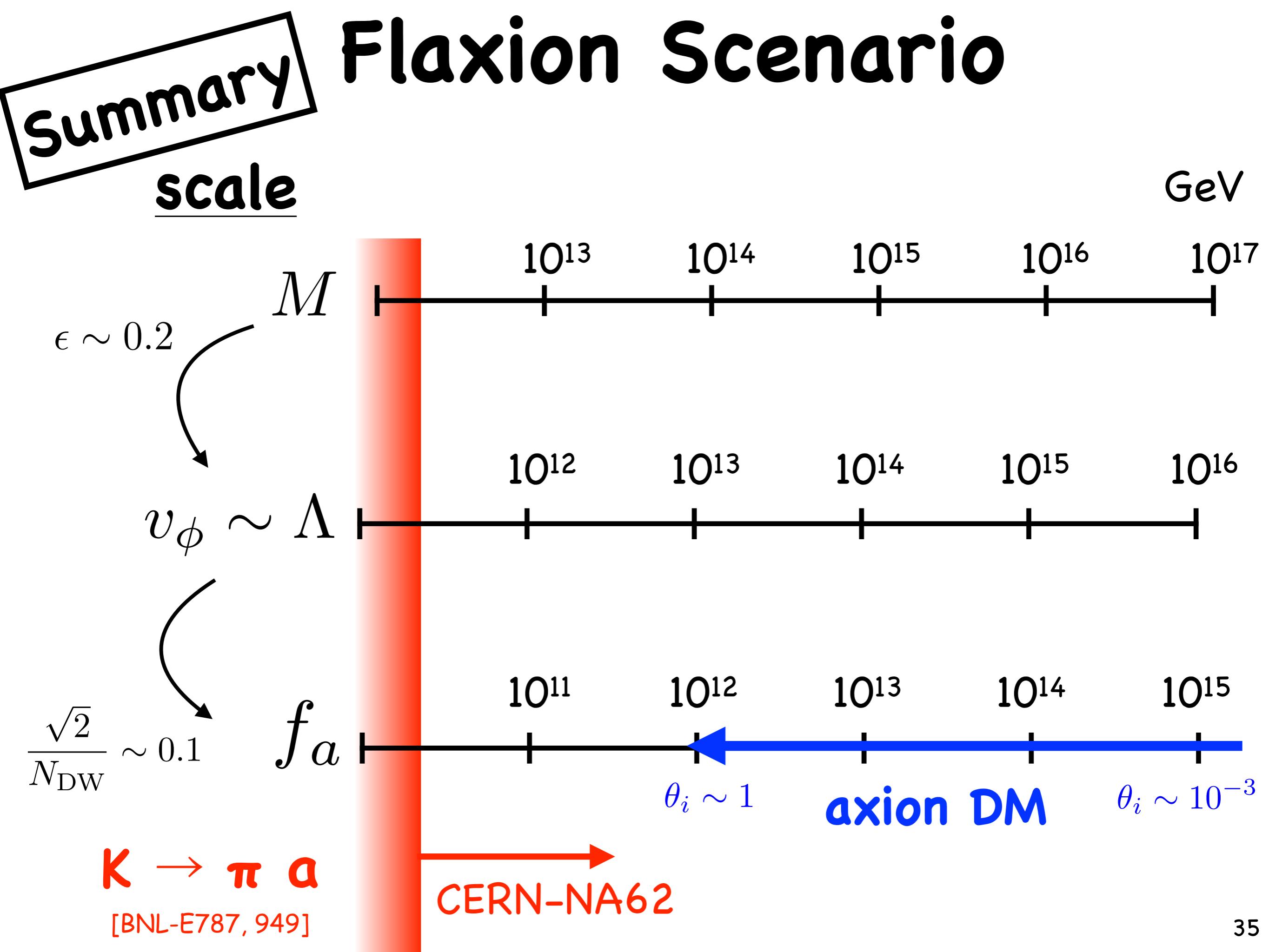
Flaxion Scenario

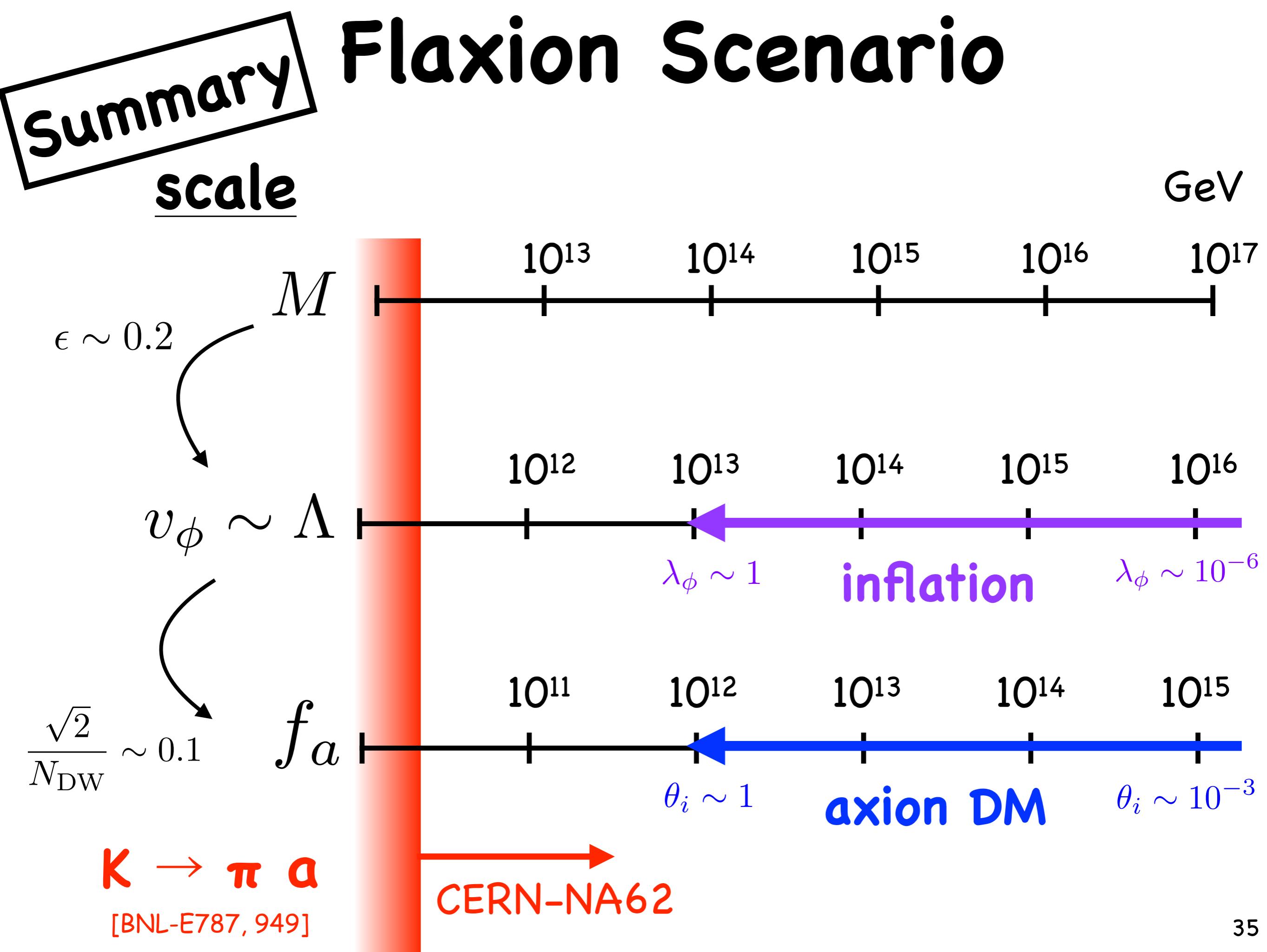
Summary

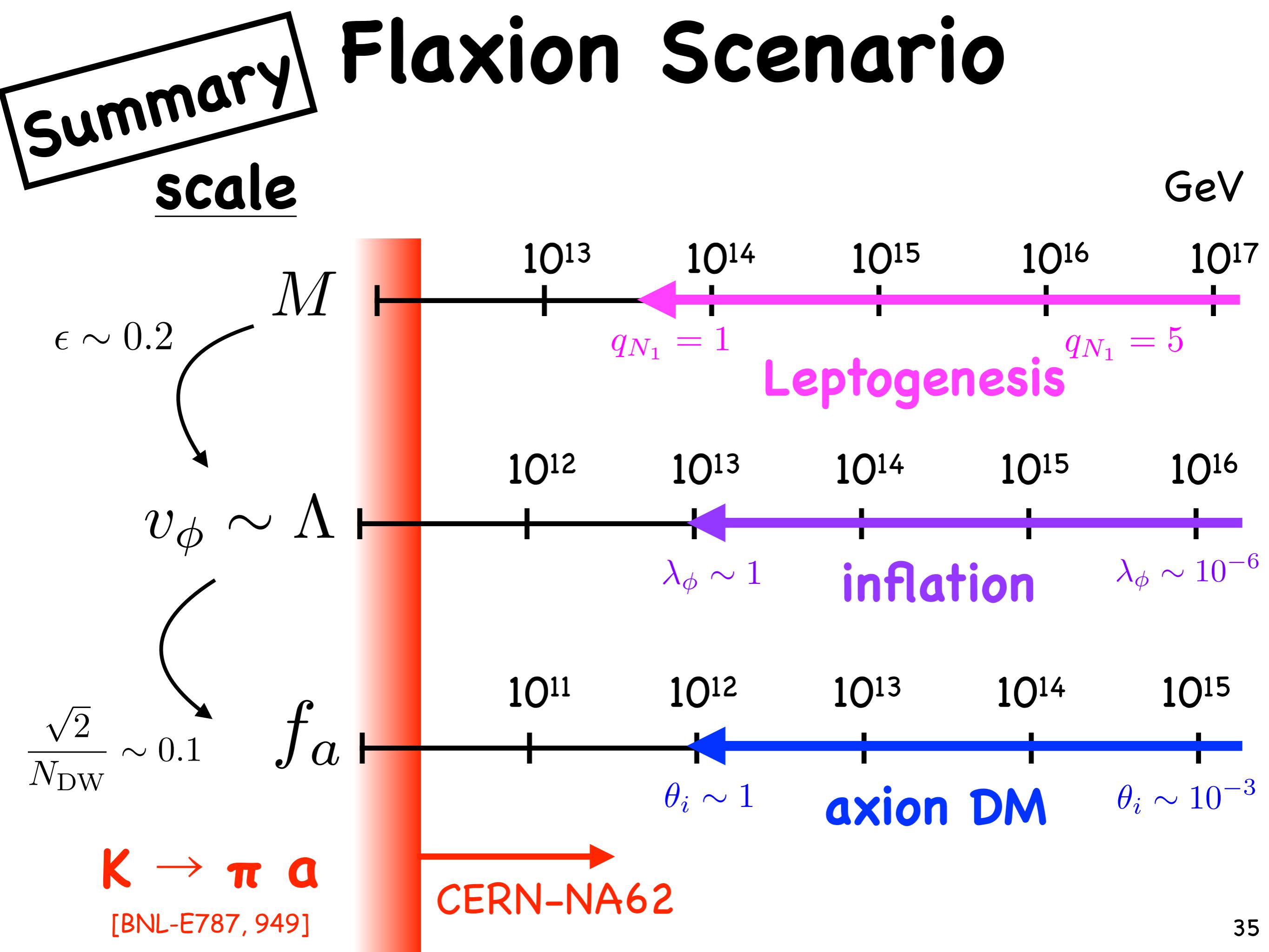
scale











Flaxion Scenario

Summary

Quark and lepton mass hierarchy and mixings.

Neutrino masses and mixings. *seesaw*

Leptogenesis

Baryon asymmetry of the Universe.

Standard Model

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with $U(1)_F = U(1)_{PQ}$

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

- + 2 (or 3)
 - right-handed neutrinos.

Inflation.

- flatness and horizon problems.
 - origin of fluctuation: (n_s, r) constraints.

characteristic
signal:
 $K \rightarrow \pi^+ \pi^-$

Strong CP problem.

Dark Matter.

solves DW and
isocurvature
problems

Backup

Supersymmetric flaxion ?

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

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

Other constraints?

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

$$f_a \gtrsim 2 \times 10^{10} \text{ GeV} \left(\frac{26}{N_{\text{DW}}} \right) \left| \frac{(\kappa_{\text{AH}}^d)_{12}}{m_s} \right|$$

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

$$\Gamma(K^+ \rightarrow \pi^+ a) = \frac{m_K^3}{32\pi v_\phi^2} \left(1 - \frac{m_\pi^2}{m_K^2}\right)^3 \left| \frac{(\kappa_{\text{AH}}^d)_{12}}{m_s - m_d} \right|^2$$

- $\mu \rightarrow e a \gamma$

$$f_a \gtrsim 1 \times 10^8 \text{ GeV} \left(\frac{26}{N_{\text{DW}}} \right) \left| \frac{(\kappa_{\text{AH}}^l)_{12}}{m_\mu} \right|$$

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

- SN1987A

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

$$\mathcal{L} = \sum_{N=p,n} \frac{C_N m_N}{f_a} i a \bar{N} \gamma_5 N,$$

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

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

$$f_a \gtrsim 7 \times 10^7 \text{ GeV} \left(\frac{26}{N_{\text{DW}}} \right) \left| \frac{(\kappa_{\text{H}}^l)_{11}}{m_e} \right|$$

$$\left(\kappa_{\text{H}}^f \right)_{ij} = \frac{1}{2} (V^{f\dagger} \hat{q}_Q V^f - U^{f\dagger} \hat{q}_f U^f)_{ij} (m_j^f + m_i^f),$$

$$\left(\kappa_{\text{AH}}^f \right)_{ij} = \frac{1}{2} (V^{f\dagger} \hat{q}_Q V^f + U^{f\dagger} \hat{q}_f U^f)_{ij} (m_j^f - m_i^f).$$

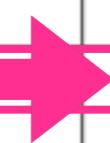
Decay	Physics	Present limit	NA62
$\pi^+ \mu^+ e^-$	LFV	$1.3 \cdot 10^{-11}$	$0.7 \cdot 10^{-12}$
$\pi^+ \mu^- e^+$	LFV	$5.2 \cdot 10^{-10}$	$0.7 \cdot 10^{-12}$
$\pi^- \mu^+ e^+$	LNV	$5.0 \cdot 10^{-10}$	$0.7 \cdot 10^{-12}$
$\pi^- e^+ e^+$	LNV	$6.4 \cdot 10^{-10}$	$2.0 \cdot 10^{-12}$
$\pi^- \mu^+ e^+$	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	$2.3 \cdot 10^{-9}$	$1.0 \cdot 10^{-11}$
$\mu^+ \nu_h, \nu_h \rightarrow \nu \gamma$	Heavy neutrino	Limits up to $M\nu_h = 350 \text{ MeV}/c^2$	$1.0 \cdot 10^{-12}$
R_K	LU	$(2.488 \pm 0.010) \cdot 10^{-5}$	2x better
$\pi^+ \gamma \gamma$	ChPT	< 500 events	10^5 events
$\pi^0 \pi^0 e^+ \nu$	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]

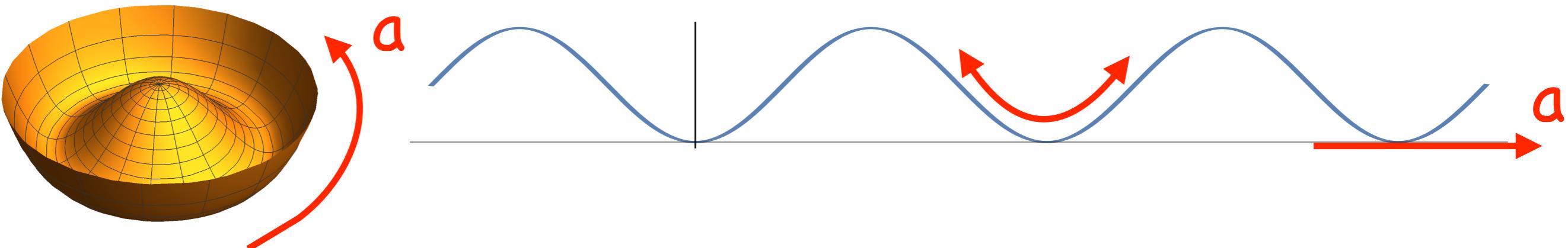
The NA62 experiment at CERN: status and perspectives
[NA62 Collaboration](#)

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

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

$$\text{BR}(B^+ \rightarrow K^+ a) \simeq 1.4 \cdot 10^{-12} \left(\frac{m_a}{0.1 \text{ meV}} \times \underbrace{\frac{\kappa_{bs}}{N}}_{\sim} \right)^2 \cdot \kappa_{bs}/N \sim \mathcal{O}(1).$$
$$\simeq \left(\frac{6 \times 10^9 \text{ GeV}}{f_a} \right)$$

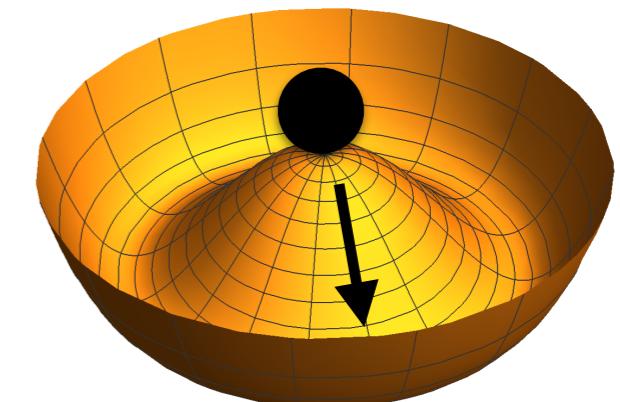
Flaxion Dark Matter:



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

→ **Domain Wall !**

In the flaxion scenario, typically $N_{\text{DW}} \neq 1$,
and this possibility is **excluded**.

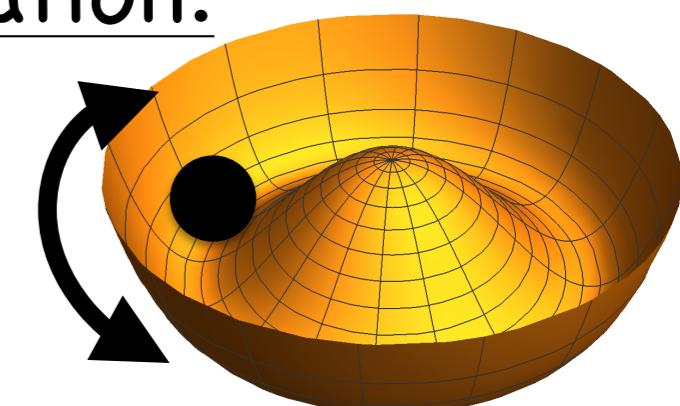


Case 2: $U(1)$ was already broken during inflation.

Quantum fluctuation during inflation
leads to **DM isocurvature** perturbation,
which is severely constrained [Planck,'15].

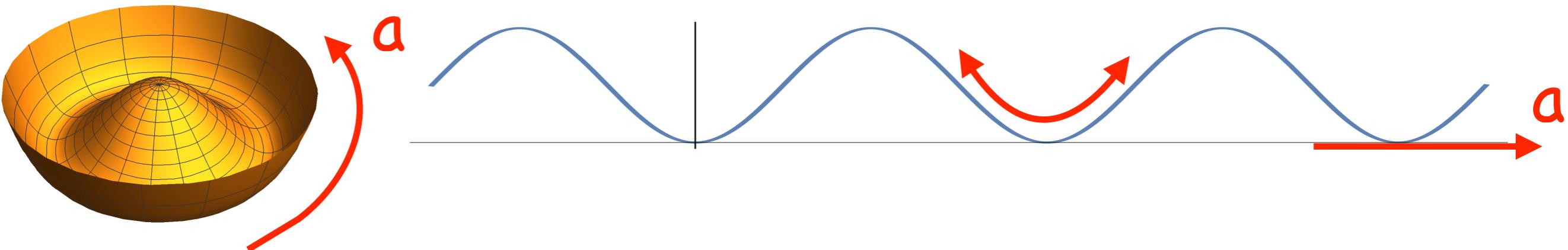
→ **Strong bound on inflation scale.**

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



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

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: $U(1)$ is unbroken

Quantum fluctuations
leads to DM
which is severe

→ Strong bound

No problem in "flaxion-inflation" scenario !

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

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



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.