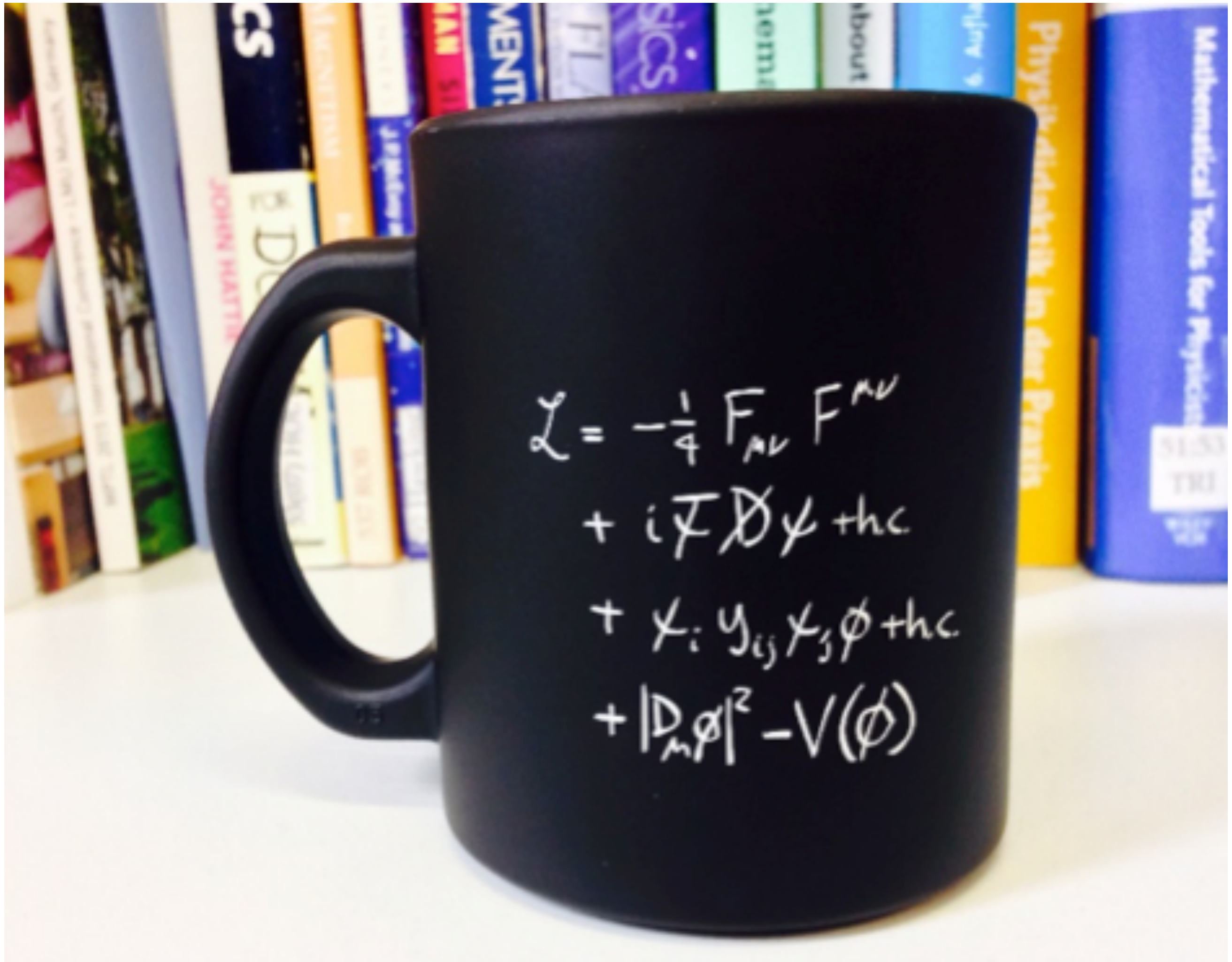
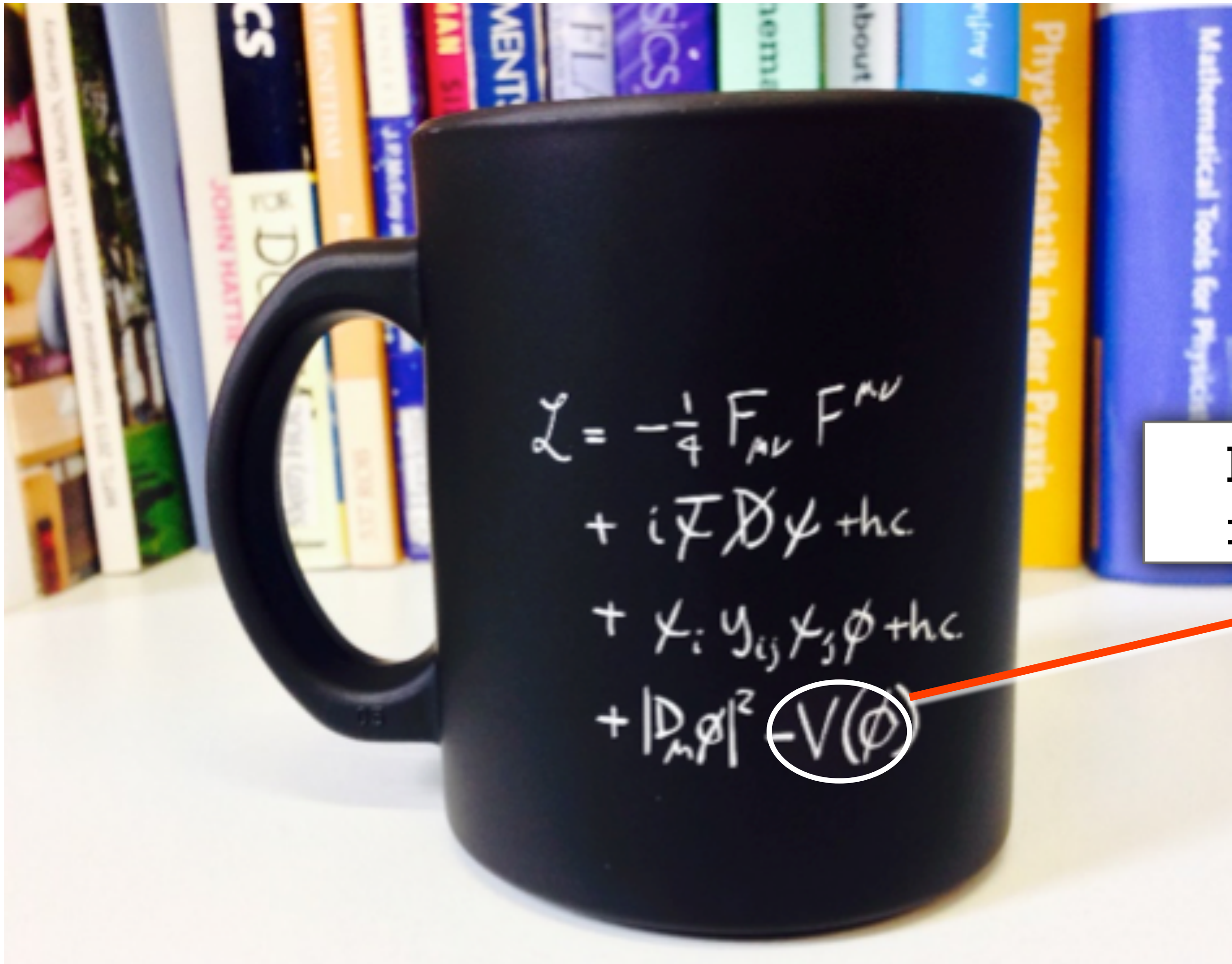
Hierarchion, a unified explanation of the SM hierarchies and neutrino masses

Rick S Gupta (IPPP Durham)

SM hierarchies

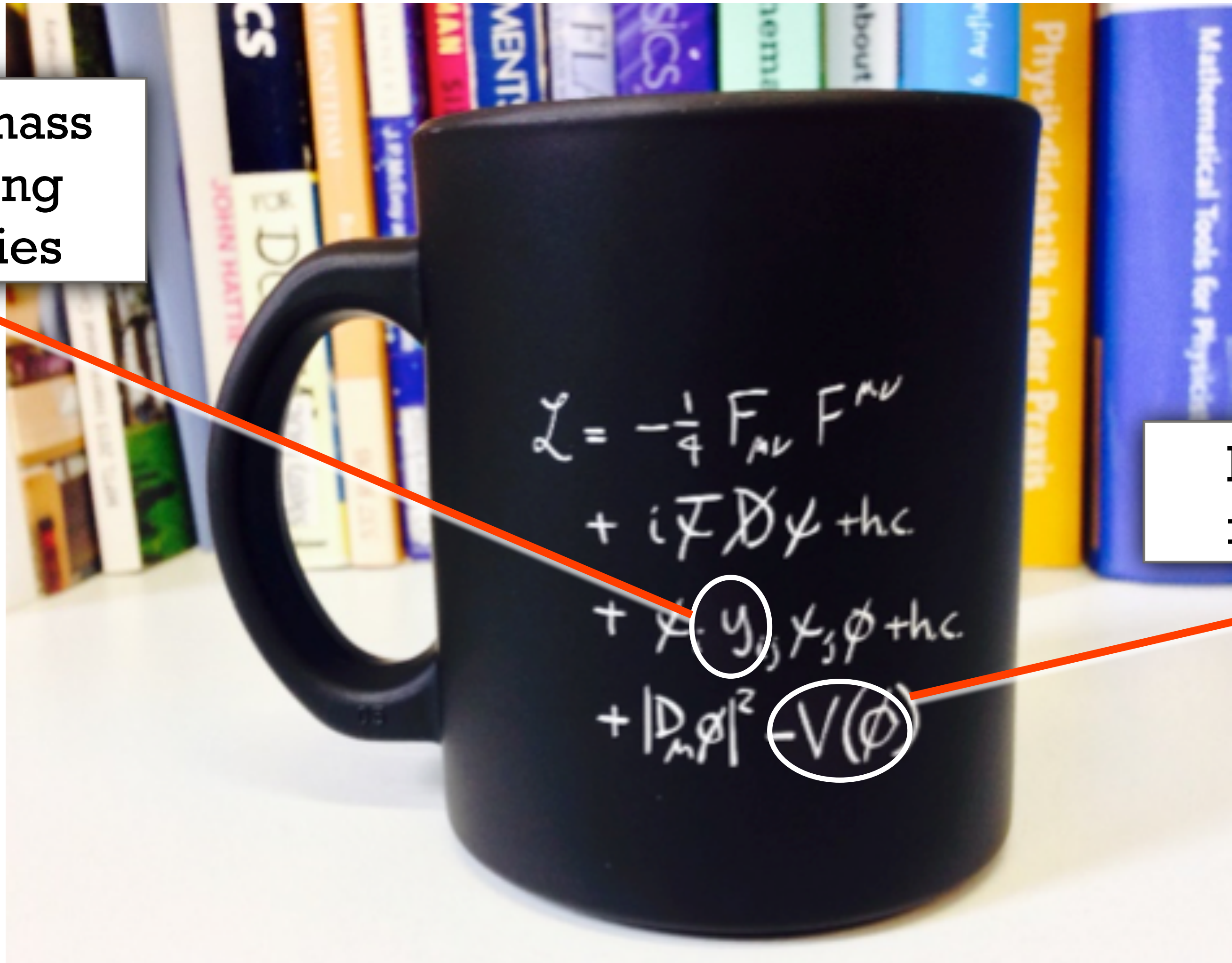


SM hierarchies



Higgs mass naturalness

SM hierarchies



Fermion mass and mixing hierarchies

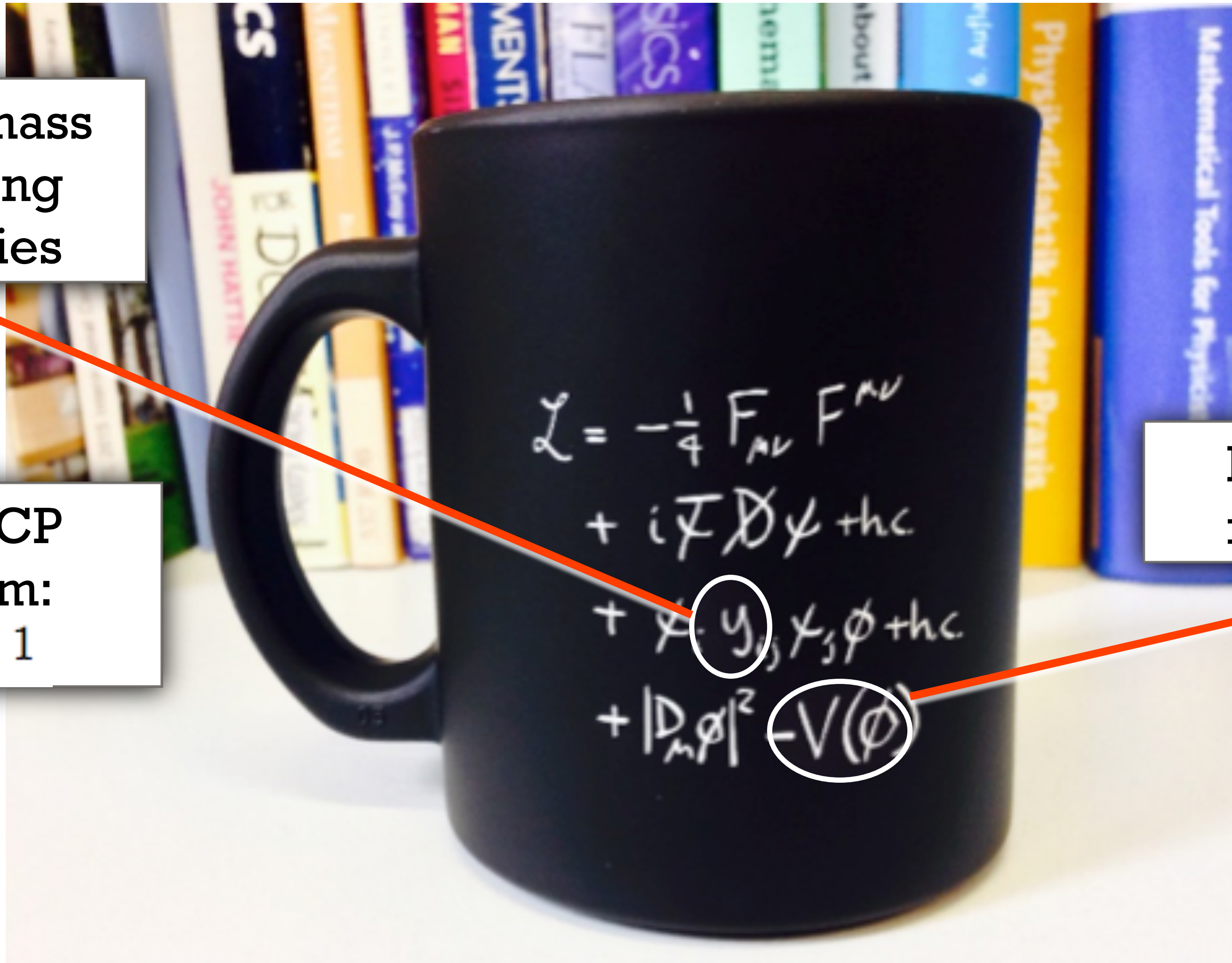
Higgs mass naturalness

SM hierarchies

Fermion mass and mixing hierarchies

Strong CP problem: $\theta_{\rm QCD} \ll 1$

Higgs mass naturalness



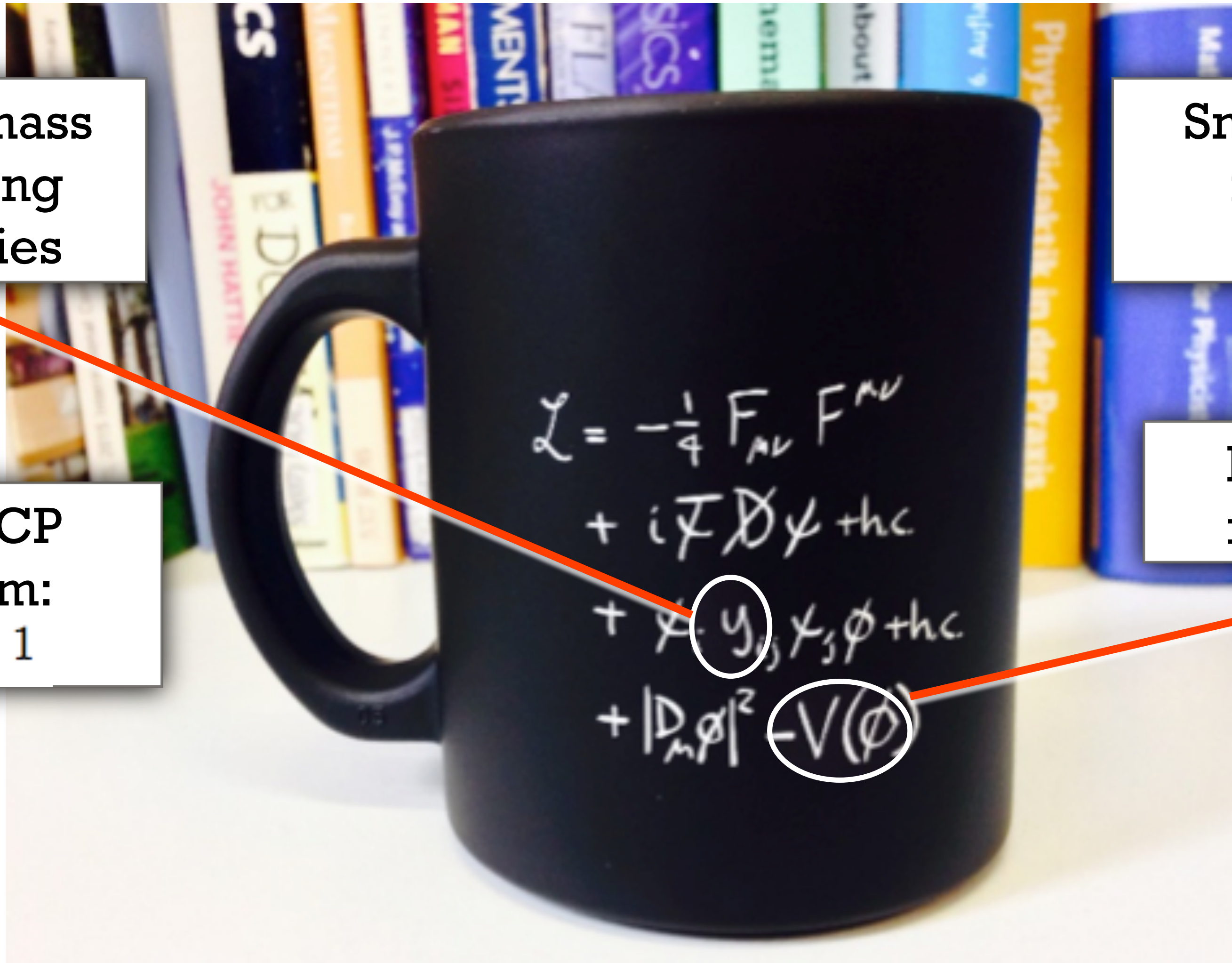
SM hierarchies+Neutrino masses

Fermion mass and mixing hierarchies

Smallness of neutrino masses

Strong CP problem: $\theta_{\rm QCD} \ll 1$

Higgs mass naturalness



The hierarchion

- We present a model where we solve all the hierarchies in SM plus neutrino masses.
- We find a way to combine

1. The Relaxion-Clockwork solution to Higgs mass hierarchy problem
2. The Nelson Barr Solution to the strong CP problem
3. The Froggatt-Nielsen solution for the SM flavour puzzle
4. The see-saw mechanism for neutrino masses

in a unified framework with a single light degree of freedom that we call the hierarchion.

Davidi, RSG, Perez, Redigolo and Shalit (arXiv: 1711.00858)
Davidi, RSG, Perez, Redigolo and Shalit (arXiv: 1712.XXXXX)

The hierarchion: basic picture

- Relaxion final phase ↔ Spontaneously breaks CP, generates CKM phase but not strong CP phase (Nelson-Barr)
- Relaxion Shift symmetry ↔ Froggatt-Nielsen U(1)
- Shift symmetry breaking (backreaction) ↔ Sterile Neutrino sector

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The hierarchion: basic picture

Relaxion final phase ↔ Spontaneously breaks CP, generates CKM phase but not strong CP phase (Nelson-Barr)

Relaxion Shi… … U(1)

Shift symmet… (backreaction)

… sector

The hierarchion is at the same time the *relaxion*,
the *familon* of a global flavor symmetry and
the *CKM phase* of NB models.

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Davidi, RSG, Perez, Redigolo and Shalit (arXiv: 1712.XXXXX)

Relaxions: basic ingredients

1. In relaxion models the value of μ^2, the Higgs mass squared term in the Higgs potential changes during the course of inflation.

$$\mu^2(\phi) = \kappa\Lambda_H^2 - \Lambda_H^2 \cos\frac{\phi}{F}$$

2. It varies with the classical value of a scalar field Φ, which slowly rolls because of a potential:

$$-\, r_{\rm roll}^2 \Lambda_H^4 \cos\frac{\phi}{F}$$

3. Backreaction potential:

$$V_{\rm br} = -\Lambda_{\rm br}^4 \cos\frac{\phi}{f}\,, \quad \Lambda_{\rm br}^4 \sim M_{\rm br}^{4-j}(v+h)^j$$

Graham, Kaplan & Rajendran, 2015

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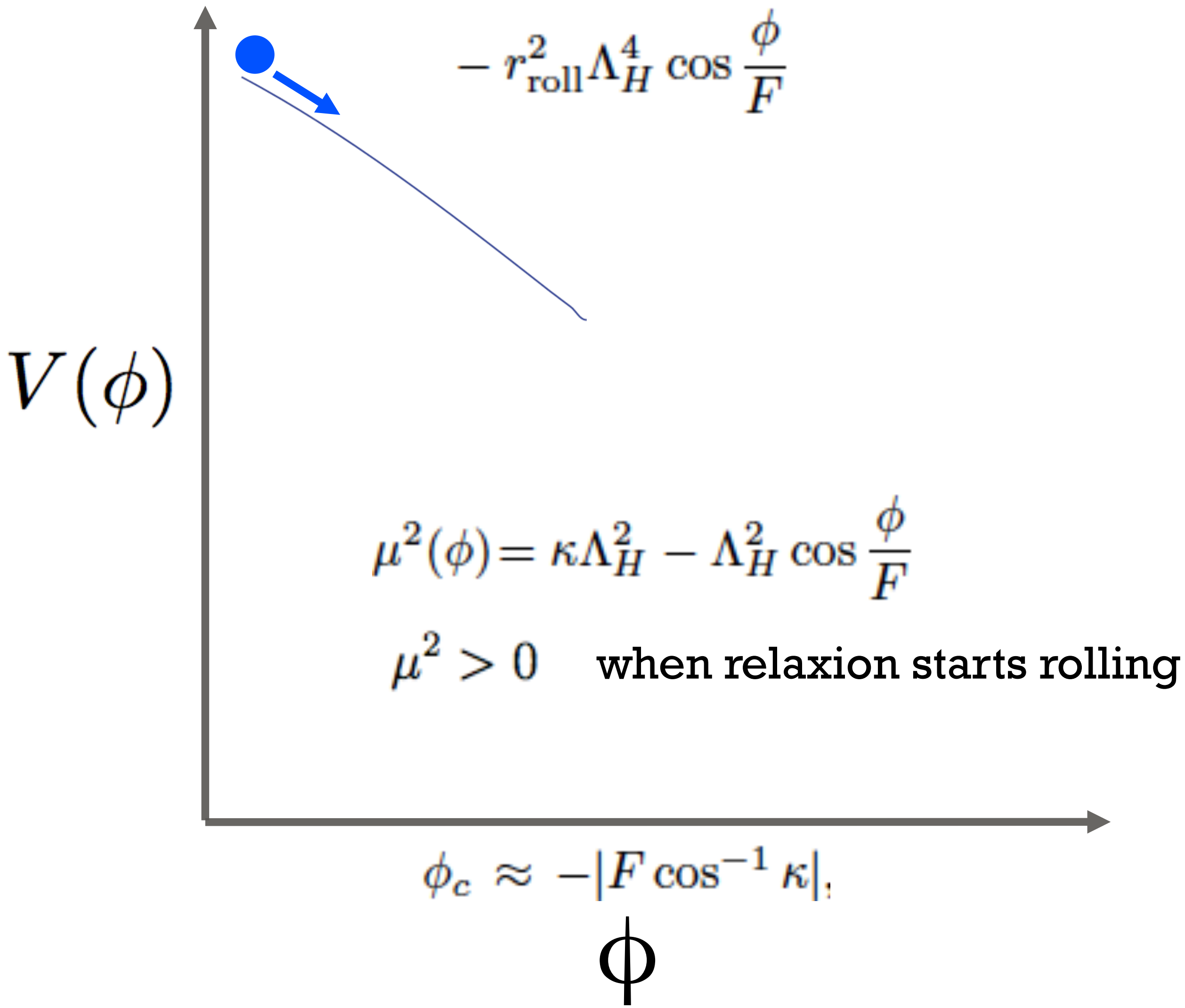
The Relaxion Mechanism



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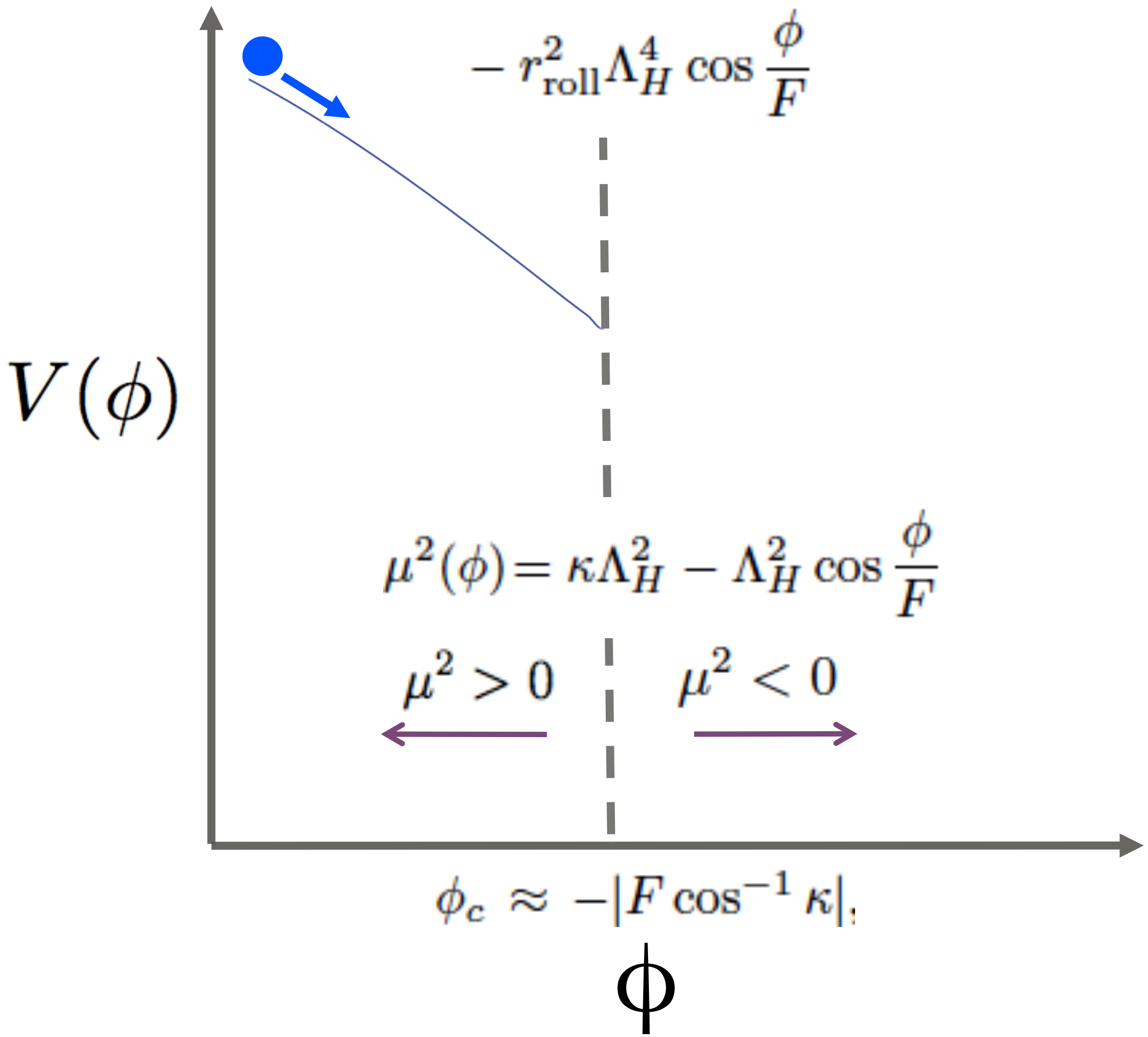

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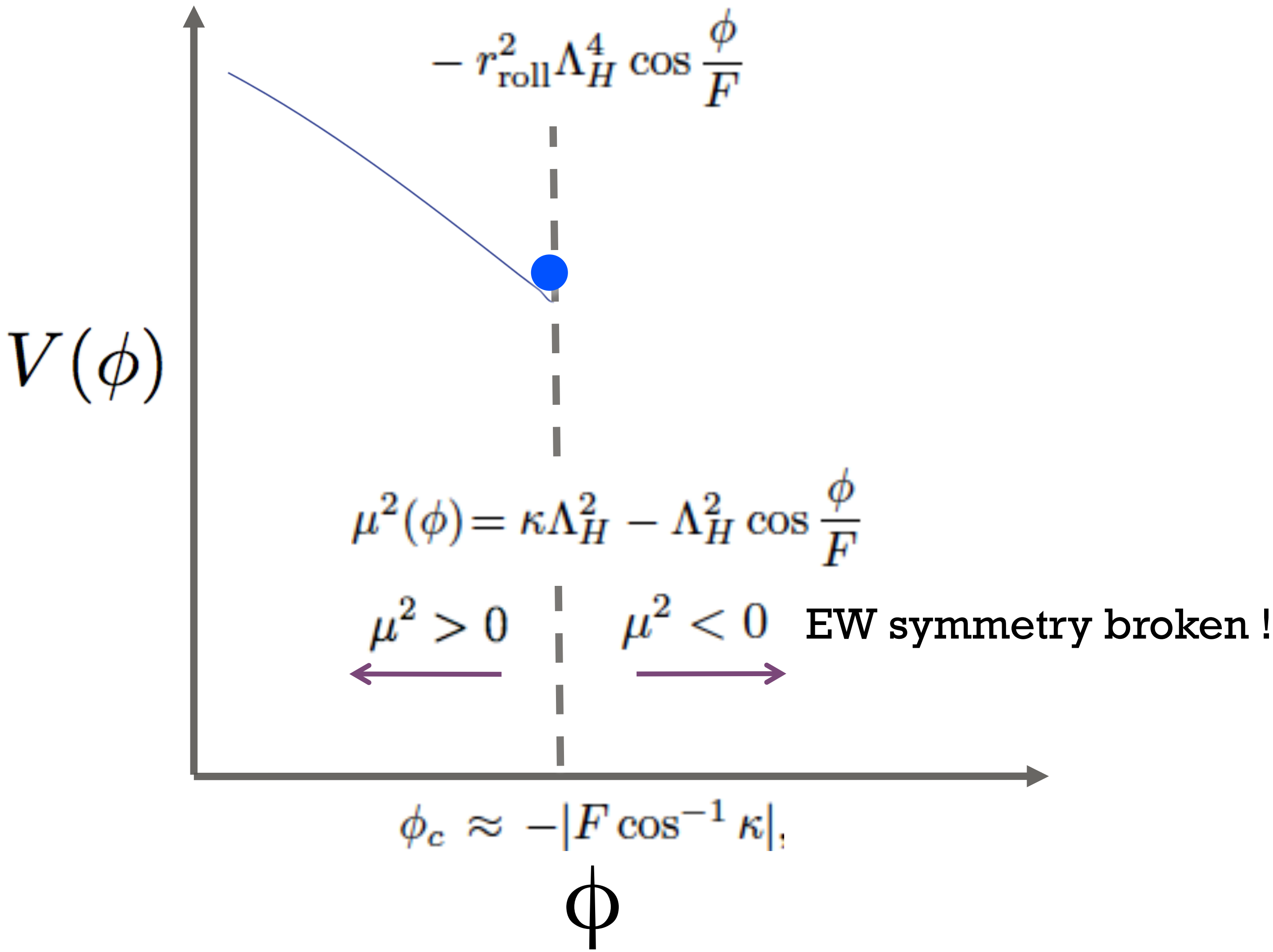


Backreaction potential

- Backreaction term in the potential turns on only when upon EWSB.

$$V_{\rm br} = -\Lambda_{\rm br}^4 \cos\frac{\phi}{f}\,, \quad \Lambda_{\rm br}^4 \sim M_{\rm br}^{4-j}(v+h)^j$$

- Example: QCD axion potential

$$\Delta V \sim y_u v f_\pi^3 \cos\left(\frac{\phi}{f_a}\right)$$

- In simplest model relaxion is QCD axion.

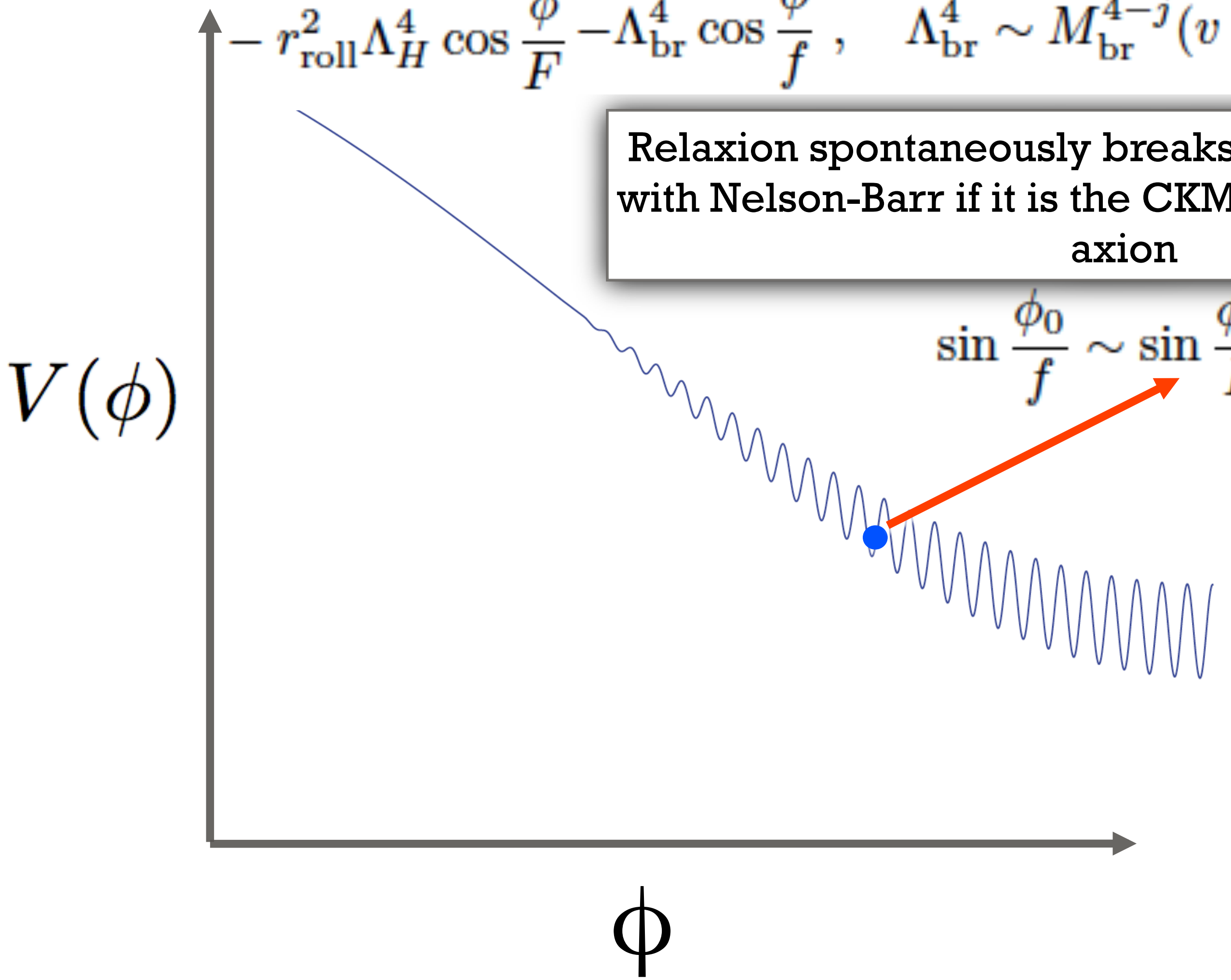
+

The Relaxion Mechanism

$$-r_{\rm roll}^2 \Lambda_H^4 \cos\frac{\phi}{F} - \Lambda_{\rm br}^4 \cos\frac{\phi}{f}\,, \quad \Lambda_{\rm br}^4 \sim M_{\rm br}^{4-j}(v+h)^j$$

Relaxion spontaneously breaks CP, can be married with Nelson-Barr if it is the CKM phase and not QCD axion

$$\sin\frac{\phi_0}{f} \sim \sin\frac{\phi_0}{F} \sim \mathcal{O}(1)$$



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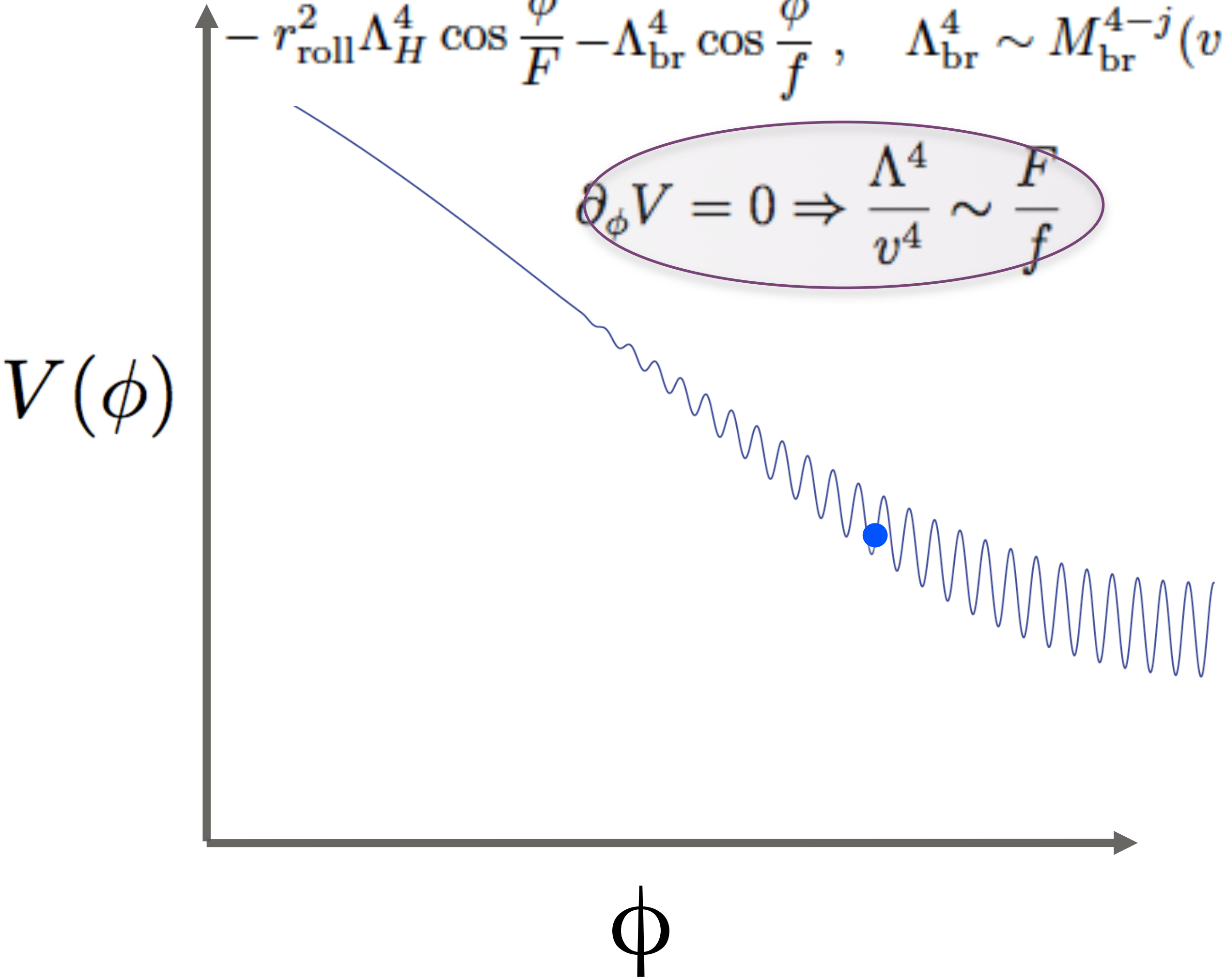

$$\partial_\phi V = 0 \Rightarrow \frac{\Lambda^4}{v^4} \sim \frac{F}{f}$$

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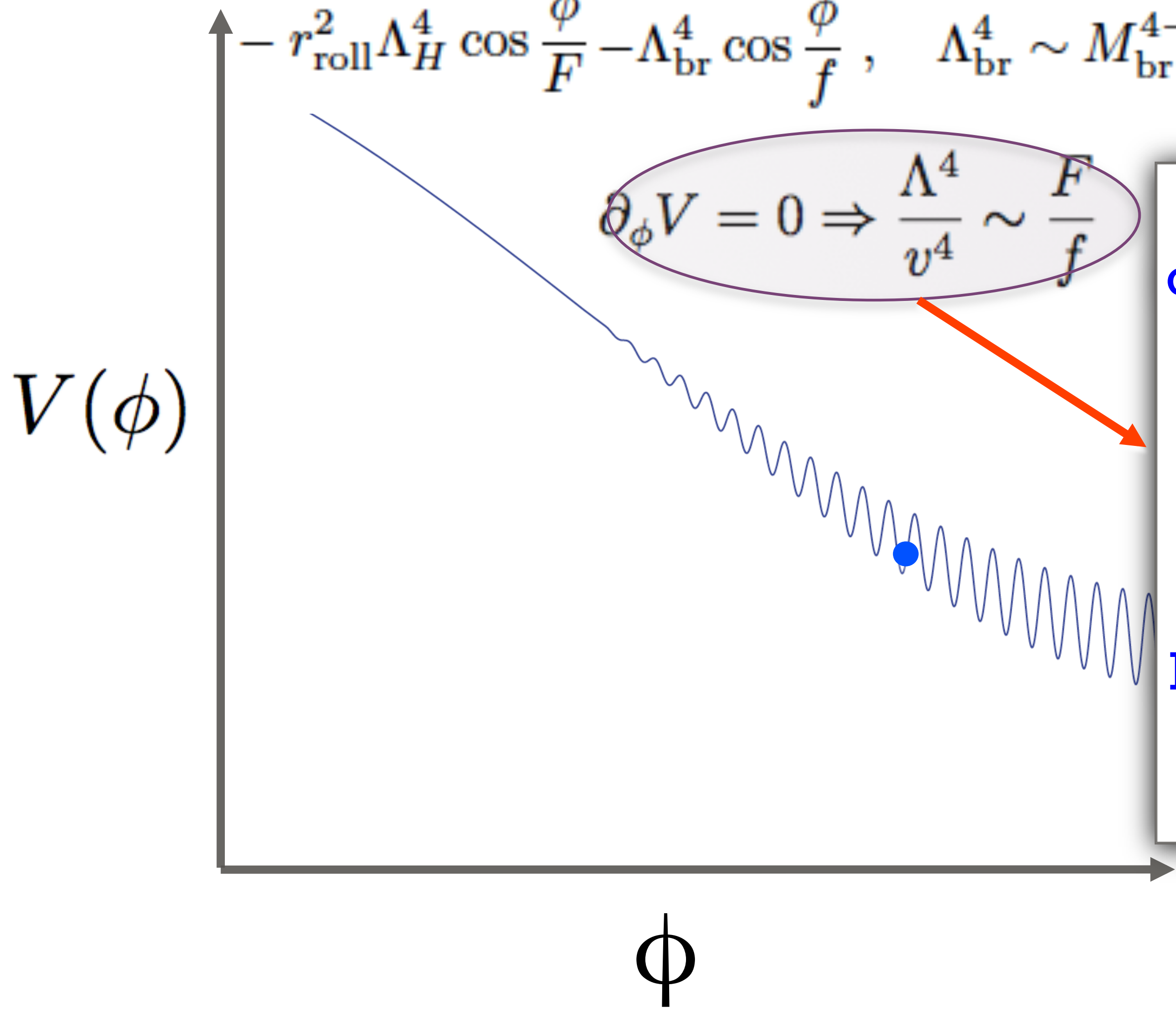

$$\partial_\phi V = 0 \Rightarrow \frac{\Lambda^4}{v^4} \sim \frac{F}{f}$$

Relaxion requires double cosine potential with large ratio of periodicities F/f >>1

For cut-off 10 TeV we need F/f $=10^8$!

.

For cut-off 10^8 GeV we need F/f $=10^{24}$! !

RSG, Komargodski, Perez and Ubaldi (2015)

The Relaxion Mechanism

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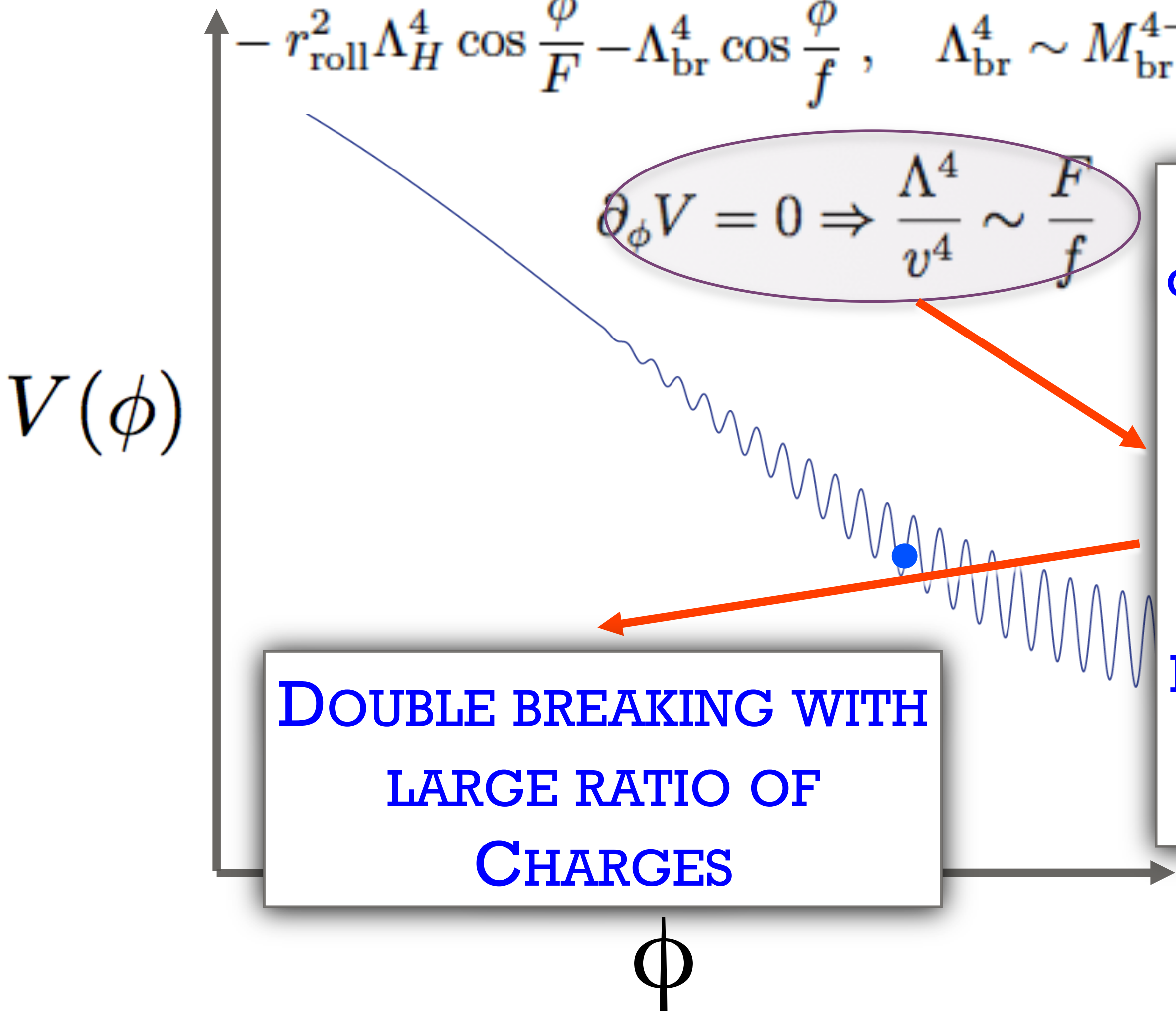

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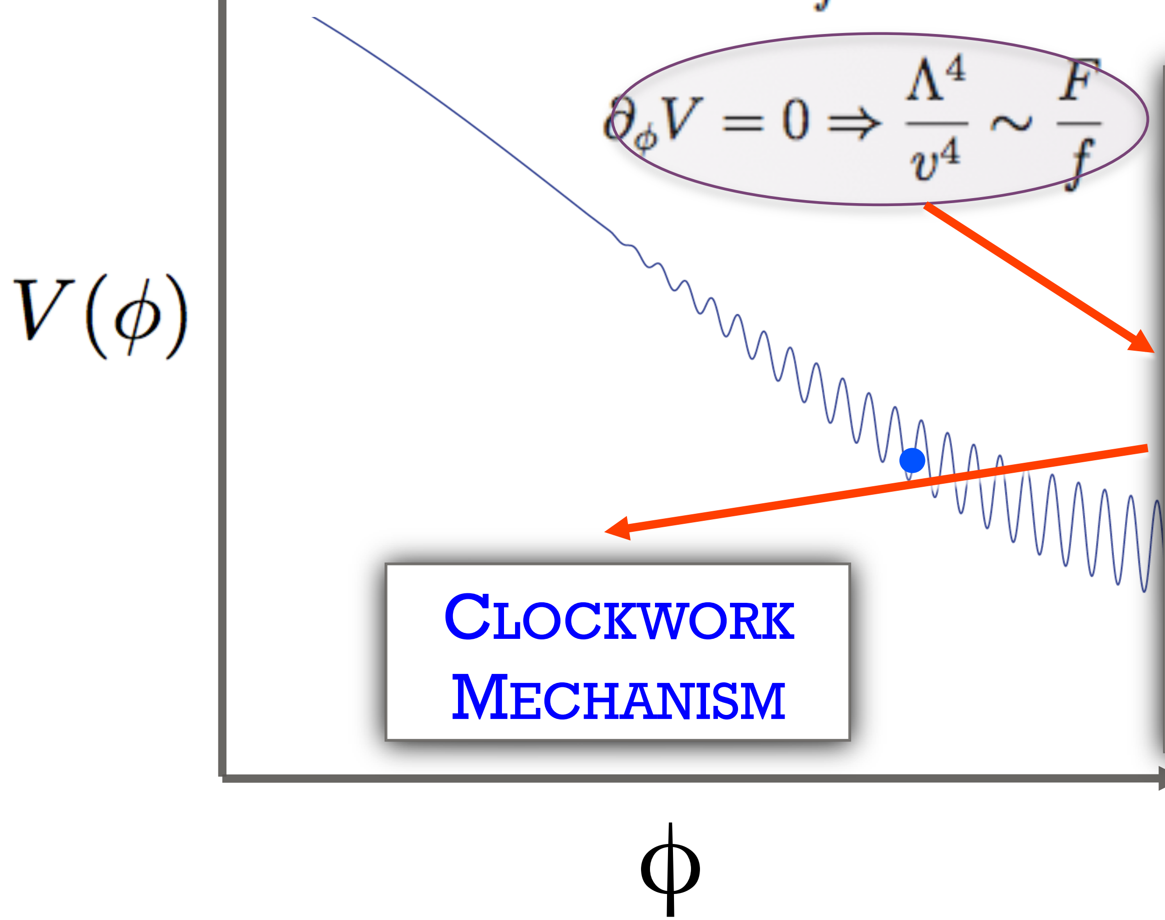
DOUBLE BREAKING WITH LARGE RATIO OF CHARGES

RSG, Komargodski, Perez and Ubaldi (2015)

The Relaxion Mechanism

$$-r_{\rm roll}^2\Lambda_H^4\cos\frac{\phi}{F}-\Lambda_{\rm br}^4\cos\frac{\phi}{f}\,,\quad \Lambda_{\rm br}^4\sim M_{\rm br}^{4-j}(v+h)^j$$



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Choi, Kim & Yun (2015)
Choi & Im (2015)
Kaplan & Rattazzi(2015)

Choi-Kim-Yun alignment/ Clockwork Mechanism

- Multiple axions. Potential for linear fields:

$$V(\phi) = \sum_{j=0}^{N} \left(-m^2 \phi_j^\dagger \phi_j + \frac{\lambda}{4} |\phi_j^\dagger \phi_j|^2 \right) + \sum_{j=0}^{N-1} \left(\epsilon \phi_j^\dagger \phi_{j+1}^3 + h.c. \right)$$

- Symmetry: the fields ϕ_j , j = 0,1,2,…,N, have charges Q = 1, 1/3,1/9,…1/3^N

Choi, Kim & Yun (2015)
Choi & Im (2015)
Kaplan & Rattazzi(2015)

Choi-Kim-Yun alignment/Clockwork Mechanism

- Substitute: $$\phi_j \to U_j \equiv f e^{i\pi_j/(\sqrt{2}f)}$$
- Potential:

$$\mathcal{L}_{pNGB} = f^2 \sum_{j=0}^{N} \partial_\mu U_j^\dagger \partial^\mu U_j + \left(\epsilon f^4 \sum_{j=0}^{N-1} U_j^\dagger U_{j+1}^3 + h.c. \right) + \cdots$$
$$= \frac{1}{2} \sum_{j=0}^{N} \partial_\mu \pi_j \partial^\mu \pi_j + \epsilon f^4 \sum_{j=0}^{N-1} e^{i(3\pi_{j+1} - \pi_j)/(\sqrt{2}f)} + h.c. + \cdots$$

- Mass matrix:

$$M_{ij}^2 = \epsilon f^2 \begin{pmatrix} 1 & -q & 0 & 0 & & & & \\ -q & 1+q^2 & -q & 0 & \cdot & \cdot & \cdot & \\ 0 & -q & 1+q^2 & -q & & & & \\ 0 & 0 & -q & 1+q^2 & & & & \\ & & & & \cdot & & & \\ & \cdot & & & & \cdot & & \\ & \cdot & & & & & \cdot & \\ & \cdot & & & & & 1+q^2 & -q \\ & & & & & & -q & q^2 \end{pmatrix}.$$

- Goldstone direction:

$$\vec{a}_{(0)}^T = \mathcal{N} \left(1 \quad \frac{1}{3} \quad \frac{1}{9} \quad \ldots \quad \frac{1}{3^N} \right)$$

Choi, Kim & Yun (2014)
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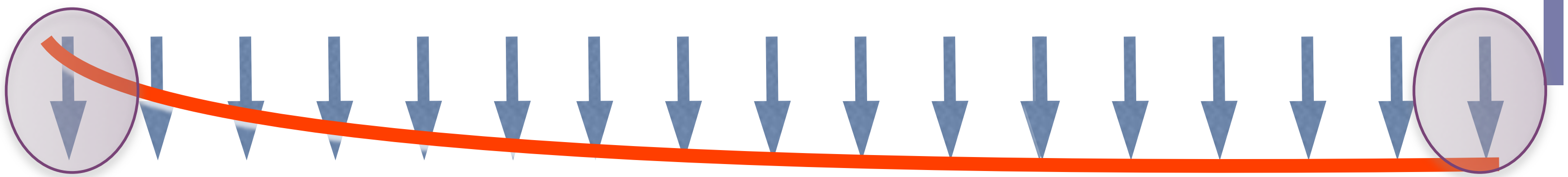
Choi-Kim-Yun alignment/ Clockwork Mechanism



$$\vec{a}^T_{(0)} = \mathcal{N}\left(1 \quad \tfrac{1}{3} \quad \tfrac{1}{9} \quad \cdots \quad \tfrac{1}{3^N}\right)$$

exponential profile

- Double breaking again on 1st and last site:

$$\frac{\pi_0}{32\pi^2 f} G_0 \tilde{G}_0 + \frac{\pi_N}{32\pi^2 f} G_N \tilde{G}_N$$

$$\Lambda_N \cos\frac{\pi_N}{f} + \Lambda_0 \cos\frac{\pi_0}{f}$$

$$\Lambda_N \cos\frac{\pi}{3^N f_a} + \Lambda_0 \cos\frac{\pi}{f_a}$$

Choi, Kim & Yun (2014)
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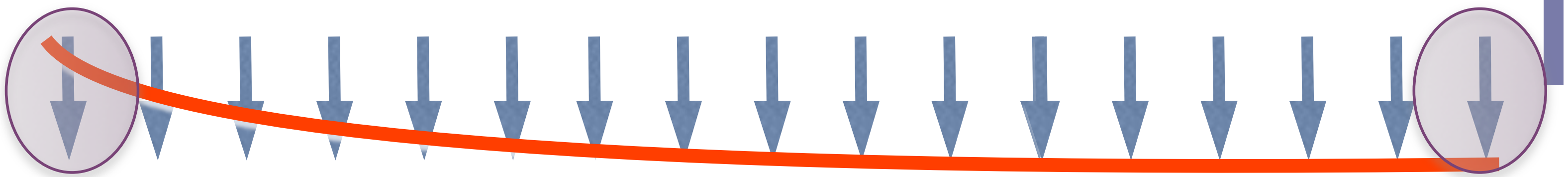

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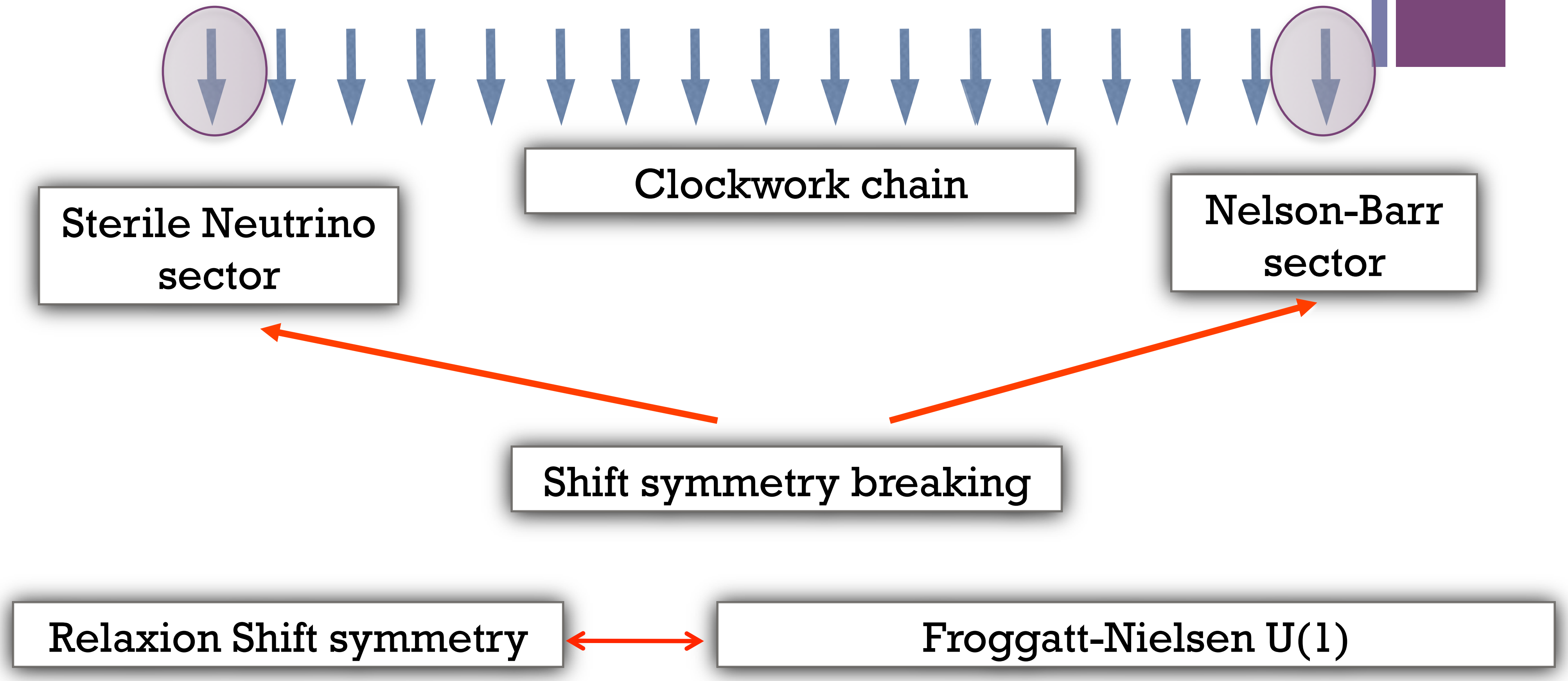
The hierarchion: basic picture



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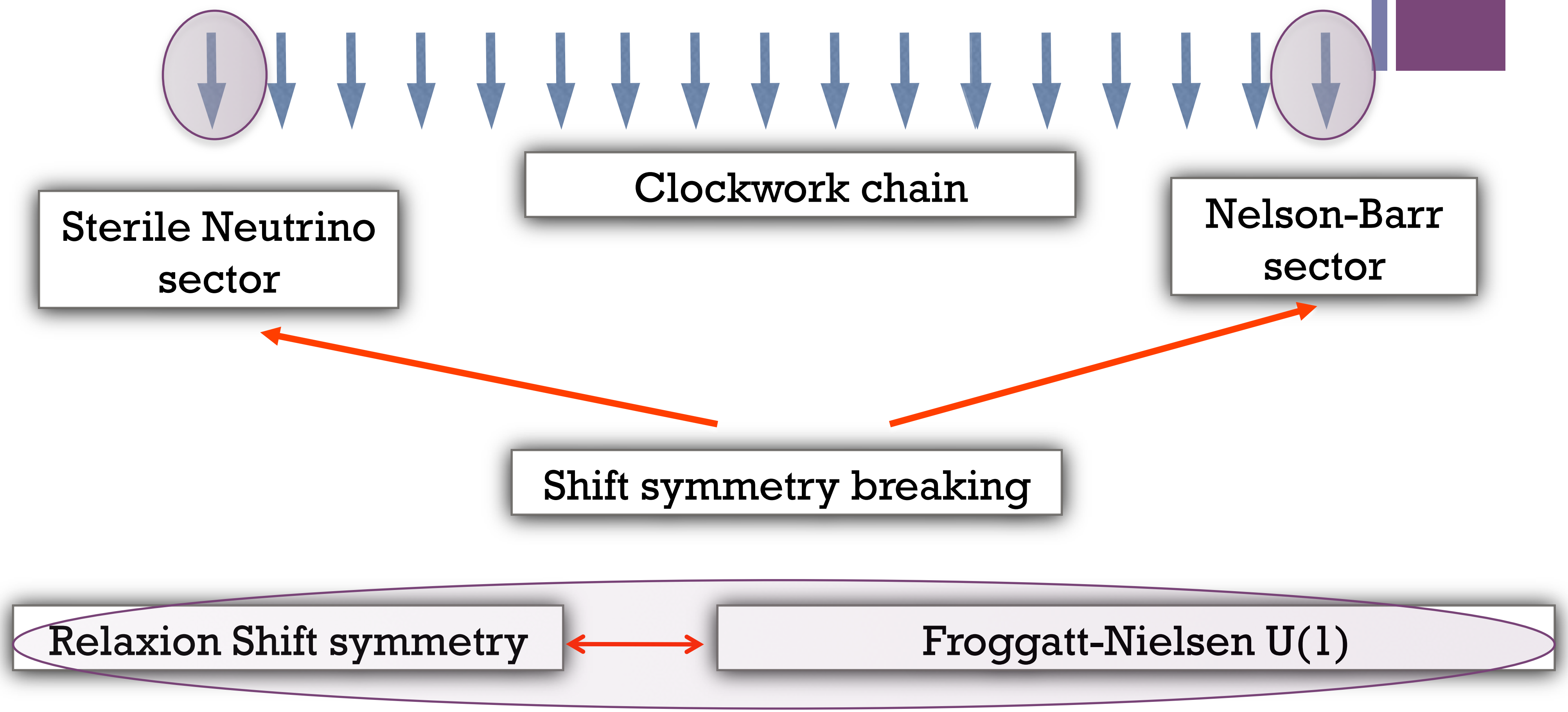

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The Froggatt-Nielsen relaxion

- The relaxion is the pseudo-goldstone boson of a global symmetry
- What if we identify this global symmetry with a flavour symmetry that explains the fermion mass hierarchies and mixings.
- For example in the Froggatt Nielsen model we can explain the lightness of the electron as follows. The electron Yukawa interaction is:

$$\left(\frac{\Phi}{\Lambda}\right)^{10} LHe^c$$

There is a U(1) symmetry under which $Q_{e^c} = 10,\ Q_L = 0,\ Q_\Phi = -1$

- Finally take: $$\frac{\langle\Phi\rangle}{\Lambda} = 0.17 \Rightarrow m_e = \mathcal{O}(MeV)$$

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- Finally take: $$\frac{\langle\Phi\rangle}{\Lambda} = 0.17 \Rightarrow m_e = \mathcal{O}(MeV)$$

The Froggatt-Nielsen relaxion

- The SM Yukawas are written as:

$$\mathcal{L}_L = y^n_{ij}\left[\frac{\hat{\Phi}_0}{\Lambda_n}\right]^{|n_{ij}|} L_i\tilde{H}N^c_j + y^c_{ij}\left[\frac{\hat{\Phi}_0}{\Lambda_c}\right]^{|c_{ij}|} L_iHe^c_j$$

$$\Phi_0 \sim \frac{(f+\rho)}{\sqrt{2}}e^{i\phi/f}$$

$$\mathcal{L}_Q = y^u_{ij}\left[\frac{\hat{\Phi}_m}{\Lambda_u}\right]^{|u_{ij}|} Q_i\tilde{H}u^c_j + y^d_{ij}\left[\frac{\hat{\Phi}_m}{\Lambda_d}\right]^{|d_{ij}|} Q_iHd^c_j$$

The Froggatt-Nielsen relaxion

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Sterile neutrinos

$$\Phi_0 \sim \frac{(f+\rho)}{\sqrt{2}}e^{i\phi/f}$$

Relaxion

The Froggatt-Nielsen relaxion

- The SM Yukawas are written as:

Sterile neutrinos

$$\mathcal{L}_L = y^n_{ij}\left[\frac{\hat{\Phi}_0}{\Lambda_n}\right]^{|n_{ij}|} L_i \tilde{H} N^c_j + y^c_{ij}\left[\frac{\hat{\Phi}_0}{\Lambda_c}\right]^{|c_{ij}|} L_i H e^c_j$$

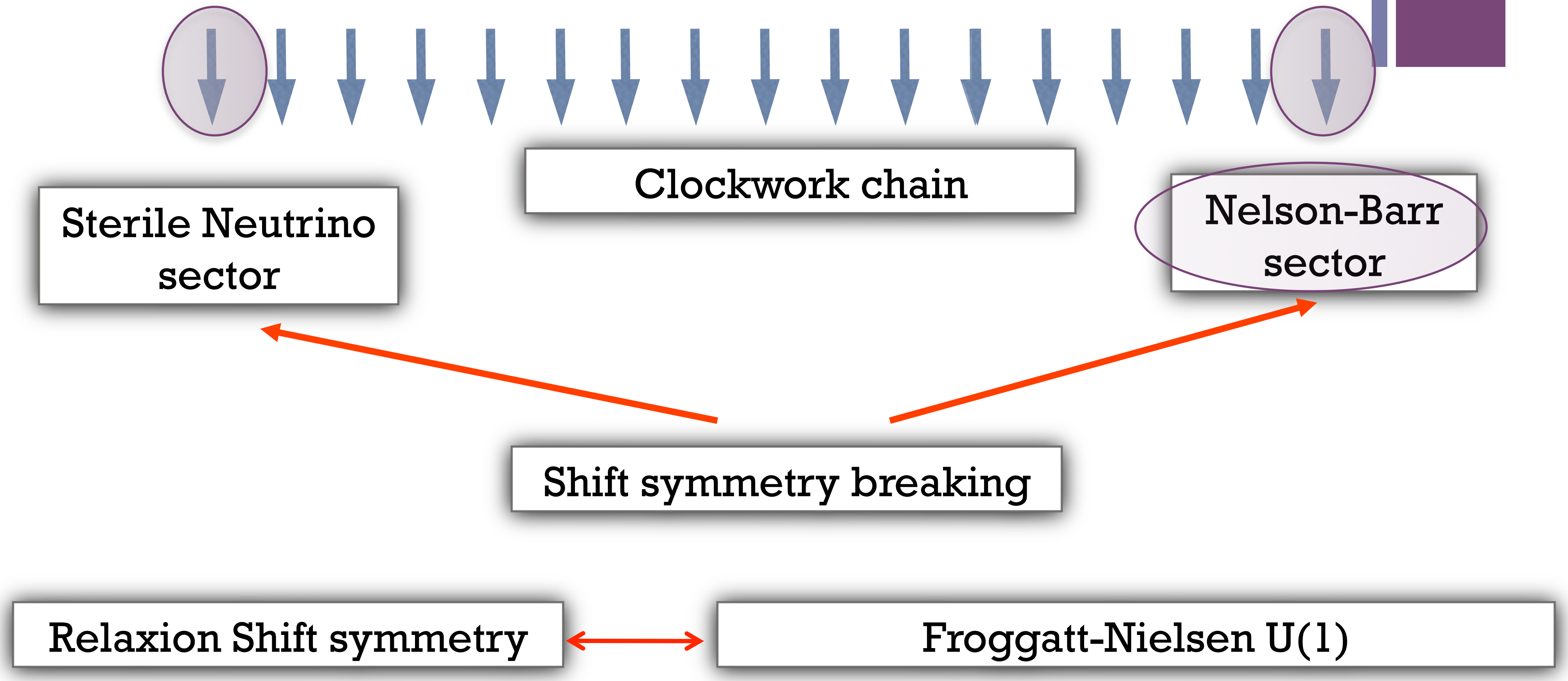
$$\Phi_0 \sim \frac{(f+\rho)}{\sqrt{2}} e^{i\phi/f}$$

$$\mathcal{L}_Q = y^u_{ij}\left[\frac{\hat{\Phi}_m}{\Lambda_u}\right]^{|u_{ij}|} Q_i \tilde{H} u^c_j + y^d_{ij}\left[\frac{\hat{\Phi}_m}{\Lambda_d}\right]^{|d_{ij}|} Q_i H d^c_j$$

Relaxion

- So far this is an exact U(1) and the relaxion is thus a massless goldstone Boson. To give the relaxion the required potential we need to break the U(1) twice. For this we will use the seesaw mechanism at the 1st site and Nelson Barr mechanism at last site..

The hierarchion: basic picture



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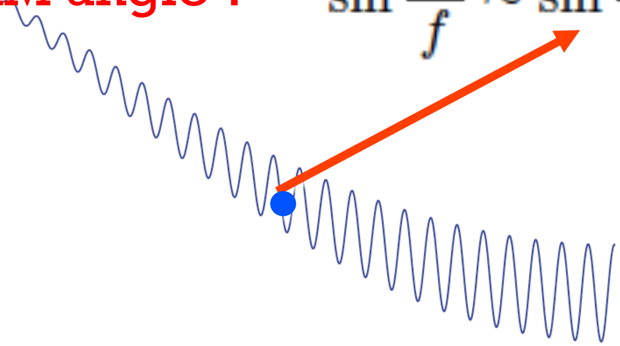
Nelson-Barr mechanism

- CP is a good symmetry of UV.
- CP broken spontaneously by a pseudoscalar whose VEV generates CKM phase but not strong CP phase.
- Once CKM phase is generated RG running generates but only at 7 loop level!
- Relaxion breaks CP spontaneously!
- Can the relaxion VEV be the CKM angle ?

$$\sin\frac{\phi_0}{f} \sim \sin\frac{\phi_0}{F} \sim \mathcal{O}(1)$$



Nelson-Barr relaxion

- Add a new vectorlike quark:

$$\mathcal{L}_Q = y^u_{ij}\left[\frac{\hat{\Phi}_m}{\Lambda_u}\right]^{|u_{ij}|} Q_i \tilde{H} u^c_j + y^d_{ij}\left[\frac{\hat{\Phi}_m}{\Lambda_d}\right]^{|d_{ij}|} Q_i H d^c_j + \mu\psi\psi^c$$

- A Z_2 symmetry under which only vectorlike pair charged forbids their couplings of SM quarks.

Nelson-Barr relaxion

- Break Z_2 and $U(1)_N$ (thus clockwork U(1))

$$\mathcal{L}_{\psi}^{\rm roll} = \left[y_i^{\psi} \Phi_N + \tilde{y}_i^{\psi} \Phi_N^* \right] \psi \, d_i^c$$

- $U(1)_N$ breaking necessary for presence of physical phase (else all terms involve $\partial_\mu \pi_N$ and vanish if π_N put to VEV) as well as generating rolling potential.

Nelson-Barr relaxion

- No strong CP phase!

$$M^d = \begin{pmatrix} (\mu)_{1\times 1} & (B)_{1\times 3} \\ (0)_{3\times 1} & (vY^d)_{3\times 3} \end{pmatrix} \quad B_i = \frac{f}{\sqrt{2}} \left(y_i^\psi e^{i\theta_N} + \tilde{y}_i^\psi e^{-i\theta_N} \right)$$

$$\bar{\theta}_{\rm QCD} = {\rm Arg}(\det(M^u)) + {\rm Arg}(\mu \cdot \det(vY^d)) = 0$$

- This assumes:

$$\mathrm{Arg}(\mu \cdot \det(vY^d)) = 0$$

- Another crucial requirement we will discuss soon.

Nelson-Barr relaxion

- CKM phase present in effective 3x3 SM quark matrix once VL quark integrated out:

$$\left[M^d_{\rm eff}M^{d\dagger}_{\rm eff}\right]_{ij} \sim v^2 Y^d_{ik} Y^d_{jk} - \frac{v^2 Y^d_{ik} B^*_k B_\ell Y^d_{j\ell}}{\mu^2 + B_n B^*_n}$$

Contains CKM phase

$$B_i = \frac{f}{\sqrt{2}}\left(y^\psi_i e^{i\theta_N} + \tilde{y}^\psi_i e^{-i\theta_N}\right)$$

+

Nelson-Barr relaxion

- $U(1)_N$ breaking generates rolling potential:

$$\mathcal{L}_{\psi}^{\text{roll}} = \left[y_i^{\psi} \Phi_N + \tilde{y}_i^{\psi} \Phi_N^* \right] \psi \, d_i^c$$

Radiatively

$$V_{\text{roll}} = \mu^2(\phi)|H|^2 + \lambda_H |H|^4 - r_{\text{roll}}^2 \Lambda_H^4 \cos\frac{\phi}{F} ,$$

$$\mu^2(\phi) = \kappa \Lambda_H^2 - \Lambda_H^2 \cos\frac{\phi}{F} ,$$

$$\Lambda^2 \sim \frac{y_i^{\psi} \tilde{y}_j^{\psi} ((Y^d)^T Y^d)_{ij}}{16\pi^2} f^2$$

+ Radiative threshold contributions to strong CP phase

- Radiative corrections to θ_{QCD} vanish in our model in the limit:

$$y_i^\psi \sim \tilde{y}_i^\psi \sim y_\psi \to 0$$

- All radiative contributions to θ_{QCD} can be systematically evaluated in powers of using symmetry arguments only (spurion analysis). This gives:

$$y_\psi \lesssim 10^{-3}$$

- CKM phase still O(1).

Anomaly free condition

- We **need**: $\bar{\theta}_{\rm QCD} = {\rm Arg}(\det(M^u)) + {\rm Arg}(\mu \cdot \det(vY^d)) = 0$

$$\mathrm{Arg}(\mu \cdot \det(vY^d)) = 0$$

- If this is non zero it can be **rotated to give** :

$$\frac{n\hat{\theta}}{32\pi^2} G_{\mu\nu} \tilde{G}^{\mu\nu} \qquad n_{\rm QCD} = \sum_{i=1}^{3} (2\,[Q_i] + [u_i^c] + [d_i^c])$$

- To have $\mathrm{Arg}(\mu \cdot \det(vY^d)) = 0$ we need,

$$n_{QCD} = 0$$

i.e. an **anomaly free Froggatt Nielsen U(1).**

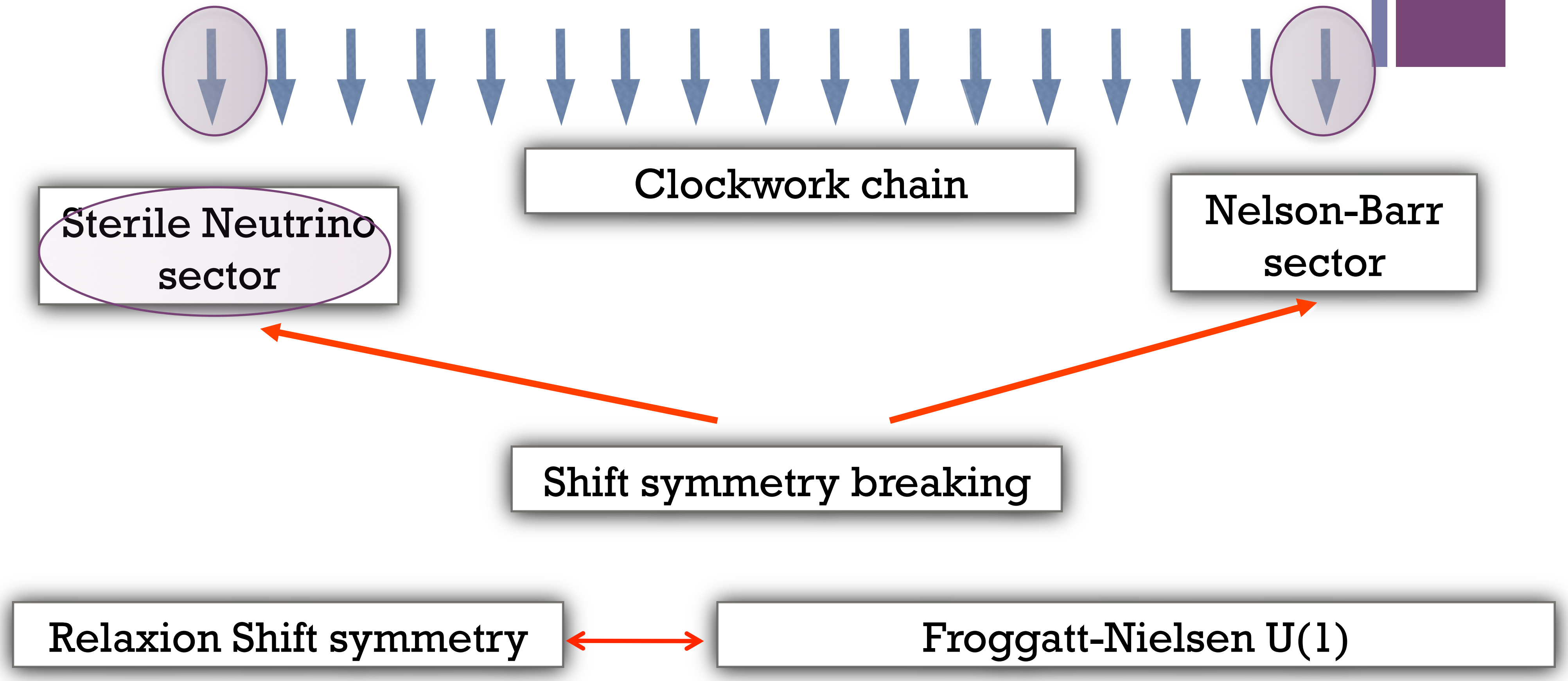
Charge assignment

- We find the anomaly free Froggatt-Nielsen charge assignment:

$$\begin{pmatrix} [Q_1] & [Q_2] & [Q_3] \\ [u_1^c] & [u_2^c] & [u_3^c] \\ [d_1^c] & [d_2^c] & [d_3^c] \end{pmatrix} = \begin{pmatrix} 3 & 2 & 0 \\ -10 & -6 & 0 \\ 2 & 2 & 2 \end{pmatrix}$$

- Can explain quark masses and mixings with single 5% tuning for the Wilson coefficient related to the 12 element of down mass matrix.

The hierarchion: basic picture



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Breaking the U(1) and neutrino masses (simplified version)

- The U(1) is broken by a Majorana mass term for the sterile neutrinos

$$\frac{1}{2}M_{ij}N_i^c N_j^c$$

- This generates neutrino masses,

$$m_\nu \sim \frac{(Y_N v)^2}{M}$$

- As well as the backreaction potential

$$V_{br} \sim (Y_N v)^2 M^2 \cos\frac{\phi}{f} \sim m_\nu M^3 \cos\frac{\phi}{f}$$

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$$\frac{1}{2} M_{ij} N_i^c N_j^c$$

- This generates neutrino masses, $\sim 10^{-6}$

Size explained by [...]gatt-Nielsen

No electroweak charged states as in other relaxion backreaction models.
Even more elusive at LHC!

- As well as the ba[...]

$$V_{br} \sim (Y_N v)^2 M^2 \cos\frac{\phi}{f} \sim m_\nu M^3 \cos\frac{\phi}{f}$$

Phenomenology

- Flavor violating decays:

$$\Gamma(\mu \to e\,\phi) \approx \frac{m_e^2 m_\mu}{16\pi f^2} \longrightarrow \quad f \gtrsim 2.8 \cdot 10^7 \text{ GeV}$$

Orders of magnitude improvement possible at MEG

$$\Gamma(K^+ \to \pi^+ \phi) \approx \frac{m_K}{64\pi} B_s^2 \left[1 - \frac{m_\pi^2}{m_K^2}\right] \frac{m_s m_d}{3^{2m} f^2} \longrightarrow f \gtrsim 8 \cdot 10^{10} \cdot (1/3)^m \text{ GeV}$$

Orders of magnitude improvement possible at NA62, KOTO.

- Also usual constraints from flavor diagonal coupling to electrons, anomaly induced coupling to photons (eg. star cooling bounds).

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Orde ble at MEG

Bounds from flavor violation in quark sector can be evaded by coupling quarks to intermediate clockwork site, giving them a larger effective *f*.

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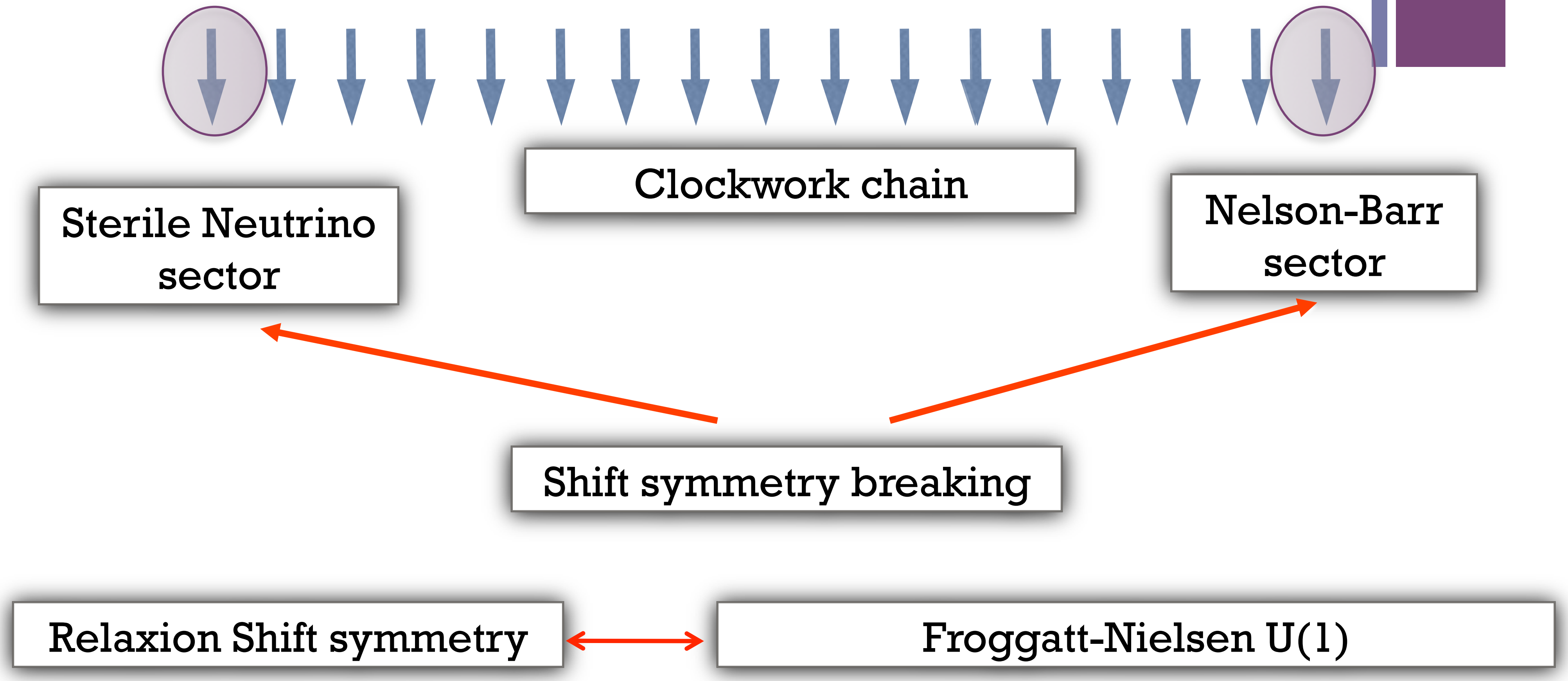
The hierarchion: basic picture



Davidi, RSG, Perez, Redigolo and Shalit (arXiv: 1711.00858)
Davidi, RSG, Perez, Redigolo and Shalit (arXiv: 1712.XXXXX)

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Conclusions

- We present a unified relaxion description for the electroweak, strong CP and flavor hierarchies of the Standard Model, including neutrino masses.
- Single light degree of freedom: the hierarchion.
- The *hierarchion* is at the same time the *relaxion*, the *familon* of a global flavor symmetry and the *CKM phase* of Nelson Barr models.
- No electroweak states accessible at LHC.
- Main Signature: Flavor violating meson and lepton decays.