Baryogenesis during relaxation

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Light scalars: origin, cosmology, astrophysics and experimental probes

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IPPP Durham

with Abel, Davidi, Perez,Redigolo, Scholtz, Shalit & Spannowsky

Cosmological Relaxation/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.

$$V(H) = \mu^2 H^\dagger H + \lambda (H^\dagger H)^2 \,,$$

$$\mu^2 = -\Lambda^2 + g\phi\Lambda + g^2\phi^2 + \ldots \,,$$

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

$$V(\phi) = g\phi\Lambda^3 + g^2\phi^2\Lambda^2 + \ldots$$

3. In the simplest model Φ is the QCD axion and has the coupling:

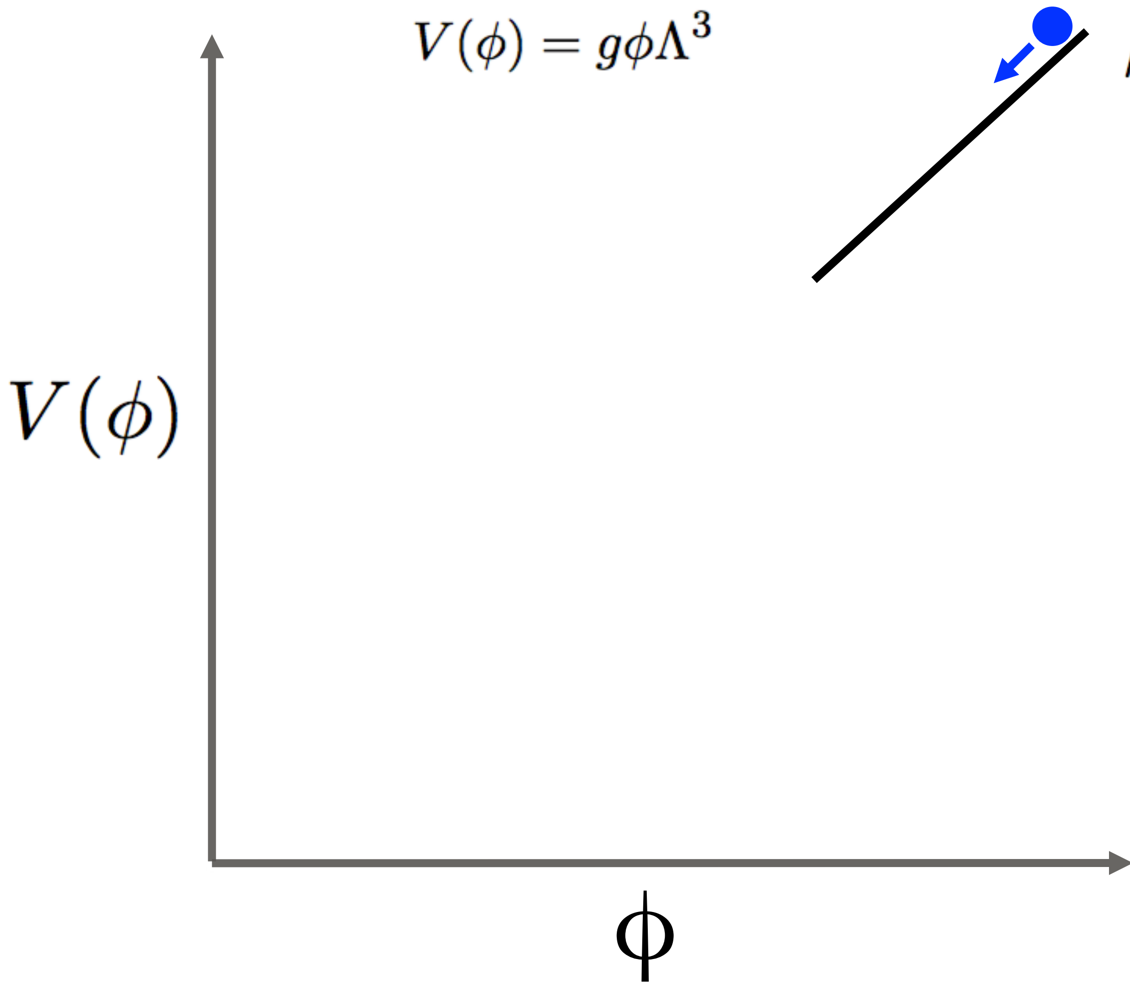
(more generally it is a PNGB).

$$\frac{1}{32\pi^2}\frac{\phi}{f}\tilde{G}^{\mu\nu}G_{\mu\nu}$$

Graham, Kaplan & Rajendran, 2015

The Relaxion Mechanism

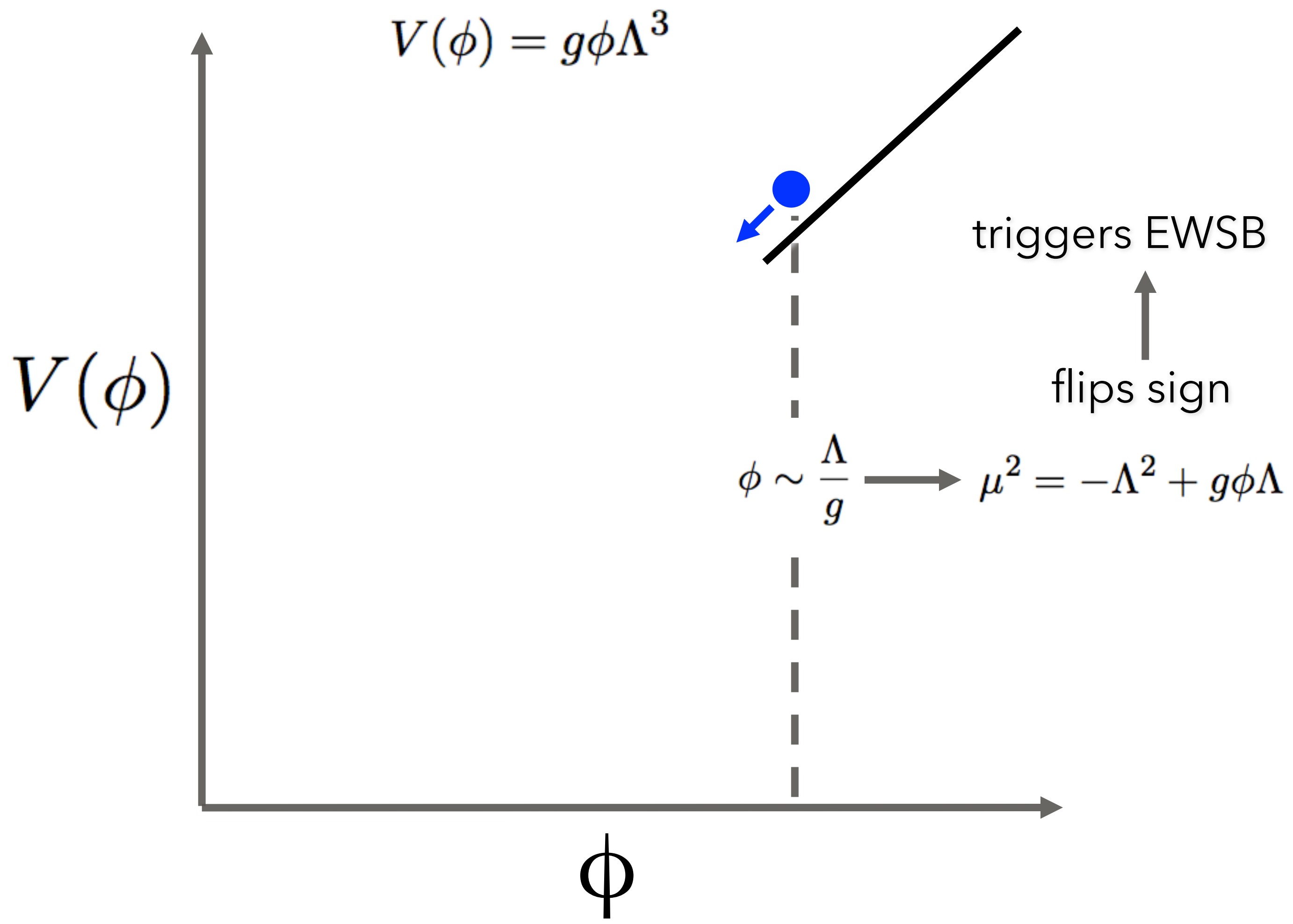
$$V(\phi) = g\phi\Lambda^3$$



$$\mu^2 = -\Lambda^2 + g\phi\Lambda > 0$$

$$\phi \gtrsim \frac{\Lambda}{g}$$

The Relaxion Mechanism



Backreaction potential

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

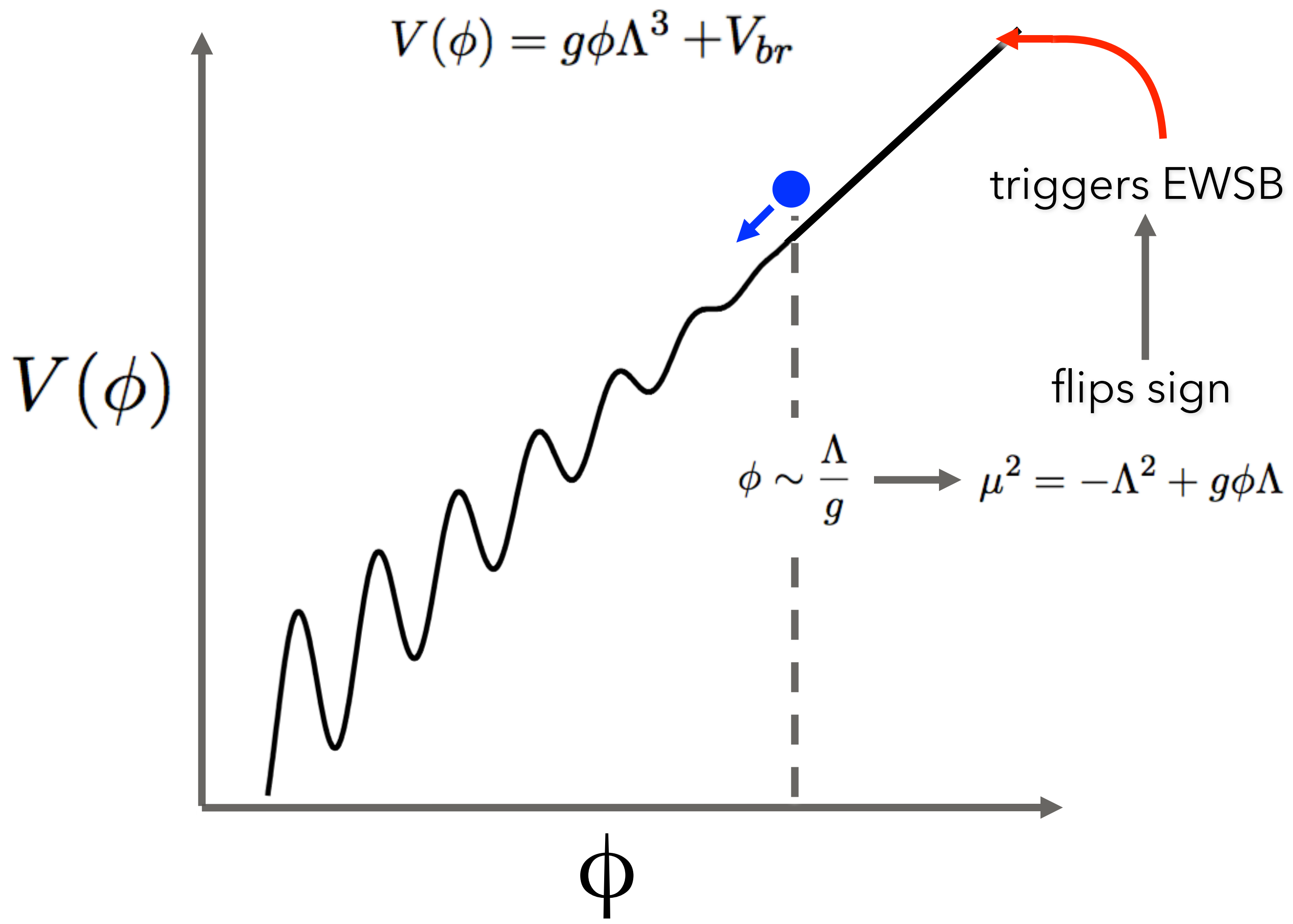
$$V_{\rm br} = -\Lambda_{\rm br}^4 \cos\frac{\phi}{f}\,, \quad \Lambda_{\rm br}^4 \sim M_{\rm br}^{4-j}(v+h)^j$$

- Example: QCD axion potential

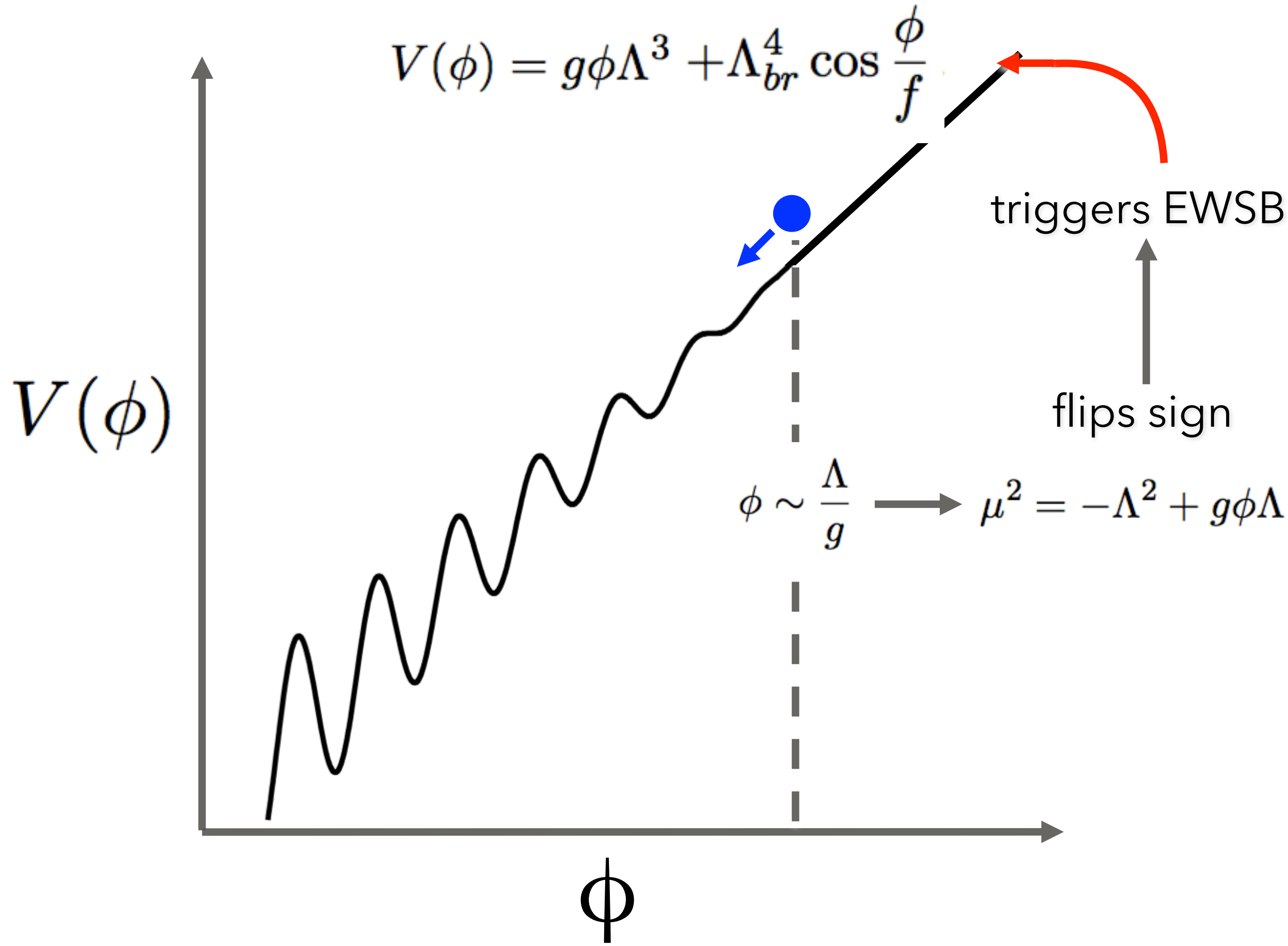
$$\Delta V \sim y_u v f_\pi^3 \cos\left(\frac{\phi}{f_a}\right)$$

- Relaxion can be axion of a non_SM group.

The Relaxion Mechanism

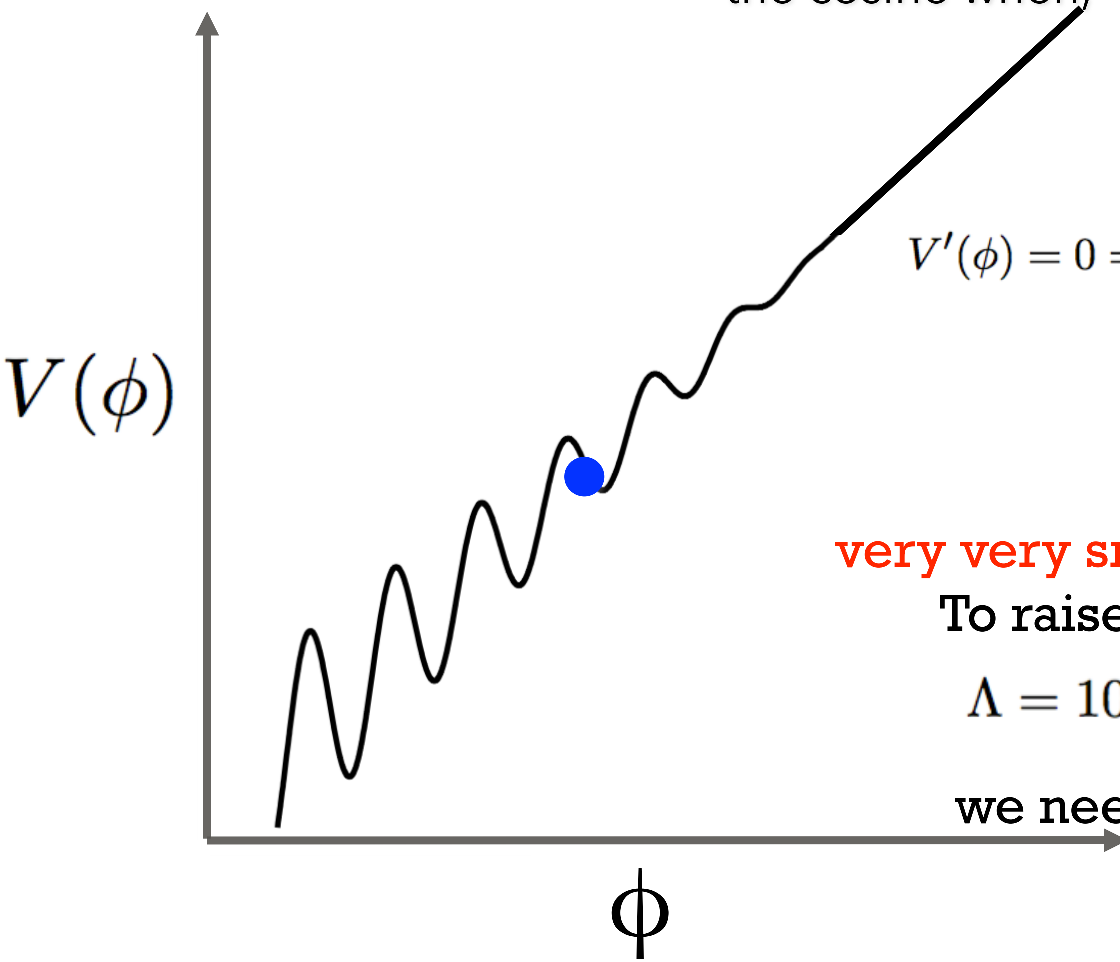


The Relaxion Mechanism



The Relaxion Mechanism

Relaxion stops at O(1) phase of the cosine when,



$$V'(\phi) = 0 \Rightarrow g\Lambda^3 - \frac{\Lambda_{br}^4}{f}\sin\frac{\phi}{f} = 0$$

$$\Lambda \sim \left(\frac{\Lambda_{br}^4}{gf}\right)^{1/3}$$

very very small g required!

To raise cut-off to

$$\Lambda = 10^7 \text{ GeV}$$

we need $g=10^{-20}$.

Spontaneous Relaxion Baryogenesis

- Standard relaxion models have all the ingredients for successful baryogenesis if SM fermions are charged under the relaxion shift symmetry.
- This leads to the coupling,

$$\frac{\partial_\mu \phi}{f} J^\mu \longrightarrow \text{must contain SM B+L current}$$

Abel, RSG, Scholtz (arXiv:1810.05153)

Spontaneous Relaxion Baryogenesis

- The rolling relaxion field breaks CP & CPT spontaneously broken
- New contribution to energy density for every particle antiparticle added:

$$\rho = -T_0{}^0 = -\sum_i c_i \frac{\dot{\phi}}{f} j_i^0 \longrightarrow -c_i(\dot{\phi}/f) j_i^0 = -c_i(\dot{\phi}/f)(n_i - \bar{n}_i)$$

- Generates equal & opposite chemical potential for particles/antiparticles

$$\frac{\partial_\mu \phi}{f} J^\mu \longrightarrow \text{Particles/Anti-particles obtain a chemical potential} \longrightarrow \mu = \pm \frac{\dot{\phi}}{f}$$

Cohen & Kaplan (1987)

Spontaneous Relaxion Baryogenesis

- This alters particle distribution wrt to antiparticle distribution provided there is a source for B-violation.

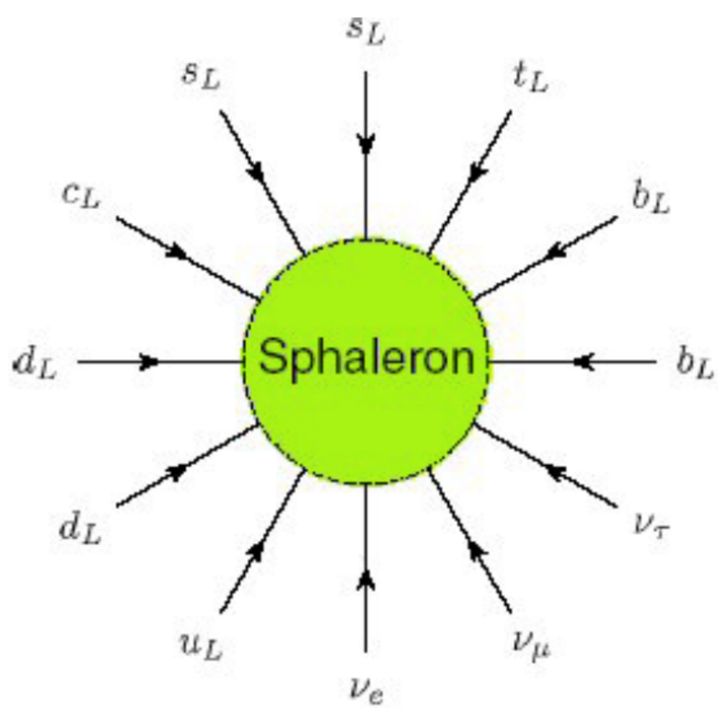
$$j_i^0 = n_i - \bar{n}_i = \frac{g_i}{(2\pi)^3} \int d^3p \left[\left\{ \exp\left(\frac{p-\mu_i}{T}\right) + 1 \right\}^{-1} - \left\{ \exp\left(\frac{p+\mu_i}{T}\right) + 1 \right\}^{-1} \right]$$
$$= \frac{g_i}{6} \mu_i T^2 \left\{ 1 + \mathcal{O}\left(\frac{\mu_i}{T}\right)^2 \right\}.$$

$$\boxed{\text{No departure from equilibrium required.}}$$

Cohen & Kaplan (1987)

+ Spontaneous Relaxion Baryogenesis

- With this term the rolling relaxion field alters particle distribution wrt to antiparticle ones provided there is a source for B-violation.

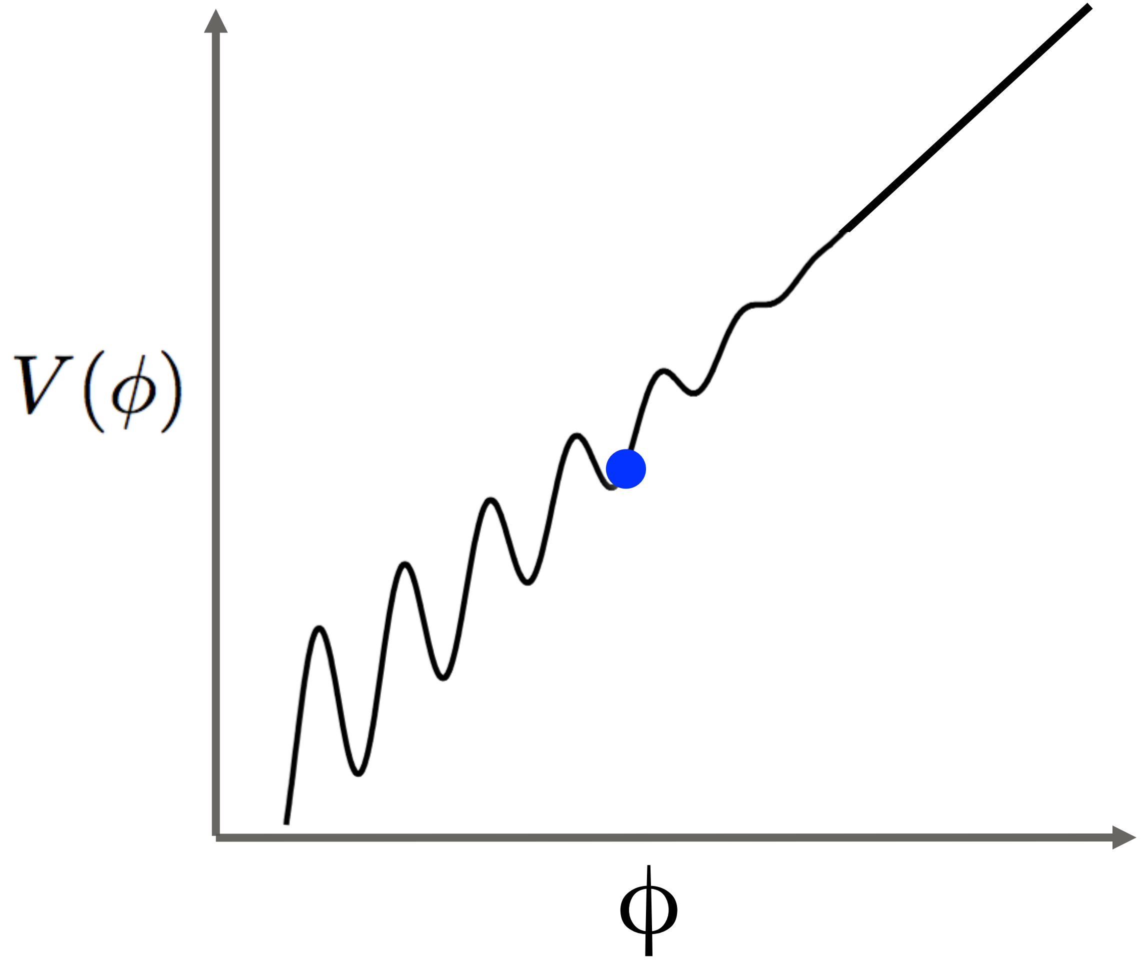


Sphalerons !!!

Not possible during inflation !

- Sphalerons not active unless we are at high temperatures.
- In any case we are assuming presence of a thermal bath
- Any B asymmetry will be diluted by rapid expansion during inflation

What happens to relaxion after inflation?



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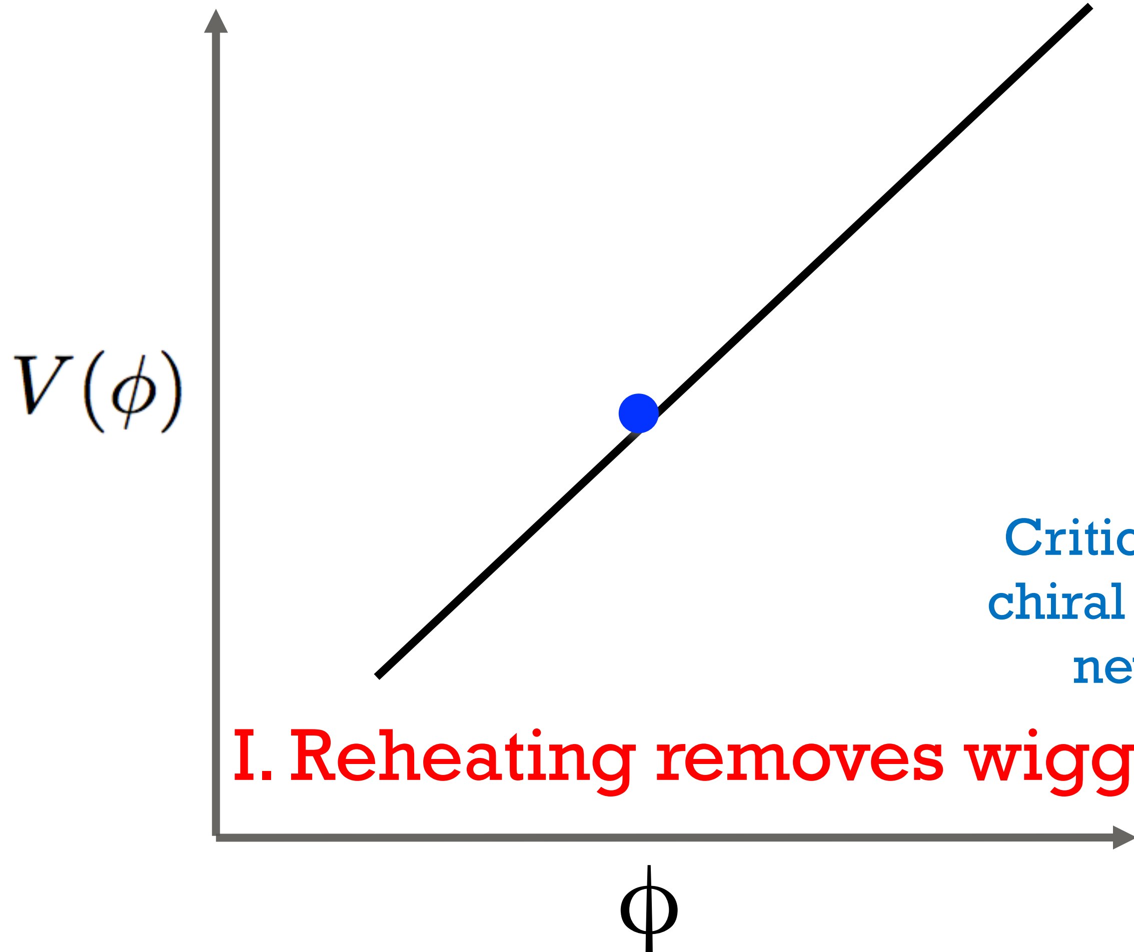
What happens to relaxion after inflation?



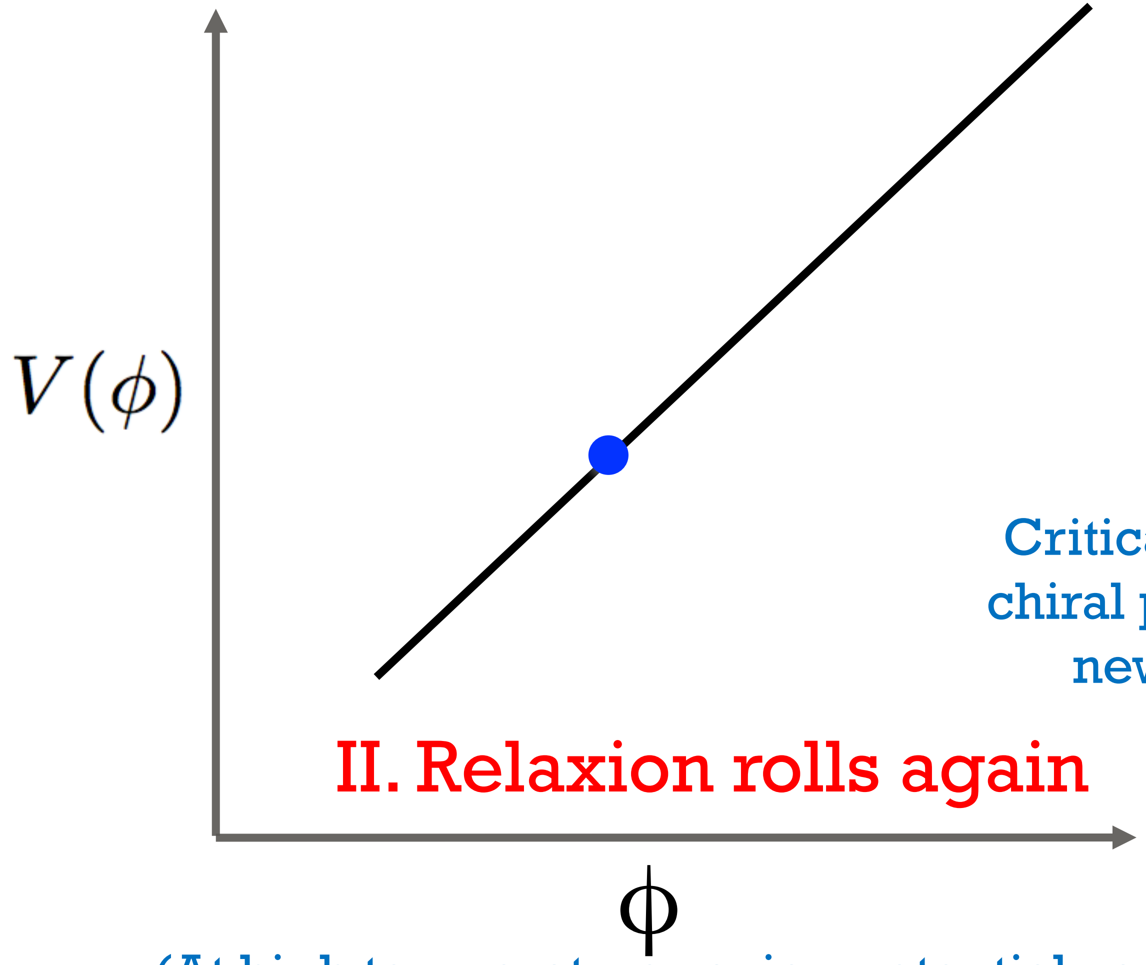
$T > T_c$

Critical Temperature of chiral phase transition of new strong group

I. Reheating removes wiggles

(At high temperatures axion potential vanishes)

What happens to relaxion after inflation?

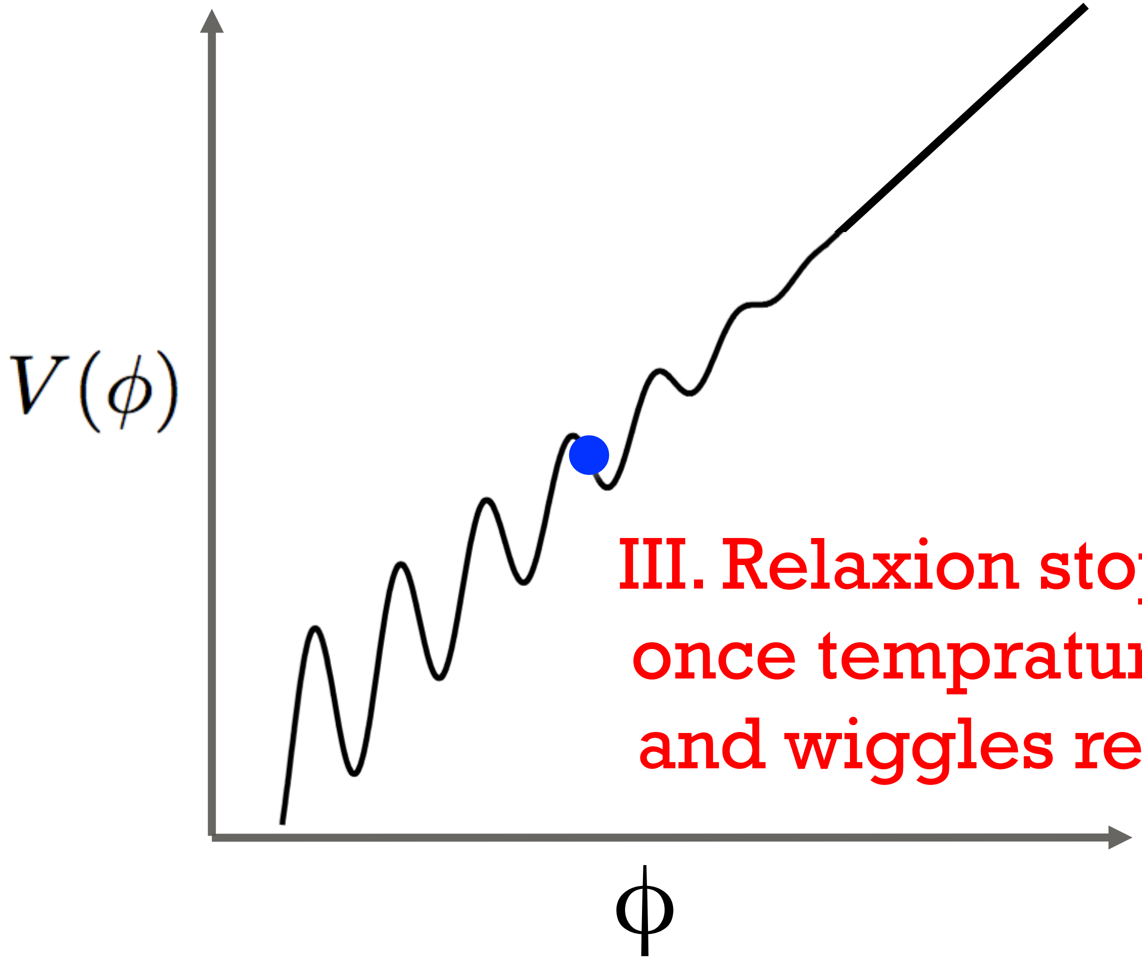


$T > T_c$

Critical Temperature of chiral phase transition of new strong group

(At high temperatures axion potential vanishes)

What happens to relaxion after inflation?



III. Relaxion stops again once temprature drops and wiggles reappear.

Does this spoil relaxion mechanism?

NO!

1) The shifting of the relaxion shifts Higgs VEV by less than O(1) value,

2) But must ensure relaxion does not overshoot barriers.

No overshooting condition

- The second phase of rolling obeys a solution similar to slow–roll:

$$V' \simeq 5H\dot{\phi}$$

- As long as:

$$m_\phi \lesssim 5H(T_c) \sim 3.8 \times 10^{-5}\,\mathrm{eV}$$

- Otherwise relaxion will overshoot barriers

Choi, Kim & Sekiguchi (arxiv: 1611.08569)

Banerjee, Kim & Perez (arXiv:1810.01889)

- For such a small mass need too large f~Mpl

- Not big enough coupling- $\frac{\partial_\mu \phi}{f} J^\mu$

Spontaneous Relaxion Baryogenesis

- In the background of the the rolling relaxion field this term alters particle distribution wrt to antiparticle ones provided there is a source for B-violation.

$$\frac{\partial_\mu \phi}{f} J^\mu \longrightarrow \text{Particles/Anti-particles obtain a chemical potential} \longrightarrow \mu = \pm \frac{\dot{\phi}}{f}$$

$$j_i^0 = n_i - \bar{n}_i = \frac{g_i}{(2\pi)^3} \int d^3p \left[\left\{ \exp\left(\frac{p-\mu_i}{T}\right) + 1 \right\}^{-1} - \left\{ \exp\left(\frac{p+\mu_i}{T}\right) + 1 \right\}^{-1} \right]$$

$$= \frac{g_i}{6} \mu_i T^2 \left\{ 1 + \mathcal{O}\left(\frac{\mu_i}{T}\right)^2 \right\}.$$

Cohen & Kaplan (1987)

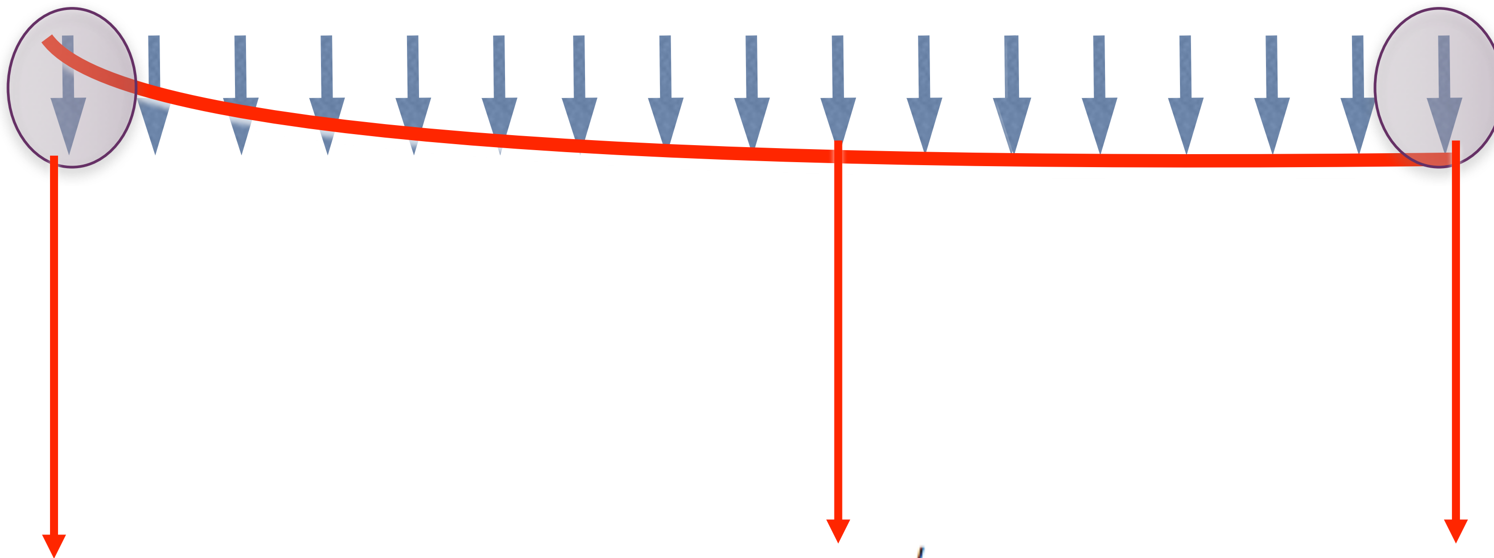
+ Obtaining correct Baryon Asymm.

$$\eta \equiv \frac{n_B}{s} = g_{\rm SB}\frac{\dot{\phi}}{f}\frac{T^2}{6}\times\frac{45}{2\pi^2 g_* T^3} = \frac{15}{4\pi^2}\frac{g_{\rm SB}}{g_*}\frac{\dot{\phi}}{fT}$$

- Sphalerons must decouple before relaxion stops. T_{sph}=130 GeV>T_c.
- After this the value of η freezes.

$$\eta \sim 10^{-10} \Rightarrow \frac{f_w}{f} \sim 10^9$$

Clockwork set-up

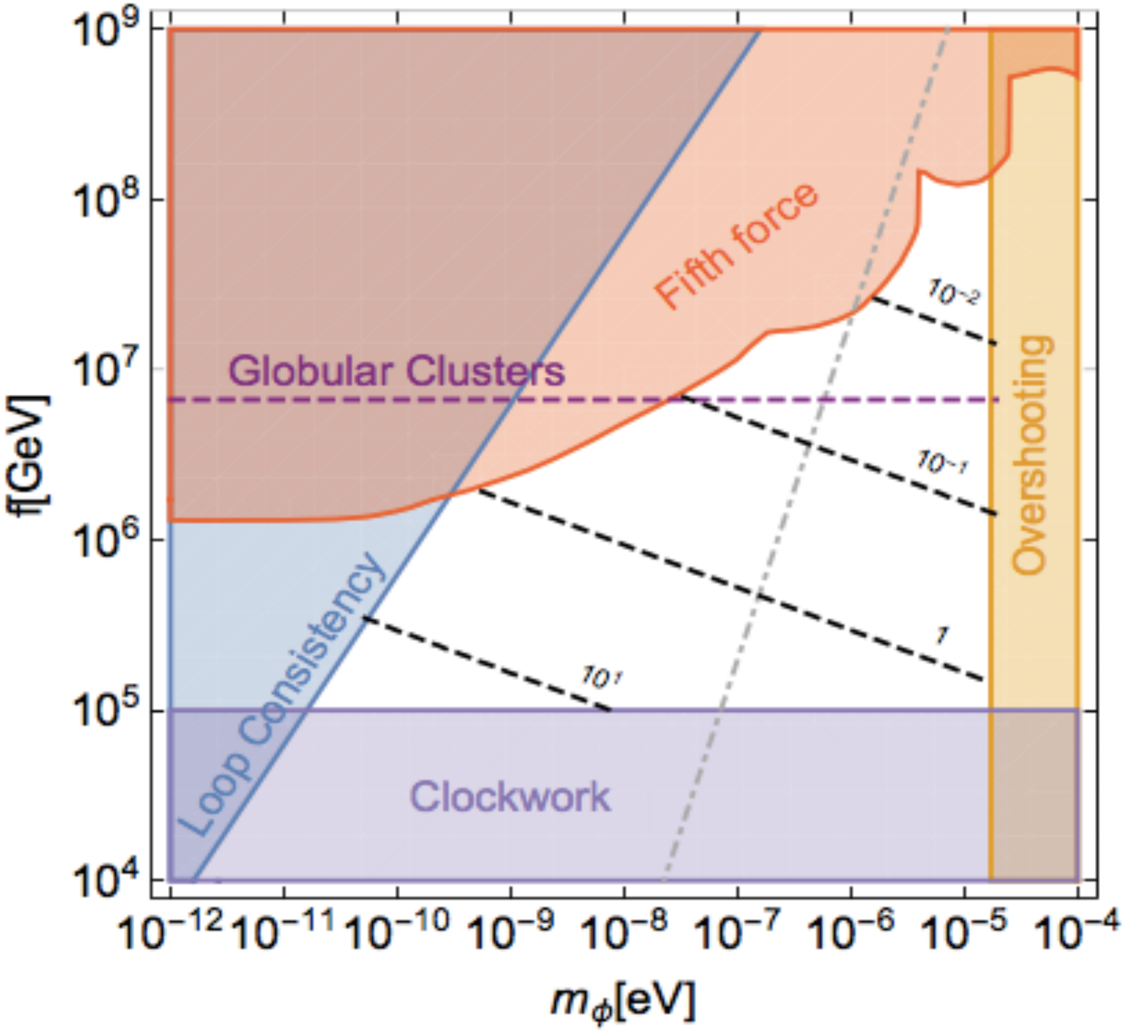


$$\frac{\partial_\mu \phi}{f} J^\mu \qquad \Lambda_{br}^4 \cos\frac{\phi}{f_w} \qquad \Lambda^4 \cos\frac{\phi}{F}$$

$$\begin{aligned} f_w &= 3^k f \\ F &= 3^N f \\ f \ll f_w &\ll F \end{aligned}$$

Choi, Kim & Yun (2014)
Choi & Im (2015)
Kaplan & Rattazzi(2015)

Finite Parameter Space



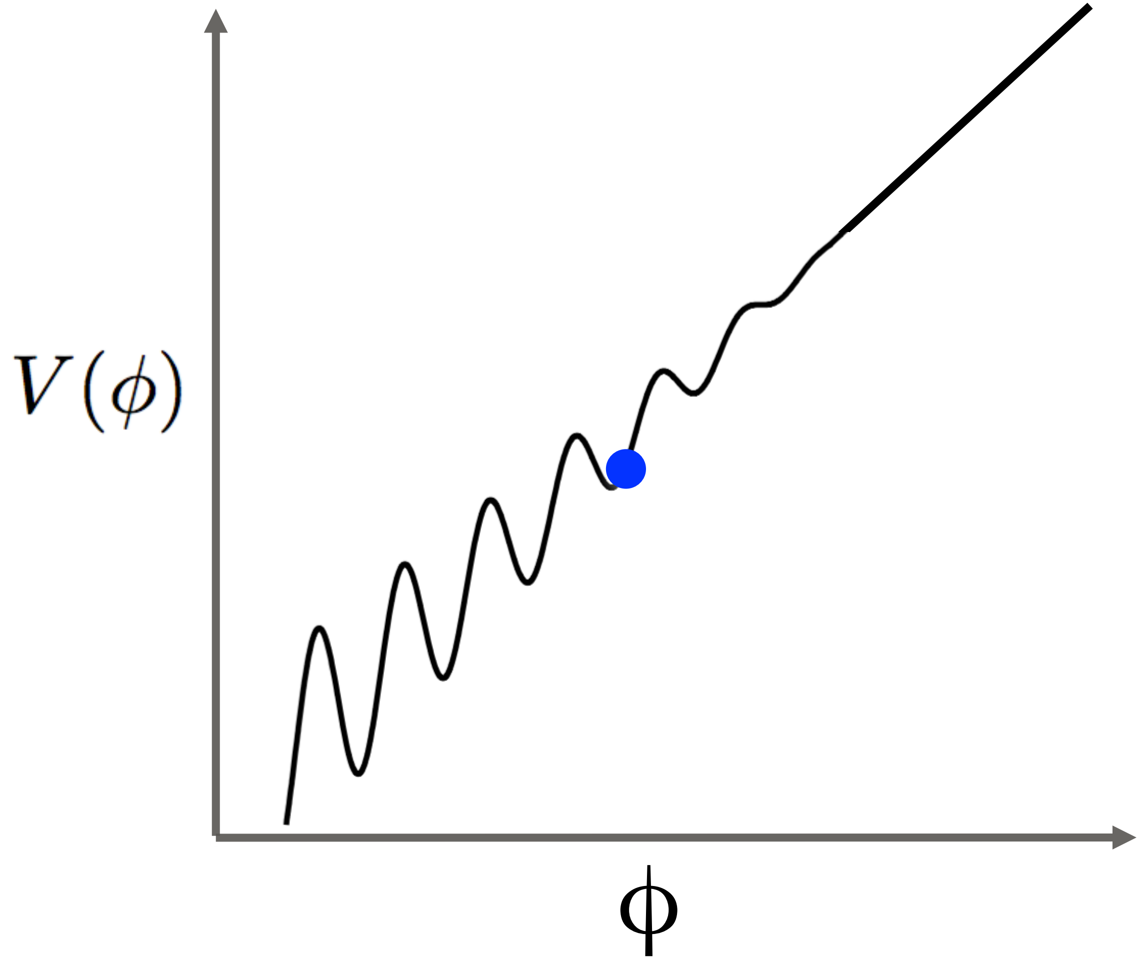
Abel, RSG, Scholtz (arXiv:1810.05153)

The Relaxion Double Miracle

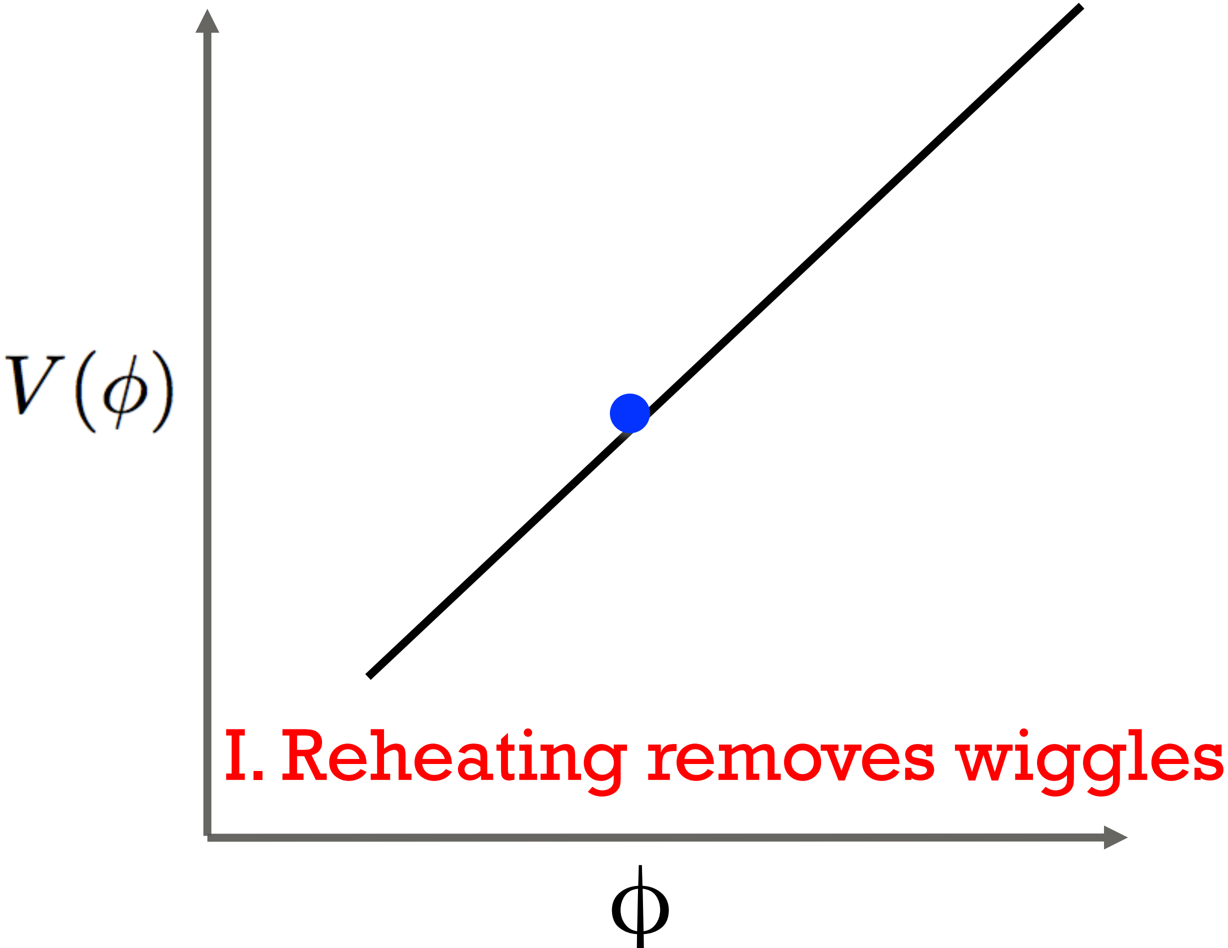
- Remarkably the same region of parameter space can produce the correct dark matter relic density through relaxion oscillations.

Banerjee, Kim & Perez (arXiv:1810.01889)

Relaxion oscillations

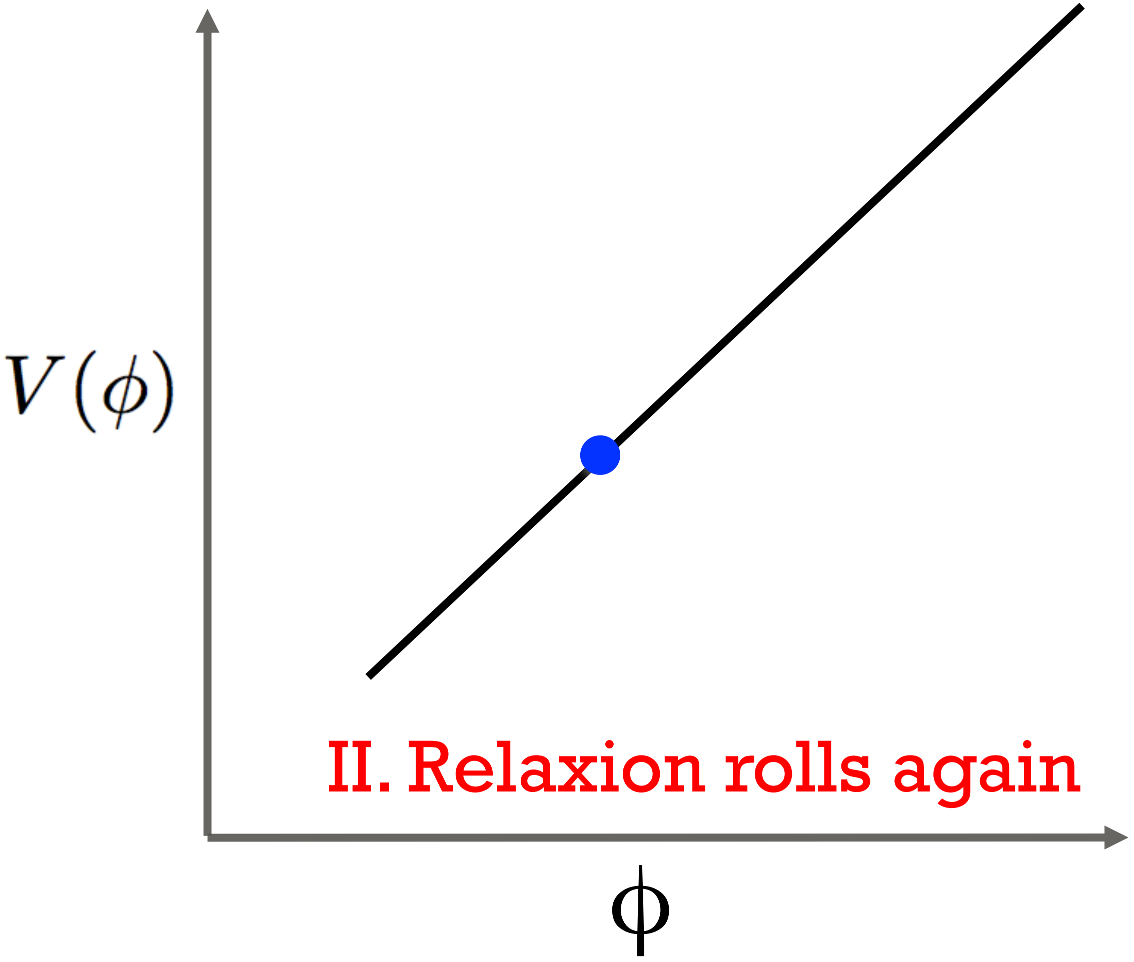


Relaxion oscillations

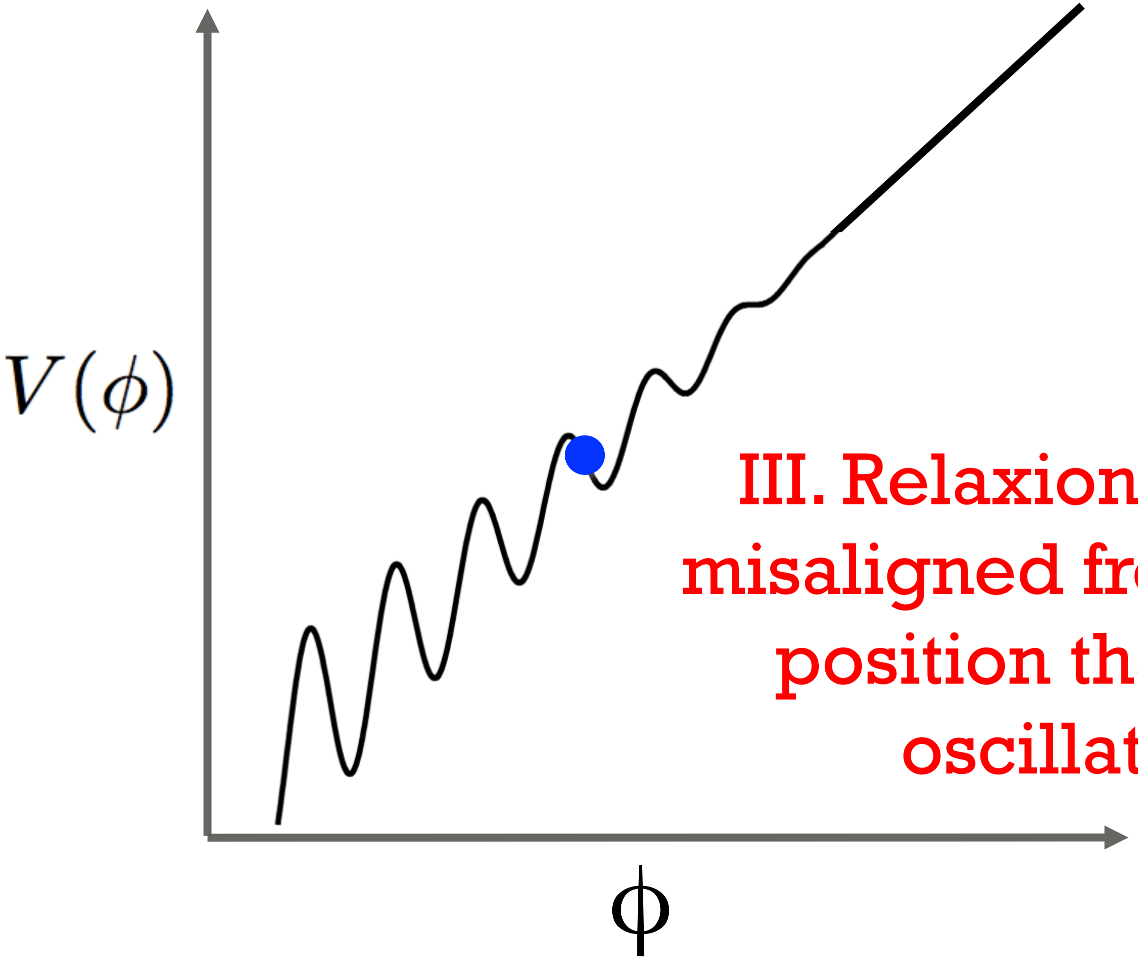


(At high temperatures axion potential vanishes)

Relaxion oscillations

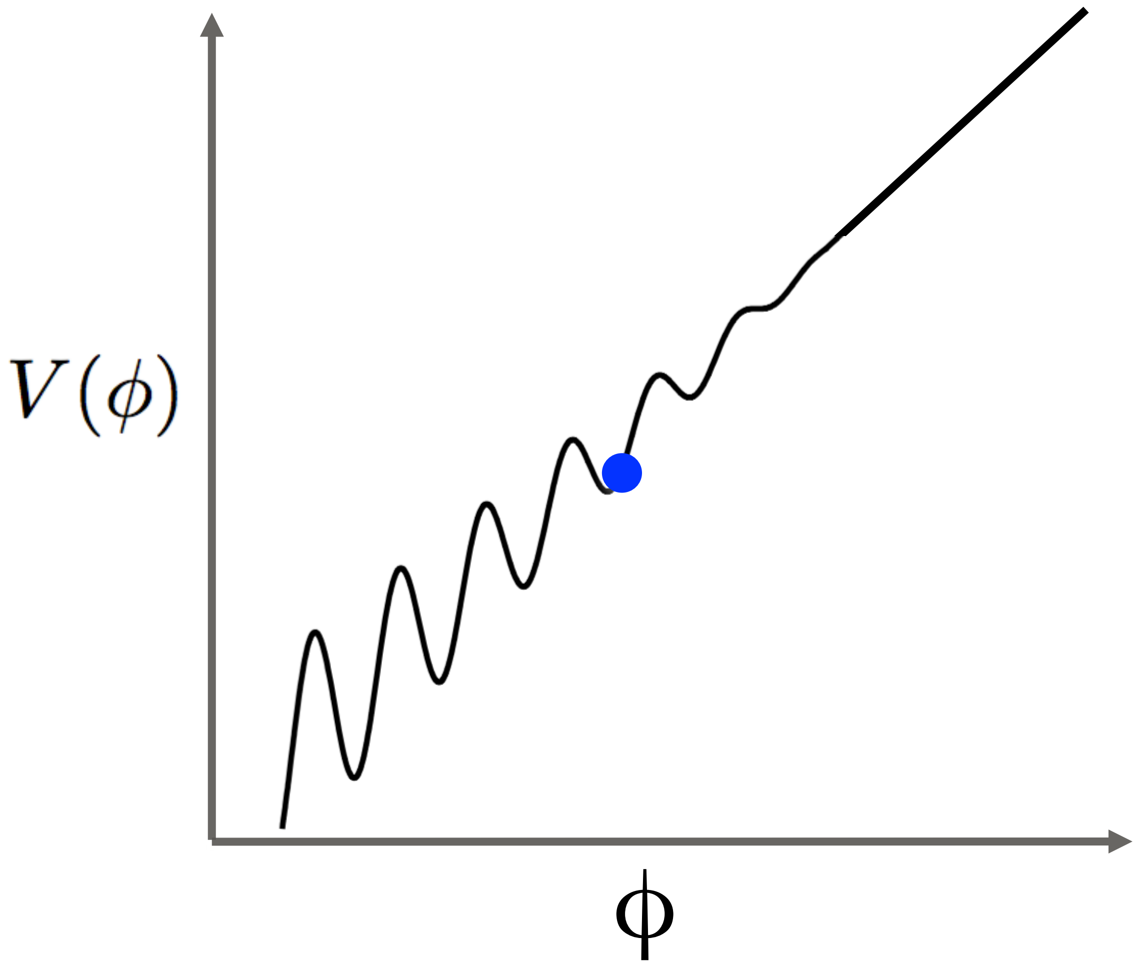


Relaxion oscillations



III. Relaxion stops but misaligned from original position that sets of oscillations.

Relaxion oscillations



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The Relaxion Double Miracle

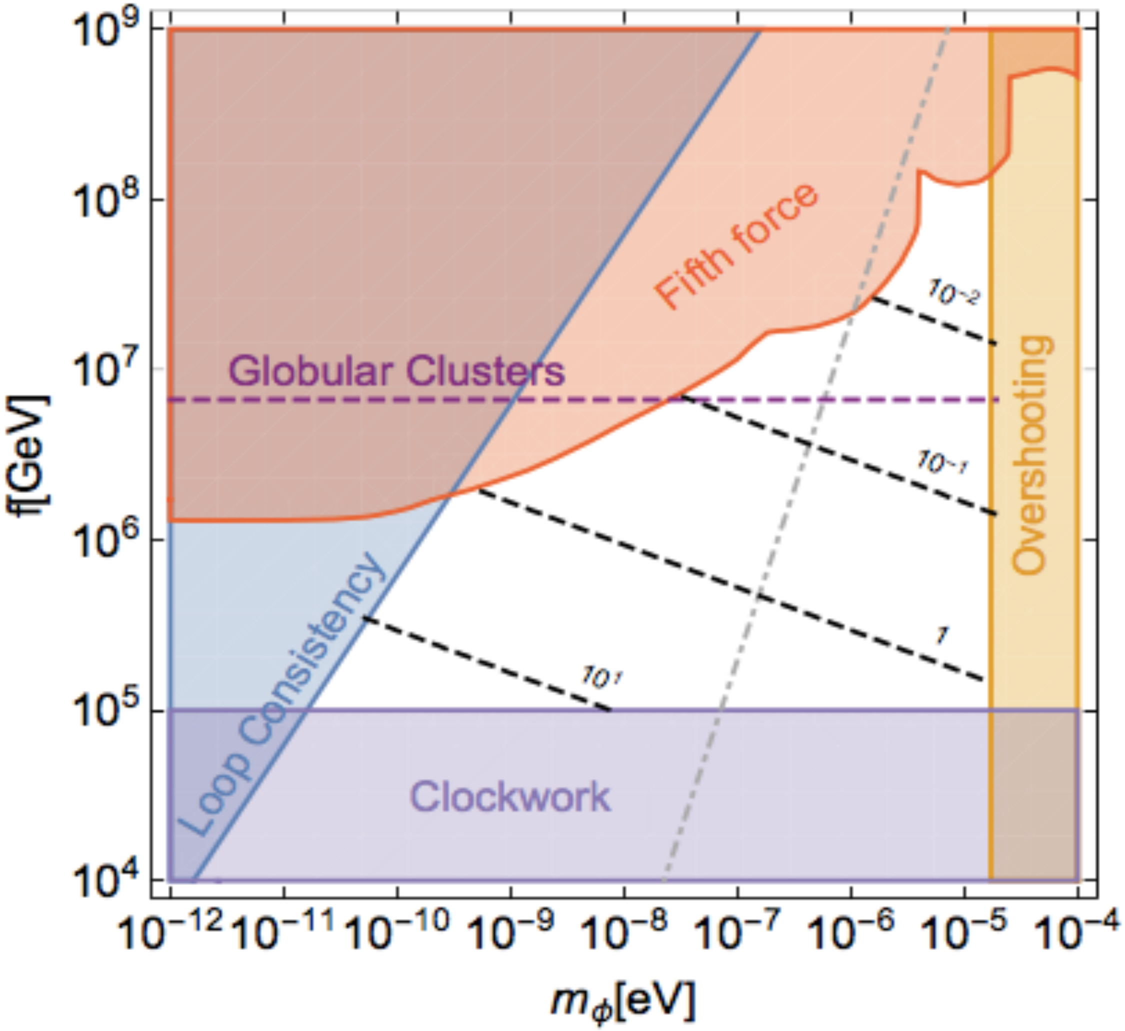
- Remarkably the same region of parameter space can produce the correct dark matter relic density through misalignment production.
- Misalignment:

$$\Delta\theta = \frac{\Delta\phi}{f_w} \simeq \frac{1}{20}\left(\frac{m_\phi}{H(T_c)}\right)^2 \tan\frac{\phi_0}{f_w}$$

- The energy density of the relaxion oscillations behaves in the same way as non-relativistic matter: $\rho \sim a^{-3}$ $p = 0$
- Relic Density:

$$\Omega h^2 \simeq 3\Delta\theta^2 \left(\frac{\Lambda_d}{1\text{ GeV}}\right)^4 \left(\frac{100\text{ GeV}}{T_{osc}}\right)^3$$

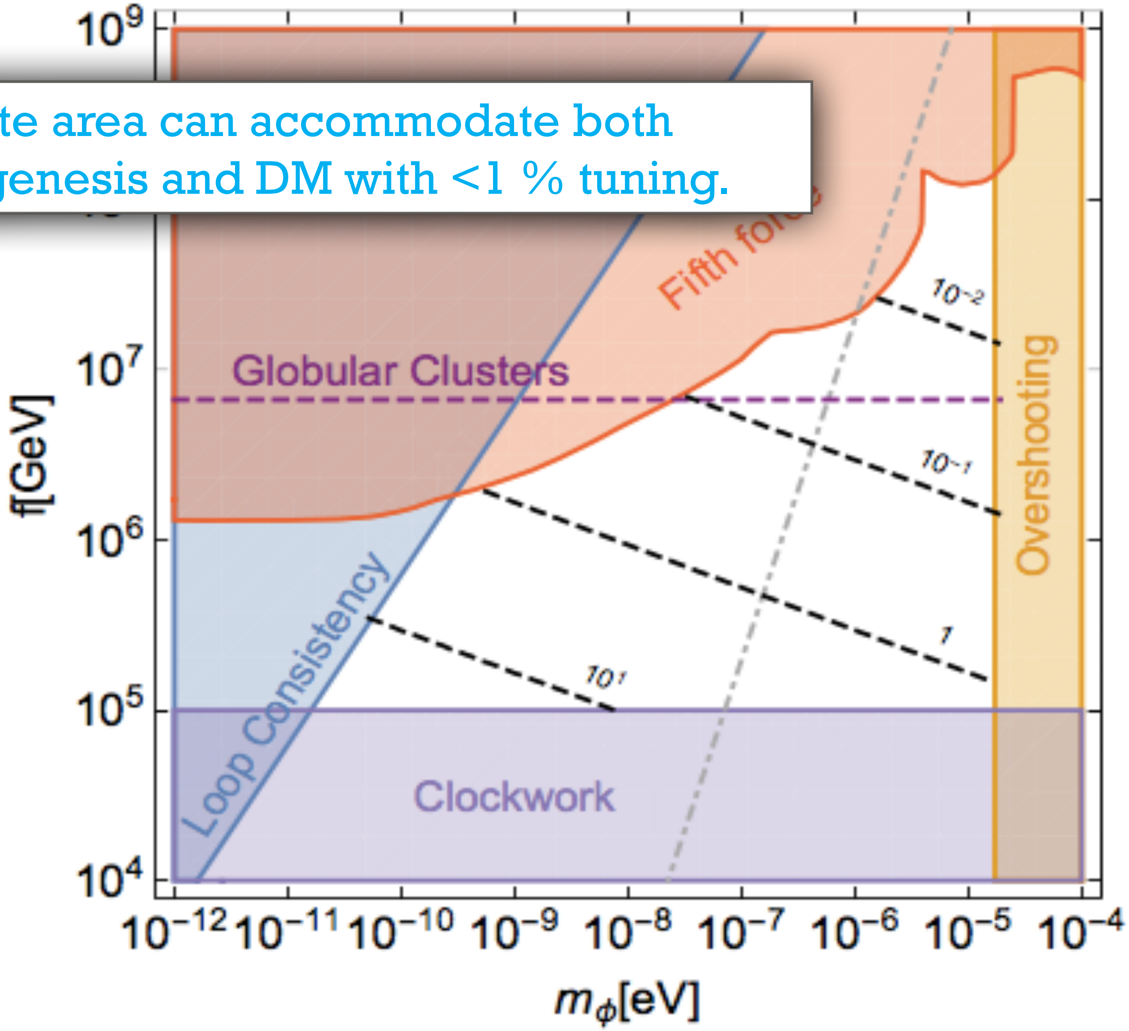
Finite Parameter Space



Abel, RSG, Scholtz (arXiv:1810.05153)

Finite Parameter Space

White area can accommodate both baryogenesis and DM with <1 % tuning.



Abel, RSG, Scholtz (arXiv:1810.05153)

No anomaly requirement

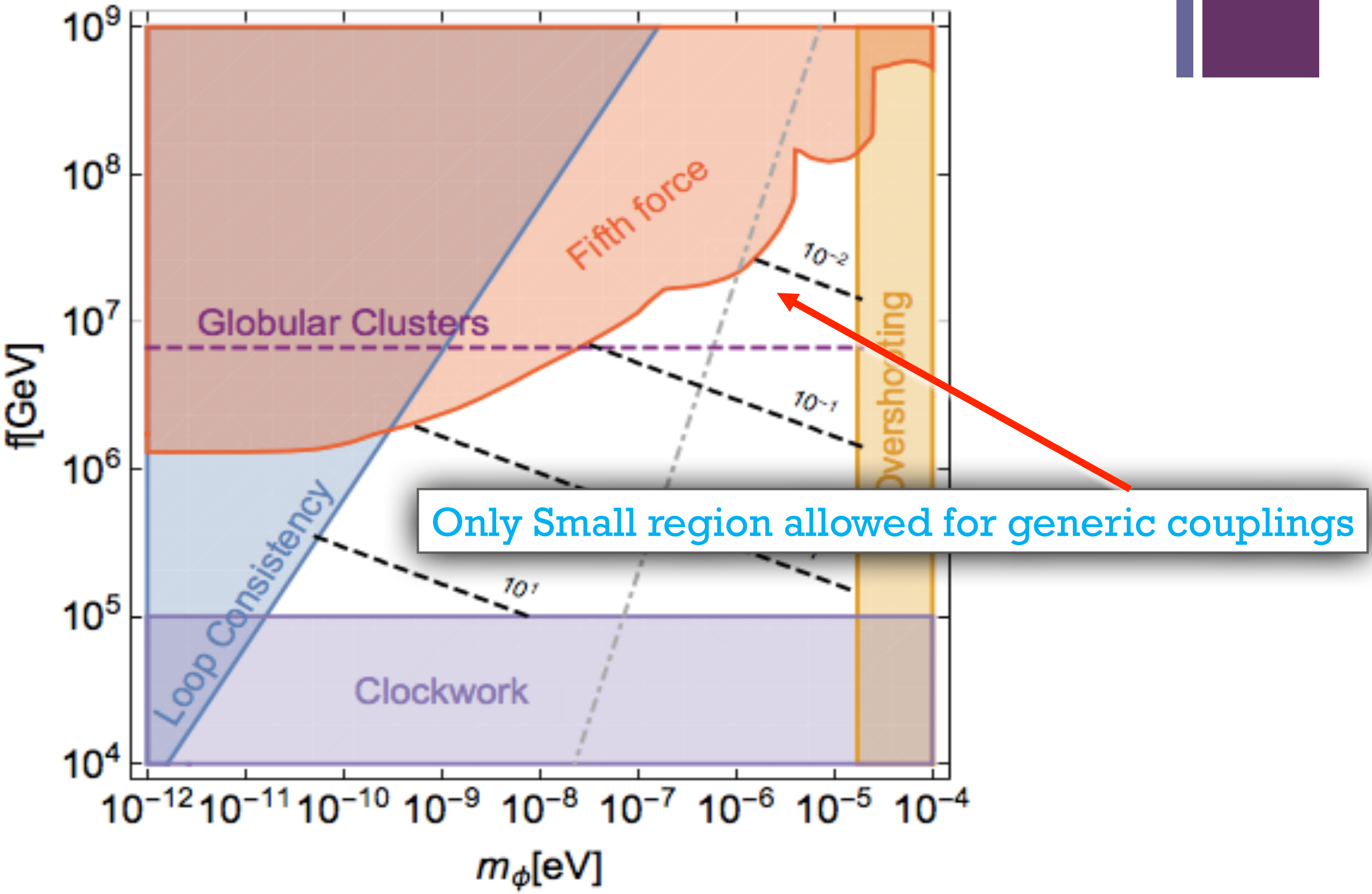
- The relaxion abelian symmetry must have no triangle anomaly with SM SU(3), or else, we have the coupling:

$$\frac{\phi}{f} G_{\mu\nu} \tilde{G}^{\mu\nu} \rightarrow \mathcal{O}(1)\ \theta_{QCD}$$

- The relaxion abelian symmetry must have no triangle anomaly with $U(1)_{em}$, or else, we have the coupling to photons which is strongly bounded by star cooling constraints:

$$\frac{\phi}{f} F_{\mu\nu} \tilde{F}^{\mu\nu} \rightarrow f \gtrsim 10^7\ \mathrm{GeV}$$

Finite Parameter Space



Abel, RSG, Scholtz (arXiv:1810.05153)

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The Neutrino option

- These requirements are automatically fulfilled if the current only contains only right handed neutrinos which are electrically neutral but do carry Lepton number.

$$\frac{\partial_\mu \phi}{f} J^\mu \longrightarrow$$

Current containing only RH neutrinos

- Such an operator can arise from a Froggatt-Nielsen+Seesaw solution to neutrino masses.

RSG, Reiness & Spannowsky(arxiv:1902.08633)

The Neutrino option

- Consider a U(1) symmetry under which only the right handed neutrinos are charged and the first scalar in clockwork has charge=-1

relaxion

$$y_n^{ij}\left(\frac{\langle\Phi_0\rangle e^{i\phi/f}}{\Lambda_{FN}}\right)^{q_{n_j}} l_i H n_j^\dagger + \left(\frac{\langle\Phi_0\rangle e^{i\phi/f}}{\Lambda_{FN}}\right)^{q_{n_i}+q_{n_j}} \hat{M}_n^{ij} n_i n_j$$

$$N^c \to N^c (e^{-i\phi/f})^{q_{N^c}} \longrightarrow \frac{\partial_\mu \phi}{f} J^\mu$$

Current containing only RH neutrinos

RSG, Reiness & Spannowsky(arxiv:1902.08633)

Sterile neutrino mass range

- RH neutrinos were assumed in equilibrium with rest of SM plasma and relativistic around sphaleron decoupling temperature T_{sph} ~130 GeV. This implies:

$$\begin{aligned} 10^{-8} \lesssim \; & Y_n \lesssim 10^{-6} \\ 30 \text{ MeV} \lesssim \; & M_n \lesssim T_{sph}. \end{aligned}$$

RSG, Reiness & Spannowsky(arxiv:1902.08633)

Neutrino Masses

- Consider **a U(1) symmetry under which only the right handed neutrinos** and the first scalar in clockwork chain are charged

$$y_n^{ij}\left(\frac{\langle\Phi_0\rangle e^{i\phi/f}}{\Lambda_{FN}}\right)^{q_{n_j}} l_i H n_j^{\dagger} + \left(\frac{\langle\Phi_0\rangle e^{i\phi/f}}{\Lambda_{FN}}\right)^{q_{n_i}+q_{n_j}} \hat{M}_n^{ij} n_i n_j$$

Need Small Yukawa
to get right neutrino mass

Need small seesaw scale

RSG, Reiness & Spannowsky(arxiv:1902.08633)

Neutrino Masses

- Consider a U(1) symmetry under which only the right handed neutrinos and the first scalar in clockwork chain are charged

$$y_n^{ij}\left(\frac{\langle\Phi_0\rangle e^{i\phi/f}}{\Lambda_{FN}}\right)^{q_{n_j}} l_i H n_j^\dagger + \left(\frac{\langle\Phi_0\rangle e^{i\phi/f}}{\Lambda_{FN}}\right)^{q_{n_i}+q_{n_j}} \hat{M}_n^{ij} n_i n_j$$

- With sterile neutrino charge = 6 and Majorana mass=100 GeV, we get,

$$Y_N = \left(\frac{\langle\Phi_0\rangle}{\Lambda}\right)^{q_{N^c}} = 10^{-6} \qquad m_\nu = \frac{Y_N^2 v^2}{M} = 0.1\ \text{eV}, \quad \text{for} \quad \frac{\langle\Phi_0\rangle}{\Lambda} = 0.1$$

RSG, Reiness & Spannowsky(arxiv:1902.08633)

Neutrino Masses

- Consider a U(1) symmetry under which only the right handed neutrinos and the first scalar in clockwork chain are charged

$$y_n^{ij}\left(\frac{\langle\Phi_0\rangle e^{i\varphi}}{\Lambda_{FN}} \cdots\right)^{\cdots+q_{n_j}} \quad \hat{M}_n^{ij} n_i n_j$$

Neutrino masses explained by combination of Froggatt-Nielsen and seesaw mechanism

- With sterile n… mass=100 GeV, we get,

$$Y_N = \left(\frac{\langle\Phi_0\rangle}{\Lambda}\right)^{q_{N^c}} = 10^{-6} \qquad m_\nu = \frac{Y_N^2 v^2}{M} = 0.1\ \text{eV}, \quad \text{for} \quad \frac{\langle\Phi_0\rangle}{\Lambda} = 0.1$$

RSG, Reiness & Spannowsky(arxiv:1902.08633)

All-in-one Relaxion

Original GKR relaxion model + RH neutrinos

solves

- Dark Matter
- Neutrino masses
- Matter-Antimatter symmetry
- Hierarchy Problem
- Strong CP problem
- SM Flavour puzzle

Abel, RSG & Scholtz (arXiv:1810.05153)

RSG, Reiness & Spannowsky(arxiv:1902.08633)

All-in-one Relaxion

Original GKR relaxion model + RH neutrinos+ up type VL fermions

solves

- Dark Matter
- Neutrino masses
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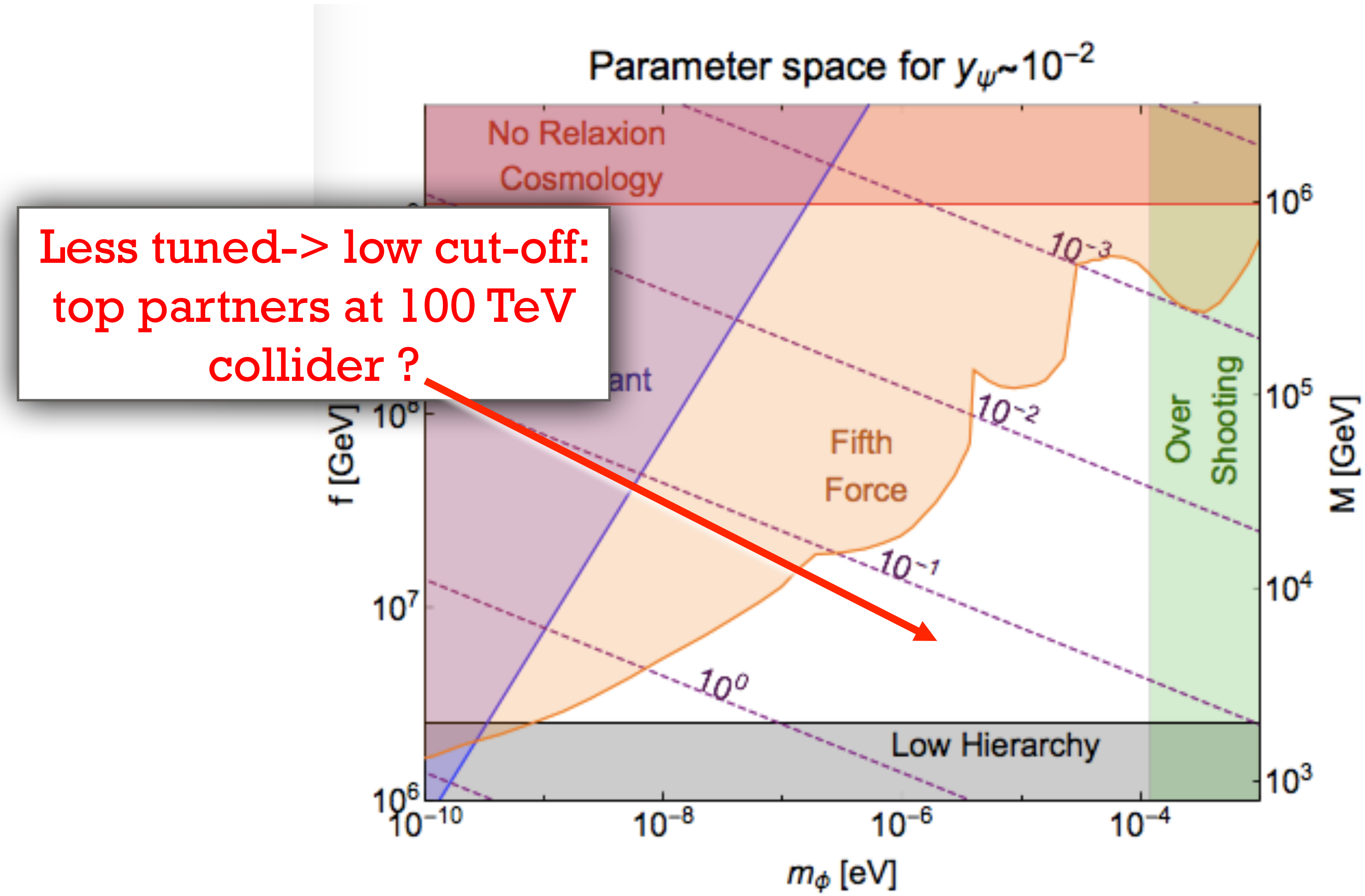
Abel, RSG & Scholtz (arXiv:1810.05153)

RSG, Reiness & Spannowsky(arxiv:1902.08633)

Davidi, RSG, Perez, Redigolo and Shalit (arXiv:1711.00858

The strong CP problem is solved in our set-up by the Nelson-Barr mechanism which utilises the fact that the relaxion breaks CP spontaneously at its stopping point. UV completion of the rolling sector!

Finite Parameter Space



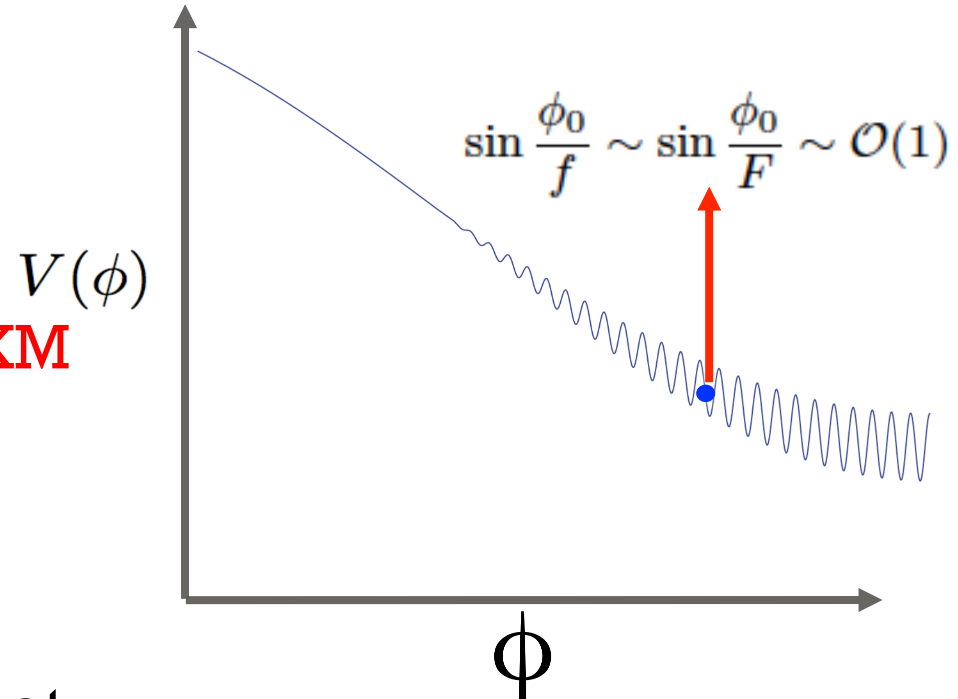
f and Λ (or M) now connected!

Back up slides

More details on the Nelson-Barr Relaxion

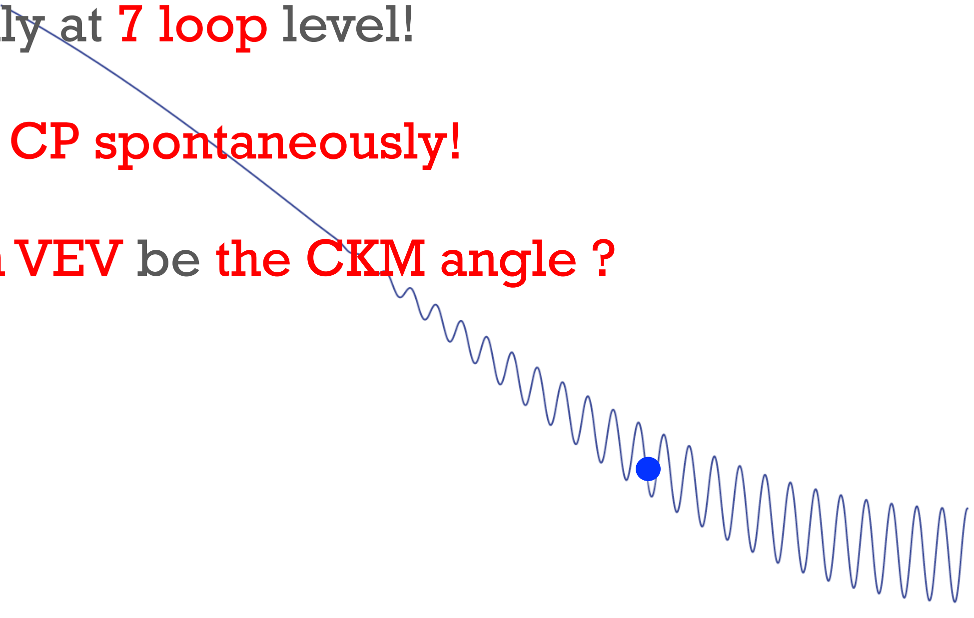
Spontaneous CP violation by the relaxion

- CP broken spontaneously by relaxion VEV.
- In simplest case Relaxion cannot be QCD axion.
- What if relaxion VEV is CKM phase and not strong CP phase?
- Unified solution of EW hierarchy and Strong CP not possible this way: Nelson Barr relaxion.

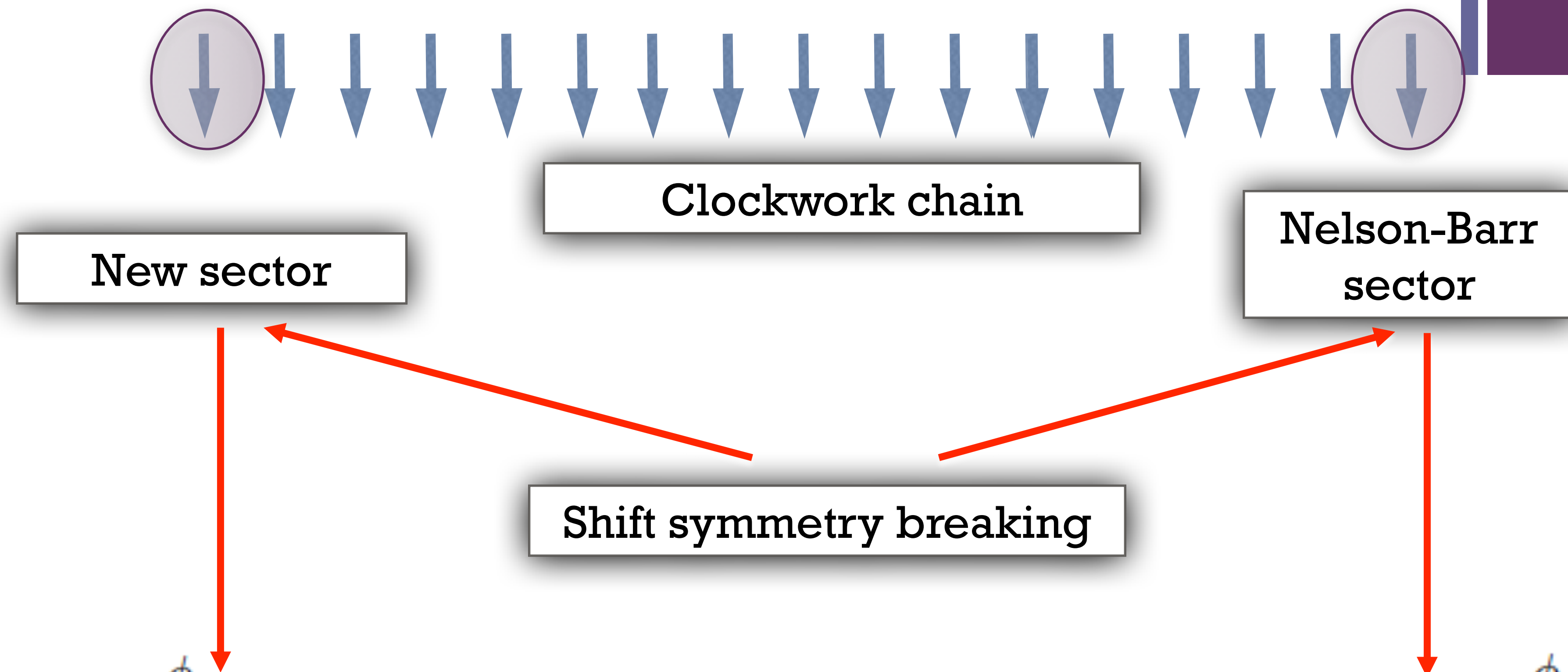


Nelson-Barr relaxion: strong CP+EW hierarchy, a unified solution

- 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 strong CP phase but only at 7 loop level!
- Relaxion breaks CP spontaneously!
- Can the relaxion VEV be the CKM angle ?



NB relaxion: basic picture



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

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

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

Nelson-Barr relaxion

- Add a new vectorlike quark:

$$\mathcal{L}_{\rm NB} = \underline{Y^u_{ij} H Q_i u^c_j} + \left[y^\psi_i \Phi_N + \tilde{y}^\psi_i \Phi^*_N \right] \psi u^c_i + \mu \psi \psi^c + \text{h.c.}$$

- A Z_2 symmetry under which vectorlike pair and Φ_N is charged forbids their couplings of SM quarks.
- $U(1)_N$ (thus clockwork U(1)) broken collectively by $y_\psi, \tilde{y}_\psi$
- $U(1)_N$ 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!

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

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

- As all couplings are real,

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

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:

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

Radiatively

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

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

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

Radiative threshold contributions to strong CP phase

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

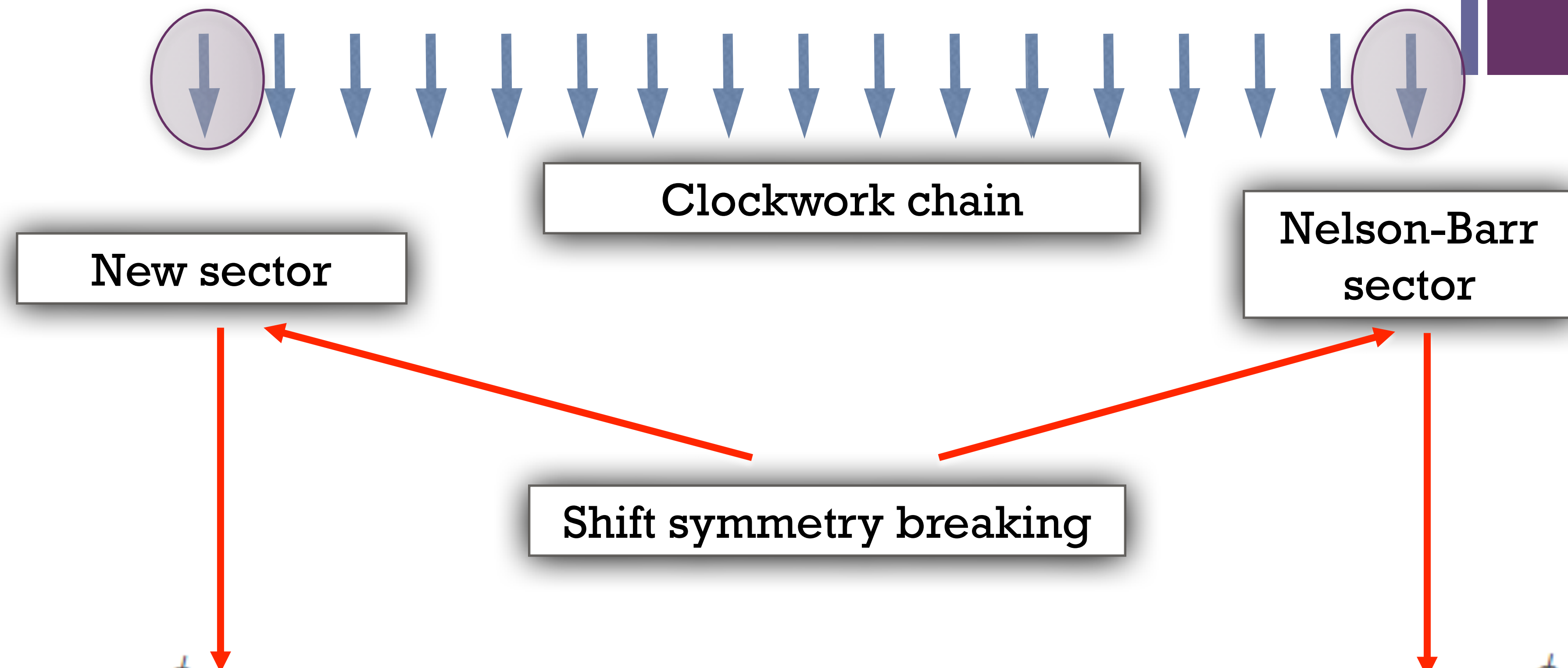
$$y_i^{\psi} \sim \tilde{y}_i^{\psi} \sim y_{\psi} \to 0$$

- 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).

NB relaxion: basic picture



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

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

Relaxion cannot be QCD axion

- Make relaxion the axion of a new strong group

$$\mathcal{L} = y_1 LHN + y_2 L^c H^\dagger N^c - m_L L L^c - m_N N N^c + h.c. + \frac{\phi}{f} G' \tilde{G}'$$

- Axion potential:

$$V_{\rm br} \simeq -4\pi f_{\pi'}^3 m_N \cos\frac{\phi}{f}$$

- Light fermion gets Higgs dependent contribution upon integrating out L.

$$\Delta m_N = \frac{y_1 y_2 \langle H \rangle^2}{m_L} \longrightarrow V_{\rm br} \simeq -4\pi f_{\pi'}^3 \frac{y_1 y_2 \langle H \rangle^2}{m_L} \cos\frac{\phi}{f}$$

Cosmological bound on cut-off

- Relaxion must carry only a fraction of the vacuum energy during inflation:

$$H_I > \frac{\Lambda^2}{M_{Pl}}$$

- Classical rolling must be larger than quantum spreading:

$$H_I < \frac{V'(\phi)}{H_I^2}$$

- This gives:

$$\Lambda < \left(\frac{\Lambda_{br}^4 M_{Pl}^3}{f}\right)^{1/6} \sim 10^8\,\mathrm{GeV}$$

Cosmological bound on cut-off

- Relaxion must carry only a fraction of the vacuum energy duri

OTHER MAJOR ISSUES

- *Cannot raise cut-off to Planck scale? Need, for eg.,SUSY at intermediate scale to solve hierarchy problem completely.*
- *Low scale inflations sector needed. Also mane many e-folds. Inflation sector challenging.*

- Classical rol um spreading:

$$H_I \quad H_I^2$$

- This gives: $$\Lambda < \left(\frac{\Lambda_{br}^4 M_{Pl}^3}{f}\right)^{1/6} \sim 10^8\,\mathrm{GeV}$$

Sterile neutrino mass range

- RH neutrinos were assumed in equilibrium with rest of SM plasma and relativistic around sphaleron decoupling temperature T_{sph} ~130 GeV. This implies:

$$\begin{aligned} 10^{-8} \lesssim\ & Y_n \lesssim 10^{-6} \\ 30\ \mathrm{MeV} \lesssim\ & M_n \lesssim T_{sph}. \end{aligned}$$

Can the Relaxion be a PGB?

- A GB from global symmetry breaking is the angular part of a field whose real part gets a vev. (all internal symmetries must be compact).

$$\Phi = \rho \exp[i\phi/f_{\rm UV}]$$

- By definition, $$\phi \to \phi + 2\pi k f_a\,, \qquad k \in \mathbb{Z}$$
- GB->PNGB we introduce some explicit breaking.

$$\Delta V_{explicit} = m^2\Phi^2 + h.c.$$

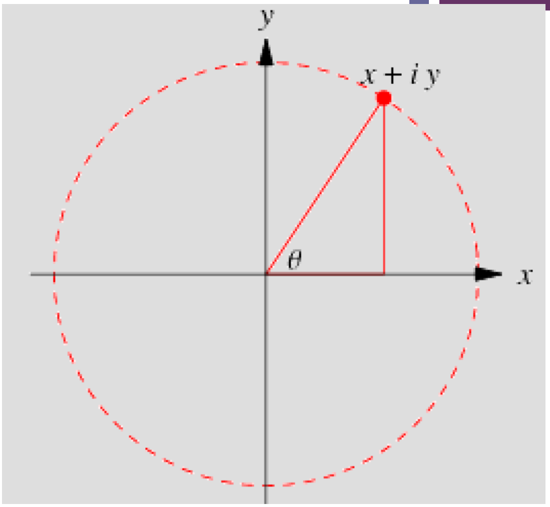
- Even explicit breaking term respects the discrete symmetry and induces a periodic term:

$$\Delta V = m^2 f^2 \cos\left(\frac{2\phi}{f}\right)$$

RSG, Komargodski, Perez and Ubaldi (arXiv:1509.00047)

Can the Relaxion be a PGB?

- Any PNGB potential must be periodic !
- Technically $\phi \to \phi + 2\pi n f_a$ is a gauge and not a global symmetry. Global symmetries relate two physically distinct points in field space.
- The discrete symmetry $\phi \to \phi + 2\pi n f_a$ relates two values of corresponding to physically the same point in field space.
- Gauge symmetries must never be broken in a consistent QFT !
- For eg. In any standard UV completion of the Peccei-Quinn axion is truly periodic and cannot accommodate the linear term.



RSG, Komargodski, Perez and Ubaldi (arXiv:1509.00047)

+ Way out: Double Cosine potential

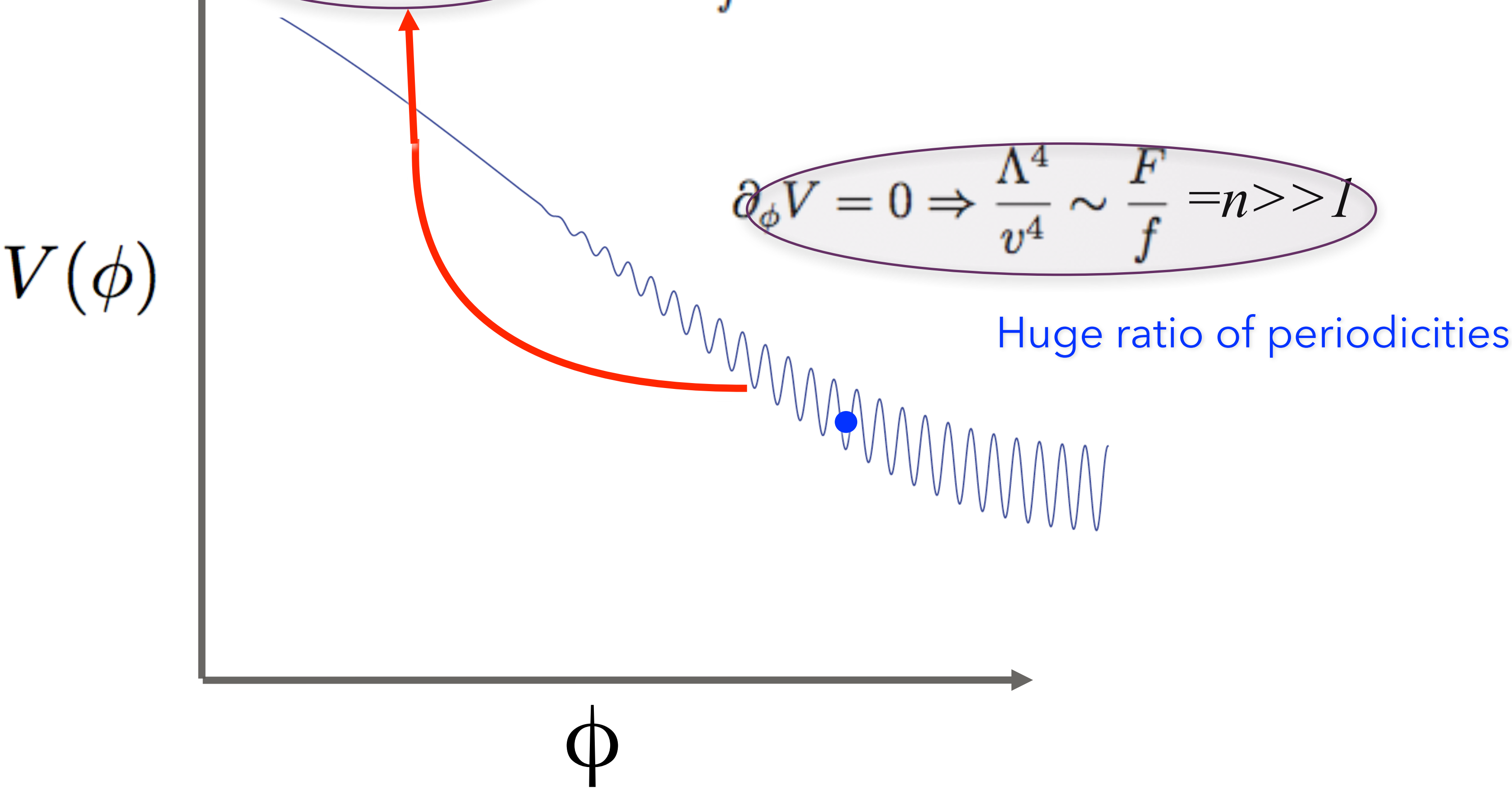
- Have both Φ and Φ^n in Lagrangian to generate two cosines of different periodicities. Cosine with the larger period can become rolling potential.

$$\Phi^2 + (\Phi^\dagger)^2 \quad \rightarrow \quad \cos\frac{2\phi}{f}$$

$$\Phi^{2n} + (\Phi^\dagger)^{2n} \quad \rightarrow \quad \cos\frac{2n\phi}{f}$$

Way out: Double Cosine potential

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



+ Way out: Double Cosine potential ?

- Have both Φ and Φ^n in Lagrangian to generate two cosines of different periodicities. **Cosine with the larger period can become rolling potential.**

$$\Phi^2 + (\Phi^\dagger)^2 \quad \rightarrow \quad \cos\frac{2\phi}{f}$$

$$\Phi^{2n} + (\Phi^\dagger)^{2n} \quad \rightarrow \quad \cos\frac{2n\phi}{f}$$

- Problem: *n* needs to be huge:

$$n \sim \frac{\Lambda^4}{v^4} \sim 10^8!$$

- BUT: we need highly irrelevant terms which would give an exponentially suppressed potential in calculable models

$$\Lambda_{br}^4 \left(\frac{\Phi}{M}\right)^{10^{18}} \rightarrow \epsilon^{10^{18}} \Lambda_{br}^4 \cos\frac{n\phi}{f} \longrightarrow 0$$

$$\epsilon = \frac{\langle\Phi\rangle}{f} < 1$$

This was circumvented by the clockwork mechanism which can generate this huge ratio of periodicities in a completely renormalizable but muti-scalar model.

+

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 , $j = 0,1,2,\ldots,N$, have charges $Q = 1, 1/3, 1/9, \ldots 1/3^N$

Choi, Kim & Yun (2014)
Choi & Im (2015)
Kaplan & Rattazzi(2015)

Clockwork Mechanism

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

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

- Mass matrix:

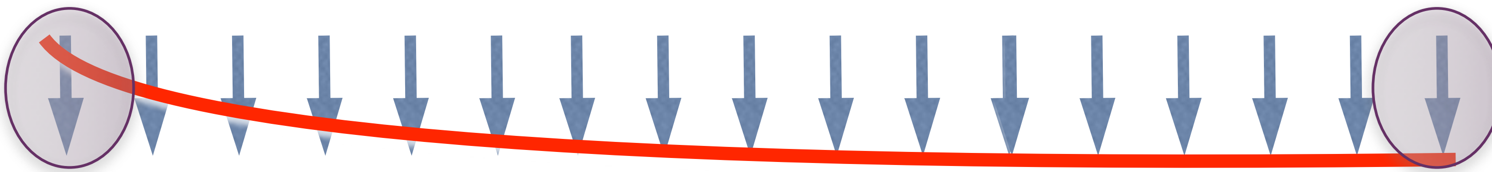
$$M_{ij}^2 = \epsilon f^2 \begin{pmatrix} 1 & -q & 0 & 0 & & & & \\ -q & 1+q^2 & -q & 0 & \cdot & \cdot & \cdot & \\ 0 & -q & 1+q^2 & -q & & & & \\ 0 & 0 & -q & 1+q^2 & & & & \\ & & & & \cdot & & & \\ & \vdots & & & & \cdot & & \\ & & & & & & \cdot & \\ & & & & & & 1+q^2 & -q \\ & & & & & & -q & q^2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

- 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)
Choi & Im (2015)
Kaplan & Rattazzi(2015)

Clockwork Mechanism



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

- Double breaking again on 1st and last site:

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

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

Choi, Kim & Yun (2014)
Choi & Im (2015)
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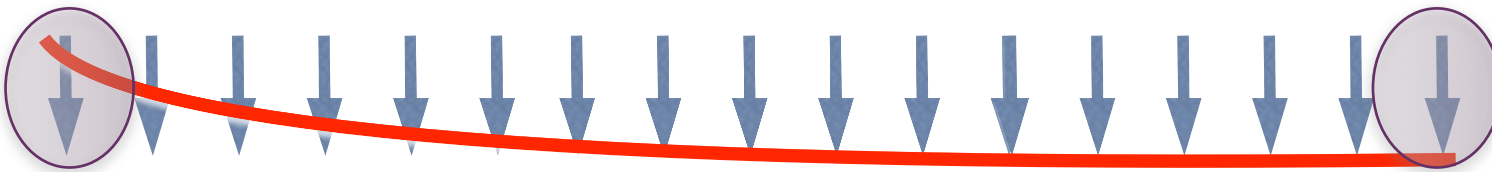
Clockwork Mechanism



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

exponential
profile

- Double breaking again on 1st and last site:

$$\Lambda_N \cos \frac{\pi_N}{f} + \Lambda$$

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

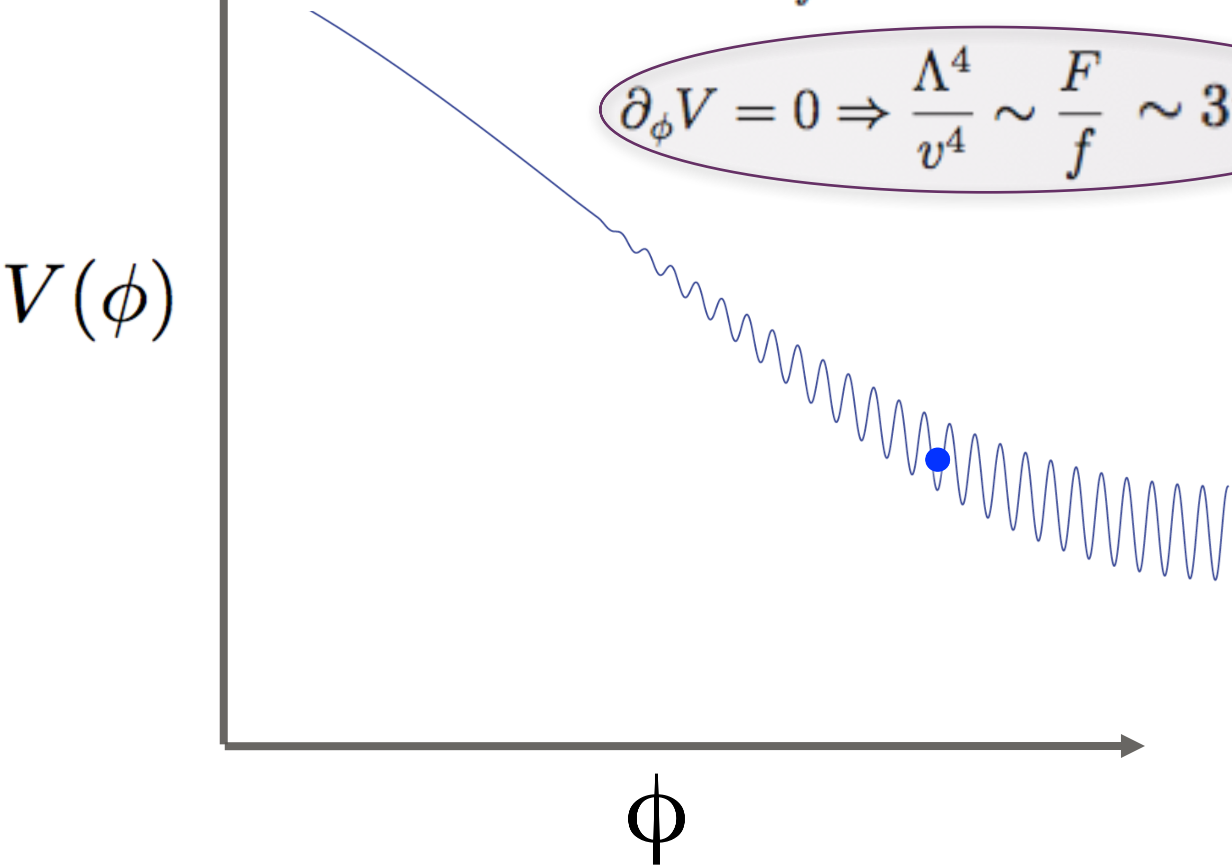
$$\Lambda_N \cos \frac{\pi}{3^N f_a} + \Lambda_0 \cos \frac{\pi}{f_a}$$

Choi, Kim & Yun (2014)
Choi & Im (2015)
Kaplan & Rattazzi(2015)

The Relaxion with double cosine potential

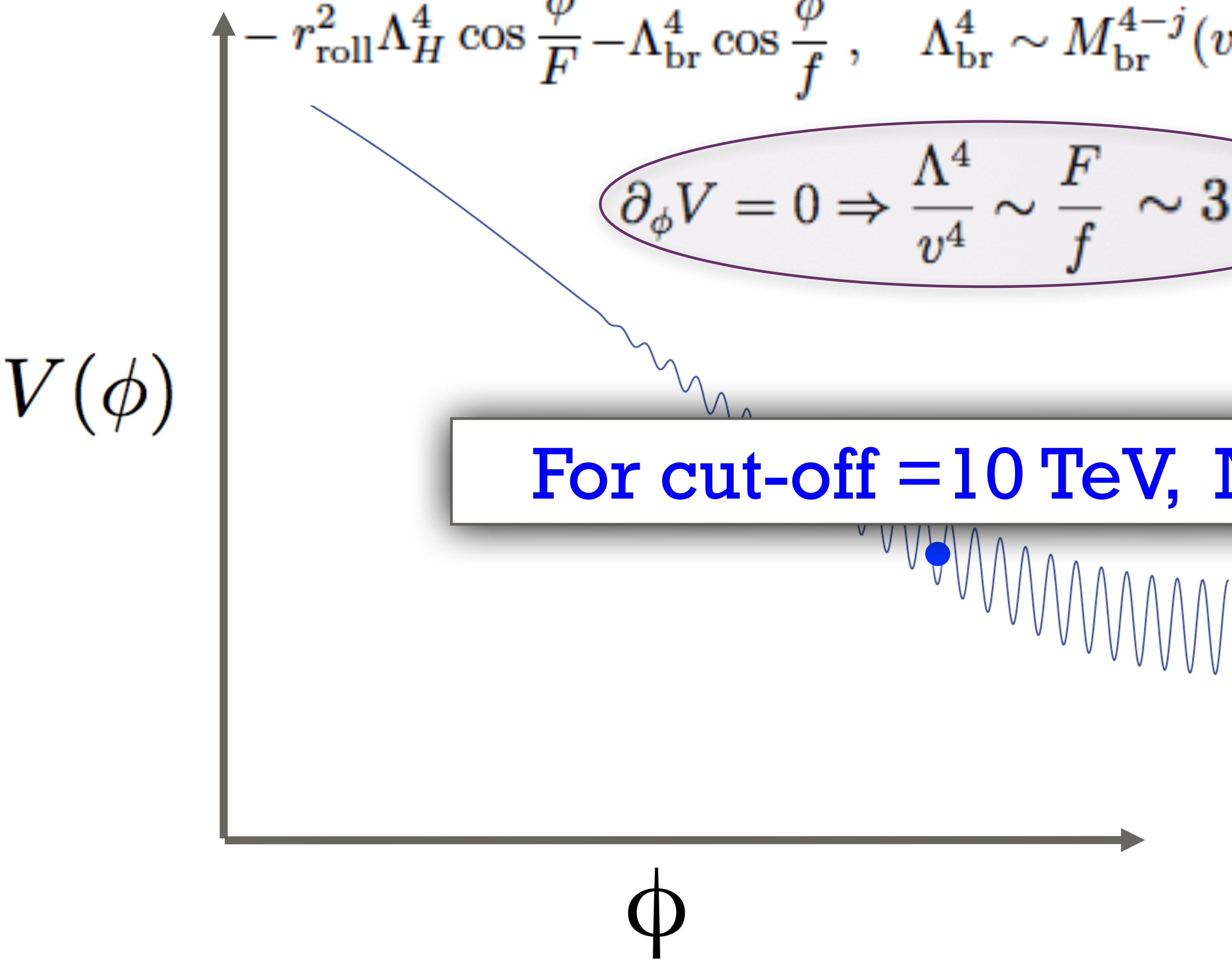
$$-\,r_{\rm roll}^2\Lambda_H^4\cos\frac{\phi}{F}-\Lambda_{\rm br}^4\cos\frac{\phi}{f}\,,\quad \Lambda_{\rm br}^4\sim M_{\rm br}^{4-j}(v+h)^j$$

$$\partial_\phi V=0\Rightarrow\frac{\Lambda^4}{v^4}\sim\frac{F}{f}\sim 3^N$$



The Relaxion with double cosine potential

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



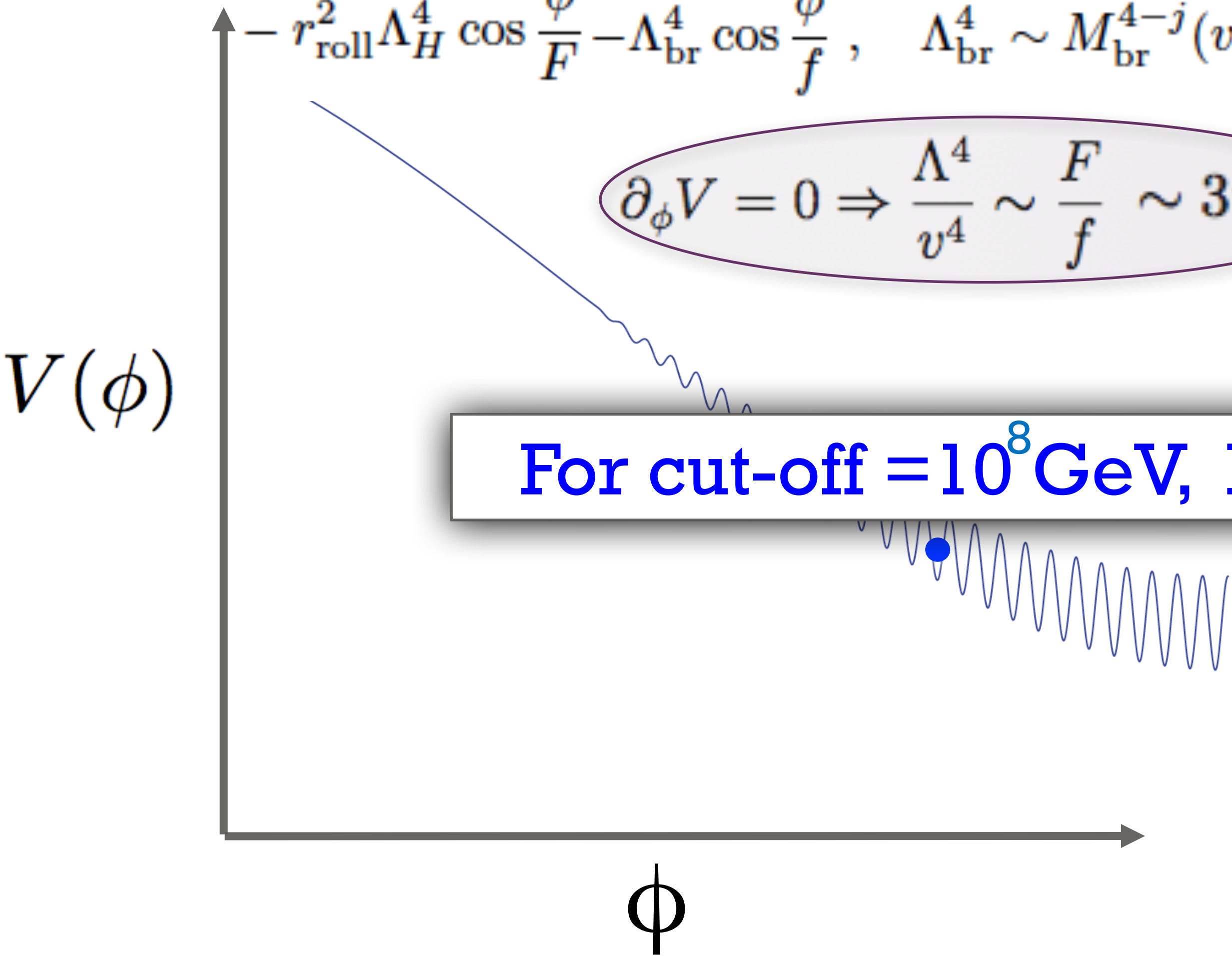
$$\partial_\phi V=0\Rightarrow\frac{\Lambda^4}{v^4}\sim\frac{F}{f}\sim 3^N$$

For cut-off =10 TeV, N=13

The Relaxion with double cosine potential

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

$$\partial_\phi V=0\Rightarrow\frac{\Lambda^4}{v^4}\sim\frac{F}{f}\sim 3^N$$



No overshooting condition

- The second phase of rolling obeys an attractor solution similar to slow–roll:

$$V' \simeq 5H\dot{\phi}$$

- As long as:

$$m_\phi \lesssim 5H(T_c) \sim 3.8 \times 10^{-5}\ \mathrm{eV}$$

- Otherwise relaxion will overshoot barriers

- For such a small mass need too large f~Mpl
- Not big enough coupling- $\frac{\partial_\mu \phi}{f} J^\mu$

+ Obtaining correct Baryon Asymm.

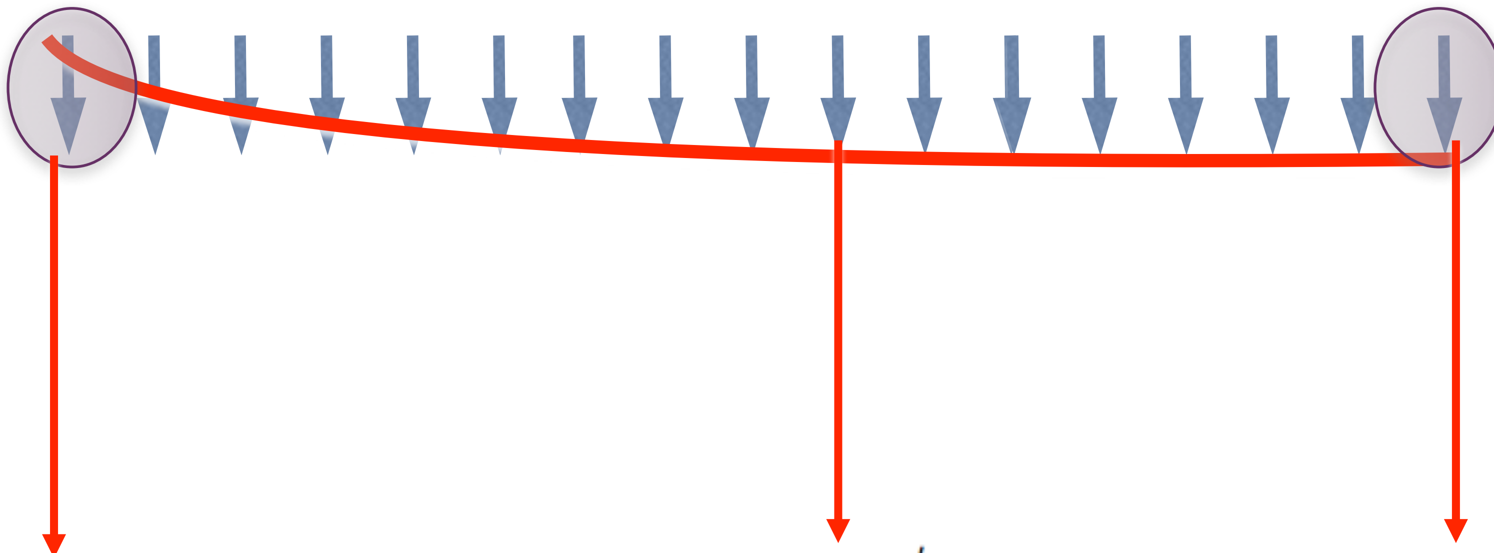
$$\eta \equiv \frac{n_B}{s} = g_{\rm SB}\frac{\dot\phi}{f}\frac{T^2}{6}\times\frac{45}{2\pi^2 g_* T^3} = \frac{15}{4\pi^2}\frac{g_{\rm SB}}{g_*}\frac{\dot\phi}{fT}$$

- Sphalerons must decouple before relaxion stops. Tsph=130 GeV>Tc.

- After this the value of η freezes.

$$\eta \sim 10^{-10} \Rightarrow \frac{f_w}{f} \sim 10^9$$

Set-up



$$\frac{\partial_\mu \phi}{f} J^\mu \qquad \Lambda_{br}^4 \cos\frac{\phi}{f_w} \qquad \Lambda^4 \cos\frac{\phi}{F}$$

$$f_w = 3^k f$$
$$F = 3^N f$$
$$f \ll f_w \ll F$$

In SUSY such effects loop suppressed because of R-Parity. Tension, instead, arises from direct searches

More observables than operators !

When expanded one operator gives rise to many deformations/vertices/observables.

TGCs

$\delta\kappa_\gamma$ $\delta\kappa_Z$

$$(H^\dagger\sigma^a H)W^a_{\mu\nu}B^{\mu\nu} \longrightarrow \hat{h}^2\left[\hat{W}^3_{\mu\nu}B^{\mu\nu} + 2igc_{\theta_W}W^-_\mu W^+_\nu(A^{\mu\nu} - t_{\theta_W}Z^{\mu\nu})\right]$$

$$\hat{h} = v + h$$

Higgs Physics

$$hA_{\mu\nu}A^{\mu\nu} \quad hA_{\mu\nu}Z^{\mu\nu} \quad hZ_{\mu\nu}Z^{\mu\nu} \quad hW_{\mu\nu}W^{\mu\nu}$$

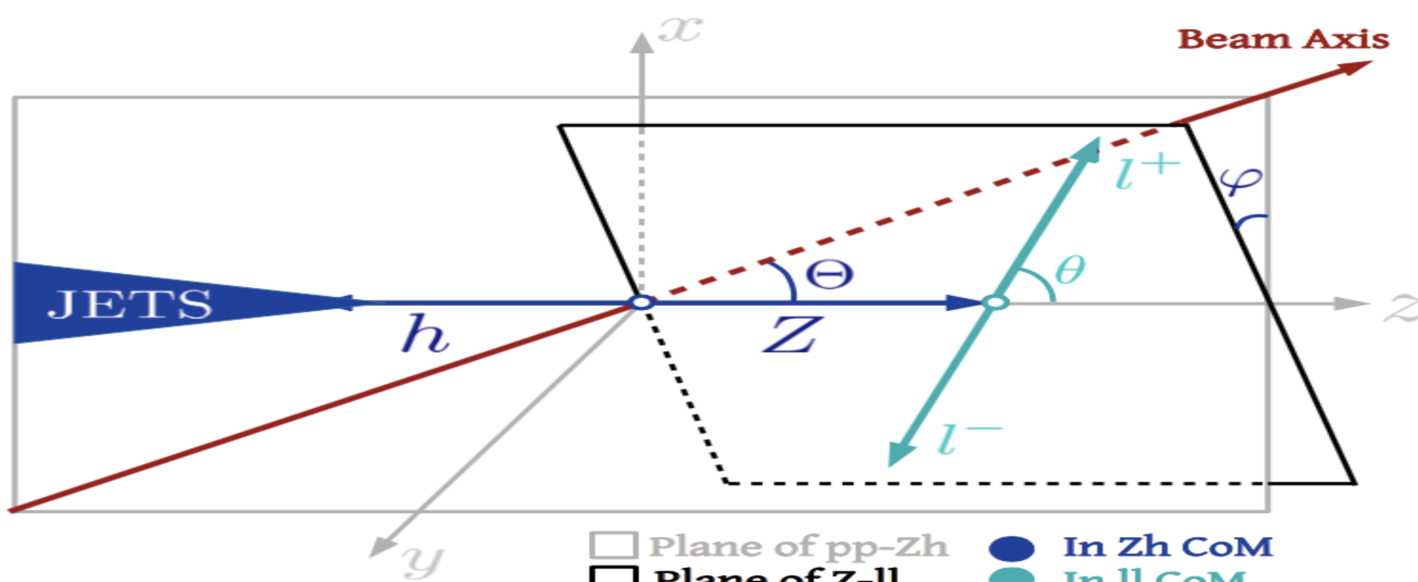
$$\hat{W}^3_{\mu\nu}B^{\mu\nu}$$

S-parameter

1 Operator but 7 observables

Other structure

- These vertices contribute mainly to transverse Z+ Higgs production. They leave a signature in angular distributions of Z decay products.



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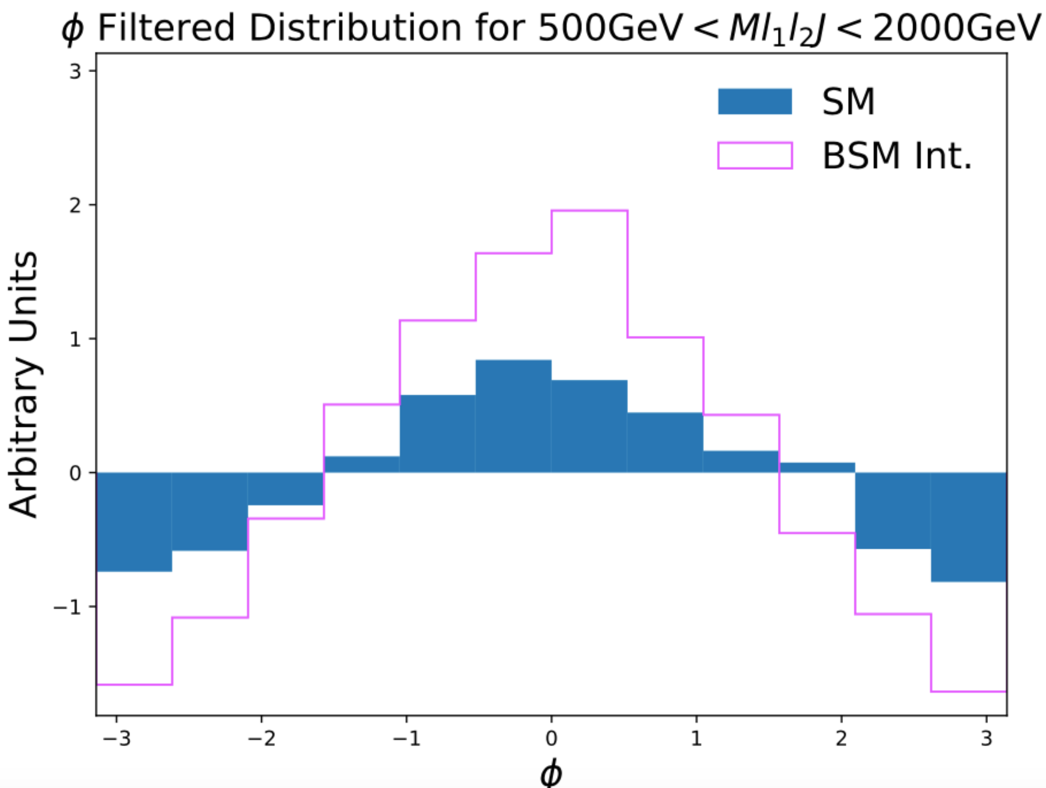


Correlations between vertices

No. of Operators >> No. of Vertices/Pseudo-observables

Invariant under full SM group

Lagrangian terms written in unitary gauge, invariant only under EM and QCD

Eg. $iH^\dagger \overleftrightarrow{D}_\mu H \, \bar{f}\gamma^\mu f, (H^\dagger\sigma^a H)W^a_{\mu\nu}B^{\mu\nu}$

Eg. $Z_\mu \bar{f}\gamma^\mu f, \; hZ_\mu \bar{f}\gamma^\mu f, \; hZ_{\mu\nu}Z^{\mu\nu}$

No. of free theory parameters

No. of independent measurements

More Symmetry=>Less in number (18)

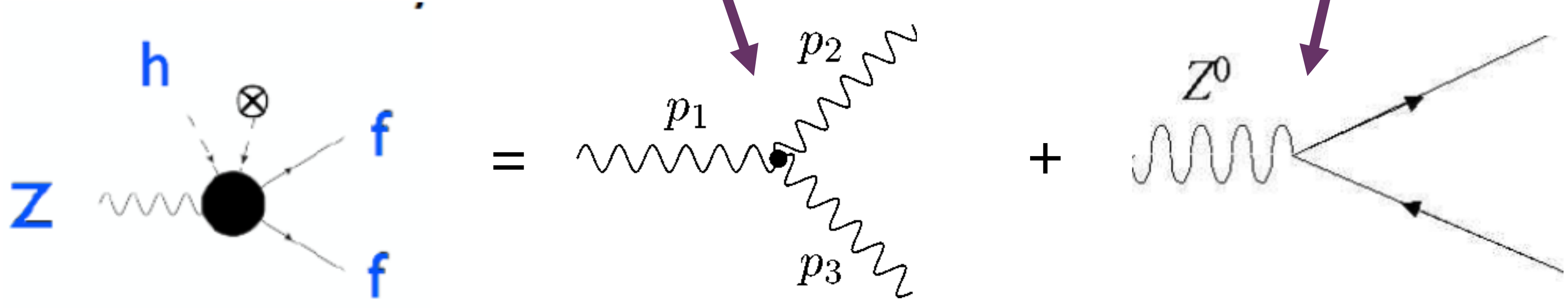
Less Symmetry=>More in number (50)

RSG, A. Pomarol and F. Riva (arxiv: 1405.0181)

Correlation Example

Including all operators:

hVff = Triple Gauge Coupling +Z decay modifications



CAN BE ONLY SEEN AT LHC

CONSTRAINED ALREADY BY LEP !

RSG, A. Pomarol and F. Riva (arxiv: 1405.0181)

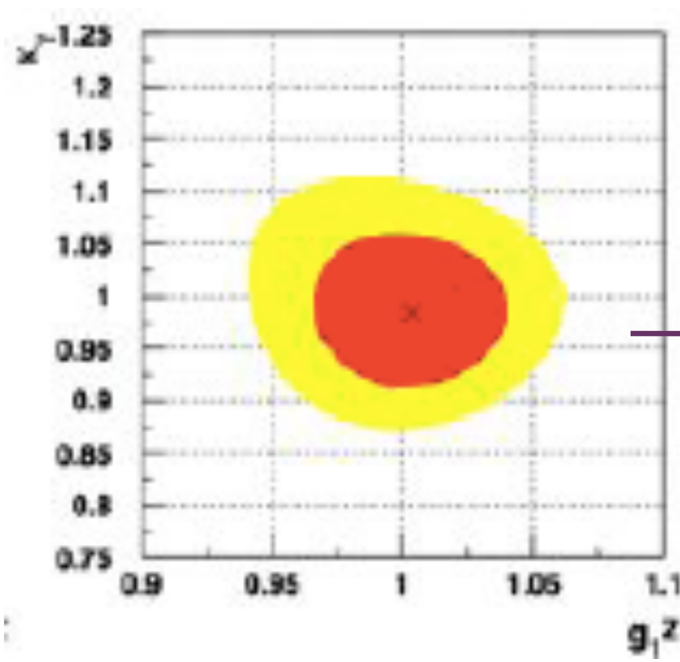
Correlations between vertices

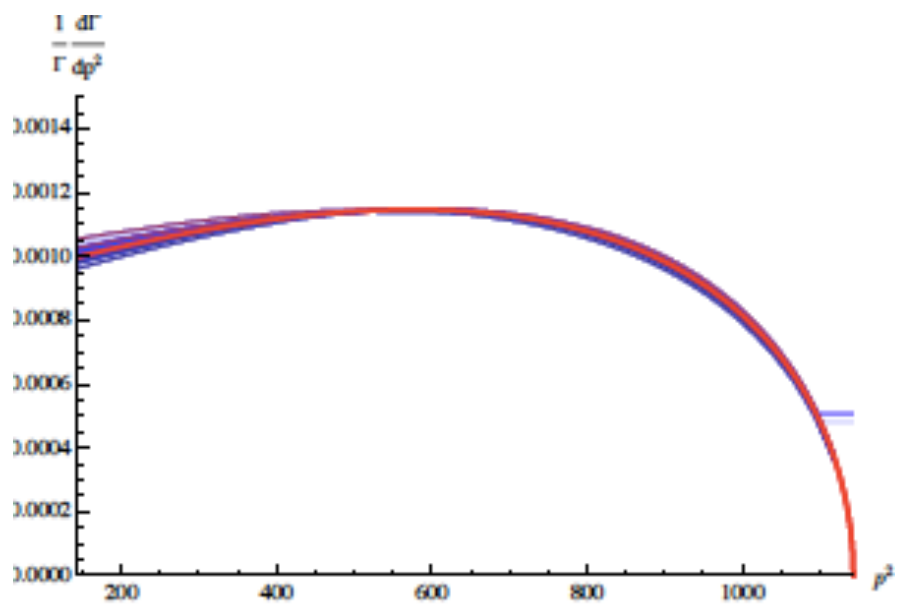
- EFT techniques show that many anomalous Higgs interactions are correlated to interactions already probed by LEP.

RSG, A. Pomarol and F. Riva (arxiv: 1405.0181)

Example: *h ->Zff*

Already constrained !





What LEP saw

What LHC can see

Slide Courtesy: F. Riva

Is *h* part of a doublet ?

If these predictions are not confirmed, one of our assumptions must have been wrong:

(1)*h* not part of a doublet.

(2) Scale of new physics not very high and dimension 8 operators cannot be ignored

RSG, A. Pomarol and F. Riva (arxiv: 1405.0181)

Utility of these correlations

(1) To what extent LHC measurements are independent of LEP ?

(2) Is the Higgs Boson singlet or part of a doublet ?

RSG, A. Pomarol and F. Riva (arxiv: 1405.0181)

- We derived all such correlations at the dim-6 level

RSG, A. Pomarol and F. Riva (arxiv: 1405.0181)

- Now mapping any violation of these correlations to dim-8 operators.

Grojean, RSG (to appear)