Beyond the SM with naturalness

(SUSY & relaxion)

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The IBS Center for Theoretical Physics of the Universe

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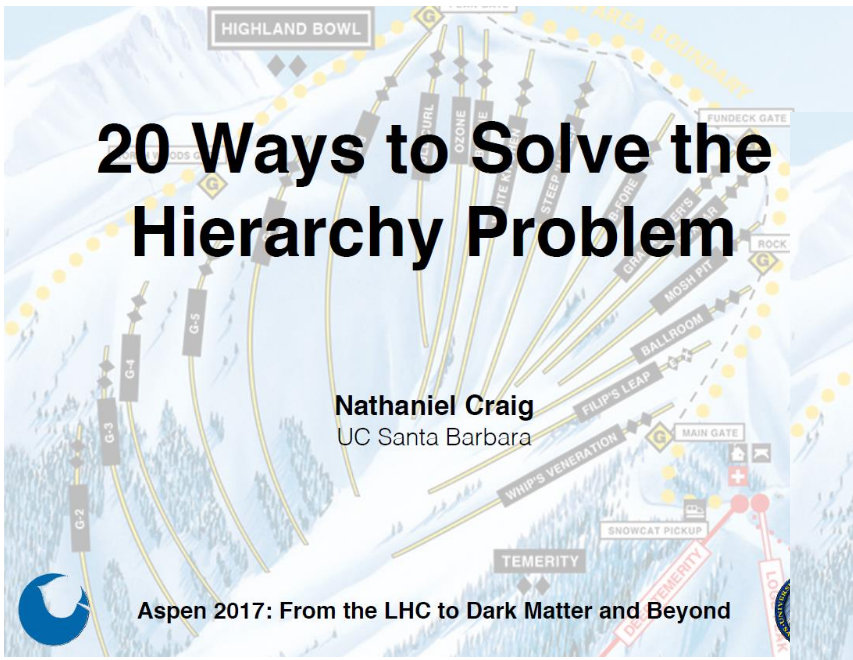
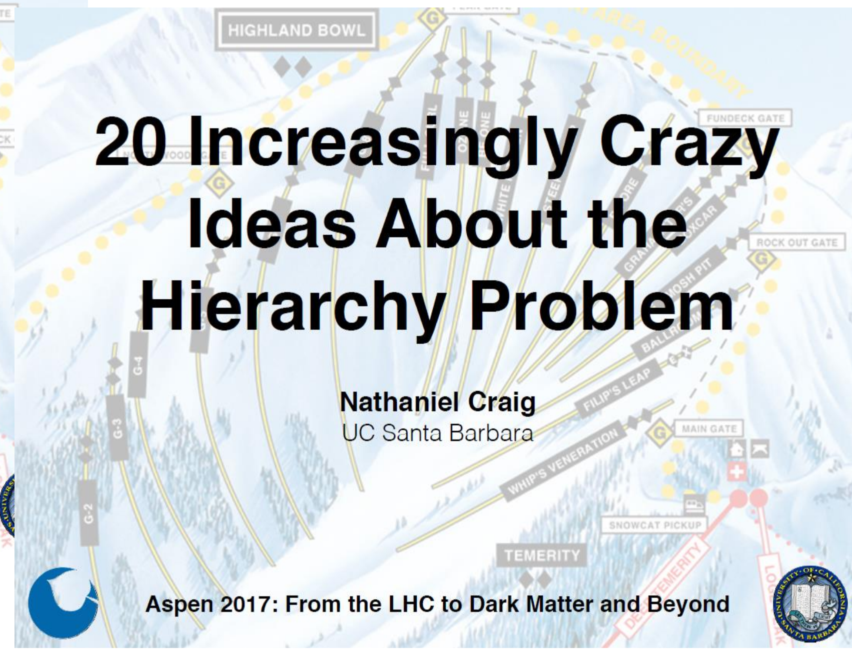
During the last several decades, the hierarchy problem has been the biggest motivation for BSM physics, yielding many interesting ideas.

$$\text{Why } m_H \ll M_{\text{Planck}} \text{ or } M_{\text{GUT}}?$$





Some of the recent developments in the hierarchy problem:

* Naturalness of SUSY with the latest LHC results

Less conventional perspective

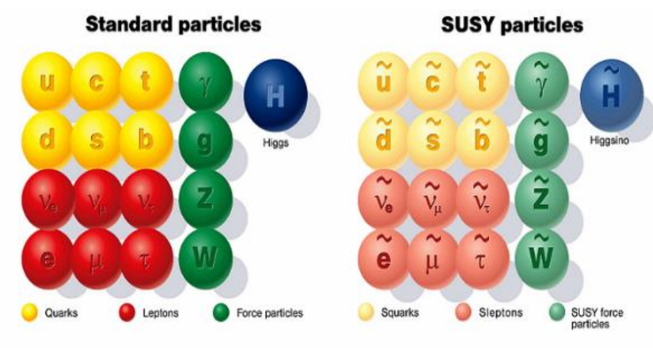
* New idea

Cosmological relaxation of the weak scale

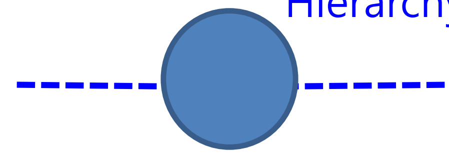
Graham, Kaplan, Rajendran '15

SUSY

Many appealing features of low energy SUSY:

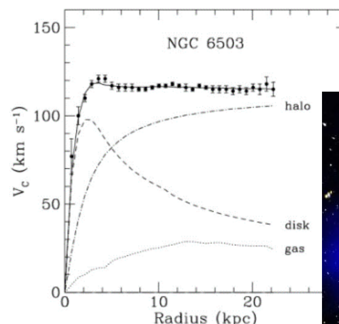


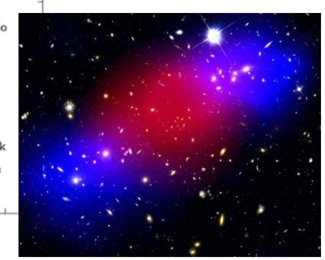
Hierarchy problem

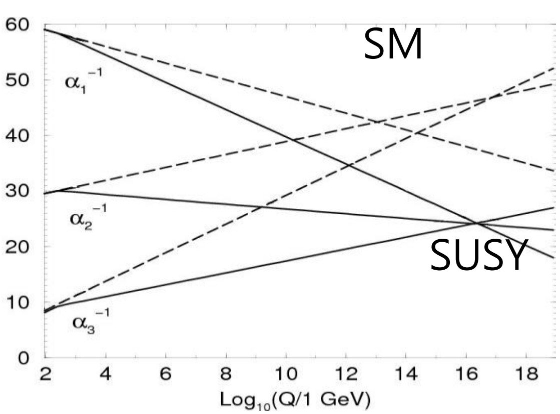


$$\delta m_H^2 \sim M_{\rm Planck}^2 \quad \Rightarrow \quad \delta m_H^2 \sim m_{\rm SUSY}^2$$

Dark matter





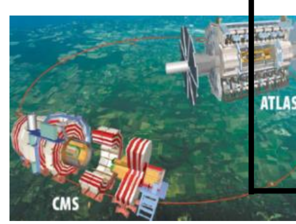


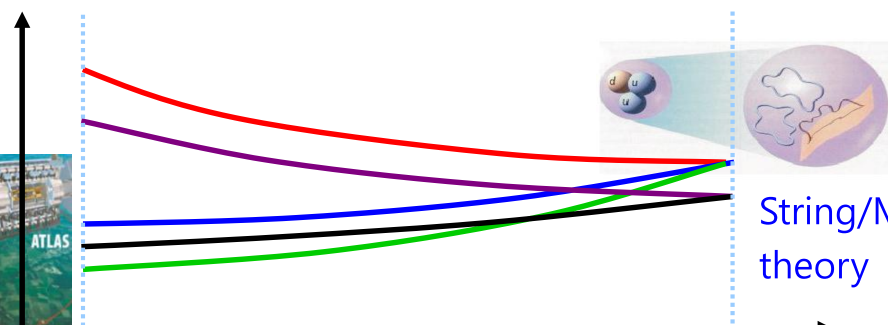
SM

SUSY

Unification

SUSY spectrum



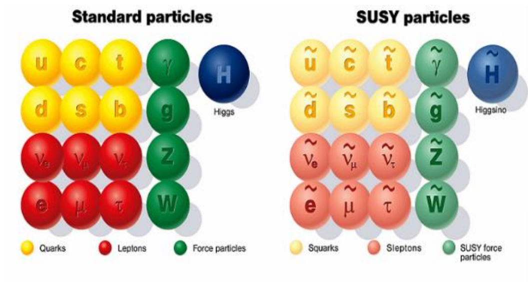


String/M theory

1 TeV

10^{16} GeV

SUSY as a solution to the hierarchy problem



: $\delta m_H^2 \sim M_{\text{Planck}}^2 \quad \Rightarrow \quad \delta m_H^2 \sim m_{\text{SUSY}}^2$

$$16\pi^2 \frac{d}{d\ln Q} m_{H_u}^2 = 6y_t^2\left(m_{H_u}^2 + m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2\right) - 6g_2^2 M_{\tilde{W}}^2 + \ldots$$

$$16\pi^2 \frac{d}{d\ln Q} m_{\tilde{t}_L}^2 = 2y_t^2\left(m_{H_u}^2 + m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2\right) - \frac{32}{3} g_3^2 M_{\tilde{g}}^2 - 6g_2^2 M_{\tilde{W}}^2 + \ldots$$

$$16\pi^2 \frac{d}{d\ln Q} m_{\tilde{t}_R}^2 = 4y_t^2\left(m_{H_u}^2 + m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2\right) - \frac{32}{3} g_3^2 M_{\tilde{g}}^2 + \ldots$$

Weak scale vs SUSY scale:

$$\frac{1}{2}M_Z^2 \simeq -|\mu|^2 - m_{H_u}^2 + \frac{m_{H_d}^2}{\tan^2\beta}$$

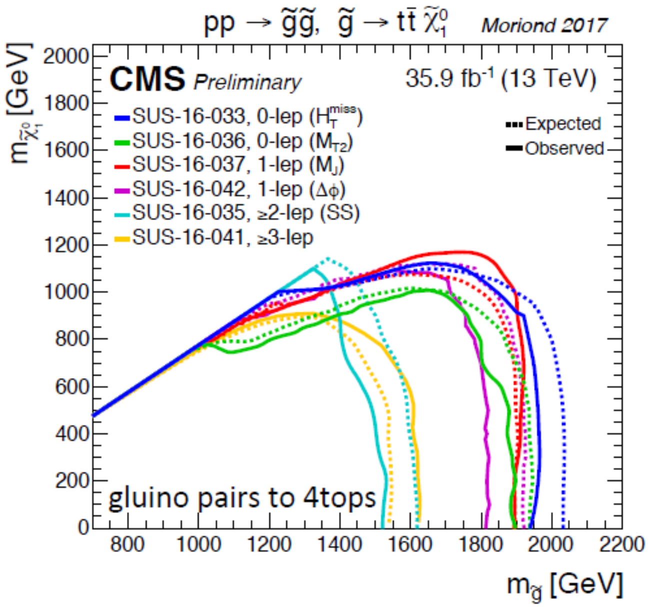
$$\simeq -0.86\bar{\mu}^2 - 0.65\bar{m}_{H_u}^2 + 0.35\bar{m}_{\tilde{t}_L}^2 + 0.3\bar{m}_{\tilde{t}_R}^2 + 1.5\bar{M}_{\tilde{g}}^2 + 0.1\bar{M}_{\tilde{g}}\bar{M}_{\tilde{W}} - 0.2\bar{M}_{\tilde{W}}^2 + \ldots$$

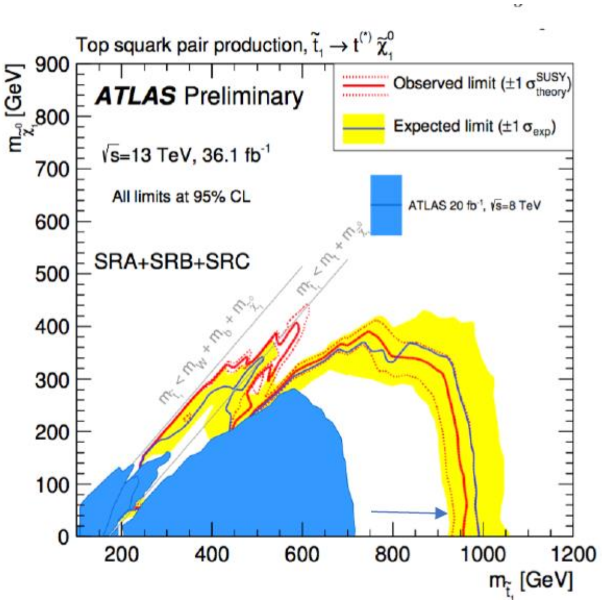
$$\left(\bar{m}_I = \text{superpartner masses at } M_{\text{GUT}}\right)$$

Natural SUSY scenario:

Higgsino, stops, and gluinos are the closest friends of the Higgs boson, so the their masses should be near the weak scale to avoid fine-tuning.

Light Higgsino near the weak scale is still on open possibility, however





Fine-tuning measure for naturalness: Ellis, Enquist, Nanopoulos, Zwirner
Barbieri, Giudice

$$\Delta = \mathrm{Max}\left(\left|\frac{\partial \ln M_Z^2}{\partial \ln \bar{m}_I^2}\right|\right) \gtrsim 200$$

Natural SUSY appears to be in trouble, however we should keep in mind that there is no clear-cut criterion for naturalness.

We may see the problem in different perspective:

What would be the pattern (or correlation) of SUSY-breaking masses at M_{GUT}, for which the weak scale is least sensitive to the SUSY scale?

This approach is something similar to the old Veltman condition on the SM, and relies on the assumption that underlying SUSY breaking dynamics provides such correlation among the SUSY-breaking masses.

cf: In string-motivated SUSY-breaking models, quite often the ratios among SUSY-breaking masses are determined by discrete parameters such as moduli weights, quantized fluxes, and group theory coefficients.

Naturalness might be saved with a specific pattern of SUSY mases, leading to a cancellation among the contributions to the weak scale:

$$\frac{1}{2}M_Z^2 = -0.86\bar{\mu}^2 - 0.65\bar{m}_{H_u}^2 + 0.35\bar{m}_{\tilde{t}_L}^2 + 0.3\bar{m}_{\tilde{t}_R}^2 + 1.5\bar{M}_{\tilde{g}}^2 + 0.1\bar{M}_{\tilde{g}}\bar{M}_{\tilde{W}} - 0.2\bar{M}_{\tilde{W}}^2 + \ldots$$
$$= -0.86\bar{\mu}^2 + \mathcal{O}\left(\frac{1}{16\pi^2}\bar{m}_{\rm SUSY}^2\right)$$

➔ light Higgsinos, heavy stops and gluinos near the current experimental bound, and possibly some other testable predictions

Some examples:

* Scalar & gaugino focus points:

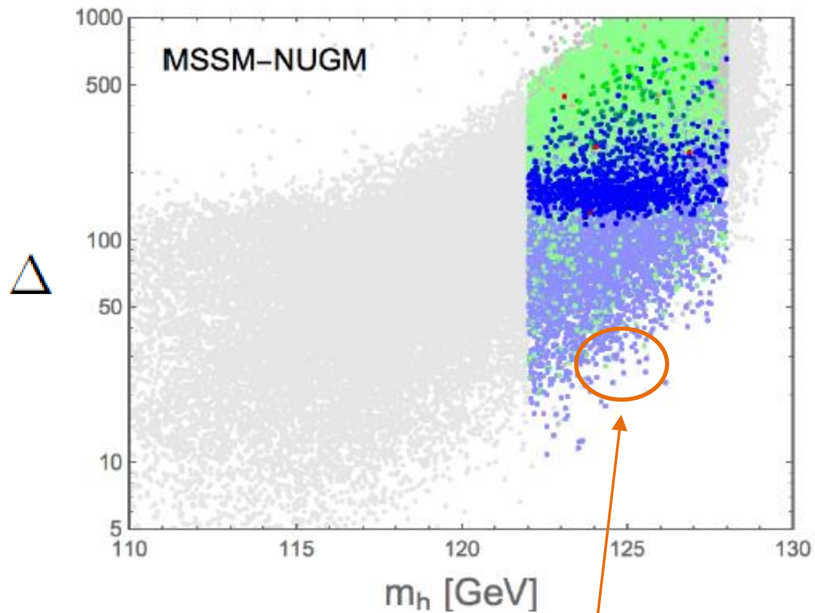
Feng, Matchev, Moroi
Abe, Kobayashi, Omura
Horton, Ross

$$\bar{m}_{H_u}^2 = \bar{m}_{\tilde{t}_L}^2 = \bar{m}_{\tilde{t}_R}^2 = \ldots, \quad \bar{M}_{\tilde{W}} \simeq 3\bar{M}_{\tilde{g}} \quad (\Leftrightarrow \quad M_{\tilde{g}} \simeq M_{\tilde{W}} \text{ at TeV scales})$$

* TeV scale mirage mediation (= mixed string-moduli & anomaly mediation)

$$M_{\tilde{g}} \simeq M_{\tilde{W}} \simeq M_{\tilde{B}} \simeq \sqrt{m_{\tilde{t}_L}^2 + m_{\tilde{t}_R}^2} \text{ at TeV scales}$$

KC, Jeong, Kobayashi, Okumura
Kitano, Nomura



Ross, Schmidt-Hoberg, Staub '17

Reasonably natural SUSY $(\Delta \lesssim \text{few} \times 10)$ is possible with

* Higgsino near the weak scale,
* stops and gluinos near the present experimental bound, with $M_{\tilde{g}} \simeq M_{\tilde{W}}$ at TeV scales

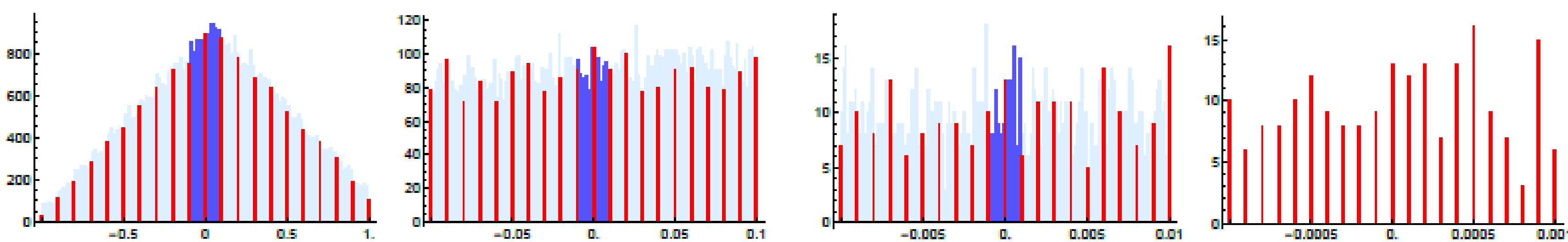
Naturalness might be saved with the complexity of SUSY models which involve many parameters contributing to the weak scale with different strength and different sign: Dermisek '16

$$\frac{1}{2}M_Z^2 = -0.86\bar{\mu}^2 - 0.65\bar{m}_{H_u}^2 + 0.35\bar{m}_{\tilde{t}_L}^2 + 0.3\bar{m}_{\tilde{t}_R}^2 + 1.5\bar{M}_{\tilde{g}}^2 + 0.1\bar{M}_{\tilde{g}}\bar{M}_{\tilde{W}} - 0.2\bar{M}_{\tilde{W}}^2$$
$$+\mathcal{O}(10^{-2}\bar{M}_{\tilde{B}}^2) + \mathcal{O}(10^{-3}\bar{m}_{\tilde{f}_L}^2) + \mathcal{O}(10^{-4}\mathrm{Tr}(Y\bar{m}_{\tilde{f}}^2)) + \mathcal{O}((10^{-3}-10^{-5})\bar{m}_{\tilde{b},H_d}^2) + \mathcal{O}(10^{-6}m_{\tilde{c}}^2)$$
$$+\mathcal{O}(10^{-11}\bar{m}_{\tilde{s}}^2)$$

Assume all SUSY mass parameters have random distribution around a similar central value $\bar{m}$, within the range of $\mathcal{O}(\bar{m})$, and with a spacing of $\mathcal{O}(0.1\bar{m})$:

$$R[x] = x\Big(1 + \{0, \pm 0.1, \pm 0.2, \pm 0.3, \pm 0.4, \pm 0.5\}\Big)$$

$$\text{Distribution of } X = -R[1] + R[1] + R[10^{-1}] + R[10^{-2}] + R[10^{-3}] :$$

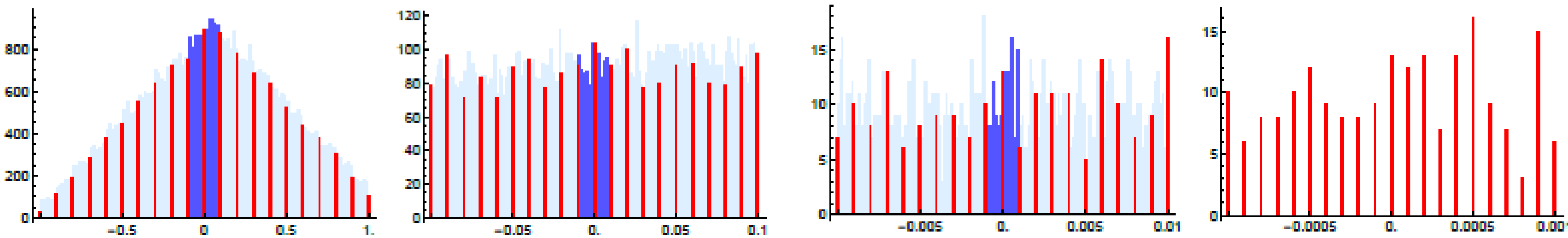


(a) (b) (c) (d)

$$\frac{1}{2}M_Z^2 = -0.86\bar{\mu}^2 - 0.65\bar{m}_{H_u}^2 + 0.35\bar{m}_{\tilde{t}_L}^2 + 0.3\bar{m}_{\tilde{t}_R}^2 + 1.5\bar{M}_{\tilde{g}}^2 + 0.1\bar{M}_{\tilde{g}}\bar{M}_{\tilde{W}} - 0.2\bar{M}_{\tilde{W}}^2$$

$$+ \mathcal{O}(10^{-2}\bar{M}_{\tilde{B}}^2) + \mathcal{O}(10^{-3}\bar{m}_{\tilde{f}_L}^2) + \mathcal{O}(10^{-4}\mathrm{Tr}(Y\bar{m}_{\tilde{f}}^2)) + \mathcal{O}((10^{-3} - 10^{-5})\bar{m}_{\tilde{b},H_d}^2) + \mathcal{O}(10^{-6}m_{\tilde{c}}^2)$$

$$+ \mathcal{O}(10^{-11}\bar{m}_{\tilde{s}}^2)$$



(a) (b) (c) (d)

Any value of M_Z in the range $[10^{-3}M_{\mathrm{SUSY}}, M_{\mathrm{SUSY}}]$ is equally probable.

SUSY anywhere in the range $[M_Z, 100\,\mathrm{TeV}]$ is equally natural.

Dermisek '16

Cosmological relaxation of the EW scale

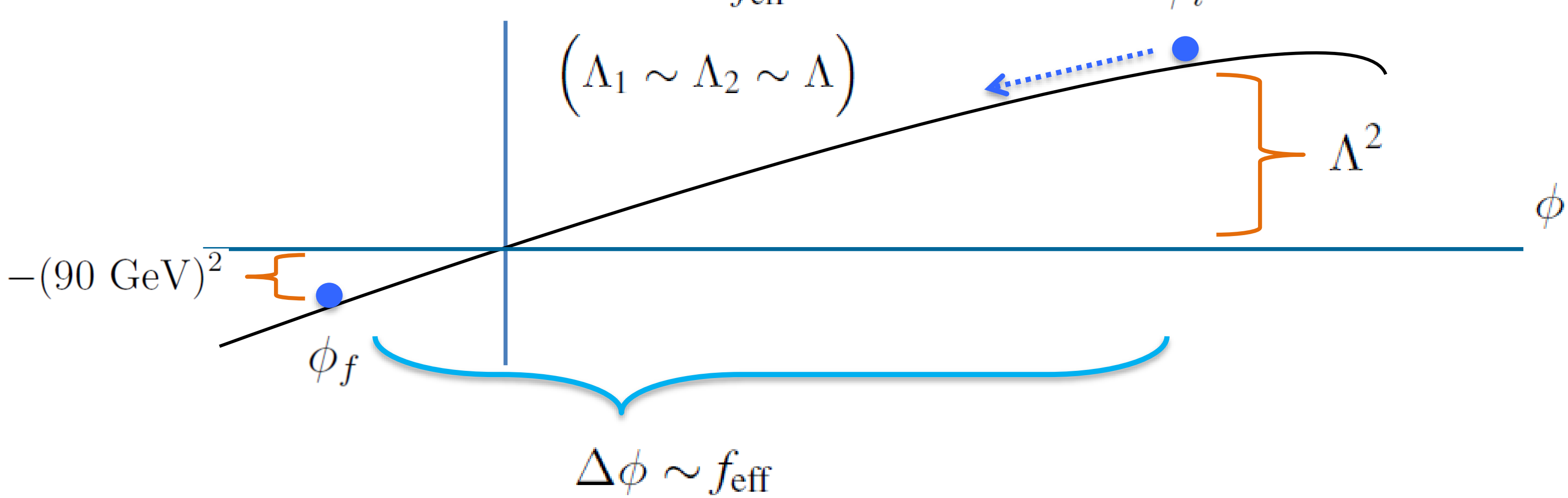
Graham, Kaplan, Rajendran '15

A pseudo-Nambu-Goldstone boson (= **relaxion**) ϕ which scans the Higgs mass-square from $m_H^2(\phi_i) \sim \Lambda^2 \gg M_Z^2$ to $m_H^2(\phi_f) \simeq -(90\,\mathrm{GeV})^2$:

Λ = Higgs mass cutoff which might be identified as $m_{\rm SUSY}$ or some other BSM scale

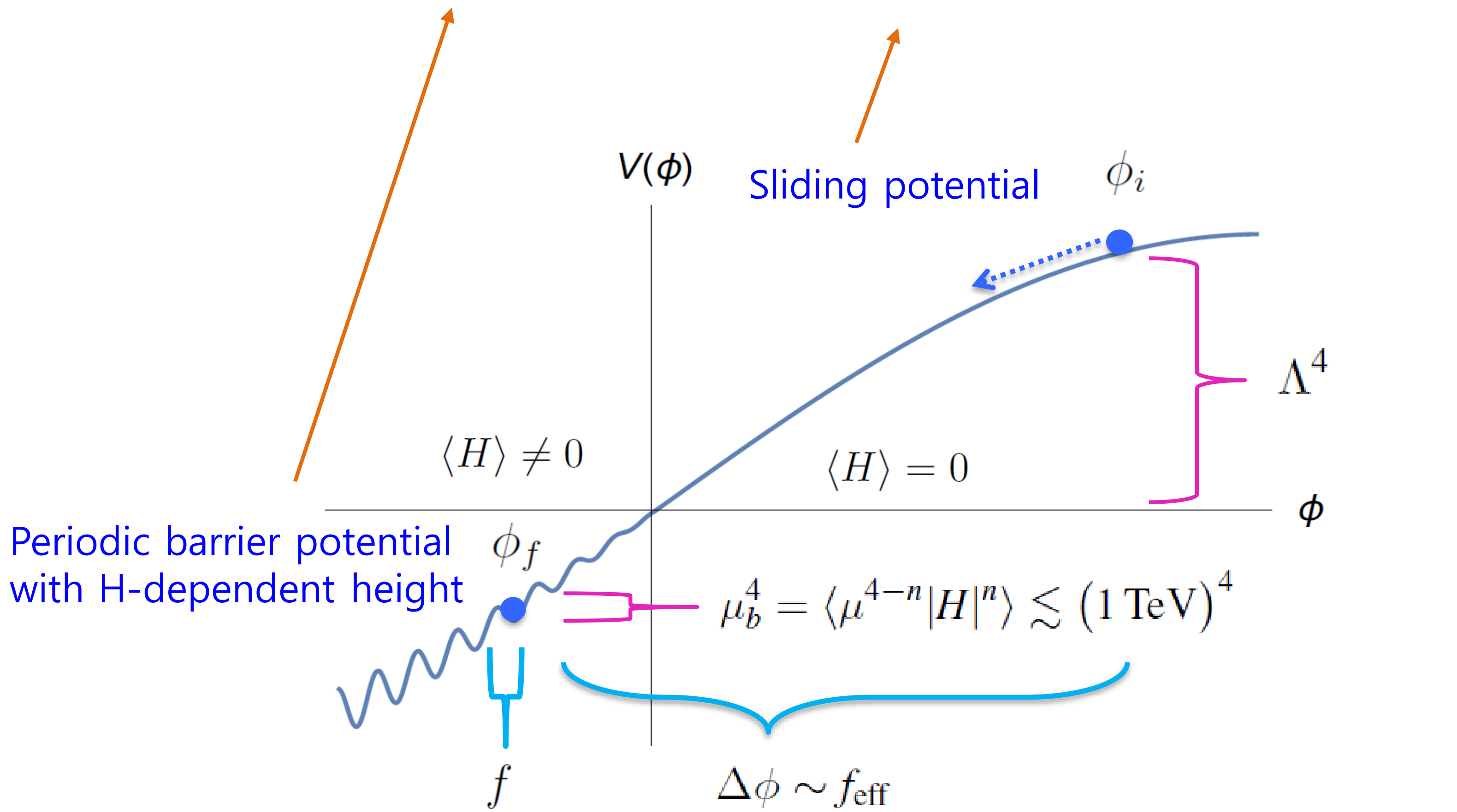
$$m_H^2(\phi) = \Lambda_1^2 + \Lambda_2^2 \frac{\phi}{f_{\rm eff}} + \ldots$$

$$\left(\Lambda_1 \sim \Lambda_2 \sim \Lambda\right)$$

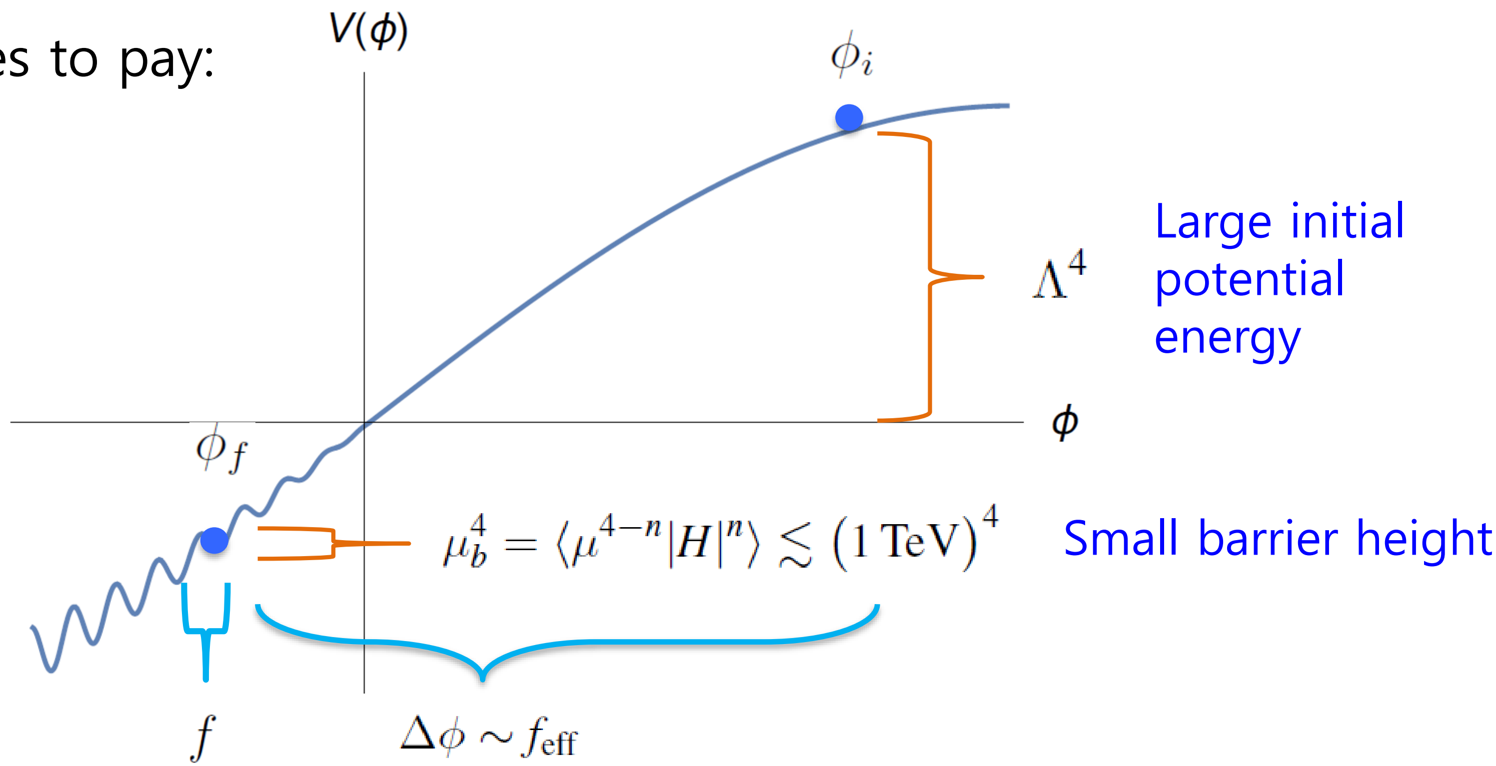


Relaxion potential:

$$V(\phi) = \left[\mu^{4-n}|H|^n \cos\left(\frac{\phi}{f}\right) + ...\right] + \left[\Lambda^4 \frac{\phi}{f_{\rm eff}} + ...\right] \quad \left(\mu \lesssim 1\,\mathrm{TeV} < \Lambda\right)$$



Prices to pay:



i) cosmological dissipation of the relaxion energy

Hubble friction, particle production, …

ii) long relaxion excursion:

$$\frac{f_{\mathrm{eff}}}{f} \sim \frac{\Lambda^4}{\mu_b^4} \gtrsim \left(\frac{\Lambda}{\mathrm{TeV}}\right)^4 \quad \text{(Stabilization condition)}$$

Relaxion converts the weak scale hierarchy to another hierarchy among the relaxion scales:

Weak scale hierarchy ➔ Relaxion scale hierarchy

$$\boxed{\Lambda \gg m_H}$$

$$\boxed{\frac{f_{\rm eff}}{f} \gtrsim \left(\frac{\Lambda}{\rm TeV}\right)^4 \gg 1}$$

The key point is that $f \ll f_{\rm eff}$ is stable against radiative corrections, thus technically natural, which can be assured by means of a discrete axionic shift symmetry.

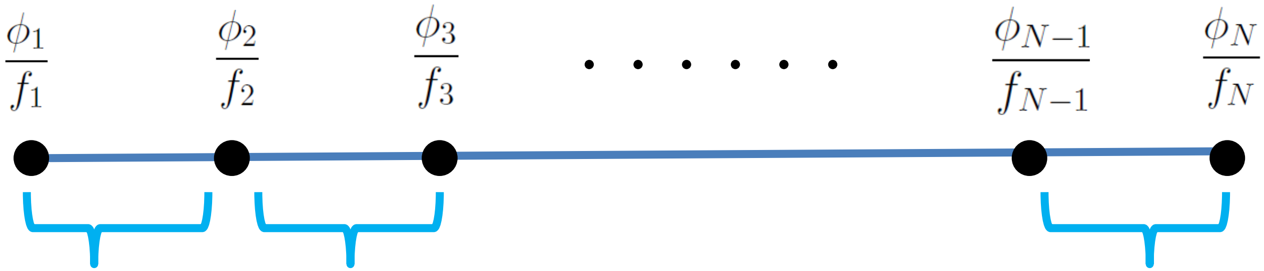
The required long relaxion excursion, i.e. the big relaxion scale hierarchy, might be achieved by the clockwork mechanism.

KC, Im, 1511.00132; Kaplan, Rattazzi, 1511.01827

As for the cosmological scenario involving a long period of relaxion energy dissipation, an interesting possibility is that the relaxion itself plays the role of inflaton with a coupling to dark photon.

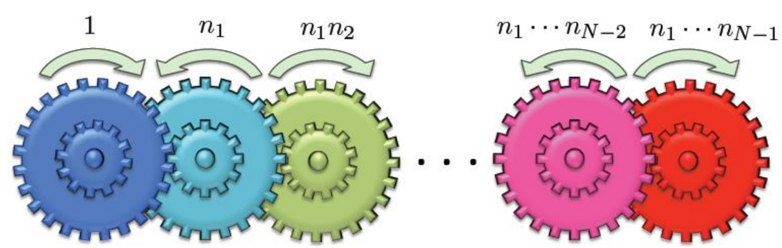
Tangarife, Tobioka, Ubaldi, Volansky, 0706.00438

Clockwork mechanism for $f_{\rm eff} \gg f$: KC, Im, 1511.00132
Kaplan, Rattazzi, 1511.01827



$$\Omega\left(\frac{\phi_2}{f_2}+n_1\frac{\phi_1}{f_1}\right)\quad \Omega\left(\frac{\phi_3}{f_3}+n_2\frac{\phi_2}{f_2}\right)\quad \cdots\cdots \quad \Omega\left(\frac{\phi_N}{f_N}+n_{N-1}\frac{\phi_{N-1}}{f_{N-1}}\right)$$

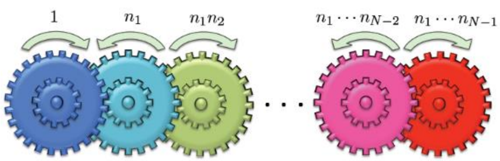
Series of periodic axion potential providing the clockwork constraint between the nearest-neighbor axions:



$$\frac{\phi_2}{f_2}=-n_1\frac{\phi_1}{f_1},\quad \frac{\phi_3}{f_3}=-n_2\frac{\phi_2}{f_2},\quad \cdots,\quad \frac{\phi_N}{f_N}=-n_{N-1}\frac{\phi_{N-1}}{f_{N-1}}$$

Lightest axion ϕ describing the collective rotation has

i) field range exponentially longer than the cutoff scale



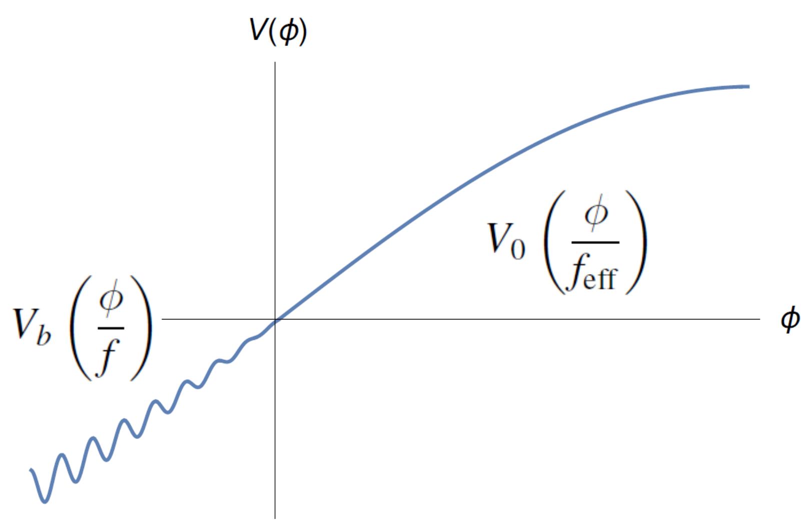
$$\Delta\phi \sim n_1 n_2 \ldots n_{N-1} f \sim e^N f \quad \left(f_i \sim f\right)$$

ii) hierarchical couplings through the boundary interactions

$$\frac{\phi_1}{f_1} = \frac{1}{n_1 n_2 \ldots n_{N-1}} \frac{\phi}{f} \equiv \frac{\phi}{f_{\rm eff}}, \qquad \frac{\phi_N}{f_N} = \frac{\phi}{f} \qquad \left(f_{\rm eff} \sim e^N f\right)$$

$$\frac{\phi_1}{f_1}\mathcal{O} + \frac{\phi_N}{f_N}\mathcal{O}'$$

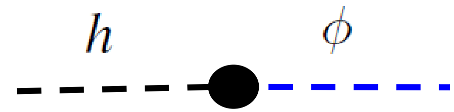
$$\Rightarrow \quad \mathcal{L}_{\rm eff} = \frac{\phi}{f_{\rm eff}}\mathcal{O} + \frac{\phi}{f}\mathcal{O}'$$



Due to the mixing with the Higgs boson, relaxion can have a variety of interesting phenomenological consequences.

KC, Im, 1610.00680, Flacke et al, 1610.02025

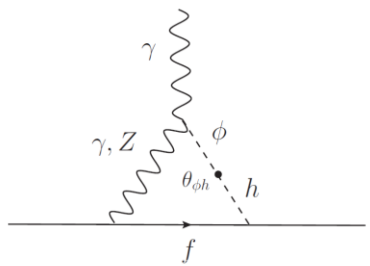
$$\mu^{4-n}|H|^n \cos\left(\frac{\phi}{f}\right) \quad \Rightarrow$$



$$\theta_{\phi h} \sim \frac{m_\phi^2}{m_h^2 - m_\phi^2}\frac{f}{v}\left(1 + \frac{f m_\phi}{v^2}\right)^{-1}$$

* LEP: $e^+e^- \to Z \to Z + \phi$

* EDMs:



* Rare meson decays:

$$B \to K + \phi \;\; (\phi \to \mu^+\mu^-)$$

* Beam dump experiments: CHARM

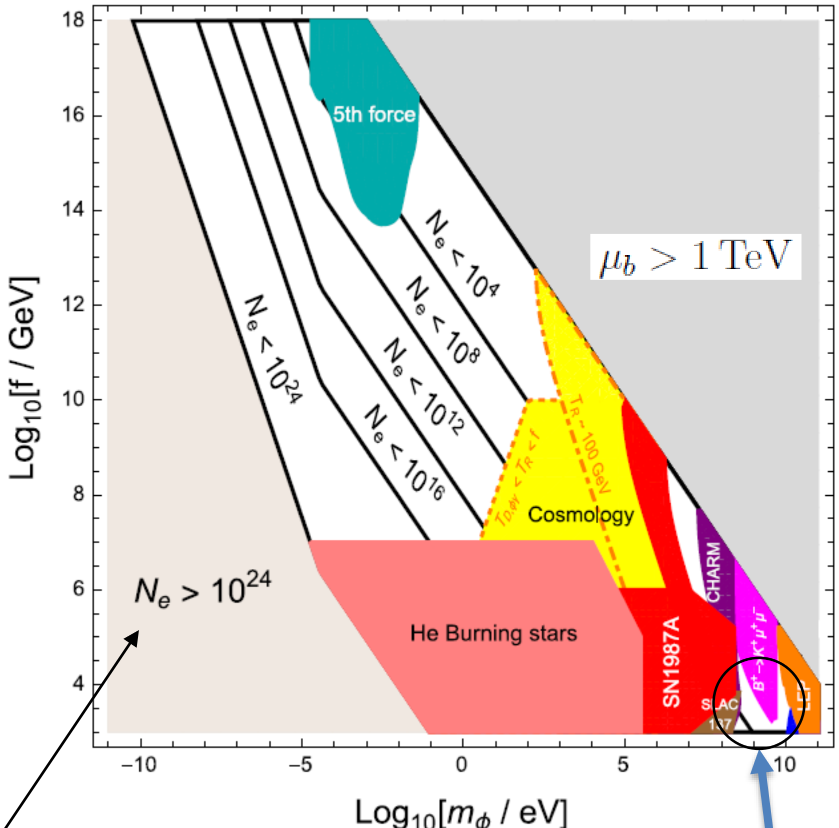
* Astrophysics: Star coolings (SN or He buring stars)

* Cosmology: Effects on BBN, CMB, dark radiation, X or γ ray backgrounds

* 5th force: $V(r) = -G_N \frac{m_A m_B}{r}\left(1 + \epsilon_A \epsilon_B e^{-m_\phi r}\right) \quad \left(\epsilon_{A,B} \propto \frac{1}{f}\left(\frac{\mu_b}{v}\right)^4 \propto m_\phi^2 f\right)$

Colored regions are excluded by LEP, EDMs , Rare meson decays , Beam dump experiments, Astrophysics, Cosmology, 5^{th} force

KC & Im, 1610.00680



Most of the parameter space with $m_\phi \gtrsim 100\ \mathrm{eV}$ is excluded.

Number of inflationary e-foldings required for relaxion energy dissipation

This region can be probed by the future beam dump (SHiP) or EDM experiments.

Summary

* Even with the latest LHC results, SUSY might provide a reasonably natural solution to the hierarchy problem, with a specific pattern of SUSY masses dictated by the underlying SUSY breaking mechanism, which predicts
    * light Higgsino near the weak scale,
    * stops and gluinos near the current experimental bound, with $M_{\tilde{g}} \simeq M_{\tilde{W}}$ at TeV scales.

* If the small weak scale emerges from the complexity of the theory involving many parameters, SUSY scale can be anywhere in the range [M_Z , 100 TeV] with essentially equal naturalness.

* Cosmological relaxation of the Higgs mass, which is a new approach to the hierarchy problem, requires a big hierarchy between the two relaxion scales:

$$\frac{f_{\rm eff}}{f} \gtrsim \left(\frac{\Lambda}{\rm TeV}\right)^4 \gg 1$$

and such a big hierarchy can be generated by the clockwork mechanism with multiple axions, yielding

$$\frac{f_{\rm eff}}{f} \sim e^N \quad (N = \text{number of axions})$$

* Due to the relaxion-Higgs mixing, relaxion mass & decay constant are severely constrained by a variety of observational data, excluding most of the region with $m_\phi \gtrsim 100\,\mathrm{eV}$.