Relaxing SUSY

PONT Avignon

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CERN

Part I

The Hierarchy Problem

What is the hierarchy problem?

- As we march to higher energies, SM cannot be the full story...

Quantum Gravity
$M_P \sim 10^{18}$ GeV

Grand Unified Theory
$M_G \sim 10^{15}$ GeV

Hypercharge Landau Pole
$\Lambda_Y \gg M_P$

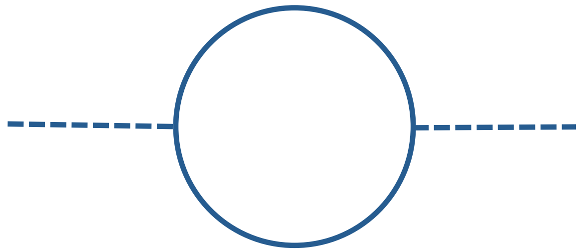
Axion
$f_a \gtrsim 10^9$ GeV

Neutrino Masses
$M_N \sim 10^{11}$ GeV

What is the hierarchy problem?

- Expect states at energies far above weak scale
- If they couple to the Higgs Boson:

H



$$H^\dagger \to m_H^2 \sim \text{Loop} \times \Lambda_{NP}^2$$

- If $\Lambda_{NP} \gg \text{TeV}$ then how come the Higgs mass, and the weak scale are below TeV?

- One answer: $V_H = \widetilde{M}_H^2 |H|^2 + \Lambda_{NP}^2 |H|^2$

HUGE! HUGE!

$$\widetilde{M}_H^2 + \Lambda_{NP}^2 \sim \text{small}$$

Experimental Status: Known solutions in some trouble!

Compositeness

Modified Higgs couplings predicted:

$$c_{ZZ} \neq \frac{m_Z^2}{v}$$

Current measurements point at SM-like Higgs boson.

New coloured states predicted:

$$\mathcal{L} \sim \lambda_t f \left(1 - \frac{h^2}{f^2}\right) \overline{T}' T'$$

None yet observed at the LHC...

Supersymmetry

Modified Higgs couplings predicted:

$$c_{ZZ} = \sin(\beta - \alpha)$$

Current measurements point at SM-like Higgs boson.

New coloured states predicted:

$$\mathcal{L} \sim \lambda_t^2 h^2 |\tilde{t}|^2$$

None yet observed at the LHC...

Part II

Relaxation

A New Structural Idea:

- In the Standard Model, light Higgs is
  - Not a point of enhanced symmetry: no reason to believe it to be special…
  - However, it may be a special region in terms of dynamics! Matter light when Higgs vev is small.
- Perhaps dynamics in the early Universe picked a small Higgs vev:

Relaxion

- Graham, Kaplan, Rajendran: 2015.

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- Radically different take on the hierarchy problem.
- Basic ingredients

Total shift symmetry.

$$\phi \to \phi + \alpha$$

$$\mathcal{L} \sim M^2 |H|^2$$

Write down an EFT consistent with all symmetries and valid at the cutoff scale "M". Throughout assume that "M" is very far above the weak scale.

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- Radically different take on the hierarchy problem.
- Basic ingredients

Discrete shift symmetry.

$$\phi \to \phi + 2\pi f$$

$$\mathcal{L} \sim M^2 |H|^2$$

Anomaly coupling breaks shift symmetry to discrete shift symmetry

$$+ \frac{\phi}{32\pi^2 f} \widetilde{G} G$$

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- Radically different take on the hierarchy problem.
- Basic ingredients

No shift symmetry.

$$\cancel{\phi \to \phi}$$

$$\mathcal{L} \sim (M^2 - g\phi)|H|^2$$

$$-gM^2\phi$$

$$+\frac{\phi}{32\pi^2 f}\widetilde{G}G$$

Anomaly coupling breaks shift symmetry to discrete shift symmetry

"g" parameter controls the explicit and complete breaking of shift symmetry

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- Radically different take on the hierarchy problem.
- Basic ingredients

Relaxion "scans" Higgs mass

$$\mathcal{L} \sim (M^2 - g\phi)|H|^2$$

Higgs mass takes large value M >> 125 GeV

$$-gM^2\phi$$

Relaxion couples to QCD like the axion

Relaxion wants to roll due to small terms in potential

$$+\frac{\phi}{32\pi^2 f}\widetilde{G}G$$

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- Radically different take on the hierarchy problem.
- Basic ingredients

$$\mathcal{L} \sim (M^2 - g\phi)|H|^2$$

$$-gM^2\phi$$

Axion-like coupling leads to usual axion potential

$$+f_\pi^2 m_\pi^2 \cos\left(\frac{\phi}{f}\right)$$

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- Radically different take on the hierarchy problem.
- Basic ingredients

$$\mathcal{L} \sim (M^2 - g\phi)|H|^2$$

$$-gM^2\phi$$

Which in terms of light quark masses scales like

$$+f_\pi^3 m_q \cos\left(\frac{\phi}{f}\right)$$

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- Radically different take on the hierarchy problem.
- Basic ingredients

$$\mathcal{L} \sim (M^2 - g\phi)|H|^2$$

$$-gM^2\phi$$

Thus in terms of the Higgs vacuum expectation value the potential is

$$+f_\pi^3 \lambda_q \langle h \rangle \cos\left(\frac{\phi}{f}\right)$$

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- Radically different take on the hierarchy problem.
- Basic ingredients

Once it has rolled far enough, Higgs will develop a small VEV.

Then axion potential turns on and Relaxion stops rolling

$$\mathcal{L} \sim (M^2 - g\phi)|H|^2$$

$$-gM^2\phi$$

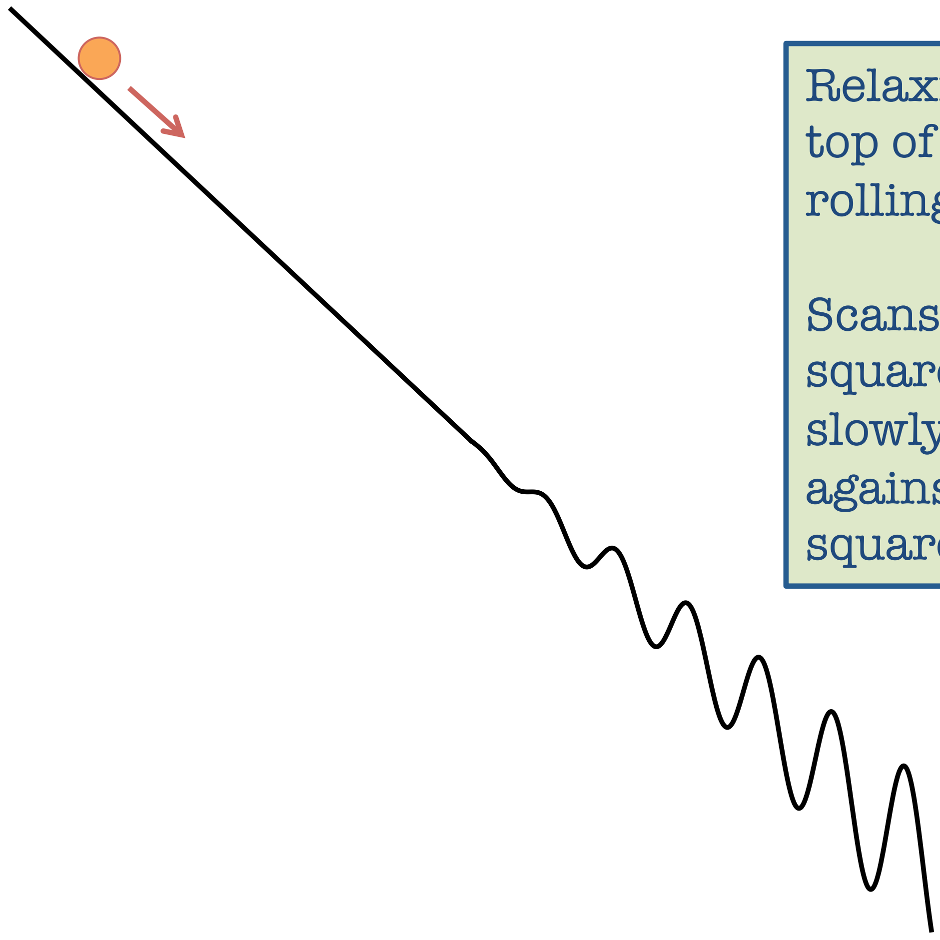
In early Universe Relaxion rolls

$$+f_\pi^3 \lambda_q \langle h \rangle \cos\left(\frac{\phi}{f}\right)$$

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- Cosmological evolution



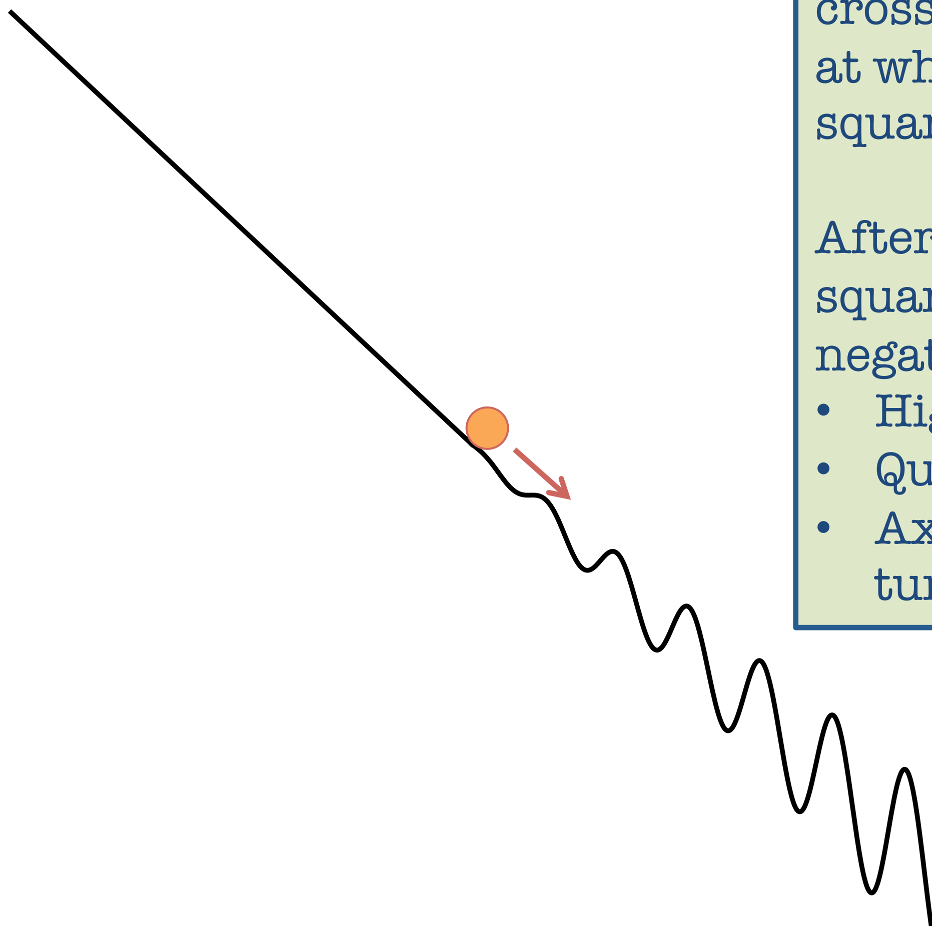
Relaxion starts at the top of potential. Starts rolling down.

Scans Higgs mass-squared while it rolls, slowly cancelling against large mass-squared.

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- Cosmological evolution



At some point relaxion crosses critical value at which Higgs mass-squared becomes zero.

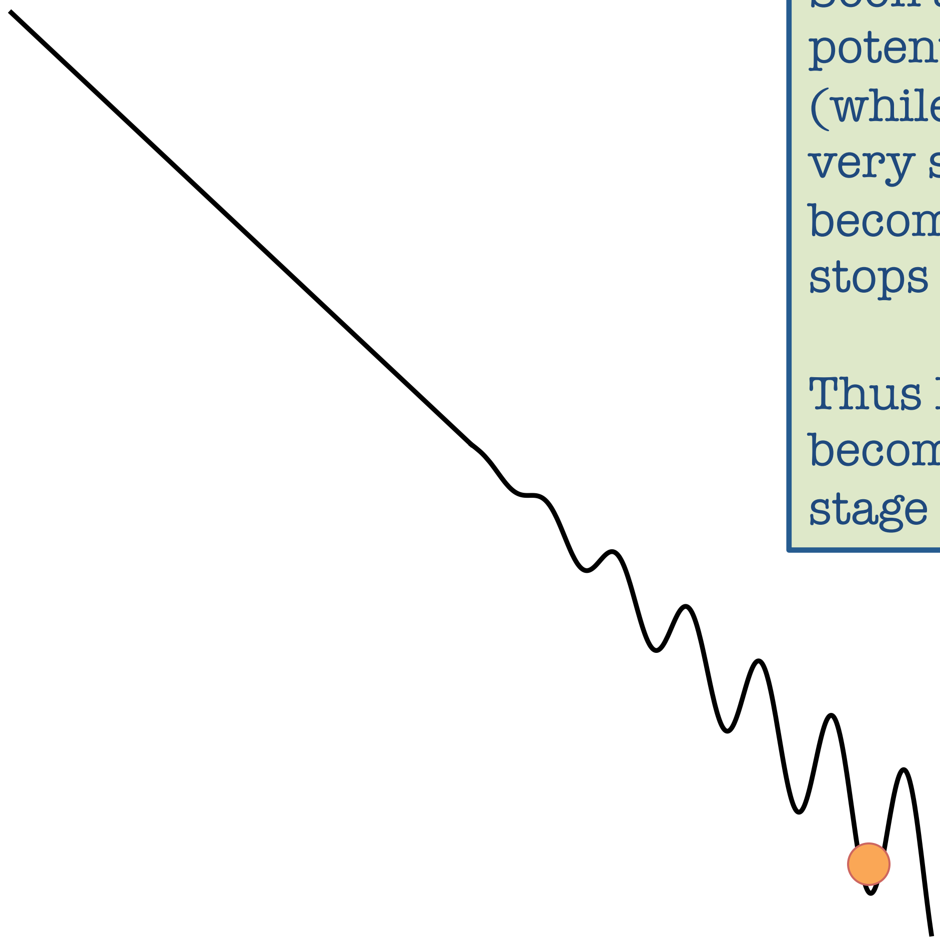
After this mass-squared becomes negative:

- Higgs gets a vev
- Quarks get mass
- Axion potential turns on

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- Cosmological evolution



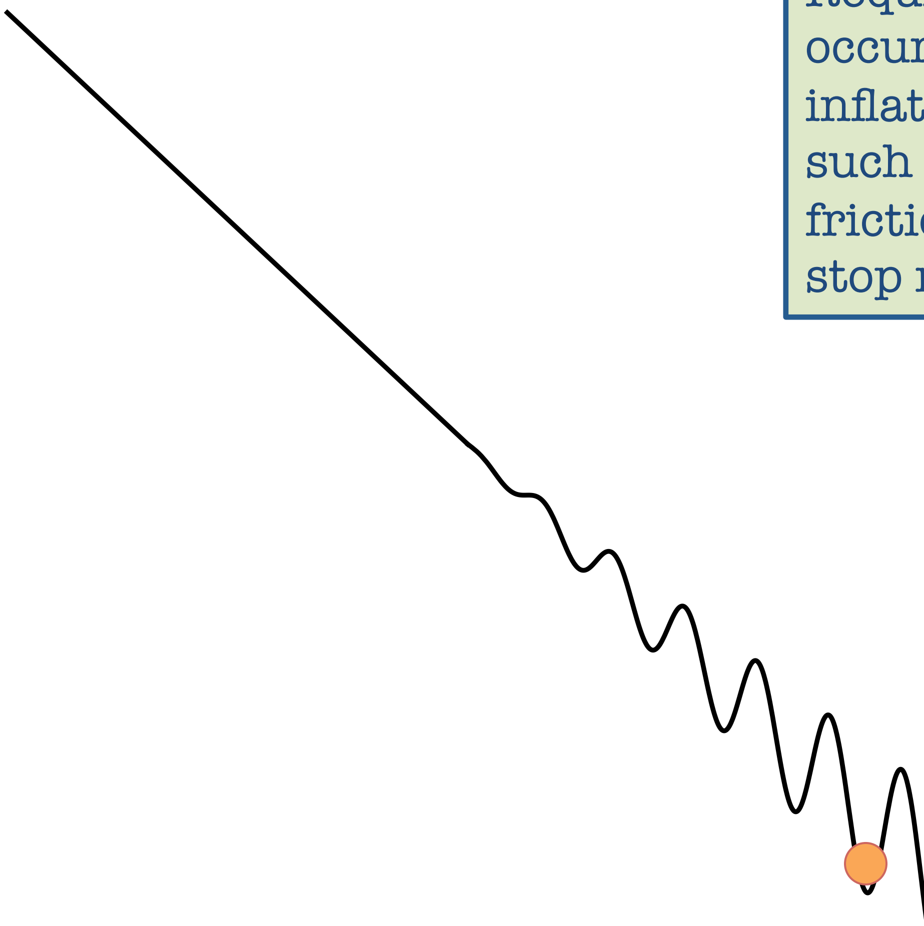
Soon after axion potential turns on (while Higgs vev is still very small), relaxion becomes trapped and stops rolling.

Thus Higgs vev becomes stuck at this stage too.

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- Cosmological evolution



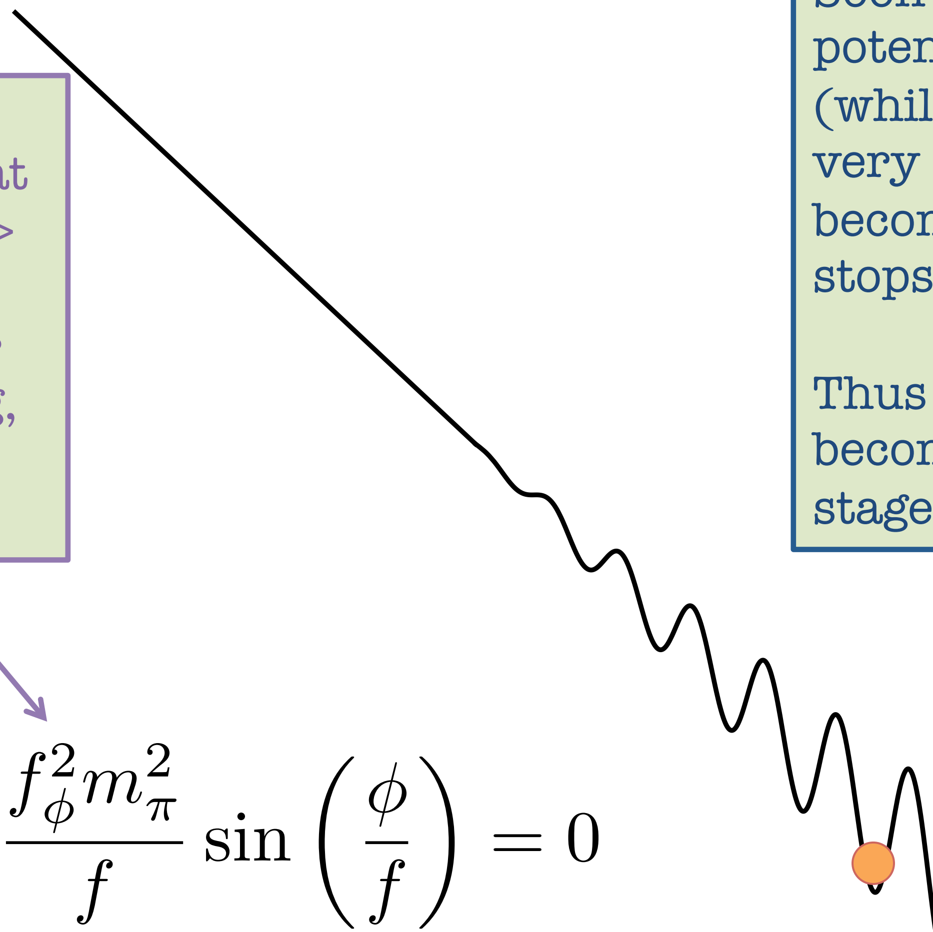
Require all of this to occur during an inflationary stage, such that Hubble friction allows field to stop rolling.

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- Cosmological evolution

Can choose “g” parameter such that field stops when <h> is still very small. This is a parameter choice, not a tuning, since radiatively stable.



Soon after axion potential turns on (while Higgs vev is still very small), relaxion becomes trapped and stops rolling.

Thus Higgs vev becomes stuck at this stage too.

$$\frac{\partial V}{\partial \phi} \sim gM^2 - \frac{f_\phi^2 m_\pi^2}{f} \sin\left(\frac{\phi}{f}\right) = 0$$

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- Problem. At min of potential, where relaxion comes to rest

$$\frac{\partial V}{\partial \phi} \sim gM^2 - \frac{f_\phi^2 m_\pi^2}{f} \sin\left(\frac{\phi}{f}\right) = 0$$

- Thus we have strong CP angle $\phi \neq 0$!
- To resolve this use a hidden sector QCD'

$$\frac{\phi}{32\pi^2 f} \widetilde{Q}' Q'$$

… with hidden sector quarks coupled to Higgs.

See also Espinosa, Grojean, Panico, Pomarol, Pujolas, Servant. 2015

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- Hubble scale during inflation is...

$$H < \Lambda_{QCD}$$

- Field excursion is...

$$\delta\phi \sim 10^{41}\ \mathrm{GeV}$$

- Number of e-foldings is...

$$N \gtrsim 10^{45}$$

- "g" parameter is...

$$g \sim 10^{-27}\ \mathrm{GeV}$$

- Maximum cutoff scale is

$$M \sim 10^{7}\ \mathrm{GeV}$$

...for typical axion parameters, variations possible.

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- A laundry list of open questions...

Can a natural inflationary model be realised?

...= worthwhile projects.

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- A laundry list of open questions...

What is the origin of the quasi-periodic potential?

...= worthwhile projects.

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- A laundry list of open questions…

Are there issues with super-duper-Planckian field excursions?

…= worthwhile projects.

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- A laundry list of open questions…

Could the QCD relaxion model be resurrected?

…= worthwhile projects.

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- A laundry list of open questions…

Are the extremely small couplings/decay constants consistent with weak gravity conjecture?

…= worthwhile projects.

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- A laundry list of open questions…

What is the UV picture?

…= worthwhile projects.

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- Slow but steady progress in a number of directions since initial proposal!

- Models:
  - Multiple scanning: Espinosa, Grojean, Panico, Pomarol, Pujolas, Servant.
  - Finite temperature: Hardy
  - Particle production/Dissipation: Hook, Marques-Tavares. Also: You.
  - Many interesting works on Monodromy…

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- Slow but steady progress in a number of directions since initial proposal!

- Phenomenology:
  - Ideas to probe with atomic force microscopy: Berengut et al.
  - Intensity frontier: Flacke, Frugiuele, Fuchs, Gupta, Perez.

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- A laundry list of open questions…

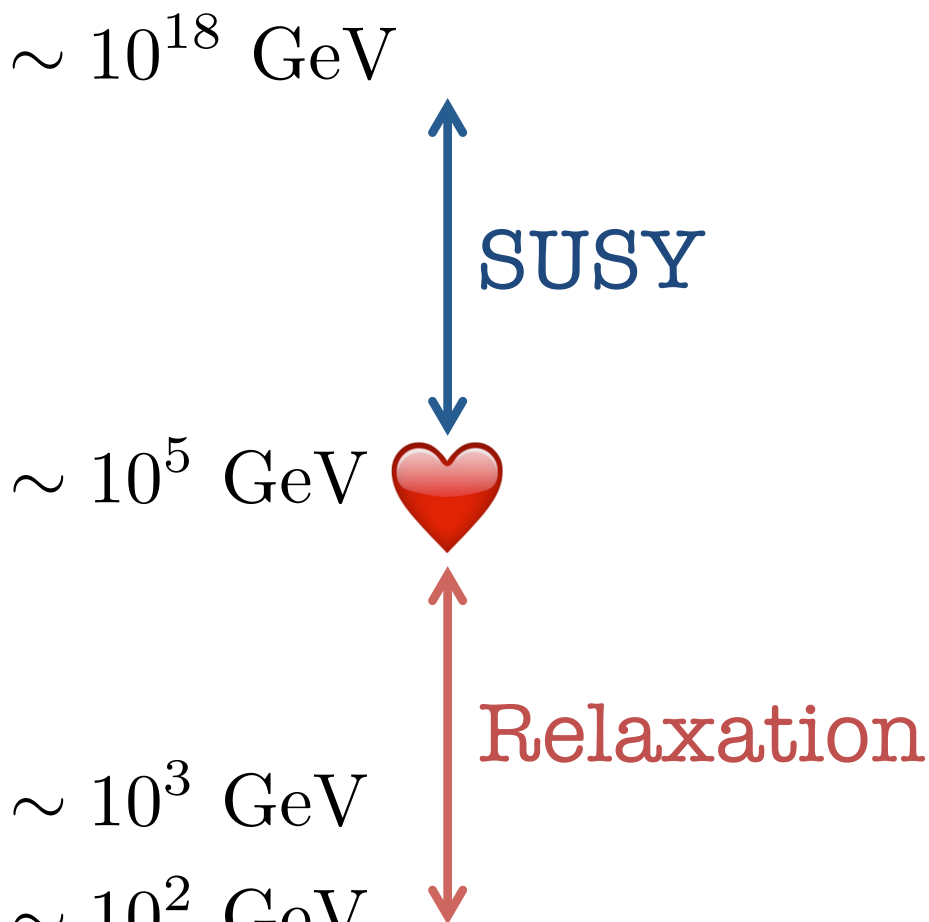
What is the UV picture?

The rest of this talk…

…= worthwhile projects.

Natural Heavy Supersymmetry

- Perhaps they are made for one other?

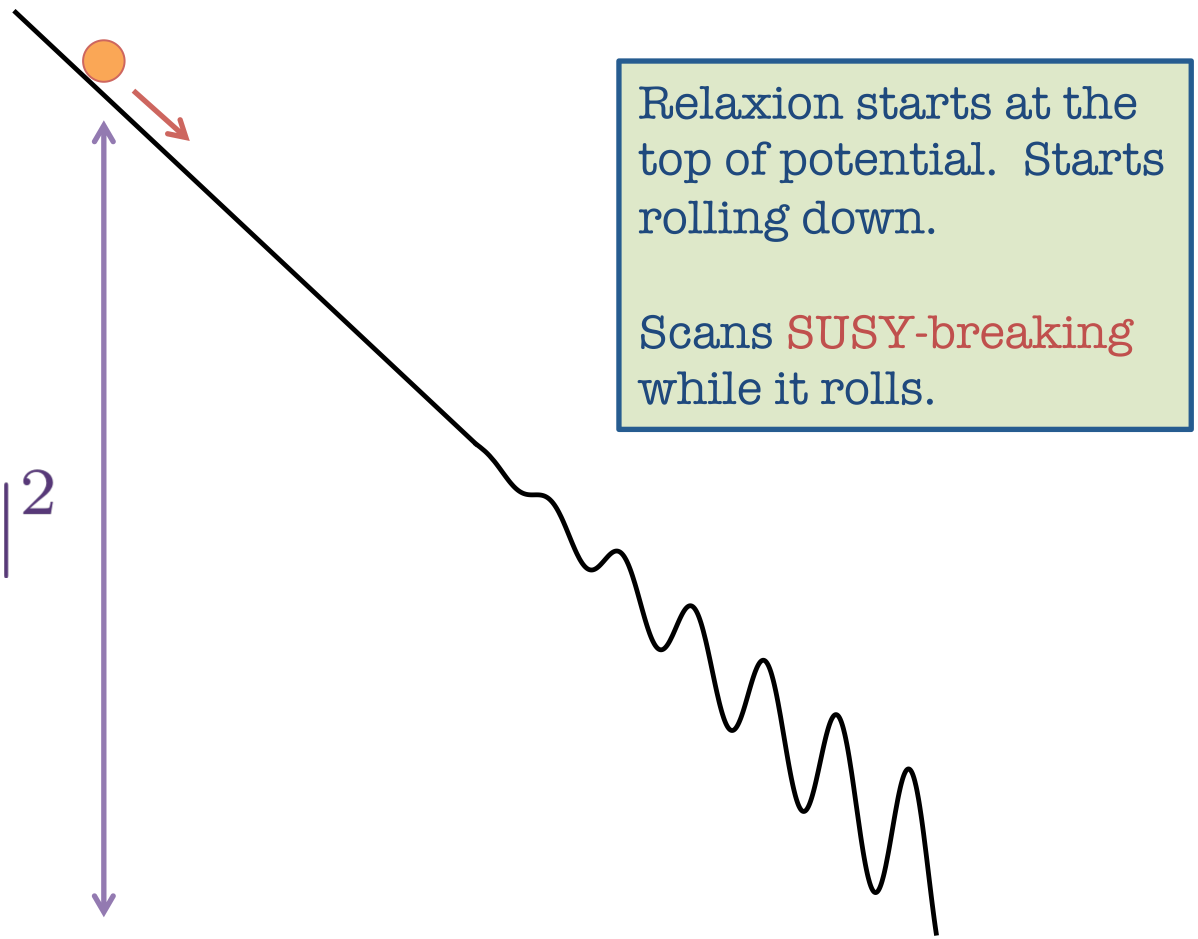


- Battell, Giudice, MM, 2015

Natural Heavy Supersymmetry

- In SUSY, scanning implies scanning of SUSY breaking

$$V = |F|^2 + |D|^2$$



Natural Heavy Supersymmetry

- Relaxation requires axion-like coupling

$$\mathcal{L} \supset \frac{\phi}{16\pi^2 f} G\widetilde{G}$$

Note loop factor

- In SUSY this requires generation of soft masses!

$$W = \frac{S}{16\pi^2} \mathcal{W}\mathcal{W}$$

- Where the relaxion superfield is

srelaxion relaxion relaxino SUSY-breaking

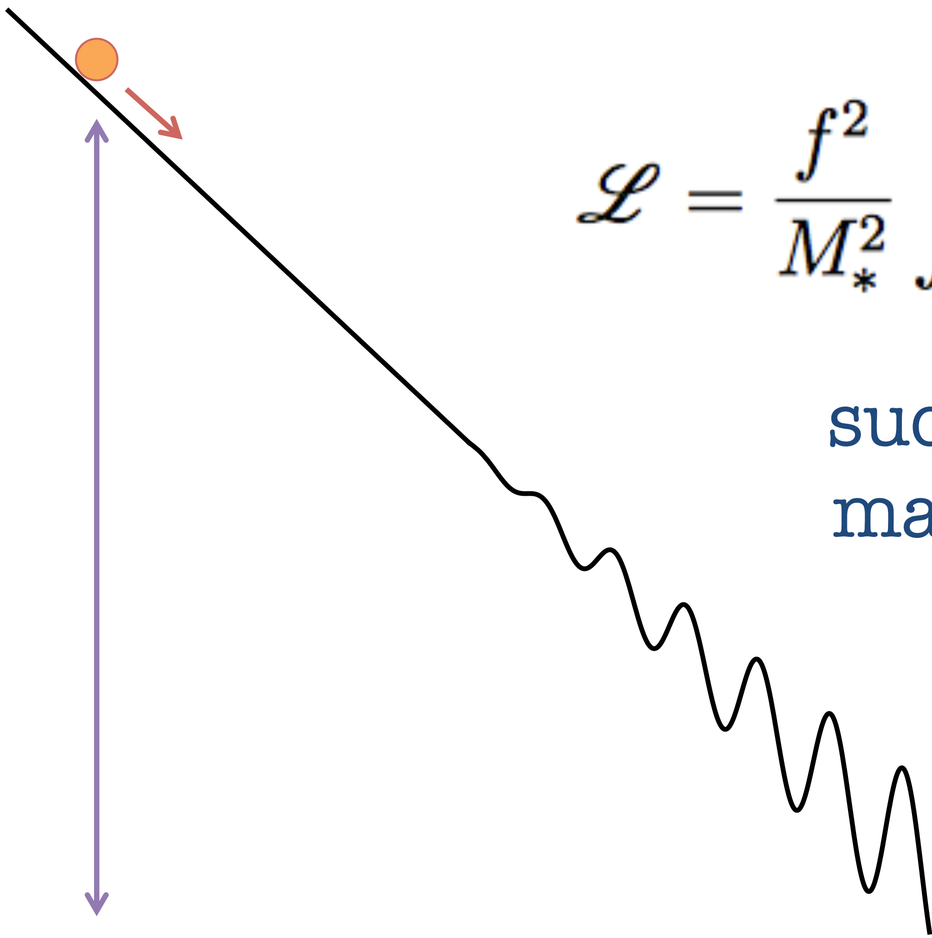
$$S = \frac{s + ia}{\sqrt{2}} + \sqrt{2}\theta\tilde{a} + \theta^2 F$$

- Note field not canonically normalised.

Natural Heavy Supersymmetry

- Typically also have Kahler interactions:

Note no loop factor



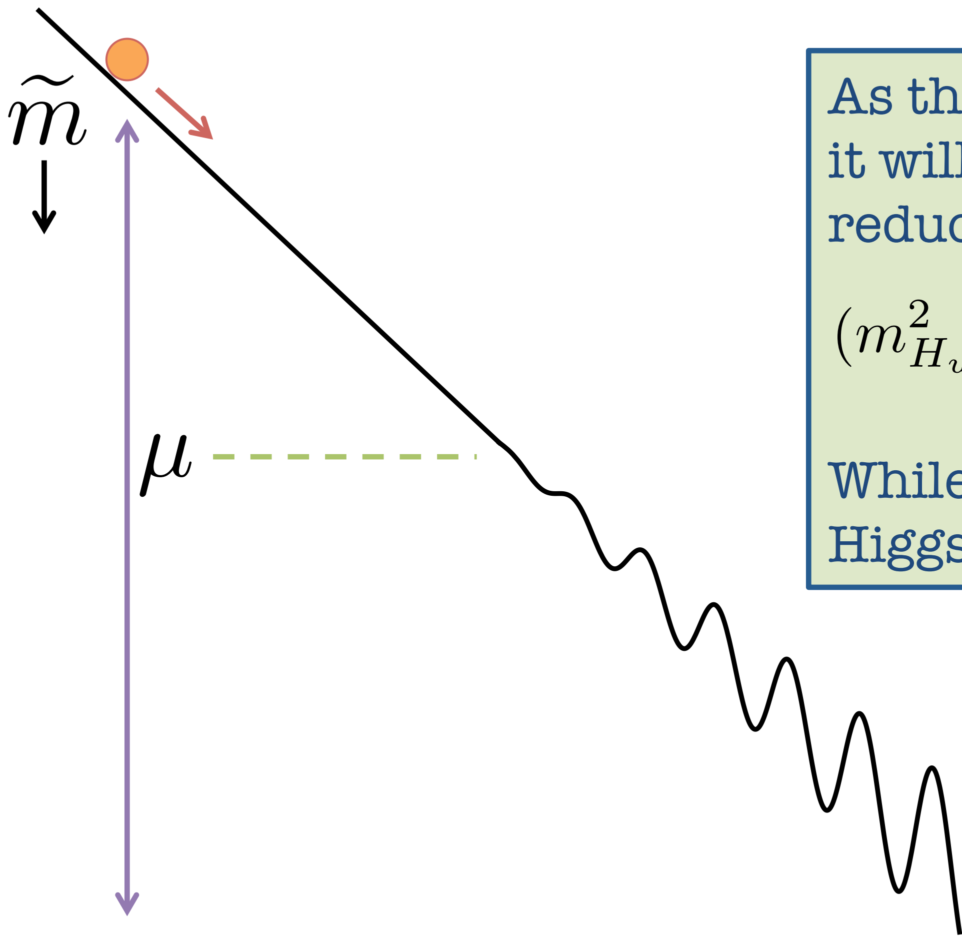
$$\mathscr{L} = \frac{f^2}{M_*^2} \int d^4\theta \, (S + S^\dagger)^2 \Phi_i^\dagger \Phi_i \, .$$

Higgs/Squarks/..

such that scalar soft masses will also scan.

Natural Heavy Supersymmetry

- Supersymmetric Higgs mass is crucial:



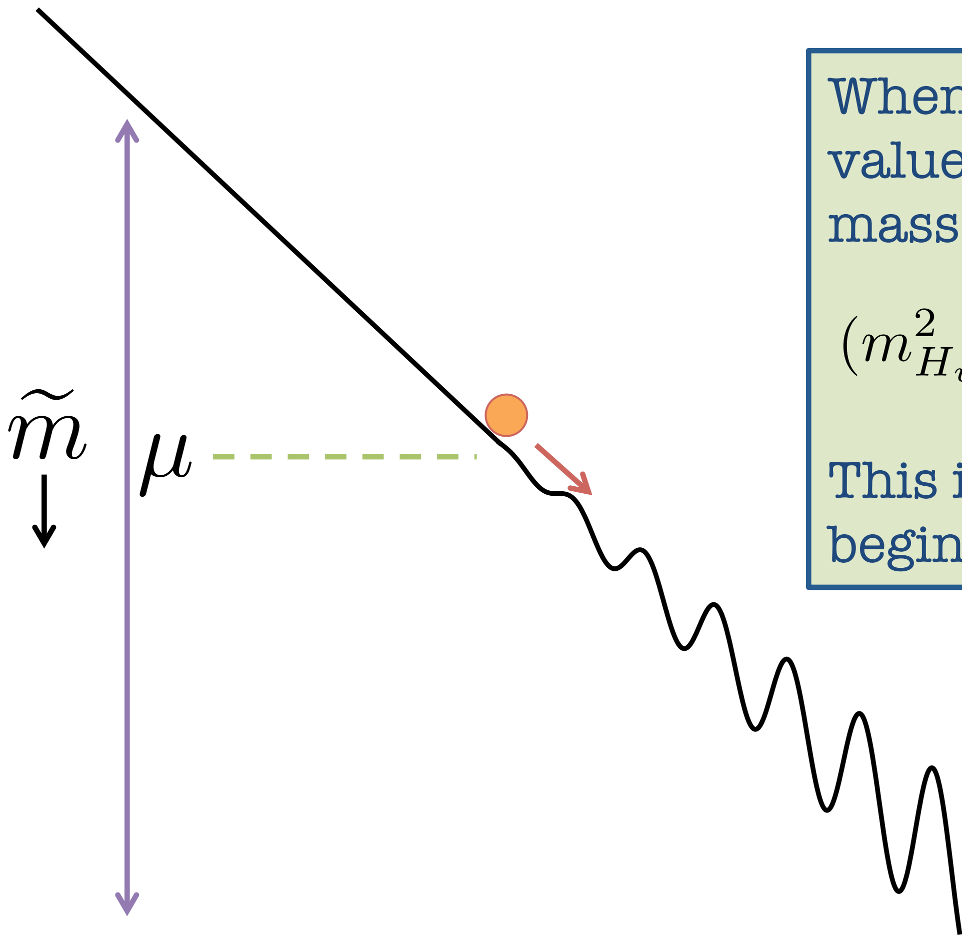
As the relaxion rolls down the potential it will scan the Higgs soft masses, reducing them as they relaxion rolls...

$$(m_{H_u}^2 + |\mu|^2)(m_{H_d}^2 + |\mu|^2) - |B_\mu|^2 > 0$$

While the soft masses are large the Higgs does not get a vev.

Natural Heavy Supersymmetry

- Supersymmetric Higgs mass is crucial:



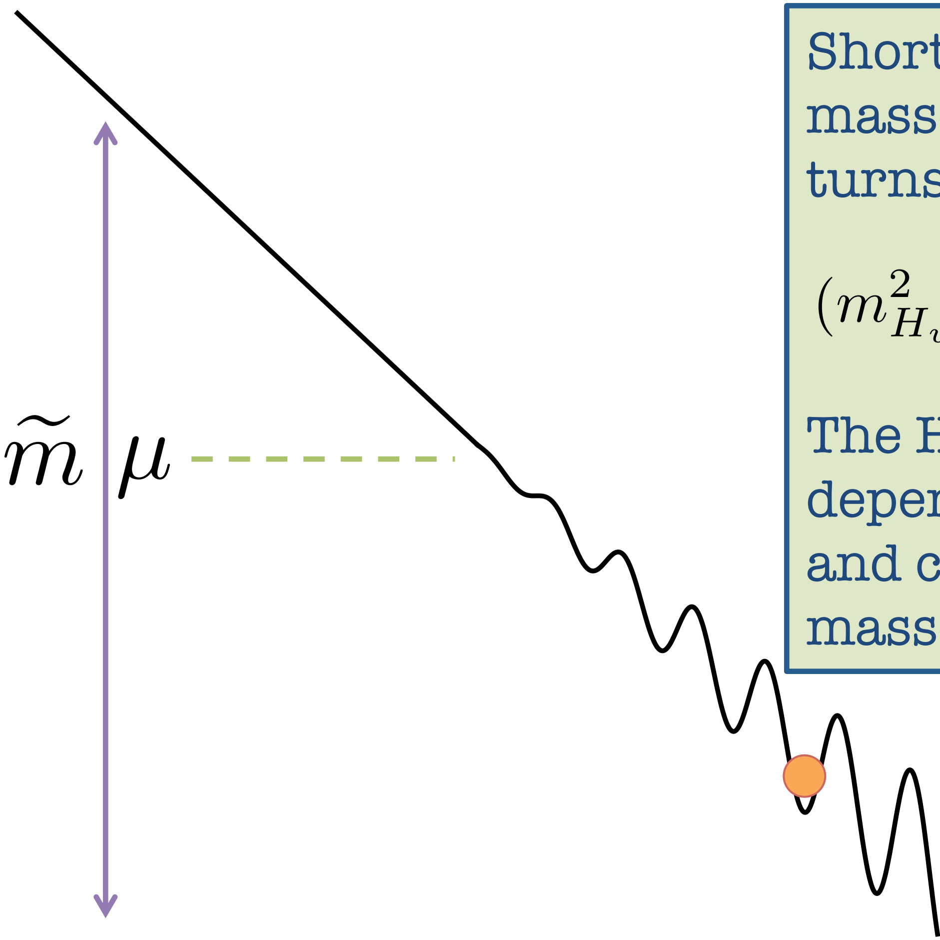
When the soft masses pass a critical value the determinant of Higgs sector mass matrix crosses zero:

$$(m_{H_u}^2 + |\mu|^2)(m_{H_d}^2 + |\mu|^2) - |B_\mu|^2 \sim 0$$

This is the critical point at which vev begins to turn on.

Natural Heavy Supersymmetry

- Supersymmetric Higgs mass is crucial:



Shortly after Higgs vev turns on quark masses also turn on, axion potential turns on, relaxion gets stuck.

$$(m_{H_u}^2 + |\mu|^2)(m_{H_d}^2 + |\mu|^2) - |B_\mu|^2 < 0$$

The Higgs vev at the stopping point depends on the slope of the potential, and can be much lower than soft masses at this point.

Natural Heavy Supersymmetry

- Combining these constraints we get

$$\mu_0 < \left(\frac{\Lambda}{300\ \mathrm{MeV}}\right)^{4/3}\left(\frac{10^9\ \mathrm{GeV}}{f}\right)^{4/3} 5\times 10^5\ \mathrm{GeV}$$

which is equivalent to an upper bound on scalar soft masses. Soft masses < 1000 TeV a prediction!

- Other parameters still odd...

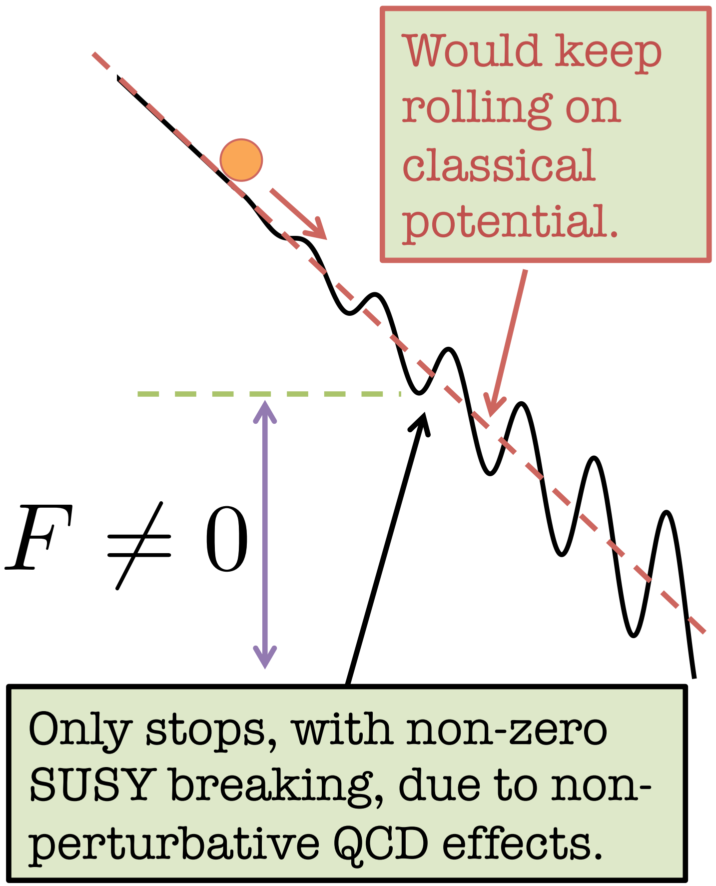
$$\Delta a > a_* = \left(\frac{300\ \mathrm{MeV}}{\Lambda}\right)^4\left(\frac{f}{10^9\ \mathrm{GeV}}\right)^2\left(\frac{\mu_0}{10^5\ \mathrm{GeV}}\right)^2 10^{30}$$

$$N > \left(\frac{300\ \mathrm{MeV}}{\Lambda}\right)^8\left(\frac{f}{10^9\ \mathrm{GeV}}\right)^6\left(\frac{\mu_0}{10^5\ \mathrm{GeV}}\right)^4 10^{42}$$

Supersymmetry Breaking

The Relaxion

$$V(a) = \frac{m^2}{2} f^2 a^2 + \Lambda^4 \cos \frac{a}{\sqrt{2}}$$

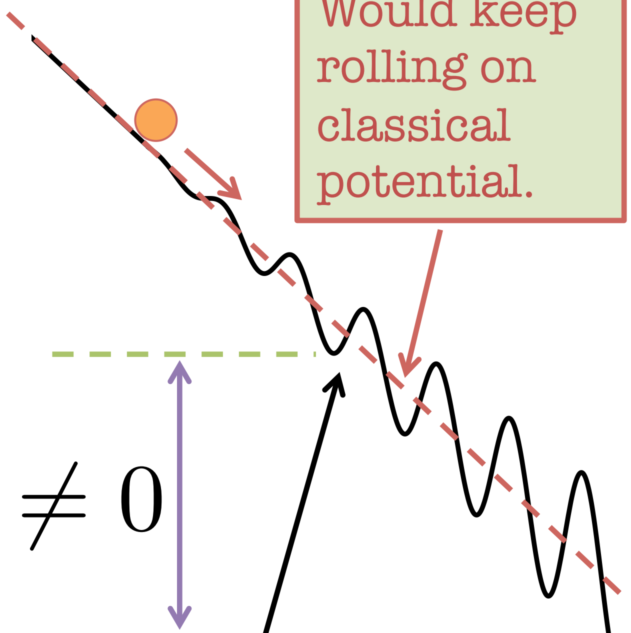


Supersymmetry Breaking

The Relaxion

$$V(a) = \frac{m^2}{2} f^2 a^2 + \Lambda^4 \cos \frac{a}{\sqrt{2}}$$

Would keep rolling on classical potential.



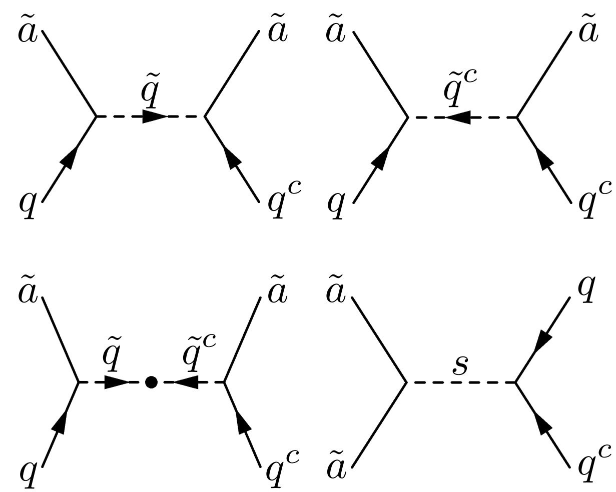
$$F \neq 0$$

Only stops, with non-zero SUSY breaking, due to non-perturbative QCD effects.

The Relaxino

$$m_{\tilde{a}} = mf$$

If SUSY spontaneously broken have massless Goldstino?



Integrating out heavy scalars:

$$\delta m_{\tilde{a}} = -\frac{1}{2\sqrt{2}am}\left(i m_q e^{ia/\sqrt{2}} q^c q + h.c.\right)$$

Supersymmetry Breaking

The Relaxion

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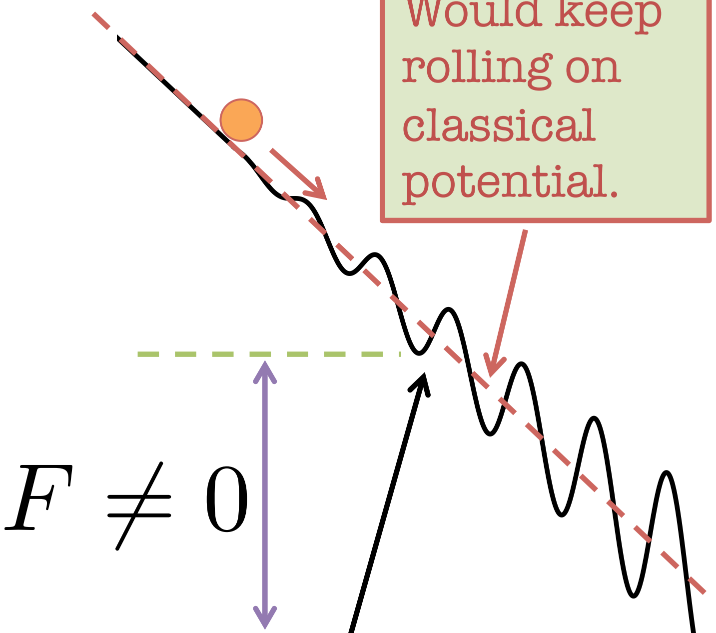


Only stops, with non-zero SUSY breaking, due to non-perturbative QCD effects.

The Relaxino

$$m_{\tilde{a}}(a) = m - \frac{\Lambda^4 \sin \frac{a}{\sqrt{2}}}{\sqrt{2}\, a m f^2}$$

From chiral condensate.

$$m^2 f^2 \langle a \rangle = \frac{\Lambda^4}{\sqrt{2}} \sin \frac{\langle a \rangle}{\sqrt{2}}$$

At minimum of relaxion potential. Thus:

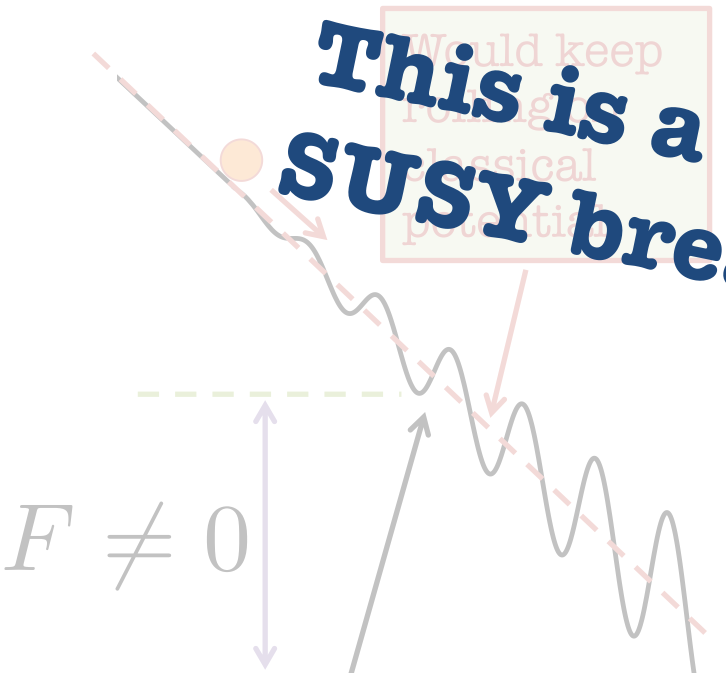
$$m_{\tilde{a}}(a) \to 0$$

The Goldstino!

Supersymmetry Breaking

The Relaxion

$$V(a) = \frac{m^2}{2} f^2 a^2 + \Lambda^4 \cos\frac{a}{\sqrt{2}}$$



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At minimum of relaxion potential. Thus:

$$m_{\tilde{a}}(a) \to 0$$

The Goldstino!

This is a new scenario for SUSY breaking, driven by QCD!

Particle Spectrum

$\tilde{q},\ \tilde{l},\ \widetilde{H}$ $\lesssim 100$ TeV

$\tilde{g},\ \widetilde{B},\ \widetilde{W}$ ~ 1 TeV

$\tilde{a} = \widetilde{G}_L$ 1 keV $\leftrightarrow$ GeV

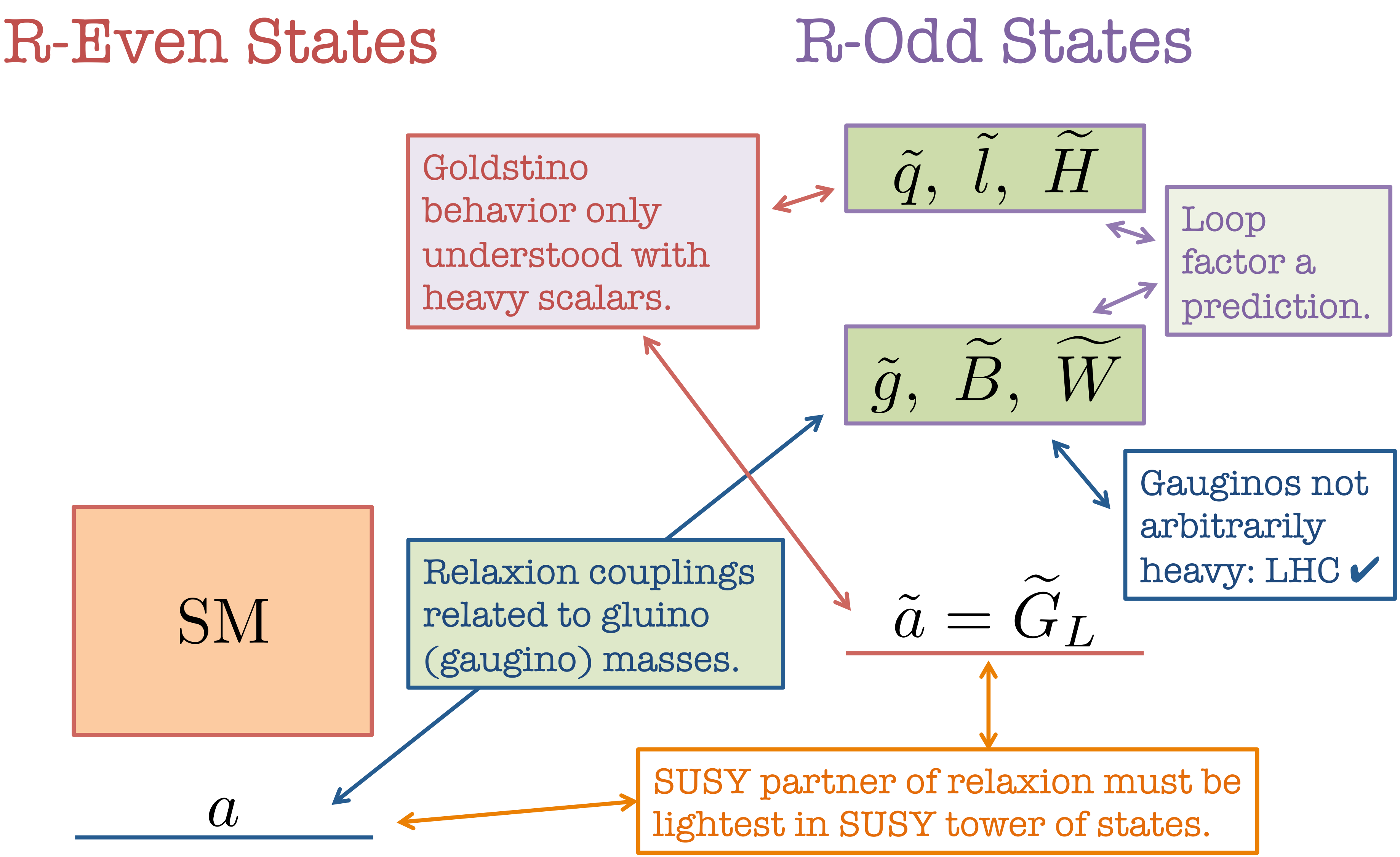
SM

a $\ll$ eV

This is a natural theory of Mini-Split SUSY!

Big hierarchy: SUSY. Little hierarchy: relaxation.

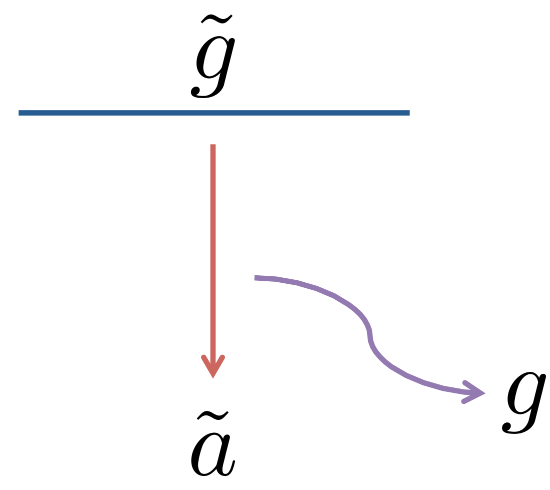
New Deep IR – Far UV Connections



LHC Phenomenology

- Scalars and Higgsinos likely to be out of reach.
- Gauginos possibly within LHC reach. Heavy Higgsinos: all gauginos pure gauge eigenstates.

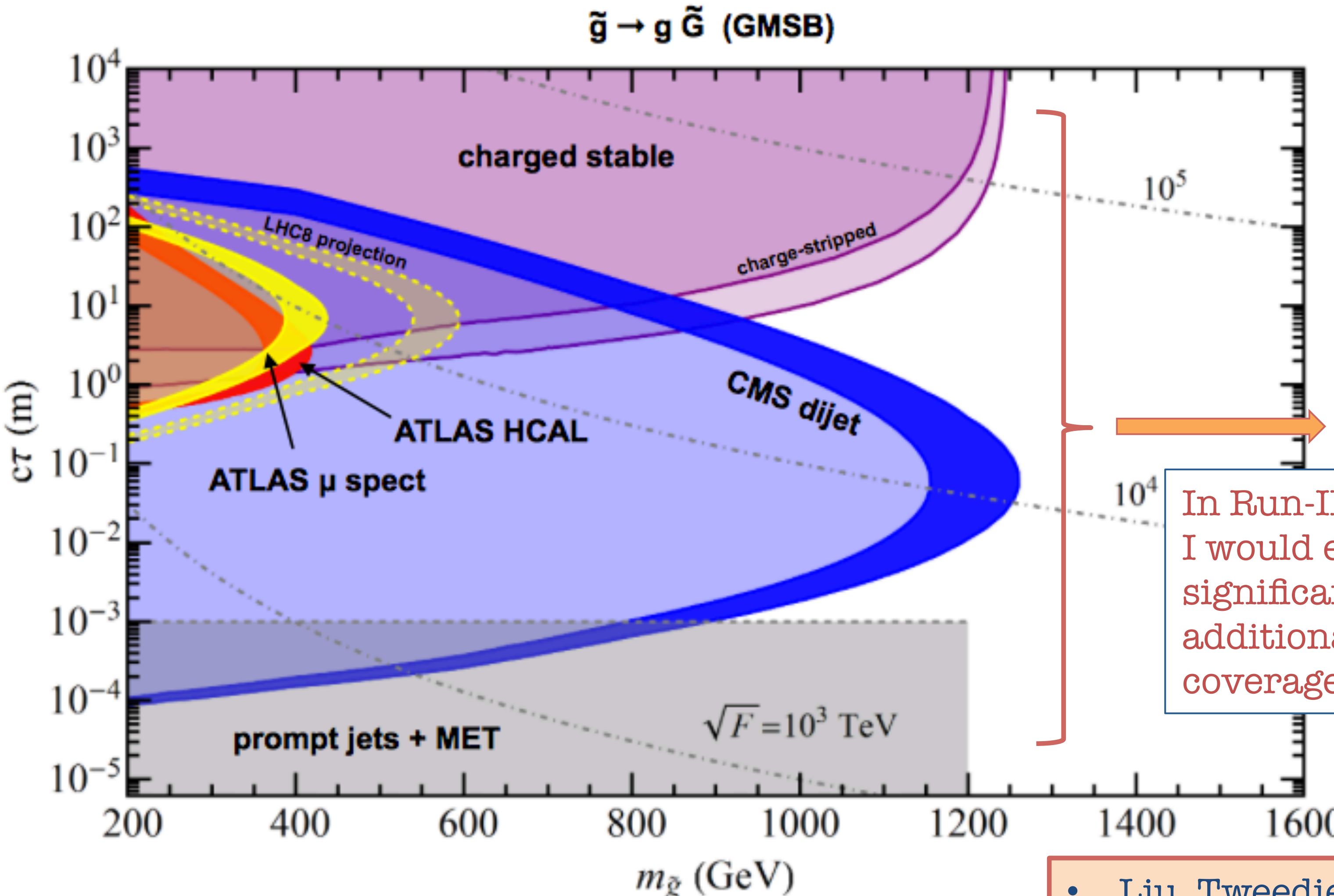
"Decay between 100 microns and a journey to the moon." (Giudice)



$$\tau_{\mathrm{NLSP}} = \left(\frac{m_{3/2}}{1\ \mathrm{MeV}}\right)^2 \left(\frac{1\ \mathrm{TeV}}{M_{\mathrm{NLSP}}}\right)^5 1.7 \times 10^2\ \mathrm{m}/c$$

LHC Phenomenology

- Displaced gluino decay limits:



In Run-II
I would expect
significant
additional
coverage.

- Liu, Tweedie, 2015

To The Future

- LHC Run I has fundamentally changed our perspective on the hierarchy problem.

- Radical new idea has emerged: "**Cosmological Relaxation**". Not yet a complete story. Work will be required to understand if this can be consistent.

- When SUSY and relaxation are married, to realize **Natural Heavy SUSY**, many intriguing new features arise that make the combination compelling.

LHC Phenomenology

- Relaxino predicted to be NLSP:
  - Looks like Mini-Split with gauge mediation.

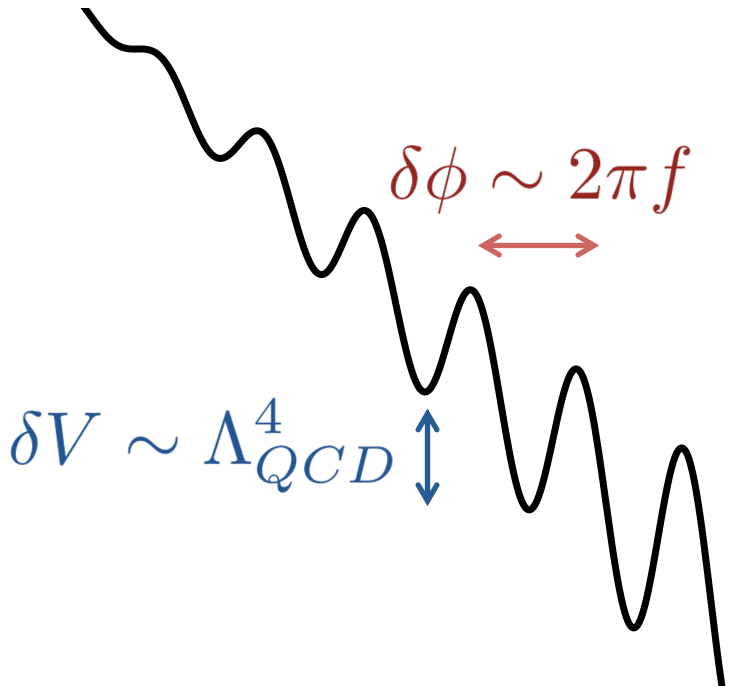
- Typical signatures (decay in detector):
  - MET: relaxino very light and neutral
  - Two displaced vertices
    - A jet at each for gluino NLSP
    - A weak gauge boson at each for bino/wino NLSP
  - Jets (2 for gluino NLSP, 4 otherwise)

- Typical signatures (decay outside detector):
  - R-hadron for gluino NLSP
  - Jets+MET for bino/wino NLSP

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- And the cosmological constant?



- Thus there are many aspects that are unfamiliar, but basic idea shows promise and a dynamical approach has never been constructed before!