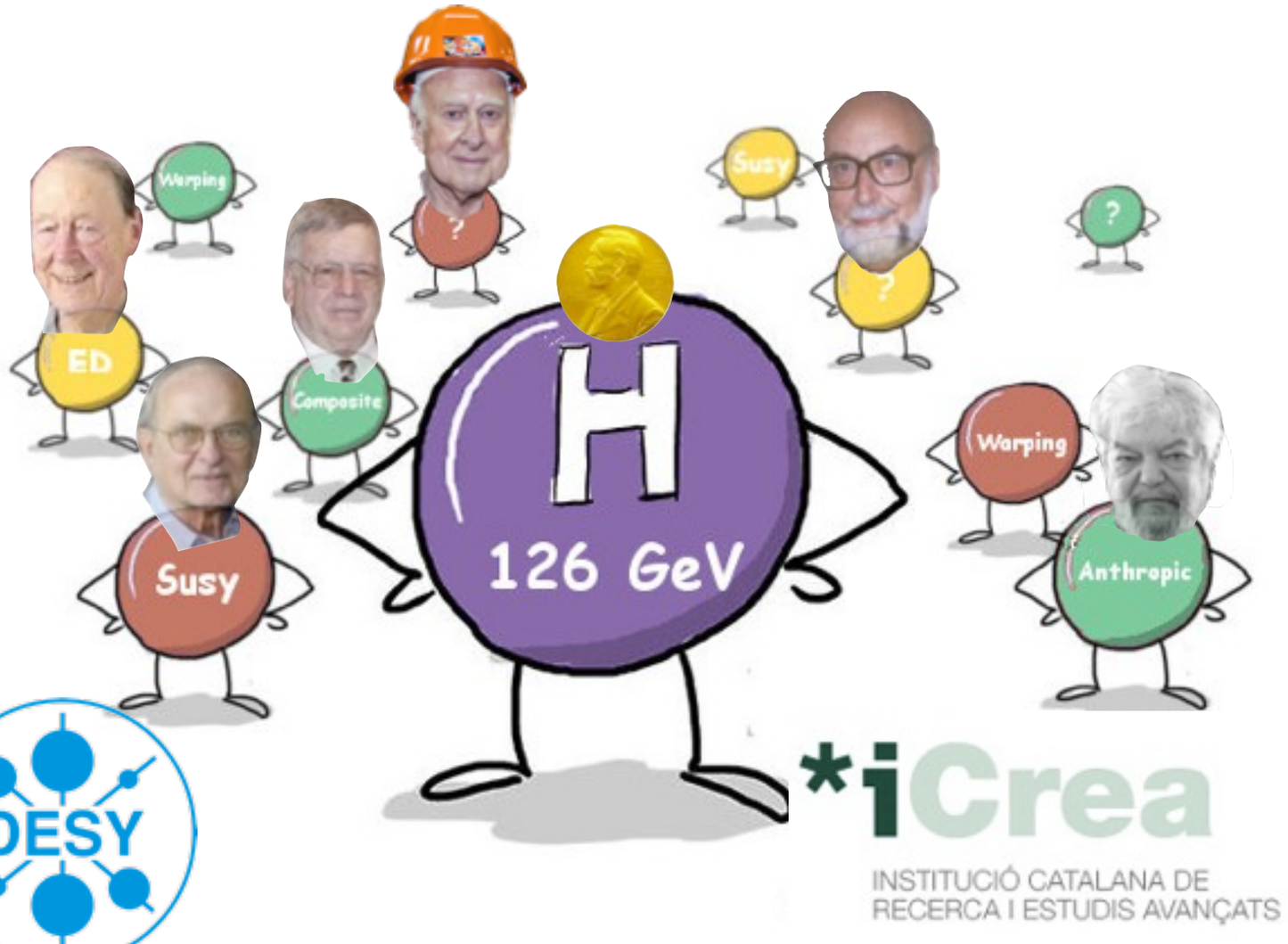
Beyond the Standard Model

CERN summer student lectures 2016



Lecture 4/4

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Outline

- Monday I
  - General introduction
  - Higgs physics as a door to BSM
- Monday II
  - Naturalness
  - Supersymmetry
  - (Grand unification, proton decay) ← not covered in the lectures but see the notes
- Tuesday
  - Composite Higgs
  - Effective field theory
- Wednesday
  - Extra dimensions
  - Cosmological relaxation
  - (Quantum gravity) ← skipped due to lack of time

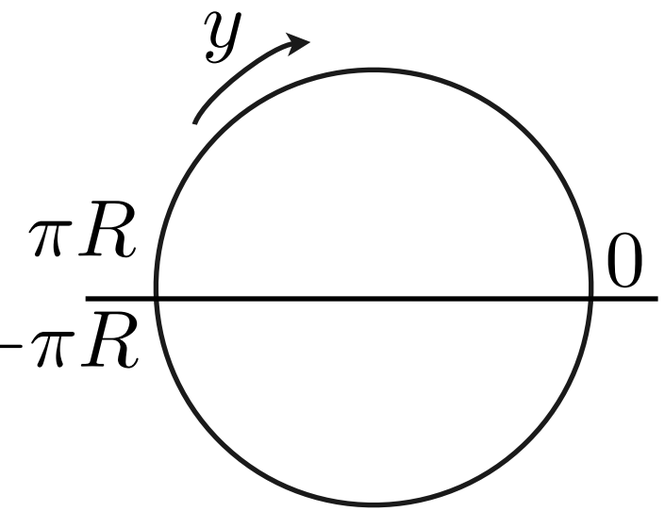
Extra dimensions

mass from motion in extra dimensions

$$m_D^2 = E^2 - \vec{p}_3{}^2 - \vec{p}_\perp{}^2 \quad \not\Rightarrow \quad m_D^2 + \vec{p}_\perp{}^2 = E^2 - \vec{p}_3{}^2 = m_4^2$$

momentum along extra dimensions ~ 4D mass

Compactification on a Circle



circle: $y \sim y + 2\pi R$

$$\phi(y + 2\pi R) = \phi(y)$$

$$\phi(x,y) = \sum_n \frac{1}{\sqrt{2^{\delta_{n0}}\pi R}} \left(\cos\left(\frac{ny}{R}\right) \phi_n^+(x) + \sin\left(\frac{ny}{R}\right) \phi_n^-(x) \right)$$

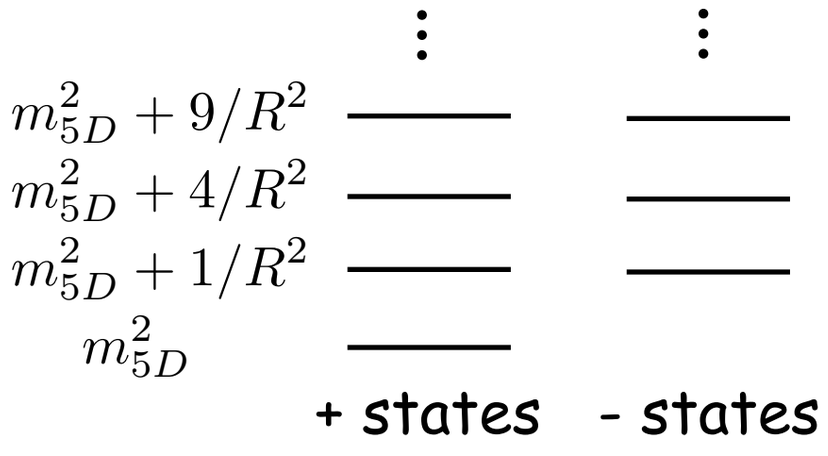
5D field

wavefunction = localization of KK mode along the xdim

4D Kaluza-Klein modes

$$m_n = p_y^n = \frac{n}{R}$$

Extra dimensions



5D field=infinite tower of massive 4D fields

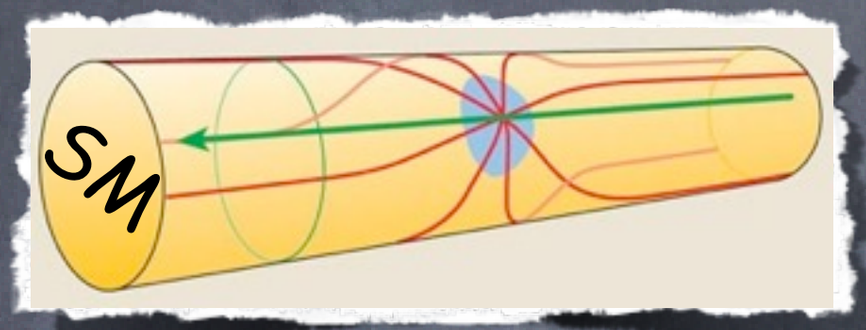
depending of the energy available, you can probe more and more of these KK modes

5D General relativity = 4D GR + U(1) gauge symmetry

gauge symmetries are emerging from
gravitational interactions in extra dimensions?
beautiful idea of Kaluza & Klein
but
quantization? non-abelian structure? different gauge couplings?
no successful realization till now

Extra Dimensions for TeV/LHC Physics

- Hierarchy problem, i.e., why is gravity so weak
  - large (mm size) extra dimensions
    - gravity is diluted into space while we are localized on a brane

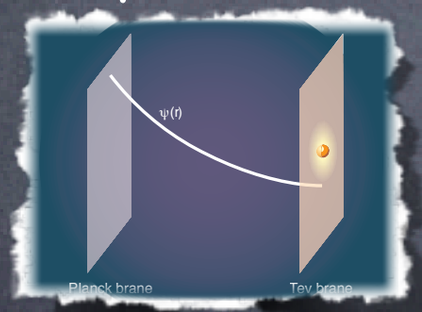


$$\int d^{4+n}x\,\sqrt{|g_{4+n}|}M_\star^{2+n}\mathcal{R} = \int d^4x\,\sqrt{|g_4|}M_{Pl}^2\mathcal{R}$$

$$M_{Pl}^2 = V_n M_\star^{2+n}$$

$M_{Pl} = 10^{19}$ GeV $M_* = 1$ TeV $V_2 = (2\text{ mm})^2$

  - warped extra dimensions
    - gravity is localized away from SM matter and we feel only the tail of the graviton



graviton wavefunction is exponentially localized away from SM brane

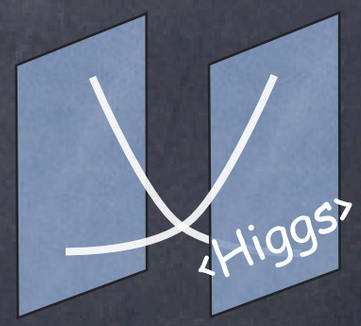
$$v = M_\star e^{-\pi R M_\star}$$

$M_* = 10^{19}$ GeV $v = 1$ TeV $R \sim 11/M_*$

- Fermion mass hierarchy & flavour structure

  fermion profiles:

  the bigger overlap with Higgs vev, the bigger the mass



- EW symmetry breaking

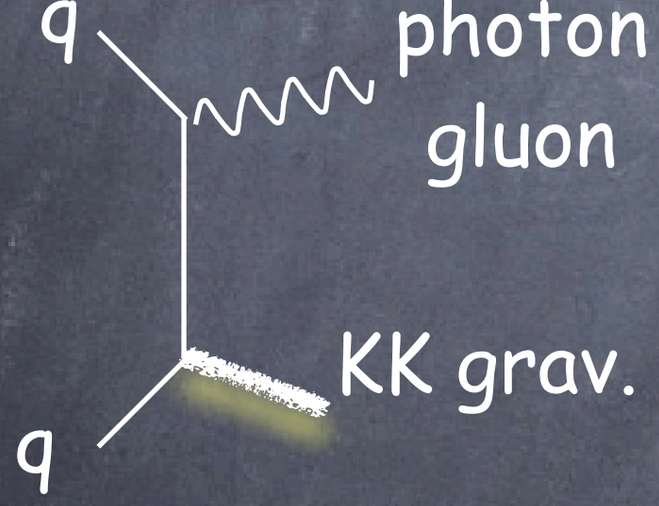
  Orbifold breaking, Higgsless

ADD phenomenology

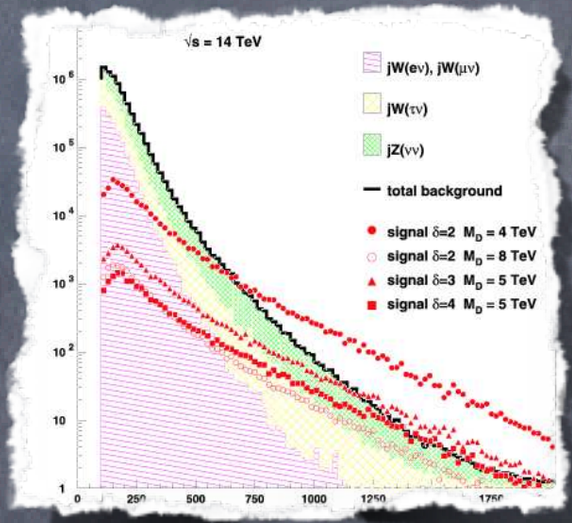
eV splitting
between KK modes

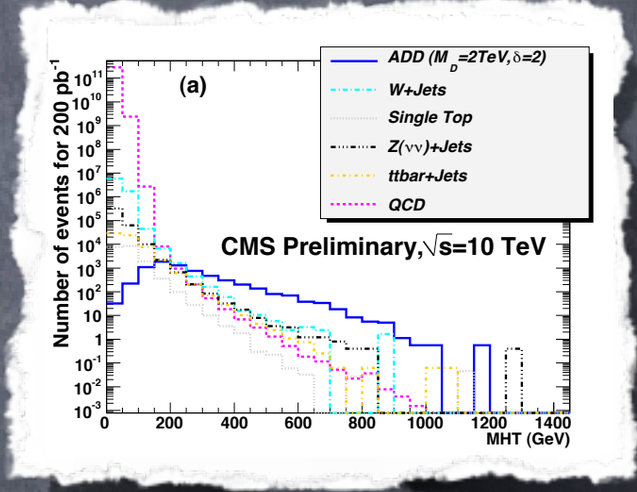
$1/M_{Pl}$ couplings of
KK modes to SM

- Graviton production in colliders



monojet+$\not{E}_T$





- Virtual graviton exchange

Vacavant, Hinchliffe '01

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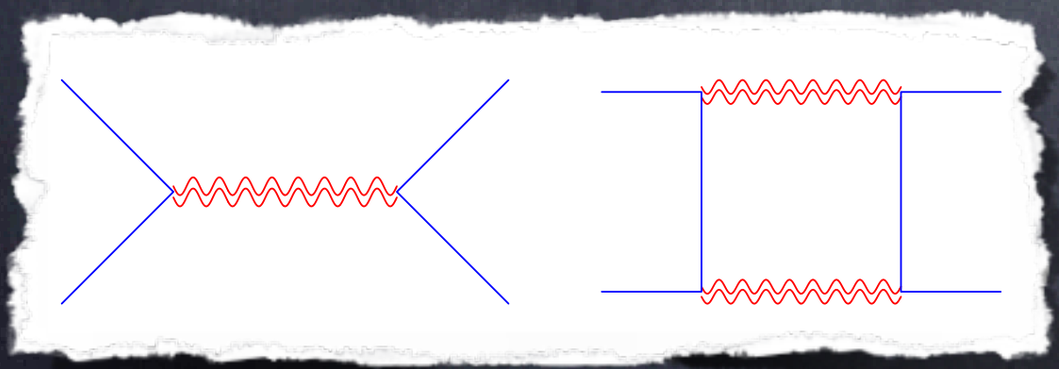
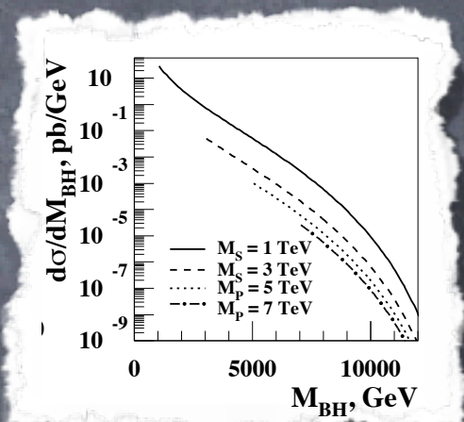


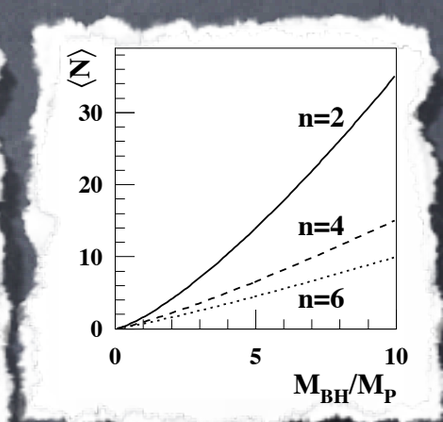
ADD phenomenology

- Supernova cooling: $M_* > 100$ TeV (for 2 xdim)

- Black Hole production

  classical production (can be very large $10^{3\text{-}4}$ pb),
  Hawking thermal decay, ie, large decay multiplicity





Dimopoulos, Landsberg, '01

- String resonance production

The Darwinian solution to the Hierarchy

Other origin of small/large numbers according to Weyl and Dirac:
hierarchies are induced/created by time evolution/the age of the Universe

Can this idea be formulated in a QFT language?
In which sense is it addressing the stability of small numbers at the quantum level?

Graham, Kaplan, Rajendran '15

Espinosa et al '15

- $m_H(t)$: $m_H^2(t=-\infty) = \Lambda^2_{\rm cutoff} \to m_H^2({\rm now}) = -(125\,{\rm GeV})^2$
- Higgs mass-squared promoted to a field.
- The field evolves in time in the early universe and scans a vast range of Higgs mass. But "Why/How/When does it stop evolving?"
- The Higgs mass-squared relaxes to a small negative value
- The electroweak symmetry breaking stops the time-evolution of the dynamical system

Self-organized criticality

dynamical evolution of a system is stopped at a critical point due to back-reaction

hierarchies result from **dynamics** not from **symmetries** anymore!

important consequences on the spectrum of new physics

Higgs-axion cosmological relaxation

Graham, Kaplan, Rajendran '15

ϕ slowly rolling field (inflation provides friction) that scans the Higgs mass

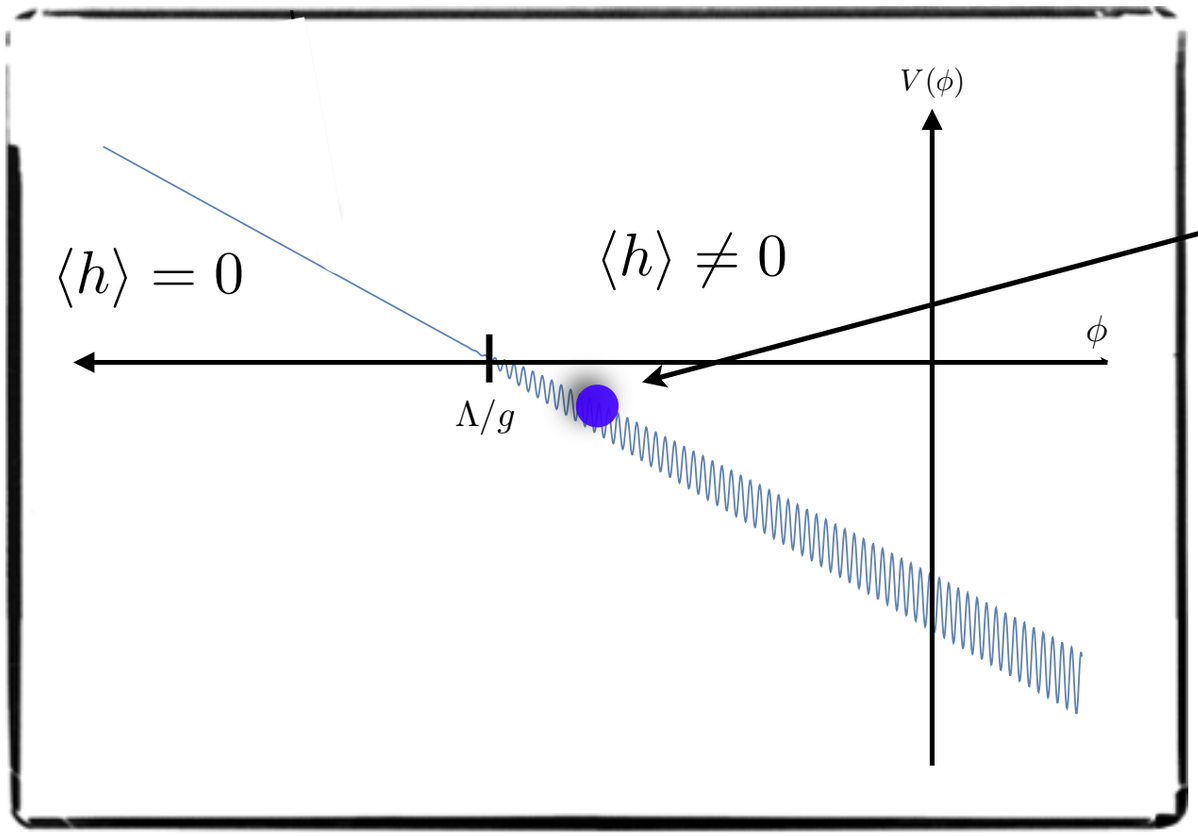
$$\Lambda^2\left(-1+f\left(\frac{g\phi}{\Lambda}\right)\right)|H|^2+\Lambda^4 V\left(\frac{g\phi}{\Lambda}\right)+\frac{1}{32\pi^2}\frac{\phi}{f}\tilde{G}^{\mu\nu}G_{\mu\nu}$$

Higgs mass depends on ϕ

potential needed to force ϕ to roll-down in time (during inflation)

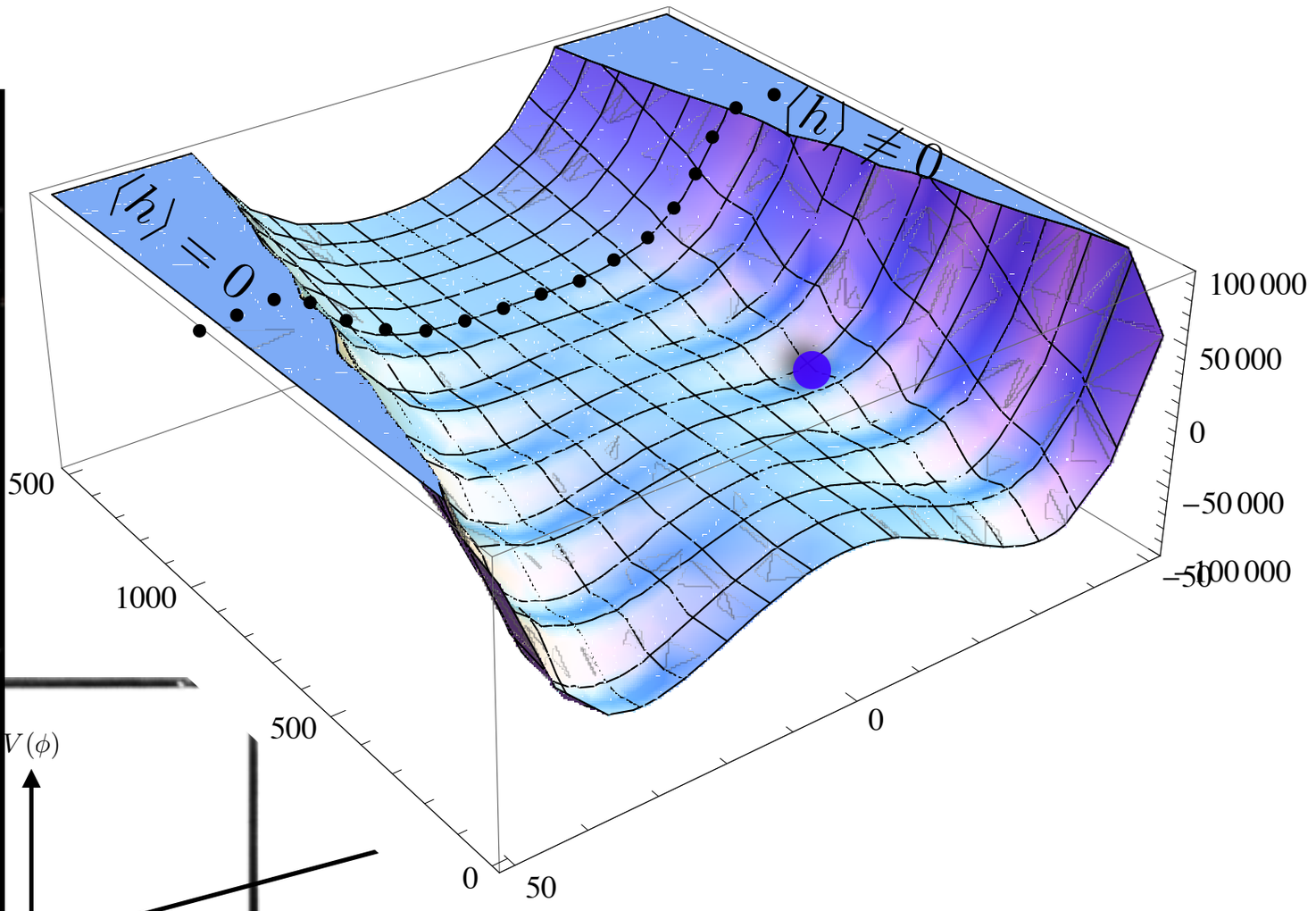
axion-like coupling that will seed the potential barrier stopping the rolling when the Higgs develops its vev

$$\Lambda_{\rm QCD}^3\, h\, \cos\frac{\phi}{f}$$



Higgs-axion cosmological relaxation

Graham, Kaplan, Rajendran '15



If ϕ continues rolling, the Higgs vev increases, the potential barrier increases and ultimately
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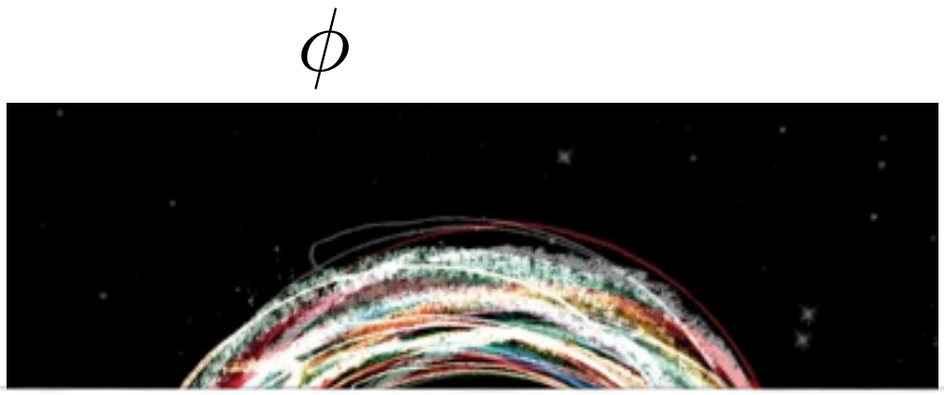
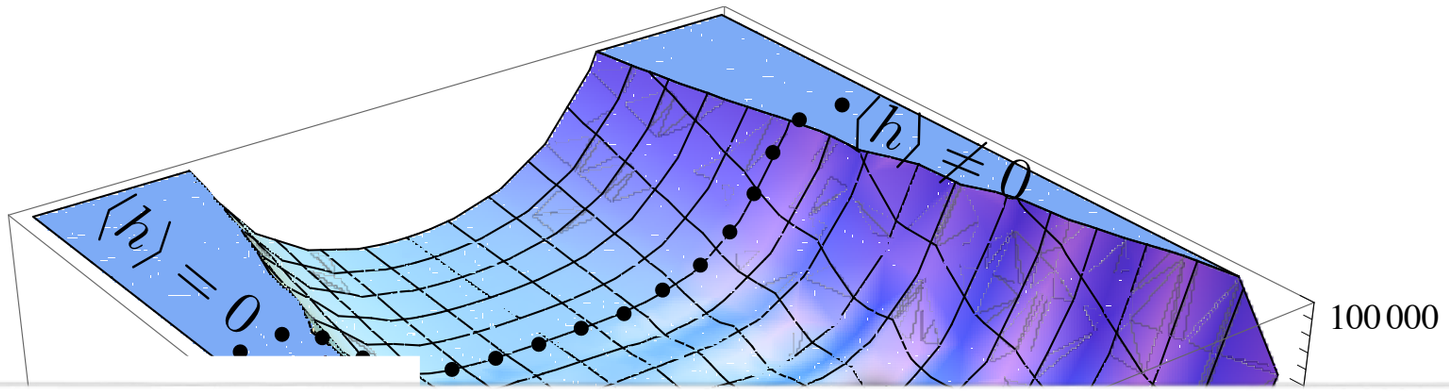
Higgs-axion cosmological relaxation

Graham, Kaplan, Rajendran '15





Hierarchy problem solved
by light weakly coupled new physics
and not by TeV scale physics

need to make sure that
the relaxion doesn't overshot the bumps
need friction to absorb its kinetic energy when rolling down its potential
Hubble expansion: energy makes the Universe expanding

Phenomenological signatures

Nothing to be discovered at the LHC/ILC/CLIC/CepC/SppC/FCC!

only BSM physics below Λ

two (very) light and very weakly coupled axion-like scalar fields

$$m_\phi \sim (10^{-20} - 10^{2})\,\mathrm{GeV}$$

$$m_\sigma \sim (10^{-45} - 10^{-2})\,\mathrm{GeV}$$

interesting signatures in cosmology

The hierarchy problem made easy

only a few eletrons are enough to lift your hair (~ 10^{25} mass of e^-)

the electric force between 2 e^- is 10^{43} times larger than their gravitational interaction

we don't know why gravity is so weak?

ie we don't know why the masses of particles are so small?

Several theoretical hypothesis

new dynamics? new symmetries? new space-time structure?

modification of special relativity? of quantum mechanics?

The quest for BSM...

So in this [~~election~~ quest] , we cannot sit back and hope that everything works out for the best. We cannot afford to be tired, or frustrated, or cynical. No, hear me – between now and [~~November~~ the next discovery], we need to do what we did [~~eight years ago and~~] four years ago: We need to knock on every door. We need to get out [every vote bit of data]. We need to pour every last ounce of our passion and our strength and our love for [~~this country~~ physics] into [~~electing Hillary Clinton as President of the United States of America~~ understanding Nature and discovering new physics.]

freely inspired from M. Obama

(Philadelphia, July 25, 2016)

One day, one of you might be in his position...

B. Clinton, Davos 2011

Hopefully, that day you'll remember
what you have learnt during your stay at CERN

Thank you for your attention.
Good luck for your studies!

if you have question/want to know more

office hours: main auditorium, wednesday July 27, 6pm