A Higgs-Eye View of the Cosmos

Joint Annual Meeting of SPS and ÖPG

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A Higgs-Eye View of the Cosmos

What does cosmology have to do with electroweak symmetry breaking and the Higgs?

$$H$$

Why might the Higgs lead us to understand:

- The nature of dark matter?
- The origin of the matter-antimatter imbalance?
- The ultimate fate of the Universe?

And recent theoretical ideas on how cosmology may explain the origin of the Higgs mass...

Out in the Fields

Whether in the laboratory or the cosmos, we model nature with fields

Here we will only consider bosonic fields, with no associated direction (scalars).

Out in the Fields

Whether in the laboratory or the cosmos, we model nature with fields

5 years ago at the LHC fluctuations of the only known potentially fundamental scalar field were discovered. The infamous Higgs boson!

(By the way, Happy 5th Birthday Higgs Boson!)

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Out in the Fields

While the human history of the Higgs field is very interesting, the true, cosmological, history of the Higgs field

$$H$$

is a story that ties together the physics of superconductors to the mysteries of the origins of matter in the distant past and even determines the ultimate fate of the Universe.

Lets start with the superconductors...

Why are you living inside a Superconductor?

Ginzburg-Landau

- The G-L Theory of superconductivity involves a complex scalar field and the photon (magnetic vector potential)

$$\Phi \qquad\qquad A$$

- The Free energy for this theory is

$$F = |(\nabla + 2ieA)\Phi|^2$$

$$+m^2(T)|\Phi|^2 + \lambda|\Phi|^4 + \ldots$$

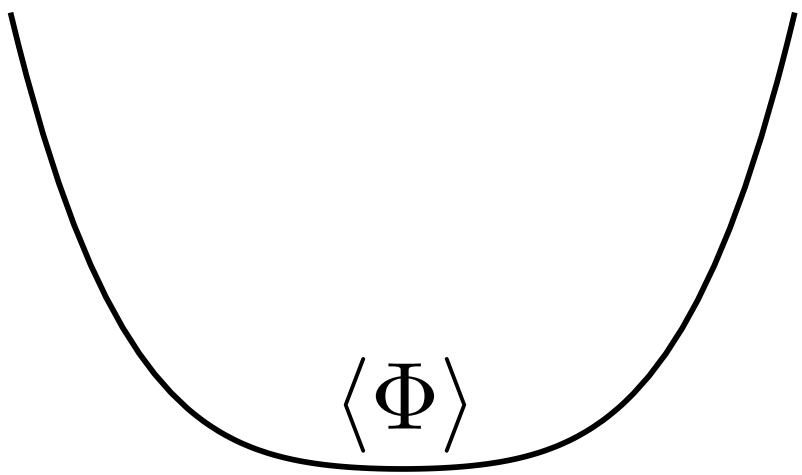
- Where the mass depends on the temperature.

Ginzburg-Landau

$$F = |(\nabla + 2ieA)\Phi|^2$$

$$+m^2(T)|\Phi|^2 + \lambda|\Phi|^4 + \ldots$$

- At high temperatures the mass-squared is positive:



- Just a hot metal.

Ginzburg-Landau

$$F = |(\nabla + 2ieA)\Phi|^2$$

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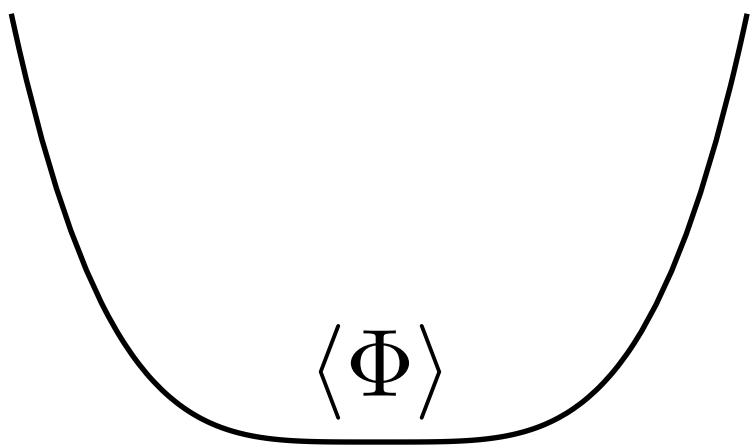
- At the critical temperature the mass-squared vanishes:



- Strange theory with massless fluctuations.

Ginzburg-Landau

$$F = |(\nabla + 2ieA)\Phi|^2$$

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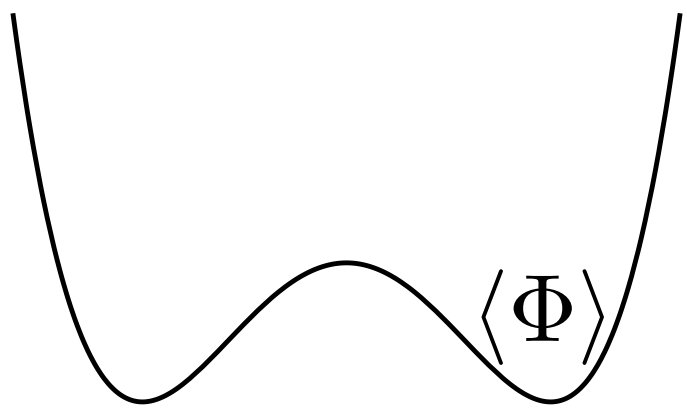
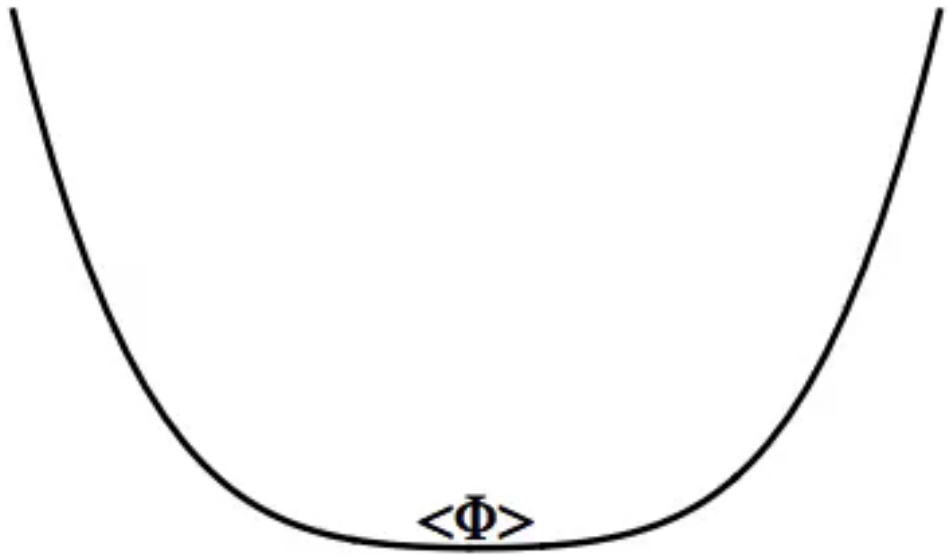
- Below the critical temperature the mass-squared is negative:



- Photon has become massive: $m_A \sim e\langle\Phi\rangle$

Ginzburg-Landau

- Thus a simplified theoretical picture of a superconductor going through the critical temperature is



- Where in the lab we may control T.

What does this have to do with the Higgs Boson?

Higgs Mechanism

- The Higgs sector of the Standard Model involves the Higgs field and the gauge fields

$$H \qquad\qquad W_\mu^a$$

- The Lagrangian for this theory is

$$\mathcal{L} = \left|(\partial_\mu + ig\sigma^a W_\mu^a)H\right|^2$$

$$-m^2(T)|H|^2 - \lambda(T)|H|^4 + \ldots$$

- This is just the relativistic non-Abelian version of Ginzburg-Landau.

Higgs Mechanism

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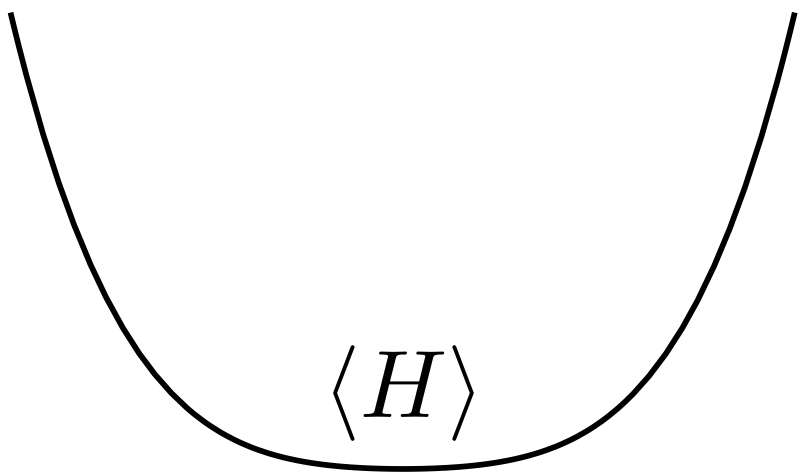

- Just a hot relativistic gas.

Higgs Mechanism

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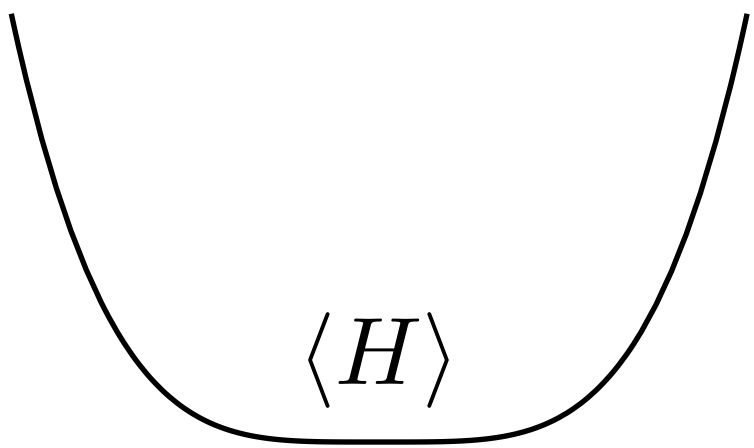

- Higgs boson is massless at this point.

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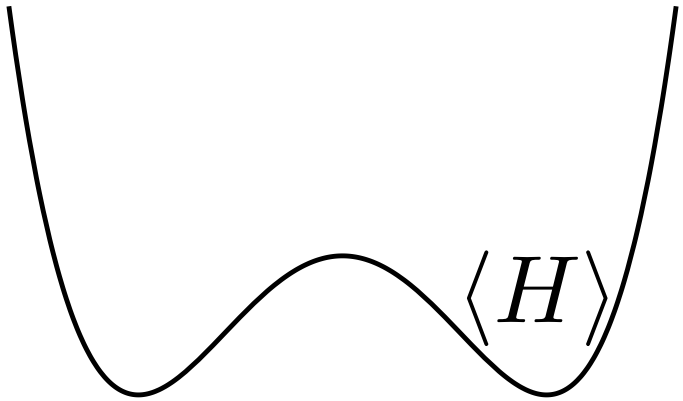
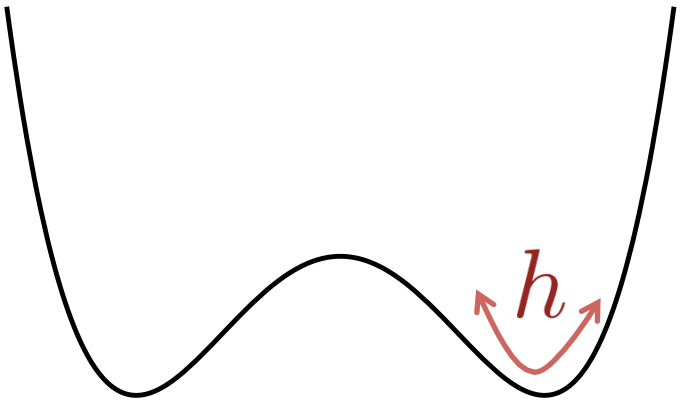


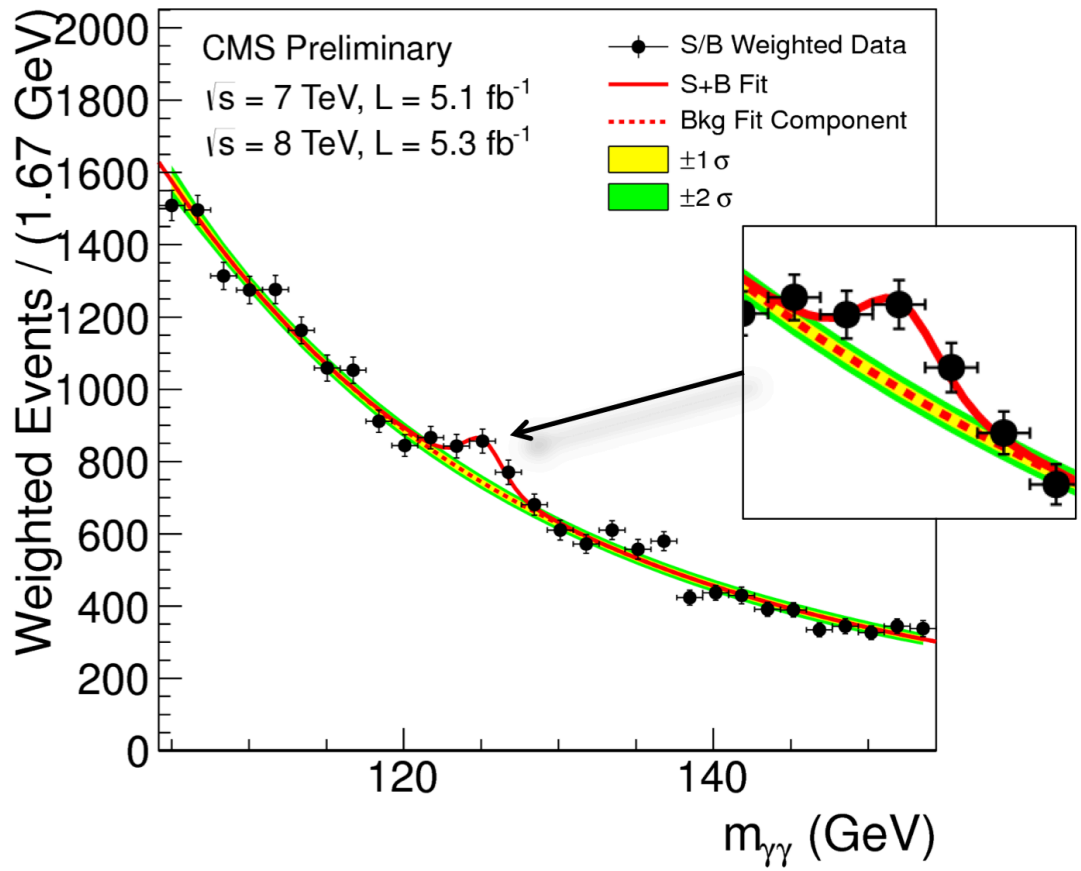
- Gauge bosons become massive: $M_W \sim g\langle H \rangle$

Thus the Higgs sector of the Standard Model is a relativistic superconductor!

Introducing Mr Higgs.

The physical excitations of the Higgs field correspond to the Higgs boson:



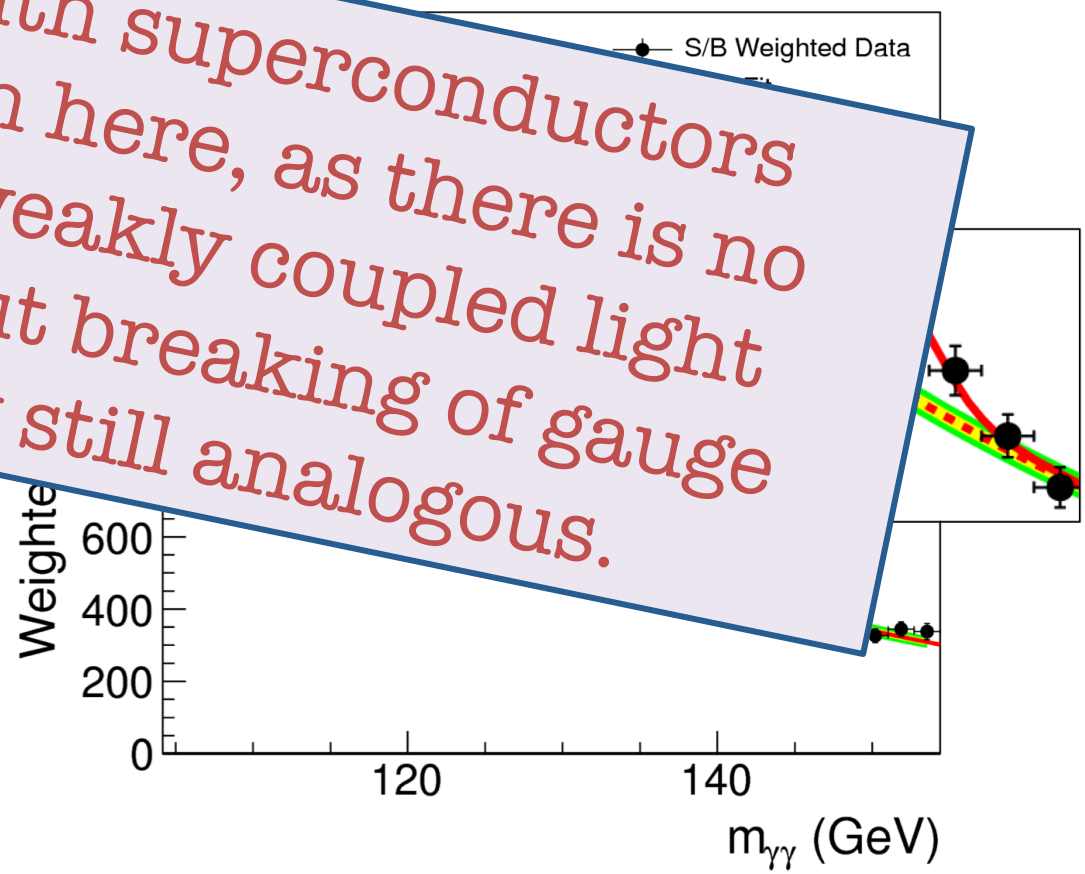


The discovery of this excitation put the entire Standard Model Higgs sector on a very firm footing. Allows us to deduce the quartic interactions (assuming the Standard Model).

Introducing Mr Higgs.

The physical excitations of the Higgs field cor[illegible]ed to the Higgs boson:

Analogy with superconductors breaks down here, as there is no analogous weakly coupled light excitation, but breaking of gauge symmetry still analogous.



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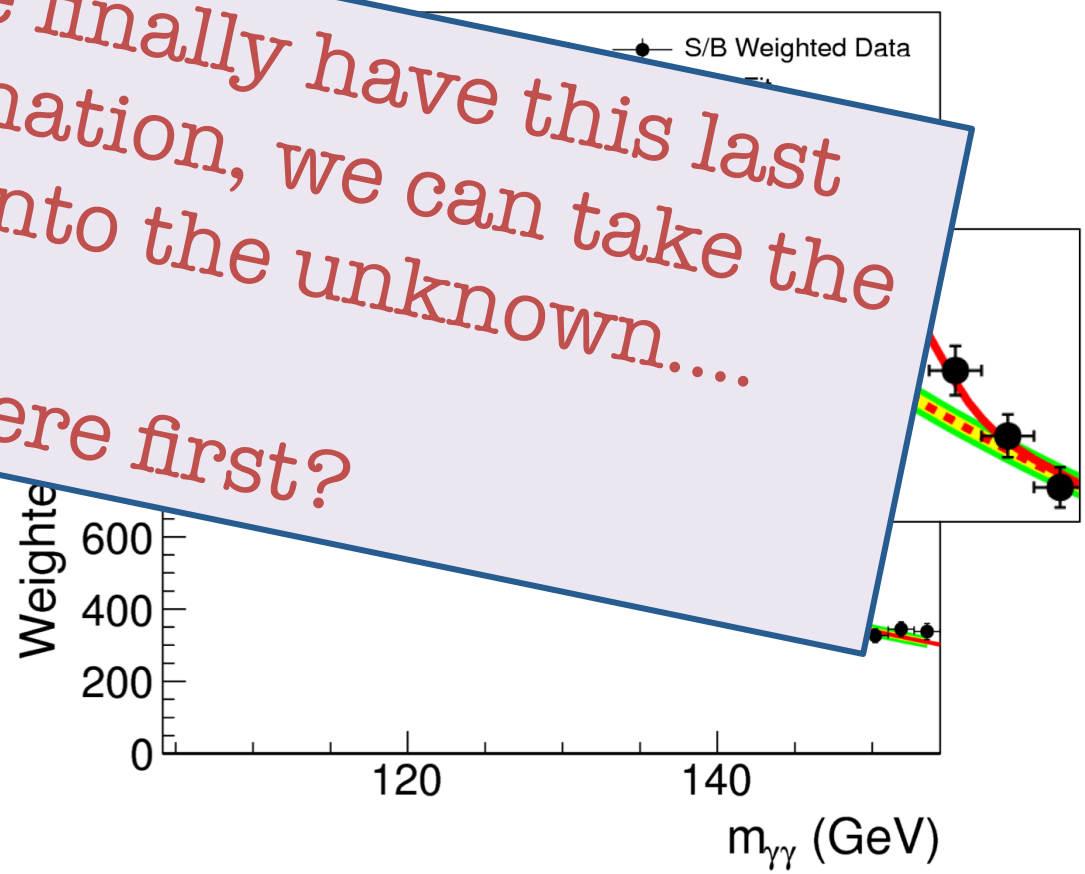
Introducing Mr Higgs.

The physical excitations of the Higgs field cor[illegible]d to the Higgs boson:

Now that we finally have this last piece of information, we can take the next steps into the unknown....

Where first?



The discovery of this excitation put the entire Standard Model Higgs sector on a very firm footing. Allows us to deduce the quartic interactions (assuming the Standard Model).

Dark Times

Evidence for dark matter is now overwhelming

- Rotation curves
- CMB
- Large scale structure
- Velocity dispersions
- Gravitational lensing (Bullet Cluster)
- ....

Yet we have no clue what it is at the particle level!

?

Dark Times

The Higgs portal term is the <u>only renormalizable</u> interaction between a Standard Model particle and a new <u>stable</u> neutral particle

$$\lambda |H|^2 X^2$$

This property is known as the “Higgs Portal”. Since we know other stable neutral particles exist (Dark Matter) then the Higgs portal could be the only window into the dark sector!

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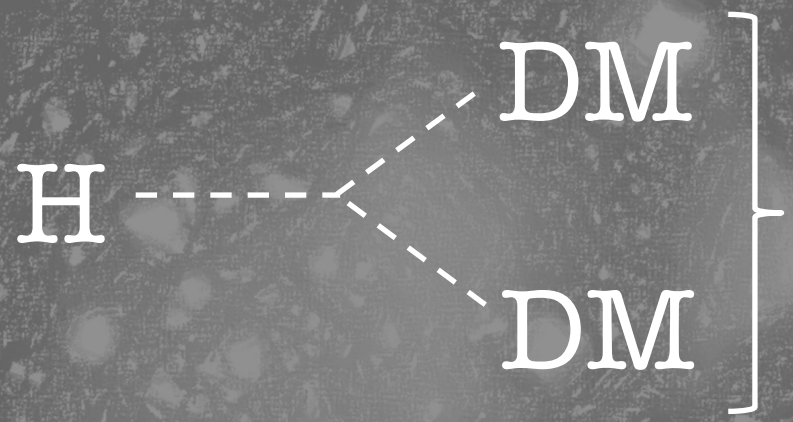
Dark Times

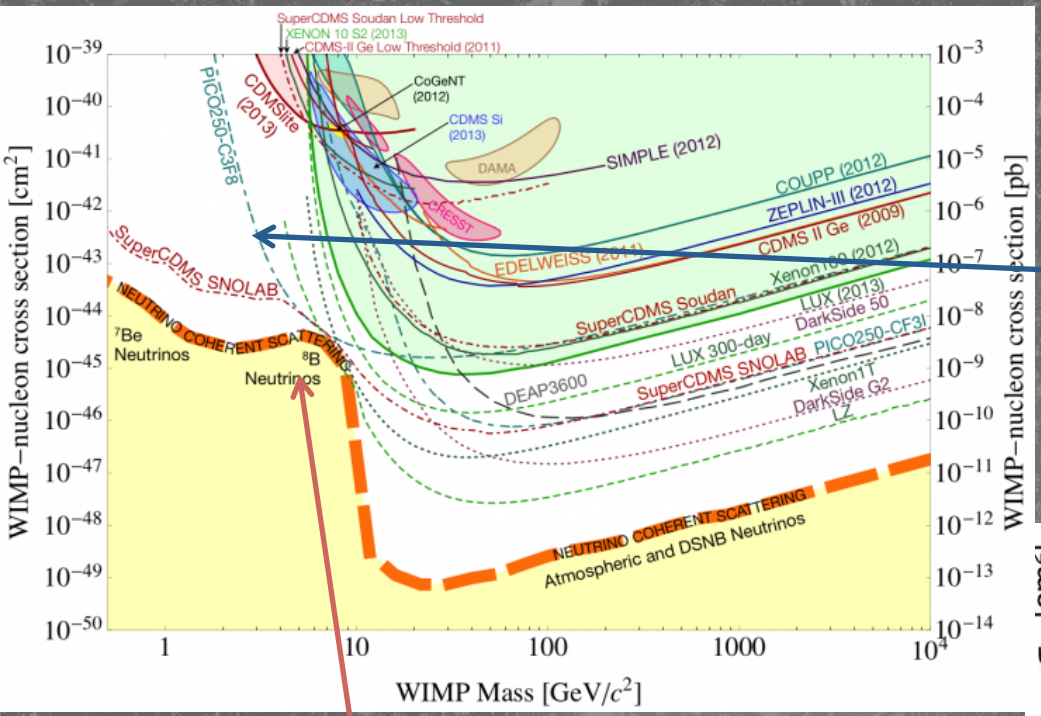
This means that we can search for new dark sector states by searching for exotic Higgs decays



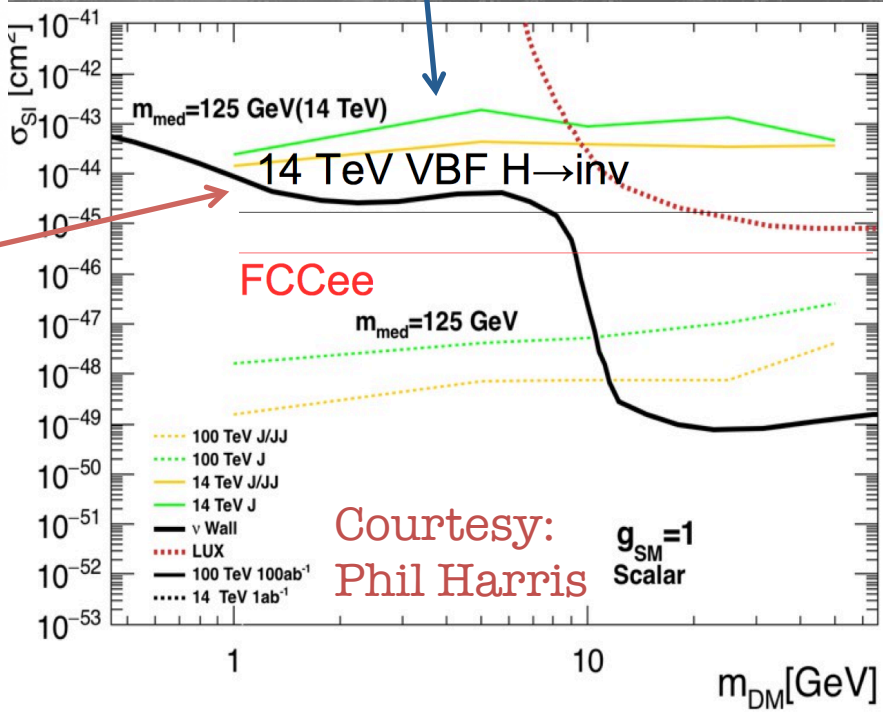
We don't know what's out there, but there is something, and the Higgs is a great place to look.

Or other quantum modifications of Higgs properties

A Portal to Hidden Worlds...



LHC Searches can cover otherwise difficult territory in the search for Higgs boson interactions with dark matter.



The laboratory search for dark matter will hit a difficult background, called the "neutrino floor".

A Portal to Hidden Worlds...

It's not guaranteed, but there is good reason to believe some of the dark sector may show it's face first through the Higgs portal.

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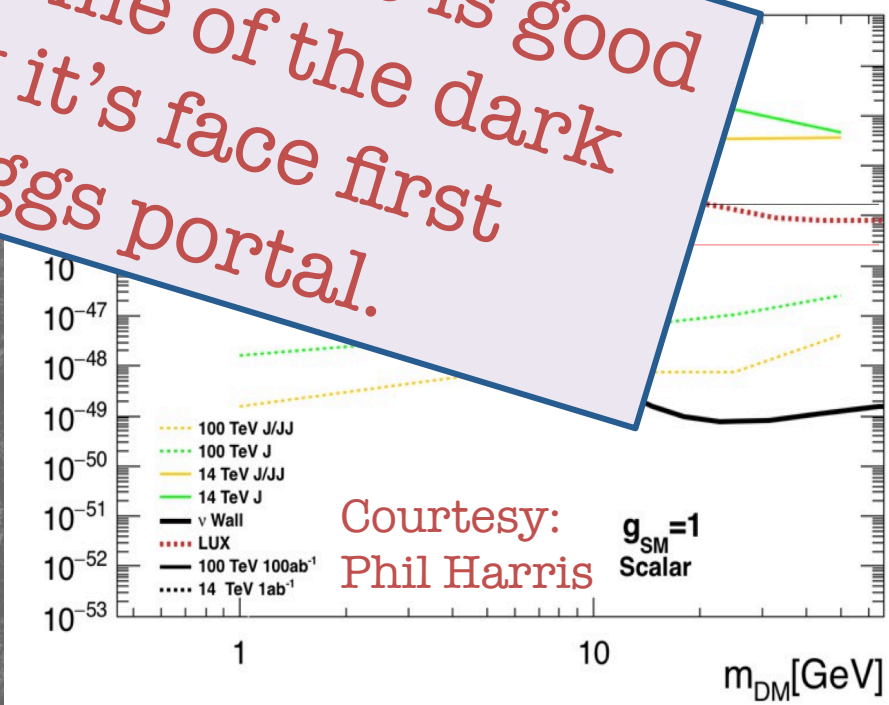


Courtesy: Phil Harris

What's the Matter?

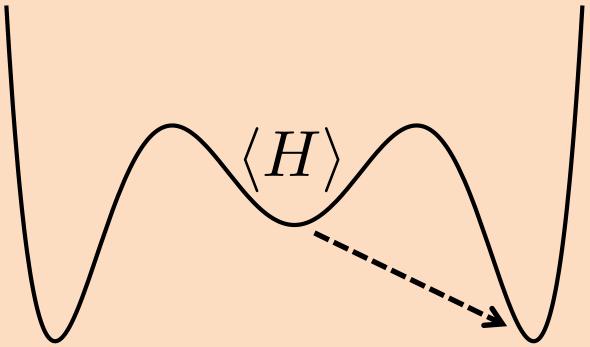
To generate more matter than antimatter, would have to satisfy Sakharov conditions:

I demand:

- Baryon-number violation
- CP-violation
- Out-of-equilibrium processes

If the phase transition had been strongly first order we could have satisfied these conditions.

But it was not (we think) ...



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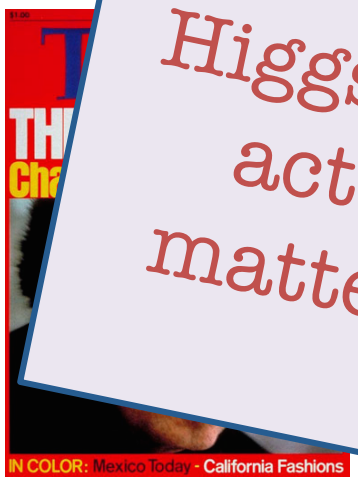

Relatively minor modifications of the Higgs sector of Standard Model can actually generate the observed matter-antimatter imbalance. I.e. You and me!

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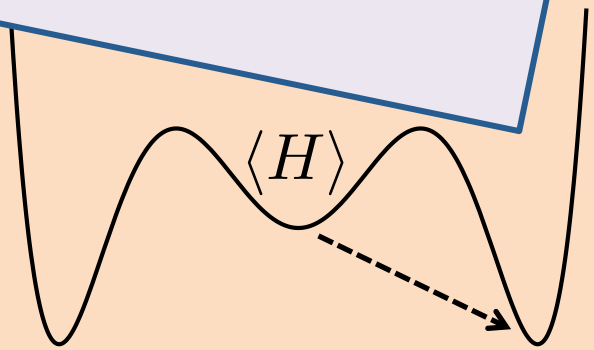


The Elephant in the Room

Ginzburg-Landau is just a phenomenological model, with no explanation of parameters. The macroscopic parameters follow from the detailed microscopic BCS theory (Gor'kov) and there are no surprises.

The order parameter at zero temperature is of the typical scale associated with underlying microscopic parameters.

The Elephant in the Room

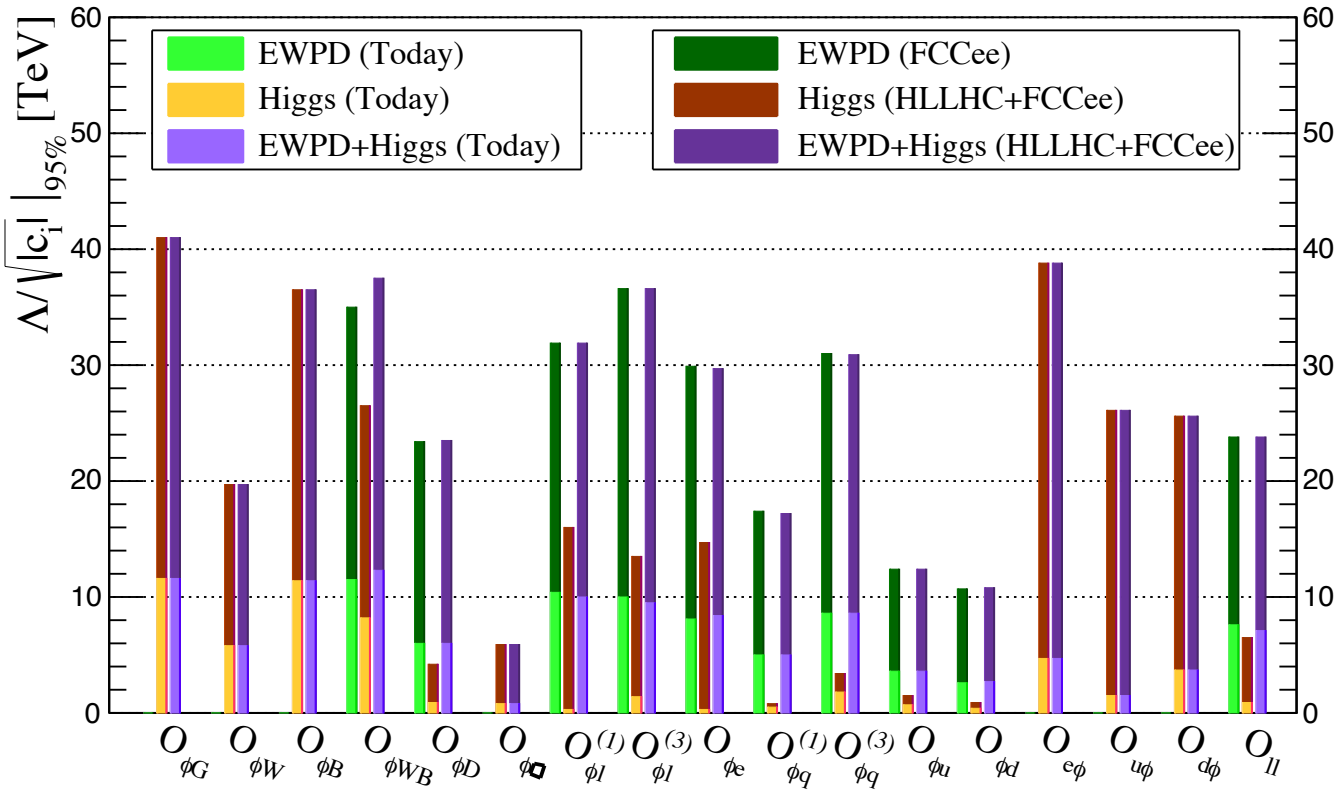
Performing the same exercise with the Higgs field.

We can look to see if the symmetry breaking is like Ginzburg-Landau

- Direct analogy, would have no light Higgs boson: Experimentally excluded.
- Perhaps not directly analogous, but similar composite story: Study the Higgs...

The size of the Higgs boson...

- Probing deep into the Higgs boson. Light purple lines show current constraints.



Measurements are different ways of probing the "compositeness of the Higgs".

No substructure has yet shown up...

$$\lambda_h \approx 10^{-17}\ \mathrm{m}$$

$$\lambda_{10\ \mathrm{TeV}} \approx 10^{-19}\ \mathrm{m}$$

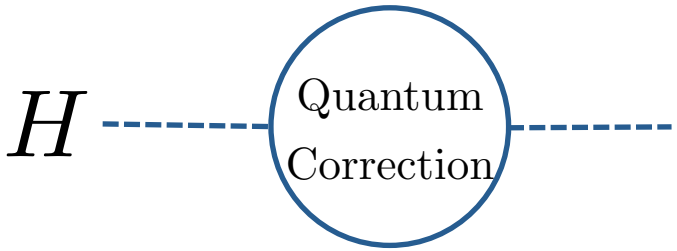
The Elephant in the Room

We expect the Higgs model is phenomenological, just like G-L. But something totally different seems to be going on.

There is a hierarchy between the model parameters and the microscopic parameters. Furthermore, this hierarchy is not protected by any symmetry: Quantum corrections do not respect such a hierarchy.

The Elephant in the Room

- Microscopic theory at high energy.
- If states couple to the Higgs Boson:



$$\rightarrow m_H^2 \sim \text{Loop} \times \Lambda_{NP}^2$$

- If $\Lambda_{NP} \gg \text{TeV}$ then howcome 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!

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

The Elephant in the Room

- Microscopic theory at high energy.
- If states couple to the Higgs Boson:

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

But this requires fine-tuning the fundamental parameters. Why would nature do that?

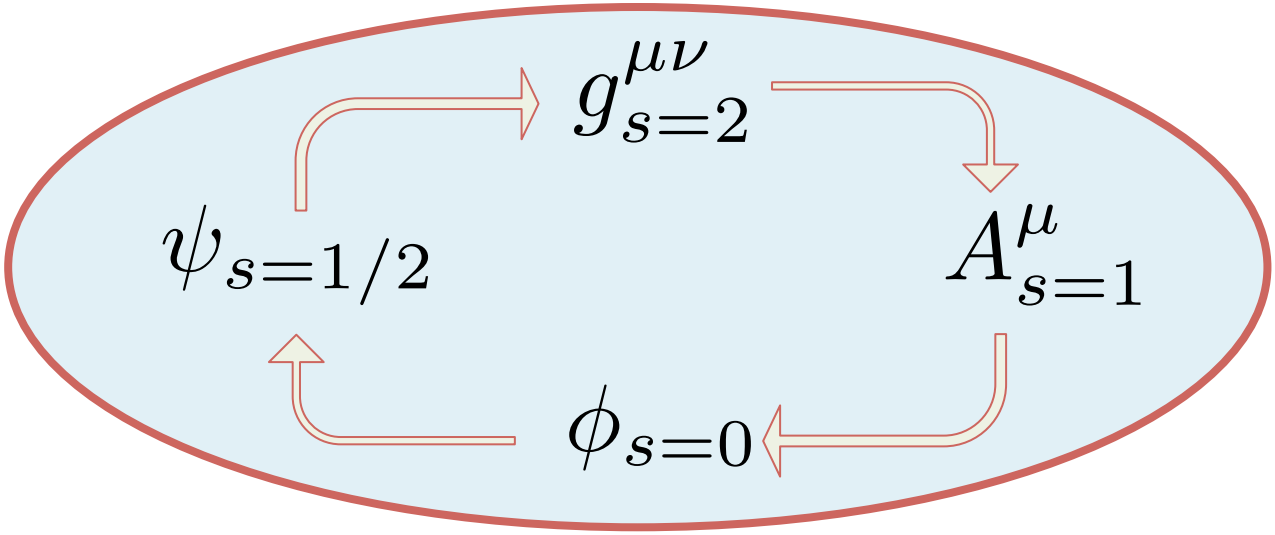
- If $\Lambda_{NP} \gg$ ... ss, and the weak scale are ...
- One answer: $V_H = \widetilde{M}_H^2 |H|^2 + \Lambda_{NP}^2 |H|^2$

HUGE! HUGE!

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

Circa 1980's

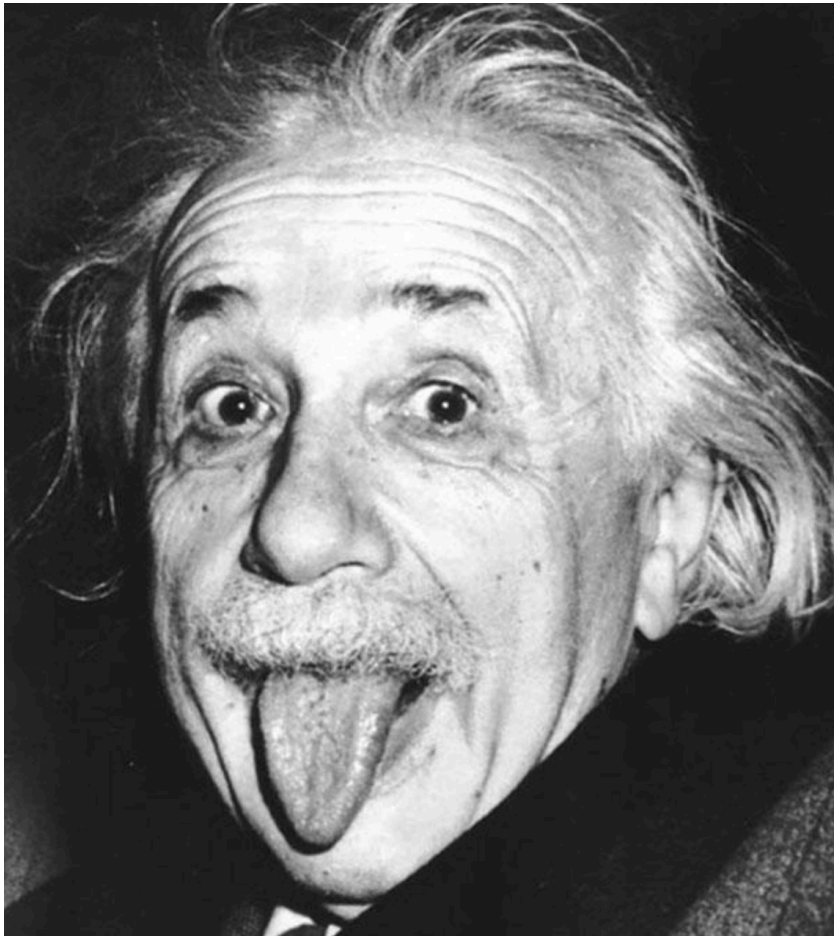
Problem solved! An entirely new spacetime symmetry, Supersymmetry, protects the Higgs!



Unifies fields into superfields, transforming into one another! Most important component: The "Stop Squark". The heavier, the more fine-tuned...

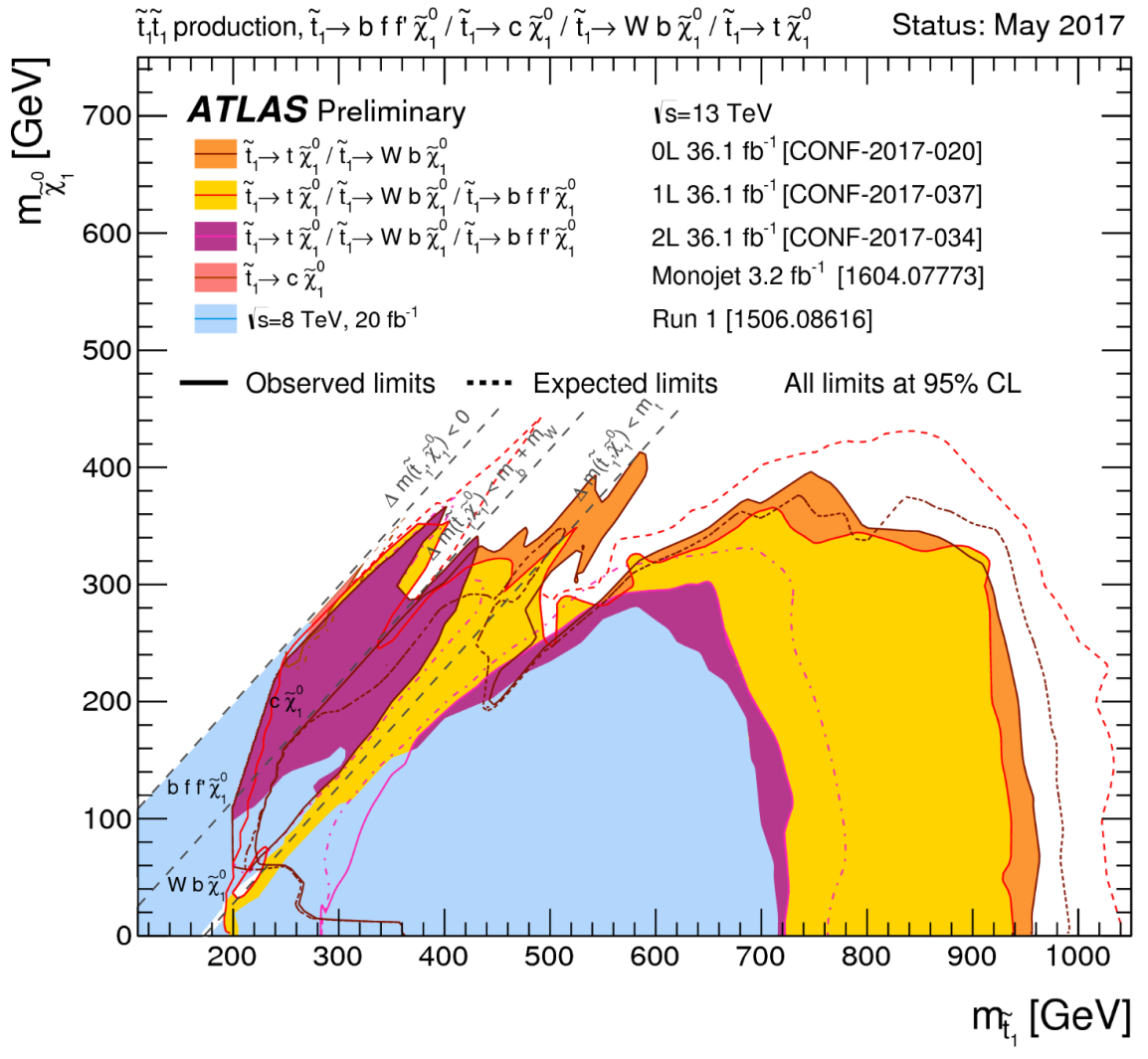
Supersymmetry

The last time a spacetime symmetry was discovered...



The ... etry

However...



Someone didn't show up to the party... yet...

Circa 1980's

<u>Problem solved</u>! The Higgs boson is like a pion, naturally light because of spontaneously broken global symmetry!

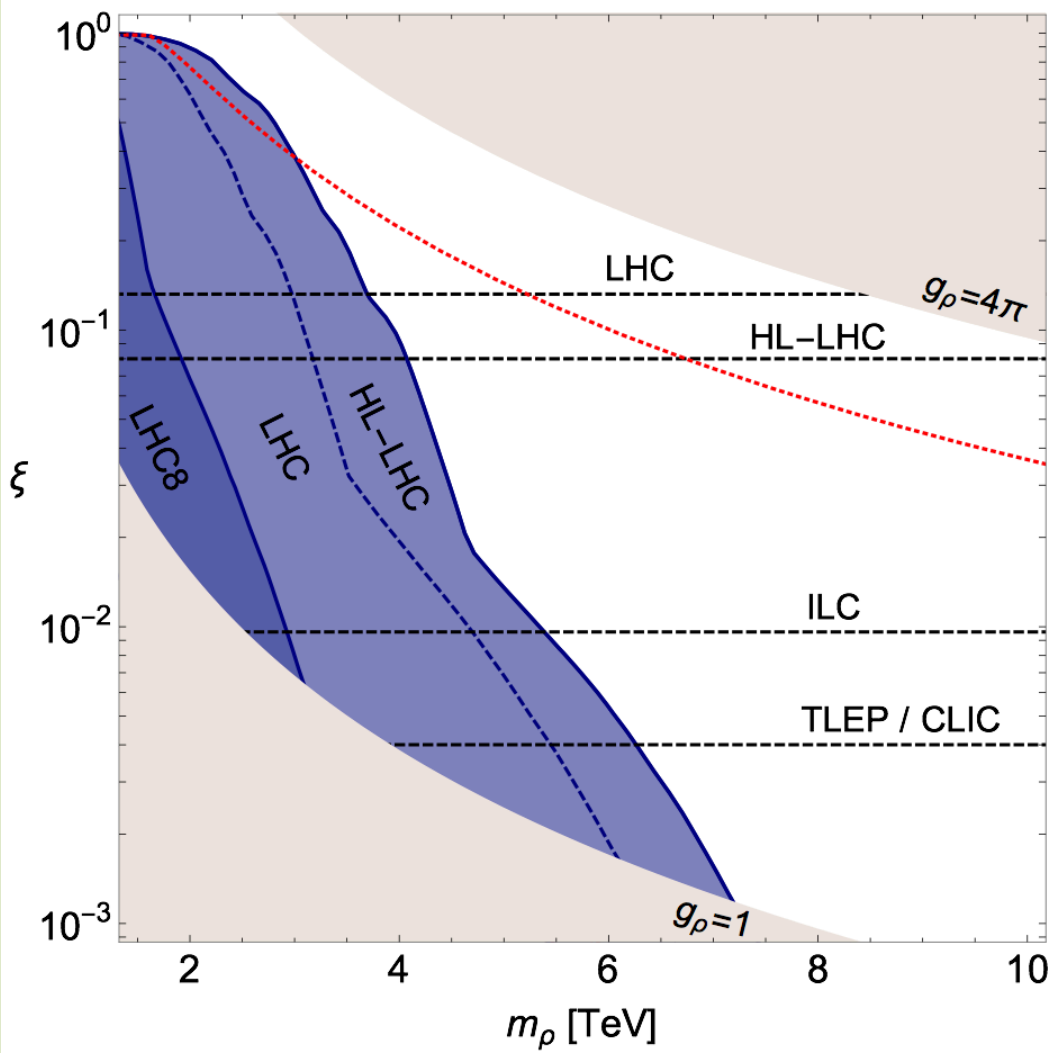
$$H = \bar{f} f \sim f \qquad \xi \sim \frac{v^2}{f^2}$$

Then no hierarchy problem, since no fundamental scalar! Realise the Higgs boson analogously to the pion in QCD.

$$\rho = \bar{f} f \sim \Lambda$$

Should also get other heavy resonances then!

However...



Someone didn't show up to the party...
yet...

Problem ... ion,
natural ... oken
global s ...

$$\frac{v^2}{f^2}$$

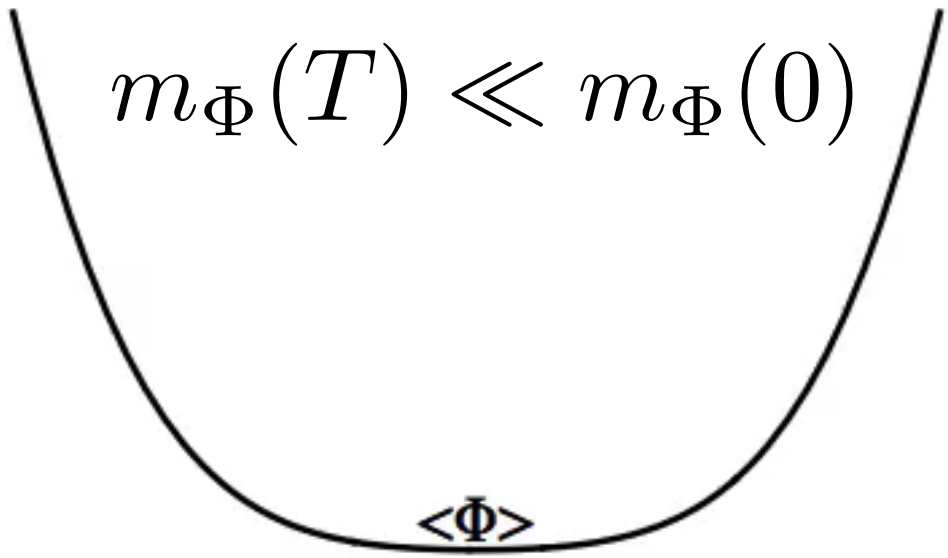
Then n ... mental
scalar! ... to the
pion in ...

Should ... !

Ok, so back to fine-tuning...

Analogous to taking a superconductor and fine-tuning the temperature to just at the phase transition, such that

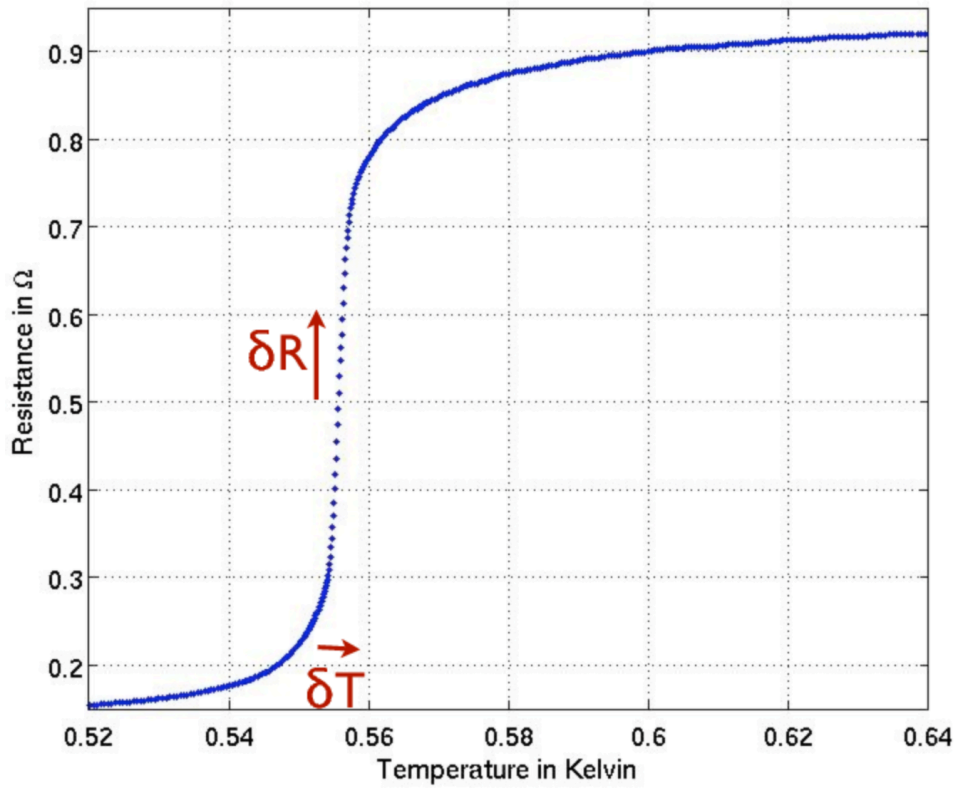
$$m_\Phi(T) \ll m_\Phi(0)$$



It can exist, physically, and we can tune parameters in a lab, but why would nature?

Back to Fine-Tuning

Essentially, it seems like the Universe is just like a Transition Edge Sensor:



- Taken from 1309.5383

A tiny change of fundamental parameters would completely change the weak scale!

Back to Fine-Tuning

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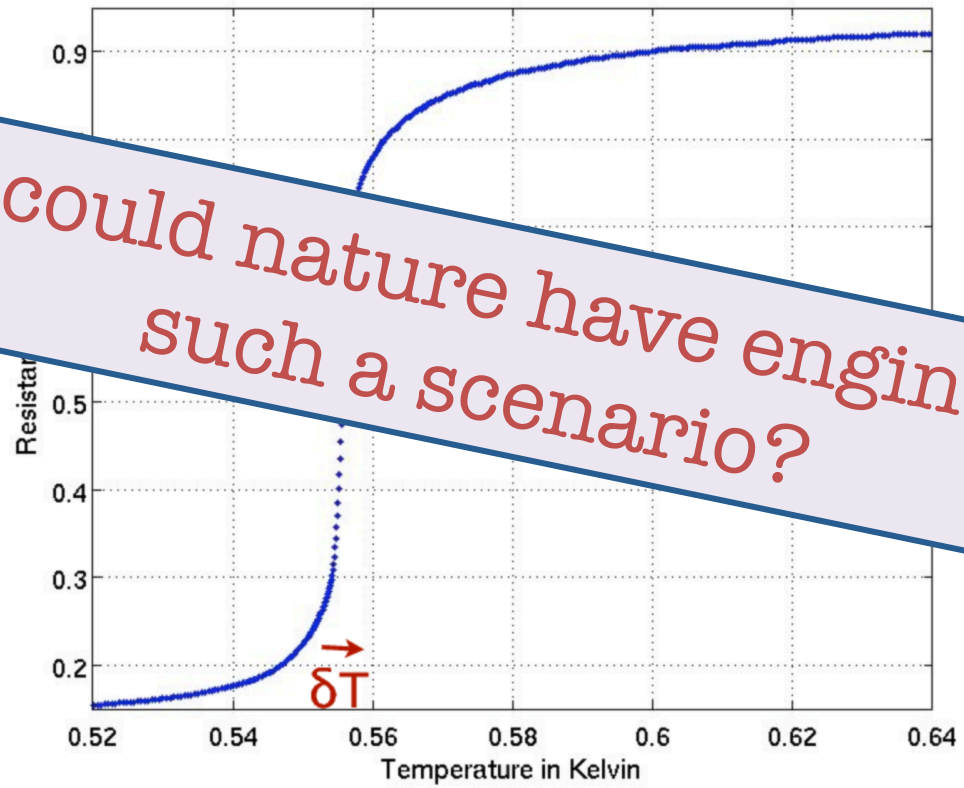


How could nature have engineered such a scenario?

- Taken from 1309.5383

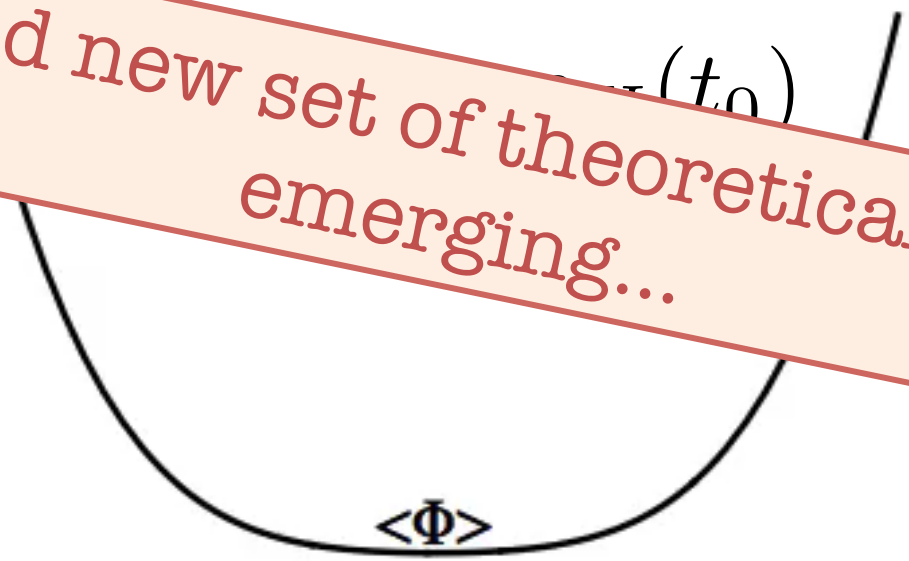
A tiny change of fundamental parameters would completely change the weak scale!

The Relaxion

- Graham, Kaplan, Rajendran, 2015

Rather than fighting with this conundrum, maybe embrace it? Perhaps this is precisely what happened in the early Universe?

Brand new set of theoretical ideas emerging...



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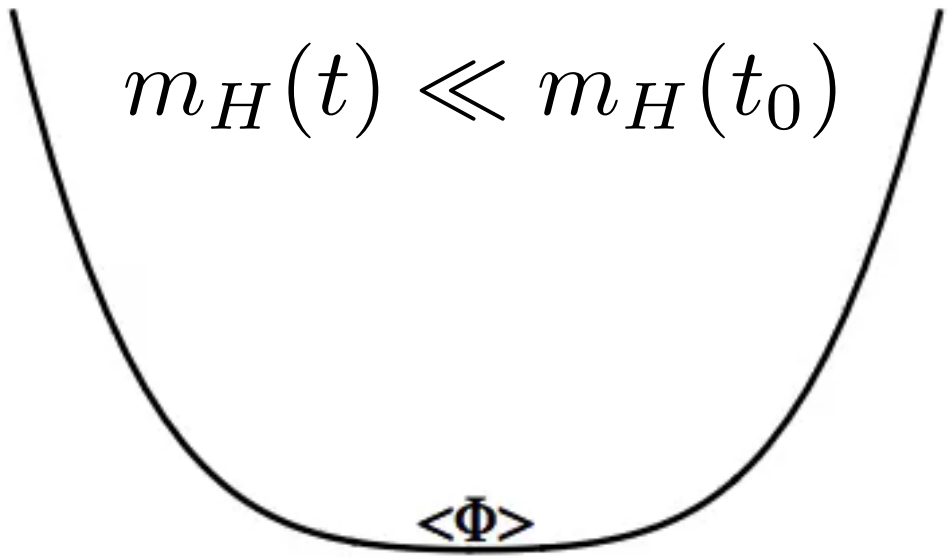


How could this have happened in the primordial Universe?

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- Radically different take on the hierarchy problem.
- Basic ingredients: Add a new scalar field.

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 wants to roll due to small terms in potential

Relaxion couples to gluons.

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

The Relaxion

- Graham, Kaplan, Rajendran, 2015

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

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

$$-gM^2\phi$$

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

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

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

Then axion potential turns on and Relaxion stops rolling

$$-gM^2\phi$$

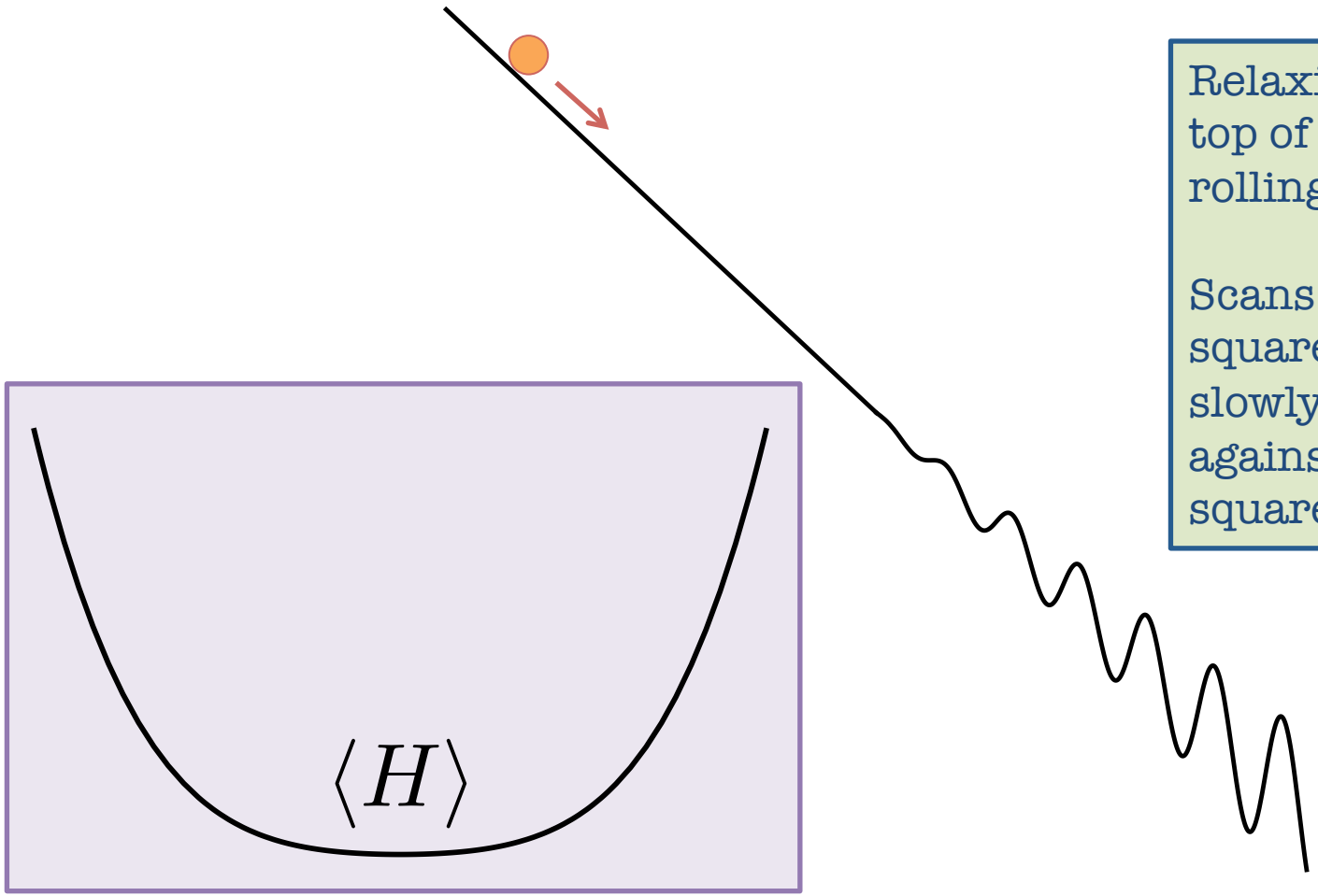
In early Universe Relaxion rolls

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

The Relaxion

- Graham, Kaplan, Rajendran, 2015

- Cosmological evolution



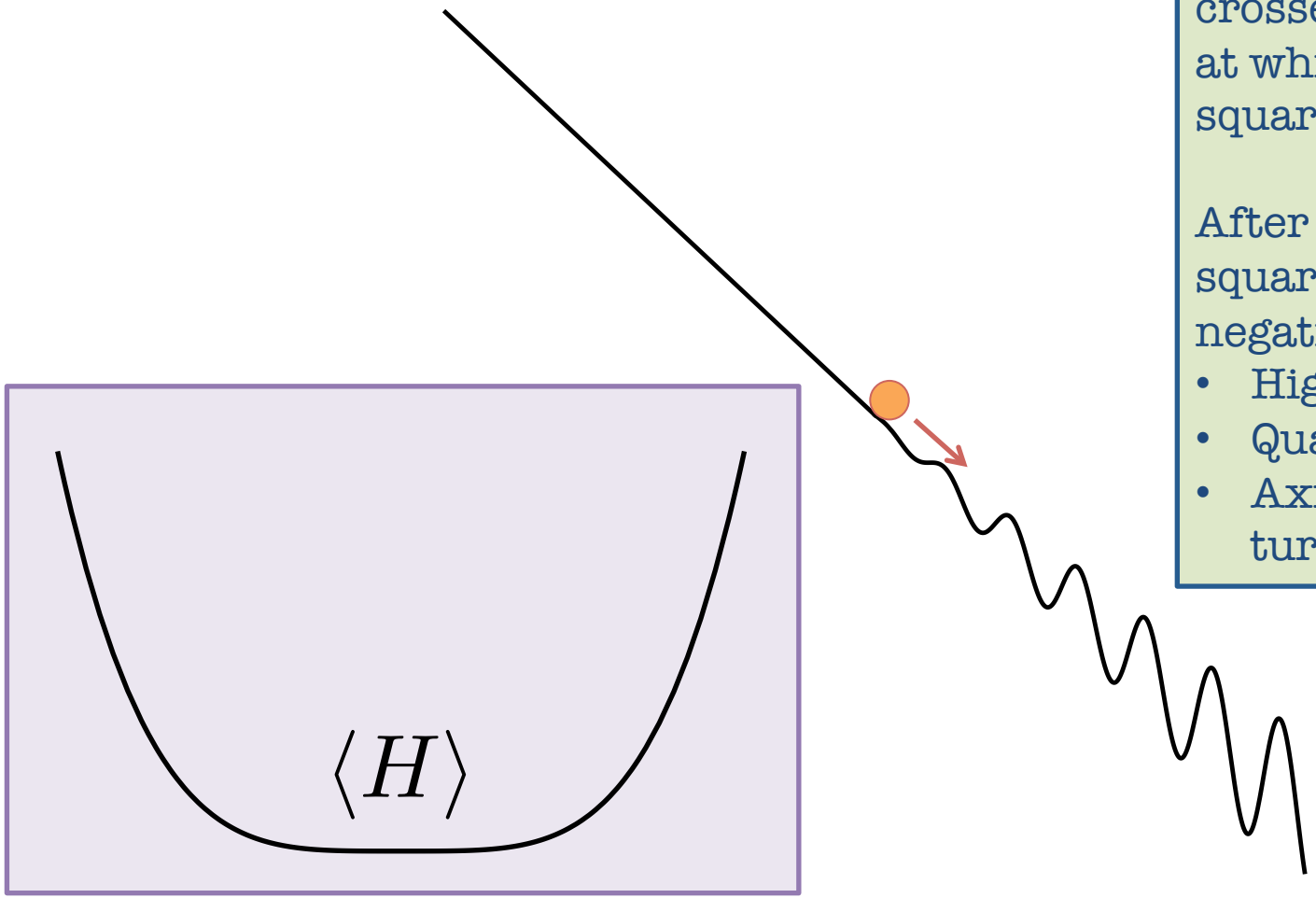
Relaxion starts at the top of potential. Starts rolling down.

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.

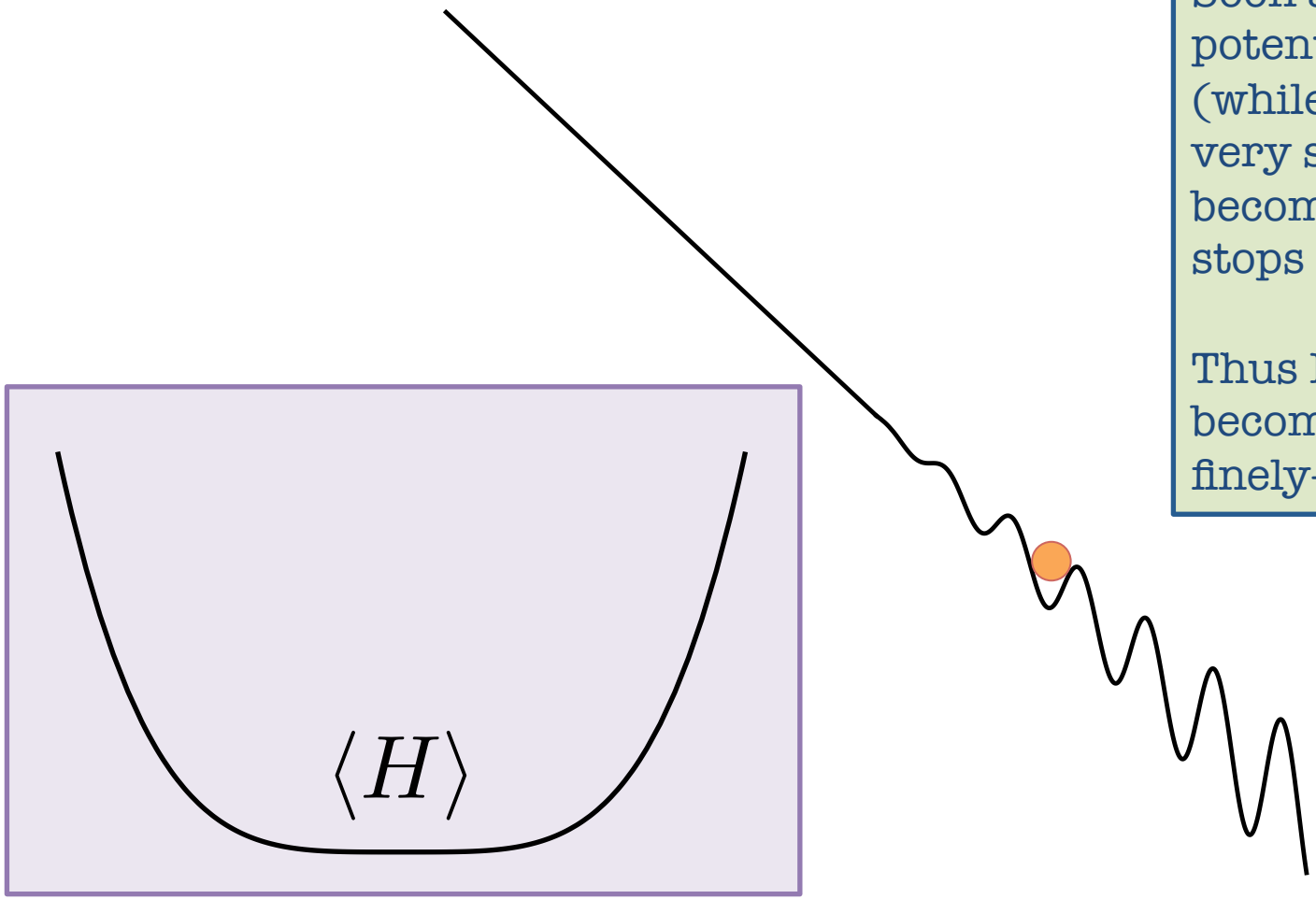
After this mass-squared becomes negative:

- 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.

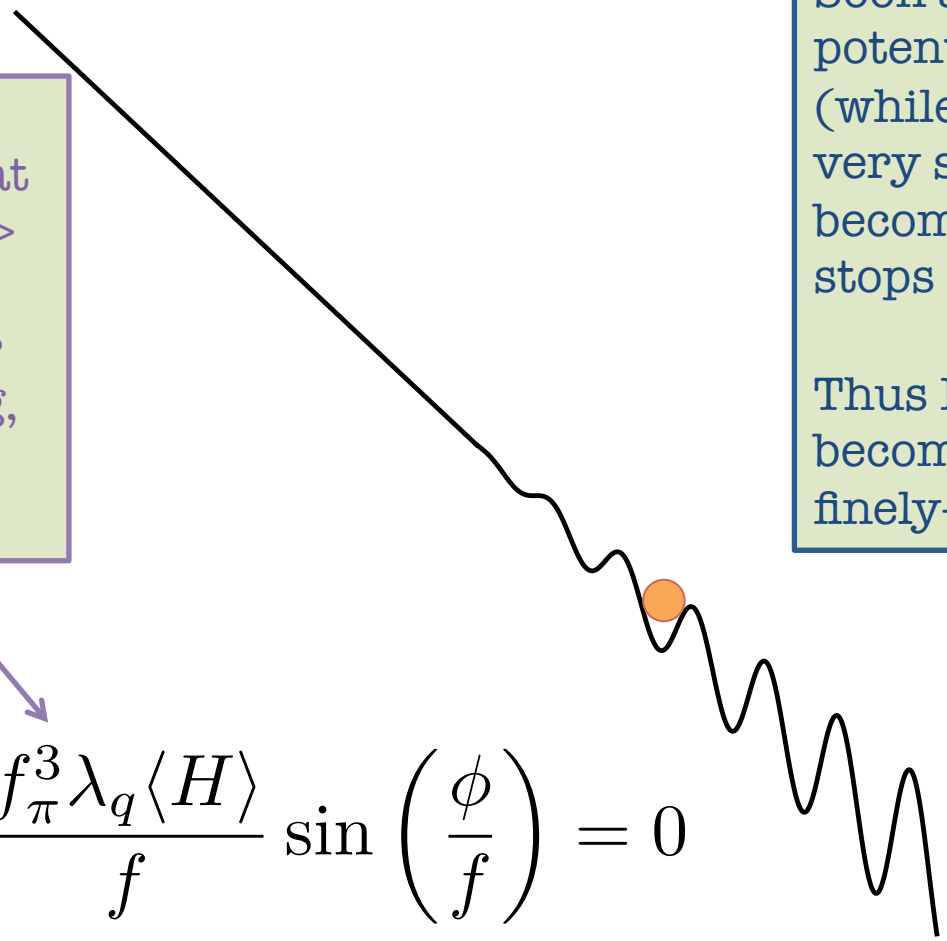
Thus Higgs vev becomes stuck at this finely-tuned point!

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.



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$$\frac{\partial V}{\partial \phi} \sim gM^2 - \frac{f_\pi^3 \lambda_q \langle H \rangle}{f} \sin\left(\frac{\phi}{f}\right) = 0$$

The Relaxion

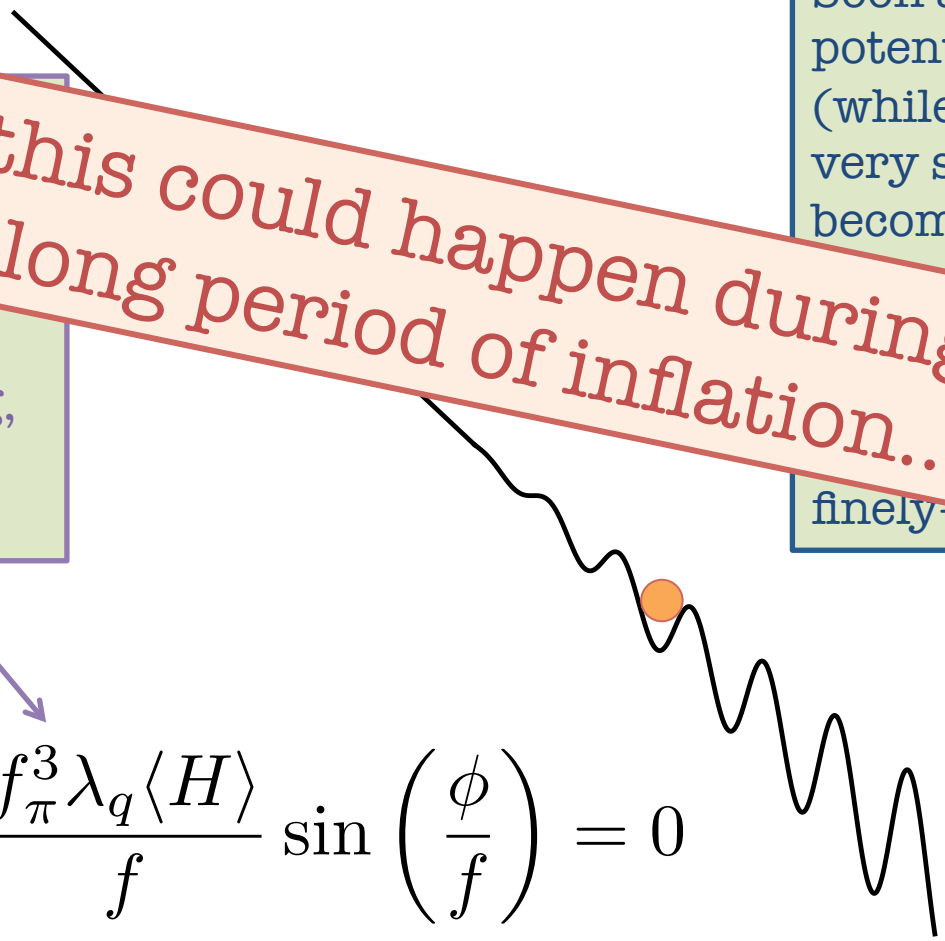
- Graham, Kaplan, Rajendran, 2015

- Cosmological evolution

Can cho
param
field st
is still very small.
This is a parameter choice, not a tuning, since radiatively stable.

All of this could happen during a very long period of inflation...

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



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The Relaxion

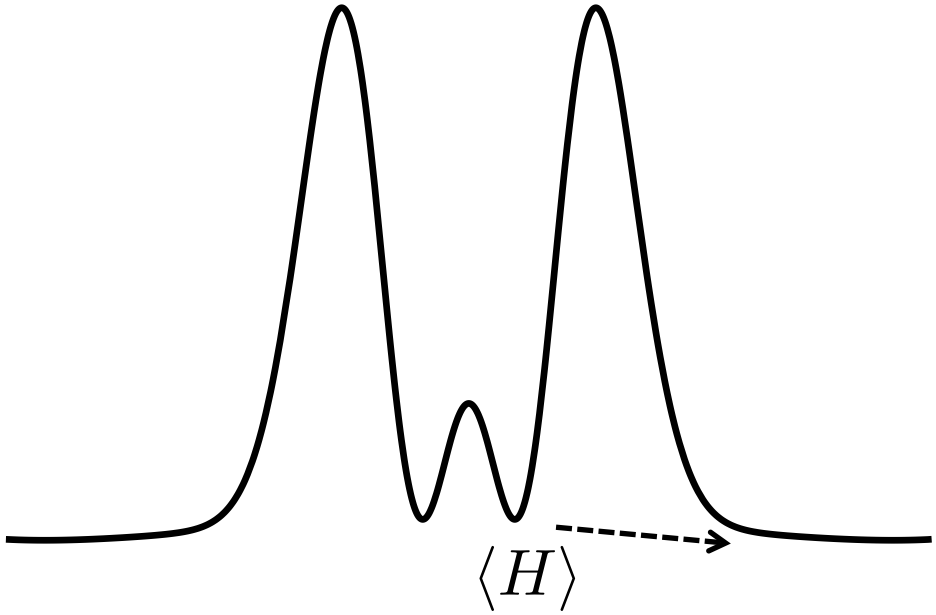
- Graham, Kaplan, Rajendran, 2015

This theory is not fully fleshed out yet, and there are many details to work out, but it is the first example of a scenario wherein cosmological dynamics explains a finely-tuned electroweak scale.

Watch this space...

The End of the Universe

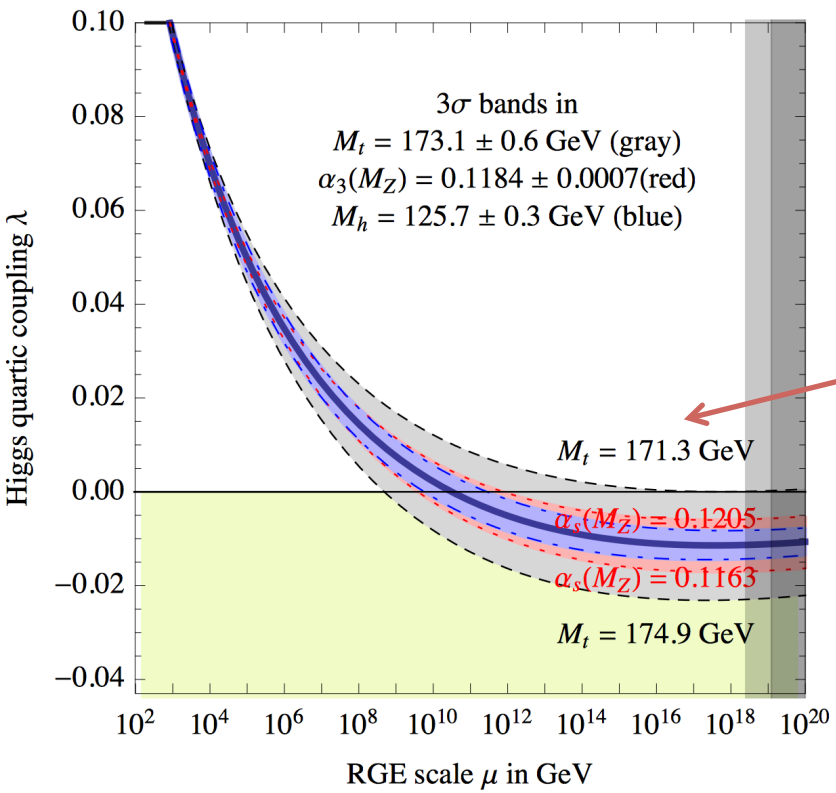
To finish our cosmological exploration of the weak scale, let's look to the distant future...

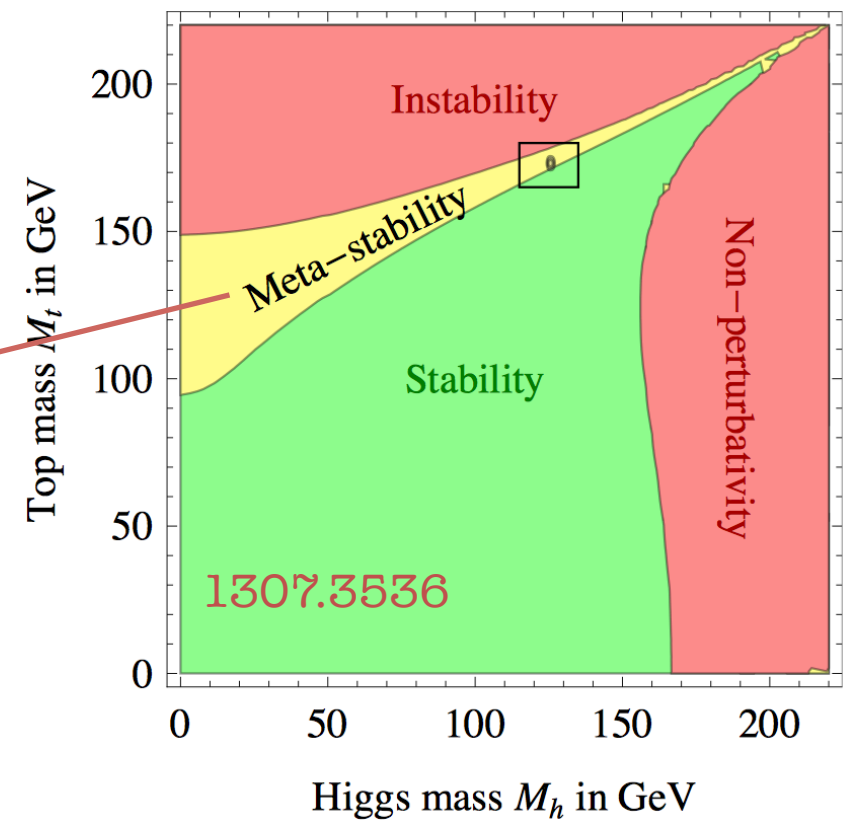


The Higgs potential may have yet another minimum that I wasn't telling you about. May be at lower energies...

The fate of the Universe...

The Higgs potential has another minimum...

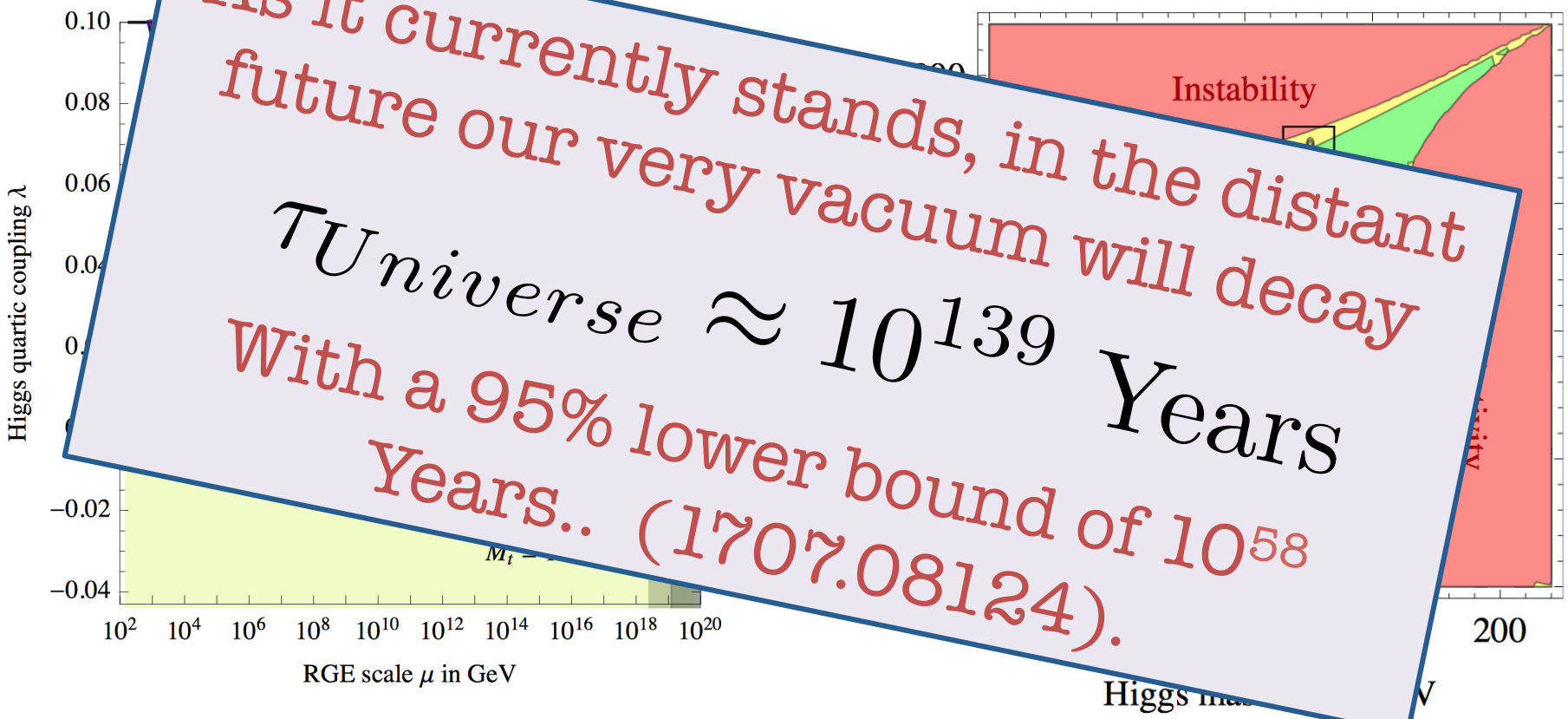




From current LHC measurements it looks like our current location on the Higgs potential is unstable!

The fate of the Universe...

The Higgs potential has another minimum...



As it currently stands, in the distant future our very vacuum will decay

$$\tau_{Universe} \approx 10^{139} \text{ Years}$$

With a 95% lower bound of 10^{58} Years.. (1707.08124).

From current LHC measurements it looks like our current location on the Higgs potential is unstable!

The Truth About the Higgs

Mark Twain: "Truth is stranger than fiction, but it is because Fiction is obliged to stick to possibilities; Truth isn't."

LHC measurements, taken at face value, are suggesting that:

- We live in a (relativistic) finely-tuned superconductor, sitting just at the threshold of the phase transition, in an unstable state, set to decay to a new Universe in the future.

The Truth About the Higgs

The o ew if this is our world is to
meas lar potential.

Mea
mea

All of these questions (microscopic theory of EW symmetry breaking, phase transition, matter-antimatter imbalance, fine-tuning, Higgs portal) boil down to the shape and overall nature of the Higgs scalar potential.

Why don't we just go and measure it?

2

Mass

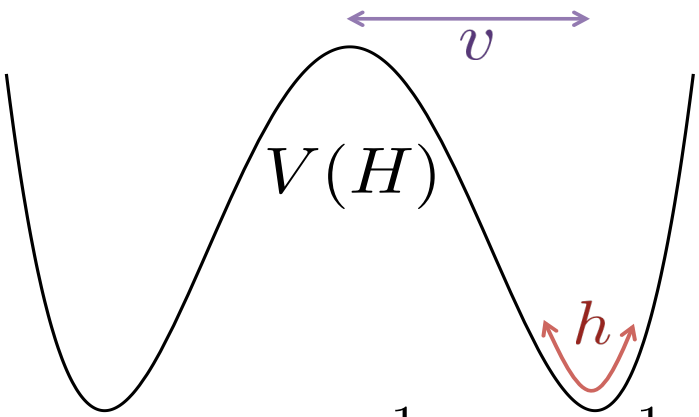
Self Interaction

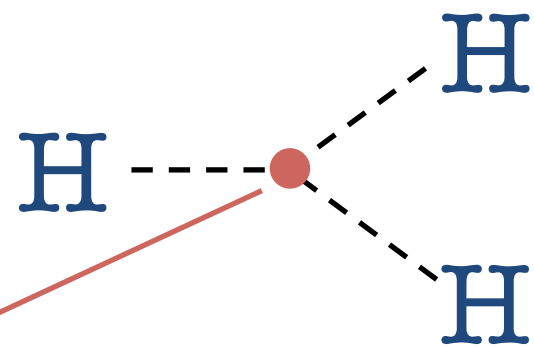
Discovering the Higgs was difficult enough, now we want to know how it behaves in private...

The Truth About the Higgs

The only way to know if this is our world is to measure the shape of the scalar potential.

Measuring the Higgs self-coupling is the only way to measure the structure of the Higgs potential.



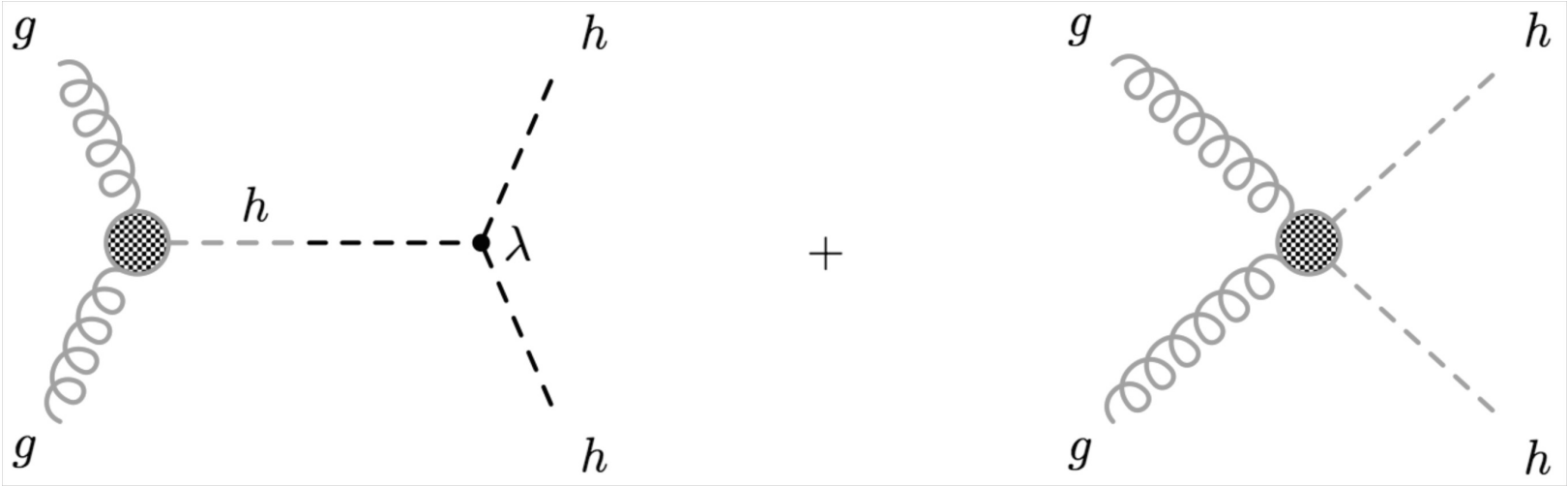


$$\underbrace{\frac{1}{2}m_h^2 h^2}_{\text{Mass}} + \underbrace{\frac{1}{6}\lambda h^3}_{\text{Self Interaction}} + \ldots$$

Discovering the Higgs was difficult enough, now we want to know how it behaves in private...

The Higgs Potential...

At colliders gain sensitivity to self-interactions by searching for pair production:



To robustly measure this we will have to look to future colliders, and only then will we really know the shape of the Higgs potential and the superconducting phase transition!

Back to work.

We now have in our hands a little particle that holds the key to the <u>biggest</u> questions we could ask:

$$H$$

- Where did matter come from?
- What is the microscopic description of EW symmetry breaking?
- What is the ultimate fate of our Universe?
- Maybe even what is the dark matter?*

Back to work.

We are only at the beginning of this story.

To piece together the pieces of the Higgs puzzle we will increasingly have to interface collider measurements with cosmology. The right now, with the distant past, and the ultimate future.

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