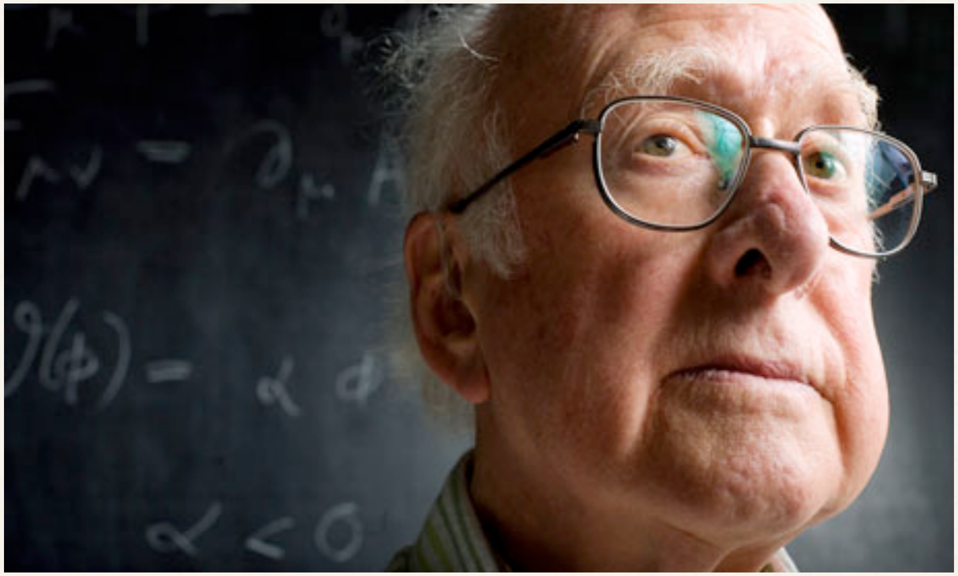
What is the Higgs boson trying to tell us?



Joseph Lykken

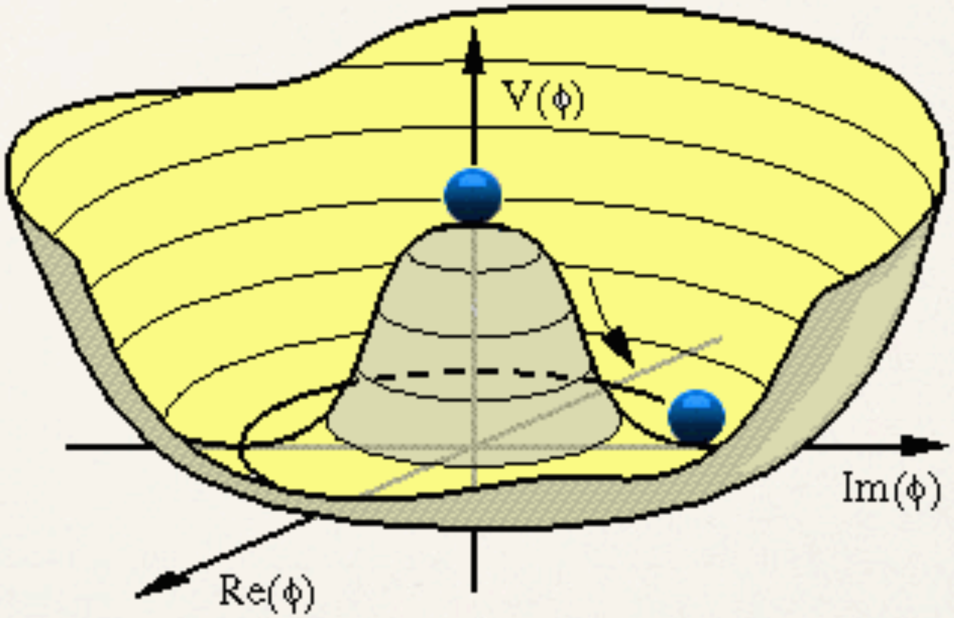
Fermilab

Tohoku Forum For Creativity, Tohoku University, Sendai, Oct 21-25, 2013

Outline

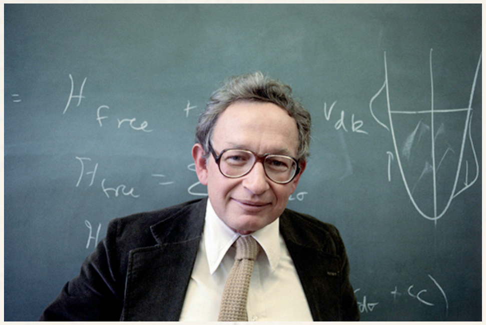
- Condensed matter physics in vacuo
- What kind of Higgs boson?
- Higgs Connections:
    - Higgs and supersymmetry
    - Higgs and vacuum stability
    - The origin of the electroweak scale
    - Higgs and dark matter
    - Higgs and the genesis of matter

Condensed matter physics in vacuo



“More is Different”

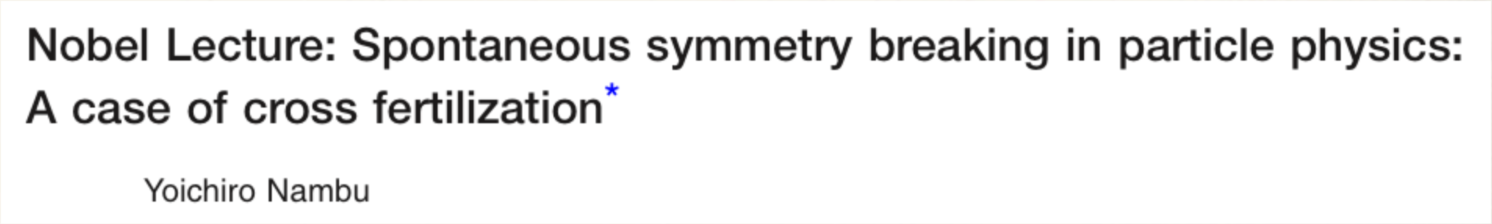
-- Phillip Anderson, 1972



- If the laws of subatomic physics have so much symmetry, why is the world around us so complex?
- Many-body systems exhibit emergent phenomena not meaningfully encoded in the laws that govern their basic constituents
- Step one on the road to complexity is that many-body systems break symmetries

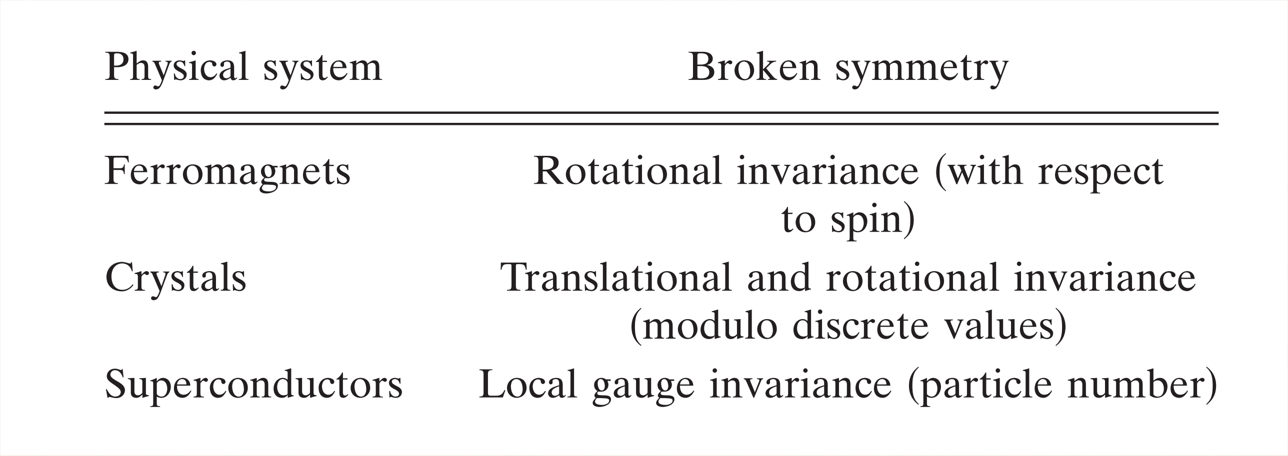
Nambu (1960)

the importance of Spontaneous Symmetry Breaking



Nobel Lecture: Spontaneous symmetry breaking in particle physics: A case of cross fertilization*

Yoichiro Nambu

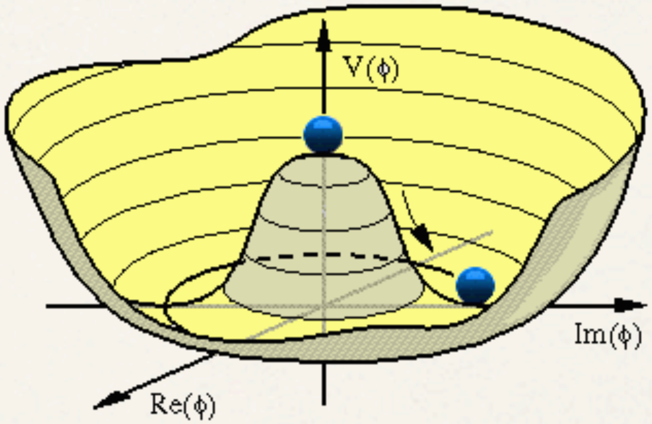


Physical system	Broken symmetry
Ferromagnets	Rotational invariance (with respect to spin)
Crystals	Translational and rotational invariance (modulo discrete values)
Superconductors	Local gauge invariance (particle number)

- Apply condensed matter ideas to **particle physics**
- **Now the quantum vacuum is the "medium"**

Goldstone (1961)

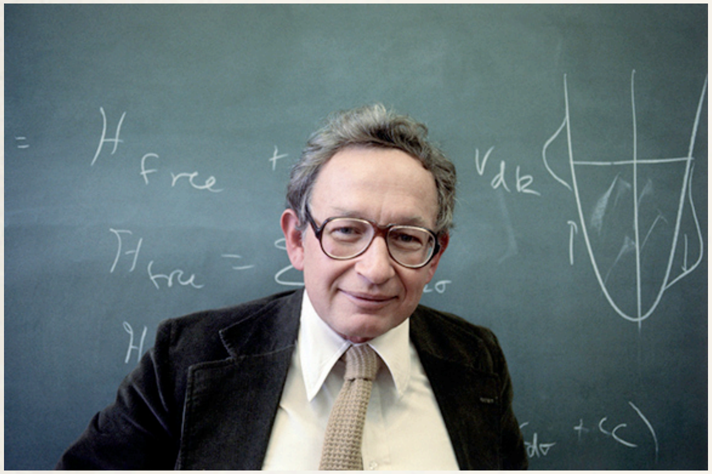
the problem of massless bosons

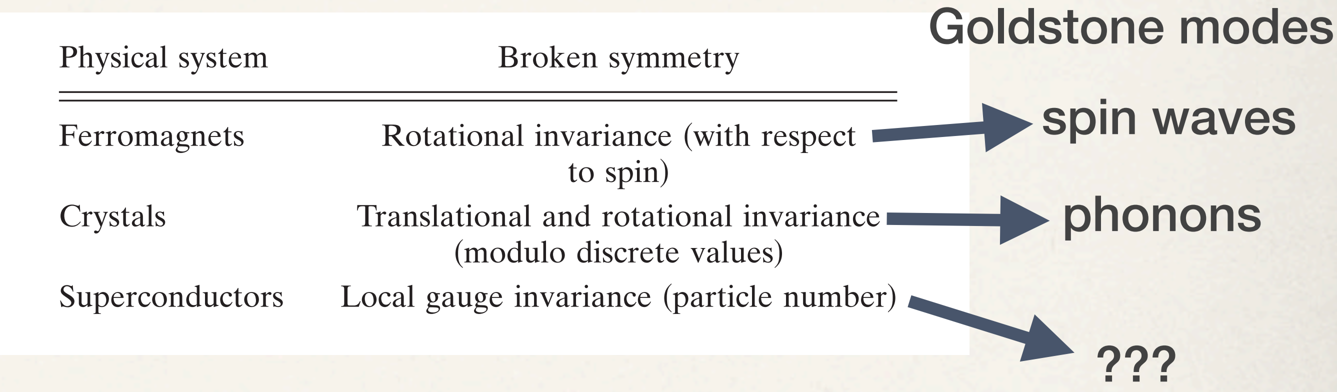


- Spontaneous breaking of continuous symmetries implies degenerate vacua
- Implies low energy “Goldstone modes”, massless spinless bosons in the ideal limit
- Fine for condensed matter systems, but particle physics doesn’t have massless spinless bosons...

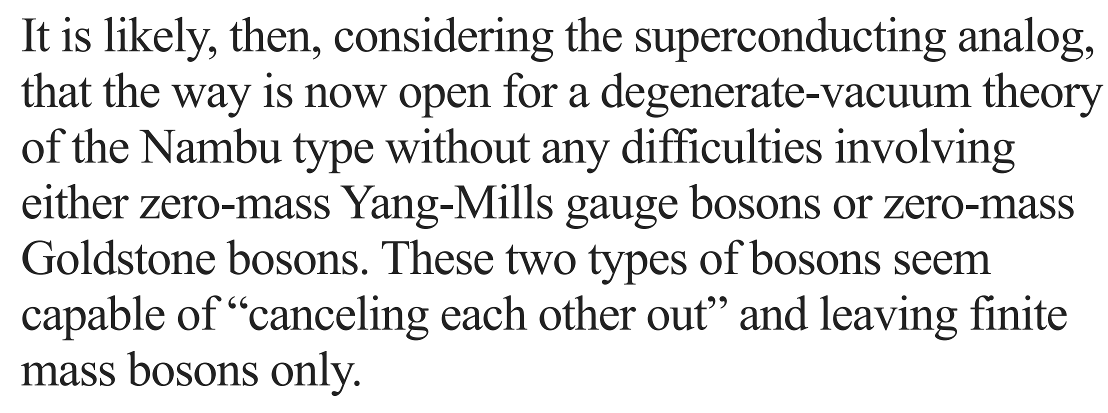
Anderson (1962)

gauge bosons “eat” Goldstone bosons and get mass, just like a photon inside a superconductor





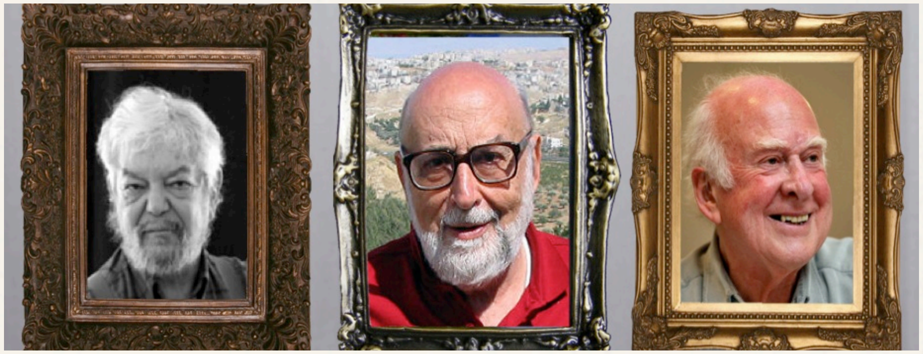
Physical system	Broken symmetry	Goldstone modes
Ferromagnets	Rotational invariance (with respect to spin)	spin waves
Crystals	Translational and rotational invariance (modulo discrete values)	phonons
Superconductors	Local gauge invariance (particle number)	???



It is likely, then, considering the superconducting analog, that the way is now open for a degenerate-vacuum theory of the Nambu type without any difficulties involving either zero-mass Yang-Mills gauge bosons or zero-mass Goldstone bosons. These two types of bosons seem capable of “canceling each other out” and leaving finite mass bosons only.

Higgs et al (1964)

- a fundamental scalar field with self-interactions
- can cause spontaneous (global) symmetry-breaking in the vacuum
- and give gauge bosons mass
- while respecting the delicate choreography of gauge symmetry with Lorentz invariance

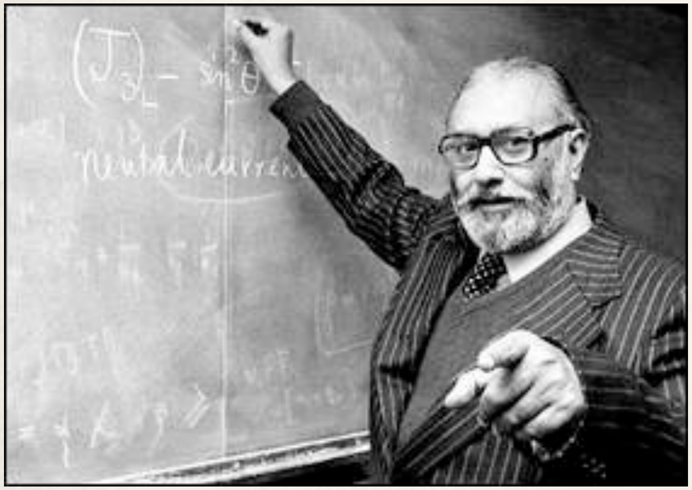


> The purpose of the present note is to report that...the spin-one quanta of some of the gauge fields acquire mass...This phenomenon is just the relativistic analog of the plasmon phenomenon to which Anderson has drawn attention

the Higgs Mechanism

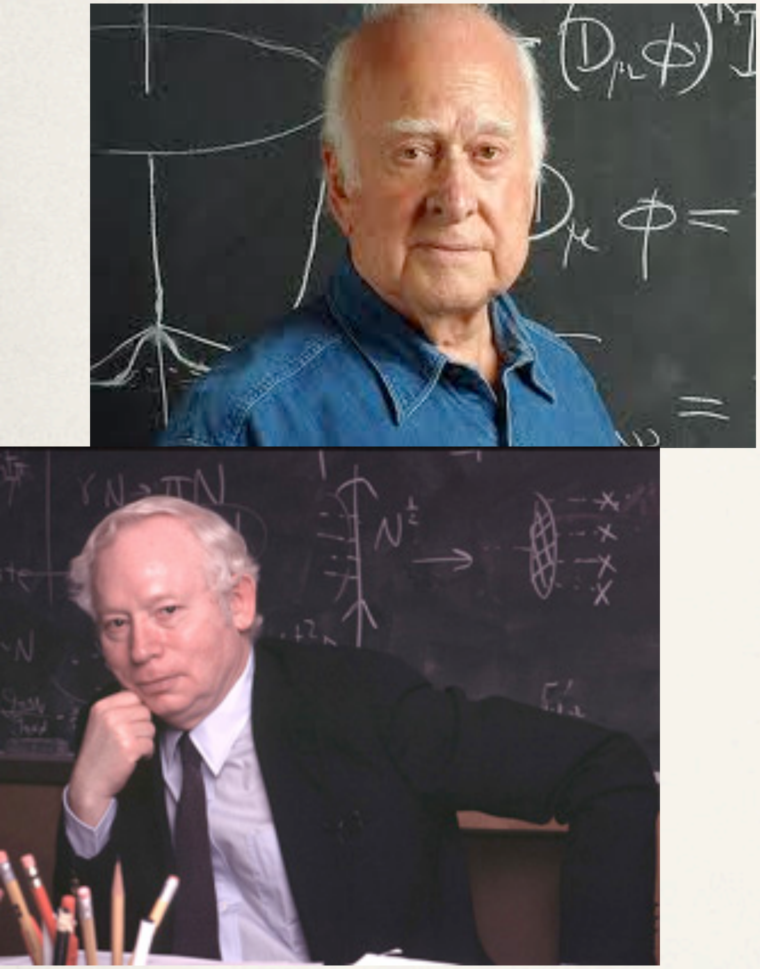
Weinberg, Salam (1967)

the Electroweak Standard Model



- An $SU(2)_L \times U(1)_Y$ nonabelian gauge theory with chiral fermions
- Spontaneously broken to electromagnetism by a nonzero vacuum value of a complex doublet Higgs field with self-interactions
- Three of the four real Higgs components are eaten to give mass to the W^+, W^-, and Z, **leaving one neutral Higgs boson** and a massless photon
- **The fermions also get mass** from their Yukawa couplings to the Higgs field

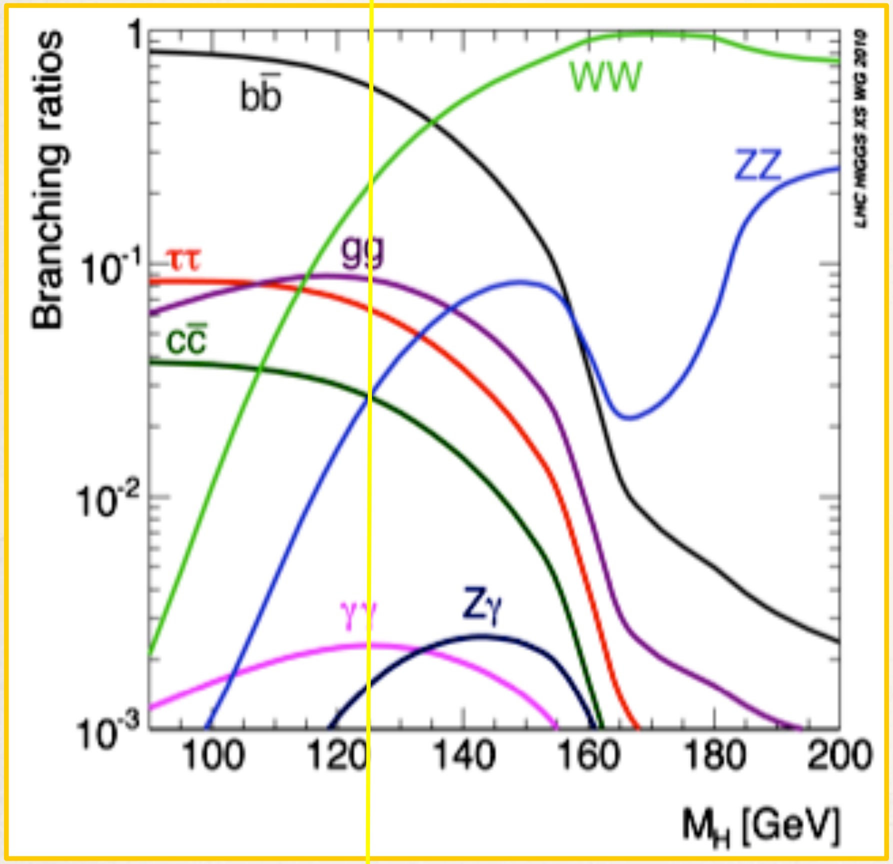
what makes a Higgs a Higgs?

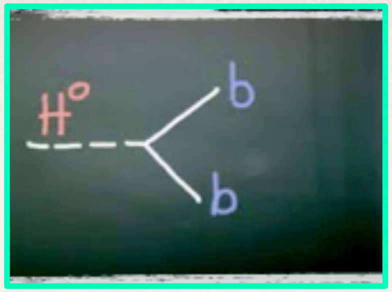


- Spin 0 boson
- Neutral CP even component of a complex SU(2) doublet with hypercharge +1
- Couples to W and Z bosons proportional to their masses
- Couples to quarks and leptons proportional to their masses
- Couples to massless photons and gluons through radiative corrections involving virtual charged/colored particles (top quarks, W bosons, ...)

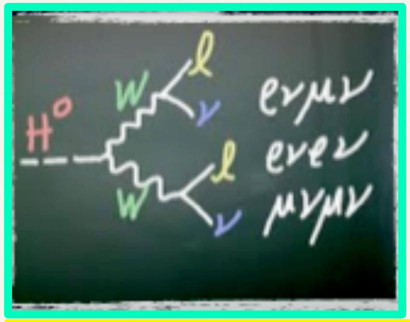
Higgs decays

The Higgs decays after about 100 yocktoseconds into various pairs of lighter particles



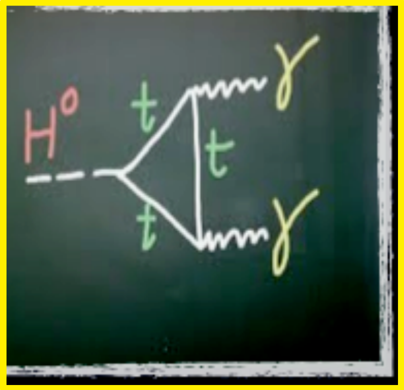


- Lots of background



- Neutrinos not detected

- Rare but "Golden" channel



- Rare but relatively clean

Higgs Imposters

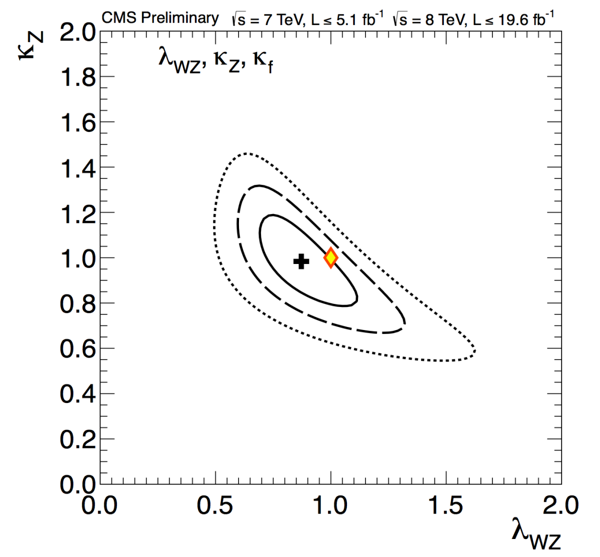
- **First job of the experiments was to rule out Higgs imposters**
- Is it spin 1? [no] or spin 2? [probably not]
- Is it a pseudoscalar? [no, but could be a CP mixture]
- From an SU(2) triplet? [no, mostly SU(2) doublet]

CMS: 95% CL interval for λ_{WZ} : [0.62,1.19]

ATLAS: $\boxed{\lambda_{WZ} = 0.80 \pm 0.15}$

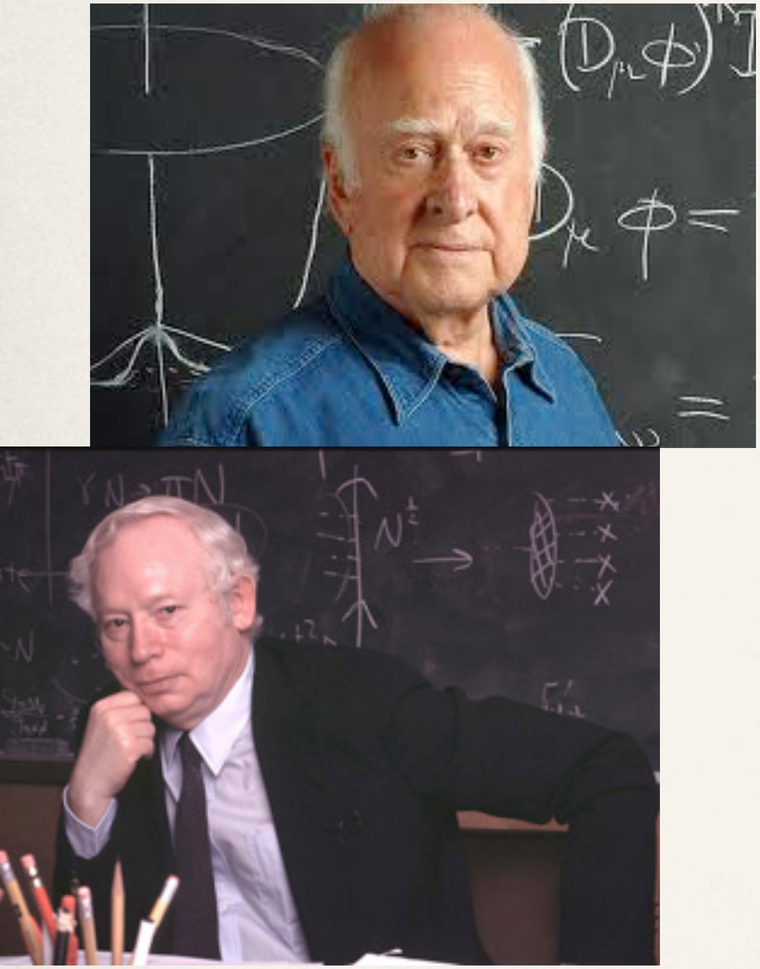
i.e. decays about 8 times more often to WW* than ZZ*, consistent with neutral member of doublet Higgs but not a custodially invariant triplet

Ian Low, JL, Gabe Shaughnessy, arXiv:1207.1093



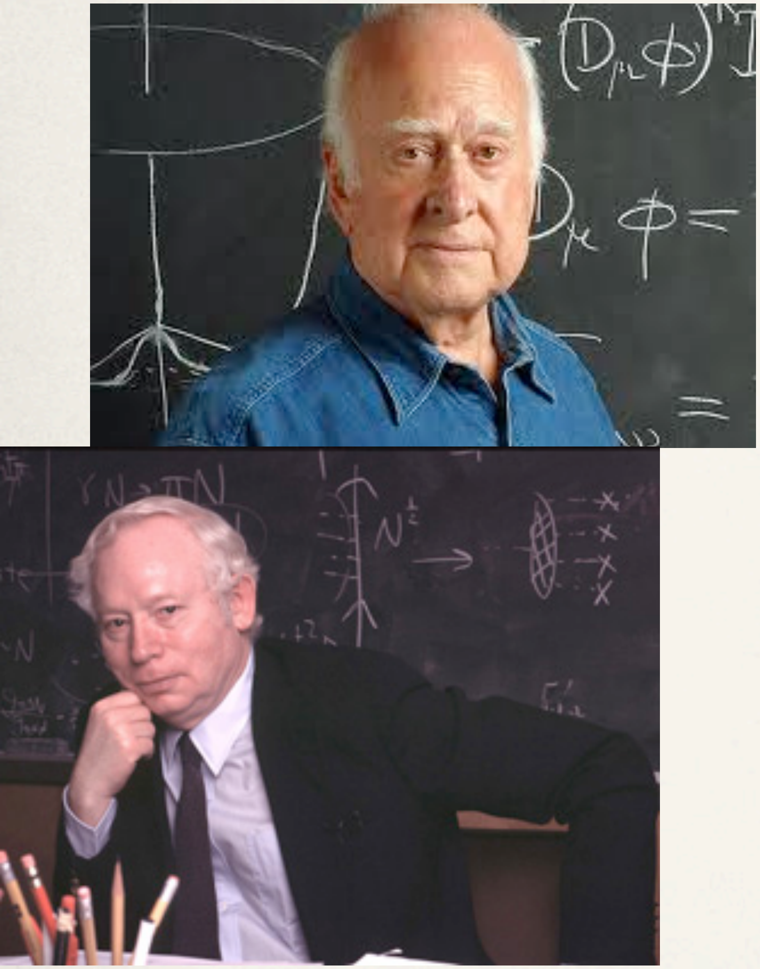
- Can still "tune" a dilaton imposter or spin 2 imposter to fit the data...

what kind of Higgs boson?



- It is now pretty well established that the particle of the July 4 discovery is the Higgs boson of electroweak symmetry breaking and fermion mass generation
- This is not the same thing as asking if it is **exactly** the Higgs boson of the Standard Model
- It could have many non-SM properties and still be “The Higgs”

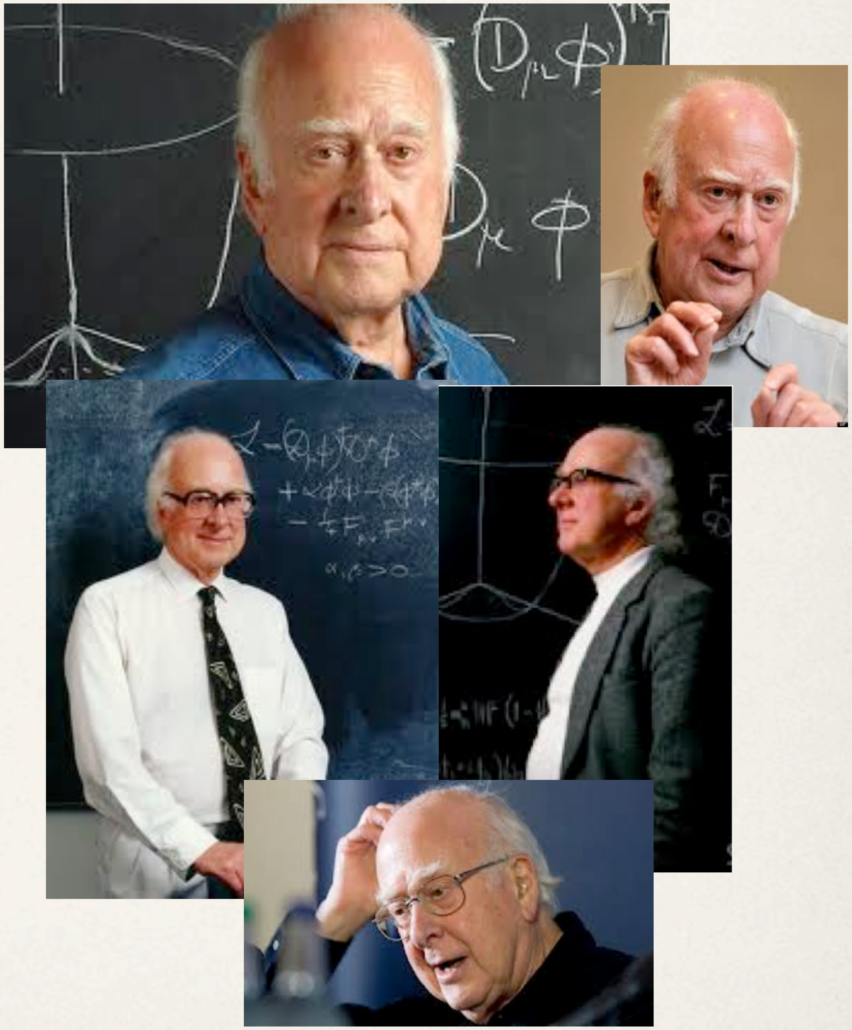
non-standard Higgs?



- Could be a mixture from more than one Higgs SU(2) doublet, singlets or triplets
- Could be a mixture of CP even and CP odd
- Could be a composite
- Could have enhanced/suppressed couplings to photons or gluons if there are exotic heavy charged or colored particles
- Could decay to exotic particles, e.g. dark matter
- May not couple to quarks and lepton precisely proportional to their masses

How many more Higgs?

- One of the critical targets for future LHC running is discovering additional varieties of Higgs-like bosons
- Finding heavy Higgs bosons with non-standard couplings is a major long-term challenge for the LHC
- Supersymmetry predicts at least five Higgs bosons, differing in their mass and other properties



what does a 126 GeV Higgs mean for minimal supersymmetry?

- SUSY predicts at least 4 **additional** Higgs bosons:
  - one CP-even H (mixed with h), one CP-odd A
  - a pair of heavy charged scalars H^+, H^-
- two distinct symmetry-breaking vevs: v_1, v_2

$$\tan\beta = v_2/v_1$$

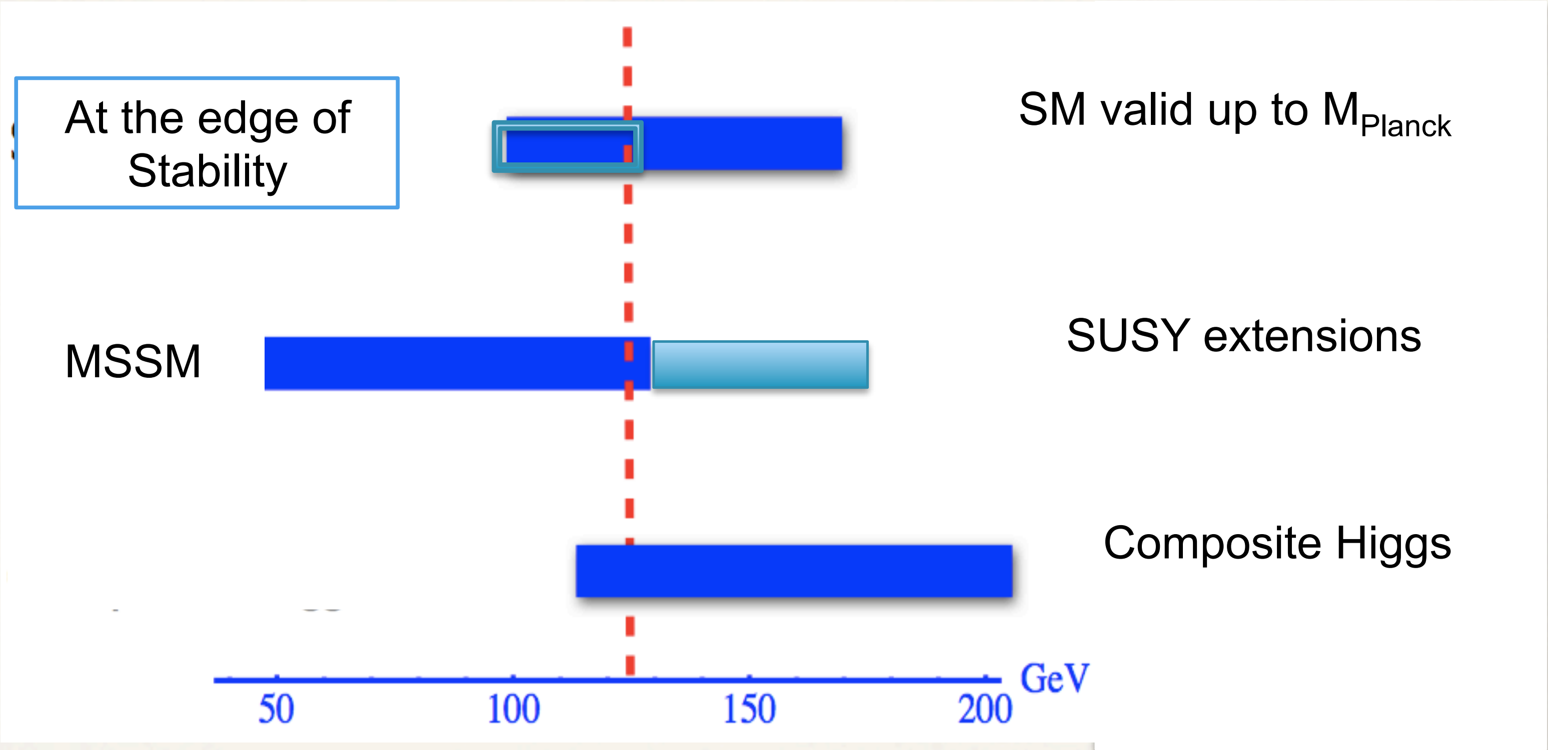
$$v = \sqrt{(v_1^2 + v_2^2)}$$

- the light Higgs has important radiative corrections to its mass:

$$\mathbf{m_h^2 < M_Z^2 \cos^2 2}\beta + \mathbf{\Delta m_h^2}$$

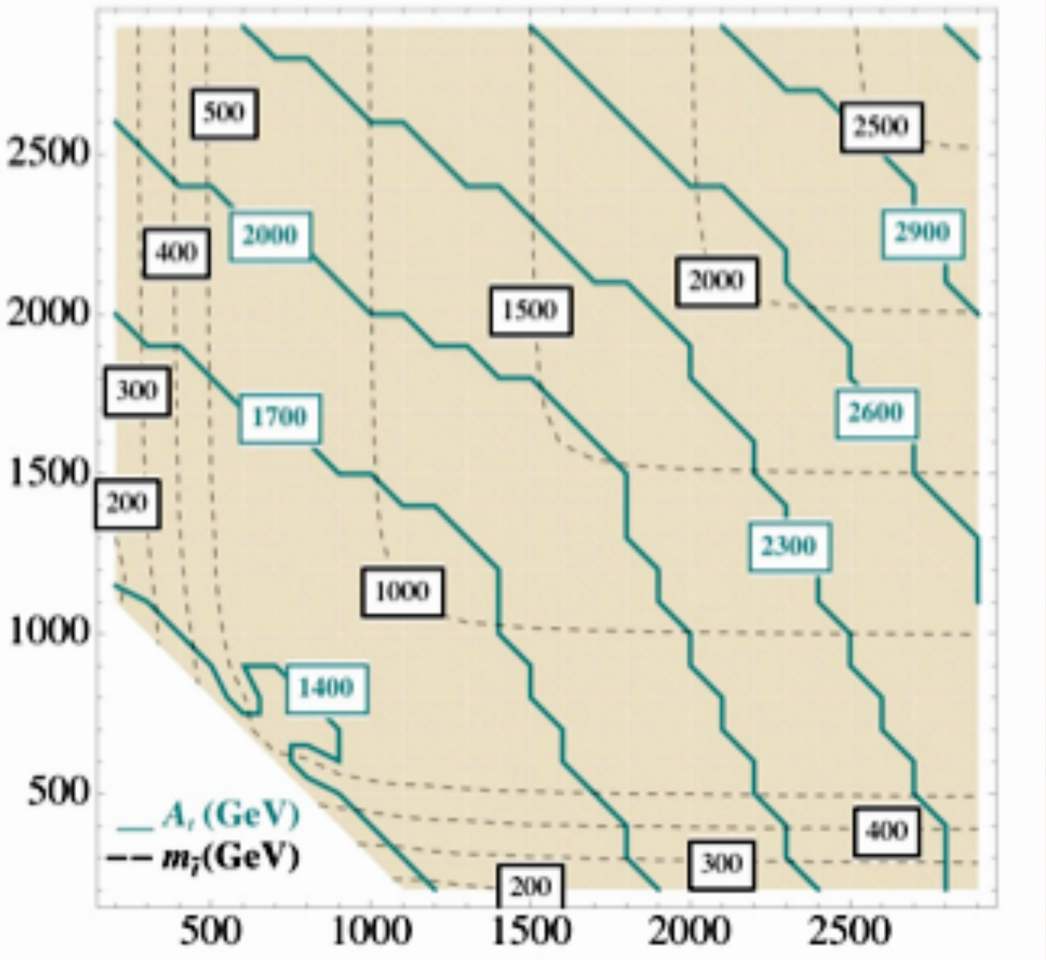
- because of radiative corrections, the light Higgs does **not** couple to other particles precisely proportional to their masses

what does a 126 GeV Higgs mean for minimal supersymmetry?



- 126 GeV is suspiciously light for a composite Higgs boson
- but it is suspiciously heavy for minimal SUSY

what does a 126 GeV Higgs mean for minimal supersymmetry?

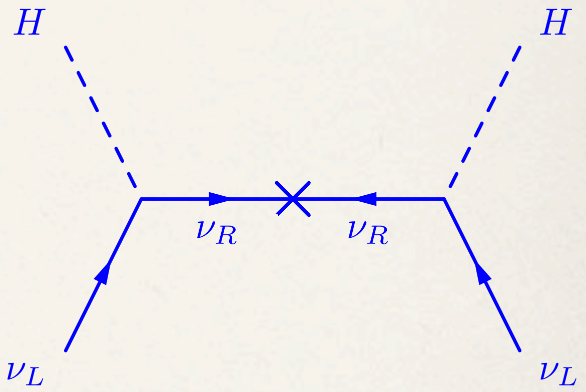


M. Carena, S. Gori, N. Shah, C. Wagner arXiv:1112.3336

- in minimal SUSY a 126 GeV Higgs implies large mixing of the two stops, the superpartners of the top quark
- because of this see-saw, one of the stops may be rather light, even if most of the other superpartners are relatively heavy (> TeV)
- if you don’t want large mixing, then you need to **enlarge the SUSY Higgs sector** to explain m_h=126 GeV

Higgs connections

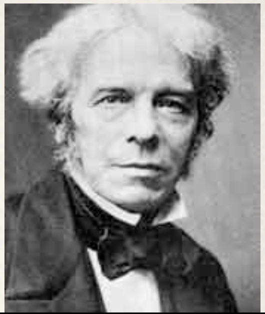
- Does the Higgs destabilize the vacuum
- What is the origin of the electroweak scale
- Is there a Higgs portal to dark matter
- Is the Higgs sector responsible for the genesis of matter in the early universe
- How does the Higgs talk to neutrinos
- Extra credit: is the Higgs related to inflation or dark energy



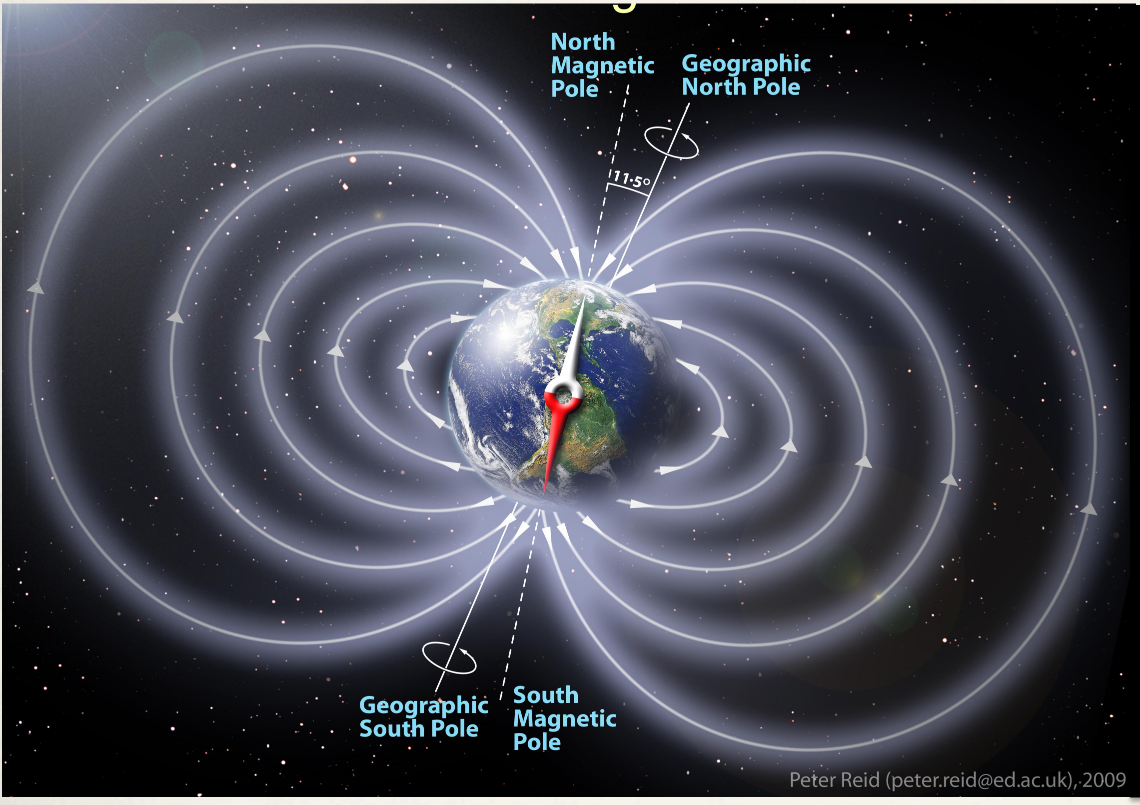
→ Motivates a global experimental effort on all three "frontiers" of particle physics: Energy, Intensity, Cosmic

Higgs and vacuum stability

invisible force fields



Michael Faraday's contemporaries thought he was nuts for suggesting the reality of invisible force fields that permeate empty space



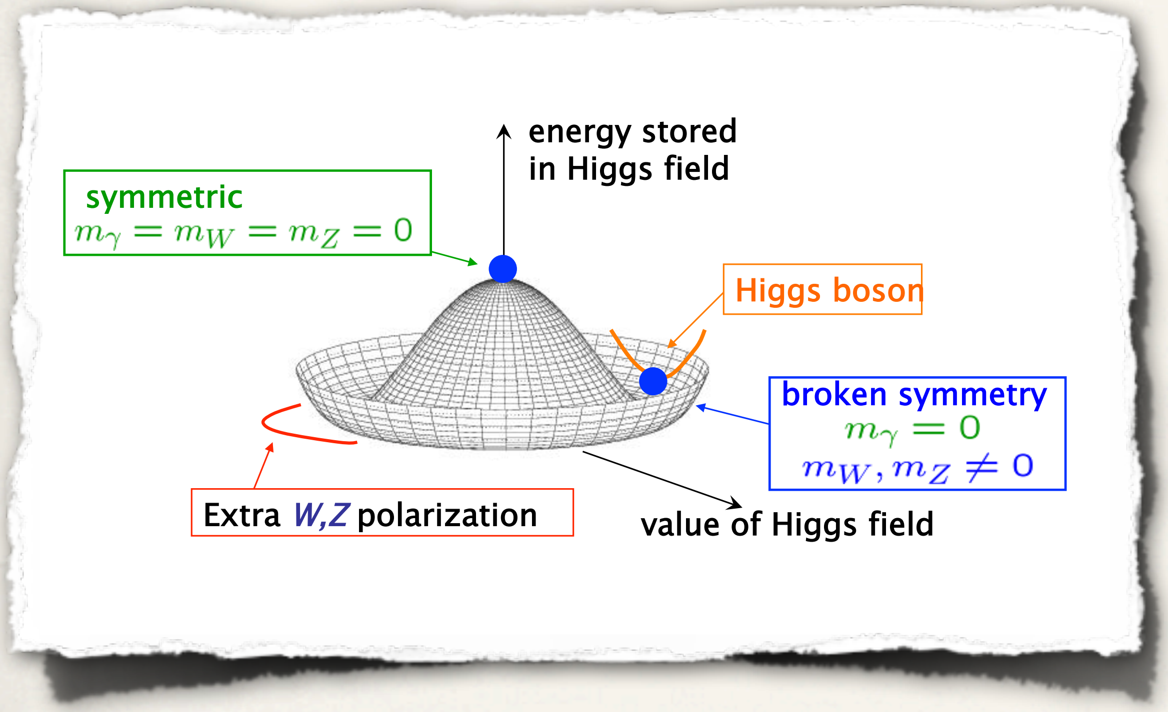
Peter Reid (peter.reid@ed.ac.uk), 2009

magnetic field sourced by the Earth permeates nearby space

Higgs field sourced by itself permeates the entire universe

What turns the Higgs field on?

- The Higgs field is self-sourcing with a quartic self-interaction λ
- The strength of this interaction has distance-dependent quantum corrections from the Higgs coupling to other particles, esp. the top quark



$$\lambda \to \lambda[\mu]$$

$$\beta_\lambda \equiv \frac{\mathbf{d}\lambda}{\mathbf{d}\log[\mu]}$$

$$\mathbf{16}\pi^{\mathbf{2}}\beta_\lambda = \mathbf{12}\lambda^{\mathbf{2}} - \mathbf{12y_t^4} + \ldots$$

- The Higgs effective potential describes the energetics of turning on the Higgs field; the global minimum defines the stable vacuum state

SM Higgs effective potential

J. Casas, J. Espinosa, M. Quiros, hep-ph/9409458
G. Degrassi, S. Di Vita, J. Elias-Miro, J. Espinosa, G. Giudice, G. Isidori, A. Strumia, arXiv:1205.6497

- Depends on the Higgs boson mass and the Higgs self-coupling λ
- Quantum corrections depend sensitively on the top quark mass
- Depends on the distance or energy scale, here represented by an energy scale μ
- Turning on the Higgs field to large values implies large μ

$$\mathbf{V}(\phi) = \mathbf{V_0}(\phi) + \mathbf{V_1}(\phi) + \mathbf{V_2}(\phi) + \ldots$$

$$\mathbf{V_0}(\phi) = \frac{1}{2}\mathbf{m_0^2}\phi^2 + \frac{1}{8}\lambda\phi^4$$

$$\mathbf{V_1}(\phi) = \frac{1}{64\pi^2}\Big[-12\mathbf{m_t^4}(\log\left(\frac{\mathbf{m_t^2}}{\mu^2} - \frac{3}{2}\right) + 6\mathbf{m_W^4}(\log\left(\frac{\mathbf{m_W^2}}{\mu^2} - \frac{5}{6}\right) + 3\mathbf{m_Z^4}(\log\left(\frac{\mathbf{m_Z^2}}{\mu^2} - \frac{5}{6}\right)$$

$$+\mathbf{m_h^4}(\log\left(\frac{\mathbf{m_h^2}}{\mu^2} - \frac{3}{2}\right) + 3\mathbf{m_\chi^4}(\log\left(\frac{\mathbf{m_\chi^2}}{\mu^2} - \frac{3}{2}\right)\Big]$$

SM Higgs vacuum instability

- For large field values we can just scale out ϕ^4 and write the RG improved effective potential in terms of a $\lambda_{\mathbf{eff}}$

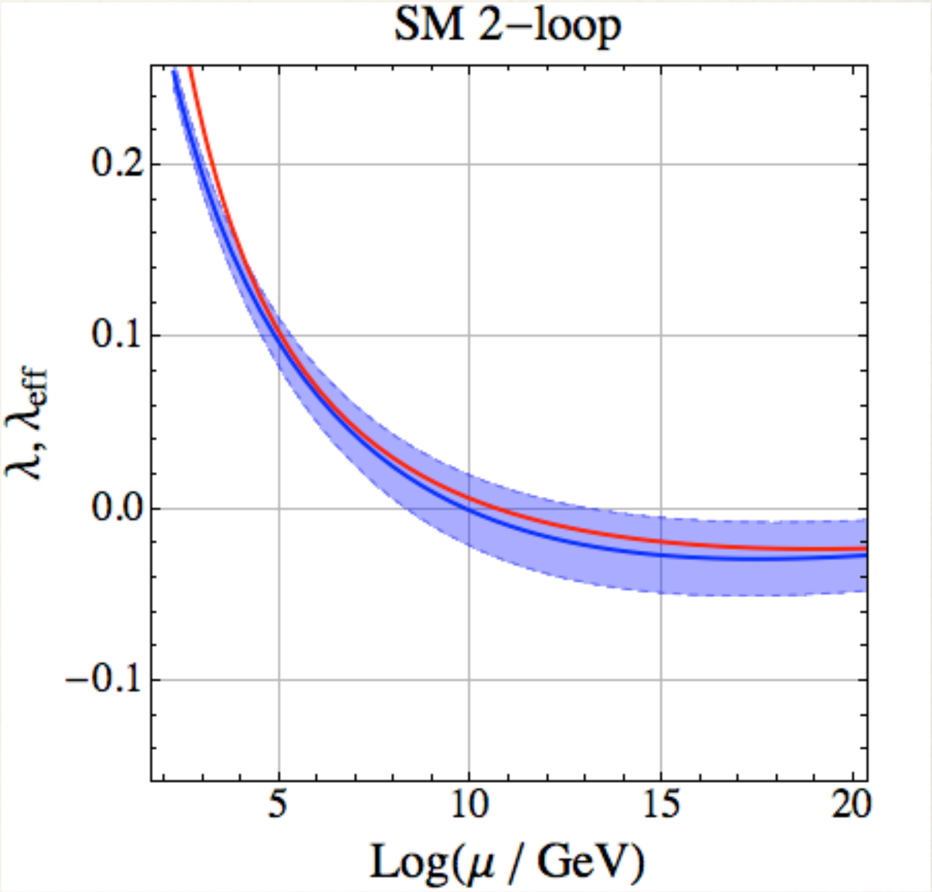
$$\mathbf{V}(\phi) = \mathbf{V_0}(\phi) + \mathbf{V_1}(\phi) \simeq \lambda_{\mathbf{eff}}\, \phi^{\mathbf{4}}$$

J. Casas, J. Espinosa, M. Quiros, hep-ph/9409458

- Then $\lambda_{\mathbf{eff}} < \mathbf{0}$ at large field values implies that the Standard Model vacuum is unstable

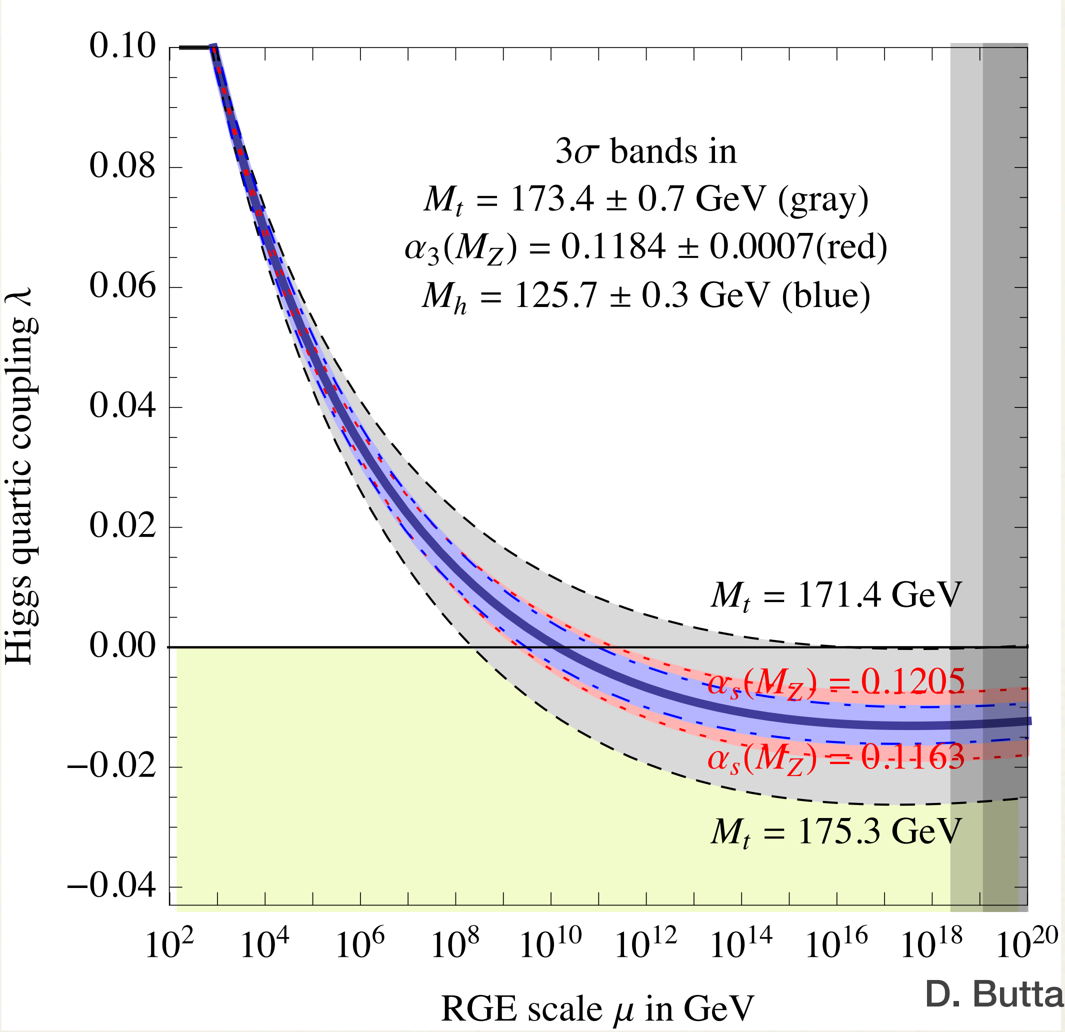
- This possibility has been studied since the 1970s, but now we can finally put in the correct numbers

D. Politzer, S. Wolfram, Phys. Lett. 82B, 1979



SM Higgs quartic self-coupling

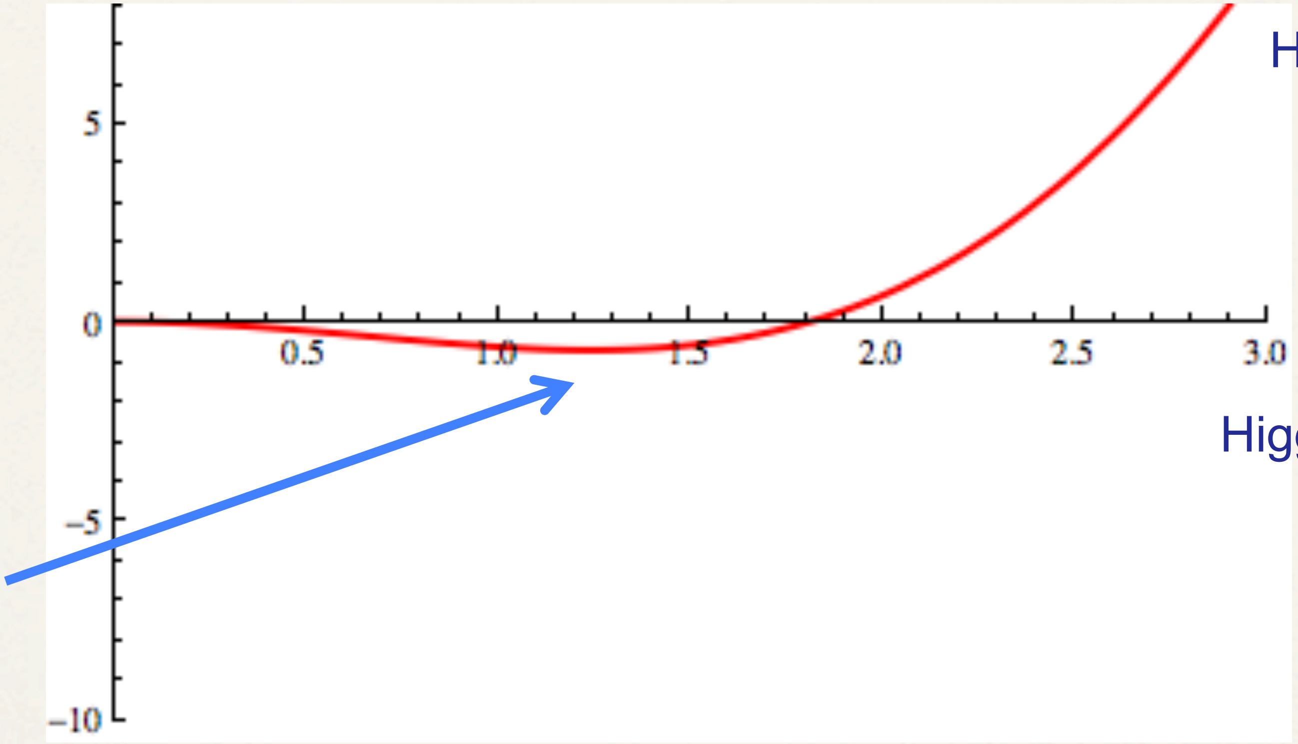
SM 3-loop running with 2-loop matching



D. Buttazzo et al, arXiv:1307.3536

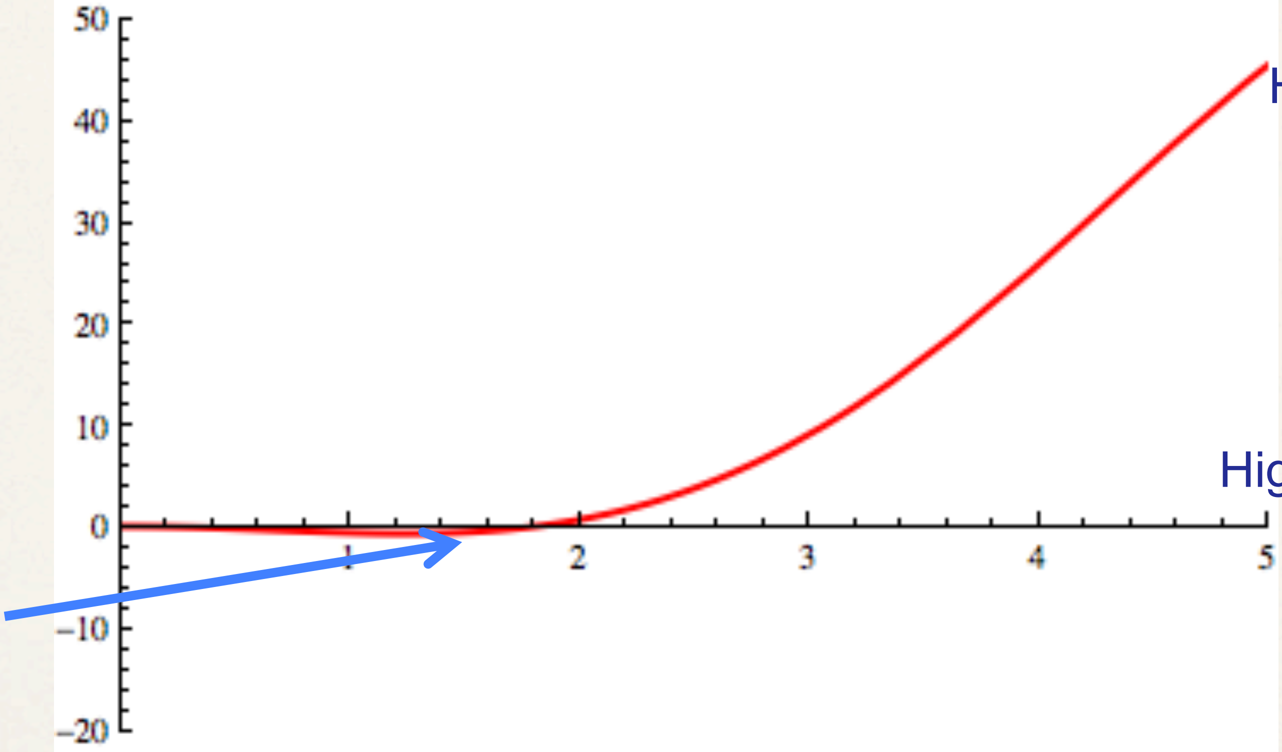
Energy

Higgs potential



Higgs field strength

You are
here



Energy

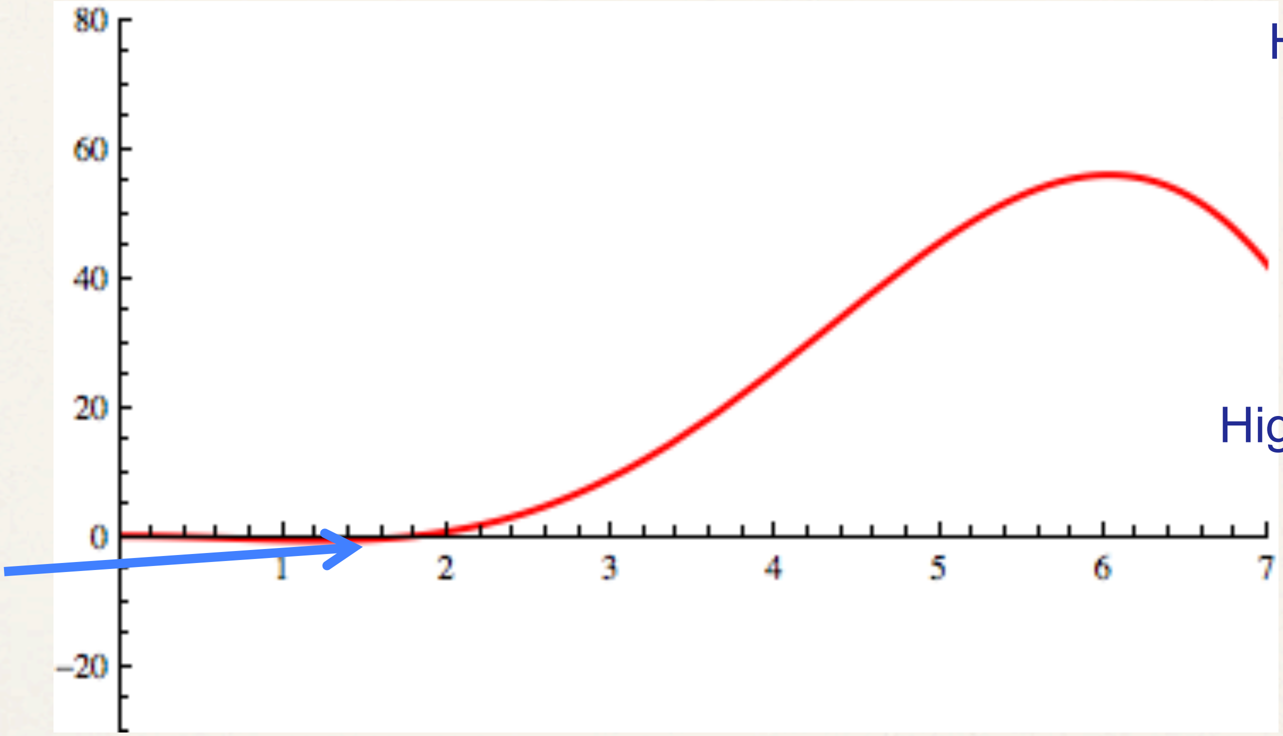
Higgs potential

Higgs field strength

You are
here

Energy

Higgs potential

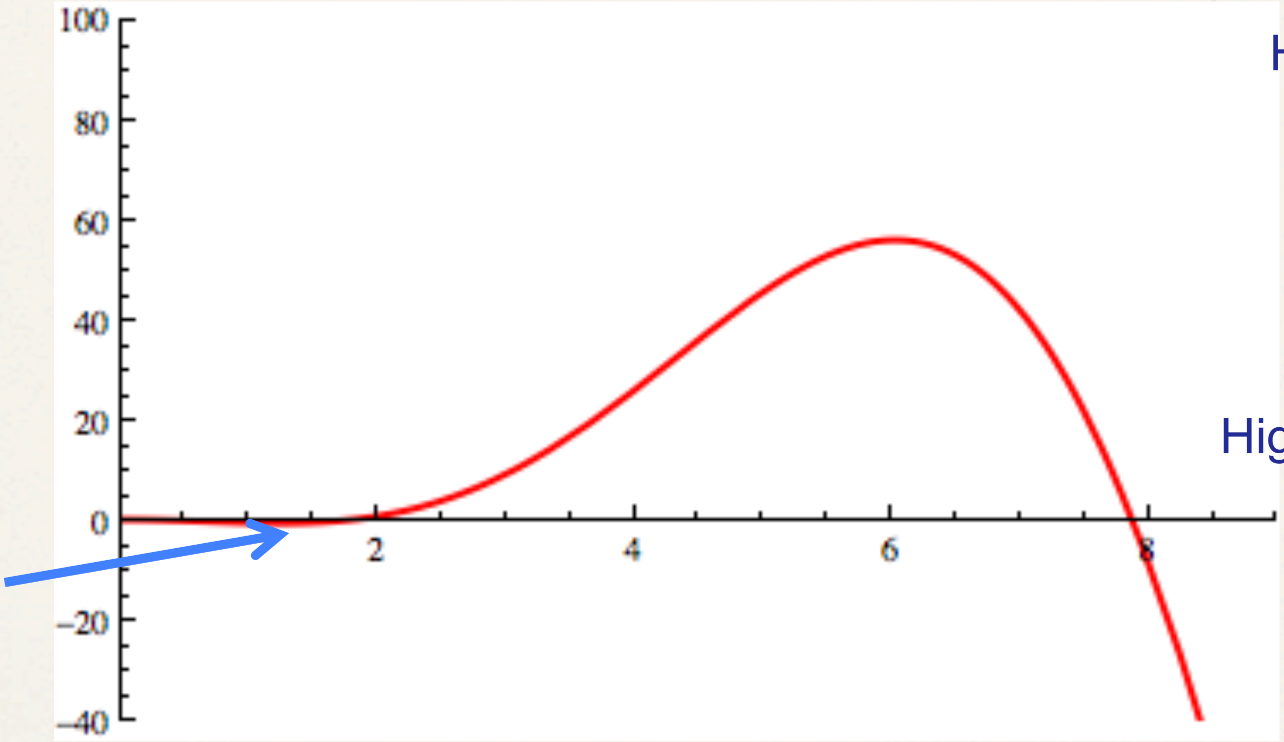


Higgs field strength

You are
here

Energy

Higgs potential

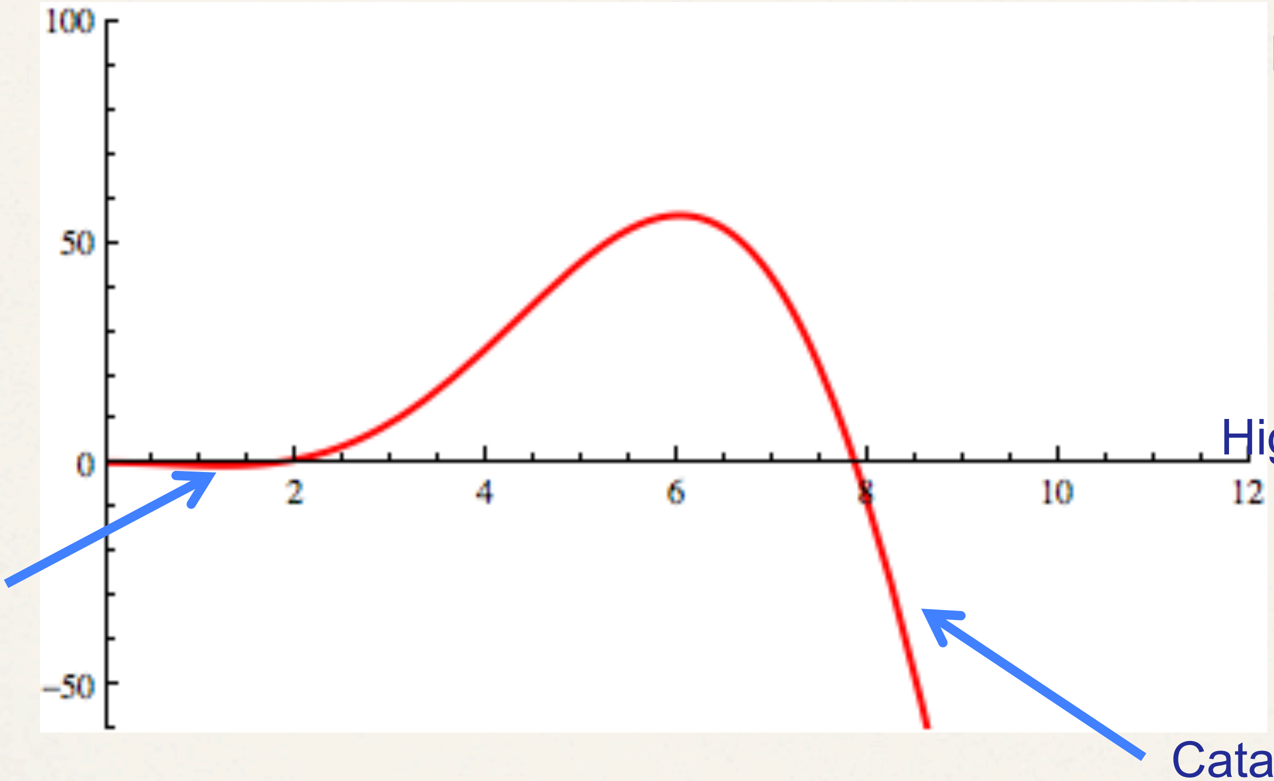


Higgs field strength

You are
here

Energy

Higgs potential

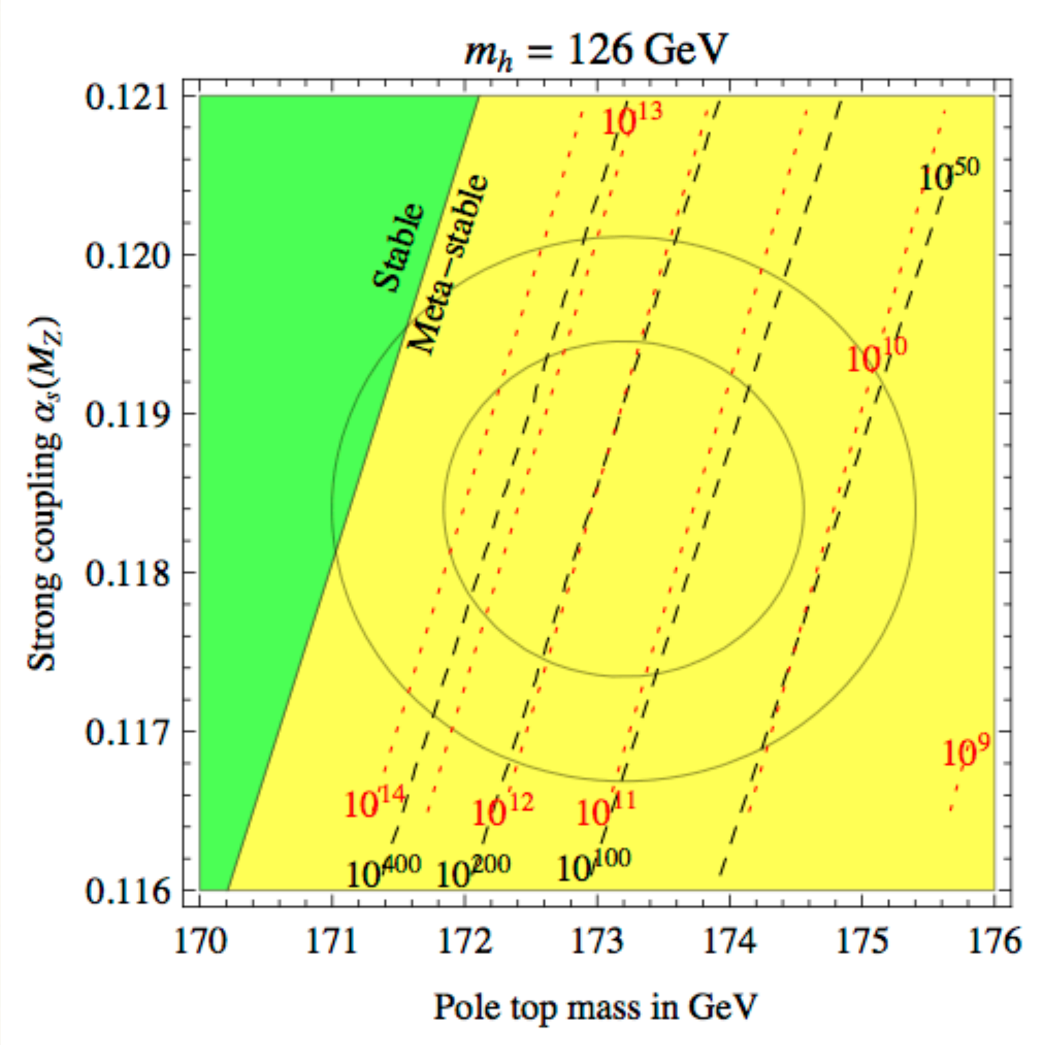


Higgs field strength

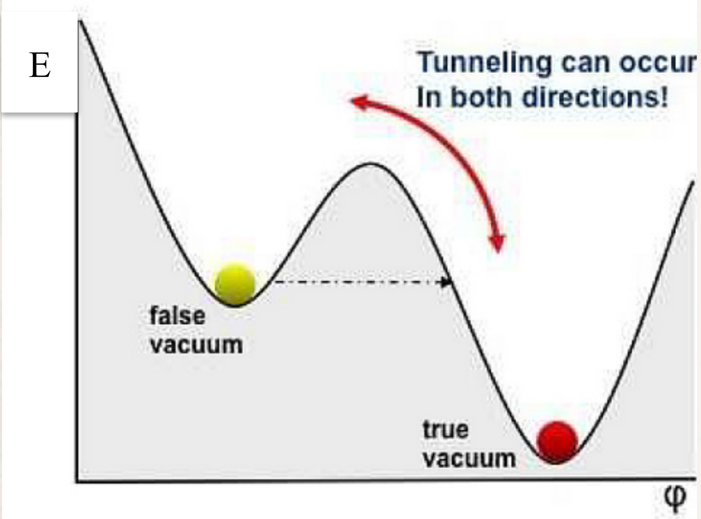
You are here

Catastrophic “runaway” instabiility

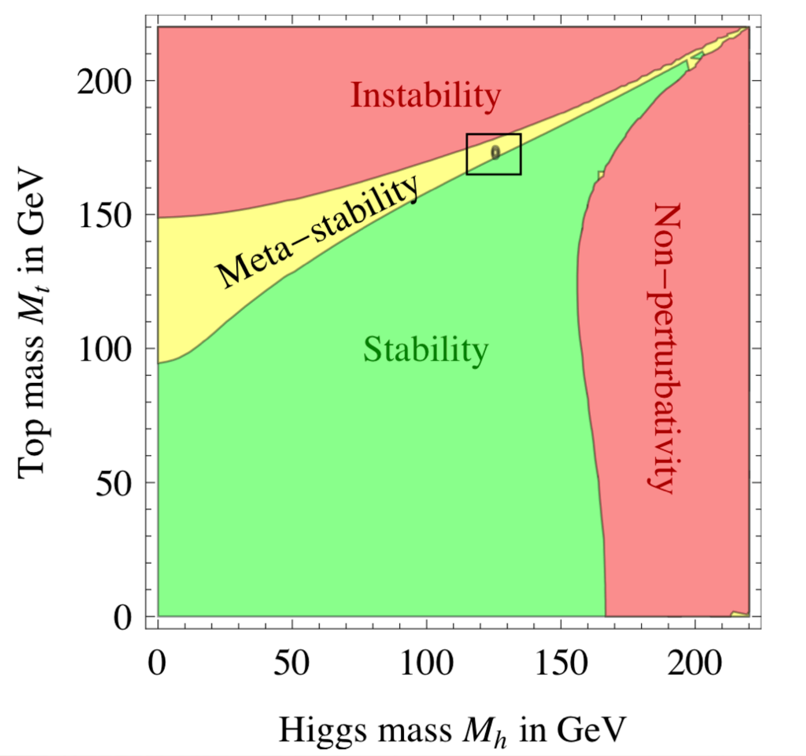
If you take this SM prediction seriously, in about 10^{100} years a fatal bubble will form through an unlucky quantum fluctuation



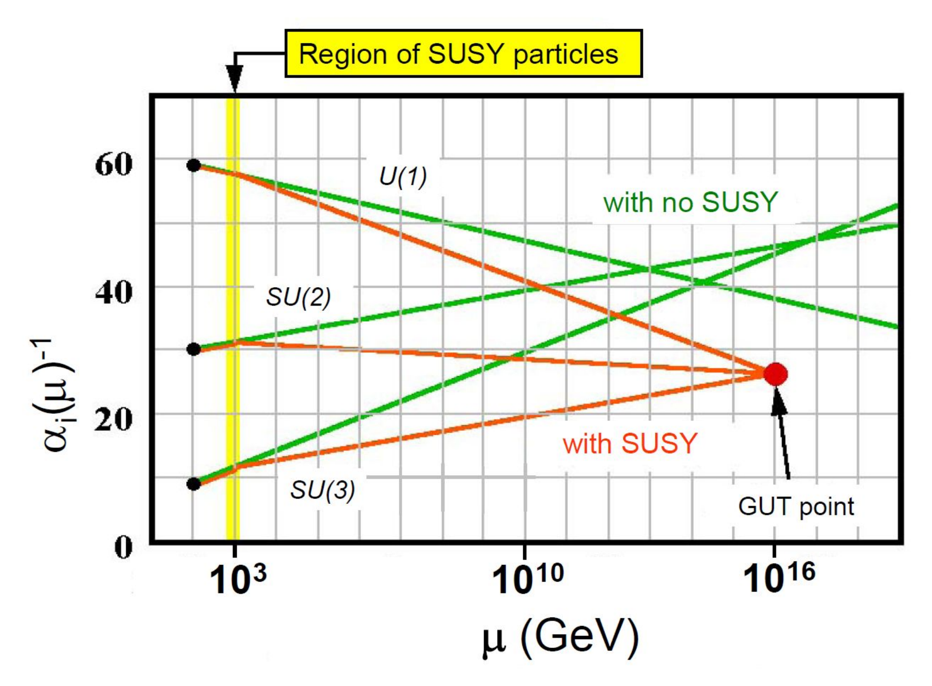
J. Elias-Miro, J. Espinosa, G. Giudice, G. Isidori, A. Riotto, A. Strumia, arXiv:1112.3022



why do we live on the ragged edge of doom?

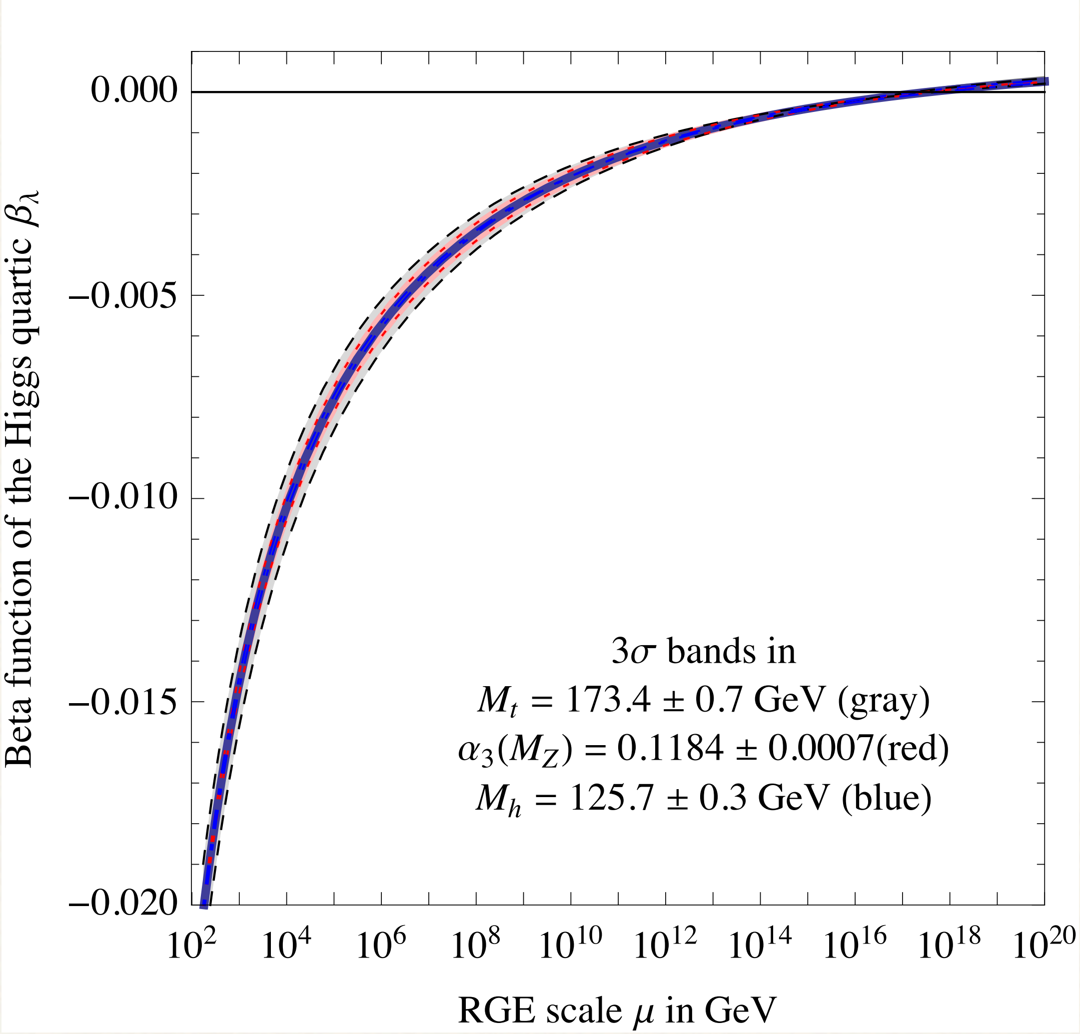


or does supersymmetry save us?



- Maybe one or both of these is just a coincidence at the few % level
- But dismissing striking features of the data as coincidence has historically not been a winning strategy in science...

SM Higgs and the Planck scale?



D. Buttazzo et al, arXiv:1307.3536

What does this mean?

A hint about Planckian fixed points? Weinberg's asymptotic safety?

M. Shaposhnikov, C. Wetterich, arXiv:0912.0208

BUT: What about the Higgs naturalness problem and resulting fine-tuning?

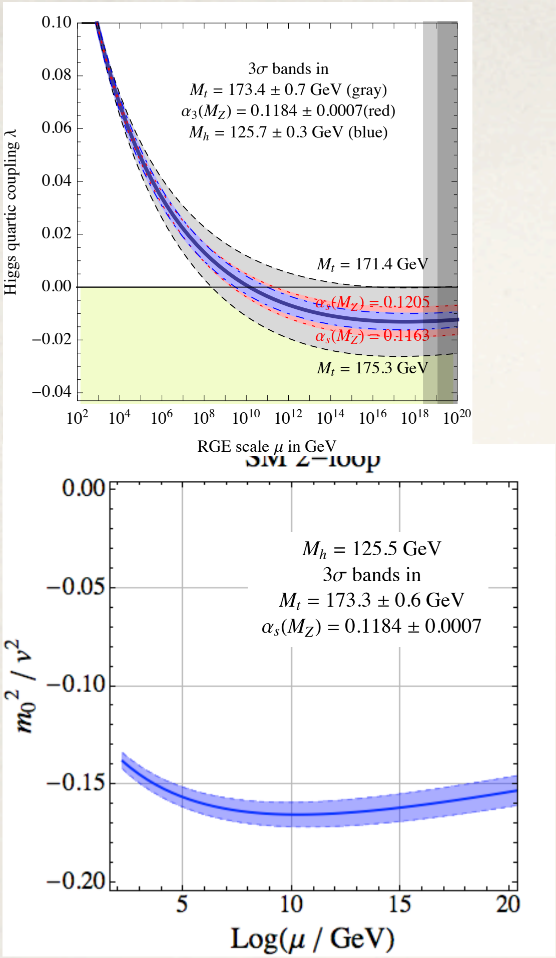
See Andy Cohen's talk

what is the origin of the electroweak scale?

- One feature of the Standard Model that should bother you is why the Higgs mass-squared parameter is set by hand to be negative (tachyonic)

$$\mathbf{V_0(\phi) = \frac{1}{2}m_0^2\phi^2 + \frac{1}{8}\lambda\phi^4} \qquad \mathbf{m_0^2(m_t) = -(132.7\ GeV)^2}$$

- Going back to Coleman and E. Weinberg, one possibility is that EWSB is in fact generated by a radiative instability
- Then the electroweak scale may be generated by dimensional transmutation, like the QCD scale, but with weak couplings



radiative EWSB?

Radiative EWSB doesn't work for the pure SM

So either you believe that Nature inputs tachyonic masses, or you need new physics to generate EWSB radiatively

- then in at high energy scales we could start with $\mathbf{m_0^2 > 0}$, as in the MSSM
- or we could imagine starting with classical scale invariance: $\mathbf{m_0^2 = 0}$

W. Bardeen

SM + a complex singlet scalar

- The simplest addition to the SM that has interesting consequences for the Higgs sector is a single complex SM-singlet scalar, with a direct dimension-four coupling to the Higgs

$$\mathbf{V_0(H,S) = m_0^2|H|^2 + \frac{1}{2}\lambda|H|^4 + \lambda_{sh}|H|^2|S|^2 + m_s^2|S|^2 + \frac{1}{2}\lambda_s|S|^4}$$

- The complex scalar in general carries a charges with respect to symmetries that may or may not be spontaneously broken

SM + a complex singlet scalar

$$\mathbf{V_0(H,S) = m_0^2|H|^2 + \frac{1}{2}\lambda|H|^4 + \lambda_{sh}|H|^2|S|^2 + m_s^2|S|^2 + \frac{1}{2}\lambda_s|S|^4}$$

- There are many families of scenarios, depending for example on
  - Does the singlet scalar get a vev?
- The generic effect of this coupling is to increase the Higgs vacuum stability at **high** energies, since at 1-loop it makes a positive contribution to β_λ

$$\beta_\lambda = \beta_\lambda^{\mathbf{SM}} + \mathbf{4}\lambda_{\mathbf{sh}}^{\mathbf{2}}$$

SM + a complex scalar with vev

$$\mathbf{V_0(H,S) = m_0^2|H|^2 + \frac{1}{2}\lambda|H|^4 + \lambda_{sh}|H|^2|S|^2 + m_s^2|S|^2 + \frac{1}{2}\lambda_s|S|^4}$$

- Even better, if $\lambda_{\mathbf{sh}} < \mathbf{0}$ the vev of the singlet can generate the negative mass-square that we need for EWSB
- Thus we can attempt a scenario in which $\mathbf{m_0 = 0,\ m_s = 0}$ at some scale, and we generate the symmetry breaking radiatively a la Coleman-Weinberg, which then causes EWSB
- In such a simple extension of the SM ***all mass scales are generated via dimensional transmutation***. Much more elegant than the SM!

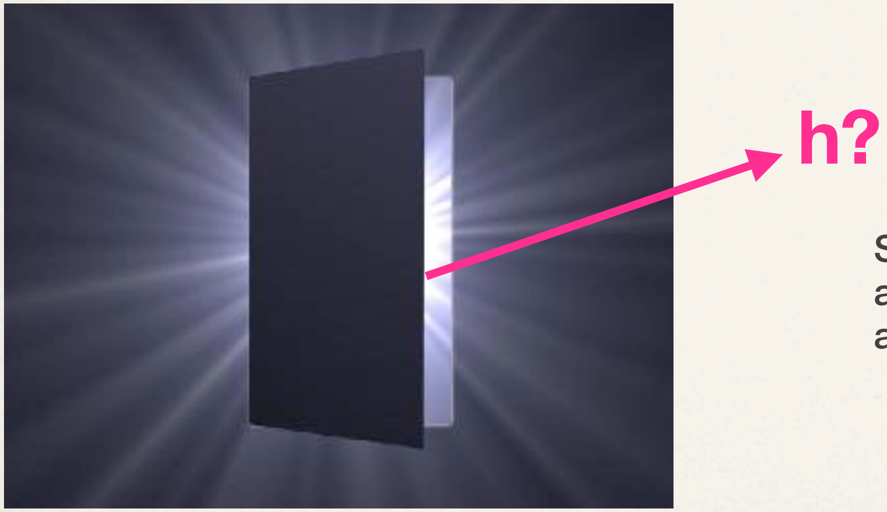
BUT: what about the Higgs naturalness problem?

Higgs portal to Dark Matter

$$\mathbf{V_0(H,S) = m_0^2|H|^2 + \frac{1}{2}\lambda|H|^4 + \lambda_{sh}|H|^2|S|^2 + m_s^2|S|^2 + \frac{1}{2}\lambda_s|S|^4}$$

- If it is stable, the extra scalar could be WIMP dark matter, or could couple to lighter "dark" fermions or scalars, or even heavier "dark" gauge bosons, that are WIMP dark matter

- This is the scenario of a dark sector with a Higgs portal...

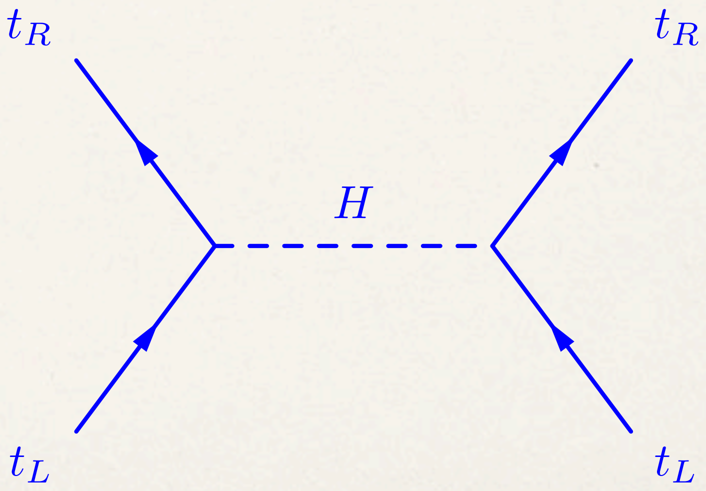


S. Kanemura, S. Matsumoto, T. Nabeshima, N. Okada,
arXiv:1005.5651
and many more...

Higgs boson = force carrier

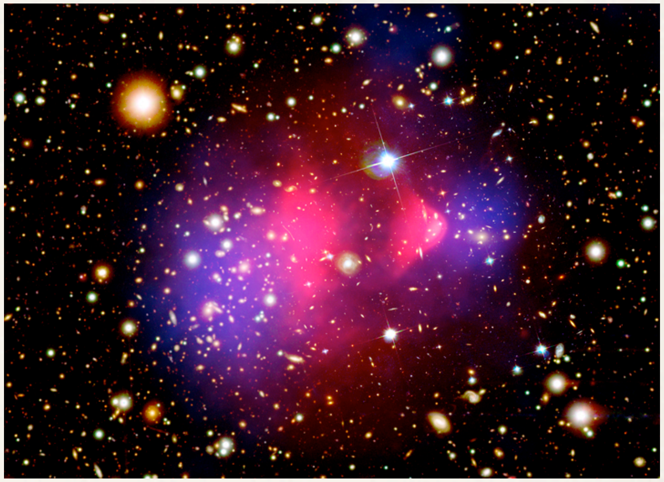
- A new **force** has been discovered, the first ever seen* not related to a gauge symmetry.
- Its **mediator** looks a lot like the SM scalar

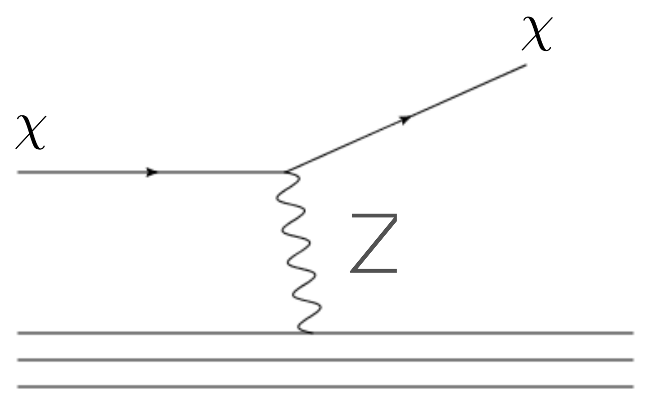
Talk by Fabio Maltoni at LHCP 2013



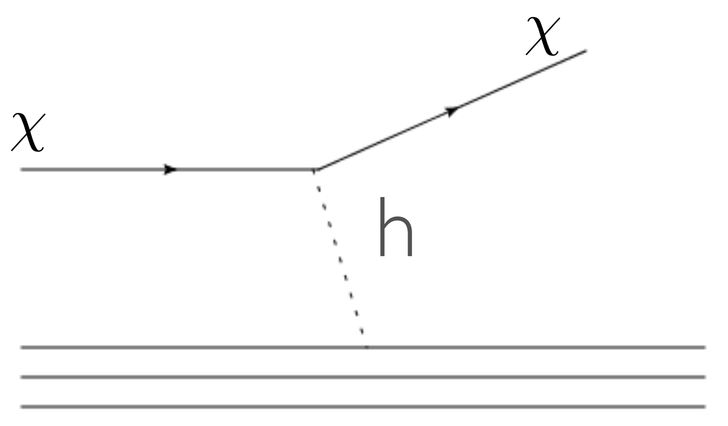
How does dark matter interact with baryonic matter?

via gravity
we know





via the Standard Model
weak interactions?

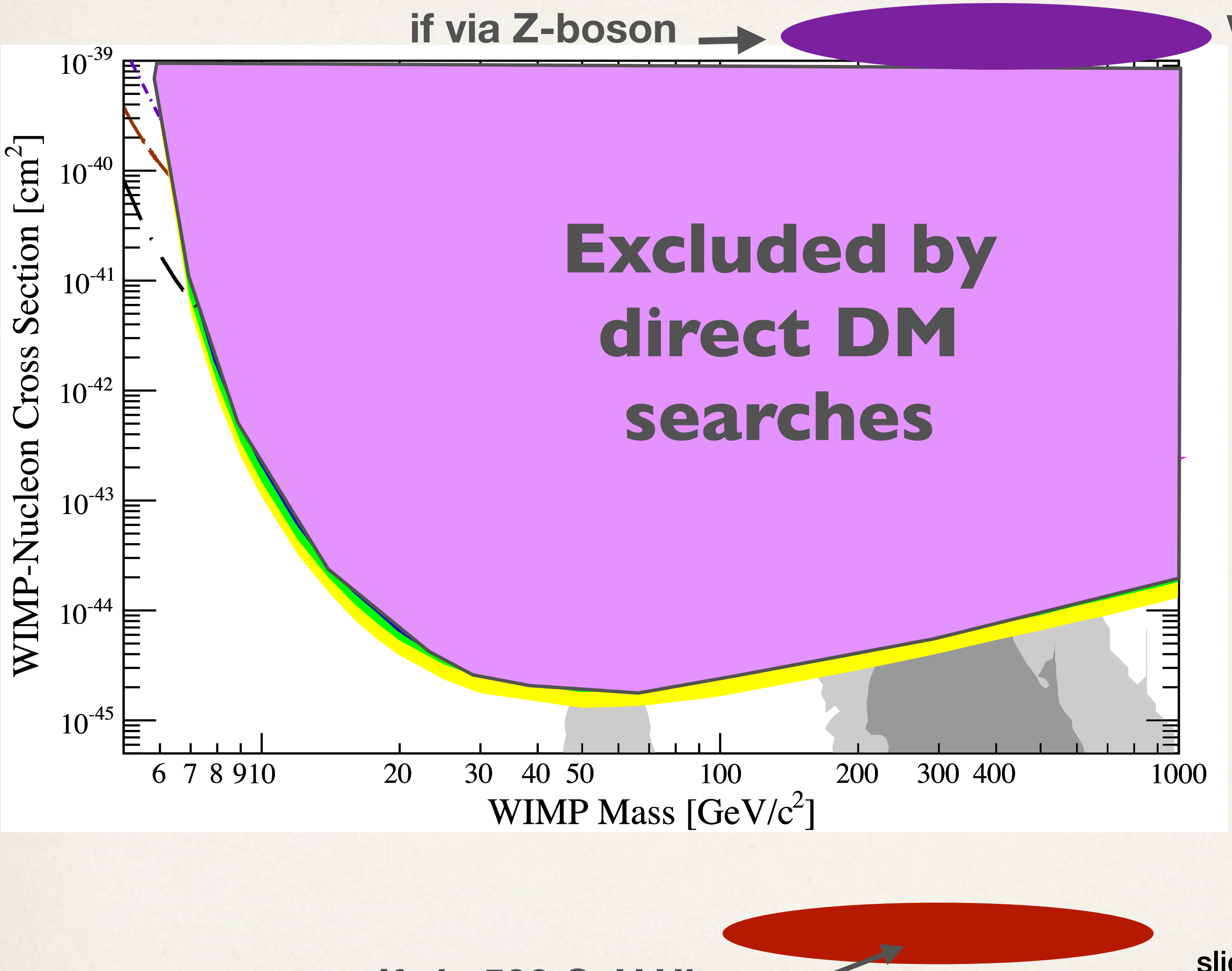


via the Higgs boson?

Direct dark matter detection via the Higgs portal?

if via Z-boson

weak interactions are not weak enough!

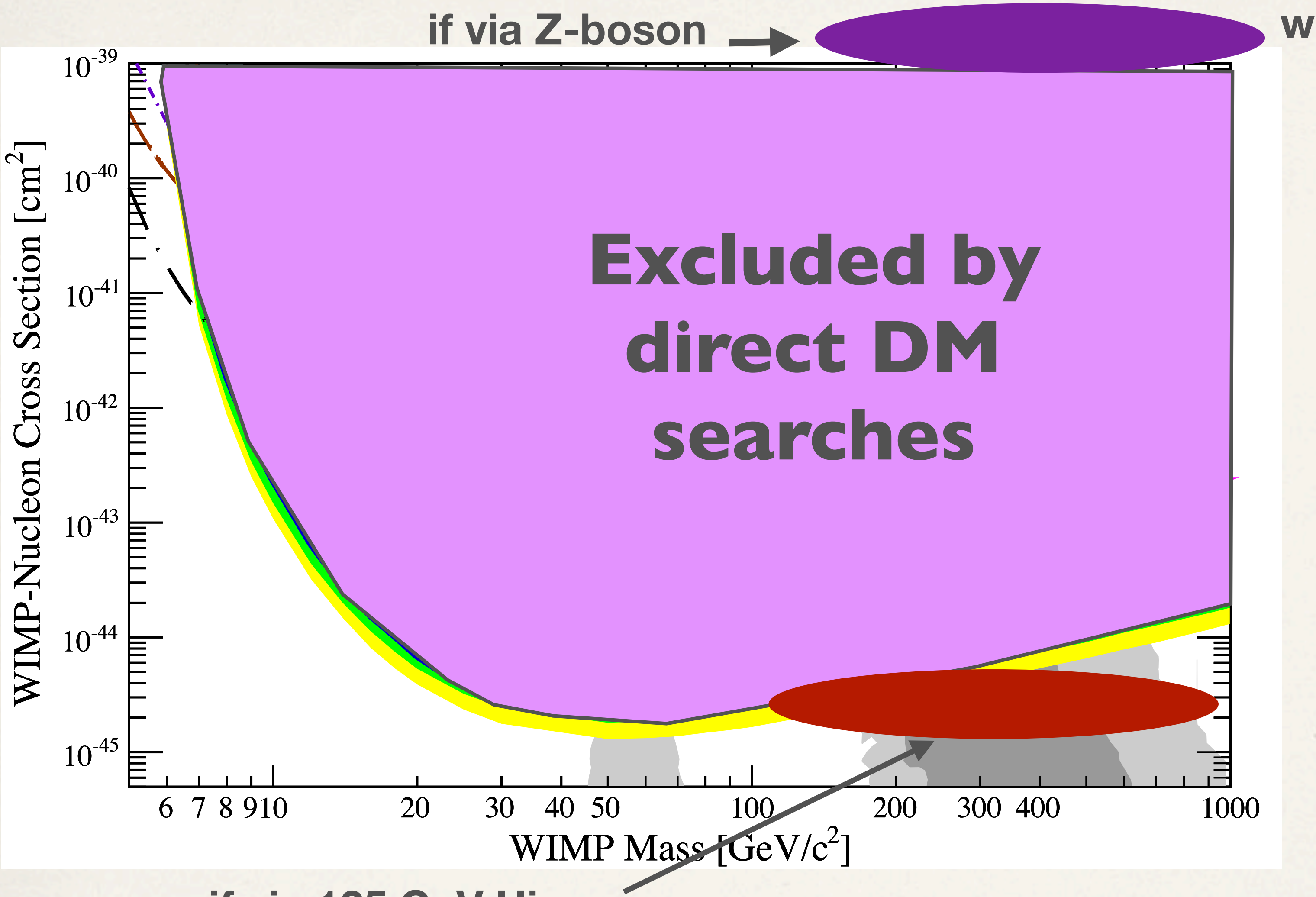


assuming here that DM is not Majorana fermions

If via 500 GeV Higgs

slide adapted from Neal Weiner

Direct dark matter detection via the Higgs portal?



if via Z-boson →

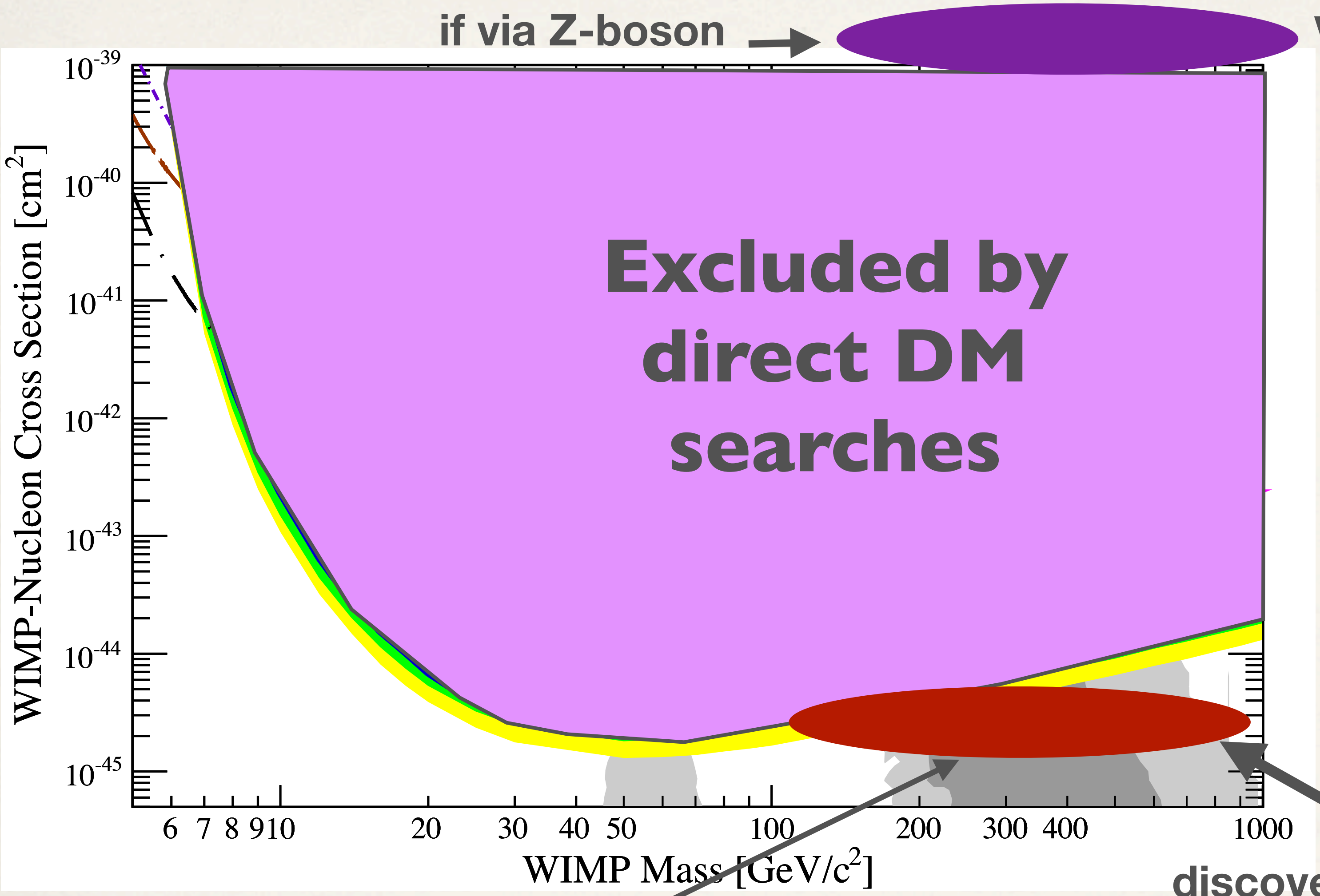
weak interactions are not weak enough!

assuming here that DM is not Majorana fermions

if via 125 GeV Higgs

slide adapted from Neal Weiner

Direct dark matter detection via the Higgs portal?



weak interactions are not weak enough!

assuming here that DM is not Majorana fermions

discovery or exclusion in the next few years!

if via 125 GeV Higgs

slide adapted from Neal Weiner

Higgs portal Dark Matter relic density

- For reasonable values of the Higgs portal coupling and O(100) GeV WIMP mass, can also get the “correct” WMAP/Planck relic density of dark matter

A. Djouadi, O. Lebedev, Y. Mambrini, J. Quevillon, arXiv:1112.3299

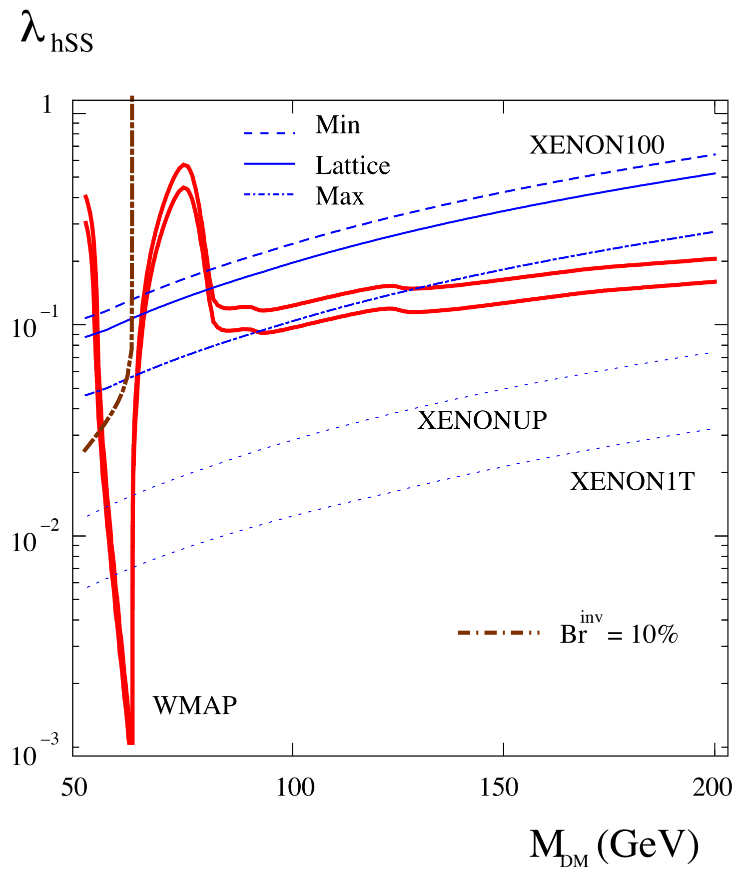
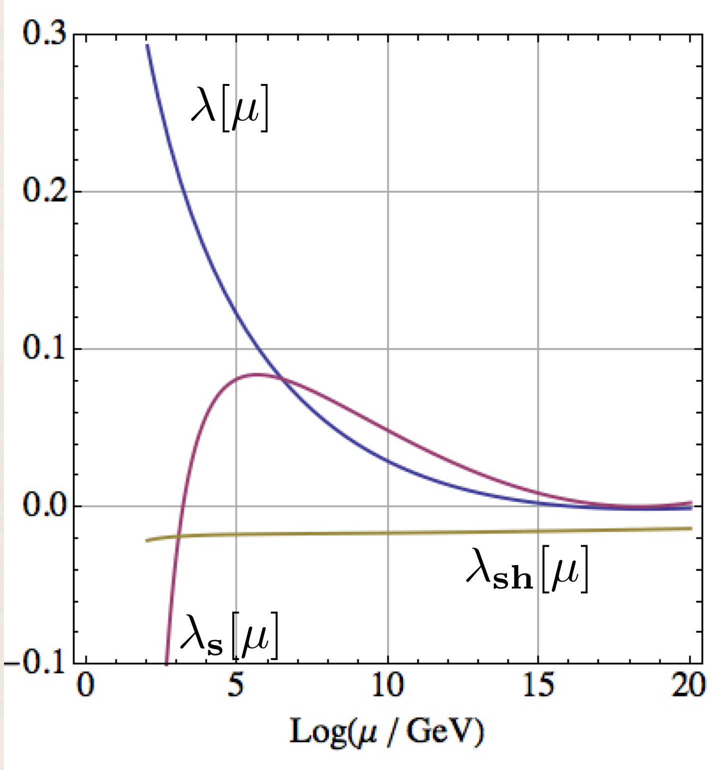


FIG. 1. Scalar Higgs-portal parameter space allowed by WMAP (between the solid red curves), XENON100 and $BR^{inv} = 10\%$ for $m_h = 125$ GeV. Shown also are the prospects for XENON upgrades.

generating the electroweak scale radiatively from the dark matter

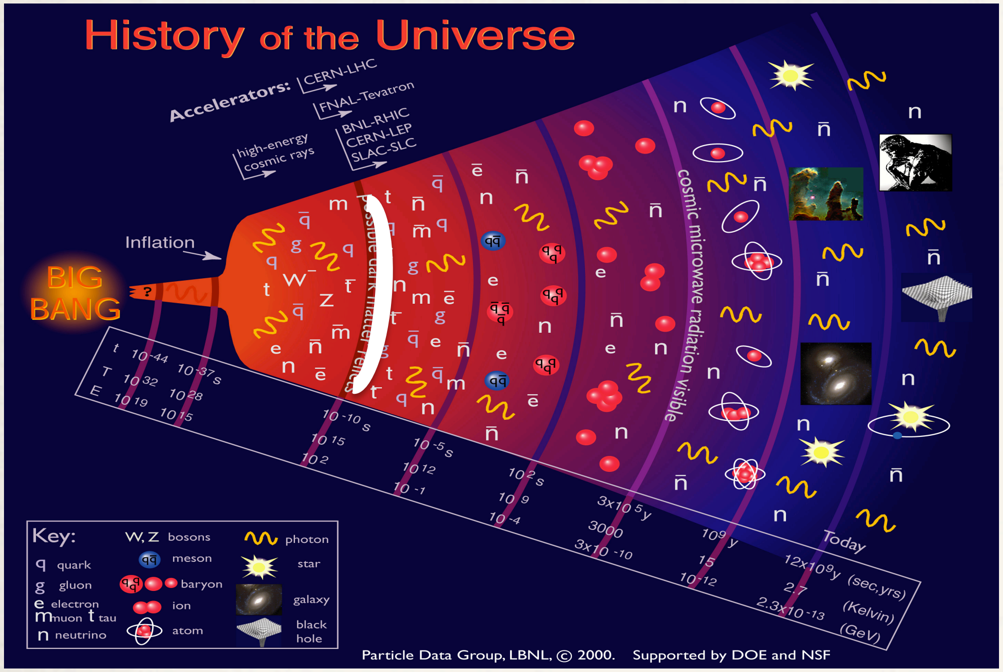


$$\mathbf{V_0(H,S)} = \frac{\mathbf{1}}{\mathbf{2}}\lambda|\mathbf{H}|^{\mathbf{4}} + \lambda_{\mathbf{sh}}|\mathbf{H}|^{\mathbf{2}}|\mathbf{S}|^{\mathbf{2}} + \frac{\mathbf{1}}{\mathbf{2}}\lambda_{\mathbf{s}}|\mathbf{S}|^{\mathbf{4}}$$

- Using the Higgs portal coupling, can make many simple viable models of dark matter
- The “dark matter scale” can be generated radiatively
- Triggering also EWSB at a nearby scale
- May or may not have an additional radiative instability at very high energies

Altmannshofer, Bardeen, Carena, JL
see also Hambye, Strumia

Higgs and the Mystery of our Existence



Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

- there was a big matter-antimatter battle in the early universe
- baryonic matter won, but just barely

Matter

10,000,000,001

Antimatter

10,000,000,000

$$\boxed{\eta = n_B / n_\gamma \approx 6.10^{-10}}$$

Did the Higgs trigger the genesis of matter?

- Some event in the early universe triggered either baryogenesis or leptogenesis
- We now know that there was an electroweak phase transition corresponding to the Higgs field turning itself on to its EWSB vev
- Even in the SM, this event has all the ingredients to generate a matter excess:
  - B and L violation (nonperturbatively)
  - Nonequilibrium conditions (1st order phase transition)
  - CP violation

Sakharov's Conditions

$$\Gamma_{\Delta B\neq 0} \cong \beta_0 \, \mathrm{T} \exp(-\mathrm{E}_{\mathrm{sph}}(\mathrm{T})/\mathrm{T})$$

$$\mathrm{E}_{\mathrm{sph}} \cong 8\pi \, \mathrm{v(T)}/\mathrm{g}$$

Did the Higgs trigger the genesis of matter?

- Some event in the early universe triggered either baryogenesis or leptogenesis
- We now know that there was an electroweak phase transition corresponding to the Higgs field turning itself on to its EWSB vev
- Even in the SM, this event has all the ingredients to generate a matter excess:
  - B and L violation (nonperturbatively)
  - Nonequilibrium conditions (1st order phase transition)
  - CP violation

Sakharov's Conditions

$$\Gamma_{\Delta B \neq 0} \cong \beta_0 \, T \exp(-E_{sph}(T)/T)$$

$$E_{sph} \cong 8 \pi \, v(T) / g$$

But the SM-generated asymmetry is much too small

Electroweak Baryogenesis

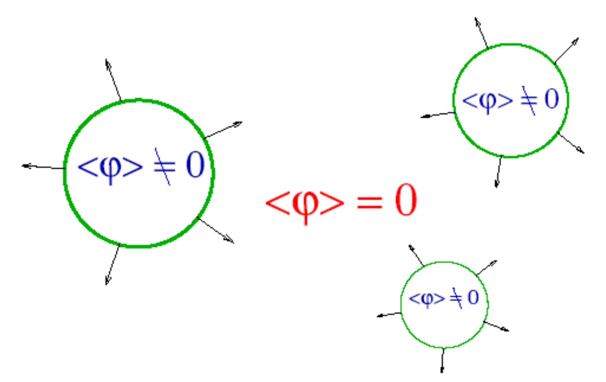
Kuzmin, Rubakov, Shaposhnikov;
Cohen, Kaplan, Nelson;
Carena, Quiros, Riotto, Vilia, Wagner

$$\Gamma_{\Delta B\neq 0} \cong \beta_0 \, \mathrm{T} \exp(-\mathrm{E}_{\mathrm{sph}}(\mathrm{T})/\mathrm{T})$$

$$\mathrm{E}_{\mathrm{sph}} \cong 8\pi \, \mathrm{v}(\mathrm{T})/\mathrm{g}$$

If $n_{\mathrm{B}} \neq 0$ generated at T_n

$$\frac{n_B}{s} = \frac{n_B(T_n)}{s}\exp\left(-\frac{10^{16}}{\mathrm{T}_n(\mathrm{GeV})}\exp\left(-\frac{\mathrm{E}_{\mathrm{sph}}(\mathrm{T}_n)}{\mathrm{T}_n}\right)\right)$$

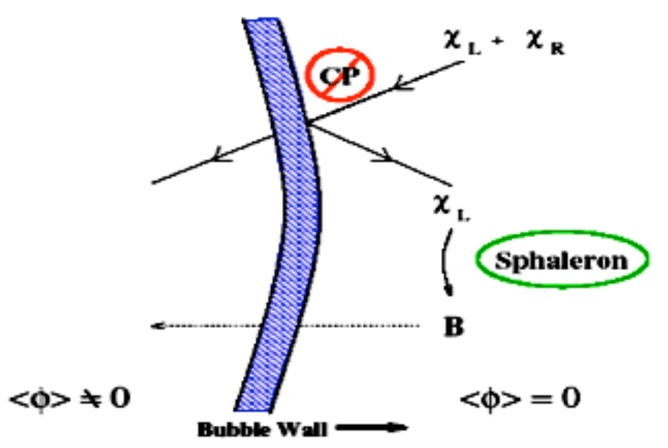


Not all vacuum instabilities are bad!

To preserve the generated baryon asymmetry:
strong first order phase transition:

$$\mathrm{v}(T_n)/T_n > 1$$

Baryon number violating processes out of equilibrium in the broken phase



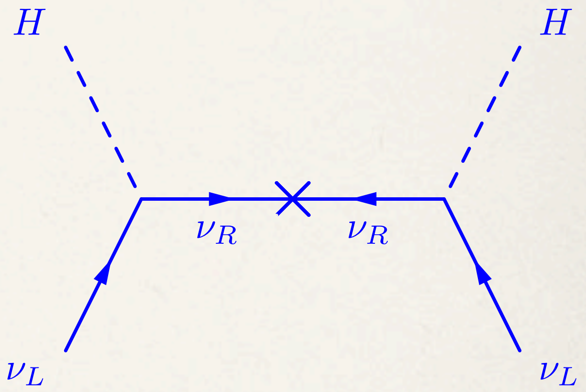
- Sphalerons violate B+L but act only on left-handed fields
- Need CP violation in the symmetric phase to create an initial chiral baryon asymmetry

Testing Electroweak Baryogenesis

- Successful Electroweak Baryogenesis requires new physics at the Terascale:
    - New particles that couple strongly to the Higgs
    - New sources of CP violation appearing in the Higgs sector
    - Could be a two-stage process involving the dark sector, as in models of asymmetric dark matter
- Implies discoveries for the LHC and ILC!
- New sources of CP violation also relevant to EDM searches
- Strong 1st order phase transition -> gravity wave signature

Higgs connections

- Does the Higgs destabilize the vacuum
- What is the origin of the electroweak scale
- Is there a Higgs portal to dark matter
- Is the Higgs sector responsible for the genesis of matter in the early universe
- How does the Higgs talk to neutrinos
- Extra credit: is the Higgs related to inflation or dark energy



→ **Motivates a global experimental effort on all three "frontiers" of particle physics: Energy, Intensity, Cosmic**

ILC on the launchpad

- The Higgs discovery marks the dawn of new era
- ILC, fueled by a global program on many fronts, should unlock some of the deepest secrets of Nature