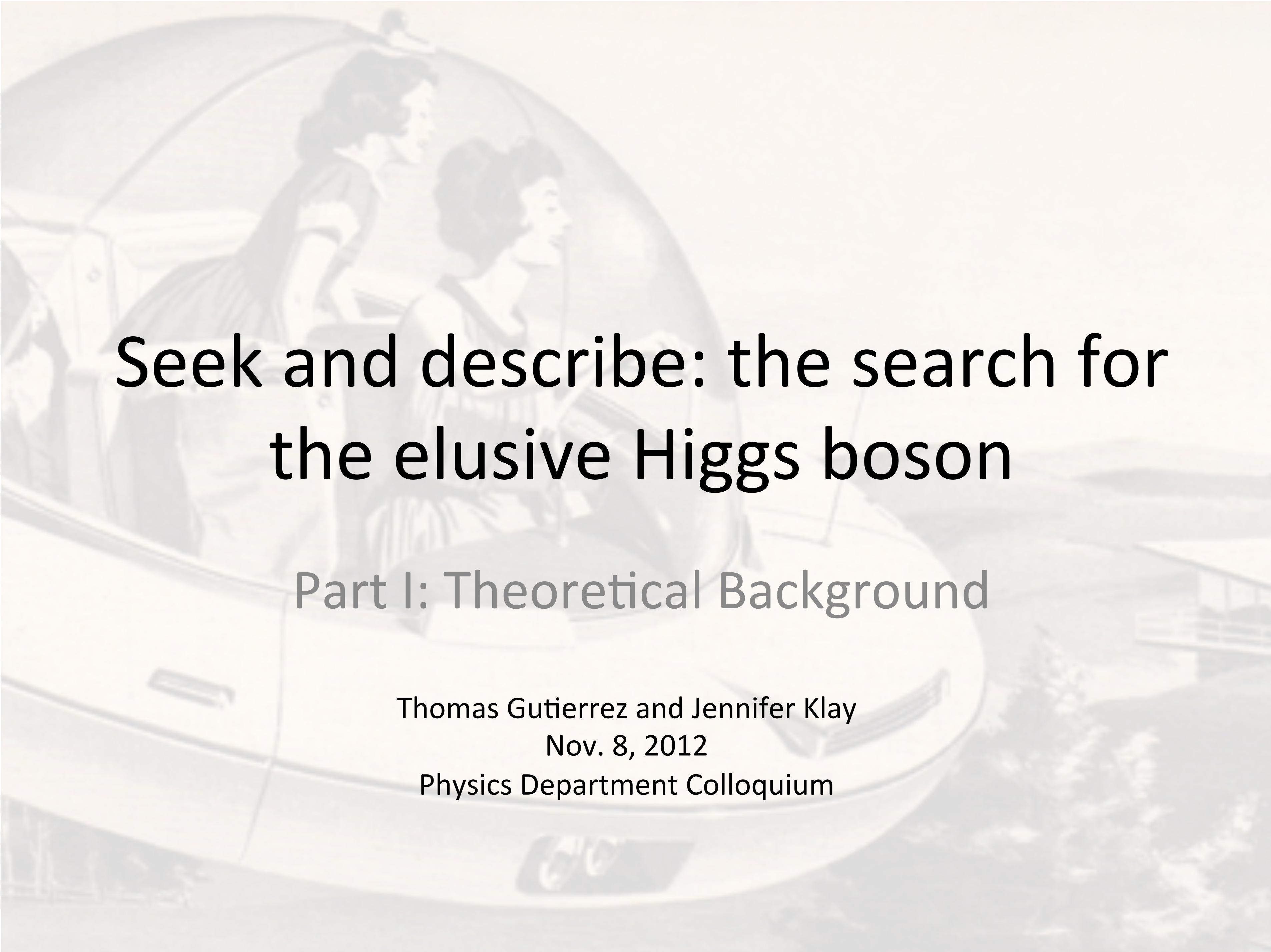


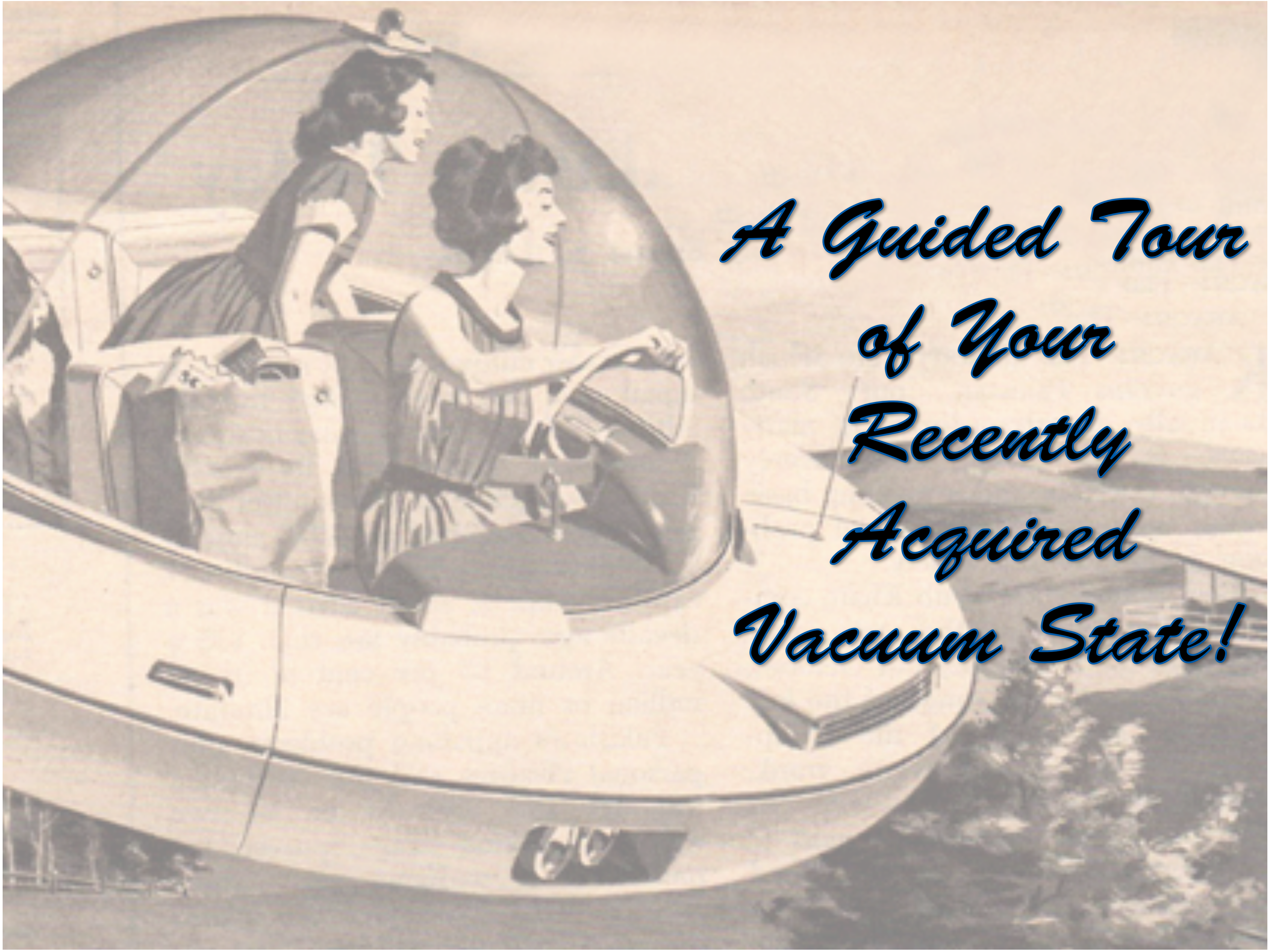
Seek and describe: the search for the elusive Higgs boson

Part I: Theoretical Background

Thomas Gutierrez and Jennifer Klay

Nov. 8, 2012

Physics Department Colloquium


A Guided Tour
of Your
Recently
Acquired
Vacuum State!

Congratulations!

- Welcome <USERNAME> to your quantum ground state known affectionately as “The Vacuum”
  - Your participation as a sentient excitation of The Vacuum surely must give you and your family great pride
  - If properly cared for and understood, you may experience many decades of enjoyment from it

My goal in ≈23 minutes

- Introduce the Standard Model of particle physics
- Develop an intuition for mass, fields, and particles
- Introduce the Higgs mechanism
- Provide a segue into Prof. Klay's experimental Higgs talk
- Shameless advertisement for 403 in the winter

The Big Picture

- Can the laws of physics we observe locally be organized into a single framework?
  - Yes*. The Standard Model.
  - But, paraphrasing Deep Thought, “There is an answer, but I really don’t think you are going to like it.”

*Well, mostly “yes.” Piss off gravity, ever the “work in progress.”

The Problem

- We are living near a ground state that make the laws we observe appear complicated
- Hypothesis: The global properties of the laws of physics are very straightforward
- Through phase transitions, the character of the law changes, hiding the simplicity

Front Matter

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin =1/2

Flavor	Mass GeV/c^2	Electric charge
ν_L lightest neutrino*	$(0-0.13)\times10^{-9}$	0
e electron	0.000511	–1
ν_M middle neutrino*	$(0.009-0.13)\times10^{-9}$	0
μ muon	0.106	–1
ν_H heaviest neutrino*	$(0.04-0.14)\times10^{-9}$	0
τ tau	1.777	–1

Quarks spin =1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.002	2/3
d down	0.005	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	173	2/3
b bottom	4.2	–1/3

?

Why are these masses so different?

Getting Started: Bosons

BOSONS force carriers
spin = 0, 1, 2, …

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.39	–1
W^+ W bosons	80.39	+1
Z^0 Z boson	91.188	0

Strong (color) spin =1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

?

Expect all masses to be zero?!

Hello World: Pushes and Pulls

Properties of the Interactions

The strengths of the interactions (forces) are shown relative to the strength of the electromagnetic force for two u quarks separated by the specified distances.

Property	Gravitational Interaction	Weak Interaction (Electroweak)	Electromagnetic Interaction	Strong Interaction
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge
Particles experiencing:	All	Quarks, Leptons	Electrically Charged	Quarks, Gluons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons
Strength at 10^{-18} m	10^{-41}	0.8	1	25
Strength at 3×10^{-17} m	10^{-41}	10^{-4}	1	60

Why are their strengths so different?

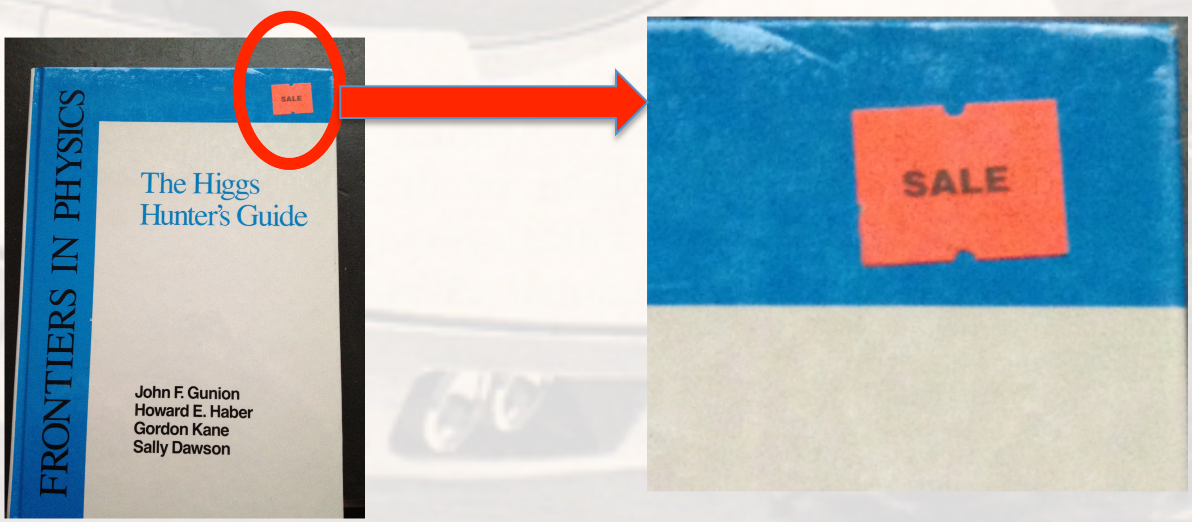
?

$$V_W = -k\frac{e^{-Mr}}{r}$$

$$V_S \sim -\frac{a}{r} + br$$

The Last Bit: Higgs

- All fundamental particles started off in a highly degenerate zero-mass state
- An extra field (Higgs) turned on spontaneously and split all the mass states into what we now observe



State of Our Vacuum!

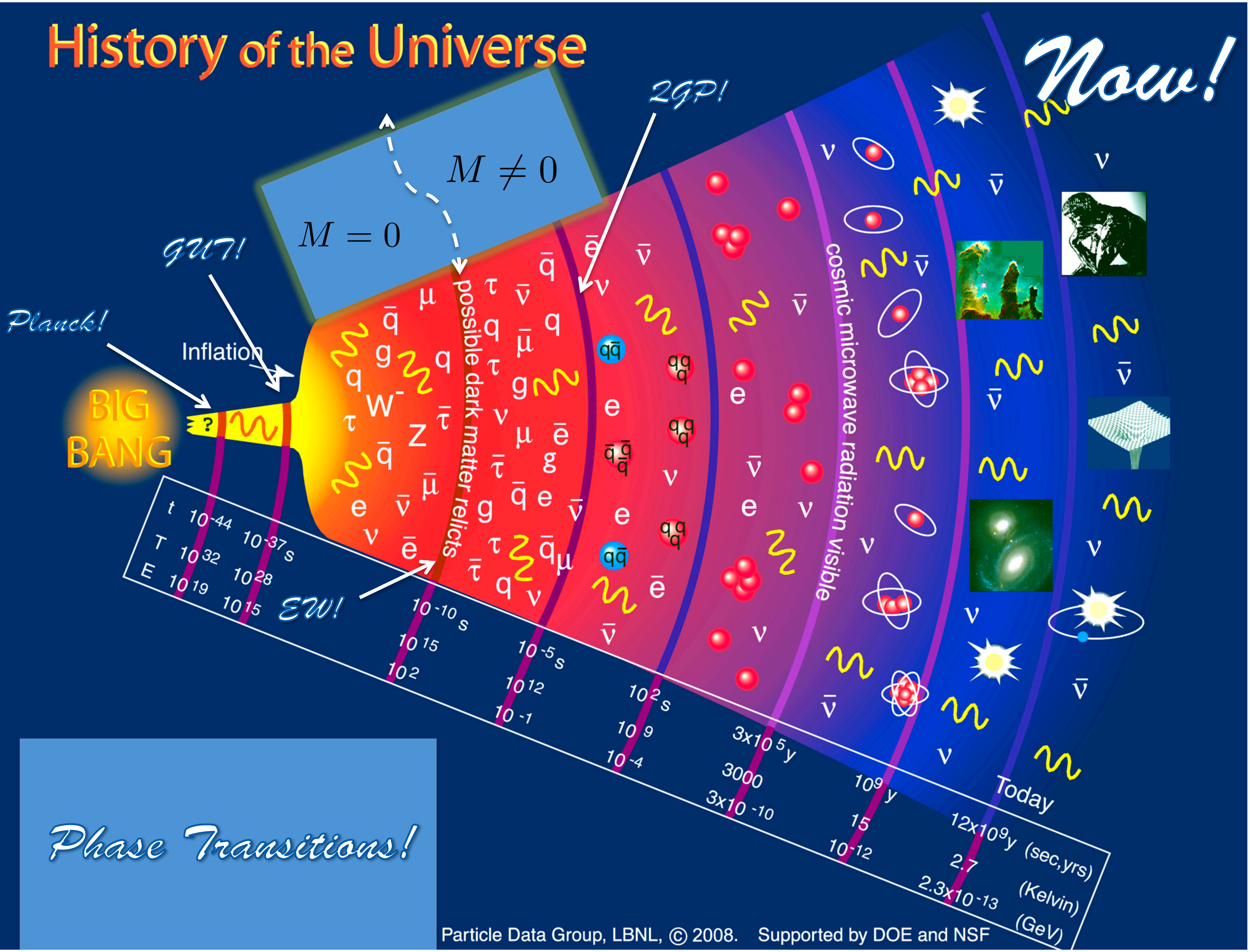
18 free parameters!

61 fundamental particles!

$$\mathcal{L}_{\rm SM} = \frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc} f^{ade} g^b_\mu g^c_\nu g^d_\mu g^e_\nu + \frac{1}{2} i g_s^2 (\bar{q}^\sigma_i \gamma^\mu q^\sigma_j) g^a_\mu +$$
$$\bar{G}^a \partial^2 G^a + g_s f^{abc}\partial_\mu \bar{G}^a G^b g^c_\mu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - M^2 W^+_\mu W^-_\mu - \frac{1}{2}\partial_\nu Z^0_\mu \partial_\nu Z^0_\mu - \frac{1}{2c_w^2} M^2 Z^0_\mu Z^0_\mu -$$
$$\frac{1}{2}\partial_\mu A_\nu \partial_\mu A_\nu - \frac{1}{2}\partial_\mu H \partial_\mu H - \frac{1}{2} m_h^2 H^2 - \partial_\mu \phi^+ \partial_\mu \phi^- - M^2 \phi^+ \phi^- - \frac{1}{2}\partial_\mu \phi^0 \partial_\mu \phi^0 -$$
$$\frac{1}{2c_w^2} M \phi^0 \phi^0 - \beta_h \left[\frac{2M^2}{g^2} + \frac{2M}{g} H + \frac{1}{2}(H^2 + \phi^0\phi^0 + 2\phi^+\phi^-)\right] + \frac{2M^4}{g^2}\alpha_h - i g c_w [\partial_\nu Z^0_\mu (W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - Z^0_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + Z^0_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - i g s_w [\partial_\nu A_\mu (W^+_\mu W^-_\nu -$$
$$W^+_\nu W^-_\mu) - A_\nu (W^+_\mu \partial_\nu W^-_\mu - W^-_\mu \partial_\nu W^+_\mu) + A_\mu (W^+_\nu \partial_\nu W^-_\mu - W^-_\nu \partial_\nu W^+_\mu)] - \frac{1}{2} g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu +$$
$$\frac{1}{2} g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2 c_w^2 (Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2 (A_\mu W^+_\mu A_\nu W^-_\nu -$$
$$A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w [A_\mu Z^0_\nu (W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - 2 A_\mu Z^0_\mu W^+_\nu W^-_\nu] - g\alpha [H^3 +$$
$$H\phi^0\phi^0 + 2H\phi^+\phi^-] - \frac{1}{8} g^2 \alpha_h [H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- +$$
$$2(\phi^0)^2 H^2] - g M W^+_\mu W^-_\mu H - \frac{1}{2} g \frac{M}{c_w^2} Z^0_\mu Z^0_\mu H - \frac{1}{2} i g [W^+_\mu (\phi^0 \partial_\mu \phi^- - \phi^- \partial_\mu \phi^0) -$$
$$W^-_\mu (\phi^0 \partial_\mu \phi^+ - \phi^+ \partial_\mu \phi^0)] + \frac{1}{2} g [W^+_\mu (H \partial_\mu \phi^- - \phi^- \partial_\mu H) - W^-_\mu (H \partial_\mu \phi^+ - \phi^+ \partial_\mu H)] +$$
$$\frac{1}{2} g \frac{1}{c_w} (Z^0_\mu (H \partial_\mu \phi^0 - \phi^0 \partial_\mu H) - i g \frac{s_w^2}{c_w} M Z^0_\mu (W^+_\mu \phi^- - W^-_\mu \phi^+) + i g s_w M A_\mu (W^+_\mu \phi^- -$$
$$W^-_\mu \phi^+) - i g \frac{1 - 2c_w^2}{2c_w} Z^0_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) + i g s_w A_\mu (\phi^+ \partial_\mu \phi^- - \phi^- \partial_\mu \phi^+) -$$
$$\frac{1}{4} g^2 W^+_\mu W^-_\mu [H^2 + (\phi^0)^2 + 2\phi^+\phi^-] - \frac{1}{4} g^2 \frac{1}{c_w^2} Z^0_\mu Z^0_\mu [H^2 + (\phi^0)^2 + 2(2s_w^2 - 1)^2 \phi^+\phi^-] -$$
$$\frac{1}{2} g^2 \frac{s_w^2}{c_w} Z^0_\mu \phi^0 (W^+_\mu \phi^- + W^-_\mu \phi^+) - \frac{1}{2} i g^2 \frac{s_w^2}{c_w} Z^0_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) + \frac{1}{2} g^2 s_w A_\mu \phi^0 (W^+_\mu \phi^- +$$
$$W^-_\mu \phi^+) + \frac{1}{2} i g^2 s_w A_\mu H (W^+_\mu \phi^- - W^-_\mu \phi^+) - g^2 \frac{s_w}{c_w} (2c_w^2 - 1) Z^0_\mu A_\mu \phi^+\phi^- - g^2 s_w^2 A_\mu A_\mu \phi^+\phi^- -$$
$$\bar{e}^\lambda (\gamma\partial + m_e^\lambda) e^\lambda - \bar{\nu}^\lambda \gamma\partial \nu^\lambda - \bar{u}_j^\lambda (\gamma\partial + m_u^\lambda) u_j^\lambda - \bar{d}_j^\lambda (\gamma\partial + m_d^\lambda) d_j^\lambda + i g s_w A_\mu [-(\bar{e}^\lambda \gamma^\mu e^\lambda) +$$
$$\frac{2}{3}(\bar{u}_j^\lambda \gamma^\mu u_j^\lambda) - \frac{1}{3}(\bar{d}_j^\lambda \gamma^\mu d_j^\lambda)] + \frac{ig}{4c_w} Z^0_\mu [(\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5) \nu^\lambda) + (\bar{e}^\lambda \gamma^\mu (4s_w^2 - 1 - \gamma^5) e^\lambda) +$$
$$(\bar{u}_j^\lambda \gamma^\mu (\frac{4}{3}s_w^2 - 1 - \gamma^5) u_j^\lambda) + (\bar{d}_j^\lambda \gamma^\mu (1 - \frac{8}{3}s_w^2 - \gamma^5) d_j^\lambda)] + \frac{ig}{2\sqrt{2}} W^+_\mu [(\bar{\nu}^\lambda \gamma^\mu (1+\gamma^5) e^\lambda) +$$
$$(\bar{u}_j^\lambda \gamma^\mu (1+\gamma^5) C_{\lambda\kappa} d_j^\kappa)] + \frac{ig}{2\sqrt{2}} W^-_\mu [(\bar{e}^\lambda \gamma^\mu (1+\gamma^5) \nu^\lambda) + (\bar{d}_j^\kappa C^\dagger_{\lambda\kappa} \gamma^\mu (1+\gamma^5) u_j^\lambda)] +$$
$$\frac{ig}{2\sqrt{2}} \frac{m_e^\lambda}{M} [-\phi^+ (\bar{\nu}^\lambda (1-\gamma^5) e^\lambda) + \phi^- (\bar{e}^\lambda (1+\gamma^5) \nu^\lambda)] - \frac{g}{2} \frac{m_e^\lambda}{M} [H(\bar{e}^\lambda e^\lambda) + i\phi^0 (\bar{e}^\lambda \gamma^5 e^\lambda)] +$$
$$\frac{ig}{2M\sqrt{2}} \phi^+ [-m_d^\kappa (\bar{u}_j^\lambda C_{\lambda\kappa} (1-\gamma^5) d_j^\kappa) + m_u^\lambda (\bar{u}_j^\lambda C_{\lambda\kappa} (1+\gamma^5) d_j^\kappa)] + \frac{ig}{2M\sqrt{2}} \phi^- [m_d^\lambda (\bar{d}_j^\lambda C^\dagger_{\lambda\kappa} (1+$$
$$\gamma^5) u_j^\kappa) - m_u^\kappa (\bar{d}_j^\lambda C^\dagger_{\lambda\kappa} (1-\gamma^5) u_j^\kappa)] - \frac{g}{2} \frac{m_u^\lambda}{M} H (\bar{u}_j^\lambda u_j^\lambda) - \frac{g}{2} \frac{m_d^\lambda}{M} H (\bar{d}_j^\lambda d_j^\lambda) + \frac{ig}{2} \frac{m_u^\lambda}{M} \phi^0 (\bar{u}_j^\lambda \gamma^5 u_j^\lambda) -$$
$$\frac{ig}{2} \frac{m_d^\lambda}{M} \phi^0 (\bar{d}_j^\lambda \gamma^5 d_j^\lambda) + \bar{X}^+ (\partial^2 - M^2) X^+ + \bar{X}^- (\partial^2 - M^2) X^- + \bar{X}^0 (\partial^2 - \frac{M^2}{c_w^2}) X^0 +$$
$$\bar{Y} \partial^2 Y + i g c_w W^+_\mu (\partial_\mu \bar{X}^0 X^- - \partial_\mu \bar{X}^+ X^0) + i g s_w W^+_\mu (\partial_\mu \bar{Y} X^- - \partial_\mu \bar{X}^+ Y) + i g c_w W^-_\mu (\partial_\mu \bar{X}^- X^0 -$$
$$\partial_\mu \bar{X}^0 X^+) + i g s_w W^-_\mu (\partial_\mu \bar{X}^- Y - \partial_\mu \bar{Y} X^+) + i g c_w Z^0_\mu (\partial_\mu \bar{X}^+ X^+ - \partial_\mu \bar{X}^- X^-) +$$

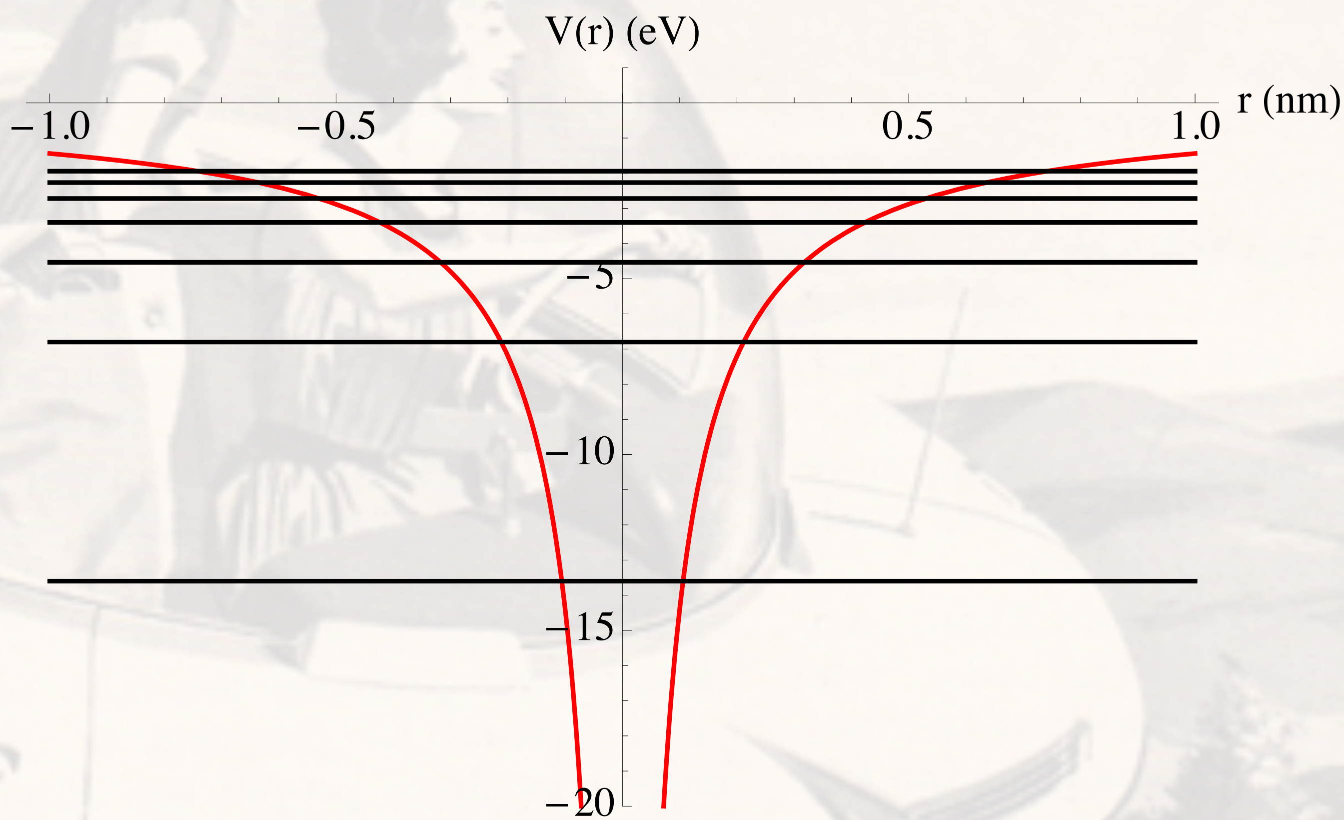
Old Friends

History of the Universe

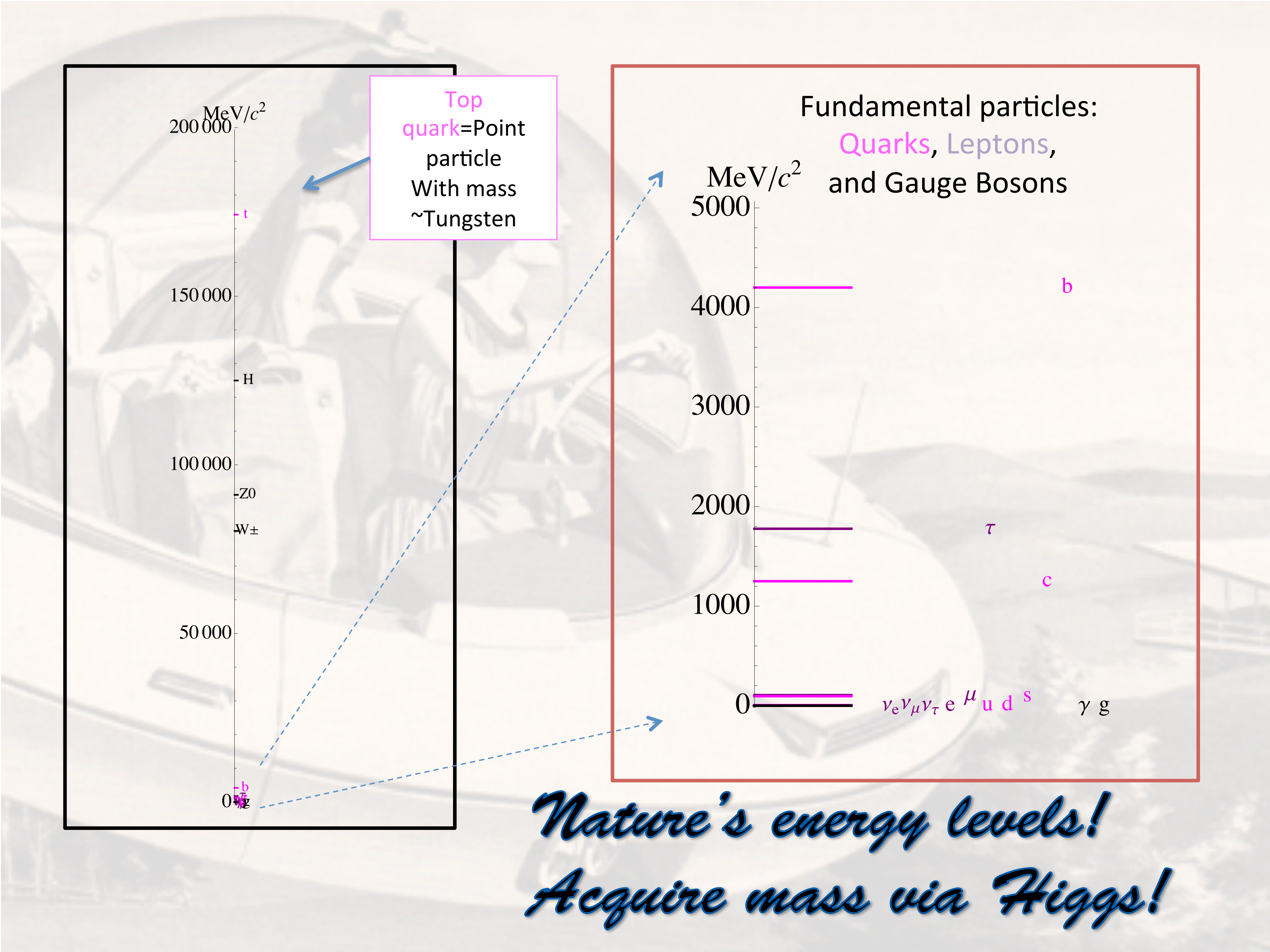


Phase Transitions!

What's Up With Mass?

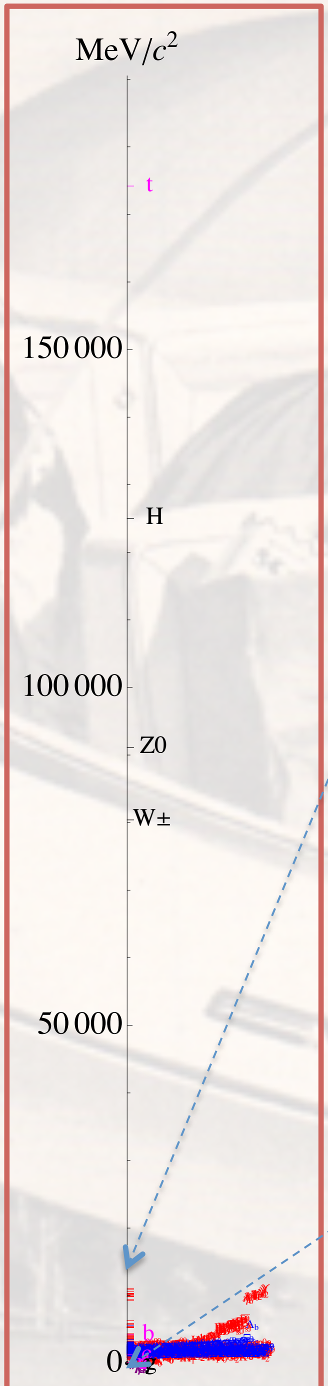


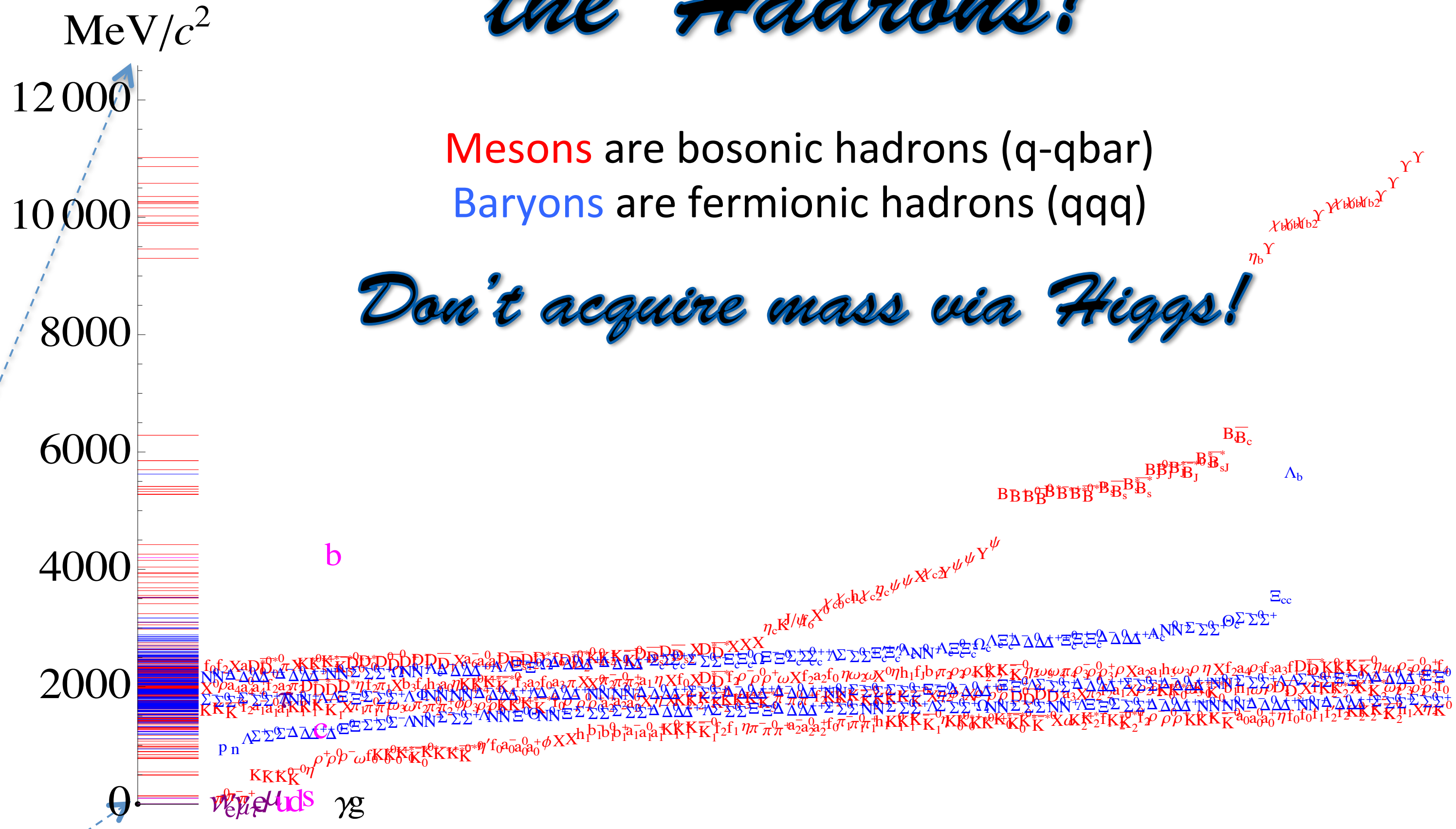
Different mass states of Hydrogen a.k.a. "energy levels";
Mass IS energy; energy levels <u>are</u> mass levels!



MeV/c²
200 000
150 000
100 000
50 000
0
t
H
Z0
W±
b
g
Top quark=Point particle With mass ~Tungsten
Fundamental particles:
Quarks, Leptons,
and Gauge Bosons
MeV/c²
5000
4000
3000
2000
1000
0
b
τ
c
νe νμ ντ e μ u d s
γ g
Nature's energy levels!
Acquire mass via Higgs!

Binding: Your Friends the Hadrons!



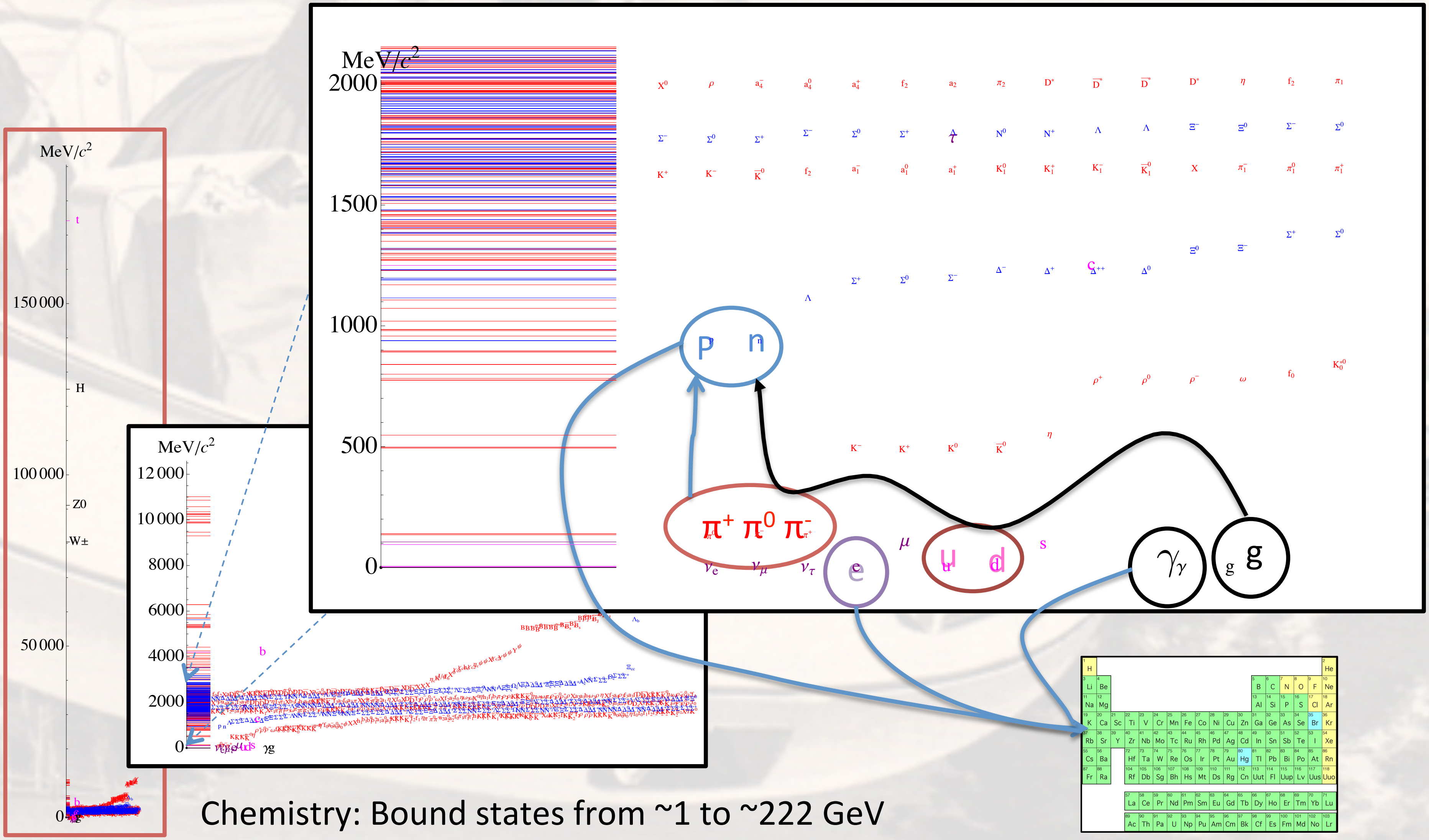


Mesons are bosonic hadrons (q-qbar)

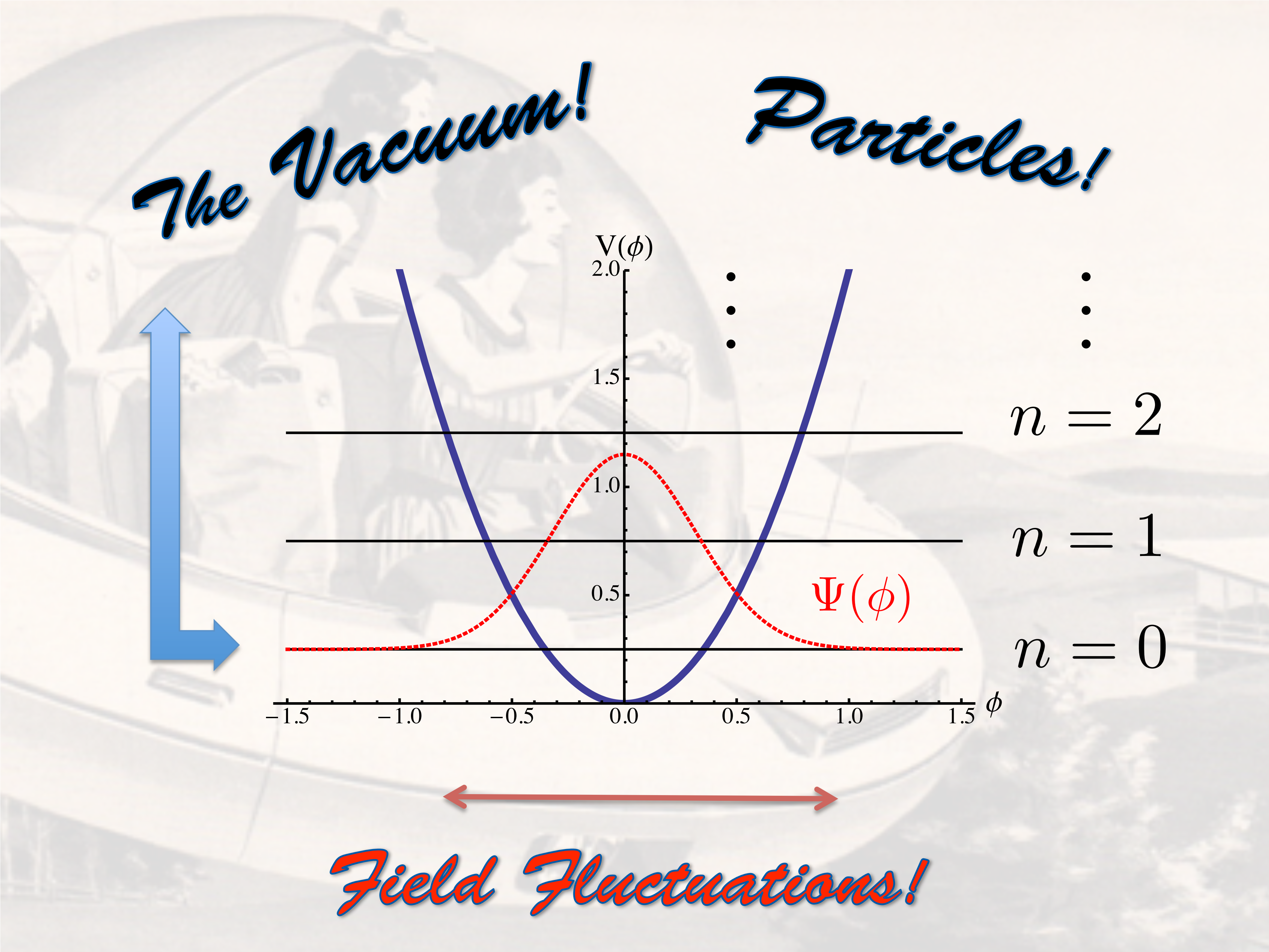
Baryons are fermionic hadrons (qqq)

Don't acquire mass via Higgs!

Mass Scale Tales



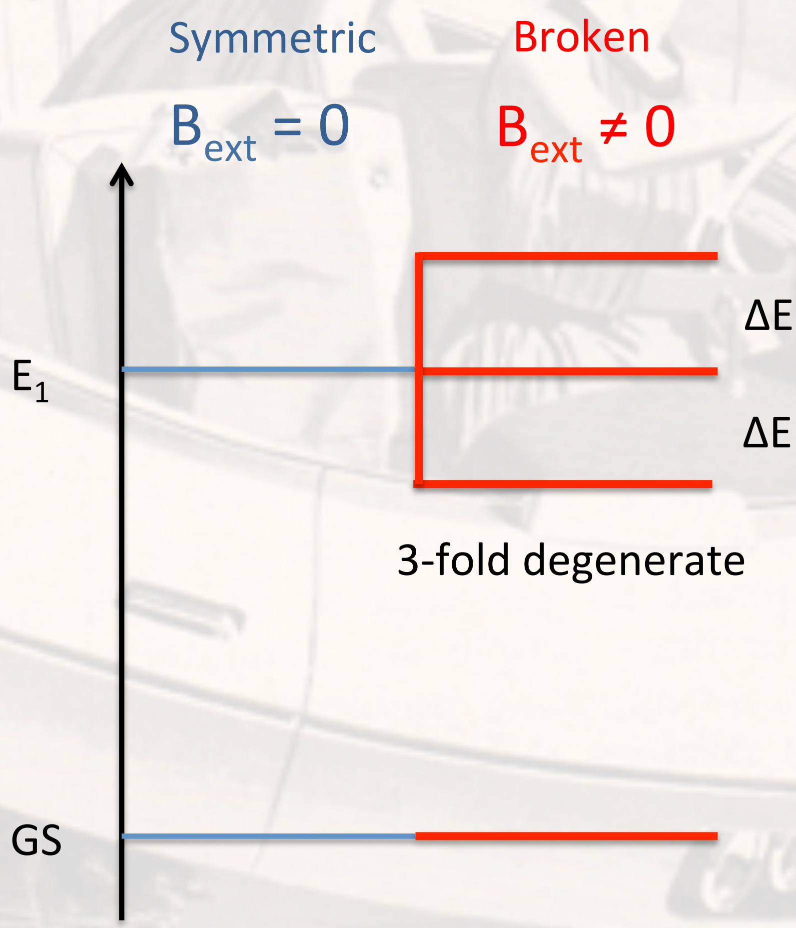
Chemistry: Bound states from ~1 to ~222 GeV



The Vacuum!
Particles!
V(ϕ)
2.0
1.5
1.0
0.5
n = 2
n = 1
n = 0
Ψ(ϕ)
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
ϕ
Field Fluctuations!

Zeeman Effect: A Field Imparting Mass

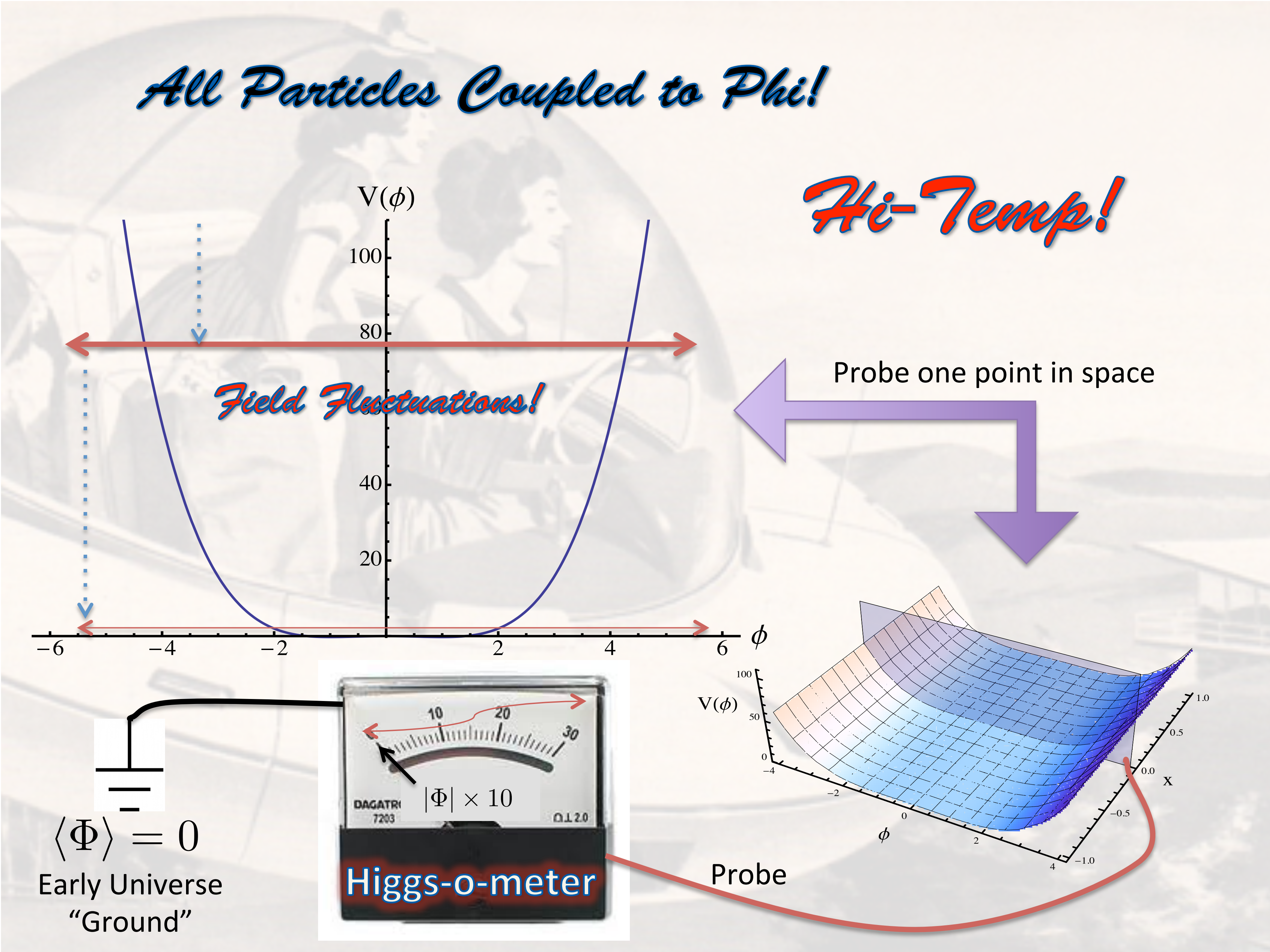
$$U_{\mathrm{L}} = -\mu_{\mathrm{L}} \cdot \vec{B}_{\mathrm{ext}} = \frac{e\hbar}{2m_{\mathrm{e}}} m_l B_{\mathrm{ext}} \propto a B_{\mathrm{ext}}$$

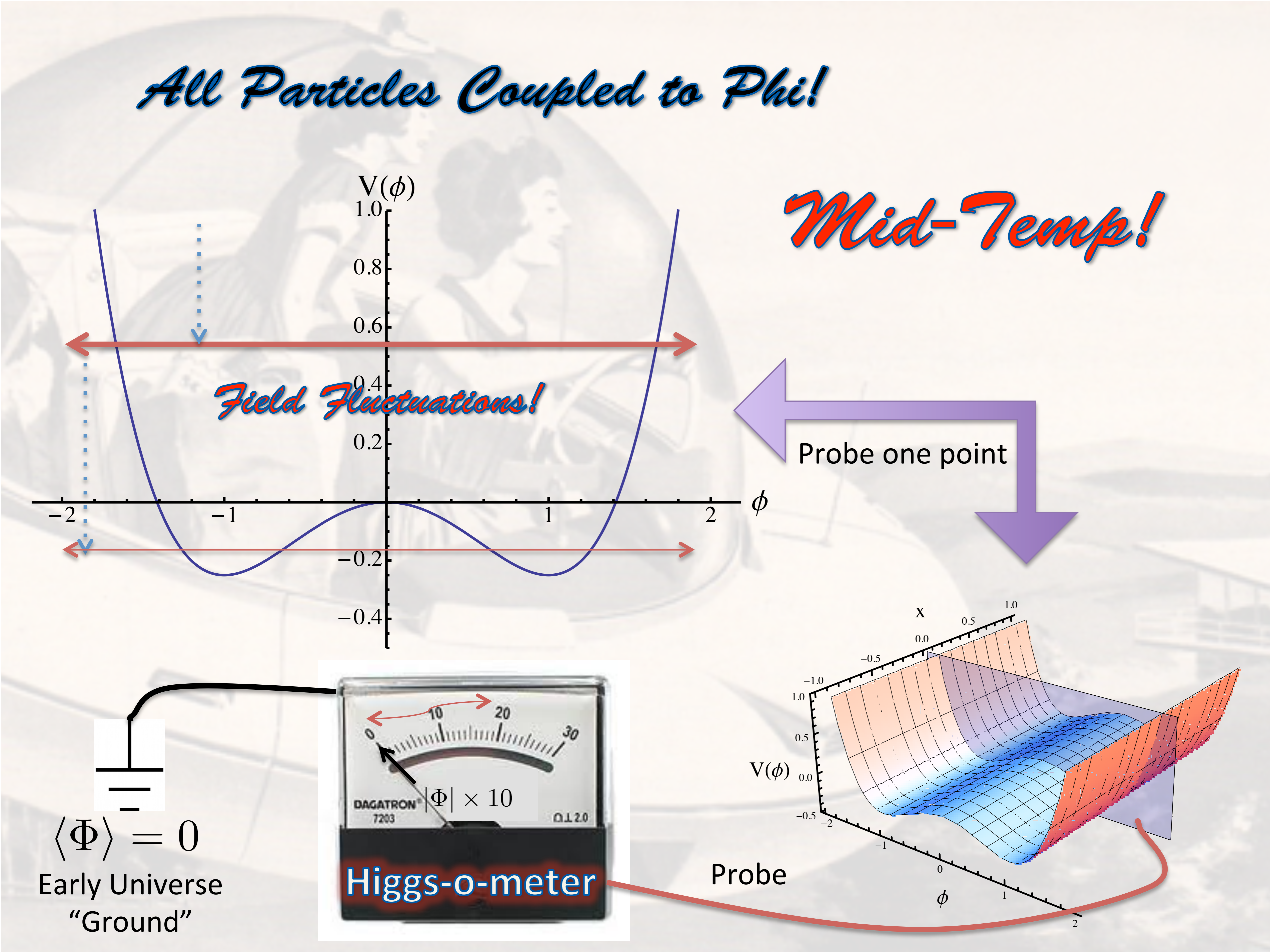


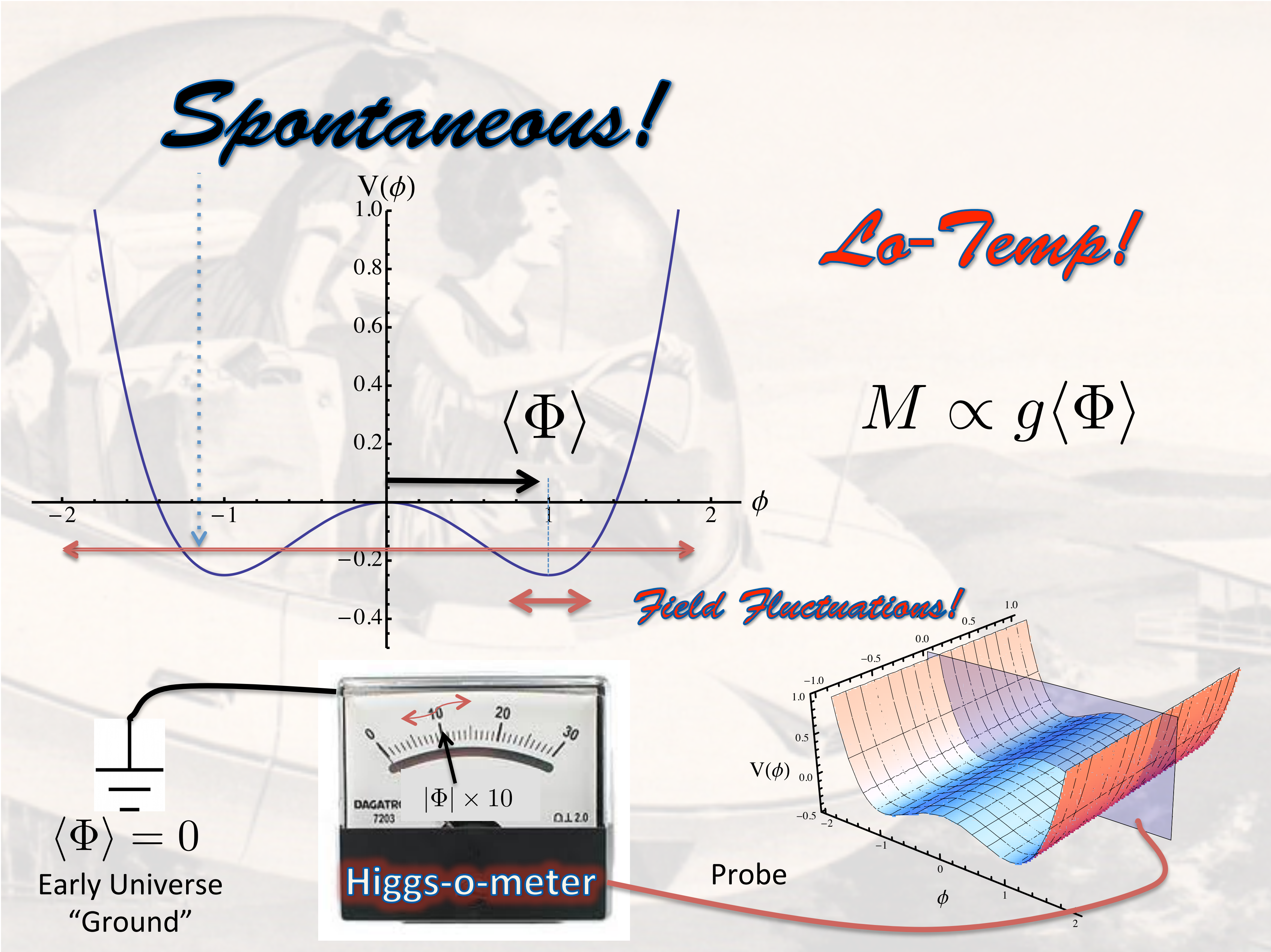
<u>(Non Spontaneous) Symmetry Breaking</u>

An applied external field breaks the symmetry of lab by selecting a preferred direction in space; the previously symmetric states respond Differently to B and identify themselves as unique;

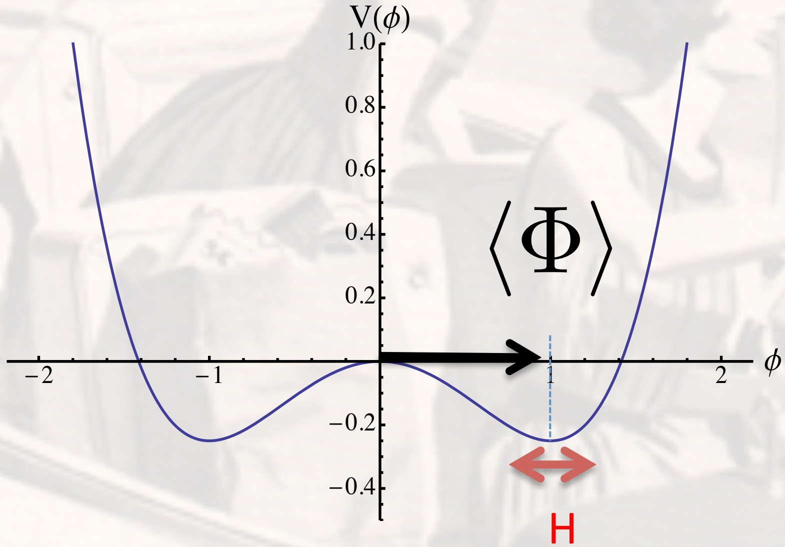
A separation in energy is also a separation in mass


All Particles Coupled to Phi!
Hi-Temp!
V(ϕ)
100
80
40
20
−6
−4
−2
2
4
6
ϕ
Field Fluctuations!
Probe one point in space
V(ϕ)
x
Probe
10
20
30
|Φ| × 10
DAGATR
7203
Higgs-o-meter
⟨Φ⟩ = 0
Early Universe
“Ground”


All Particles Coupled to Phi!
Mid-Temp!
V(ϕ)
1.0
0.8
0.6
0.4
0.2
−0.2
−0.4
−2
−1
1
2
ϕ
Field Fluctuations!
Probe one point
10
20
30
DAGATRON
7203
|Φ| × 10
Higgs-o-meter
⟨Φ⟩ = 0
Early Universe
"Ground"
Probe
x
V(ϕ)
ϕ


Spontaneous!
Lo-Temp!
V(ϕ)
1.0
0.8
0.6
0.4
0.2
−0.2
−0.4
−2
−1
1
2
ϕ
$\langle \Phi \rangle$
$M \propto g\langle \Phi \rangle$
Field Fluctuations!
$|\Phi| \times 10$
$\langle \Phi \rangle = 0$
Early Universe
"Ground"
Higgs-o-meter
Probe

Mass Generation



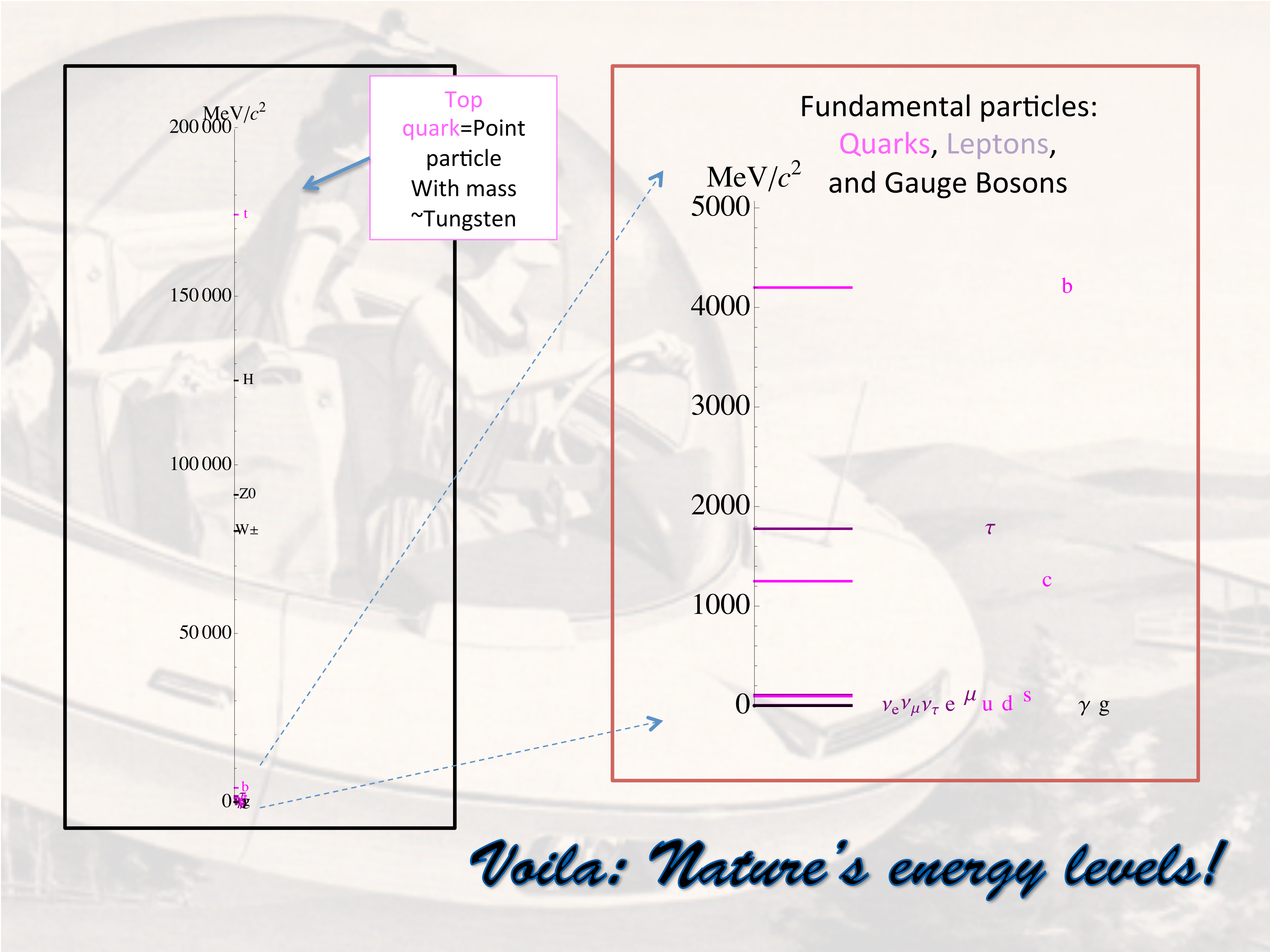
$$M \propto g\langle\Phi\rangle$$

$$U_L = -\mu_{\mathrm{L}} \cdot \vec{B}_{\mathrm{ext}}$$

$$\langle\Phi\rangle = 246\ \mathrm{GeV}$$

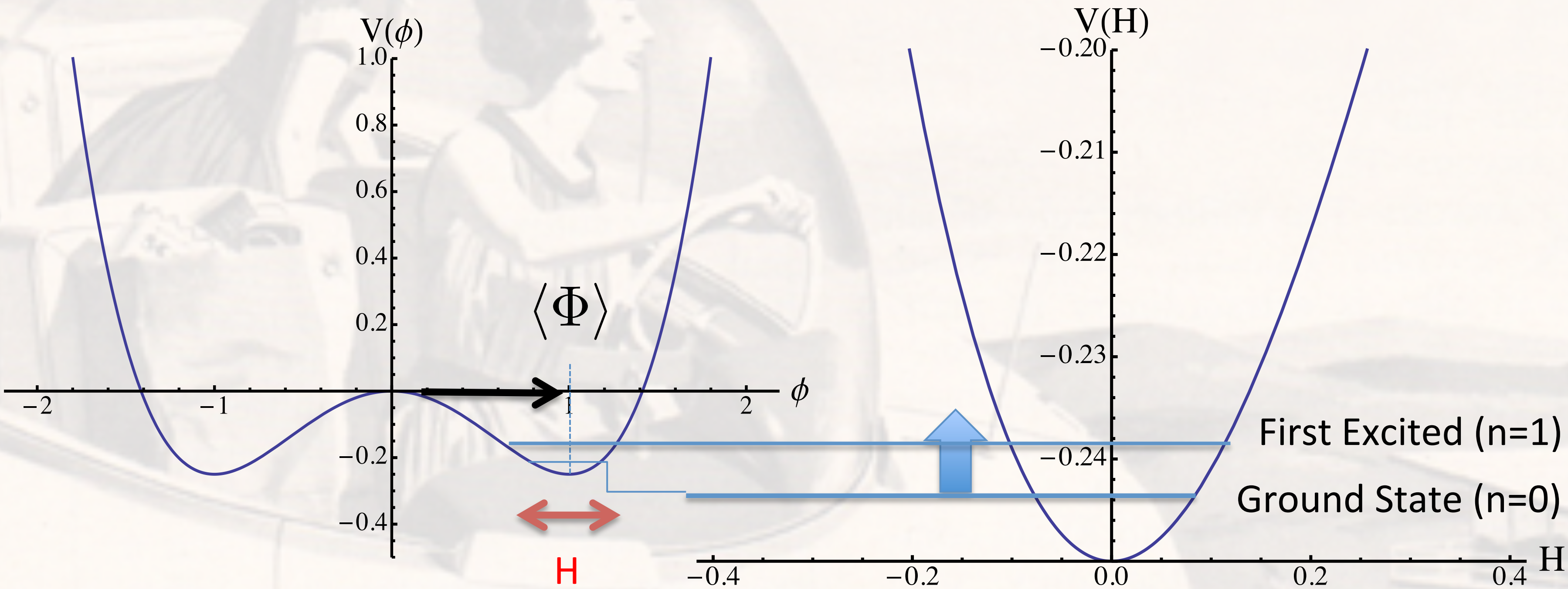
Your Recently Acquired Vacuum State!

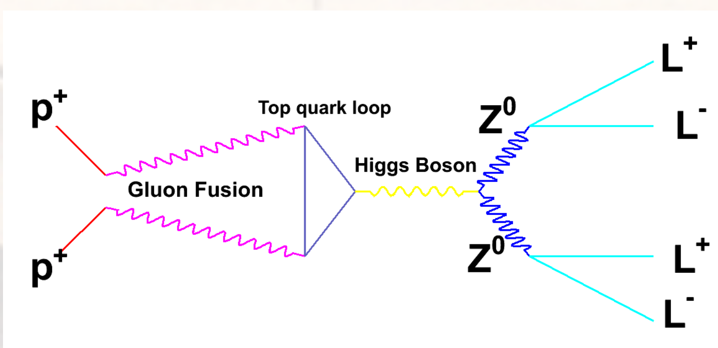
Each individual particle couples to Phi (g) proportional to its mass

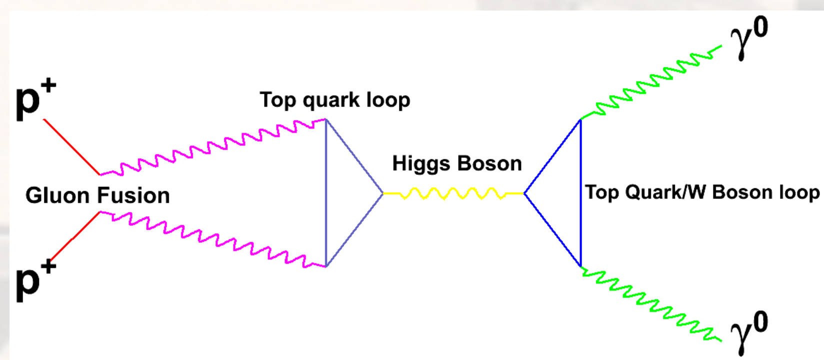


MeV/c^2
200 000
150 000
100 000
50 000
0
t
H
Z0
W±
b
g
Top quark=Point particle With mass ~Tungsten
Fundamental particles: Quarks, Leptons, and Gauge Bosons
MeV/c^2
5000
4000
3000
2000
1000
0
b
τ
c
ν_e ν_μ ν_τ e μ u d s
γ g
Voila: Nature's energy levels!

Physical Higgs Particle







Now: Consult CERN Wizards