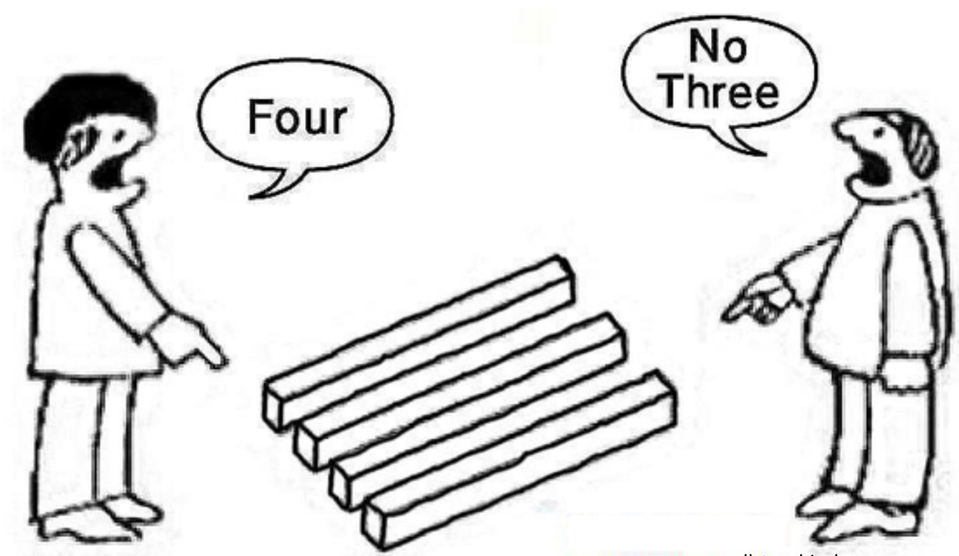
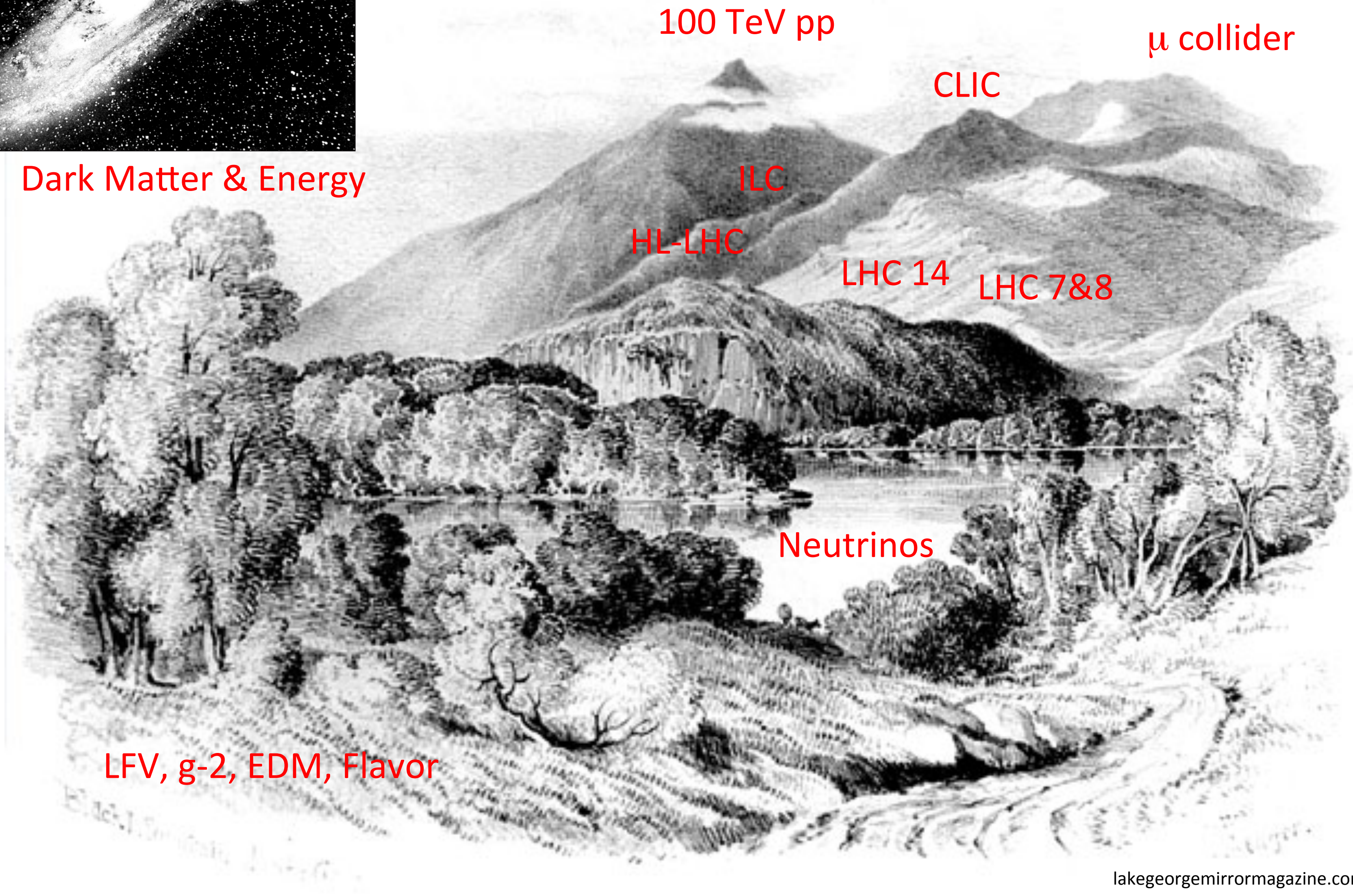


smallstepsbigchanges.com

# HEP: Perspectives

James Wells
University of Michigan, Ann Arbor

Pheno 2015 Conference
May 4-6, 2015




lakegeorgemirrormagazine.com

Most important "future HEP perspective" :

Many interesting questions to answer ….

*Always will have many interesting questions….*

Our field *by definition* is perpetually primed for dramatic insights (by expt or by pure thought).

E.g., the *frontier* of energy gives us the frontier of reductionist (particle, field, string, etc.) construction and the frontier of early time (cosmology).

16$^{th}$ century woodcut of Archimedes

## Many questions we face today and have been addressed here:

What is the nature of the electroweak vacuum?

How did EWSB take place?

Why are there more baryons over antibaryons?

What accounts for flavor existence and hierarchies?

What explains the Dark Matter signals?

What explains the current Dark Energy?

Is there an additional symmetry relating fermions to bosons?

Are there extra spatial dimensions beyond the 3 we know?

How is gravity ultimately realized in quantum theory?

ETC.

A key question of our time is the electroweak vacuum

- How is EW symmetry broken? (We still don't know)

- What are all the dynamical d.o.f. left over?

- What entourage does the Higgs boson need to be stable?

- Is it really *the* Standard Model Higgs boson we found?

HISTORICAL SLIDE – 4 YEARS OLD

# Should we believe in the Higgs boson?

The Higgs boson is a speculative particle explanation for elementary particle masses.

Cons:

1. One particle carries all burdens of mass generation?
2. Fundamental scalar not known in nature.
3. Hasn't been found yet.
4. Too simplistic -- dynamics for vev not built in.
5. Idea not stable to quantum corrections.

Pros: Still consistent with experimental facts!

# Physicists Find Elusive Particle Seen as Key to Universe

Pool photo by Denis Balibouse

Scientists in Geneva on Wednesday applauded the discovery of a subatomic particle that looks like the Higgs boson.

By DENNIS OVERBYE
Published: July 4, 2012 | 122 Comments

New York Times

The Higgs boson discovery was an extraordinary achievement of the human capacity.

Subtle hints turned into a *outrageous speculation* (Higgs boson)

Technical theory prowess of theory (devising signatures) and experiment (designing and building experiments)

Political organization.

Scientific organization and cooperation.

➔ Discovery. *Is there any intellectual achievement that matches?*

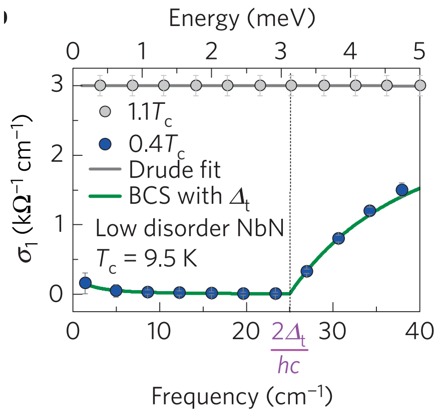
Nevertheless, while we celebrate…

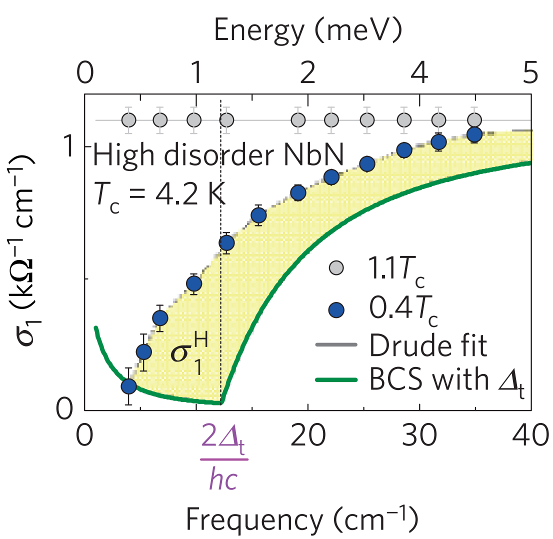
Our condensed matter friends that are paying attention think we are naïve.

January 26, 2015 Nature

# The Higgs mode in disordered superconductors close to a quantum phase transition

**Daniel Sherman[1,2†], Uwe S. Pracht[2], Boris Gorshunov[2,3,4], Shachaf Poran[1], John Jesudasan[5], Madhavi Chand[5], Pratap Raychaudhuri[5], Mason Swanson[6], Nandini Trivedi[6], Assa Auerbach[7], Marc Scheffler[2], Aviad Frydman[1★] and Martin Dressel[2]**




BCS theory → $m_H \sim 2\Delta$ and very short lived and hidden

Highly disordered SC (HDSC):
- high resistivity in normal state
- Elastic scattering length reduces ~ $\lambda_F$
- e's localize, cooper pairs not made of "free electrons"
- Localization leads to insulator – cooper pairs in insulators
- $T_c$ can reduce near zero, Quantum Critical Point (QCP)

Higgs signal:
- Higgs boson softens below 2Δ in HDSC (Podolsky et al. 2011)
- Excess conductivity in sub-gap region
- Tunneling and THz spectroscopy probes of HDSC
- Thin films (2d) of NbN and InO near criticality (insulator-SC transition)

$$\hat{\sigma}(\omega) = \sigma_1(\omega) + i\sigma_2(\omega) = \underbrace{A\rho_s\delta(\omega) + \hat{\sigma}^{qp}(\omega)}_{\hat{\sigma}^{BCS}(\omega)} + \hat{\sigma}^{H}(\omega)$$

$$\sigma_1^H(\omega) = \sigma_1^{exp}(\omega) - \sigma_1^{BCS}(\omega)$$

Feedback Like 2.4m Follow @MailOnline

Thursday, Feb 26th 2015

Daily Mail .com

Home | U.K. | News | Sports | U.S. Showbiz | Australia | Femail | Health Science Money | Video

Science Home Pictures

America's Next Top Model contestant

Three Brooklyn men arrested for

Is YOUR name sexy? Scarlett and

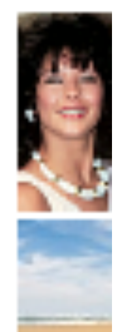
Mother, 47, who plotted to kill her

I'm overwe I hoard thi

# 'God Particle' analogue spotted outside a supercollider: Scientists find Higgs mode in a superconductor

- God Particle is believed to be responsible for all the mass in the universe
- Particle was discovered in 2012 using a Cern's supercollider in Geneva
- Superconductor experiment suggests the particle could be detected without the huge amounts of energy used at by the Large Hadron Collider

Site



Nature, published 26 January 2015

news & views

SUPERCONDUCTIVITY

# Higgs, Anderson and all that

The Higgs mechanism is normally associated with high energy physics, but its roots lie in superconductivity. And now there is evidence for a Higgs mode in disordered superconductors near the superconductor–insulator transition.

Philip W. Anderson

There is one further question. If superconductivity does not require an explicit Higgs in the Hamiltonian to observe a Higgs mode, might the same be true for the 126 GeV mode? As far as I can interpret what is being said about the numbers, I think that is entirely plausible. Maybe the Higgs boson is fictitious!

Deep connection between superconductivity and the theory of electroweak interactions.

# Pre-history

1896: Radiation discovered Becquerel

1911 Onnes discovered superconductivity -- Hg with $T_c$ = 4.2 K

1914: (A,Z) → (A,Z+1) + $\beta^-$ with $\beta$ particles understood to be electrons well understood

1930: Pauli introduces neutrino (A,Z) → (A,Z+1) + $\beta^-$ + $\nu$ to retain energy conservation

1932: Chadwick discovers neutron.

1933 Meissner effect -- Superconductors expel magnetic fields (perfect diamagnet)

1934 Londons theory (J ~ A) -- explained Meissner effect, derived penetration depth

1933: Heisenberg, Majorana, Ivanenko posited nuclei are bound states of protons and neutrons.

1934: Fermi's theory of $\beta$ decay : "effective theory" of the electroweak interactions

# Superconductivity :: 1950 - 1957

# Development of Ginzburg-Landau Theory

# Landau theory of Phase Transitions applied to Superconductivity

Londons' theory success (explained Meissner) but had problems, including surface interface energy, not allowing destruction of SC state by a current, etc.

When you have a hammer (Landau theory of P.T. 1937) everything looks like a nail (superconductivity).

Superconductivity is a P.T. with order parameter $n_s$ (Ginzburg-Landau 1950).

Superconducting state is macroscopic QM wavefunction $\psi(r)$ with $n_s \sim |\psi|^2$.

Candidate for application of Landau's general mean-field theory of phase transitions

1) Identify $\psi$ as order parameter where $\psi=0$ for $T > T_c$ and $\psi$ nonzero with $T < T_c$.

2) Expand free energy difference between SC state and normal state and minimize.

$$F_{SC} - F_N = \alpha|\psi|^2 + \frac{\beta}{2}|\psi|^4 + \cdots + \frac{(-i\hbar\nabla - qA)^2}{2m} - \int_0^B \vec{M} \cdot d\vec{B}$$

# Ginzburg-Landau Theory (cont.)

Let B=0 and ignore spatial variations at the moment. Order parameter is density of superconducting carriers $|\psi|^2 \sim n_s$

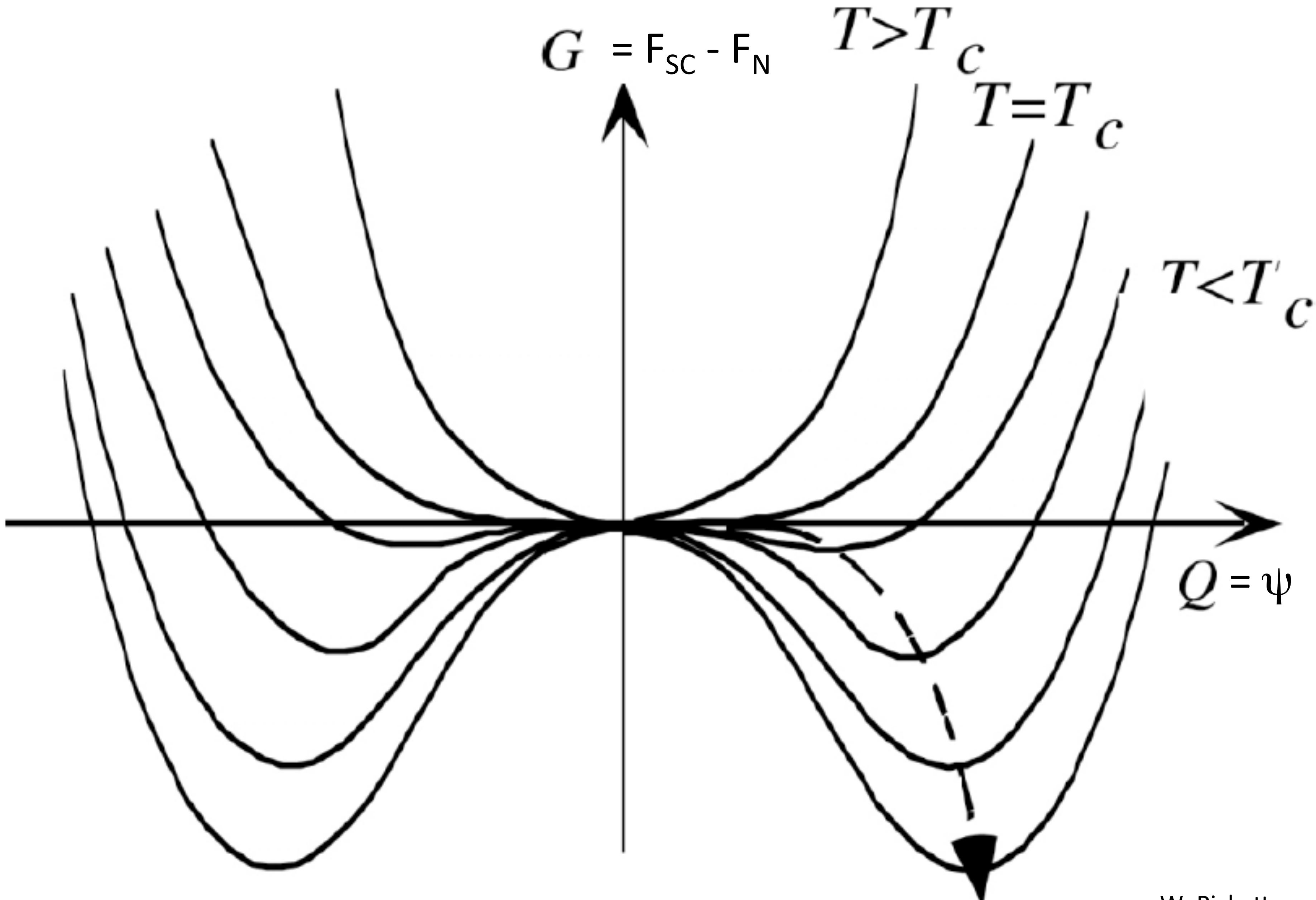
$$F_{SC} - F_N = \alpha|\psi|^2 + \frac{\beta}{2}|\psi|^4$$

Minimize the free-energy:

$$|\psi|^2 = -\frac{\alpha}{\beta} > 0 \ \ (\text{if } \alpha < 0,\ \beta > 0)$$

$$F_{SC} - F_N = -\frac{\alpha^2}{2\beta} < 0 \ \ (F_{SC} \text{ is lower energy state})$$

With finite temperature $\alpha \rightarrow \alpha\,(1-T/T_c)$ :: $T > T_c$ changes $\alpha$ sign



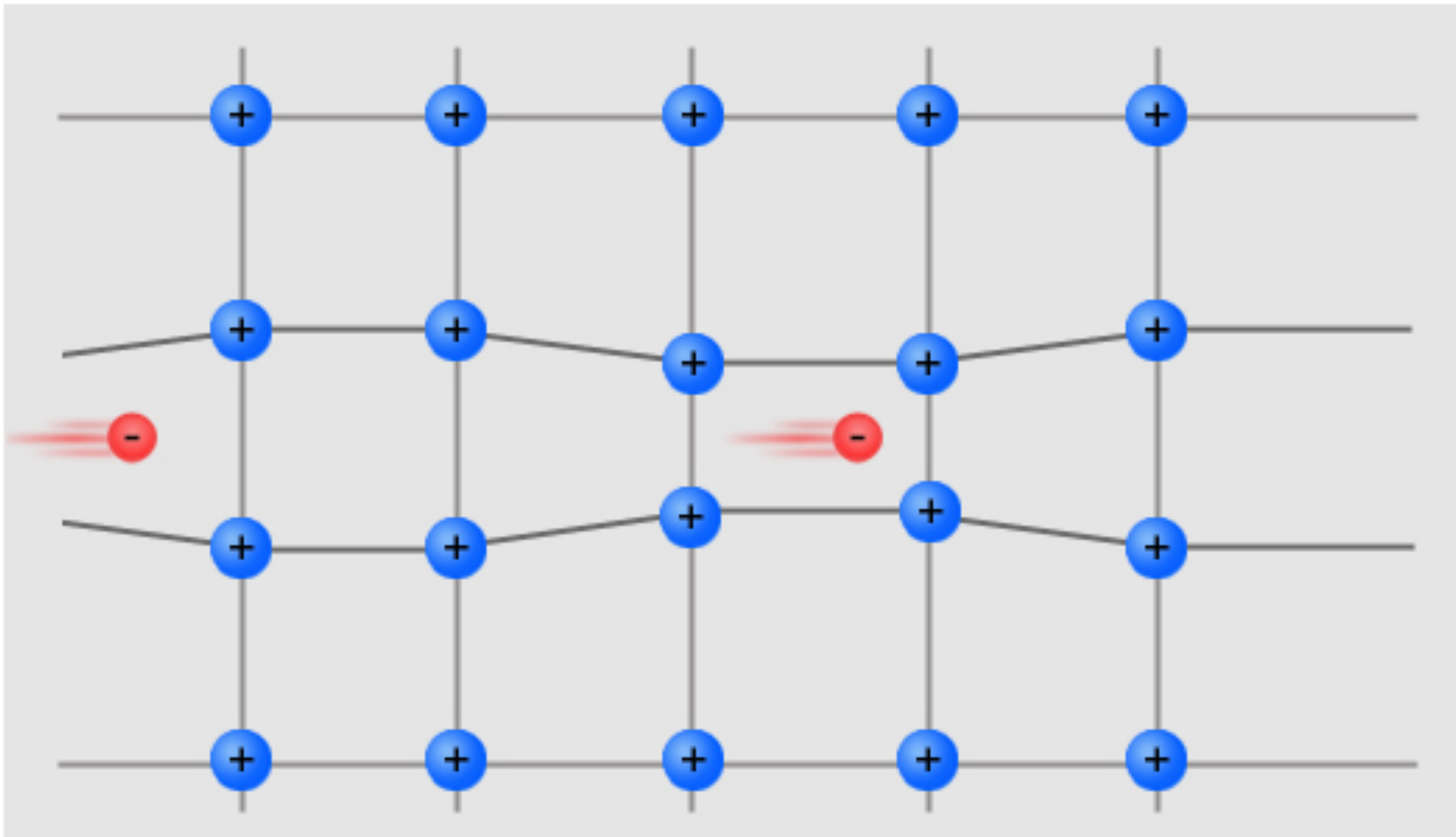

W. Pickett

Superconductivity :: 1957

BCS Theory

# Brief BCS theory redux (1957)

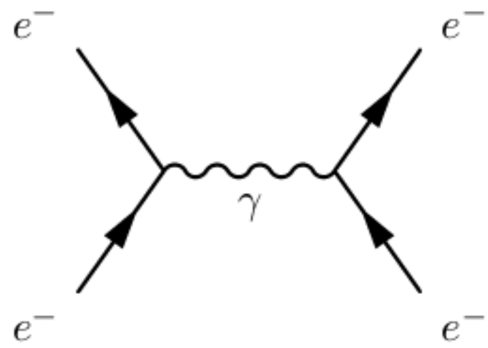
Cooper pairs make super conductors



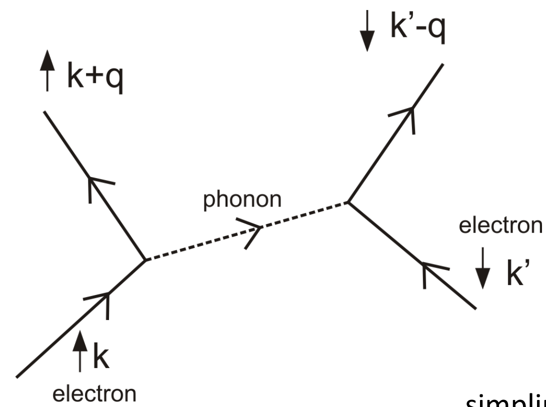
At extremely low temperatures, an electron can draw the positive ions in a superconducting material towards it. This movement of the ions creates a more positive region that attracts another electron to the area.

abc.net.au

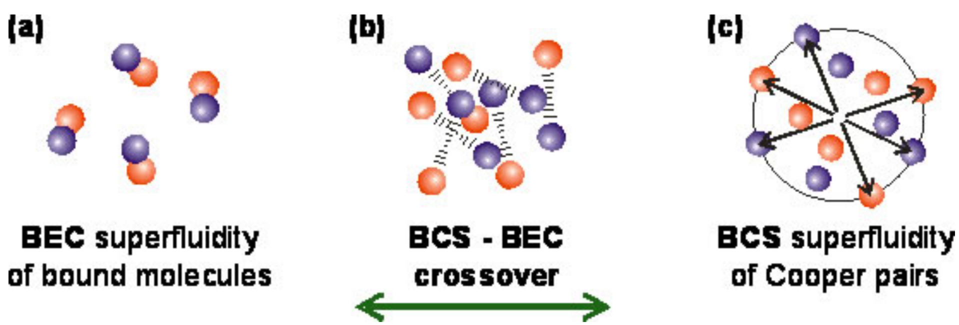
**Repulsive** photon-mediated interactions dominate at short distances, but **attractive** phonon-mediated interactions dominate at larger distances.

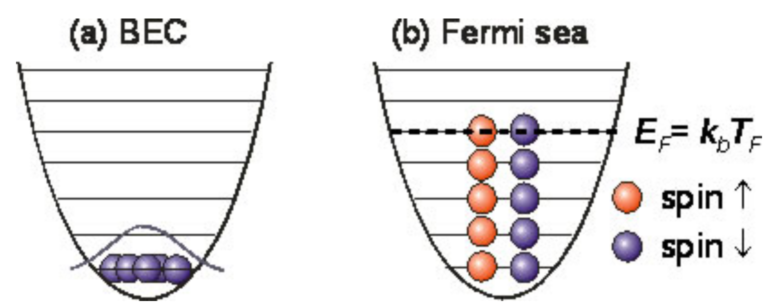



stackexchange




simpliphy




greiner.harvard.edu

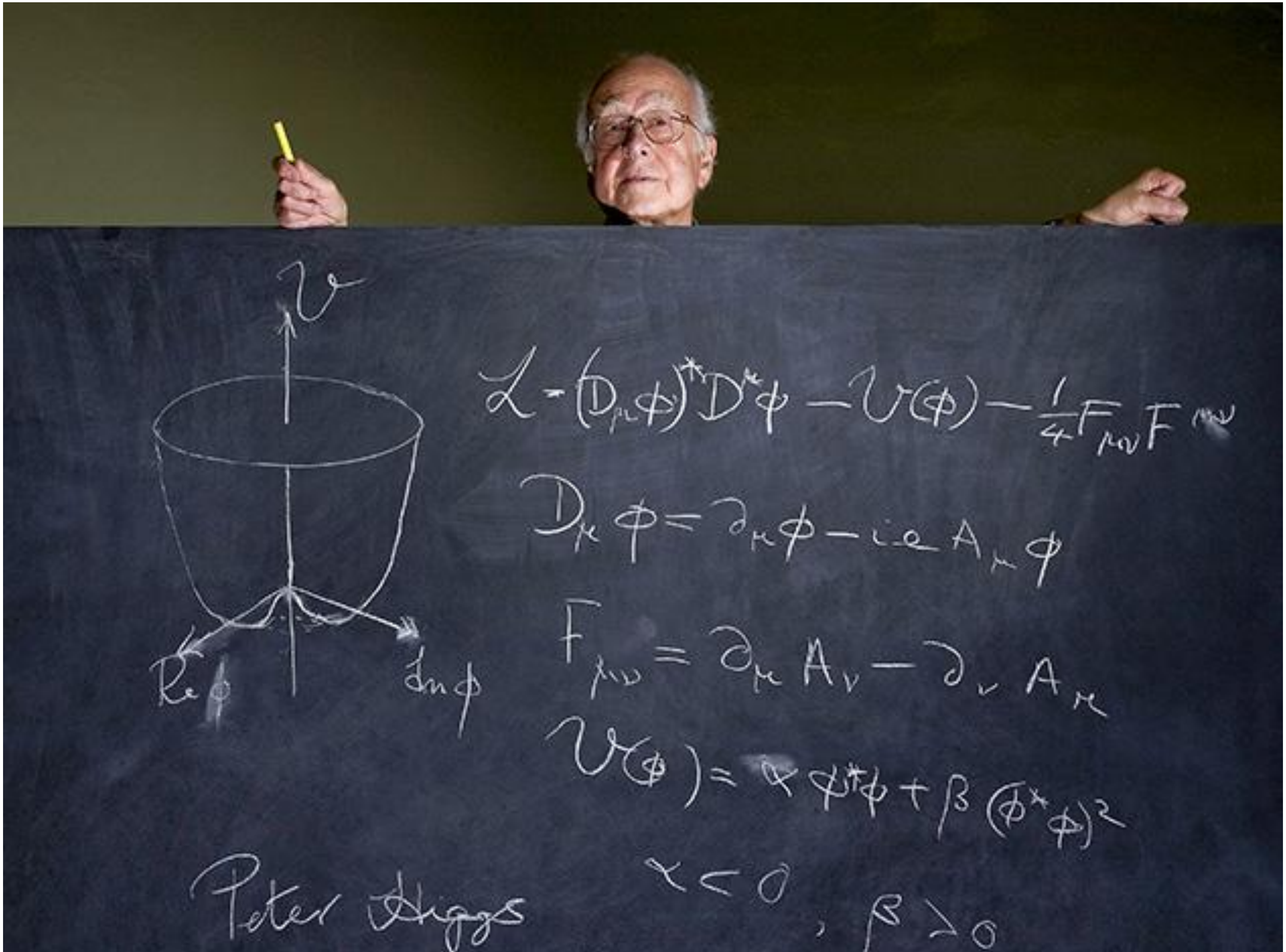
This is 1950s physics.

Simple MFT place-holder theory (Ginzburg-Landau theory) – this was obviously not the fundamental theory.

Sophisticated dynamical theory (BCS) – the “true theory”

However,
Our CM friends open up newspapers and magazines today and they see pictures like this (next page):

Here's the theory!  Higgs, Brout, Englert as well as Guralnik, Hagen, Kibble.




davyking.com

Just what did Peter Higgs (and others – Brout and Englert in particular) do?

1. Understood spontaneous symmetry breaking in *relativistic* QFT setting (there was confusion before).

2. Showed how gauge fields (abelian and non-abelian) eat massless goldstone modes.

3. First (Higgs) to explicitly say there should be a propagating massive scalar particle ("incomplete multiplets" propagating)

This was of course important, ground-breaking work

Nevertheless, such a simple theory being the end of the story is hard to believe.

Even our Condensed Matter colleagues must agree we are not done.

Next faculty meeting tell everyone:

“The entire universe is a superconductor but we are only in the Ginzburg-Landau stage of understanding!”

They will feel sorry for us.

All lovers of knowledge agree:

We have to know what's behind Higgs boson.

Maybe it's supersymmetry : find the superpartners (not so easy)

Maybe it's composite Higgs ideas : find the evidence ($\rho$, etc.)

Maybe the effective potential is not simply $\phi^4$ : measure it

Maybe it's an idea we haven't thought of : comprehensive exploration of the effective theory and resonances

All reasonable ideas are worth pursuing, and all relevant experiments/colliders worth supporting.

# Pursuing signs of “fictitious”

Standard Model Higgs theory has unambiguous predictions for its productions and decays once we know its mass which is known now (125 GeV).

However, its production rates and its probabilities of decaying into various other particles would be slightly different if “fictitious”.

$$
\begin{aligned}
Br(H \to bb)_{SM} &= 60\% \\
Br(H \to WW)_{SM} &= 20\% \\
Br(H \to \tau\tau)_{SM} &= 6\% \\
Br(H \to \gamma\gamma)_{SM} &= 0.2\%
\end{aligned}
$$

$$
\begin{aligned}
Br(H \to bb) &= Br(H \to bb)_{SM}\,(1+\epsilon_b) \\
Br(H \to WW) &= Br(H \to WW)_{SM}\,(1+\epsilon_W) \\
Br(H \to \tau\tau) &= Br(H \to \tau\tau)_{SM}\,(1+\epsilon_\tau) \\
Br(H \to \gamma\gamma) &= Br(H \to \gamma\gamma)_{SM}\,(1+\epsilon_\gamma)
\end{aligned}
$$

$\varepsilon \sim v^2/\Lambda^2$ where $\Lambda$ is
- Compositeness scale, or
- Supersymmetry scale, or
- Size of X-dimensions, or
- Or CFT breaking scale, or

The deviations from these ε's may be only a few percent or less. Will take many years to be sensitive to that, and probably requires another collider (e+e-).

- Gupta, Rzehak, JW, ‘13

## Conclusions

Good time to be doing fundamental science.

We know a lot from prior experiment.

Our understanding of flavor and neutrino physics is reaching new heights, and must go further.

We are cornering good ideas of dark matter.

Dark energy and CMB measurements impacting fundamental physics theories.

We are born into the Higgs boson era and it's our lot to sort it out.
*Copernicus had the solar system, and we have the Higgs boson*.