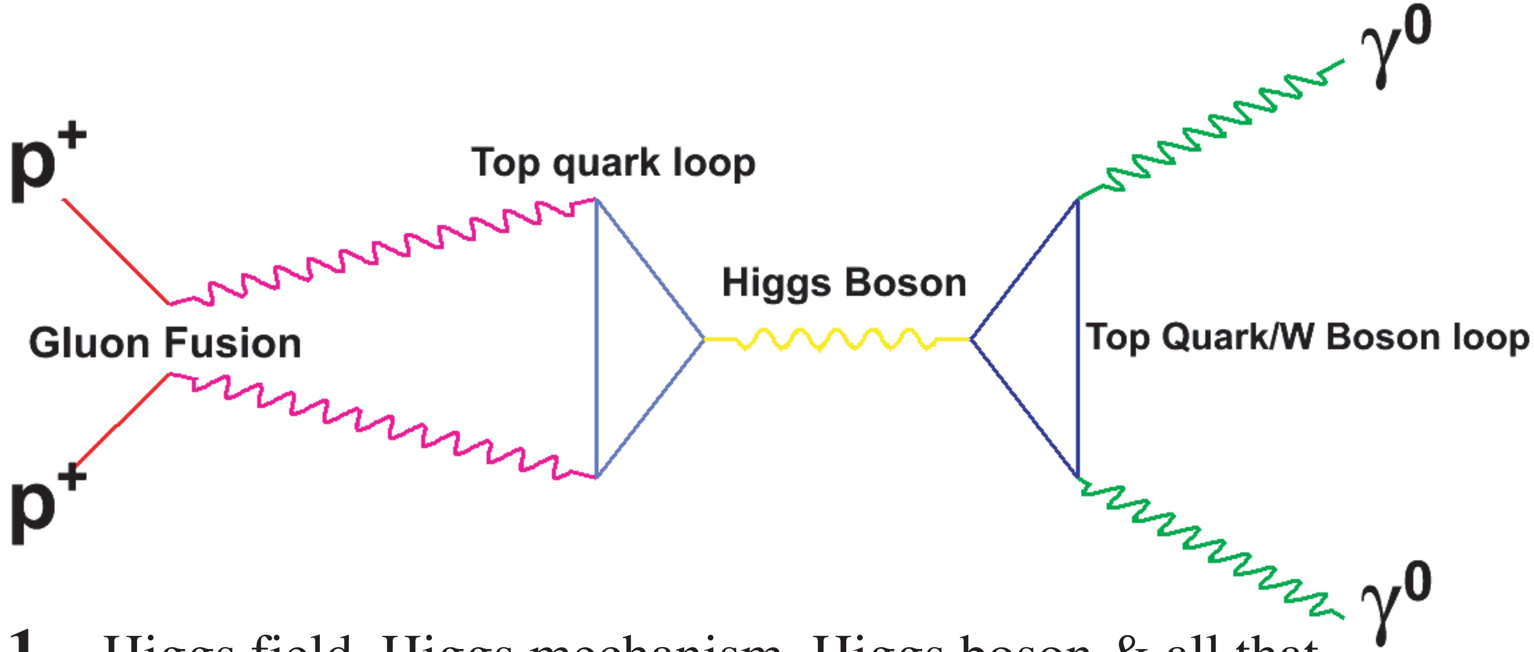
Higgs bosons in particle physics & condensed matter

Aalto University

G. Volovik

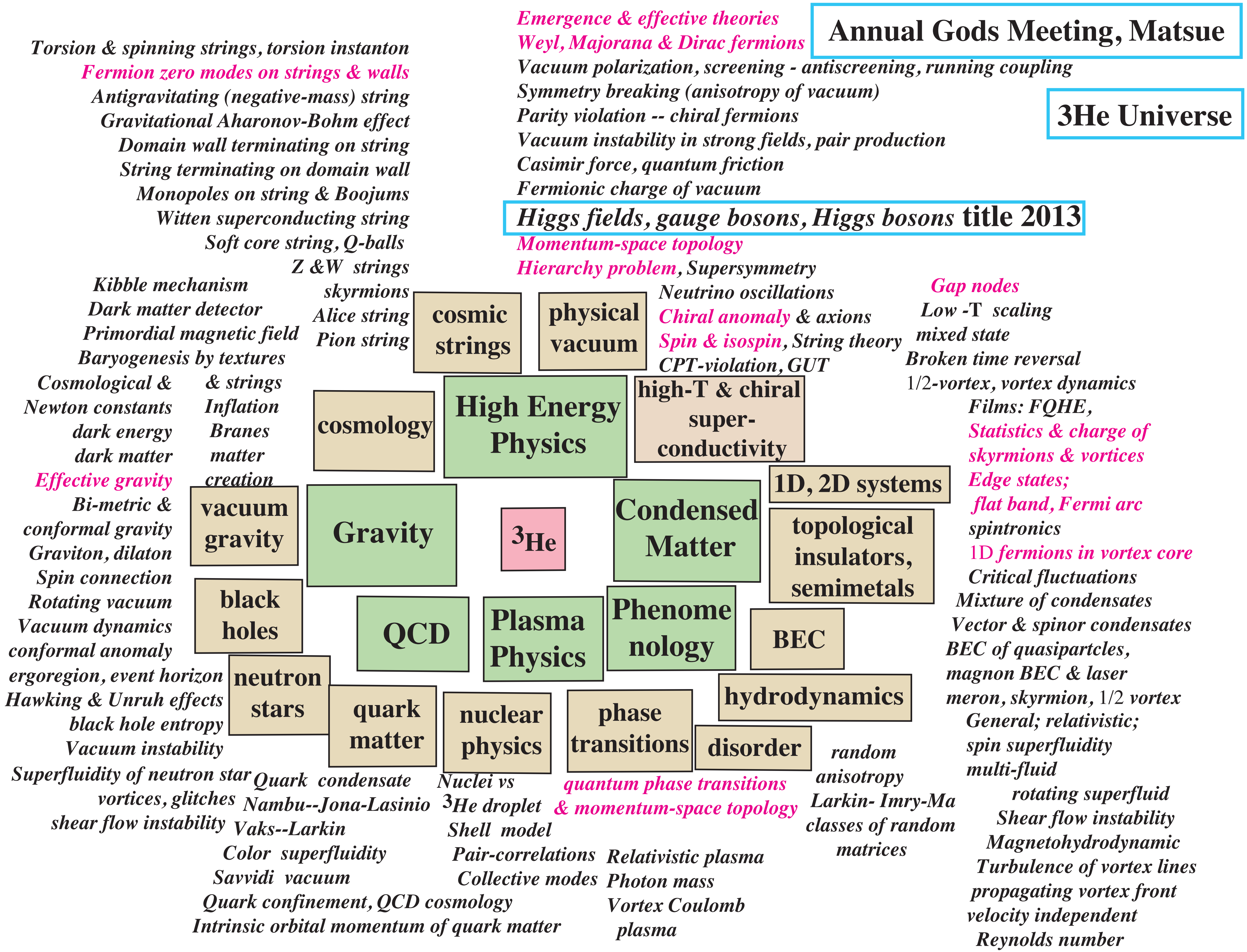
Landau Institute

Russian Academy of Sciences
L.D Landau Institute for Theoretical Physics



1. Higgs field, Higgs mechanism, Higgs boson & all that
2. ^{3}He-B & Nambu conjecture on masses of fermions & bosons
3. from ^{3}He-B to Standard Model: application of Nambu sum rule
4. do we see extra Higgs bosons ?
5. Higgs bosons from quench (cosmology & superconductors)
6. Majorana & Majorino

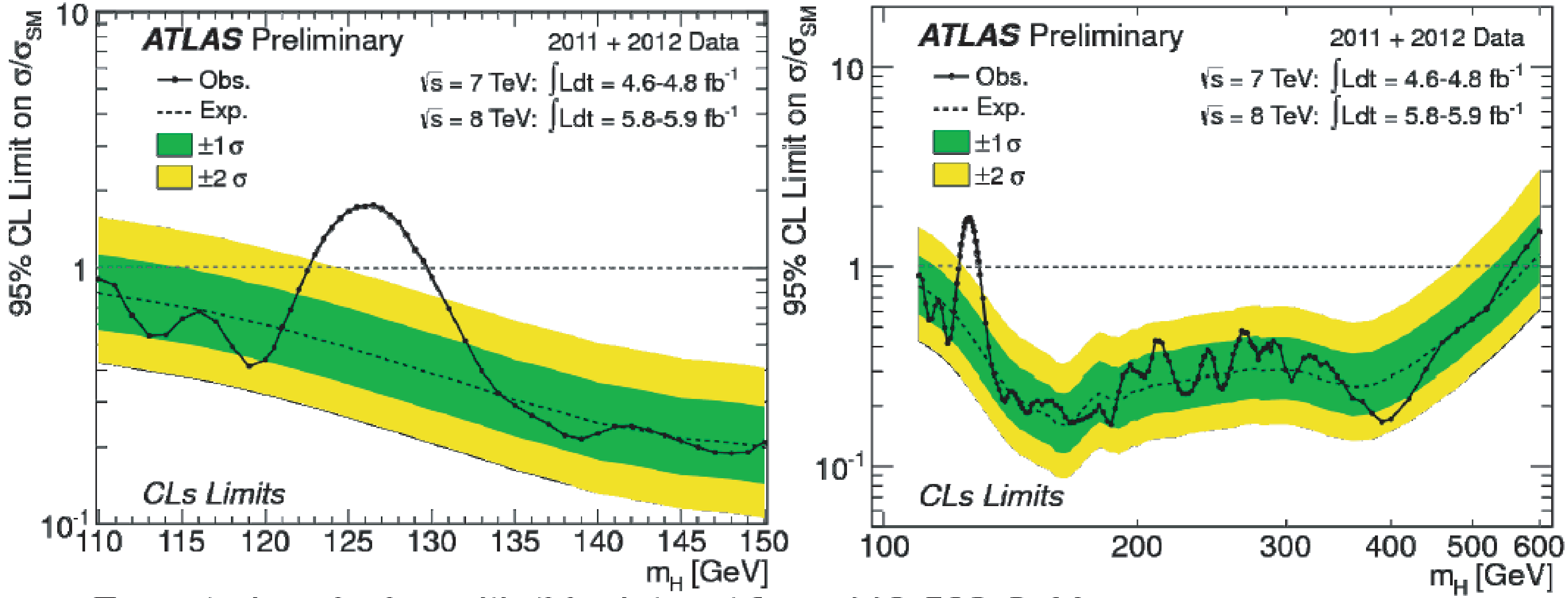
in collaboration with Mikhail Zubkov, ITEP, Moscow



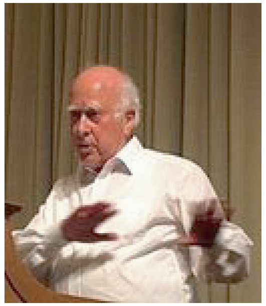
Annual Gods Meeting, Matsue
3He Universe
Emergence & effective theories
Weyl, Majorana & Dirac fermions
Vacuum polarization, screening - antiscreening, running coupling
Symmetry breaking (anisotropy of vacuum)
Parity violation -- chiral fermions
Vacuum instability in strong fields, pair production
Casimir force, quantum friction
Fermionic charge of vacuum
Higgs fields, gauge bosons, Higgs bosons title 2013
Momentum-space topology
Hierarchy problem, Supersymmetry
Neutrino oscillations
Chiral anomaly & axions
Spin & isospin, String theory
CPT-violation, GUT
Torsion & spinning strings, torsion instanton
Fermion zero modes on strings & walls
Antigravitating (negative-mass) string
Gravitational Aharonov-Bohm effect
Domain wall terminating on string
String terminating on domain wall
Monopoles on string & Boojums
Witten superconducting string
Soft core string, Q-balls
Z &W strings
skyrmions
Alice string
Pion string
cosmic strings
physical vacuum
Kibble mechanism
Dark matter detector
Primordial magnetic field
Baryogenesis by textures
& strings
Cosmological & Newton constants
dark energy
dark matter
Effective gravity
Inflation
Branes
matter creation
cosmology
High Energy Physics
high-T & chiral super-conductivity
Gap nodes
Low -T scaling
mixed state
Broken time reversal
1/2-vortex, vortex dynamics
Films: FQHE,
Statistics & charge of skyrmions & vortices
Edge states;
flat band, Fermi arc
spintronics
1D fermions in vortex core
1D, 2D systems
Bi-metric & conformal gravity
Graviton, dilaton
Spin connection
Rotating vacuum
Vacuum dynamics
conformal anomaly
vacuum gravity
Gravity
3He
Condensed Matter
topological insulators, semimetals
Critical fluctuations
Mixture of condensates
Vector & spinor condensates
BEC of quasipartcles,
magnon BEC & laser
meron, skyrmion, 1/2 vortex
black holes
QCD
Plasma Physics
Phenome nology
BEC
ergoregion, event horizon
Hawking & Unruh effects
black hole entropy
Vacuum instability
neutron stars
quark matter
nuclear physics
phase transitions
hydrodynamics
disorder
General; relativistic;
spin superfluidity
multi-fluid
rotating superfluid
Shear flow instability
Magnetohydrodynamic
Turbulence of vortex lines
propagating vortex front
velocity independent
Reynolds number
Superfluidity of neutron star
vortices, glitches
shear flow instability
Quark condensate
Nambu--Jona-Lasinio
Vaks--Larkin
Color superfluidity
Savvidi vacuum
Quark confinement, QCD cosmology
Intrinsic orbital momentum of quark matter
Nuclei vs
3He droplet
Shell model
Pair-correlations
Collective modes
quantum phase transitions
& momentum-space topology
Relativistic plasma
Photon mass
Vortex Coulomb plasma
random anisotropy
Larkin- Imry-Ma
classes of random matrices

Updated combined SM Higgs exclusion

- Combining updated 2011+2012 γγ and 4-lepton analysis with others as before



- Expected exclusion with this dataset from 110-582 GeV
  - Observed exclusion from 110-122.6 GeV and 129.7-558 GeV
    - 111.7-121.8 GeV and 130.7-523 GeV excluded at 99% CL
  - Region around 126 GeV cannot be excluded



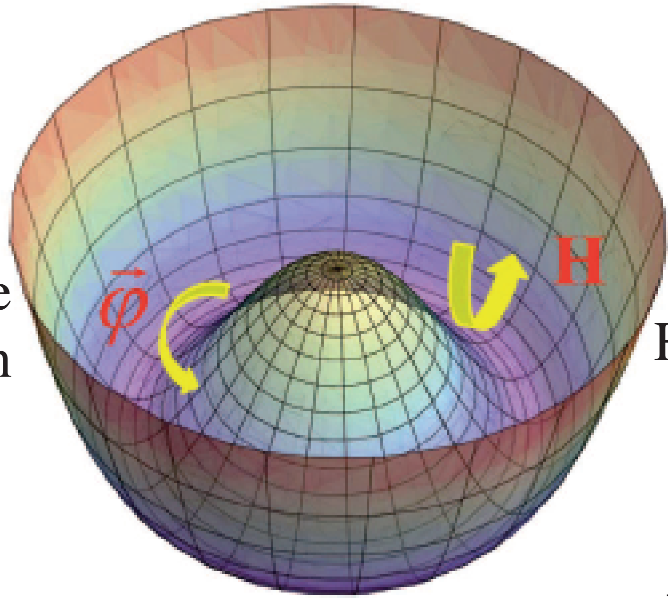
author of Higgs mechanism & massive Higgs bosons

co-authors of Higgs mechanism

Kibble **Guralnik** **Hagen** **Englert** **Brout**

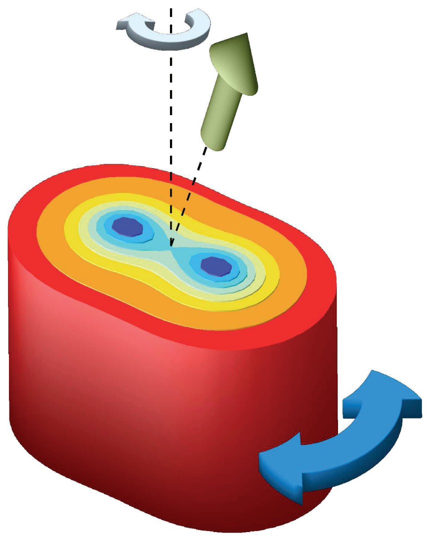
Symmetry breaking, Higgs mechanism & massive particles

Nambu-Goldstone (NG) boson



Higgs boson

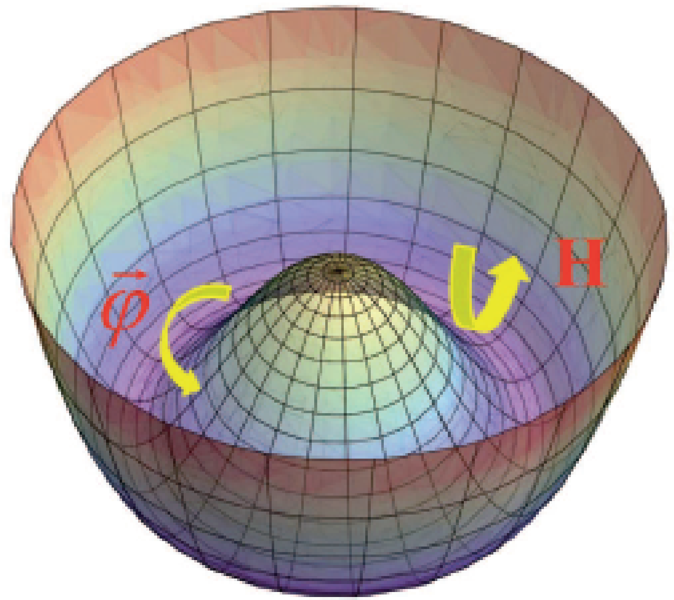
twistino on double-core vortex



Standard Model	***cond-mat***
NG bosons	
no NG bosons !	phonon, spin wave, orbital wave, Kelvon (Kelvin wave), twistino, Tkachenko wave, ripplon, Parshin (crystallization) wave, ...
massive particles	
Higgs boson(s)	order parameter modes
W & Z gauge bosons	Meissner effect (expulsion of magnetic field)
quarks & leptons	gapped quasiparticles

Nambu-Goldstone (NG) bosons

Goldstone's theorem:



spontaneous breakdown of a global continuous symmetry
leads to massless particle – Nambu-Goldstone boson

Y. Nambu, Phys. Rev. Lett. **4** (1960) 380
J. Goldstone, Nuovo Cim. **19** (1961) 154
J. Goldstone, A. Salam, S. Weinberg, Phys. Rev. **127** (1962) 965

cond-mat order parameter = Higgs field

$$\Psi = |\Psi|\, e^{i\varphi}$$

$$\Psi = \begin{pmatrix} \Psi_1 \\ \Psi_2 \end{pmatrix}$$

cond-mat NG bosons = gapless modes of order parameter:
phonons, spin waves, orbital waves

no NG bosons had been observed in particle physics

Why ?

Higgs mechanism

spontaneous breaking of gauge symmetry does not require Goldstone bosons,
their degrees of freedom deliver the longitudinal polarization modes of gauge bosons,
gauge bosons become massive (Z-boson, W-boson)

P. Anderson, Plasmons, gauge invariance and mass, Phys. Rev. **130** (1963) 439
F. Englert, R. Brout, Phys. Rev. Lett. **13** (1964) 321
P. W. Higgs, Phys. Lett. **12** (1964) 132 and Phys. Rev. Lett. **13** (1964) 508
G. S. Guralnik, C. R. Hagen, T. W. B. Kibble, Phys. Rev. Lett. **13** (1964) 585

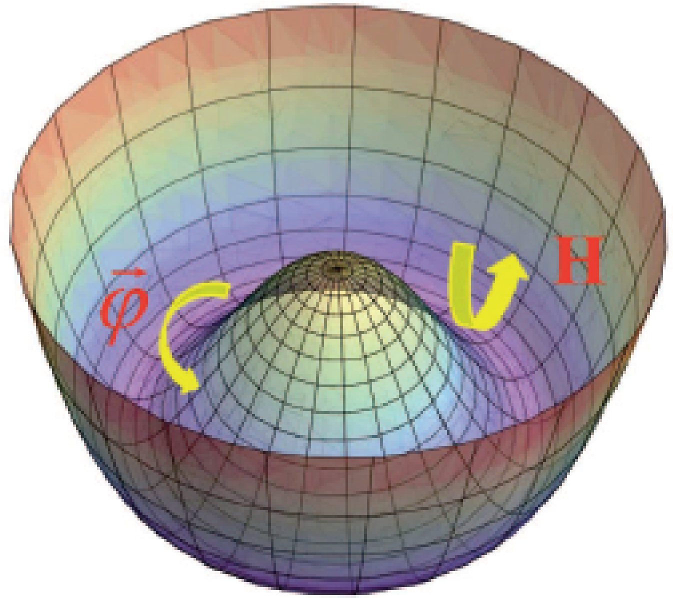
cond-mat analog: Cooper pairing and Meissner effect in superconductors

Higgs, PRL **13** (1964) 508:

"It is to be expected that this feature will appear also in theories
in which the symmetry-breaking scalar fields are not elementary dynamic variables
but bilinear combinations of Fermi fields."

"In the theory of superconductivity the scalar fields are associated with fermion pairs;
the doubly charged excitation responsible for the quantization of magnetic flux
is then the surviving member of a U(1) doublet."

How many Higgs bosons ?



amplitude H-modes of Higgs field

P. W. Higgs, PRL **13** (1964) 508:

"The model of the most immediate interest is that in which the scalar fields form an **octet** under **SU(3)**... There are **2** massive scalar bosons ... (**2 *Higgs bosons***) ... ; the remaining **6** components of the scalar octet combine with the corresponding components of the gauge-field octet to describe massive vector bosons (**6 *massive gauge bosons***)."

Vdovin (1963)

Bosons in superfluid ^{3}He-B: collective modes of order parameter

9-plet $A_{\alpha i}$ under **SO(3)** x **SO(3)** x **U(1)**

14 *Higgs bosons* + 4 *NG modes* (**4 *massive gauge bosons*** in gauged ^{3}He-B)

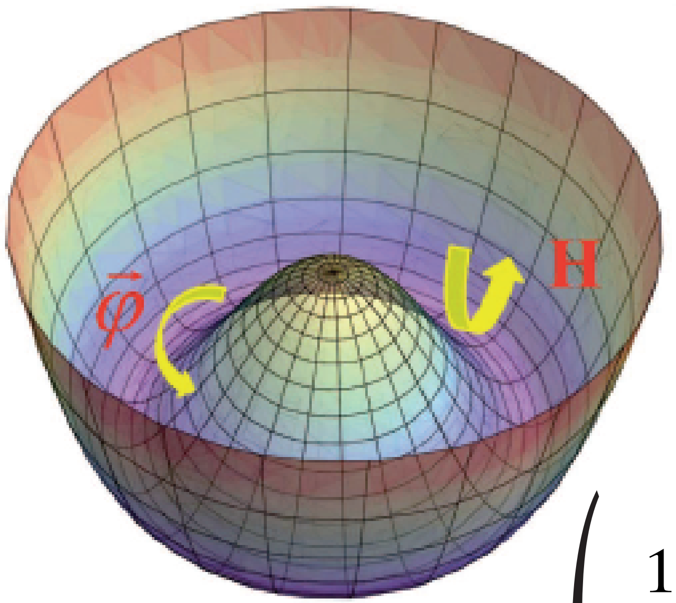
Masses of elementary particles

elementary particles acuire mass due to interaction with Higgs field

cond-mat mass of elementary particles:

Bogoliubov- de Gennes particles with gap in superconductors and 3He-B

Ginzburg-Landau vs Standard Model



Ginzburg-Landau

Order parameter:
complex scalar field

$$\Psi = |\Psi| \, e^{i\varphi}$$

2 = 1+1 collective modes:

$$\Psi = 1 + (H + i\varphi)$$

1 NG mode (phase φ mode)

1 amplitude H mode (Higgs boson)

Meissner effect:
mass of gauge vector boson = inverse penetration length

Standard Model

Higgs field: complex spinor

$$\Psi = \begin{pmatrix} \Psi_1 \\ \Psi_2 \end{pmatrix}$$

4 = 3+1 collective modes

$$\Psi = \begin{pmatrix} 1 \\ 0 \end{pmatrix} + H \begin{pmatrix} 1 \\ 0 \end{pmatrix} + \underset{\text{3 rotations}}{\delta\Psi}$$

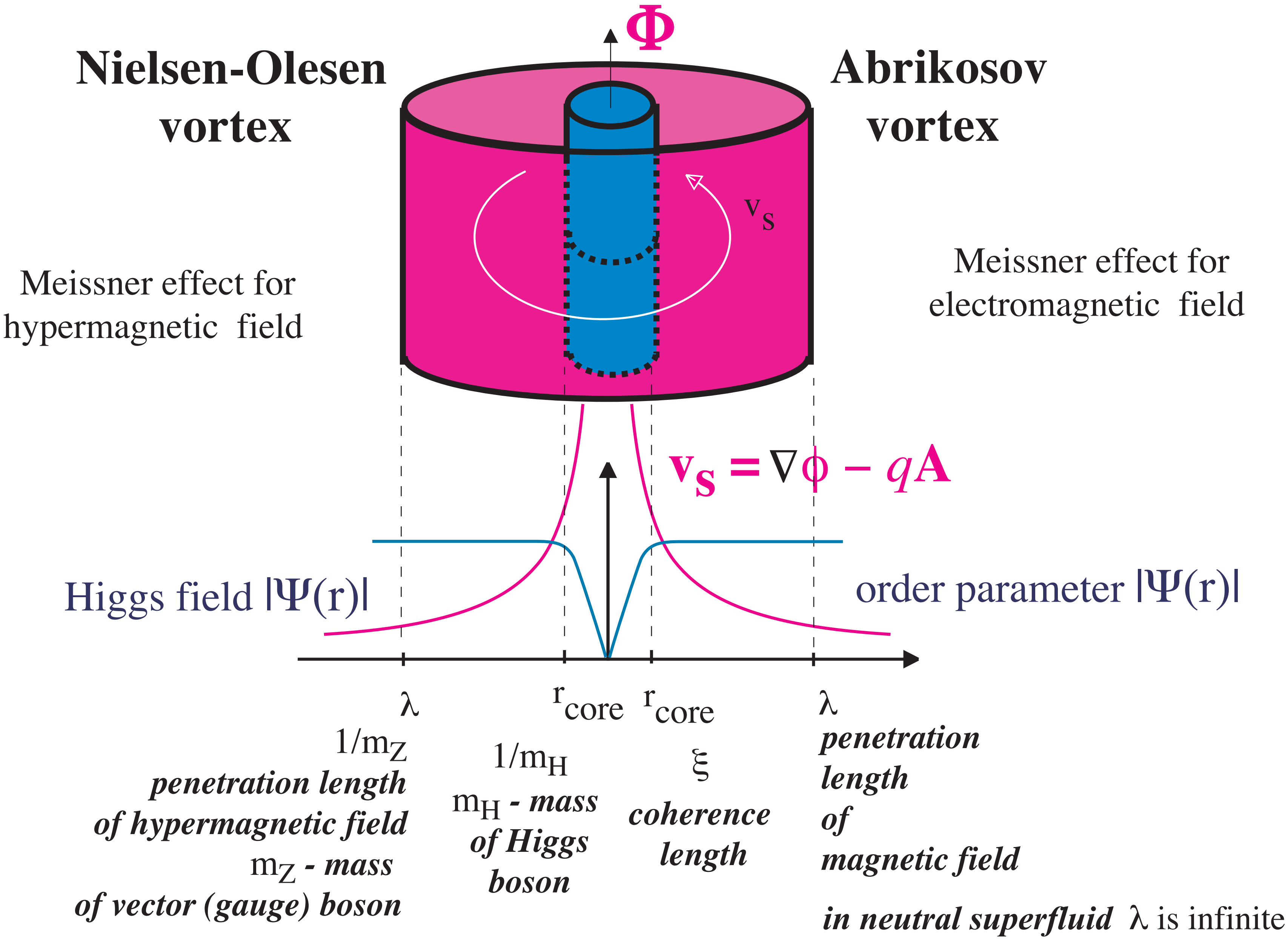
3 NG modes

1 amplitude H mode (Higgs boson H)

Standard Model requires only one Higgs boson

3 NG modes are absorbed into longitudinal modes of 3 massive vector bosons (charged W^+, W^- and neutral Z)
this is called **Higgs mechanism**

Higgs mechanism in Standard Model & superconductor



$$E = |\nabla\Psi - iq\mathbf{A}\Psi|^2 = |\Psi|^2(\nabla\phi - q\mathbf{A})^2 = \lambda^{-2}(\nabla\phi - q\mathbf{A})^2 = \rho_s \mathbf{v_s}^2$$

from Standard Model Ginzburg-Landau to Standard Model BEC

nobody now believes that SM is complete theory,
all believe SM is effective low energy theory

composite Higgs is more natural than fundamental

Higgs, PRL **13** (1964) 508:

"... the symmetry-breaking scalar fields
are not elementary dynamic variables
but ***bilinear combinations of Fermi fields***."

Higgs field can be composite object as Cooper pair in superconductors

$$\Psi = \langle \bar{\chi}_L \chi_R \rangle$$

Standard Model as BCS theory in semimetal

BCS Cooper pairing

Order parameter as composite object

$$\Psi = \langle \chi \chi \rangle$$

phase & amplitude modes

$$\Psi = \langle \chi \chi \rangle_{vac} + \delta\Psi$$

Ψ mixes electron and hole

Hamiltonian for Bogoliubov-Nambu quasiparticles

$$H = \begin{pmatrix} \varepsilon(\mathbf{p}) & \Psi \\ \Psi^{*} & -\varepsilon(\mathbf{p}) \end{pmatrix}$$

order parameter induces gap

$$E^2(\mathbf{p}) = \varepsilon^2(\mathbf{p}) + |\Psi|^2$$

dynamical mixing of left & right particles

Higgs field as composite object

$$\Psi = \langle \bar{\chi}_L \chi_R \rangle$$

Higgs bosons

$$\Psi = \langle \bar{\chi}_L \chi_R \rangle_{vac} + \delta\Psi$$

Ψ mixes left and right Weyl particles

Hamiltonian for Dirac particles

$$H = \begin{pmatrix} c\sigma\cdot\mathbf{p} & \Psi \\ \Psi^{+} & -c\sigma\cdot\mathbf{p} \end{pmatrix}$$

Higgs field induces Dirac mass $M = |\Psi|$

$$E^2(\mathbf{p}) = c^2 p^2 + |\Psi|^2$$

generalization of Standard Model using hints from superfluid ^{3}He

superfluid 3He

order parameter $A_{\alpha j} = < \chi \, \sigma_\alpha \nabla_j \chi > = < \chi \, \hat{O} \, \chi >$

in superfluid 3He

$$\hat{O} = \sigma_\alpha \nabla_j$$

$\hat{O}$ is in general operator, which may include generators of different symmetry groups

general composite Higgs field

Higgs field $\Psi = < \bar{\chi} \, \hat{O} \, \chi >$

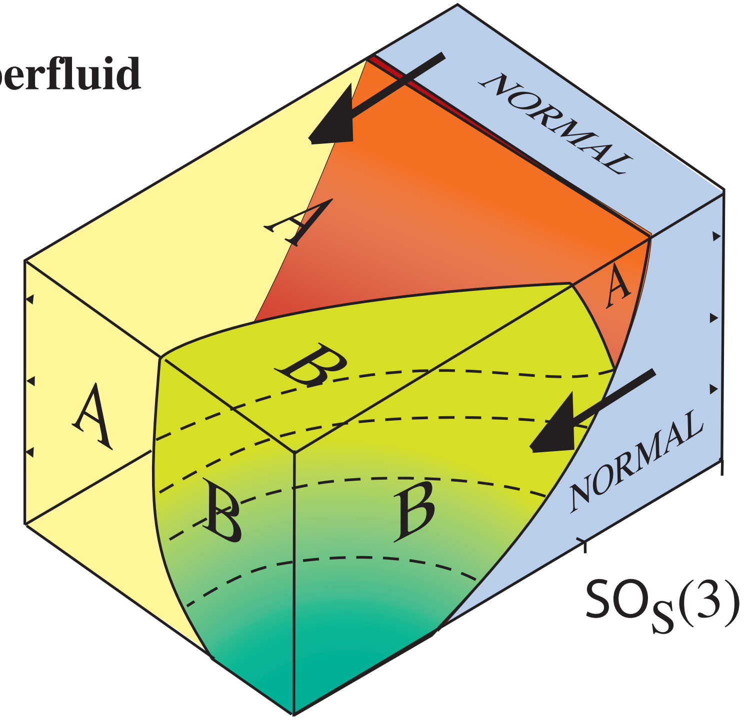
***GUT in* Standard Model**
symmetry breaking phase transitions

$SO(10) \rightarrow SU(3) \times SU_L(2) \times U(1) \rightarrow SU(3) \times U_Q(1)$

symmetry breaking phase transitions
***in* superfluid ^{3}He**

$SO_S(3) \times SO_L(3) \times U(1) \rightarrow SO_S(2) \times U_Q(1)$ Q is analog of electric charge

^{3}He-A
topological chiral Weyl superfluid
two Dirac cones



^{3}He-B
time-reversal symmetric
topological superfluid

$SO_S(3) \times SO_L(3) \times U(1) \rightarrow SO_J(3)$

multiple Higgs bosons from superfluid ^{3}He

superfluid 3He

composite Higgs

order parameter $A_{\alpha j} = <\chi\, \sigma_\alpha \nabla_j \chi>$

Higgs field $\Psi = <\bar{\chi}\, \hat{O}\, \chi>$

pair breaking & squashing modes

multiple Higgs bosons

$A_{\alpha j} = \delta_{\alpha j} + u_{\alpha j} + i\, v_{\alpha j}$

$\Psi = <\bar{\chi}\, \hat{O}\, \chi>_{vac} + \delta\Psi$

$\hat{O}$ is operator, which may include generators of different symmetry groups

Bogoliubov-Nambu quasiparticles

massive quarks & leptons

$$H = \begin{pmatrix} \varepsilon(\mathbf{p}) & A_{\alpha j}\sigma_\alpha \cdot p_j \\ A^*_{\alpha j}\sigma_\alpha \cdot p_j & -\varepsilon(\mathbf{p}) \end{pmatrix}$$

$$H = \begin{pmatrix} c\sigma\cdot\mathbf{p} & & & \\ & c\sigma\cdot\mathbf{p} & \Psi & \\ & & -c\sigma\cdot\mathbf{p} & \\ \Psi^+ & & & -c\sigma\cdot\mathbf{p} \end{pmatrix}$$

4 Goldstone & 14 Higgs modes in ^{3}He-B

$$SO_S(3) \times SO_L(3) \times U(1) \longrightarrow SO_J(3)$$

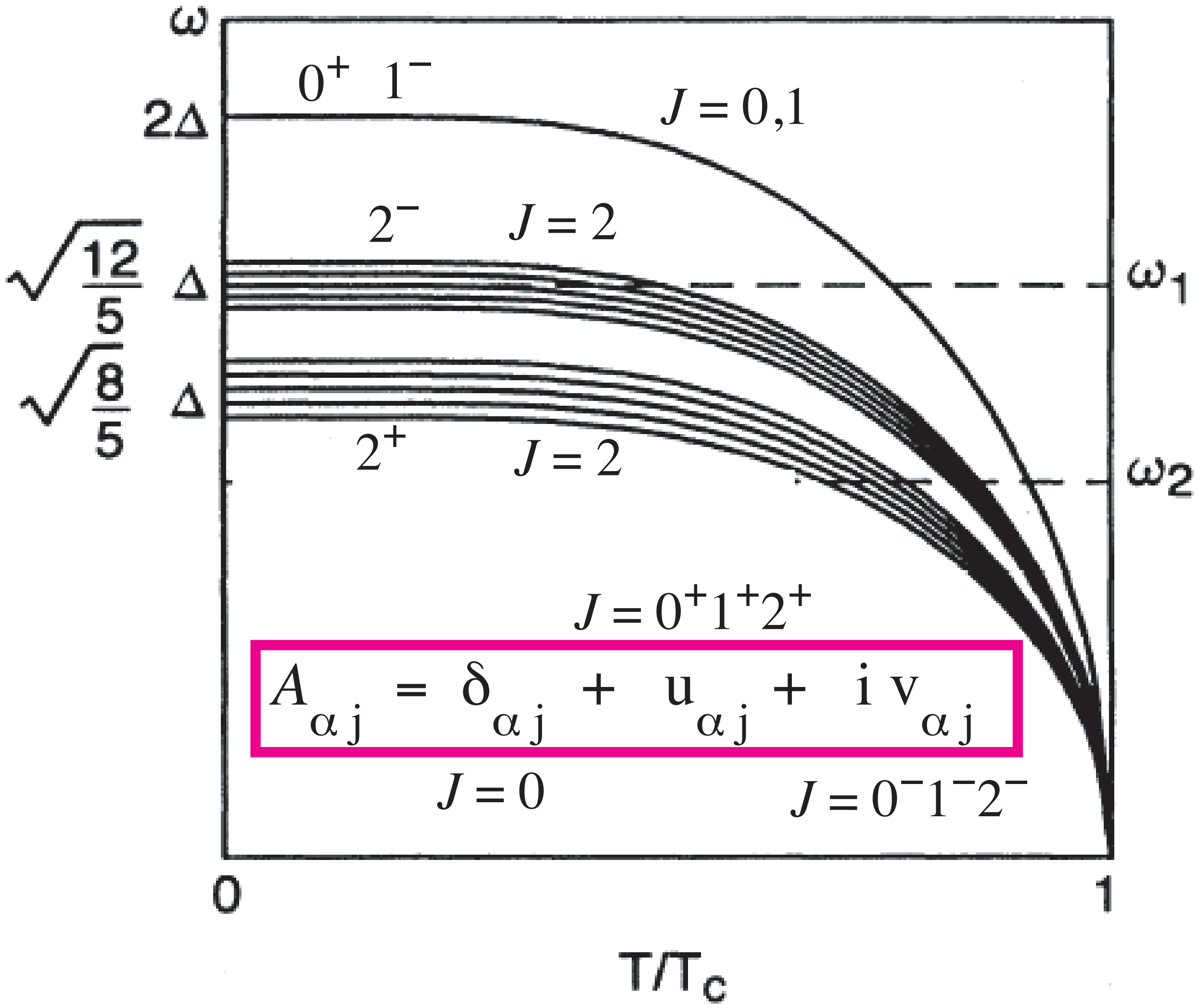


FIG. 3. A schematic plot in ω vs T space for pair breaking, the squashing mode, and the real squashing modes. The Zeeman splitting (not to scale) of the collective modes in an applied magnetic field is shown in the plot. The dashed lines labeled ω_1 and ω_2 correspond to two sound frequencies.

4 Goldstone modes

$$E_{0-} = E_{1+} = 0$$

14 Higgs bosons

$$E_{1-} = E_{0+} = 2\Delta$$

$$E_{2-} = (12/5)^{1/2}\Delta$$

$$E_{2+} = (8/5)^{1/2}\Delta$$

9 pairs of Nambu partners

$$E_{2-}^2 + E_{2+}^2 = 4\,\Delta^2$$

$$E_{0-} + E_{0+} = 4\,\Delta^2$$

$$E_{1-} + E_{1+} = 4\,\Delta^2$$

Nambu sum rule: from 3He-B to Standard Model

relation between energies E_B & E_F of bosonic & fermionic excitations in BCS type theories

$$\boxed{E_{B1}^2} + \boxed{E_{B2}^2} = \boxed{4\,E_F^2}$$

3He-B	$E_{B1} = (8/5)^{1/2}\Delta$	$E_{B2} = (12/5)^{1/2}\Delta$	$E_F = \Delta$
	real squashing mode	squashing mode	gap in quasiparticle spectrum

Application of Nambu rule to masses of Higgs fields and top quarks

$$\boxed{m_{H1}^2} + \boxed{m_{H2}^2} = \boxed{4\,m_t^2}$$

125 GeV	325 GeV	174 GeV
discovered Higgs	Nambu partner Higgs	top quark

Sum rule for ^{3}He-B: symmetry consideration

$$m_Q^2 = 2m_f^2 (1 +/- \eta^{(Q)})$$

$$m_{Q+}^2 + m_{Q-}^2 = 4 m_f^2$$

parameter dictated by symmetry

$$\eta^{(Q)} = \mathrm{Tr}\,(VO^{(Q)}VO^{(Q)})$$

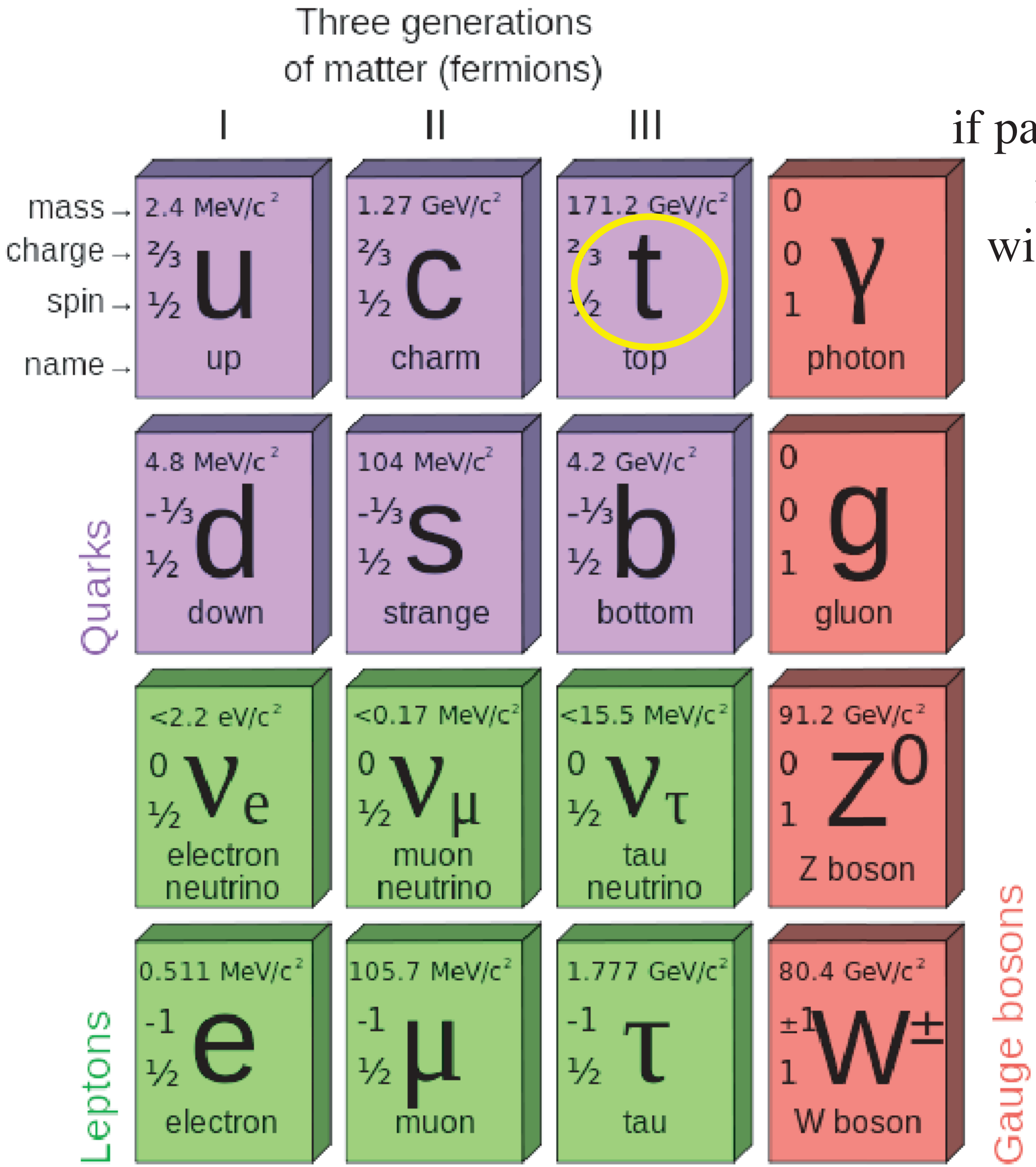
^{3}He-B: quantum number Q = J (total angular momentum), $m_f = \Delta$ gap

$$E_J{}^2 = 2\,\Delta^2 (1 +/- \eta^{(J)})$$

J=2 , $\eta^{(J)} = 1/5$	$E_{2-} = (8/5)^{1/2}\Delta$ real squashing mode	$E_{2+} = (12/5)^{1/2}\Delta$ squashing mode
J=0 , $\eta^{(J)} = 1$	$E_{1-} = 0$ Goldstone (sound mode)	$E_{1+} = 2\,\Delta$ pair breaking mode
J=1 , $\eta^{(J)} = 1$	$E_{0-} = 0$ 3 Goldstone modes (spin waves)	$E_{0+} = 2\,\Delta$ pair breaking modes

which fermion is responsible?

Standard Model



if pairing occurs in one channel
fermion in this channel
will have largest gap (mass)

Nambu sum rule: from 3He-B to Standard Model

relation between energies E_B & E_F of bosonic & fermionic excitations in BCS type theories

$$E_{B1}^2 \quad + \quad E_{B2}^2 \quad = \quad 4\,E_F^2$$

3He-B $\quad E_{B1} = (8/5)^{1/2}\Delta \quad E_{B2} = (12/5)^{1/2}\Delta \quad E_F = \Delta$

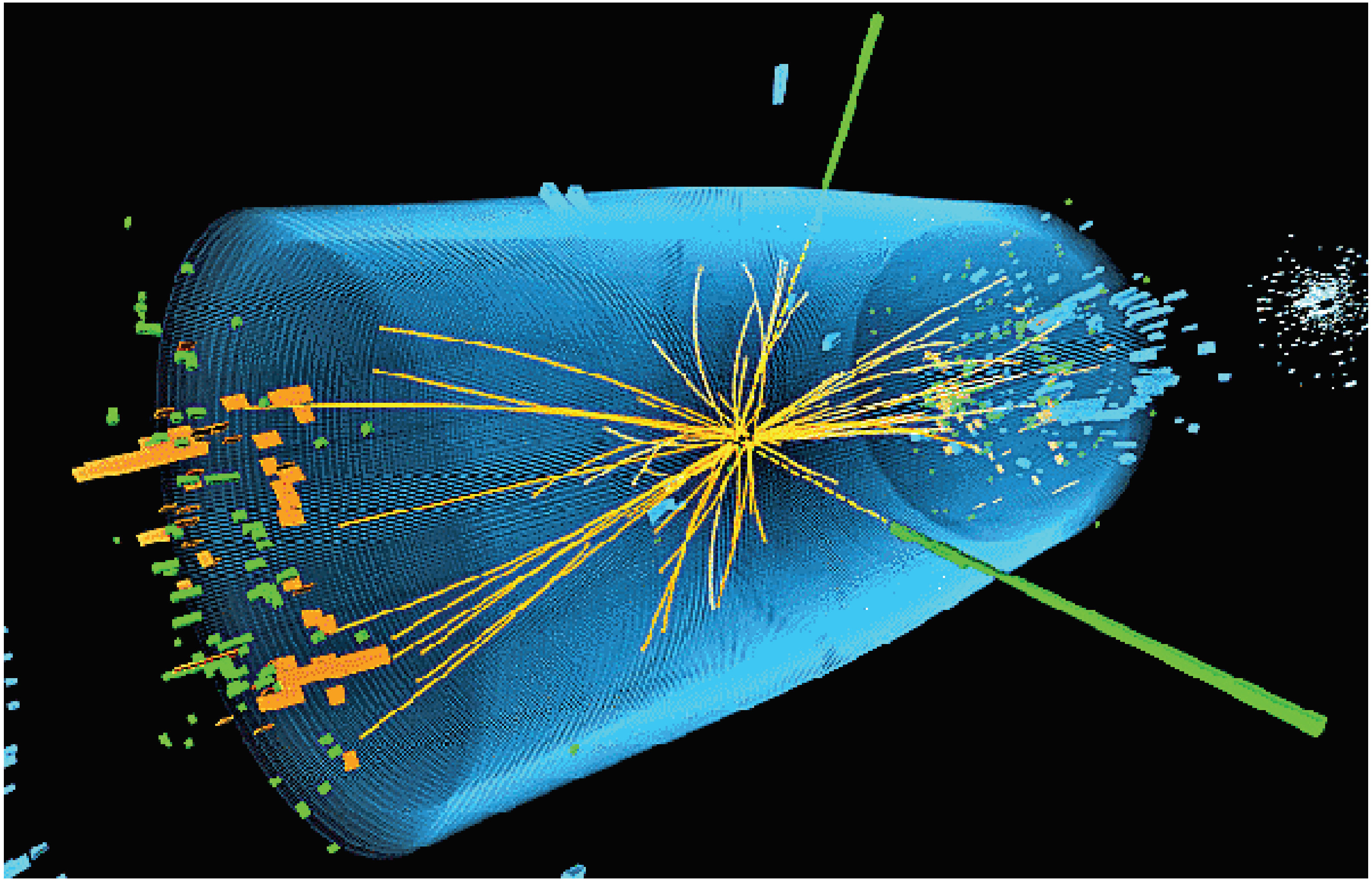
real squashing mode $\quad$ squashing mode $\quad$ gap in quasiparticle spectrum

Application of Nambu rule to masses of Higgs fields and top quarks

$$m_{H1}^2 \quad + \quad m_{H2}^2 \quad = \quad 4\,m_t^2$$

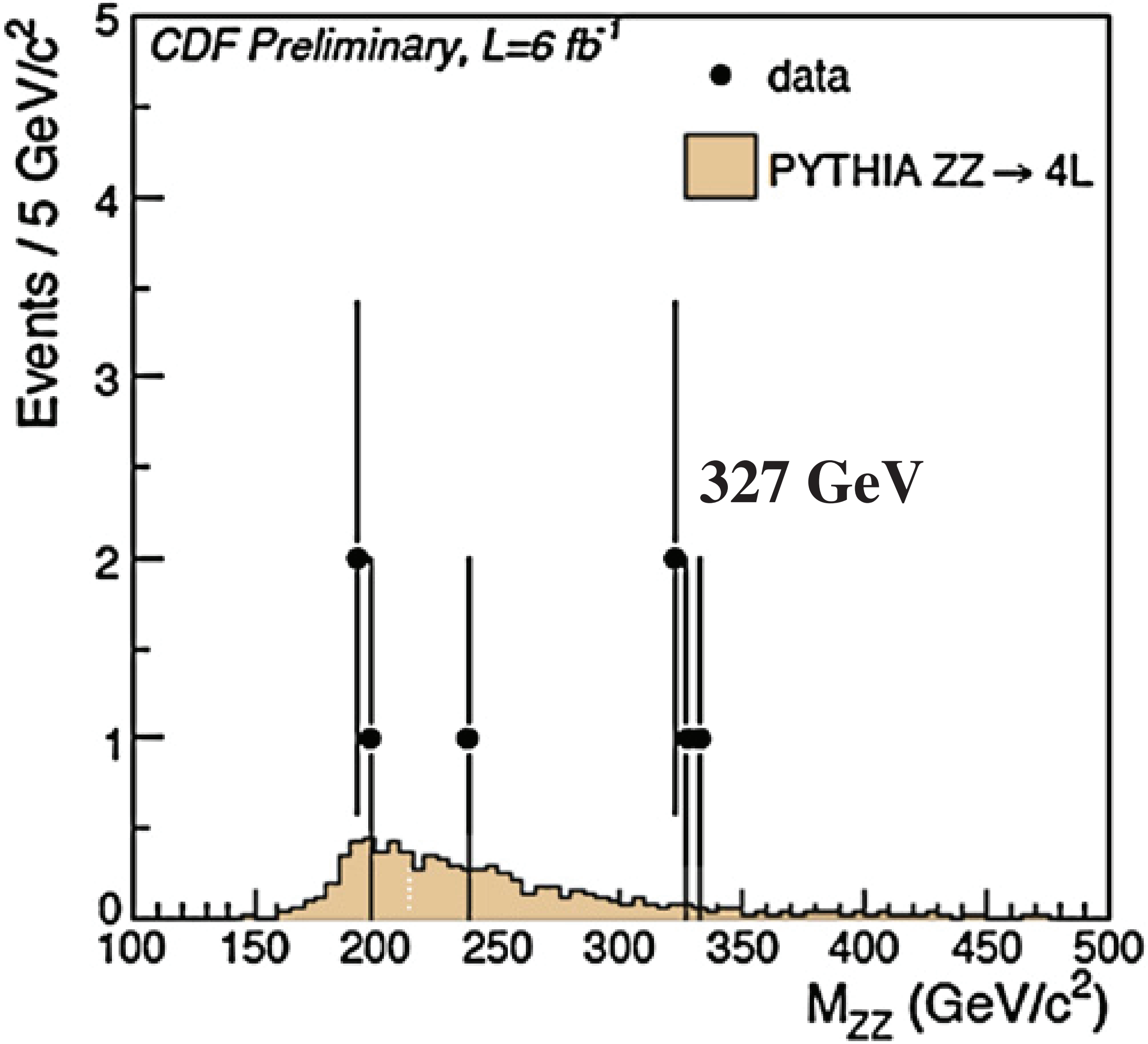
125 GeV $\quad$ 325 GeV $\quad$ 174 GeV

discovered Higgs $\quad$ Nambu partner Higgs $\quad$ top quark



A narrow scalar resonance at 325 GeV?

Krzysztof A. Meissner & Hermann Nicolai
Phys. Lett. B **718** (2013) 943



"We propose to identify the excess of events with four charged leptons at E ~ 325 GeV seen by the CDF Collaboration (2012) [1] & CMS Collaboration (2012) [2] with a new 'sterile' scalar particle characterized by a very narrow resonance of the same height and branching ratios as the Standard Model Higgs boson, as predicted in the framework of the so-called Conformal Standard Model (K.A. Meissner & H. Nicolai 2007) [3]."

Fig. 1. The four lepton events reported by the CDF Collaboration [1].

hints of 325 GeV Higgs boson in earlier experiments

* CDF/PUB/EXOTICS/PUBLIC/10603 July 17, 2011
Search for High-Mass Resonances Decaying
into ZZ in $p\bar{p}$ Collisions at $s^{1/2} = 1.96$TeV

"The invariant masses of four events are clustered around 325 GeV"

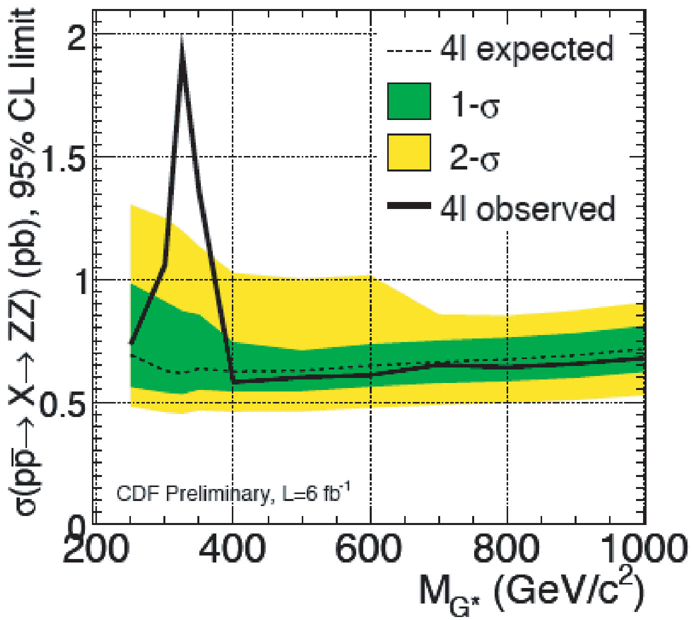
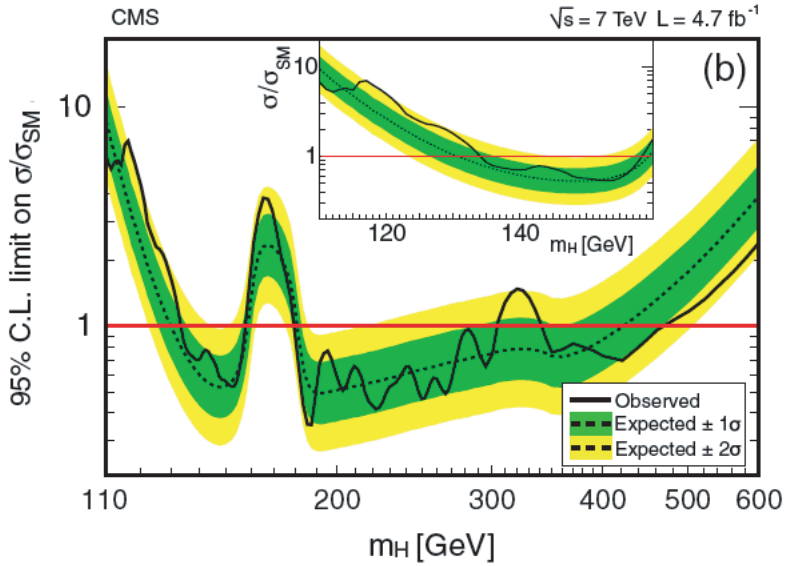


FIG. 13: Expected and observed 95% CL limits on $\sigma(p\bar{p} \to X \to ZZ)$ from the $ZZ \to \ell^+\ell^-\ell^+\ell^-$ channel; the four events with M_{ZZ}=327 GeV/c^2 result in a deviation from the expected limit.

* Search for the Standard Model Higgs Boson in CMS Collaboration @ LHS (Compact Muon Solenoid))

PRL 108, 111804 (2012)

"Small excesses of events are observed around masses of 119, 126 & 320 GeV "



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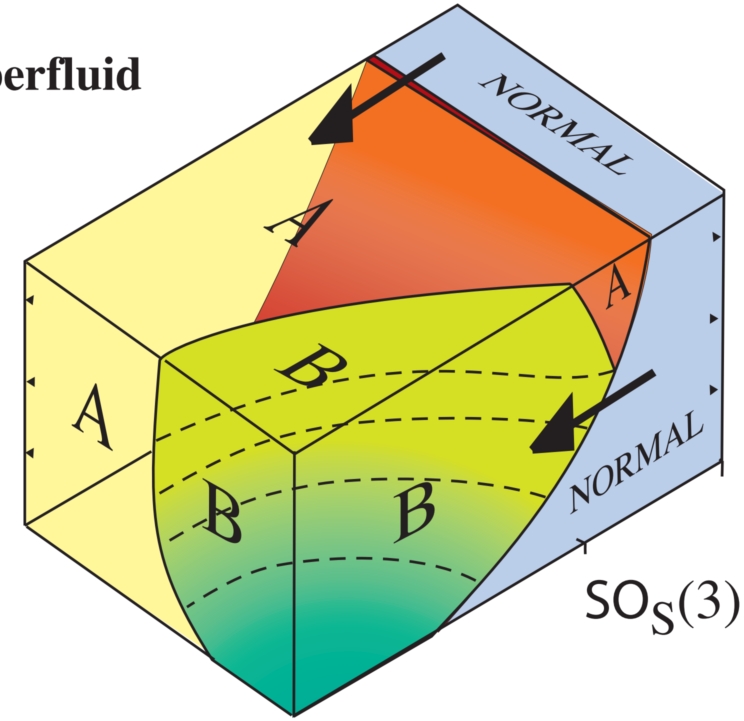
symmetry breaking phase transitions

$SO(10) \rightarrow SU(3) \times SU_L(2) \times U(1) \rightarrow SU(3) \times U_Q(1)$

symmetry breaking phase transitions
***in* superfluid ^{3}He**

$SO_S(3) \times SO_L(3) \times U(1) \rightarrow SO_S(2) \times U_Q(1)$ Q is analog of electric charge

^{3}He-A
topological chiral Weyl superfluid
two Dirac cones



^{3}He-B
time-reversal symmetric
topological superfluid

$SO_S(3) \times SO_L(3) \times U(1) \rightarrow SO_J(3)$

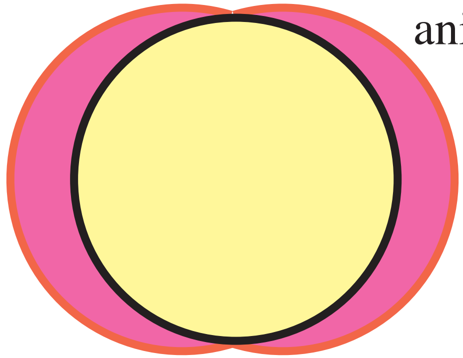
9 Goldstone + 9 Higgs modes in bulk ^{3}He-A

$U_Q(1)$ - analog of electromagnetic group

quantum number Q - analog of electric charge

$SO_S(3) \times SO_L(3) \times U(1) \longrightarrow SO_S(2) \times U_Q(1)$

Modes		Variables	In the absence of dipole interaction and magnetic field			
			Q	P^3	S_z	P^1
Sound	$E = 0$	$u_{23} - v_{13}$	0	−1	0	+1
Spin waves	$E = 0$	$u_{11} + v_{21}$, $u_{12} + v_{22}$	0	+1	±1	—
Orbital modes		u_{33}, v_{33}	±1	–	0	−1
Spin-orbit modes	$E = 0$	u_{31}, v_{31}, u_{32}, v_{32}	±1	–	±1	–
		$u_{13} + v_{23}$	0	+1	0	+1
	$E^2 = 8/3\ \Delta_0^2$	$u_{22} - v_{12}$, $v_{11} - u_{21}$	0	−1	±1	–
"Clapping" modes	$E^2 = 4/3\ \Delta_0^2$	$u_{23} + v_{13}$, $u_{13} - v_{23}$	±2	–	0	+1
		$u_{11} - v_{21}$, $u_{21} + v_{11}$, $u_{12} - v_{22}$, $u_{22} + v_{12}$	±2	–	±1	–



anisotropic gap with nodes

$$\Delta(\theta) = \Delta_0 \sin\theta$$

$$< \Delta^2 > = 2/3\ \Delta_0^2$$

3 Goldstones + 9 Higgs form 6 Nambu pairs

$$E_{0-}^2 + E_{0+}^2 = 4 < \Delta^2 >$$

$$E_{0-}^2 + E_{0+}^2 = 4 < \Delta^2 >$$

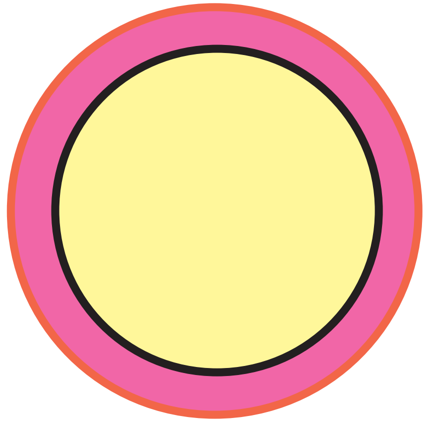
$$E_{-2}^2 + E_{+2}^2 = 4 < \Delta^2 >$$

6 Goldstones (2 "photons" + 4 from hidden symmetry) have no Nambu partners

3 Goldstone + 9 Higgs modes in ^{3}He-A film

$SO_S(3) \times SO_L(2) \times U(1) \longrightarrow SO_S(2) \times U_Q(1)$

$$m_{Q+}^2 + m_{Q-}^2 = 4\, m_f^2$$



isotropic gap Δ in 2D

3He-A film: quantum number Q is analog of electric charge, $m_f = \Delta$ gap

Q=0 $\quad E_{0-} = 0$ Goldstone (sound mode) $\quad E_{0+} = 2\,\Delta$ pair breaking mode $\quad E_{0+}^2 + E_{0-}^2 = 4\,\Delta^2$

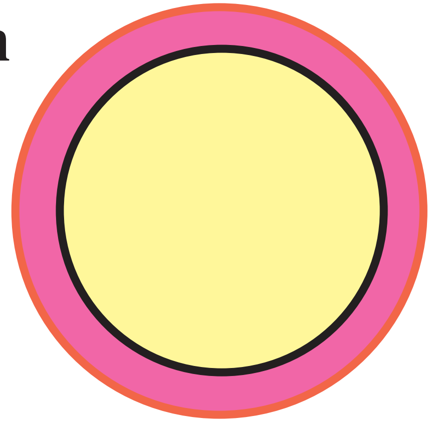
|Q|=1 $\quad E_{-1} = 2^{1/2}\Delta \quad E_{+1} = 2^{1/2}\Delta \quad E_{-2}^2 + E_{+2}^2 = 4\,\Delta^2$

clapping modes
analogs of charged Higgs bosons

Nambu sum rule for ^{3}He-A film: symmetry consideration

$$m_Q^2 = 2m_f^2 (1 +/- \eta^{(Q)})$$

$$\eta^{(Q)} = \mathrm{Tr}\,(VO^{(Q)}VO^{(Q)})$$



isotropic gap Δ in 2D

$$m_{Q+}^2 + m_{Q-}^2 = 4\, m_f^2$$

3He-A film: quantum number Q is analog of electric charge, $m_f = \Delta$ gap

$$E_Q^{\ 2} = 2\,\Delta^2 (1 +/- \eta^{(Q)})$$

Q=0 , $\eta^{(Q)} = 1$

$E_{0-} = 0$
Goldstone
(sound mode)

$E_{0+} = 2\,\Delta$
pair breaking mode

$$E^2_{0+} + E^2_{0-} = 4\,\Delta^2$$

Q=1 , $\eta^{(Q)} = 0$

$E_{-1} = 2^{1/2}\Delta$

$E_{+1} = 2^{1/2}\Delta$

$$E^2_{-2} + E^2_{+2} = 4\,\Delta^2$$

clapping modes
analogs of charged Higgs bosons

Nambu sum rule: from ^{3}He-A to Standard Model

relation between energies E_B & E_F of bosonic & fermionic excitations in BCS type theories

$$\boxed{E_{B1}^2} + \boxed{E_{B2}^2} = \boxed{4\,E_F^2}$$

2D 3He-A $E_{B+} = 2^{1/2}\Delta$ $E_{B-} = 2^{1/2}\Delta$ $E_F = \Delta$

clapping modes

gap in quasiparticle spectrum

Application of Nambu rule to masses of charged Higgs fields and top quarks

$$\boxed{m_{H+}^2} + \boxed{m_{H-}^2} = \boxed{4\,m_t^2}$$

245 GeV 245 GeV 174 GeV

charged Higgs charged Higgs top quark

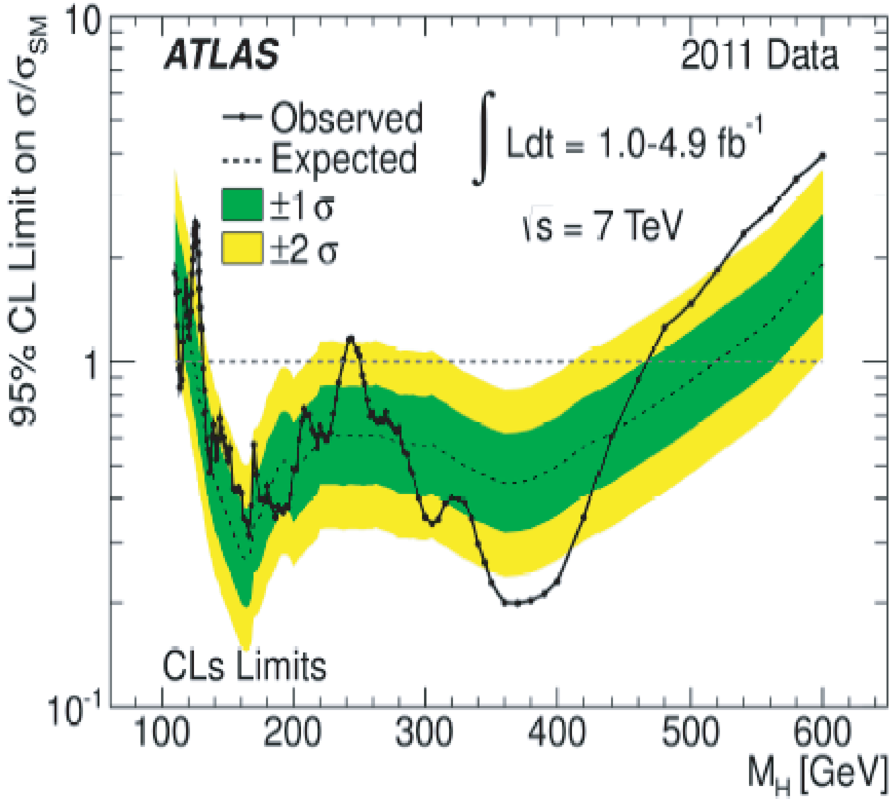
experimental evidence ?

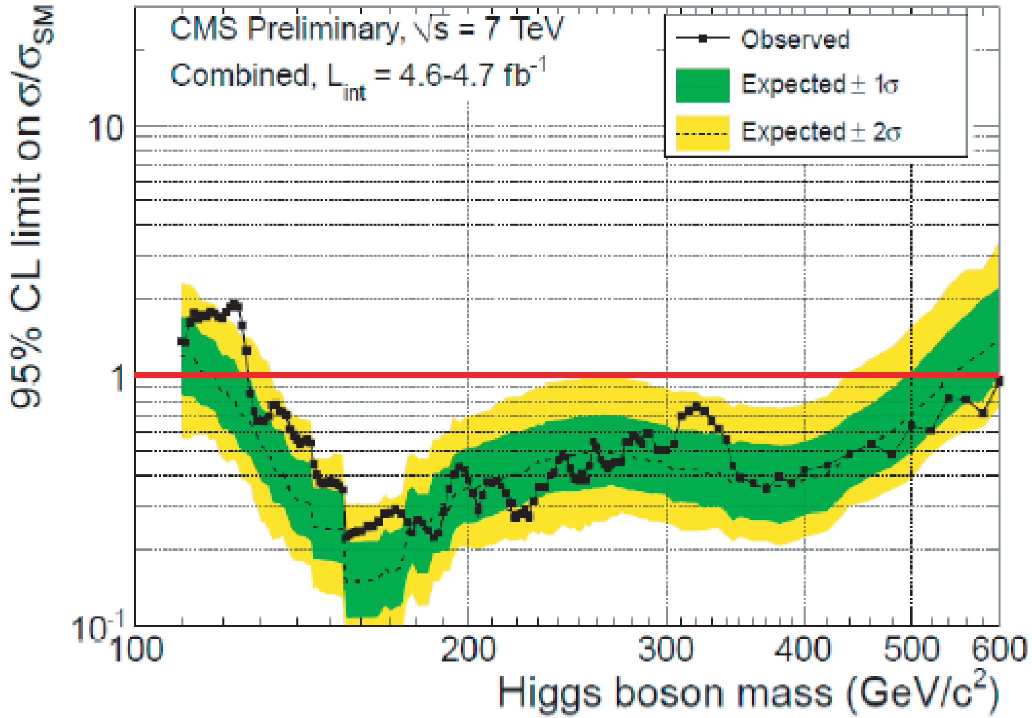
ATLAS @ LHC
PLB **710** 49 (2012)

hints of 245 GeV Higgs bosons in earlier experiments

* ATLAS-CONF-2011-135 August 21, 2011
Update of the Combination of Higgs Boson Searches

"The second was peaking at a Higgs boson mass hypothesis of 245 GeV"





Excess of events in $H \to \gamma\gamma, H \to ZZ$

ATLAS near $M_H \sim$ 126 GeV
and near $M_H \sim$ 245 GeV

CMS near $M_H \sim$ 124 GeV
and near $M_H \sim$ 119.5 GeV

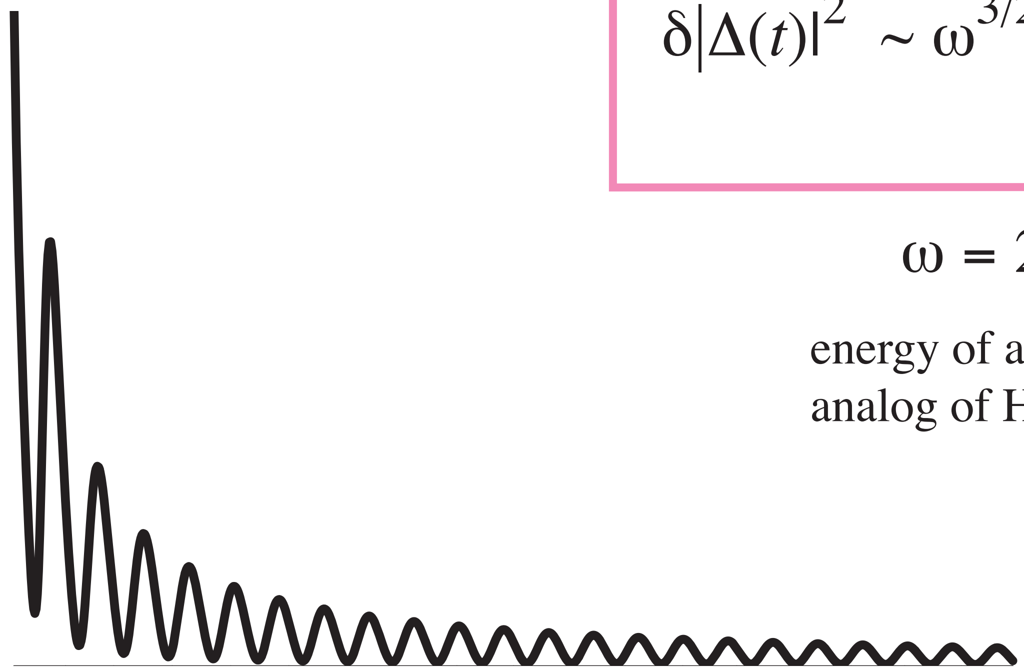
excitation of Higgs boson by quench

dynamics of vacuum energy Λ in cosmology

$$\Lambda(t) \sim \omega^2 \frac{\sin^2 \omega t}{t^2}$$

$\omega \sim M_{\text{inflaton}}$

mass of Higgs inflation



dynamics of gap Δ in superconductor

$$\delta|\Delta(t)|^2 \sim \omega^{3/2} \frac{\sin \omega t}{t^{1/2}}$$

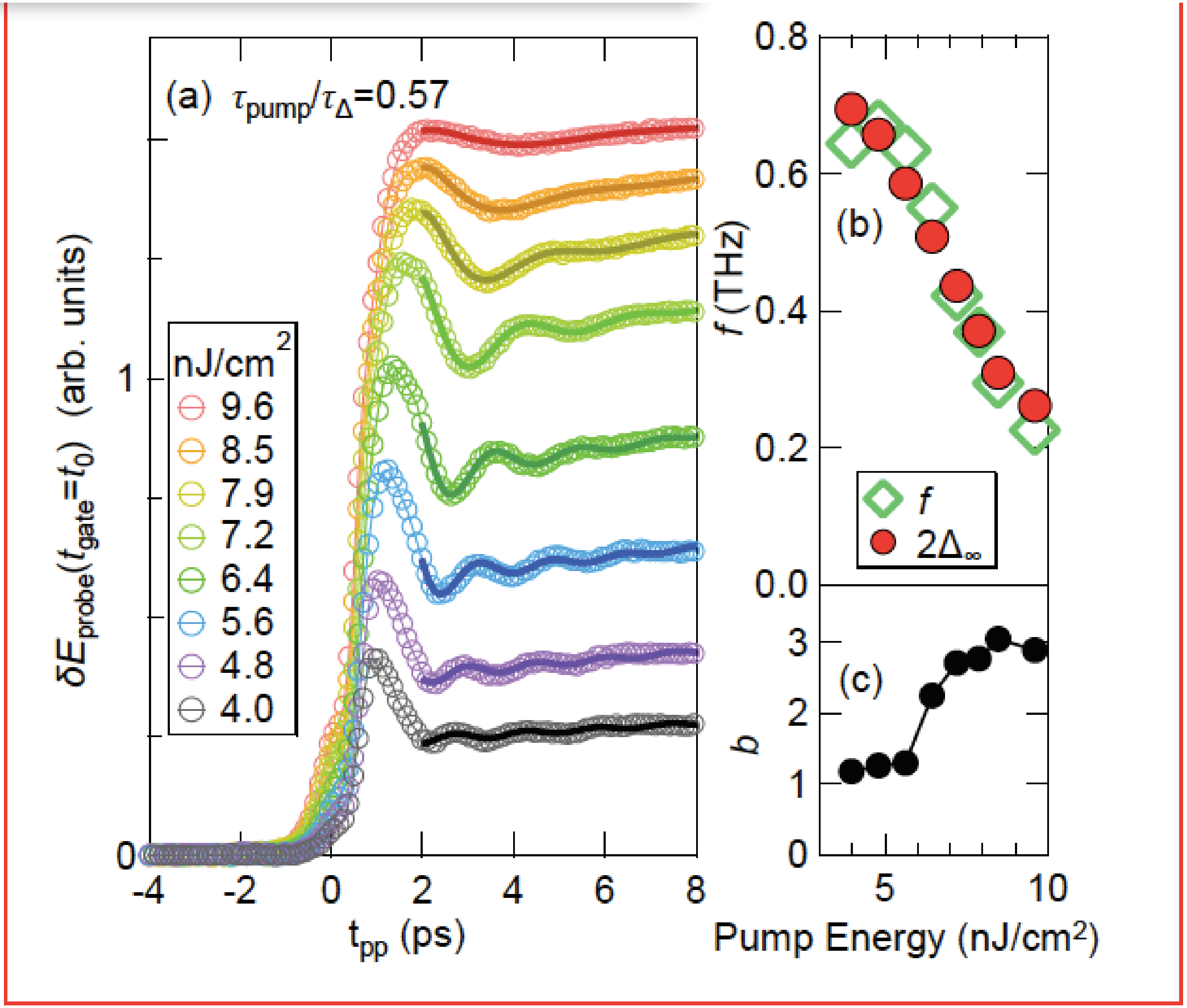
$\omega = 2\Delta$

energy of amplitude mode:
analog of Higgs mass

Starobinsky Higgs inflation

V. Gurarie, 0905.4498, 1307.1485, 1307.2256
A.F. Volkov & S.M. Kogan, JETP **38**, 1018 (1974)
Barankov & Levitov, ...

Higgs amplitude mode after quench



Higgs Amplitude Mode in BCS Superconductors
$Nb_{1-x}Ti_x$ induced by Terahertz Pulse Excitation
R. Matsunaga, et al. arXiv:1305.0381

Majorana fermions in particle physics & cond-mat

Majorana

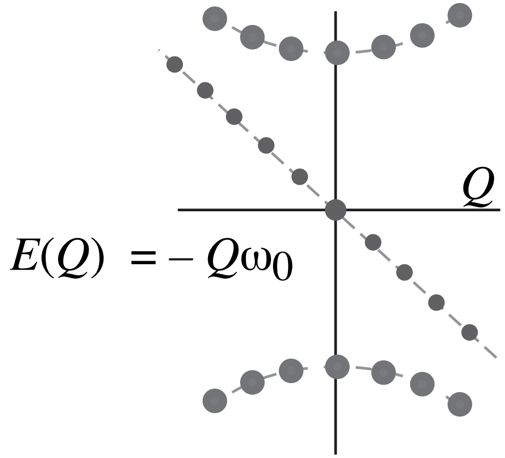
(propagating fermions)

Majorino

(zero-dimensional Majorana zero mode, Wilczek)

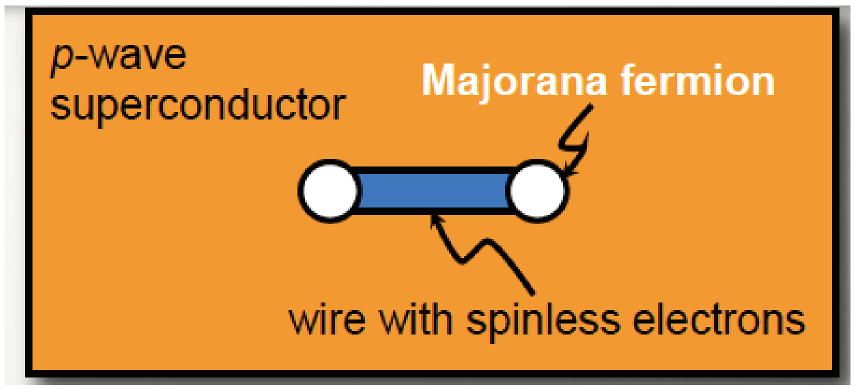
$a^+ = a$

zero mode in core of 2+1 p-wave superconductor



fermions in supersymmetric theories

edge states in nanowires on superconductor



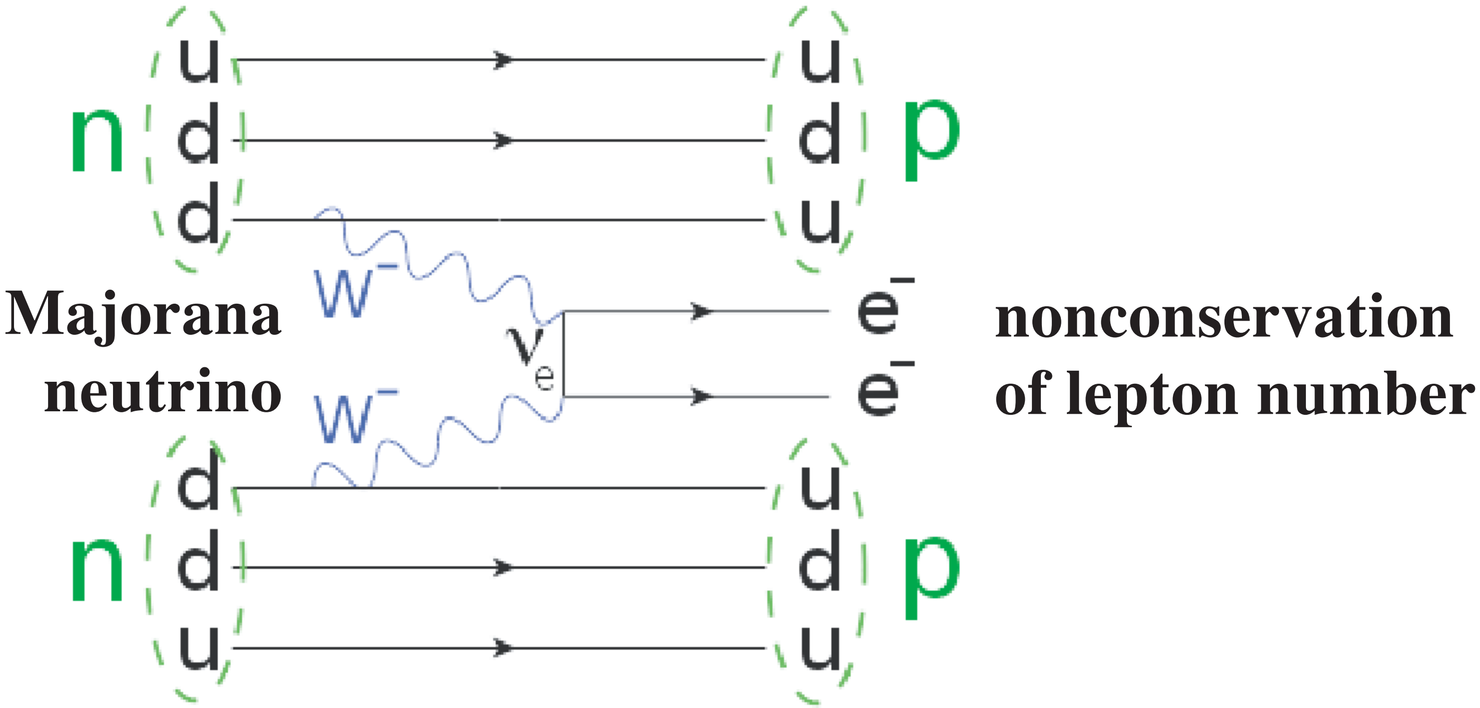
Weyl "relativistic" fermions in bulk ^{3}He-A

Majorana edge states on surface of ^{3}He-B

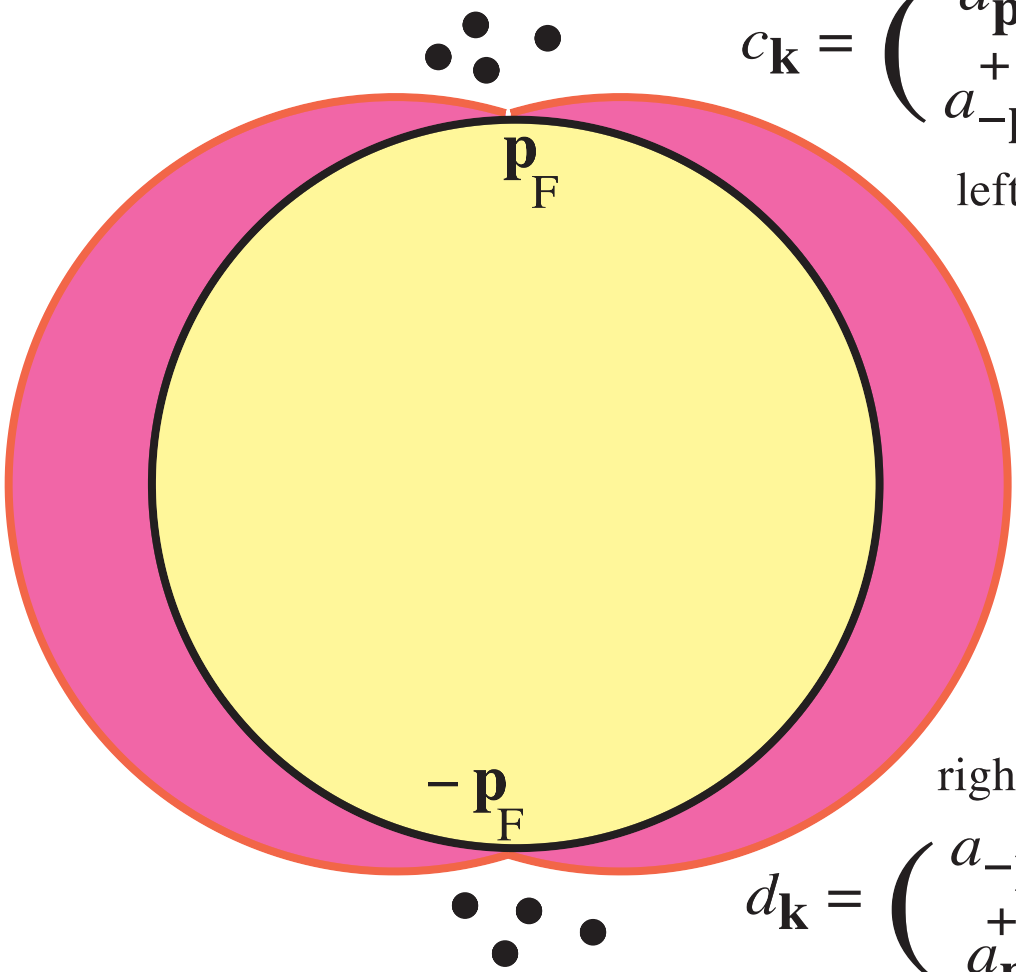
Majorana Valley: Fermi arc on surface of ^{3}He-A

neutrinoless double beta decay

observation of neutrinoless double beta decay
necessarily implies Majorana nature of neutrinos

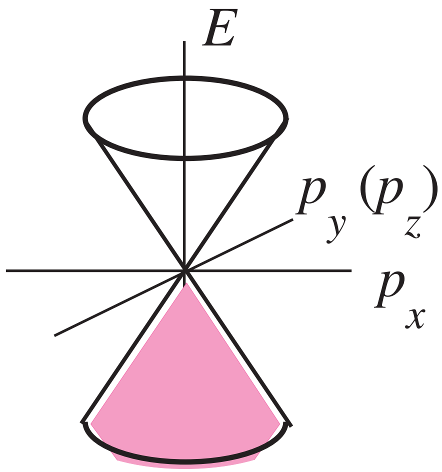


Weyl fermions in ^{3}He-A



$$c_{\mathbf{k}} = \begin{pmatrix} a_{\mathbf{p}_F+\mathbf{k}} \\ a^{+}_{-\mathbf{p}_F-\mathbf{k}} \end{pmatrix}$$

left electrons

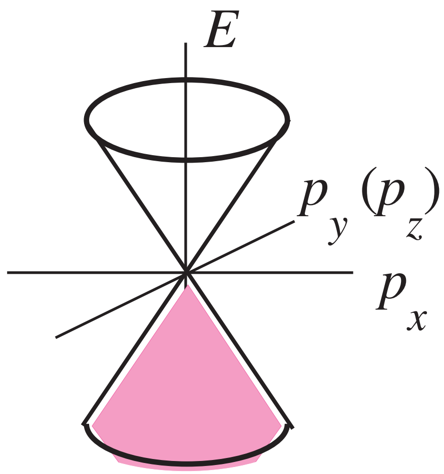


$$d_{\mathbf{k}} = \tau_1 c^{+}_{-\mathbf{k}}$$

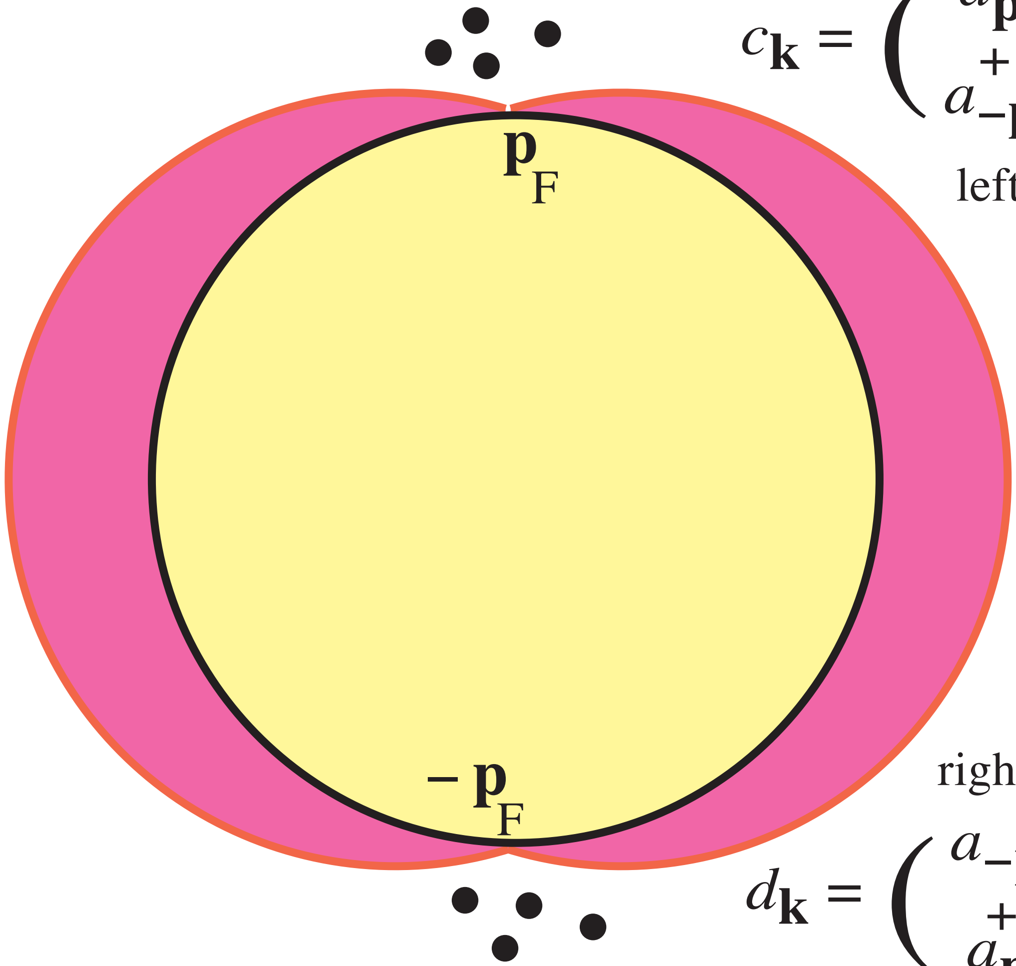
particles in two valleys are antiparticles

right antielectrons

$$d_{\mathbf{k}} = \begin{pmatrix} a_{-\mathbf{p}_F+\mathbf{k}} \\ a^{+}_{\mathbf{p}_F-\mathbf{k}} \end{pmatrix}$$

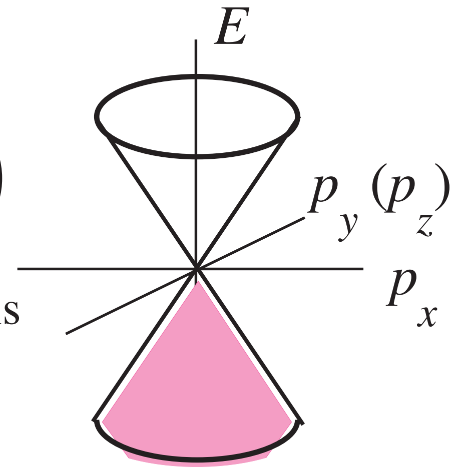


maybe all particles in our world are Majorana ?



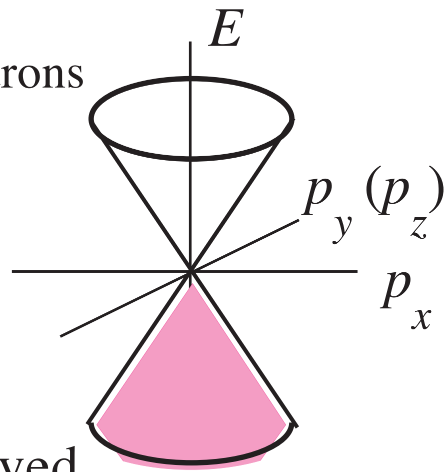
$$c_{\mathbf{k}} = \begin{pmatrix} a_{\mathbf{p}_F+\mathbf{k}} \\ a^{+}_{-\mathbf{p}_F-\mathbf{k}} \end{pmatrix}$$

left electrons



$$d_{\mathbf{k}} = \tau_1 c^{+}_{-\mathbf{k}}$$

right antielectrons



$$d_{\mathbf{k}} = \begin{pmatrix} a_{-\mathbf{p}_F+\mathbf{k}} \\ a^{+}_{\mathbf{p}_F-\mathbf{k}} \end{pmatrix}$$

$$H = d_{\mathbf{k}}\, d_{-\mathbf{k}} V_{2\mathbf{p}_F}$$

in each of two worlds lepton number is not conserved
neutrinoless double β-decay is possible
but only due to very short wavelength perturbation

conclusion

* composite Higgs field is extension of Standard Model:
  from Ginzburg-Landau to BCS in Weyl semimetal

* sum rule derived by Nambu for ^{3}He-B can be extended to Standard Model

* Nambu sum rule (if valid) may express masses of neutral & charged Higgs bosons
  via quark masses

* more accurate analysis near 325 GeV and 245 GeV is needed

* rigorous derivation of Nambu sum rule & its range of validity in fermionic systems:
  relativistic QFT, superconductors, magnetics, cold Fermi gases, graphene,...