Title: Emergent physics a condensed matter primer.

Date: Oct 13, 2004 12:45 PM

URL: http://pirsa.org/04100011

Abstract:

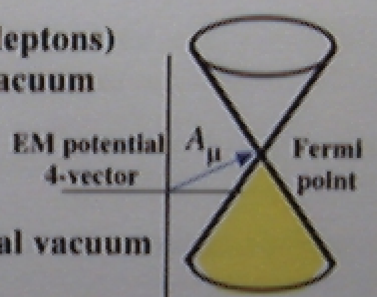
Emergent physics:
a condensed matter primer

G. Volovik
Low Temperature Lab, Helsinki & Landau Institute, Moscow

*** Emergent relativity from many *Theories of Everything:***

universality classes of *Theories of Everything*
from p-*space topology* of *quantum vacua*

*** Fermi point in p-space and emergent physical laws**



emergence of chiral particles (quarks and leptons)
as fermion zero modes of quantum vacuum
emergence of relativistic spin
and effective Lorentz invariance
effective gauge fields
as bosonic collective modes of physical vacuum
effective gauge invariance
effective metric and gravity
as bosonic collective modes of physical vacuum
quantization of physical parameters, ...

$$F_{\mu\nu} = \nabla_\mu A_\nu - \nabla_\nu A_\mu$$

$$(\sqrt{-g}/12\pi^2) \ln(\Lambda/T)\; g^{\alpha\beta} g^{\mu\nu} F_{\alpha\mu} F_{\beta\nu}$$

*** Application to yet uknown physics of quantum vacuum**

dark matter and dark energy
cosmological constant problems
vacuum instability, ergoregion instability
chiral anomaly and baryogenesis, ...

$\Lambda\sqrt{-g}$ $\quad \Lambda=0$ *in equilibrium*

baryoproduction

$$\dot{B} = (1/4\pi^2)(\mathbf{B}\cdot\mathbf{E})\,[\,B_R e_R^2 - B_L e_L^2\,]$$

momentoproduction

$$\dot{\mathbf{P}} = (1/4\pi^2)(\mathbf{B}\cdot\mathbf{E})\,[\,\mathbf{P}_R - \mathbf{P}_L\,]$$

a condensed matter primer

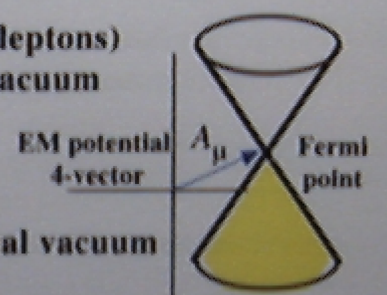
G. Volovik
Low Temperature Lab, Helsinki & Landau Institute, Moscow

*** Emergent relativity from many *Theories of Everything:***

universality classes of ***Theories of Everything***
from **p-*space topology*** of ***quantum vacua***

*** Fermi point in p-space and emergent physical laws**

emergence of chiral particles (quarks and leptons)
as fermion zero modes of quantum vacuum
emergence of relativistic spin
and effective Lorentz invariance
effective gauge fields
as bosonic collective modes of physical vacuum
effective gauge invariance
effective metric and gravity
as bosonic collective modes of physical vacuum
quantization of physical parameters, ...



$$F_{\mu\nu} = \nabla_\mu A_\nu - \nabla_\nu A_\mu$$

$$(\sqrt{-g}/12\pi^2) \ln(\Lambda/T)\, g^{\alpha\beta} g^{\mu\nu} F_{\alpha\mu} F_{\beta\nu}$$

*** Application to yet uknown physics of quantum vacuum**

dark matter and dark energy
cosmological constant problems
vacuum instability, ergoregion instability
chiral anomaly and baryogenesis, ...

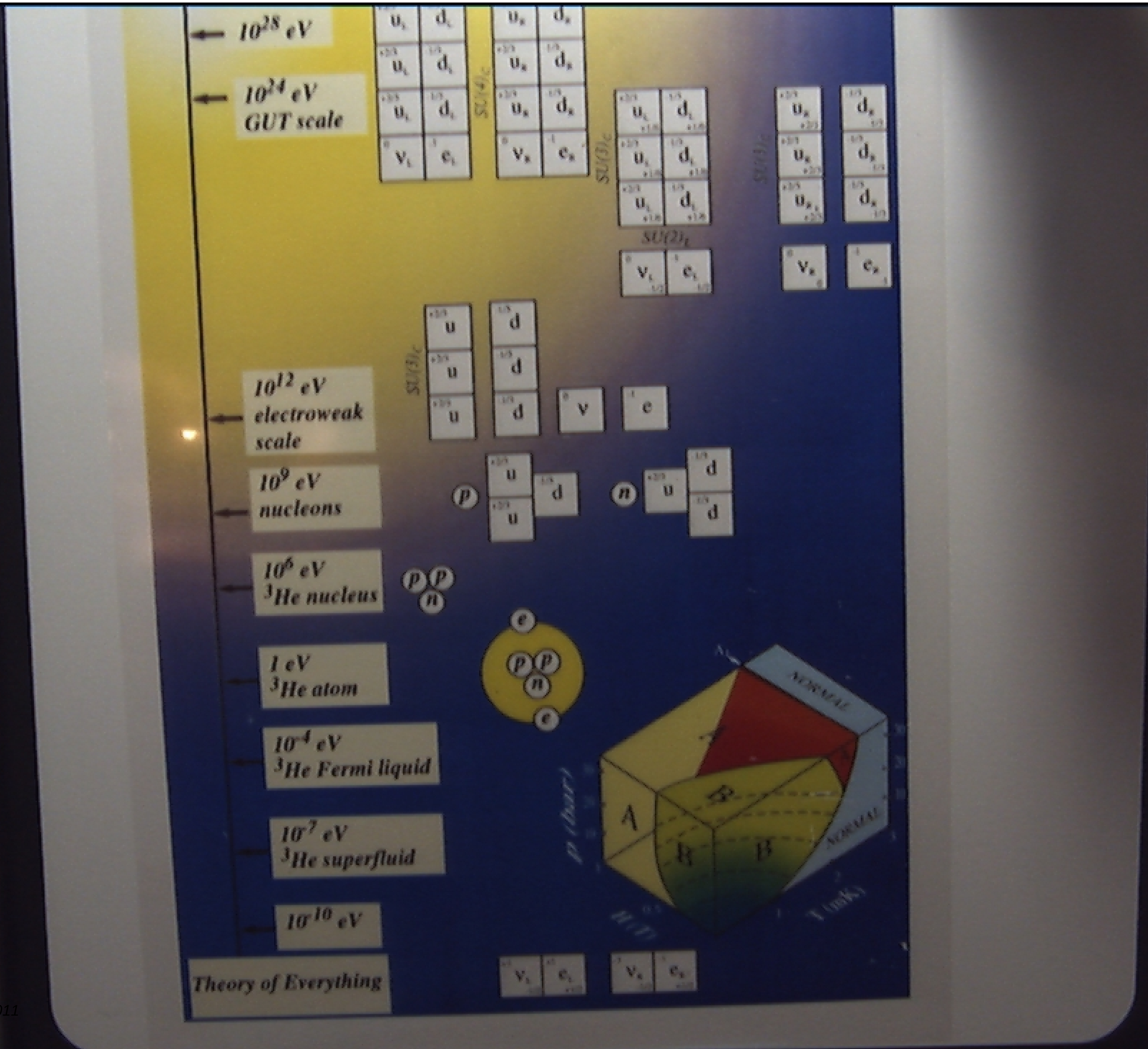
$\Lambda\sqrt{-g} \quad \Lambda=0$ *in equilibrium*

baryoproduction

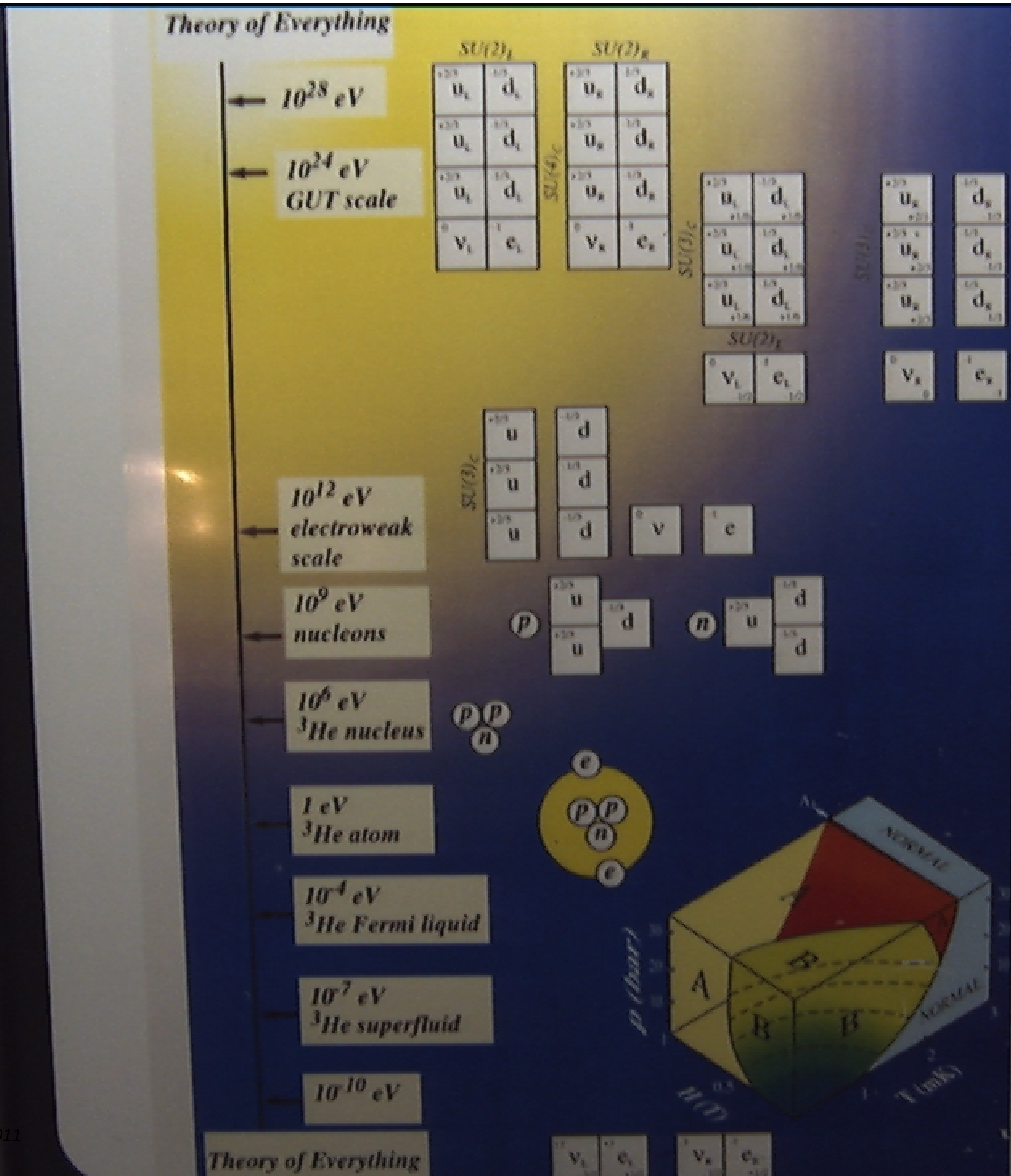
$$\dot{B} = (1/4\pi^2)\,(\mathbf{B}\cdot\mathbf{E})\,[\,B_R e_R^2 - B_L e_L^2\,]$$

momentoproduction

$$\dot{\mathbf{P}} = (1/4\pi^2)\,(\mathbf{B}\cdot\mathbf{E})\,[\,\mathbf{P}_R - \mathbf{P}_L\,]$$



10^{28} eV
10^{24} eV
GUT scale
10^{12} eV
electroweak scale
10^{9} eV
nucleons
10^{6} eV
^{3}He nucleus
1 eV
^{3}He atom
10^{-4} eV
^{3}He Fermi liquid
10^{-7} eV
^{3}He superfluid
10^{-10} eV
Theory of Everything
SU(4)$_C$
SU(3)$_C$
SU(2)$_L$
NORMAL


Theory of Everything
10^{28} eV
10^{24} eV
GUT scale
10^{12} eV
electroweak
scale
10^{9} eV
nucleons
10^{6} eV
^{3}He nucleus
1 eV
^{3}He atom
10^{-4} eV
^{3}He Fermi liquid
10^{-7} eV
^{3}He superfluid
10^{-10} eV
Theory of Everything
$SU(2)_L$
$SU(2)_R$
$SU(4)_C$
$SU(3)_C$
NORMAL
A
B
p (bar)
T (mK)
H (T)

Landau concept of quasiparticles

Quantum Bose liquid

Bangalore
18.02.2004

India-Finland Workshop

liquid ^{4}He

10^{23} atoms

complicated many-body system of strongly interacting strongly correllated non-relativistic atoms

Theory of Everything: huge amount of degrees of freedom

analog of Planck scale

Effective theory in low temperature limit $T << 1^oK$

Quasiparticles (phonons) + Collective hydrodynamic modes = QFT

dilute system of elementary particles of effective theory

analog of gravity

bosonic

$$H_{eff} = E_{vac} + \sum_p cp\, a_p^+ a_p$$

$E_{vac} = 0$

hint for solution of cosmological problem

speed of sound

velocity and density fields provide effective acoustic metric for phonons

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu$$

$g_{\mu\nu}$ *obey hydrodynamic equations rather than Einstein equations*

Quantum Bose liquid

Bangalore
18.02.2004

India-Finland
Workshop

liquid ^{4}He

10^{23} atoms

complicated many-body system of strongly interacting strongly correllated non-relativistic atoms

Theory of Everything:
huge amount of degrees of freedom

analog of Planck scale

Effective theory in low temperature limit $T << 1^oK$

Quasiparticles (phonons) + Collective hydrodynamic modes = QFT

dilute system of elementary particles of effective theory

analog of gravity

bosonic

$$H_{eff} = E_{vac} + \sum_p cp\, a^+_p a_p$$

$E_{vac} = 0$

speed of sound

hint for solution of cosmological problem

velocity and density fields provide effective acoustic metric for phonons

$$ds^2 = g_{\mu\nu} dx^\mu dx^\nu$$

$g_{\mu\nu}$ ***obey hydrodynamic equations rather than Einstein equations***


ESSELTE
56066
Kom-ihåg-lappar (peterbergfund)
on, aug 25, 2004
Description:
The Theoretical Division
Institute of Physical Problems, 1956. Standing, L-R: Gershtein,
Pitaevskii, Arkhipov,
Seated, L-R: Prozorova, Aleksei Abrikosov, Khalatnikov, Lev
Davidovich Landau, Evgenii
Lifshitz.
Scan ©American Institute of Physics

liquid ^{3}He

10^{23} atoms

complicated many-body system of strongly interacting strongly correllated atoms

normal ^{3}He, ^{3}He-A, ^{3}He-B, normal metals, semiconductors, superconductors, etc

Effective theory ↓ in low temperature limit

Fermionic quasiparticles + Bosonic collective modes = QFT

elementary particles of effective theory

Type of Quantum Field Theory depends on universality class

universality class of Fermi points

^{3}He-A, Standard Model

Effective theory ↓ in low temperature limit

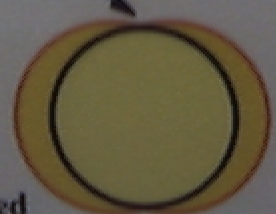
Chiral fermions + Gauge fields & gravity = Relativistic QFT

↓

emergent phenomena:

Gauge invariance
Lorentz invariance
General covariance (partly)
chiral fermions
gauge fields
gravity
spin

left-handed fermions live here



right-handed fermions live here

and emergent effective QFT

quasiparticles: propagating particle-like excitations
above the ground state (vacuum) of system

* quasiparticle does not scatter on atoms of system, if system is in the ground state

for quasiparticle:
ground state = vacuum

* quasiparticles obey effective Quantum Field Theory

physical laws in effective QFT are more symmetric than physical laws in the underlying microscopic `Planck-scale' system

* type of effective QFT depends on Universality Class

details of underlying `Planck-scale' physics are irrelevant: they are lost in coarse-grained description

many `Theories of Everything'
give the same Effective QFT

acoustic phonons in crystals
do not depend on details of Atomic Structure of Solid;
electronic excitations near Fermi surface
do not depend on details of Electronic Structure of Solid

* cond-mat provides us with a broad class of Hamiltonians for fermions, (in RQFT they are very restricted due to Lorentz invariance) General consideration of the Hamiltonians (actually, of Green's functions) revealed that properties of a given QFT are determined by momentum-space topology

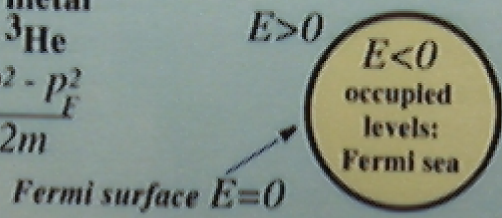
* p-space topology determines Universality Class of QFT

Universality classes of fermionic vacua

Systems with Fermi surface

Normal metal
Normal ^{3}He

$$E = \frac{p^2 - p_F^2}{2m}$$

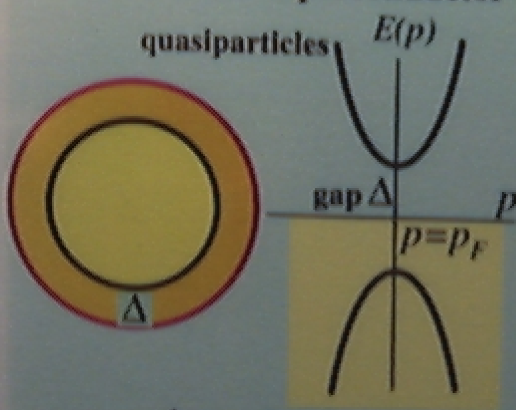


Quark matter

Vacuum within black hole

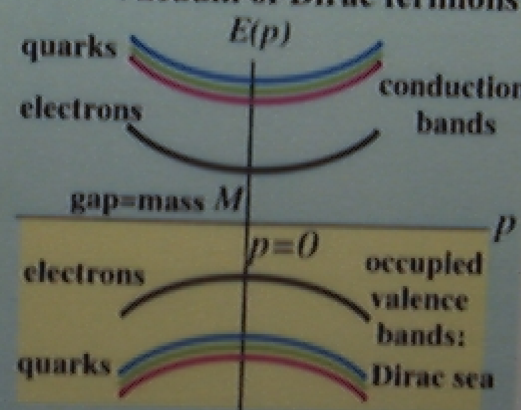
Fully gapped Fermi systems

Ground state of superconductor



$$E^2 = v_F^2 (p-p_F)^2 + \Delta^2$$

Vacuum of Dirac fermions

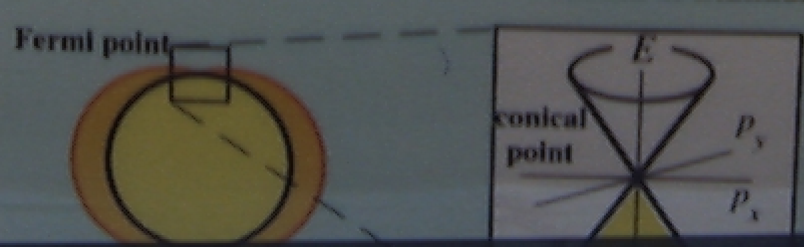


$$E^2 = p^2c^2 + M^2$$

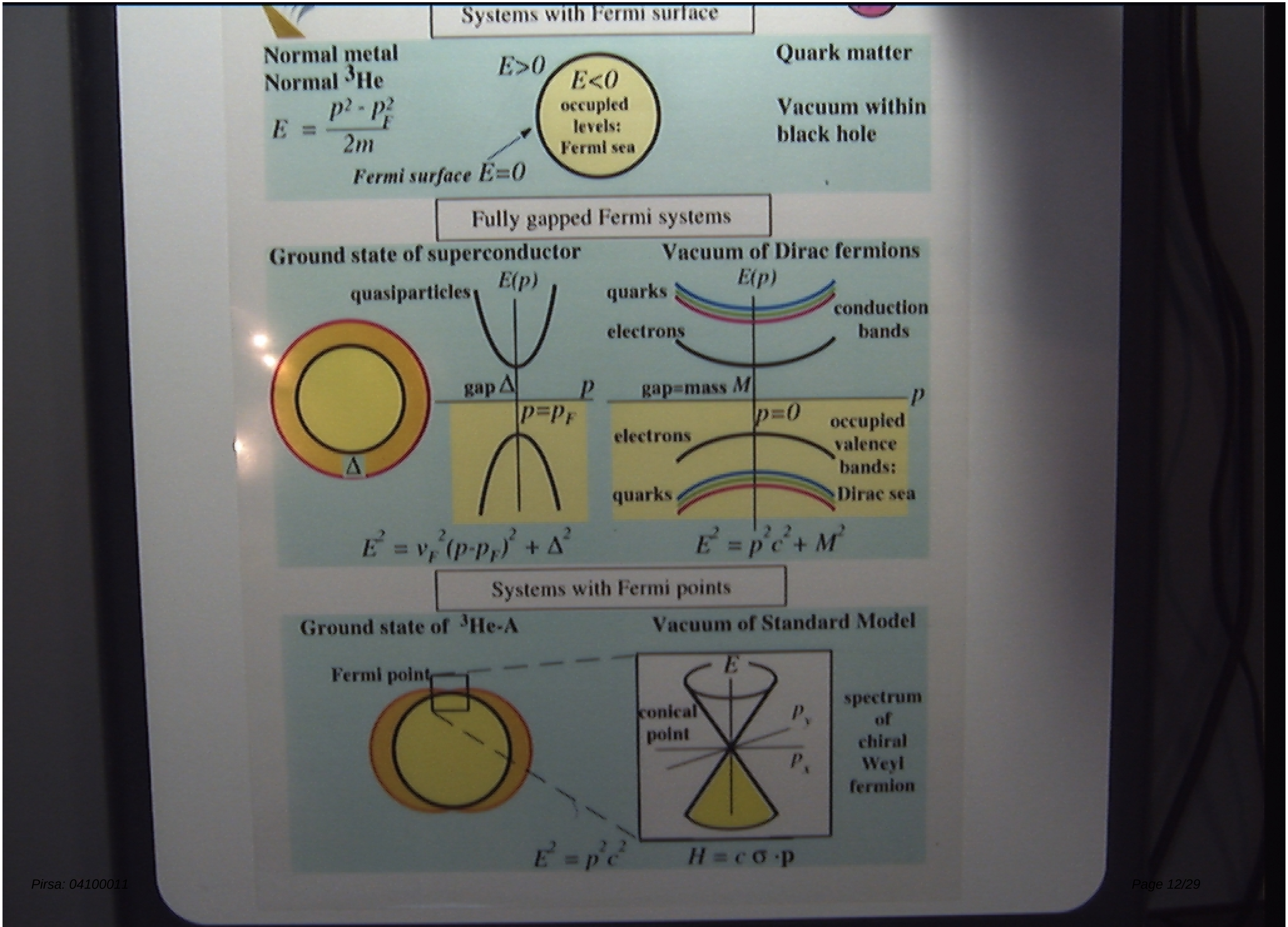
Systems with Fermi points

Ground state of ^{3}He-A

Vacuum of Standard Model



spectrum of chiral Weyl

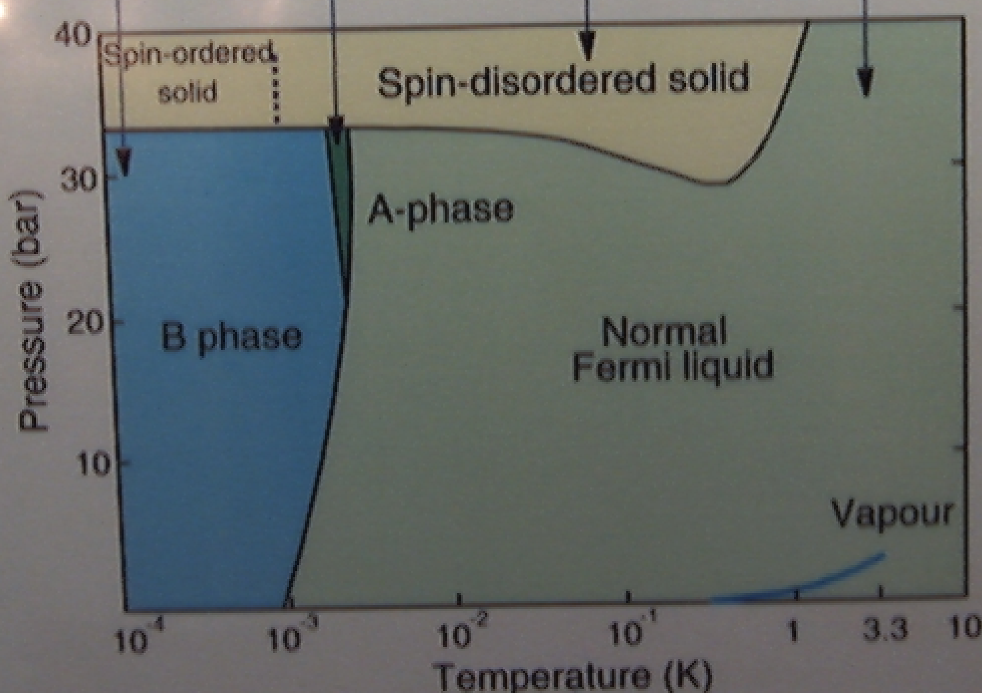

Systems with Fermi surface
Normal metal
Normal ^{3}He
$E = \frac{p^2 - p_F^2}{2m}$
$E>0$
$E<0$
occupied levels: Fermi sea
Fermi surface $E=0$
Quark matter
Vacuum within black hole
Fully gapped Fermi systems
Ground state of superconductor
quasiparticles
$E(p)$
gap Δ
p
$p=p_F$
Δ
$E^2 = v_F^2(p-p_F)^2 + \Delta^2$
Vacuum of Dirac fermions
quarks
electrons
conduction bands
gap=mass M
$p=0$
occupied valence bands: Dirac sea
$E^2 = p^2c^2 + M^2$
Systems with Fermi points
Ground state of ^{3}He-A
Fermi point
Vacuum of Standard Model
E
conical point
p_y
p_x
spectrum of chiral Weyl fermion
$E^2 = p^2c^2$
$H = c\,\sigma \cdot \mathbf{p}$

Theory of Everything
(in system of ^{3}He atoms)

Many-body Schrödinger quantum mechanics for N atoms

$$\hat{H} = -\frac{\hbar^2}{2m}\sum_{i=1}^{N}\Delta_i + \sum_{i=1}^{N}\sum_{j=i+1}^{N} V(\mathbf{r}_i - \mathbf{r}_j)$$

Fully gapped vacuum | **Fermi point class** | **Crystalline vacuum** | **Fermi surface class**

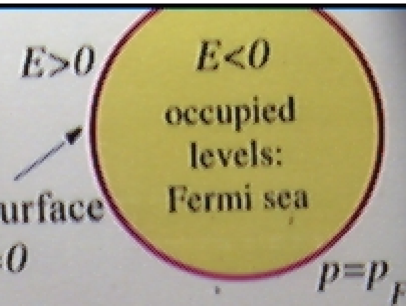


the only role of microscopic parameters $V(\mathbf{r}_i - \mathbf{r}_j)$: to choose between 4 classes of quantum vacua

* Fermi gas $E = \frac{p^2}{2m} - \mu$

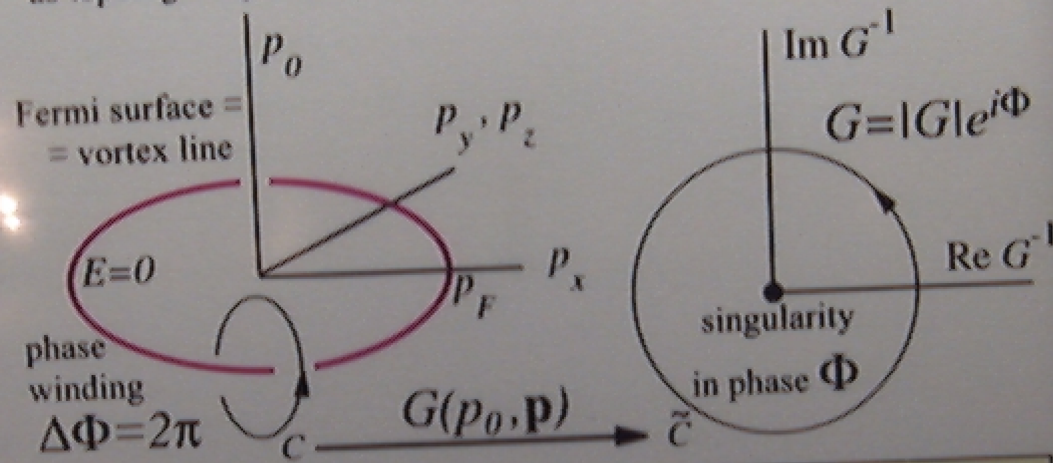
$$E = \frac{p^2 - p_F^2}{2m}$$

Fermi surface $E=0$



* Vortex in 4-momentum space

Fermi surface is robust to perturbations and interactions as topologically stable singularity of Green function: $G^{-1} = ip_0 - E$



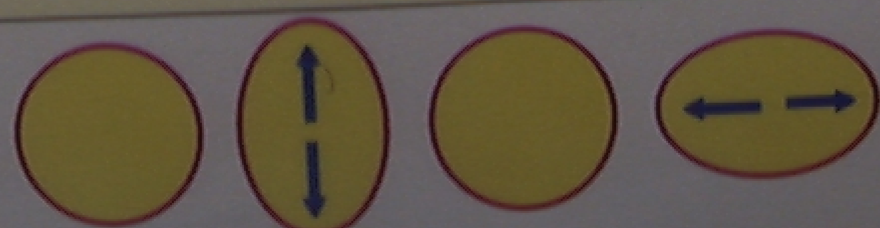
* Interacting Fermi system: general topological invariant

$$N_1 = \frac{1}{2\pi i}\, \mathrm{tr} \oint_{\substack{\text{around}\\ \text{Fermi surface}}} dp^{\mu}\, G\, \partial_{p_\mu} G^{-1}$$

* Collective bosonic modes of fermionic vacua:

how quasiparticles view collective motion of vacuum

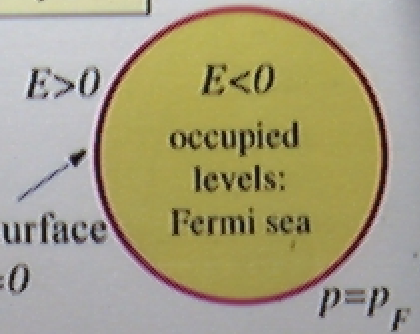
Oscillations of shape of Fermi surface (zero sounds)



Fermi surface Universality class

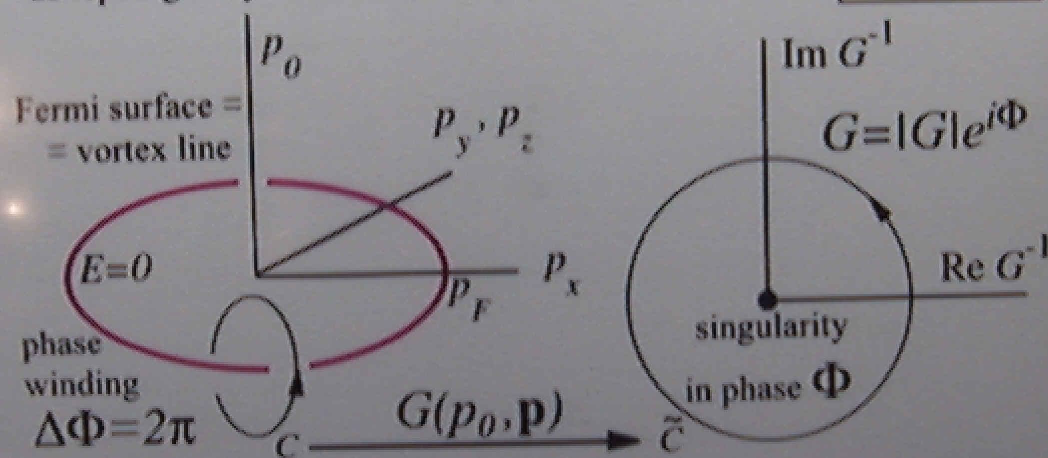
* Fermi gas $E = \frac{p^2}{2m} - \mu$

$$E = \frac{p^2 - p_F^2}{2m}$$



* Vortex in 4-momentum space

Fermi surface is robust to perturbations and interactions as topologically stable singularity of Green function: $G^{-1} = ip_0 - E$

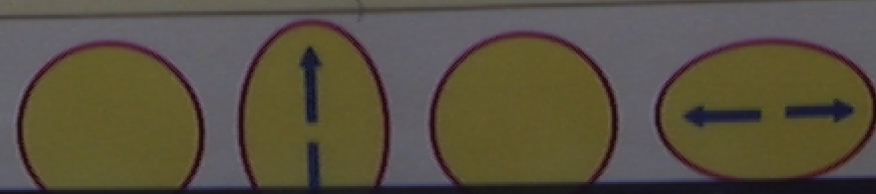


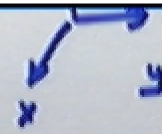
* Interacting Fermi system: general topological invariant

$$N_1 = \frac{1}{2\pi i}\, \mathbf{tr} \oint_{\substack{\text{around} \\ \text{Fermi surface}}} dp^{\mu}\, \mathbf{G}\, \partial_{p_\mu} \mathbf{G}^{-1}$$

* Collective bosonic modes of fermionic vacua:
how quasiparticles view collective motion of vacuum

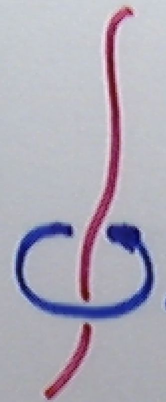
Oscillations of shape of Fermi surface (zero sounds)





$$\Psi = |\Psi| e^{i\Phi}$$

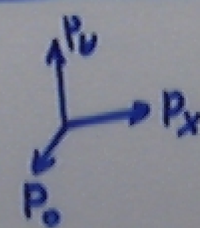
$\Phi(\vec{r})$ - phase of condensate

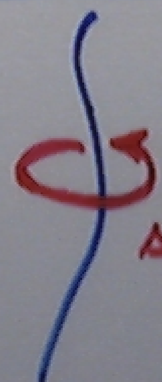


$$\Delta\Phi = 2\pi N$$

↓ integer

Fermi surface — vortex in momentum space





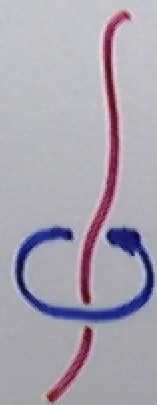
$$\Delta\Phi = 2\pi N$$

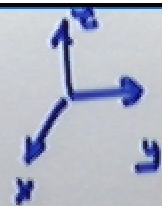
↓ integer

$$\mathcal{G} = |\mathcal{G}| e^{i\Phi}$$

$$\Phi(\vec{p}, p_0)$$

Vortex in $\vec{r}$-space





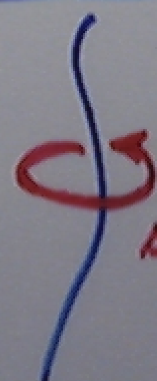
$\Psi = |\Psi| e^{i\Phi}$

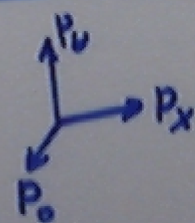
$\Phi(\vec{r})$ - phase of condensate

$\Delta\Phi = 2\pi N$

N → integer

Fermi surface - vortex in momentum space





$\Delta\Phi = 2\pi N$

N → integer

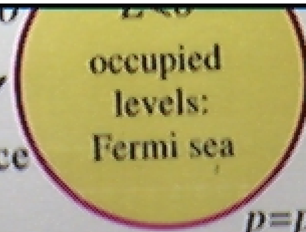
$\mathcal{G} = |\mathcal{G}| e^{i\Phi}$

$\Phi(\vec{p}, p_0)$

* Fermi gas $E = \frac{p^2}{2m} - \mu$

$$E = \frac{p^2 - p_F^2}{2m}$$

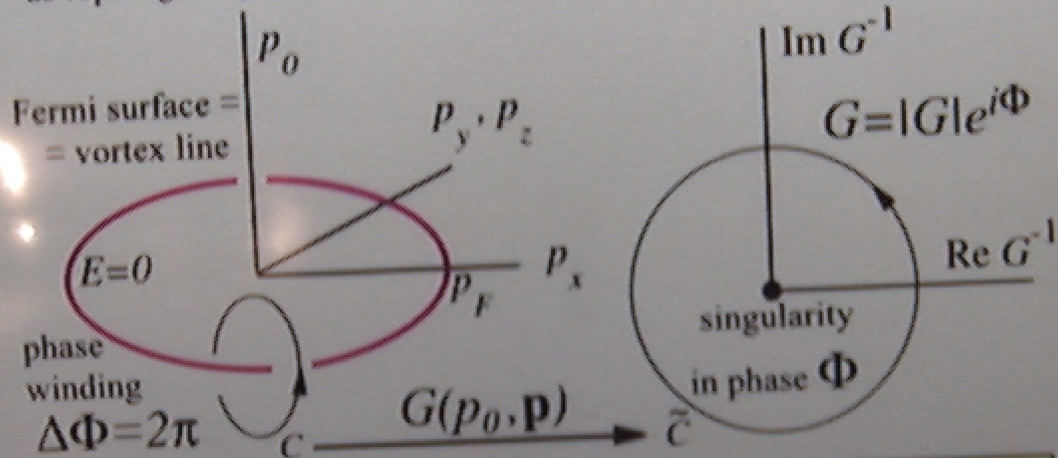
Fermi surface $E=0$



* Vortex in 4-momentum space

Fermi surface is robust to perturbations and interactions as topologically stable singularity of Green function:

$$G^{-1} = ip_0 - E$$



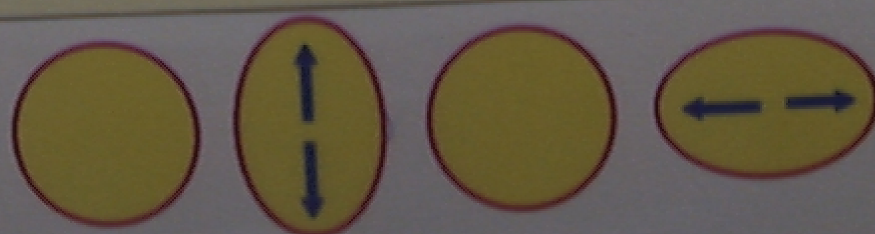
* Interacting Fermi system: general topological invariant

$$N_1 = \frac{1}{2\pi i}\, \mathrm{tr} \oint_{\substack{\text{around} \\ \text{Fermi surface}}} dp^\mu\, G\, \partial_{p_\mu} G^{-1}$$

* Collective bosonic modes of fermionic vacua:

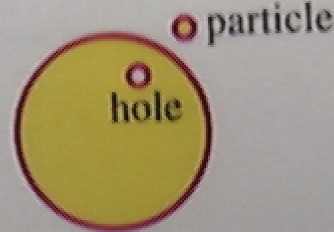
how quasiparticles view collective motion of vacuum

Oscillations of shape of Fermi surface (zero sounds)



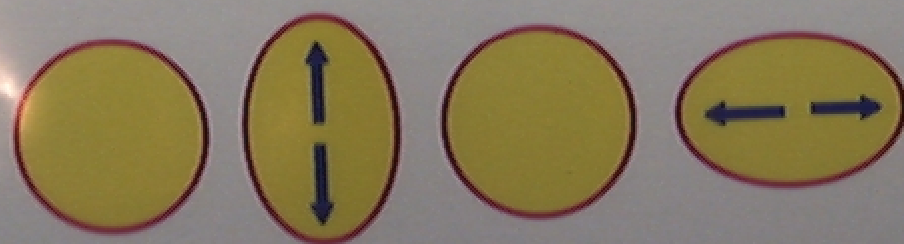
Effective nonrelativistic Quantum Field Theory:
interacting fermions and bosons

* fermions



hole = antiparticle

* bosons



bosons are not fundamental.
they are `composite' or effective:
collective modes of fermionic vacuum emerging
in the low-energy corner

Can Relativistic Quantum Field Theory naturally emerge in fermionic vacuum ?

Compare these Hamiltonians

Bogoliubov-Nambu quasiparticle in QFT for ^{3}He-A & chiral superconductors

$$H = \begin{pmatrix} \frac{p^2 - p_F^2}{2m} & c_\perp(p_x + ip_y) \\ c_\perp(p_x - ip_y) & -\frac{p^2 - p_F^2}{2m} \end{pmatrix}$$

left-handed meutrino

$$H = -c\,\boldsymbol{\sigma}\cdot\mathbf{p}$$

right-handed meutrino

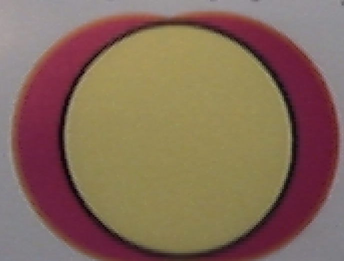
$$H = +c\,\boldsymbol{\sigma}\cdot\mathbf{p}$$

What is common for them?

$$H(\mathbf{p}) = \boldsymbol{\sigma}\cdot\mathbf{m}(\mathbf{p}) \qquad E^2(\mathbf{p}) = \mathbf{m}^2(\mathbf{p})$$

1. $E(\mathbf{p}) = 0$ ***at points*** **(Fermi points)**

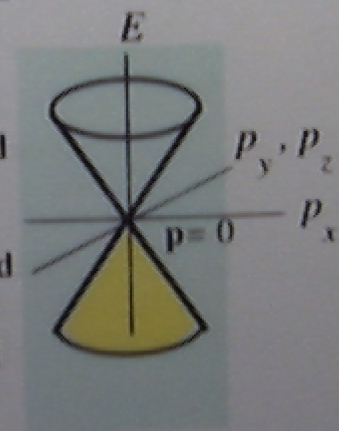
$\mathbf{p} = +p_F\mathbf{e}_z$ $\quad N_3 = +1$



$\mathbf{p} = -p_F\mathbf{e}_z$ $\quad N_3 = -1$

$N_3 = +1$
right-handed meutrino

left-handed meutrino
$N_3 = -1$



2. Fermi points are topologically stable & described by topological invariant in momentum space

$$N_3 = \frac{1}{8\pi}\, e_{ijk} \int dS^i\, \hat{\mathbf{m}}\cdot(\partial^j \hat{\mathbf{m}} \times \partial^k \hat{\mathbf{m}})$$

over 2D surface around Fermi point

3. Close to Fermi points (quasi)particles are relativistic left or right-handed chiral Weyl fermions

$$L = e^\mu{}_a \sigma^a (p_\mu - eA_\mu)$$

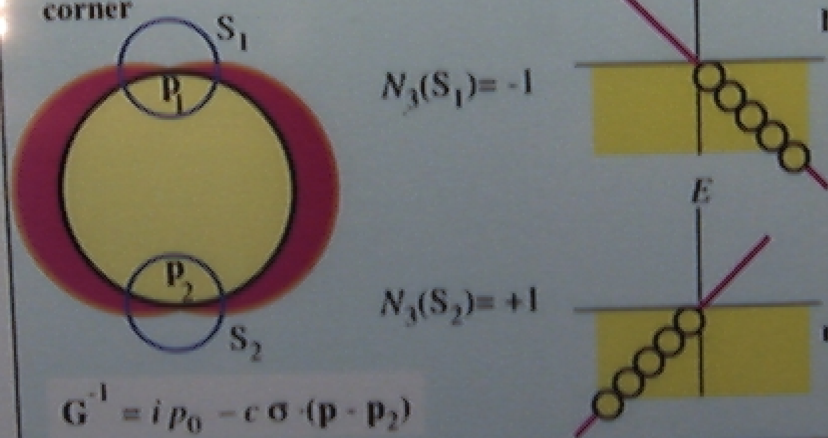
Topological stability of Fermi point
(general case)

Topological invariant in 4D momentum space $(\mathbf{p}\ ,\ p_0)$
in terms of fermionic propagator:
matrix Green's function $\mathbf{G}(\mathbf{p}\ ,\ p_0)$

$$N_3 = \frac{1}{24\pi^2}\, e_{\mu\nu\lambda\gamma}\, \mathbf{tr} \int dS^\gamma\, \mathbf{G}\, \partial^\mu\, \mathbf{G}^{-1}\, \mathbf{G}\, \partial^\nu\, \mathbf{G}^{-1} \mathbf{G}\, \partial^\lambda\, \mathbf{G}^{-1}$$

over 3D surface S in 4D momentum space

in low-energy corner $\mathbf{G}^{-1} = i\,p_0 + c\,\boldsymbol{\sigma}\cdot(\mathbf{p} - \mathbf{p}_1)$



$N_3(S_1) = -1$

$N_3(S_2) = +1$

left-handed particles

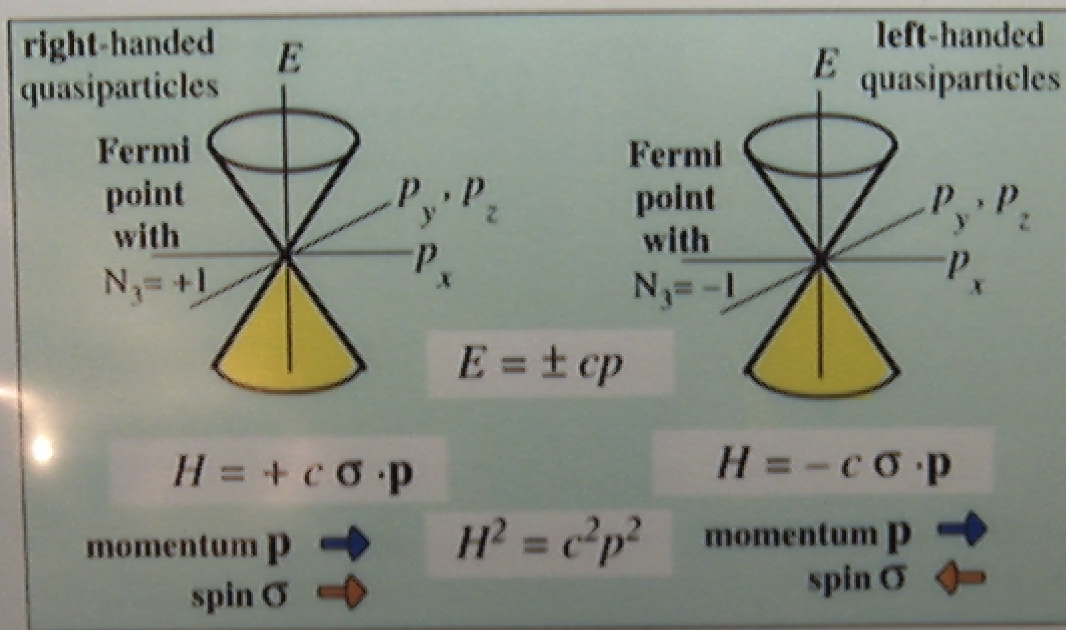
top. invariant determines chirality in low-energy corner

right-handed particles

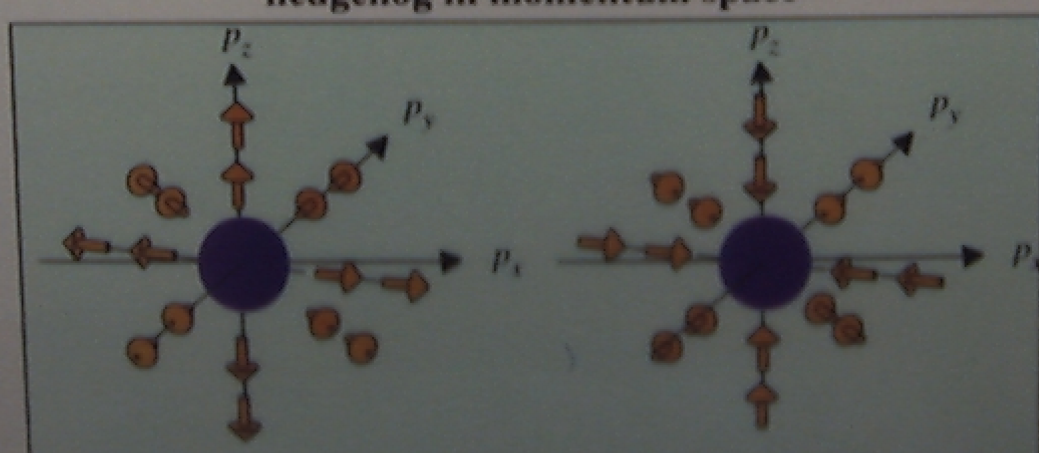
$\mathbf{G}^{-1} = i\,p_0 - c\,\boldsymbol{\sigma}\cdot(\mathbf{p} - \mathbf{p}_2)$

Chiral particles

Quasiparticles near Fermi points are relativistic: left or right-handed chiral Weyl fermions



Topological stability of Fermi point: hedgehog in momentum space



hedgehog with spines (spins) outward ($N_3 = +1$)

hedgehog with spines (spins) inward ($N_3 = -1$)

Classes of quantum field theories

Compare these Hamiltonians

Bogoliubov-Nambu quasiparticle in QFT for ^{3}He-A & chiral superconductors

$$H = \begin{pmatrix} \frac{p^2 - p_F^2}{2m} & c_\perp(p_x + ip_y) \\ c_\perp(p_x - ip_y) & -\frac{p^2 - p_F^2}{2m} \end{pmatrix}$$

left-handed neutrino

$$H = -c\,\boldsymbol{\sigma}\cdot\mathbf{p}$$

right-handed neutrino

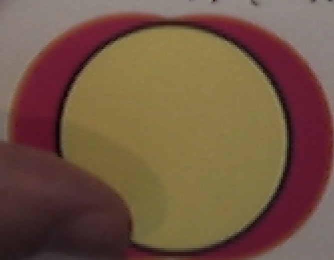
$$H = +c\,\boldsymbol{\sigma}\cdot\mathbf{p}$$

What is common for them?

$$H(\mathbf{p}) = \boldsymbol{\sigma}\cdot\mathbf{m}(\mathbf{p}) \qquad E^2(\mathbf{p}) = \mathbf{m}^2(\mathbf{p})$$

1. $E(\mathbf{p}) = 0$ *at points* **(Fermi points)**

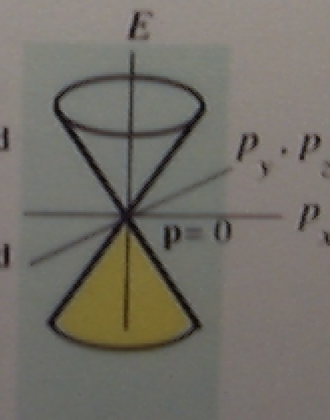
$\mathbf{p} = +p_F\,\mathbf{e}_z$ $\quad N_3 = +1$



$\mathbf{p} = -p_F\,\mathbf{e}_z$ $\quad N_3 = -1$

$N_3 = +1$ **right**-handed neutrino

left-handed neutrino $N_3 = -1$



2. **Fermi points are topologically stable & described by topological invariant in momentum space**

$$N_3 = \frac{1}{8\pi}\, e_{ijk} \int dS^i\, \hat{\mathbf{m}}\cdot(\partial^j \hat{\mathbf{m}} \times \partial^k \hat{\mathbf{m}})$$

over 2D surface around Fermi point

3. **Close to Fermi points** (quasi)particles are **relativistic left** or **right**-handed **chiral Weyl fermions**

Classes of quantum field theories

Compare these Hamiltonians

Bogoliubov-Nambu quasiparticle in QFT for ^{3}He-A & chiral superconductors

$$H = \begin{pmatrix} \frac{p^2 - p_F^2}{2m} & c_\perp(p_x + ip_y) \\ c_\perp(p_x - ip_y) & -\frac{p^2 - p_F^2}{2m} \end{pmatrix}$$

left-handed neutrino

$$H = -\, c\, \boldsymbol{\sigma} \cdot \mathbf{p}$$

right-handed neutrino

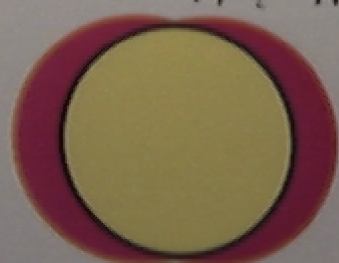
$$H = +\, c\, \boldsymbol{\sigma} \cdot \mathbf{p}$$

What is common for them?

$$H(\mathbf{p}) = \boldsymbol{\sigma} \cdot \mathbf{m}(\mathbf{p}) \qquad E^2(\mathbf{p}) = \mathbf{m}^2(\mathbf{p})$$

1. $E(\mathbf{p}) = 0$ *at points* (Fermi points)

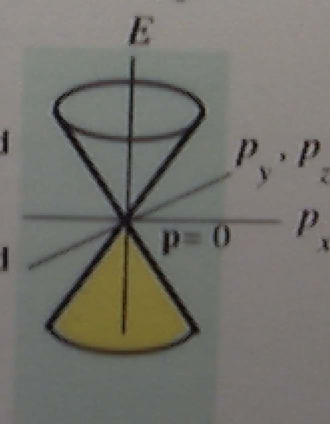
$\mathbf{p} = +p_F \mathbf{e}_z$ $\quad N_3 = +1$



$\mathbf{p} = -p_F \mathbf{e}_z$ $\quad N_3 = -1$

$N_3 = +1$ **right**-handed neutrino

left-handed neutrino $N_3 = -1$



2. **Fermi points are topologically stable & described by topological invariant in momentum space**

$$N_3 = \frac{1}{8\pi}\, e_{ijk} \int dS^i\, \hat{\mathbf{m}} \cdot (\partial^j \hat{\mathbf{m}} \times \partial^k \hat{\mathbf{m}})$$

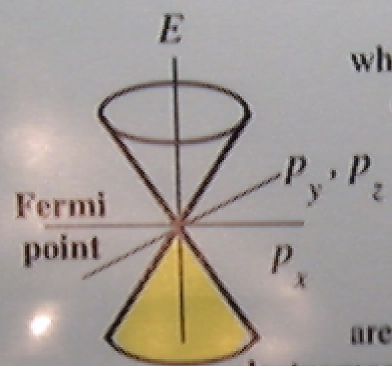
over 2D surface around Fermi point

3. **Close to Fermi points** (quasi)particles are **relativistic left** or **right**-handed **chiral Weyl fermions**

of Fermi-point Universality Class:

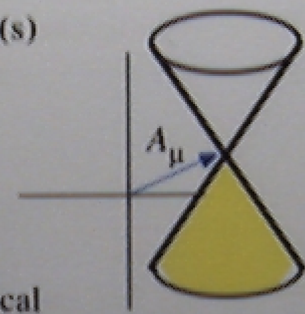
gauge fields & gravity

Vacuum low-energy dynamics cannot destroy the Fermi point.
Shifts **A** and slopes g^{ik} are propagating collective modes:.

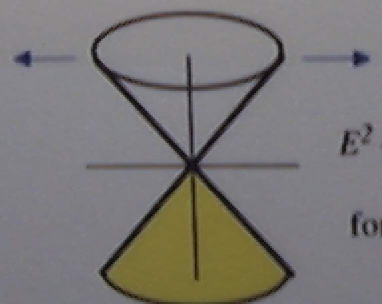


vacuum modes
which shift **position**(s)
of Fermi point(s)

$$p_\mu \rightarrow p_\mu - eA_\mu$$

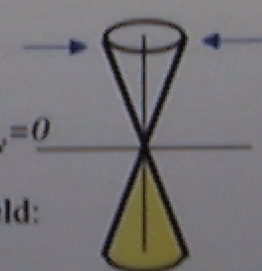


are effective dynamical
electromagnetic and other **gauge fields**



vacuum modes
where **slopes** vary

$$E^2 - c^2p^2 = 0 \rightarrow g^{\mu\nu}p_\mu p_\nu = 0$$



form effective metric field:
gravitational field

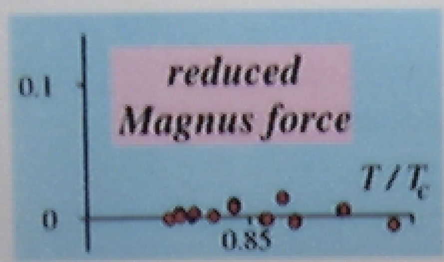
Quasiparticle near **Fermi point** is
left or **right** particle moving in effective
gravitational, electromagnetic, weak fields

$$g^{\mu\nu}(p_\mu - eA_\mu - e\tau\cdot\mathbf{W}_\mu)(p_\nu - eA_\nu - e\tau\cdot\mathbf{W}_\mu) = 0$$

chiral fermions,
gauge fields and **gravity**
appear
in low-energy corner
together with spin and
physical laws:
Lorentz and gauge invariance,
and general covariance

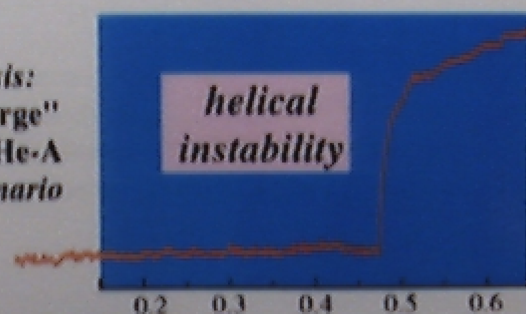
properties of quantum vacuum

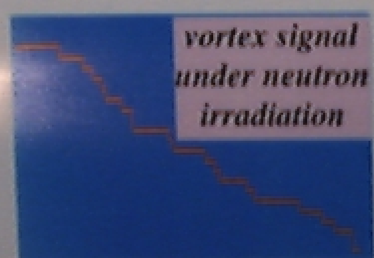
With superfluid ^{3}He we simulated:



(Manchester) **Axial anomaly: creation of charge from *vacuum* was demonstrated in ^{3}He-A**

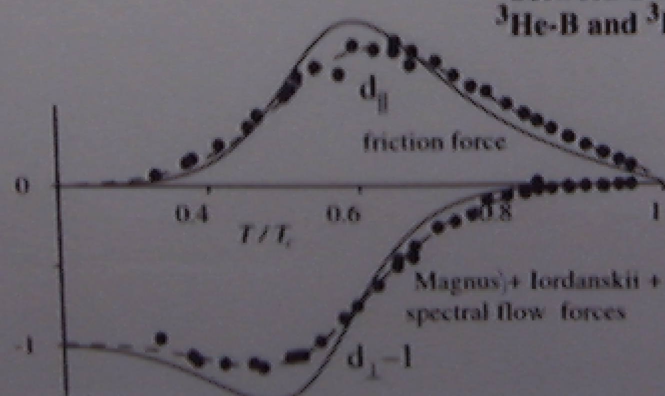
(Helsinki) Magnetogenesis:
Transformation of "charge" to "magnetic field" in ^{3}He-A
Joyce-Shaposhnikov scenario





(Helsinki, Grenoble, Lancaster)
***Kibble-Zurek* scenario of defect formation was tested in ^{3}He-B**

(Helsinki)
ergoregion instability
at the brane between 2 vacua ^{3}He-B and ^{3}He-A



(Manchester)
Gravitational Aharonov-Bohm effect:
Iordanskii force
was measured in ^{3}He-B

in ^{3}He-A

Bevan, *et al.* Nature **386**, 689 (1997)

$\dot{\mathbf{P}} = (1/4\pi^2)\ \mathbf{B}\cdot\mathbf{E} \sum_a P_a C_a e_a^2$ ***Momentogenesis*** *vs* ***baryogenesis*** $\dot{\mathbf{B}} = (1/4\pi^2)\ \mathbf{B}_Y\cdot\mathbf{E}_Y \sum_a B_a C_a Y_a^2$

P_a -- momentum

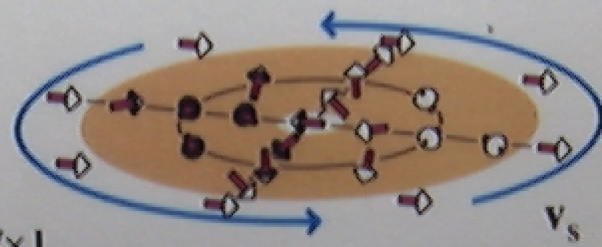
e_a -- effective charge

C_a = +1 for right

-1 for left

Effective magnetic field $\mathbf{B}=p_F\ \nabla\times\mathbf{l}$ ***is produced by vortex skyrmion***

Effective electric field $\mathbf{E}=p_F\ d\mathbf{l}/dt$ ***is produced by motion of skyrmion***

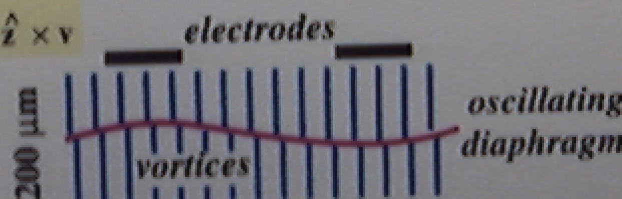


vortex $\mathbf{l}$-texture (skyrmion)

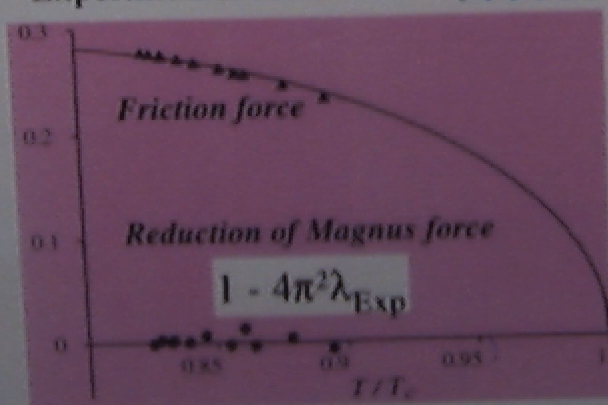
* Extra force on moving vortex due to chiral anomaly

$$\mathbf{F} = \int d^3r\ \dot{\mathbf{P}} = \hbar\,(1/3\pi^2)\,p_F^3\ \hat{\mathbf{z}}\times\mathbf{v}$$

* Experimental set-up



* Experimental result



$\dot{\mathbf{P}} = \lambda\, p_F\, \mathbf{l}\,(\mathbf{B}\cdot\mathbf{E})$

λ_{Exp}
measured parameter in anomaly equation

$\lambda_{Theory} = 1/4\pi^2$
theoretical value

Experimental verification of Adler-Bell-Jackiw equation in ^{3}He-A

Bevan, *et al*, Nature **386**, 689 (1997)

$$\dot{P} = (1/4\pi^2)\, \mathbf{B}\cdot\mathbf{E} \sum_a P_a C_a e_a^2$$

Momentogenesis *vs* **baryogenesis**

$$\dot{B} = (1/4\pi^2)\, \mathbf{B}_Y\cdot\mathbf{E}_Y \sum_a \dot{B}_a C_a Y_a^2$$

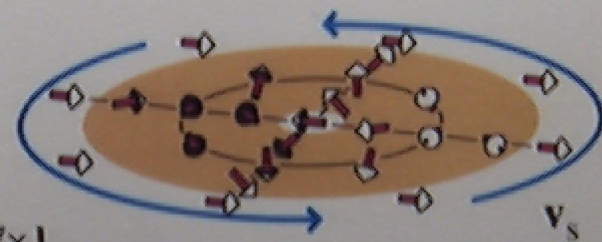
P_a -- momentum

e_a -- effective charge

$C_a = +1$ for right
$\quad\quad -1$ for left

Effective magnetic field $\mathbf{B}=p_F\, \nabla\times \mathbf{l}$ *is produced by vortex skyrmion*

Effective electric field $\mathbf{E}=p_F\, d\mathbf{l}/dt$ *is produced by motion of skyrmion*

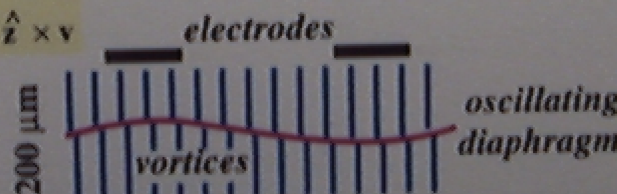


vortex $\mathbf{l}$-texture (skyrmion)

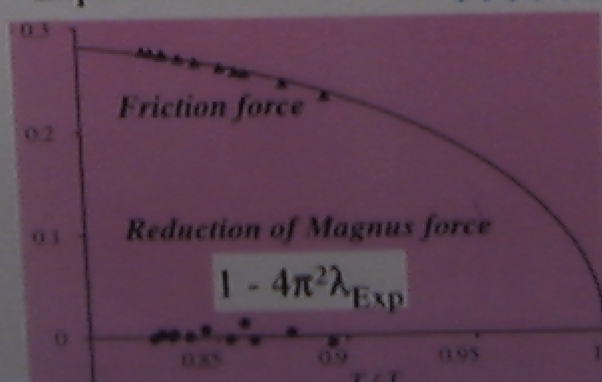
* Extra force on moving vortex due to chiral anomaly

$$F = \int d^3r\, \dot{P} = h\,(1/3\pi^2)\, p_F^3\ \hat{z}\times v$$

* Experimental set-up



* Experimental result



$$\dot{P} = \lambda\, p_F\, \mathbf{l}\, (\mathbf{B}\cdot\mathbf{E})$$

λ_{Exp} measured parameter in anomaly equation

$\lambda_{Theory} = 1/4\pi^2$ theoretical value

Conclusion

The momentum-space topology determines
universality classes of QFT vacua

Vacuum of Standard Model belongs to Fermi-point universality class

Elementary (quasi)particles in vacua of this universality class are
chiral fermions emerging near Fermi points

Gravity and gauge fields are low-energy collective modes,
either fundamental or emerging due to Fermi points

If RQFT is emergent, spin and speed of light are not fundamental,
but fundamental for low-energy observers

If RQFT is emergent, quantum gravity does not exist:
gravity is the classical output of the quantum vacuum
and one should not quantize gravity again (except for gravitons)

Equilibrium quantum vacuum does not gravitate ($\Lambda = 0$)
$\Lambda = 0$ before and after cosmological phase transition
Λ is on order of E_{matter} or of other perturbations of vacuum

Horizon can be constructed at AB-brane
Vacuum behind horizon can be unstable
due to interaction with extra-dimensional environment
Vacuum can resist to formation of horizon