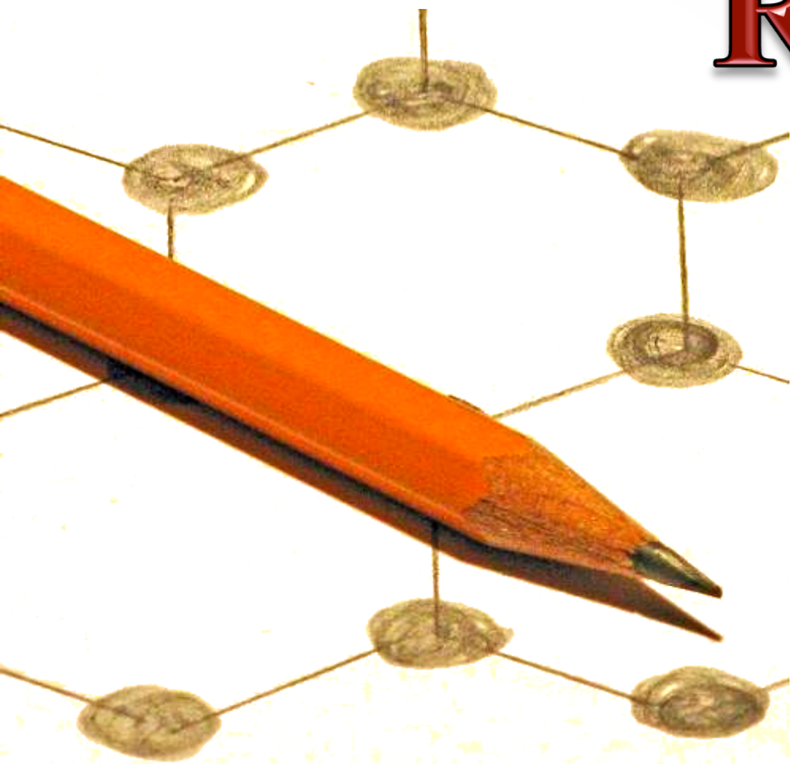
ASU College of Letters & Sciences
ARIZONA STATE UNIVERSITY

Science & Mathematics
APR 8, 2015
Letters & Sciences

Research at the tip of a pencil



Igor Shovkovy

College of Letters and Sciences
Arizona State University

"If anybody says he can think about quantum physics without getting giddy, that only shows he has not understood the first thing about it."

Niels Bohr

INTRODUCTION

Nature Extremes

– **Relativistic systems** (~ speed of light)

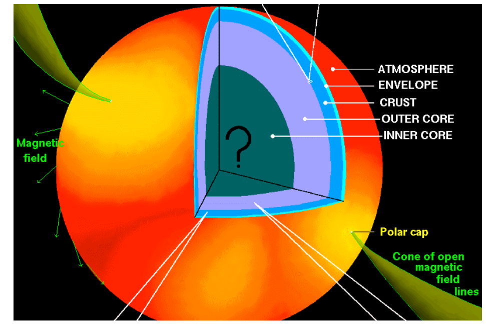
– **Extreme densities** ($\sim 5n_0$, $n_0 \approx 3\times10^{17}$ kg/m^3)

– **Extreme temperatures** ($\sim 10^{12}$ Kelvin)

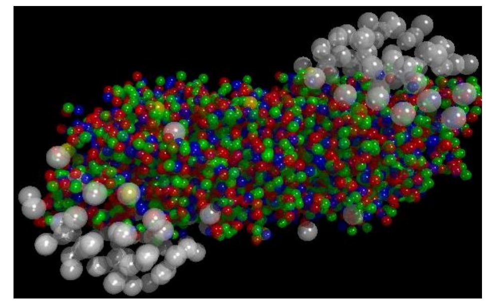
– **Extreme magnetic fields** ($\sim 10^{18}$ Gauss)

EXTREME ENVIRONMENTS

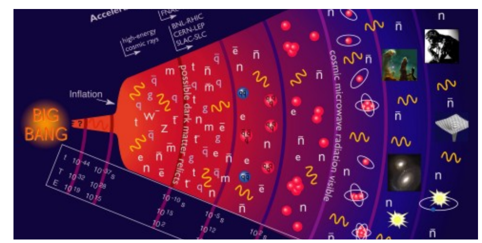
- Examples of relativistic matter
  - **Electrons, protons, quarks** inside compact stars (very dense matter)



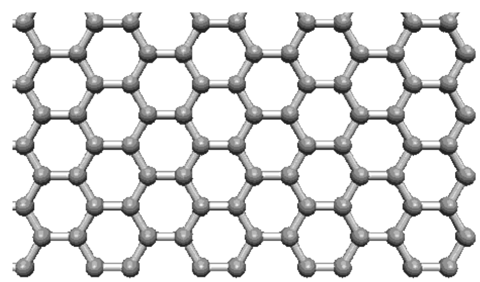
  - **Quark gluon plasma** in heavy ion collisions (a very hot fireball)



  - **Hot matter** in the Early Universe (an extremely hot world)



  - **Massless particles** (e.g., quasiparticles in graphene and Dirac semimetals)



RELATIVISTIC MATTER

- **Non-relativistic**
  - Particles move much slower than the speed of light
  - Kinetic energies are much smaller than the rest energy

$$E_{\text{kin}} << E_{\text{rest}} : \quad E = c\sqrt{p^2 + m^2c^2} \approx mc^2 + \frac{p^2}{2m}$$

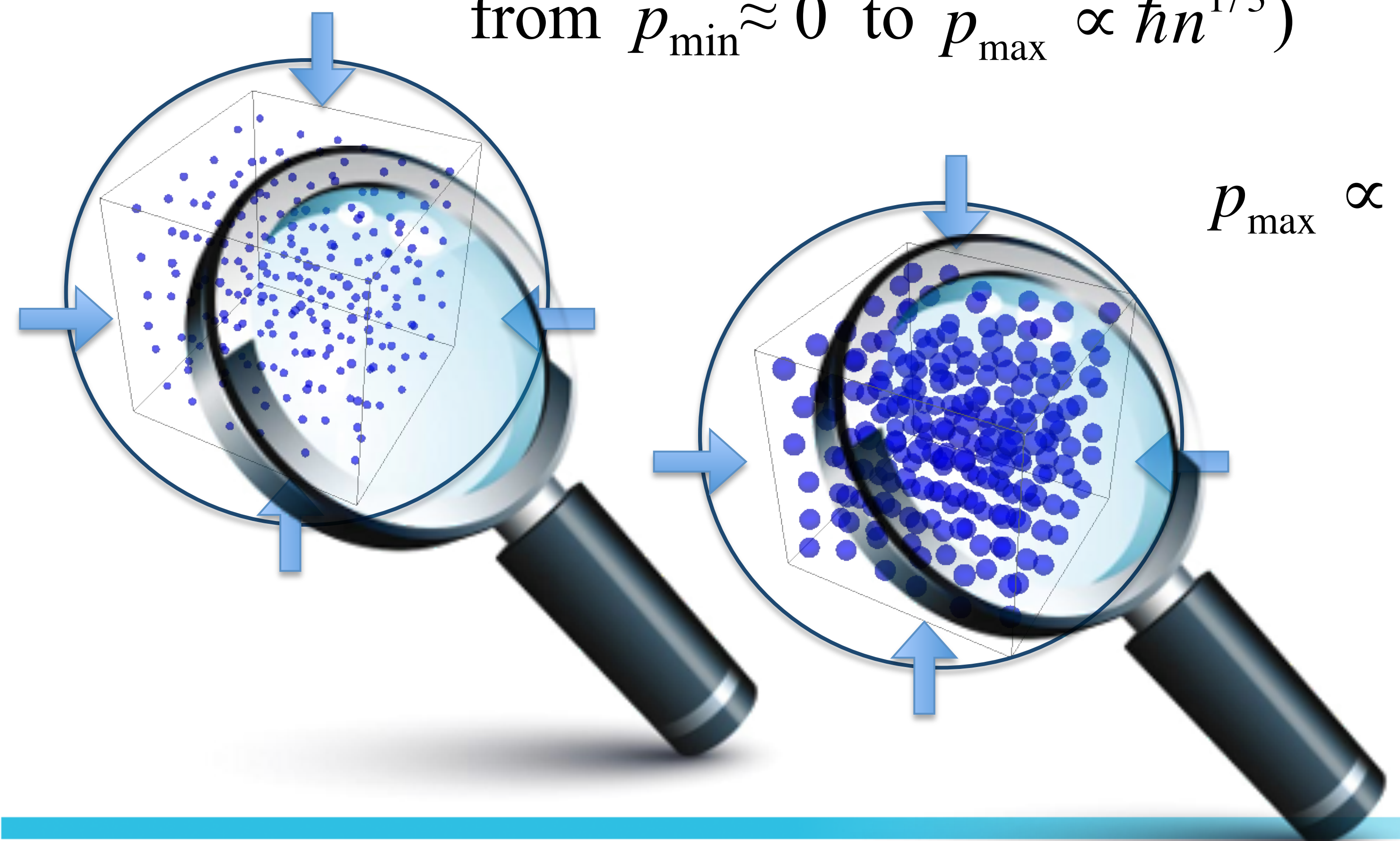
- **Relativistic**
  - Particle velocities approach the speed of light
  - Kinetic energies are comparable to, or larger than E_{rest}

$$E_{\text{kin}} \geq E_{\text{rest}} : \quad E = c\sqrt{p^2 + m^2c^2} \approx c\,p$$

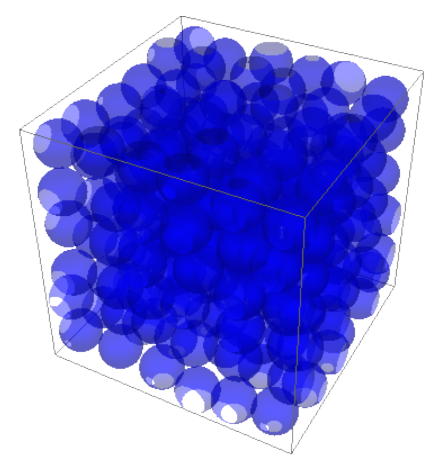
Super-dense Matter

- **What happens when you squeeze matter to very high density?** (e.g., neutrons inside neutron stars)

Pauli exclusion principle: fermions cannot occupy same states (they end up filling out all quantum states from $p_{\min} \approx 0$ to $p_{\max} \propto \hbar n^{1/3}$)

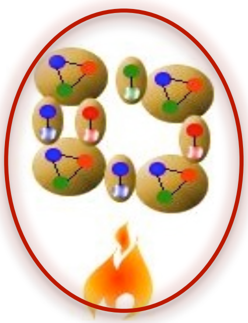


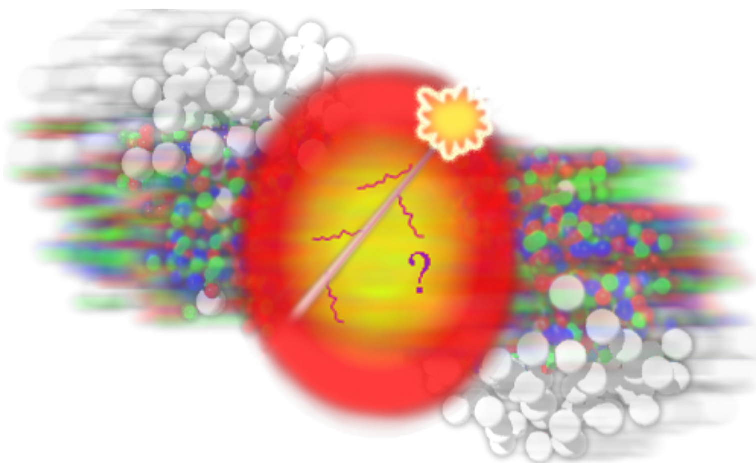
$$p_{\max} \propto 200 \left(\frac{n}{1\,\mathrm{fm}^3} \right)^{1/3} \mathrm{MeV/c}$$

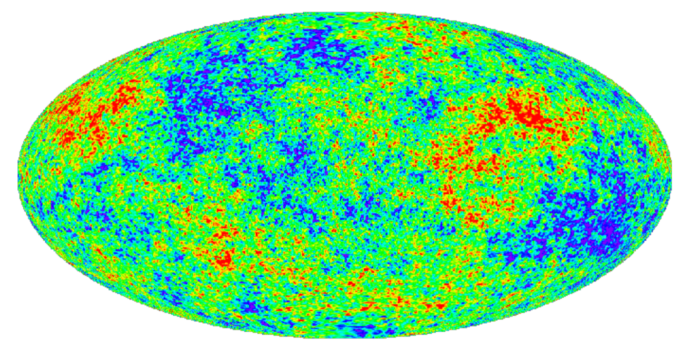


SUPER-HOT MATTER

- **What happens when you heat matter to very high temperature?** (e.g., matter in heavy ion collisions)







Heat is equivalent to **kinetic energy**: average kinetic energy of particles is proportional to temperature:

$$p \propto k_B T / c \sim 200 \left(\frac{k_B T}{200 \text{ MeV}} \right) \text{MeV/c}$$

MASSLESS PARTICLES

- **Can matter be made of massless particles?**

  Yes! Electron quasiparticles masquerade as massless particles in some materials (no rest mass energy)

- **Examples:**
  - Graphene

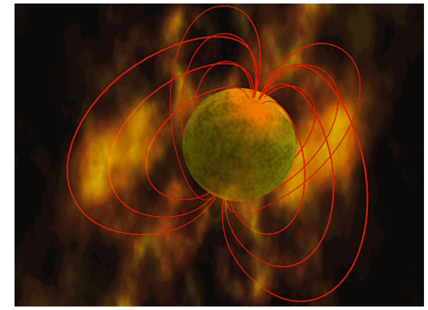
2D (planar) materials

  - $Bi_{1\text{-}x}Sb_x$ alloy with $x \approx 0.03$
  - cadmium arsenide Cd_3As_2
  - potassium bismuthide Na_3Bi

3D materials

Magnetic Fields in Nature

- Strong magnetic fields are common inside compact stars
  - **10^{10} to 10^{15} Gauss**



- In heavy ion collisions, positive ions generate short-lived ($\Delta t \approx 10^{-24}$ s) magnetic fields
  - **10^{18} to 10^{19} Gauss**

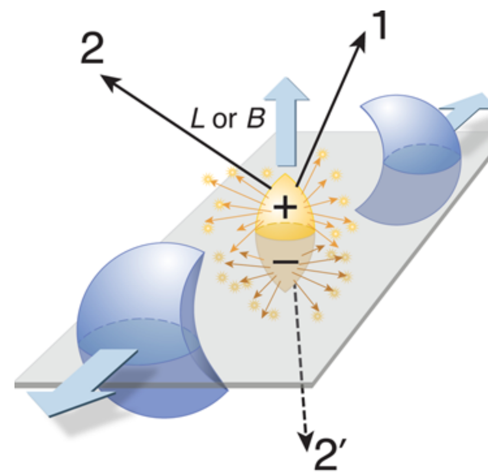


Illustration by Carin Cain

- Early Universe
  - **up to 10^{24} Gauss**
- High Magnetic Field Laboratory
  - **4.5×10^5 Gauss**

Some Research Directions

– Dynamical origin of mass

– Interplay of symmetry and dynamics

– Exotic phases of matter at extreme densities/ temperatures

– Effect of superstrong magnetic fields on vacuum/matter

“It is only slightly overstating the case to say that physics is the study of symmetry”

Philip W. Anderson

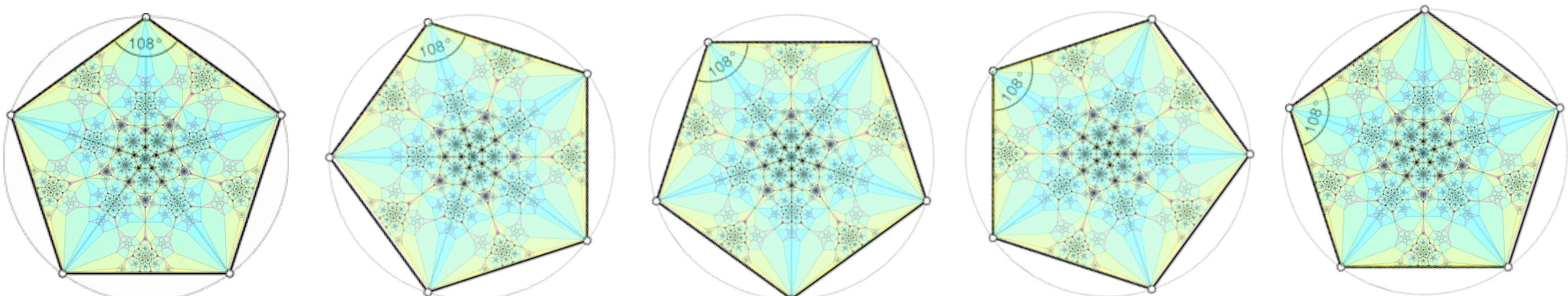
SYMMETRY & ORIGIN OF MASS

What is symmetry?

- Wikipedia:
  - sense of harmonious and beautiful proportion and balance
  - invariance under certain transformation

- Example:

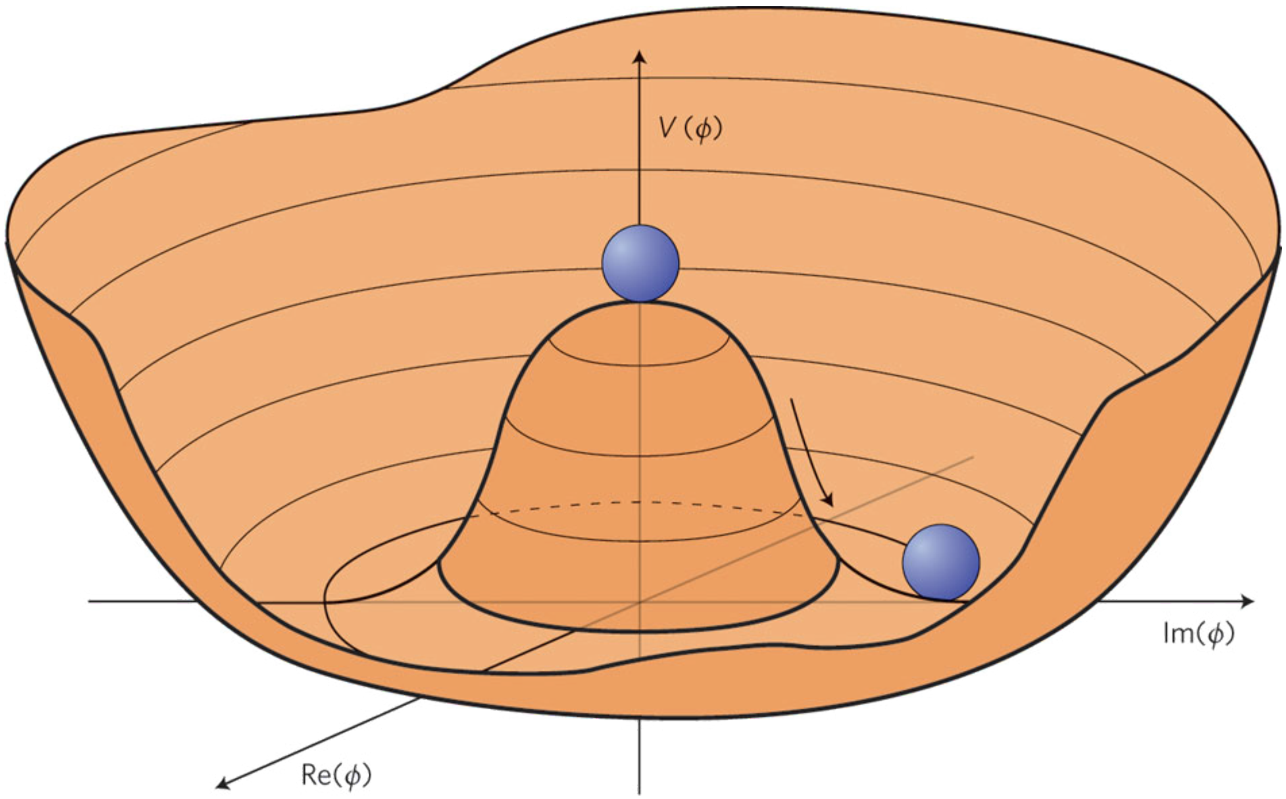
original rotate 18° rotate 36° rotate 54° rotate 72°



Invariance under 72° rotation

Symmetry & Its Breaking

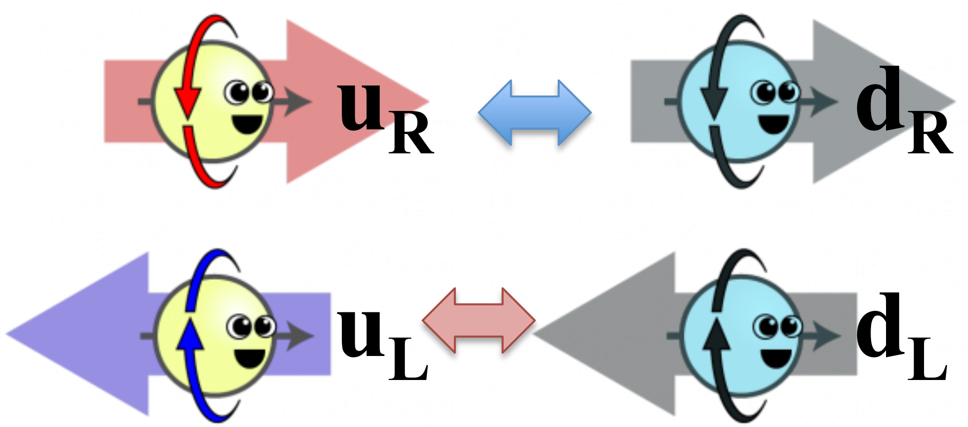
- Underlying laws are symmetric, but the system/ground state changes under a symmetry transformation



- Symmetry may refer to "internal" symmetries (e.g. rotations in color/flavor spaces, rescaling, etc.)

Mass vs. Symmetry

- **Massless** (m=0) fermions enjoy chiral symmetry ("rotation" of left-handed and right-handed particles in flavor space)

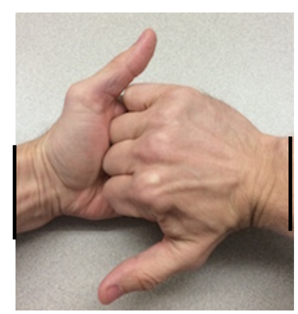


Righ-handed

Left-handed

- Introduction of a **nonzero mass** for fermions breaks chiral symmetry

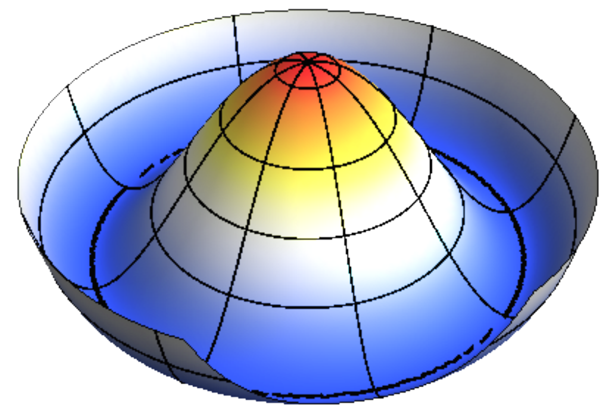
$$|m\rangle \propto C_1|L\rangle + C_2|R\rangle \approx \langle L|$$



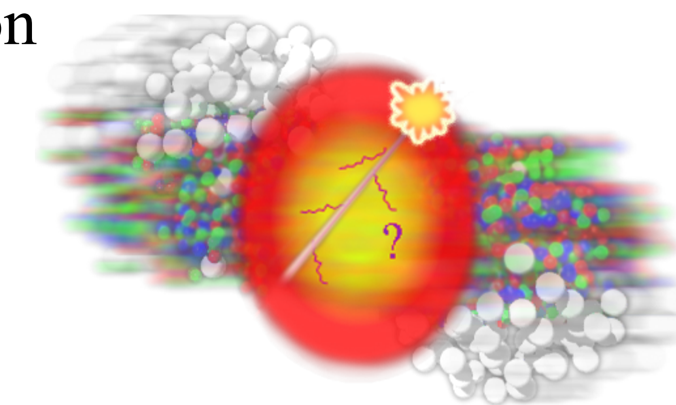
$$|R\rangle$$

Symmetry of Hardons

- Hadron properties strongly suggest an approximate chiral symmetry that is broken "spontaneously"

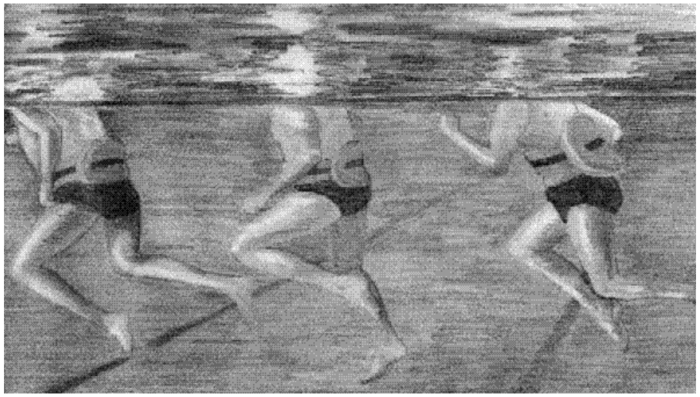


  – Mass hierarchy of pions and nucleons ($m_\pi << m_N$)
  – Energy dependence of pion-nucleon interaction
  – Discovery of multiplets of hadrons with similar properties
  – Relationships between various interaction strengths
  – Properties of quark-gluon plasma in heavy-ion collision

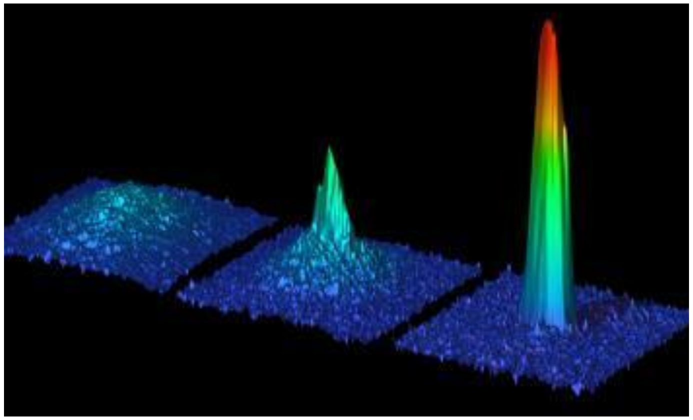


How Symmetry Breaks?

- Because of strong interactions, almost massless quarks (m~5 Mev/c^2) become heavy (m~300 Mev/c^2)

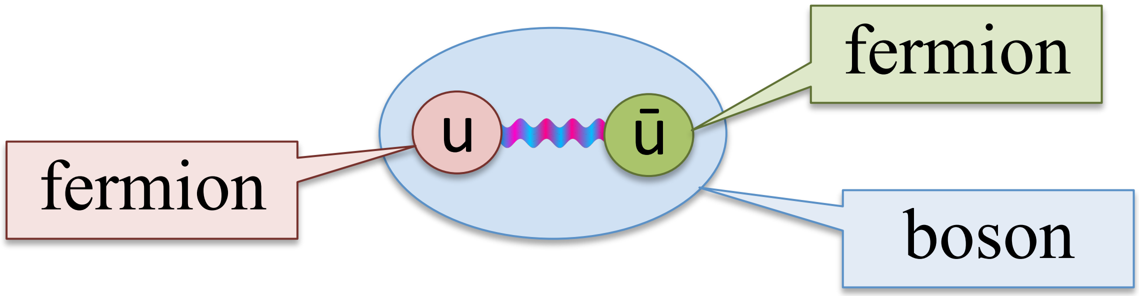


- The analogue of water is a certain (quark-antiquark) Bose condensate in the physical vacuum



Some Key Points

- Interaction must be sufficiently strong



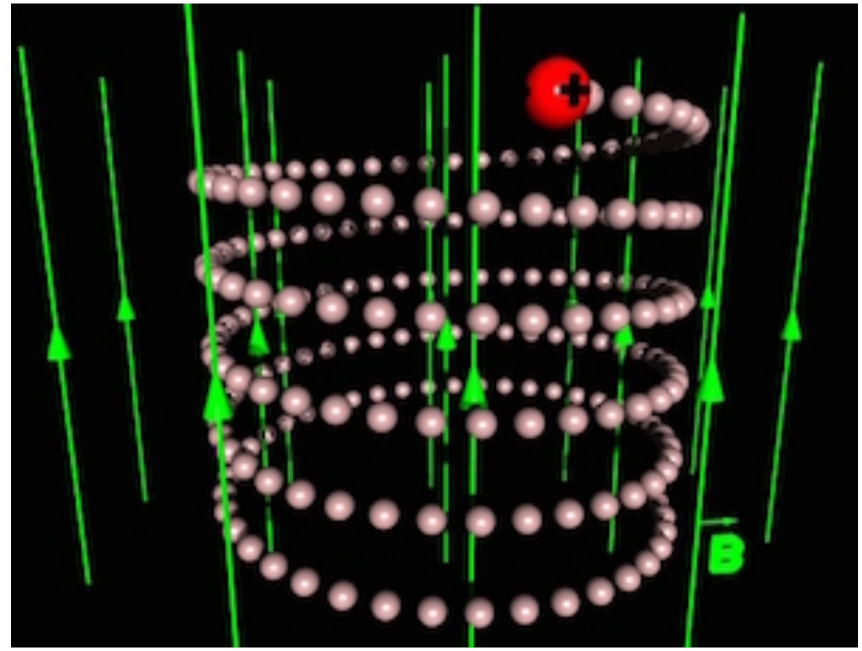
- Bose condensate fills/defines the vacuum
- Fermions (e.g., quarks, protons, etc.) become massive
- Light (massless) pions are predicted
- Mass can be "melted" away by high temperature/ density

MAGNETIC CATALYSIS

Review: Lect. Notes Phys. 871 (2013) 13-49

Idea of Magnetic Catalysis

- Magnetic field *constrains* perpendicular motion of charged particles
- Even *arbitrarily* weak attractive interaction is sufficient to form bound states



- Condensate forms & symmetry breaks down
- Fermions become massive!

This is the essence of **magnetic catalysis**

DYNAMICAL MASS

- A nonzero "dynamical" mass m_{dyn} is generated

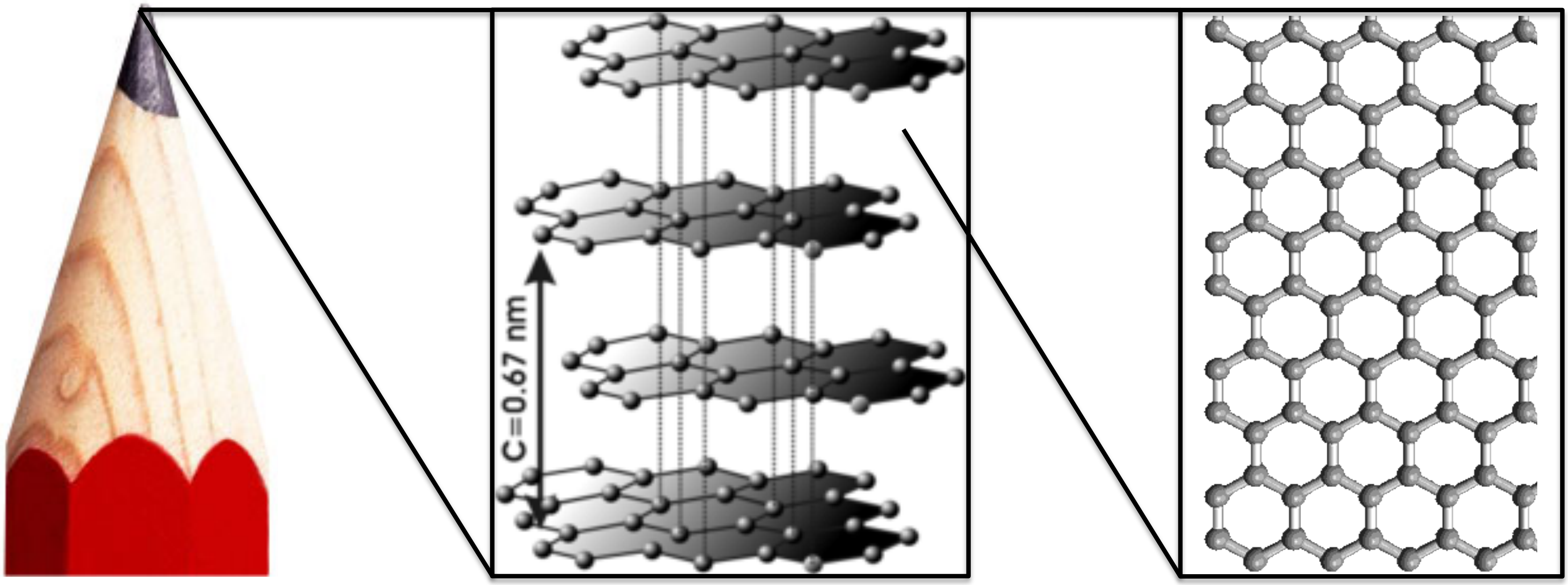
$$m_{dyn}^{(2D)} \propto \sqrt{\alpha}\sqrt{|eB|}\,, \quad \text{and} \quad m_{dyn}^{(3D)} \propto \sqrt{|eB|}\, e^{-C/\alpha}$$

- This happens even at the *weakest* interaction ("catalysis")
- The phenomenon is *universal* (most model details are irrelevant)
- Dimensional *reduction* is the key ingredient (it makes interaction more efficient)

APPLICATIONS

GRAPHENE

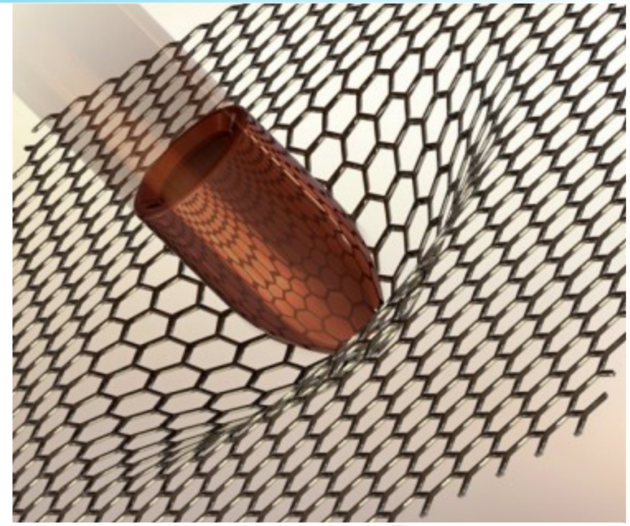
- It is a single atomic layer of graphite
  [Novoselov et al., Science **306**, 666 (2004)]
- 2D crystal with hexagonal lattice of carbon atoms

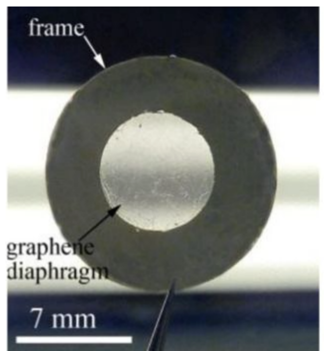


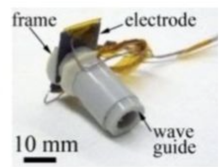
- Interesting basic physics
- Great promise for applied physics …

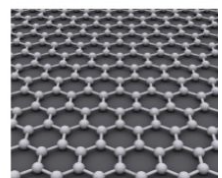
GRAPHENE

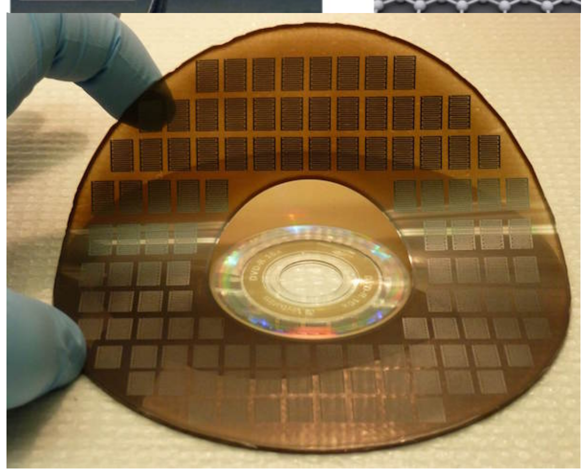
- 100 times stronger than steel
- great heat conductor
- great conductor of electricity
- nearly transparent







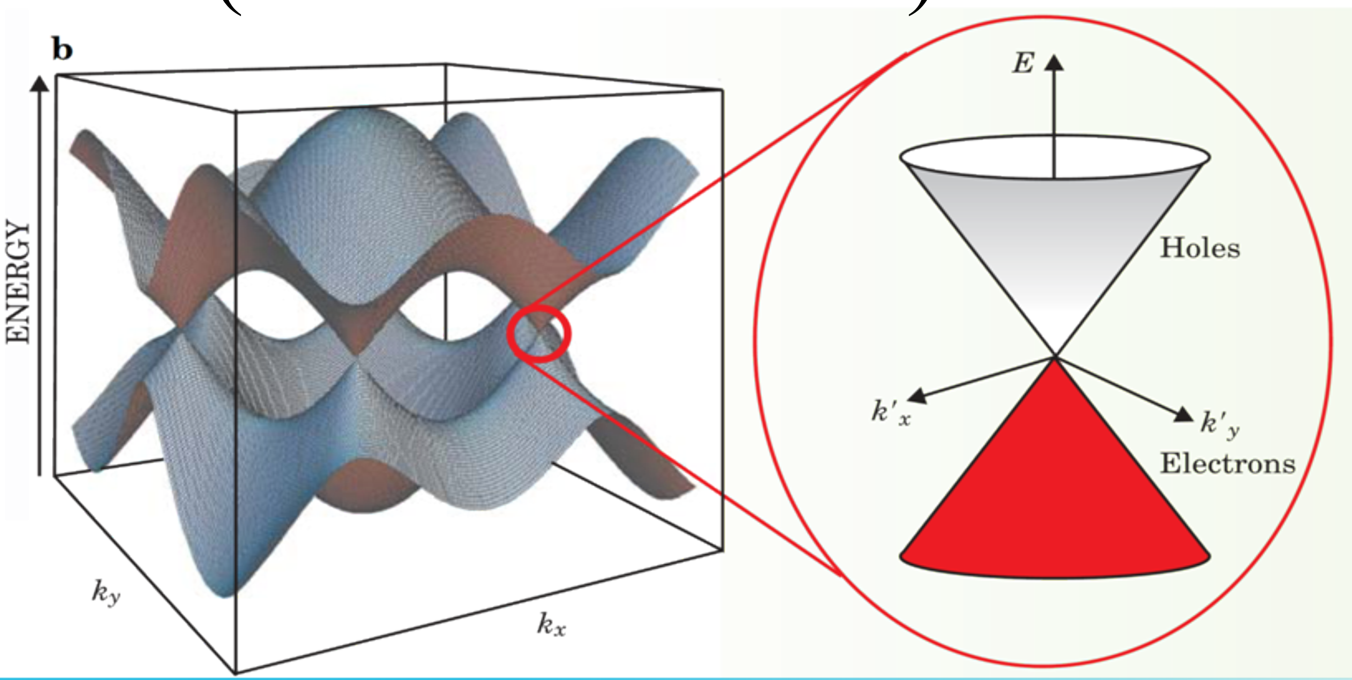




Galapad Settler retails for US$399. Photo: Galapad

DIRAC FERMIONS

- Charge carriers (~ electrons)
  - spin-½ fermions
  - have large speed, v ≈ c/300
  - behave like massless particles
- In essence, they behave like relativistic particles ("Dirac fermions") in vacuum



MAGNETIC CATALYSIS IN GRAPHENE

- **Prediction:**

  A nonzero dynamical mass should be generated in a strong magnetic field

  [Khveshchenko, PRL **87**, 206401 (2001)]

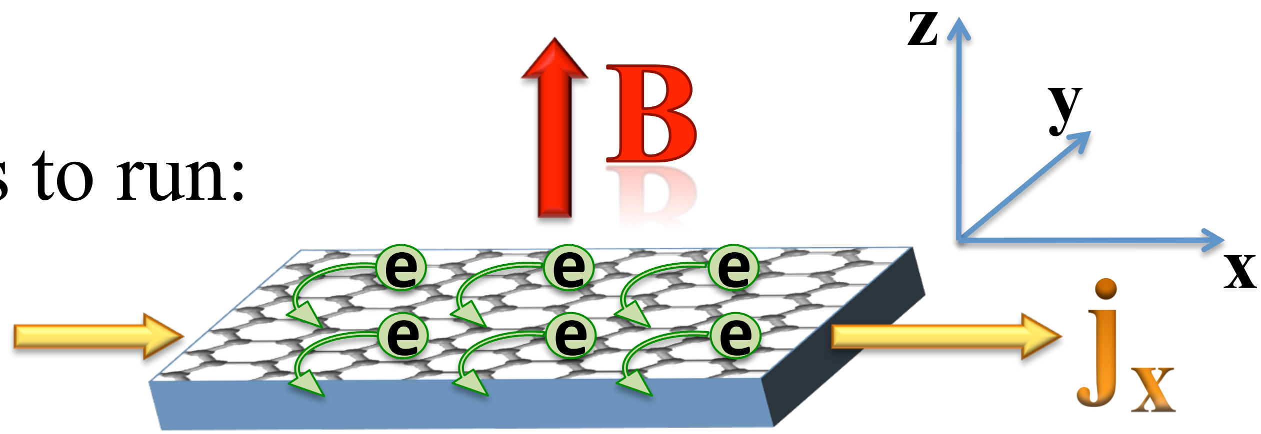
  [Gorbar, Gusynin, Miransky, Shovkovy, PRB **66** (2002) 045108]

- Possible complications:
  - many types of "Dirac" masses in **2D**
  - competition with quantum Hall ferromagnetism
  - nonzero electron/hole density
  - impurities, lattice defects, ripples, etc.

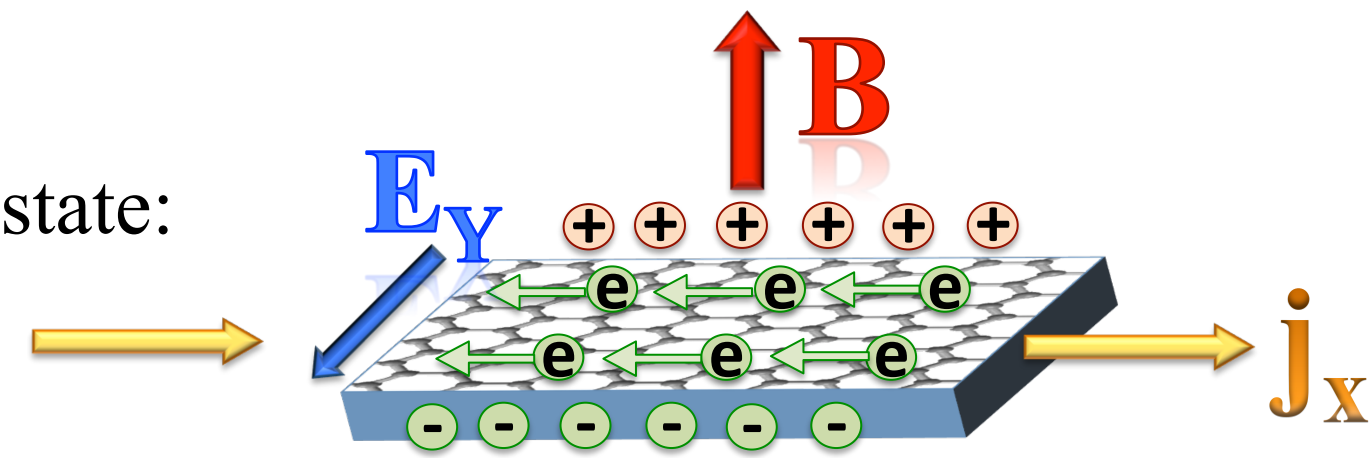
- How to test this experimentally?

Quantum Hall Effect

- General setup
  - Current starts to run:



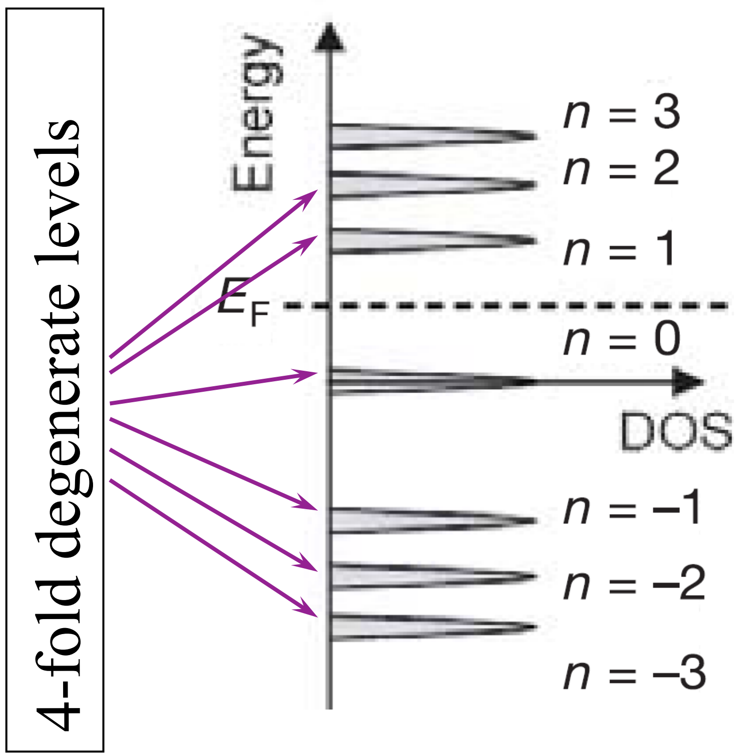
  - Steady state:

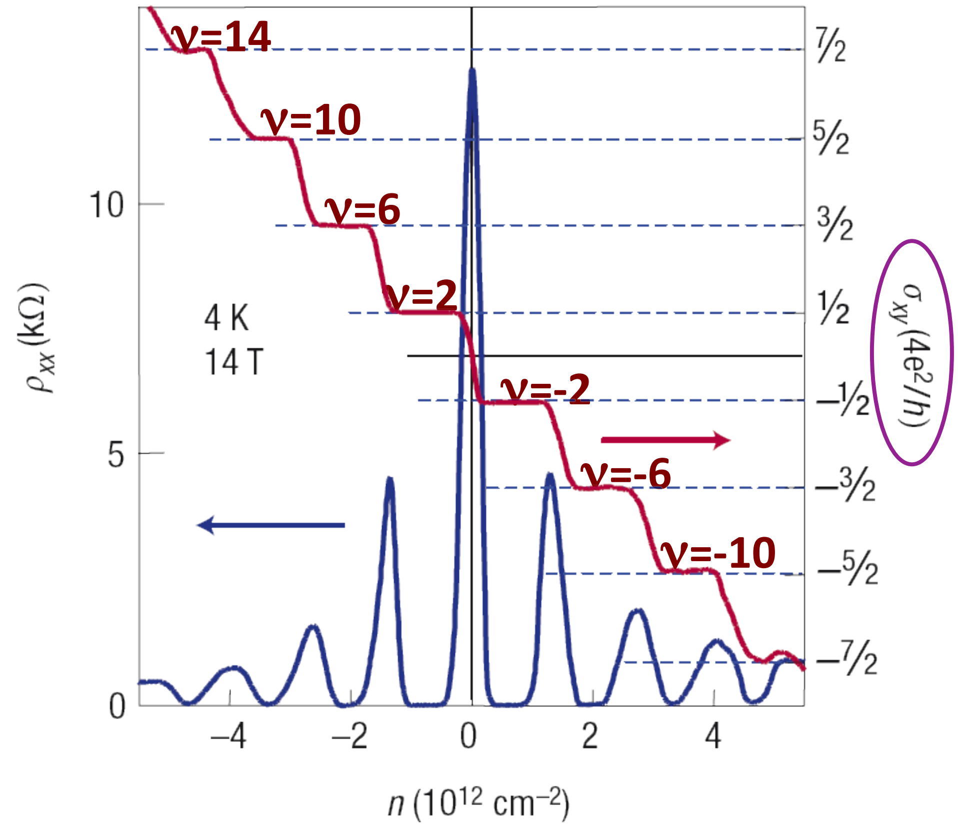


  - Hall conductivity $\boldsymbol{\sigma}_{\mathbf{xy}}$:

$$j_x = \sigma_{xy} E_y$$

QHE in Graphene





$$E_n = \mathrm{sgn}(n)\sqrt{2e\hbar v_F^2 |n| B}$$

$$\sigma_{xy} = \frac{\nu e^2}{h} = \frac{4e^2}{h}\left(n + \frac{1}{2}\right)$$

[Gusynin, Sharapov, PRL **95**, 146801 (2005)]
[Peres, Guinea, Castro Neto, PRB **73**, 125411 (2006)]
} **Theory**

[Novoselov et al., Nature **438**, 197 (2005)]
[Zhang et al., Nature **438**, 201 (2005)]
} **Experiment**

ANOMALOUS QHE

- New plateaus are observed at

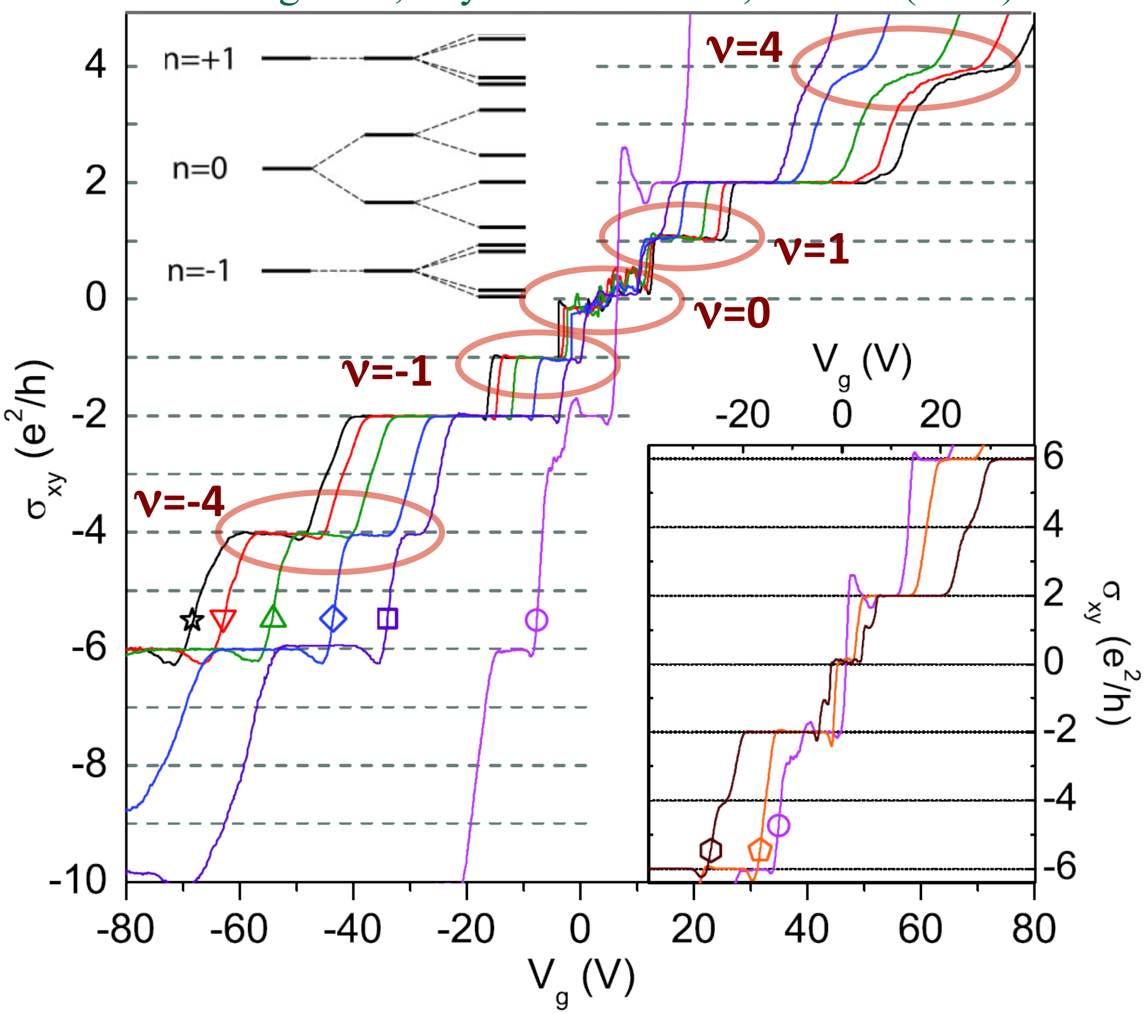
  $\nu=0$

  $\nu=\pm1$

  $\nu=\pm3$

  $\nu=\pm4$

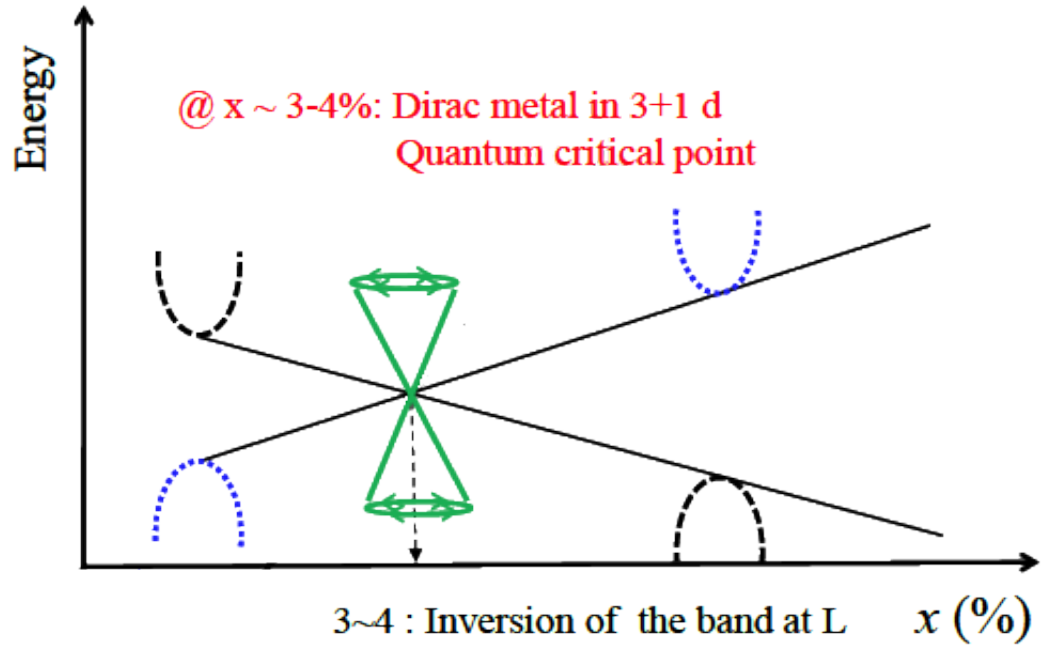
Zhang et al., Phys. Rev. Lett. **96,** 136806 (2006)



[Novoselov et al., Science **315**, 1379 (2007)]
[Abanin et al., Phys. Rev. Lett. **98**, 196806 (2007)]
[Checkelsky et al., Phys. Rev. Lett. 100, 206801 (2008)]
[Xu Du et al., Nature **462**, 192 (2009)]

Is "3D Graphene" Possible?

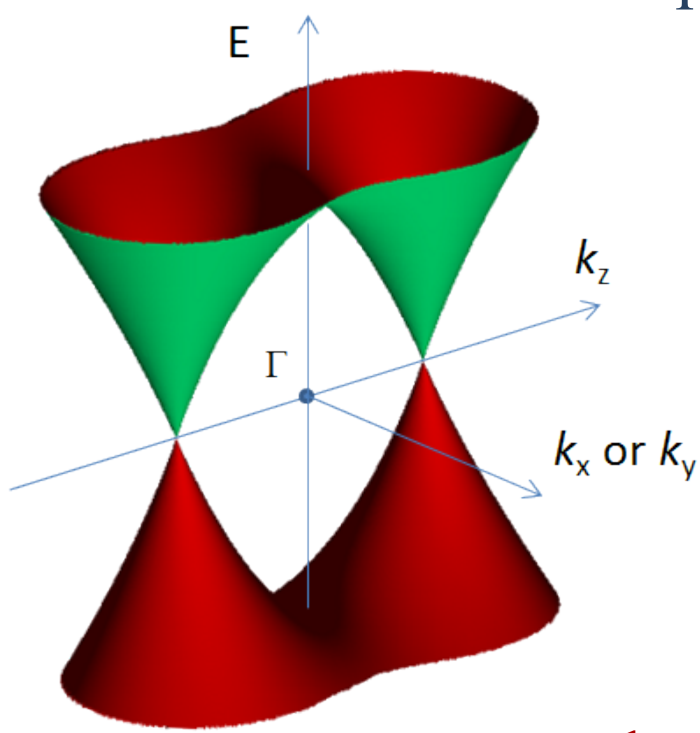
- "Old" 3D materials with Dirac quasiparticles:
  - $Bi_{1-x}Sb_x$ alloy



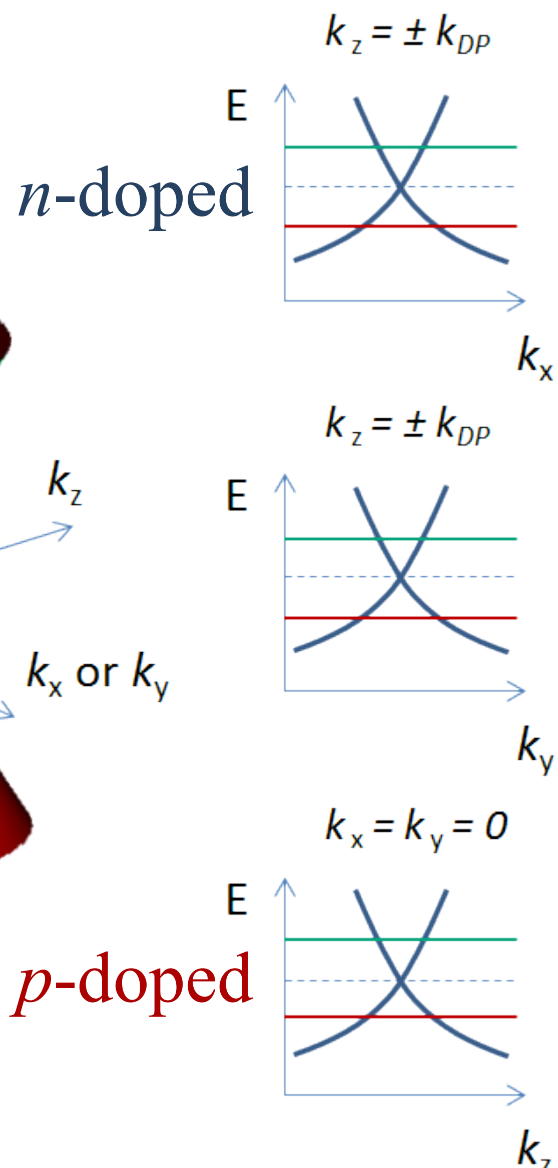
- "New" 3D Dirac materials:
  - Na_3Bi [Liu et al., Science 343, 864 (2014)]
  - Cd_3As_2 [Neupane et al., Nat. Commun. 5, 3786 (2014)]
    [Borisenko et al., Phys. Rev. Lett. 113, 027603 (2014)]

CADMIUM ARSENIDE

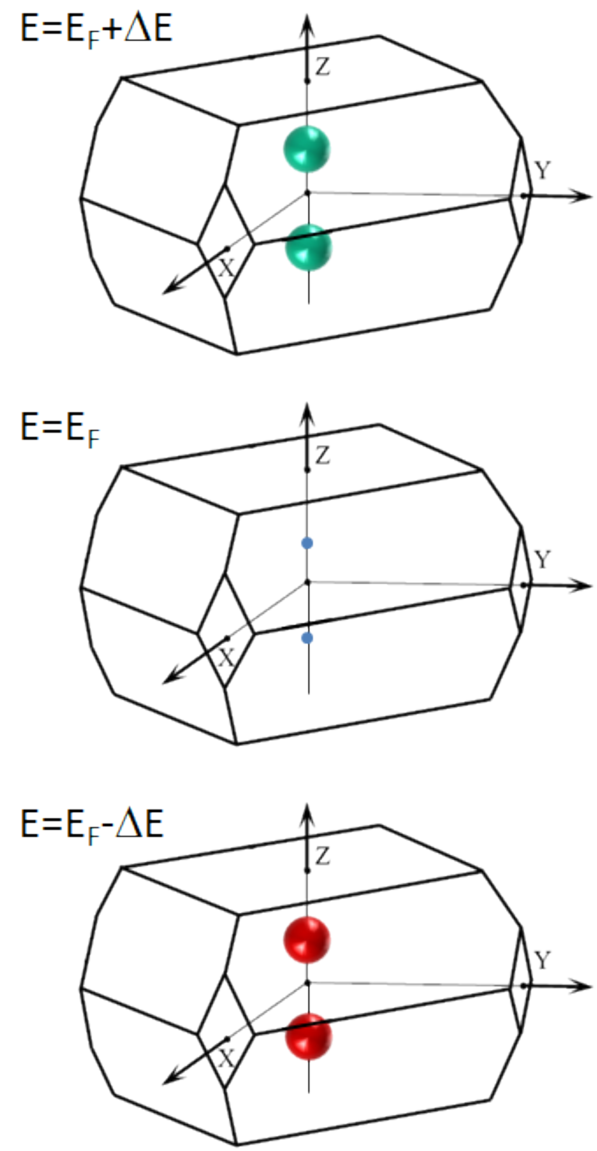
3D Dirac semimetal Cd_3As_2



Dispersion

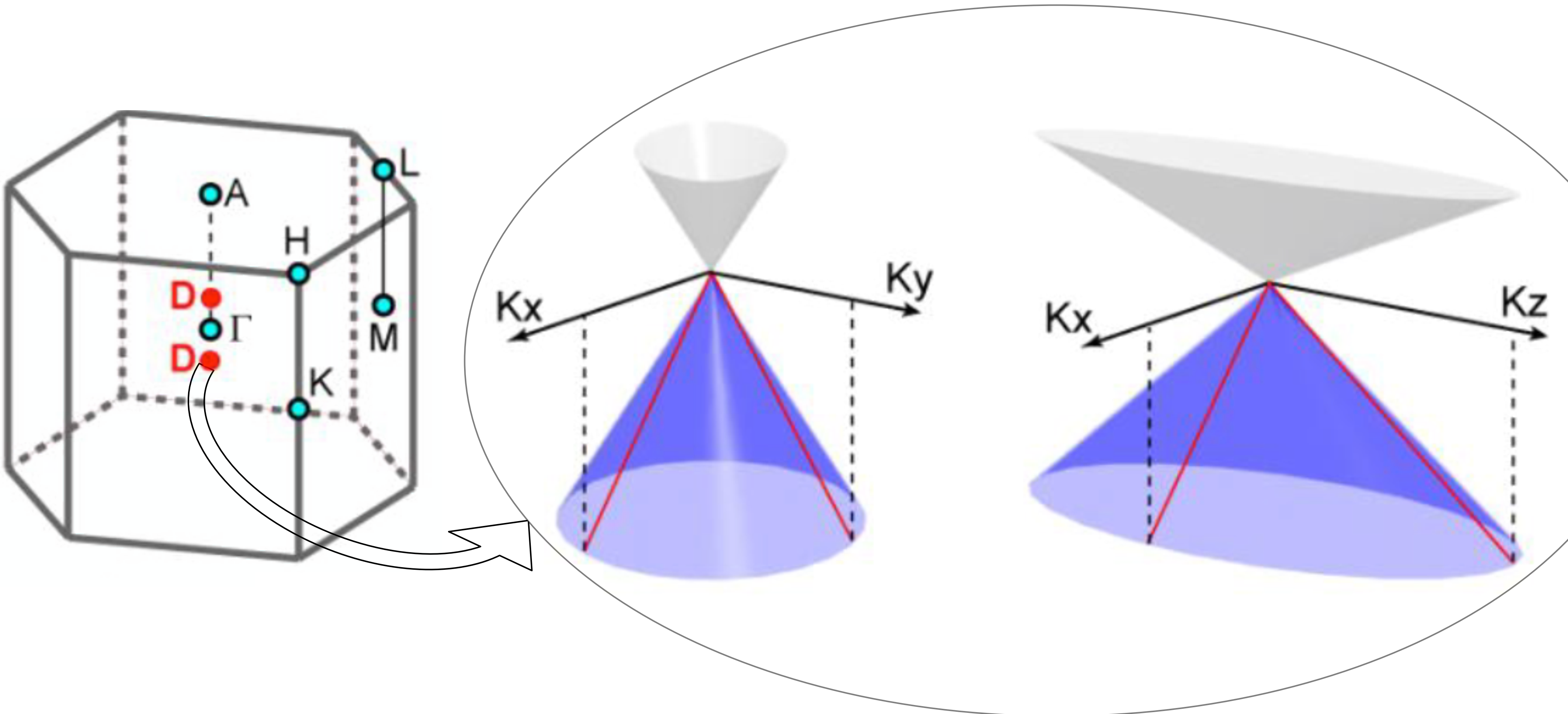


Fermi surface



[Borisenko et al., Phys. Rev. Lett. 113, 027603 (2014)]

POTASSIUM BISMUTHIDE



In the vicinity of 3D Dirac points:

$$E = v_x k_x + v_y k_y + v_z k_z$$

[Liu et al., Science 343, 864 (2014)]

SUMMARY

- Relativistic matter in magnetic field is relevant for many branches of physics
- The underlying physics is very rich
- A partial list of phenomena
  - Magnetic catalysis
  - Chiral magnetic effect
  - Chiral shift
  - Chiral magnetic spiral
  - Magnetic properties of Dirac semimetals
  - Quantum Hall Effect in graphene
  - …

REVIEW

ELSEVIER

Physics Reports

Available online 9 March 2015

In Press, Corrected Proof — Note to users

Quantum field theory in a magnetic field: From quantum chromodynamics to graphene and Dirac semimetals

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