Multi-terminal Josephson junctions as topological materials

Happy birthday!
Dear Quantronics

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FOM
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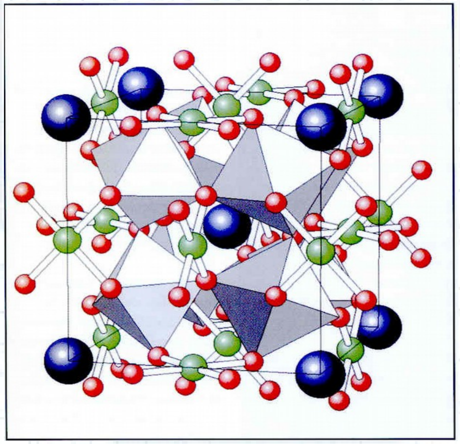
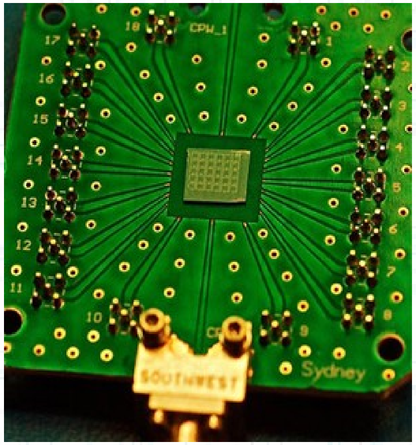
JSPS

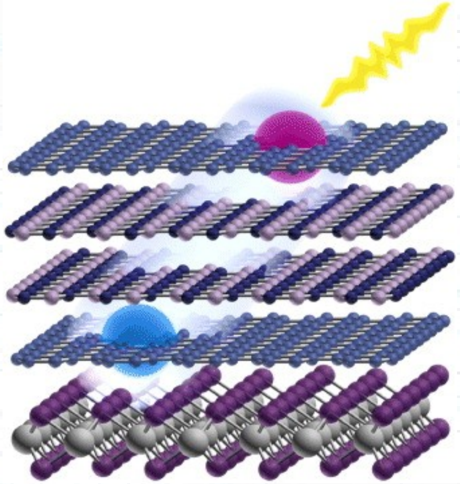
The summary

material

device







material :
say, 5 d

Nanodevice
(multi-terminal
sup.junction)

The back-to-the-future summary

- 1982 Quantum Hall Effect
- A challenge to super-electronics
- 1988 Likharev Zorin: Bloch+Josephson synchro
- 2013 Hriscu Nazarov: synchro!
- Now: 2015 simplest way to achieve QHE

Outline

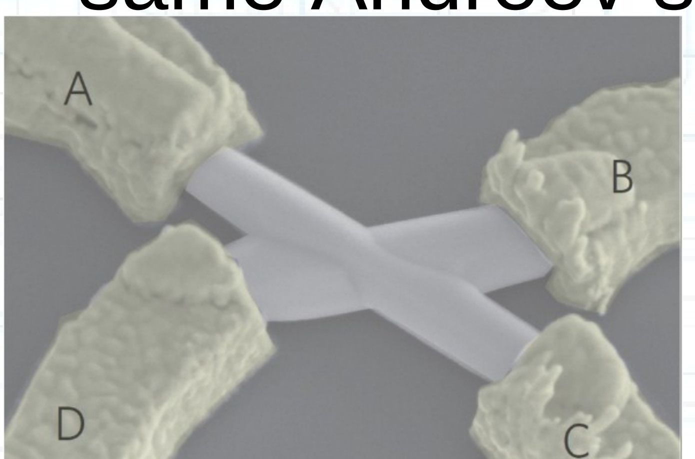
- Topological materials
- Superconducting junctions
- The analogy
- Weyl singularities in 3D
- Tunable 2D from 3D
- Transconductance quantization => Quantum Hall effect
- Perspectives

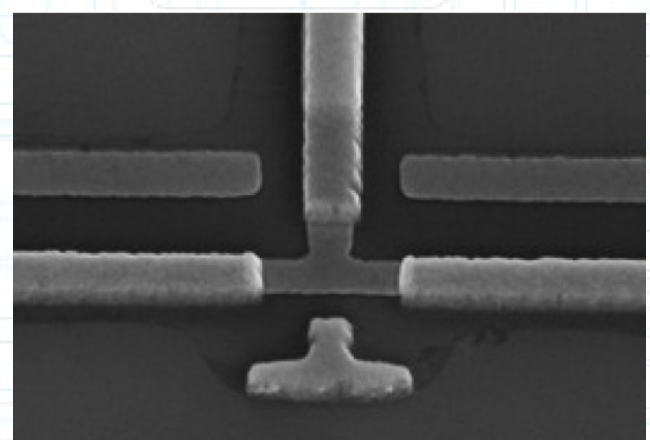
Topological materials

- Bandstructure: Eigenenergies $E(q_x,q_y,q_z)$
- From eigenstates: Berry curvature field
- $B_z(\vec{q}) = i\left(\langle \frac{\partial\Psi}{\partial q_x} \middle| \frac{\partial\Psi}{\partial q_y}\rangle - \langle \frac{\partial\Psi}{\partial q_y} \middle| \frac{\partial\Psi}{\partial q_x}\rangle\right)$
- 2D topological invariant(Chern number)
- $C = \frac{1}{2\pi}\int dq_x dq_y B_z(\vec{q})$
- Manifestation: Quantum Hall effect $\rightarrow$ quantized transconductance
- +much-much more (Z_2, spin Hall, surface modes, surface structuring, 1d wires, Majorana)

Superconducting junctions

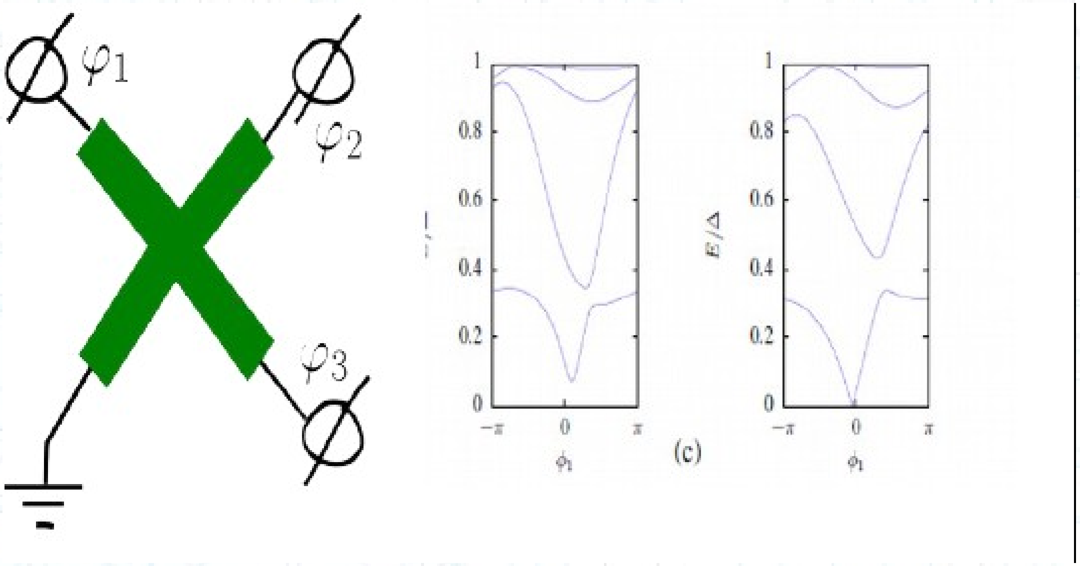
- Josephson junction $E = -E_J \cos\varphi$
- More transparent – Andreev bound states
- $E = -\frac{1}{2}\sum_p E_p$
- $E_p = \Delta\sqrt{1 - T_p \sin(\varphi/2)^2}$
- More terminals – more superconducting phases $E_p(\phi_1, \ddots, \phi_{n-1})$
- same Andreev states





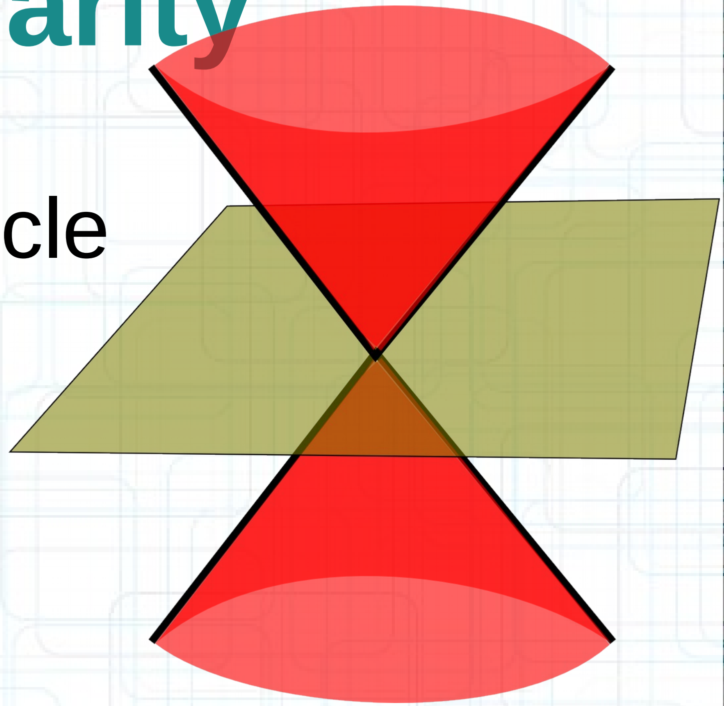
The analogy

- Bandstructure <=> Andreev spectrum
- $q_x, q_y, q_z \leftrightarrow \varphi_1, \varphi_2, \varphi_3$

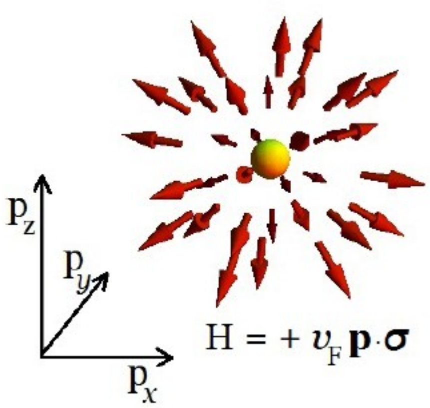


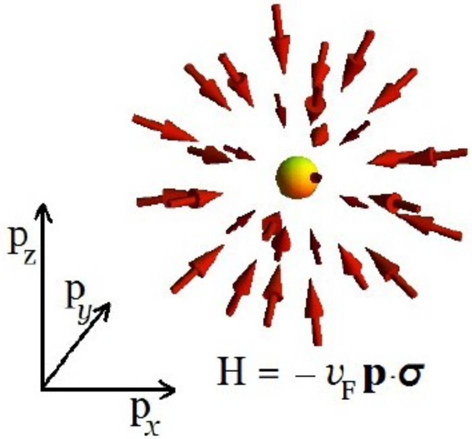
- Incomplete
  - Gap edge, continuous spectrum
  - Filling: all quasimomenta, phases - one

Weyl singularity



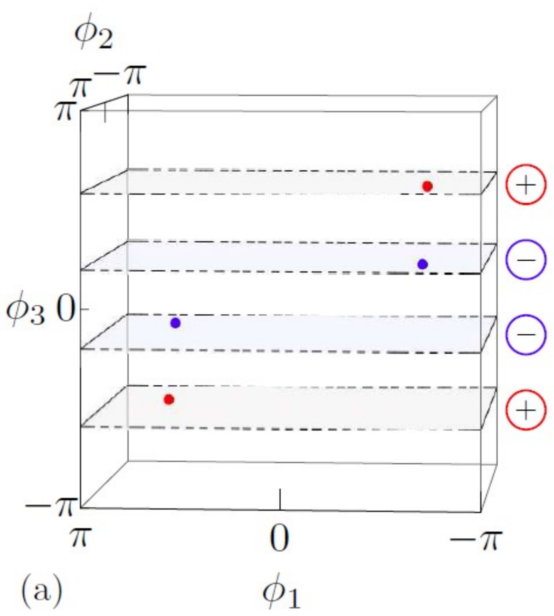
- Massless relativistic particle
- Conical spectrum
- In the vicinity of certain q
- $\hat{H} = \vec{\sigma} \cdot (\delta \vec{q})$
- Occurrence in materials – predicted :)
- A monopole of the Berry curvature field





Weyl singularities in 4-terminal junctions

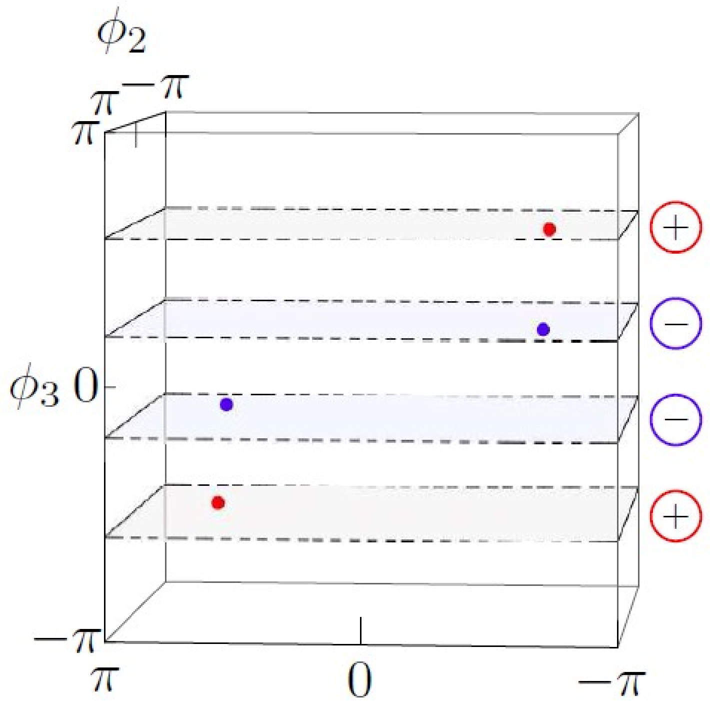
- At zero energy – important
- Three fields – three parameters – three phases – one-goal game
- Beenakker formula – from scatt.matrix
- Come in pairs of 4
- (+- and
- inversion symmetry)



From 3D to 2D

- Flexibiliby of dimensions
- 2D bandstructure – a moving plane
- φ_3 – control parameter
- Plane passes W.S =
- Change of Chern number
- Topologically non-trivial

  2D material
- Tunable by φ_3



(a)

Berry curvature and transport

- Currents – functions of the phases
- Change the phases adiabatically

$$I_\alpha(t) = \frac{2e}{\hbar}\frac{\partial E}{\partial \phi_\alpha} - 2e\dot{\phi}_\beta B^{\alpha\beta}$$

Leading order

First correction

- Sensitive to the local Berry curvature

Role of quasiparticles

- Single – level contribution
-
-
-

$$I_\alpha(t) = \frac{2e}{\hbar}\frac{\partial E}{\partial \phi_\alpha} - 2e\dot{\phi}_\beta B^{\alpha\beta}$$

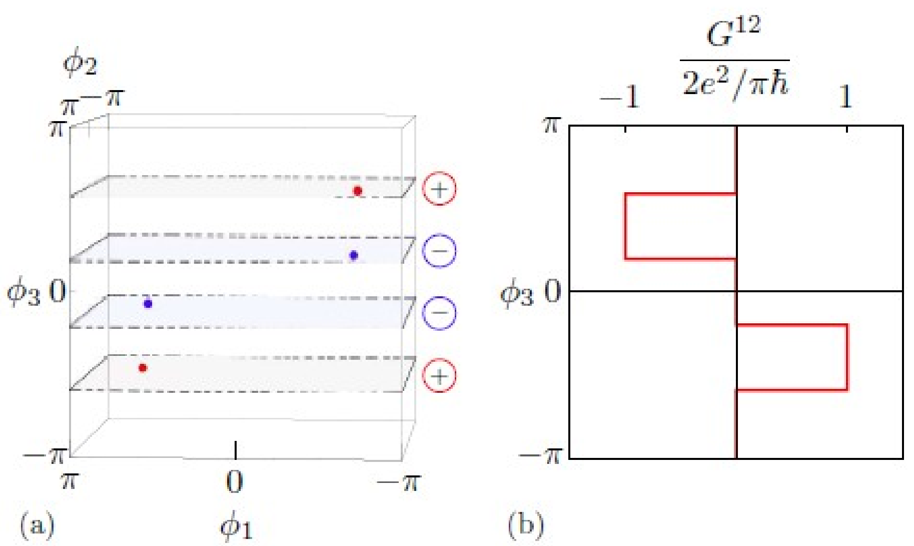
Leading order

First correction

- *No qp: I*
- *1 qp: 0*
- *2qp: - I*
- Sensitive to the quasiparticle poisonning
- Let's be optimistic

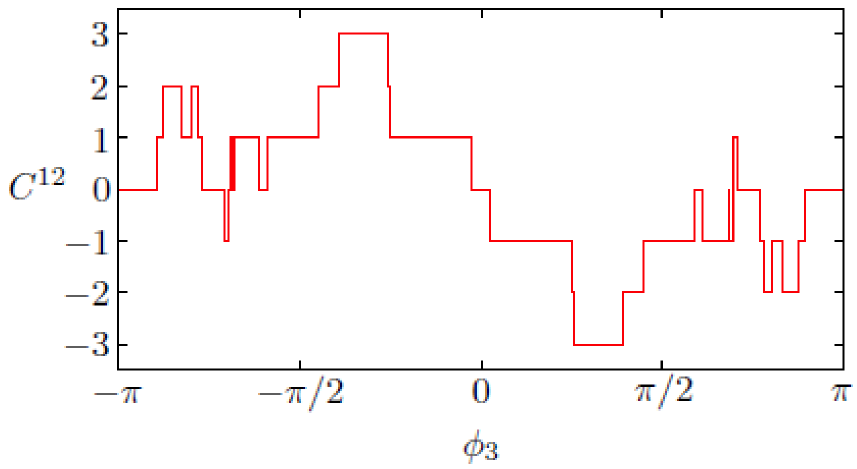
Transconductance quantization

- Apply (incommensurate) voltages
- Phases are swept over BZ
- Sup.current vanishes
- What remains?
- $I_1 = G_{12}V_2;\ I_2 = -G_{12}V_1;\ G_{12} \equiv (2e^2/\pi\hbar)C$



Experiment to do

- Instead of Quantum Hall bar
- Make 4 – terminal sup. Junction
- Shake it till Weyl singularities
- Apply voltages to 2 leads
- Measure d.c. currents in the leads
- Tune it by the 3rd phase



Outlook

- Multi -dimensional materials!
- More complex topologies
- Edge? Edge!
  - Structuring in charge space