Tipping the Weyl cone

- **Quantum transport in Dirac materials: Signatures of tilted and anisotropic Dirac and Weyl cones**

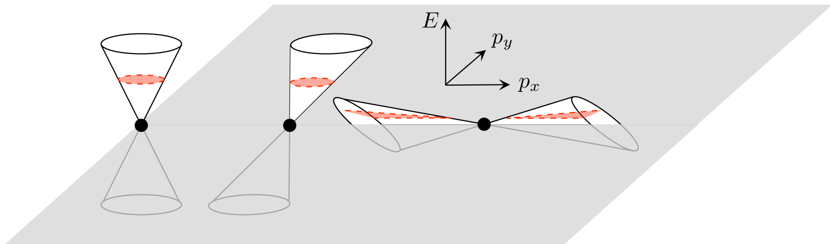
  M. Trescher, B. Sbierski, P. W. Brouwer, and E. J. Bergholtz,
  Phys. Rev. B **91**, 115135 (2015) [arXiv:1501.04034]

- **A new type of Weyl semimetals**

  A. A. Soluyanov, D. Gresch, Z. Wang, Q. Wu, M. Troyer, Z. Dai, and B. A. Bernevig, arXiv:1507.01603

Recommended with a commentary by Carlo Beenakker, Leiden University

The Weyl cone of massless fermions is a diabolo-shaped surface in energy-momentum space that separates electron-like states (moving in the direction of the momentum) from hole-like states (moving opposite to the momentum). This concept from particle physics first appeared in condensed matter in two-dimensional structures (graphene and various layered organic compounds), where it is more commonly referred to as a Dirac cone. Three-dimensional realizations have now also been reported (see Vishwanath's JCCMP contribution from last February).



Conical band structure without any distortion (left), slightly tilted (center, elliptic equi-energy contours), and tipped over (right, hyperbolic equi-energy contours).

The counterpart of the Weyl cone in spacetime is the light cone, separating events in the future from events in the past. The gravitational field from a massive object tilts the light cone, and may even tip it over. For the Weyl cone such a distortion is forbidden by particle-hole symmetry, but that is not a fundamental symmetry in condensed matter. While in graphene the high symmetry of the honeycomb lattice keeps the cone upright, tilting is generic in 3D Weyl semimetals. The paper by Trescher et al. identifies transport signatures of tilted Weyl cones, while Soluyanov et al. predict that in WTe_2 the symmetry can be broken so strongly that the Weyl cone tips over — transforming the equi-energy contours from elliptic to hyperbolic (see the figure). This topological phase transition was noticed as a mathematical possibility in the 2D context (arXiv:1201.5175), but no materials were known where it might be realizable.

The appropriate low-energy Hamiltonian has a 2×2 matrix structure,

$$H = \sum_{ij} v_{ij} p_i \sigma_j + \sum_i a_i p_i \sigma_0 \Rightarrow E = \sum_i a_i p_i \pm \sqrt{\sum_{ijk} v_{ik} v_{jk} p_i p_j},$$

in terms of Pauli matrices σ_i. This socalled tilted Weyl Hamiltonian was applied to layered organic conductors under pressure (doi:10.1143/JPSJ.76.034711) and to mechanically strained graphene (arXiv:0803.0912). In those 2D applications $i \in \{x, y\}$. For the 3D Weyl semimetals of current interest $i \in \{x, y, z\}$. The coefficients a_i, multiplied by the unit matrix σ_0, are responsible for the tilting of the cone. The equi-energy contours are elliptic, shrinking to a point at $E = 0$ (the Weyl point or Dirac point), provided that the a_i's are small enough. Pairs of hyperbolic contours, touching at $E = 0$, appear when the cone tips over. The condition for this is

$$\text{Det}\, M = 0, \quad M_{ij} = \textstyle\sum_k v_{ik} v_{jk} - a_i a_j.$$

Trescher et al. study how tilting of the Weyl cone affects the semimetal to metal transition as a function of disorder strength. This transition is signaled by a change in the Fano factor (the ratio of shot noise power and electrical current), from the universal value $F_{\text{metal}} = 1/3$ of a diffusive metal to a larger value $F_{\text{semimetal}}$ in the semimetal phase. It is remarkable that breaking rotational symmetry has no effect on $F_{\text{semimetal}}$, while breaking particle-hole symmetry does: The untilted Weyl cone gives $F_{\text{semimetal}} = 1/3 + 1/6 \ln 2$, irrespective of anisotropies, while tilting in a direction perpendicular to the current flow increases the semimetallic Fano factor further above the metallic value.

Soluyanov et al. propose a material in which particle-hole symmetry is broken sufficiently strongly that the Weyl cone tips over. It is a 3D layered structure, with single layers of W separated by bilayers of Te. Band structure calculations of this WTe_2 crystal, including strong spin-orbit coupling, reveal 8 Weyl cones with hyperbolic equi-energy contours. The opening of the Fermi surface should have a strong qualitative effect on the response to a magnetic field: The absence of closed cyclotron orbits is expected to produce a nonsaturating magnetoresistance, increasing linearly with field strength. Linear magnetoresistance has actually been reported in a similar material (arXiv:1408.2183), and an alternative semiclassical explanation (not involving open orbits) has been proposed (arXiv:1507.04730). I would expect the quantum transport properties to be unusual as well: does the Weyl cone remain protected from localization as it is tipped over?