Black Hole Quantum Matter

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Based on work t.a.h.s.

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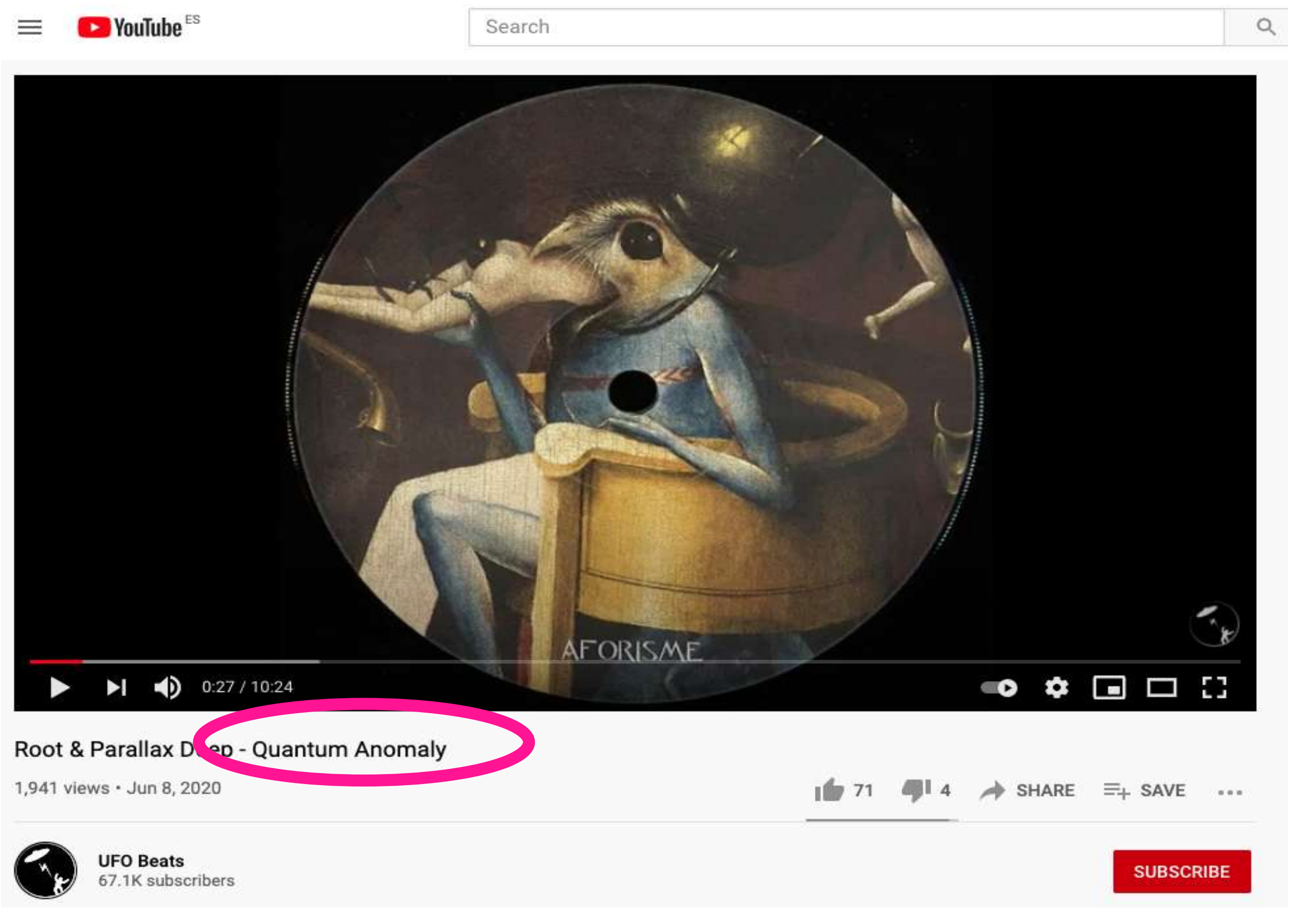
Outline

- What is a quantum anomaly?
  - Experimental demonstration !!
- Topological quantum matter = Chern Simons on Black holes
  - Quantum Hall physics
    - CME
    - CVE
    - Superfluids

Quantum Anomalies

Popular views at times somewhat inaccurate...



Anomalies

Ingredients to an anomaly:

- ➔ Classical symmetry broken by quantization
- ➔ Topology

Anomalies

Can one see this anomaly in experiment?

20 October 1975

Volume 54A, number 6 PHYSICS LETTERS 20 October 1975

VERIFICATION OF COHERENT SPINOR ROTATION OF FERMIONS ☆

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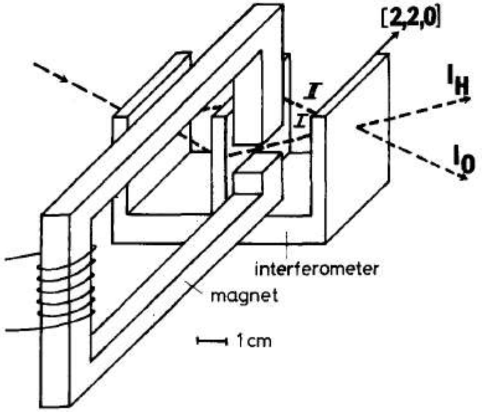


Fig. 1. Sketch of the experimental setup.

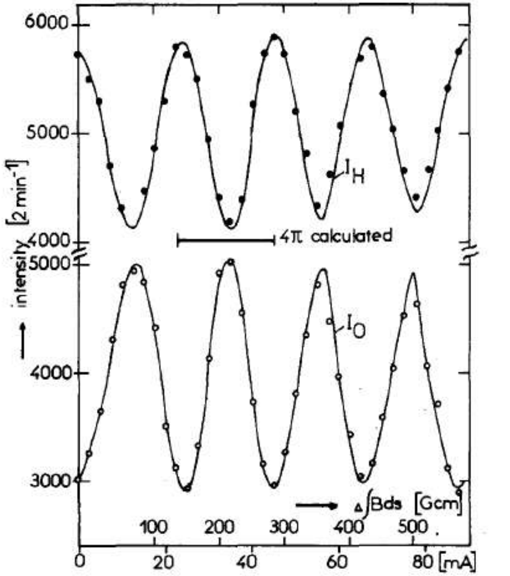


Fig. 2. Observed intensity oscillations of the 0- and H-beam as a function of the difference of the magnetic field action on beam I and II ($\Delta \int B ds = \int B_z ds$ (path I) $- \int B_z ds$ (path II).

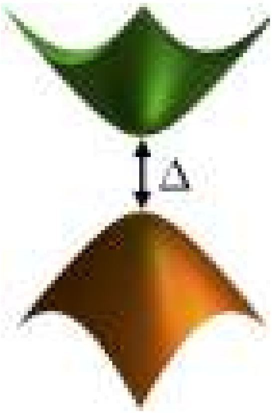
The oscillation period clearly shows that the identical wave function is reproduced after a spinor rotation of 4π and a -1 occurs for a 2π rotation.

Quantum Anomalous Hall Effect

Cond-mat/Hep dictionary:

"Edge Current"

"Band structure"



empty	particles
gap	mass
occupied	anti-particles

$$(i\not{\partial} - m)\psi = 0$$

Berry connection: $\mathcal{A}_i = \psi(p)^\dagger \frac{\partial \psi(p)}{\partial p_i}$

Berry curvature: $\mathcal{F} = \nabla_p \times \mathcal{A}$

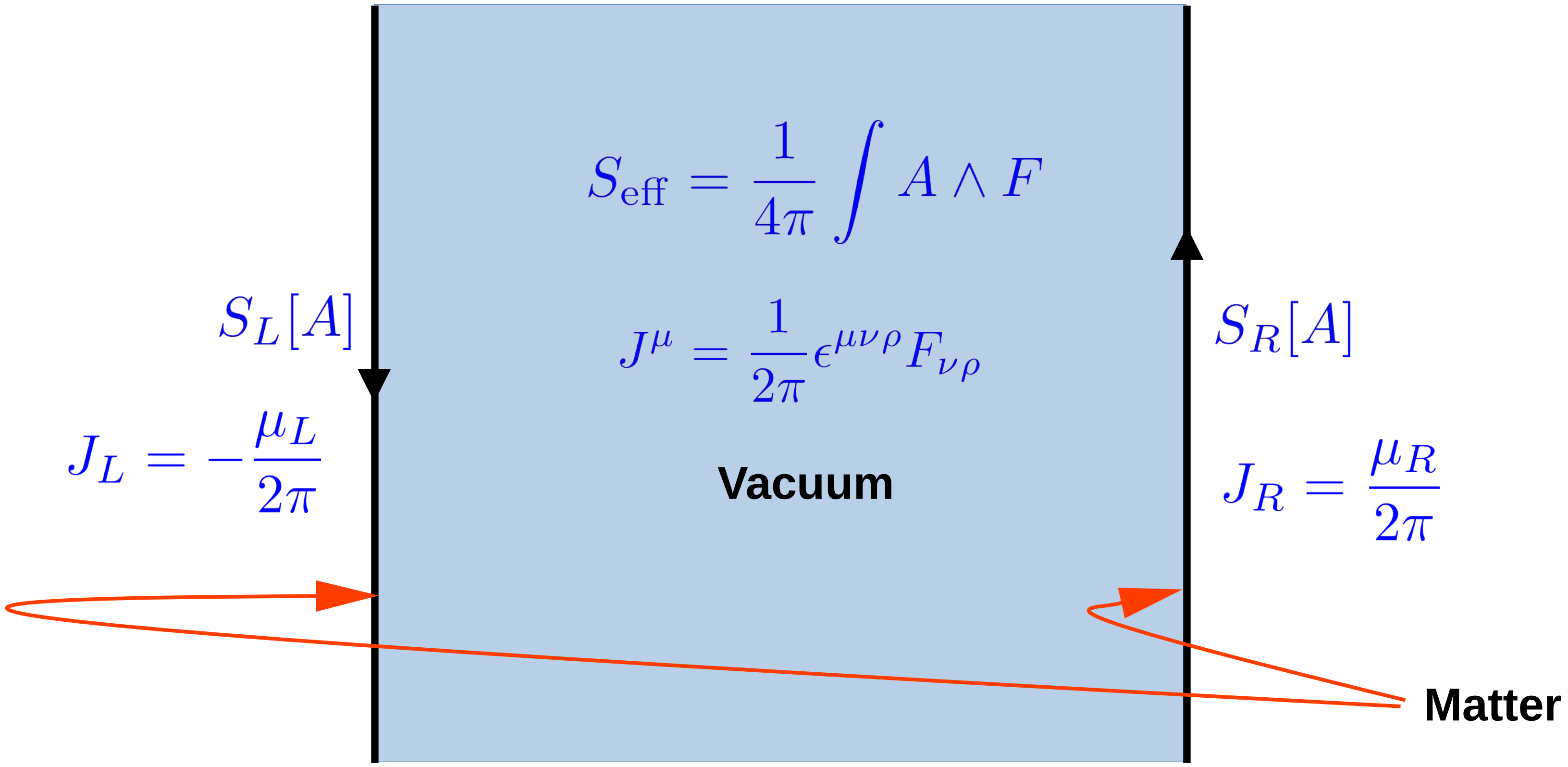
Topological invariant: $\int_{BZ} \mathcal{F} = \pm 2\pi$

Quantized hall conductivity: $J^i = \frac{e^2}{h} \epsilon_{ij} E_j$

[TKNN] 1982
[Haldane] 1988
[Golterman, Jansen, Kaplan] 1992

QAHE

Quantum field point of view:



Matter = μ and T

Anomalies

Chiral Fermions have anomalies

➔ "Gauge" anomaly $\mathcal{A} = c \int d^2x \, \lambda \, F$

➔ Non-local in 2D $c \int d^2x \, d^2y \frac{\partial A(x) F_{\mu\nu}(y) \epsilon^{\mu\nu}}{\Box_{xy}}$ $\delta A_\mu = \partial_\mu \lambda$

➔ Local term in 3D $S_{\text{CS}} = c \int_{\text{M}} A \wedge F$

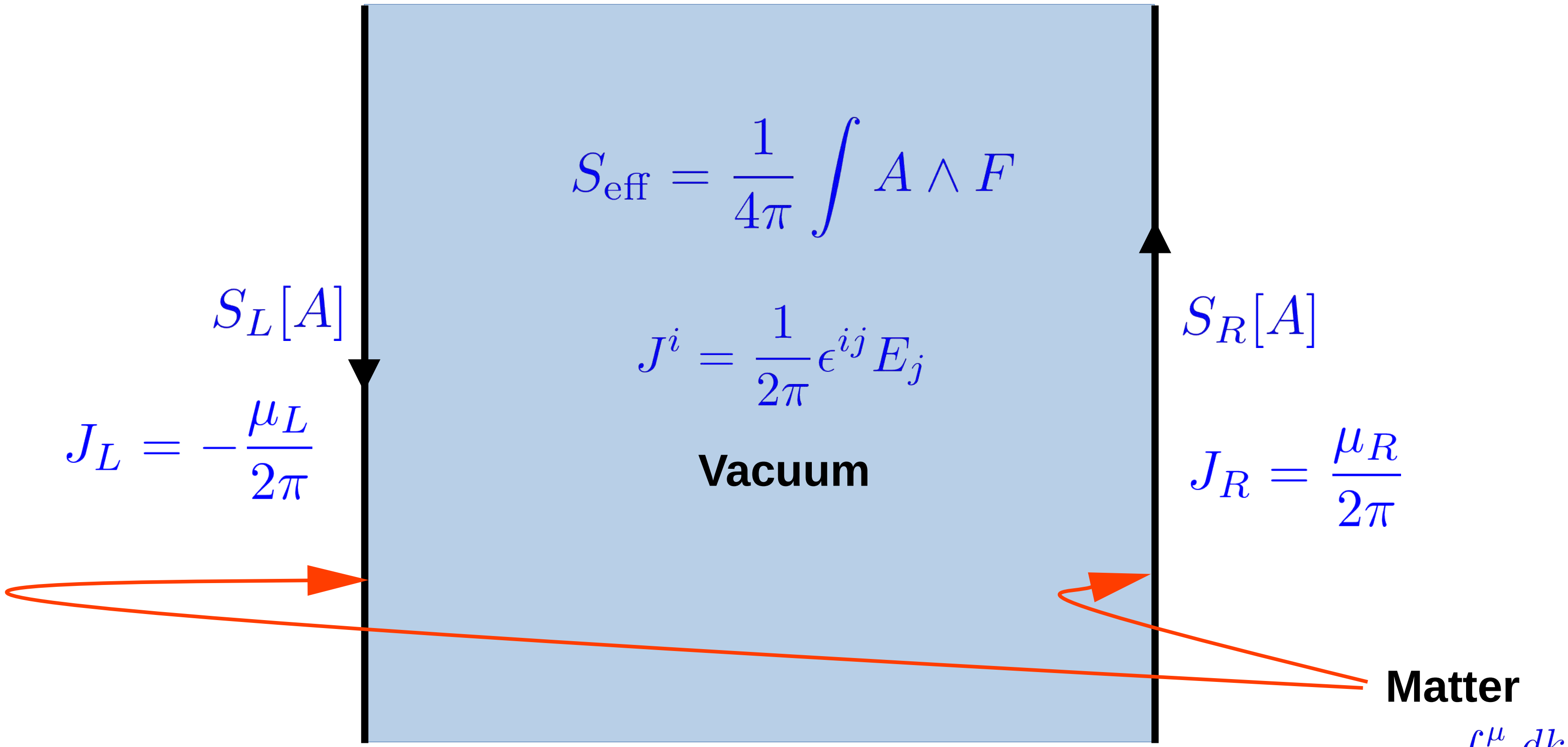
➔ Gauge Trafo: $\delta S_{\text{CS}} = c \int_{\partial M} \lambda F$

(Anomaly Inflow)

[Callan, Harvey] 1985

QAHE

Quantum field point of view:



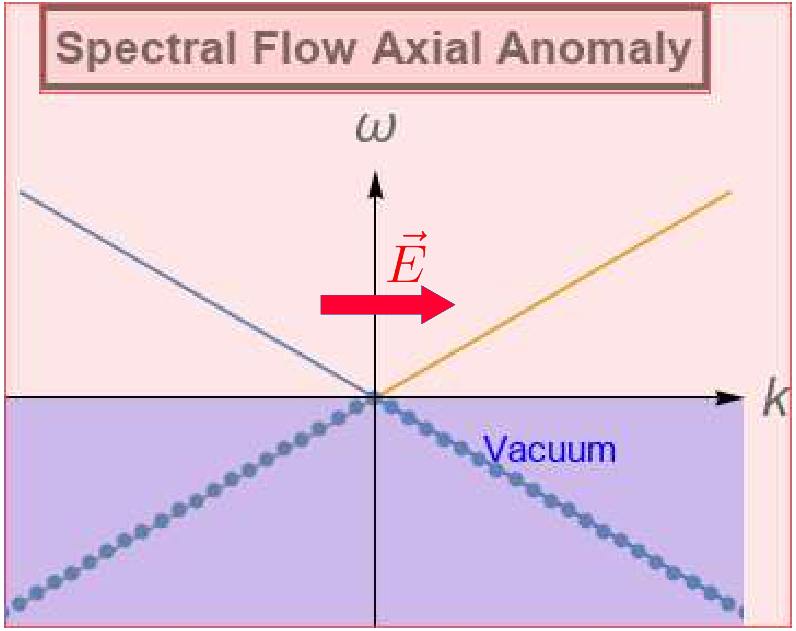
$$J = \int_0^{\mu} \frac{dk}{2\pi}$$

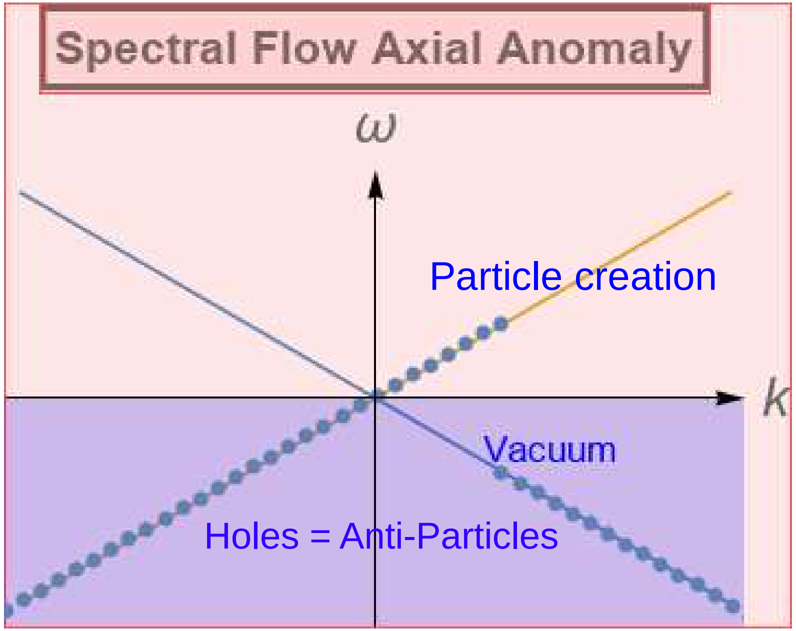
Edge currents are also determined by anomaly

Matter = μ (and T)

(Edge) Anomaly

1 left handed + 1 right handed





$$\frac{dn_{R,L}}{dt} = \pm\frac{1}{2\pi}E \qquad \frac{d}{dt}(n_R + n_L) = 0$$

nature materials

Article

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Direct visualization of electronic transport in a quantum anomalous Hall insulator

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Check for updates

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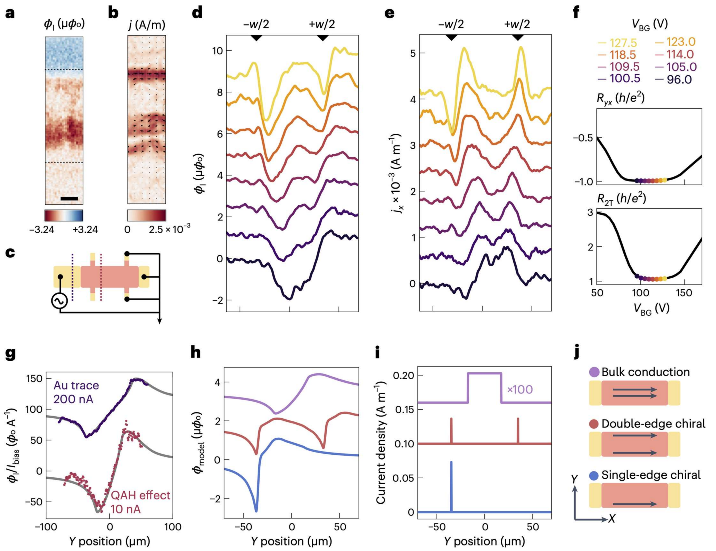
A quantum anomalous Hall (QAH) insulator is characterized by quantized Hall and vanishing longitudinal resistances at zero magnetic field that are protected against local perturbations and independent of sample details. This insensitivity makes the microscopic details of the local current distribution inaccessible to global transport measurements. Accordingly, the current distributions that give rise to transport quantization are unknown. Here we use magnetic imaging to directly visualize the transport current in the QAH regime. As we tune through the QAH plateau by electrostatic gating, we clearly identify a regime in which the sample transports current primarily in the bulk rather than along the edges. Furthermore, we image the local response of equilibrium magnetization to electrostatic gating. Combined, these measurements suggest that the current flows through incompressible regions whose spatial structure can change throughout the QAH regime. Identification of the appropriate microscopic picture of electronic transport in QAH insulators and other topologically non-trivial states of matter is a crucial step towards realizing their potential in next-generation quantum devices.



Chern Simons and Black Holes

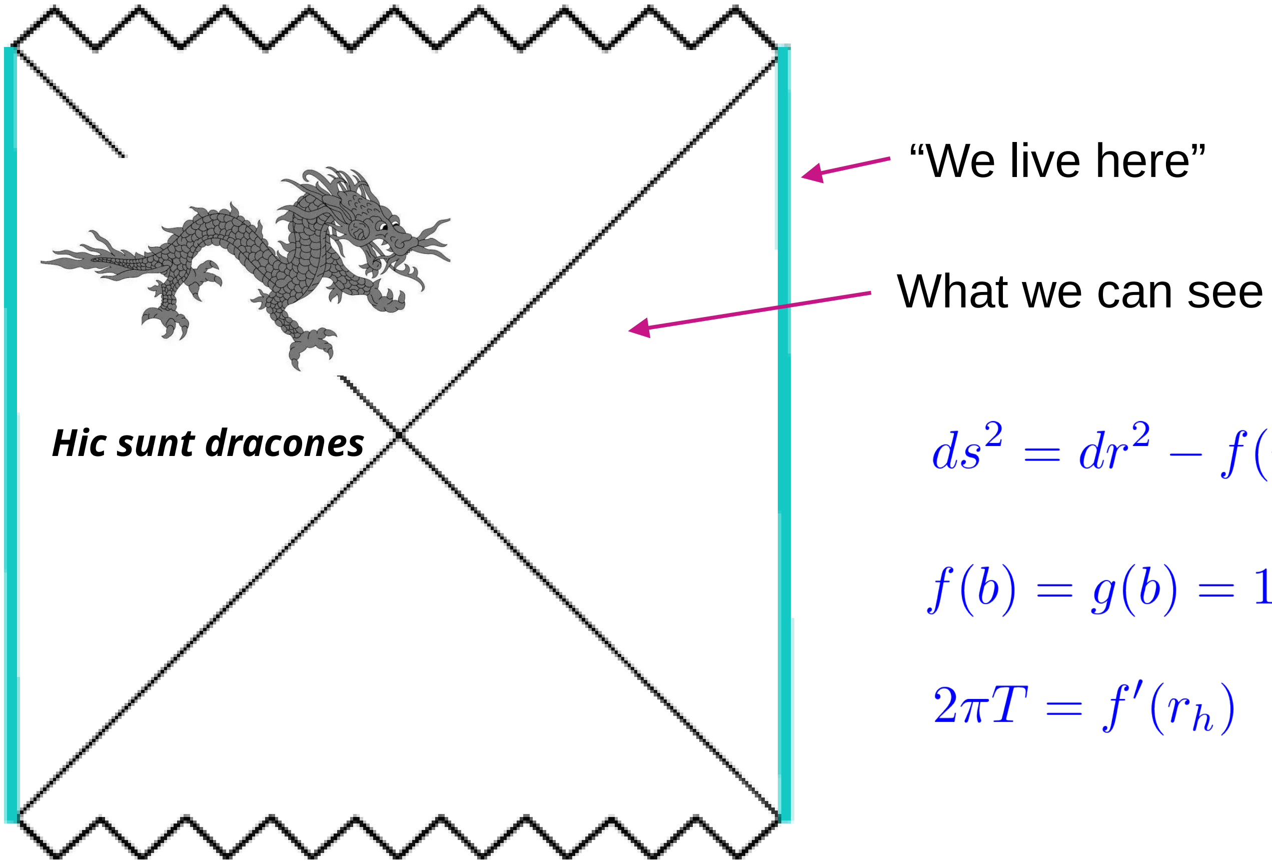
- ➔ Bulk insulator is described by effective Chern-Simons action
- ➔ Gauge invariance restored by chiral anomaly from edge modes
- ➔ Claim: edge modes are described by Chern-Simons on Black hole

$$S_{\text{eff}} = c \int_M A \wedge F - c \int_{BH} A \wedge F$$

$$\partial M = \partial(BH)$$

Anomalous currents from black holes

Black Hole encodes “quantum matter” = T,μ



$$ds^2 = dr^2 - f(r)^2 dt^2 + g(r)^2 d\vec{x}^2$$

$$f(b) = g(b) = 1$$

$$2\pi T = f'(r_h)$$

Anomalous currents from black holes

3 dimensions:

$$S_{\text{eff}} = \int_{BH} A \wedge F$$

$$\delta S = 2 \int_{BH} \delta A \wedge F + (\delta A \wedge A)|_{\partial BH}$$

$$F = \partial_r A_t dr \wedge dt$$

$$\mu = A_t(b) - A_t(r_h)$$

Encodes chemical potential µ

$$\delta S = \delta A.J$$

$$J = 2\mu - A_t(b)$$

Current of 2D Chiral Fermionl

(covariant vs consistent anomaly)

[Bardeen, Zumino] 1984

Anomalous currents from black holes

Gravitational CS term: $$S = \int_{BH} (\Gamma d\Gamma + \frac{2}{3}\Gamma^3)$$

$$x^\mu \to x^\mu + \xi^\mu$$

$$\delta\Gamma = (\mathrm{i}_\xi d + d\mathrm{i}_\xi)\,\Gamma - D\Lambda_\xi$$

$$(\Lambda_\xi)^\alpha_\beta = \frac{\partial \xi^\alpha}{\partial x^\beta} \qquad D\cdot\ = d\cdot\ + [\Gamma, \cdot]$$

$$\delta S = \int_\partial \Lambda_\xi R$$

2D Gravitational anomaly on boundary

Important detail: vanishing extrinsic curvature on boundary!

Anomalous currents from black holes

Calculate current as before:

$$ds^2 = dr^2 - f(r)^2(dt - \delta A_g dx)^2 + g(r)^2 dx^2)$$

"Gravito-electric" potential
(Source for energy current)

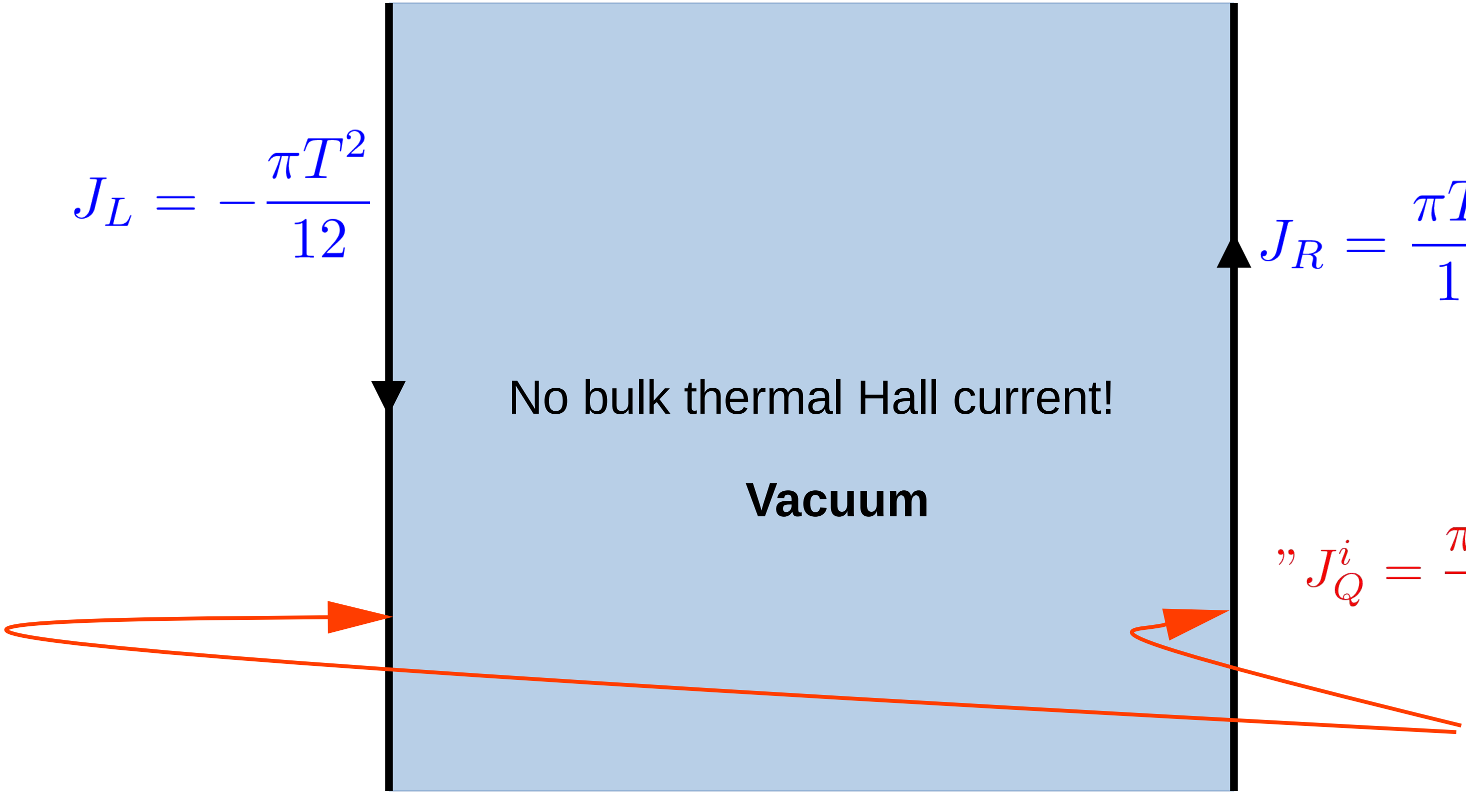
$$\delta S = 2A_g \int_{r_H}^{b} [\frac{f f' g'}{g} - (f')^2]' dr$$

$$T^{tx} = J_E = 8\pi^2 T^2$$

Energy current of chiral fermion

Application: thermal QHE

$$S = c_g \int_M (\Gamma d\Gamma + \frac{2}{3}\Gamma^3) - c_g \int_{BH} (\Gamma d\Gamma + \frac{2}{3}\Gamma^2)$$



Application: CME

4D anomalies and 5D Chern-Simons forms:

- Chiral Magnetic Effect: $S_{\text{eff}} = C \int_{\mathcal{BH}} A \wedge F_V \wedge F_V$

$$\vec{J} = 2C(\mu_5 - A_t)\vec{B}$$

- Chiral Separation Effect: $S_{\text{eff}} = C \int_{\mathcal{BH}} A \wedge F_V \wedge F_V$

$$\vec{J}_5 = 2C\mu\vec{B}$$

- Chiral Vortical Effect: $S_{\text{eff}} = C_g \int_{\mathcal{BH}} A \wedge \text{tr}(R \wedge R)$

$$\vec{J} = 16\pi^2 C_g T^2 \vec{\Omega}$$

➔ Superfluidity as BF theory: $S_{\text{eff}} = \int_{\mathcal{BH}} B_3 \wedge F$

$$\omega^2 - v_s k^2 = 0$$

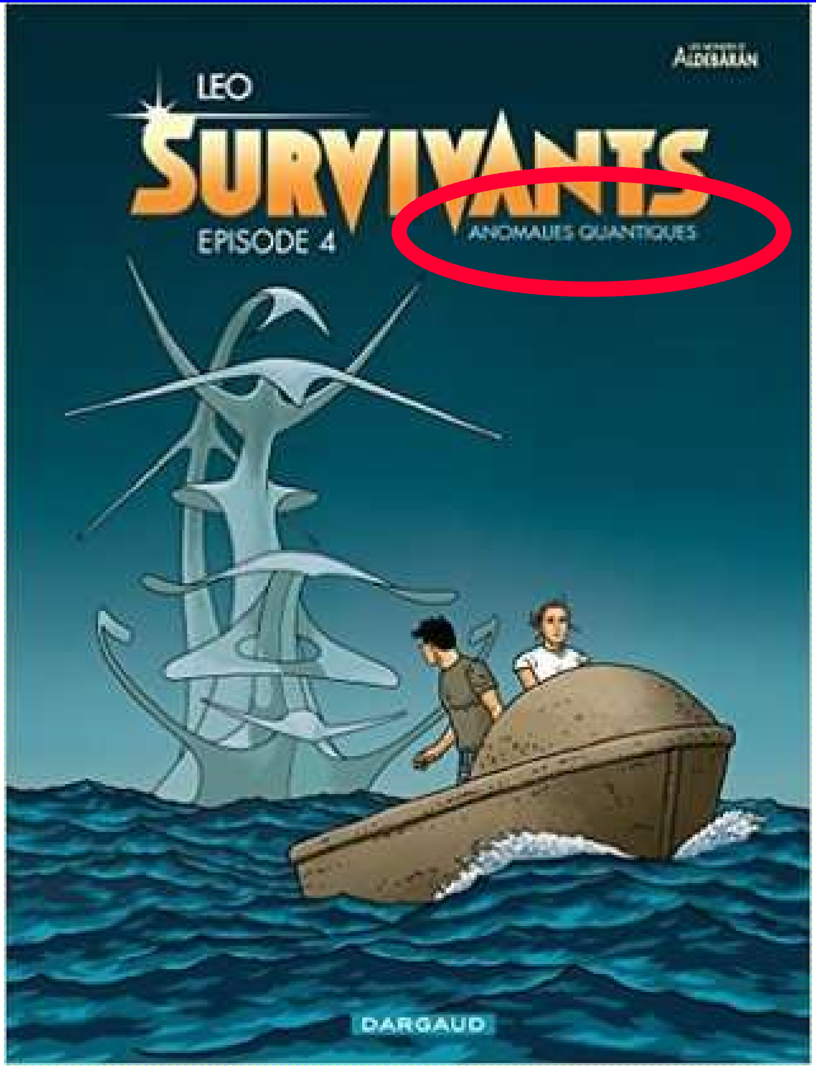
2nd sound

"anomaly" in higher form symmetry = vortex creation

[Delacretaz, Hofman, Mathys] 2019

Quantum Anomalies

The good news:
you can survive them



Summary

[Fan Zhang]

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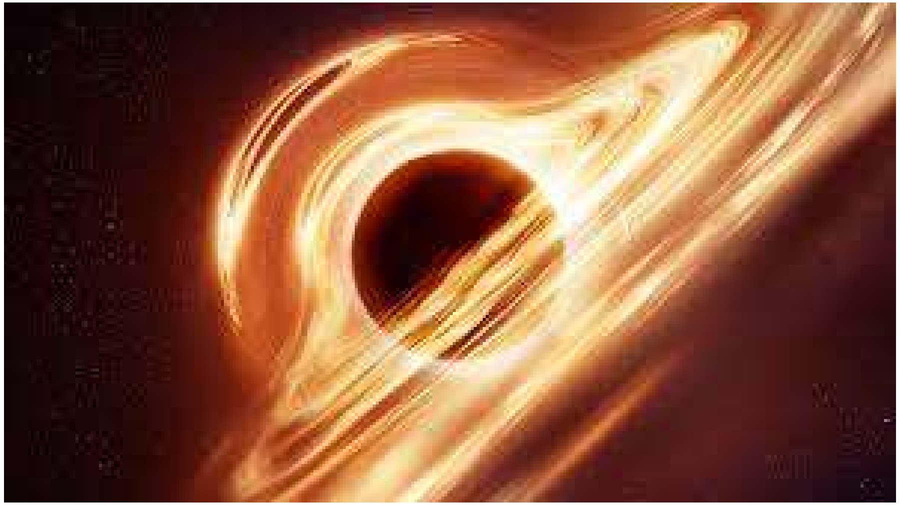

Thank you!