Odd transport and holography

Carlos Hoyos
Tel Aviv University

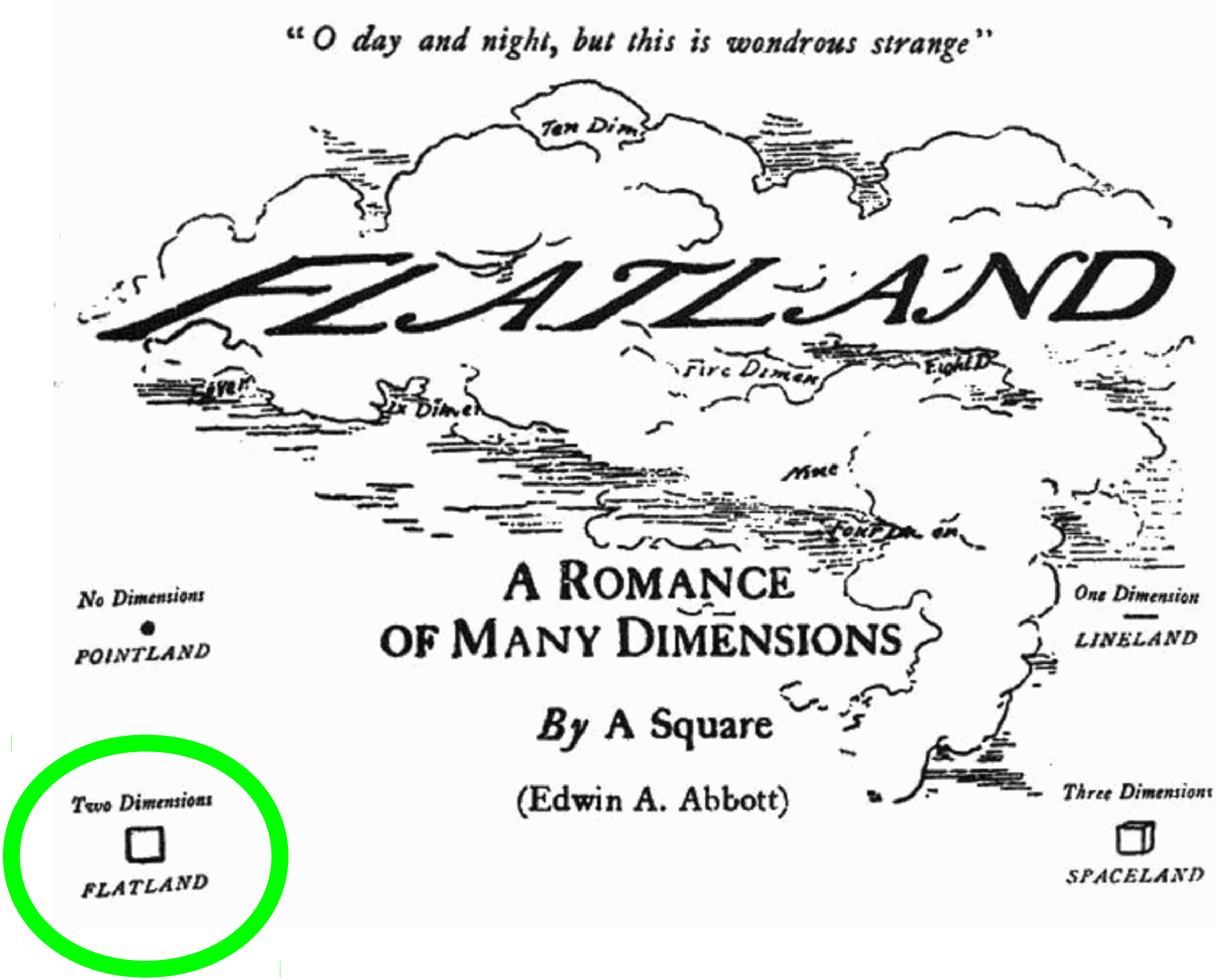
Gravity Theories and their Avatars
Heraklion, Crete

This talk is biased towards a few topics

I apologize for any omissions and missed references

I skip many details about the stringy bits

Please interrupt me if there is any question


"O day and night, but this is wondrous strange"
Ten Dim
FLATLAND
Five Dimen
A ROMANCE OF MANY DIMENSIONS
By A Square
(Edwin A. Abbott)
No Dimensions
POINTLAND
One Dimension
LINELAND
Two Dimensions
FLATLAND
Three Dimensions
SPACELAND

I will focus in D=2+1, but a lot of progress has been made in D=3+1 fluids lately

- Anomalies and hydrodynamics

Son, Surowka '09
plus ~ 100 more

- Effects due to mixed and gravitational anomaly

Landsteiner, Megias, Melgar, Pena-Benitez '11

- Berry phase in Fermi liquids and chiral anomaly

Son, Yamamoto '12

- Probably more that I'm forgetting

MOTIVATION

arxiv.org/abs/hep-th/9209013

Cornell University Library

The Universe is a Quantum Hall conductor

High Energy Physics - Theory

The String Universe: High T_c Superconductor or Quantum Hall Conductor?

John Ellis, N.E. Mavromatos, D.V. Nanopoulos

(Submitted on 4 Sep 1992)

Our answer is the latter. Space-time singularities, including the initial one, are described by world-sheet topological Abelian gauge theories with a Chern-Simons term. Their effective $N=2$ supersymmetry provides an initial fixed point where the Bogomolny bound is saturated on the world-sheet, corresponding to an extreme Reissner-Nordstrom solution in space-time. Away from the singularity the gauge theory has world-sheet matter fields, bosons and fermions, associated with the generation of target space-time. Because the fermions are complex (cf the Quantum Hall Effect) rather than real (cf high-T_c superconductors) the energetically-preferred vacuum is not parity or time-reversal invariant, and the associated renormalization group flow explains the cosmological arrow of time, as well as the decay of real or virtual black holes, with a monotonic increase in entropy.

Comments:	19 pages
Subjects:	**High Energy Physics - Theory (hep-th)**
Journal reference:	Phys.Lett.B296:40-50,1992
DOI:	10.1016/0370-2693(92)90801-A
Report number:	CERN-TH.6536/92
Cite as:	**arXiv:hep-th/9209013v1**

Submission history

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Outline

- Basic stuff
- Odd transport in 2+1 dimensions
- Odd transport and quantization
- Holographic models
- Open questions

Response at very low frequencies and momenta

External electric fields: conductivities

$$\langle \delta J^i_I \rangle (q) \simeq \sigma^{ij}_{IJ} E^J_j (q)$$

Deformations of the space: viscosity

$$x^i \to x^i + u^i$$

$$\delta g_{ij} = \partial_i u_j + \partial_j u_i \equiv u_{ij}, \quad \delta g_{i0} = \partial_t u_i \equiv \boxed{\delta v_i}$$

velocity

$$\langle \delta T^{ij} \rangle \simeq \eta^{ij,kl} \partial_{(k} \delta v_{l)}$$

Some symmetry relations

Symmetries of the viscosity tensor:

$$\eta^{ij,kl} = \eta^{ji,kl} = \eta^{ij,lk}$$

Onsager's relations:

$$\sigma^{ij}_{IJ} = \sigma^{ji}_{JI}, \qquad \eta^{ij,kl} = \eta^{kl,ij}$$

(Derived from time reversal invariance)

Parity assignments in D=2+1

	T^{ij}	J^i_I	$\partial_{(i}v_{j)}$	E^I_i	B^I	$\omega = \epsilon^{ij}\partial_i v_j$
P	$(-1)^i(-1)^j$	$(-1)^i$	$(-1)^i(-1)^j$	$(-1)^i$	-1	-1

Allowed by rotational invariance:

A_{IJ} Anti-Symmetric $\qquad$ S_{IJ} Symmetric

$$\sigma^{ij}_{IJ} = S_{IJ}\delta^{ij} + \left(S_{IJ}\epsilon^{ij}\right) + \left(A_{IJ}\delta^{ij}\right) + \left(A_{IJ}\epsilon^{ij}\right)$$

T-odd

P-odd

$$\eta^{ij,kl} = \eta_S^{ij,kl} + \eta_A^{ij,kl},$$

$$\eta_S^{ij,kl} = \eta_S^{kl,ij}, \quad \eta_A^{ij,kl} = -\eta_A^{kl,ij}$$

Allowed by rotational invariance:

$$\eta_S^{ij,kl} = \eta(\delta^{ik}\delta^{jl} + \delta^{il}\delta^{jk} - \delta^{ij}\delta^{kl}) + \zeta\delta^{ij}\delta^{kl}$$

$$\eta_A^{ij,kl} = \boxed{\eta_H}(\epsilon^{ik}\delta^{jl} + \epsilon^{il}\delta^{jk} + \epsilon^{jk}\delta^{il} + \epsilon^{jl}\delta^{ik})$$

T-odd, P-odd

Avron, Seiler, Zograf '95, Avron '97

First law of thermodynamics

$$dE = TdS - T^{ij}du_{ij} + \mu^I dJ_I^t$$

$$0 = \partial_t E = T\partial_t s - T^{ij}\partial_{(i}\delta v_{j)} - \mu^I \partial_i J_I^i$$

$$T\partial_t s = p\partial_i \delta v^i + \eta^{ij,kl}\partial_{(i}\delta v_{j)}\partial_{(k}\delta v_{l)} + \mu^I \sigma_{IJ}^{ij}\partial_i E_j^J$$

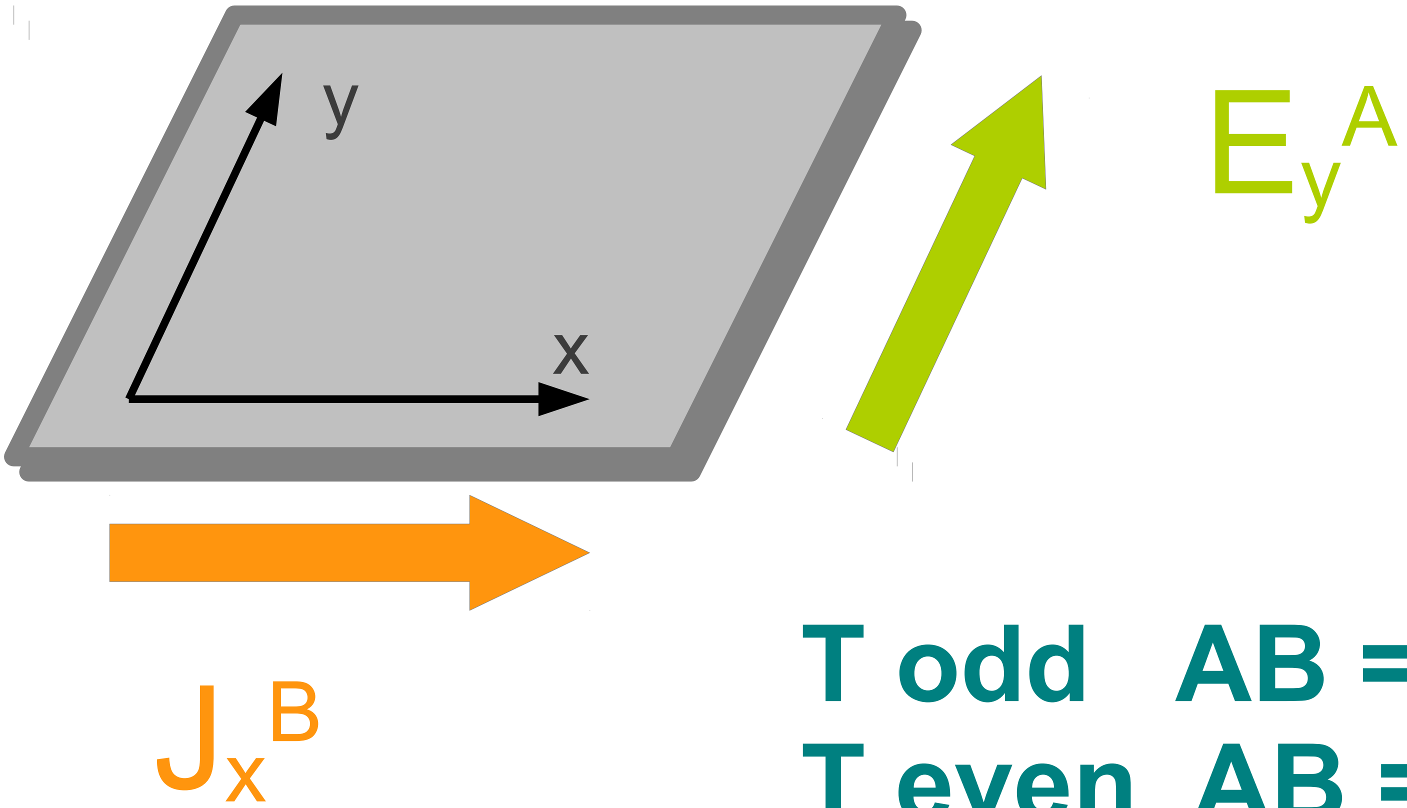
Incompressible fluid

$$\partial_i \delta v^i = 0 \qquad \partial_t B^I = 0$$

P-odd coefficients are antisymmetric

$$T\partial_t s = 0$$

P-odd transport

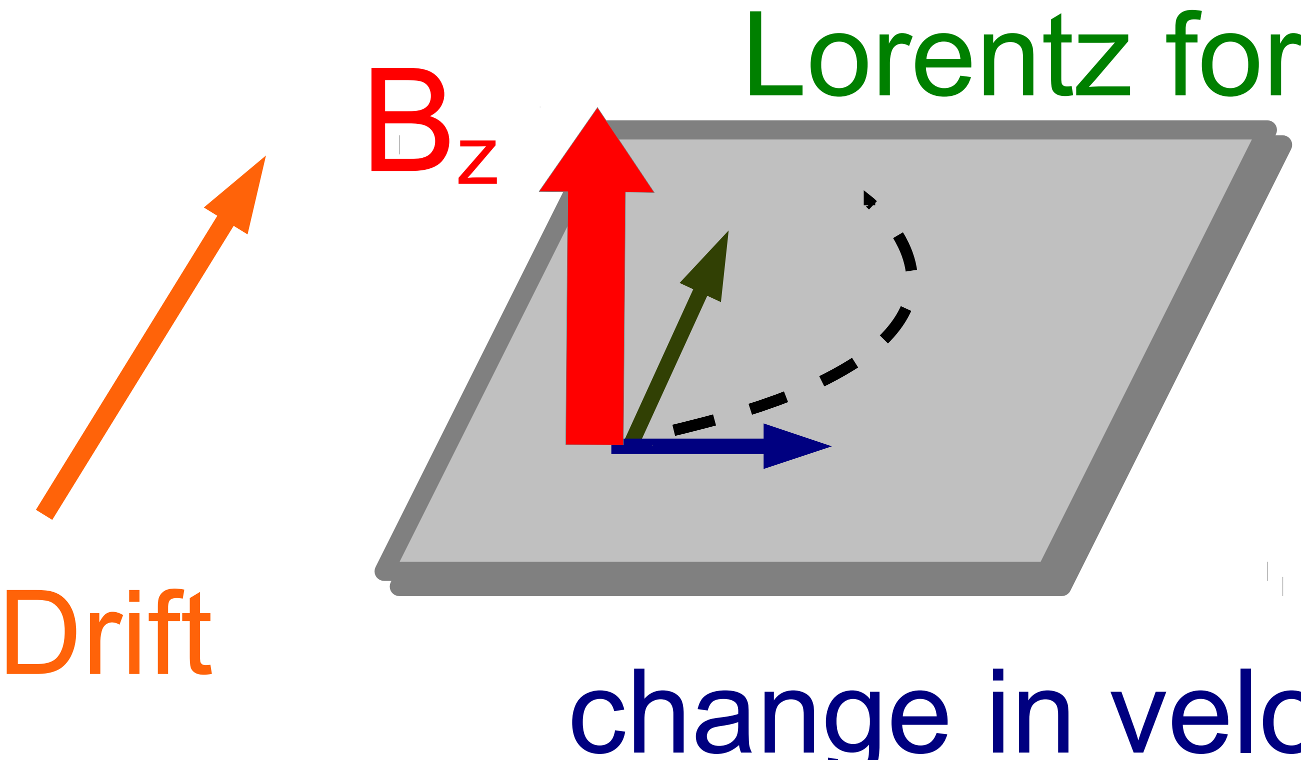


T odd AB = BA

T even AB = -BA

Hall conductivities

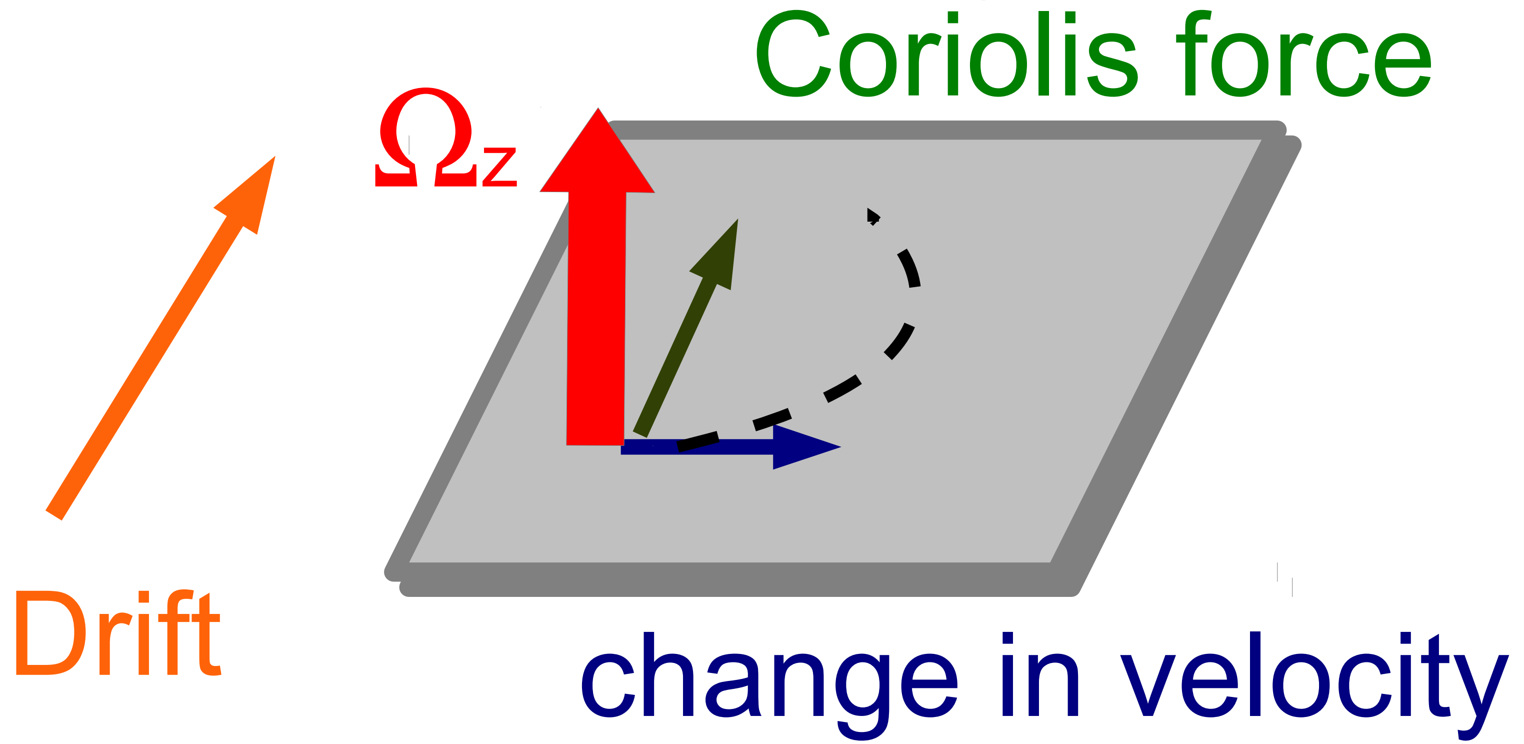
Classical Hall Effect: Lorentz force



$$J^i = \sigma_H \epsilon^{ij} E_j, \quad \sigma_H = \frac{nec}{B}$$

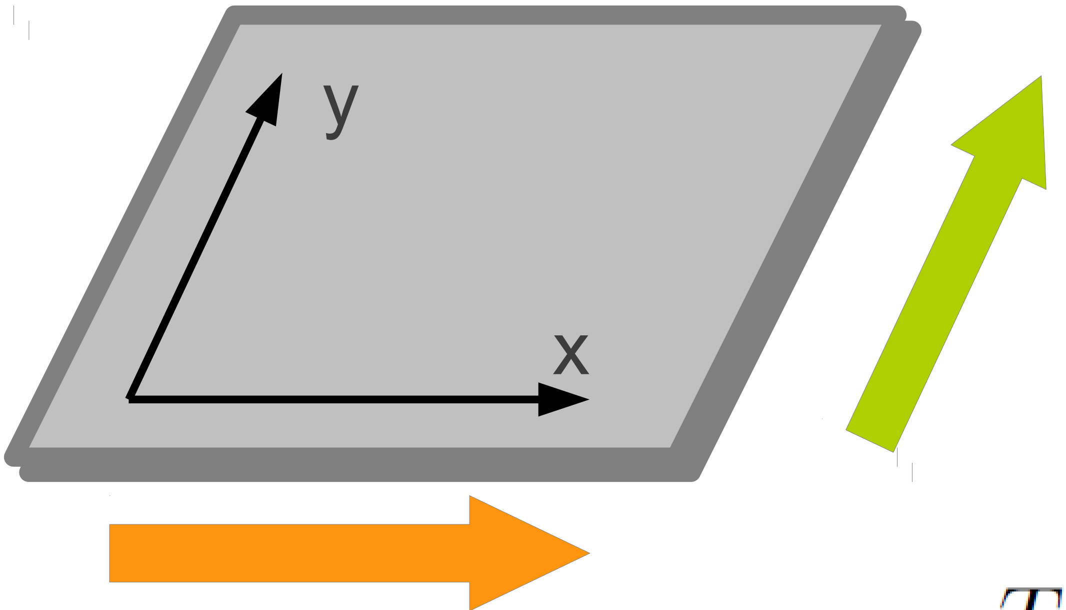
Rotational Hall Effect: Coriolis force

Rest frame of a rotating fluid



$$T^{i0} = \zeta_H \epsilon^{ij} \partial_t g_{jt} \qquad \zeta_H = \frac{\varepsilon + p}{\Omega}$$

P-odd transport



dT/dy

dg_{00}/dy

$J_x \; T_{0x}$

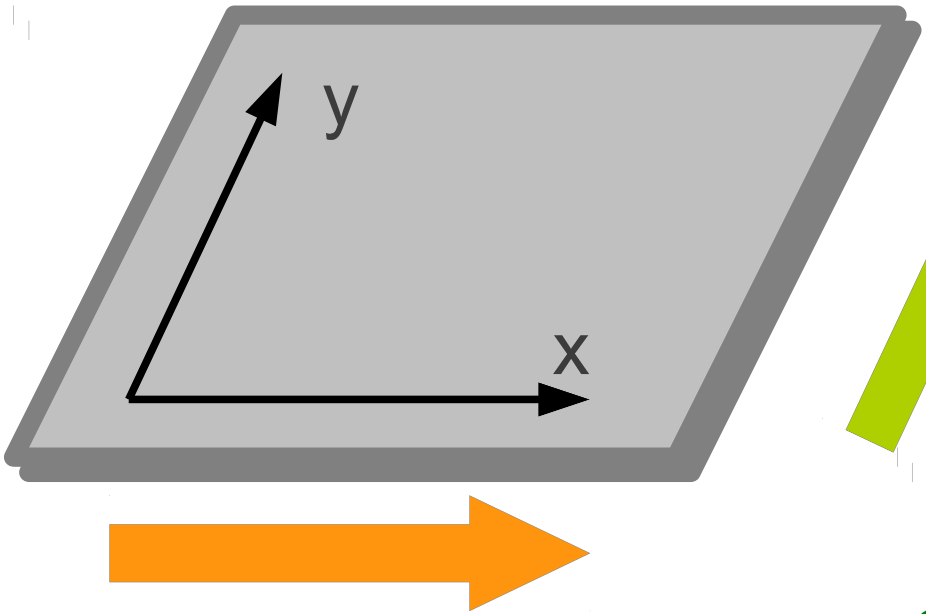
Nernst effect

$$T^{i0} = \kappa_H \epsilon^{ij} \partial_j T$$

$$J^i = \alpha_H \epsilon^{ij} \partial_j T$$

Thermal and thermoelectric conductivities

P-odd transport



dv_x/dy

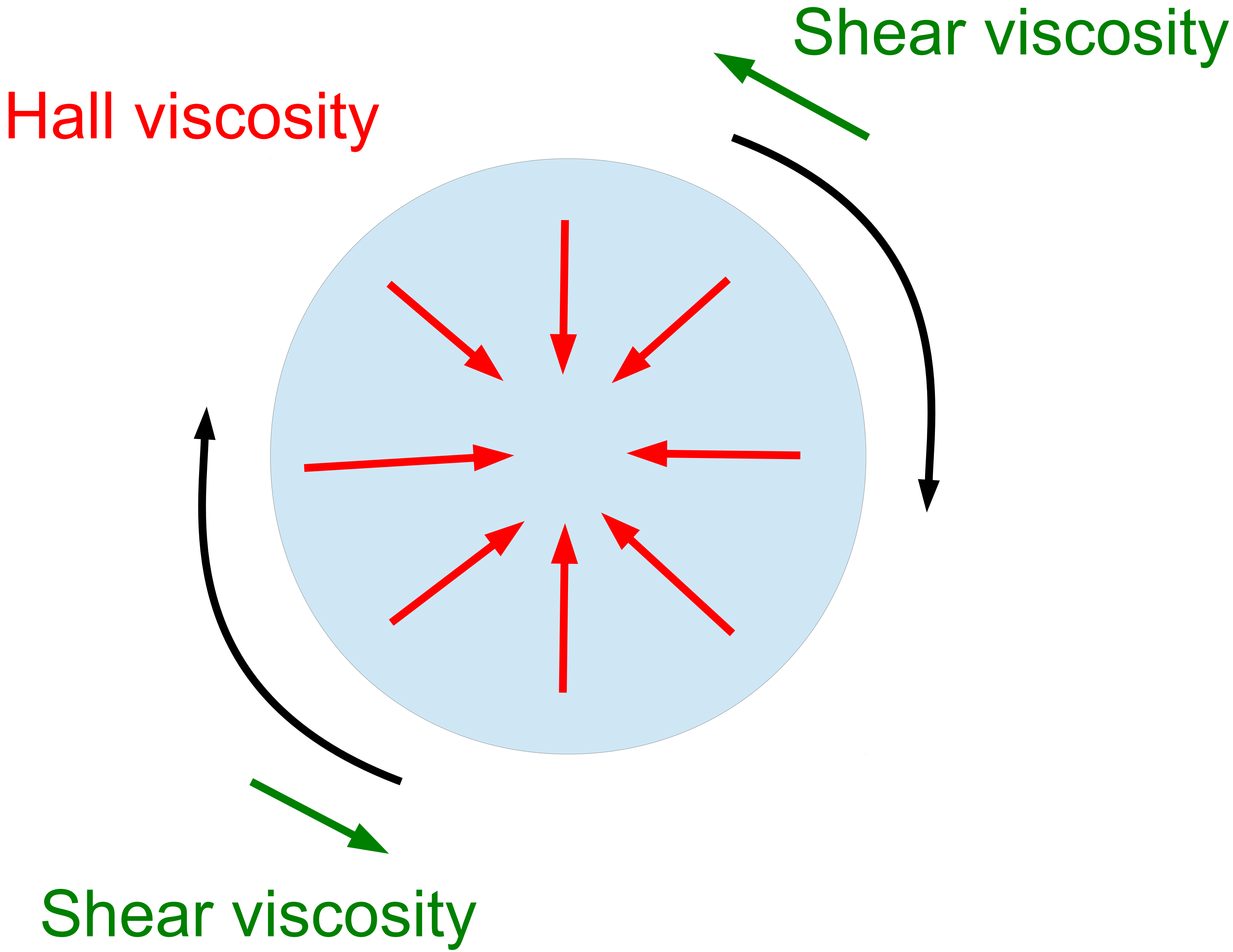
dg_{xy}/dt

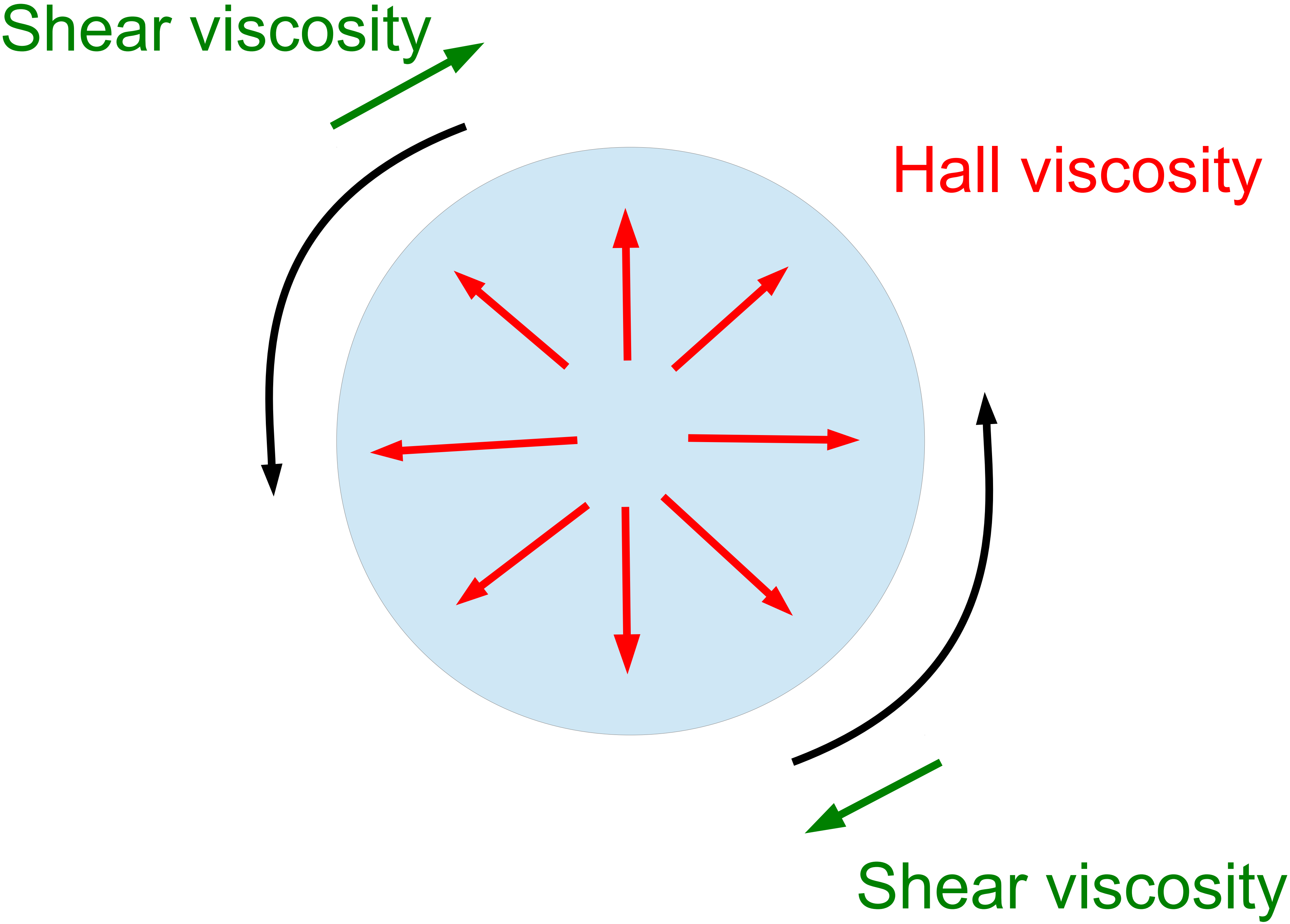
$T_{xx}=-T_{yy}$

$dT_{ty}/dt = dT_{yy}/dy$

$dT_{tx}/dt = -dT_{yy}/dx$

Hall viscosity


Shear viscosity
Hall viscosity
Shear viscosity


Shear viscosity
Hall viscosity
Shear viscosity

Odd transport coefficients to leading order

- Angular momentum density ★
- Magnetization ★

$$T^{\mu\nu} = \epsilon_0 u^\mu u^\nu + P_0 \Delta^{\mu\nu} - (\zeta \nabla_\lambda u^\lambda + \tilde{\zeta}_A \Omega + \tilde{\zeta}_B B)\Delta^{\mu\nu} - \eta \sigma^{\mu\nu} - \tilde{\eta}_A \tilde{\sigma}^{\mu\nu},$$

$$J^\mu = \rho u^\mu + \sigma E^\mu - \kappa \Delta^{\mu\nu} \nabla_\nu \frac{\mu}{T} + \tilde{\sigma} \epsilon^{\mu\nu\rho} u_\nu E_\rho + \tilde{\kappa} \epsilon^{\mu\nu\rho} u_\nu \nabla_\rho \frac{\mu}{T} + \tilde{\xi} \epsilon^{\mu\nu\rho} u_\nu \nabla_\rho T.$$

- Hall conductivity ★
- Hall viscosity ★
- Hall thermal conductivity ★
- Nernst coefficient ★

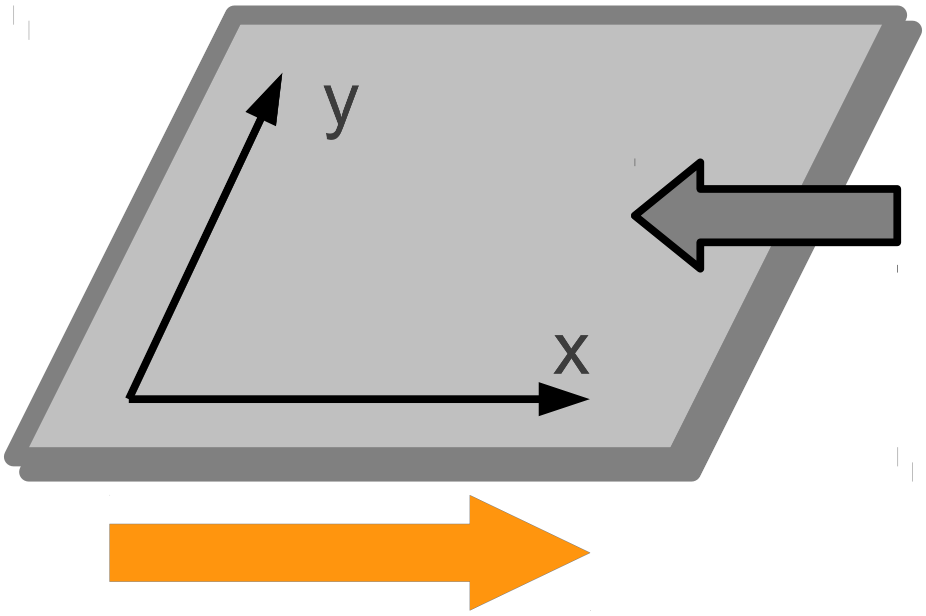
Jensen, Kaminski, Kovtun, Meyer, Ritz, Yarom '11

So far all was classical physics

Quantum theories can have quantized transport coefficients

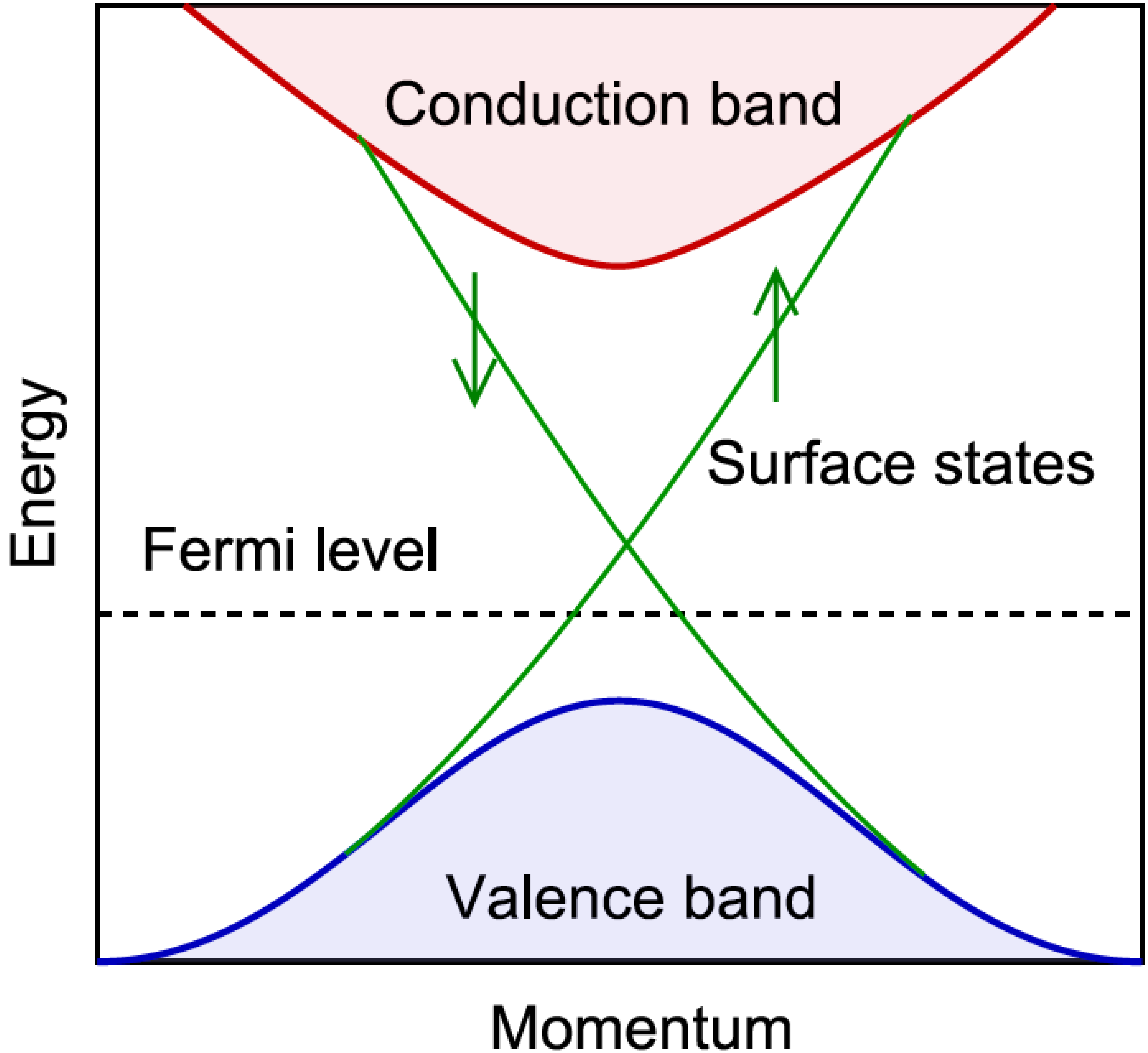
In condensed matter systems quantization is usually related to topology in momentum space

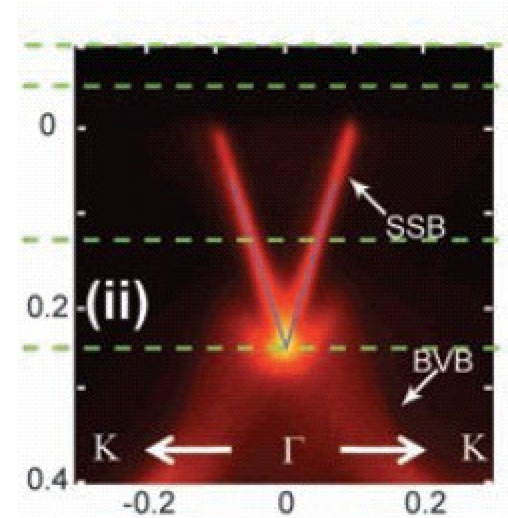
P-odd transport



Massless edge states

Chiral, protected → *"Topological"*





ARPES
view of edge state

Toy model: massive fermions coupled to external sources

$$\mathcal{L}_m = \frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \overline{\psi} \left(i\gamma^\mu D_\mu - m \right) \psi$$

Fermions in general produce anomalies:

Topological Effective Theories

Topological effective theories

$$S_\sigma = \frac{1}{2}\sigma_{IJ}\int d^3x\, A^I \wedge dA^J$$

$$\langle J_i^I \rangle = \frac{\delta S_\sigma}{\delta A_i^I} \sim \sigma_{IJ}\epsilon^{ij}E_j^J$$

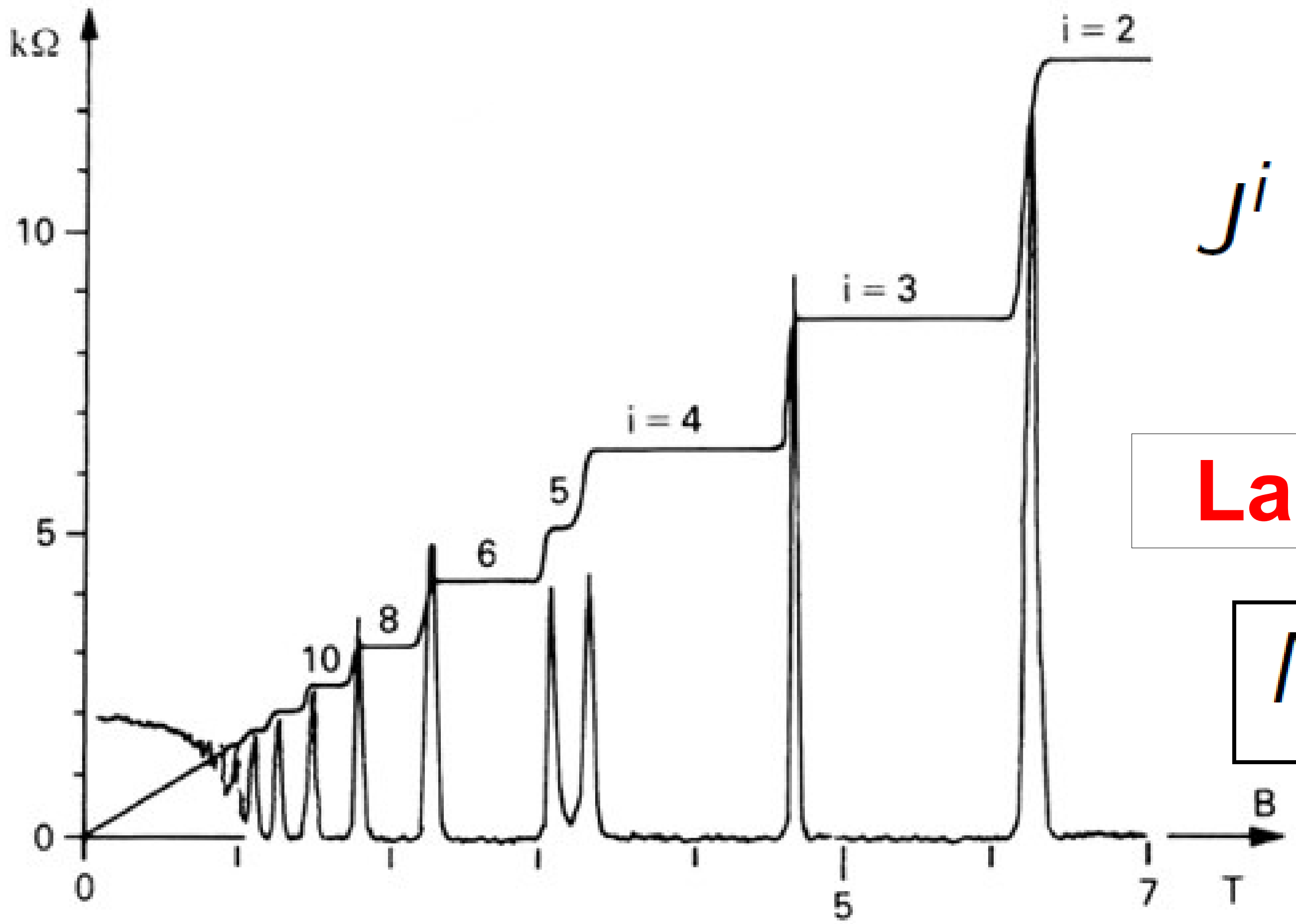
Girvin, McDonald; Zhang, Hansson, Kivelson ~'85-'89

$$S_\eta = \frac{1}{2}\eta_H\int d^3x\, \eta_{ab}e^a \wedge de^b$$

$$\langle T^{ij} \rangle = \frac{\delta S_\eta}{\delta g_{ij}} \sim \eta_H\epsilon^{ik}\partial^j g_{0k} \sim \eta_H\epsilon^{ik}\partial^j v_k$$

Hughes, Leigh, Fradkin '11

Quantization of Hall conductivity



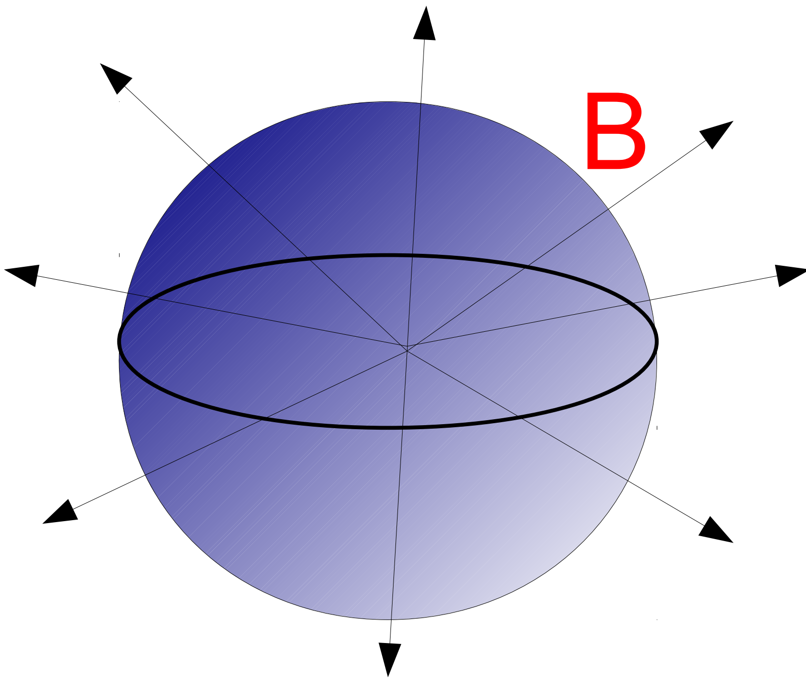
$$J^i = \frac{\nu}{2\pi}\epsilon^{ij}E_j$$

Landau levels

$$N_e = \nu N_\phi$$

Fractional QHE: Störmer, Tsui, Gossard '82, Laughlin '83

Quantization of Hall viscosity



Landau levels on a sphere

$$n = \frac{\nu}{2\pi}(B + \mathcal{S}R)$$

$$N_e = \nu N_\phi + \nu \mathcal{S} \chi_E$$

Wen, Zee '92

$$\boxed{\frac{\eta_H}{n} = \frac{\hbar}{2}\mathcal{S}}$$

Read, Rezayi '11

Values that were confirmed:

- Free fermions with L filled Landau levels

$$\nu = L, \quad \mathcal{S} = \frac{L}{2}$$

- Laughlin states

$$\nu = \frac{1}{2k+1}, \quad \mathcal{S} = k + \frac{1}{2}$$

Trivial Remark:
Combining filling fraction and shift one can distinguish among a larger class of theories

General values in TET:

$$\mathcal{L} = \frac{1}{4\pi}\left[K^{IJ} a_I \wedge da_J + 2(t^I A + s^I \omega) \wedge da_I\right]$$

$$\begin{pmatrix} N_e \\ N_s \end{pmatrix} = \begin{pmatrix} t^I K^{-1}_{IJ} t^J & t^I K^{-1}_{IJ} s^J \\ s^I K^{-1}_{IJ} t^J & s^I K^{-1}_{IJ} s^J \end{pmatrix} \begin{pmatrix} N_\phi \\ \chi_E \end{pmatrix}$$

$$\nu = t^I K^{-1}_{IJ} t^J \qquad \mathcal{S} = t^I K^{-1}_{IJ} s^J$$

Quasiparticles: vortices

charge

$$Q_I = t^J K^{-1}_{JI}$$

spin

$$S_I = s^J K^{-1}_{JI}$$

Statistical angle ℓ and m vertex

$$\frac{\theta}{\pi} = l^I K^{-1}_{IJ} m^J$$

Fermions in a magnetic field (can) have quantized Hall conductivity and viscosity

A couple of questions...

- Can there be quantization if T is not broken? (no magnetic fields)
- Can there be similar quantized transport coefficients in different dimensions?

Fermions in a magnetic field (can) have quantized Hall conductivity and viscosity

A couple of questions...

- Can there be quantization if T is not broken? (no magnetic fields)
- Can there be similar quantized transport coefficients in different dimensions?

The answer to both is yes!

Table of topological insulators

Schnyder, Ryu Furusaky, Ludwig 2008-10; Kitaev 2009

Cartan\\d	0	1	2	3	4	5	6	7	8	9	10	11
A	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0
AIII	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$
AI	$\mathbb{Z}$	0	0	0	$2\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0
BDI	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$2\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0
D	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$2\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0
DIII	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$2\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$
AII	$2\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$2\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$
CII	0	$2\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$2\mathbb{Z}$	0	$\mathbb{Z}_2$
C	0	0	$2\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$2\mathbb{Z}$	0
CI	0	0	0	$2\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$2\mathbb{Z}$

- Edge states produce transport
- Protected by topology in momentum space

Integer Hall effect

^{3}He

Cartan\\d	0	1	2	3	4	5	6	7	8	9	10	11
A	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0
AIII	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$	0	$\mathbb{Z}$
AI	$\mathbb{Z}$	0	0	0	$2\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0
BDI	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$2\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0
D	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$2\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0
DIII	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$2\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$
AII	$2\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$2\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$
CII	0	$2\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$2\mathbb{Z}$	0	$\mathbb{Z}_2$
C	0	0	$2\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$2\mathbb{Z}$	0
CI	0	0	0	$2\mathbb{Z}$	0	$\mathbb{Z}_2$	$\mathbb{Z}_2$	$\mathbb{Z}$	0	0	0	$2\mathbb{Z}$

T odd

Topological insulators

σ^{ij}_{IJ}	T even	T odd
P odd	**Spin Hall**	Hall

Predicted in:

- Graphene, '05 (Kane, Mele)
- HgCdTe quantum well structures, '06 (Bernevig, Hughes, Zhang)

Measured in HgCdTe, '07
(König, Wiedmann, Brne, Roth, Buhmann, Molenkamp, Qi, Zhang)

First T-even topological insulator!

T-even topological insulators in D=3+1

(Fu, Kane, Mele, Moore, Balents; Roy '06)

BiSb predicted to be one in '07
(Fu, Kane, Mele)

Edge states observed in BiSb, '08
(Hsieh, Qian, Wray, Xia, Hor, Cava, Hasan)

First D=3+1 topological insulator!

Other materials have also been found

Hall viscosity has not been measured yet

Systems that may have it:

- Fermions in a magnetic field ☀
  (graphene, topological insulators)

- p+ip superfluids (more than one component)
  (alkali gases, ^{3}He, ruthenates,)

☀ It could be measured using inhomogeneous electromagnetic fields (C.H., Son '11)

Holographic models

Hall effect in holography comes in three flavors:

“Dynamical”

“Anomalous”

“Topological”

“Anomalous” Hall Effect

The Hall conductivity is non-zero at B=0

The Hall conductivity in the bulk is non-zero

The dual field theory has Chern-Simons term

- 2+1 D-brane intersections
- AdS_4 or similar with theta term

“Dynamical” Hall Effect

The Hall conductivity is zero at B=0

The Hall conductivity in the bulk is non-zero

- Flavor branes with magnetic fields

O'Bannon '07

- AdS_4 black holes with magnetic charge

Hartnoll, Kovtun '07

“Topological” Hall Effect

The Hall conductivity is non-zero at $B=0$

The Hall conductivity in the bulk is zero

- 1+1 D-brane intersections

One can have a mixture of some of them

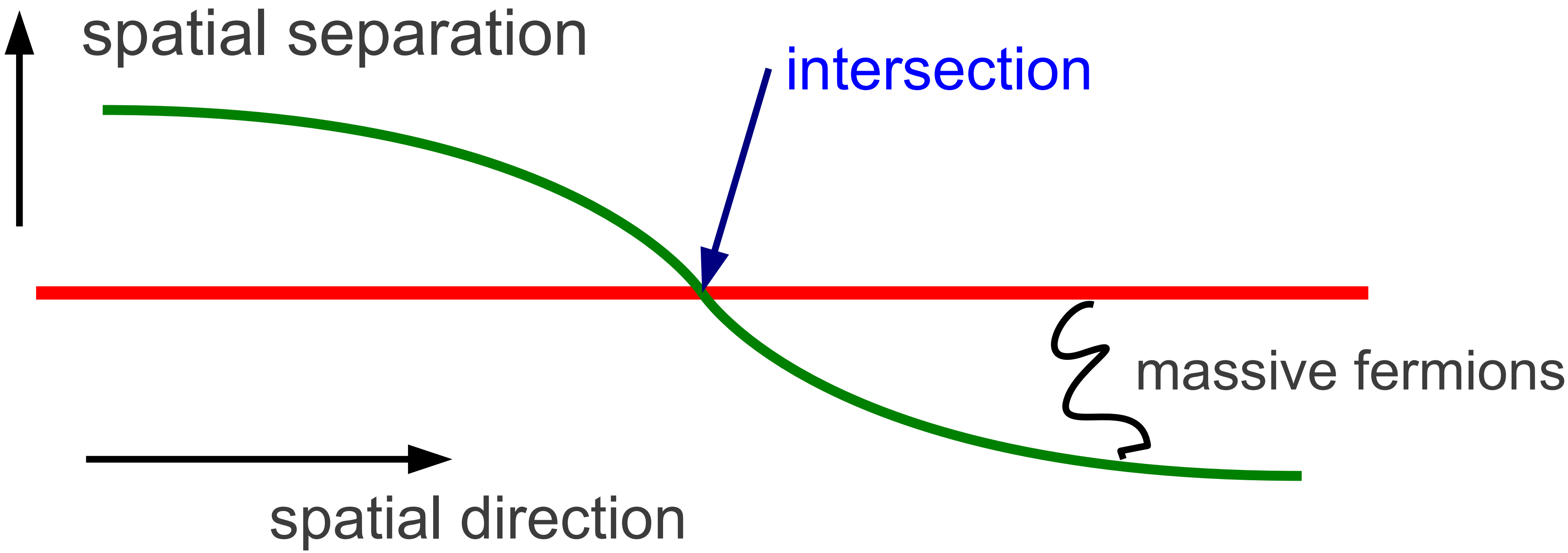
Is this possible?

The Hall conductivity is zero at B=0
The Hall conductivity in the bulk is zero

“Anomalous”

D-brane intersections

- Massive states due to separation between branes
- Massless states at the intersection
- Holographic topological insulators



Example: D3/D7

	0	1	2	3	4	5	6	7	8	9
D3	X	X	X	X						
D7	X	X	X	X		X	X	X	X	

$$S_{D7} \supset \int C_4 \wedge F \wedge F \sim N_c \int \theta(x) F \wedge F$$

At the intersection: $S \simeq N_c \int A \wedge F$

Holographic topological insulators

- Natural extension to holography
  (backreacted geometry + probe branes)

C.H., Jensen, Karch '10; Karch, Maciejko,Takayanagi '10

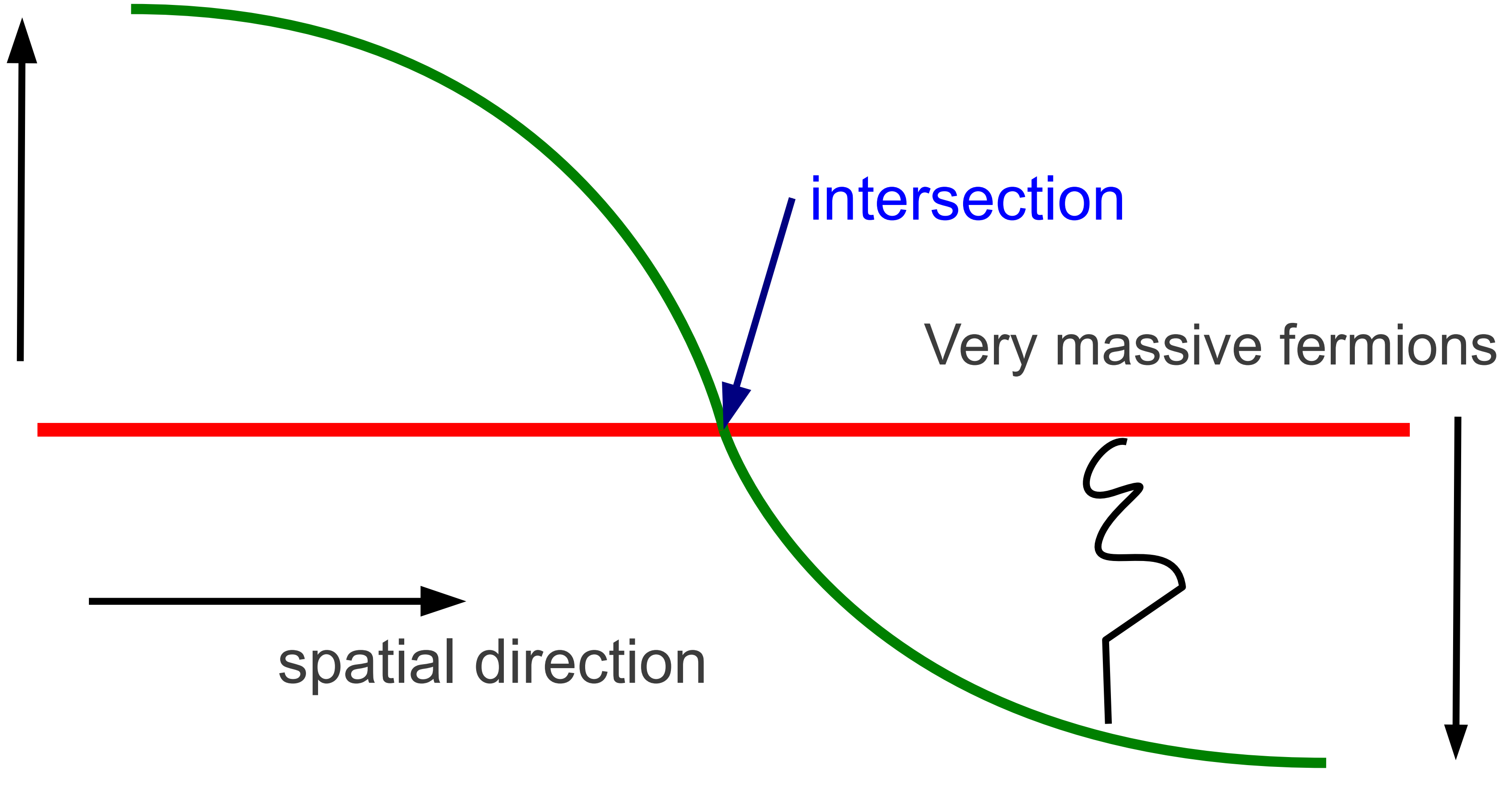
- Fractional effects in non-Abelian gauge theories

- Topological insulators and D-brane configurations related through K-theory
  (Ryu,Takayanagi '10)

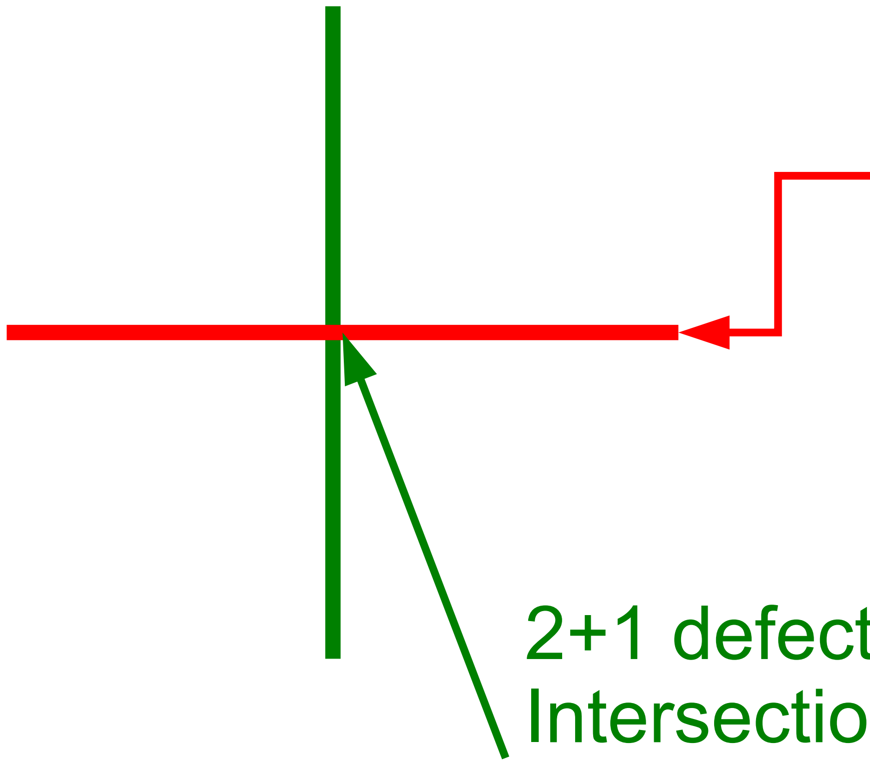
There may be instabilities!

SUSY: Ammon, Gutperle '12

If the separation on both sides is taken to infinity, the massive states disappear from the spectrum and one is left only with the massless states at the intersection



Defects



Bulk theory lives in 3+1 brane (CFT)

2+1 defect:
Intersection with another D-brane
or
Boundary of space

Integer or Fractional Hall effect at the defect

Holographic topological insulators

Class	Bulk dimensions	Intersection	Symmetries
Top. insulator	3+1	D3/D7	T-even
Spin Hall	2+1	D3/D5	T-even
★ D	1+1	D3/D5	C-even
DIII	1+1	D3/D3	T-even C-even

★ Unstable embeddings if there are no additional fluxes

2+1 Defects

	Hall Effect	Hall Effect B=0	Authors
D3/D5	Integer	Yes, axion	Myers, Wapler '08
★ D3/D7	Fractional	Yes, axion (Integer)	Davis, Kraus, Shah; Rey 08 Myers, Wapler '08
D3/D7'	Fractional	Yes, massive fermions ★	Myers, Wapler '08 Bergman, Jokela, Lifschytz, Lippert '10
D2/D8	Integer	Maybe?	Jokela, Jarvinen, Lippert '11

Unstable embeddings

Jokela, Lifschytz , Lippert '12

AdS_4 with theta term

$$S = \int d^4x \, \theta(x) F \wedge F$$

A constant term gives non-zero conductivity

Witten '03

Top-down models: ABJM with flavor

Alanen, Keski-Vakkuri, Kraus, Suus-Uski '09
Hikida, Li, Takayanagi '09

If the axion vanishes at the boundary, the Hall conductivity is proportional to the value of the axion at the horizon

Jensen, Kaminski, Kovtun, Meyer, Ritz, Yarom '11

AdS_4 with theta term

$$S = \int d^4x\, \theta(x) F \wedge F$$

With a dilaton, one can have $SL(2, \mathbb{R})$

acting on $\sigma = \sigma_{xy} + i\sigma_{xx}$

(Interesting for plateau transitions)

Goldstein, Iizuka, Kachru, Prakash, Trivedi, Westphal '10
Bayntun, Burguess, Jolan, Lee '10

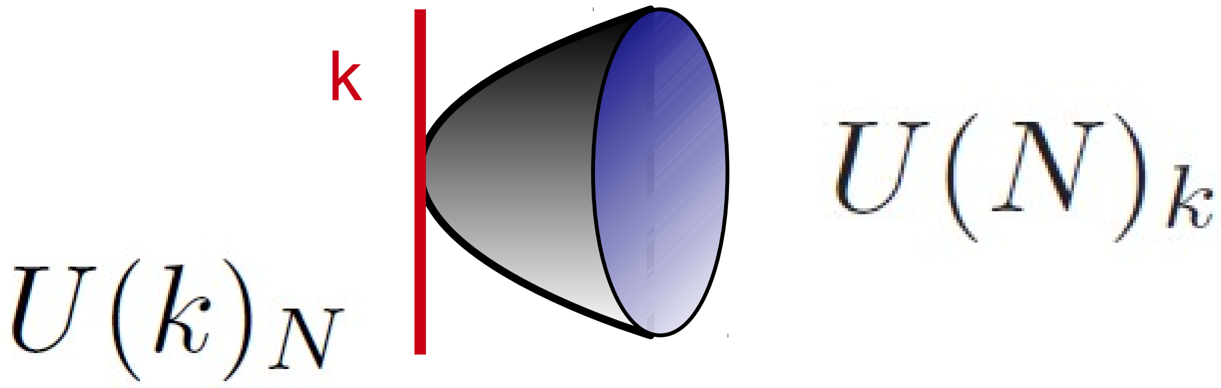
Also S-duality in AdS/BCFT
Fujita, Kaminski, Karch '12

Non-AdS4 model

AdS5 soliton with D7 at the tip

Non-supersymmetric

Fujita, Li, Ryu, Takayanagi '09

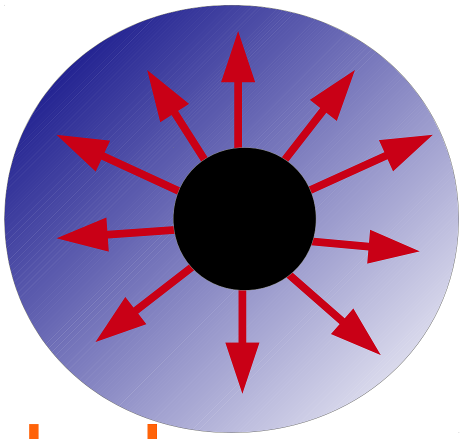


“Dynamical”

AKA Vanilla

AdS_4 dyonic black hole

Hartnoll, Kovtun; Hartnoll, Kovtun, Muller, Sachdev; Hartnoll, Herzog, '07



AdS_4 dyonic/axionic black hole

Goldstein, Iizuka, Kachru, Prakash, Trivedi, Westphal '10
Bayntun, Burguess, Jolan, Lee '10

$$\sigma_{xy} = \frac{n}{B}$$

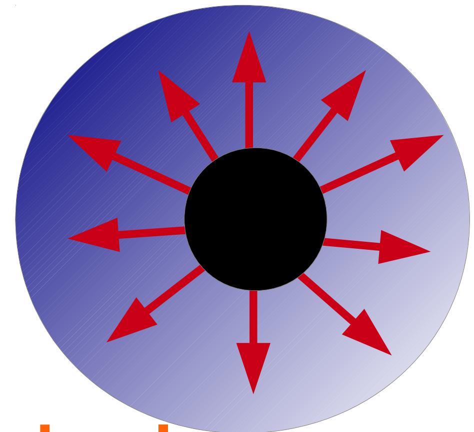
$$SL(2,\mathbb{R})$$

$$\sigma = \sigma_{xy} + i\sigma_{xx}$$

Classical Hall conductivity. Quantization expected

AdS_4 dyonic black hole

Hartnoll, Kovtun; Hartnoll, Kovtun, Muller, Sachdev; Hartnoll, Herzog, '07



AdS_4 dyonic/axionic black hole

Goldstein, Iizuka, Kachru, Prakash, Trivedi, Westphal '10
Bayntun, Burguess, Jolan, Lee '10

- Thermal conductivity
- Thermoelectric conductivity (Nernst coefficient)

$$\frac{\kappa}{\sigma} \propto T$$

Weidemann-Franz law

“Topological”

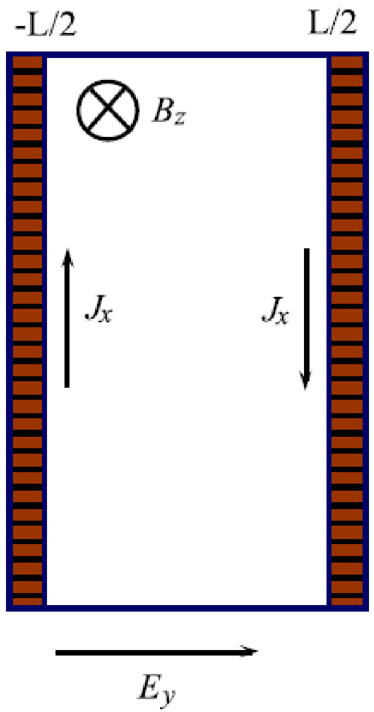
1+1 Defects

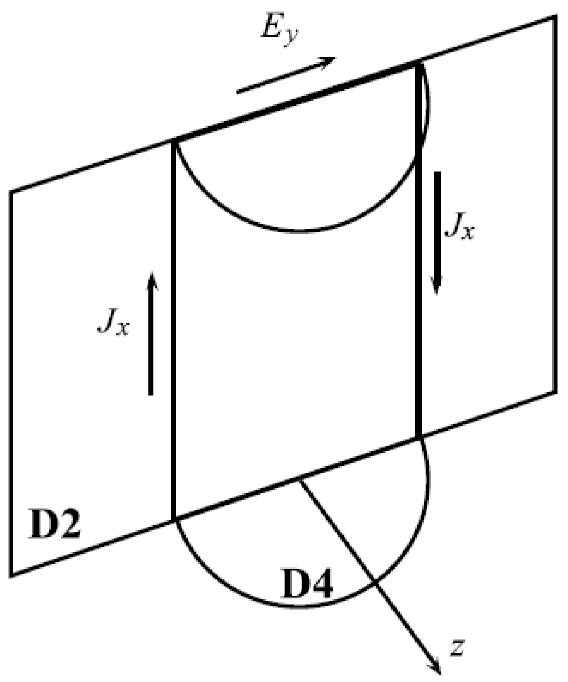
There are no massive modes in the bulk

There are massless states at the defect

The Hall conductivity is determined by the edge states

Example: D4 defect in ABJM





Fujita, Li, Ryu,Takayanagi '09

Generalizations: (D8, M5)

Fujita, Li, Ryu,Takayanagi '09, Fujita '10

Recent progress on odd viscosities

AdS4 black hole

Add new term to the bulk action:

$$S = \int d^4 x a(x) R \wedge R$$

breaking of parity by pseudo-scalar operator

Hall viscosity! $\eta_H \propto \partial_r a(r_H)$

Saremi, Son '11

If no background axion,
correction to viscosity ~q^4

Delsate, Cardoso, Pani '11

Anomalous conductivity + viscosity

$$S = \alpha \int d^4 x a(x) R \wedge R + \beta \int d^4 x a(x) F \wedge F$$

If the axion is zero, no odd transport coefficients, otherwise

- Odd transport coefficients even for B=0
- Non-zero magnetization
- Non-zero angular momentum density
- Hall viscosity vanishes if α =0

Jensen, Kaminski, Kovtun, Meyer, Ritz, Yarom '11
Chen, Dai, Lee, Maity, '12

Fluids with vorticity

- Non-zero vorticity
- P broken
- T broken

$$\zeta_H = \frac{\varepsilon + p}{\Omega}$$

AdS$_4$ rotating black hole
or Taub-NUT

Classical effect: Coriolis analog of Lorentz force

Leigh, Petkou, Petropolous '12

Summary

- Axionic and magnetic fields induce odd transport coefficients, as expected
- Hall effects are also present in the absence of magnetic fields if topological terms are added
- Quantized integer and fractional effects appear naturally in brane constructions
- Hall conductivity is quite generic, Hall viscosity is more picky
- Other odd transport coefficients at finite temperature, thermal conductivity, thermoelectric conductivity

Some related interesting topics

- Phase transitions between Hall plateaus
- Disorder in holography
- Janus/defect solutions in gravity
- Entanglement entropy

Some questions

Puzzling fact: in a simple AdS_4 model
the Hall viscosity is zero unless there is a term like

$$S = \int d^4 x a(x) R \wedge R$$

- Is this generic?
- If so, is this necessary in order to describe fermions in the dual theory?
- Maybe something else in electron stars? Hartnoll '10
- What is the Hall viscosity in D-brane intersections with fermions?

- What is the shift in models with Hall effect?
- Is the shift related to the Hall viscosity as found by Read and Rezayi?
- Are there other topological quantities? (for instance, Berry holonomies)
- S-duality of Hall viscosity? (by Elias)

- Puzzle: Although the R ^ R term is fourth order in derivatives of the metric it contributes to a first order transport coefficient

- Odd transport in superfluids:
  new transport coefficients?

- Magnetohydrodynamics? Buchbinder, Buchel '09

many more...

… but probably I've run out of time already … 

Thank you!