The holographic Weyl semi-metal

Karl Landsteiner

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[K.L., Yan Liu PLB 753, 453, arXiv:1505:04772]
[K.L., Yan Liu, Ya-Wen Sun, PRL 116, 081602, arXiv:1511:05505]

Gauge/gravity workshop, BIRS Banff **29-02**-2016

Outline:

- Weyl semi-metals
- The QFT WSM
- The holographic WSM
- Summary & Outlook

Weyl semi-metals:

Big cond-mat story of 2015 !

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And now, Weyl fermions

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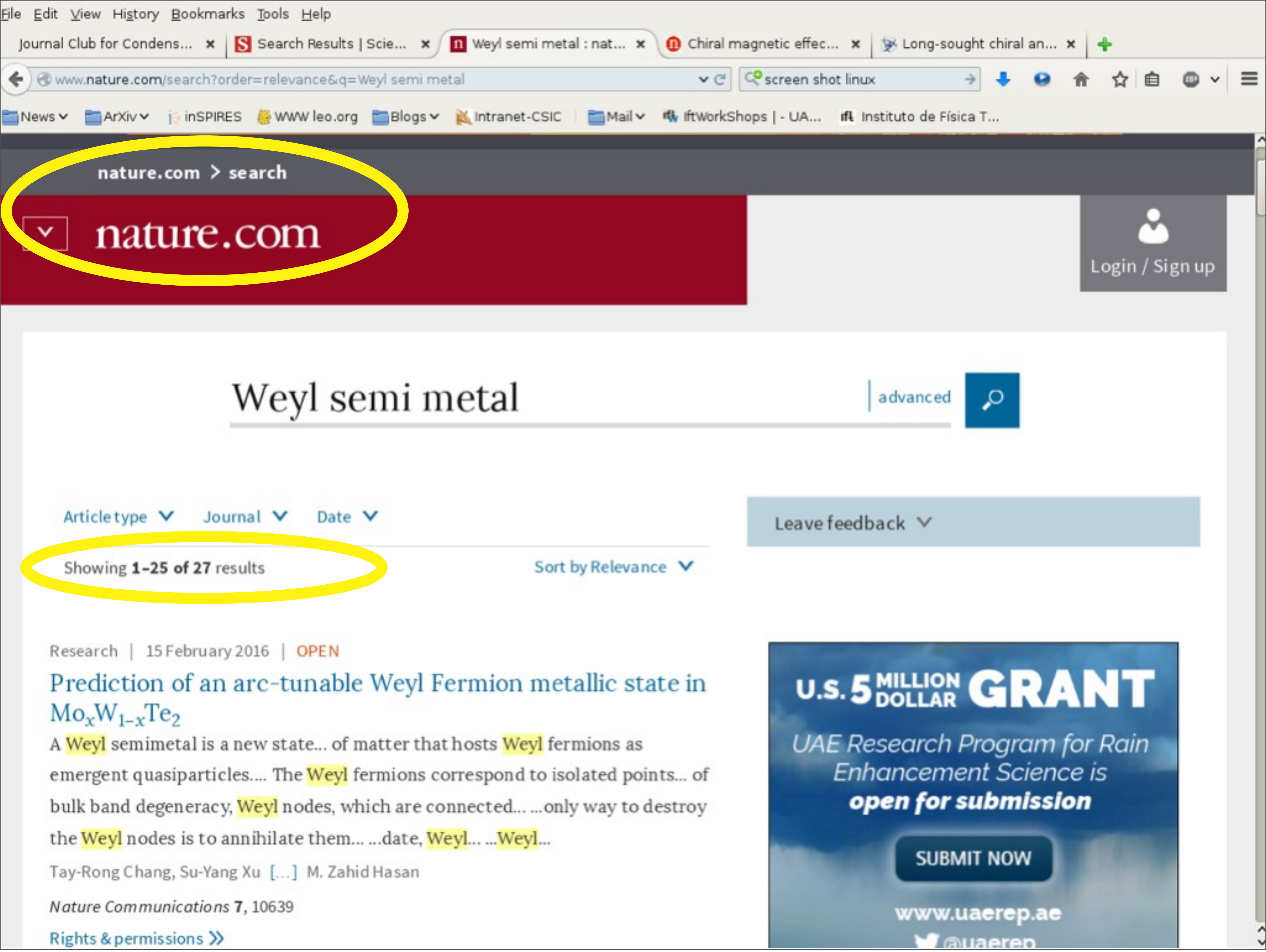

Thursday, March 3, 2016

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NATURE PHYSICS | LETTER

Chiral magnetic effect in $ZrTe_5$

Qiang Li, Dmitri E. Kharzeev, Cheng Zhang, Yuan Huang, I. Pletikosić, A. V. Fedorov, R. D. Zhong, J. A. Schneeloch, G. D. Gu & T. Valla

Affiliations | Contributions | Corresponding authors

Nature Physics (2016) | doi:10.1038/nphys3648

Received 19 December 2014 | Accepted 04 January 2016 | Published online 08 February 2016

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The chiral magnetic effect is the generation of an electric current induced by chirality imbalance in the presence of a magnetic field. It is a macroscopic manifestation of the quantum anomaly[1,2] in relativistic field theory of chiral fermions (massless spin 1/2

Authors with **Loop profiles** beta

Dmitri Kharzeev

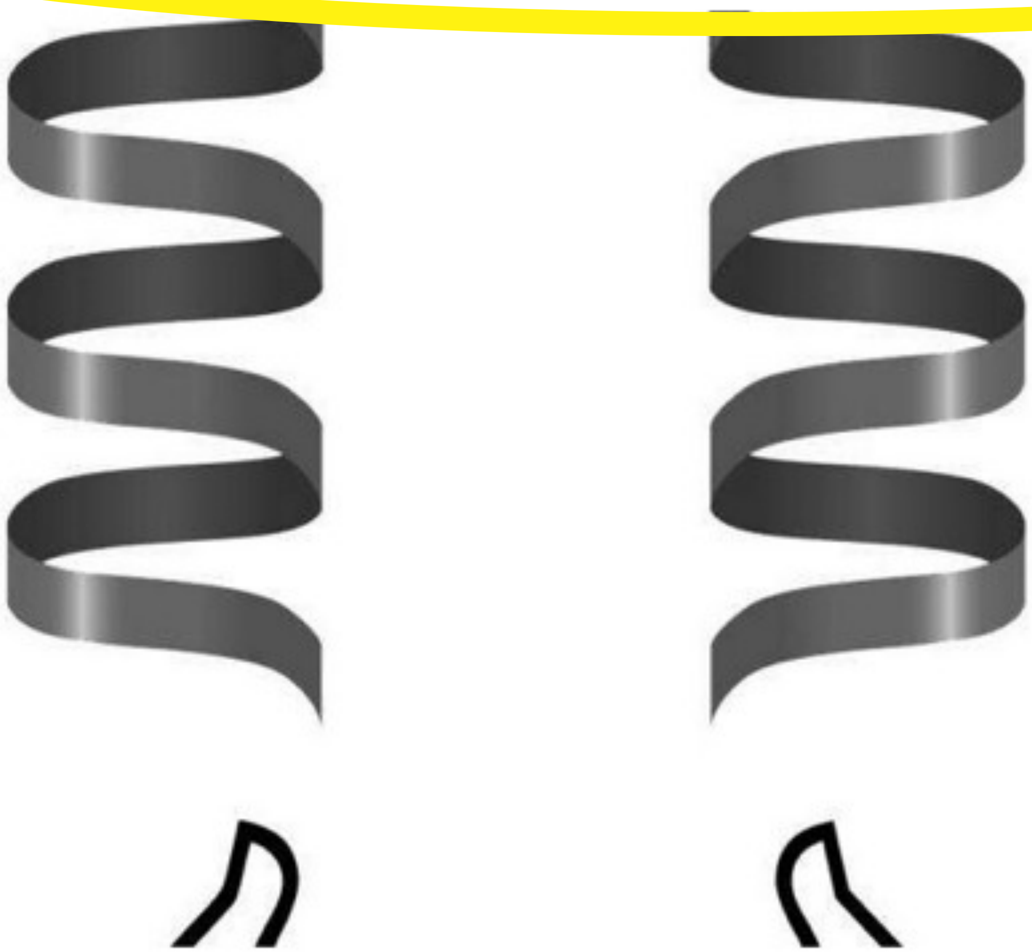
Ivo Pletikosic

More on Lo

Thursday, March 3, 2016

Long-sought chiral anomaly detected in crystalline material

September 3, 2015



This sketch illustrates the notion of handedness, or chirality, which is found throughout nature. Most chemical structures and many elementary particles come in right- and left-handed forms. Credit: Princeton University

A study by Princeton researchers presents evidence for a long-sought phenomenon—first theorized in the 1960s and predicted to be found in crystals in 1983—called the "chiral anomaly" in a metallic compound of sodium and bismuth. The additional finding of an increase in conductivity in the material may suggest ways to improve electrical conductance and minimize energy consumption in future

AdS/CFT

Motto:

"... if the gravitational field didn't exist, one could invent it for the purposes of this paper..."

"Theory of Thermal Transport Coefficients"
Luttinger Phys. Rev. 135, A1505, (1964)

AdS/CFT

"... if string theory didn't exist, one could invent it for the purposes of computing transport coefficients in strongly coupled theories..."

- Shear viscosity in QGP
- Relativistic 2nd oder hydrodynamics
- Relativistic superfluids
- CME + CVE
- Weyl semi-metals

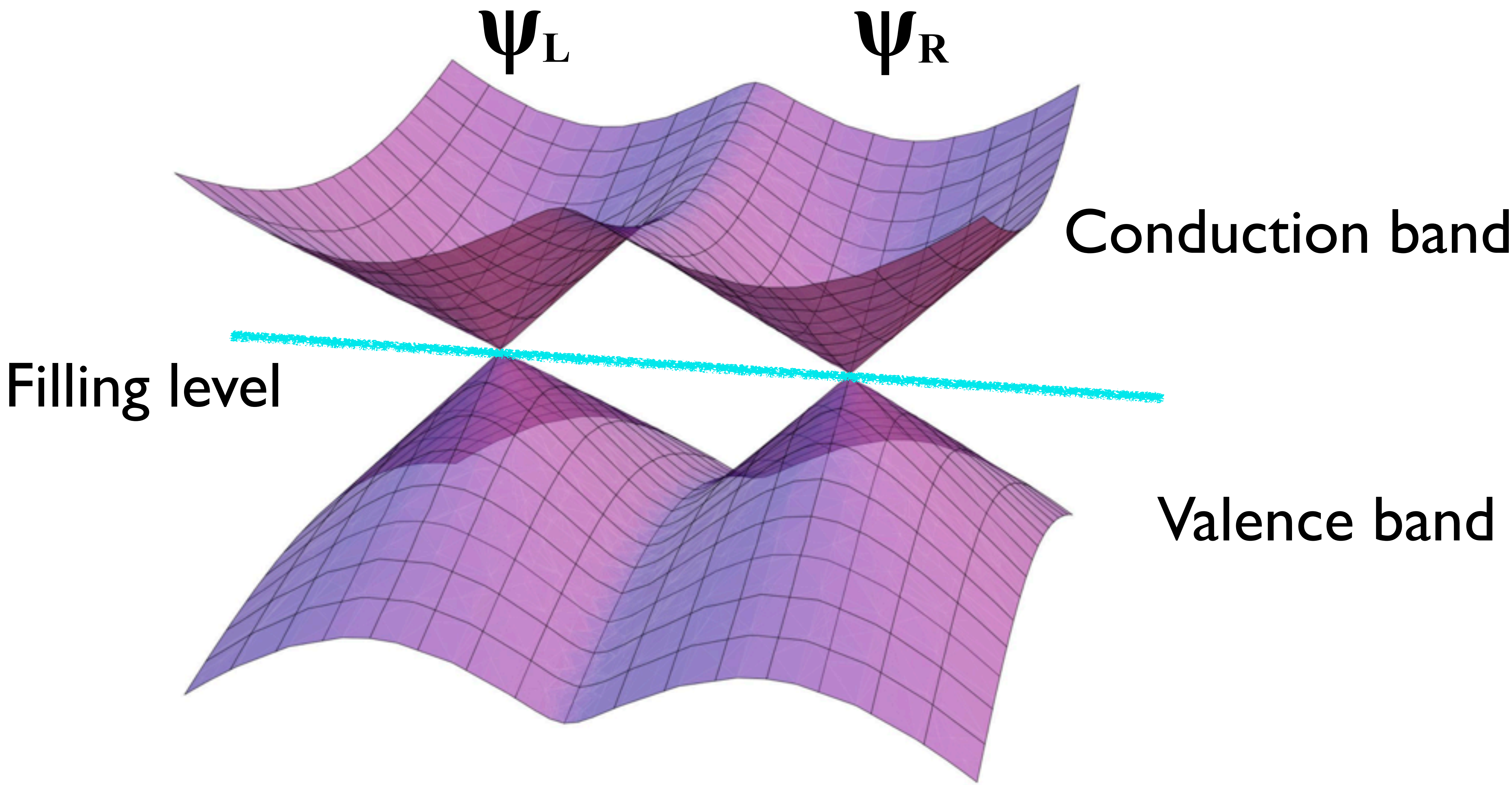
AdS/CMT

in a crystal

in AdS

Weyl semi-metal

Linear band touching



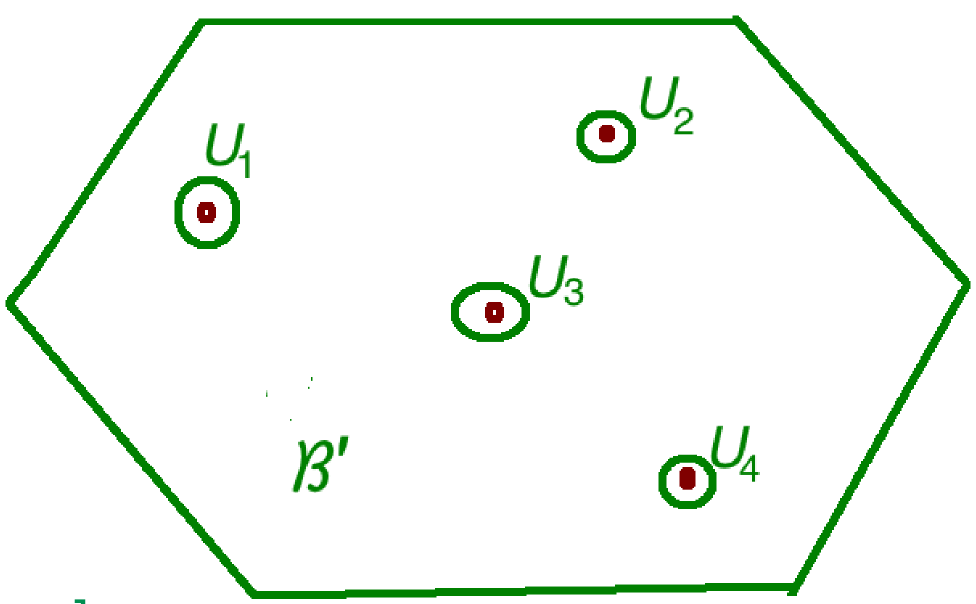
Weyl semi-metal

Topological constraint: Nielsen-Ninomiya theorem

Berry connection $$\mathcal{A} = \langle \psi(k) | \frac{\partial}{\partial k_i} | \psi(k) \rangle dk_i$$

$$\mathcal{F}_B = d\mathcal{A}$$

$$d\mathcal{F}_B = 0$$



[Witten]

$$\int \frac{d\mathcal{F}_B}{2\pi} = \sum_i \oint_{U_i} \frac{\mathcal{F}_B}{2\pi} = 0$$

[Kiritsis]

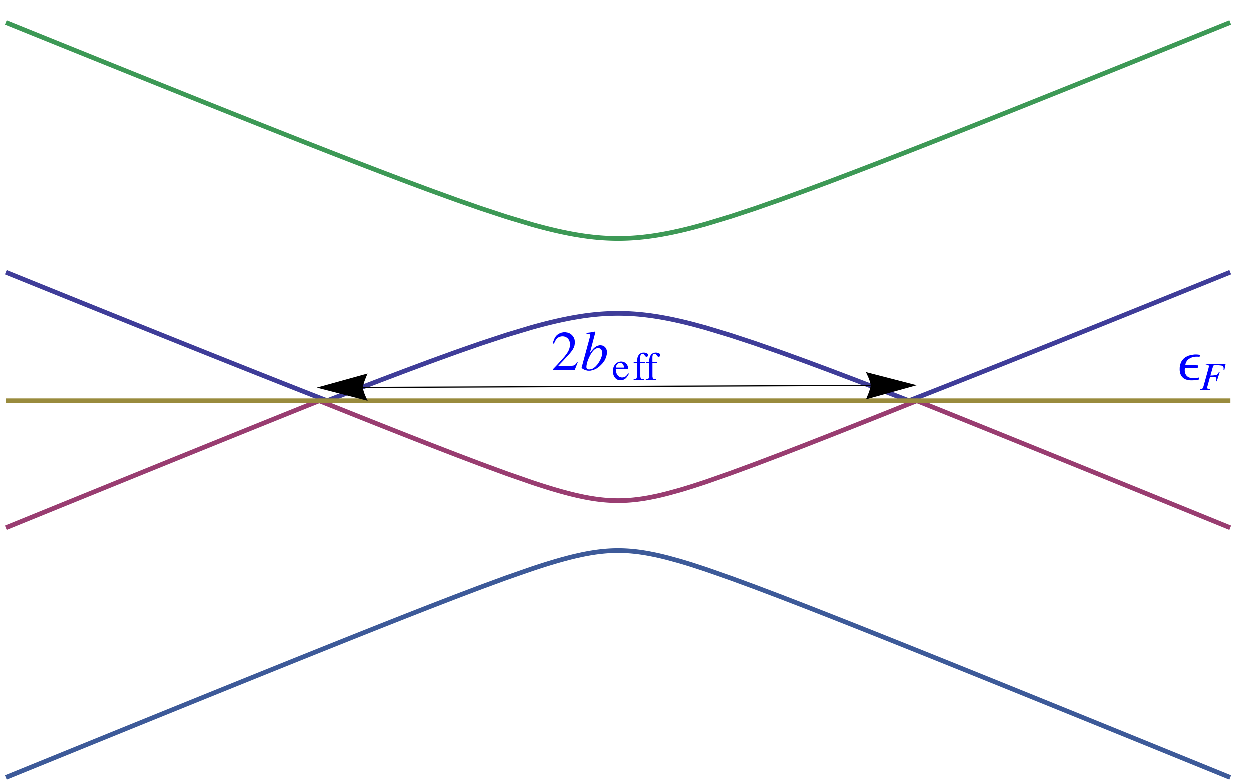
BZ has no boundary !

QFT model

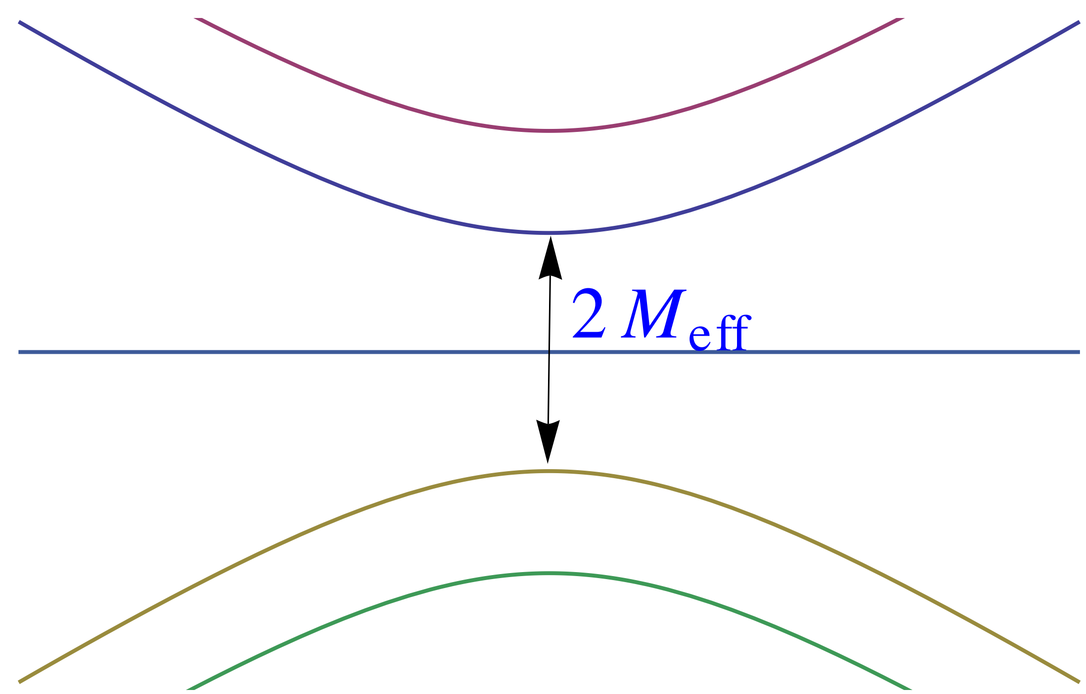
$$\mathcal{L} = \bar{\psi}(i\gamma^\mu \partial_\mu + M + \gamma_5 \gamma_z b)\psi$$

spectrum:

$M < b: \quad b_{\text{eff}} = \sqrt{b^2 - M^2}$



$M > b: \quad M_{\text{eff}} = \sqrt{M^2 - b^2}$



QFT model

$M < b: \quad b_{\rm eff} = \sqrt{b^2 - M^2}$ $\quad \mathcal{L}_{\rm eff} = \bar{\psi}(i\gamma^\mu \partial_\mu + \gamma_5 \gamma_z b_{\rm eff})\psi$

constant gauge field $\quad b_{\rm eff} = A^5_z$

axial gauge trafo $\quad \theta_5 = b_{\rm eff}\, z$

axial anomaly $\quad \Gamma = \int d^4x \theta_5 F \wedge F$

electric current $\quad J^\mu = \dfrac{\delta \Gamma}{\delta A_\mu}$

AHE

[Haldane]

$$\vec{J} = \frac{1}{2\pi^2} \vec{b}_{\rm eff} \times \vec{E}$$

"order parameter" for topological semi-metal state

QFT model

$M > b:$ $M_{\text{eff}} = \sqrt{M^2 - b^2}$ $\mathcal{L}_{\text{eff}} = \bar{\psi}(i\gamma^\mu \partial_\mu + M_{\text{eff}})\psi$

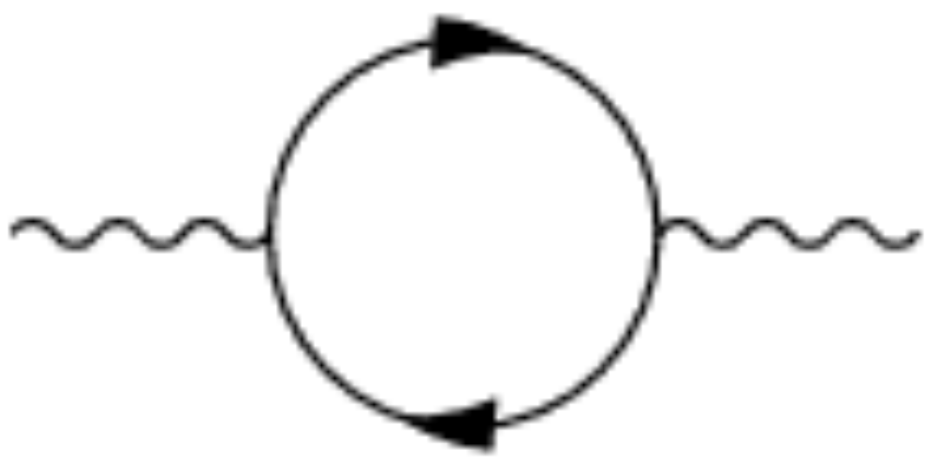
gapped phase $b_{eff} = 0$

More generally: more Dirac cones could be present that are inert: topologically trivial semi-metal

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu \partial_\mu + M + \gamma_5 \gamma_z b)\psi + \sum_{j=1}^{N} \bar{\psi}(i\gamma^\mu \partial_\mu)\psi$$

QFT model

Instead of constructing effective low energy theory: compute AHE directly in UV model

odd part of  $= \text{undetermined}$

[Jackiw: "When radiative corrections are finite but undetermined" hep-th/9903044]

however:

$$\partial_\mu J^\mu_5 = \frac{1}{48\pi^2}(F_5 \wedge F_5 + 3\mathcal{F} \wedge \mathcal{F}) - i2M\bar{\Psi}\gamma_5\Psi$$

$$\partial_\mu J^\mu = 0$$

fixes the result!

The holographic WSM

Why wanno do this? WSM is weakly coupled !

Motivation:

- Weakly coupled up to now
- How does WSM work without quasiparticles
- How does WSM work without notion of Berry phase
- Anomalous transport in holography
- Transport in general is easy in holography
- Holography can teach interesting qualitative lessens
- its fun ..

[Jacobs, Stoof, Vandoren] [Gursoy Jacobs, Plauschin, Stoof, Vandoren]

The holographic WSM

Minimal ingredients

- One AdS gauge field for electric current
- One AdS gauge field for axial current
- One scalar field charged under axial symmetry
- Boundary Value of charged scalar = Mass M
- Boundary Value of axial gauge field = b
- Metric to get the dynamics

Action of HoloWSM

$$\mathcal{L} = \frac{1}{2\kappa^2}(R+12) - \frac{1}{4}\mathcal{F}^2 - \frac{1}{4}F_5^2 +$$
$$+ \frac{\alpha}{3}A_5 \wedge (F_5 \wedge F_5 + 3\mathcal{F}\wedge\mathcal{F}) +$$
$$+ |(\partial_\mu + iqA_\mu^5)\Phi|^2 - V(\Phi)$$

- Cosmological constant = AdS
- Very specific CS term = form of Anomaly
- Scalar potential determines dimension of dual scalar operator (we chose dim=3) i.e. mass deformation

Holographic WSM

Currents:

$$J^\mu = \lim_{r\to\infty} \sqrt{-g}\left(\mathcal{F}^{\mu r} + 4\alpha\epsilon^{r\mu\nu\rho\lambda}A^5_\beta \mathcal{F}_{\rho\sigma}\right)$$

$$J^\mu_5 = \lim_{r\to\infty} \sqrt{-g}\left(F_5^{\mu r} + \frac{4\alpha}{3}\epsilon^{r\mu\nu\rho\lambda}A^5_\beta F^5_{\rho\sigma}\right)$$

Note contribution from CS term: consistent currents

Anomalies:

$$\partial_\mu J^\mu = 0$$

$$\partial_\mu J^\mu_5 = \frac{\alpha}{3}(F_5\wedge F_5 + 3\mathcal{F}\wedge\mathcal{F} - iq\sqrt{-g}[\Phi(D_r\Phi^*) - \Phi^*(D_r\Phi)]|_{r=\infty}$$

Holographic WSM

Couplings = Boundary conditions:

Metric: $$ds^2|_{r\to\infty} = \frac{dr^2}{r^2} + r^2(-dt^2 + d\vec{x}^2)$$

"electric" gauge field: $$A_\mu|_{r\to\infty} = 0$$

axial gauge field: $$A^5_\mu|_{r\to\infty} = b\hat{e}^z_\mu$$

scalar field: $$r\Phi|_{r\to\infty} = M$$

Holographic WSM

Solving the eoms with above boundary conditions and we find 3 distinct classes of solutions

- Topological phase: M<0.744b $A_z^5(0) = b_{\text{eff}}$ $\Phi(0) = 0$

- Critical point: M=0.744b $A_z^5 = r^\beta$ $\phi(0) = \phi_0$

$$ds^2 = u_0 r^2(-dt^2 + dx^2 + dy^2) + h_1 r^{2\beta} dz^2 + \frac{dr^2}{u_0 r^2}$$

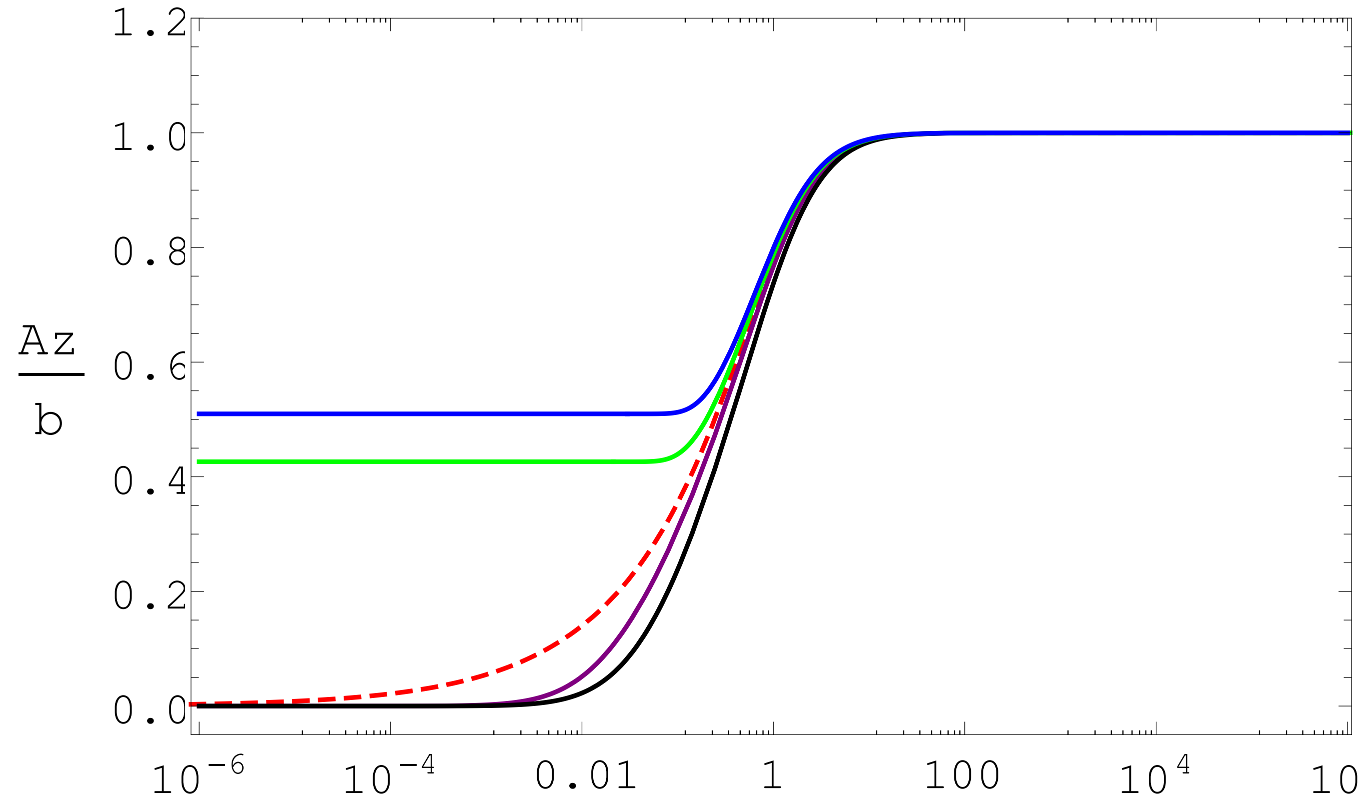
$\beta \approx 0.4\ ,\ u_0 \approx 1.47$

- Trivial phase: M>0.744b $A_z^5(0) = 0$ $\phi(0) = \phi_{\text{min}}$

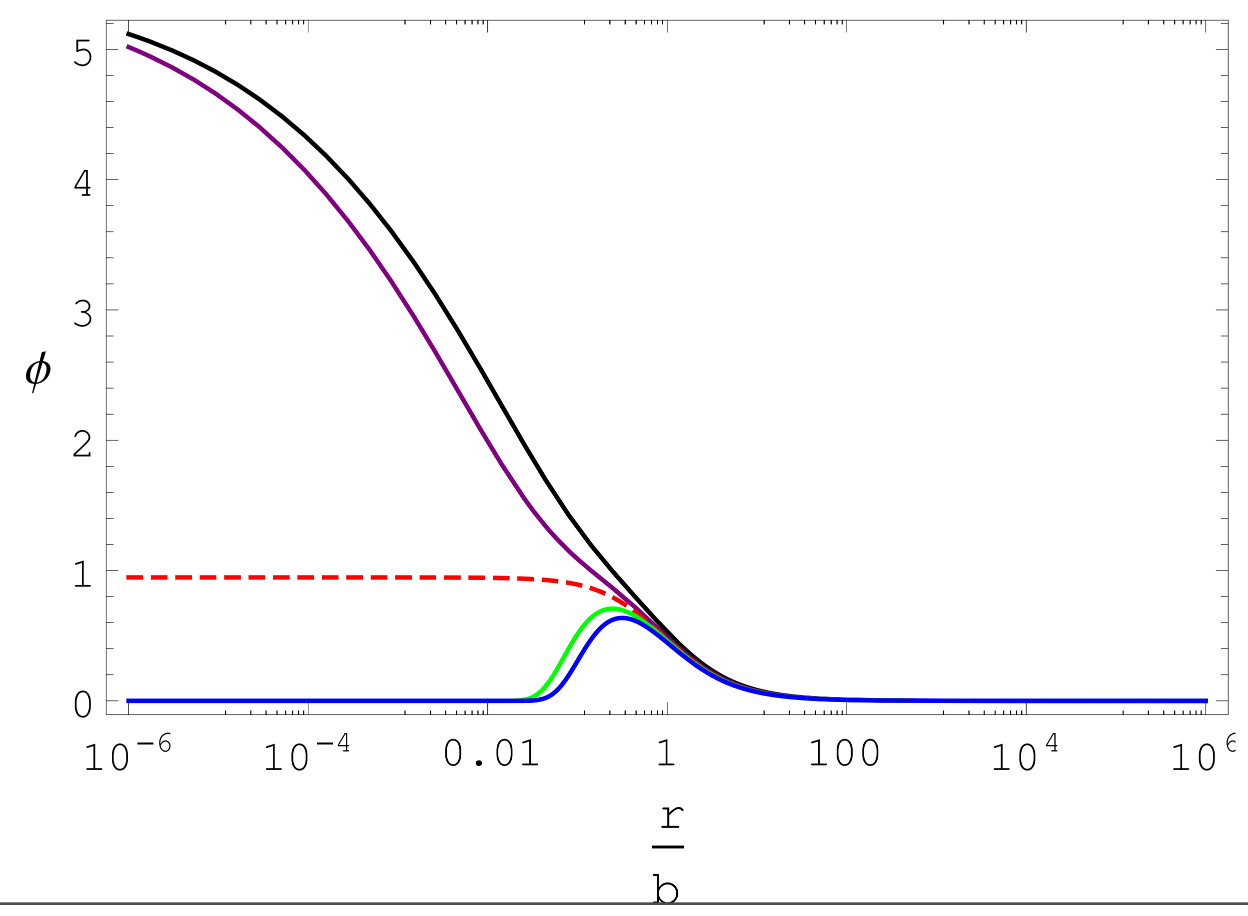
$$\frac{dV}{d\Phi}(\phi_{\text{min}}) = 0$$

Holographic WSM

Running of axial gauge field:



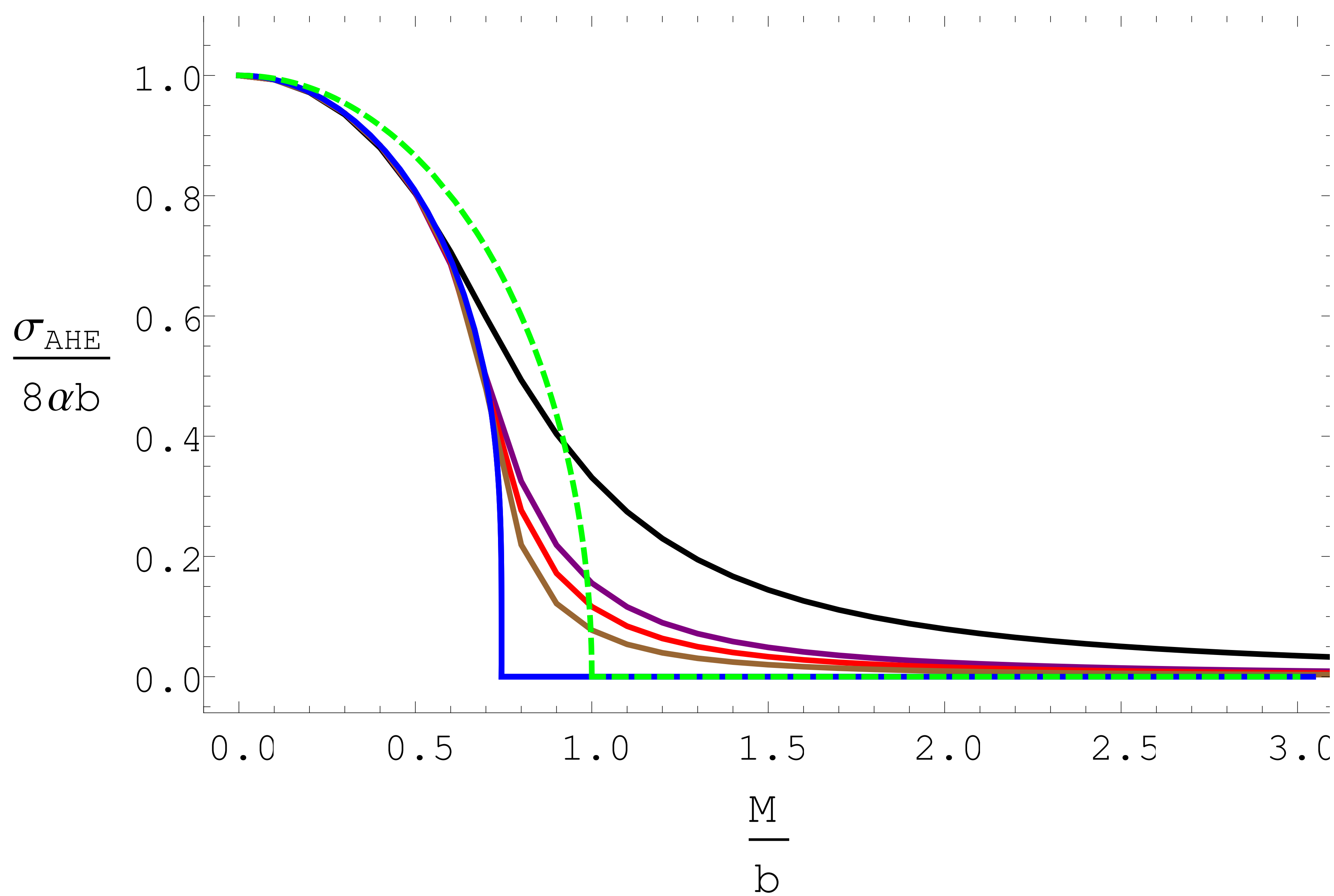
Running of scalar field:



Holographic WSM

Smoking gun of topological state of matter : AHE

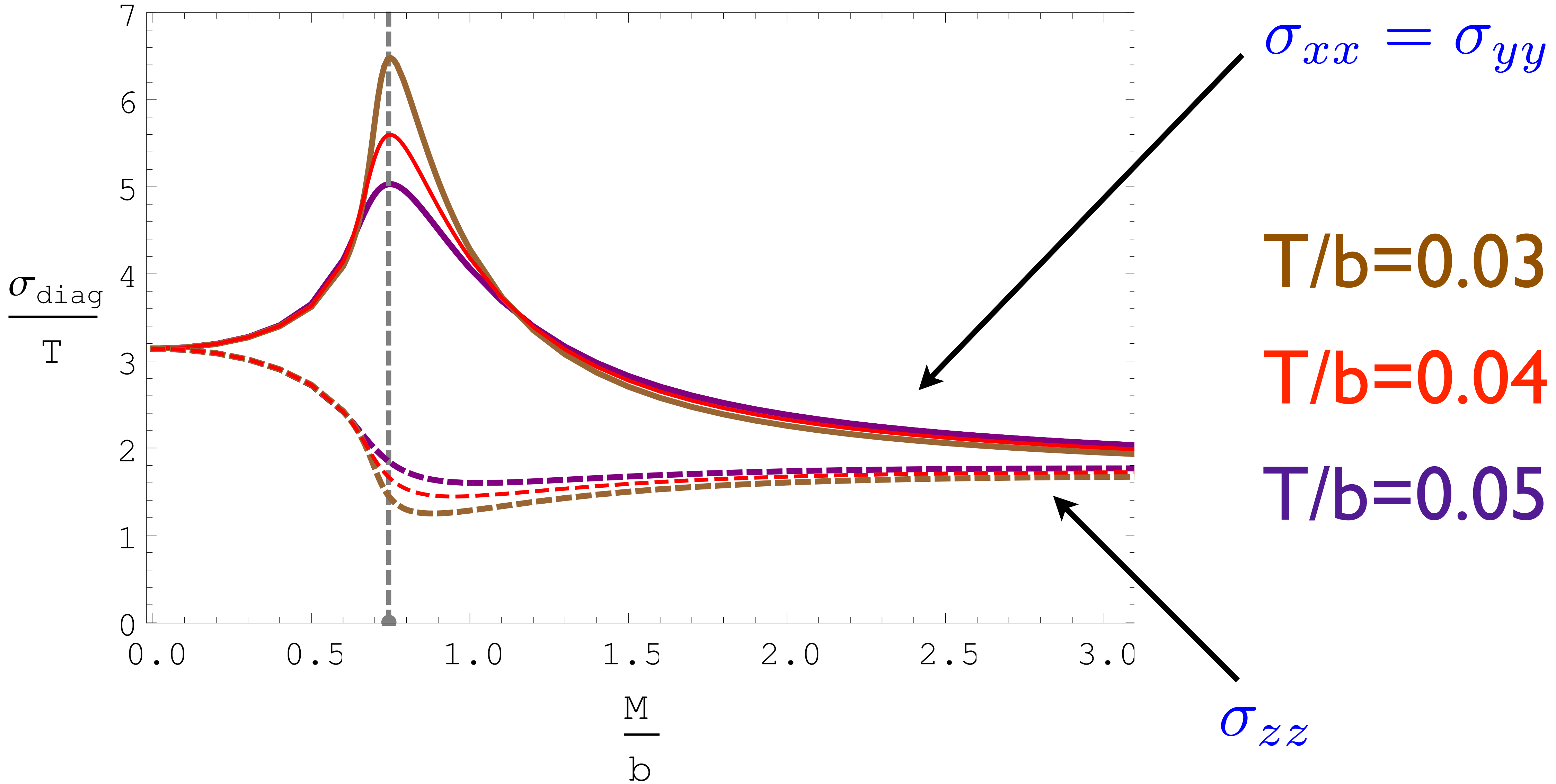
$$\sigma_{xy} = 8\alpha A_z^5(0)$$



Holographic WSM

Diagonal conductivities at T=0: $\sigma_{xx} = \sigma_{yy} = \sigma_{zz} = 0$

Diagonal conductivities at T>0:



Summary

- Holographic model with topological quantum phase transition
- Order parameter = AHE
- RG flow interpretation
- Correct anomaly structure is important
- Axial symmetry is broken by mass term (intervalley coupling)
- Diagonal conductivities vanish at T=0
- For T>0 anisotropic conductivities with peak/dip at $(M/b)_c$

Outlook

- Beyond AHE study CME, CSE, AME, NMR CMV, ...
- Beyond conductivities study viscosities
- Different forms of potentials (bulk scalar mass)
- Intervalley scattering rates
- Disorder
- Holographic Fermi arcs
- ....

Outlook

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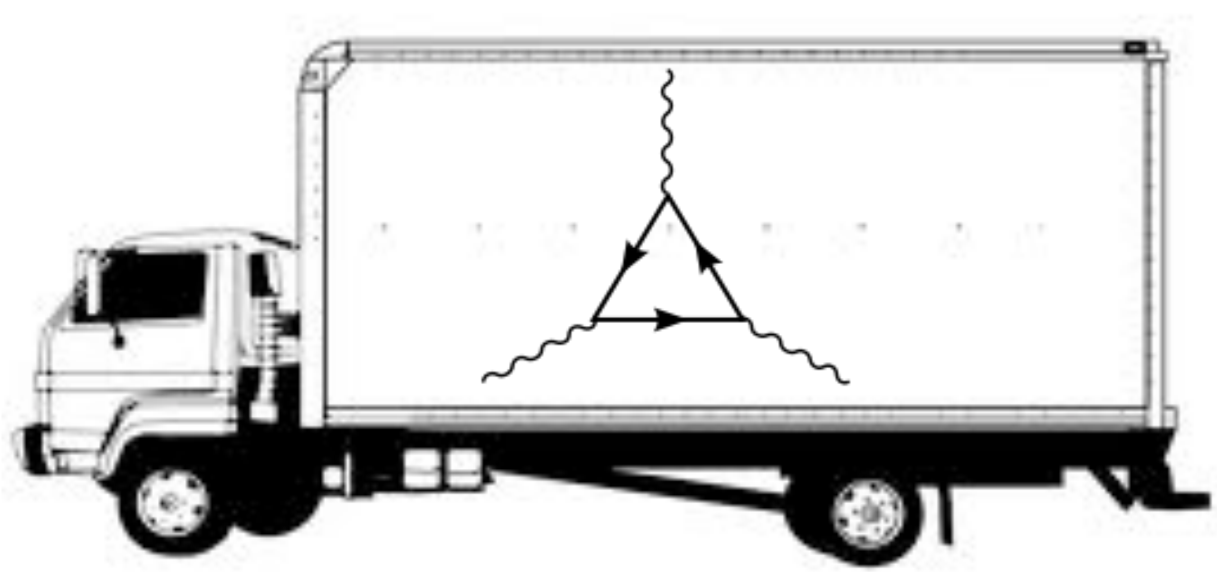

Thank You!