RHIC & AGS Annual Users' Meeting, BNL, June 9-12, 2015

Quantum Fluids: the XXI century hydrodynamics

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Outline

1. Hydrodynamics:

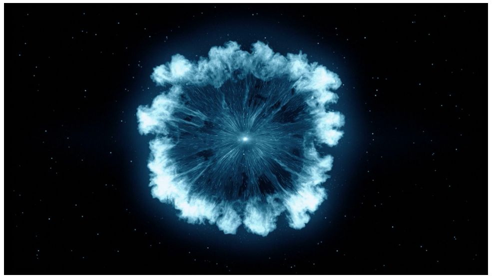
   the low-energy Theory of Everything

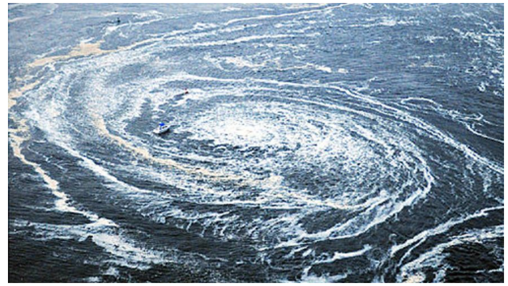
2. The XXI century hydrodynamics motivated by RHIC:

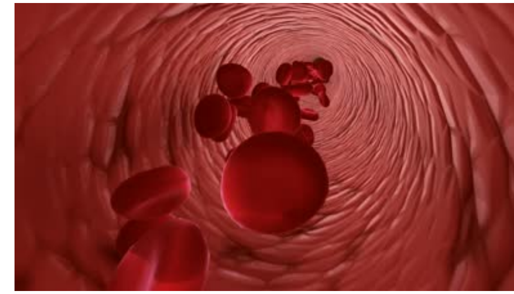
   a) quantum bounds on "conventional"
      transport coefficients
   b) new transport phenomena of entirely
      quantum origin

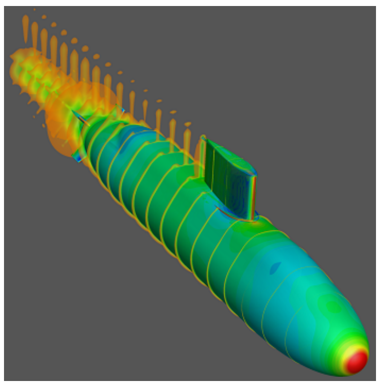
3. The future of hydrodynamics and BNL experiments

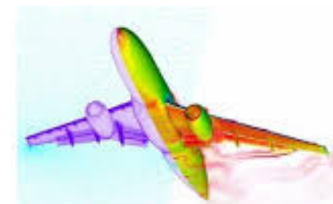
The many facets of fluid mechanics

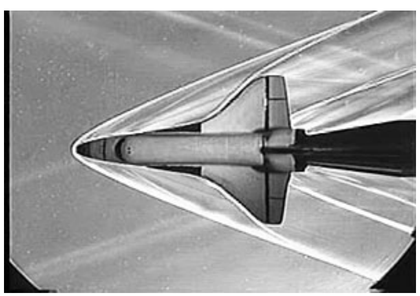


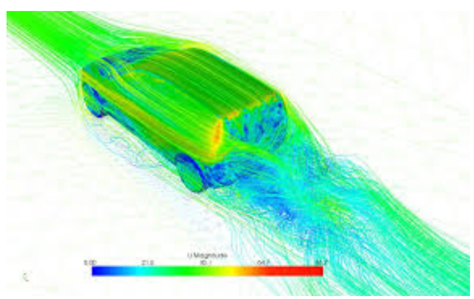


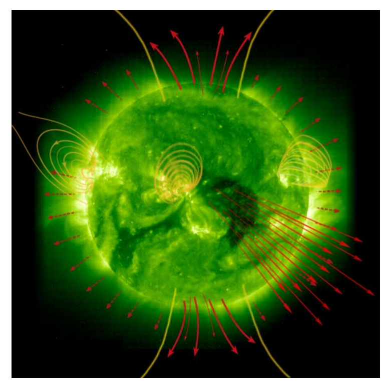


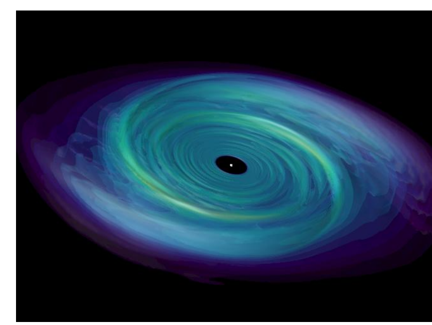


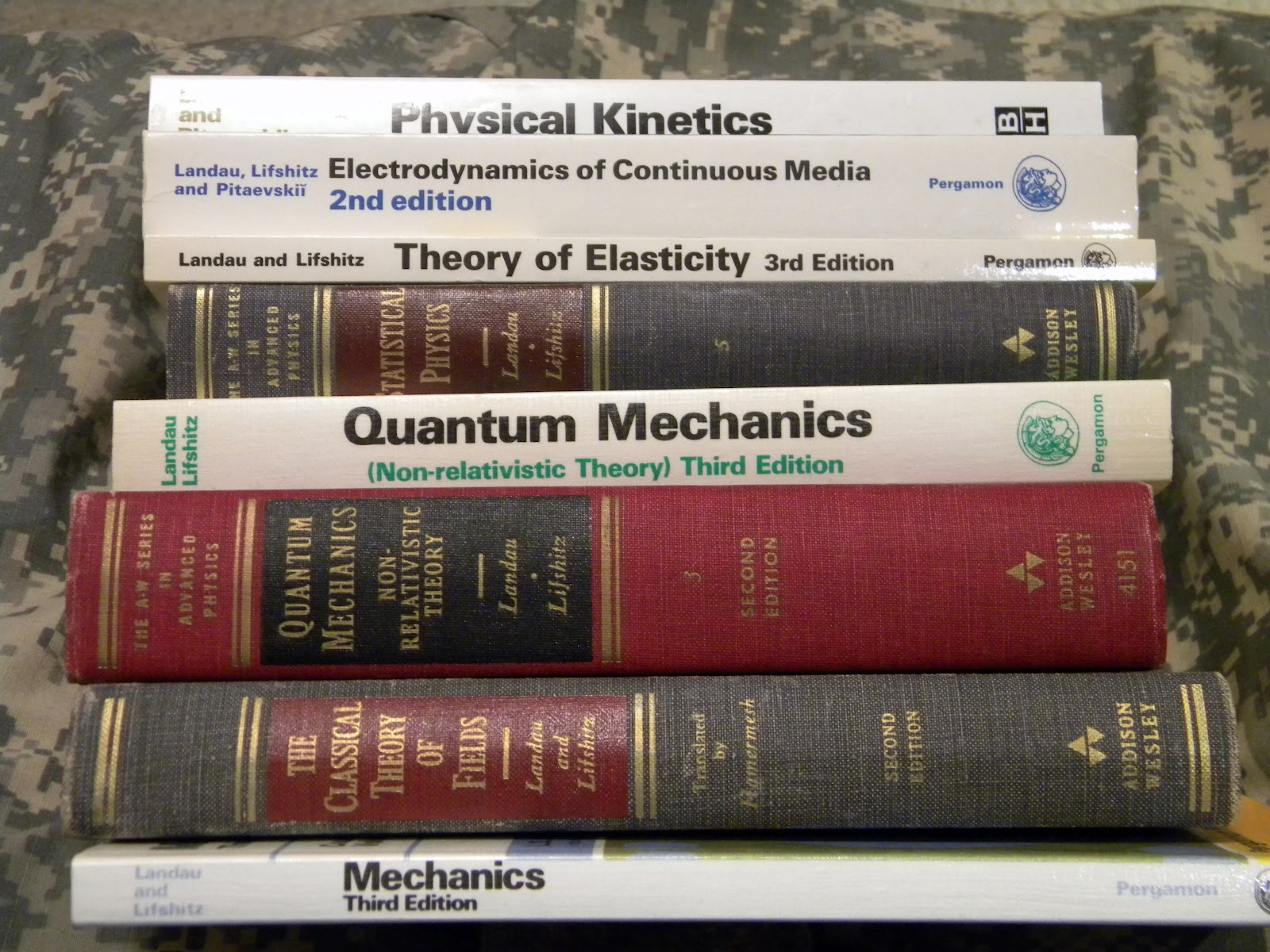








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Physical Kinetics
BH
Landau, Lifshitz
and Pitaevskiĭ
Electrodynamics of Continuous Media
2nd edition
Pergamon
Landau and Lifshitz
Theory of Elasticity
3rd Edition
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Quantum Mechanics
(Non-relativistic Theory) Third Edition
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Landau and Lifshitz
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and
Lifshitz
Mechanics
Third Edition
Pergamon

Hydrodynamics and experiment

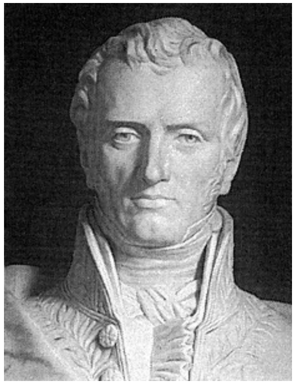
L.D.Landau and E.M.Lifshitz, Preface to the “Mechanics of continuous media”, Moscow, 1952:

“…The equations of hydrodynamics are nonlinear, and their direct solutions can be found only in a limited number of cases. Because of this, the **development of modern hydrodynamics is possible only in a close connection with experiment**.”

“…here we discuss neither approximate methods of calculation in fluid mechanics, nor empirical theories devoid of physical significance…”

“…the equations of relativistic hydrodynamics find a new use in the description of **multiparticle production in collisions**…”

XIX century hydrodynamics: Navier-Stokes and viscosity



Claude-Louis Navier
1785-1836

$$\underbrace{\rho\,(\frac{\partial \vec{u}}{\partial t} + \vec{u}\cdot\nabla\vec{u})}_{\text{Acceleration}} = \underbrace{-\nabla p}_{\text{Pressure}} + \underbrace{\nu\,\Delta\vec{u}}_{\text{Viscosity}}$$

$$\underbrace{\nabla\cdot\vec{u} = 0}_{\text{Continuity Equation}}$$

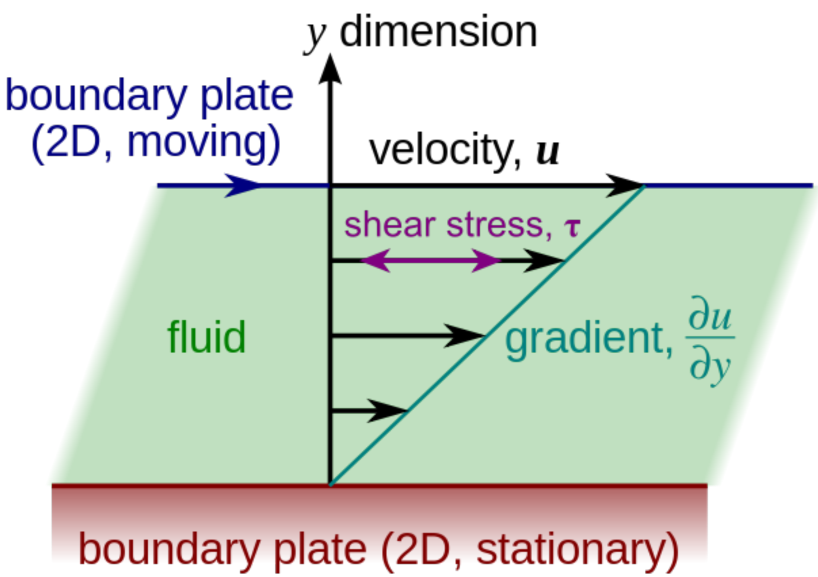
Sir George Stokes
1819-1903

Clay Mathematics Institute
Millenium Prize problems

Prove or give a counter-example of the following statement:
In three space dimensions and time, given an initial velocity field, there exists a vector velocity and a scalar pressure field, which are both smooth and globally defined, that solve the **Navier–Stokes equations**.

This problem is: Unsolved

Viscosity: how to measure it?



"Couette flow": laminar shear of fluid between a stationary and a moving plate

A – area of the plate
y – distance between the plates
u – velocity of the moving plate

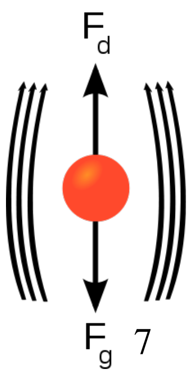
The force needed to move the plate is

$$F = \eta \ A \ \frac{u}{y}$$

Shear (dynamic) viscosity

A different viscometer: falling particle of radius R. Stokes force: "creeping flow" solution of Navier-Stokes:

$$F = 6\pi \ R \ \eta \ v$$



Drag due to shear viscosity: the terminal velocity

Terminal speed for skydivers
in free-fall position:
195 km/h

Head-down position
(reduce R):
530 km/h

World record:
F. Baumgartner, 2012

Height = 39 km (stratosphere)
Terminal speed = 1358 km/h

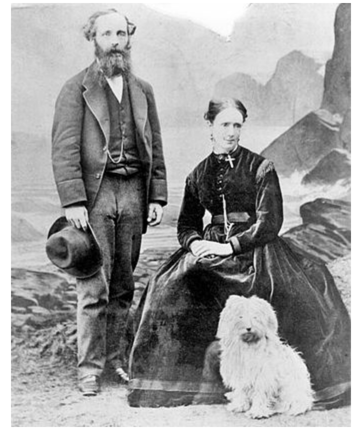
Fluid mechanics, XIX century

Maxwell's experiment, 1865

Maxwell's estimate of viscosity:

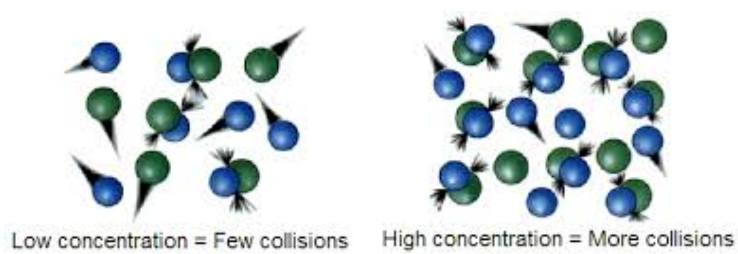
$$\eta \sim \rho \, v \, \lambda$$

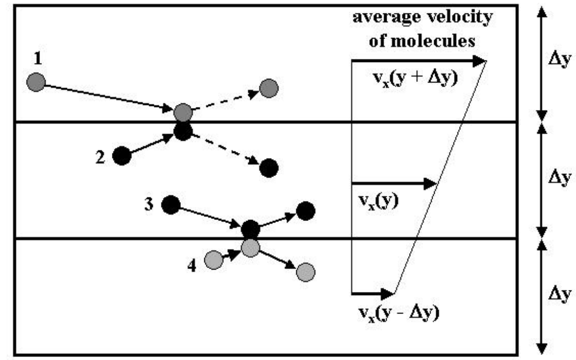
mass density x velocity x mean free path



independent of density! $\lambda \sim 1/(\sigma \rho)$

As the strength of the interactions grows, **is there a lower bound on viscosity?**

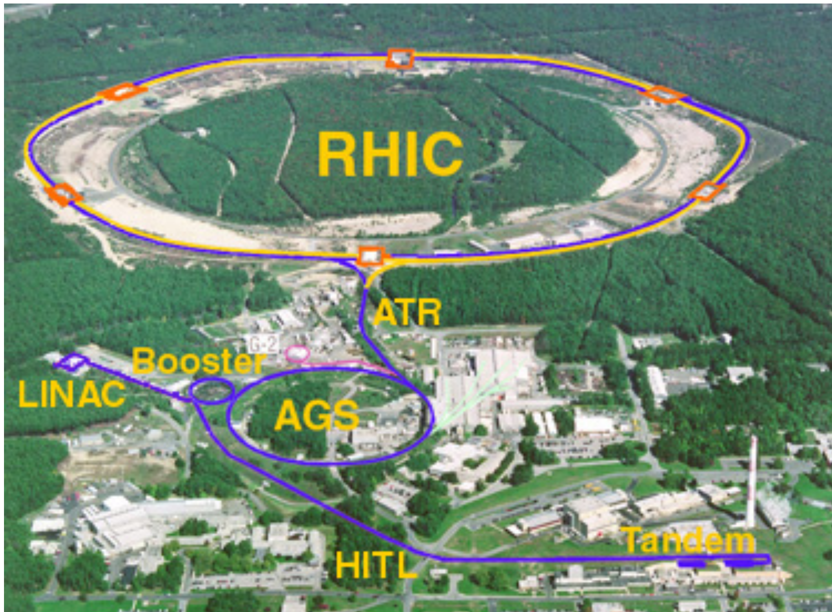




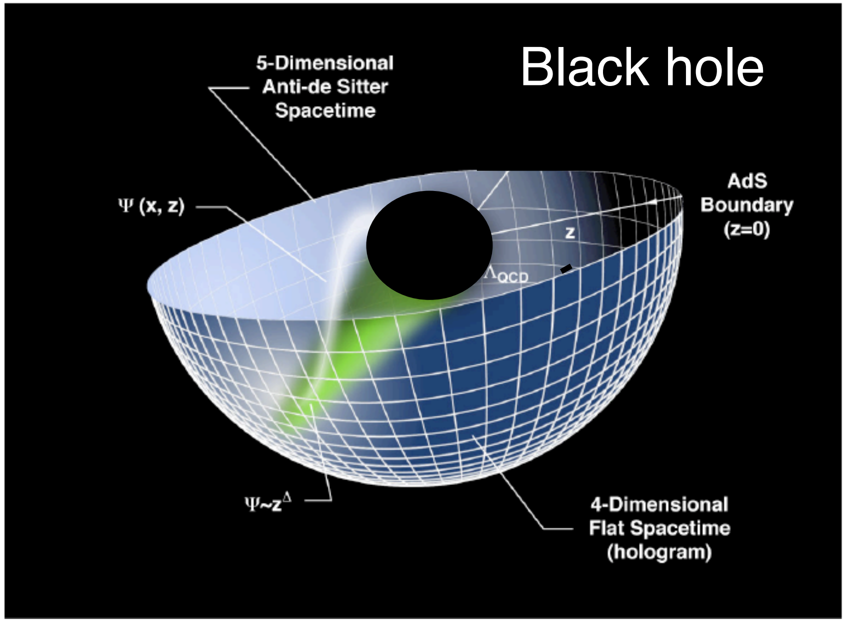
"Such a consequence of the mathematical theory is very startling and the only experiment I have met with on the subject does not seem to confirm it."

Maxwell, 1860

Fluid mechanics, XXI century



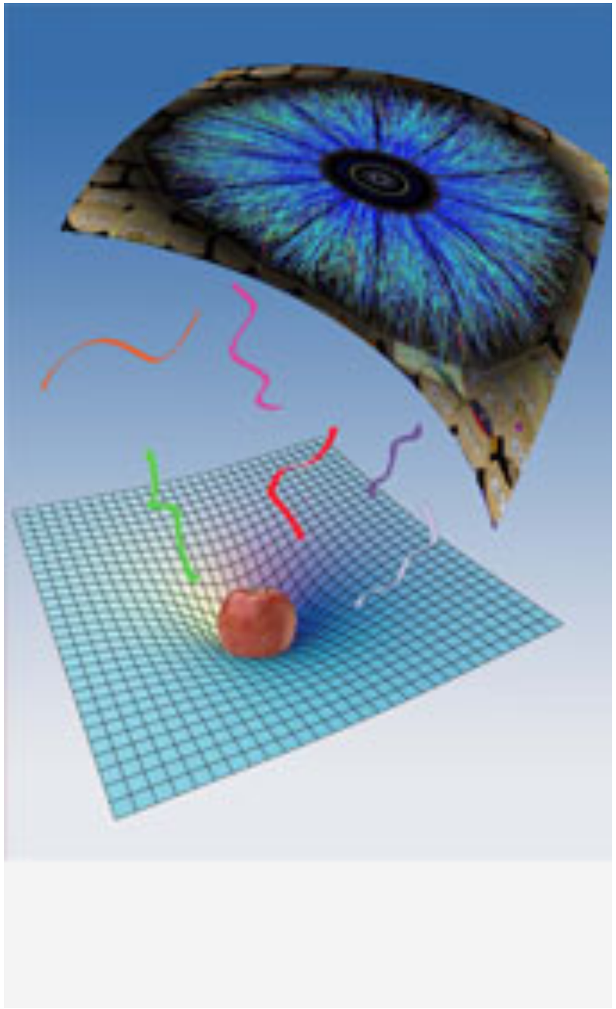
RHIC, ca AD 2000



The strong interaction limit: holography

Fluids and horizons: correspondence between Navier-Stokes equation in D dimensions and near-horizon Einstein equation in D+1 dimensions

"Measuring" viscosity through response to gravitational waves

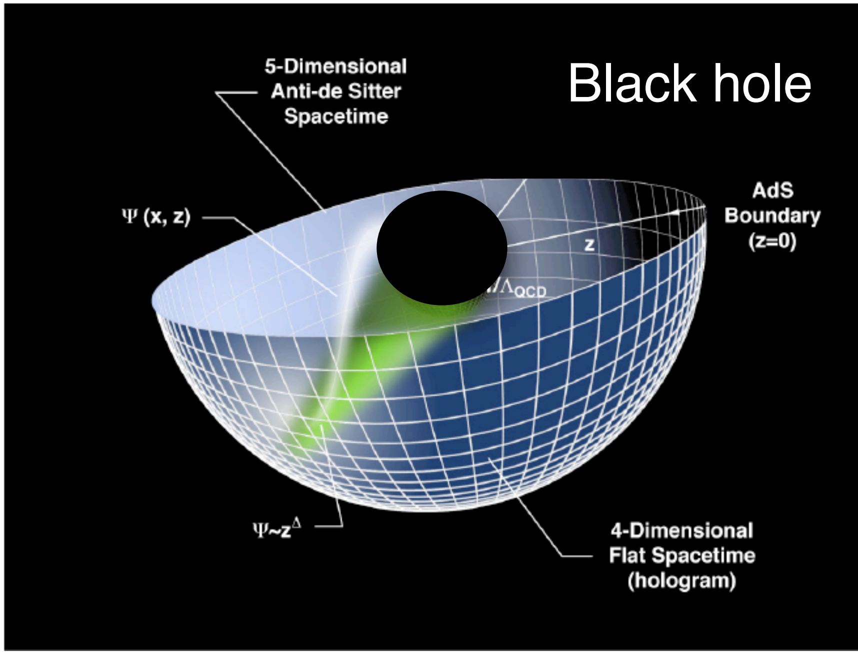


$$G^R_{xy,xy}(\omega,\mathbf{0}) = \int dt\, d\mathbf{x}\, e^{i\omega t}\theta(t)\langle[T_{xy}(t,\mathbf{x}),\, T_{xy}(0,\mathbf{0})]\rangle = -i\eta\omega + O(\omega^2)$$

$$\frac{\eta}{s} = \frac{1}{4\pi}$$

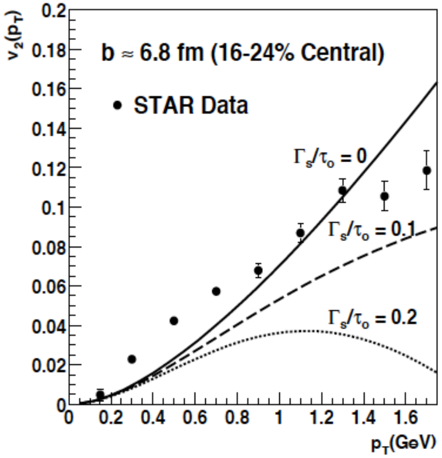
Universal (?) lower bound on viscosity

Kovtun, Son, Starinets, 2005

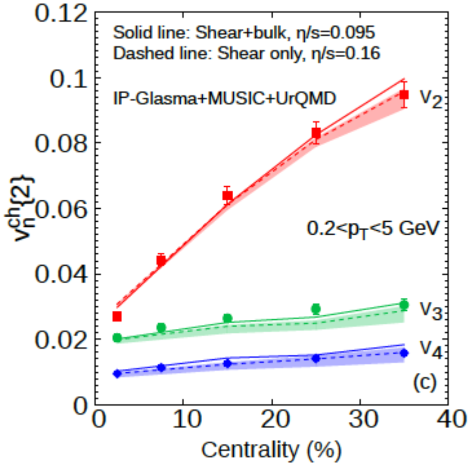


http://quark.itp.tuwien.ac.at/~ads/

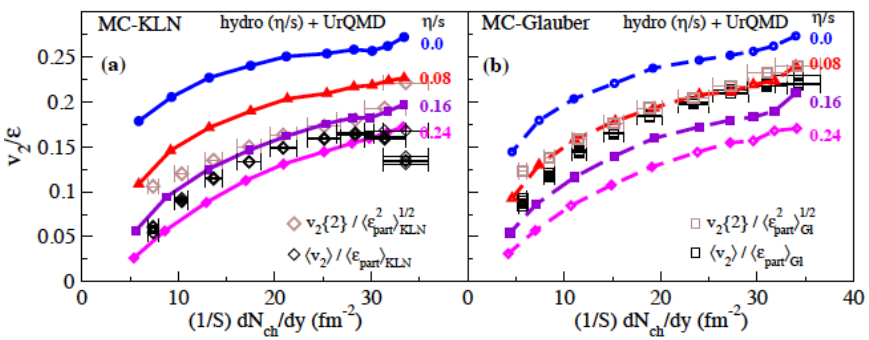
Measuring the viscosity at RHIC



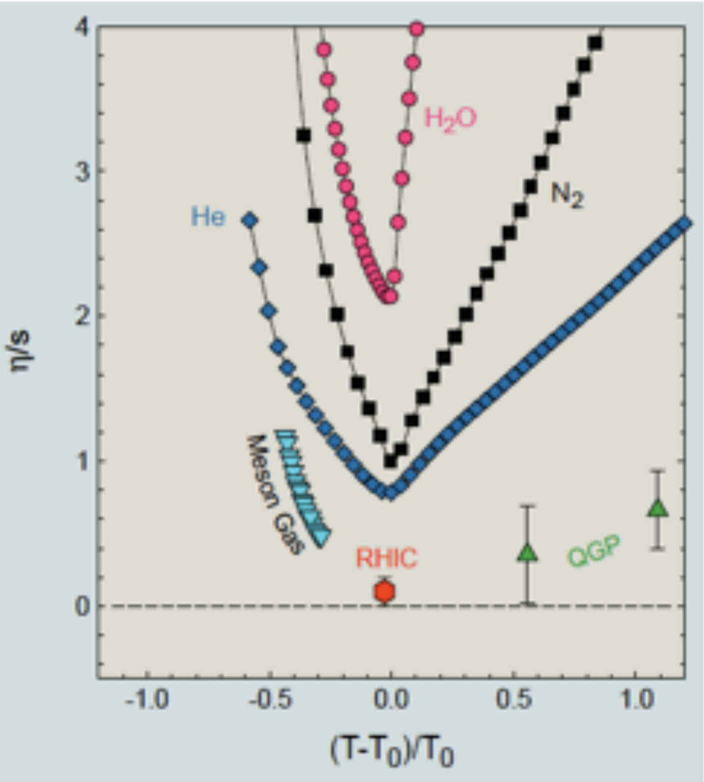
D.Teaney ‘03



S.Ryu et al 1502.01675



U.Heinz, C.Shen, H.Song ‘11



Talk by W. Zajc

Measuring the viscosity: from quark-gluon plasma to cuprates

Nearly Perfect Fluidity in a High Temperature Superconductor

J.D. Rameau and T.J. Reber, H.-B. Yang, S. Akhanjee, G.D. Gu and P.D. Johnson

Condensed Matter Physics and Materials Science Department,

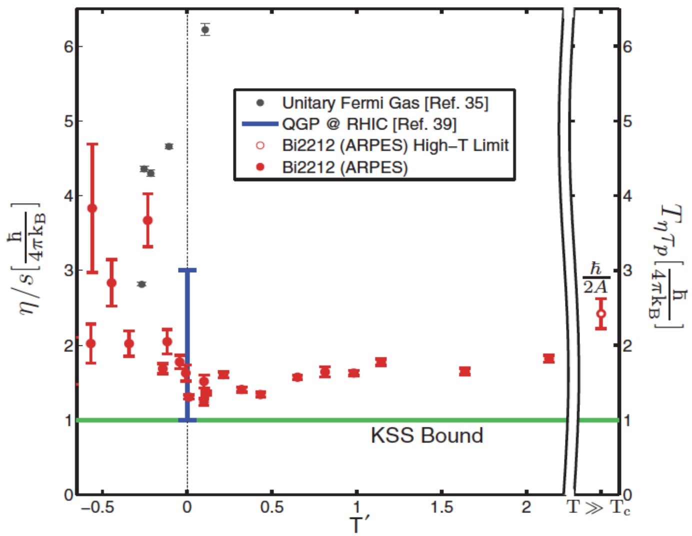
*Brookhaven National Lab, Upton, NY, 11973, USA**

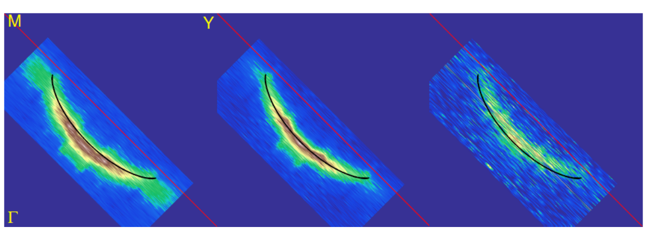
S. Campbell

Department of Physics and Astronomy,

Iowa State University, Ames, IA, 50011, USA

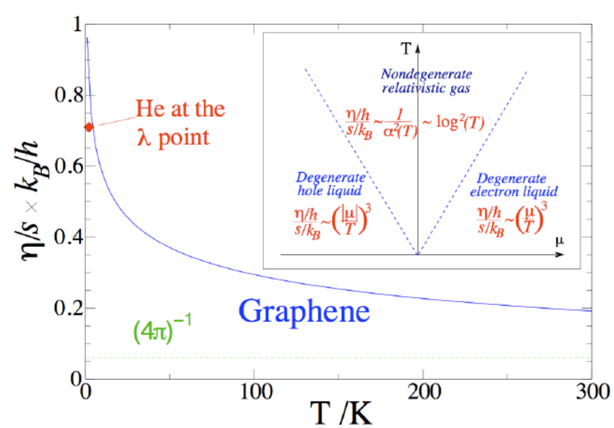
Phys.Rev.B90, 134509 (2014)





BNL NSLS data (ARPES)

Another example: graphene

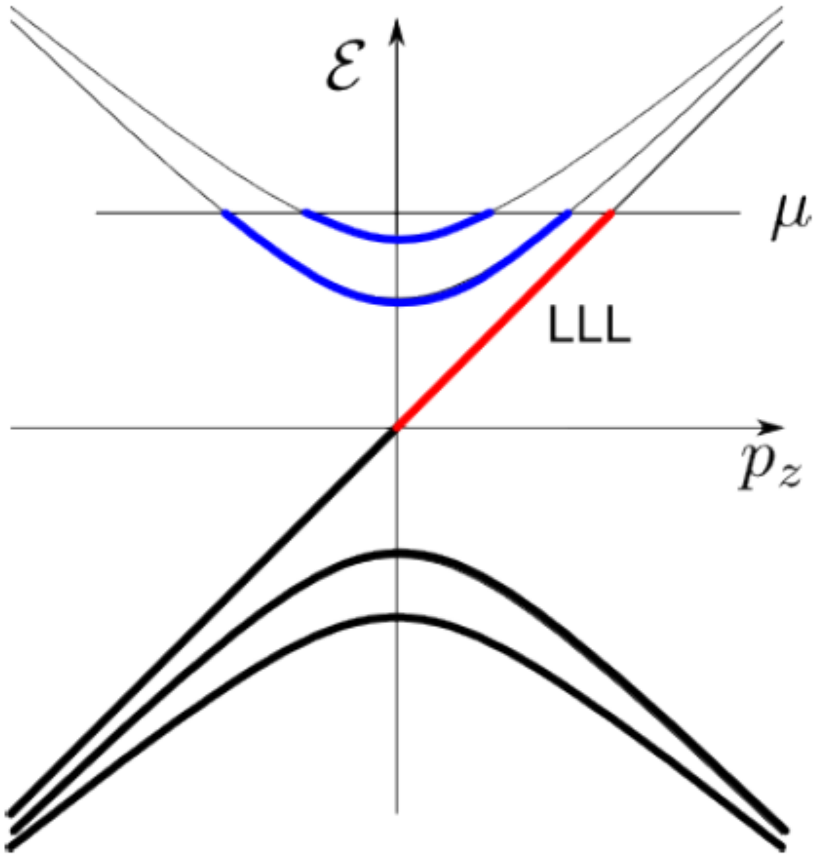


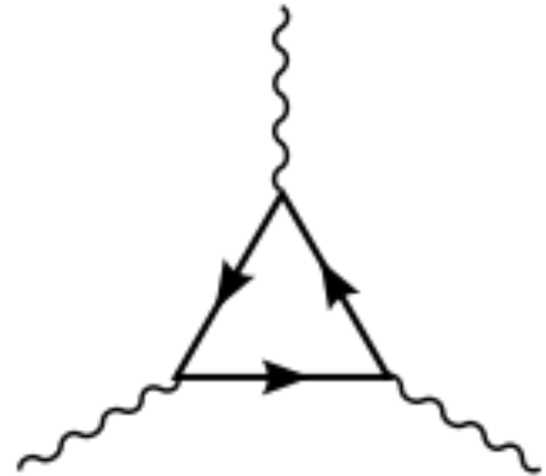
M.Muller, J.Schmalian, L.Fritz, PRL103 (2009)

Hydrodynamics and symmetries

- Hydrodynamics: an effective low-energy TOE. States that the response of the fluid to slowly varying perturbations is completely determined by conservation laws (energy, momentum, charge, ...)
- Conservation laws are a consequence of symmetries of the underlying theory
- What happens to hydrodynamics when these symmetries are broken by quantum effects (anomalies of QCD and QED)?

Quantum anomalies





In classical background fields (E || B), chiral anomaly induces a collective motion in the Dirac sea

Classical symmetries and Quantum anomalies

Anomalies: The classical symmetry of the Lagrangian is broken by quantum effects -

examples: chiral symmetry - axial anomaly

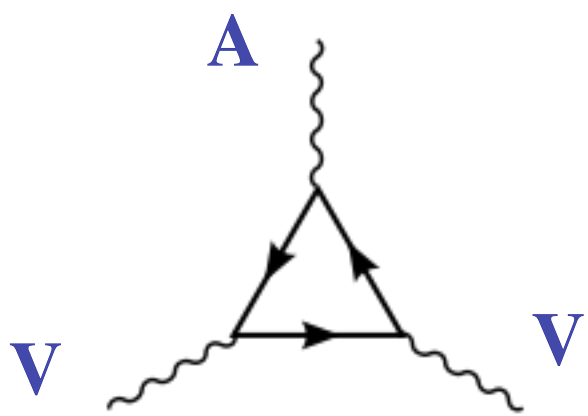
scale symmetry - scale anomaly

Anomalies imply correlations between currents:

e.g.

$$\pi^0 \to \gamma\gamma$$

decay



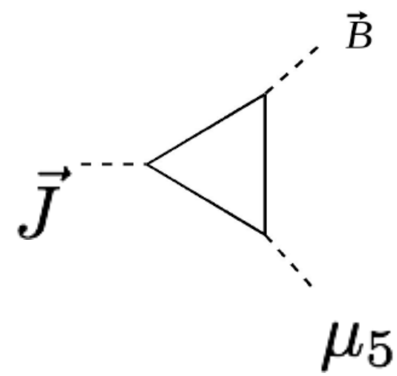
if A, V are background fields, V is not conserved!

Chiral Magnetic Effect in a chirally imbalanced plasma

Fukushima, DK, Warringa, PRD '08

Chiral chemical potential is formally equivalent to a background chiral gauge field: $\mu_5 = A_5^0$

In this background, and in the presence of B, vector e.m. current is generated:



$$\partial_\mu J^\mu = \frac{e^2}{16\pi^2} \left(F_L^{\mu\nu} \tilde{F}_{L,\mu\nu} - F_R^{\mu\nu} \tilde{F}_{R,\mu\nu} \right)$$

Compute the current through

$$J^\mu = \frac{\partial \log Z[A_\mu, A_\mu^5]}{\partial A_\mu(x)}$$

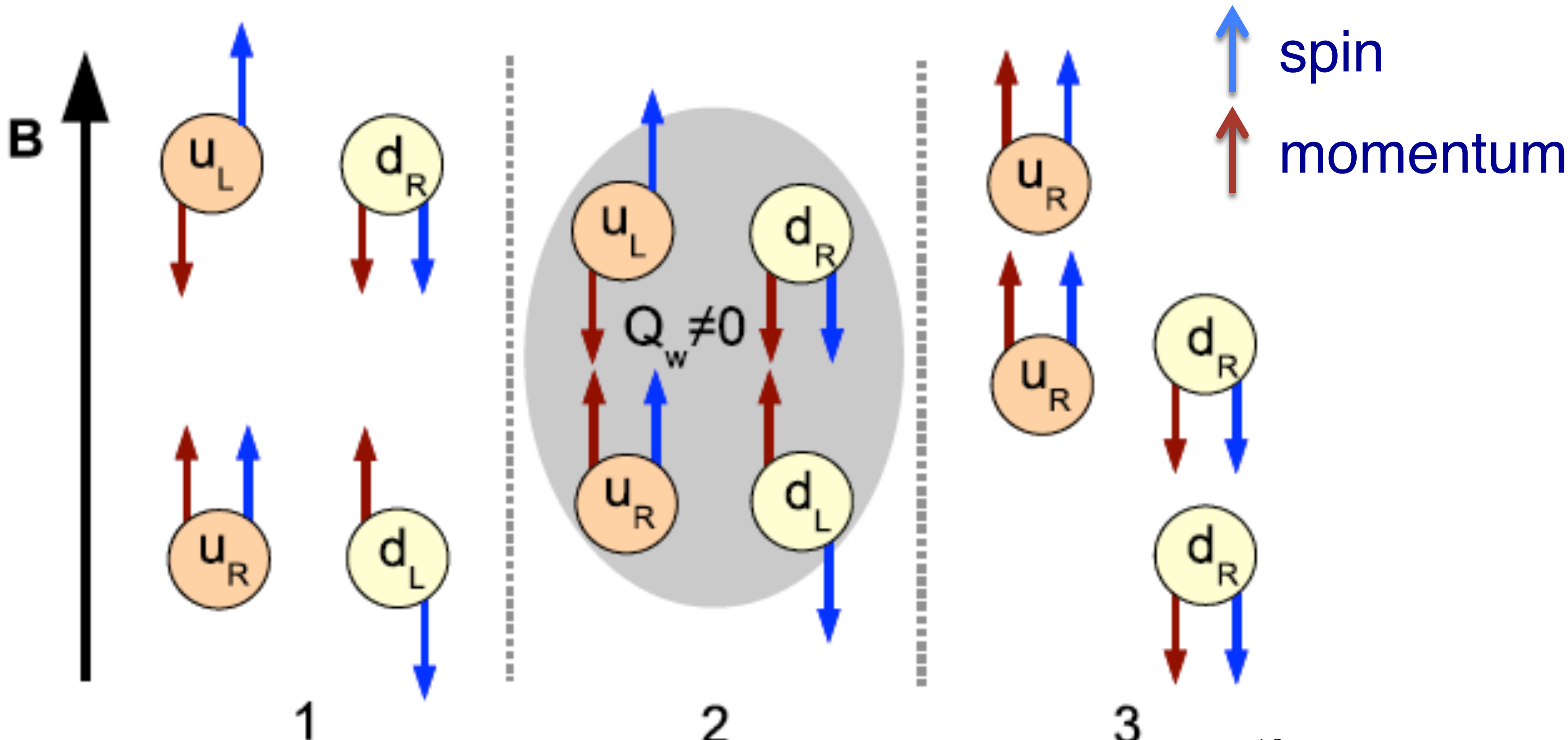
The result:

$$\vec{J} = \frac{e^2}{2\pi^2}\, \mu_5\, \vec{B}$$

Coefficient is fixed by the axial anomaly, no corrections

Chiral Magnetic Effect:

chirality + magnetic field = current



DK, L.McLerran, H.Warringa '08; DK '04

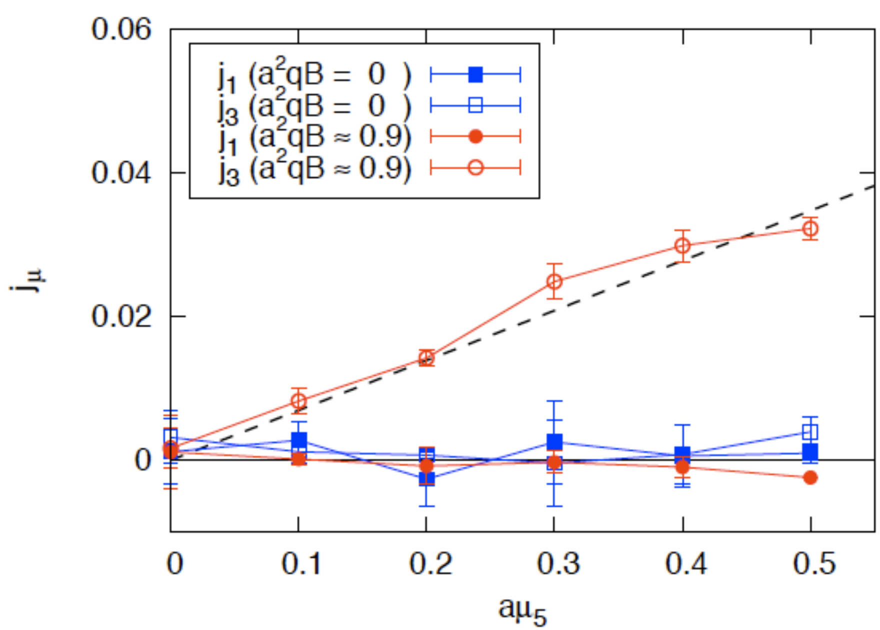
CME on supercomputers

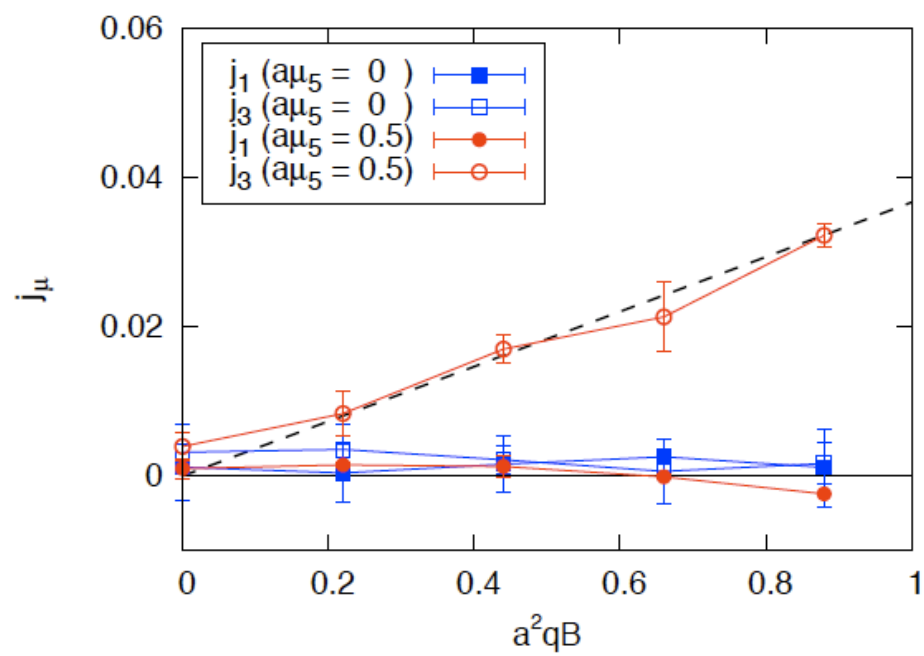
arXiv:1105.0385, PRL

Chiral magnetic effect in lattice QCD with chiral chemical potential

Arata Yamamoto
Department of Physics, The University of Tokyo, Tokyo 113-0033, Japan
(Dated: May 3, 2011)

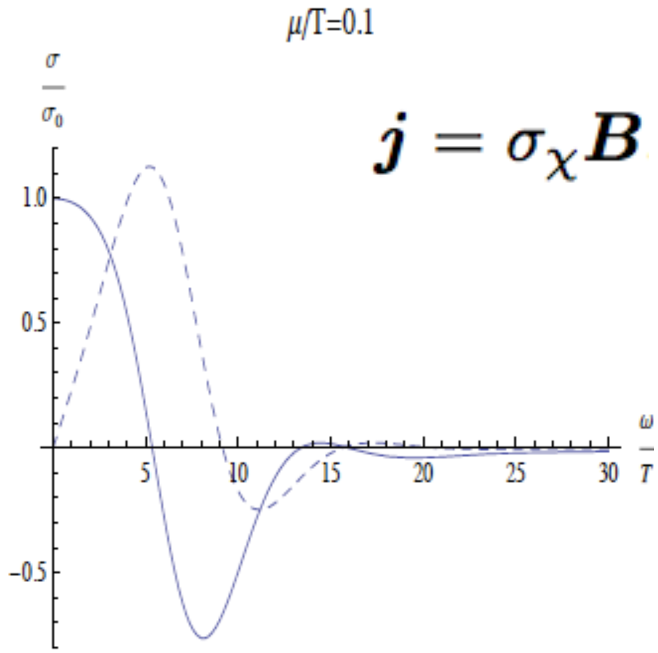
We perform a first lattice QCD simulation including two-flavor dynamical fermion with chiral chemical potential. Because the chiral chemical potential gives rise to no sign problem, we can exactly analyze a chirally asymmetric QCD matter by the Monte Carlo simulation. By applying an external magnetic field to this system, we obtain a finite induced current along the magnetic field, which corresponds to the chiral magnetic effect. The obtained induced current is proportional to the magnetic field and to the chiral chemical potential, which is consistent with an analytical prediction.





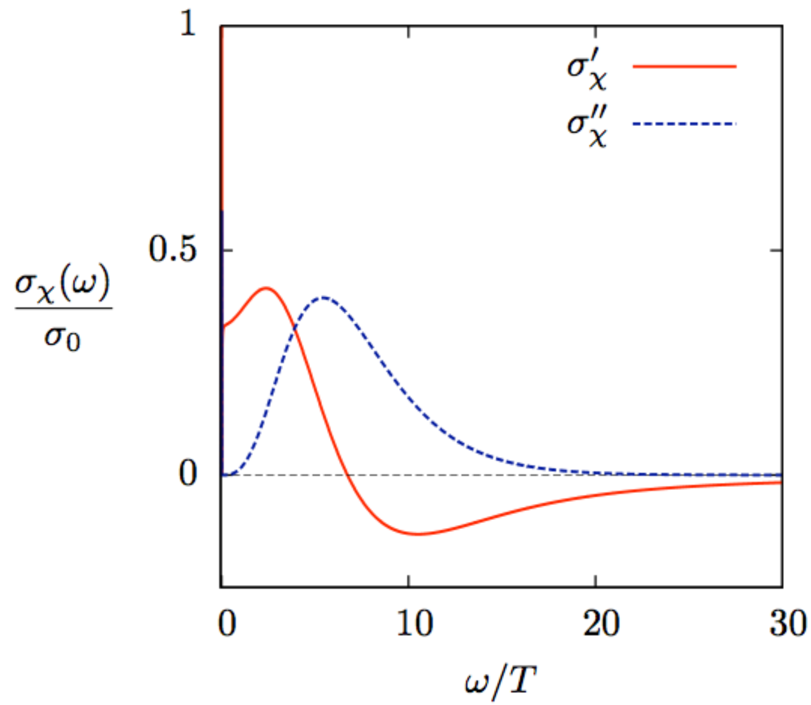
Holographic chiral magnetic effect: the strong coupling regime (AdS/CFT)

Strong coupling



H.-U. Yee, arXiv:0908.4189, JHEP 0911:085, 2009;

Weak coupling



D.K., H. Warringa
Phys Rev D80 (2009) 034028

A.Rebhan, A.Schmitt, S.Stricker JHEP 0905, 084 (2009), G.Lifshytz, M.Lippert, arXiv:0904.4772;.A. Gorsky, P. Kopnin, A. Zayakin, arXiv:1003.2293, A.Gynther, K. Landsteiner, F. Pena Benitez, JHEP 1102 (2011) 110; V. Rubakov, arXiv:1005.1888, C. Hoyos, T. Nishioka, A. O'Bannon, JHEP1110 (2011) 084

CME persists at strong coupling - **hydrodynamical formulation?**

The CME in relativistic hydrodynamics:
The Chiral Magnetic Wave

DK, H.-U. Yee,
arXiv:1012.6026 [hep-th]; PRD

$$\vec{j}_V = \frac{N_c\, e}{2\pi^2}\mu_A \vec{B}; \qquad \vec{j}_A = \frac{N_c\, e}{2\pi^2}\mu_V \vec{B},$$

CME — Chiral separation

$$\begin{pmatrix} \vec{j}_V \\ \vec{j}_A \end{pmatrix} = \frac{N_c\, e\vec{B}}{2\pi^2}\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}\begin{pmatrix} \mu_V \\ \mu_A \end{pmatrix}$$

Propagating chiral wave: (if chiral symmetry is restored)

$$\left(\partial_0 \mp \frac{N_c e B \alpha}{2\pi^2}\partial_1 - D_L \partial_1^2\right) j^0_{L,R} = 0$$

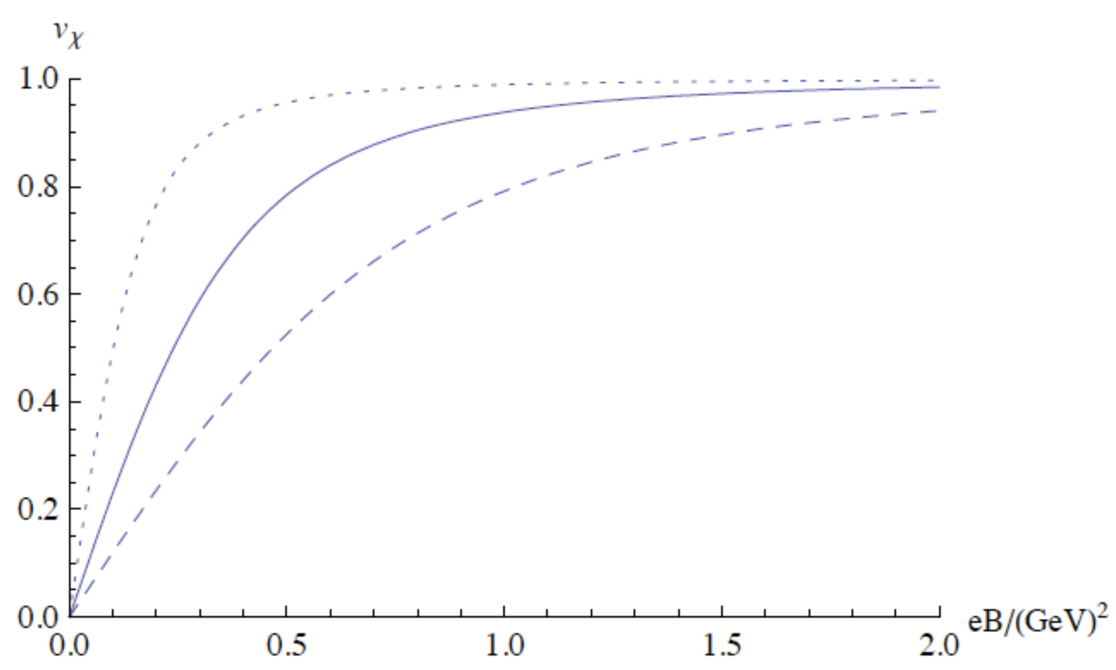
Gapless collective mode is the carrier of CME current in MHD:

$$\omega = \mp v_\chi k - i D_L k^2 + \cdots$$

The Chiral Magnetic Wave:

oscillations of electric and chiral charges coupled by the chiral anomaly

In strong magnetic field, CMW propagates with the speed of light!



DK, H.-U. Yee, Phys Rev D'11

Chiral MagnetoHydroDynamics (CMHD) - relativistic hydrodynamics with triangle anomalies and external electromagnetic fields

First order (in the derivative expansion) formulation:
D. Son and P. Surowka, arXiv:0906.5044, PRL'09

Constraining the new anomalous transport coefficients:
positivity of the entropy production rate, $\partial_\mu s^\mu \geq 0$

$$\nu^\mu = -\sigma T P^{\mu\nu}\partial_\nu\left(\frac{\mu}{T}\right) + \sigma E^\mu + \underline{\xi\omega^\mu + \xi_B B^\mu},$$

$$s^\mu = s u^\mu - \frac{\mu}{T}\nu^\mu + D\omega^\mu + D_B B^\mu,$$

not present in Landau-Lifshitz!

CME (for chirally imbalanced matter)

$$\xi = C\left(\mu^2 - \frac{2}{3}\frac{n\mu^3}{\epsilon + P}\right), \quad \xi_B = C\left(\mu - \frac{1}{2}\frac{n\mu^2}{\epsilon + P}\right).$$

Chiral MagnetoHydroDynamics (CMHD) - relativistic hydrodynamics with triangle anomalies and external electromagnetic fields

First order hydrodynamics has problems with causality and is numerically unstable, so second order formulation is necessary;

Second order formulation of CMHD with anomaly:
DK and H.-U. Yee, 1105.6360; Phys Rev D

Many new transport coefficients - use conformal/Weyl invariance;
still 18 independent transport coefficients related to the anomaly.
15 that are specific to 2nd order:

$$\sigma_{\mu\nu} = \frac{1}{2}\left(\mathcal{D}_\mu u_\nu + \mathcal{D}_\nu u_\mu\right) \quad , \quad \omega_{\mu\nu} = \frac{1}{2}\left(\mathcal{D}_\mu u_\nu - \mathcal{D}_\nu u_\mu\right)$$

$$\Delta_{\mu\nu} \equiv (g_{\mu\nu} + u_\mu u_\nu)$$

new

$$\begin{aligned}
&\sigma^{\mu\nu}\mathcal{D}_\nu\bar{\mu} \ , \ \omega^{\mu\nu}\mathcal{D}_\nu\bar{\mu} \ , \ \Delta^{\mu\nu}\mathcal{D}^\alpha\sigma_{\nu\alpha} \ , \ \Delta^{\mu\nu}\mathcal{D}^\alpha\omega_{\nu\alpha} \ , \ \sigma^{\mu\nu}\omega_\nu \ , \\
&\sigma^{\mu\nu}E_\nu \ , \ \sigma^{\mu\nu}B_\nu \ , \ \omega^{\mu\nu}E_\nu \ , \ \omega^{\mu\nu}B_\nu \ , u^\nu\mathcal{D}_\nu E^\mu \ , \\
&\epsilon^{\mu\nu\alpha\beta}u_\nu E_\alpha\mathcal{D}_\beta\bar{\mu} \ , \ \epsilon^{\mu\nu\alpha\beta}u_\nu B_\alpha\mathcal{D}_\beta\bar{\mu} \ , \ \epsilon^{\mu\nu\alpha\beta}u_\nu E_\alpha B_\beta \ , \ \epsilon^{\mu\nu\alpha\beta}u_\nu\mathcal{D}_\alpha E_\beta \ , \ \epsilon^{\mu\nu\alpha\beta}u_\nu\mathcal{D}_\alpha B_\beta \ .
\end{aligned} \quad (2.60)$$

Many new anomaly-induced phenomena!

No entropy production from T-even anomalous terms

DK and H.-U. Yee, 1105.6360

$$\vec{J} = \frac{e^2}{2\pi^2}\,\mu_5\,\vec{B}$$

P-odd
T-odd

P-even
T-odd

P-odd

P-odd effect!

T-even

Non-dissipative current!

(time-reversible - no arrow of time, no entropy production)

cf Ohmic conductivity:

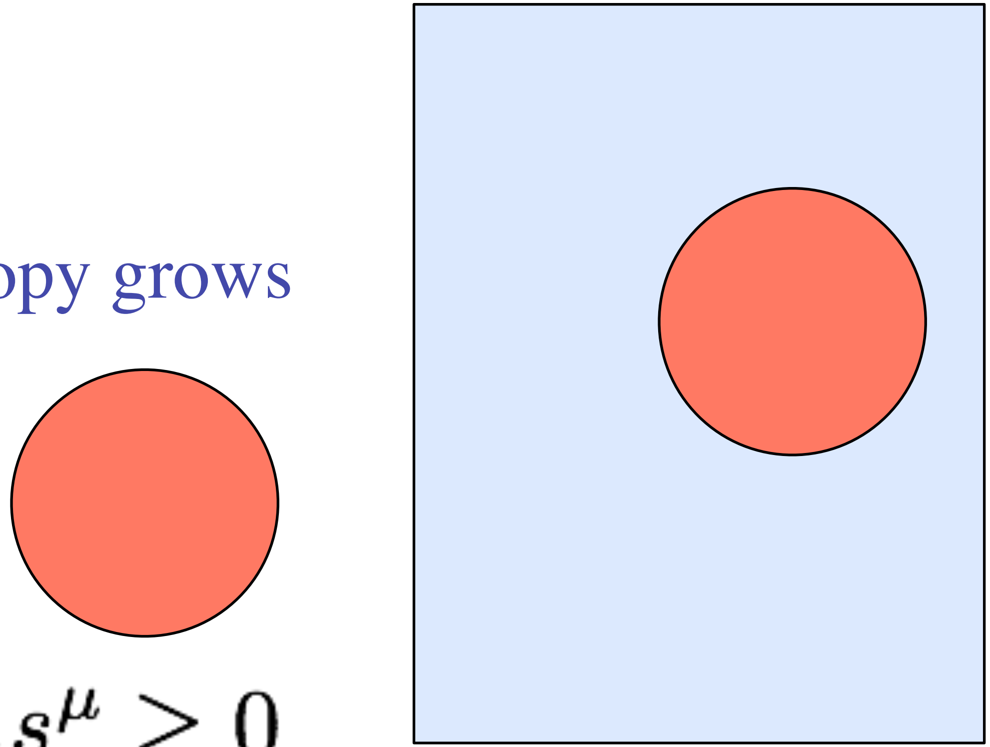
$$\vec{J} = \sigma \vec{E}$$

T-odd, dissipative

No entropy production from P-odd anomalous terms

DK and H.-U. Yee, 1105.6360

Entropy grows



$$\partial_\mu s^\mu \geq 0$$

Mirror reflection:
entropy decreases ?

$$\partial_\mu s^\mu \leq 0$$

Decrease is ruled out by 2nd law of thermodynamics

$$\partial_\mu s^\mu = 0$$

No entropy production from T-even anomalous terms

1st order hydro: Son-Surowka results are reproduced

2nd order hydro: 13 out of 18 transport coefficients are computed; but is the "guiding principle" correct?

DK and H.-U. Yee, 1105.6360

Can we check the resulting relations between the transport coefficients?

e.g.

$$\bar{\lambda}_1 = \frac{2\bar{\eta}}{\bar{n}}\left(\bar{\xi} - 2\bar{D}_B\right) ,$$

$$\bar{\lambda}_2 + \bar{\xi}_1 = \left(\frac{2\bar{\eta}}{\bar{n}}\left(\bar{\xi} - 2\bar{D}_B\right)\right)' + \left(\frac{\bar{\eta}}{\bar{p}} - \frac{2\bar{\eta}'}{\bar{n}}\right)\left(\bar{\xi} - 2\bar{D}_B\right)$$

The fluid/gravity correspondence

Long history:

Hawking, Bekenstein, Unruh;
Damour '78;
Thorne, Price, MacDonald '86 (membrane paradigm)

Recent developments motivated by AdS/CFT:

Policastro, Kovtun, Son, Starinets '01 (quantum bound)
Bhattacharya, Hubeny, Minwalla, Rangamani '08
(fluid/gravity correspondence)

Some of the transport coefficients of 2nd order hydro computed;
enough to check some of our relations, e.g.

J. Erdmenger et al, 0809.2488;
N. Banerjee et al, 0809.2596

$$\bar{\lambda}_1 = \frac{2\bar{\eta}}{\bar{n}}\left(\bar{\xi} - 2\bar{D}_B\right) ,$$

$$\bar{\lambda}_2 + \bar{\xi}_1 = \left(\frac{2\bar{\eta}}{\bar{n}}\left(\bar{\xi} - 2\bar{D}_B\right)\right)' + \left(\frac{\bar{\eta}}{\bar{p}} - \frac{2\bar{\eta}'}{\bar{n}}\right)\left(\bar{\xi} - 2\bar{D}_B\right)$$

<u>It works</u>

Other holographic checks work as well:

DK and H.-U. Yee, 1105.6360

The chiral magnetic current is
non-dissipative:
protected from (local) scattering and dissipation by (global) topology

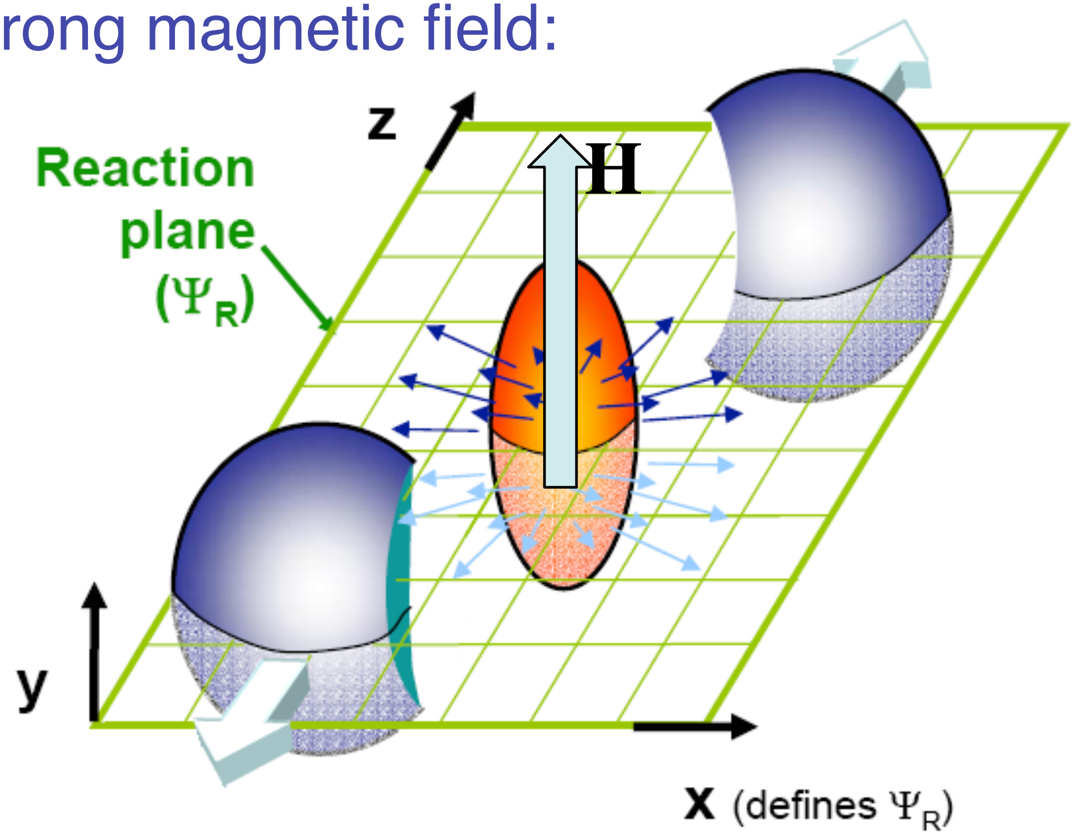
Somewhat similar to superconductivity, but exists at any temperature! (?)

Anomalous transport coefficients in hydrodynamics describe dissipation-free processes (unlike e.g. shear viscosity)

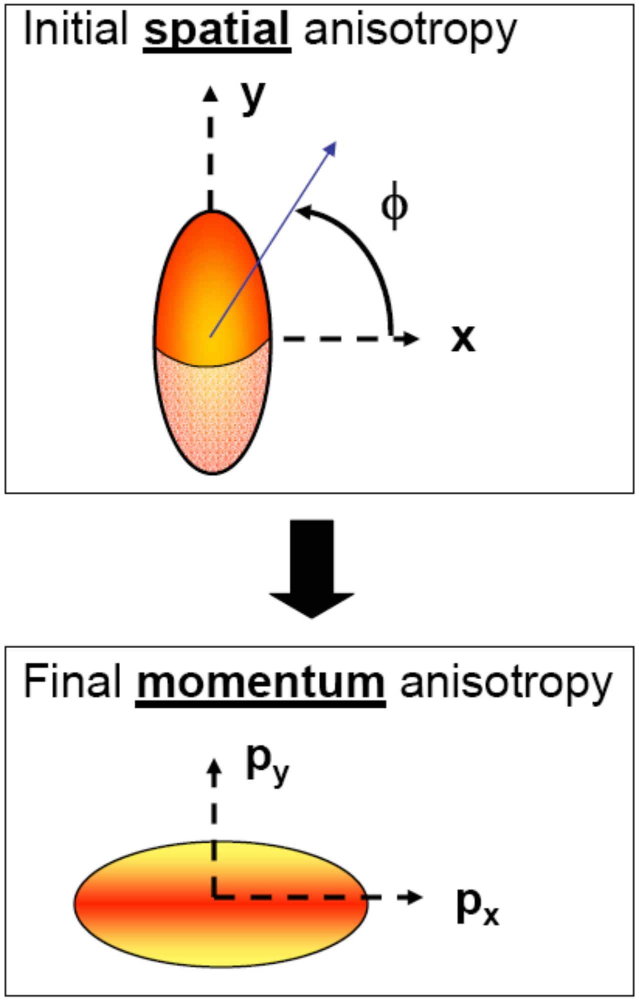

CME

Is there a way to observe CME in nuclear collisions at RHIC?

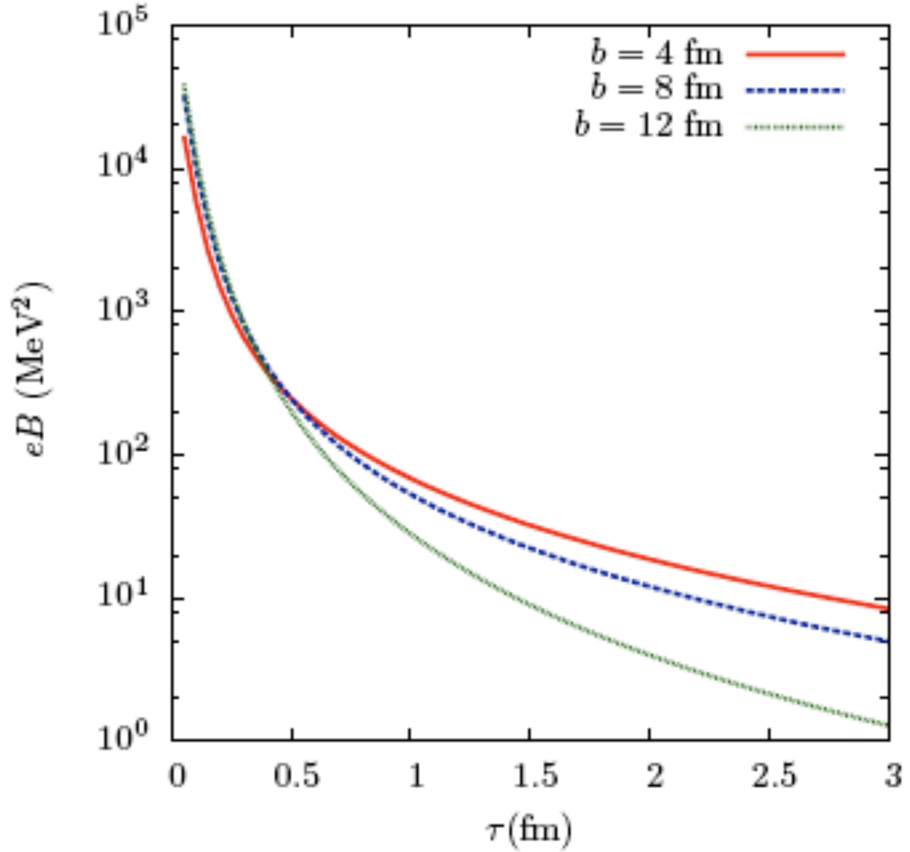
Relativistic ions create a strong magnetic field:



DK, McLerran, Warringa '07



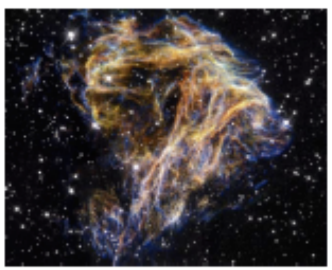
Heavy ion collisions as a source of the strongest magnetic fields available in the Laboratory



DK, McLerran, Warringa, Nucl Phys A803(2008)227

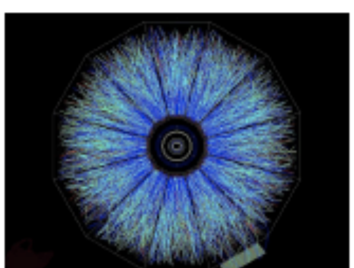
Fig. A.2. Magnetic field at the center of a gold-gold collision, for different impact parameters. Here the center of mass energy is 200 GeV per nucleon pair ($Y_0 = 5.4$).

Comparison of magnetic fields



The Earths magnetic field	0.6 Gauss
A common, hand-held magnet	100 Gauss
The strongest steady magnetic fields achieved so far in the laboratory	4.5×10^5 Gauss
The strongest man-made fields ever achieved, if only briefly	10^7 Gauss
Typical surface, polar magnetic fields of radio pulsars	10^{13} Gauss
Surface field of Magnetars	10^{15} Gauss

http://solomon.as.utexas.edu/~duncan/magnetar.html

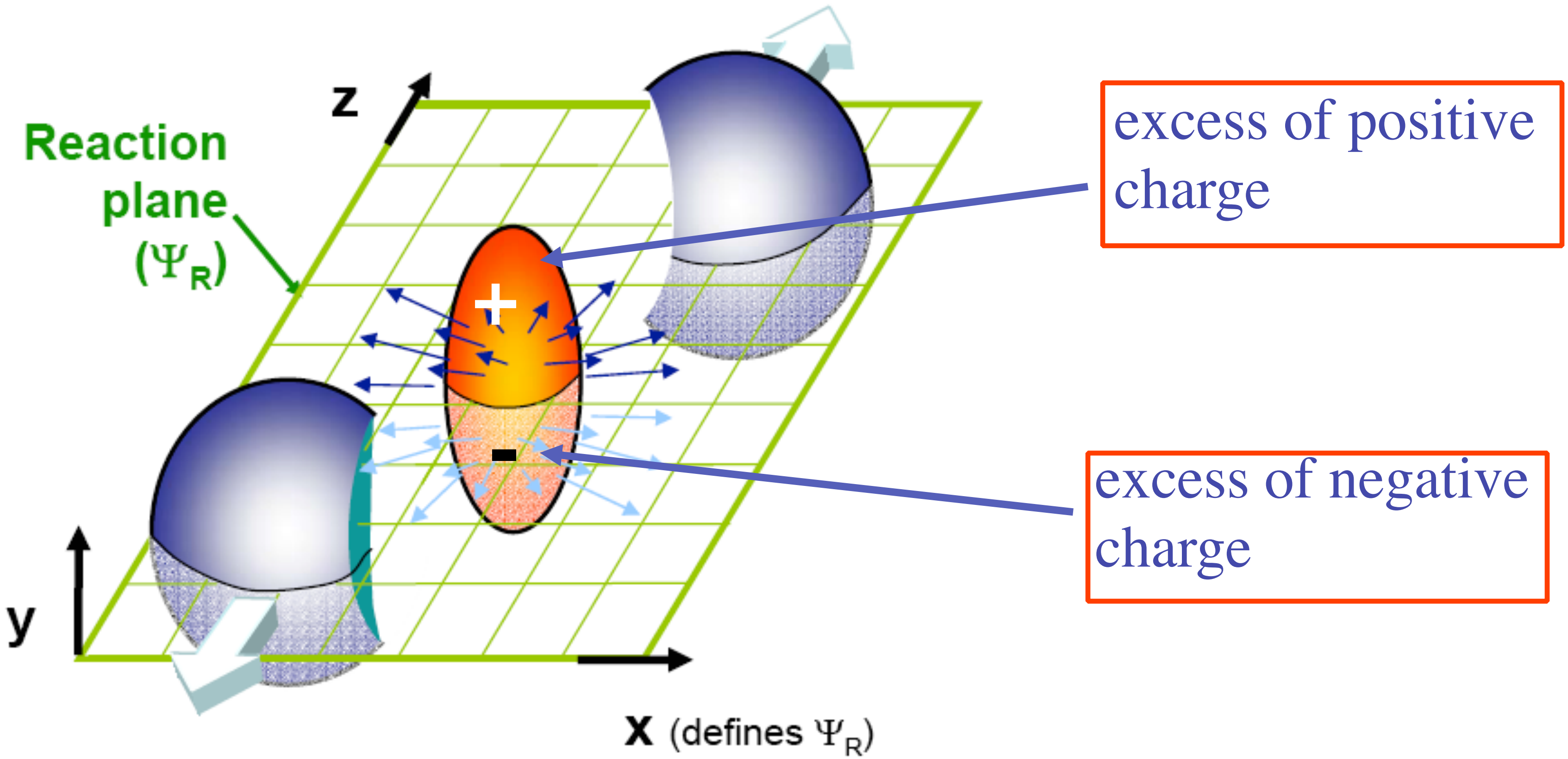


Heavy ion collisions: the strongest magnetic field ever achieved in the laboratory

Off central Gold-Gold Collisions at 100 GeV per nucleon

$$e\,B(\tau = 0.2\,\mathrm{fm}) \;=\; 10^3 \sim 10^4\ \mathrm{MeV}^2 \sim 10^{17}\,\mathrm{Gauss}$$

Charge asymmetry w.r.t. reaction plane as a signature of chirality imbalance

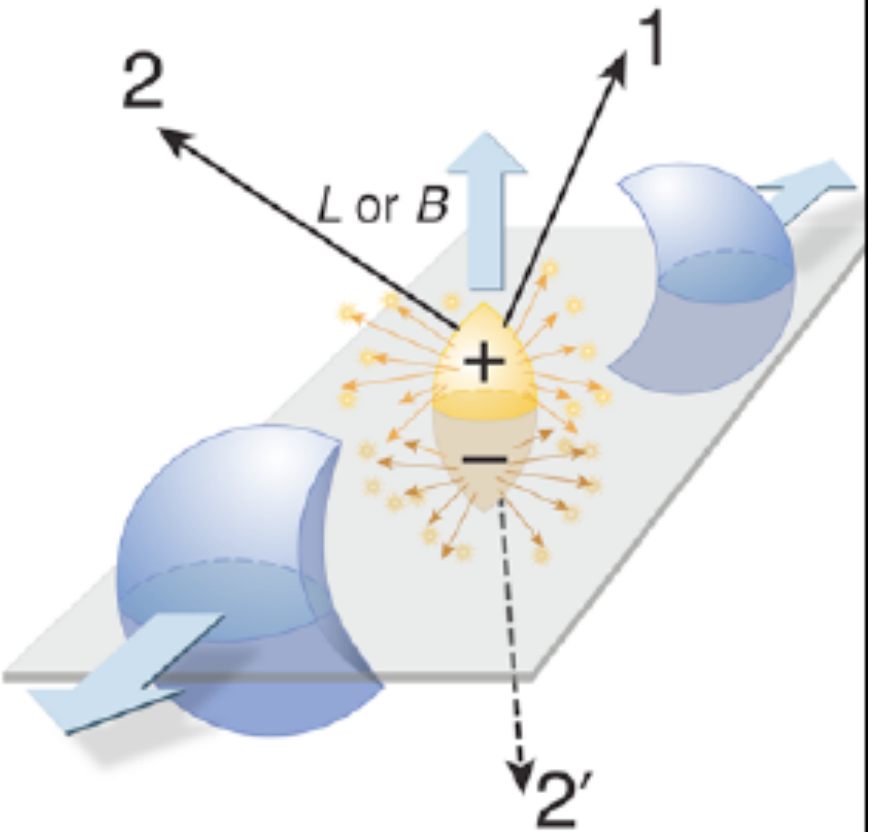


Electric dipole moment due to chiral imbalance

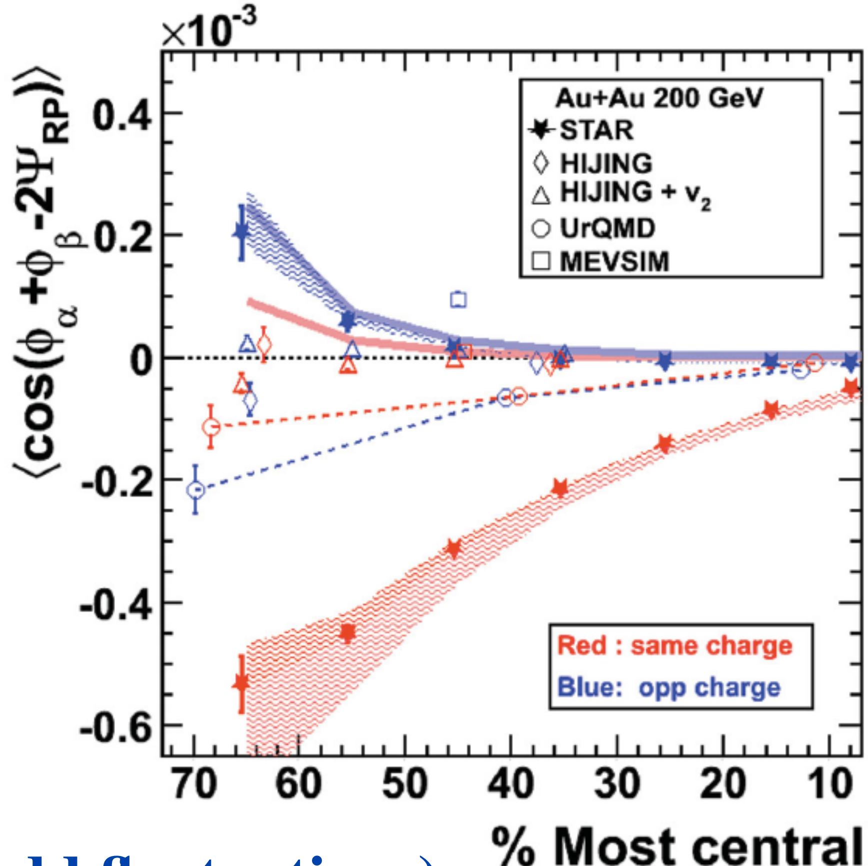
DK, hep-ph/0406125; Phys.Lett.B633(2006)260

Selected for a Viewpoint in *Physics*
PRL **103**, 251601 (2009) PHYSICAL REVIEW LETTERS week ending 18 DECEMBER 2009

Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation



(STAR Collaboration)



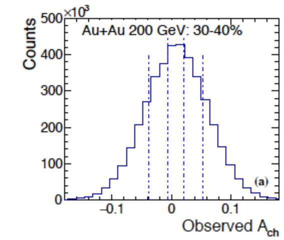
NB: P-even quantity (strength of P-odd fluctuations)

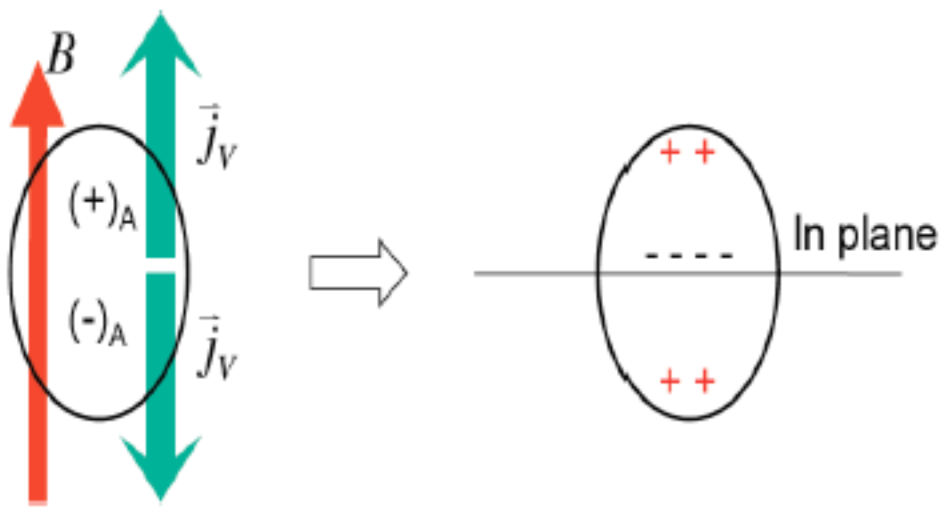
Testing the Chiral Magnetic Wave

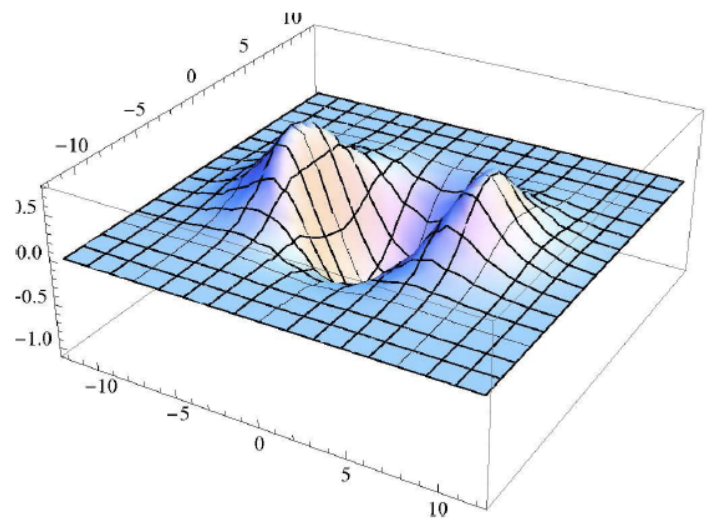
Finite baryon density + CMW = electric quadrupole moment of QGP

Signature - difference of elliptic flows of positive and negative pions determined by total charge asymmetry of the event A:

at A>0, $v_2(-) > v_2(+)$;   at A<0, $v_2(+) > v_2(-)$







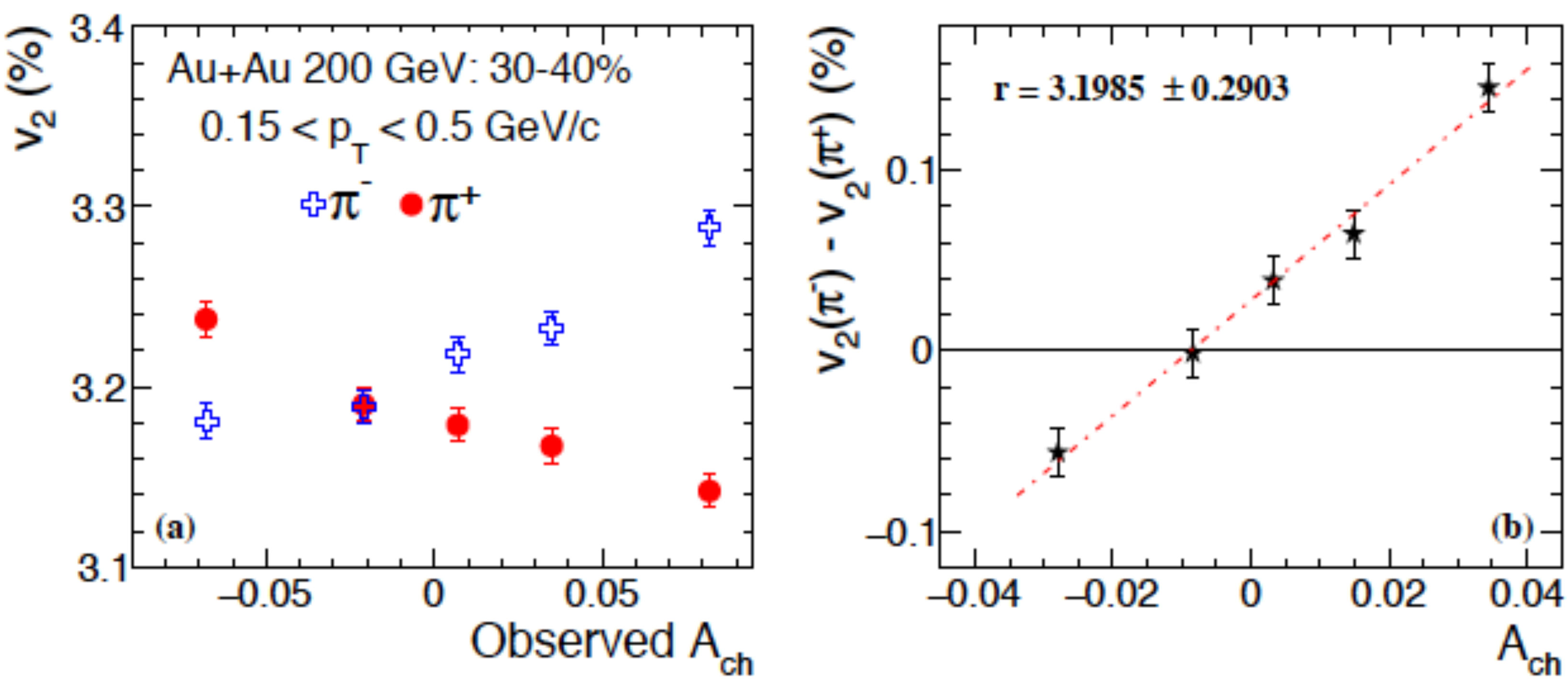
$$v_2^- - v_2^+ = C + 2\left(\frac{q_e}{\bar{\rho}_e}\right)A_\pm$$

$$A_\pm = (\bar{N}_+ - \bar{N}_-)/(\bar{N}_+ + \bar{N}_-)$$

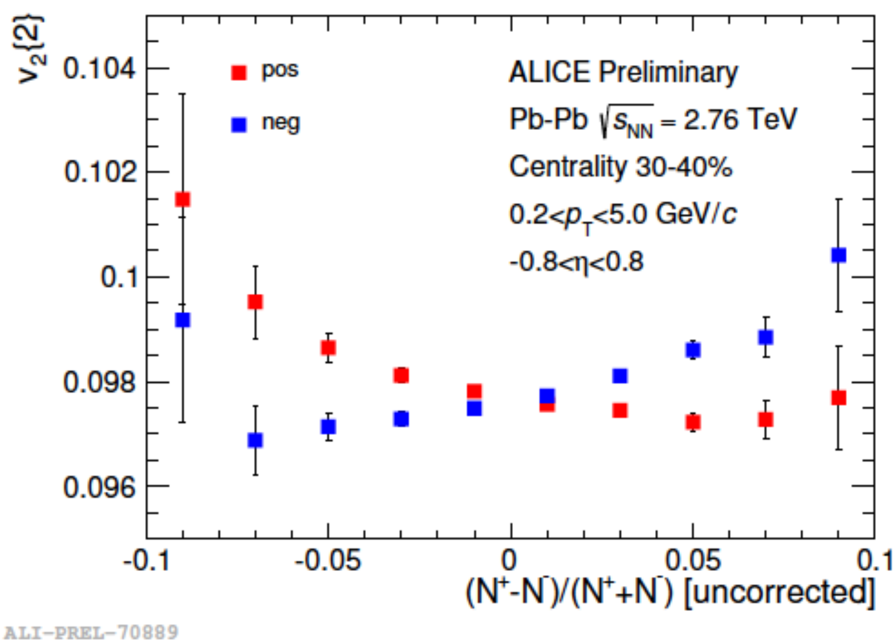
Y.Burnier, DK, J.Liao, H.Yee, PRL 2011

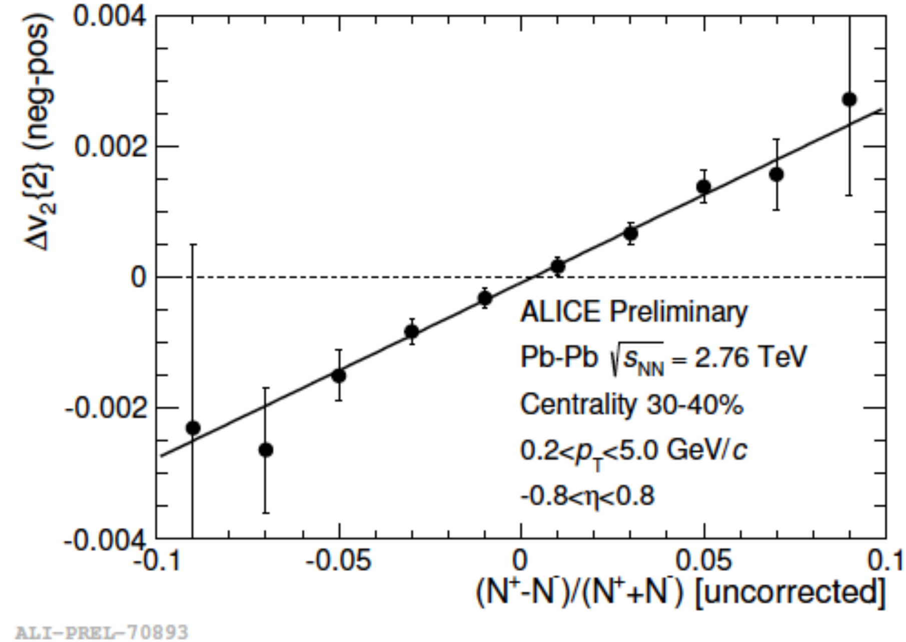
Observation of charge asymmetry dependence of pion elliptic flow and the possible chiral magnetic wave in heavy-ion collisions

(STAR Collaboration) arXiv:1504.02175



ALICE Coll. at the LHC



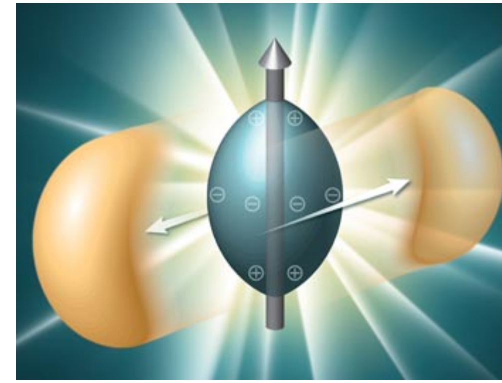


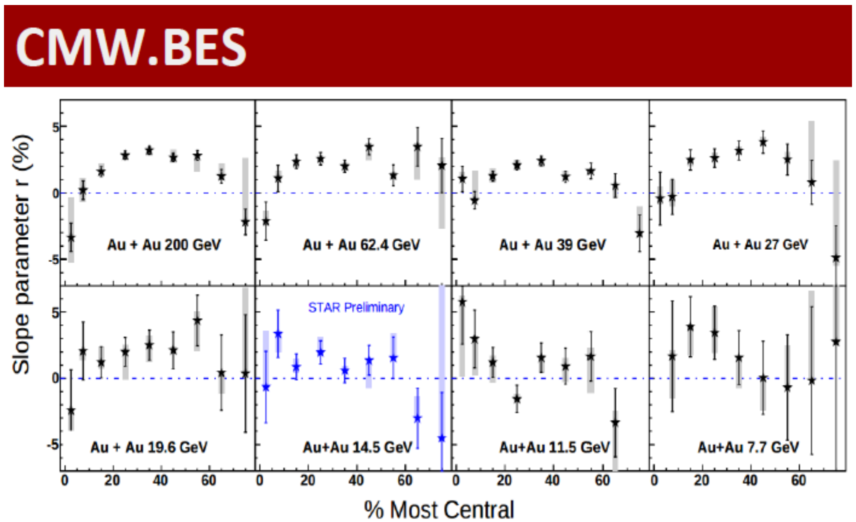
ALICE Coll,
R.Belmont et al (2014)

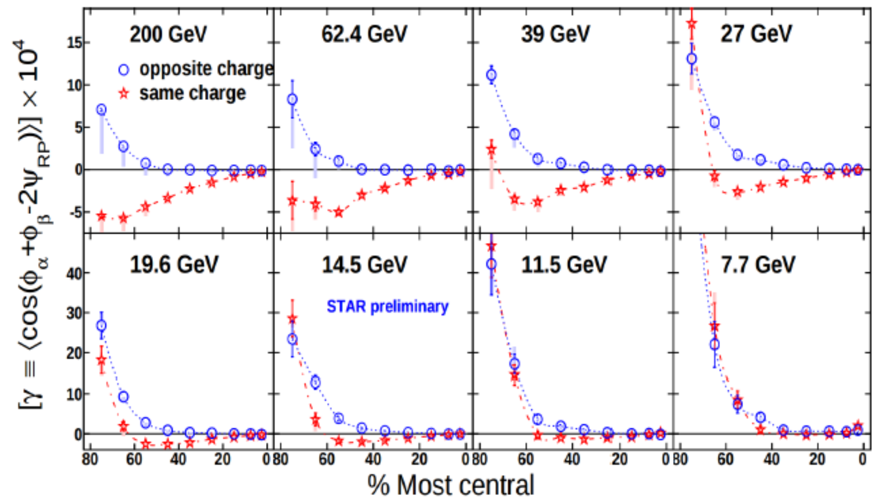
By Karen McNulty Walsh | June 8, 2015

Scientists See Ripples of a Particle-Separating Wave In Primordial Plasma

Key sign of quark-gluon plasma (QGP) and evidence for a long-debated quantum phenomenon





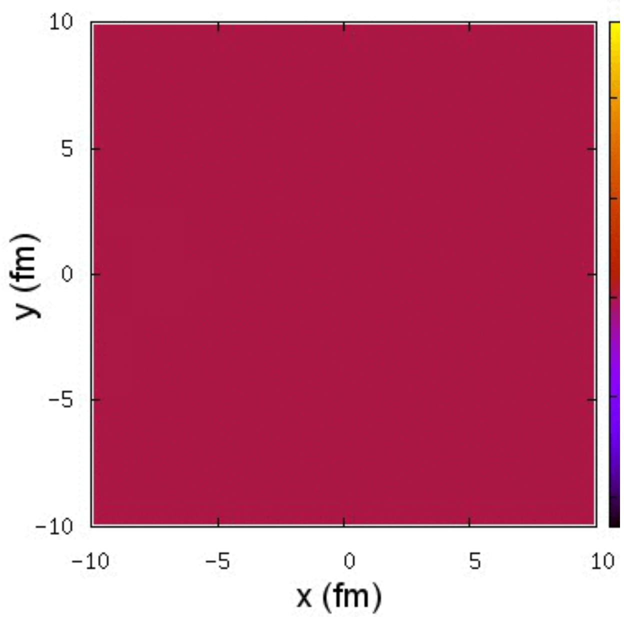


Talk by Liwen Wen (STAR)

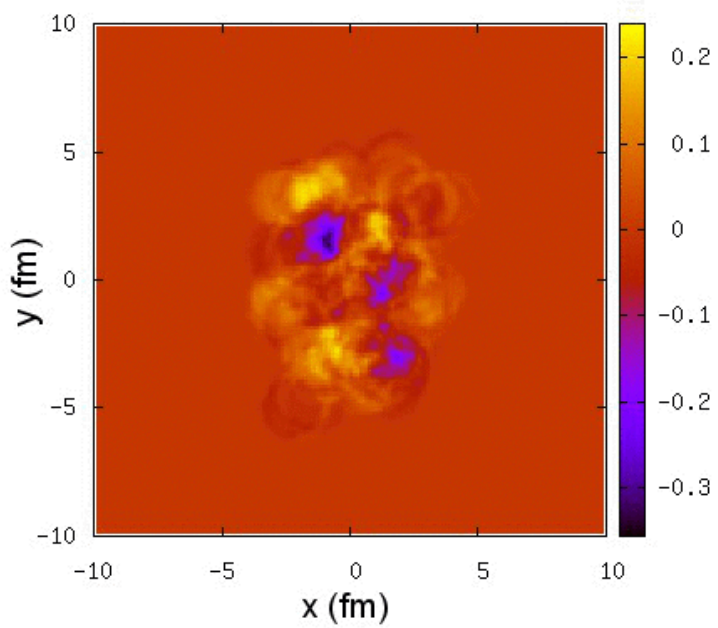
Need for systematic studies at BES-II

Quantitative CMHD simulations have begun:

Electric charge



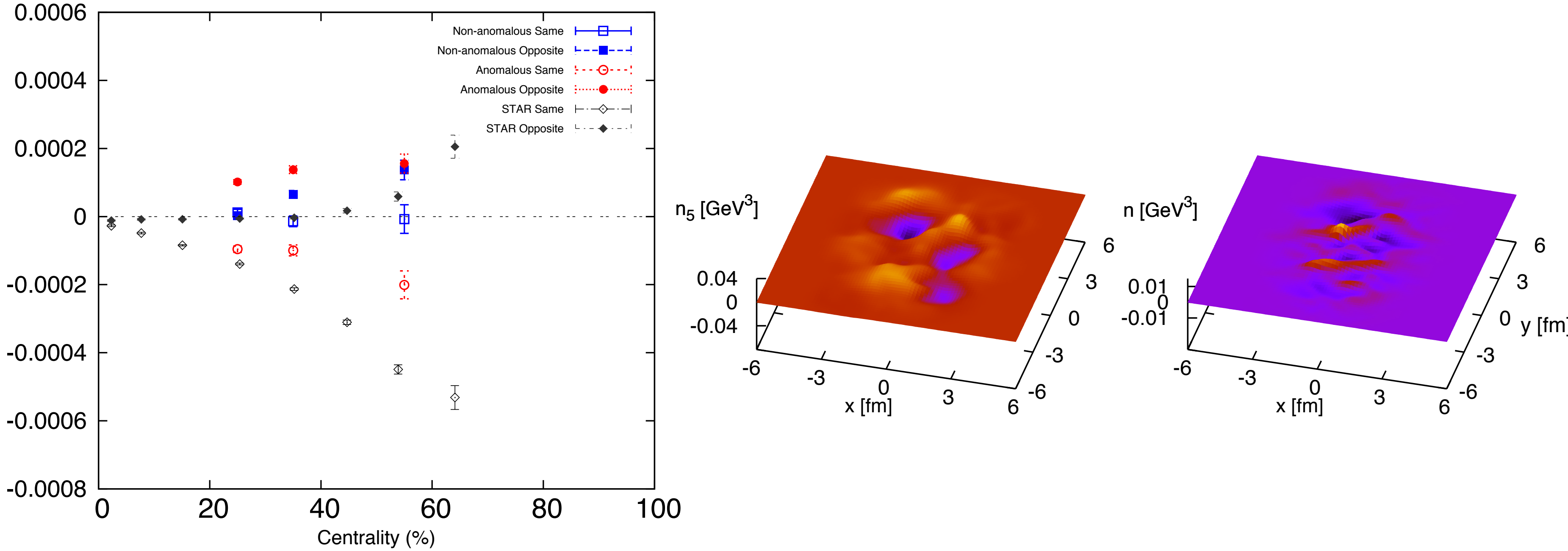
Chiral charge



Y.Hirono, T.Hirano, DK, (Stony Brook – Tokyo), arxiv:1412.0311
(3+1) ideal CMHD

Talk by Yuji Hirono

Quantitative CMHD simulations have begun:



Y.Hirono, T.Hirano, DK, (Stony Brook – Tokyo), arxiv:1412.0311
(3+1) ideal CMHD

Need to develop full CMHD – major effort, **BES Theory Collaboration**

Vorticity and baryon current

DK, D.T.Son
arXiv:1010.0038; PRL

$$\vec{J} = \frac{N_c \mu_5}{2\pi^2}[\mathrm{tr}(VAQ)\vec{B} + \mathrm{tr}(VAB)2\mu\vec{\omega}]$$

CME

Vorticity-induced
"Chiral Vortical Effect"

$$J_E^{CME} \sim \frac{2}{3} \;\; (N_f = 3) \;\; \text{or} \;\; \frac{5}{9} \;\; (N_f = 2)$$

$$J_B^{CME} = 0 \;\; (N_f = 3) \;\; \text{or} \;\; \sim \frac{1}{9} \;\; (N_f = 2).$$

CME:
(almost) only
electric charge

$$J_E^{CVE} = 0 \;\; (N_f = 3) \;\; \text{or} \;\; \sim \frac{1}{3} \;\; (N_f = 2);$$

CVE:
(almost) only
baryon charge

$$J_B^{CVE} \sim 1 \;\; (N_f = 3) \;\; \text{or} \;\; \sim \frac{2}{3} \;\; (N_f = 2).$$

Hydrodynamics + anomalies + electromagnetic fields = Chiral Magneto-Hydrodynamics (CMHD)

Consistent theory of relativistic fluids
with chiral fermions –
XXI century development in hydrodynamics!

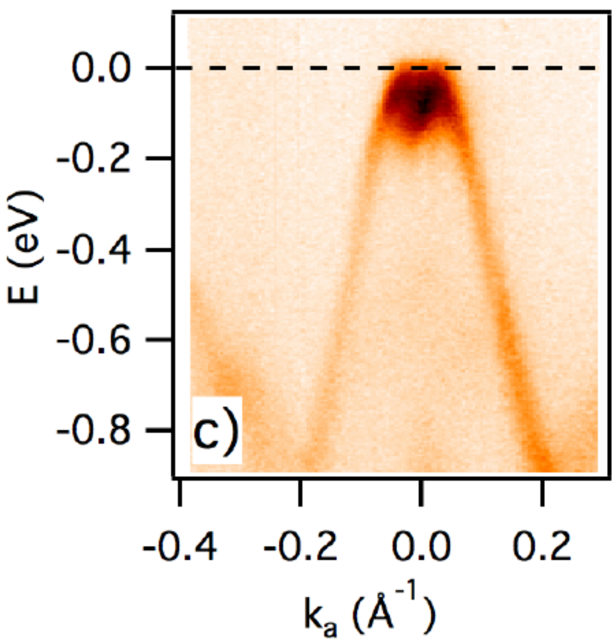
Describes qualitatively new phenomena:
Chiral Magnetic Effect (CME), Chiral Vortical Effect (CVE), Chiral Magnetic Wave (CMW),…

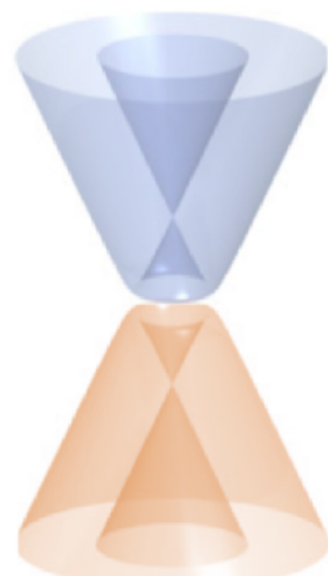
CME in condensed matter:

Observation of the chiral magnetic effect in $ZrTe_5$

Qiang Li,[1] Dmitri E. Kharzeev,[2,3] Cheng Zhang,[1] Yuan Huang,[4] I. Pletikosić,[1,5]
A. V. Fedorov,[6] R. D. Zhong,[1] J. A. Schneeloch,[1] G. D. Gu,[1] and T. Valla[1]

BNL - Stony Brook - Princeton - Berkeley





arXiv:1412.6543 [cond-mat.str-el]

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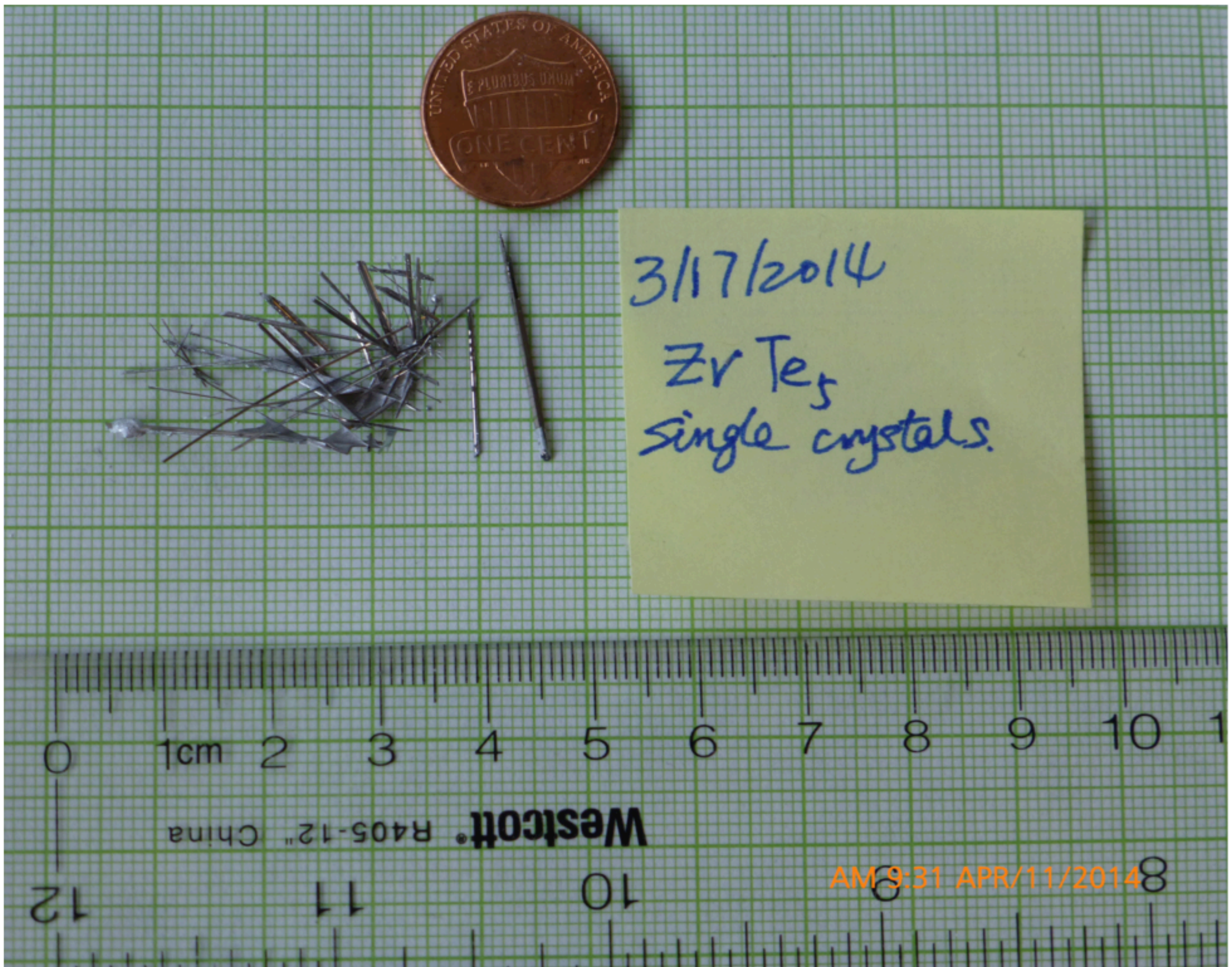

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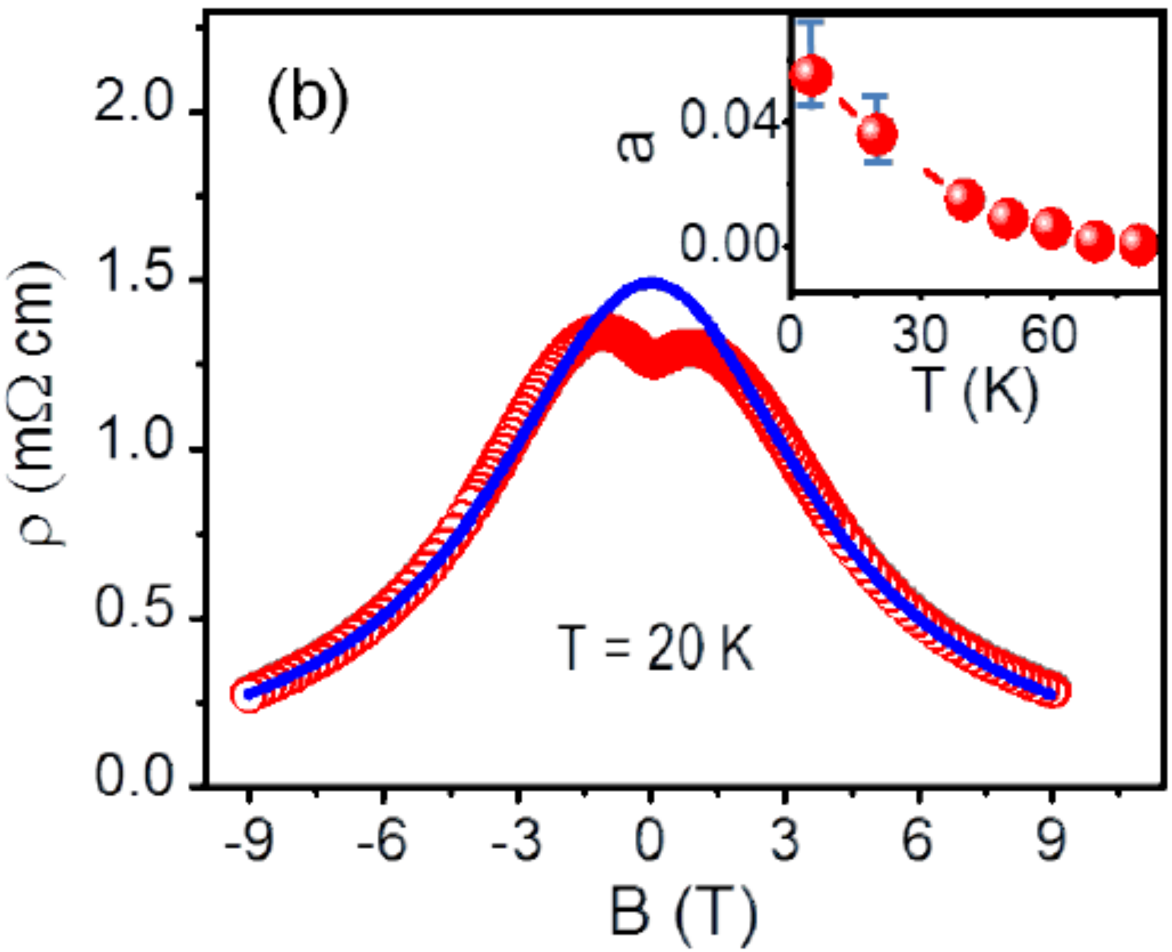
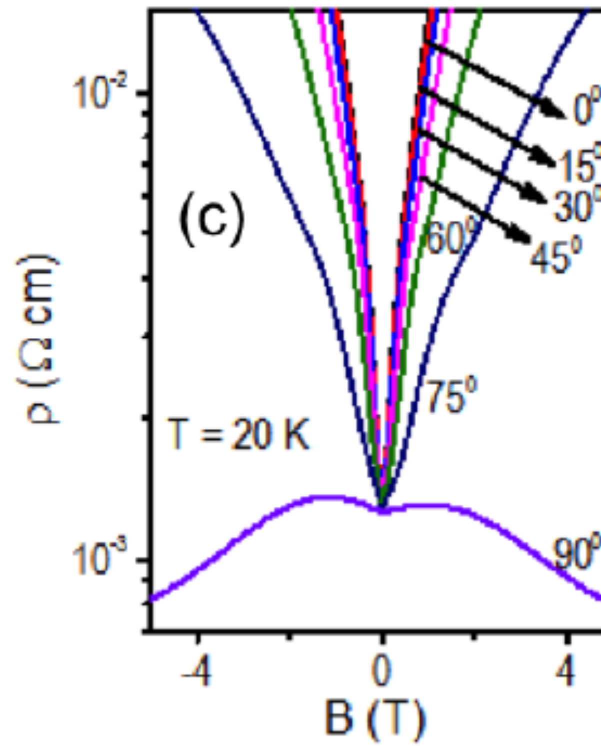
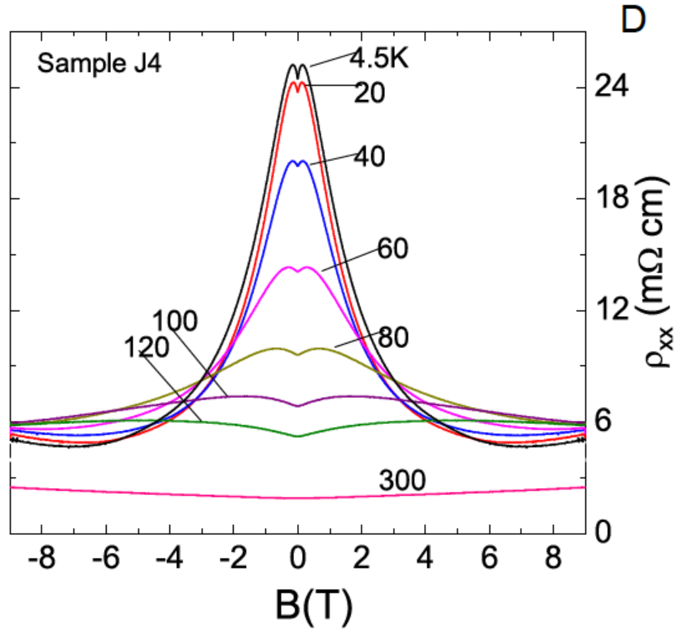




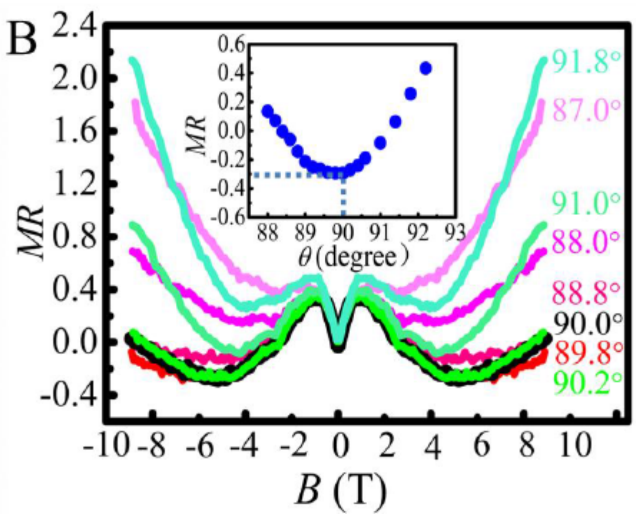
potential for applications

Na_3Bi: arxiv:1503.08179
J.Xiong et al (Princeton)

Confirmed by several recent observations

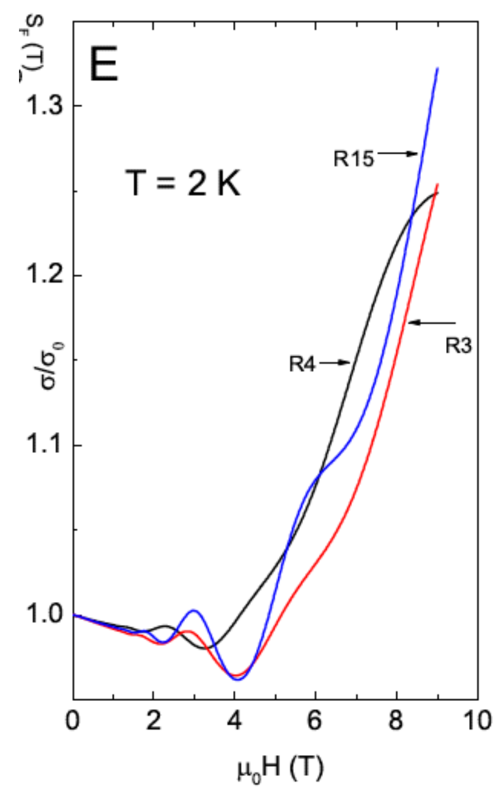


TaAs: arxiv:1503.01304
X.Huang et al (Beijing)

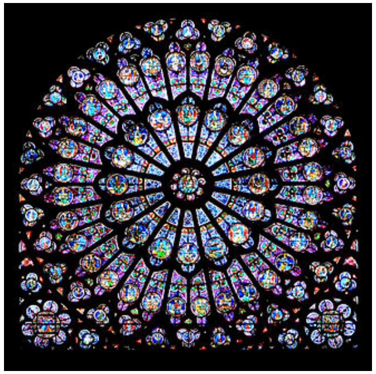


β-Ag_2Se
arxiv:1502.02324
C.Zhang et al
(Beijing-Princeton-Taiwan)

Magnetoconductance

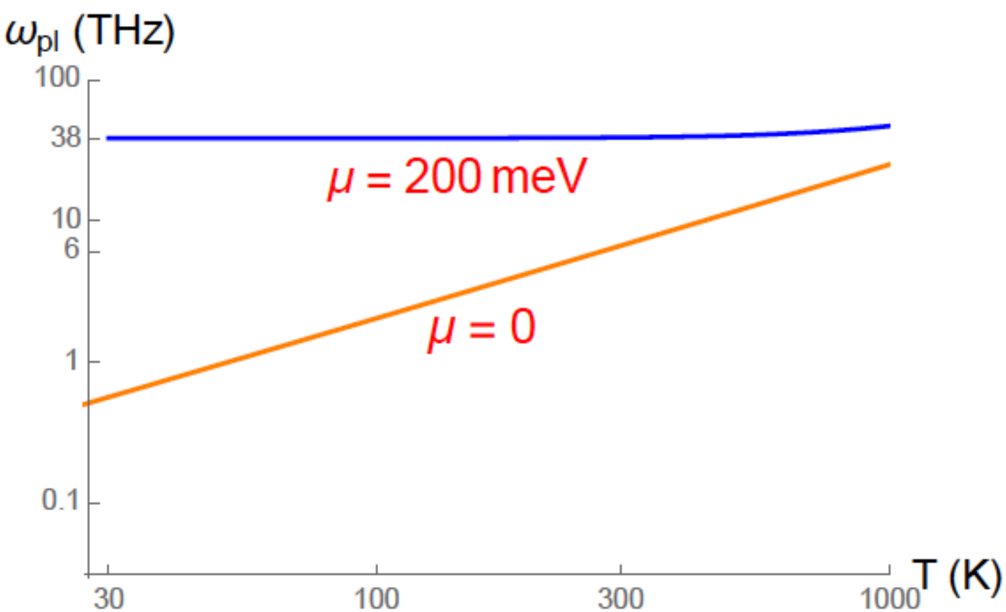


Plasmons in Dirac semimetals



DK, R. Pisarski, H.-U. Yee, arxiv: 1412.6106

Expect **universal** properties of plasmons in all Dirac semimetals



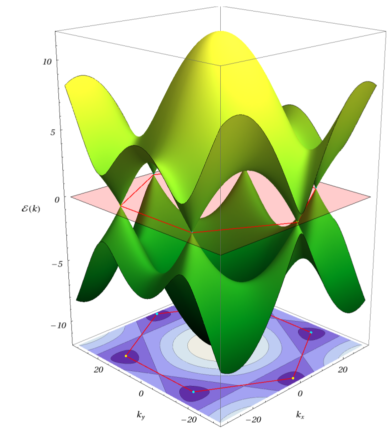
Strong coupling – but analysis made possible by **large N**

Dimensional transmutation – universality

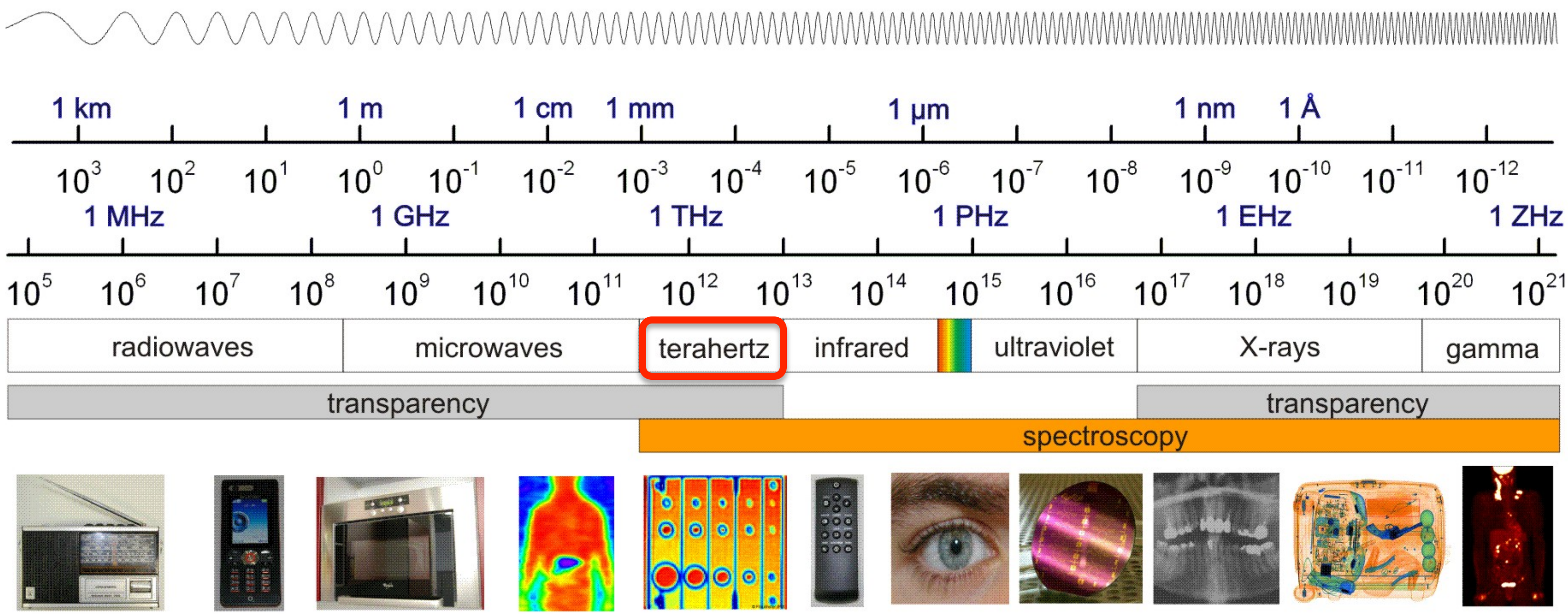
Next step: in magnetic field, plasmons mix with the CMW DK, H.U.Yee, '11

Measure at NSLS-II !

THz radiation (T-rays): the "last frontier" in electromagnetic spectrum



non-ionizing!



References: Fraunhofer IPM (9), Smiths Detection (1), Forschungszentrum Rossendorf (1)

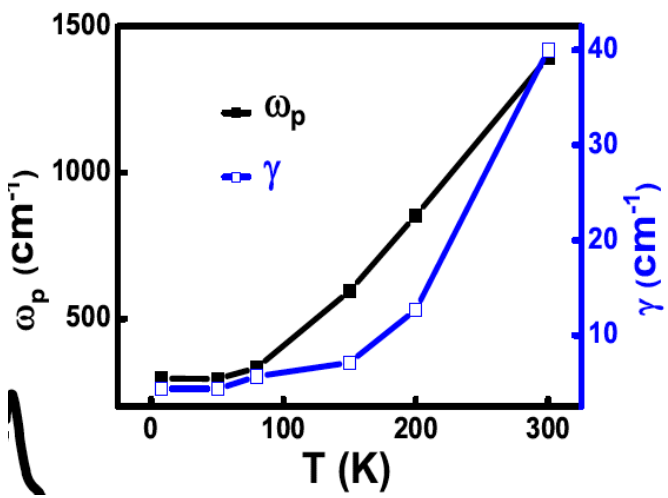
Plasmons in Dirac semimetals

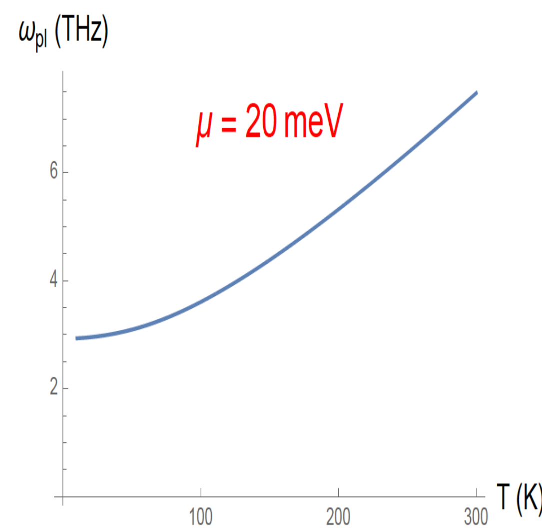
Optical spectroscopy study of three dimensional Dirac semimetal $ZrTe_5$

R. Y. Chen,[1] S. J. Zhang,[1] J. A. Schneeloch,[2] C. Zhang,[2] Q. Li,[2] G. D. Gu,[2] and N. L. Wang[1,3]

[1]International Center for Quantum Materials, School of Physics, Peking University, Beijing 100871, China
[2]Condensed Matter Physics and Materials Science Department, Brookhaven National Lab, Upton, New York 11973, USA
[3]Collaborative Innovation Center of Quantum Matter, Beijing, China

arXiv:1505.00307



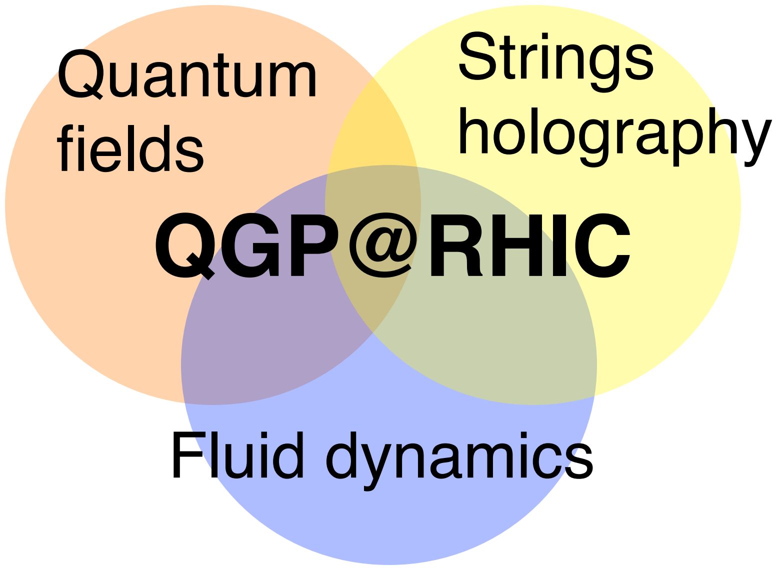


Study the CMW in Dirac semimetals at NSLS-II !

Summary

Nuclear physics

Particle physics



Condensed matter physics

Real-world applications

Cosmology

Astrophysics