PHENO 2010 Symposium, Madison, Wisconsin, May 12, 2010

Local P and CP violation in strongly interacting matter

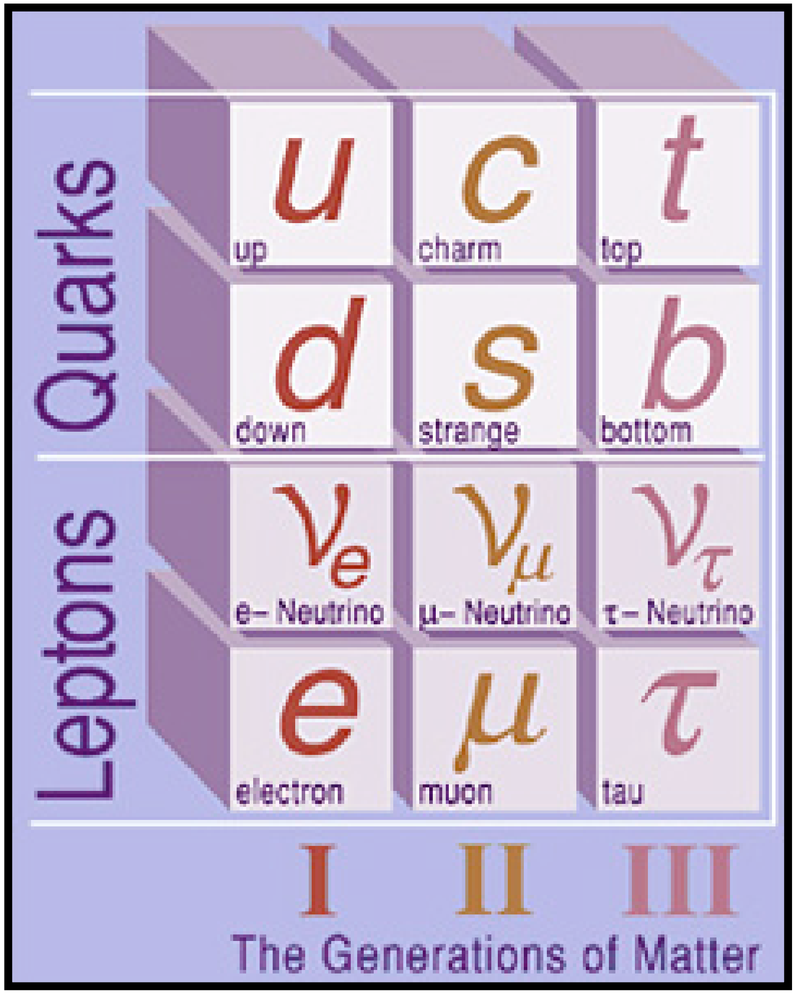
D. Kharzeev

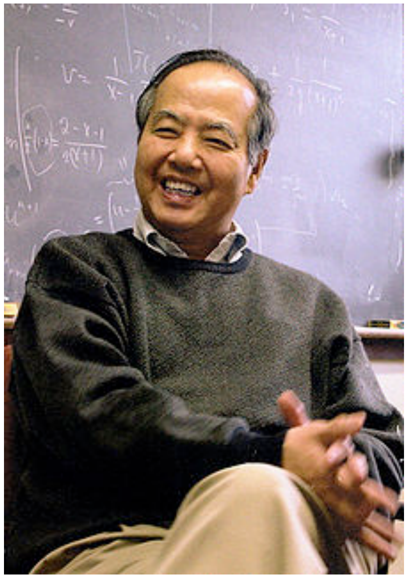
BNL

Outline

- QCD topology and the “strong CP problem”
- Chiral magnetic effect (CME) and topologically induced local P and CP violation in QCDxQED
- Recent experimental evidence at RHIC
- P and CP violation in the Early Universe

P and CP invariances are violated by weak interactions





T.D.Lee

C.N.Yang

1957

CP violation J.W.Cronin, V.L.Fitch

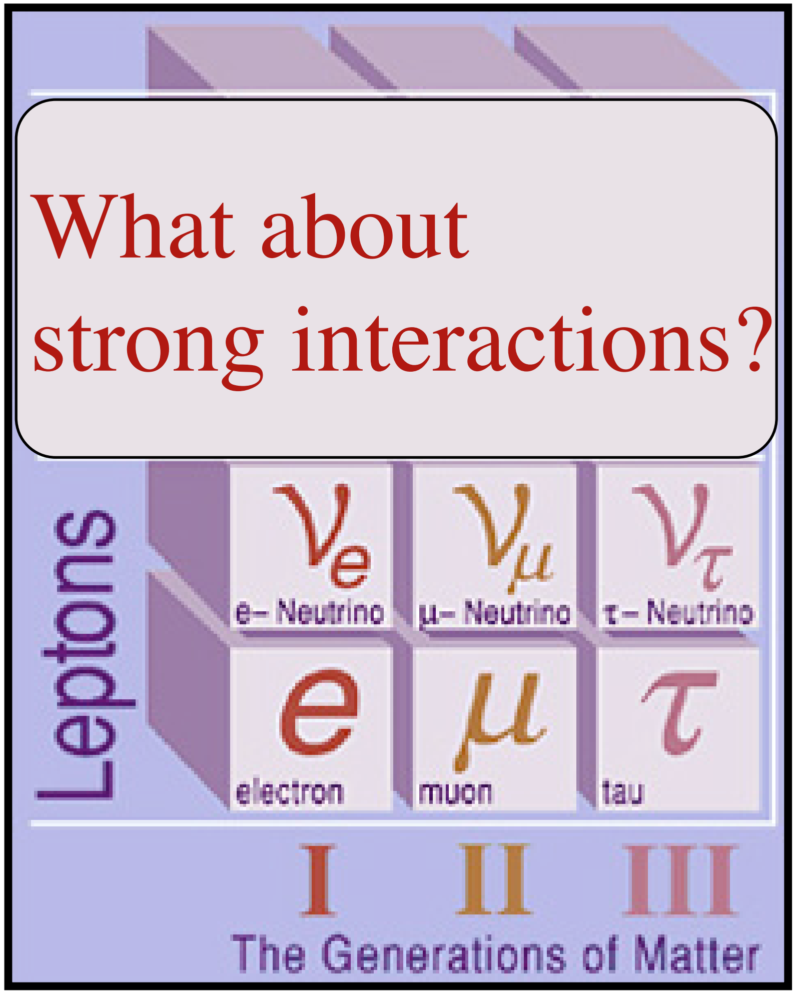
1980

Complex CKM mass matrix

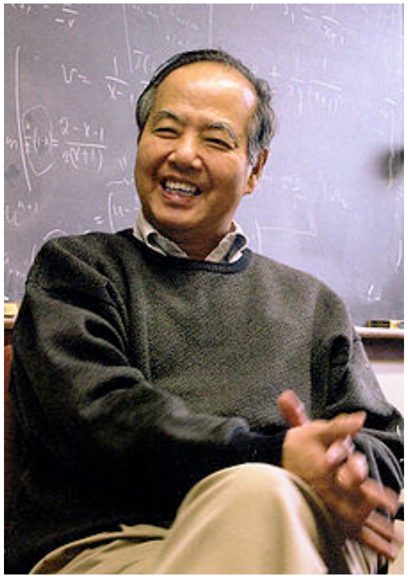
Y. Nambu, M. Kobayashi, T. Maskawa

2008

P and CP invariances are violated by weak interactions



What about strong interactions?



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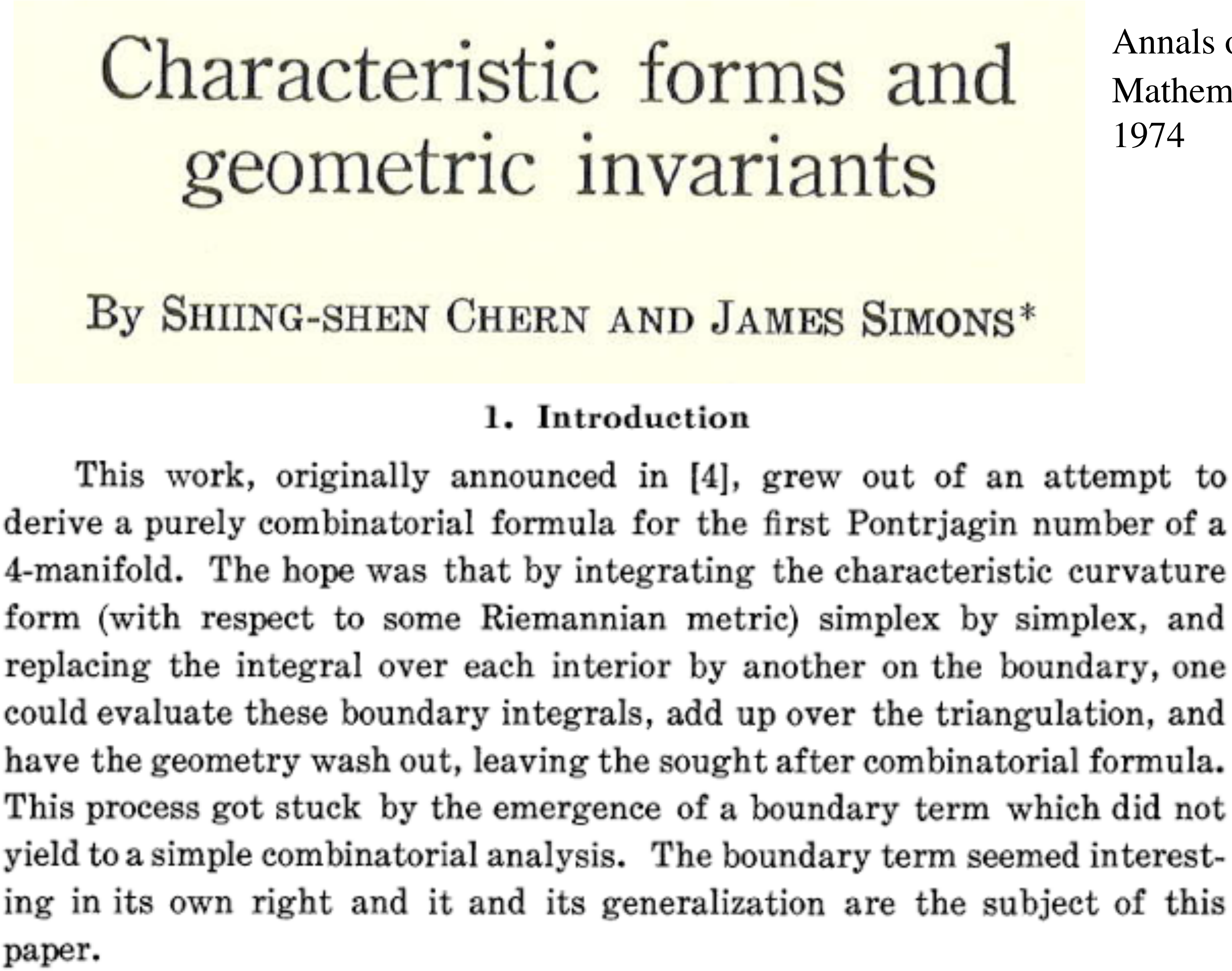
2008

Very strict experimental limits exist on the amount of global violation of P and CP invariances in strong interactions (mostly from electric dipole moments)

But: P and CP conservation in QCD is by no means a trivial issue...

Can a local P and CP violation occur in QCD matter?

Annals of
Mathematics,
1974



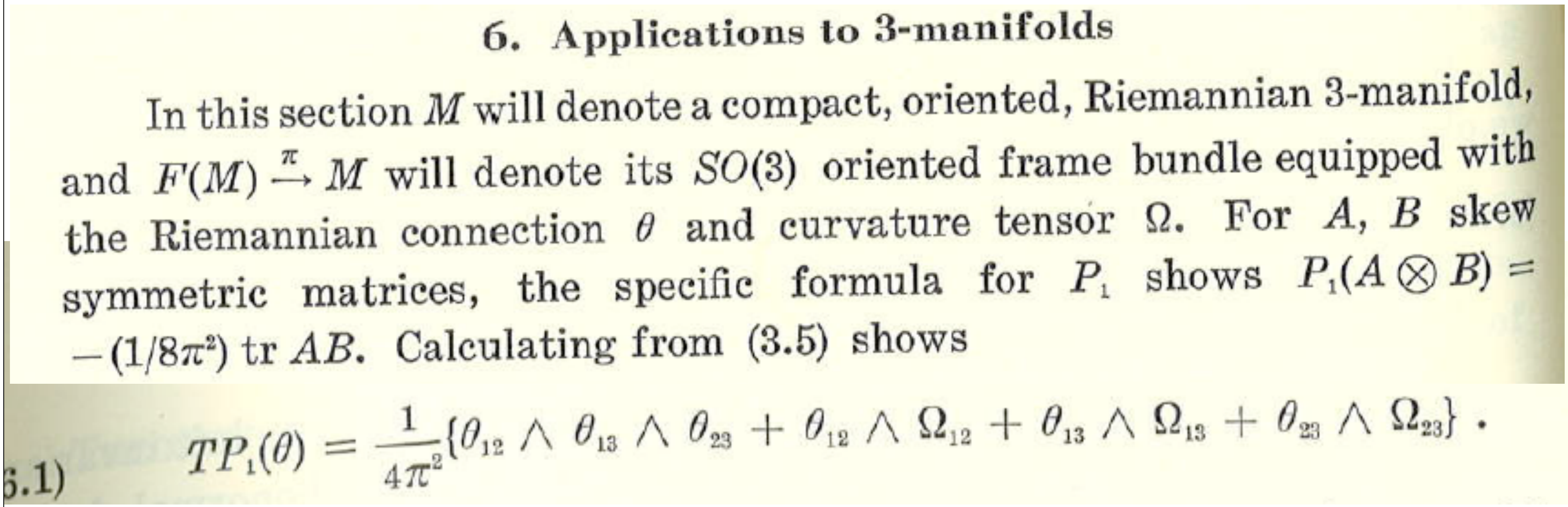
Characteristic forms and geometric invariants

By Shiing-shen Chern and James Simons*

1. Introduction

This work, originally announced in [4], grew out of an attempt to derive a purely combinatorial formula for the first Pontrjagin number of a 4-manifold. The hope was that by integrating the characteristic curvature form (with respect to some Riemannian metric) simplex by simplex, and replacing the integral over each interior by another on the boundary, one could evaluate these boundary integrals, add up over the triangulation, and have the geometry wash out, leaving the sought after combinatorial formula. This process got stuck by the emergence of a boundary term which did not yield to a simple combinatorial analysis. The boundary term seemed interesting in its own right and it and its generalization are the subject of this paper.

Chern-Simons forms



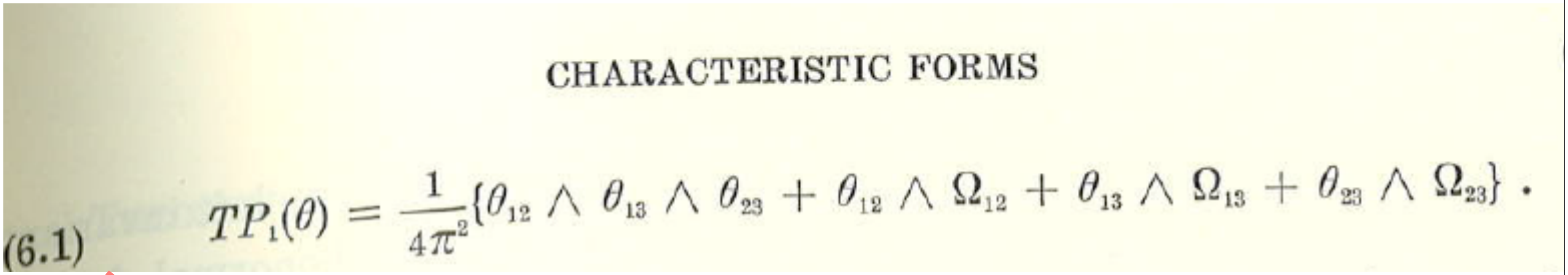
6. Applications to 3-manifolds

In this section M will denote a compact, oriented, Riemannian 3-manifold, and $F(M) \xrightarrow{\pi} M$ will denote its $SO(3)$ oriented frame bundle equipped with the Riemannian connection θ and curvature tensor Ω. For A, B skew symmetric matrices, the specific formula for P_1 shows $P_1(A \otimes B) = -(1/8\pi^2)\ \mathrm{tr}\ AB$. Calculating from (3.5) shows

6.1)
$$TP_1(\theta) = \frac{1}{4\pi^2}\{\theta_{12} \wedge \theta_{13} \wedge \theta_{23} + \theta_{12} \wedge \Omega_{12} + \theta_{13} \wedge \Omega_{13} + \theta_{23} \wedge \Omega_{23}\}\ .$$

What does it mean for a gauge theory?

Chern-Simons theory



CHARACTERISTIC FORMS

$$TP_1(\theta) = \frac{1}{4\pi^2}\{\theta_{12}\wedge\theta_{13}\wedge\theta_{23} + \theta_{12}\wedge\Omega_{12} + \theta_{13}\wedge\Omega_{13} + \theta_{23}\wedge\Omega_{23}\}\,. \tag{6.1}$$

What does it mean for a gauge theory?

Geometry ↔ **Physics**

Riemannian connection ↔ Gauge field

Curvature tensor ↔ Field strength tensor

$$\boxed{S_{CS} = \frac{k}{8\pi}\int_M d^3x\ \epsilon^{ijk}\left(A_iF_{jk} + \frac{2}{3}A_i[A_j, A_k]\right)}$$

Abelian non-Abelian

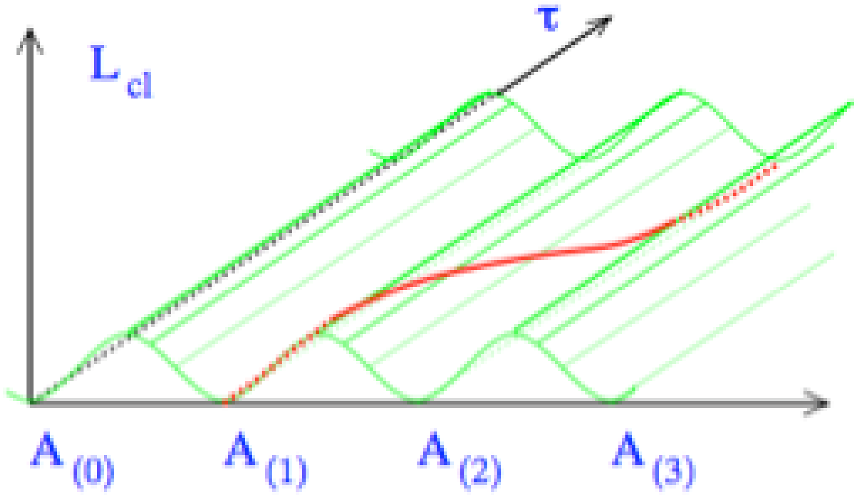
Chern-Simons theory

$$S_{CS} = \frac{k}{8\pi} \int_M d^3x \; \epsilon^{ijk} \left(A_i F_{jk} + \frac{2}{3} A_i [A_j, A_k] \right)$$

Remarkable novel properties:

- gauge invariant, up to a boundary term
- topological - does not depend on the metric, knows only about the topology of space-time **M**
- when added to Maxwell action, induces a mass for the gauge boson - different from the Higgs mechanism!
- **breaks Parity invariance**

QCD vacuum as a Bloch crystal



"θ - vacuum"

$$|\theta\rangle = \sum_q e^{i\theta q}|q\rangle$$

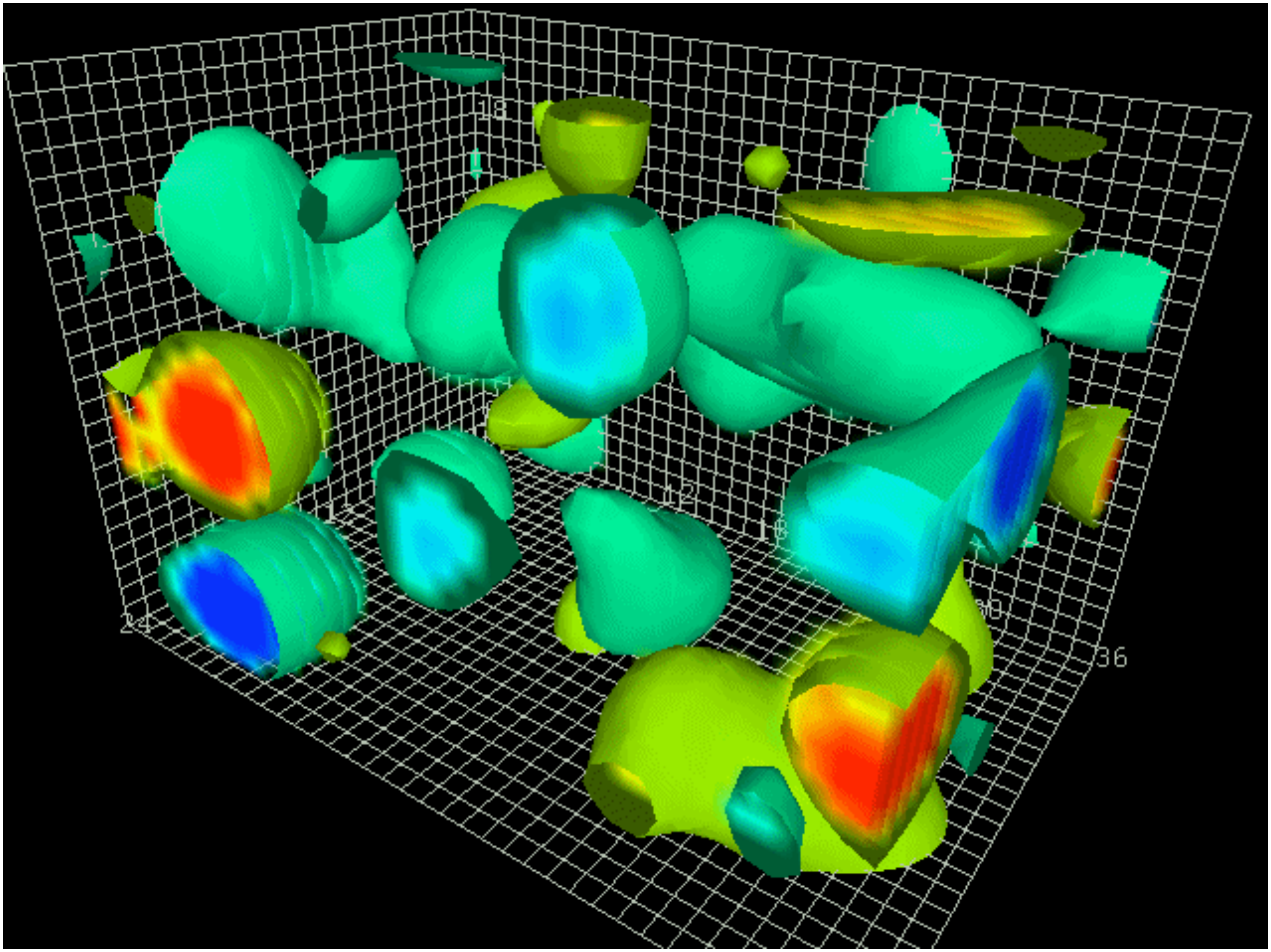
$$\langle\mathcal{O}\rangle = \sum_q f(q)\int_q D[\psi]D[\bar{\psi}]D[A]\exp(iS_{QCD})\mathcal{O}(\psi,\bar{\psi},A)$$

$$f(q_1+q_2) = f(q_1)f(q_2) \longrightarrow f(q) = \exp(i\theta q)$$

85

"quasi-momentum" "coordinate"

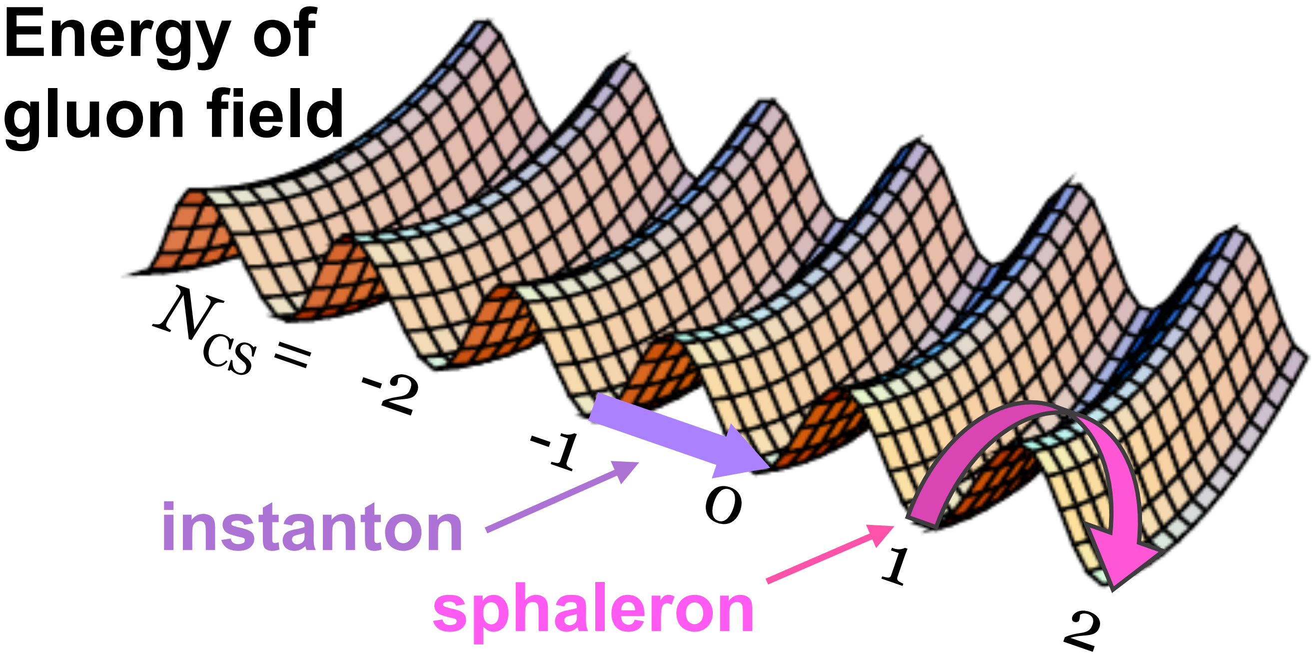
Topological number fluctuations in QCD vacuum



D. Leinweber

Sphaleron transitions
at finite energy or temperature

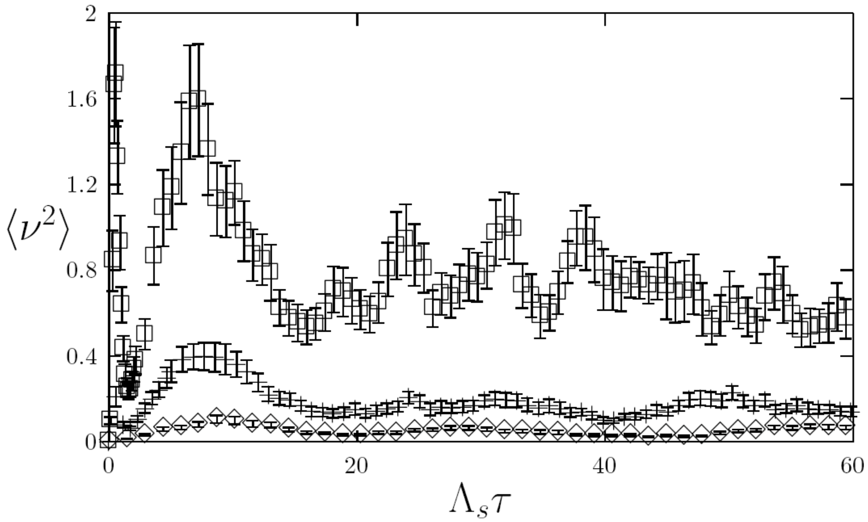
$$\Gamma = \frac{1}{2} \lim_{t\to\infty} \lim_{V\to\infty} \int_0^t \langle (q(x)q(0) + q(0)q(x)) \rangle d^4x$$



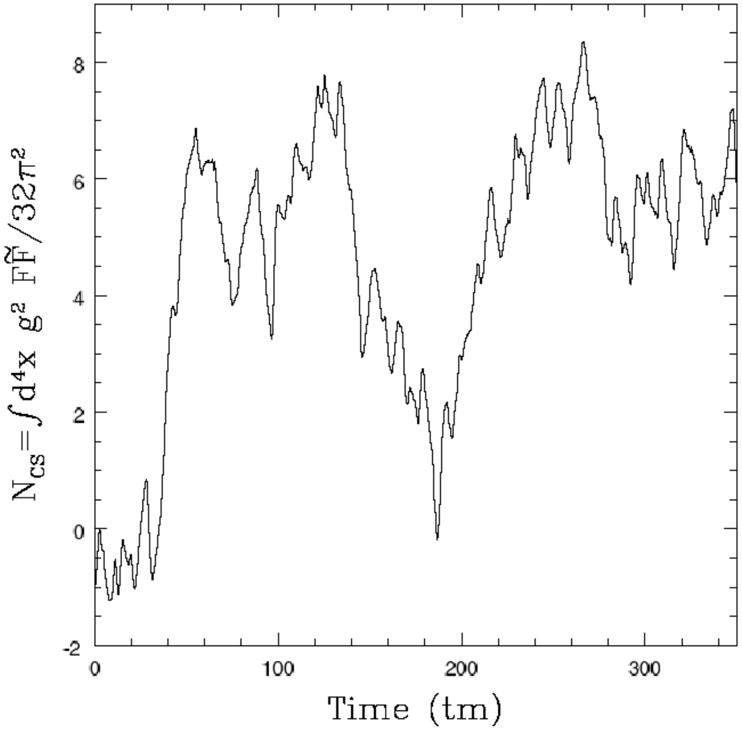
Sphalerons:
random walk of
topological charge at finite T:

$$\langle Q^2 \rangle = 2\Gamma V t, \quad t \to \infty$$

Diffusion of Chern-Simons number in QCD: real time lattice simulations

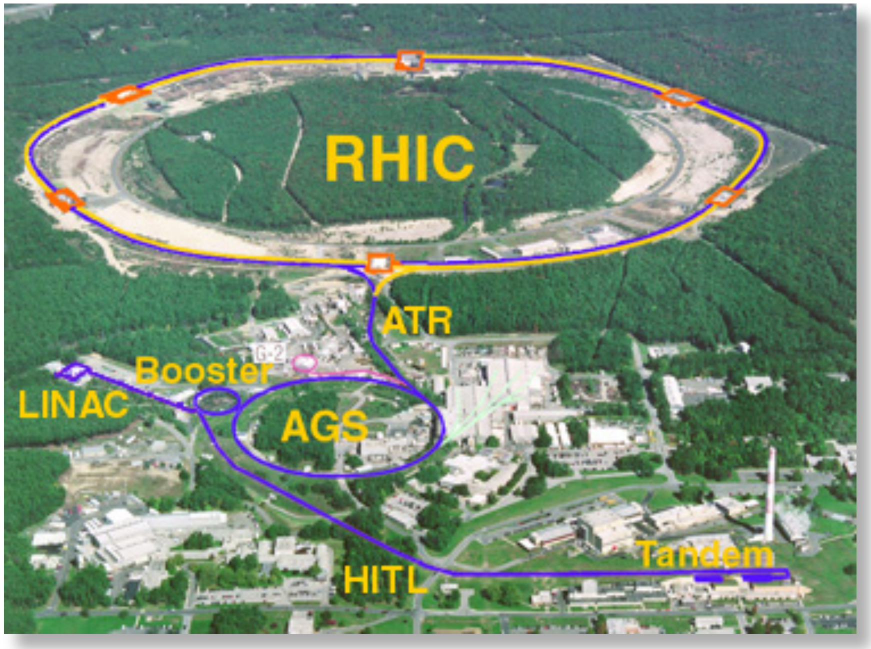


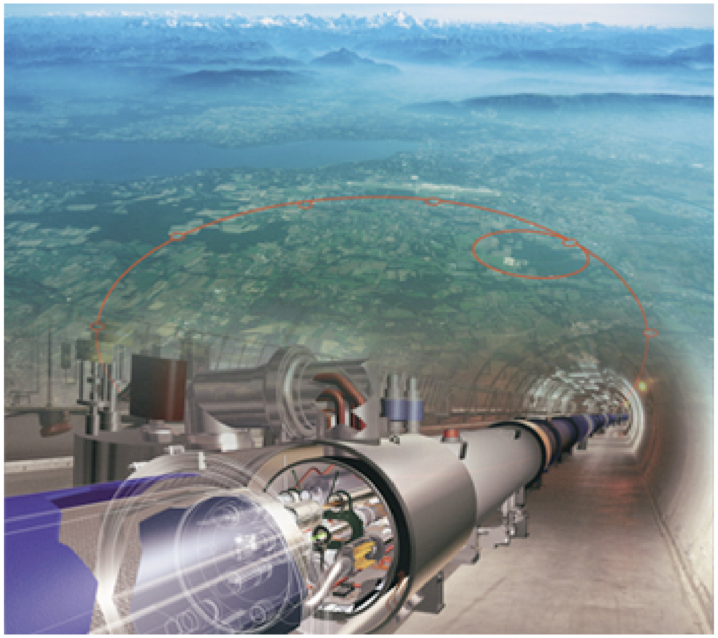
DK, A.Krasnitz and R.Venugopalan,
Phys.Lett.B545:298-306,2002



P.Arnold and G.Moore,
Phys.Rev.D73:025006,2006

Experimental test of Chern-Simons dynamics in hot QCD: Heavy ion collisions



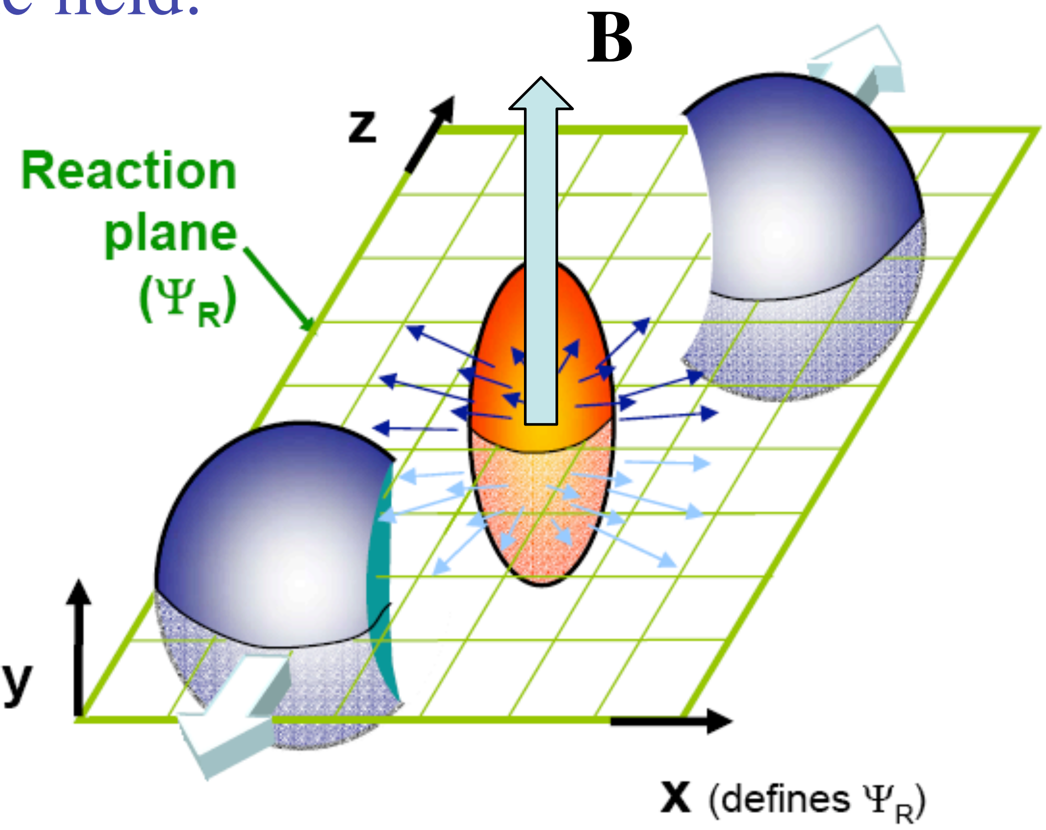


LHC

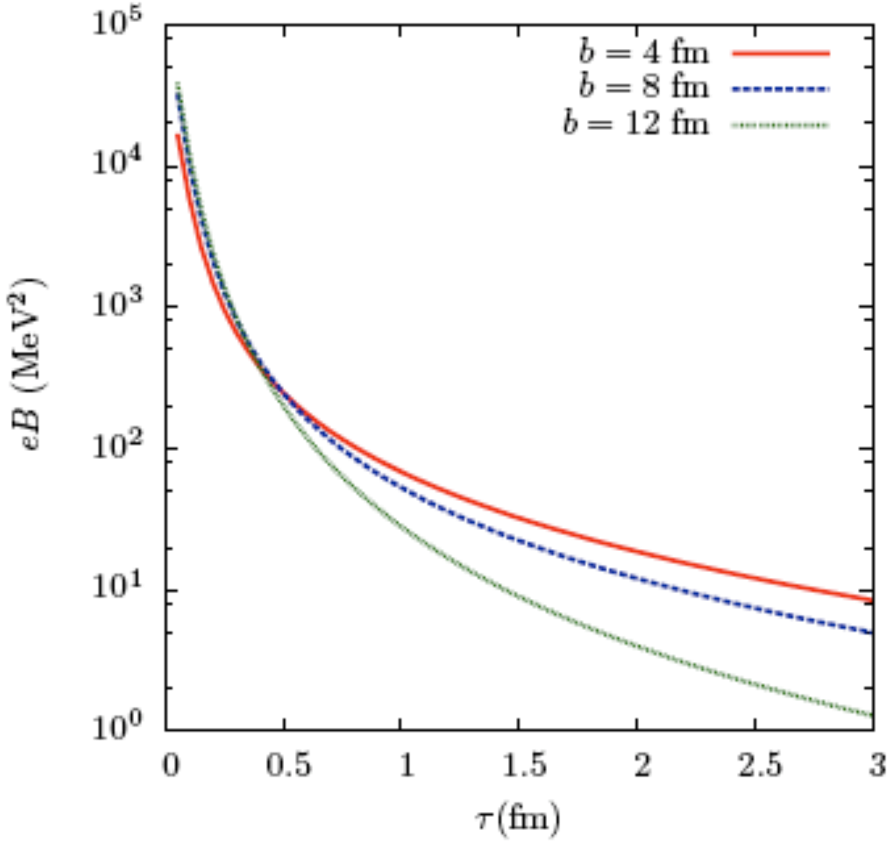
NICA,
JINR

Is there a way to observe topological charge fluctuations in experiment?

Relativistic ions create
a strong magnetic field:



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



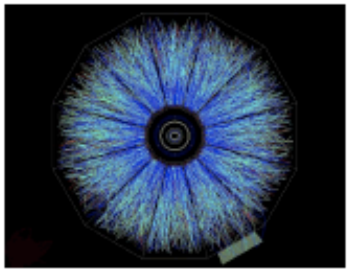
DK, McLerran, Warringa,
Nucl Phys A803(2008)227

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 x 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

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

From QCD back to electrodynamics: Maxwell-Chern-Simons (axion) theory

$$\mathcal{L}_{\mathrm{MCS}} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} - A_\mu J^\mu + \frac{c}{4}\, P_\mu J^\mu_{CS}$$

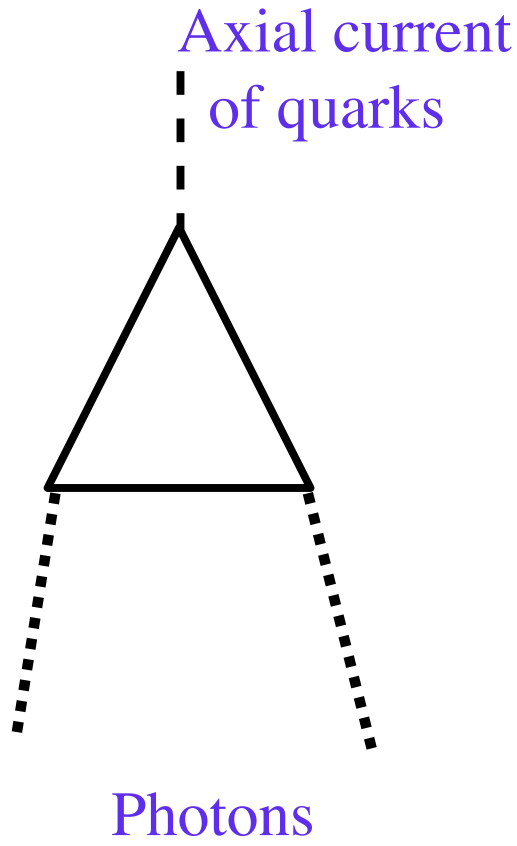
$$J^\mu_{CS} = \epsilon^{\mu\nu\rho\sigma}A_\nu F_{\rho\sigma} \qquad P_\mu = \partial_\mu \theta = (\dot{\theta}, \vec{P})$$

$$\vec{\nabla}\times\vec{B} - \frac{\partial \vec{E}}{\partial t} = \vec{J} + \underline{c\left(\dot{\theta}\vec{B} - \vec{P}\times\vec{E}\right)},$$

$$\vec{\nabla}\cdot\vec{E} = \rho + \underline{c\vec{P}\cdot\vec{B},}$$

$$\vec{\nabla}\times\vec{E} + \frac{\partial \vec{B}}{\partial t} = 0,$$

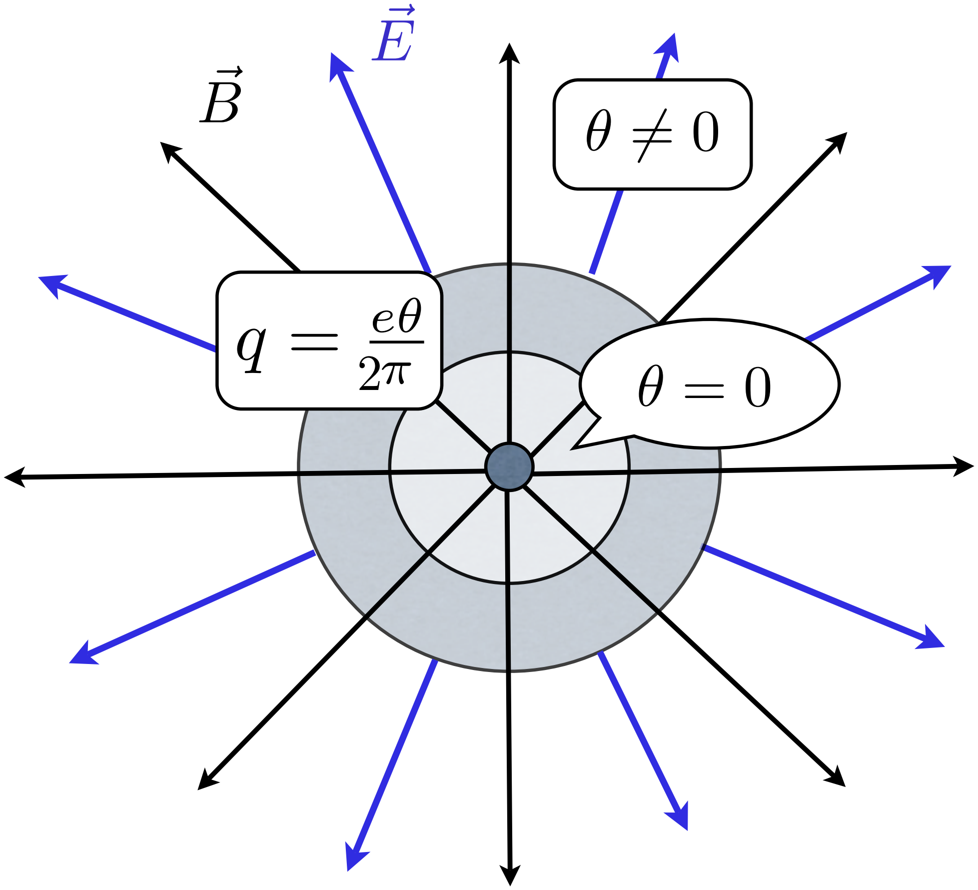
$$\vec{\nabla}\cdot\vec{B} = 0,$$



Magnetic monopole at finite θ : the Witten effect

$$\vec{\nabla} \cdot \vec{E} = \rho + c\vec{P} \cdot \vec{B}$$

$$\vec{P} \equiv \vec{\nabla}\theta$$



E. Witten;

F. Wilczek

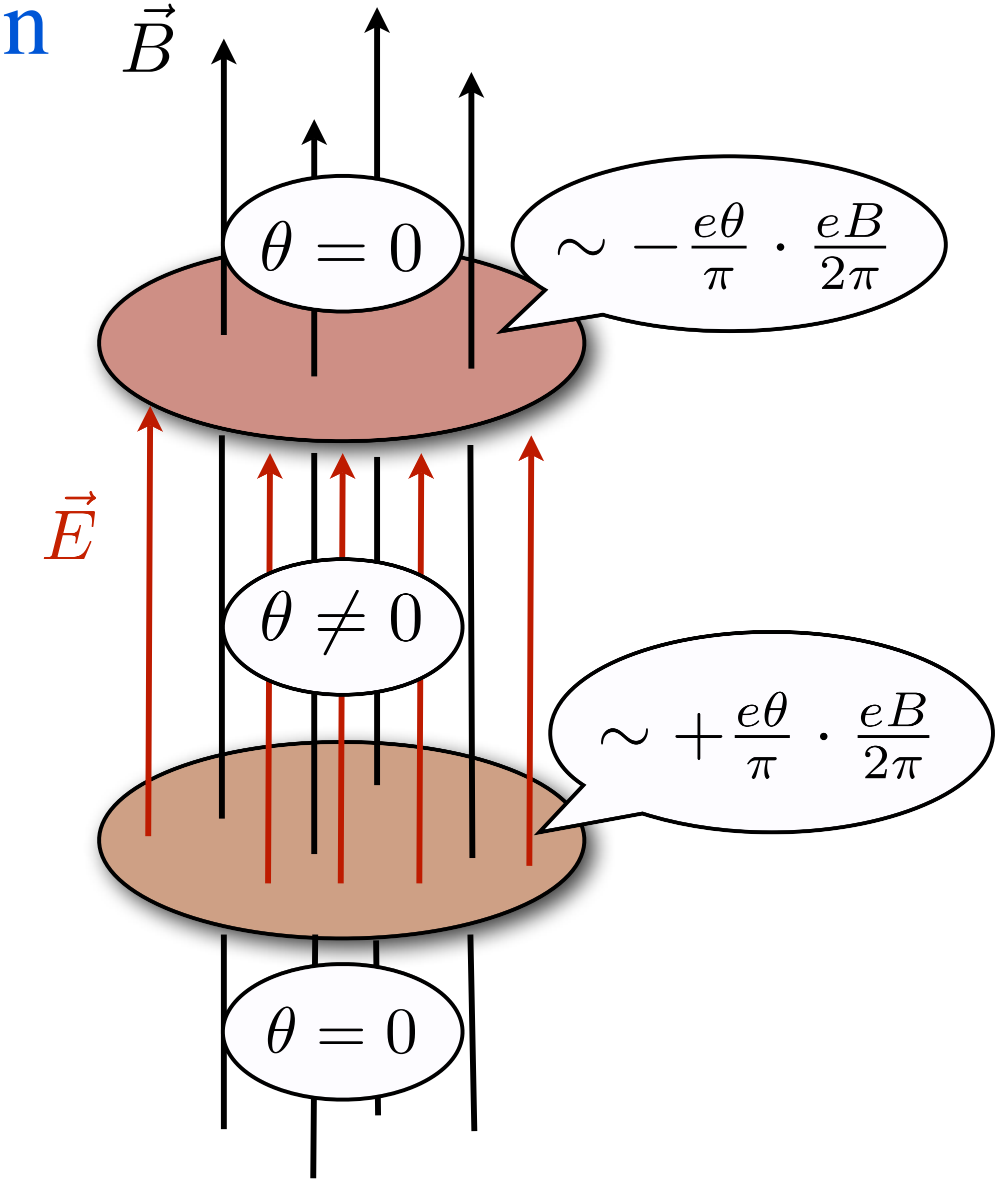
Induced electric charge: $q = c\,\theta\,g = \frac{e^2}{2\pi^2}\,\theta\,g = \frac{e}{2\pi^2}\,\theta\,(eg) = e\,\frac{\theta}{2\pi}$

The Chiral Magnetic Effect I:
Charge separation

$$\vec{\nabla} \cdot \vec{E} = \rho + c\vec{P} \cdot \vec{B}$$

$$\vec{P} \equiv \vec{\nabla}\theta$$

$$\boxed{d_e = \sum_f q_f^2 \left(e\,\frac{\theta}{\pi}\right) \left(\frac{eB \cdot S}{2\pi}\right) L}$$

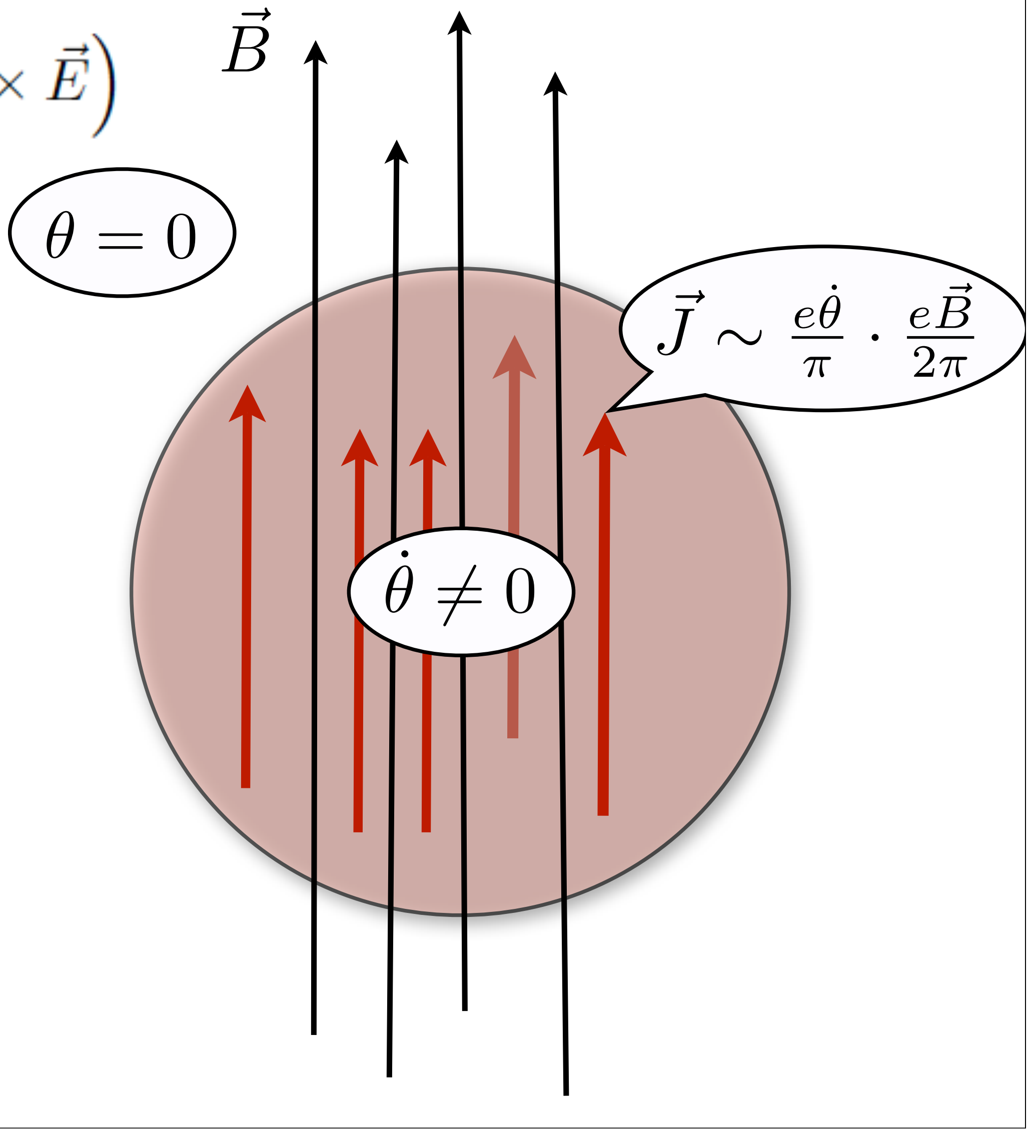


DK ’04;
DK, A. Zhitnitsky ’06;
DK arXiv:0911.3715; Annals of Physics (2010)

The chiral magnetic effect II: chiral induction

$$\vec{\nabla} \times \vec{B} - \frac{\partial \vec{E}}{\partial t} = \vec{J} + c\left(\dot{\theta}\vec{B} - \vec{P} \times \vec{E}\right)$$

$$\boxed{\vec{J} = -\frac{e^2}{2\pi^2}\dot{\theta}\vec{B}}$$



DK, L. McLerran, H. Warringa ’07;
K. Fukushima, DK, H. Warringa ’08;
DK, H.Warringa arXiv:0907.5007

Computing the induced current

Fukushima, DK, Warringa, ‘08

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

In this background, vector e.m. current is not conserved:

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

Compute the current through

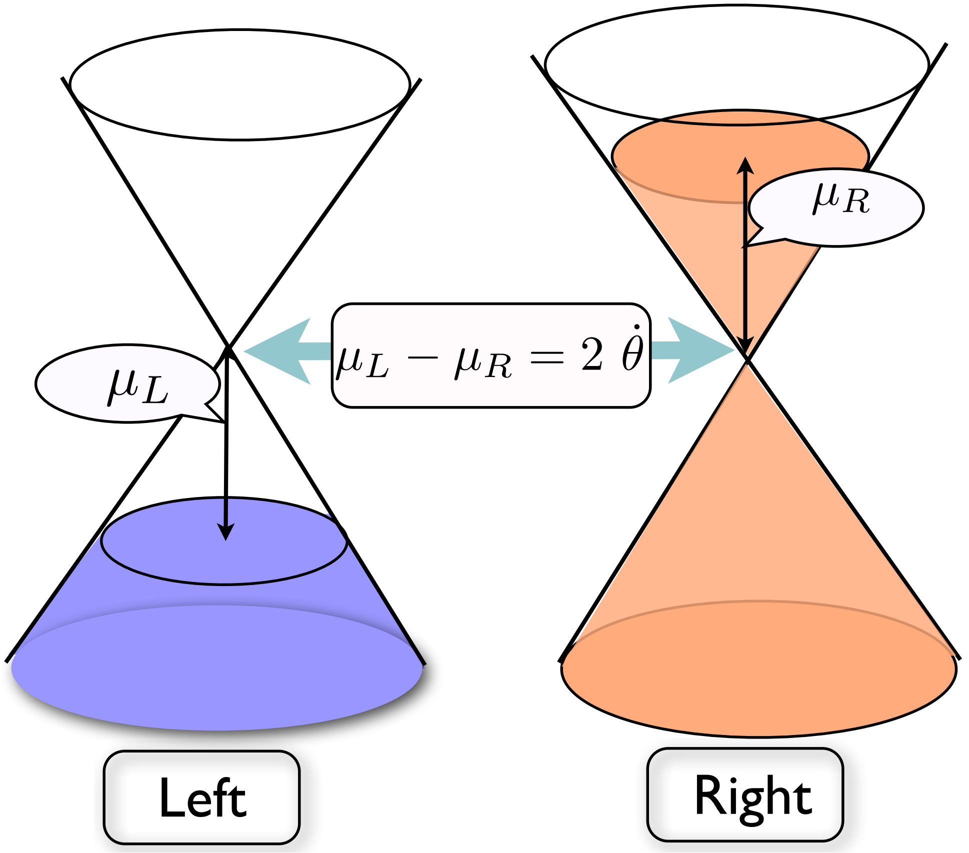
$$J^\mu = \frac{\partial \log Z[A_\mu, A_\mu^5]}{\partial A_\mu(x)}$$

The result:

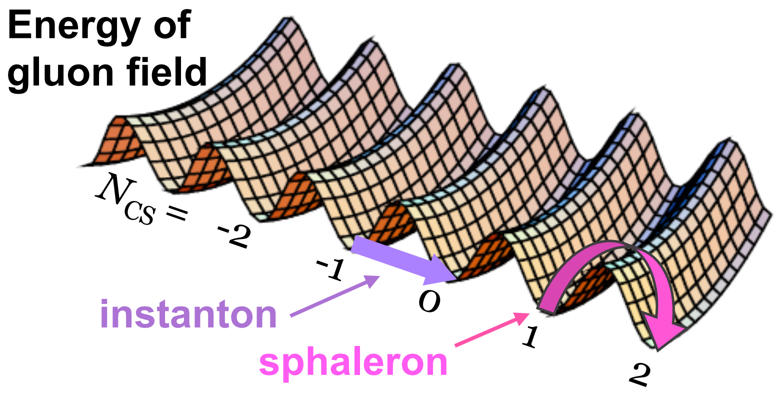
$$\boxed{\vec{J} = \frac{e^2}{2\pi^2}\, \mu_5\, \vec{B}}$$

Coefficient is fixed by the axial anomaly, no corrections

What powers the CME current?



$$\mu_L - \mu_R = 2\,\dot{\theta}$$



$$\text{Power} = \text{Force} \times \text{Velocity}$$

$$P = \int d^3x\; \vec{J}\cdot\vec{E} = -\dot{\theta}\,\frac{e^2}{2\pi^2}\int d^3x\; \vec{E}\cdot\vec{B} = -\dot{\theta}\;\dot{Q}_5$$

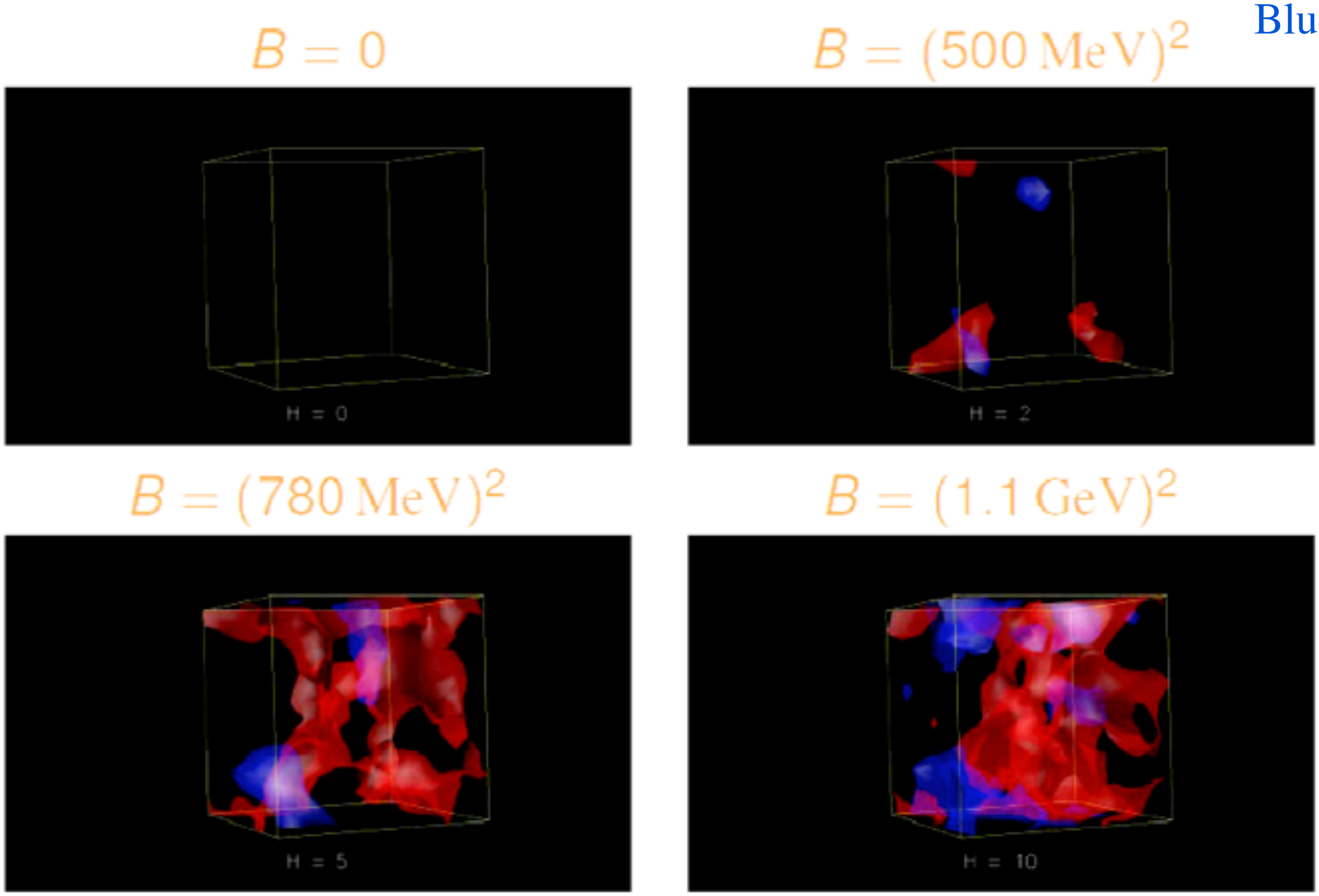
“Numerical evidence for chiral magnetic effect in lattice gauge theory”,

P. Buividovich, M. Chernodub, E. Luschevskaya, M. Polikarpov, ArXiv 0907.0494; PRD’09

Density of the electric charge vs. magnetic field, 3D time slices

Red - positive charge

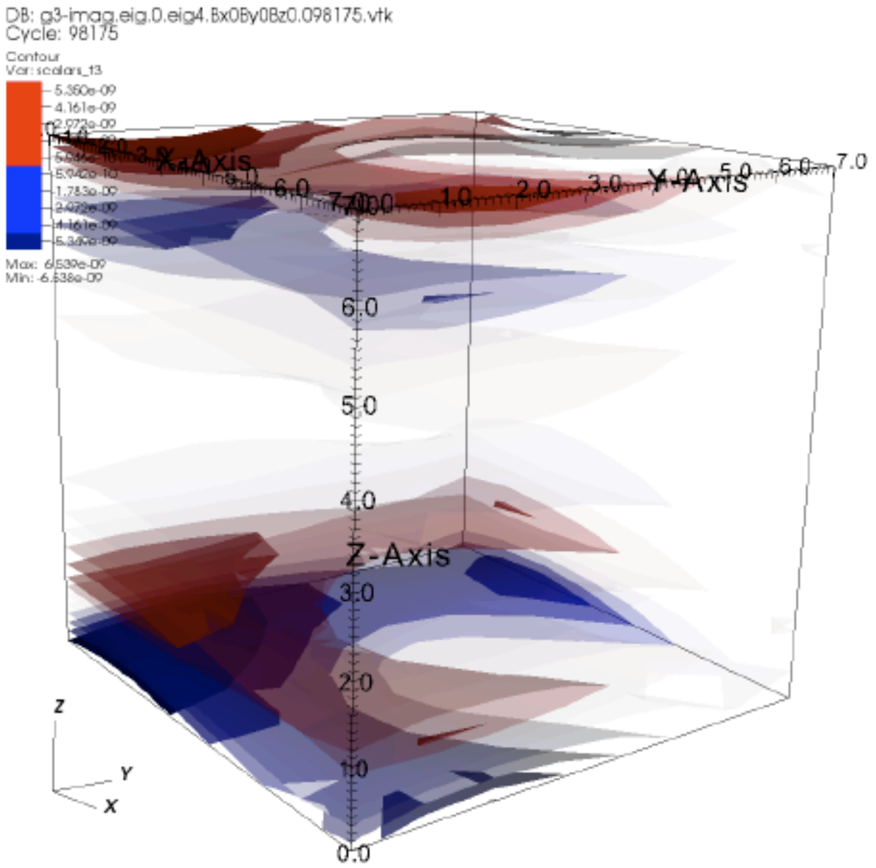
Blue - negative charge

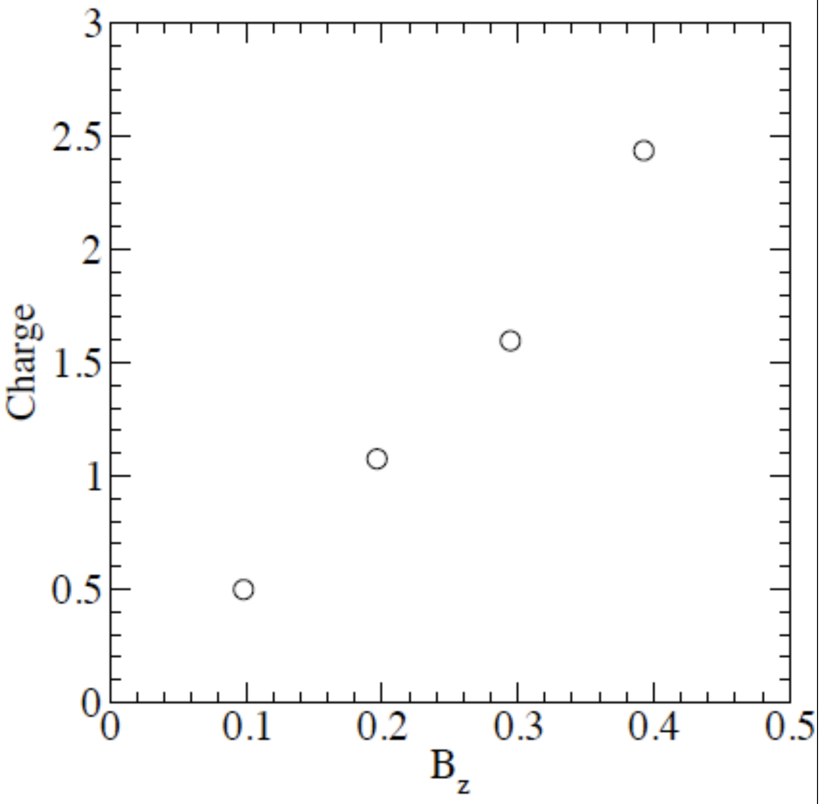


“Chiral magnetic effect in 2+1 flavor QCD+QED”,

M. Abramczyk, T. Blum, G. Petropoulos, R. Zhou, ArXiv 0911.1348;
Columbia-Bielefeld-RIKEN-BNL

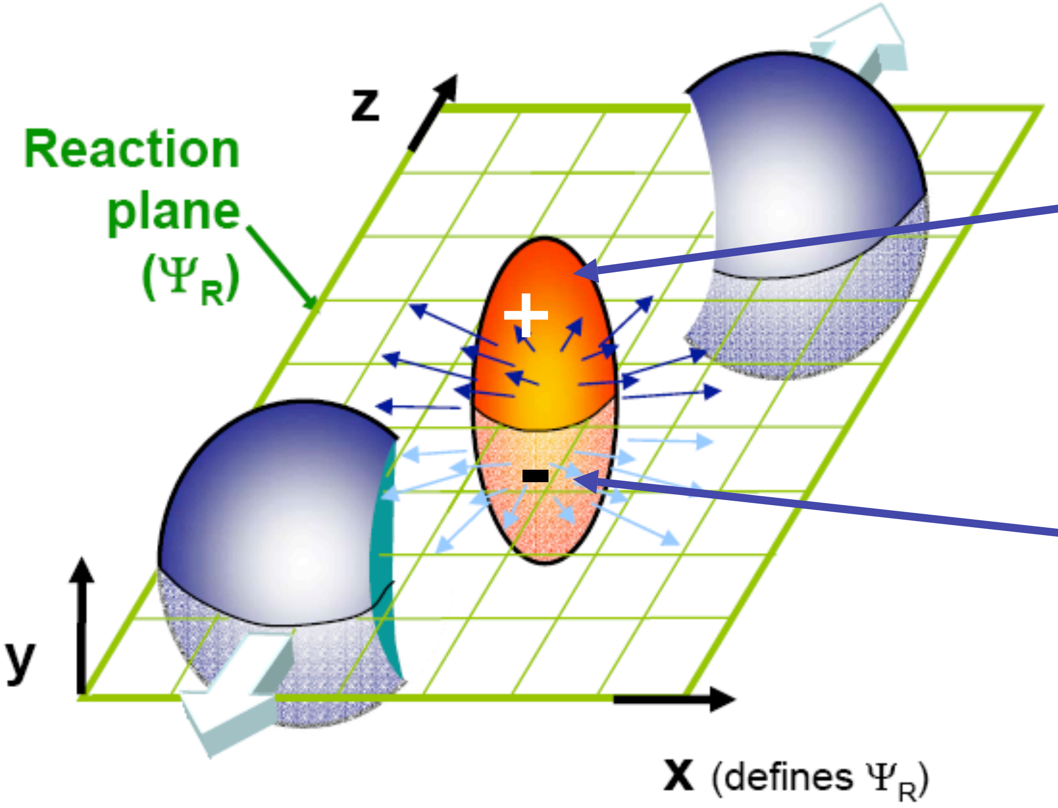
Red - positive charge
Blue - negative charge





2+1 flavor Domain Wall Fermions, fixed topological sectors, 16^3 x 8 lattice

Charge asymmetry w.r.t. reaction plane as a signature of local strong P violation



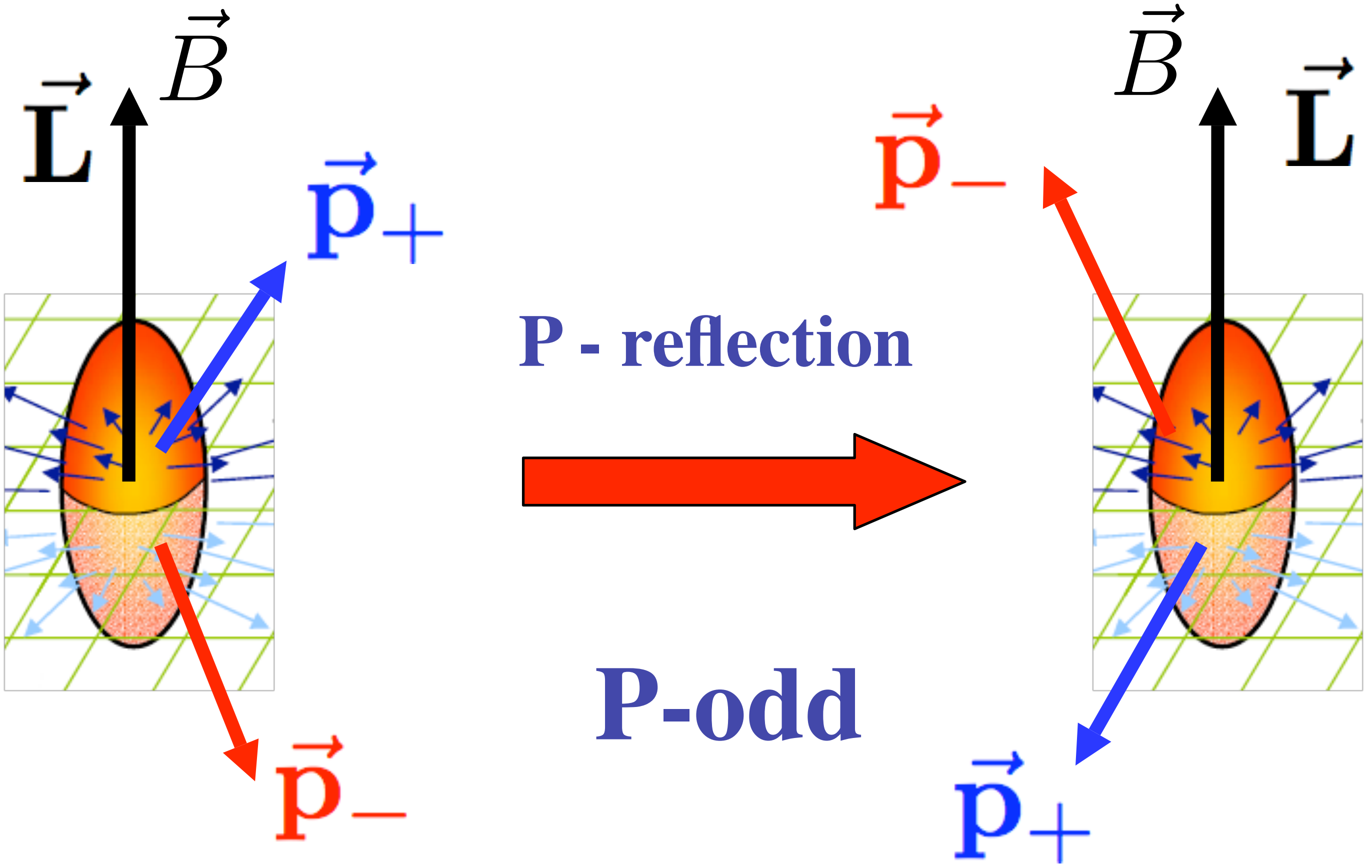
excess of positive charge

excess of negative charge

Electric dipole moment of QCD matter!

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

Charge separation = parity violation:



P-odd

$$\mathcal{P}: \quad \vec{p} \longrightarrow -\vec{p}; \quad \vec{B} \longrightarrow \vec{B}; \quad \vec{L} \longrightarrow \vec{L}$$

PRL **103,** 251601 (2009)

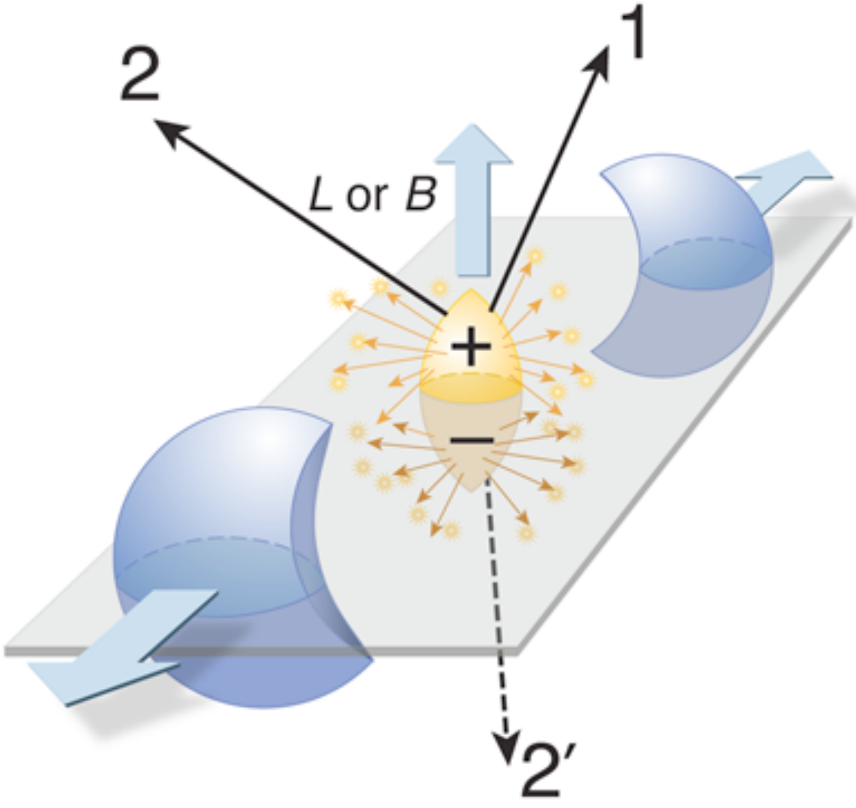
Selected for a Viewpoint in *Physics*

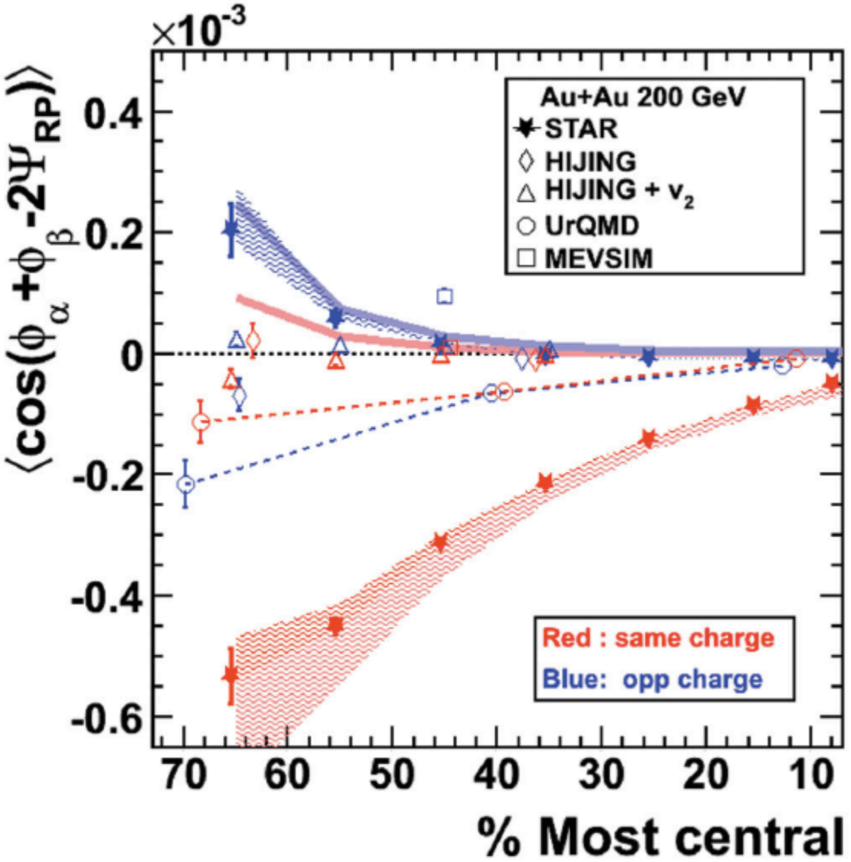
PHYSICAL REVIEW LETTERS

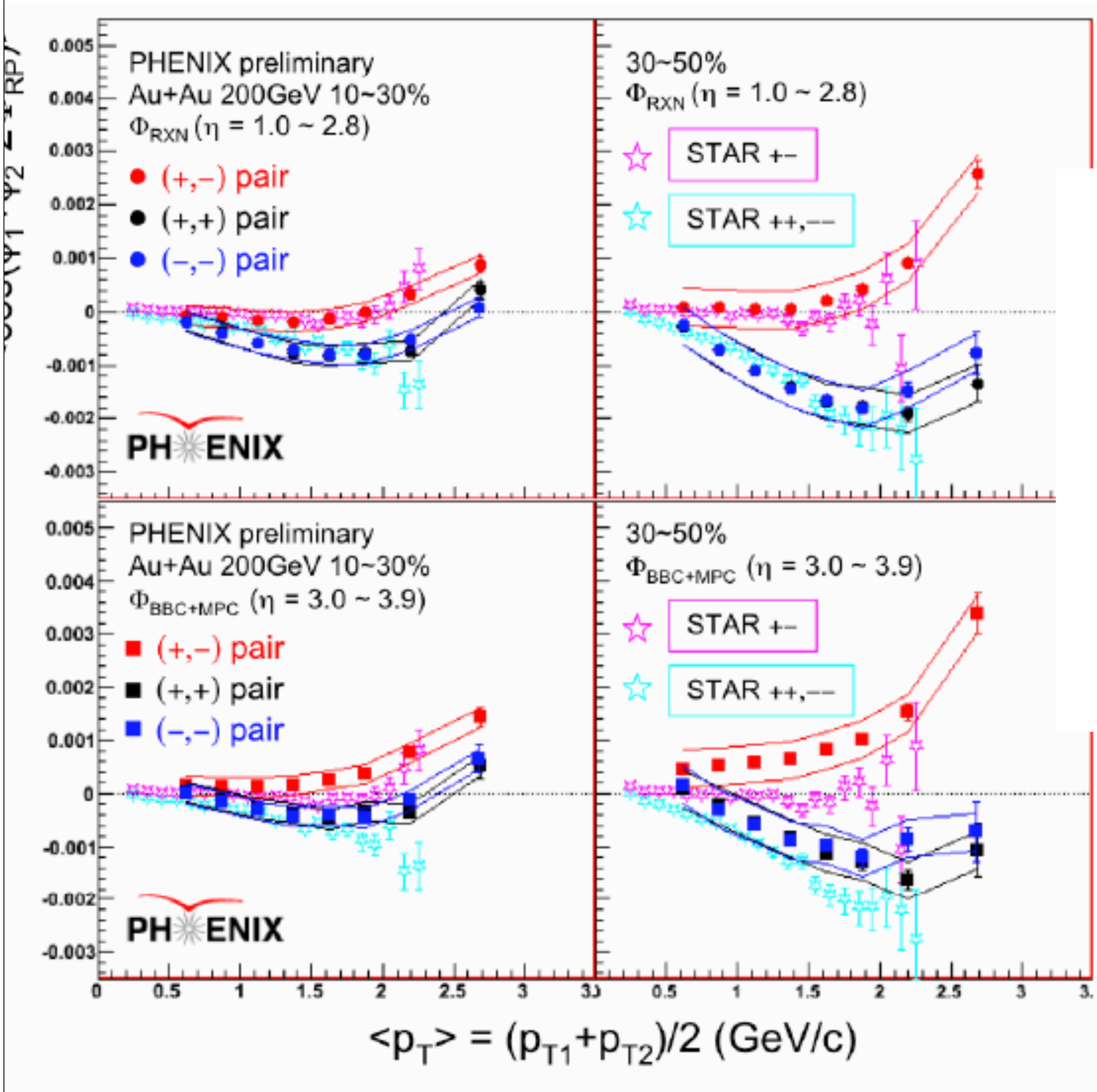
week ending
18 DECEMBER 2009

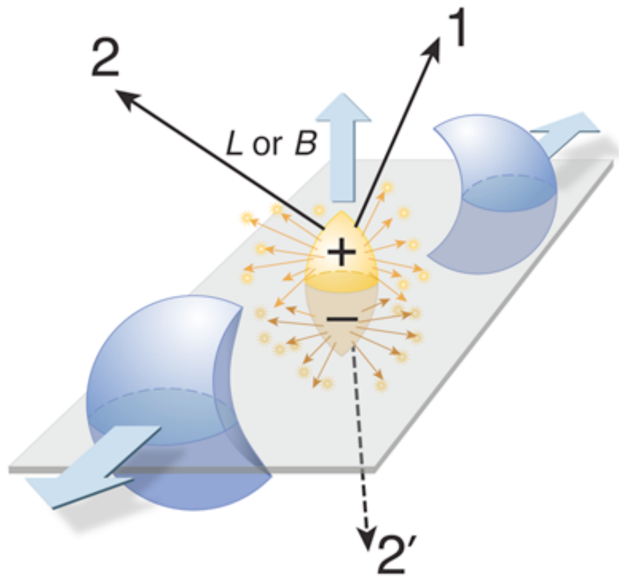
Azimuthal Charged-Particle Correlations and Possible Local Strong Parity Violation

(STAR Collaboration)









Relatively good agreement between PHENIX & STAR

The New York Times

In Brookhaven Collider, Scientists Briefly Break a Law of Nature

By DENNIS OVERBYE
Published: February 15, 2010

Physicists said Monday that they had whacked a tiny region of space with enough energy to briefly distort the laws of physics providing the first laboratory demonstration of the kind of process that scientists suspect has shaped cosmic history.

Newsweek

Quark Soup

Physicists create conditions not seen since the big bang.

Feb 16, 2010

Sharon Begley

Atom smasher shows vacuum of space in a twist

NewScientist

17:27 15 February 2010 by Rachel Courtland

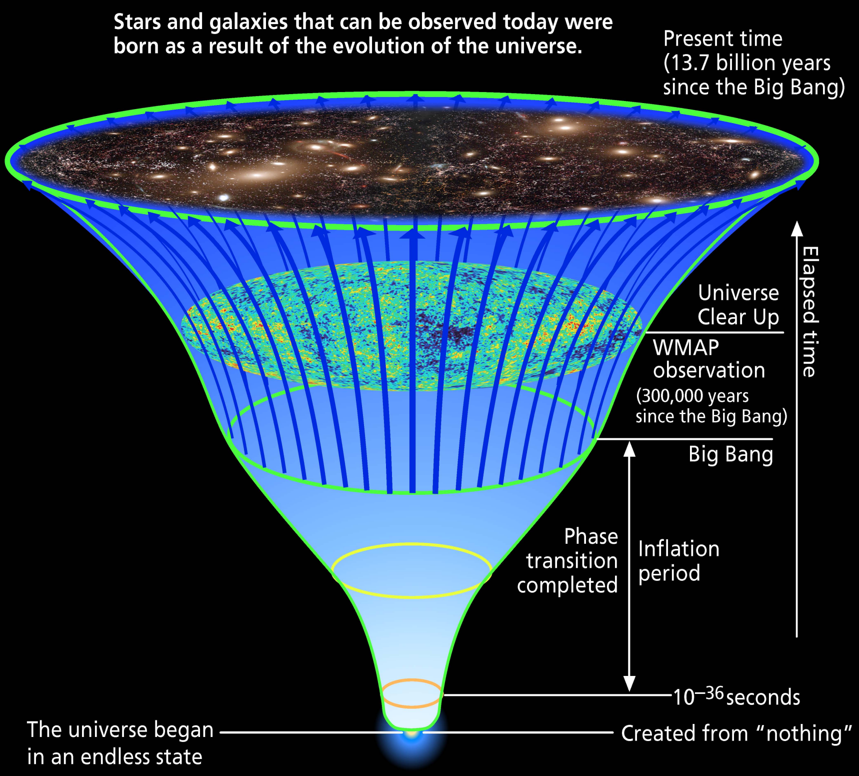
USA TODAY

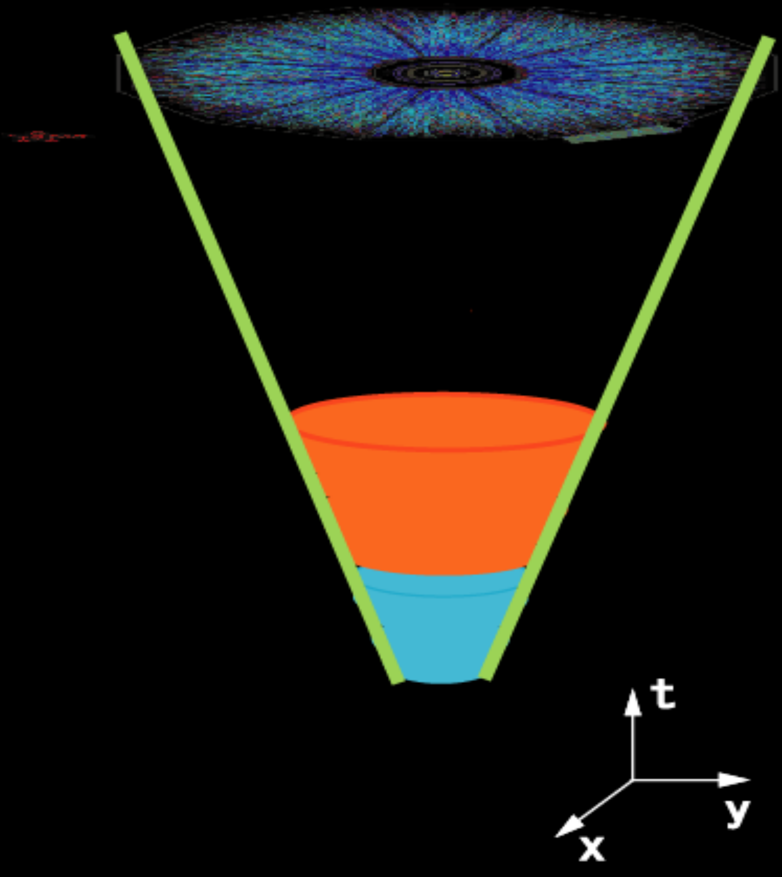
Scientists re-create high temperatures from Big Bang

REUTERS

Hottest Temperature Ever Heads Science to Big Bang

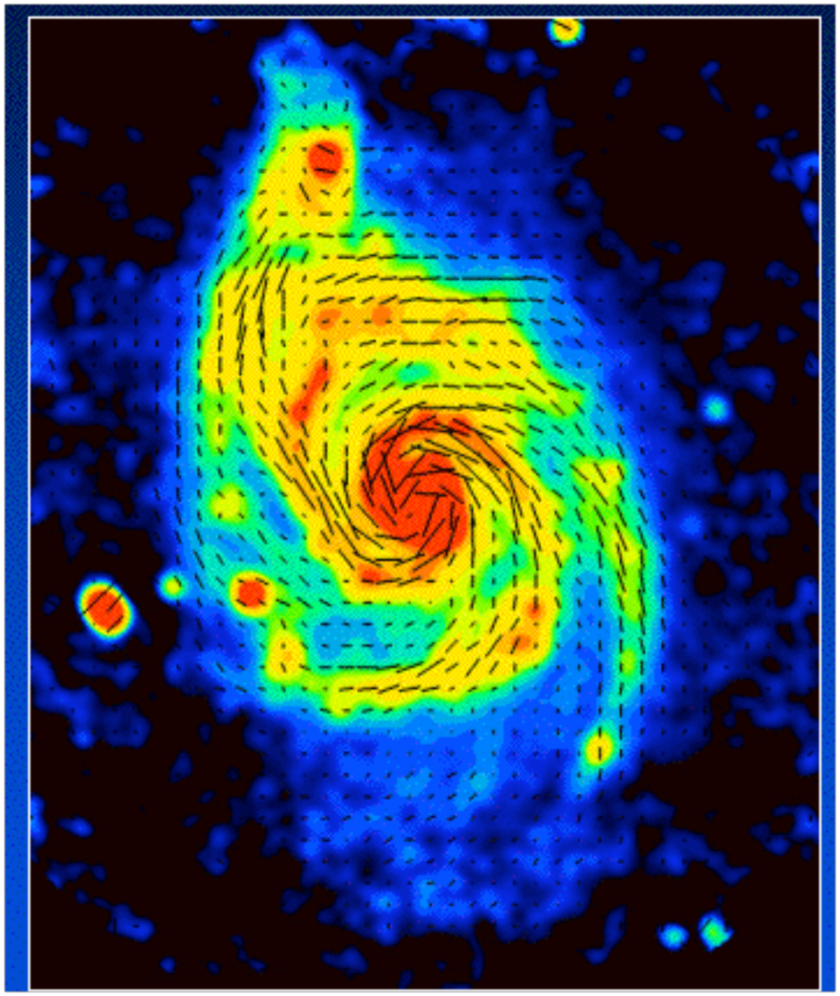
What are the implications for the Early Universe?





T.Hatsuda

What is the origin of cosmic magnetic fields?



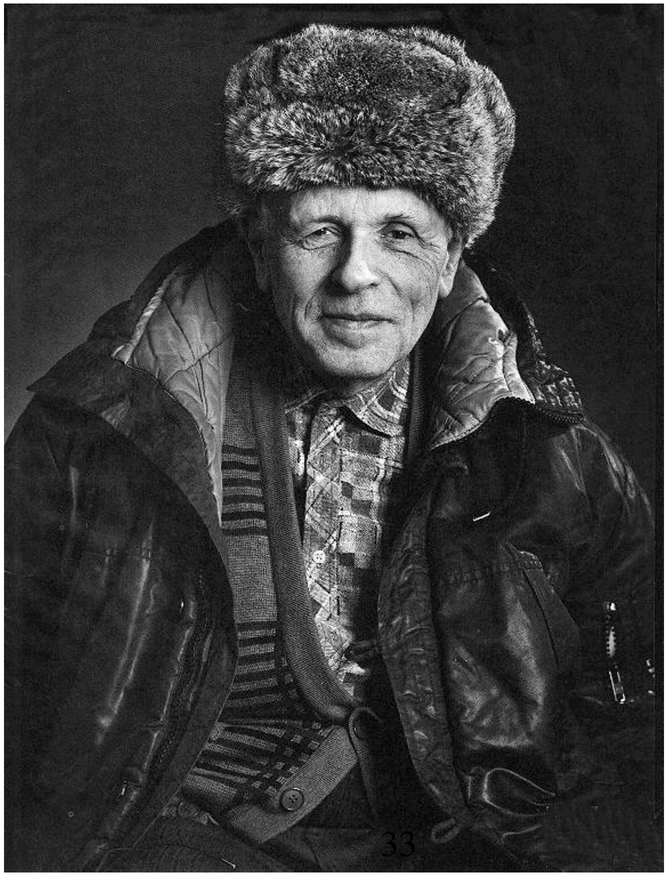
Primordial magnetic field (E.Fermi, 1949)?

Primordial magnetic field generation from P-odd effects at the QCD phase transition?

Magnetic field in M51:
Polarization of emission
Beck 2000

What is the origin of the matter-antimatter asymmetry in the Universe?

1. B violation
2. CP violation
3. Non-equilibrium dynamics

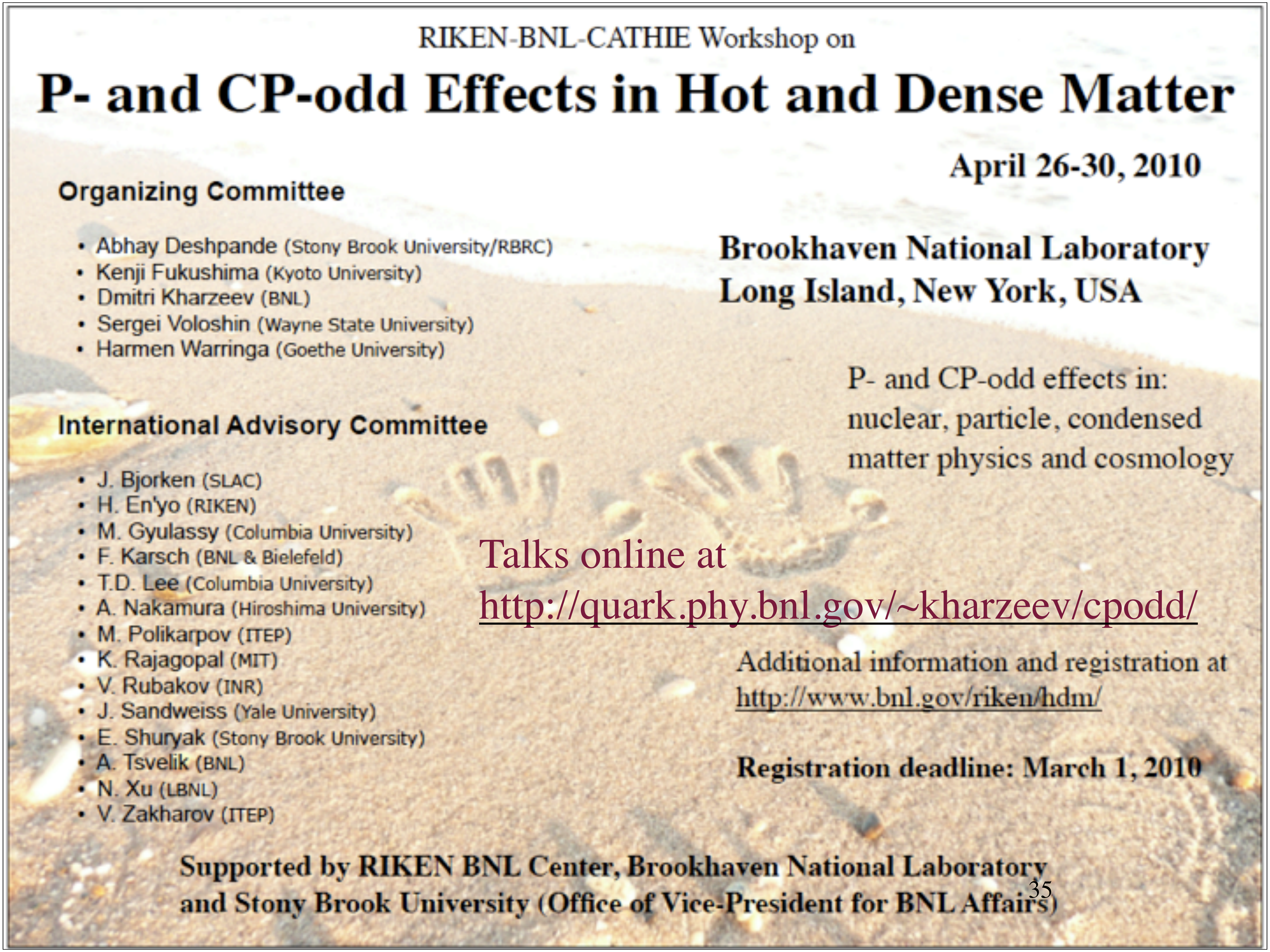


A.D. Sakharov, 1967

Generation of Chern-Simons number at the QCD phase transition is analogous to baryon number generation in the electroweak phase transition: sphaleron transitions are responsible for both

Summary

- The existence of topological solutions is an indispensable property of non-Abelian gauge theories that form the Standard Model
- Local parity violation in the background magnetic field allows a **direct** observation of a topological effect in QCD
- The existence of the Chiral Magnetic Effect (CME) has been confirmed in first-principle lattice QCD calculations
- There is a recent observation of dynamical fluctuations in charge asymmetry at RHIC - an evidence for the CME



RIKEN-BNL-CATHIE Workshop on

P- and CP-odd Effects in Hot and Dense Matter

April 26-30, 2010

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Brookhaven National Laboratory
Long Island, New York, USA

P- and CP-odd effects in:
nuclear, particle, condensed
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Talks online at
http://quark.phy.bnl.gov/~kharzeev/cpodd/

Additional information and registration at
http://www.bnl.gov/riken/hdm/

Registration deadline: March 1, 2010

Supported by RIKEN BNL Center, Brookhaven National Laboratory and Stony Brook University (Office of Vice-President for BNL Affairs)