PAC meeting, BNL, June 15, 2009

Local P and CP violation in hot QCD matter and the low-energy scan at RHIC

D. Kharzeev

BNL

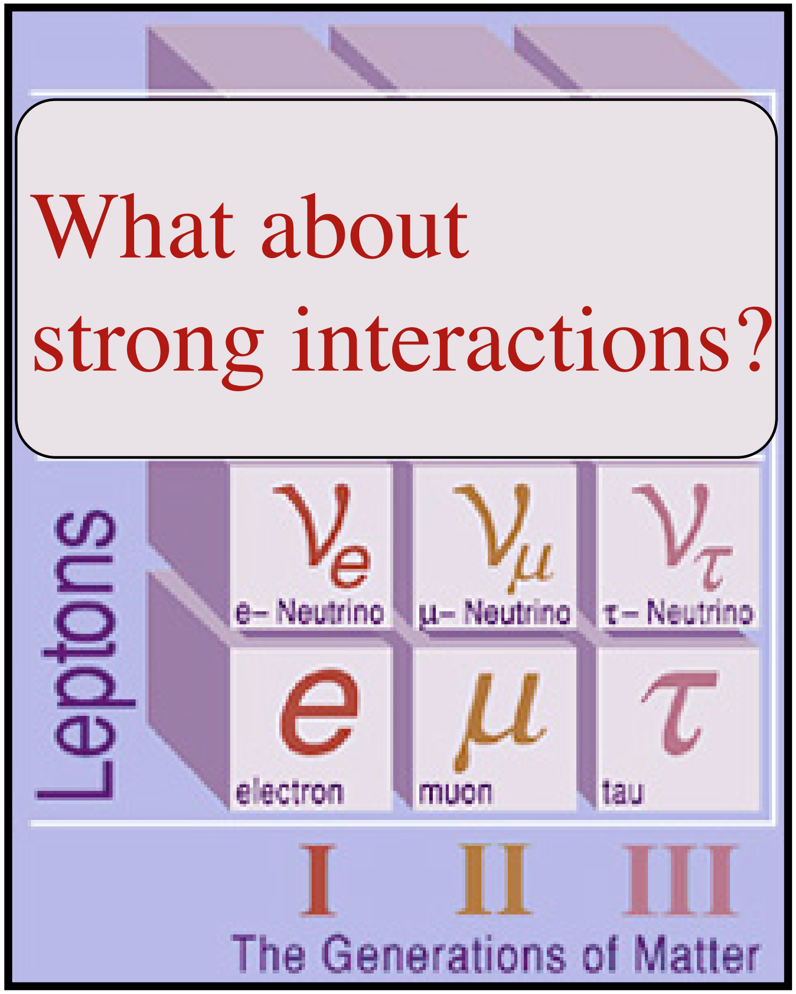
Outline

- Topological solutions in QCD and the strong CP problem
- Topologically induced local P and CP violation in hot and dense matter at RHIC
- P and CP violation and the Early Universe

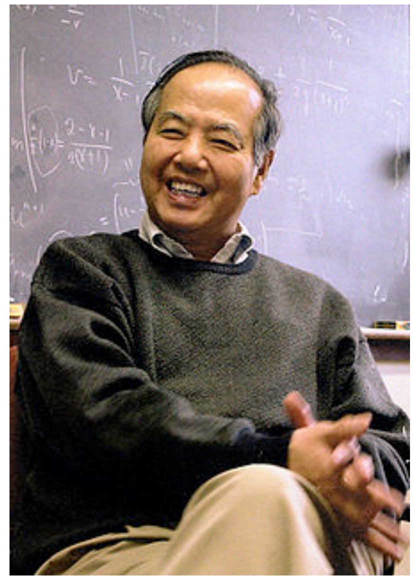
Based on work with (1997 - 2009) :

Rob Pisarski, Michel Tytgat,
Alex Krasnitz, Raju Venugopalan,
Eric Zhitnitsky, Larry McLerran,
Harmen Warringa, Kenji Fukushima,
Kevin Dusling

P and CP invariances are violated by weak interactions



What about strong 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

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

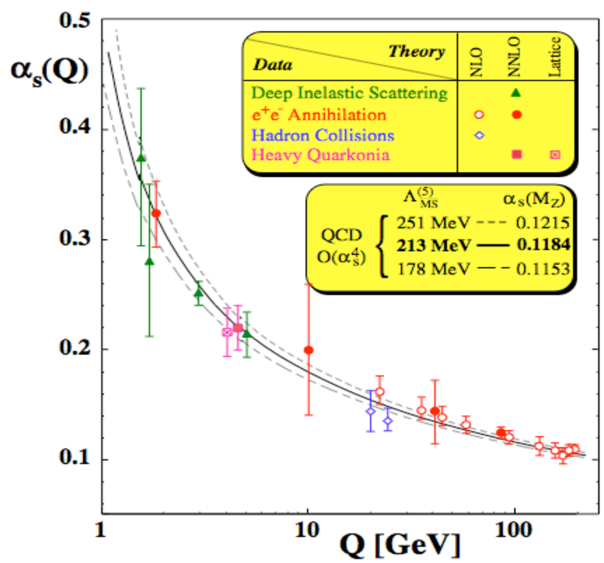
But: P and CP conservation in QCD is by no means a trivial issue ("strong CP problem")

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

local |ˈlōkəl|
adjective
belonging or relating to a particular area or neighborhood, typically exclusively so

QCD is a non-Abelian gauge theory;

<u>quantum</u> effects at short distances - asymptotic freedom.



What are the non-Abelian effects on the <u>classical</u> dynamics?

Solution of Yang-Mills equations in the vacuum

Equation:

$$D^{\mu} F^{a}_{\mu\nu} = 0$$

Belavin, Polyakov, Tyupkin, Schwartz

A. Polyakov

Solution:

$$(F^{a}_{\mu\nu})^2 = \frac{192\rho^4}{(x^2+\rho^2)^4}$$

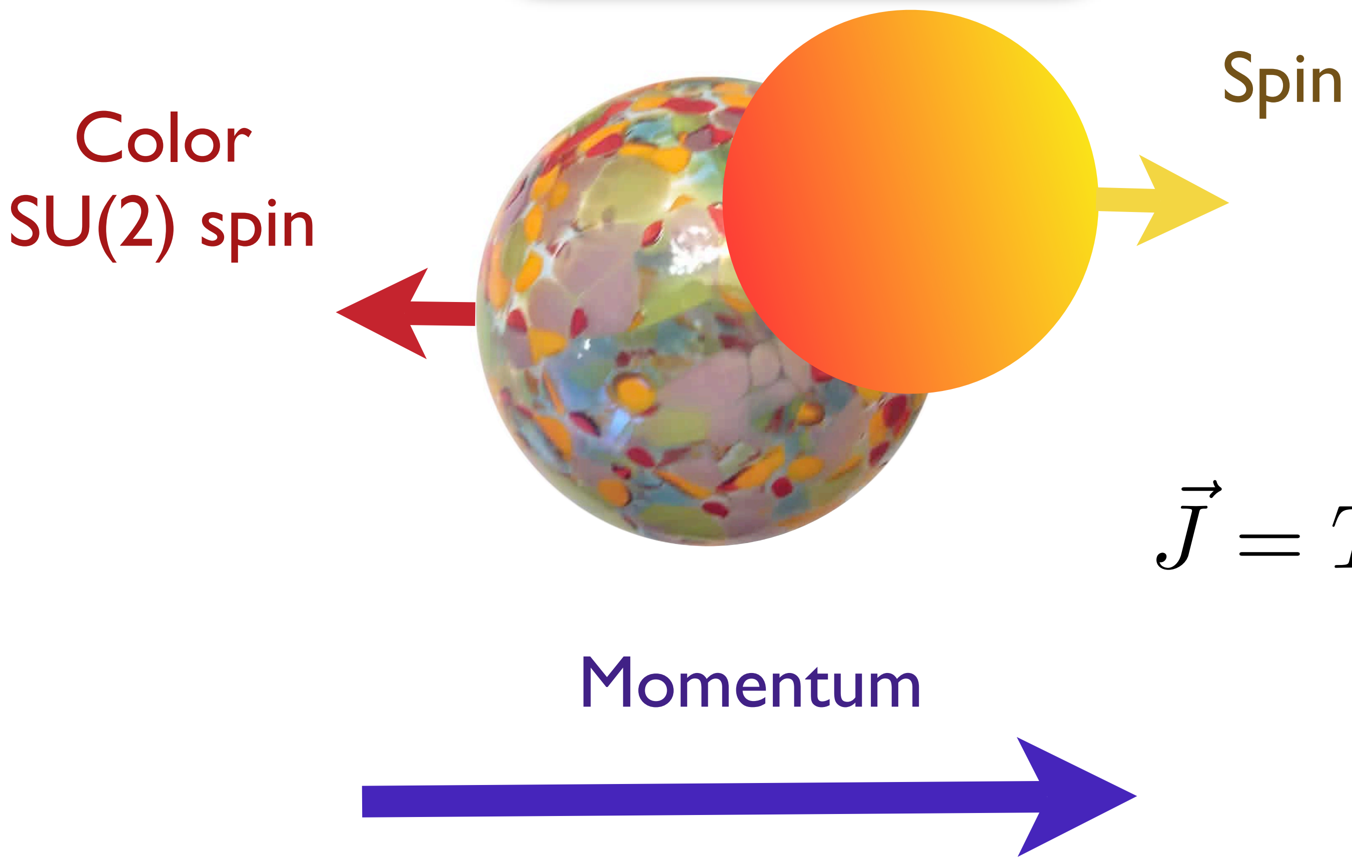
Coupling of space-time and color:

$$A^{a}_{\mu}(x) = \frac{2\eta_{a\mu\nu}x_{\nu}}{x^2+\rho^2}, \qquad \eta_{a\mu\nu} = \begin{cases} \epsilon_{a\mu\nu} & \mu,\nu = 1,2,3, \\ \delta_{a\mu} & \nu = 4, \\ -\delta_{a\nu} & \mu = 4. \end{cases}$$

Even the classical vacuum is not empty

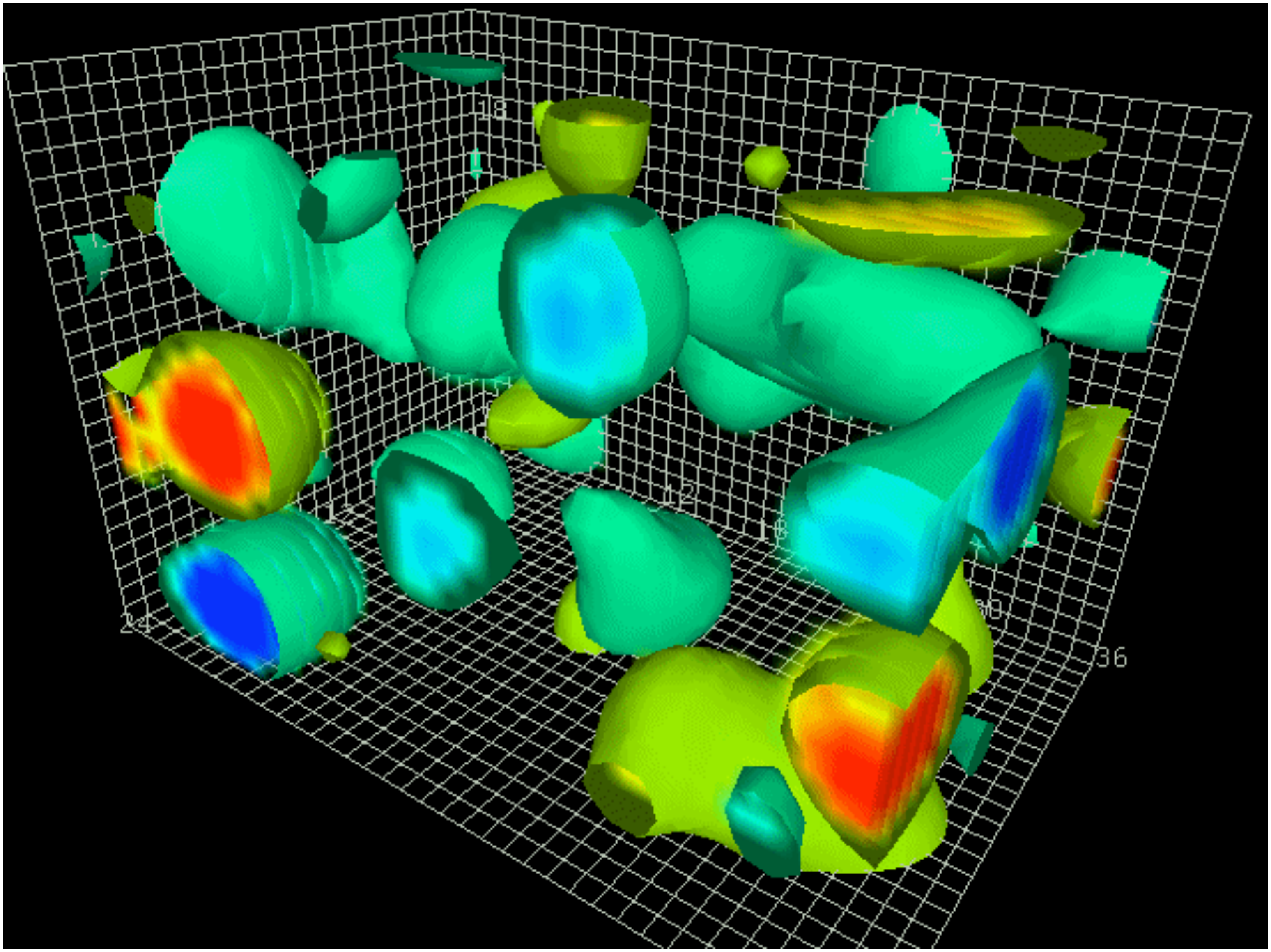
Topology-induced change of chirality

Right ↔ Left



$$\vec{J} = \vec{T} + \vec{S}$$

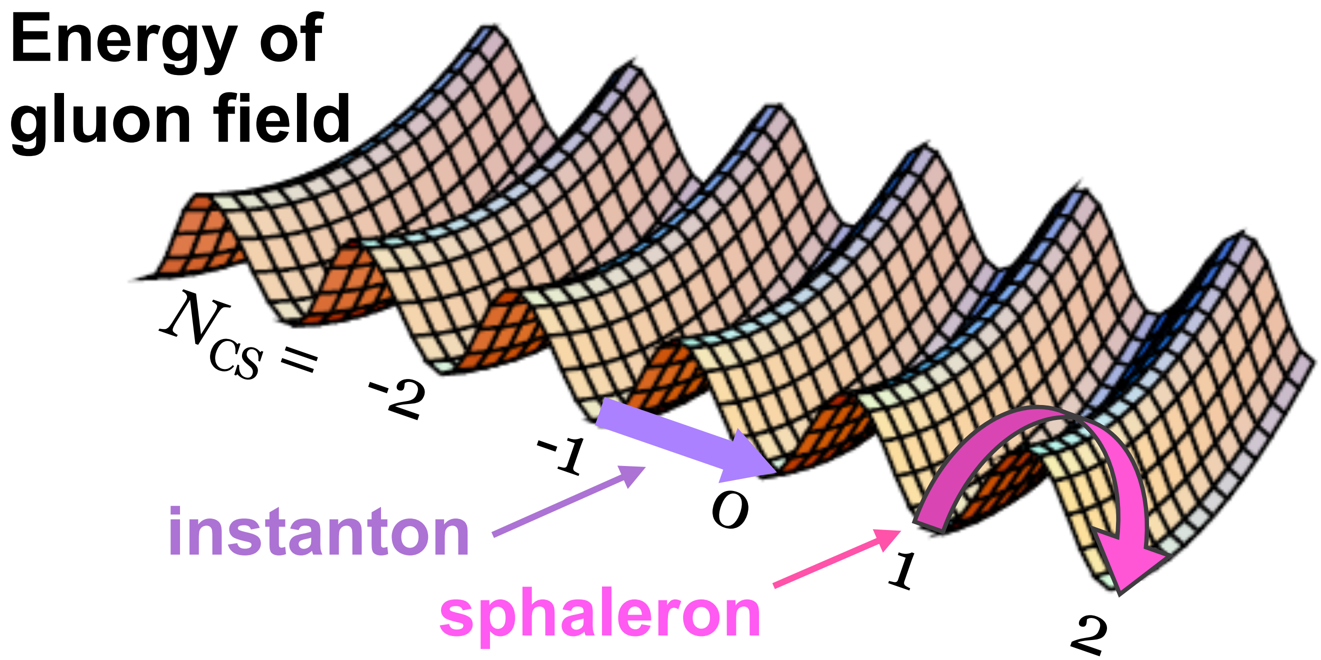
Topological number fluctuations in QCD vacuum



D. Leinweber

Sphaleron transitions at finite energy or temperature

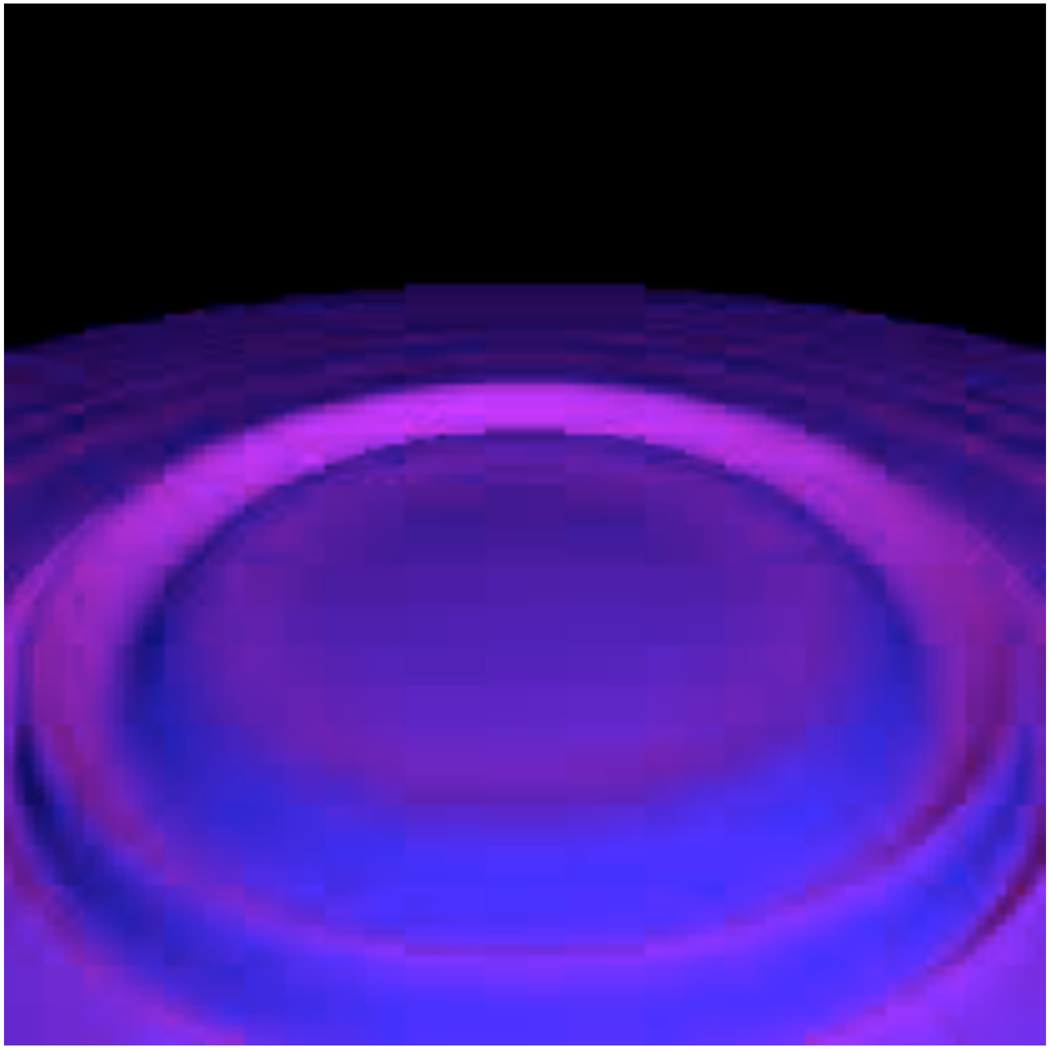
$$\Gamma = \frac{1}{2} \lim_{t\to\infty} \lim_{V\to\infty} \int_0^t \langle (q(x)q(0) + q(0)q(x)) \rangle d^4x$$



Sphalerons:
random walk of
topological charge at finite T:

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

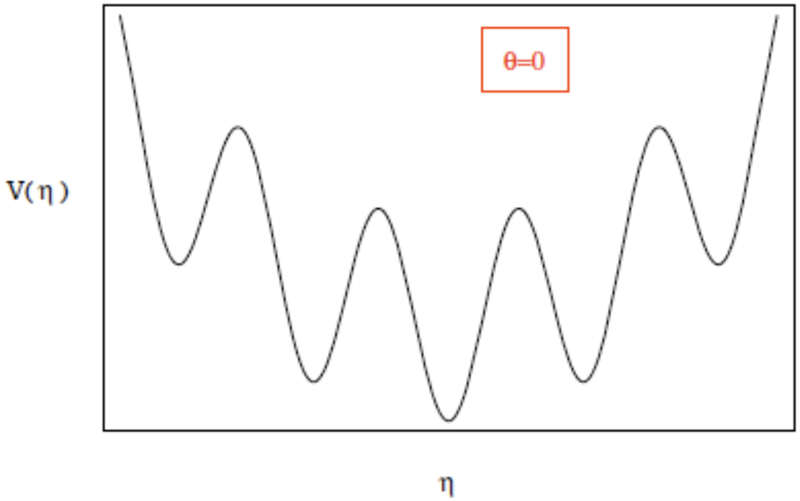
Sphaleron transitions at finite energy or temperature



C. Rebbi, http://scv.bu.edu/visualization/gallery

Chern-Simons number in hot QCD

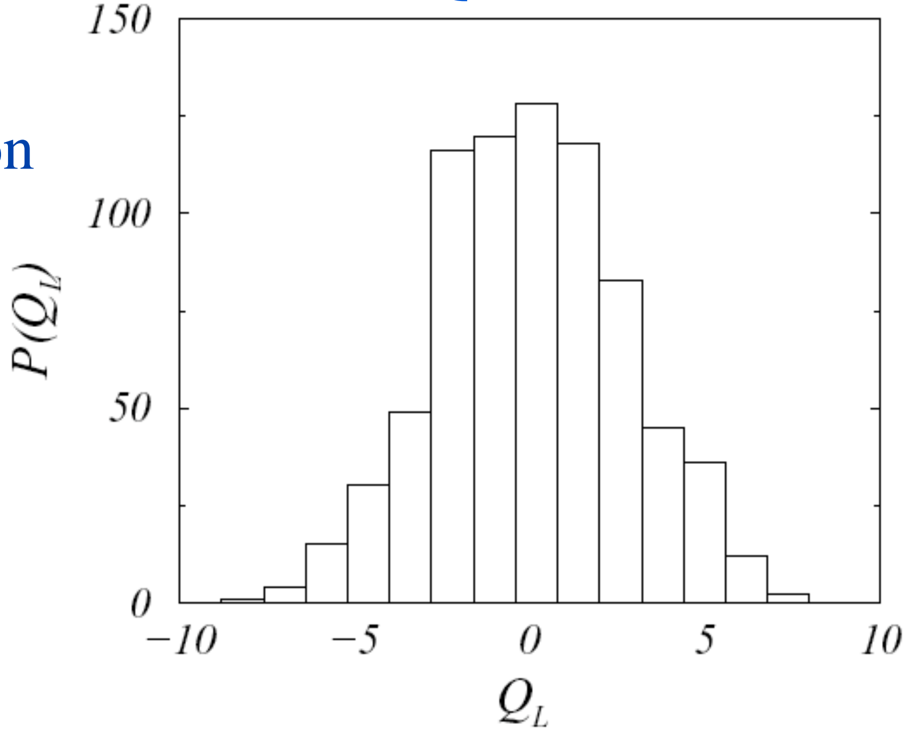
The existence of P and CP odd domains expected close to the deconfinement phase transition



DK, R. Pisarski, M. Tytgat,

Phys.Rev.Lett.81:512-515,1998

Lattice QCD results:



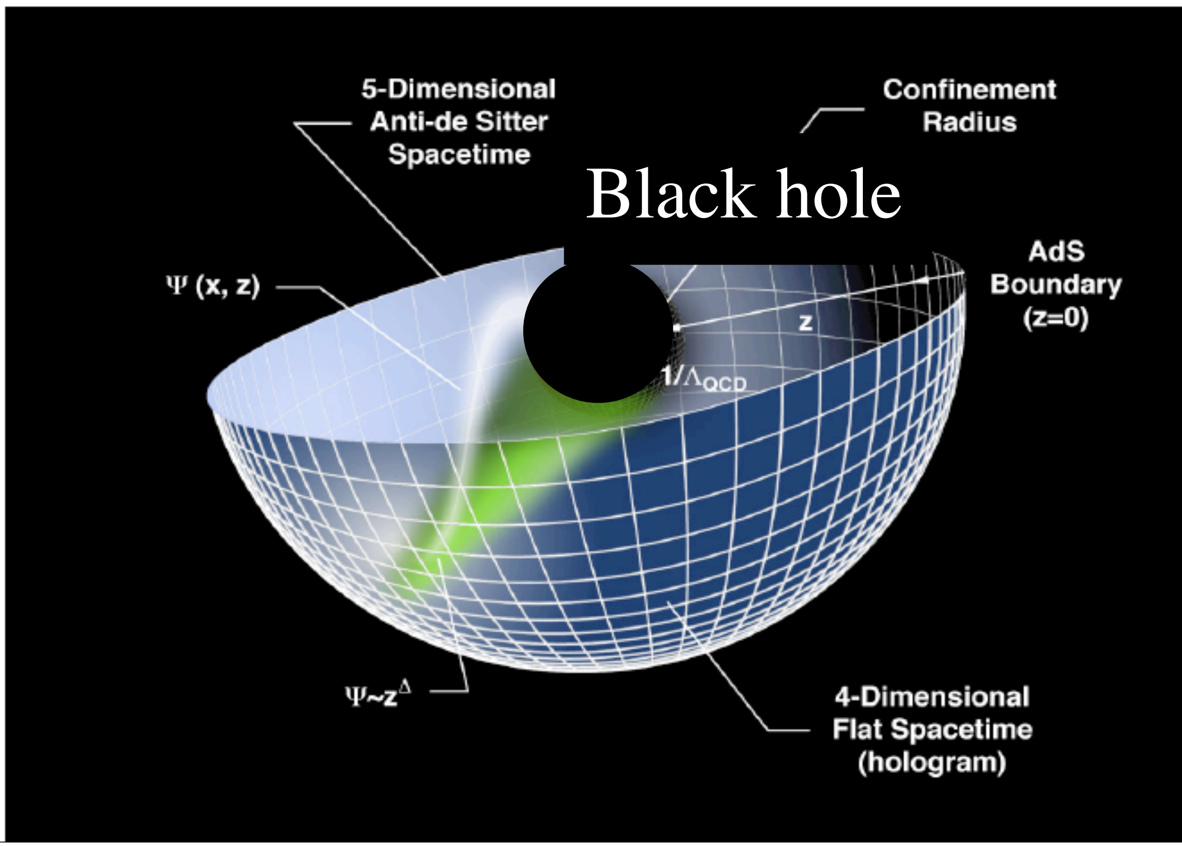
B.Alles, M.D'Elia and A.DiGiacomo, hep-lat/0004020

Perfect liquid contains fluctuating topological charge

Chern-Simons number
diffusion rate
at strong coupling

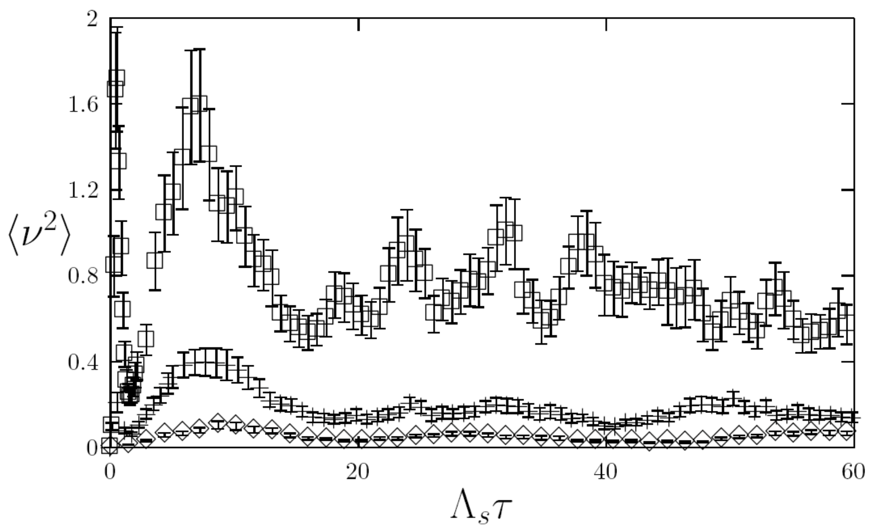
$$\Gamma = \frac{(g_{\rm YM}^2 N)^2}{256\pi^3} T^4$$

D.Son,
A.Starinets
hep-th/
020505

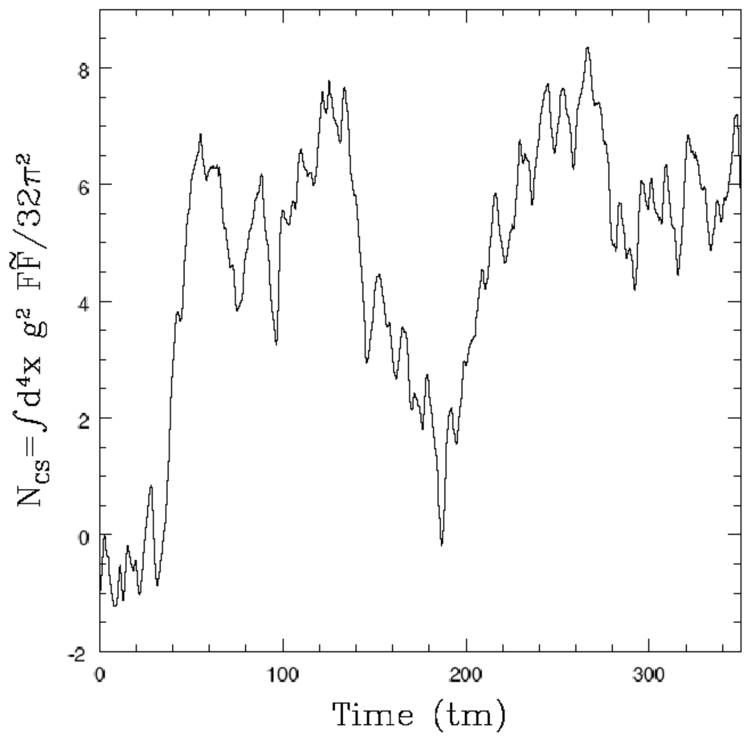


NB: This calculation is completely analogous to the calculation of shear viscosity that led to the "perfect liquid"

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

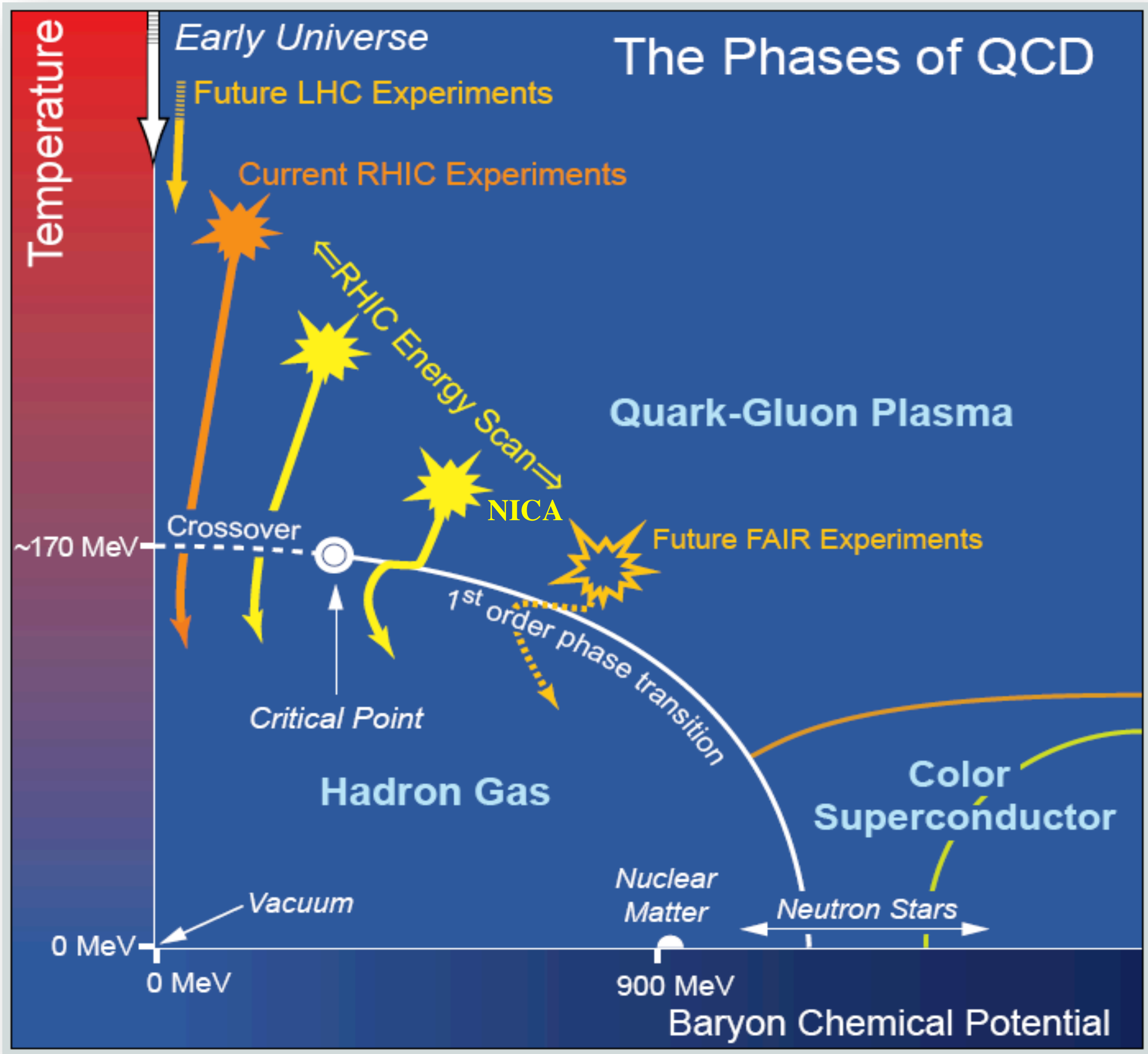


DK, A.Krasnitz and R.Venugopalan, Phys.Lett.B545:298-306,2002



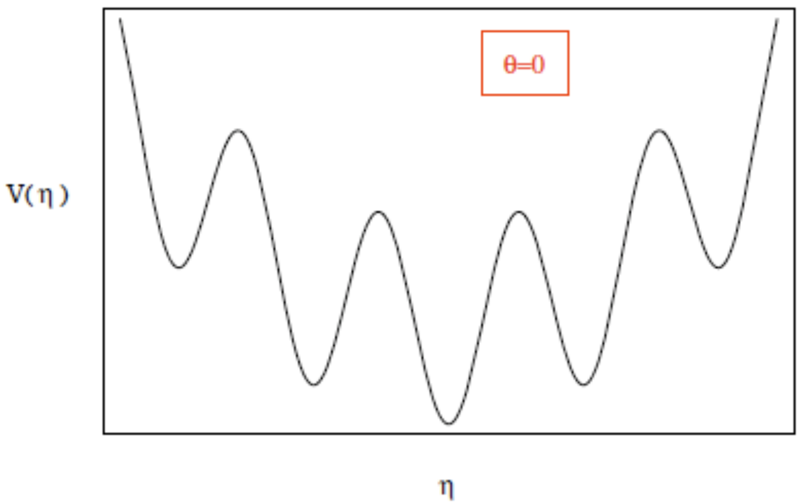
P.Arnold and G.Moore, Phys.Rev.D73:025006,2006

The phase diagram of hot and dense QCD and the Critical Point



Chern-Simons number in hot QCD

The existence of P and CP odd domains expected close to the deconfinement phase transition



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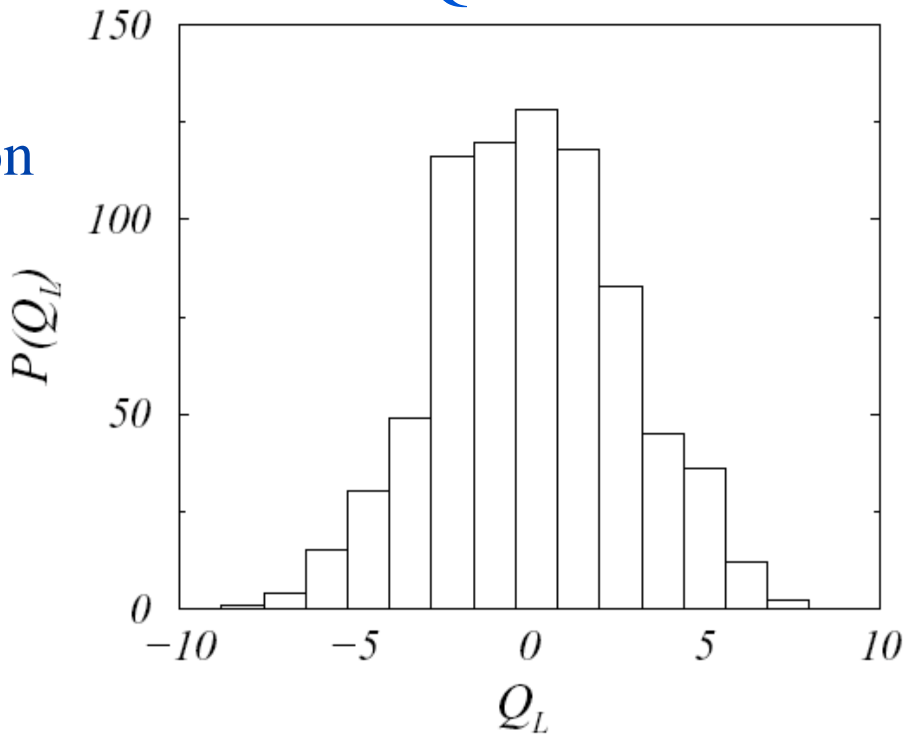
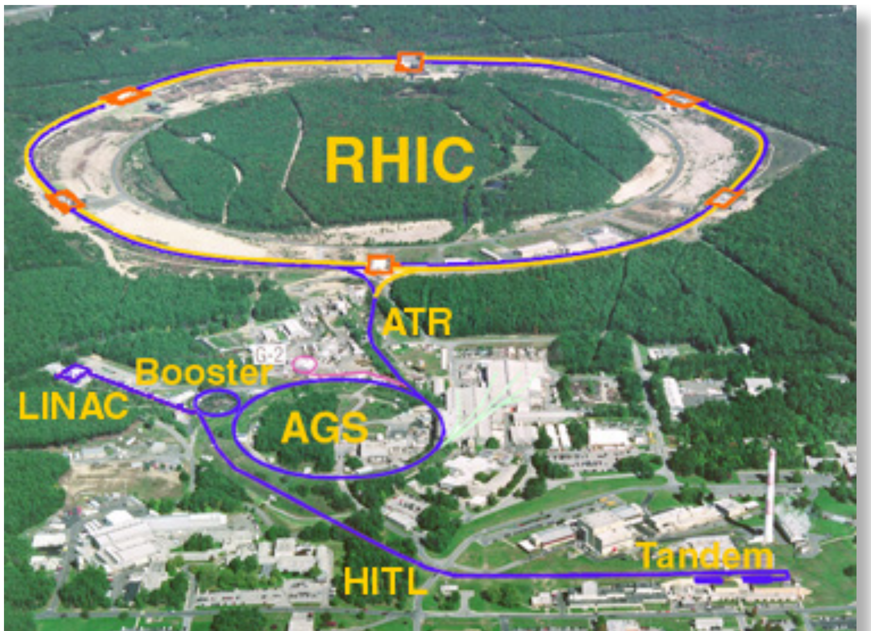
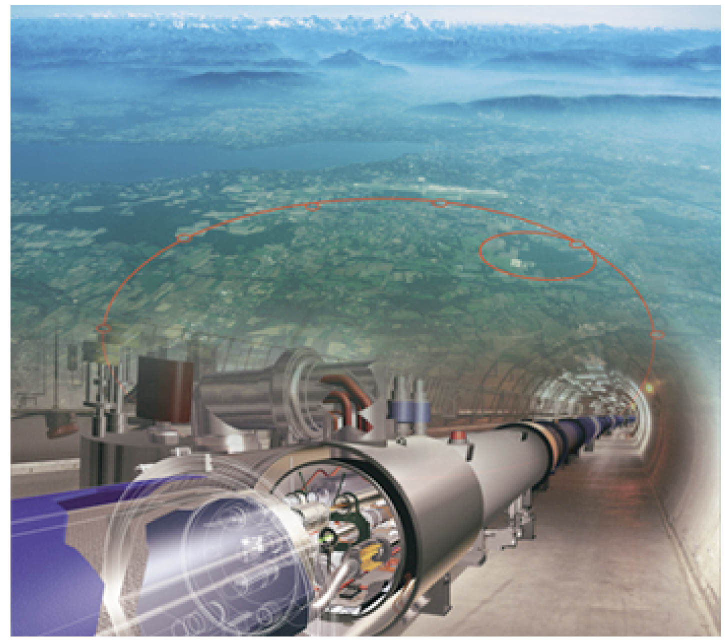


B.Alles, M.D'Elia and A.DiGiacomo, hep-lat/0004020

Experimental tests: Heavy ion collisions





RHIC II

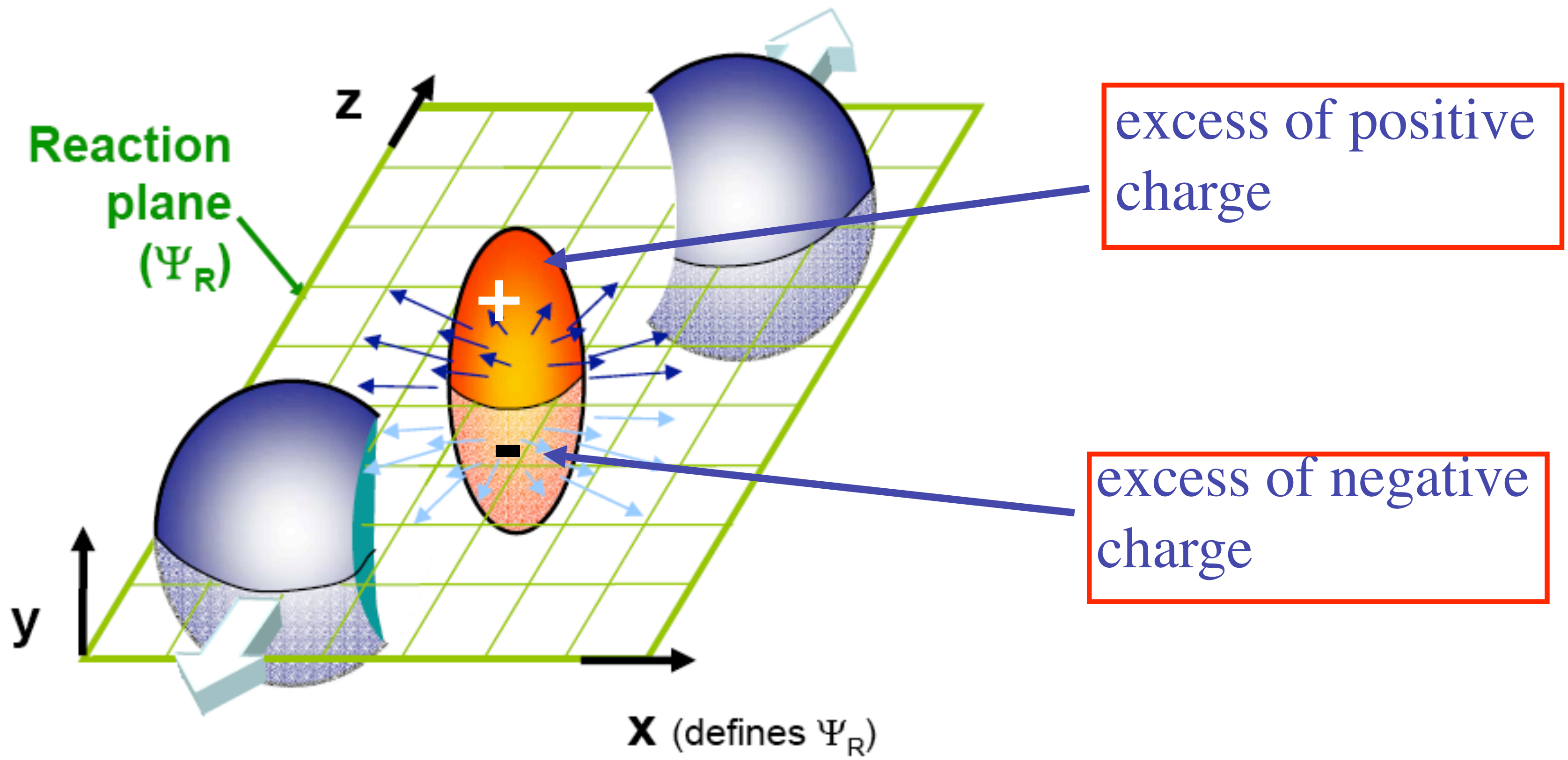
LHC

NICA, JINR

FAIR Facility for Antiproton and Ion Research

GSI

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



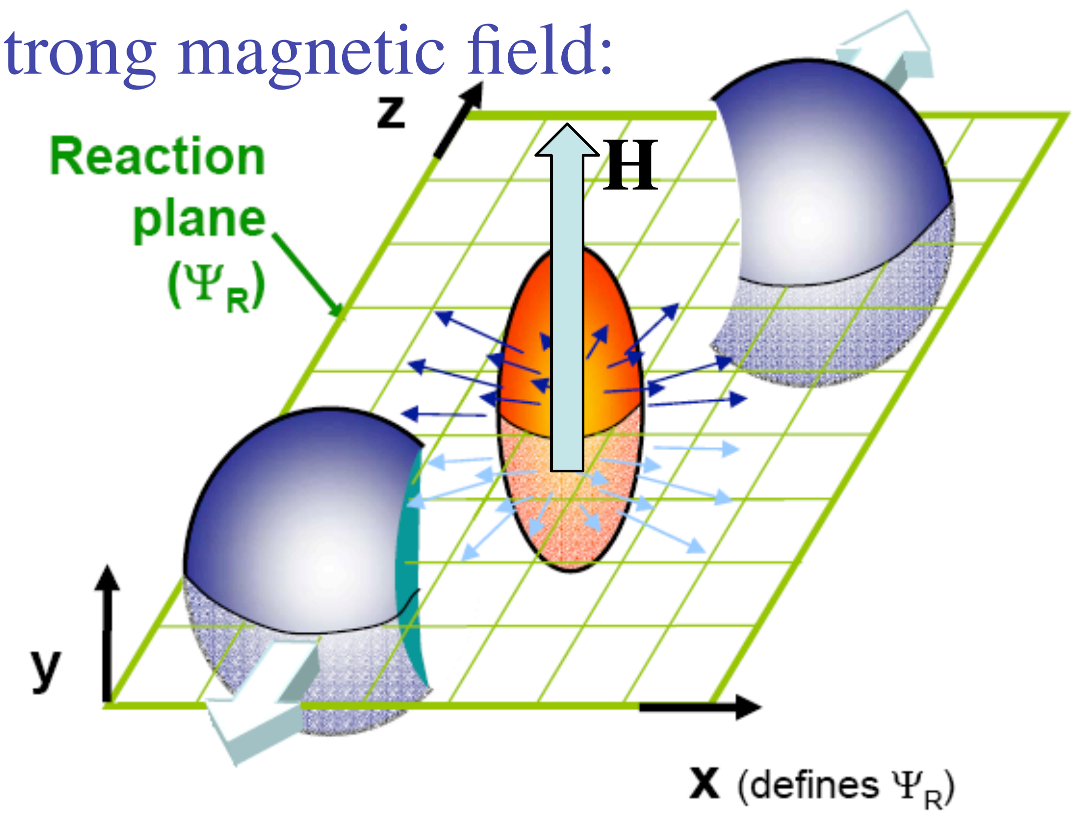
Electric dipole moment of QCD matter!

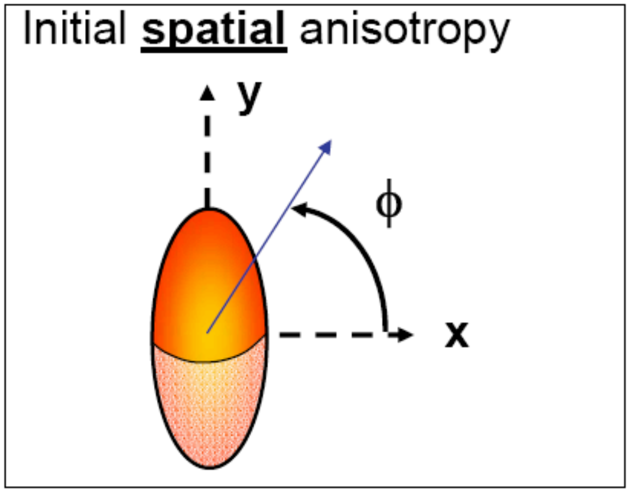
DK, Phys.Lett.B633(2006)260 [hep-ph/0406125]

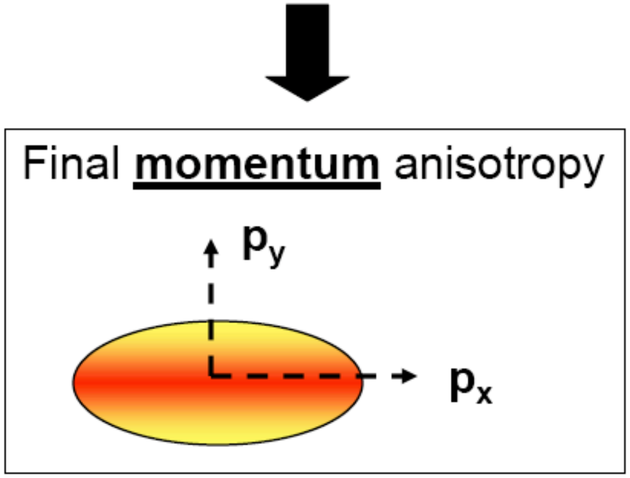
Submitted on 10 June 2004

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

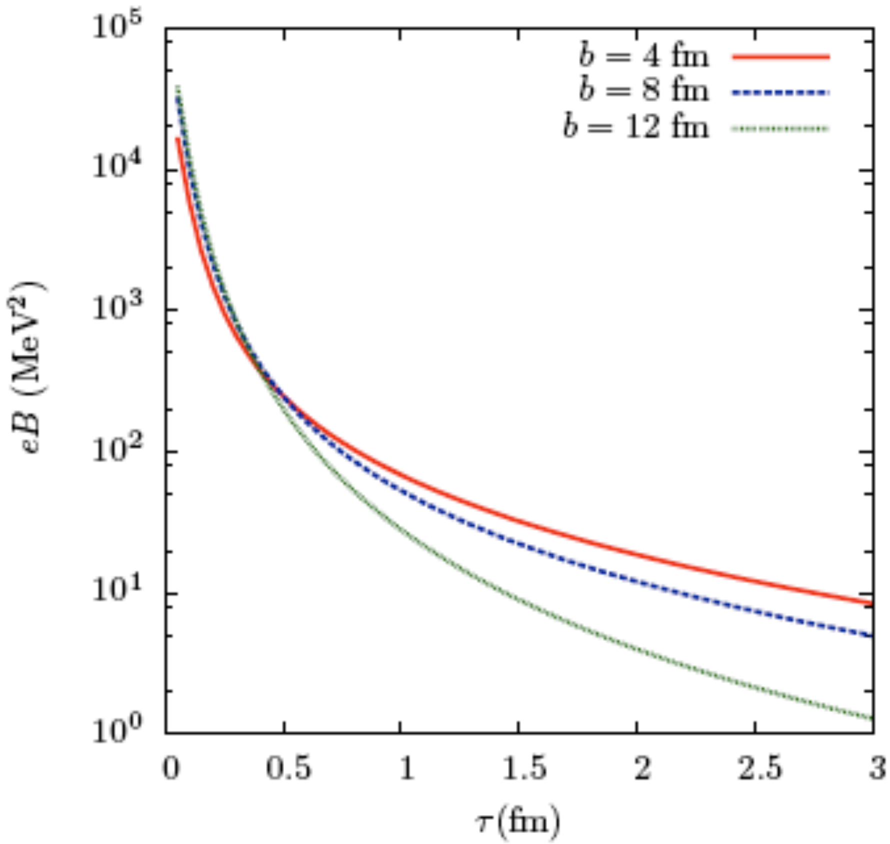
Relativistic ions create
a strong magnetic field:







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



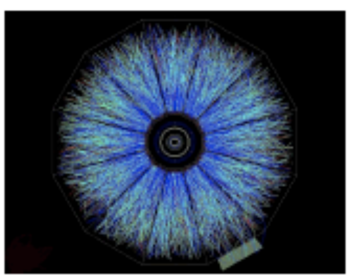
DK, McLerran, Warringa

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

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

From QCD back to electrodynamics: Maxwell-Chern-Simons theory

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

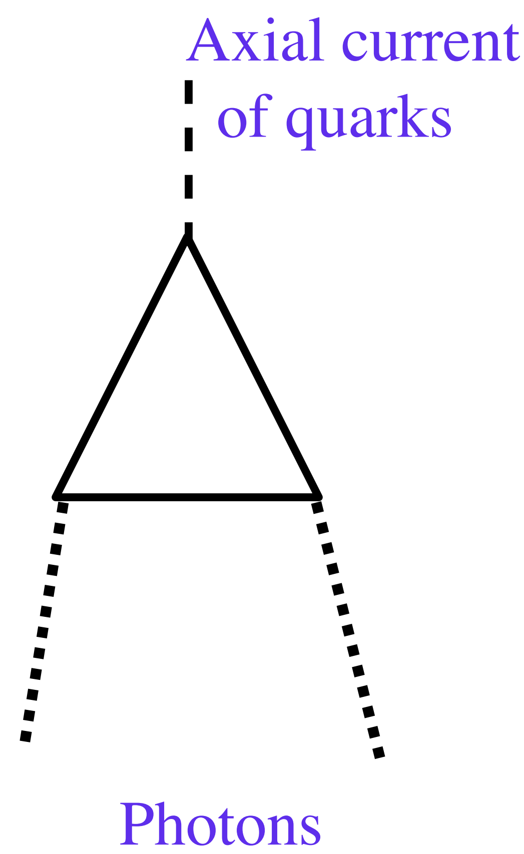
$$J^\mu_{CS} = \epsilon^{\mu\nu\rho\sigma}A_\nu F_{\rho\sigma} \qquad P_\mu = \partial_\mu\theta = (M, \vec{P})$$

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

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

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

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



Maxwell-Chern-Simons electrodynamics in action

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

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

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

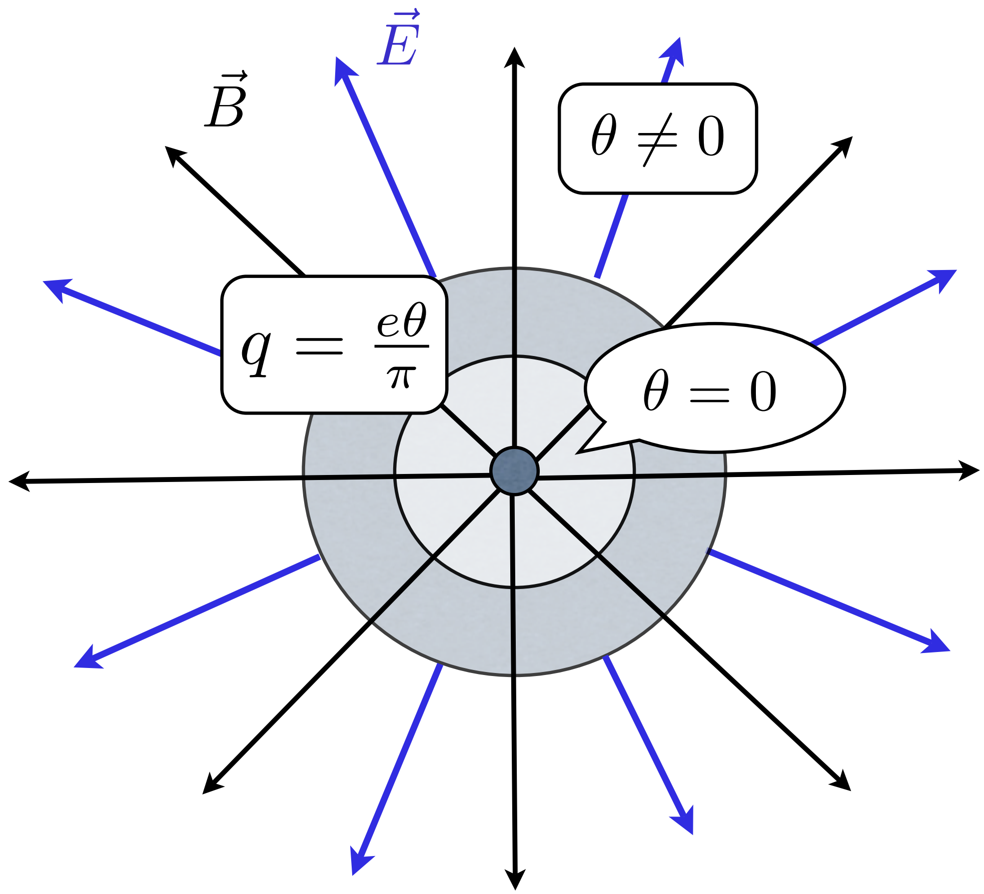
$$\vec{\nabla} \cdot \vec{B} = 0,$$

S.S. Chern, 1911-2004

J.H. Simons

Magnetic monopole at finite θ : the Witten effect

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



E. Witten;

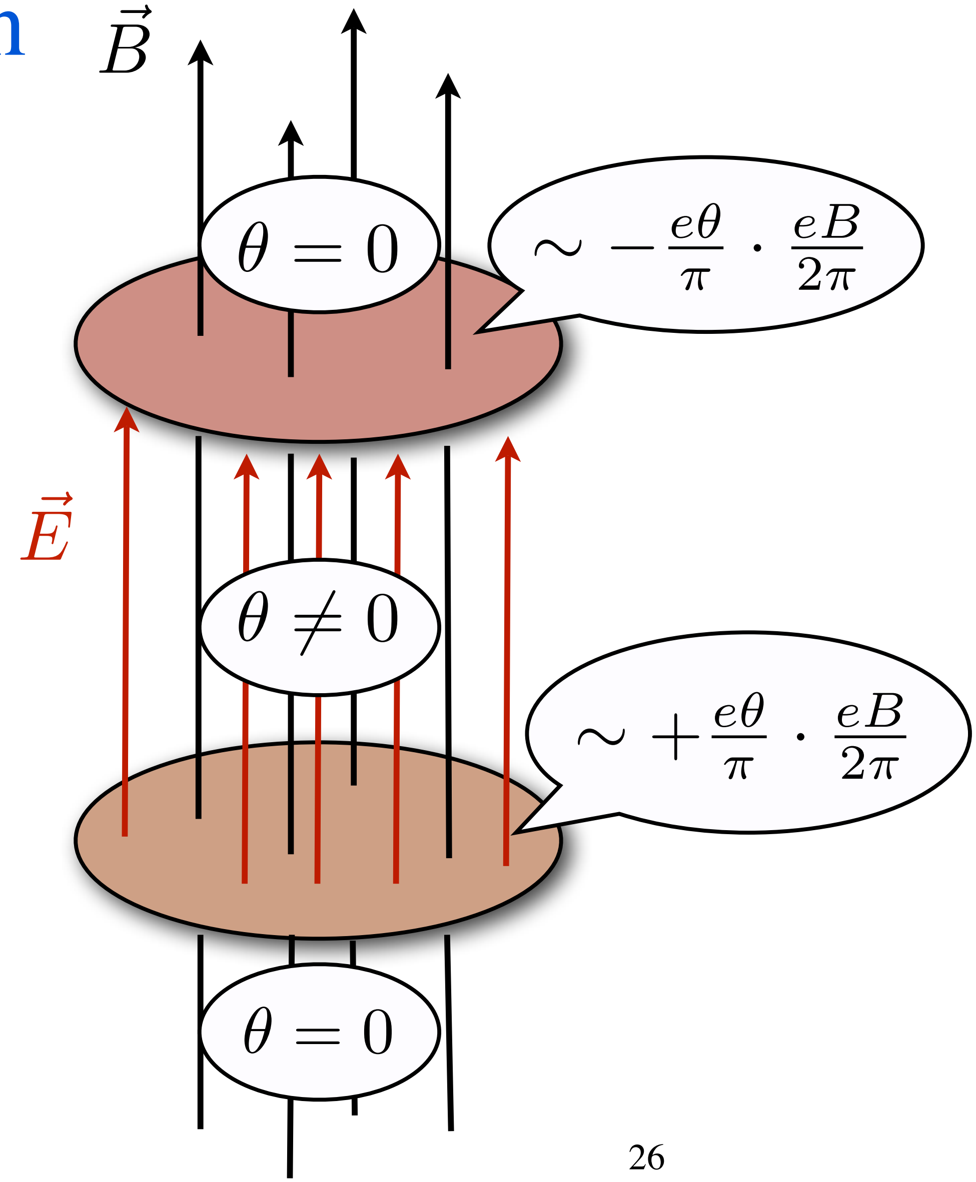
F. Wilczek

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

The Chiral Magnetic Effect I: Charge separation

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

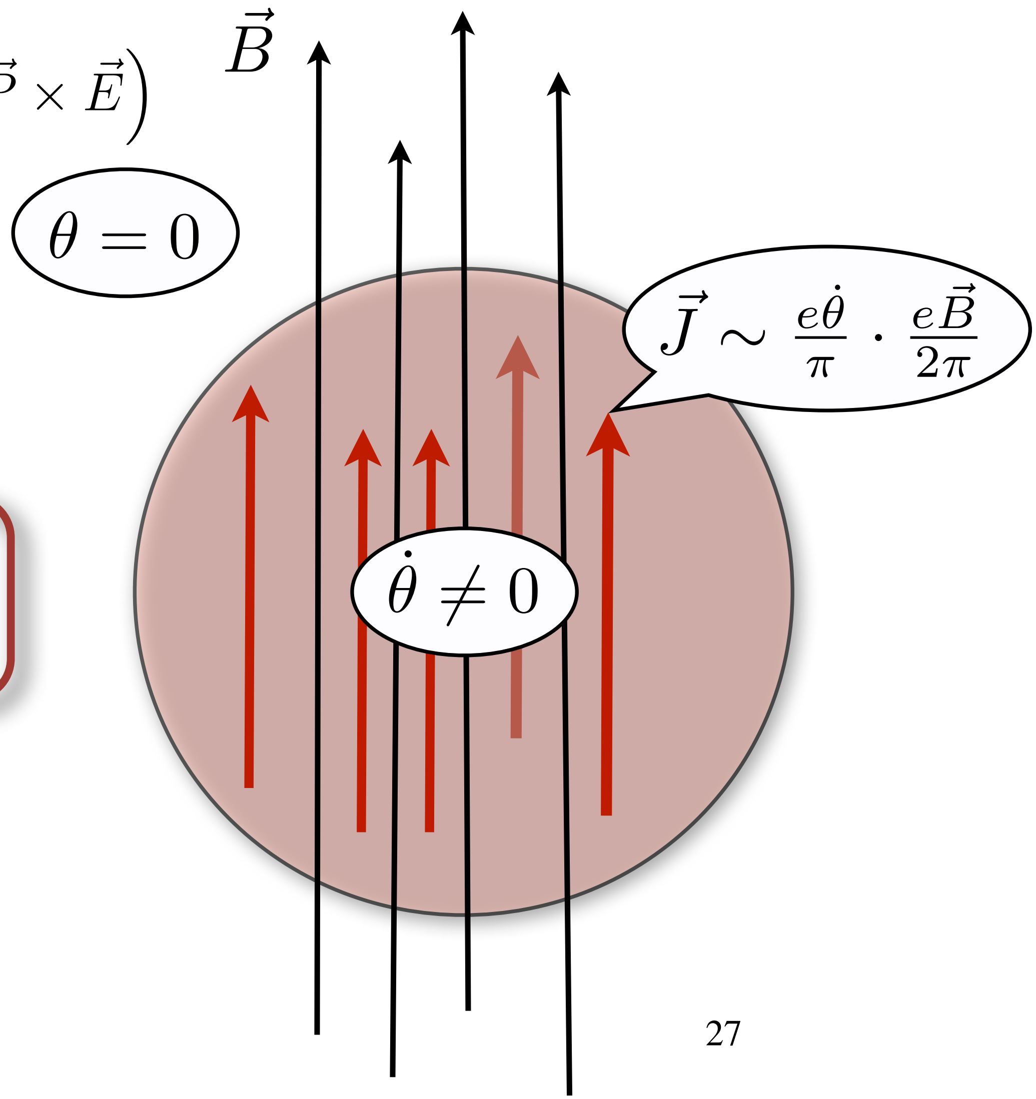
$$d_e = \sum_f q_f^2 \left(e \, \frac{\theta}{\pi} \right) \left(\frac{eB \cdot S}{2\pi} \right) L$$



DK ’04;
DK, A. Zhitnitsky ‘06

The chiral magnetic effect II: chiral induction

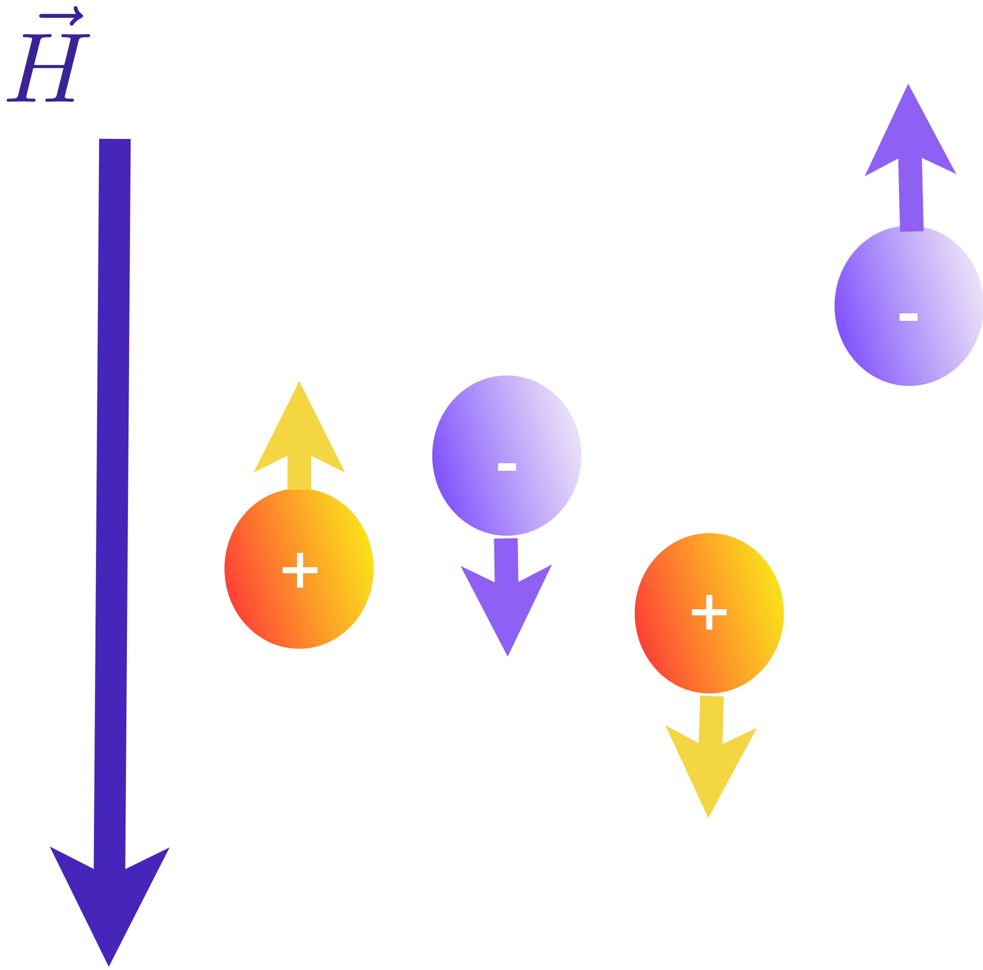
$$\vec{\nabla} \times \vec{B} - \frac{\partial \vec{E}}{\partial t} = \vec{J} + c\left(M\vec{B} - \vec{P} \times \vec{E}\right)$$



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

DK, L. McLerran, H. Warringa '07;
K. Fukushima, DK, H. Warringa '08

The Chiral Magnetic Effect

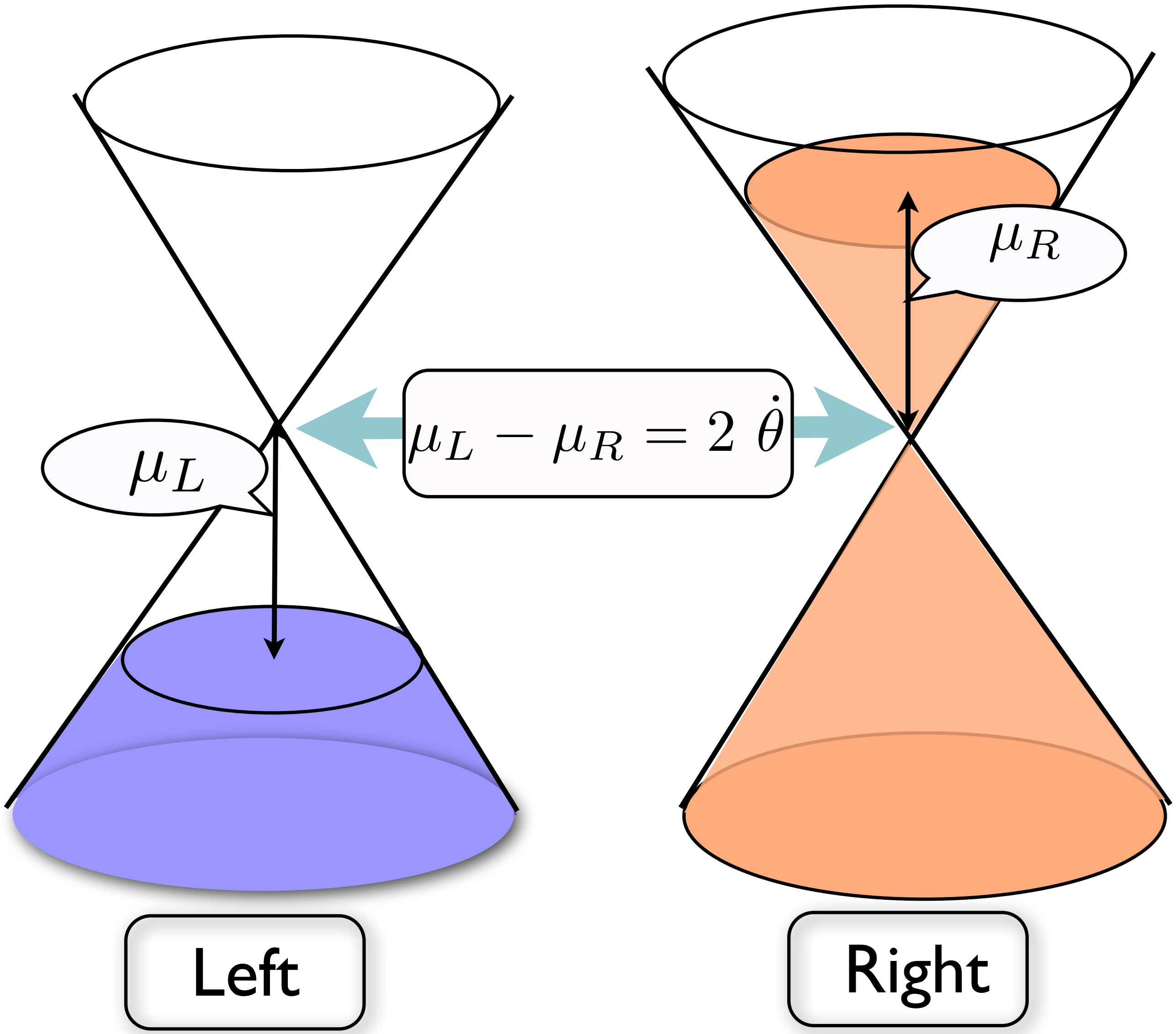


Let all fermions
be right-handed,
$Q = N_R - N_L > 0$

this means the spin
is parallel to momentum.

Magnetic field pins down
the directions of spins
and thus induces
an electric current

The chiral charge of quarks



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

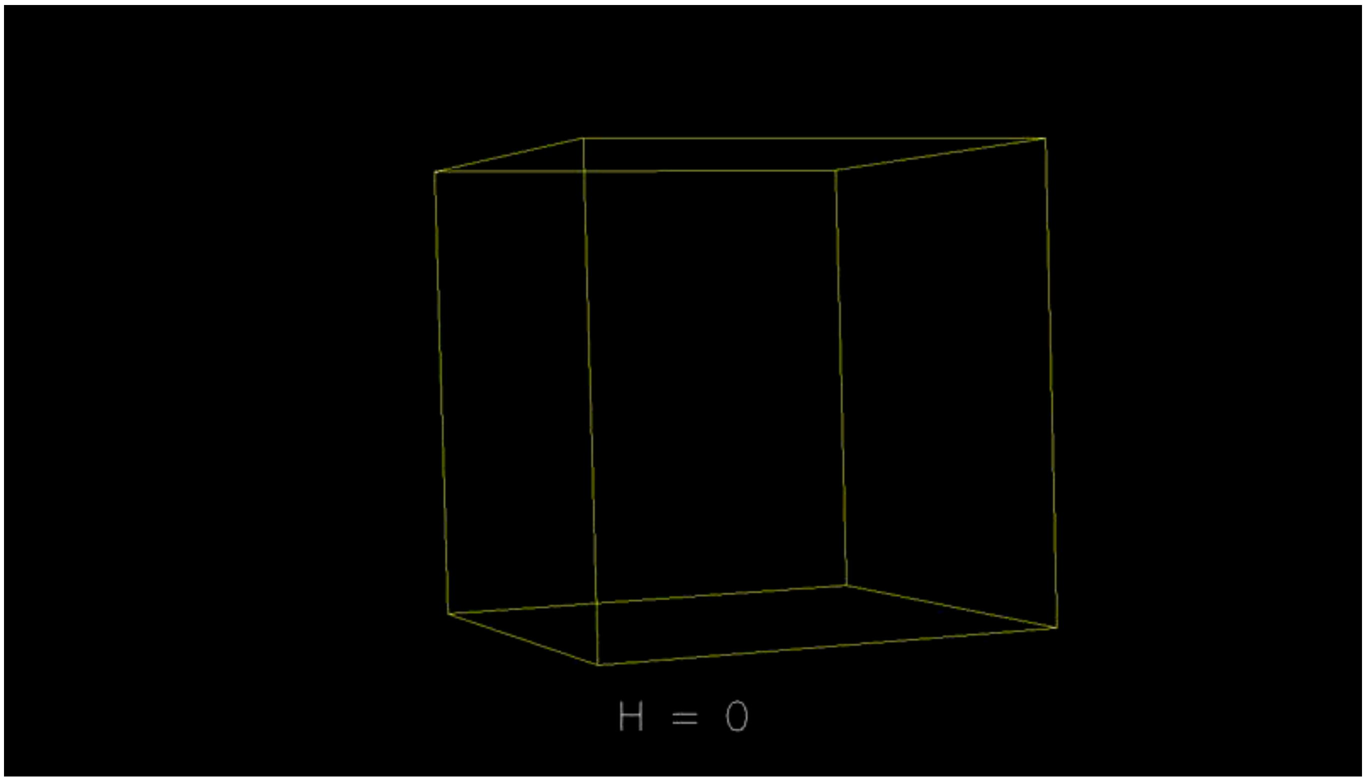
$$J^\mu = \frac{\partial \log Z[A_\mu, A_\mu^5]}{\partial A_\mu(x)}$$

The result:

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

Coefficient is fixed by the axial anomaly, no corrections

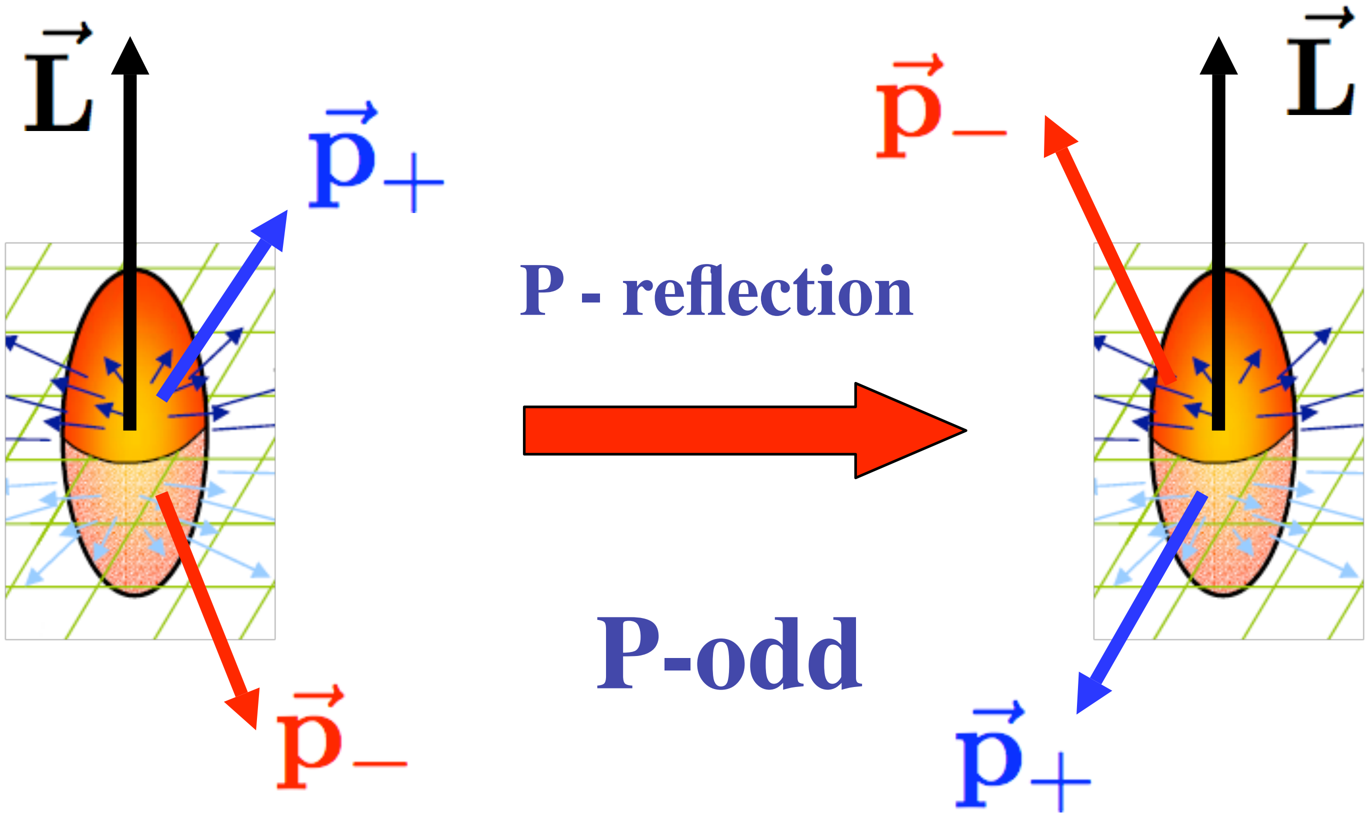
“Evidence for chiral magnetic effect from lattice gauge theory”,
P. Buividovich, M. Chernodub, E. Luschevskaya, M. Polikarpov,
to appear; see also ArXiv 0812.174



Red - positive charge
Blue - negative charge

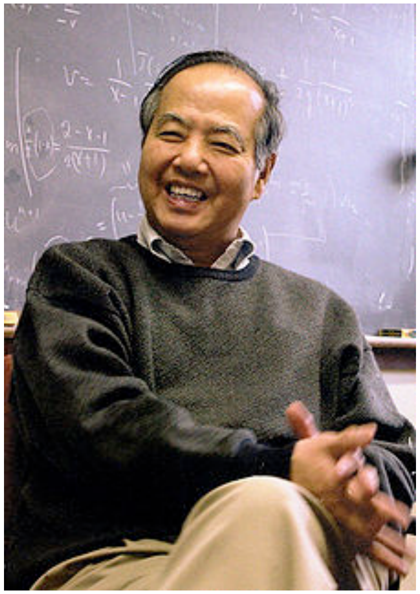
SU(2) quenched, Q = 3; Electric charge density (H) - Electric charge density (H=0)

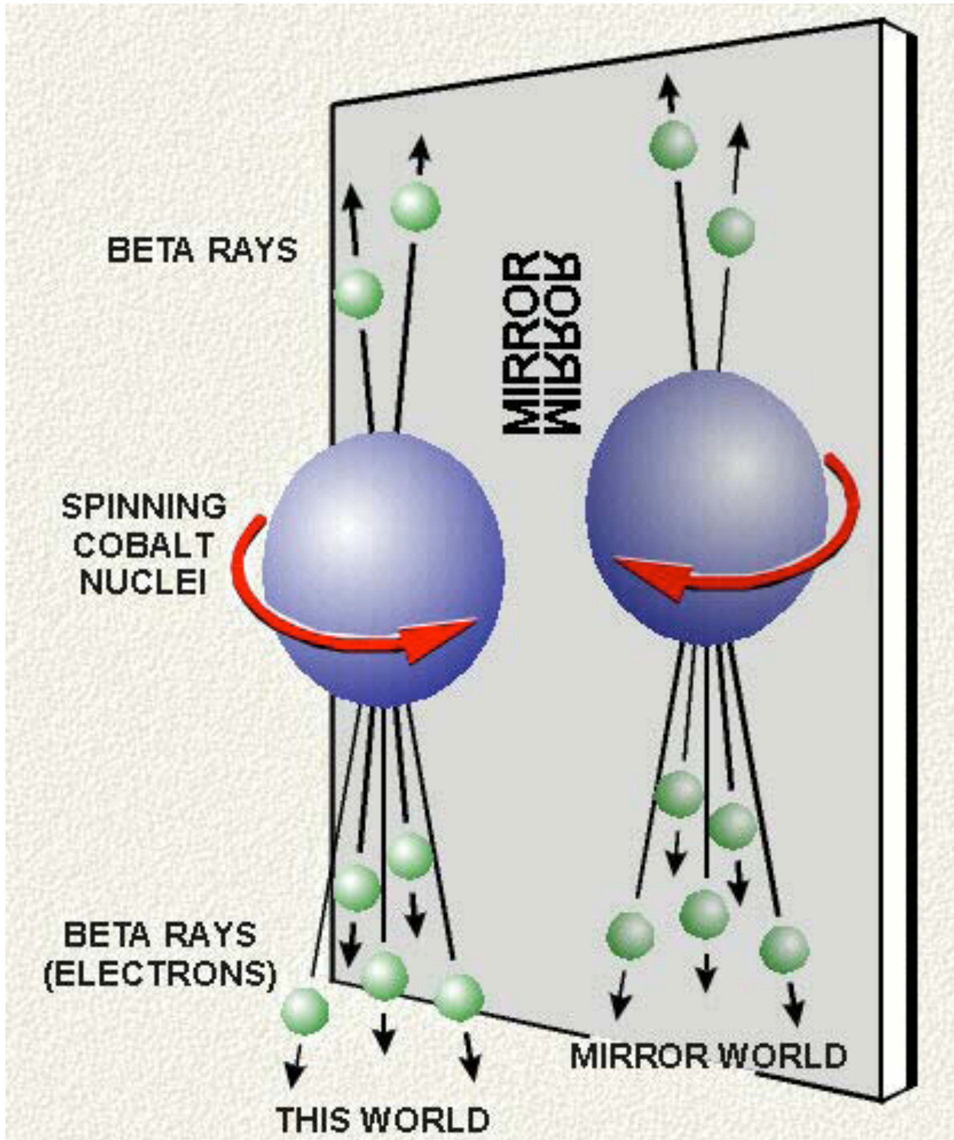
Charge separation = parity violation:



$$\mathbf{P}: \quad \vec{p} \to -\vec{p}; \quad \vec{L} = \vec{r} \times \vec{p} \to \vec{L}$$

Analogy to P violation in weak interactions

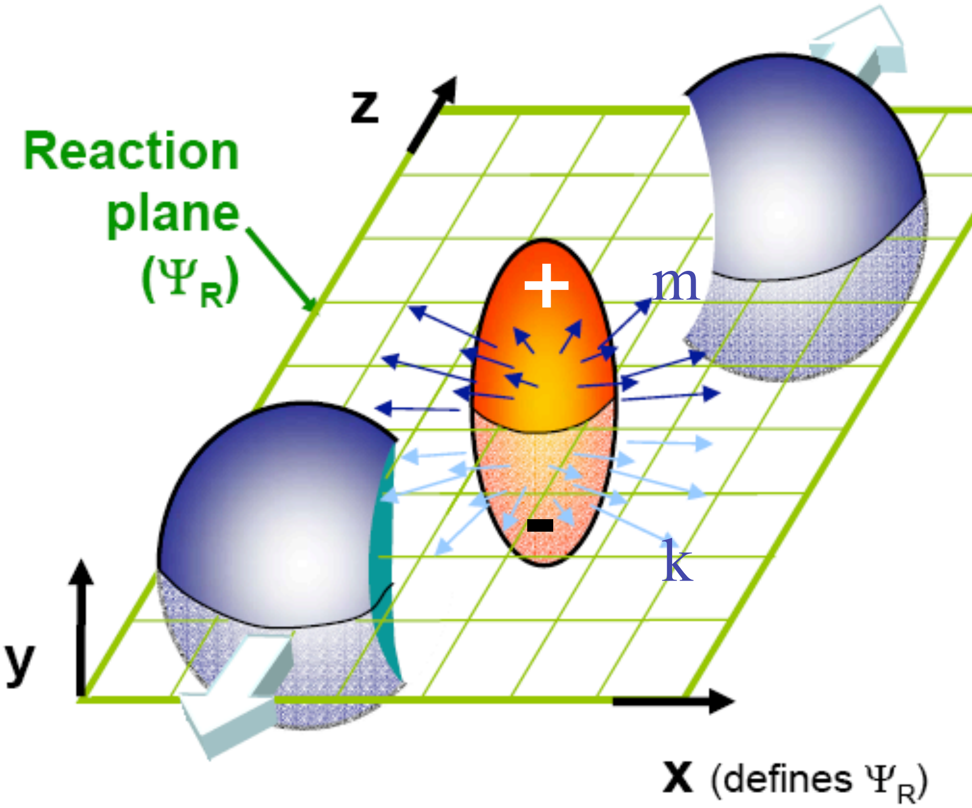




C.S. Wu, 1912-1997

BUT:
the sign of
the asymmetry
fluctuates
event by event

Charge asymmetry w.r.t. reaction plane: how to detect it?



$$\langle\cos(\phi_\alpha + \phi_\beta - 2\Psi_{RP})\rangle =$$
$$= \langle\cos\Delta\phi_\alpha \cos\Delta\phi_\beta\rangle - \langle\sin\Delta\phi_\alpha \sin\Delta\phi_\beta\rangle$$
$$= [\langle v_{1,\alpha}v_{1,\beta}\rangle + B^{in}] - [\langle a_\alpha a_\beta\rangle + B^{out}].$$

S.Voloshin, hep-ph/0406311

A sensitive (but P-even) measure of the asymmetry:

$$a^k a^m = \langle\sum_{ij}\sin(\varphi_i^k - \Psi_R)\ \sin(\varphi_j^m - \Psi_R)\rangle$$

Expect $a^+a^+ = a^-a^- > 0; \quad a^+a^- < 0$

Global polarization and parity violation study in Au+Au collisions

Ilya Selyuzhenkov for the STAR Collaboration

Department of Physics and Astronomy, Wayne State University, USA

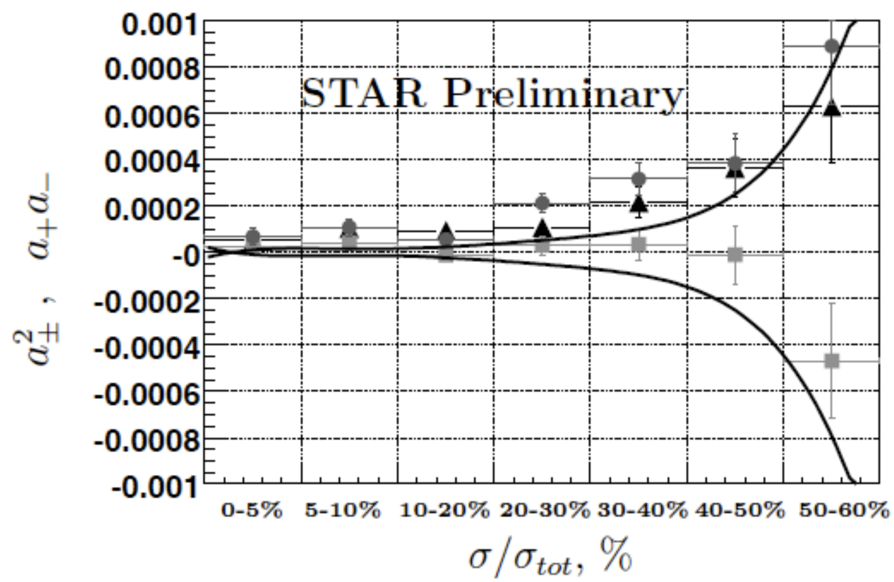
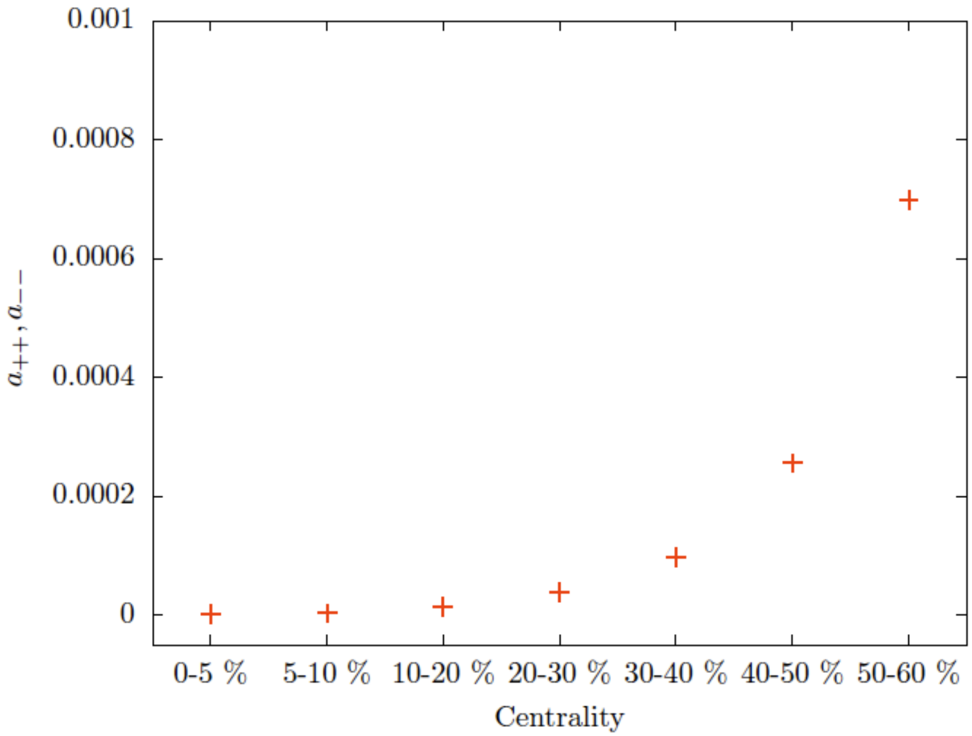
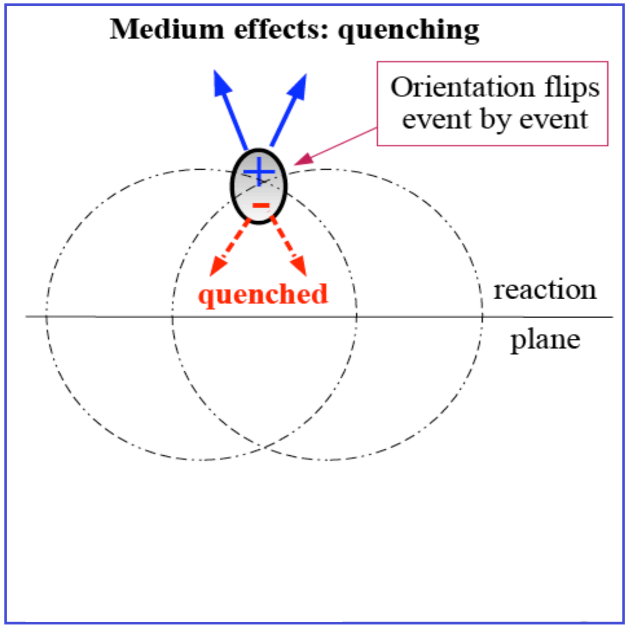


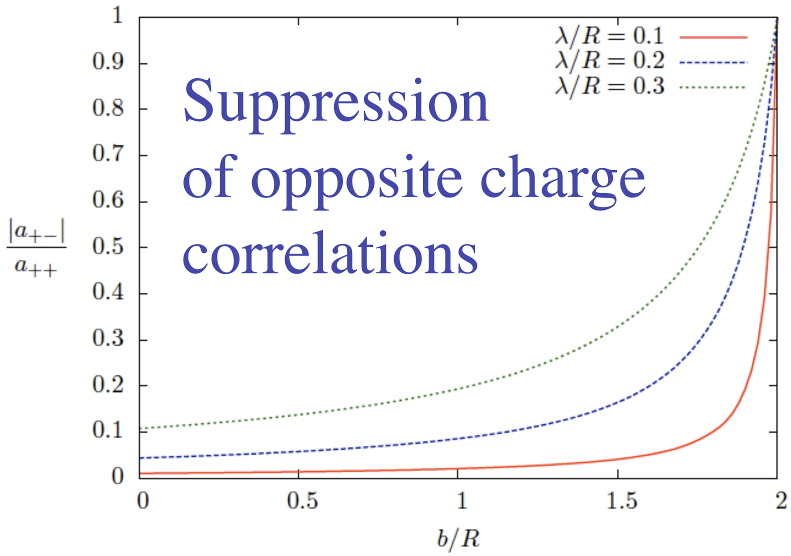
Figure 2: Charged particle asymmetry parameters as a a function of standard STAR centrality bins selected on the basis of charged particle multiplicity in $|\eta| < 0.5$ region. Points are STAR preliminary data for Au+Au at $\sqrt{s_{NN}} = 62$ GeV: circles are a_+^2, triangles are a_-^2 and squares are a_+a_-. Black lines are theoretical prediction [1] corresponding to the topological charge $|Q| = 1$.

nucl-ex/0510069

Theory estimates for Au-Au collisions



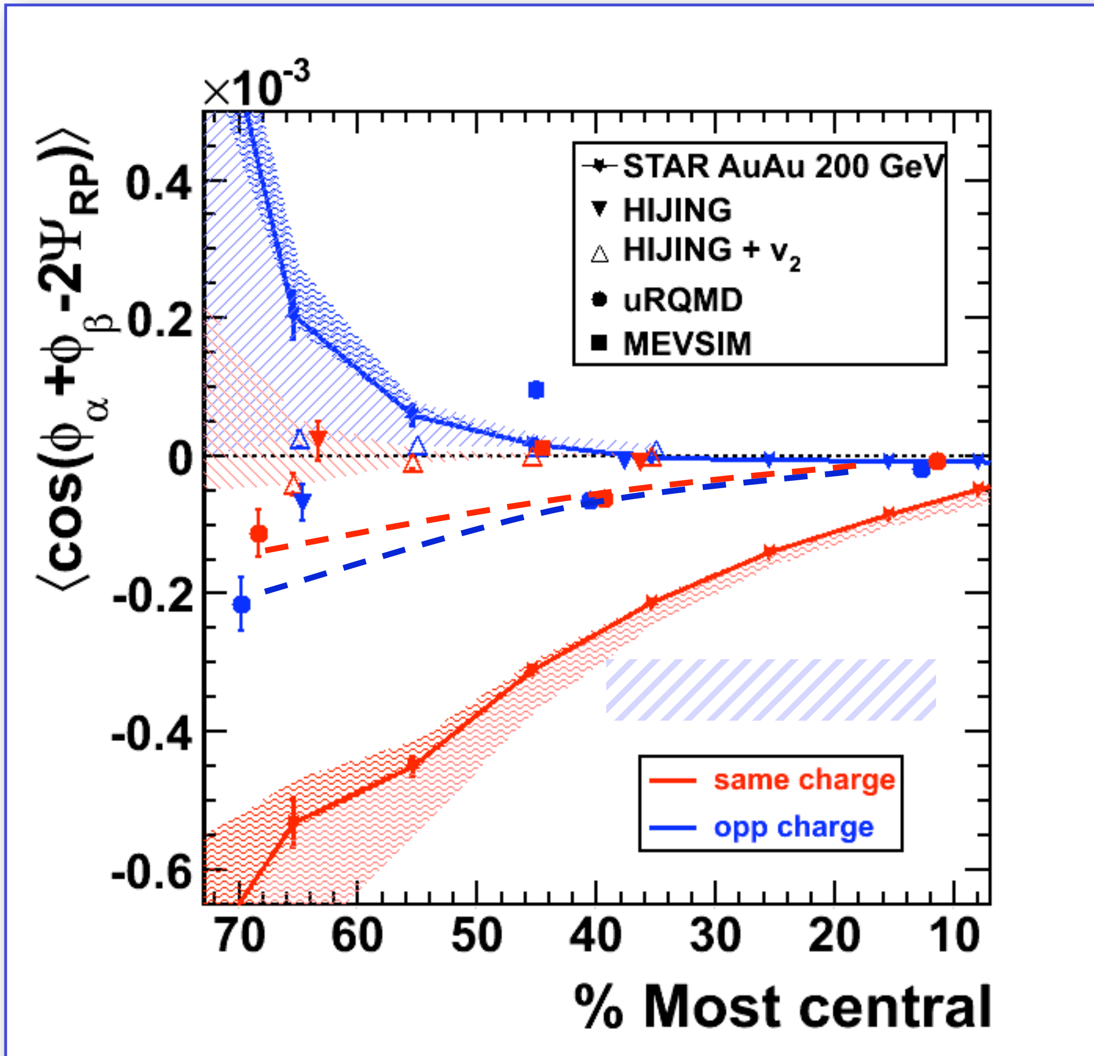




DK, L.McLerran, H.Warringa '07

Strong P, CP violation at high T ?

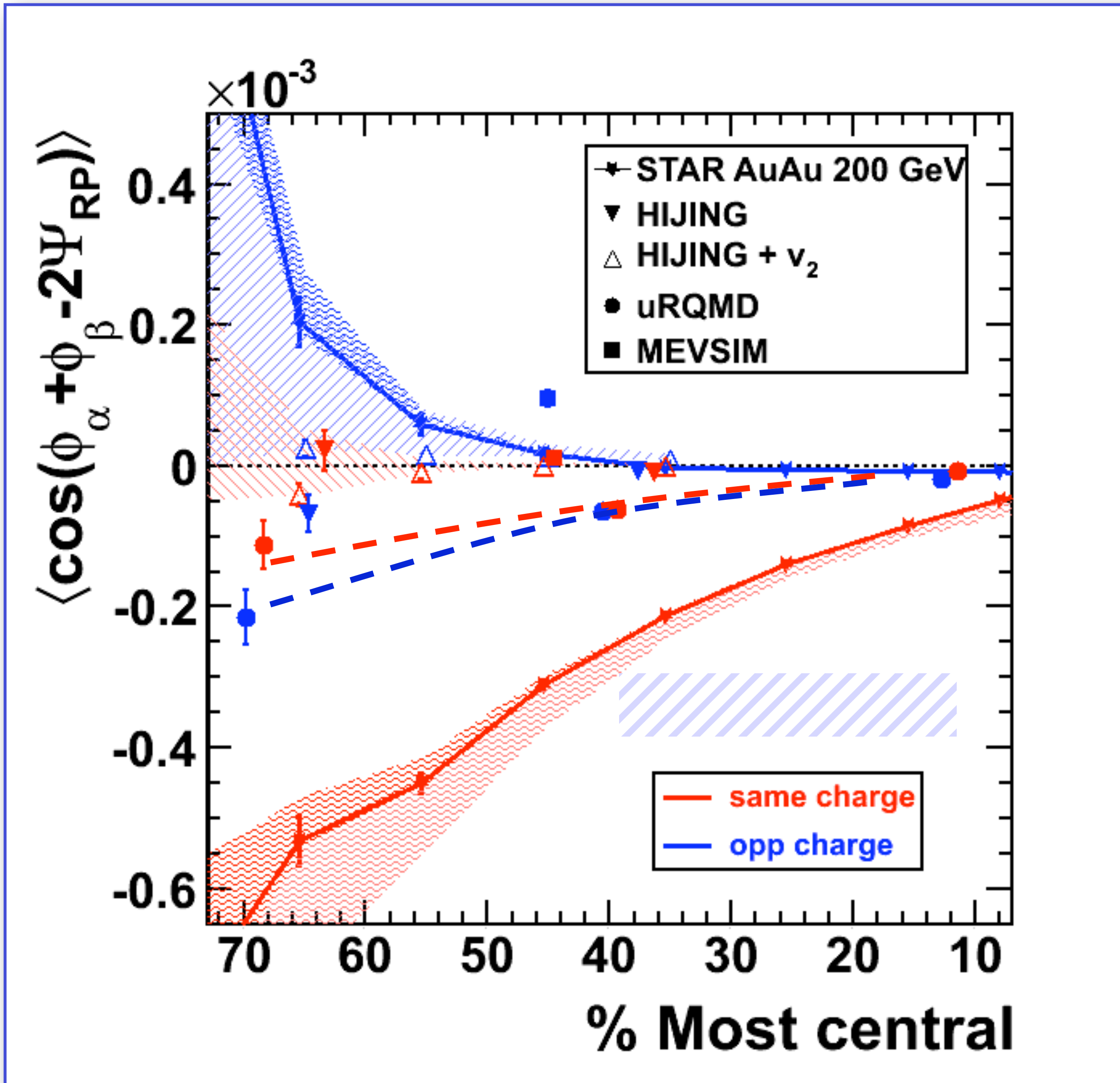
Charge asymmetry w.r.t. reaction plane, ~ - $a^k a^m$



STAR detector
Full azimuthal coverage

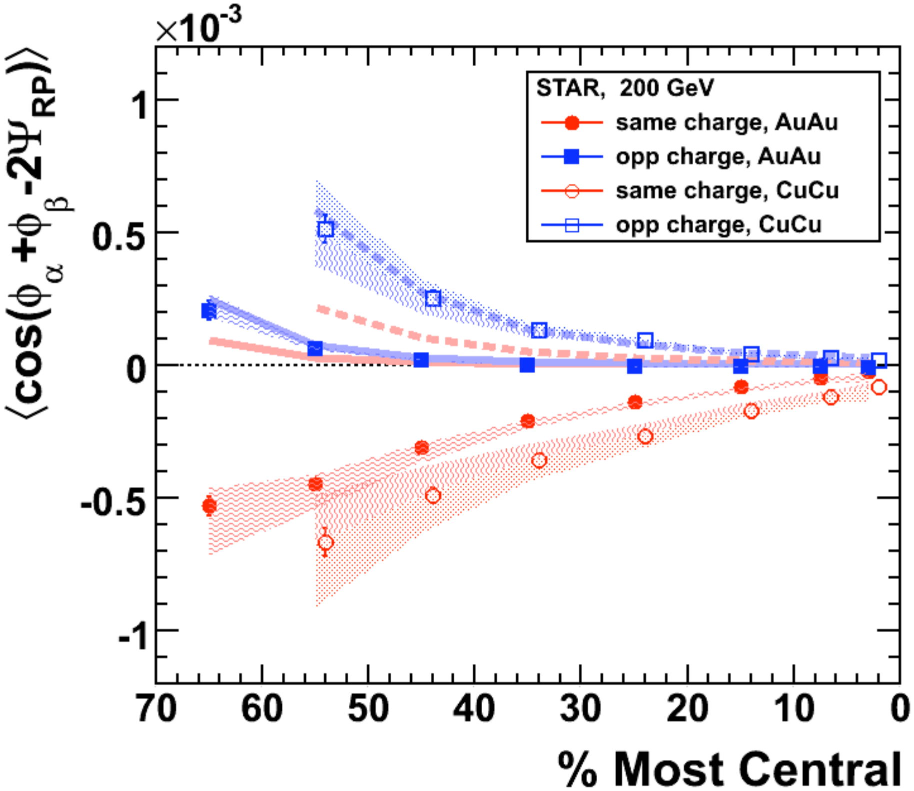
+QM'09 Posters by E. Finch and I. Selyuzhenkov; RHIC/AGS: J. Thomas; CPOD: E. Finch

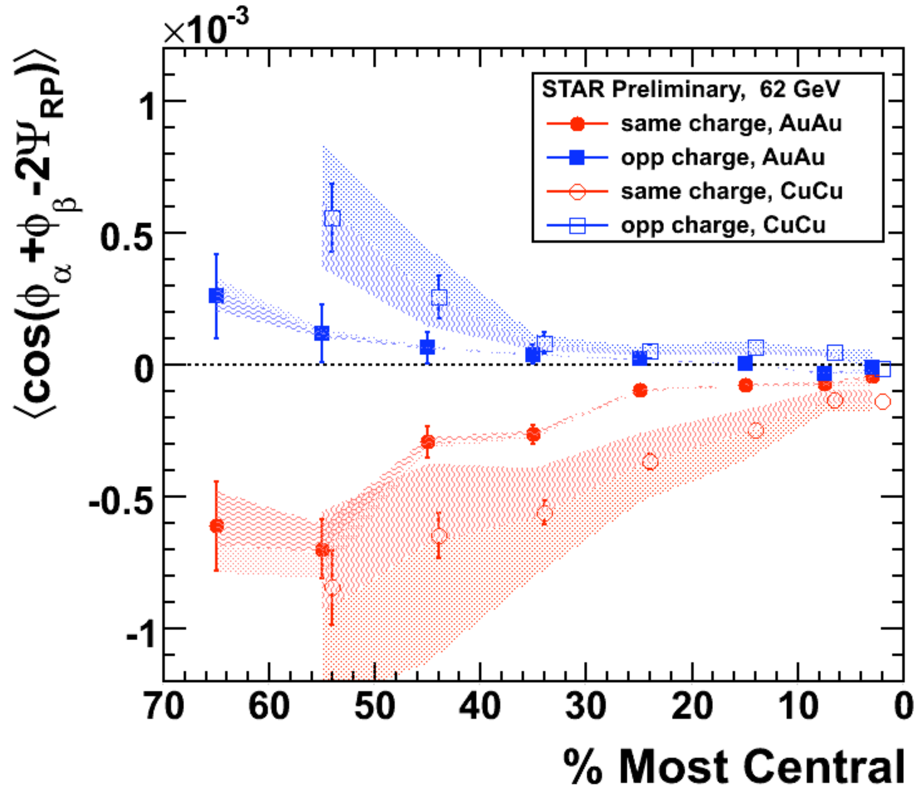
Plenary talk by S.Voloshin [STAR Coll.] at Quark Matter '09



S. Voloshin et al [STAR Coll.]; **Quark Matter '09**

Mass number and energy dependences

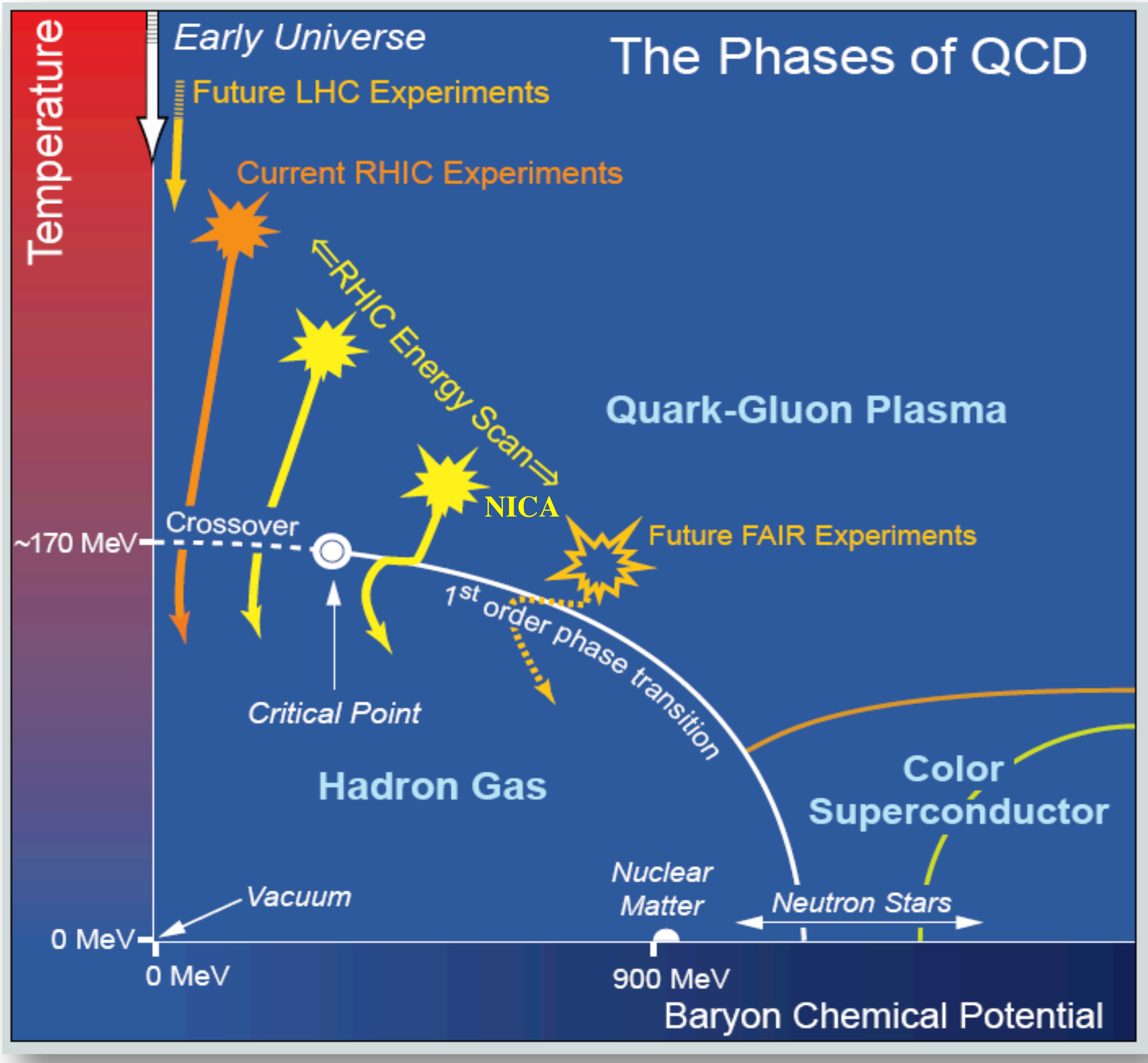




Talk by E. Finch;
RHIC/AGS: J. Thomas

Expectations for the energy dependence:
slow growth towards low energies
reflecting longer-lived magnetic field,
then gradual disappearance (no QGP):
there has to be a maximum somewhere

The phase diagram of hot and dense QCD and the Critical Point



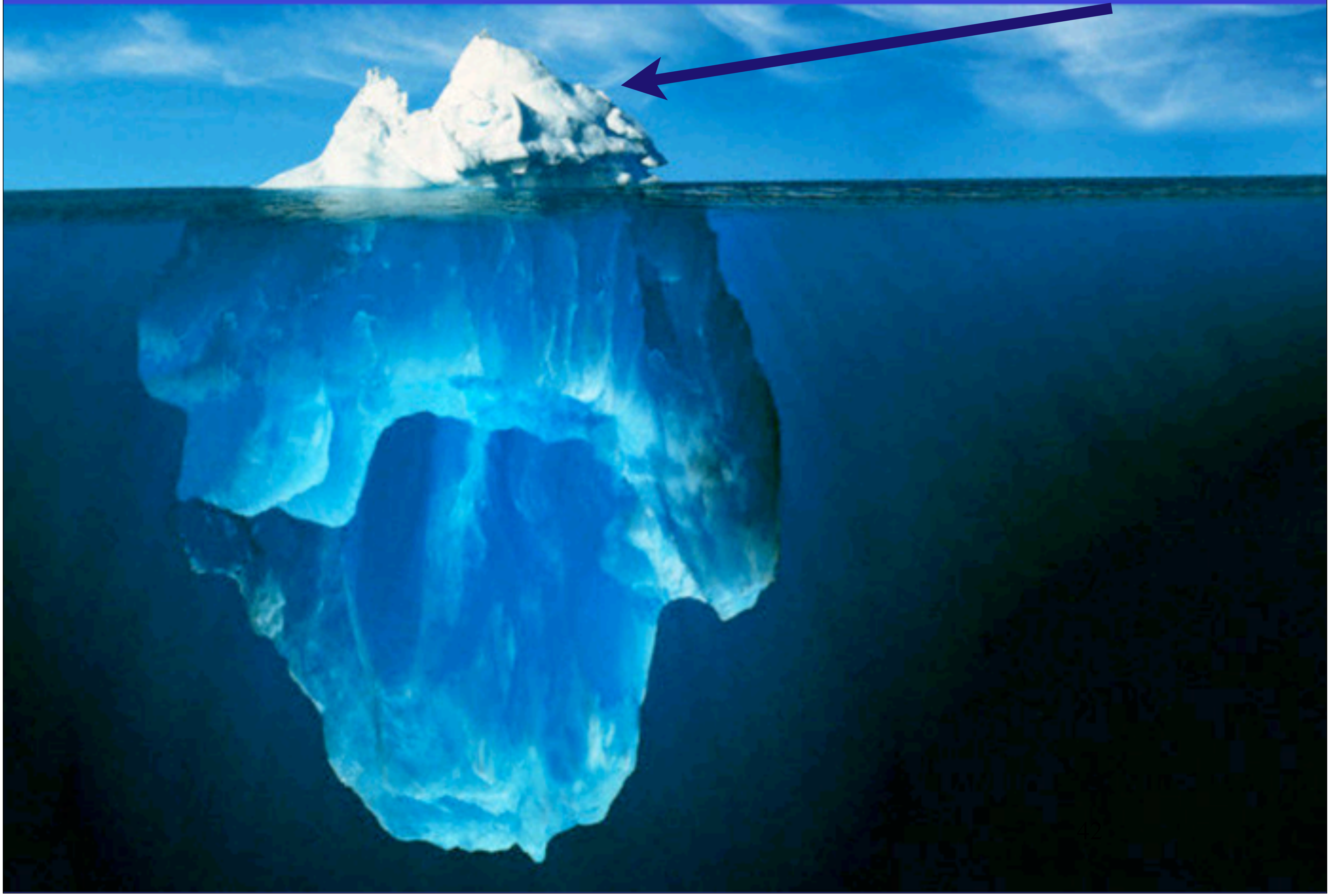
Interesting physics questions:

1. Do the charge asymmetries disappear at low energies?
   if yes, at what energy? is there a maximum?
   - pin down the critical energy density for deconfinement

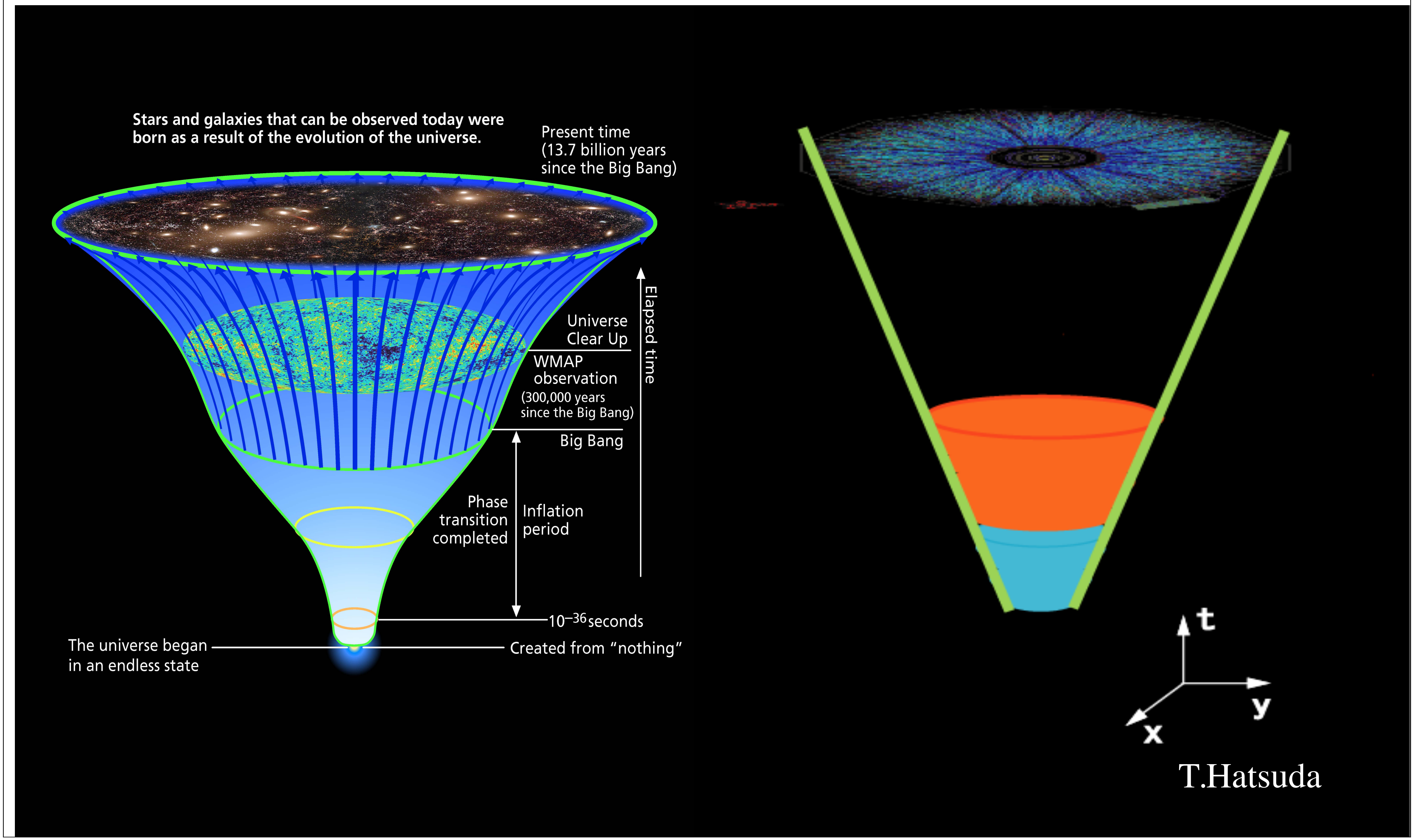
2. At low energy, magnetic field can live long enough to affect the phase transition -
   what is the influence of magnetic field on the phase transition and the Critical Point?
   is the chiral phase transition driven first order?

3. What happens to the fluctuations in the vicinity of the Critical Point?
   - "all" size bubbles possible? critical slowing down?
   this would enhance the parity violation signal

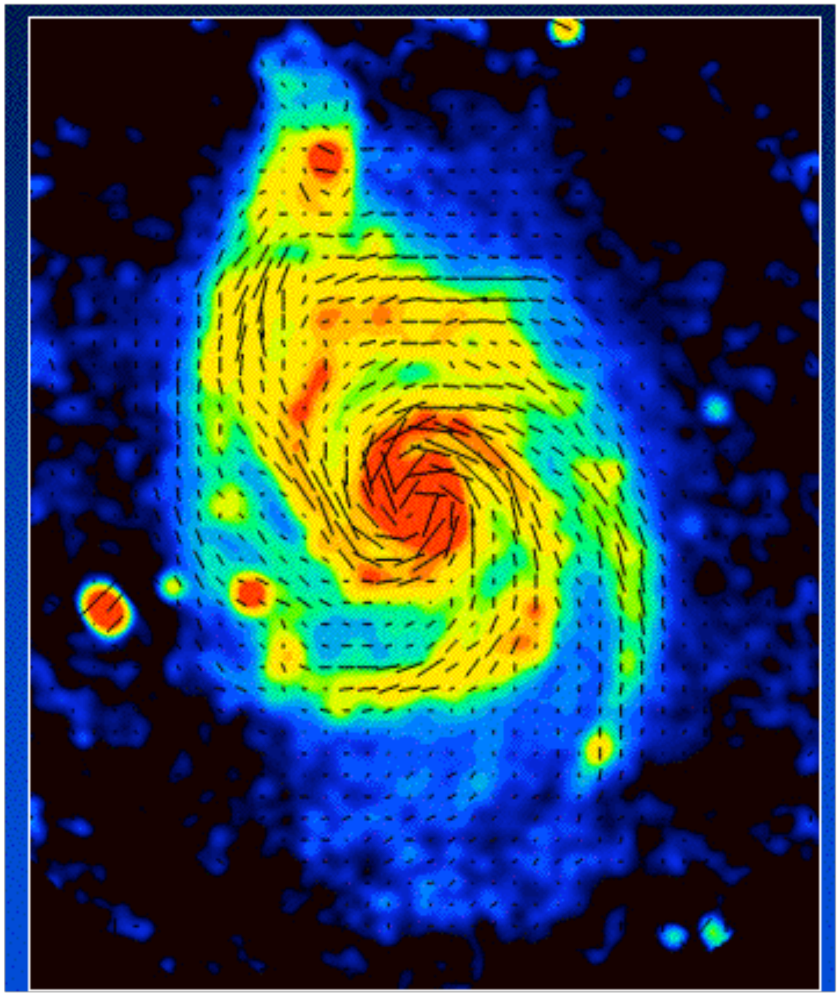
Topology - Induced Parity violation (TIP)



What are the implications for the Early Universe?



What is the origin of cosmic magnetic fields?



Magnetic fields are abundant in the Universe at large scales:

3 μG field in Milky Way;

1-40 μG fields in clusters of galaxies

Is the entire Universe chiral?

e.g. M.Longo, arXiv:0812.3437;

thanks to J.Bjorken

Magnetic field in M51:
Polarization of emission
Beck 2000

What is the origin of magnetic fields in the Universe?

Primordial magnetic field (E.Fermi, 1949)?

Dynamo in proto-galaxy? Stars? Galaxy?

Domain walls and vortices associated with the θ vacua carry magnetic field;

Primordial magnetic field generation at the QCD phase transition?

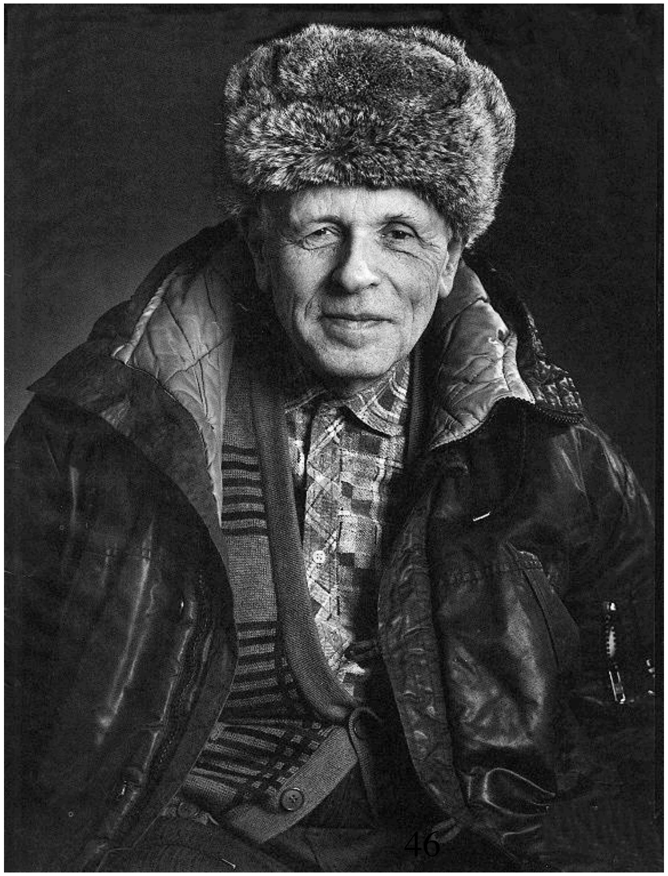
e.g.
DK, R.Pisarski, M.Tytgat '98;

R.Brandenberger, A.Zhitnitsky'00

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,
JETP Lett. 5 (1967) 24



Baryon asymmetry in the Universe and strong CP violation

1. Generation of Chern-Simons number at the QCD phase transition is analogous to baryon number generation in the electroweak phase transition

e.g. V.Kuzmin, V.Rubakov and M.Shaposhnikov, Phys.Lett.B155(1985)36

2. Strong CP violation can lead to the separation of matter and antimatter in the Universe at the QCD phase transition

e.g. R.Brandenberger, I.Halperin and A.Zhitnitsky, hep-ph/9903318
DK, A.Zhitnitsky, arXiv 0706.1026

Summary

- Topological structure of QCD vacuum makes P and CP violation possible in strong interactions
- Even in the absence of a global parity violation, sphaleron transitions in the QGP can induce P-and CP-odd fluctuations
- In heavy ion collisions this topology-induced parity violation can be observed through the event-by-event charge asymmetries
- Since charge asymmetry requires separation of quarks by “macroscopic” distance, it is a signature of deconfinement in AA collisions; for the electric current to persist, chiral symmetry must be restored
- Important implications for the Early Universe