Quark-Gluon plasma at Strong Magnetic Fields

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ITEP Lattice

arXiv:1104.3767, arXiv:1011.3001, arXiv:1011.3795, arXiv:1003.2180, arXiv:0910.4682, arXiv:0909.2350, arXiv:0909.1808, arXiv:0907.0494, arXiv:0906.0488, arXiv:0812.1740

Научно-координационная сессия "Исследования неидеальной плазмы"

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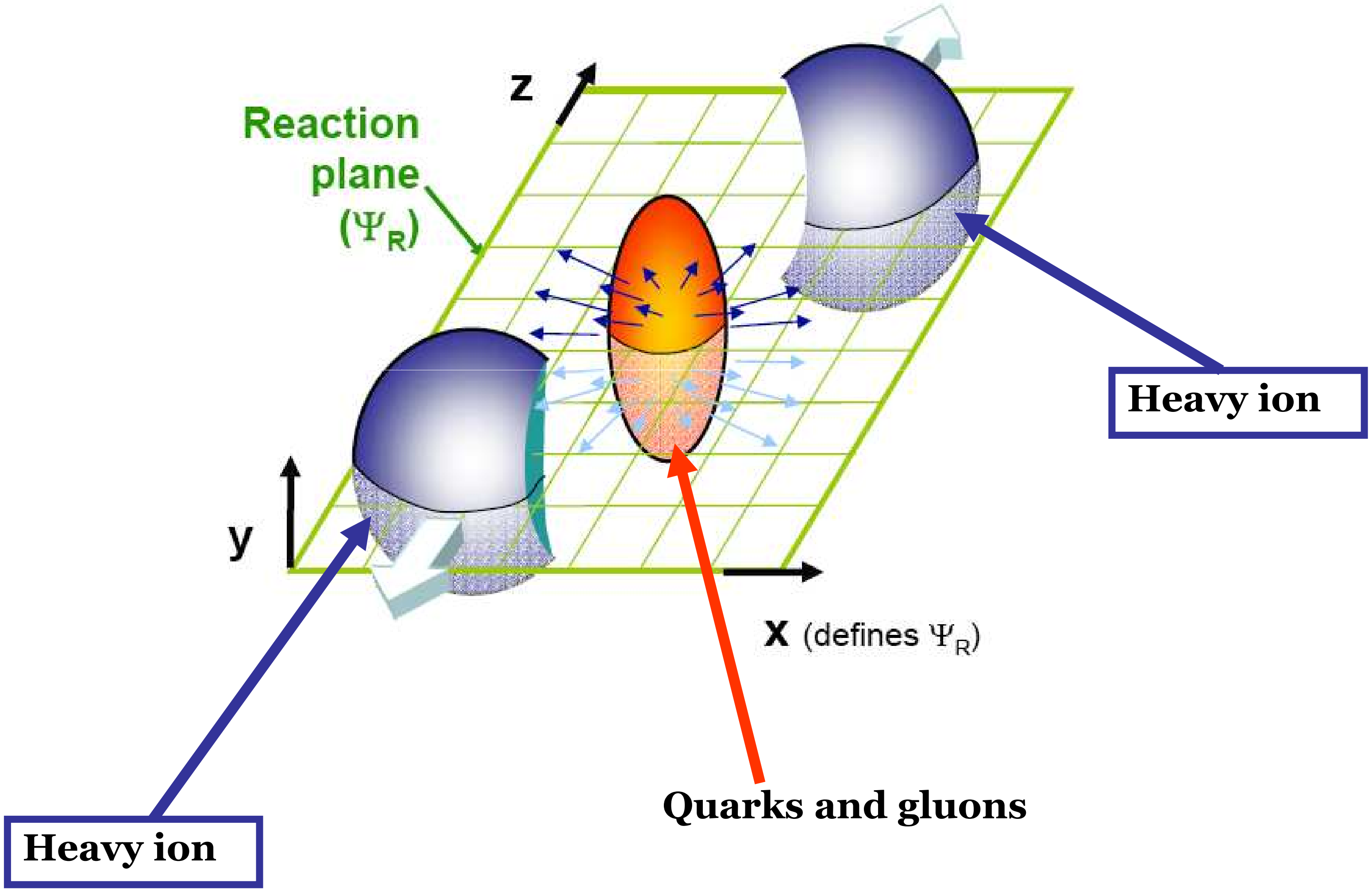
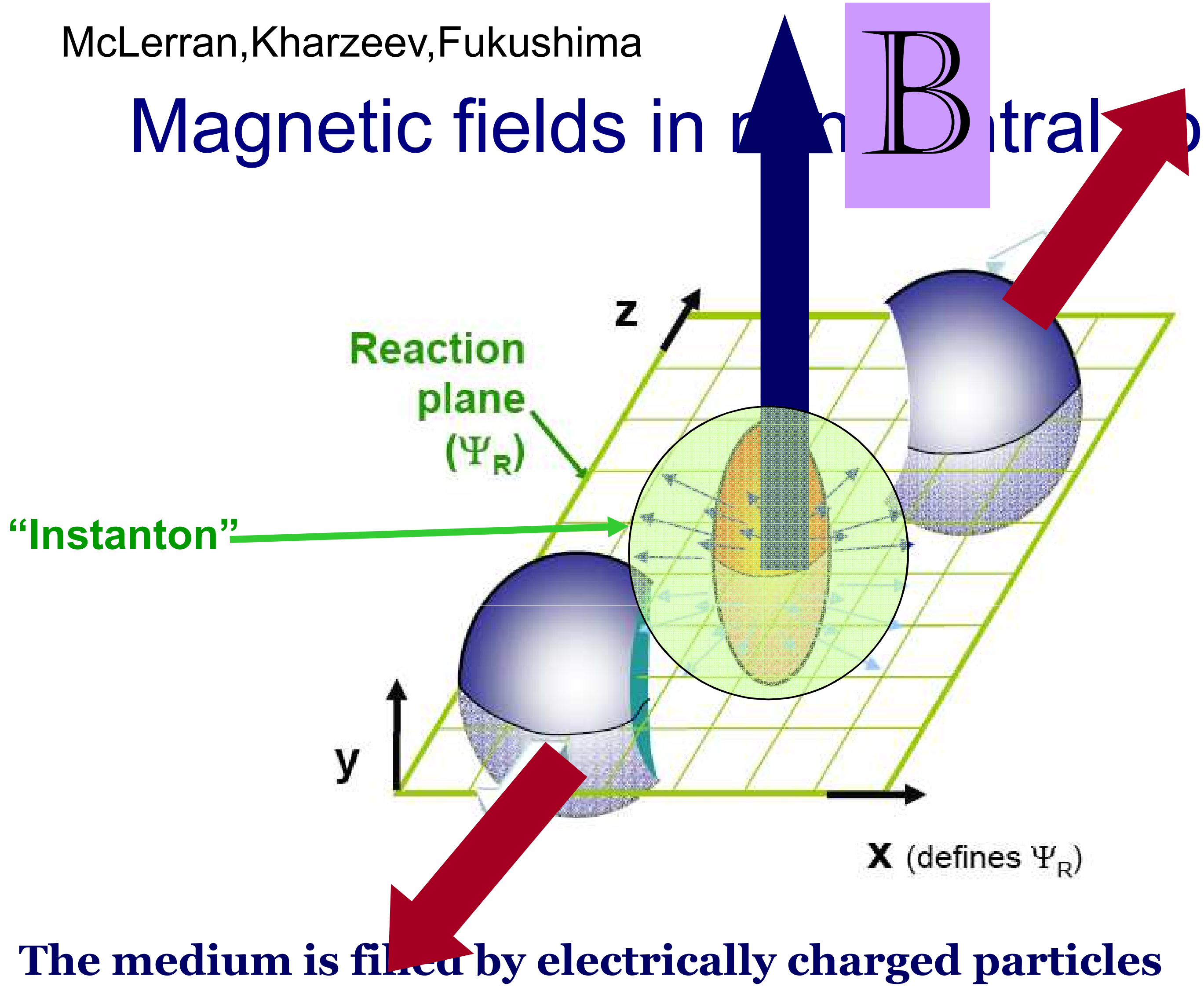
Magnetic fields in non-central collisions

[Fukushima, Kharzeev, Warringa, McLerran '07-'08]



McLerran,Kharzeev,Fukushima

Magnetic fields in non-central collisions



Two very big currents produce a very *big magnetic field*

The medium is filled by electrically charged particles

Large orbital momentum, perpendicular to the reaction plane

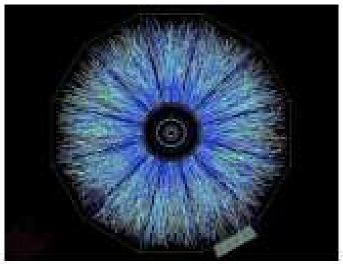
Large magnetic field along the direction of the orbital momentum

Comparison of magnetic fields

D.Kharzeev

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



Off central Gold-Gold Collisions at 100 GeV per nucleon

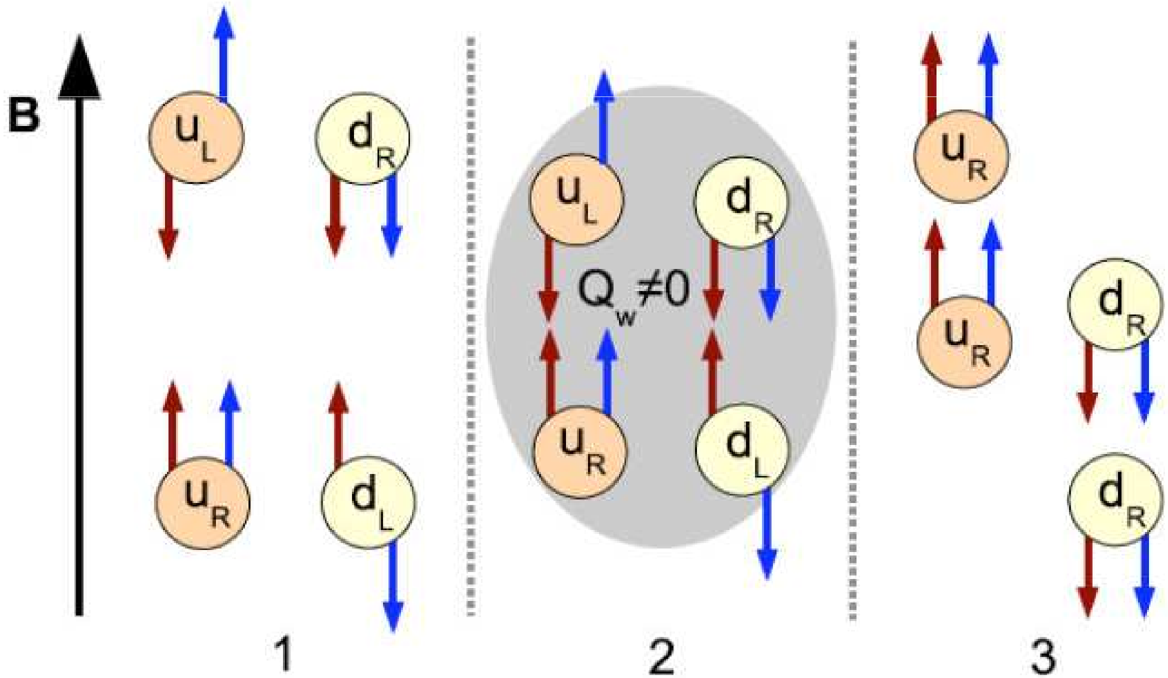
$$e B(\tau=0.2\,\mathrm{fm}) = 10^3 \sim 10^4\ \mathrm{MeV}^2 \sim 10^{17}\,\mathrm{Gauss}$$

In heavy ion collisions magnetic forces are of the order of strong interaction forces

$$eB \approx \Lambda^2_{QCD}$$

Chiral Magnetic Effect by
Fukushima, Kharzeev, Warringa, McLerran

3. Electric current is along magnetic field
In the *instanton* field

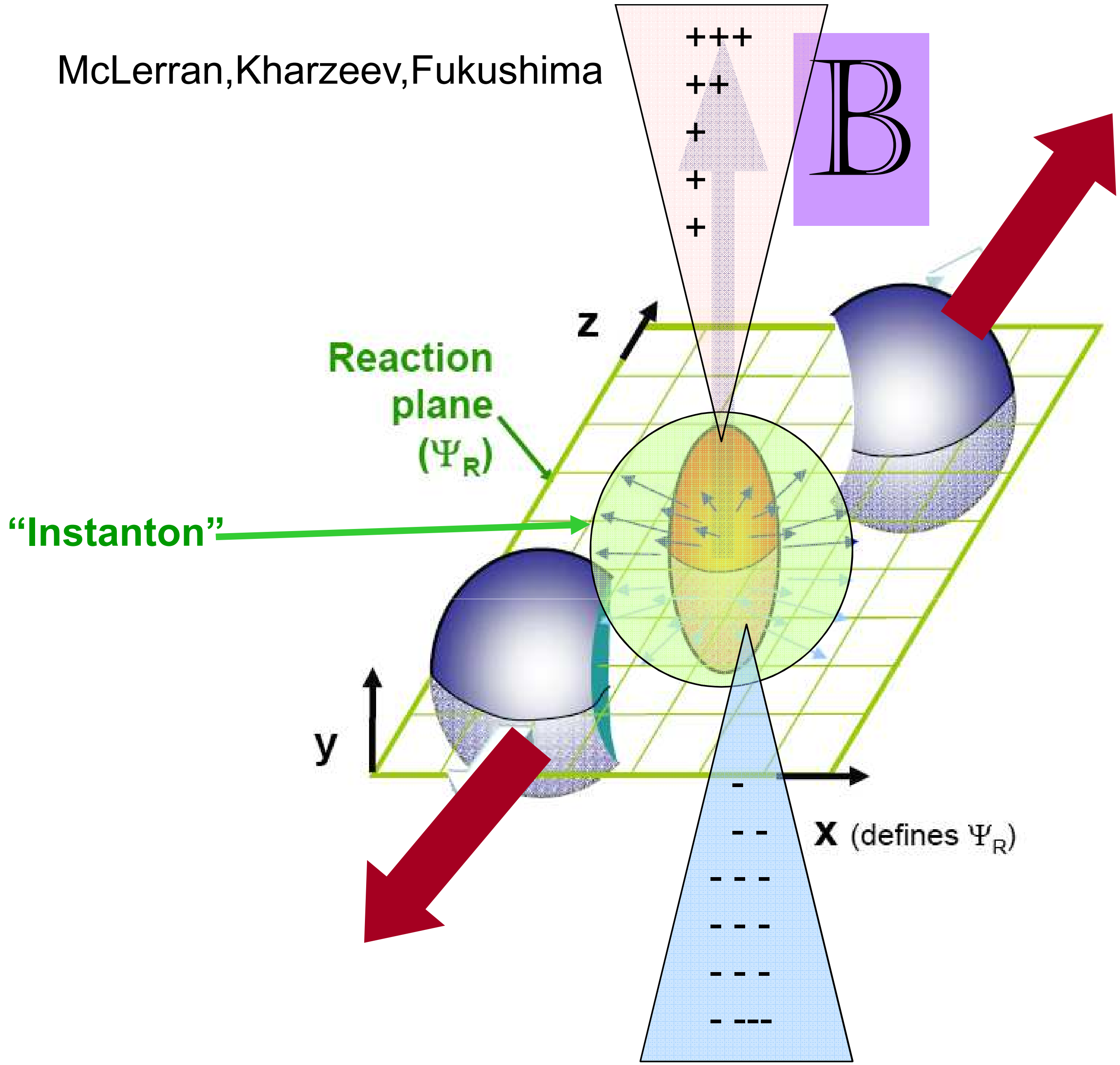


Red: momentum
Blue: spin

Effect of topology:
$u_L \rightarrow u_R$
$d_L \rightarrow d_R$

u-quark: q=+2/3
d-quark: q= - 1/3

McLerran,Kharzeev,Fukushima



Two very big currents produce a very *big magnetic field*

- ***Charge***
- ***asymmetry***

Magnetic forces are of the order of strong interaction forces

$$eB \approx \Lambda^2_{QCD}$$

We expect the influence of magnetic field on strong interaction physics

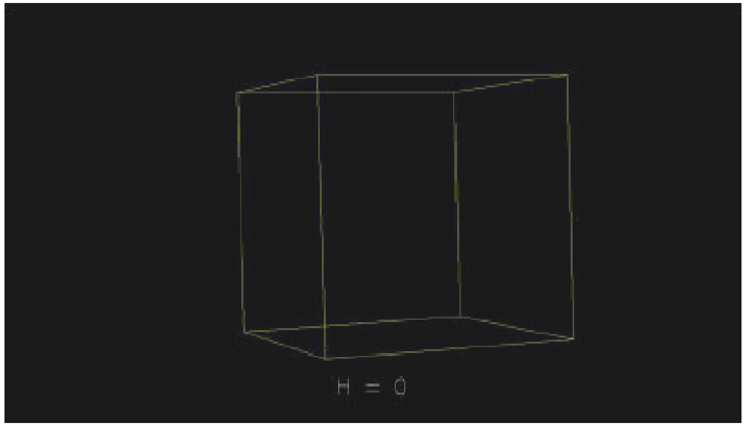
The effects are nonperturbative,

and we use

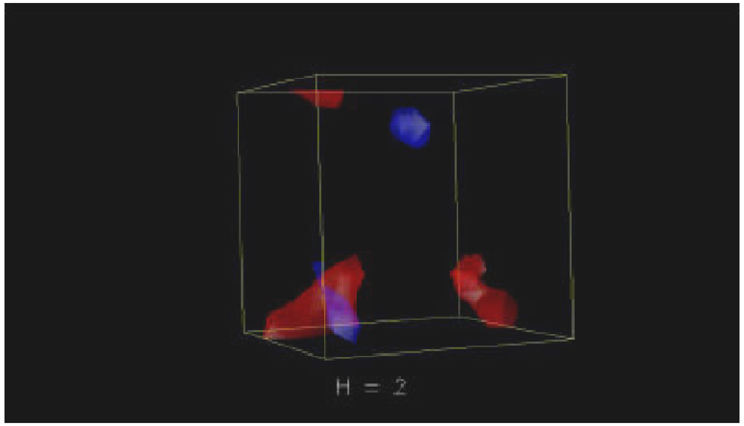
"Lattice (super)computer simulations"

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

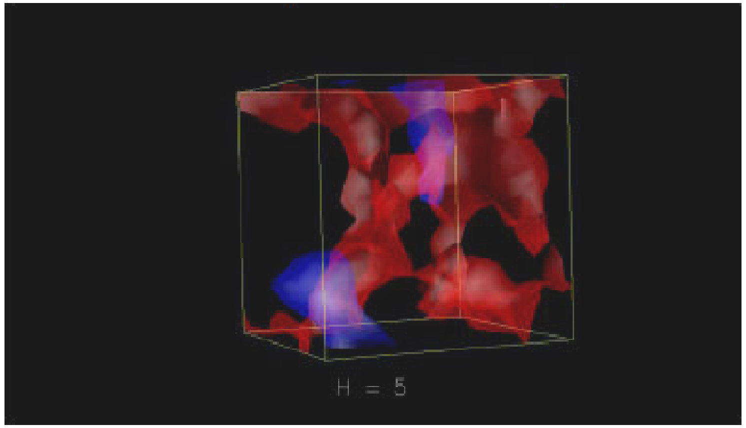
$B = 0$



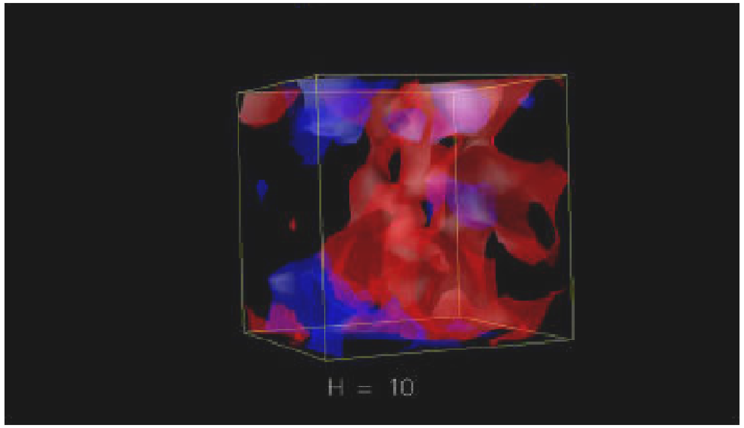
$B = (500\,\mathrm{MeV})^2$



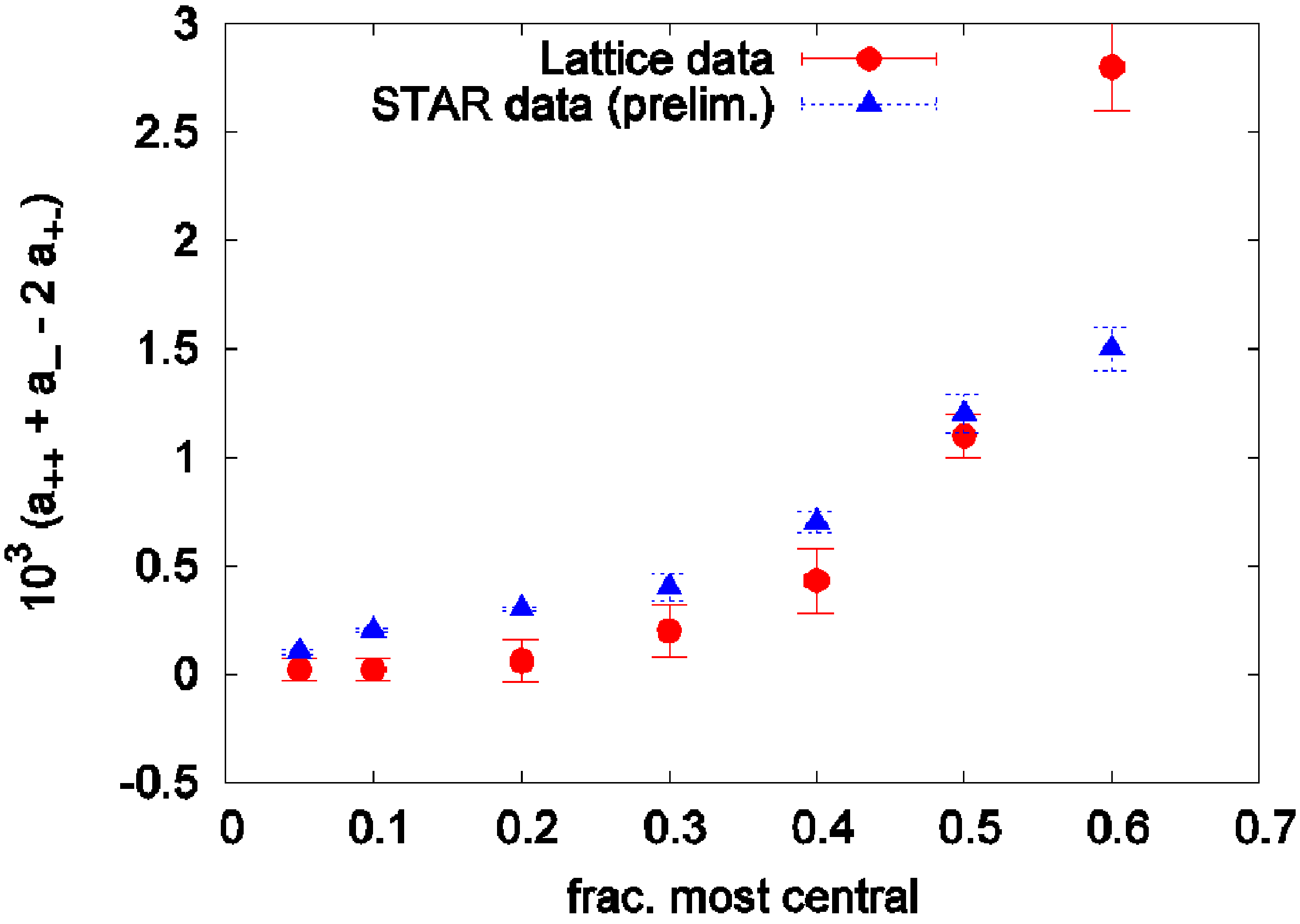
$B = (780\,\mathrm{MeV})^2$



$B = (1.1\,\mathrm{GeV})^2$



Chiral Magnetic Effect,
EXPERIMENT VS LATTICE DATA (Au+Au)



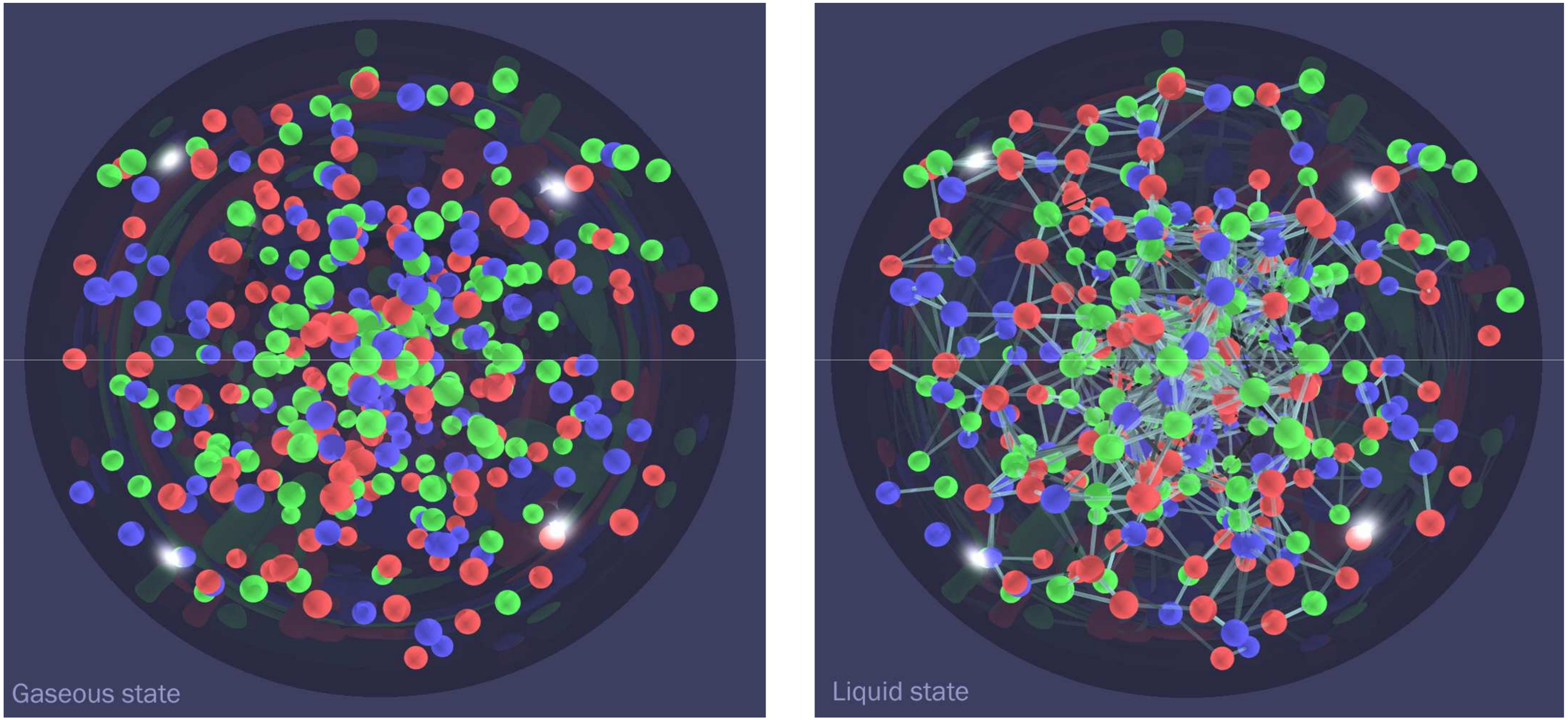
when they are in *local* thermal equilibrium. Macroscopic currents in one region of the plasma can interact magnetically with other currents in other regions, over tremendous distance scales, creating complicated structures like Fig. 1. Non-Abelian plasmas, however, are somewhat different. From theoretical studies of the equilibrium properties of such plasmas, we know that the non-Abelian interactions cause magnetic *confinement* over distances of order $1/(g^2T)$. It is reasonable to assume that, even dynamically, color magnetic fields cannot exists on distance scales larger than the confinement length. So, unlike traditional electromagnetic plasmas, there are no large-distance magnetic fields. As far as the color degrees of freedom are concerned, the long-distance effective theory of a non-Abelian plasma is hydrodynamics rather than magneto-hydrodynamics.

QUARK-GLUON PLASMA THERMALIZATION AND PLASMA INSTABILITIES
PETER ARNOLD

arXiv:hep-ph/0409002v1

Figure 1. Image of a solar coronal filament from NASA's TRACE satellite, from ⟨http://antwrp.gsfc.nasa.gov/apod/ap000809.html⟩.

QGP is the thermalized strongly correlated liquid



Collision time is very short and how thermalization occurs it is a question

New Relativistic Hydrodynamics

corrections to L.L. volume 6

triangle anomaly changes hydrodynamic equations

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D. T. Son, P. Surowka, Hydrodynamics with Triangle Anomalies **Phys.Rev.Lett. 103 (2009) 191601**

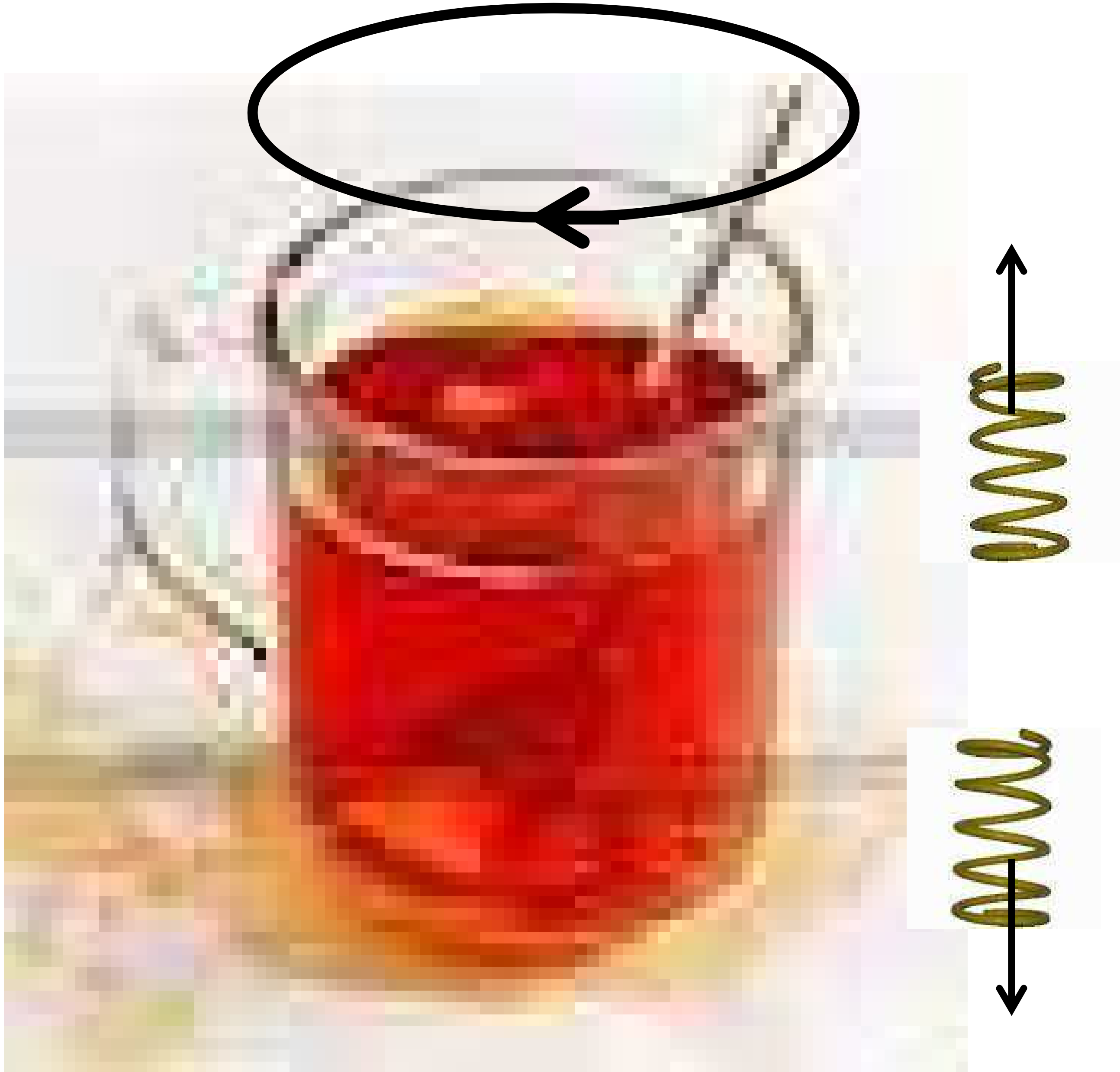
The idea of the next few slides with the tea is due to D.T. Son

TEA

Add
left

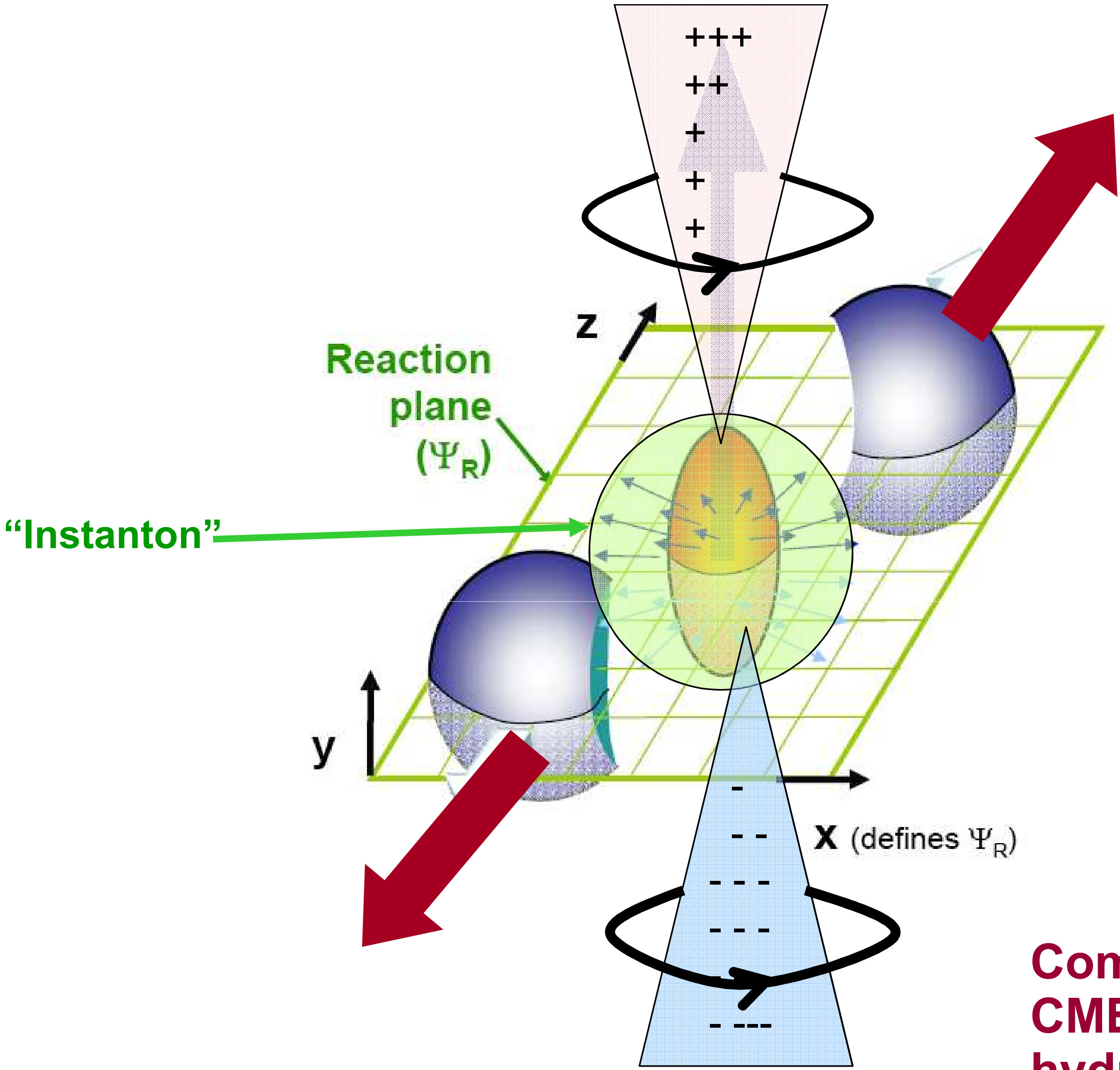
and
right

sugar



Tea is
sweet!

Tea is not sweet!



Combination of CME and NEW hydrodynamics

Summary

1. In noncentral heavy ion collisions the extremely intensive magnetic field is generated and interfierence of electromagnetic and strong interactions takes place
2. CME effect is clearly seen in computer simulations
3. “New hydrodynamics” + CME = additional rotation of charged particles

Lattice simulations with magnetic fields

1. Conductivity and Superconductivity of the vacuum
1.1 CME on the lattice
1.2 Vacuum conductivity induced by magnetic field
1.3 Quark mass dependence of CME
1.4 Dilepton emission rate
1.5 Superconductivity of the vacuum

2. Other effects induced by magnetic field
2.1 Chiral symmetry breaking
2.2 Magnetization of the vacuum
2.3 Electric dipole moment of quark along the direction of the magnetic field
2.4 Vector – Axial transitions $< \bar{\psi}\gamma_\mu\psi(x)\,\bar{\psi}\gamma_\mu\gamma_5\psi(y) >$

Magnetic Field Induced Conductivity of the Vacuum
Can exist only at T>0

Qualitative definition of conductivity, σ

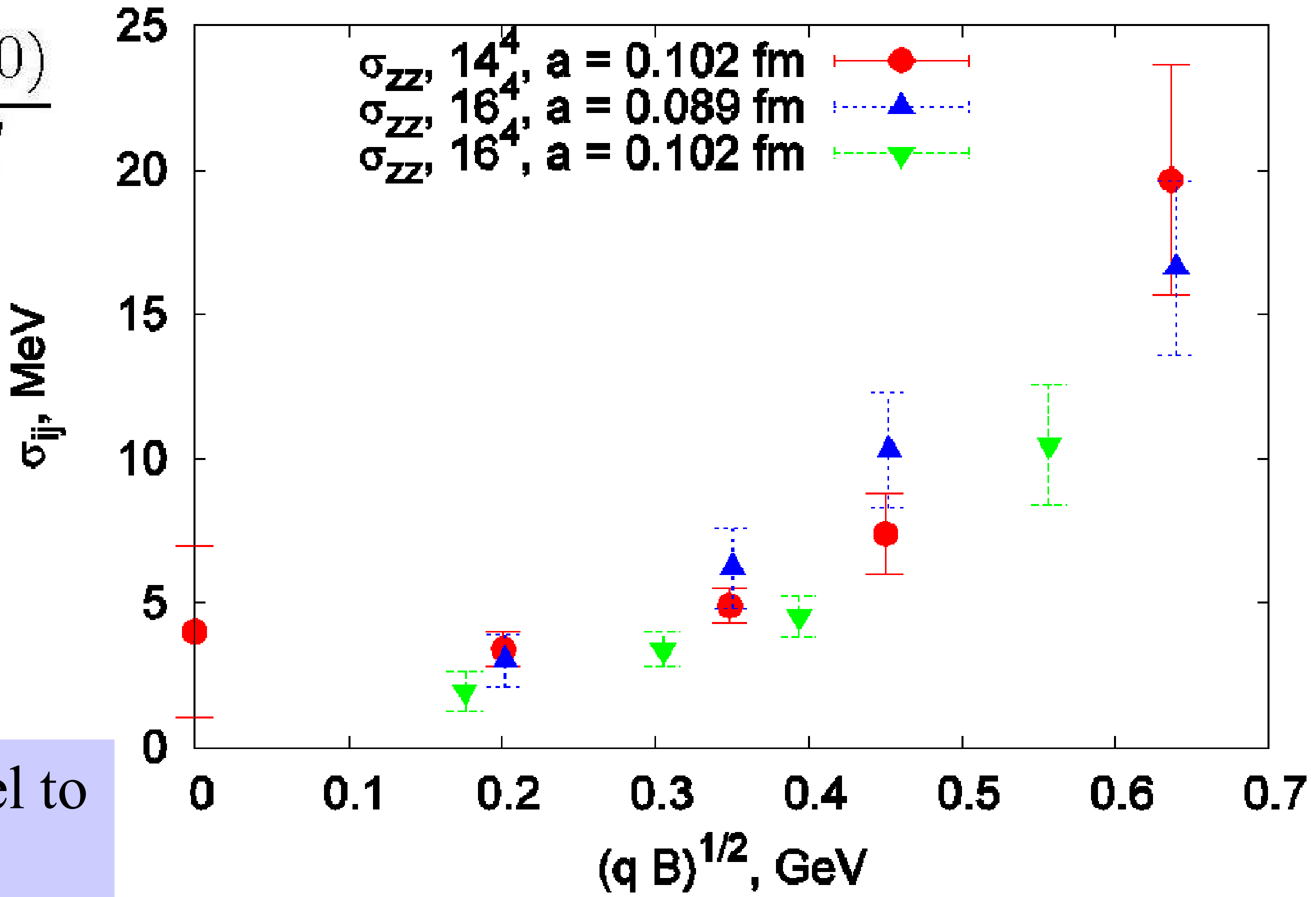
$$< j_{\mu}(x) j_{\nu}(y) > = C + A \cdot \frac{\exp\{-m|x-y|\}}{r^{\alpha}}$$

$$j_{\mu}(x) = \bar{q}(x)\gamma_{\mu} q(x)$$

$$\sigma \propto C$$

Calculations in SU(2) gluodynamics, conductivity along magnetic field at *T/Tc=0.45*

$$\sigma_{ij} = \frac{\rho_{ij}(0)}{4T}$$

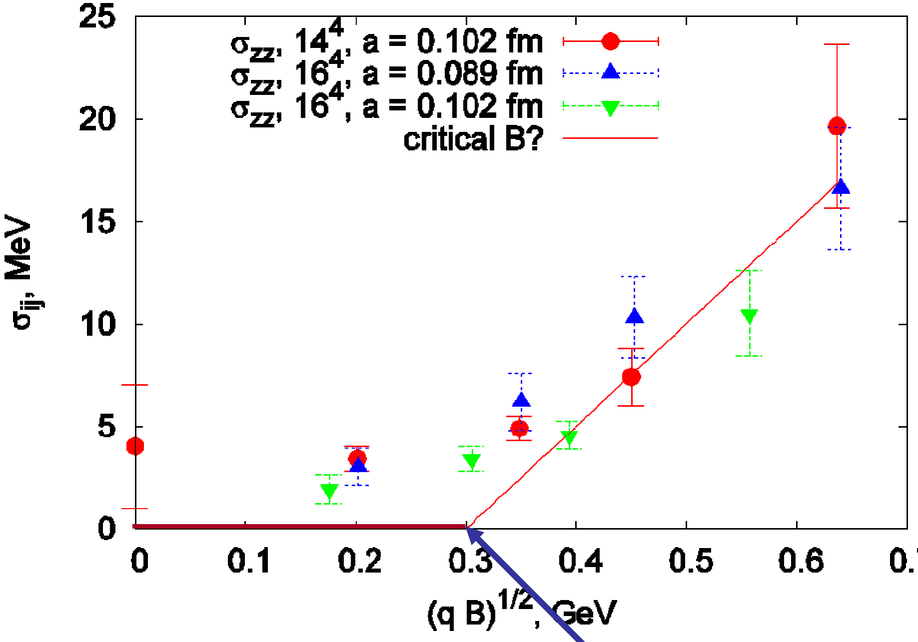


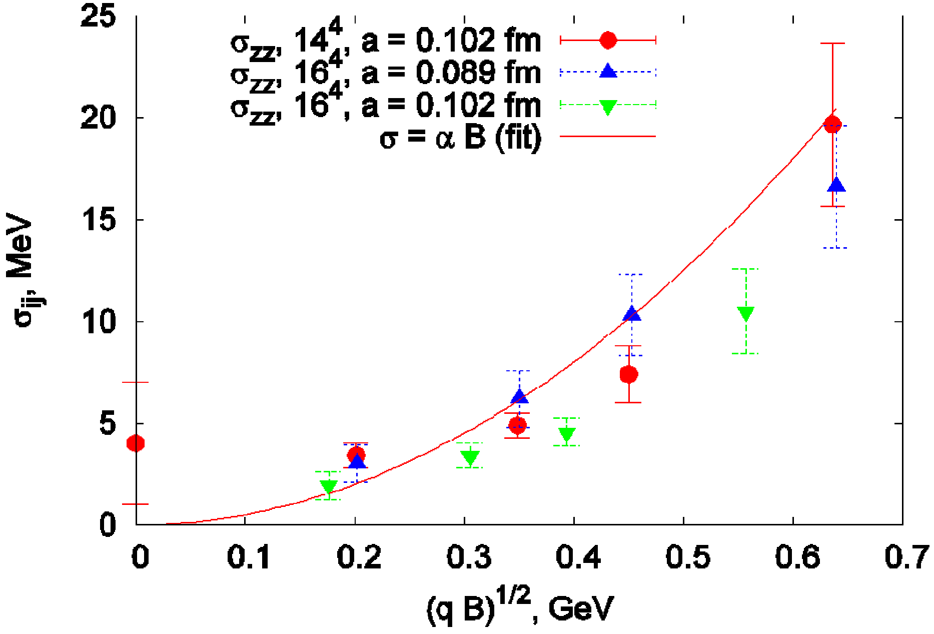
$\vec{B}$ is parallel to $0Z$ axis

Calculations in SU(2) gluodynamics, conductivity along magnetic field at *T/Tc=0.45*

$$\sigma_{ij} = \frac{\rho_{ij}(0)}{4T}$$

At T=0, B=0 vacuum is insulator





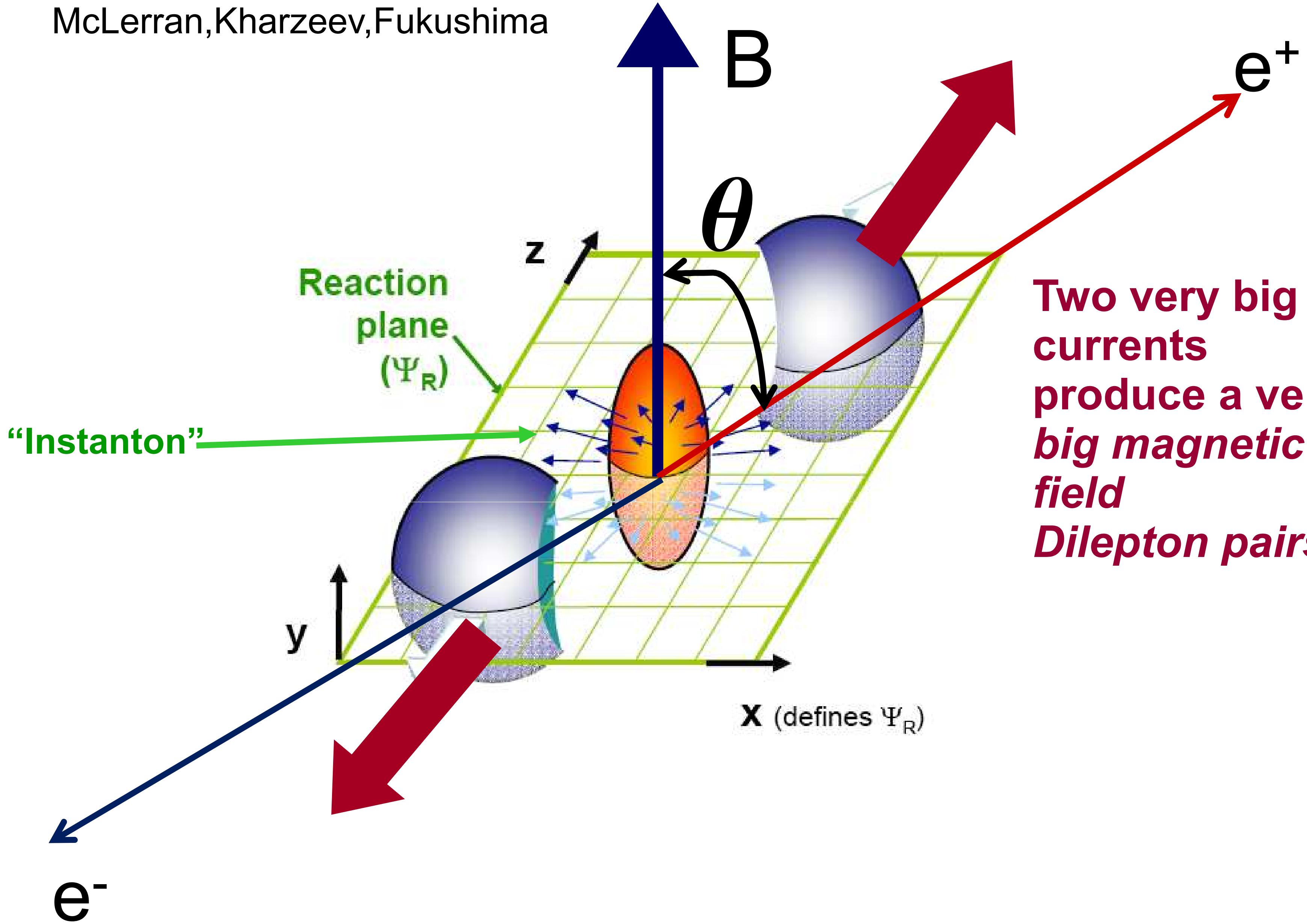
Critical value of magnetic field?

- There should be more soft dileptons in the direction ***perpendicular*** to magnetic field

$$\frac{d\sigma}{dp_1 dp_2} \propto \frac{|B|}{m_\pi} \sin^2 \theta$$

θ is the angle between the spatial momentum of the leptons and the magnetic field, in the center of mass of dilepton pair

McLerran,Kharzeev,Fukushima



Two very big currents produce a very *big magnetic field*

Dilepton pairs

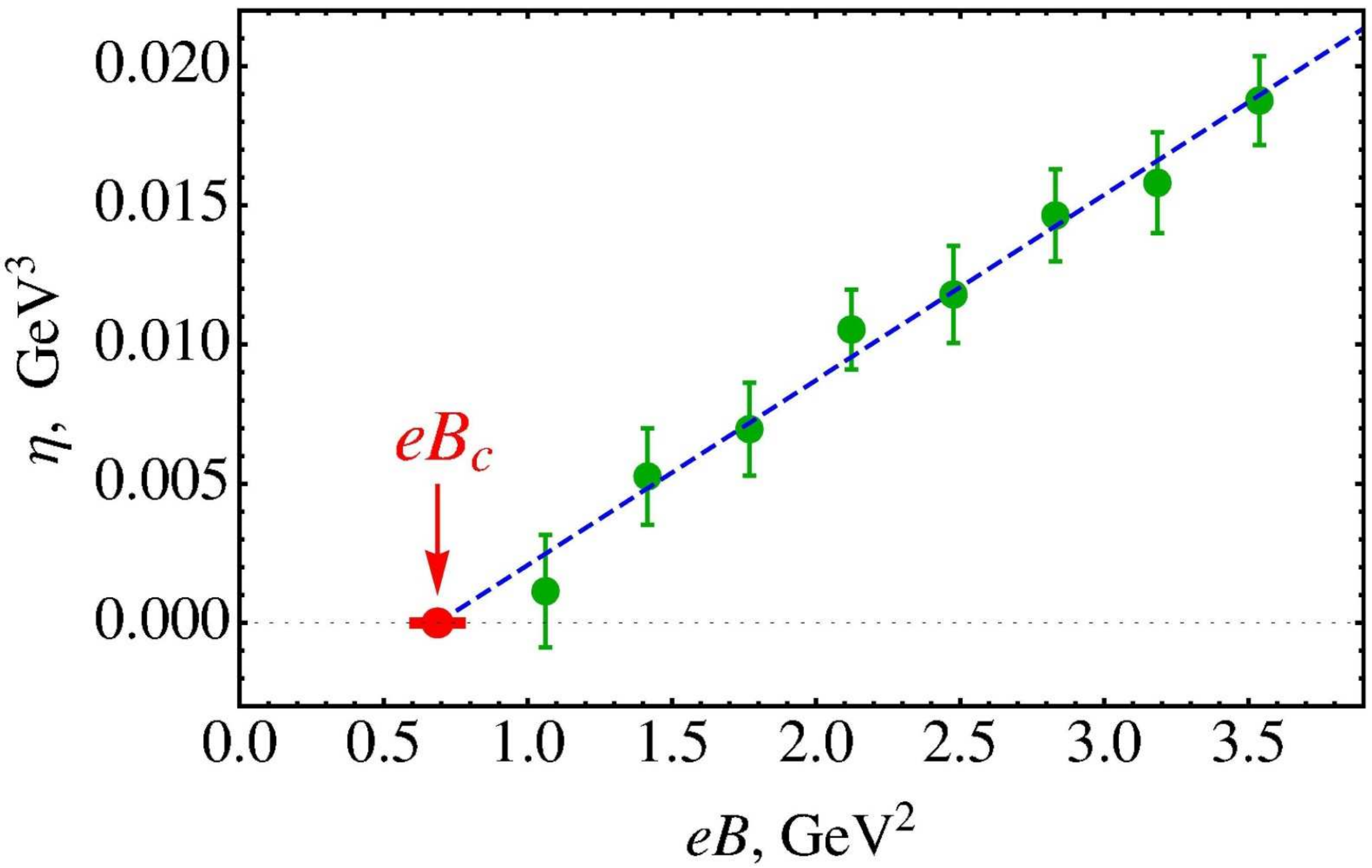
Superconductivity of the Vacuum

Can nothing be a superconductor and a superfluid?
M.N. Chernodub arXiv:1104.4404

Superconductivity of the vacuum can exist at T=0

Superconductivity is due to the condensation of the ρ mesons

Preliminary lattice results



Condensate of the charged ρ-mesons vs value of the magnetic field