

Кварки, невылетание цвета, и суперкомпьютеры

М.И. Поликарпов (ИТЭФ, Москва)

- Введение: кварки и глюоны
- Невылетание цвета –задача тысячелетия
- Моделирование сильных взаимодействий на компьютерах и суперкомпьютерах
- Перемешивание сильных и электромагнитных взаимодействий
- Теория невылетания цвета

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Experiment

LHC

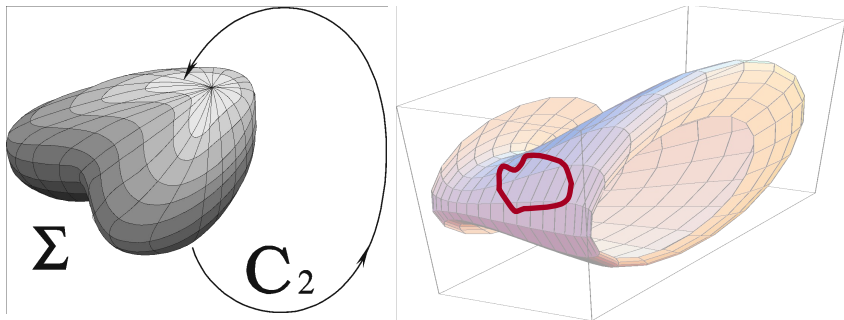


RHIC



Theory

$$L = -\frac{1}{g^2} \text{Tr} F_{\mu\nu}^2 + \sum_f \bar{\psi}_f (D + m) \psi_f$$



Supercalculations



Основные результаты получены в сотрудничестве группы ИТЭФ с

ДЭЗИ (Германия),

Университет Каназава (Япония),

Национальная Лаборатория Брукхэвен (США)

Университет Сан Франциско (США)



F.V. Gubarev, A.V.Kovalenko, S.M. Morozov, MIP, S.V. Syritsyn, V.I. Zakharov, P.Yu Boyko,
P.V. Buividovich, M.N. Chernodub, V.G. Bornyakov, E.N. Luschevskaya, A.I.Veselov, A.A.
Slavnov

DESY, Gumboldt University, Germany

G.Schierholz, D.Pleiter, T.Streuer, H.Stuben, F. Weinberg, M. Mueller-Proyssker, E.M. Ilgenfritz

Kanazawa University, Japan

H.Ichie, S.Kitahara, Y.Koma, Y.Mori, Y.Nakamura, T.Suzuki, A. Nakamura

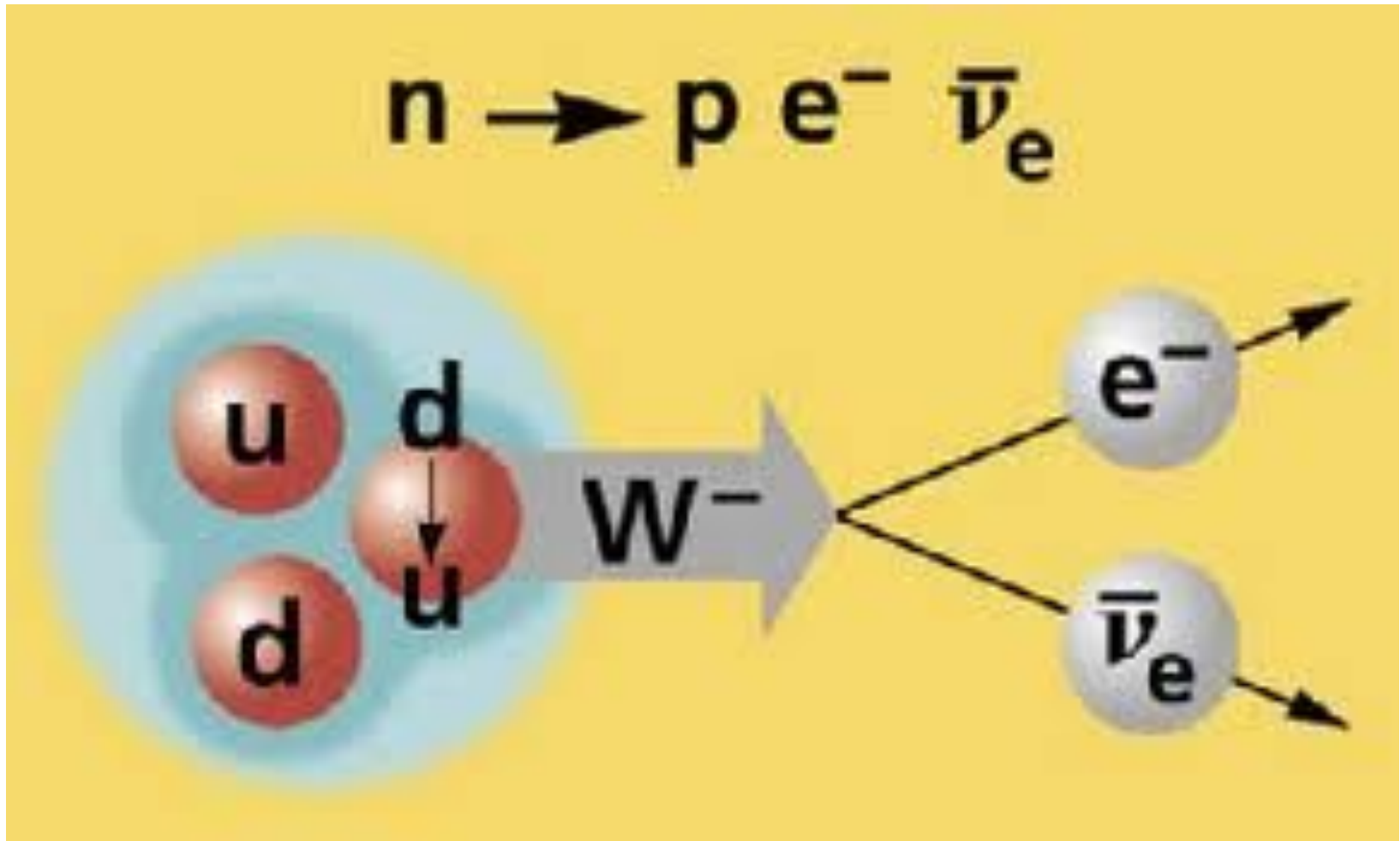
BNL, San Francisco University, USA

D. Kharzeev, J. Greensite, S. Olejnik (+ Bratislava University, Slovakia)

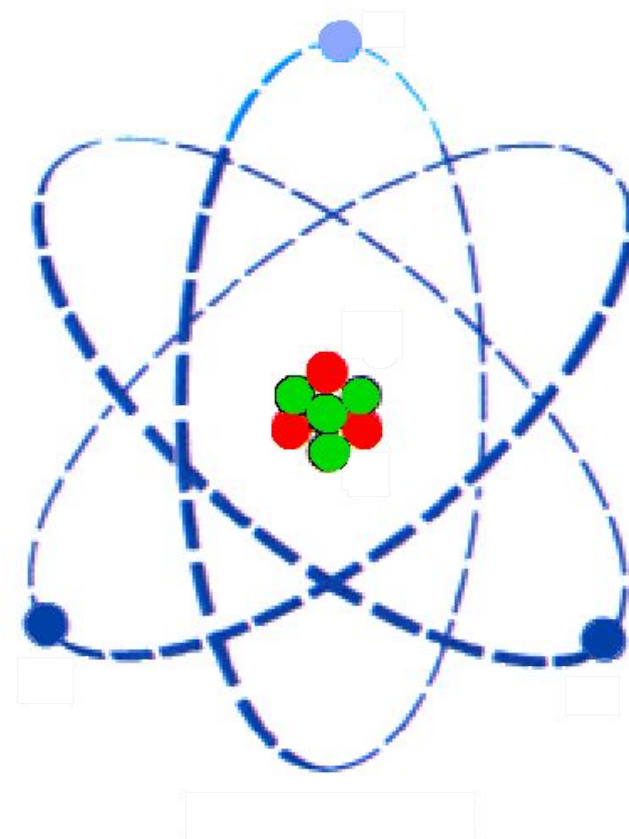
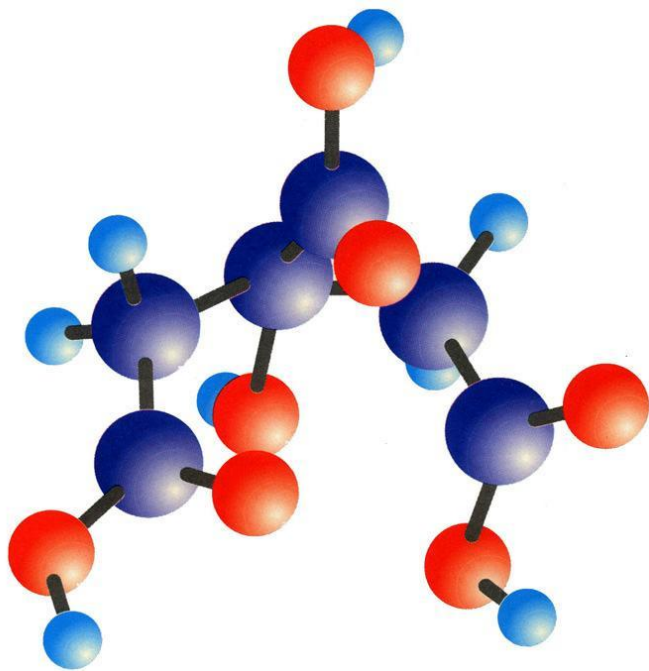
Взаимодействия – 1. Гравитационное



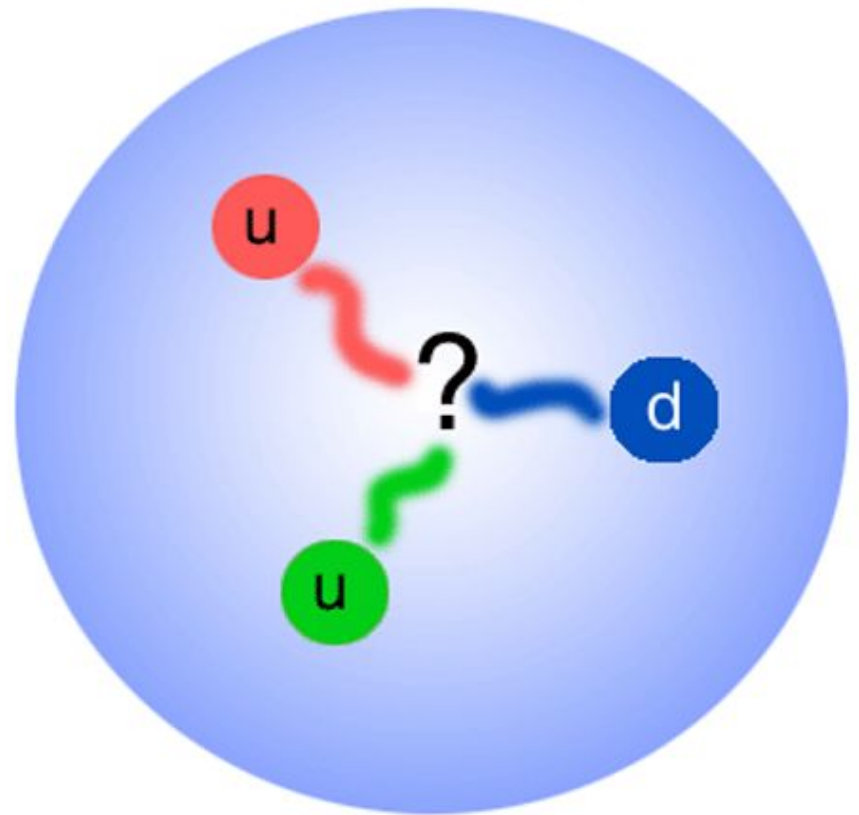
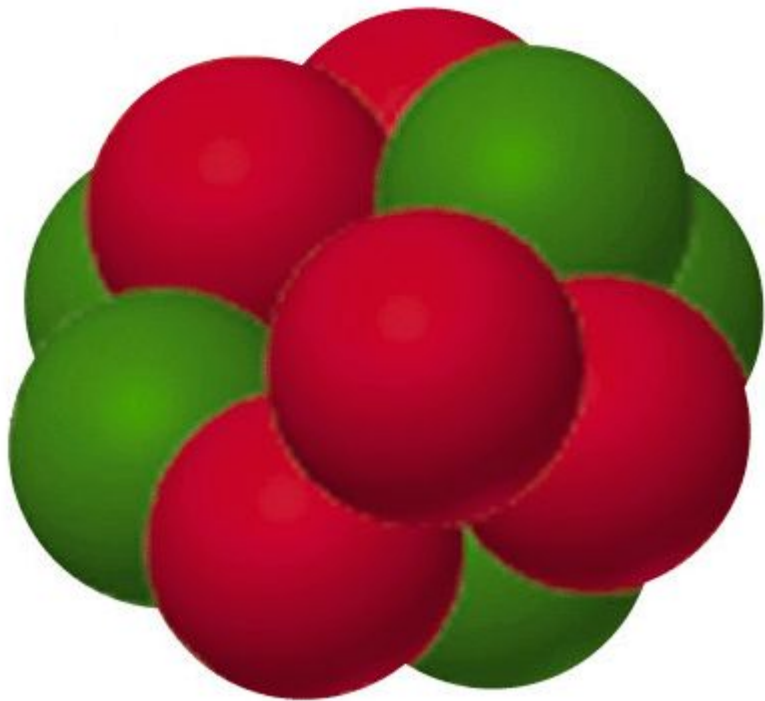
Взаимодействия – 2. Слабое



Взаимодействия – 3. Электромагнитное



Взаимодействия – 4. Сильное

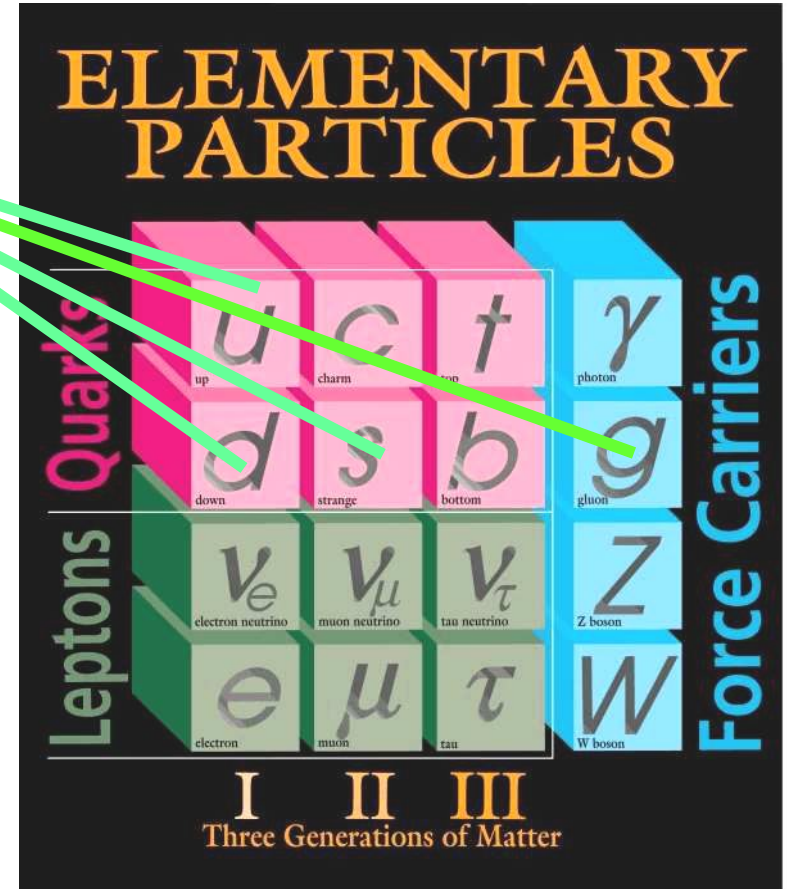


Основные задачи теории сильных взаимодействий

Стартуя с Лагранжиана КХД

$$L = -\frac{1}{g^2} \text{Tr} F_{\mu\nu}^2 + \sum_f \bar{\psi}_f (D + m)\psi_f$$

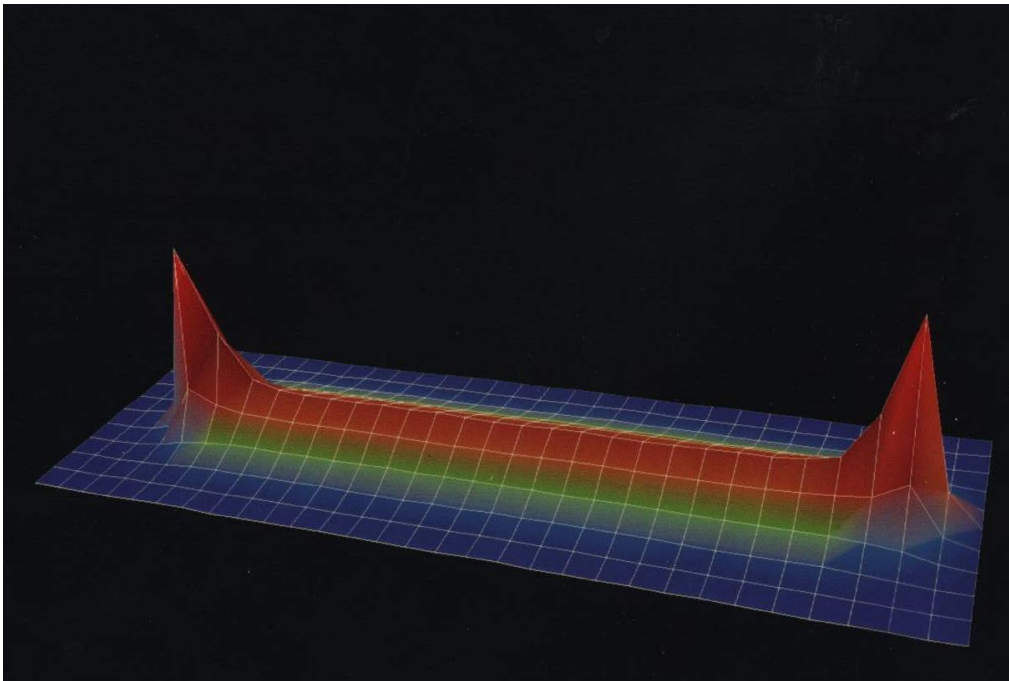
- 1) Получить спектр адронов,
- 2) Посчитать матричные элементы,
- (3) Описать фазовую диаграмму теории
- (4) **Объяснить невылетание цвета**



Невылетание цвета

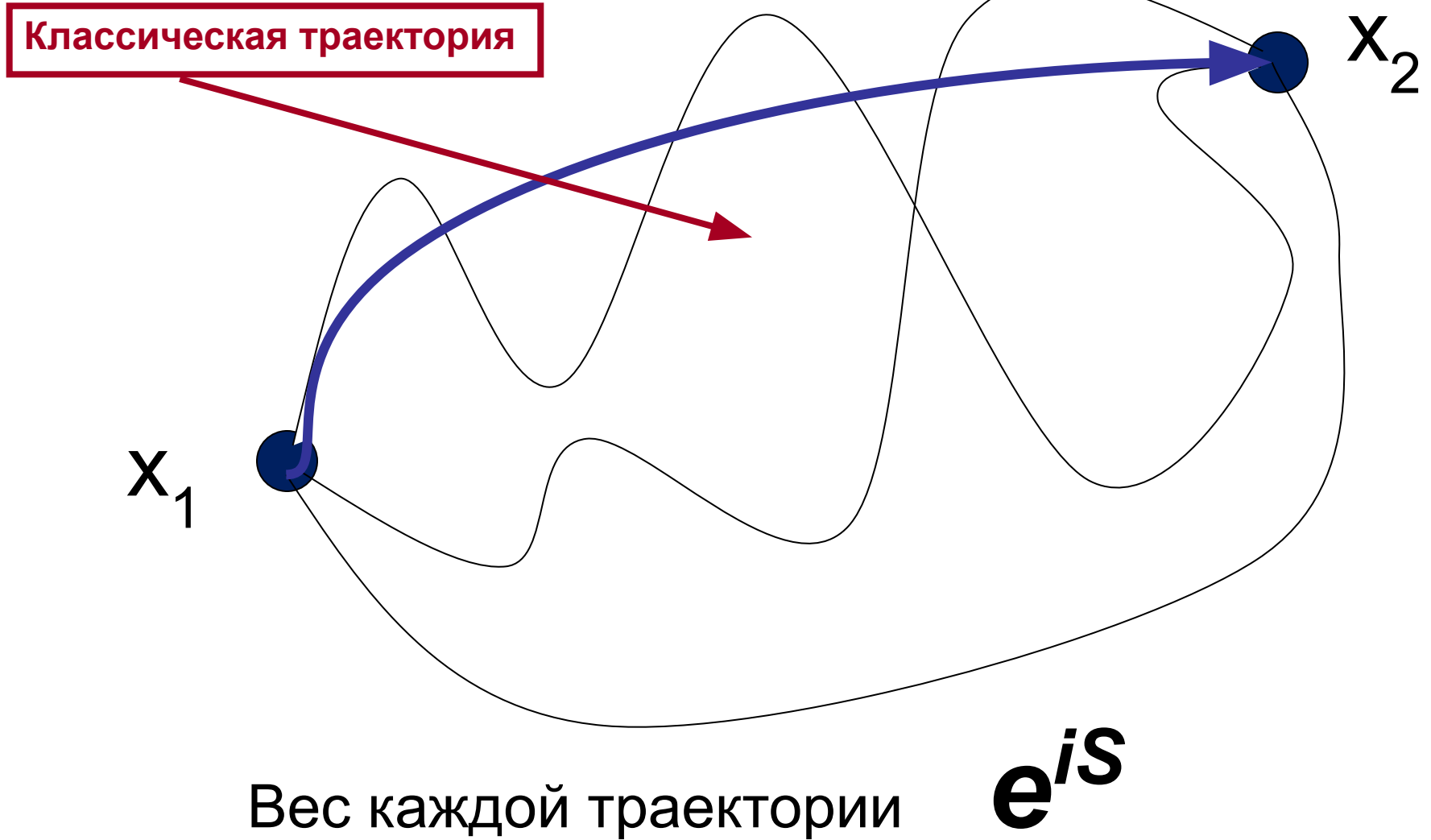
(почему мы не видим свободных кварков и глюонов?)

Основная сложность – отсутствие аналитических методов для описания теории сильных взаимодействий, но (супер)компьютеры могут многое предсказывать исходя из Лагранжиана КХД



**Сила между
кварком и
антикварком
12 тонн!!!**

Квантовая механика частицы



Квантовая теория поля

$$A_\mu(x) = A_\mu(x, y, z, t)$$

$$-\infty < A_\mu(x) < +\infty$$

$$Z = \int \int \int \dots \int \int \int \int D A_\mu(x) e^{iS[A_\mu]}$$

Methods

- Imaginary time $t \rightarrow it$

$$Z = \int D\varphi \exp\{i S[\varphi]\} \rightarrow Z = \int D\varphi \exp\{-S[\varphi]\}$$

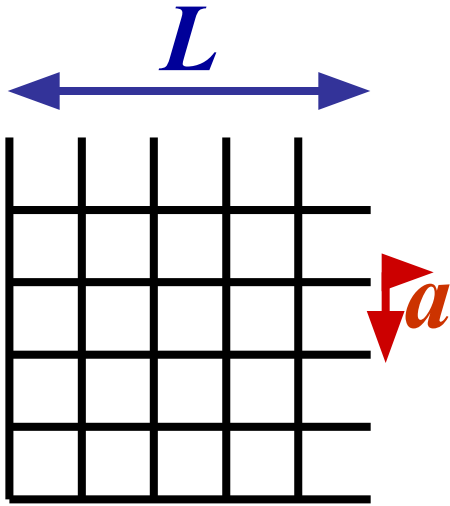
- Space-time discretization

$$D\varphi(x) \Rightarrow \prod_x d\varphi_x \quad Z = \int \prod_x d\varphi_x \exp\{-S[\varphi]\}$$

- Thus we get from functional integral the partition function for statistical theory in four dimensions

INTRODUCTION

Three limits



Lattice spacing

Lattice size

Quark mass

$$a \rightarrow 0$$

$$L \rightarrow \infty$$

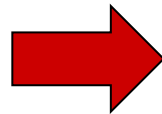
$$m_q \rightarrow 0$$

Typical values

$$a \approx 0.1 \text{ fm}$$

$$L \approx 2 \div 4 \text{ fm}$$

$$m_q \approx 100 \text{ Mev}$$



Extrapolation

+

Chiral perturbation
theory

Типичная кратность интегралов

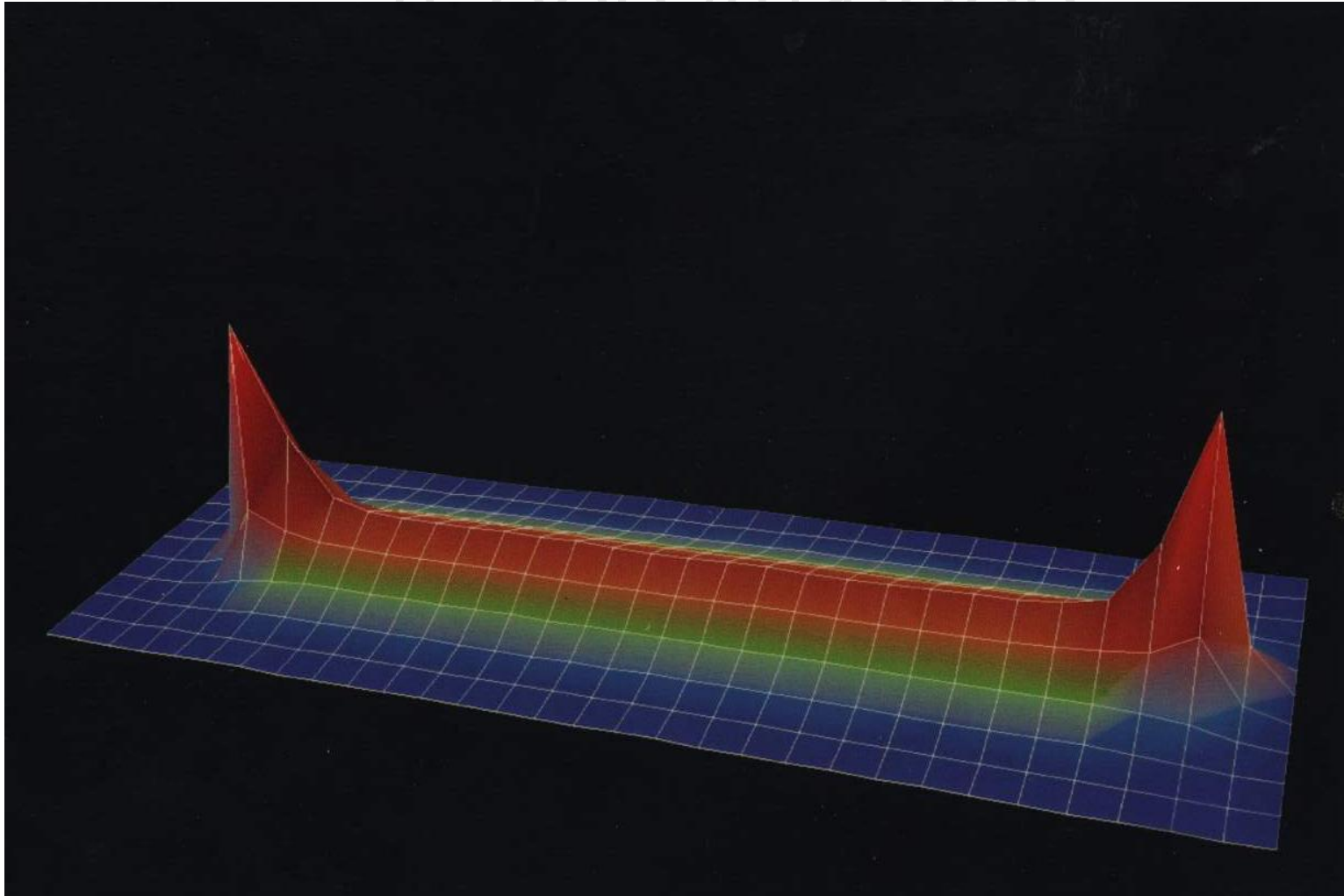
Для решетки L^4
($L=48$, $L^4=5,308,416$)

- Мы считаем интегралы кратности $32L^4$ ($L=48$, $32L^4=169,869,312$)
- И работаем с матрицами $12L^4 \times 12L^4$ ($L=48$, $12L^4=63,700,992$)

$$\int d\psi d\bar{\psi} \exp\{\bar{\psi} M \psi\} = \det M$$

SU(2) glue SU(3) glu

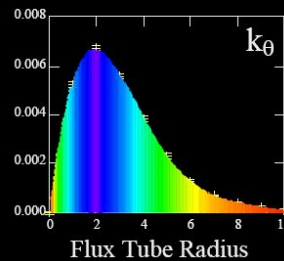
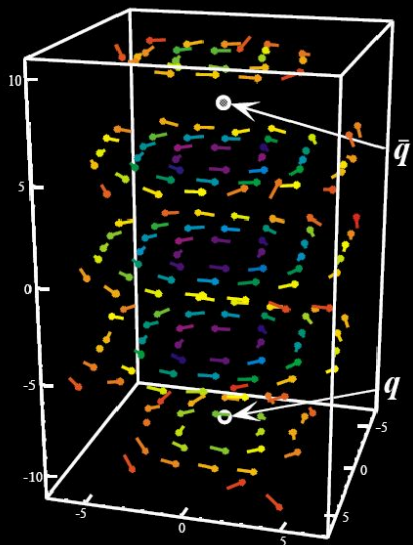
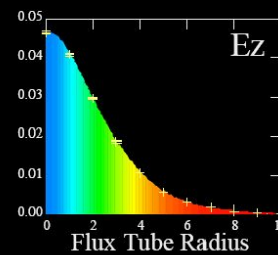
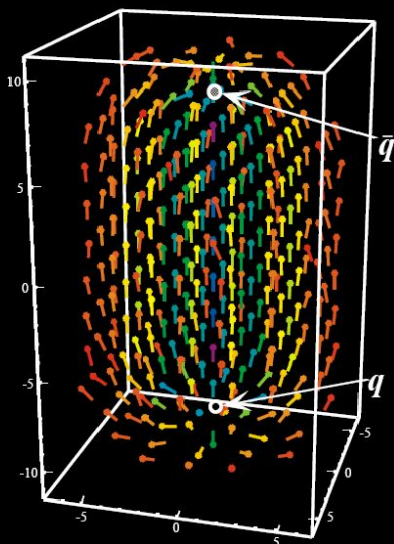
Сила между кварком и антикварком 12 тонн!!!



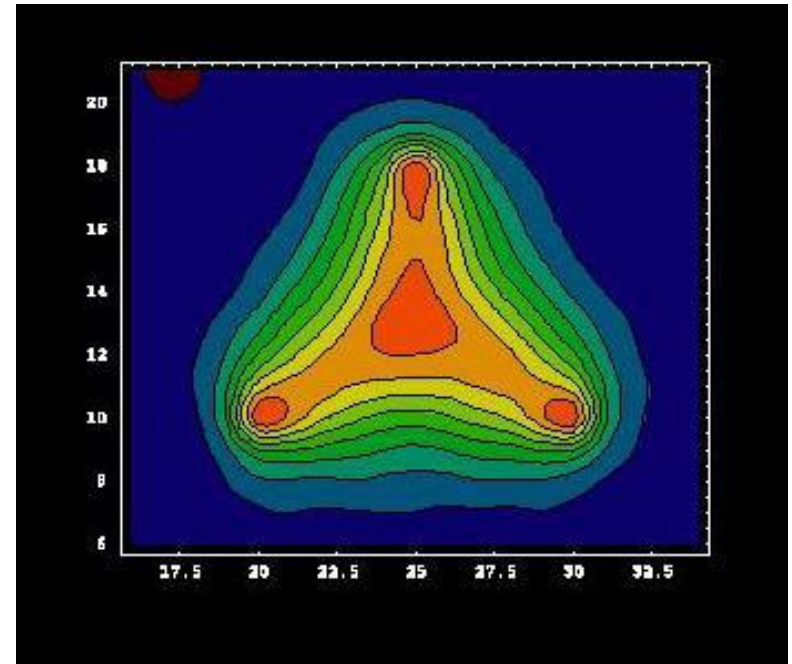
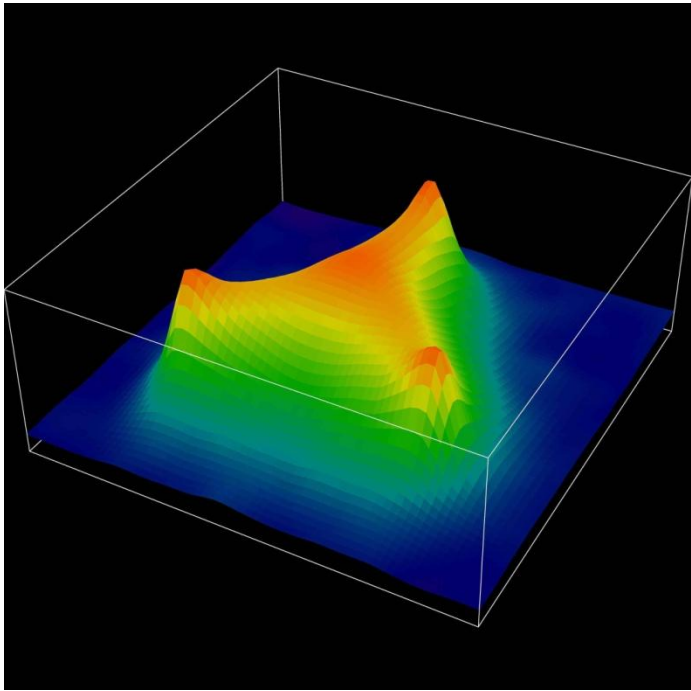
SU(2) glue

SU(2) glue 2+1 QCD (2+1)QCD

AP-SU(2) FLUX-TUBE PROFILE



SU(2) glue SU(3) glue 2qQCD (2+1)QCD
Three body forces!



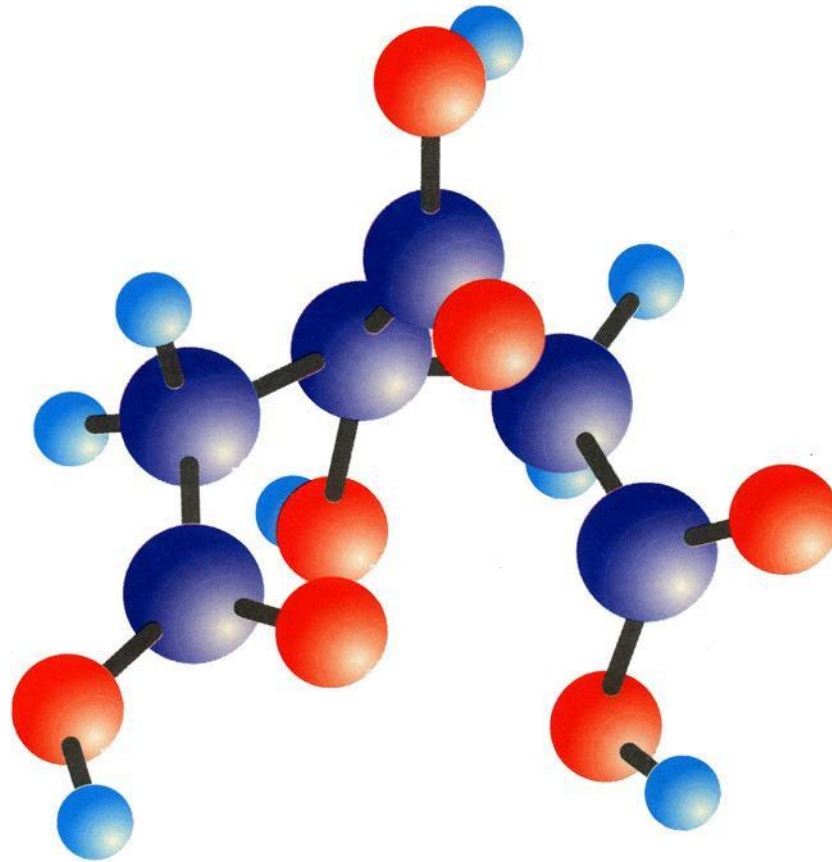
$$V(r_1, r_2, r_3) \neq V(r_1 - r_2) + V(r_2 - r_3) + V(r_3 - r_1)$$

← 1 м →

Происхождение массы

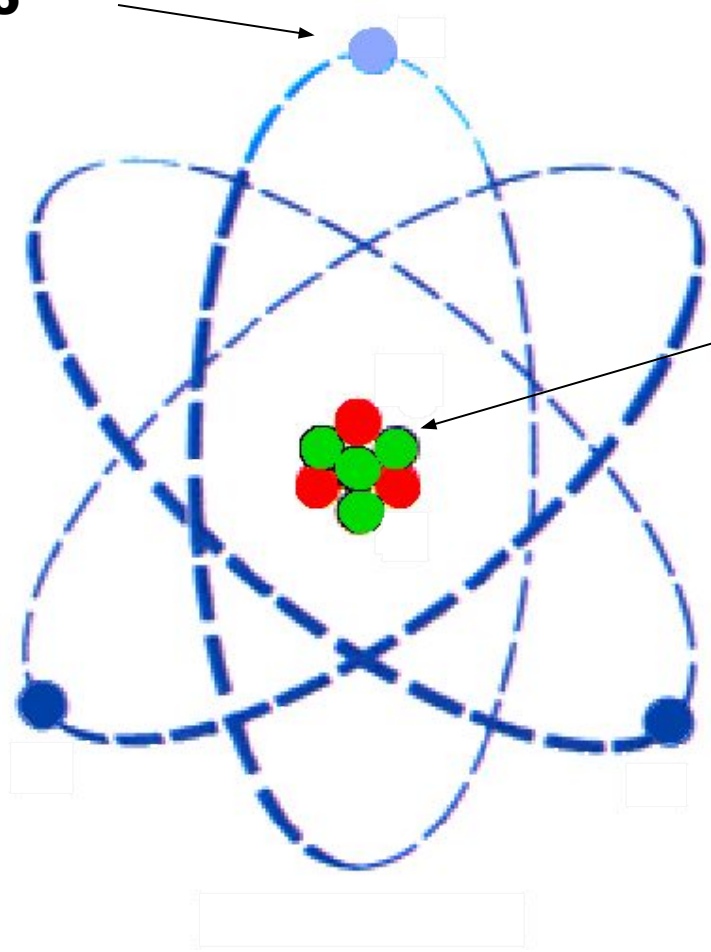


← $10^{-8..10}$ M →



$\longleftrightarrow 10^{-10} \text{ M} \longrightarrow$

$m_e \approx 0.5$
MeV

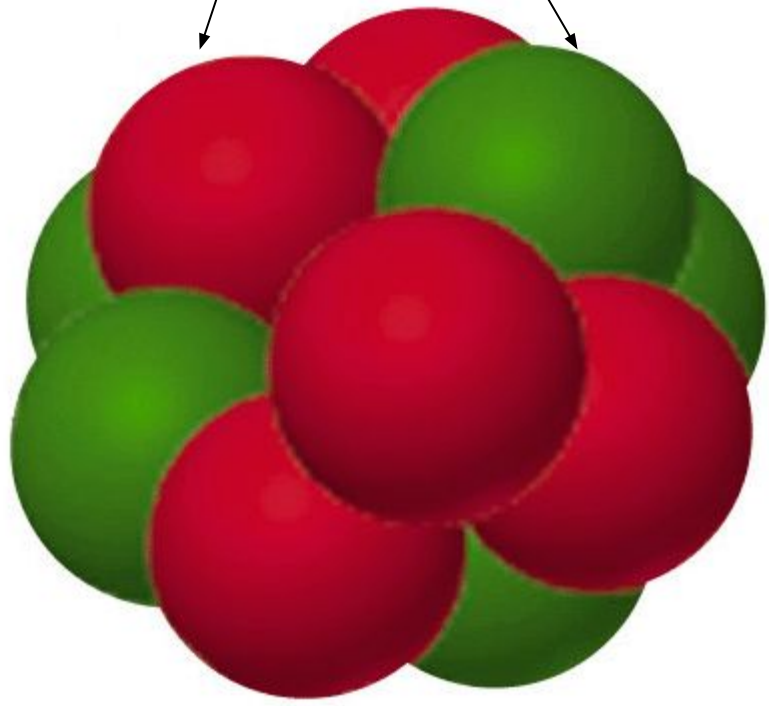


$m_n \approx 1000$
MeV

← $10^{-14..15}$ M →

m_p
 m_n

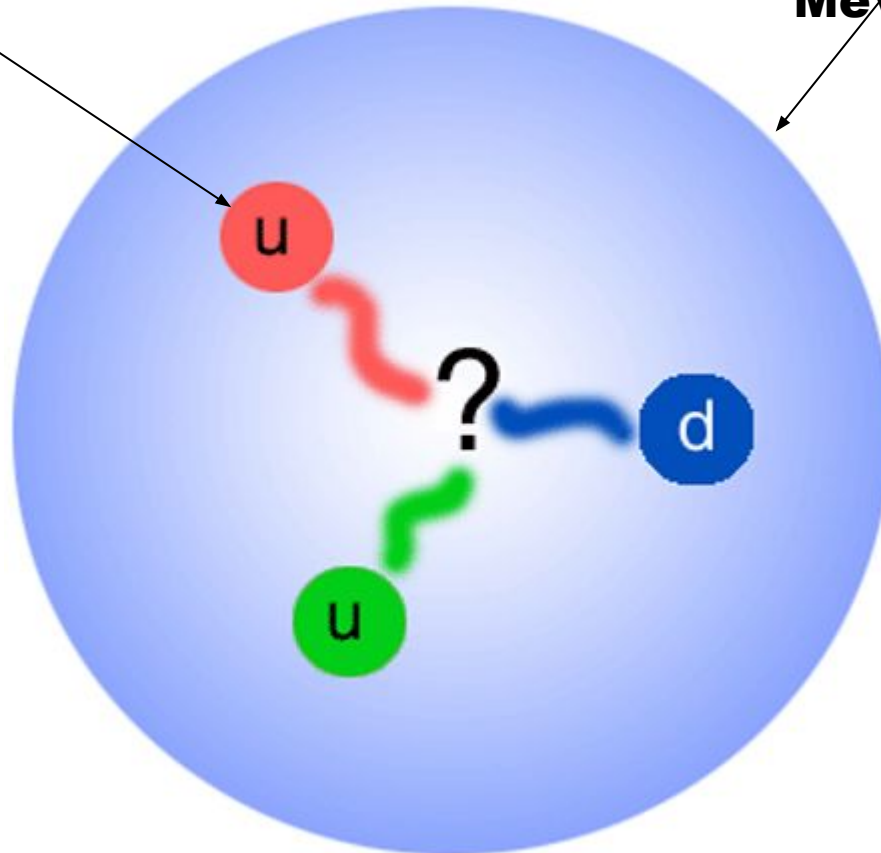
\approx



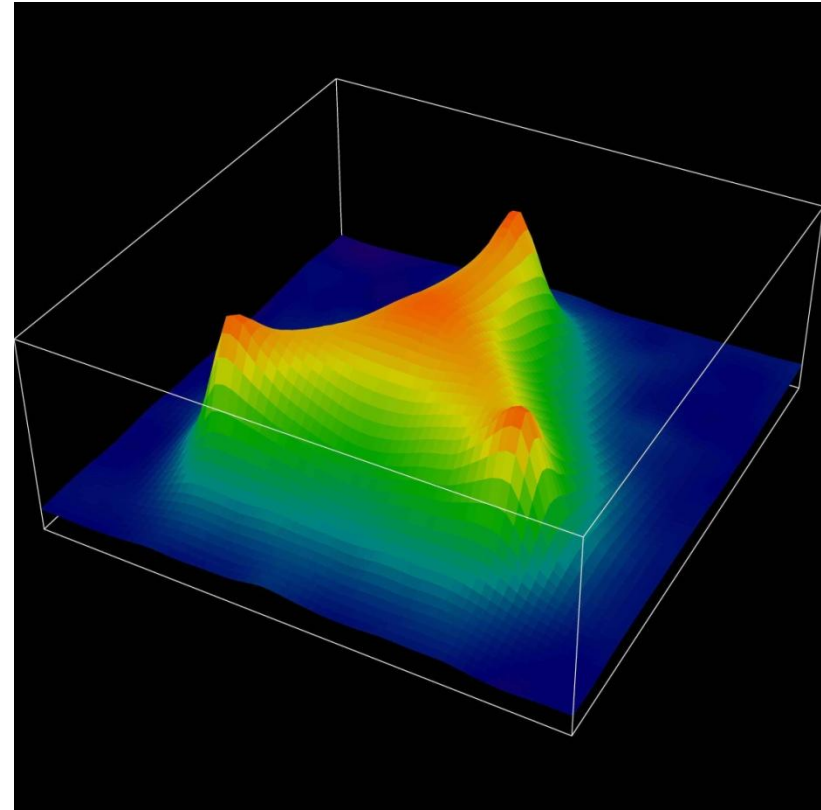
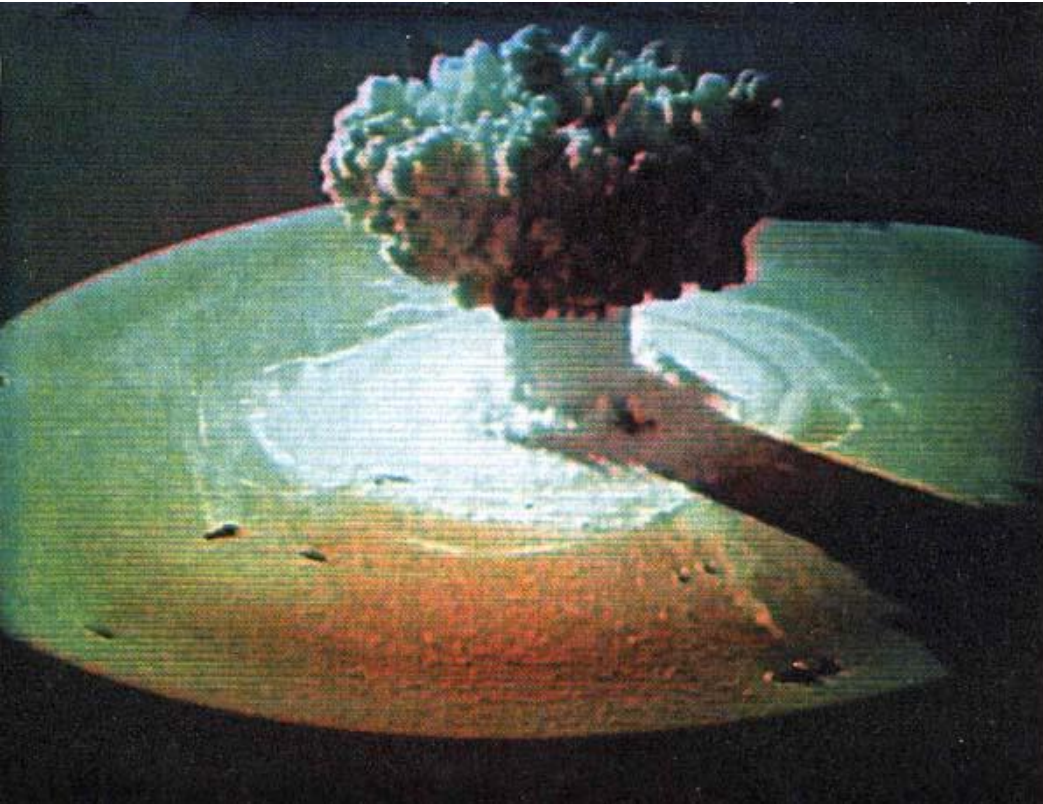
$\longleftrightarrow 10^{-15} \text{ M} \longrightarrow$

$m_{u,d} \approx 3..5$
MeV

$m_p \approx 1000$
MeV



Masses of material objects is due to gluon fields inside baryon



$$E = m_0 c^2$$

$$3m_q / m_{baryon} \approx 1/100$$

$$m_0 = \frac{E}{c^2}$$

Three body forces!

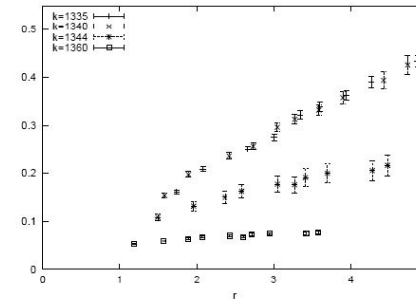
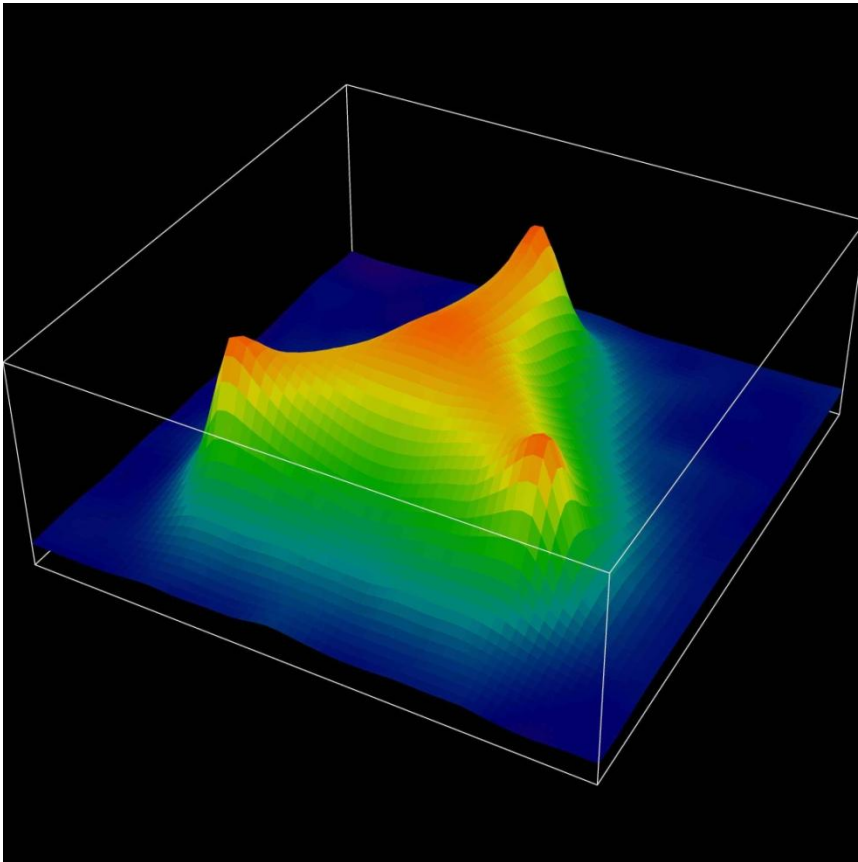


Figure 9: The monopole part of the baryon potential at finite temperature in full QCD as a function of L_Y ($T < T_c$) and L_Δ ($T > T_c$), respectively, in units of *God knows what*.

In Fig. 9 we show the baryon potential on the $16^3 8$ lattice at $\beta = 5.2$ for several values of κ . At this β value

$$T \propto \exp(-2.81/\kappa), \quad (4.1)$$

Increasing κ thus increases the temperature. We cross the finite temperature phase transition at $\kappa = 0.1344$ [14]. We see that the potential flattens off while we approach the transition point. However, the distances we were able to probe are not large enough to make any statement about string breaking.

To compute the action density ρ_A^{3Q} and the electric field and monopole correlators E_i^{3Q} and k^{3Q} , respectively, we need to reduce the statistical noise. Note that the Polyakov loops span an area of $\approx 16 \times 8$ lattice spacings. We do that by using extended operators

$$\begin{aligned} \rho_A^{3Q}(s) \longrightarrow & \frac{1}{8} \{ \rho_A^{3Q}(s) + \rho_A^{3Q}(s - \hat{x} - \hat{y} - \hat{z}) + \rho_A^{3Q}(s - \hat{x} - \hat{y}) \\ & + \rho_A^{3Q}(s - \hat{x} - \hat{z}) + \rho_A^{3Q}(s - \hat{y} - \hat{z}) + \rho_A^{3Q}(s - \hat{x}) \\ & + \rho_A^{3Q}(s - \hat{y}) + \rho_A^{3Q}(s - \hat{z}) \}, \end{aligned} \quad (4.2)$$

$$\begin{aligned} E_i^{3Q}(s) \longrightarrow & \frac{1}{4} \{ E_i^{3Q}(s) + E_i^{3Q}(s - \hat{x} - \hat{t}) \\ & + E_i^{3Q}(s - \hat{x}) + E_i^{3Q}(s - \hat{t}) \}, \end{aligned} \quad (4.3)$$

$$k^{3Q}(*s, \mu) \longrightarrow \frac{1}{2} \{ k^{3Q}(*s, \mu) + k^{3Q}(*s - \hat{z}, \mu) \}, \quad (4.4)$$

where (again) we have assumed that the quarks lie in the (x, y) plane, and we call the direction of the Polyakov lines the t direction.

Usually the teams are rather big, 5 - 10 -15 people

arXiv:hep-lat/0401026v1

arXiv:hep-lat/0401026v2

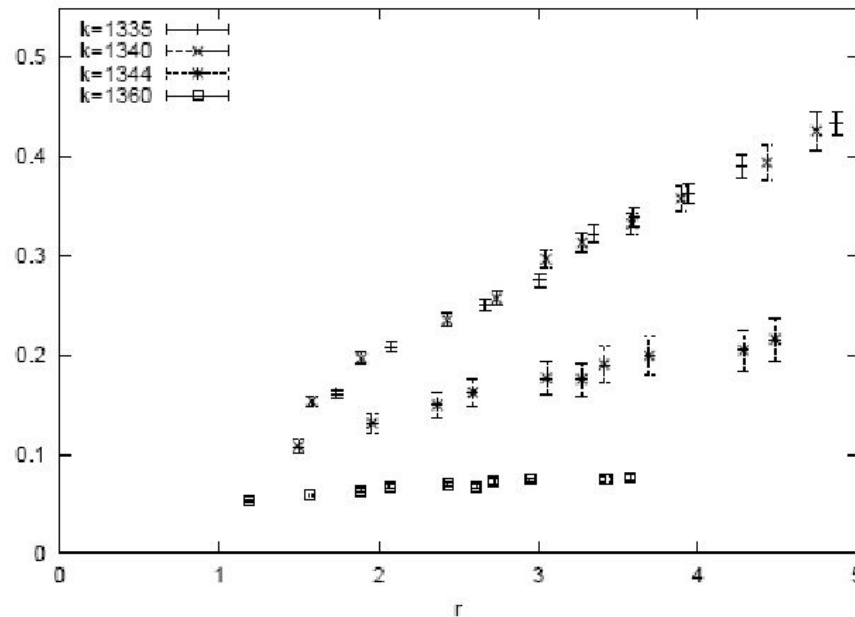
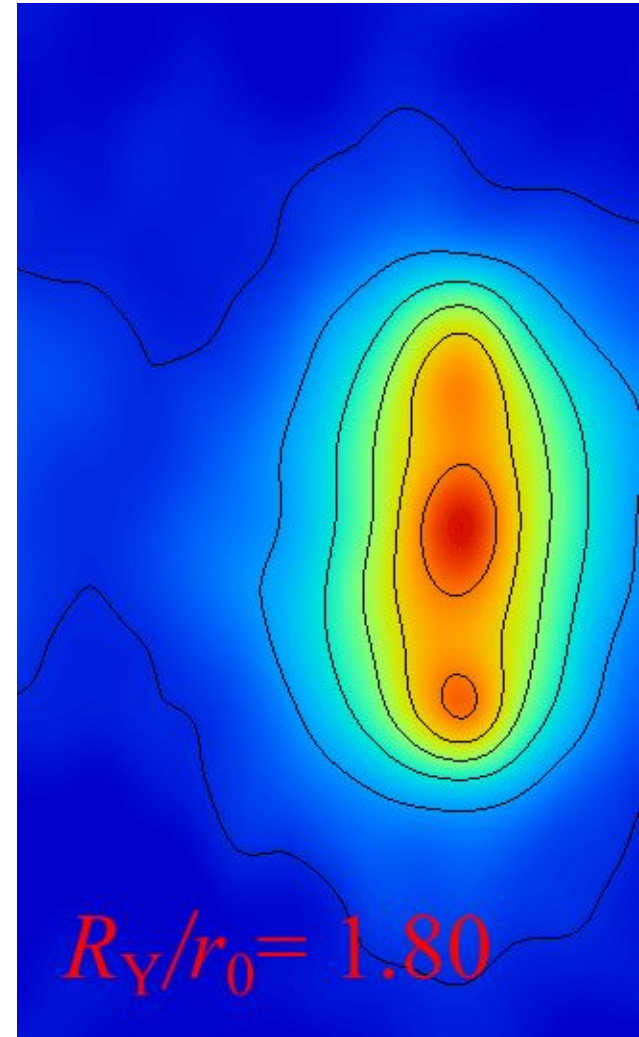
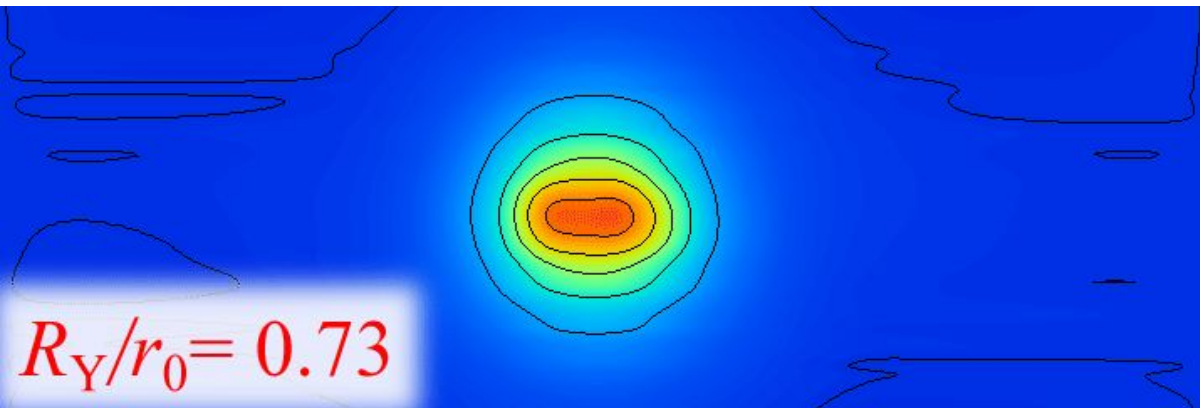


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In Fig. 9 we show the baryon potential on the $16^3 \times 8$ lattice at $\beta = 5.2$ for several values of κ . At this β value

SU(2) glue SU(3) glue 2qQCD (2+1)QCD
String Breaking (DIK collaboration)



SU(2) glue SU(3) glue 2qQCD (2+1)QCD

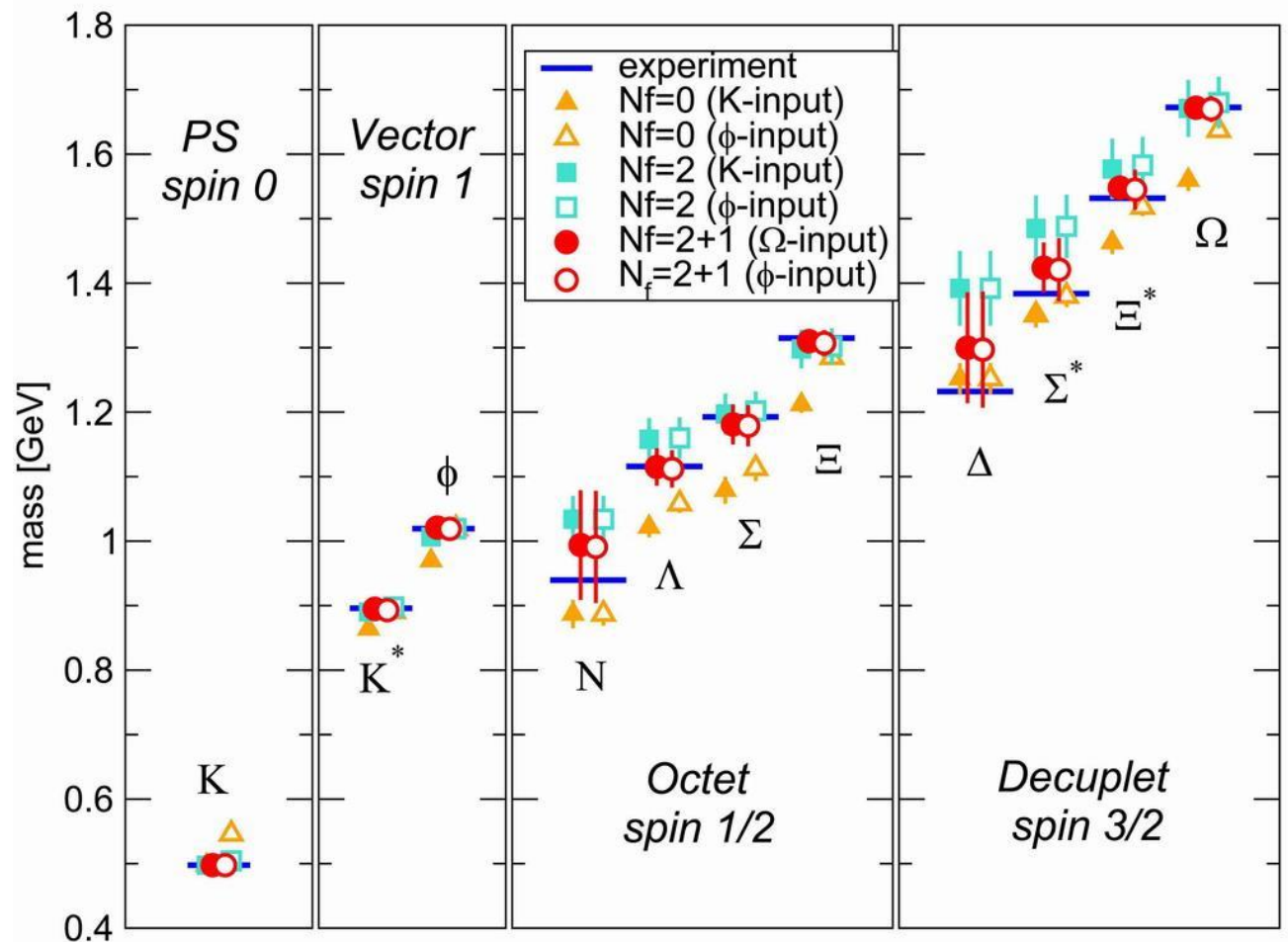
Hadron Mass Spectrum

SU(2) glue SU(3) glue 2qQCD (2+1)QCD

Wilson non-perturbatively improved Fermions
“WORKING HORSE” of lattice QCD calculations

Y. Kuramashi Lattice 2007

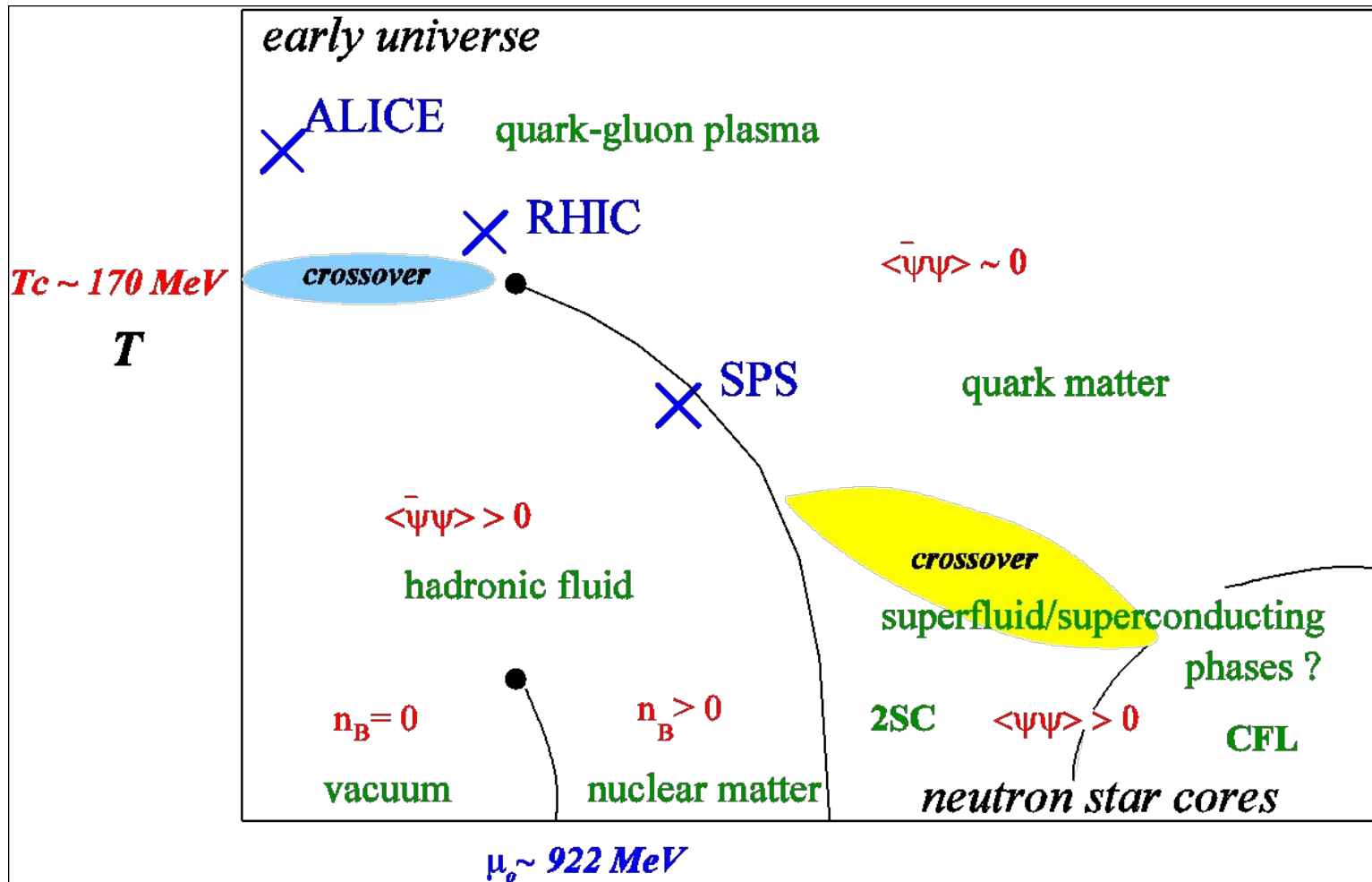
Iwasaki gauge action +
clover quarks
 $a^{-1} = 2.2\text{GeV}$,
lattice size: $32^3 \times 64$



SU(2) glue SU(3) glue 2qQCD (2+1)QCD

Finite Temperature

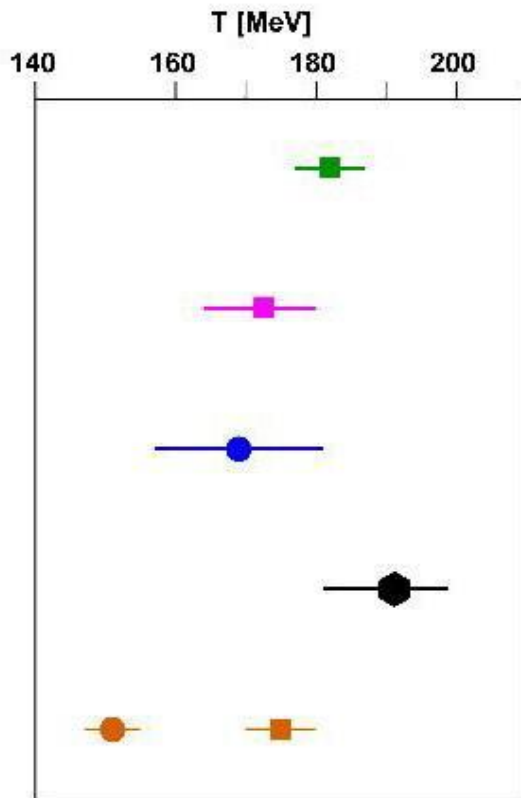
Фазовая Диаграмма КХД



μ

Фазовая Диаграмма КХД

Summary of recent results on T_c



use $T=0$ scale: $r_0=0.469\text{fm}$

$N_f=2$:

V.G. Bornyakov et al, POS Lat2005, 157 (2006)
 (improved Wilson, $N_t=8, 10$; input: $r_0=0.5\text{ fm}$)
 (added $N_t=12$, Lattice'07) (rescaled to r_0)

Y. Maezawa et al., hep-lat/0702005 (QM'2006)
 (improved Wilson, $N_t=4, 6$; input: $m-\rho$)
 (no cont. exp. yet)

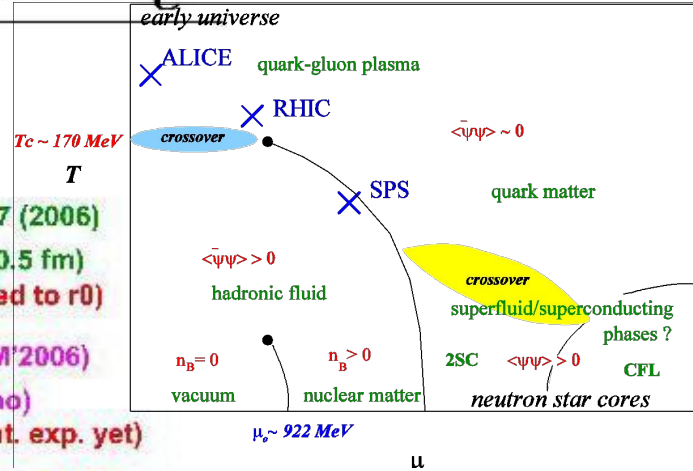
$N_f=2=1$:

C. Bernard et al., Phys.Rev. D71, 034504 (2005)
 (improved staggered (asqtad), $N_t=4,6,8$, input r_1)
 (rescaled to r_0)

M. Cheng et al., Phys.Rev D74, 054507 (2006)
 (improved staggered (p4), $N_t=4,6$; input r_0)

Y. Aoki et al., Phys. Lett. B643, 46 (2006)
 (staggered (stout), $N_t=4,6,8,10$; input f_K)
 (converted to r_0)

● chiral ■ deconfinement ● chiral+deconfinement



Моделирование К-Г плазмы в США

Proceedings of the DPF-9009 Conference, Detroit, MI, July 27-31, 2009

1

Equation of State and the Finite Temperature Transition in QCD

Rajan Gupta [HotQCD Collaboration]

Theoretical Division, Los Alamos National Laboratory, Los Alamos, NM 87545, USA

This talk provides a summary of the results obtained by the HotQCD collaboration on the equation of state and the crossover transition in 2+1 flavor QCD. We investigate bulk thermodynamic quantities - energy density, pressure, entropy density, and the speed of sound over the temperature range $140 < T < 540$ MeV. These results have been obtained on lattices of temporal size $N_t = 6$ and 8 and with two improved staggered fermion actions, asqtad and p4. Our most extensive results are with masses of the two degenerate light quarks set at $m_l = 0.1m_\pi$, corresponding to the Goldstone pion mass m_π between 220 - 260 MeV. In these simulations, the strange quark mass is tuned to its physical value and constant values of m_l/m_π define lines of constant physics. We also summarize the current state of results on observables sensitive to the chiral and deconfining physics - the light and strange quark number susceptibilities, the chiral condensate and its susceptibility, and the renormalized Polyakov loop. Our results indicate that the deconfinement and chiral symmetry restoration occur in the same narrow temperature interval.

1. Introduction

Ongoing experiments at RHIC and proposed experiments at LHC aim to understand the properties of hot dense nuclear matter created in the collision of two relativistic nuclei. At sufficiently high temperatures and densities RHIC data support the creation of a quark-gluon plasma in the central region that undergoes a transition back to hadronic matter as it expands and cools. The goal is to explain the creation and evolution of this medium. Hydrodynamic descriptions used to model this evolution provide a good fit to the data and are thus the phenomenological tool of choice. First principle calculations using lattice QCD yield a number of properties of QCD as a function of temperature that are essential inputs in these hydrodynamical analyses. These properties include the nature of the transition (with respect to both confinement and chiral symmetry breaking) between the quark-gluon plasma and hadronic matter, the transition temperature, the equation of state of QCD and transport coefficients as a function of temperature in the range 140 - 700 MeV.

HotQCD is a US wide collaboration engaged in the study of QCD at finite temperature and density using lattice QCD. It brought together members of the MILC and RBC-Bielefeld collaborations to carry out large scale simulations on IBM BlueGene/L supercomputers at the Lawrence Livermore National Lab and on the NYBlue at the New York Center for Computational Sciences at BNL.

Our goals are to perform detailed simulations of

2+1 flavor QCD using staggered fermions at the physical values of the strange and light quark masses. Most of the results presented here are for $m_l = 0.1m_\pi$, about a factor of two heavier than the mean physical u and d quark mass, $m_l \approx 0.038m_\pi$. Improvements in algorithms and computer resources are being used to incrementally approach the physical up and down quark masses and the continuum limit, thus providing high precision results. Also, in the current simulations the up and down quark masses are taken to be degenerate.

The physical quantities we are calculating include:

- The Equation of State (EoS) of QCD over the temperature range 140 - 700 MeV that is being probed by relativistic heavy ion experiments at Brookhaven and will be studied in more detail in the future at the LHC.
- The nature of the deconfinement transition between the hadronic phase at low temperature and the quark-gluon plasma at high temperatures. All simulations with staggered fermions show a rapid crossover rather than a genuine phase transition for physical values of the light quark masses. In the absence of a phase transition, there is a priori no unique transition temperature as it can depend on the probe. Thus, the temperature at which this transition takes place remains a subject of investigations. The status of current estimates is discussed at the end of this paper.
- The restoration of chiral symmetry at high temperature and whether this chiral transition is coincident with the deconfining transition.
- A detailed understanding of the physics in the transition region and the approach of thermodynamics quantities such as pressure, entropy, energy density and the speed of sound, to the Stefan-Boltzmann limit.

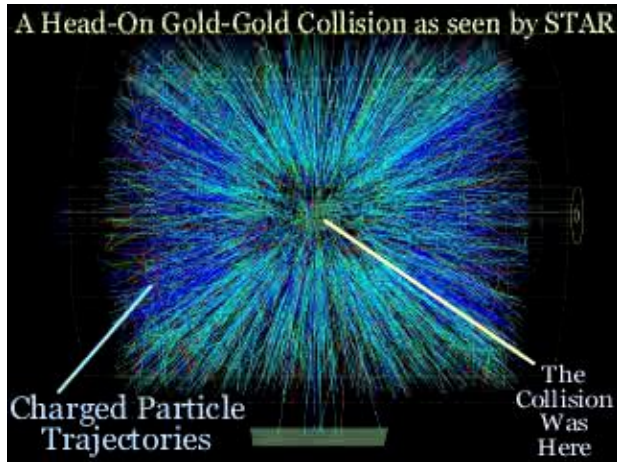
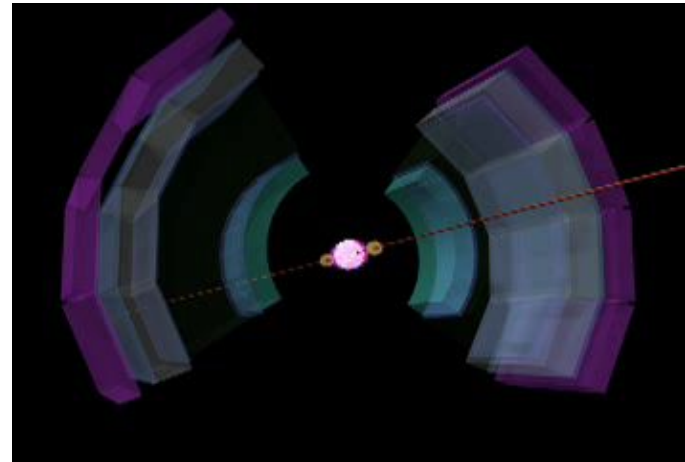
¹HotQCD Collaboration members are: A. Bazavov, T. Bhattacharya, M. Cheng, N.H. Christ, C. DeTar, S. Ejiri, S. Gottlieb, R. Gupta, U.M. Heller, K. Hasegawa, C. Jung, F. Karich, E. Laermann, L. Levkova, C. Miao, R.D. Mawhinney, P. Patrascu, C. Schmidt, R.A. Soltz, W. Soeldner, R. Sugar, D. Toussaint and P. Vranas

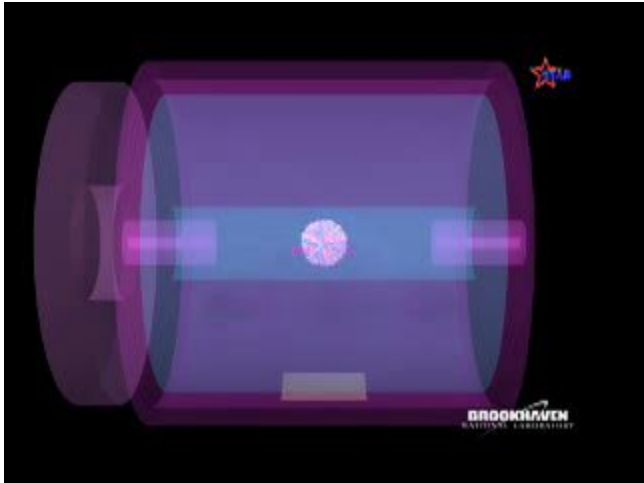
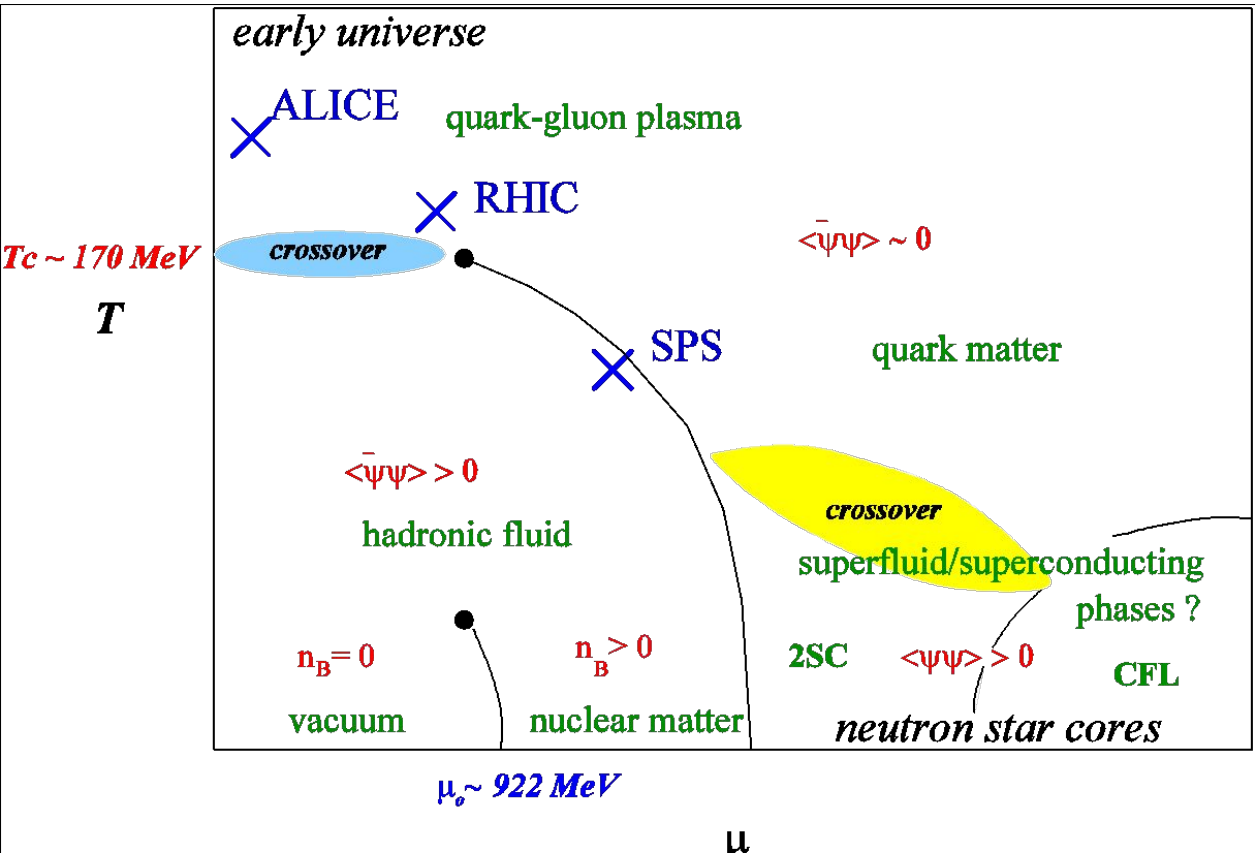
Моделирование К-Г плазмы в США

HotQCD is a US wide collaboration engaged in the study of QCD at finite temperature and density using lattice QCD ¹. It brought together members of the MILC and RBC-Bielefeld collaborations to carry out large scale simulations on IBM Bluegene/L supercomputers at the Lawrence Livermore National Lab and on the NYBlue at the New York Center for Computational Sciences at BNL.

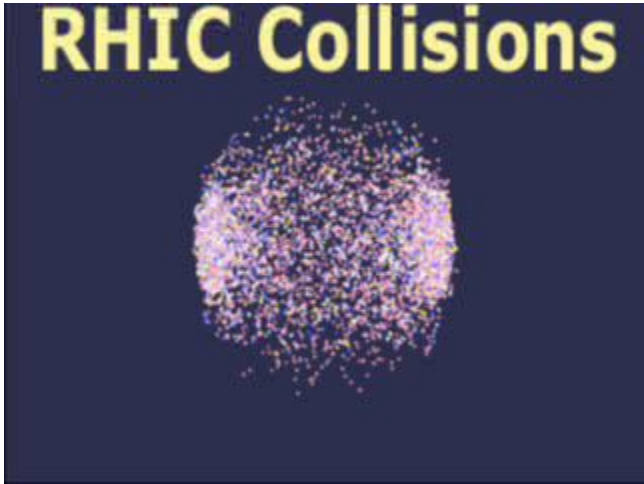
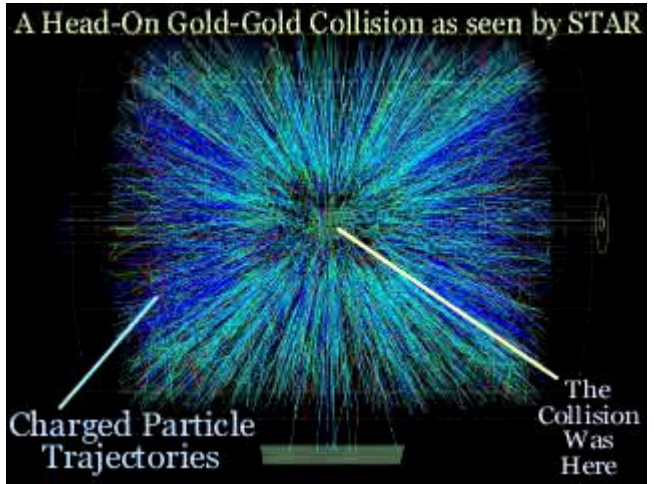
RHIC
relativistic heavy ion collider

SU(2) glue SU(3) glue
2qQCD(2+1)QCD

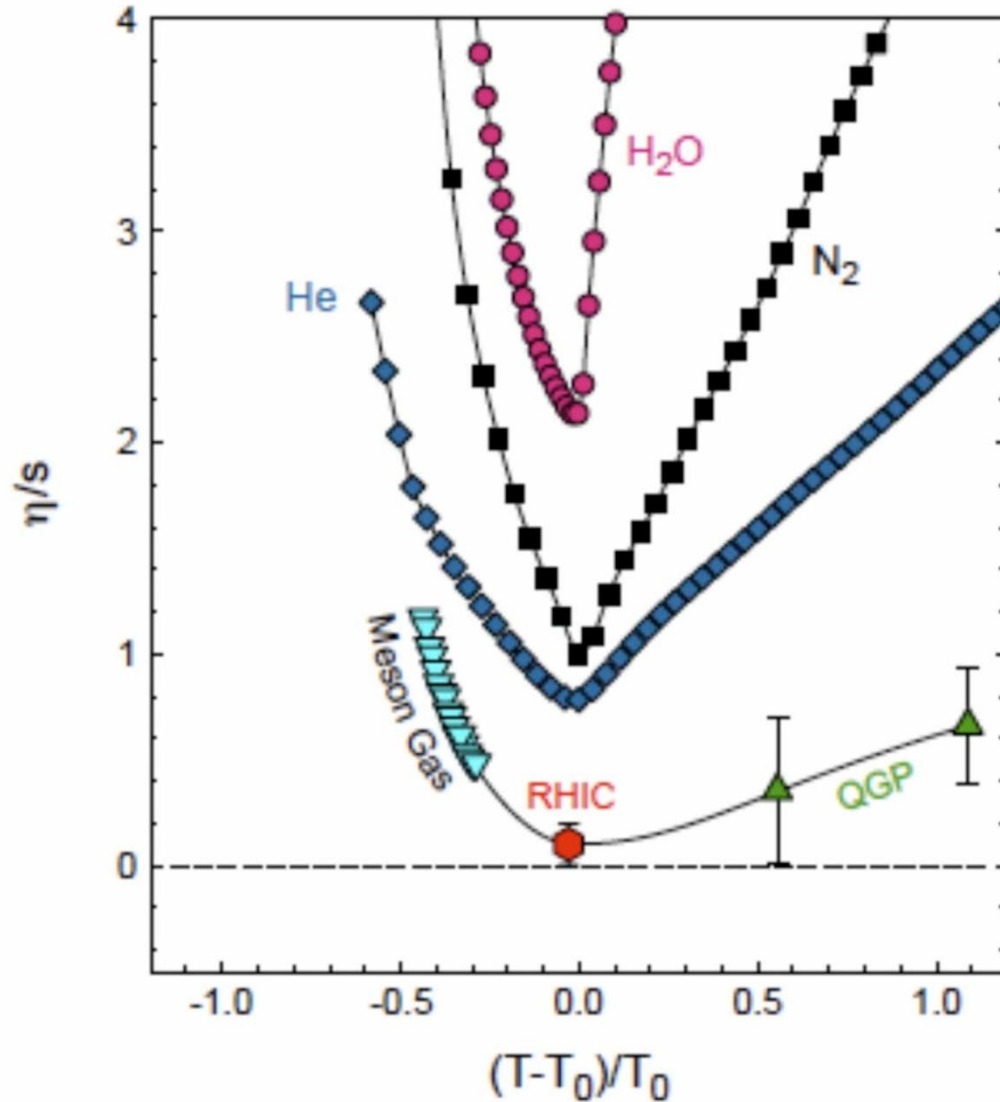




RHIC



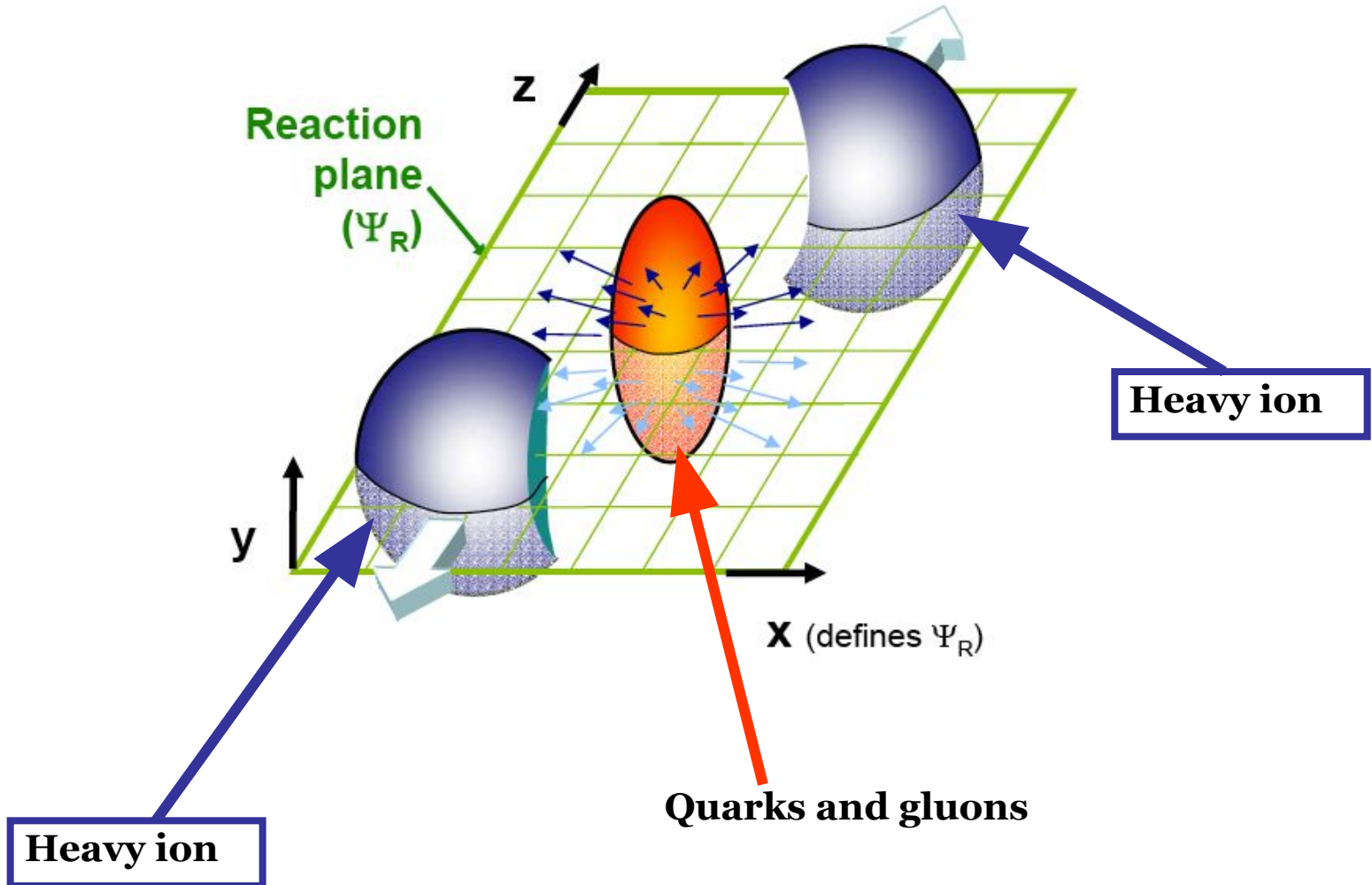
Вязкость К-Г плазмы чрезвычайно мала



Below I use a lot of slides made
by
M.N. Chernodub, P.V.
Buividovich and D.E. Kharzeev

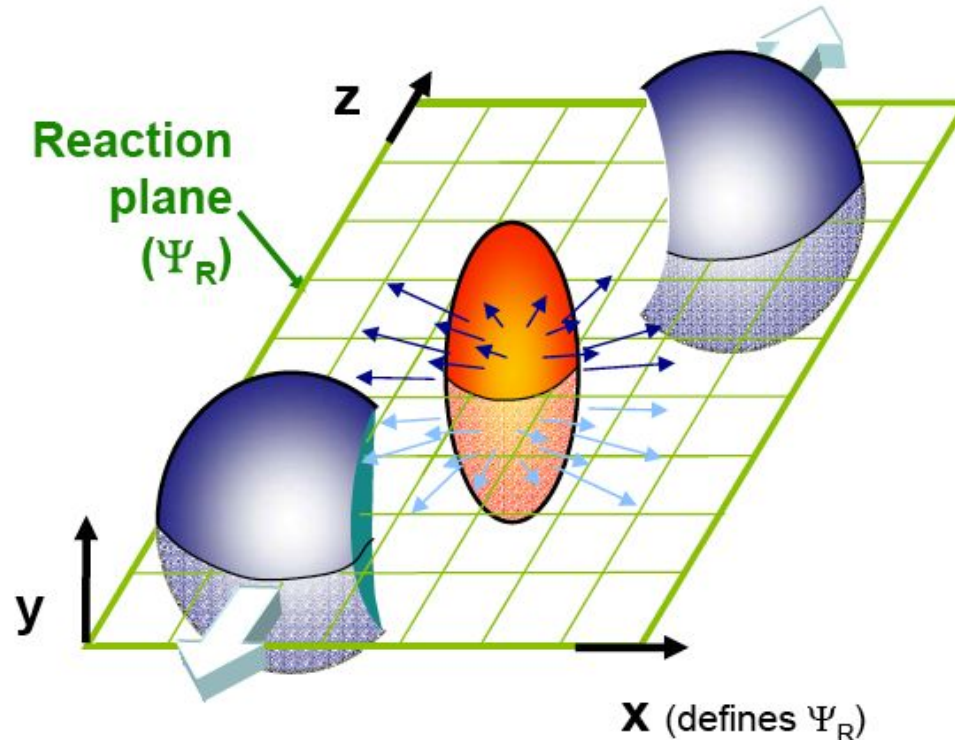
Magnetic fields in non-central collisions

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



Magnetic fields in non-central collisions

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



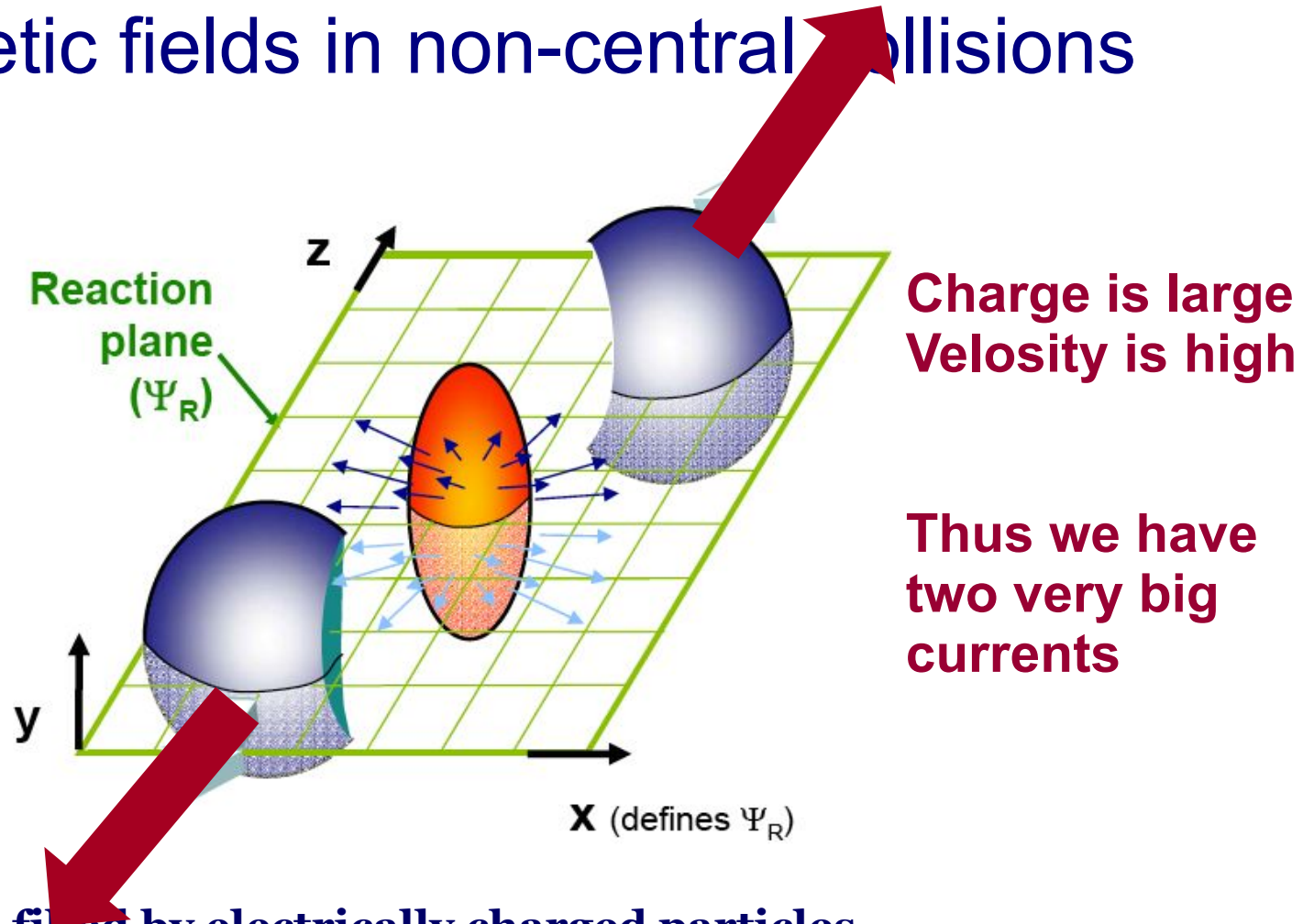
[1] K. Fukushima, D. E. Kharzeev, and H. J. Warringa, Phys. Rev. D 78, 074033 (2008),
URL <http://arxiv.org/abs/0808.3382>.

[2] D. Kharzeev, R. D. Pisarski, and M. H. G. Tytgat, Phys. Rev. Lett. 81, 512 (1998),
URL <http://arxiv.org/abs/hep-ph/9804221>.

[3] D. Kharzeev, Phys. Lett. B 633, 260 (2006), URL <http://arxiv.org/abs/hep-ph/0406125>.

[4] D. E. Kharzeev, L. D. McLerran, and H. J. Warringa, Nucl. Phys. A 803, 227 (2008),
URL <http://arxiv.org/abs/0711.0950>.

Magnetic fields in non-central collisions

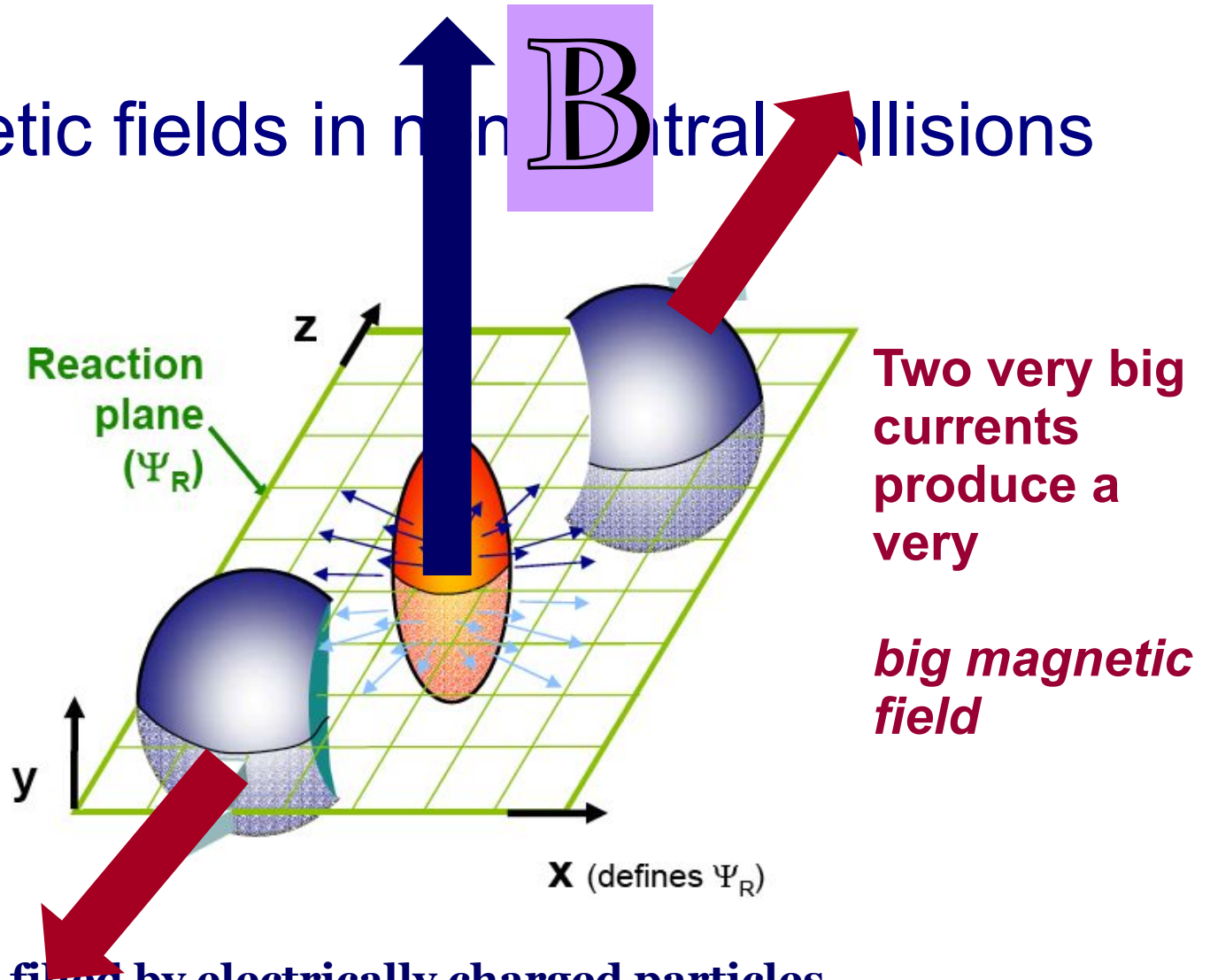


The medium is filled by electrically charged particles

Large orbital momentum, perpendicular to the reaction plane

Large magnetic field along the direction of the orbital momentum

Magnetic fields in neutral collisions



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 Earth's 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



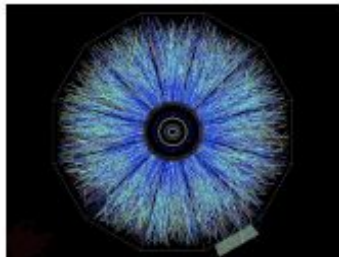
Typical surface, polar magnetic fields of radio pulsars

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

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

Magnetic forces are of the order of strong interaction forces

first time in my life I see such effect

$$eB \approx \Lambda_{QCD}^2$$

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$$eB \approx \Lambda_{QCD}^2$$

We expect the influence of magnetic field on strong interaction physics

Magnetic forces are of the order of strong interaction forces

first time in my life I see such effect

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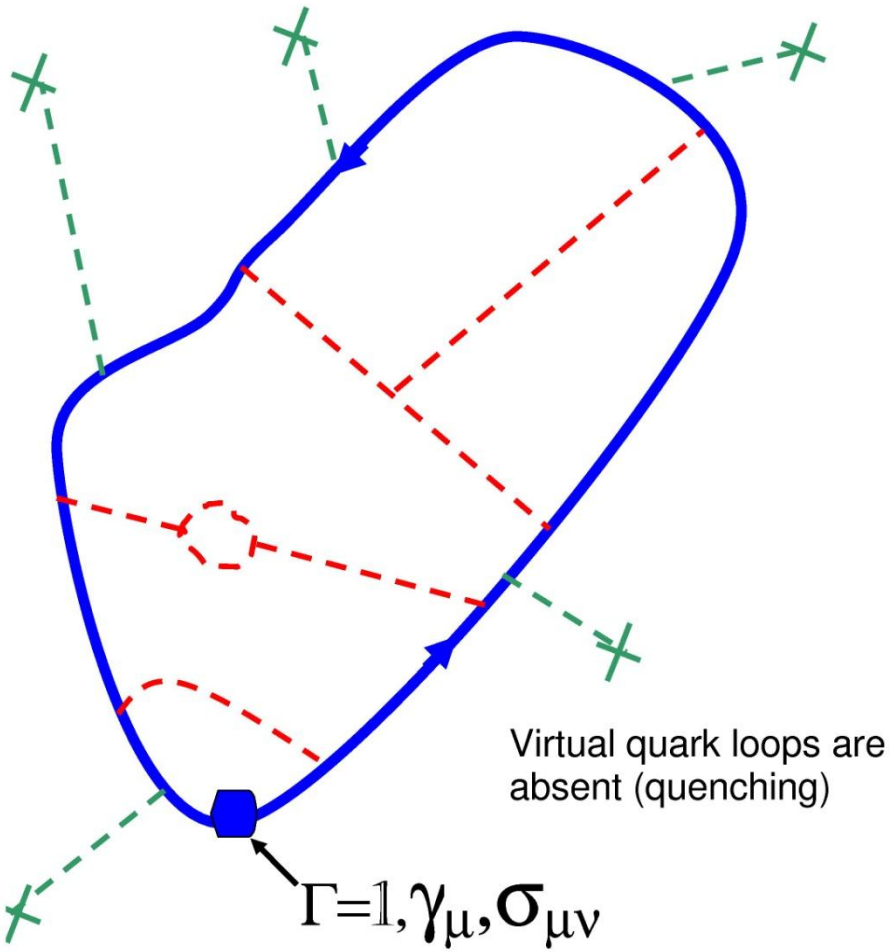
We expect the influence of magnetic field on strong interaction physics

The effects are nonperturbative, it is impossible to perform analytic calculations and we use

Lattice Calculations

We calculate

in the external magnetic field and in the presence of the vacuum gluon fields



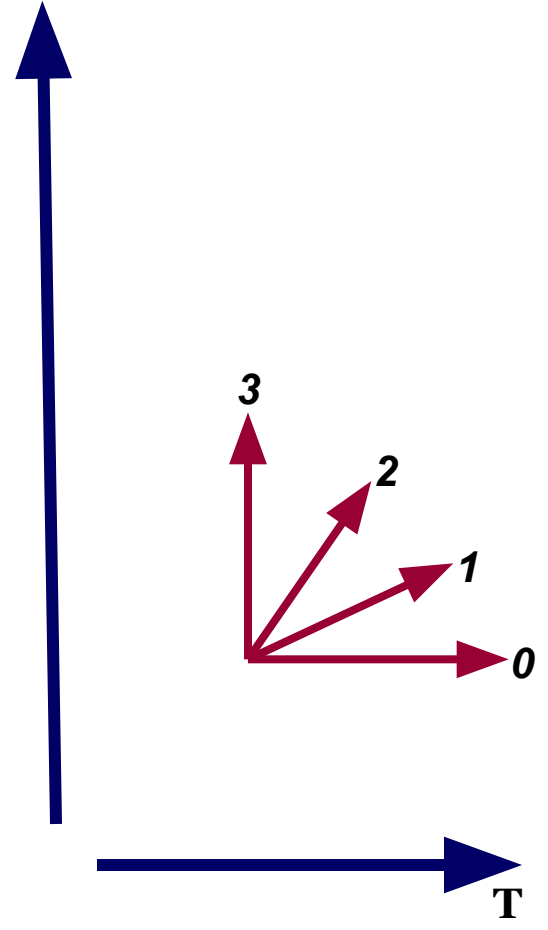
Virtual quark loops are absent (quenching)

$\Gamma=1, \gamma_\mu, \sigma_{\mu\nu}$

External quark

Virtual gluon

Photon (external magnetic field)



Quenched vacuum, overlap Dirac operator, external magnetic field

$$eB = \frac{2\pi qk}{L^2}; eB \geq 250 \text{ Mev}$$

Chiral Magnetic Effect

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

Electric current appears at regions

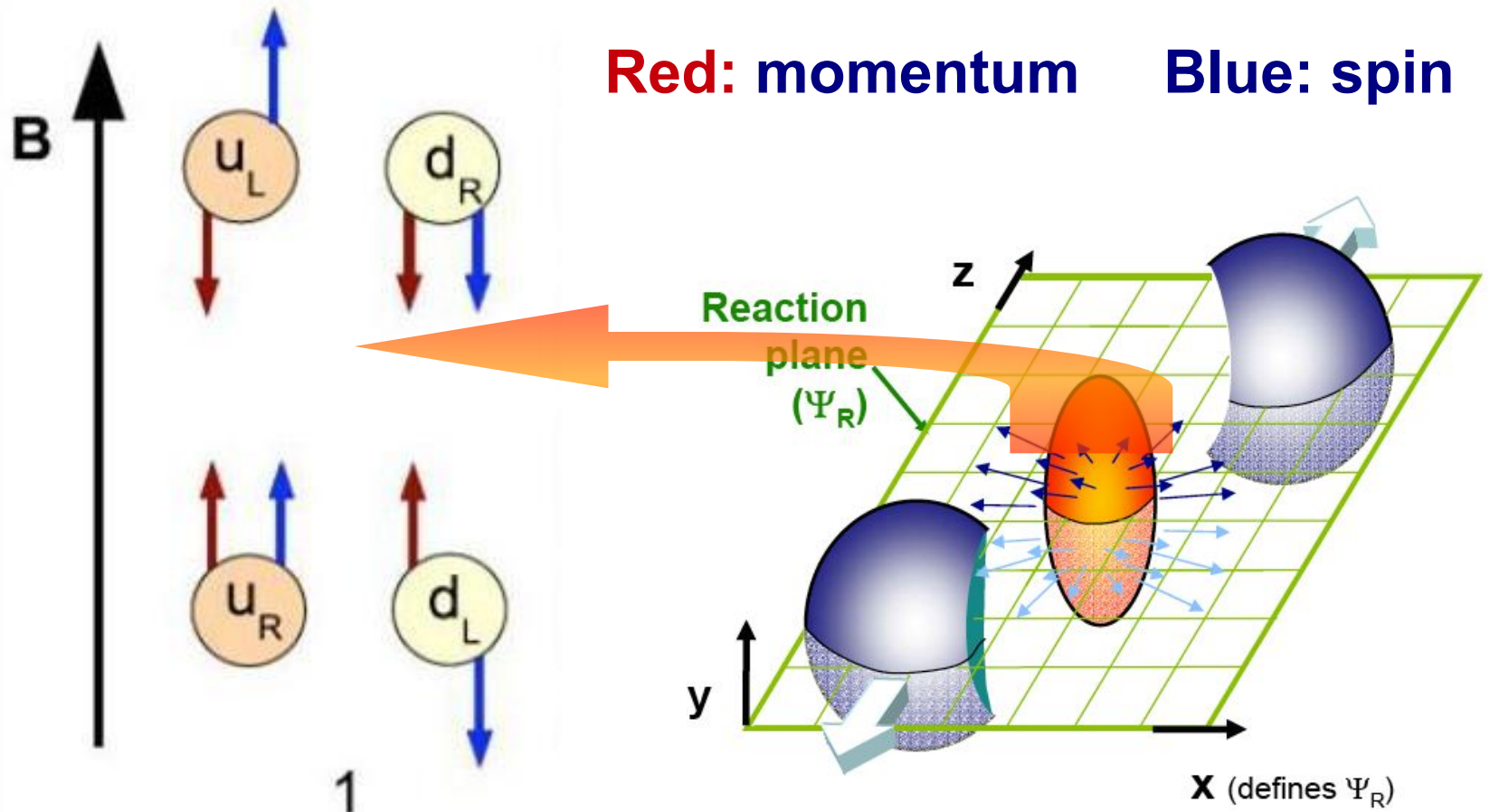
- 1. with non-zero topological charge density**
- 2. exposed to external magnetic field**

Experimentally observed at RHIC :

charge asymmetry of produced particles at heavy ion collisions

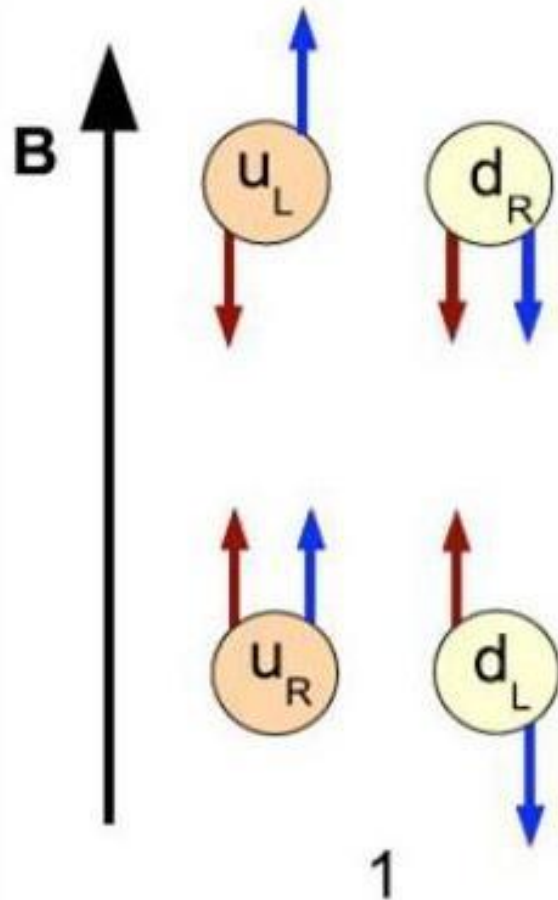
Chiral Magnetic Effect by Fukushima, Kharzeev, Warringa, McLerran

1. Massless quarks in external magnetic field.



Chiral Magnetic Effect by Fukushima, Kharzeev, Warringa, McLerran

1. Massless quarks in external magnetic field.

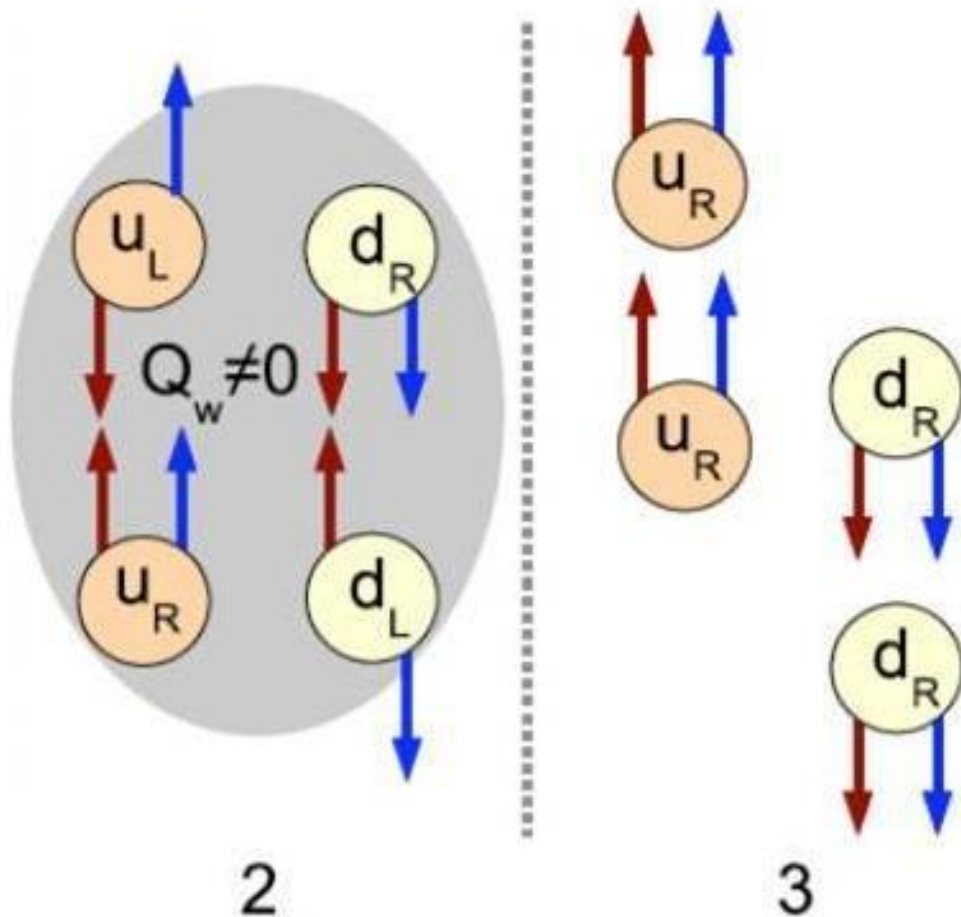


Red: momentum **Blue: spin**



Chiral Magnetic Effect by Fukushima, Kharzeev, Warringa, McLerran

2. Quarks in the instanton field.



Red: momentum
Blue: spin

Effect of topology:

$$u_L \rightarrow u_R$$

$$d_L \rightarrow d_R$$

Chiral Magnetic Effect by Fukushima, Kharzeev, Warringa, McLerran

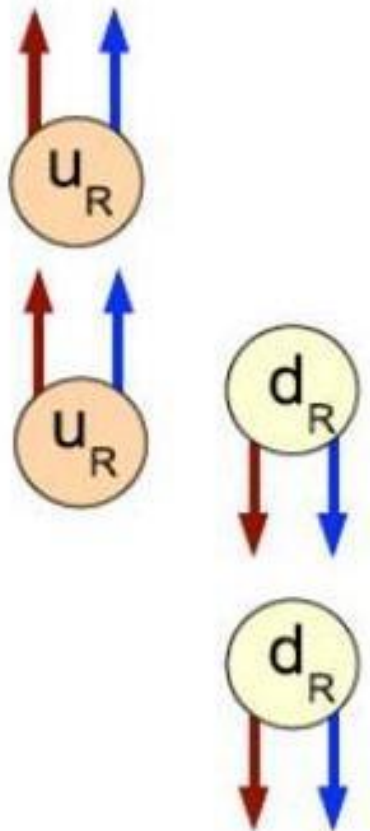
3. Electric current along magnetic field

Red: momentum
Blue: spin

Effect of topology:

$$u_L \rightarrow u_R$$

$$d_L \rightarrow d_R$$

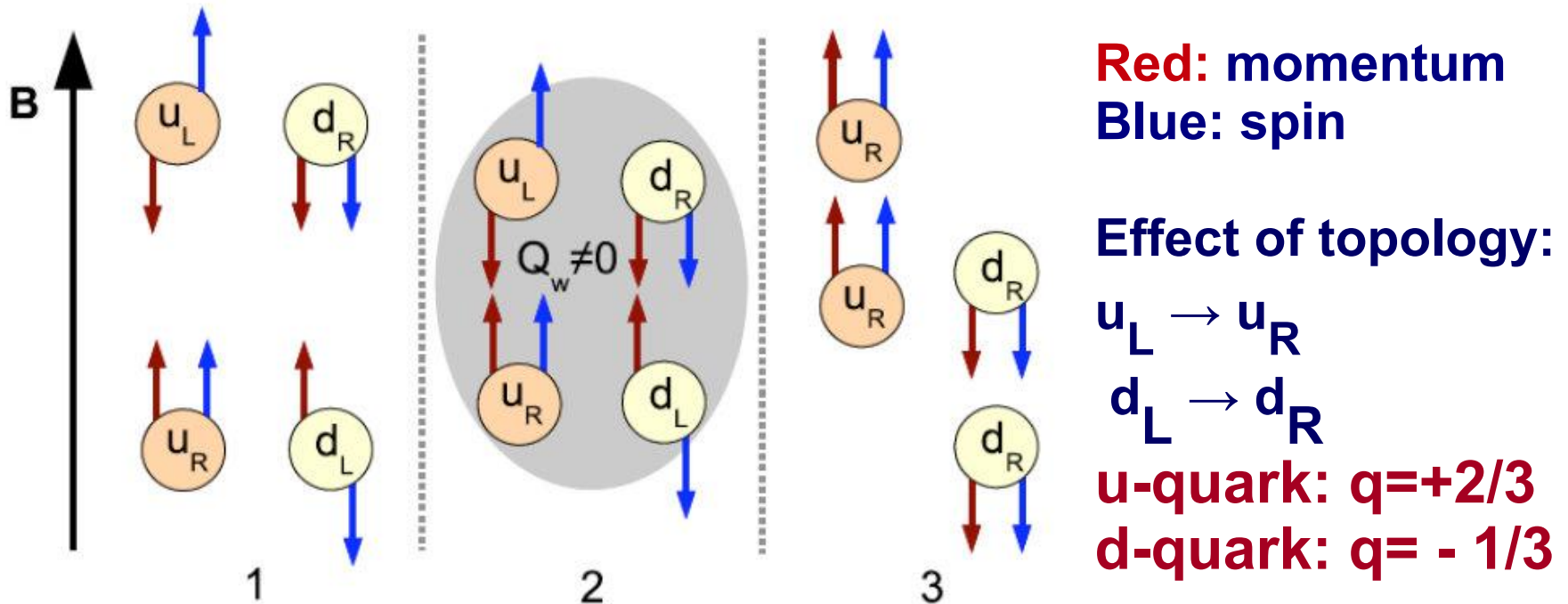


u-quark: $q=+2/3$

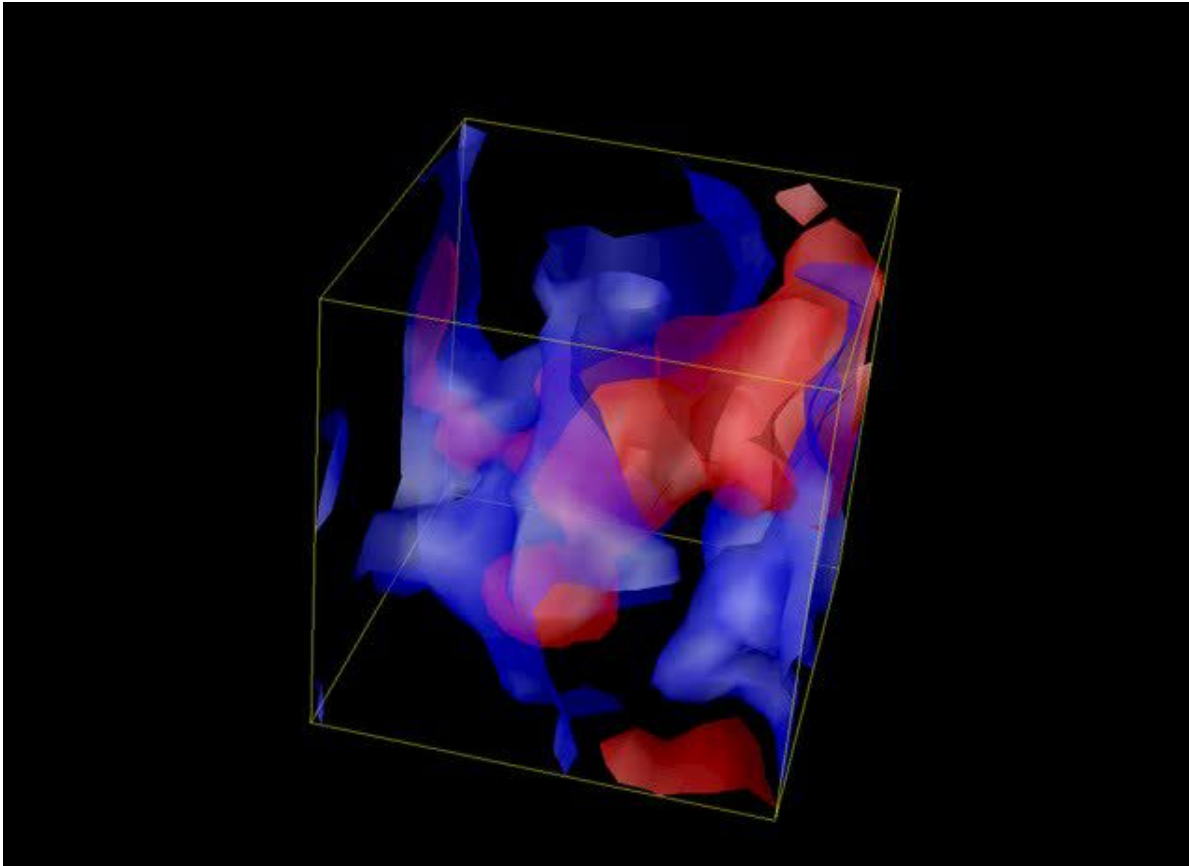
d-quark: $q=-1/3$

Chiral Magnetic Effect by Fukushima, Kharzeev, Warringa, McLerran

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



Topological charge density in quantum QCD vacuum has fractal structure



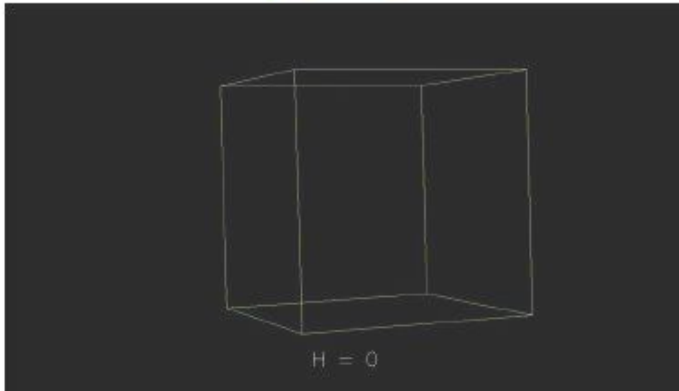
**In quantum vacuum we expect
big fluctuations of charge squared**

$$\langle j_3 \rangle = 0; \quad \langle j_3^2 \rangle \neq 0;$$

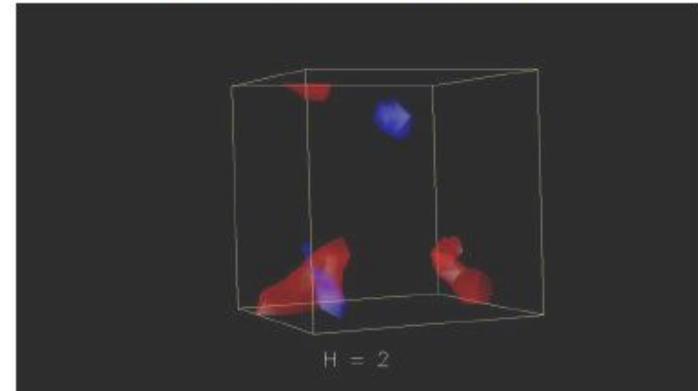
Chiral Magnetic Effect on the lattice, charge separation

Density of the electric charge vs. magnetic field

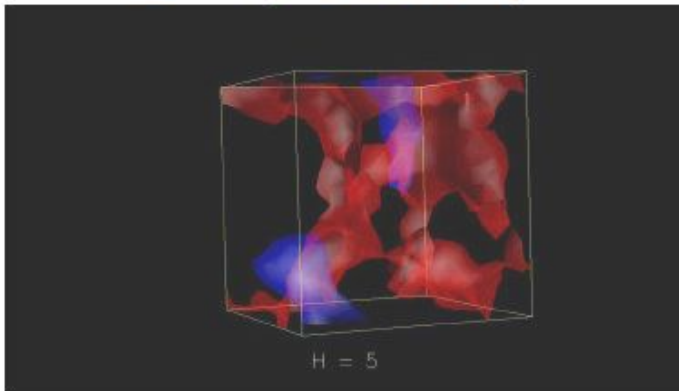
$$B = 0$$



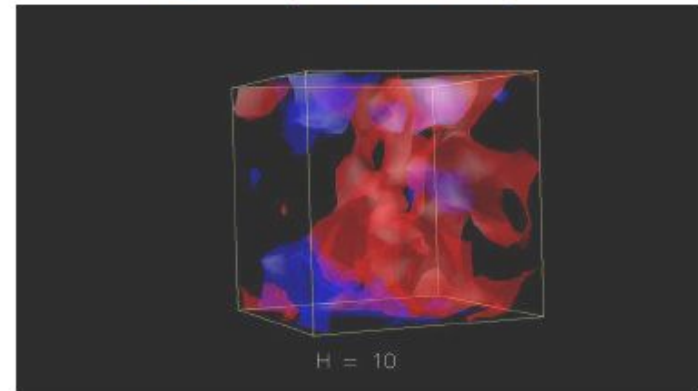
$$B = (500 \text{ MeV})^2$$



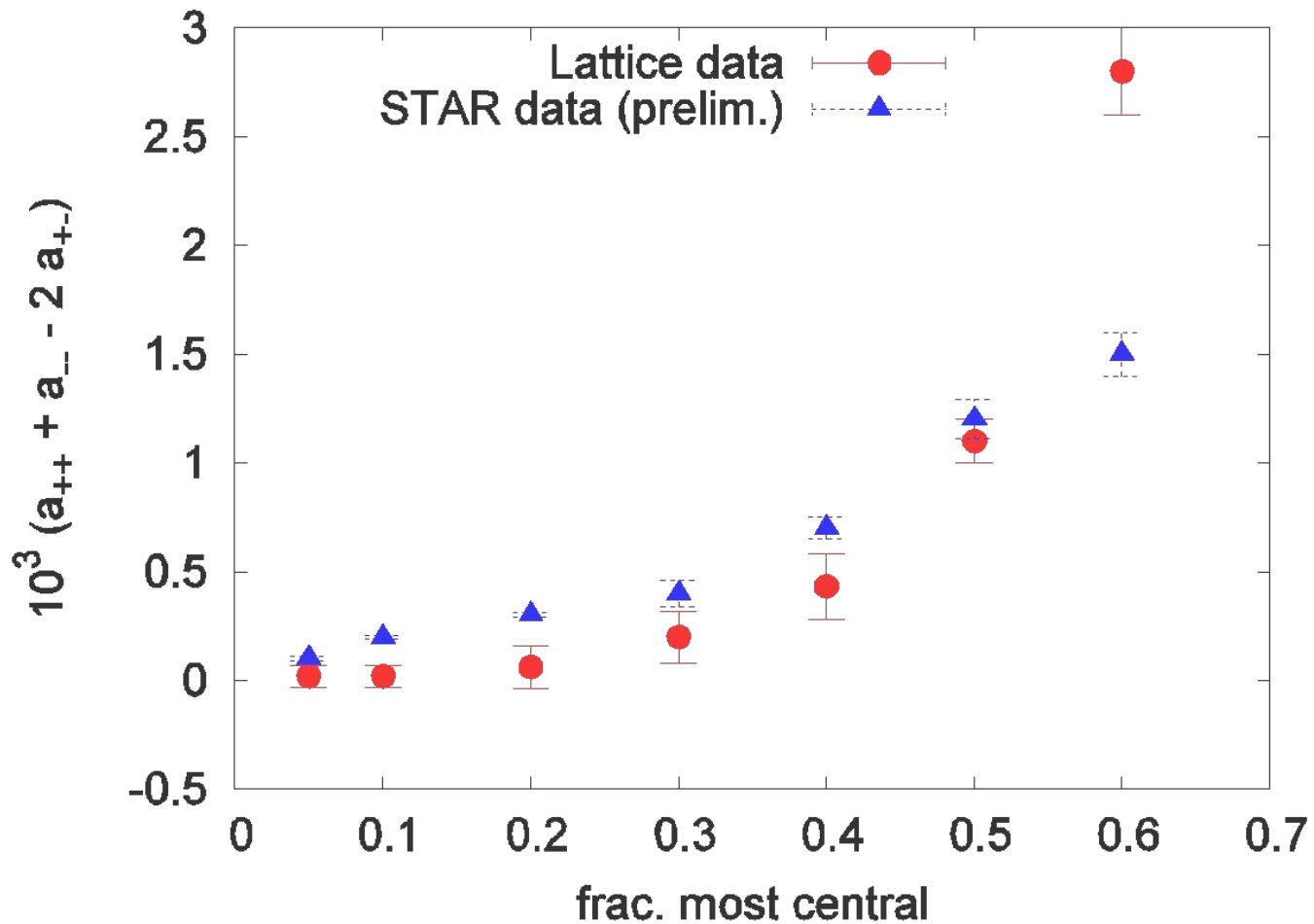
$$B = (780 \text{ MeV})^2$$



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



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



Chiral Magnetic Effect, EXPERIMENT VS LATTICE DATA

$$a_{ab} = \frac{1}{N_e} \sum_{e=1}^{N_e} \frac{1}{N_a N_b} \sum_{i=1}^{N_a} \sum_{j=1}^{N_b} \cos(\phi_{ia} + \phi_{jb})$$

experiment

$$\frac{\langle (\Delta Q)^2 \rangle}{N_q^2} = a_{++} + a_{--} - 2a_{+-}$$

our fit

$$R \approx 5 \text{ fm}$$

$$\rho \approx 0.2 \text{ fm}$$

$$\tau \approx 1 \text{ fm}$$

D. E. Kharzeev,
L. D. McLerran, and
H. J. Warringa,
Nucl. Phys. A 803,
227 (2008),

$$= \frac{4\pi\tau^2\rho^2R^2}{3N_q^2} \left(\langle j_{\parallel}^2 \rangle + 2\langle j_{\perp}^2 \rangle \right)$$

our lattice data at $T=350 \text{ Mev}$

Preliminary results: conductivity of the vacuum

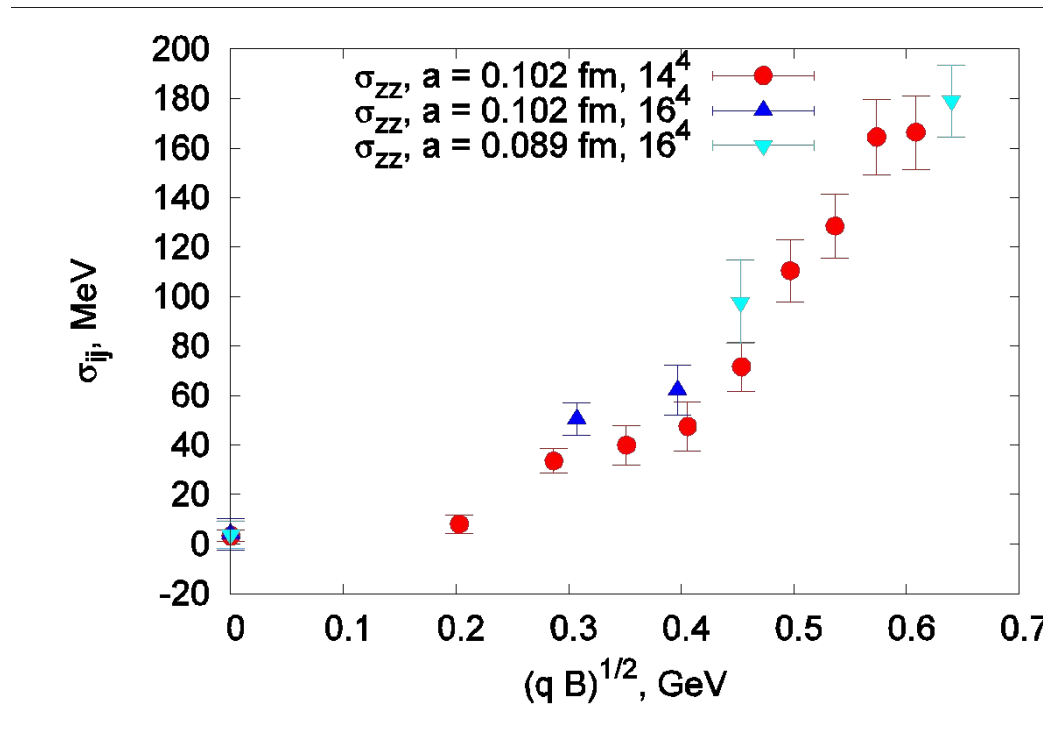
Qualitative definition of conductivity σ

$$\langle j_\mu(x) j_\nu(y) \rangle = C + A \cdot \exp\{-m|x-y|\}$$

$$\sigma \propto C$$

Preliminary results: conductivity of the vacuum

Conductivity at T=0

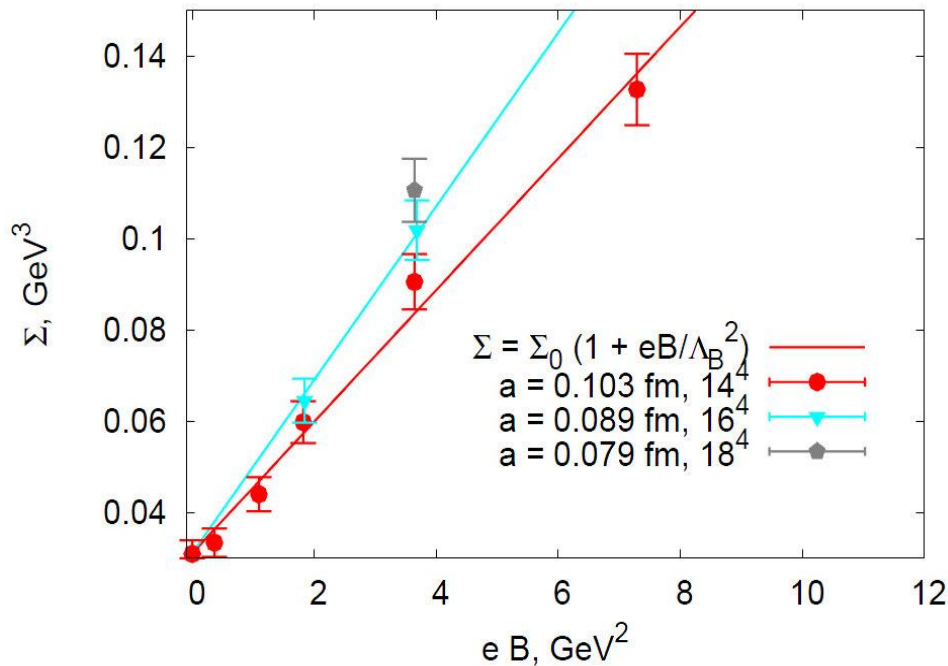


2. Chiral condensate in QCD

$$\Sigma = - \langle \bar{\psi} \psi \rangle$$

$$m_{\pi}^2 f_{\pi}^2 = m_q \langle \bar{\psi} \psi \rangle$$

Chiral condensate vs. field strength



$$\Sigma = \Sigma_0 \left(1 + \frac{eB}{\Lambda_B^2}\right)$$

- Our value for Λ_B :

$$\Lambda_B^{\text{fit}} = (1.41 \pm 0.14 \pm 0.20) \text{ GeV}$$

- χ PT result:

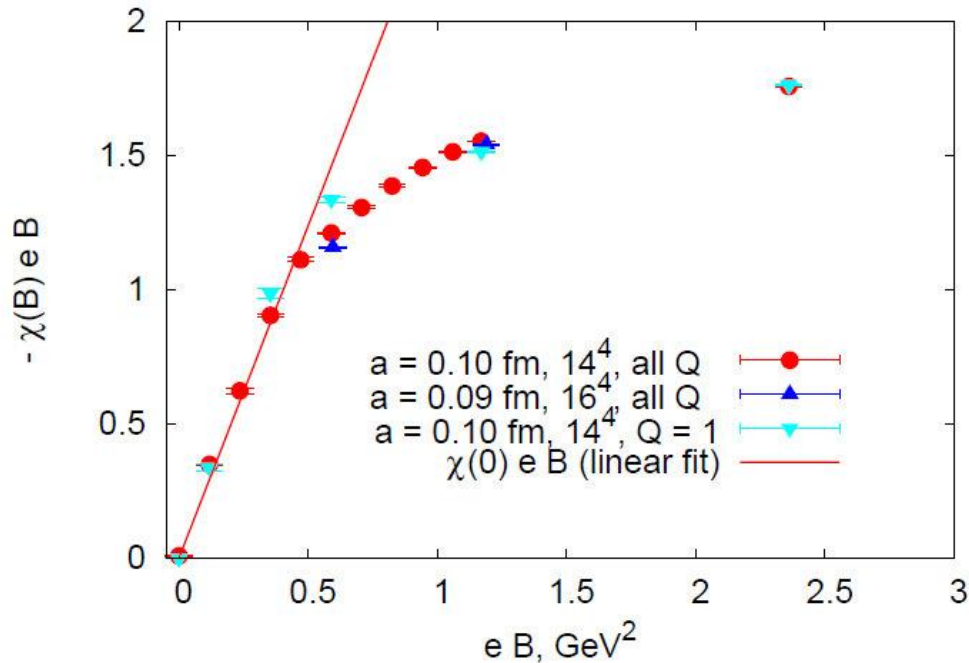
$$\Lambda_B^{\chi PT} = 1.96 \text{ GeV} \quad (F_\pi = 130 \text{ MeV} - \text{real world})$$

$$\Lambda_B^{\chi PT} = 1.36 \text{ GeV} \quad (F_\pi = 90 \text{ MeV} - \text{quenched})$$

- Chiral condensate at $B = 0$: $\Sigma_0^{\text{fit}} = [(310 \pm 6) \text{ MeV}]^3$

We are in agreement with the chiral perturbation theory: the chiral condensate is a linear function of the strength of the magnetic field!

3. Magnetization of the vacuum as a function of the magnetic field



Spins of virtual quarks turn parallel to the magnetic field



$$\langle \bar{\psi} \sigma_{\alpha\beta} \psi \rangle = \chi \langle \bar{\psi} \psi \rangle F_{\alpha\beta}$$

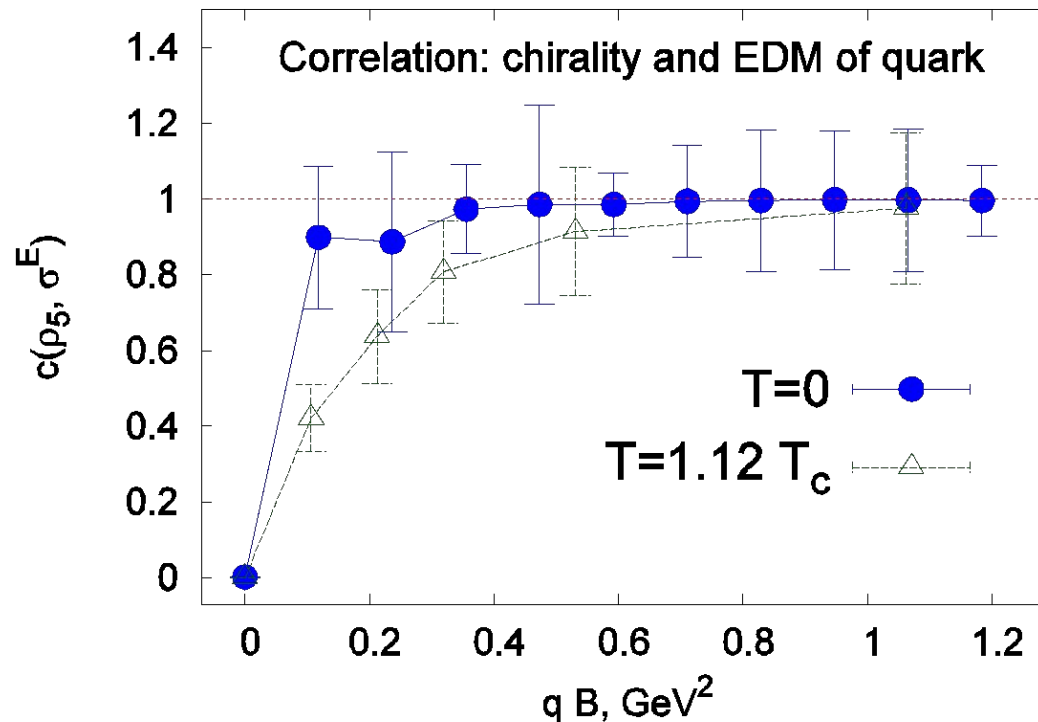
$$\sigma_{\alpha\beta} = \frac{1}{2i} [\gamma_{\alpha}, \gamma_{\beta}]$$

$\langle \bar{\psi} \psi \rangle \chi = -46(3) \text{ Mev} \leftrightarrow$ our result
 $\langle \bar{\psi} \psi \rangle \chi \approx -50 \text{ Mev} \leftrightarrow$ QCD sum rules
 (I. I. Balitsky, 1985, P. Ball, 2003.)

4. Generation of the anomalous quark electric dipole moment along the axis of magnetic field

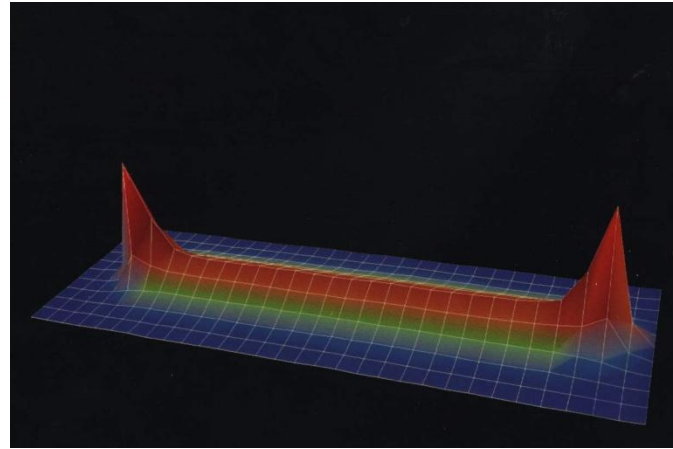
Large correlation between square of the electric dipole moment

$$\sigma_{0i} = i\bar{\psi}[\gamma_0, \gamma_i]\psi \quad \text{and chirality} \quad \rho_5 = \bar{\psi}\gamma_5\psi$$



THEORY

To explain



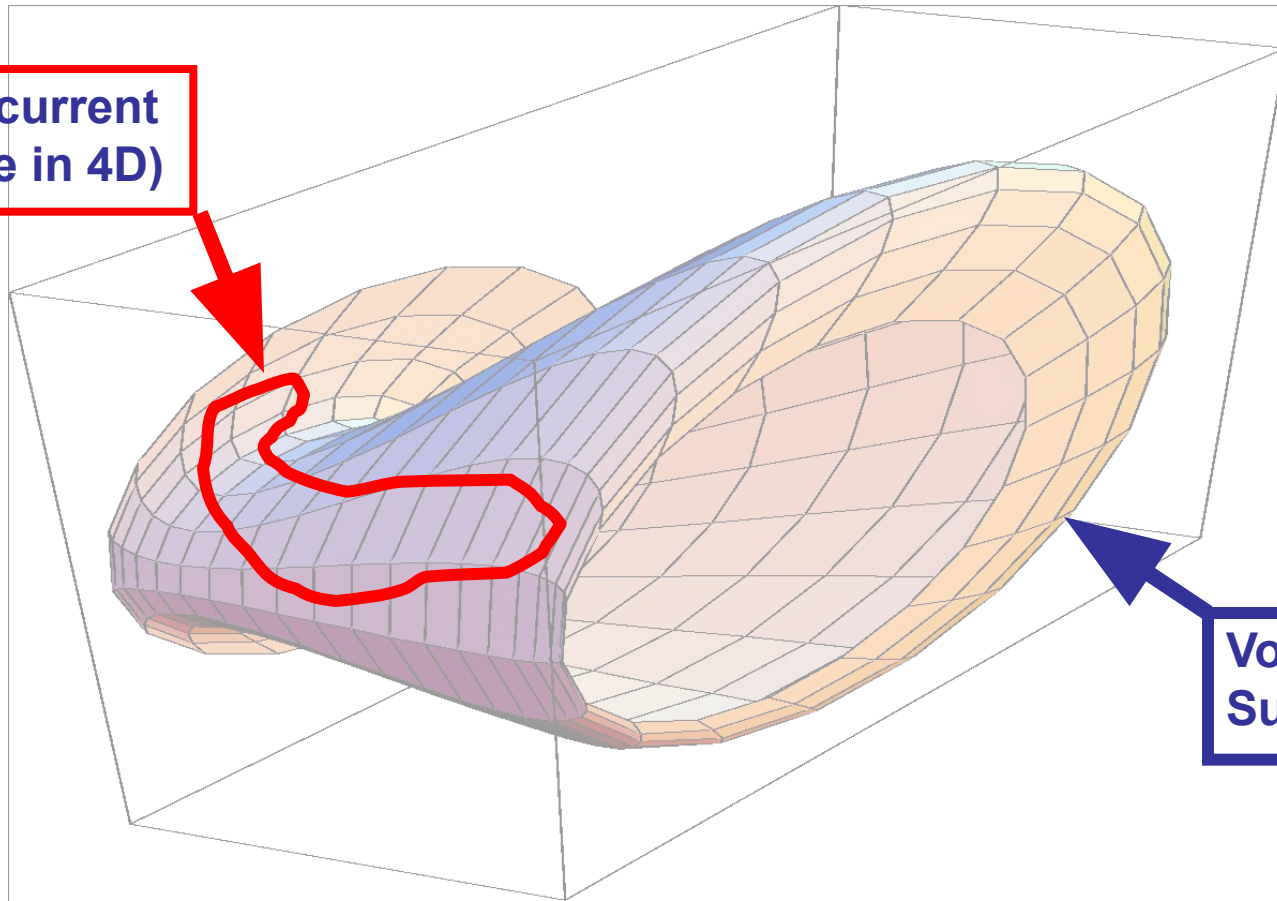
We have to prove in gluodynamics that

$$\langle W(C) \rangle = \langle \text{Tr} P \exp \left\{ \oint_C i A_\mu dx_\mu \right\} \rangle \propto \exp \{ -\sigma \cdot \text{Area} \}$$

SU(2) gauge theory

J.Ambjorn, J.Giedt and J.Greensite, JHEP 0002 (2000) 033. A.V.Kovalenko, M.I.Polikarpov, S.N.Syritsyn and V.I.Zakharov, Phys. Rev. D71 (2005) 054511; Phys. Lett. B613 (2005) 52; Ph. de Forcrand and M. Pepe, Nucl. Phys. B598 (2001) 557.

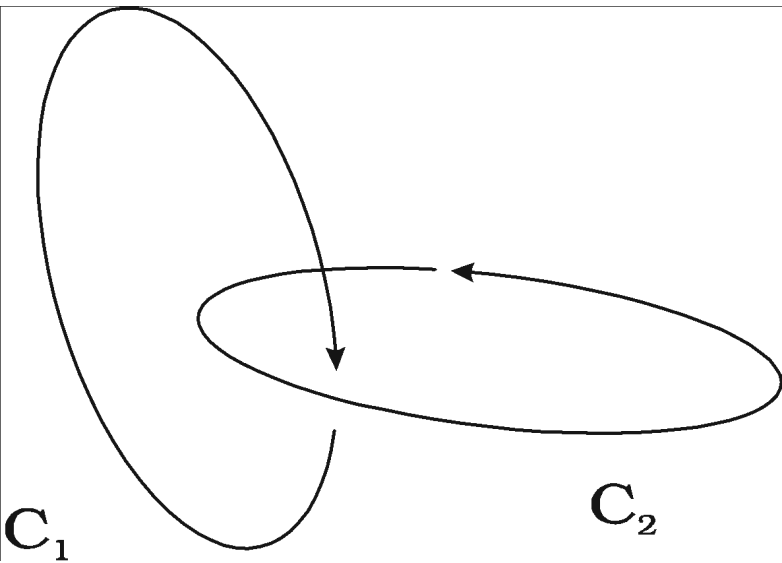
**Monopole current
(closed line in 4D)**



**Vortex (closed
Surface in 4D)**

Linking number

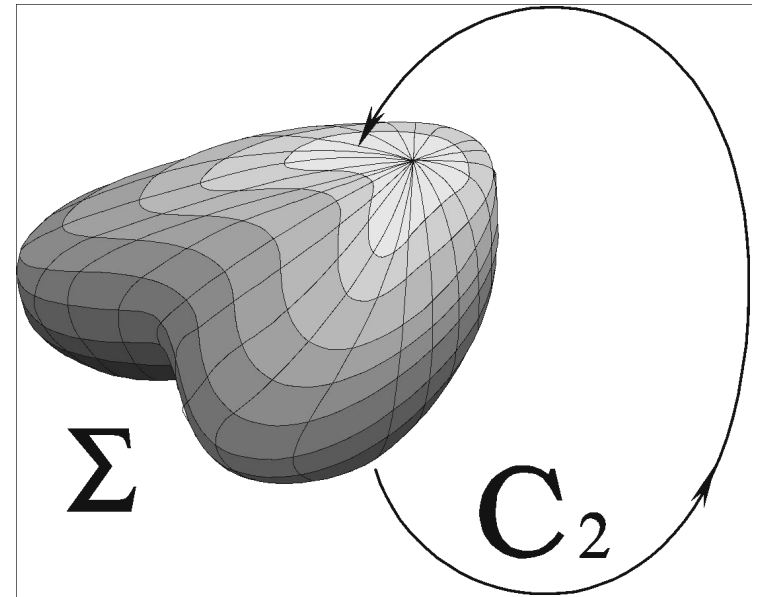
3D



$$L = \frac{1}{4\pi} \oint_{C_1} dx_i \oint_{C_2} dy_k \varepsilon_{ikl} \partial_l \frac{1}{|x-y|}$$

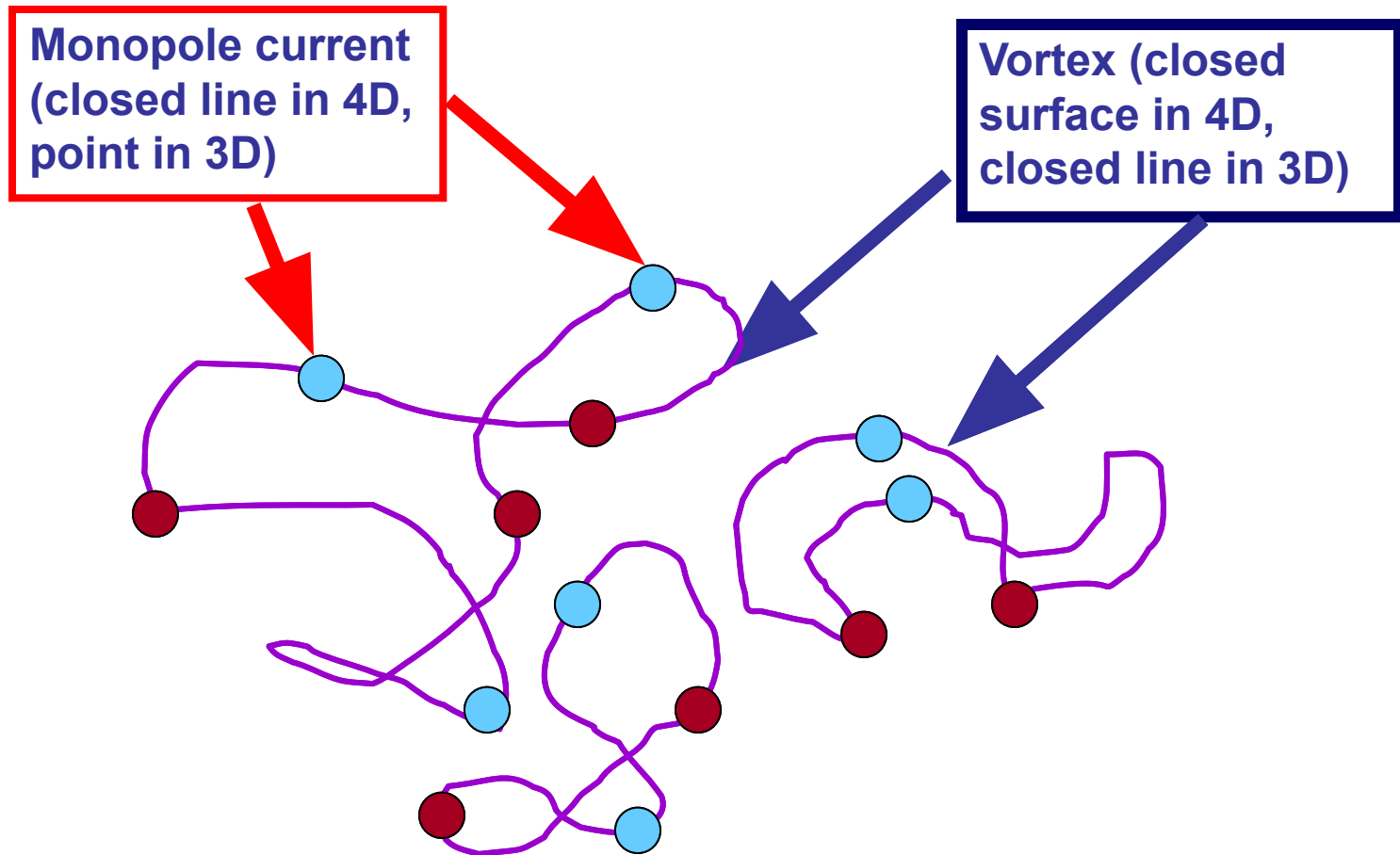
4D

$$L = \frac{1}{8\pi^2} \oint_{C_1} d\Sigma_{\alpha\beta}(x) \oint_{C_2} dy_\gamma \varepsilon_{\alpha\beta\gamma\delta} \partial_\delta \frac{1}{|x-y|}$$



Pure gauge theory

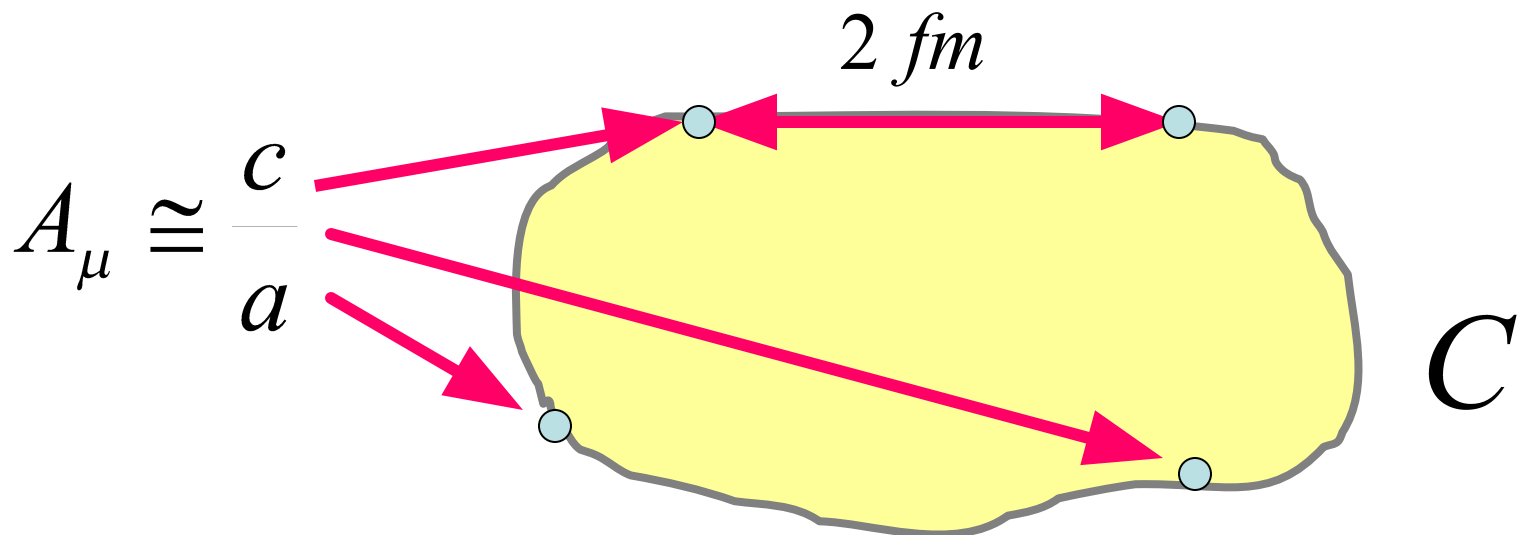
(what we see on 3d slice of 4D lattice)



THEORY

All information about confinement, quark condensate and any Wilson loop is encoded in 3d branes

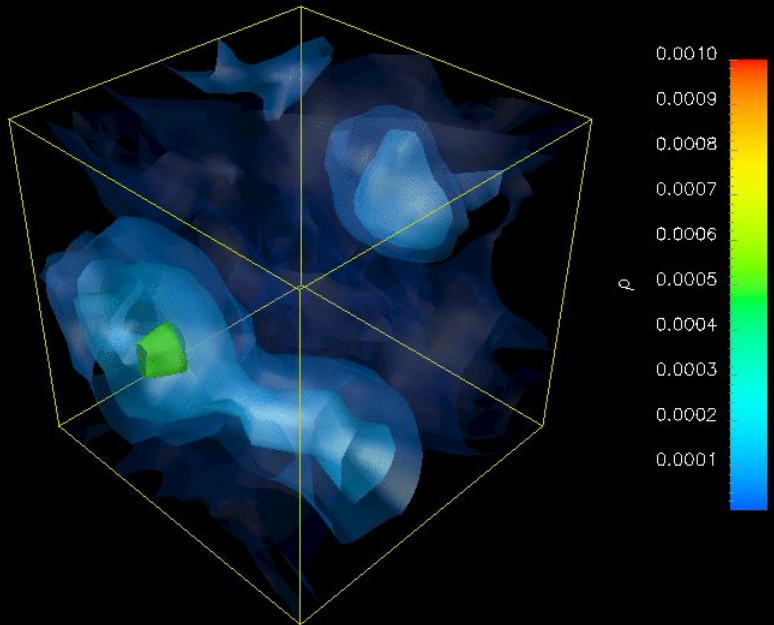
Holography



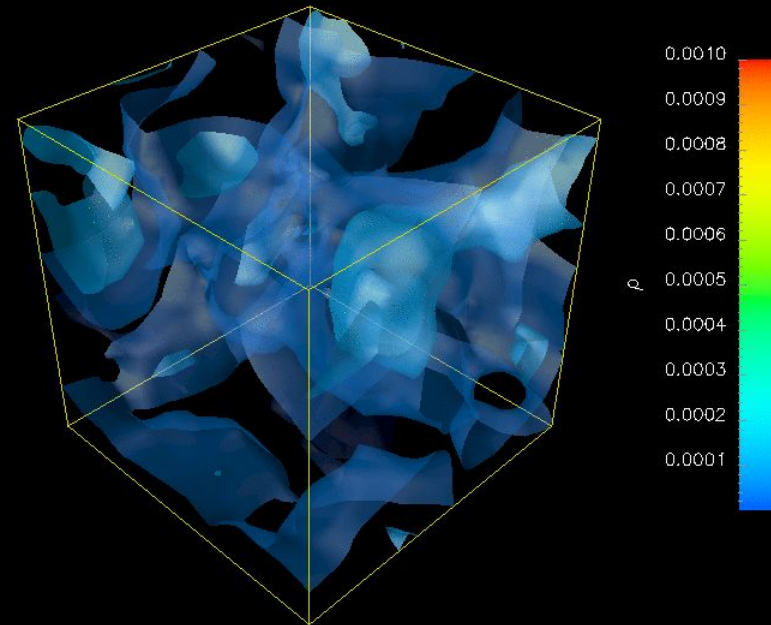
THEORY

Chiral symmetry breaking and topological susceptibility
is due to low-dimensional regions

Time slices for ρ^2 , $\rho_\lambda(x) = \psi_\lambda^+(x)\psi_\lambda(x)$

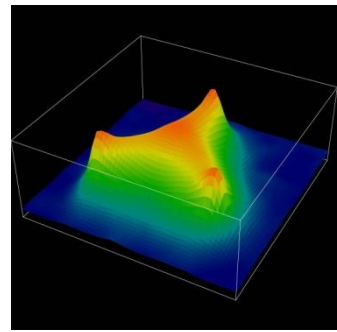
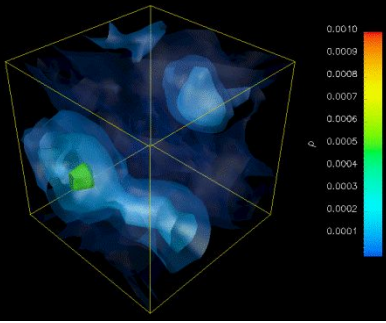


IPR=5.13
chirality=-1

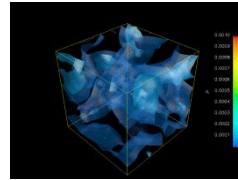


IPR=1.45
chirality=0

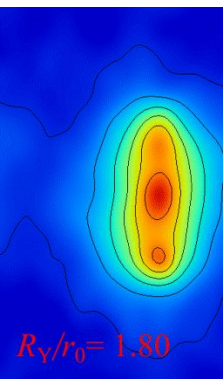
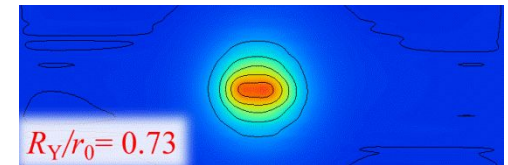
Instead of Conclusions



Computer simulations a) reproduce well known hadron properties b) predict new phenomena c) help to create new theoretical ideas.

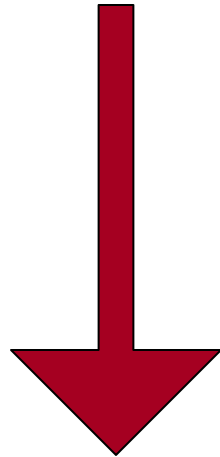


- Low dimensional objects (regions) are responsible for most interesting nonperturbative effects: chiral symmetry breaking, topological susceptibility and confinement.



The era of traditional quantum field theory (Feynman graphs, perturbation theory) is over, nonperturbative field theory is close in spirit to solid state theory; we have to study dislocations, fractals, phase transitions etc.

<http://www.lattice.itcp.ru>



Education

Московский физико-технический институт
Факультет общей и прикладной физики
кафедра теоретической астрофизики и проблем
термоядерной физики

**Специализация: квантовая гравитация и калибровочные
поля**

Базовая организация
"Государственный Научный Центр Российской
Федерации -
Институт Теоретической и Экспериментальной
Физики"
Москва, ул. Большая Черемушkinsкая, 25

Руководит новой
специализацией
всемирно
известный физик -
теоретик **Валентин
Иванович Захаров**



Наш студент это тот, кому
интересна теоретическая
физика и/или
информатика и/или
математическая физика
и/или суперкомпьютеры
(или все вместе).