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
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Яндекс *22 декабря 2010*

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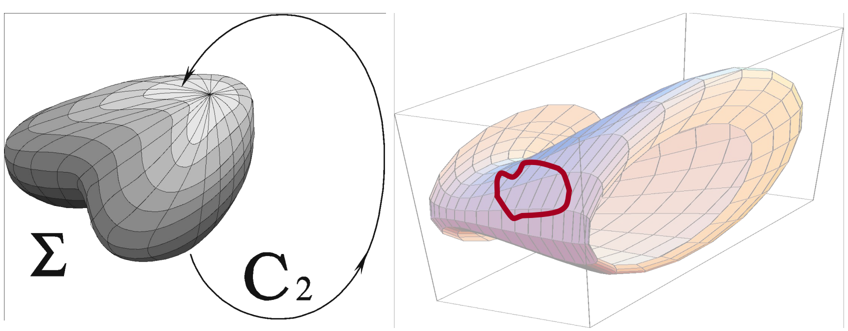
Experiment

LHC

RHIC

Theory

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



Supercalculations

Основные результаты получены в сотрудничестве группы ИТЭФ с

ДЭЗИ (Германия),
Университет Каназава (Япония),
Национальная Лаборатория Брукхэвен (США)
Университет Сан Франциско (США)

ITEP

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

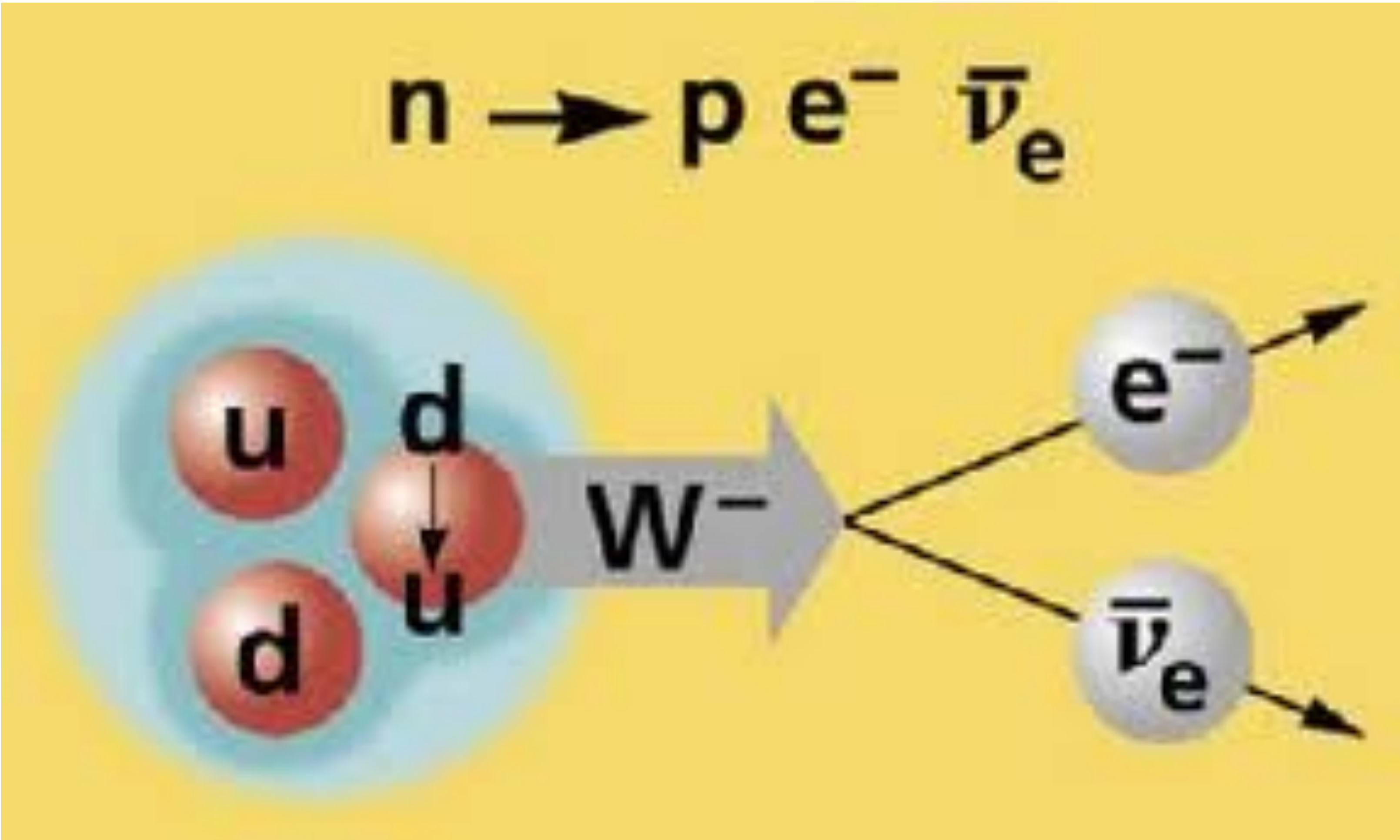
H.Ichie, S.Kitahara, Y.Koma,Y.Mori, Y.Nakamura, T.Suzuki, A. Nakamura

BNL, San Francisko University, USA

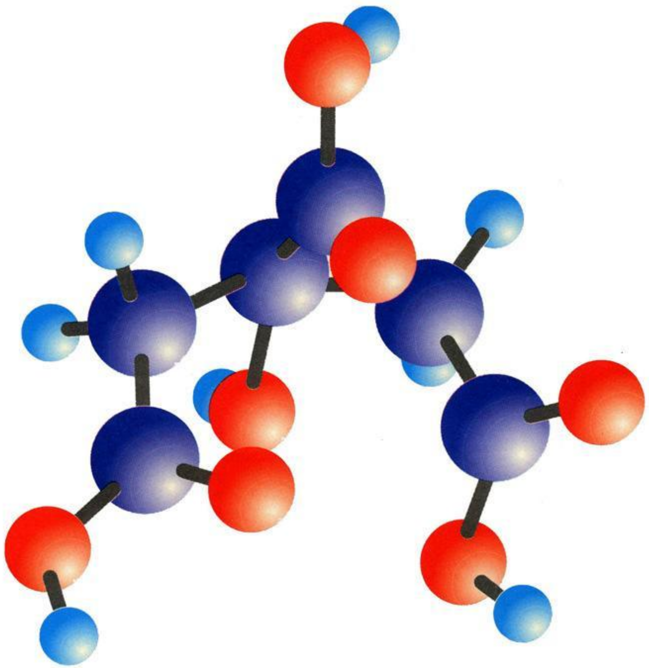
D. Kharzeev, J. Greensite, S. Olejnik (+ Bratislava University, Slovakia)

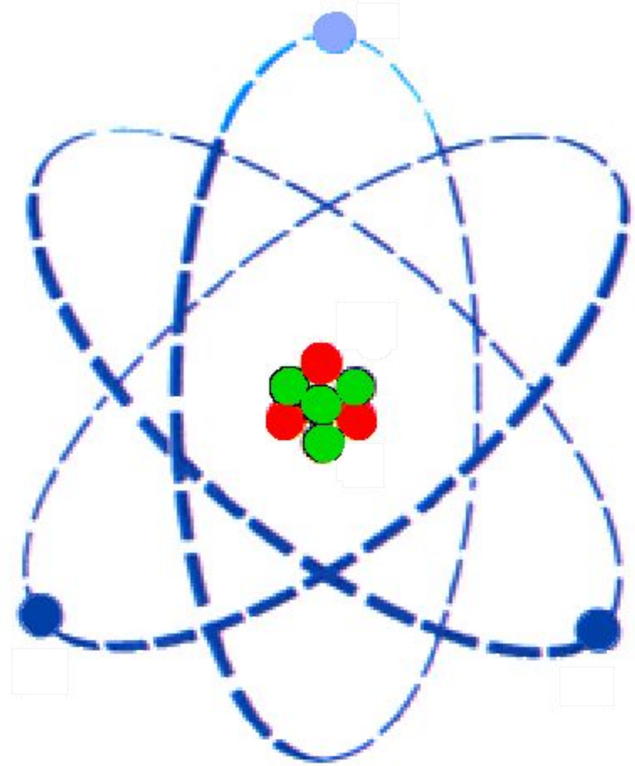
Взаимодействия – 1. Гравитационное

Взаимодействия – 2. Слабое

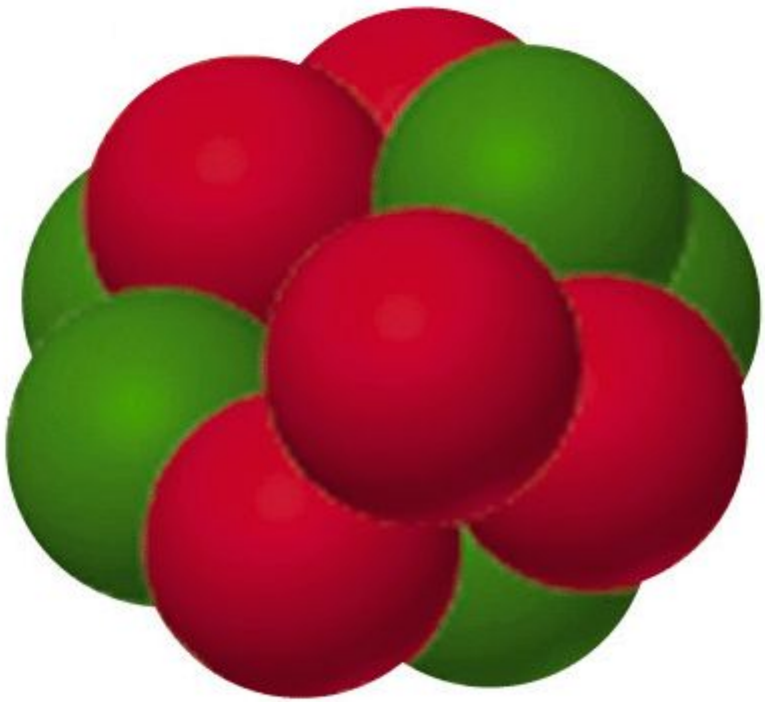


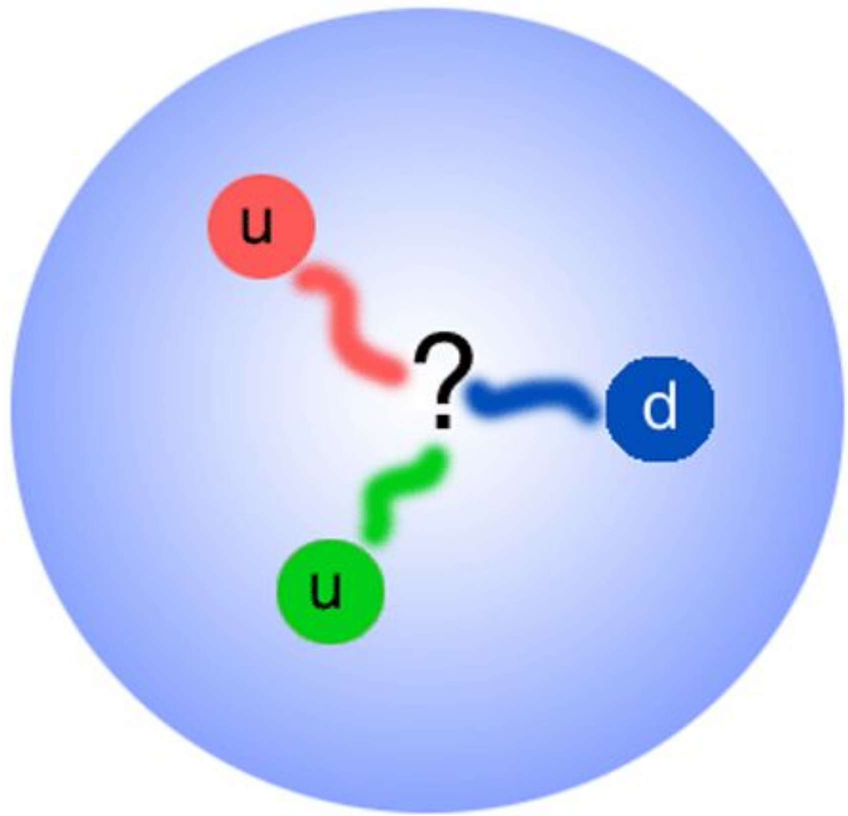
Взаимодействия – 3. Электромагнитноеное





Взаимодействия – 4. Сильное

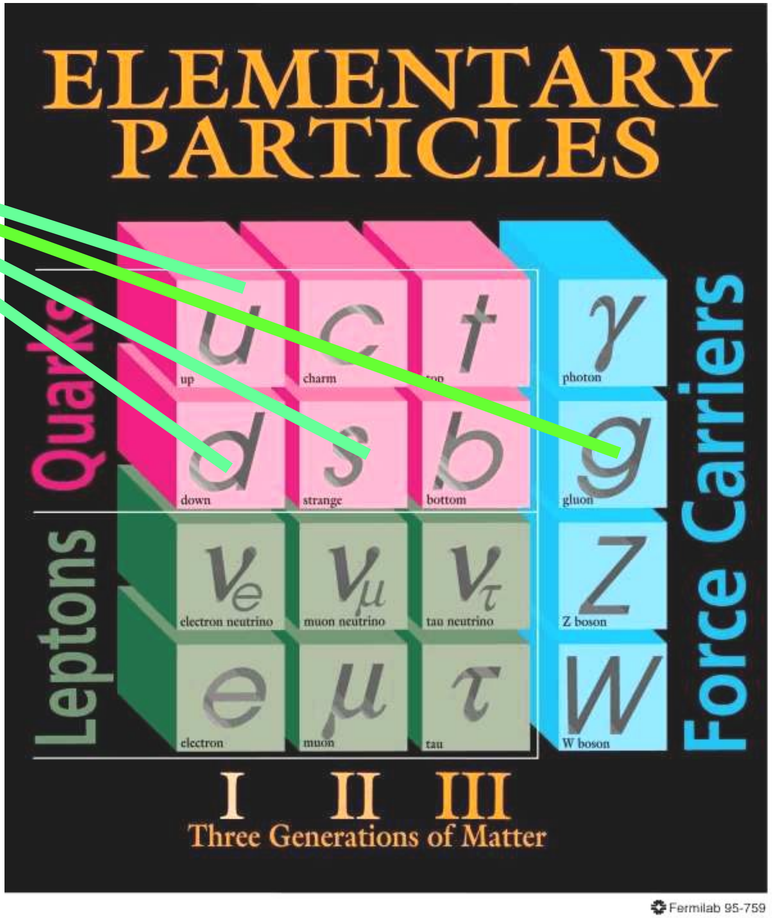




Основные задачи теории сильных взаимодействий

Стартуя с Лагранжиана КХД

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



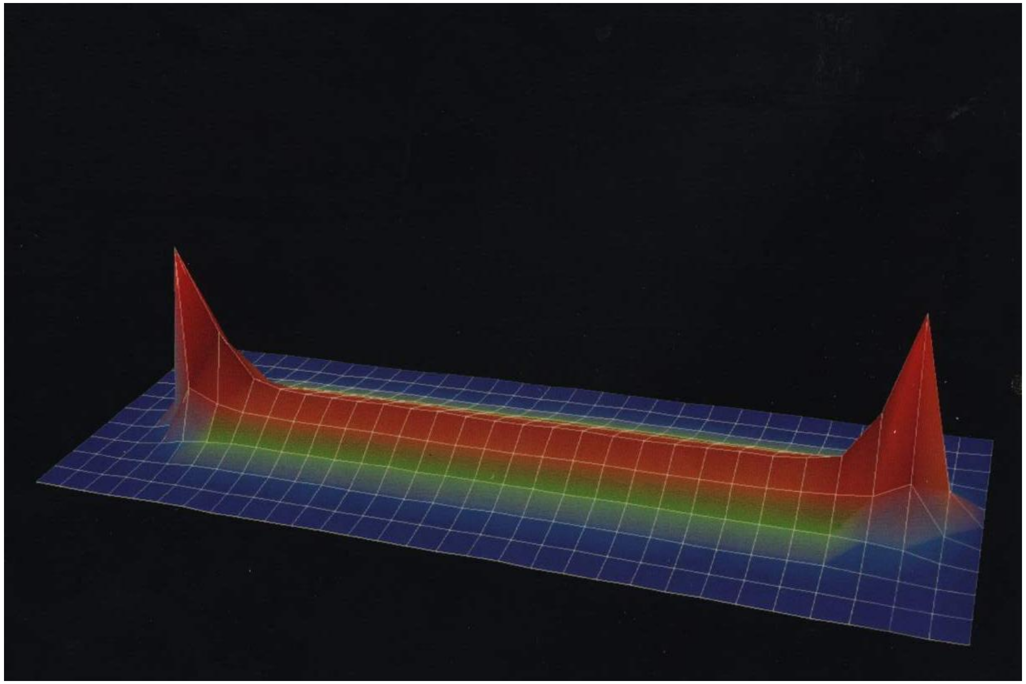
1) Получить спектр адронов,
2) Посчитать матричные элементы,
(3) Описать фазовую диаграмму теории
(4) Объяснить невылетание цвета

http://www.claymath.org/millennium/Yang-Mills_Theory/ (1 000 000 $US)

Невылетание цвета

(почему мы не видим свободных кварков и глюонов?)

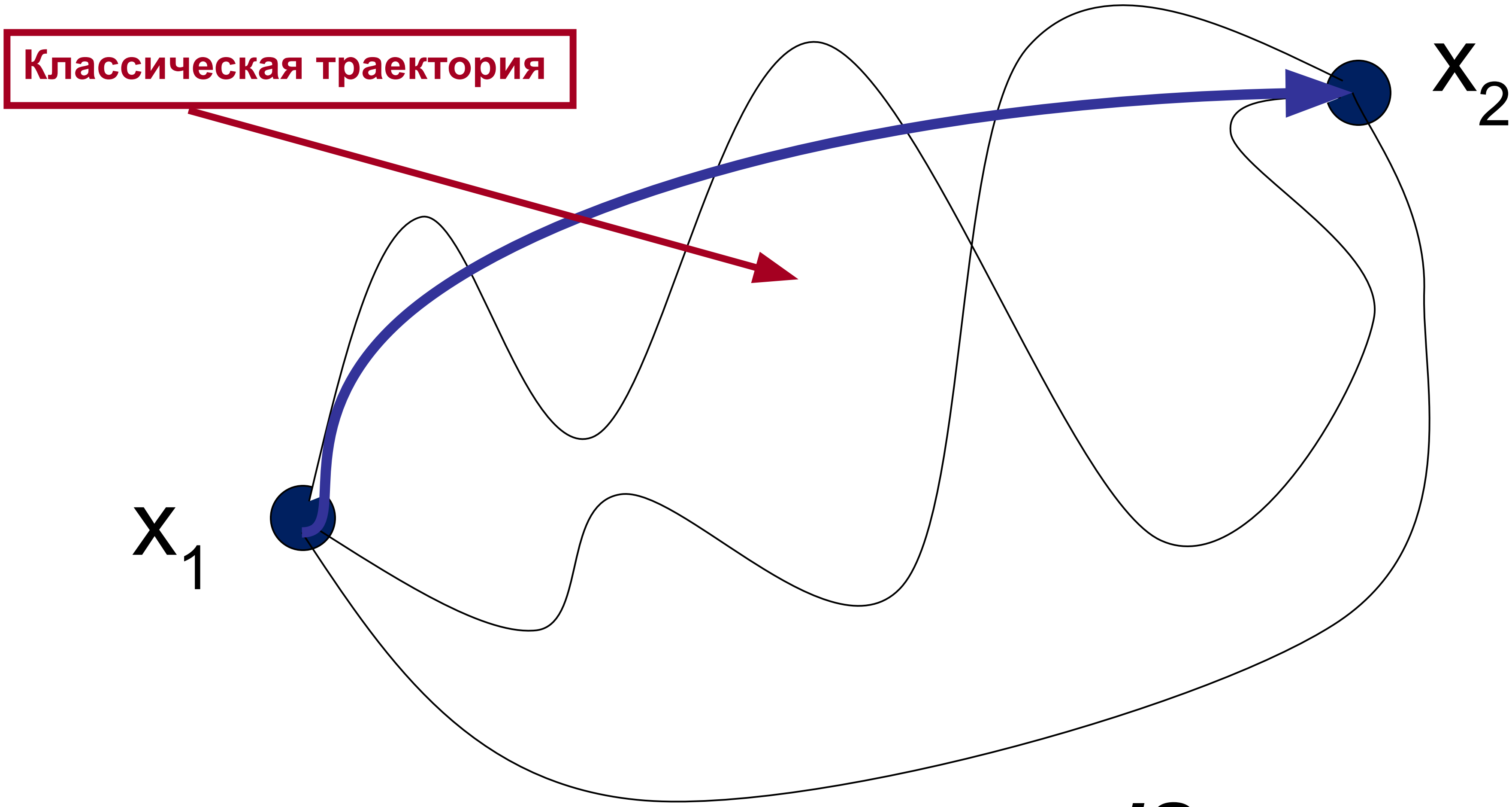
Основная сложность – отсутствие аналитических методов для описания теории сильных взаимодействий, но (супер)компьютеры могут многое предсказывать исходя из Лагранжиана КХД



Сила между кварком и антикварком 12 тонн!!!

http://www.claymath.org/millennium

Квантовая механика частицы



Вес каждой траектории e^{iS}

Квантовая теория поля

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

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

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

Methods

- Imaginary time ***t→it***

$$Z = \int D\varphi \, \exp\{i\,S[\varphi]\} \quad \Rightarrow \quad Z = \int D\varphi \, \exp\{-S[\varphi]\}$$

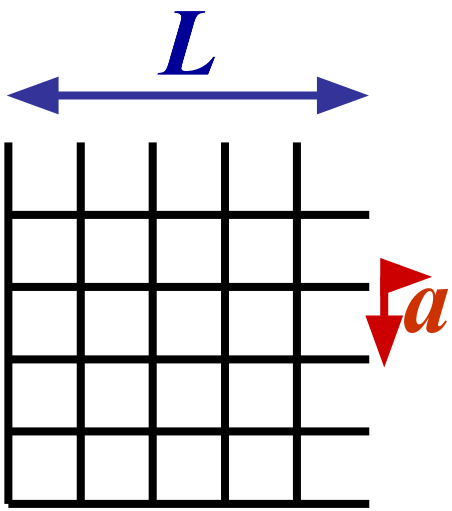
- Space-time discretization

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

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

INTRODUCTION

Three limits



Lattice spacing $a \to 0$

Lattice size $L \to \infty$

Quark mass $m_q \to 0$

Typical values

$a \approx 0.1\ fm$

$L \approx 2 \div 4\ fm$

$m_q \approx 100\ Mev$

Extrapolation

+

Chiral perturbation theory

Типичная кратность интегралов

Для решетки L^4

($L=48$, $L^4=5{,}308{,}416$)

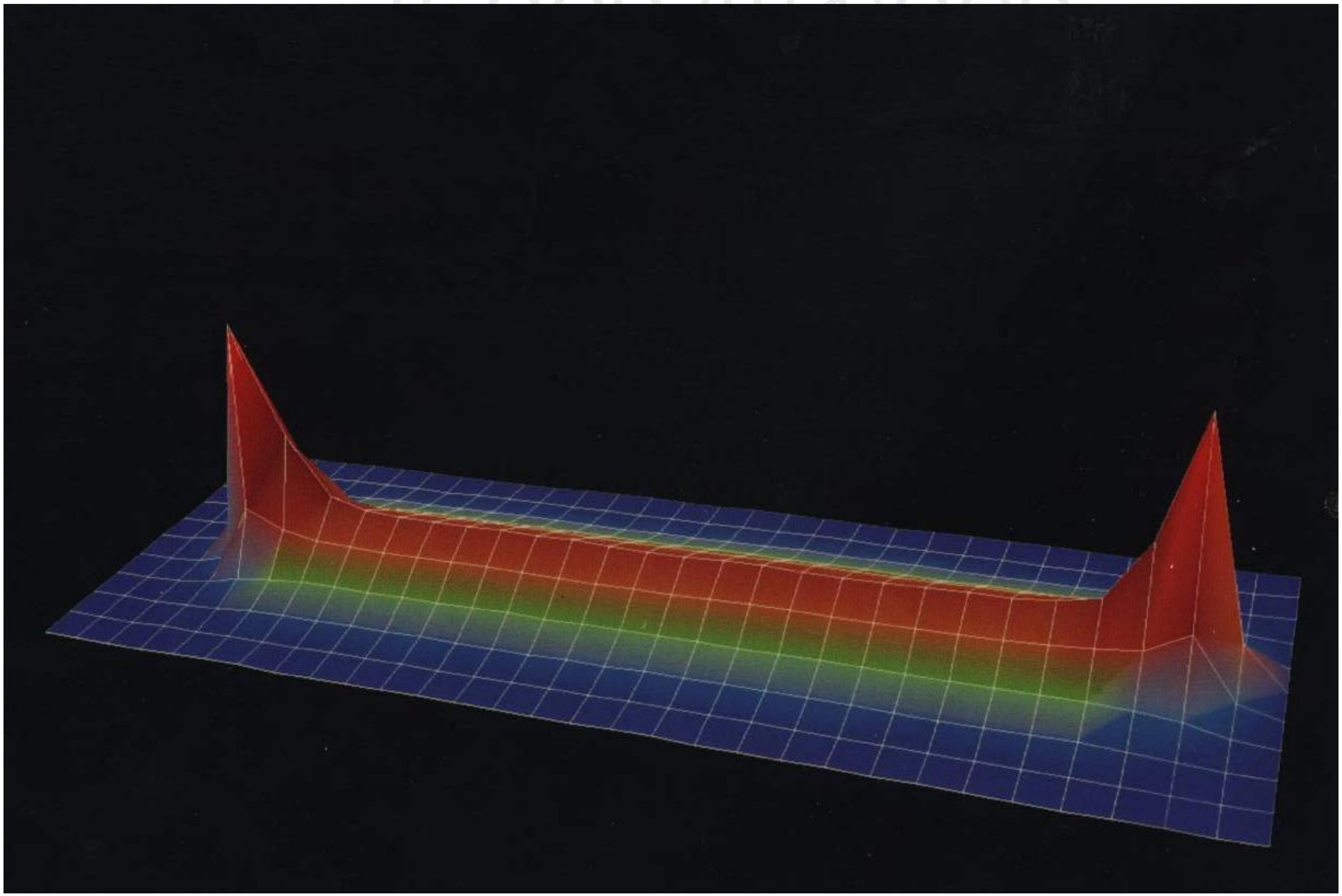
- **Мы считаем интегралы кратности $32L^4$** ($L=48$, $32L^4=169{,}869{,}312$)
- **И работаем с матрицами $12L^4 \times 12L^4$**

($L=48$, $12L^4=63{,}700{,}992$)

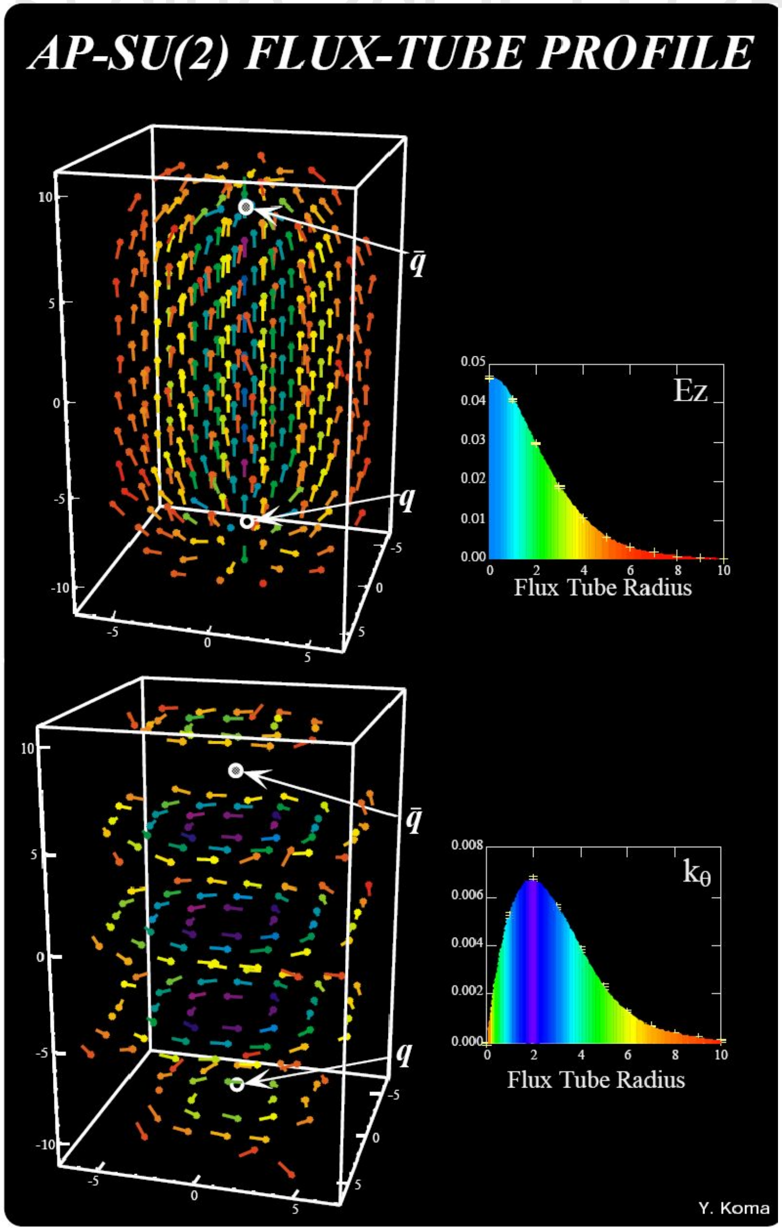
$$\boxed{\int d\psi \; d\bar{\psi} \; \exp\{\bar{\psi} M \psi\} = \det M}$$

SU(2) glue SU(3) glu

Сила между кварком и антикварком 12 тонн!!!

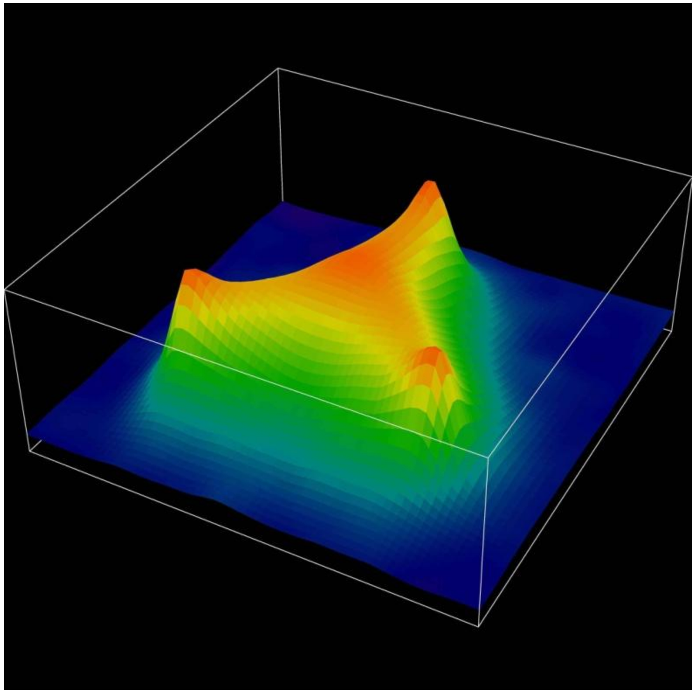


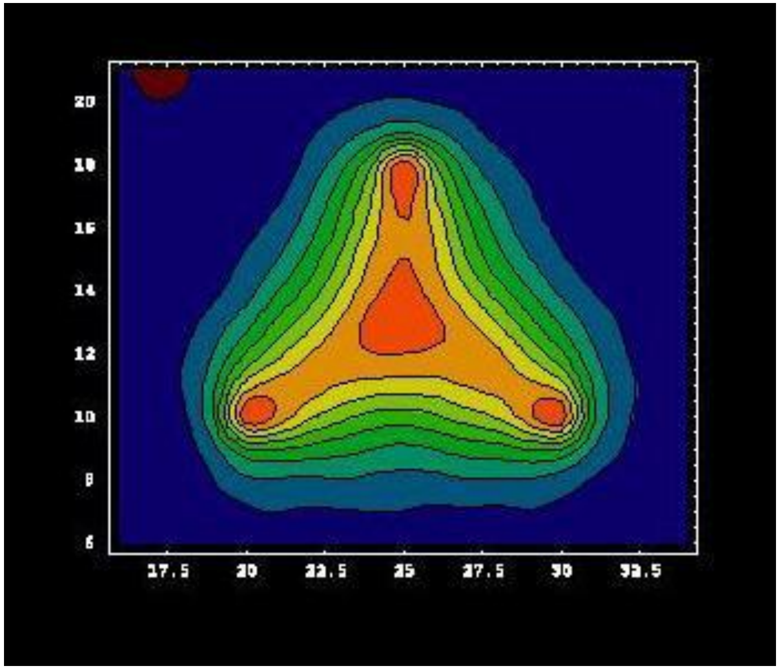
SU(2) glue SU(3) glue 2cQCD (2+1)QCD



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

Three body forces!



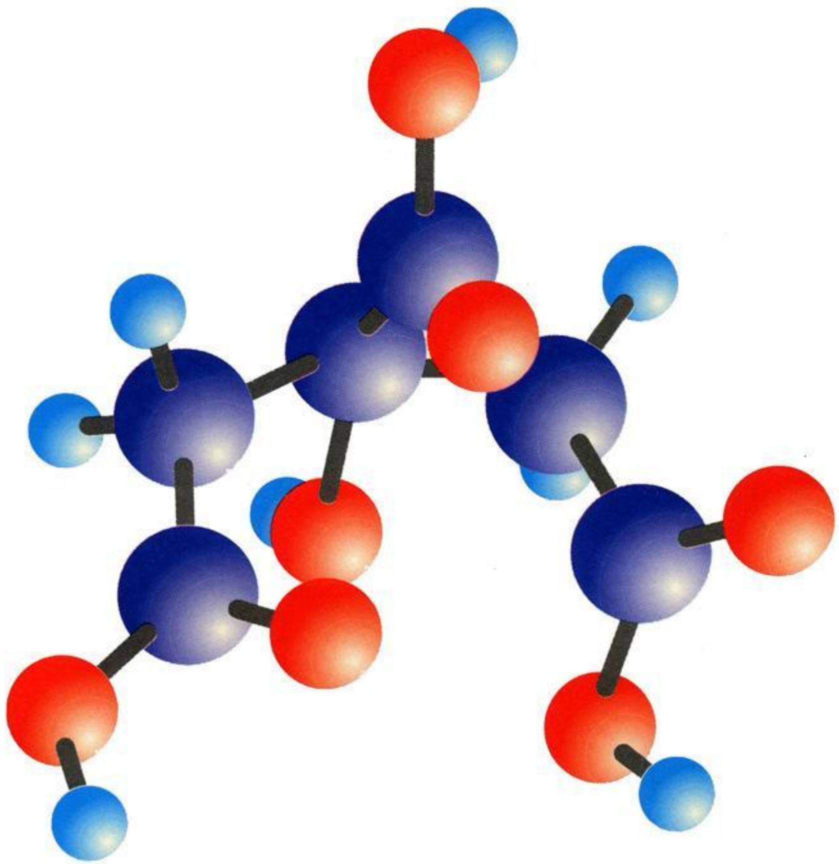


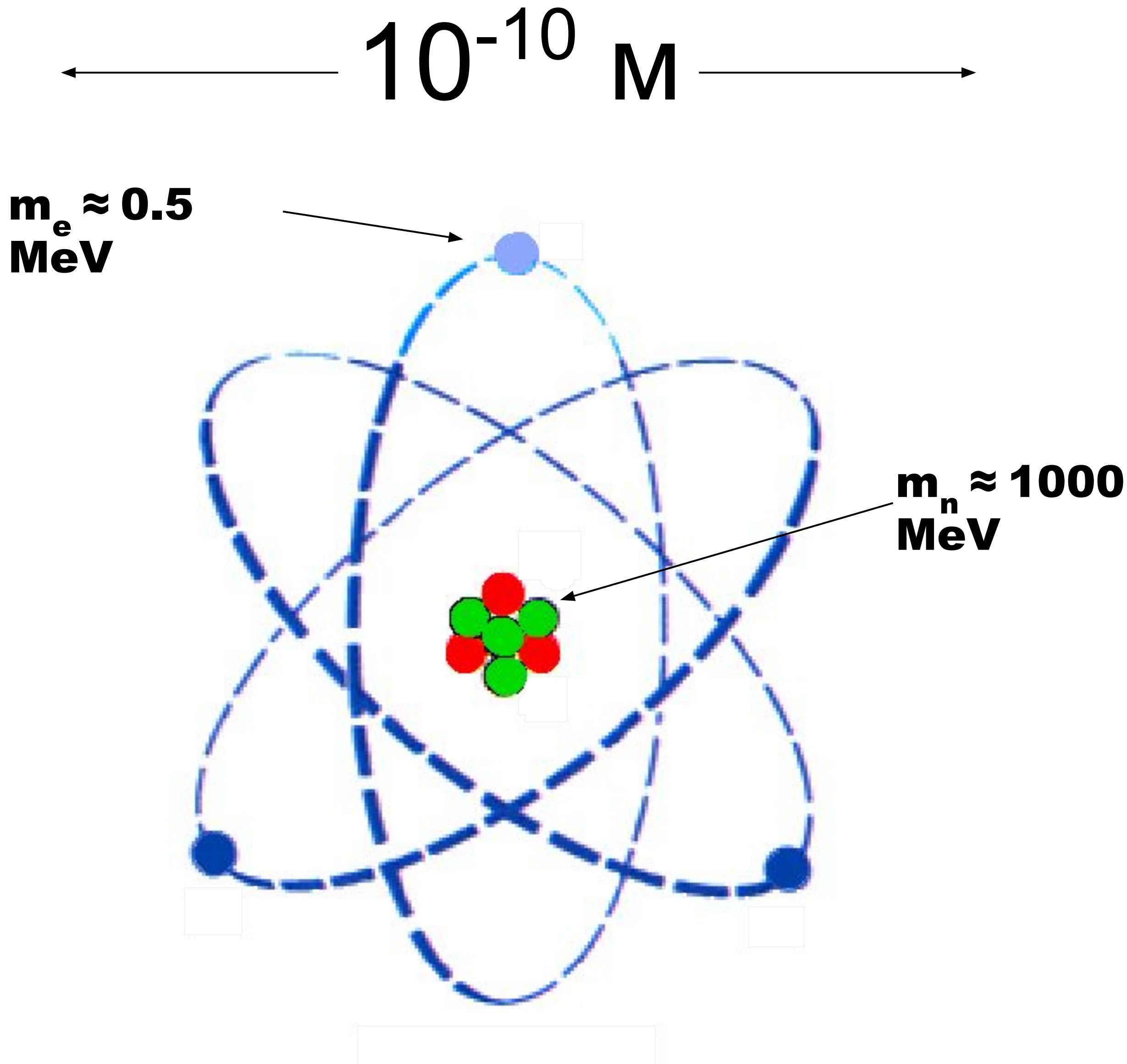
$$V(r_1, r_2, r_3) \neq V(r_1 - r_2) + V(r_2 - r_3) + V(r_3 - r_1)$$

1 м

Происхождение массы

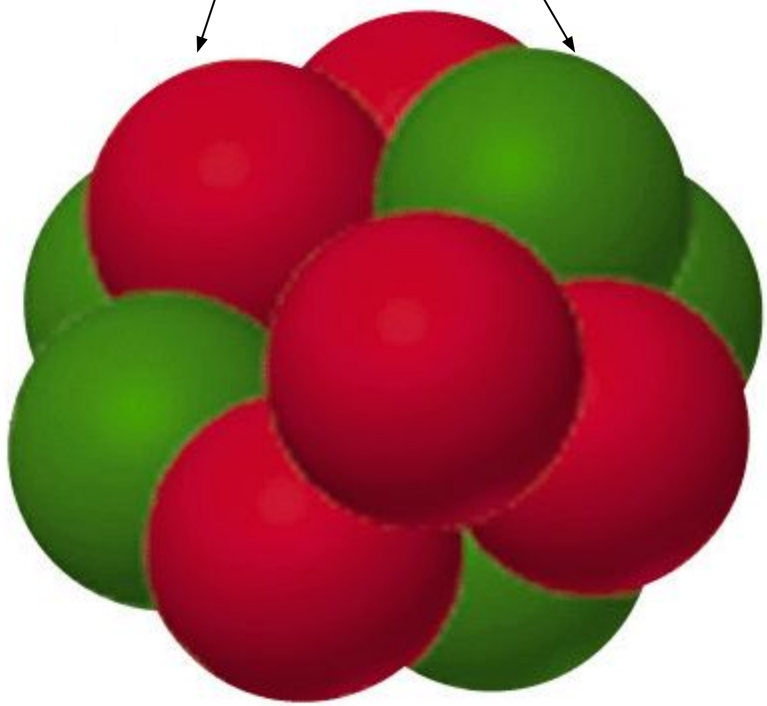
$10^{-8..10}$ м

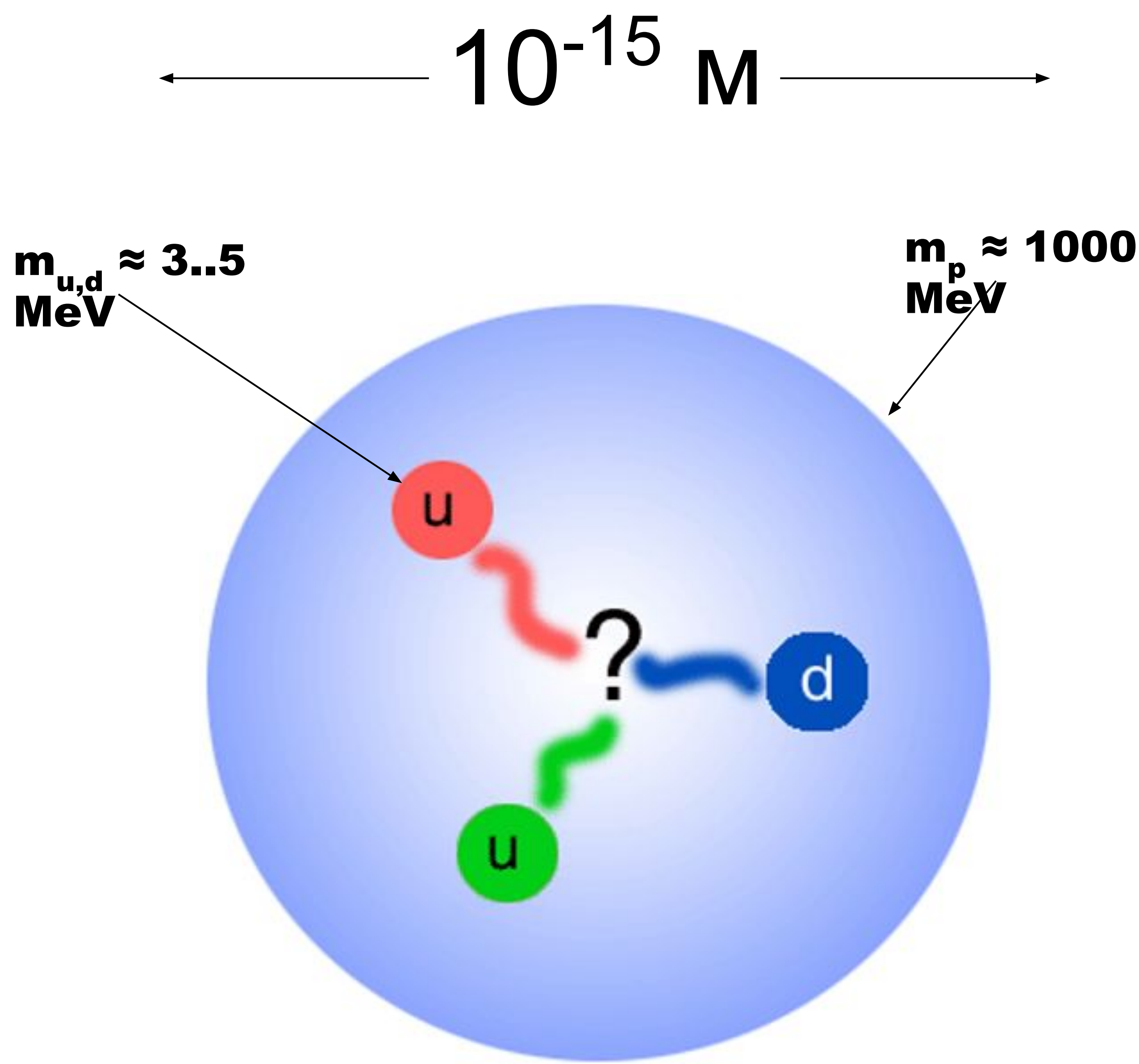



10^{-10} M
$m_e \approx 0.5$ MeV
$m_n \approx 1000$ MeV

$10^{-14..15}$ м

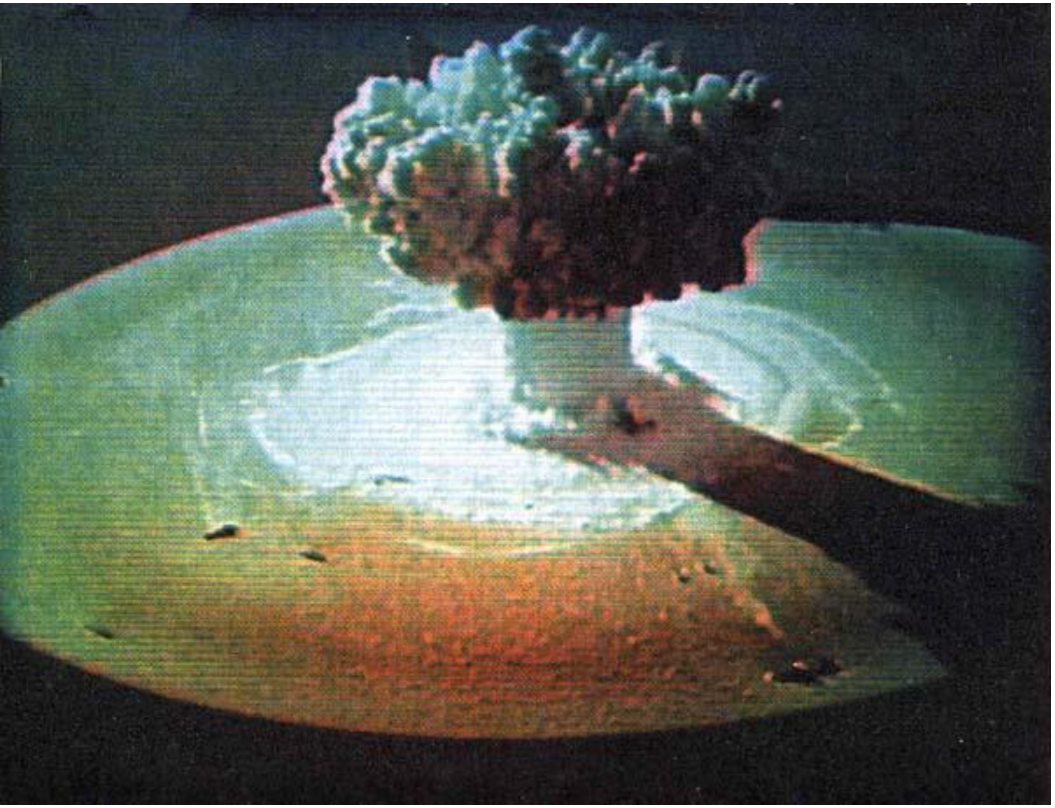
$m_p \approx m_n$

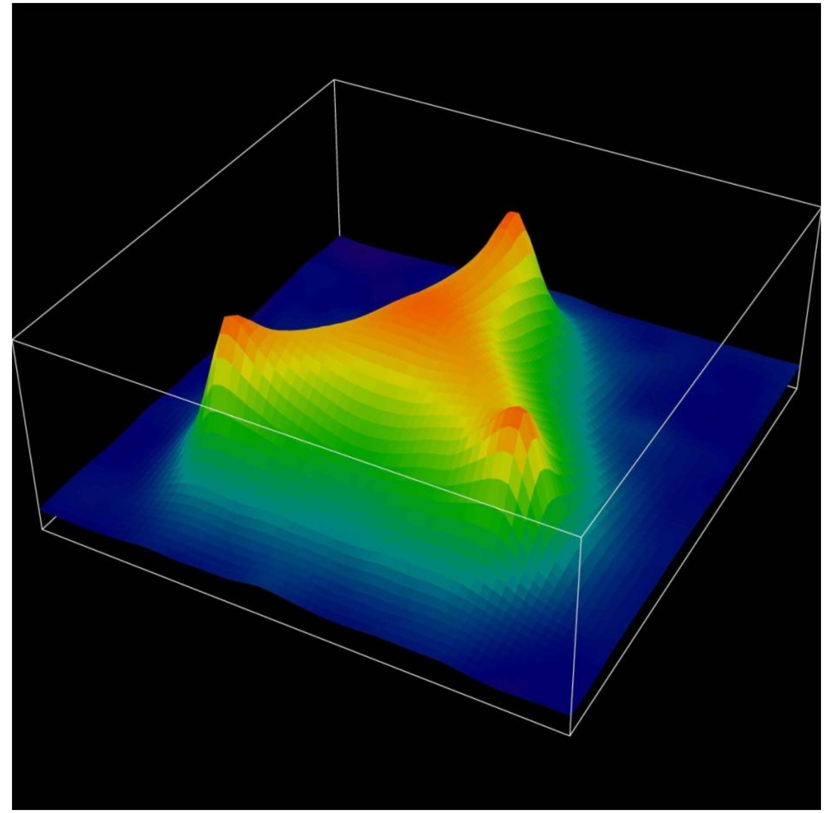




10-15 M
mu,d ≈ 3..5 MeV
mp ≈ 1000 MeV
u
?
d
u

Masses of material objects is due to gluon fields inside baryon





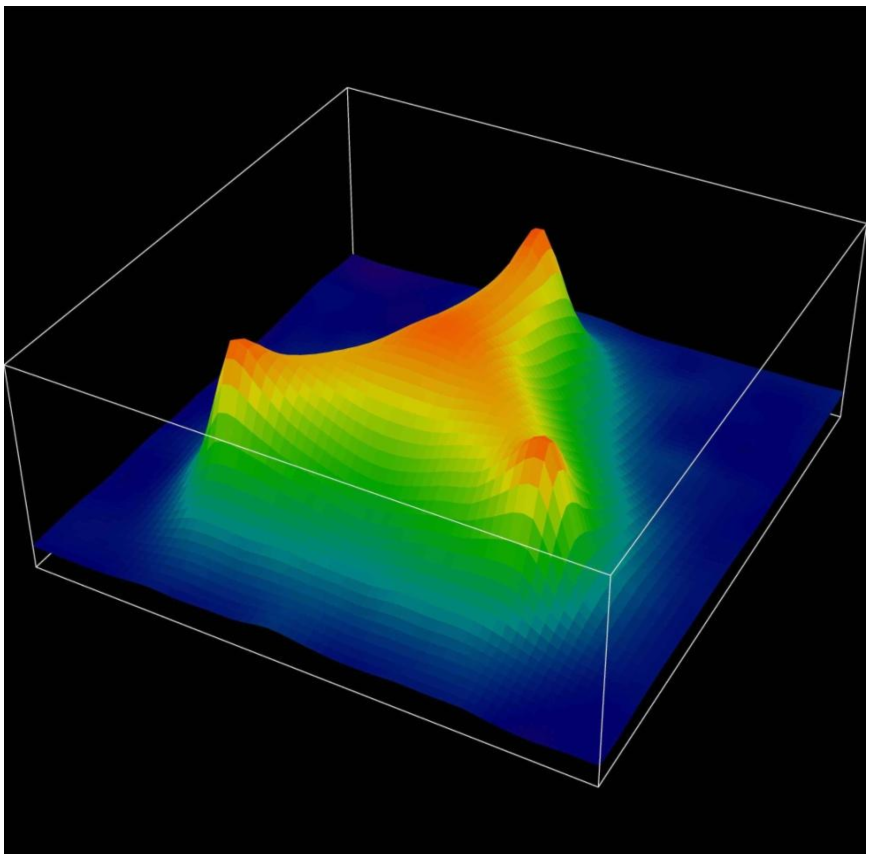
$$E = m_0 c^2$$

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

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

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

Three body forces!



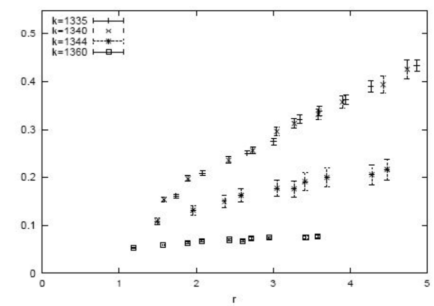


Figure 9: The monopole part of the baryon potential at finite temperature in full QCD as a function of L_Y ($T < T_c$) and L_Δ ($T > T_c$), respectively, in units of *God knows what.*

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

$$T \propto \exp(-2.81/\kappa)\,. \tag{4.1}$$

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

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

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

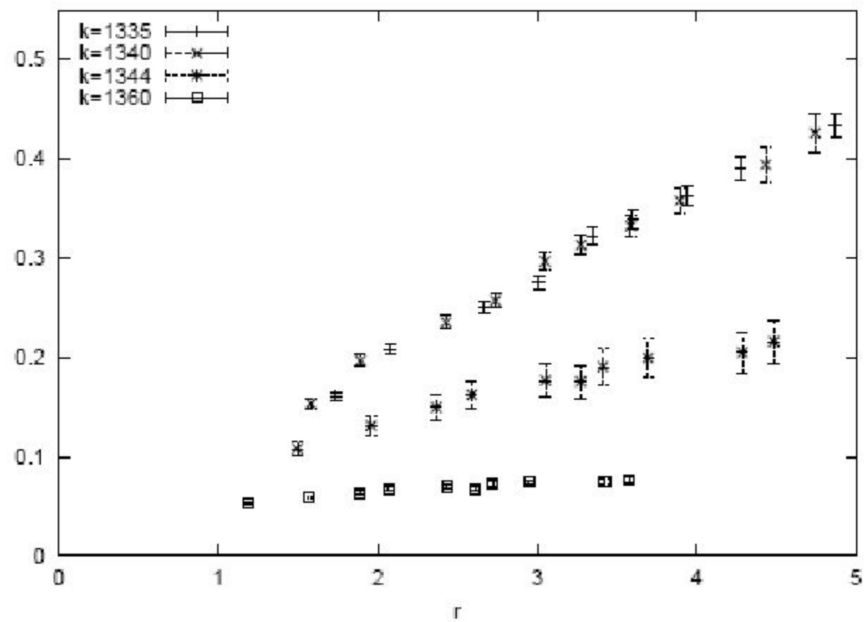
$$k^{3Q}({}^*s,\mu) \longrightarrow \frac{1}{2}\{k^{3Q}({}^*s,\mu) + k^{3Q}({}^*(s-\hat{z}),\mu)\}\,, \tag{4.4}$$

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.

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

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

arXiv:hep-lat/0401026v1 arXiv:hep-lat/0401026v2



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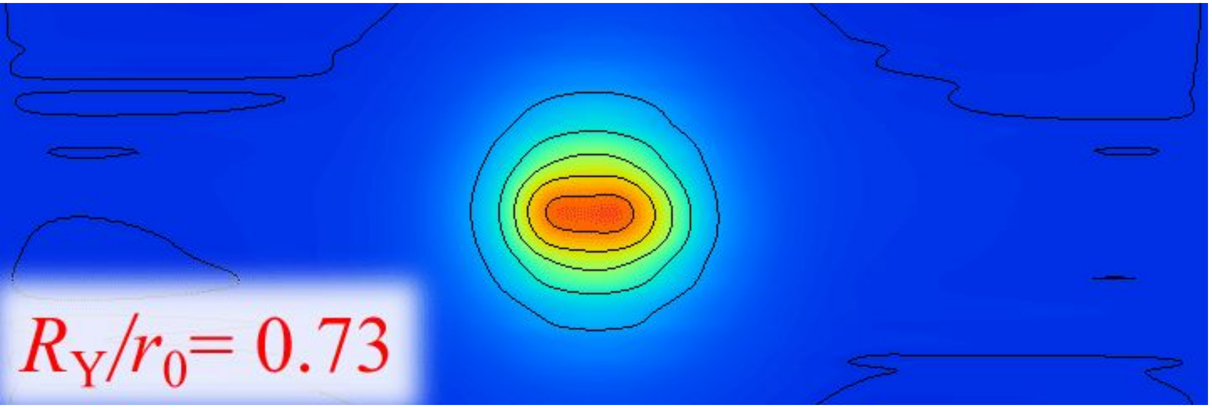
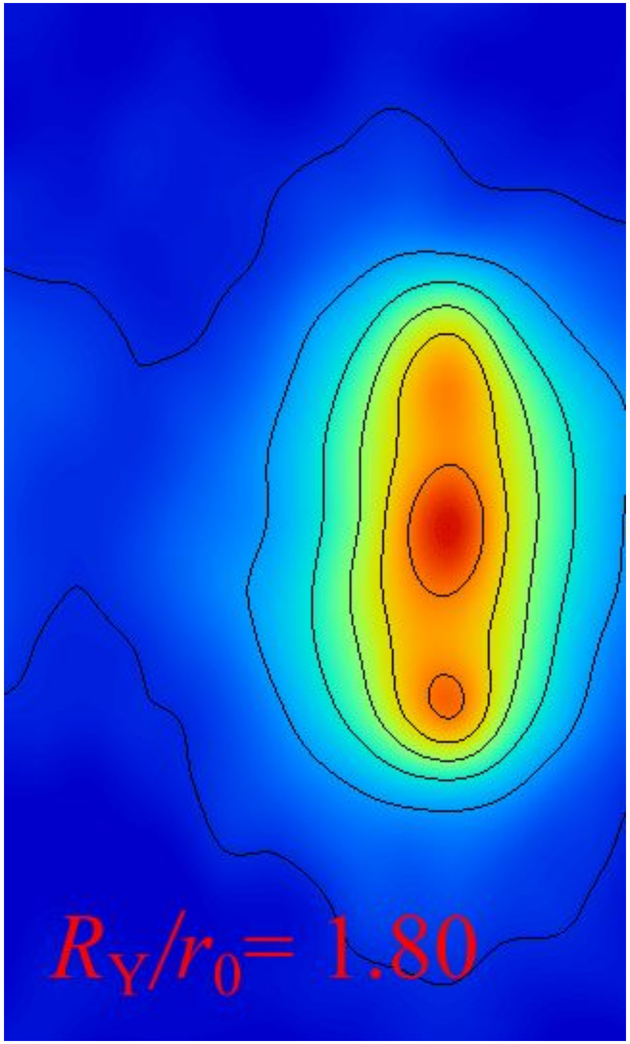
In Fig. 9 we show the baryon potential on the $16^3\,8$ lattice at $\beta = 5.2$ for several values of κ. At this β value

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

String Breaking (DIK collaboration)





Hadron Mass Spectrum

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

Meson Summary Table

See also the table of suggested $q\bar{q}$ quark-model assignments in the Quark Model section.

• Indicates particles that appear in the preceding Meson Summary Table. We do not regard the other entries as being established.
† Indicates that the value of J given is preferred, but needs confirmation.

LIGHT UNFLAVORED ($S = C = B = 0$)

	$I^G(J^{PC})$		$I^G(J^{PC})$
• $\pi^\pm$	$1^-(0^-)$	• $\pi_2(1670)$	$1^-(2^{-+})$
• π^0	$1^-(0^{-+})$	• $\phi(1680)$	$0^-(1^{--})$
• η	$0^+(0^{-+})$	• $\rho_3(1690)$	$1^+(3^{--})$
• $f_0(600)$	$0^+(0^{++})$	• $\rho(1700)$	$1^+(1^{--})$
• $\rho(770)$	$1^+(1^{--})$	$a_2(1700)$	$1^-(2^{++})$
• $\omega(782)$	$0^-(1^{--})$	• $f_0(1710)$	$0^+(0^{++})$
• $\eta'(958)$	$0^+(0^{-+})$	$\eta(1760)$	$0^+(0^{-+})$
• $f_0(980)$	$0^+(0^{++})$	• $\pi(1800)$	$1^-(0^{-+})$
• $a_0(980)$	$1^-(0^{++})$	$f_2(1810)$	$0^+(2^{++})$
• $\phi(1020)$	$0^-(1^{--})$	$X(1835)$	$?^?(?^{-+})$
• $h_1(1170)$	$0^-(1^{+-})$	• $\phi_3(1850)$	$0^-(3^{--})$
• $b_1(1235)$	$1^+(1^{+-})$	$\eta_2(1870)$	$0^+(2^{-+})$
• $a_1(1260)$	$1^-(1^{++})$	$\rho(1900)$	$1^+(1^{--})$
• $f_2(1270)$	$0^+(2^{++})$	$f_2(1910)$	$0^+(2^{++})$
• $f_1(1285)$	$0^+(1^{++})$	• $f_2(1950)$	$0^+(2^{++})$
• $\eta(1295)$	$0^+(0^{-+})$	$\rho_3(1990)$	$1^+(3^{--})$
• $\pi(1300)$	$1^-(0^{-+})$	• $f_2(2010)$	$0^+(2^{++})$
• $a_2(1320)$	$1^-(2^{++})$	$f_0(2020)$	$0^+(0^{++})$
• $f_0(1370)$	$0^+(0^{++})$	• $a_4(2040)$	$1^-(4^{++})$
$h_1(1380)$	$?^-(1^{+-})$	• $f_4(2050)$	$0^+(4^{++})$
• $\pi_1(1400)$	$1^-(1^{-+})$	$\pi_2(2100)$	$1^-(2^{-+})$
• $\eta(1405)$	$0^+(0^{-+})$	$f_0(2100)$	$0^+(0^{++})$
• $f_1(1420)$	$0^+(1^{++})$	$f_2(2150)$	$0^+(2^{++})$
• $\omega(1420)$	$0^-(1^{--})$	$\rho(2150)$	$1^+(1^{--})$
$f_2(1430)$	$0^+(2^{++})$	$f_0(2200)$	$0^+(0^{++})$
• $a_0(1450)$	$1^-(0^{++})$	$f_J(2220)$	$0^+(2 \text{ or } 4^{++})$
• $\rho(1450)$	$1^+(1^{--})$	$\eta(2225)$	$0^+(0^{-+})$
• $\eta(1475)$	$0^+(0^{-+})$	$\rho_3(2250)$	$1^+(3^{--})$
• $f_0(1500)$	$0^+(0^{++})$	• $f_2(2300)$	$0^+(2^{++})$
$f_1(1510)$	$0^+(1^{++})$	$f_4(2300)$	$0^+(4^{++})$
• $f_2'(1525)$	$0^+(2^{++})$	• $f_2(2340)$	$0^+(2^{++})$
$f_2(1565)$	$0^+(2^{++})$	$\rho_5(2350)$	$1^+(5^{--})$
$h_1(1595)$	$0^-(1^{+-})$	$a_6(2450)$	$1^-(6^{++})$
• $\pi_1(1600)$	$1^-(1^{-+})$	$f_6(2510)$	$0^+(6^{++})$
$a_1(1640)$	$1^-(1^{++})$	**OTHER LIGHT**	
$f_2(1640)$	$0^+(2^{++})$	Further States	
• $\eta_2(1645)$	$0^+(2^{-+})$		
• $\omega(1650)$	$0^-(1^{--})$		
• $\omega_3(1670)$	$0^-(3^{--})$		

STRANGE ($S = \pm1$, $C = B = 0$)

	$I(J^P)$
• $K^\pm$	$1/2(0^-)$
• K^0	$1/2(0^-)$
• K^0_S	$1/2(0^-)$
• K^0_L	$1/2(0^-)$
$K^*_0(800)$	$1/2(0^+)$
• $K^*(892)$	$1/2(1^-)$
• $K_1(1270)$	$1/2(1^+)$
• $K_1(1400)$	$1/2(1^+)$
• $K^*(1410)$	$1/2(1^-)$
• $K^*_0(1430)$	$1/2(0^+)$
• $K^*_2(1430)$	$1/2(2^+)$
$K(1460)$	$1/2(0^-)$
$K_2(1580)$	$1/2(2^-)$
$K(1630)$	$1/2(?^?)$
$K_1(1650)$	$1/2(1^+)$
• $K^*(1680)$	$1/2(1^-)$
• $K_2(1770)$	$1/2(2^-)$
• $K^*_3(1780)$	$1/2(3^-)$
• $K_2(1820)$	$1/2(2^-)$
$K(1830)$	$1/2(0^-)$
$K^*_0(1950)$	$1/2(0^+)$
$K^*_2(1980)$	$1/2(2^+)$
• $K^*_4(2045)$	$1/2(4^+)$
$K_2(2250)$	$1/2(2^-)$
$K_3(2320)$	$1/2(3^+)$
$K^*_5(2380)$	$1/2(5^-)$
$K_4(2500)$	$1/2(4^-)$
$K(3100)$	$?^?(?^{??})$

CHARMED ($C = \pm1$)

• $D^\pm$	$1/2(0^-)$
• D^0	$1/2(0^-)$
• $D^*(2007)^0$	$1/2(1^-)$
• $D^*(2010)^\pm$	$1/2(1^-)$
$D^*_0(2400)^0$	$1/2(0^+)$
$D^*_0(2400)^\pm$	$1/2(0^+)$
• $D_1(2420)^0$	$1/2(1^+)$
$D_1(2420)^\pm$	$1/2(?^?)$
$D_1(2430)^0$	$1/2(1^+)$
• $D^*_2(2460)^0$	$1/2(2^+)$
• $D^*_2(2460)^\pm$	$1/2(2^+)$
$D^*(2640)^\pm$	$1/2(?^?)$

CHARMED, STRANGE ($C = S = \pm1$)

• $D_s^\pm$	$0(0^-)$
• $D_s^{*\pm}$	$0(?^?)$
• $D^*_{s0}(2317)^\pm$	$0(0^+)$
• $D_{s1}(2460)^\pm$	$0(1^+)$
• $D_{s1}(2536)^\pm$	$0(1^+)$
• $D_{s2}(2573)^\pm$	$0(?^?)$

BOTTOM ($B = \pm1$)

	$I^G(J^{PC})$
• $B^\pm$	$1/2(0^-)$
• B^0	$1/2(0^-)$
• $B^\pm/B^0$ ADMIXTURE	
• $B^\pm/B^0/B^0_s/b$-baryon ADMIXTURE	
V_{cb} and V_{ub} CKM Matrix Elements	
• B^*	$1/2(1^-)$
$B^*_J(5732)$	$?(?^?)$

BOTTOM, STRANGE ($B = \pm1$, $S = \mp1$)

• B^0_s	$0(0^-)$
B^*_s	$0(1^-)$
$B^*_{sJ}(5850)$	$?(?^?)$

BOTTOM, CHARMED ($B = C = \pm1$)

• $B_c^\pm$	$0(0^-)$

$c\bar{c}$

• $\eta_c(1S)$	$0^+(0^{-+})$
• $J/\psi(1S)$	$0^-(1^{--})$
• $\chi_{c0}(1P)$	$0^+(0^{++})$
• $\chi_{c1}(1P)$	$0^+(1^{++})$
$h_c(1P)$	$?^?(?^{??})$
• $\chi_{c2}(1P)$	$0^+(2^{++})$
• $\eta_c(2S)$	$0^+(0^{-+})$
• $\psi(2S)$	$0^-(1^{--})$
• $\psi(3770)$	$0^-(1^{--})$
• $X(3872)$	$0^?(?^{?+})$
• $\chi_{c2}(2P)$	$0^+(2^{++})$
$Y(3940)$	$?^?(?^{??})$
• $\psi(4040)$	$0^-(1^{--})$
• $\psi(4160)$	$0^-(1^{--})$
$Y(4260)$	$?^?(1^{--})$
• $\psi(4415)$	$0^-(1^{--})$

$b\bar{b}$

$\eta_b(1S)$	$0^+(0^{-+})$
• $\Upsilon(1S)$	$0^-(1^{--})$
• $\chi_{b0}(1P)$	$0^+(0^{++})$
• $\chi_{b1}(1P)$	$0^+(1^{++})$
• $\chi_{b2}(1P)$	$0^+(2^{++})$
• $\Upsilon(2S)$	$0^-(1^{--})$
$\Upsilon(1D)$	$0^-(2^{--})$
• $\chi_{b0}(2P)$	$0^+(0^{++})$
• $\chi_{b1}(2P)$	$0^+(1^{++})$
• $\chi_{b2}(2P)$	$0^+(2^{++})$
• $\Upsilon(3S)$	$0^-(1^{--})$
• $\Upsilon(4S)$	$0^-(1^{--})$
• $\Upsilon(10860)$	$0^-(1^{--})$
• $\Upsilon(11020)$	$0^-(1^{--})$

NON-$q\bar{q}$ CANDIDATES

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Baryon Summary Table

This short table gives the name, the quantum numbers (where known), and the status of baryons in the Review. Only the baryons with 3- or 4-star status are included in the main Baryon Summary Table. Due to insufficient data or uncertain interpretation, the other entries in the short table are not established as baryons. The names with masses are of baryons that decay strongly. For N, Δ, and Ξ resonances, the partial wave is indicated by the symbol $L_{2I,2J}$, where L is the orbital angular momuntum (S, P, D, ...), I is the isospin, and J is the total angular momentum. For Λ and Σ resonances, the symbol is $L_{I,2J}$.

p	P_{11}	****	$\Delta(1232)$	P_{33}	****
n	P_{11}	****	$\Delta(1600)$	P_{33}	***
$N(1440)$	P_{11}	****	$\Delta(1620)$	S_{31}	****
$N(1520)$	D_{13}	****	$\Delta(1700)$	D_{33}	****
$N(1535)$	S_{11}	****	$\Delta(1750)$	P_{31}	*
$N(1650)$	S_{11}	****	$\Delta(1900)$	S_{31}	**
$N(1675)$	D_{15}	****	$\Delta(1905)$	F_{35}	****
$N(1680)$	F_{15}	****	$\Delta(1910)$	P_{31}	****
$N(1700)$	D_{13}	***	$\Delta(1920)$	P_{33}	***
$N(1710)$	P_{11}	***	$\Delta(1930)$	D_{35}	***
$N(1720)$	P_{13}	****	$\Delta(1940)$	D_{33}	*
$N(1900)$	P_{13}	**	$\Delta(1950)$	F_{37}	****
$N(1990)$	F_{17}	**	$\Delta(2000)$	F_{35}	**
$N(2000)$	F_{15}	**	$\Delta(2150)$	S_{31}	*
$N(2080)$	D_{13}	**	$\Delta(2200)$	G_{37}	*
$N(2090)$	S_{11}	*	$\Delta(2300)$	H_{39}	**
$N(2100)$	P_{11}	*	$\Delta(2350)$	D_{35}	*
$N(2190)$	G_{17}	****	$\Delta(2390)$	F_{37}	*
$N(2200)$	D_{15}	**	$\Delta(2400)$	G_{39}	**
$N(2220)$	H_{19}	****	$\Delta(2420)$	$H_{3,11}$	****
$N(2250)$	G_{19}	****	$\Delta(2750)$	$I_{3,13}$	**
$N(2600)$	$I_{1,11}$	***	$\Delta(2950)$	$K_{3,15}$	**
$N(2700)$	$K_{1,13}$	**			
			$\Theta(1540)^+$		*

Λ	P_{01}	****	Σ^+	P_{11}	****
$\Lambda(1405)$	S_{01}	****	Σ^0	P_{11}	****
$\Lambda(1520)$	D_{03}	****	Σ^-	P_{11}	****
$\Lambda(1600)$	P_{01}	***	$\Sigma(1385)$	P_{13}	****
$\Lambda(1670)$	S_{01}	****	$\Sigma(1480)$		*
$\Lambda(1690)$	D_{03}	****	$\Sigma(1560)$		**
$\Lambda(1800)$	S_{01}	***	$\Sigma(1580)$	D_{13}	*
$\Lambda(1810)$	P_{01}	***	$\Sigma(1620)$	S_{11}	**
$\Lambda(1820)$	F_{05}	****	$\Sigma(1660)$	P_{11}	***
$\Lambda(1830)$	D_{05}	****	$\Sigma(1670)$	D_{13}	****
$\Lambda(1890)$	P_{03}	****	$\Sigma(1690)$		**
$\Lambda(2000)$		*	$\Sigma(1750)$	S_{11}	***
$\Lambda(2020)$	F_{07}	*	$\Sigma(1770)$	P_{11}	*
$\Lambda(2100)$	G_{07}	****	$\Sigma(1775)$	D_{15}	****
$\Lambda(2110)$	F_{05}	***	$\Sigma(1840)$	P_{13}	*
$\Lambda(2325)$	D_{03}	*	$\Sigma(1880)$	P_{11}	**
$\Lambda(2350)$	H_{09}	***	$\Sigma(1915)$	F_{15}	****
$\Lambda(2585)$		**	$\Sigma(1940)$	D_{13}	***
			$\Sigma(2000)$	S_{11}	*
			$\Sigma(2030)$	F_{17}	****
			$\Sigma(2070)$	F_{15}	*
			$\Sigma(2080)$	P_{13}	**
			$\Sigma(2100)$	G_{17}	*
			$\Sigma(2250)$		***
			$\Sigma(2455)$		**
			$\Sigma(2620)$		**
			$\Sigma(3000)$		*
			$\Sigma(3170)$		*

Ξ^0	P_{11}	****
Ξ^-	P_{11}	****
$\Xi(1530)$	P_{13}	****
$\Xi(1620)$		*
$\Xi(1690)$		***
$\Xi(1820)$	D_{13}	***
$\Xi(1950)$		***
$\Xi(2030)$		***
$\Xi(2120)$		*
$\Xi(2250)$		**
$\Xi(2370)$		**
$\Xi(2500)$		*
Ω^-		****
$\Omega(2250)^-$		***
$\Omega(2380)^-$		**
$\Omega(2470)^-$		**
Λ_c^+		****
$\Lambda_c(2593)^+$		***
$\Lambda_c(2625)^+$		***
$\Lambda_c(2765)^+$		*
$\Lambda_c(2880)^+$		**
$\Sigma_c(2455)$		****
$\Sigma_c(2520)$		***
$\Sigma_c(2800)$		***
Ξ_c^+		***
Ξ_c^0		***
$\Xi_c'^+$		***
$\Xi_c'^0$		***
$\Xi_c(2645)$		***
$\Xi_c(2790)$		***
$\Xi_c(2815)$		***
Ω_c^0		***
Ξ_{cc}^+		*
Λ_b^0		***
Ξ_b^0, Ξ_b^-		*

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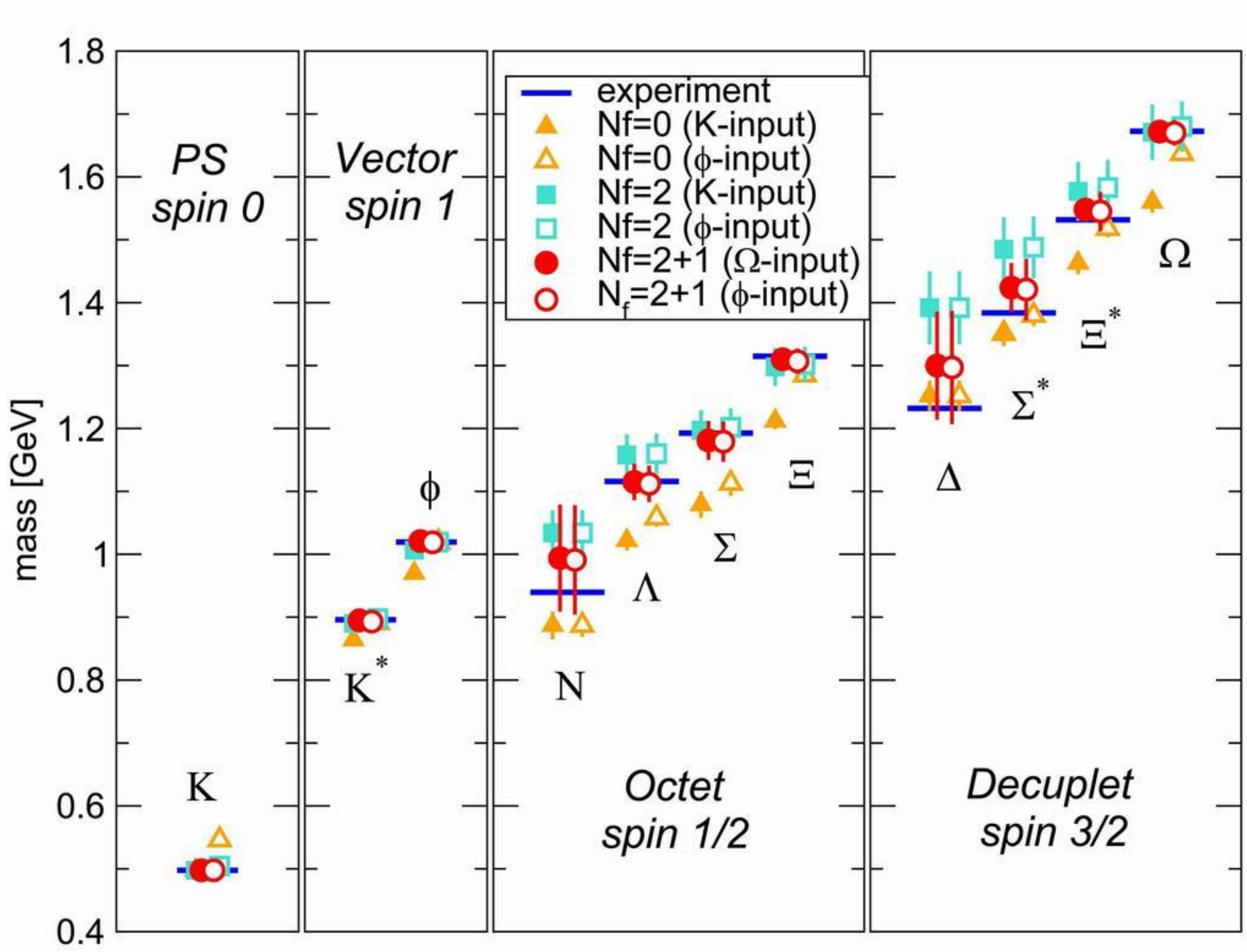
**** Existence is certain, and properties are at least fairly well explored.
*** Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, etc. are not well determined.
** Evidence of existence is only fair.
* Evidence of existence is poor.

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

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

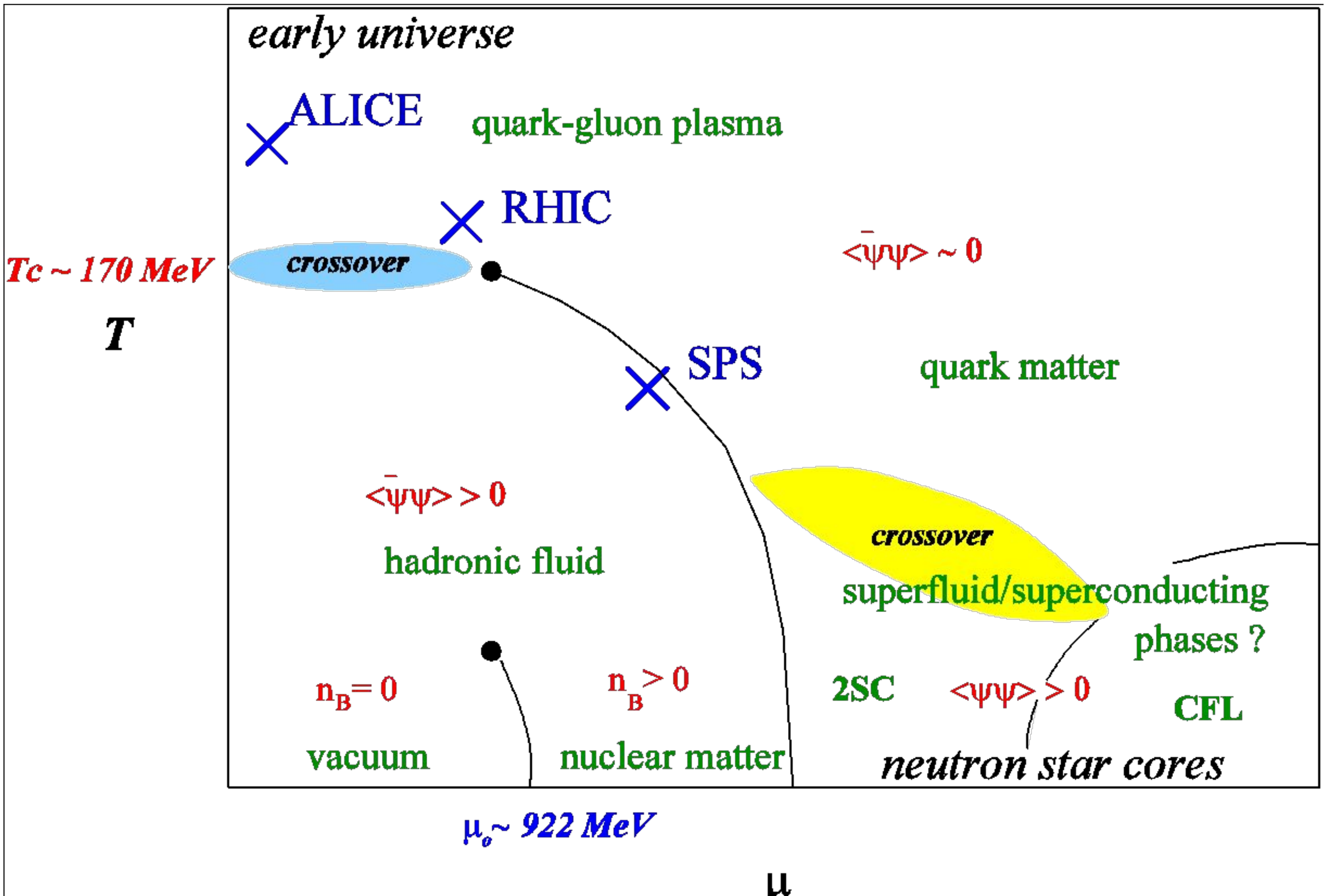
Y. Kuramashi Lattice 2007

Iwasaki gauge action +
clover quarks
a^(−1) = 2.2GeV,
lattice size: 32^3 × 64

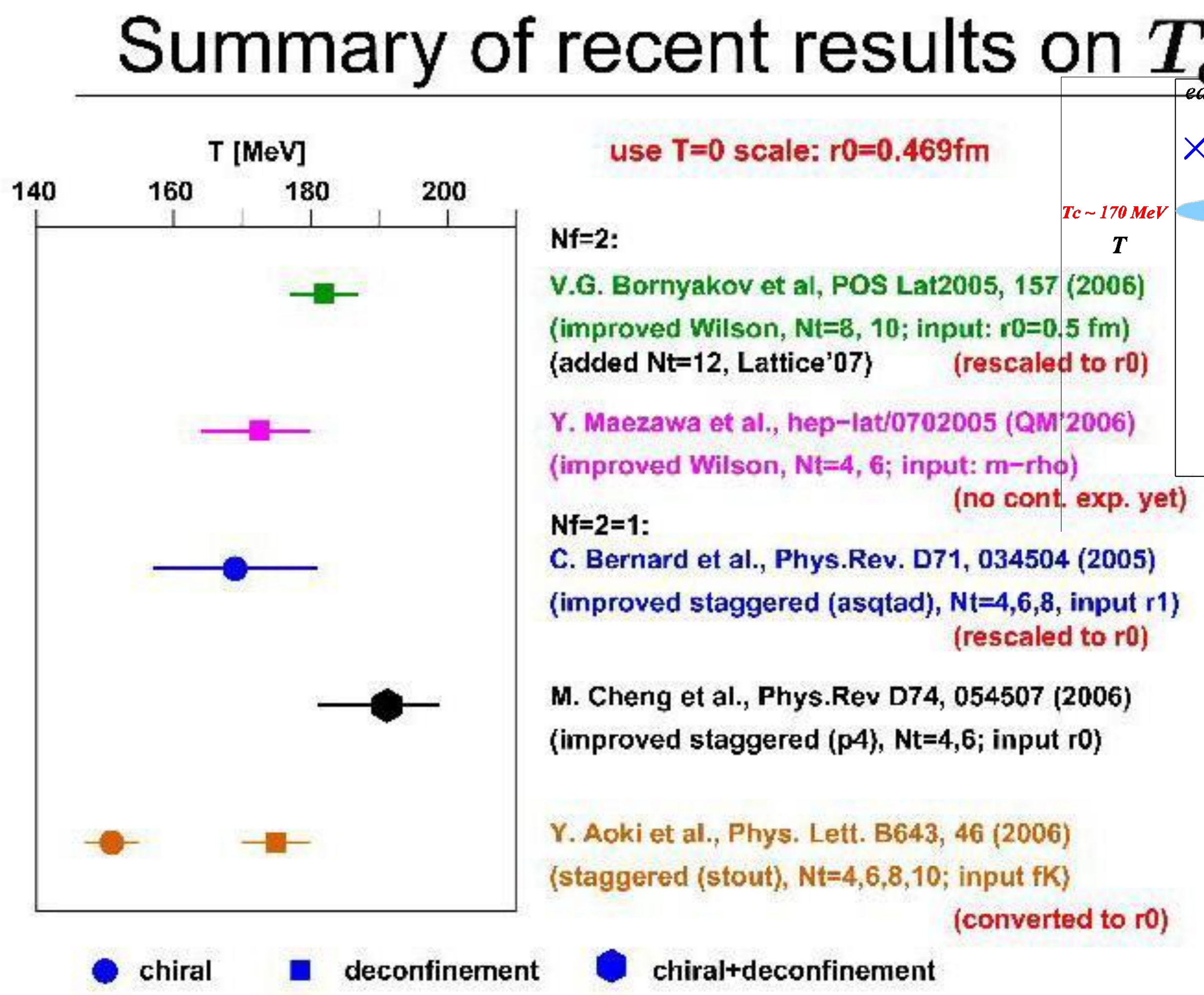


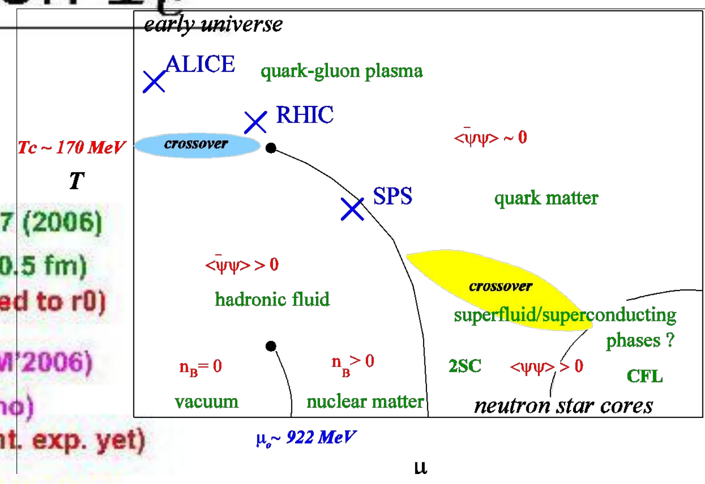
Finite Temperature

Фазовая Диаграмма КХД



Фазовая Диаграмма КХД





Моделирование К-Г плазмы в США

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

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 $N_\tau = 6$ 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 $m_l = 0.1 m_s$ 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_s 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 relativisitic 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 evoluton 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 [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.

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 $m_l = 0.1 m_s$, about a factor of two heavier than the mean physical u and d quark mass, $m_l \approx 0.038 m_s$. 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.

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

Моделирование К-Г плазмы в США

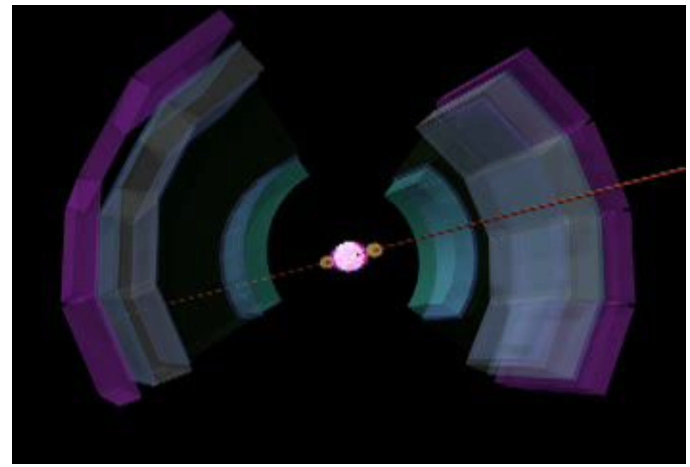
HotQCD is a US wide collaboration engaged in the study of QCD at finite temperature and density using lattice QCD [1]. It brought together members of the MILC and RBC-Bielefeld collaborations to carry out large scale simulations on IBM Bluegene/L supercomputers at the Lawrence Livermore National Lab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

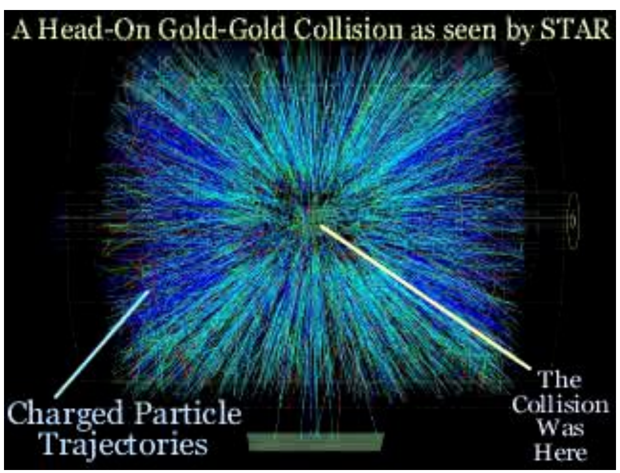
RHIC

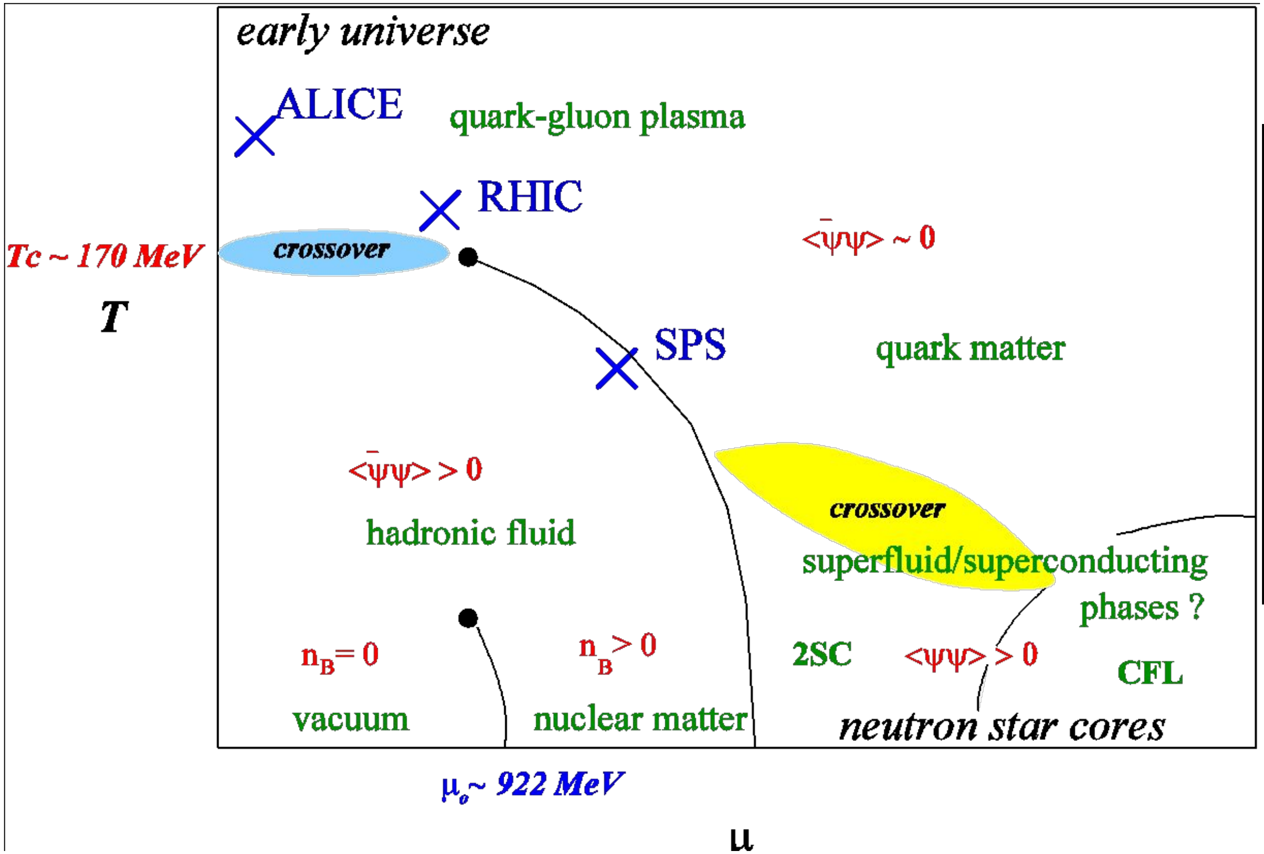
relativistic heavy ion collider

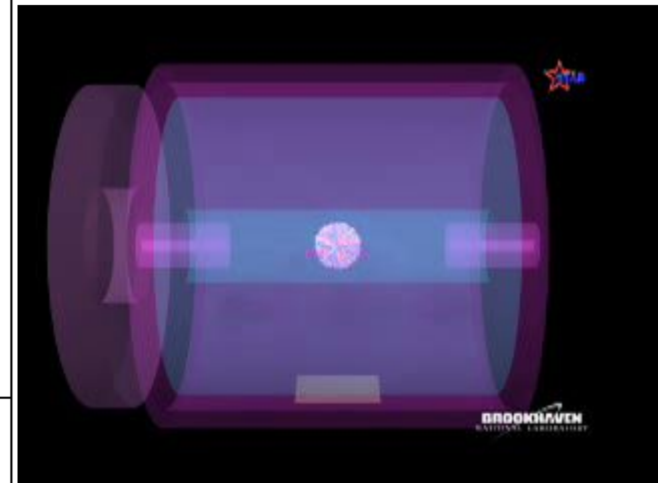
SU(2) glue SU(3) glue

2qQCD(2+1)QCD

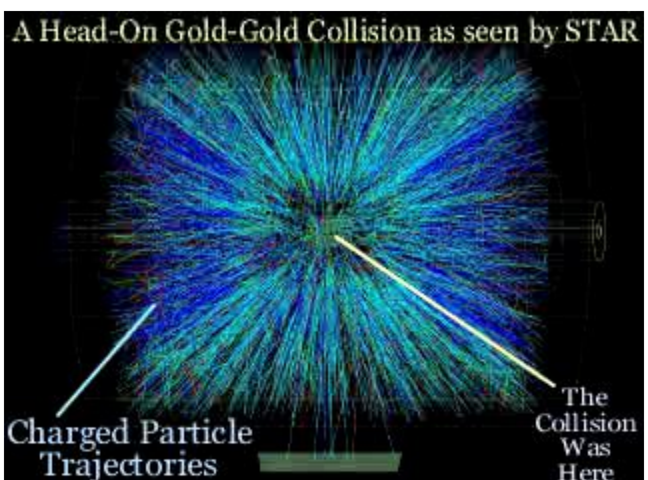





early universe
ALICE
quark-gluon plasma
RHIC
Tc ~ 170 MeV
T
crossover
$<\bar{\psi}\psi> \sim 0$
SPS
quark matter
$<\bar{\psi}\psi> > 0$
crossover
hadronic fluid
superfluid/superconducting
phases ?
$n_B = 0$
$n_B > 0$
2SC
$<\psi\psi> > 0$
CFL
vacuum
nuclear matter
neutron star cores
$\mu_o \sim 922$ MeV
μ

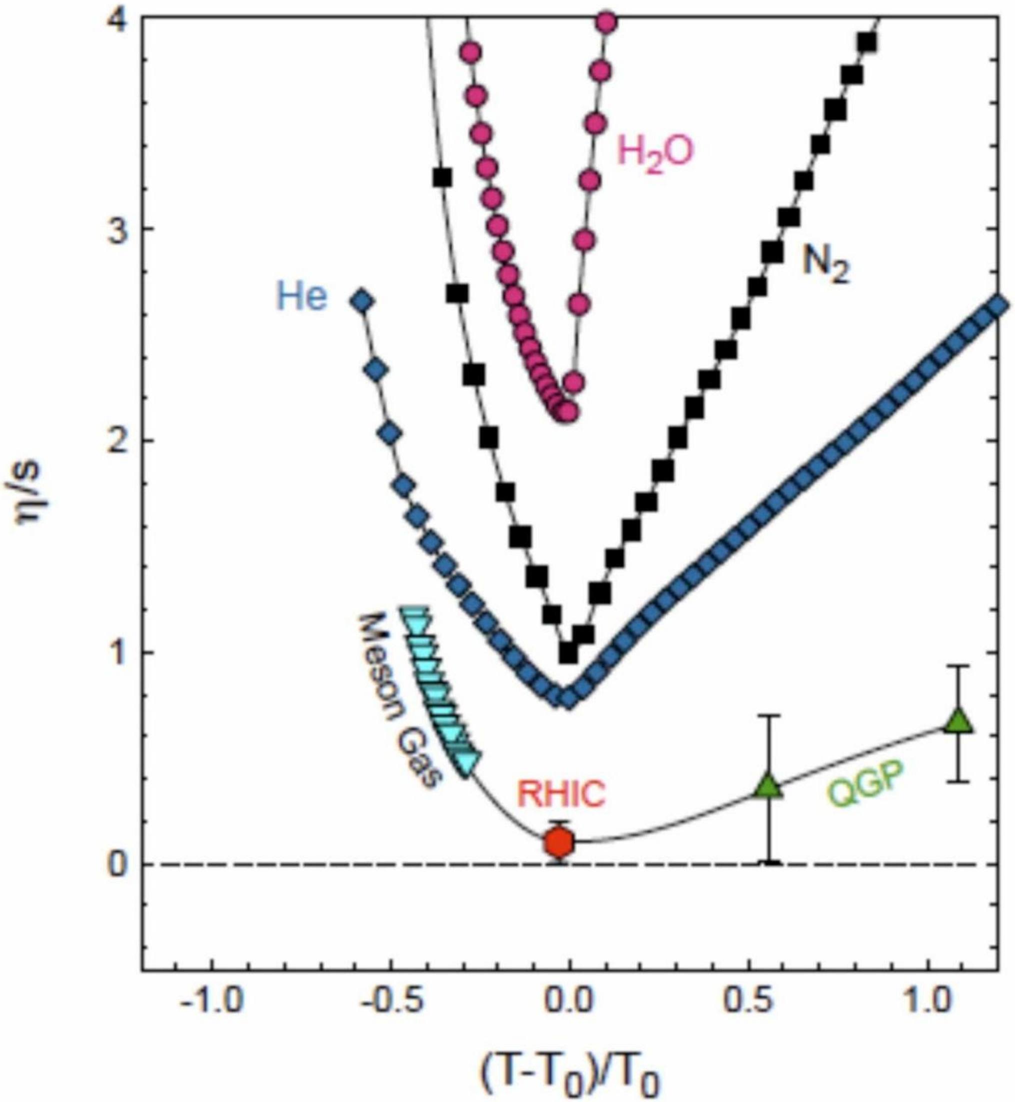

BROOKHAVEN

RHIC


A Head-On Gold-Gold Collision as seen by STAR
Charged Particle Trajectories
The Collision Was Here


RHIC Collisions

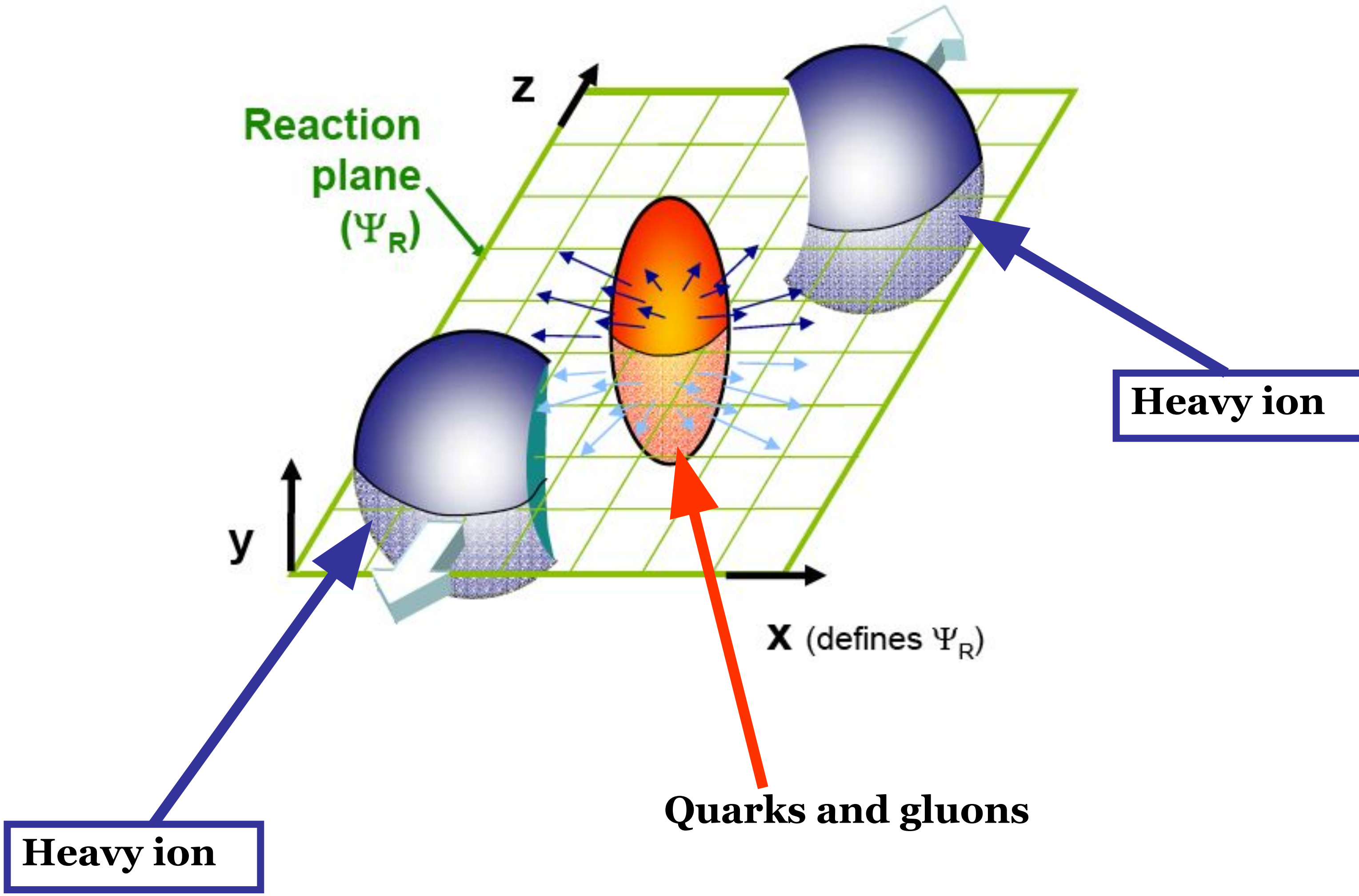
Вязкость К-Г плазмы чрезвычайно мала



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

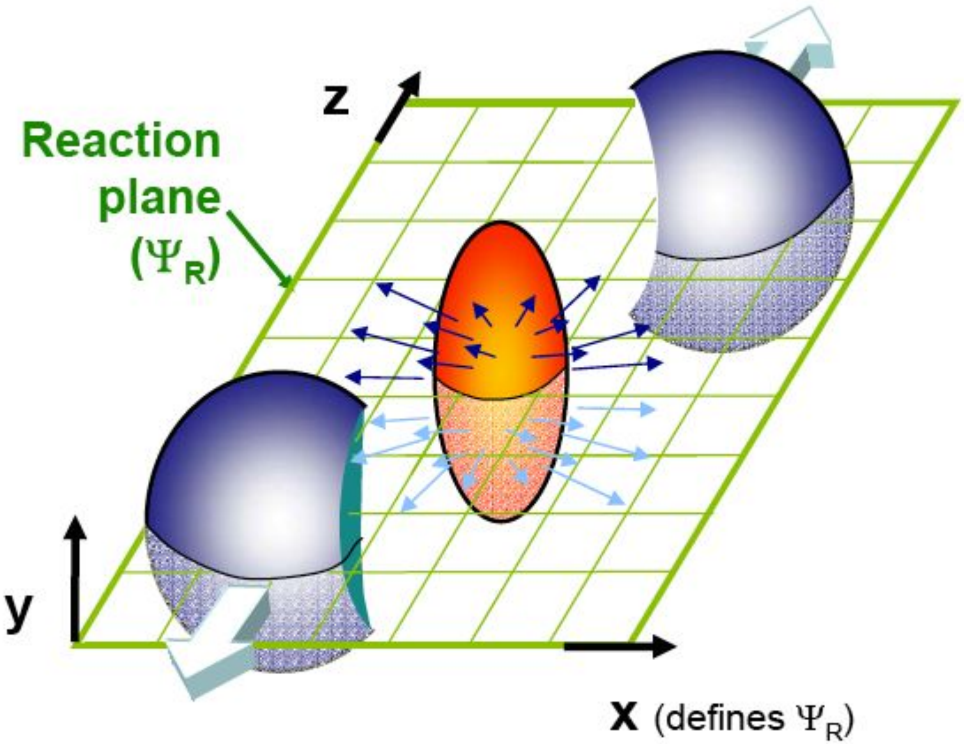
Magnetic fields in non-central collisions

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



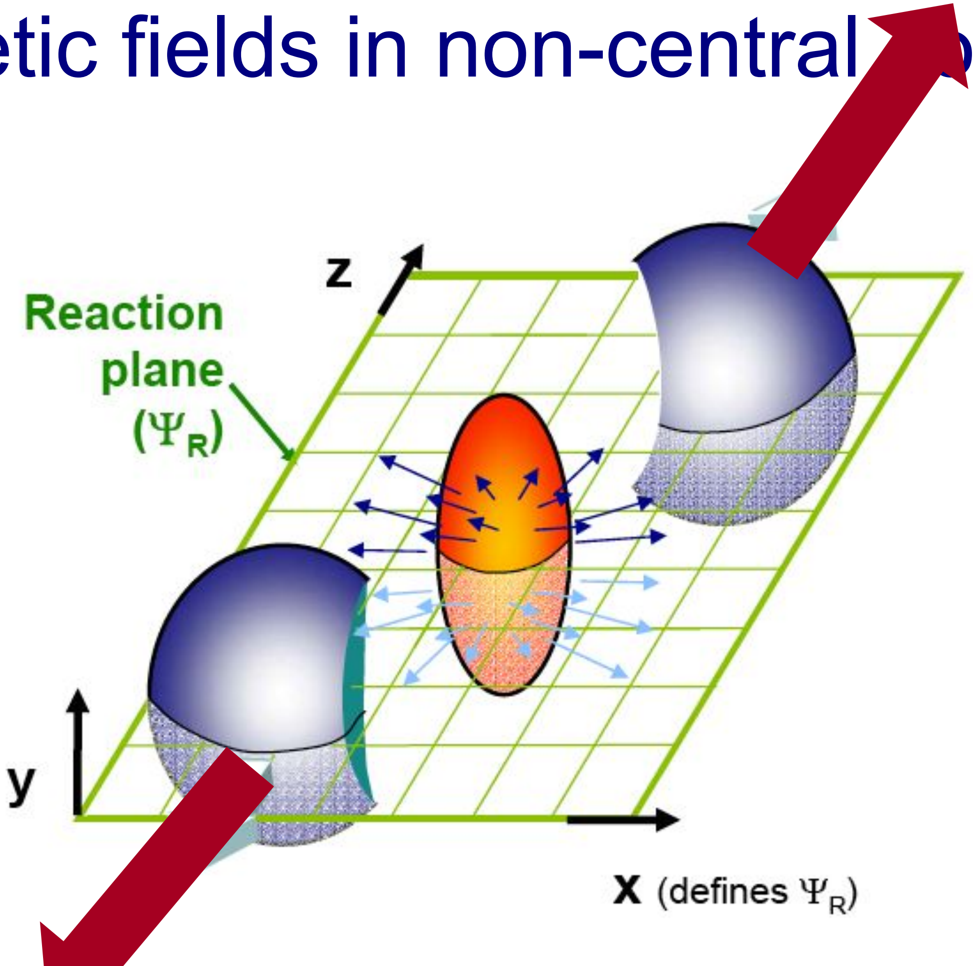
Magnetic fields in non-central collisions

[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



Charge is large
Velosity is high

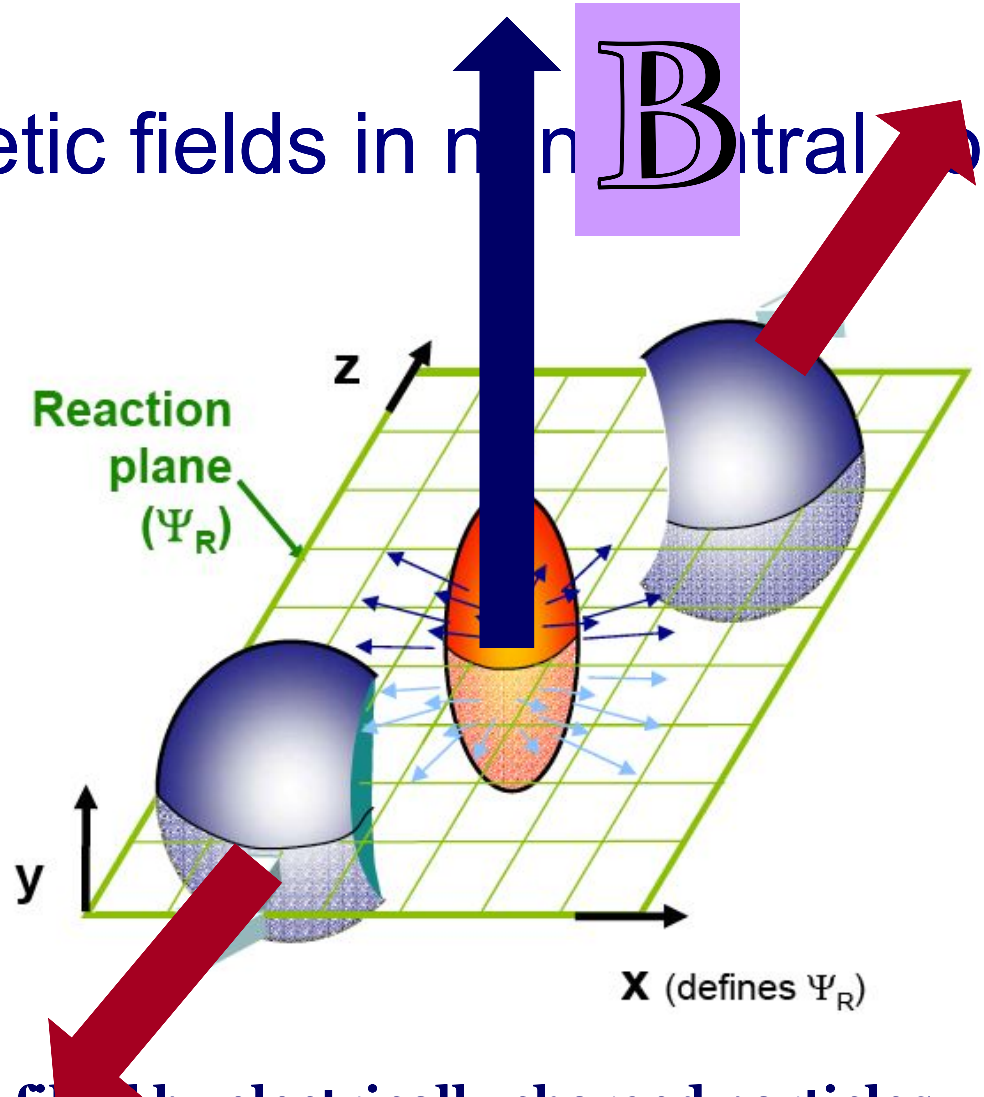
Thus we have two very big currents

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 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

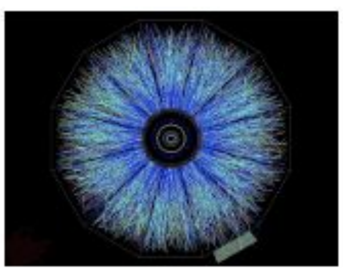
Large magnetic field along the direction of the orbital momentum

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

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

Magnetic forces are of the order of strong interaction forces

first time in my life I see such effect

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

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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

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

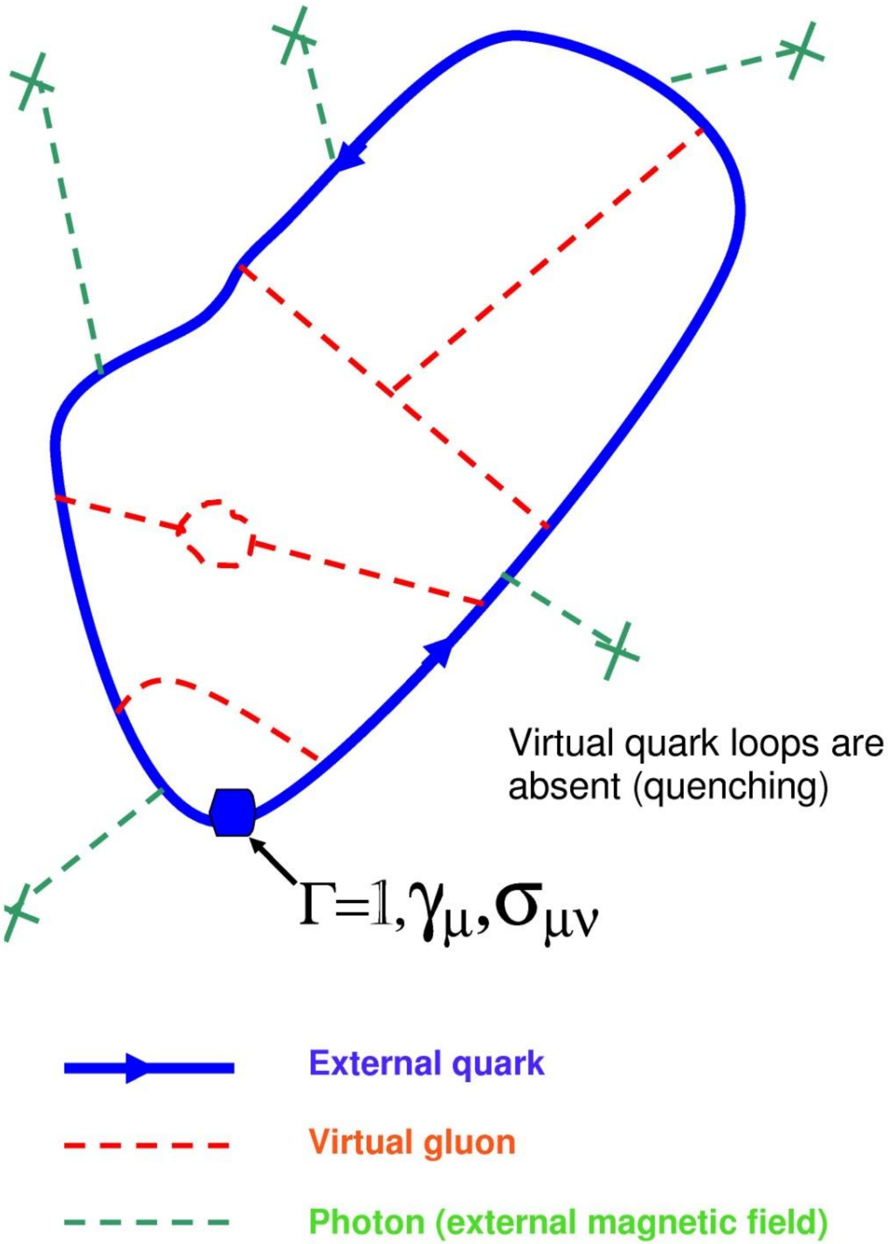
We expect the influence of magnetic field on strong interaction physics

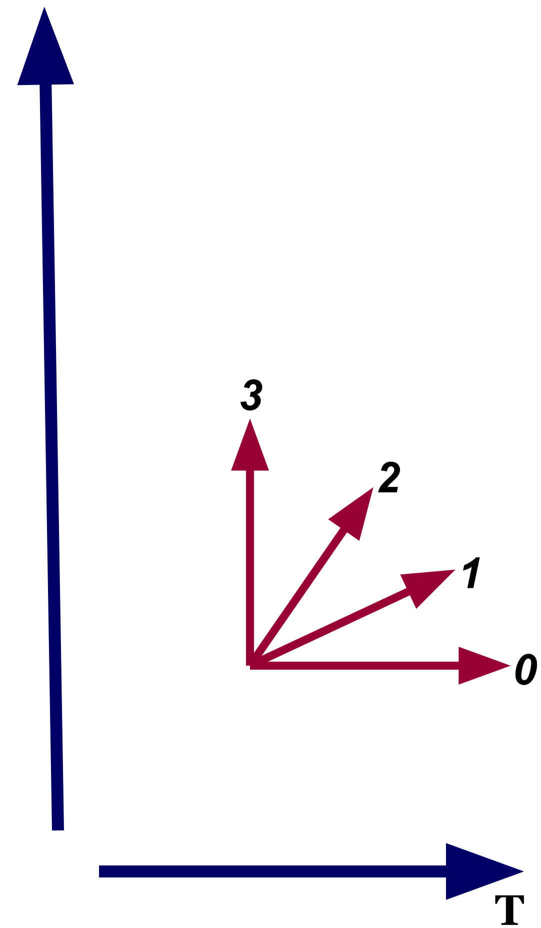
The effects are nonperturbative,
it is impossible to perform analytic calculations
and we use

Lattice Calculations

We calculate

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





Quenched vacuum, overlap Dirac operator, external magnetic field

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

Chiral Magnetic Effect

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

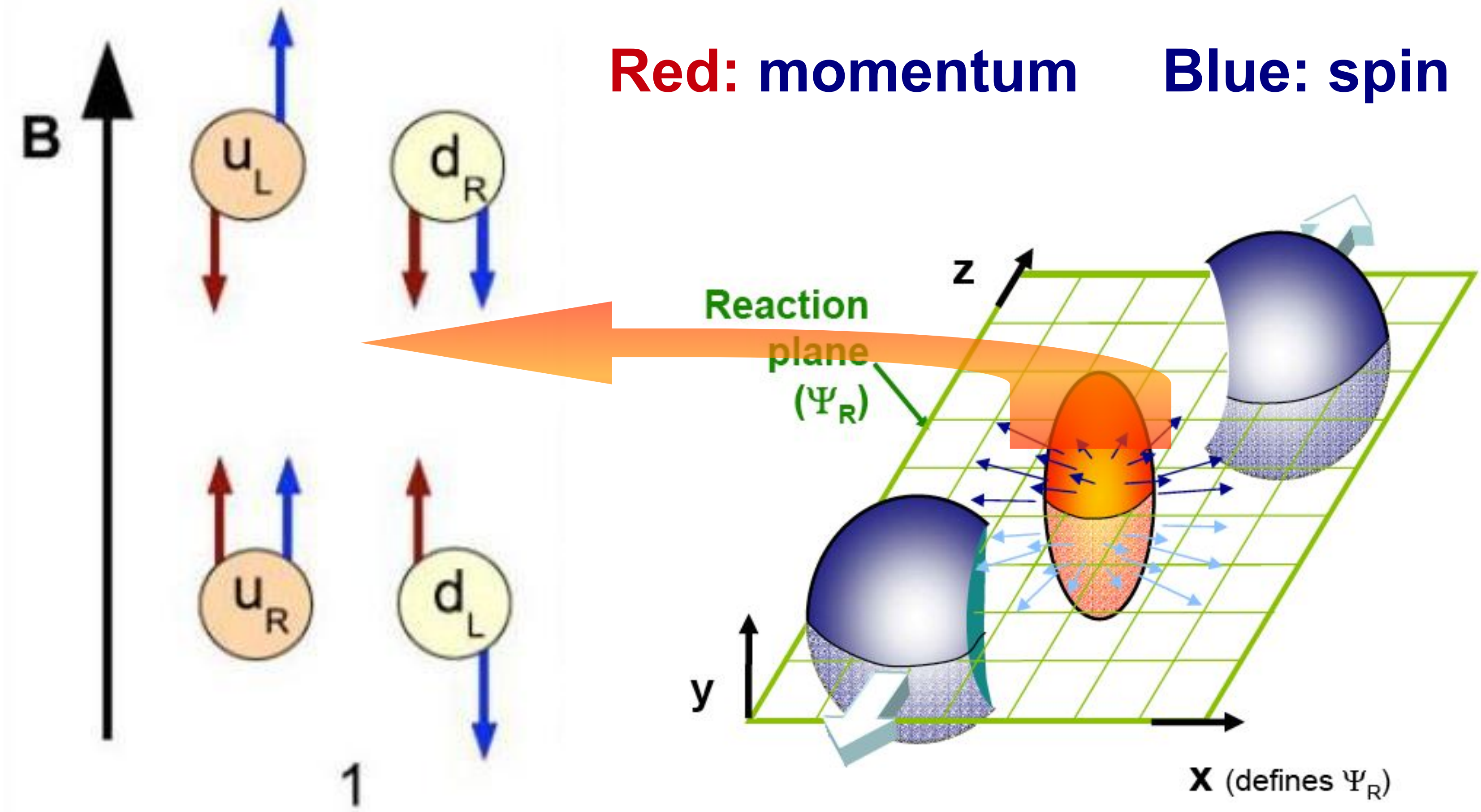
Electric current appears at regions
1. with non-zero topological charge density
2. exposed to external magnetic field

Experimentally observed at RHIC **:**
charge asymmetry of produced particles at heavy ion collisions

Chiral Magnetic Effect by
Fukushima, Kharzeev, Warringa, McLerran

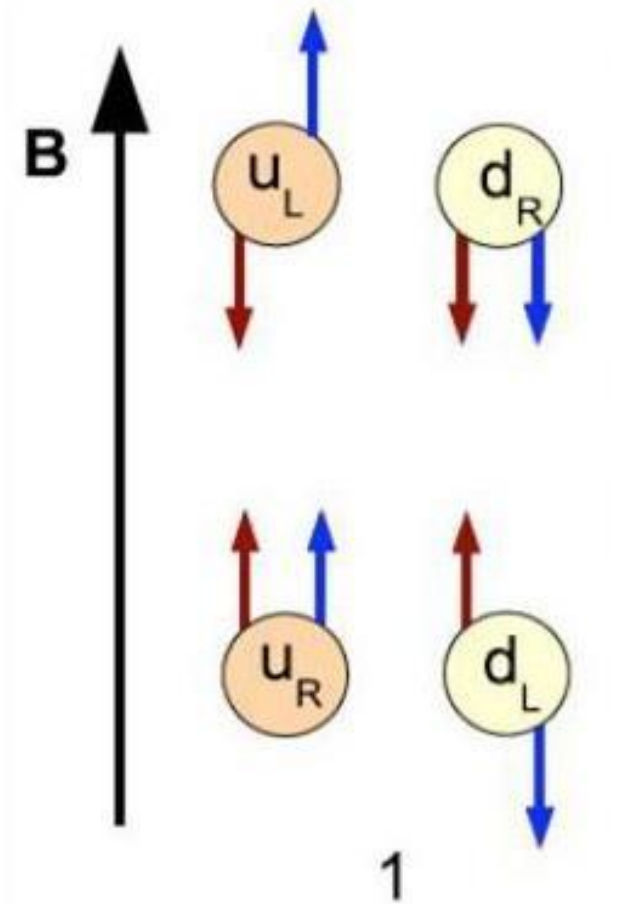
1. Massless quarks in external magnetic field.

Red: momentum **Blue: spin**



Chiral Magnetic Effect by
Fukushima, Kharzeev, Warringa, McLerran

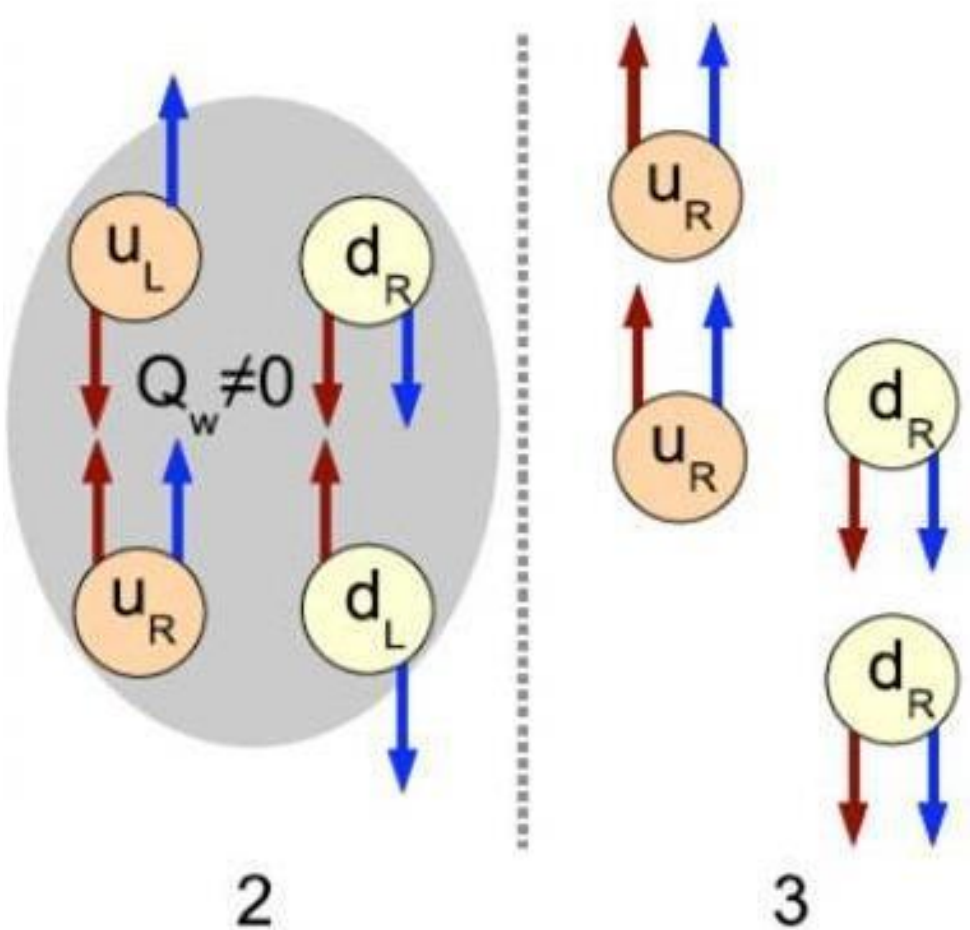
1. Massless quarks in external magnetic field.



Red: momentum　**Blue: spin**

Chiral Magnetic Effect by
Fukushima, Kharzeev, Warringa, McLerran

2. Quarks in the instatnton field.



Red: momentum
Blue: spin

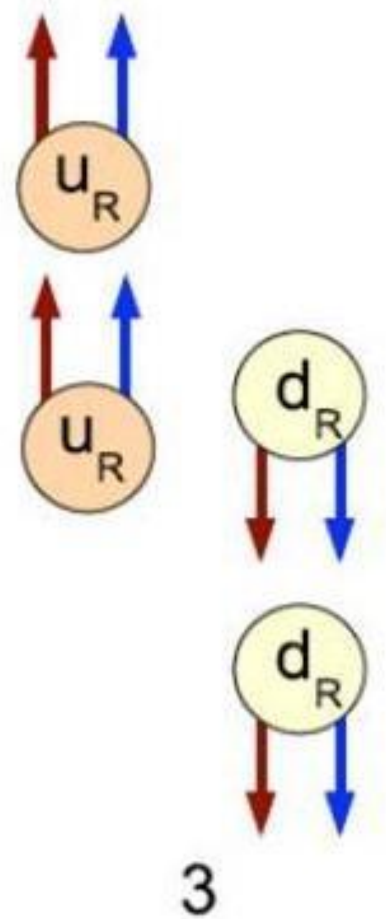
Effect of topology:

$u_L \rightarrow u_R$

$d_L \rightarrow d_R$

Chiral Magnetic Effect by **Fukushima, Kharzeev, Warringa, McLerran**

3. Electric current along magnetic field



Red: momentum
Blue: spin

Effect of topology:

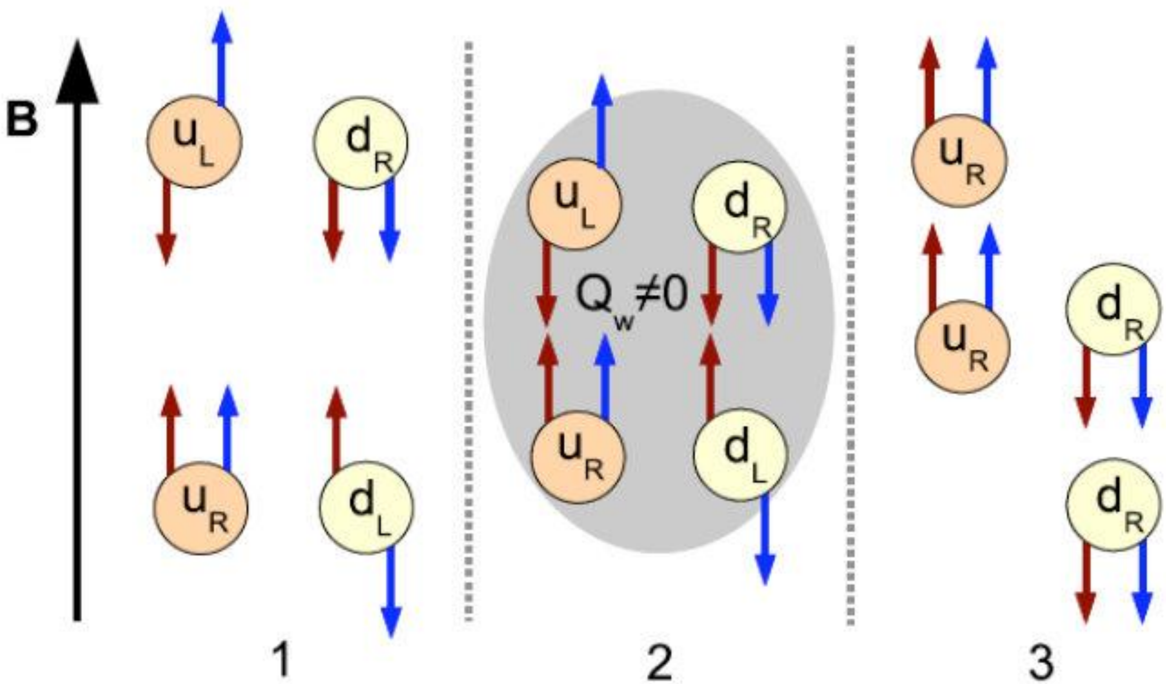
$u_L \rightarrow u_R$

$d_L \rightarrow d_R$

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



Red: momentum
Blue: spin

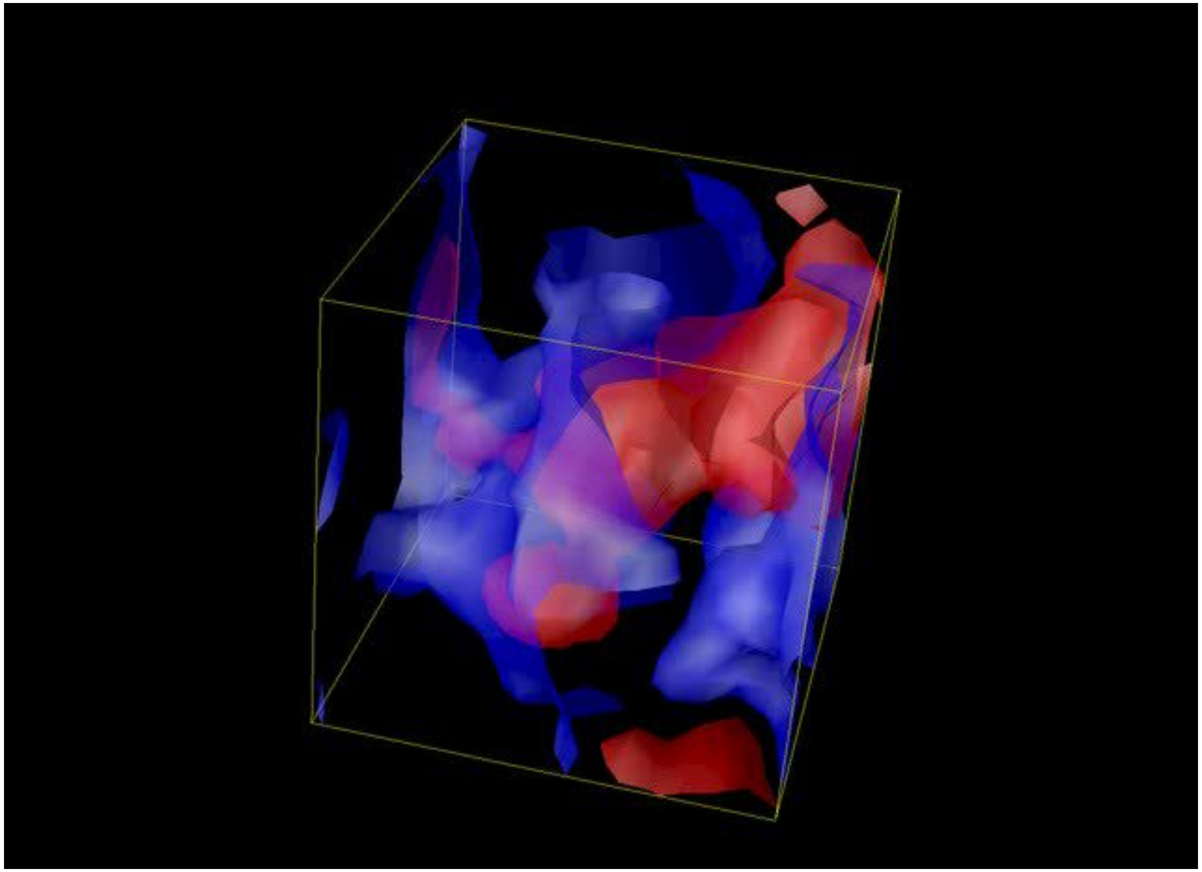
Effect of topology:

$u_L \rightarrow u_R$

$d_L \rightarrow d_R$

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

Topological charge density in quantum QCD vacuum has fractal structure

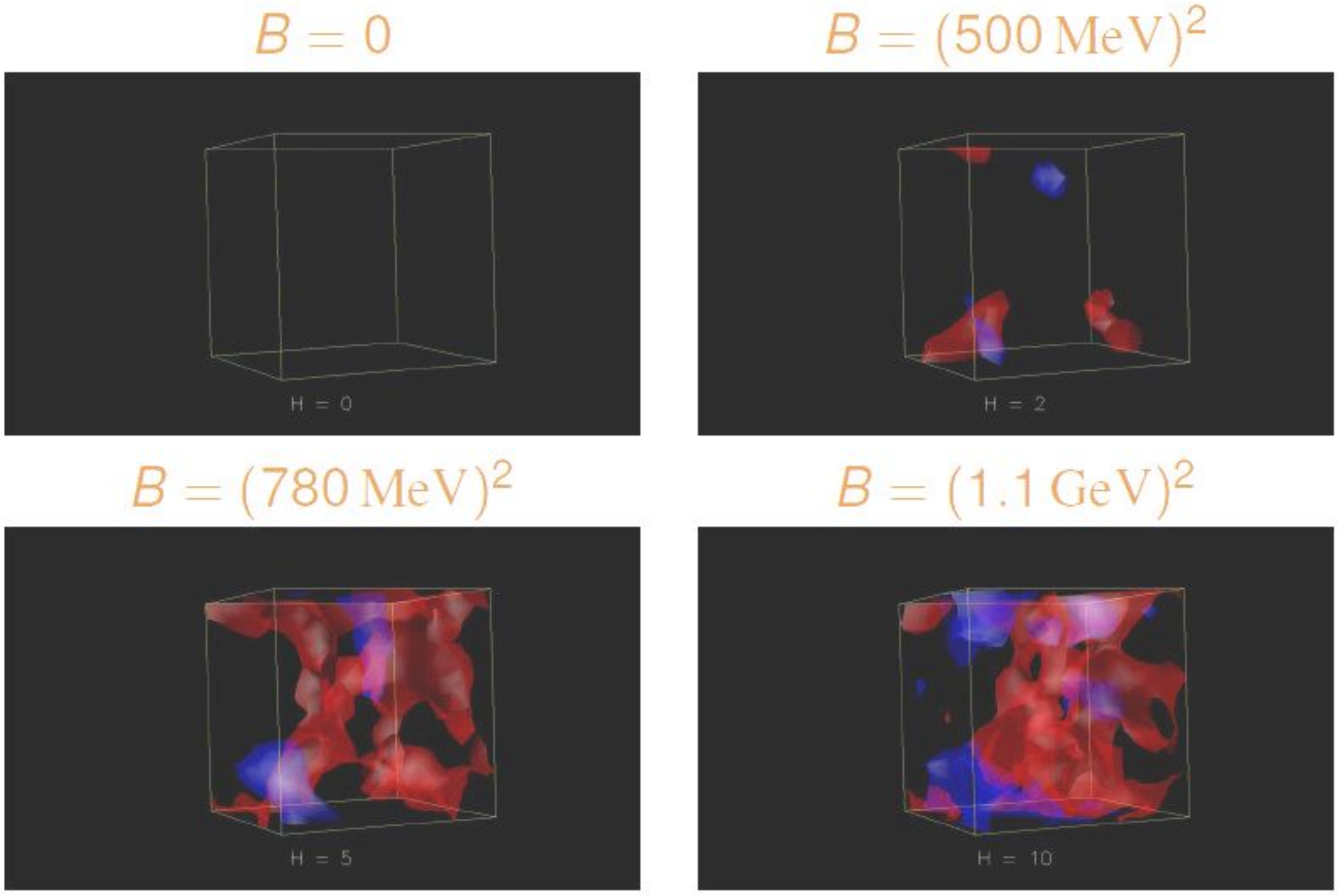


In quantum vacuum we expect big fluctuations of charge squared

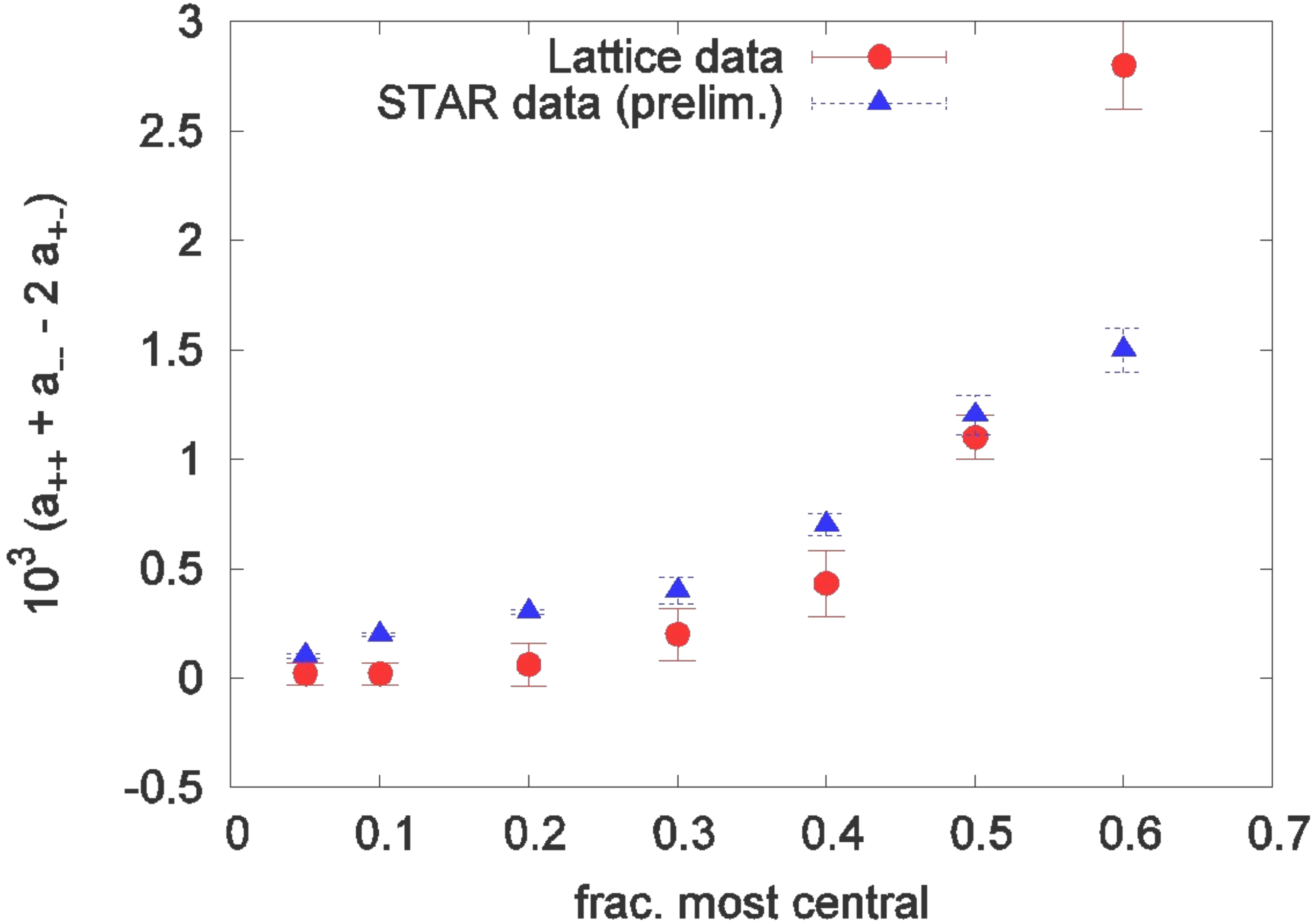
$$< j_3 >= 0; \quad < j_3^2 >\neq 0;$$

Chiral Magnetic Effect on the lattice, charge separation

Density of the electric charge vs. magnetic field



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



Chiral Magnetic Effect,
EXPERIMENT VS LATTICE DATA

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

experiment

$R \approx 5\ fm$

$\rho \approx 0.2\ fm$

$\tau \approx 1\ fm$

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

our fit

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

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

our lattice data at *T=350 Mev*

Preliminary results: conductivity of the vacuum

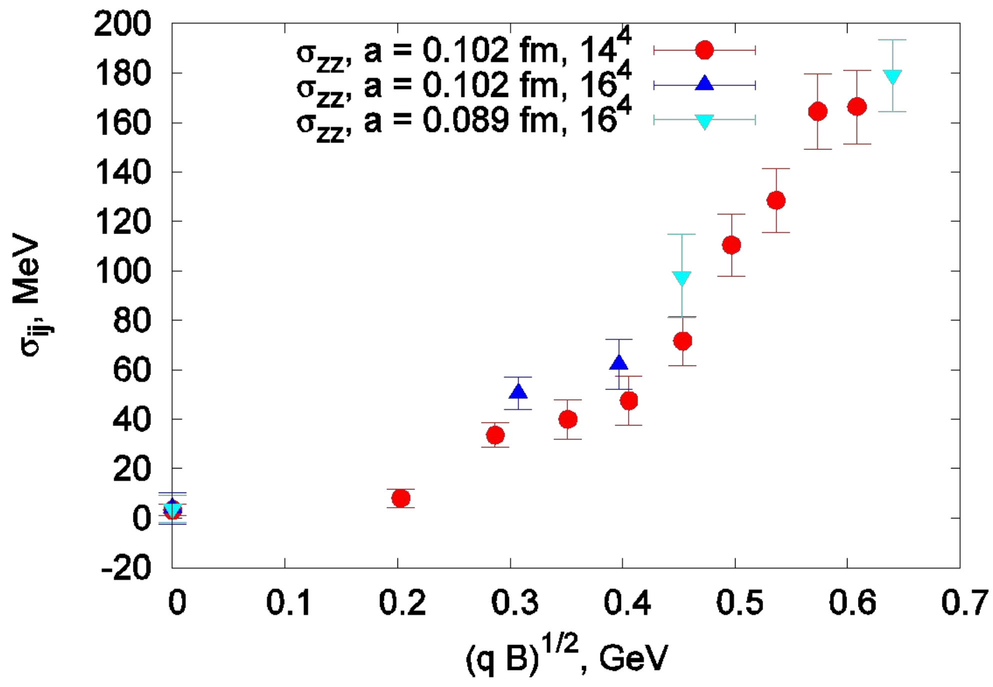
Qualitative definition of conductivity σ

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

$$\sigma \propto C$$

Preliminary results: conductivity of the vacuum

Conductivity at T=0

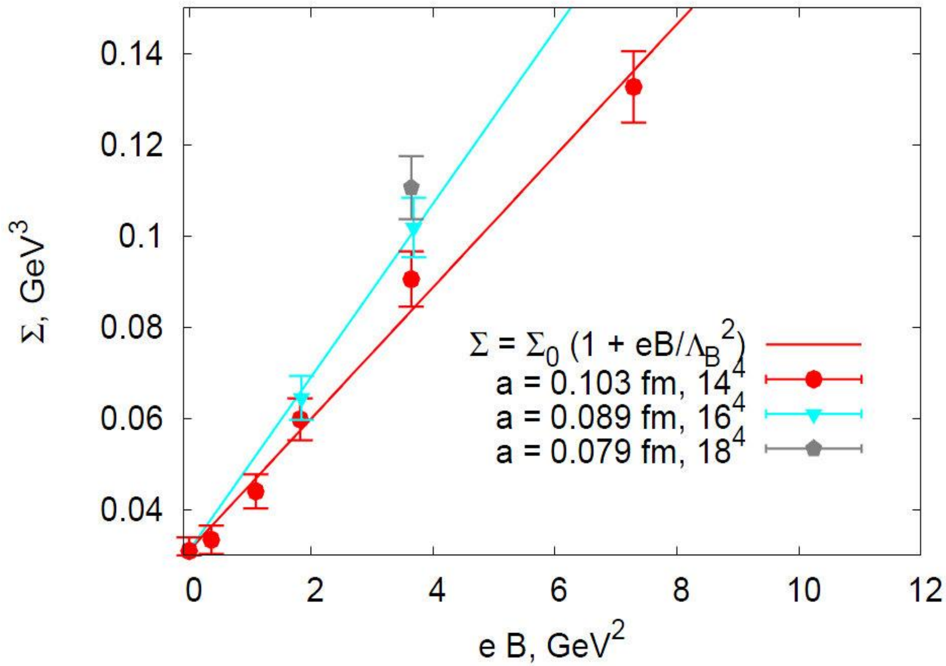


2. Chiral condensate in QCD

$$\Sigma = -<\bar{\psi}\psi>$$

$$m_\pi^2 f_\pi^2 = m_q <\bar{\psi}\psi>$$

Chiral condensate vs. field strength



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

- Our value for Λ_B:

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

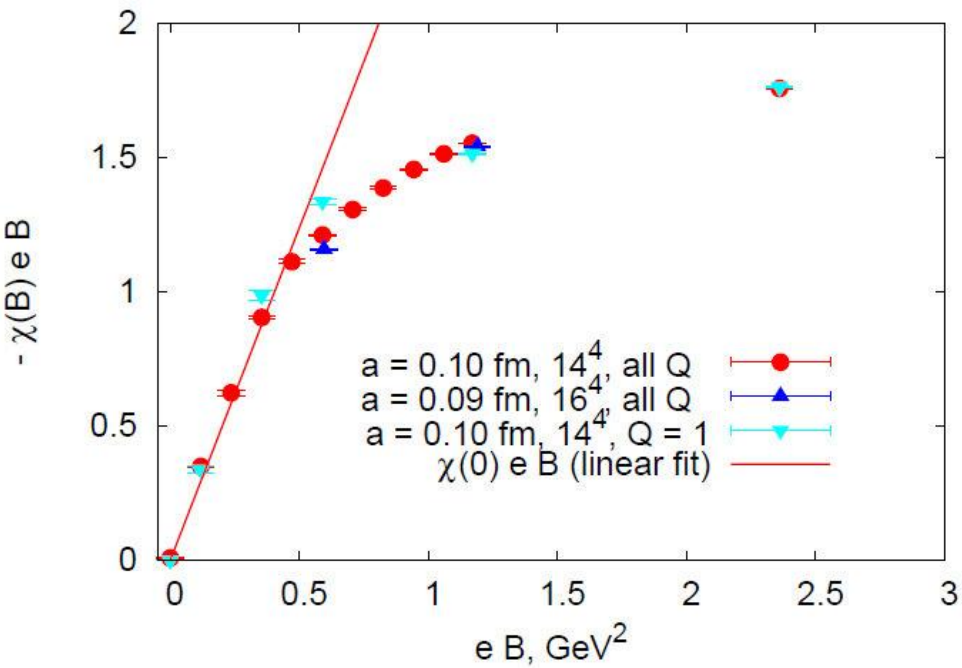
- χPT result:

$$\Lambda_B^{\chi PT} = 1.96\,GeV \quad (F_\pi = 130\,MeV - real\ world)$$
$$\Lambda_B^{\chi PT} = 1.36\,GeV \quad (F_\pi = 90\,MeV - quenched)$$

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

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

$$<\bar{\psi}\sigma_{\alpha\beta}\psi> = \chi <\bar{\psi}\psi> F_{\alpha\beta}$$

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

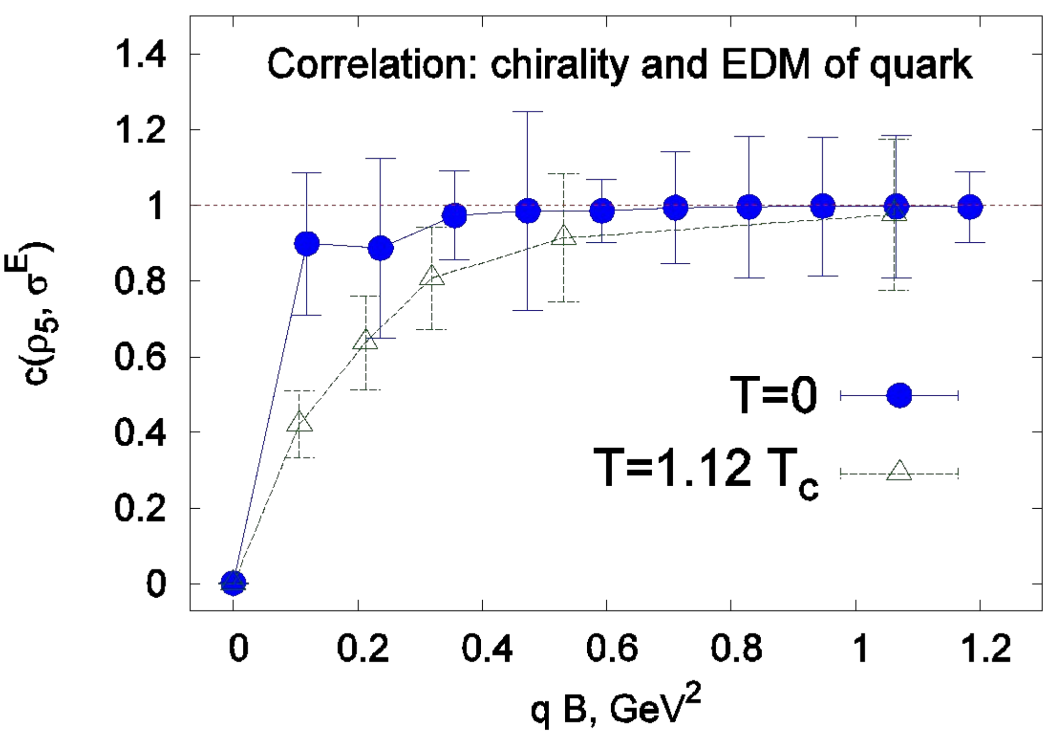
$<\bar{\psi}\psi>\chi = -46(3)Mev \leftrightarrow$ our result

$<\bar{\psi}\psi>\chi \approx -50Mev \leftrightarrow$ QCD sum rules

(I. I. Balitsky, 1985, P. Ball, 2003.)

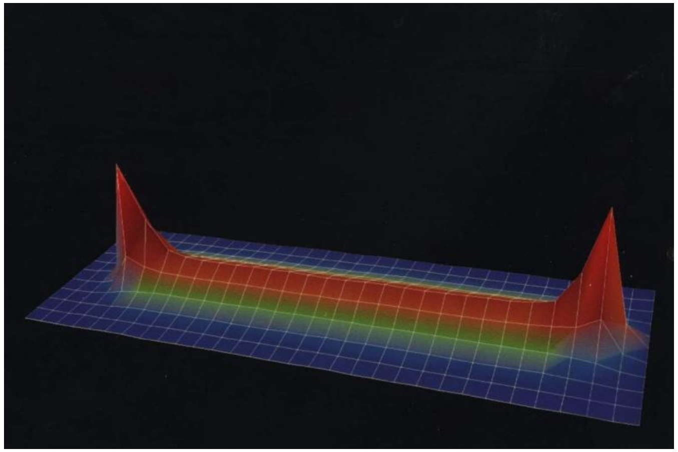
4. Generation of the anomalous quark electric dipole moment along the axis of magnetic field

- **Large correlation between square of the electric dipole moment** $\sigma_{0i} = i\overline{\psi}[\gamma_0, \gamma_i]\psi$ **and chirality** $\rho_5 = \overline{\psi}\gamma_5\psi$



THEORY

To explain

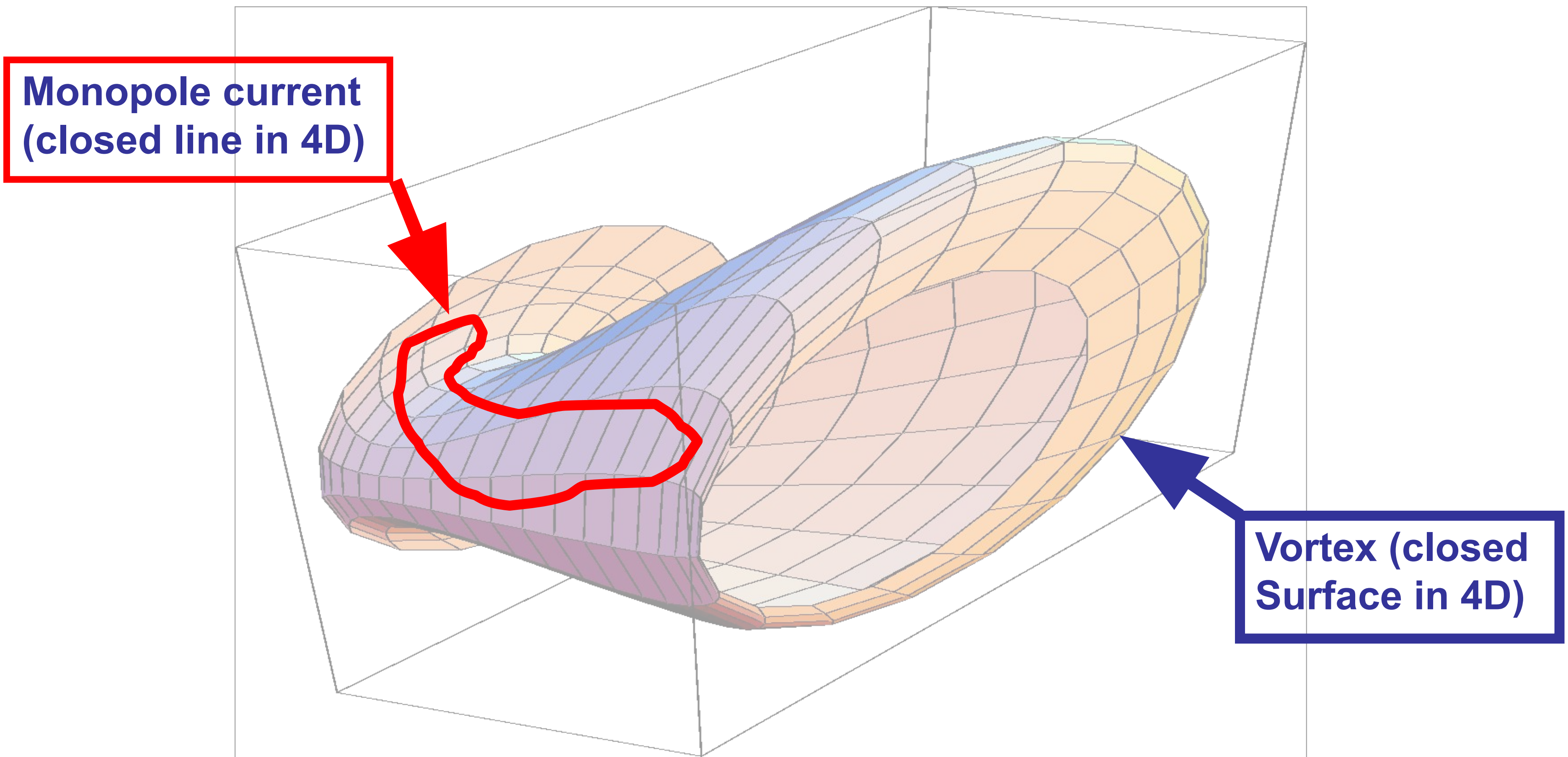


We have to prove in gluodynamics that

$$\boxed{< W(C) > = < Tr\, P \exp\{\oint_C iA_\mu dx_\mu\} > \propto \exp\{-\sigma \cdot Area\}}$$

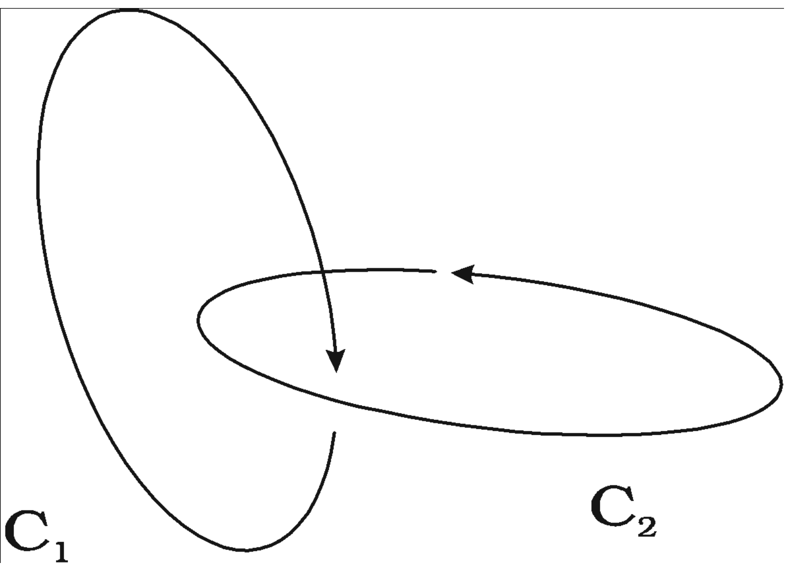
SU(2) gauge theory

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.



Linking number

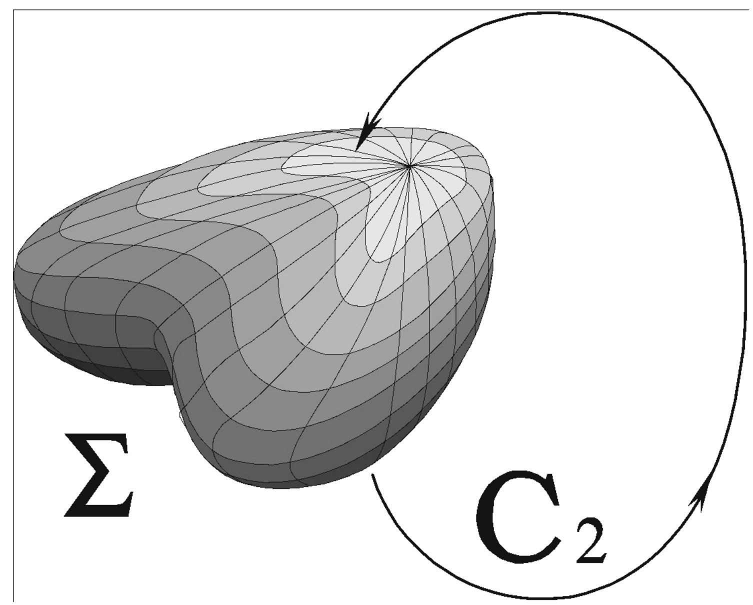
3D



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

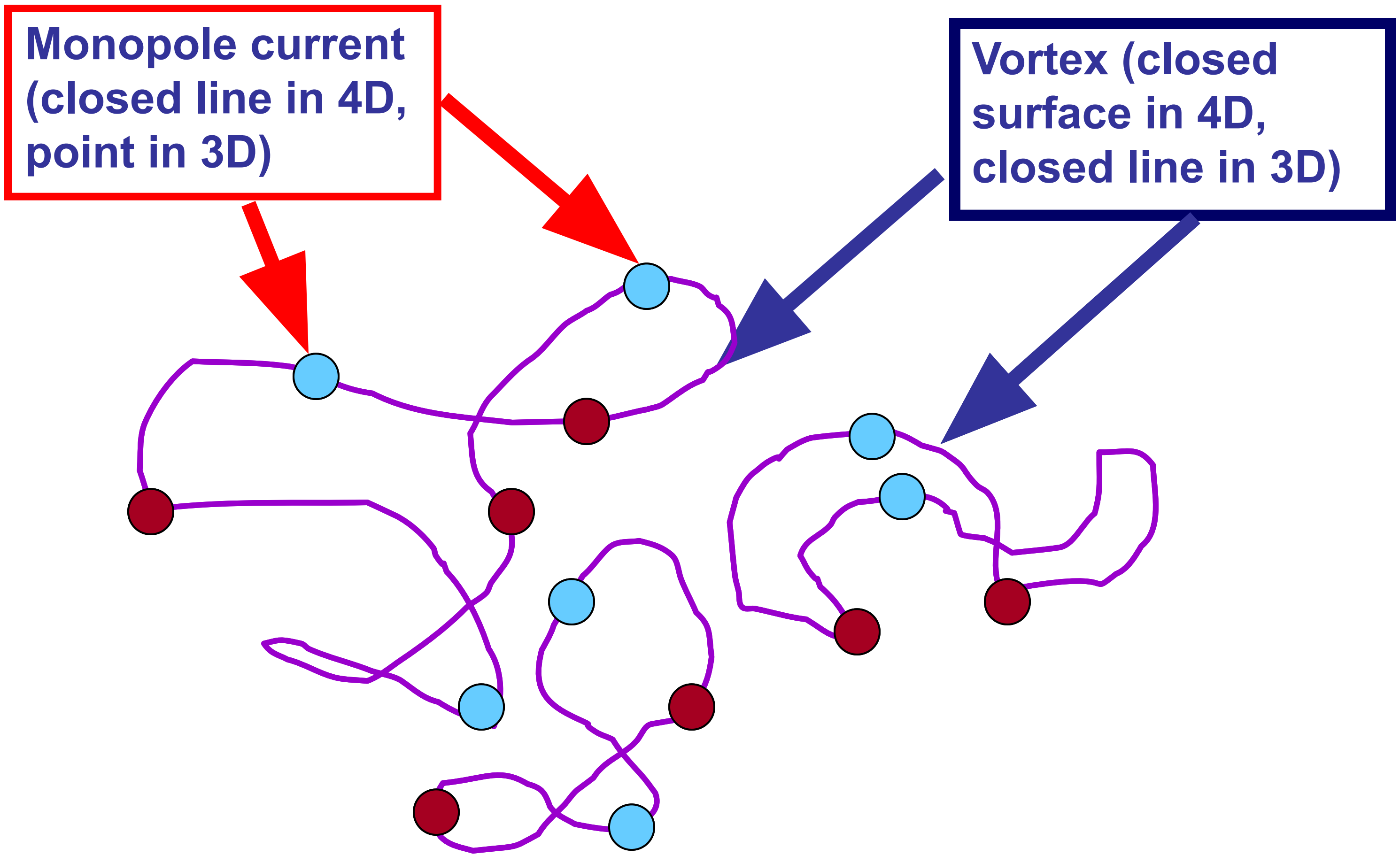
4D

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



Pure gauge theory

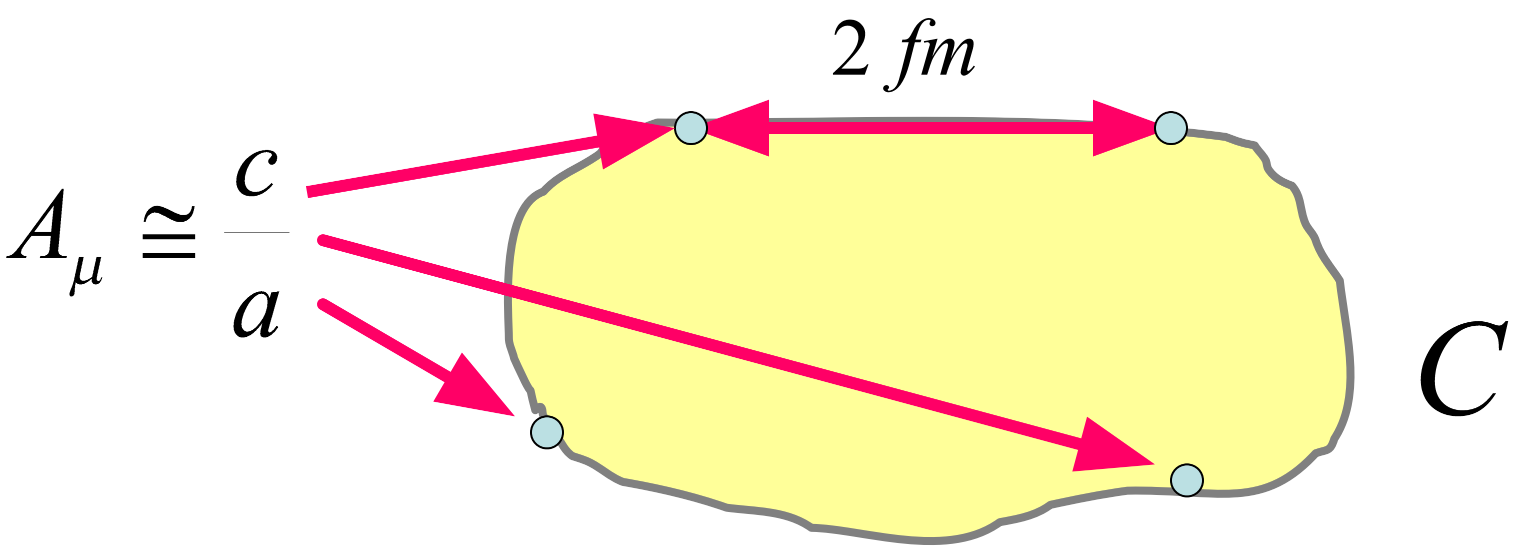
(what we see on 3d slice of 4D lattice)



THEORY

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

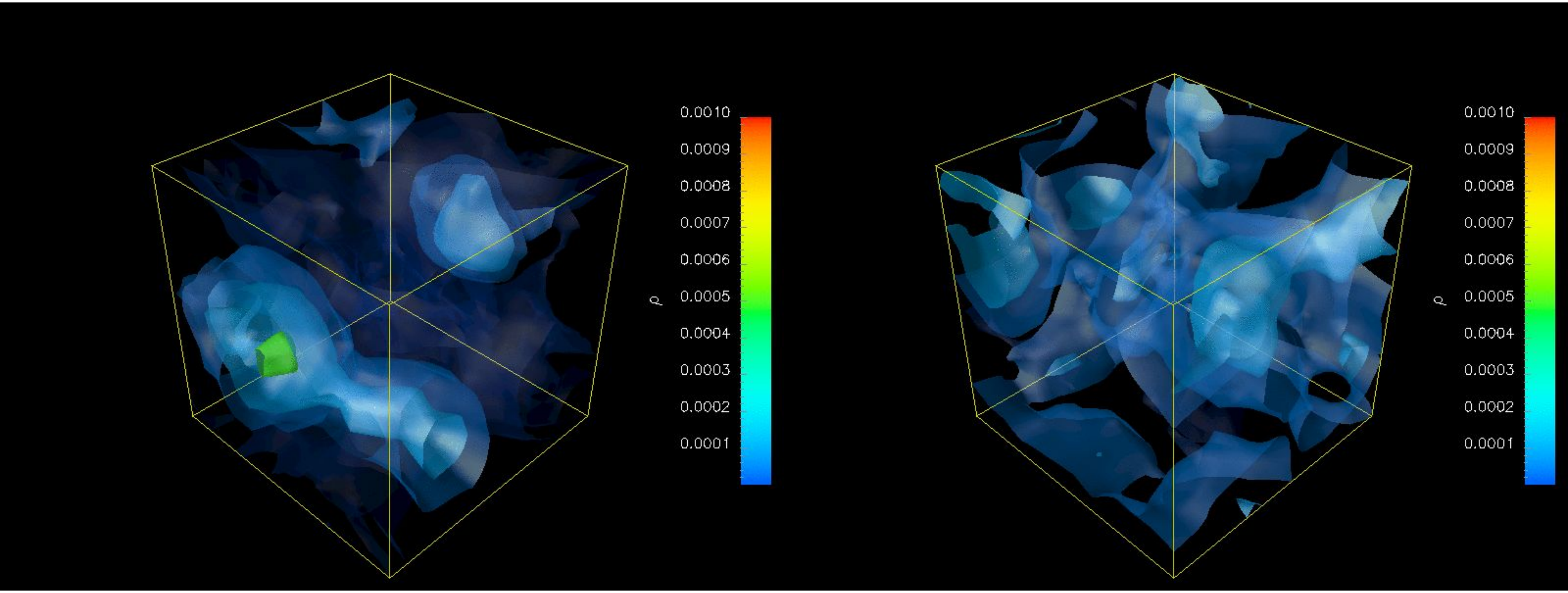
Holography



THEORY

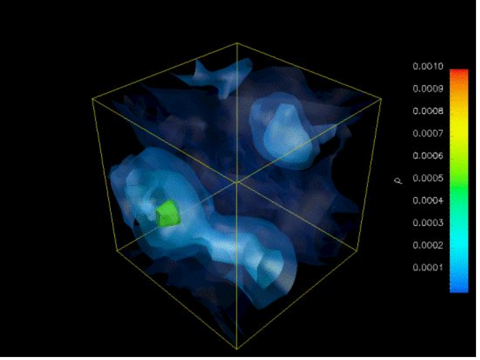
Chiral symmetry breaking and topological susceptibility is due to low-dimensional regions

Time slices for $\rho^2, \quad \rho_\lambda(x) = \psi^+_\lambda(x)\psi_\lambda(x)$

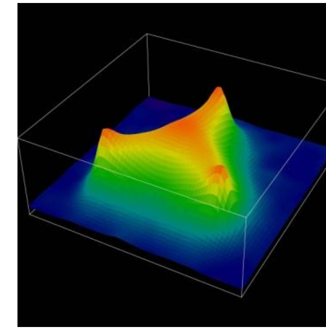


IPR=5.13
chirality=-1

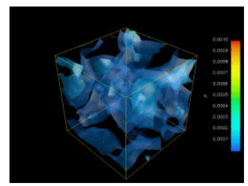
IPR=1.45
chirality=0



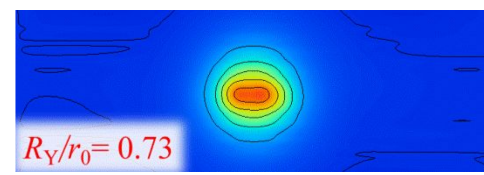
Instead of Conclusions

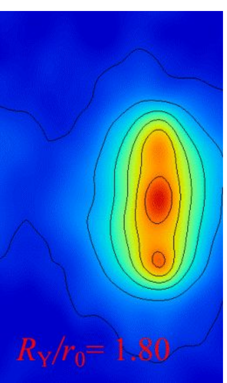


- Computer simulations a) reproduce well known hadron properties b) predict new phenomena c) help to create new theoretical ideas.



- 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.itep.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 Черемушкинская, 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 суперкмпьютеры (или все вместе).