QCD, heavy ion collisions, condensed matter physics and supercomputers

M.I. Polikarpov, ITEP, Moscow

- Introduction: quarks, gluons and QCD
- Millennium problem: Confinement
- Supercomputers and strong interactions
- Heavy ion collisions and computers
- Graphene and computers

Physics of high energy density in matter

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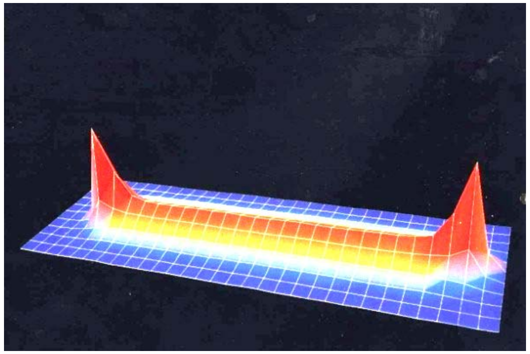
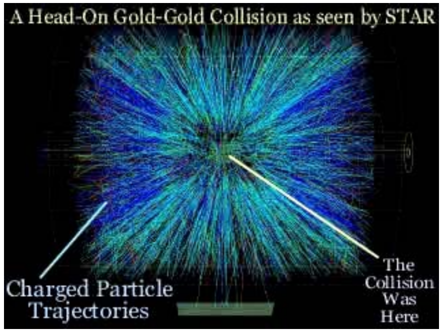
Three examples of computer simulations of strongly interacting systems

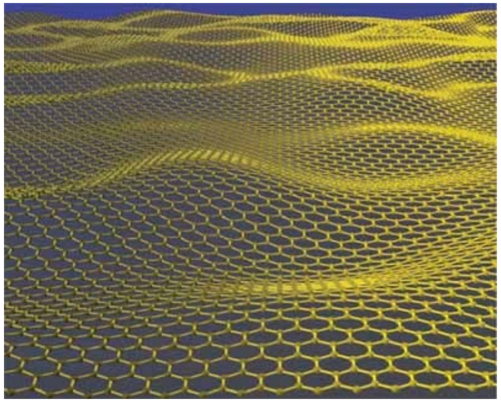
1. Confinement problem in QCD



2. Interference of strong and electromagnetic interactions in heavy ion collisions



3. Graphene as quantum field theory



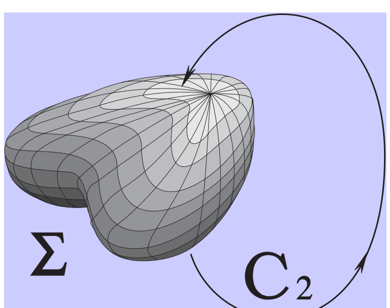
Experiment

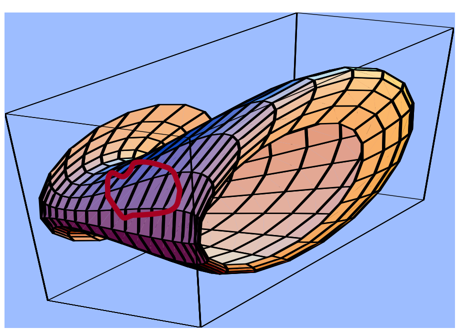
LHC

RHIC

Theory

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

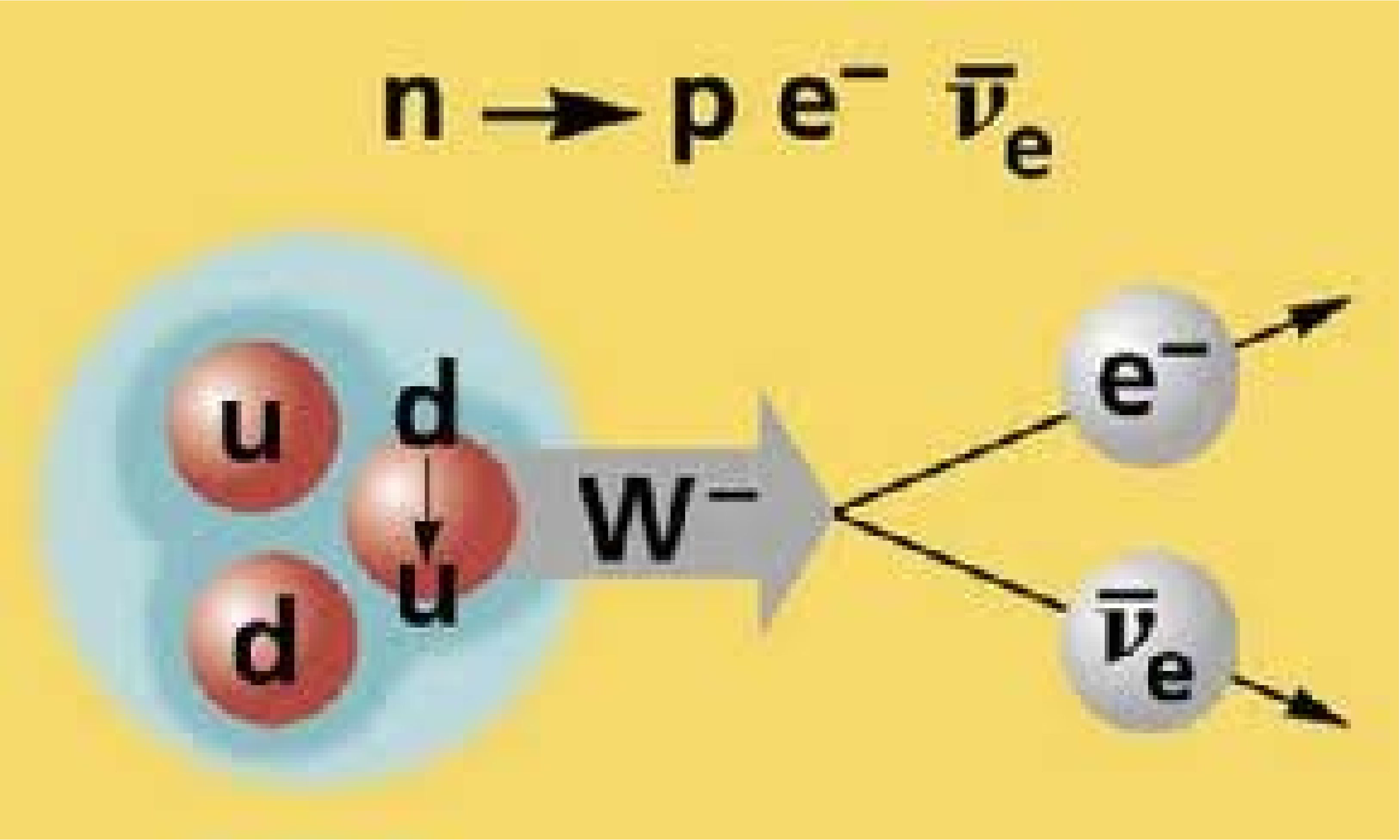




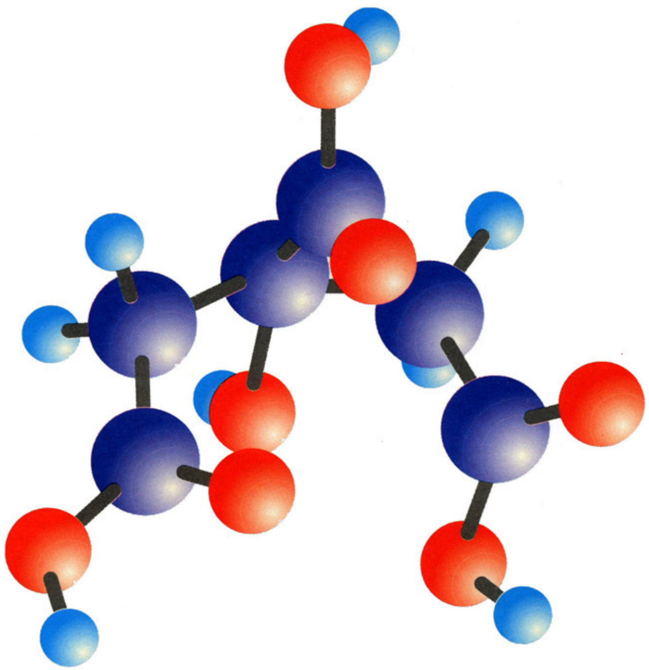
Supercalculations

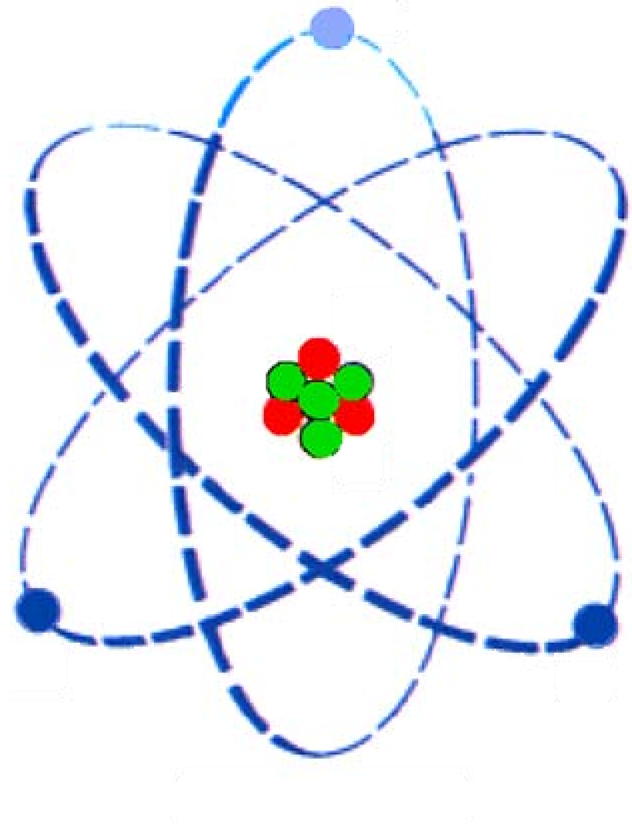
Interactions – 1. Gravity

Interactions – 2. Weak

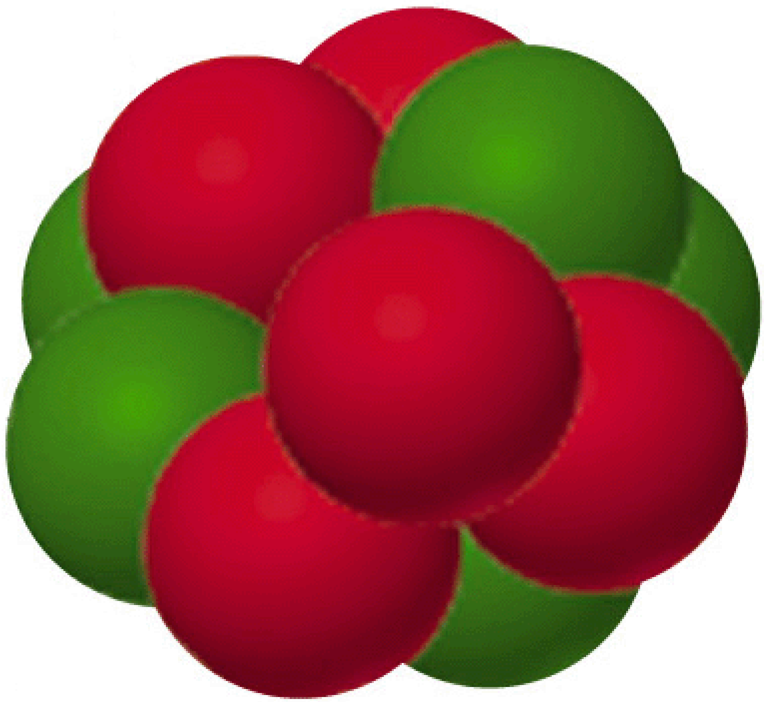


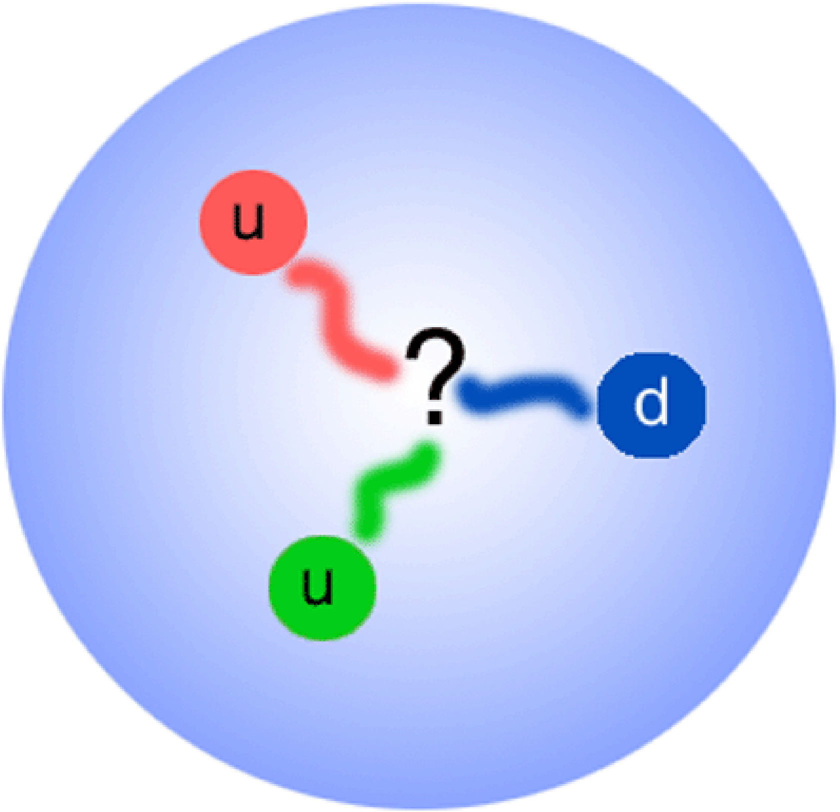
Interactions – 3. Electromagnetism





Interactions – 4. Strong

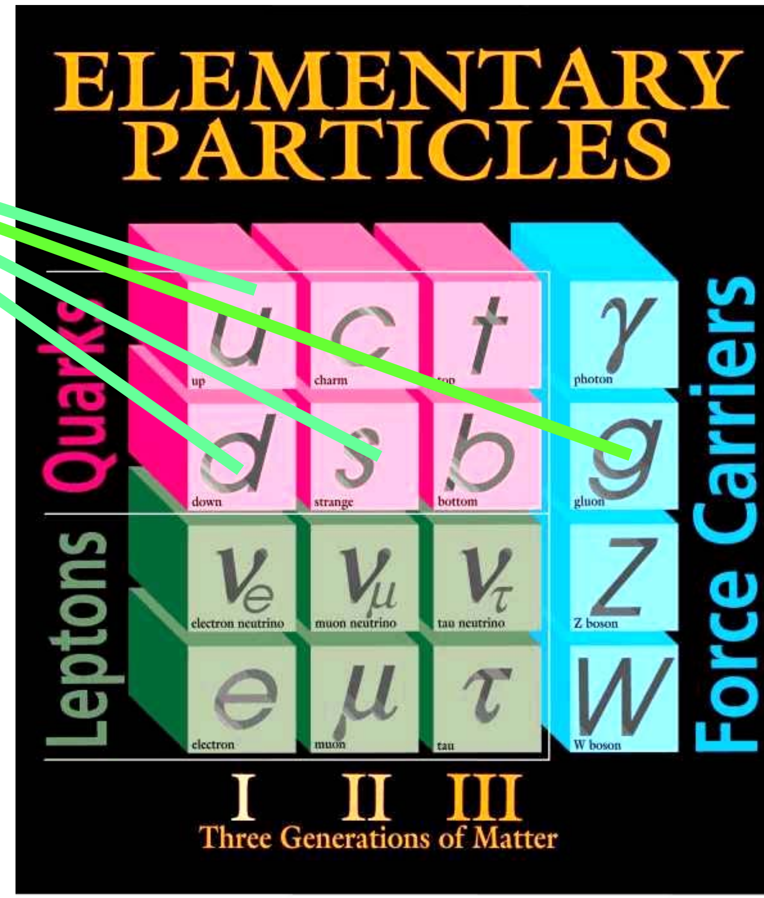




Main problems of strong interaction theory, QCD

Derive from QCD Lagrangian

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



Fermilab 95-759

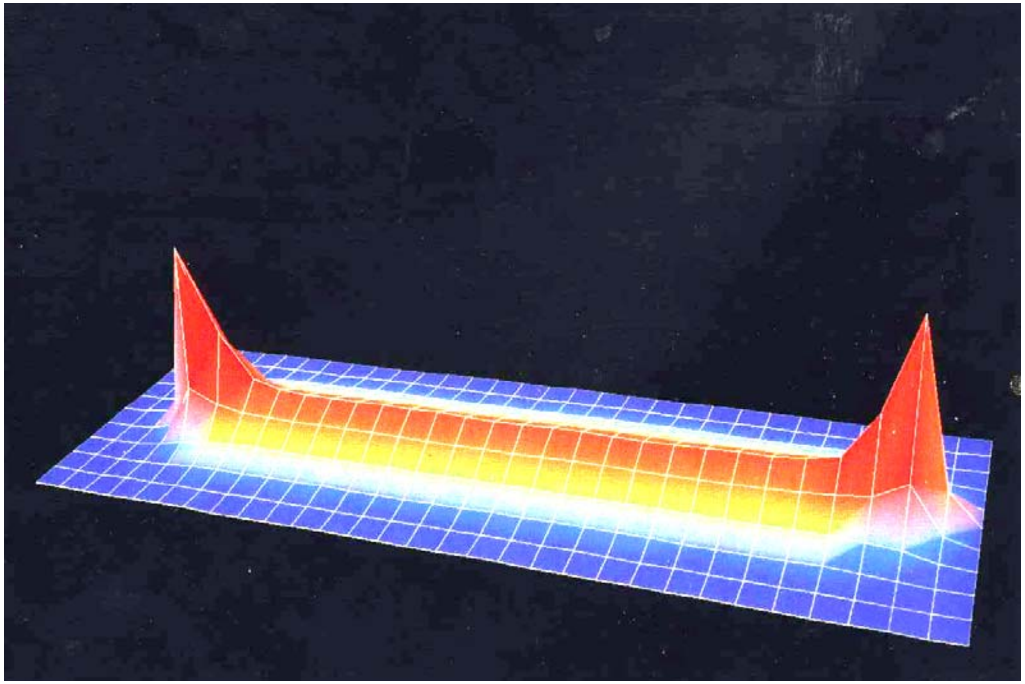
(1) Hadron spectrum,
(2) Matrix elements,
(3) Phase diagram
(4) Explain color confinement

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

Color confinement

(Why we do not observe free quarks and gluons?)

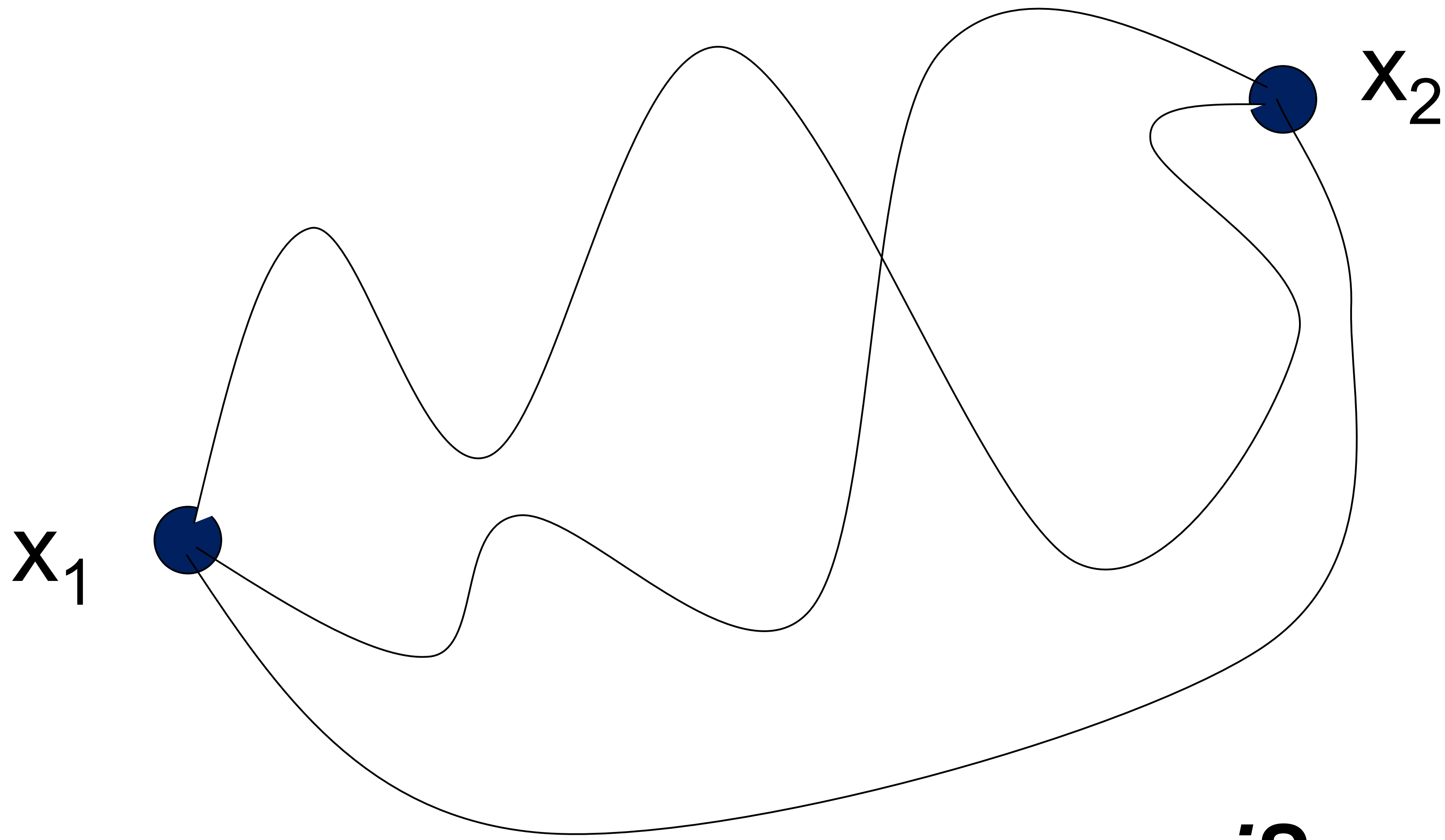
The main difficulty is the absence of first-principle nonperturbative methods in QCD. Computers can prove confinement "numerically"



Force between quark and antiquark is12 tons!!!

http://www.claymath.org/millennium

Quantum mechanics of a particle



The weight of each trajectory is e^{iS}

Quantum field theory

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

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

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

Methods

- Imaginary time ***t→it***

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

- Space-time discretization

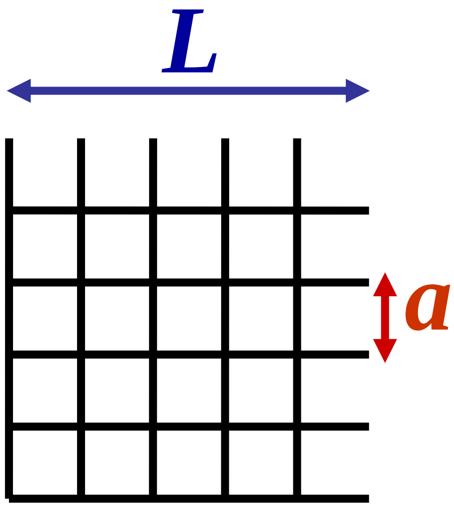
$$D\varphi(x) \Rightarrow \prod_x d\,\varphi_x$$

$$Z = \int \prod_x d\varphi_x \exp\{-S[\varphi]\}$$

- 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

$a \approx 0.1\ fm$

$L \approx 2 \div 4\ fm$

$m_q \approx 100\ Mev$

$\Rightarrow$

Extrapolation

+

Chiral perturbation theory

Typical multiplicity of integrals

For lattice *L^4*

(L=48, L^4=5,308,416)

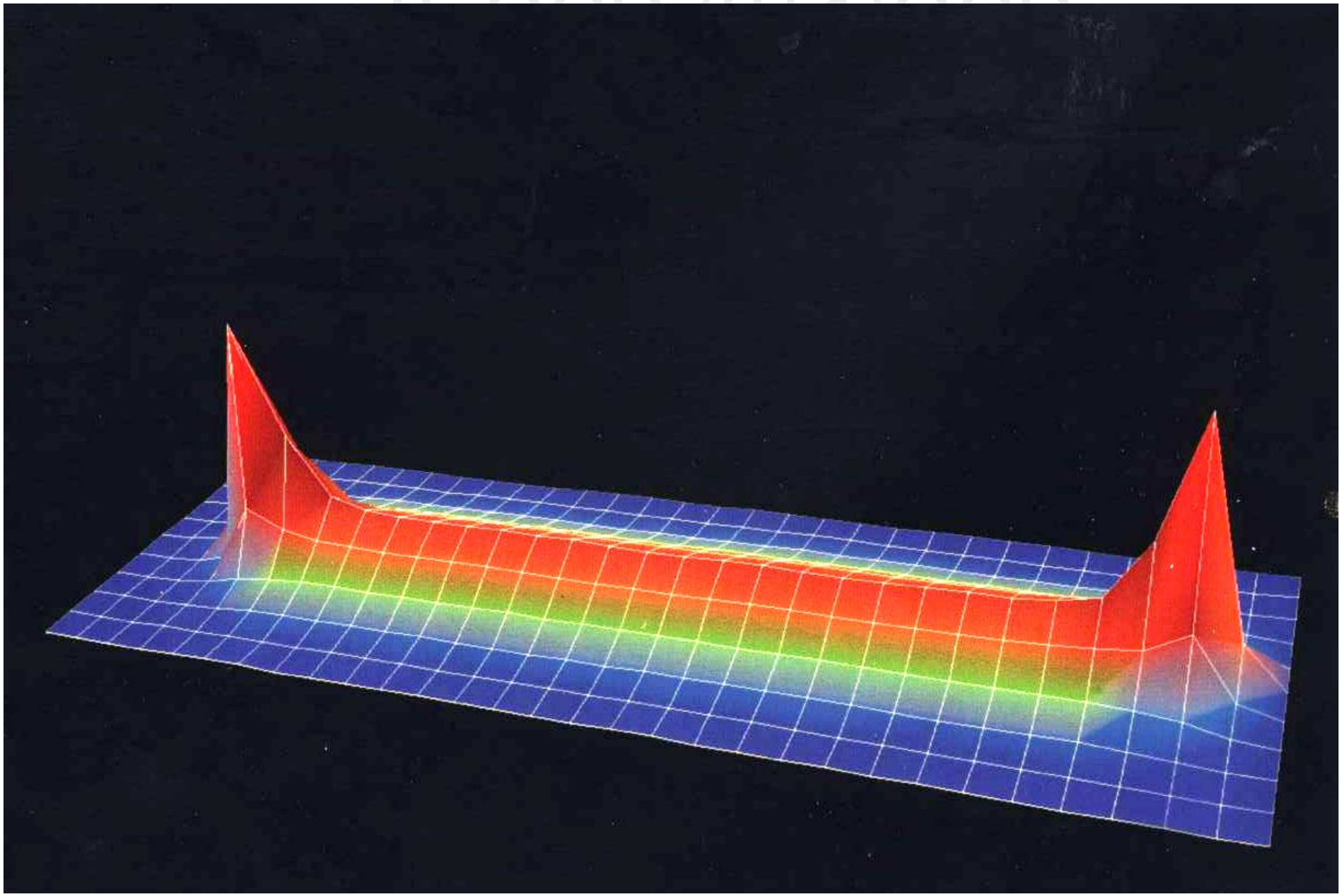
- **Te multiplicity of integralsover gluon fields is *$32L^4$*** *(L=48, $32L^4$=169,869,312)*

- **For quark fields we work with matrices** ***$12L^4$ x $12L^4$*** *(L=48, $12L^4$=63,700,992)*

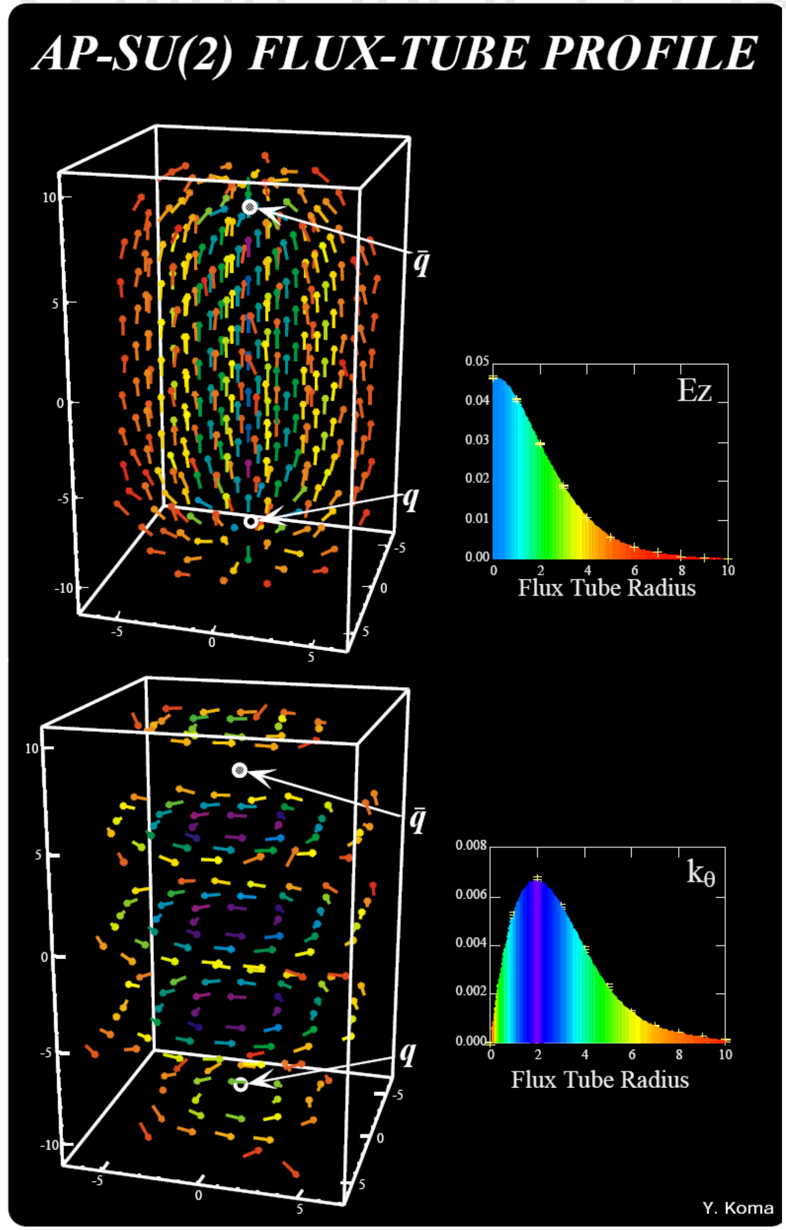
$$\int d\psi\, d\bar{\psi}\, \exp\{\bar{\psi} M \psi\} = \det M$$

SU(2) glue SU(3) glu

The force between quark and antiquark is 12 tons!!!



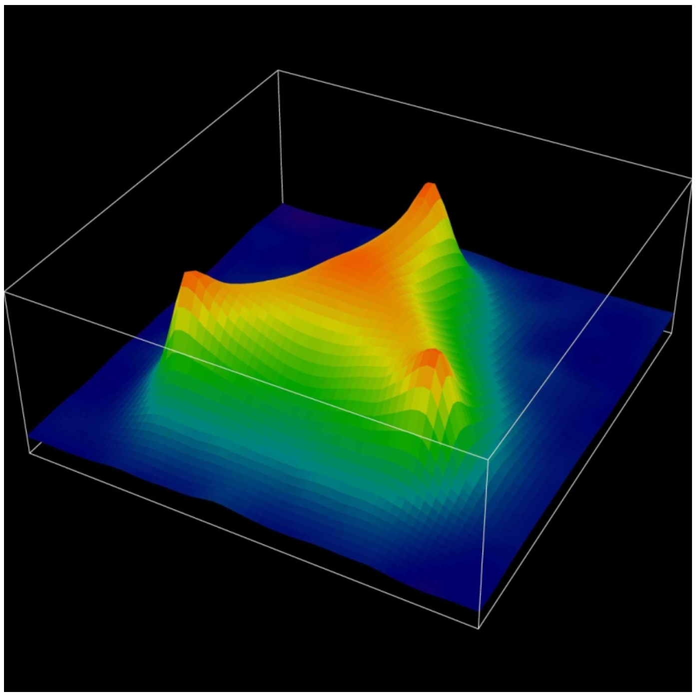
SU(2) glue

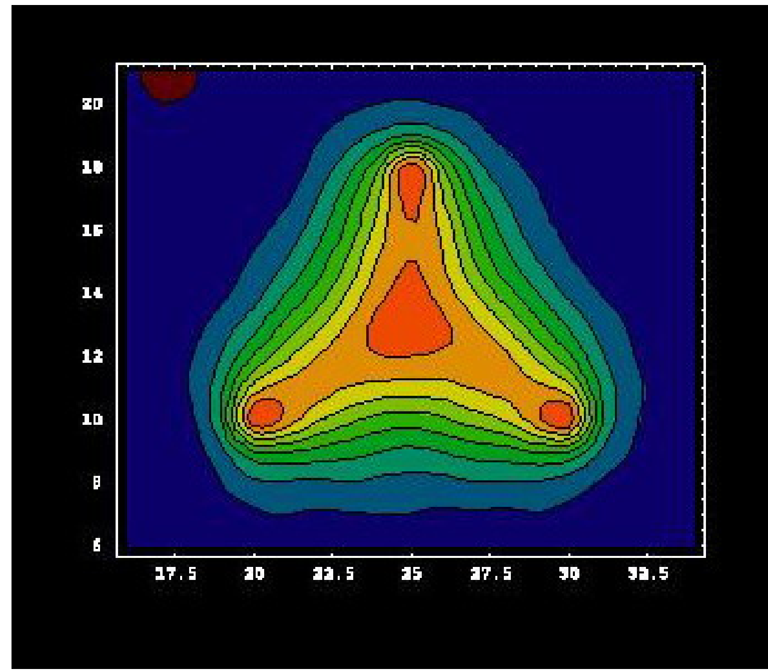


AP-SU(2) FLUX-TUBE PROFILE
$\bar{q}$
q
Ez
Flux Tube Radius
k_θ
Flux Tube Radius
Y. Koma

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

Three body forces!



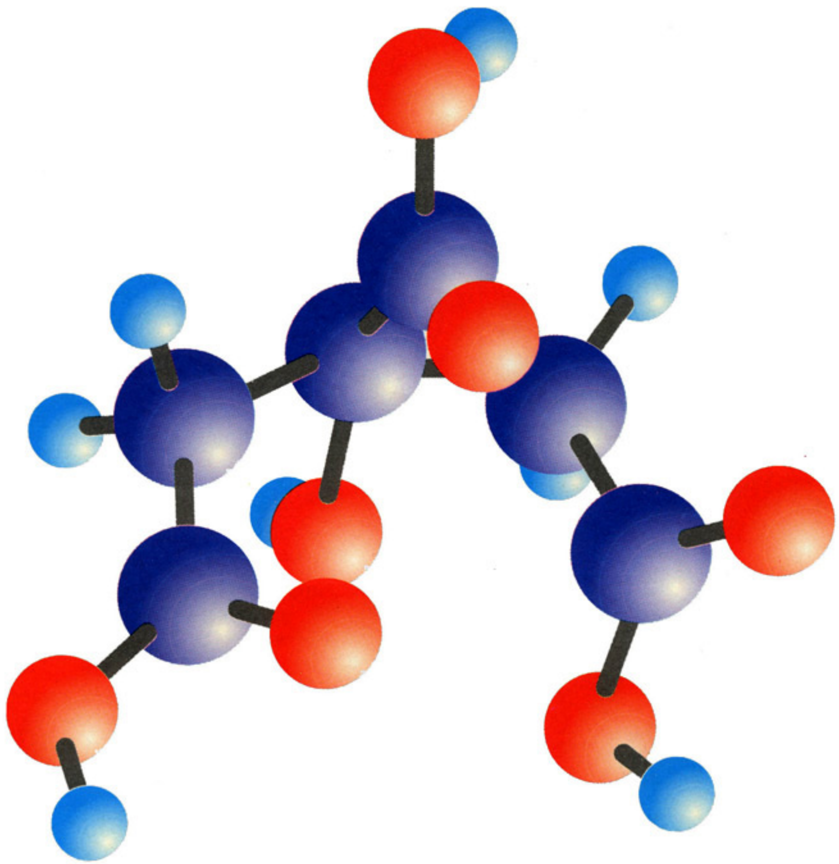


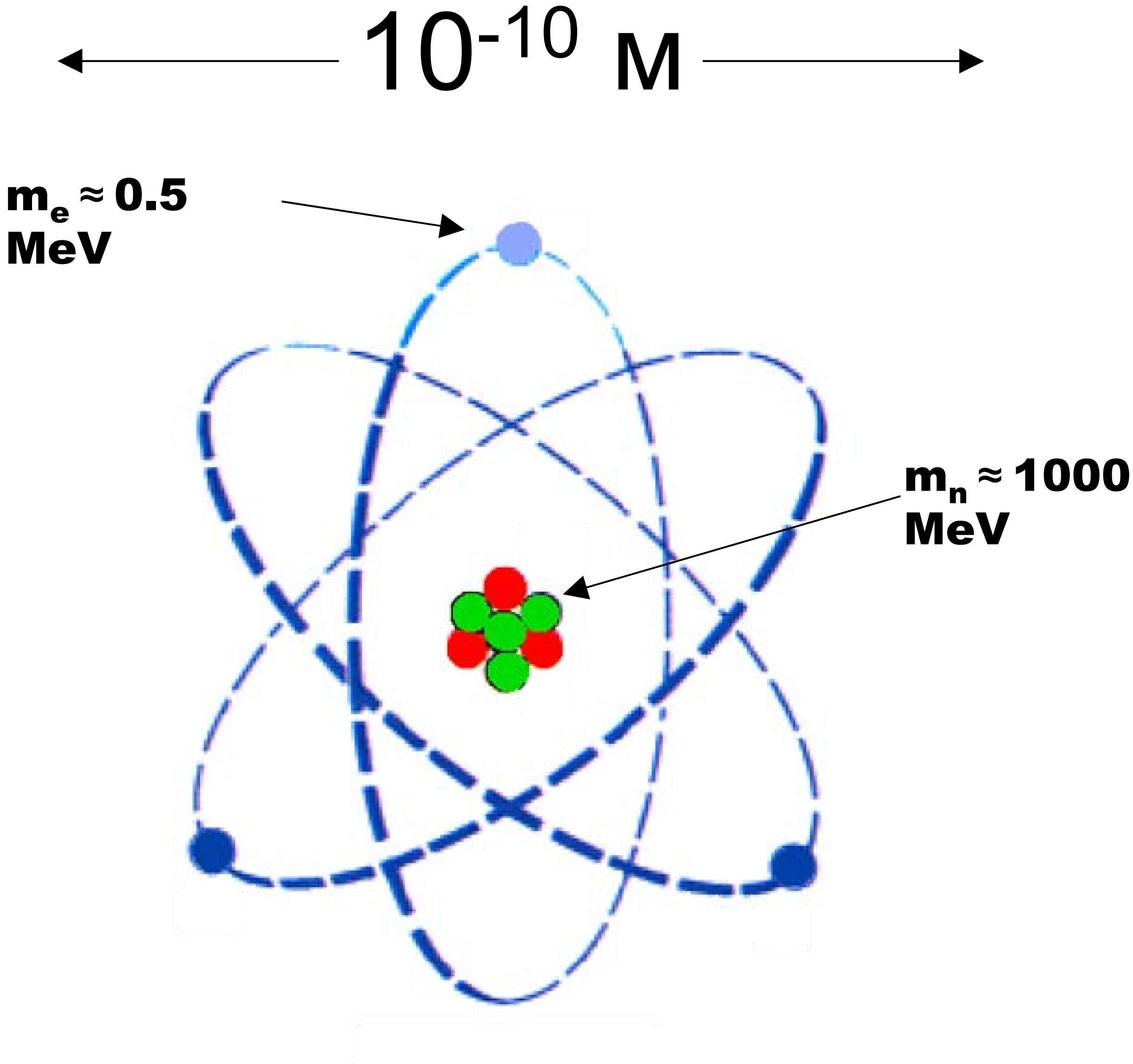
$$V(r_1, r_2, r_3) \neq V(r_1 - r_2) + V(r_2 - r_3) + V(r_3 - r_1)$$

1 м

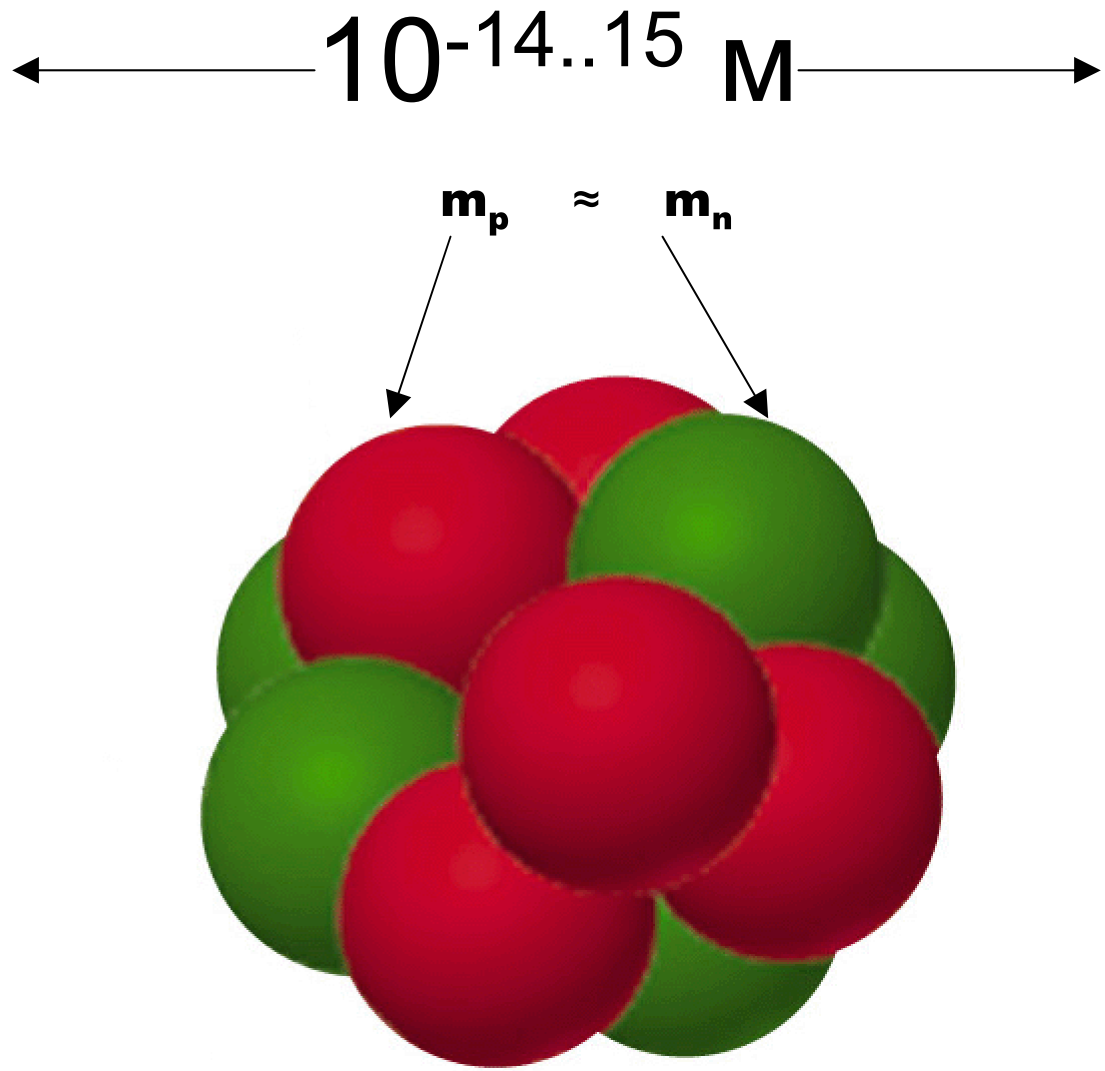
The origine of the mass

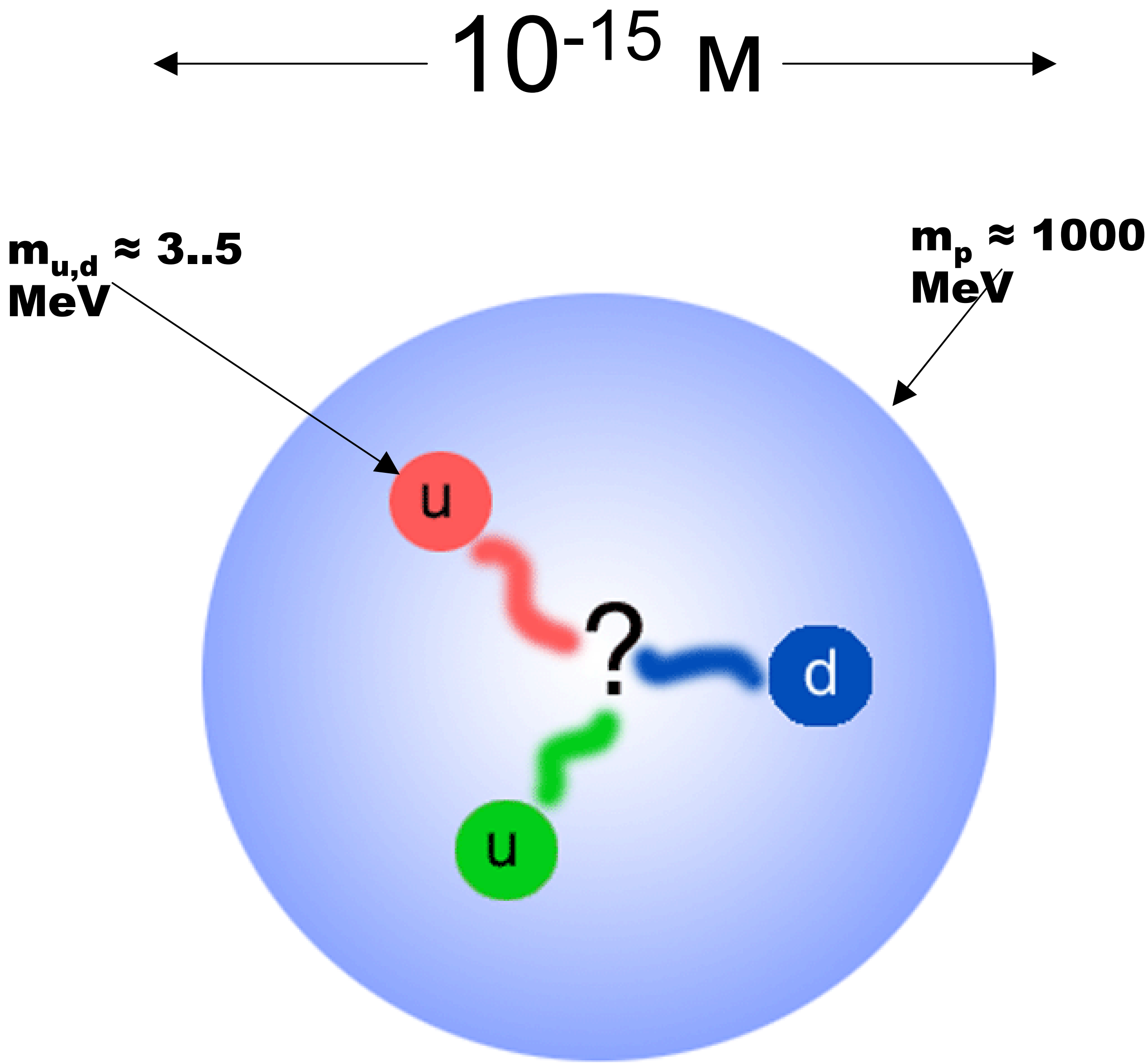
$10^{-8..10}$ м



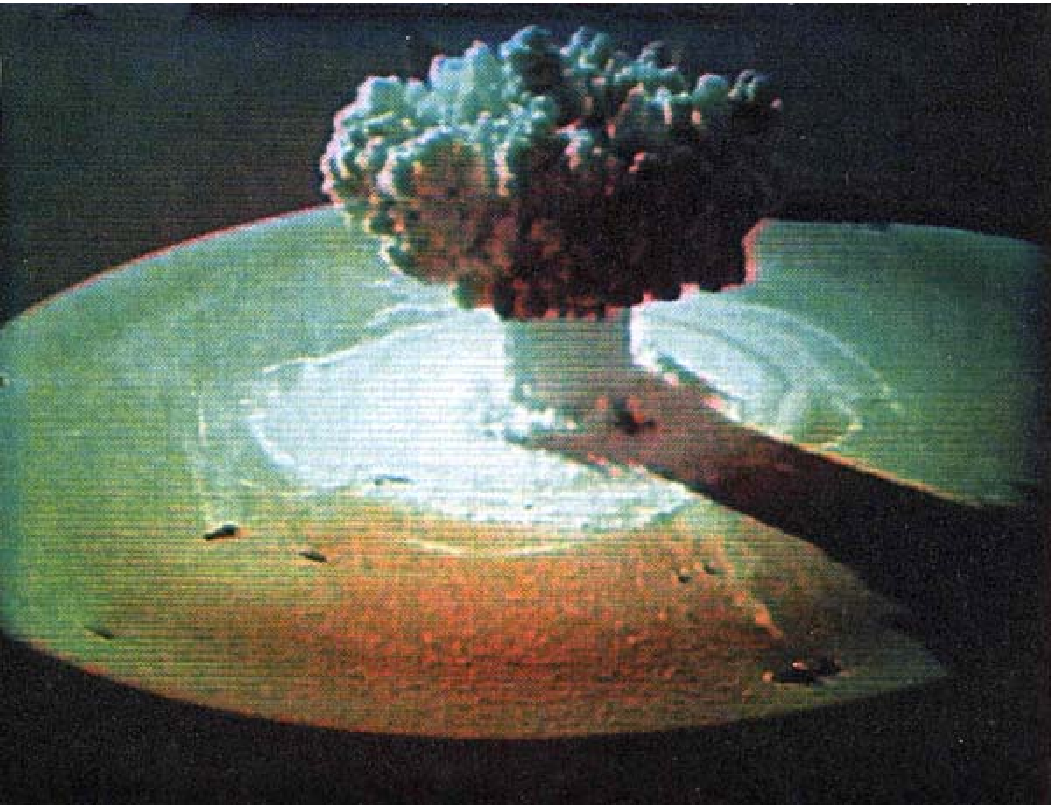


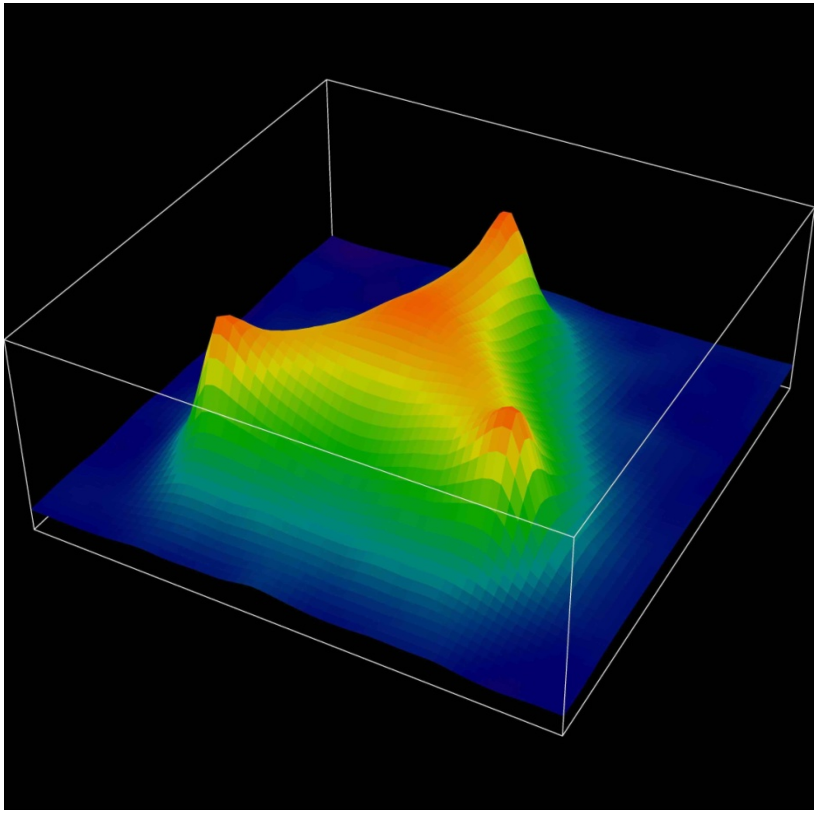
10-10 M
me ≈ 0.5 MeV
mn ≈ 1000 MeV


10-14..15 м
mp ≈ mn


10^{-15} M
$m_{u,d} \approx 3..5$ MeV
$m_p \approx 1000$ MeV
u
?
d
u

Masses of material objects is due to gluon fields inside baryon





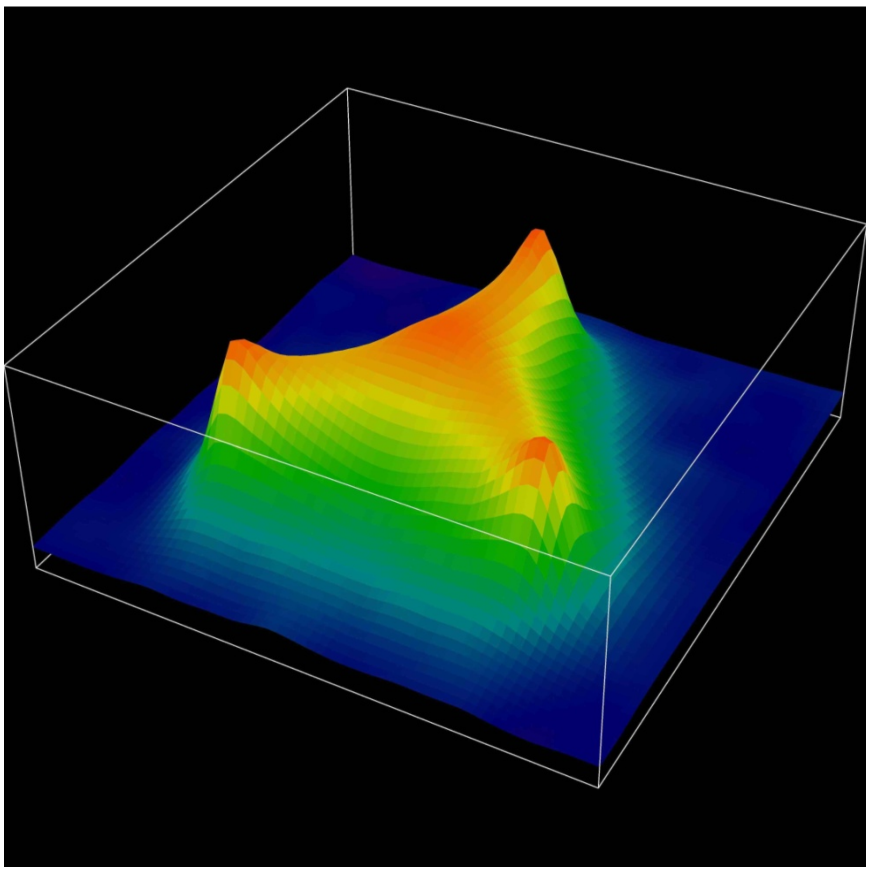
$$E = m_0 c^2$$

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

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

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

Three body forces!



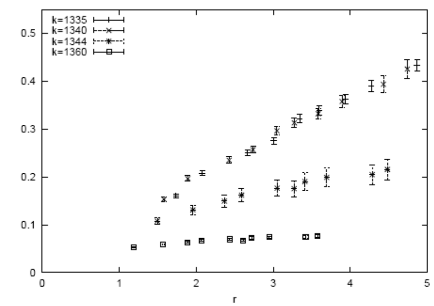


Figure 9: The monopole part of the baryon potential at finite temperature in full QCD as a function of L_{Υ} $(T < T_c)$ and L_{Δ} $(T > T_c)$, respectively, in units of *God knows what.*

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

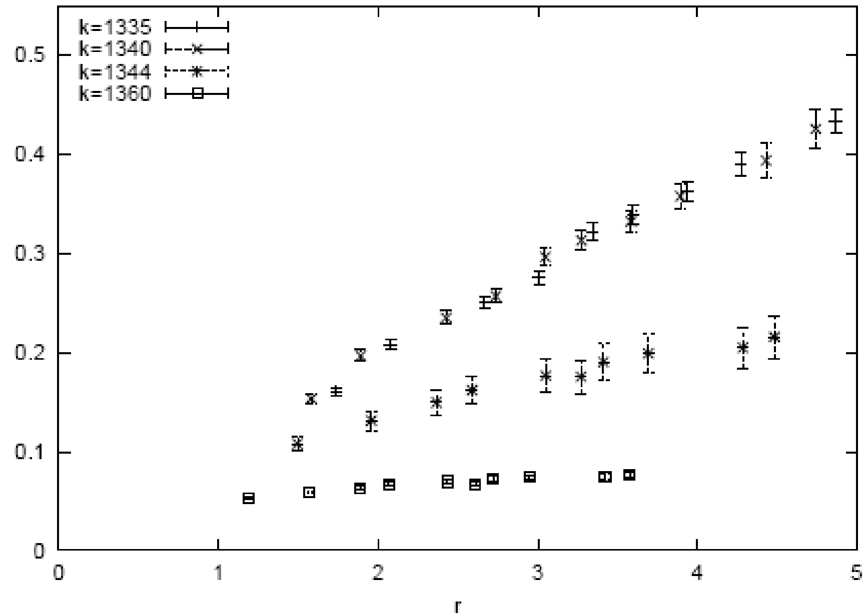
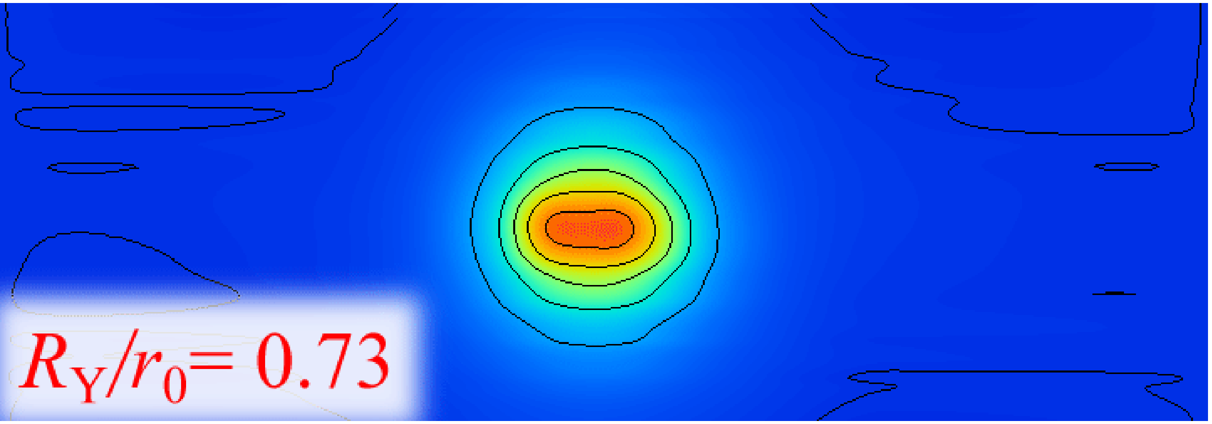


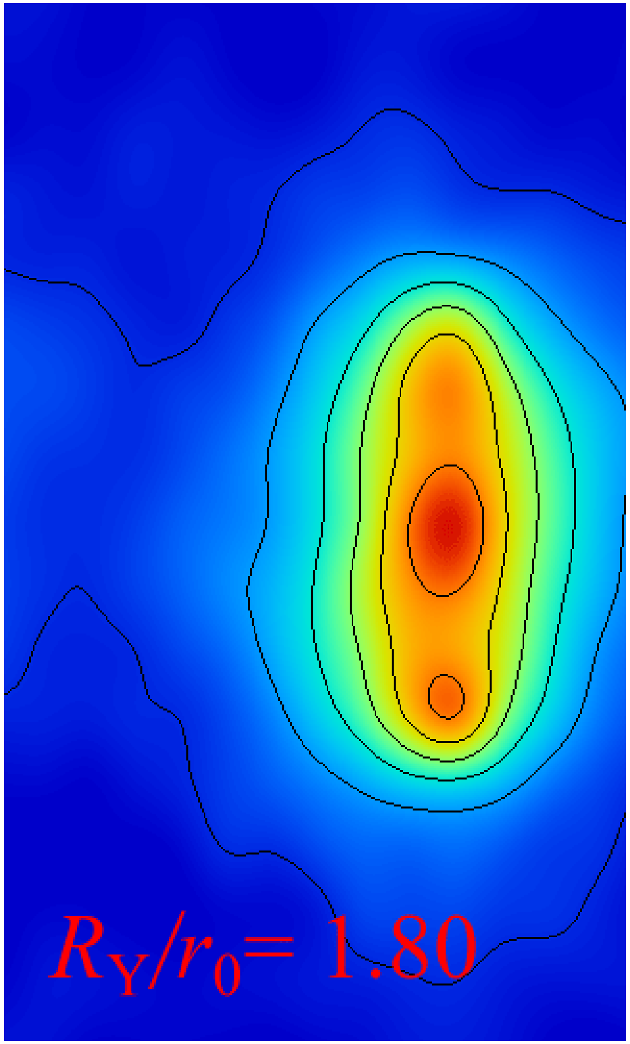
Figure 9: The monopole part of the baryon potential at finite temperature in full QCD as a function of L_Y ($T < T_c$) and L_Δ ($T > T_c$), respectively in units of *God knows what.*

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

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

OTHER LIGHT

Further States

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_s^0	$0(0^-)$
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}	****
n	P_{11}	****
$N(1440)$	P_{11}	****
$N(1520)$	D_{13}	****
$N(1535)$	S_{11}	****
$N(1650)$	S_{11}	****
$N(1675)$	D_{15}	****
$N(1680)$	F_{15}	****
$N(1700)$	D_{13}	***
$N(1710)$	P_{11}	***
$N(1720)$	P_{13}	****
$N(1900)$	P_{13}	**
$N(1990)$	F_{17}	**
$N(2000)$	F_{15}	**
$N(2080)$	D_{13}	**
$N(2090)$	S_{11}	*
$N(2100)$	P_{11}	*
$N(2190)$	G_{17}	****
$N(2200)$	D_{15}	**
$N(2220)$	H_{19}	****
$N(2250)$	G_{19}	****
$N(2600)$	$I_{1,11}$	***
$N(2700)$	$K_{1,13}$	**

$\Delta(1232)$	P_{33}	****
$\Delta(1600)$	P_{33}	***
$\Delta(1620)$	S_{31}	****
$\Delta(1700)$	D_{33}	****
$\Delta(1750)$	P_{31}	*
$\Delta(1900)$	S_{31}	**
$\Delta(1905)$	F_{35}	****
$\Delta(1910)$	P_{31}	****
$\Delta(1920)$	P_{33}	***
$\Delta(1930)$	D_{35}	***
$\Delta(1940)$	D_{33}	*
$\Delta(1950)$	F_{37}	****
$\Delta(2000)$	F_{35}	**
$\Delta(2150)$	S_{31}	*
$\Delta(2200)$	G_{37}	*
$\Delta(2300)$	H_{39}	**
$\Delta(2350)$	D_{35}	*
$\Delta(2390)$	F_{37}	*
$\Delta(2400)$	G_{39}	**
$\Delta(2420)$	$H_{3,11}$	****
$\Delta(2750)$	$I_{3,13}$	**
$\Delta(2950)$	$K_{3,15}$	**
$\Theta(1540)^+$		*

Λ	P_{01}	****
$\Lambda(1405)$	S_{01}	****
$\Lambda(1520)$	D_{03}	****
$\Lambda(1600)$	P_{01}	***
$\Lambda(1670)$	S_{01}	****
$\Lambda(1690)$	D_{03}	****
$\Lambda(1800)$	S_{01}	***
$\Lambda(1810)$	P_{01}	***
$\Lambda(1820)$	F_{05}	****
$\Lambda(1830)$	D_{05}	****
$\Lambda(1890)$	P_{03}	****
$\Lambda(2000)$		*
$\Lambda(2020)$	F_{07}	*
$\Lambda(2100)$	G_{07}	****
$\Lambda(2110)$	F_{05}	***
$\Lambda(2325)$	D_{03}	*
$\Lambda(2350)$	H_{09}	***
$\Lambda(2585)$		**

Σ^+	P_{11}	****
Σ^0	P_{11}	****
Σ^-	P_{11}	****
$\Sigma(1385)$	P_{13}	****
$\Sigma(1480)$		*
$\Sigma(1560)$		**
$\Sigma(1580)$	D_{13}	*
$\Sigma(1620)$	S_{11}	**
$\Sigma(1660)$	P_{11}	***
$\Sigma(1670)$	D_{13}	****
$\Sigma(1690)$		**
$\Sigma(1750)$	S_{11}	***
$\Sigma(1770)$	P_{11}	*
$\Sigma(1775)$	D_{15}	****
$\Sigma(1840)$	P_{13}	*
$\Sigma(1880)$	P_{11}	**
$\Sigma(1915)$	F_{15}	****
$\Sigma(1940)$	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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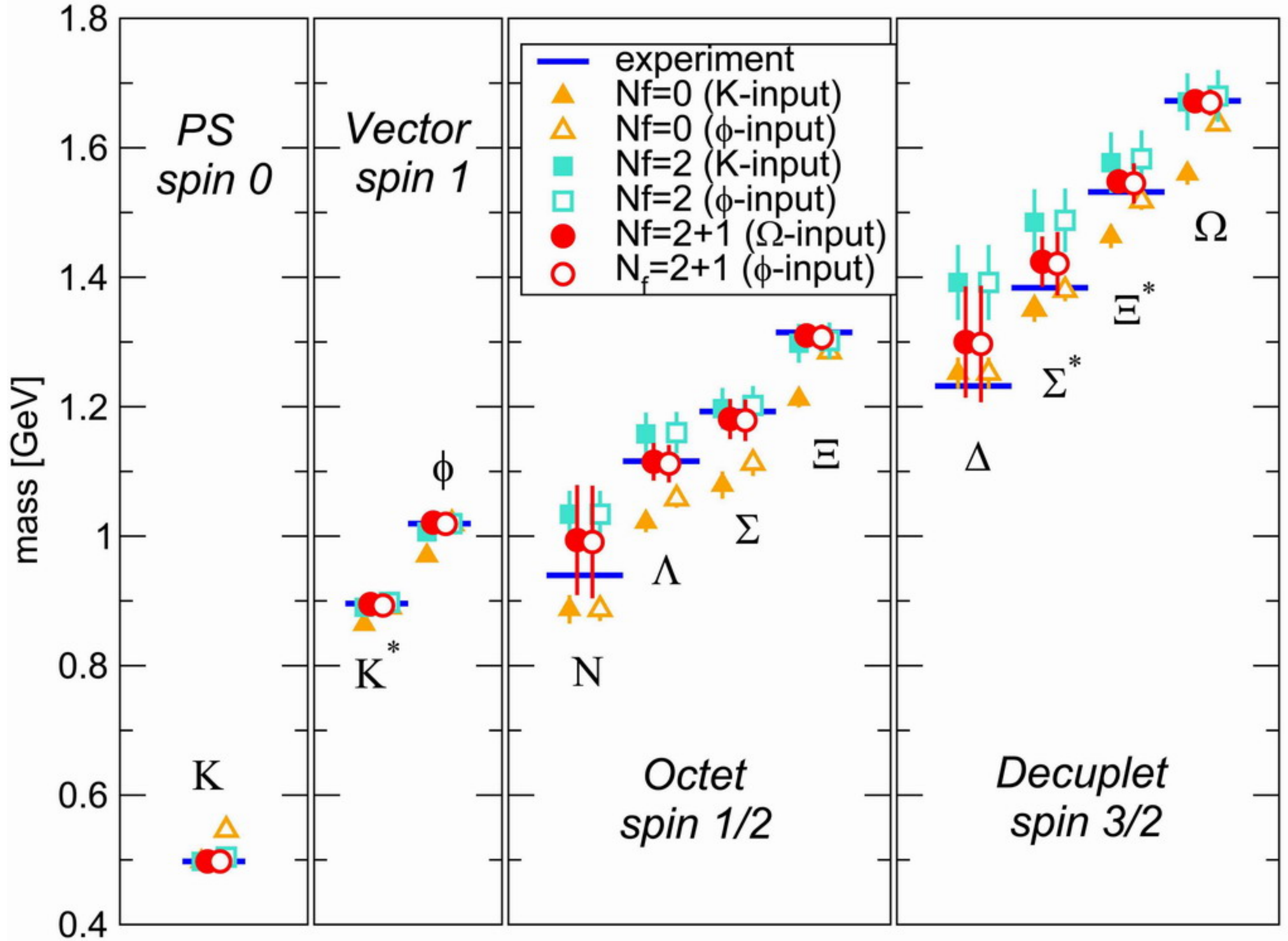
**** Existence is certain, and properties are at least fairly well explored.
*** Existence ranges from very likely to certain, but further confirmation is desirable and/or quantum numbers, branching fractions, etc. are not well determined.
** Evidence of existence is only fair.
* Evidence of existence is poor.

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

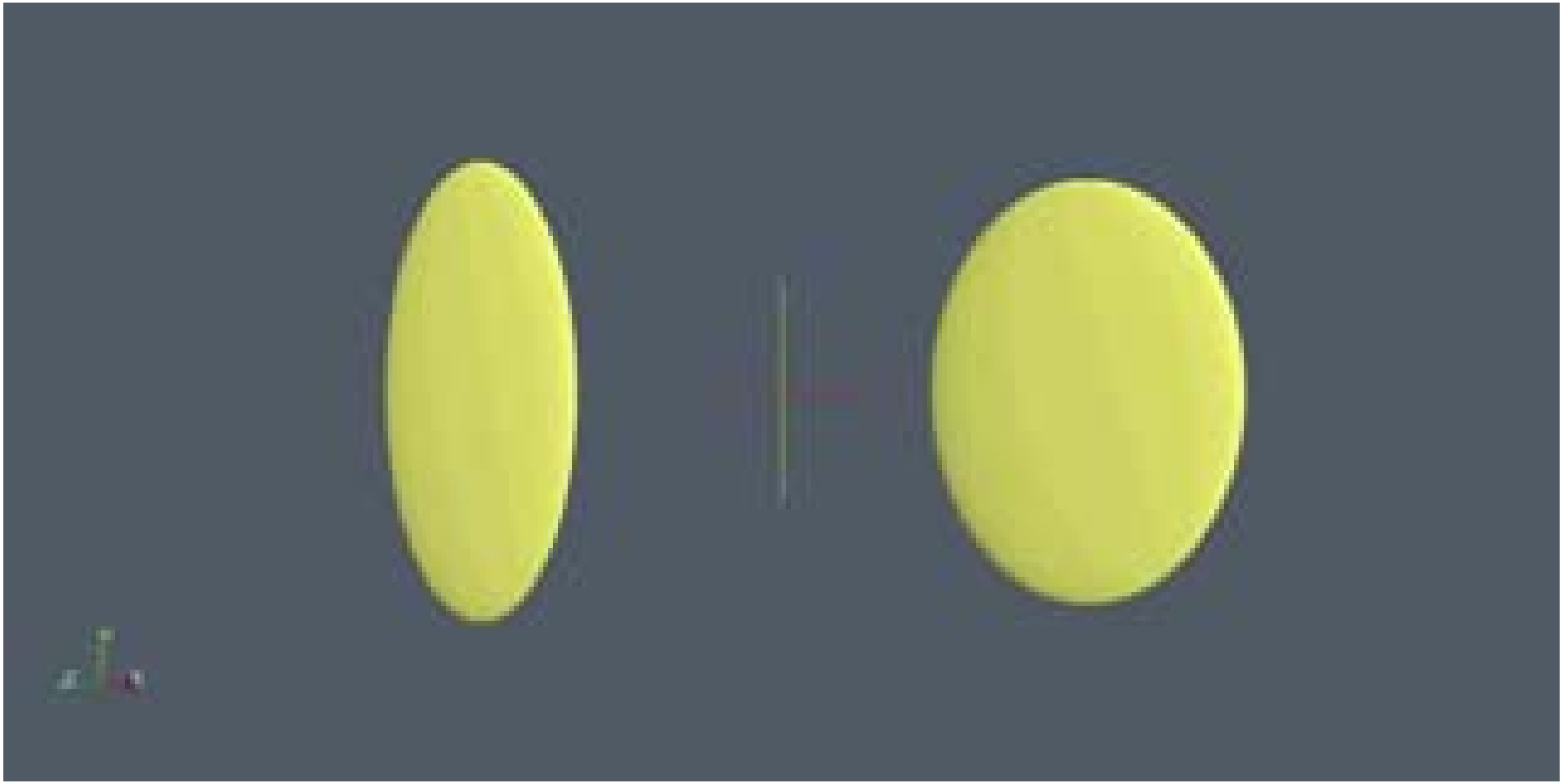
Wilson non-perturbatively improved Fermions
"WORKING HORSE" of lattice QCD calculations

Y. Kuramashi Lattice 2007

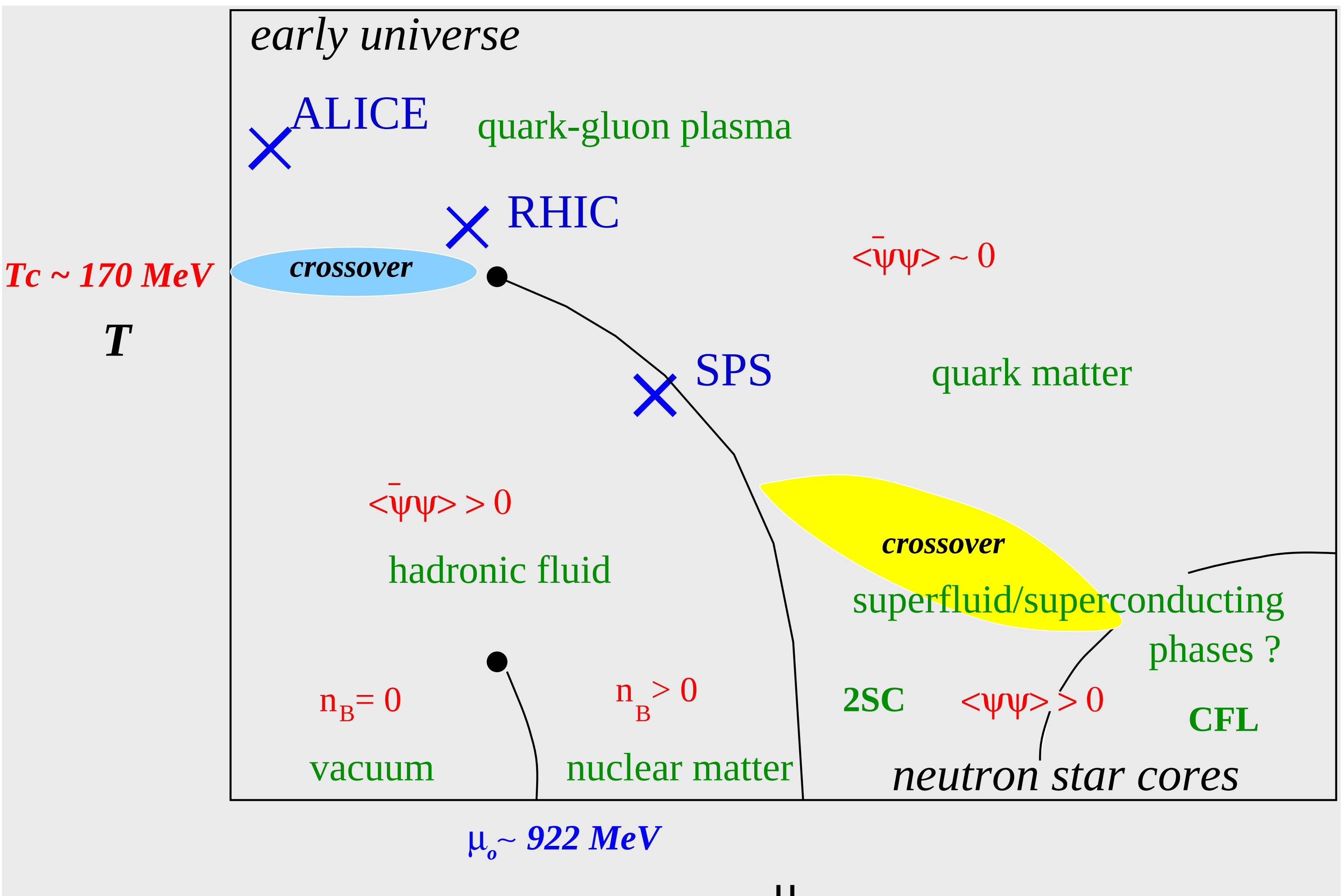
Iwasaki gauge action +
clover quarks
a^(−1) = 2.2GeV,
lattice size: 32^3 × 64



Heavy Ions Collisions and Quark- Gluon Plasma



Phase diagram of QCD

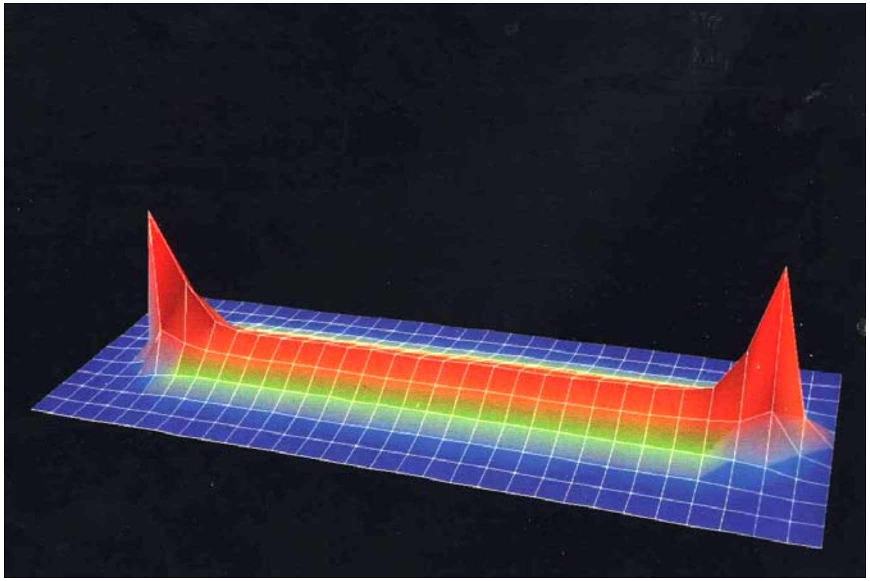


The closer our calculations to nature the more complicated they are

2 dimensional gluodynamics
(no dynamical quarks)
can be solved analytically

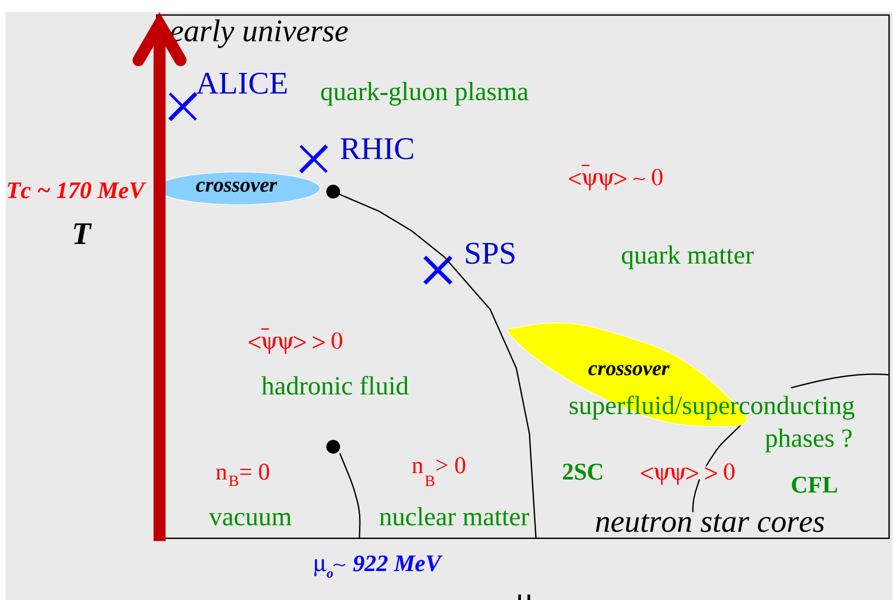
The closer our calculations to nature the more complicated they are

4 dimensional gludynamics (no dynamical quarks) can be "solved" on laptop



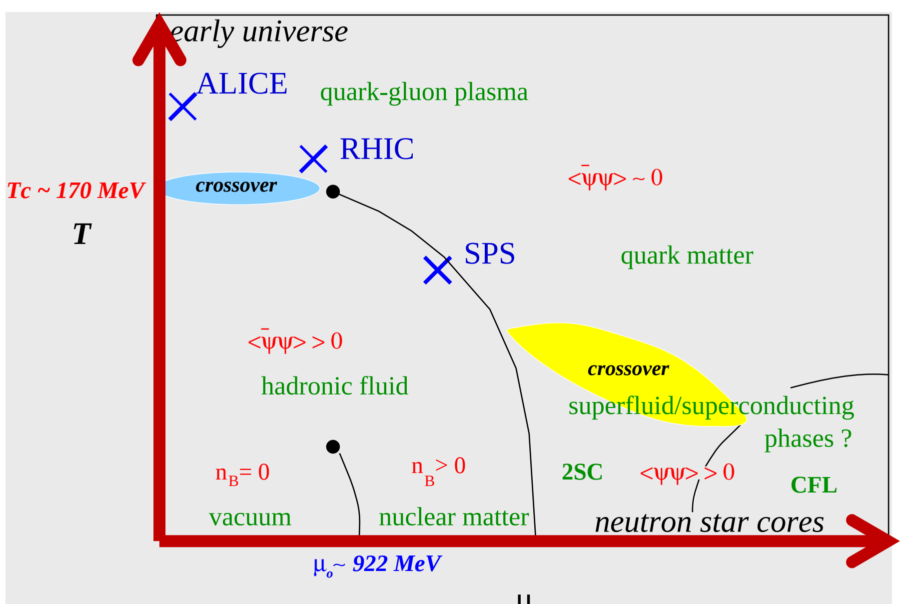
The closer our calculations to nature the more complicated they are

4 dimensional QCD (with dynamical quarks) needs 100-100000 times more CPU time than gluodynamics (we need supercomputers)

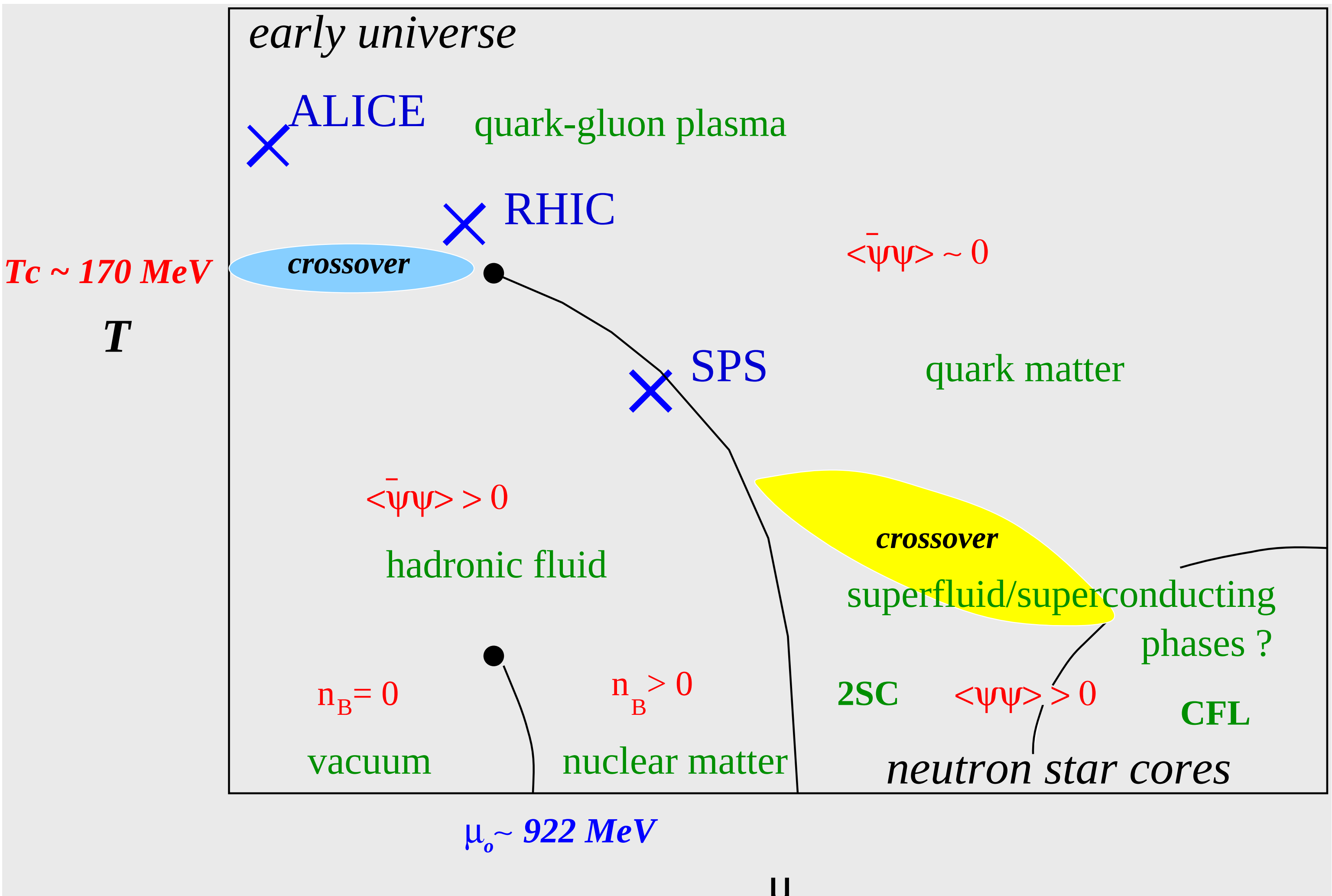


The closer our calculations to nature the more complicated they are

<u>We do not know</u> how to solve 4 dimensional QCD (with dynamical quarks) at finite chemical potential

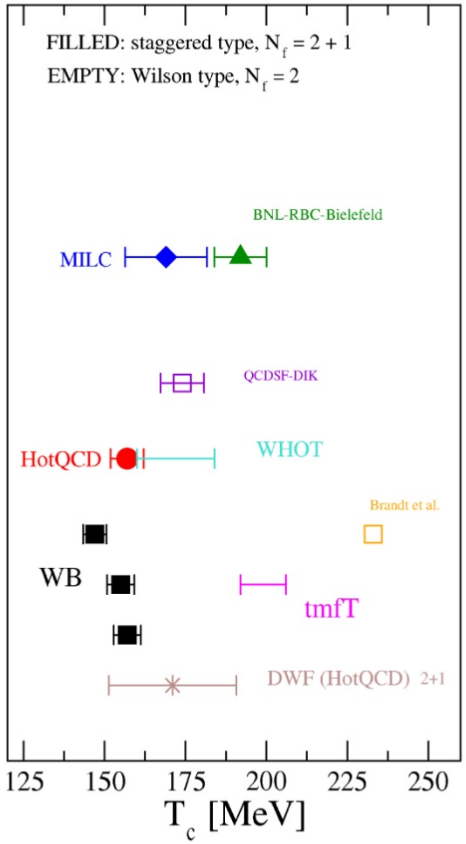


Phase diagram of QCD



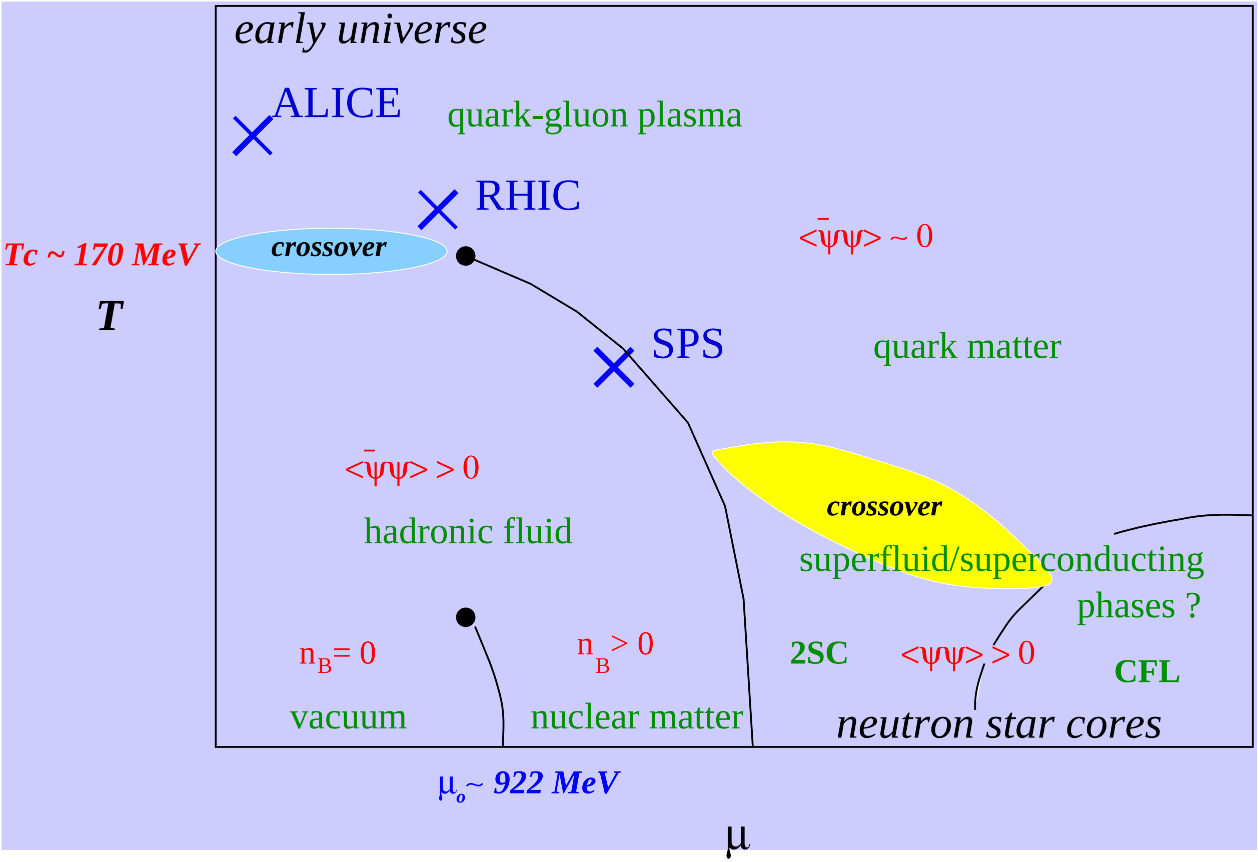
Critical temperature

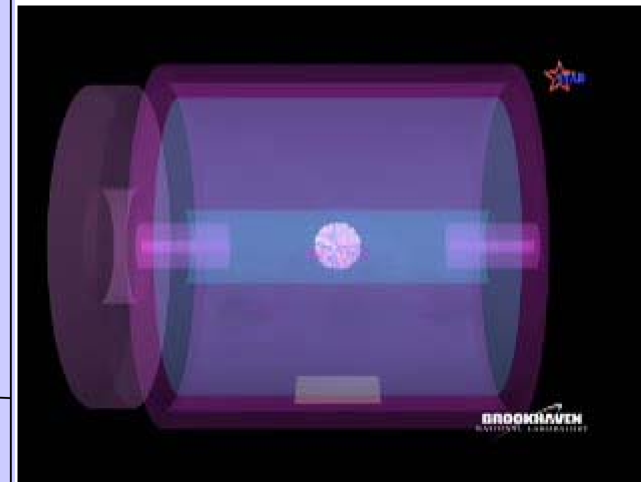
Transition temperature from a variety of studies



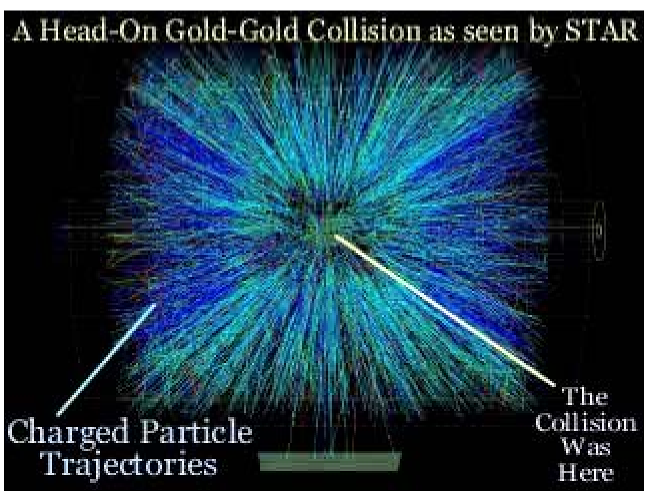
- Staggered types, $N_f = 2+1$: p4, asqtad, HISQ, stout — already introduced. Data from only chiral type observables.
- Wilson types, $N_f = 2$:
  - QCDSF-DIK [arXiv:0910.2392], clover + plaquette, $N_t = 8-14$
  - WHOT-QCD [arXiv:0909.2121], clover + Iwasaki, $N_t = 4-6$
  - Brandt et al. [arXiv:1011.6172], clover, $N_t = 16$
  - tmfT (Florian Burger talk), mtmWilson + tree-level Symazik, $N_t = 8-12$
- DWF (HotQCD), $N_f = 2+1$:+Iwasaki, $N_t = 8$, $L_s = 32-96$

L. Levkova; Talk at Lattice 2011


early universe
ALICE
quark-gluon plasma
RHIC
Tc ~ 170 MeV
crossover
T
<ψ̄ψ> ~ 0
SPS
quark matter
<ψ̄ψ> > 0
hadronic fluid
crossover
superfluid/superconducting
phases ?
n_B = 0
n_B > 0
2SC
<ψψ> > 0
CFL
vacuum
nuclear matter
neutron star cores
μ_o ~ 922 MeV
μ



RHIC


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


RHIC Collisions

AMS 2005, Tampa meeting

created matter at a temperature of about 4 trillion degrees Celsius —
the hottest temperature ever reached in a laboratory, about 250,000
times hotter than the center of the Sun

using a giant atom smasher said on they have created a new state of matter - a hot, dense liquid made out of basic atomic particles - and said it shows what the early universe looked like for a very, very brief ime.

"We think we are looking at a phenomenon ... in the universe 13 billion years ago when free quarks and gluons ... cooled down to the particles that we know today," Aronson told a news conference carried by telephone from a meeting of the American Physical Society in Tampa, Fla.

Liquid, not a gas
The quark-gluon plasma was made in the Relativistic Heavy Ion Collider — a powerful atom smasher at Brookhaven National Laboratory in Upton, N.Y. Unexpectedly, the quark-gluon plasma behaved like a perfect liquid of quarks, instead of a gas, the physicists said.

Evidence of 5-th state of matter in heavy ions collisions

1. Thermalisation
2. Elliptic flow
3. Jets quenching
4. Spectrum of photons
5. Share viscosity eta/s and hydrodynamic approach
6. Lattice calculations vs experiment
…………………………

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.

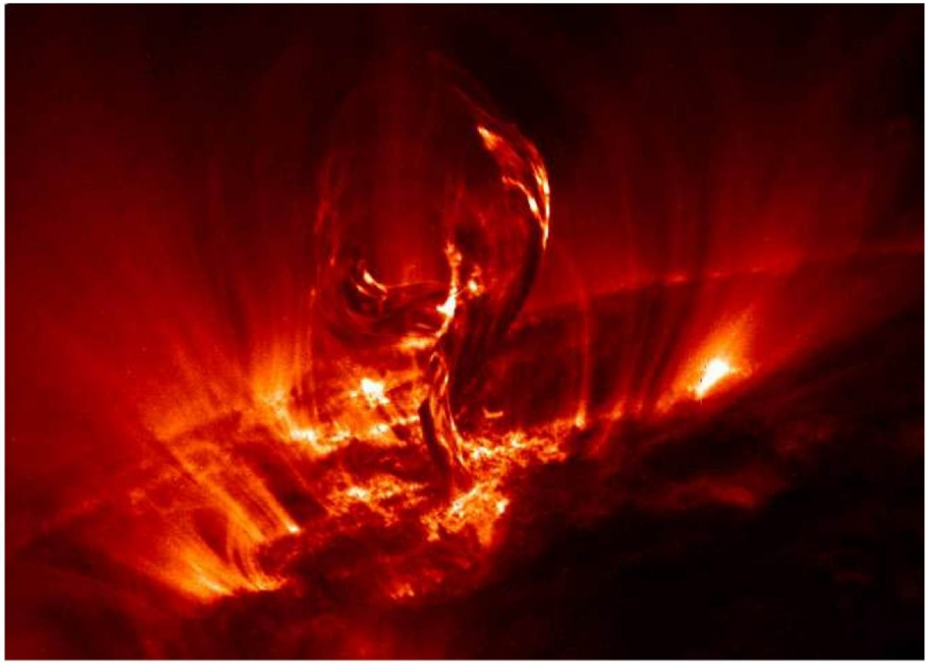


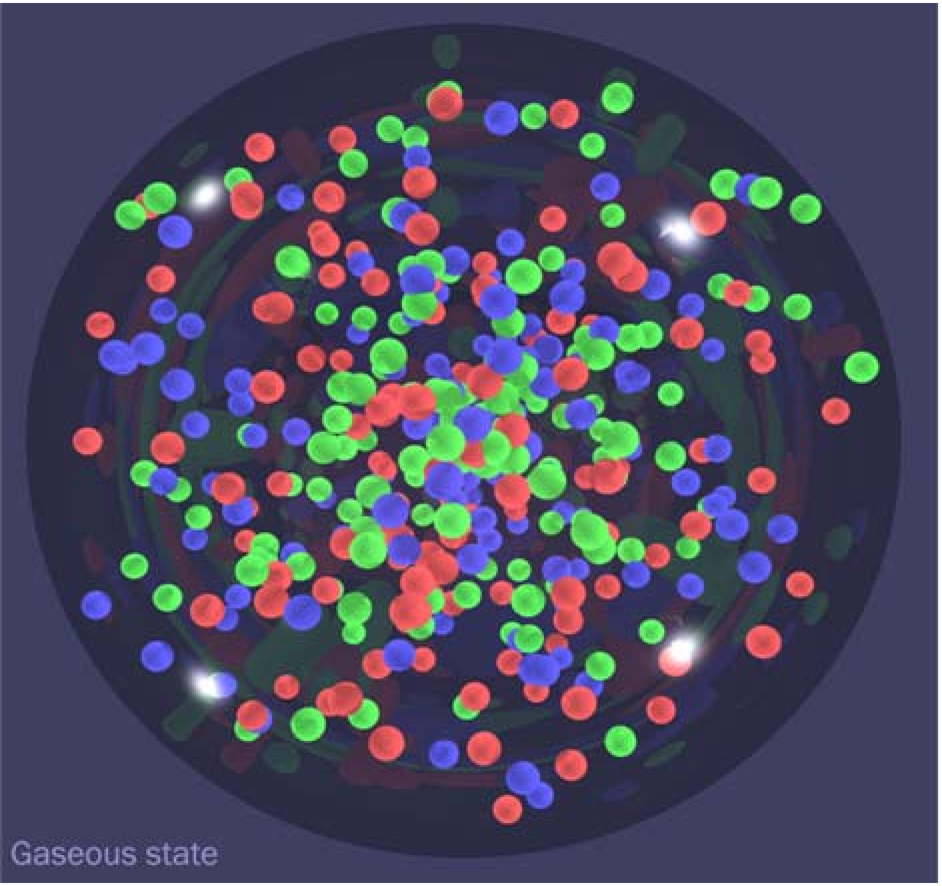
Figure 1. Image of a solar coronal filament from NASA's TRACE satellite, from ⟨http://antwrp.gsfc.nasa.gov/apod/ap000809.html⟩.

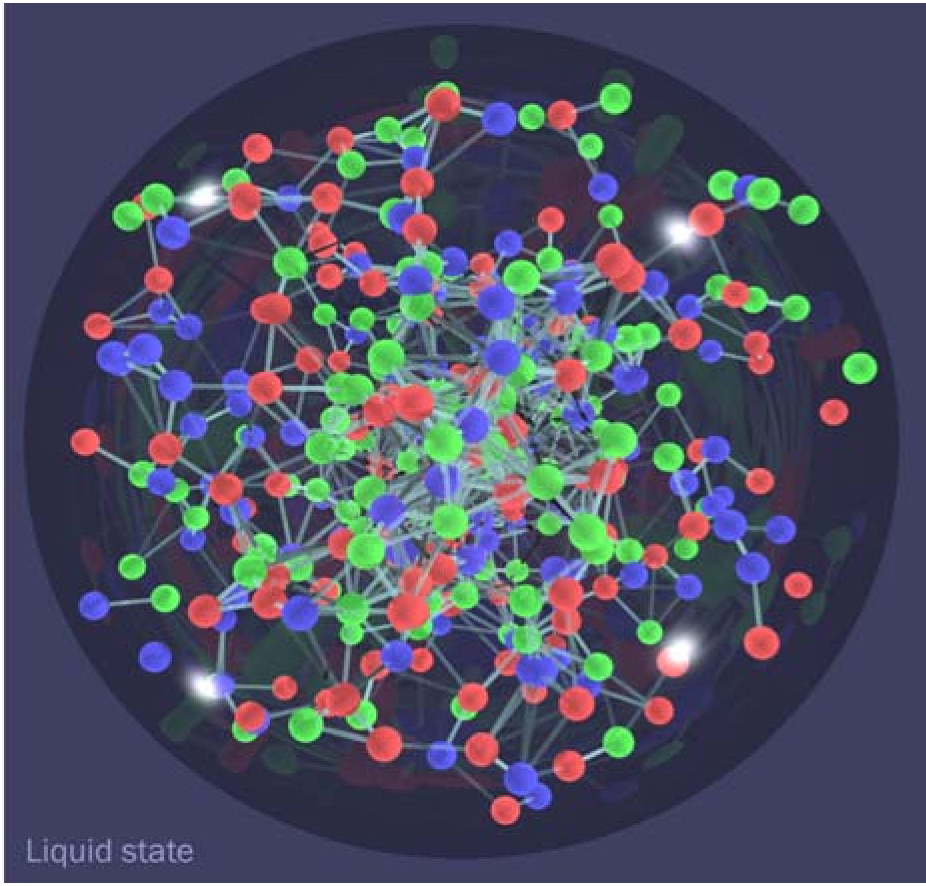
QUARK-GLUON PLASMA THERMALIZATION AND PLASMA INSTABILITIES

PETER ARNOLD

arXiv:hep-ph/0409002v1

QGP is the thermalized strongly correlated liquid





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

Below I use a lot of slides made by

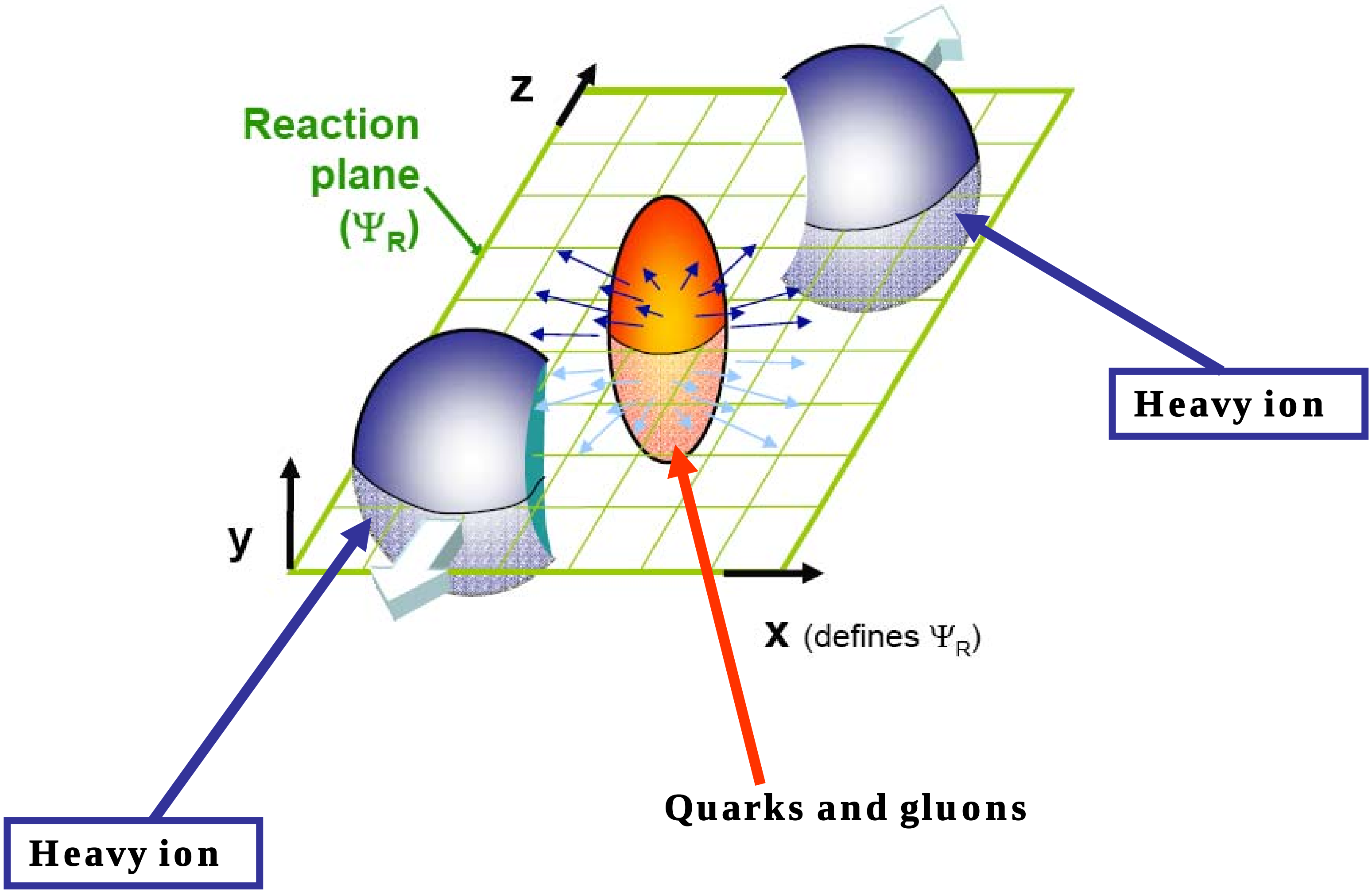
M.N. Chernodub,

P.V. Buividovich and

D.E. Kharzeev

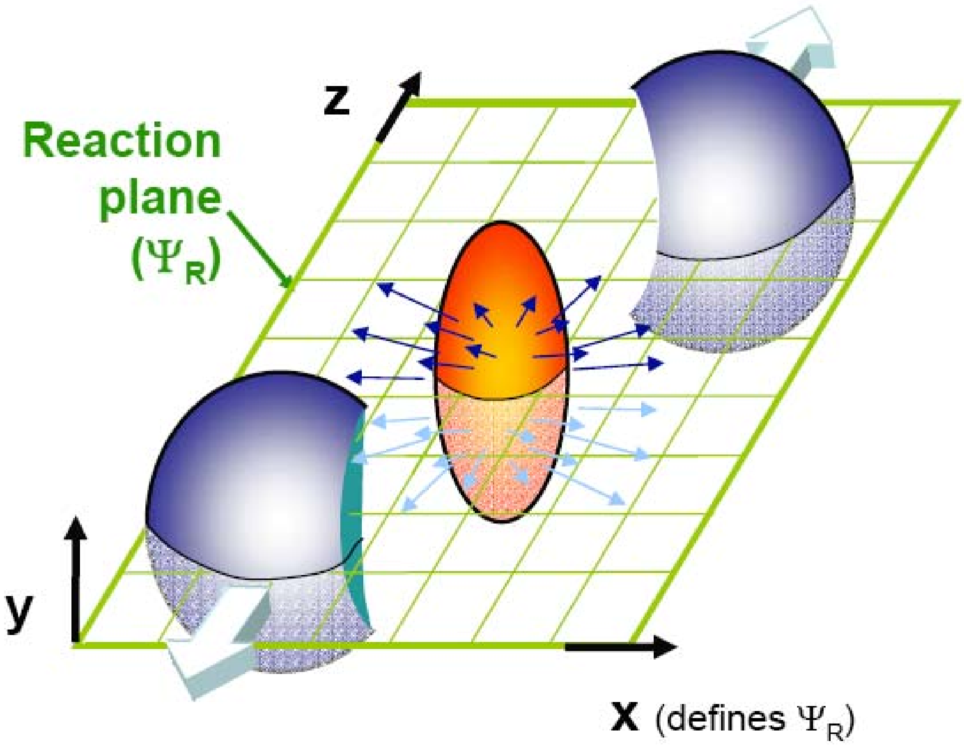
Magnetic fields in non-central collisions

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



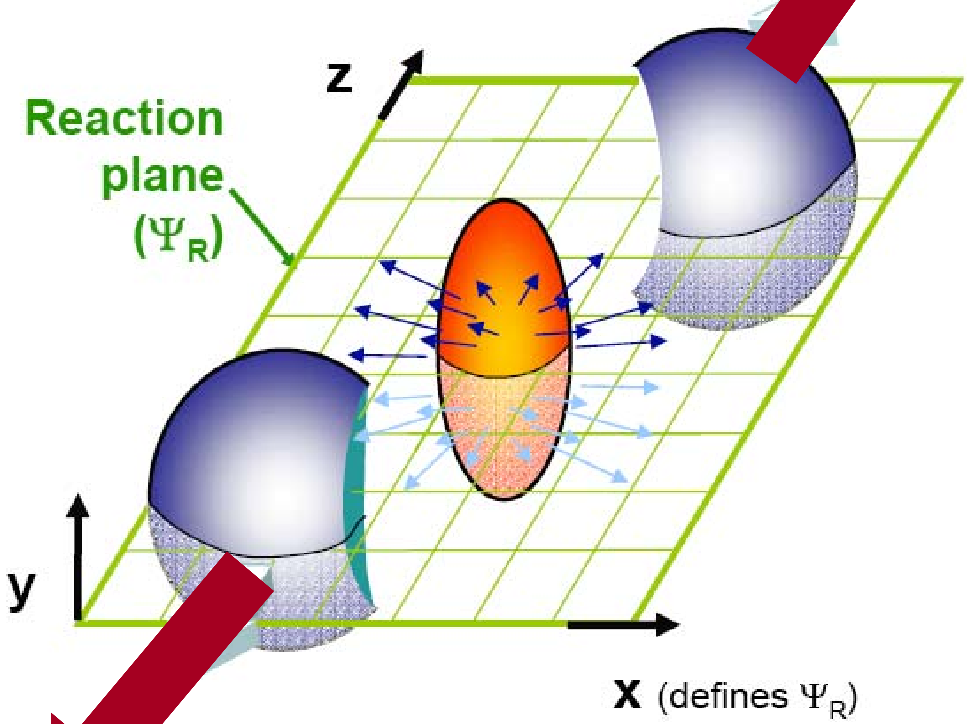
Magnetic fields in non-central collisions

[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

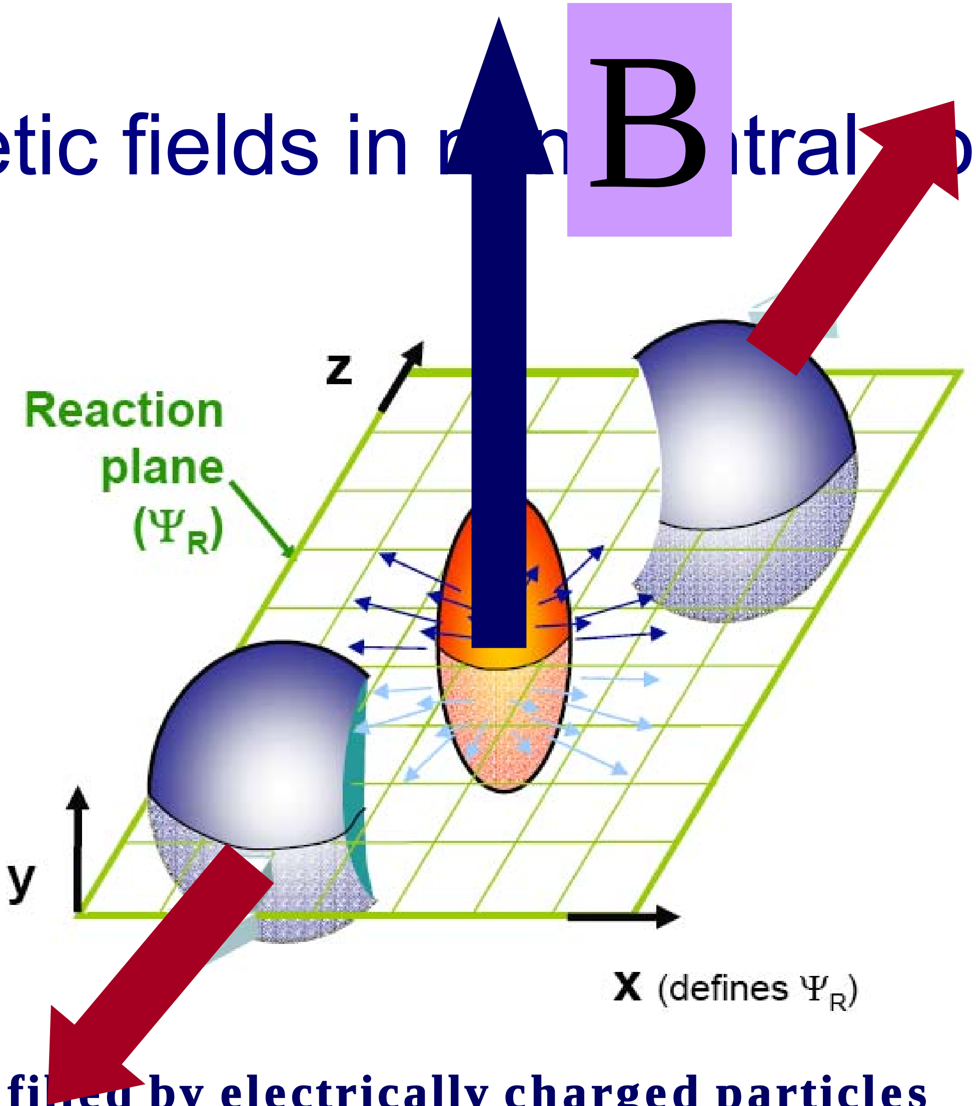
Thus we have two very big currents

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

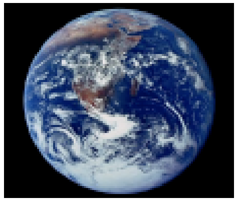
The medium is filled by electrically charged particles

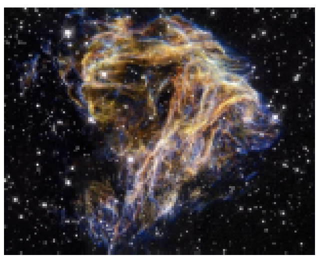
Large orbital momentum, perpendicular to the reaction plane

Large magnetic field along the direction of the orbital momentum

Comparison of magnetic fields

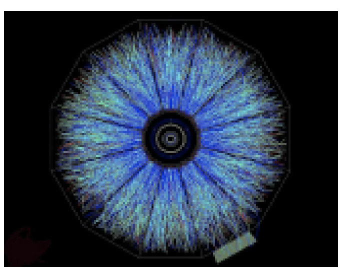
D.Kharzeev





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

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

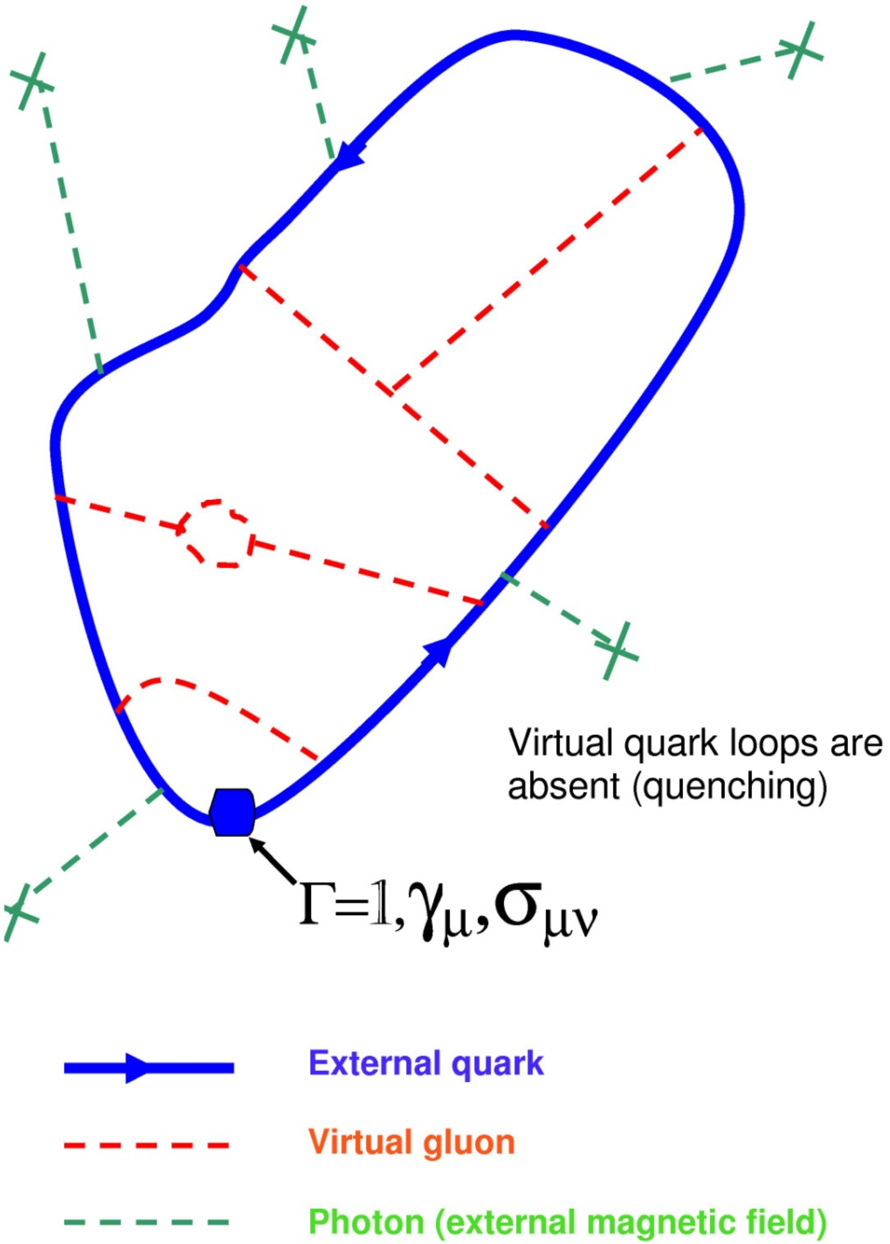
We expect the influence of magnetic field on strong interaction physics

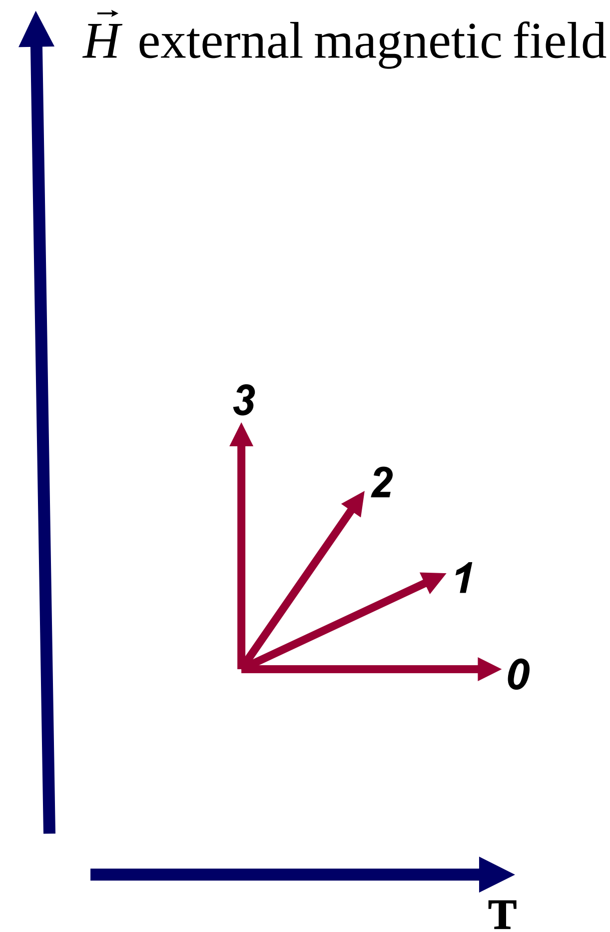
The effects are nonperturbative,
it is impossible to perform analytic calculations
and we use

Lattice Calculations

We calculate $<\overline{\psi}\,\Gamma\,\psi>;\ \Gamma=1,\gamma_{\mu},\sigma_{\mu\nu}$

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





Chiral Magnetic Effect

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

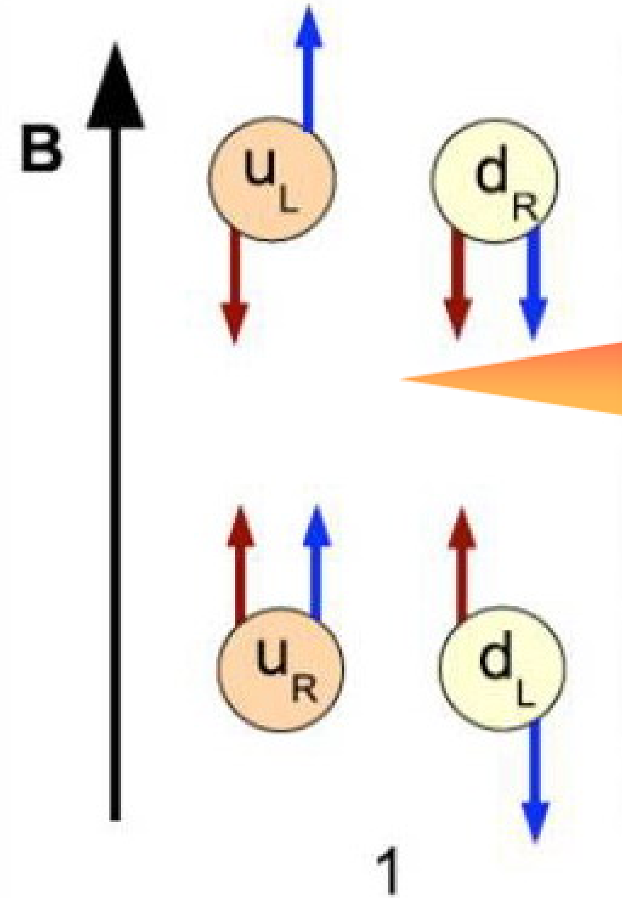
Electric current appears at regions
1. with non-zero topological charge density
2. exposed to external magnetic field

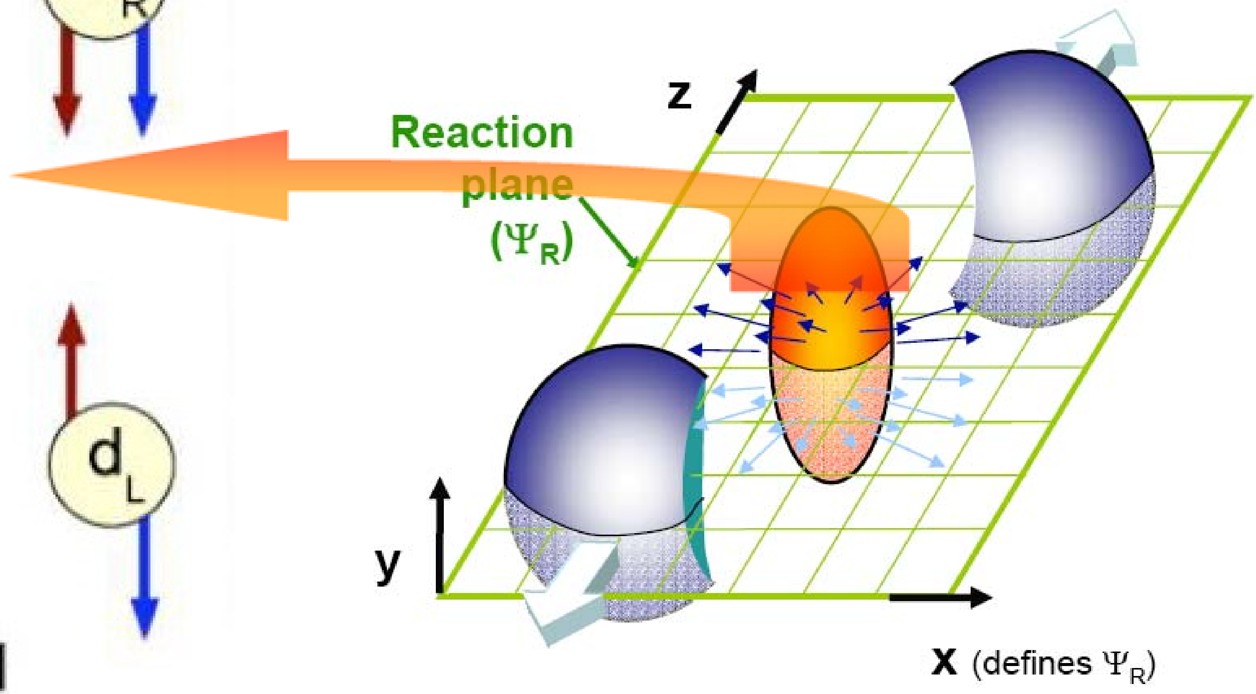
Experimentally observed at RHIC **:**
charge asymmetry of produced particles at heavy ion collisions

Chiral Magnetic Effect by
Fukushima, Kharzeev, Warringa, McLerran

1. Massless quarks in external magnetic field.

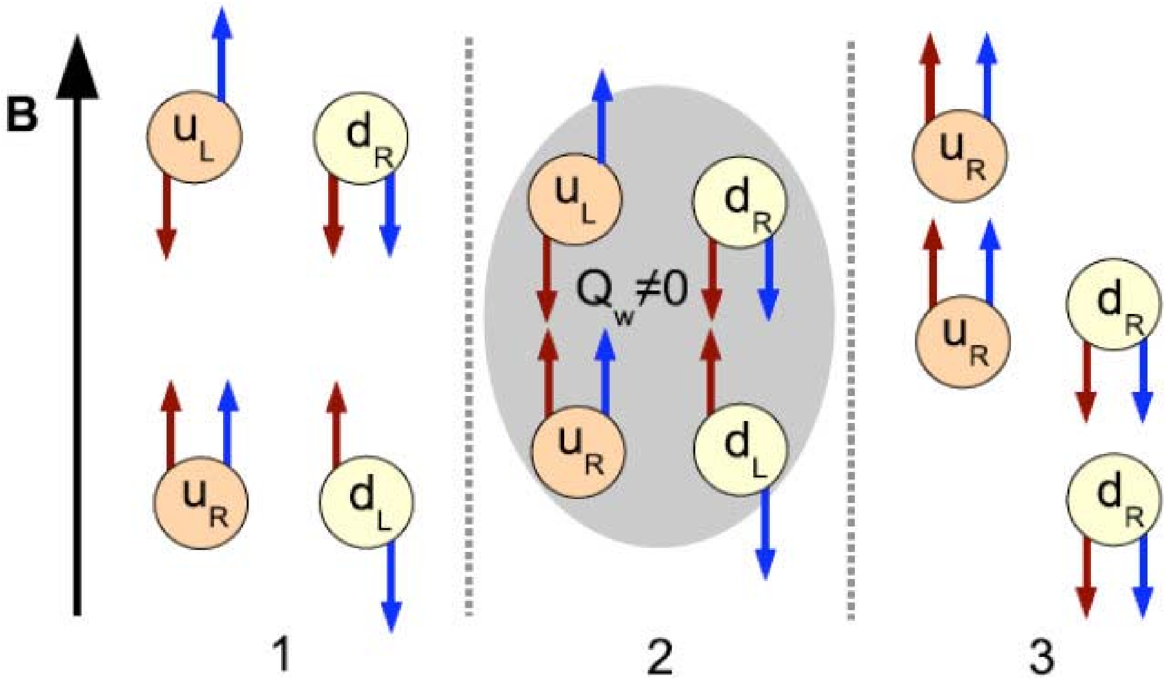
Red: momentum **Blue: spin**





Chiral Magnetic Effect by
Fukushima, Kharzeev, Warringa, McLerran

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

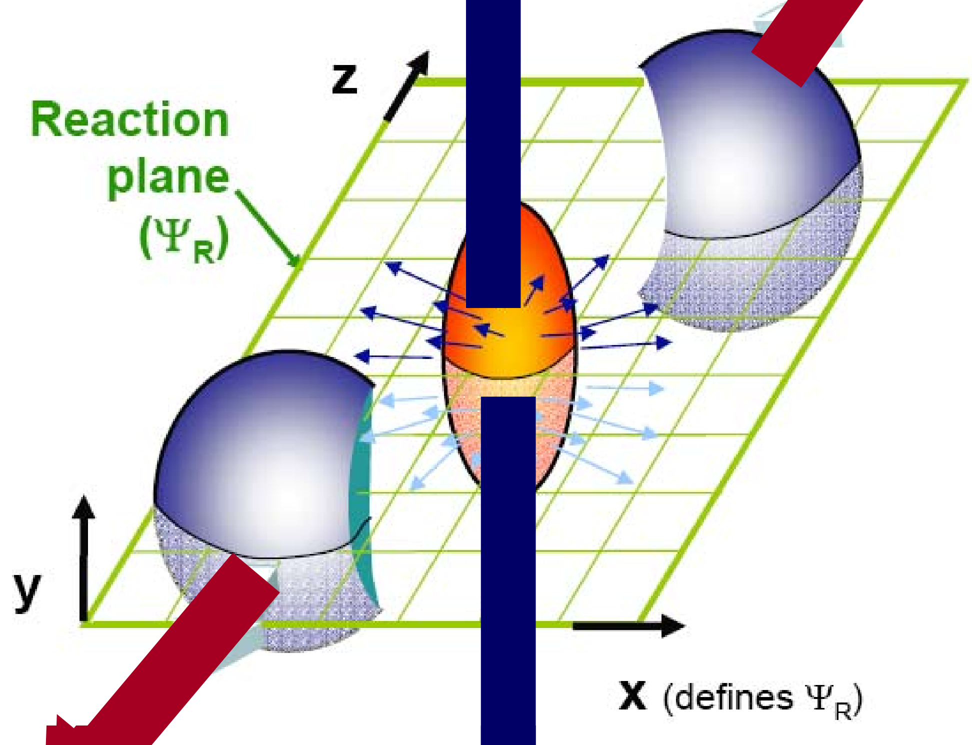


Red: momentum
Blue: spin

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

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

Magnetic fields in non-central collisions



Two very big currents produce a very big magnetic field

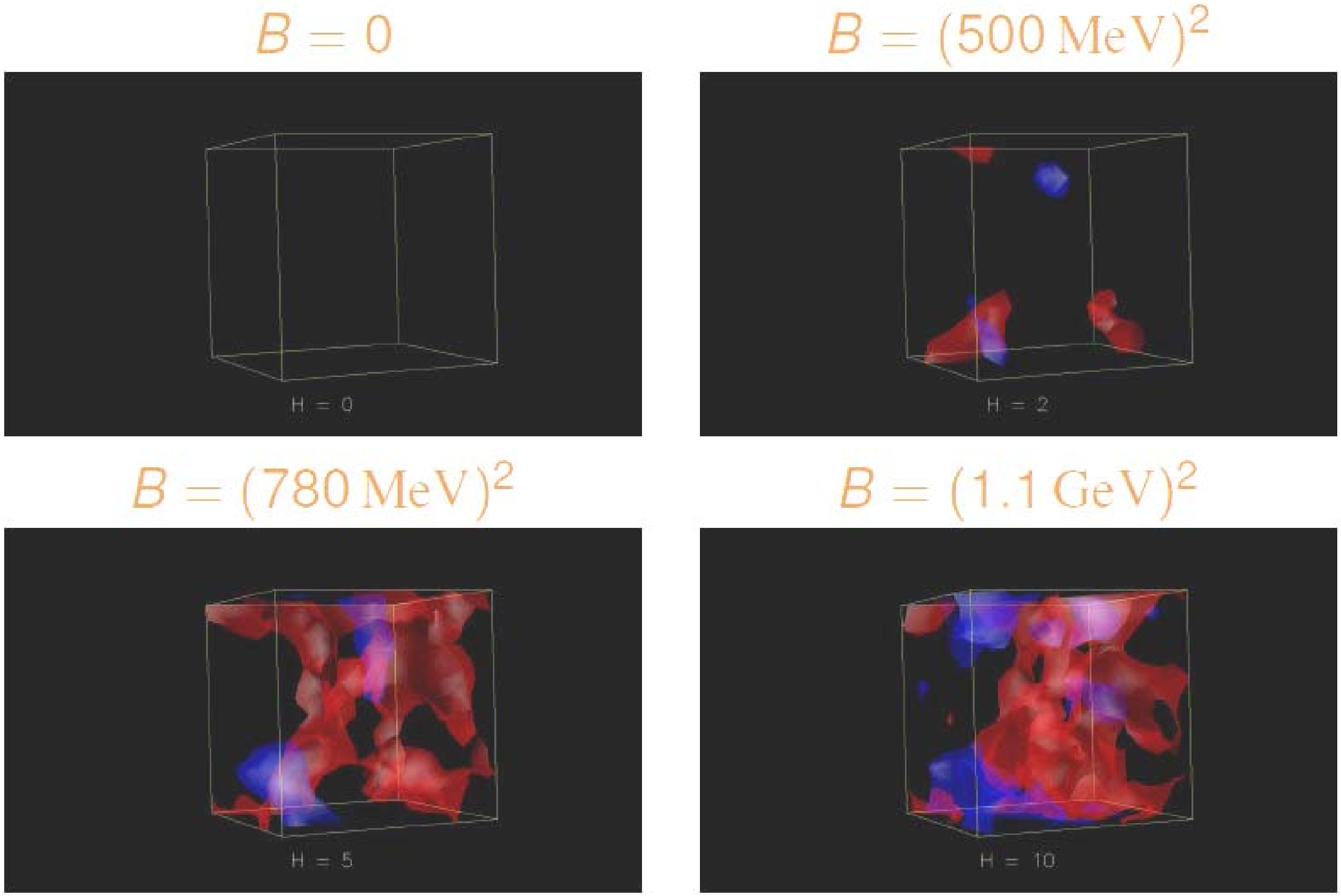
The medium is filled by electrically charged particles

Large orbital momentum, perpendicular to the reaction plane

Large magnetic field along the direction of the orbital momentum

Chiral Magnetic Effect on the lattice, charge separation

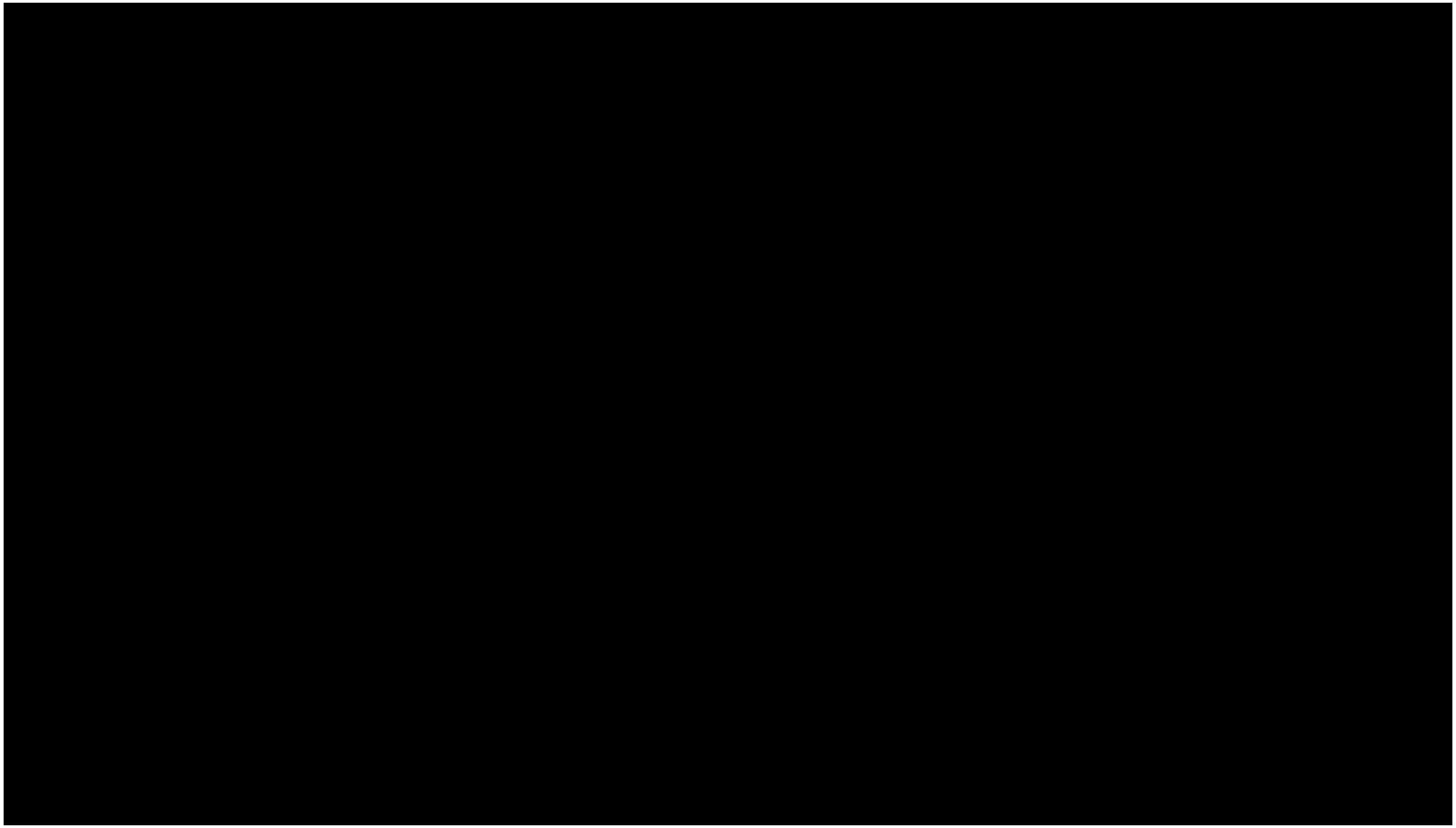
Density of the electric charge vs. magnetic field



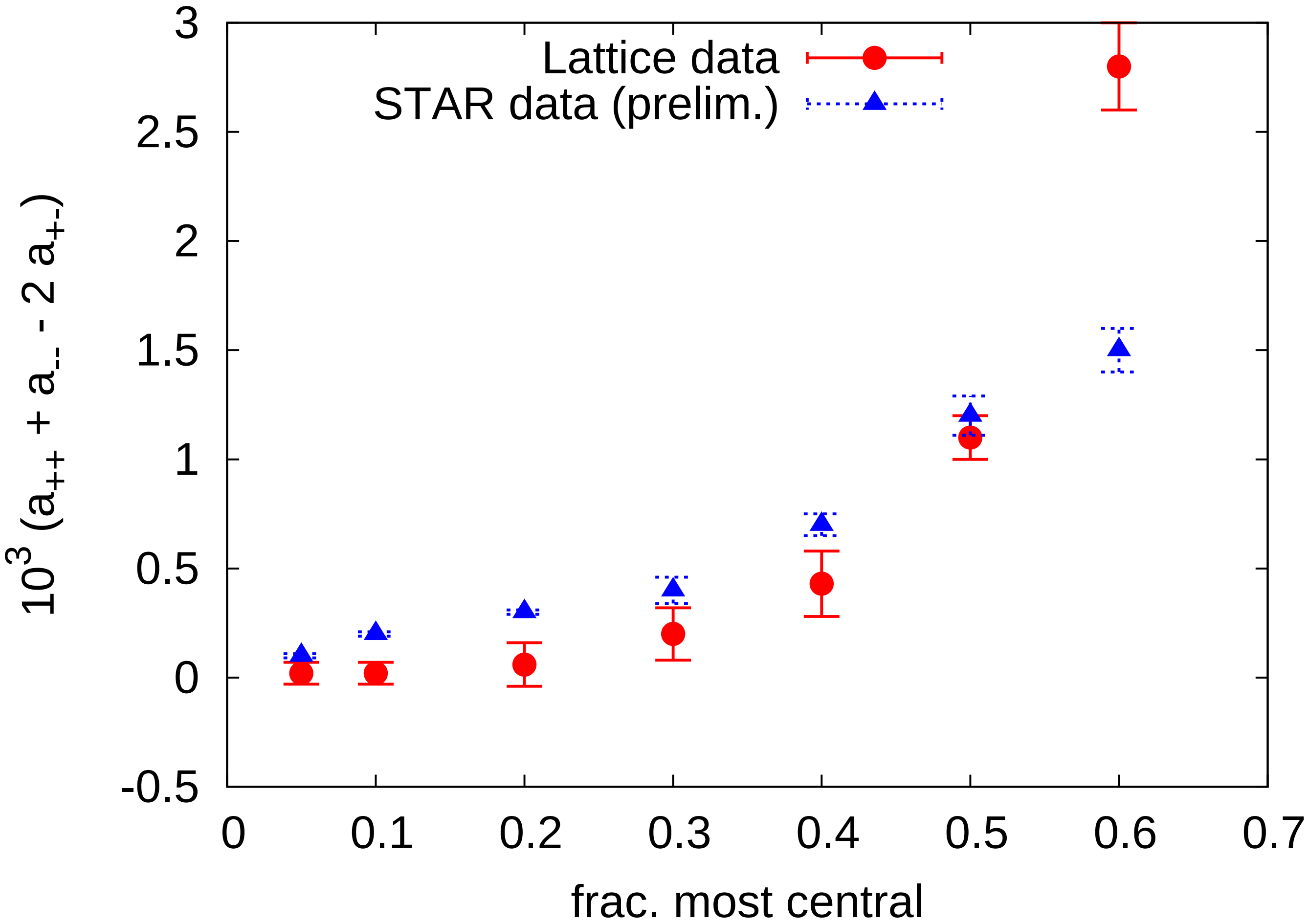
Chiral Magnetic Effect on the lattice,

Non-zero field, subsequent time slices

Electric charge density



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



Preliminary results: conductivity of the vacuum

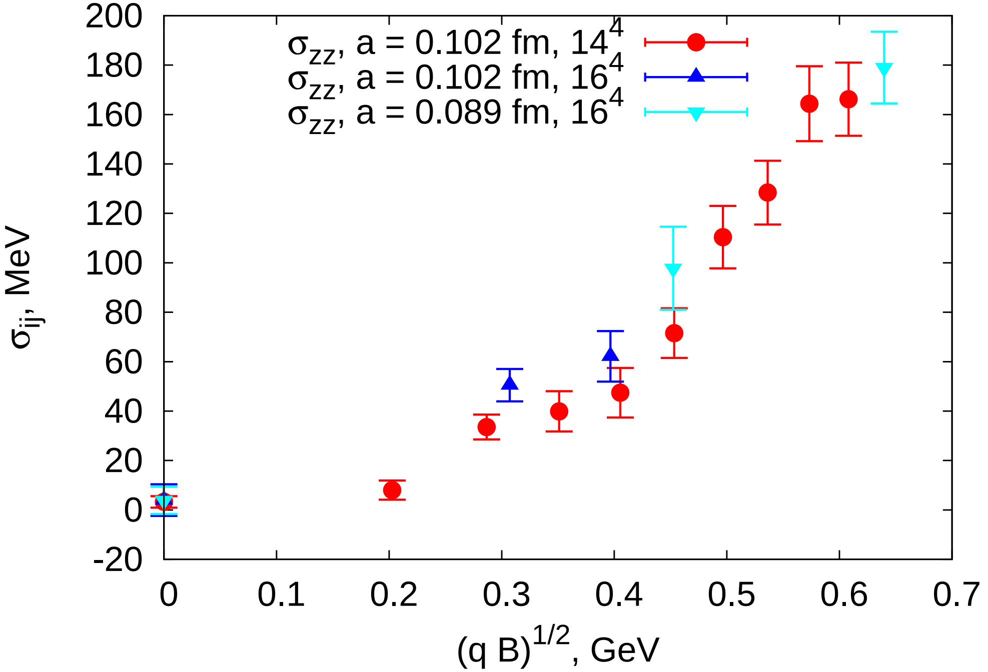
Qualitative definition of conductivity ♦

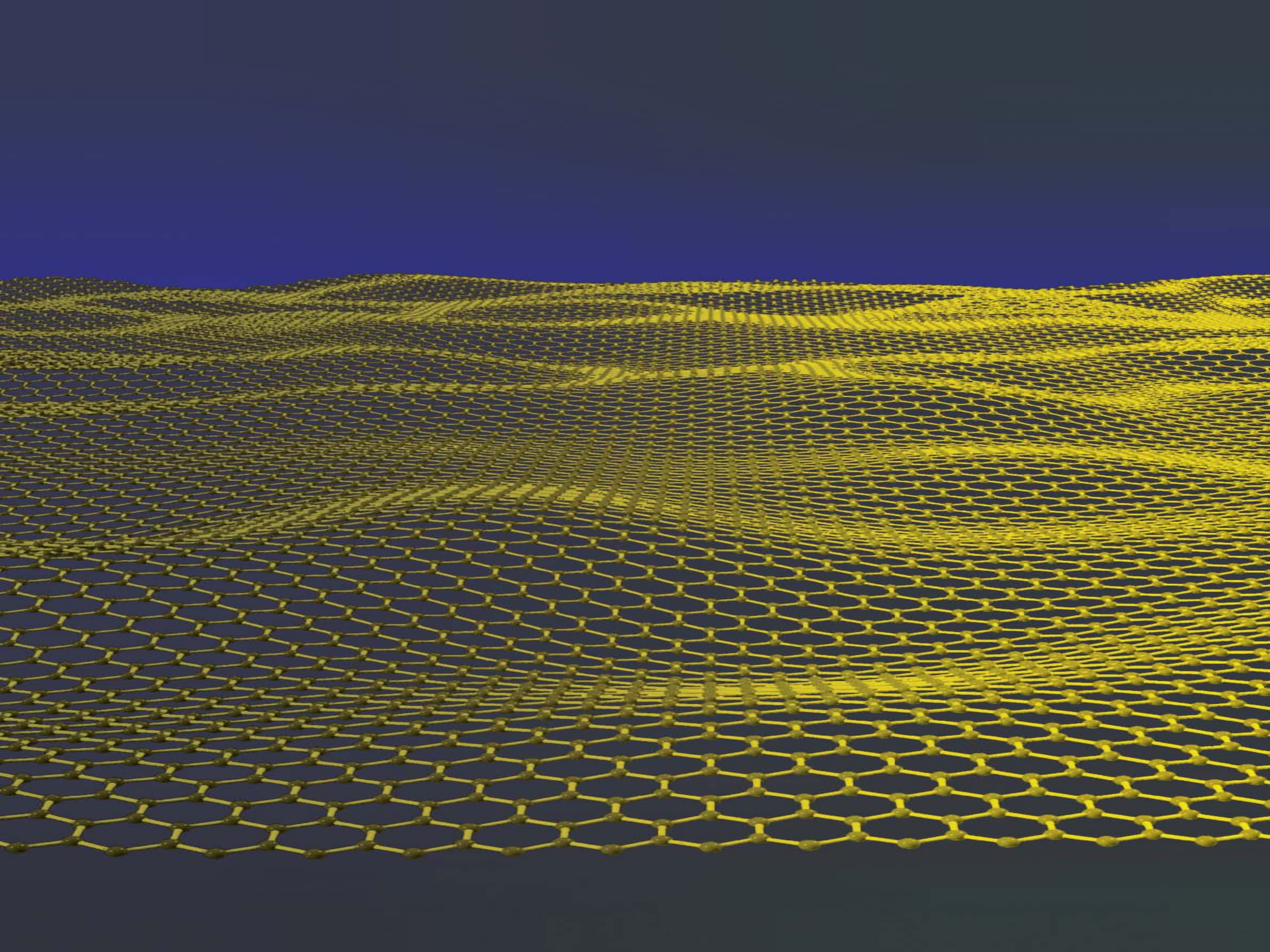
$$< j_\mu(x) j_\nu(y) > = C + A \cdot \exp\{-m|x-y|\}$$

$$\sigma \propto C$$

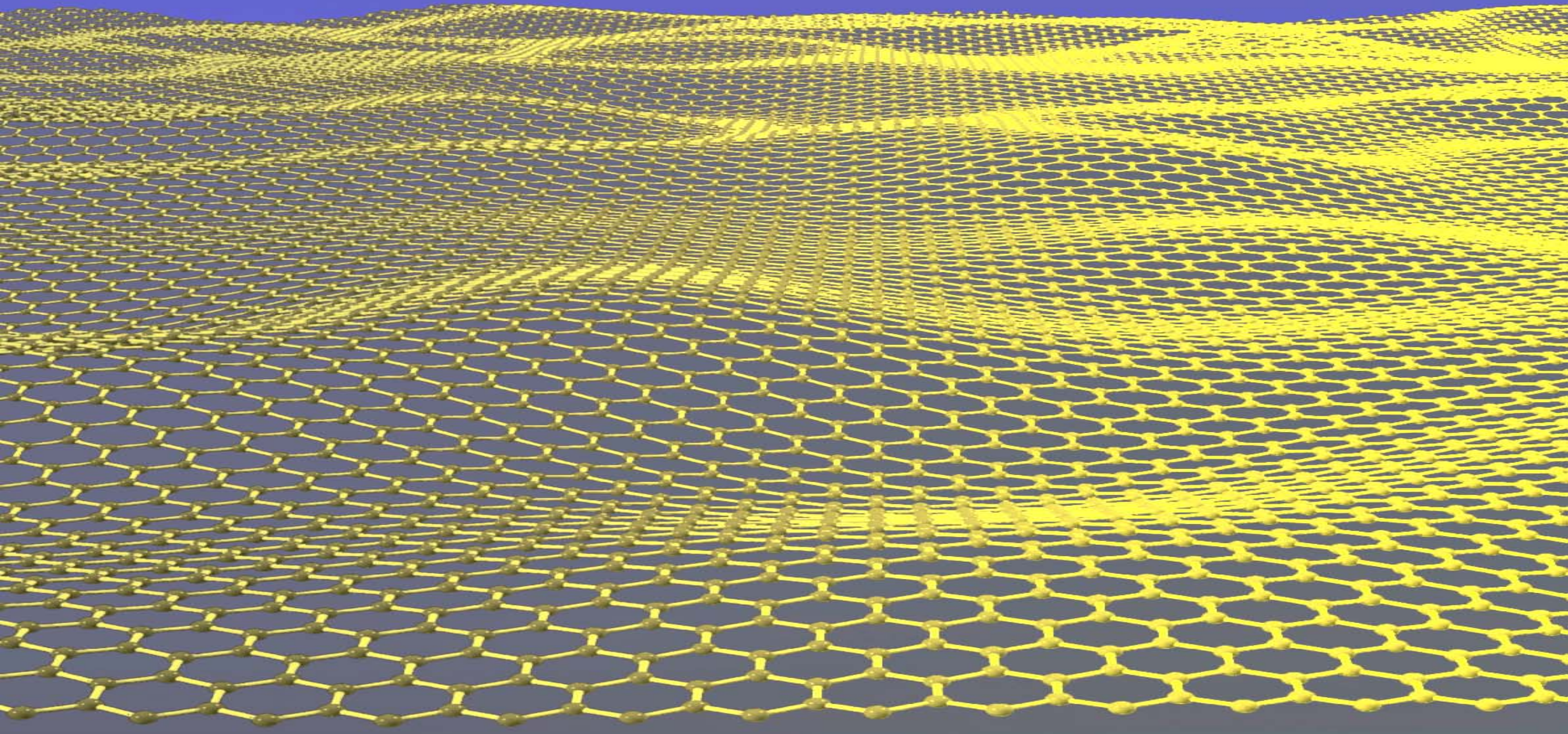
Preliminary results: conductivity of the vacuum

Conductivity at T>0

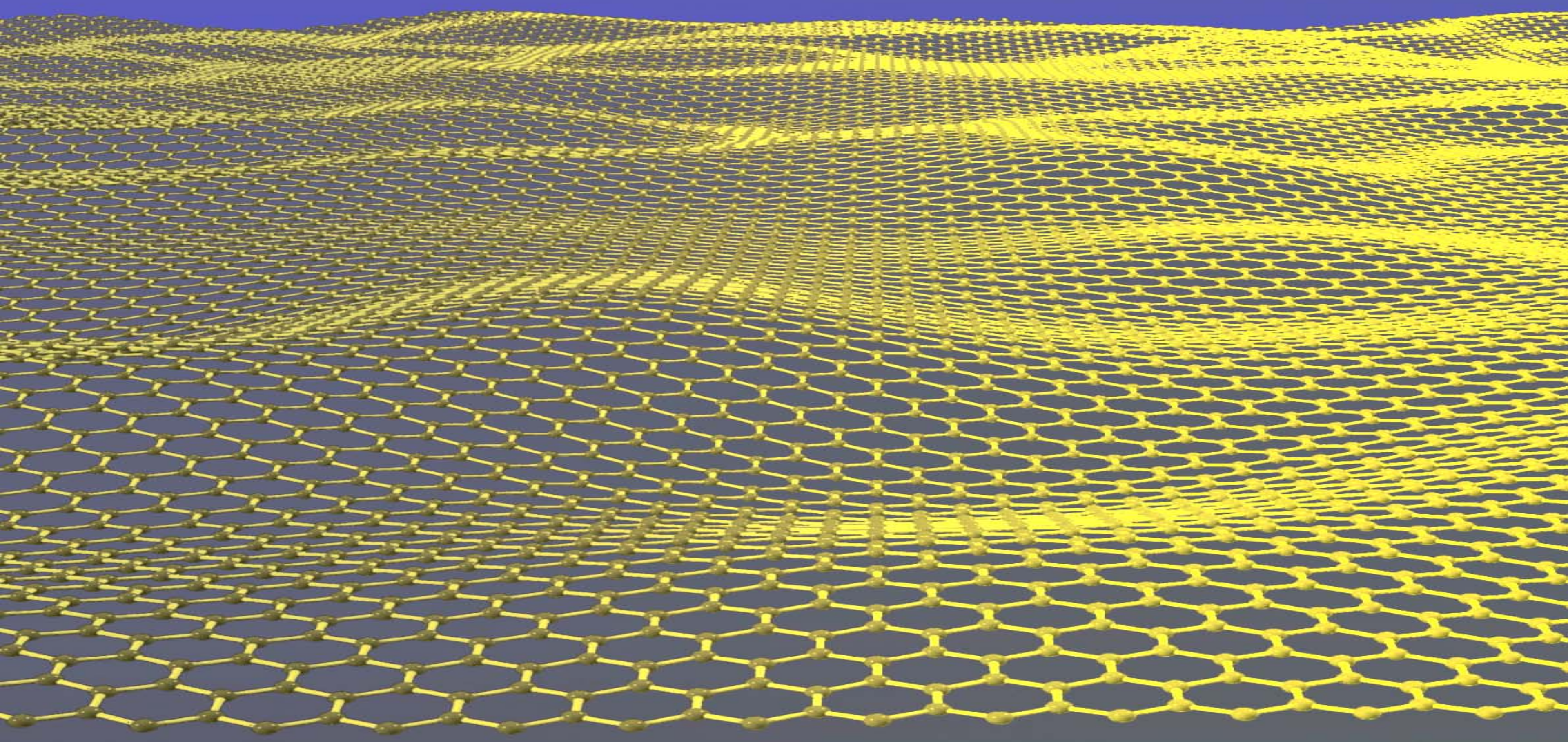




Graphene



The Nobel Prize in Physics for 2010 was awarded to Andre Geim and Konstantin Novoselov "for groundbreaking experiments regarding the two-dimensional material graphene"



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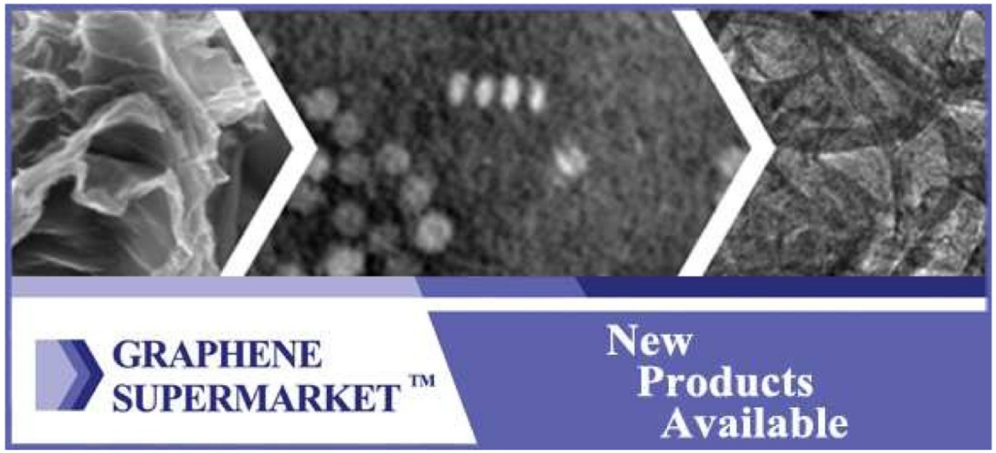

Featured products

Single Layer Graphene on Copper foil: 4"x2"

Graphene Nanopowder: 8 nm Flakes- 5 g

Q-graphene: 1 gram

https://graphene-supermarket.com/home.php

Our price: $450.00

Quantity 1

Buy Now

Our price: $99.00

Quantity 1

Buy Now

Our price: $100.00

Quantity 1

Buy Now

Reduced Graphene Oxide: 60 mg, Dry Nanopowder

Our price: $175.00

Quantity 1

Buy Now

Trial pack: 10 CVDGraphene TEM Grids

Our price: $175.00

Quantity 1

Buy Now

Graphene Oxide Paper

Our price: $300.00

Quantity 1

Buy Now

Relativistic particle $E = \sqrt{m^2c^4 + p^2c^2}$

Massless particle $E = cp$

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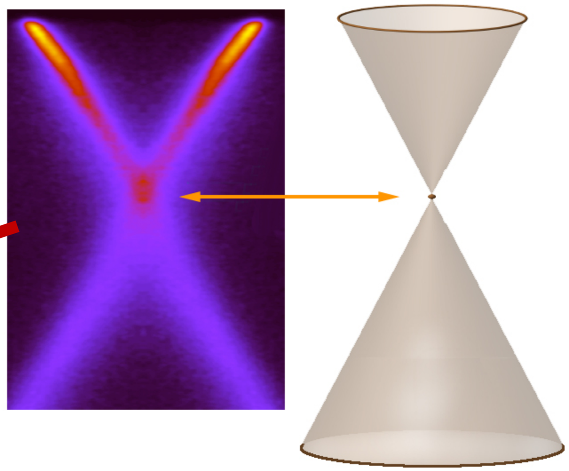
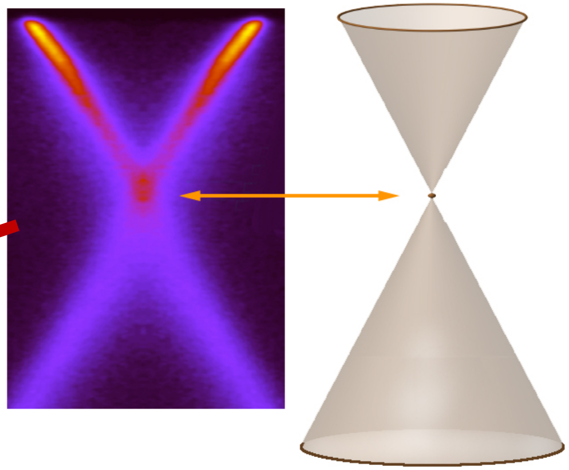
Massless particle $E = cp$



Graphene $E = v_F\, p; \quad v_F = \frac{c}{300};$



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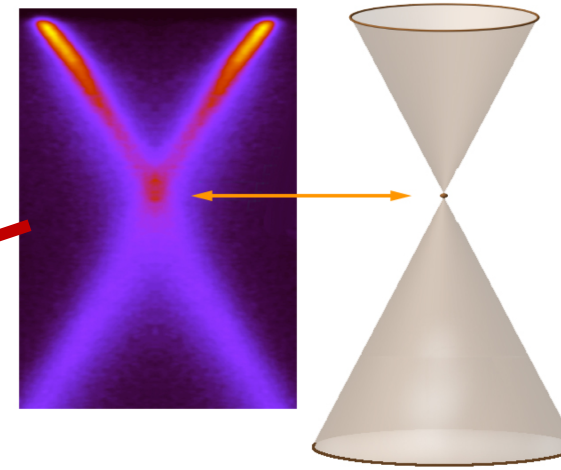
Massless particle $E = cp$

Graphene $E = v_F\, p;\quad v_F = \dfrac{c}{300};$

$\alpha_g = 300\alpha = 2.16 > 1$

$\alpha_g > \alpha_g^{crit} = 1.11 \pm 0.06$ Pure graphene is the insulator!



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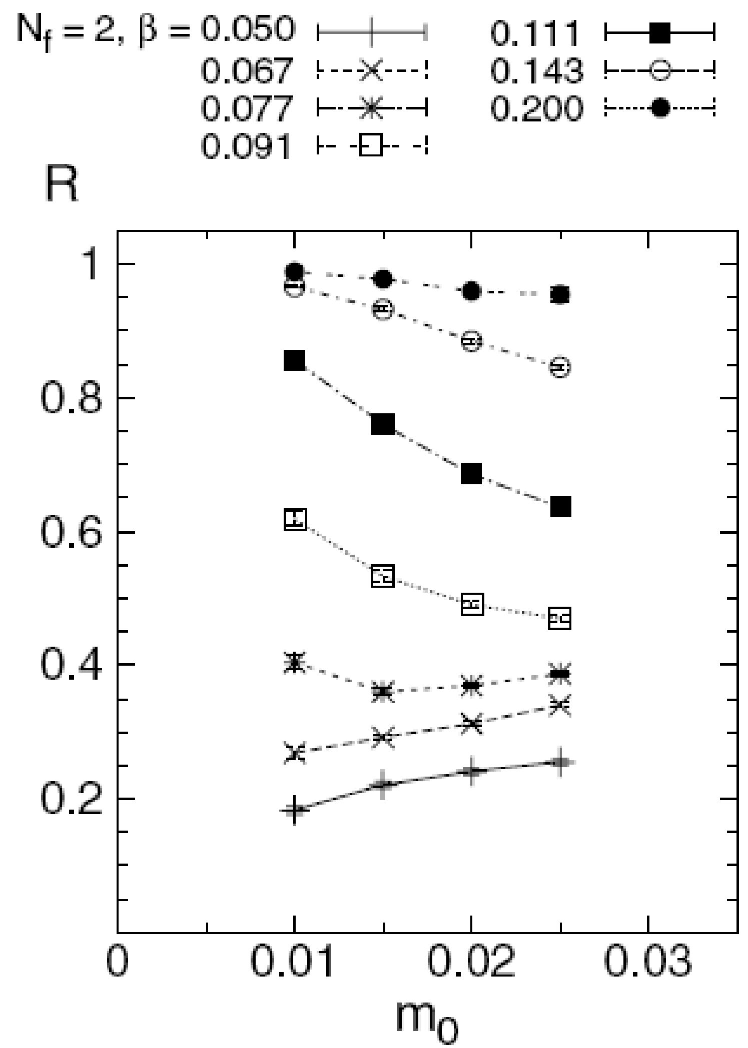
$$\alpha_g = 300\alpha = 2.16 > 1$$

$\alpha_g > \alpha_g^{crit} = 1.11 \pm 0.06$ Pure graphene is the insulator!

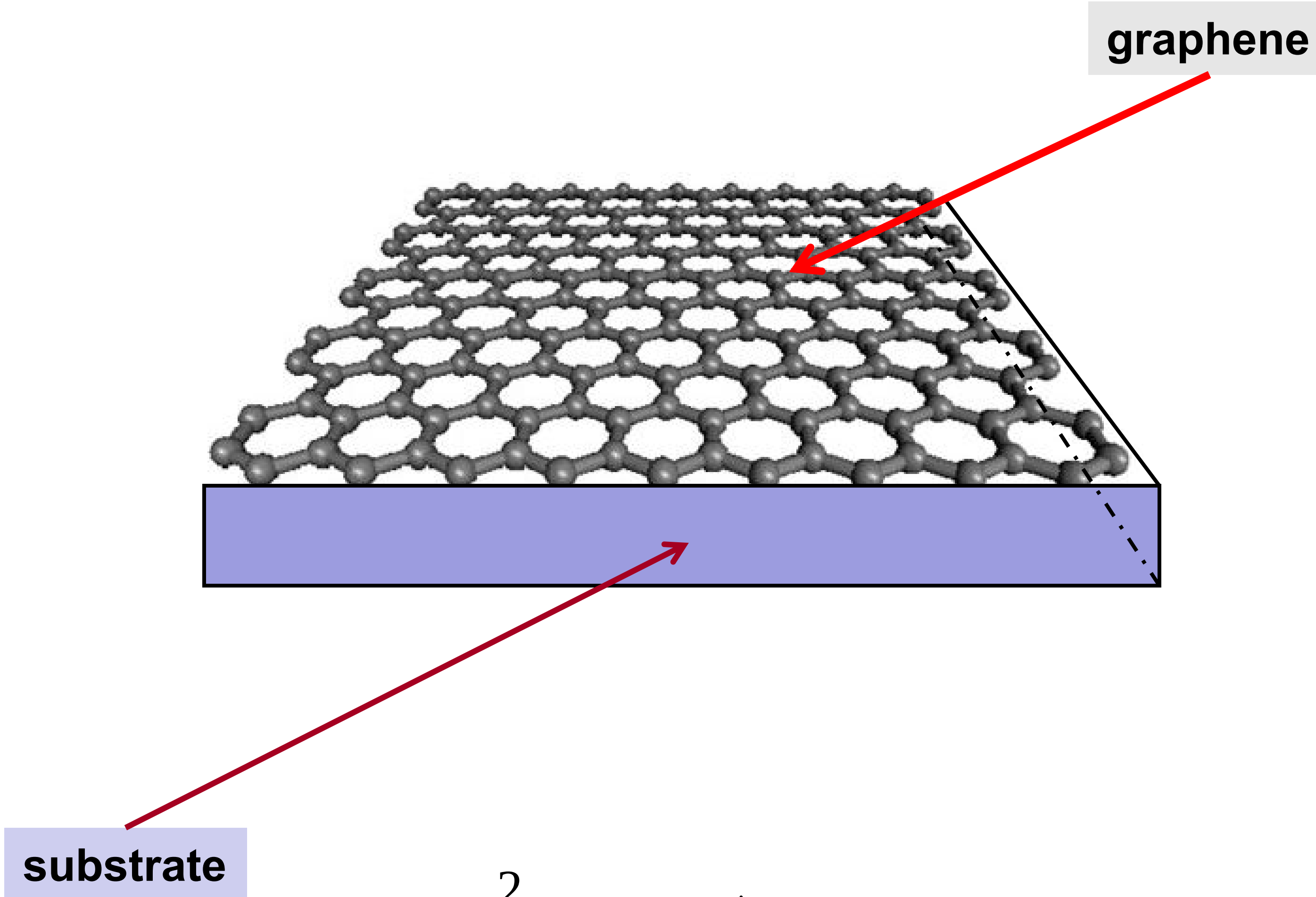
If we put graphene on a substrate we can get conductor: $\alpha_g \to \frac{2}{1+\varepsilon}\alpha_g$

Numerical calculation of α_g^{crit}

Is graphene in vacuum an insulator?.
Joaquin E. Drut Timo A. Lahde
e-Print: **arXiv:0807.0834 [cond-mat.str-el], PRL (2009)**



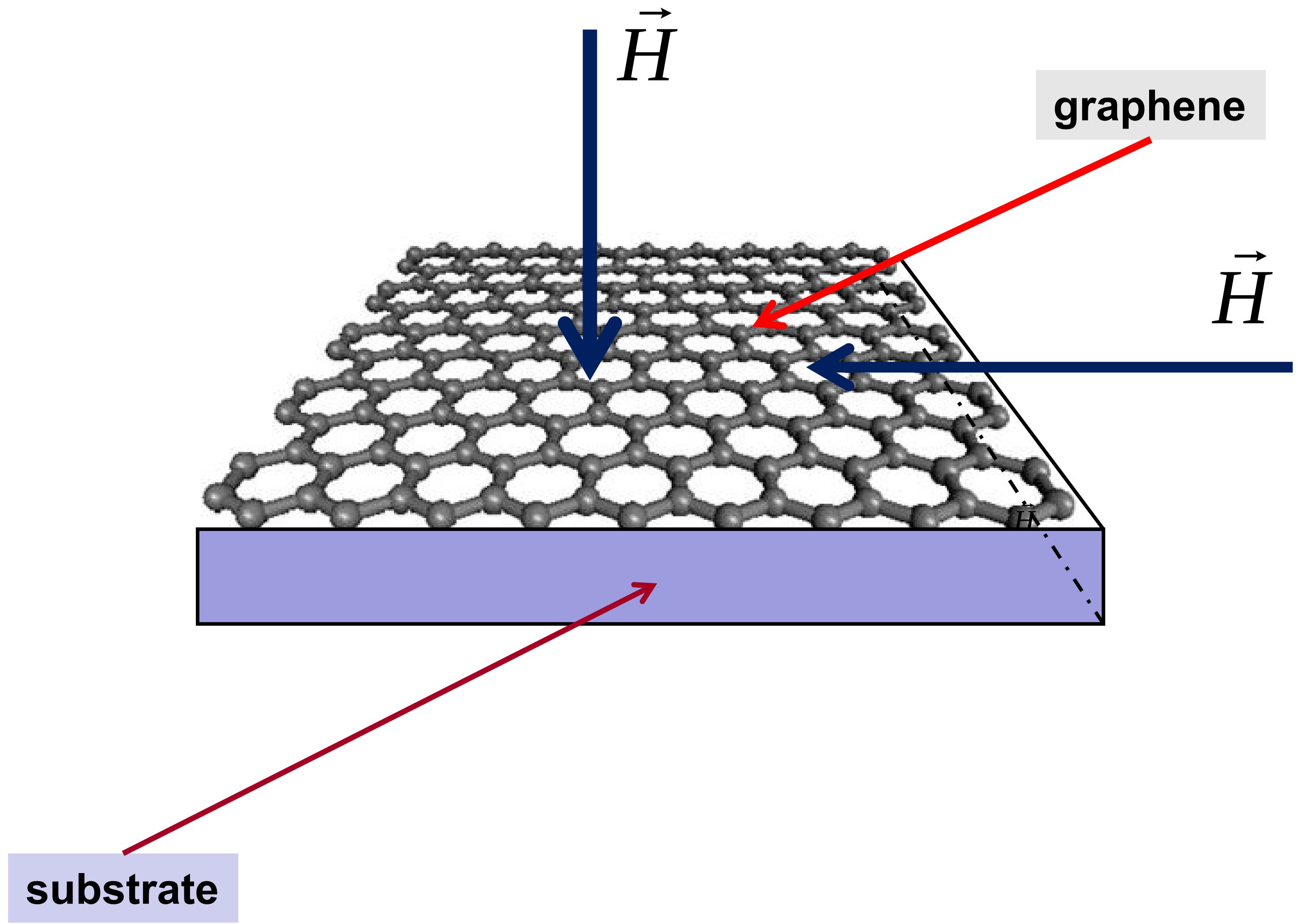
Monte Carlo Simulation of the Semimetal-Insulator Phase Transition in Monolayer Graphene.
W. Armour , Simon Hands, Costas Strouthos
Published in **Phys.Rev. B81 (2010) 125105**
e-Print: **arXiv:0910.5646 [cond-mat.str-el]**



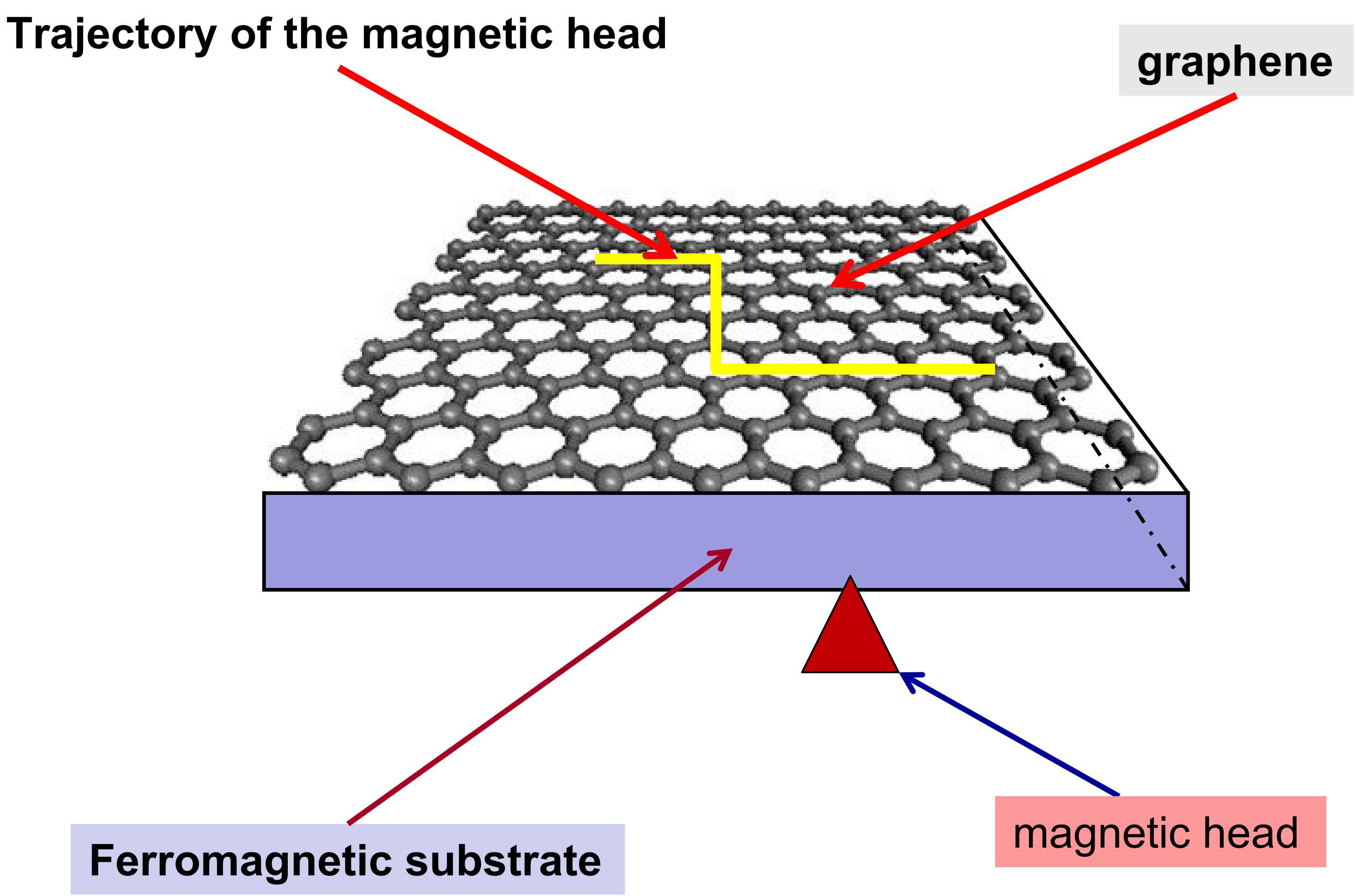
if $\frac{2}{1+\varepsilon}\alpha_g > \alpha_g^{crit}(=1.11)$ graphene is the conductor

We can numerically simulate conductor – insulator phase transition!

Magnetic Field and Graphene



Graphene changes its properties when an external magnetic field is applied, we can numerically simulate all that

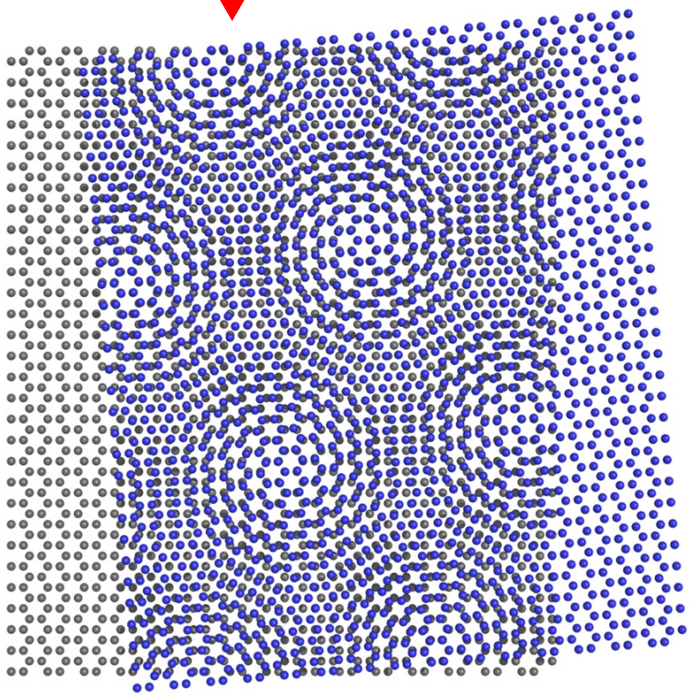


Along the trajectory of the magnetic head graphene becomes the conductor!

We can draw (construct) chips! All that we can simulate on computers

Problems for graphene numerical simulations

Magnetic field
Finite temperature
Impurities
2-3-4 layers
Conductivity
Viscosity – Entropy
Optical properties
Critical indices



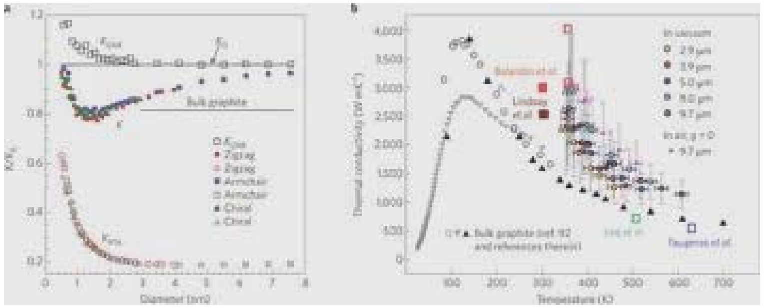
Monte Carlo simulation of monolayer graphene at non-zero temperature

Wesley Armour[a,b], Simon Hands[c], and Costas Strouthos[d]

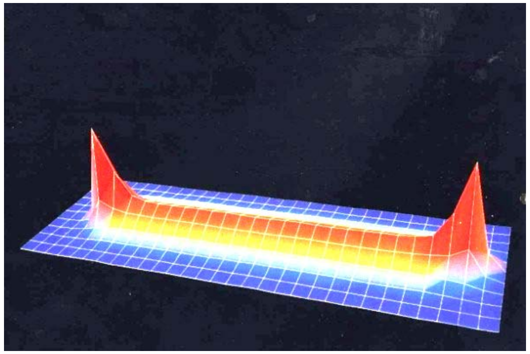
arXiv:1105.1043v1 [cond-mat.str-el] 5 May 2011

Graphene has relations with many theoretical problems

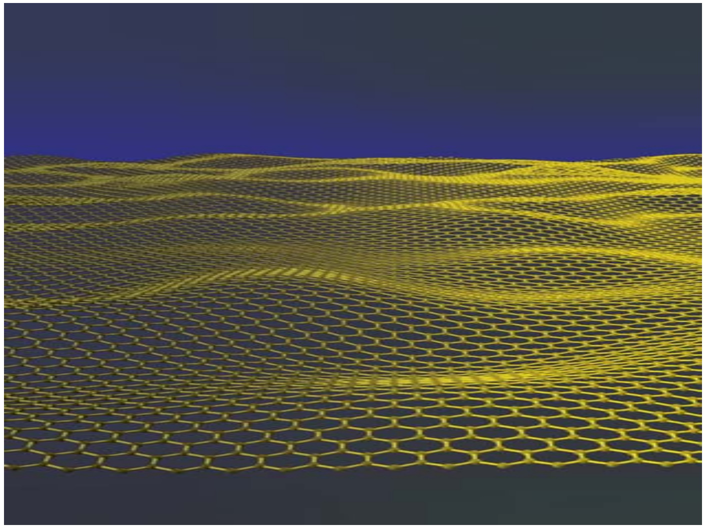
Insulator – Conductor



Confinement - Deconfinement



Curvature of the graphene leads to two dimensional gravity for fermions



Computer simulations help to unify physical systems

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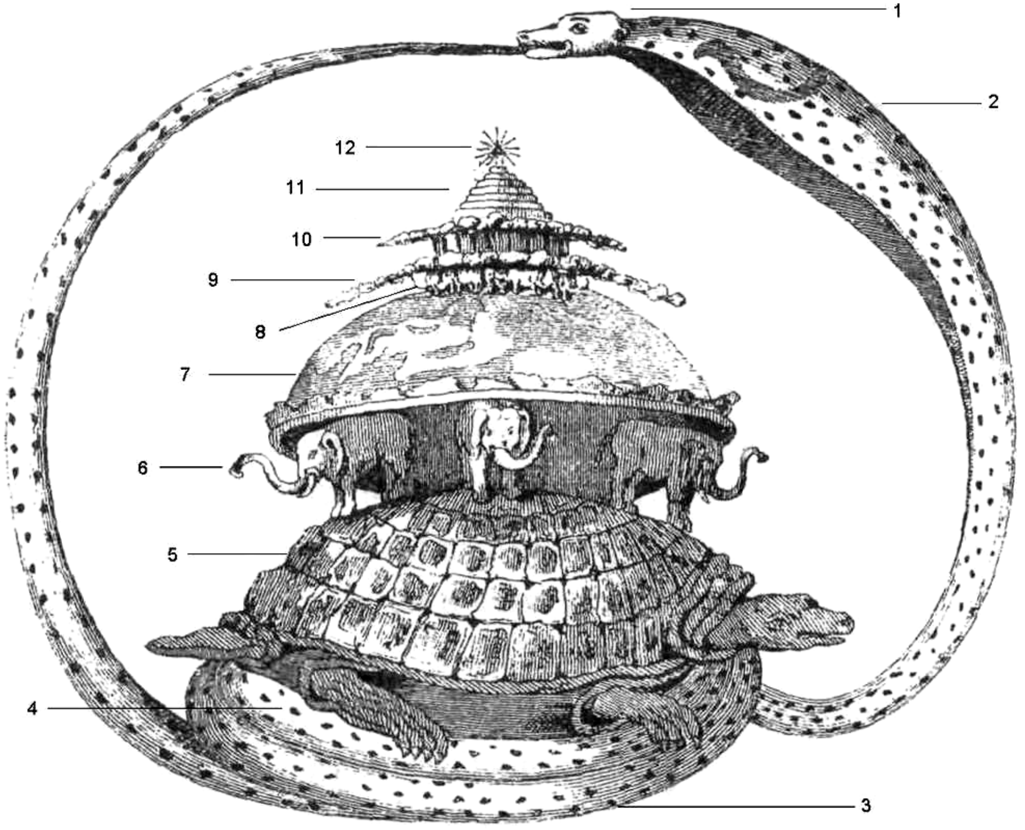
QCD confinement problems
Quark-Gluon plasma in heavy ion collisions
Graphene

Computer simulations help to unify physical systems



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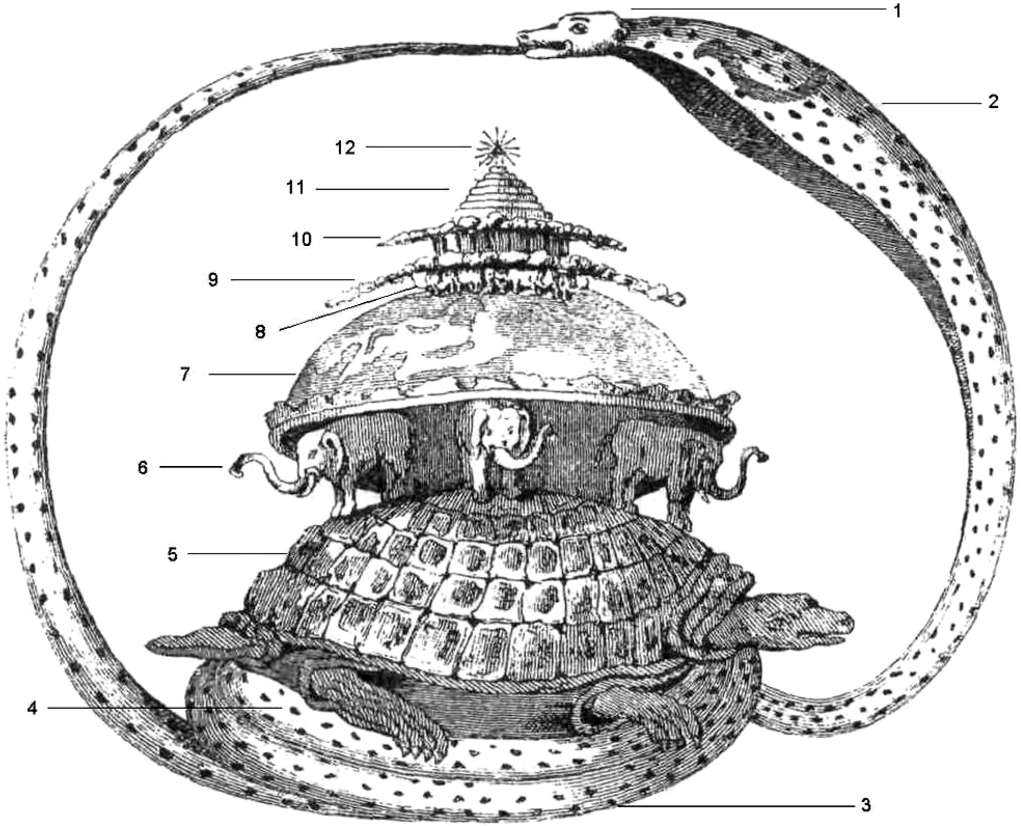

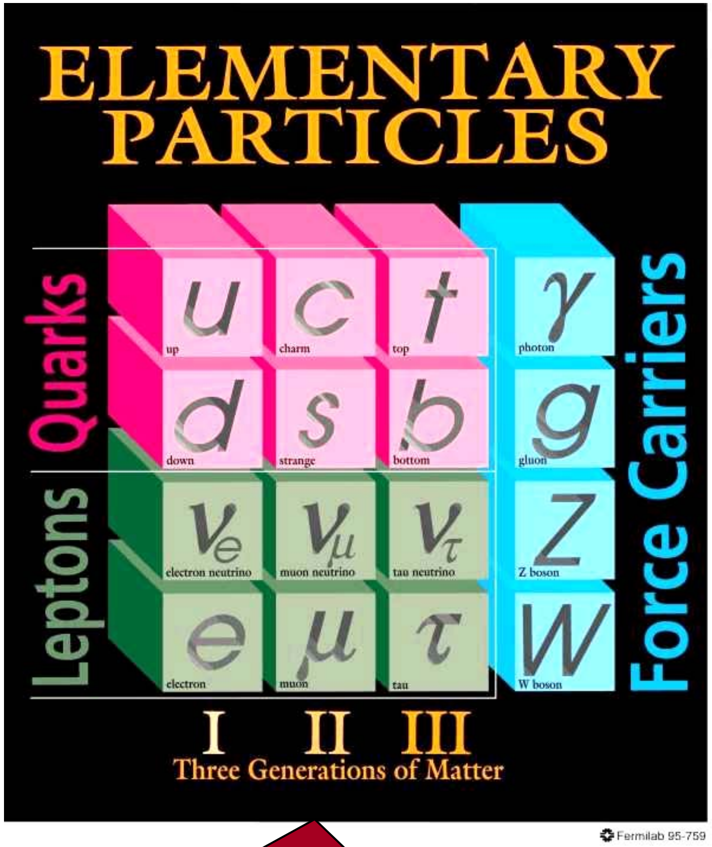

QCD confinement problems
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