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, QG plasma and computers
- Graphene and computers

Extreme state of matter

24 February 2012, Bekasovo

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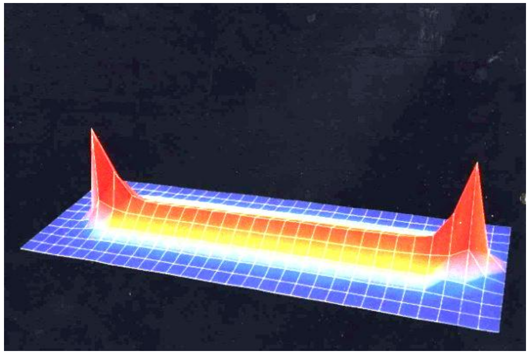
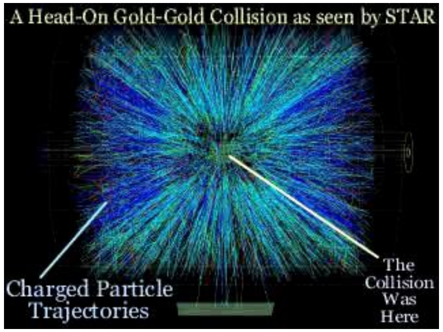
Three examples of computer simulations of strongly interacting systems

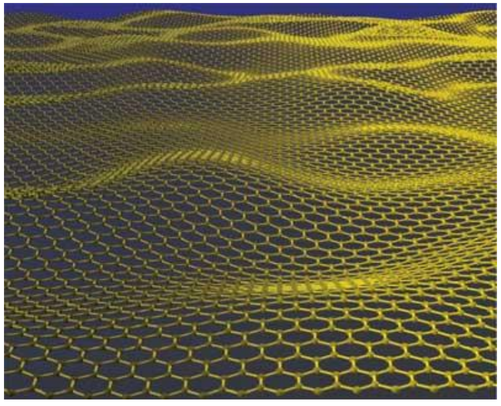
1. Confinement problem in QCD



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



3. Graphene as quantum field theory



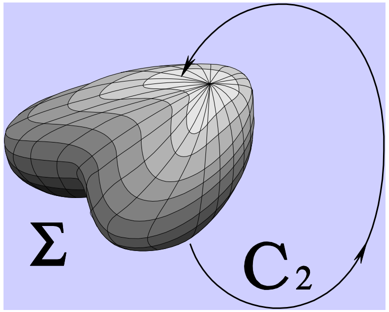
Three branches of Physics

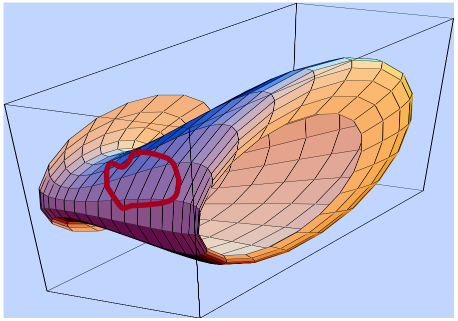
Experiment

LHC **RHIC**

Theory

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

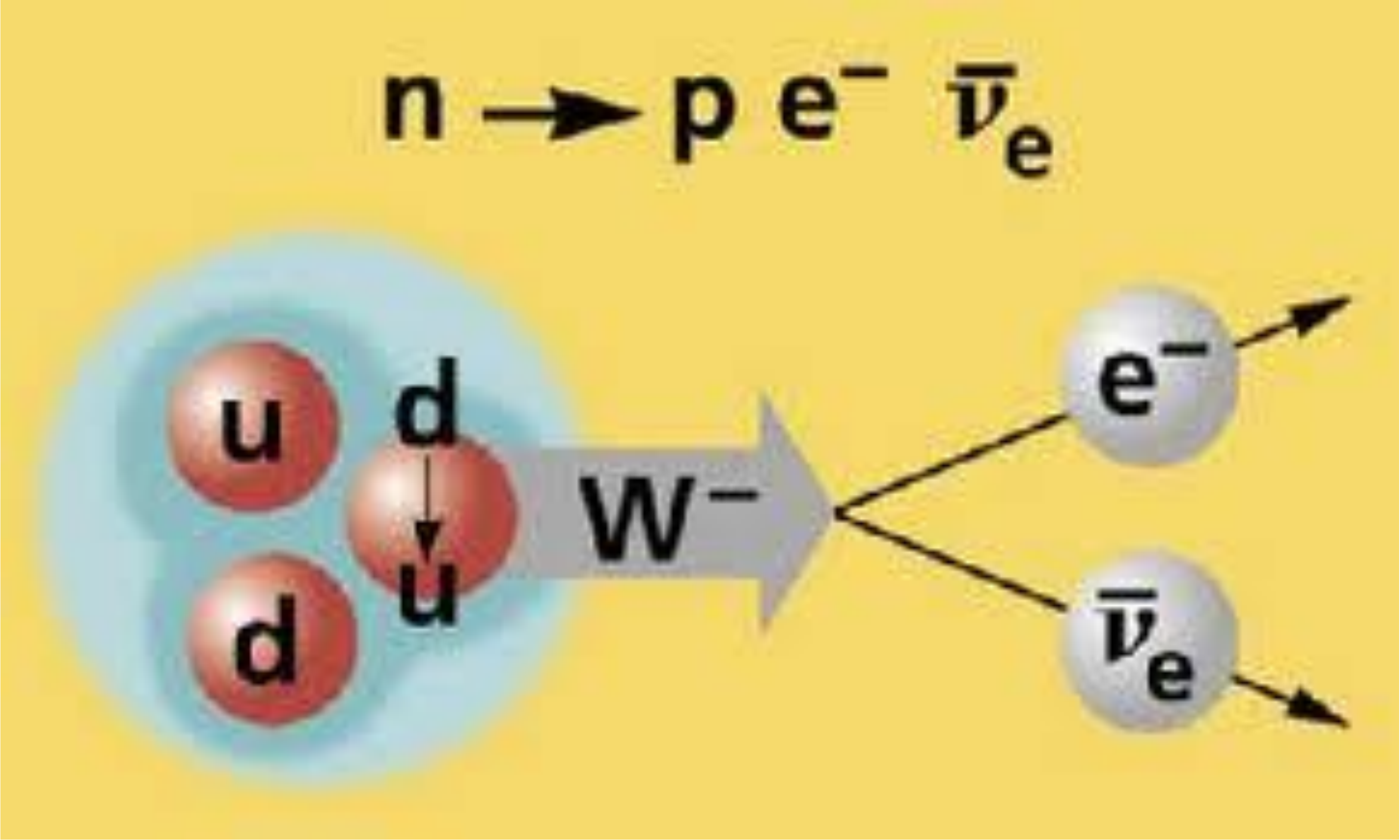




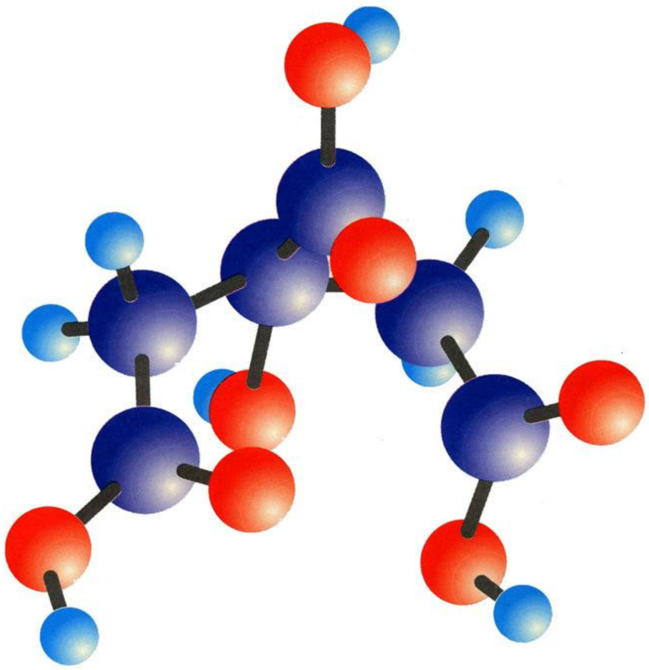
Supercalculations

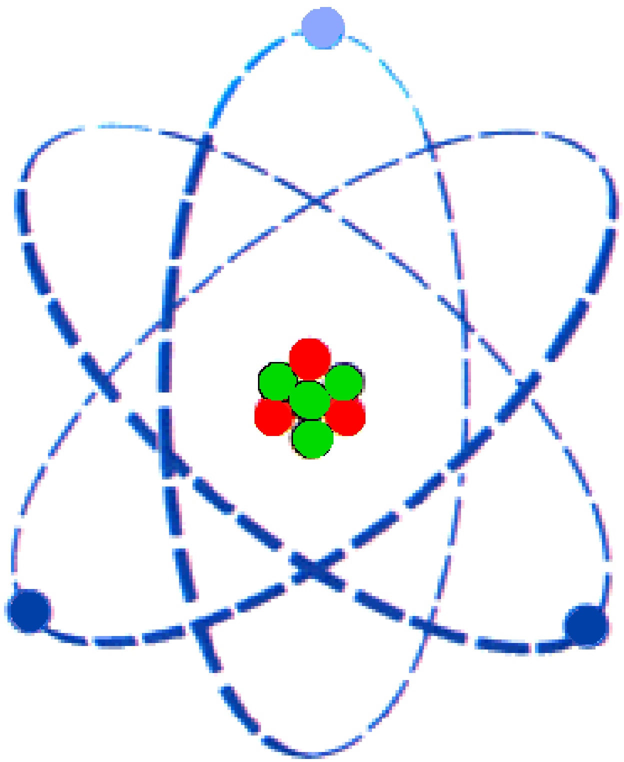
Interactions – 1. Gravity

Interactions – 2. Weak

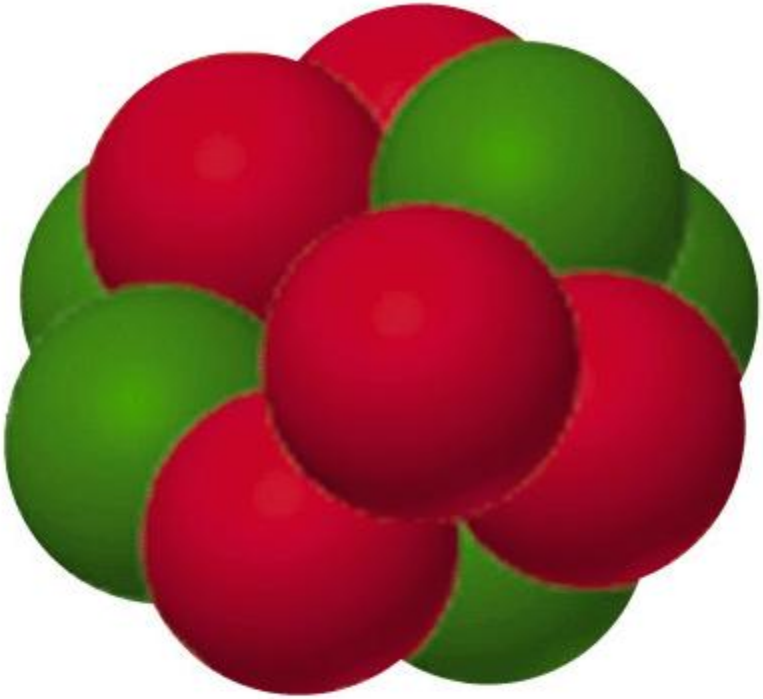


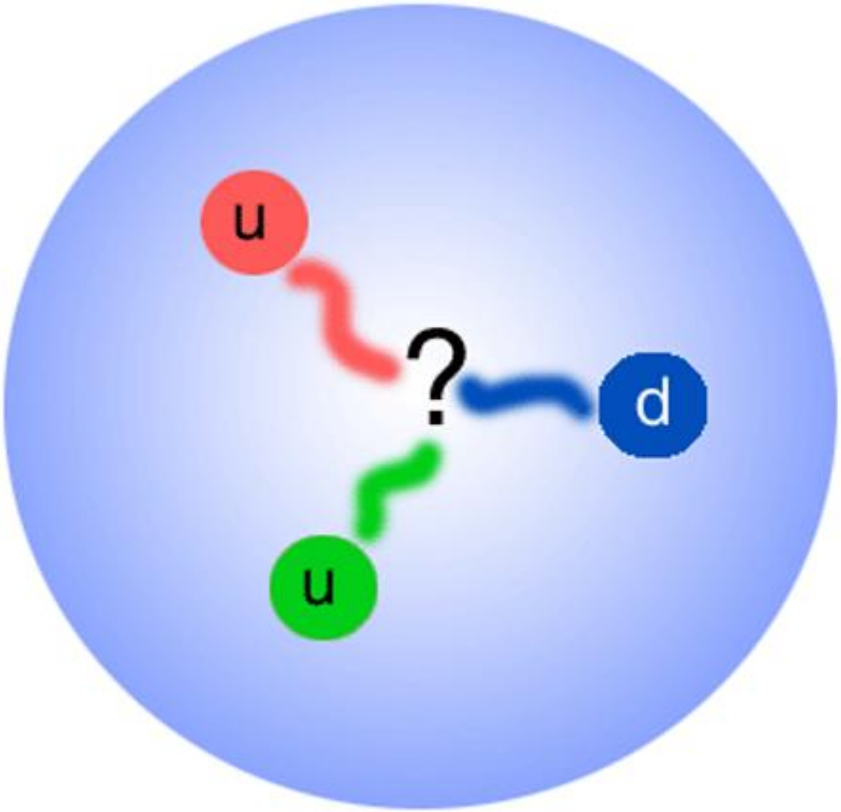
Interactions – 3. Electromagnetism





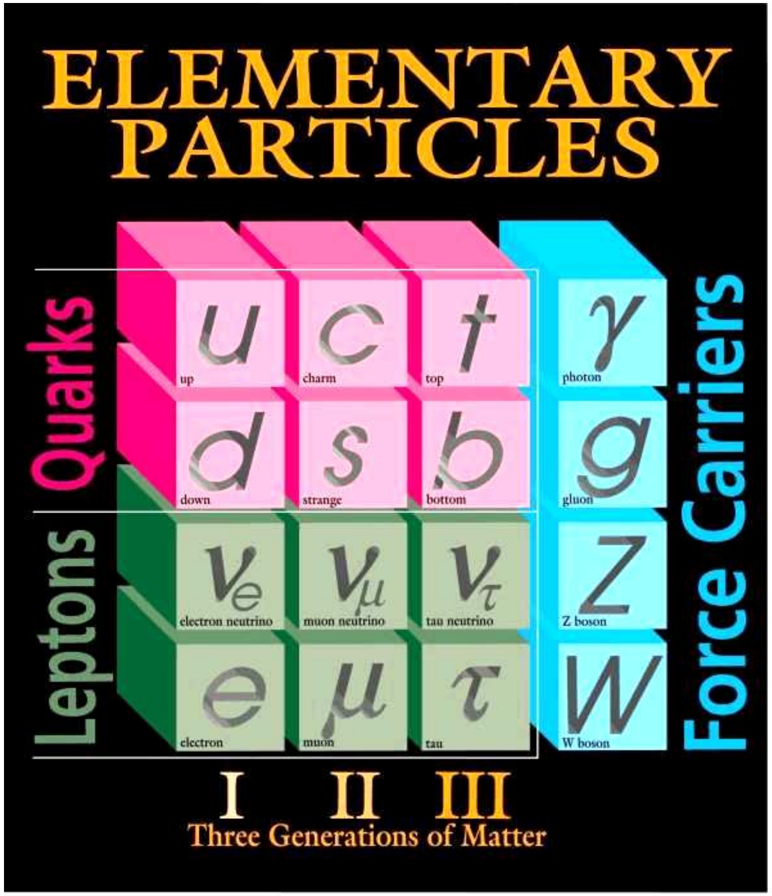
Interactions – 4. Strong





QCD

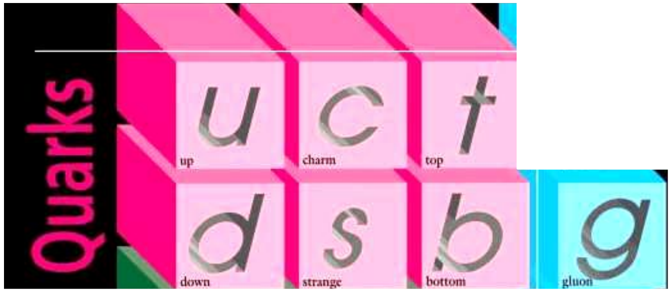
Standard Model



Fermilab 95-759

QCD

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

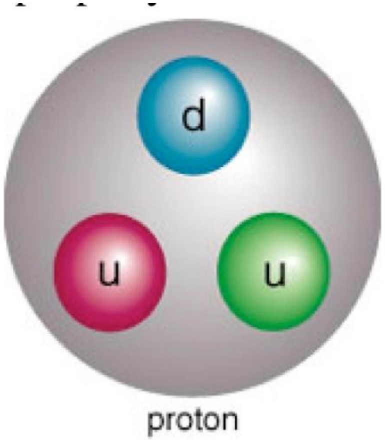


Fermilab 95-759

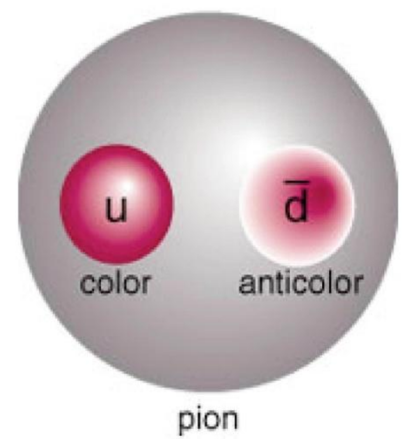
QCD

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

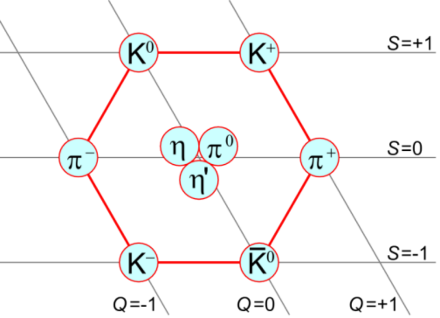
baryon
3q

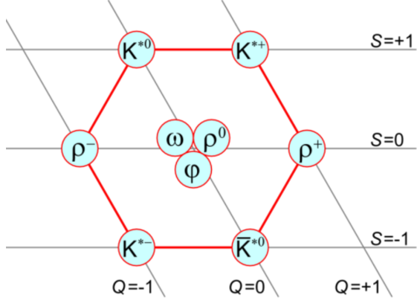


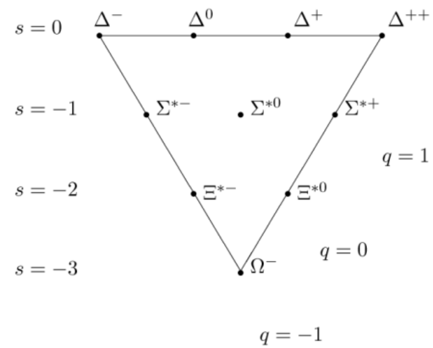
meson
q-anti q

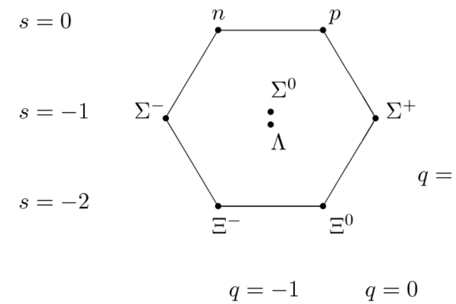


Fermilab 95-759









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

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}	****
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.

Masses of Hadrons?

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

$$m_h = C_1 \exp\{-C_2 \frac{1}{g^2}\}$$

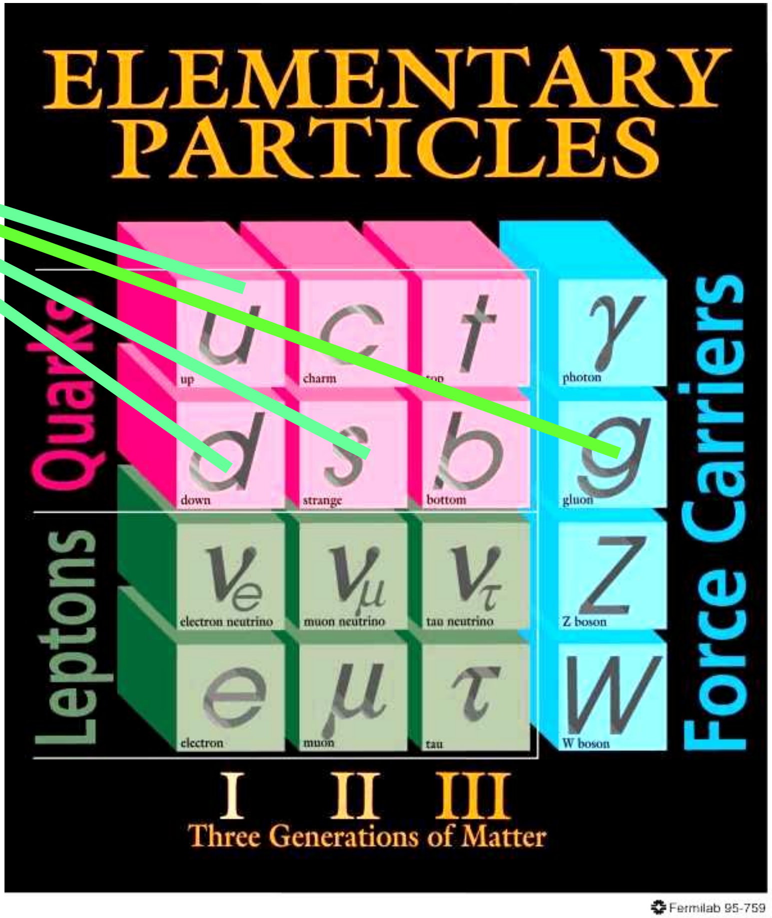
$$m_h = ?\sum_k a_k g^{2k} \qquad ?????$$

(super)computer calculations

Main problems of strong interaction theory, QCD

Derive from QCD Lagrangian

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



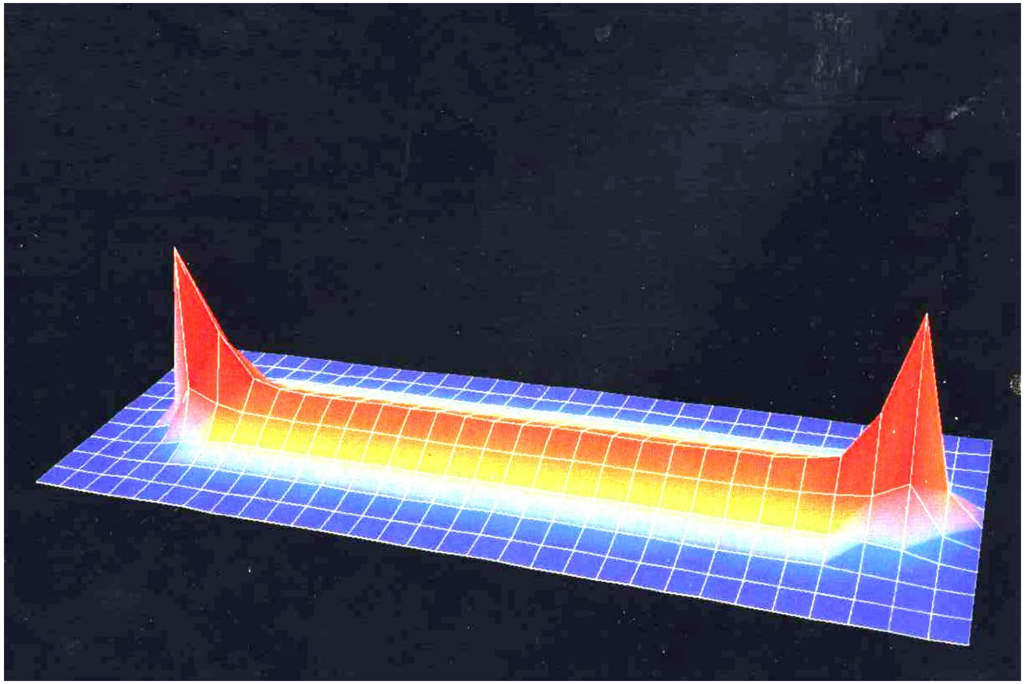
(1) Hadron spectrum,
(2) Matrix elements,
(3) Phase diagram
(4) Explain color confinement

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

Color confinement

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

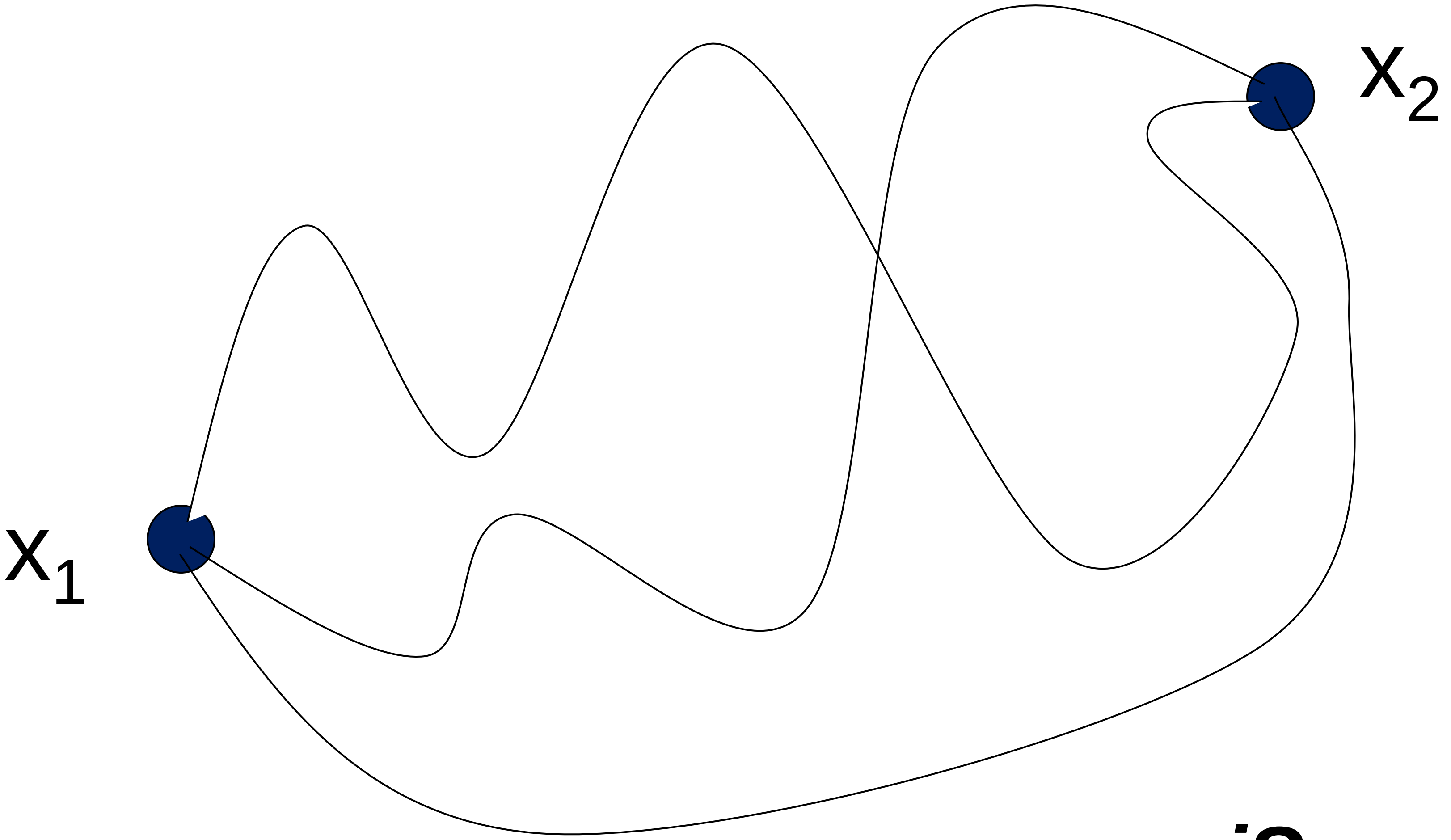
The main difficulty is the absence of first-principle nonperturbative methods in QCD. Computers can prove confinement "numerically"



http://www.claymath.org/millennium

Force between quark and antiquark is12 tons!!!

Quantum mechanics of a particle



The weight of each trajectory is e^{iS}

Quantum field theory

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

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

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

Methods

- Imaginary time ***t*⟶*it***

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

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

- Space-time discretization

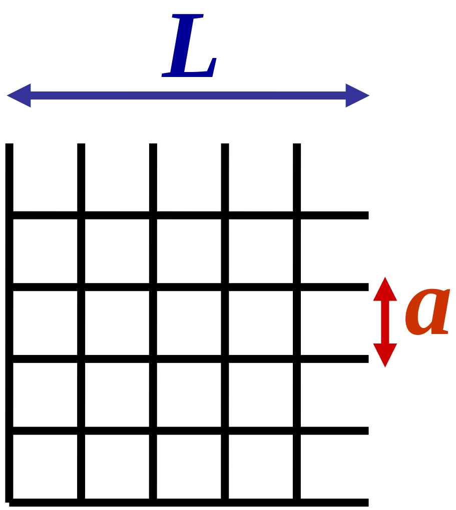
$$D\varphi(x) \Rightarrow \prod_x d\,\varphi_x$$

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

- 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

$a \approx 0.1\ fm$

$L \approx 2 \div 4\ fm$

$m_q \approx 100\ Mev$

Extrapolation

+

Chiral perturbation theory

Typical multiplicity of integrals

For lattice *L^4*

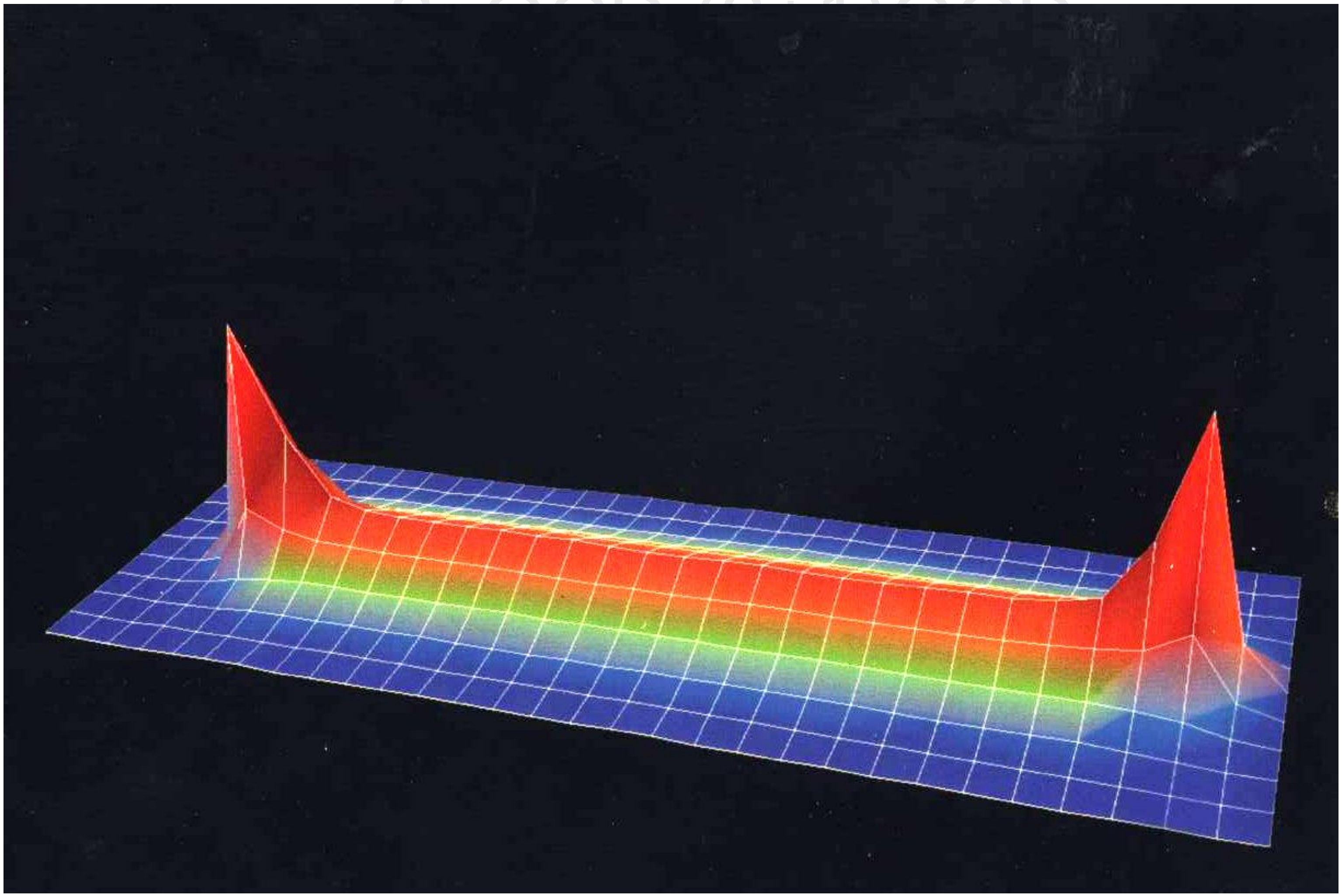
(L=48, L^4=5,308,416)

- **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)***

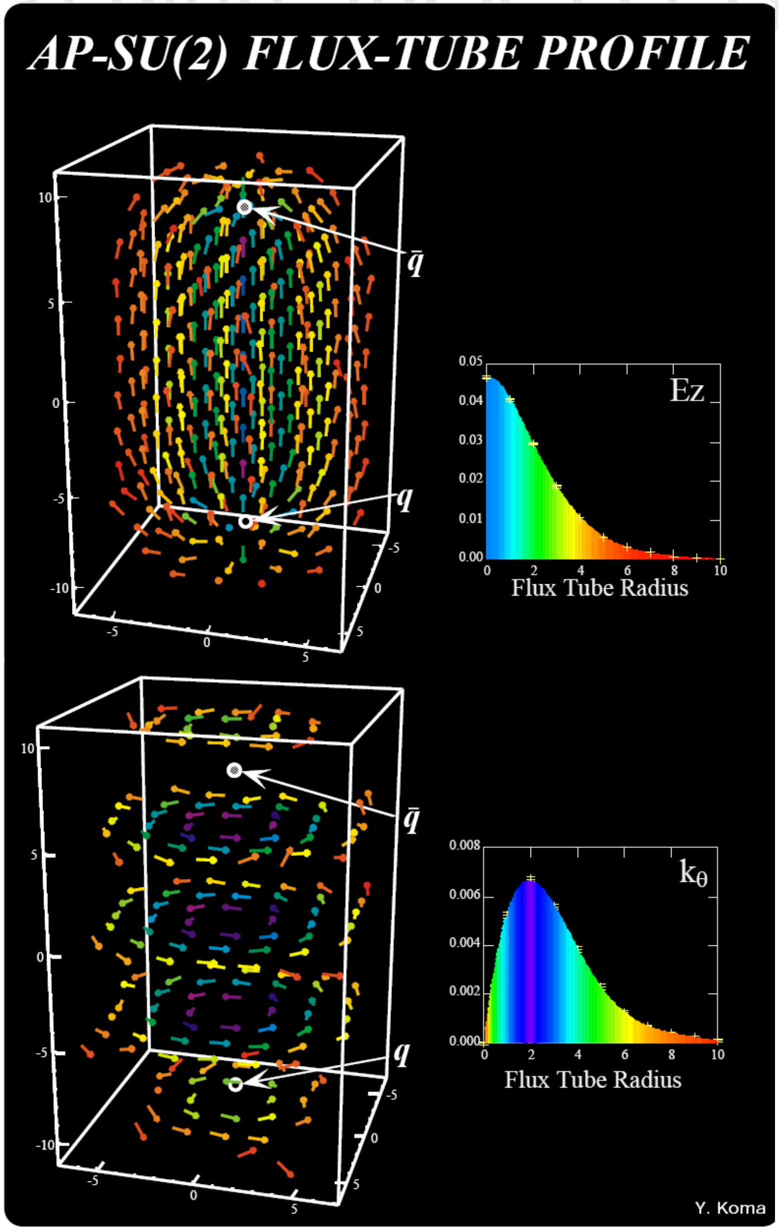
$$\boxed{\int d\psi\, d\overline{\psi}\, \exp\{\overline{\psi} M \psi\} = \det M}$$

SU(2) glue SU(3) glu

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

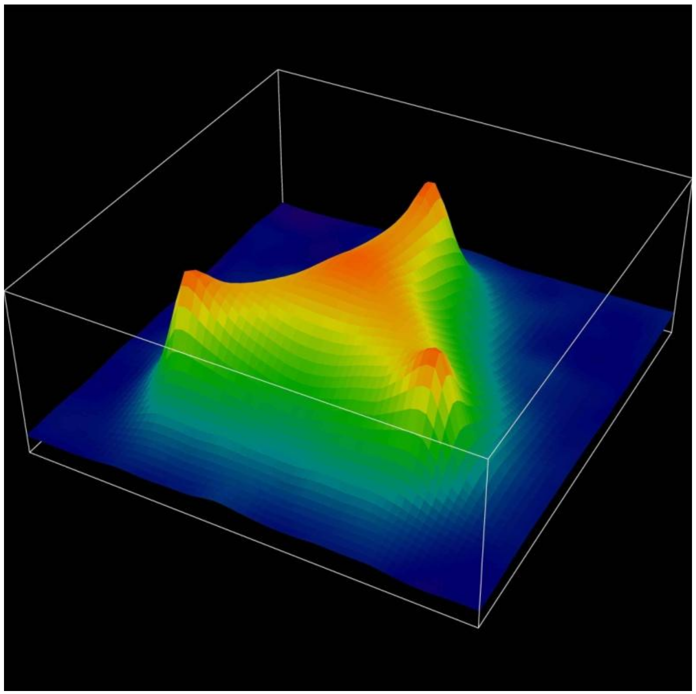


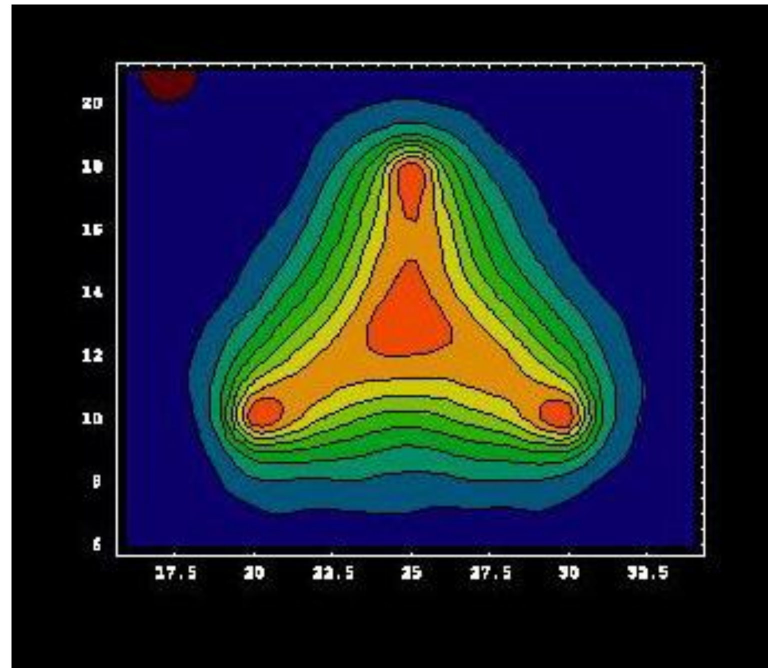
SU(2) glue


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!



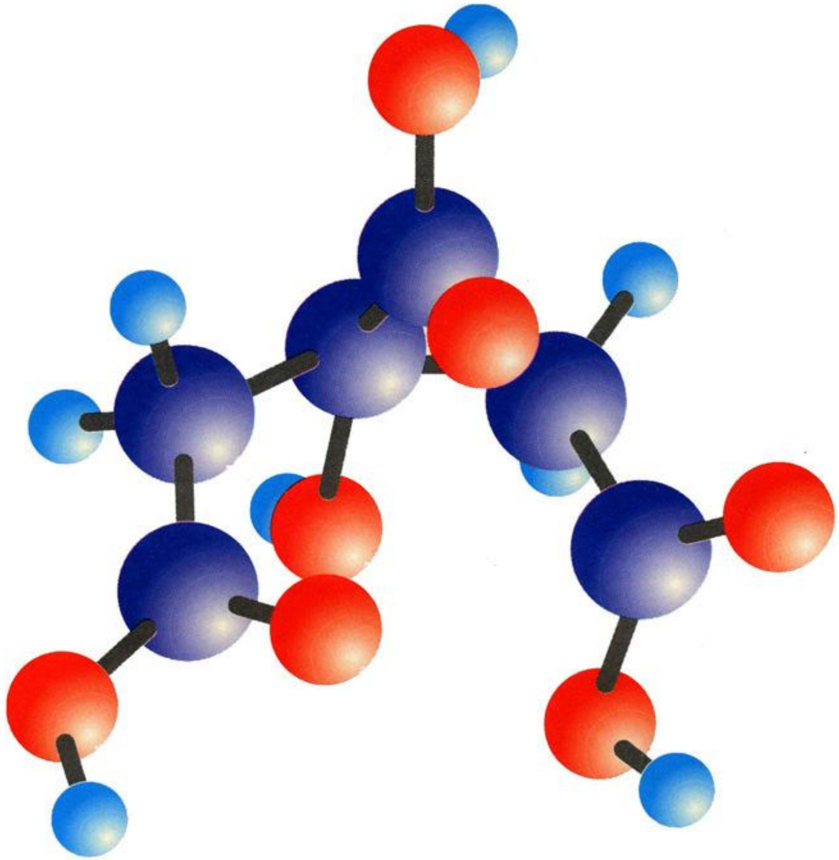


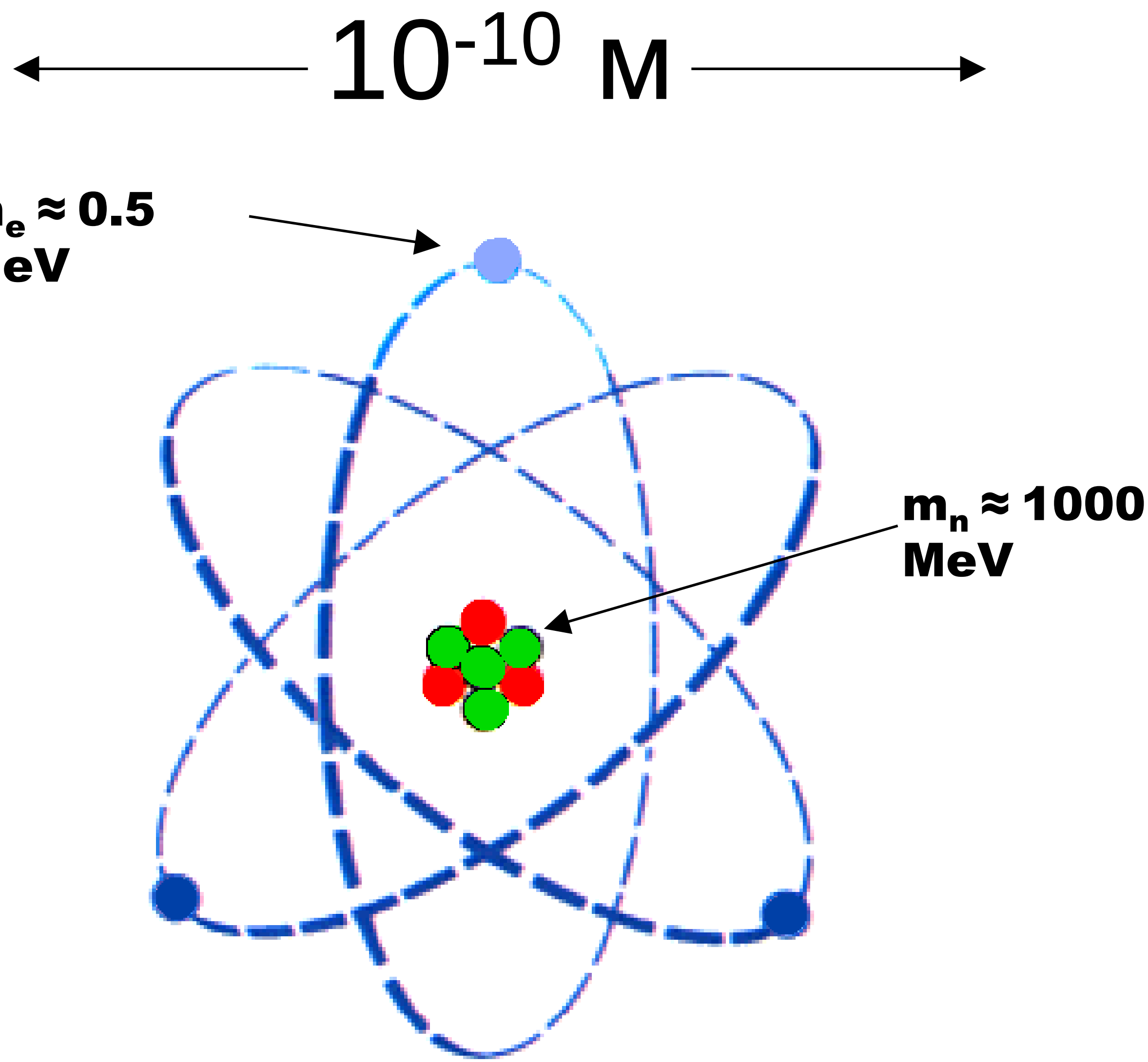
$$V(r_1, r_2, r_3) \neq V(r_1 - r_2) + V(r_2 - r_3) + V(r_3 - r_1)$$

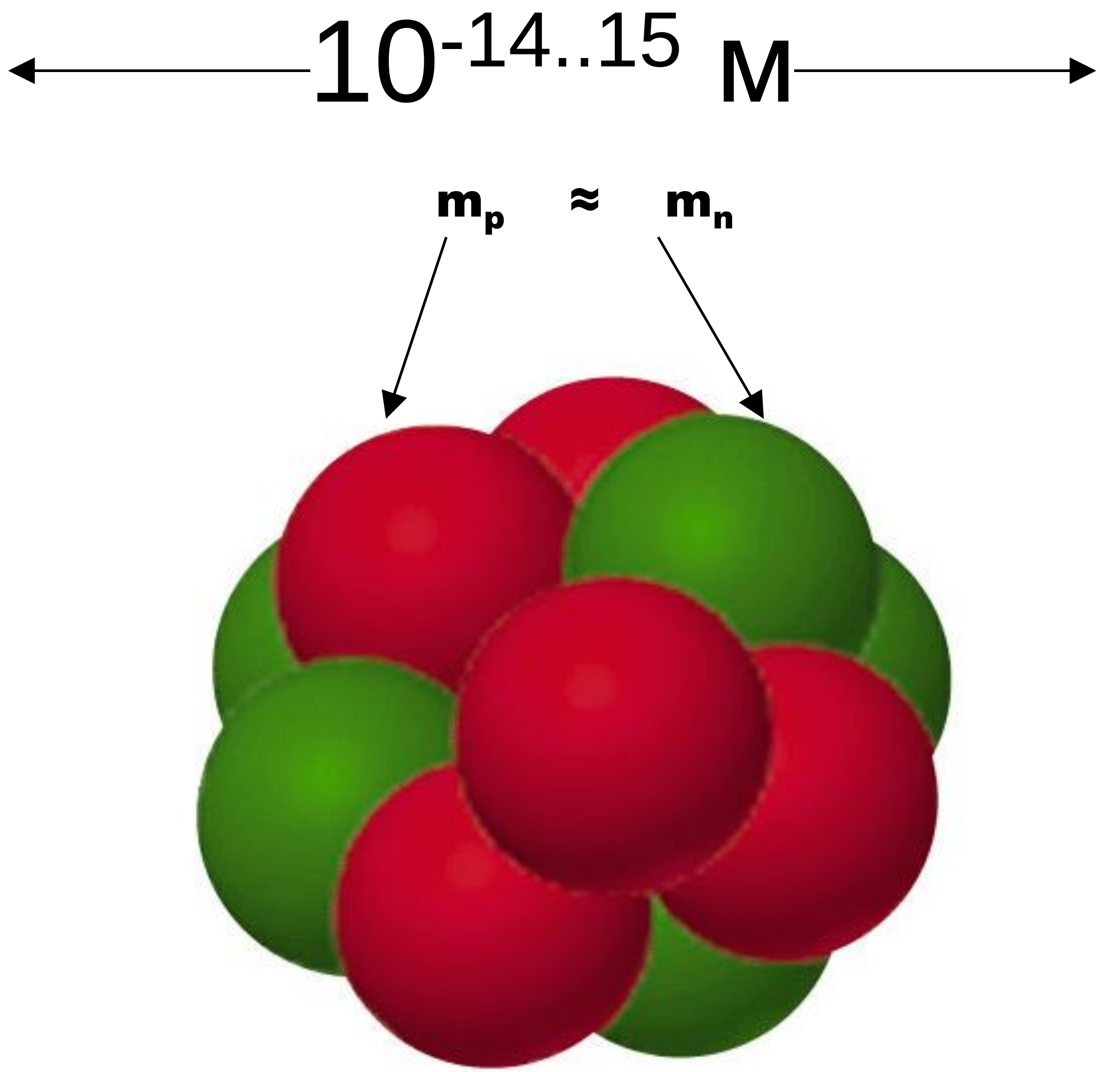
1 м

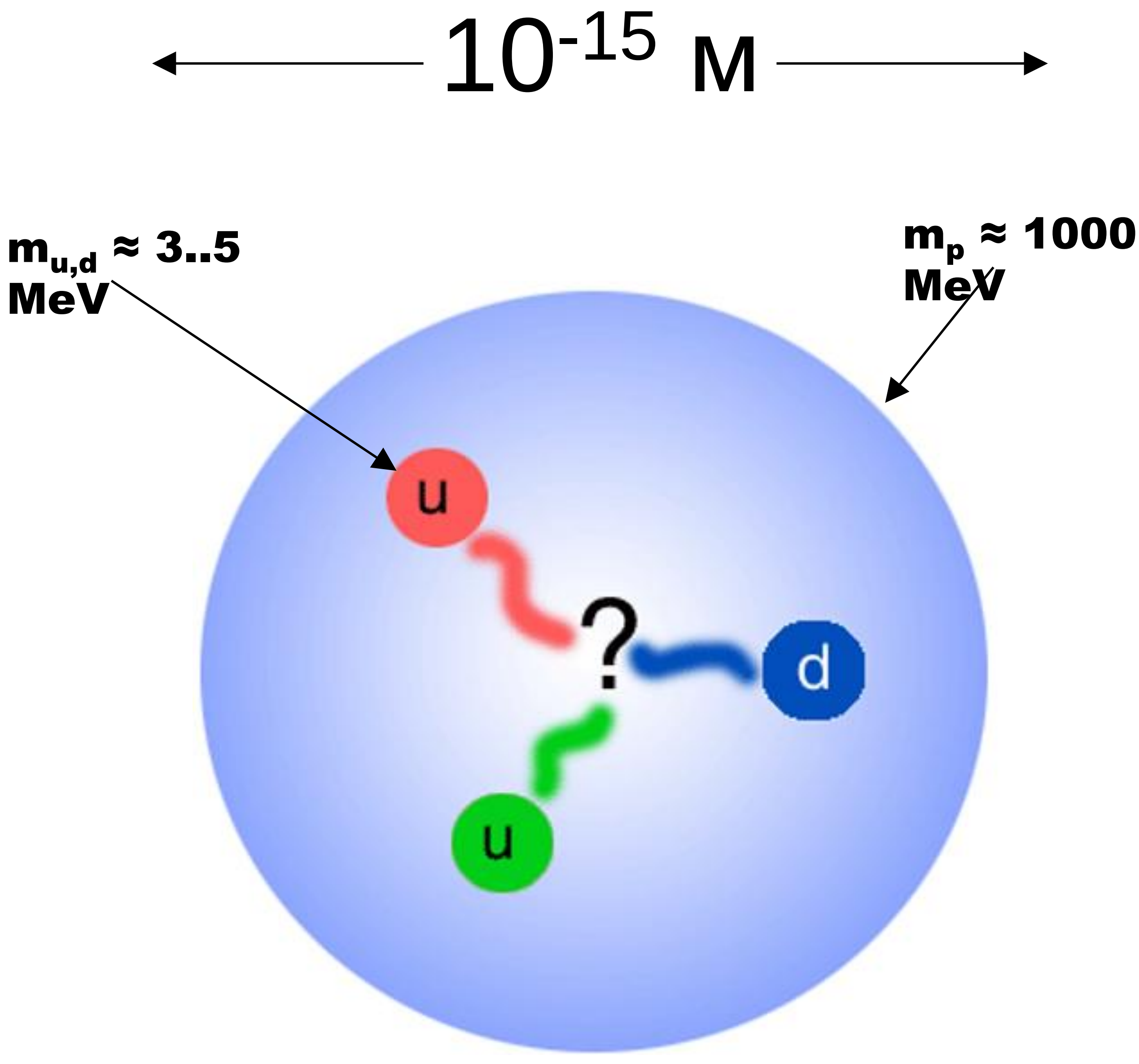
The origine of the mass

$10^{-8..10}$ м

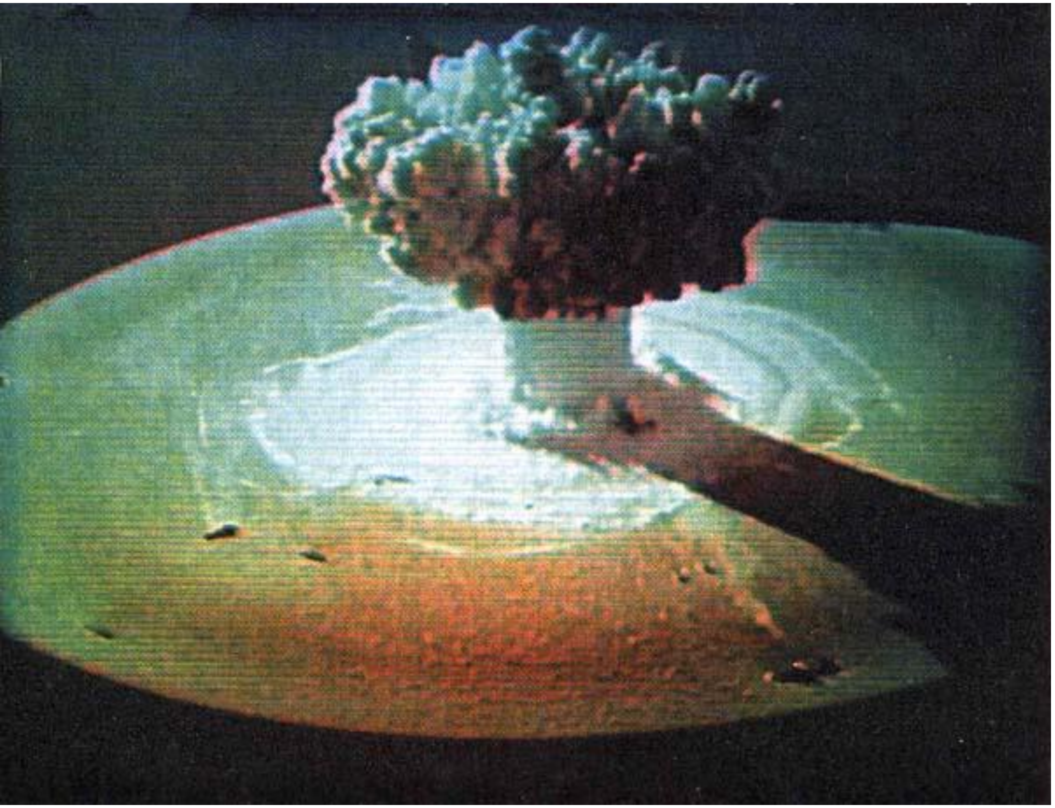


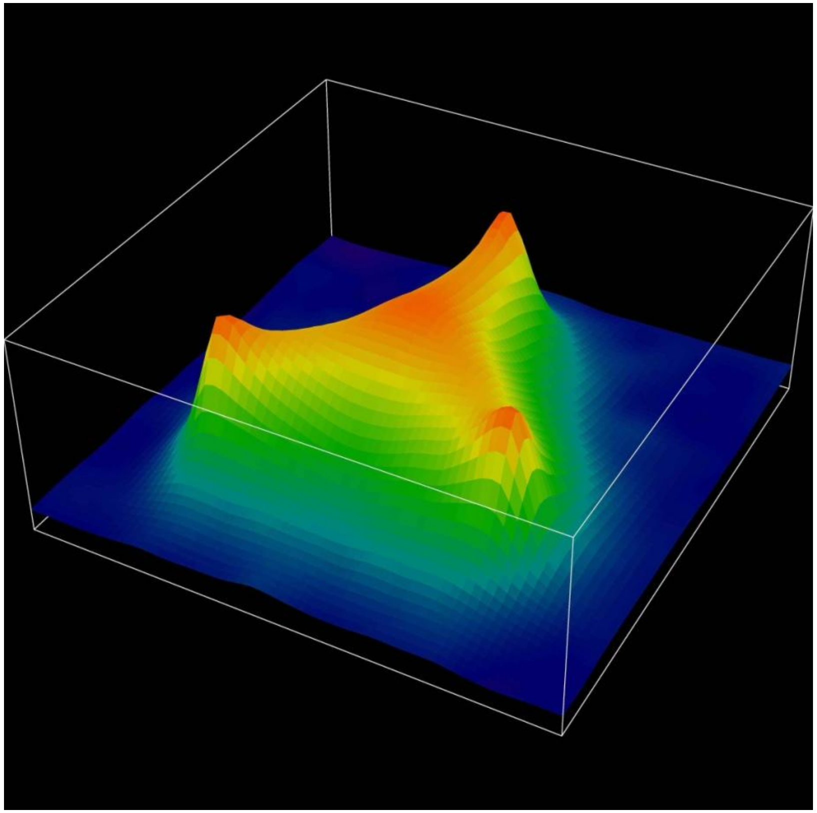

10^{-10} M
$m_e \approx 0.5$ MeV
$m_n \approx 1000$ MeV


$10^{-14..15}$ М
$m_p \approx m_n$


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

Masses of material objects is due to gluon fields inside baryon





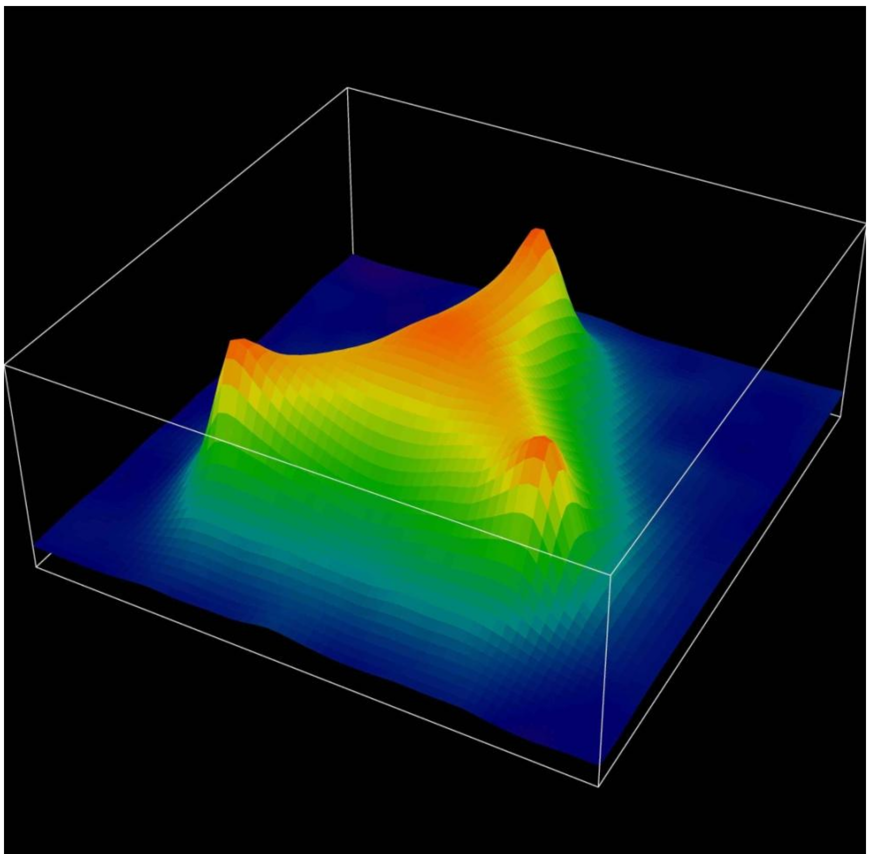
$$E = m_0 c^2$$

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

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

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

Three body forces!



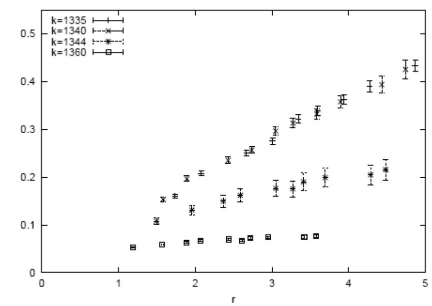


Figure 9: The monopole part of the baryon potential at finite temperature in full QCD as a function of L_Y ($T < T_c$) and L_Δ ($T > T_c$), respectively, in units of *God knows what*.

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

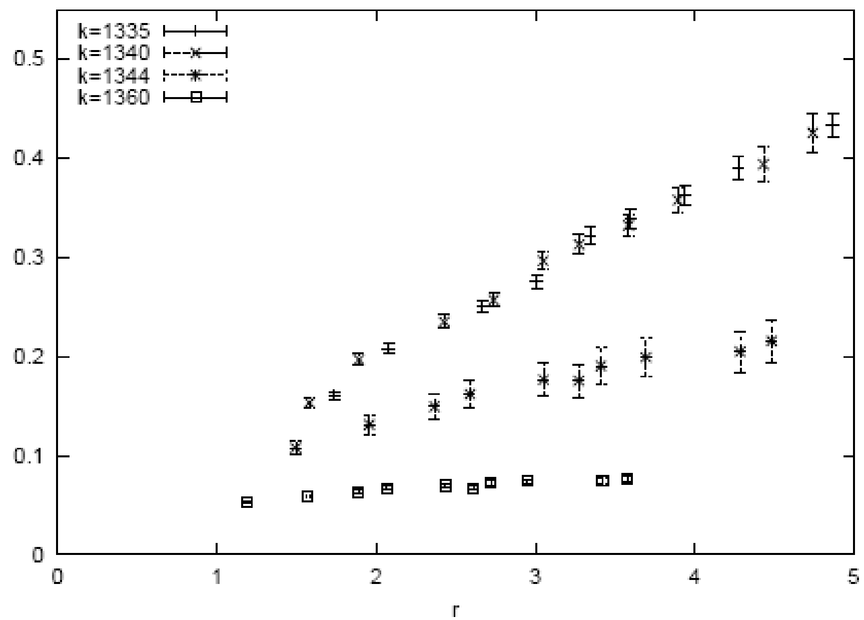
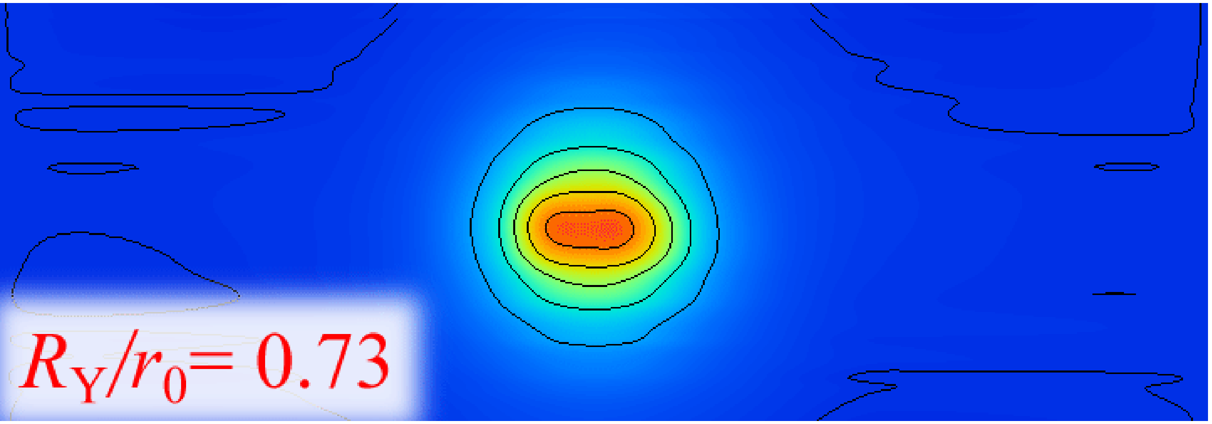


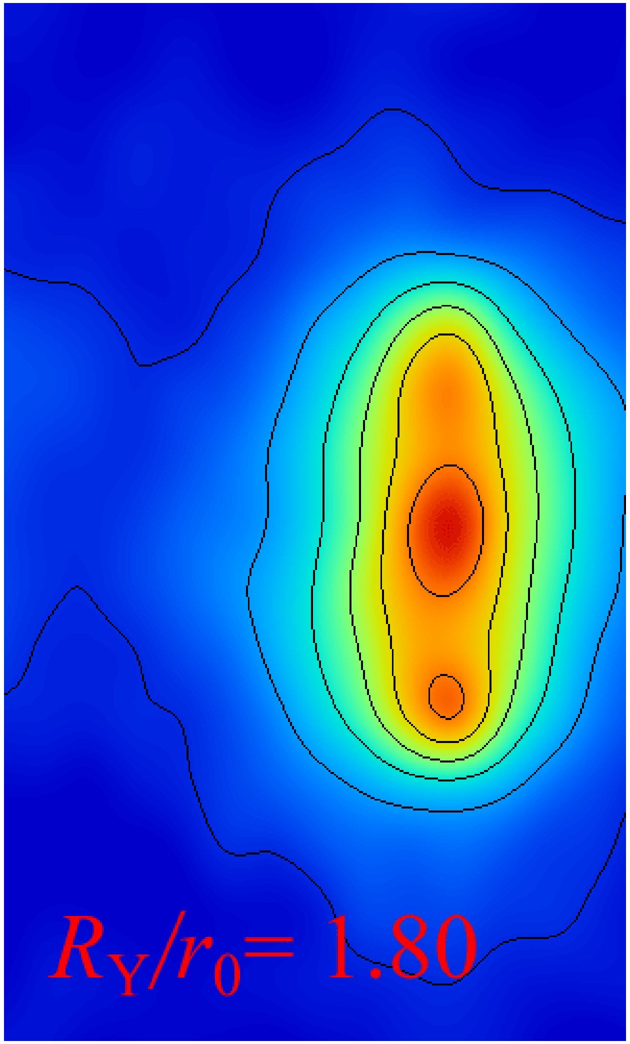
Figure 9: The monopole part of the baryon potential at finite temperature in full QCD as a function of L_Y ($T < T_c$) and L_Δ ($T > T_c$), respectively, in units of *God knows what.*

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 ($S = C = B = 0$)

	$I^G(J^{PC})$
• $\pi^\pm$	$1^-(0^-)$
• π^0	$1^-(0^{-+})$
• η	$0^+(0^{-+})$
• $f_0(600)$	$0^+(0^{++})$
• $\rho(770)$	$1^+(1^{--})$
• $\omega(782)$	$0^-(1^{--})$
• $\eta'(958)$	$0^+(0^{-+})$
• $f_0(980)$	$0^+(0^{++})$
• $a_0(980)$	$1^-(0^{++})$
• $\phi(1020)$	$0^-(1^{--})$
• $h_1(1170)$	$0^-(1^{+-})$
• $b_1(1235)$	$1^+(1^{+-})$
• $a_1(1260)$	$1^-(1^{++})$
• $f_2(1270)$	$0^+(2^{++})$
• $f_1(1285)$	$0^+(1^{++})$
• $\eta(1295)$	$0^+(0^{-+})$
• $\pi(1300)$	$1^-(0^{-+})$
• $a_2(1320)$	$1^-(2^{++})$
• $f_0(1370)$	$0^+(0^{++})$
$h_1(1380)$	$?^-(1^{+-})$
• $\pi_1(1400)$	$1^-(1^{-+})$
• $\eta(1405)$	$0^+(0^{-+})$
• $f_1(1420)$	$0^+(1^{++})$
• $\omega(1420)$	$0^-(1^{--})$
$f_2(1430)$	$0^+(2^{++})$
• $a_0(1450)$	$1^-(0^{++})$
• $\rho(1450)$	$1^+(1^{--})$
• $\eta(1475)$	$0^+(0^{-+})$
• $f_0(1500)$	$0^+(0^{++})$
$f_1(1510)$	$0^+(1^{++})$
• $f_2'(1525)$	$0^+(2^{++})$
$f_2(1565)$	$0^+(2^{++})$
$h_1(1595)$	$0^-(1^{+-})$
• $\pi_1(1600)$	$1^-(1^{-+})$
$a_1(1640)$	$1^-(1^{++})$
$f_2(1640)$	$0^+(2^{++})$
• $\eta_2(1645)$	$0^+(2^{-+})$
• $\omega(1650)$	$0^-(1^{--})$
• $\omega_3(1670)$	$0^-(3^{--})$

	$I^G(J^{PC})$
• $\pi_2(1670)$	$1^-(2^{-+})$
• $\phi(1680)$	$0^-(1^{--})$
• $\rho_3(1690)$	$1^+(3^{--})$
• $\rho(1700)$	$1^+(1^{--})$
$a_2(1700)$	$1^-(2^{++})$
• $f_0(1710)$	$0^+(0^{++})$
$\eta(1760)$	$0^+(0^{-+})$
• $\pi(1800)$	$1^-(0^{-+})$
$f_2(1810)$	$0^+(2^{++})$
$X(1835)$	$?^?(?^{-+})$
• $\phi_3(1850)$	$0^-(3^{--})$
$\eta_2(1870)$	$0^+(2^{-+})$
$\rho(1900)$	$1^+(1^{--})$
$f_2(1910)$	$0^+(2^{++})$
• $f_2(1950)$	$0^+(2^{++})$
$\rho_3(1990)$	$1^+(3^{--})$
• $f_2(2010)$	$0^+(2^{++})$
$f_0(2020)$	$0^+(0^{++})$
• $a_4(2040)$	$1^-(4^{++})$
• $f_4(2050)$	$0^+(4^{++})$
$\pi_2(2100)$	$1^-(2^{-+})$
$f_0(2100)$	$0^+(0^{++})$
$f_2(2150)$	$0^+(2^{++})$
$\rho(2150)$	$1^+(1^{--})$
$f_0(2200)$	$0^+(0^{++})$
$f_J(2220)$	$0^+(2 \text{ or } 4^{++})$
$\eta(2225)$	$0^+(0^{-+})$
$\rho_3(2250)$	$1^+(3^{--})$
• $f_2(2300)$	$0^+(2^{++})$
$f_4(2300)$	$0^+(4^{++})$
• $f_2(2340)$	$0^+(2^{++})$
$\rho_5(2350)$	$1^+(5^{--})$
$a_6(2450)$	$1^-(6^{++})$
$f_6(2510)$	$0^+(6^{++})$

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 ($C = \pm1$)

	$I(J^P)$
• $D^\pm$	$1/2(0^-)$
• 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 ($C = S = \pm1$)

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

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}	****
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^-		*

**** 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.

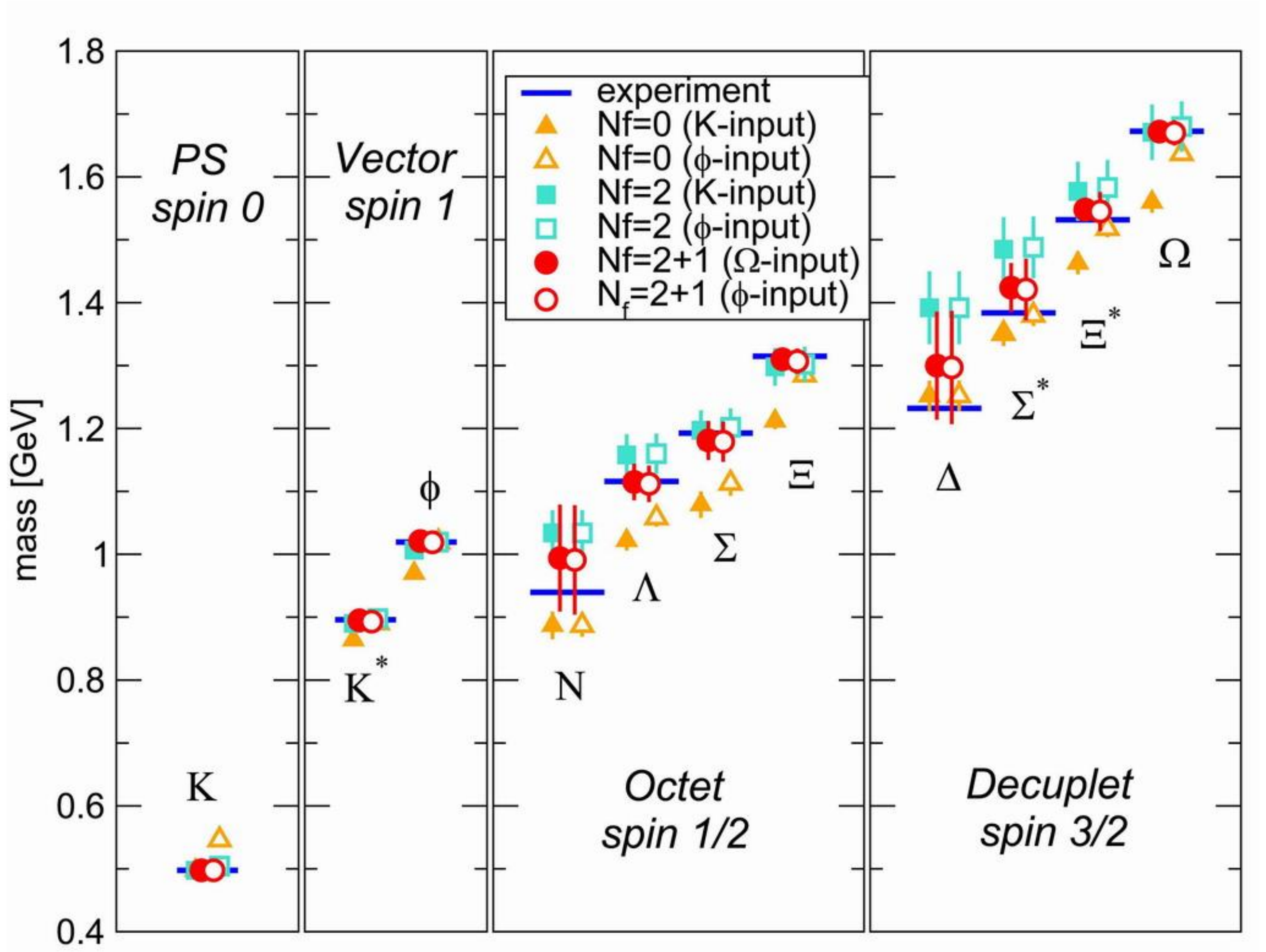
130

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

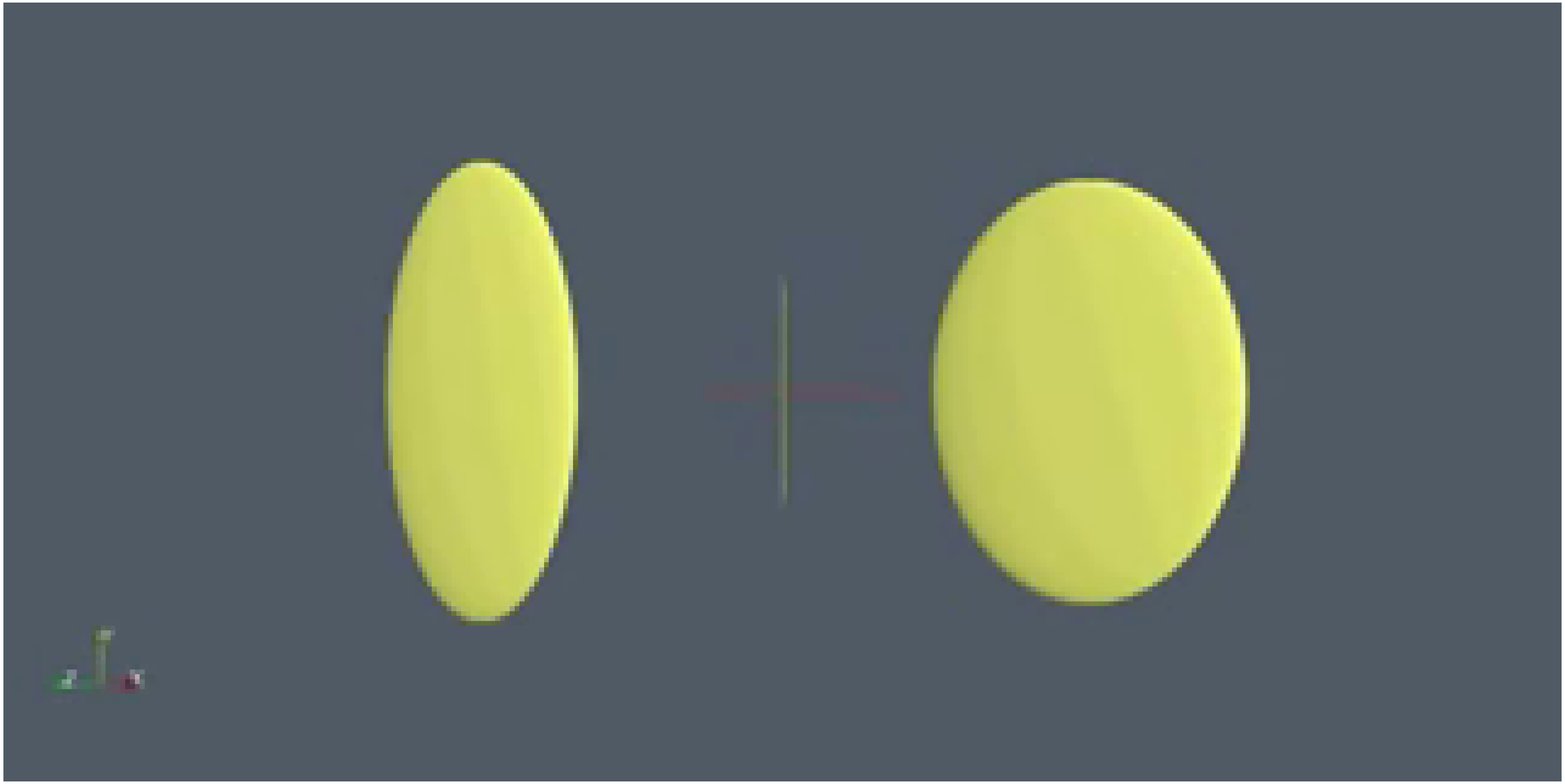
Wilson non-perturbatively improved Fermions
"WORKING HORSE" of lattice QCD calculations

Y. Kuramashi Lattice 2007

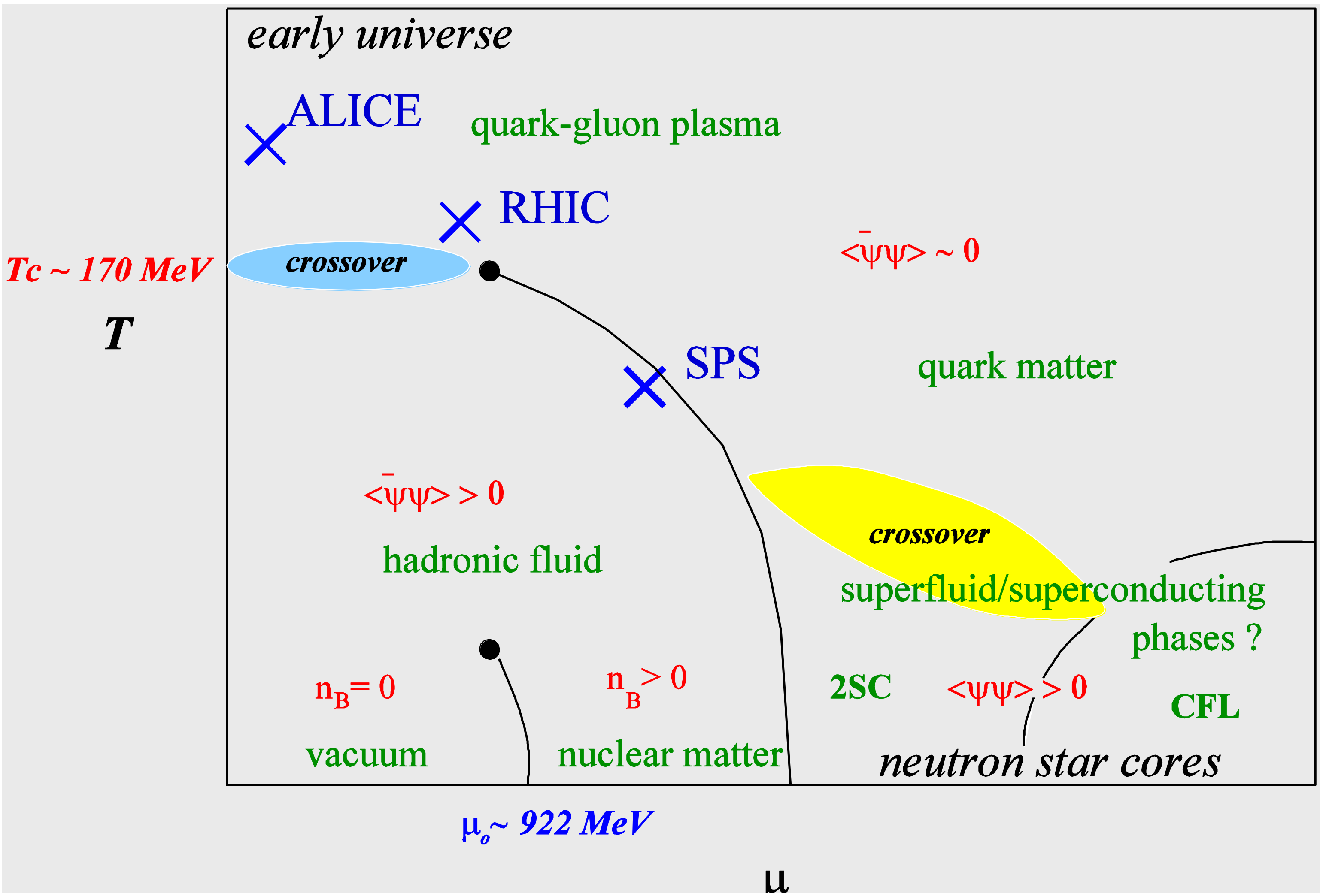
Iwasaki gauge action +
clover quarks
a^(−1) = 2.2GeV,
lattice size: 32^3 × 64

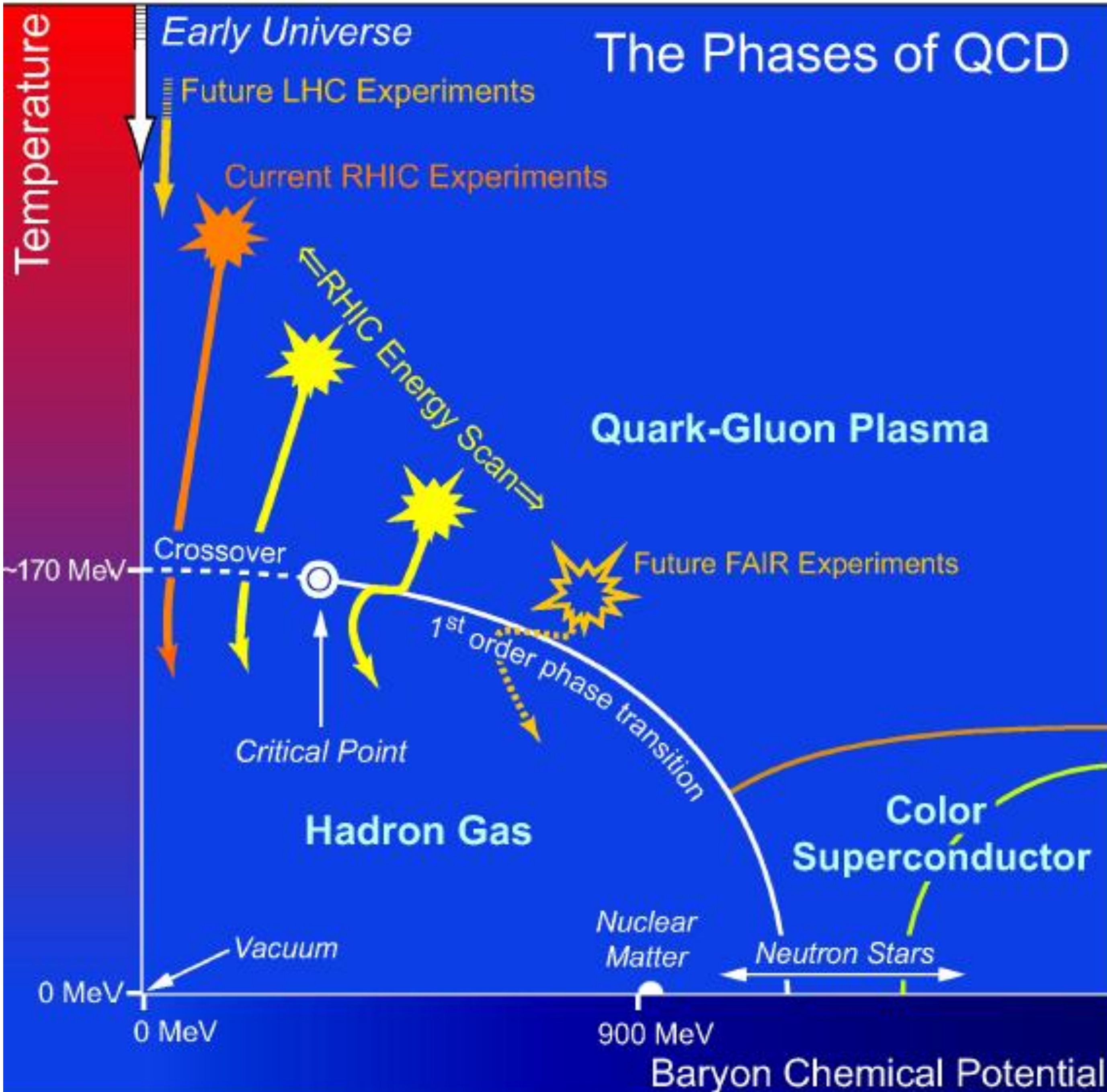


Heavy Ions Collisions and Quark- Gluon Plasma



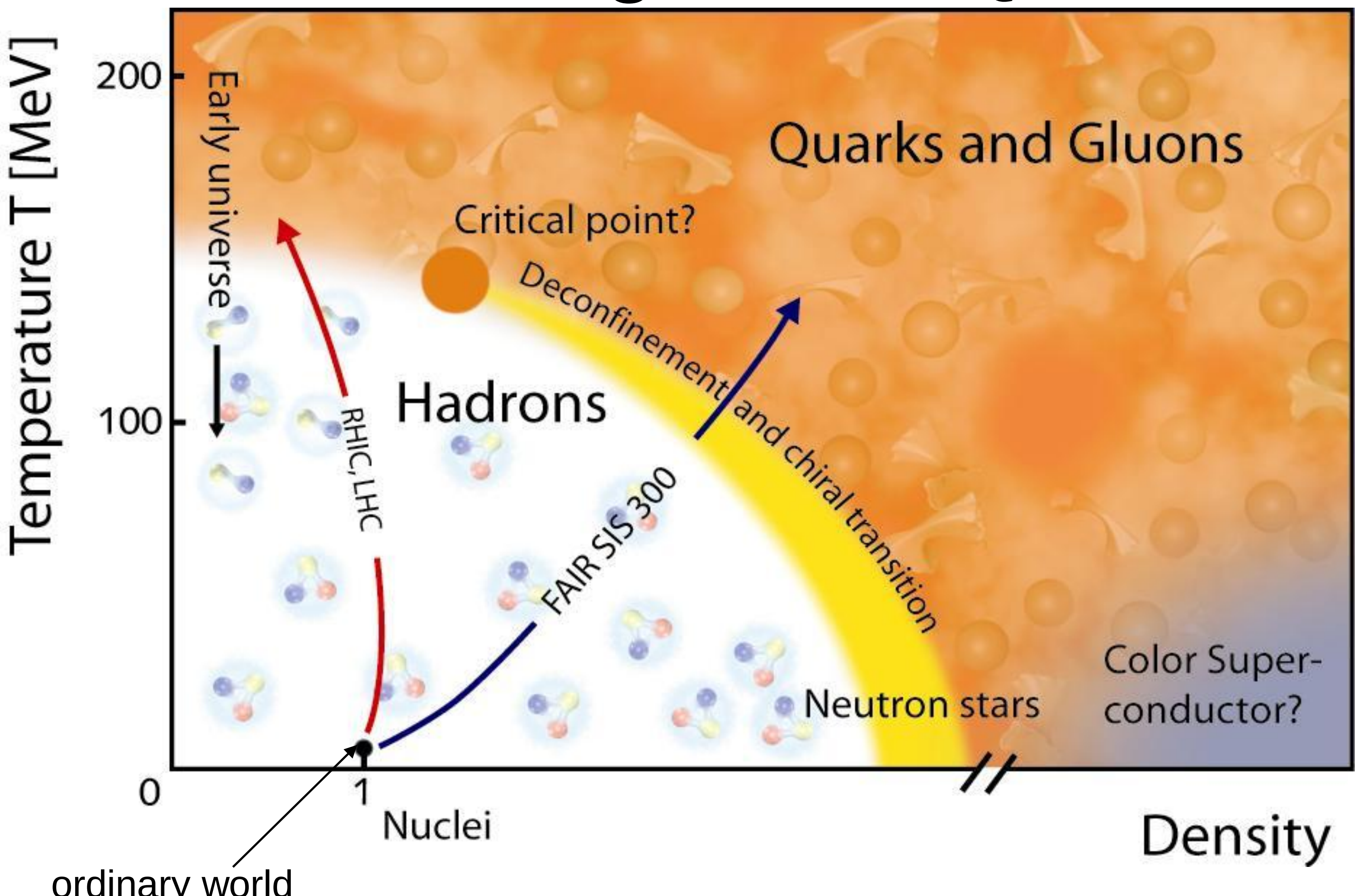
Phase diagram of QCD



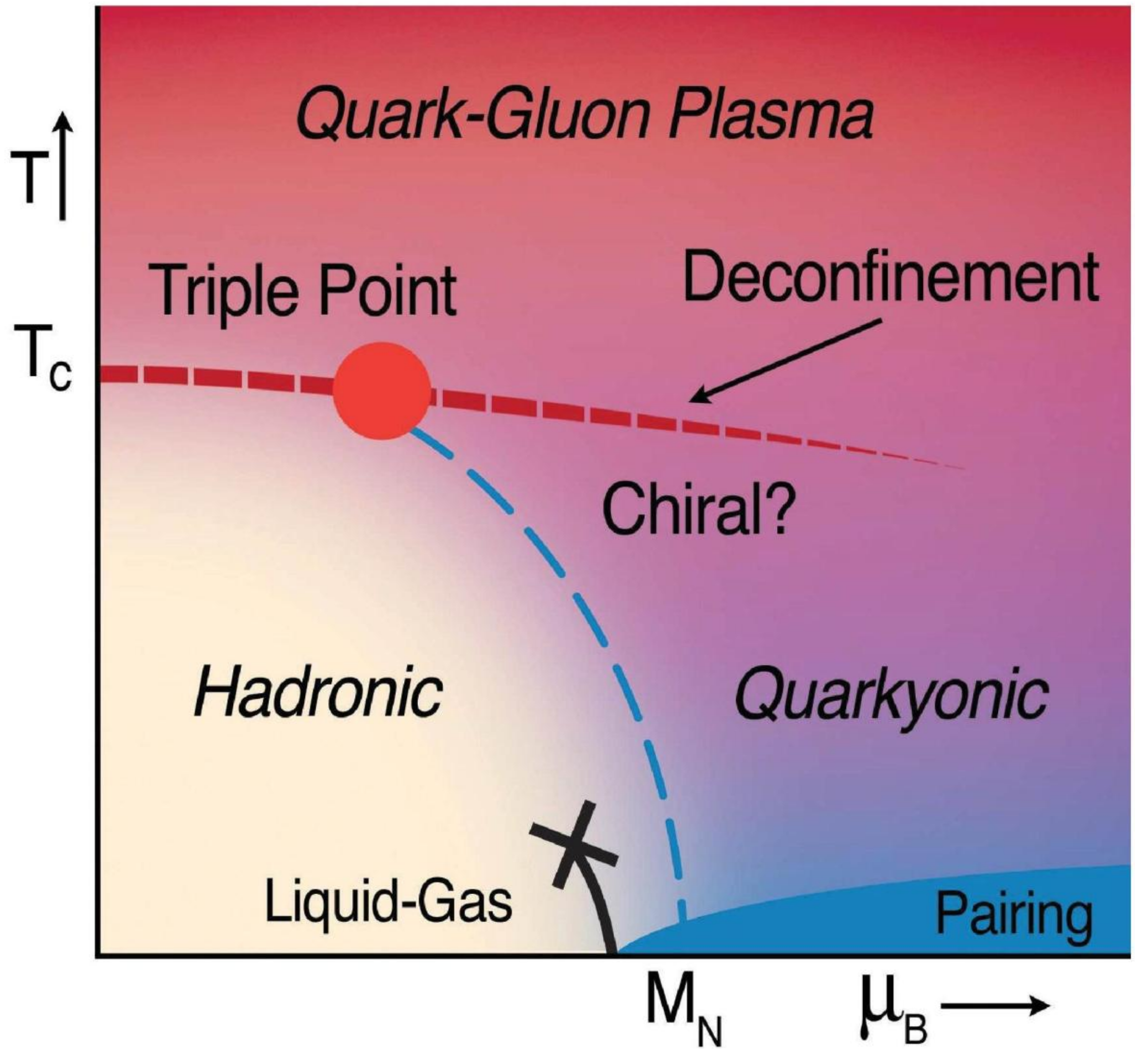


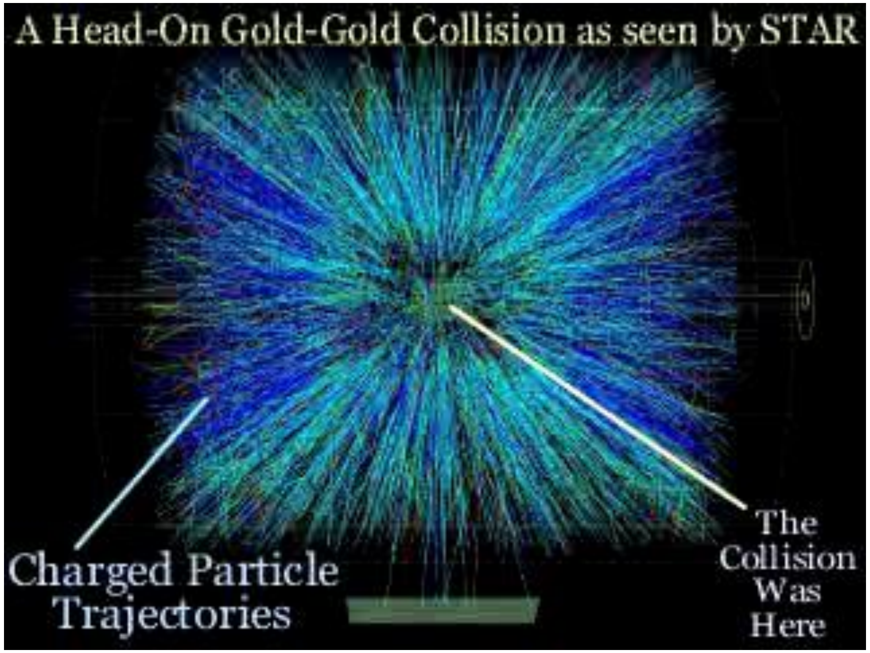
The Phases of QCD
Temperature
Early Universe
Future LHC Experiments
Current RHIC Experiments
⇐RHIC Energy Scan⇒
Quark-Gluon Plasma
Crossover
~170 MeV
Future FAIR Experiments
1st order phase transition
Critical Point
Hadron Gas
Color Superconductor
Nuclear Matter
Neutron Stars
Vacuum
0 MeV
0 MeV
900 MeV
Baryon Chemical Potential

Phase diagram of QCD

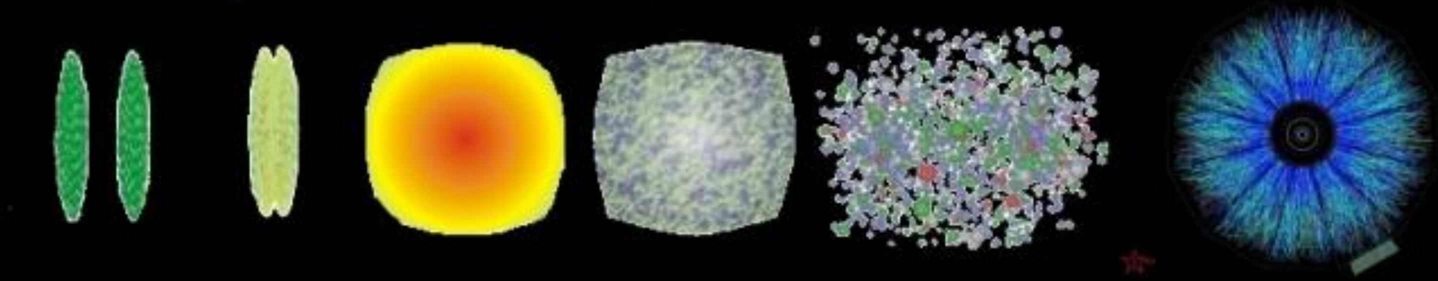


Phase diagram of QCD





devoted to the Physics of the QGP & Relativistic Heavy-Ion Collisions
- moderated by Steffen A. Bass, Berndt Mueller and William A. Zajc -



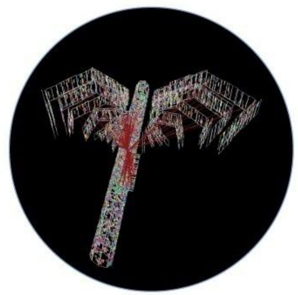
BNL -73847-2005
Formal Report

Hunting the Quark Gluon Plasma

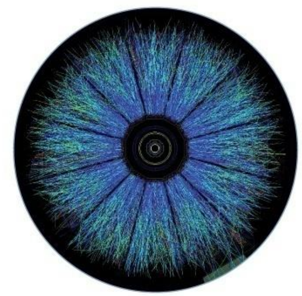
Results from the first 3 years at RHIC

Assessments by the experimental collaborations

April 18, 2005

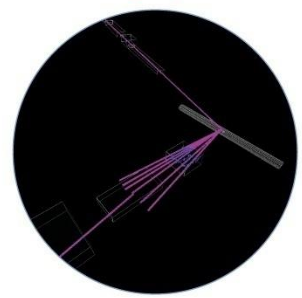


PHOBOS



STAR

PHENIX



BRAHMS

Relativistic Heavy Ion Collider (RHIC) • Brookhaven National Laboratory, Upton, NY 11974-5000

Office of Science
U.S. DEPARTMENT OF ENERGY

BROOKHAVEN
NATIONAL LABORATORY

APS 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 time.

"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. Jet quenching
4. Spectrum of photons
5. Shear viscosity eta/s and hydrodynamic approach
6. Lattice calculations vs experiment

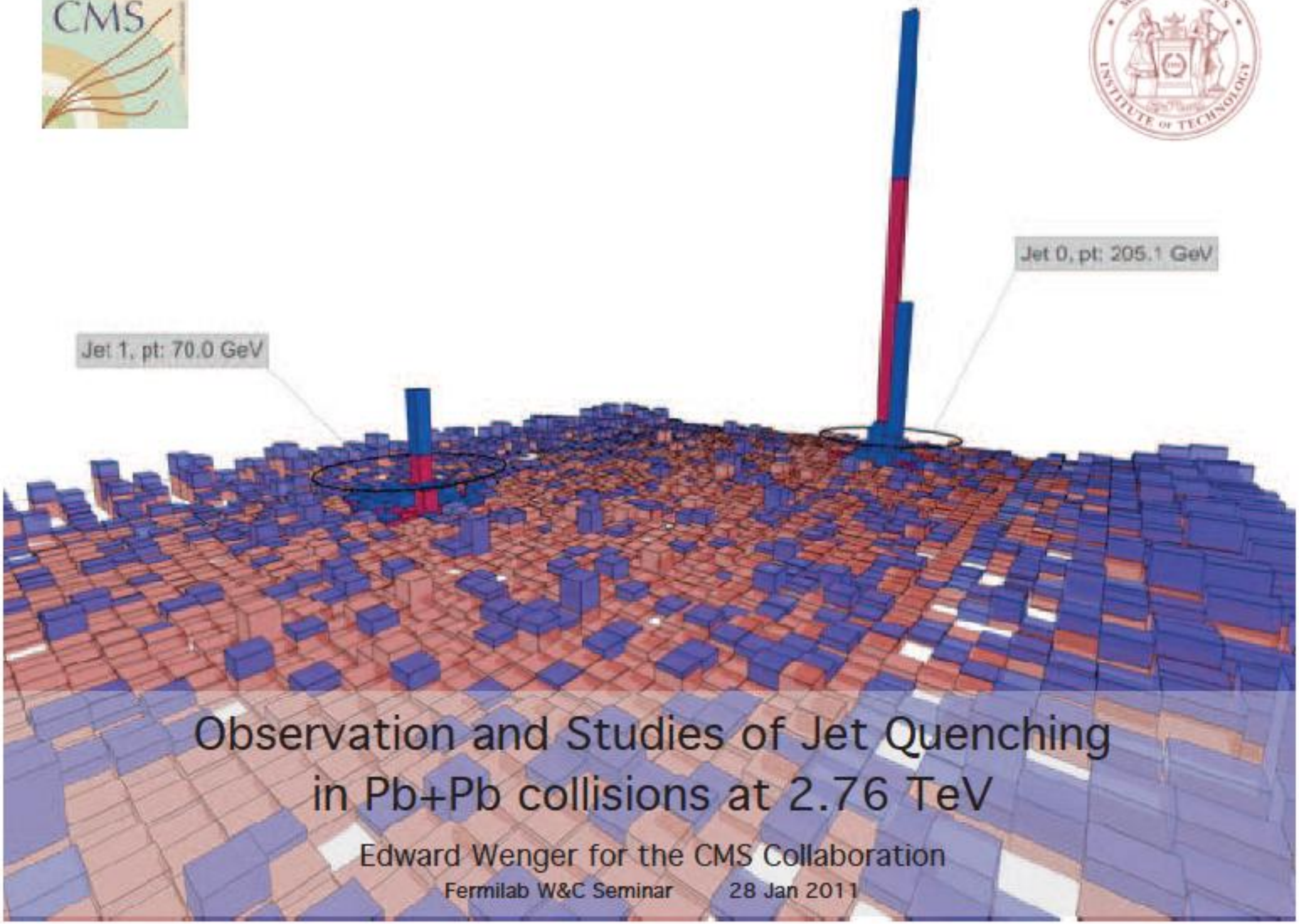
……………………….

JET QUENCHING

JET QUENCHING IN DENSE MATTER.

By Miklos Gyulassy, Michael Plumer

Phys.Lett.B243:432-438,1990



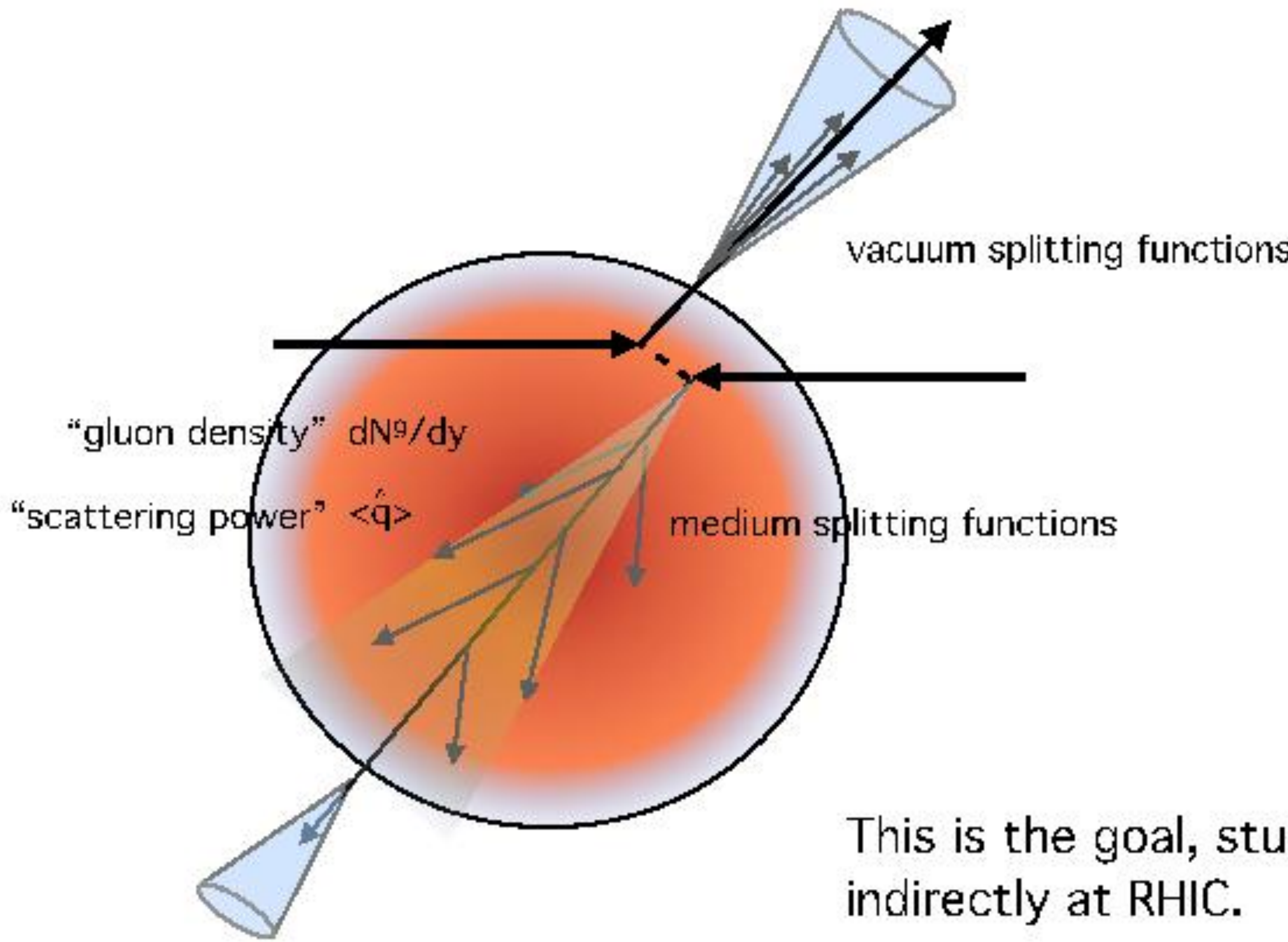
Observation and Studies of Jet Quenching in Pb+Pb collisions at 2.76 TeV

Edward Wenger for the CMS Collaboration

Fermilab W&C Seminar 28 Jan 2011

Probing the QGP

Jet Quenching = Tomographic QGP Probe



This is the goal, studied more indirectly at RHIC.

Dihadron correlations at RHIC

- Correlation of charged hadrons with:

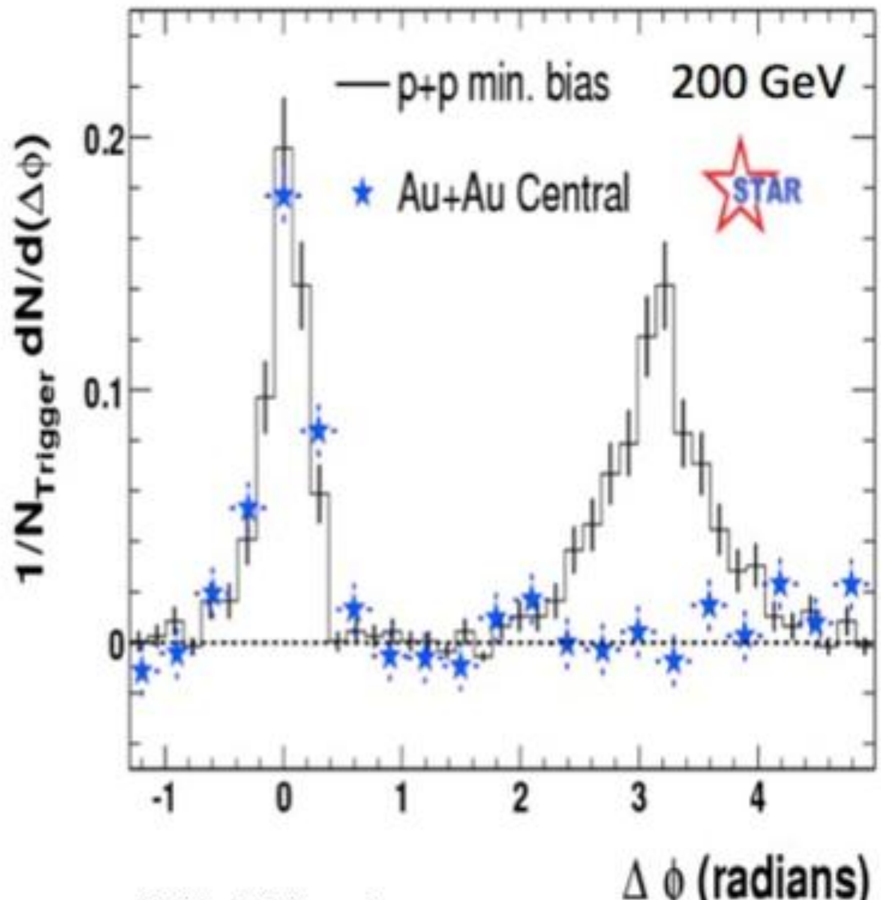
  $2\ GeV/c < p_{T,partner} < p_{T,trigger}$

  $4\ GeV/c < p_{T,trigger} < 6\ GeV/c$

- Near-side peak shows little modification

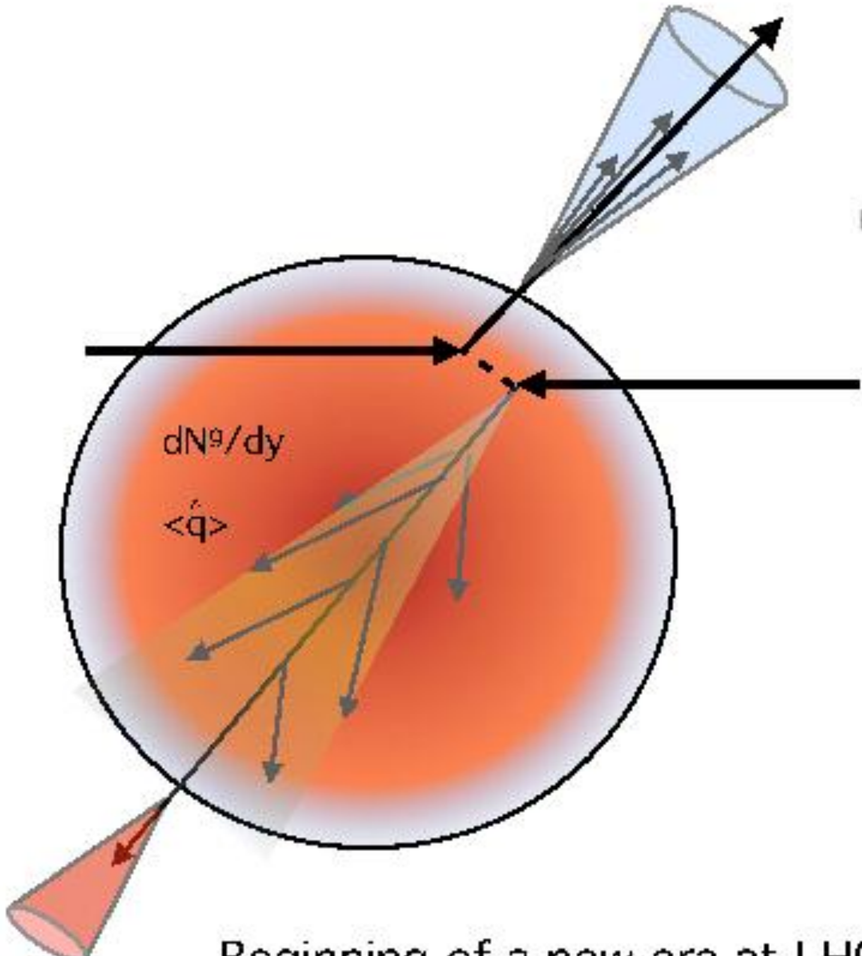
- Away-side jet correlation nearly extinguished in this p_T range

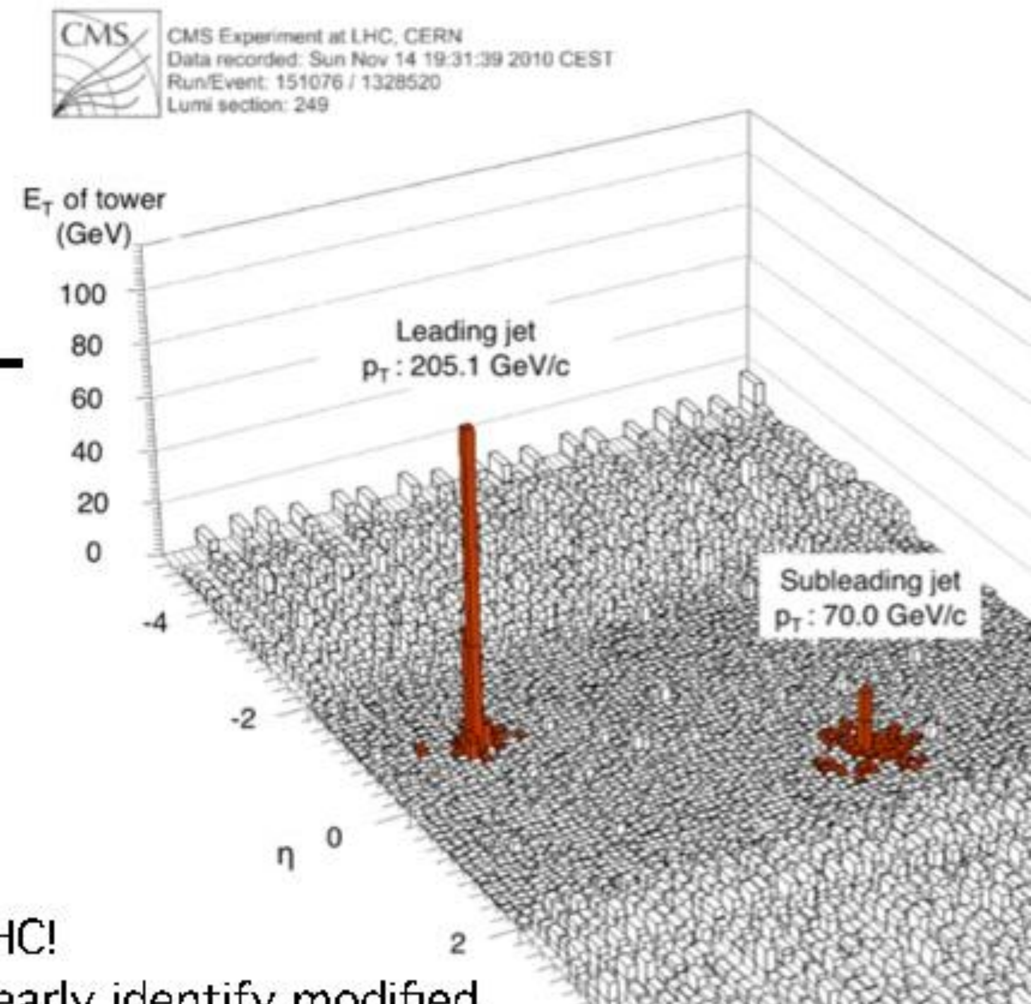
Dihadron Correlations (STAR)



STAR Collaboration
Phys. Rev. Lett. 91 (2003) 072304

A New Era in Jet Quenching



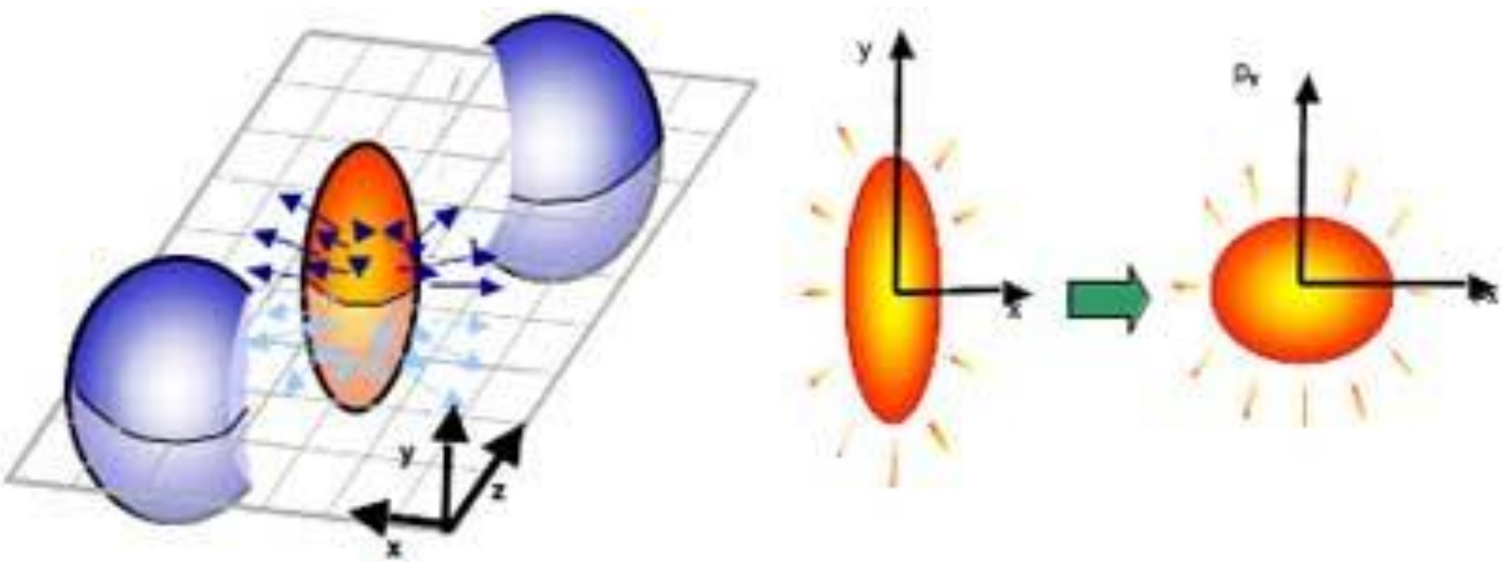


Beginning of a new era at LHC!
For the first time, we can clearly identify modified dijet partners.

Elliptic flow

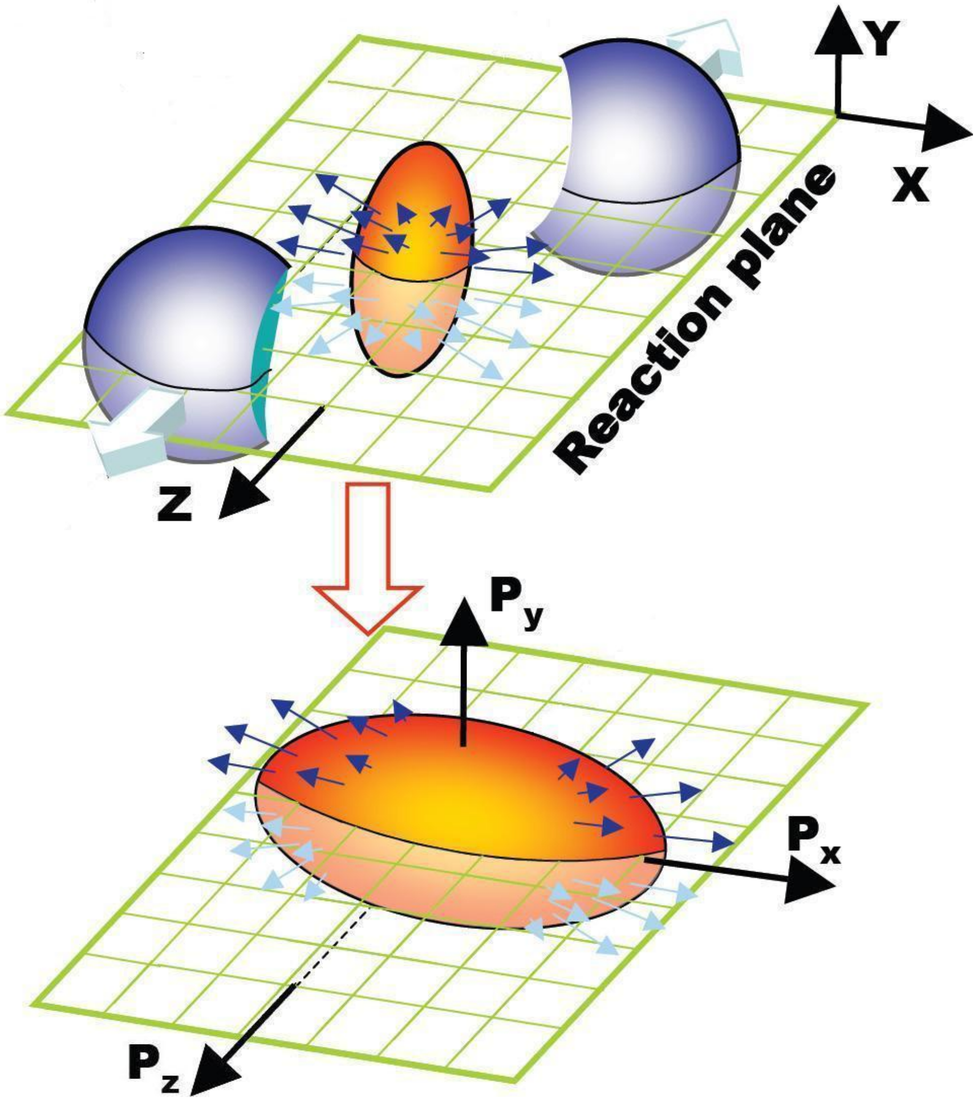
Wikipedia

The **elliptic flow**[1][2] is described as one of the most important observations measured at the Relativistic Heavy Ion Collider (RHIC).



Left: Schematic of the collision zone between two incoming nuclei. Right: Initial-state anisotropy in the collision zone converting into final-state elliptic flow, measured as anisotropy in particle momentum. RHIC **Strange Brew …** by Jamie Dunlop

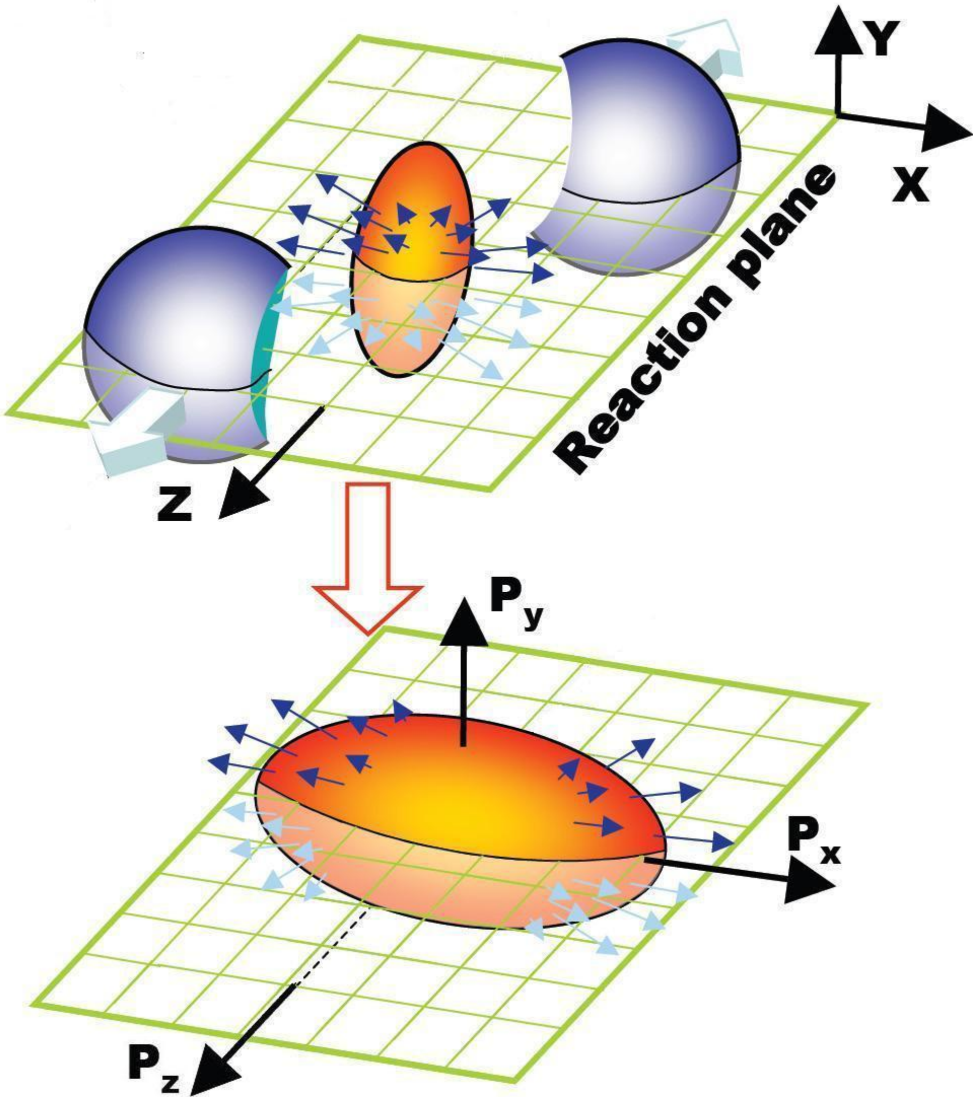
HYDRODYNAMICS explains elliptic flow



K. Dusling and D. Teaney, Phys. Rev. C 77, 034905 (2008)
H. Song and U. W. Heinz, Phys. Rev. C 77, 064901 (2008)
M. Luzum and P. Romatschke, Phys. Rev. C 78, 034915 (2008) [Erratum-ibid. C 79, 039 P. Huovinen and D. Molnar 903 (2009)]
P. Huovinen and D. Molnar, Phys. Rev. C 79, 014906 (2009)

Slide by Art Poskanzer

HYDRODYNAMICS explains elliptic flow



K. Dusling and D. Teaney, Phys. Rev. C 77, 034905 (2008)
H. Song and U. W. Heinz, Phys. Rev. C 77, 064901 (2008)
M. Luzum and P. Romatschke, Phys. Rev. C 78, 034915 (2008) [Erratum-ibid. C 79, 039 P. Huovinen and D. Molnar 903 (2009)]
P. Huovinen and D. Molnar, Phys. Rev. C 79, 014906 (2009)

Slide by Art Poskanzer

HYDRODYNAMICS explains elliptic flow, the equations are not very simple

conservation

$$\partial_\mu T^{\mu\nu}(x) = 0 \quad , \qquad \partial_\mu N^\mu(x) = 0 \ , \tag{1}$$

and the equation of state $p(e, n)$. *Ideal* (Euler) hydrodynamics assumes local equilibrium in which case

$$T^{\mu\nu}_{LR,id} = diag(\varepsilon, p, p, p) \quad , \qquad N^\mu_{LR,id} = (n, \mathbf{0}) \qquad\qquad [u^\mu_{LR} = (1, \mathbf{0})] \tag{2}$$

in the fluid rest frame LR. Extension of the theory with additive corrections *linear* in flow and temperature gradients[20]

$$\delta T^{\mu\nu}_{NS} \ = \ \eta_s(\nabla^\mu u^\nu + \nabla^\nu u^\mu - \frac{2}{3}\Delta^{\mu\nu}\partial^\alpha u_\alpha) + \zeta\Delta^{\mu\nu}\partial^\alpha u_\alpha \quad , \tag{3}$$

$$\delta N^\mu_{NS} \ = \ \kappa_q \left(\frac{nT}{\varepsilon + p}\right)^2 \nabla^\mu \left(\frac{\mu}{T}\right) \qquad\qquad (\Delta^{\mu\nu} \equiv g^{\mu\nu} - u^\mu u^\nu \quad , \quad \Delta^\mu \equiv \Delta^{\mu\nu}\partial_\nu) \tag{4}$$

leads via (1) to the relativistic Navier-Stokes (NS) equations. (We use the Landau frame convention $u_\mu \delta T^{\mu\nu} \equiv 0$ throughout this paper, i.e., the flow velocity is chosen such that momentum flow vanishes in the LR frame.) Here

HYDRODYNAMICS explains elliptic flow, the equations are not very simple

III. ISRAEL-STEWART HYDRODYNAMICS AND BOOST INVARIANCE

A. Israel-Stewart equations

There seems to be some confusion regarding Israel-Stewart theory[22, 23] in the recent literature, therefore we start with reviewing the key ingredients. The starting point of Israel and Stewart (IS) is an entropy current that includes terms up to quadratic order in dissipative quantities[45]

$$S^\mu = u^\mu \left[s_{eq} - \frac{1}{2T}\left(\beta_0 \Pi^2 - \beta_1 q_\nu q^\nu + \beta_2 \pi^{\lambda\nu}\pi_{\lambda\nu}\right)\right] + \frac{q^\mu}{T}\left(\frac{\mu n}{\varepsilon + p} + \alpha_0 \Pi\right) - \frac{\alpha_1 q_\nu \pi^{\nu\mu}}{T} \tag{14}$$

(we follow the Landau frame convention). Here μ is the chemical potential, and s_{eq} is the entropy density in local equilibrium. The coefficients $\{\alpha_i(e,n)\}$ and $\{\beta_i(e,n)\}$ encode additional matter properties that complement the equation of state and the transport coefficients. Most importantly, $\{\beta_i\}$ control the relaxation times for dissipative quantities:

$$\tau_\Pi = \zeta\beta_0 \ , \qquad \tau_q = \kappa_q T \beta_1 \ , \qquad \tau_\pi = 2\eta_s\beta_2 \ . \tag{15}$$

The entropy current and relaxation times in Navier-Stokes theory are recovered when all the coefficients are set to zero $\beta_0 = \beta_1 = \beta_2 = 0 = \alpha_0 = \alpha_1$ (but as discussed previously, the IS and NS transport coefficients differ in general).

The requirement of entropy non-decrease ($\partial_\mu S^\mu \geq 0$), which IS satisfy via a positive semi-definite[46] quadratic ansatz

$$T\partial_\mu S^\mu = \frac{\Pi^2}{\zeta} - \frac{q_\mu q^\mu}{\kappa_q T} + \frac{\pi_{\mu\nu}\pi^{\mu\nu}}{2\eta_s} \geq 0 \ , \tag{16}$$

leads to the identification of the dissipative currents:

$$\Pi = \zeta\left[-\nabla_\mu u^\mu - \frac{1}{2}\Pi T \partial_\mu\left(\frac{\beta_0 u^\mu}{T}\right) - \beta_0 D\Pi + \alpha_0 \partial_\mu q^\mu - a_0' q^\mu D u_\mu\right] \tag{17}$$

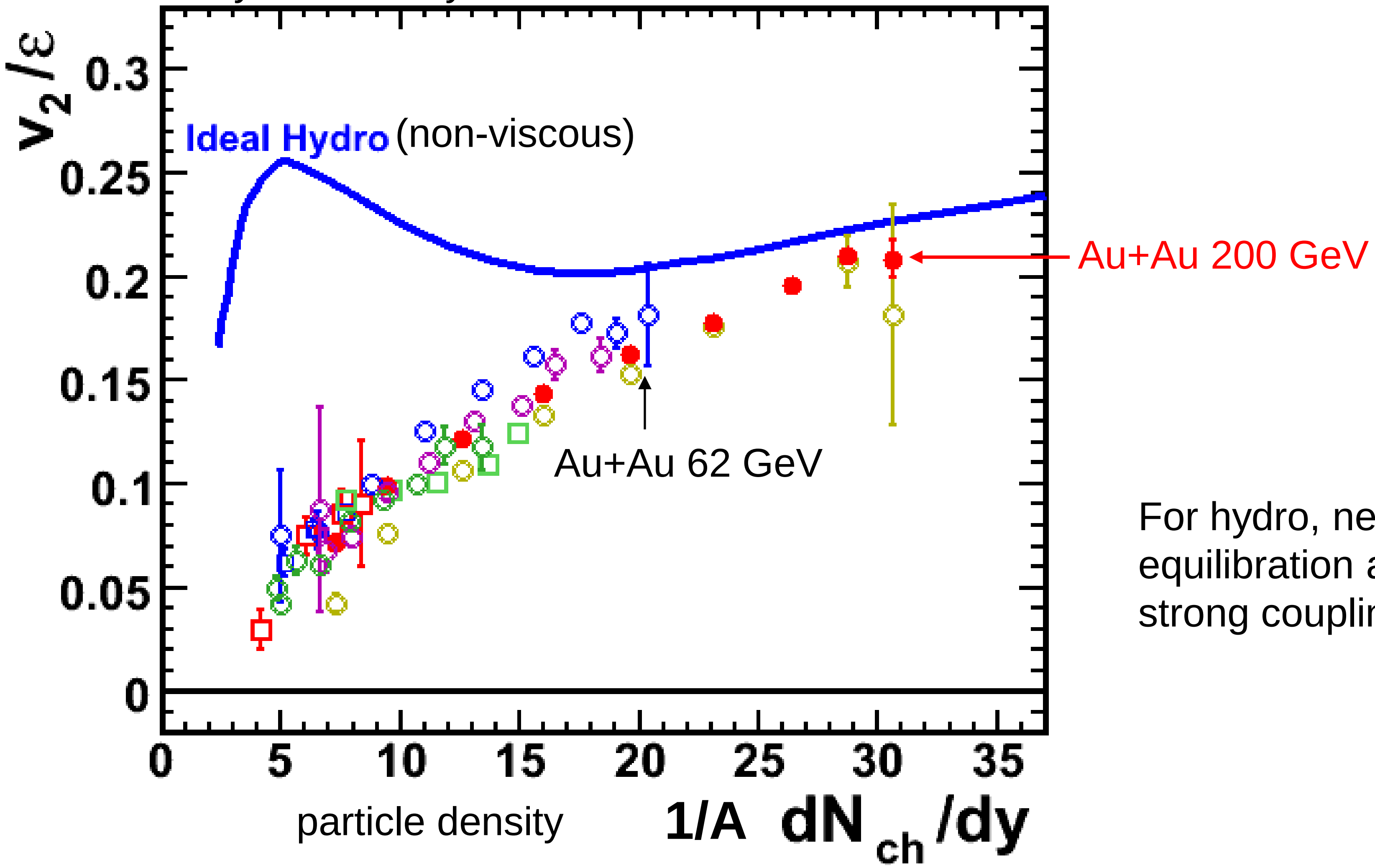
$$q^\mu = -\kappa_q T \Delta^{\mu\nu}\left[\frac{Tn}{\varepsilon+p}\nabla_\nu\left(\frac{\mu}{T}\right) + \frac{1}{2} q_\nu T \partial_\lambda\left(\frac{\beta_1 u^\lambda}{T}\right) + \beta_1 D q_\nu + \alpha_0 \nabla_\nu \Pi - \alpha_1 \partial^\lambda \pi_{\lambda\nu} - a_0 \Pi D u_\nu + a_1 \pi_{\lambda\nu} D u^\lambda\right] \tag{18}$$

$$\pi^{\mu\nu} = 2\eta_s\left[\nabla^{\langle\mu}u^{\nu\rangle} - \frac{1}{2}\pi^{\mu\nu} T \partial_\lambda\left(\frac{\beta_2 u^\lambda}{T}\right) - \beta_2 \langle D\pi^{\mu\nu}\rangle - \alpha_1 \nabla^{\langle\mu} q^{\nu\rangle} + a_1' q^{\langle\mu} D u^{\nu\rangle}\right] \tag{19}$$

$$a_i' \equiv \left.\frac{\partial(\alpha_i/T)}{\partial(1/T)}\right|_{\mu/T=const} - a_i \ . \tag{20}$$

Approach to Hydro

flow scaled by eccentricity

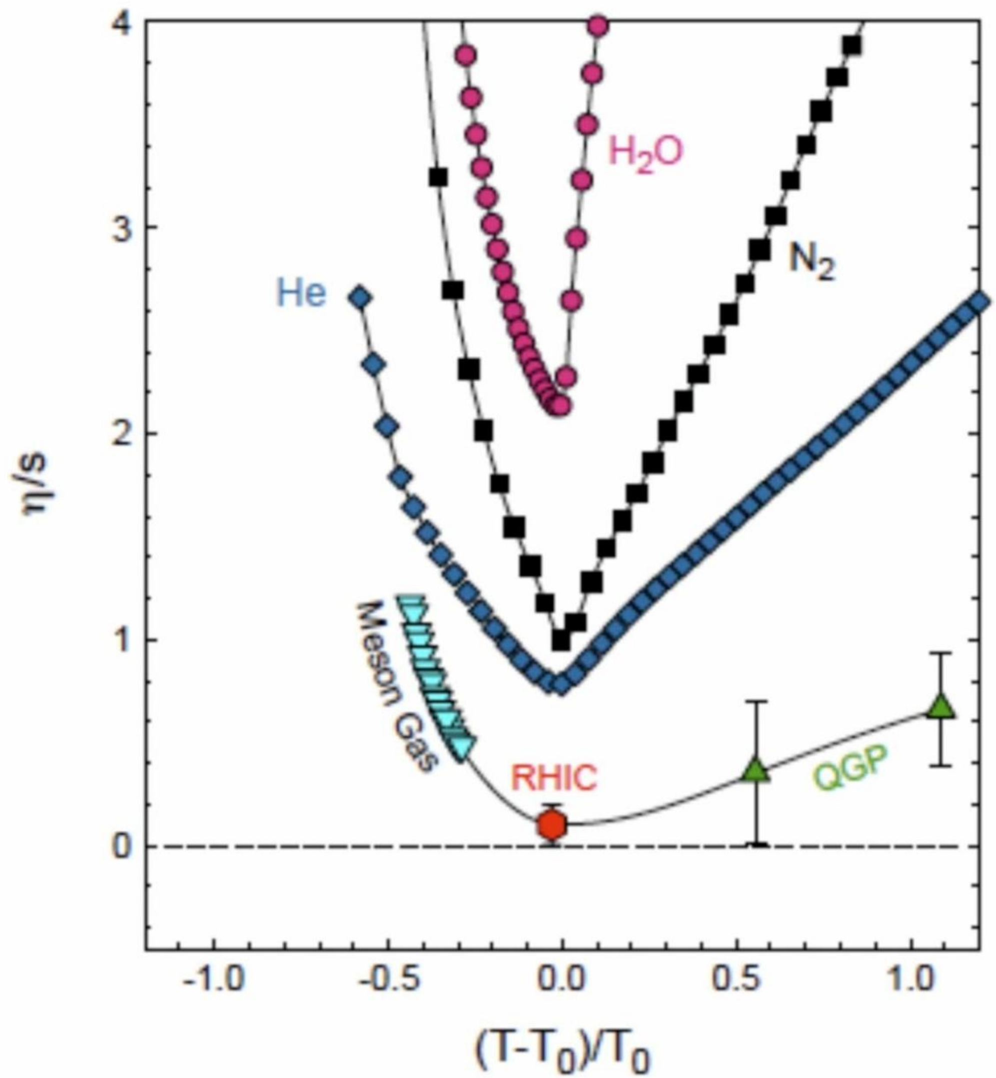


For hydro, need early equilibration and strong coupling

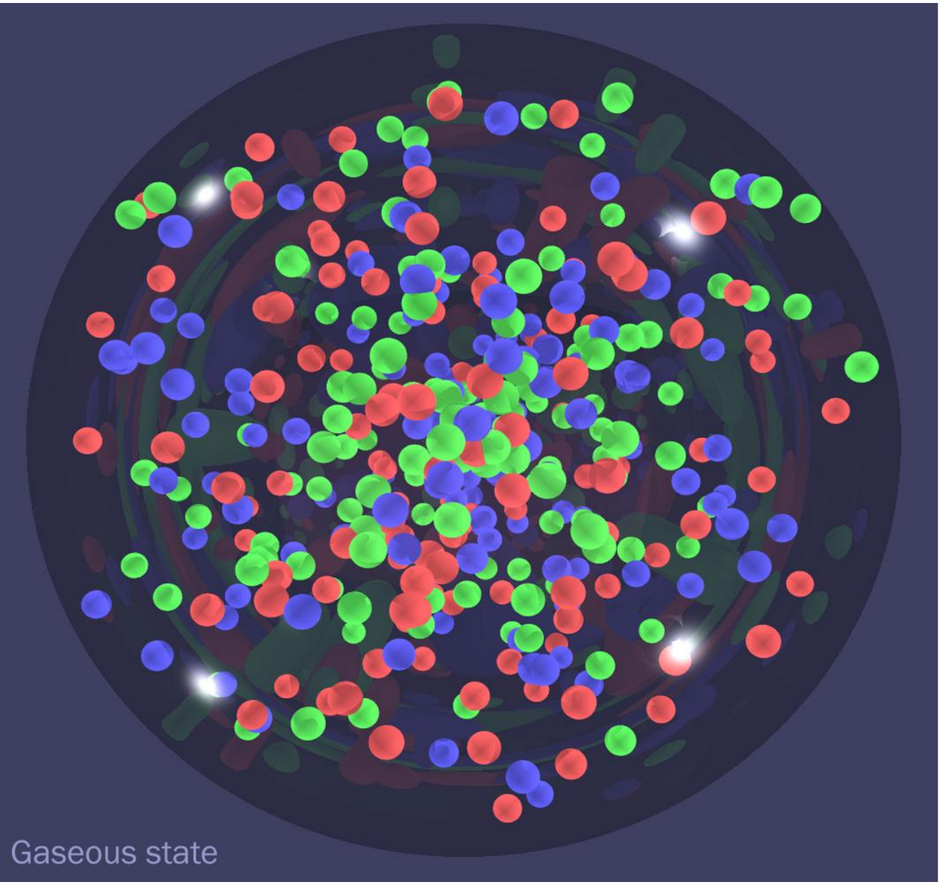
Slide by Art Poskanzer

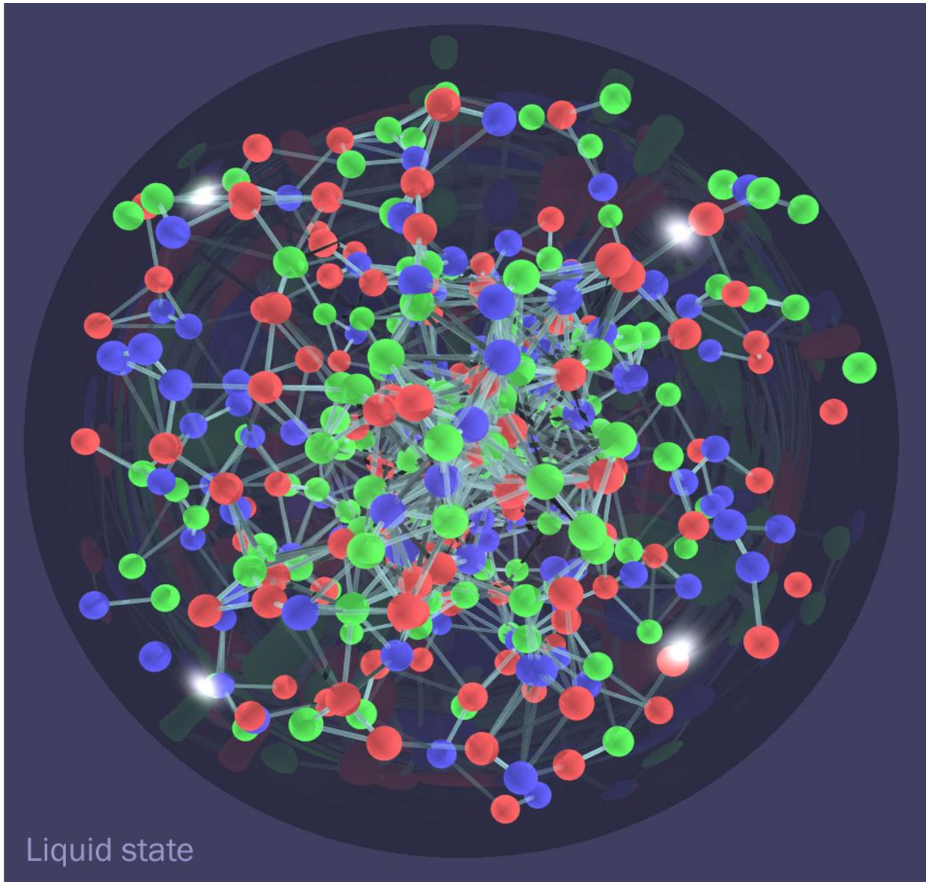
Sergei Voloshin, QM06, S883 (2007)
Hydro: Kolb, Sollfrank, and Heinz PRC **62**, 0544909 (2000)

HYDRODYNAMICS explains elliptic flow, and give very small value of the shear viscosity from the fit of the experimental data



QGP is the thermalized strongly correlated liquid





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

QUARK-GLUON PLASMA THERMALIZATION AND PLASMA INSTABILITIES
PETER ARNOLD

arXiv:hep-ph/0409002v1

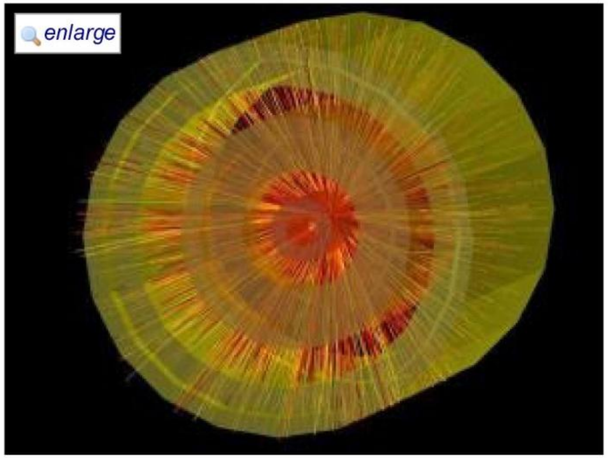
when they are in *local* thermal equilibrium. Macroscopic currents in one region of the plasma can interact magnetically with other currents in other regions, over tremendous distance scales, creating complicated structures like Fig. 1. Non-Abelian plasmas, however, are somewhat different. From theoretical 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⟩.

Science News

Early Universe Was a Liquid, Nuclei Collisions at the Large Hadron Collider Show

ScienceDaily (Nov. 23, 2010) — In an experiment to collide lead nuclei together at CERN's Large Hadron Collider physicists from the ALICE detector team including researchers from the University of Birmingham have discovered that the very early Universe was not only very hot and dense but behaved like a hot liquid.



Another Real lead-lead collision in ALICE inner detector. (Credit: CERN)

See Also:

Space & Time
- Astrophysics
- Cosmic Rays
- Big Bang

Matter & Energy
- Quantum Physics
- Physics
- Nature of Water

Reference
- List of phases of matter
- Nucleosynthesis
- Proton

By accelerating and smashing together lead nuclei at the highest possible energies, the ALICE experiment has generated incredibly hot and dense sub-atomic fireballs, recreating the conditions that existed in the first few microseconds after the Big Bang. Scientists claim that these mini big bangs create temperatures of over ten trillion degrees.

At these temperatures normal matter is expected to melt into an exotic, primordial 'soup' known as quark-gluon plasma. These first results from lead collisions have

Thermalisation

After freezeout we have thermalized hadron gaz!

Chemical equilibrium,a hadro-chemical equilibrium model.

We know that from experimental distributions

Grand Canonical Ensemble for ideal gaz

$$Z = \sum_{N=0}^{\infty} \sum_{\{n_i\}} \prod_i e^{-\beta n_i(\varepsilon_i - \mu)}, \quad \beta = \frac{1}{kT}$$

❍ is the chemical potential; n_i is the number of particles in the i-th state.

Hadron production in central nucleus-nucleus collisions at chemical freeze-out
A.Andronic a, P.Braun-Munzinger , J. Stachel
arXiv:nucl-th/0511071

The basic quantity required to compute the thermal composition of hadron yields measured in heavy ion collisions is the partition function $Z(T, V)$. In the grand canonical (GC) ensemble, the partition function for species i is ($\hbar = c = 1$):

$$\ln Z_i = \frac{V g_i}{2\pi^2} \int_0^\infty \pm p^2 \mathrm{d}p \ln[1 \pm \exp(-(E_i - \mu_i)/T)], \quad (1)$$

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from which the density is then calculated according to:

$$n_i = N_i/V = -\frac{T}{V}\frac{\partial \ln Z_i}{\partial \mu} = \frac{g_i}{2\pi^2} \int_0^\infty \frac{p^2 \mathrm{d}p}{\exp[(E_i - \mu_i)/T] \pm 1}, \tag{2}$$

where $g_i = (2J_i{+}1)$ is the spin degeneracy factor, T is the temperature and $E_i = \sqrt{p^2 + m_i^2}$ is the total energy. The (+) sign is for fermions and (–) is for bosons. For hadron i of baryon number B_i, third component of the isospin I_{3i}, strangeness S_i, and charmness C_i, the chemical potential is $\mu_i = \mu_b B_i + \mu_{I_3} I_{3i} + \mu_S S_i + \mu_C C_i$. The chemical potentials related to baryon number (μ_b), isospin (μ_{I_3}), strangeness (μ_S) and charm (μ_C) ensure the conservation (on average) of the respective quantum numbers: i) baryon number: $V\sum_i n_i B_i = N_B$; ii) isospin: $V\sum_i n_i I_{3i} = I_3^{tot}$; iii) strangeness: $V\sum_i n_i S_i = 0$; iv) charm: $V\sum_i n_i C_i = 0$. The (net) baryon number N_B and the total isospin I_3^{tot} of the system are input values which need to be specified according to the colliding nuclei studied.

The following hadrons are included in the calculations:
i) mesons: non-strange (37), strange (28), charm (15), bottom (16); sum=96

ii) baryons: non-strange (30), strange (33), charm (10); sum=73

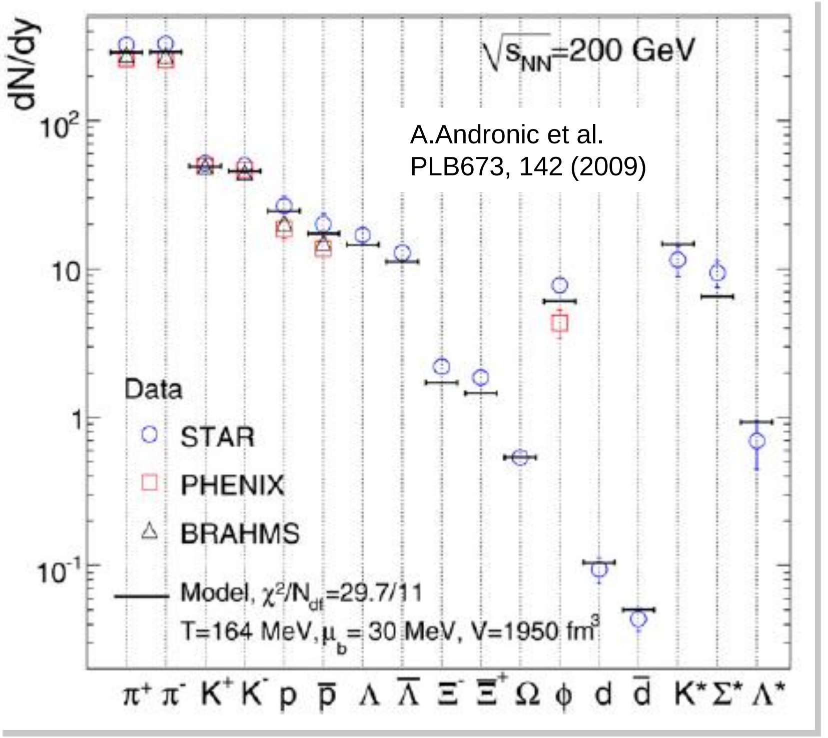
iii) ”composites” (nuclei up to 4He and K−-clusters [28], 18). sum=18

The corresponding anti-particles are of course also included

Total =187 hadrons

Statistical Models

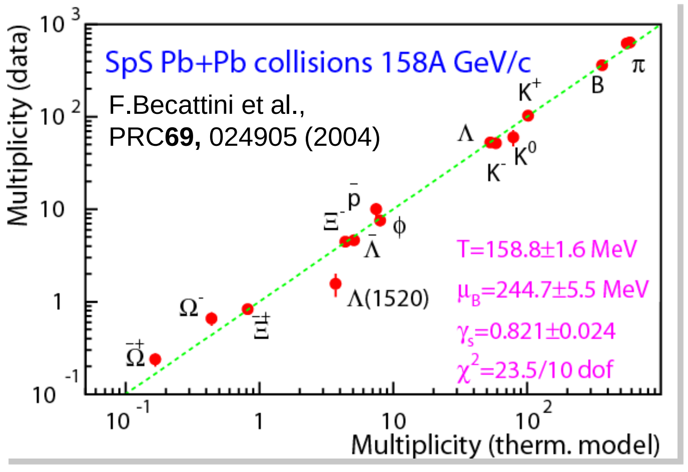
Multiplicities determined by statistical weights
(⇒ chemical equilibrium)



Grand-canonical partition function:

$$\boxed{\langle n_j \rangle = \frac{(2J_j+1)V}{(2\pi)^3} \int d^3p \left[e^{\sqrt{p^2+m_j^2}/T + \mu \cdot q_j/T} \pm 1 \right]^{-1}}$$

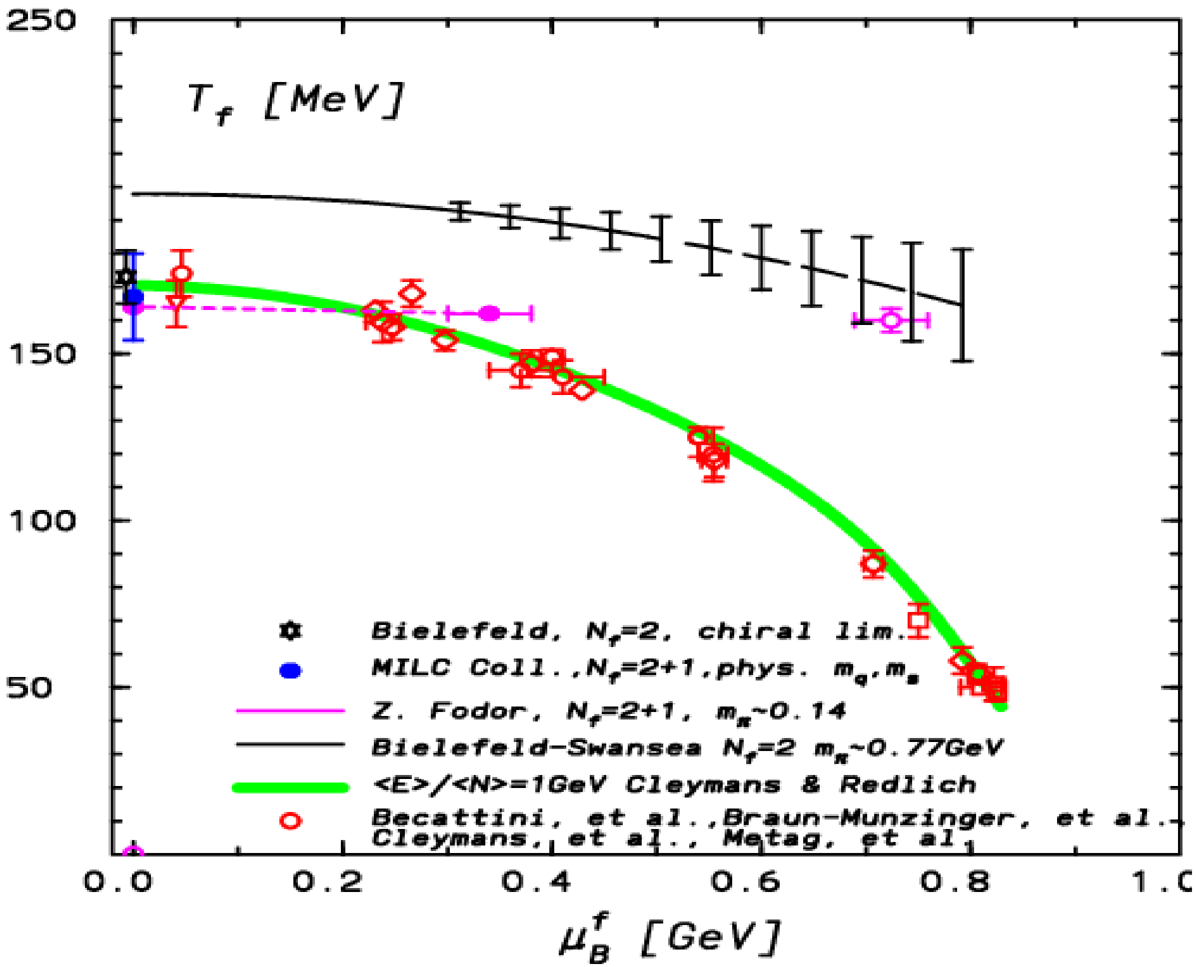
⇒ Parameters: ***V*, *T*, μ_B, γ_S**



Details: see F. Becattini's lecture

SLIDE by

Lattice calculations
QCD on supercomputers



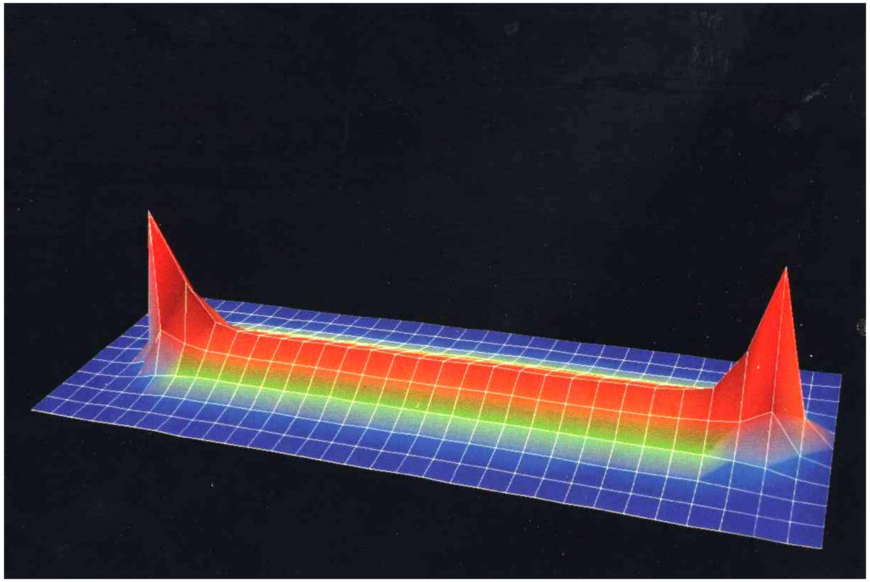
The main result of these investigations was that the extracted temperature values rise rather sharply from low energies on towards √sNN ≃10 GeV and reach afterwards constant values near T=160 MeV, while the baryochemical potential decreases smoothly as a function of energy. arXiv:1106.6321v1, A. Andronic, P. Braun-Munzinger, K. Redlich, J. Stachel

The closer our calculations to nature the more complicated they are

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

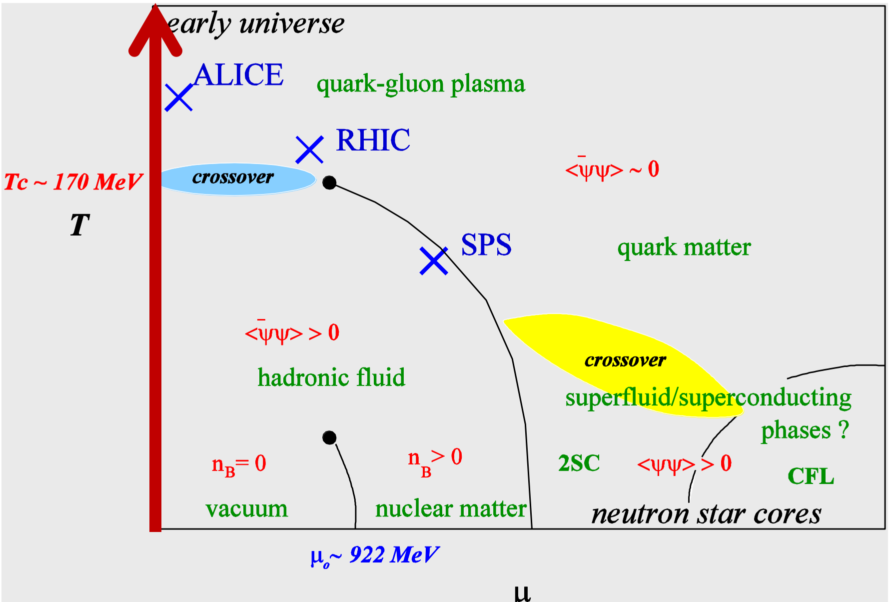
The closer our calculations to nature the more complicated they are

4 dimensional gluodynamics (no dynamical quarks) can be “solved” on laptop



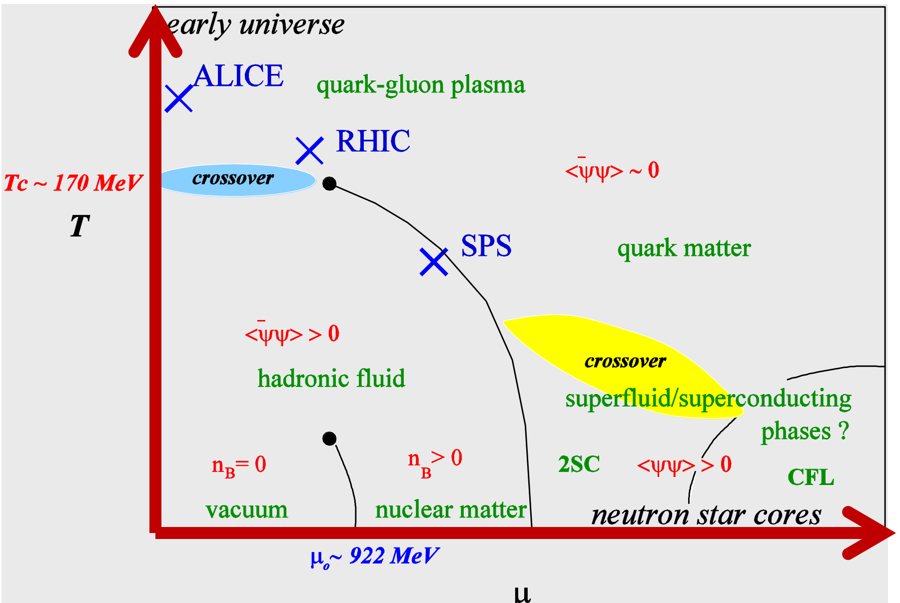
The closer our calculations to nature the more complicated they are

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

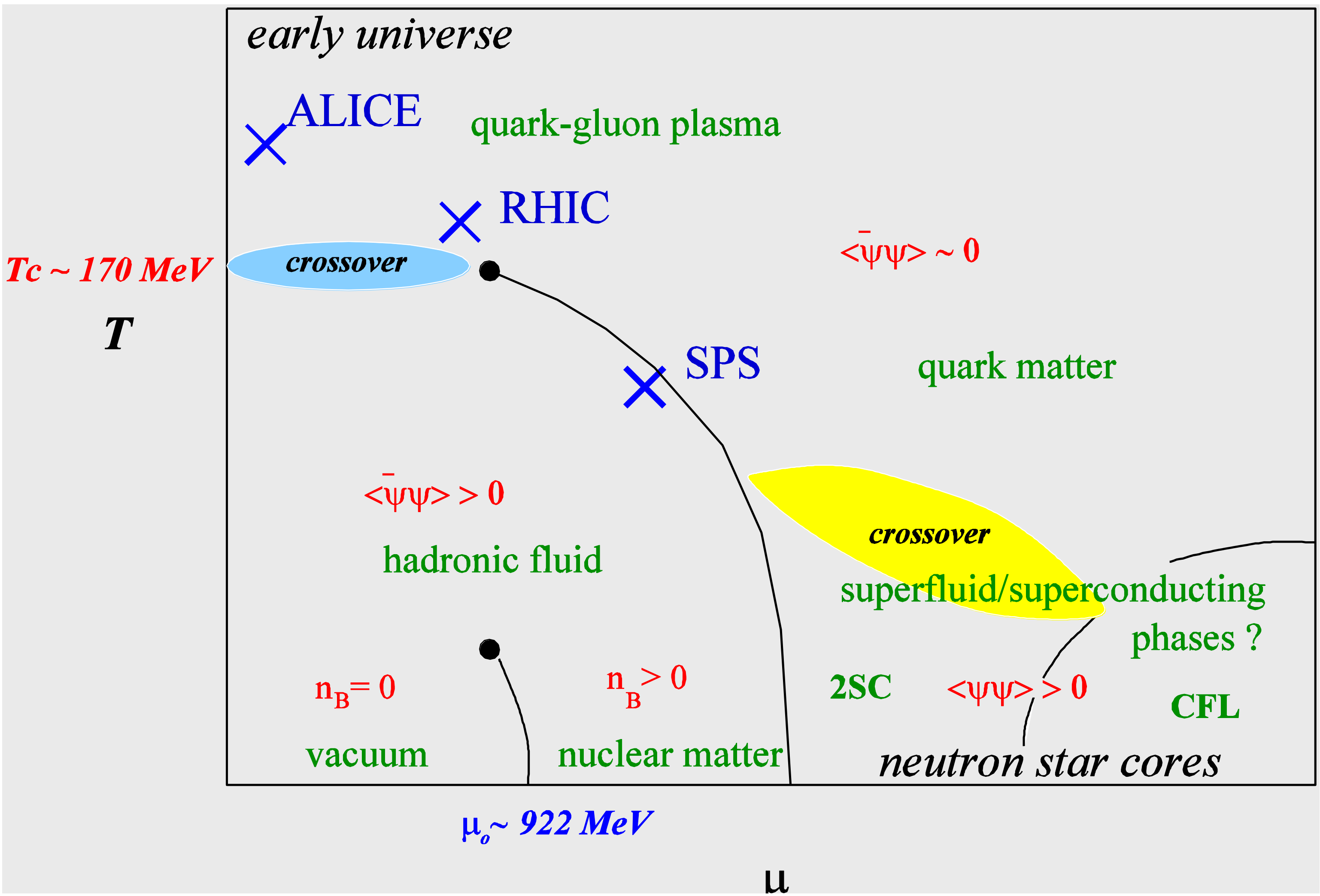


The closer our calculations to nature the more complicated they are

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

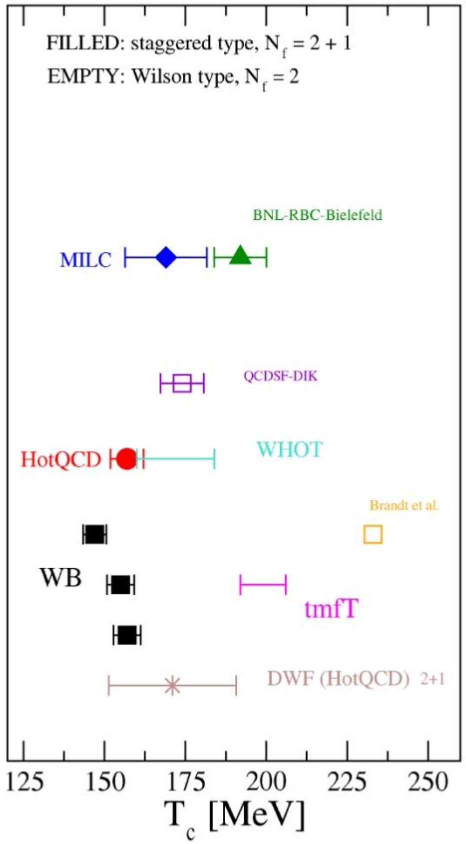


Phase diagram of QCD



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

Critical temperature

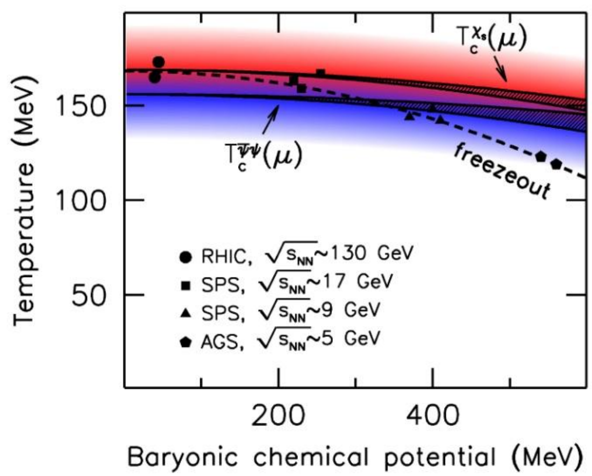
Critical line in the $\mu_B - T$ plane for $N_f = 2+1$

- Results from G. Endrödi et al. [arXiv:1102.1356] with Taylor expansion method, $N_t = 6, 8, 10$, physical quarks and stout action; continuum limit taken:

$$T_c(\mu_B^2) = T_c\left(1 - \kappa \cdot \mu_B^2/T_c^2\right), \qquad \kappa = -T_c \left.\frac{dT_c(\mu_B^2)}{d(\mu_B^2)}\right|_{\mu_B=0} = -T_c\left[-\left.\left(\frac{\partial\phi}{\partial\mu_B^2}\right)\right|_{T_c,\mu_B=0} \Big/ \left.\left(\frac{\partial\phi}{\partial T}\right)\right|_{T_c,\mu_B=0}\right]$$

$$\kappa^{(\chi_s/T^2)} = 0.0089(14), \qquad \kappa^{(\bar\psi\psi_r)} = 0.0066(20).$$

- Kaczmarek et al. [PRD83 2011] for 2+1 flavors: $\kappa = 0.0066(5)$.
- Compare with $N_f = 2$ (Leonardo Cosmai talk) $\kappa = 0.0059(1)$, WHOT-QCD (2010) $\kappa \approx 0.0078$. Freezeout curve: $\kappa \approx 0.02$.

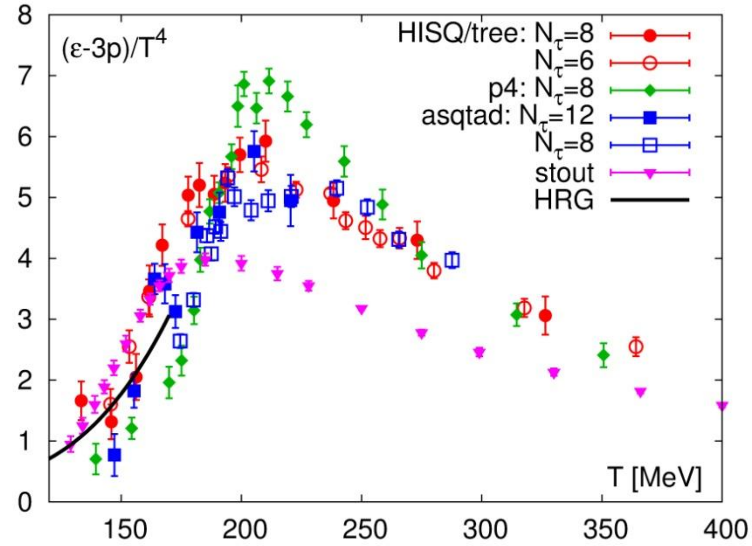


L. Levkova; Talk at Lattice 2011

Equation of State

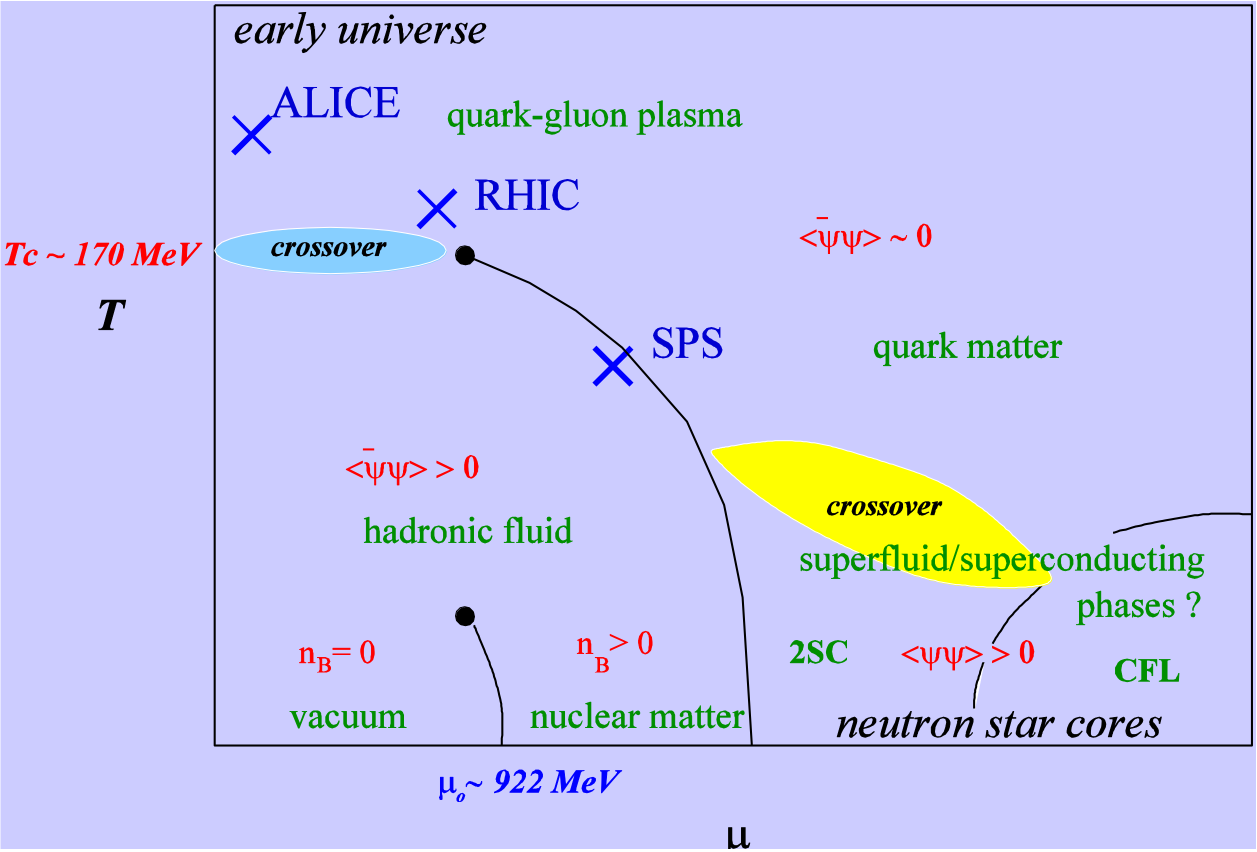
Integral method for the EOS

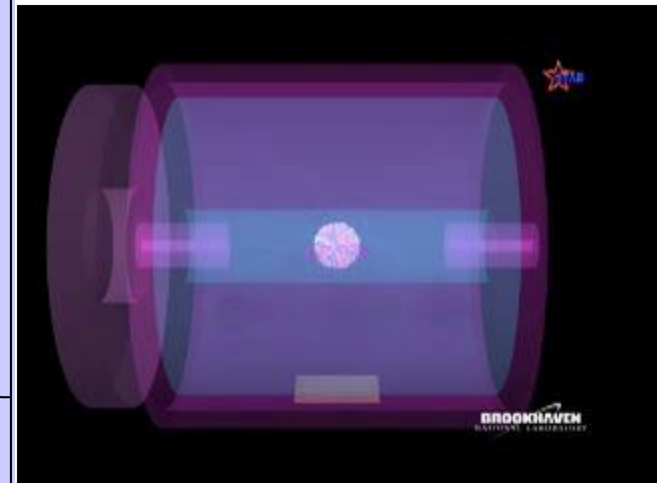
$$\varepsilon V = -\left.\frac{\partial \ln Z}{\partial(1/T)}\right|_V, \quad \frac{p}{T} = \left.\frac{\partial \ln Z}{\partial V}\right|_T \approx \frac{\ln Z}{V}, \quad \Theta^{\mu\mu} = \varepsilon - 3p = -\frac{T}{V}\frac{d\ln Z}{d\ln a}$$



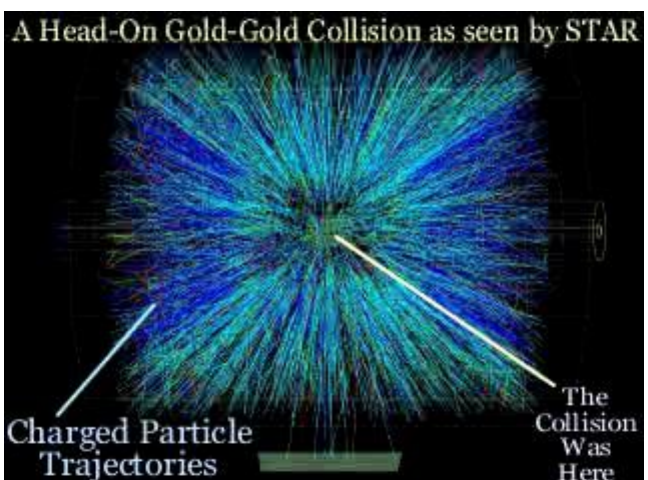
- Comparison of the WB and HotQCD data for 2+1 flavors. Discrepancies due to m_l/m_s (0.037 vs 0.10) ? Need to resolve discrepancies at high T — runs at $N_t = 12$ HISQ may help.

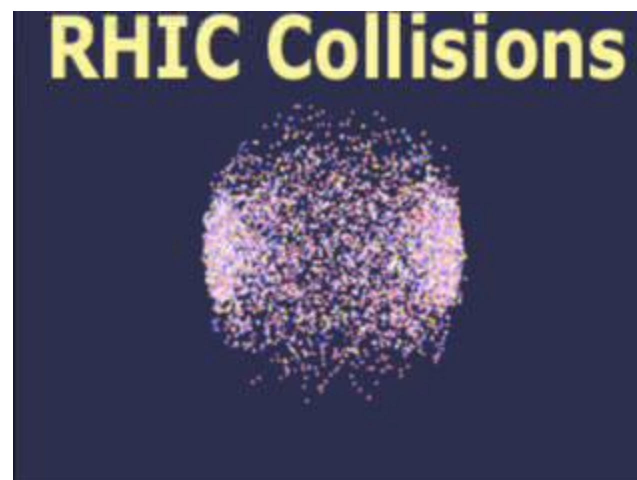
L. Levkova; Talk at Lattice 2011


early universe
ALICE
quark-gluon plasma
RHIC
Tc ~ 170 MeV
crossover
$\langle\bar{\psi}\psi\rangle \sim 0$
T
SPS
quark matter
$\langle\bar{\psi}\psi\rangle > 0$
crossover
hadronic fluid
superfluid/superconducting
phases ?
$n_B = 0$
$n_B > 0$
2SC
$\langle\psi\psi\rangle > 0$
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

Magnetic Field in Noncentral Heavy Ion Collisions

Below I use a lot of slides made by

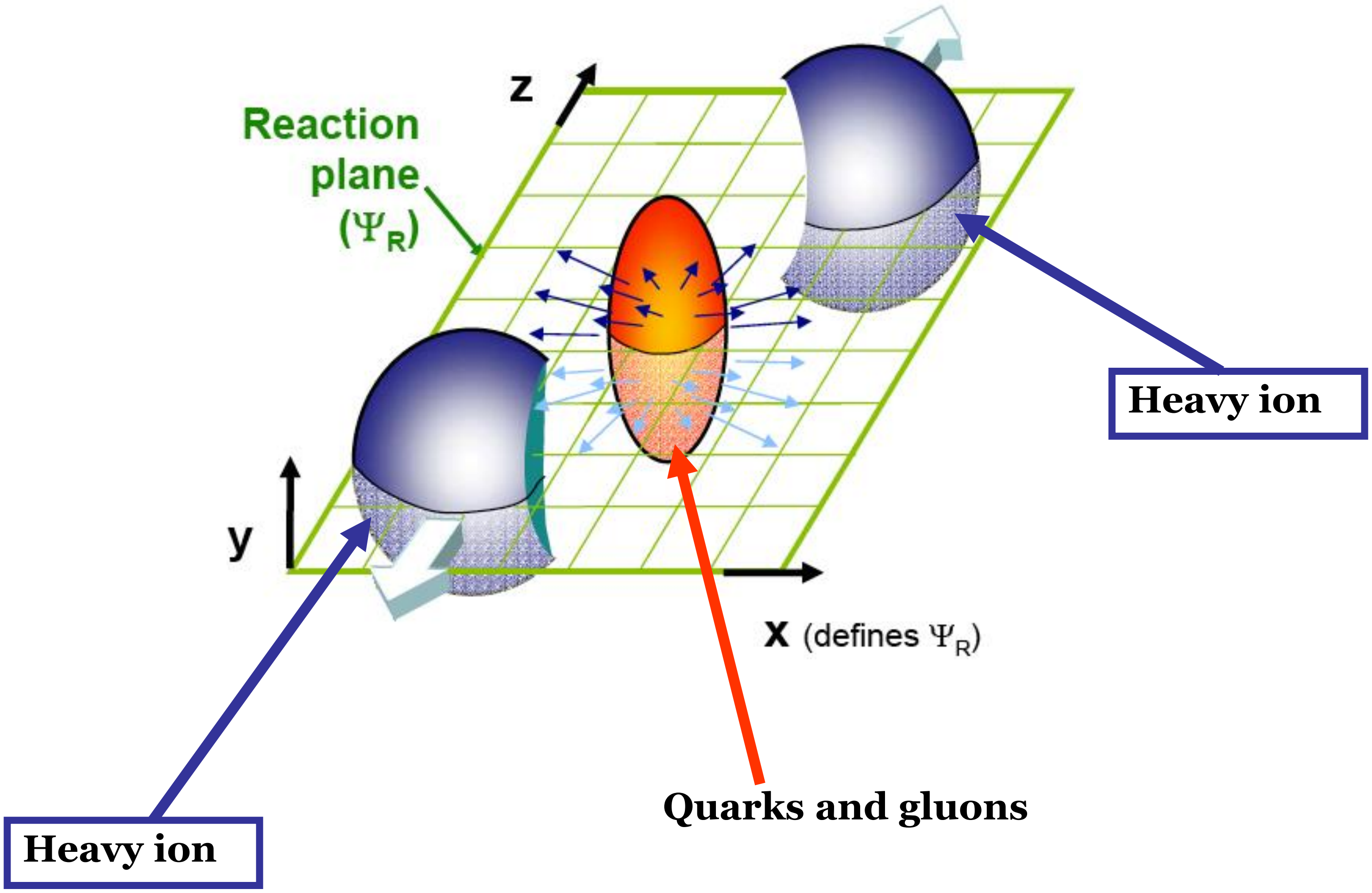
M.N. Chernodub,

P.V. Buividovich and

D.E. Kharzeev

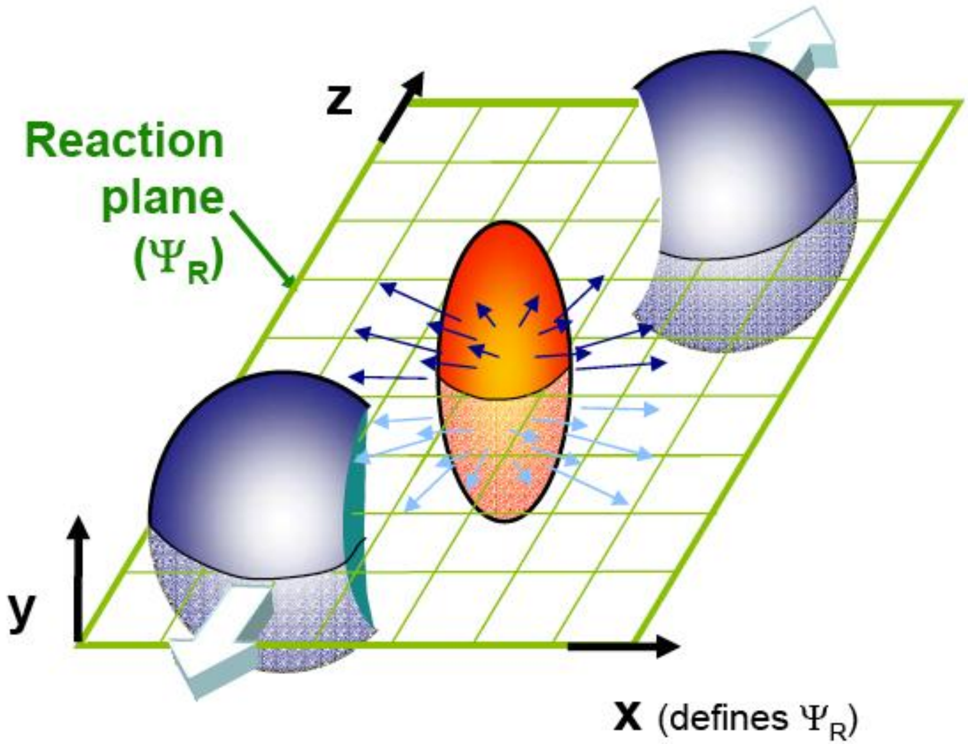
Magnetic fields in non-central collisions

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



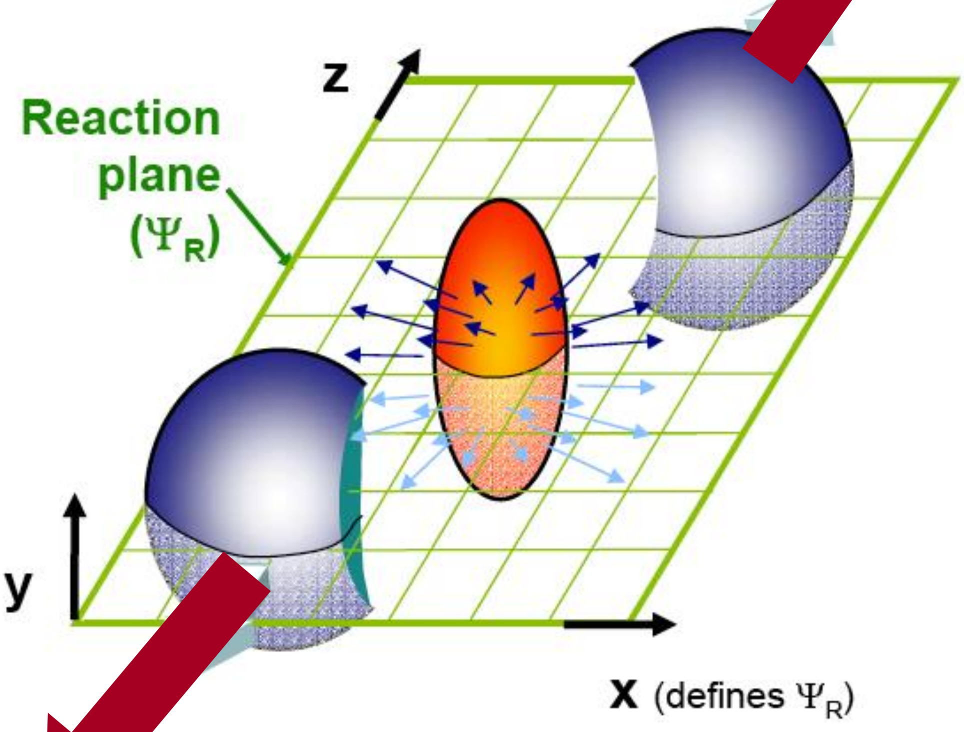
Magnetic fields in non-central collisions

[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

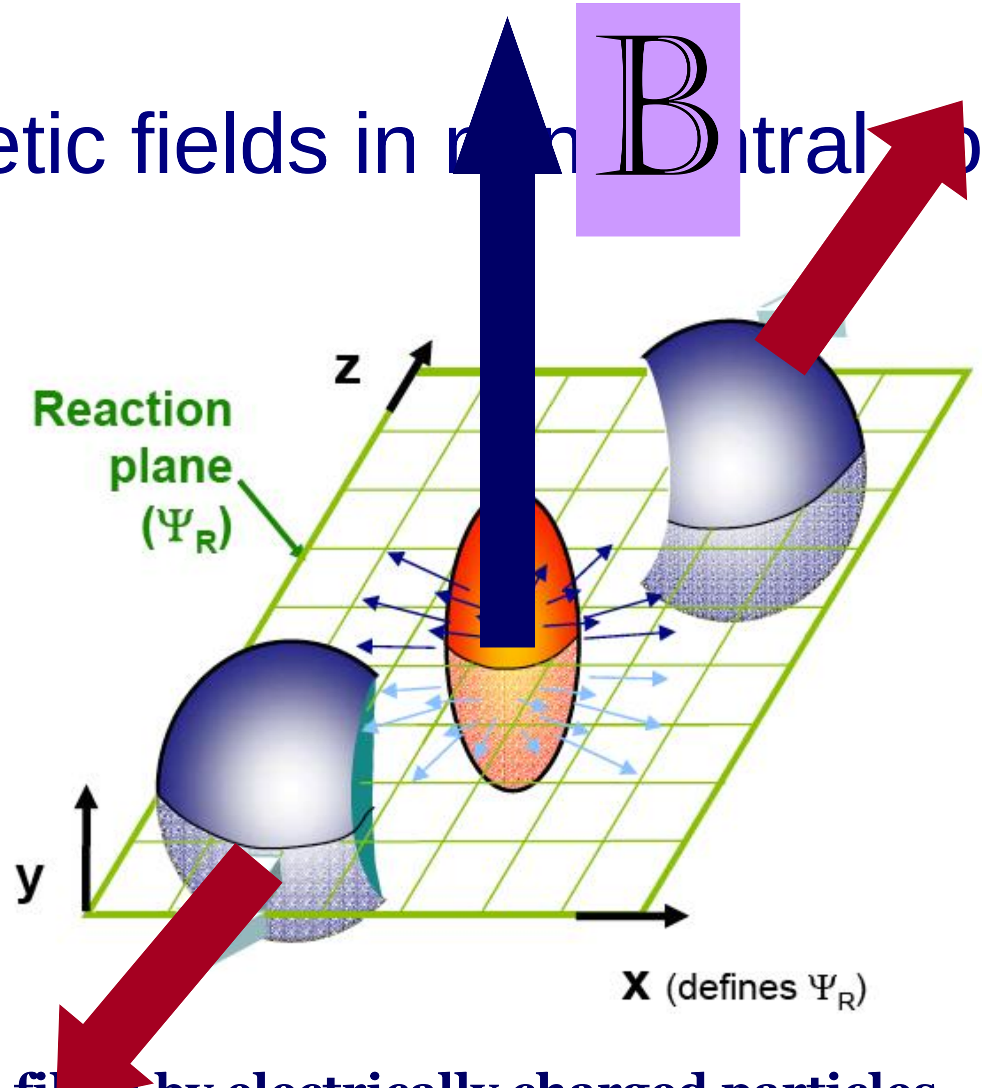
Thus we have two very big currents

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

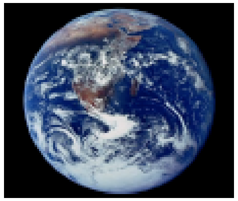
The medium is filled by electrically charged particles

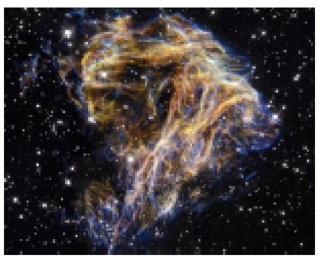
Large orbital momentum, perpendicular to the reaction plane

Large magnetic field along the direction of the orbital momentum

Comparison of magnetic fields

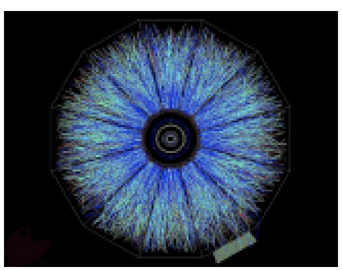
D.Kharzeev





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 field in noncentral heavy ion collisions (calculations for relativistic non-interacting uniformally charged spheres, R=7*fm*)

Skokov et al (2009)

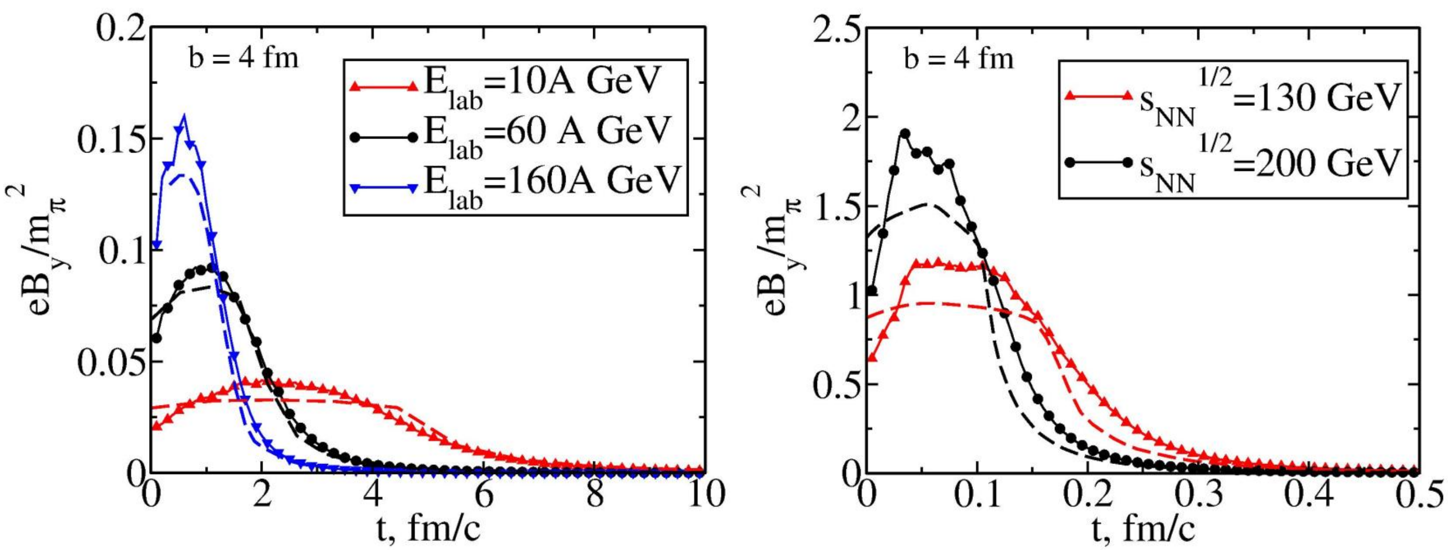


Fig. 3. The time evolution of the magnetic field strength eB_y at the central point O (see Fig.1) in Au–Au collisions with impact parameter, $b = 4$ fm, in the UrQMD model, for different bombarding energies. The symbols are plotted every $\Delta t = 0.2$ fm/c for $E_{lab} = 60A$ GeV and $\Delta t = 0.01$ fm/c for $\sqrt{s_{NN}} = 200$ GeV. The magnetic field obtained by modelling the gold ions as two Lorenz contracted non-interacting uniformly charged spheres with radius $R = 7$ fm are shown by dashed lines.

Magnetic forces are of the order of strong interaction forces

first time in my life I see such effect

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

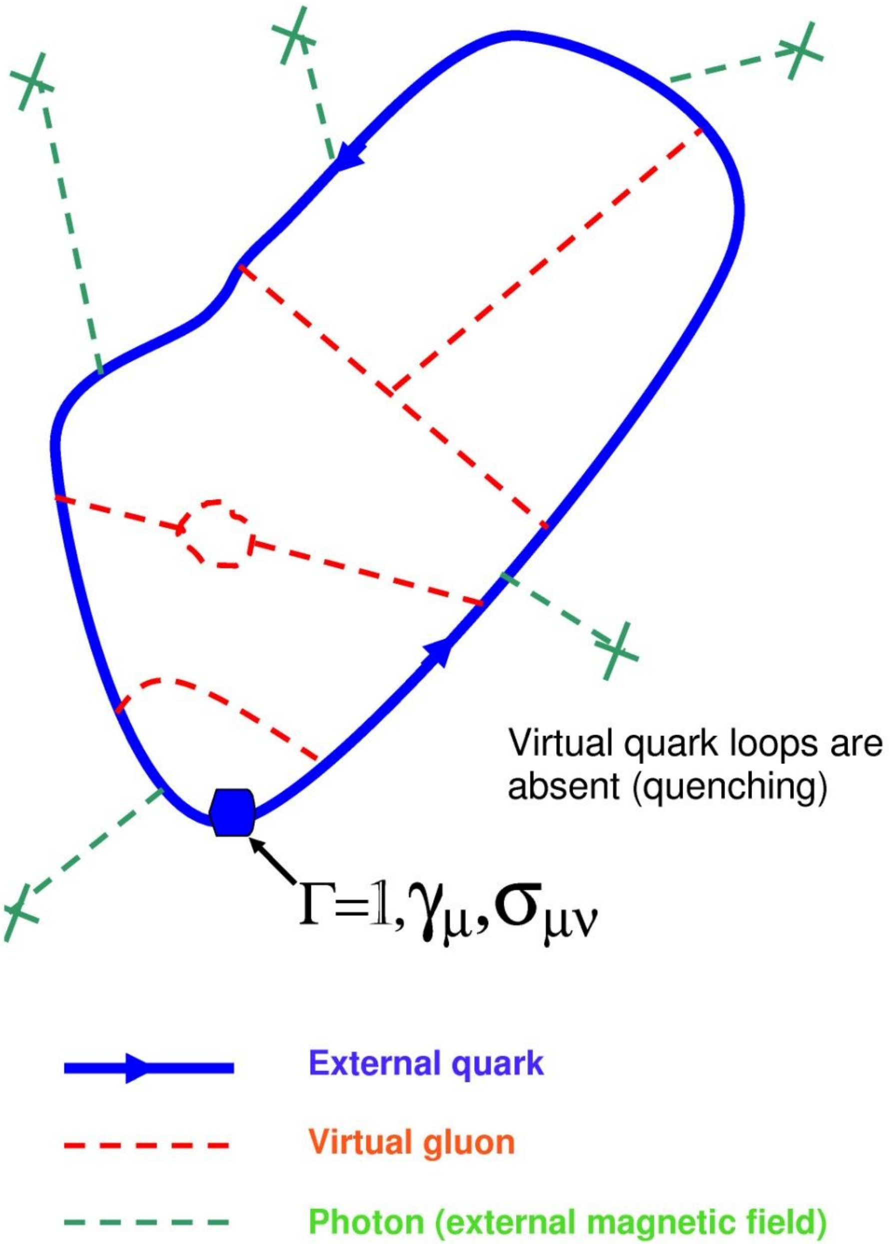
We expect the influence of magnetic field on strong interaction physics

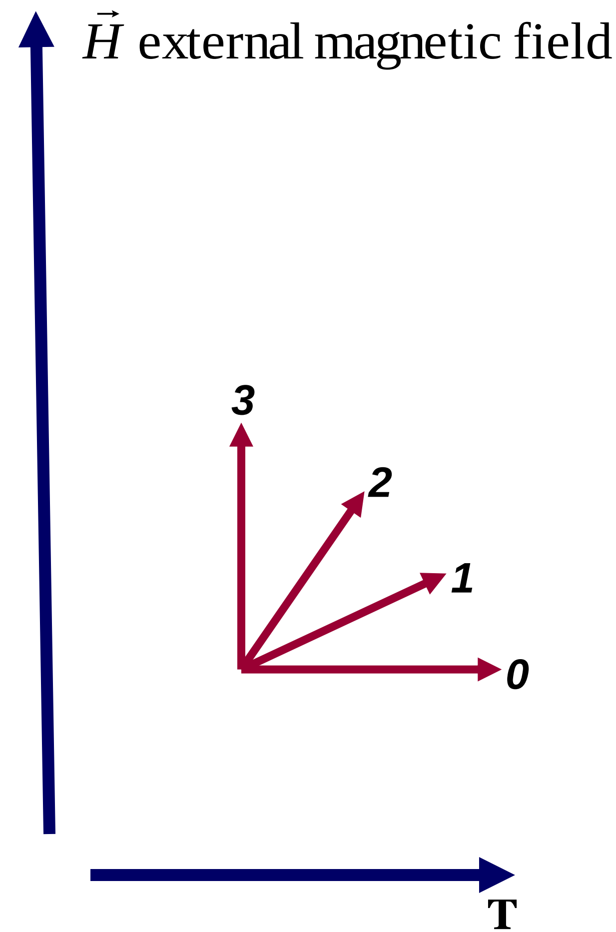
The effects are nonperturbative,
it is impossible to perform analytic calculations
and we use

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]

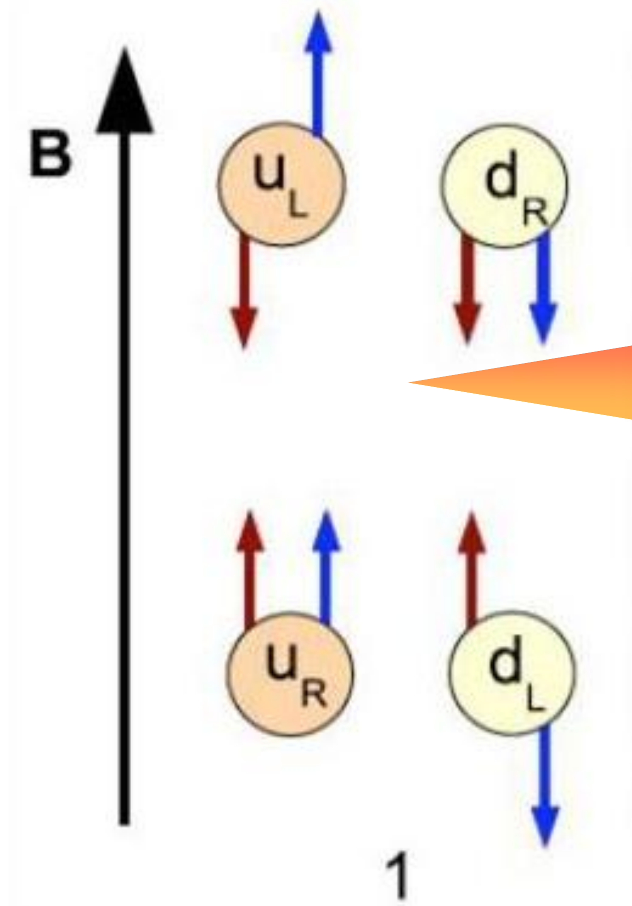
Electric current appears at regions
1. with non-zero topological charge density
2. exposed to external magnetic field

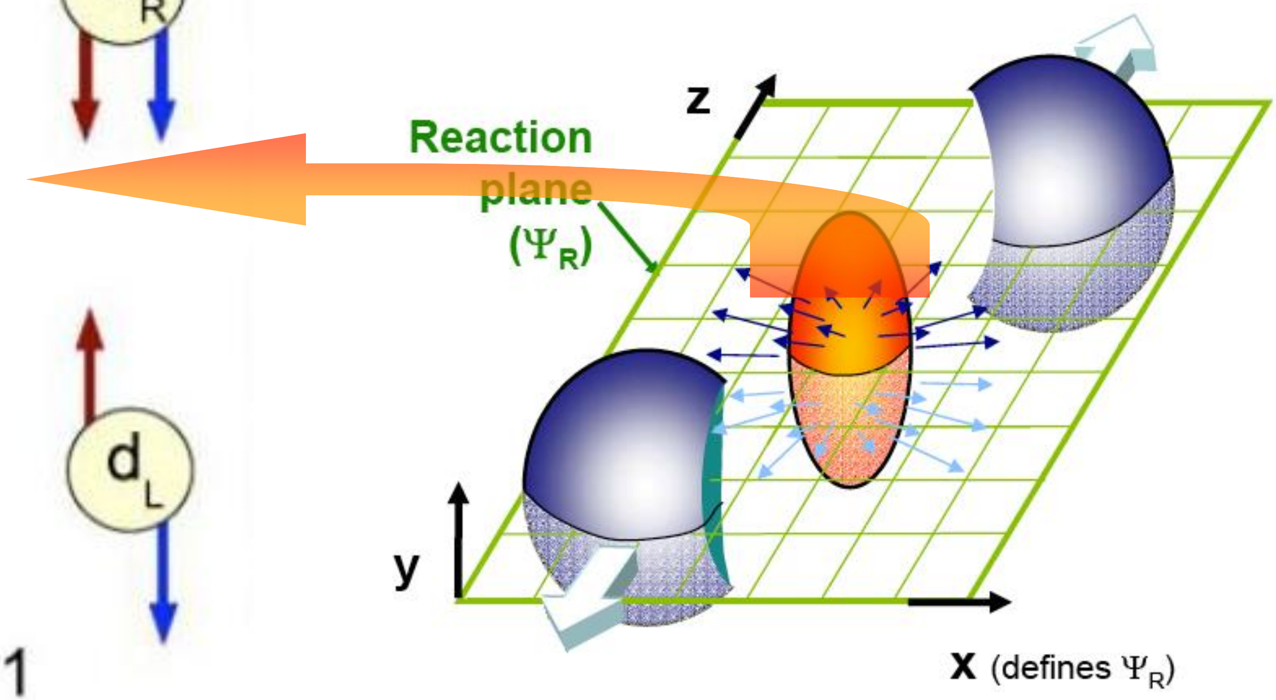
Experimentally observed at RHIC **:**
charge asymmetry of produced particles at heavy ion collisions

Chiral Magnetic Effect by
Fukushima, Kharzeev, Warringa, McLerran

1. Massless quarks in external magnetic field.

Red: momentum **Blue: spin**

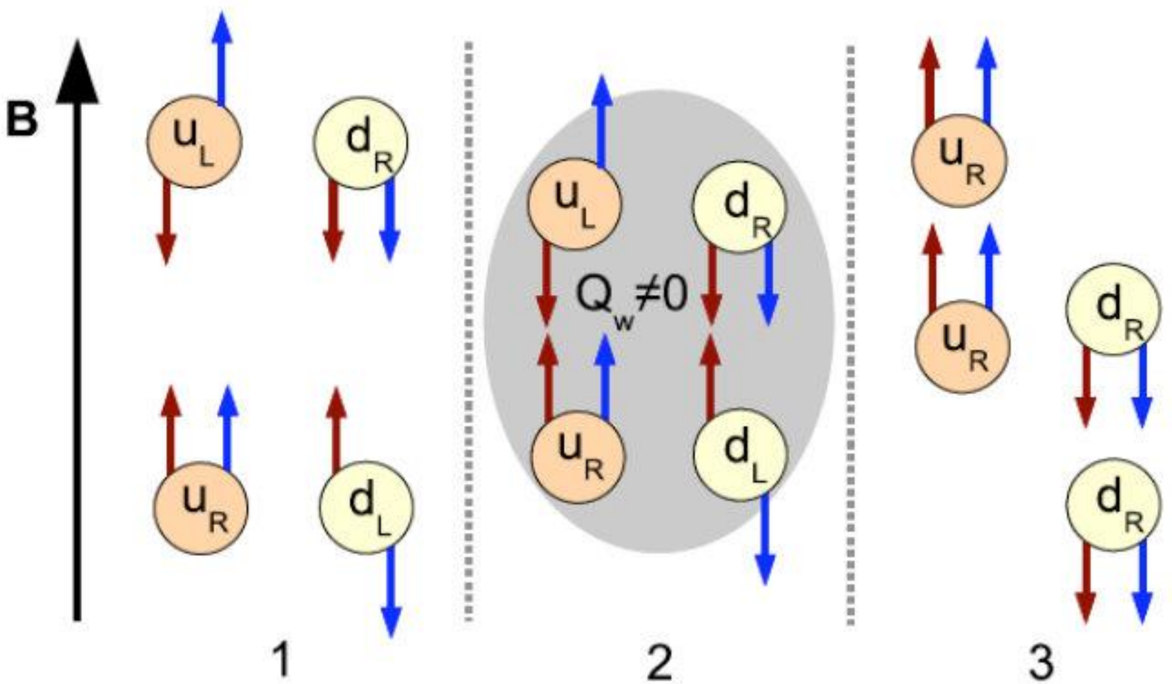




Chiral Magnetic Effect by

Fukushima, Kharzeev, Warringa, McLerran

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

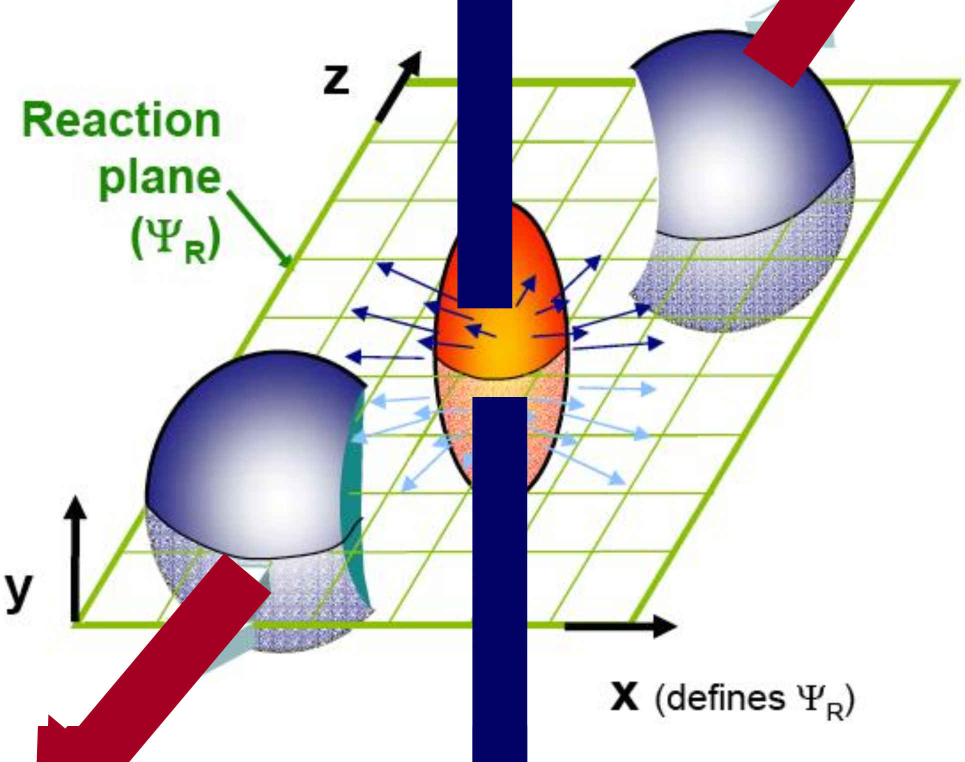


Red: momentum
Blue: spin

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

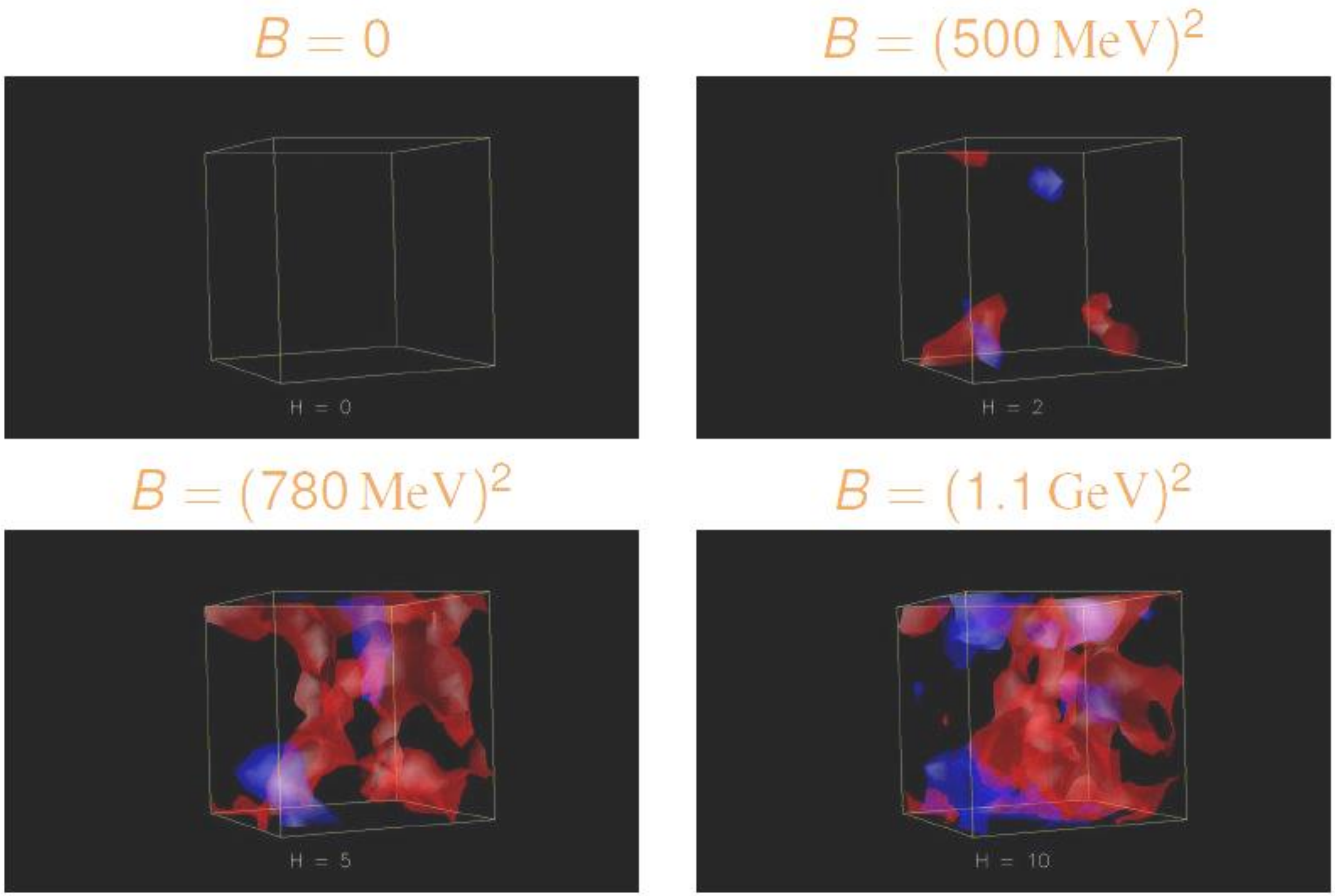
The medium is filled by electrically charged particles

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

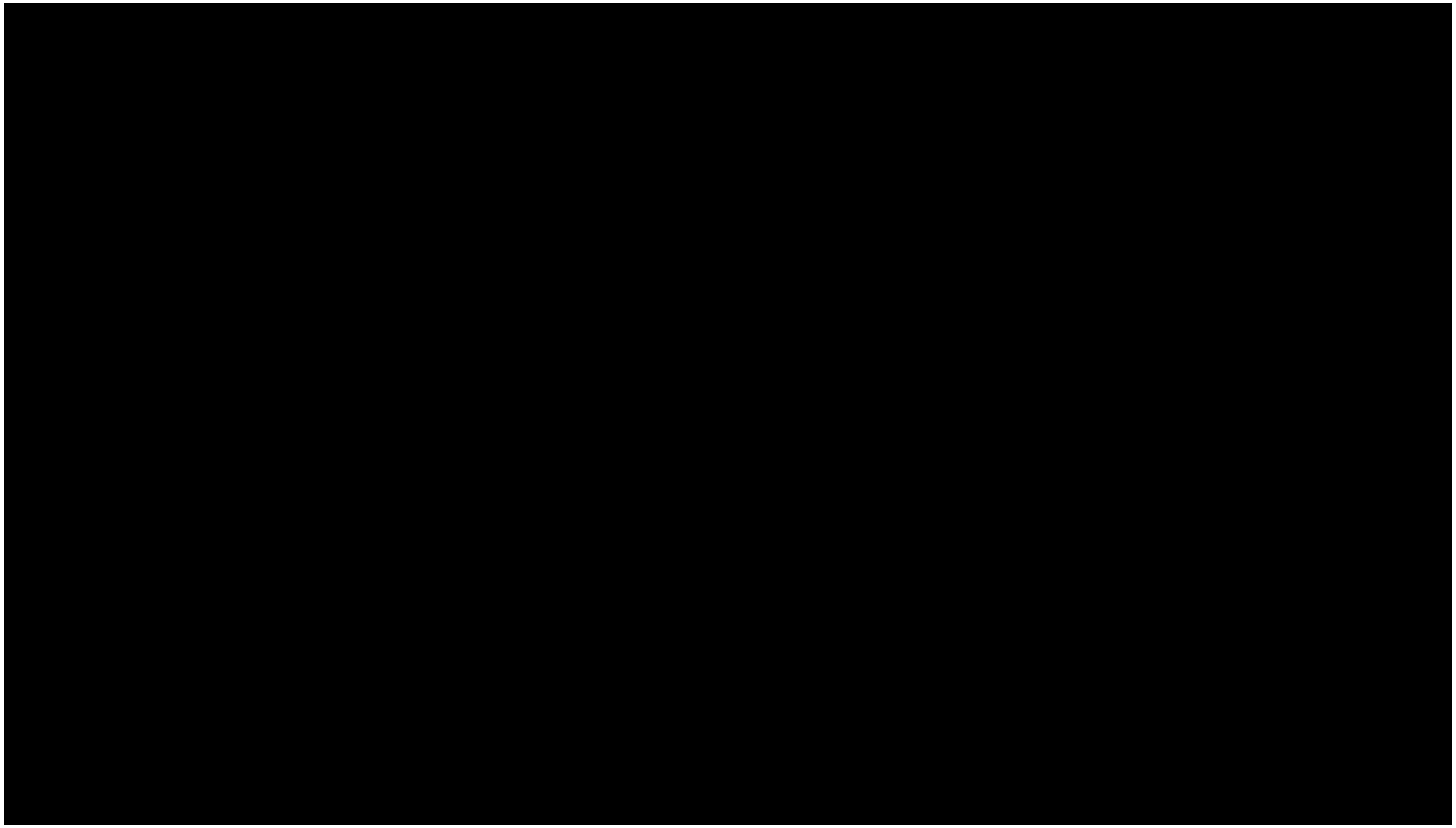
Density of the electric charge vs. magnetic field



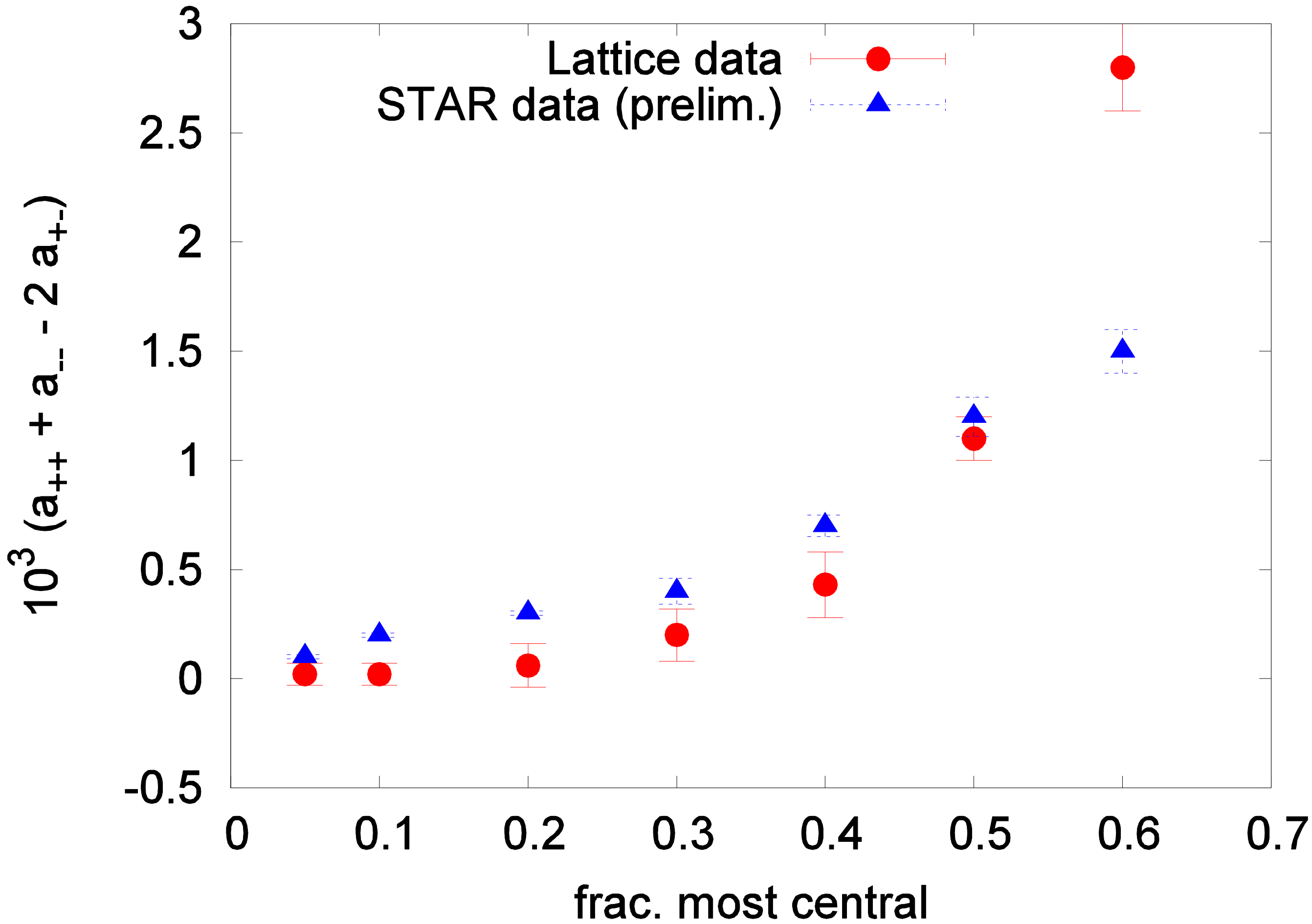
Chiral Magnetic Effect on the lattice,

Non-zero field, subsequent time slices

Electric charge density



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



Preliminary results: conductivity of the vacuum

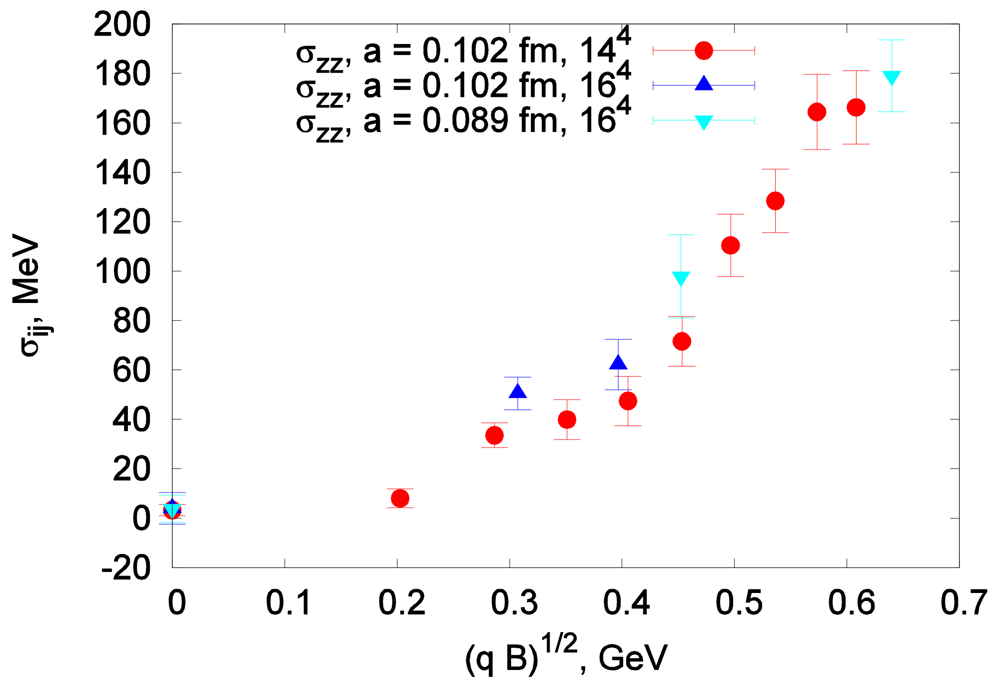
Qualitative definition of conductivity ♦

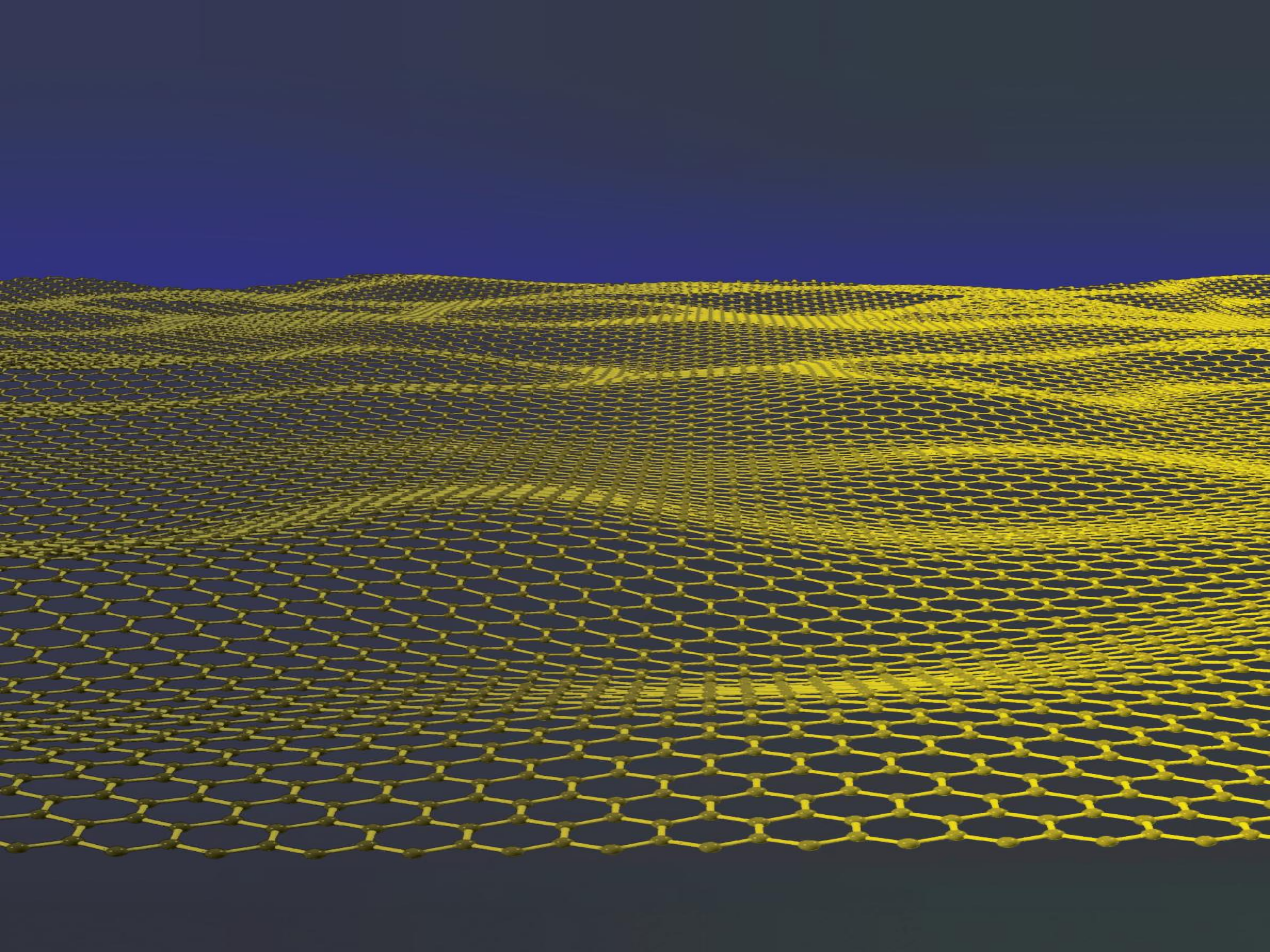
$$< j_\mu(x) j_\nu(y) > = C + A \cdot \exp\{-m|x-y|\}$$

$$\sigma \propto C$$

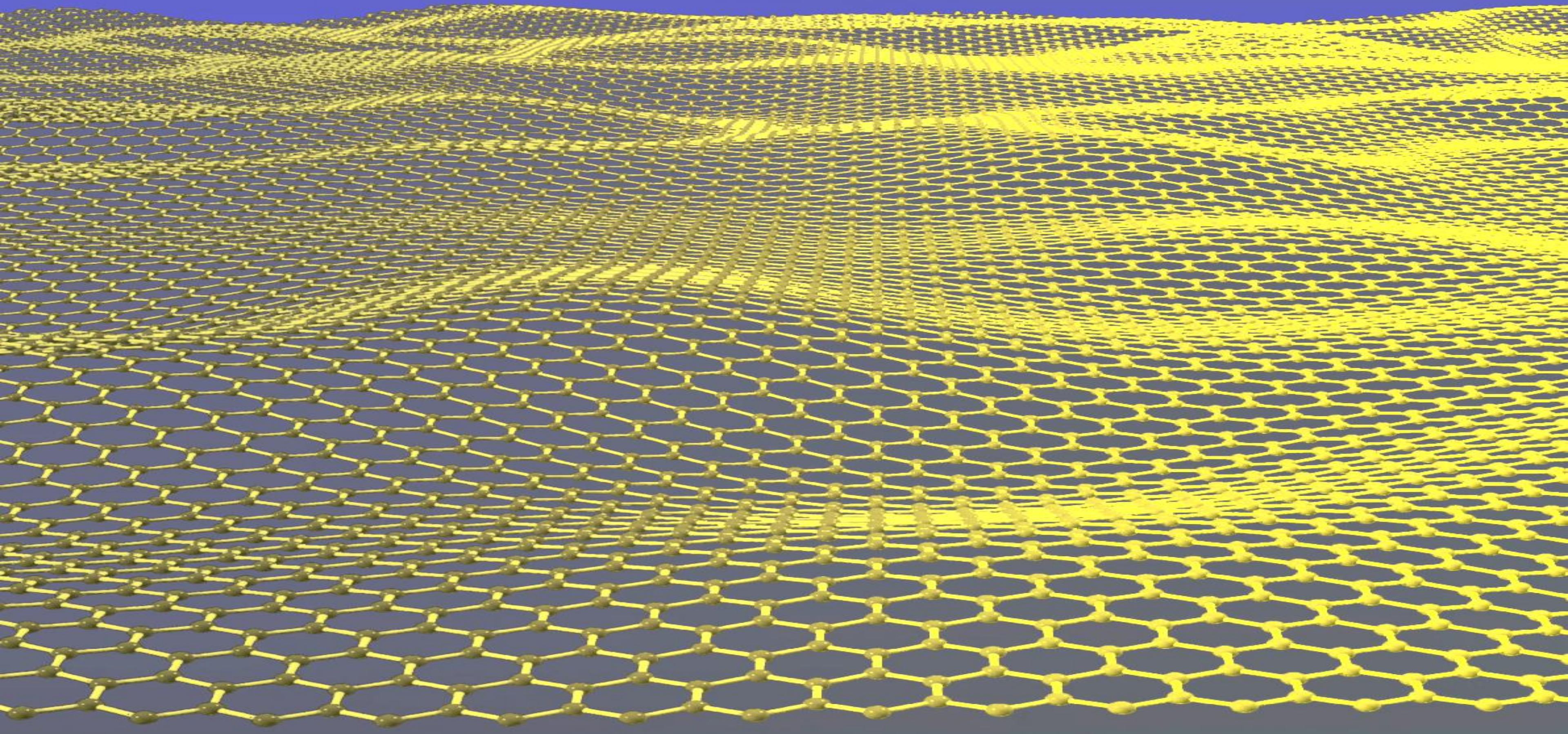
Preliminary results: conductivity of the vacuum

Conductivity at T>0

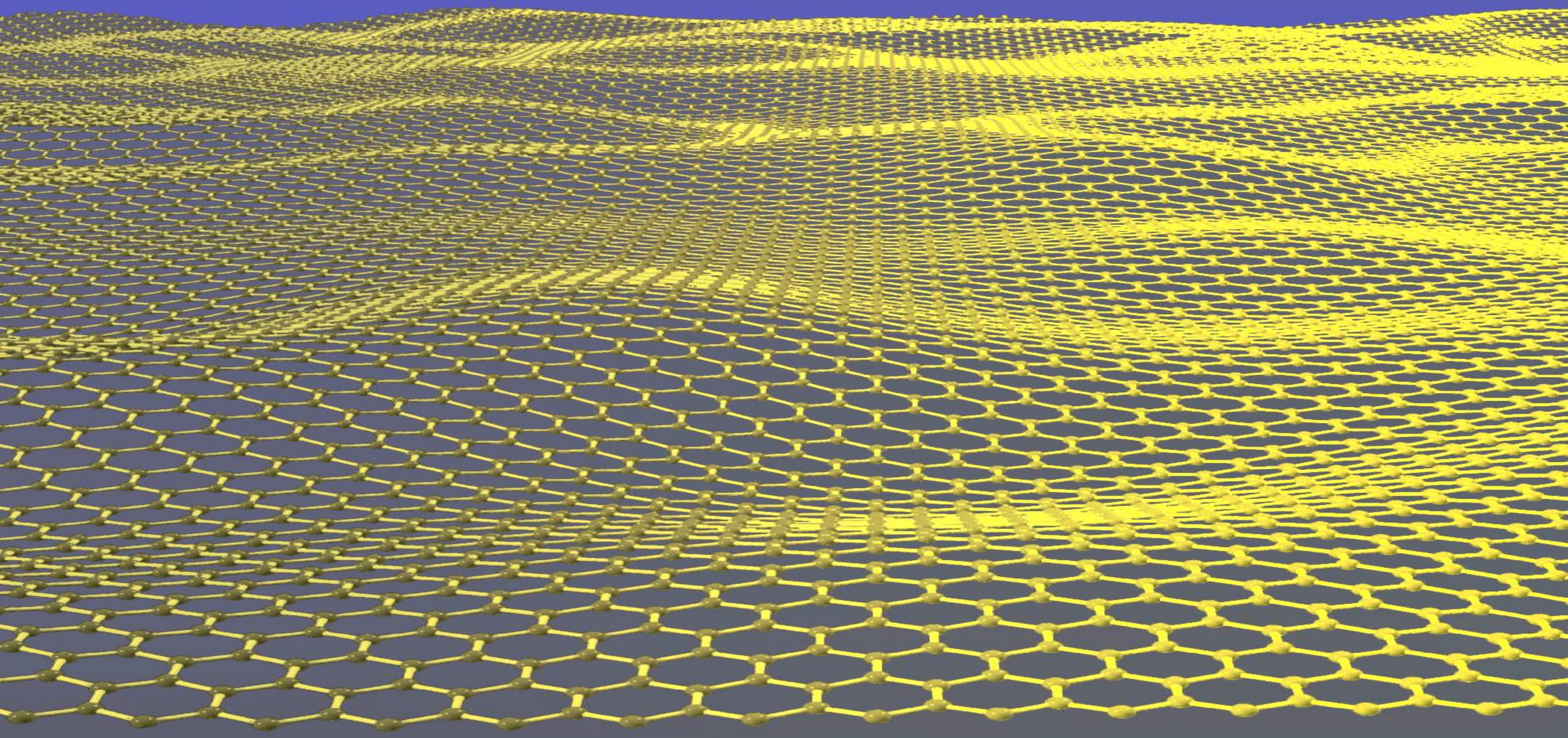




Graphene



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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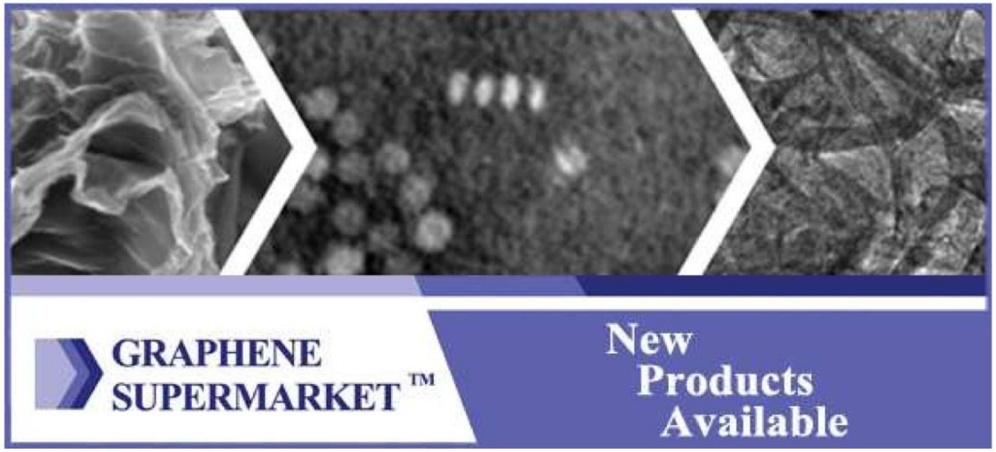


Featured products

Single Layer Graphene on Copper foil: 4"x2"

Graphene Nanopowder: 8 nm Flakes- 5 g

Q-graphene: 1 gram

Our price: $450.00

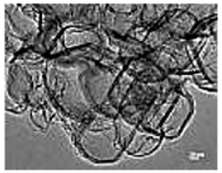
Quantity 1

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

Nonrelativistic particle

$$E = \frac{mv^2}{2}$$

Relativistic particle

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

Relativistic particle

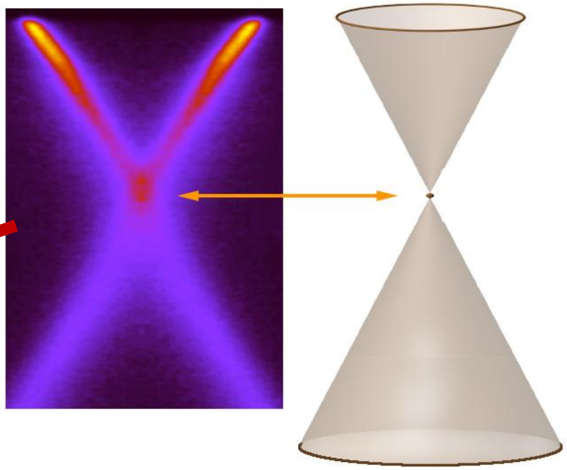
$$E = \sqrt{m^2 c^4 + p^2 c^2}$$

Massless particle

$$E = cp$$

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

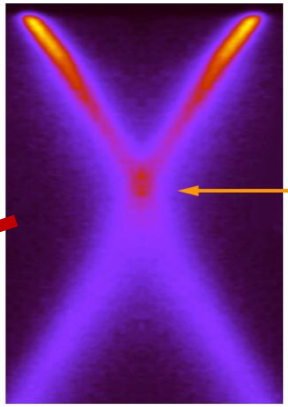
Massless particle $E = cp$

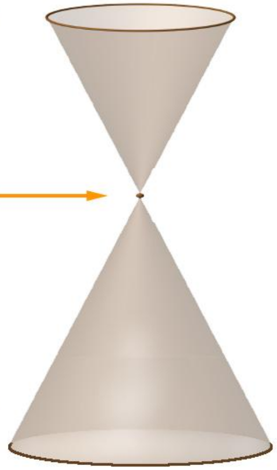


Graphene $E = v_F\, p; \quad v_F = \dfrac{c}{300};$

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

Massless particle $E = cp$





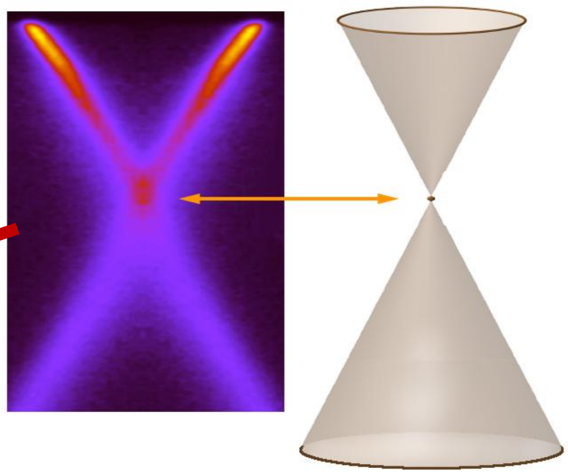
Graphene $E = v_F\, p;\quad v_F = \dfrac{c}{300};$

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

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

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

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!

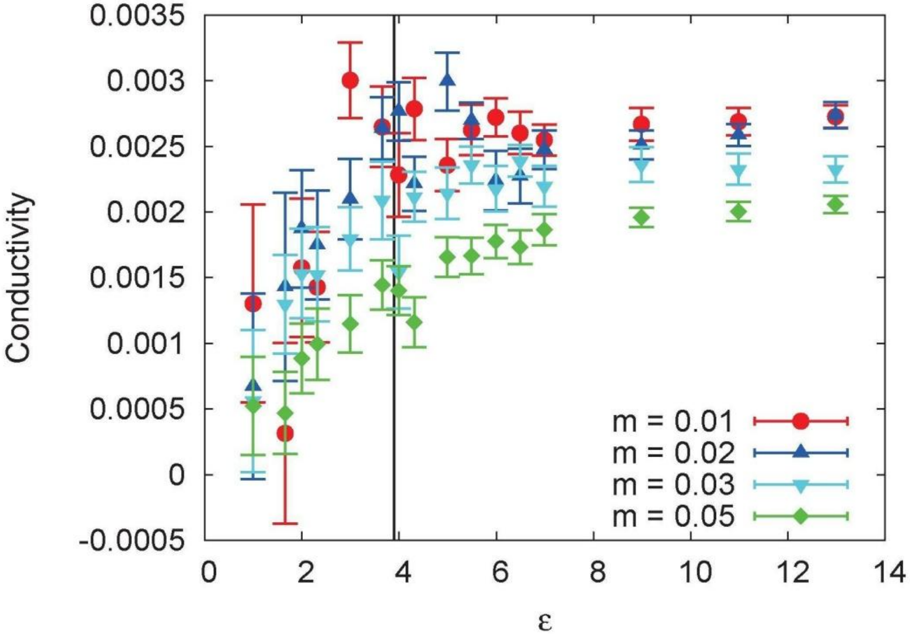
If we put graphene on a substrate we can get conductor: $\alpha_g \to \dfrac{2}{1+\varepsilon}\alpha_g$

Numerical calculation of α_g^{crit}

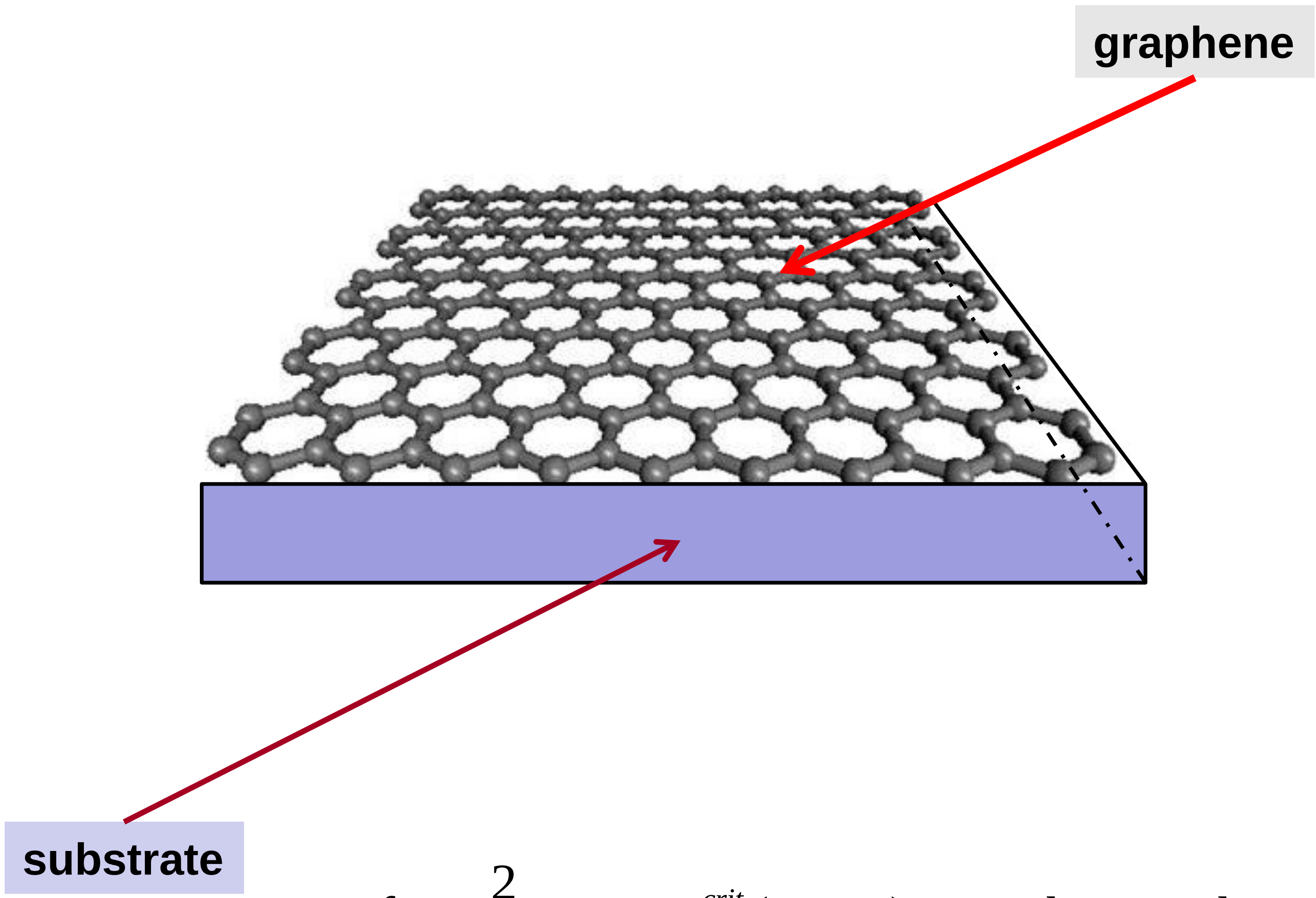
Is graphene in vacuum an insulator?.
Joaquin E. Drut Timo A. Lahde
e-Print: **arXiv:0807.0834 [cond-mat.str-el],**
PRL (2009)

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]**

ITEP (Moscow) results



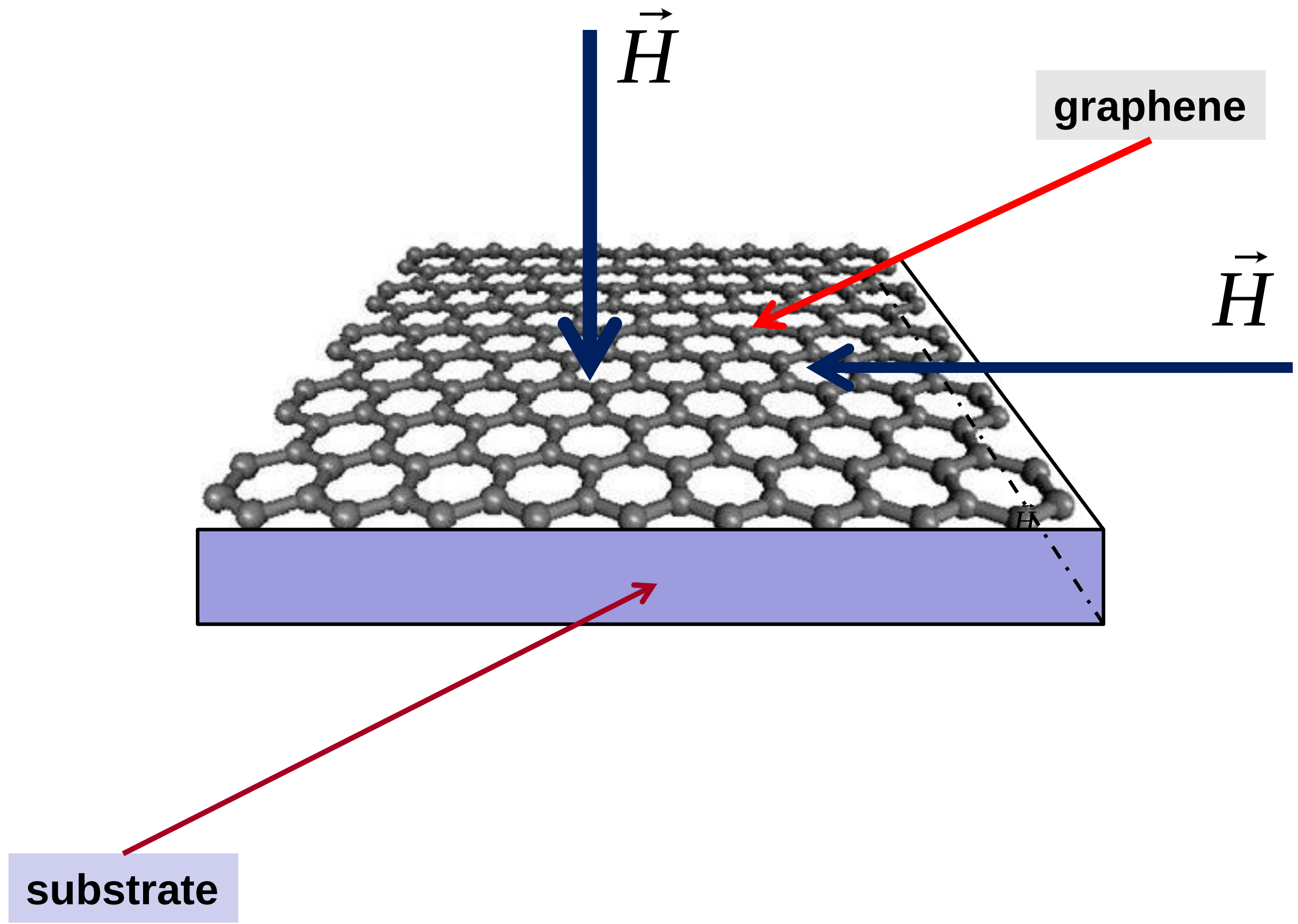
20x20x20x20 lattice



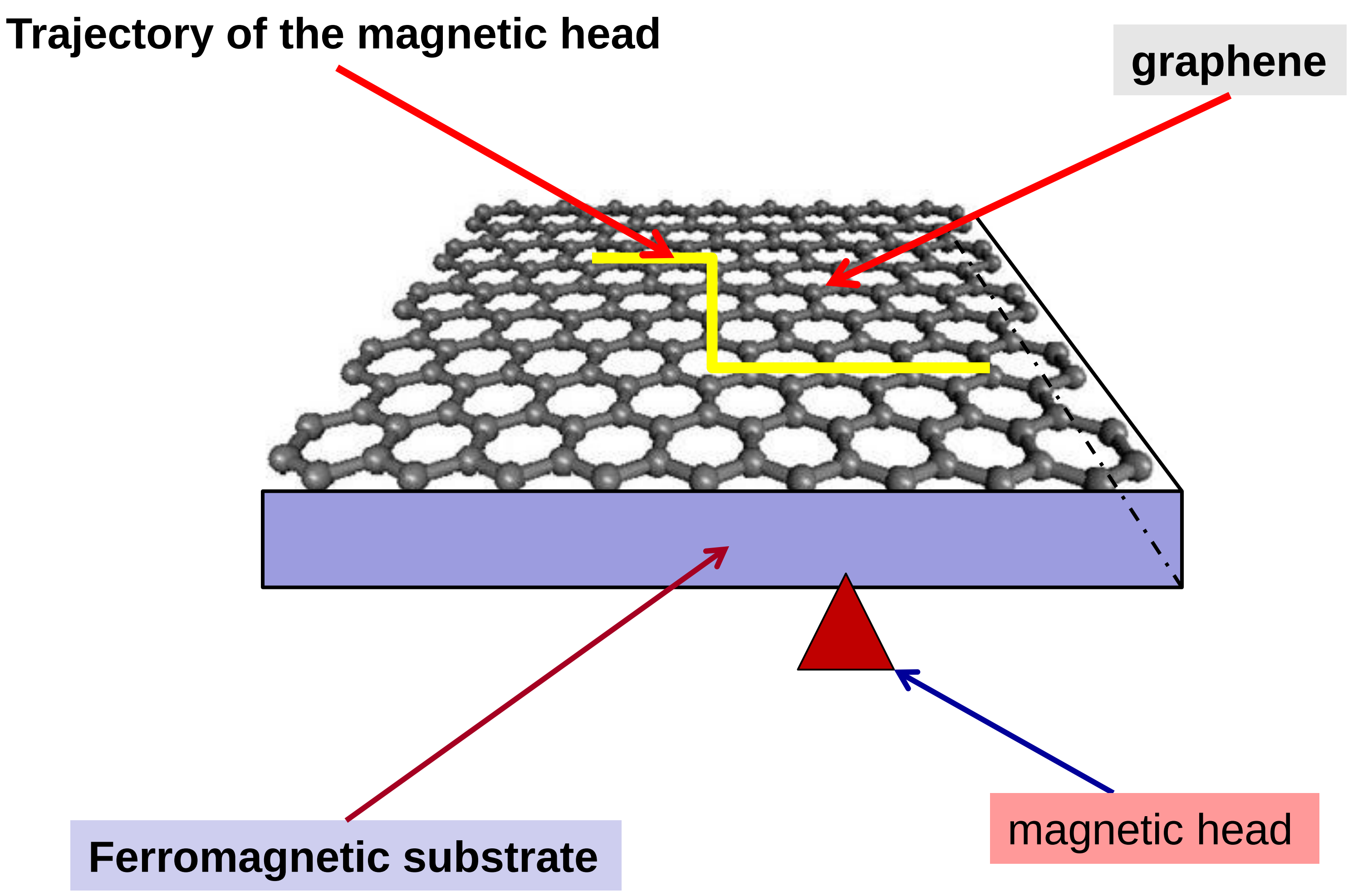
if $\frac{2}{1+\varepsilon}\alpha_g > \alpha_g^{crit}(=1.11)$ graphene is the conductor

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

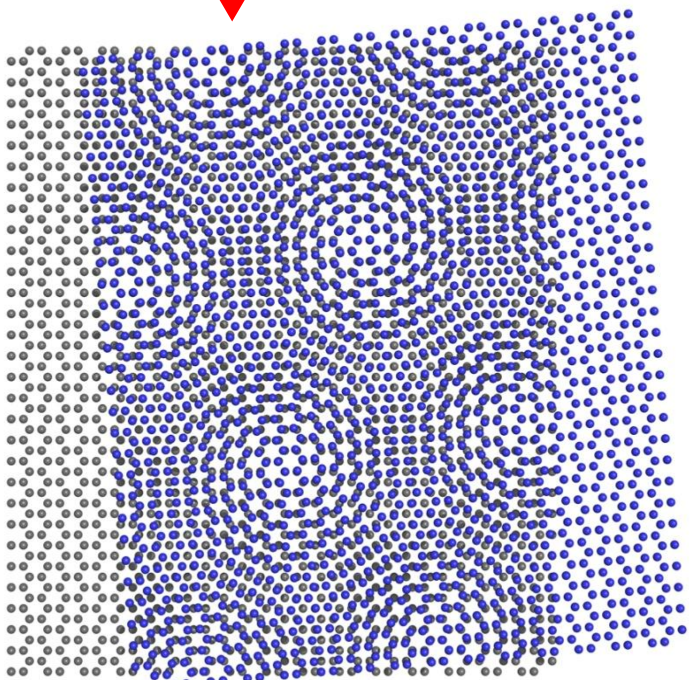


Along the trajectory of the magnetic head graphene becomes the conductor!

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



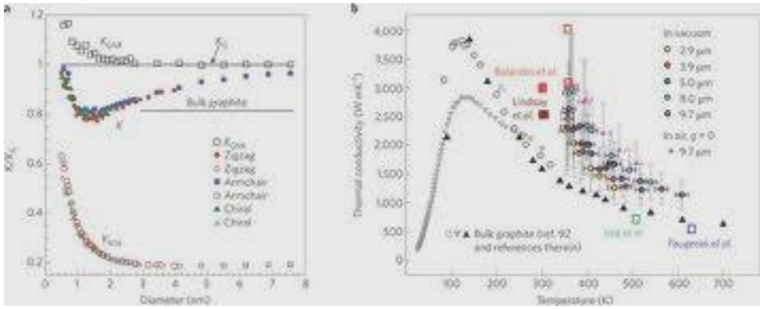
Monte Carlo simulation of monolayer graphene at non-zero temperature

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

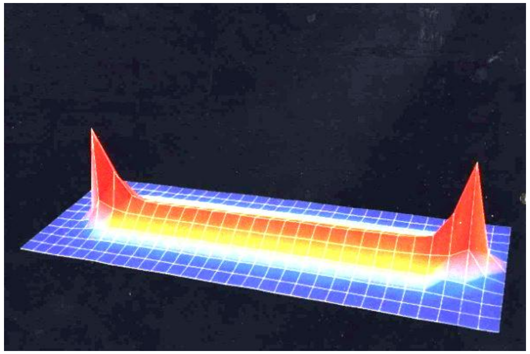
arXiv:1105.1043v1 [cond-mat.str-el] 5 May 2011

Graphene has relations with many theoretical problems

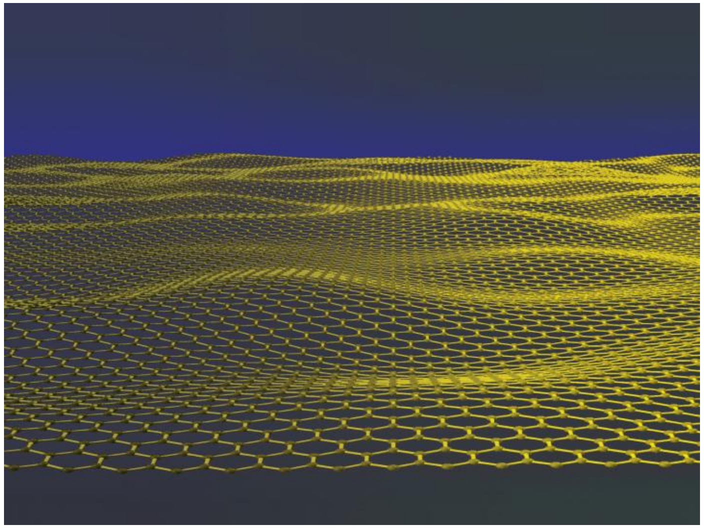
Insulator – Conductor



Confinement - Deconfinement



Curvature of the graphene leads to two dimensional gravity for fermions

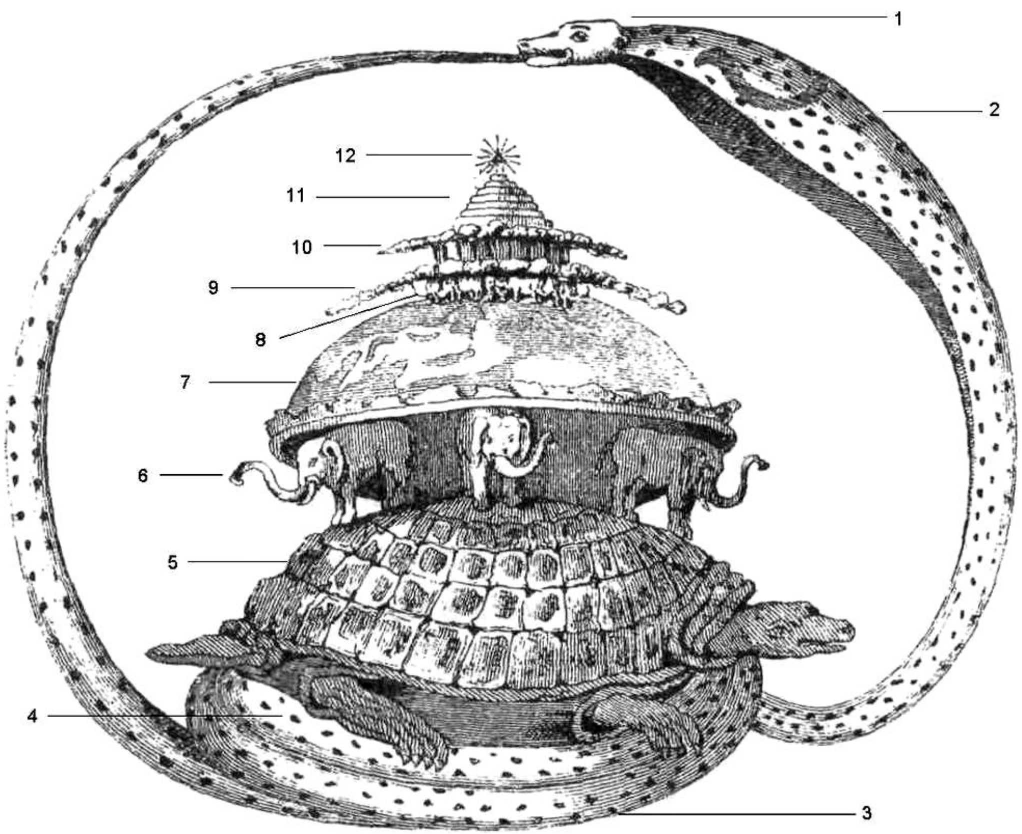


Computer simulations help to unify physical systems

Computer simulations help to unify physical systems

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

Computer simulations help to unify physical systems



QCD confinement problems
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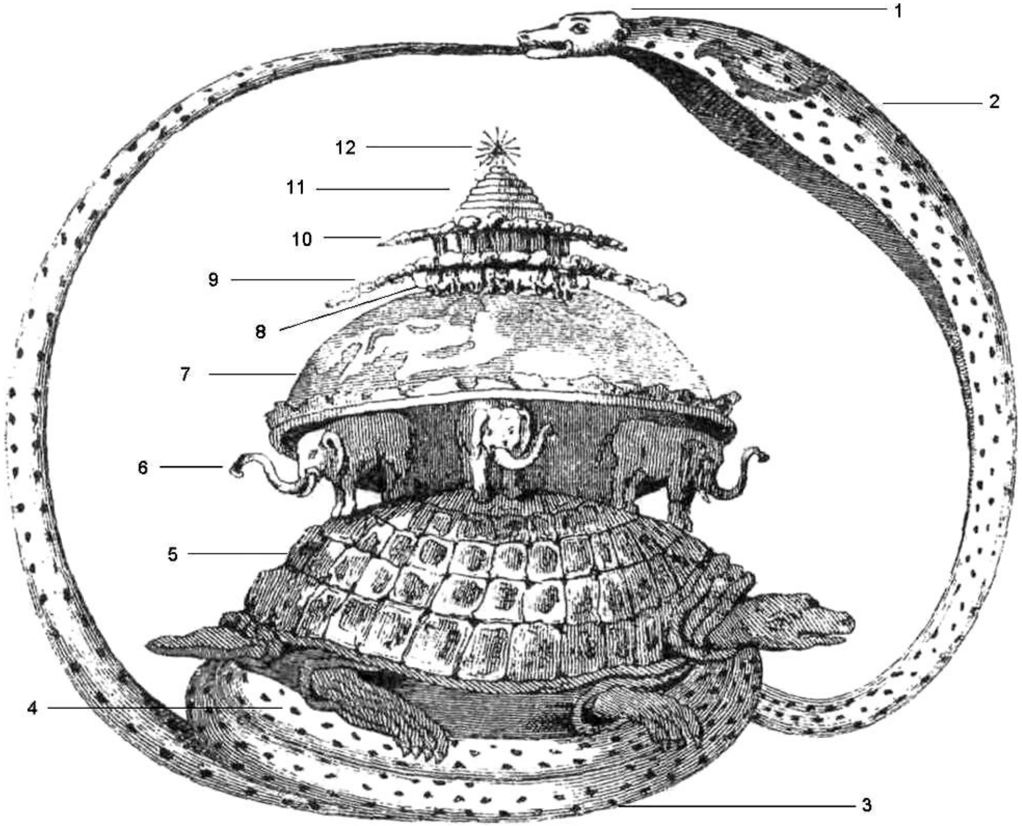
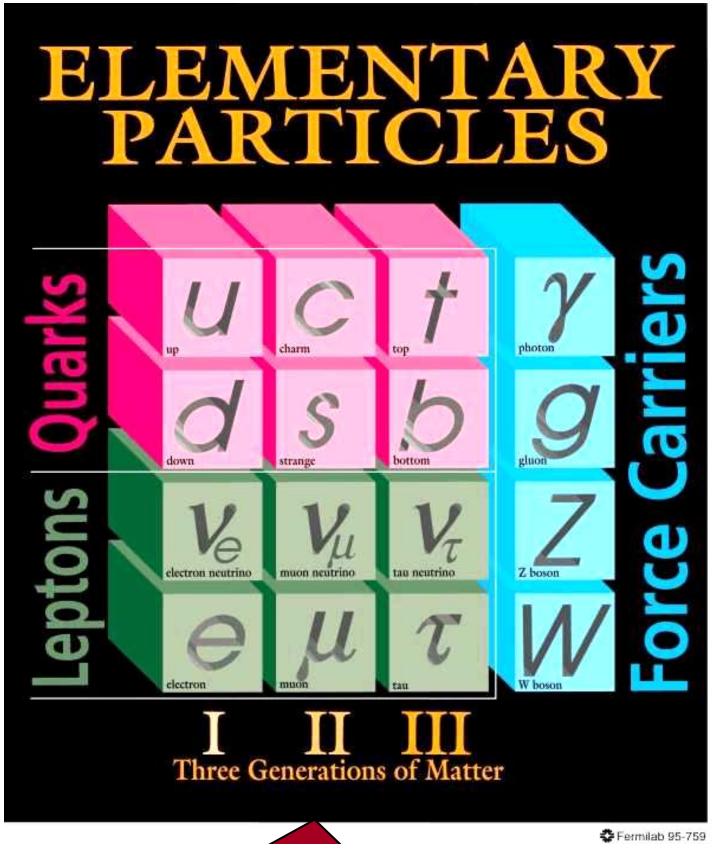
Computer simulations help to unify physical systems





QCD confinement problems
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