Background – high energy physics motivation and situation of the study of QCD

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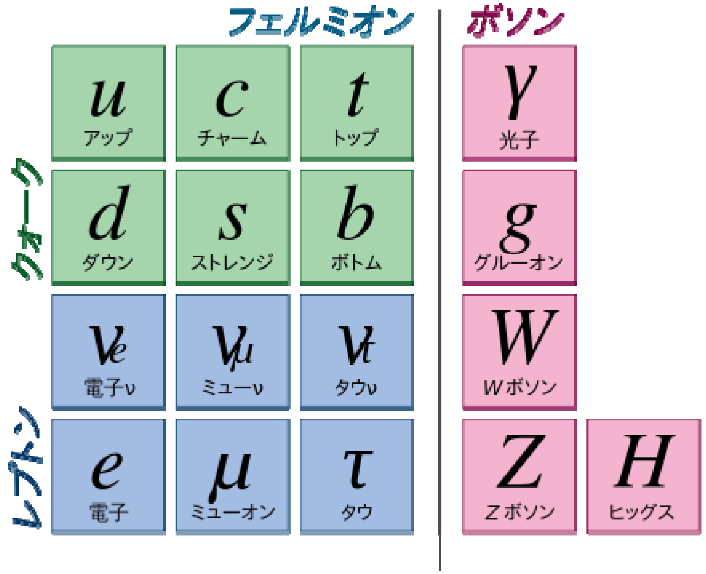
Introduction – strong interactions and its applications

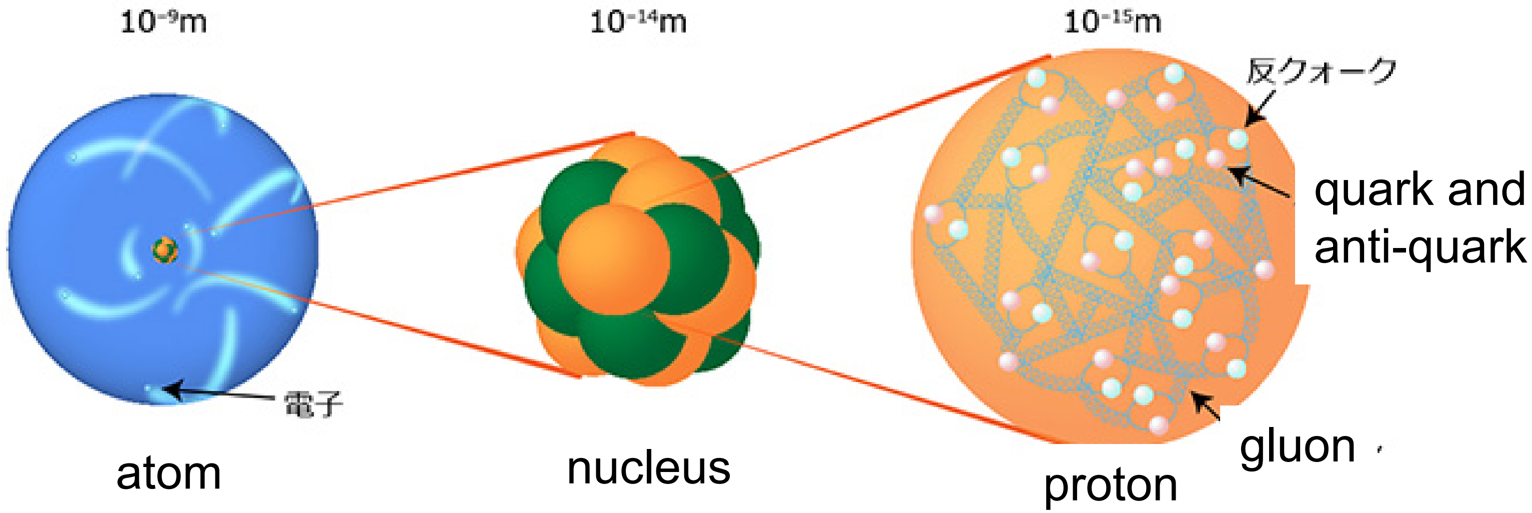
Introduction

Four fundamental forces
- gravity
- weak interaction
- electromagnetism
- strong interaction



Motivations in particle/nuclear physics
- uniification of the forces
- understanding microscopic theory
- microscopic description of nature
- etc

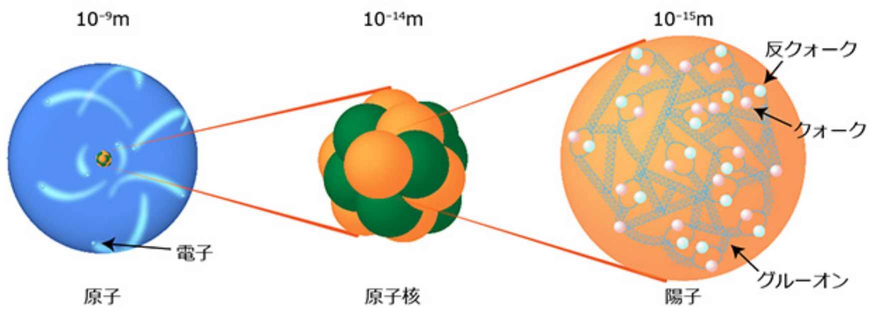
Quarks, gluons and QCD



- Nuclei are electromagnetically unstable
  - nuclear force ~ pion exchange

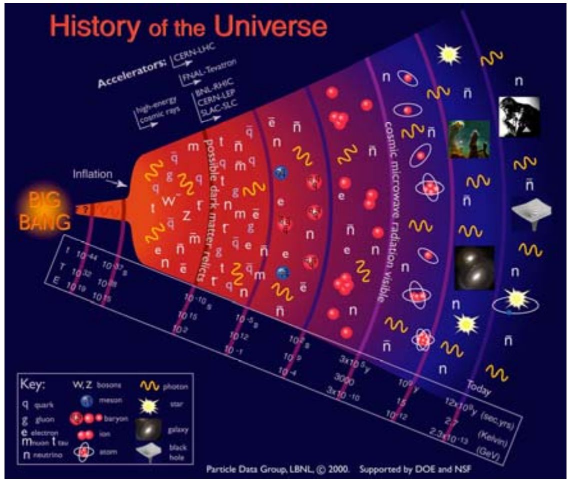
- Even protons, neutrons are not elementary particles
  - Elementary particles : quarks and gluons
  - Fundamental theory : QCD = SU(3) gauge theory

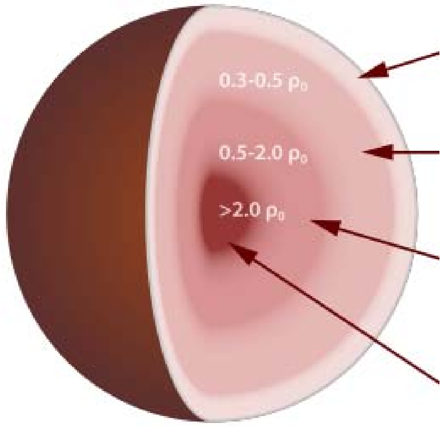
Applications of QCD



heated

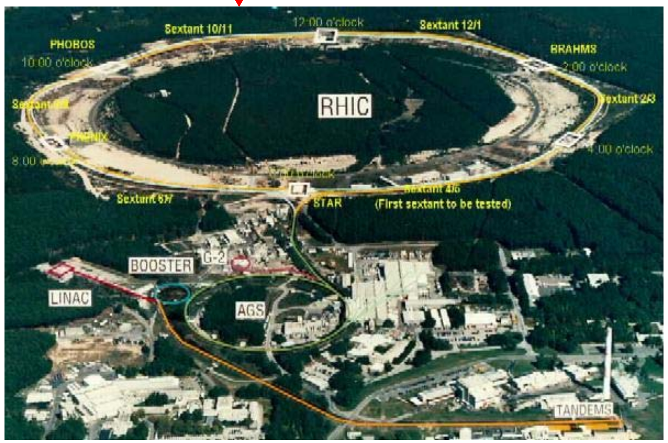
compressed





collided

T > 100 MeV



density > normal
nuclear density

Basic properties of QCD

QCD

quark (fermion)

$$\mathcal{L} = \frac{-1}{4}(F^a_{\mu\nu})^2 + \bar{\psi}(iD_\mu\gamma^\mu - m)\psi$$

$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + igf^{abc}A^b_\mu A^c_\nu \qquad D_\mu = \partial_\mu - igA^a_\mu t^a$$

From Itou san's slide

gluon (gauge boson),
(a=1,..., 8, μ=1,…,4)

non-Abelian term
(does not exist in QED)

Quarks have three internal d.o.f

- spin
- color (r, g, b)
- flavor (up, down, strange, charm, botom, top), (cf : e, μ, tau)

- The bare quark mass is approximately zero for light quarks
- Only color singlet states are physical states

QED and QCD

$$\mathcal{L} = \frac{-1}{4}(F^a_{\mu\nu})^2 + \bar{\psi}(iD_\mu\gamma^\mu - m)\psi$$

From Itou san's slide

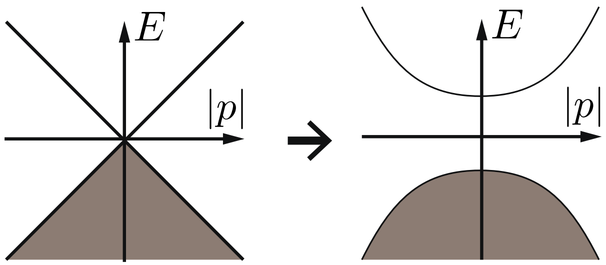
$$F^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + igf^{abc}A^b_\mu A^c_\nu \qquad D_\mu = \partial_\mu - igA^a_\mu t^a$$

	QED	QCD
quantum #	electric charge U(1)	color SU(3)
	electron	quark (flavor and color)
gauge bosons	photon(A_μ)	gluon (A_μ^a ,a=1~8) (self-interacting)
$\alpha = g^2/4\pi$	1/137	O(1)

Features of QCD - symmetry breaking

- Chiral symmetry (for light flavor) is spontaneously broken $SU(N_f)_L x SU(N_f)_R \rightarrow SU(N_f)_V$
- pion mass ~ 140 MeV << proton mass ~ 940 MeV
  - pions are NG bosons [Nambu-Jona-Lasinio(1961)]
  - small pion mass is generated by small quark mass
  - responsible for moderate range of nuclear force

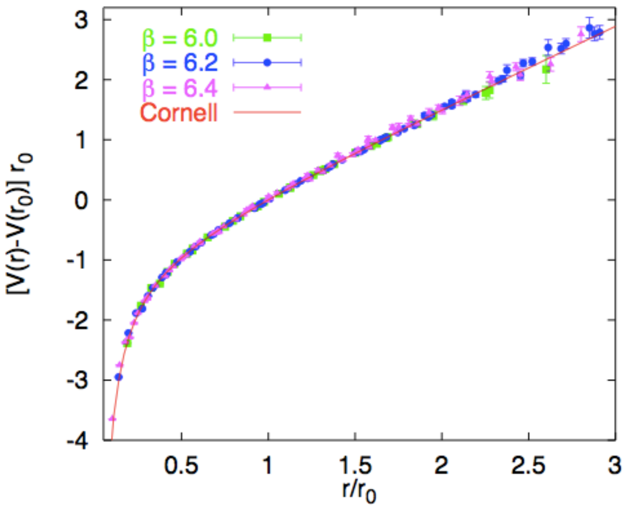
- quark mass is dynamically generated



SBCS is a good example for analog between QCD and condensed matter physics

Features of QCD - confinement

- Only color singlet states are allowed to exist asymptotically
- phenomenological explanation is given by e.g. quark-anti-quark potential



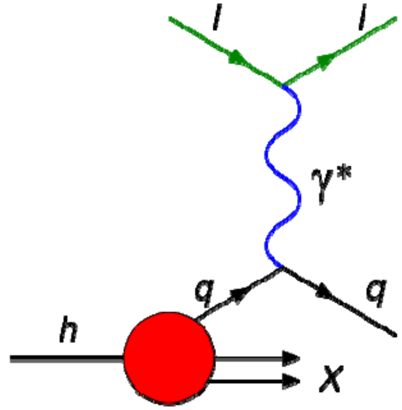
heavy quark-anti quark potential

Bali (2000)

Still there are many studies about confinement, including its definition

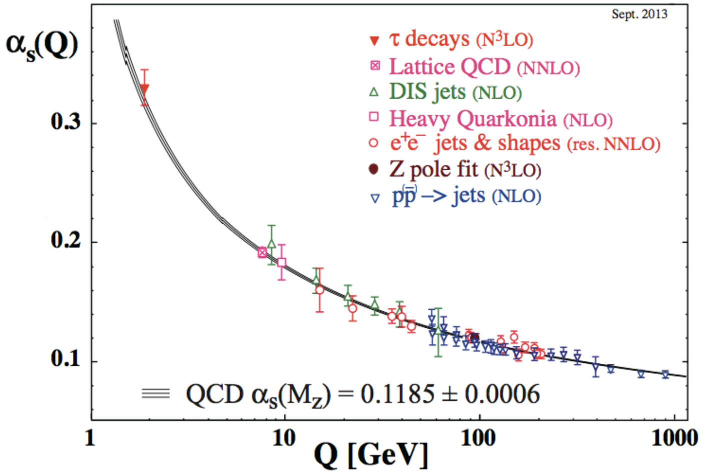
Features of QCD - asymptotic freedom

- Deep inelastic scattering
  - SLAC (1968)
  - point object at high energy



wikipedia

- Asymptotic freedom (1973)



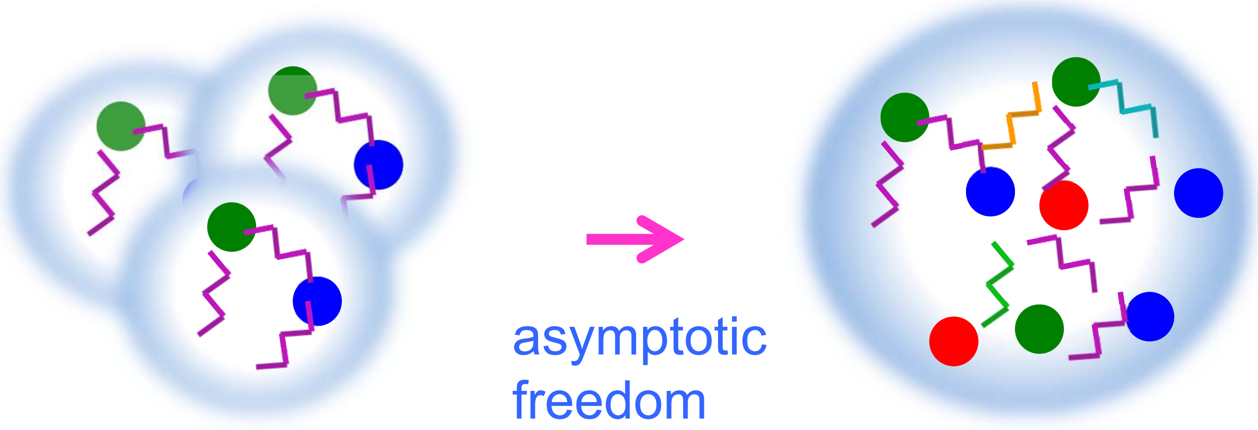
Particle Data Group 2015

Interaction in QCD

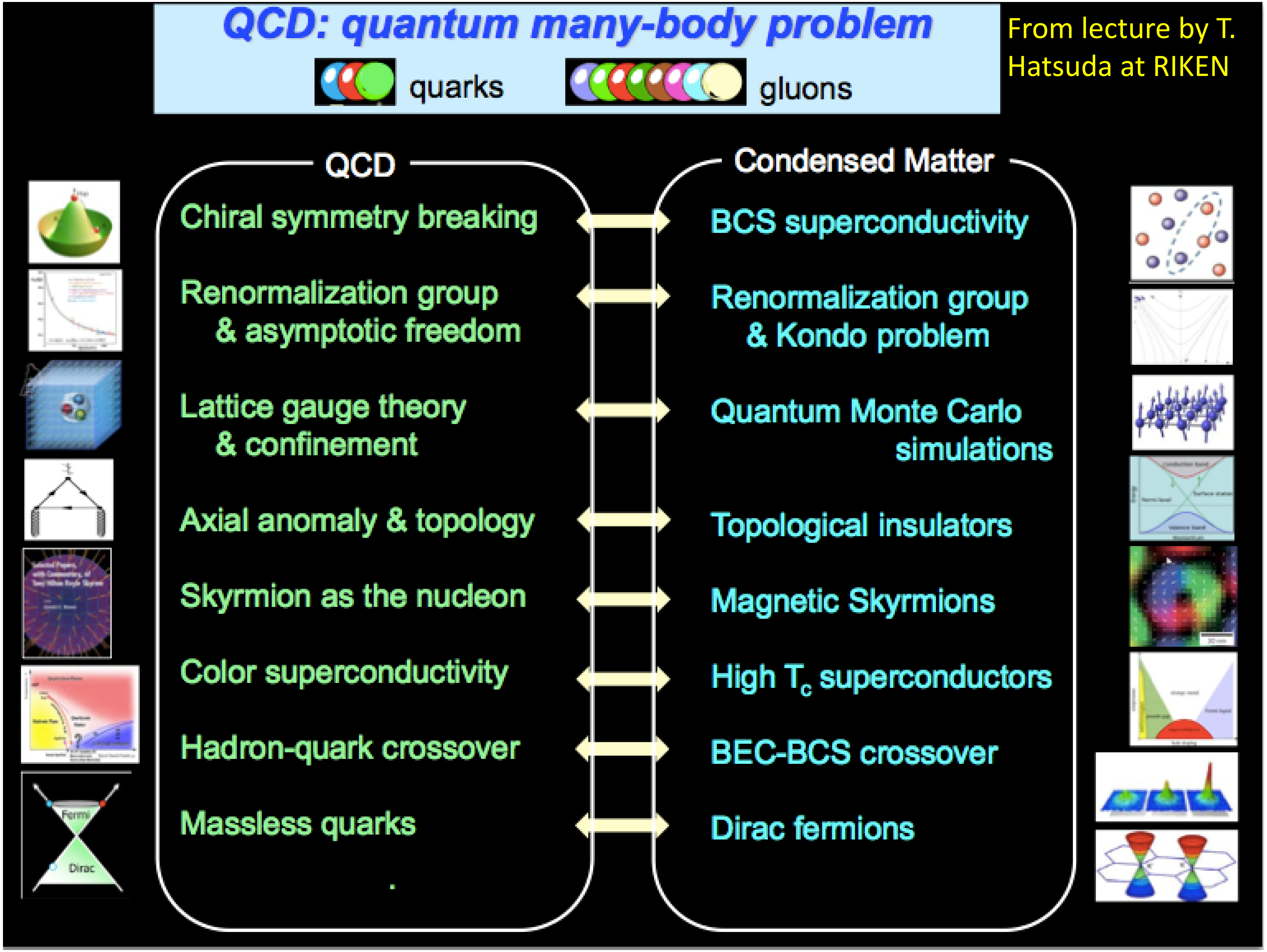
- weak at short distance or high energy
- strong at long distance
- QCD vacuum is anti-screening

QCD at high temperature and density

- QCD is expected to undergo phase transitions at finite temperature and density
  - deconfinement/chiral phase transitions



- Such phase transitions are related to early universe and structure of neutron stars


QCD: quantum many-body problem
quarks
gluons
From lecture by T. Hatsuda at RIKEN
QCD
Condensed Matter
Chiral symmetry breaking
BCS superconductivity
Renormalization group & asymptotic freedom
Renormalization group & Kondo problem
Lattice gauge theory & confinement
Quantum Monte Carlo simulations
Axial anomaly & topology
Topological insulators
Skyrmion as the nucleon
Magnetic Skyrmions
Color superconductivity
High T_c superconductors
Hadron-quark crossover
BEC-BCS crossover
Massless quarks
Dirac fermions
Fermi
Dirac

Current status of study of QCD

- QCD is non-perturbative theory, not easy to study.
  - perturbative expansion of Feynman diagrams does not converge in general

  - phenomenological approaches : qualitative understanding

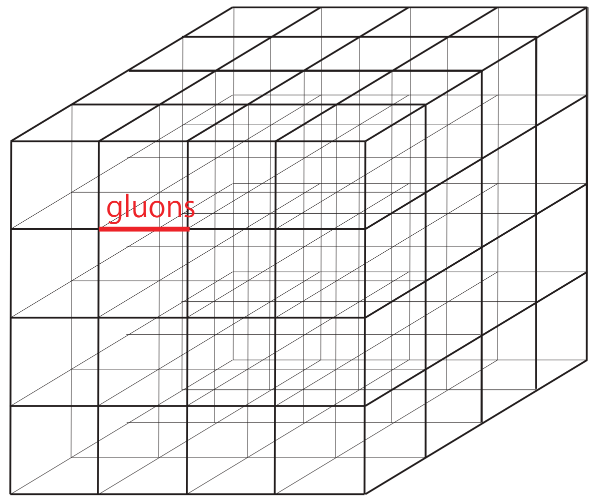
  - Lattice QCD is unique tool to study QCD non-perturbatively at this moment
    - powerful for some quantities
    - but limited application

Current status of study of QCD

$$Z = \int \mathcal{D}U [\det \Delta]^{N_f} e^{-S_G}$$

$$\int \mathcal{D}[\bar{\psi}\psi] \exp\left(\int d^4x \bar{\psi} A \psi \right) = \det A$$

Formula for Grassmann integral
(A : general matrix)



4d Euclidian lattice
eight gluons on each link
-> importance sampling

- Lattice QCD useful for
  - ground state hadron spectrum
  - nuclear force
  - phase transition at high temperature
  - etc

Current status of study of QCD

- Lattice QCD
  - formulated with imaginary time
  - needs real positive action (Monte Calro)
  - expectation value of observables

- difficult for some applications
  - real time simulation :
  - at finite quark density, action becomes complex: sign problem
  - some quantities are difficult to calculate : excitated states, viscositiy, etc

Today's talks

- Entanglement Entropy (Itou)
  - It is quite new concept in QCD
  - deeper insight for confinement of QCD ?
- AdS/CFT correspondance(Nakamura)
  - new approach to study CFT
  - success to reproduce small viscosity
  - how is for other quantities ?
- Tensor Network(Saito)
  - new approach without Monte Carlo, expected for solution to sign problem.
  - application to gauge theory with confinement and chiral symmetry breaking