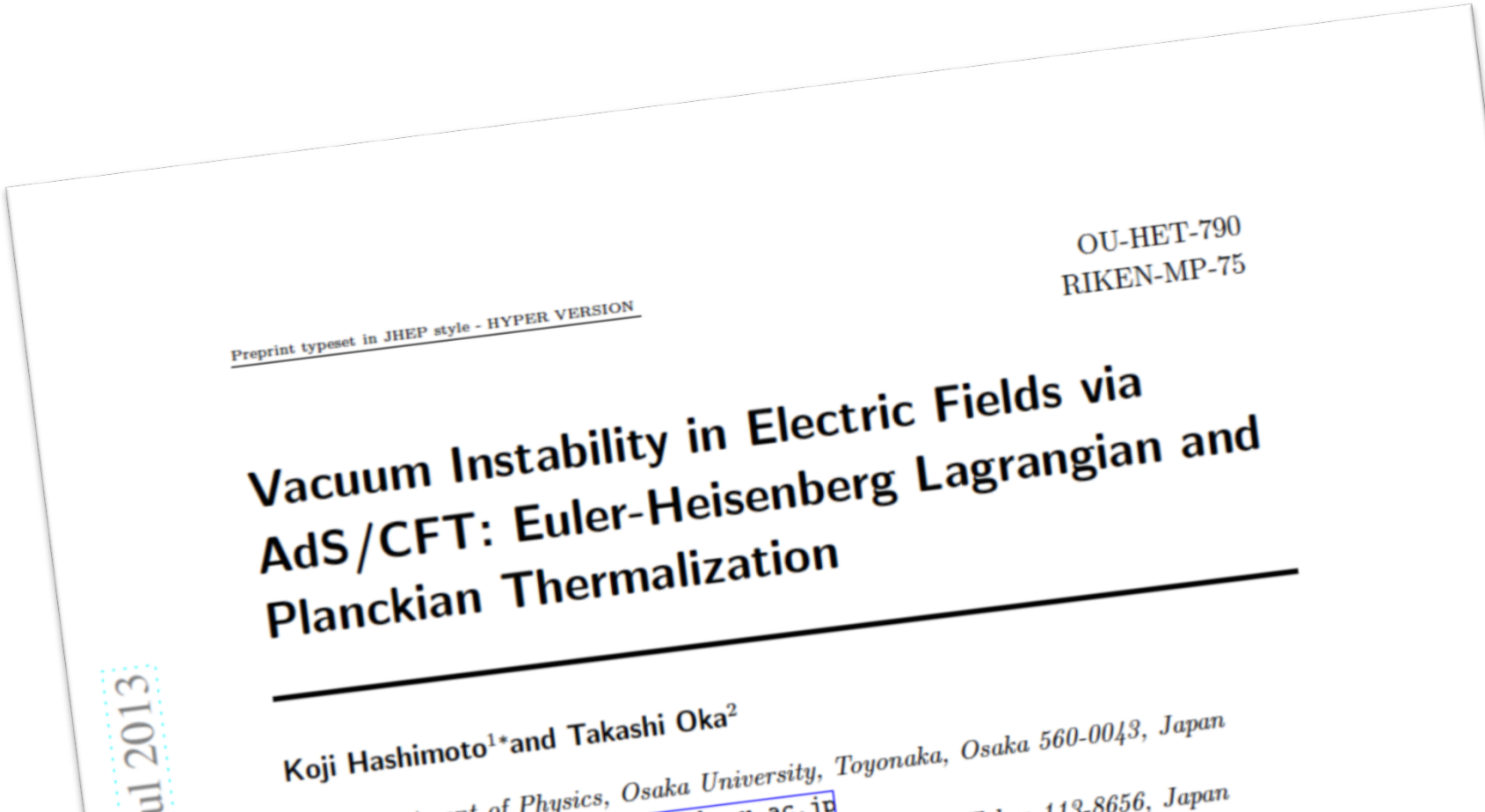
From Superstring to Cond-Mat

Koji Hashimoto 橋本幸士（Osaka-u / RIKEN）



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Preprint typeset in JHEP style - HYPER VERSION

Vacuum Instability in Electric Fields via AdS/CFT: Euler-Heisenberg Lagrangian and Planckian Thermalization

Koji Hashimoto[1]*and Takashi Oka[2]

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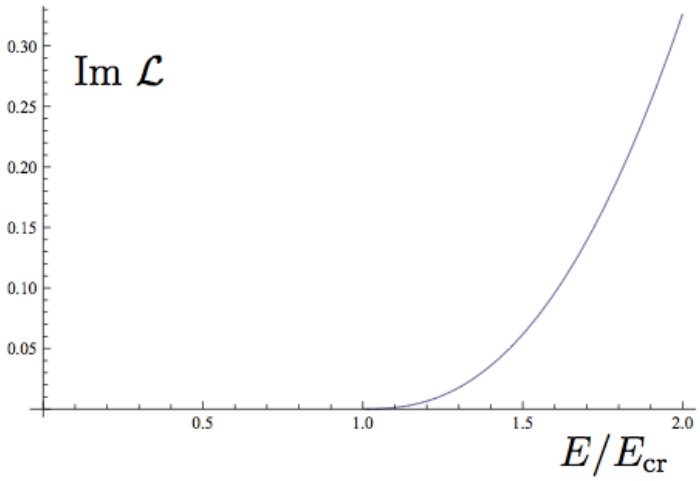
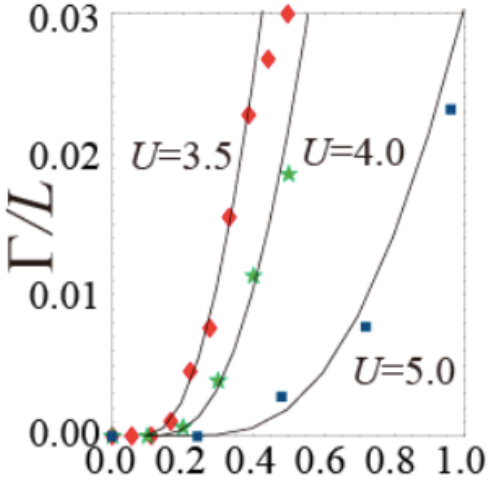
Supersymmetric QCD



[Oka, KH 1307.7423]

"QCD-matter"

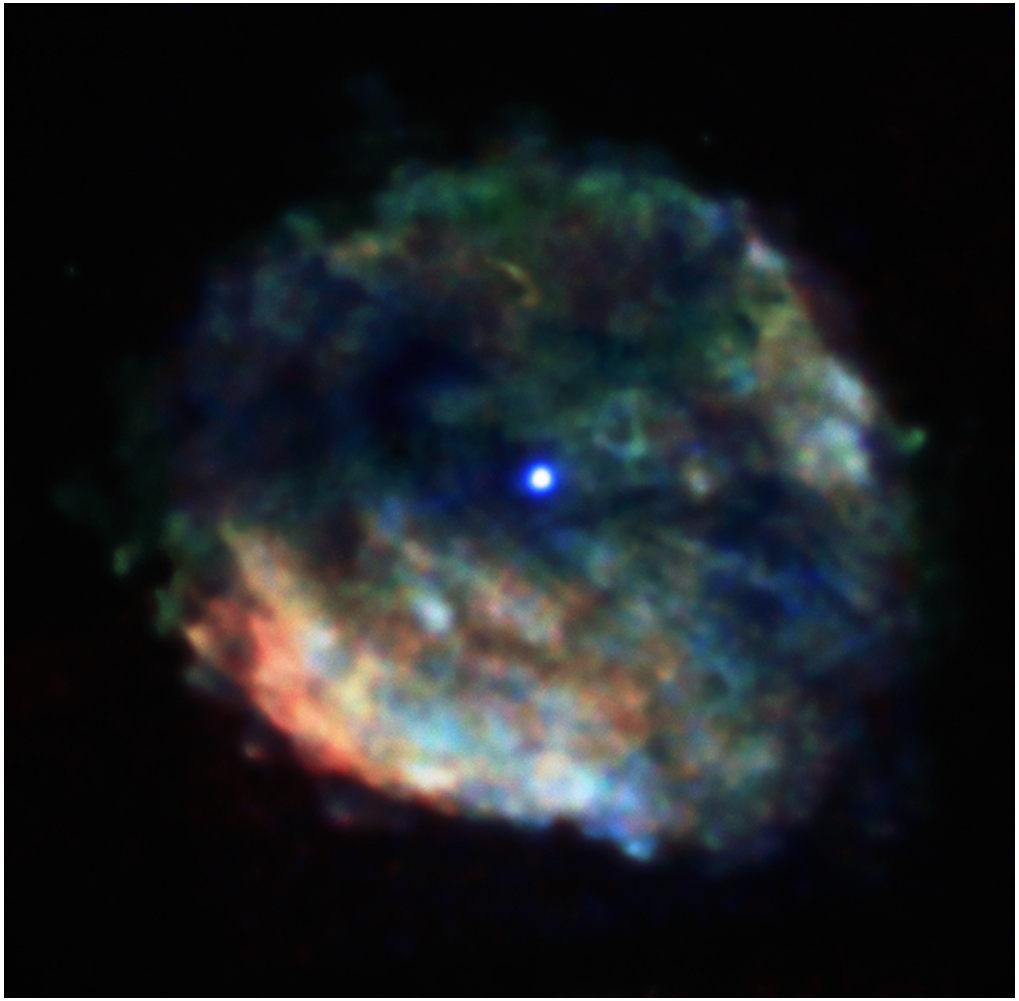
1d Mott insulator



[Oka, Aoki, PRL 95 (2005) 137601]

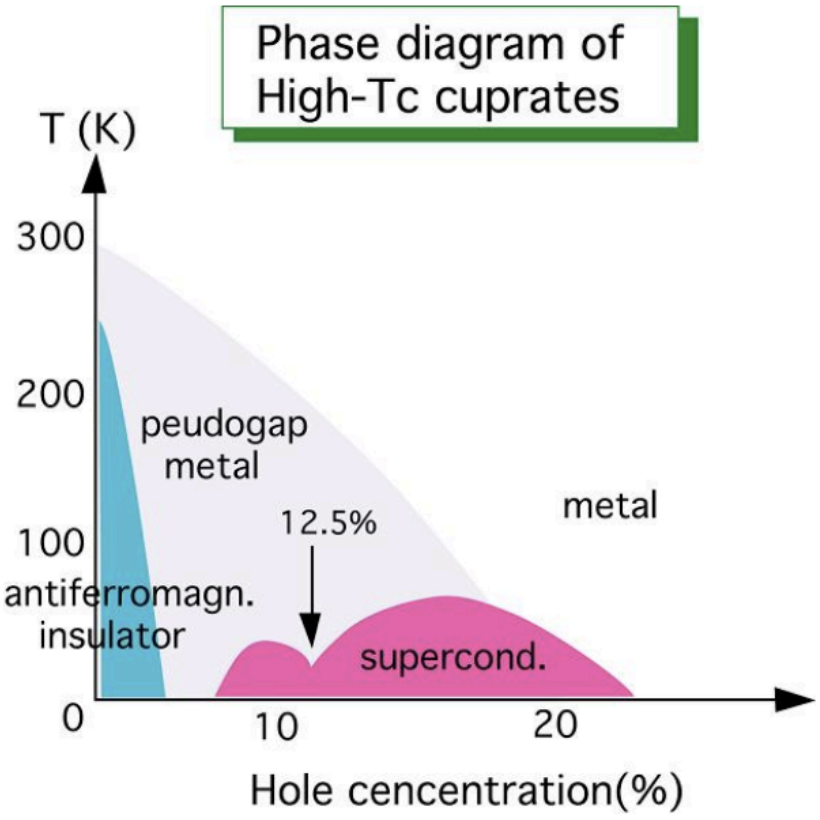
Condensed matter

What resides inside neutron stars?



Supernova remnant RCW103

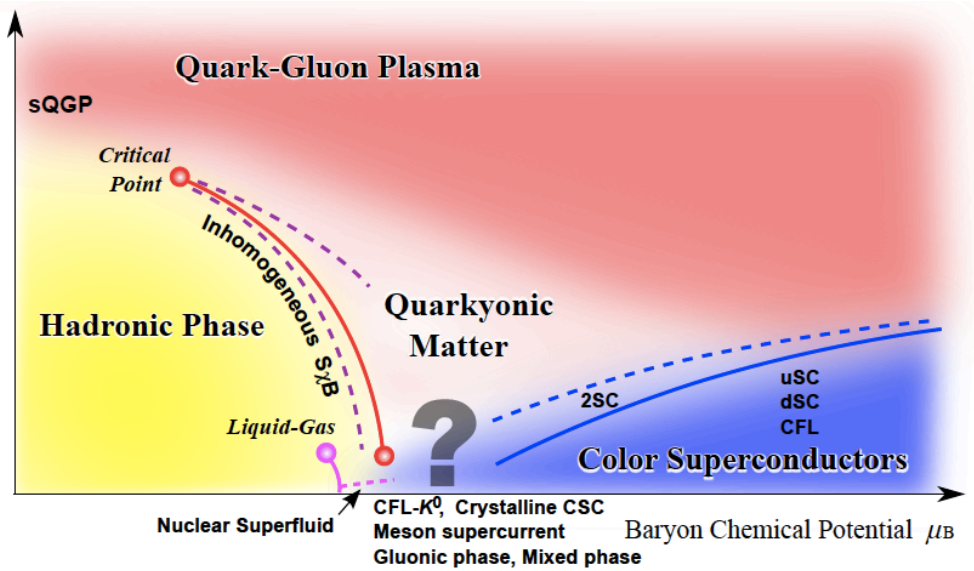
``QCD matter" : frontier in quark physics



[藤森研講義録]

$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + \bar{\psi}_i \left(i\gamma^\mu D_\mu - m_i \right) \psi_i$$

Phase diagram of QCD

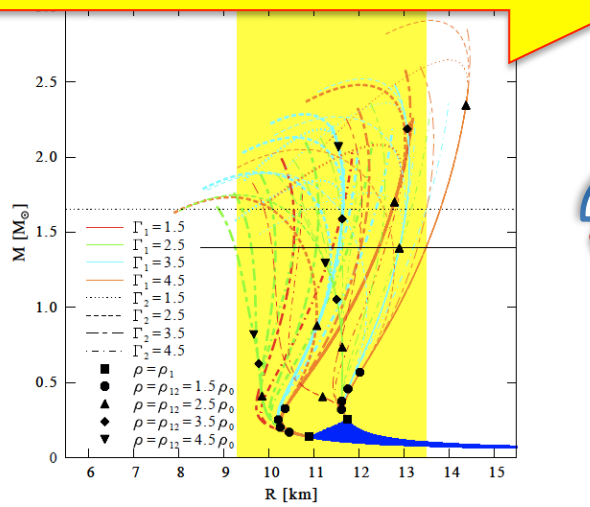


[Fukushima, Hatsuda 1005.4814]

Meeting point for … observation and theory

Obs.

Equation of state



[Hebeler et.al (2010 PRL)]

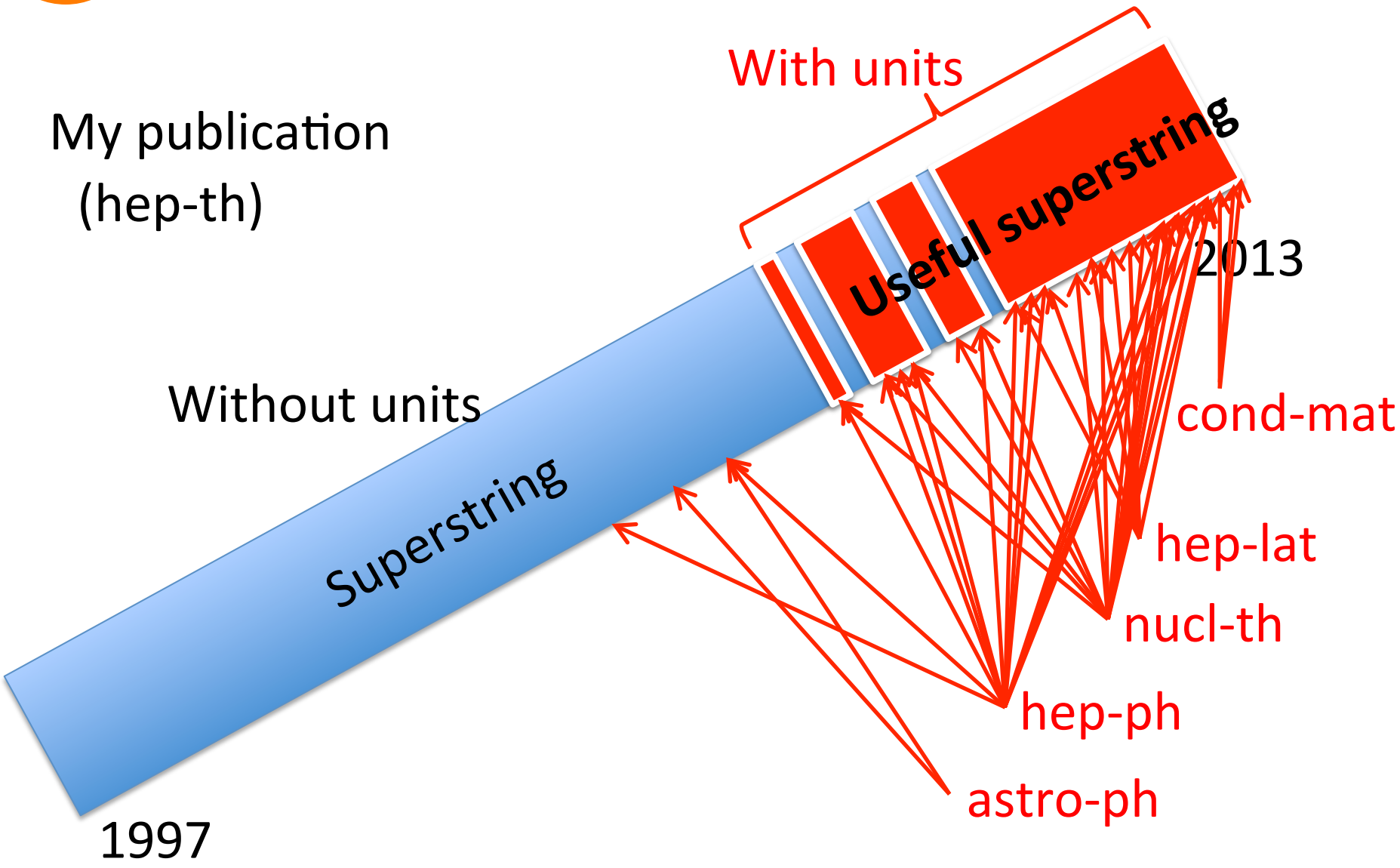
Theory
（QCD）

Superstringy mathematics resolves mysteries in strongly correlated systems

Road map

1. Is superstring useful? 7 pages
2. Duality connecting theories 5 pages
3. Challenge to neutron stars 7 pages

1-1 Superstring gets useful in these 7 years



1-2 Isolation between particle and nuclear physics

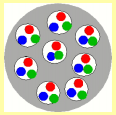
Quarks and gluons

Lattice QCD

Superstring

Nucleons and hadrons

Nuclear physics



Atomic nuclei, neutron stars

1-3 QCD is strongly coupled, hard to calculate

QCD action for quarks and gluons: simple but highly nonlinear

$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + \bar{\psi}_i \left(i\gamma^\mu D_\mu - m_i \right) \psi_i$$

Strong nonlinearity (strong coupling), perturbation impossible

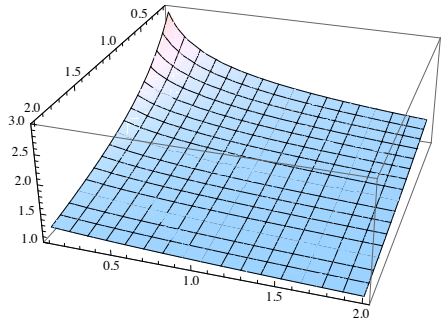
Linear $$\int_{-\infty}^{\infty} dx \;\; e^{-mx^2} = \sqrt{\frac{\pi}{m}}$$

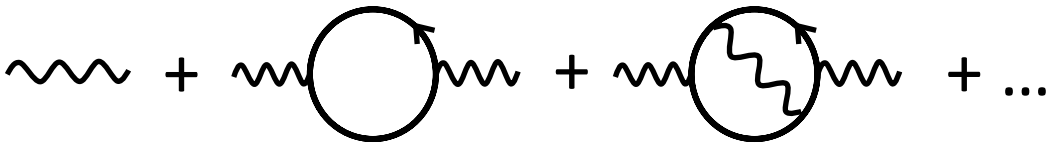
Nonlinear $$\int_{-\infty}^{\infty} dx \;\; e^{-mx^2 - gx^4}$$

$$= \int_{-\infty}^{\infty} dx \;\; e^{-mx^2} \left(1 - gx^4 + \frac{g^2 x^8}{2} + \cdots \right)$$

$$= \sqrt{\frac{\pi}{m}} \left(1 - \frac{3g}{4m^2} + \frac{105 g^2}{32 m^4} + \cdots \right)$$ Perturbation

Numerical calculation?





1-4 Useful superstring as a math tool

Solve equivalent system via duality

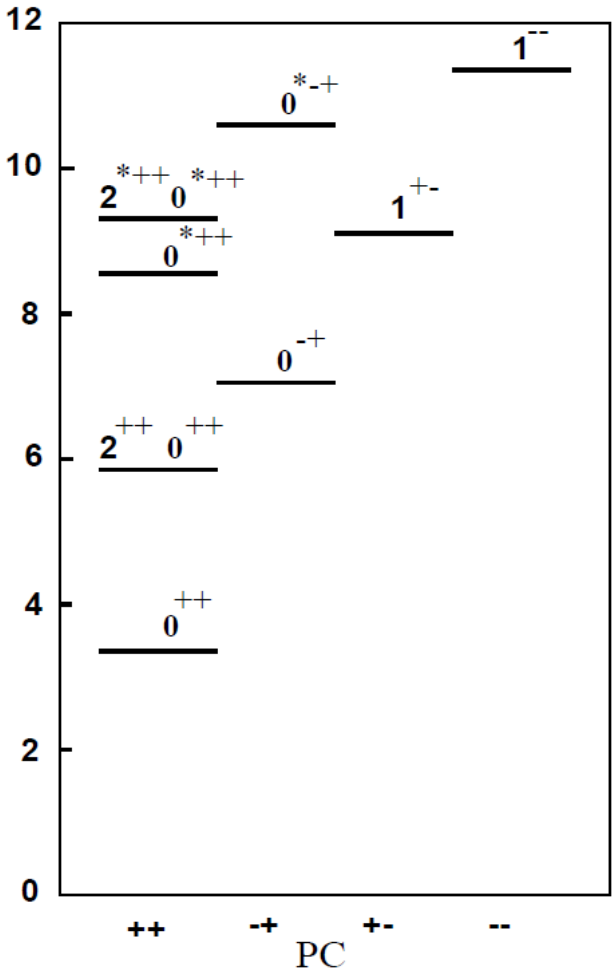
Problems : Strong coupling, many body, solitons, …

Note: no need for theories to be really stringy.

QCD	Insulator	Hypothetical higher dim. gravity
Glueball	Phonon	Graviton excitation
Meson	Exciton	$U(N_f)$ gauge theory
Baryon	Impurity	Soliton
Deconfinement	Conduction	Black hole
Finite temp	Heat bath	Hawking temp
Quark density	electrons	Electric field in $U(N_f)$
Plasma	Thermalize	Event horizon formation

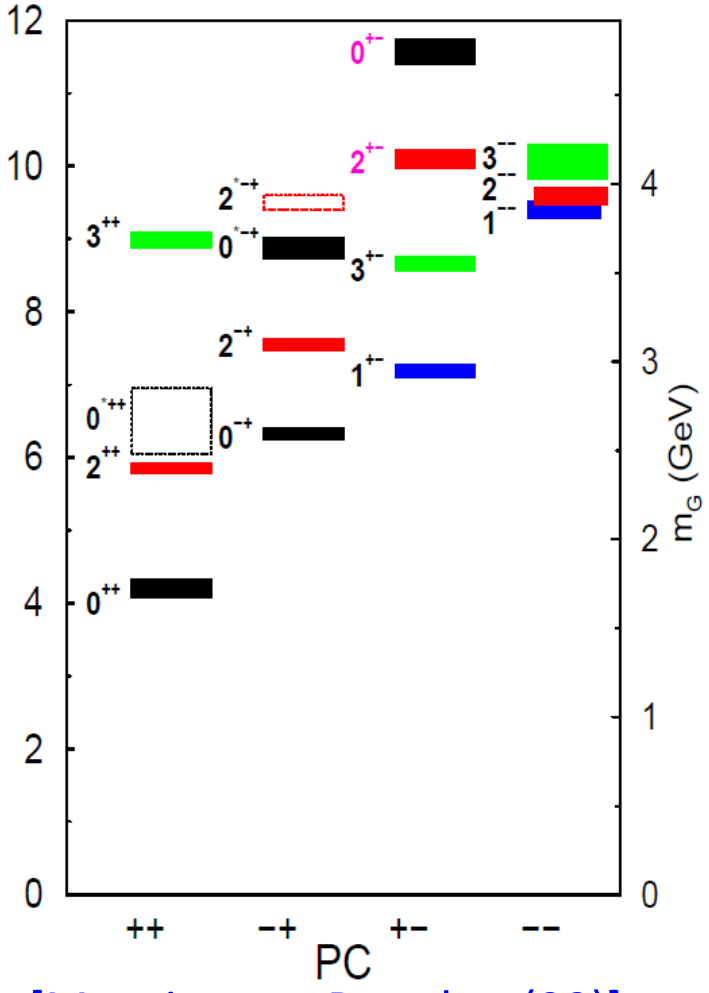
1-5 Superstring: better than simulations?

Superstring



[Brower,Mathur,Tan (03)]

Lattice



[Morningstar,Peardon (99)]

Ex) Proton radius from superstring

Radii of proton/neutron [Sakai,Sugimoto,KH (0806.3122)]

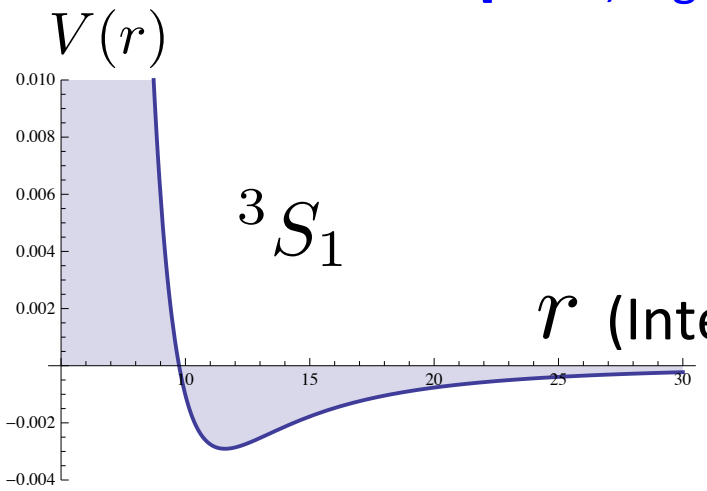
	Superstring	Experiment	
$\langle r^2 \rangle_{E,\mathrm{p}}$	$(0.74\ \mathrm{fm})^2$	$(0.875\ \mathrm{fm})^2$	
$\langle r^2 \rangle_{E,\mathrm{n}}$	0	$-0.116\ \mathrm{fm}^2$	
$\langle r^2 \rangle_A^{1/2}$	0.54 fm	0.674 fm	
μ_p	2.2	2.79	
μ_n	– 1.3	–1.91	
g_A	0.73	1.27	
$g_{\pi NN}$	7.5	13.2	
$g_{\rho NN}$	5.8	4.2 – 6.5	Lattice
$\mu_{\Delta^{++}}$	4.4	3.7 – 7.5	4.99
$\mu_{\Delta^{+}}$	2.3	–	2.49
$\mu_{\Delta^{0}}$	0.20	–	0.06
$\mu_{\Delta^{-}}$	–1.9	–	–2.45

1-7 Ex) Nuclear force from superstring

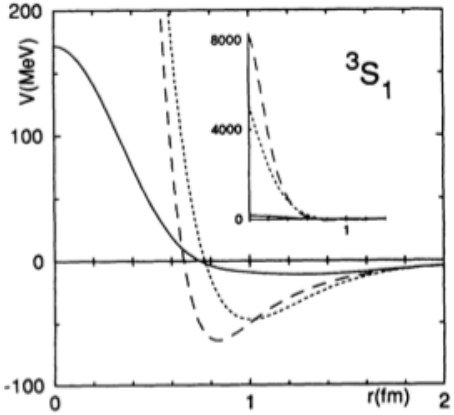
[Sakai,Sugimoto,KH (0901.4449)]

Nuclear forces

Superstring :

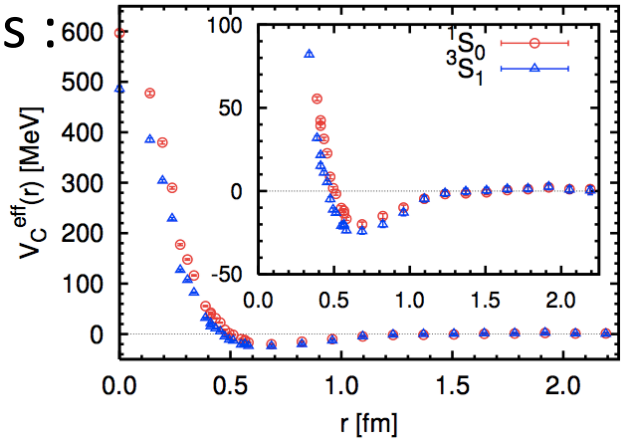


Experiments:



[Stoks,Klomp,Terheggen,deSwart (‘94)]

Lattice QCD simulations :



[Aoki,Ishii,Hatsuda (‘07)]

Superstringy mathematics resolves mysteries in strongly correlated systems

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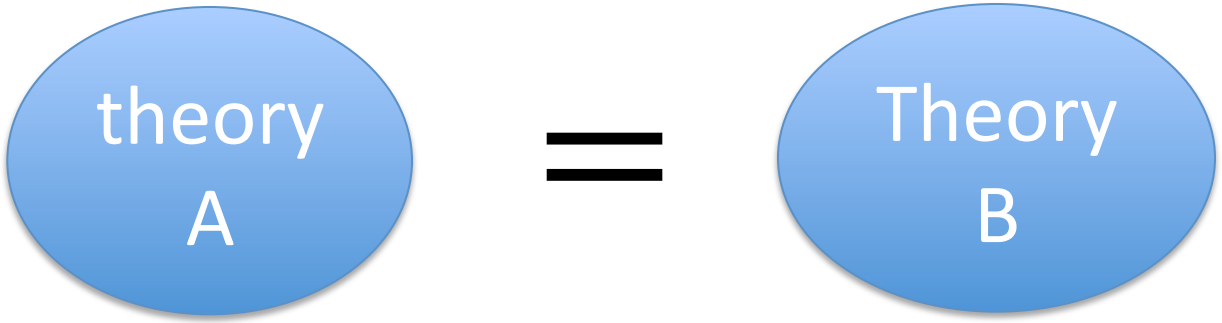
Duality



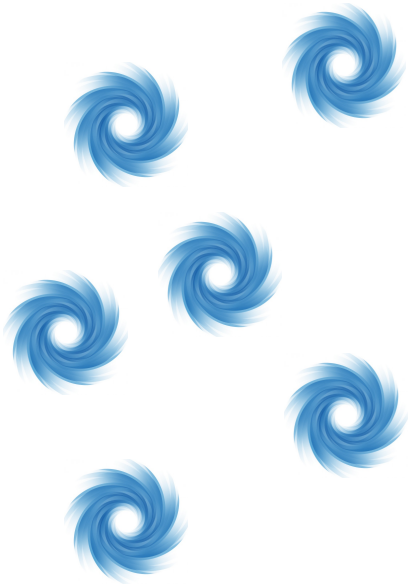
Strongly coupled (correlated)

Too nonlinear to solve

Too many DoF

Weakly coupled, solvable

Holographic equivalence



Describe multi vortices.

A) Field theory of order parameter

$$S = \int d^3x \left(|\partial_\mu \phi(x,y,t)|^2 - V(|\phi|) \right)$$

B) Particle-like vortices

$$S = \int dt \left[\sum_k (\dot{X}^i_{(k)}(t))^2 + \sum_{k_1 \neq k_2} V(|X_{(k_1)}(t) - X_{(k_2)}(t)|) \right]$$

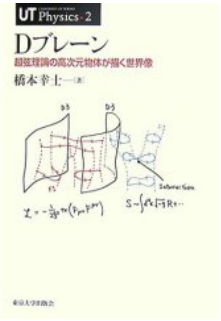
For full equivalence?

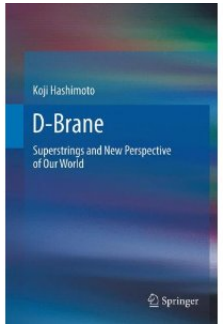
- Topological number fixed?
- Near-vortices?
- Vortices on top of each other?
- Low energy excitations only?

Explicit examples:
ADHM construction of instantons
Nahm construction of monopoles

2-3

Stringy duality: Gauge/gravity duality





D-brane = vortices in superstring theory

- Characterized by mass and charges
- Gauge theories on the D-branes

Gauge/Gravity duality:

A) Gauge theory Strongly coupled, large N

$$S = -\frac{1}{2g^2}\int d^4x \ \mathrm{tr}\ F_{\mu\nu}F^{\mu\nu} + \cdots$$

B) Gravity Weakly coupled, curved higher dimensional space

$$S = \frac{1}{16\pi G_N}\int d^5x \ \sqrt{-g}\,(R + 2\Lambda) + \cdots$$

[Maldacena '98]

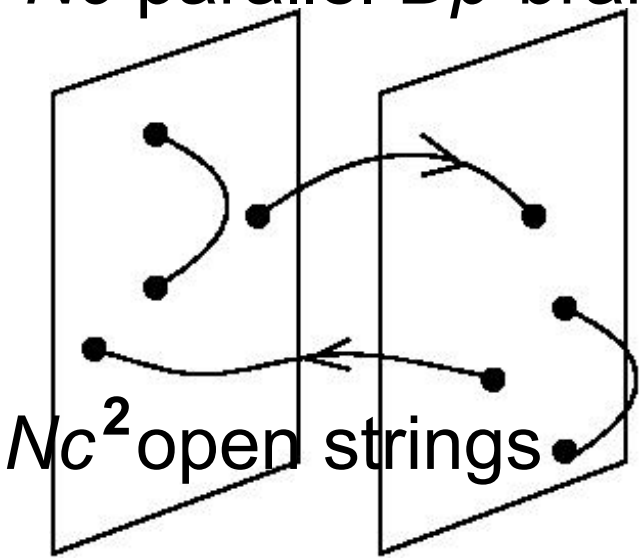
D-brane giving the duality

Quantizing strings defined in 10D spacetime

Open string ⟶ Massless gauge field
Closed string ⟶ Massless graviton

D-branes = Object on which open strings can end

Nc parallel D*p*-branes



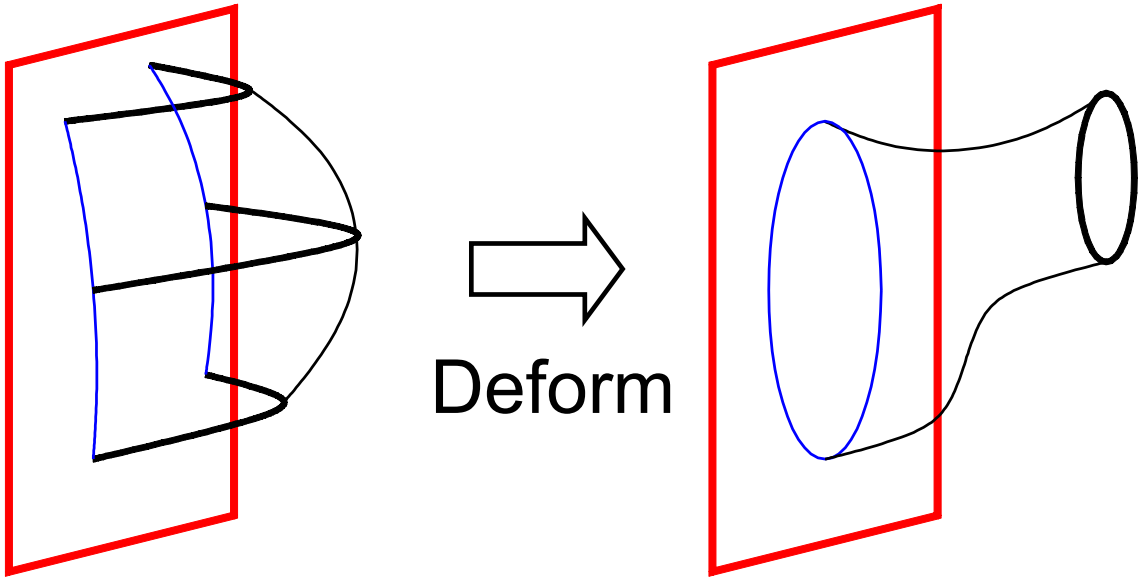
Open string theory on the Dp-brane is :
SU(Nc) gauge theory in *p+1* dimensions

D-brane giving the duality

Quantizing strings defined in 10D spacetime

Open string ⟶ Massless gauge field
Closed string ⟶ Massless graviton

D-branes = Object on which open strings can end



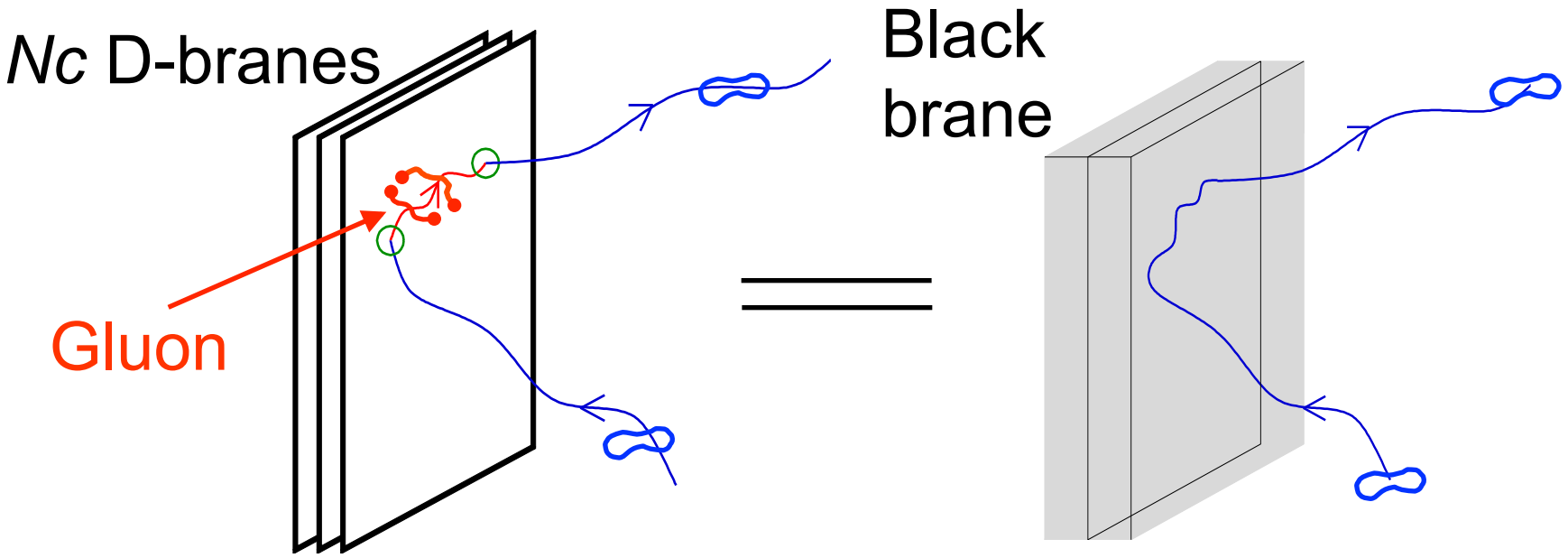
D-brane giving the duality

Quantizing strings defined in 10D spacetime

Open string ⟶ Massless gauge field
Closed string ⟶ Massless graviton

D-branes = Object on which open strings can end
= Source of closed strings
= Source of gravity
= Extended blackhole
"blackbrane" in 10D

Deriving the Gauge/gravity duality



Propagation of
SU(Nc) gauge theory
composite states

$\mathrm{tr} F_{\mu\nu} F^{\mu\rho}$

(Glueball)

Large N_c
Large λ

Propagation of graviton
in near-horizon geometry
of black p-brane

$g_\nu{}^\rho$

Superstringy mathematics resolves mysteries in strongly correlated systems

Road map

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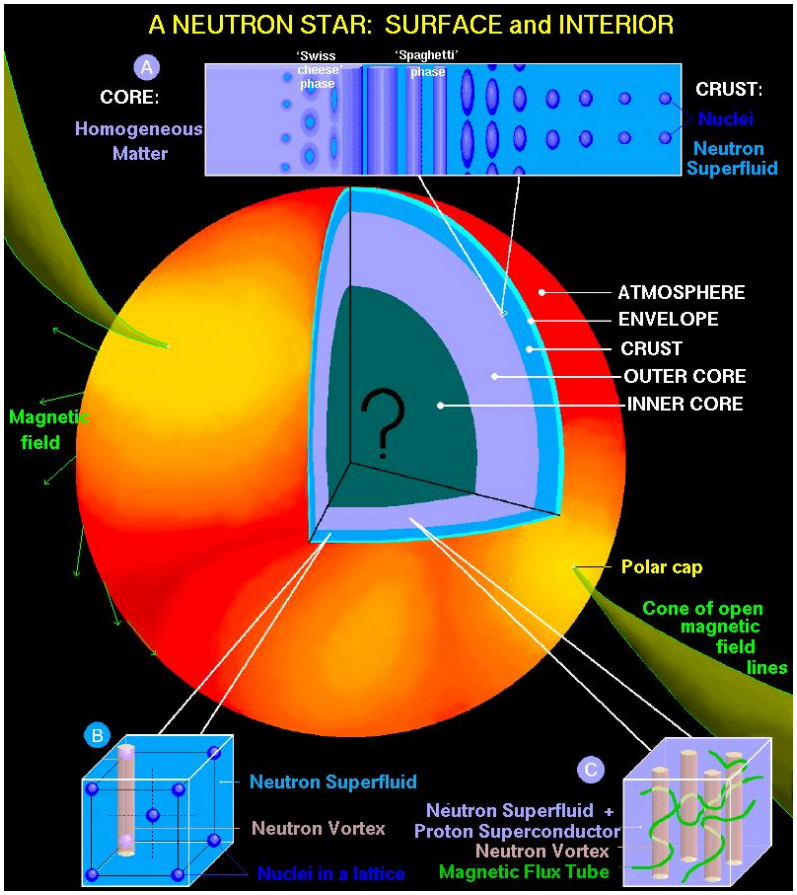
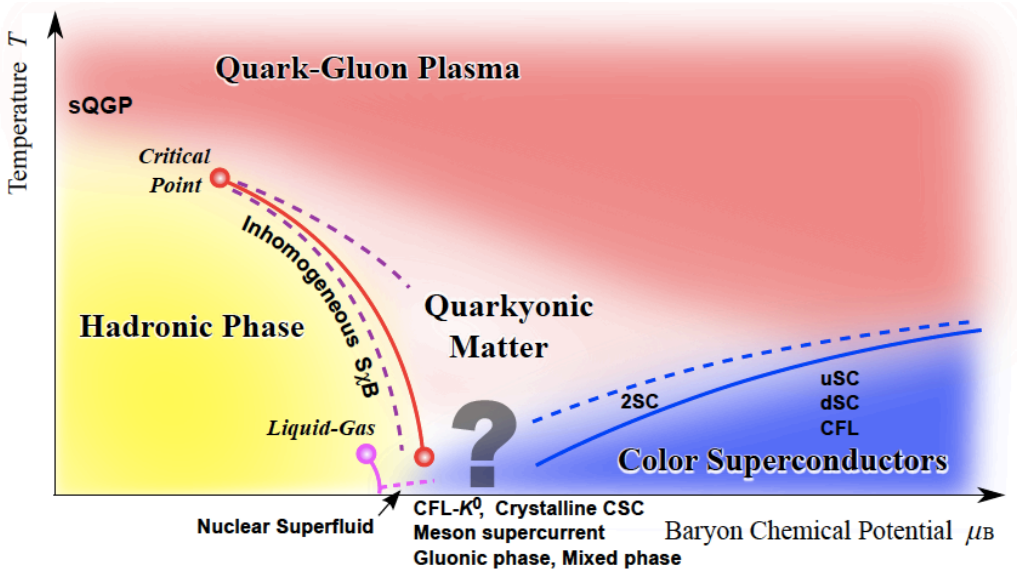
3-1 What resides inside the neutron stars?



[D.Page]

$$\mathcal{L}_{\mathrm{QCD}} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + \bar{\psi}_i \left(i\gamma^\mu D_\mu - m_i \right) \psi_i$$

Phase diagram of QCD



[Fukushima, Hatsuda 1005.4814]

3-2 From hypothetical QCD to real QCD

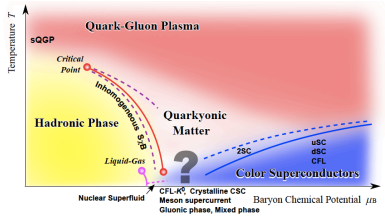
(1) Gauge theory with 4 supersymmetries (N=4 Super Yang-Mills)

(2) Supersymmetric gauge theory + quarks (N=2 Super QCD)

(3) Non-supersymmetric SU(N) gauge theory + quarks (Large N QCD)

(4) Non-supersymmetric SU(3) gauge theory + quarks (QCD)

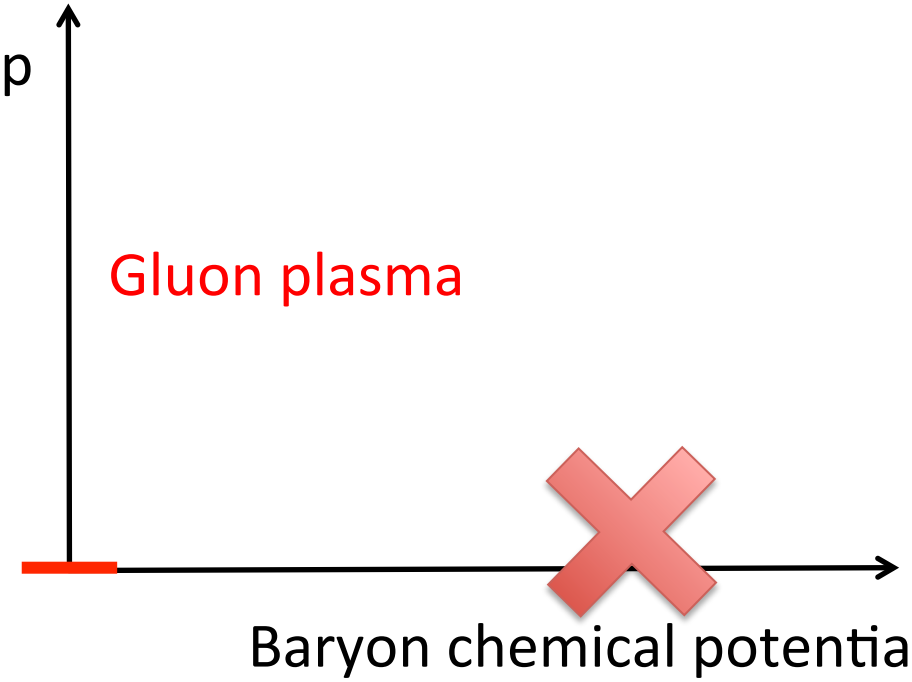
3-3 The road to real QCD: (1)

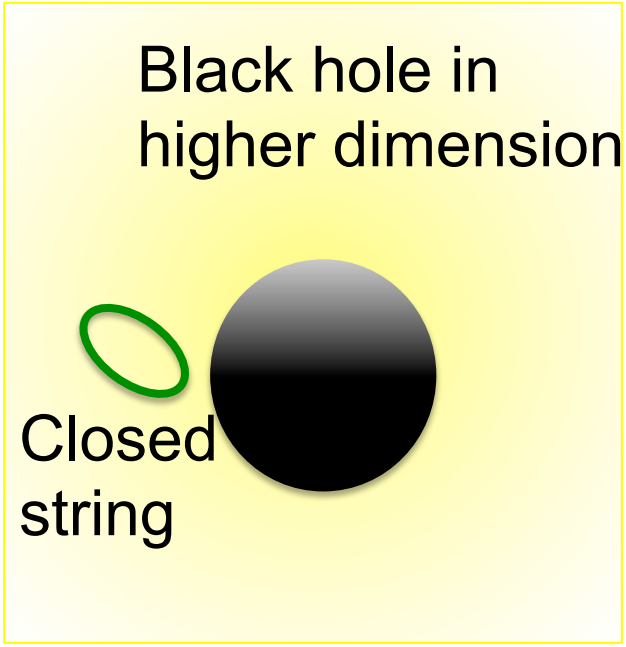


(1) Gauge theory with 4 supersymmetries (N=4 Super Yang-Mills)

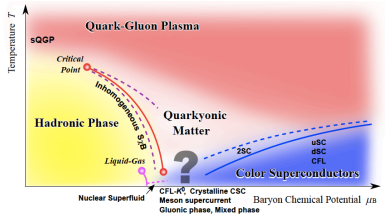
Gluon sector: gluons + 4 gluinos + 6 scalars

Quark sector: Not allowed





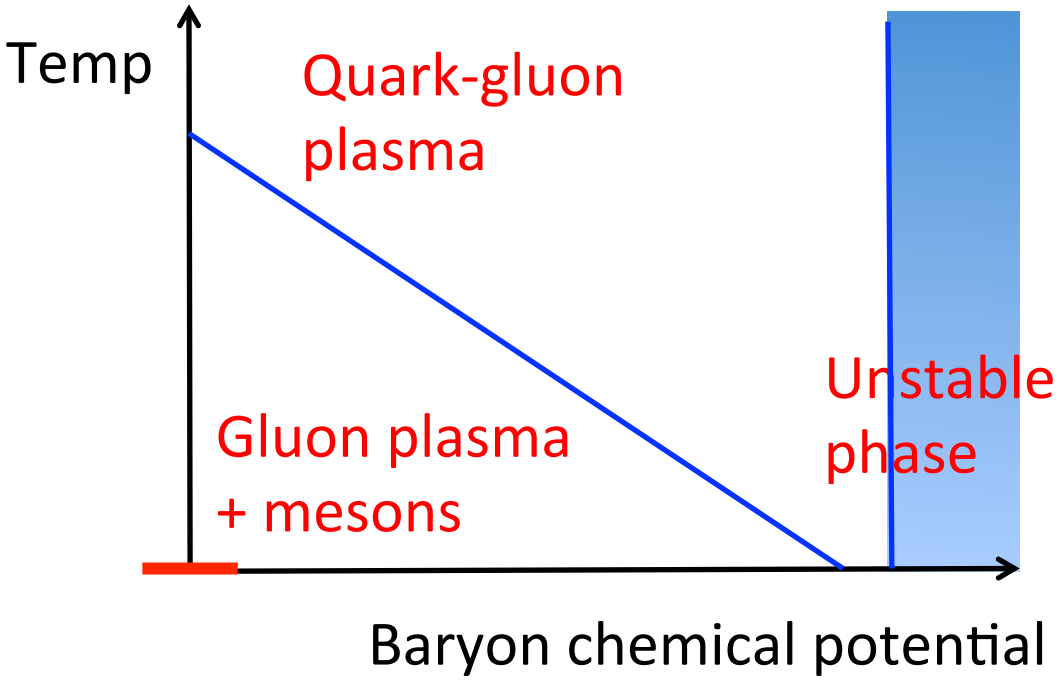
3-4 The road to real QCD: (2)

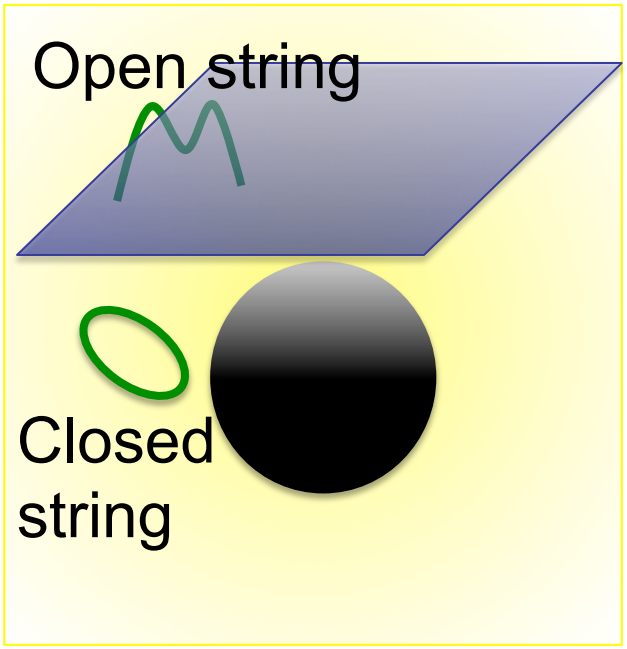


(2) Supersymmetric gauge theory + quarks (N=2 Super QCD)

Gluon sector: gluons + 2 gluinos + 2 scalars

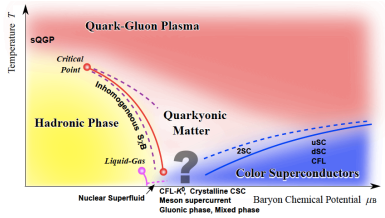
Quark sector: quarks + scalar quarks





[Ghoroku, Ishihara, Nakamura '07]

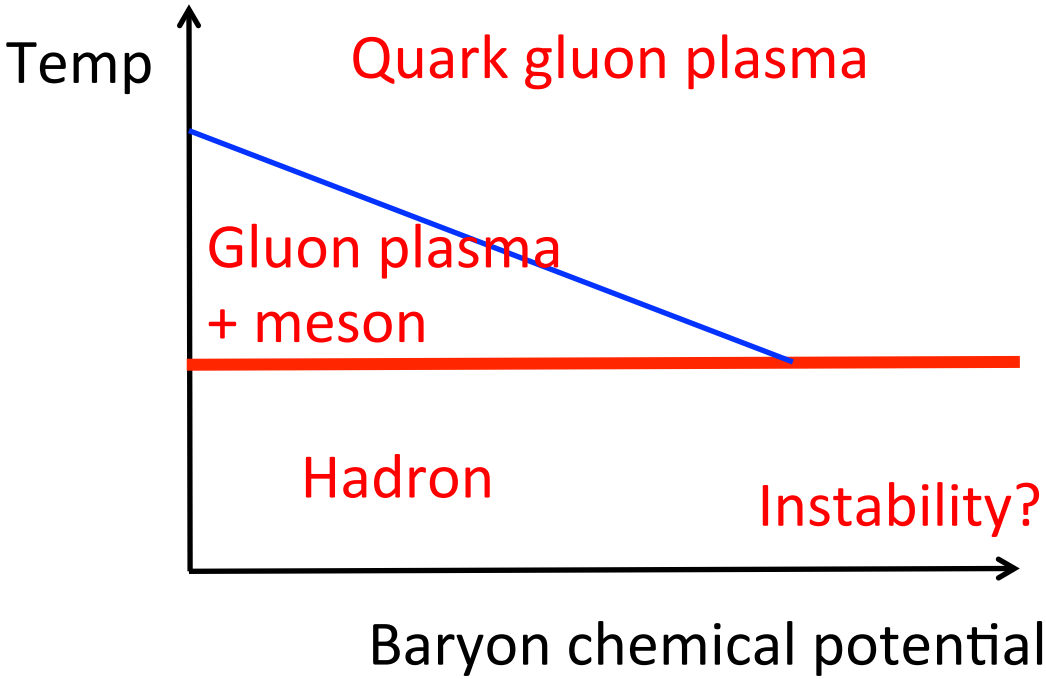
3-5 The road to real QCD: (3)

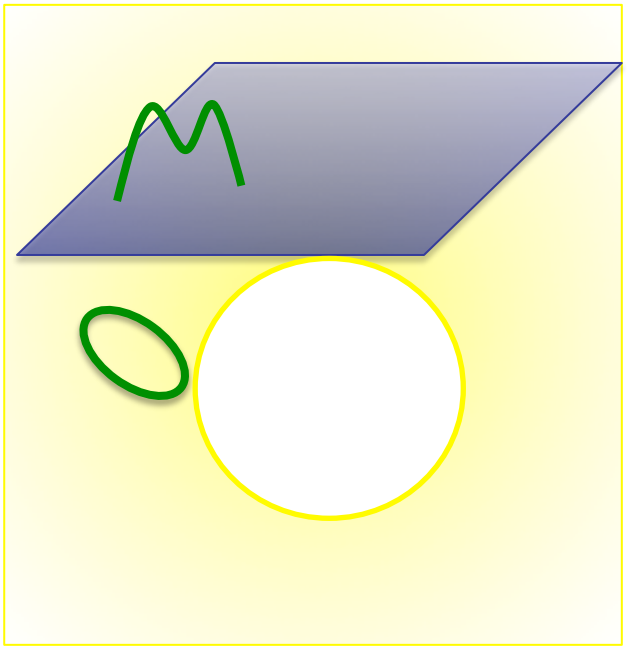


(3) Non-supersymmetric SU(N) gauge theory + quarks (Large N QCD)

Gluon sector: gluons + heavy gluinos

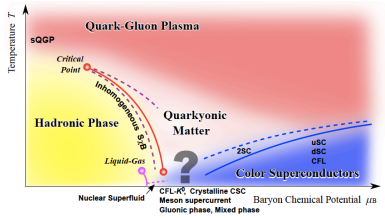
Quark sector: quarks





[Aharony, Sonnenschein, Yankielowicz '06]

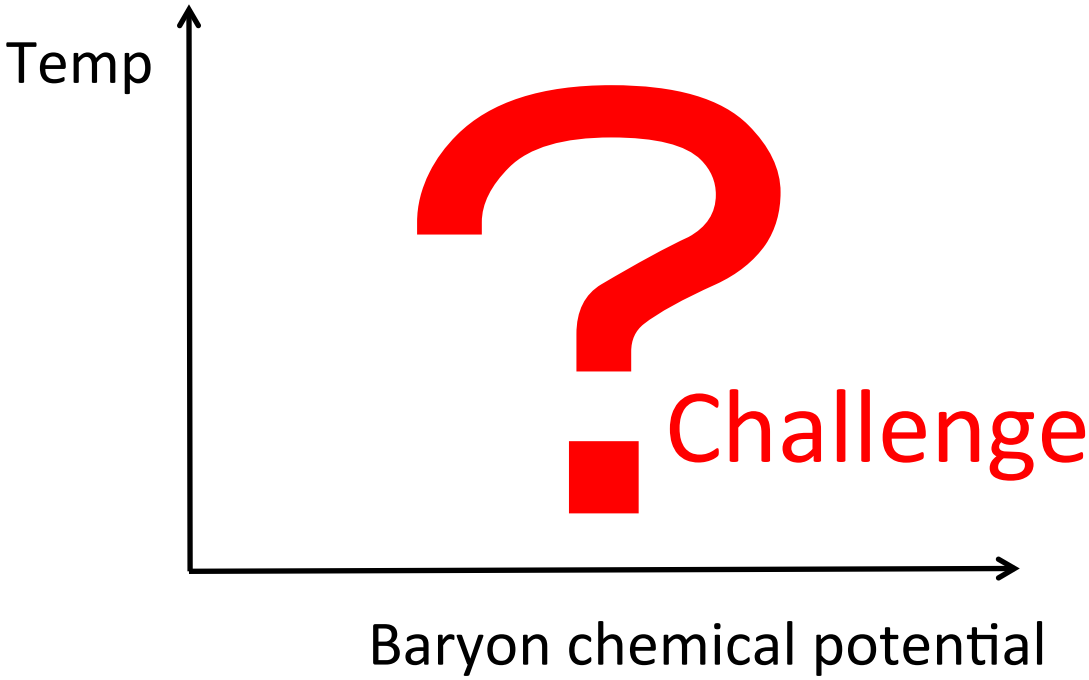
3-6 The road to real QCD: (4)

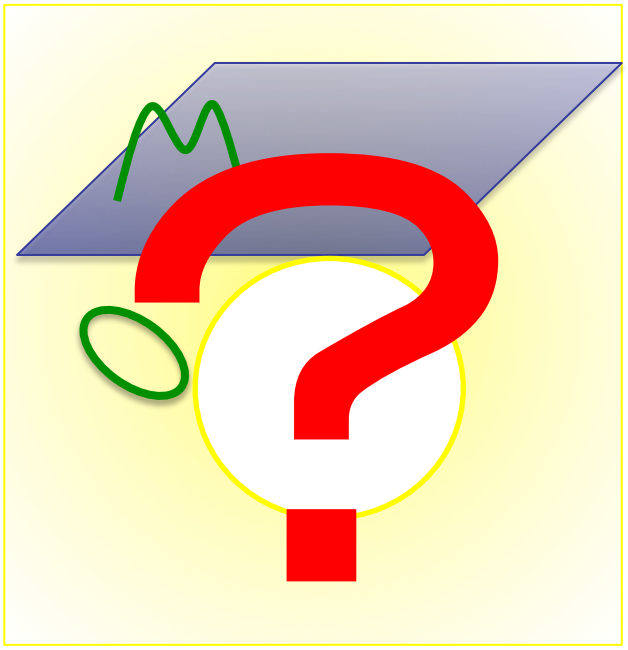


(4) Non-supersymmetric SU(3) gauge theory + quarks (QCD)

Gluon sector: gluons

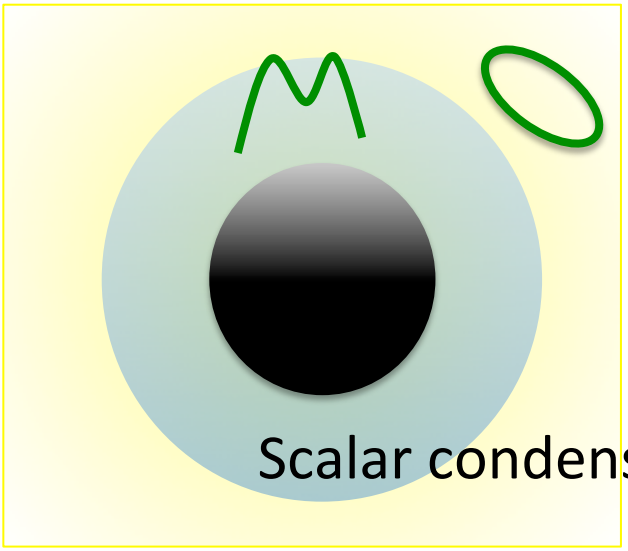
Quark sector: quarks



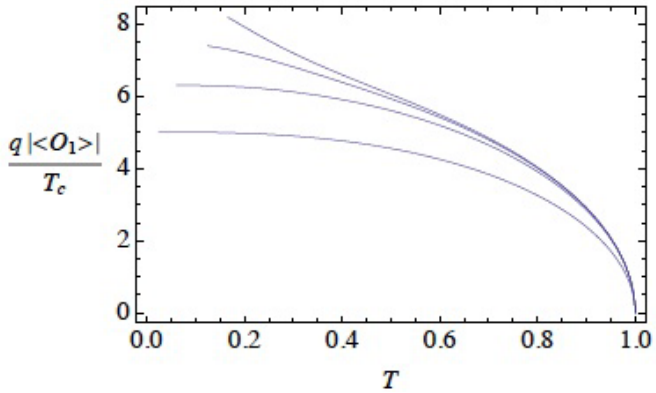


Various applications to cond-mat

Holographic superconductivity

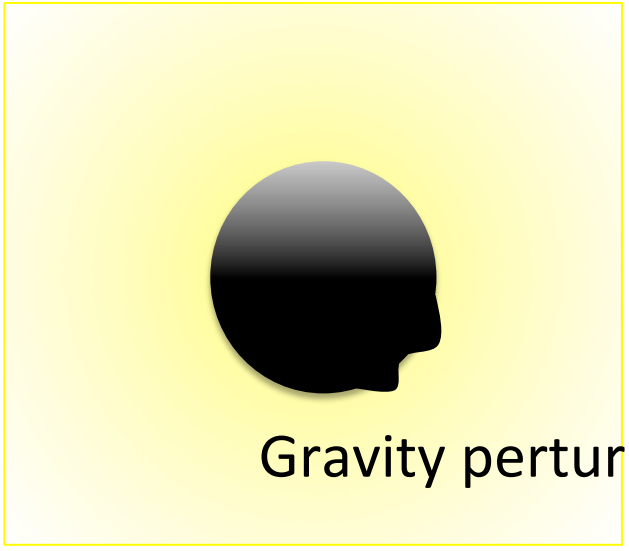


Scalar condensation

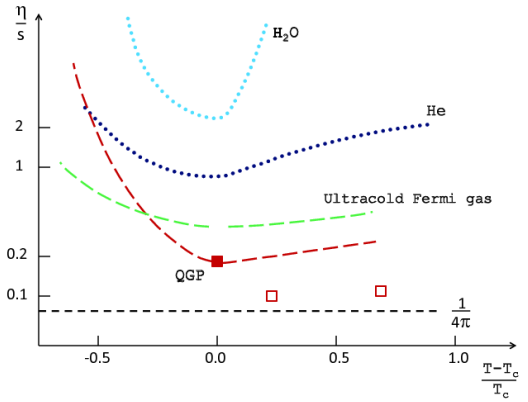


[Hartnoll, Herzog, Horowitz '08]

Holographic viscosity



Gravity perturbation



[Kovtun, Son, Starinets '04]

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