Kavli IPMU MS Seminar

Study of dense QCD matter and its application to physics of compact stars

-The 2nd densest object in the Universe-

Motoi Tachibana (Saga U.)

2015, July 6th

Topics

1. Study of dense QCD matter

Ginzburg-Landau analysis

[work w/ T. Hatsuda, N. Yamamoto, G. Baym:
A. Schmitt and S. Stetina: M. Ruggieri]

Gauge/Gravity duality approach

[work w/ K. Ghoroku, M. Ishihara, K. Kubo,
T. Taminato and F. Toyoda]

2. Astrophysical applications

Dark matter capture in neutron stars

[in progress w/ T. Hatsuda: Y. Sanematsu]

Interesting connection between matters and universe

Dense QCD matter and Neutron Stars

Harmony of particle, astro-, and condensed matter physics

Physics Orchestra !

Basic profile of Neutron Star

(Typical) radius: $R \sim 10 km$

(Typical) mass: $M \sim 1.4 M_{SUN}$

Temperature: $T < 10 MeV$

Magnetic field: $B \sim 10^{12-15} G$

Rotation period: $P \sim 2-3\ ms$

M_{SUN}: solar mass

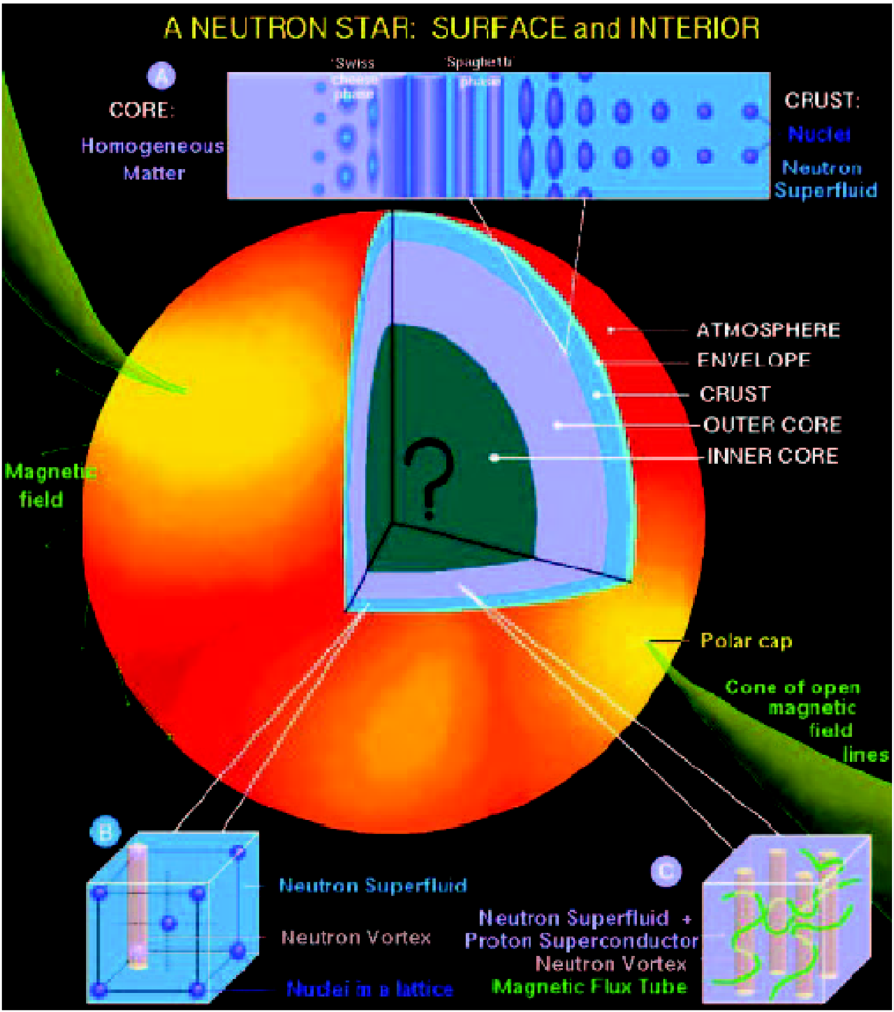
Earth's B field ~ 0.6G

1eV ~ 10^4 K

Major questions

1. How to be born and evolve?
2. Why so compact?
3. How it cools down?
4. Why so huge magnetic field?
5. Why so rapidly rotating?

Theorist’s view of NS structures



① Atmosphere: hydrogen, a mix of heavy elements
(providing info. of temperature)

② Envelope: a few tens of meters
(acts as a thermal insulator)

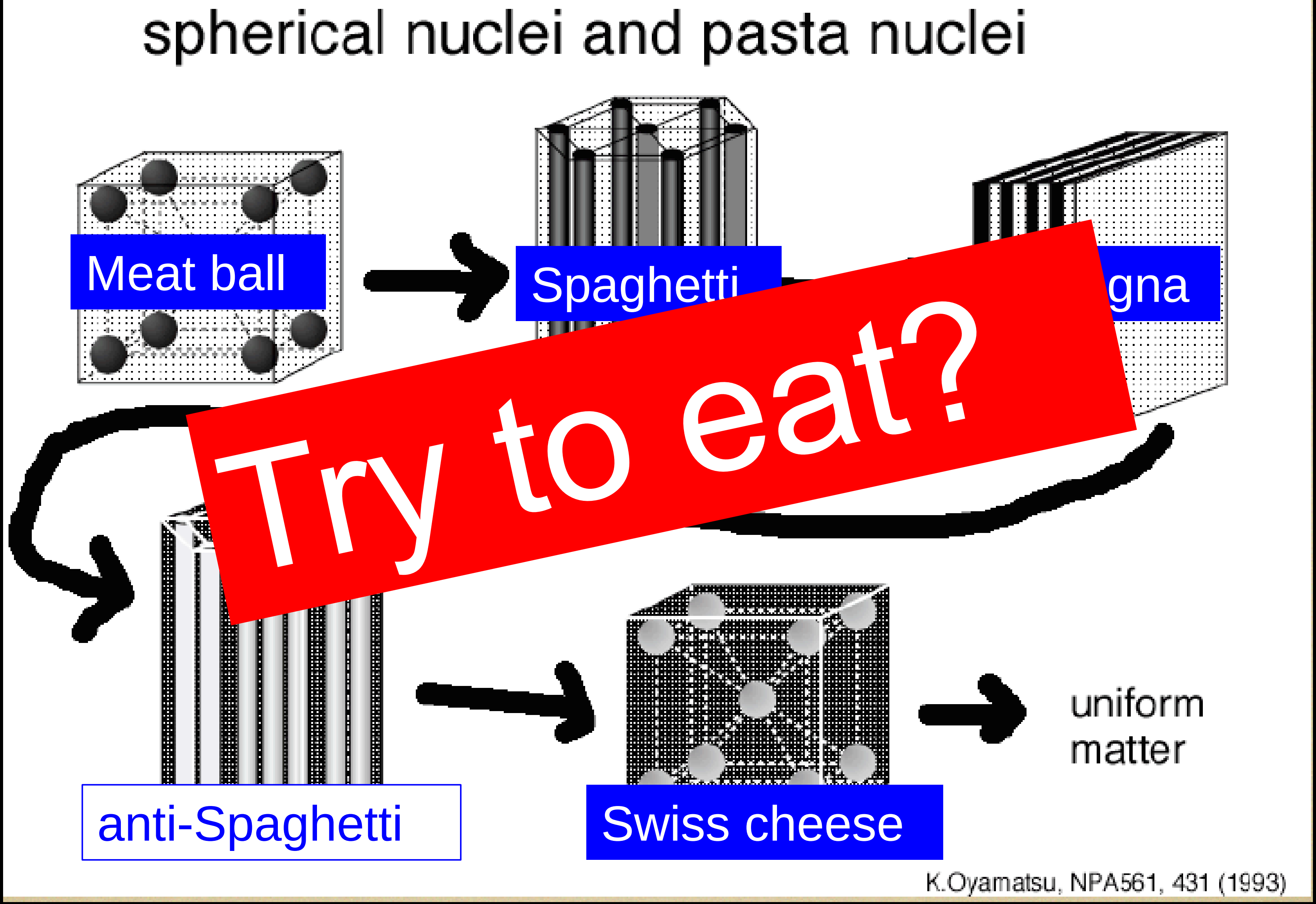
③ Crust: 500-1000m thickness

④ Nuclear Pasta: In-btw crust/core

⑤ Outer Core: a few kilometers

⑥ Inner Core: Big question mark!

Nuclear "Pasta"



Try to eat?

K.Oyamatsu, NPA561, 431 (1993)

Yes! We love Exotica!

New states of matter present in NS !

Superfluid neutron/Superco

Bose-Einstein con esons

Hyperons (eness)

D

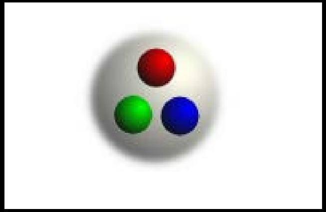
Neutron star = laboratories for studying matter in Xtreme!

Quantitative differences among them?

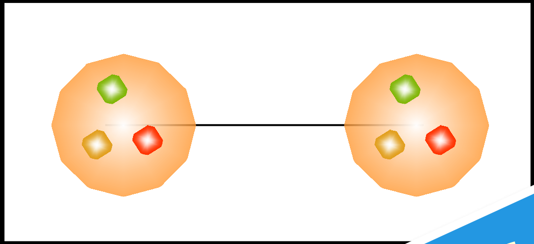
Study of QCD matter

Grand Challenge

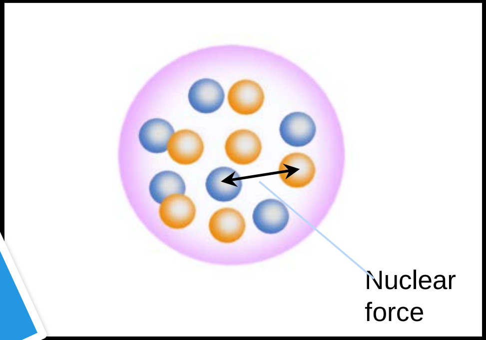
- Space-time evolution of QCD matter -



Hadrons



Nucleon

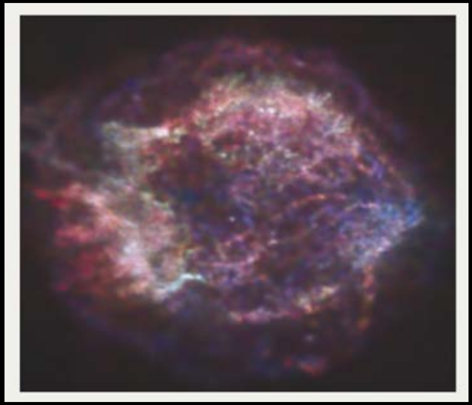


Nuclei

No QCD, no life

Early universe

Neutron/quark star



Supernovae

The answer to the ultimate question

“Why the matter of our universe can be stable?”

QCD Lagrangian

(Han-Nambu, 1965)

$$L_{QCD} = \bar{q}^{\alpha}\left(i\gamma_{\mu}D^{\mu} \qquad \right)_{\alpha\beta} q^{\beta} - \frac{1}{4}F^{a}_{\mu\nu}F^{a\mu\nu}$$

Yes! We love QCD ♥

Simple, bu ery fertile in physics and math.

Providing testing field for any new idea.

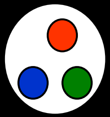
Unsolved problems (inexhaustible spring)

Basic properties of QCD

- Asymptotic freedom (Gross-Politzer-Wilczek, 1973)

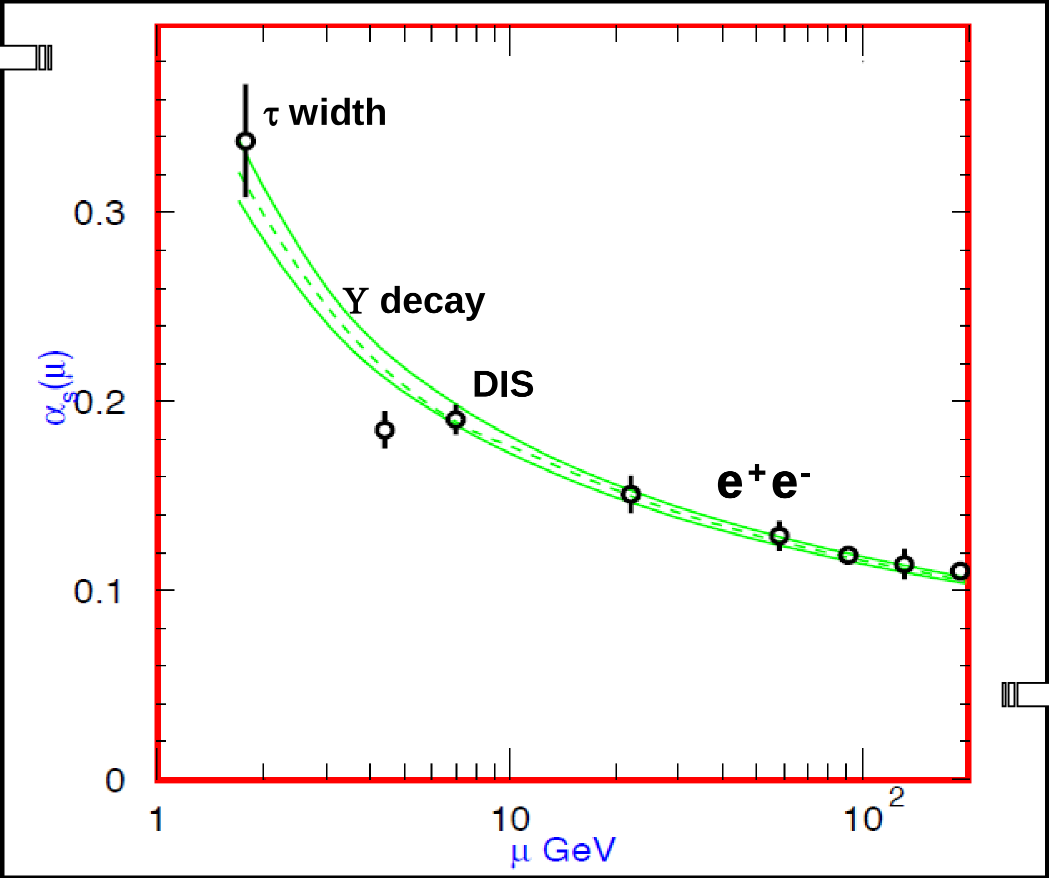
“QCD coupling gets weaker as the energy grows”

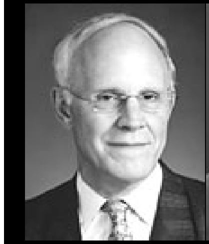
Color Confinement



Coupling constant

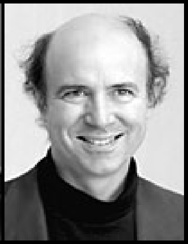
$\alpha_s(\kappa)$





D. Gross

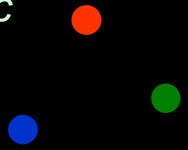
H. Politzer



F. Wilczek

(2004, Nobel Prize)

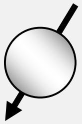
Asymptotic freedom



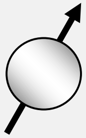
long distance ← *energy scale* κ (GeV) → short distance

■Symmetries in QCD and their breaking pattern

Chiral basis :



$$q_{\rm L} = \frac{1}{2}(1-\gamma_5)q, \qquad q_{\rm R} = \frac{1}{2}(1+\gamma_5)q$$



QCD Lagrangian :

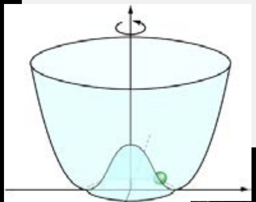
$$\mathcal{L}_{\rm cl} = \mathcal{L}_{\rm cl}(q_{\rm L}, A) + \mathcal{L}_{\rm cl}(q_{\rm R}, A) - (\bar{q}_{\rm L} m q_{\rm R} + \bar{q}_{\rm R} m q_{\rm L})$$

classical QCD symmetry (m=0)

$$\mathcal{G} = SU(3)_C \times [SU(N_f)_L \times SU(N_f)_R] \times U(1)_B \times U(1)_A$$

Quantum QCD vacuum (m=0)

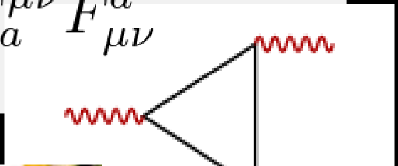
Chiral condensate :
spontaneous mass generation



$$\langle \bar{q}_R q_L \rangle \neq 0$$

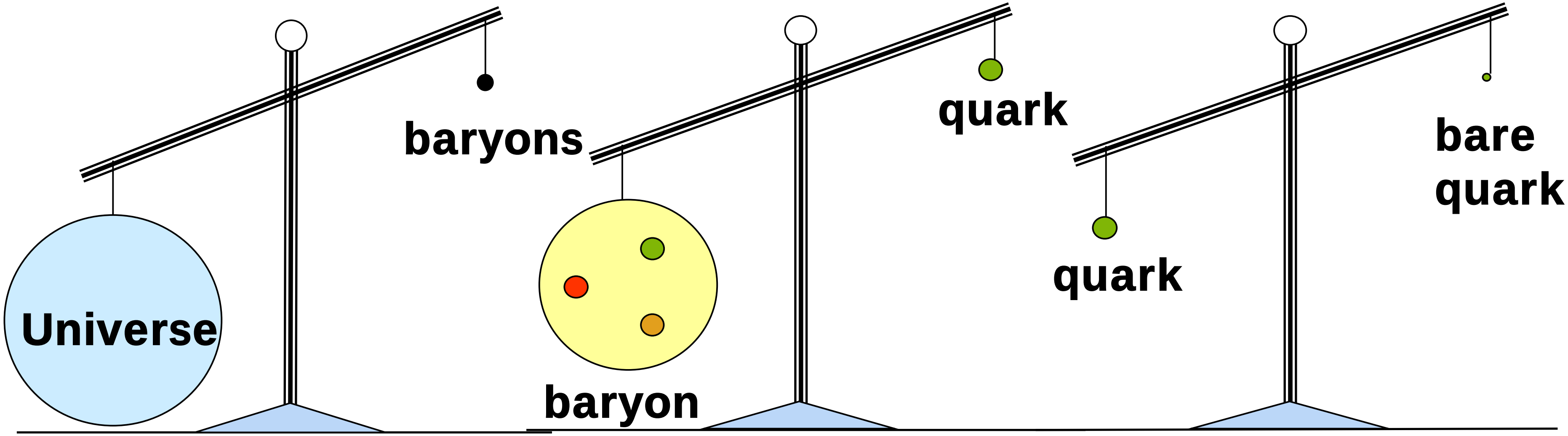
Axial anomaly :
quantum violation of U(1)$_A$

$$\partial_\mu J^\mu_A = -2N_f \frac{\alpha_s}{8\pi} F^{\mu\nu}_a \tilde{F}^a_{\mu\nu}$$



$$SU(3)_C \times SU(N_f)_{L+R} \times U(1)_B$$

Origin of masses $\Longleftrightarrow$ Structure of the vacuum



$$\begin{aligned} 4\% &= \text{baryons} \\ 23\% &= \text{dark matter} \\ 73\% &= \text{dark energy} \end{aligned}$$

Cosmological constant

Einstein (1917)

WMAP, Planck

$$\begin{aligned} m_q &\simeq 10 \text{ MeV} \\ m_N &\simeq 1000 \text{ MeV} \end{aligned}$$

“Chiral” condensate

Nambu (1960)

RHIC, LHC

$$\begin{aligned} m_0 &= 0 \\ m_q &\simeq 10 \text{ MeV} \end{aligned}$$

“Higgs” condensate

Anderson (1963)
Englert-Brout, Higgs (1964)

LHC, ILC

Confinement of quarks/gluons (Origin of us)

Chiral symmetry breaking (Origin of m

Strong coupling nature of cuum

Moreover recently quarks/gluons at

mode temperature/density

een intensively investigated, indicating
the created matter is yet *strongly-interacting*
(e.g., QCD equation of state, shear viscosity)

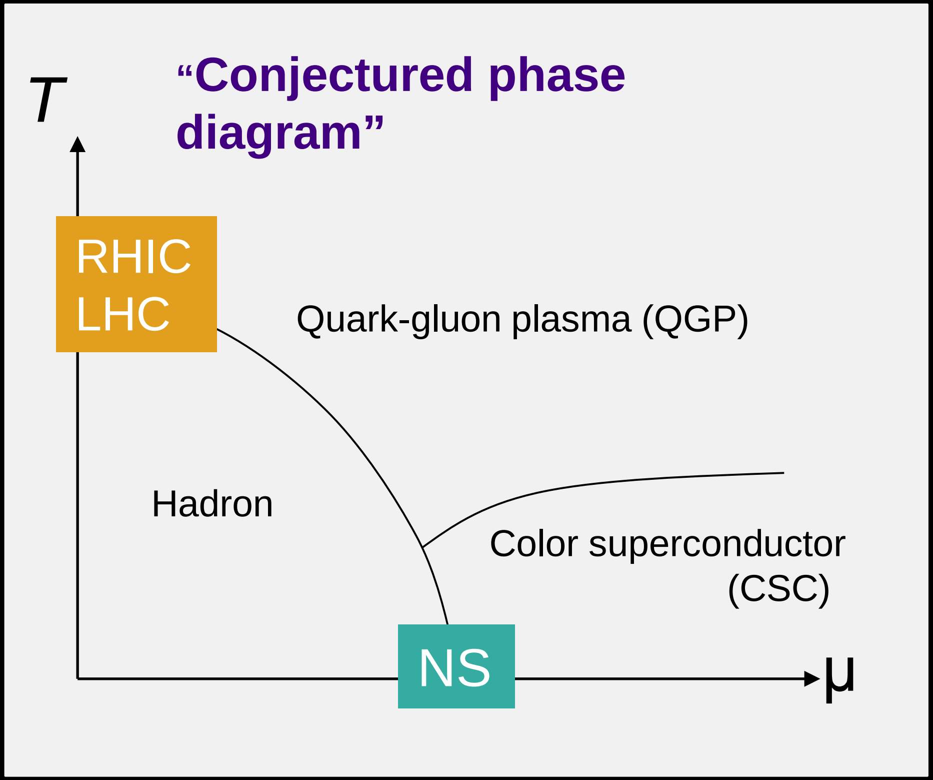
Condensed matter physics of QCD

Content

QCD@high temperature(T)/density(ρ)

[Collins-Perry (1975)]

QCD vacuum undergoes **a phase change** at some values of T and ρ!



Each phase characterized by

$\langle \bar{q}q \rangle$: chiral condensate

$\langle qq \rangle$: diquark condensate

”order parameters”

Dense QCD: Why so difficult ?

1. Lattice QCD: *tough*

   Violation of the positivity of the action (sign problem)

2. Experiment: *hard*

   Entropy production brings us to higher temperature regime

3. Supersymmetry: *hopeless*

   Nuclear world would be a very different place with bosonic quarks

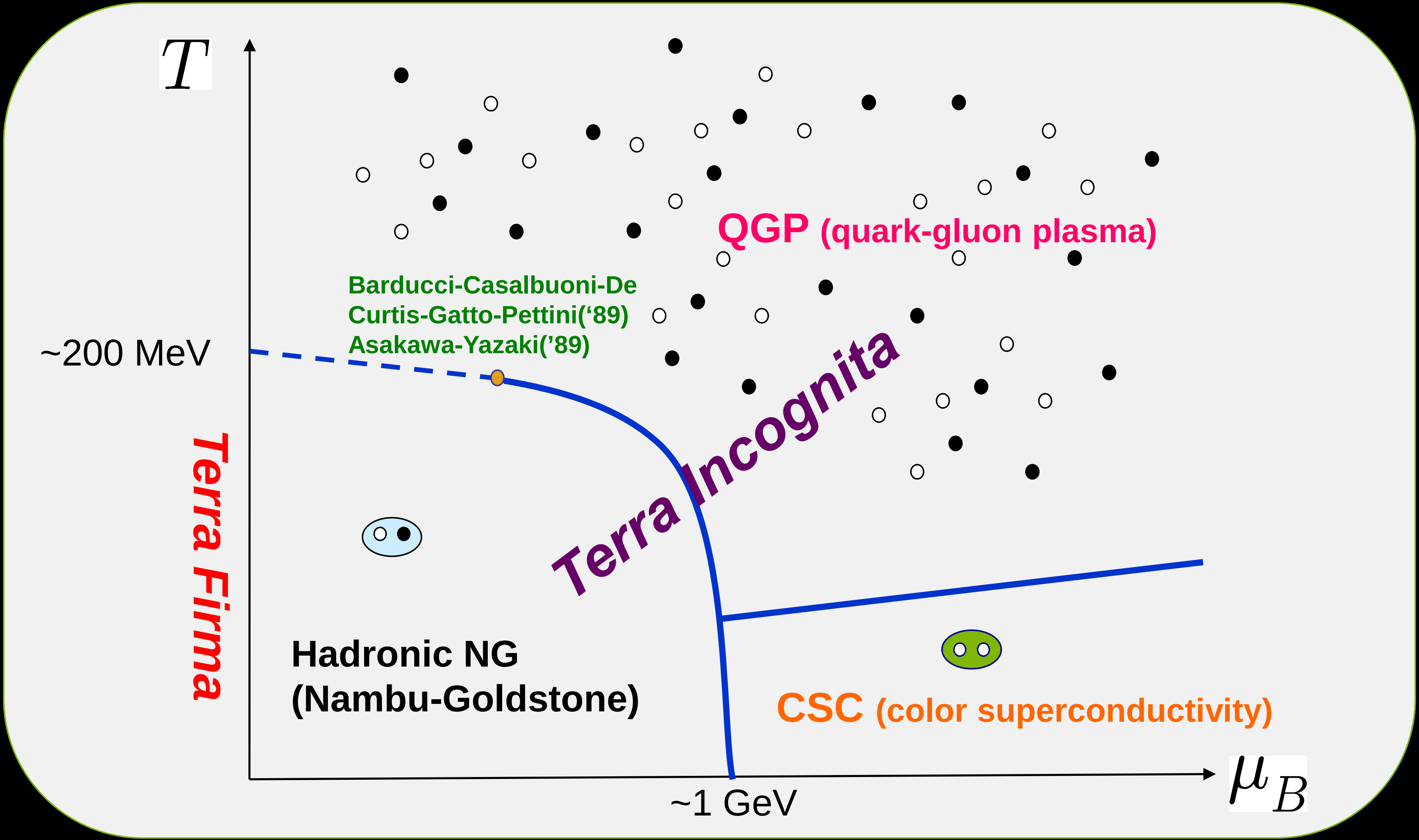
4. Quantum phase transition: *rich*

   Entanglement among different orders

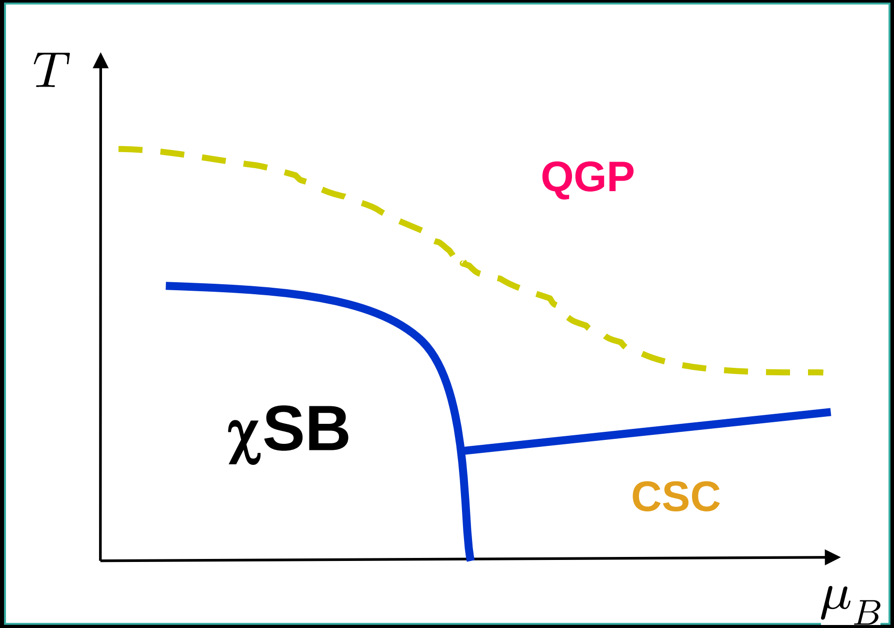
As some trial, see

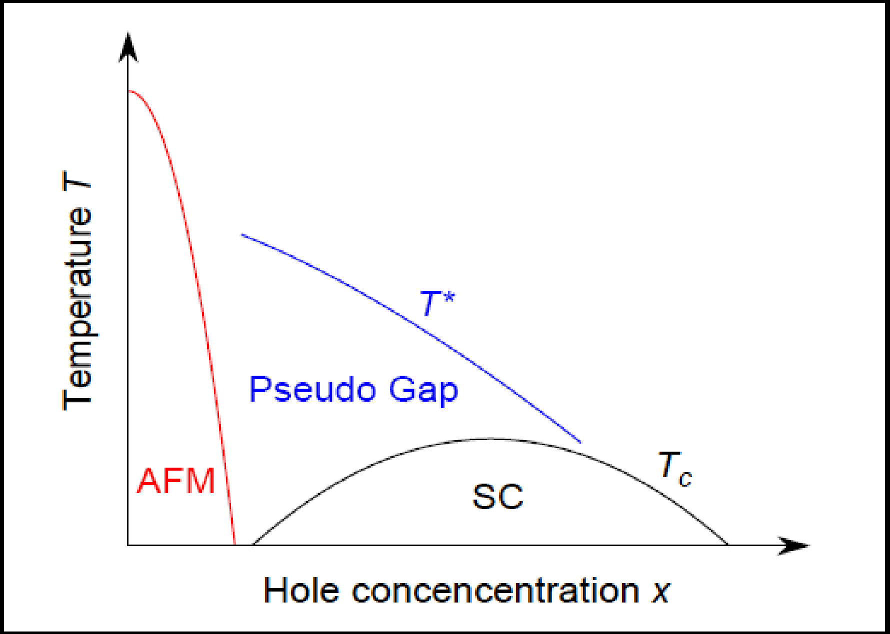
N. Maru and M. Tachibana,
“Color superconductivity from Supersymmetry”, hep-ph/0411079

A possible phase diagram (via Occam's razor)



Similarity between QCD and High T_c Superconductor





Common features in QCD, HTS, and ultracold atoms

1. Competition between different orders
2. Strong coupling

Content

Ginzburg-Landau (GL) analysis

Ginzburg-Landau (GL) approach : model independent, analytic

1. Topological structure of the phase diagram
2. Order of the phase transition
3. Critical properties

Recipe

$$Z = \int [d\sigma] \exp\left(-\int dx L_{eff}\left(\sigma(x);K\right)\right)$$

$\sigma(x)$: Order parameter field

$$L_{eff} = \frac{1}{2}(\nabla\sigma)^2 + \sum_n a_n(K)\sigma^n$$

Same symmetry with underlying theory

K = {*T*, *m*, *μ*, … } : External parameters

Ginzburg-Landau = Saddle point approximation

Wilson = Fluctuations by renormalization group method

Ginzburg-Landau study in dense QCD

$$SU(3)_C \times \left[SU(N_f)_L \times SU(N_f)_R \right] \times U(1)_B \times \cancel{U(1)_A}$$

Order parameters

Chiral field

$$\Phi_{ij} \sim \left(\bar{q}_R\right)^j_a \left(q_L\right)^i_a$$

$$\Phi \rightarrow e^{-2i\alpha_A} V_L \Phi V_R^+$$

Diquark field

$$\left(d_L\right)_{ia} \sim \varepsilon_{ijk}\varepsilon_{abc}\left(q_L\right)^j_b \left(q_L\right)^k_c$$

$$d_L \rightarrow e^{2i\alpha_A} e^{2i\alpha_B} V_L d_L V_C^T$$

Underlying sym. (QCD)

GL potential

$$\mathcal{V}(\Phi, d) = \mathcal{V}_\chi(\Phi) + \mathcal{V}_d(d_L, d_R) + \mathcal{V}_{\chi d}(\Phi, d_L, d_R)$$

Chiral part

$$\mathcal{V}_\chi = \frac{a_0}{2}\mathrm{tr}\ \Phi^\dagger\Phi + \frac{b_1}{4!}\left(\mathrm{tr}\ \Phi^\dagger\Phi\right)^2 + \frac{b_2}{4!}\mathrm{tr}\left(\Phi^\dagger\Phi\right)^2$$
$$\boxed{-\frac{c_0}{2}\left(\det\Phi + \det\Phi^\dagger\right),}$$

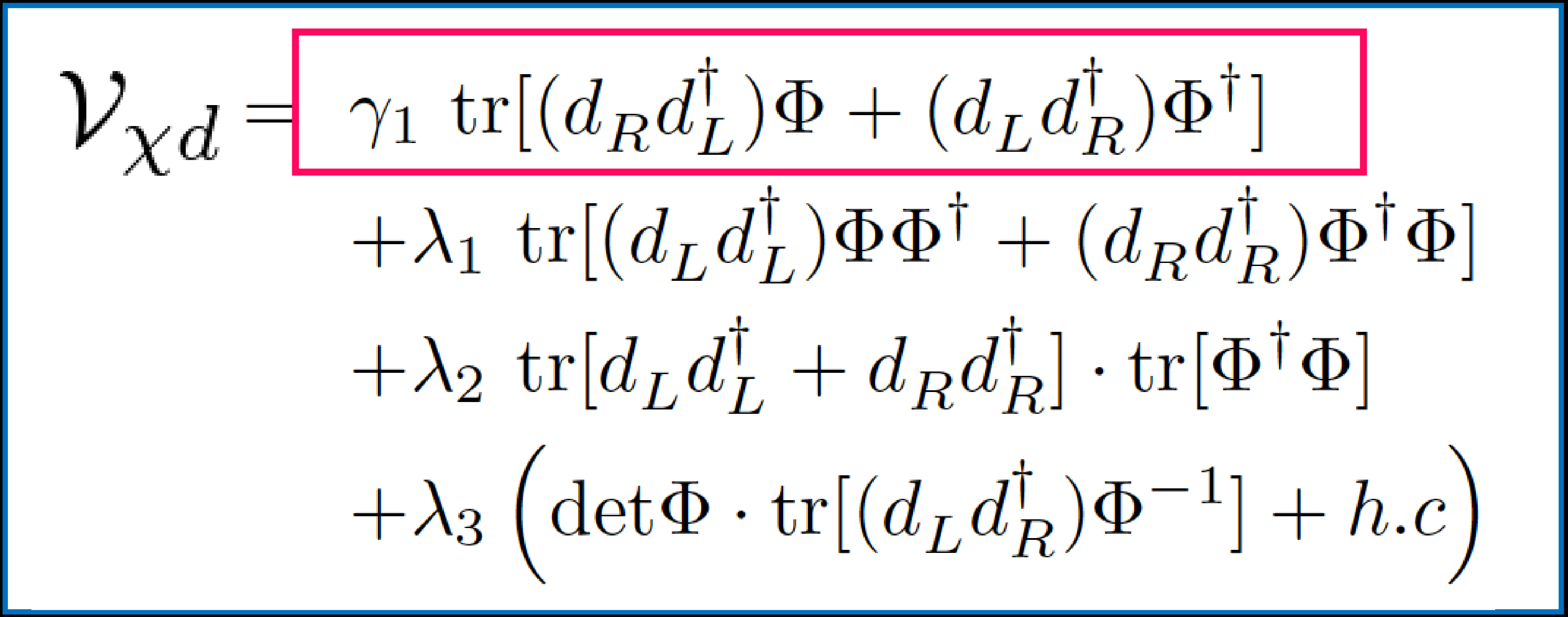
Pisarski-Wilczek (1984)

Diquark part

$$
\begin{aligned}
\mathcal{V}_d = \ & \alpha_0 \ \mathrm{tr}[d_L d_L^\dagger + d_R d_R^\dagger] \\
+ \ & \beta_1 \left([\mathrm{tr}(d_L d_L^\dagger)]^2 + [\mathrm{tr}(d_R d_R^\dagger)]^2 \right) \\
+ \ & \beta_2 \left(\mathrm{tr}[(d_L d_L^\dagger)^2] + \mathrm{tr}[(d_R d_R^\dagger)^2] \right) \\
+ \ & \beta_3 \ \mathrm{tr}[(d_R d_L^\dagger)(d_L d_R^\dagger)] + \beta_4 \ \mathrm{tr}(d_L d_L^\dagger)\mathrm{tr}(d_R d_R^\dagger)
\end{aligned}
$$

Iida-Baym (2000)

Interplay part

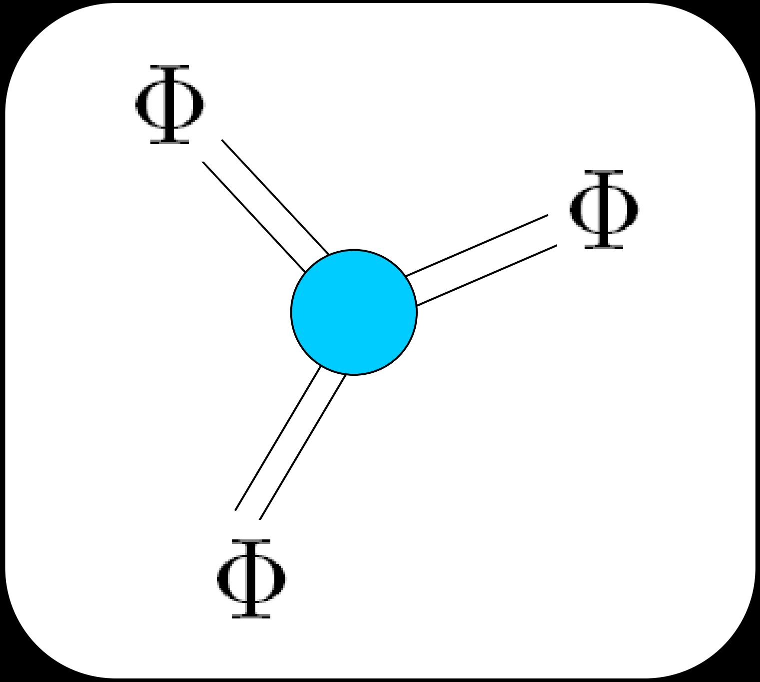


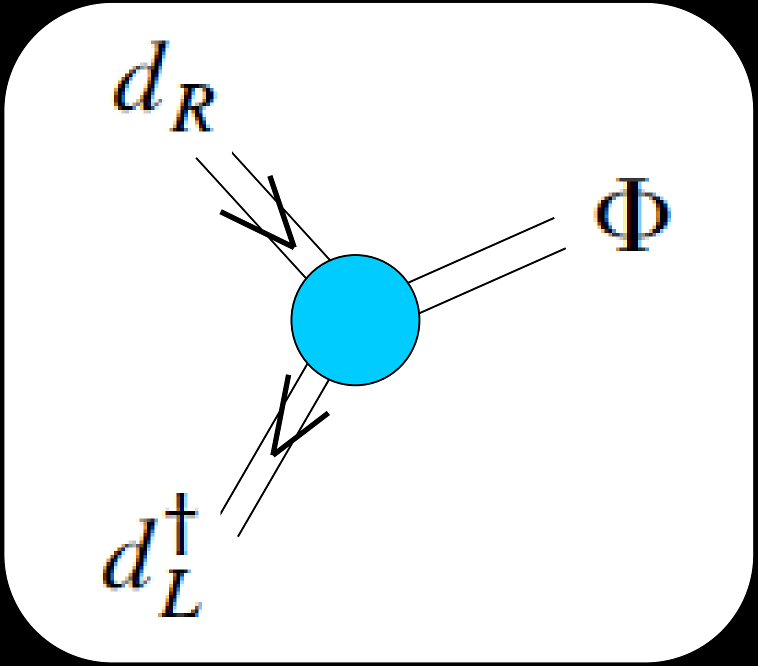
$$\begin{aligned}\mathcal{V}_{\chi d} = & \boxed{\gamma_1 \ \mathrm{tr}[(d_R d_L^\dagger)\Phi + (d_L d_R^\dagger)\Phi^\dagger]} \\ & +\lambda_1 \ \mathrm{tr}[(d_L d_L^\dagger)\Phi\Phi^\dagger + (d_R d_R^\dagger)\Phi^\dagger\Phi] \\ & +\lambda_2 \ \mathrm{tr}[d_L d_L^\dagger + d_R d_R^\dagger] \cdot \mathrm{tr}[\Phi^\dagger\Phi] \\ & +\lambda_3 \left(\det\Phi \cdot \mathrm{tr}[(d_L d_R^\dagger)\Phi^{-1}] + h.c\right)\end{aligned}$$

Hatsuda-Tachibana-Yamamoto-Baym (2006)

Kobayashi-Maskawa-’tHooft (KMT) interaction

Axial anomaly





2 possible ways of contracting
6-q KMT vertex in dense QCD

A simple ansatz for condensate fields

3-flavor massless quark matter $\left(m_u = m_d = m_s = 0\right)$

$$\Phi = \begin{pmatrix} \sigma & & \\ & \sigma & \\ & & \sigma \end{pmatrix} \qquad d_L = -d_R = \begin{pmatrix} d & & \\ & d & \\ & & d \end{pmatrix}$$

Color-Flavor Locking (CFL)

Alford-Rajagopal-Wilczek (1998)

$$\left\langle q_a^i C\gamma_5 q_b^j \right\rangle = \varepsilon_{abc}\varepsilon^{ijk}\left(d_L\right)_k^c \propto \varepsilon_{abA}\varepsilon^{ijA} = \delta_a^i\delta_b^j - \delta_a^j\delta_b^i$$

$$SU(3)_c \times SU(3)_L \times SU(3)_R \to SU(3)_{c+L+R}$$

CFL breaks chiral symmetry!

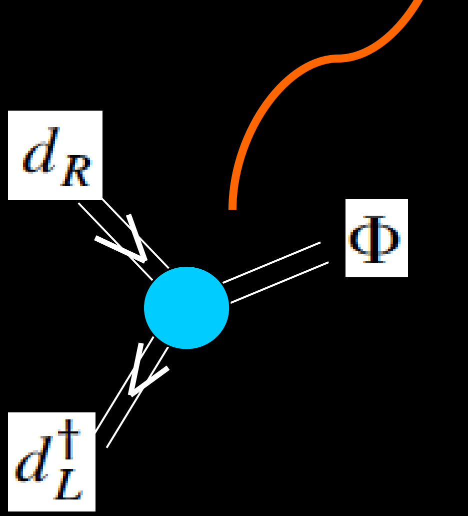
Srednicki-Susskind (1981)

$$\Omega_{3F} = \left(\frac{a}{2}\sigma^2 - \frac{c}{3}\sigma^3 + \frac{b}{4}\sigma^4\right) + \left(\frac{\alpha}{2}d^2 + \frac{\beta}{4}d^4\right) - \gamma d^2\sigma$$

σ : Chiral condensate

d : Diquark condensate (CFL)

$a, b, c, \alpha, \beta, \gamma$: GL parameters



Possible phases

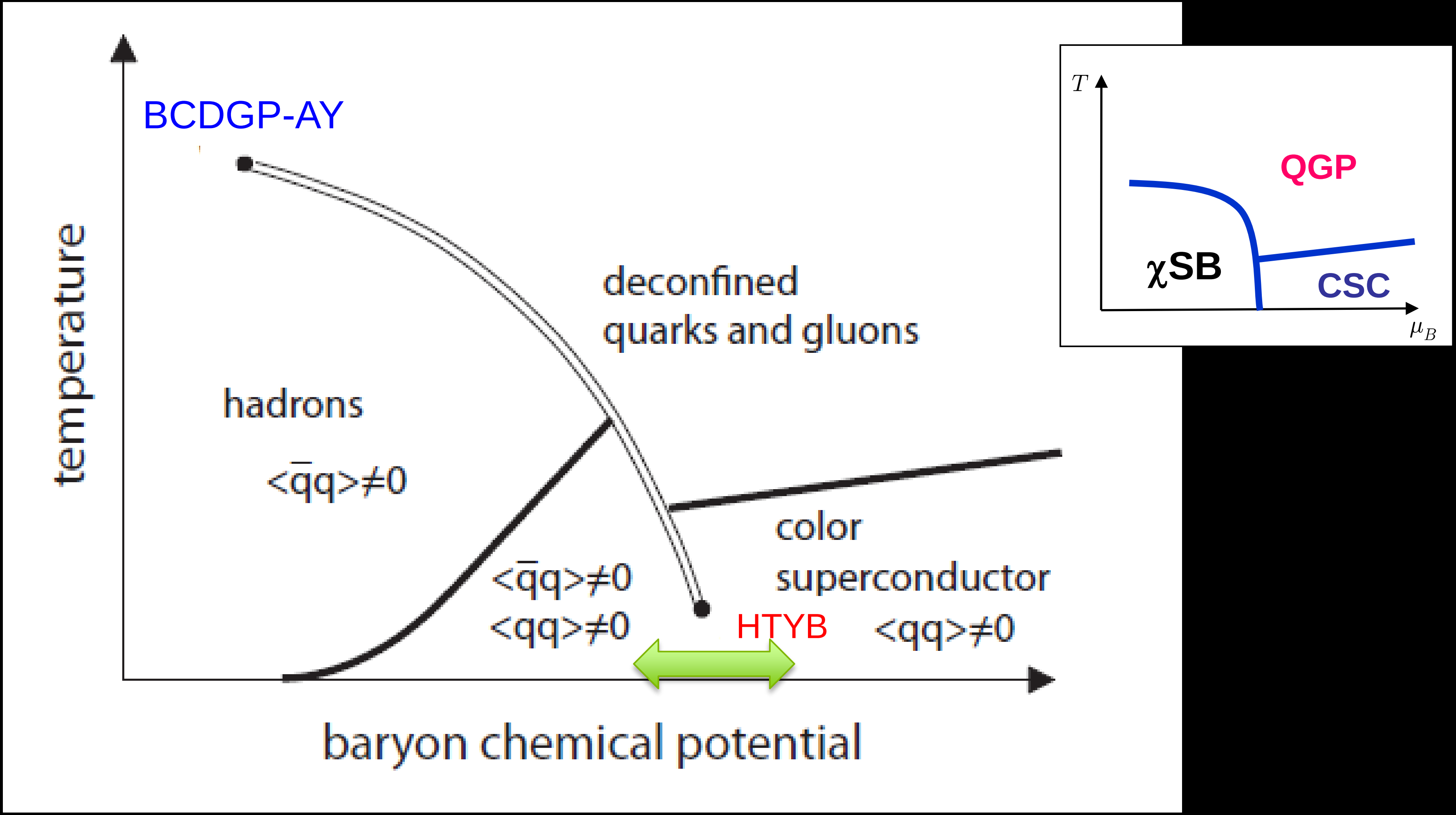
$\sigma = d = 0$	NOR
$\sigma \neq 0$	NG
$d \neq 0$	CSC
$\sigma \neq 0, d \neq 0$	COE

- *d ,$\sigma \neq 0$ is favored*
- *ext. source for σ*

Equivalent to Ising-ferro !

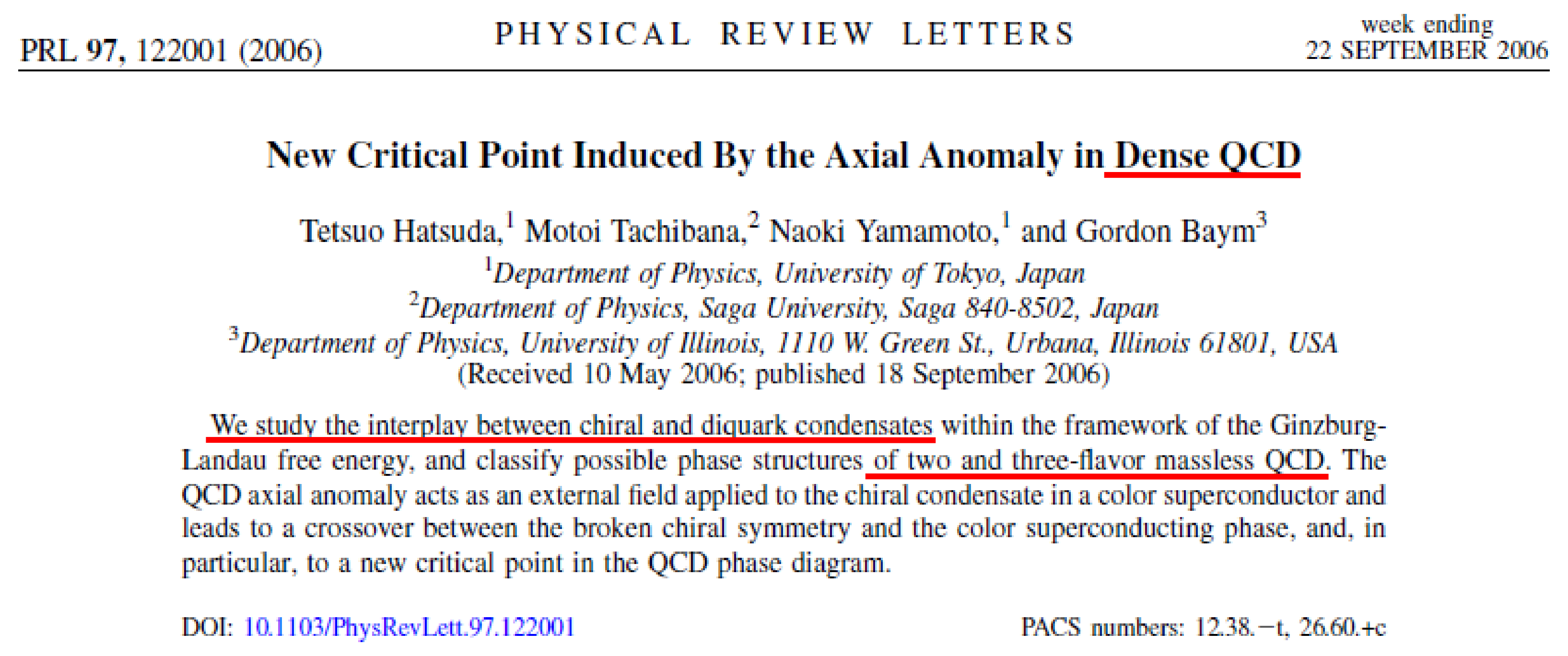
Critical point !

Possible phase diagram in QCD



"Anomaly-induced critical point in dense QCD"

Hatsuda, Tachibana, Yamamoto & Baym, PRL('06)



PRL **97,** 122001 (2006) PHYSICAL REVIEW LETTERS week ending 22 SEPTEMBER 2006

New Critical Point Induced By the Axial Anomaly in Dense QCD

Tetsuo Hatsuda,[1] Motoi Tachibana,[2] Naoki Yamamoto,[1] and Gordon Baym[3]
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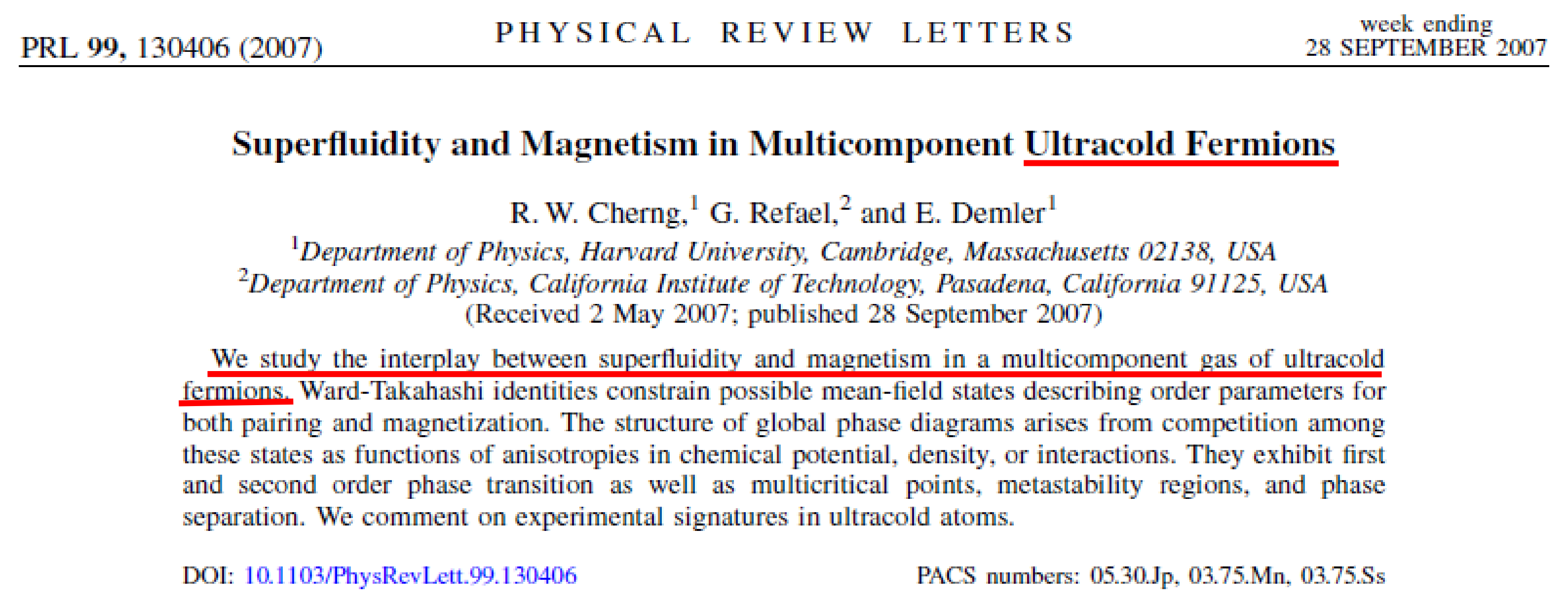
(Received 10 May 2006; published 18 September 2006)

We study the interplay between chiral and diquark condensates within the framework of the Ginzburg-Landau free energy, and classify possible phase structures of two and three-flavor massless QCD. The QCD axial anomaly acts as an external field applied to the chiral condensate in a color superconductor and leads to a crossover between the broken chiral symmetry and the color superconducting phase, and, in particular, to a new critical point in the QCD phase diagram.

DOI: 10.1103/PhysRevLett.97.122001 PACS numbers: 12.38.−t, 26.60.+c



PRL **99,** 130406 (2007) PHYSICAL REVIEW LETTERS week ending 28 SEPTEMBER 2007

Superfluidity and Magnetism in Multicomponent Ultracold Fermions

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(Received 2 May 2007; published 28 September 2007)

We study the interplay between superfluidity and magnetism in a multicomponent gas of ultracold fermions. Ward-Takahashi identities constrain possible mean-field states describing order parameters for both pairing and magnetization. The structure of global phase diagrams arises from competition among these states as functions of anisotropies in chemical potential, density, or interactions. They exhibit first and second order phase transition as well as multicritical points, metastability regions, and phase separation. We comment on experimental signatures in ultracold atoms.

DOI: 10.1103/PhysRevLett.99.130406 PACS numbers: 05.30.Jp, 03.75.Mn, 03.75.Ss

Content

§1. Introduction

§2. QCD at finite baryon density

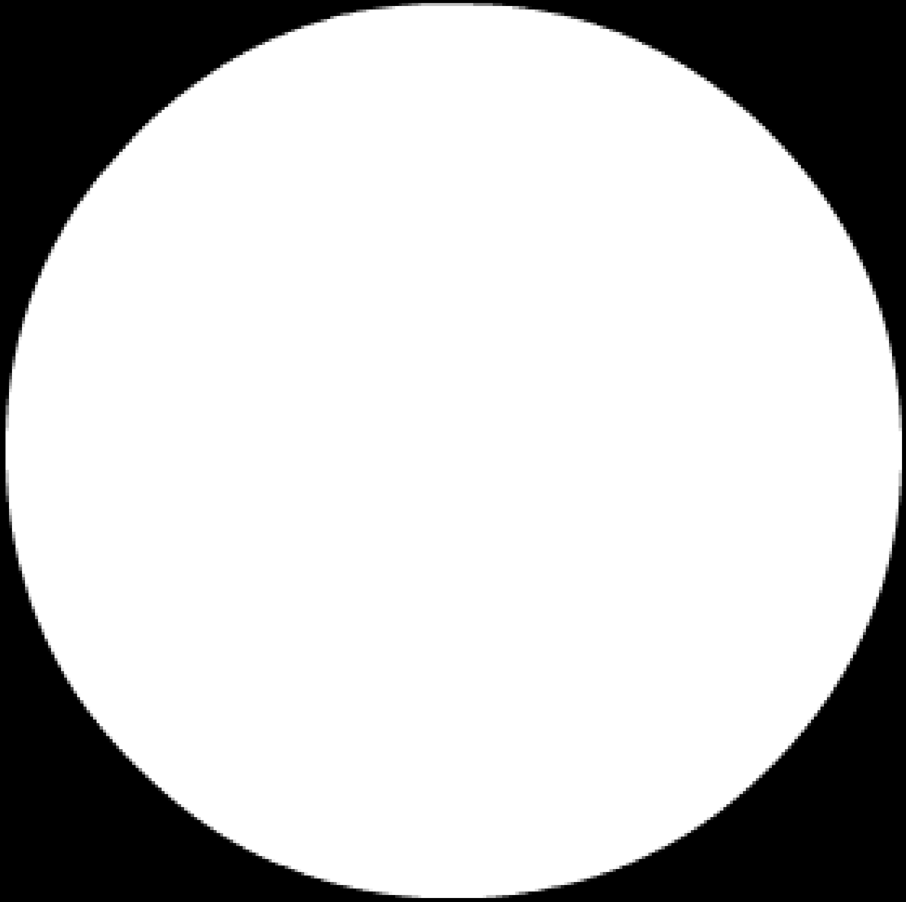
§3. Ginzburg-Landau study in dense QCD

§4. Astrophysical application

§5. Summary

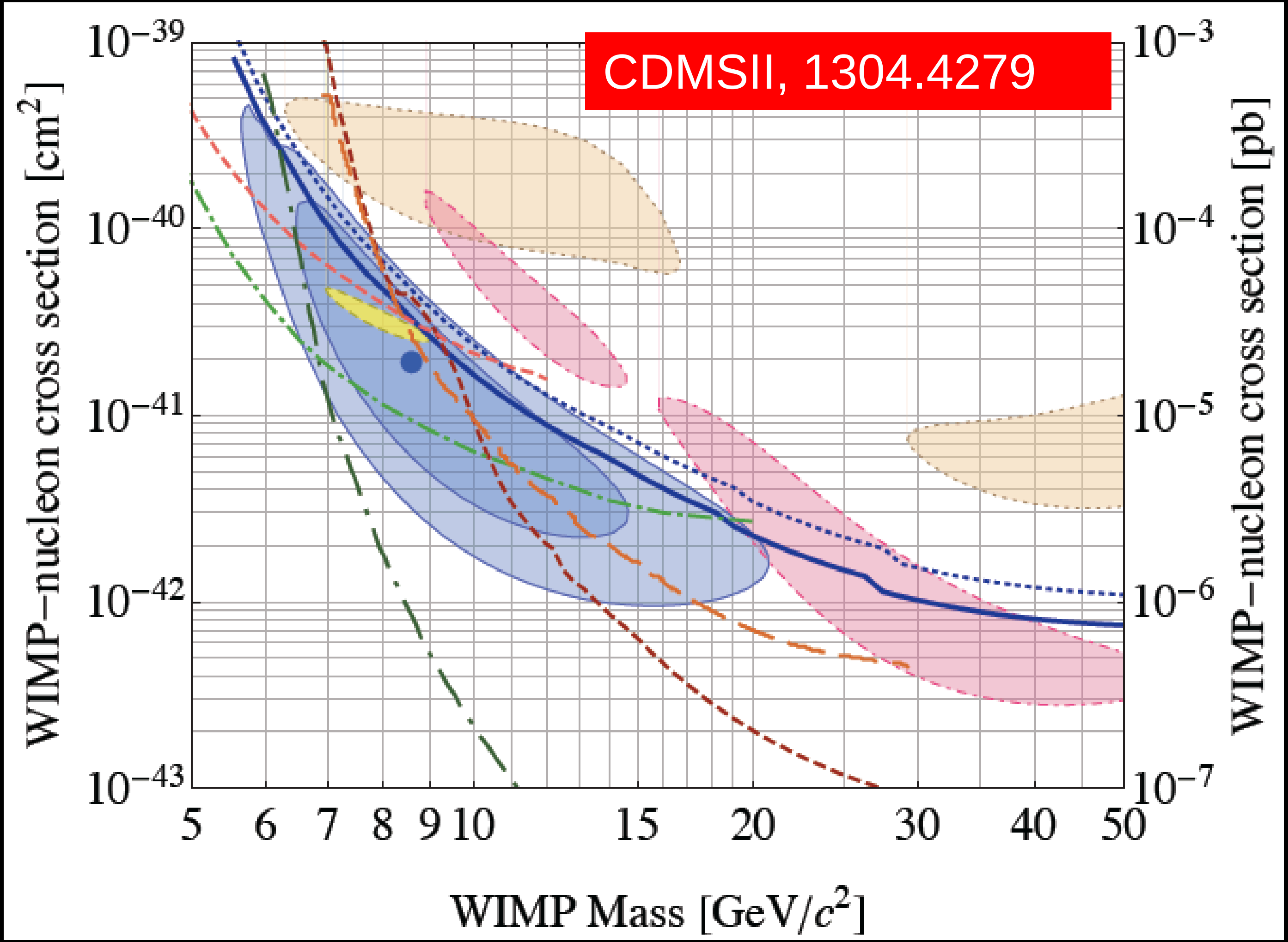
Dark matter capture

in neutron stars



Why the connection between DM and NS?

Possibly constraining WIMP-DM properties via NS



Impacts of dark matter on NS

- NS mass-radius relation with dark matter EOS
- NS heating via dark matter annihilation

:

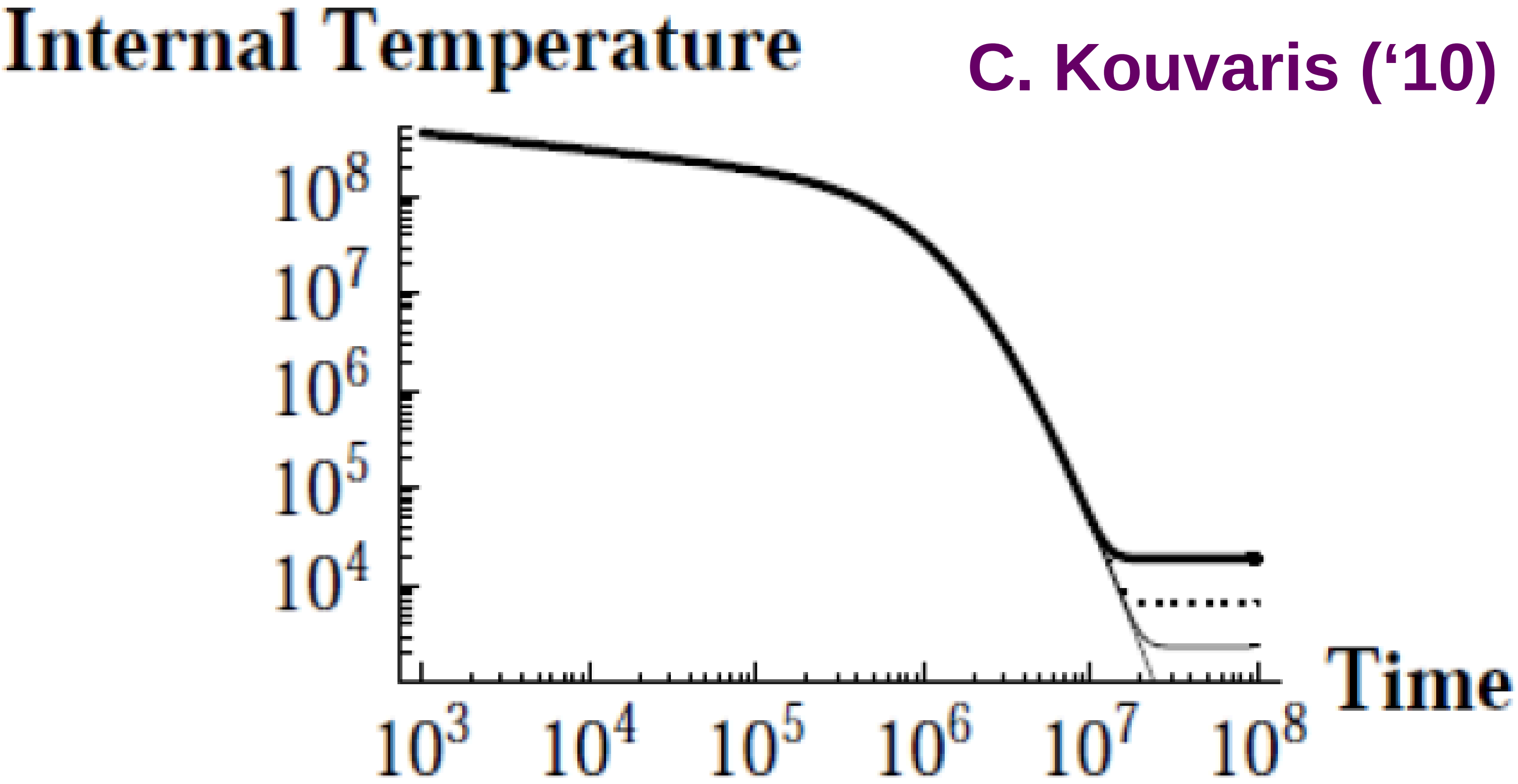
- Dark matter capture in NS and formation of black-hole to collapse host neutron stars

cf) This is not so a new idea. People have considered the DM capture by Sun and the Earth since 80's.

cosmion W. Press and D. Spergel (1984)

Application to NS : Goldman-Nussinov (1989)

Cooling curves of Neutron Star



C. Kouvaris ('10)

(1) Accretion of DM

$$\frac{dN_\chi}{dt} = C_B(N_\chi) \quad C_B : DM\ capture\ rate$$

(1) Thermalization of DM (energy loss)

$$\frac{dE}{dt} = -\xi n_B \sigma_{N\chi} v \delta E \quad \sigma_{N\chi} : DM - nucleon\ cross\ section$$

(2) BH formation and destruction of host NS

$$\frac{N_{self} m_\chi}{4\pi r_{th}^3 / 3} = \rho_B \quad r_{th} : thermal\ radius$$

condition of
self-gravitation

Capturable number of DMs in NS

$$\frac{dN_\chi}{dt} = C_{\chi N} + C_{\chi\chi} N_\chi - C_{\chi a} N_\chi^2$$

Capture rate due to DM-nucleon scattering

Self-capture rate due to DM-DM scattering

DM self-annihilation rate

$C_{\chi\chi} = C_{\chi a} = 0$ (no self-capture/annihilation)

$$N_{\chi} = C_{\chi N} t$$

Just linearly grows and $C_{\chi N}$ the growth rate.

Realized when DM carries a conserved charge,

analogous to baryon number.

Below we consider this case

① DM capture rate

The accretion rate (A. Gould, 1987)

$$C_{\chi N} = 4\pi \int_0^{R_n} r^2 \frac{dC_{\chi N}(r)}{dV} dr$$

neutron-DM elastic cross section

$$\frac{dC_{\chi N}(r)}{dV} = \sqrt{\frac{6}{\pi}}\, n_\chi(r) n_B(r) \xi \frac{v(r)^2}{\bar{v}^2} (\bar{v}\sigma_{N\chi}) \left[1 - \frac{1-e^{-B^2}}{B^2}\right]$$

$n_\chi(r) : DM\ \ density \quad n_B(r) : baryon\ density$

$\bar{v} = 220\, km/s : DM\ \ velocity \quad v(r) : escape\ velocity$

$$B^2 = \frac{3}{2}\frac{v(r)^2}{\bar{v}^2}\frac{4\mu}{(\mu-1)^2}, \quad \mu = \frac{m_\chi}{m_B}, \quad m_r = \frac{m_\chi m_B}{m_\chi + m_B}$$

② Thermalization of DM

After the capture, DMs lose energy via scattering with neutrons and eventually get thermalized

DM mass ≦ 1GeV,

$$t_{th} \approx 7.7\times10^{-5} yrs \left(\frac{2.1\times10^{-45}cm^2}{\sigma_{N\chi}}\right)\left(\frac{0.1GeV}{m_\chi}\right)\left(\frac{10^5K}{T}\right)$$

DM mass ≧ 1GeV,

$$t_{th} \approx 0.054 yrs \left(\frac{2.1\times10^{-45}cm^2}{\sigma_{N\chi}}\right)\left(\frac{m_\chi}{100GeV}\right)^2\left(\frac{10^5K}{T}\right)$$

③ Self-gravitation of DM

Then, the DM gets self-gravitating once the total # of DM particles is larger than a critical value

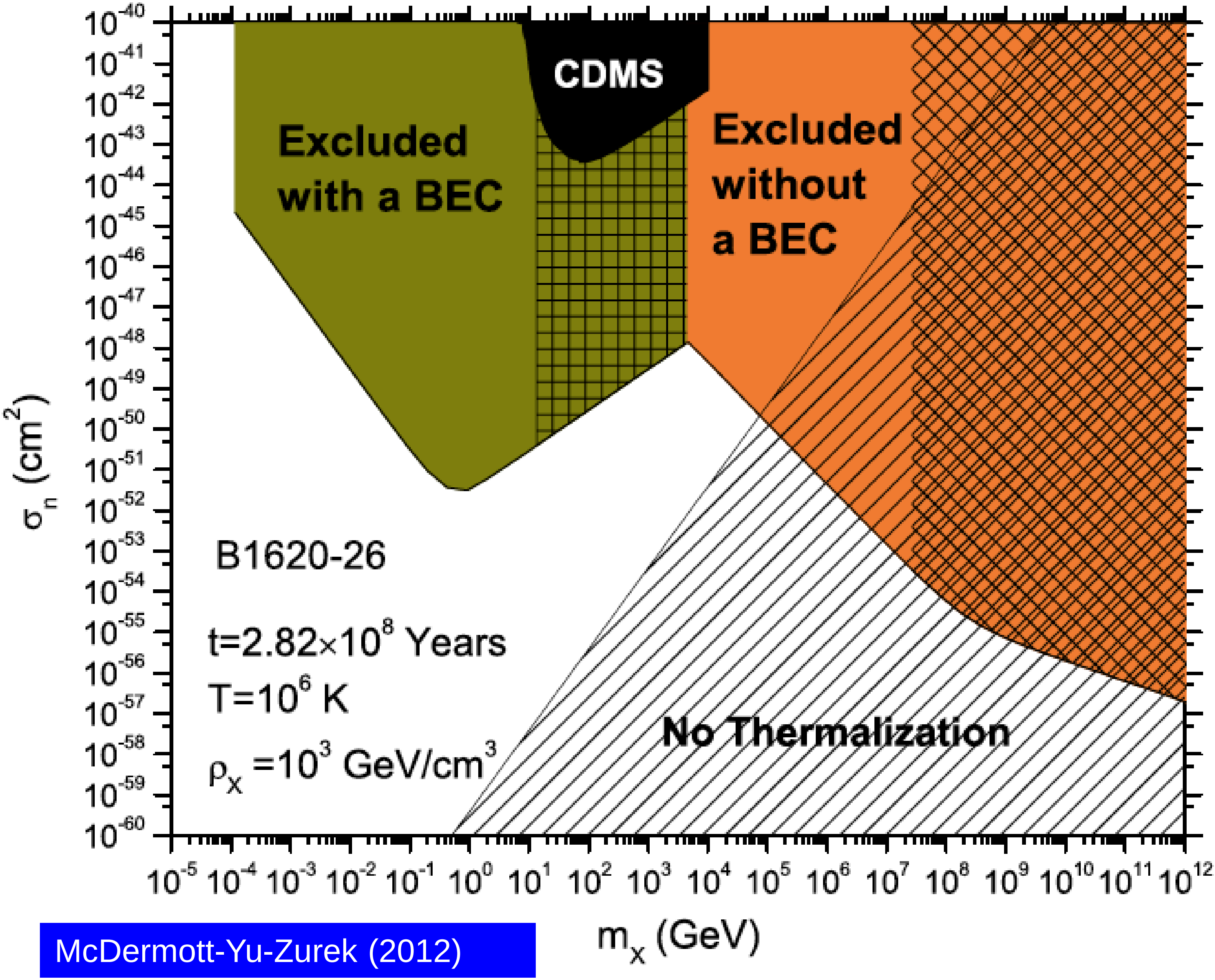
$$\frac{GN_{\chi}m_{\chi}^{2}}{r} > \frac{4\pi G\rho_{B}m_{\chi}}{3}r^{2}$$

$$\Rightarrow \qquad \frac{N_{self}m_{\chi}}{4\pi r_{th}^{3}/3} = \rho_{B}$$

If this condition is met, gravitational collapse takes place.

Condition

$$N_{\chi} < N_{self}$$



McDermott-Yu-Zurek (2012)

However…

Hadrons inside NS are in EXTREME,
and exotic matter states could appear.

(e.g.) neutron superfluidity
meson condensation
quark superconductivity

What if those effects are incorporated?

Some work in progress

w/ T. Hatsuda

① DM thermalization

(Ref.) Bertoni-Nelson-Reddy (2013)

Hyperon degrees of freedom?

② NS mass-radius relation

(Ref.) Ciarcelluti-Sandin (2011)

TOV eq. w/ dark star core

Summary

Stellar constraints on dark matter properties

Dark matter capture in neutron stars
--Accretion, thermalization and BH formation—

Models for DM, but not considering NS seriously

Proposal of medium effects for hadrons in NS
--modified vacuum structures and collective modes--

DM study via NS is interesting!

Summary

Study of dense QCD matter

1. Dense QCD world as “Terra Incognita”
2. Ginzburg-Landau study in dense QCD
3. A realization of quark-hadron continuity

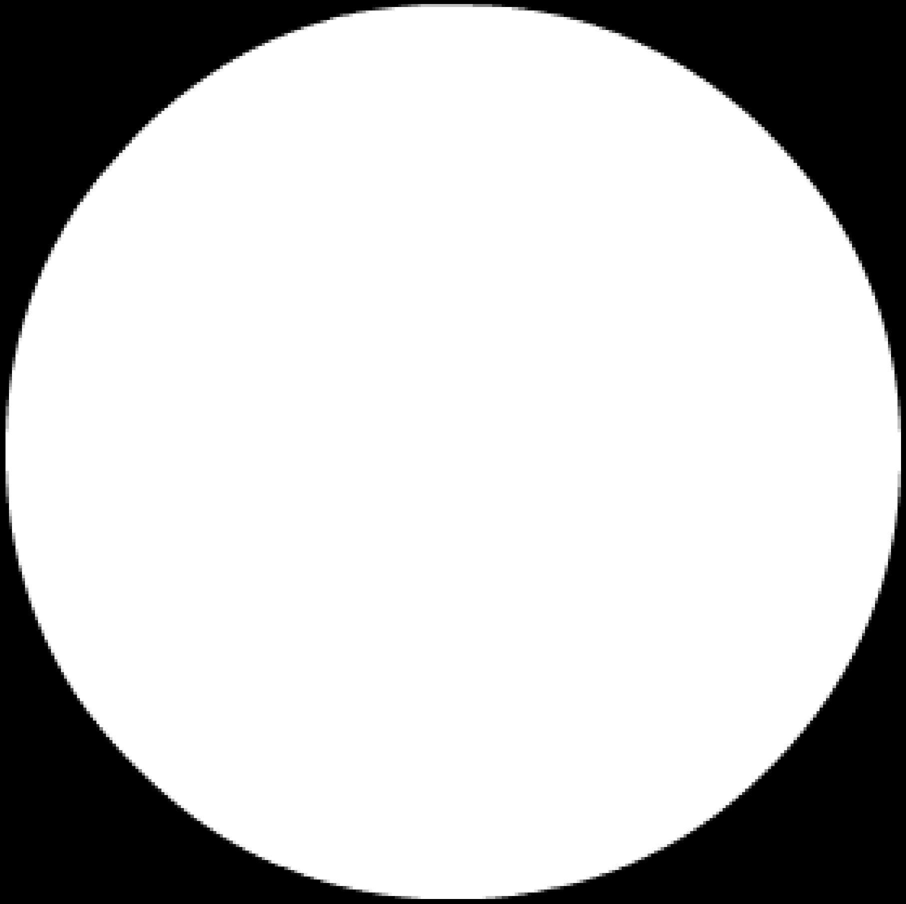
Astrophysical applications of dense matter

1. Neutron star(NS) as our “laboratory”
2. Recent topic for the NS observations
3. Vortex dynamics of CFL quark matter

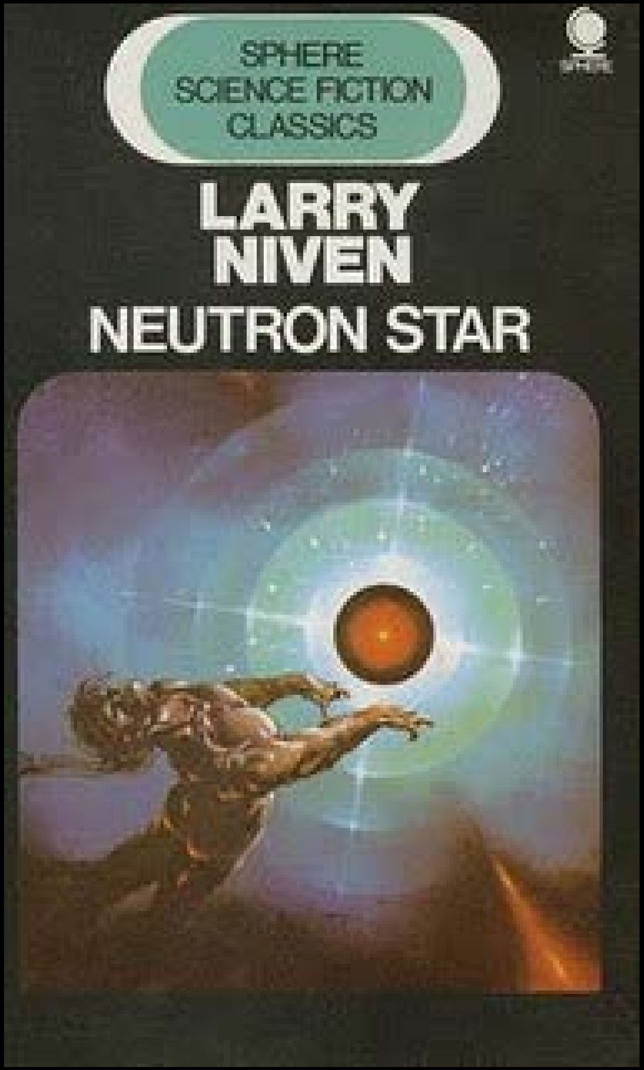
Thank you！

感謝

Summary Anime



What is Neutron Star ?



Ask our Maestro, Wikipedia

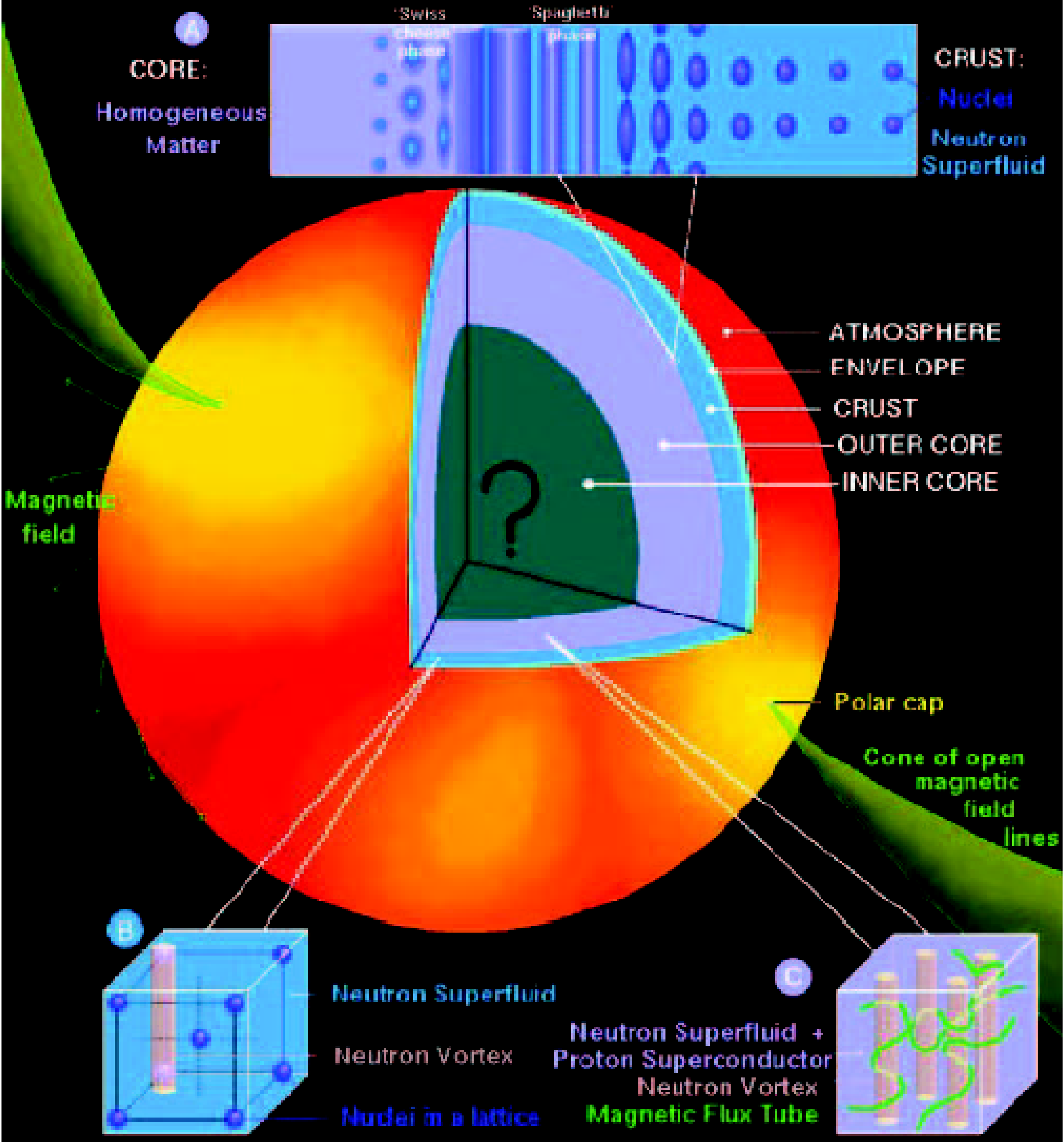
- A stellar remnant after supernova explosion
- Literally, composed almost entirely of neutrons
- Its density is approximately equivalent to the human population condensed to the size of a sugar cube.

something extraordinary

Major questions

1. How to be born and evolve?
2. Why so compact?
3. Why so huge magnetic field?
4. Why so rapidly rotating?

A NEUTRON STAR: SURFACE and INTERIOR



Oh, yes! We love Exotica!

New states of matter present in NS !

Superfluid neutron/Supercond. Proton

Bose-Einstein condensate (BEC) of mesons

Hyperons (hadrons w/ strangeness)

Deconfined quarks

Neutron star = *laboratories* for
studying matter in extreme!

We can even sing Neutron Star!

Our hearts combined like a neutron star collision

Let’s karaoke!

Study of QCD matter

QCD Lagrangian

(Han-Nambu, 1965)

$$L_{QCD} = \bar{q}^{\alpha}\left(i\gamma_{\mu}D^{\mu} \quad \right)_{\alpha\beta} q^{\beta} - \frac{1}{4}F^{a}_{\mu\nu}F^{a\mu\nu}$$

We love QCD ♥

Simple, bu ery fertile in physics and math.

Providing testing field for any new idea.

Unsolved problems (inexhaustible spring)

A memory of Prof. Nambu

- In 2003, I gave a seminar in front of Nambu san and some other people including Yanagida san.
- That was the most exciting talk I’ve ever had.
- After the seminar, we went lunch and there, Yanagida san asked Nambu san why he could identify pion as the Nambu-Goldstone boson.
- After some time, he replied “I intuitively thought so from the mass ratio btw pion and nucleons.”

A child-like question

What happens to matter,
as we make it hotter and hotter
an ?

Phases of QCD

Dense QCD: Why so difficult ?

1. Lattice QCD: *tough*

   Violation of the positivity of the action (sign problem)

2. Experiment: *hard*

   Entropy production brings us to higher temperature regime

3. Supersymmetry: *hopeless*

   Nuclear world would be a very different place with bosonic quarks

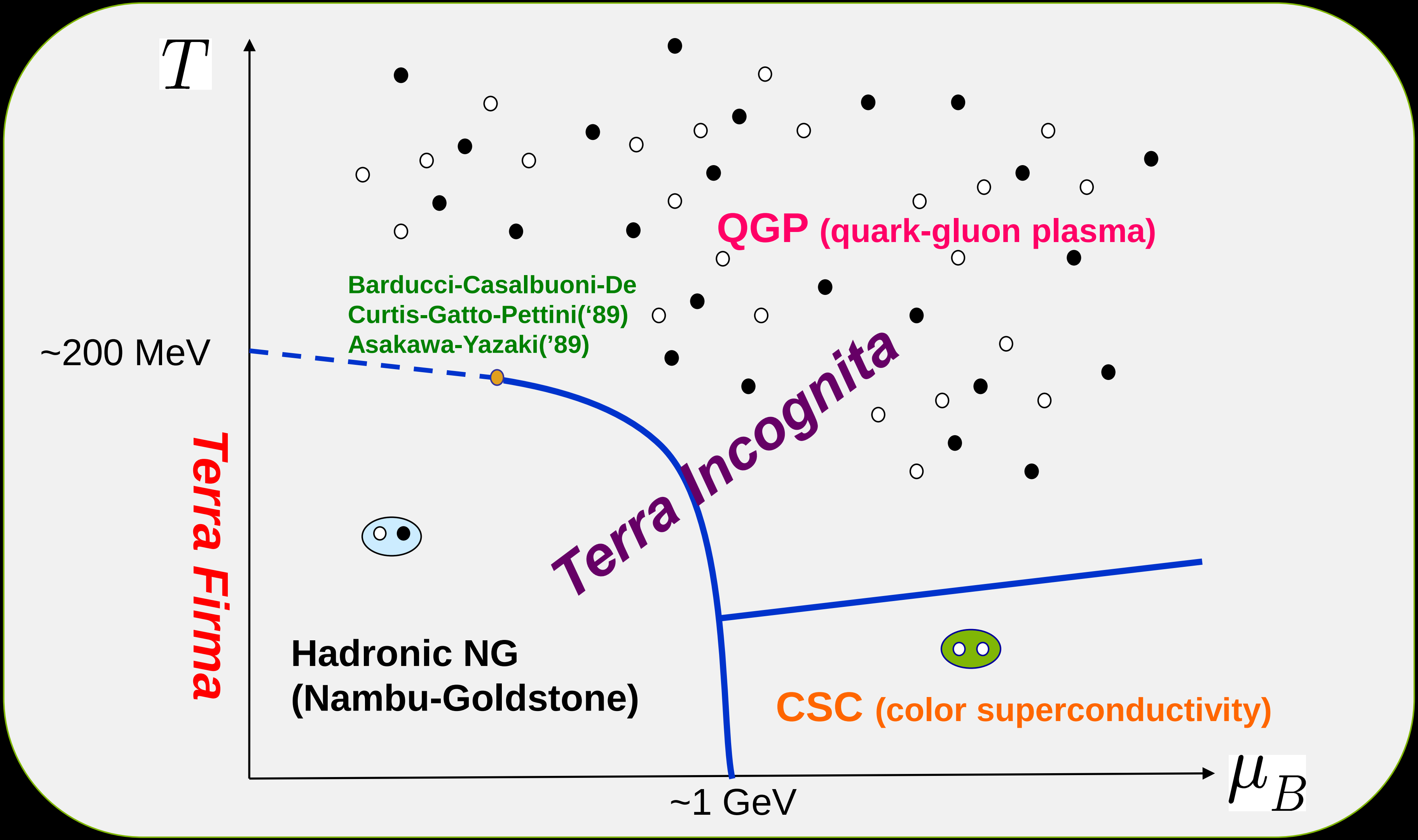
4. Quantum phase transition: *rich*

   Entanglement among different orders

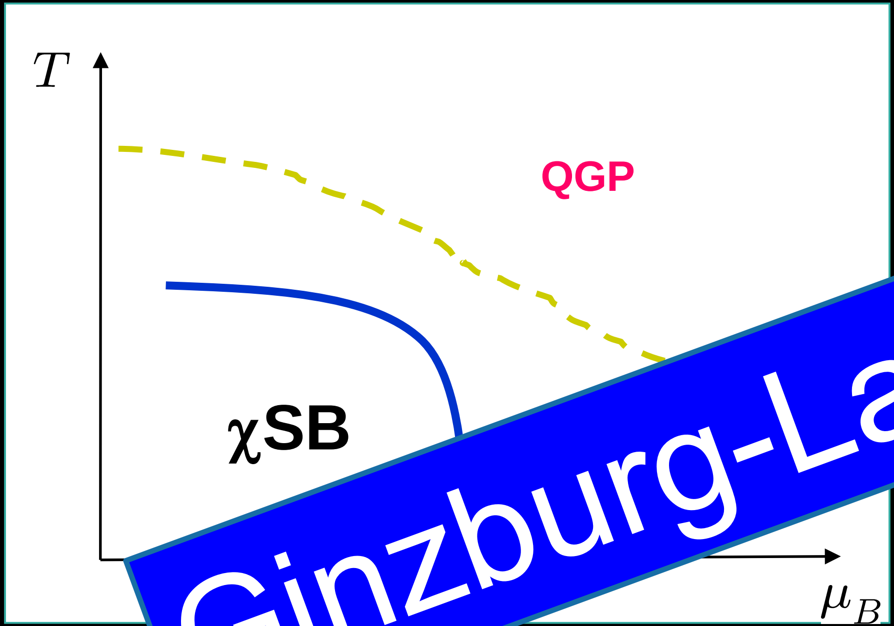
As some trial, see

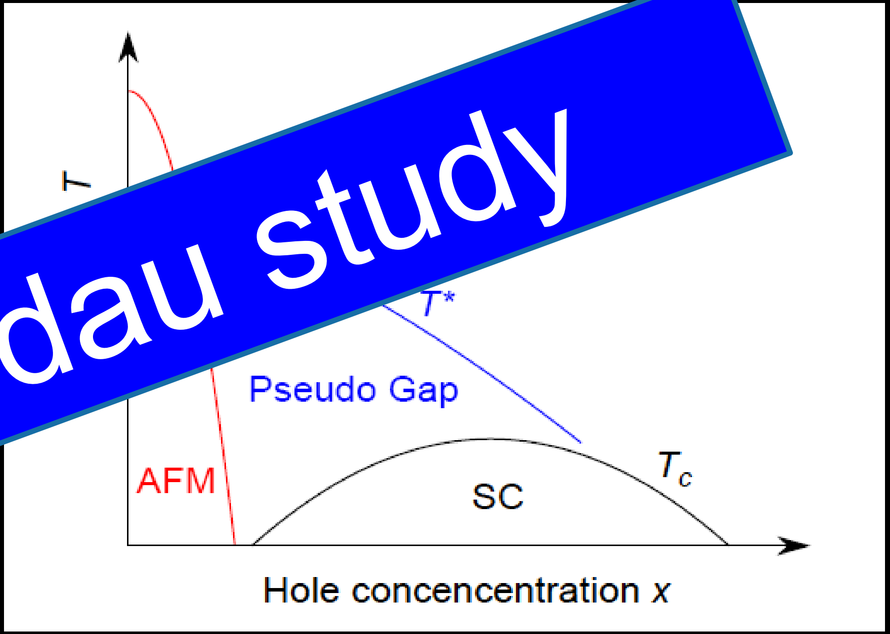
N. Maru and M. Tachibana,
"Color superconductivity from Supersymmetry", hep-ph/0411079

A possible phase diagram (via Occam's razor)



Similarity between QCD and High T_c Superconductor





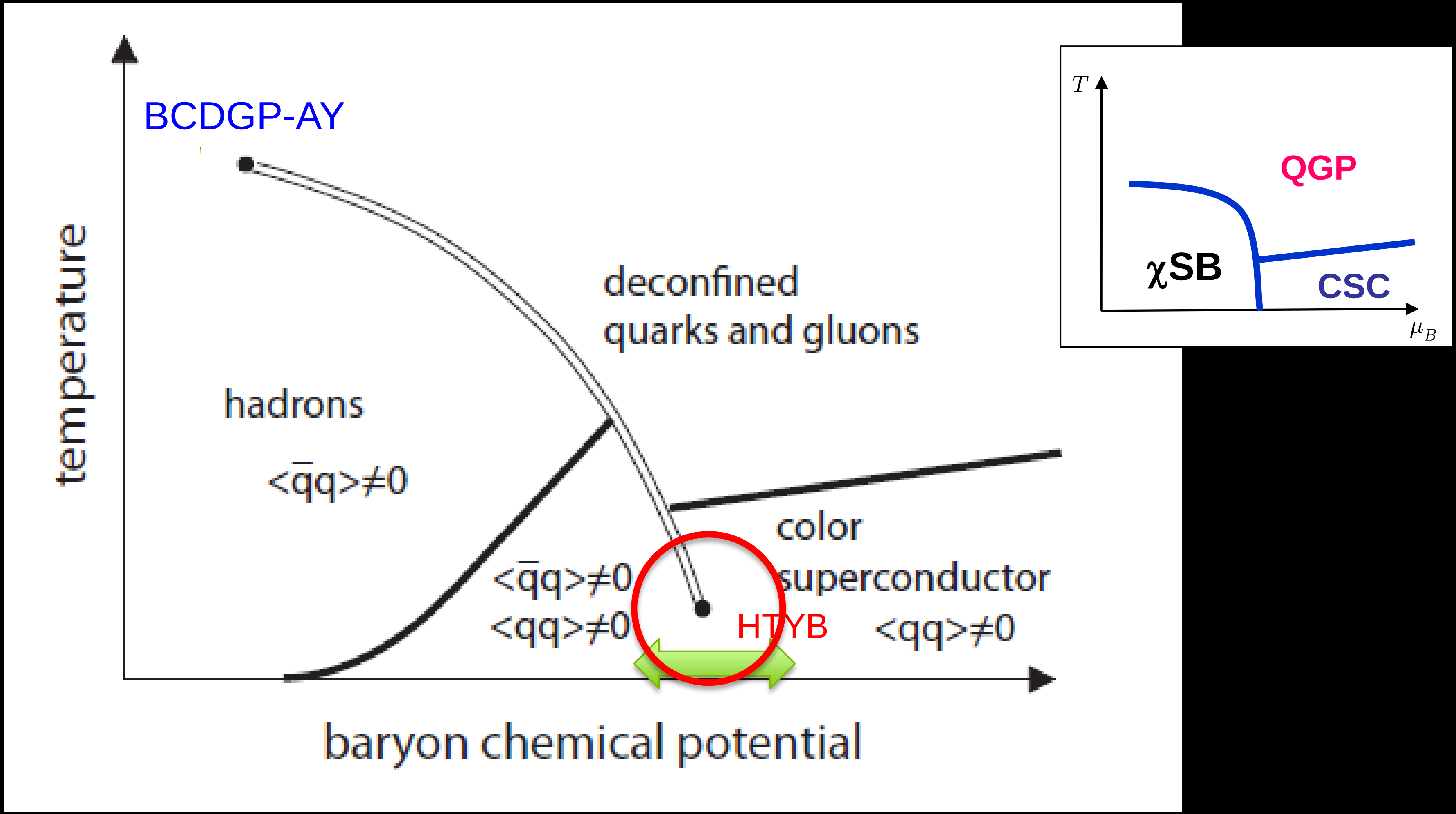
Ginzburg-Landau study

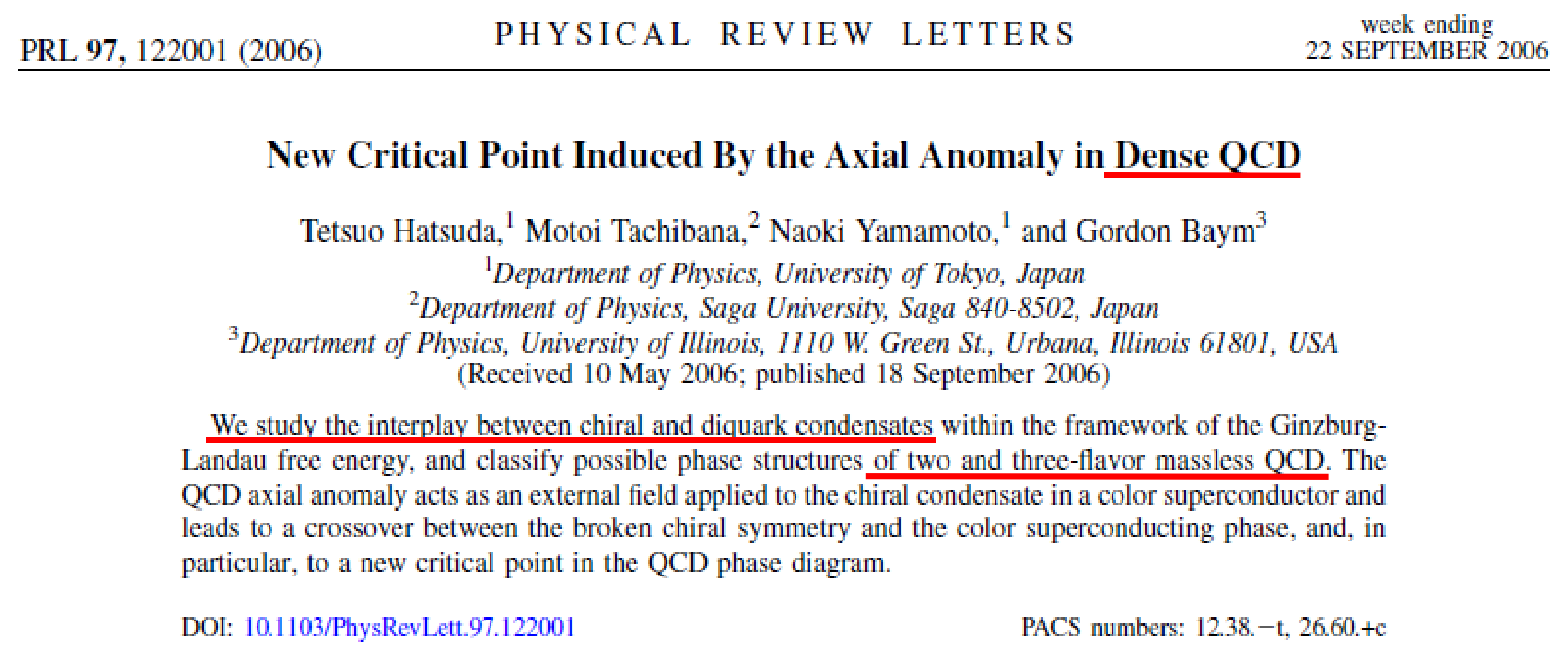
Common features in QCD, HTS, and ultracold atoms

1. Competition between different orders
2. Strong coupling

“Anomaly-induced critical point in dense QCD”

Hatsuda, Tachibana, Yamamoto & Baym, PRL(’06)





PRL **97,** 122001 (2006) PHYSICAL REVIEW LETTERS week ending
22 SEPTEMBER 2006

New Critical Point Induced By the Axial Anomaly in Dense QCD

Tetsuo Hatsuda,[1] Motoi Tachibana,[2] Naoki Yamamoto,[1] and Gordon Baym[3]
[1]*Department of Physics, University of Tokyo, Japan*
[2]*Department of Physics, Saga University, Saga 840-8502, Japan*
[3]*Department of Physics, University of Illinois, 1110 W. Green St., Urbana, Illinois 61801, USA*
(Received 10 May 2006; published 18 September 2006)

We study the interplay between chiral and diquark condensates within the framework of the Ginzburg-Landau free energy, and classify possible phase structures of two and three-flavor massless QCD. The QCD axial anomaly acts as an external field applied to the chiral condensate in a color superconductor and leads to a crossover between the broken chiral symmetry and the color superconducting phase, and, in particular, to a new critical point in the QCD phase diagram.

DOI: 10.1103/PhysRevLett.97.122001 PACS numbers: 12.38.−t, 26.60.+c

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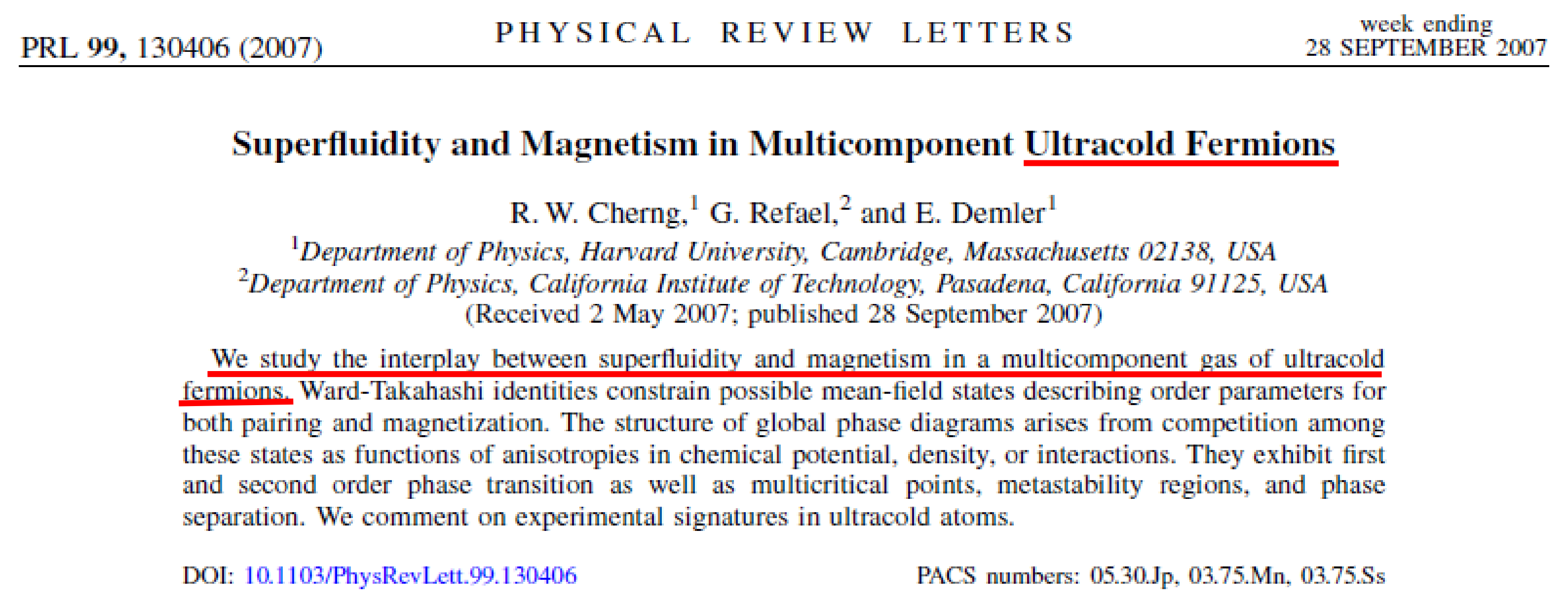

PRL **99,** 130406 (2007) PHYSICAL REVIEW LETTERS week ending
28 SEPTEMBER 2007

Superfluidity and Magnetism in Multicomponent Ultracold Fermions

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(Received 2 May 2007; published 28 September 2007)

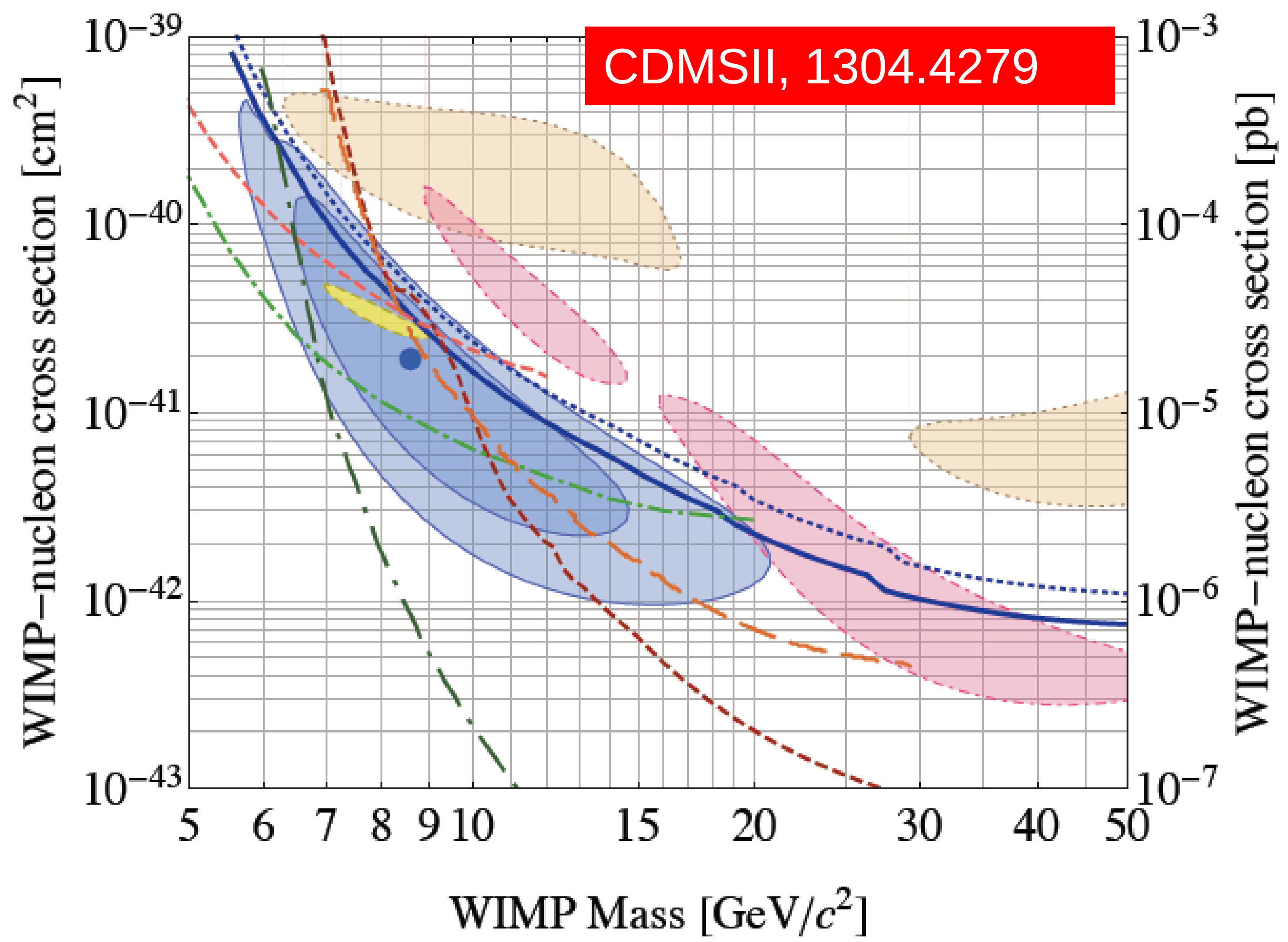
We study the interplay between superfluidity and magnetism in a multicomponent gas of ultracold fermions. Ward-Takahashi identities constrain possible mean-field states describing order parameters for both pairing and magnetization. The structure of global phase diagrams arises from competition among these states as functions of anisotropies in chemical potential, density, or interactions. They exhibit first and second order phase transition as well as multicritical points, metastability regions, and phase separation. We comment on experimental signatures in ultracold atoms.

DOI: 10.1103/PhysRevLett.99.130406 PACS numbers: 05.30.Jp, 03.75.Mn, 03.75.Ss

Dark matter capture
in neutron stars

Why the connection between DM and NS?

Possibly constraining WIMP-DM properties via NS



Impacts of dark matter on NS

- NS mass-radius relation with dark matter EOS
- NS heating via dark matter annihilation

:

- Dark matter capture in NS and formation of black-hole to collapse host neutron stars

cf) This is not so a new idea. People have considered the DM capture by Sun and the Earth since 80's.

cosmion W. Press and D. Spergel (1984)

Application to NS : Goldman-Nussinov (1989)

Interesting connection between matters and universe

⬇

Dense QCD matter and Neutron Stars

Harmony of particle, astro-, and condensed matter physics

Physics Orchestra !

Thank you !

感謝