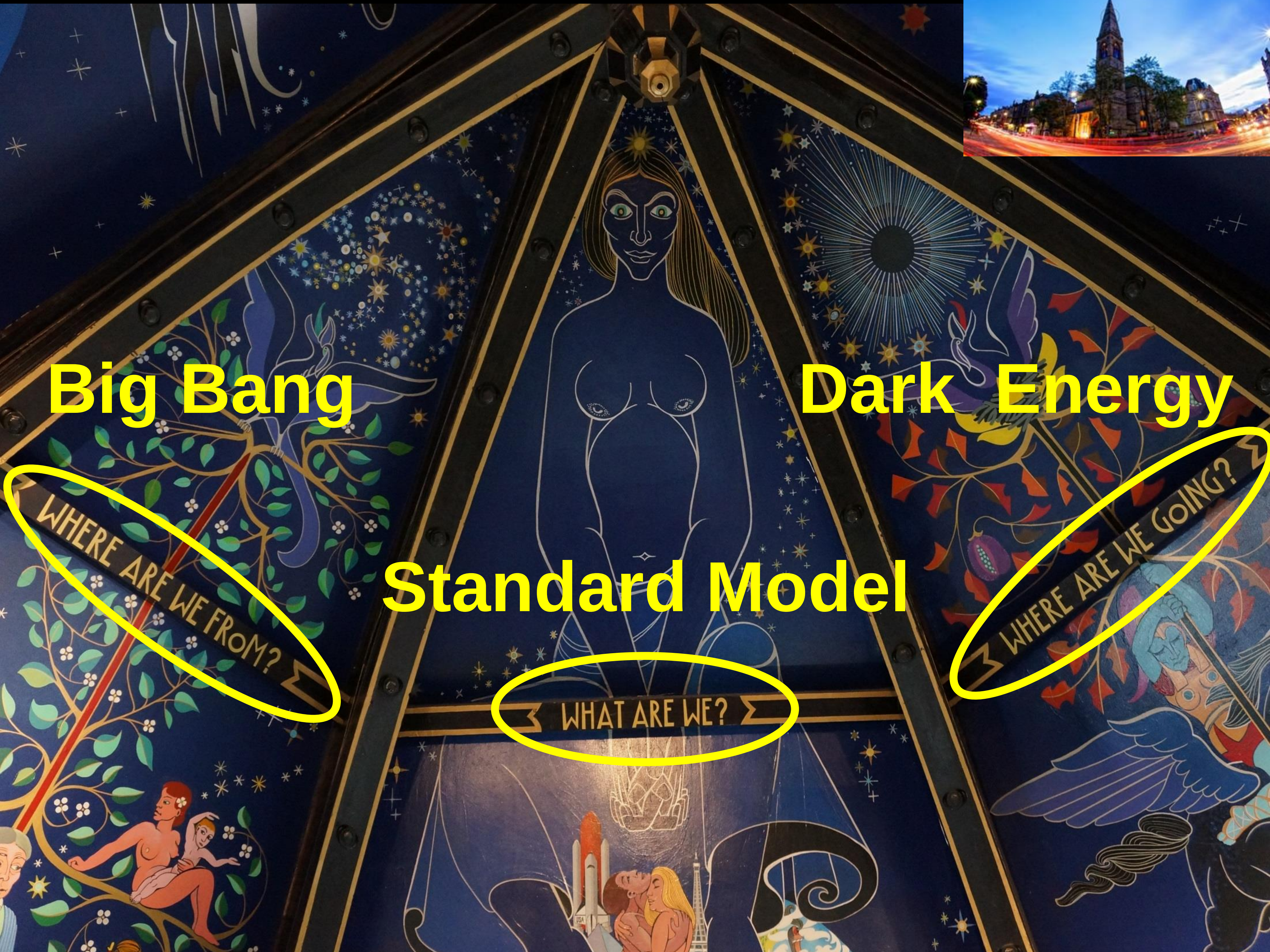
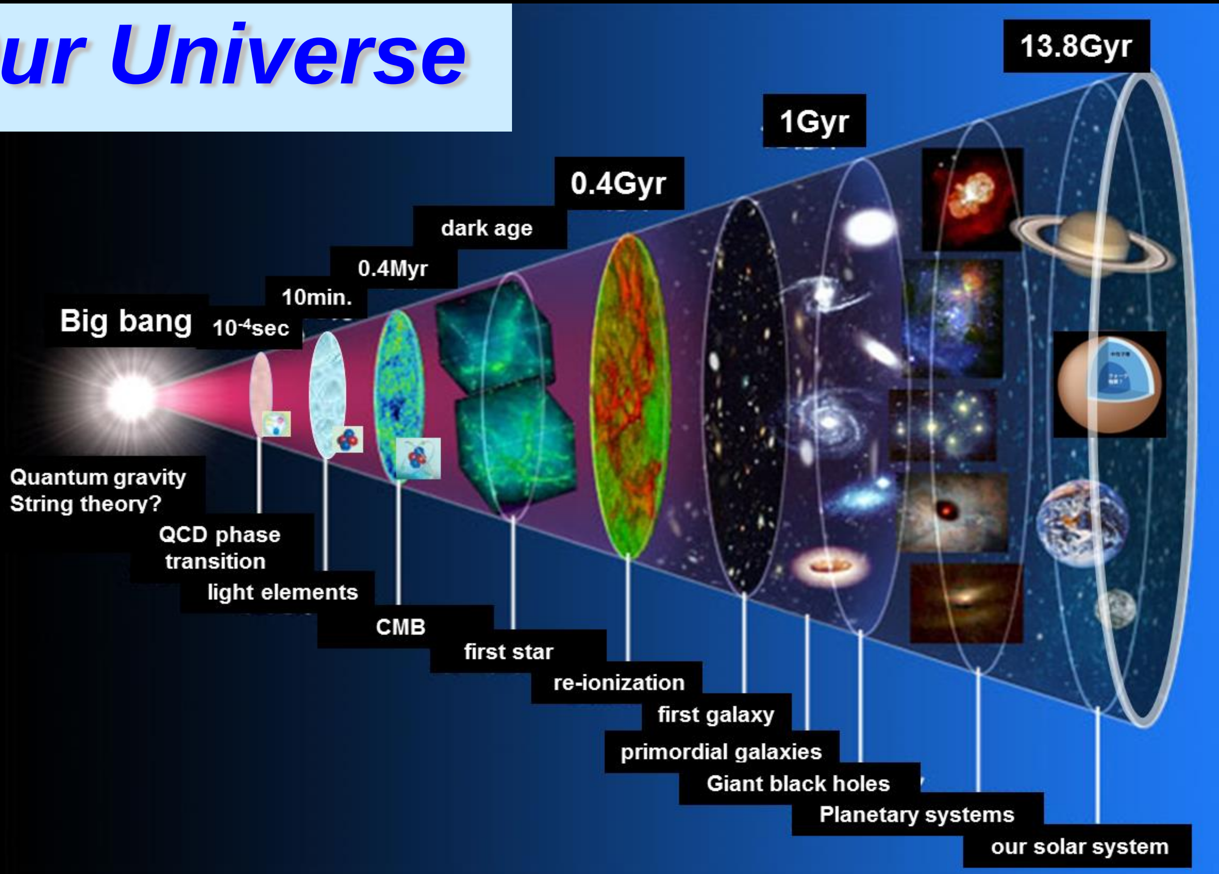
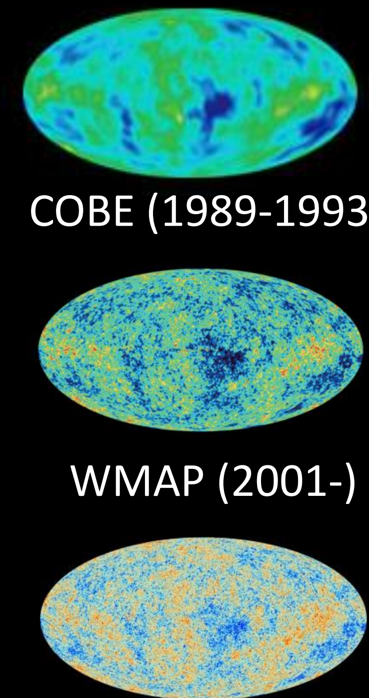
QCD Theory Overview

T. Hatsuda (Nishina Center & iTHES, RIKEN)


Big Bang
Dark Energy
Standard Model
WHERE ARE WE FROM?
WHAT ARE WE?
WHERE ARE WE GOING?

Our Universe





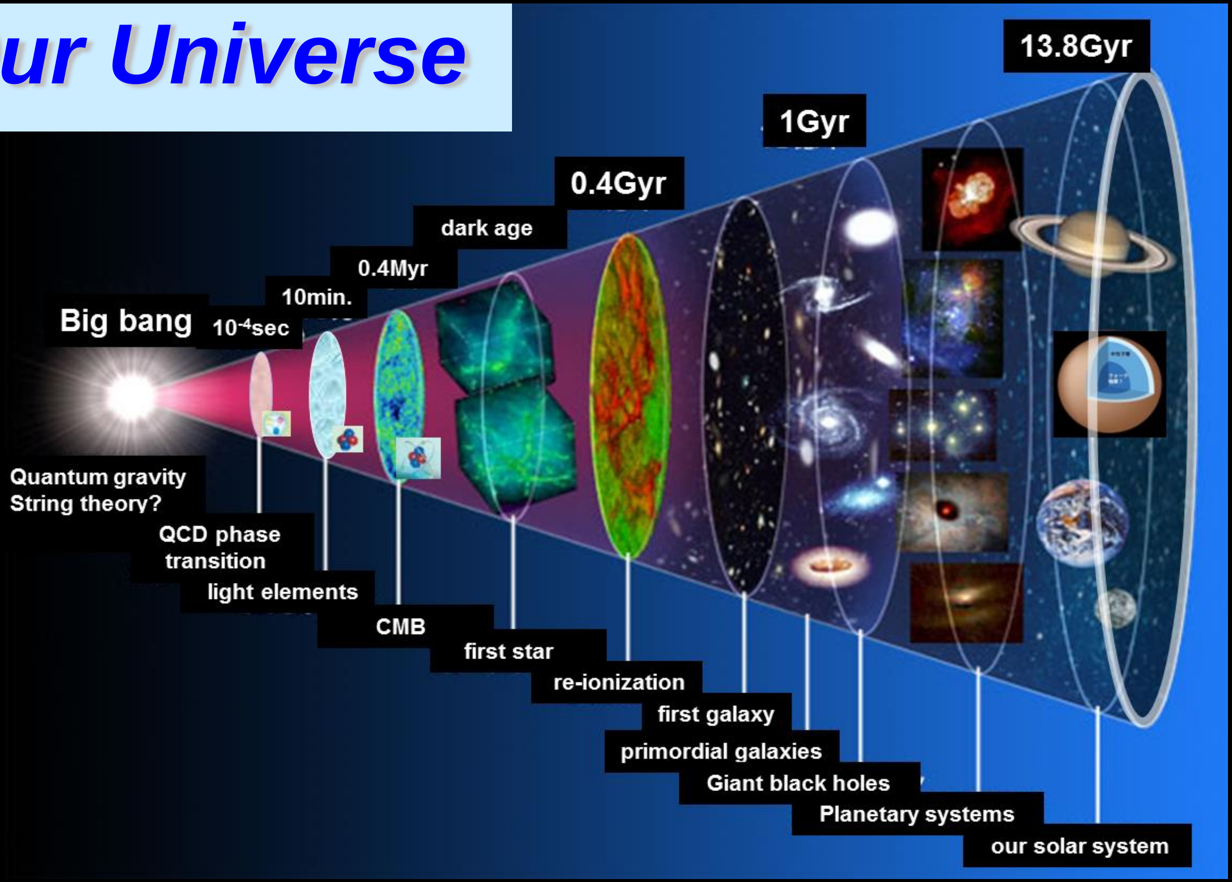
68.3% **Accelerating the Universe**

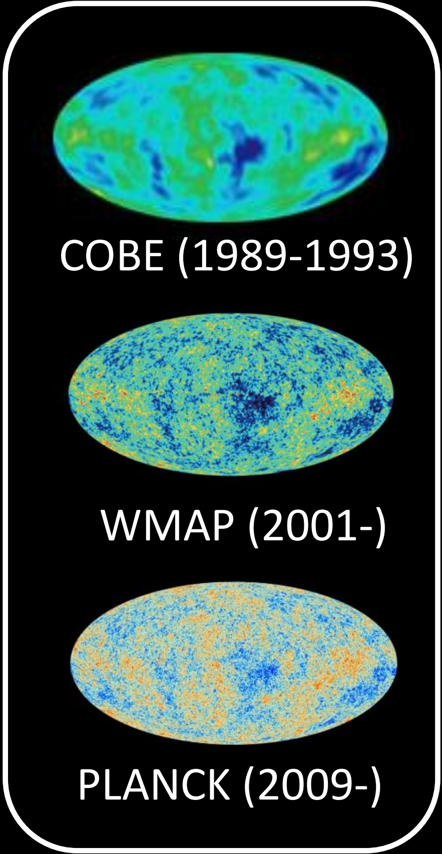
4.9% **Shining the Universe**

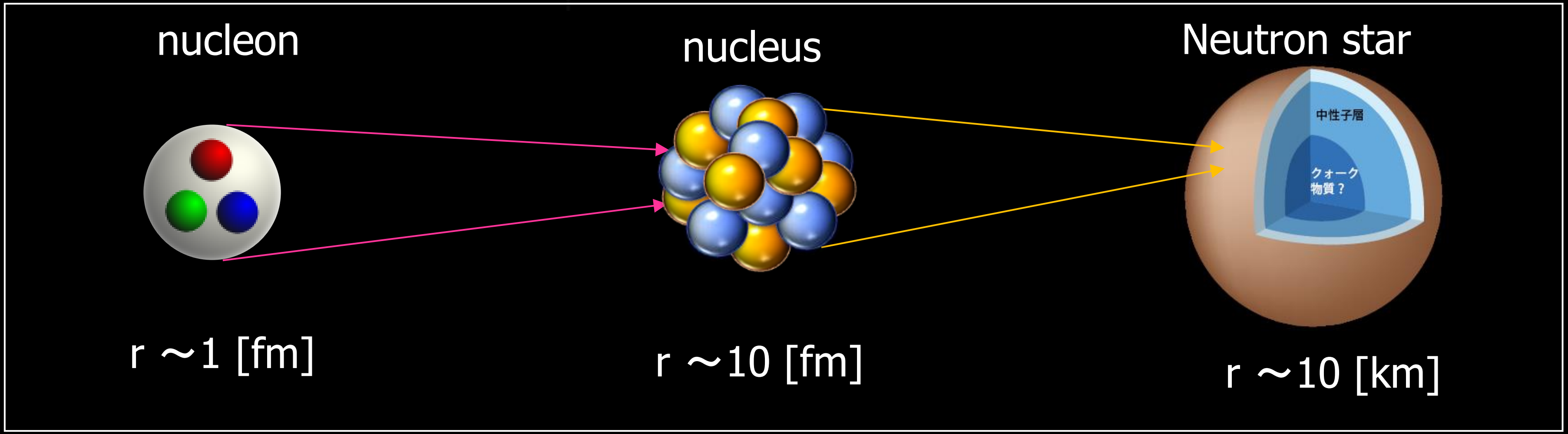
26.8% **Holding the galaxies**

Planck (March 21, 2013)

Our Universe







Quantum Chromo Dynamics (QCD)

Y. Nambu

1966	color SU(3) gauge theory for strong interaction	(Nambu)
1973	Asymptotic freedom	(Gross & Wilczek, Politzer)
1974	Quark confinement	(Wilson)

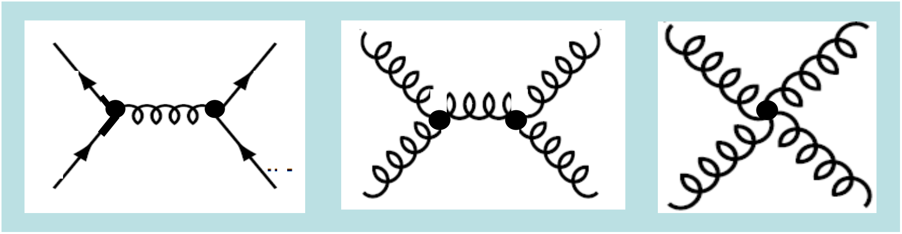
QCD = SU(3) gauge theory for color charges（**B**, **R**, **G**)

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G_a^{\mu\nu} + \bar{q}\gamma^\mu (i\partial_\mu - g t^a A^a_\mu) q - m\bar{q}q$$

$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f_{abc} A^b_\mu A^c_\nu$$

$$[t^a, t^b] = i f_{abc} t^c$$

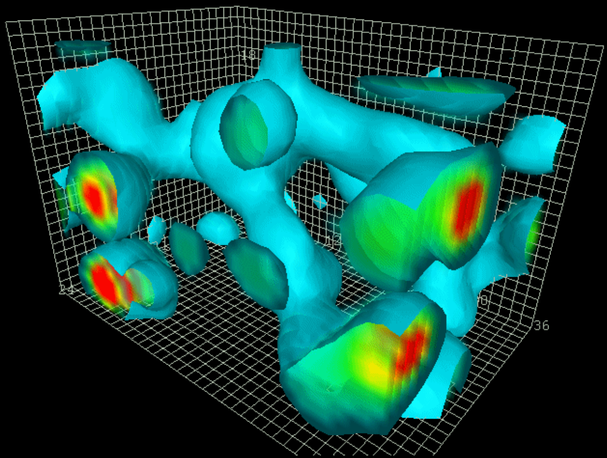
- Intrinsic parameters: *m, g*
- External parameters: *Q, T,* ρ_B etc



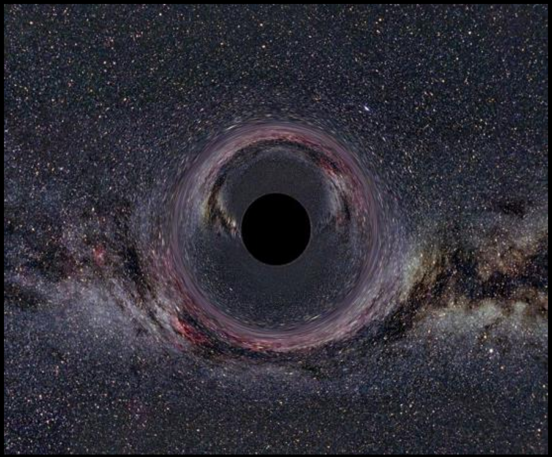
Challenges in QCD

QCD: Non-linear
Strong coupling
Quantum

GR: Non-linear
Weak coupling
Classical



Holography



1. Mathematical challenge ⇔ one of the seven millennium problems
2. Tool to search physics beyond SM ⇔ B-factory, LHC, ILC
3. Nucleon structure (spin, glue, …) ⇔ Jlab, RHIC
4. Multi-quarks ⇔ B-factory, Spring-8,Jlab, GSI, J-PARC
5. New states of matter (QGP, QM) ⇔ RHIC, LHC, $N_{\star}$, $Q_{\star}$

Yang-Mills and Mass gap : One of seven Millennium Problems by Clay Mathematics Institute (May 24, 2000)

Official description (A. Jaffe and E. Witten)

QCD must have....

(1) It must have a "mass gap," that is, there must be some strictly positive constant Δ such that every excitation of the vacuum has energy at least Δ.

(2) It must have "quark confinement," that is, even though the theory is described in terms of elementary fields, such as the quarks, that transform non-trivially under $SU(3)$, the physical particle states – such as the proton, neutron, and pion – are $SU(3)$-invariant.

(3) It must have "chiral symmetry breaking," which means that the vacuum is potentially invariant (in the limit that the quark bare masses vanish) only under a certain subgroup of the full symmetry group that acts on the quark fields.

The first point is necessary to explain why the nuclear force is strong but short-ranged; the second is needed to explain why we never see individual quarks; and the third is needed to account for the "current algebra" theory of soft pions that was developed in the 1960's.

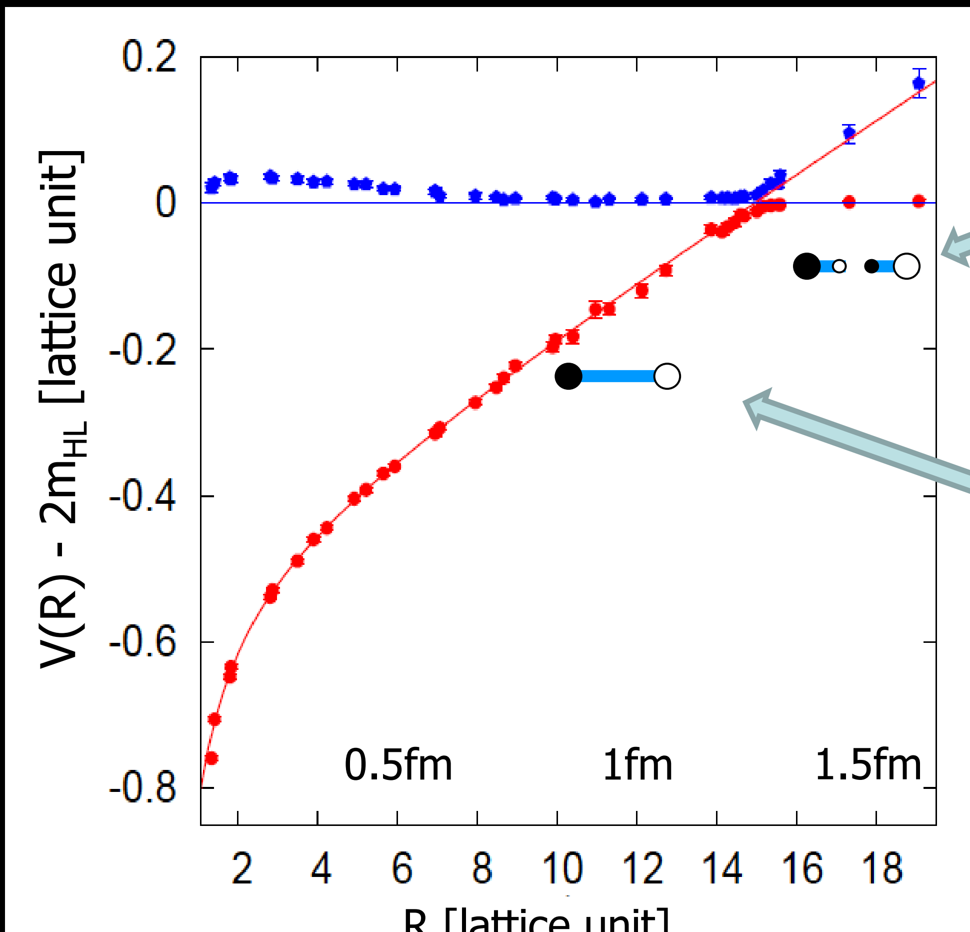
Now we can state the Millenium Problem:

Yang-Mills Existence And Mass Gap: *Prove that for any compact simple gauge group G, quantum Yang-Mills theory on $\mathbf{R}^4$ exists and has a mass gap $\Delta > 0$.*

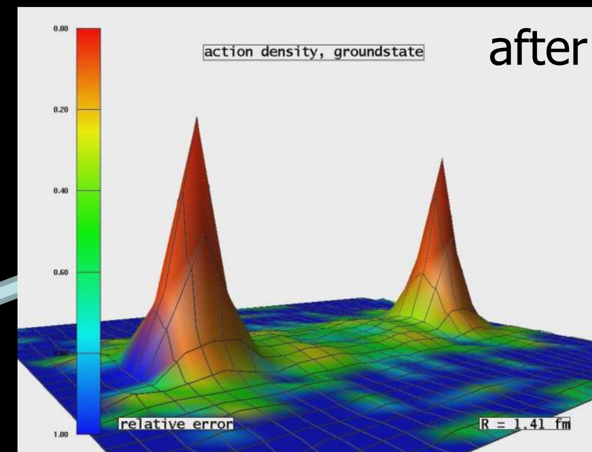
P2: Confinement from lattice QCD

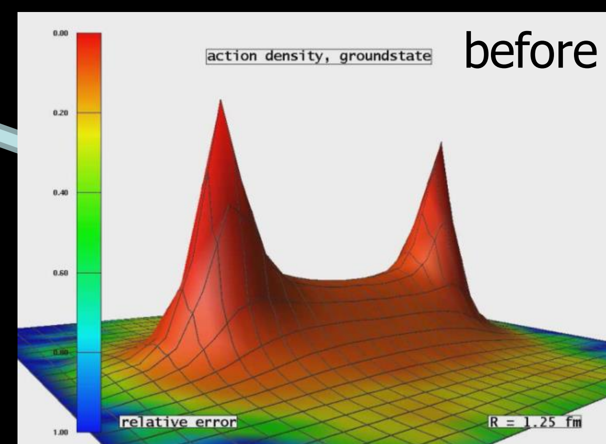
Heavy Q-Qbar potential

$$V(R) = \left(c - \frac{a}{R} + \sigma R\right)\theta(R_0 - R)$$



SESAM Coll., Phys.Rev.D71 ('05)





Bali et al., Nucl.Phys.Proc.Suppl. 153 ('06)

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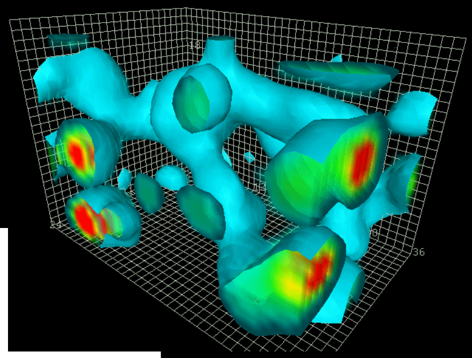
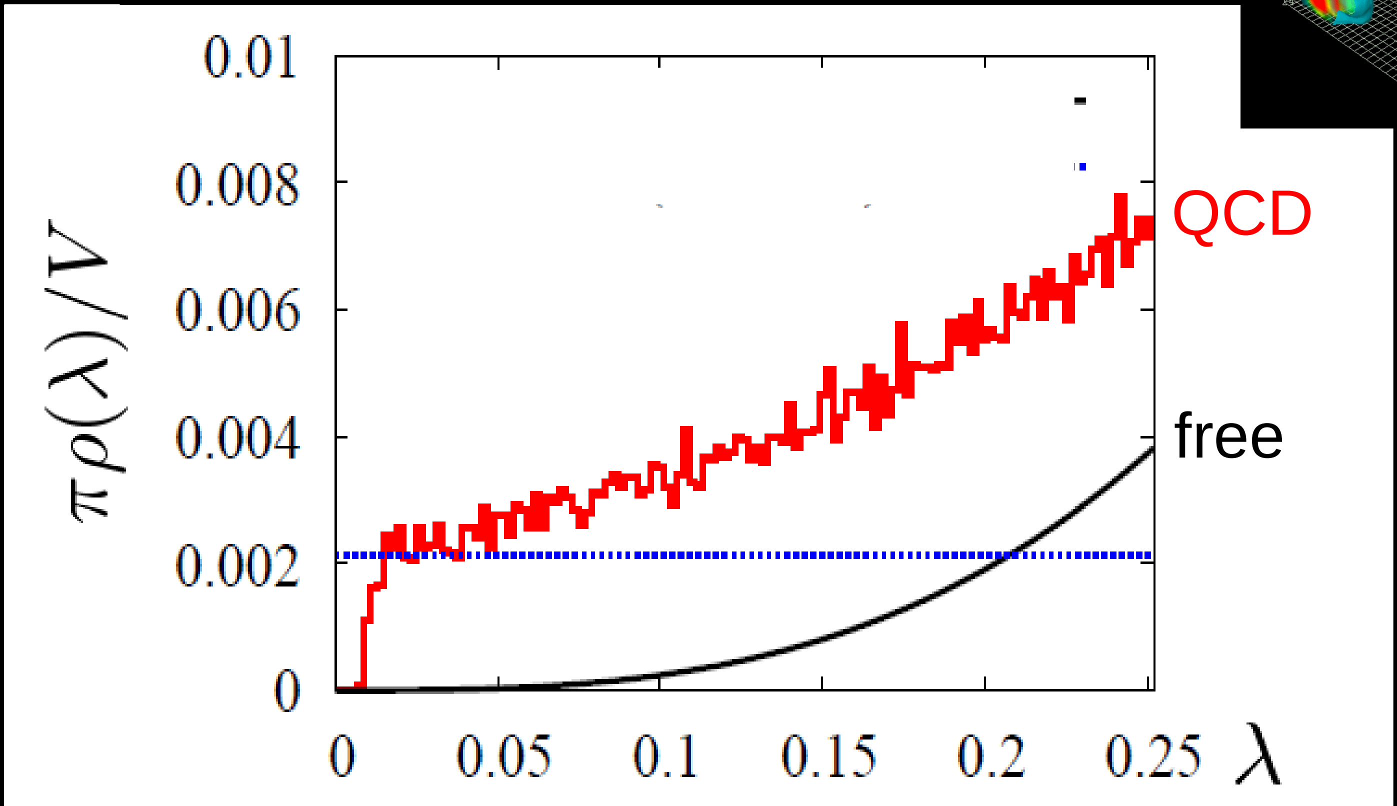
P3: Chiral condensate from lattice QCD





$$\langle \bar{q}q \rangle = -(251 \pm 7 \pm 11\ \mathrm{MeV})^3 \quad \text{at 2 GeV}$$

Dynamical overlap fermion, 2-flavor
S. Hashimoto (JLQCD Coll.) arXiv:0811.1257 [hep-lat]

Yang-Mills and Mass gap : One of seven Millennium Problems by Clay Mathematics Institute (May 24, 2000)

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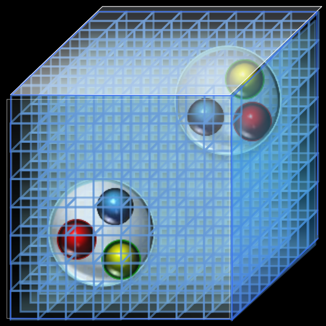
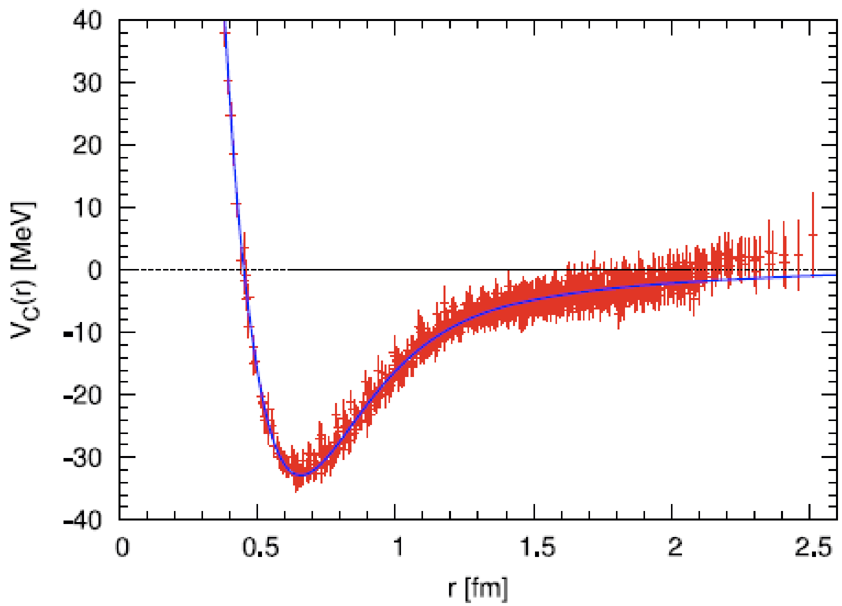
P1: Nuclear Force from lattice QCD

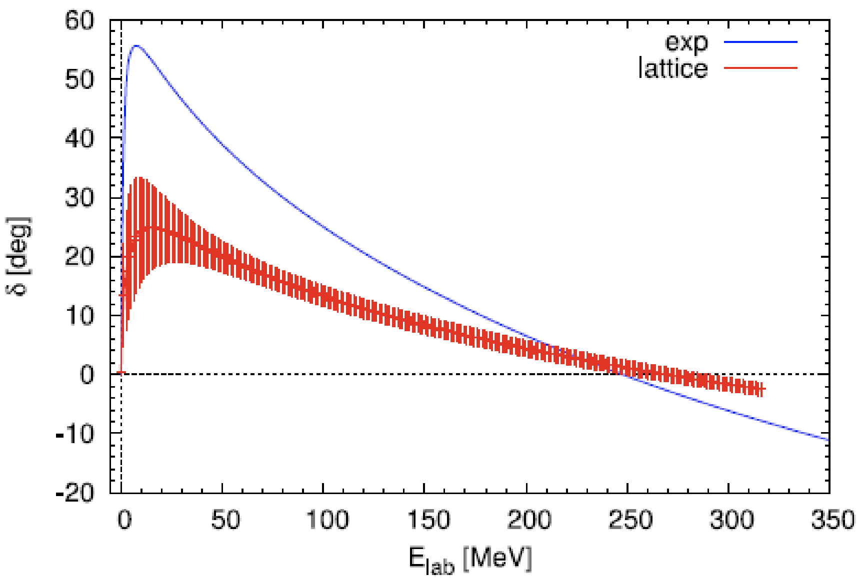


Ishii, Aoki & Hatsuda, Phys. Rev. Lett. 92 (2007) 022001
Ishii et al., [HAL QCD Coll.], Phys. Lett. 712 (2012) 437

$^1S_0$ NN potential (Lattice QCD)



$^1S_0$ NN phase shift (Lattice QCD)



$M_\pi \sim 3\ M_\pi$(phys.) ➔ $M_\pi = M_\pi$(phys.) , NN, NNN
by K-Computer

Precision QCD

$$\mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G_a^{\mu\nu} + \bar{q}\gamma^\mu (i\partial_\mu - g t^a A^a_\mu) q - m\bar{q}q$$

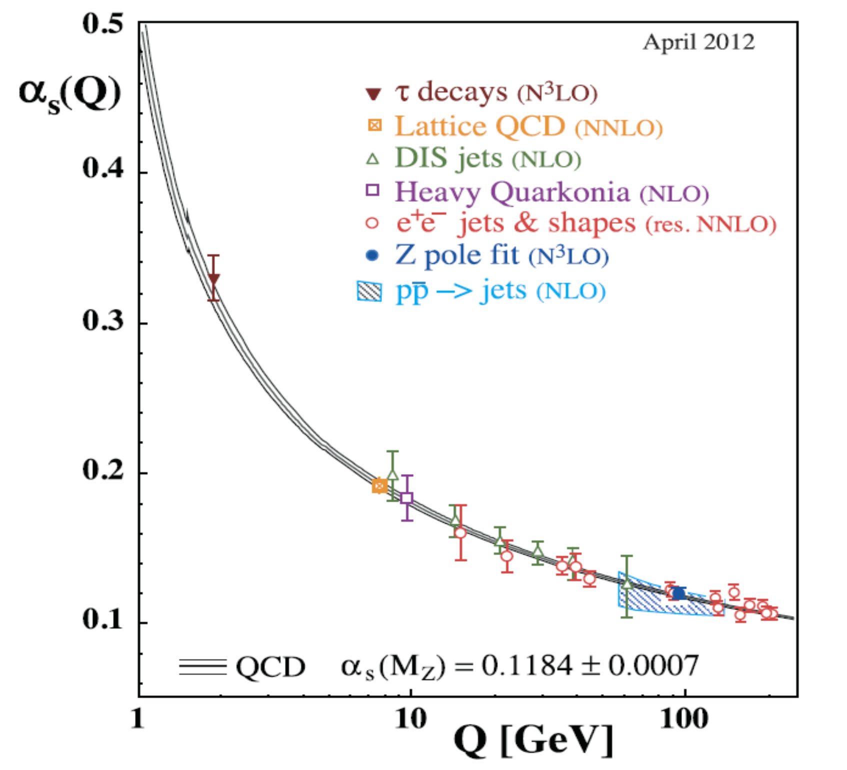
$$G^a_{\mu\nu} = \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + g f_{abc} A^b_\mu A^c_\nu$$

Running masses: $m_q(Q)$

quark masses (from lattice QCD)	**[MeV]** (MS-bar @ 2GeV)
m_u	2.16(9)(7)
m_d	4.68(14)(7)
m_s	93.8(2.4)

FLAG Collaboration update(July 26, 2013)
http://itpwiki.unibe.ch/flag/

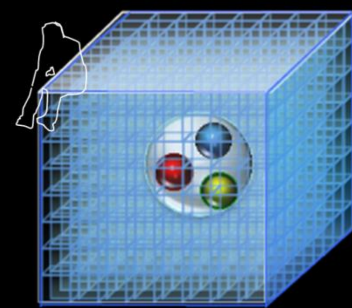
Running coupling: $\alpha_s(Q)=g^2/4\pi$

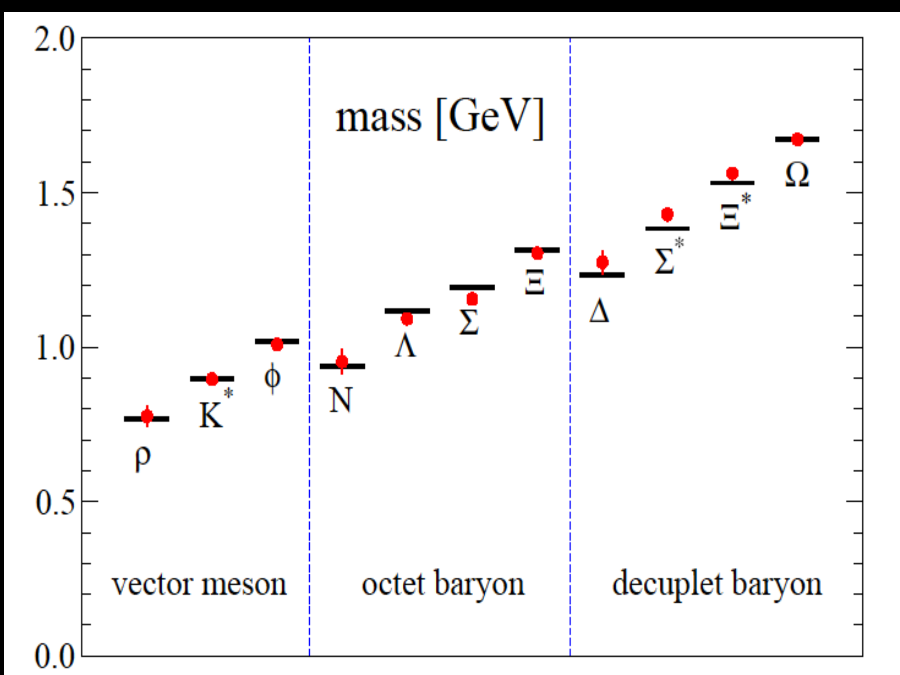


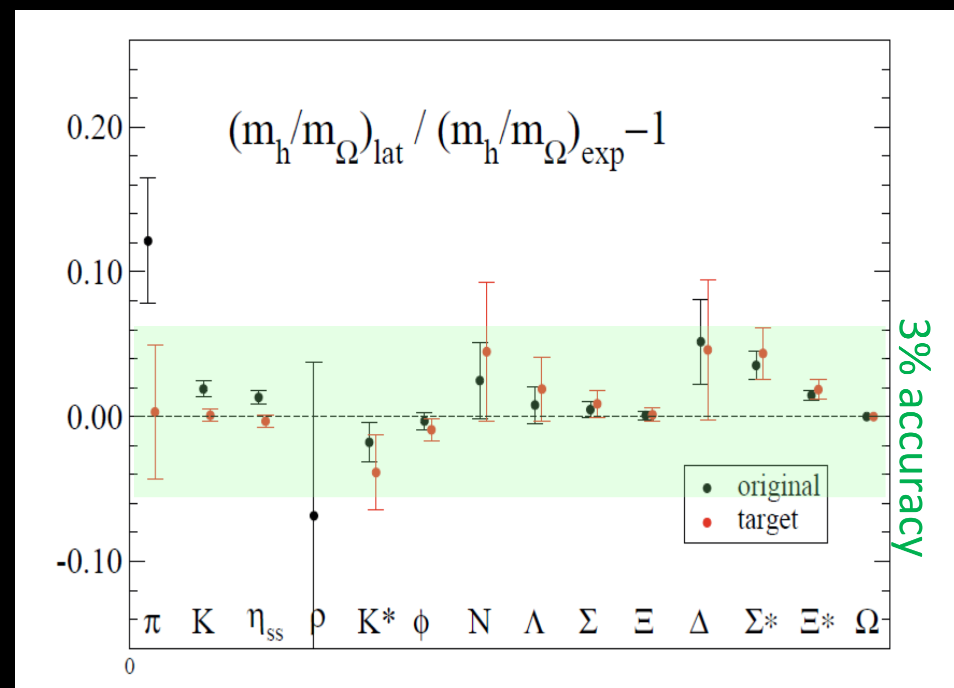
PDG (2012) http://pdg.lbl.gov/

Hadron masses @ 2009
m_π > 156 MeV

Hadron masses @ 2010
m_π =135 MeV



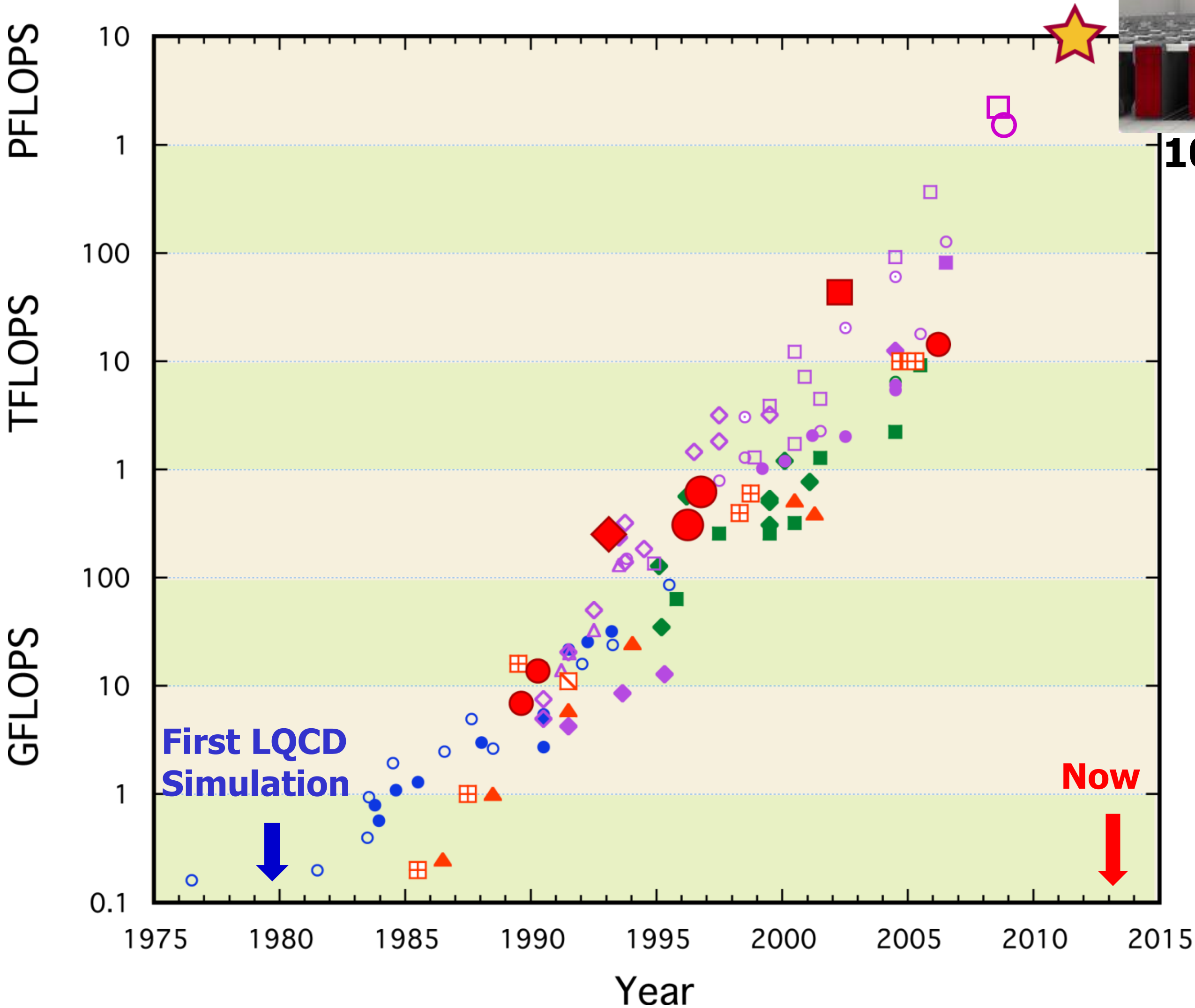




PACS-CS Collaboration, Phys.Rev.D79 (2009)034503

PACS-CS Coll.: Phys. Rev.D81 (2010) 074503

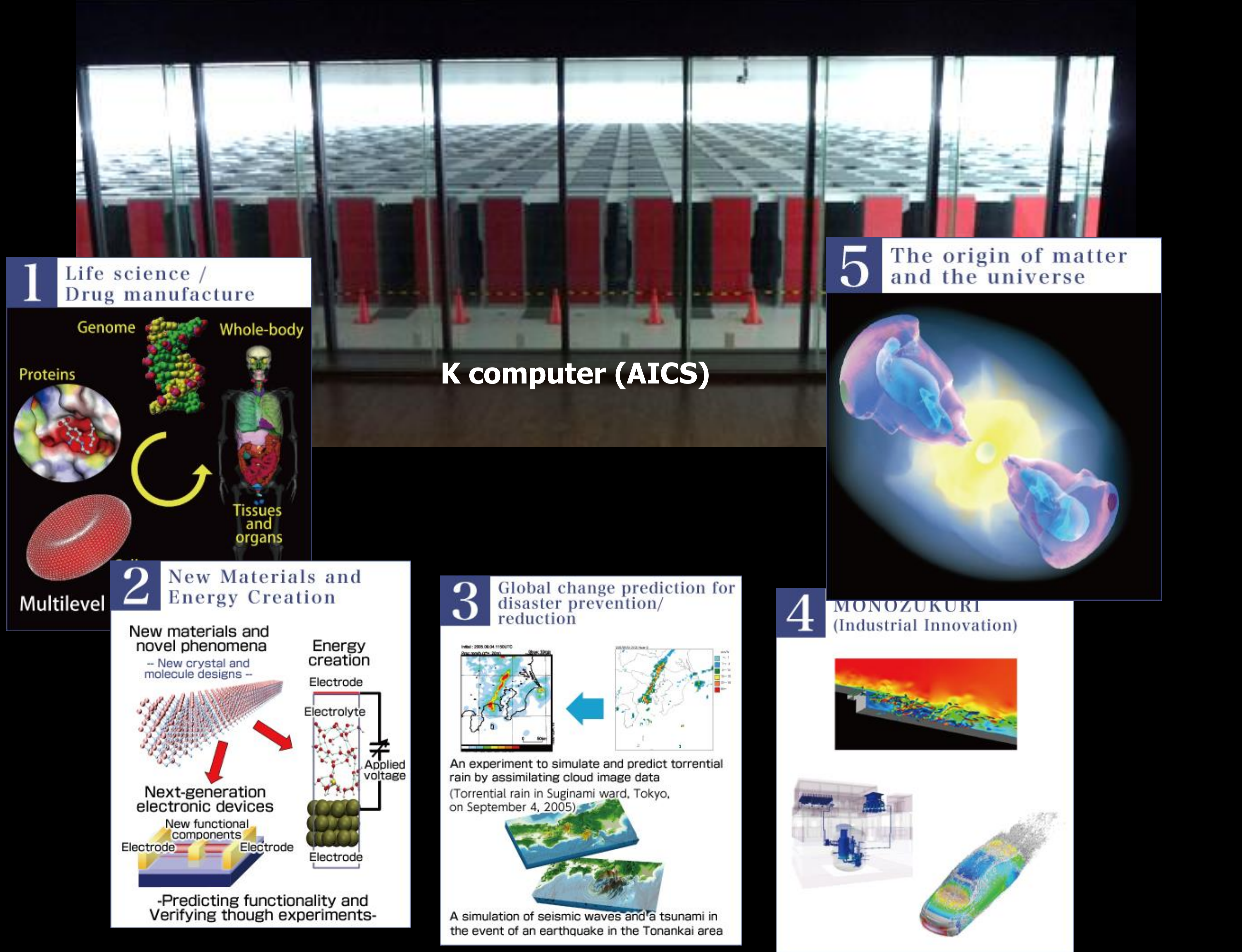
Toward large-scale Physical-point simulations



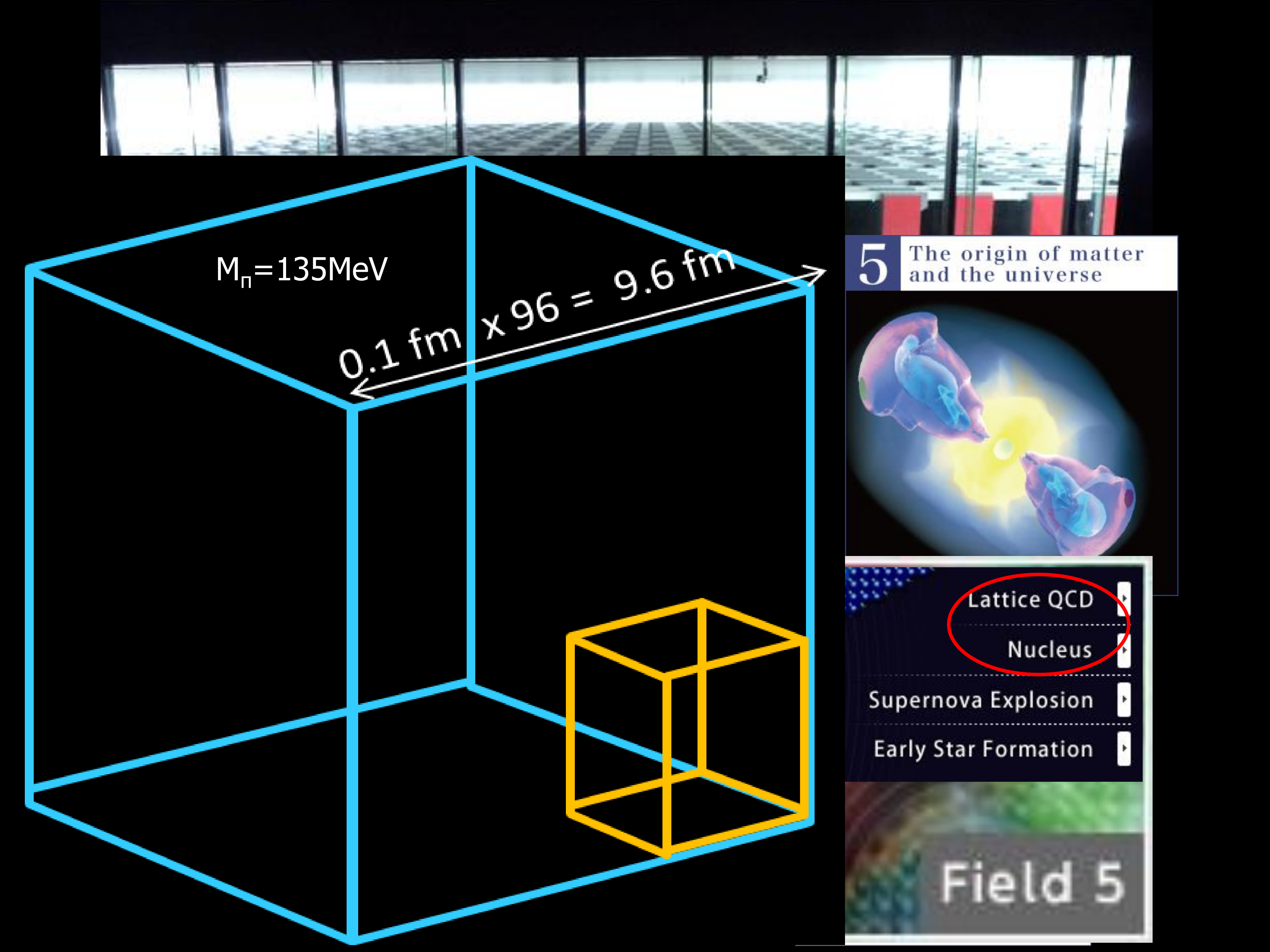
http://www.aics.riken.jp/en/

10PFlops K computer (RIKEN)

original plot by A. Ukawa

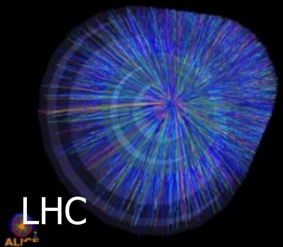

K computer (AICS)
1 Life science / Drug manufacture
Genome
Whole-body
Proteins
Tissues and organs
Multilevel
2 New Materials and Energy Creation
New materials and novel phenomena
-- New crystal and molecule designs --
Energy creation
Electrode
Electrolyte
Applied voltage
Next-generation electronic devices
New functional components
Electrode
Electrode
Electrode
-Predicting functionality and Verifying though experiments-
3 Global change prediction for disaster prevention/ reduction
An experiment to simulate and predict torrential rain by assimilating cloud image data
(Torrential rain in Suginami ward, Tokyo, on September 4, 2005)
A simulation of seismic waves and a tsunami in the event of an earthquake in the Tonankai area
4 MONOZUKURI (Industrial Innovation)
5 The origin of matter and the universe

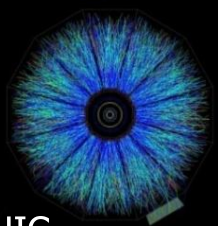

K computer (AICS)
1
Life science /
Drug manufacture
Genome
Whole-body
Proteins
Tissues
and
organs
5
The origin of matter
and the universe
The origin of matter
and the universe
Lattice QCD
Nucleus
Supernova Explosion
Early Star Formation
Field 5

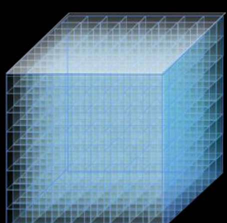


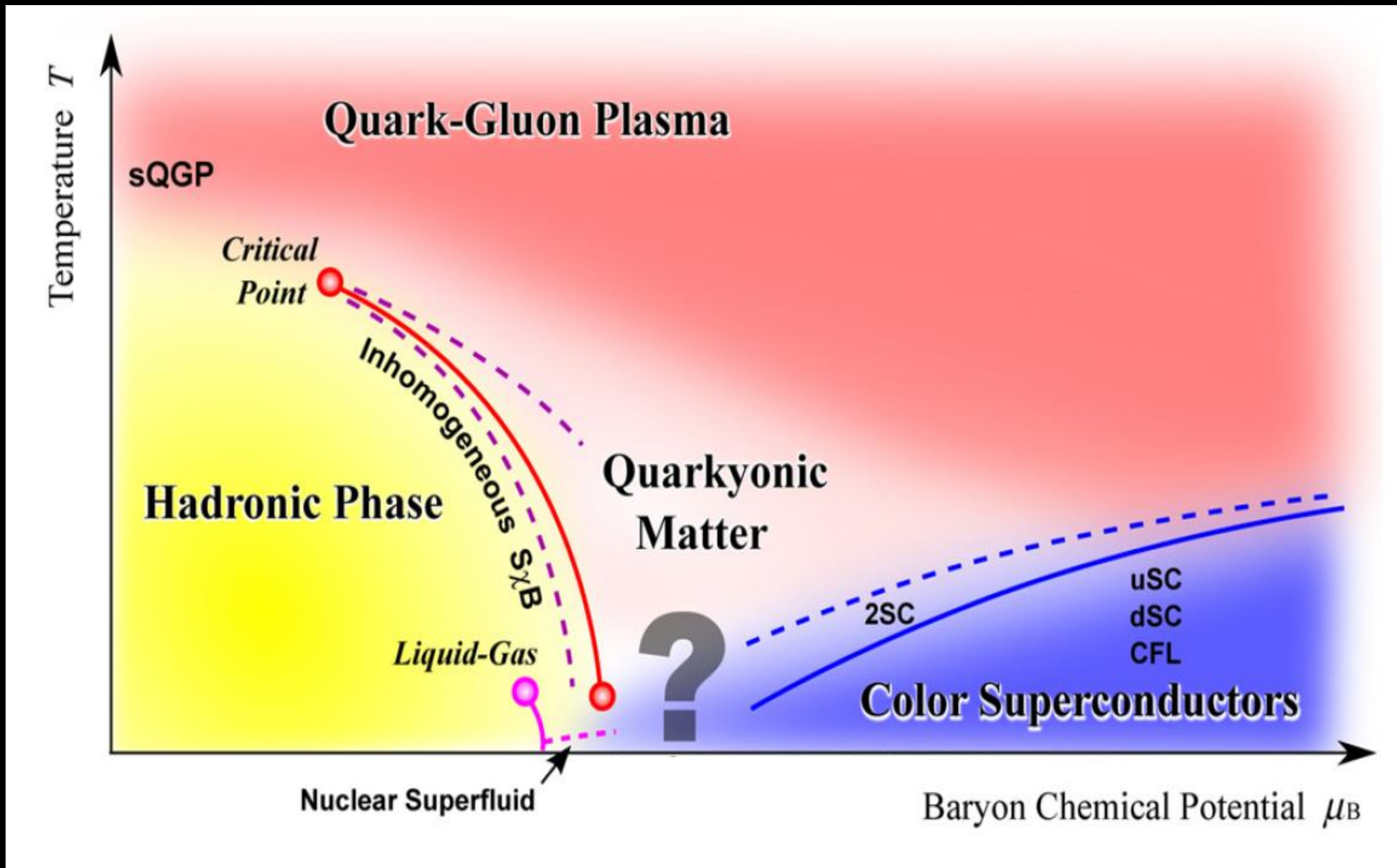
M_π=135MeV
0.1 fm x 96 = 9.6 fm
5
The origin of matter and the universe
Lattice QCD
Nucleus
Supernova Explosion
Early Star Formation
Field 5

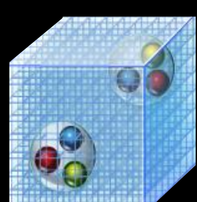
QCD Phase Diagram

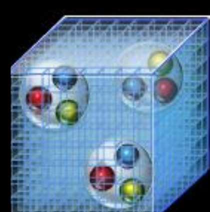


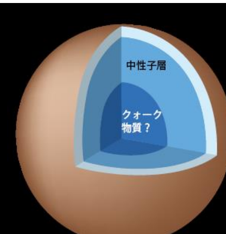






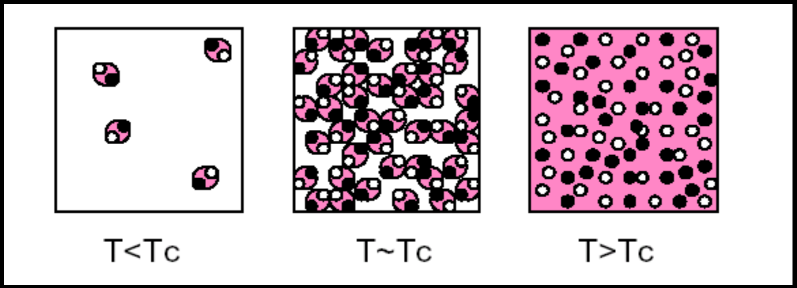


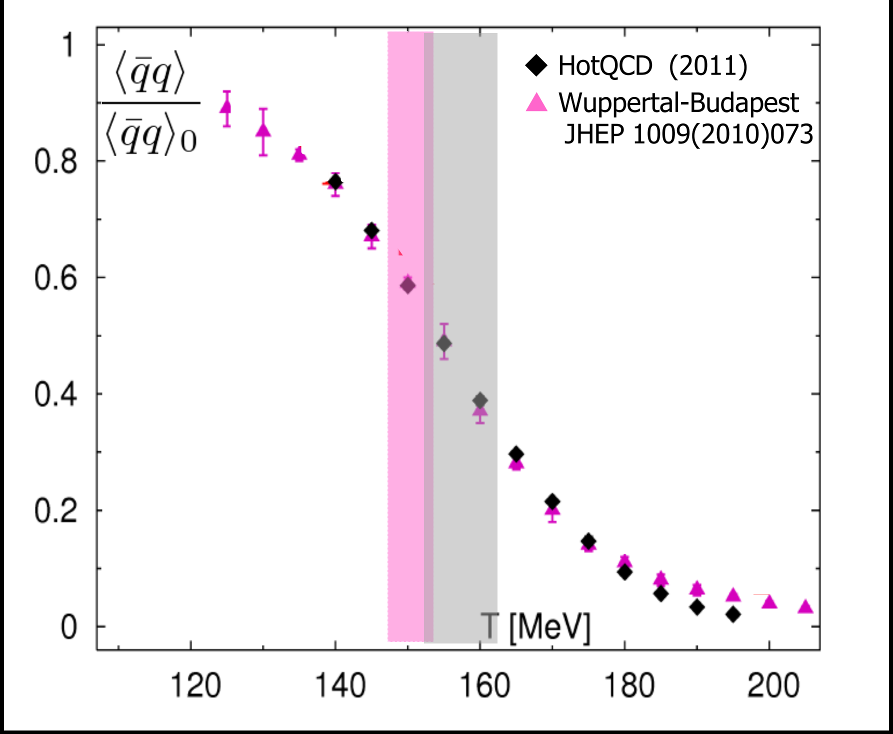


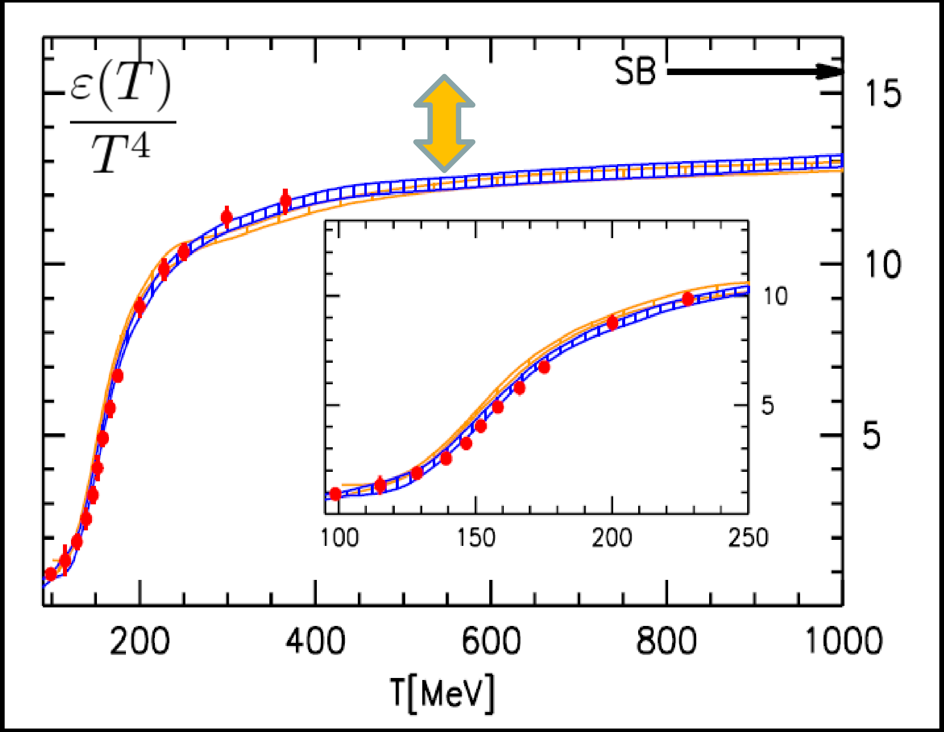


K. Fukushima and T. Hatsuda,
"The Phase Diagram of Dense QCD"
Rep. Prog. Phys. 74 (2011) 014001

Hadron-Quark Crossover in hot QCD



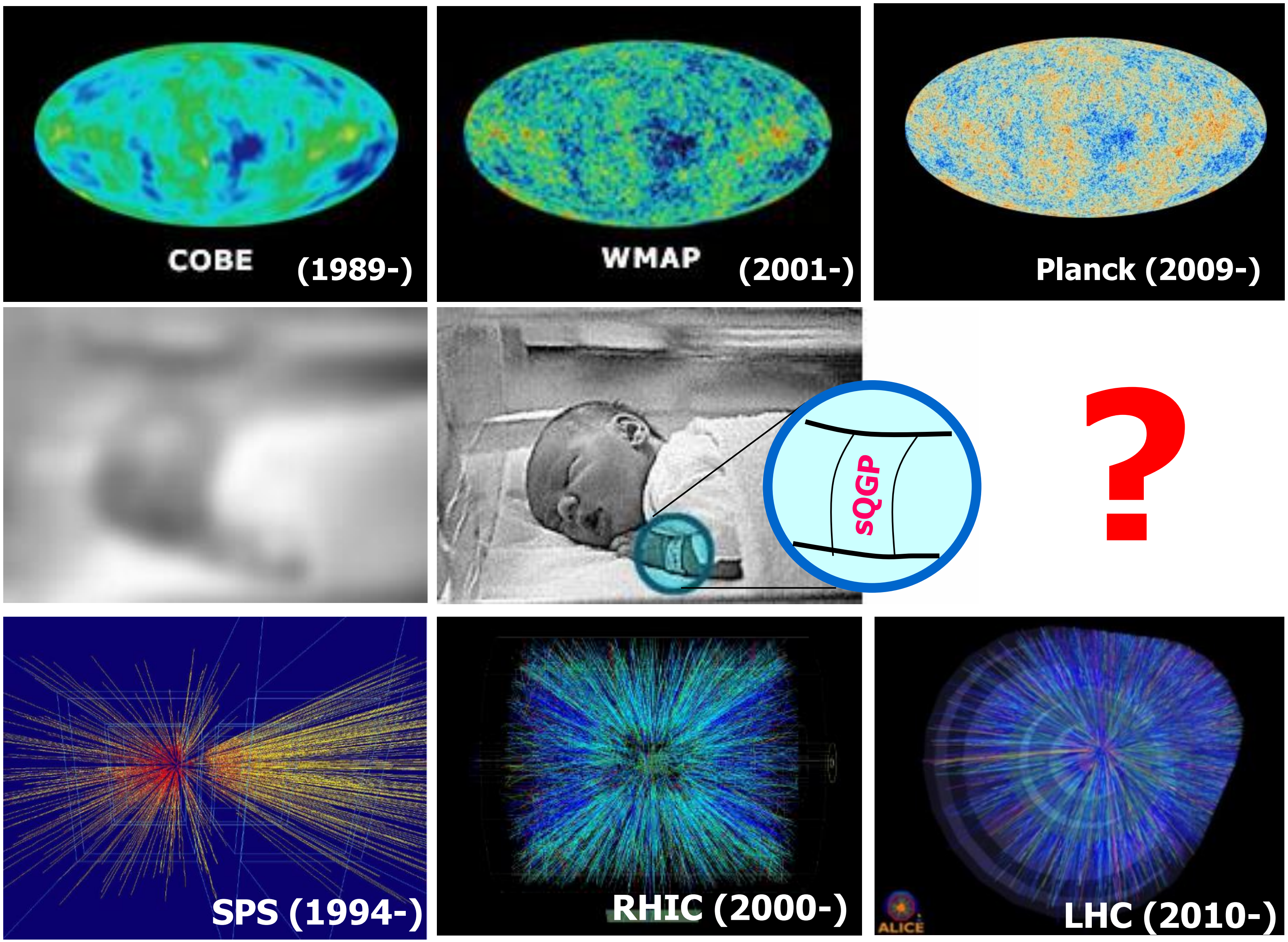




Wuppertal-Budapest Coll. JHEP 1011 (2010) 77

T_{pc}=150-160MeV

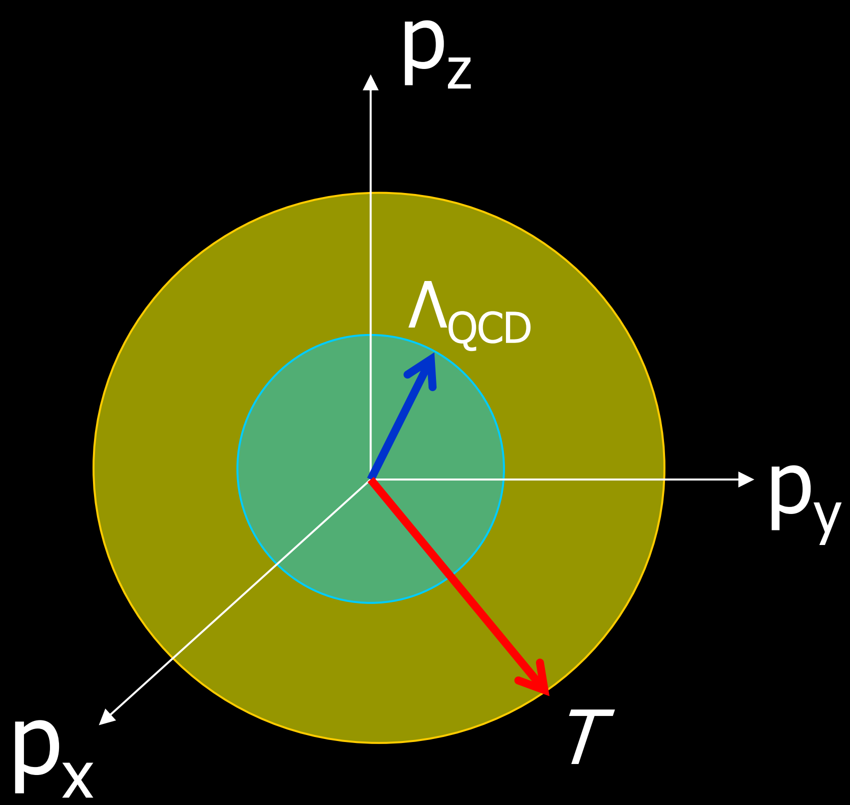
Big Bang

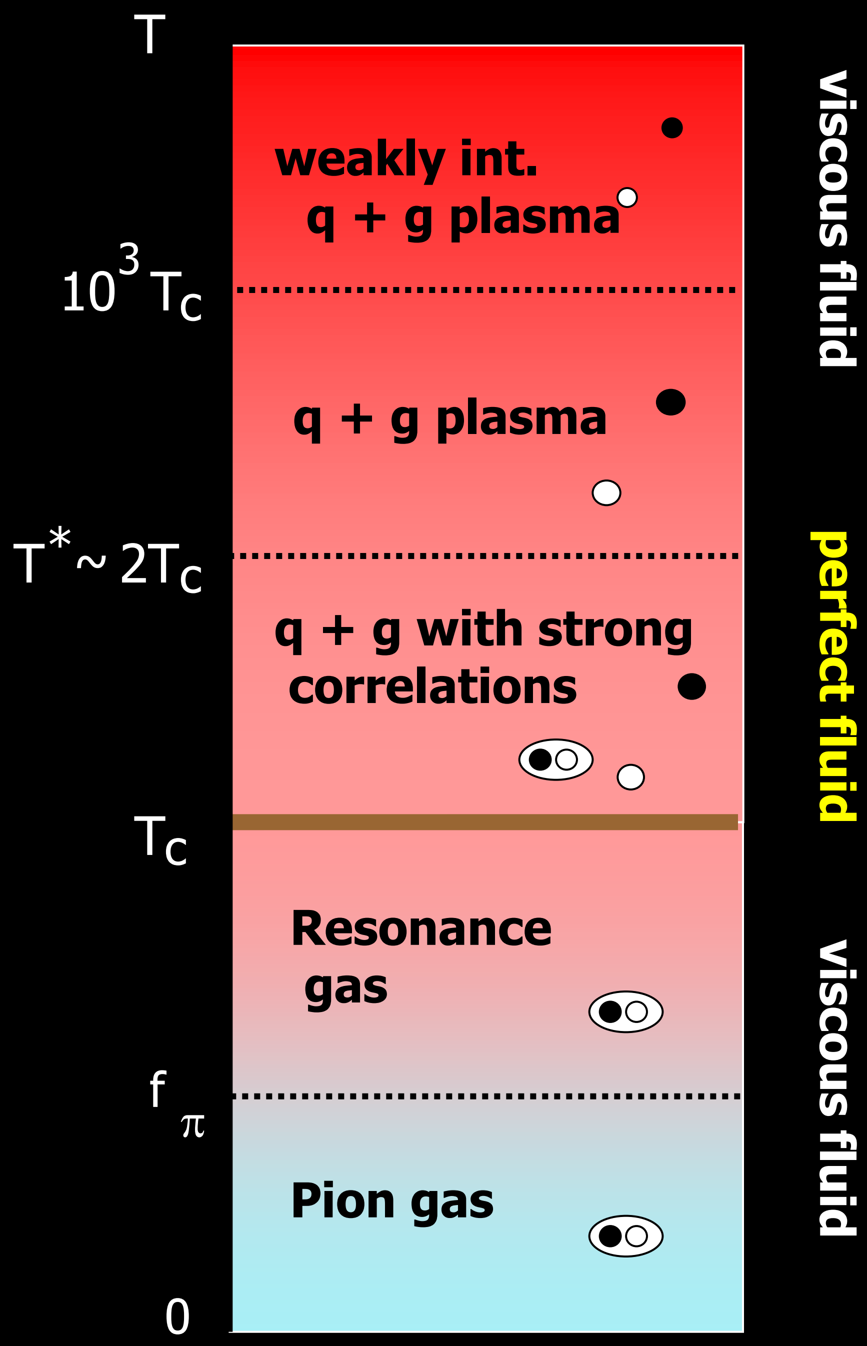


Little Bang

K. Yagi, T. Hatsuda & Y. Miake,
"Quark-Gluon Plasma", Cambridge UP (2008)

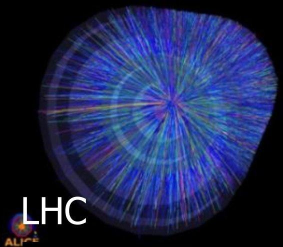
Strongly correlated QGP

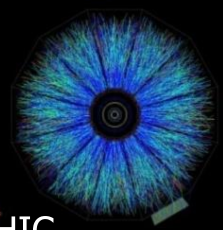


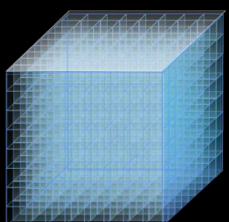


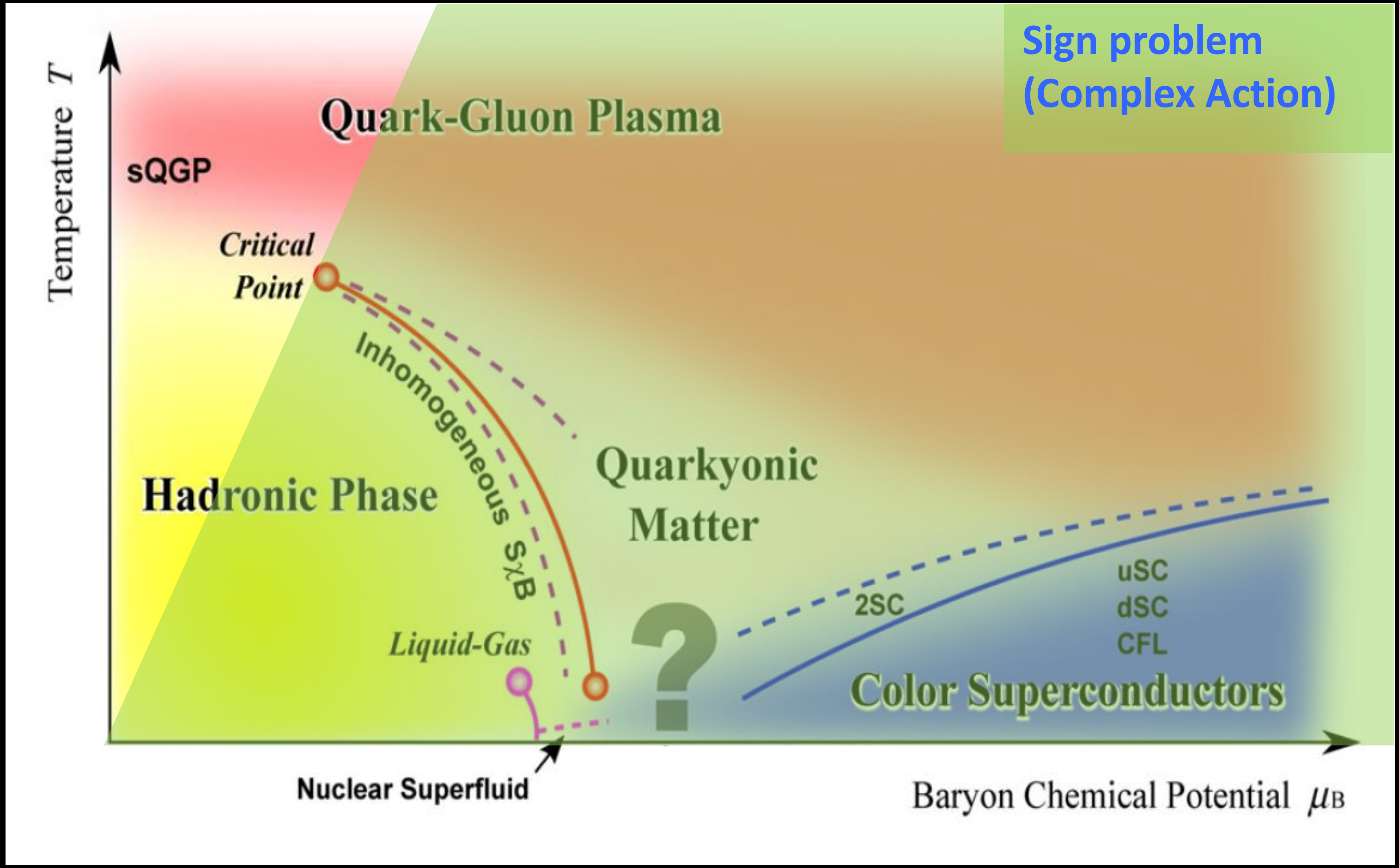
Hatsuda & Kunihiro, PRL 51 (1985)
DeTar, PRD 32 (1985)
Nakamura & Sakai, PRL 94 (2005)

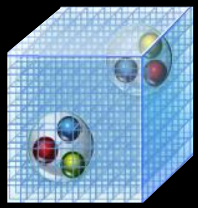
QCD Phase Diagram

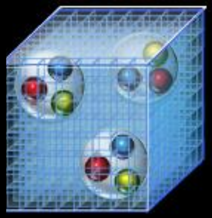


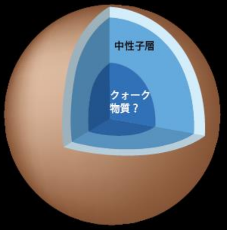












K. Fukushima and T. Hatsuda,
“The Phase Diagram of Dense QCD”
Rep. Prog. Phys. 74 (2011) 014001

$N_\star$ observations

Current:

$M=(1.97\pm0.04)M_\odot$ (Nature 2010)
$M=(2.01\pm0.04)M_\odot$ (Science 2013)
⇔ cold EOS

X-ray bursts ⇔ cold EOS

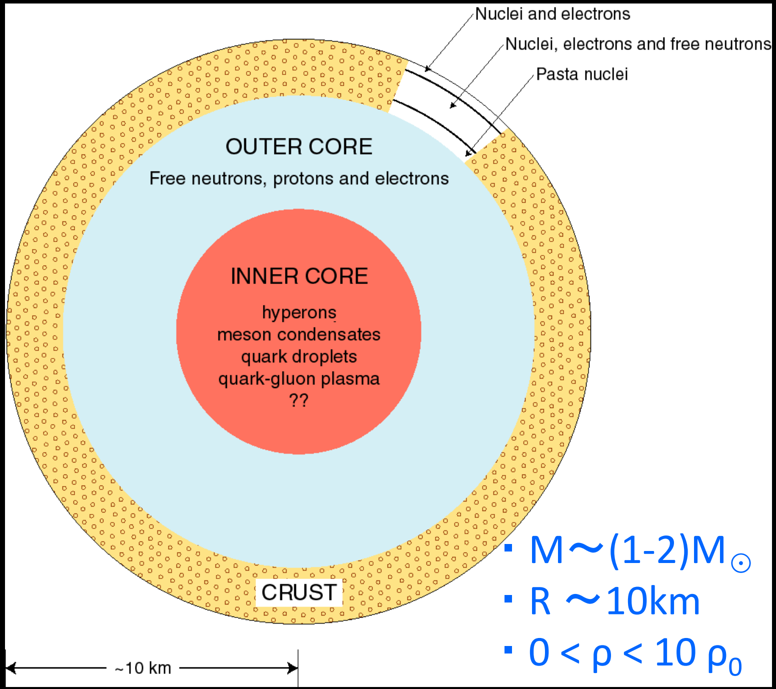
Cooling of CAS-A ⇔ $^3P_2$ superfluid?

Magnetars ⇔ ferromagnetic core?

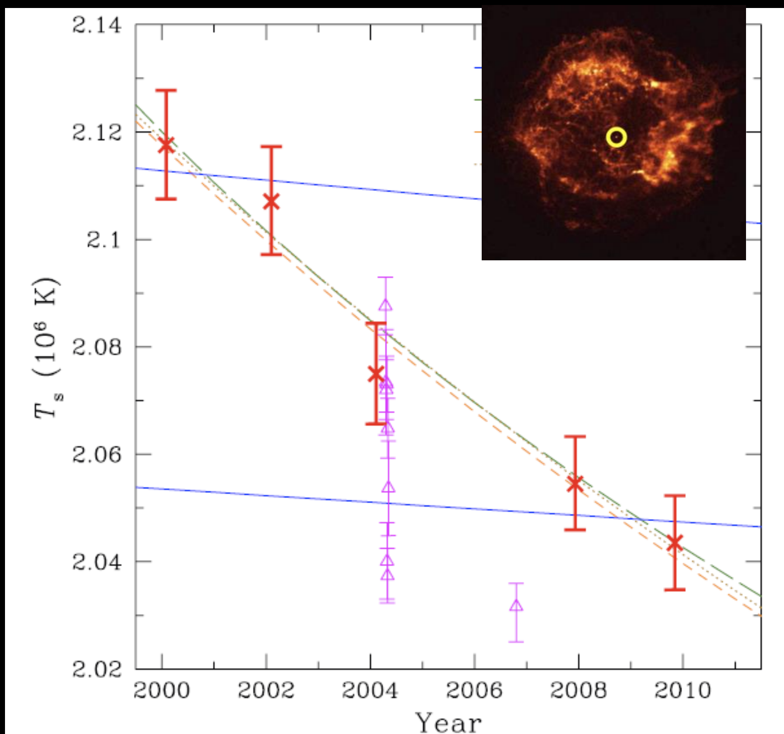
Future:

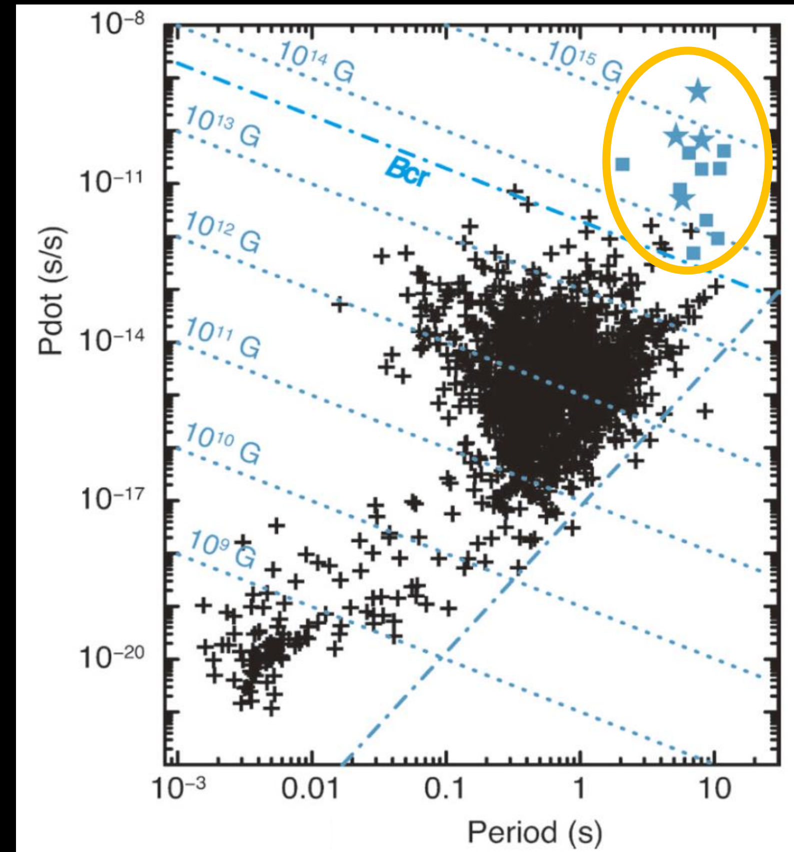
GW from $N_\star$ merger ⇔ hot EOS

Seismology ⇔ crust structure



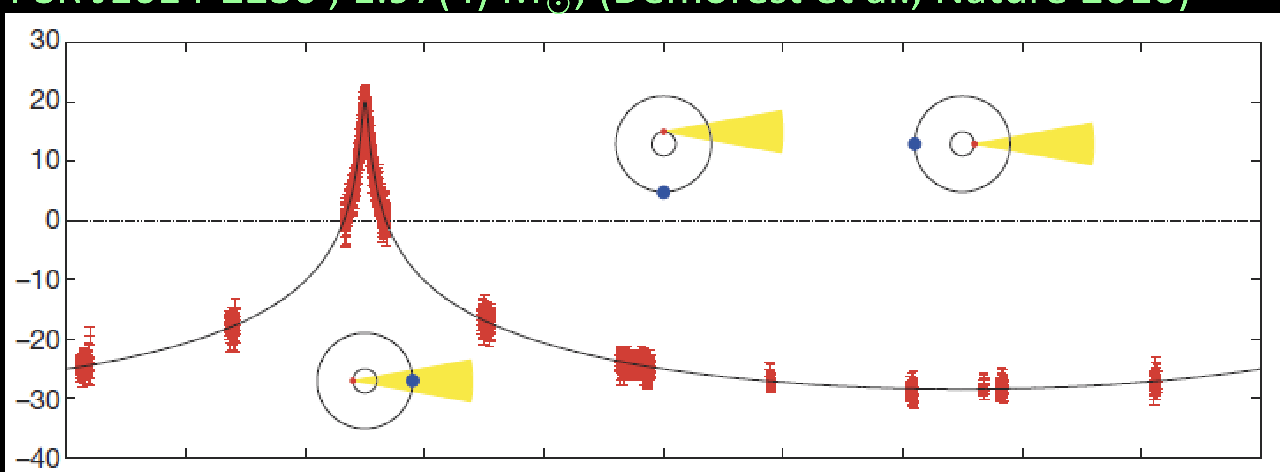
Cassiopeia A Cooling, 4% decrease in 9 years
(Heinke & Ho, ApJ 2010)





Magnetars
(from Enoto, 2012)
$B_s = 3.2 \times 10^{19} \sqrt{(P\dot{P})}$ [G]

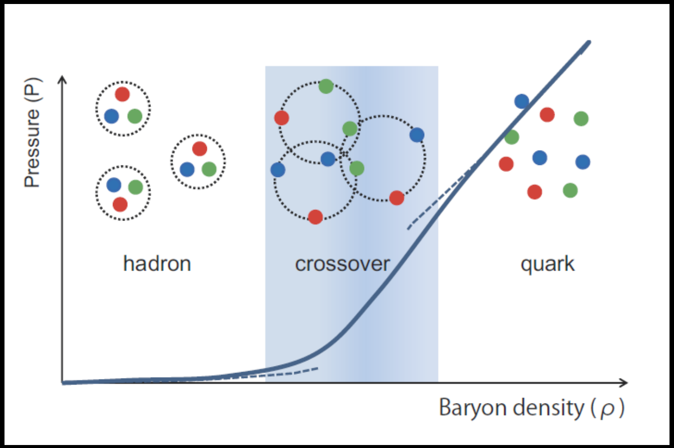
PSR J1614-2230 , 1.97(4) $M_\odot$, (Demorest et al., Nature 2010)

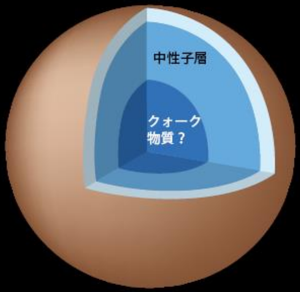


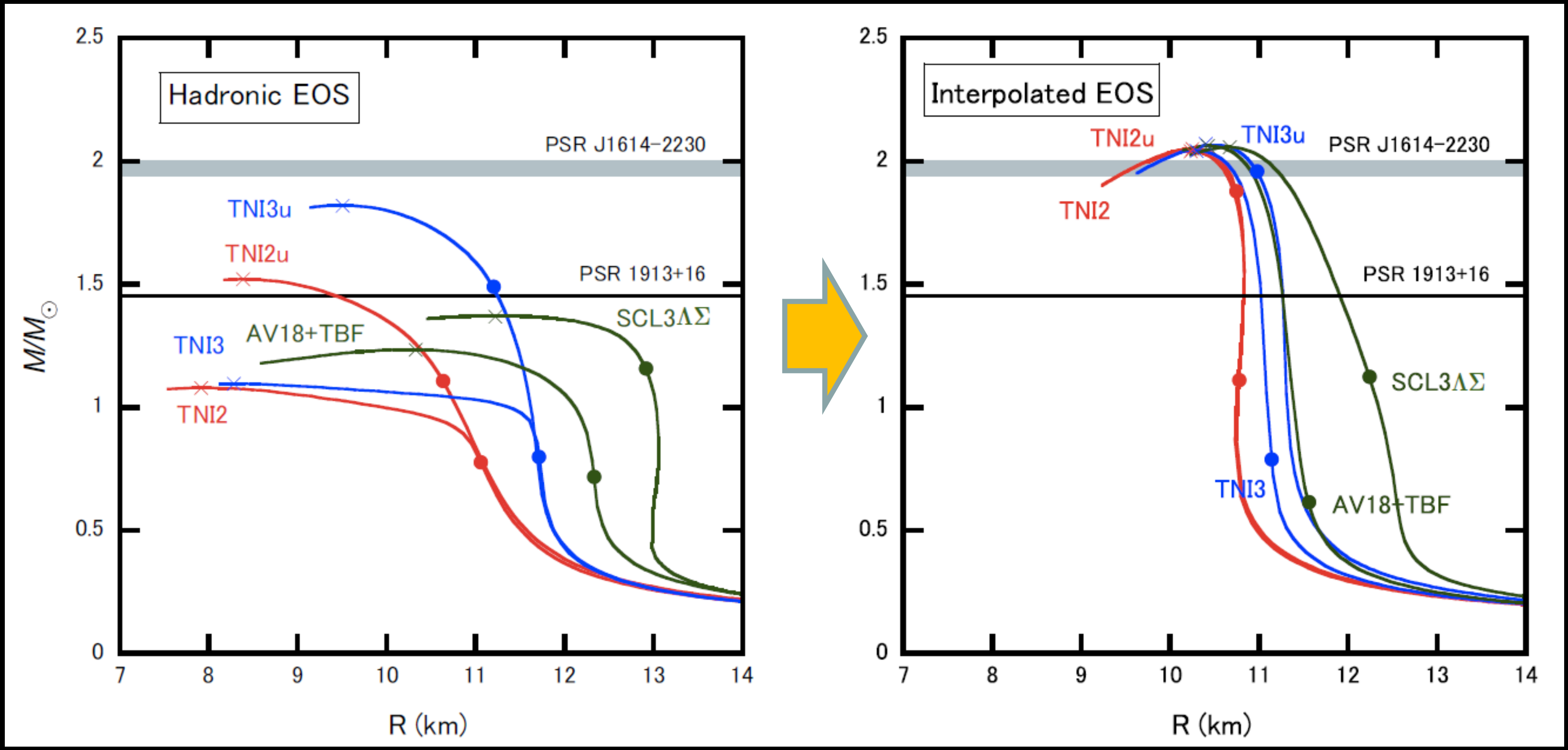
T, B, M

Hadron-Quark crossover in dense QCD

Hatsuda, Tachibana, Yamamoto & Baym, Phys. Rev. Lett. 97, 122001 (2006)



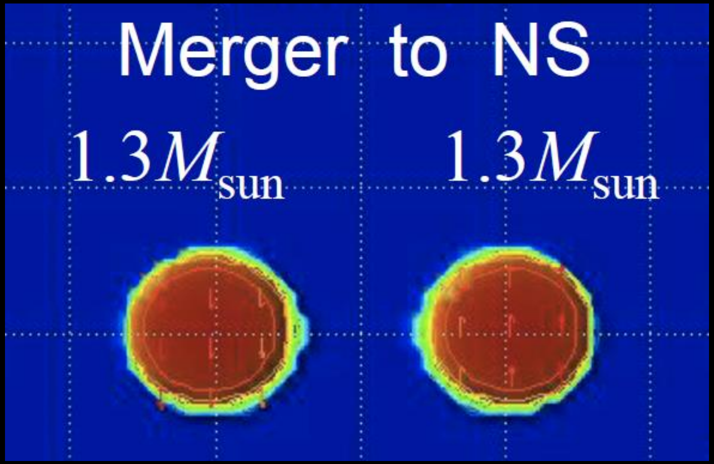




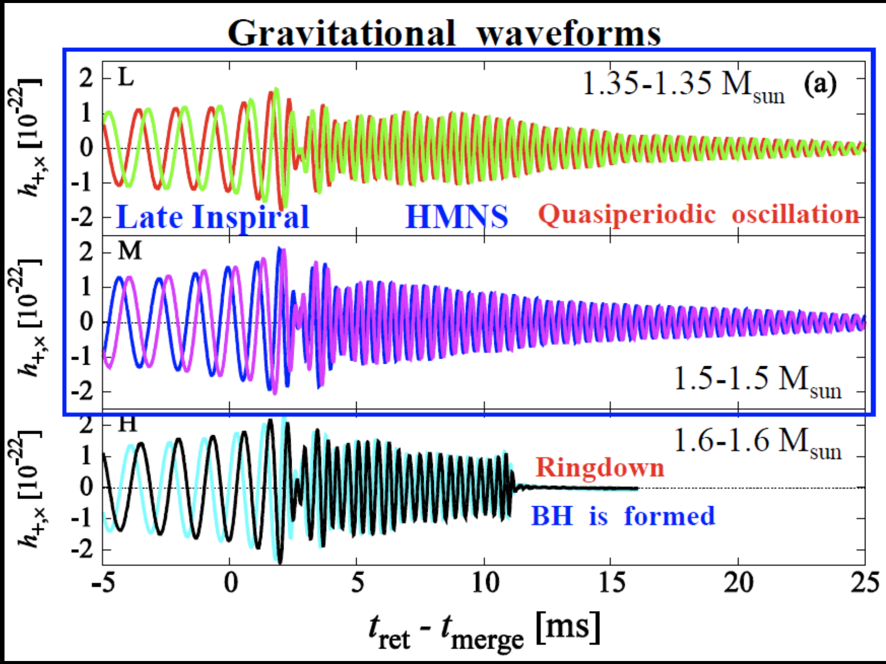
Masuda, Hatsuda & Takatsuka, Astrophysical Journal Letters 764 (2013) 12

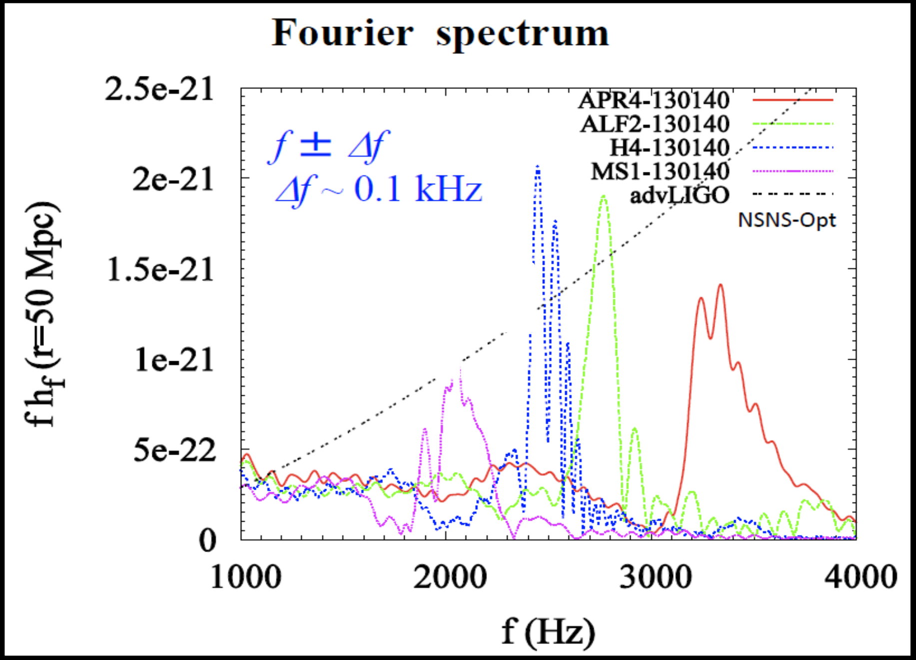
Gravitational wave from $N_{\star}$ merger

EOS from Gravitational Wave Detection



Sekiguchi, Kiuchi, Kyutoku & Shiata, PRL (2011)





Did we understand QCD better than before after all ?

1. Impressive progress for past 40 years

   ・ Theory : pQCD, lattice QCD, holography
   ・ Expt. : e-p, p-p, p-A, A-A expt., astro. obs.

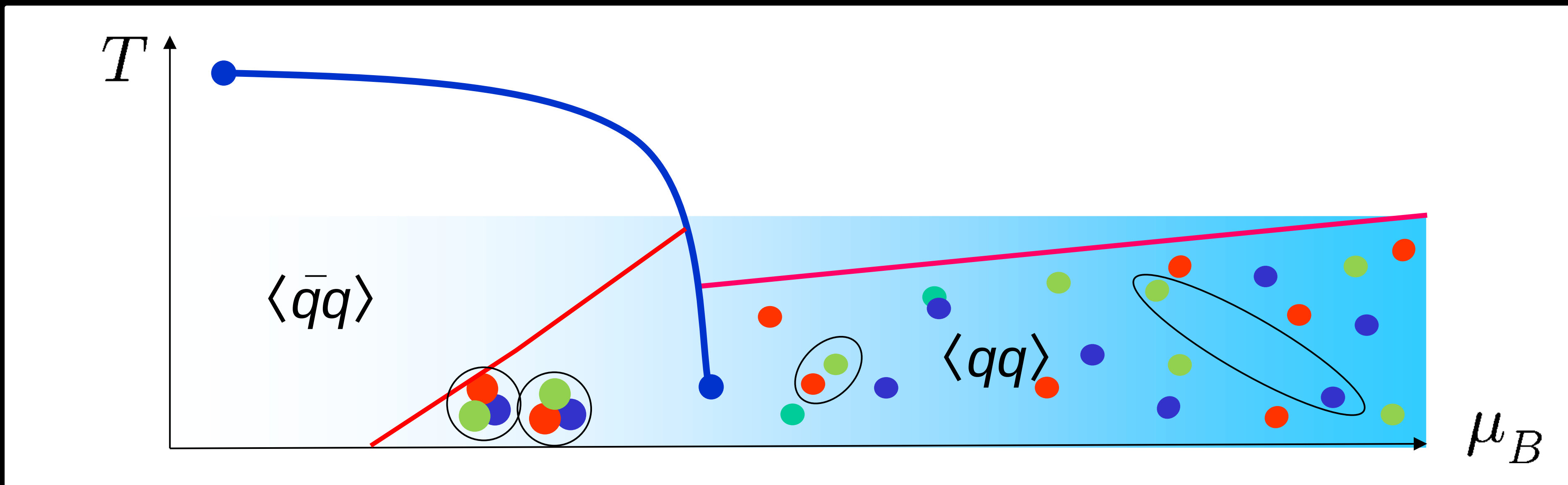
2. Understanding of QCD ~ understanding of glue

   ・ Asymptotic freedom : chromo para-magnetism (Nielsen, Hughes, 1981)
   ・ Confinement : no simple understanding yet
   ・ sQGP, sQM, CGC: <u>IR - UV crossover</u> (Q = T, μ, x)

3. Probe the role of glue through "Diquark" ?

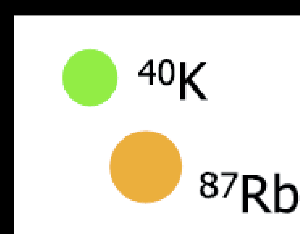
   ・ <u>Possible agent</u> to bridge IR - UV crossover in dense matter ?

Hadron-Quark Phase Transition and the role of "Diquarks"



Nuclear superfluid ⇔ Fermion+Diquark ⇔ Diquark superfluid

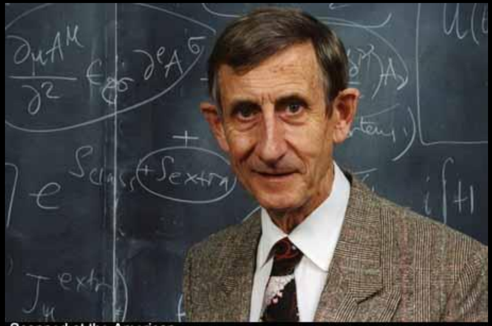
Induced superfluid ⇔ Fermi-Bose mixture



$$a_{\rm NN}^{\rm Born} = -\frac{m_{\rm N}}{2m_{\rm R}} a_{\rm bf}$$

Maeda, Baym & Hatsuda, Phys. Rev. Lett. 103 ('09)

Summary


Scanned at the American Institute of Physics

"The Scientist as Rebel"
by Freeman J. Dyson

It often happens that the understanding of the mathematical nature of an equation is impossible without a detailed understanding of its solutions. The black hole is a case in point.

→ GR

→ QCD

→ BH

→ Proton, QGP

The progress of science requires the growth of understanding in both directions, downward from the whole to the parts and upward from the parts to the whole.