Aug 30th. 2012
in Kyoto Univ

Quark-Hadron Phase Transition Including Finite Size Effects in Protoneutron Stars and Neutron Stars

2009a PRD, 2012 PRD submitted (arXiv1202.0143)

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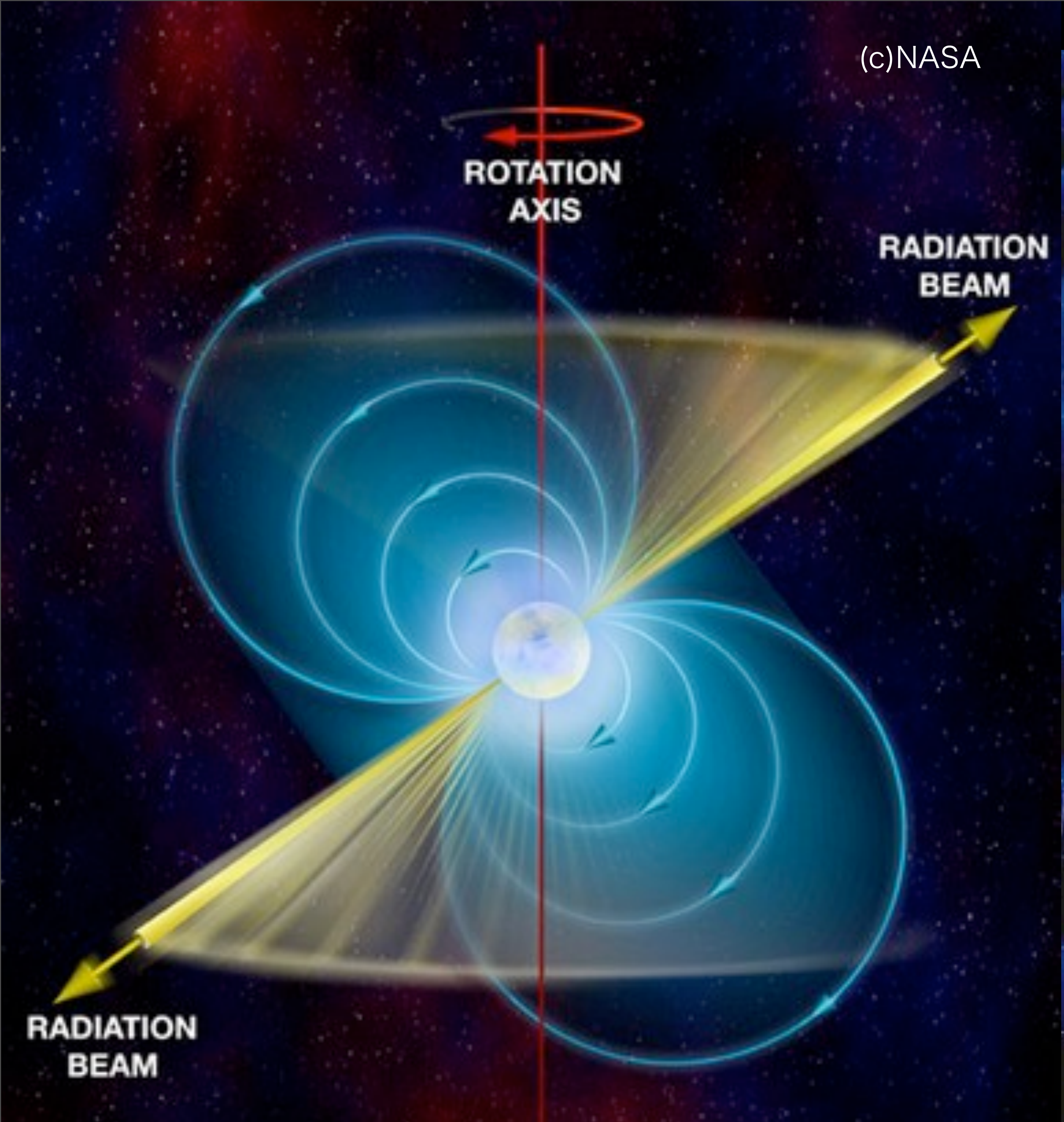
Toshitaka Tatsumi

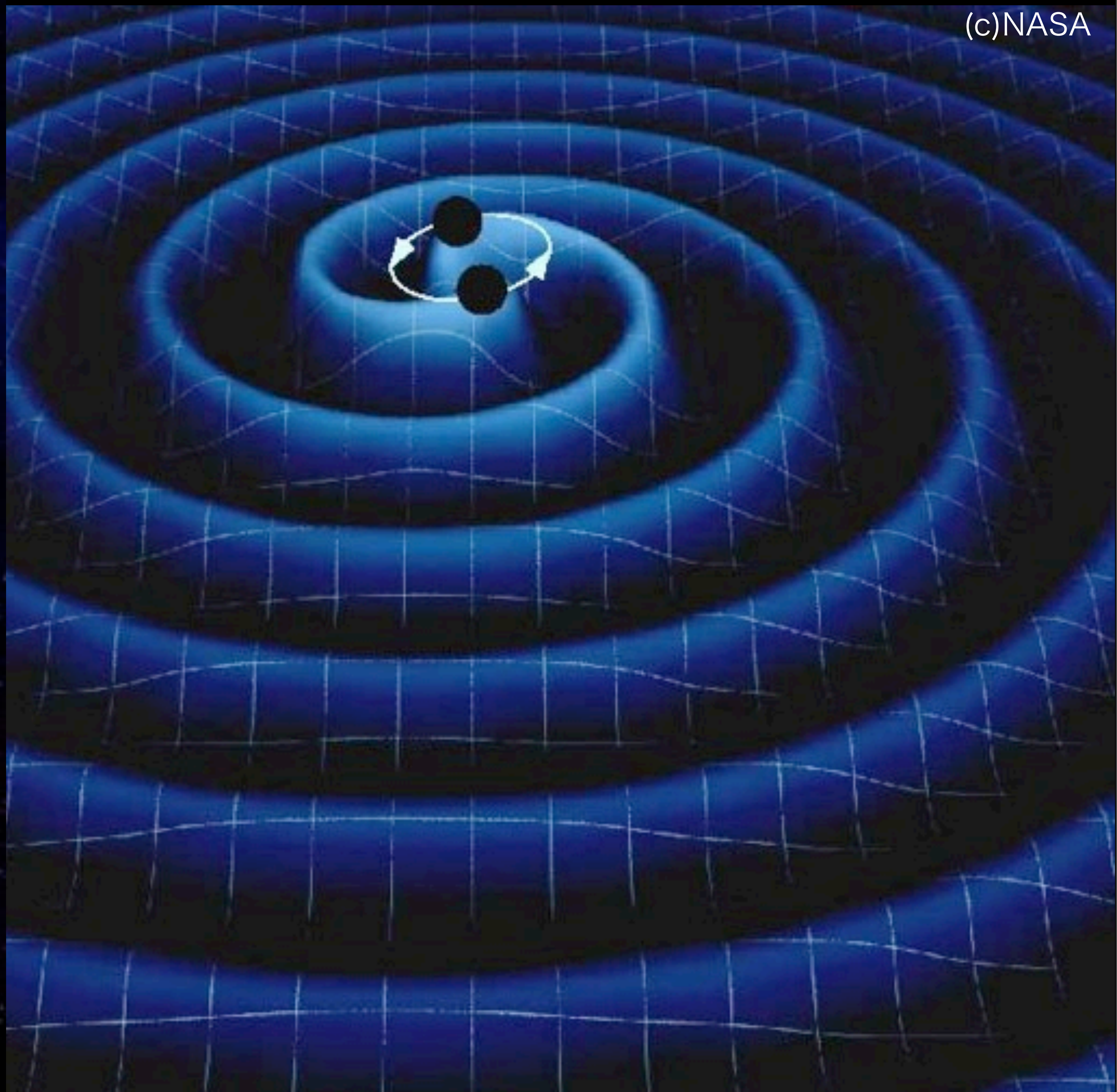


1967

Detection of a pulsar (neutron star)

1974

Nobel prize Hewish & Ryle

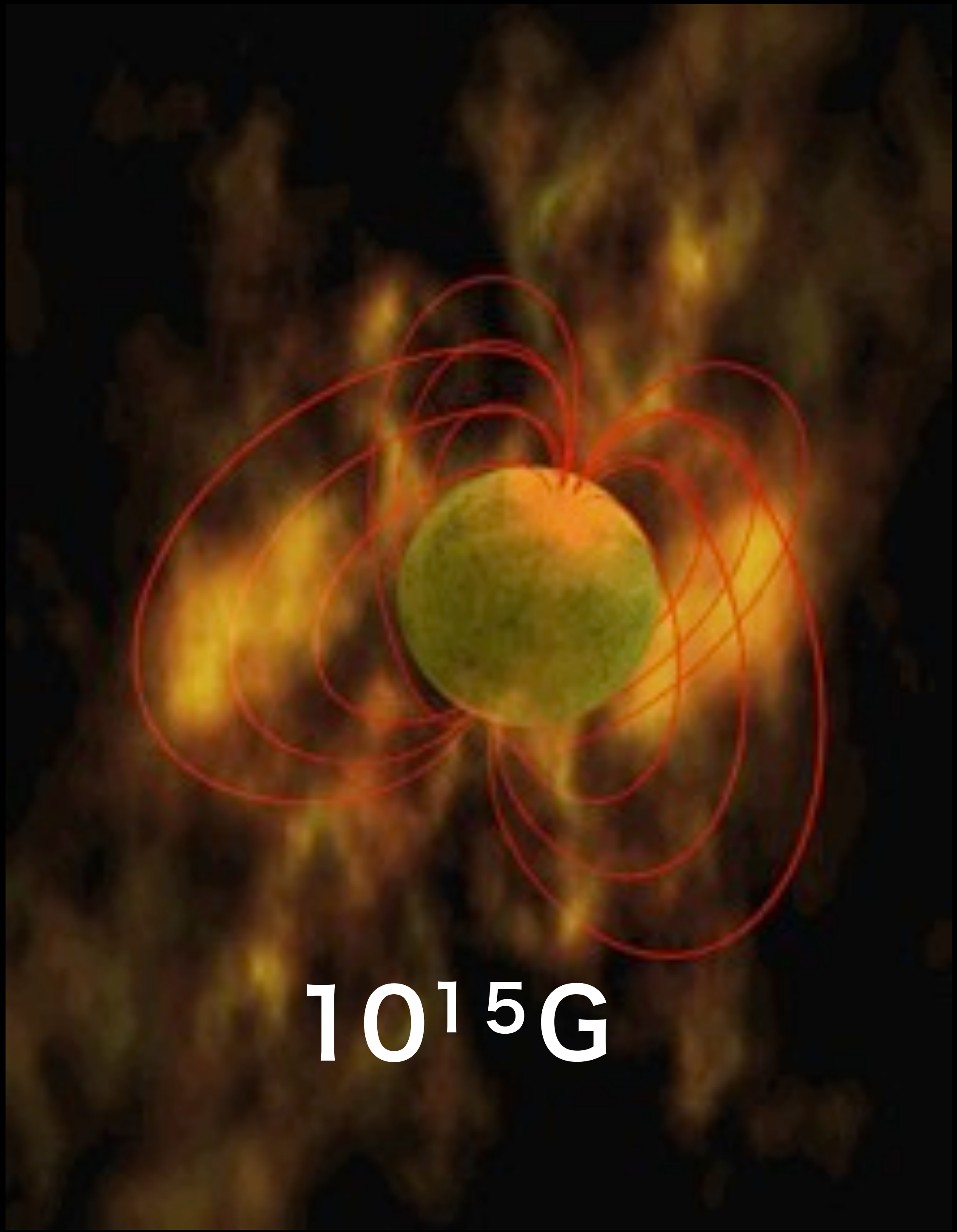


1974

Detection of binary pulsar (gravitational wave)

1993

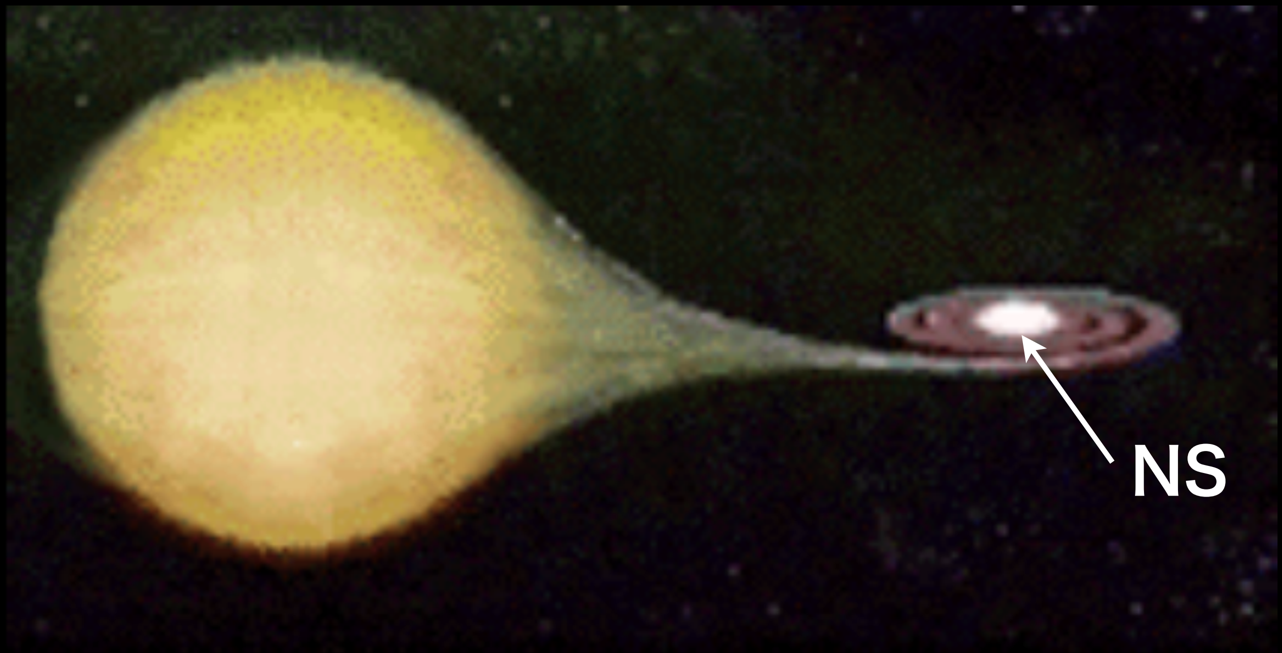
Nobel prize Hulse & Taylor



1979～

observation of magnetars

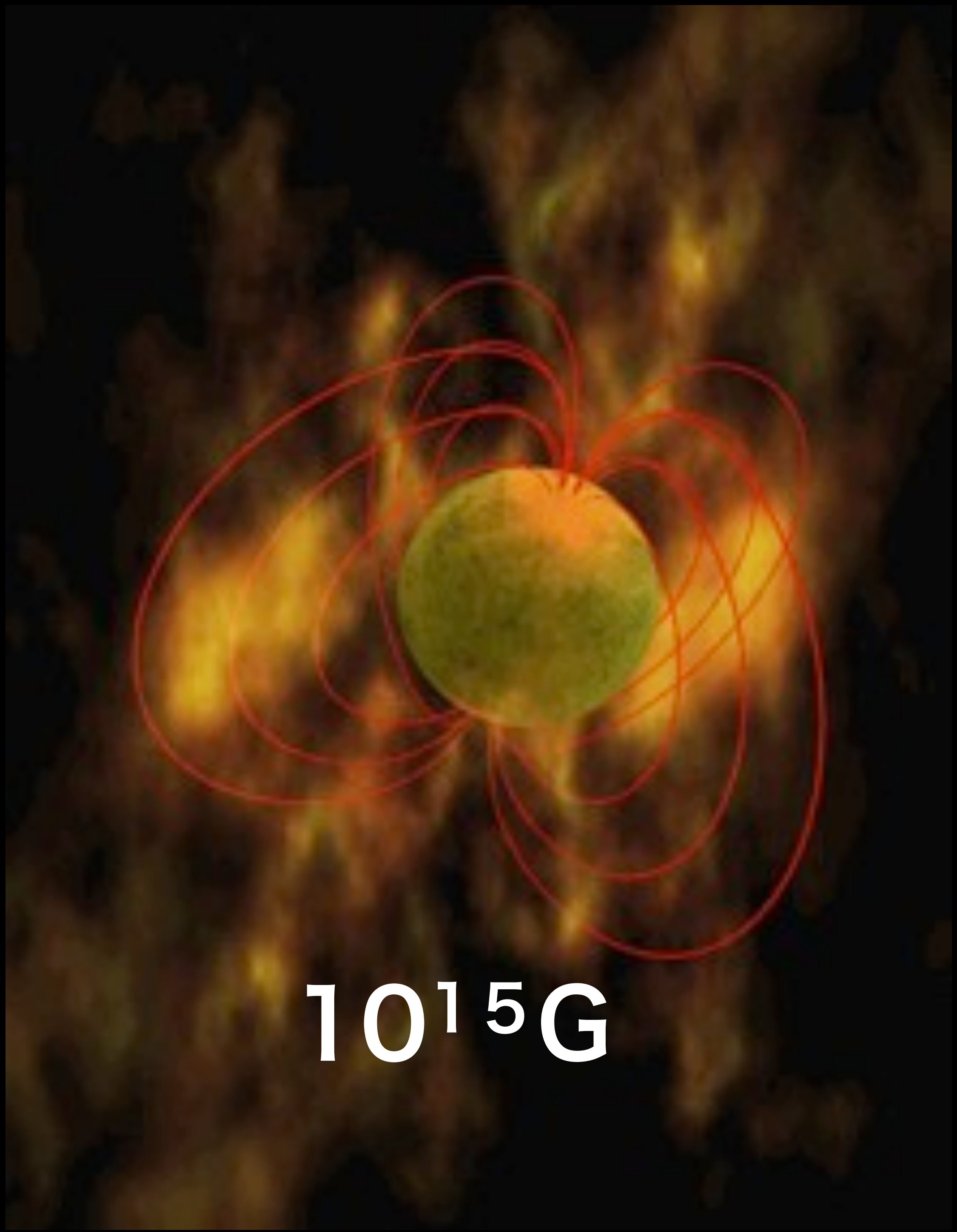
→What is the mechanism?
What does exist inside?



2007

Some X-ray transits have strong cooling mechanism.

→ Exotic matter



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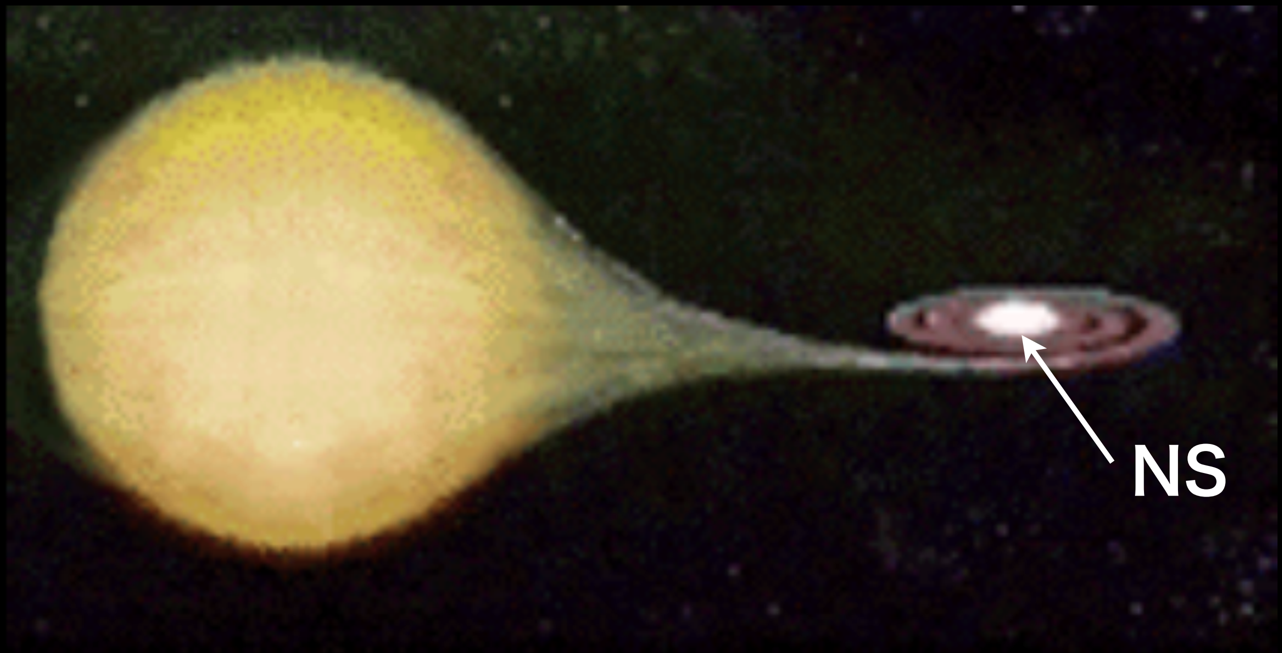


2007
Some X-ray transits have strong cooling mechanism.
→ Exotic matter

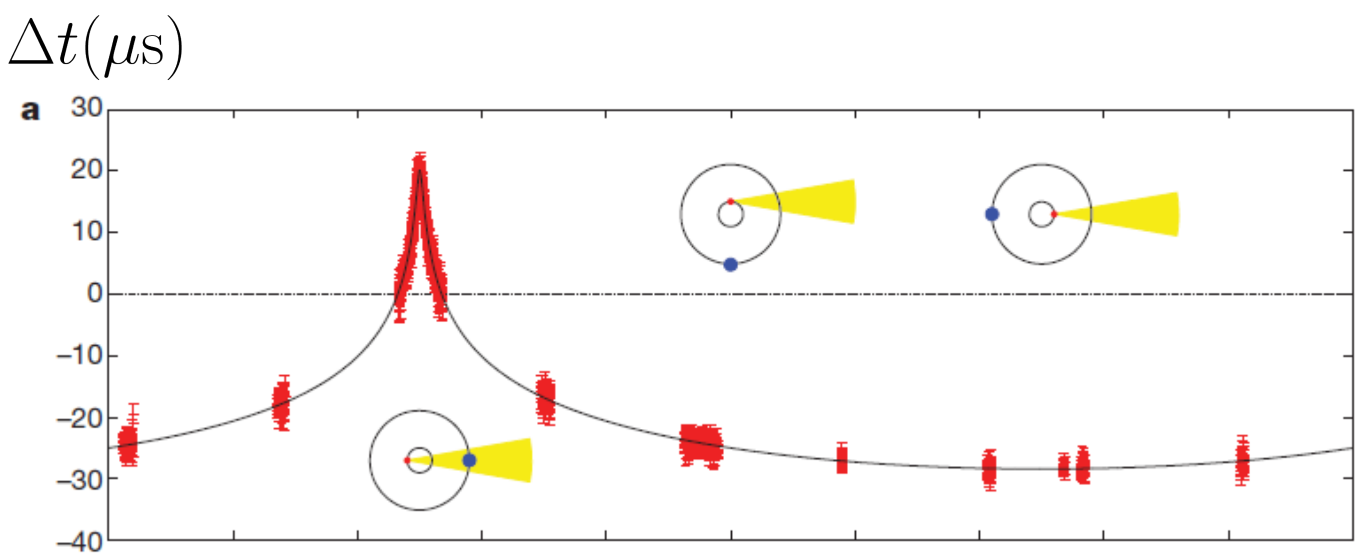
Matter inside of NSs

TWO SOLAR MASS PROBLEM

Demorest al. 2010 nature

A two-solar-mass neutron star measured using Shapiro delay

P. B. Demorest[1], T. Pennucci[2], S. M. Ransom[1], M. S. E. Roberts[3] & J. W. T. Hessels[4,5]



M~1.97 Ms

Shapiro delay

Radar signals passing near a massive object take slightly longer to travel to a target and longer to return than they would if the mass of the object were not present.

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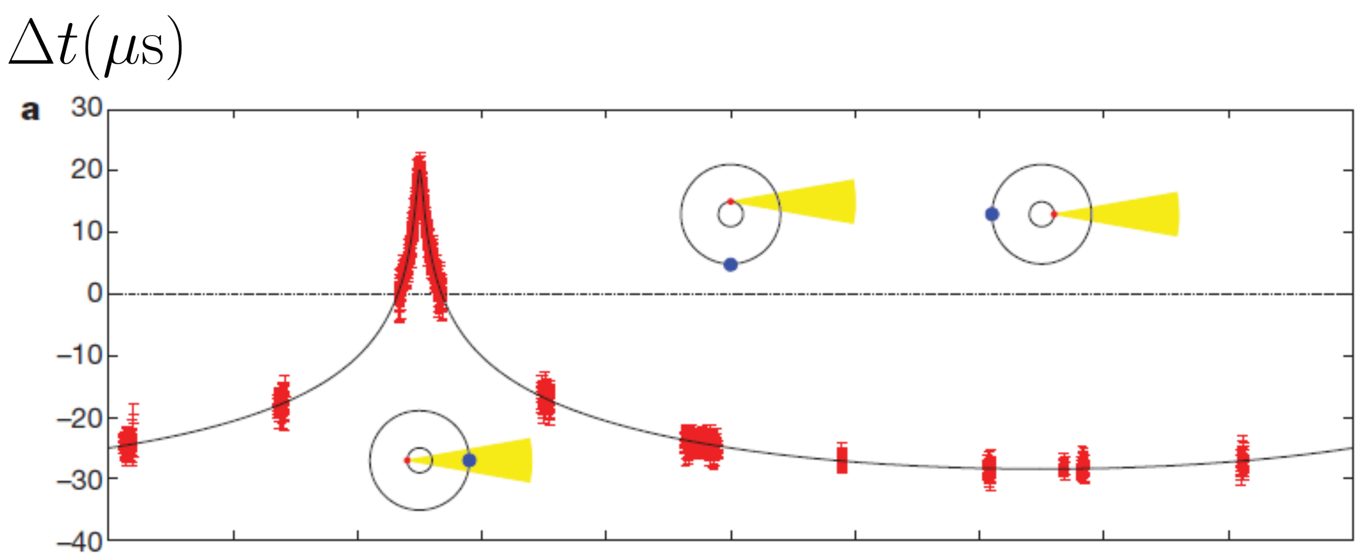

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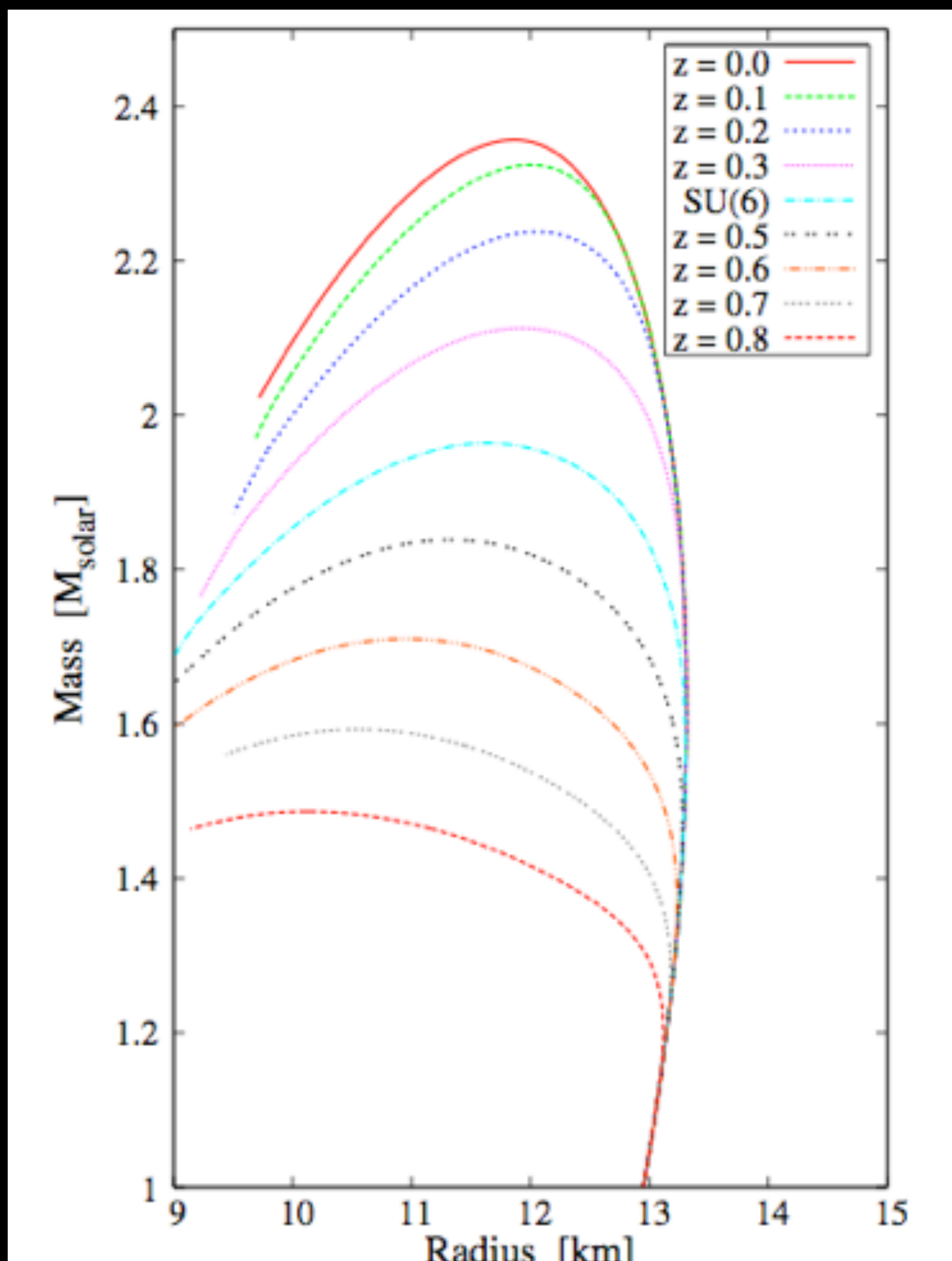
No Exotic matter ?

NSS WITH TWO SOLAR MASS CONSIDERING EXOTIC MATTER

Hyperon matter



S. Weissenborn, D. Chatterjee, and J. Schaffner-Bielich
PRC 85, 065802 (2012)

Hyperon + Quark matter (cross over)

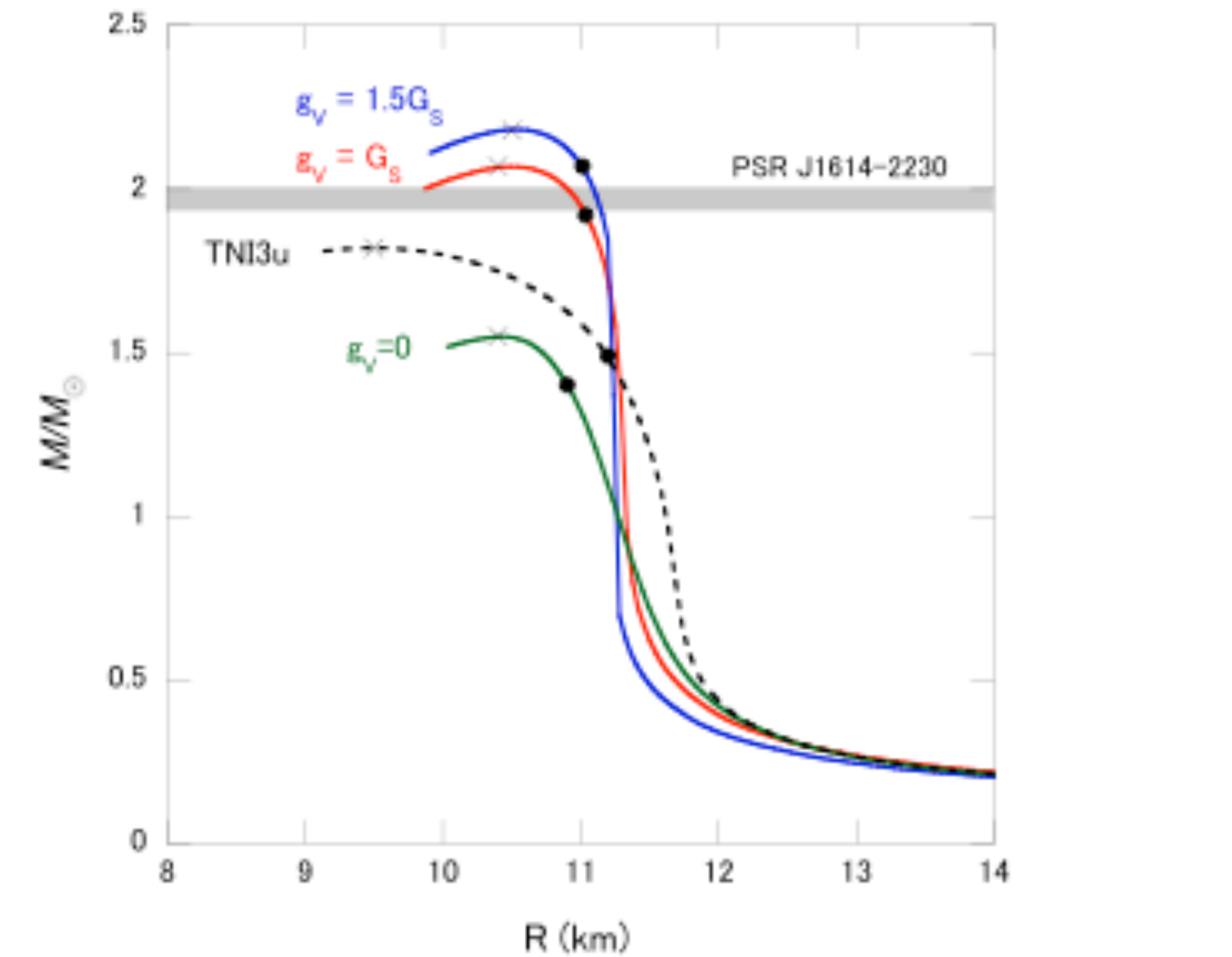


FIG. 5.— Solid lines: M-R relation of the NSs with the interpolated EOSs for $g_V/G_S = 0, 1.0, 1.5$. Dashed line: The same quantity for H-EOS with TNI3u. The cross symbols denote the points where M reaches $M_{\rm max}$. The filled circles denote the point beyond which the strangeness appears. The gray band denotes $M = (1.97 \pm 0.04)M_\odot$ for PSR J1614-2230 (Demorest et al. (2010).)

Masuda, Hatsuda, Takatsuka
arXiv:1205.3621

SITUATIONS OF NUCLEAR PHYSICS

“BARYON-BARYON INTERACTIONS MAY BE CLEARED IN A FEW YEARS ”

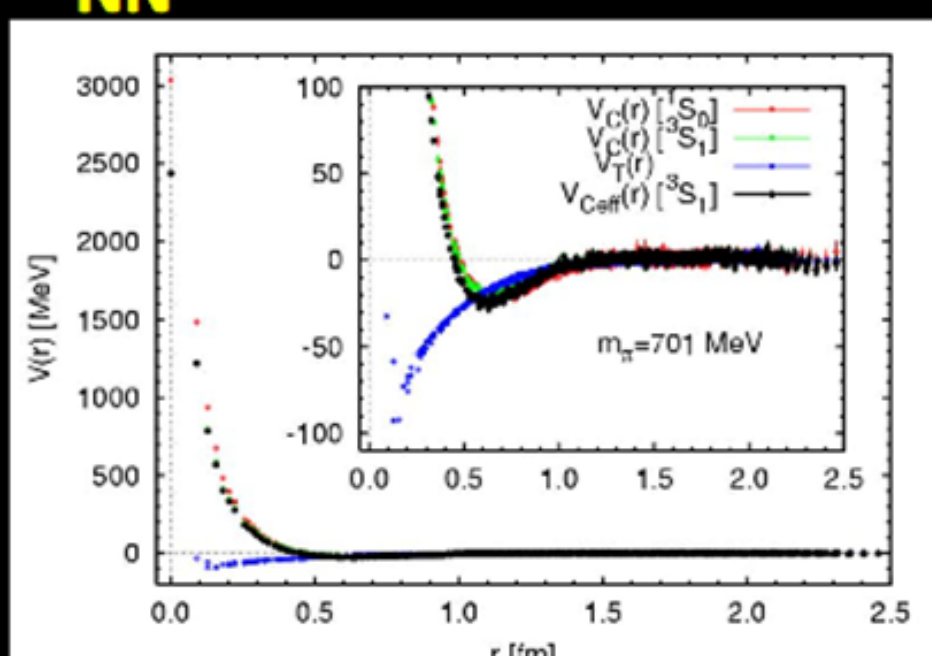
J-PARC starts to operate in 2009

?

Full QCD (m_π=701 MeV, a=0.09 fm, L=2.9 fm

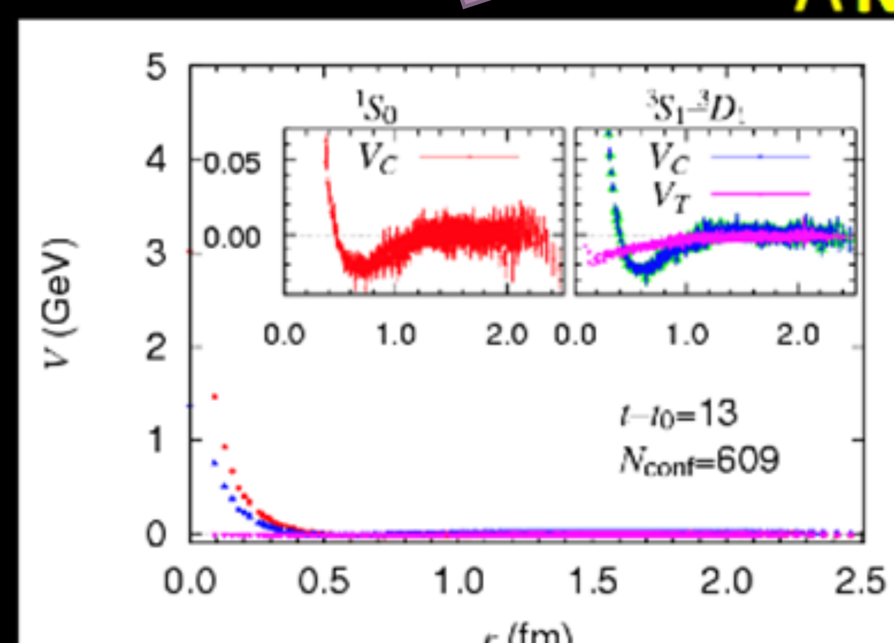
using PACS-CS configuration

NN



Ishii, Aoki & Hatsuda (2009)

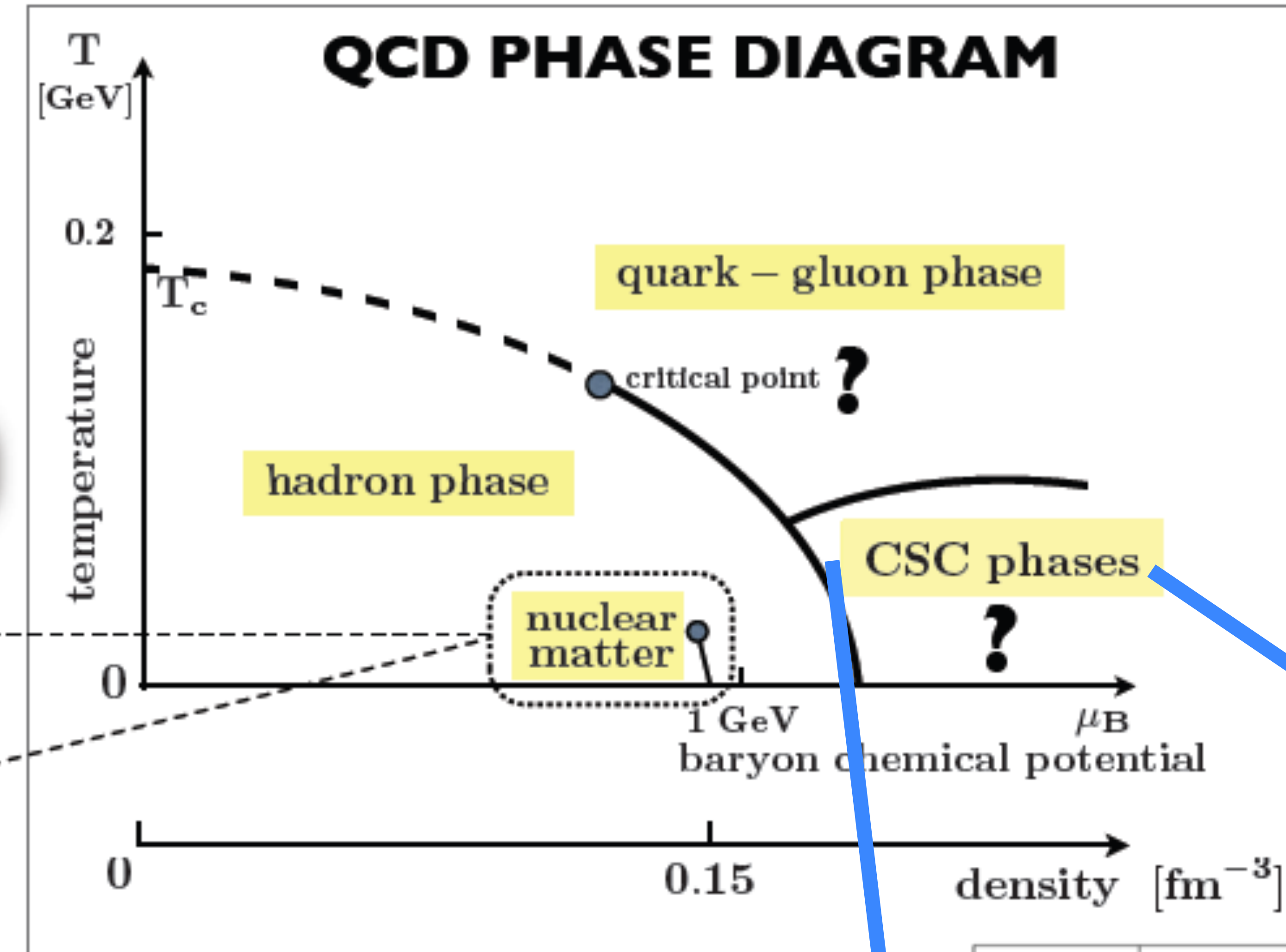
ΛN



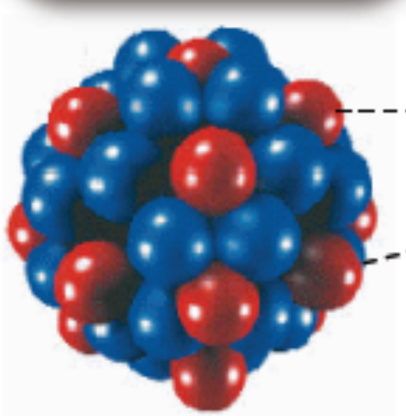
Nemura, Ishii, Aoki & Hatsuda (2009)

1 Prelude: PHASES and STRUCTURES of QCD

(c) Weise

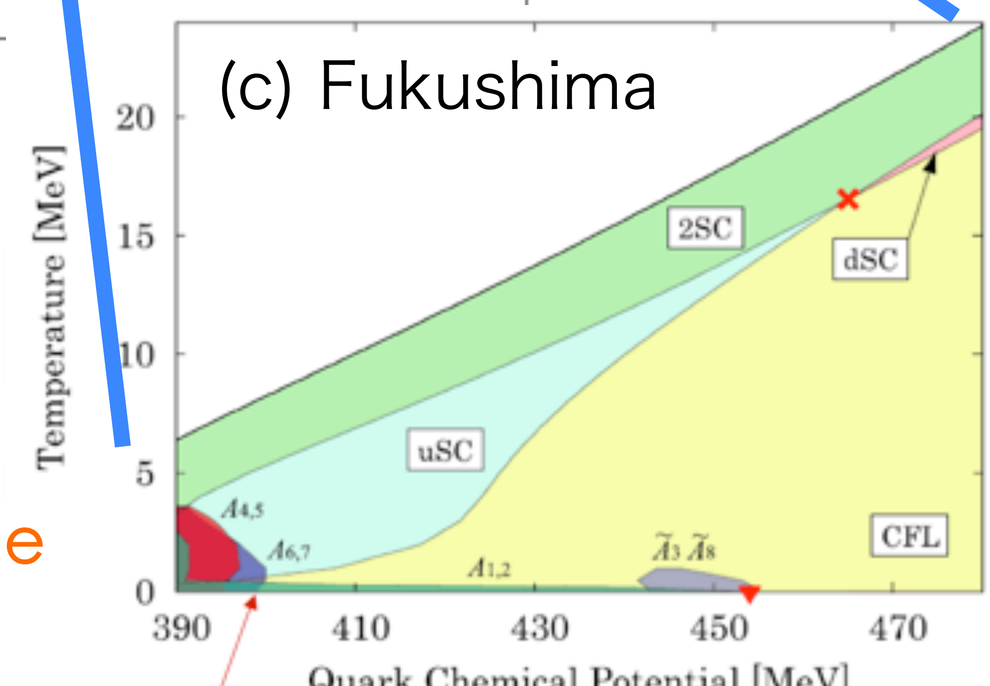


nuclei



Astrophysical Topic

- Origin of magnetic field ?
- Mechanism of cooling?
- Why M > 2 Ms?

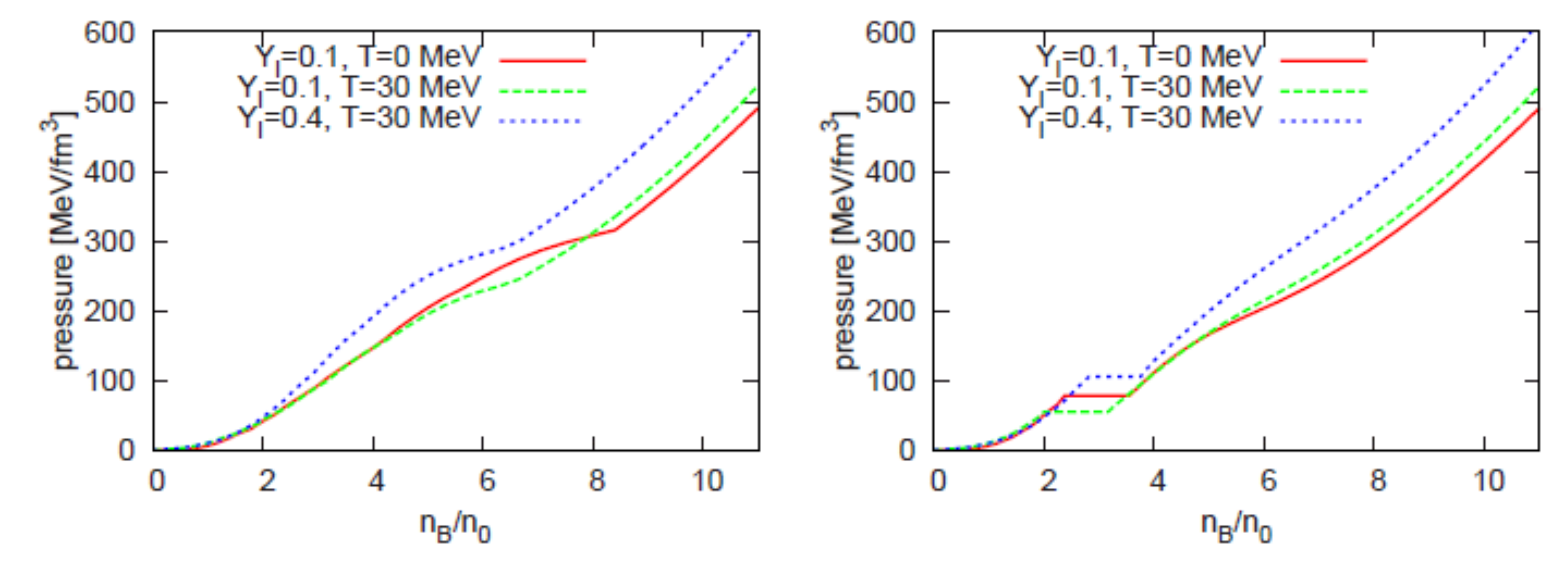


We can not see them by Supernovae and black hole formation.

Another uncertainty of finite size effects in quark-hadron phase transition

NY & Kashiwa, PRD, (2009)

Shen EOS + NJL model



the bulk Gibbs condition

the Maxwell construction

↑

the finite effects

Uncertainty of phase transition

Schaffner group (Heiderberg Univ.) 2009

TABLE III. As Table II, but now for the hadron-quark phase transition. $\mu_d = \mu_s$ is valid if strangeness is in equilibrium.

Case	Conserved densities/fractions Globally	Locally	Equilibrium conditions	Construction of mixed phase
0		n_B, (Y_p), (Y_L), n_C	-	Direct
Ia	n_B	Y_p, Y_L, n_C	$(1-Y_p)\mu_n + Y_p(\mu_p + \mu_e^H) + (Y_L - Y_p)\mu_\nu^H = (2-Y_p)\mu_d + (1+Y_p)\mu_u + Y_p\mu_e^Q + (Y_L - Y_p)\mu_\nu^Q$	Maxwell
Ib	n_B	Y_L, n_C	$\mu_n + Y_L\mu_\nu^H = 2\mu_d + \mu_u + Y_L\mu_\nu^Q$	Maxwell
Ic	n_B	Y_p, n_C	$(1-Y_p)\mu_n + Y_p(\mu_p + \mu_e^H) = (2-Y_p)\mu_d + (1+Y_p)\mu_u + Y_p\mu_e^Q$	Maxwell
Id	n_B	n_C	$\mu_n = 2\mu_d + \mu_u$	Maxwell
IIa	n_B, Y_L	Y_p, n_C	$(1-Y_p)\mu_n + Y_p(\mu_p + \mu_e^H) = (2-Y_p)\mu_d + (1+Y_p)\mu_u + Y_p\mu_e^Q$, $\mu_\nu^H = \mu_\nu^Q$	Maxwell/Gibbs
IIb	n_B, Y_L	n_C	$\mu_n = 2\mu_d + \mu_u$, $\mu_\nu^H = \mu_\nu^Q$	Gibbs
IIIa	n_B, Y_p	Y_L, n_C	$\mu_n + Y_L\mu_\nu^H = 2\mu_d + \mu_u + Y_L\mu_\nu^Q$, $\mu_p - \mu_n - \mu_\nu^H + \mu_e^H = \mu_u - \mu_d - \mu_\nu^Q + \mu_e^Q$	Gibbs
IIIb	n_B, Y_p	n_C	$\mu_n = 2\mu_d + \mu_u$, $\mu_p + \mu_e^H = 2\mu_u + \mu_d + \mu_e^Q$	Gibbs
IV	n_B, Y_L, Y_p	n_C	$\mu_n = 2\mu_d + \mu_u$, $\mu_\nu^H = \mu_\nu^Q$, $\mu_p + \mu_e^H = 2\mu_u + \mu_d + \mu_e^Q$	Gibbs
V	n_B, Y_L, Y_p, n_C		$\mu_n = 2\mu_d + \mu_u$, $\mu_\nu^H = \mu_\nu^Q$, $\mu_p = 2\mu_u + \mu_d$, $\mu_e^H = \mu_e^Q$	Gibbs

INSIDE MATTER AND NATURAL FREQUENCY

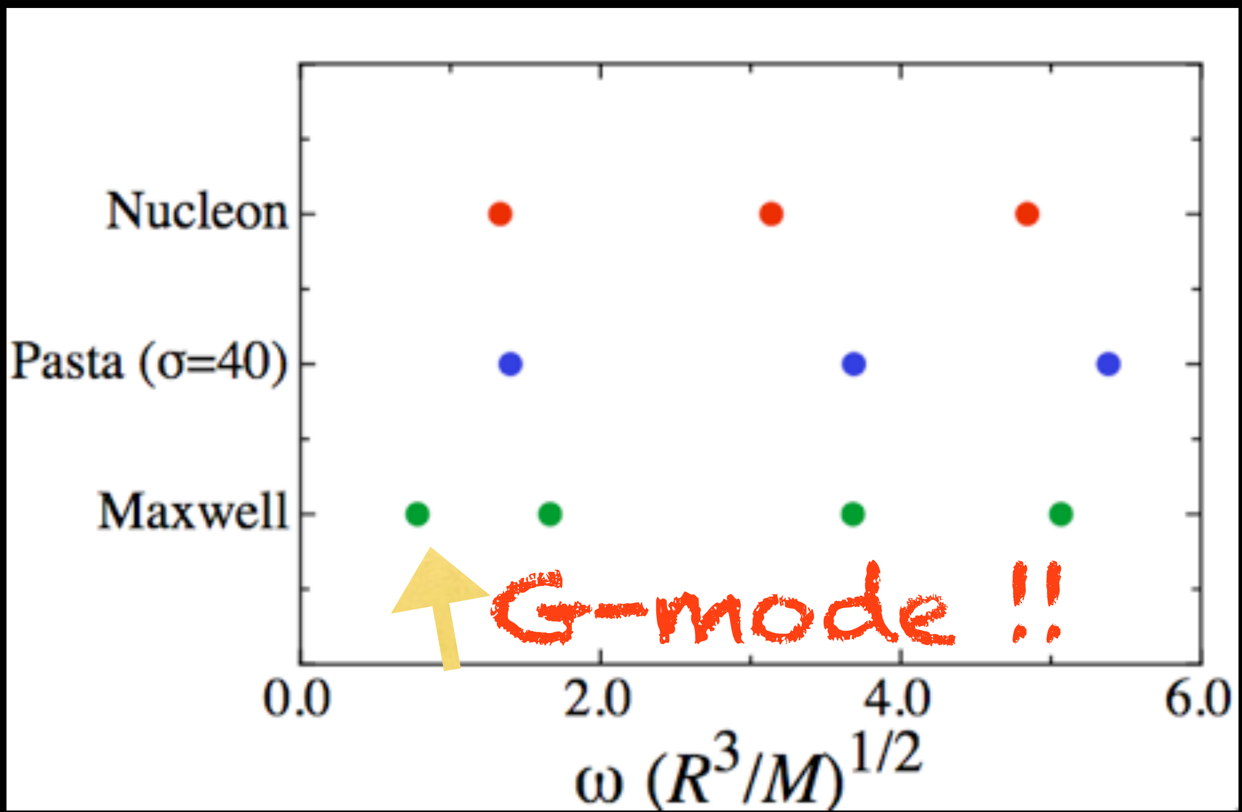
Sotani, **NY**, Maruyama, Tatsumi 2011 PRD

Neutron Star

【Astrophysical Phenomena】

- Giant Flare from magnetars
- Sudden accretion to NSs

Analytic method



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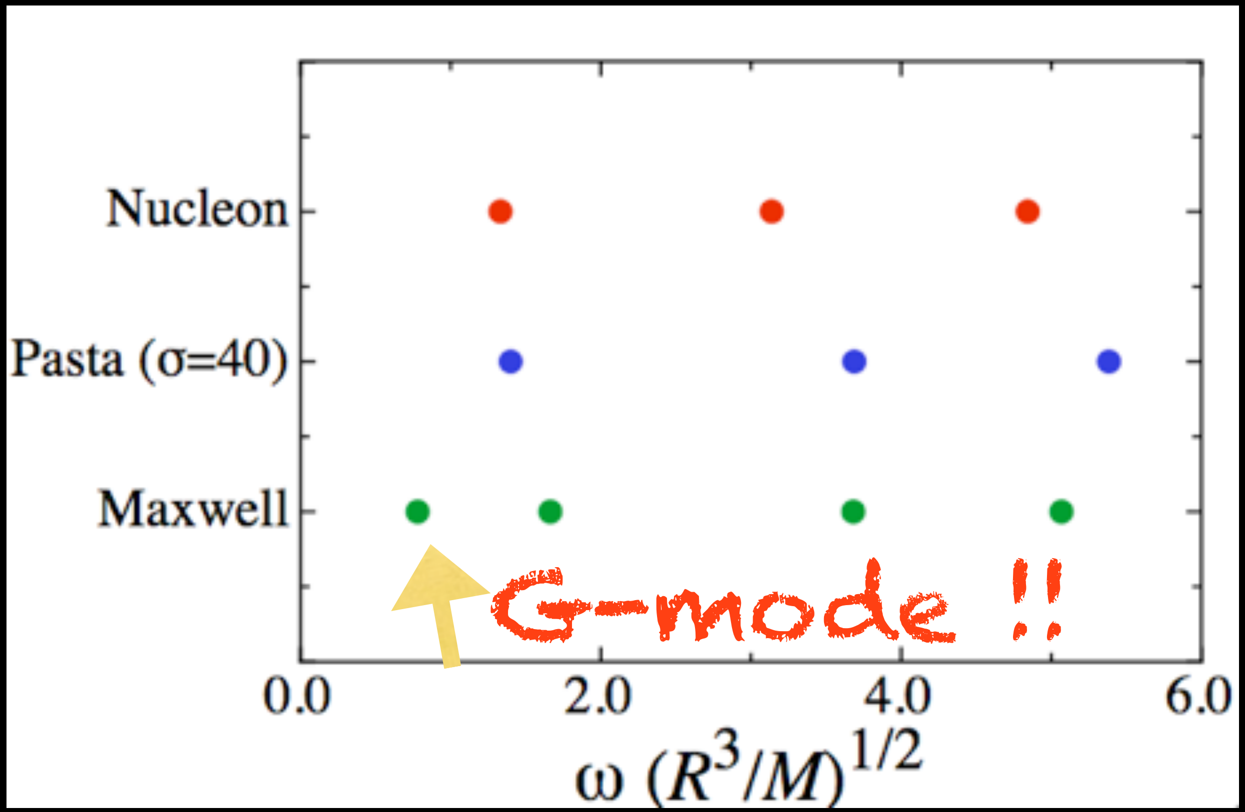
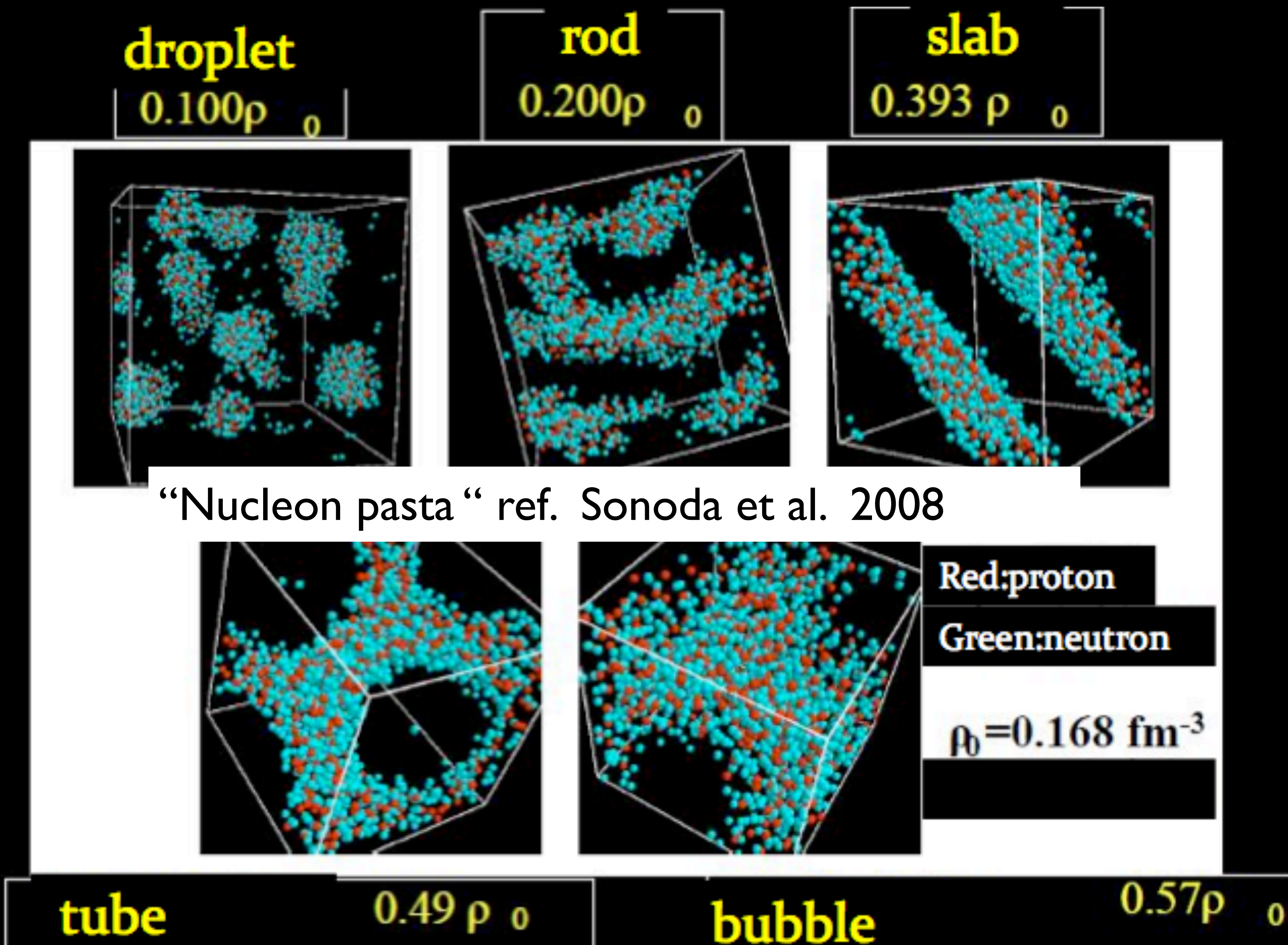


FIRST ORDER PHASE TRANSITION IN MULTI-COMPONENT SYSTEM



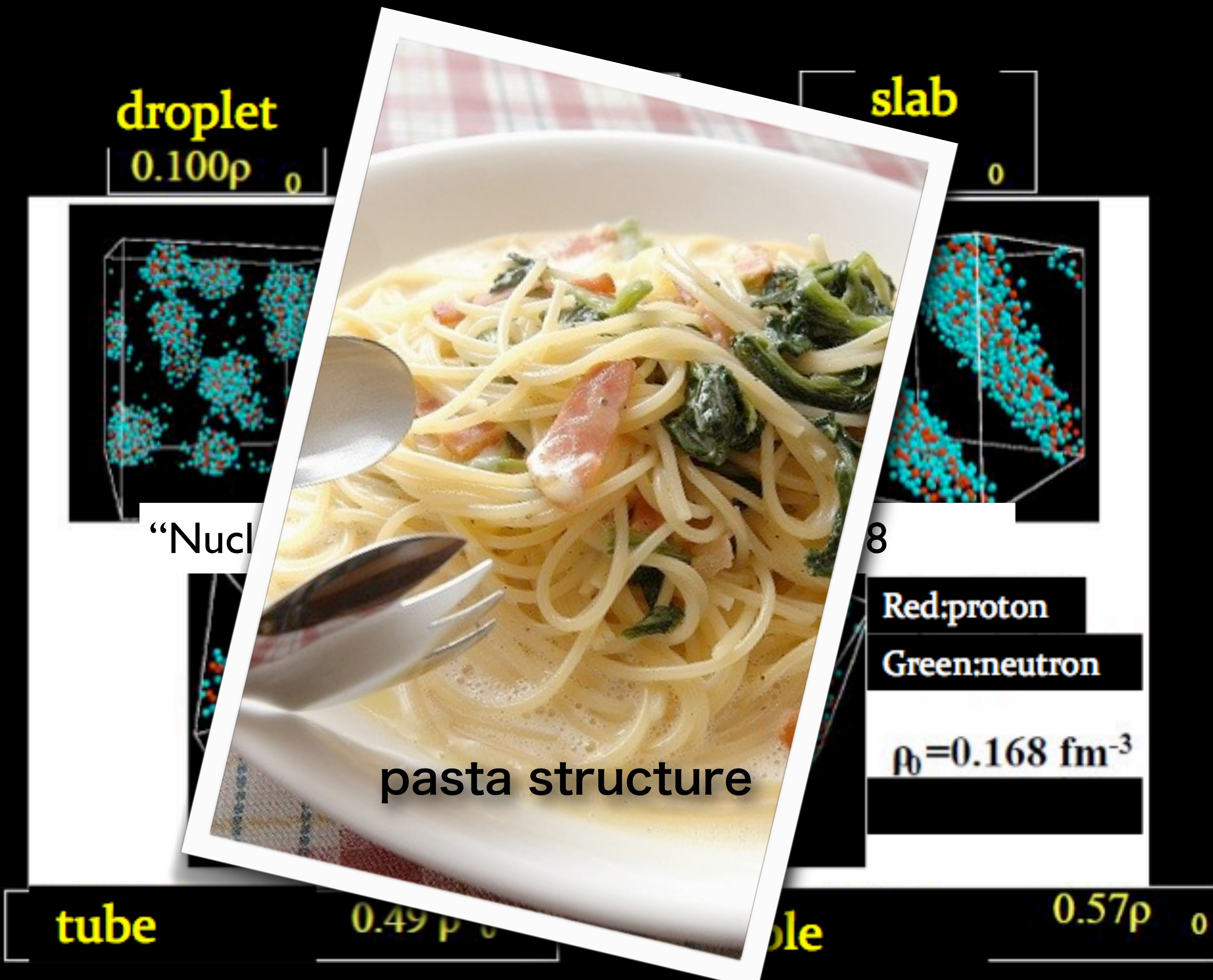
“Nucleon pasta“ ref. Sonoda et al. 2008

Depended on

- density
- temperature
- Coulomb interactions
- surface tension

→ neutron drip / quark-hadron phase transition etc.

FIRST ORDER PHASE TRANSITION IN MULTI-COMPONENT SYSTEM



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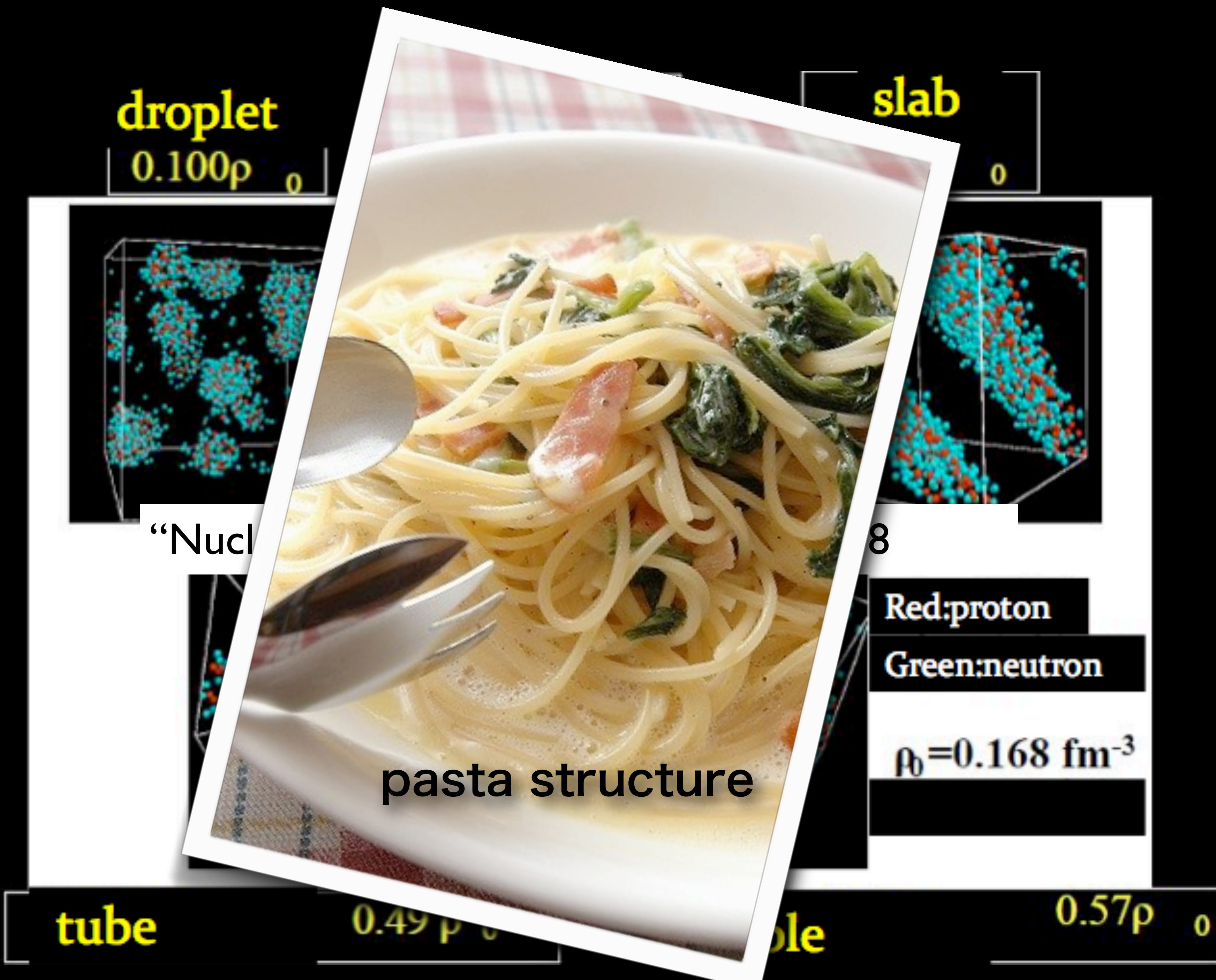


Depended on

- density
- temperature
- Coulomb interactions
- surface tension

→ neutron drip / quark-hadron phase transition etc.

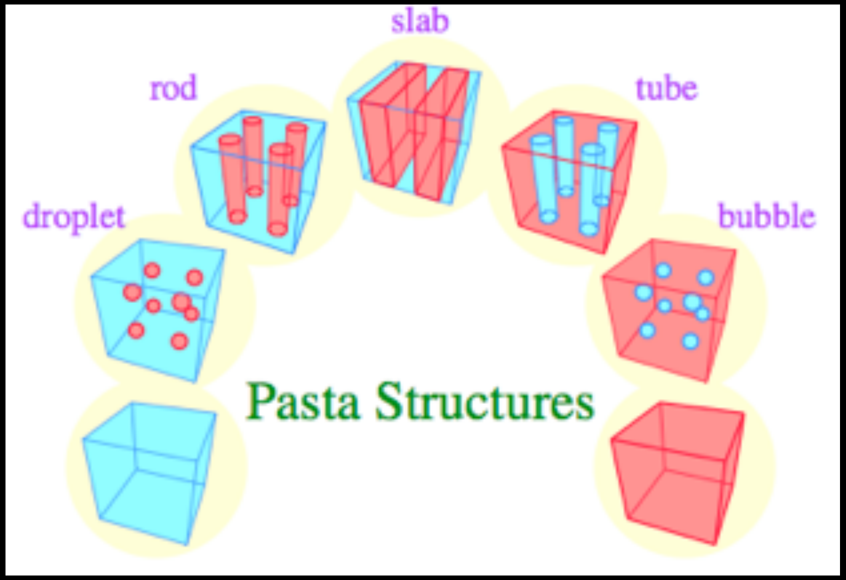
CALCULATION DETAILS

Hadron matter
Brueckner-Hartree-Fock model with hyperons (Baldo et al. 1998, Schulze et al. 1995)
NN interaction → Argonne V18 potential + UIX phenomenological three body forces
NY interaction → Nijmegen soft-core 89 potential
(**We will update the interactions by the results of “ lattice QCD ” and/or “ J-PARC ”.**)

+

Quark matter
Thermodynamic bag model (“bag constant” or “density dependent bag model”)
(We will change this simple model to (p)NJL model or DSE.)

We assume the pasta structures of the mixed phase as droplet, rod, slab, tube, and bubble under Wigner-Seitz cell approximation (right panel).



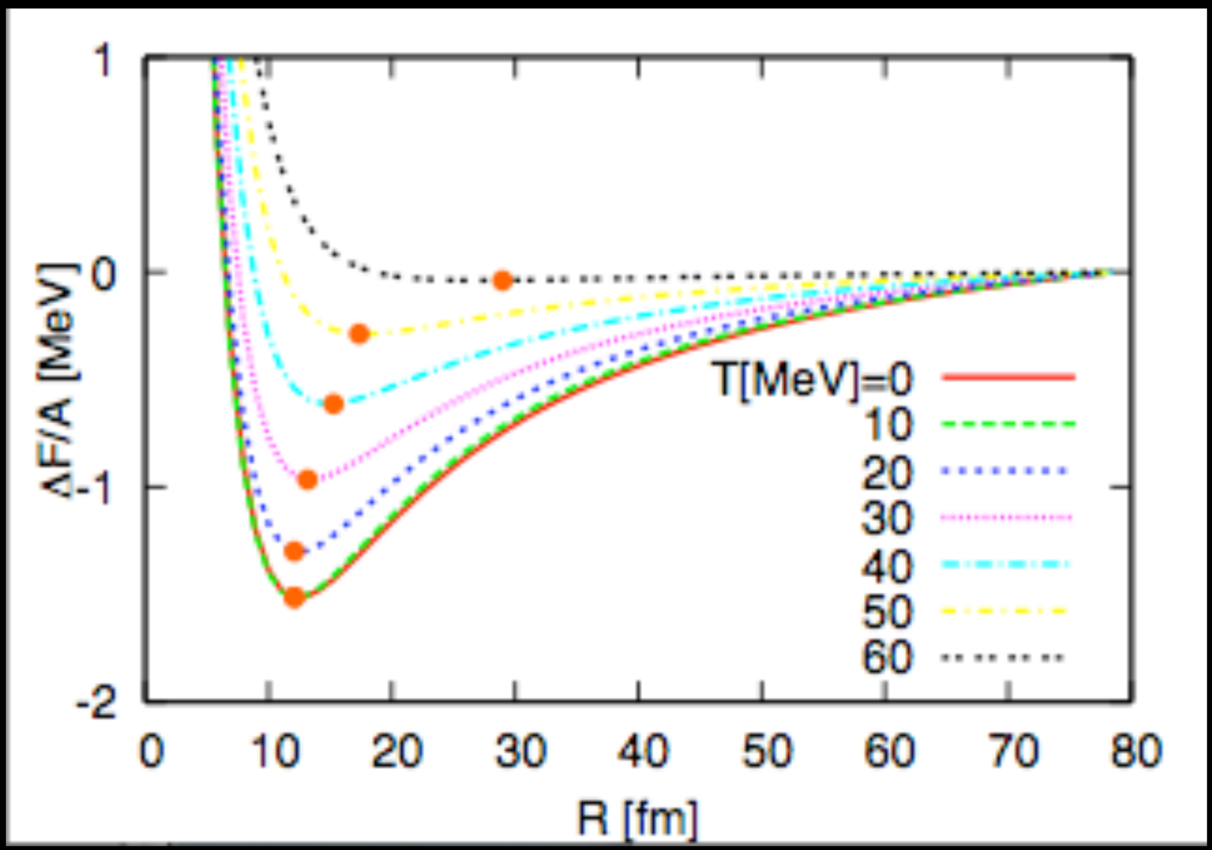
In calculations of mixed phase, we consider

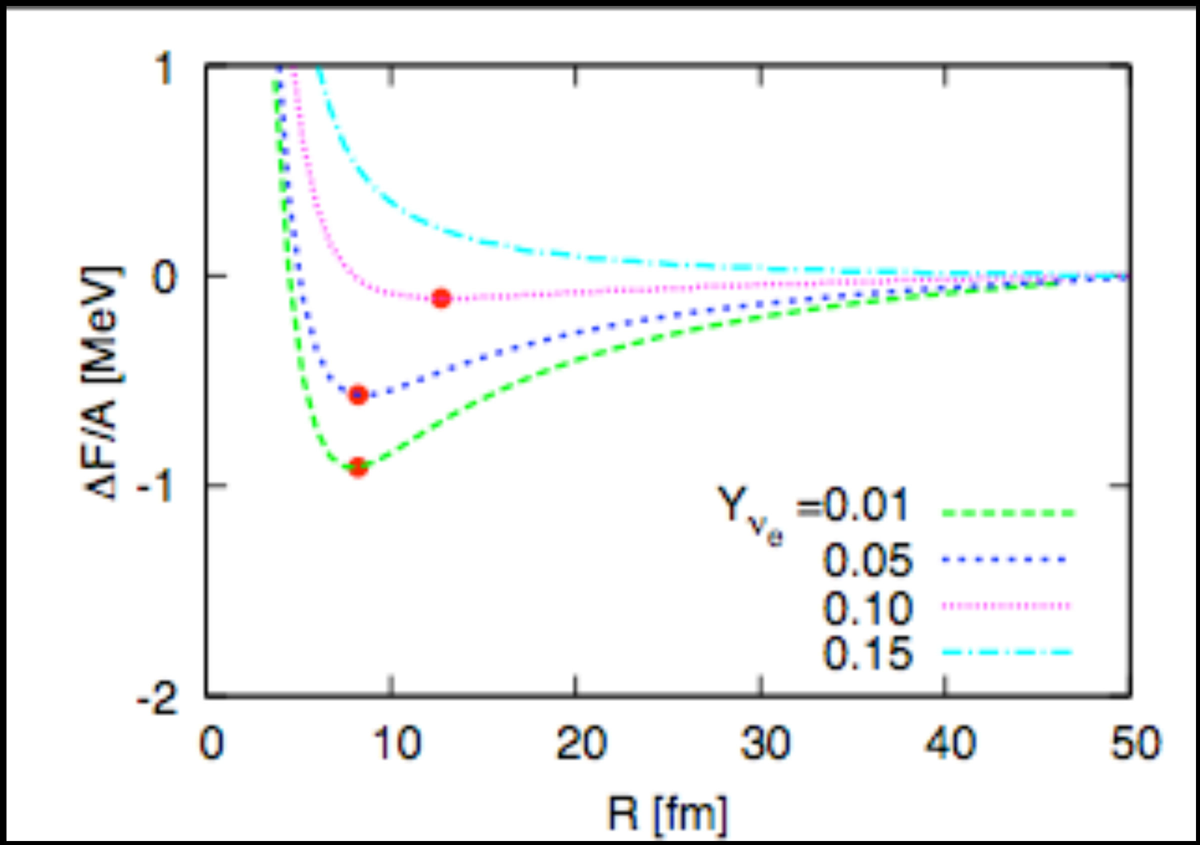
- charge neutrality
- chemical equilibrium
- baryon number conservation
- balance between “surface tension” and “Coulomb interaction”

STABILITY CURVES OF MIXED PHASE

"Temperature" and "neutrino fraction" makes pasta structures unstable.

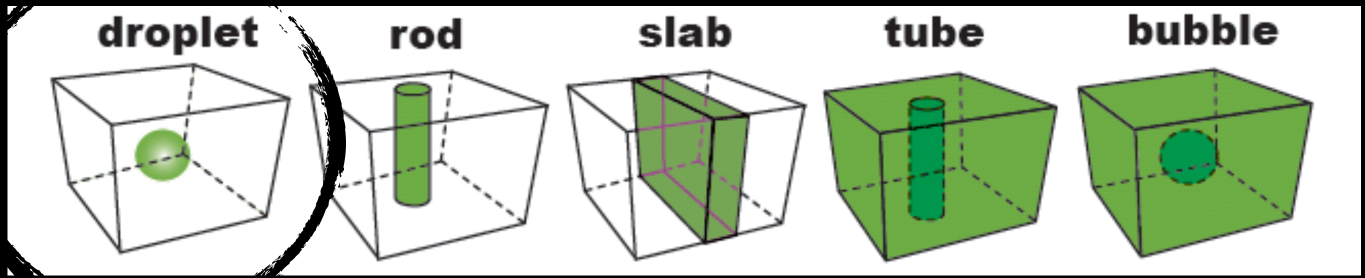
NY et al. 2009b PRD, 2012 PRD submitted.





$\rho=2\rho_0$, constant B = 100 MeV/fm^3

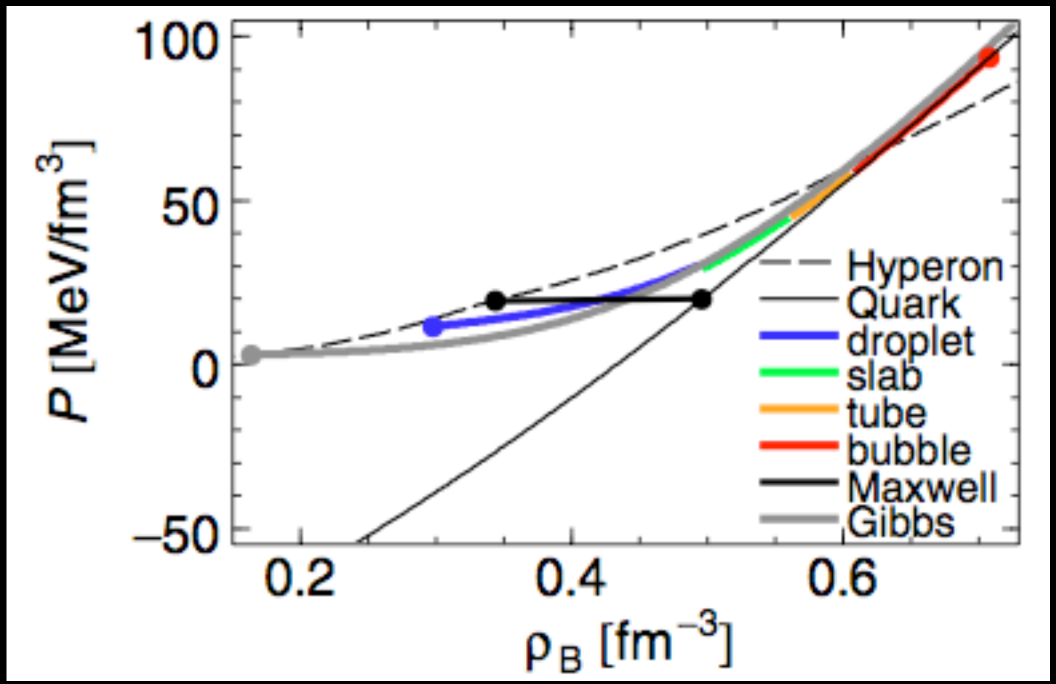
$\rho=2.5\rho_0$, density dependent B



σ = 40 MeV/fm^3

THERMAL EFFECTS ON EOS

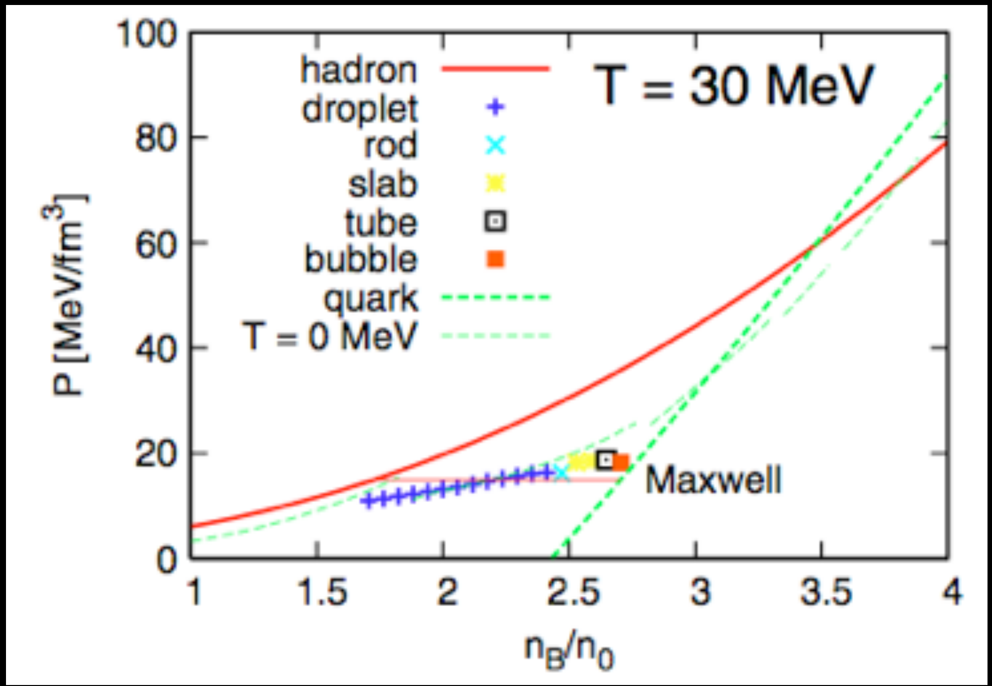
Maruyama et al. 2007 PRC



NS matter (weak σ)
→ No density jump

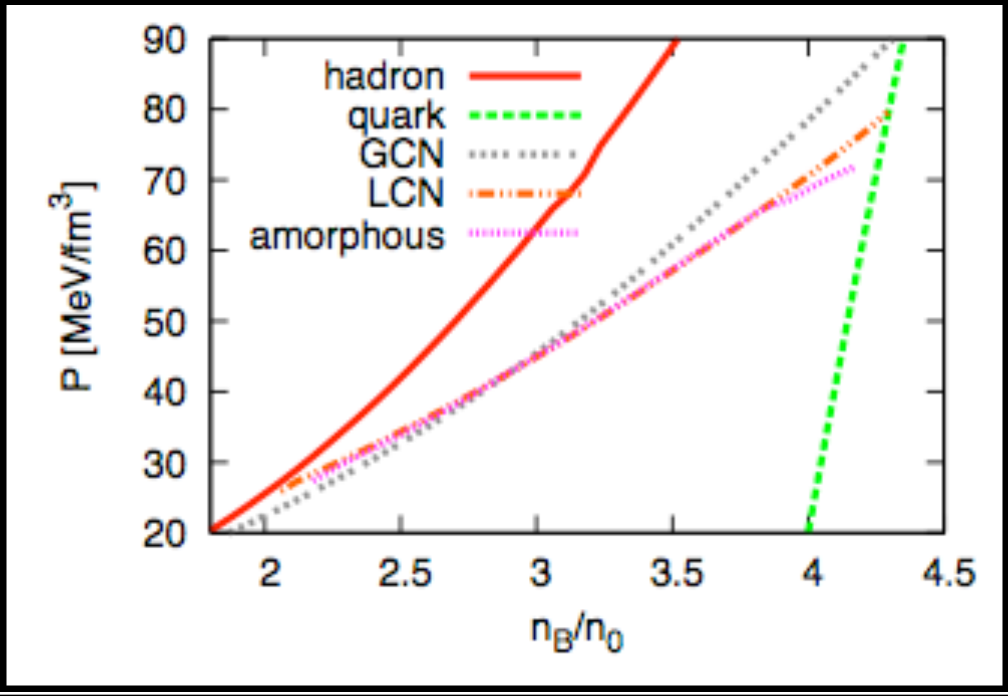
NS matter (strong σ)
→ Density jump

NY et al. 2009b PRD



MG matter → Density jump

NY et al. 2012 submitted



PNS matter →No density jump

SYSTEM OF QH PHASE TRANSITION

Chemical equilibrium for quarks, hadrons, and leptons

$$\mu_u = \frac{1}{3}\mu_B + \frac{2}{3}\mu_{C,Q}, \qquad \mu_d = \mu_s = \frac{1}{3}\mu_B - \frac{1}{3}\mu_{C,Q},$$

$$\mu_n = \mu_\Lambda = \mu_B, \qquad \mu_p = \mu_B + \mu_{C,H}, \qquad \mu_{\Sigma^-} + \mu_p = 2\mu_B,$$

$$\mu_{L,H(Q)} = \mu_{\nu_e,H(Q)}, \qquad \mu_{C,H(Q)} = \mu_L - \mu_{e,H(Q)},$$

$\rightarrow$

3 identical components

- μ_B (baryon number)
- μ_L (lepton number)
- μ_C (charge number)

Table 1. Comparison of conditions for the HQ phase transition.

	finite-size effects	globally conserved variables	locally conserved variables	equilibrium conditions	system
Maxwell	No	n_B	Y_L, Y_C	$\mu_B^H = \mu_B^Q$	pure
bulk Gibbs (GCN)	No	n_B, Y_L, Y_C		$\mu_B^H = \mu_B^Q,\ \mu_L^H = \mu_L^Q,\ \mu_C^H = \mu_C^Q$	ternary
bulk Gibbs (LCN)	No	n_B, Y_L	Y_C	$\mu_B^H = \mu_B^Q,\ \mu_L^H = \mu_L^Q$	binary
pasta	Yes	n_B, Y_L, Y_C		$\mu_B^H = \mu_B^Q,\ \mu_L^H = \mu_L^Q,\ \mu_C^H = \mu_C^Q$	ternary
NS matter pasta	Yes	n_B, Y_C		$\mu_B^H = \mu_B^Q,\ \mu_C^H = \mu_C^Q$	binary
NS matter pasta (large σ)	Yes	n_B, Y_C		$\mu_B^H = \mu_B^Q,\ \mu_C^H = \mu_C^Q$	"pure"
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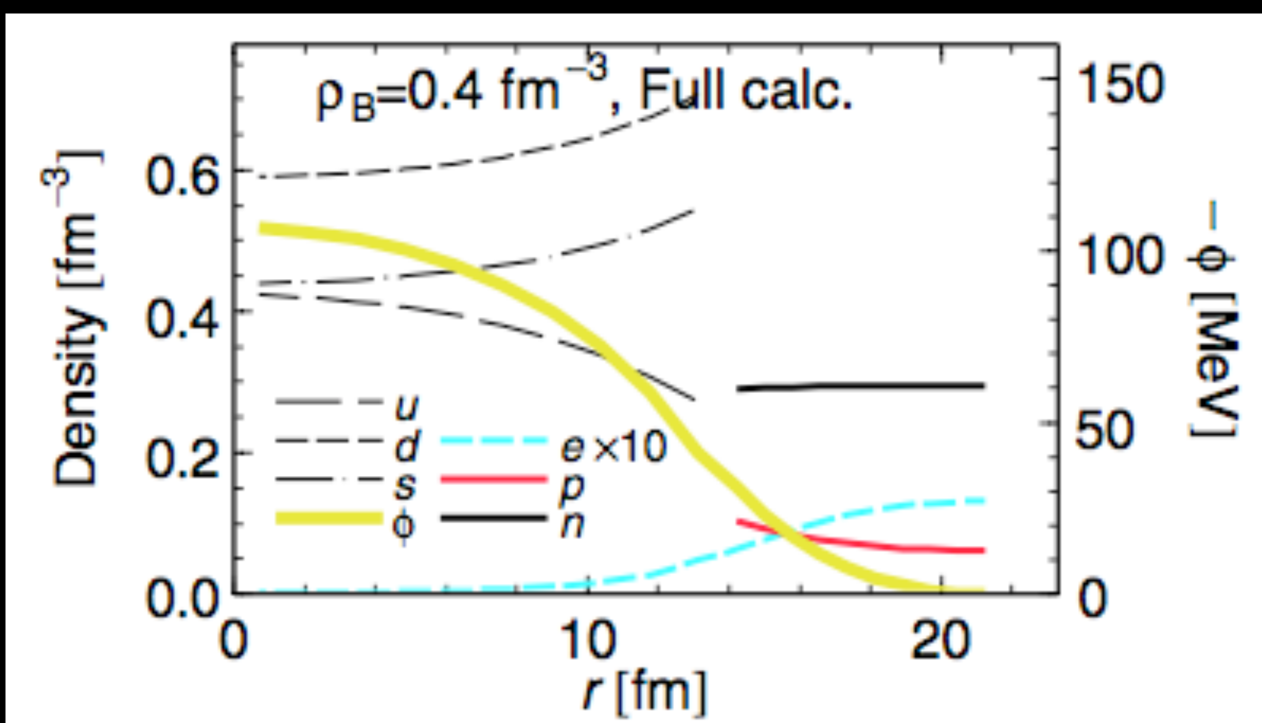
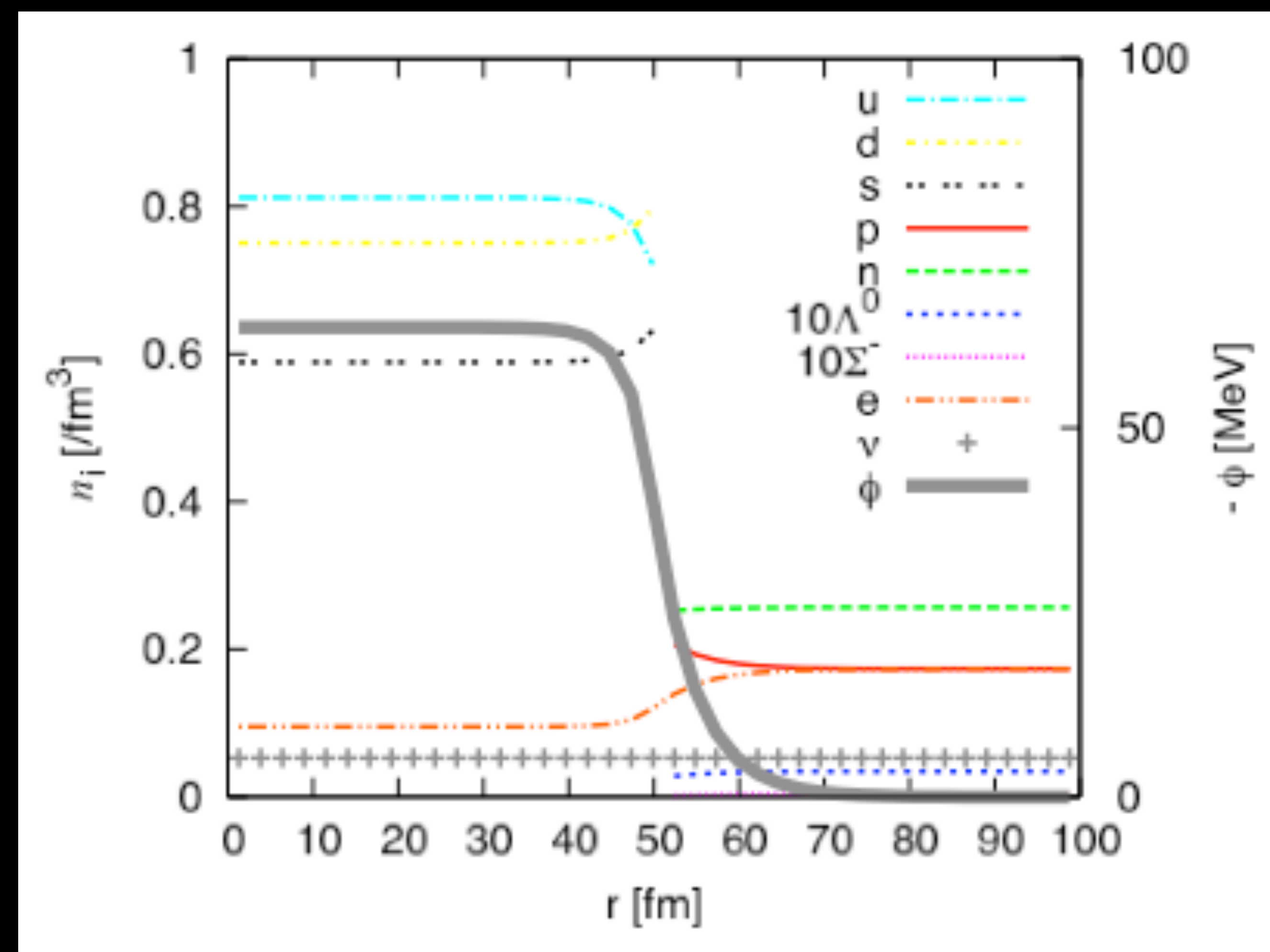
EQUILIBRIUM OF CHARGE CHEMICAL POTENTIAL

Maruyama et al. 2007 PRC



NY et al. 2012 submitted



NS matter (pasta)

$\mu_C^H = \mu_C^Q$

→ **Gibbs(GCN)**

PNS matter (amorphous)

~~$\mu_C^H = \mu_C^Q$~~

→ **Gibbs(LCN)=Maxwell without neutrinos**

SUMMARY OF THE FIRST TOPIC

"The quark-hadron phase transition in astrophysical topics"

① Our EOSs include hyperons, quarks, finite size effects, etc.

② Neutrino traping and temperature change the EOS from ternary system to pure/binary system.

cf.) Tc > 60 MeV for neutrino free case (**NS-NS merger case**)

Y_ν > 0.1 for T=10 MeV (**supernovae case**)

③ Uncertainty of EOS is between ``Gibbs(GCN) and Gibbs (LCN)" for all cases of PNSs(supernovae), NS-NS mergers, NSs.

DISCUSSION

① NN, NY interactions from Lattice QCD / J-PARC.

② Other quark models may change the results.

cf.) NJL, PNJL models, Dyson Schwinger Eq.

Uncertainty of phase transition

Schaffner group (Heiderberg Univ.) 2009

TABLE III. As Table II, but now for the hadron-quark phase transition. $\mu_d = \mu_s$ is valid if strangeness is in equilibrium.

Case	Conserved densities/fractions Globally	Locally	Equilibrium conditions	Construction of mixed phase
0		n_B, (Y_p), (Y_L), n_C	-	Direct
Ia	n_B	Y_p, Y_L, n_C	$(1 - Y_p)\mu_n + Y_p(\mu_p + \mu_e^H) + (Y_L - Y_p)\mu_\nu^H$ $= (2 - Y_p)\mu_d + (1 + Y_p)\mu_u + Y_p\mu_e^Q + (Y_L - Y_p)\mu_\nu^Q$	Maxwell
Ib	n_B	Y_L, n_C	$\mu_n + Y_L\mu_\nu^H = 2\mu_d + \mu_u + Y_L\mu_\nu^Q$	Maxwell
Ic	n_B	Y_p, n_C	$(1 - Y_p)\mu_n + Y_p(\mu_p + \mu_e^H) = (2 - Y_p)\mu_d + (1 + Y_p)\mu_u + Y_p\mu_e^Q$	Maxwell
Id	n_B	n_C	$\mu_n = 2\mu_d + \mu_u$	Maxwell
IIa	n_B, Y_L	Y_p, n_C	$(1 - Y_p)\mu_n + Y_p(\mu_p + \mu_e^H)$ $= (2 - Y_p)\mu_d + (1 + Y_p)\mu_u + Y_p\mu_e^Q$, $\mu_\nu^H = \mu_\nu^Q$	Maxwell/Gibbs
IIb	n_B, Y_L	n_C	$\mu_n = 2\mu_d + \mu_u$, $\mu_\nu^H = \mu_\nu^Q$	Gibbs
IIIa	n_B, Y_p	Y_L, n_C	$\mu_n + Y_L\mu_\nu^H = 2\mu_d + \mu_u + Y_L\mu_\nu^Q$, $\mu_p - \mu_n - \mu_\nu^H + \mu_e^H = \mu_u - \mu_d - \mu_\nu^Q + \mu_e^Q$	Gibbs
IIIb	n_B, Y_p	n_C	$\mu_n = 2\mu_d + \mu_u$, $\mu_p + \mu_e^H = 2\mu_u + \mu_d + \mu_e^Q$	Gibbs
IV	n_B, Y_L, Y_p	n_C	$\mu_n = 2\mu_d + \mu_u$, $\mu_\nu^H = \mu_\nu^Q$, $\mu_p + \mu_e^H = 2\mu_u + \mu_d + \mu_e^Q$	Gibbs
V	n_B, Y_L, Y_p, n_C		$\mu_n = 2\mu_d + \mu_u$, $\mu_\nu^H = \mu_\nu^Q$, $\mu_p = 2\mu_u + \mu_d$, $\mu_e^H = \mu_e^Q$	Gibbs

終

END