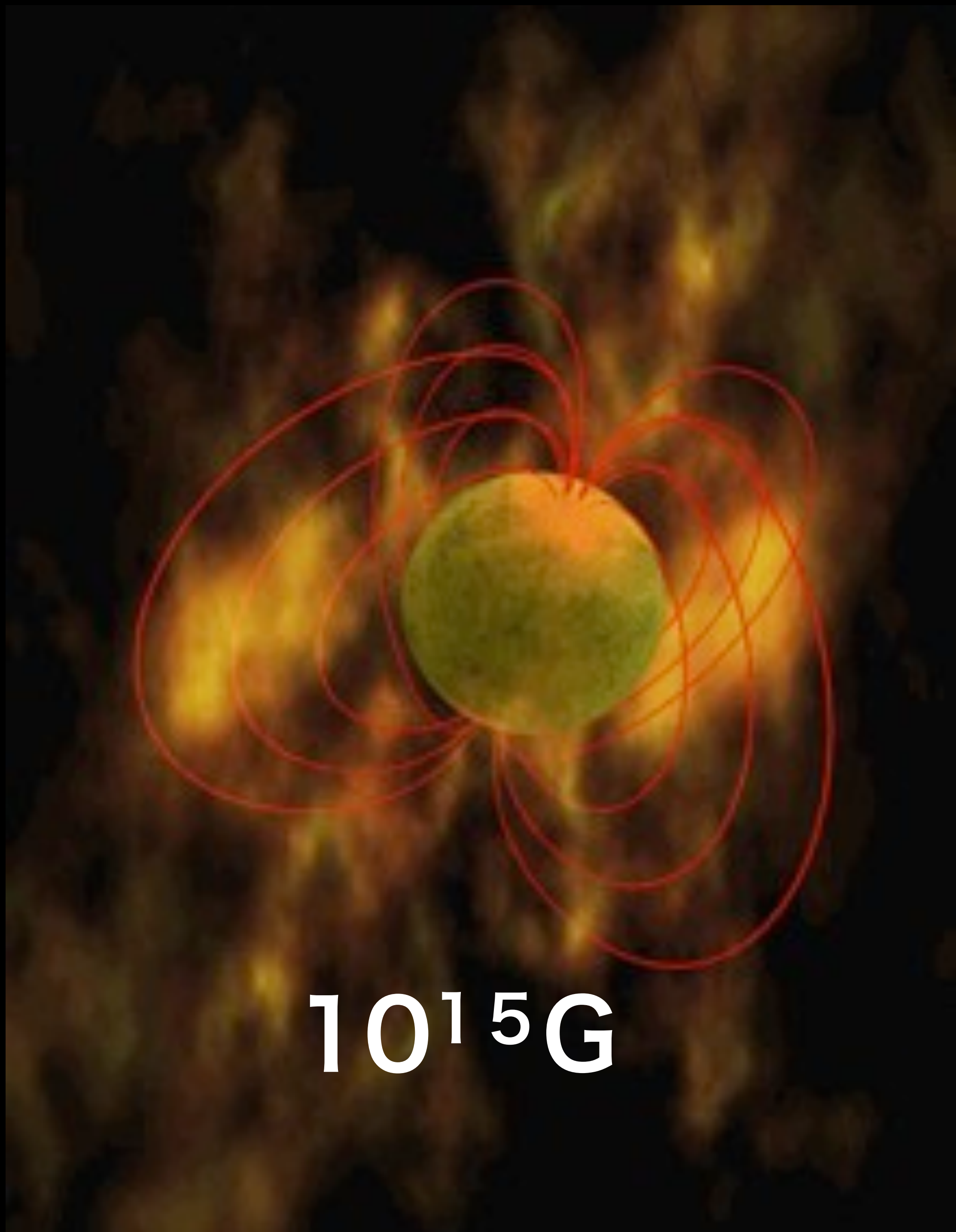
Dec. 1st. 2012
in CIT

Thermodynamical description of hadron-quark phase transition and its implication on compact stars

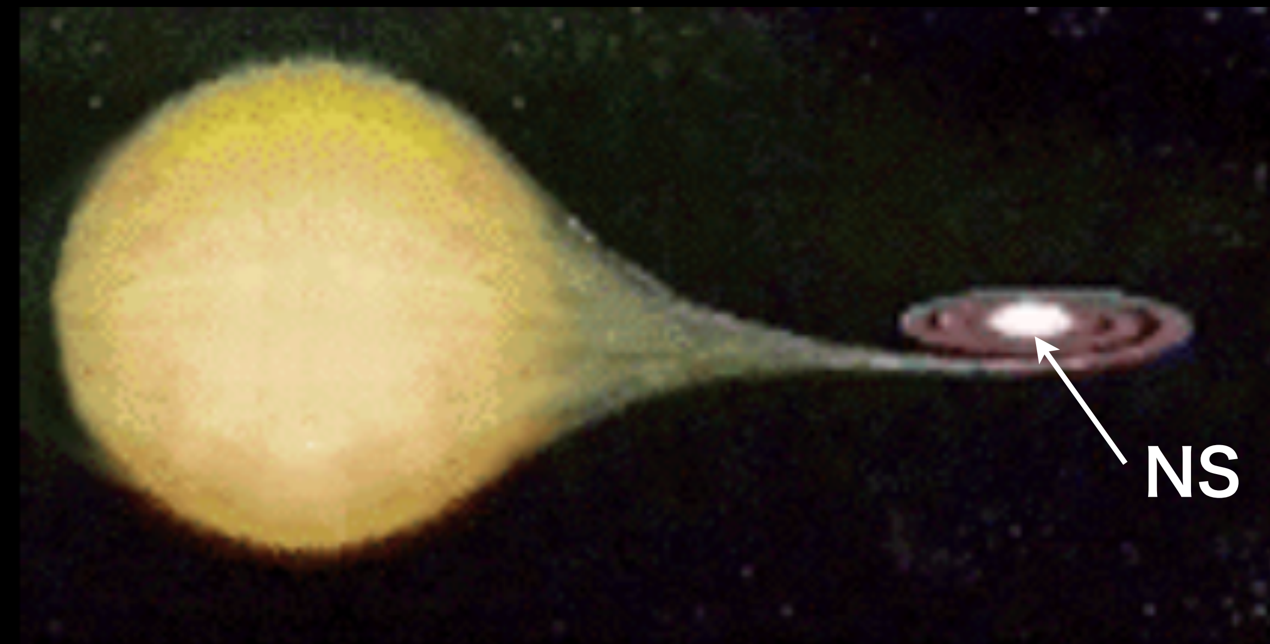
Chiba Institute of Technology
Nobutoshi Yasutake



1979～

observation of magnetars

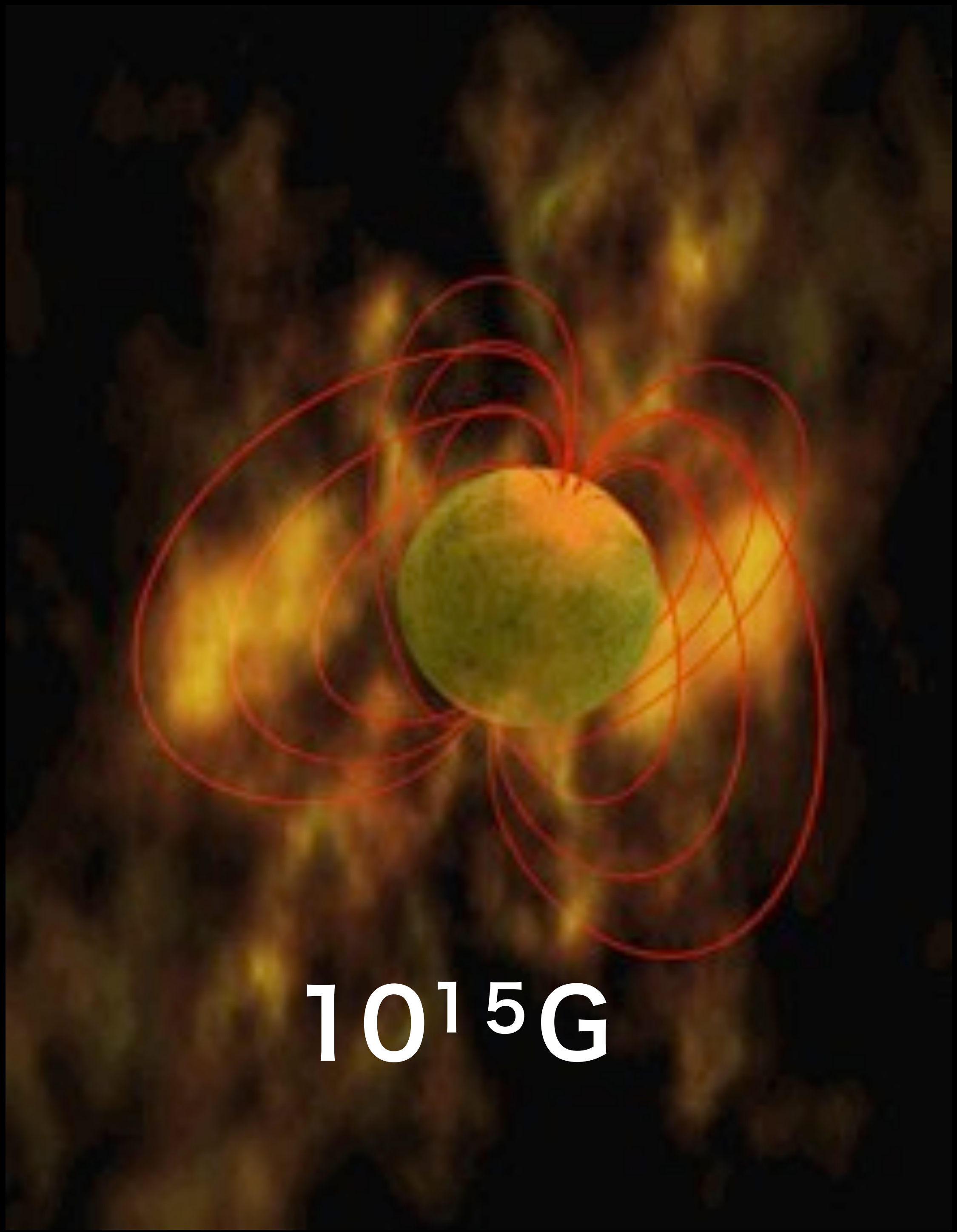
→What is the mechanism?
What does exist inside?



2007

Some X-ray transits have strong cooling mechanism.

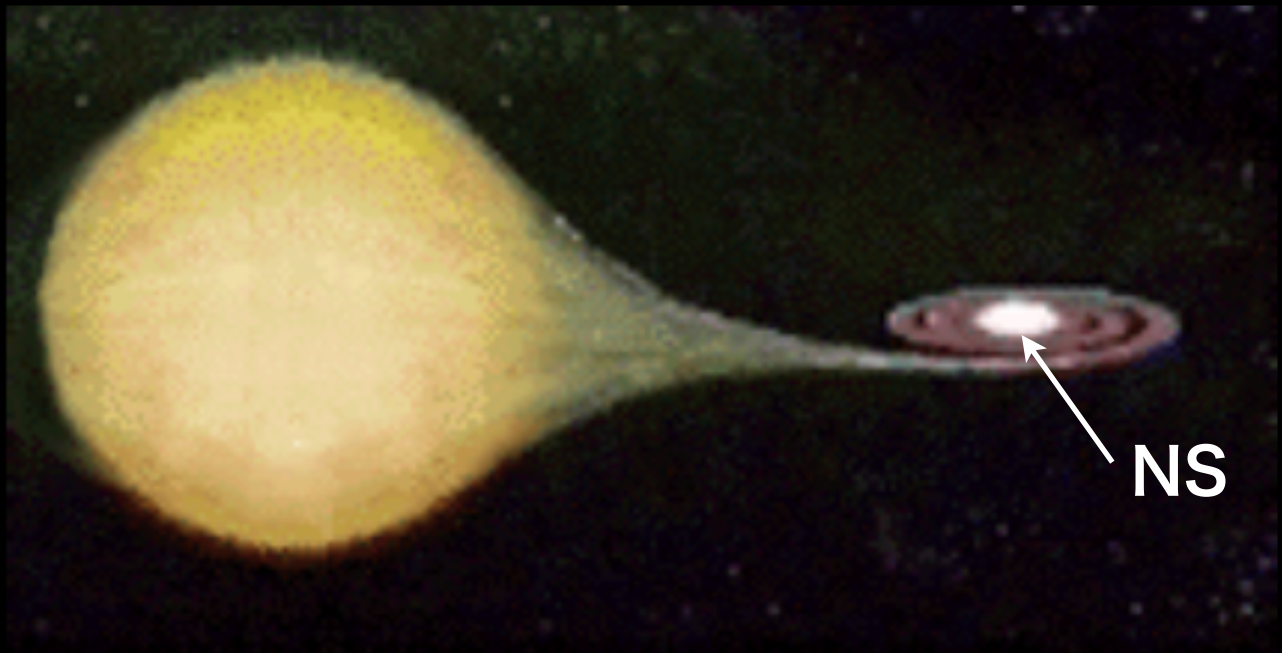
→ Exotic matter



1979～

observation of magnetars

→What is the mechanism?
What does exist inside?



2007

Some X-ray transits have strong cooling mechanism.

→ Exotic matter

Matter inside of NSs

PRD2009b, PRD accepted (arXiv 1202.0143.)

Matter inside of NSs

Toshiki Maruyama(JAEA)、Toshitaka Tatsumi(Kyoto univ.)

+

2012 in prep.

Cooling of magnetars

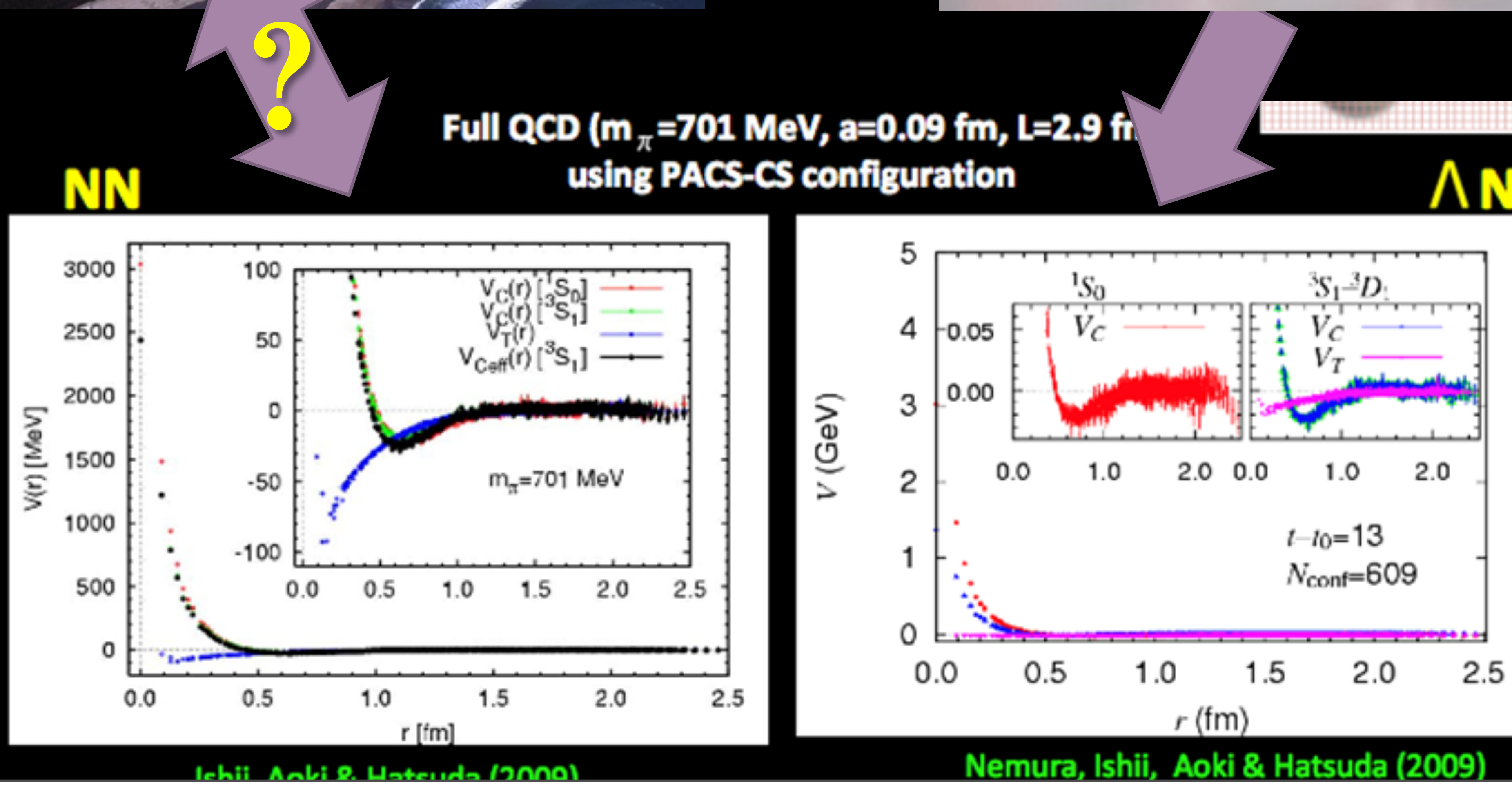
Kei Kotake(NAOJ)、Masamichi Kutsuna、Toshikazu Shigeyama(Tokyo univ.)

I. Pasta structures and amorphous state of quark-hadron phase transitions

NY, Maruyama, Tatsumi
2009a PRD, 2012 PRD accepted
(arXiv1202.0143)

SITUATIONS OF NUCLEAR PHYSICS

"BARYON-BARYON INTERACTIONS MAY BE CLEARED IN A FEW YEARS"



SITUATIONS OF NUCLEAR PHYSICS

"BARYON-BARYON INTERACTIONS MAY BE CLEARED IN A FEW YEARS "

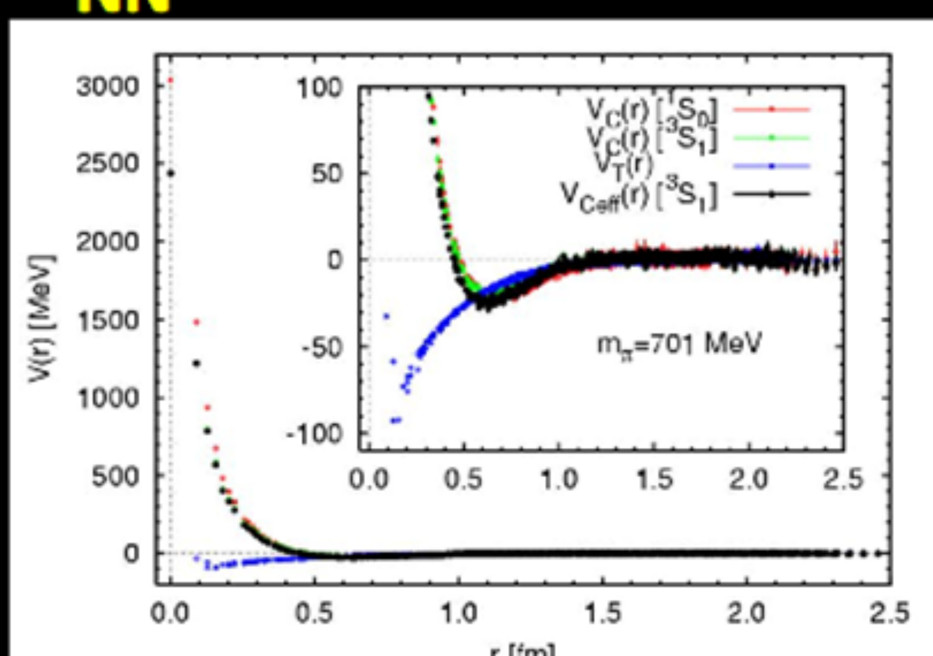
できたとしても，

?

近接力はあやしい

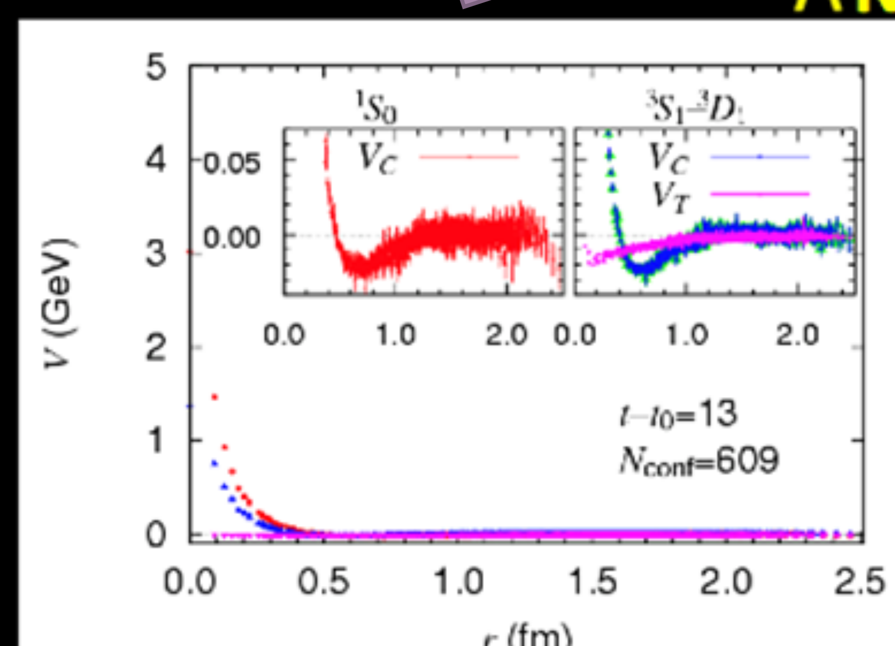
Full QCD (m_π=701 MeV, a=0.09 fm, L=2.9 f
using PACS-CS configuration

NN



Ishii, Aoki & Hatsuda (2009)

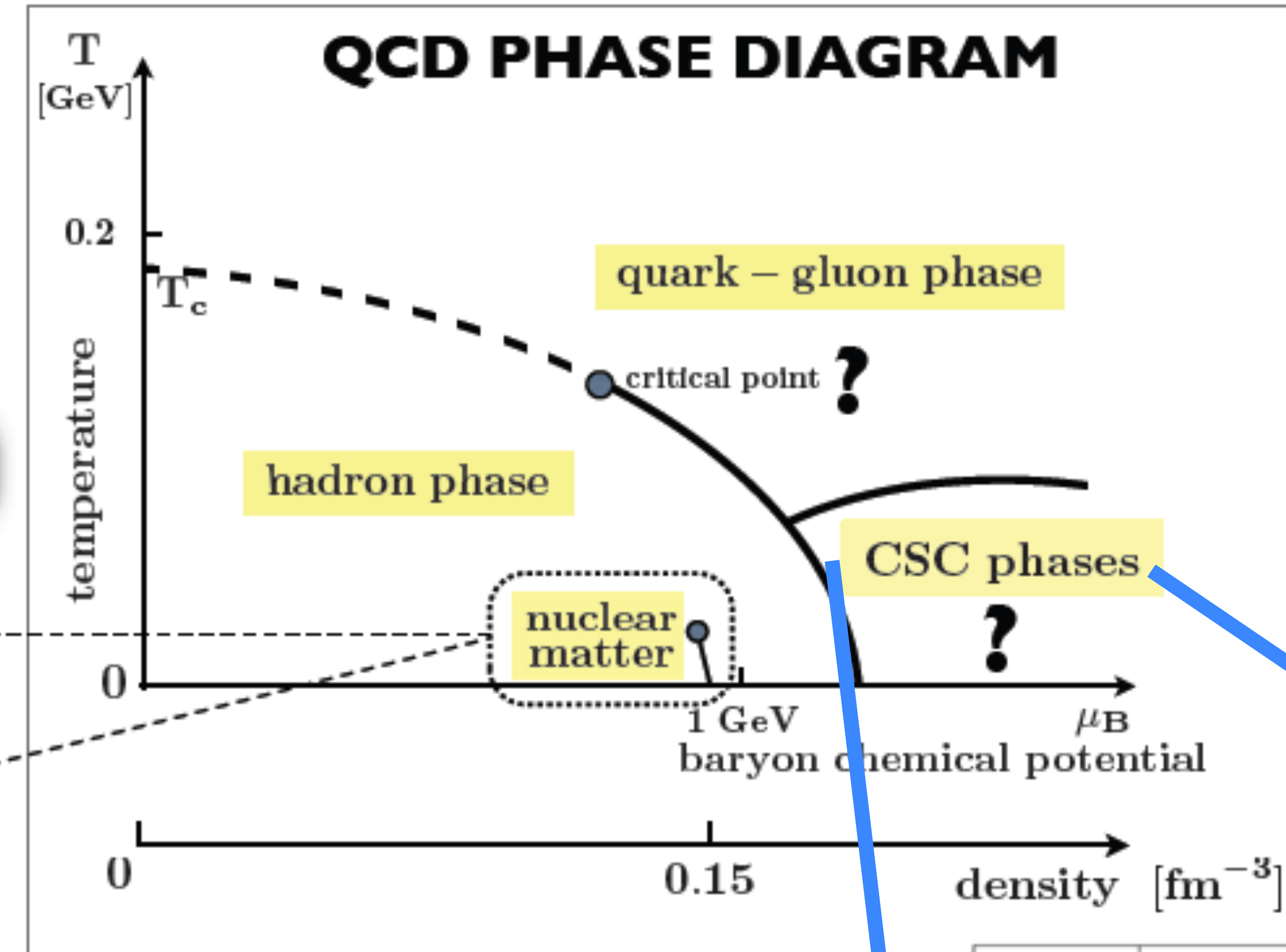
ΛN



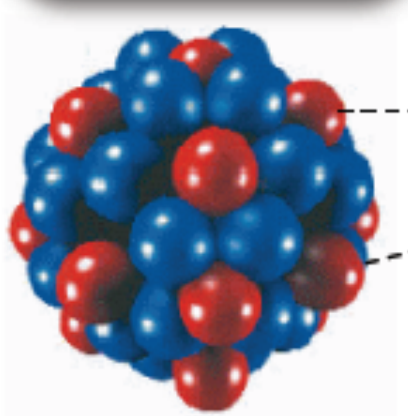
Nemura, Ishii, Aoki & Hatsuda (2009)

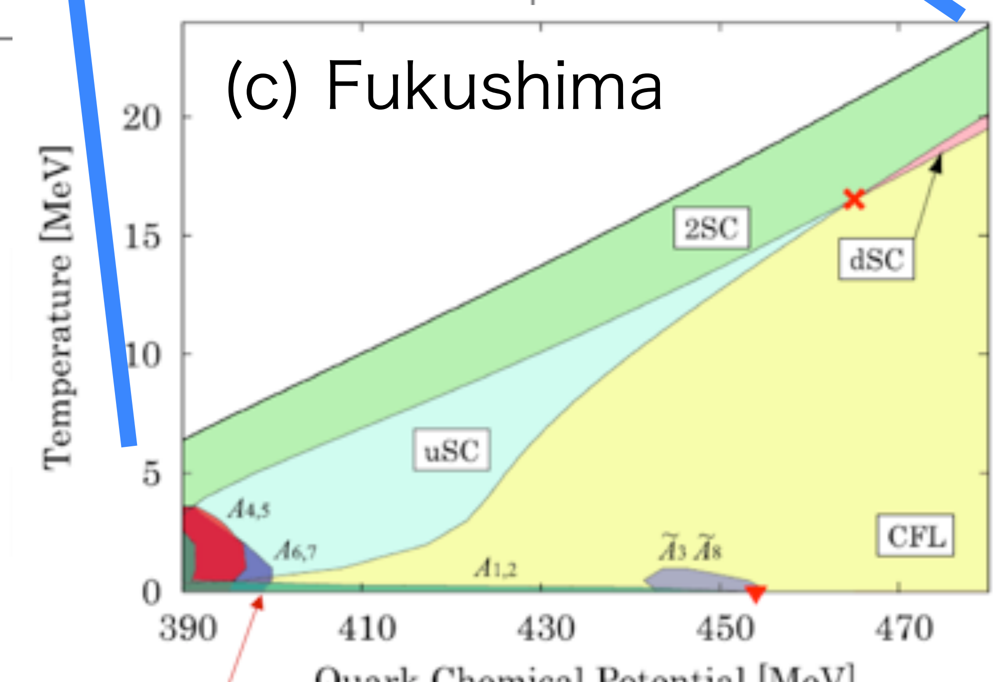
1 Prelude: PHASES and STRUCTURES of QCD

(c) Weise



nuclei





Astrophysical phenomena at T =0.

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

ヒッグス粒子、今年末に新たな性質の発見も

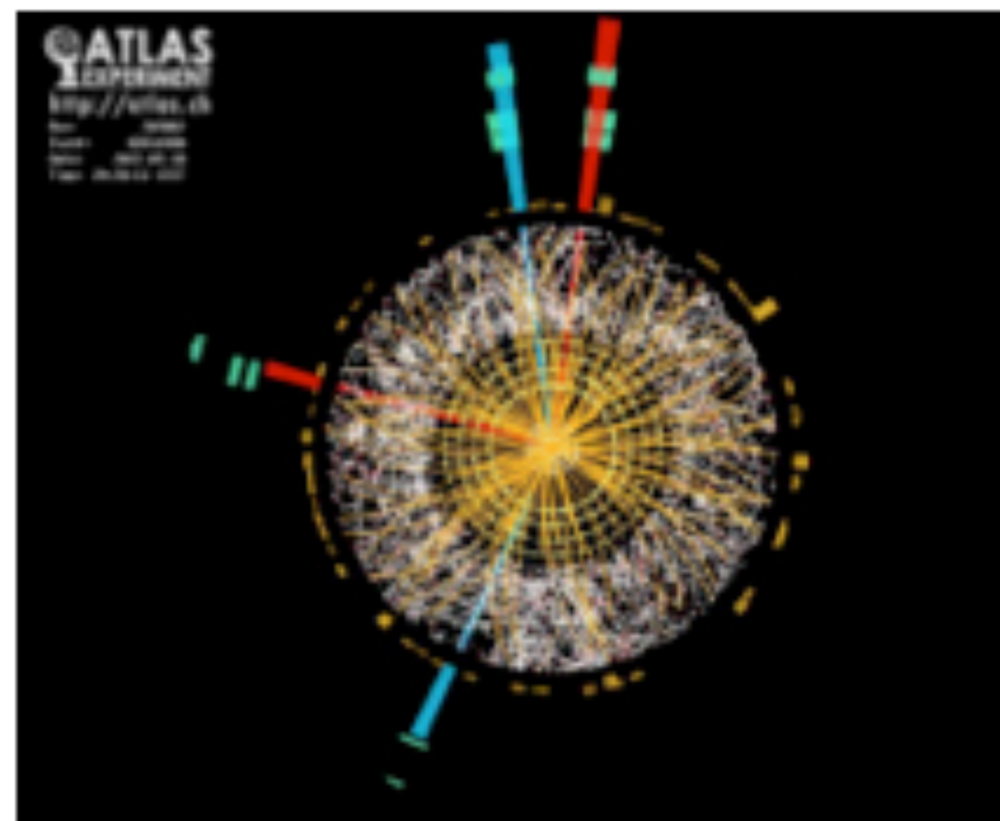
日経サイエンス

2012/7/24 7:00

印刷

万物に質量を与える素粒子であるヒッグス粒子とみられる新粒子が、スイス・ジュネーブ郊外の欧州合同原子核研究機構（ＣＥＲＮ）にある世界最強の大型ハドロン衝突型加速器（ＬＨＣ）を用いた実験で発見された。今回の発見は現代物理学における新たな革命の幕開けを意味する。ＬＨＣでの実験は現在も続いており、今年末には、新粒子が持つ性質がさらに詳しくわかる。多くの物理学者は、現在の素粒子物理学の枠組みである「標準モデル」では説明できない性質が浮かび上がってくる可能性があるとみている。

標準モデルは物質はどのような素粒子で構成されているのか、そうした素粒子にはどんな力が働き、それらの力はどんな振る舞いをするのかをまとめたものだ。1970年代半ばに完成の域に達し、90年代末までに物質と力を担う素粒子が全部そろった。残るは唯一ヒッグス粒子だけだった。標準モデルではヒッグス粒子が持つ性質がいくつか定められているが、これまでの実験で合うことがわかったのは、そうした性質の一部。その範囲でいえば標準モデルとの不一致はない。残された部分は今年末までの実験で、標準モデルと合致するかどうかが、ほぼ判明する。



画像の拡大

ＬＨＣを用いた実験（ＡＴＬＡＳ実験）の

ヒッグス粒子、今年末に新たな性質の発見も

日経サイエンス

2012/7/24 7:00

印刷

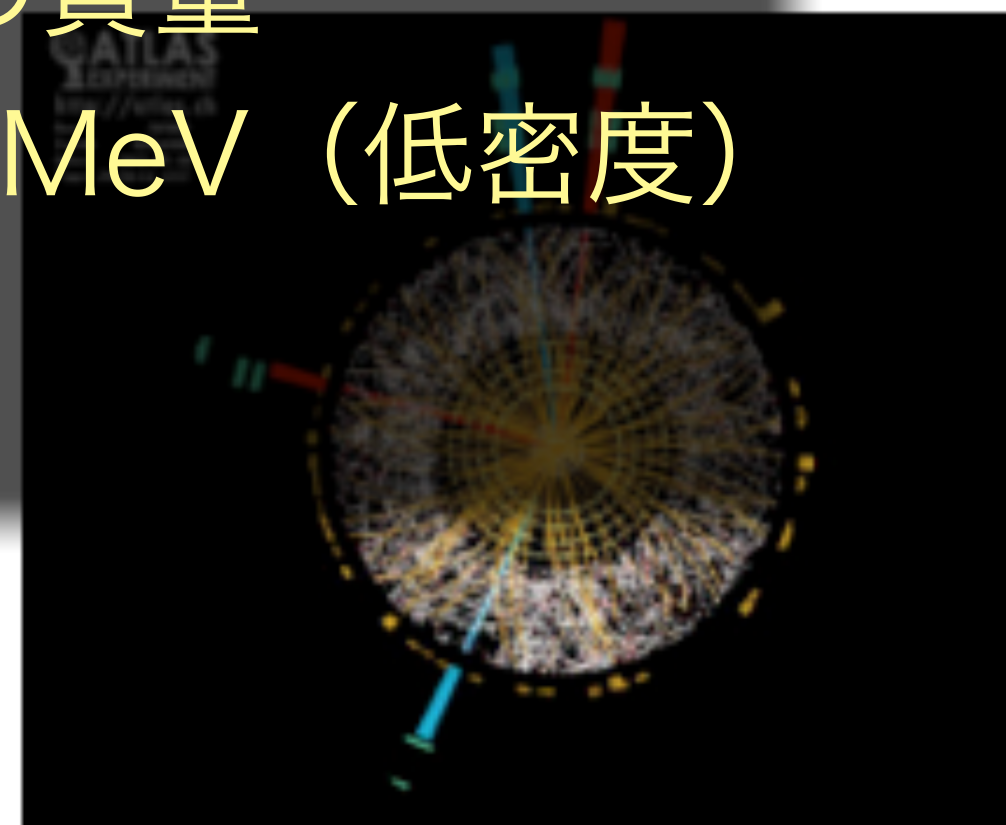
質量の９割はカイラル凝縮から来る

クォーク(３つ分)の質量

１５MeV（高密度）⇄ 938MeV（低密度）

万物に質量を与える素粒子であるヒッグス粒子とみられる新粒子が、スイス・ジュネーブ郊外の欧州合同原子核研究機構（ＣＥＲＮ）にある世界最強の大型ハドロン衝突型加速器（ＬＨＣ）を用いた実験で[illegible]。今回の発見は現代物理学における新たな革命の幕開けを意味する。ＬＨＣでの実験は現在も続いており、今年末には、新粒子が持つ性質がさらに詳しくわかる。多くの物理学者は、現在の素粒子物理学の枠組みである「標準モデル」では説明できない性質が浮かび上がってくる可能性があるとみている。

標準モデルは物質はどのような素粒子で構成されているのか、そうした素粒子は[illegible]どんな振る舞いをするのかをまとめたものだ。1970年代半ばに完成の域に達し、90年代末までに物質と力を担う素粒子が全部そろった。残るは唯一ヒッグス粒子だけだった。標準モデルではヒッグス粒子が持つ性質がいくつか定められているが、これまでの実験で合うことがわかったのは、そうした性質の一部。その範囲でいえば標準モデルとの不一致はない。残された部分は今年末までの実験で、標準モデルと合致するかどうかが、ほぼ判明する。



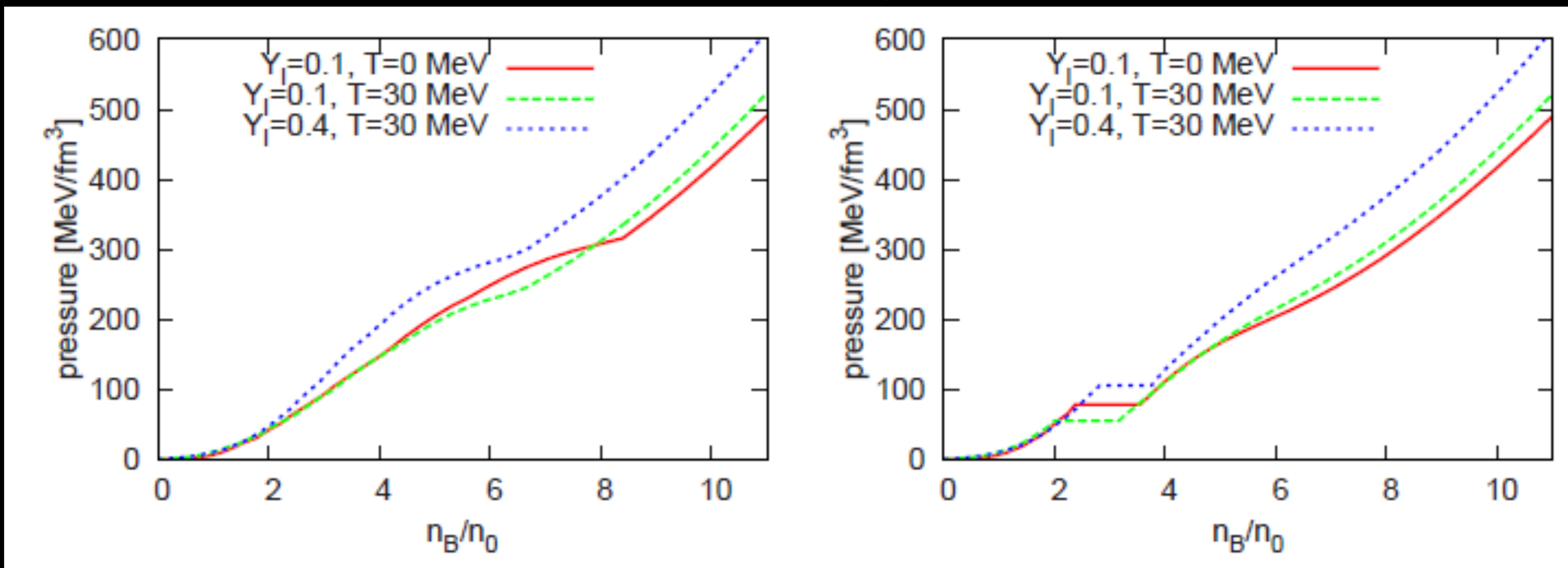
画像の拡大

ＬＨＣを用いた実験（ＡＴＬＡＳ実験）のデータ。ヒッグス粒子とみられる粒子が実験

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

カイラル対称性の回復がいかにNSs, SNe, MGsで効くか(EOSのみ)を調べた。

Shen EOS + NJL model **NY** & Kashiwa, PRD, (2009)



the bulk Gibbs condition the Maxwell construction

↑

the finite size effects

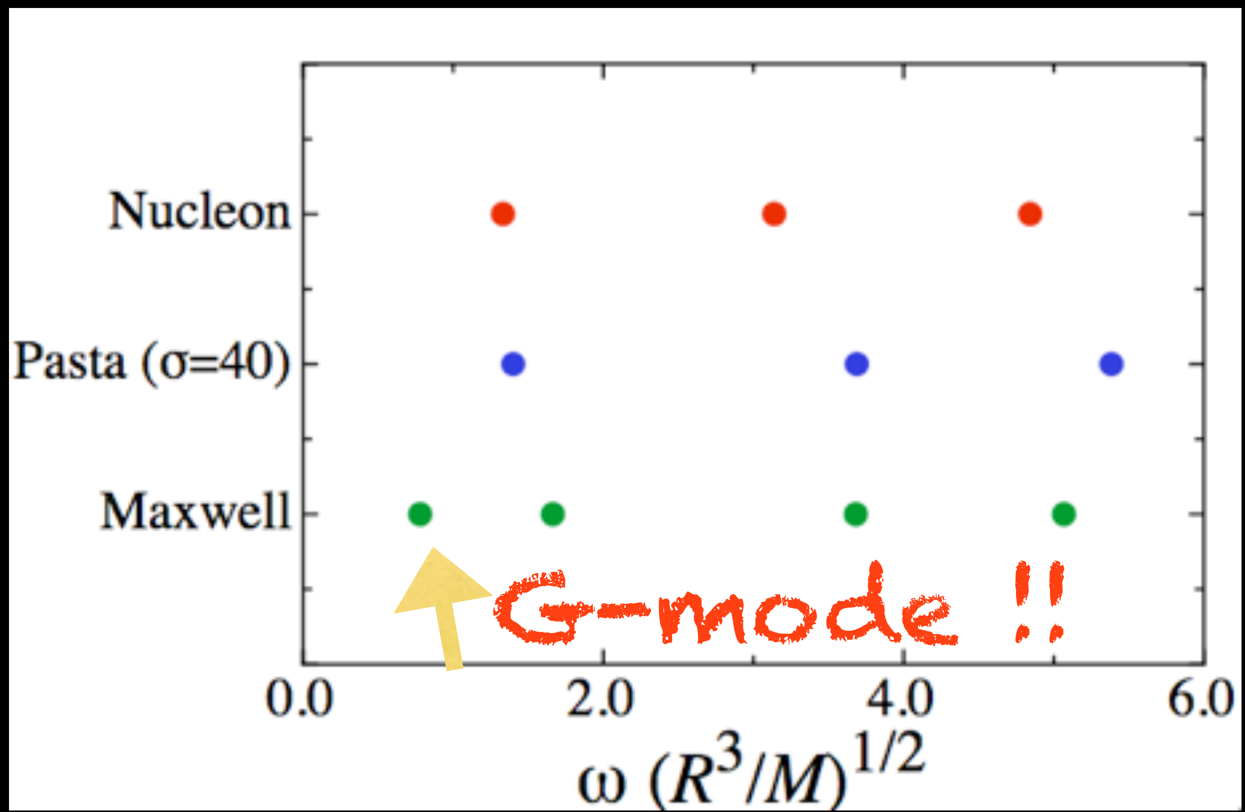
Maruyama et al., PRC, (2008)

INSIDE MATTER AND NATURAL FREQUENCY

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

【Astrophysical Phenomena】
- Giant Flare from magnetars
- Sudden accretion to NSs

Analytic method



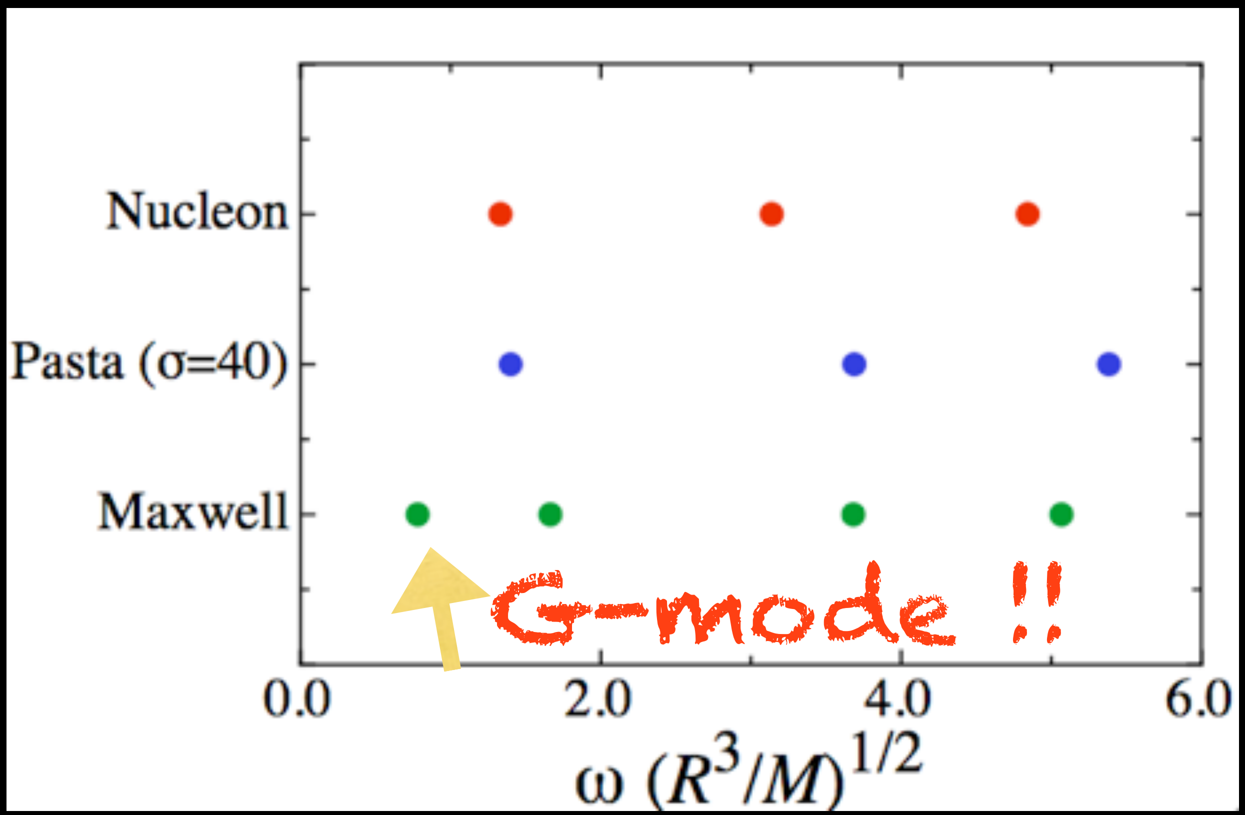
INSIDE MATTER AND NATURAL FREQUENCY

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

【Astrophysical Phenomena】

- Giant Flare from magnetars
- Sudden accretion to NSs

Analytic method



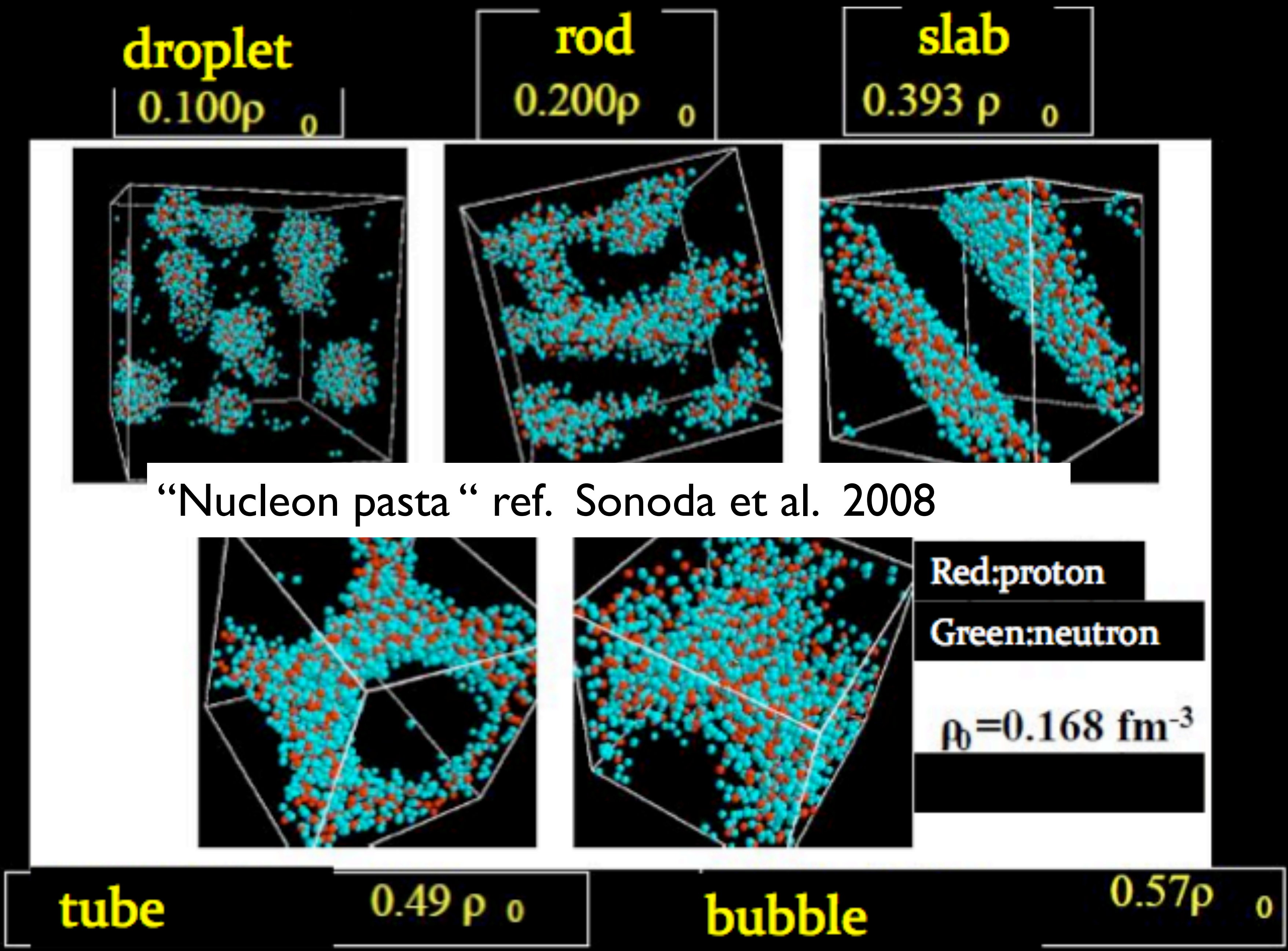
Uncertainty of phase transition

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

FIRST ORDER PHASE TRANSITION IN MULTI-COMPONENT SYSTEM



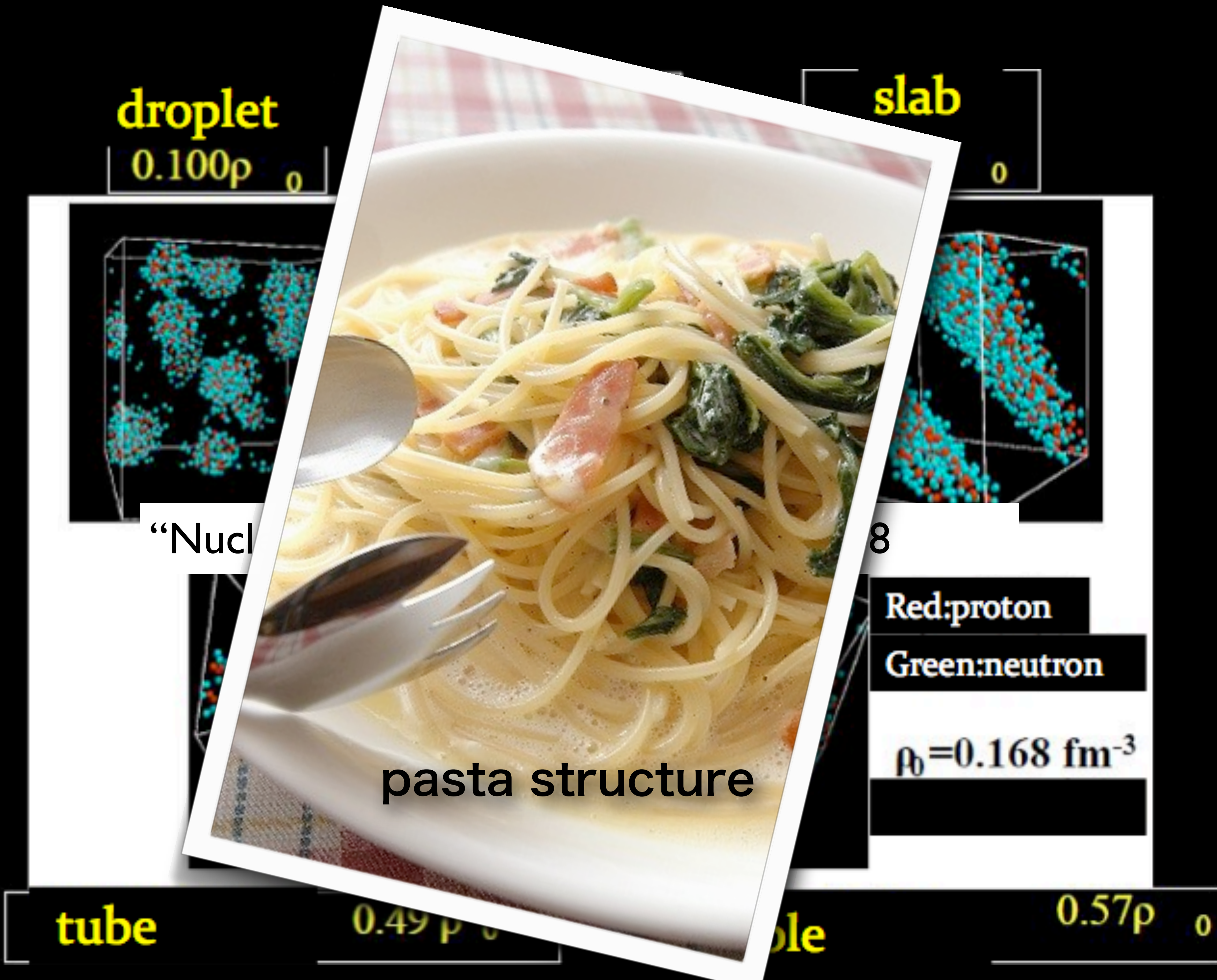
"Nucleon pasta" ref. Sonoda et al. 2008

Depended on

- density
- temperature
- Coulomb interactions
- surface tension

→ neutron drip / quark-hadron phase transition etc.

FIRST ORDER PHASE TRANSITION IN MULTI-COMPONENT SYSTEM

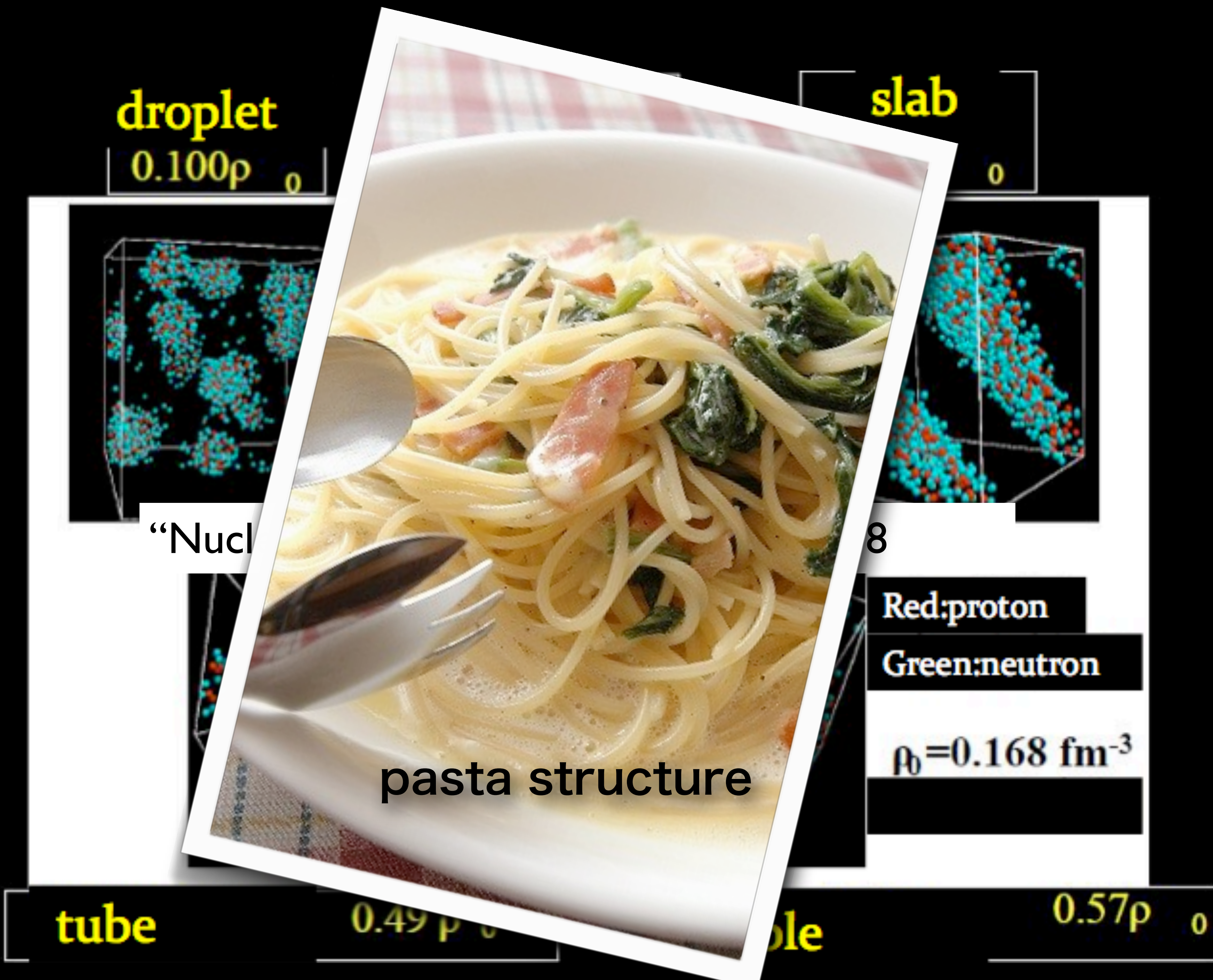


Depended on

- density
- temperature
- Coulomb interactions
- surface tension

→ neutron drip / quark-hadron phase transition etc.

FIRST ORDER PHASE TRANSITION IN MULTI-COMPONENT SYSTEM



Depended on

- density
- temperature
- Coulomb interactions
- surface tension

→ neutron drip / quark-hadron phase transition etc.

Pasta ?

Pasta ?

or

Pasta ?

or

Amorphous ?

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 ”.**)

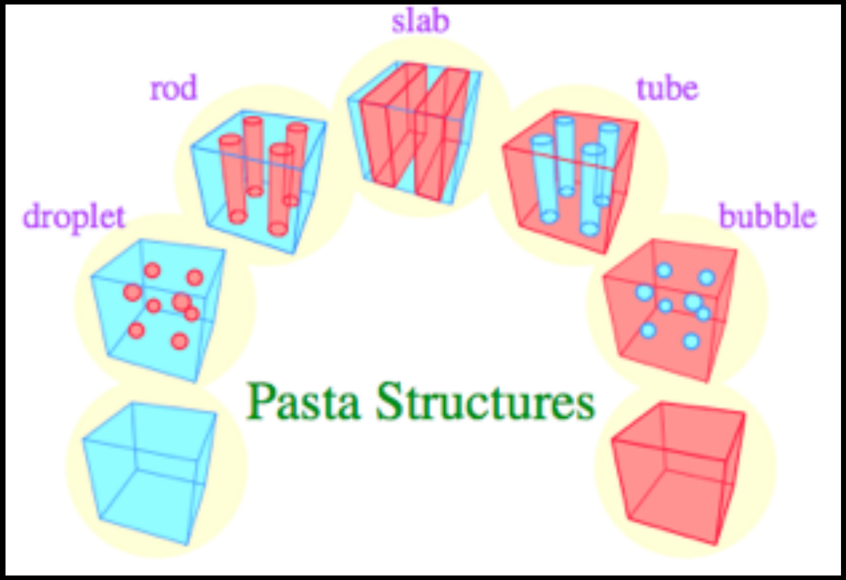
+

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).



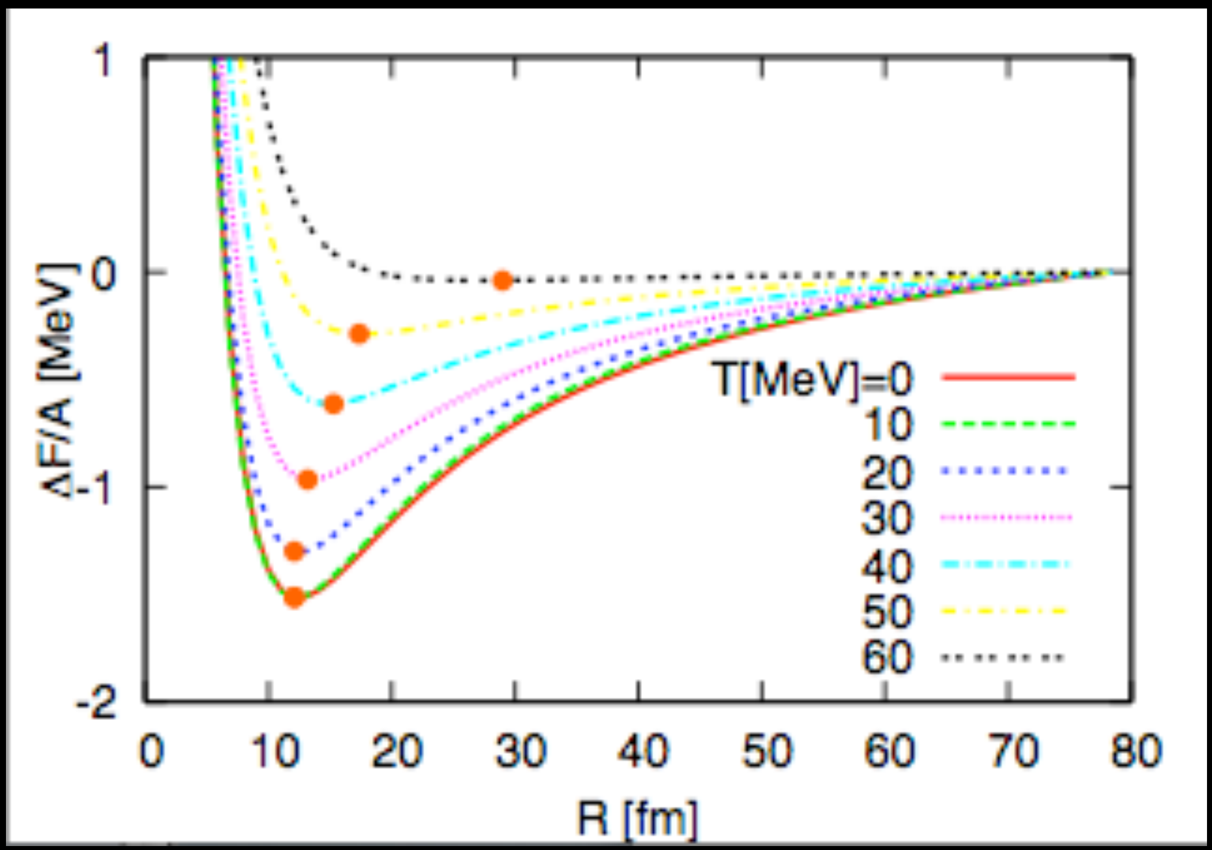
In calculations of mixed phase, we consider

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

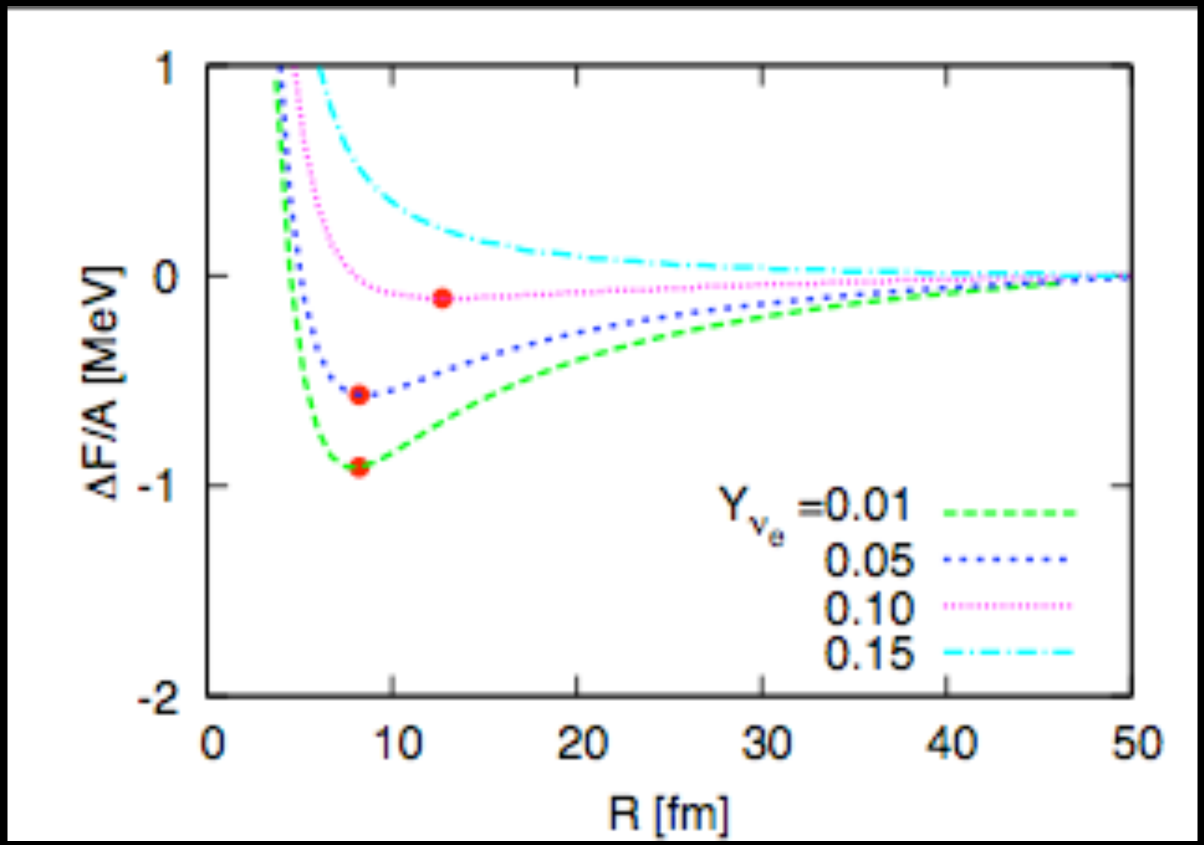
STABILITY CURVES OF MIXED PHASE

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

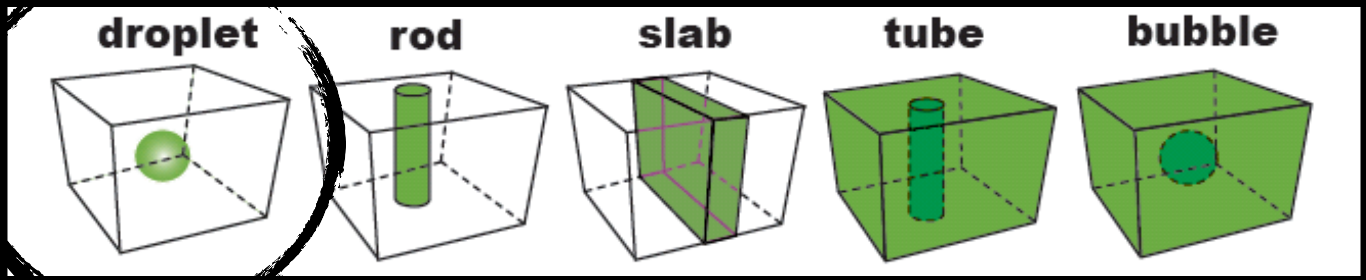
NY et al. 2009b PRD, 2012 PRD submitted.



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



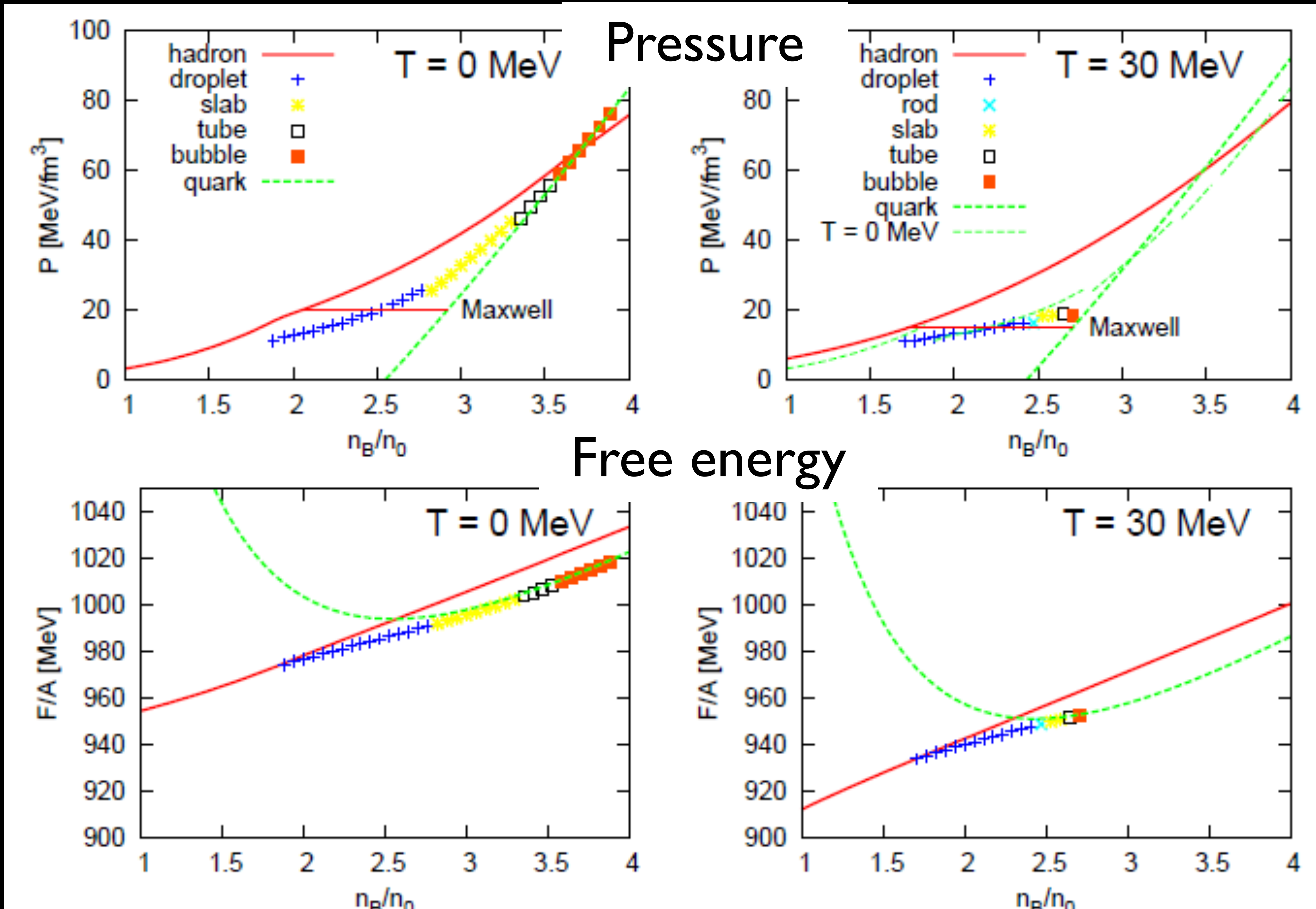
$\rho=2.5\rho_0$, density dependent B



σ = 40 MeV/fm^3

THERMAL EFFECTS ON EOS

NY et al. 2009b PRD



high temperature (wo neutrinos) → Maxwell-like mixed phase

NEUTRINO EFFECTS ON EOS

high temperature (with neutrinos) ≠ Maxwell-like mixed phase

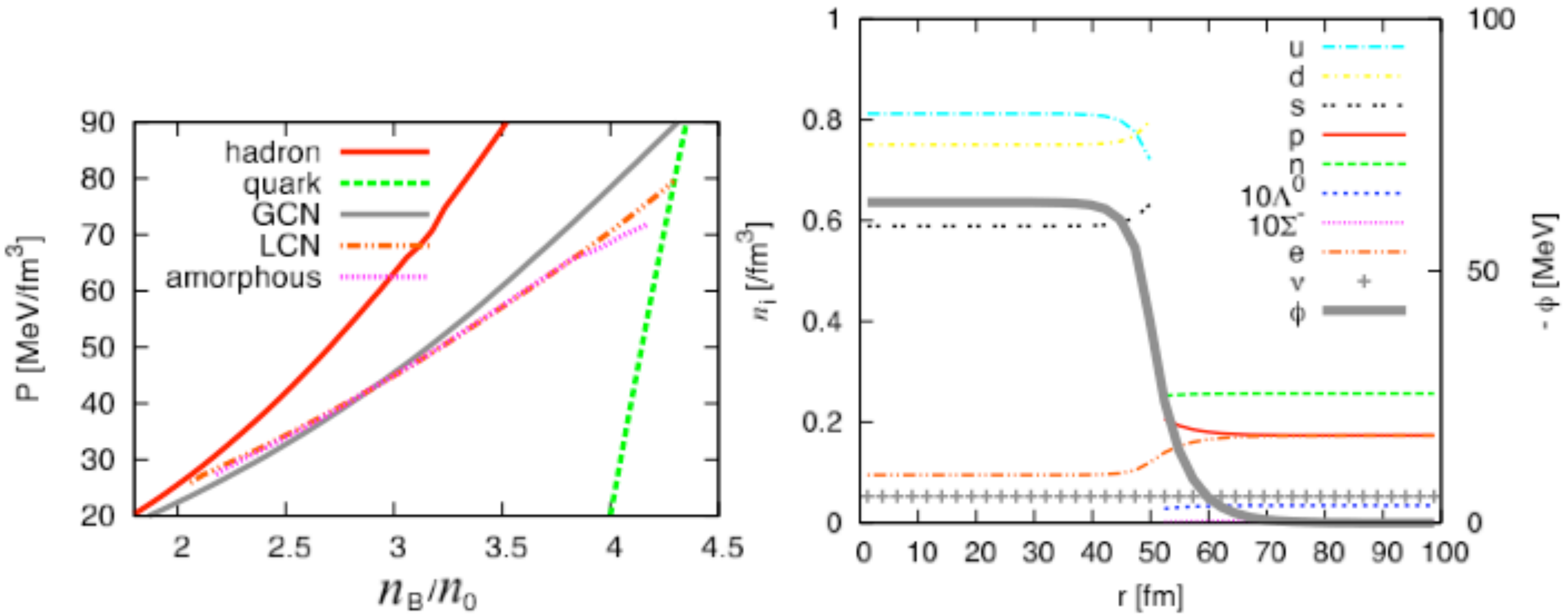


Figure 10: Left panel shows the pressure for PNS matter of $T = 30$MeV and $Y_l = 0.4$. The nuclear density is denoted by n_0. Right panel shows the density profile and the Coulomb potential $3n_0$ assuming the rod structure for the same PNS matter.

SYSTEM OF QH PHASE TRANSITION

Chemical equilibrium for quarks, hadrons, and leptons

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

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

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

→ 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"
MG matter pasta	Yes	n_B, Y_C		$\mu_B^H = \mu_B^Q,\ \mu_C^H = \mu_C^Q$	"pure"
PNS matter amorphous	Yes	n_B, Y_L, Y_C		$\mu_B^H = \mu_B^Q,\ \mu_L^H = \mu_L^Q,\ \mu_C^H = \mu_C^Q$	"binary"

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"
MG matter pasta	Yes	n_B, Y_C		$\mu_B^H = \mu_B^Q$, ~~$\mu_C^H = \mu_C^Q$~~	"pure"
PNS matter amorphous	Yes	n_B, Y_L, Y_C		$\mu_B^H = \mu_B^Q,\ \mu_L^H = \mu_L^Q,\ \mu_C^H = \mu_C^Q$	"binary"

SYSTEM OF QH PHASE TRANSITION

Chemical equilibrium for quarks, hadrons, and leptons

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

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

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

→ 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"
MG matter pasta	Yes	n_B, Y_C		$\mu_B^H = \mu_B^Q,\ \mu_C^H = \mu_C^Q$	"pure"
PNS matter amorphous	Yes	n_B, Y_L, Y_C		$\mu_B^H = \mu_B^Q,\ \mu_L^H = \mu_L^Q,\ \mu_C^H = \mu_C^Q$	"binary"

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

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

SUMMARY

"The quark-hadron phase transition in astrophysical topics"

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

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

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

Yν > 0.1 for T=10 MeV **(supernovae case)**→ **NO DENSITY JUMP !!**

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.

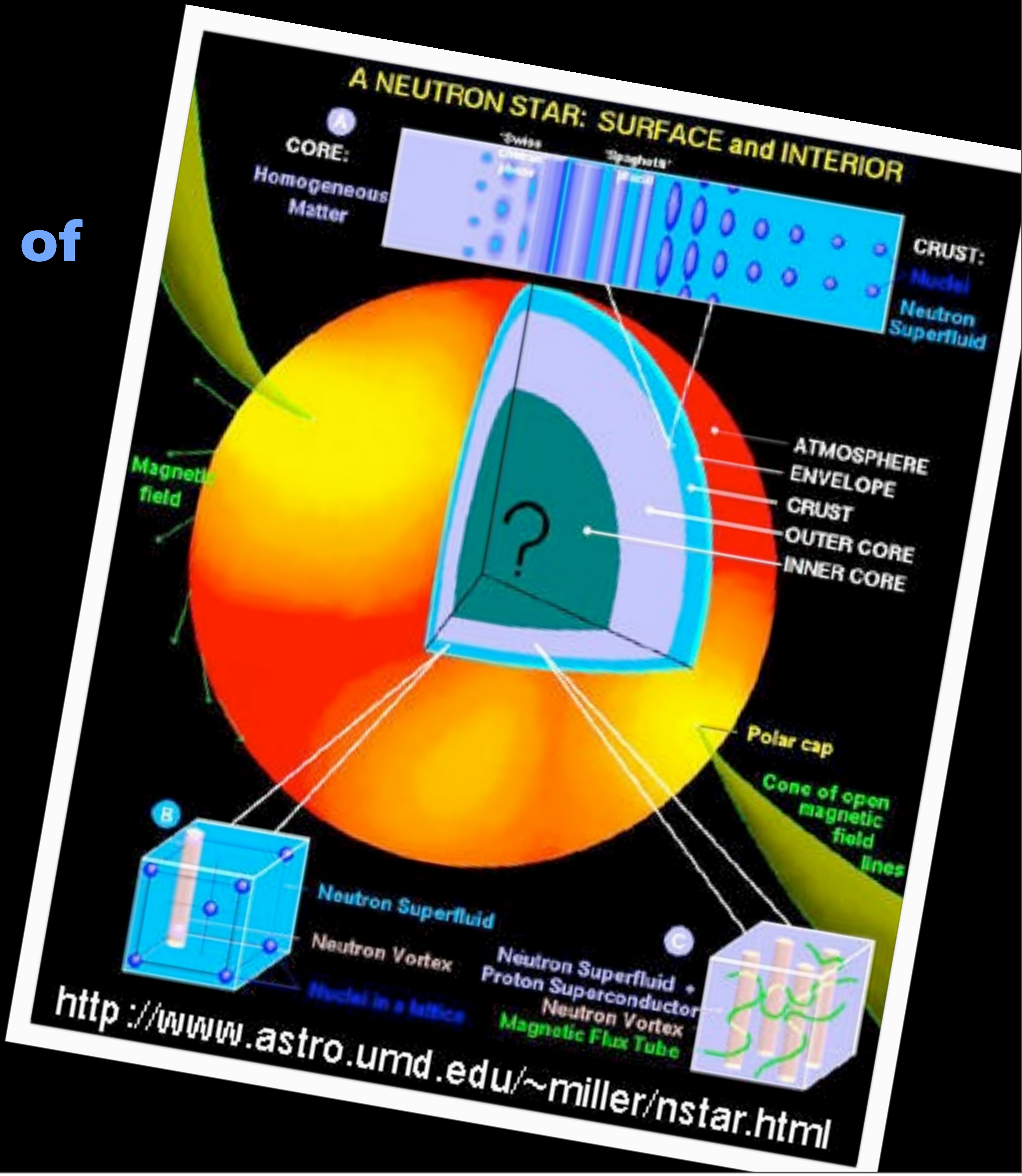
② Other quark models may change the results.

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

II. Thermal evolution of magnetars/NSs

NY, Kotake, Kutsuna, Shigeyama
in prep.

Noda, Hashimoto, Matsuo,
NY, Maruyama, Tatsumi, Fujimoto
2012 ApJ submitted

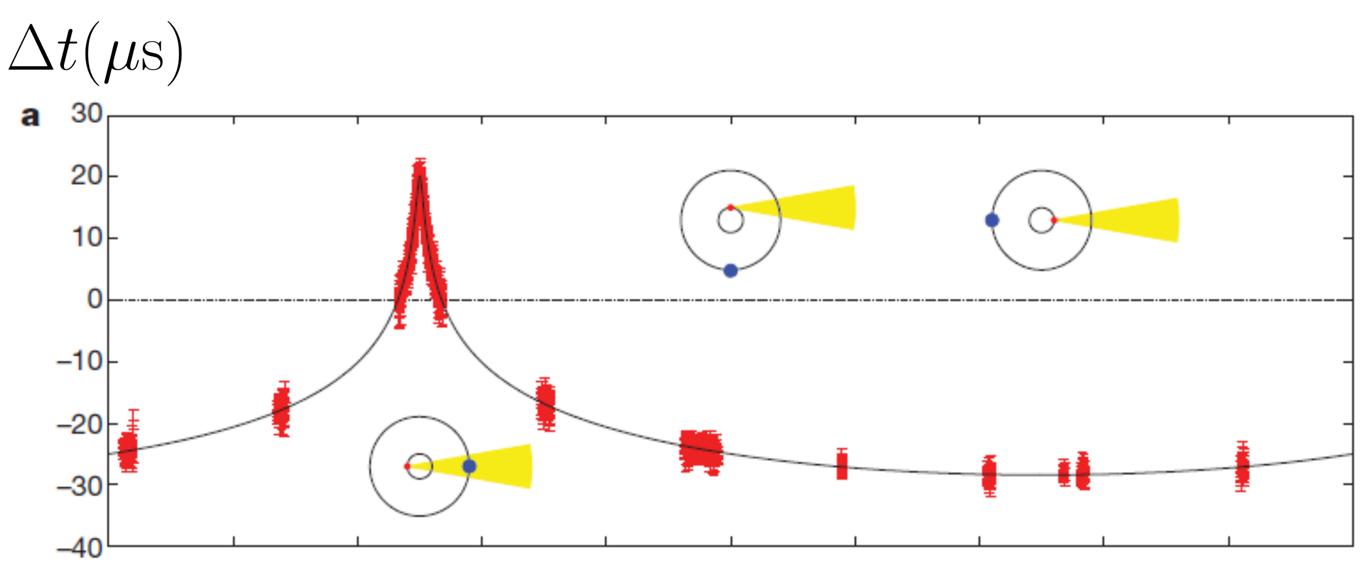


TWO SOLAR MASS PROBLEM

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

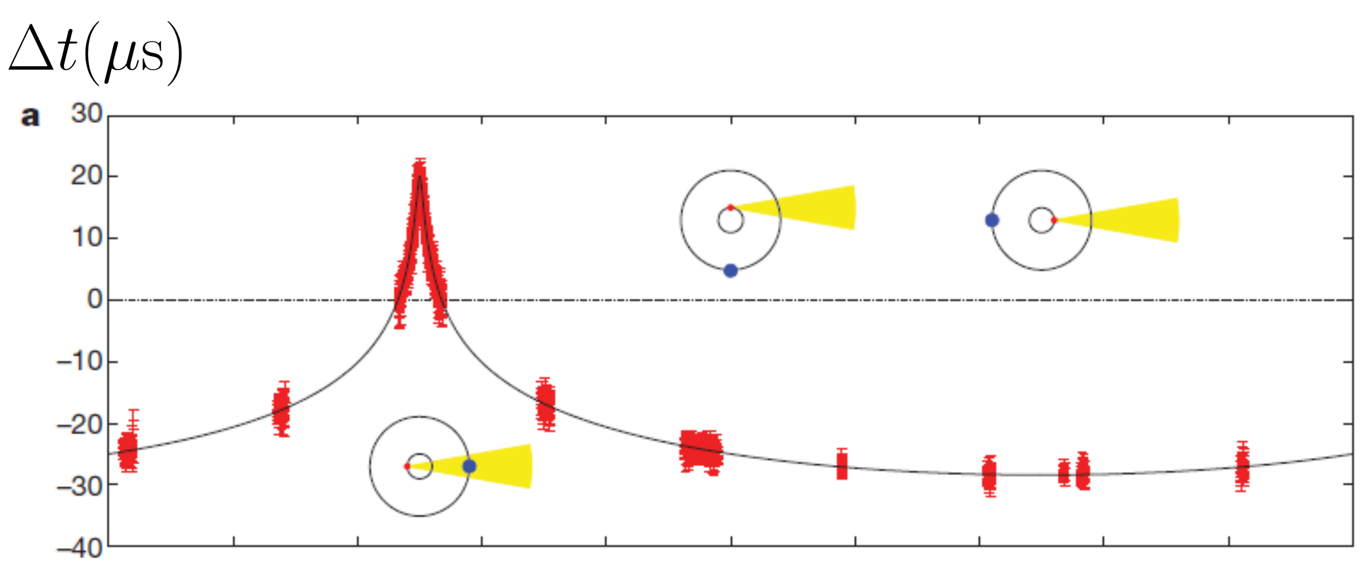
Radar signals passing near a massive object take slightly longer to travel to a target and longer to return than they would if the mass of the object were not present.

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

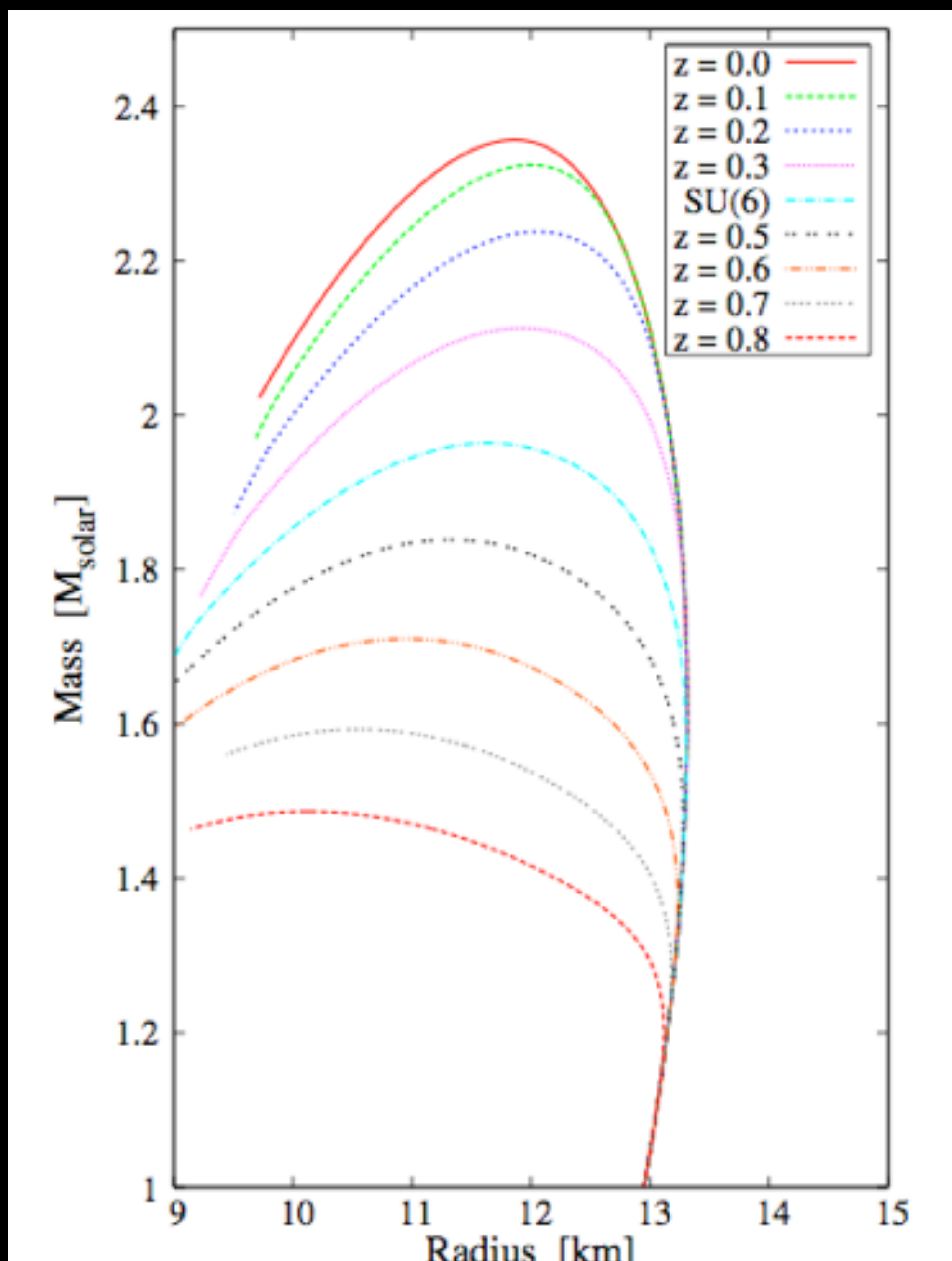
Shapiro delay

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.

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)

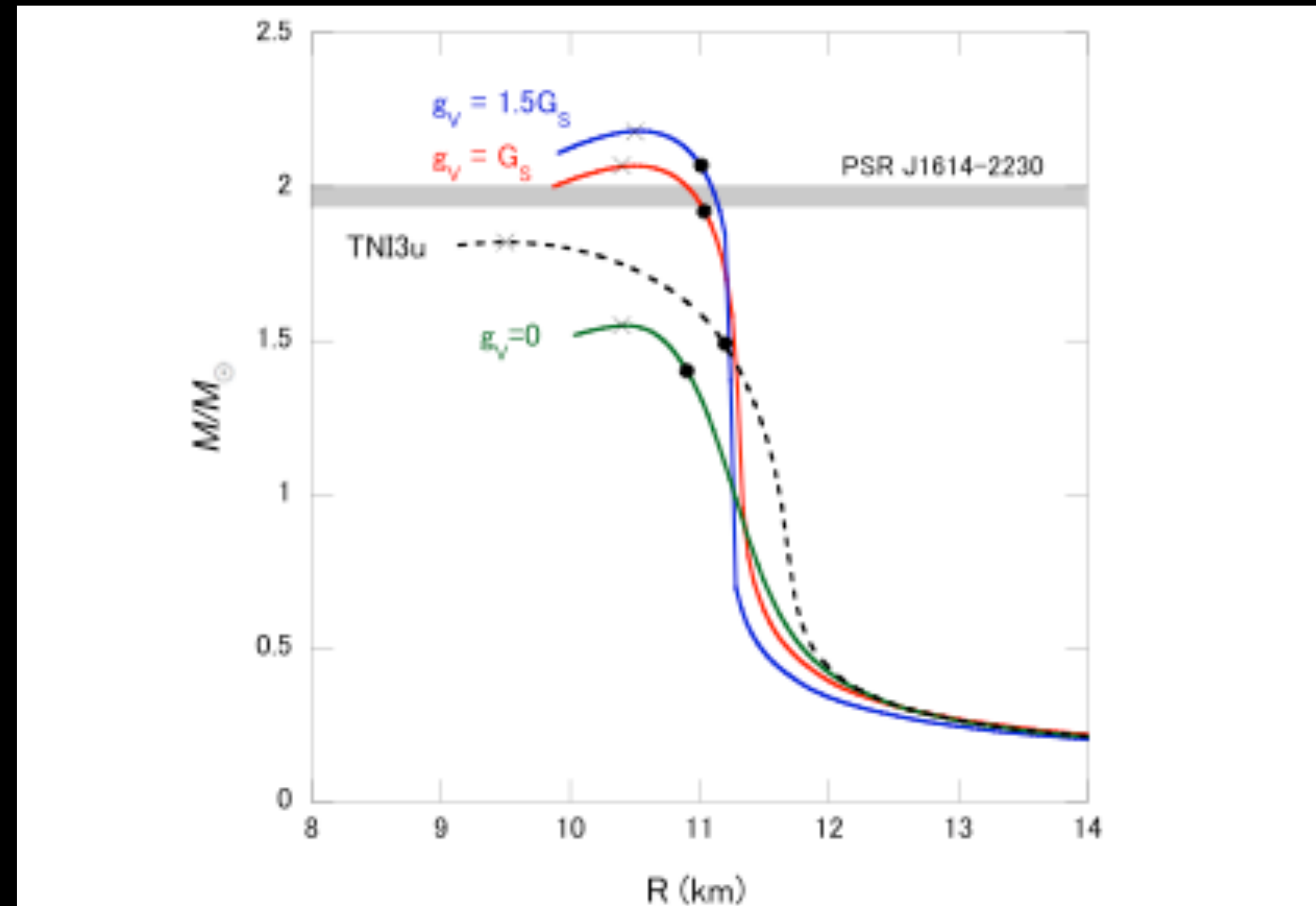
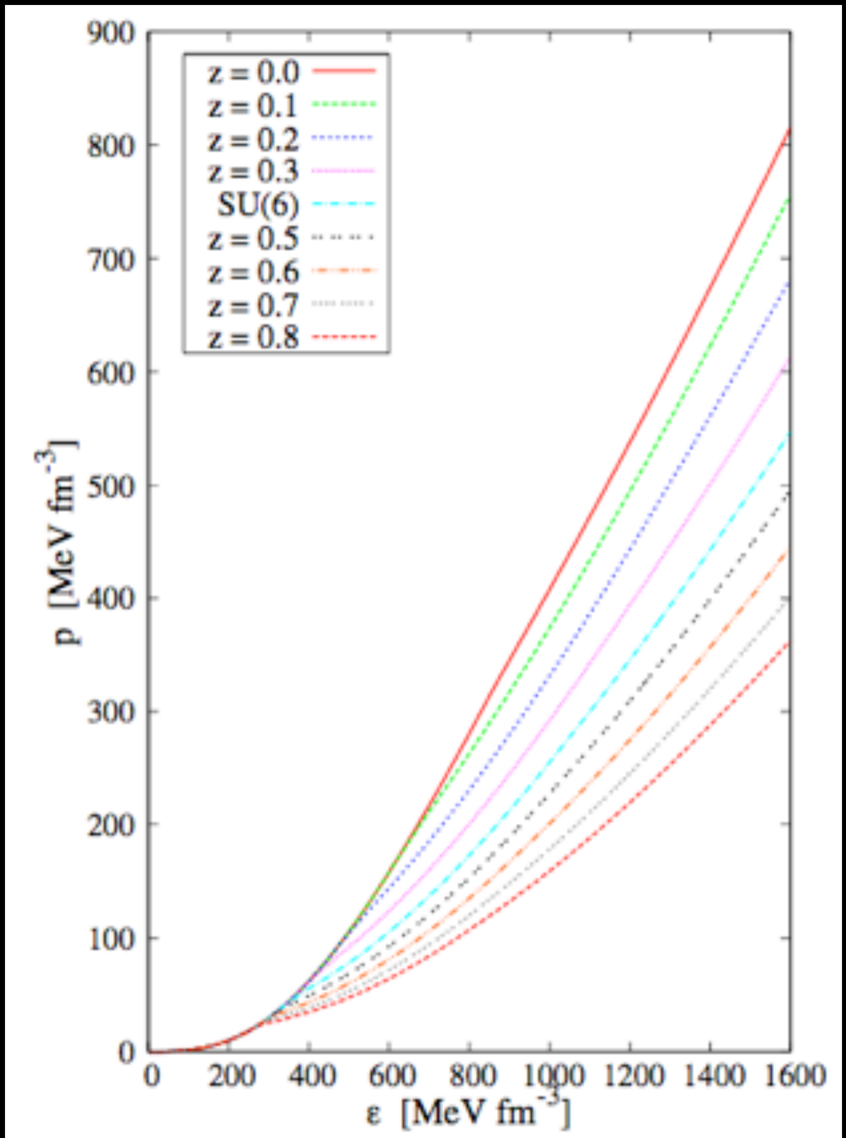


FIG. 5.— Solid lines: M-R relation of the NSs with the interpolated EOSs for $g_V/G_S = 0, 1.0, 1.5$. Dashed line: The same quantity for H-EOS with TNI3u. The cross symbols denote the points where M reaches $M_{\max}$. The filled circles denote the point beyond which the strangeness appears. The gray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

Masuda, Hatsuda, Takatsuka
arXiv:1205.3621

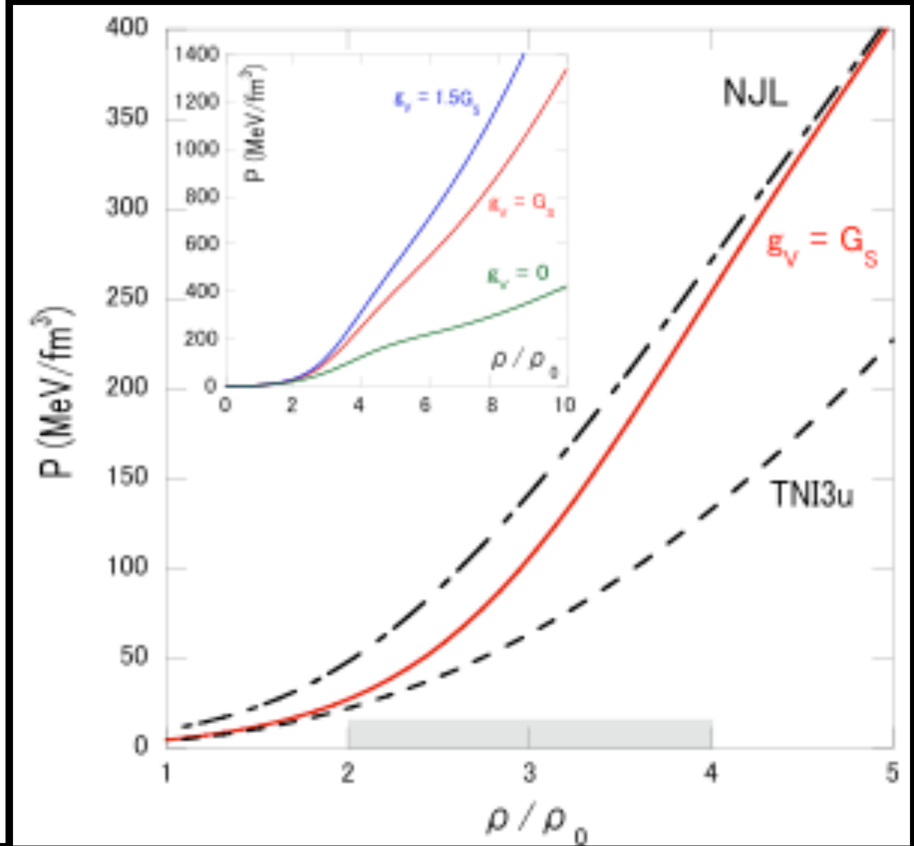
HOW TO DISTINGUISH EOSS WO DENSITY KINKS?

Hyperon matter



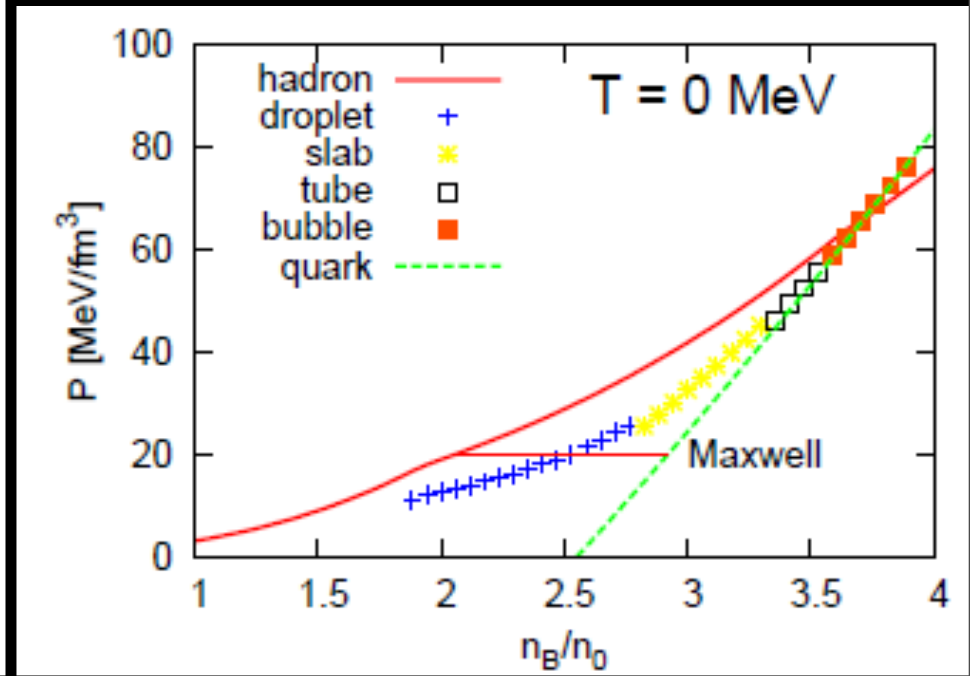
S. Weissenborn, et al.
PRC 85, 065802 (2012)

Hyperon + Quark (cross over)



Masuda, Hatsuda, Takatsuka
arXiv:1205.3621

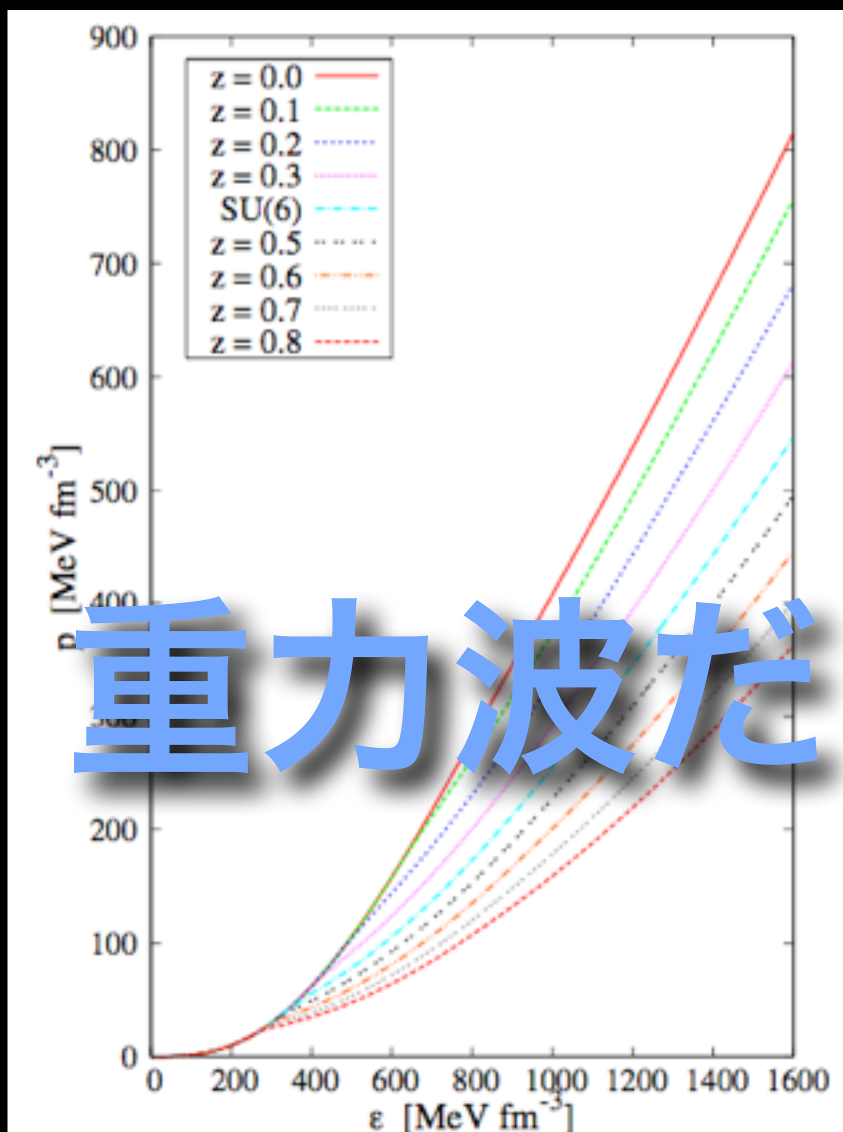
Hyperon + Quark (pasta)



NY, Maruyama, Tatsumi
PRD 2009a

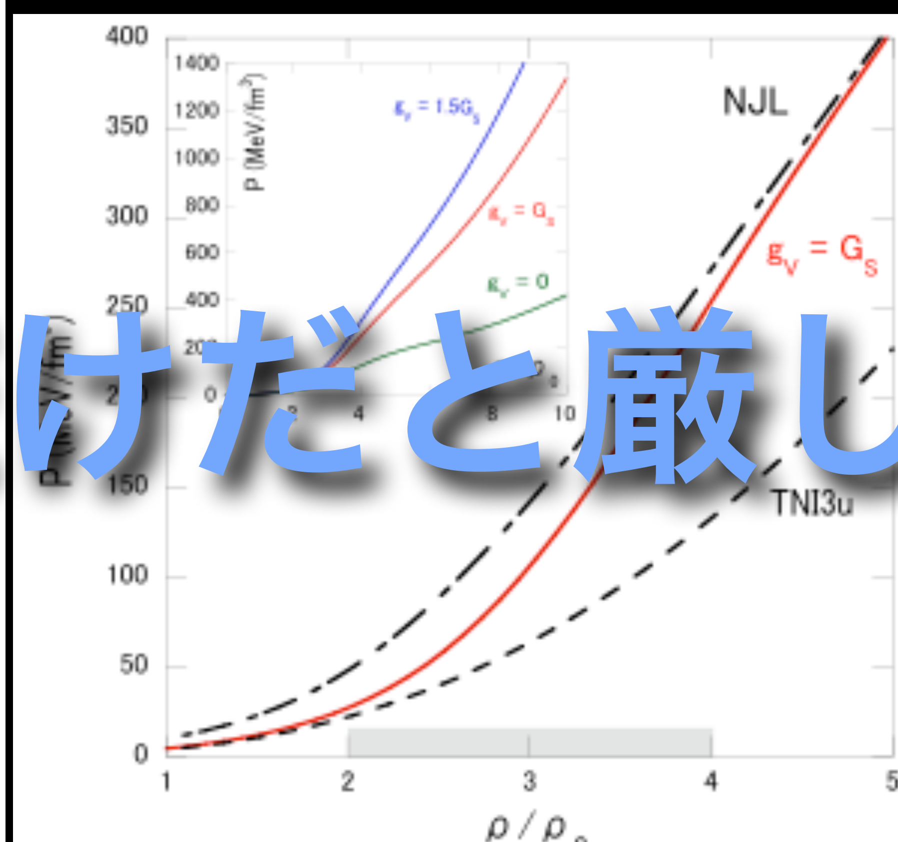
HOW TO DISTINGUISH EOSS WO DENSITY KINKS?

Hyperon matter



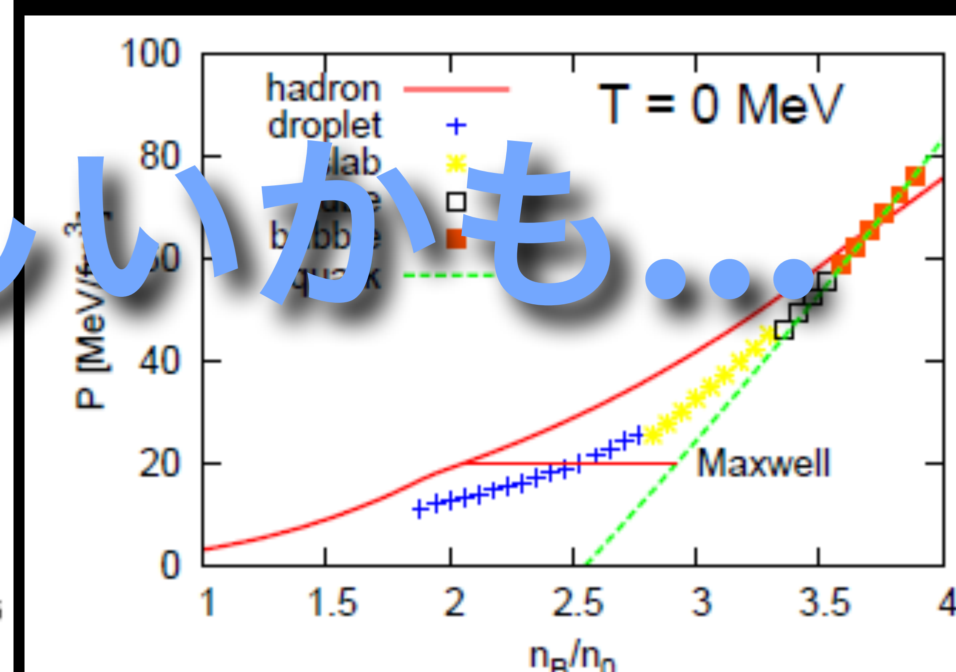
S. Weissenborn, et al.
PRC 85, 065802 (2012)

Hyperon + Quark (cross over)



Masuda, Hatsuda, Takatsuka
arXiv:1205.3621

Hyperon + Quark (pasta)



NY, Maruyama, Tatsumi
PRD 2009a

重力波だけだと厳しいかも…

COOLING OF NEUTRON STARS

GWs …
only hardness of EOS

Cooling…
other physical properties

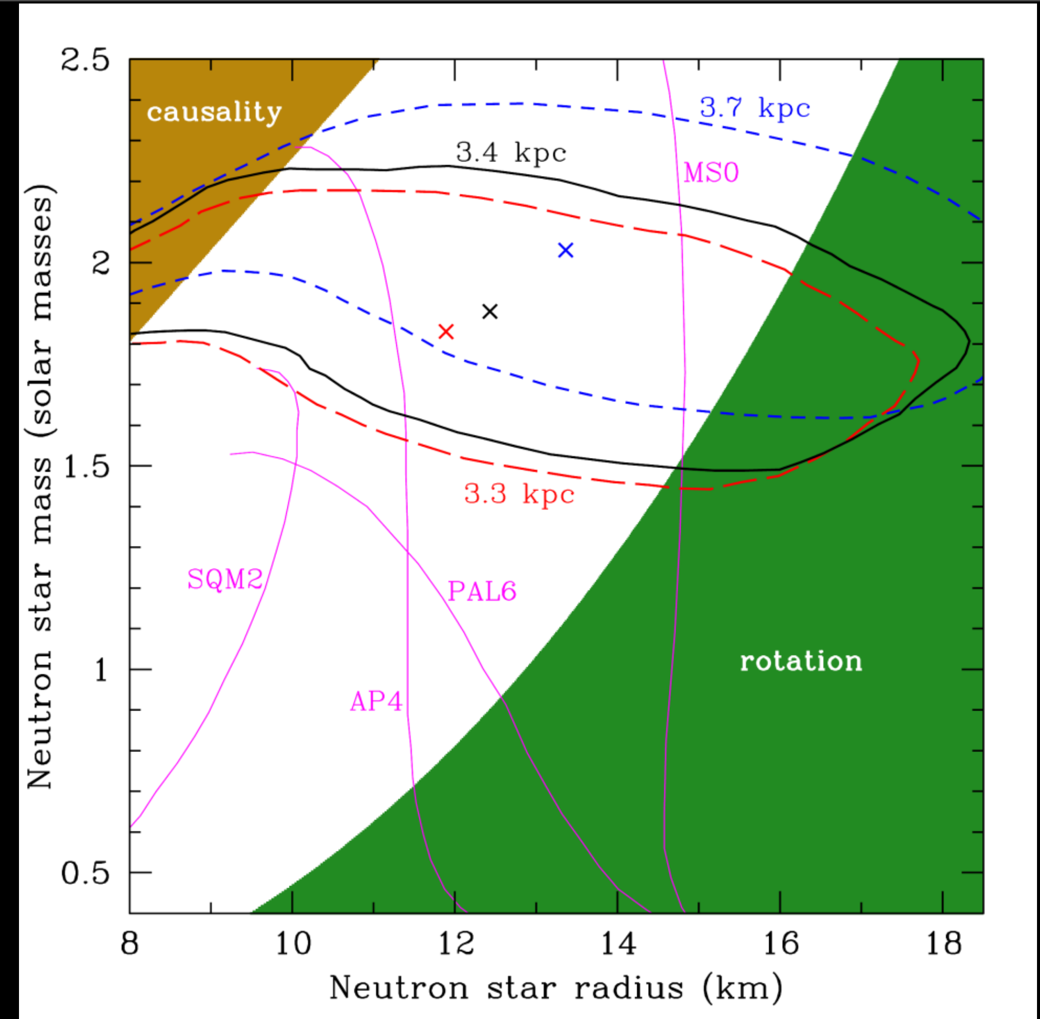
$$c_v e^{\Phi}\frac{\partial T}{\partial t} + \nabla\cdot(e^{2\Phi}F) = e^{2\Phi}Q$$

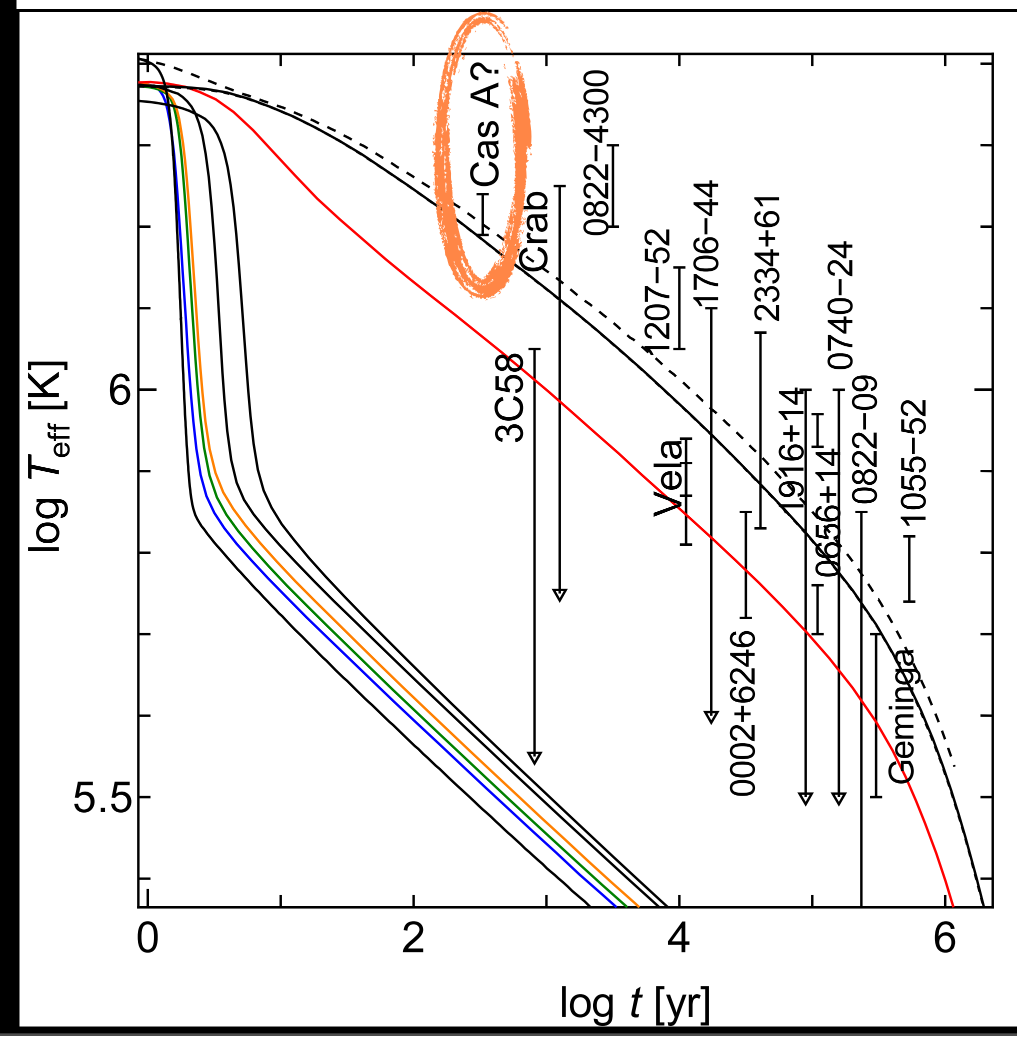
thermal diffusion eq.

heat capacity

flux (thermal conductivity)

cooling rate (neutrino) + heating rate (magnetic field)





How to calculate the thermal evolution of compact stars ?

EOS

Quark, hyperon, normal matter,
pion-condensation, kaon-condensation, etc.
(P)NJL, (D)BHF, RMF, variational principle etc.
Landau effects magnetization etc.

structure

w/wo rotation, w/wo magnetic field, axi symetric etc.

cooling

URCA, MURCA, HURCA, quark beta decay, superconductivity etc.

heating

Ohmic decay, Hall effect, ambipoler diffusion etc.
vortex etc.

evolution

thermal conduction in strong magnetic field etc.

atmosphere

Fe including effects strong magnetic field

||

Comparison with observations

How to calculate the thermal evolution of compact stars ?

Hardness of EOS

EOS	Quark, hyperon, normal matter, pion condensation, kaon condensation, etc. RMF, variational principle etc. Landau effects magnetization etc.
structure	w/wo rotation, w/wo magnetic field, axi symetric etc.
cooling	URCA, MURCA, HURCA, quark beta decay, superconductivity etc.
heating	Ohmic decay, Hall effect, ambipoler diffusion etc. vortex etc.
evolution	thermal conduction in strong magnetic field etc.
atmosphere	Fe including effects strong magnetic field

| |

Comparison with observations

How to calculate the thermal evolution of compact stars ?

Hardness of EOS

EOS

Quark, hyperon, normal matter,
pion condensation, kaon condensation, etc.
BHF (DBHF), RMF, variational principle etc.
Landau effects magnetization etc.

structure

w/wo rotation, w/wo magnetic field, axi symetric etc.

Other pysical properties

cooling

URCA, MURCA, HURCA, quark beta decay, superconductivity etc.

heating

Ohmic decay, Hall effect, ambipoler diffusion etc.
vortex etc.

evolution

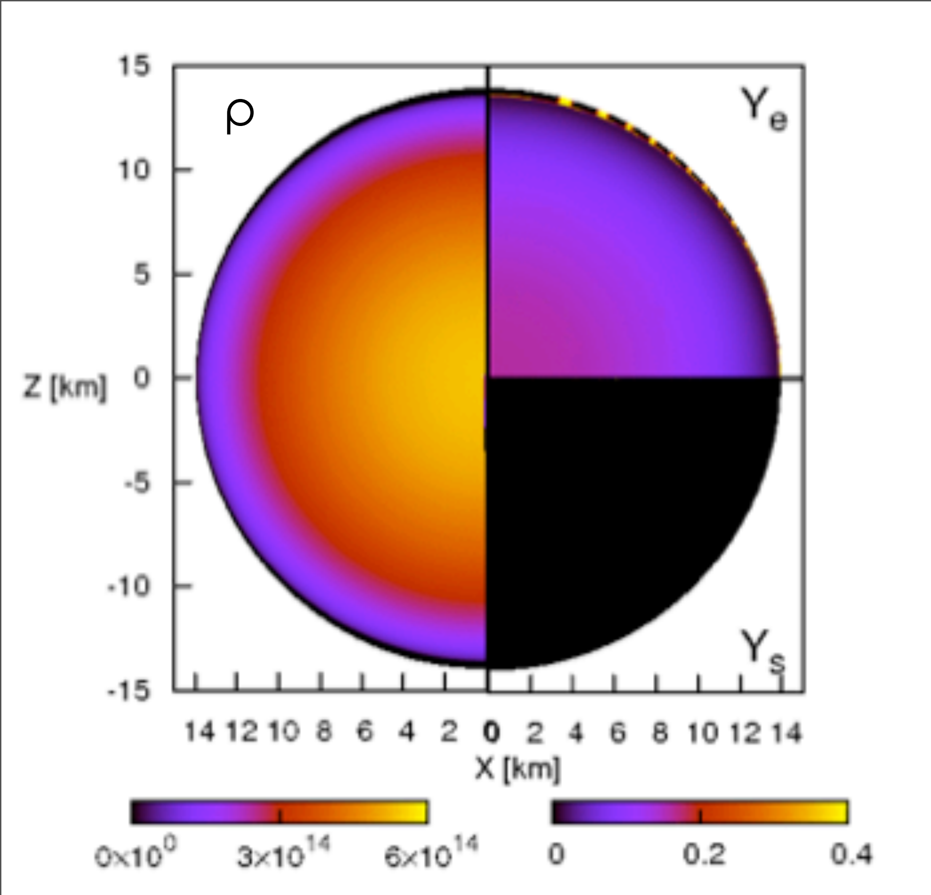
thermal conduction in strong magnetic field etc.

atmosphere

Fe including effects strong magnetic field

||

Comparison with observations



Tomimura & Eriguchi 2005
(1) axi symmetric
(2) equatorial symmetric
(3) no convection
etc.

GR correction
on the gravitational potential
ref) Mareck et al. 2006

$$-\frac{1}{\rho}\,\mathrm{grad}\,p - \mathrm{grad}\,\Phi_g + \mathrm{grad}\,\Phi_r + \frac{1}{\rho}\,(\boldsymbol{j} \times \boldsymbol{H}) = 0,$$

$$\Delta\Phi_g = 4\pi G\rho,$$

$$\mathrm{rot}\,\boldsymbol{H} = 4\pi\boldsymbol{j},$$

$$\mathrm{div}\,\boldsymbol{H} = 0,$$

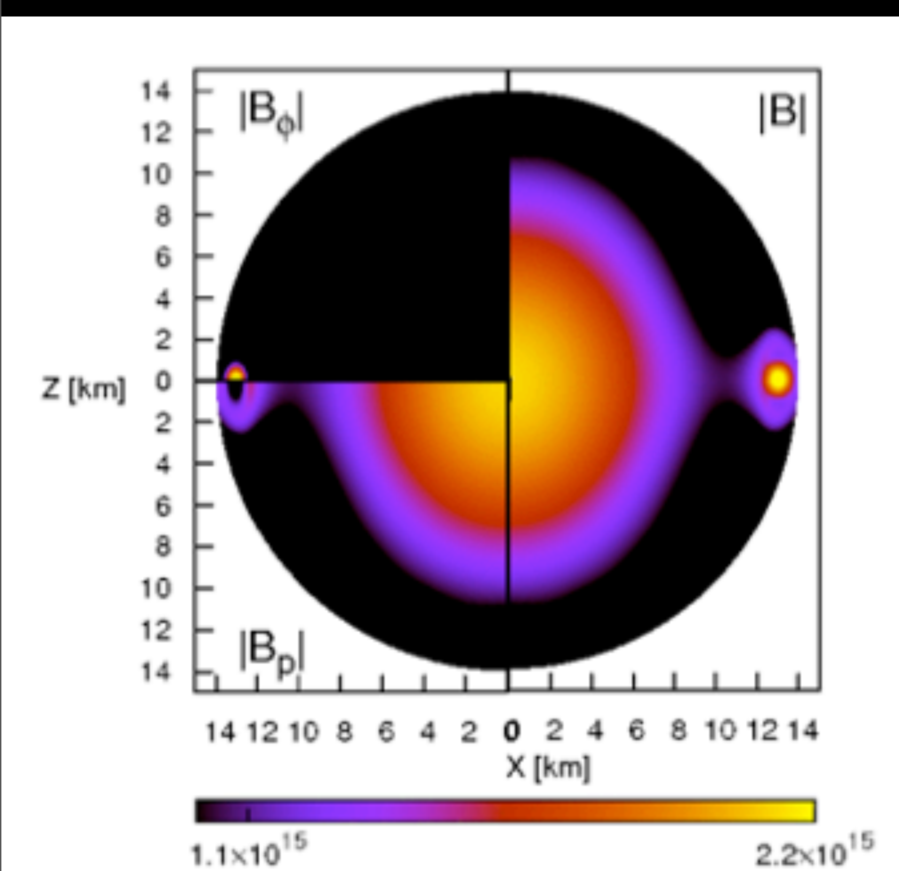
↓ integrability condition
etc.

$$\int \frac{\mathrm{d}p}{\rho} = -\Phi_g + \Phi_r + \int \mu(RA_\phi)\,\mathrm{d}(RA_\phi) + C,$$

$$\Phi_g(\boldsymbol{r}) = -G\int \frac{\rho(\boldsymbol{r}')}{|\boldsymbol{r}-\boldsymbol{r}'|}\mathrm{d}^3\boldsymbol{r}',$$

$$A_\phi(\boldsymbol{r})\sin\phi = -\frac{1}{4\pi}\int \frac{\left(-\frac{\kappa}{R}\int\kappa\,\mathrm{d}(RA_\phi) - 4\pi\mu\rho R'\right)}{|\boldsymbol{r}-\boldsymbol{r}'|}\sin\phi'\mathrm{d}^3\boldsymbol{r}',$$

Structures with rotation and magnetic field



*arbitrary function for magnetic field

$$\boldsymbol{j} = \frac{\kappa}{4\pi}\boldsymbol{H} + \mu\rho R_e\boldsymbol{e}_\phi.$$

$$B_\phi = a(u - u_{\max})^{\kappa+1}/(\kappa+1).$$

*arbitrary rotational law

Thermal conduction in strong magnetic field

$$c_v e^{\Phi}\frac{\partial T}{\partial t} + \nabla\cdot(e^{2\Phi}\boldsymbol{F}) = e^{2\Phi}Q$$

$$\boldsymbol{F}_e = -e^{\Phi}\kappa_e^{\perp}\left[\nabla\tilde{T} + (\omega_B\tau)^2\left(\boldsymbol{b}\cdot\nabla\tilde{T}\right)\cdot\boldsymbol{b} + \omega_B\tau\left(\boldsymbol{b}\times\nabla\tilde{T}\right)\right]$$

- implicit scheme
- operator splitting

Geppert et al.2004

the thermal conductivity

$$\kappa = \begin{pmatrix} \kappa_\perp & \kappa_\wedge & 0 \\ -\kappa_\wedge & \kappa_\perp & 0 \\ 0 & 0 & \kappa_\parallel \end{pmatrix}$$

here

$$\begin{cases} \kappa_0 = \frac{1}{3}c_V\bar{v}^2\tau = \frac{\pi^2 k_B^2 T n_e}{3m_e^*}\tau \\ \kappa_\parallel = \kappa_0 \\ \kappa_\perp = \frac{\kappa_0}{1+(\omega_B\tau)^2} \\ \kappa_\wedge = \frac{\kappa_0\,\omega_B\tau}{1+(\omega_B\tau)^2} \end{cases}$$

cooling rate(L) & heating rate(H)

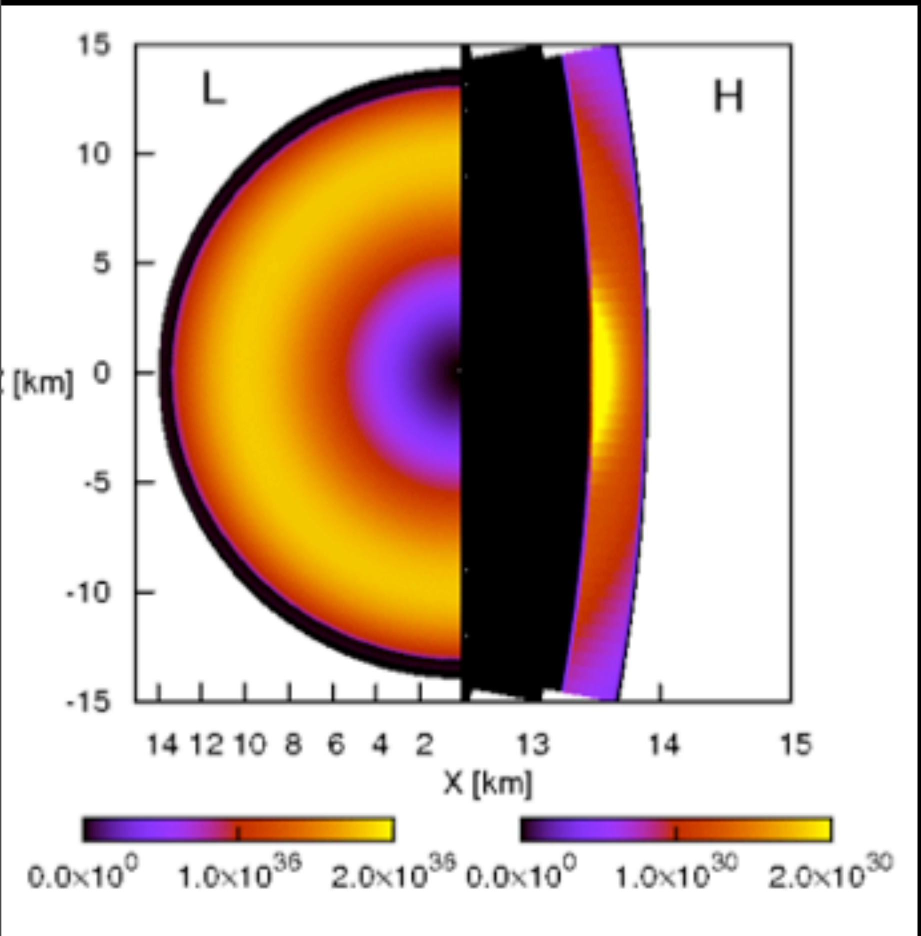


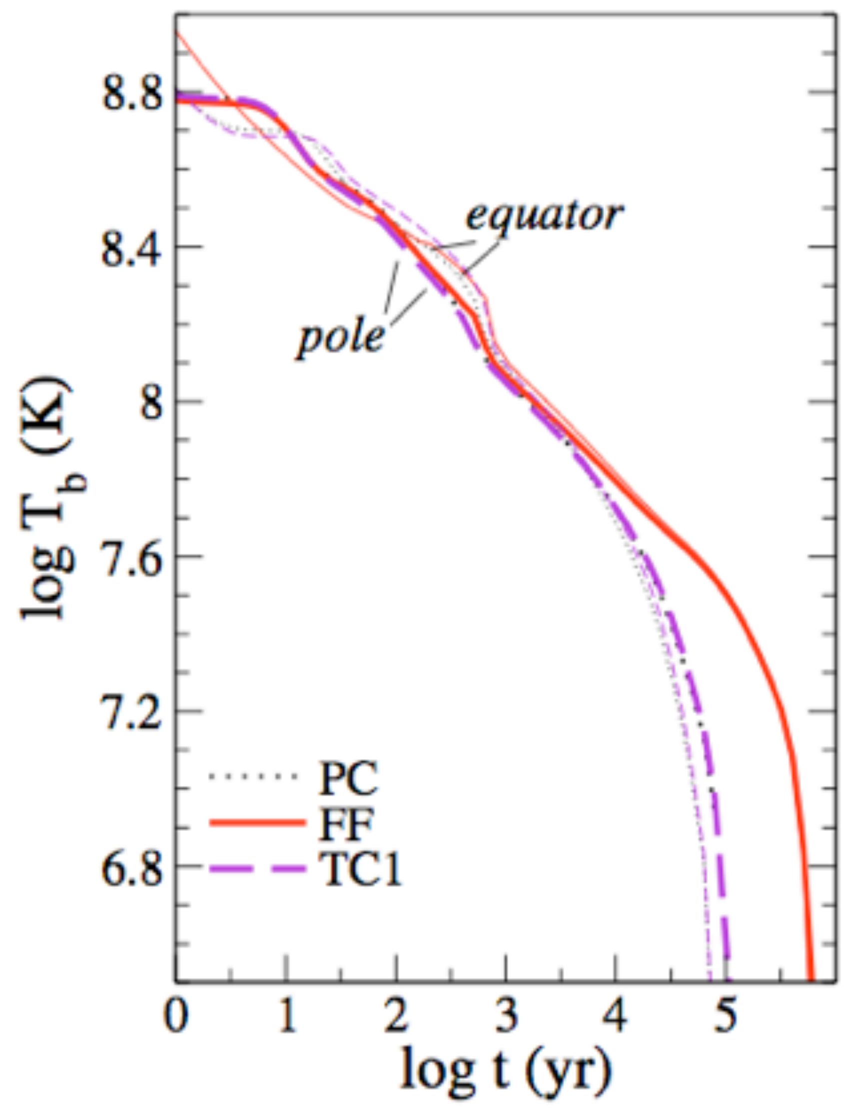
TABLE III: Cooling ratio in the cores and crusts we adopt
The details are shown in the references.

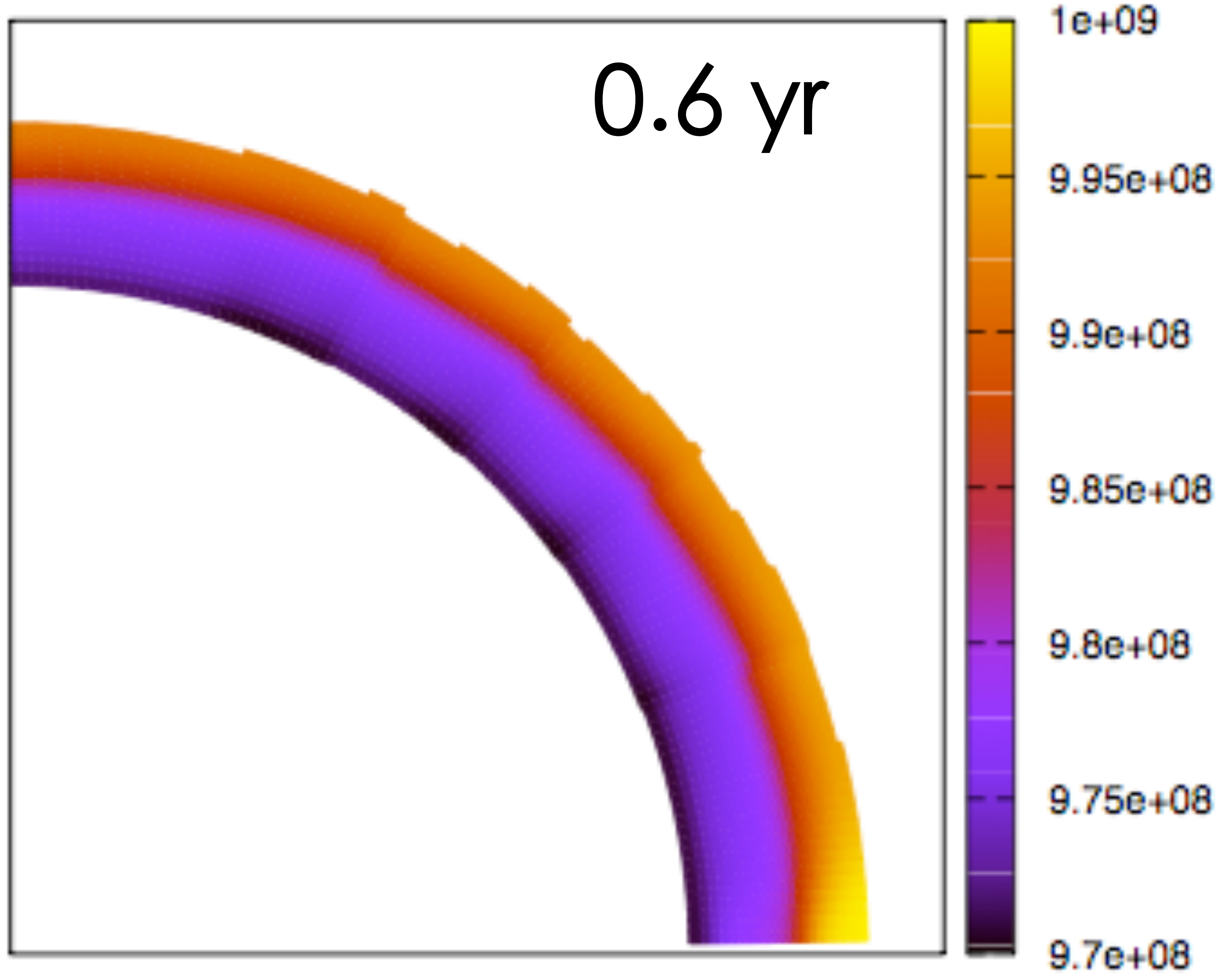
process	ratio	referenc
Core		
"Modified URCA processes (n-branch)"		
$nn \to nn\nu\bar{\nu}$		
$pne \to nn\bar{\nu}_e$	$8\times10^{21}(n_p)^{1/3}T_9^8$	[31]
"Modified URCA processes (p-branch)"		
$nn \to nn\nu\bar{\nu}$	$7\times10^{19}(n_n)^{1/3}T_9^8$	[31]
$np \to np\nu\bar{\nu}$	$1\times10^{20}(n_p)^{1/3}T_9^8$	[31]
$pp \to pp\nu\bar{\nu}$	$7\times10^{19}(n_p)^{1/3}T_9^8$	[31]
"$N-N$ Bremsstrahlung"		
$nn \to nn\nu\bar{\nu}$	$7\times10^{19}Zn_e^{1/3}T_9^8$	[31]
$np \to np\nu\bar{\nu}$	$1\times10^{20}Zn_e^{1/3}T_9^8$	[31]
$pp \to pp\nu\bar{\nu}$	$7\times10^{19}Zn_e^{1/3}T_9^8$	[31]
Crust		
"$e-A$ Bremsstrahlung"		
$e(A,Z)\to e(A,Z)\nu\bar{\nu}$	$3\times10^{12}Zn_eT_9^8$	[32]
"$N-N$ Bremsstrahlung"		
$nn \to nn\nu\bar{\nu}$	$7\times10^{19}Zn_e^{1/3}T_9^8$	[32]

Thermal distribution in crust of NSs

NY, Kotake, Kutsuna, Shigeyama 2012 in prep.

* The crust is extended five times for radial direction.



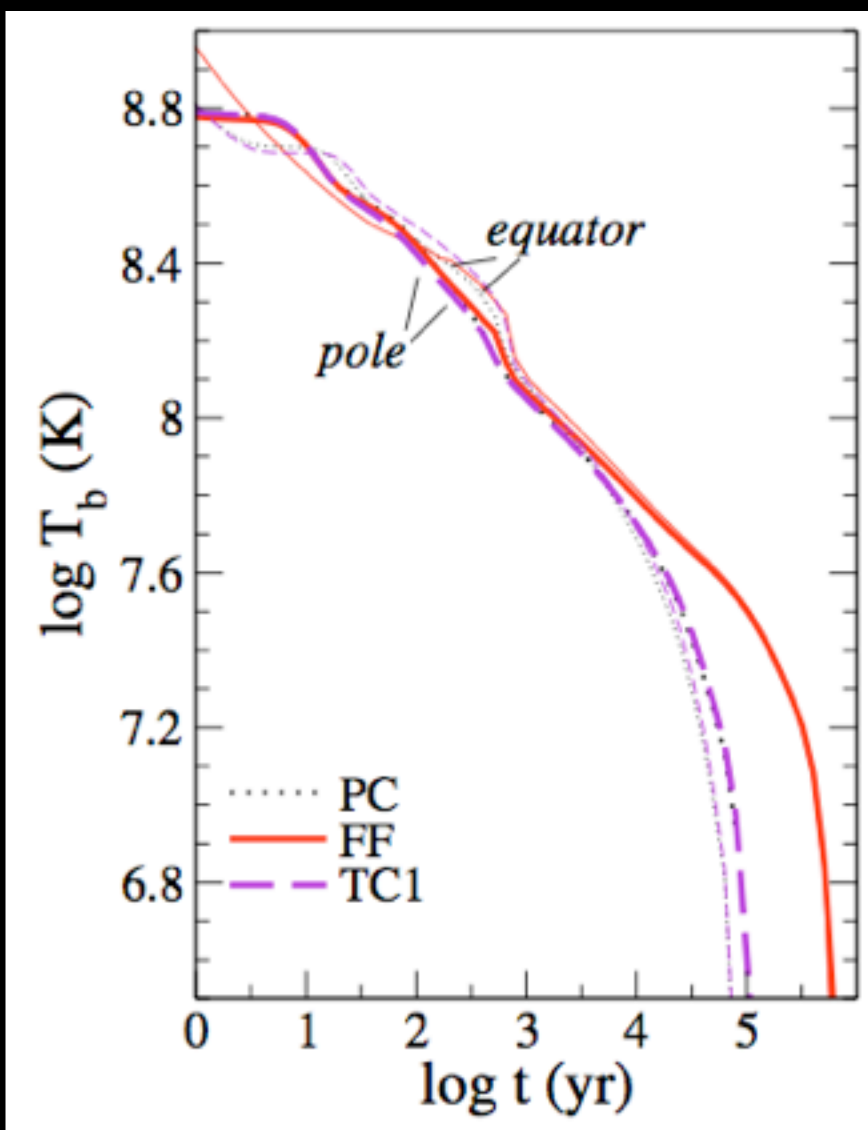


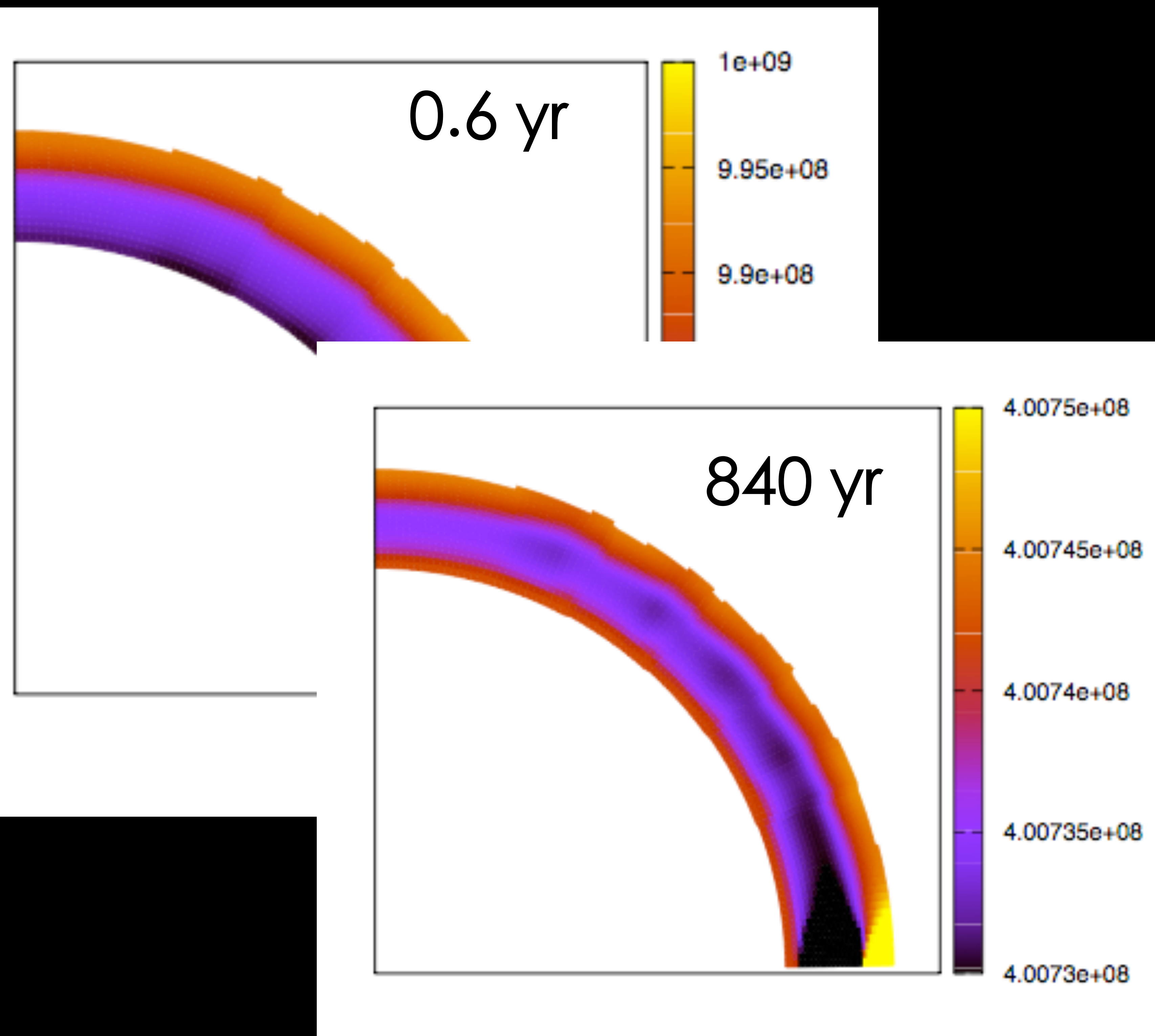
D. N. Aguilera, J. A. Pons, and J. A. Miralles(2008)

Thermal distribution in crust of NSs

NY, Kotake, Kutsuna, Shigeyama 2012 in prep.

* The crust is extended five times for radial direction.





D. N. Aguilera, J. A. Pons, and J. A. Miralles(2008)

Temperature distribution

NY, Kotake, Kutsuna, Shigeyama 2012 in prep.

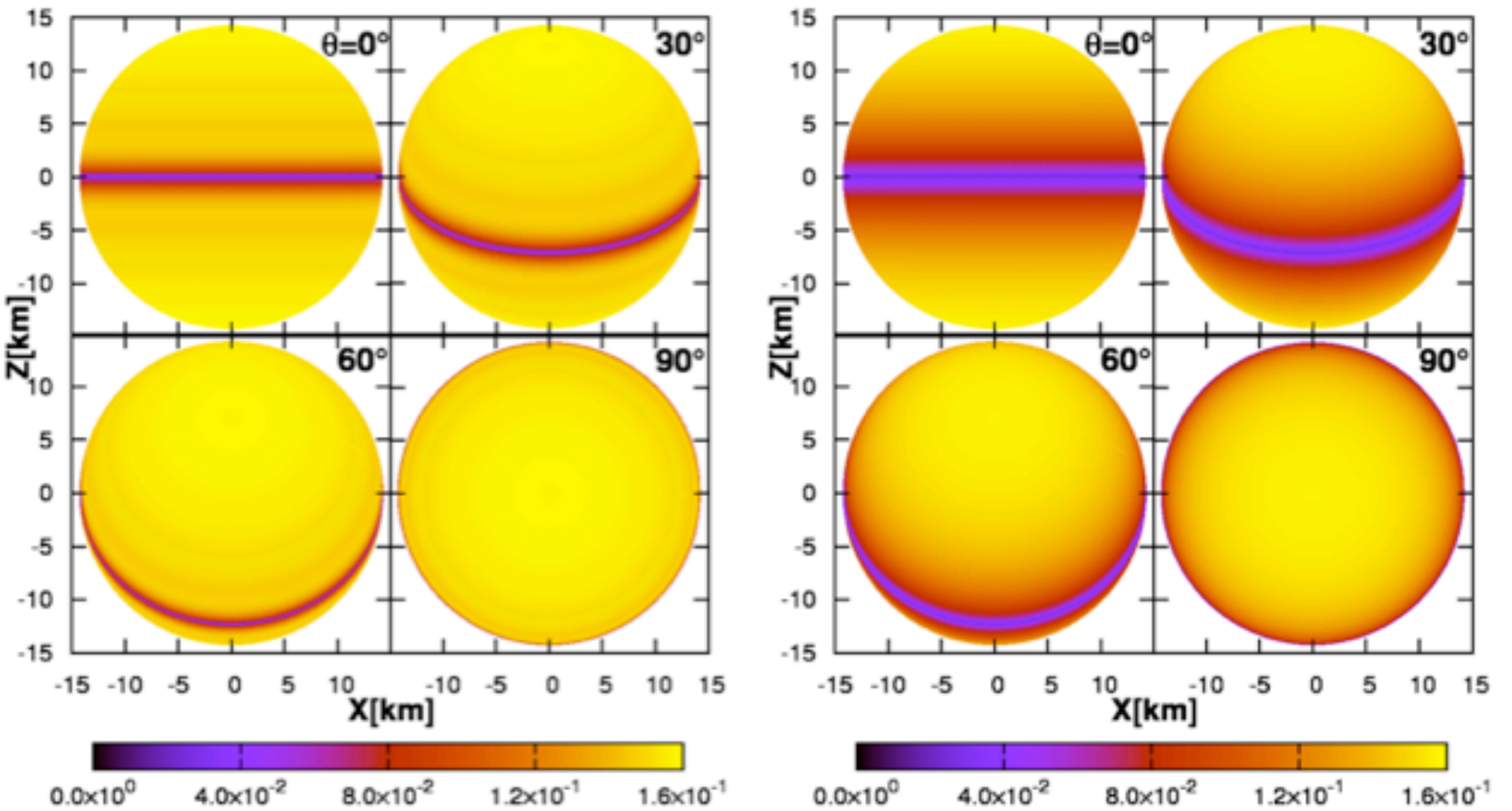
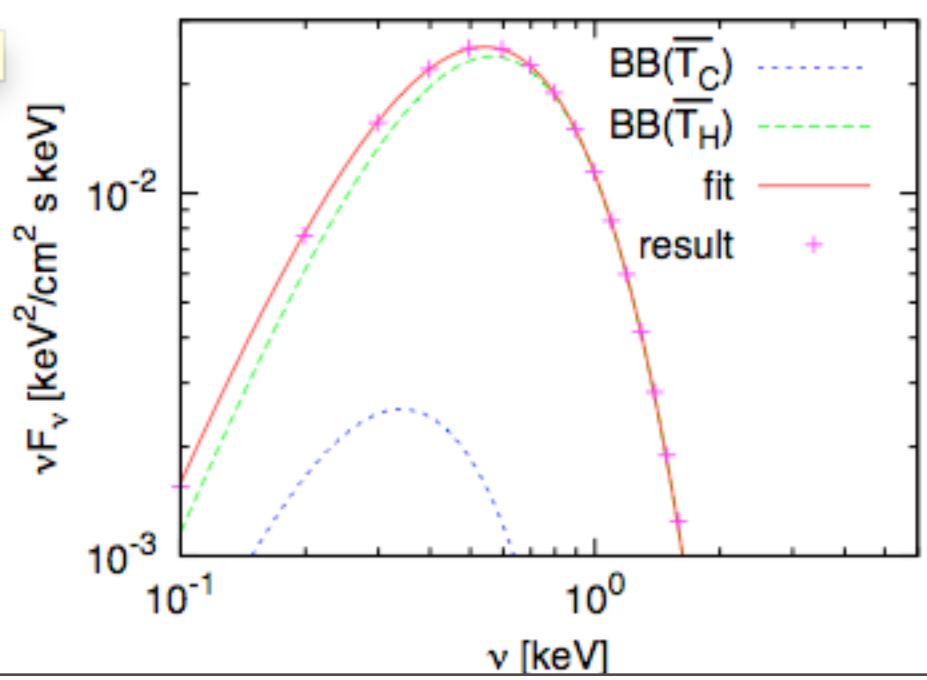


FIG. 7: (Color online) Temperature distribution for model "mSUK" after 10^4 years depended on the inclination angle θ . The unit of color contour is [keV].



Our results

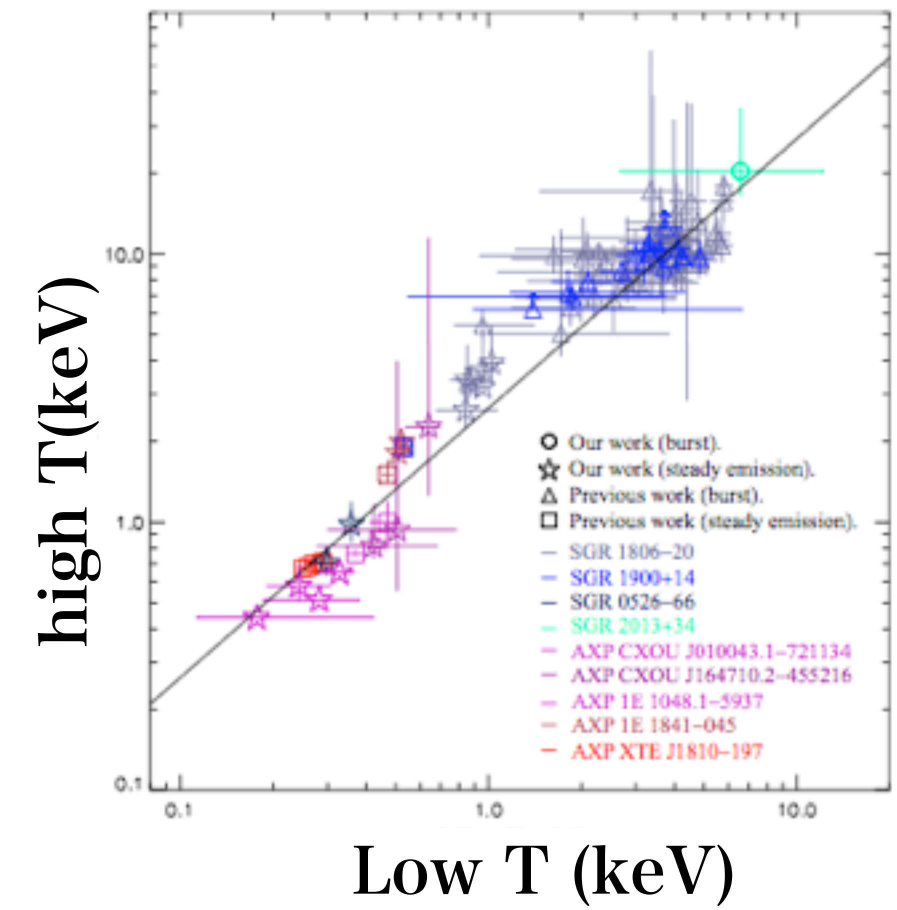


Fig. 3. Relationship between the 2BB temperatures kT_{LT} and kT_{HT}. The triangles and squares denote the previous work on the bursts (Feroci et al. 2004; Olive et al. 2004; Götz et al. 2006a; Nakagawa et al. 2007) and the quiescent emission (Morii et al. 2003; Gotthelf et al. 2004; Gotthelf & Halpern 2005; Tiengo et al. 2005; Mereghetti et al. 2006a), respectively. The circles and stars denote our work on the bursts and the quiescent emission, respectively. The line represents the best-fit power law model.

Observation, Yujin, et al. (2009)

SUMMARY OF THE SECOND TOPIC

"Thermal evolution of magnetars"

① We could show the non-uniform temperature of magnetars.

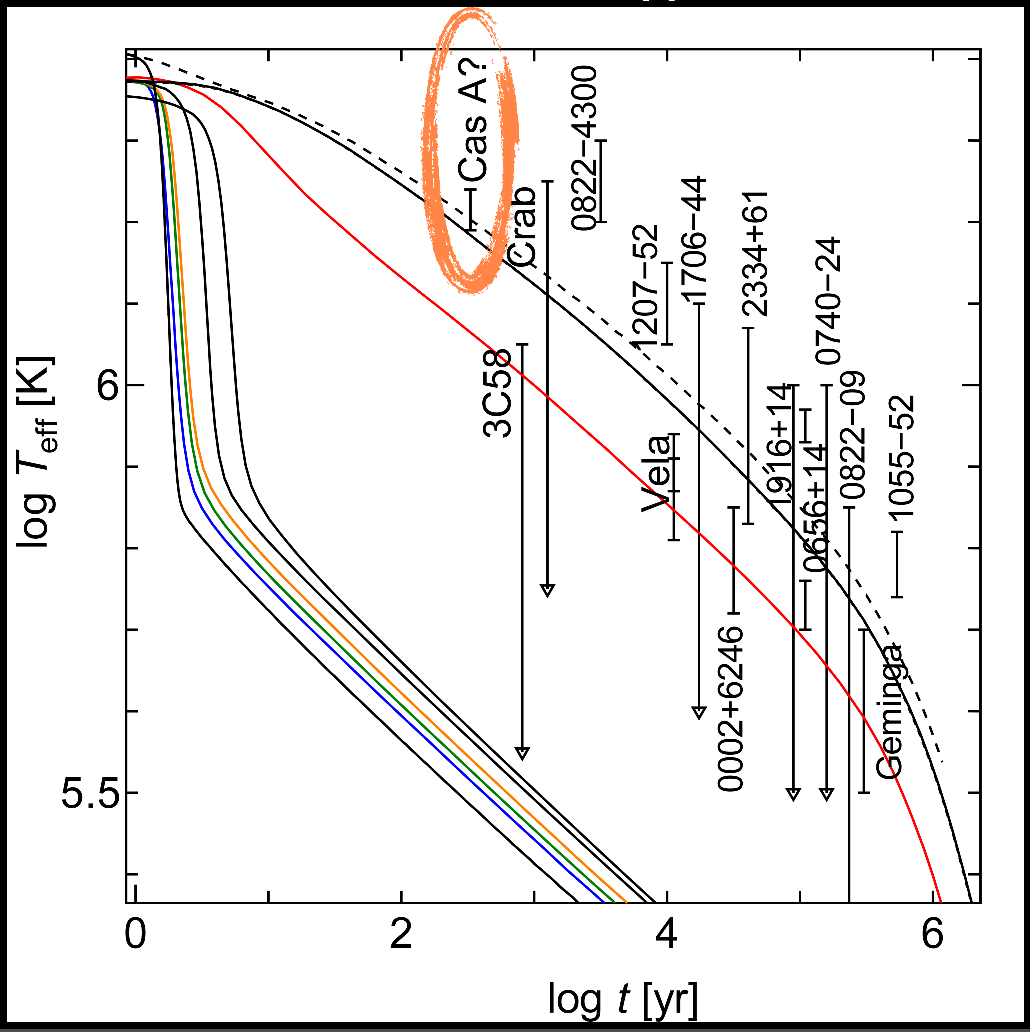
② Our results are not consistent with the observations, quantitatively.

Noda, Hashimoto, Matsuo,
NY, Maruyama, Tatsumi, Fujimoto
2012 ApJ submitted

DISCUSSION

① We adopted only standard EOS, and cooling process.
→Other exotic model may change our results.

cf.) CSC, superfluid of hadron, pion condensation, hyperon direct URCA, etc.



Matter inside of NSs

+

Cooling of magnetars

- Pasta/amorphous state of QH phase transition

・Matter of NS-NS merger shows Maxwell-like behavior (It has a density jump.)
・Supernovae matter shows the Gibbs (LCN)-like behavior (It does not have a density jump.)

Matter inside of NSs
+
Cooling of magnetars

- Pasta/amorphous state of QH phase transition
  - Matter of NS-NS merger shows Maxwell-like behavior (It has a density jump.)
  - Supernovae matter shows the Gibbs (LCN)-like behavior (It does not have a density jump.)

Matter inside of NSs
+
Cooling of magnetars

- 2D simulation with implicit shceme
  - We could show the non-uniform temperature.
  - We should extend our model to the one eith exotic matter.

終