Beijin 21th. Oct. (2014)

Quark-Hadron Phase Transition with Finite-Size Effects in Neutron Stars

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Phys.Rev.C, (2014), 89, 5803
NY, R. Łastowiecki, D . Blaschke(Wroclow univ.), **S. Benic**(Zagreb univ.), **T. Maruyama**(JAEA), **T.Tatsumi**(Kyoto univ.)

in prep. arXiv:1309.1954
NY, H. Chen(Wuhan CUG), **T. Maruyama**(JAEA), **T.Tatsumi**(Kyoto univ.)

Phys.Rev.C (2014) accepted, and in press
Y. Yamamoto(RIKEN), **T. Furumoto**(Ichinoseki College), **NY**, **T.Rijiken**(Nijimegen univ,)

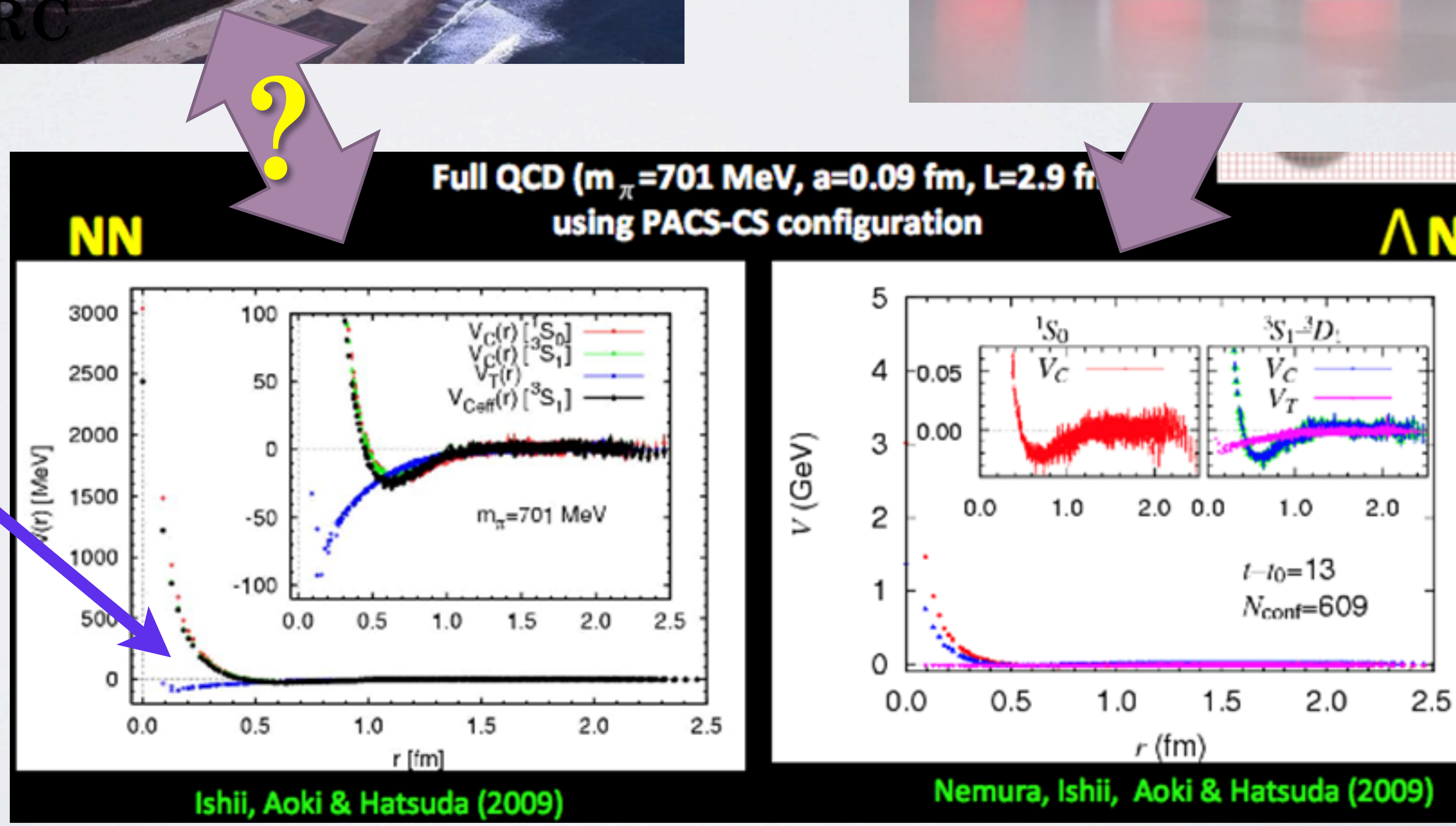
PASJ (2014) 66, 50
NY, **K.Kotake**(Fukuoka univ.),**M.Kutsuna, T.Shigeyama**(Univ,. of Tokyo)

Mon. Not. Roy. Astro. Soc. Letter (2014)accepted, and in press
NY, **K.Fujisawa, S.Yamada**(Waseda univ.)

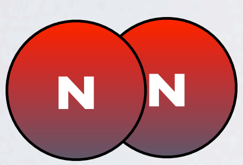
Part I

Background

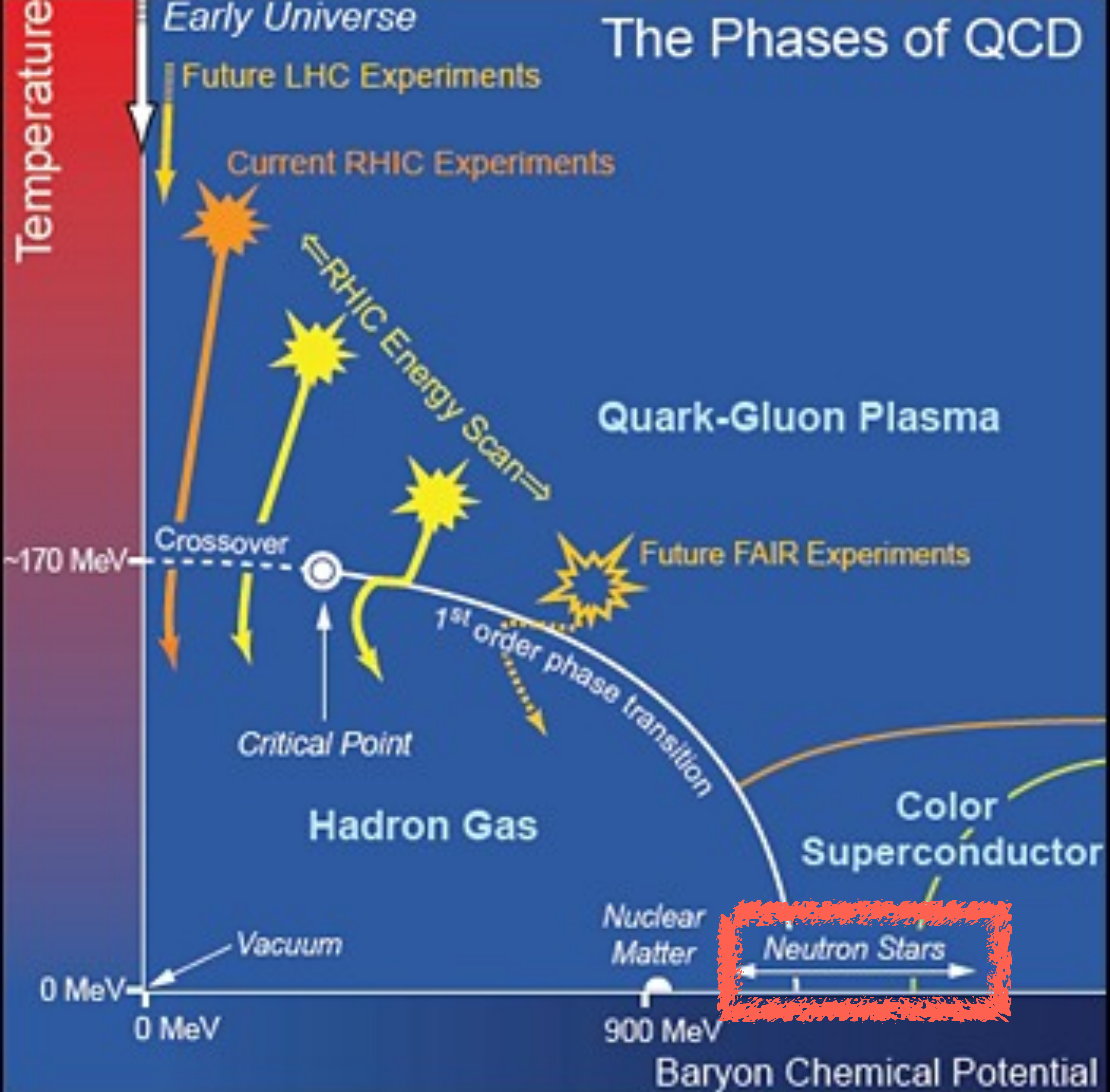
"BARYON-BARYON INTERACTIONS WILL BE CLARIFIED IN A FEW YEARS"



overlapped



- quarks
- 3body

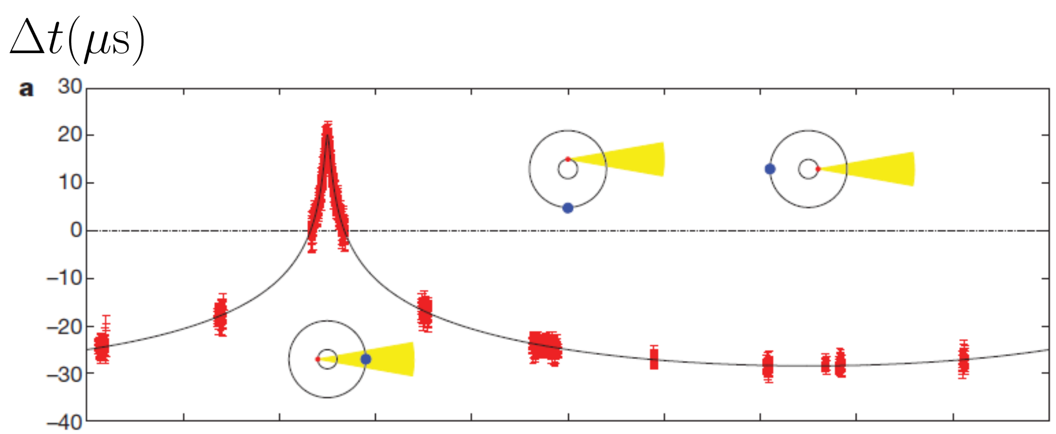


From a webpage of Brookhaven National Laboratory

CONSTRAINTS ON EOS

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]



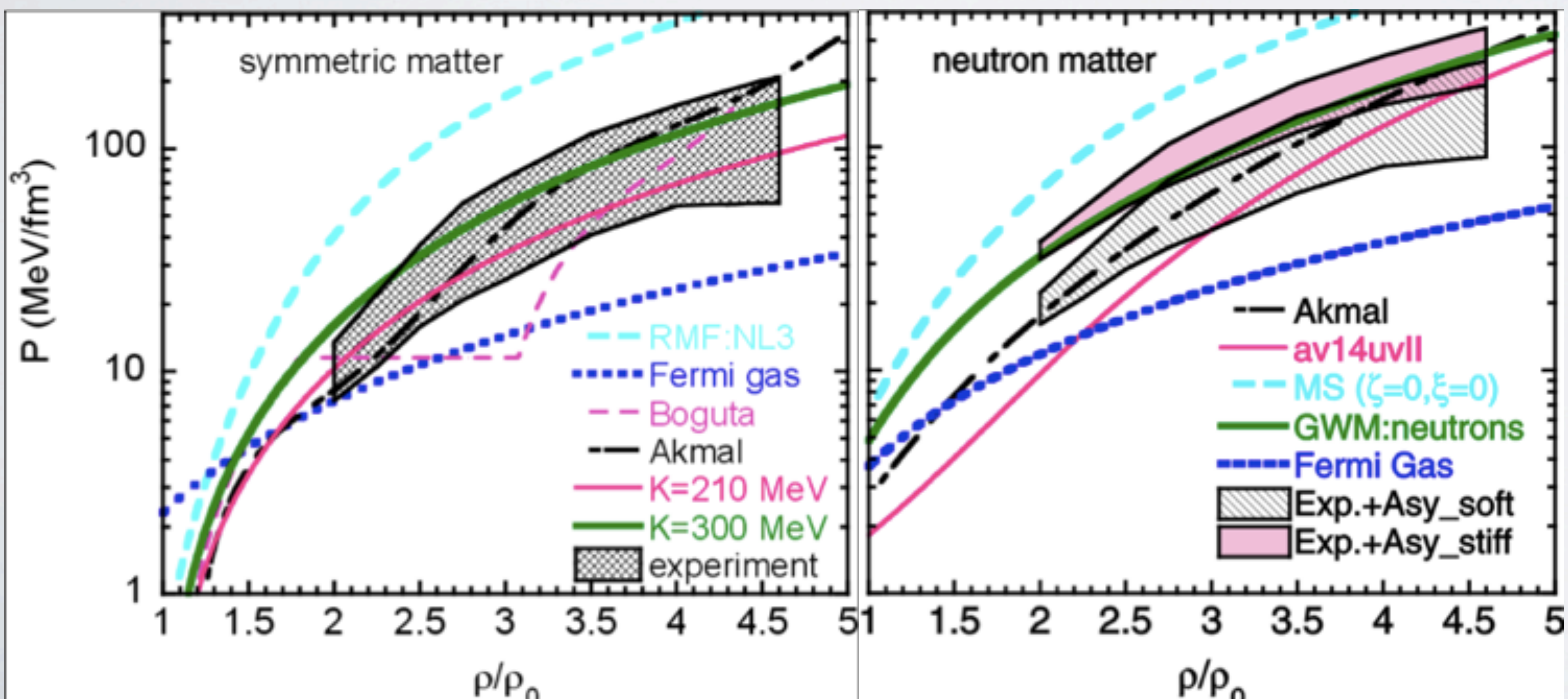
Demorest et al. 2010 nature

"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.

M_{max} > 2 Ms

Antoniadis et al. 2013 science is also.



Danielewiez et al. 2012 science

"Constraint by Experiment"

There is the upper limit of hard EOS.

Part II

Finite Size Effects
in
Quark-Hadron Phase Transition

FORMALISM

NY, et al. (2013) *Recent Advances in Quarks Research*, Nova, Chap.4, pp.63, ISBN 9781622579709, arXiv:1208.0427[astro-ph].

Hadron matter

- **Brueckner-Hartree-Fock model** (Baldo et al. 1998, Schulze et al. 1995, Yamamoto et al. 2014)

NN interaction → Argonne V18 potential or Bonn B potential + three body forces
NY interaction → ESC 08 potential + multi-Pomeron interaction(three body foreces) etc.

(We will update the interactions by the results of lattice QCD and/or J-PARC.)

↕ **Finite size effects**

Quark matter

- **non local (P)NJL model** (Blaschke et al. 2012, Benic et al.2014)
- **Dyson-Schwinger method** (Huan et al. 2012, etc.).

We assume the non-uniform structures of the mixed phase as droplet, rod, slab, tube, and bubble under Wigner-Seitz cell approximation.

In calculations of mixed phase, we consider

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

Changing all of them, we search the minimum free energy.

3-BODY FORCE IN HADRONS

Yamamoto, Furumoto, NY, Rijken, 2014 PRC accepted

$^{16}O+^{16}O$ scattering → BHF+3body forces → MR relations
(multi-Pomeron)

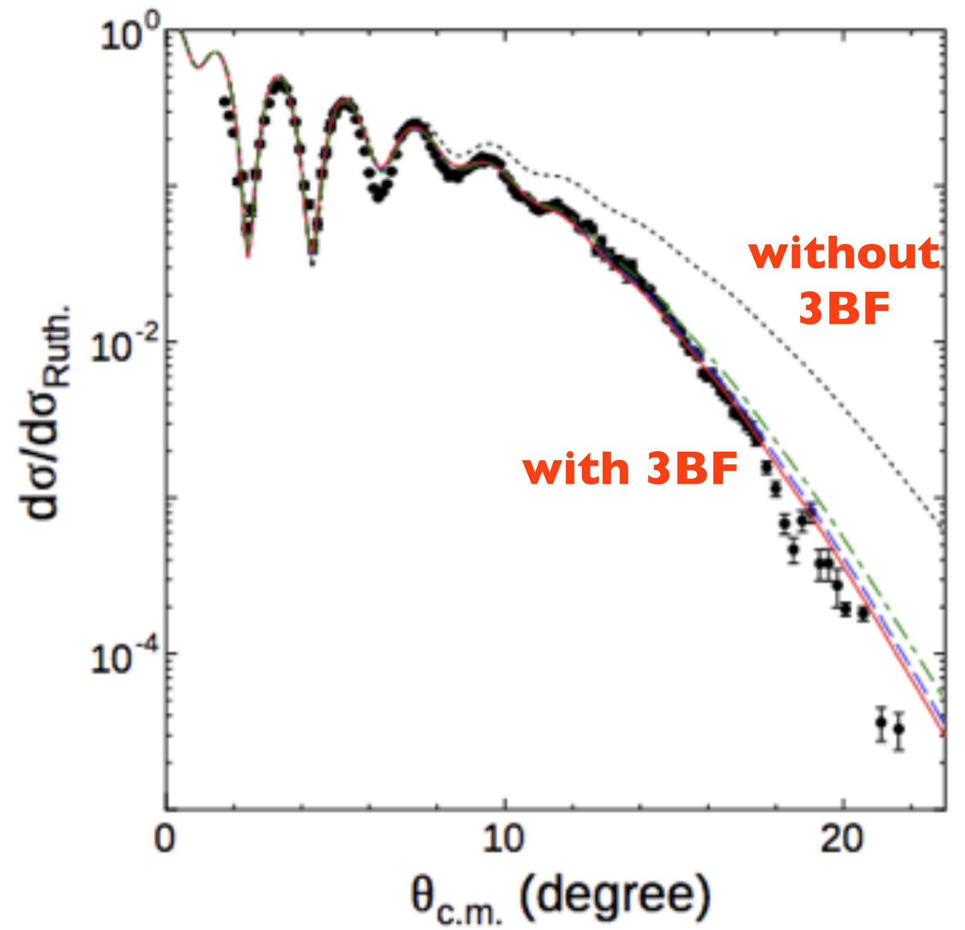


FIG. 1: (Color online) Differential cross sections for $^{16}O+^{16}O$ elastic scattering at E/A = 70 MeV calculated with the G-matrix folding potentials. Solid, dashed and dot-dashed curves are for MPa, MPb and MPc, respectively. Dotted curve is for ESC.

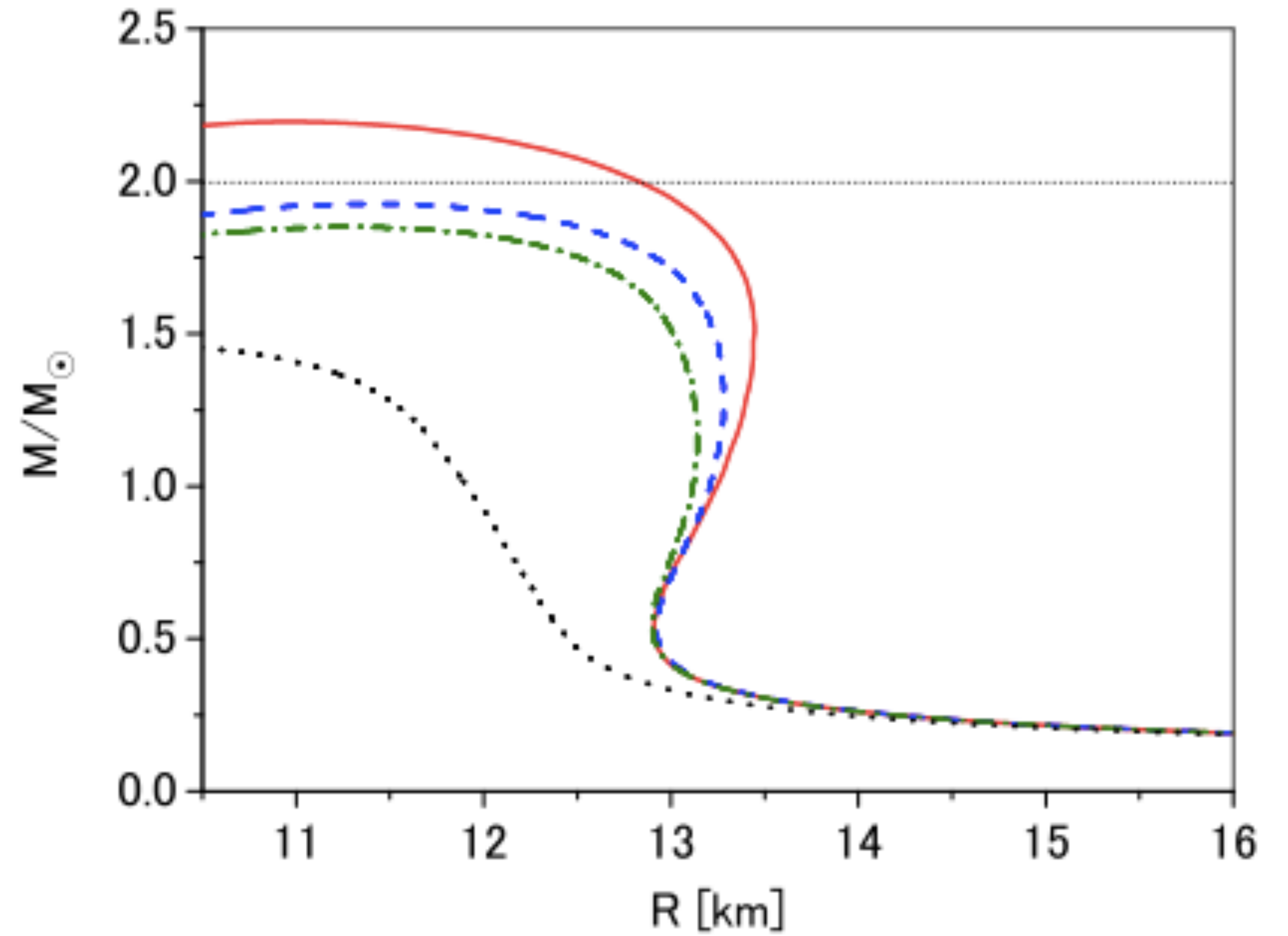


FIG. 9: (Color online) Neutron-star masses as a function of the radius R. Solid, dashed, dot-dashed and dotted curves are for MPa/b/c and ESC, respectively.

waiting results of LQCD/J-PARC.

NON-LOCALITY OF QCD

Contrera et al. 2010 PRD, Benic, Blaschke, Contrera and Horvatic 2014 PRD

Huan et al. 2011 PRD

ex). Non-local NJL

In mean field approximation,

$$\Omega = \Omega_{\rm cond} + \Omega^{\rm reg}_{\rm kin} + \Omega^{\rm reg}_{\rm free} \ ,$$

$$\Omega_{\rm cond} = \frac{1}{2G_S}\left(\sigma_B^2 + \kappa_{\bf p}^2\sigma_A^2 + \kappa_{p_4}^2\sigma_C^2\right) - \frac{\omega^2}{2\eta_V G_S} \ ,$$

$$\Omega^{\rm reg}_{\rm kin} = -N_f N_c \int \frac{d^4p}{(2\pi)^4} {\rm tr}_D \log\left[\frac{S^{-1}(\tilde{p})}{S_0^{-1}(\tilde{p})}\right] \ ,$$

and

$$\Omega^{\rm reg}_{\rm free} = -\frac{N_f N_c}{24\pi^2}\Big\{2\tilde{\mu}^3\tilde{p}_F - 5m^2\tilde{\mu}\tilde{p}_F + 3m^4\log\left(\frac{\tilde{p}_F + \tilde{\mu}}{m}\right)\Big\} \ ,$$

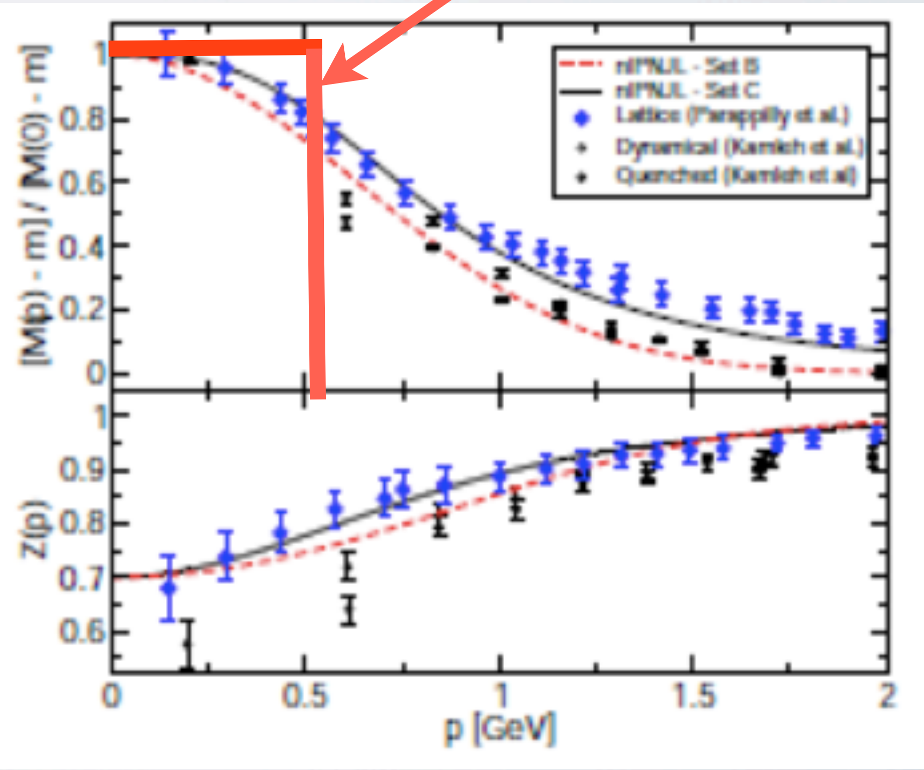
$$\tilde{p}_F = \sqrt{\tilde{\mu}^2 - m^2} \ .$$

Dressed quark propagator,

$$S^{-1}(\tilde{p}) = -(\boldsymbol{\gamma}\cdot{\bf p})\ A(\tilde{p}^2) - \gamma_4\tilde{p}_4 C(\tilde{p}^2) + B(\tilde{p}^2)$$

$$A(p^2) = 1 + \sigma_A f(p^2),$$
$$B(p^2) = m + \sigma_B g(p^2),$$
$$C(p^2) = 1 + \sigma_C f(p^2)$$

normal(local) NJL



Parapilly et al. 2006 PRD

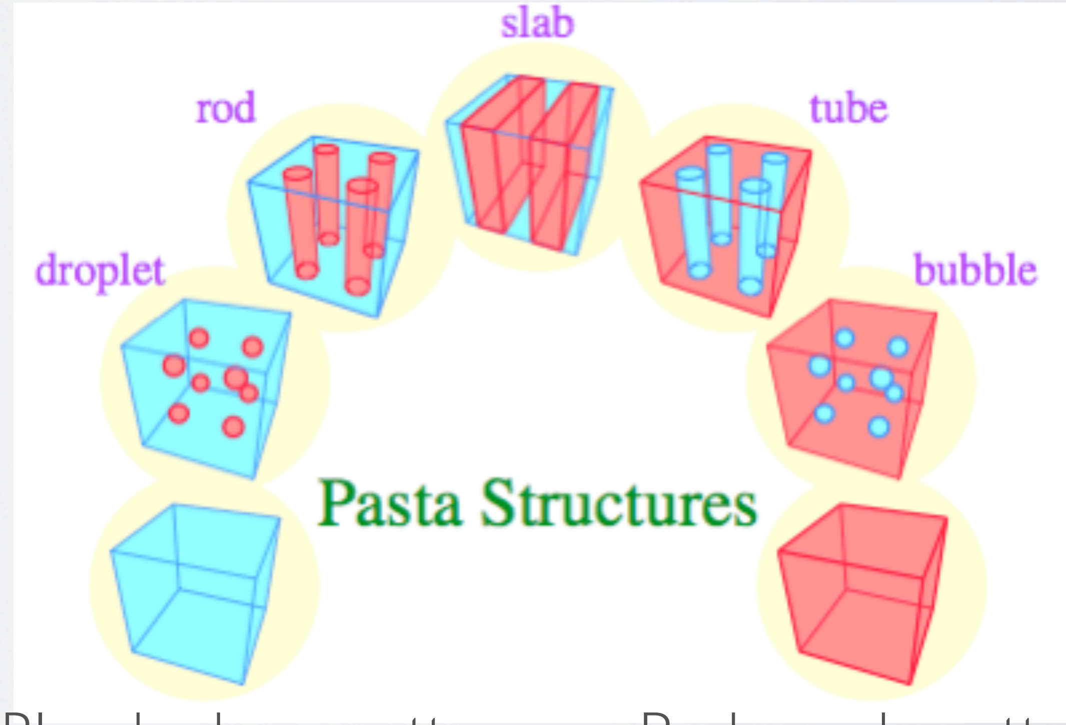
FINITE SIZE EFFECTS (PASTA STRUCTURES)

What are "pasta structures" ?

↓

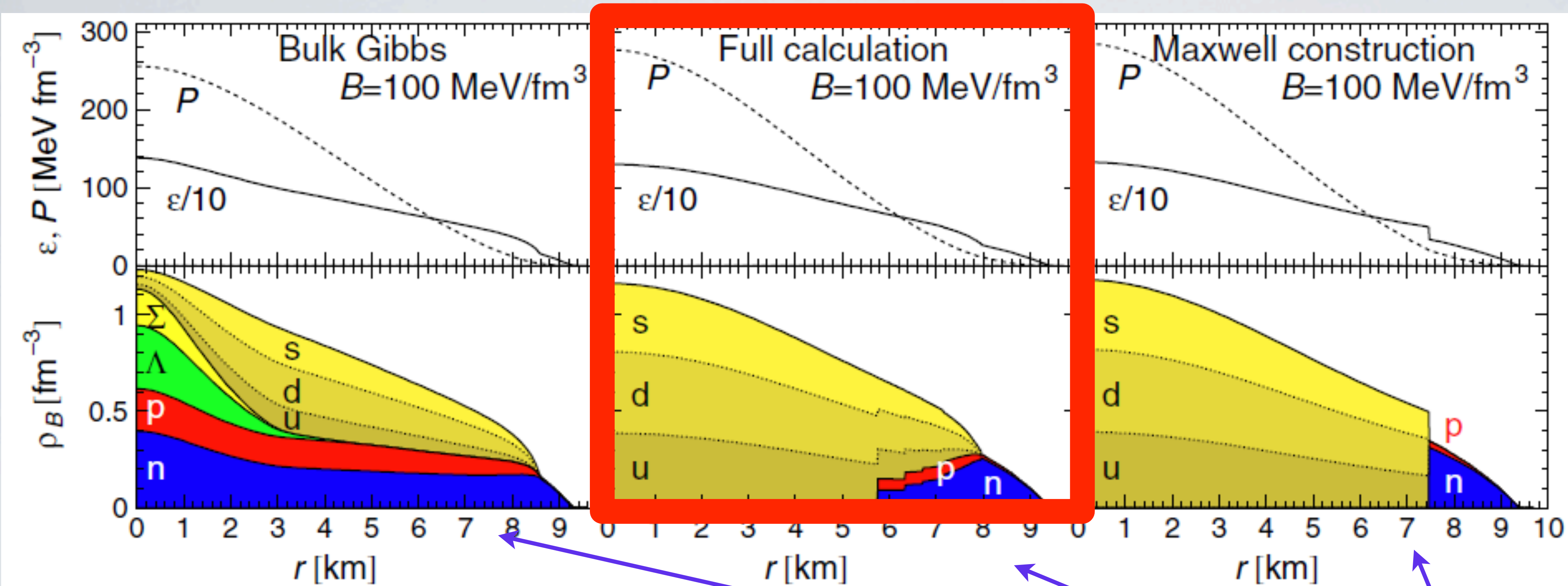
Generally, inhomogeneous structures appear in the phase transition under multi-component system. Namely, we call them as the pasta structures.

Depended on "density" and temperature", each charged particle clusterizes automatically by "Coulomb interactions " and "surface tensions" ; i.e. ***finite size effects.*** As a result, they construct non-uniform structures.



Blue: hadron matter Red: quark matter

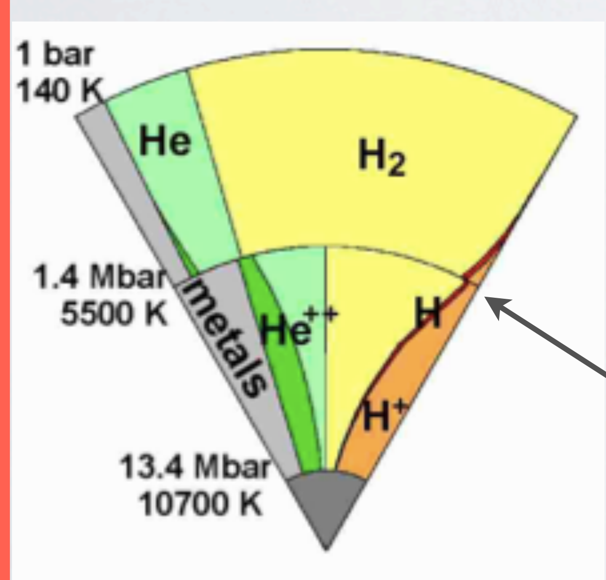
Structures “NS Structures with mixed phase”



Maruyama et al. 2007 PRC

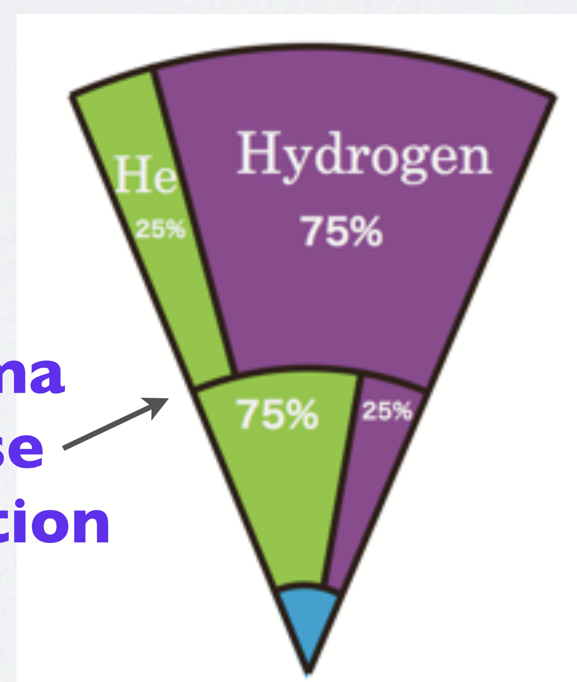
“fraction”

➡Cooling process etc.



Nettelmann 2009 PhD Thesis

plasma phase transition



Saumon et al. 1992

“Saturn-Structure with mixed phase”

Uncertainty of phase transition

Hempel et al., PRD 80, 125014 (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	Conserved densities/fractions 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

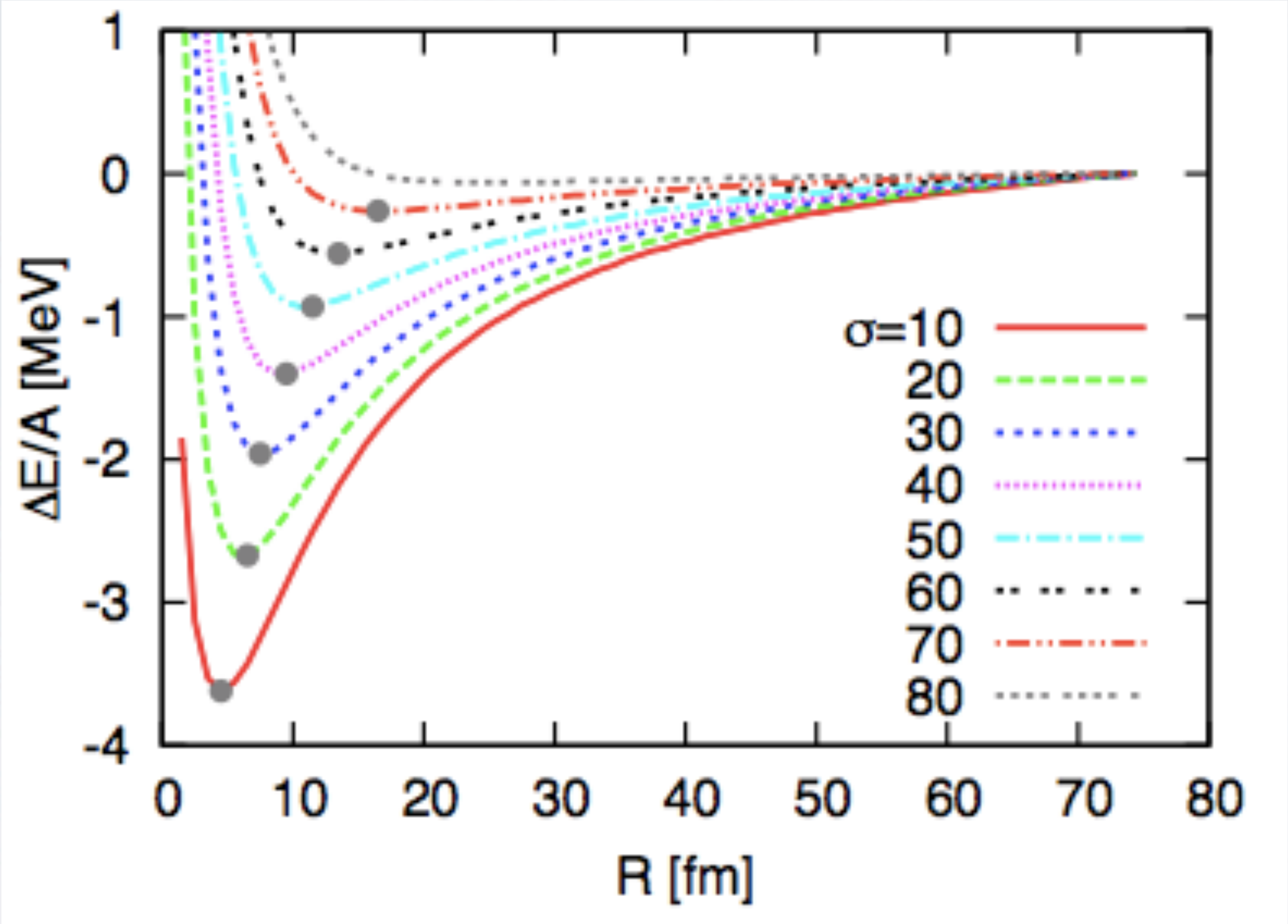
Part III

Results

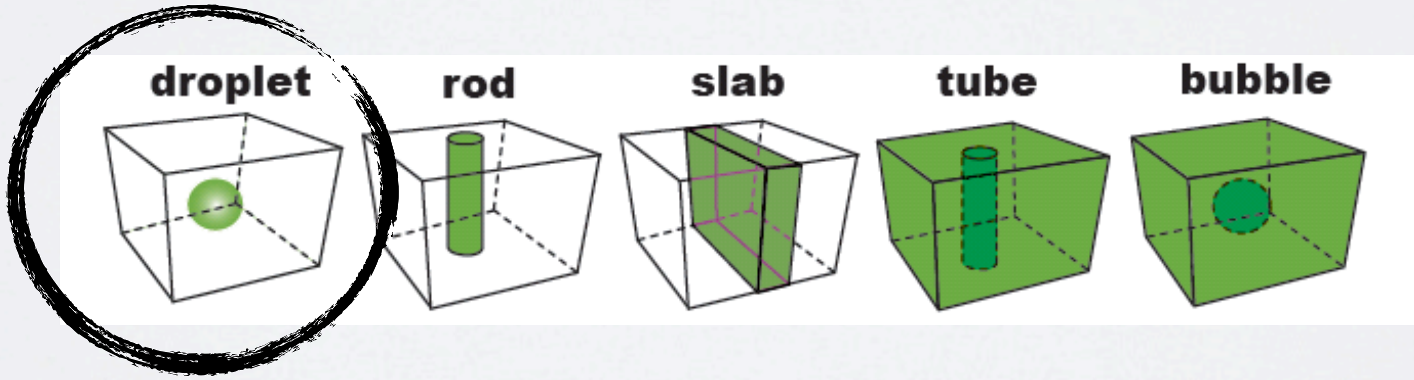
STABILITY CURVES OF MIXED PHASE

FOR NLNJL + BHF

NY, R. Łastowiecki, D . Blaschke, S. Benic, T. Maruyama, T.Tatsumi, 2014 PRC



ρ=0.70 /fm^3

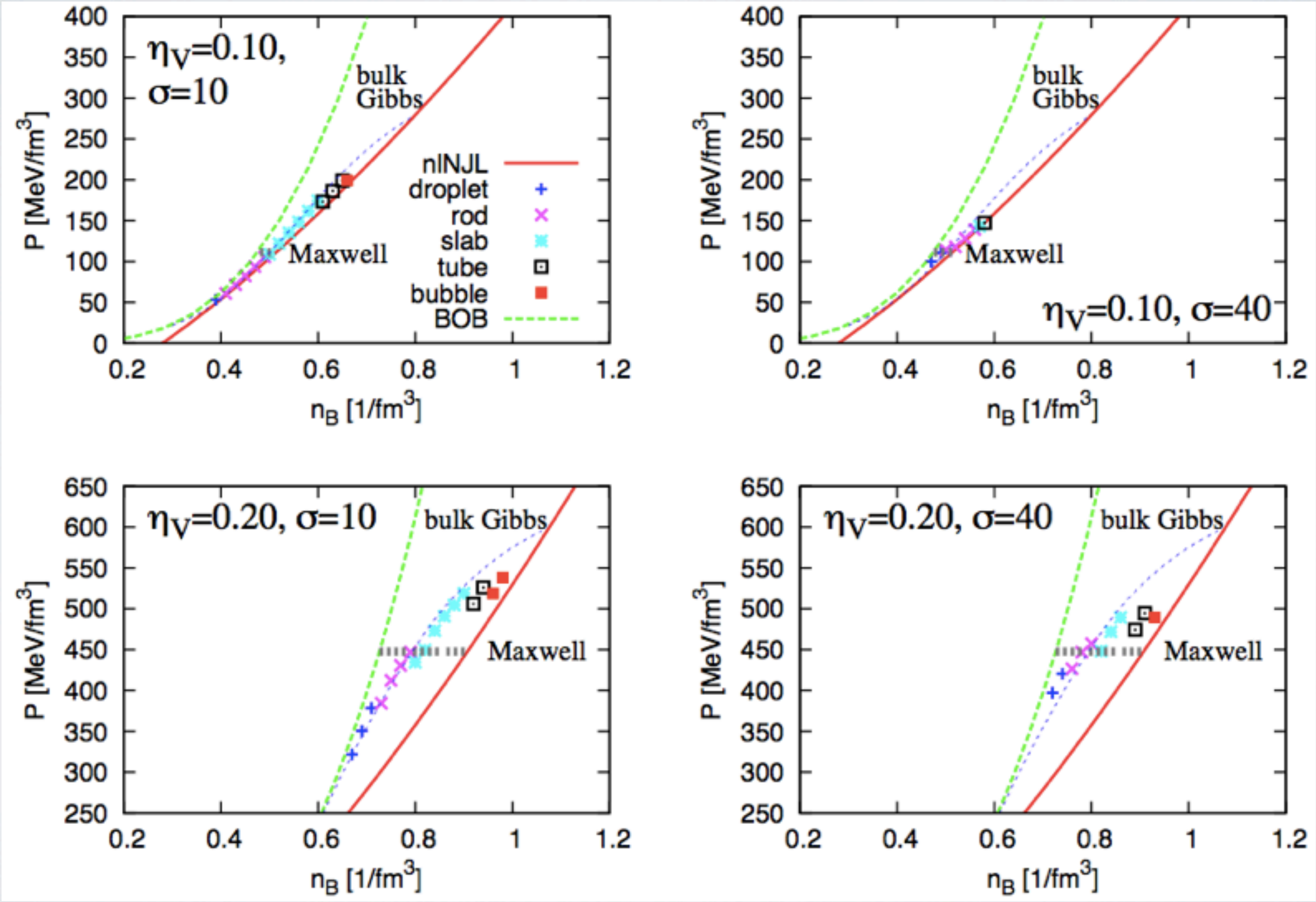


“Surface tension” makes pasta structures unstable.

EOS

FOR NLNJL + BHF

NY, **R. Łastowiecki, D . Blaschke, S. Benic, T. Maruyama, T.Tatsumi, 2014 PRC**



"Surface tension" makes EOS Maxwell-like.

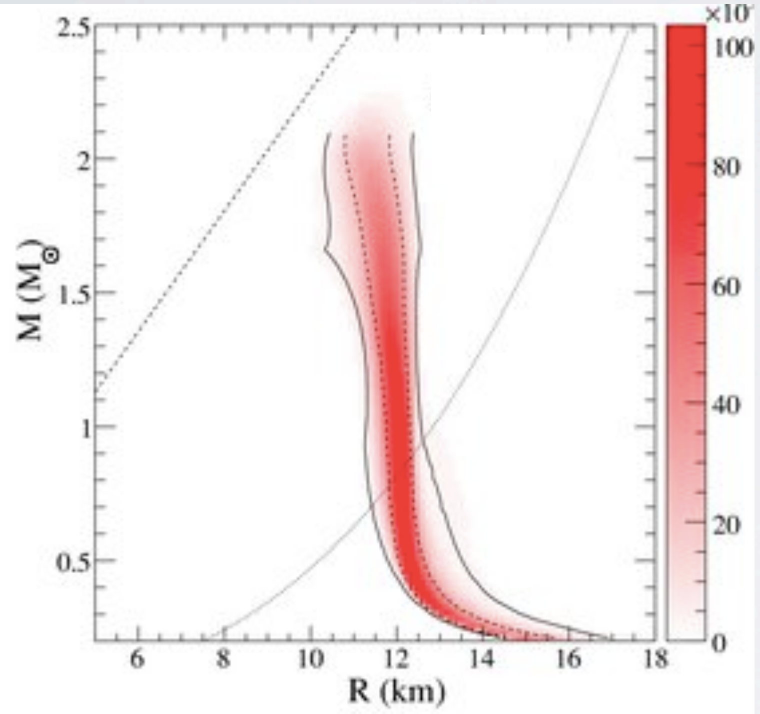
MR-RELATION

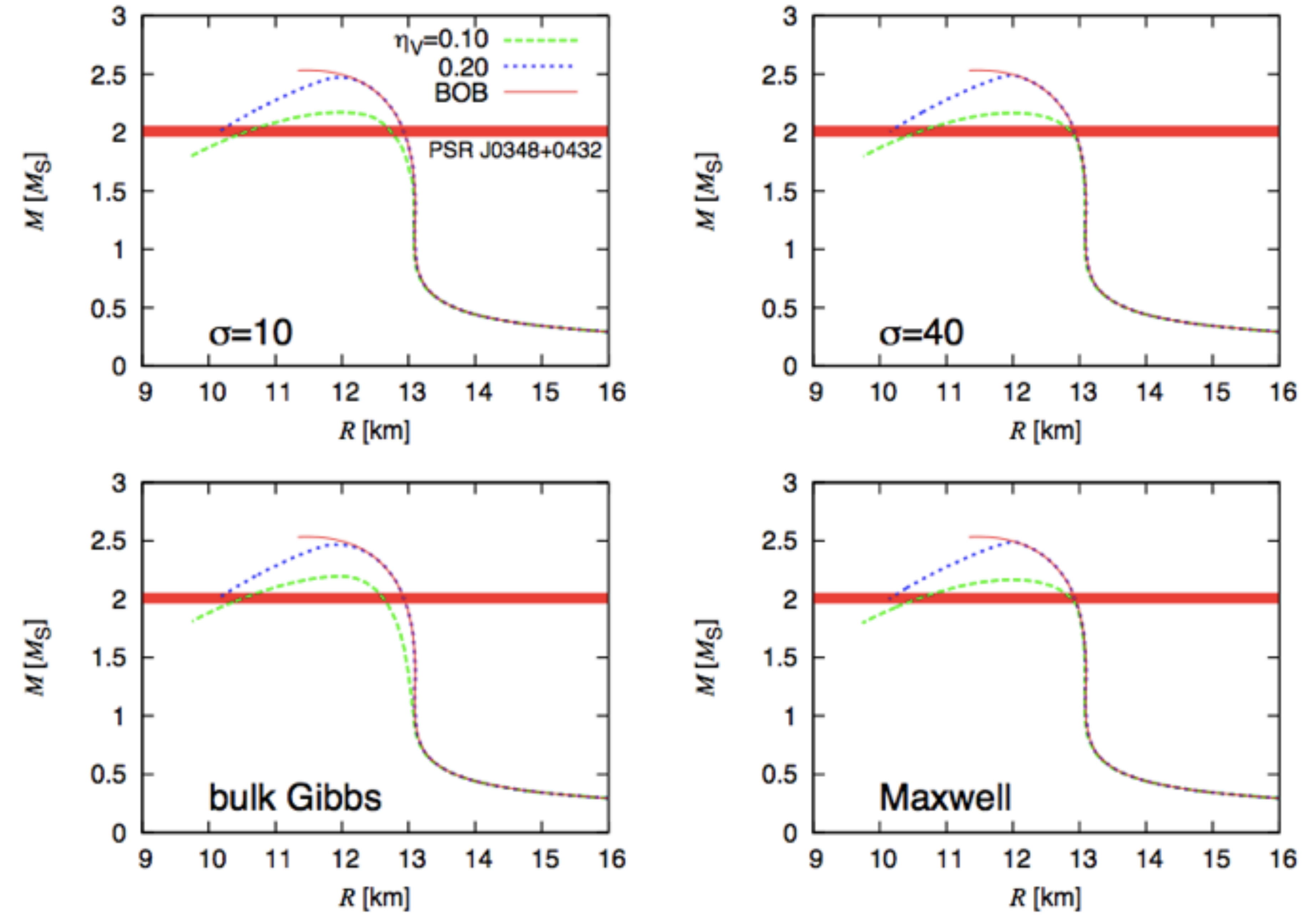
FOR NLNJL + BHF

NY, R. Łastowiecki, D . Blaschke, S. Benic, T. Maruyama, T.Tatsumi, 2014 PRC

Our result nlNJL+BHF(BOB+TBF) with pasta

A.W.Steiner,
J.M.Lattimer,
E.F.Brown
ApJ **722** (2010) 33

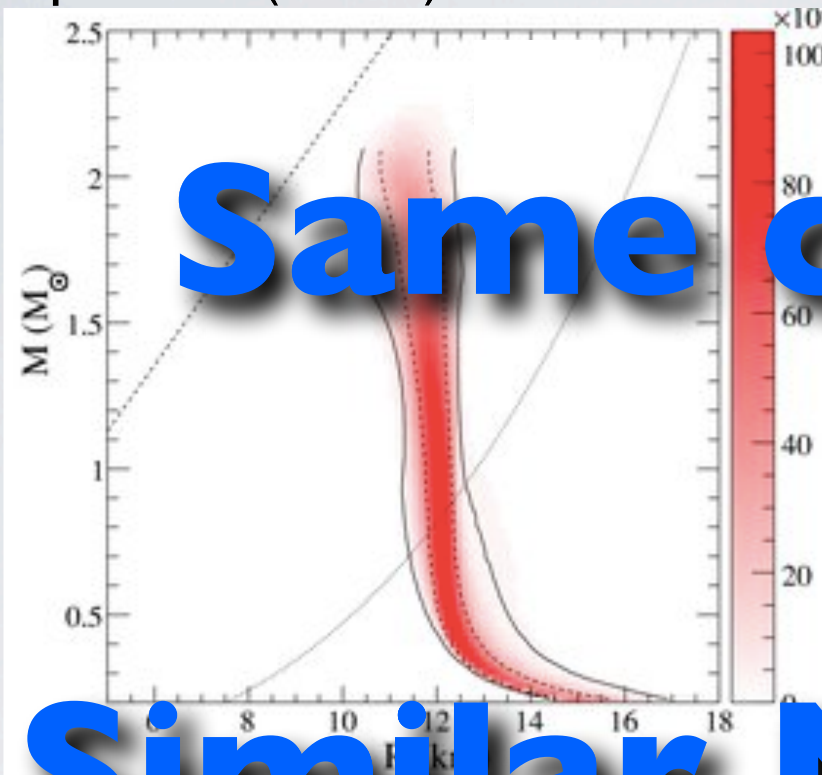




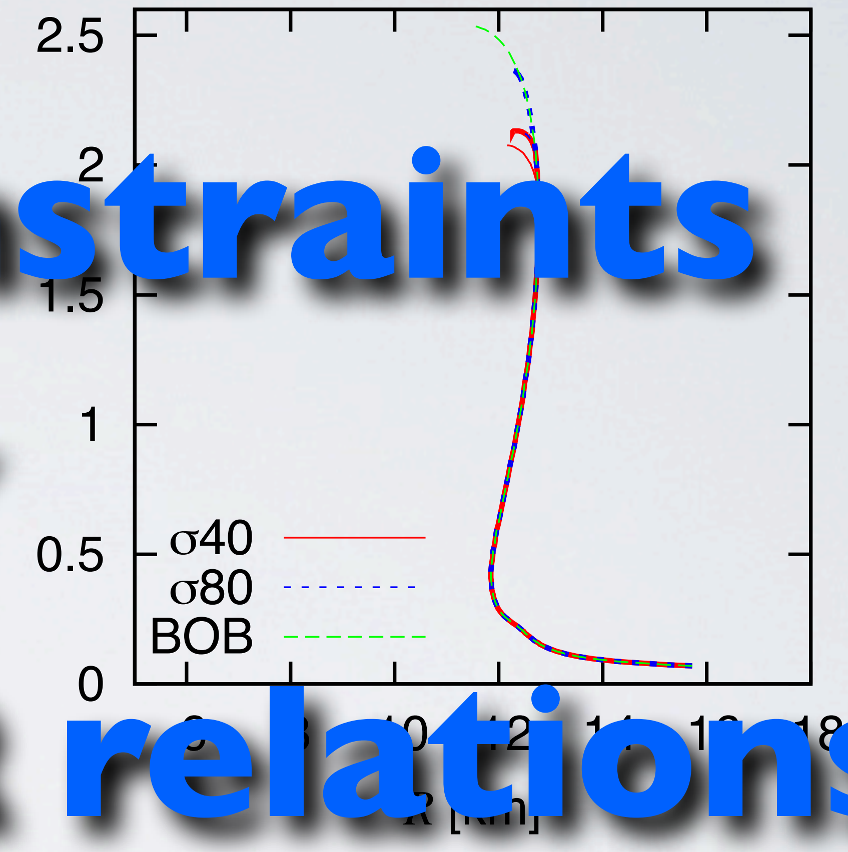
"Vector coupling" makes EOS hard.
Our EOS is consistent with observations.

Observations

A.W.Steiner, J.M.Lattimer, E.F.Brown
ApJ **722** (2010) 33



DS+BHF(BOB+TBF)
with pasta
[**NY** et al. in prep.]

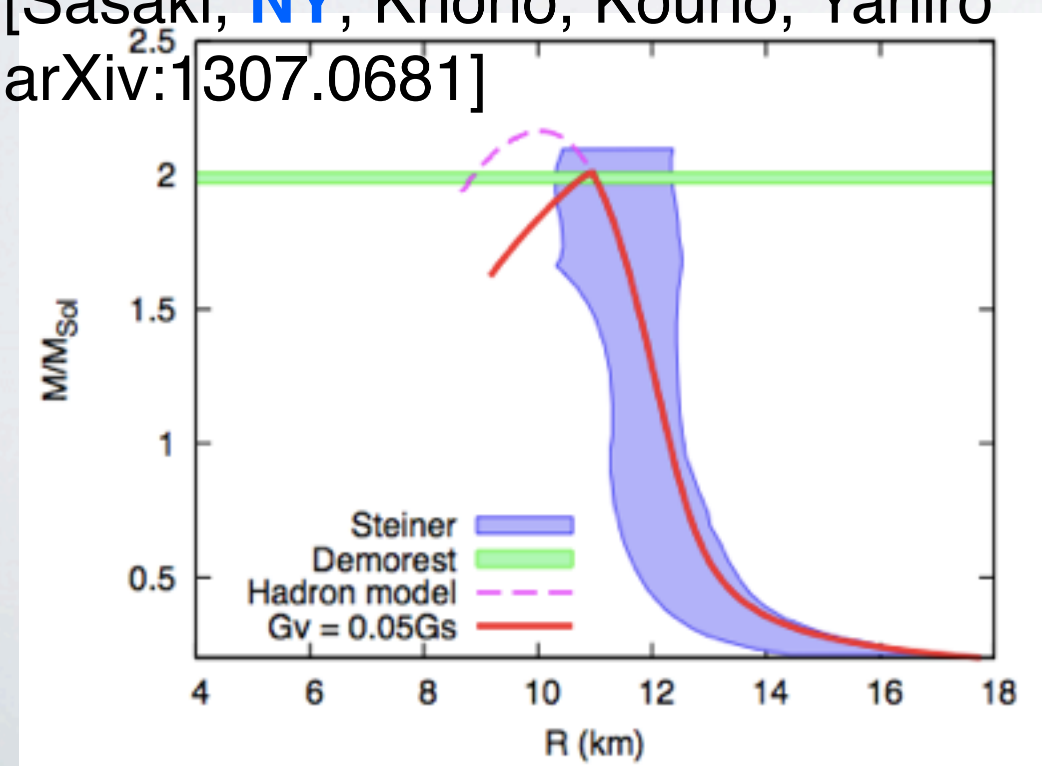


Same constraints

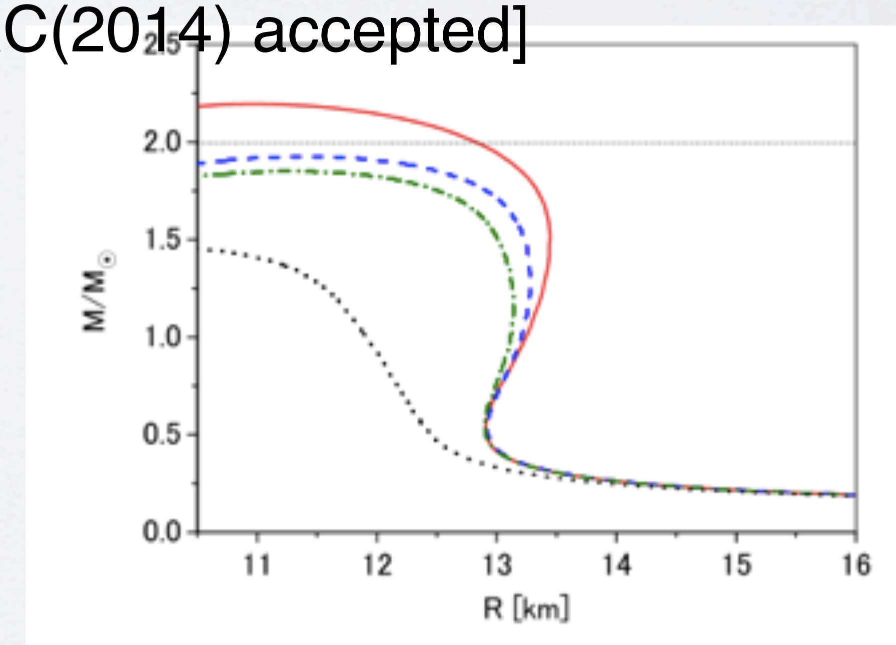
↓

Similar MR relations

EPNJL+χPT
[Sasaki, **NY**, Khono, Kouno, Yahiro
arXiv:1307.0681]



BHF(UTBF by Pomeron without quarks)
[Yamamoto, Furumoto, **NY**, Rijken
PRC(2014) accepted]



Part IV

Discussions

Evolution of NSs

NY, Kotake, Kutsuna, Shigeyama 2014 PASJ

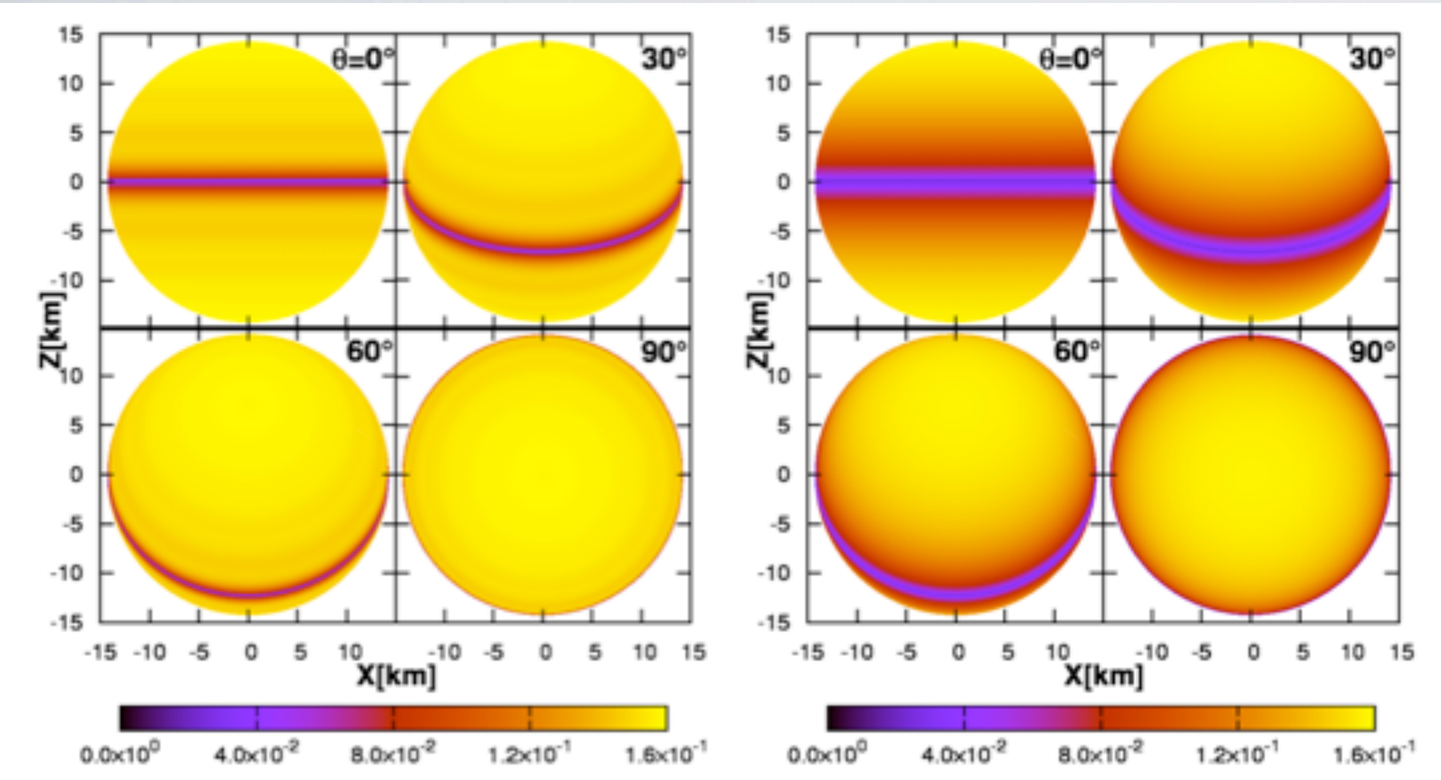
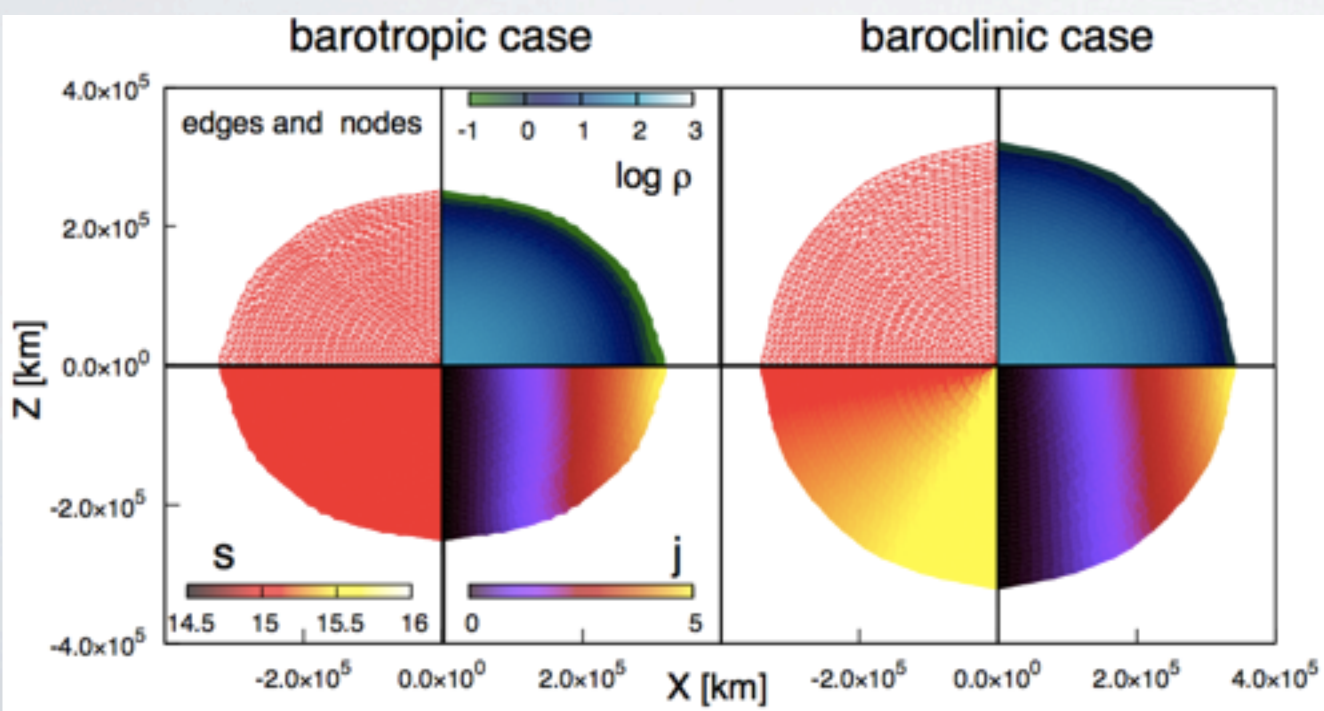
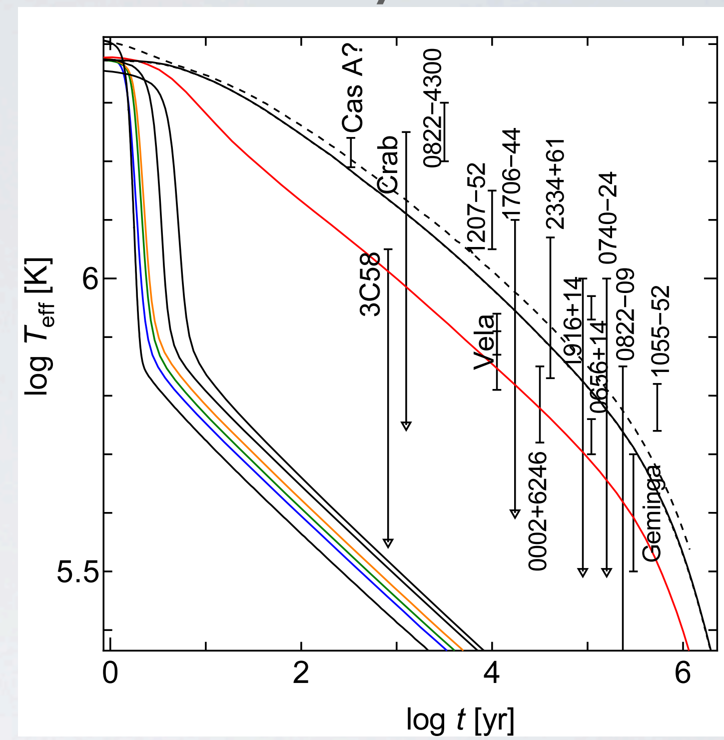


FIG. 7: (Color online) Temperature distribution for model "mSUK" after 10^4 years depended on the inclination angle θ . The unit of color contour is [keV].

NY, K.Fujisawa, S.Yamada 2014, MNRAS letter accepted



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



thermal diffusion eq.

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

heat capacity

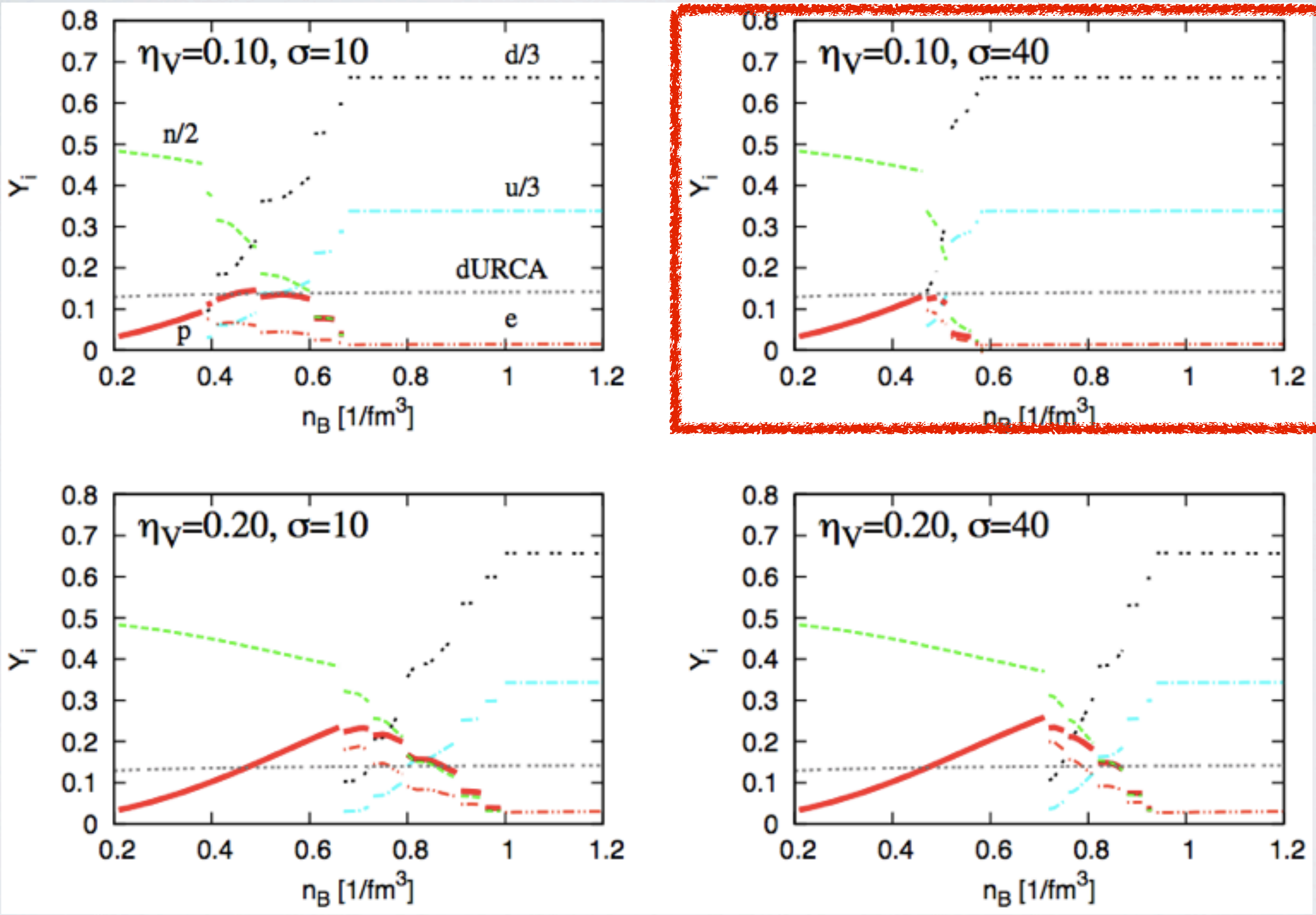
flux (thermal conductivity)

cooling rate + heating rate

FRACTION

FOR NLNJL + BHF

NY, R. Łastowiecki, D . Blaschke, S. Benic, T. Maruyama, T.Tatsumi, 2014 PRC



"Weak vector coupling" and "strong surface tension" reduce the region of mixed phase, and direct URCA.

SUMMARY

Finite size effects in hadron-quark phase transition (nlNJL + BHF)

"Surface tension" makes pasta structures unstable, and EOS Maxwell-like.
"Vector coupling" makes EOS hard.
"Weak vector coupling" + "strong surface tension" → Reduced Direct URCA.

Finite size effects in hadron-quark phase transition (Dyson-Schwinger + BHF)

Similar result with the other models'
→Finite size effects appear for any cases.

3-body forces with/without hyperons

Consistent with $^{16}O+^{16}O$ scattering (2 body can not be consistent !!)
EOS becomes hard ($\Delta M \sim +0.3$ Ms).

2D evolutions of NSs with magnetic field and rotation

Consistent with observations ``qualitatively" → Hot and cold spot appears.
Now, we are constructing ``Post Henyey method (full 2D evolution)".
Effects of exotic matter ?

Future works: Combine them all !