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DENET/RESCEU Summer school

Matter effects on thermal evolutions of compact stars

Nobutoshi Yasutake (RESCEU)

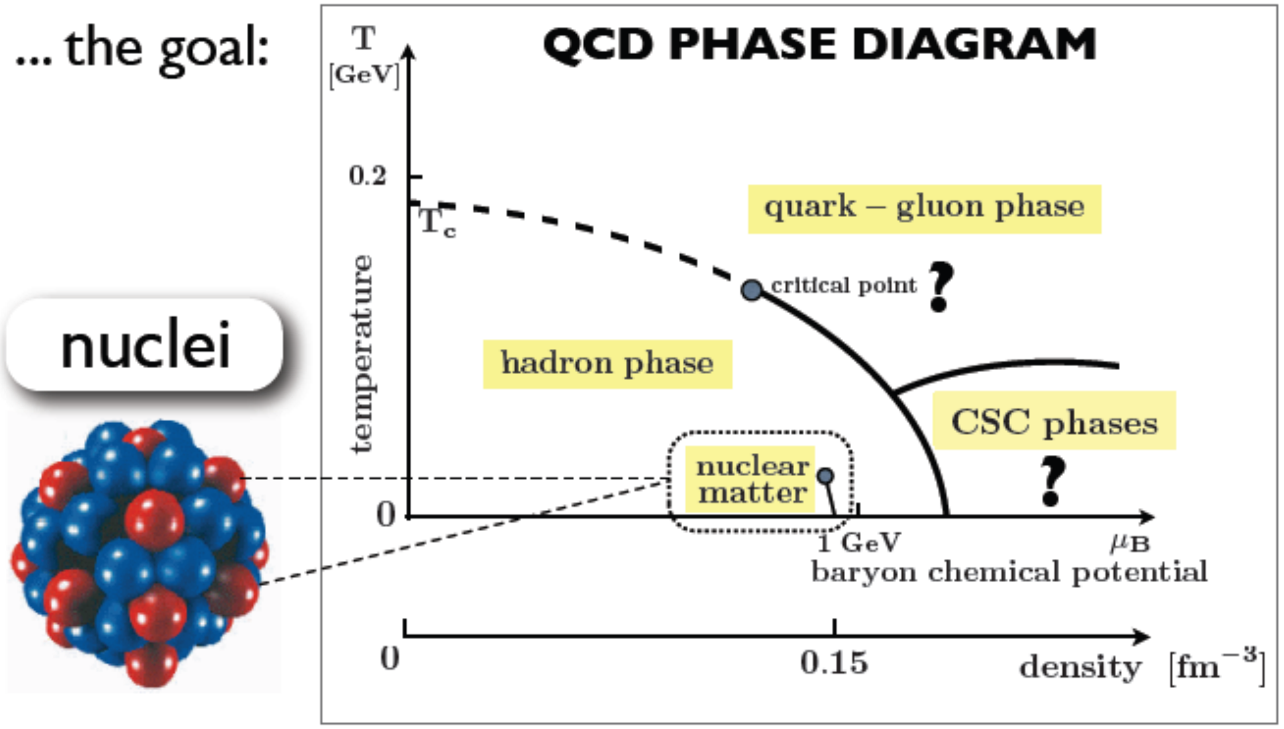
Kei Kotake (NAOJ),
Masamichi Kutsuna(RESCEU),
Toshikazu Shigeyama(RESCEU)

background & motivation

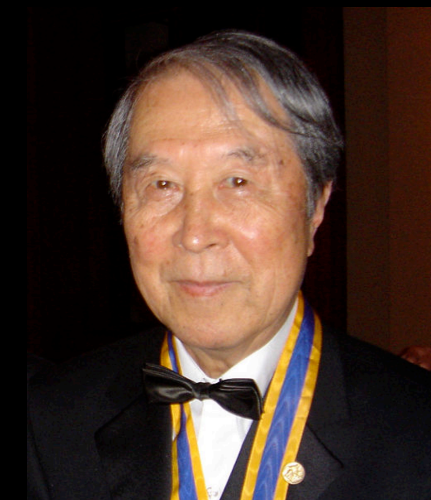
QCD phase diagram

1 Prelude: **PHASES** and **STRUCTURES** of **QCD**

... the goal:



(c) Weise



Y. Nambu

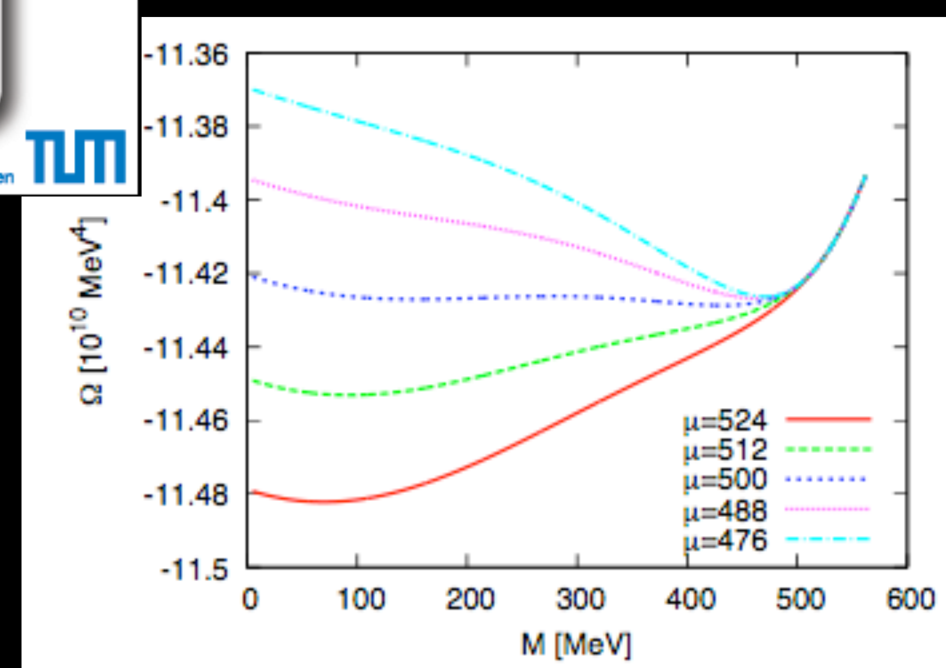
Novel prize 2008

Scales in **nuclear matter**

- momentum scale: **Fermi momentum** — $k_F \simeq 1.4\ fm^{-1} \sim 2m_\pi$
- NN distance: — $d_{NN} \simeq 1.8\ fm \simeq 1.3\ m_\pi^{-1}$
- energy per nucleon: — $E/A \simeq -16\ MeV$
- compression modulus: — $K = (260 \pm 30)\ MeV$

Technische Universität München

thermodynamic potential
in NJL model



zero density region
--> well known by Lattice QCD simulations.
high density region
--> we can know by astrophysical phenomena.

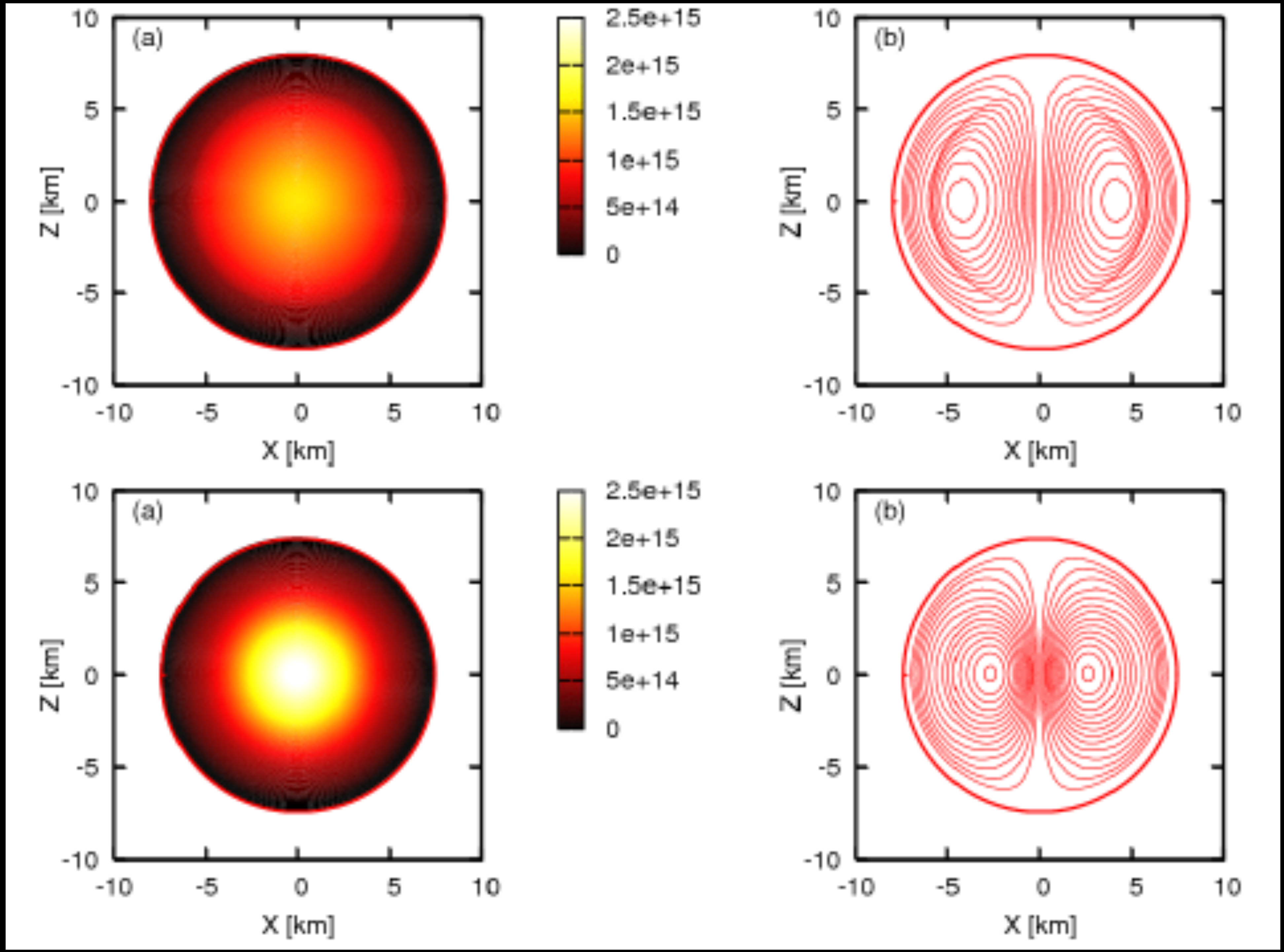
Quark-hadron phase transition and magnetic field

Yasutake, Kiuchi, Kotake 2010 MNRAS etc.

density magnetic field

hadron matter (BHF theory) + Quark matter

hadron matter



Non-spherical temperature distribution

Theory

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

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

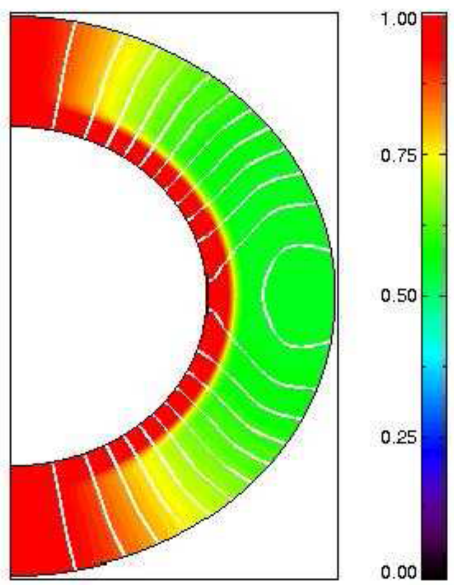


Fig. 5 Temperature distribution in a strongly magnetized neutron star crust (whose thickness has been stretched by a factor five for easier reading). The choosen field scale parameters are $B_0^{\rm core} = 7.5 \times 10^{13}$ G, $B_0^{\rm crust} = 2.5 \times 10^{13}$ G, $B_0^{\rm tor} = 3 \times 10^{15}$ G, and the toroidal component's generating functions T is the model "T1" of Fig. 4). The color code maps the relative temperature, i.e., $T(r,\theta)/T_{\rm core}$, with a core temperature $T_{\rm core} = 6 \times 10^7$ K. White lines show field lines of $\mathbf{B}^{\rm pol}$, the field lines of $\mathbf{B}^{\rm tor}$ being perpendicular to the plane of the figure. The heat blanketing effect of the toroidal component is clearly visible. (From Geppert et al. 2006.)

observation

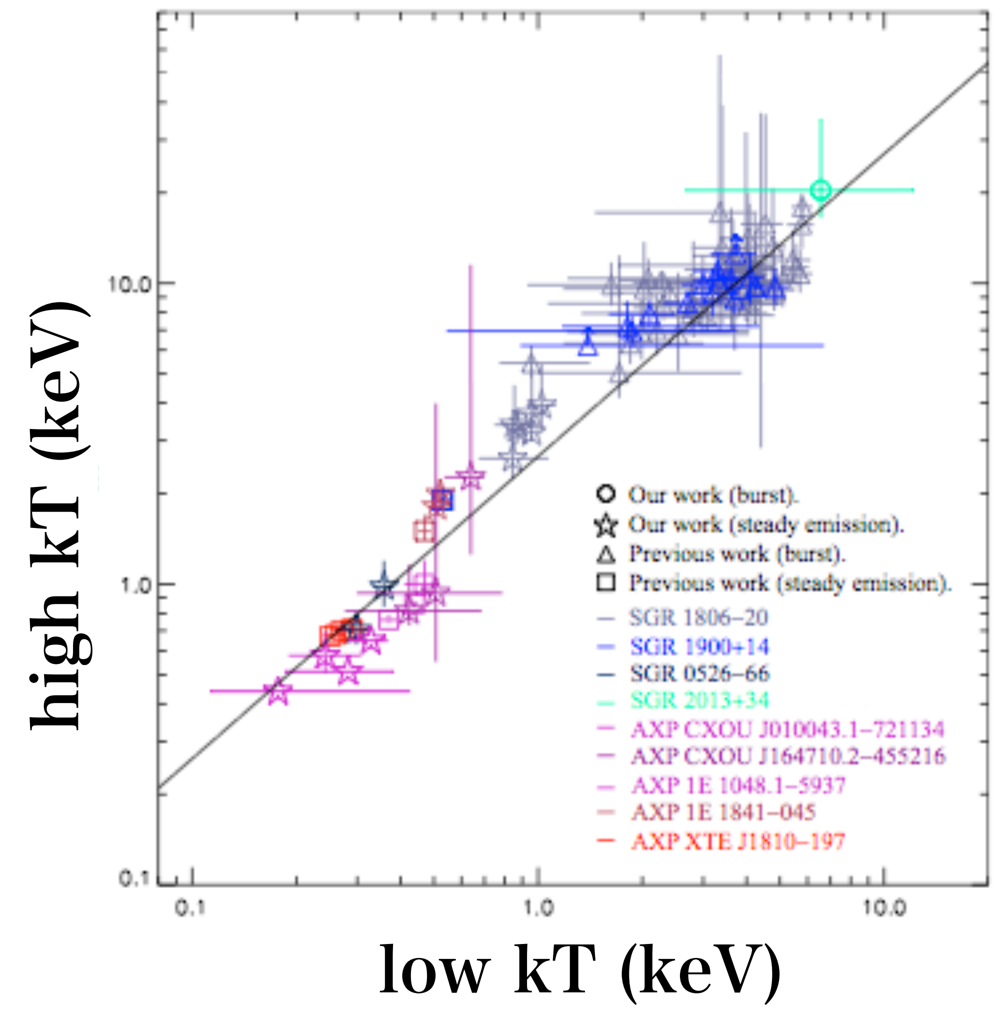


Fig. 3. Relationship between the 2BB temperatures $kT_{\rm LT}$ and $kT_{\rm HT}$. The triangles and squares denote the previous work on the bursts (Feroci et al. 2004; Olive et al. 2004; Götz et al. 2006a; Nakagawa et al. 2007) and the quiescent emission (Morii et al. 2003; Gotthelf et al. 2004; Gotthelf & 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.

Yujin E. Nakagawa, Atsumasa Yoshida, Kazutaka Yamaoka, Noriaki Shibazaki (2009)

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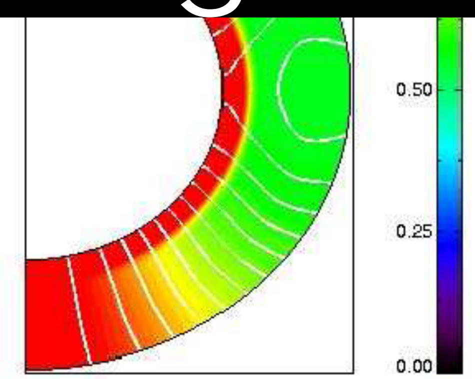
Effects of magnetic field appear through the thermal evolution.



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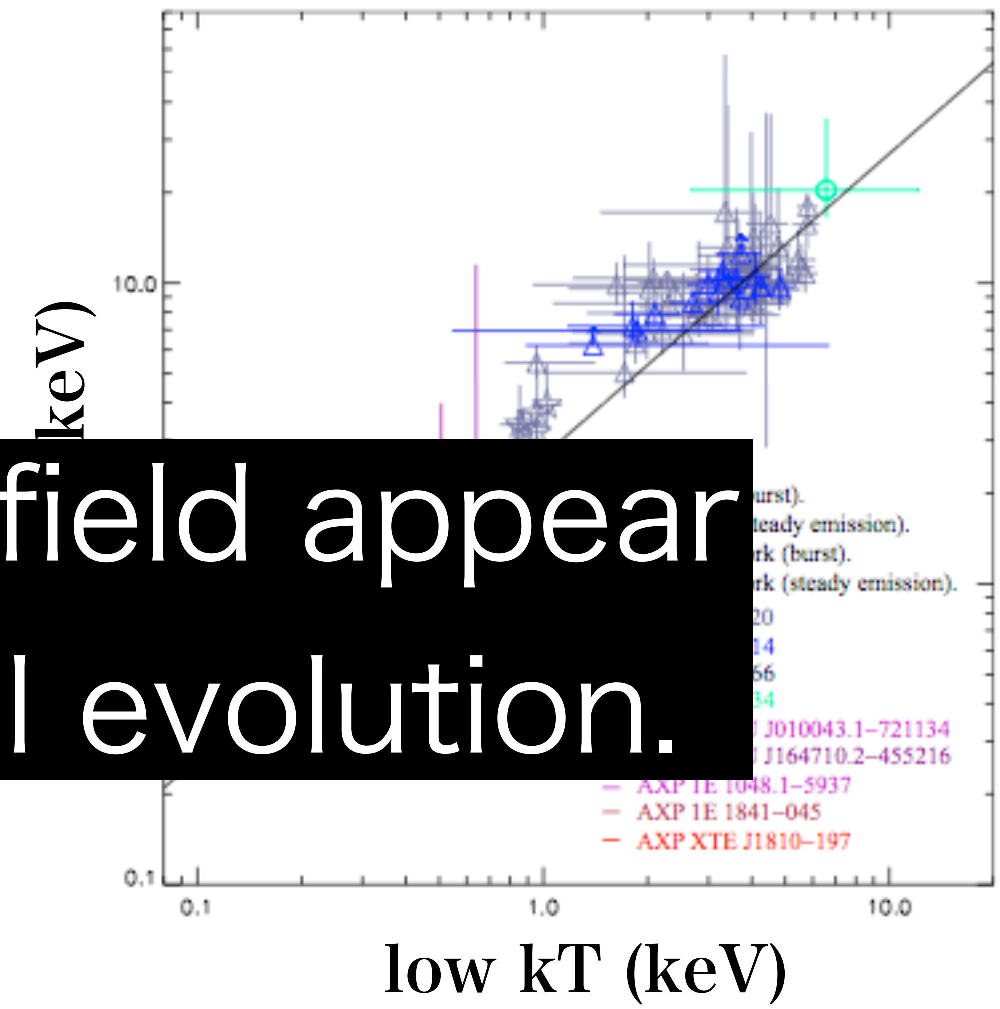

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How to calculate thermal evolutions ?

How to calculate the thermal evolution of compact stars ?

EOS

Quark, hyperon, normal matter,
pion-condesation, 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 difution etc.
vortex etc.

evolution

thermal conduction in strong magnetic field
etc.

||

Comparison with observations

Equation of state

Yasutake Maruyama, Tatsumi, 2009b, 2011 in prep.

Hadron matter

Brueckner-Hartree-Fock theory including hyperons (Schulze et al. 1995)

NN interaction → Argonne V18 + UIX phenomenological three body forces

NY interaction → Nijmegen soft-core 89

→ We can update these interactions by LQCD and J-PARC.

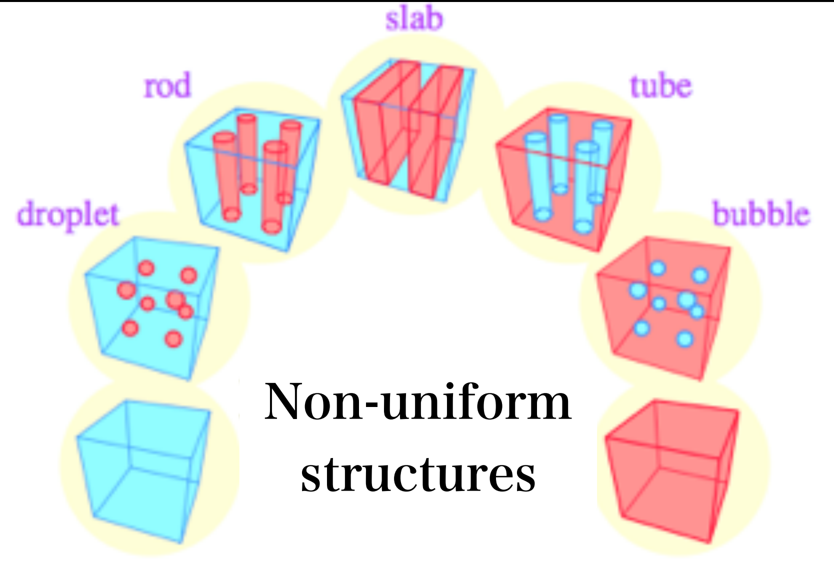
+

Quark matter

Thermodynamic bag model ("density dependent bag model")

→ We can change them to other models. cf.) NJL, pNJL, DSE

- We impose the Wigner-Seitz cell approximations for mixed phase



We must solve following conditions self-consistently;

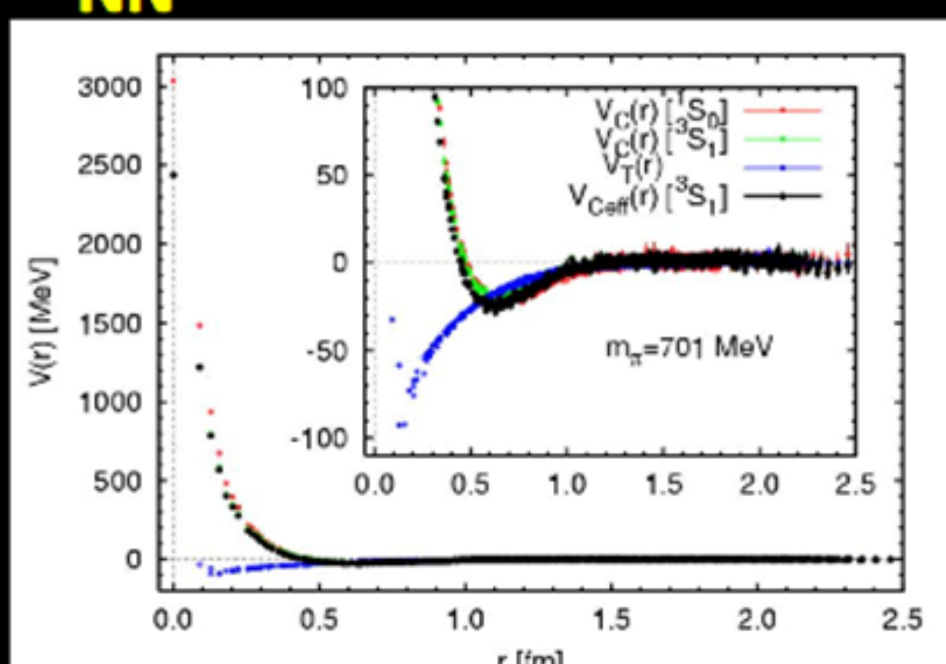
- charge neutrality
- chemical equilibrium
- conservation of number
- balance between "surface tention" and "Coulomb interaction" .

Break though in studies about "Baryon-Baryon interactions"

?

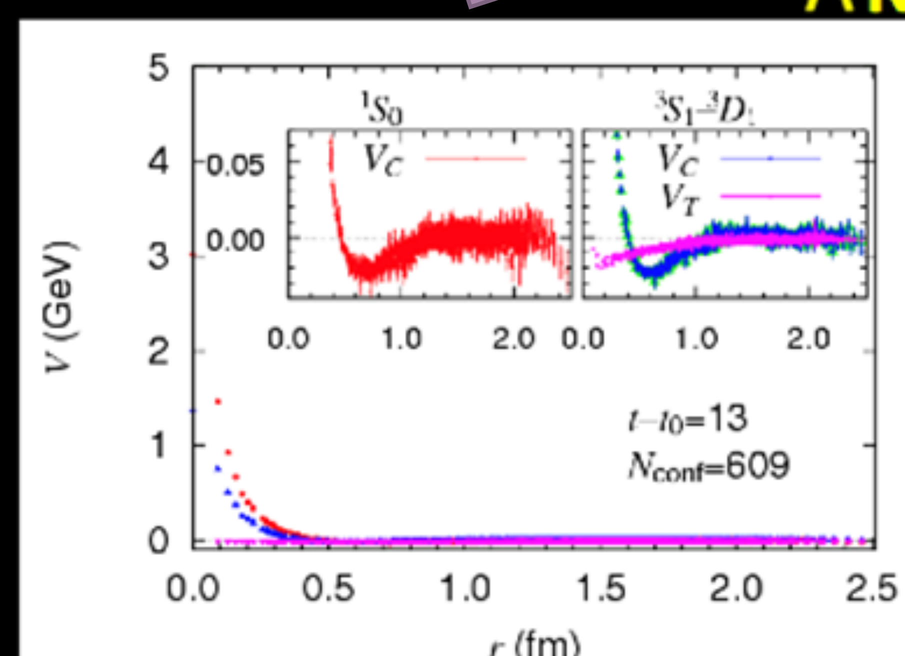
Full QCD (m_π=701 MeV, a=0.09 fm, L=2.9 fm)
using PACS-CS configuration

NN



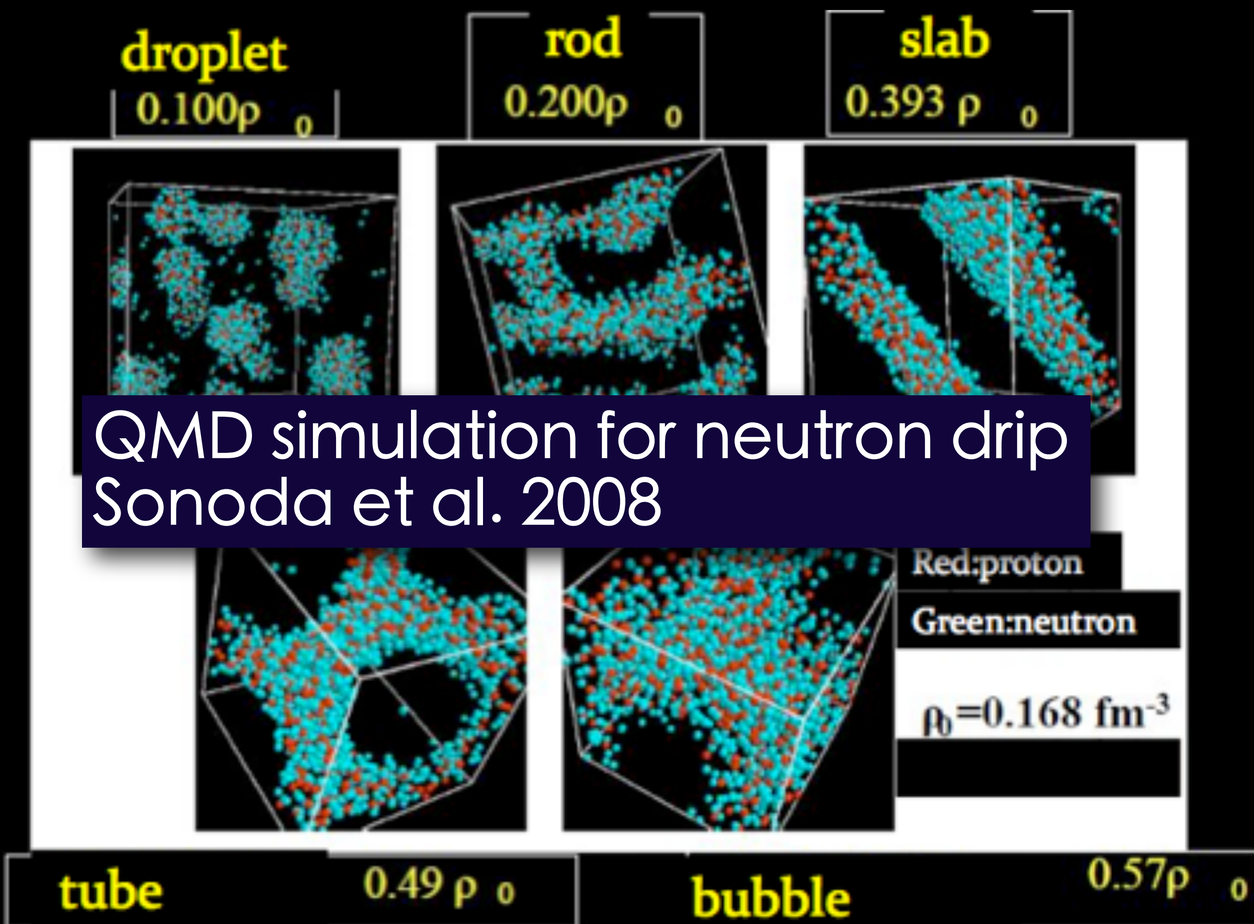
Ishii, Aoki & Hatsuda (2009)

ΛN

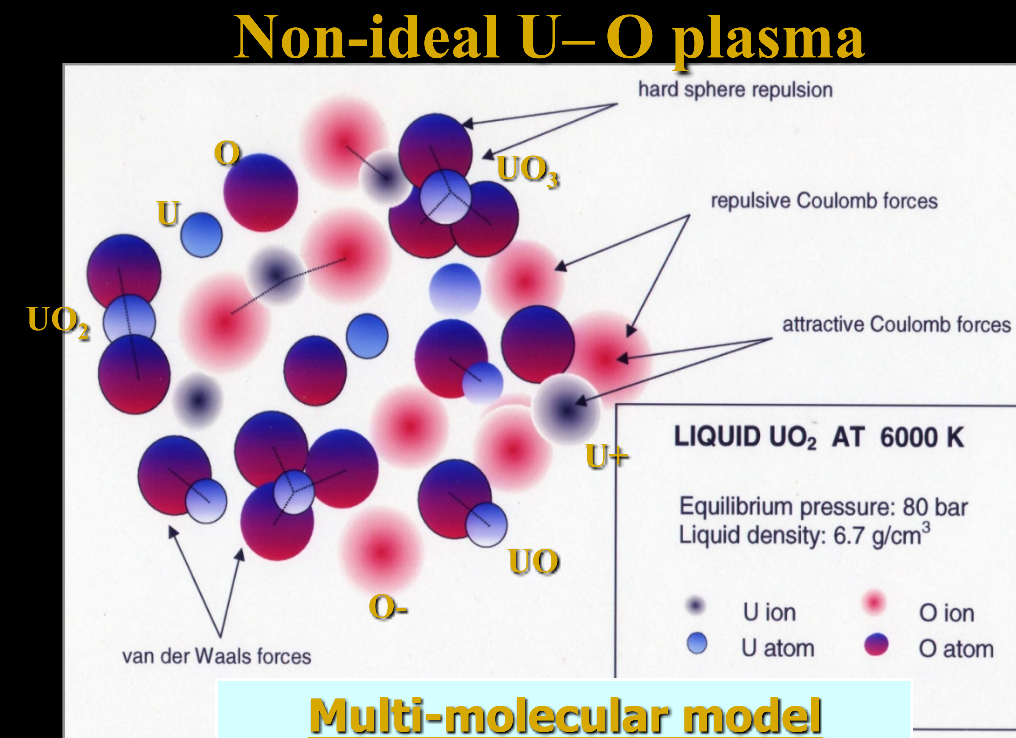


Nemura, Ishii, Aoki & Hatsuda (2009)

Non uniform phase transition



QMD simulation for neutron drip
Sonoda et al. 2008



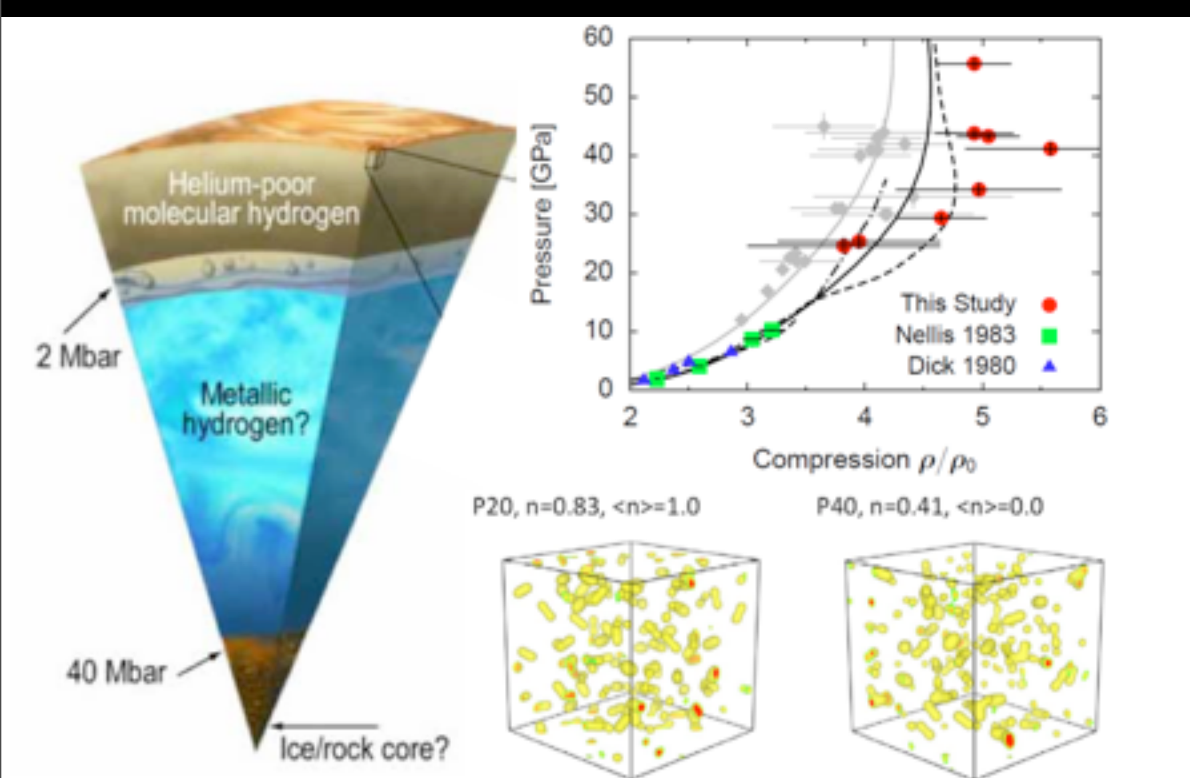
Multi-molecular model
(*Liquid & Gas*)

$U + O + O_2 + UO + UO_2 + UO_3$

$U^+ + UO^+ + UO_2^+ + O^- + UO_3^- + e^-$

$U + 2O \Leftrightarrow UO_2$ $2O \Leftrightarrow O_2$ $U^+ + e \Leftrightarrow U$ $UO_3 + e \Leftrightarrow UO_3^-$ ……	$\Leftrightarrow$	$\mu_U + 2\mu_U = \mu_{UO2}$ $2\mu_O = \mu_{O2}$ $\mu_{U+} + \mu_e = \mu_U$ $\mu_{UO3} + \mu_e = \mu_{UO3-}$ …………

nuclear reaction in atomic reactor
Iosilevskiy et al. 2009



QMD simulation for plasma phase
transition in Jupiter (Ehime group)

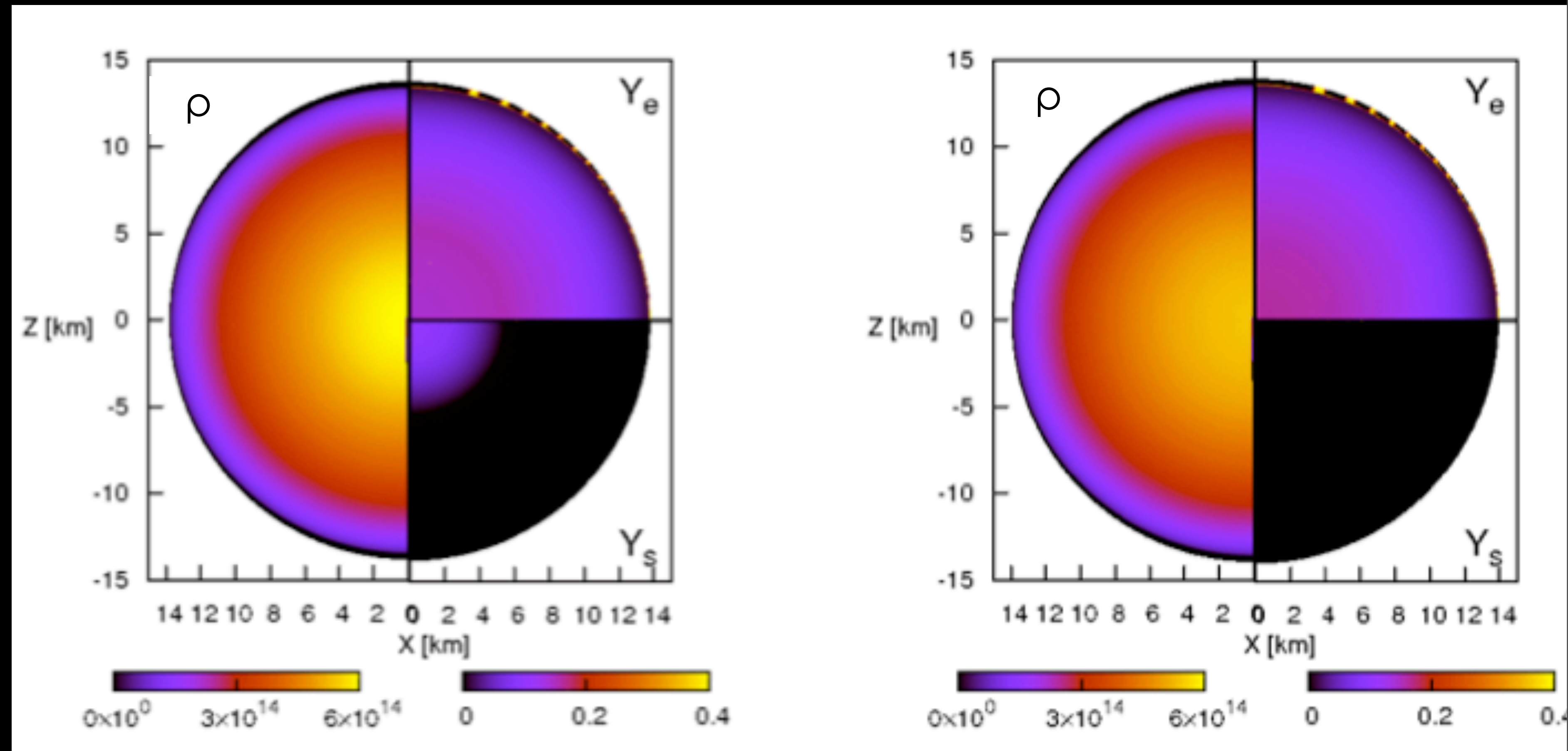
EOS

\+

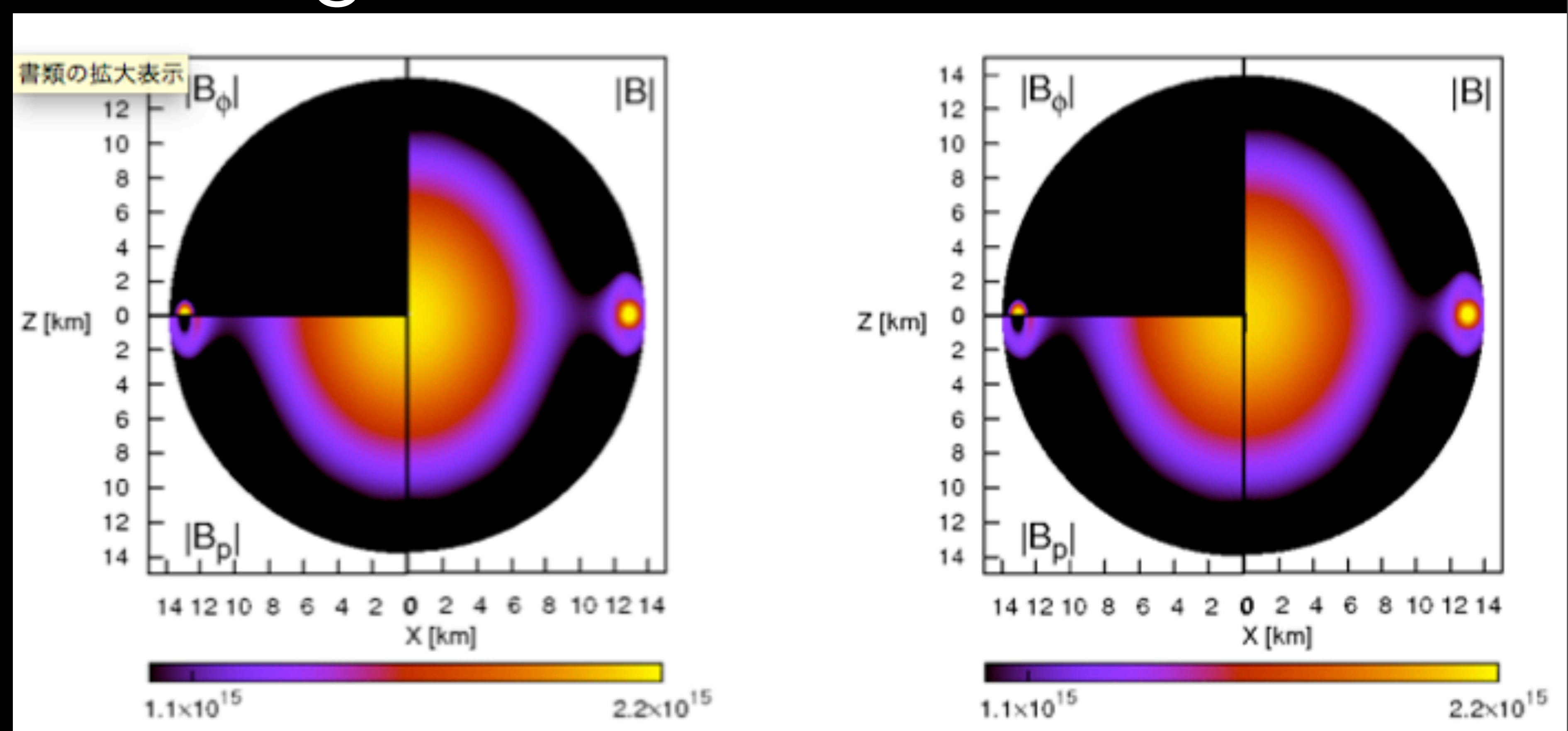
Tomimura & Eriguchi 2005
(1) axi symmetric
(2) equatorial symmetric
(3) no convection
etc.

\+

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

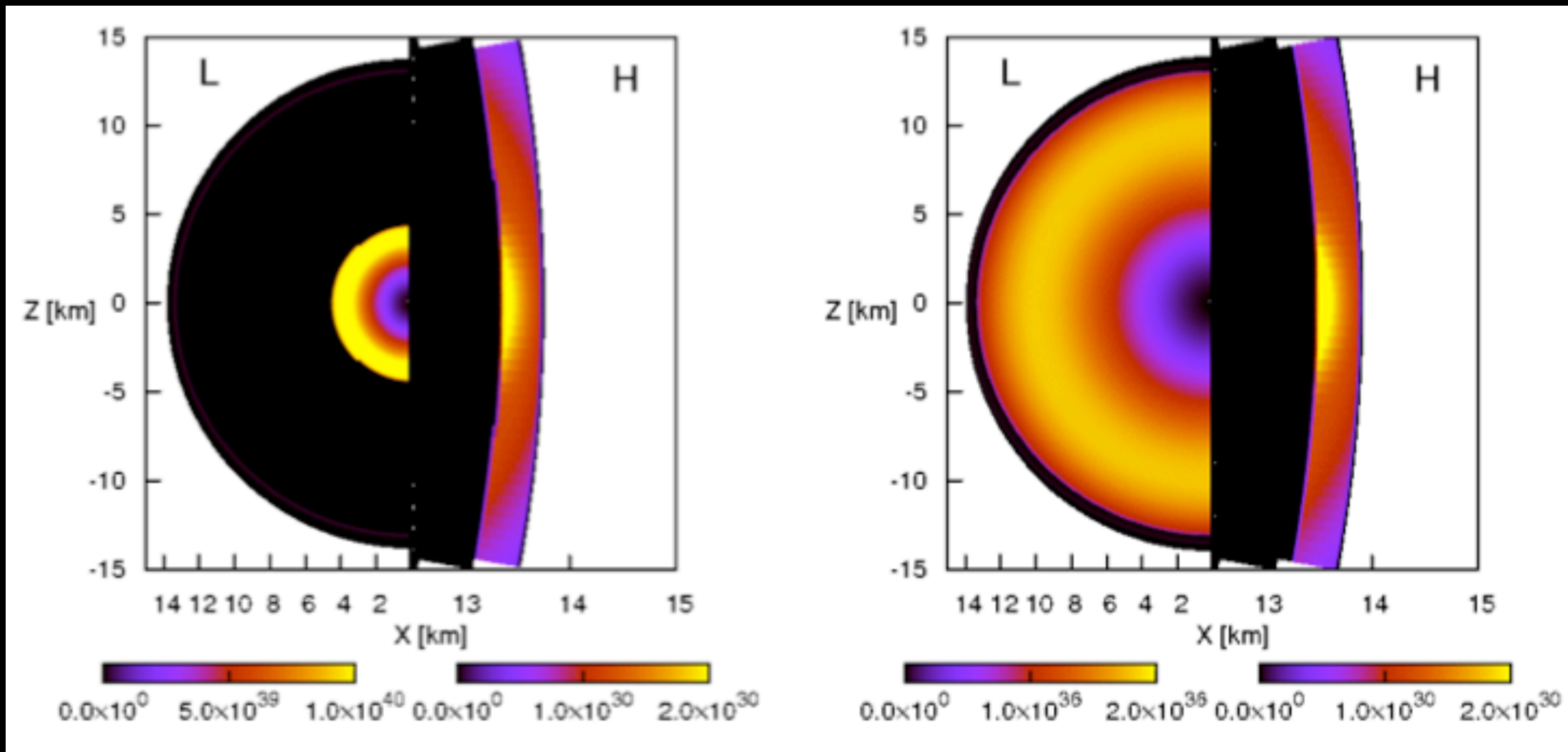


Structures with rotation and magnetic field



cooling rate(L) & heating rate(H)

hyperon matter　　　　normal matter



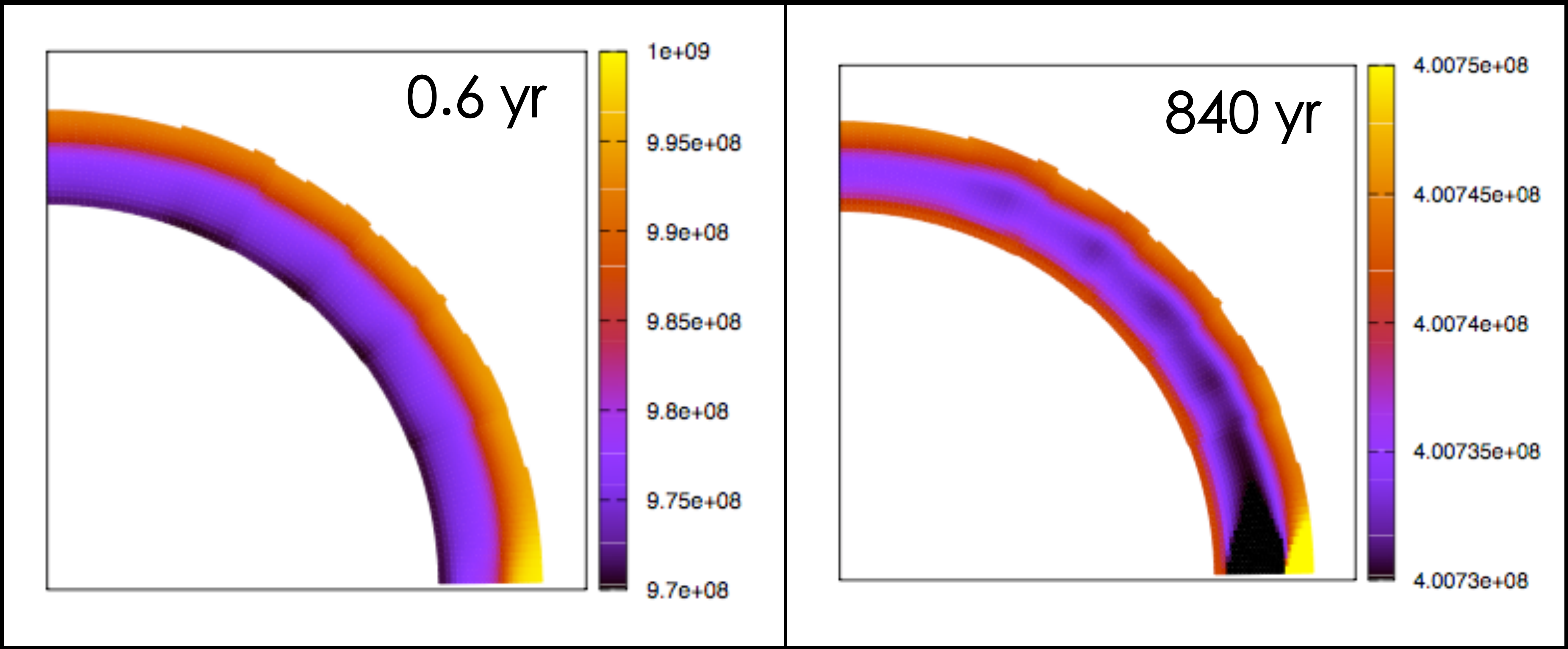
Thermal conduction in strong magnetic field

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

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

results & summary

Crust temperature in strong magnetic field



Thermal conduction is suppressed in equatorial region by toroidal magnetic field ("blanket effect").

Summary

- We get EOSs using NN, NY interactions directly, and can update them by LQCD and JPARC.
- Using realistic EOSs, we calculated thermal evolutions of compact stars.
- As the result, non-spherical temperature distribution appears as shown in observations.
- We must compare our results with the observations.

"Future work"
cf) Color super conductivity, Landau effect etc.

Acknowledgment

K. Makishima(RESCEU), K. Kiuchi (Kyoto)

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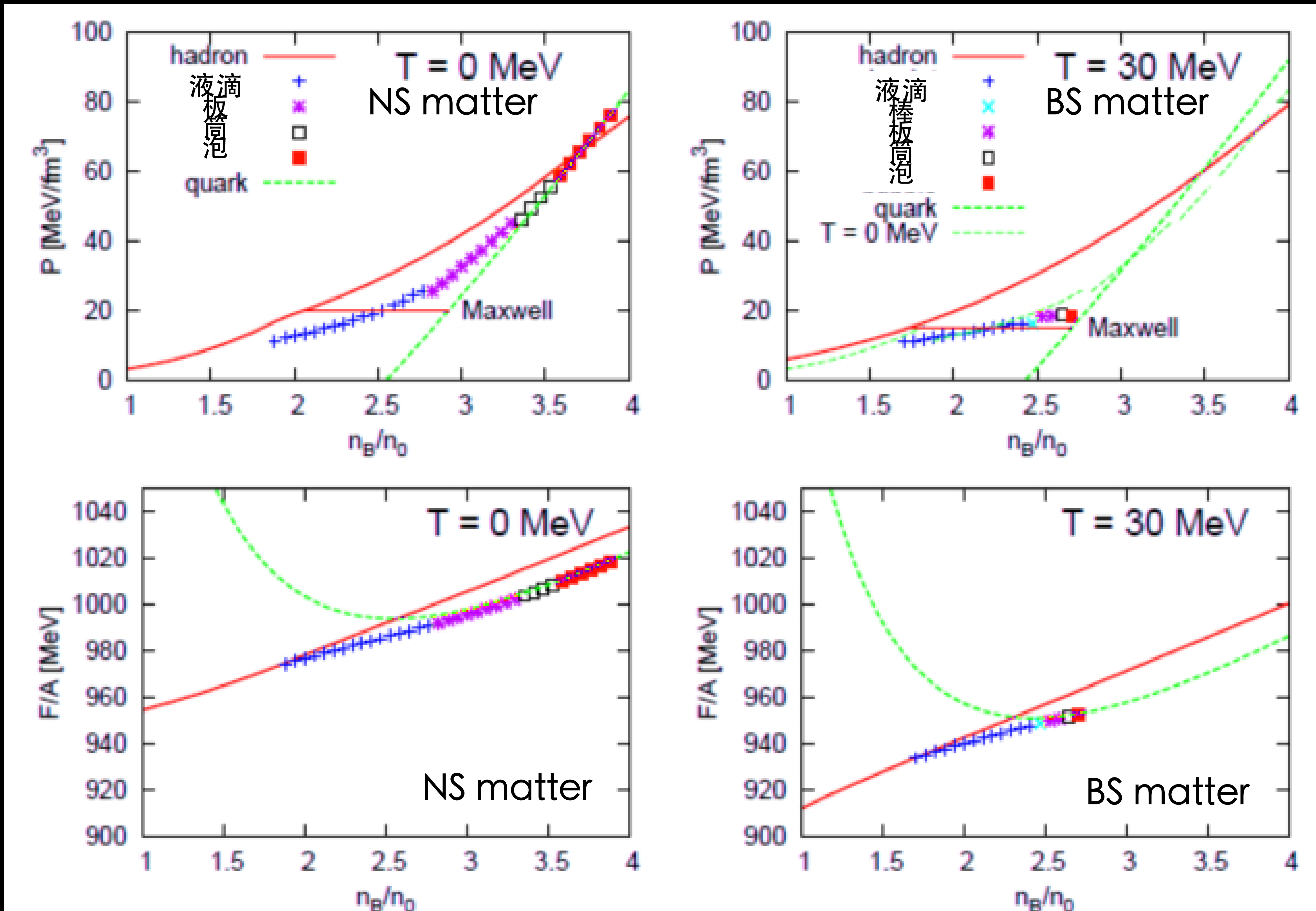
EOS①

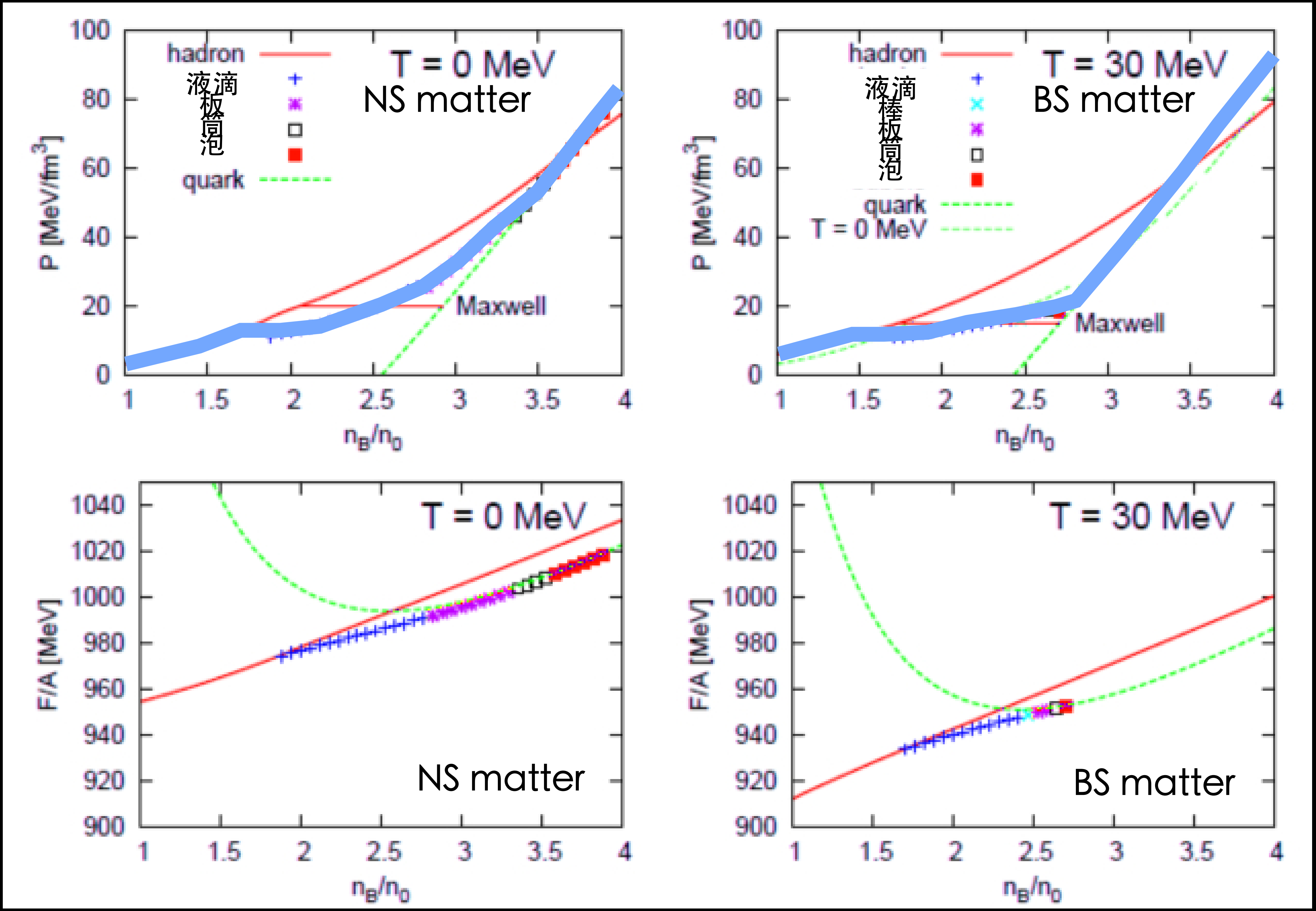
Yasutake et al. PRD2009b



high T → discontinuity of density appears → It will appear in NS-NS mergers.
→ The discontinuity is suppressed in NSs.

EOS①

Yasutake et al. PRD2009b



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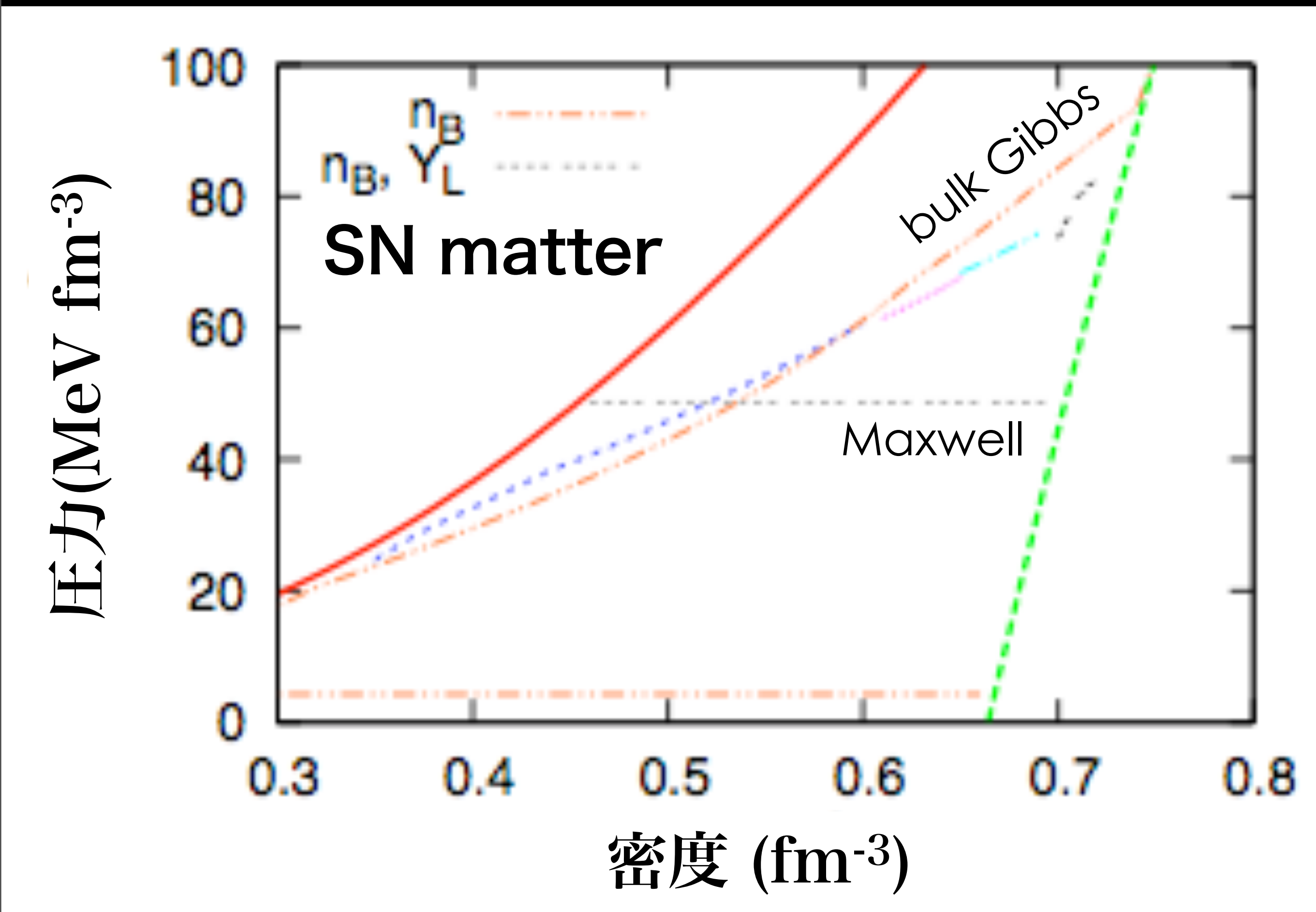
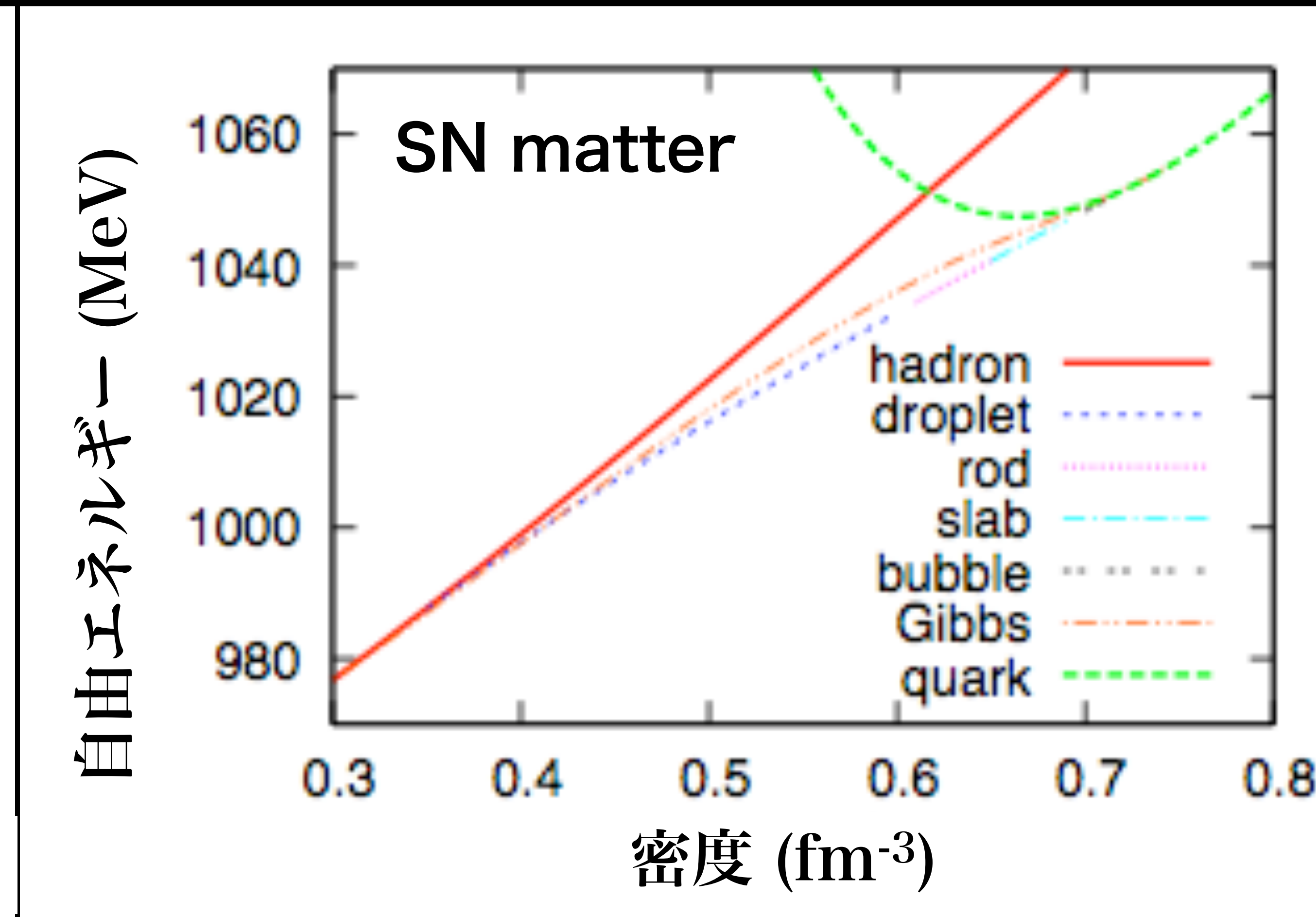
EOS②

Yasutake et al. 2011 PRD in prep

Yl=0.4, T=30MeV





high Yl → EOSs become close to the ones under the local charge neutrarity.

→ The phase transitions are not sharp in PNSs.

EOS②

Yasutake et al. 2011 PRD in prep

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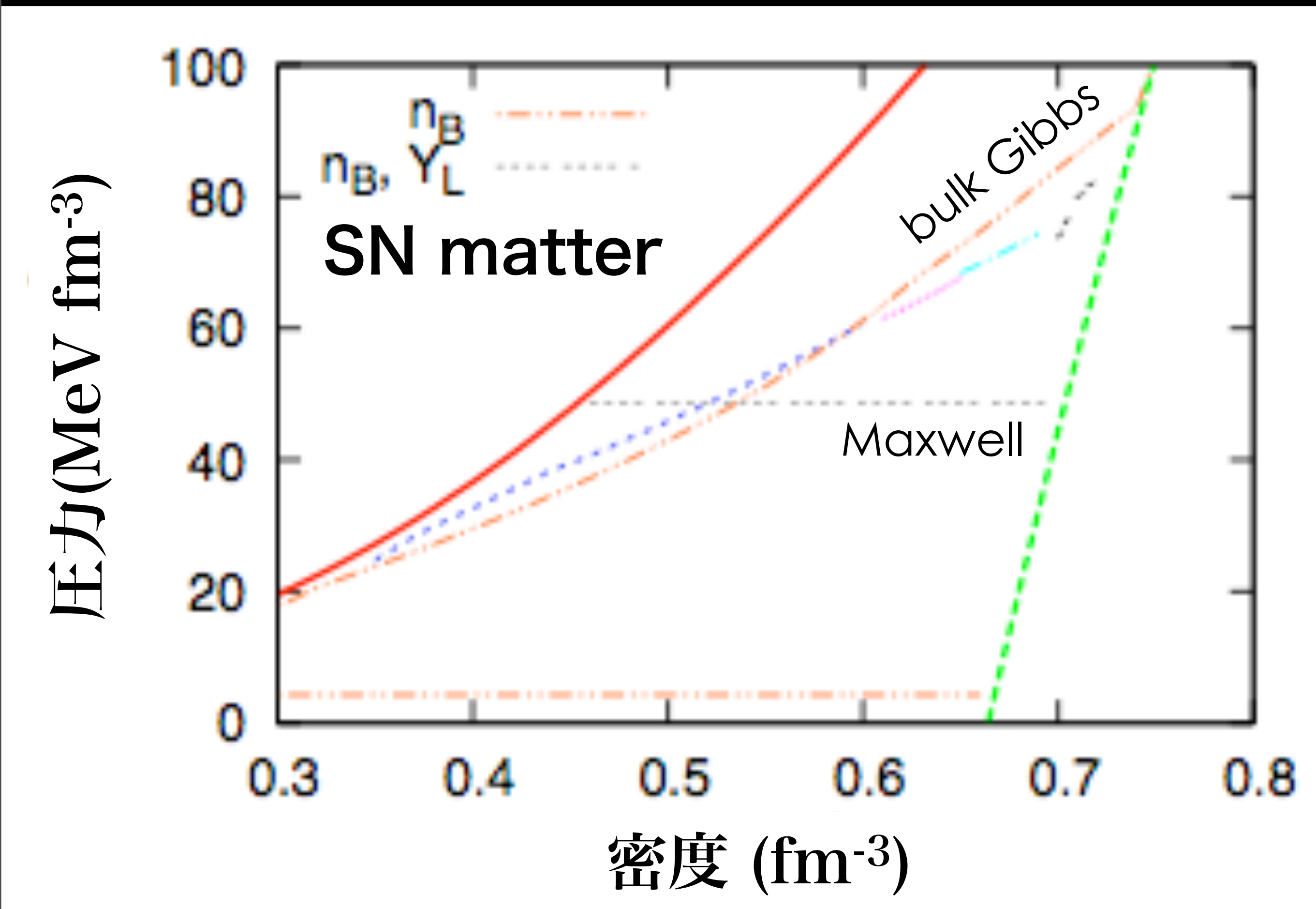

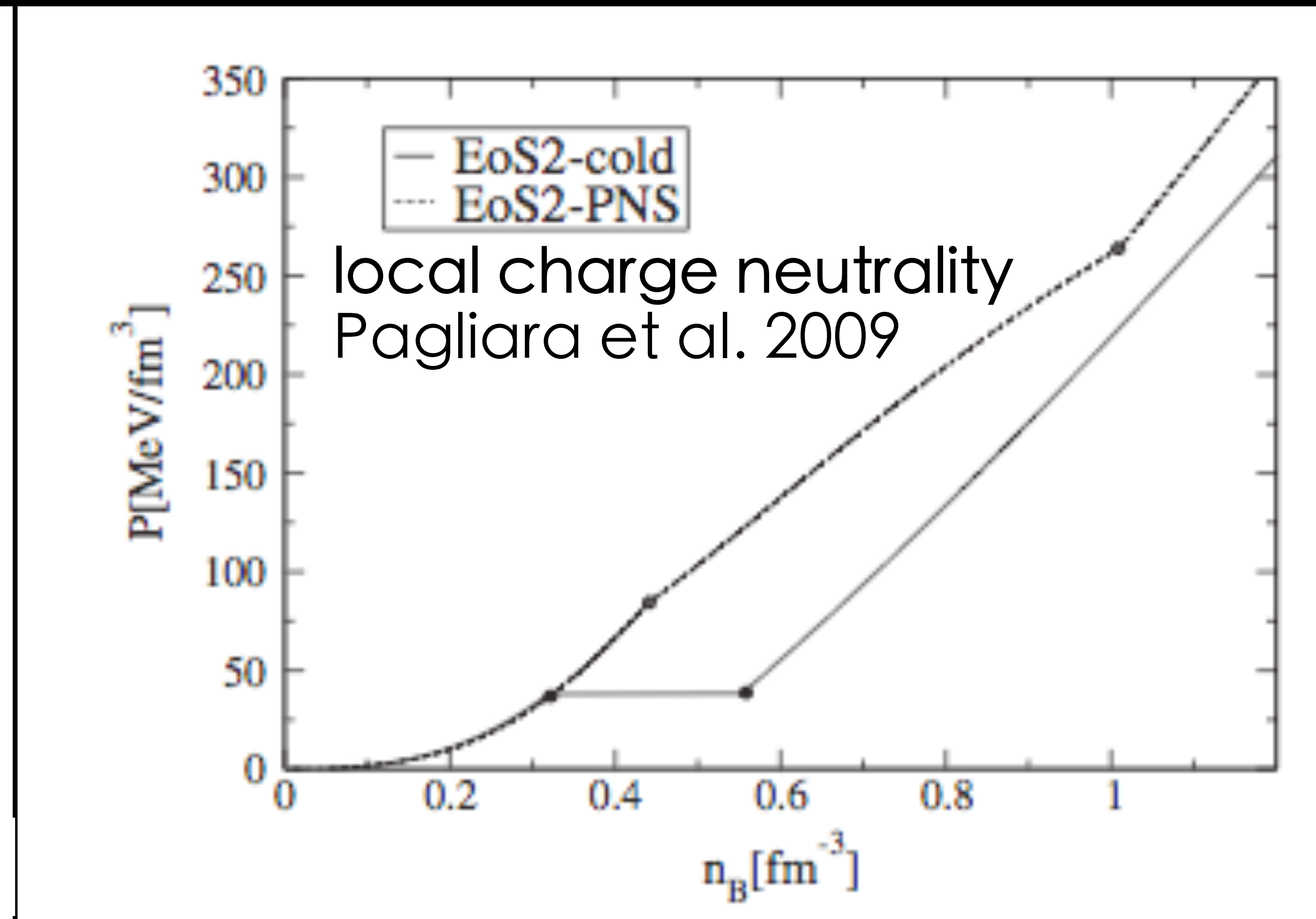

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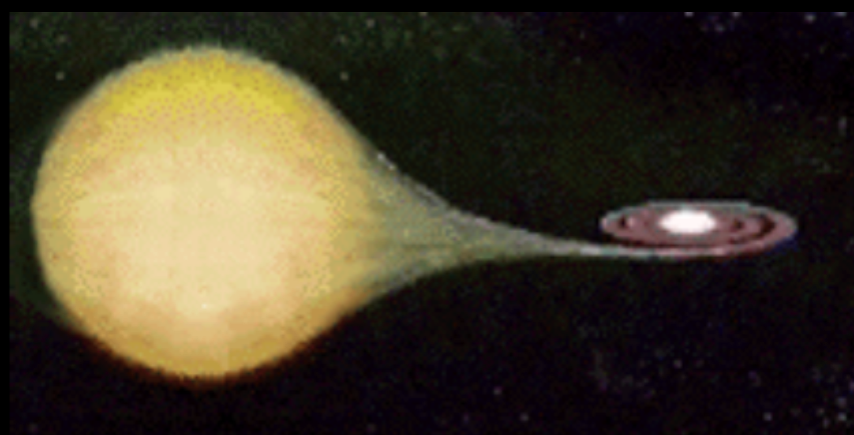
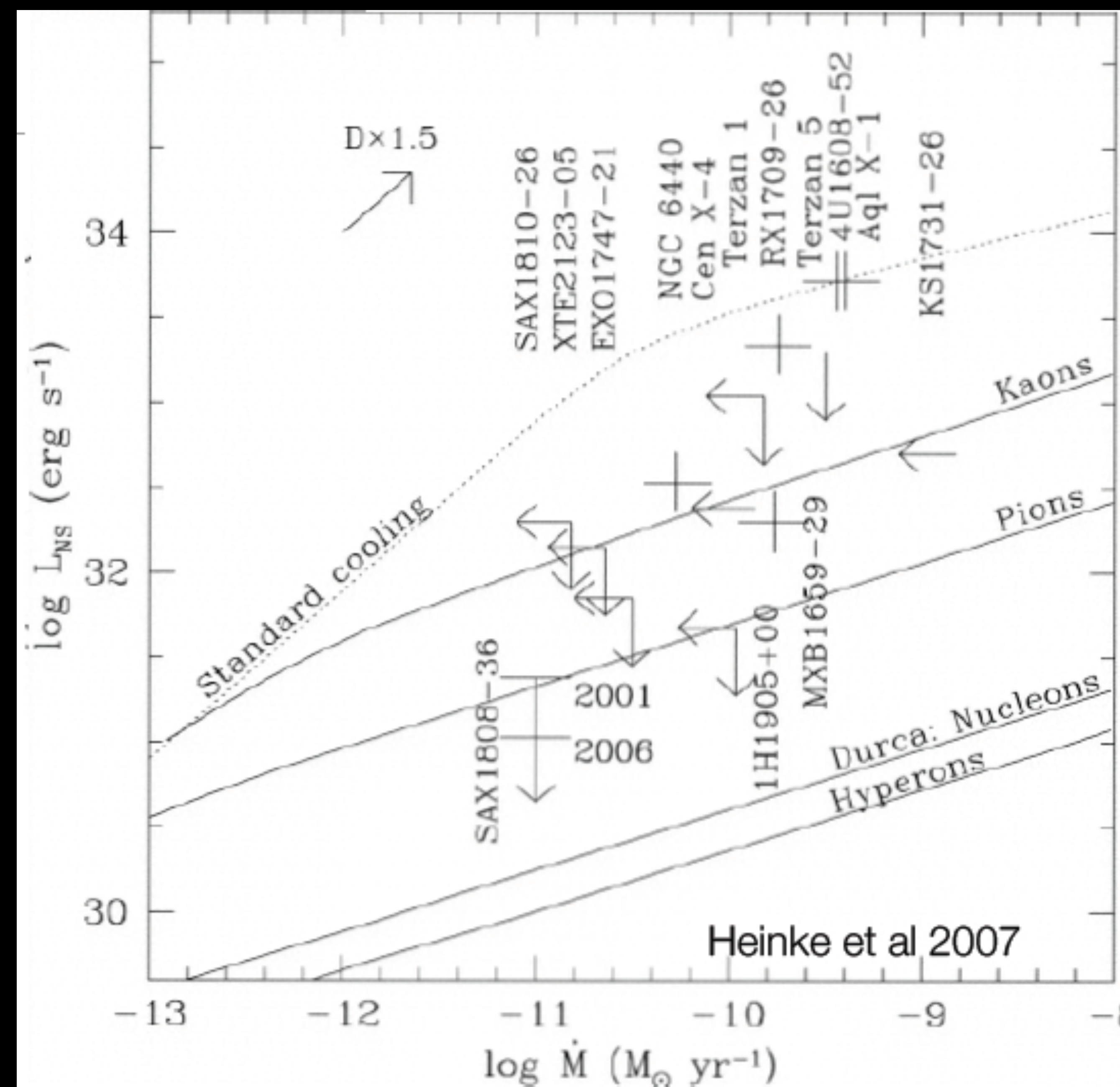
X-ray transit　objects

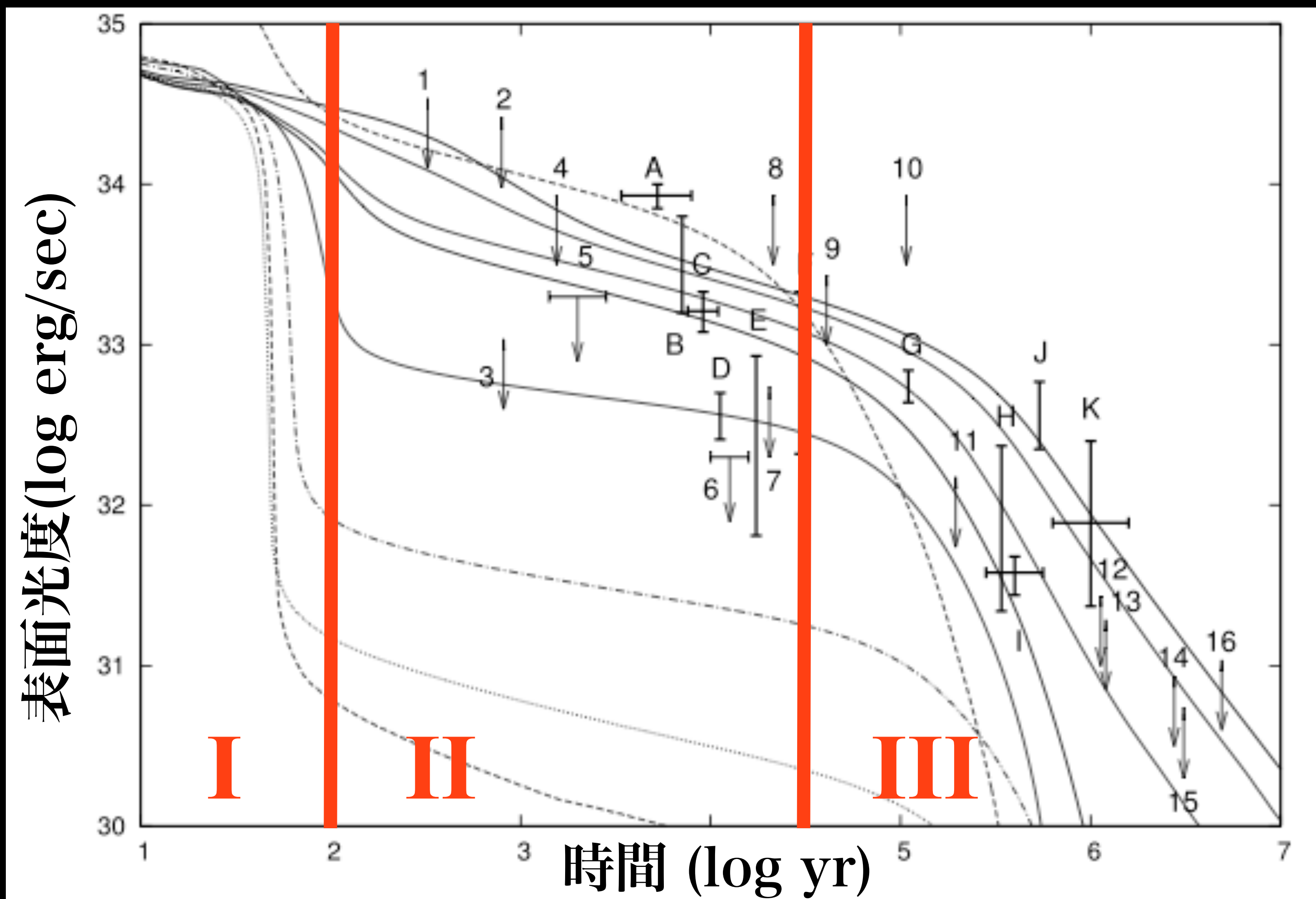




Heating by accretion
→cooling by neutrinos
→Standard cooling can not be
consistent with the observations.

Thermal evolutions (1D)

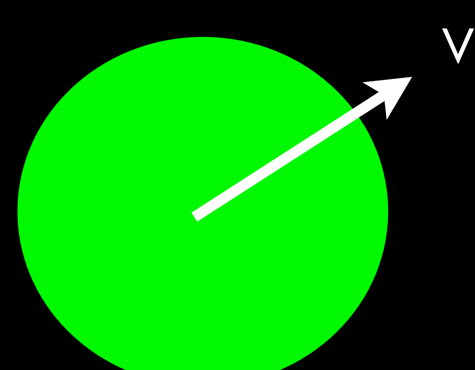
S. Tsuruta, J. Sadino, A. Kobelski, M. A. Teter, A. C. Liebmann, T. Takatsuka, K. Nomoto, and H. Umeda (2009)



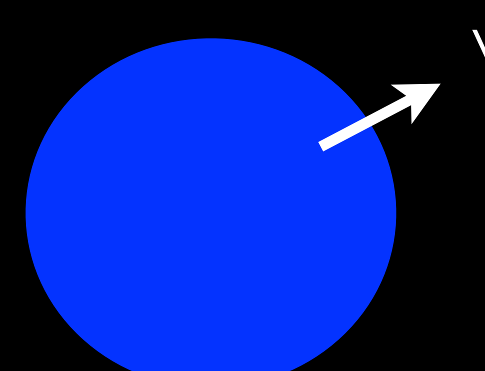
* Magnetars have been observed in 2nd era.

Ist era not thermal eq.

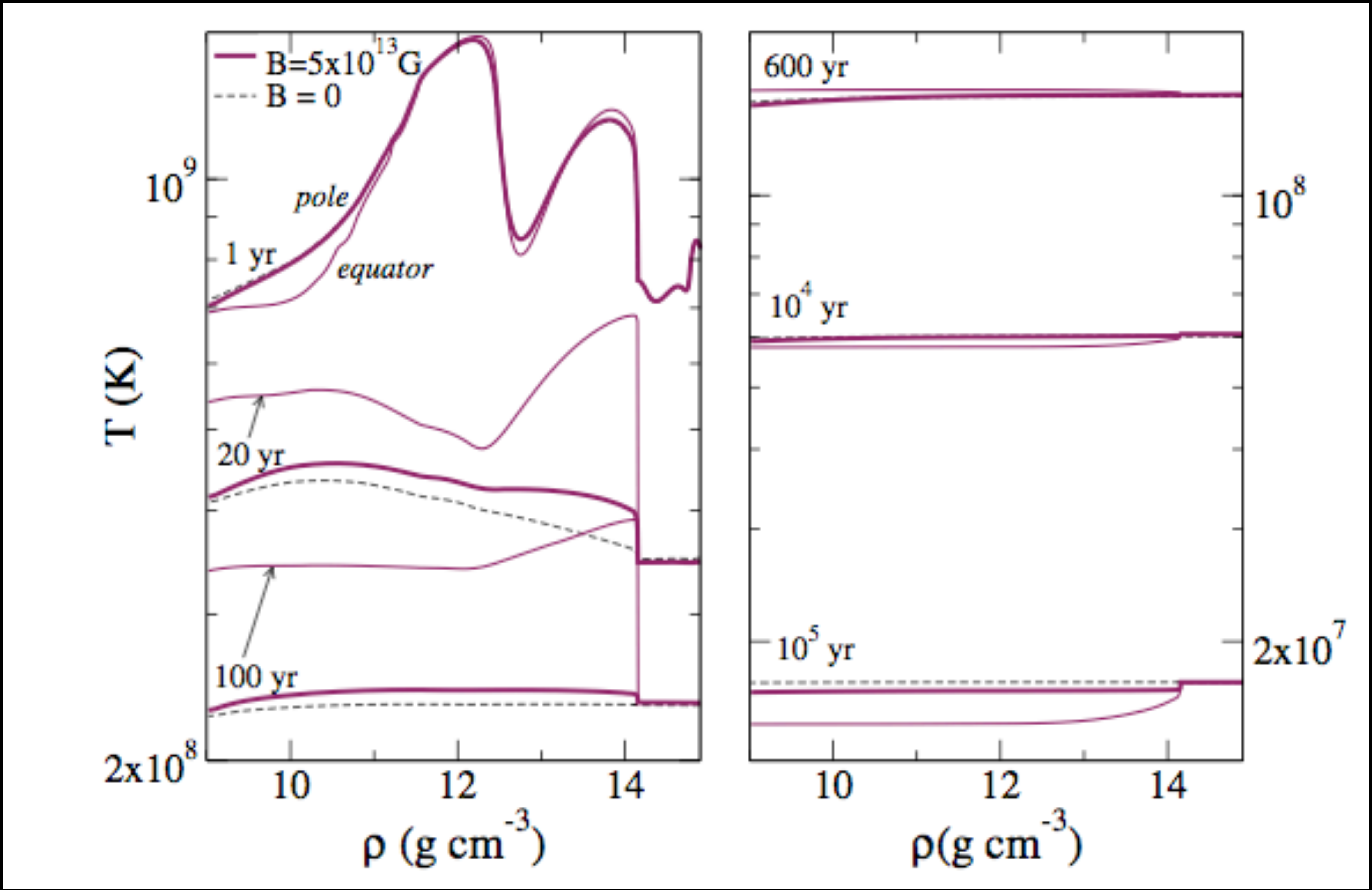
2nd era



3rd. era

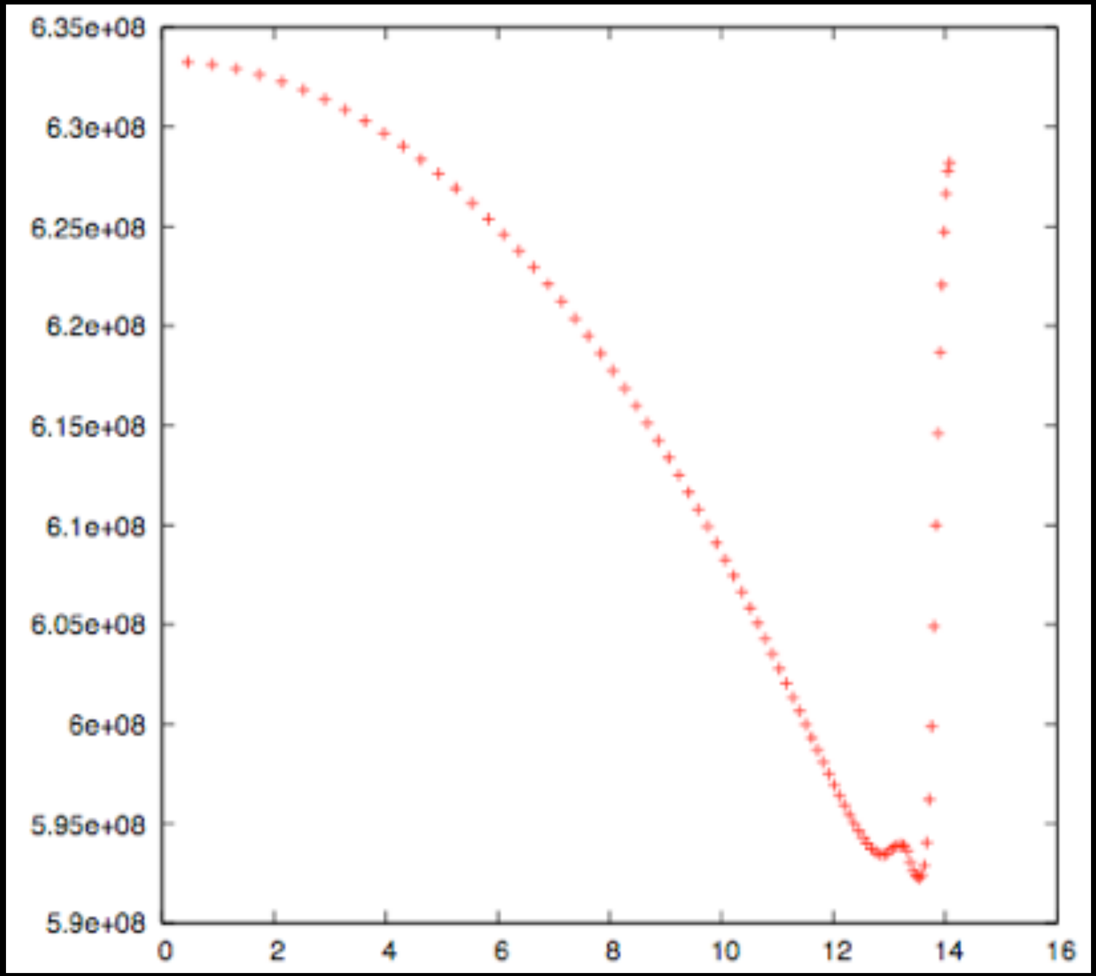


previous works



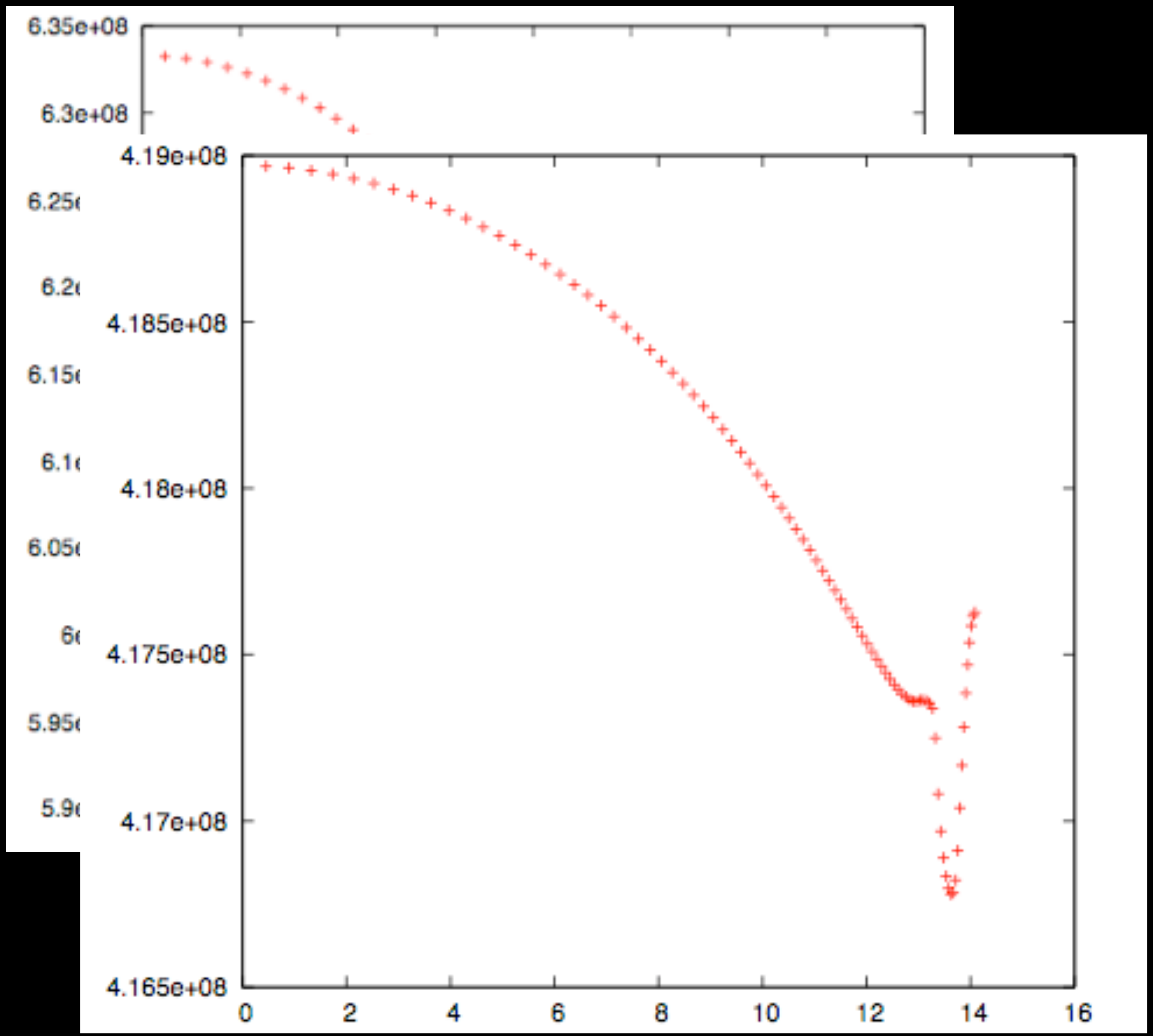
Our 1D simulations

Our 1D simulations



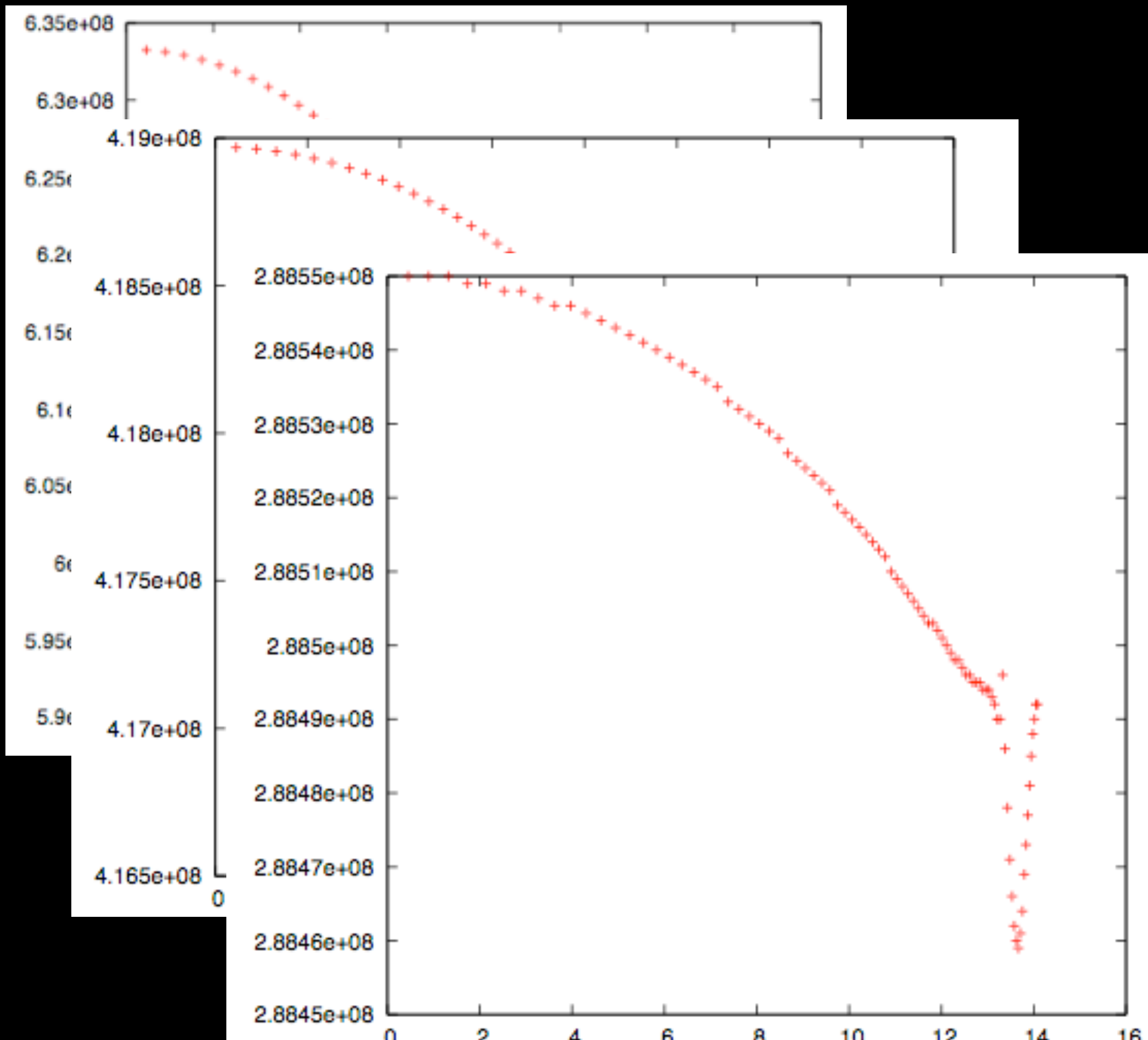
1yr

Our 1D simulations



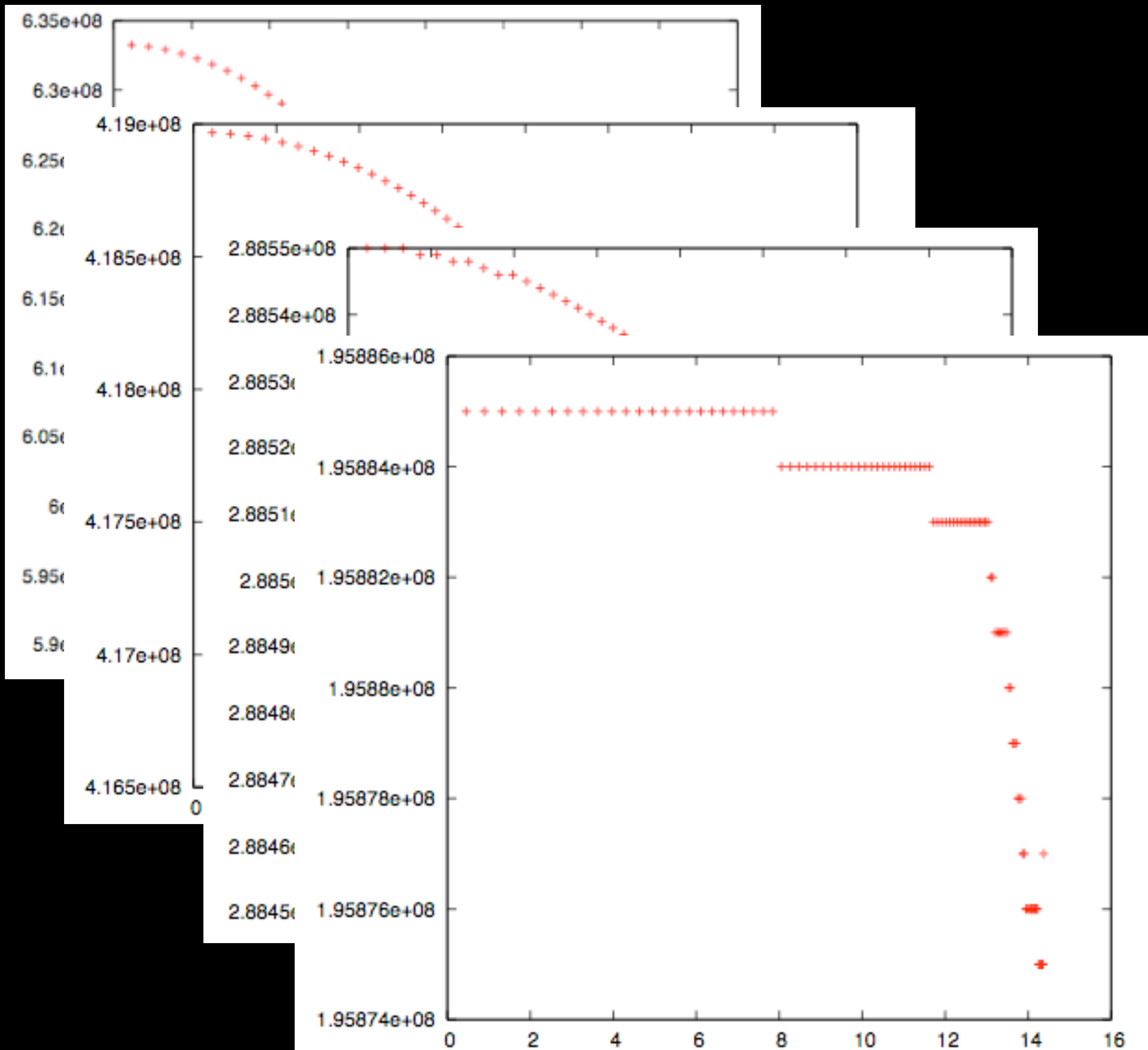
10yr

Our 1D simulations



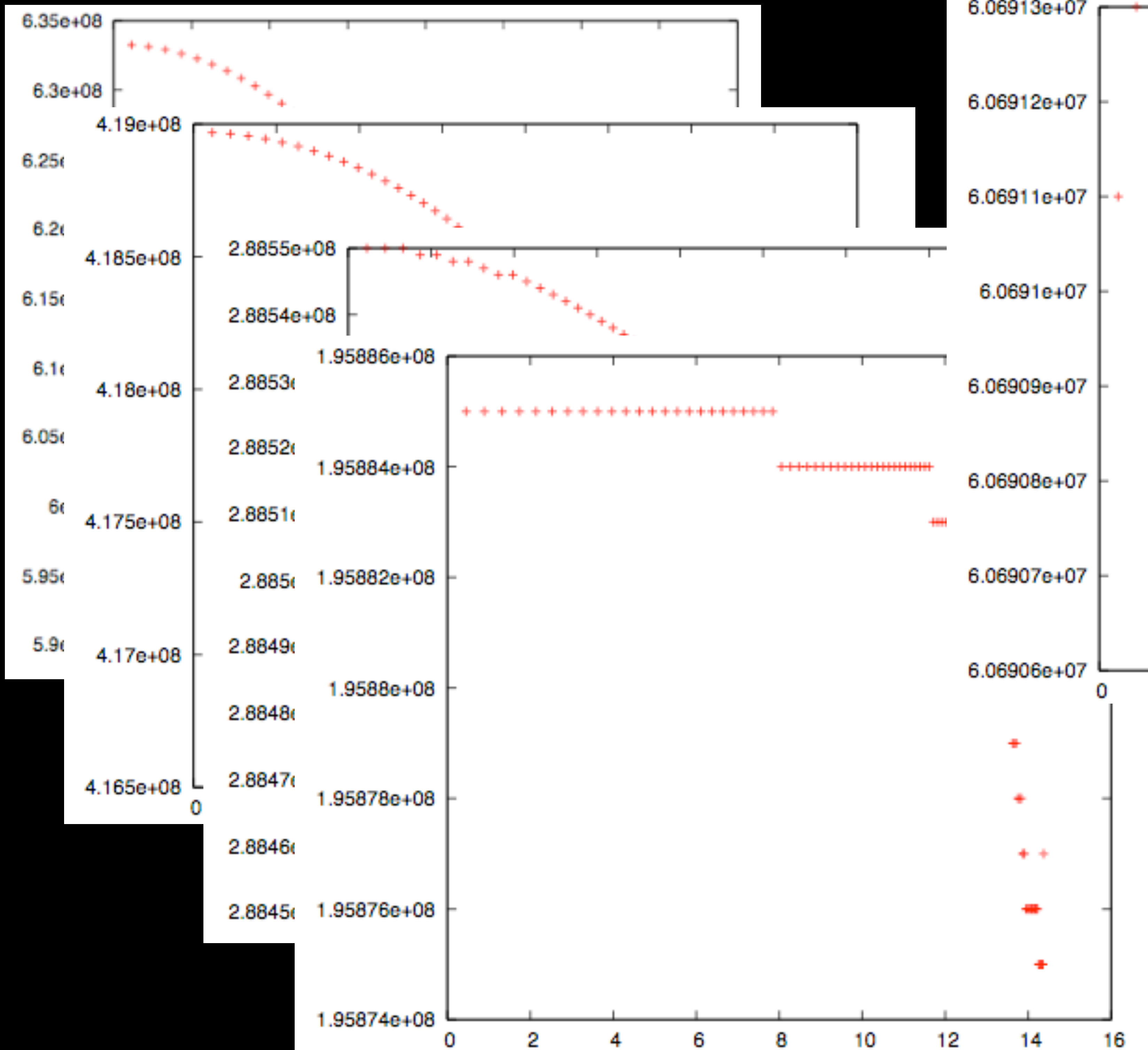
1e2yr

Our 1D simulations

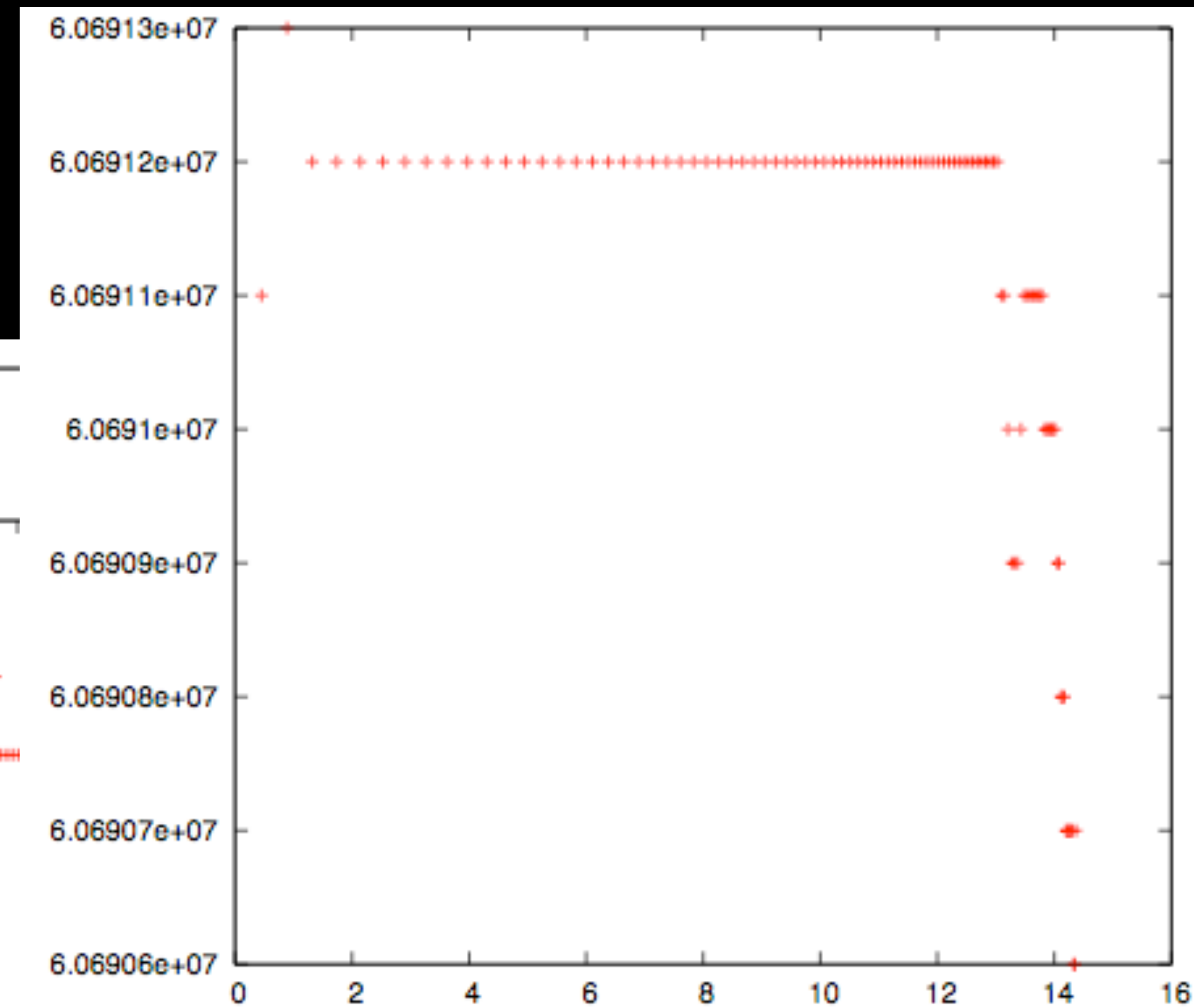


1e3yr

Our 1D simulations



1e3yr



1e6yr

Uncertainty of phase transition

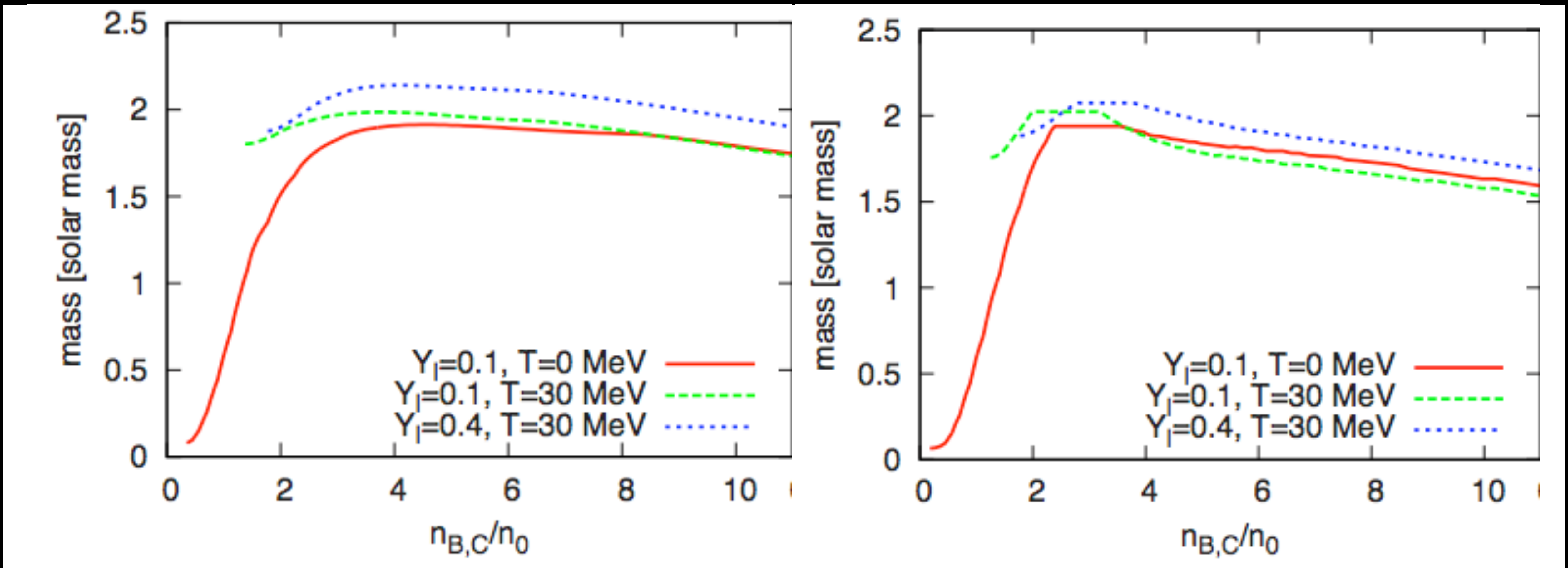
Schaffner group (Heiderberg Univ.) 2009

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	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

Uncertainties of phase transition

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



the bulk Gibbs condition

the Maxwell condition

Brueckner-Hartree-Fock model

Using baryon-baryon interaction,
we calculate the energy self-consistently.

$$\epsilon_H = \sum_{i=n,p,\Lambda,\Sigma^-} \sum_{k<k_F^{(i)}} \left[T_i(k) + \frac{1}{2} U_i(k) \right],$$

$$U_i^{(j)}(k) = \sum_{k'<k_F^{(j)}} \mathrm{Re}\langle kk' | G_{(ij)(ij)}[E_{(ij)}(k,k')] | kk' \rangle.$$

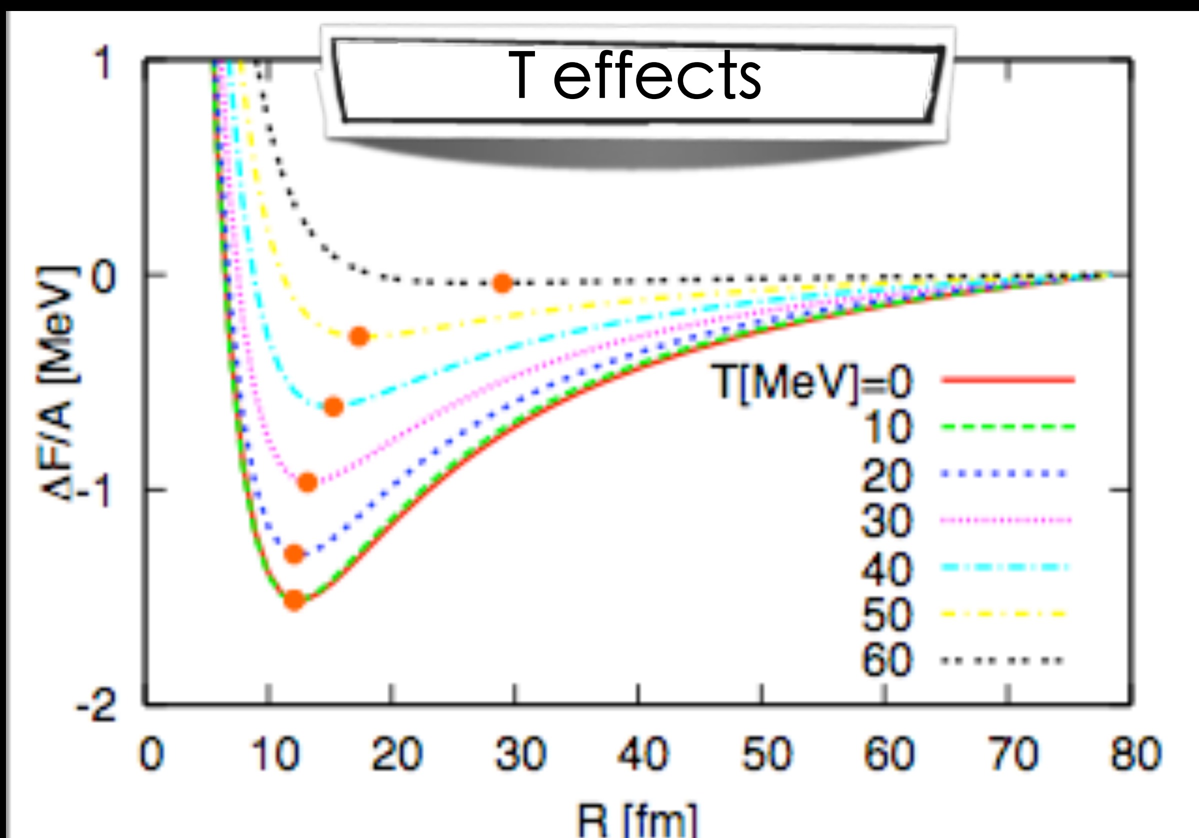
$$G_{ab}[W] = V_{ab} + \sum_c \sum_{p,p'} V_{ac} | pp' \rangle \frac{Q_c}{W - E_c + i\epsilon} \times \langle pp' | G_{cb}[W],$$

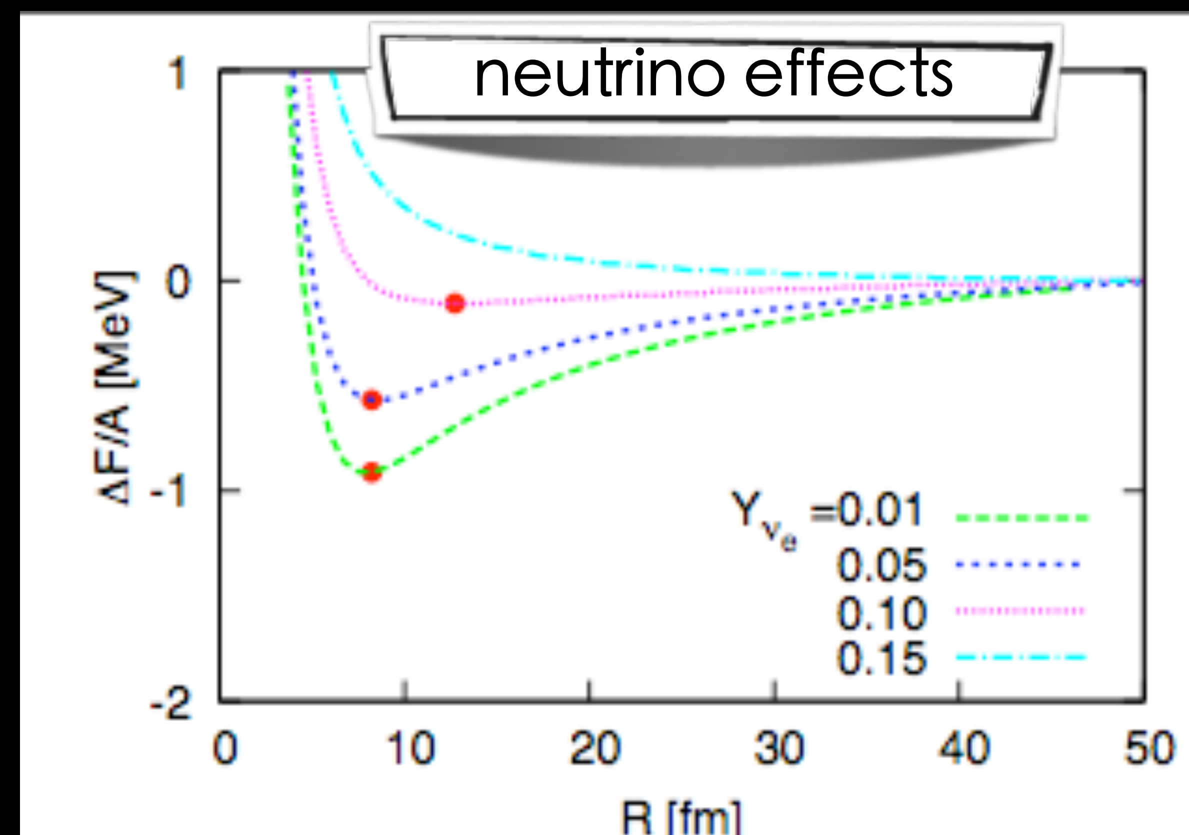
$$U_i(k) = \sum_{j=n,p,\Lambda,\Sigma^-} U_i^{(j)}(k)$$

G−matrix

Stability of pasta phase

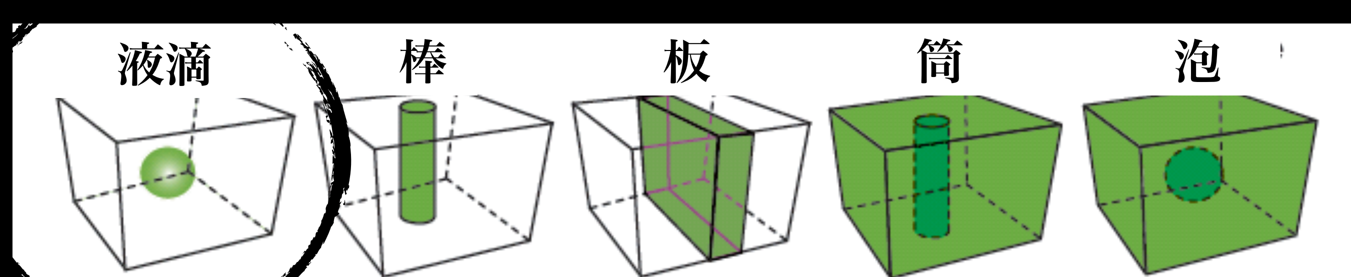
Yasutake Maruyama, Tatsumi, 2009b, 2011 in prep.





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

$\rho=2.5\rho_0$,
density dependent bag model

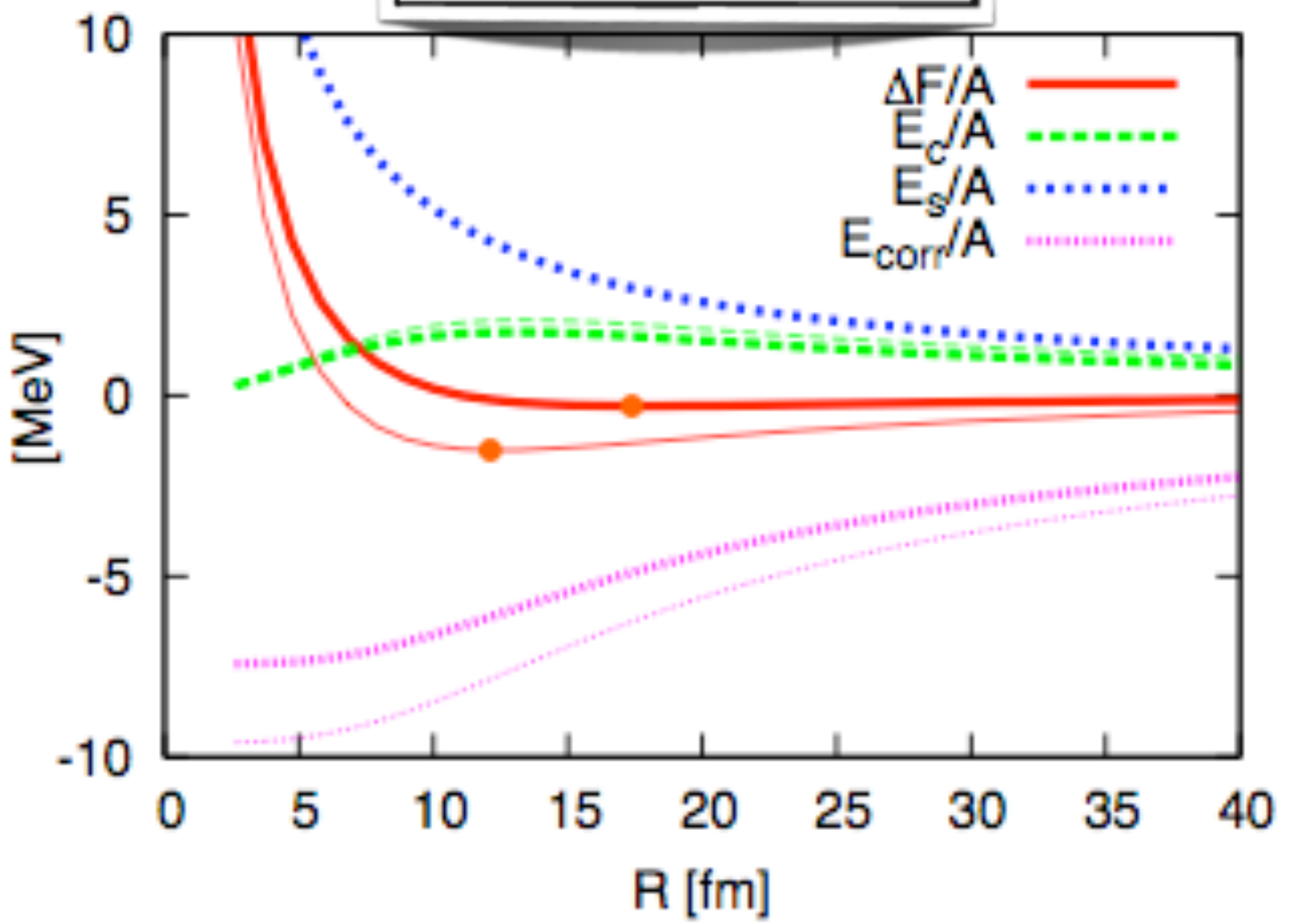


surface tension
= 40 MeV/fm^3

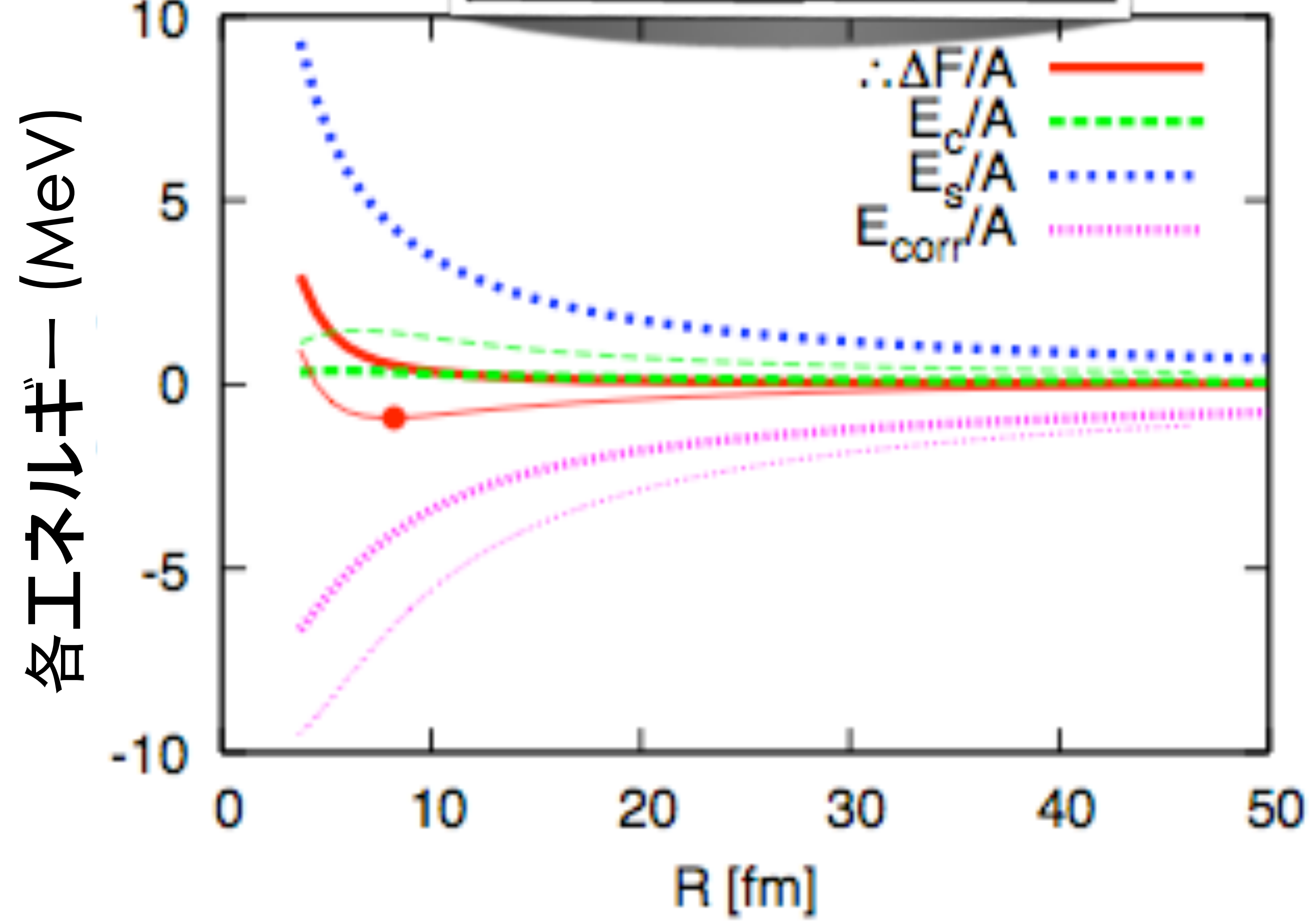
Energy components

Yasutake Maruyama, Tatsumi, 2009b, 2011 in prep.

Effects of T



Effects of Yv



thin lines ・・・zero temperature

thick lines・・・T=50 MeV

Main component is " Ecorr"

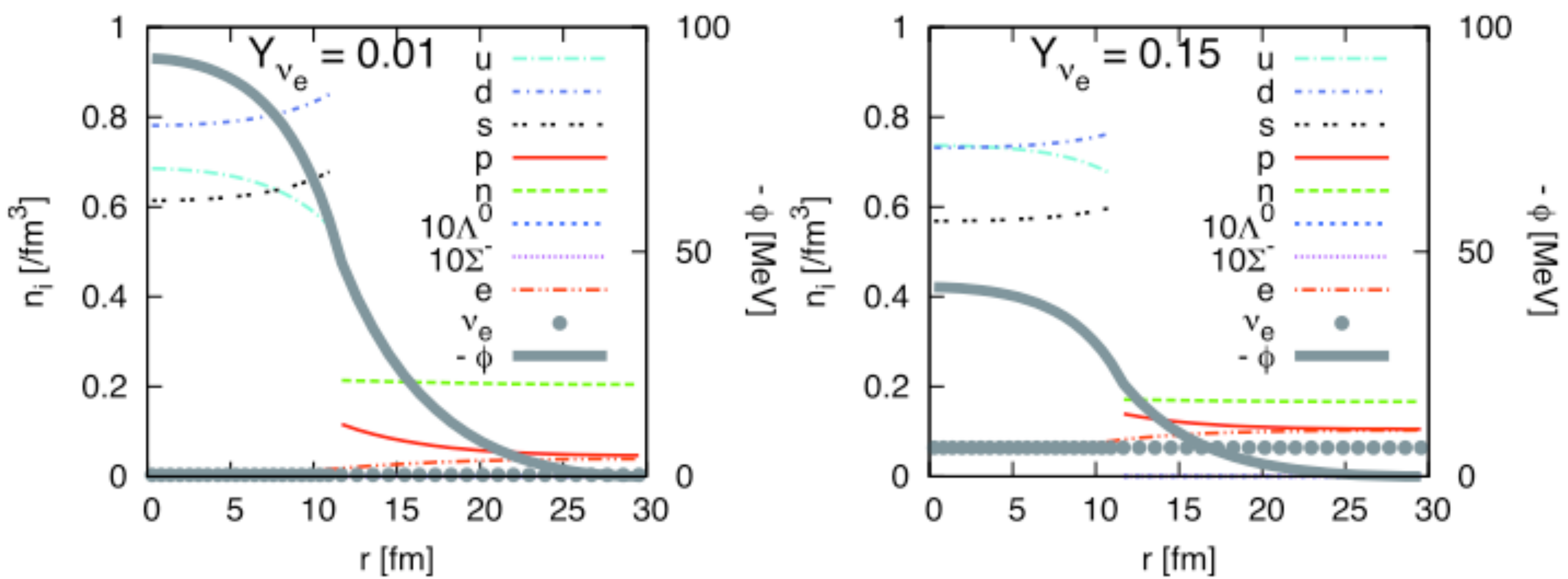
thin lines ・・・Yv = 0.01

thick lines・・・Yv= 0.15

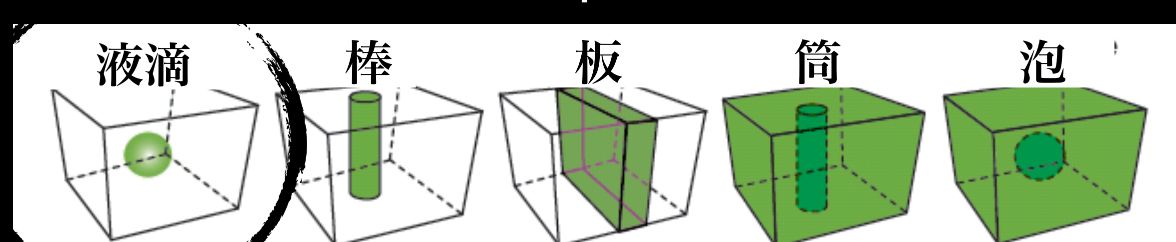
Main components are "Ecorr , Ec"

Particle distribution and Coulomb potential

Yasutake Maruyama, Tatsumi, 2009b, 2011 in prep.



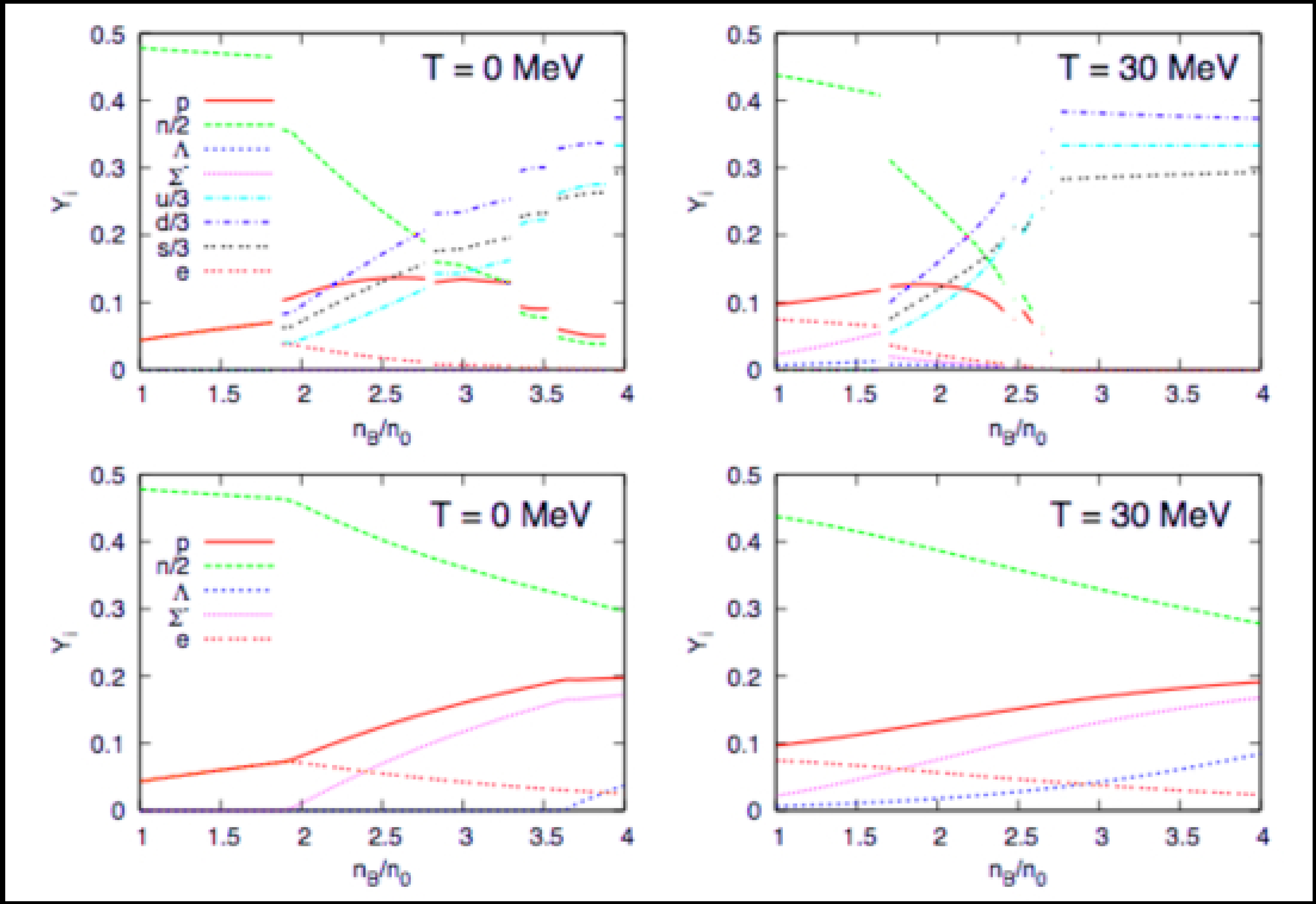
Existence of neutrinos changes the chemical equilibrium and then the Coulomb potential.



Yasutake et al. PRD2009b

with Quarks

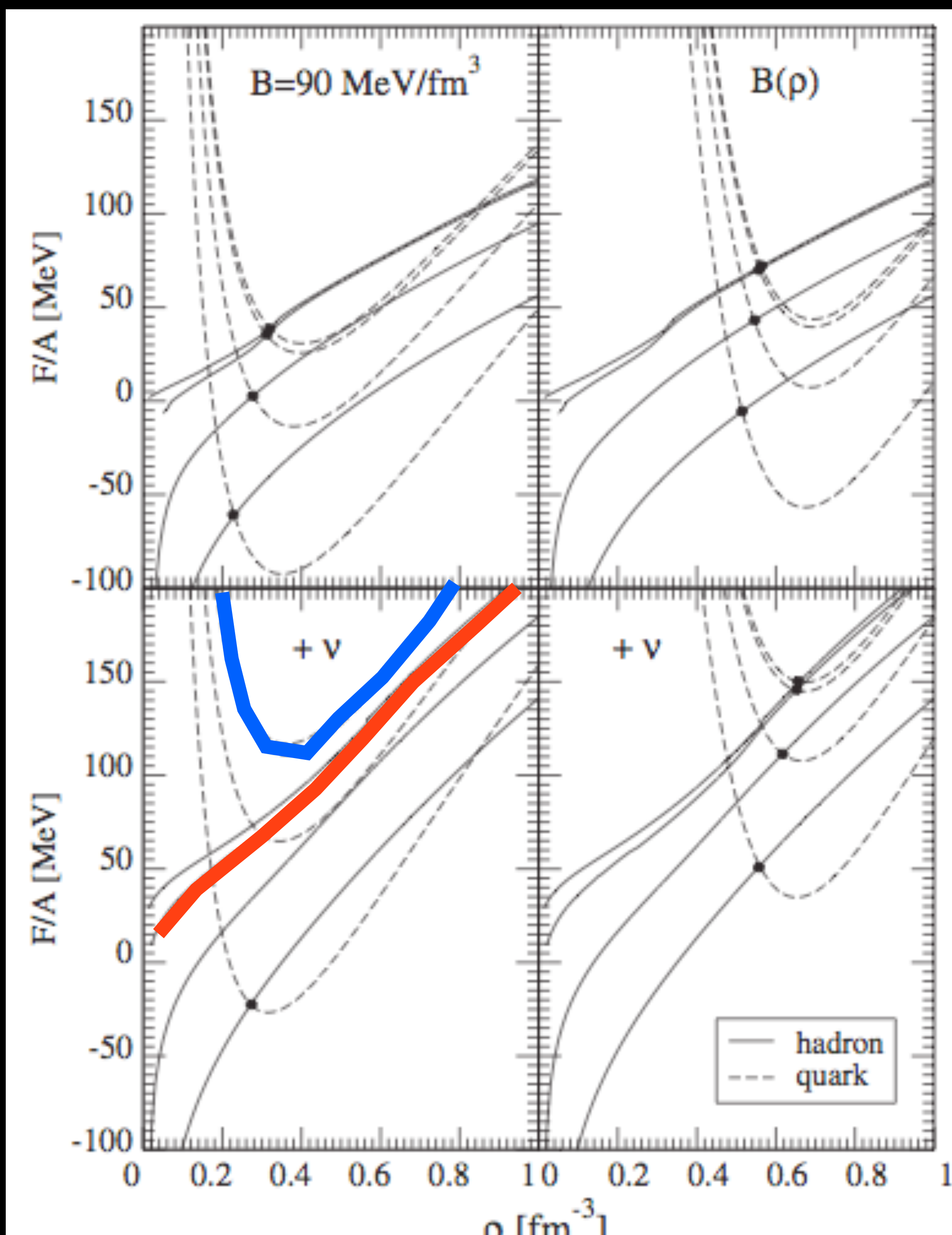
without



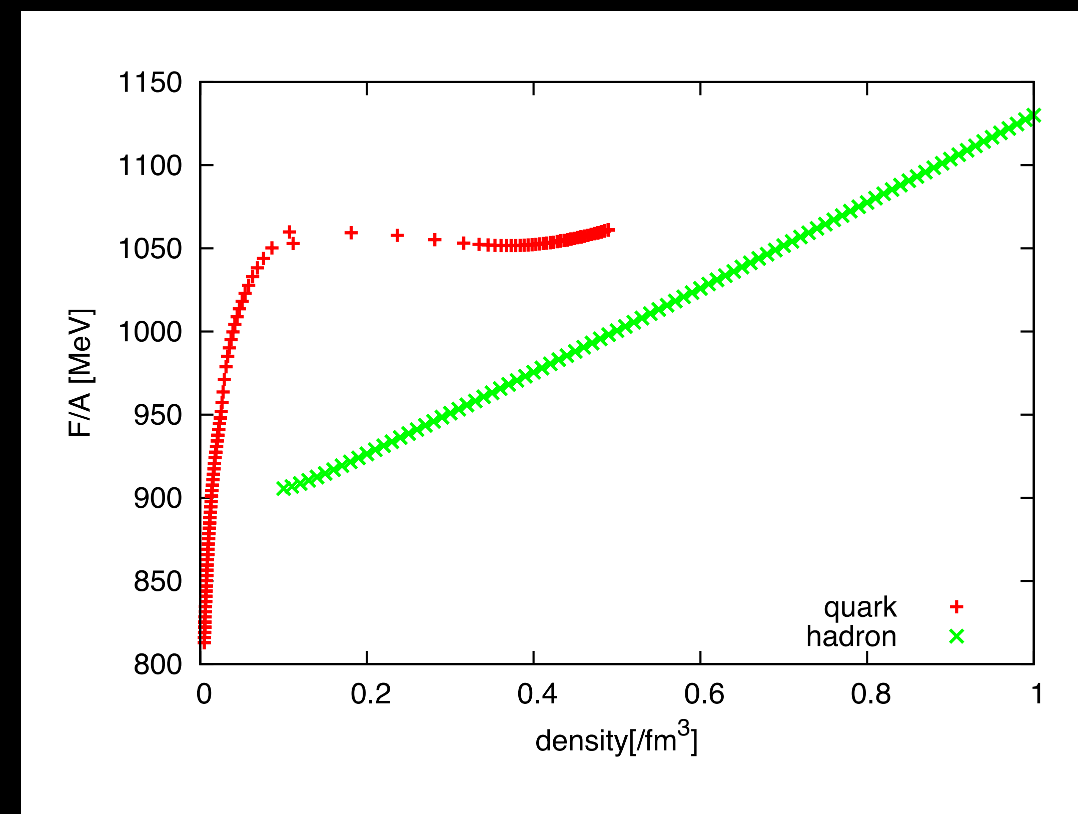
Hyperon number densities are suppressed.

補足

【期待しているさらなる研究成果】
現状でもっとも手堅いクォーク=ハドロン相転移 → クォーク模型を制限



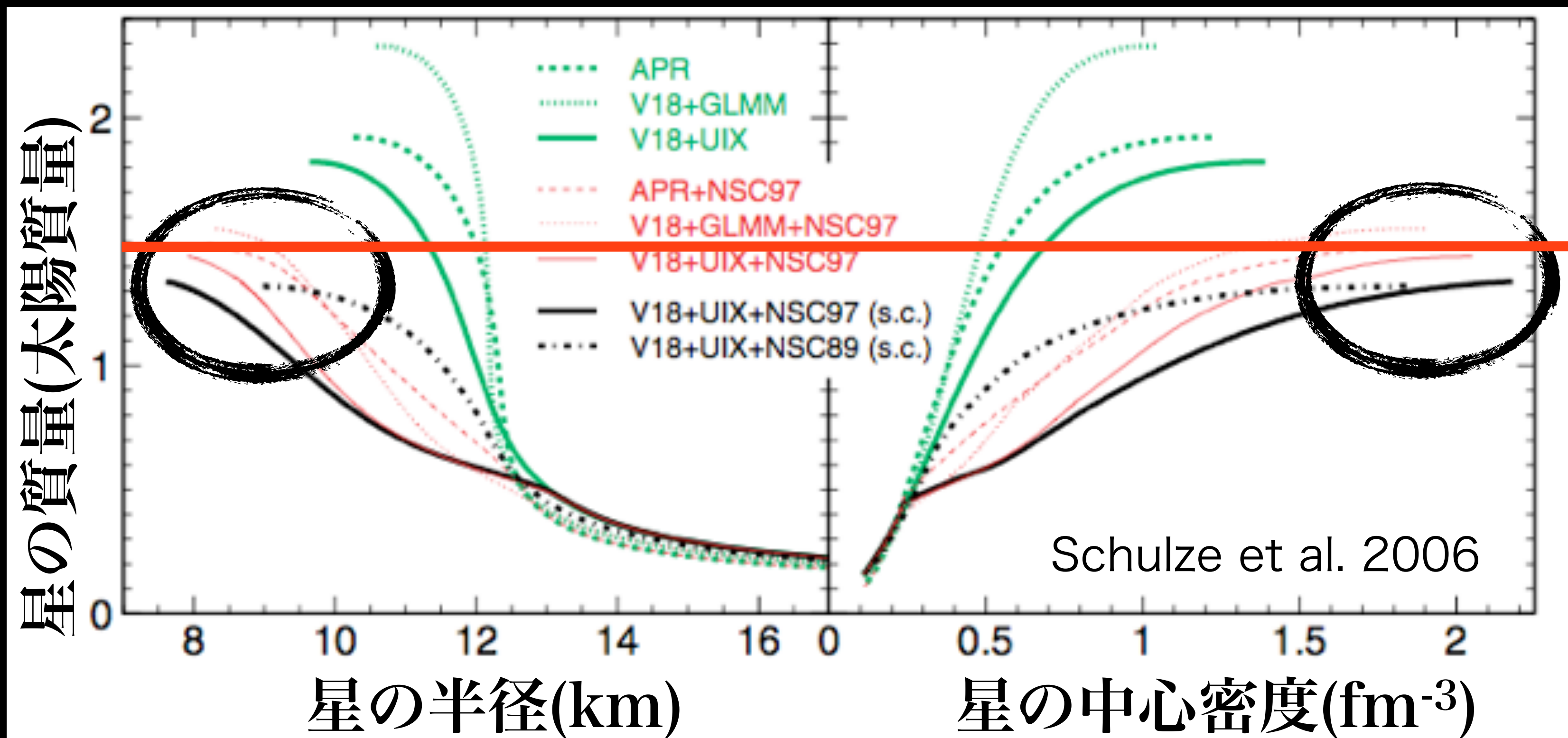
BHF vs MIT bag
Nicotra et al. 2006



BHF vs NJL
テスト計算

“低質量問題”

ハイペロンは必然的に現れるはず！ だけど観測と矛盾！



観測から決まる下限値
NS-NS binary

〜2Msの可能性も
Shapiro delay
J 1614-2230

解決案

①. 三体力による斥力効果

ref) BHF + three body force including hyperons (Takatsuka & Tamagaki (2004) etc.)

②. 相対論的効果

cf) Dirac-Brueckner-Hartree-Fock theory
cf) Relativistic mean field theory

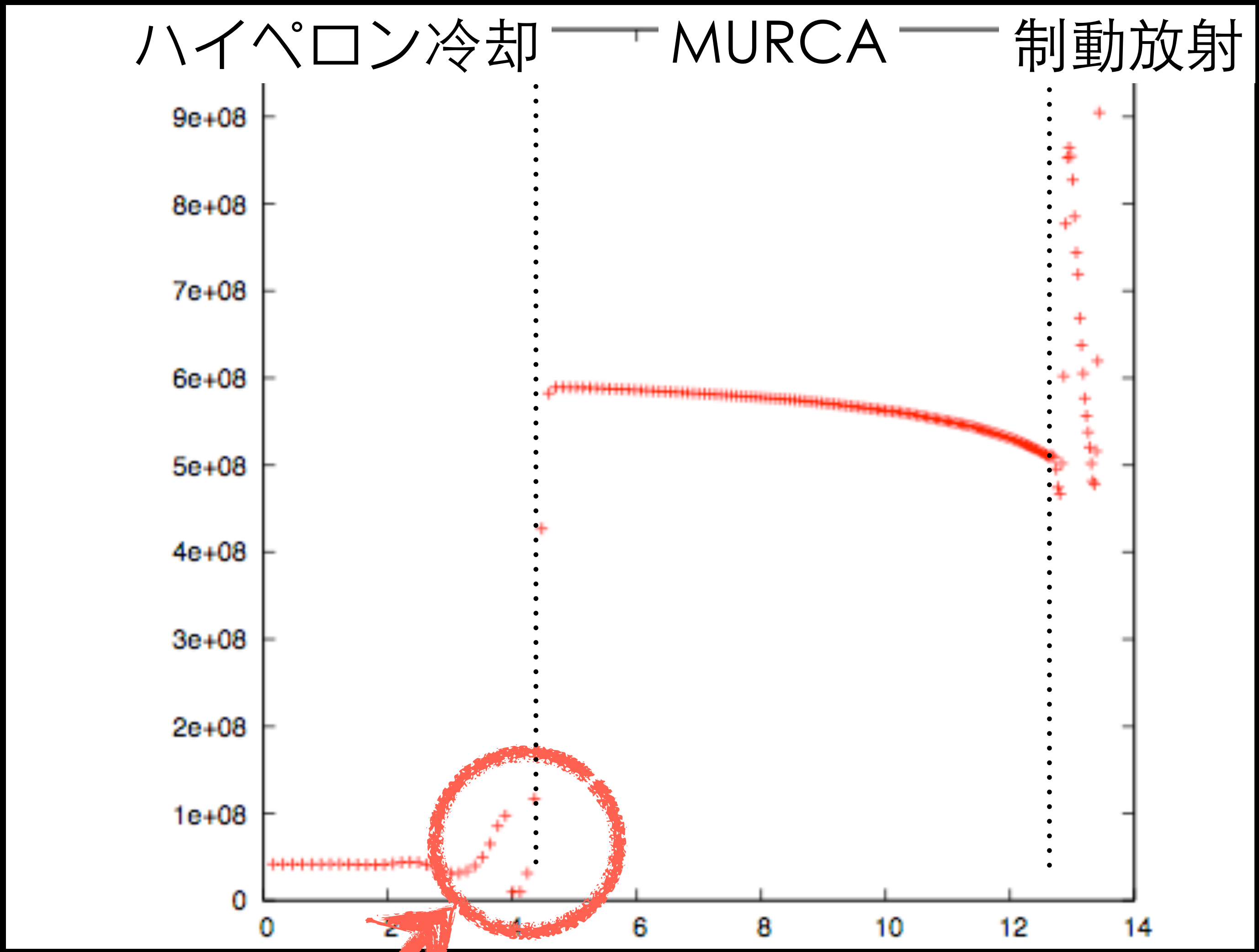
③. クォーク＝ハドロン相転移

ref) G.F. Burgio et al. Phys. Rev. C66(2002), 5802

問題点 1

- 温度勾配が不連続のところのfluxが不安定

T [K]



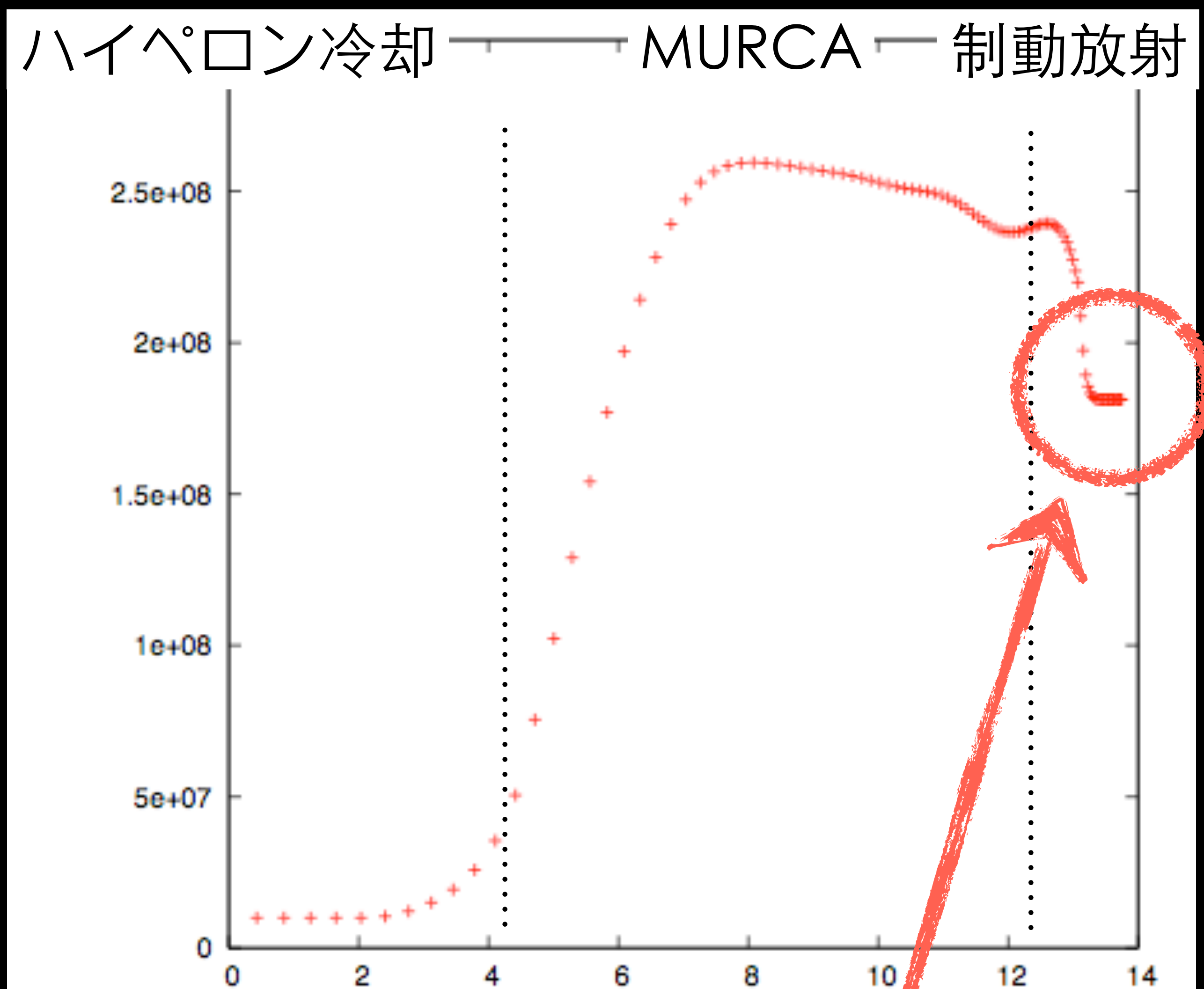
r [km]

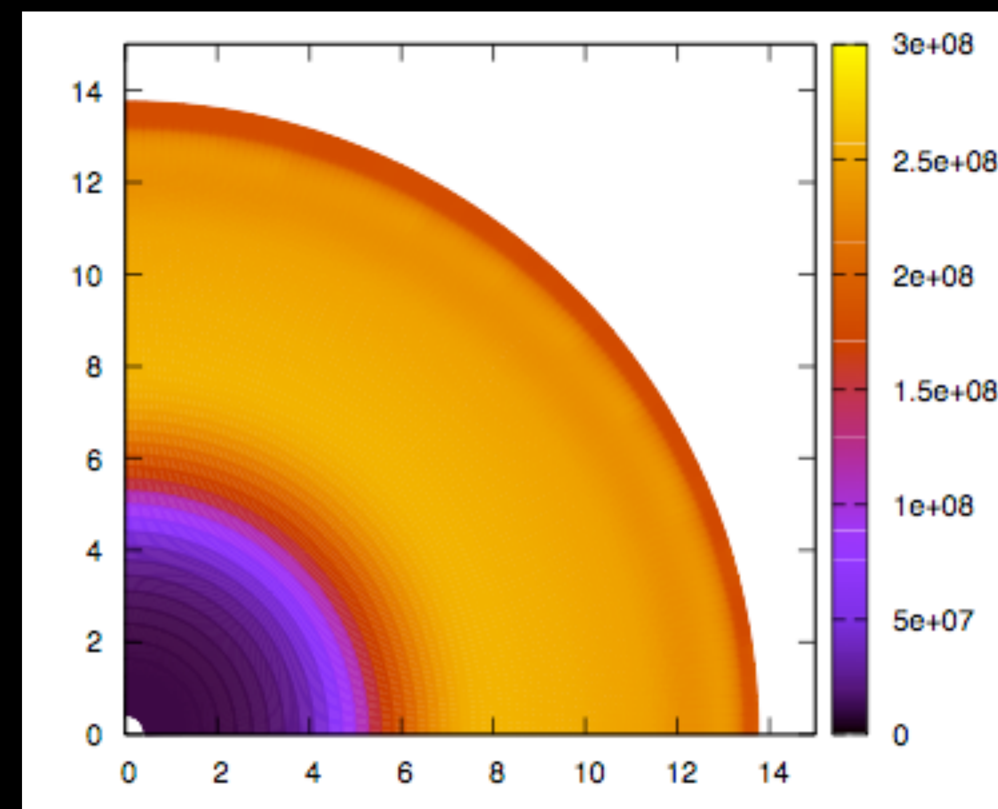
温度がここで負になったり、ギザギザができる。一旦、そうなると、dtimeが異常に短くなり計算が進まなくなる。本来は、だんだん温度勾配がなまるのでdtimeは増えるはず。hydroでいうshockの取り扱いのようなものが必要?

問題点 2

人口粘性がうまくいった。　128 yr 後

T [K]





r [km]

“次なる問題：表面がパタつき、時間が進まない。”

→　①陰解法?

②dt=dt * fac の facを緩める? もう一桁稼げる。

③エネルギー収支を乱さないように表面にだけ何か処方。、もう二桁は稼げる。