Neutron star structure explored with a family of unified equations of state of neutron star matter

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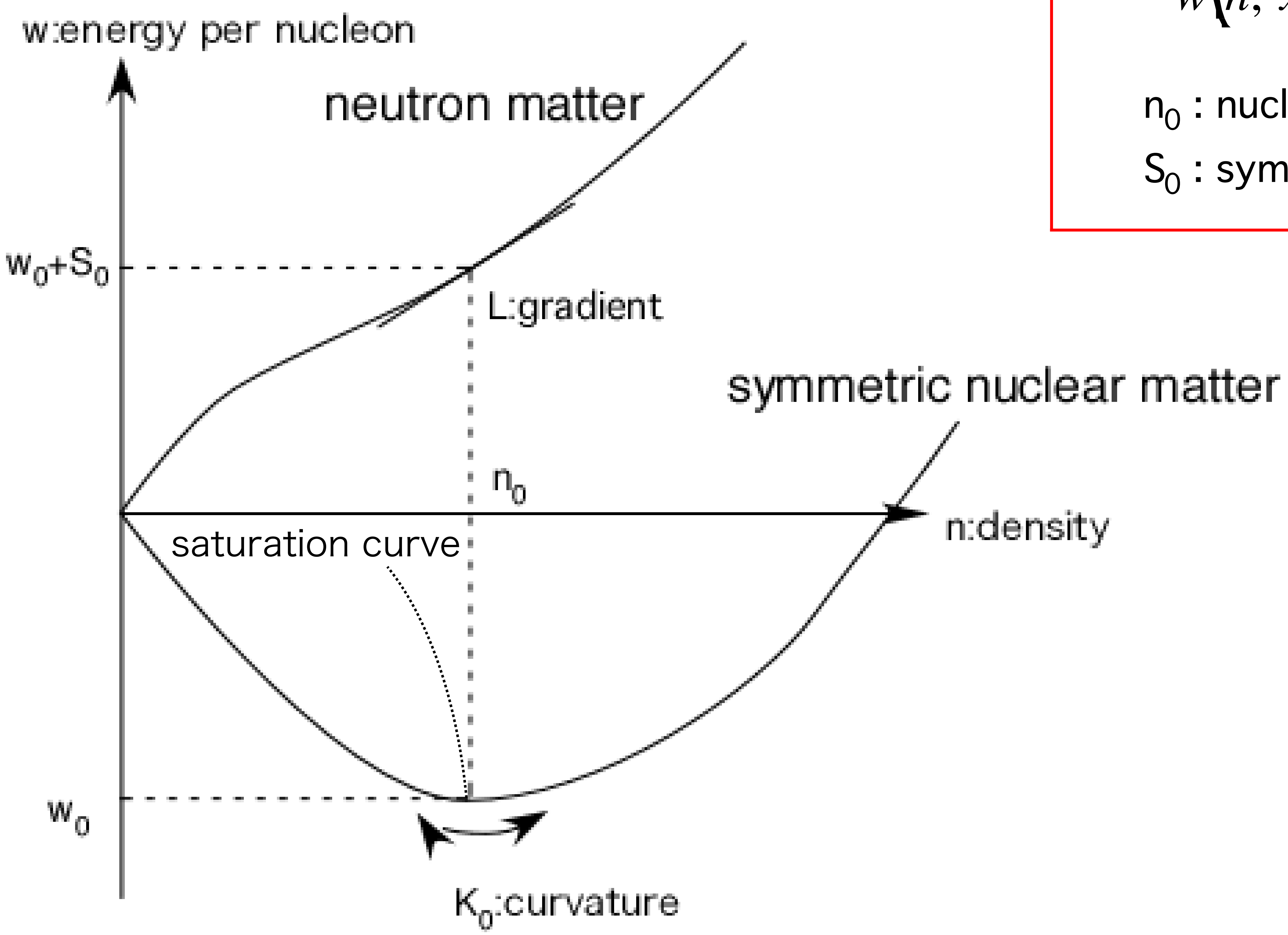
Oyamatsu-Iida (OI) unified EOS family

- Unified EOS family which covers from laboratory nuclei to neutron star matter
- Each EOS is labeled with the empirical uncertain saturation parameters: the incompressibility K_0, and the density gradient of symmetry energy L
- A simplified Thomas-Fermi model description of nuclei (the same method as popular Shen EOS (NPA1998,2011) for supernova matter)

Saturation parameters and auxiliary empirical constraint



Energy per nucleon of nearly symmetric nuclear matter

$$w(n,x) \approx w_0 + \frac{K_0}{18n_0^2}(n-n_0)^2 + (1-2x)^2\left[S_0 + \frac{L}{3n_0}(n-n_0)\right]$$

n_0 : nuclear density, w_0 :saturation energy, K_0 : incompressibility

S_0 : symmetry energy at $n=n_0$, L: its density derivative coefficient

Symmetry energy S_0 and its density gradient L

$$S_0 = S(n_0) \qquad L = \left.\frac{dS(n)}{dn}\right|_{n=n_0}$$

Saturation point of asymmetric matter $(x \approx 0.5)$

$$n_s = n_0 - \frac{3n_0 L}{K_0}\alpha^2 \qquad w_s = w_0 + S_0\alpha^2 \qquad \alpha = 1-2x$$

slope of saturation curve

$$y = -\frac{S_0 K_0}{3n_0 L}$$

Auxiliary empirical constraint

$$-1800 \le y \le -200$$

Adopted macroscopic model

Energy per cell

(or Energy of a nucleus)

$$W = \int_{cell} d\mathbf{r} \left[\varepsilon_0(n_n, n_p) + m_n n_n + m_p n_p \right] + \int_{cell} d\mathbf{r}\, F_0 \left| \nabla n_i \right|^2 + \left(electron\ kinetic\ energy \right) + \left(Coulomb \right)$$

n_n (n_p) : local neutron (proton) density, $n = n_n + n_p$: total density

$\varepsilon_0(n_n, n_p)$: EOS of uniform nuclear matter (energy density)

F_0 : surafce energy parameter

Parametrization of the EOS (energy density)

$$\varepsilon_0(n_n, n_p) = \frac{3}{5}\left(3\pi^2\right)^{2/3}\left(\frac{\hbar^2}{2m_n} n_n^{5/3} + \frac{\hbar^2}{2m_p} n_p^{5/3}\right) + \left[1 - \left(1 - 2Y_p\right)^2\right] v_s(n) + \left(1 - 2Y_p\right)^2 v_n(n)$$

Fermi kinetic energy density — potential energy density

potential energy densities of symmetric and neutron matter

$$v_s(n) = a_1 n^2 + \frac{a_2 n^3}{1 + a_3 n} \qquad v_n(n) = b_1 n^2 + \frac{b_2 n^3}{1 + b_3 n}$$

★$a_1 \sim b_2$ and F_0 : masses and radii of stable nuclei (b_3=1.59 fm^3, a fit to FP EOS)

★very flexible function form: a_3 can vary K_0 widely. (better than Skyrme)

The function can be fitted to SIII and TM1 EOS very well.

Simplified Thomas-Fermi calculation

energy minimization with respect to parameters of $n_n(r)$ and $n_p(r)$ (and lattice constant)

neutron (proton) density distribution n_n (n_p)

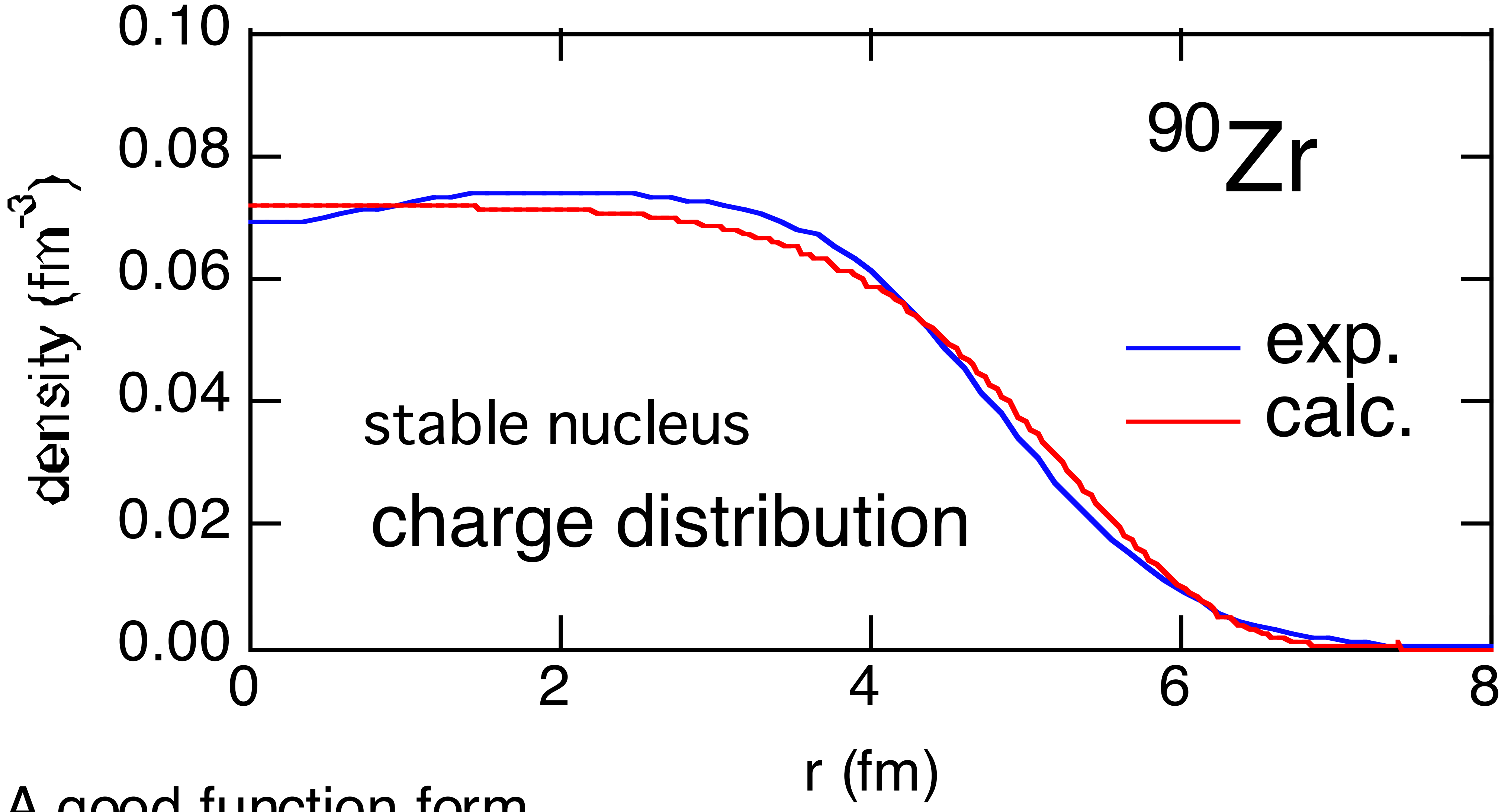
$$n_i(r) = \begin{cases} \left(n_i^{in} - n_i^{out}\right)\left[1 - \left(\frac{r}{R_i}\right)^{t_i}\right]^3 + n_i^{out} & r < R_i \\ n_i^{out} & r < R_i \end{cases}$$

R_n (R_p) : neutron (proton) radius parameter

t_n (t_p) : neutron (proton) surface thickness parameter

n_i^{in} : central density

n_n^{out} : neutron gas density (n_p^{out}=0)



A good function form

The n and p distributions are independent.

=> neutron skin

The empirical information is limited: radius and thickness.

The gradient term in Euler Eq. is continuous.

The density is zero beyond the classical turning point.

The values of parameters $a_1 \sim b_3$(EOS) and F_0 are determined to fit masses and radii of stable nuclei.

=> about 200 sets of empirical EOS+F_0

EOS parameters and liquid drop mass formula

	OI EOS	saturation parameters	liquid drop mass formula
symmetric matter	a_1, a_2, a_3	n_0, w_0, K_0	a_v (volume) => w_0 a_c (Coulomb) => n_0
Symmetry energy **neutron matter**	b_1, b_2, b_3(=1.59)	S_0, L w_{n0}, L (, K_{n0})	a_i (symmetry)
surface	F_0	(F_0)	a_s (surafce)

K_0 and L are not constrained well from nuclear masses.

=> Each OI EOS is labeled with (K_0, L).

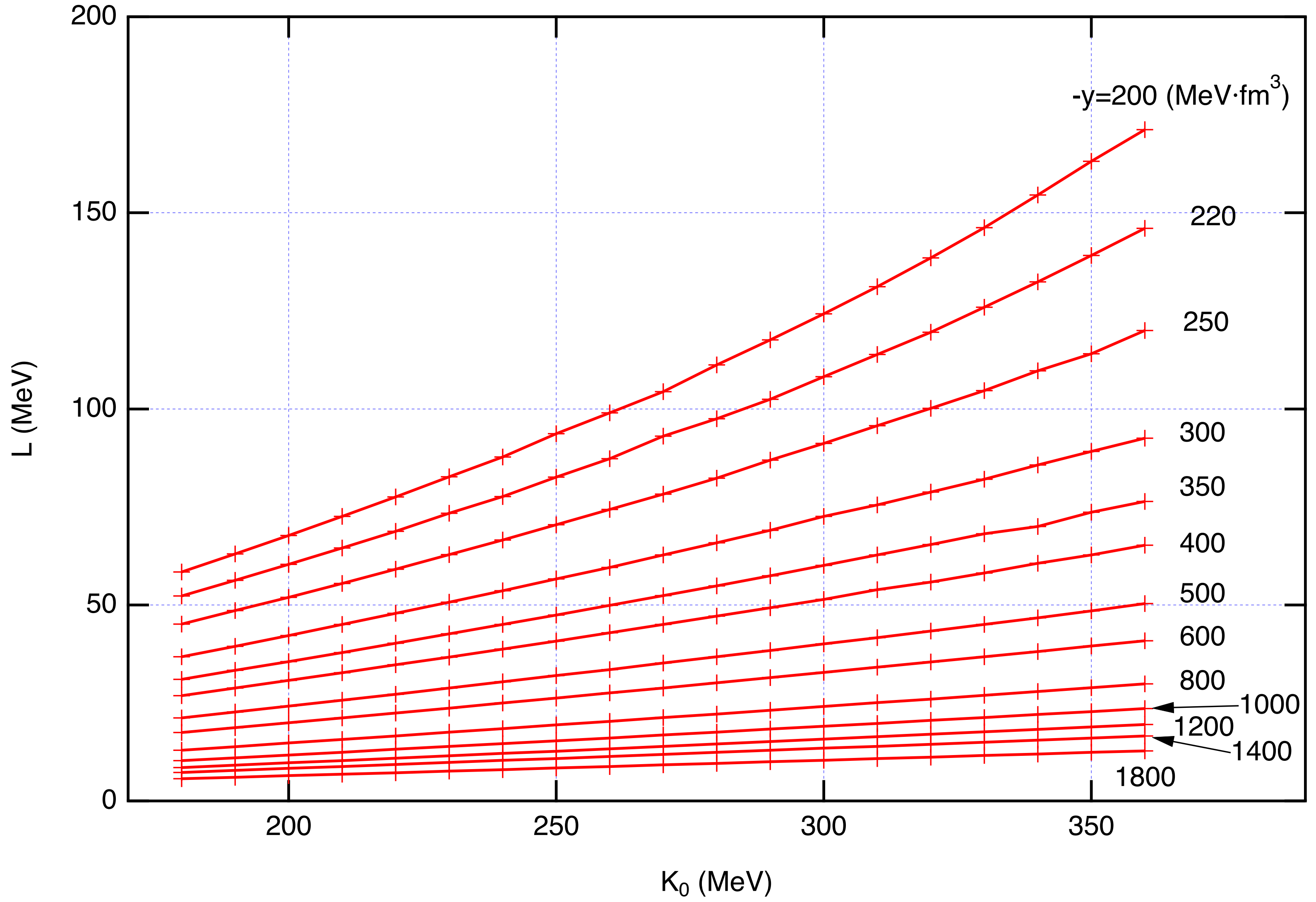
Saturation parameters of OI EOS family

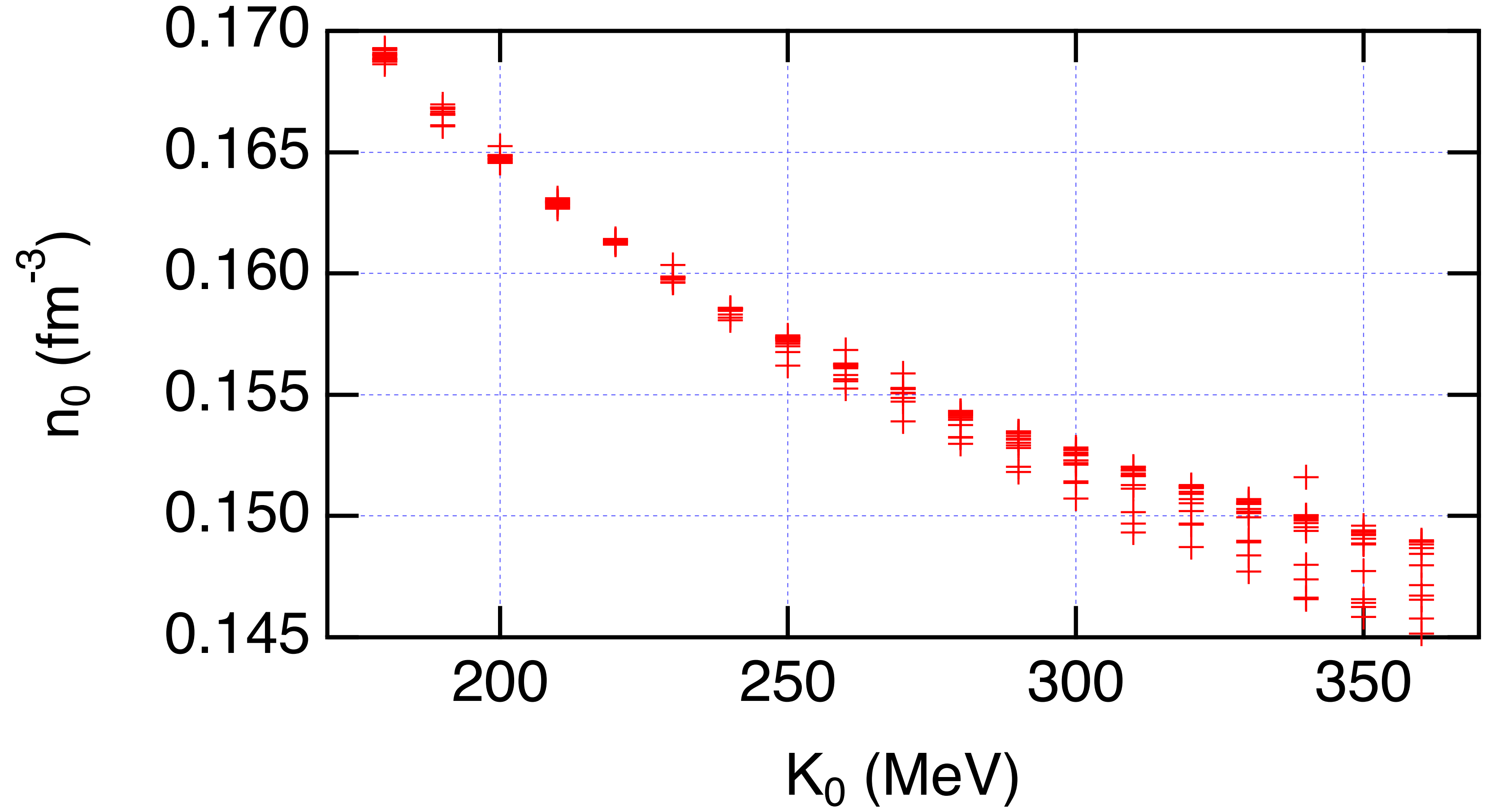
Values of n_0, w_0 and F_0 are almost constant.

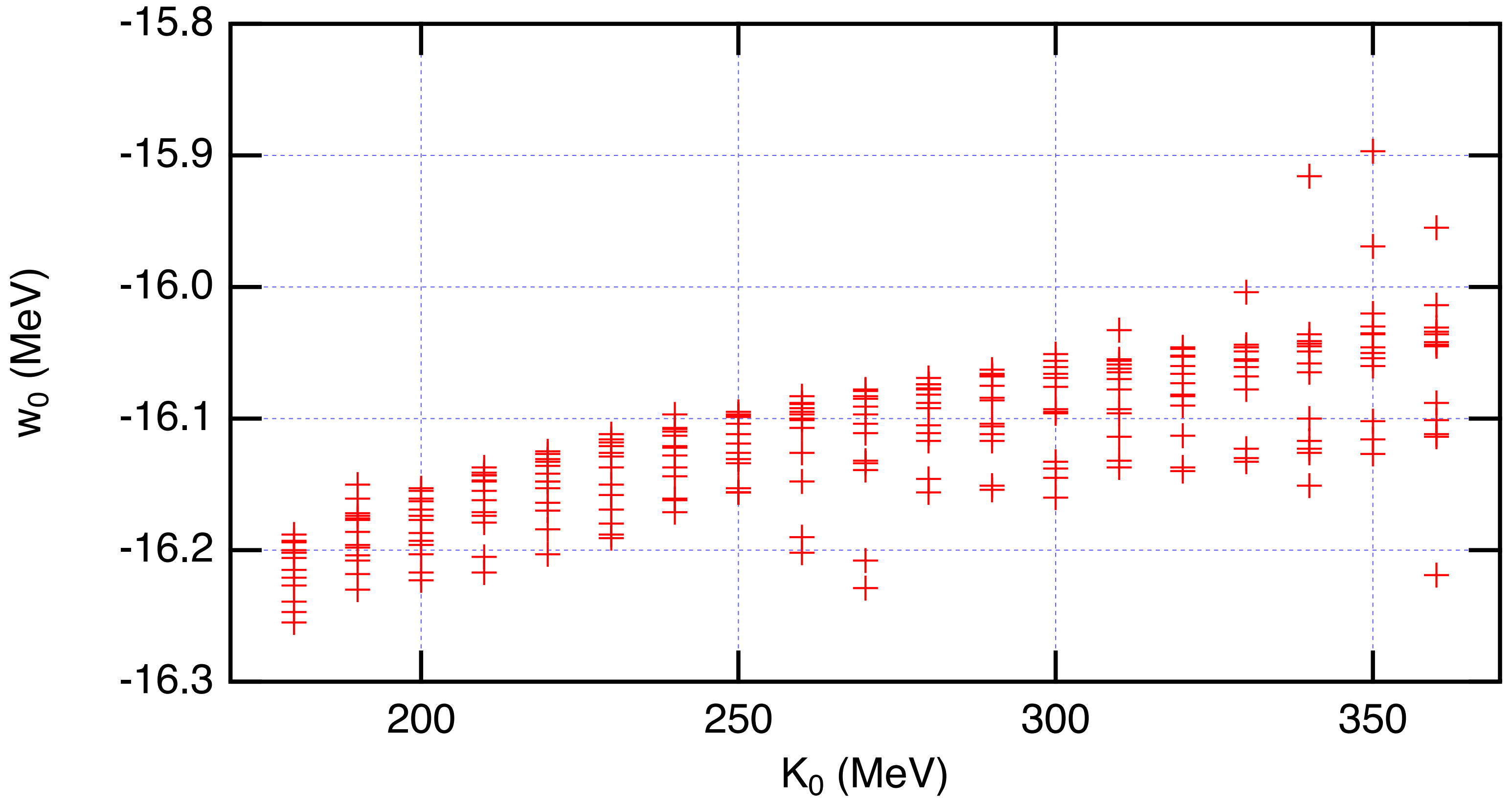
They have slight K_0 dependence

and their L dependence is much smaller.

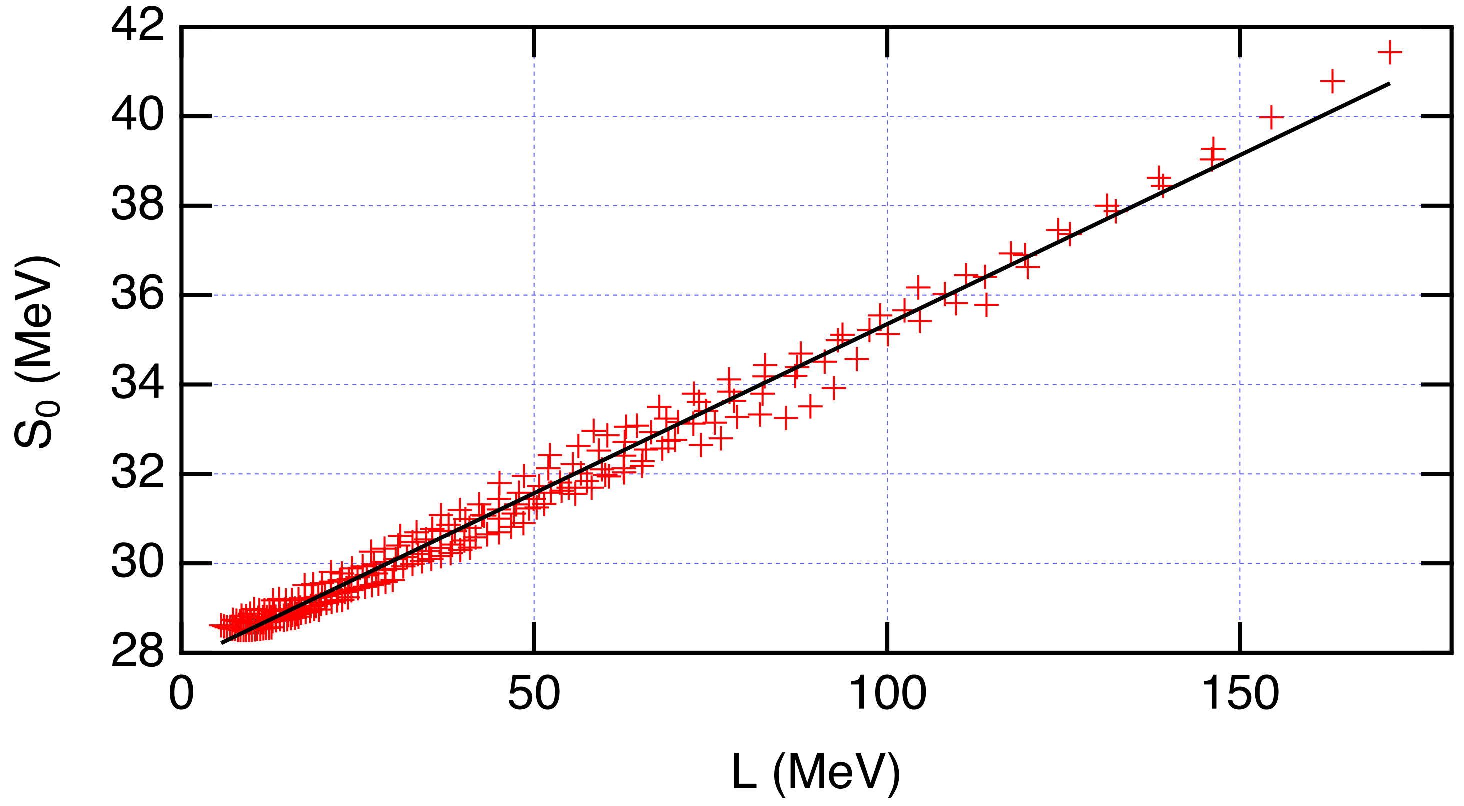
(K_0, L) values (crosses)

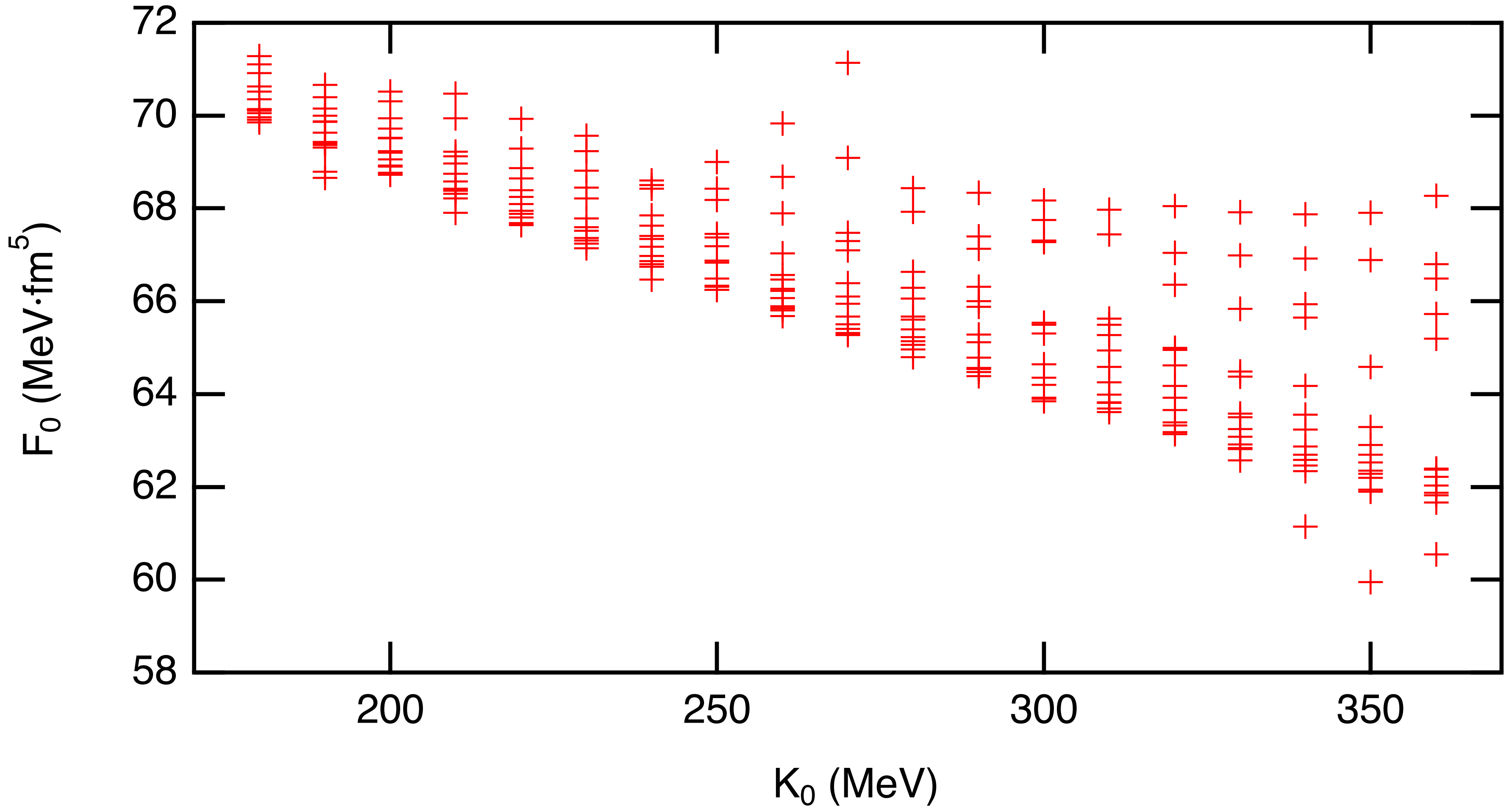






S_0 has strong correlation with L.

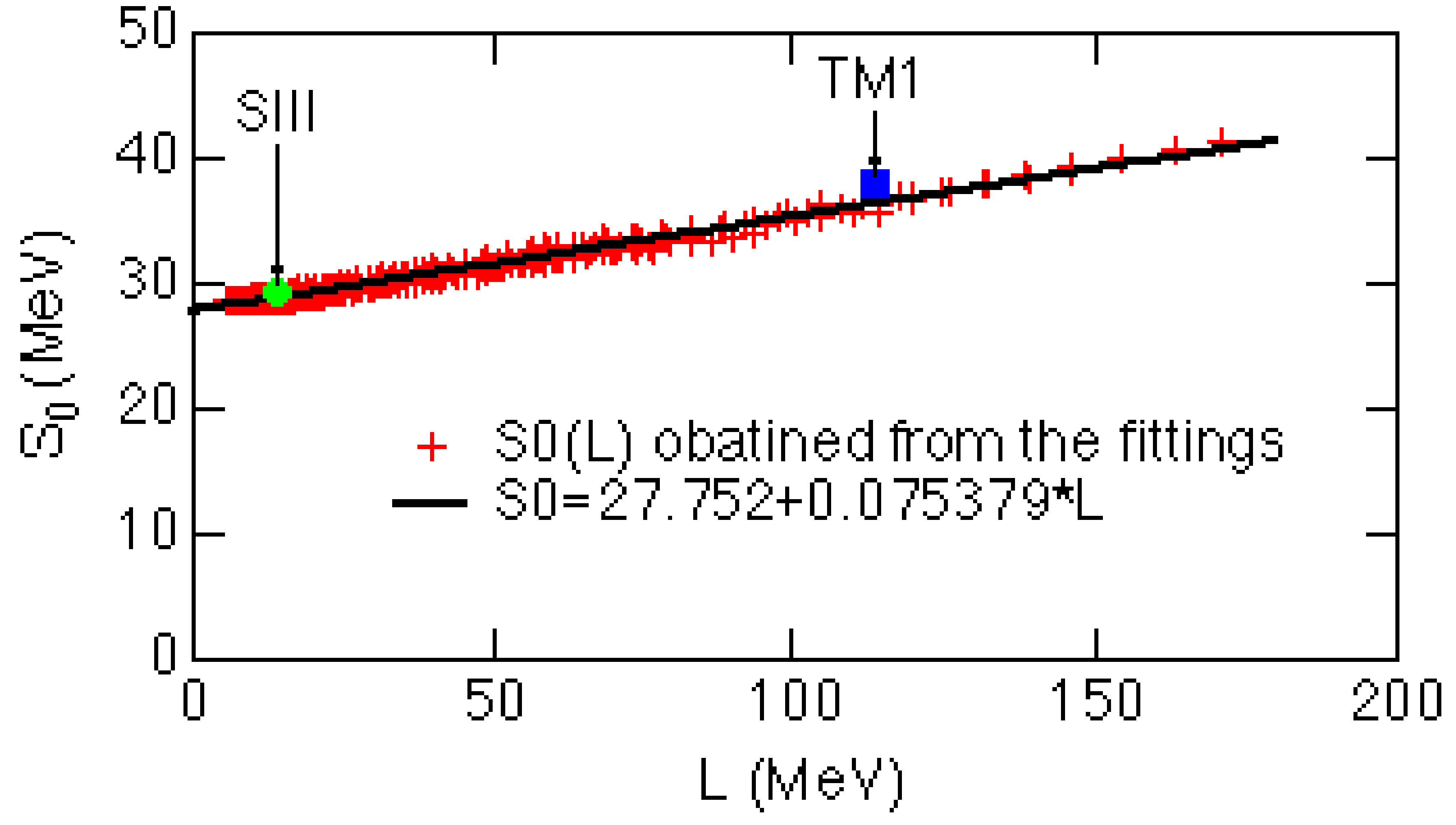


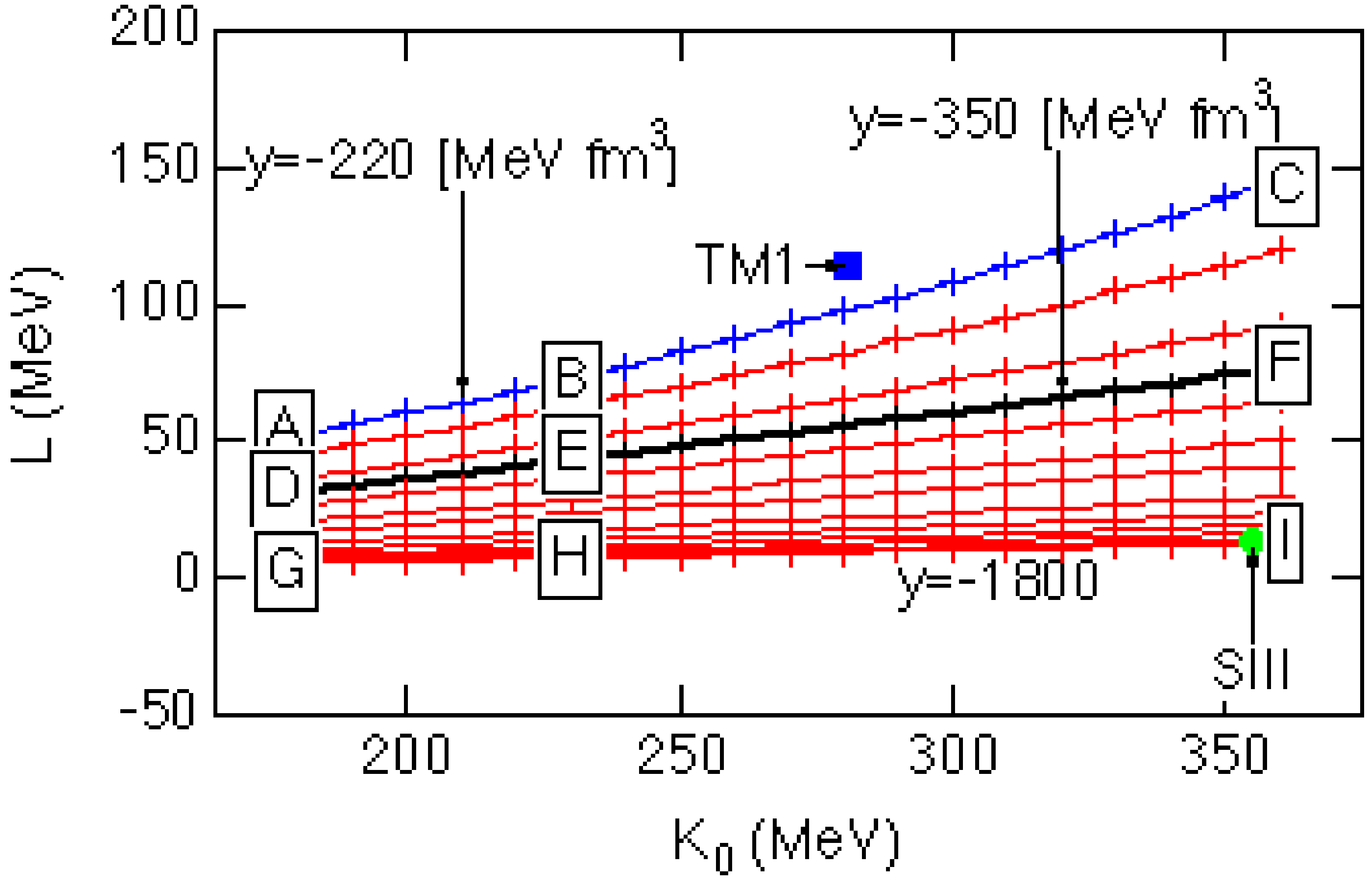


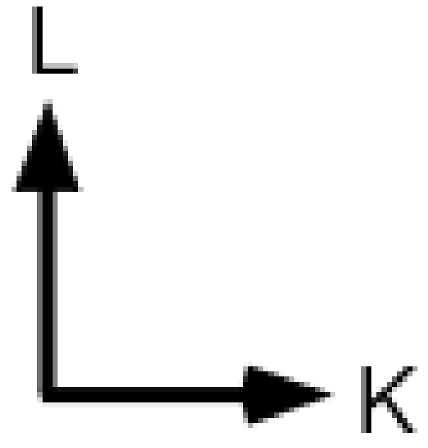
EOS parameter values obtained from stable nuclei

S_0:symmetry energy

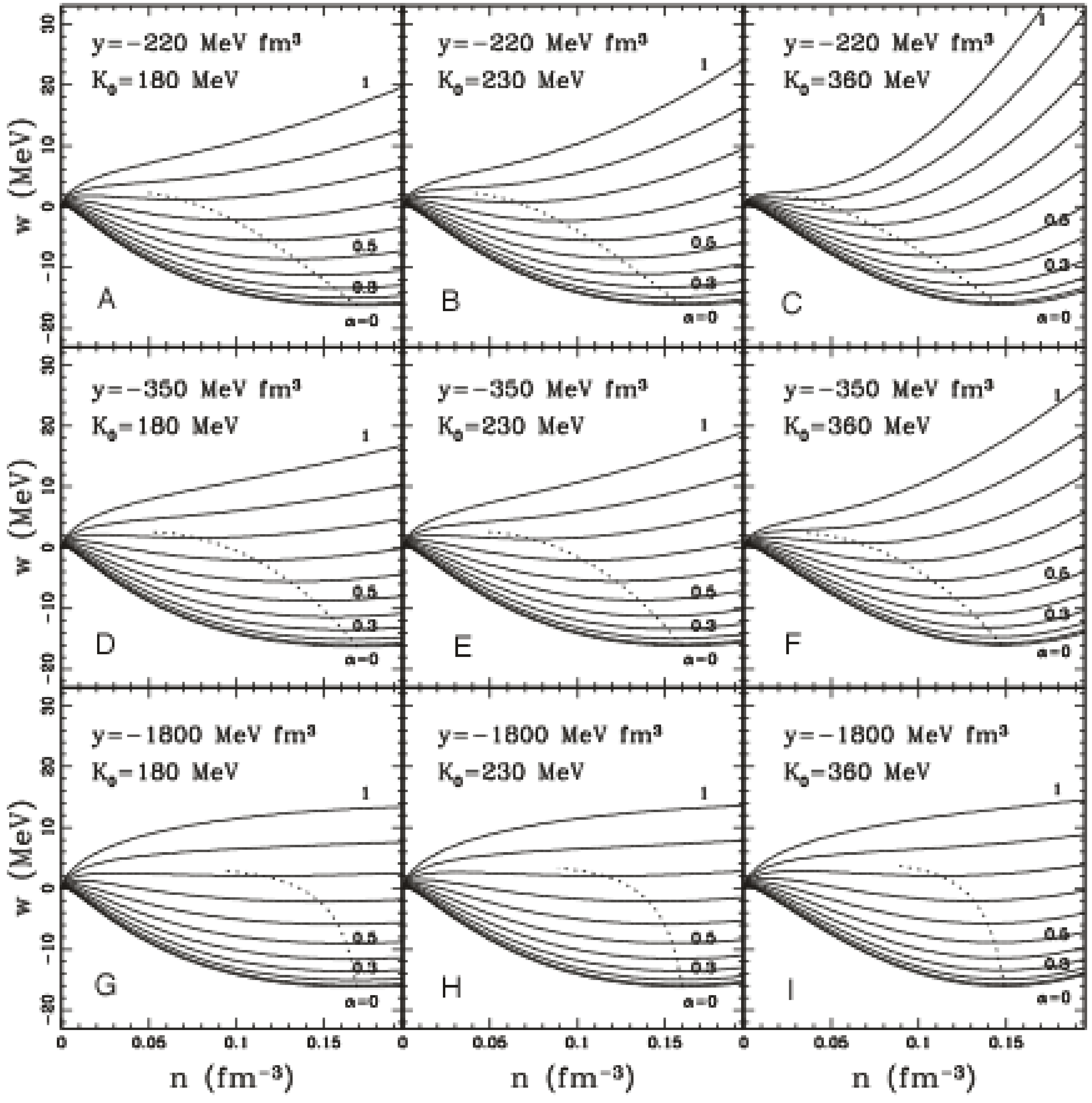
L : density symmetry coefficient





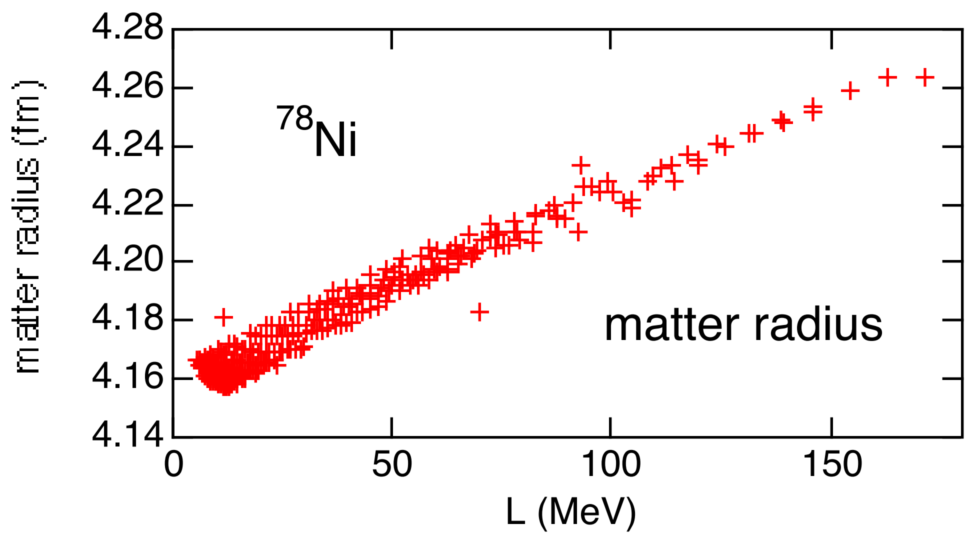


9 representative EOS A-I

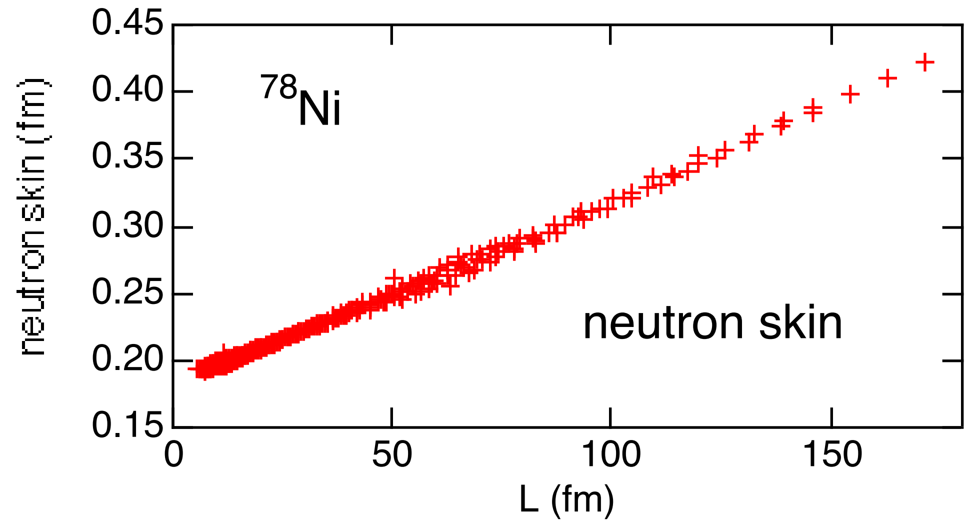


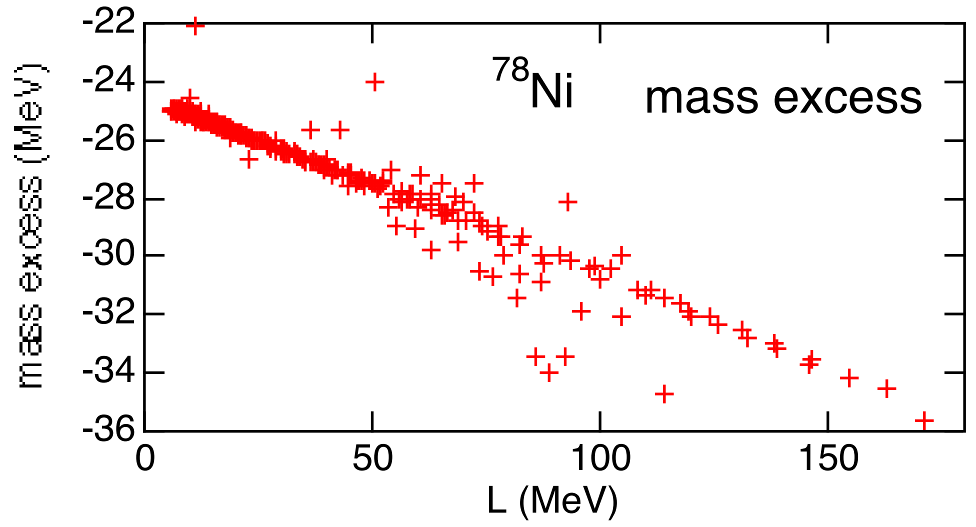
neutron rich nuclei in laboratory

mass, radius and neutron skin are sensitive to L but not to K_0.



Larger L => larger neutron radius
and neutron skin

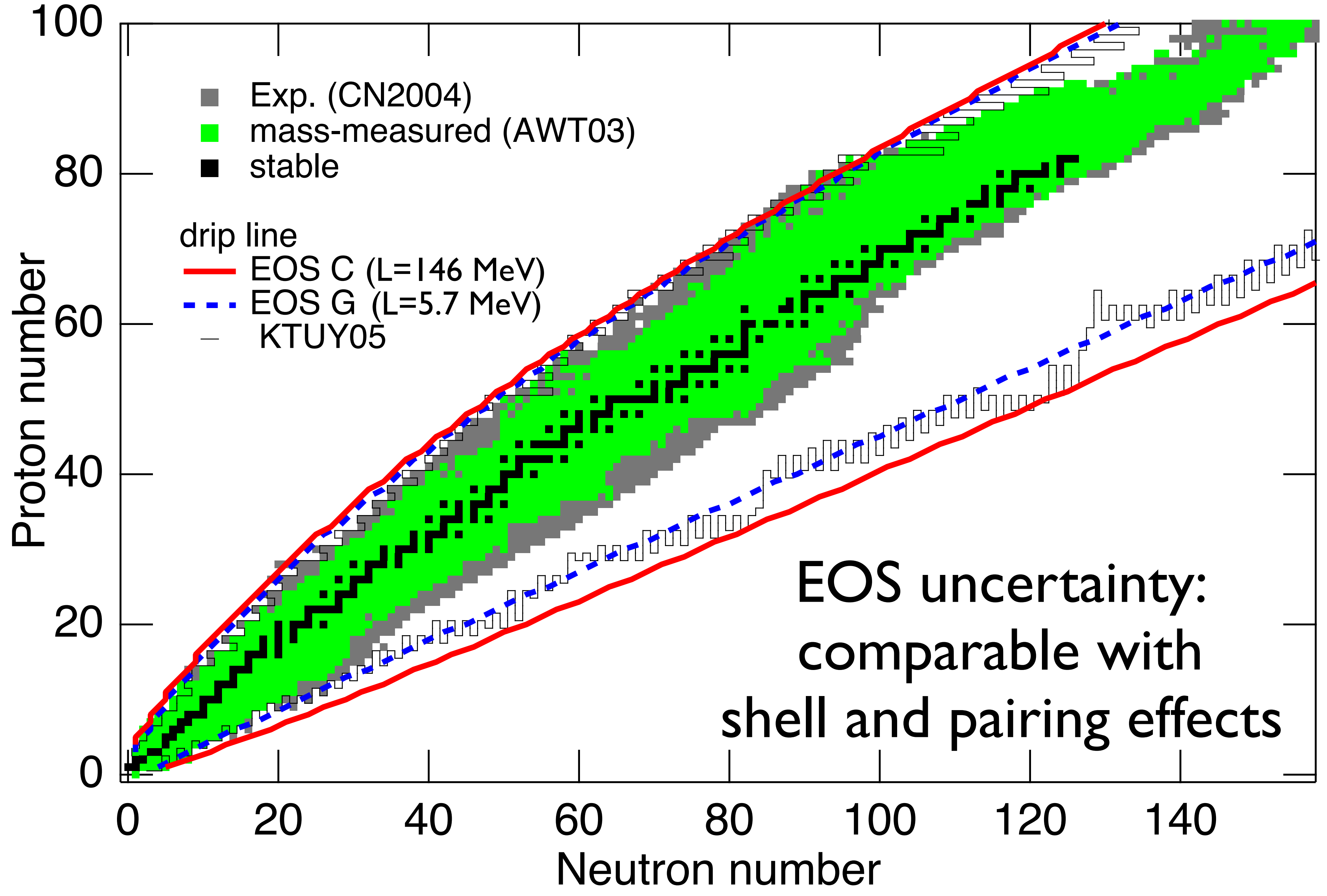




Larger L => smaller mass
not simple
(surface symmetry)

Oyamatsu and Iida, PRC81, 054302, 2010.

neutron and proton drip lines



Oyamatsu, Iida and H. Koura, PRC 82, 027301, 2010.

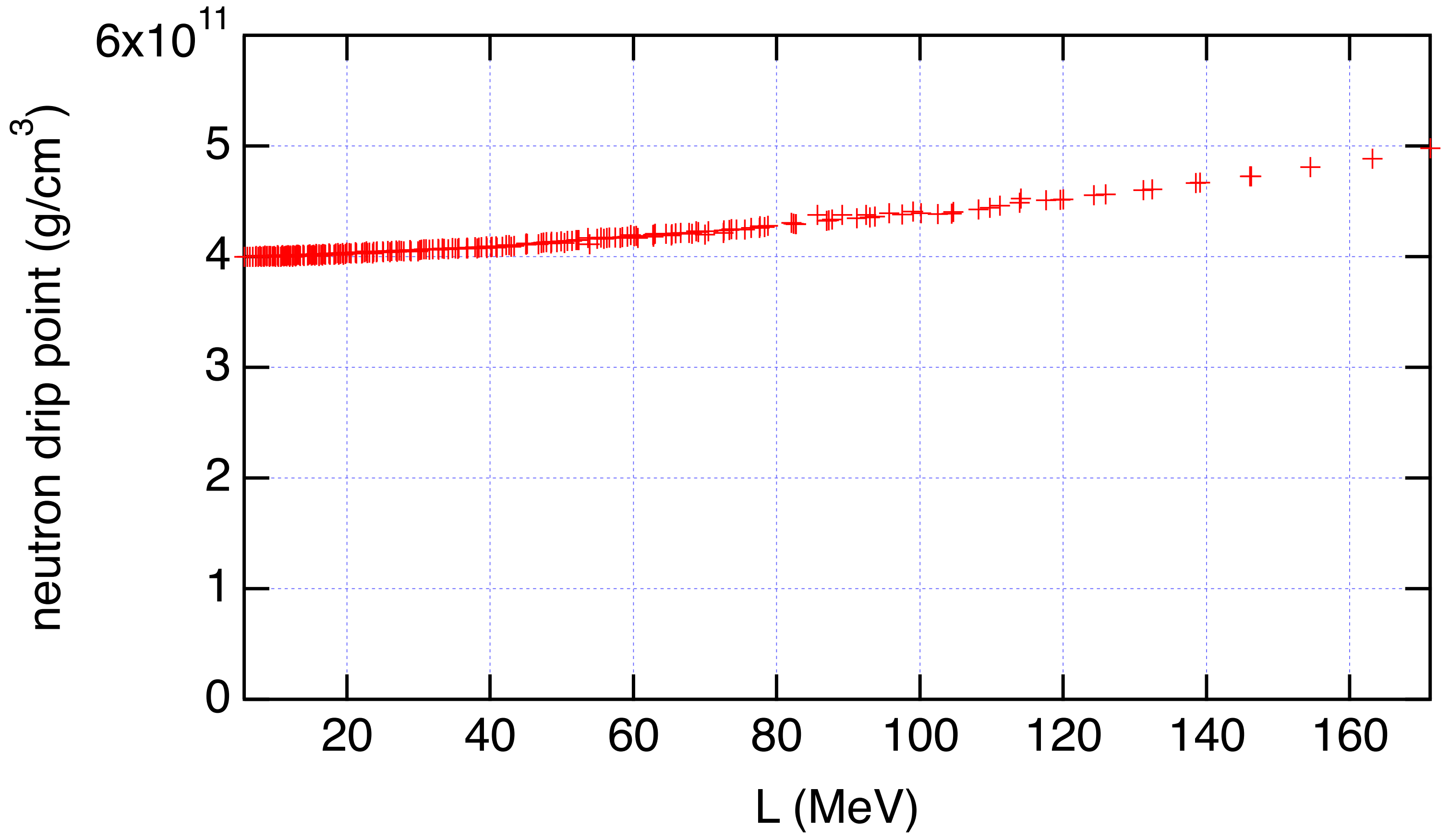
neutron star crust

nuclei in neutron-star crusts

neutron drip poit (NDP)

onset density of neutron drip

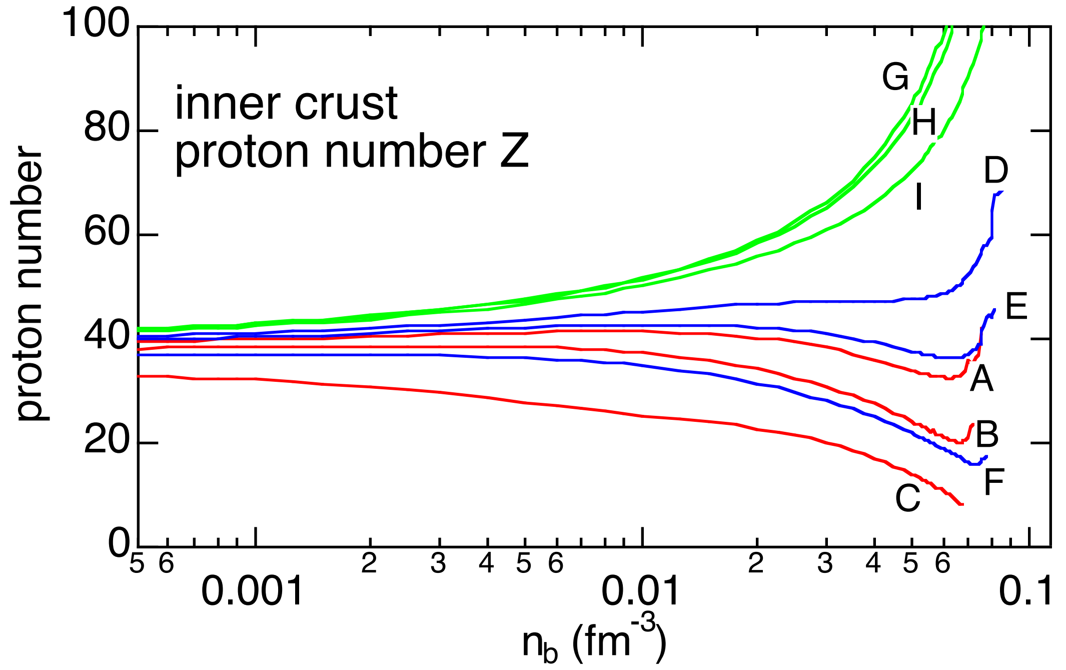
bundary of outer and inner crust

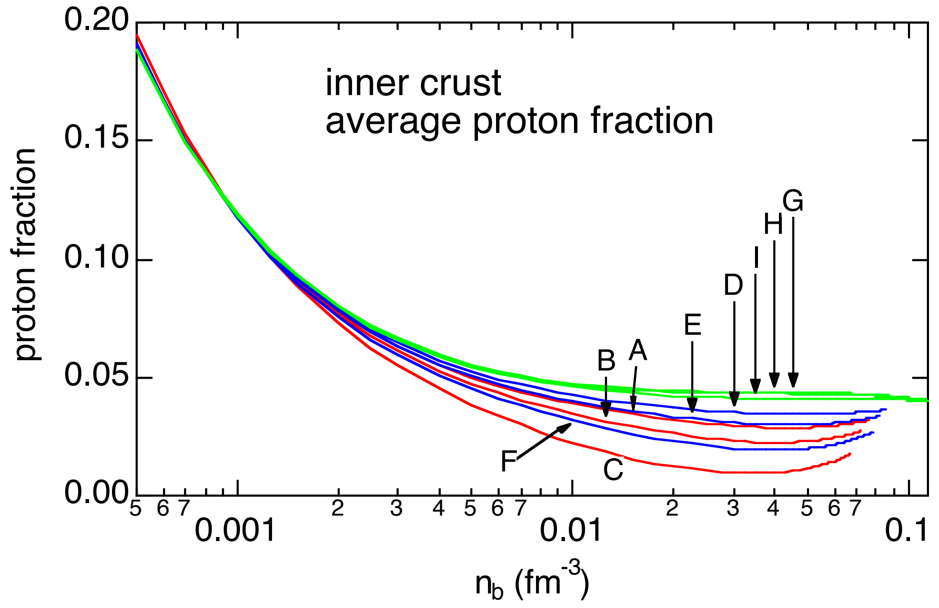


NDP slightly increases with L.

Inner crust nuclei

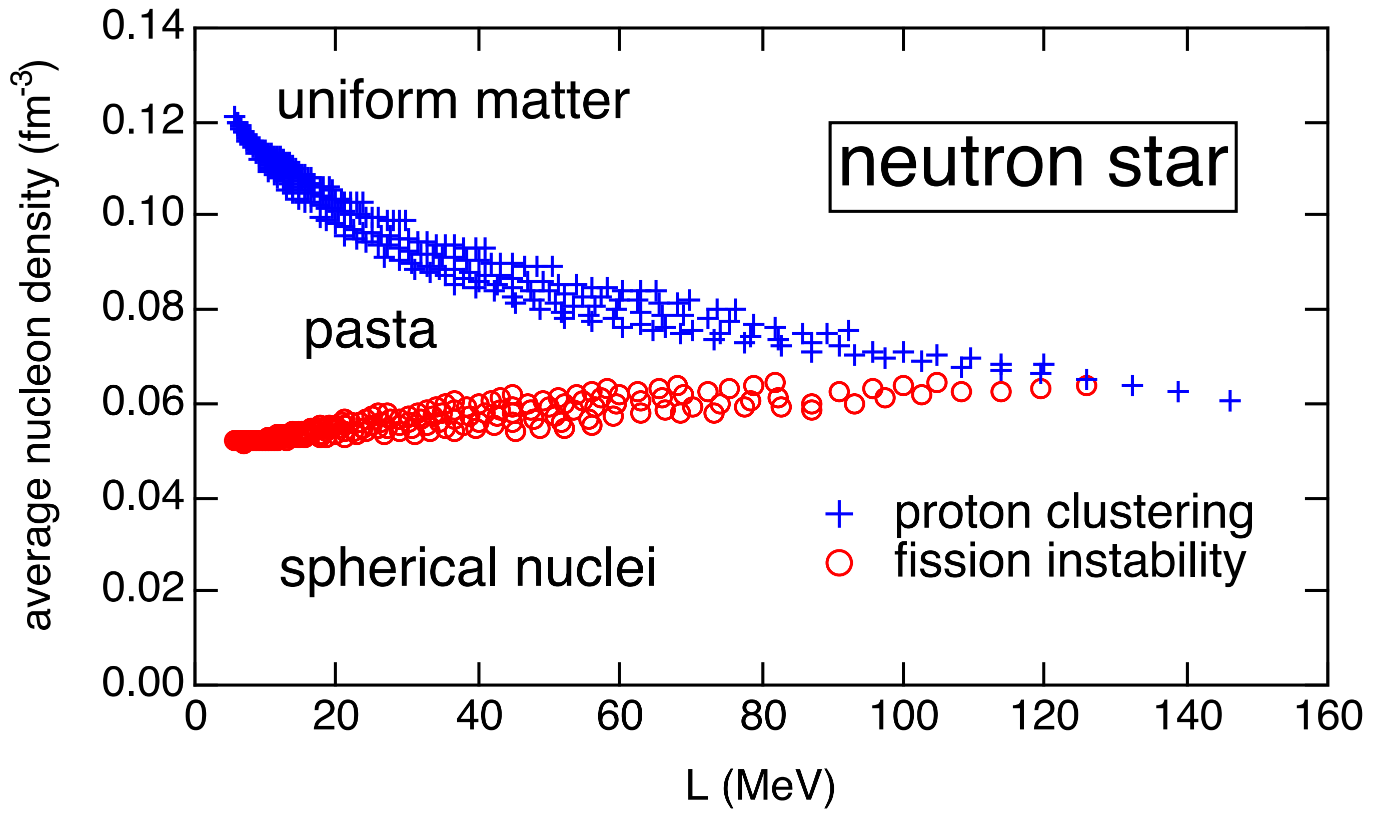
Z and Yp decrrease with L.



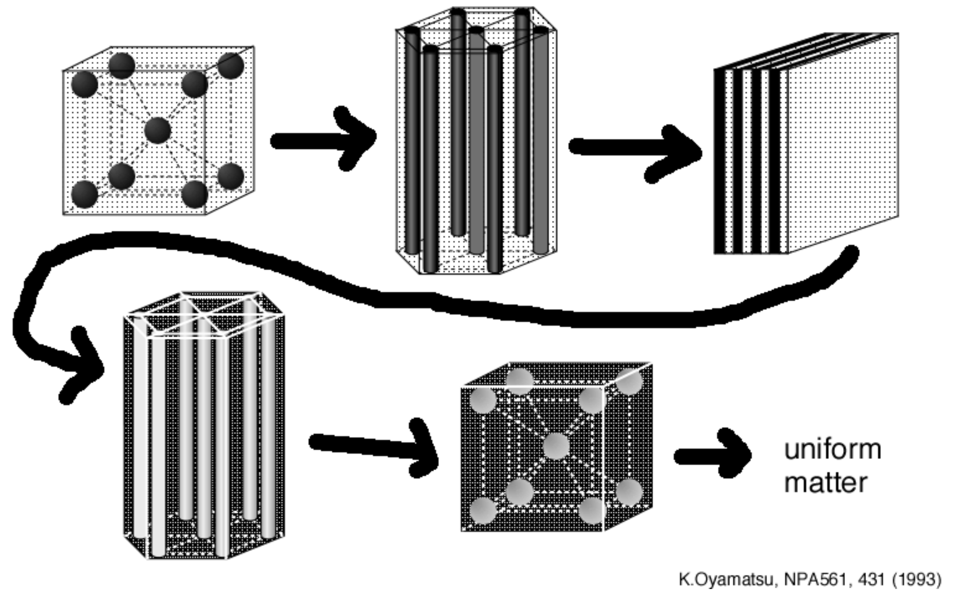


For large L, S(n) at n<n_0 is small
so that nuclei become more neutron-rich.

crust-core boundary density decrease with L.



spherical nuclei and pasta nuclei

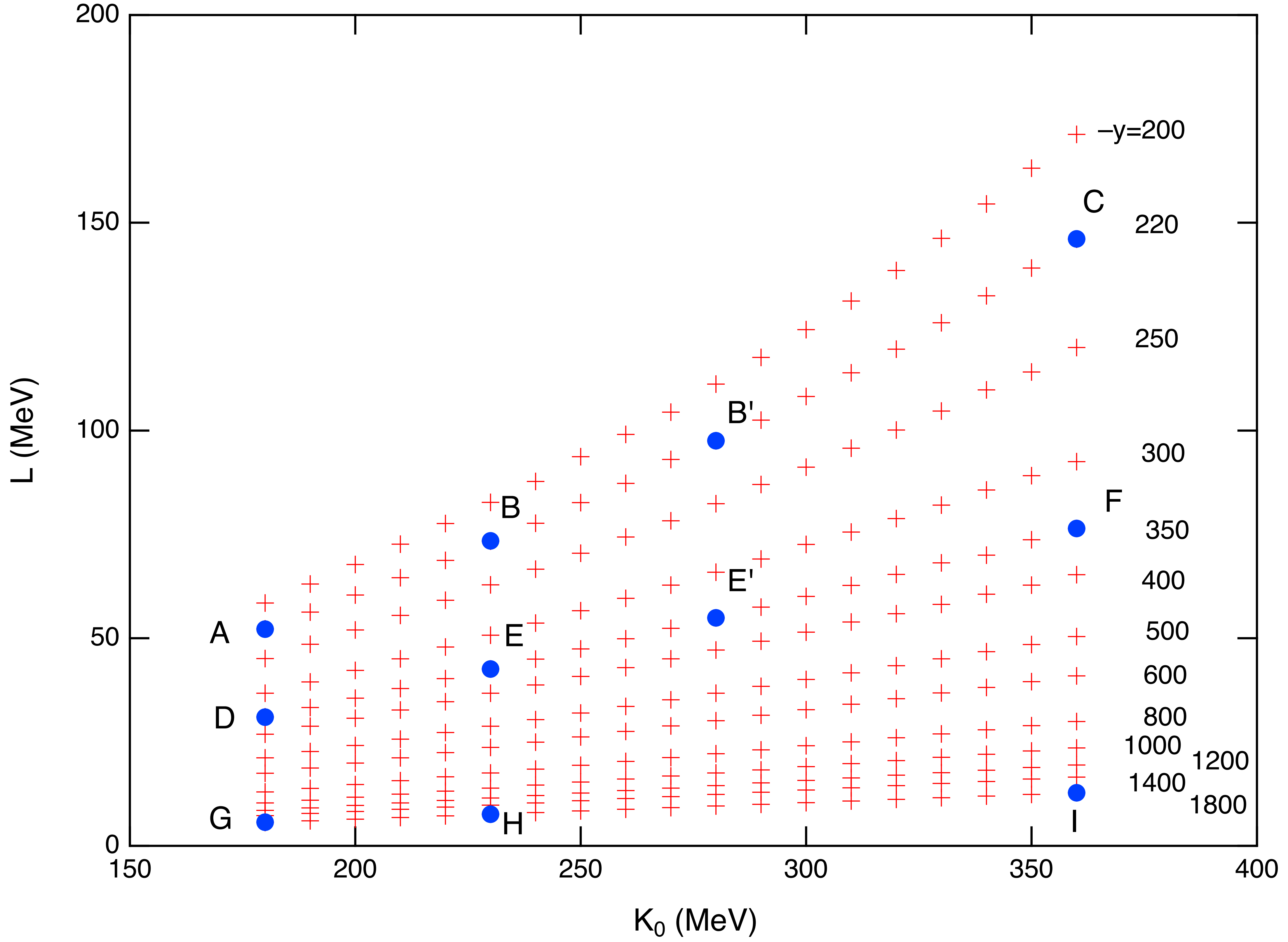


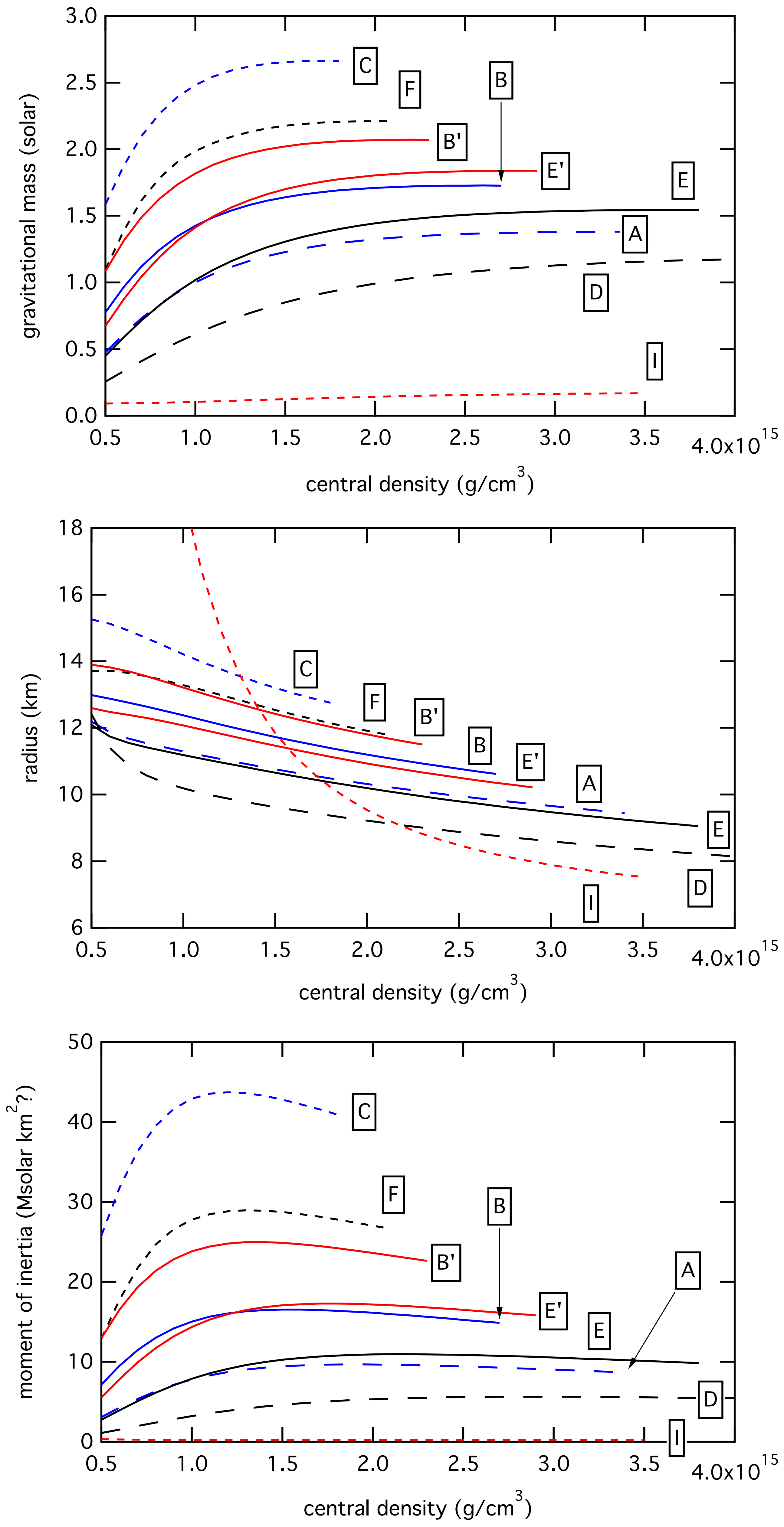
Existence of pasta nuclei depends on the EOS.

Neutron star mass

Neutron Star with typical EOS's

(K_0, L) and y values for typical EOS's

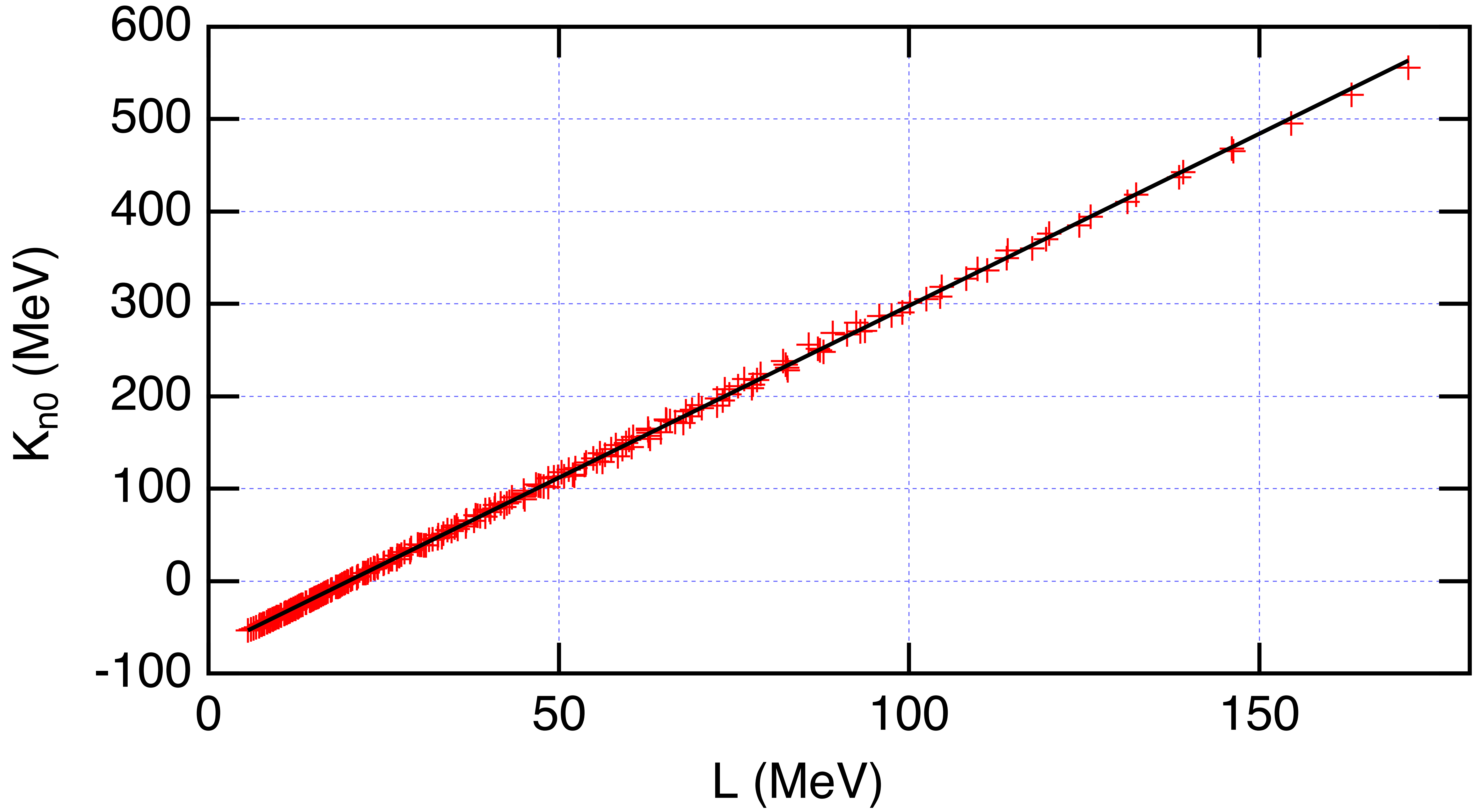




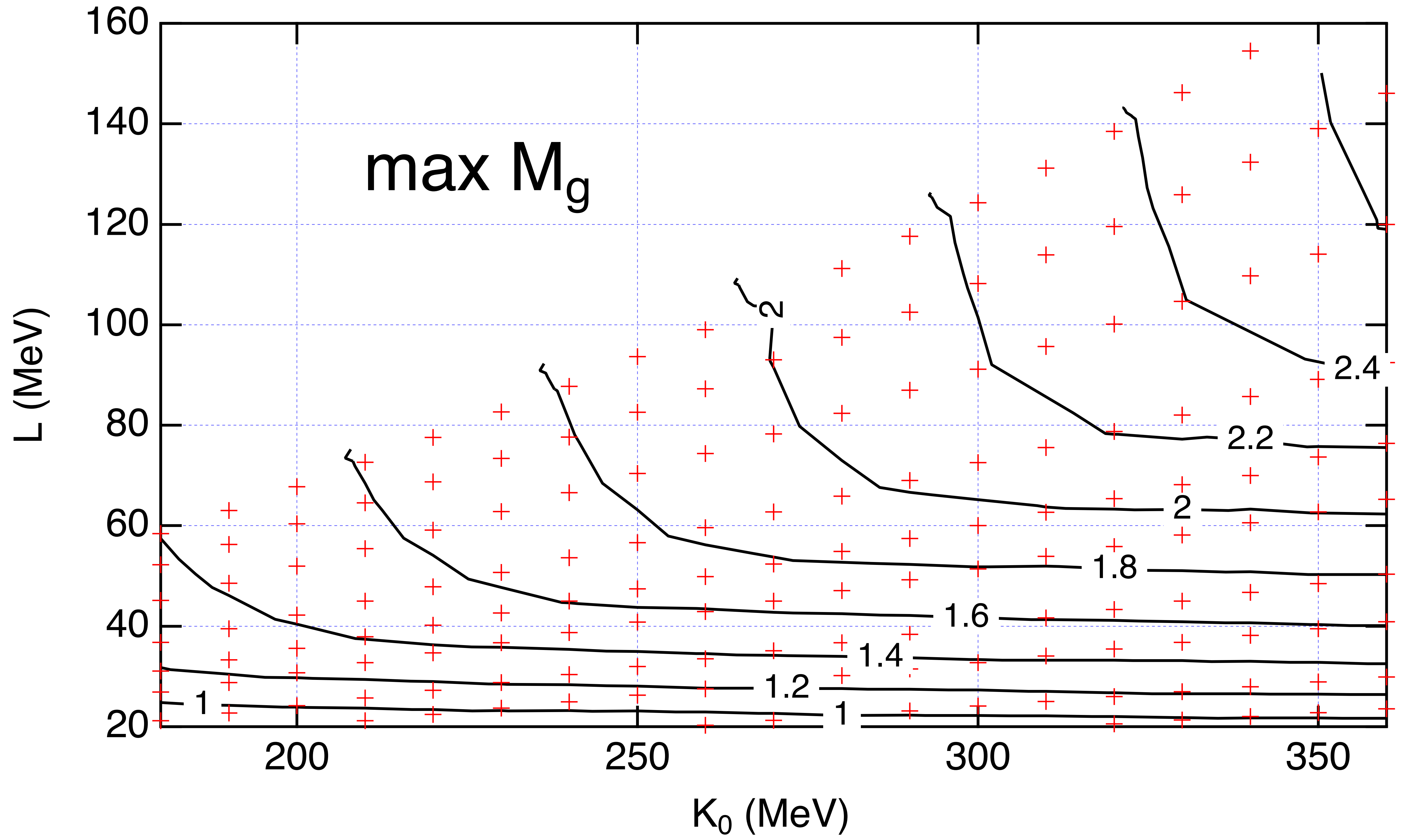
The neutron star mass increases with L, and also with K_0.

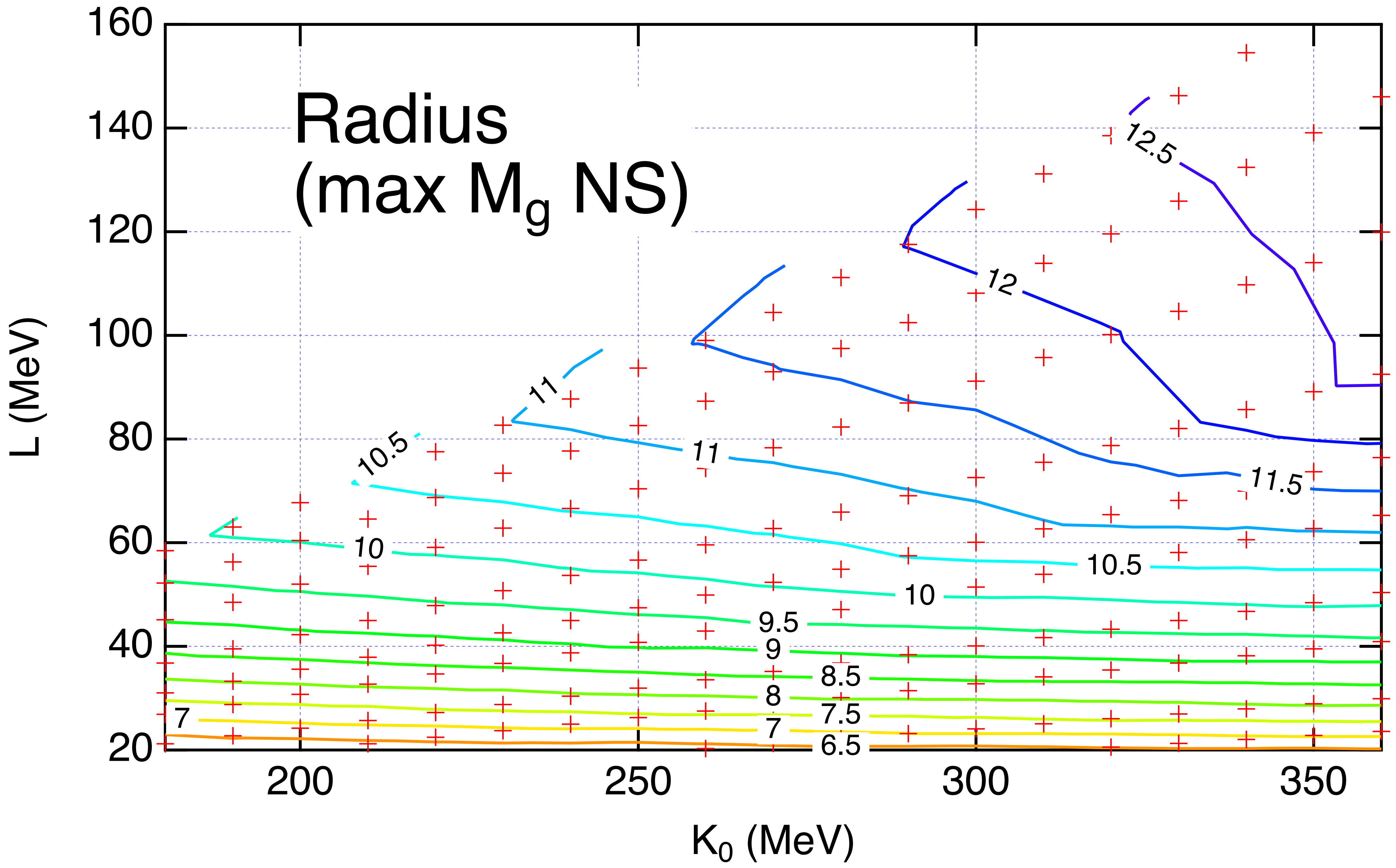
EOS's G and H (smallest L) can't support a neutron star.

Incompressibility of neutron matter $K_{n0} > 0$, then L> 20 MeV.



Mass and radius of max Mg neutron Star with OI EOS family





L > 20 MeV from K_{n0} > 0.

EOS's with L > 40 MeV can support 1.4 solar mass star.

Summary

- OI EOS family describes the structure of neutron rich nuclei and neutron stars as function of (K_0, L) related to nuclear compressibility.
- The structure of neutron rich nuclei and neutron star crusts are mainly dominated by L.
  - This is the result of nuclear saturation properties.
- The neutron star mass and radius increase with L and also with K_0.*
  - This depends on the behavior of high density EOS (b_3=1.59).

* For low mass neutron stars,
see Sotani, Iida, Oyamatsu and Ohnishi, Prog. Theor. Exp. Phys. (2014) 051E01.

NEXT : High Density => Oyamatsu-Sotani-Iida EOS family

- Empirical description of high density EOS using different value for 3 body energy coefficient b_3 in the potential energy density.

$$v_n(n) = b_1 n^2 + \frac{b_2 n^3}{1 + b_3 n}$$

- Each EOS is labeled with (K_0, L, b_3).
- Values of saturation parameters are almost the same as OI EOS's (b_3=1.59).
    - L > 20 MeV from K_{n0}>0 independently of b_3.
- The choice of b_3 value does not affect nuclei and crusts very much but will alter core structure.