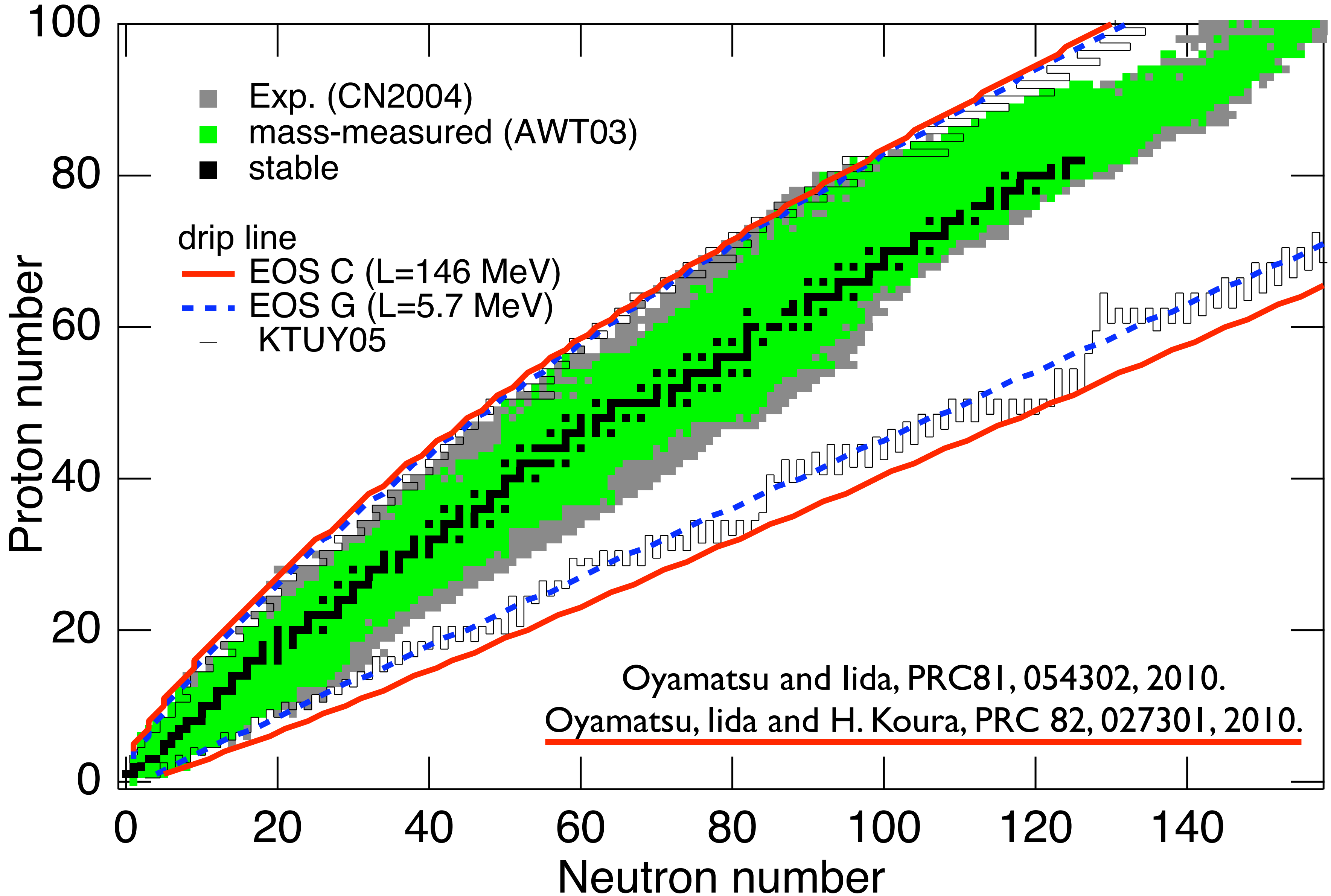
核物質の状態方程式と中性子過剰核

親松和浩（愛知淑徳大），飯田圭（高知大理），小浦寛之（原子力機構）



Oyamatsu and Iida, PRC81, 054302, 2010.

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

TM1とSIIIの予測が著しく異なる原因は ?

1998年

- neutron drip line
  - TM1は安定線から遠く、SIIIは近い
- neutron skin
  - TM1は大きく、SIIIは小さい
  - S_n-S_pと相関
- EOSの違いである
  - Oyamatsu, Tanihata, Sugahara, Sumiyoshi, Toki, NPA634(1998)

Collaborator Meeting

Kurotama

radius

σ_R

Kohama

(σ_R :Kurotama)

Koura

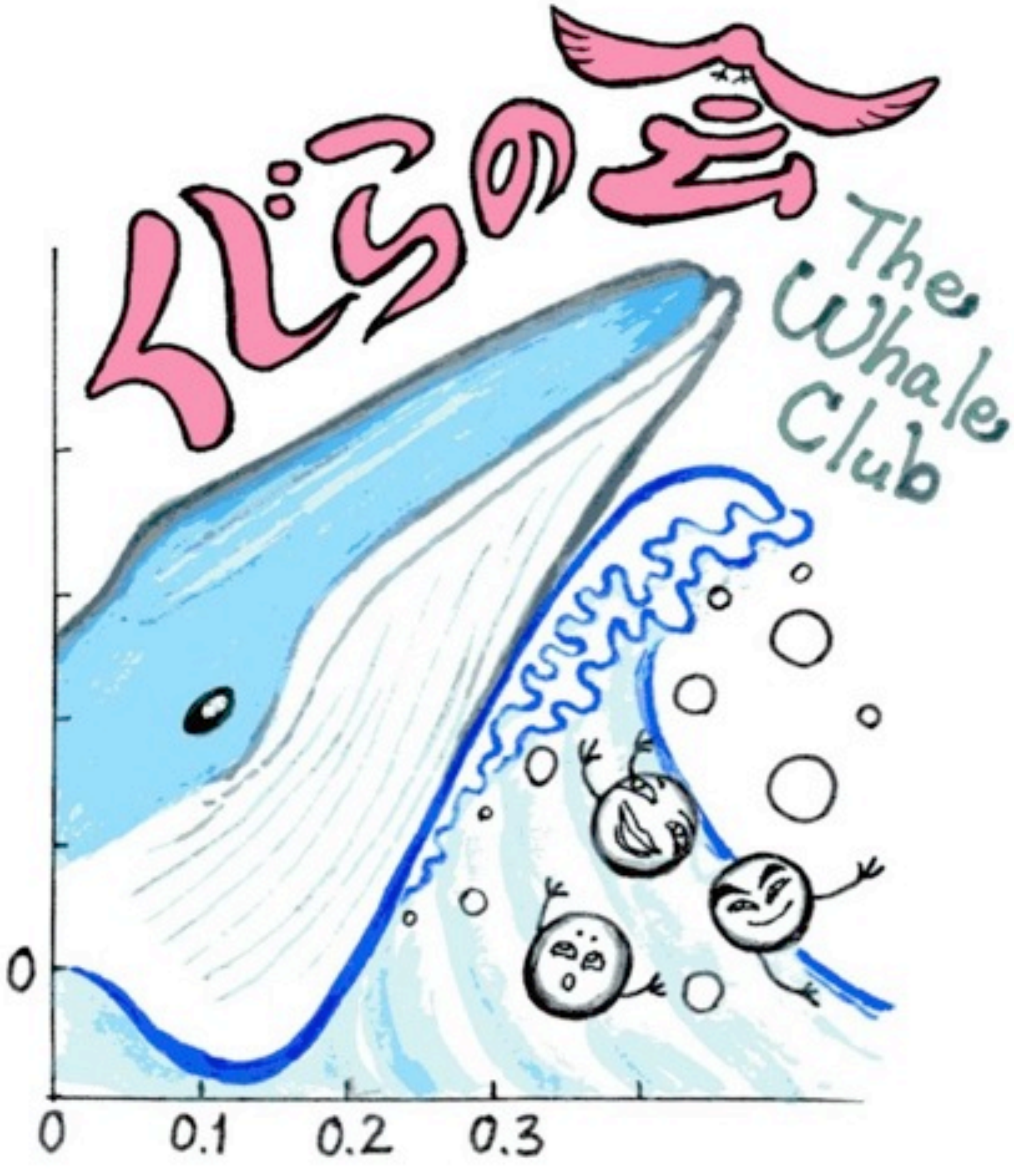
(mass formula)

Iida Oyamatsu

This talk

mass

We are focusing on the EOS



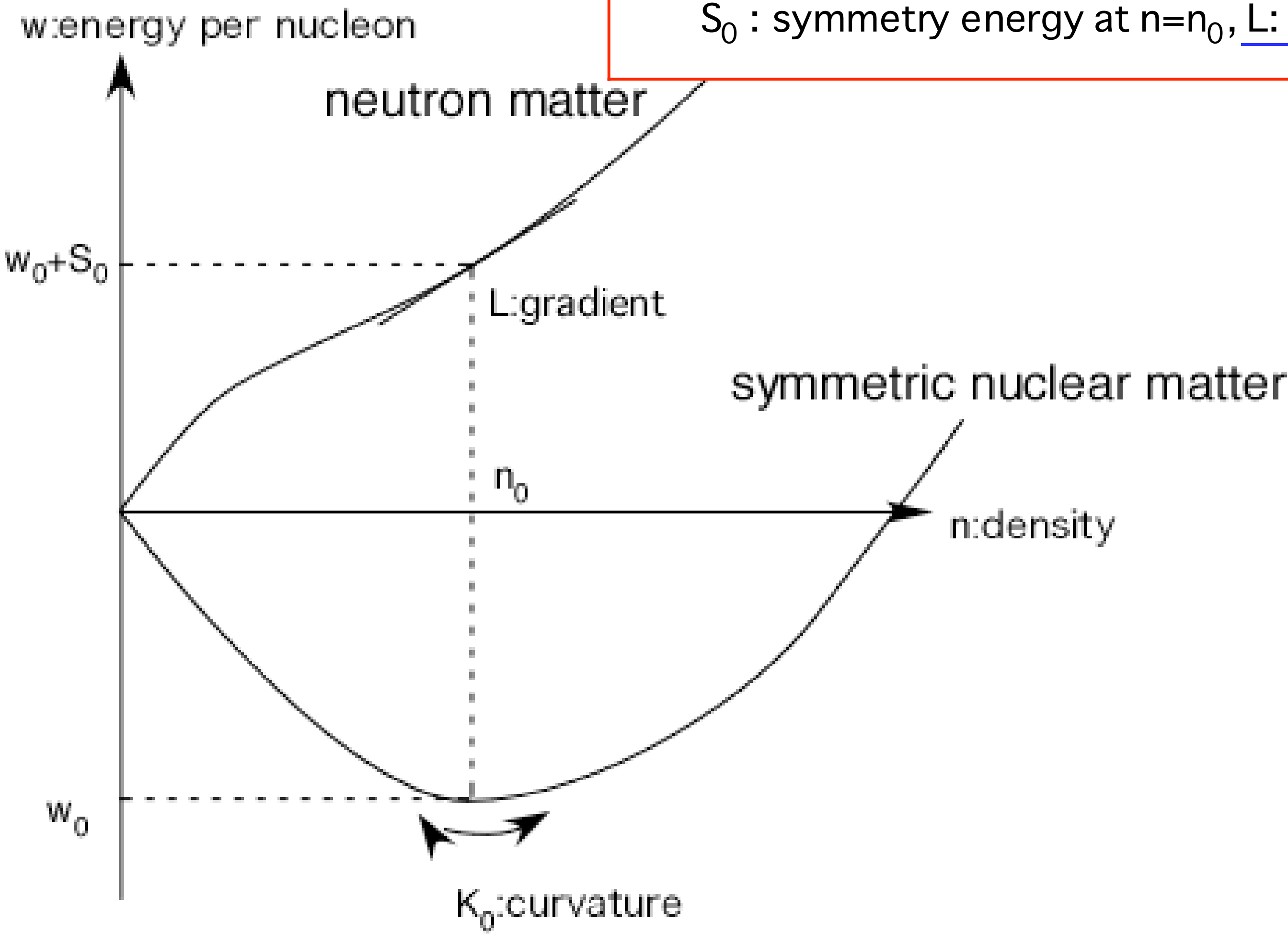
Which EOS parameter dominates macroscopic properties of neutron-rich nuclei in laboratory and in neutron-star crusts?

Energy per nucleon of nearly symmetric nuclear matter

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

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

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



$$L = 3n_0 \left.\frac{dS(n)}{dn}\right|_{n=n_0}$$

$$S_0 = S(n_0)$$

Approaches to obtain the EOS of (uniform) nuclear matter

approach	starts from	ingredients	Theory/Model
empirical	parametrized EOS	nuclear mass, size, ...	Liquid-Drop Model Droplet Model Thomas-Fermi Theory ......
Phenomenological	effective NN int. (Hamiltonian, Lagrangean)	nuclear mass, size, ...	Skyrme HF RMF AMD ....
microscopic	bare NN int. (AV18, Bonn, Paris,...)	NN scattering, ...	Variational Calc. DBHF ....

Outline

We focus on macroscopic nuclear properties and adopt a macroscopic nuclear model.

1. From masses and radii of stable nuclei, we generate family of EOS and examine allowed regions of EOS parameter values.

2. We calculate neutron-rich nuclei in laboratories and identify key EOS parameter.

   *** mass (2p, 2n separation energies), radius (matter, neutron skin) ***

   *** neutron and proton drip line ***

   main topic

3. We calculate nuclei in neutron-star crusts and identify key EOS parameter.

   *** proton number and ratio ***
   *** core-crust boundary density ***
   *** existence of pasta nuclei ***

Step 1

Generate all empirically allowed EOS's systematically

K. Oyamatsu and K. Iida, Prog. Theor. Phys. 109, 631 (2003).

Adopted macroscopic model

Energy per cell (or Energy of a nucleus)

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

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 (The same method as Shen EOS)

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)

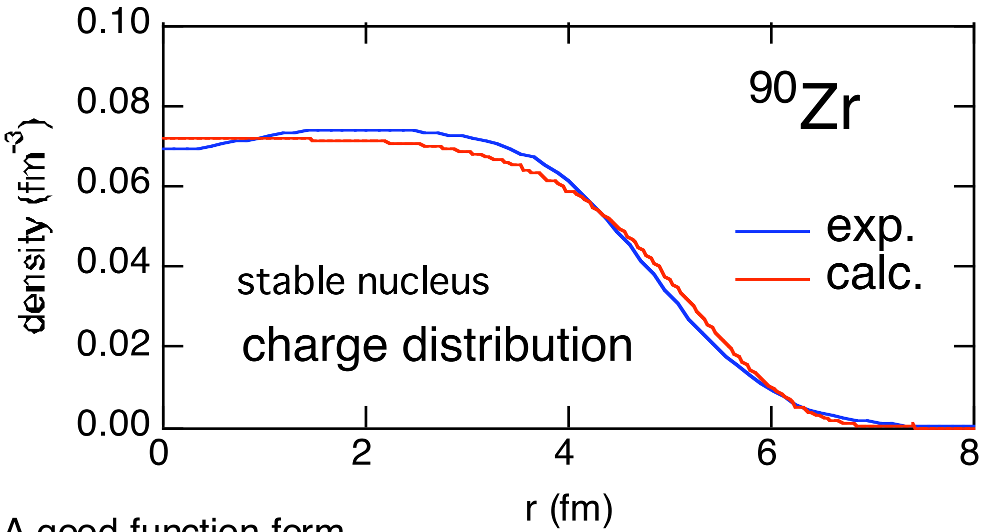
$$n_i(r) = \begin{cases} \left(n_i^{in} - n_i^{out}\right)\left[1 - \left(\frac{r}{R_i}\right)^{t_i}\right]^3 + n_i^{out} & r < R_i \\ n_i^{out} & r < R_i \end{cases}$$

R_n (R_p) : neutron (proton) radius parameter

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

n_i^{in} : central desnity

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.

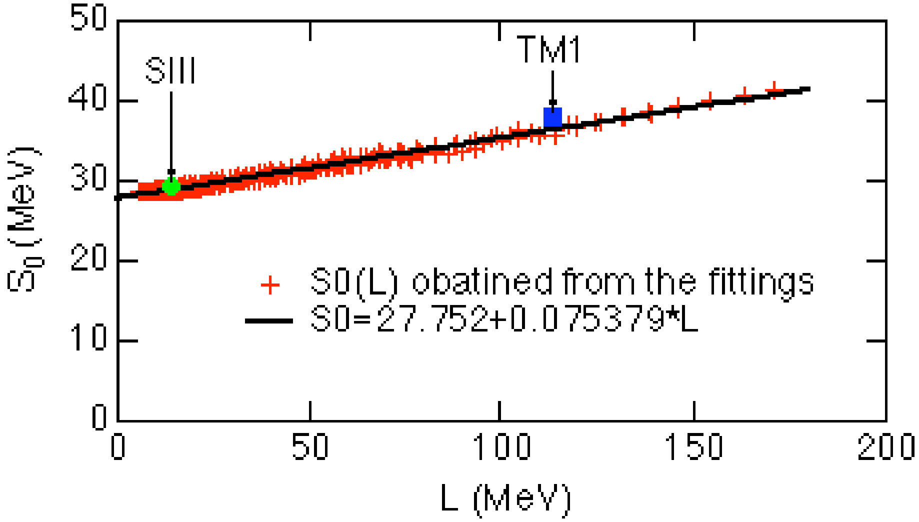
The values of parameters $a_1 \sim b_3$(EOS) and F_0 are determined to fit masses and radii of stable nuclei.

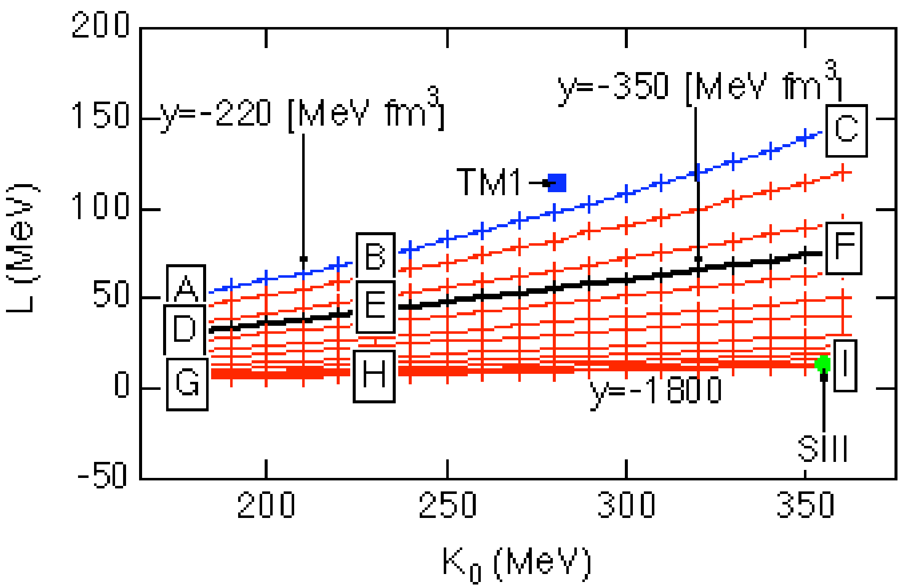
=> about 200 sets of empirical EOS+F_0

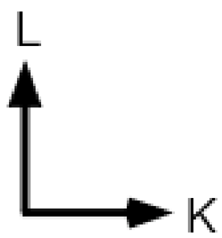
EOS parameter values obtained from stable nuclei

S_0:symmetry energy

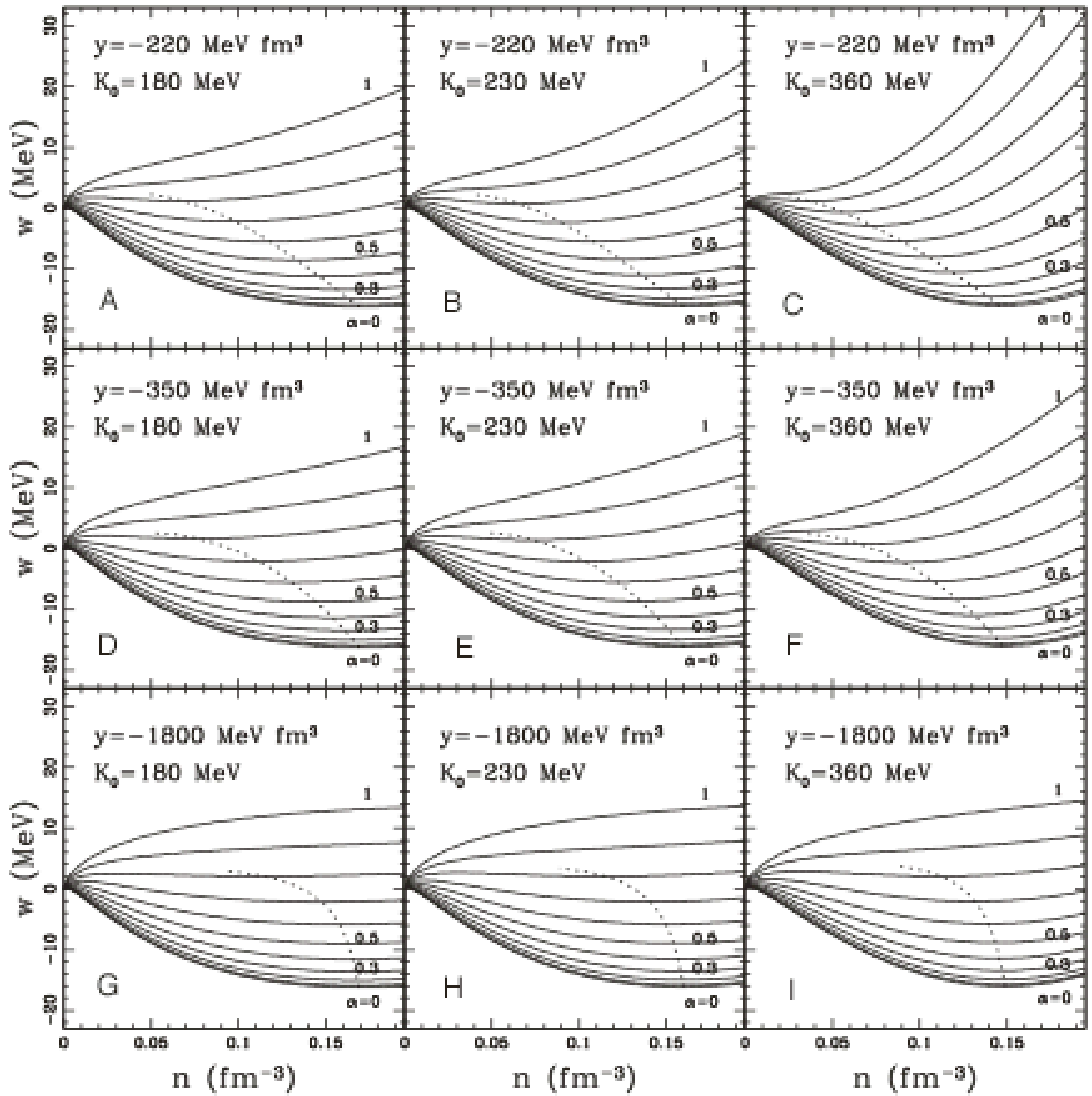
L : density symmetry coefficient







9 representative EOS A-I



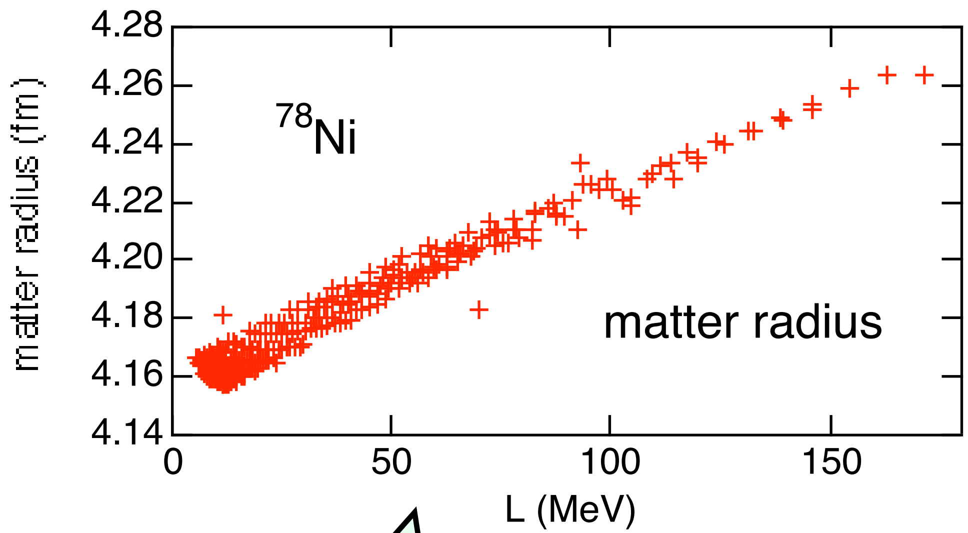
Step 2

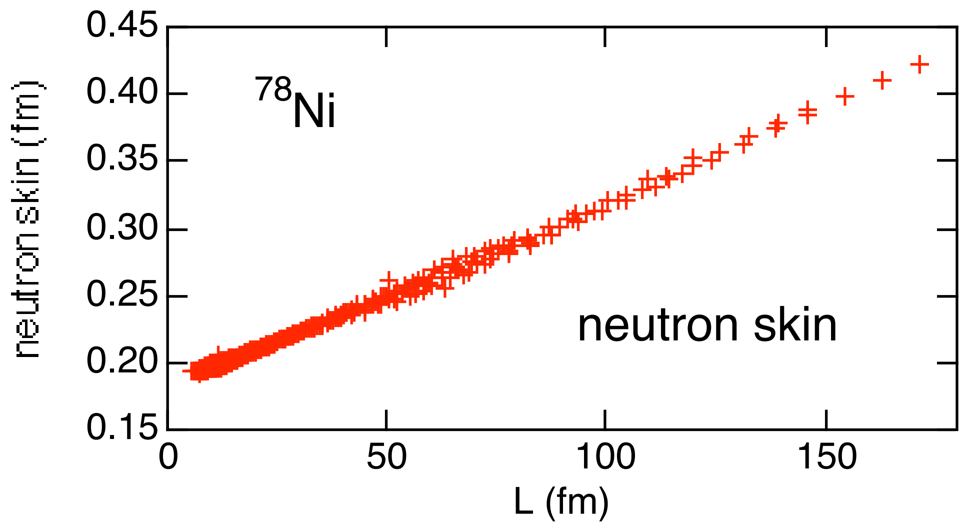
Calculate neutron-rich nuclei in labs with the 200 EOS's

K. Oyamatsu and K. Iida, Prog. Theor. Phys. 109, 631 (2003).

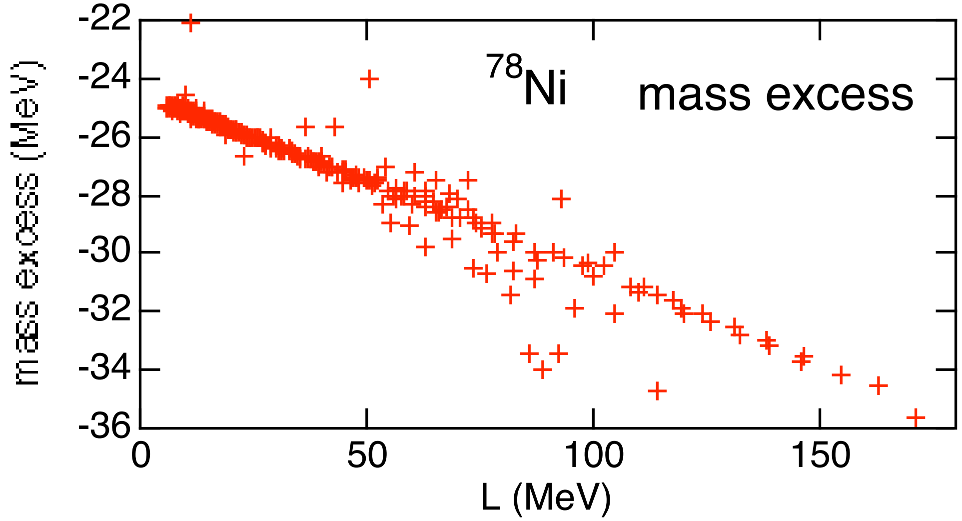
Oyamatsu and Iida, PRC81, 054302, 2010.

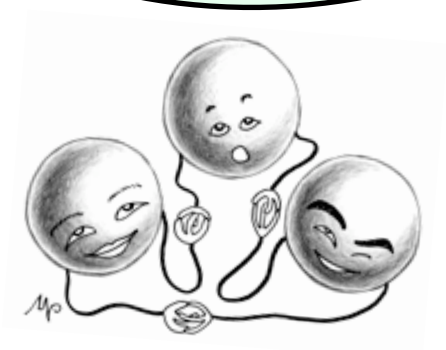
The mass, radius and neutron skin are dependent on L but not on K_0.





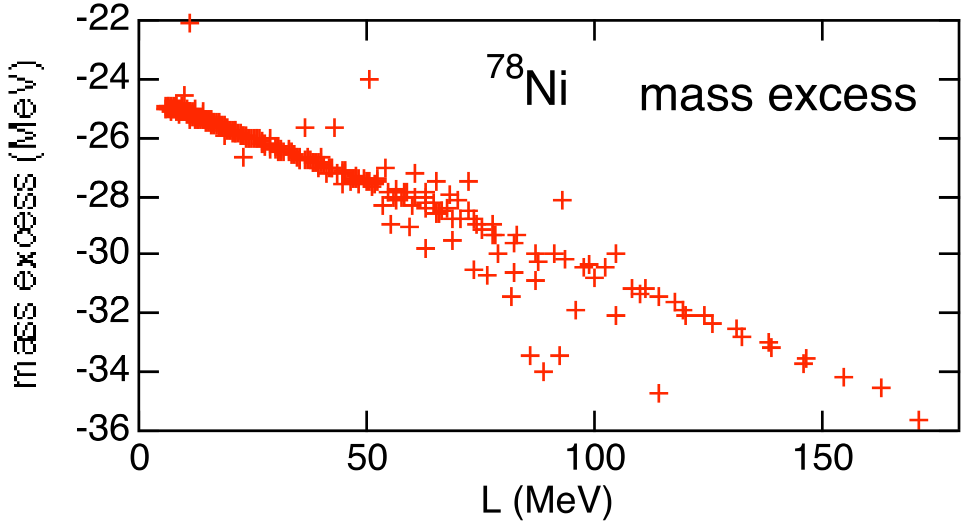
To be studied by Kurotama





Let's examine the L dependence of mass.

L dependence comes from surface symmetry energy



Larger L => smaller mass

(>_<) volume symmetry energy

Larger L => larger volume symmetry energy S_0 => larger mass

(^_^) surface symmetry energy

Oyamatsu and Iida, PRC81, 054302, 2010.

Surface energy comes from ...

in the cases of beta-stable nuclei
in neutron-star crusts and in laboratories

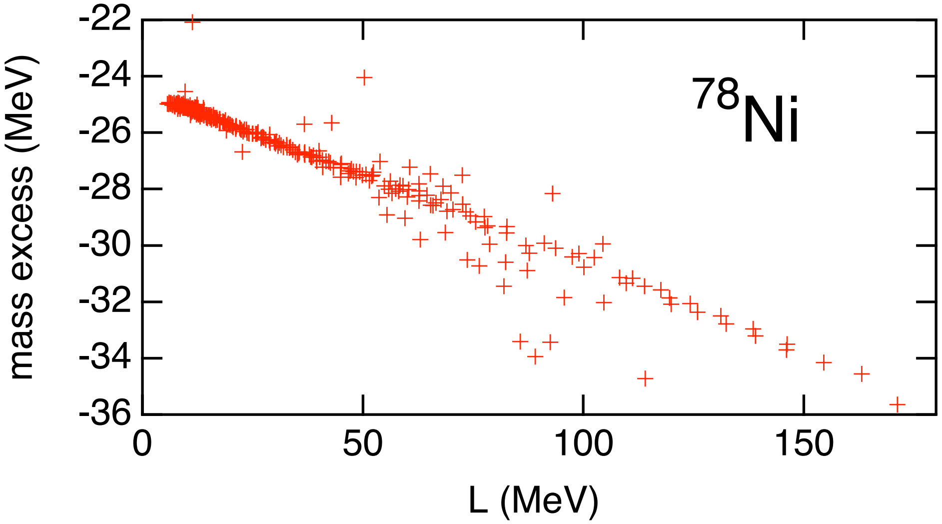
1/2 from $$F_0 \int d\mathbf{r} \left| \nabla n(\mathbf{r}) \right|^2$$

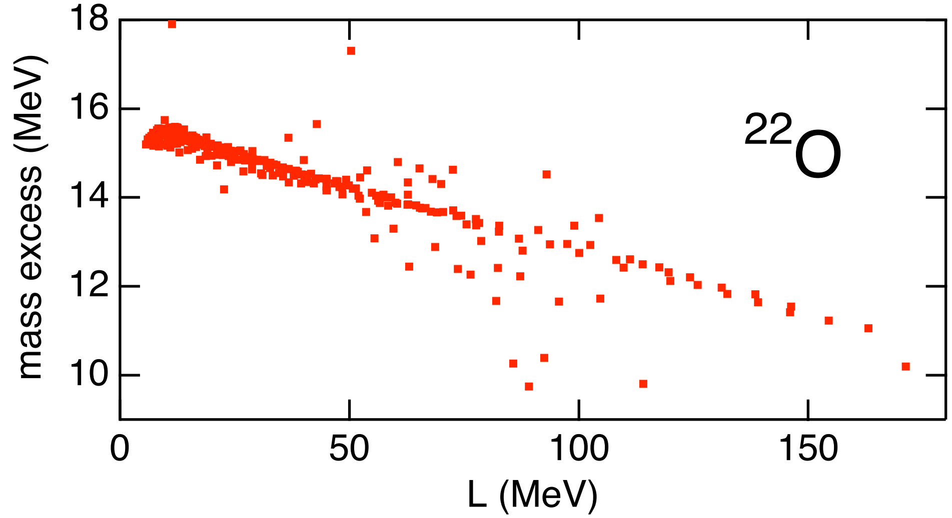
the remaining 1/2 mainly from $$\int d\mathbf{r}\, \varepsilon\left(n_n(\mathbf{r}), n_p(\mathbf{r}) \right)$$ (EOS)

Anyway, L dependence emerge through density distribution.

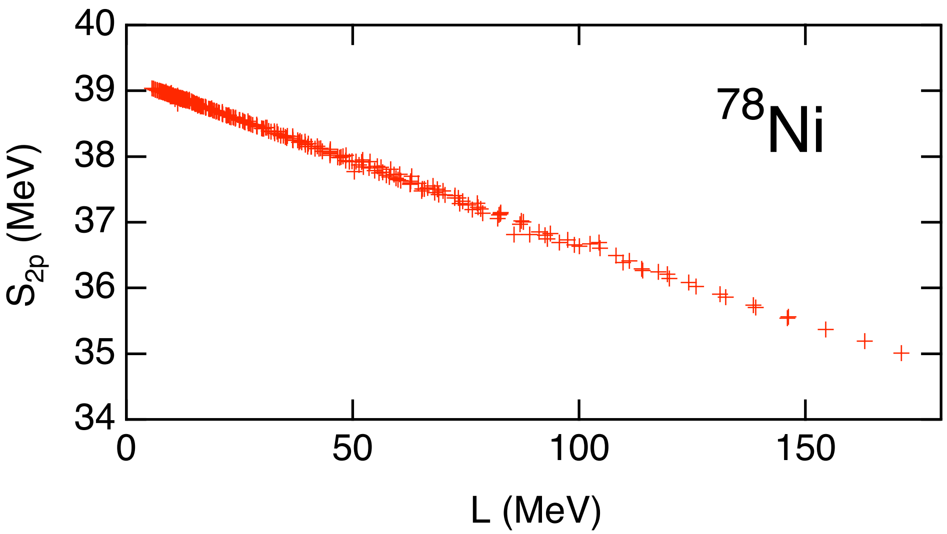
Oyamatsu and Iida, PTP109, 631-650, 2003.

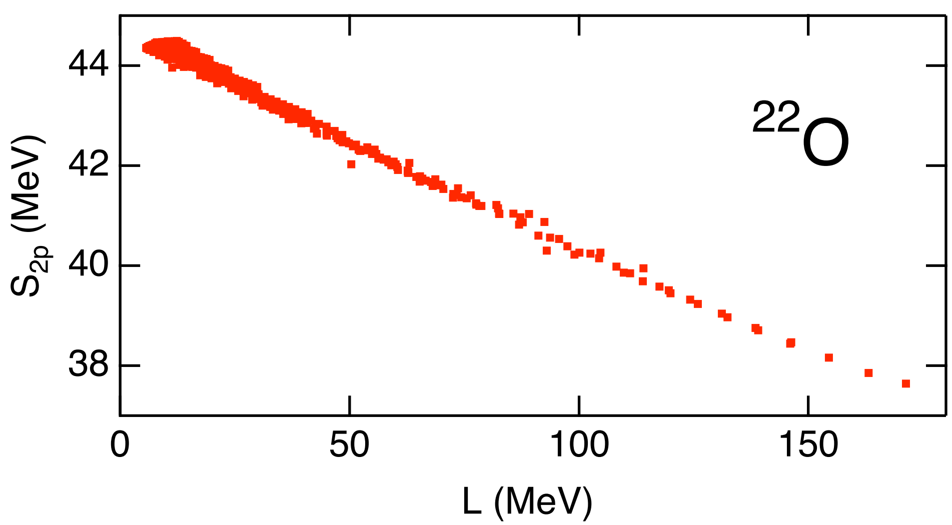
S_{2p}, S_{2n} : clear L dependence better than mass





scatterings due to numerical errors in optimizing n_0, w_0, and K_0





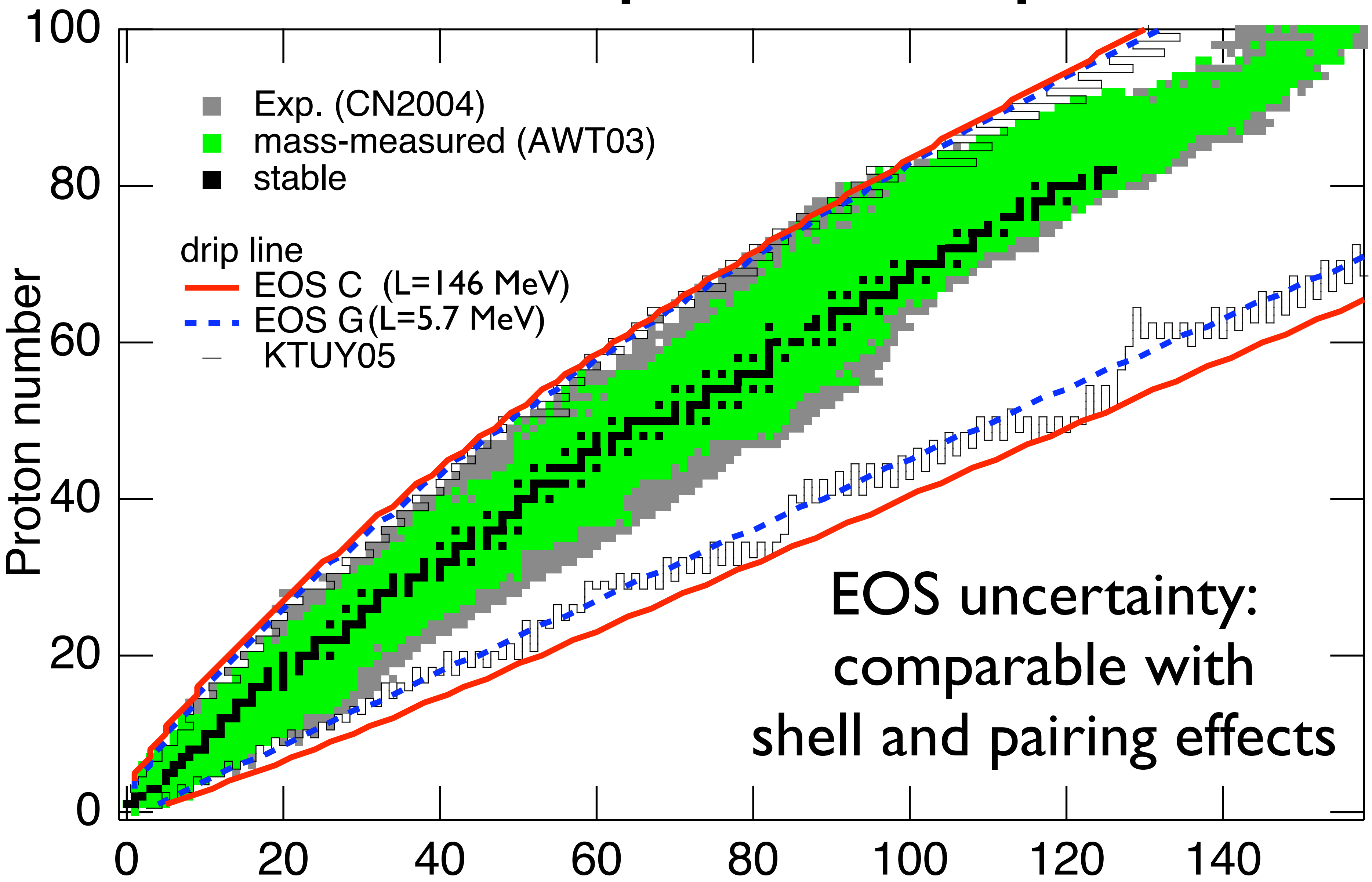
Oyamatsu and Iida, PRC81, 054302, 2010.

Question :

How the drip line is affected by the EOS uncertainties?

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

neutron and proton drip lines

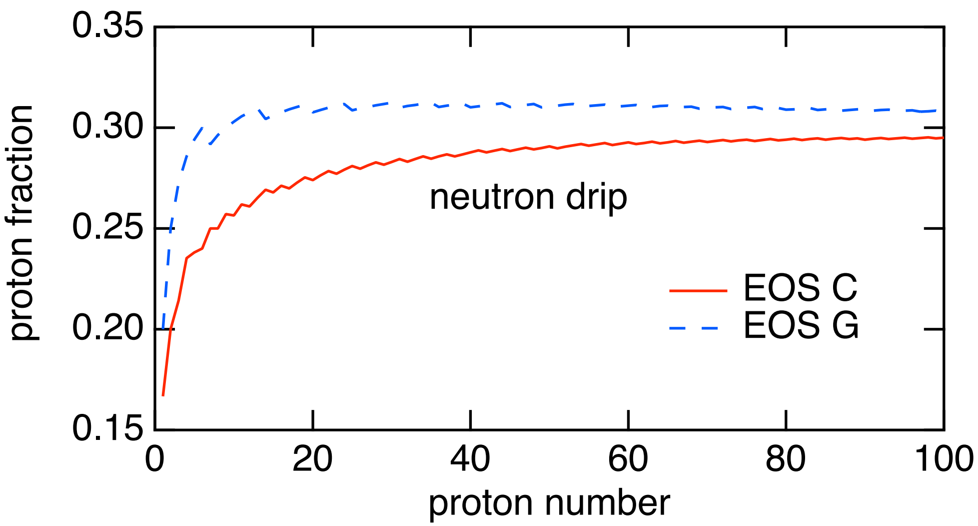


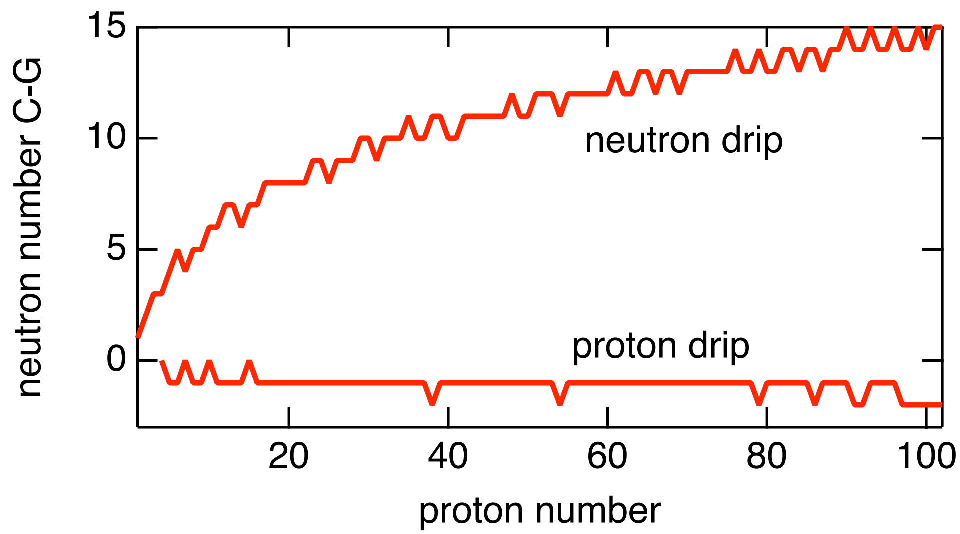
EOS uncertainty:
comparable with
shell and pairing effects

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

Difference between C and G

L=147 MeV   L=6 MeV





中性子ドリップライン

陽子数比の違いは軽い核で大きい

中性子数は重い核で差が大きい

まとめ

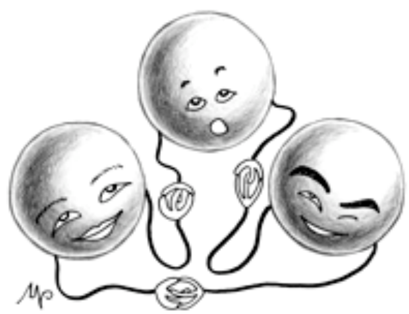
- ★ 安定核の質量半径からはLとK_0の値は決まらない

- ★ S_{2n} と S_{2p} は きれいなL依存性を示す
  - ★ 表面対称エネルギーの効果である
  - ★ 核子密度分布を通して出てきたEOSの効果である

- ★ 中性子ドリップラインもLに感度を持つ
  - ★ 殻効果や対相関効果と同程度
  - ★ 軽い核で効果が比較的大きい

- ★ 状態方程式を考える
  - ★ 半径と表面の厚さを考えるということ

- ★ 今後の楽しみ
  - ★ 核子密度分布のL依存性
    σ_R＝＞「くろたま」で探りたい
  - ★ 中性子スキン

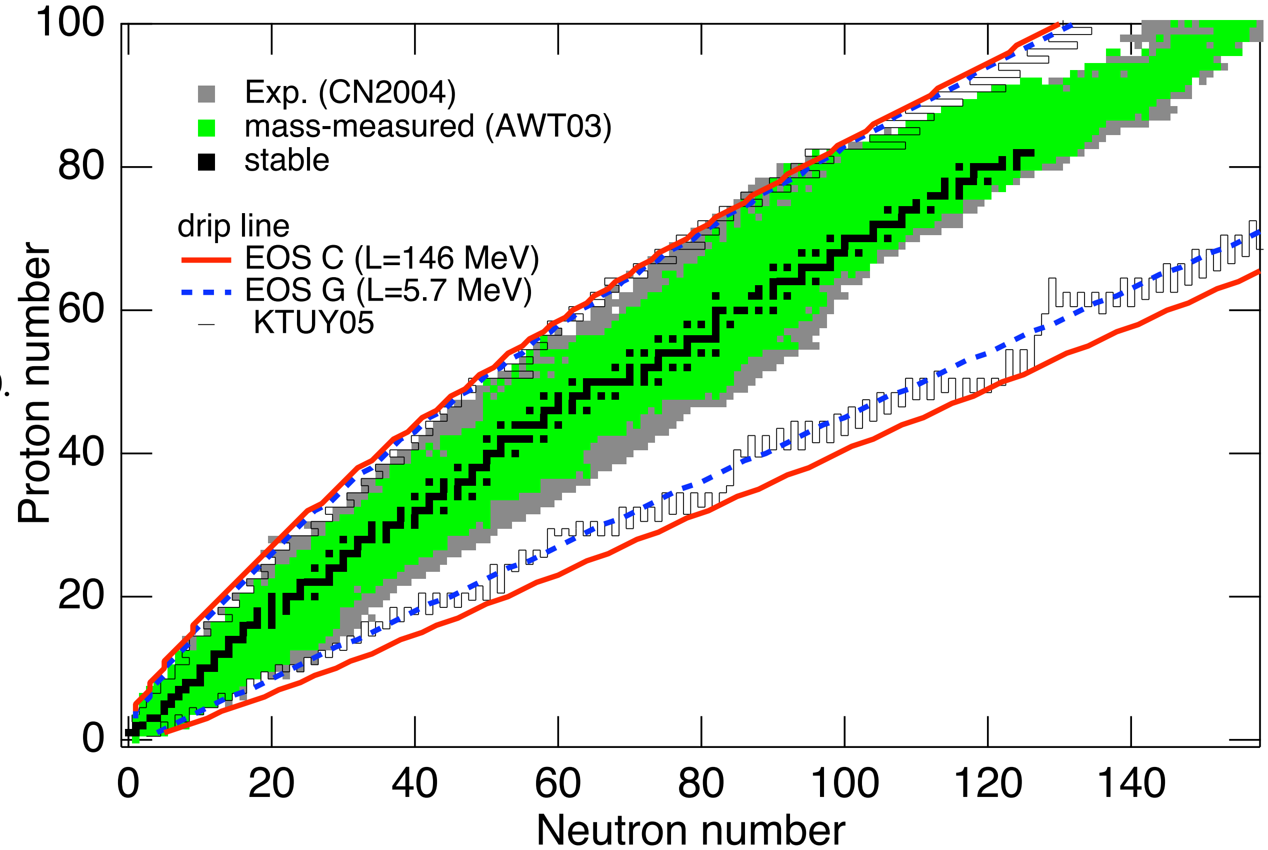


実験室

中性子ドリップラインの

平均的な位置

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



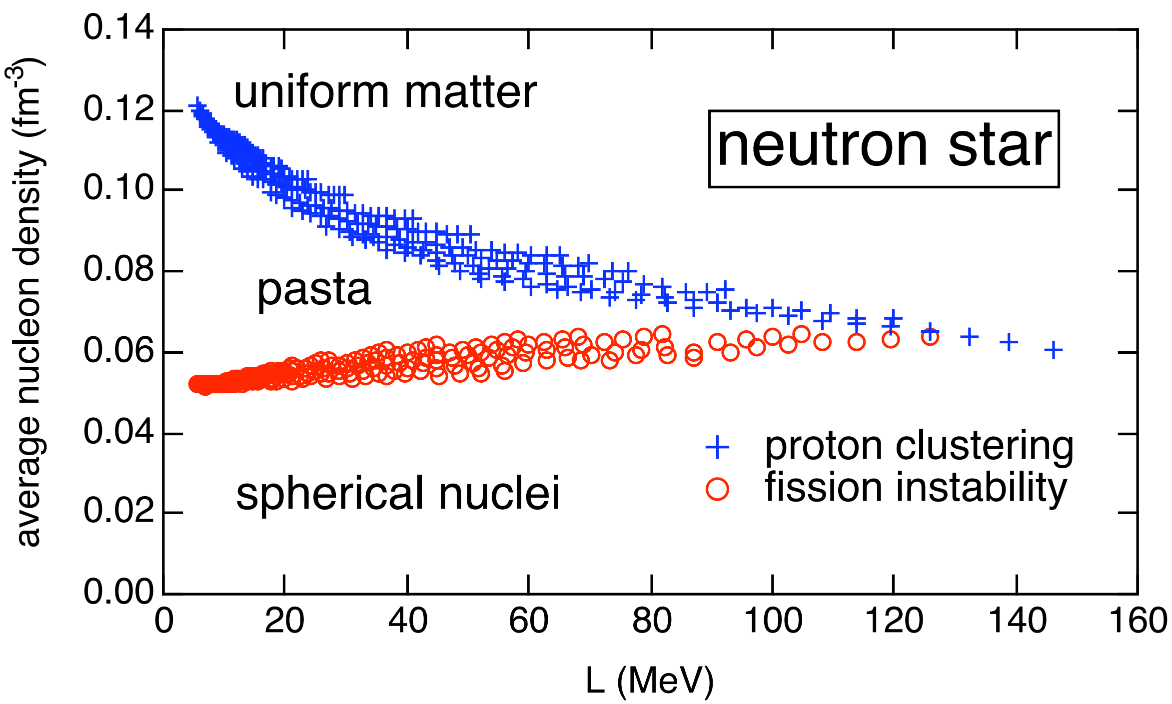
中性子星

クラストコアの境界密度（青）

パスタ原子核の存在領域

球形核存在領域の最大密度（赤）

Oyamatsu and Iida, PRC75, 015801, 2007.



If L < 100 MeV,
gyroid could appear at finite temperarure.

Nakazato, Oyamatsu and Yamada, PRL103, 132501, 2009.