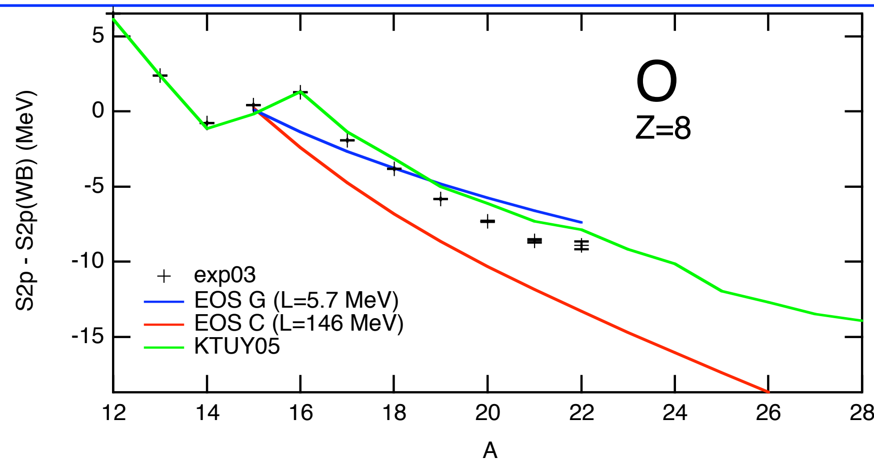
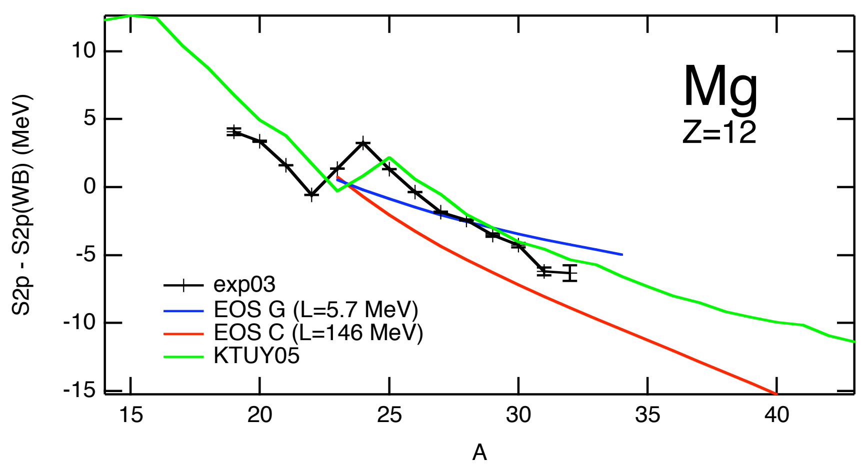
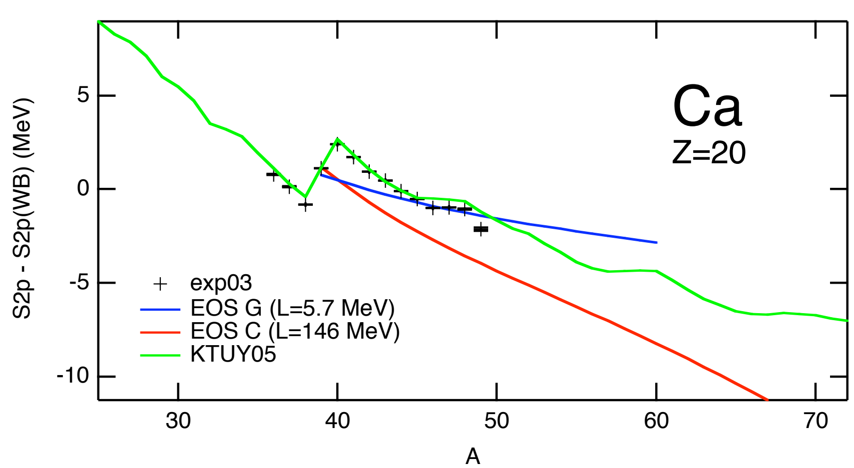
Unstable nuclei and the equation of state of nuclear matter

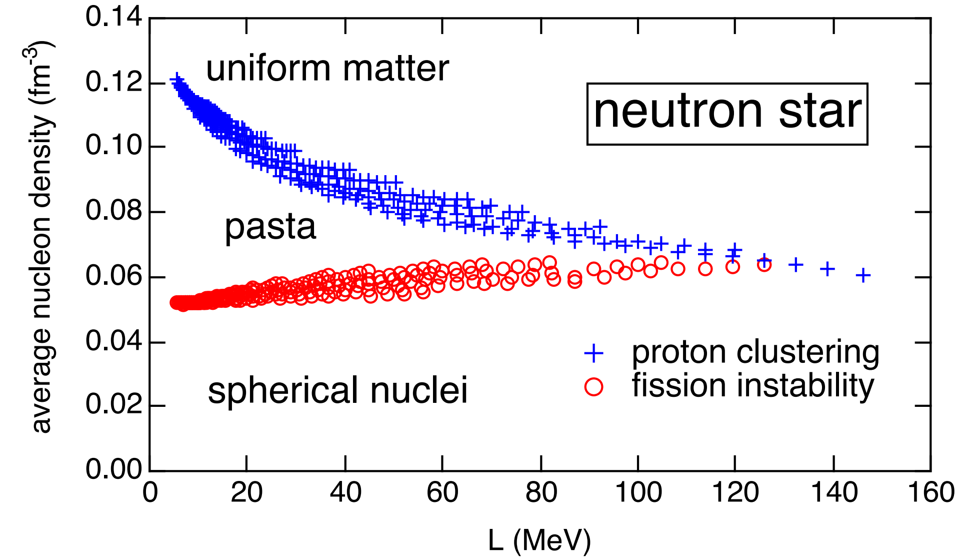
Kazuhiro Oyamatsu (Aichi Shukutoku U.)

The L value of the EOS
could be constrained from the systematics of S_{2p} for light unstable nuclei
and dominates the inner crust structure of a neutron star.

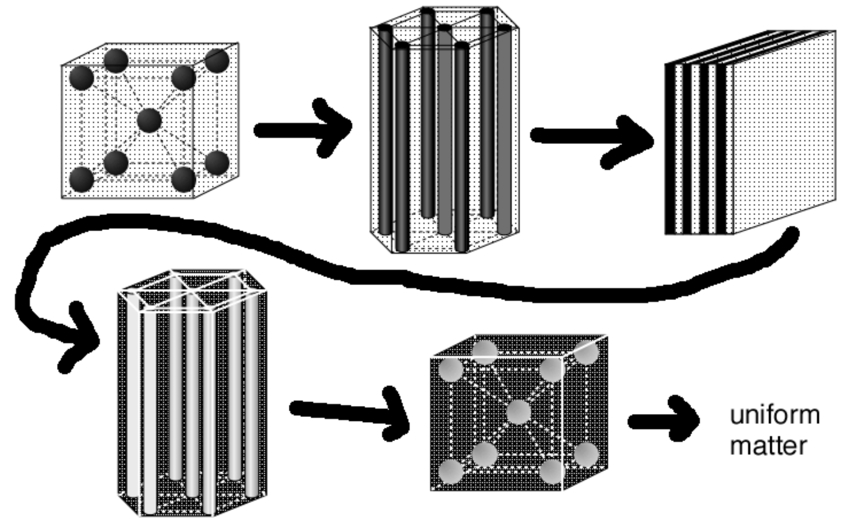






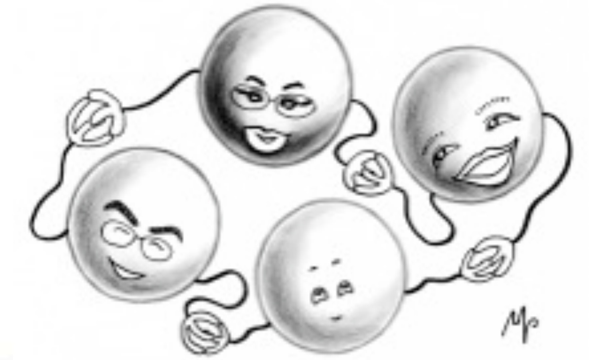


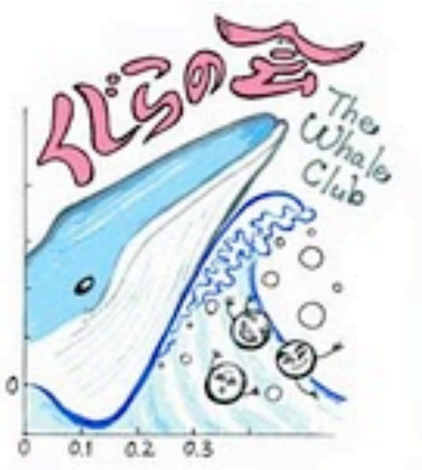
spherical nuclei and pasta nuclei



K.Oyamatsu, NPA561, 431 (1993)

Collaborator Meeting





くじらの会 at 入野

2008年10月29日（水）～31日（金）

Kurotama

radius

σ_R

Kohama
(σ_R :Kurotama)

Koura
(mass formula)

Iida Oyamatsu

Empirical
EOS

mass
radius
pasta

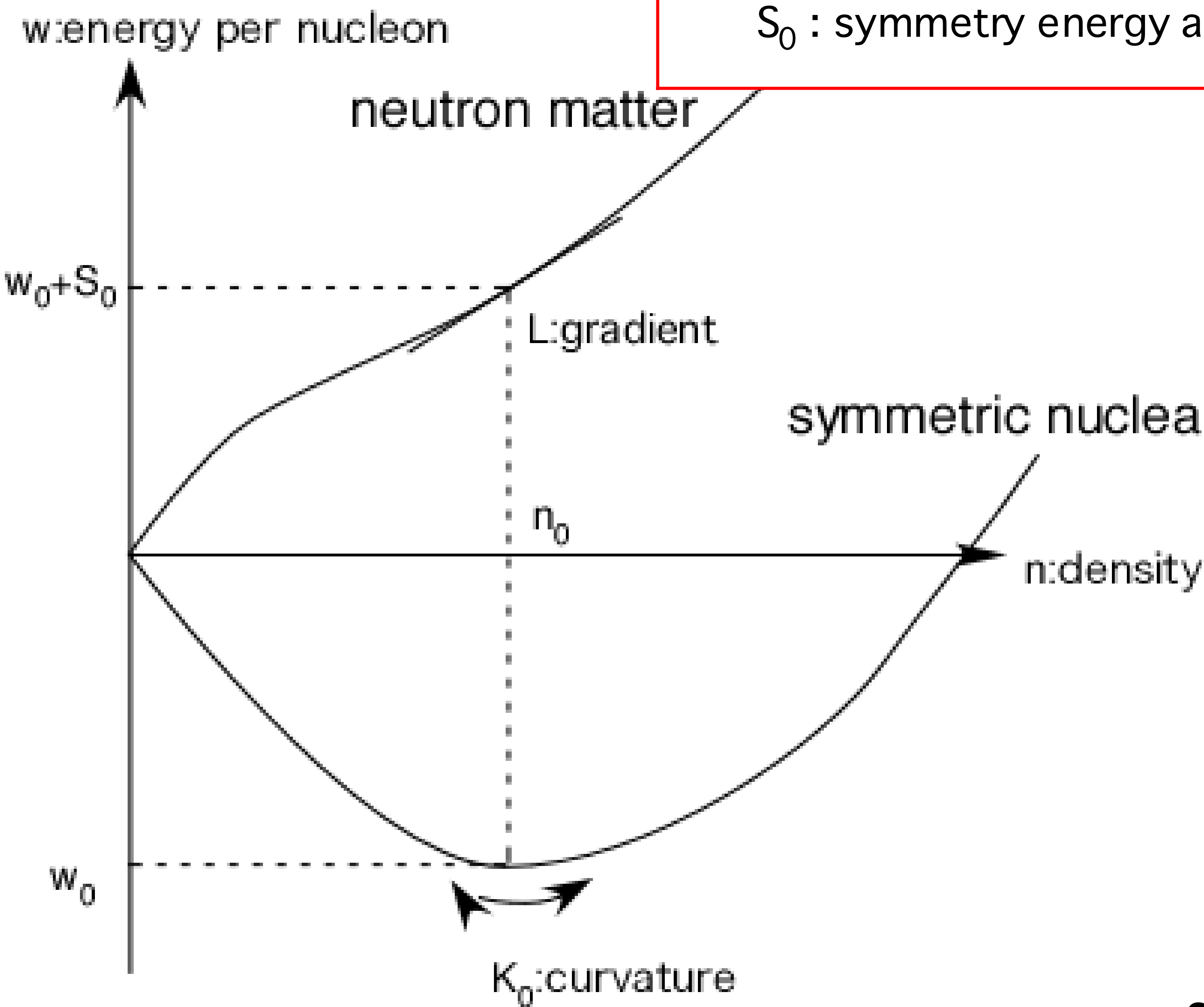
Which EOS parameter dominates macroscopic properties of neutron-rich nuclei in laboratory and in neutron-star crusts?

Energy per nucleon of nearly symmetric nuclear matter

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

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

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



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

$$S_0 = S(n_0)$$

$$w_s = w_0 + S_0 \alpha^2$$

$$n_s = n_0 - \frac{3 n_0 L}{K_0} \alpha^2 .$$

$$\alpha = 1 - 2x$$

saturation of asymmetric matter

Asymmetric nuclear matter

saturation energy w_s and density n_s for proton fraction x

$$w_s = w_0 + S_0 \alpha^2$$

$$\alpha = 1 - 2x$$

$$n_s = n_0 - \frac{3 n_0 L}{K_0} \alpha^2.$$

L dependence in unstable nuclei
energy => nuclear mass : through surface (discussed later)
density => nuclear size : straight forward (Kurotama)

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 ***

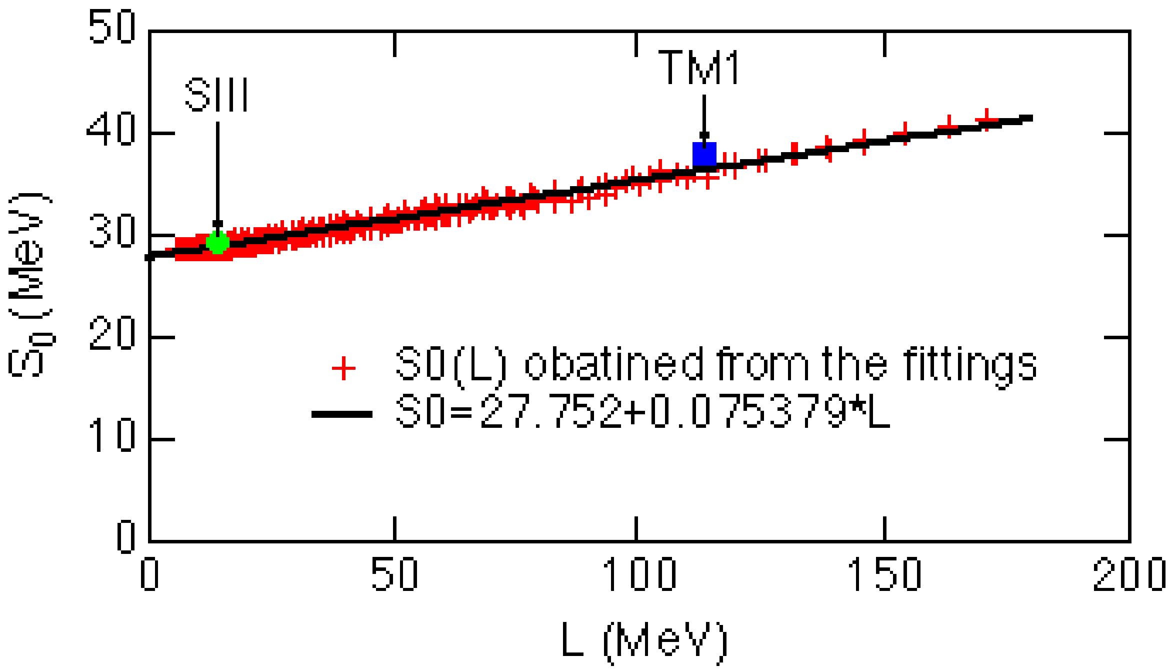
3. We calculate nuclei in neutron-star crusts and identify key EOS parameter.

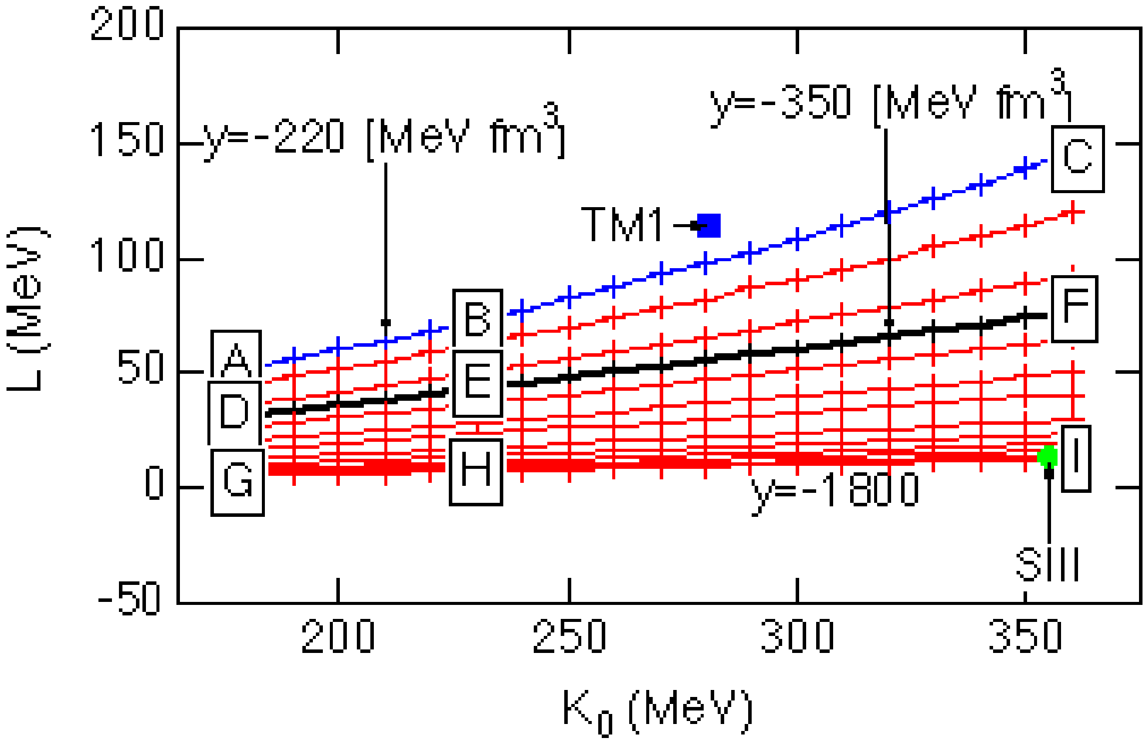
*** proton number and ratio ***
*** core-crust boundary density ***
*** existence of pasta nuclei ***

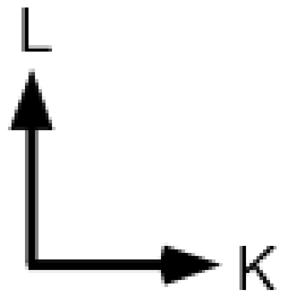
EOS parameter values obtained from stable nuclei

S_0:symmetry energy

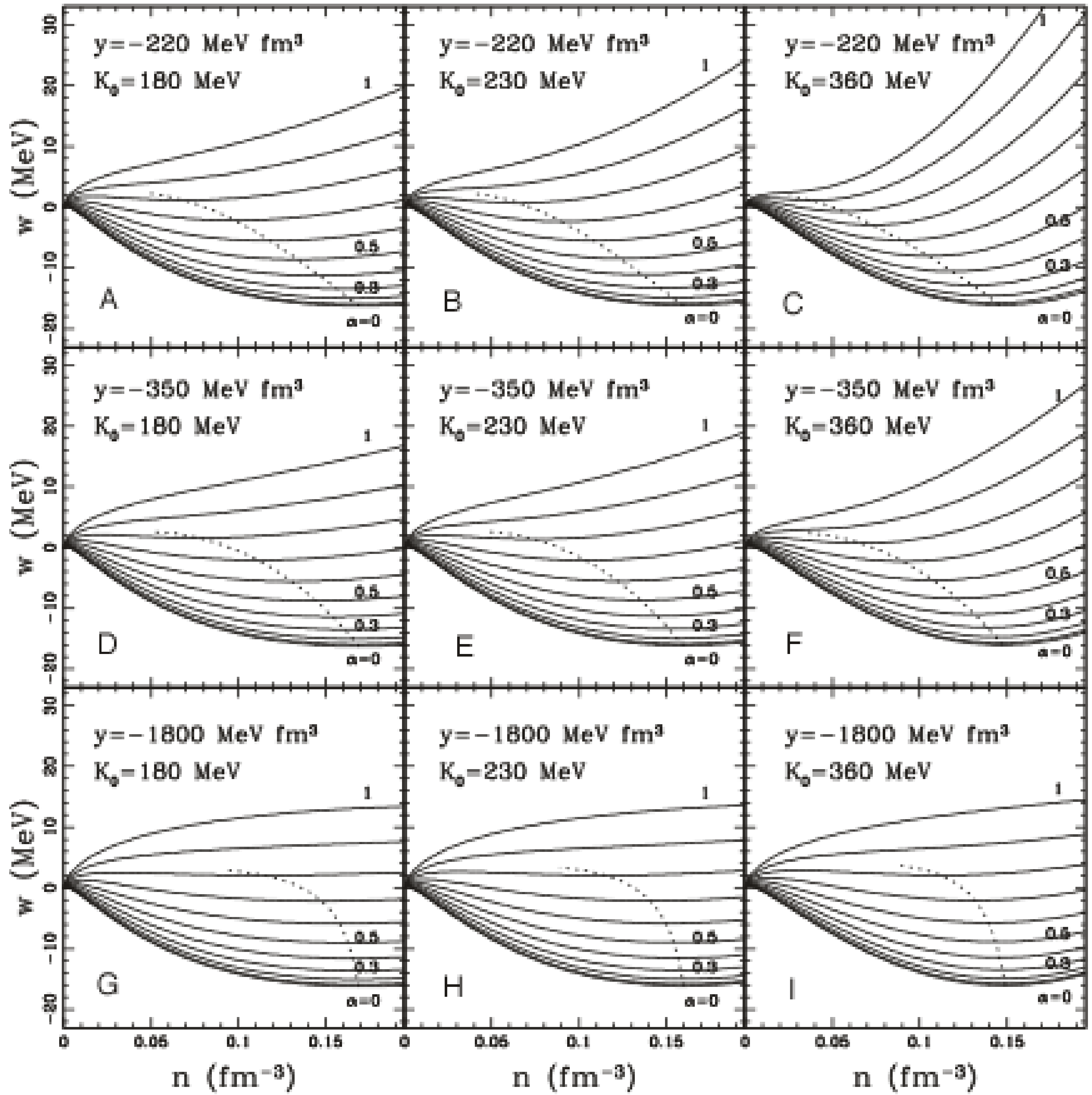
L : density symmetry coefficient





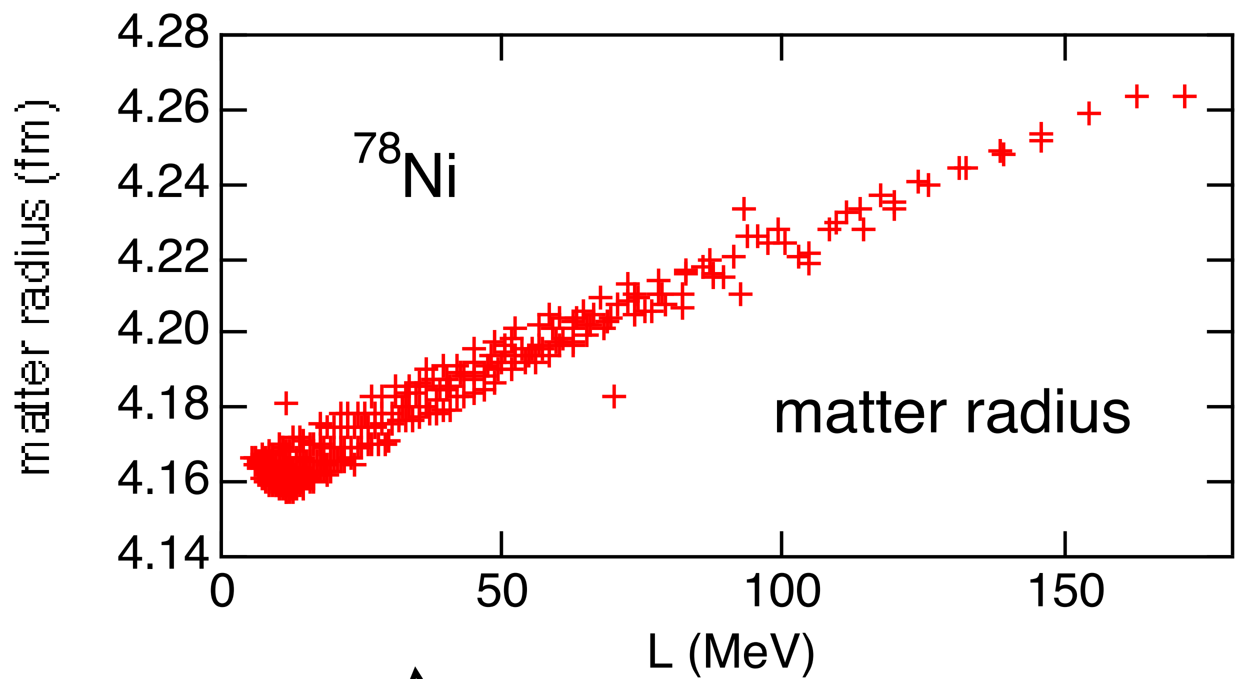


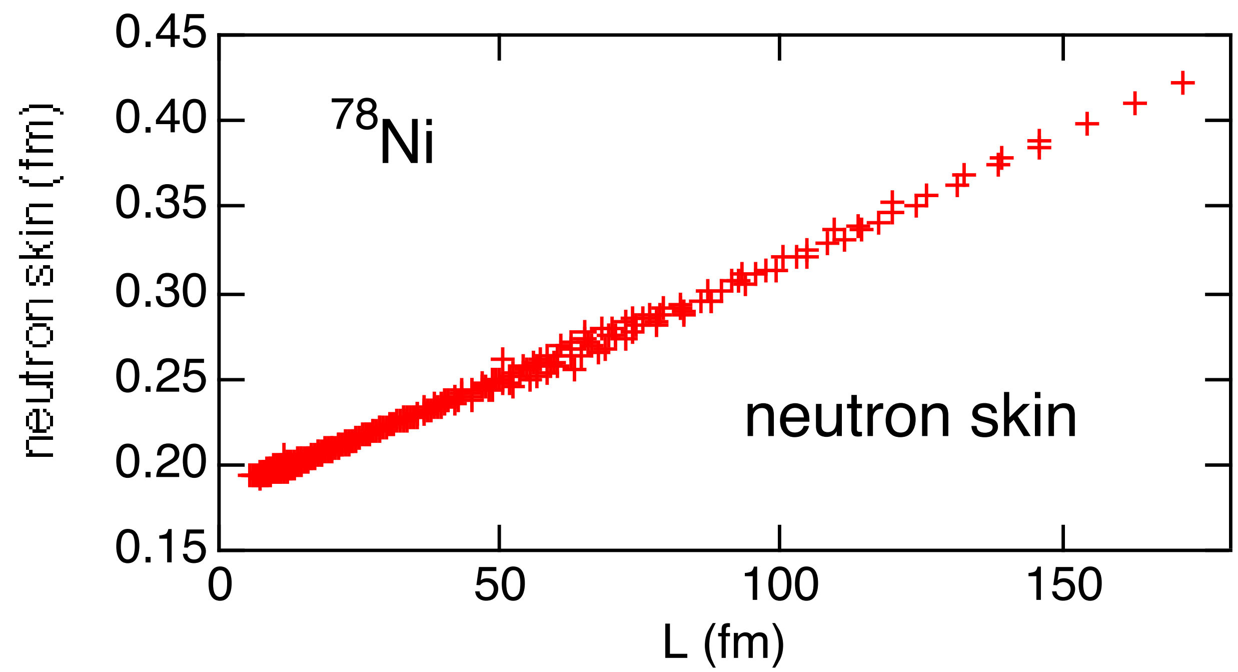
9 representative EOS A-I



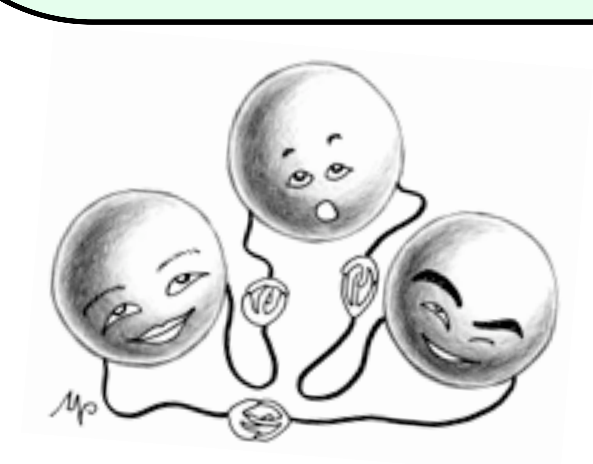
$$\alpha = 1 - 2x$$

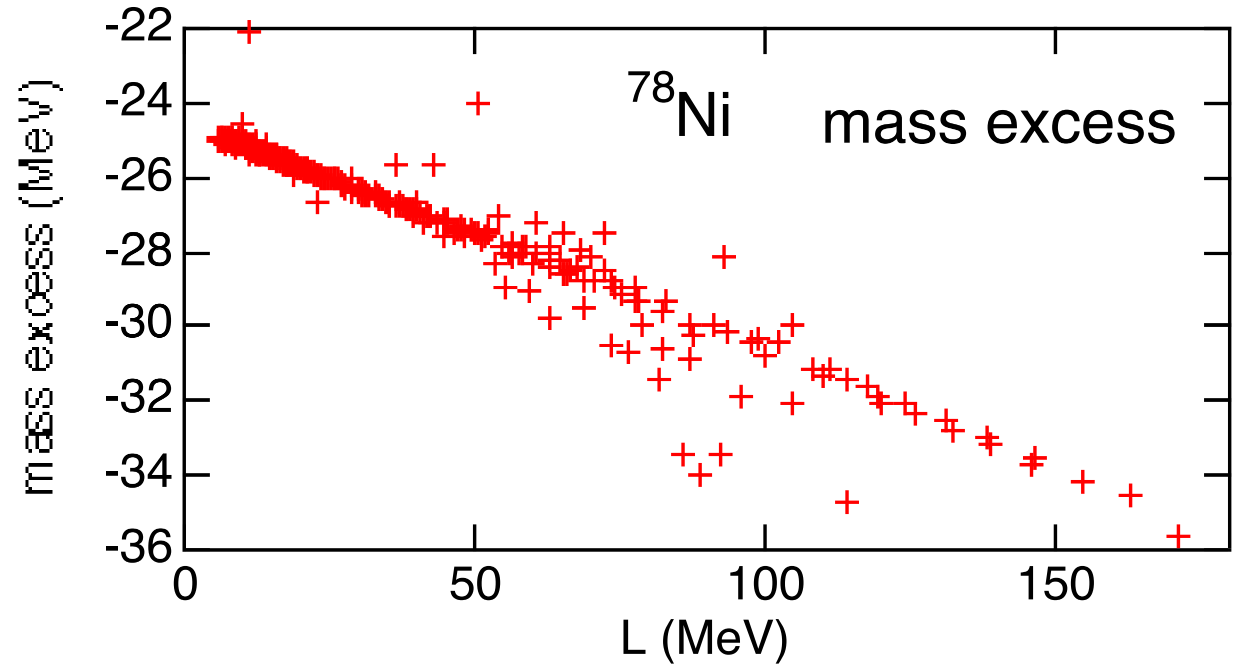
The mass, radius and neutron skin are dependent on L but not on K_0.





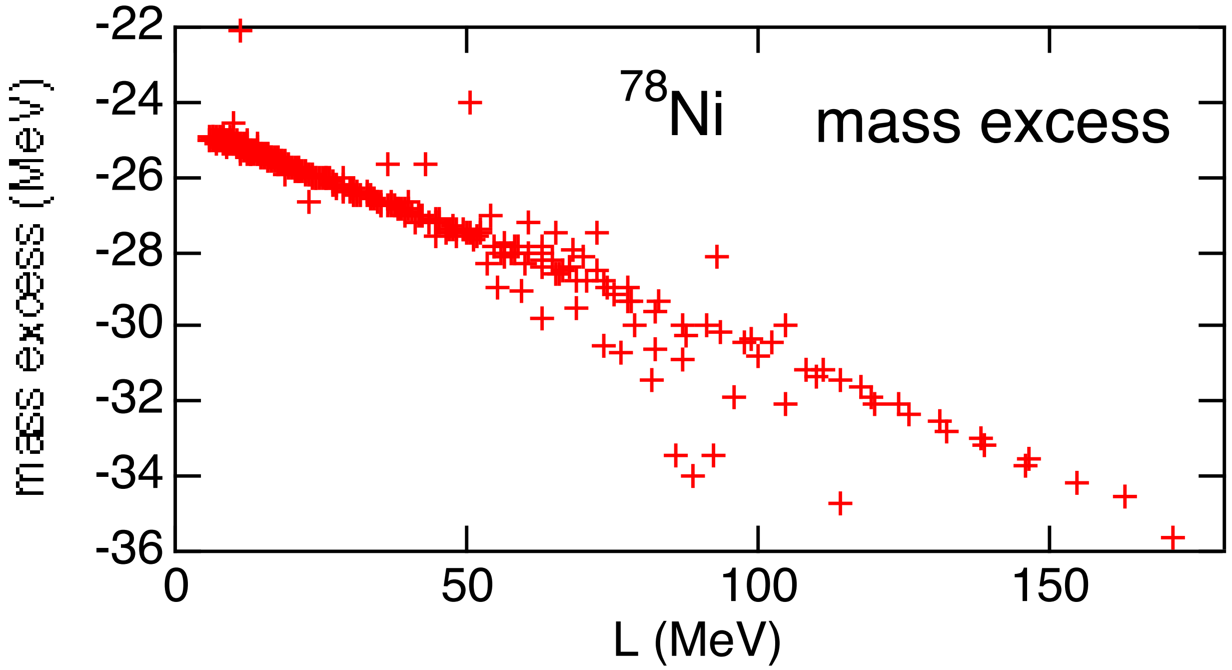
To be studied by Kurotama





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

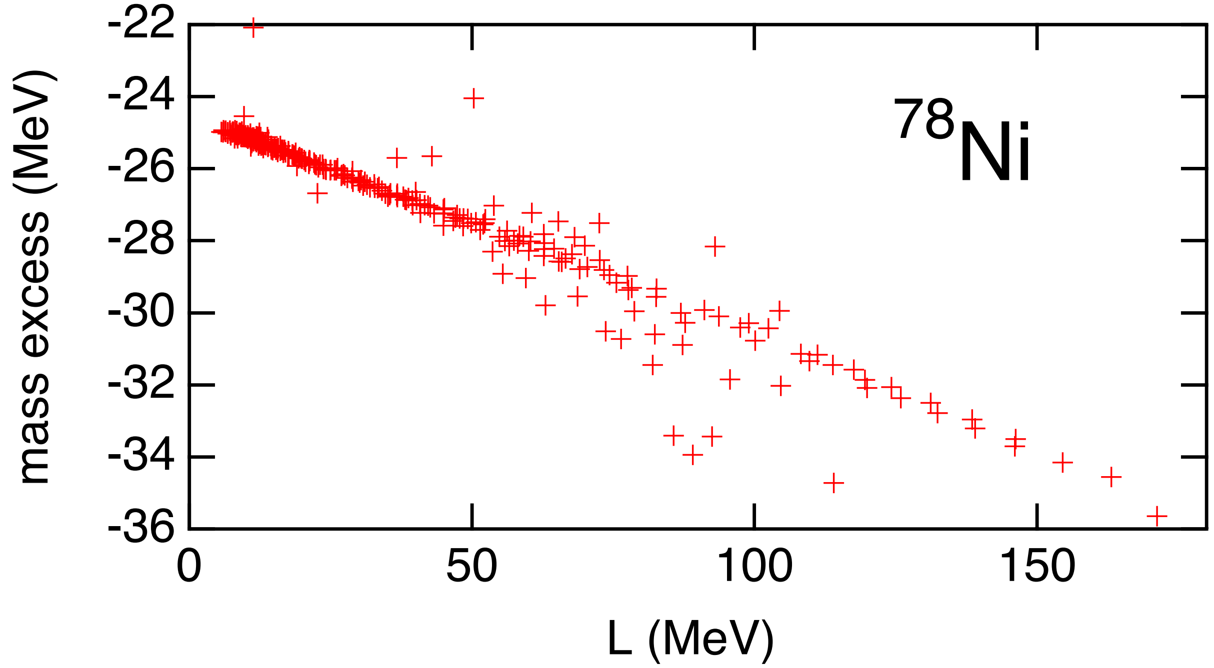
1/2 from $$F_0 \int d\mathbf{r} \left|\nabla n(\mathbf{r})\right|^2$$

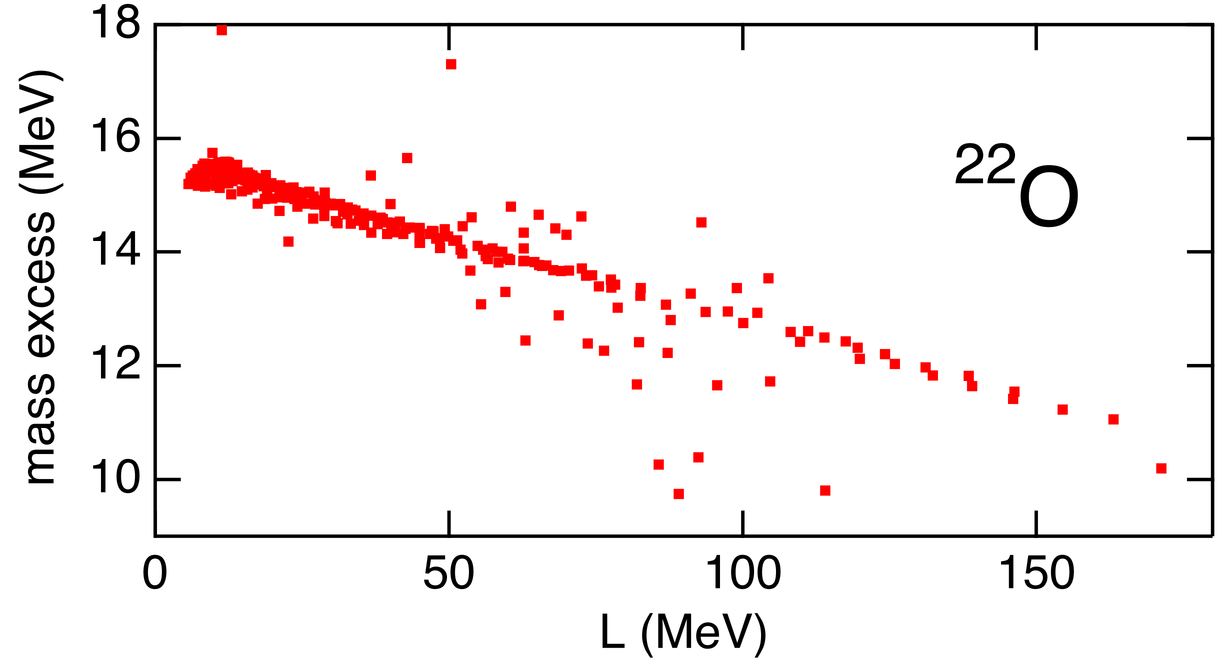
the remaining 1/2 mainly from $$\int d\mathbf{r}\, \varepsilon\left(n_n(\mathbf{r}), n_p(\mathbf{r})\right)$$ (EOS)

The L dependence emerge through density distribution.

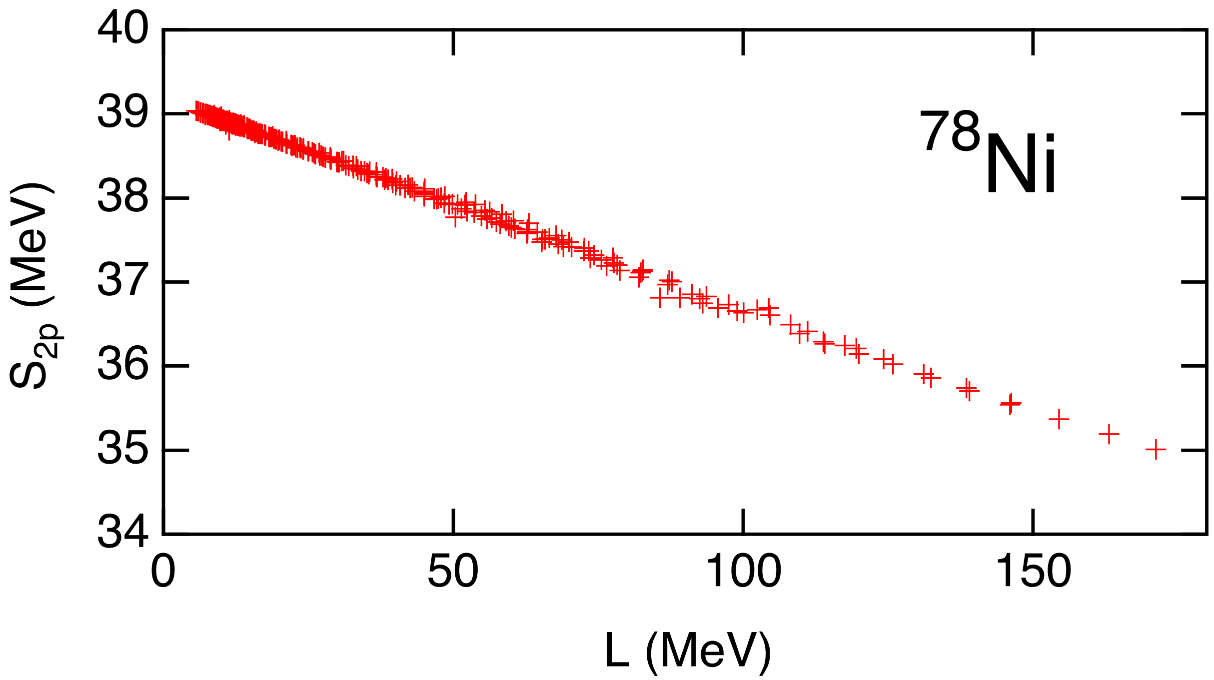
Oyamatsu and Iida, PTP109, 631-650, 2003.

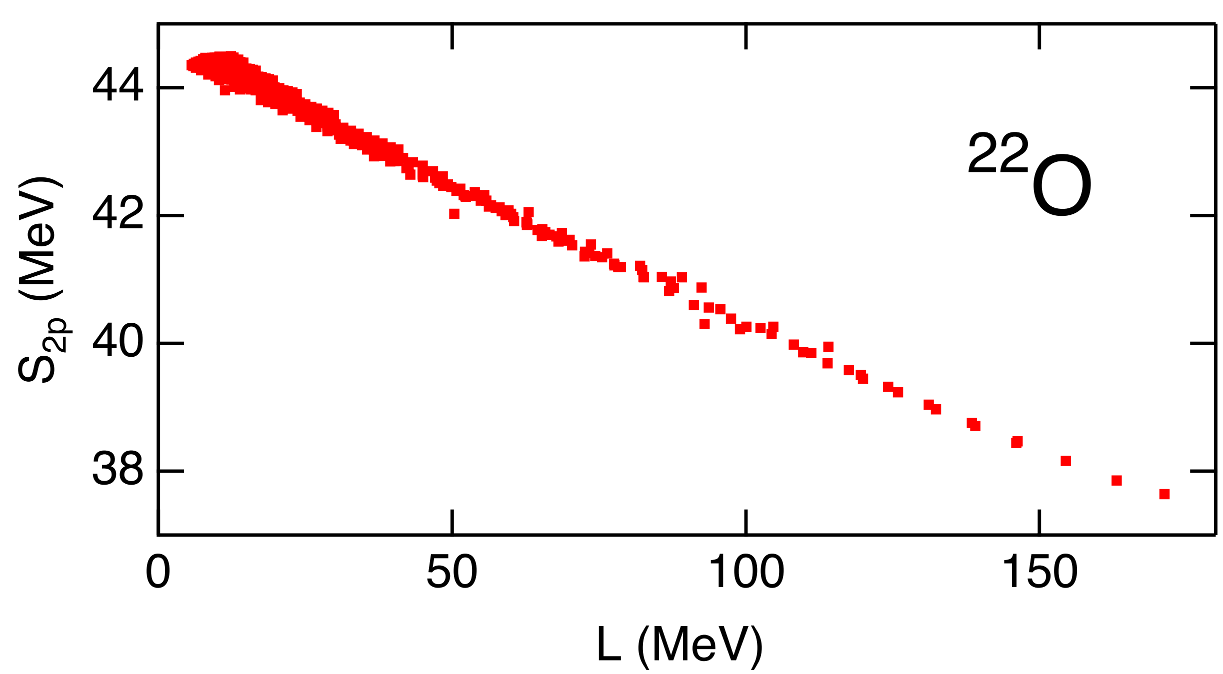
S_{2p}, S_{2n} : clear L dependence better than mass





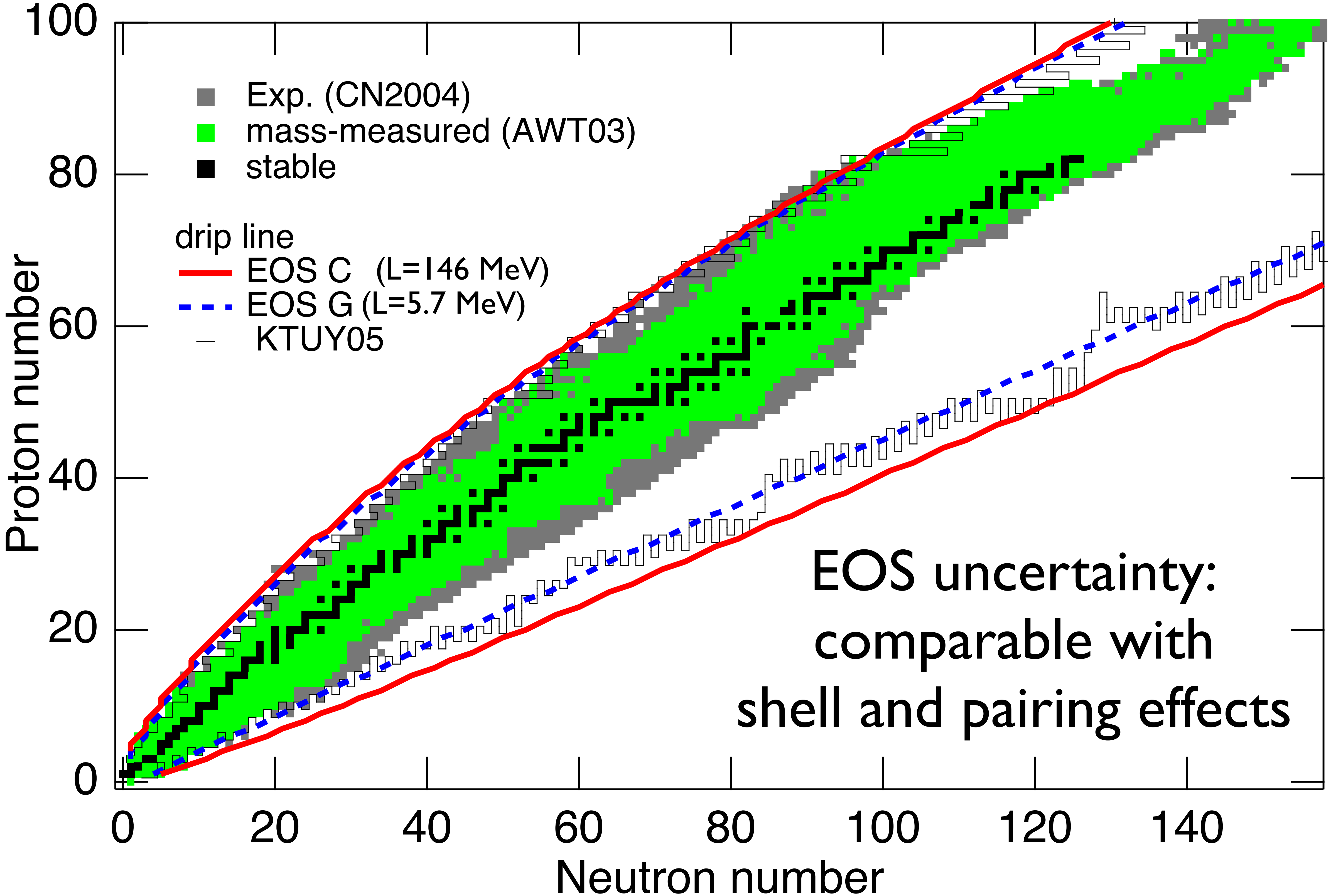
scatterings due to numerical errors in optimizing n_0, w_0, and K_0





Oyamatsu and Iida, PRC81, 054302, 2010.

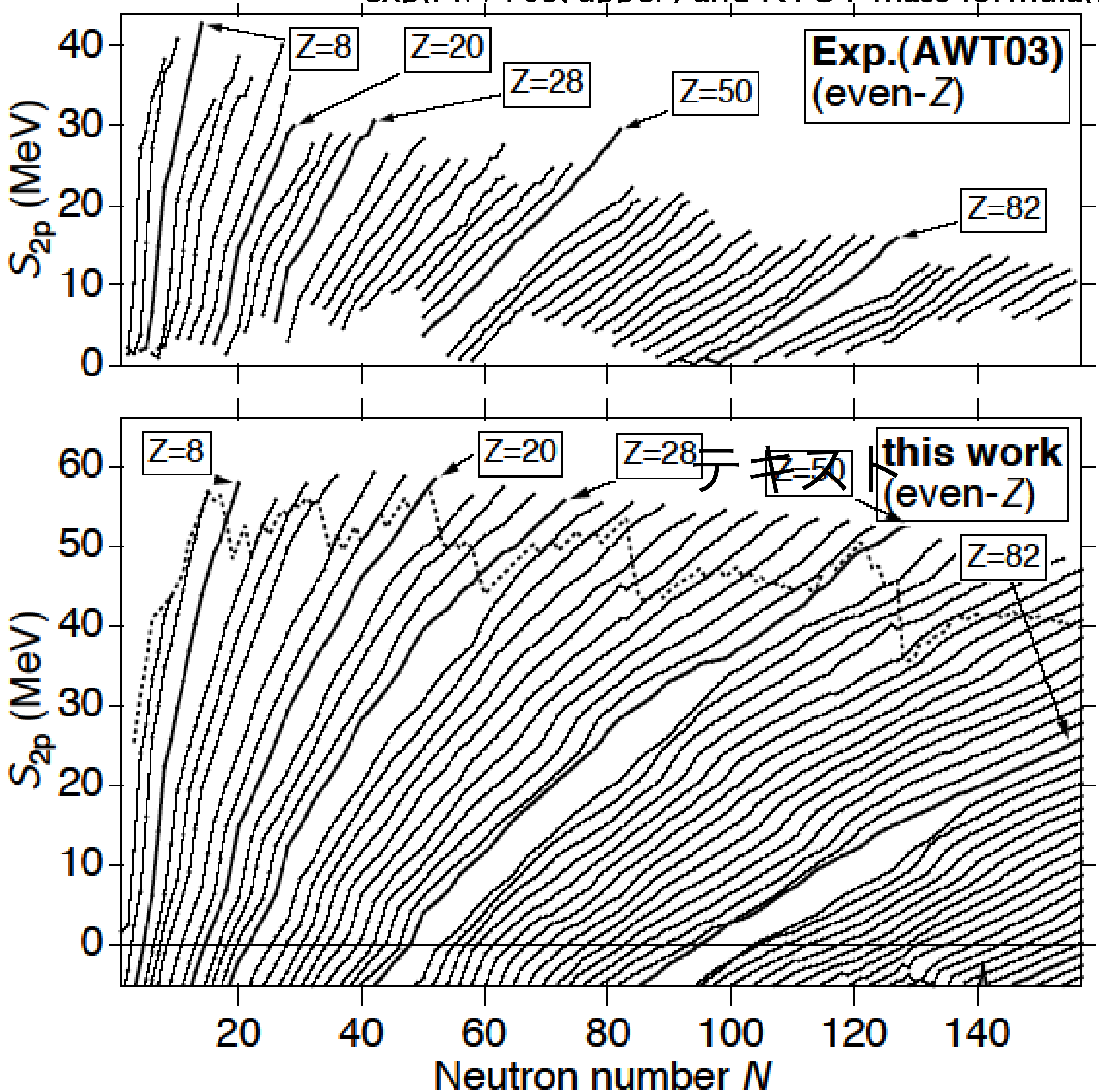
neutron and proton drip lines



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

Systematics of S_{2p}

exp(AWT03, upper) and KTUY mass formula(lower)



S_{2p} for constant Z shows smooth behavior because proton configuration is same.

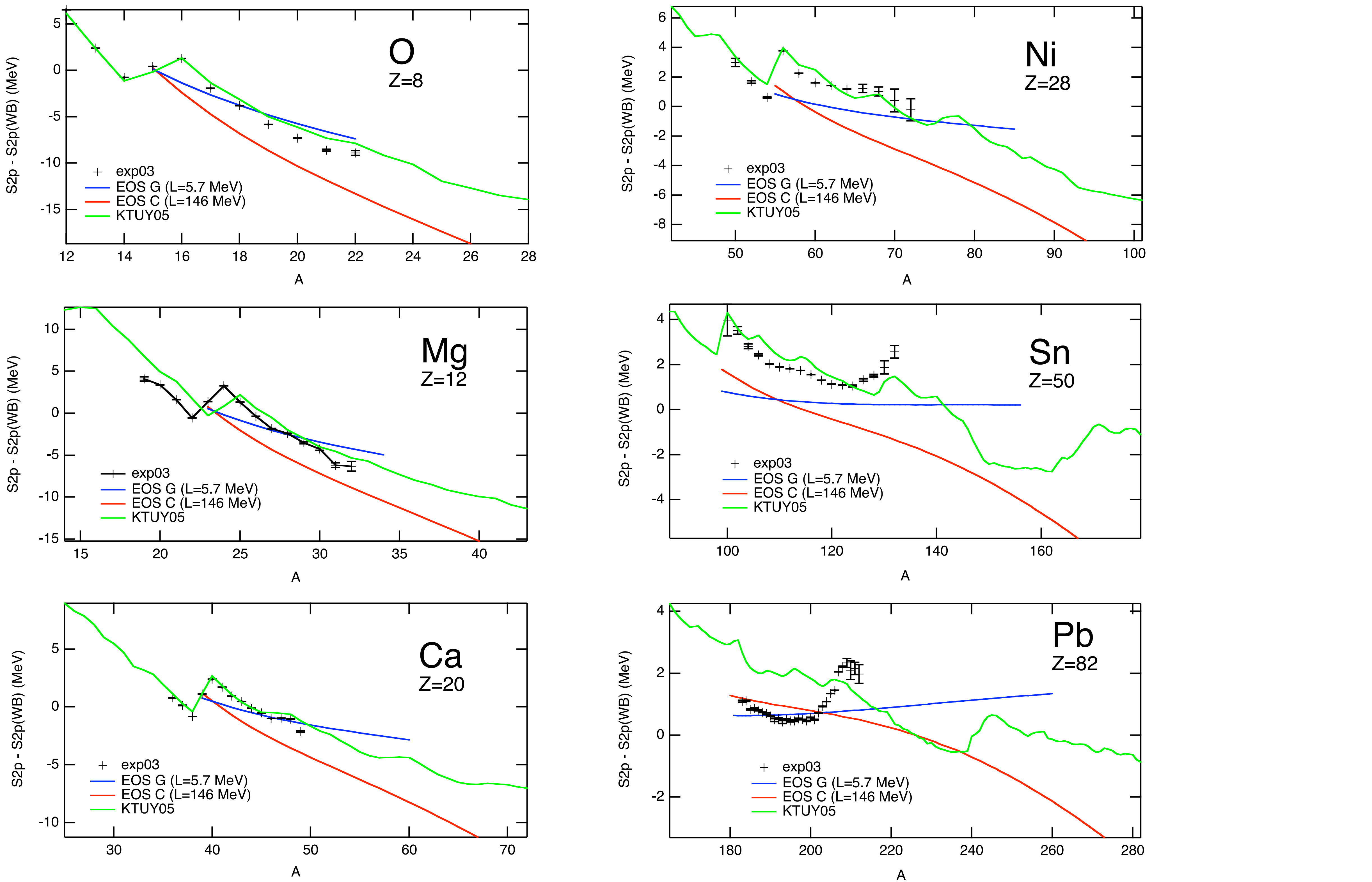
Slopes of S_{2p} seems good to examine systematics.

- pairing≈-12/A^(3/2) MeV
  A=100: -0.012MeV
  A=16: -0.2MeV

Slope of S_{2p}

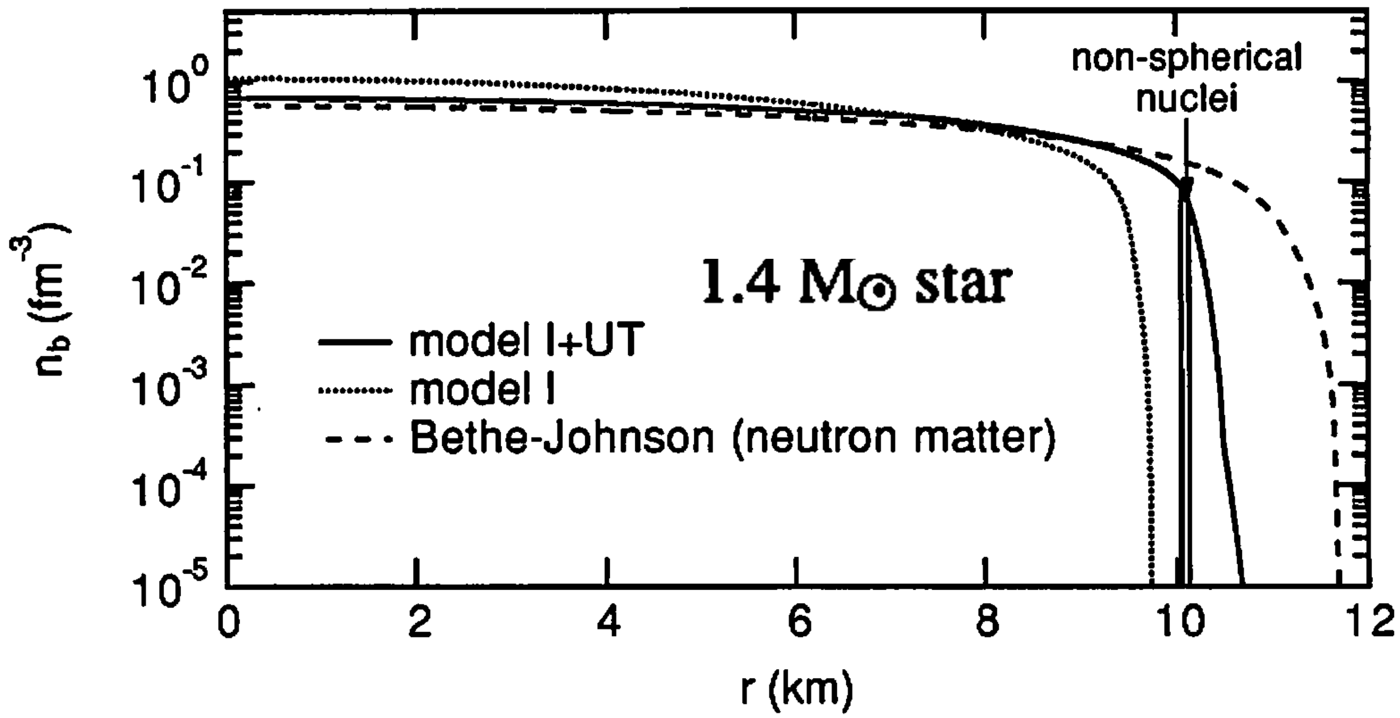
- δVnp=(S_{2p}(Z,N)-S_{2p}(Z,N-2))/4≈2(a_{sym}+a_{ssym}/A^(1/3))/A
  - For large A, δVnp is quite small and sensitive to pairing and deformation (M.Stoitsov et. al., PRL 98, 132502 (2007))
- For small A (say, less than 80), δVnp is large enough to discuss the liquid-drop terms, thus the L value of the EOS.

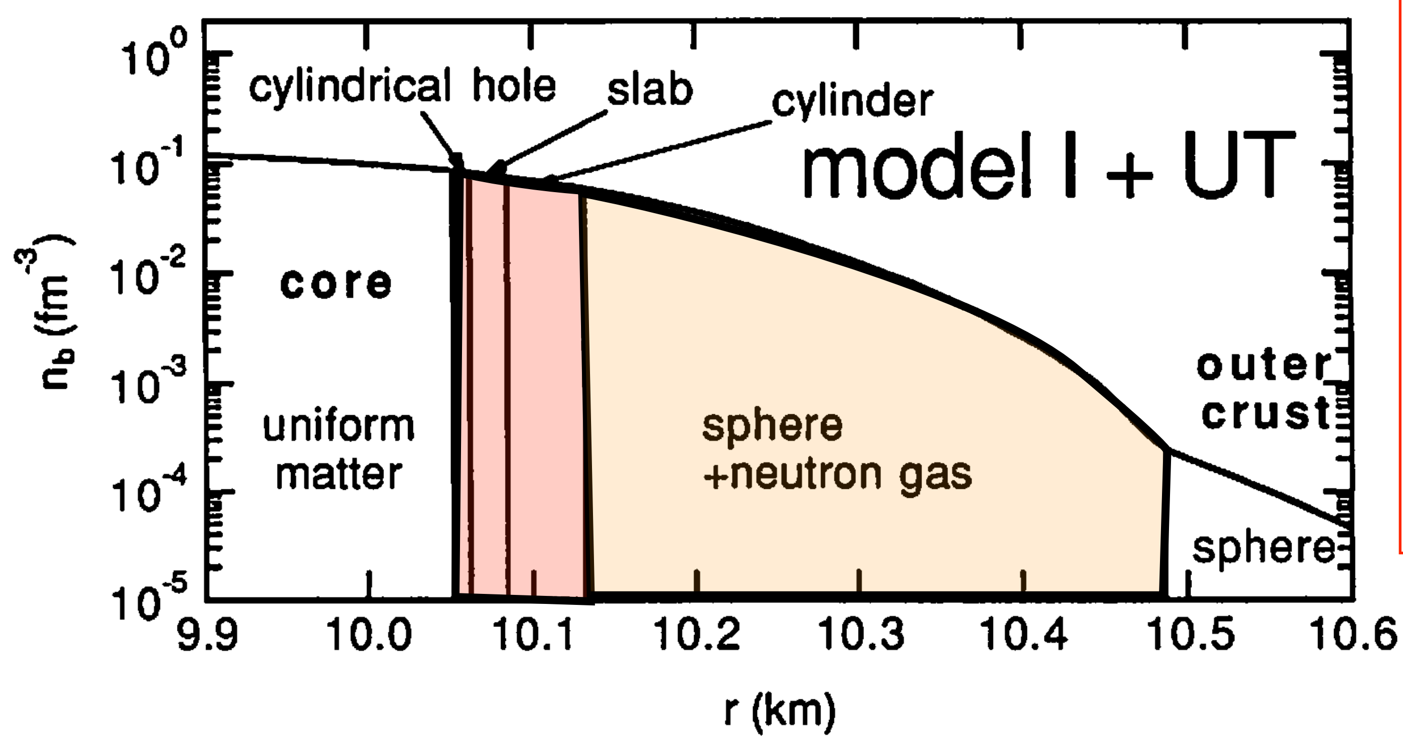
Light unstable nuclei seems good, but we need to deal with discontinuities at N=Z (Wigner energy).



A short trip to a neutron star

a typical model of the neutron-star crust





K. Oyamatsu, doctoral dissertation 1994 (unpublished).

core-crust boundary density sensitive to L value

$\rho=(1/3 - 2/3)\rho_0$

$n_b=(0.06 - 0.1)$ (fm^{-3})

inner and outer crust boundary

(NDP: Neutron Drip Point)

determined by S_0

$\rho_{NDP}=4\times10^{11}$ (g/cm^3)

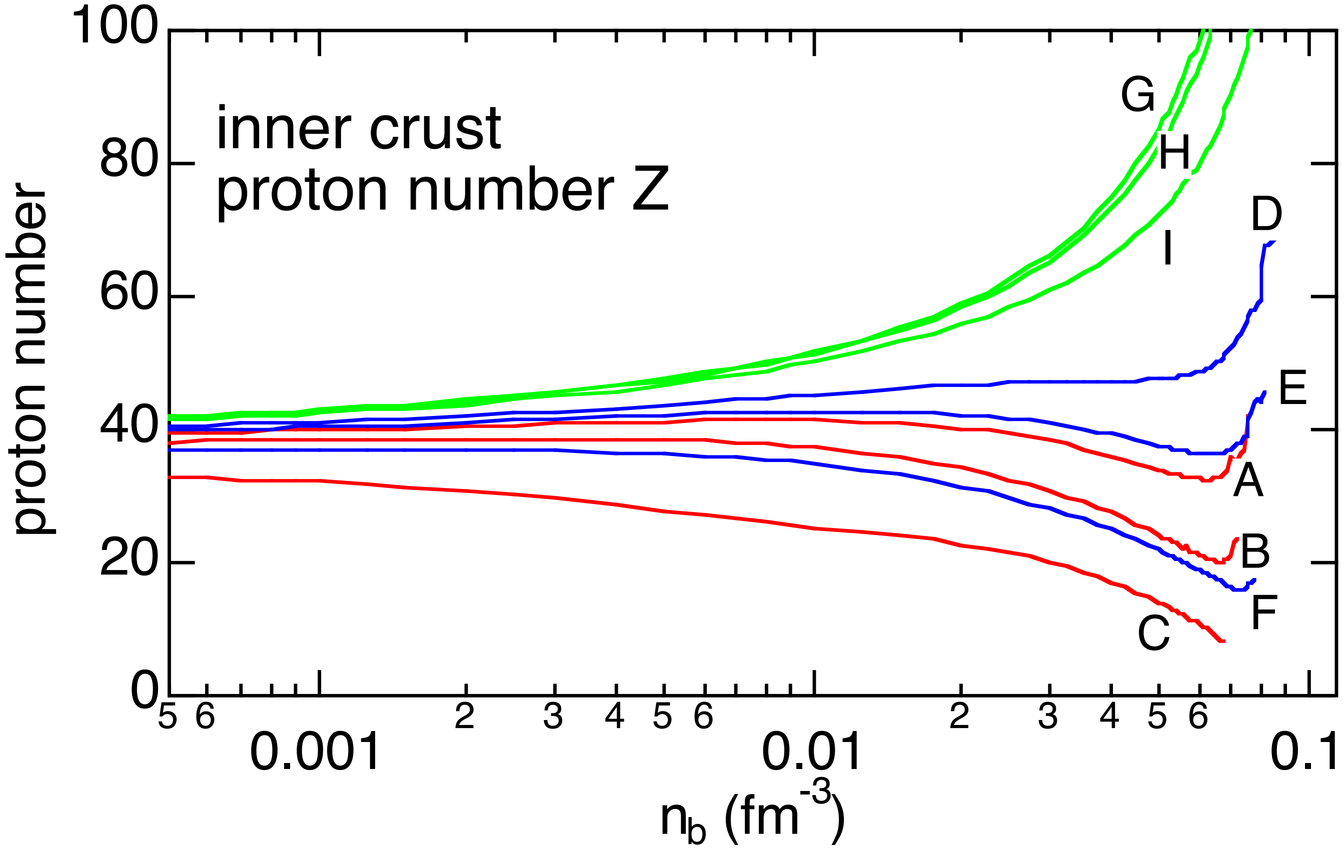
layer of pasta nuclei : 70 m thick

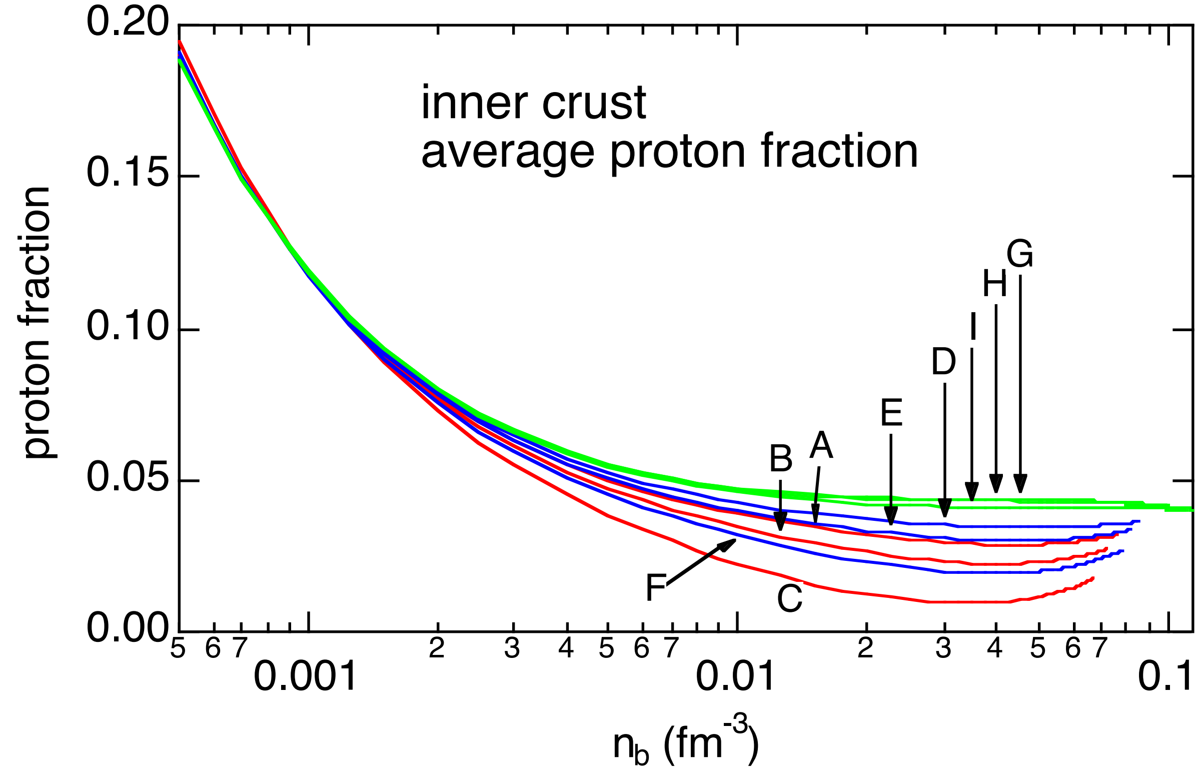
contains the most part of crustal mass and moment of inertia

n_b : average nucleon number density

normal nuclear density : $n_0=0.16$ (fm^{-3})

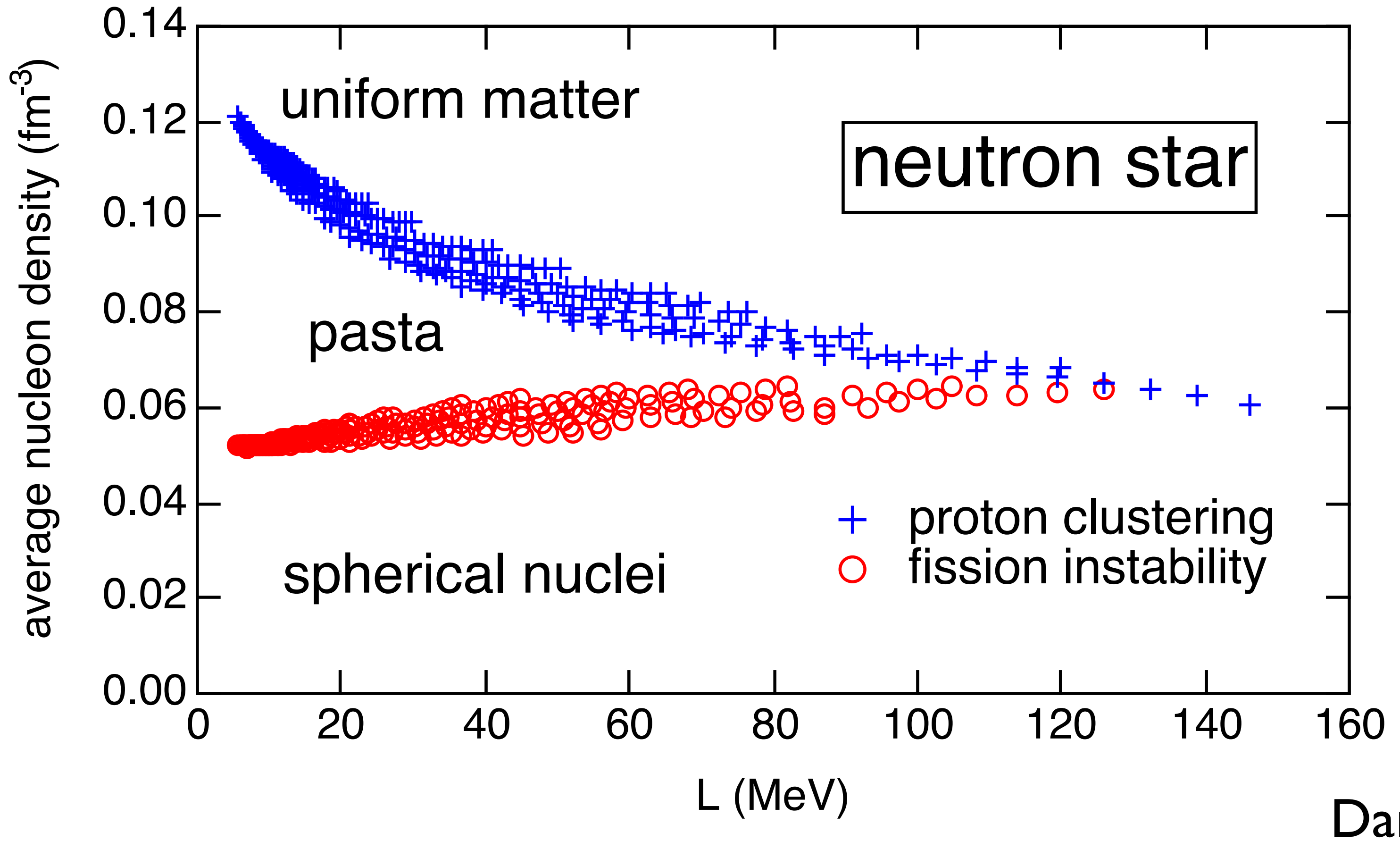
Inner-crust nuclei: Proton number and fraction decrease with L

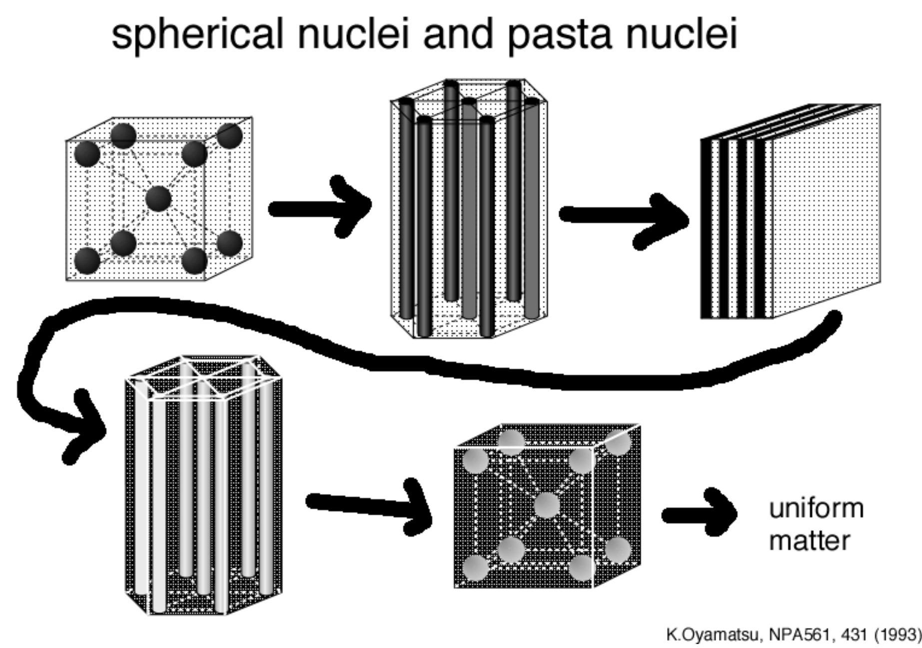




For large L, S(n) at $n<n_0$ is small so that nuclei become more neutron-rich.

Core-crust boundary of a neutron star





core-crust boundary density (blue cross +)
layer of pasta nuclei
spherical nuclei (red circle o)

Oyamatsu and Iida, PRC75, 015801, 2007.

Dark domains means nuclei (proton clusters).
At low densities in neutron-star crusts, we have nuclei which are more or less spherical.
In the core we have uniform matter. Pasta nuclei could exists in between.

Existence of pasta nuclei depends on the EOS.

Estimate of density region of pasta nuclei

C.J. Pethick and D.G. Ravenhall, Annu. Rev. Nucl. Part. Sci.**45**, 429 (1995).

lower boundary

stability against fission of spherical nuclei

In the liquid drop model, (Coulomb self energy)=2*(surface energy)

==> (volume fraction of nucleus) = 1/8

upper boundary (core-crust boundary)

instability against forming proton clusters

$$v(Q) = v_0 + 2(4\pi e^2\beta)^{1/2} - \beta k_{\mathrm{TF}}^2 > 0$$

$$Q^2 = \left(\frac{4\pi e^2}{\beta}\right)^{1/2} - k_{\mathrm{TF}}^2$$

$$v(Q) \approx v_0 = \frac{\partial\mu_p}{\partial n_p} - \frac{(\partial\mu_p/\partial n_n)^2}{\partial\mu_n/\partial n_n} = \left(\frac{\partial\mu_p}{\partial n_p}\right)_{\mu_n,\mu_e}$$

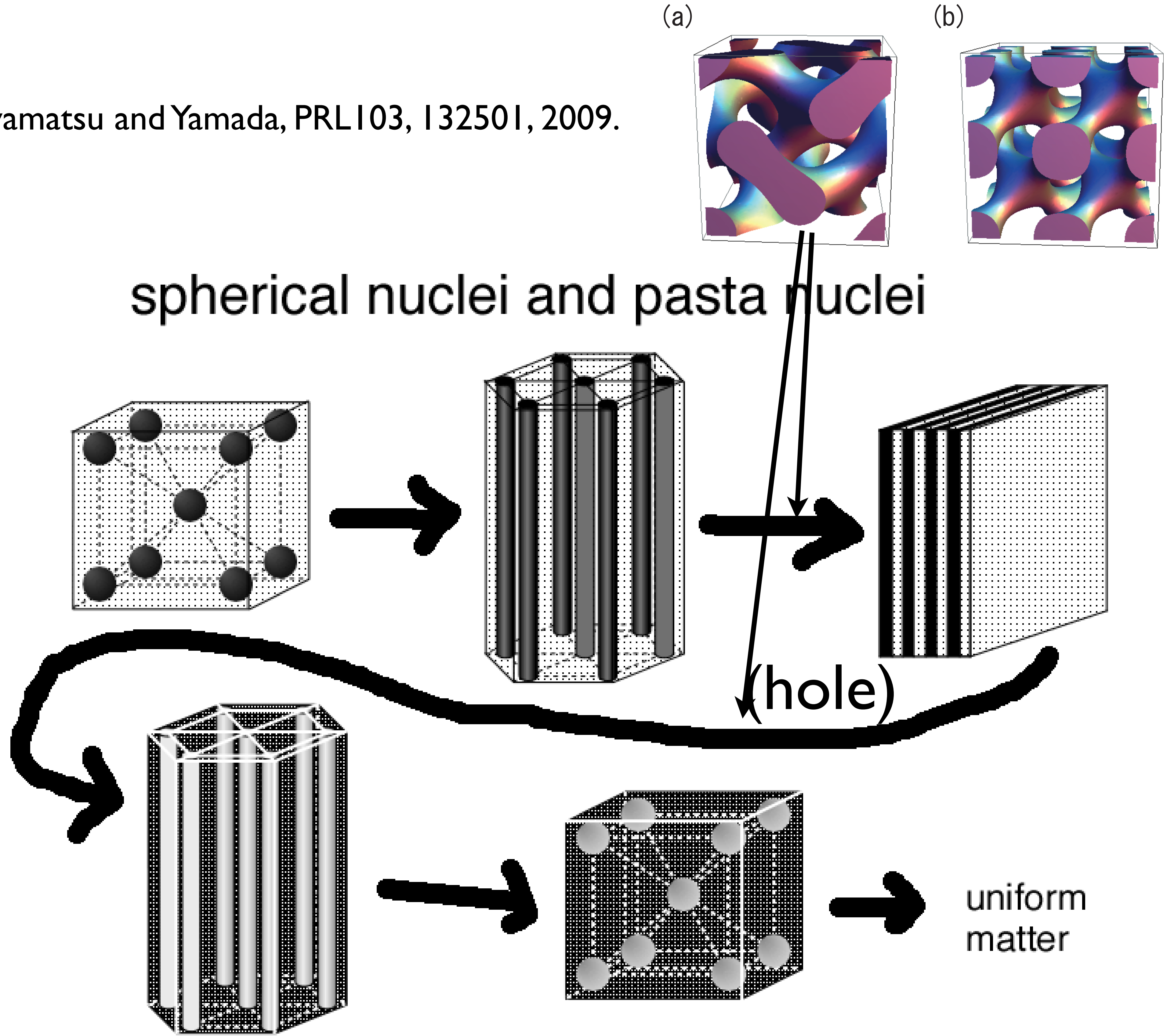
The derivative of μ implies the L dependensce

$$\beta = D_{pp} + 2D_{np}\zeta + D_{nn}\zeta^2, \qquad \zeta = -\frac{\partial\mu_p/\partial n_n}{\partial\mu_n/\partial n_n},$$

$$k_{\mathrm{TF}}^2 = \frac{4\pi e^2}{\partial\mu_e/\partial n_e} = \frac{4\alpha}{\pi}(3\pi^2 n_e)^{1/3}.$$

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

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



Summary : S_0 or L?

- S_0 dominates masses and sizes of stable nuclei
  - The sensitivities to L is not very large : neutron drip line, neutron drip point of neutron stars
- L is density slope of the symmetry energy S(n)
  - L => energy and density distribution at nuclear surface
  - It requires differentiation (probably of 2nd order), not easy to determine from a single nuclide.
  - Z/A dependence of S_{2p}(, S_{2n}), size and neutron skin
  - Light unstable nuclei (A<50) seem suitable to constrain L but we need to take relatively large Wigner energy into account.
- Impacts on the inner crust structure of neutron stars
  - core-crust boundary, existence of pasta nuclei