Quantum simulations of nuclear pasta

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University of Tennessee

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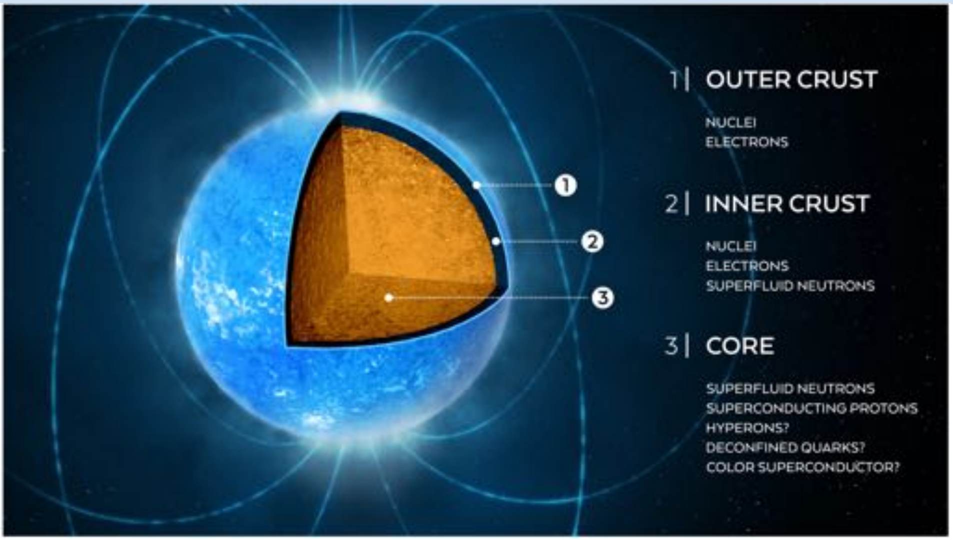
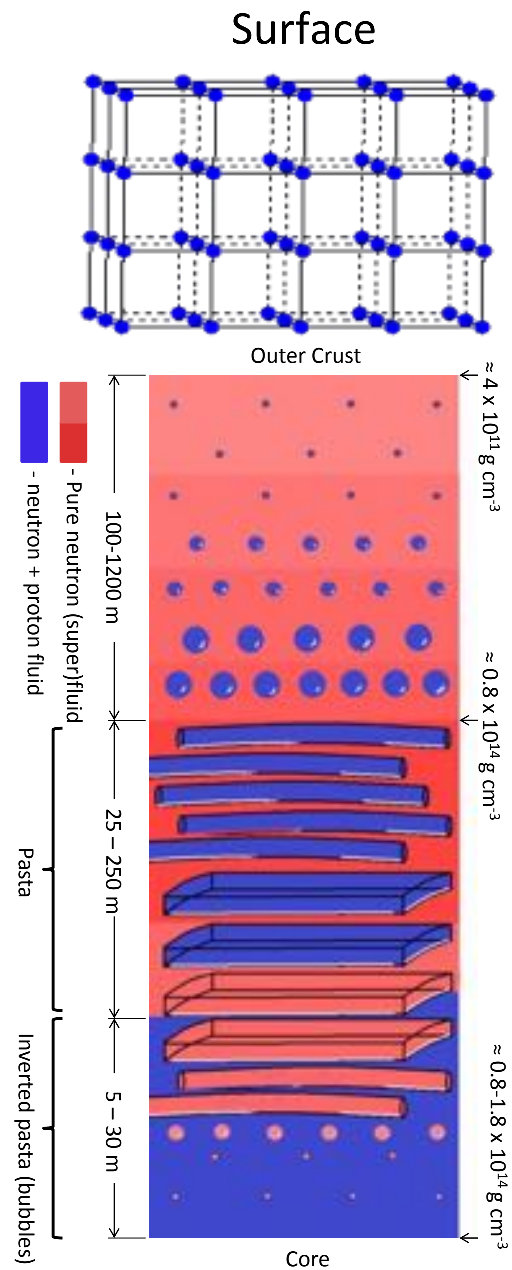
Frustration leads to pasta formation at the base of the inner crust



Outer Crust

Watts et al, arxiv:1602.01081



Pasta: Ravenhall, Pethick and Wilson Phys. Rev. Lett. 50, 2066, 1983

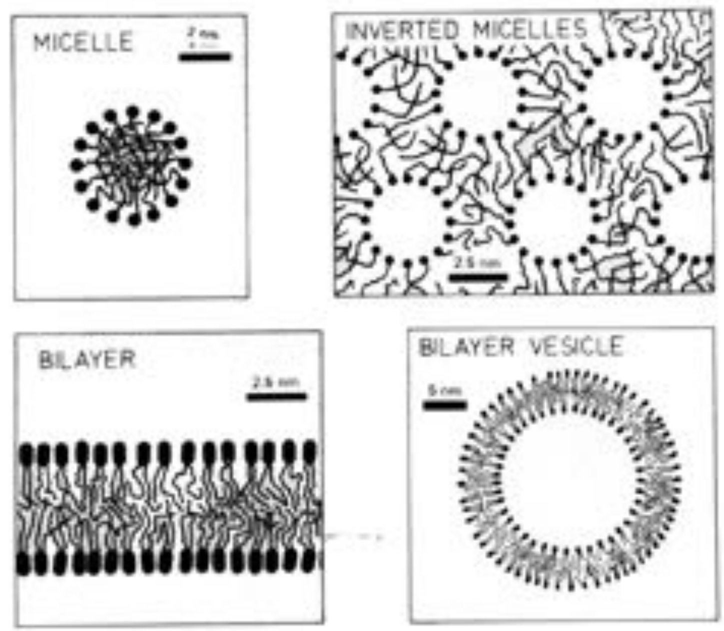
"… after all, the cooking of spaghetti, while it spoils the perfect straightness of the strands, does not destroy the characteristic short range order"

Pasta phenomenologically similar to terrestrial soft condensed matter

Amphiphilic molecules. On the left is sodium dodecyl sulphonate, a typical synthetic detergent whose structure is very similar to soap. On the right is diphosphatidyl choline, a phospholipid which is a major component of cell membranes as well as being the main ingredient of the food emulsifier lecithin.

Pasta phenomenologically similar to terrestrial soft condensed matter

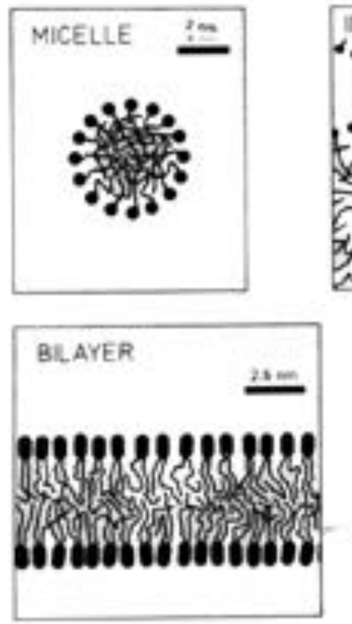
Amphiphilic molecules. On the l
synthetic detergent whose structu
diphosphatidyl choline, a phosph
membranes as well as being the
lecithin.



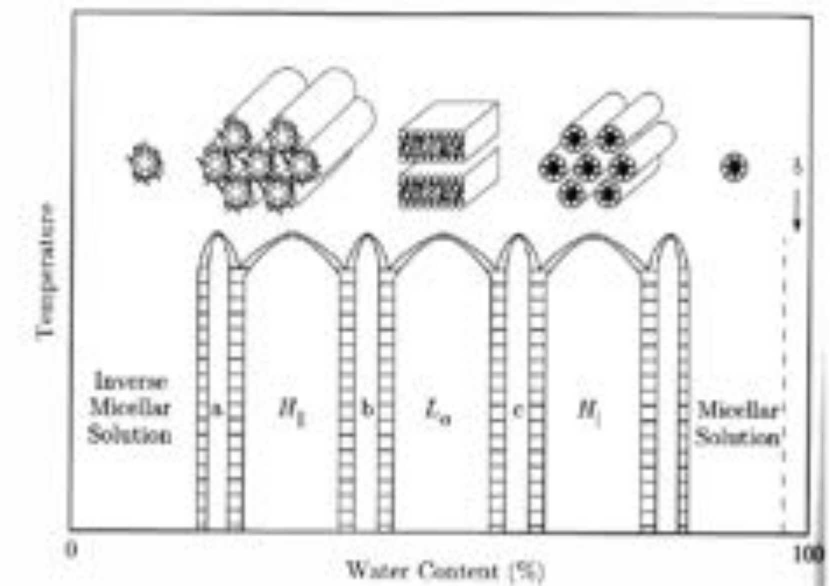
Self-assembled structures in surfactant solutions. From Israelachvili.

Pasta phenomenologically similar to terrestrial soft condensed matter

Amphiphilic molecules. On the l... synthetic detergent whose structu... diphosphatidyl choline, a phosph... membranes as well as being the ... lecithin.

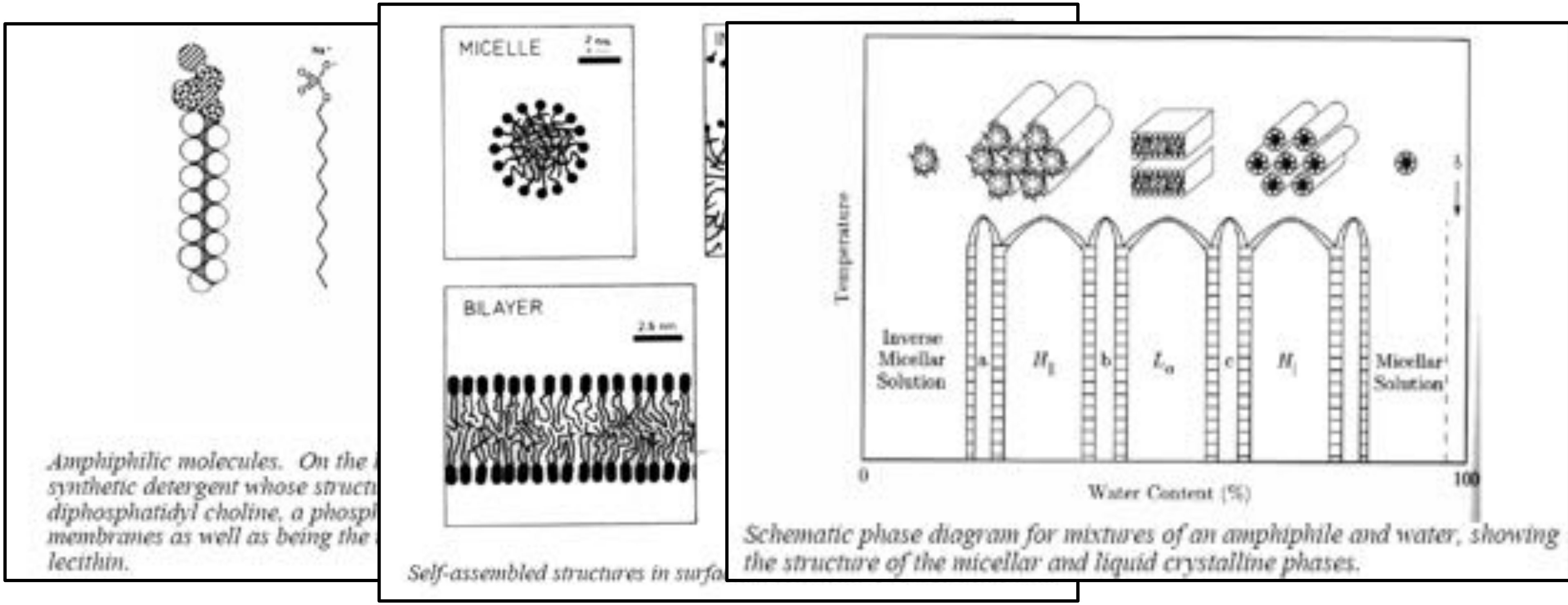


Self-assembled structures in surfa...



Schematic phase diagram for mixtures of an amphiphile and water, showing the structure of the micellar and liquid crystalline phases.

Pasta phenomenologically similar to terrestrial soft condensed matter



A wide range of mechanical properties are exhibited (liquid crystal – Pethick, Potehkin, Phys Lett B427, 1998)

See Caplan,Horowitz arxiv:1606.03646

Modeling pasta

Semi-classical:

Compressible Liquid Drop model (BBP 1971)

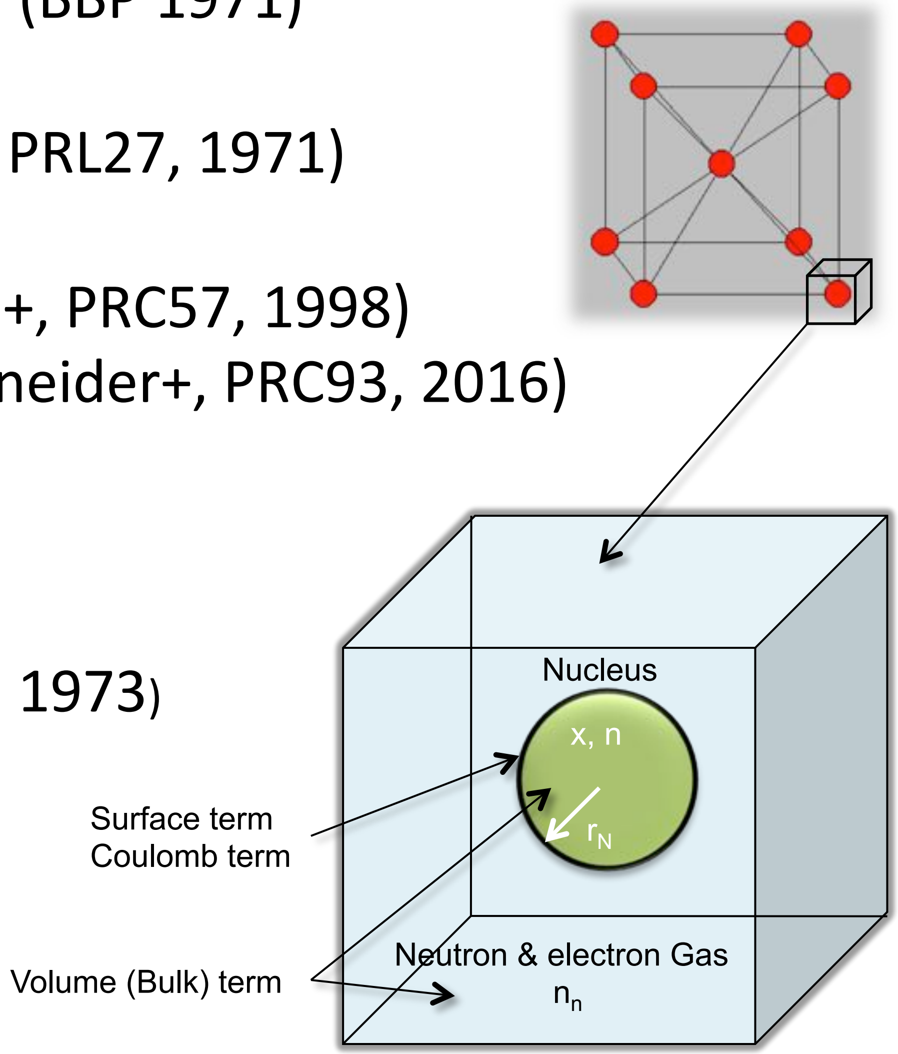
Thomas-Fermi (Buchler&Barkat, PRL27, 1971)

Molecular Dynamics (Maruyama+, PRC57, 1998)
(400,000+ nucleons, e.g. Schneider+, PRC93, 2016)

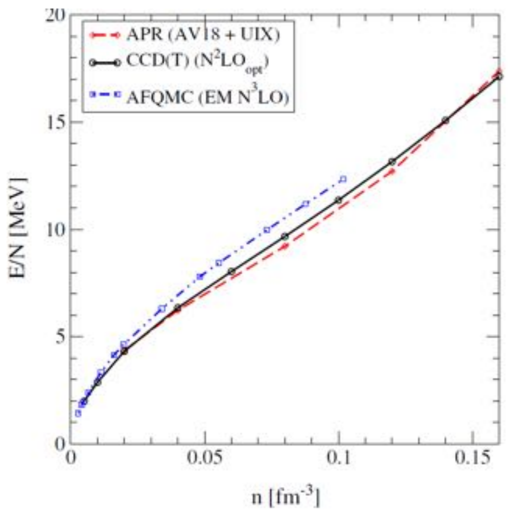
Quantum:

Hartree-Fock
(Negele&Vautherin, NPhysA207, 1973)

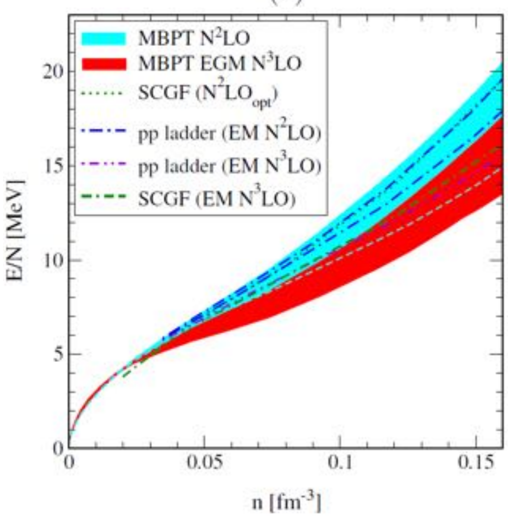
5000+ nucleons



Systematic EOS modeling



(a)



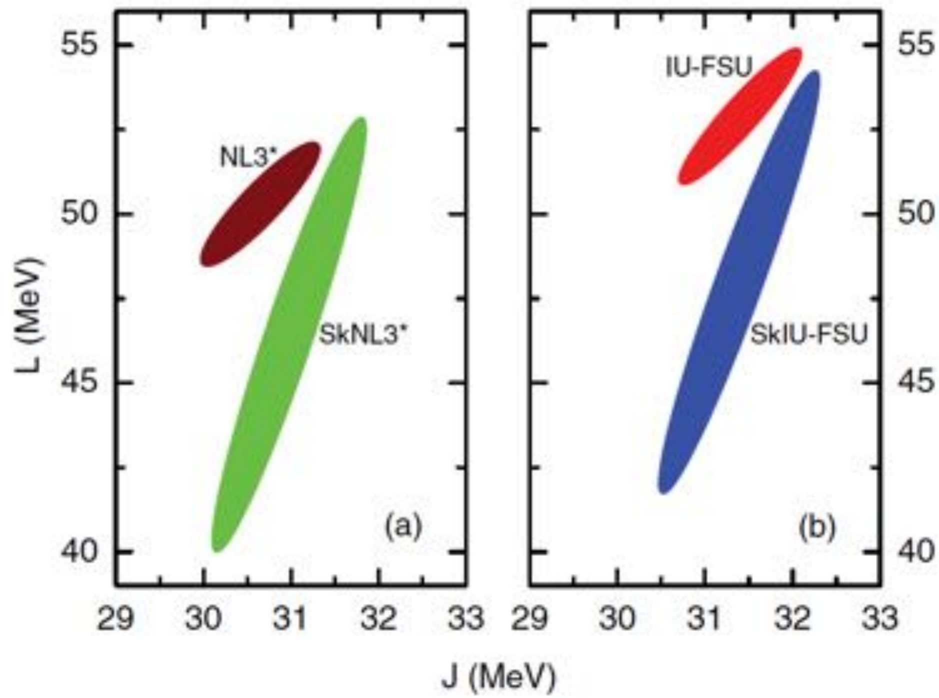
(b)

Gandolfi, Gezerlis, Carlson, ARNPS 65 (2015)

Use our best calculations of PNM properties to constrain our EOS models.

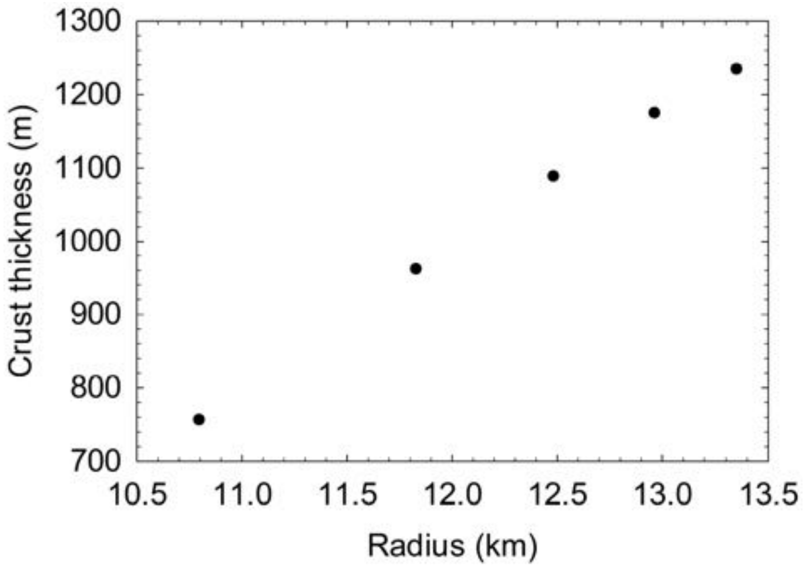
2 purely isovector parameters in Skyrme and RMF energy density functionals – allows us to take a baseline model and refit those two parameters to PNM "data"

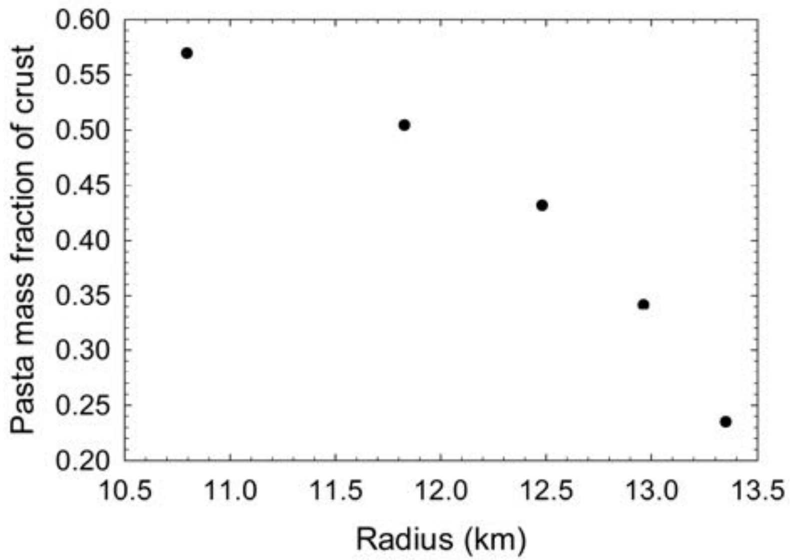
Polytropes above $1.5n_0$ tuned to give desired max mass 2+M_{sun}



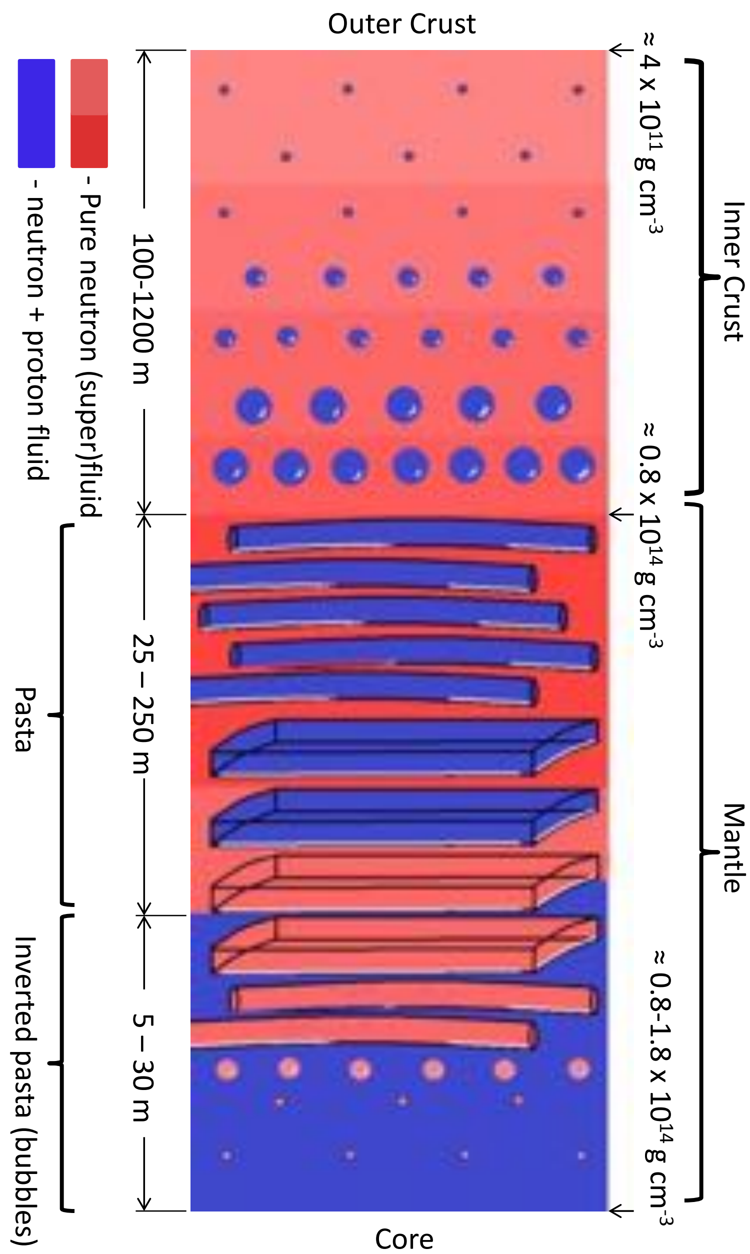
Fattoyev, Newton, Xu, Li, PRC86, 025804 (2012)
Brown, Schwenk, PRC89, 011307 (2014)

How much pasta is there?





Newton, Fattoyev, in prep.



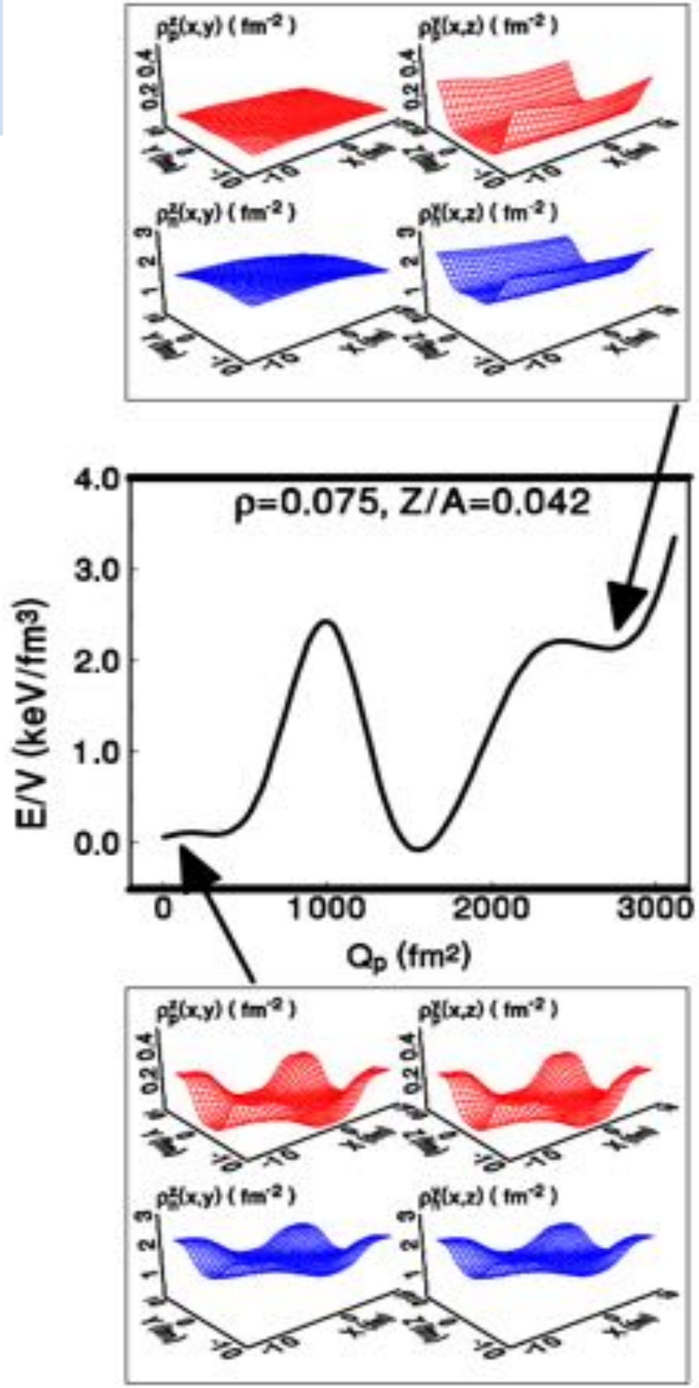
3D Hartree-Fock Simulations of Pasta

Shell structure of unbound neutrons (scattering from Pasta structures) means many low-lying energy minima (Quantum frustration)

Disordered, amorphous

(Magierski & Heenen PRC 045804 2002)

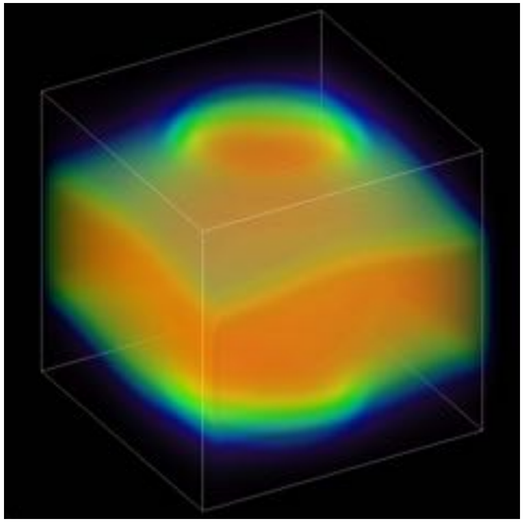
“Fermionic Casimir Effect”, effective attraction between certain structures

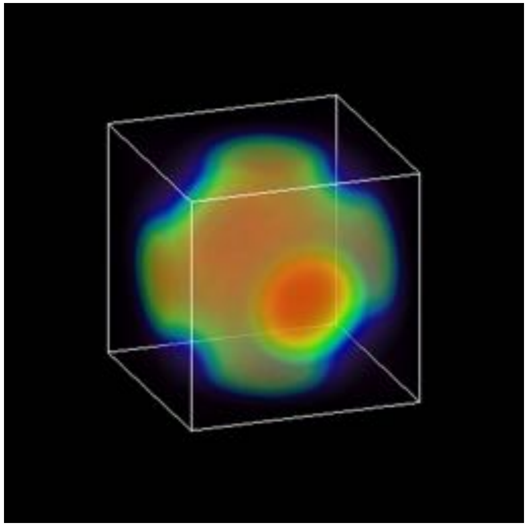


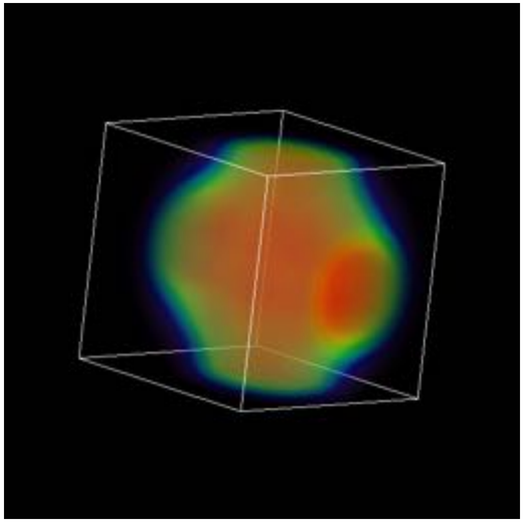
3D Hartree-Fock Simulations of Pasta

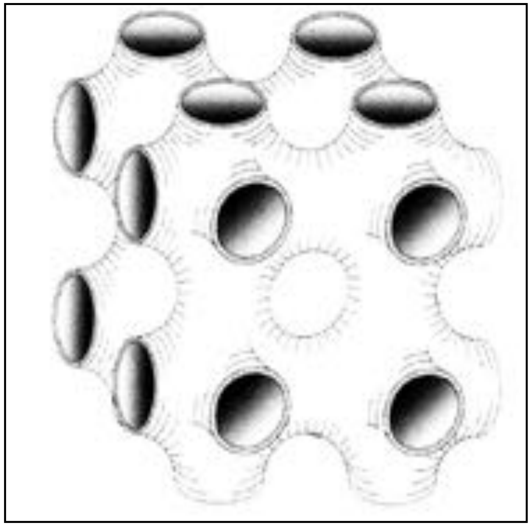
Finite Temperature, $y_p = 0.3$;

Newton+, PhD Thesis, Jphys Conf Series 46, 2006; PRC 055801, 2009



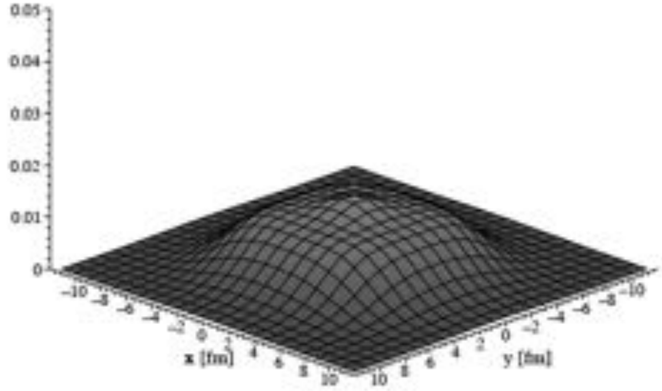


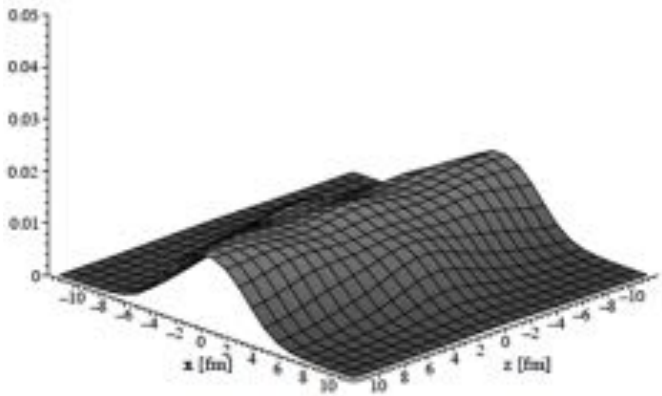


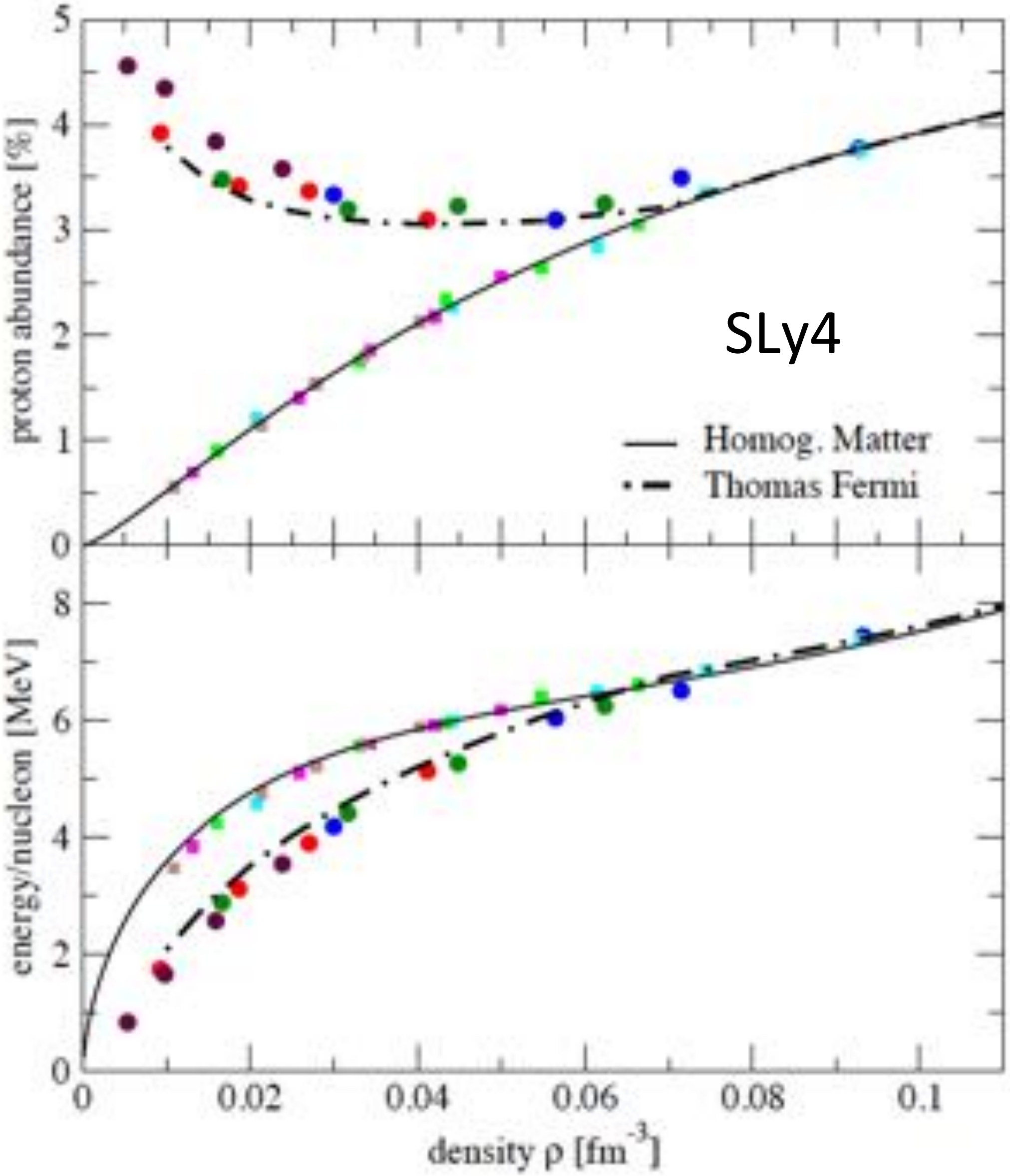


Amphiphilic Bicontinuous Cubic-P Phase

3D Hartree-Fock Simulations of Pasta



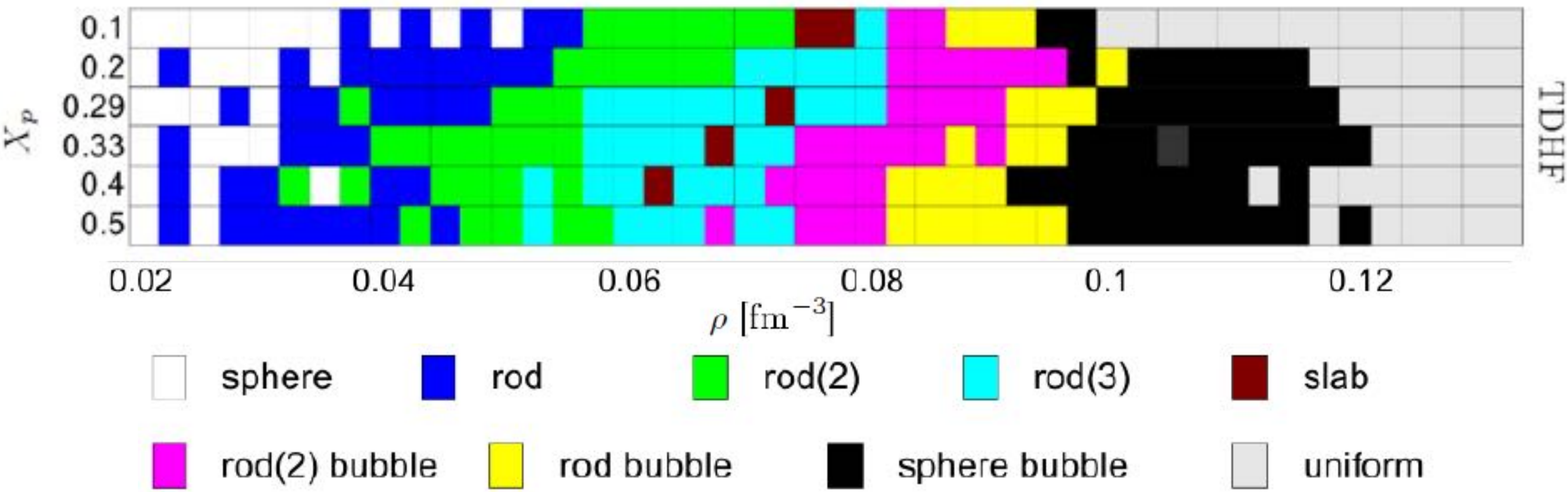


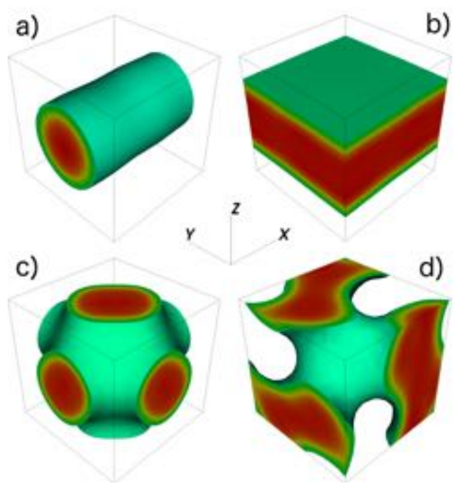


Gögelein&Müther, PRC 024312, 2007

Skyrme and RMF simulations

3D Hartree-Fock Simulations of Pasta



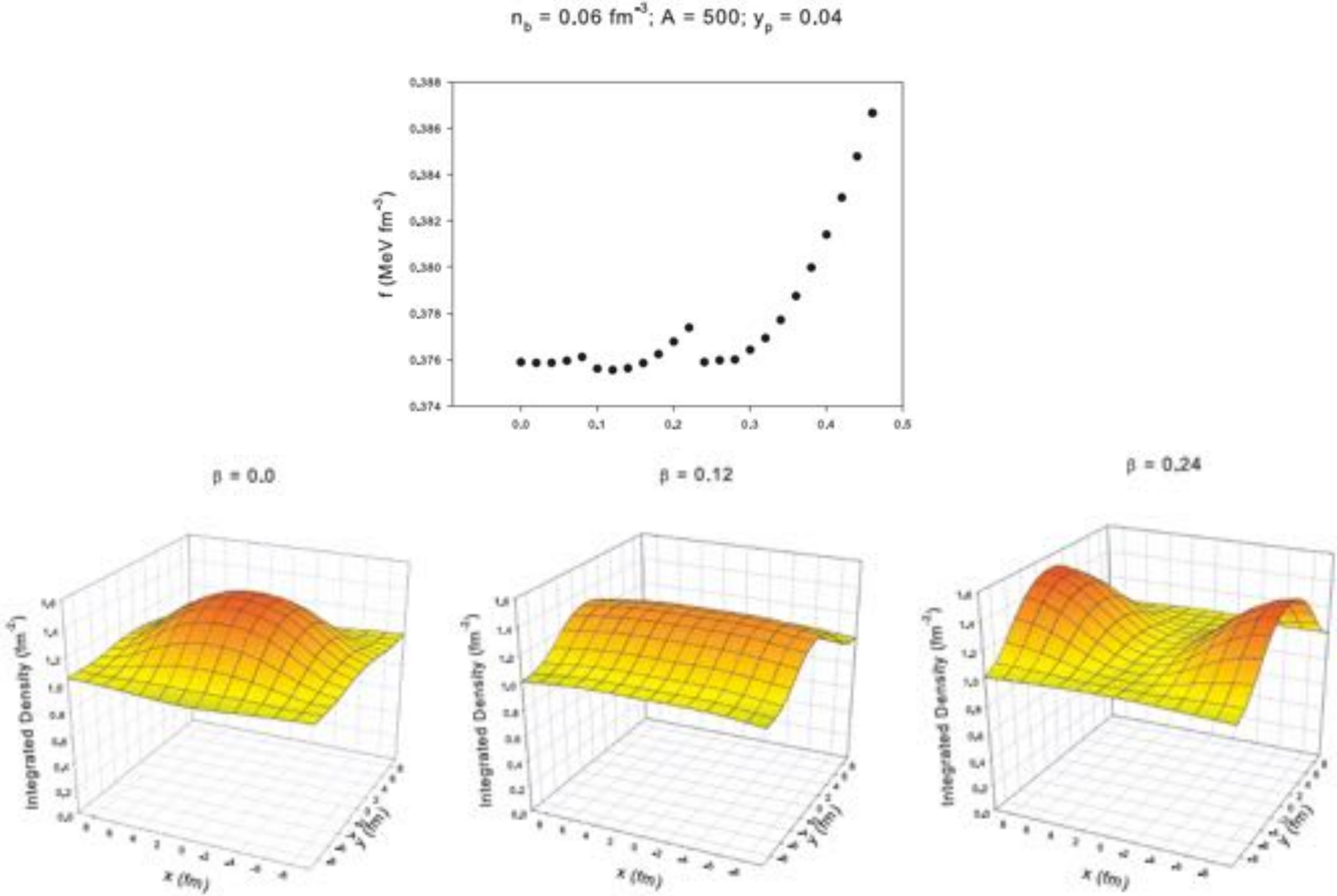


y_p=0.1 – 0.3

Guiding potentials to obtain gyroid shapes

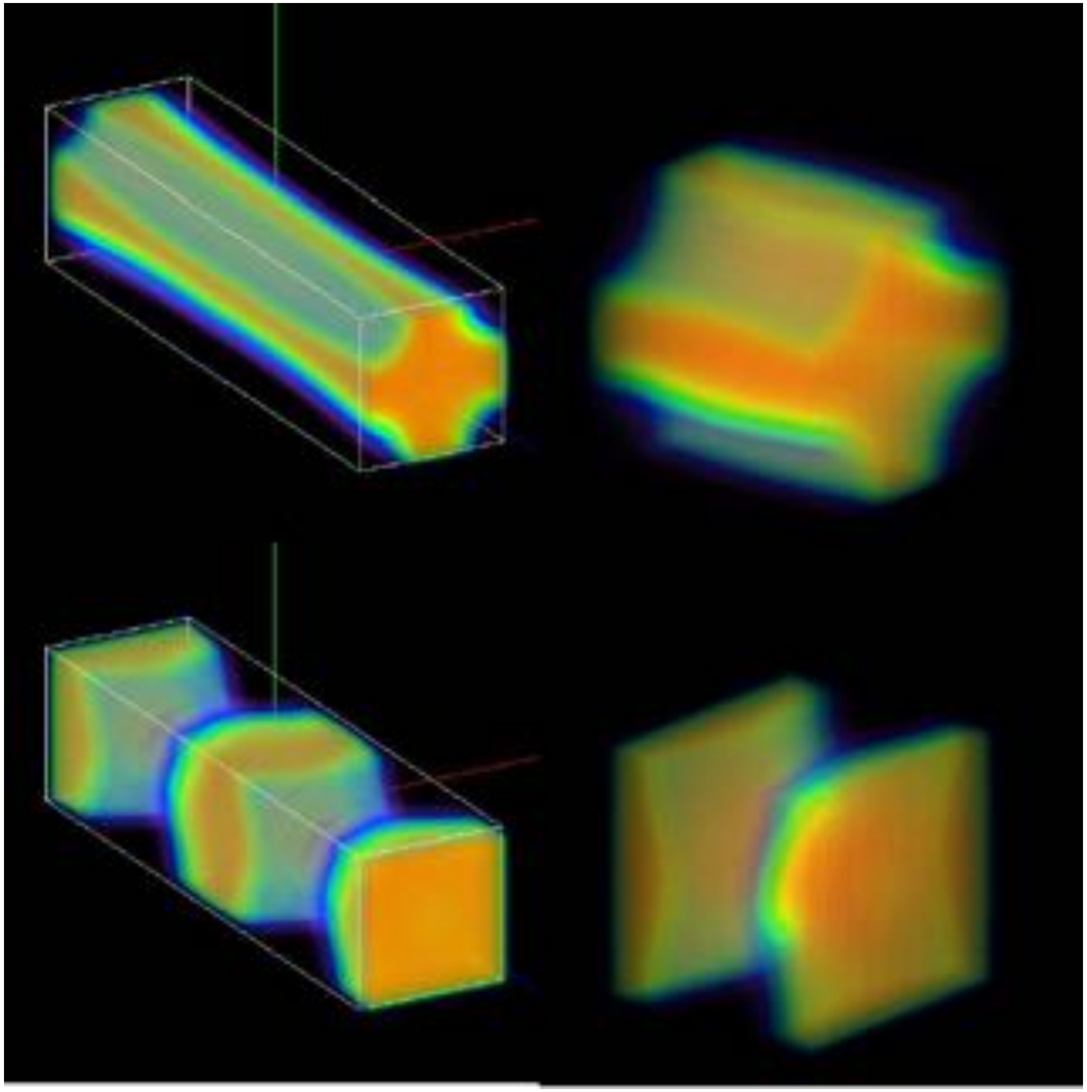
Schuetrumpf+ PRC 025801, 2015; 045806, PRC 2015

3D Hartree-Fock: Boundary Conditions



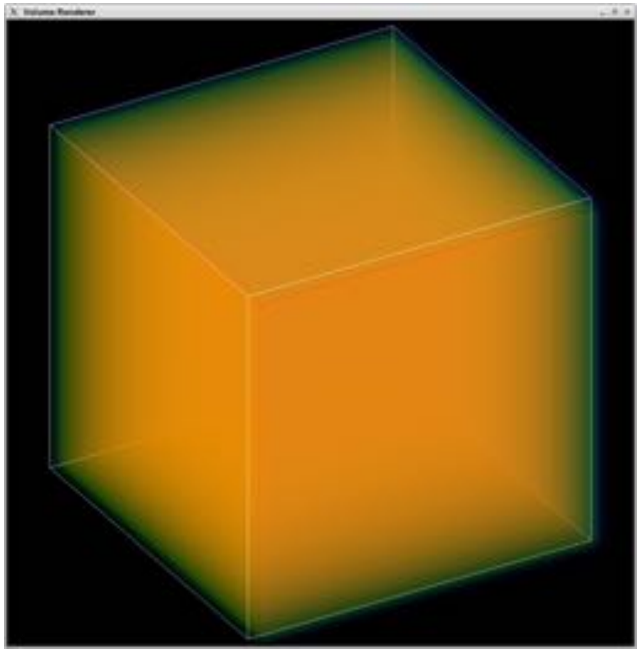
Newton+, PhD Thesis, Jphys Conf Series 46, 2006; PRC 055801, 2009

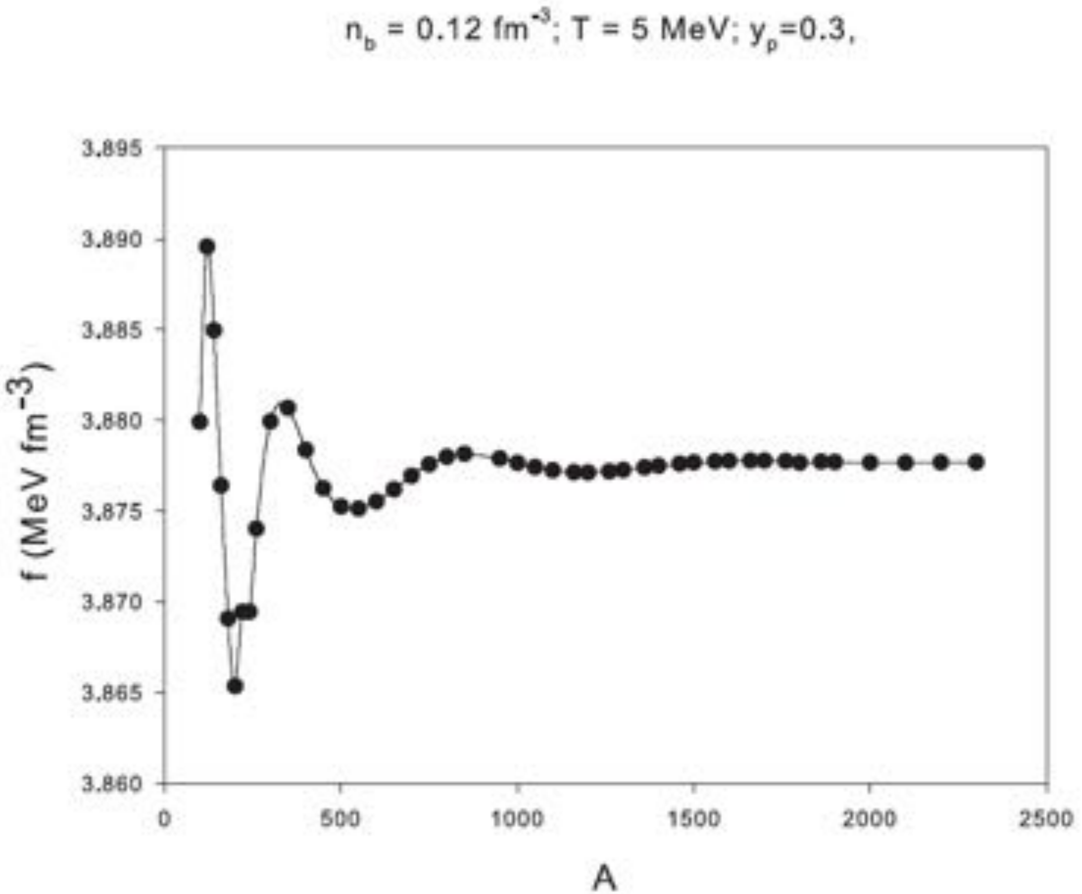
3D Hartree-Fock: Boundary Conditions



Newton+, PhD Thesis, Jphys Conf Series 46, 2006; PRC 055801, 2009

3D Hartree-Fock: Boundary Conditions – spurious shell effects



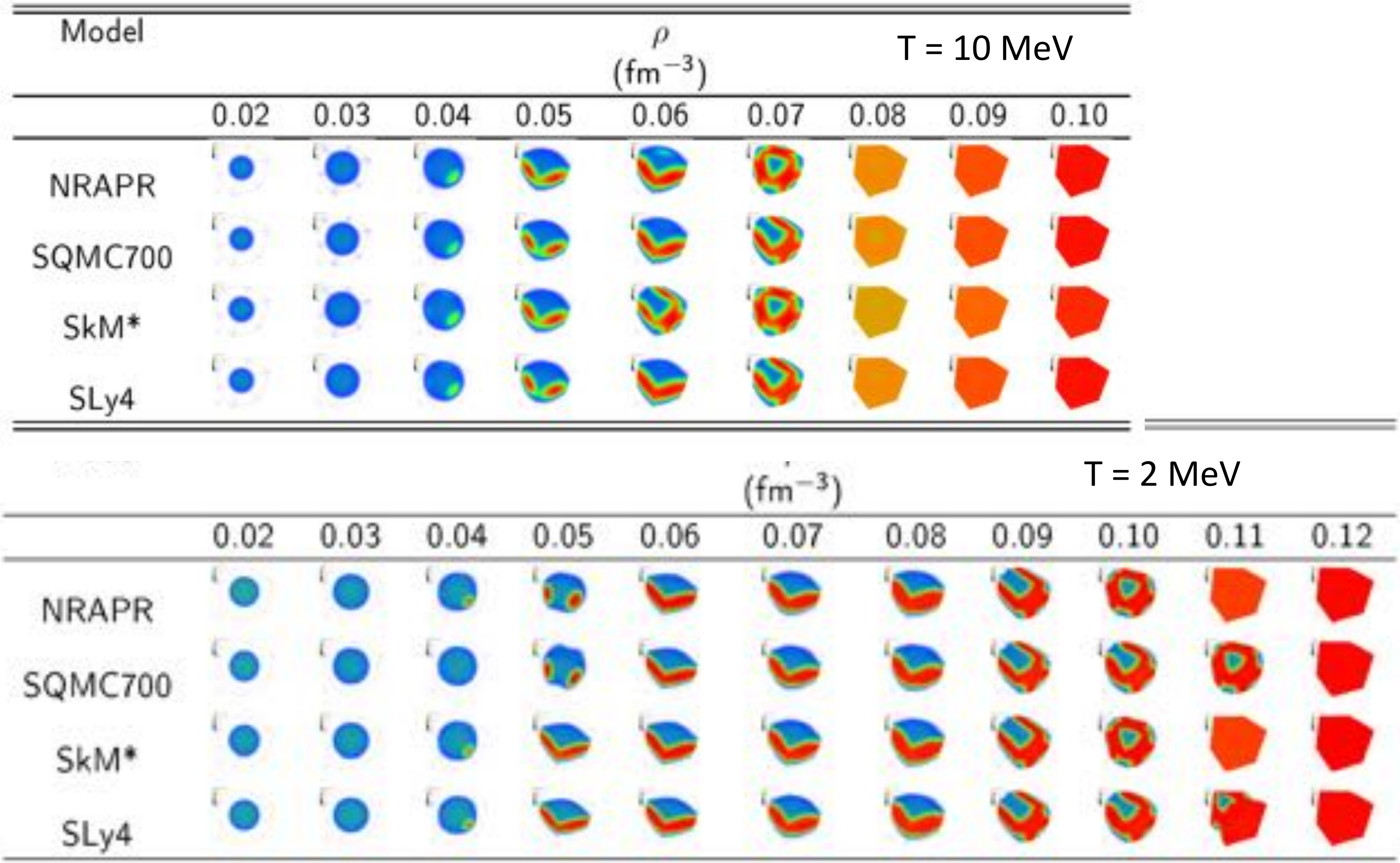


Solution: average over Bloch momentum covectors

$$\psi_{k,q}(\mathbf{r} + \mathbf{T}) = e^{i\mathbf{K}\cdot\mathbf{T}}\psi_{k,q}(\mathbf{r}),$$

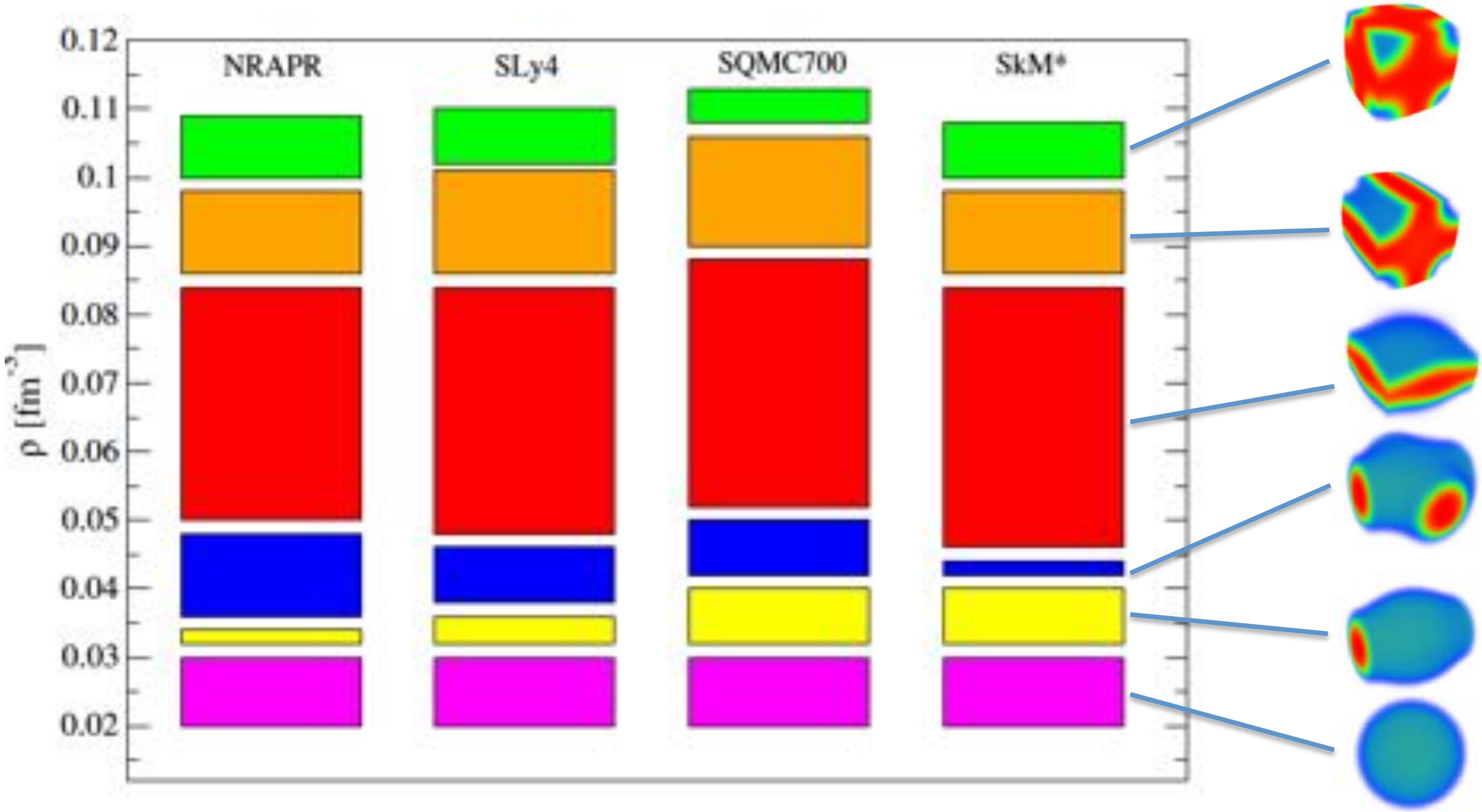
Schuetrumpf+ 045806, PRC 2015

Pasta in hot, “proton rich” matter $y_p = 0.3$



Newton, Stone, PRC 055801, 2009; Pais, Newton, PRL 151101, 2012
Pais, Newton, Stone PRC 065802, 2014

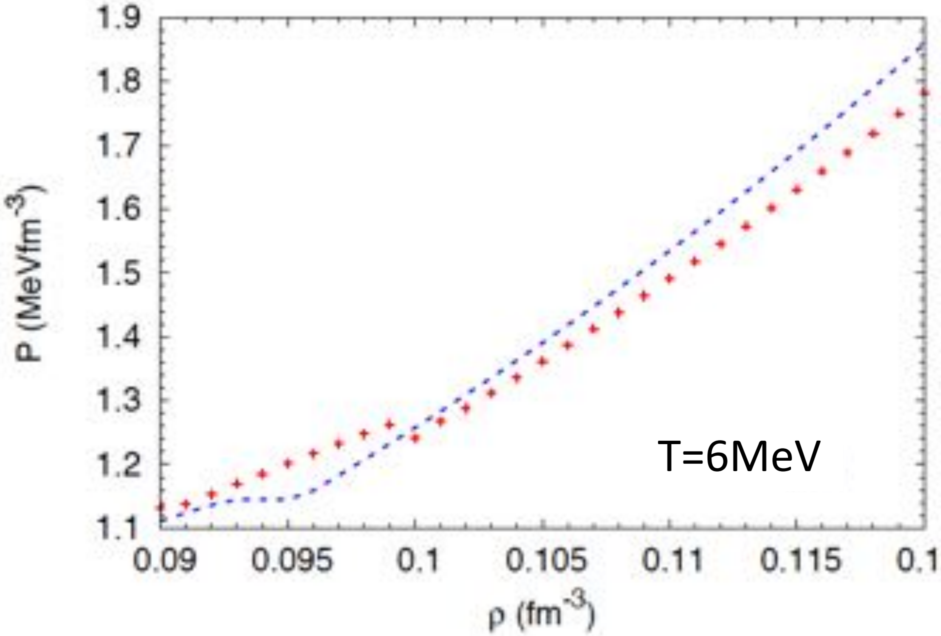
Pasta in hot, "proton rich" matter $y_p = 0.3$

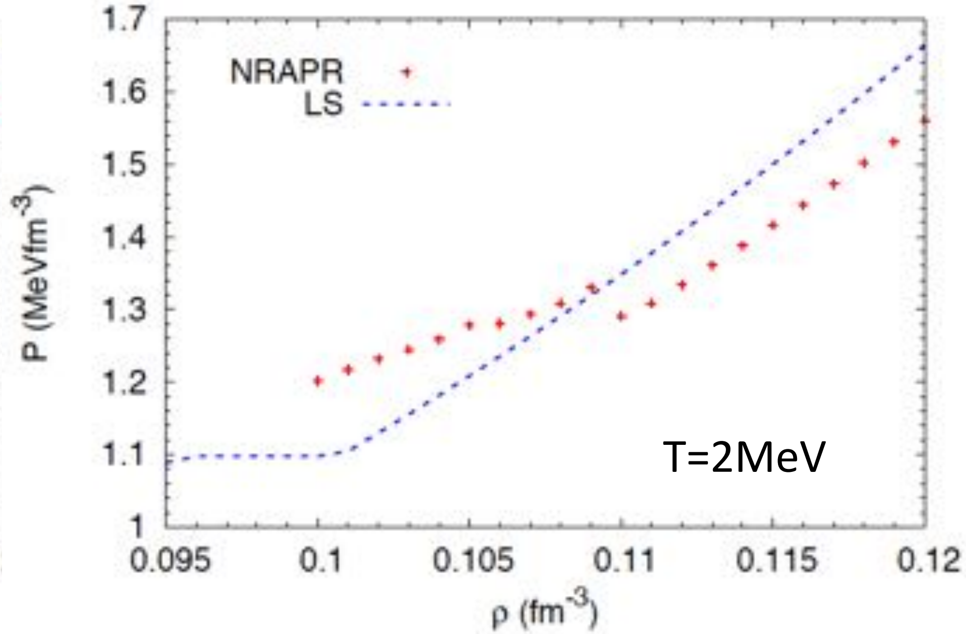


T = 2 MeV

Pais+, PRL 151101, 2012

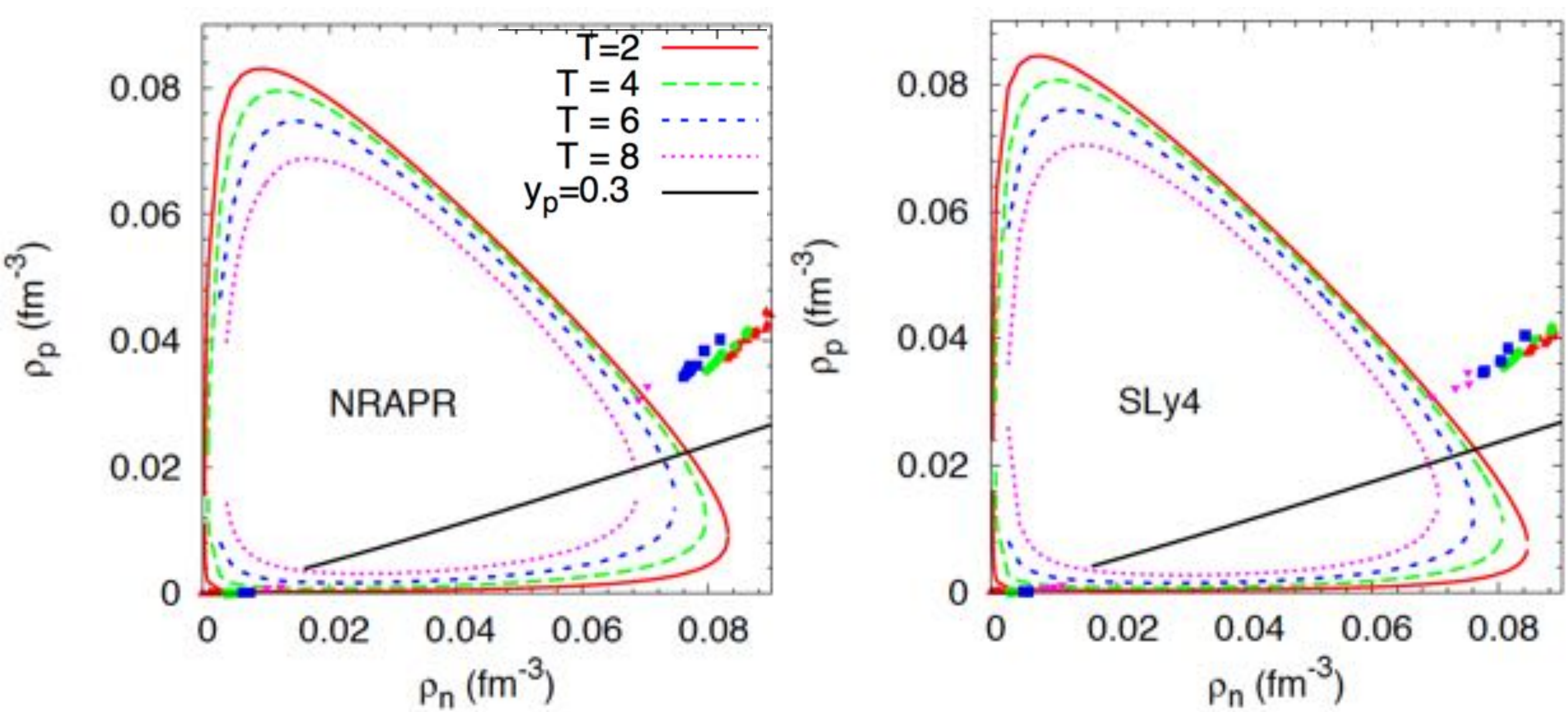
Pasta in hot, "proton rich" matter $y_p = 0.3$





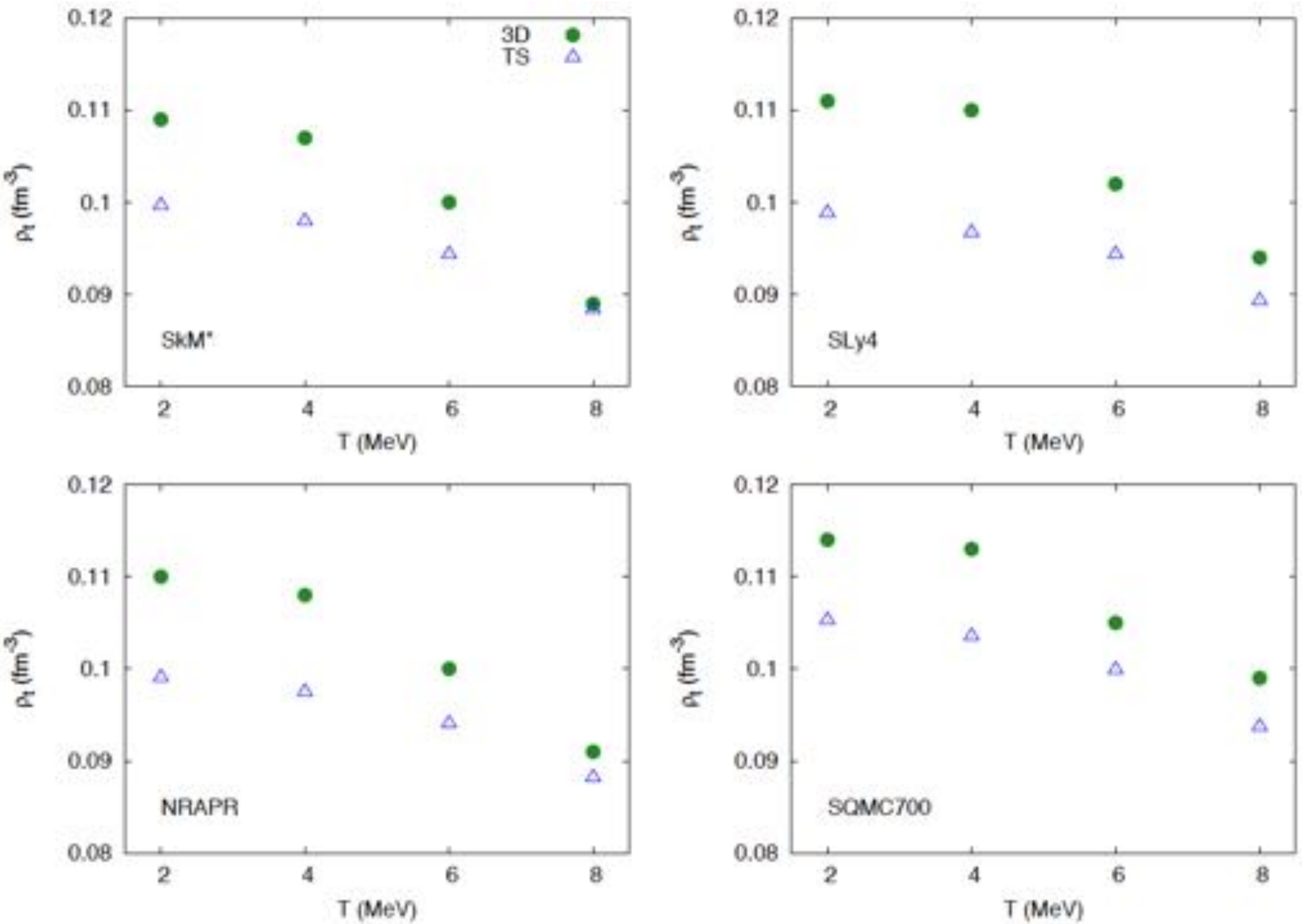
Pais, Newton, Stone, PRC 065802, 2014

Pasta in hot, "proton rich" matter $y_p = 0.3$



Pais, Newton, Stone, PRC 065802, 2014

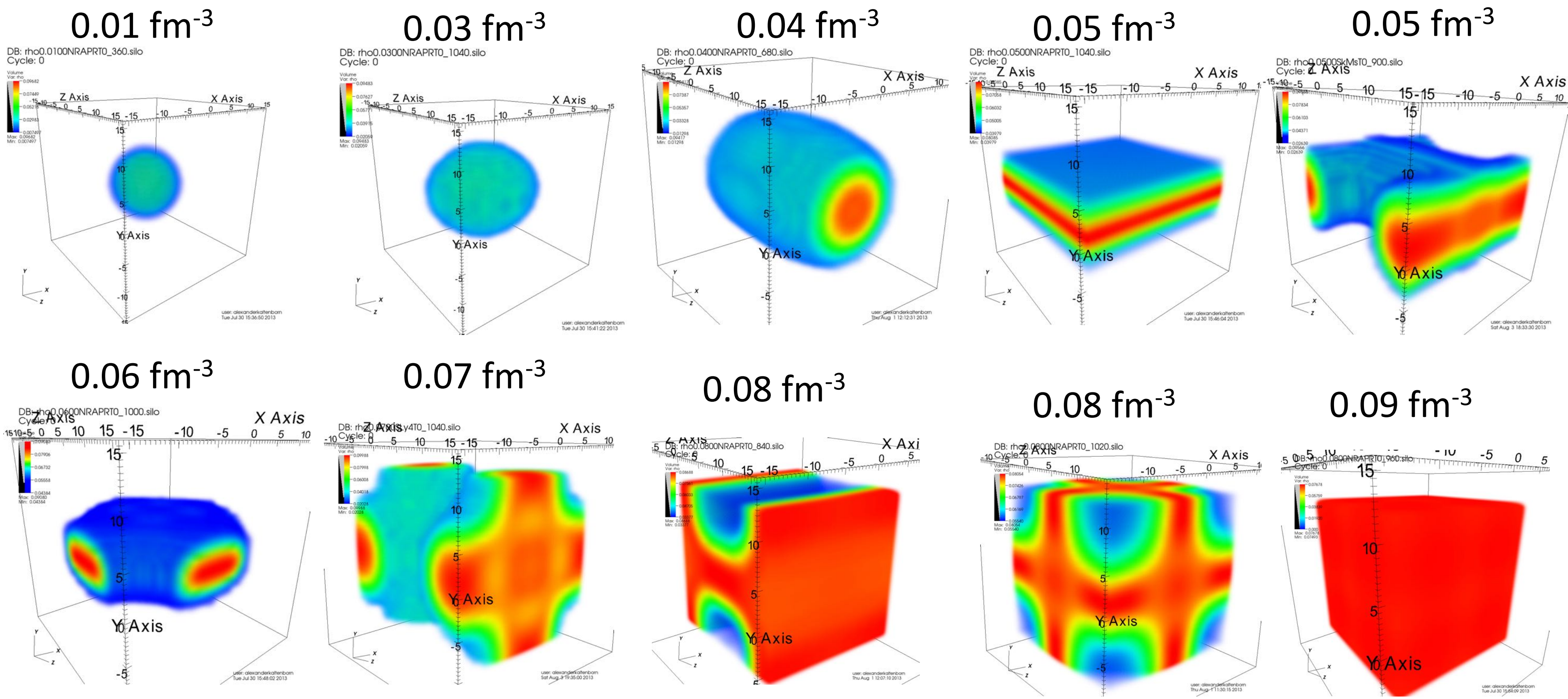
Pasta in hot, "proton rich" matter $y_p = 0.3$



Pais, Newton, Stone, PRC 065802, 2014

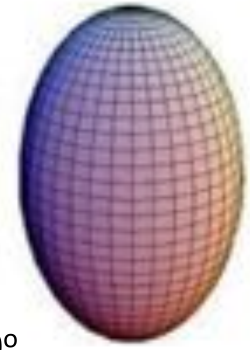
Pasta transitions in the neutron star crust

NRAPR, $y_p = 0.02 - 0.03$; Pasta starts appearing at $n_b \approx 0.04\ \text{fm}^{-3}$



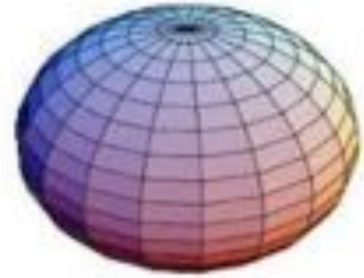
Newton, Stone, Kaltenborn, *in prep*

Disordered pasta

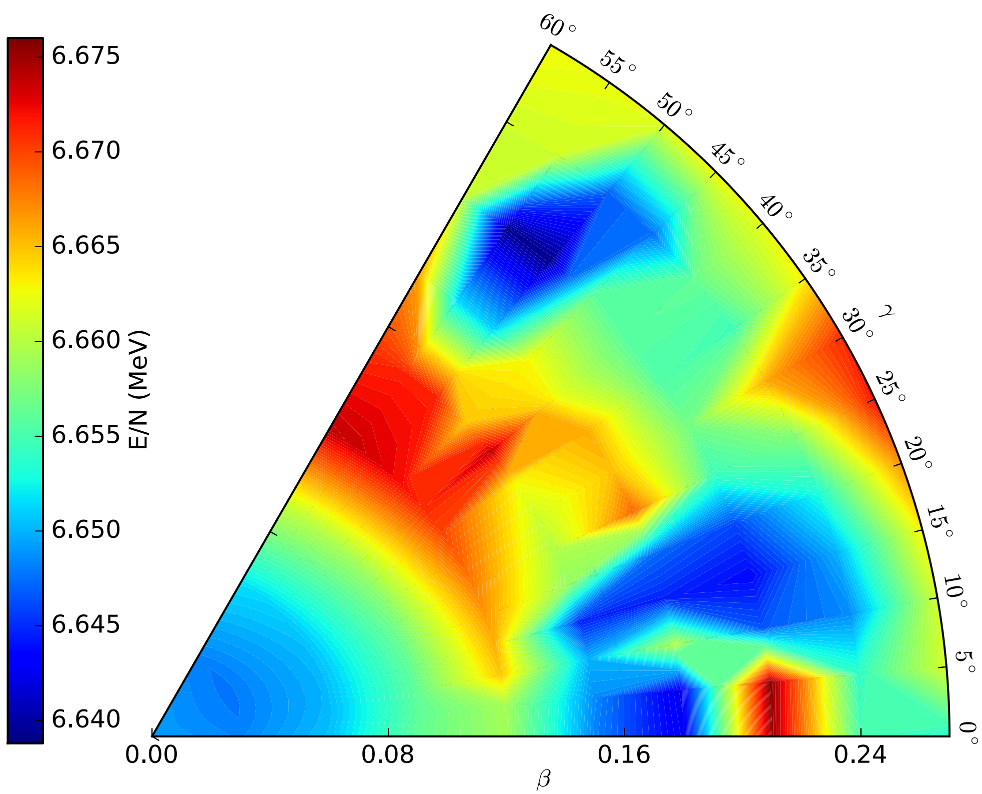


Prolate: $\gamma=0^o$
Increasingly deformed with β

Spherical: $\beta=0$

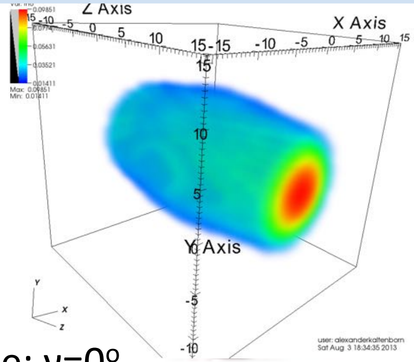


Oblate: $\gamma=60^o$
Increasingly deformed with β

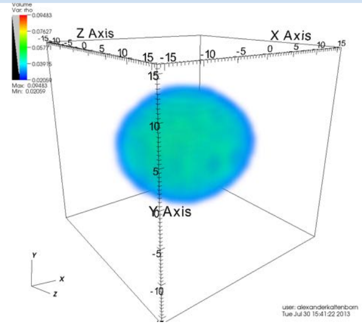


Newton, Kaltenborn and Stone, in prep

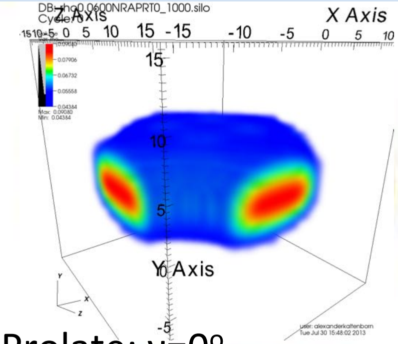
Disordered pasta



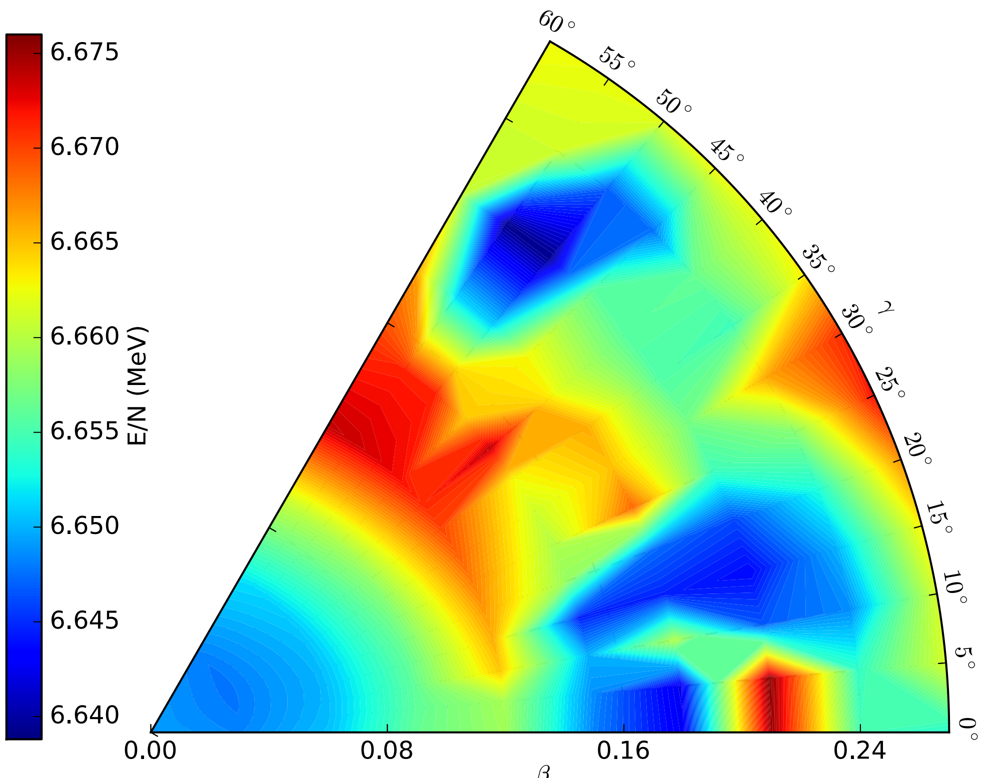
Prolate: $\gamma=0^{o}$
Increasingly deformed with β



Spherical: $\beta=0$



Prolate: $\gamma=0^{o}$
Increasingly deformed with β



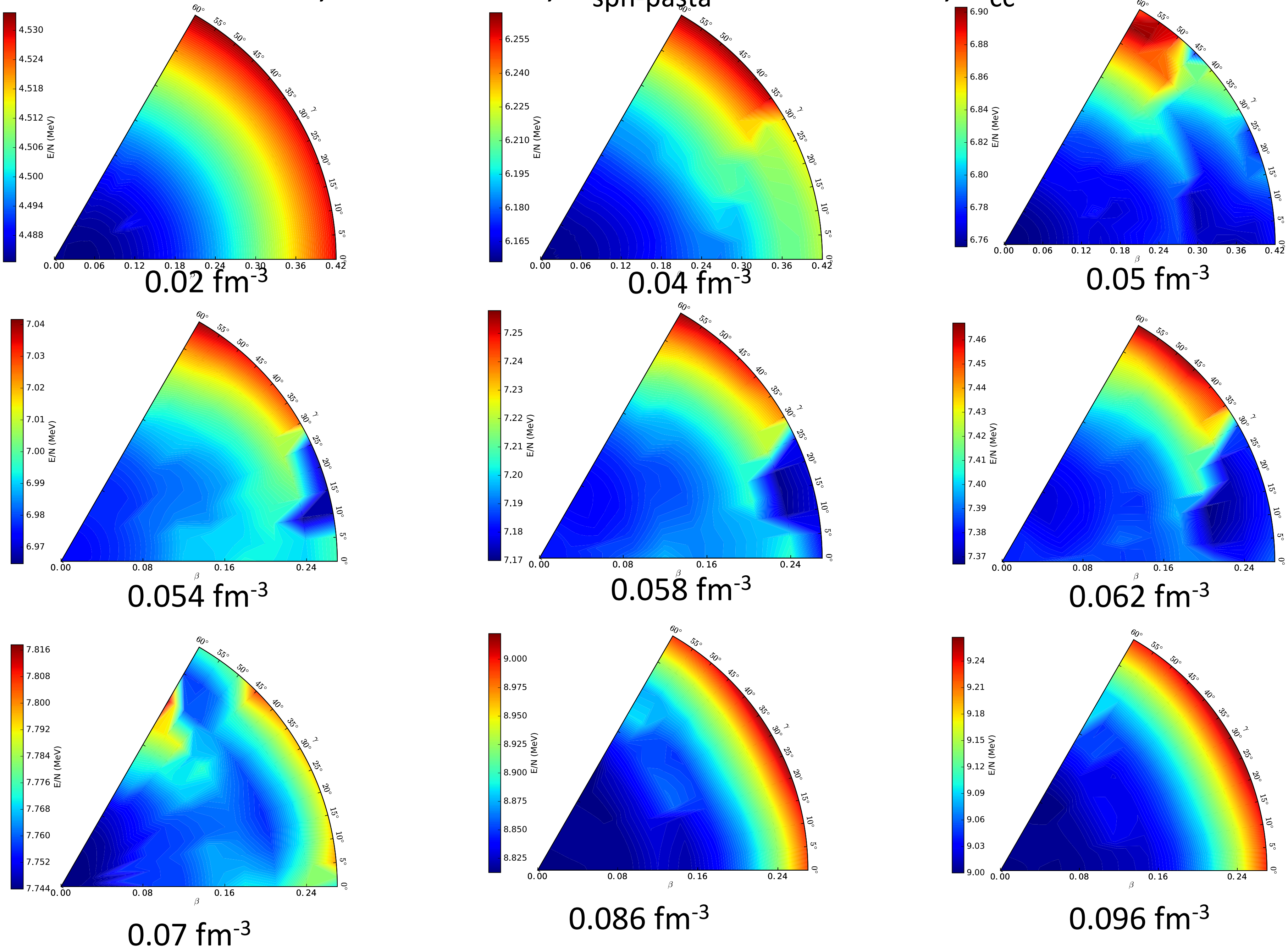
Newton, Kaltenborn and Stone, in prep

Minima separated by energy barriers <10 keV/particle

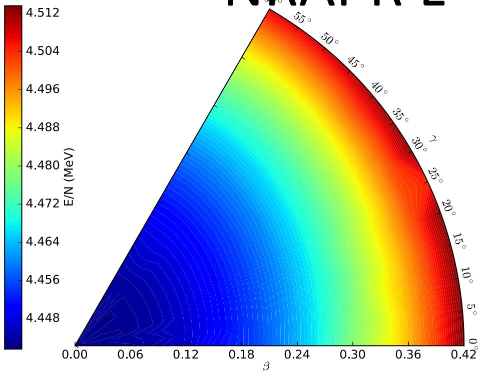
As mantle cools below $10^{8\text{-}9}$K, pasta phases may organize into microscopic domains containing different geometries coexisting at the same density

Highly disordered

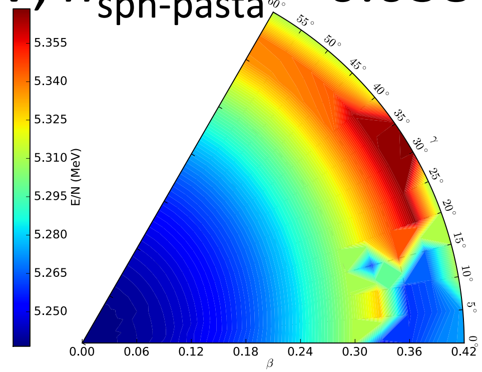
SkIUFSU; L = 30 MeV; $n_{\text{sph-pasta}}$ = 0.045 fm^{-3}; n_{cc} = 0.098 fm^{-3}



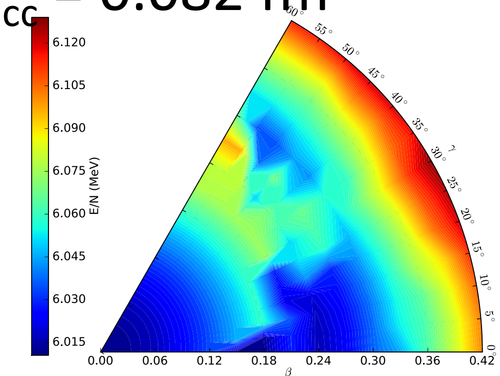
NRAPR L = 60 MeV; $n_{\text{sph-pasta}}$ = 0.038 fm^{-3}; n_{cc} = 0.082 fm^{-3}



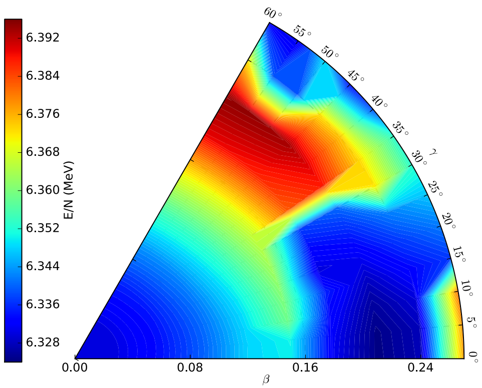
0.02 fm^{-3}



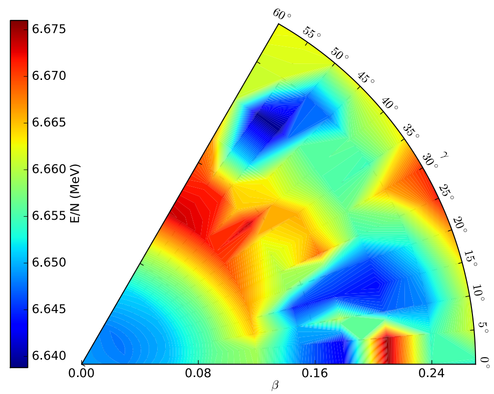
0.04 fm^{-3}



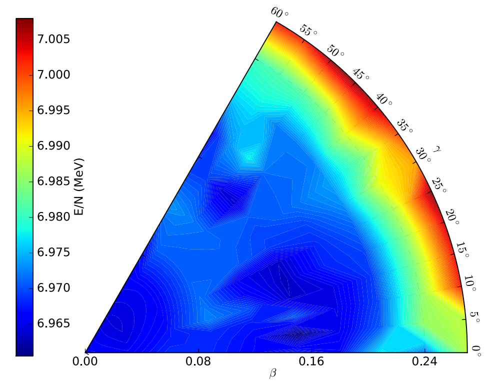
0.05 fm^{-3}



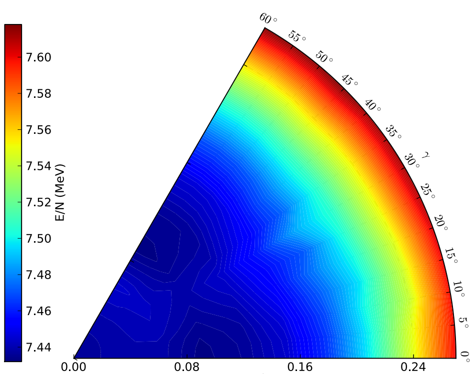
0.054 fm^{-3}



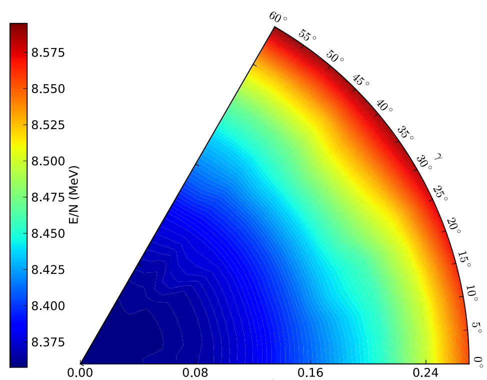
0.058 fm^{-3}



0.062 fm^{-3}

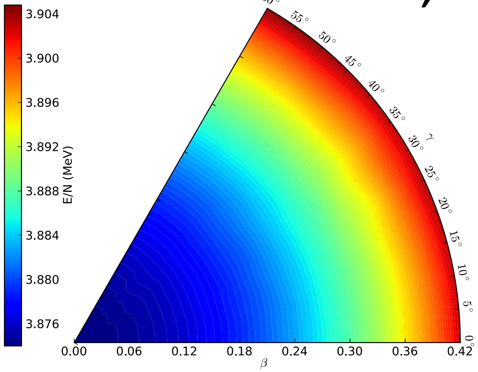


0.07 fm^{-3}

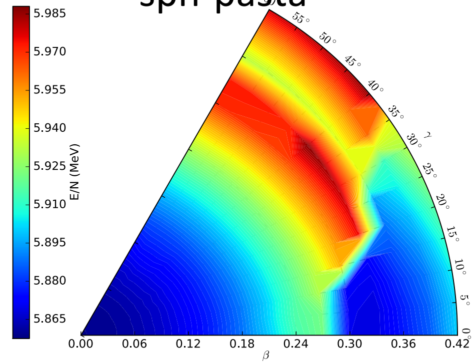


0.08 fm^{-3}

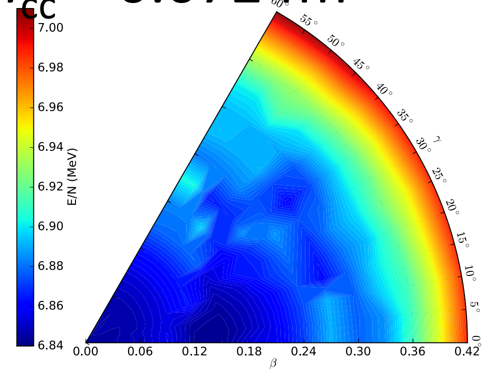
SkIUFSU; L = 90 MeV; $n_{\text{sph-pasta}}$ = 0.039 fm^{-3}; n_{cc} = 0.072 fm^{-3}



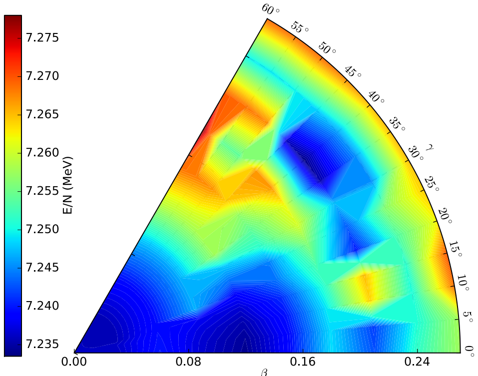
0.02 fm^{-3}



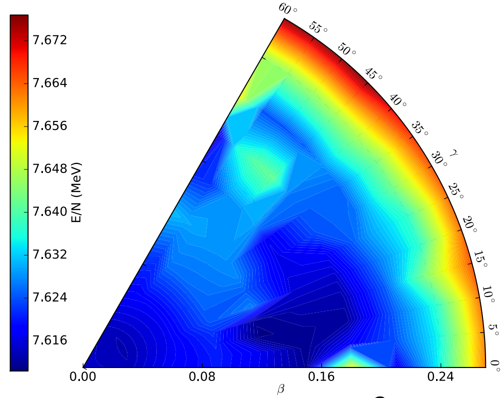
0.04 fm^{-3}



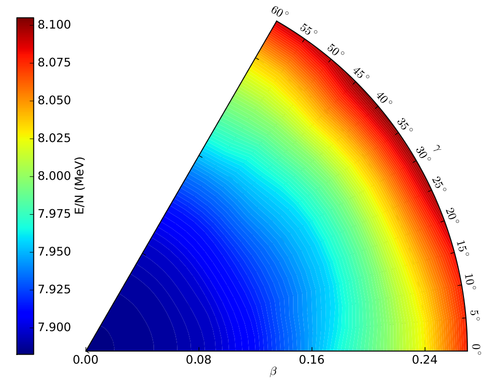
0.05 fm^{-3}



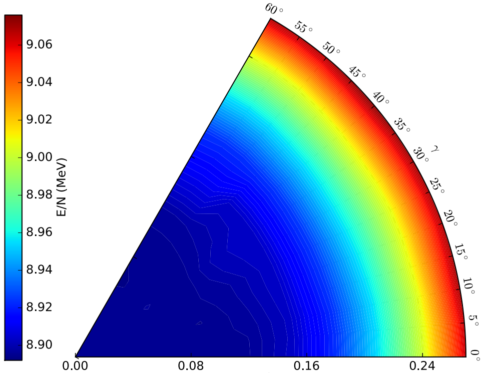
0.054 fm^{-3}



0.058 fm^{-3}

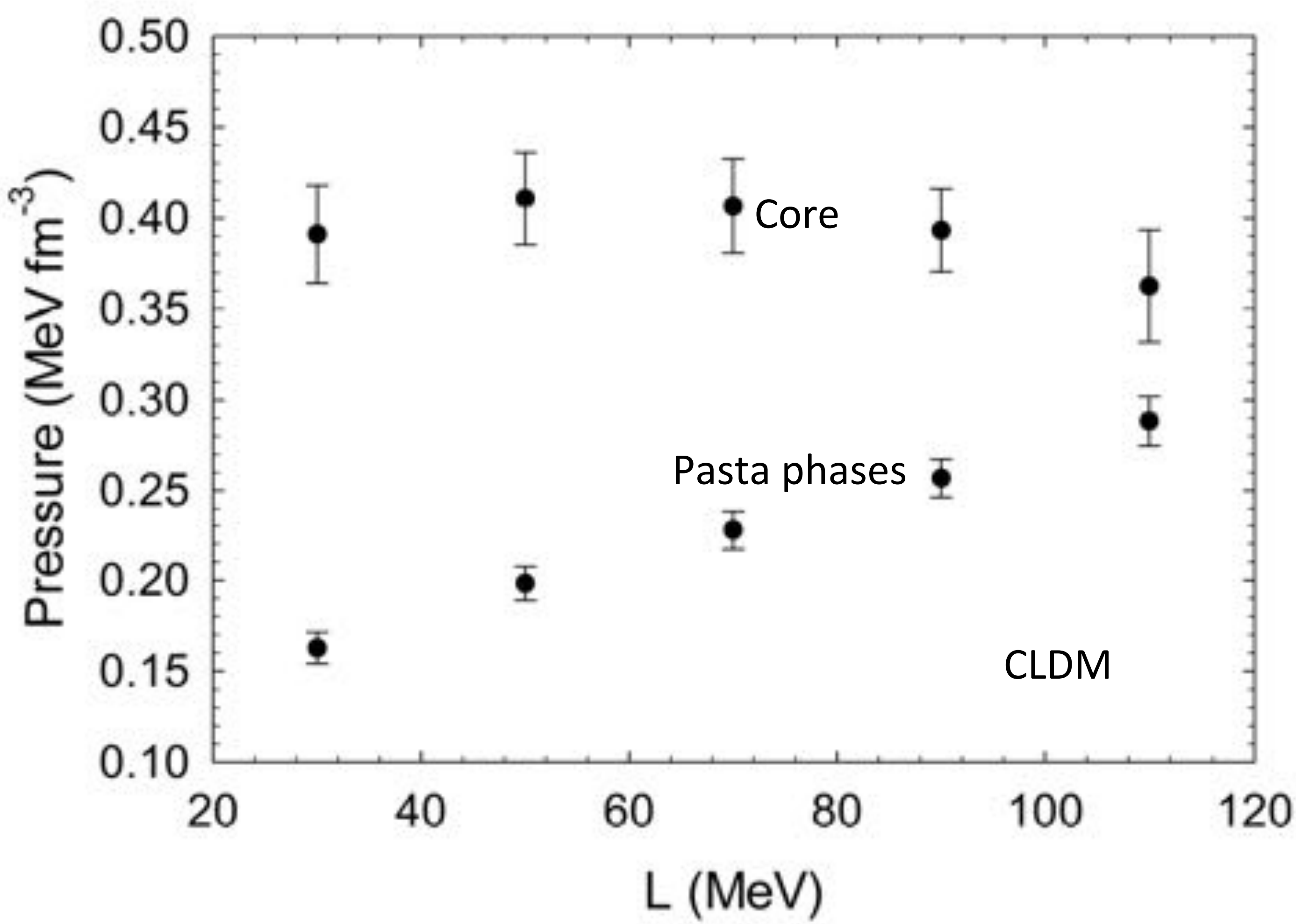


0.062 fm^{-3}



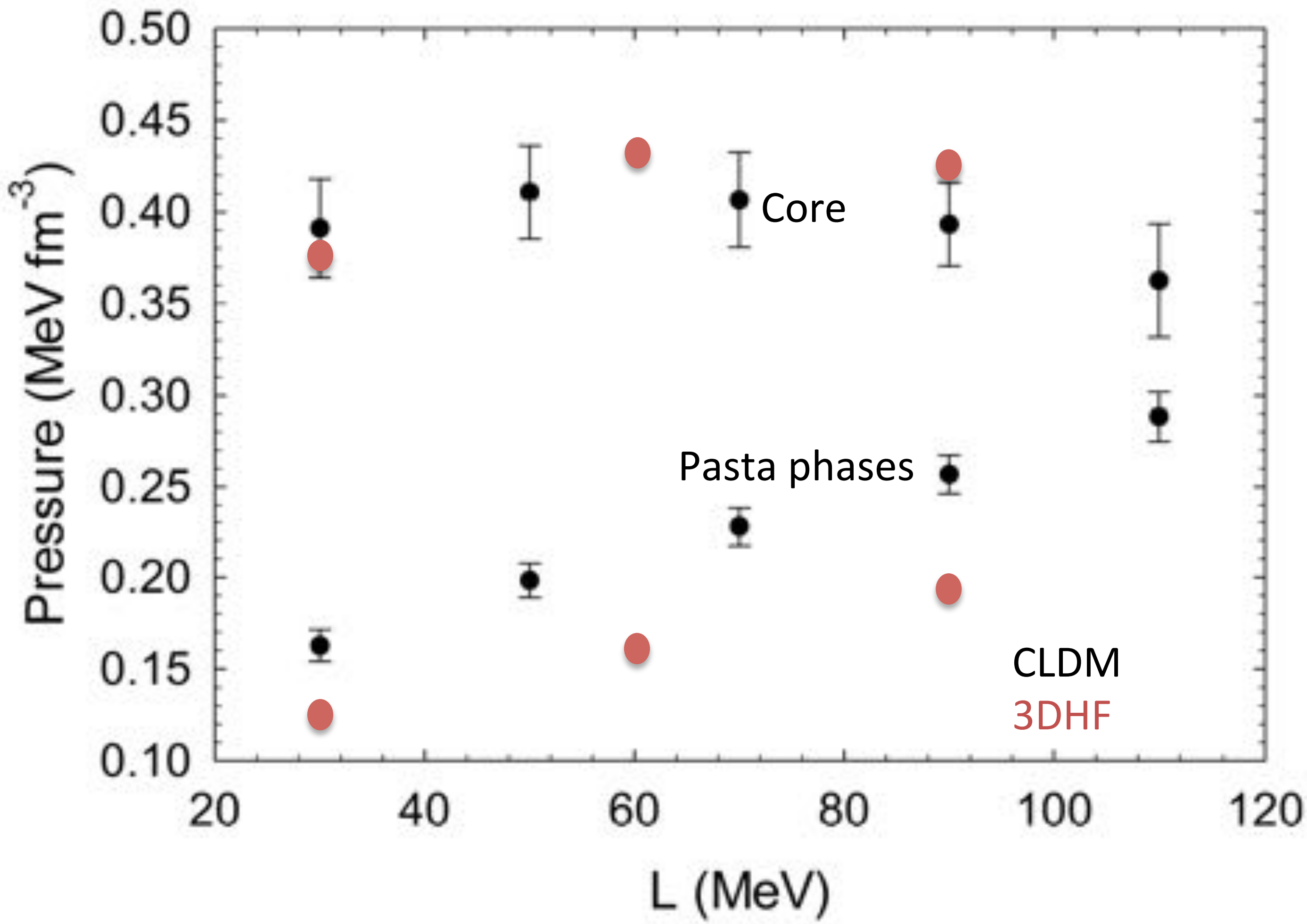
0.07 fm^{-3}

Transition pressures



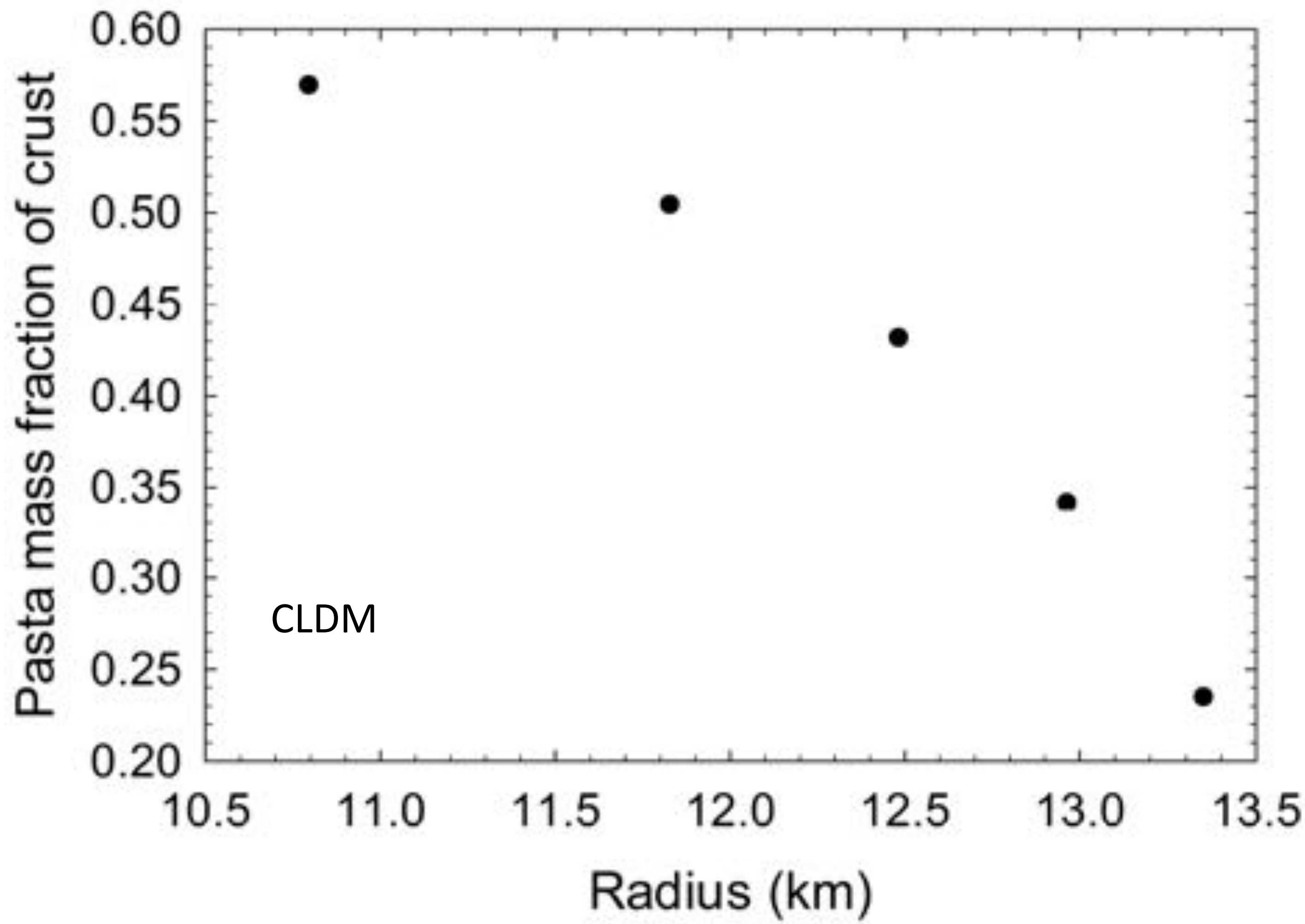
Fattoyev, Newton, Xu, Li, PRC86, 025804 (2012)
Newton & Fattoyev, in prep.
Newton, Stone, Kaltenborn, in prep.

Transition pressures



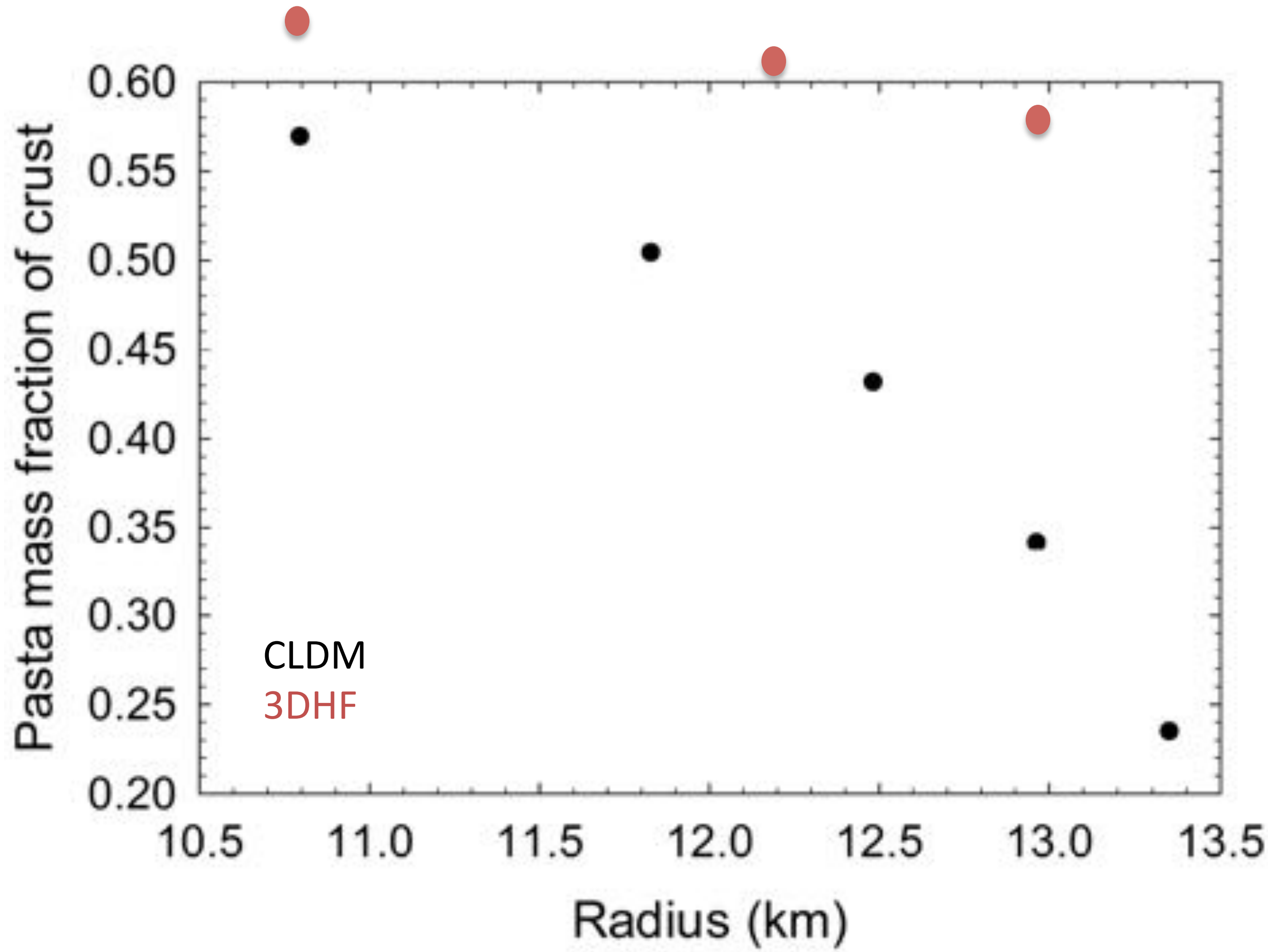
Fattoyev, Newton, Xu, Li, PRC86, 025804 (2012)
Newton & Fattoyev, in prep.
Newton, Stone, Kaltenborn, in prep.

Pasta mass fraction



3DHF predicts over 50%

Pasta mass fraction

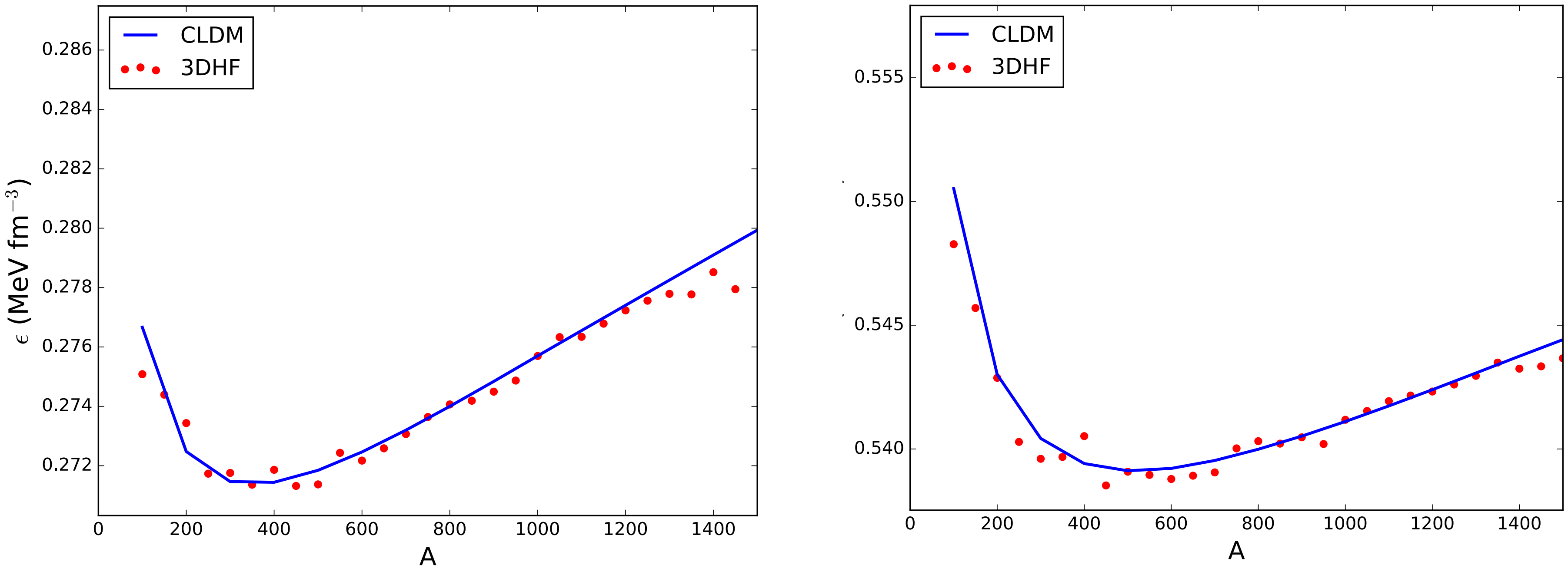


3DHF predicts over 50%

Calibrating CLDM using 3DHF

$y_p = 0.02$

$n_b = 0.025$ fm^{-3} $n_b = 0.040$ fm^{-3}

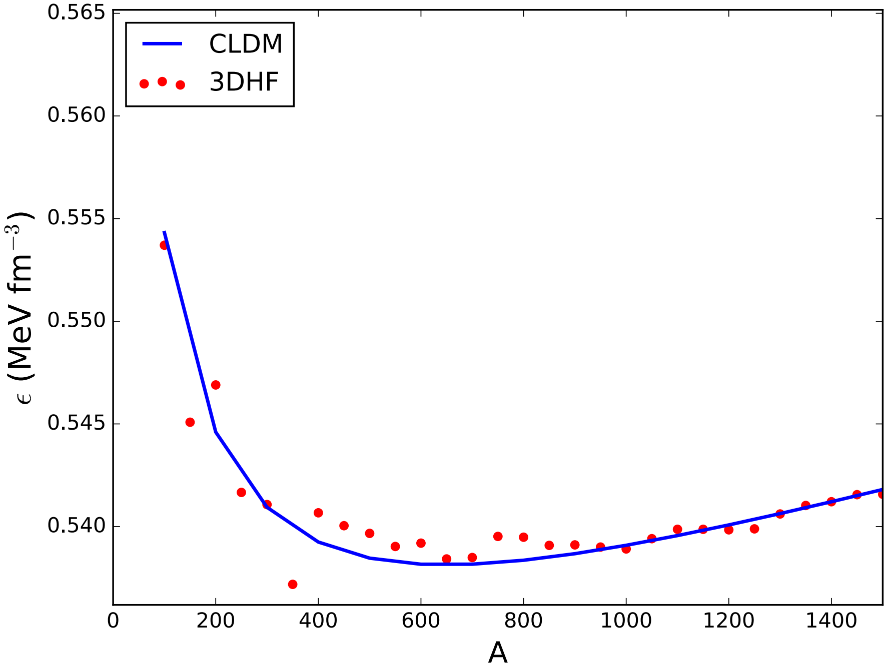


NRAPR (L=60 MeV)

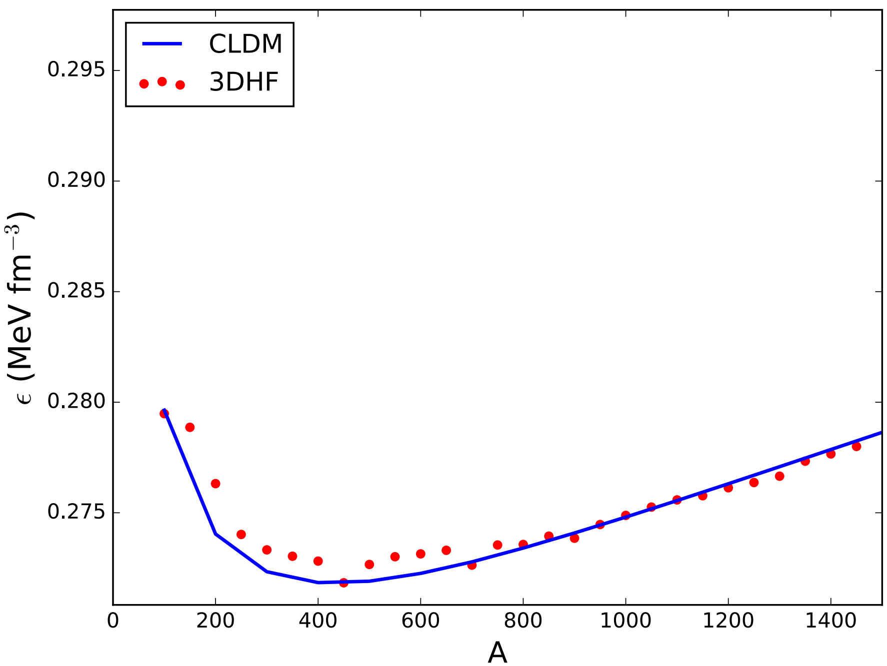
Calibrating CLDM using 3DHF

$y_p = 0.02$

$n_b = 0.025$ fm^{-3}

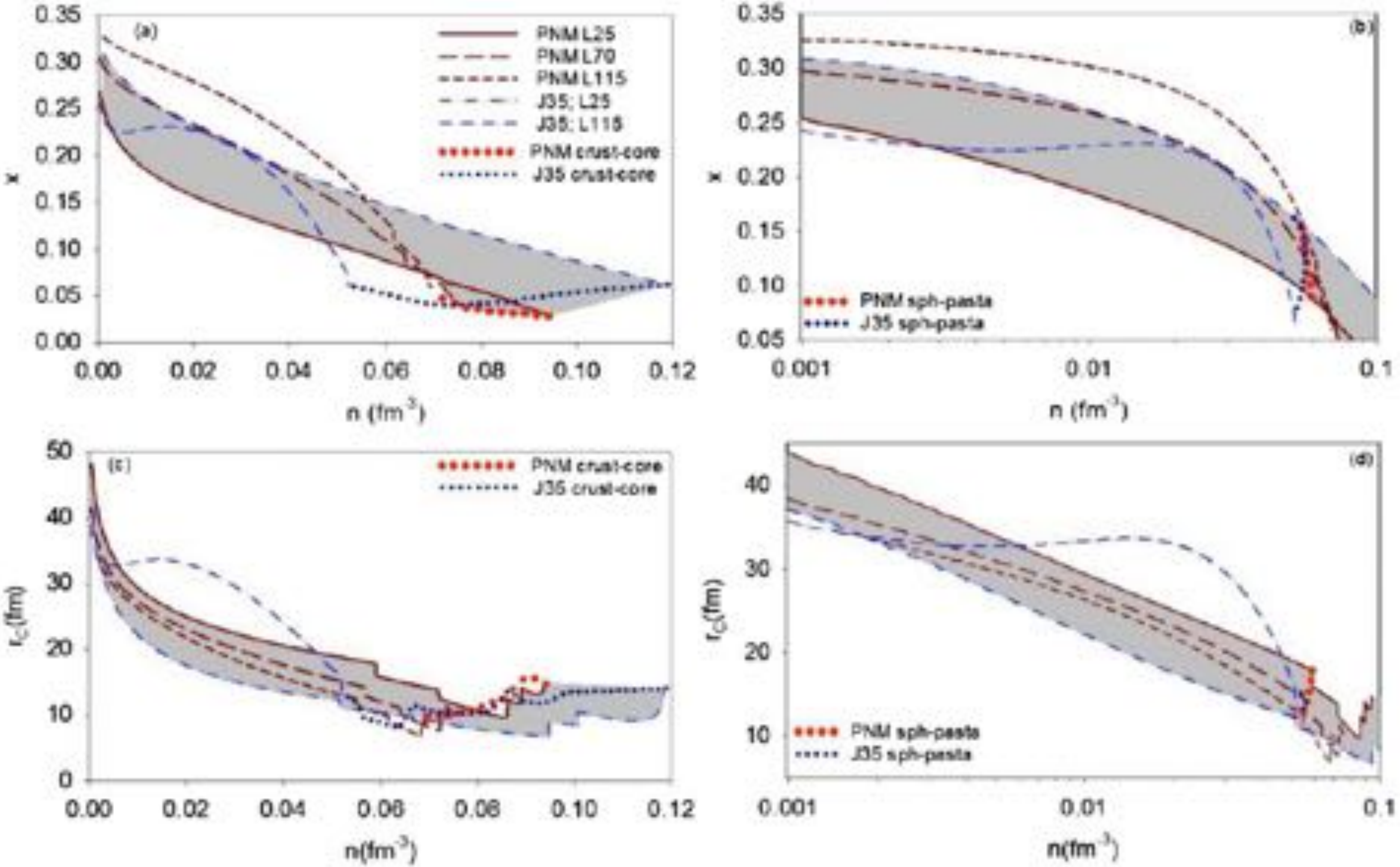


$n_b = 0.040$ fm^{-3}



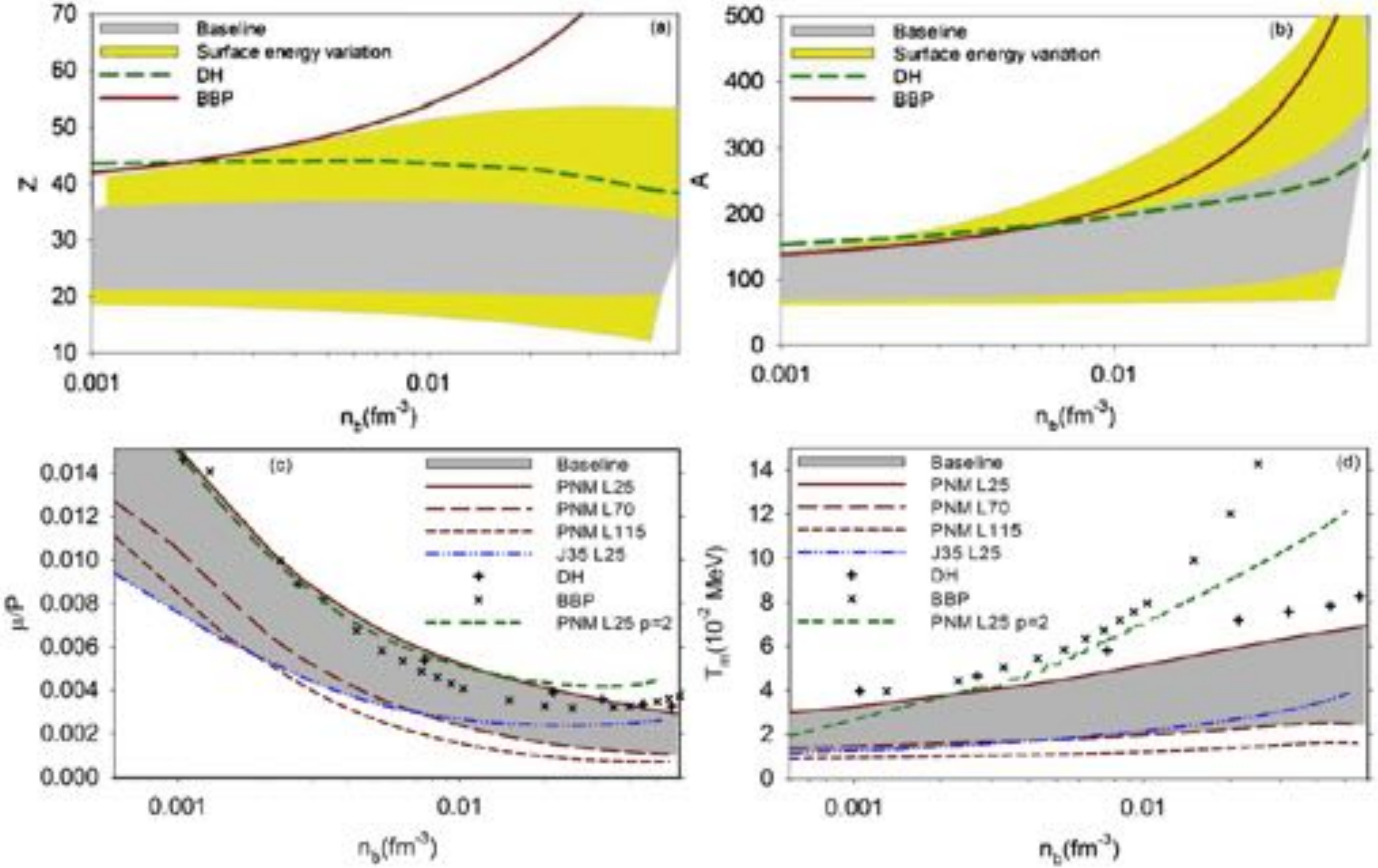
SkIUFSU (L=30 MeV)

How well do we know the crust?



Newton, Gearheart, Li, ApJS 204, 2013

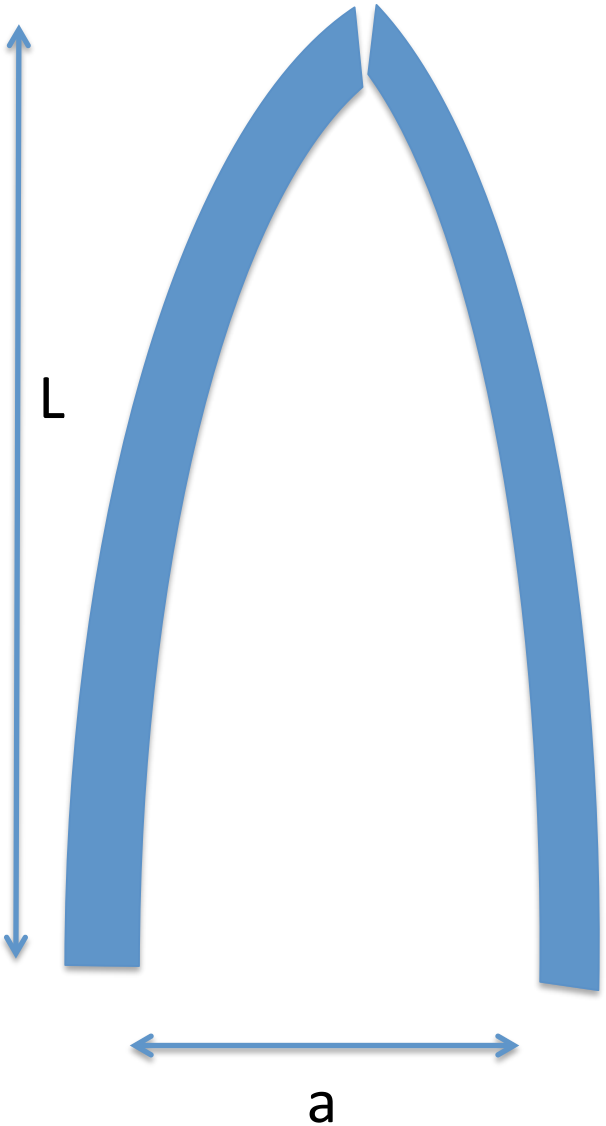
How well do we know the crust?

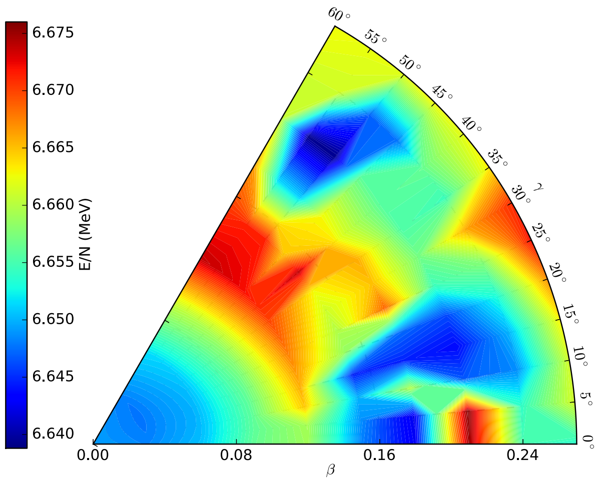


Newton, Gearheart, Li, ApJS 204, 2013

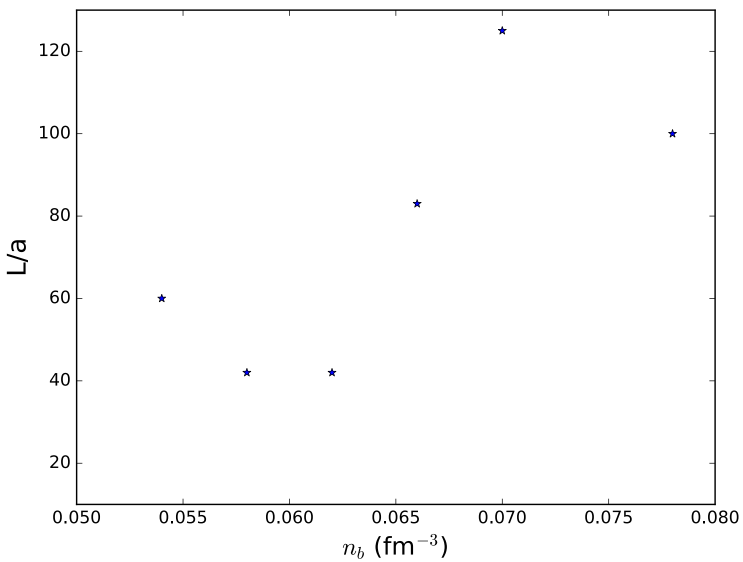
Long range order of pasta


Long range order at pasta "freezing" point





NRAPR



(See Watanabe+, NPhysA 676, 2003)

Conclusions and open questions

Quantum predicts larger region of pasta matter than semi-classical methods (shell effects)

Pasta mass of crust > 50%

Effect of symmetry energy indirect – through equilibrium proton fraction

Magnetic field ordering?

Anisotropic transport properties

Importance of various types of disorder (what happens as pasta cools?

- topological defects
- quantum frustration
- thermodynamic fluctuations