Nuclear symmetry energy and neutron star cooling

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Outline

1. Importance of symmetry energy for neutron star cooling
2. Effective interactions
3. EOS and pressure
4. Symmetry energy and proton fraction

- Hoang Sy Than, Dao Tiên Khoa, NVG
  Phys. Rev. C 80, 064312 (2009)
- B.Y. Sun, W.H. Long, J. Meng, U. Lombardo
  Phys. Rev. C 78, 065805 (2008)

Cooling scenarios

Direct URCA (DU) process:

$$n \rightarrow p + e^- + \bar{\nu}_e, \qquad p + e^- \rightarrow n + \nu_e.$$

is possible if proton fraction x is larger than a threshold value x_thr >1/9

x is determined by symmetry energy:

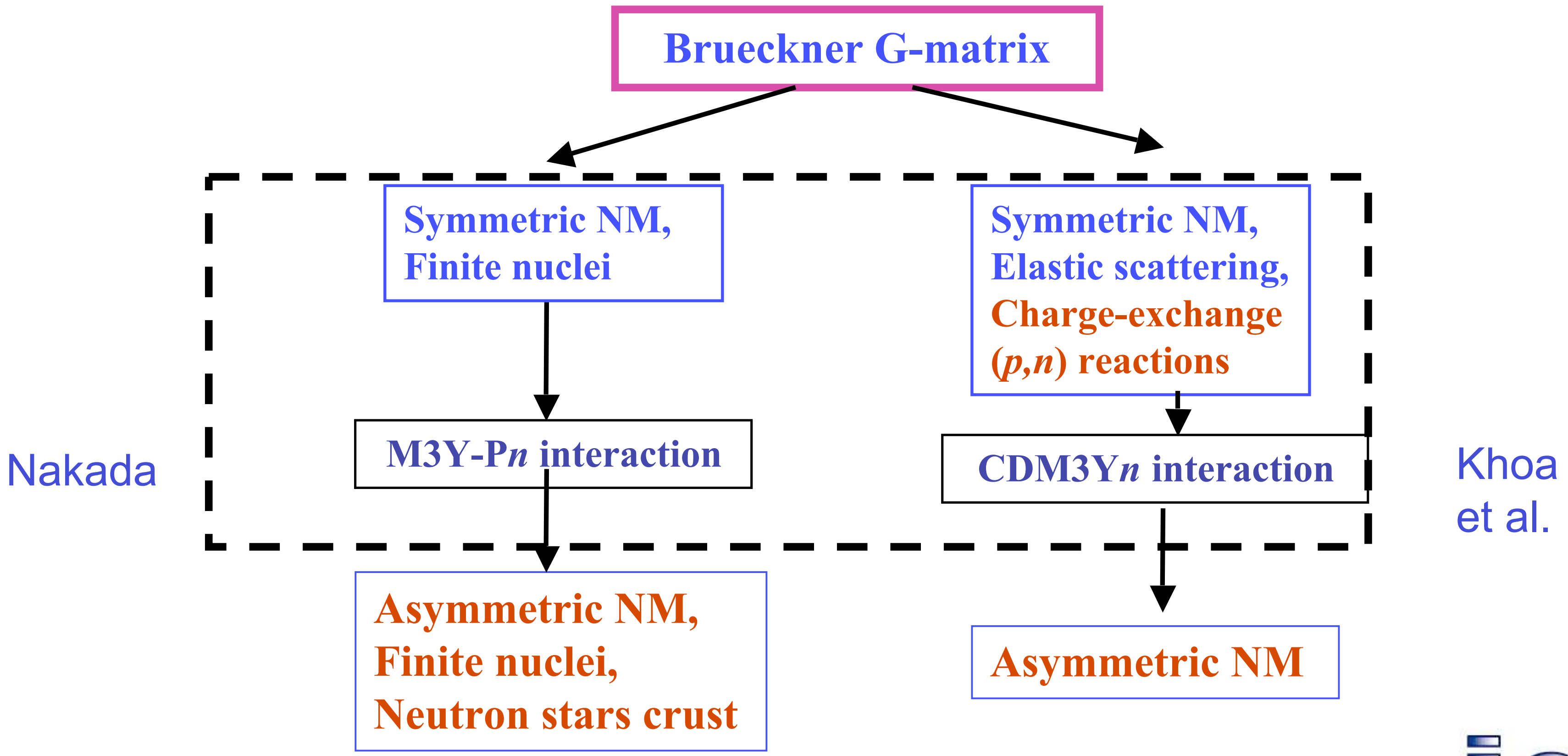
$$\hbar c(3\pi^2 \rho x_p)^{1/3} = 4S_{sym}(\rho)(1 - 2x_p).$$ Balance Equation

Modified URCA process:

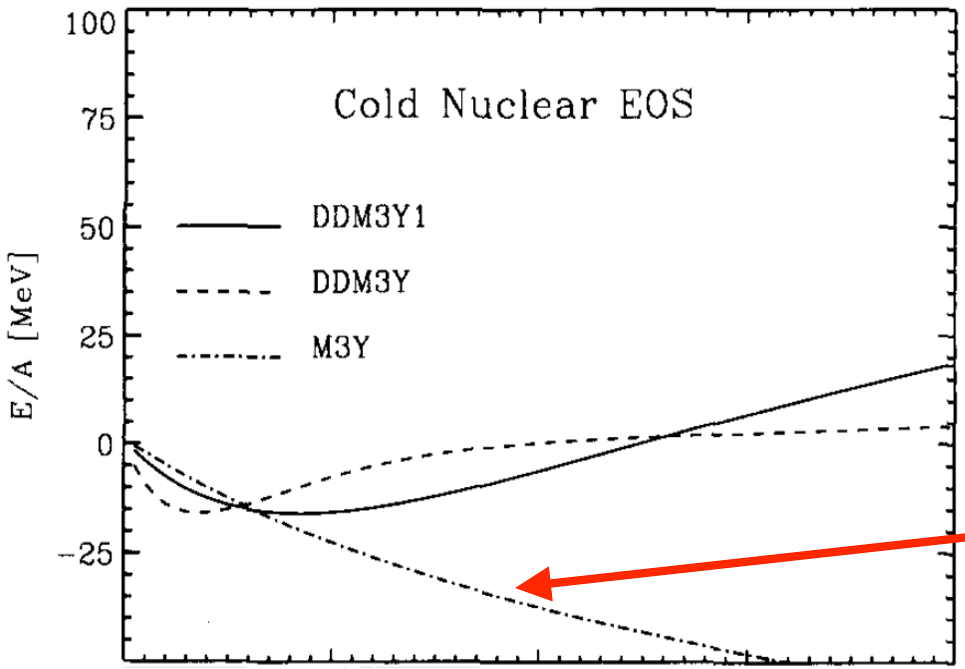
$$n + (n,p) \rightarrow p + (n,p) + e^- + \bar{\nu}_e, \qquad p + e^- + (n,p) \rightarrow n + (n,p) + \nu_e.$$

Reaction rate 10^4 - 10^5 times smaller!

G-matrix related interactions



G-matrix related interactions



(D.T. Khoa and W. von Oertzen, *Phys. Lett.* **B 304**, 8 (1993)).

M3Y-Paris interaction:
constructed by the MSU group to reproduce the G-matrix elements of the Paris NN potential in an oscillator basis.
N. Anantaraman, H. Toki, G.F. Bertsch, *Nucl. Phys*. A **398**, 269 (1983).

The original density-independent **M3Y** interaction gives no saturation point of symmetric NM.

By introducing a density dependence the modified effective M3Y interaction can describe the known NM properties. In this work, we will consider two different density dependent versions of M3Y interaction:

- **M3Y-P*n*** type of Nakada: add a zero-range density-dependent force to the original M3Y interaction (H. Nakada, *Phys. Rev.* C 78, 054301 (2008)).
- **CDM3Y*n*** type of Khoa: multiply the original M3Y interaction with a density-dependent factor (D.T. Khoa *et al.*, *Phys. Rev.* C56, 954 (1997)).

a) M3Y-P*n* type interactions (H. Nakada, *Phys. Rev.* C **78**, 054301 (2008).)

+ Finite-range density-independent term *plus* a zero-range density-dependent term.

The M3Y-P*n* interactions has been parametrized to reproduce the saturation properties of symmetric NM, and give a good description of g.s. shell structure in double-closed shell nuclei and unstable nuclei close to the neutron dripline.

b) CDM3Y*n* type interactions *(complex)* (D.T. Khoa *et al.*, *Phys. Rev.* **C 76**, 014603 (2007).)

+ Finite-range density-dependence (multiplied with a density-dependent factor $F_{IS(IV)}(E,\rho)$).

• ***Isoscalar part***:

+ The real isoscalar part: parameters were chosen to reproduce saturation properties of symmetric NM. (D.T. Khoa, G.R. Satchler, W. von Oertzen, *Phys. Rev.* **C56** (1997) 954)

+ The imaginary isoscalar part: use the same density dependent functional as the real part.

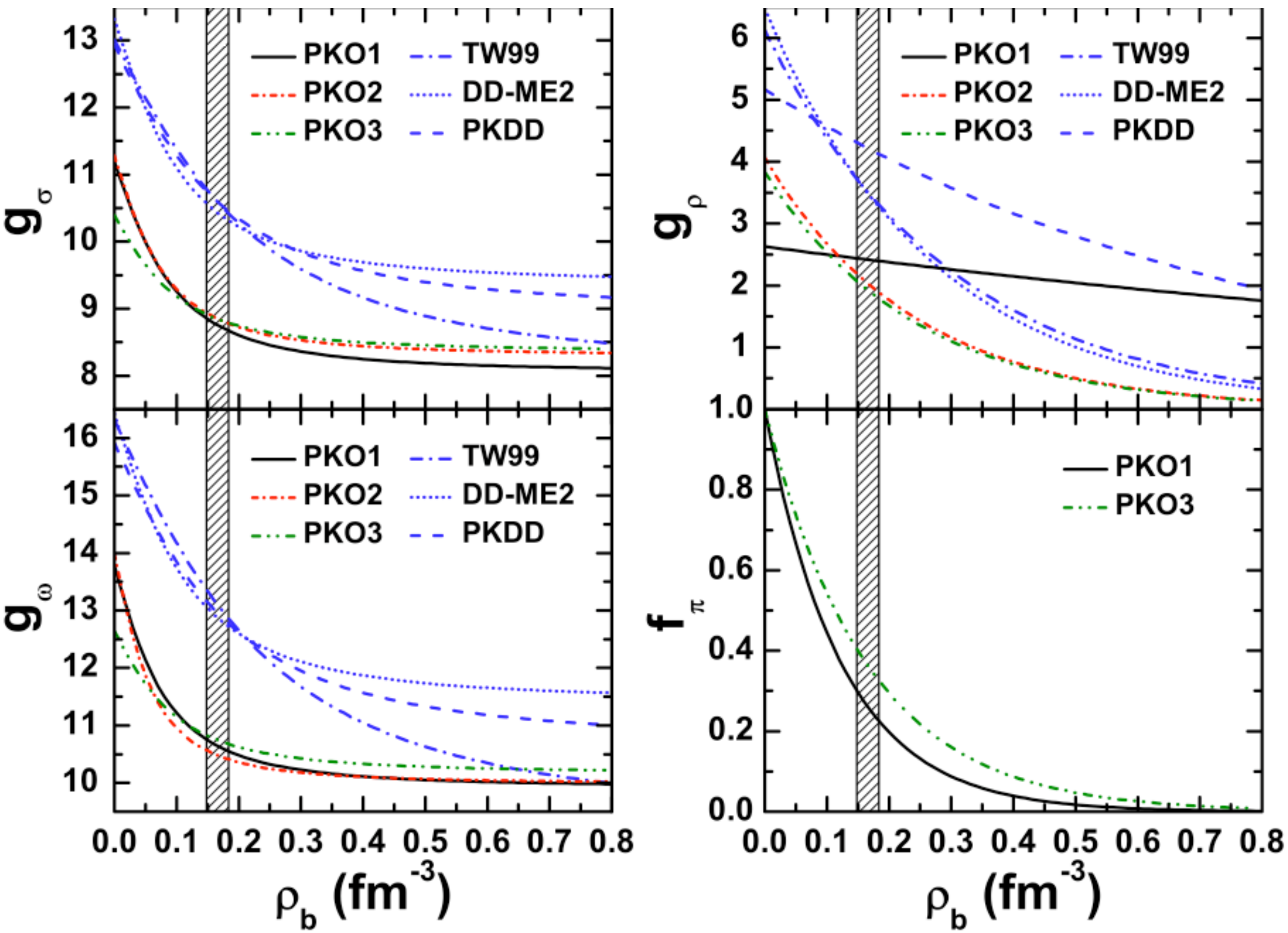
• ***Isovector part***:

Use the similar form for the density dependence to construct separately the real (u=V) and imaginary (u=W) parts of the isovector CDM3Y*n* interaction.

Parameters of $F_{IS(IV)}(E,\rho)$ are determined based on the BHF results by J.P. Jeukenne, A. Lejeune and C. Mahaux, *Phys. Rev.* C 16, 80 (1977).

The isoscalar part of the CDM3Y*n* interaction has been well tested in the folding model analysis of the elastic and α-nucleus scattering. The isovector part can be probed in the study of IAS excitation by charge-exchange (*p,n*) reactions on 48Ca, 90Zr, 120Sn, 208Pb at E_p= 35 and 45 MeV.

Covariant models: RMF and RHF



Some definitions

EOS

$$\frac{E}{A}(\rho,\delta) = \frac{E}{A}(\rho,\delta=0) + S(\rho)\delta^2 + O(\delta^4) + \ldots$$

Pressure

$$P(\rho,\delta) = \rho^2 \frac{\partial}{\partial\rho}\left[\frac{E}{A}(\rho,\delta)\right]$$

Incompressibility

$$K(\rho,\delta) = 9\rho^2 \frac{\partial^2}{\partial\rho^2}\left[\frac{E}{A}(\rho,\delta)\right]$$

Symmetry energy

$$S(\rho) = J + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2 + \ldots$$

Bulk properties (1)

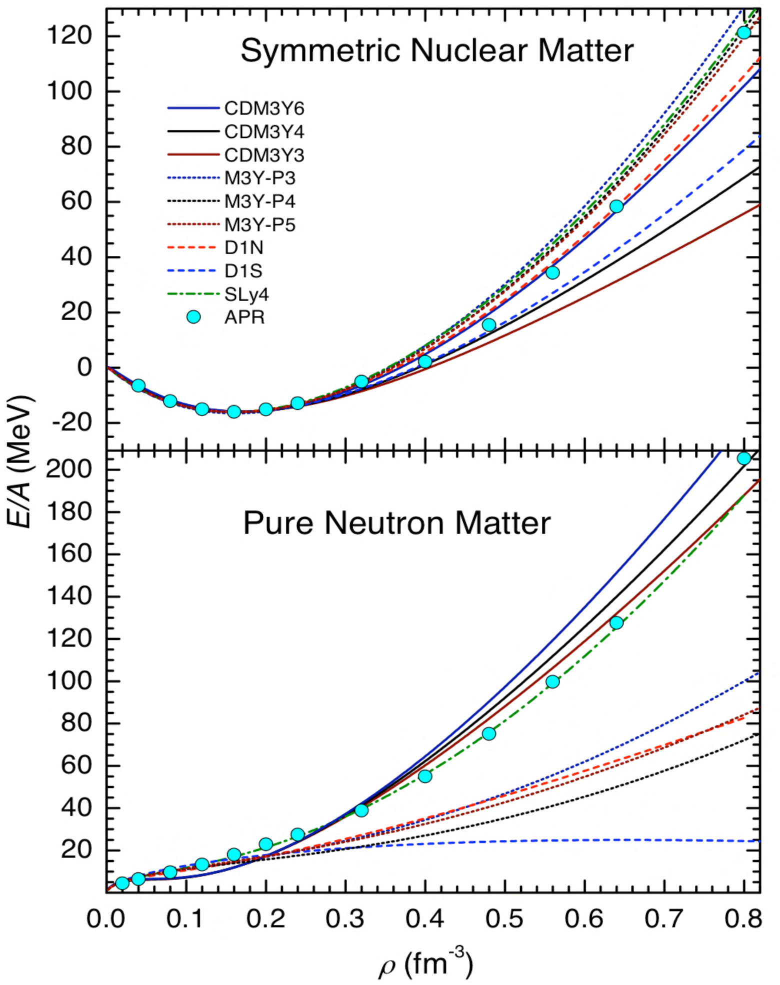
Inter.	ρ_0 (fm^{-3})	E_0 (MeV)	K (MeV)	J (MeV)	L (MeV)	K_{sym} (MeV)	K_τ (MeV)	Ref.
CDM3Y6	0.17	-15.9	252	29.8	62.5	39.0	-336	[18, 20]
CDM3Y4	0.17	-15.9	228	29.0	62.9	49.8	-328	[18]
CDM3Y3	0.17	-15.9	217	29.0	62.5	46.2	-329	[18]
M3Y-P3	0.16	-16.5	245	31.0	28.3	-213	-383	[24]
M3Y-P4	0.16	-16.1	234	30.0	21.1	-234	-361	[24]
M3Y-P5	0.16	-16.1	235	30.9	27.9	-217	-384	[24]
D1S	0.16	-16.0	203	31.9	23.7	-248	-390	[26]
D1N	0.16	-16.0	221	30.1	32.4	-182	-376	[27]
SLy4	0.16	-16.0	230	32.1	46.0	-120	-396	[28]
DBHF	0.18	-16.1	230	34.3	70.1	6.88	-414	[47]
V_{lowk}+CT	0.16	-16.0	258	33.4	86.8	-44.6	-565	[48]
MDI (x=-1)	0.16	-16.0	211	31.6	107	94.1	-550	[39]
MDI (x=1)	0.16	-16.0	211	30.6	16.4	-270	-369	[39]
G2	0.15	-16.1	215	36.4	100.7	-7.5	-612	[40]
FSUGold	0.15	-16.3	230	32.6	60.5	-51.3	-414	[41]
Hybrid	0.15	-16.2	230	37.3	119	111	-603	[42]

Bulk properties (2)

	ρ_0	E_B/A	K	J	M_S^*/M
PKO1	0.1520	-15.996	250.239	34.371	0.5900
PKO2	0.1510	-16.027	249.597	32.492	0.6025
PKO3	0.1530	-16.041	262.469	32.987	0.5862
GL-97	0.1531	-16.316	240.050	32.500	0.7802
NL1	0.1518	-16.426	211.153	43.467	0.5728
NL3	0.1483	-16.249	271.730	37.416	0.5950
NLSH	0.1459	-16.328	354.924	36.100	0.5973
TM1	0.1452	-16.263	281.162	36.892	0.6344
PK1	0.1482	-16.268	282.694	37.642	0.6055
TW99	0.1530	-16.247	240.276	32.767	0.5549
DD-ME1	0.1520	-16.201	244.719	33.065	0.5780
DD-ME2	0.1518	-16.105	250.296	32.271	0.5722
PKDD	0.1496	-16.268	262.192	36.790	0.5712

Equation of state (1)

Non relativistic
Mean field



P3,P4,P5,SLy4

D1N,Y6

D1S,Y4,Y3

Y3,Y4,Y6

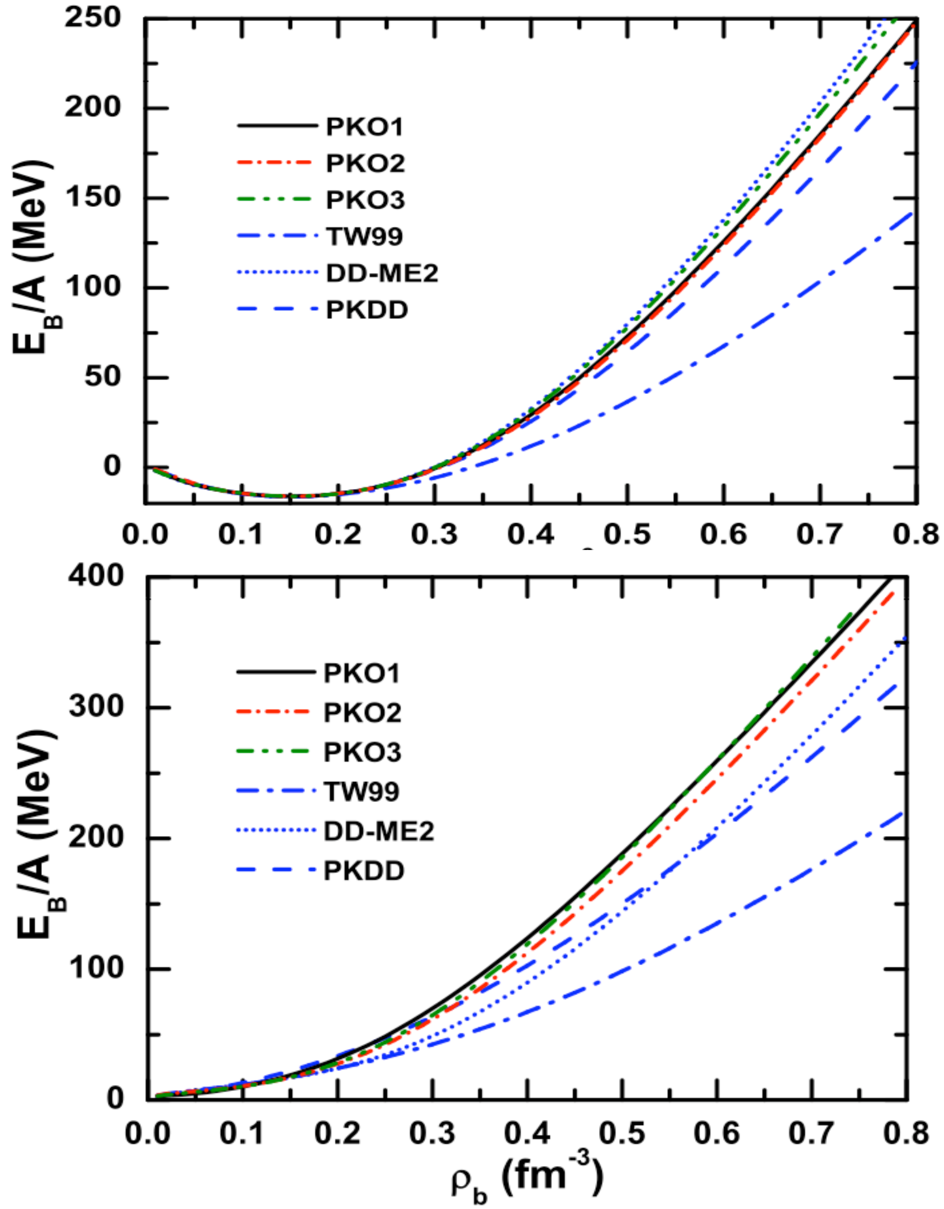
SLy4

P3,P5,D1N,P4

D1S

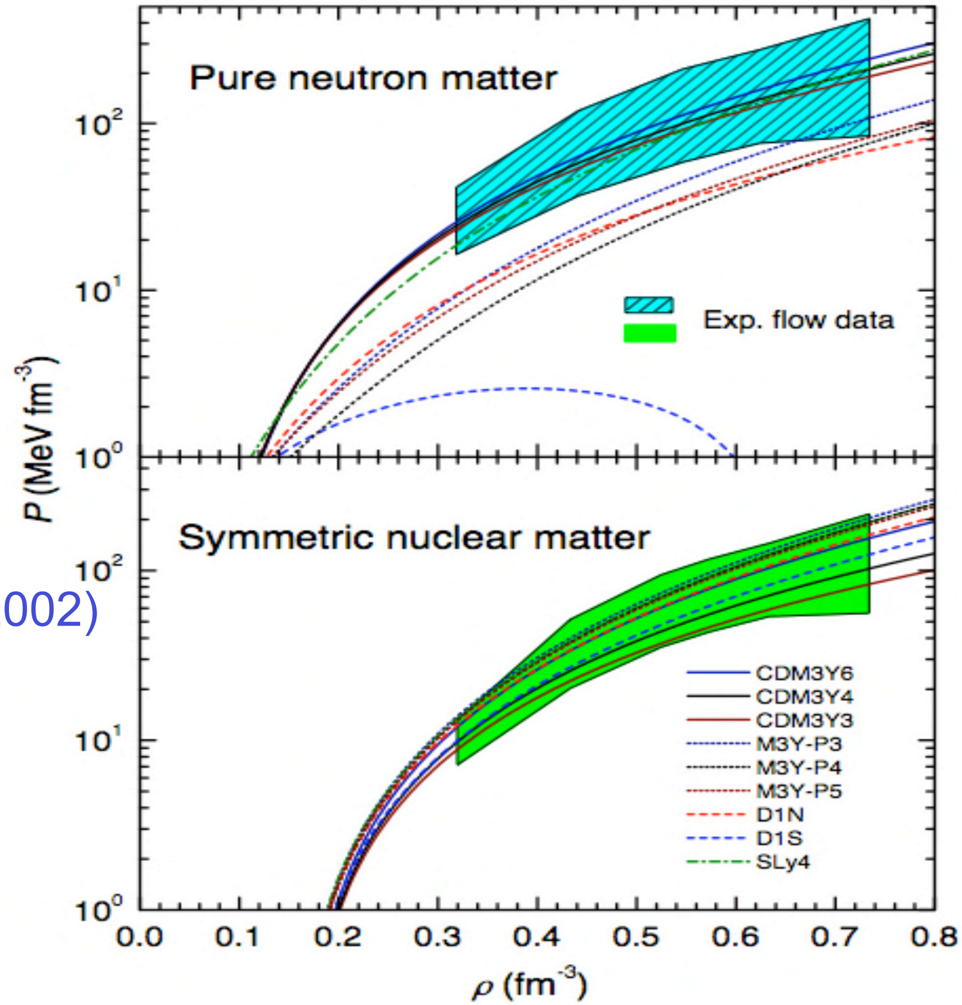
Equation of state (2)

Relativistic
Mean field



Symmetric
matter

Neutron
matter

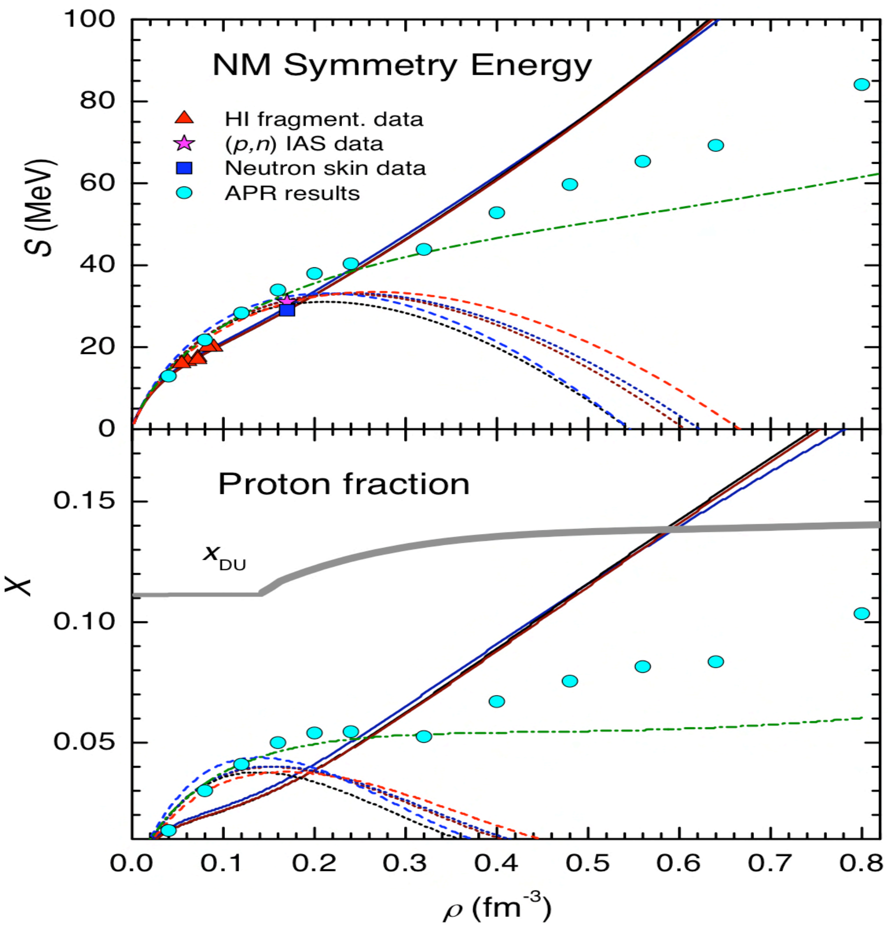


P3,P4,P5
D1N

D1S

Exp:Danielewicz,
Lacey, Wynch,
Science 298, 1592 (2002)

Symmetry energy and proton fraction (1)

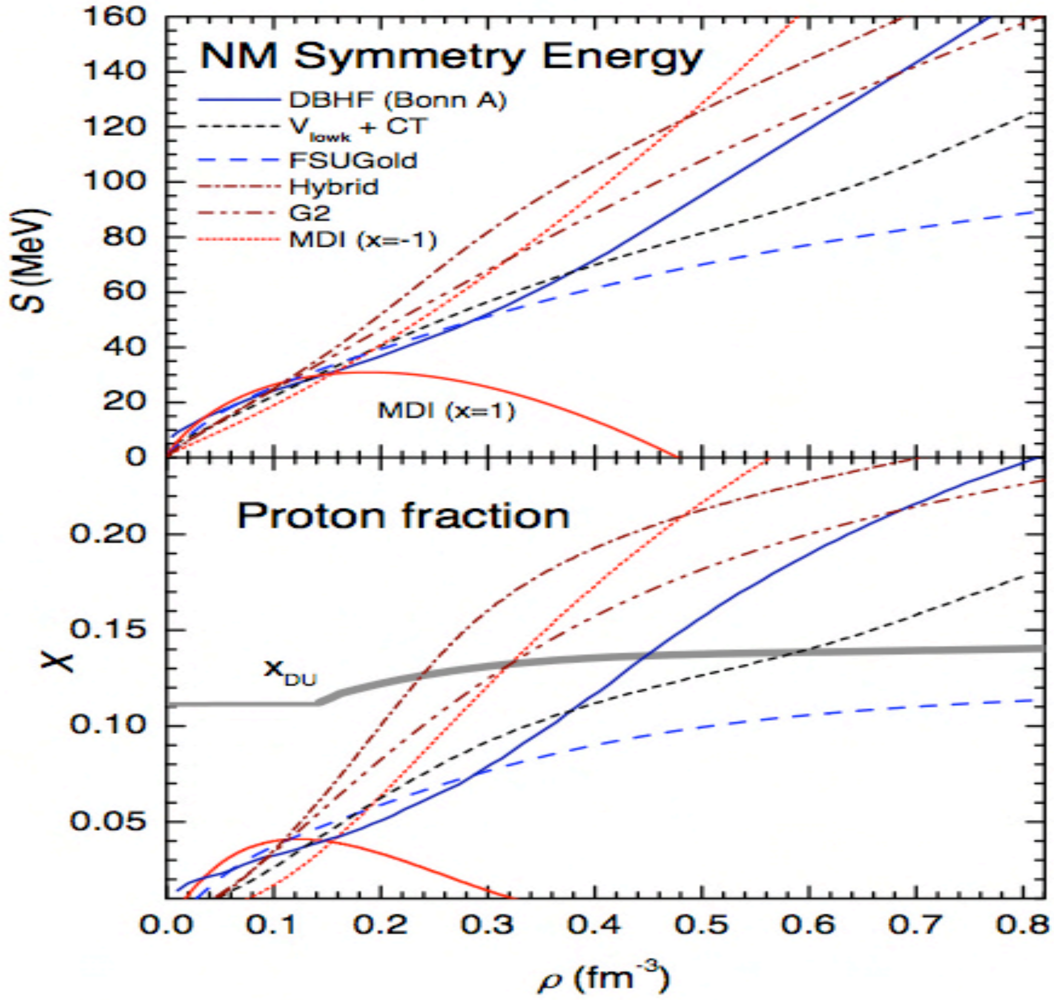


Y3,Y4,Y6

SLy4

D1S
P3,P4,P5
D1N

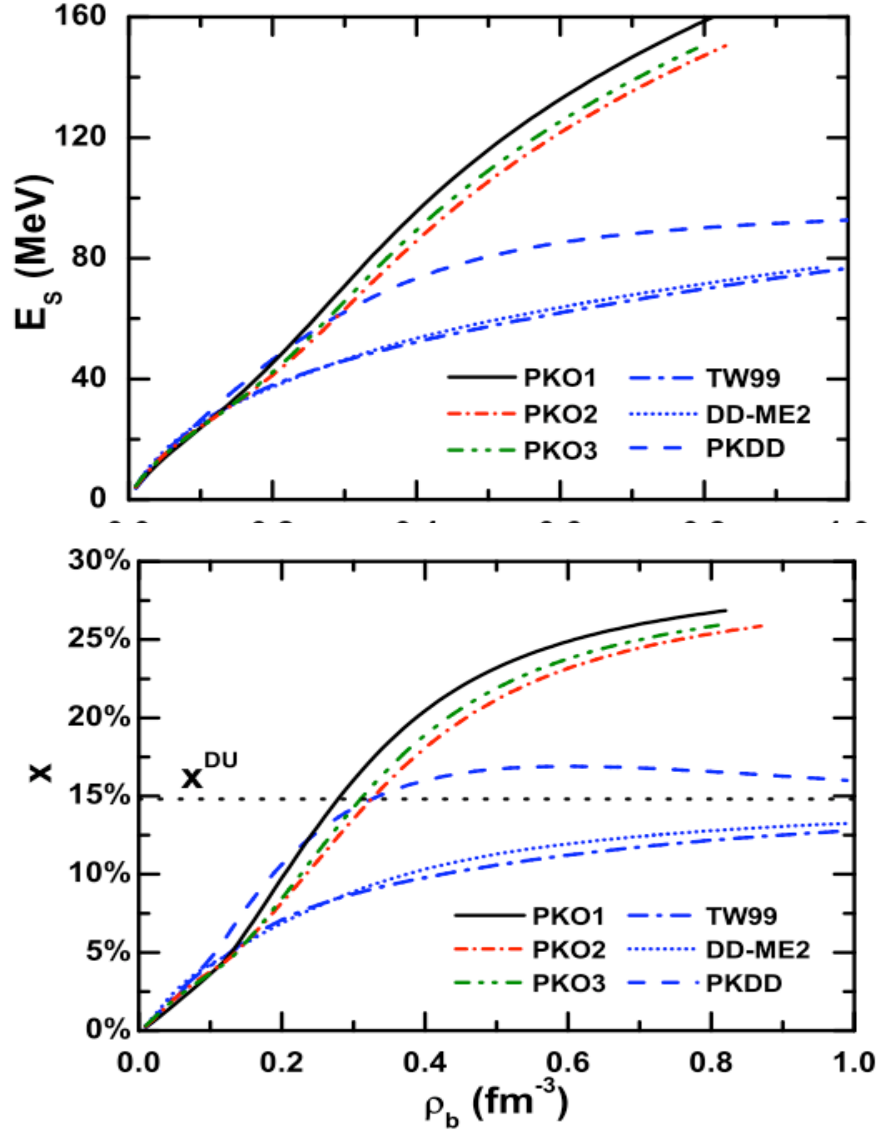
Symmetry energy and proton fraction (2)



Symmetry energy and proton fraction (3)

Symmetry energy

Proton fraction



Conclusion

- For symmetric matter, all models more or less agree with APR predictions and empirical pressure from HI flow data.
- For neutron matter the models are divided into 2 families (asy-soft and asy-stiff symmetry energies).
- Only asy-stiff comply with empirical pressure.
- The 2 families correspond to different proton fractions at beta-equilibrium
- Non-relativistic models which describe well finite nuclei are generally asy-soft ---> disagree with empirical flow data? No direct URCA process?