Probing the Equation of State of Neutron-Rich Matter with Heavy-Ion Reactions

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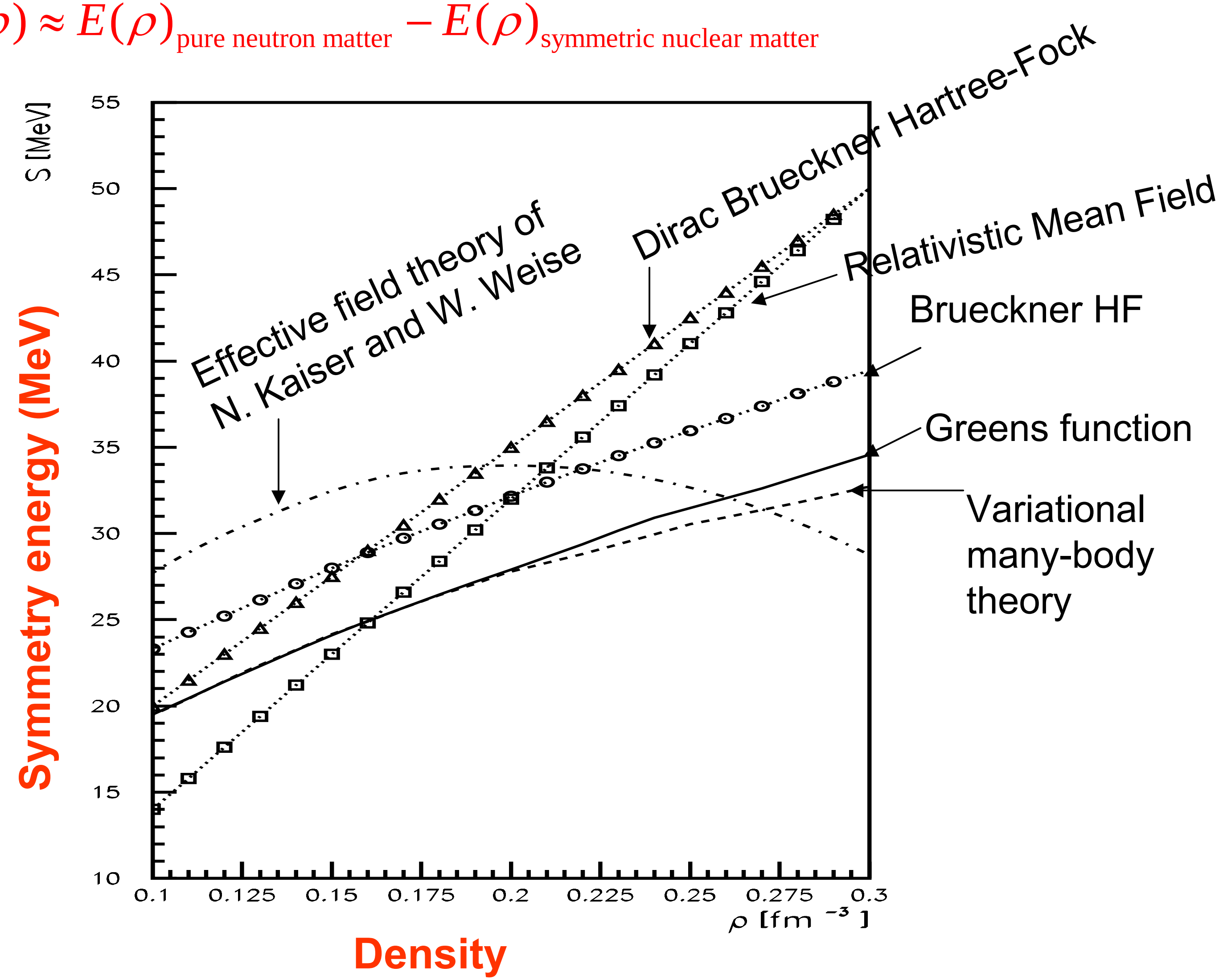
Andrew W. Steiner, Los Alamos National Laboratory
Gao-Chan Yong and Wei Zuo, Chinese Academy of Science

1. **EOS and symmetry energy of neutron-rich matter**
   - **Current status, importance for nuclear physics and astrophysics**
2. **Major physical issues in modeling nuclear reactions induced by neutron-rich nuclei**
   - **Momentum dependence of the symmetry potential**
   - **Neutron-proton effective mass splitting in neutron-rich matter**
   - **Isospin dependence of in-medium nucleon-nucleon cross sections**
3. **Experimental probes of the symmetry energy**
   - **An example: isospin diffusion/transport in heavy-ion reactions**
4. **Impacts of the symmetry energy constrained by available data on the isospin diffusion and the size of neutron-skin in ^{208}Pb**
   - **Nuclear effective interactions**
   - **Cooling mechanisms of proto-neutron stars**
   - **Radii of neutron stars**

E_{sym} (ρ) predicted by microscopic many-body theories

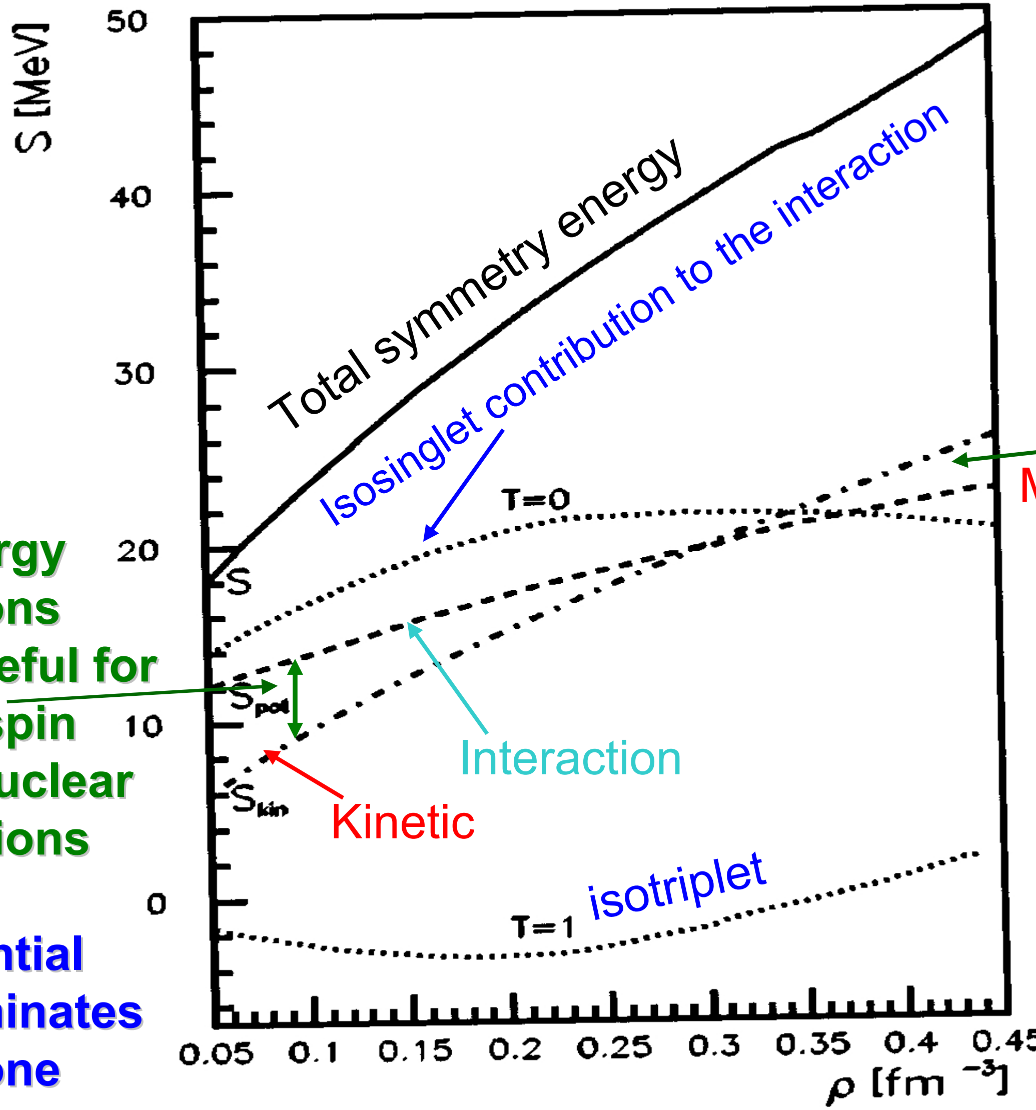
EOS: $E(\rho,\delta) = E(\rho,0) + E_{sym}(\rho)\delta^2 + o(\delta^4)$, where $\delta \equiv (\rho_n - \rho_p)/\rho$

$$E_{sym}(\rho) \approx E(\rho)_{\text{pure neutron matter}} - E(\rho)_{\text{symmetric nuclear matter}}$$



A.E. L. Dieperink, Y. Dewulf, D. Van Neck, M. Waroquier and V. Rodin, Phys. Rev. C68 (2003) 064307

Components of the symmetry energy



High energy
Heavy-ion reactions

Much more challening

For $\rho > 2\rho_0$ kinetic contribution dominates

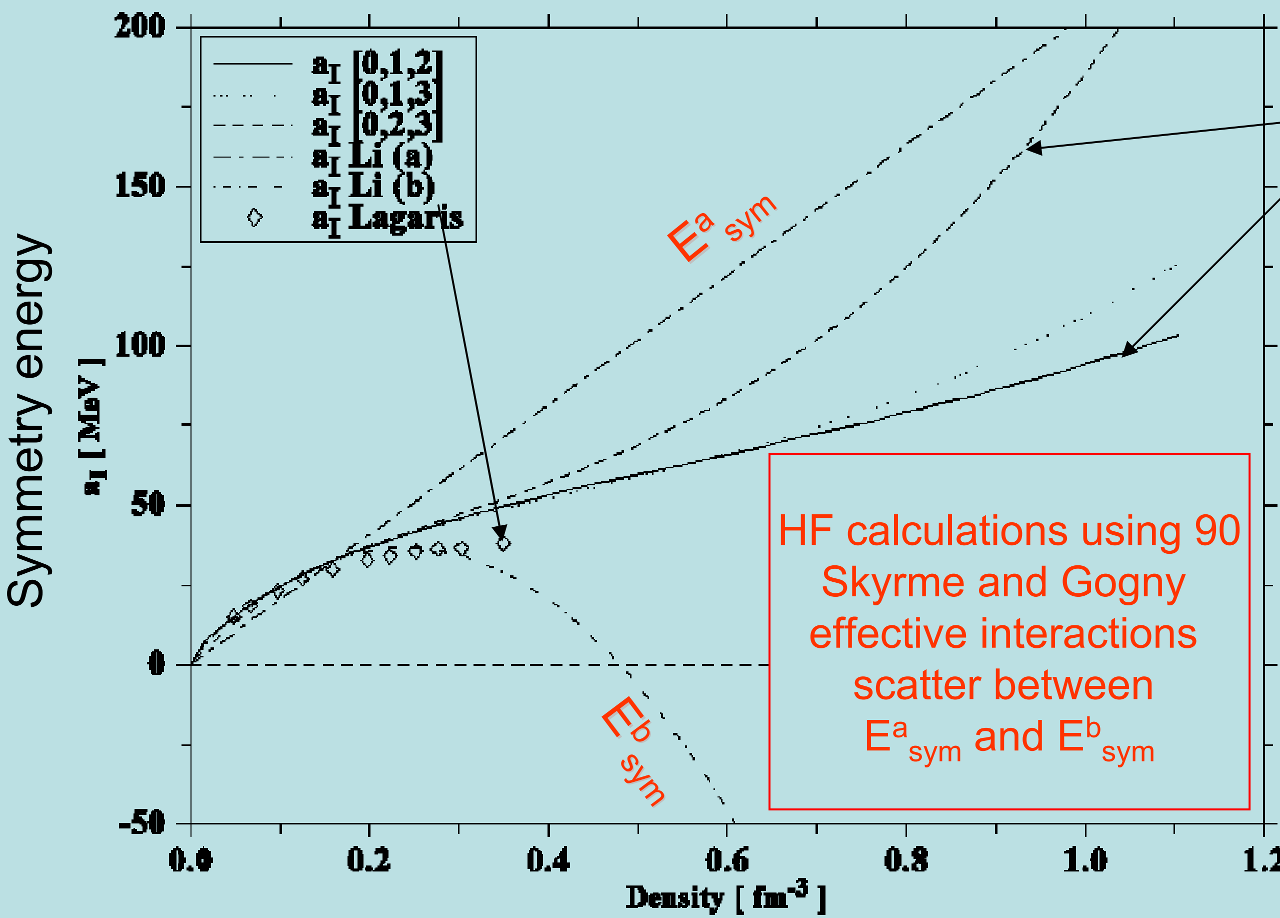
Intermediate energy heavy-ion reactions are especially useful for studying the isospin dependence of nuclear effective interactions

For $\rho \leq 2\rho_0$, potential contribution dominates over the kinetic one ($\sim \rho^{2/3}$) !

A.E. L. Dieperink, Y. Dewulf, D. Van Neck, M. Waroquier and V. Rodin, Phys. Rev. C68 (2003) 064307

$E_{sym}(\rho)$ from Hartree-Fock approach using different effective interactions

B. Cochet, K. Bennaceur, P. Bonche, T. Duguet and J. Meyer, Nucl. Phys. **A731**, 34 (2004).
J. Stone, J.C. Miller, R. Koncewicz, P.D. Stevenson and M.R. Strayer, PRC **68**, 034324 (2003).
Bao-An Li, PRL **88,** 192701 (2002) (where paramaterizations of E^a_{sym} and E^b_{sym} are given)



New Skyrme interactions with more than one density-dependent terms

HF calculations using 90 Skyrme and Gogny effective interactions scatter between $E^a{}_{sym}$ and $E^b{}_{sym}$

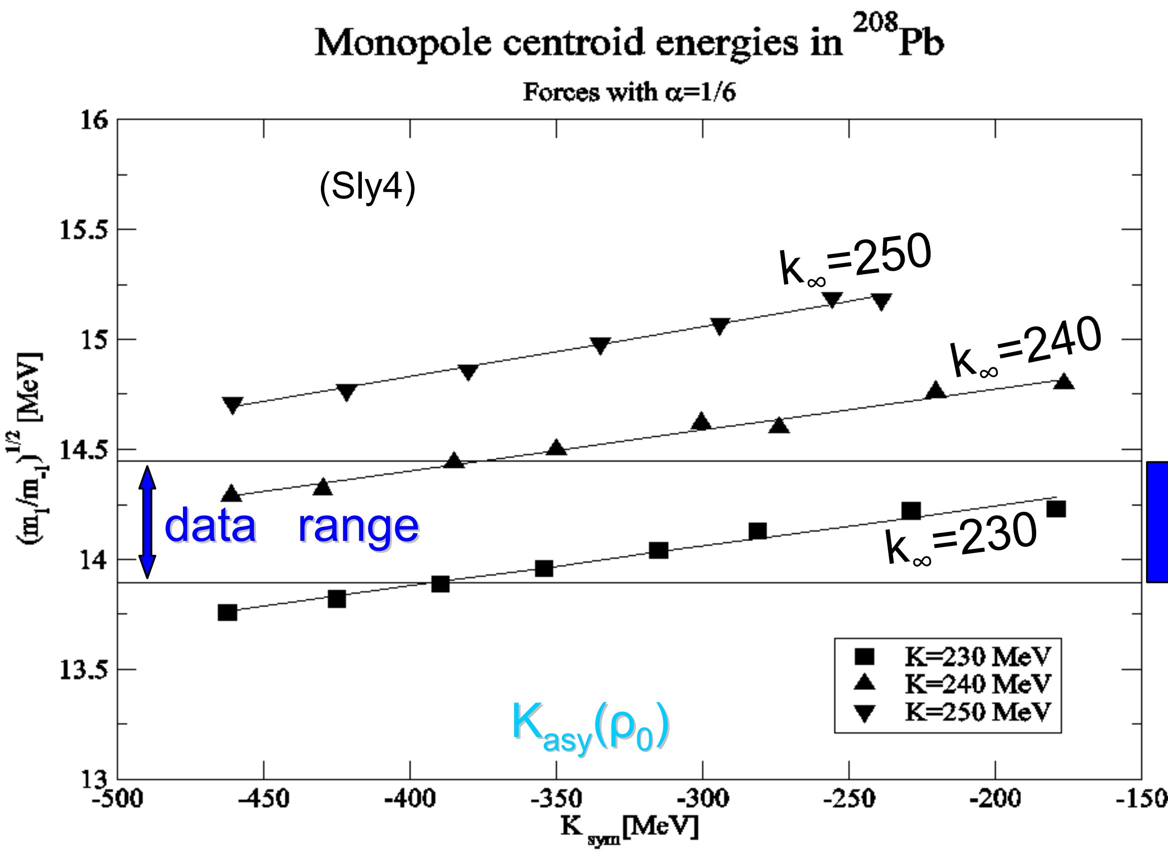
The major remaining uncertainty in determining the EOS of *symmetric* nuclear matter is due to the poor knowledge about $E_{sym}(\rho)$

Example 1: On extracting the incompressibility $K_\infty(\rho_0)$ from isoscalar giant monopole resonance, J. Piekarewicz, PRC 69, 041301 (2004); G. Colo, et al., PRC 70, 024307 (2004).

Liquid-drop formula for finite nuclei: $K_A = m\langle r^2\rangle_0 E^2_{ISGMR} = K_\infty(1+cA^{-1/3}) + K_{asy}\delta^2 + K_{Coul} Z^2 A^{-4/3}$

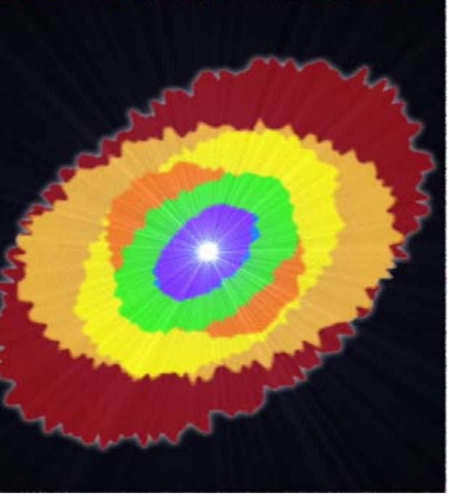
Isobaric incompressibility of asymmetric matter: $K_\infty(\rho,\delta) = K_\infty(\rho) + K_{asy}(\rho)\delta^2$

$$K_\infty(\rho_0) \equiv 9\rho_0^2(d^2E/d\rho^2)_{\rho_0} \text{ and } K_{asy}(\rho_0) \equiv 9\rho_0^2(d^2E_{sym}/d\rho^2)_{\rho_0} - 18\rho_0(dE_{sym}/d\rho)_{\rho_0}$$



The extraction of K_∞ depends on $K_{asy}(\rho_0)$=?

$-566 < K_{asy} < 139$ MeV
Shlomo and Youngblood, PRC 47, 529 (1993)



The multifaceted influence of symmetry energy in astrophysics and nuclear physics

J.M. Lattimer and M. Prakash, *Science Vol. 304 (2004) 536-542.*

A.W. Steiner, M. Prakash, J.M. Lattimer and P.J. Ellis, *Phys. Rep. 411, 325 (05)*

Expanding fireball and gamma-ray burst (GRB) from the superdense neutron star (magnetar) SGR 1806-20 on 12/27/2004. RAO/AUI/NSF

GRB and nucleosynthesis in the expanding fireball after an explosion of a supermassive object depends on the n/p ratio

In pre-supernova explosion of massive stars $e^- + p \rightarrow n + \nu_e$ **is easier with smaller symmetry energy**

Isospin Dependence of Strong Interactions

n/p π^-/π^+

γ

$t/^3He$ K^+/K^0

Nuclear Masses
Neutron Skin Thickness
Isovector Giant Dipole Resonances
Fission

Isospin physics in Terrestrial Labs

Heavy Ion Flows
Multi-Fragmentation
Nuclei Far from Stability
Rare Isotope Beams

isodiffusion
isotransport
isocorrelation
isofractionation
isoscaling

Many-Body Theory

Symmetry Energy
(Magnitude and Density Dependence)

Supernovae
Weak Interactions
Early Rise of $L_{\nu\,e}$
Bounce Dynamics
Binding Energy

Proto-Neutron Stars
ν Opacities
ν Emissivities
SN r-Process
Metastability

Neutron Stars
Observational Properties

Binary Mergers
Decompression/Ejection of Neutron-Star Matter
r-Process

QPO's
Mass
Radius

NS Cooling
Temperature
R_∞, z
Direct Urca
Superfluid Gaps

X-ray Bursters
R_∞, z

Gravity Waves
Mass/Radius
dR/dM

Pulsars
Masses
Spin Rates
Moments of Inertia
Magnetic Fields
Glitches - Crust

Maximum Mass, Radius
Composition:
Hyperons, Deconfined Quarks
Kaon/Pion Condensates

The proton fraction x at ß-equilibrium in proto-neutron stars is determined by

$$x \simeq 0.048[E_{sym}(\rho)/E_{sym}(\rho_0)]^3(\rho/\rho_0)(1-2x)^3$$

The critical proton fraction for direct URCA process to happen is X_p=0.14 for npeμ matter obtained from energy-momentum conservation on the proton Fermi surface

Slow cooling: modified URCA:

$$n+(n,p)\rightarrow p+(n,p)+e^-+\overline{\nu_e}$$

$$p+(n,p)\rightarrow n+(n,p)+e^++\nu_e$$

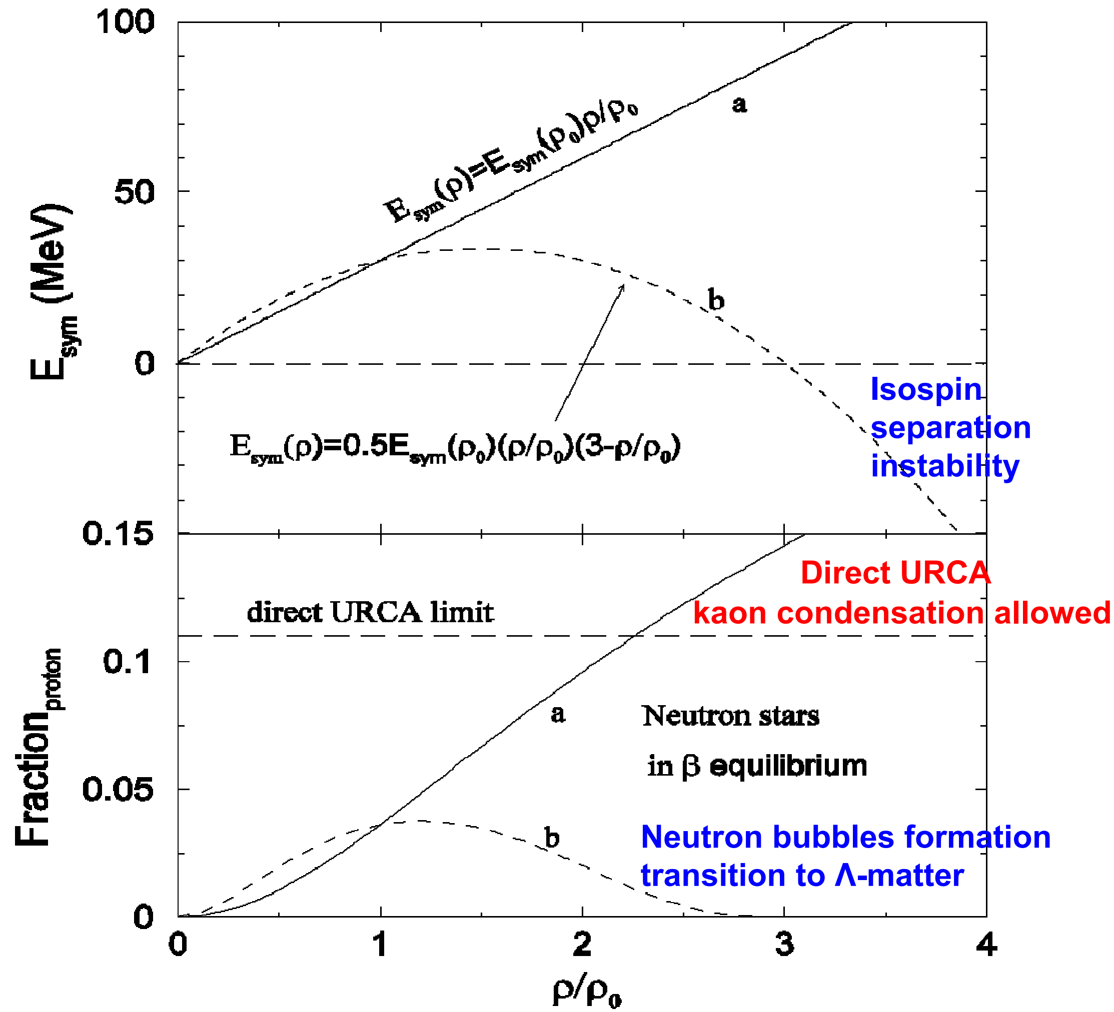
Consequence: long surface thermal emission up to a few million years

Faster cooling by 4 to 5 orders of magnitude: direct URCA

$$n \rightarrow p + e^- + \overline{\nu}_e$$

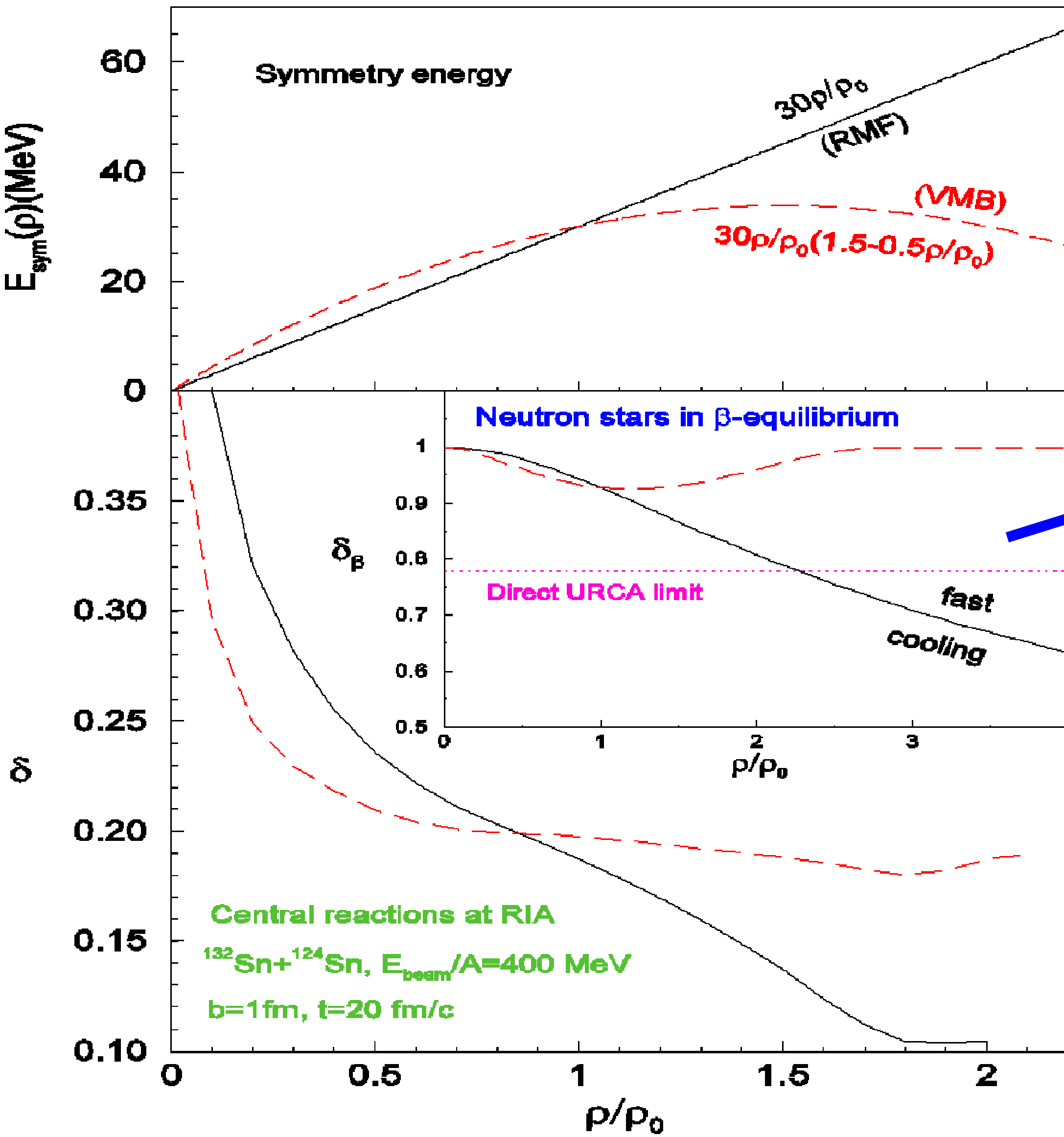
$$p \rightarrow n + e^+ + \nu_e$$

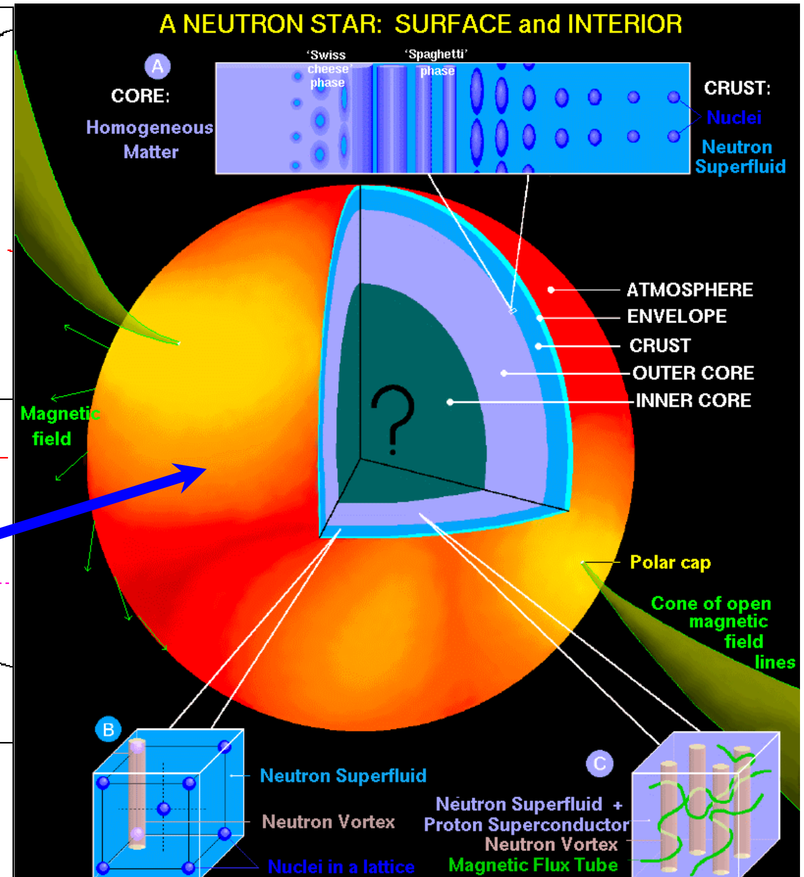
PSR J0205+6449 in 3C58 was suggested as a candidate



B.A. Li, Nucl. Phys. **A708**, 365 (2002).

Probing the EOS of neutron-rich matter in terrestrial labs

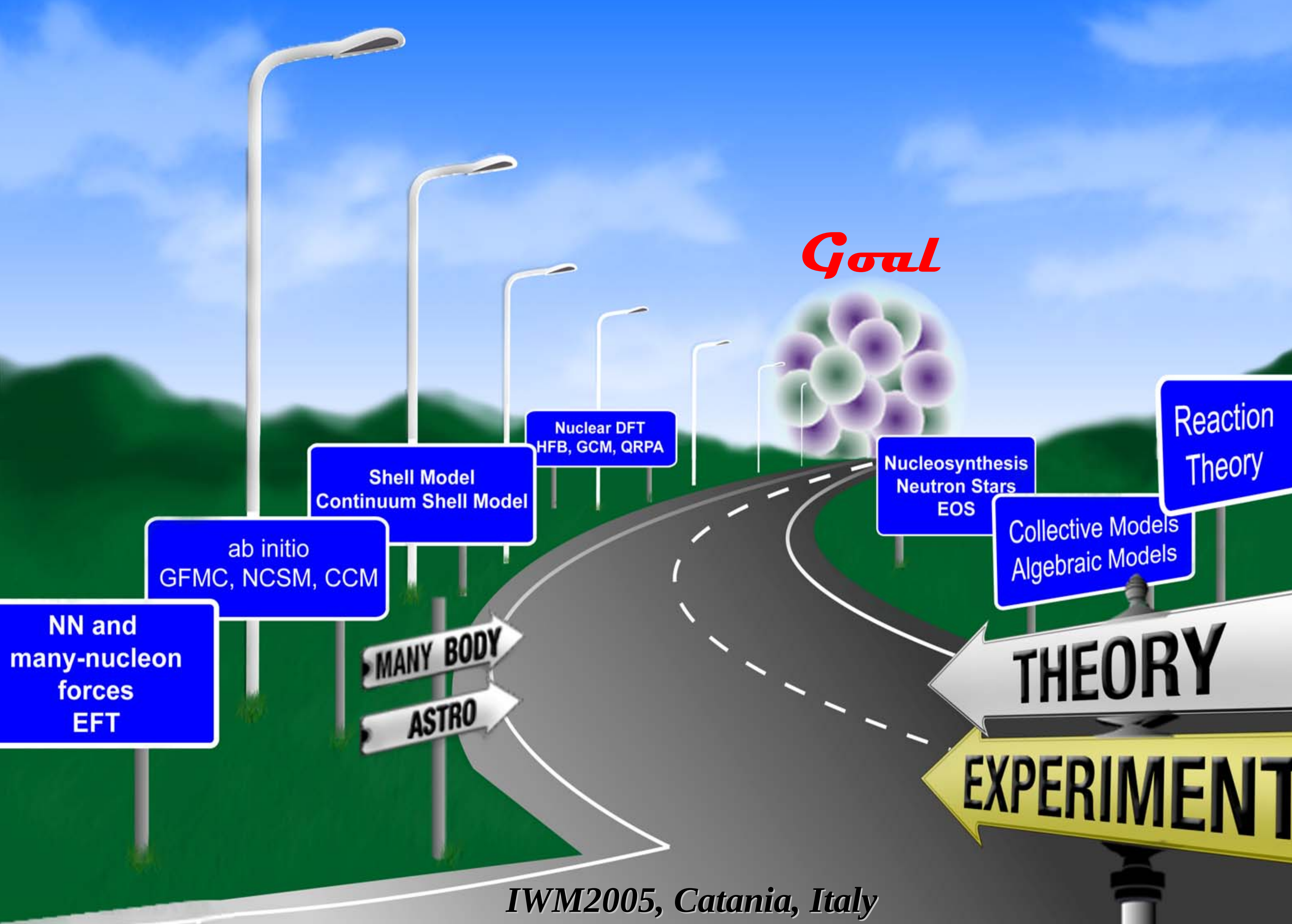




J.M. Lattimer and M. Prakash, *Science Vol. 304 (2004) 536*

Bao-An Li, Phys. Rev. Lett. 88, 192701 (2002).

A road map towards determining the nature of neutron-rich nucleonic matter



IWM2005, Catania, Italy

Hadronic transport equations for the reaction dynamics of nucleus-nucleus collisions:

Baryons: $$\frac{\partial f_b}{\partial t} + \frac{\vec{p}}{E_b}\cdot\vec{\nabla}_r f_b - \vec{\nabla}_r U_b \cdot \vec{\nabla}_p f_b = I_{bb}^{b} + I_{bm}^{b}$$

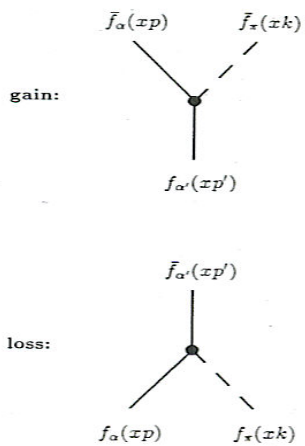
U_b is the mean-field potential for baryons

Mesons: $$\frac{\partial f_m}{\partial t} + \frac{\vec{k}}{E_m}\cdot\vec{\nabla}_r f_m = I_{mm}^{m} + I_{bm}^{m}$$

The phase space distribution functions, mean fields and collisions integrals are all isospin dependent

An example:

Collision integral $I^{\pi}_{b\pi}$: changing rate of pion phase space distribution $f_\pi(\vec{r},\vec{p},t)$ due to baryon-pion scatterings



$$\Delta \rightarrow \pi + N$$

$$f_\pi(\vec{r},\vec{p},t)$$

$$\pi + N \rightarrow \Delta$$

Simulate solutions of the coupled transport equations using test-particles and Monte Carlo:

$$f(\vec{r},\vec{p},t) \cong \frac{1}{N_t}\sum_i \delta(\vec{r}-\vec{r}_i)\delta(\vec{p}-\vec{p}_i)$$

The evolution of $f(\vec{r},\vec{p},t)$ is followed on a 6D lattice

$$I^{\pi}_{b\pi}(xk) =$$
$$\frac{\pi}{16}\sum_{\alpha\alpha'}\int\int \frac{M_\alpha M_{\alpha'}}{E_\alpha(p)E_{\alpha'}(p')} W^{\pi}_{b\pi}(\alpha p,\alpha' p',\pi k)\cdot\delta^{(4)}(p'-p-k)\frac{1}{(2\pi)^6}d\vec{p}d\vec{p}$$
$[(1+f_\pi(xk))f_{\alpha'}(xp')(1-f_\alpha(xp))$ (gain)
$-f_\pi(xk)f_\alpha(xp)(1-f_{\alpha'}(xp'))]$ (loss)

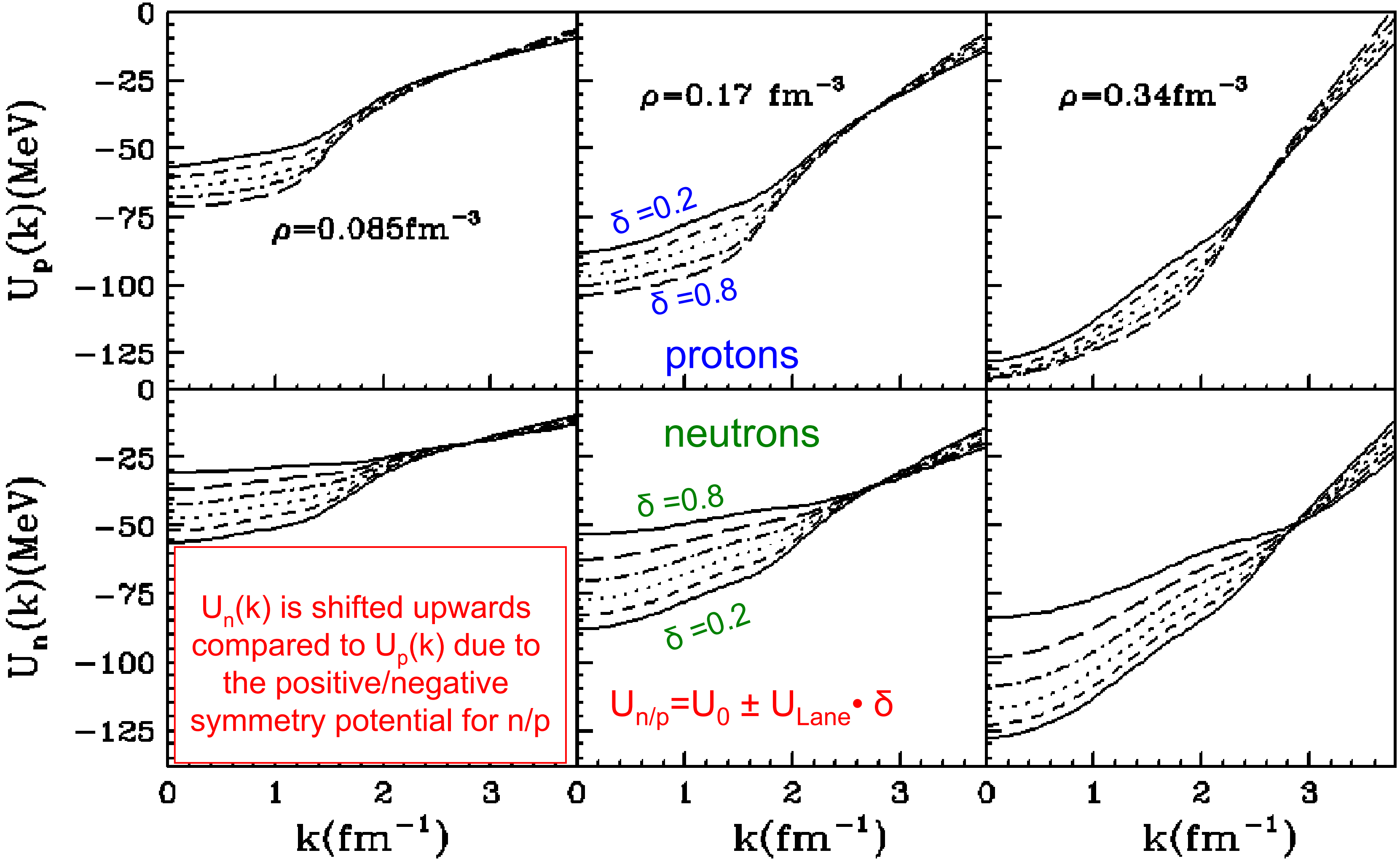
Bao-An Li and Wolfgang Bauer, Phys. Rev. C44, (1991) 450.

Main features:

Pauli bolcking (1-f_α) for Fermions and Bose enhancement ($1+f_\pi$) for bosons are included.

Isospin splitting and momentum dependence of nucleon mean field in neutron-rich matter

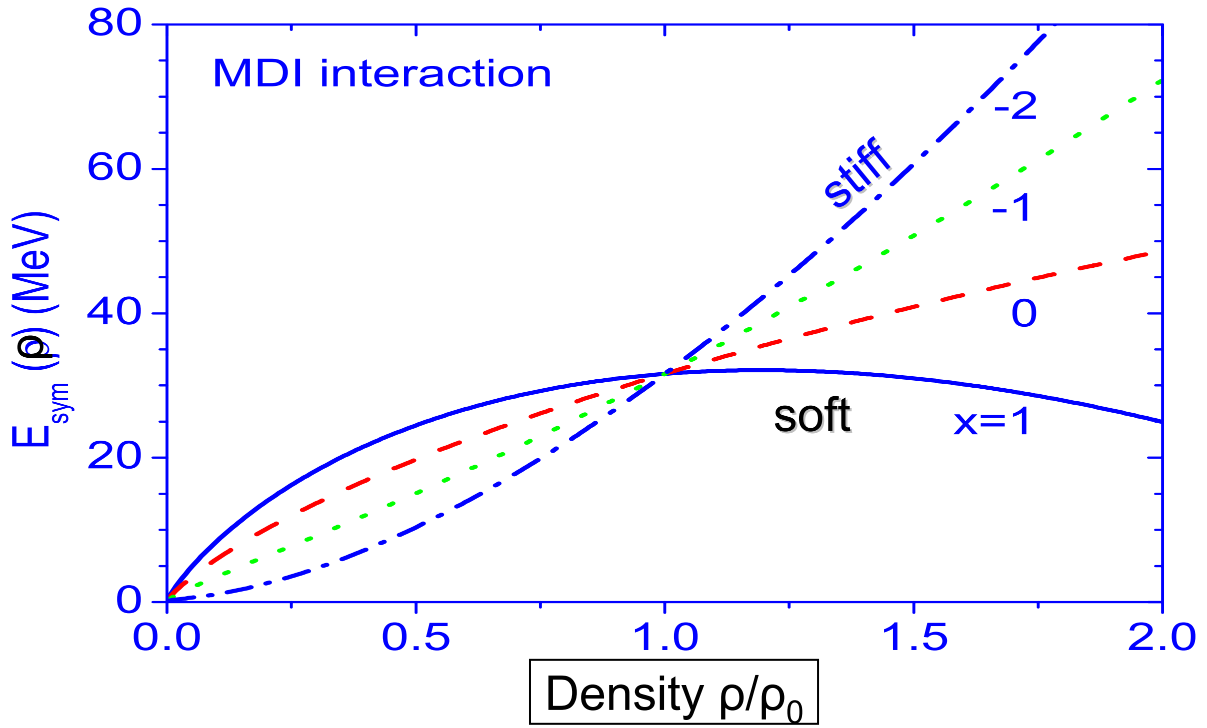
Predictions of Brueckner-Hartree-Fock including 3-body forces



The momentum dependence of the nucleon potential is a result of the non-locality of nuclear effective interactions and the Pauli exclusion principle

I. Bombaci and U. Lombardo, Phys. Rev. C44, 1892 (1991);
W. Zuo, L.G. Gao, B.A. Li, U. Lombardo and C.W. Shen, Phys. Rev. C72, 014005 (2005).

Symmetry energy and single nucleon potential used in the IBUU04 transport model



Single nucleon potential within the HF approach using a modified Gogny force:

$$U(\rho,\delta,\vec{p},\tau,x) = A_u(x)\frac{\rho_{\tau'}}{\rho_0} + A_l(x)\frac{\rho_\tau}{\rho_0} + B\left(\frac{\rho}{\rho_0}\right)^\sigma (1 - x\delta^2) - 8\tau x \frac{B}{\sigma+1}\frac{\rho^{\sigma-1}}{\rho_0^\sigma}\delta\rho_{\tau'}$$

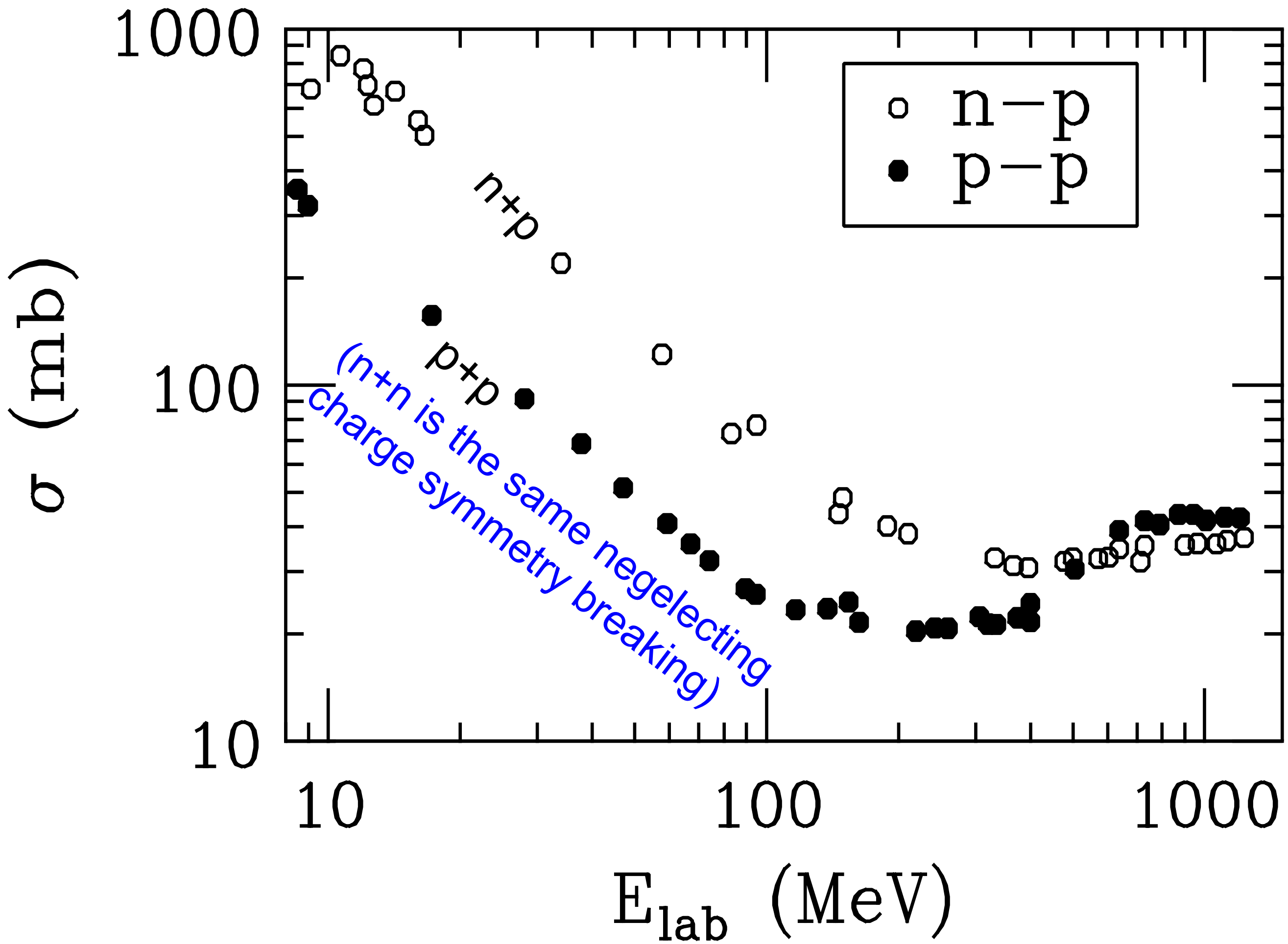
$$+ \frac{2C_{\tau,\tau}}{\rho_0}\int d^3p' \frac{f_\tau(r,p')}{1+(p-p')^2/\Lambda^2} + \frac{2C_{\tau,\tau'}}{\rho_0}\int d^3p' \frac{f_{\tau'}(r,p')}{1+(p-p')^2/\Lambda^2}$$

$$\tau,\tau' = \pm\frac{1}{2}, A_l(x) = -121 + \frac{2Bx}{\sigma+1}, A_u(x) = -96 - \frac{2Bx}{\sigma+1}, K_0 = 211 MeV$$

C.B. Das, S. Das Gupta, C. Gale and B.A. Li, PRC 67, 034611 (2003).

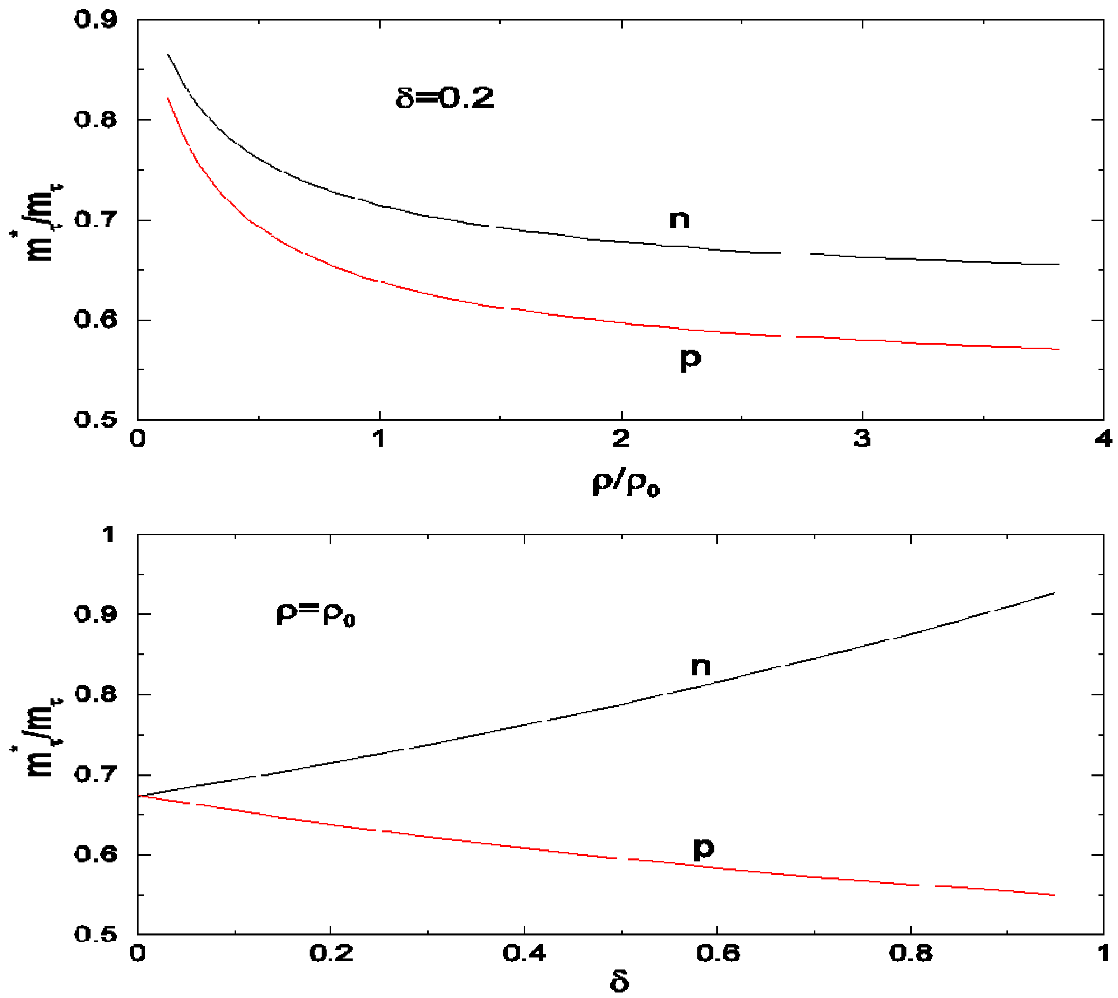
B.A. Li, C.B. Das, S. Das Gupta and C. Gale, PRC **69**, 034614; NPA **735**, 563 (2004).

Nucleon-nucleon cross section in free-space



Neutron-proton effective k-mass splitting
in neutron-rich matter at zero temperature

$$\frac{m_\tau^*}{m_\tau} = [1 + \frac{m_\tau}{p}\frac{\partial U}{\partial p}]^{-1}_{p_F^\tau}$$



With the modified Gogny effective interaction

Isospin-dependence of nucleon-nucleon cross sections in neutron-rich matter

The effective mass scaling model:

$$\sigma_{medium}/\sigma_{free} \approx \left(\frac{\mu^*_{NN}}{\mu_{NN}}\right)^2$$

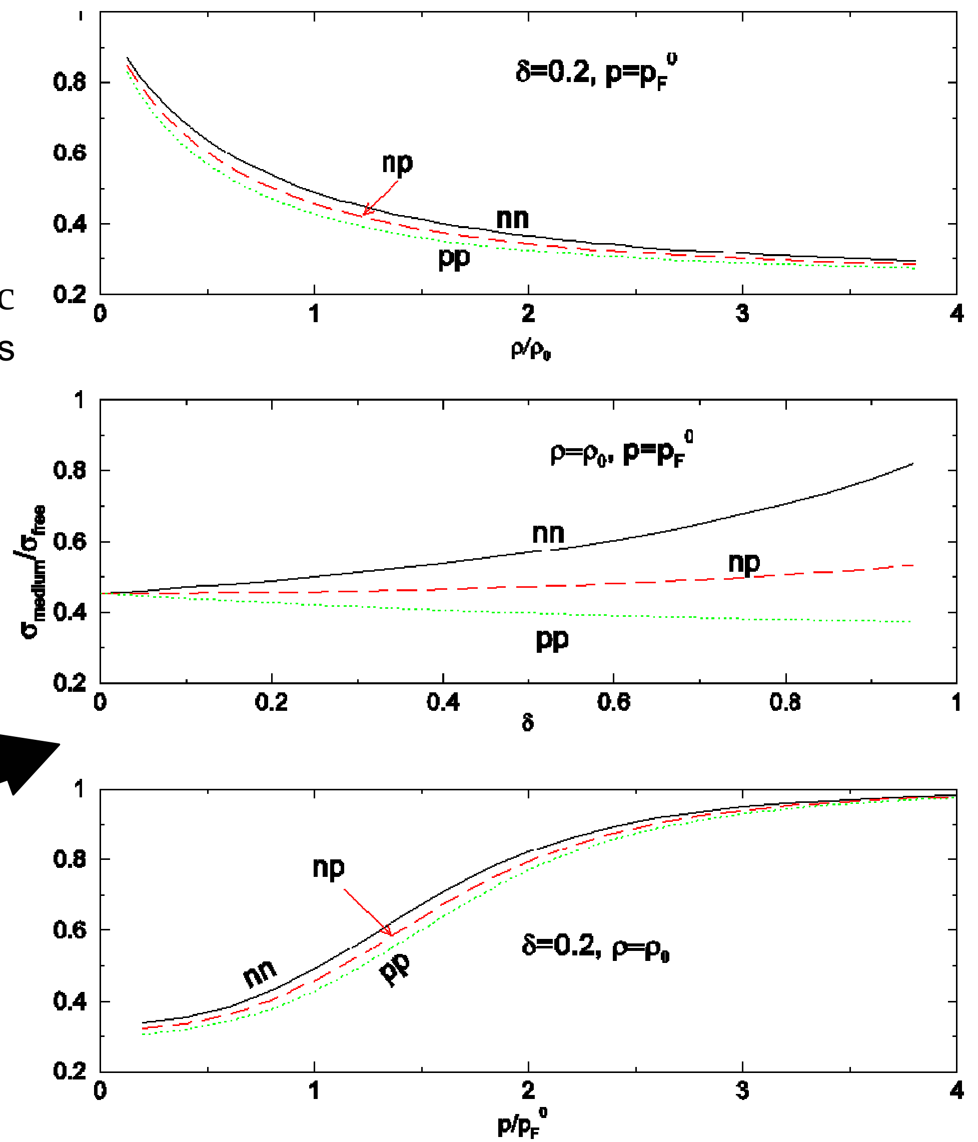
μ^*_{NN} is the reduced effective mass of the colliding nucleon pair NN

valid for $\rho \le 2\rho_0$ and relative momenta $\le$ 240 MeV/c according to Dirac-Brueckner-Hatree-Fock calculations

F. Sammarruca and P. Krastev, nucl-th/0506081

Phys. Rev. C (2005) in press.

$\sigma_{medium}/\sigma_{free}$ in neutron-rich matter at zero temperature



Applications in symmetric nuclear matter:

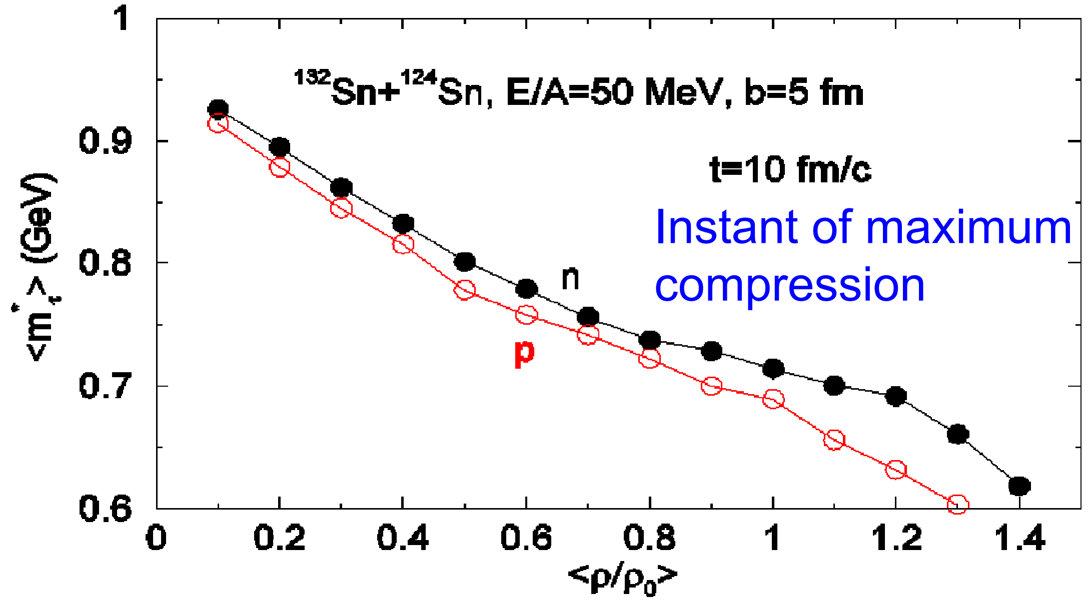
J.W. Negele and K. Yazaki, PRL 47, 71 (1981)
V.R. Pandharipande and S.C. Pieper, PRC 45, 791 (1992)
M. Kohno et al., PRC 57, 3495 (1998)
D. Persram and C. Gale, PRC65, 064611 (2002).

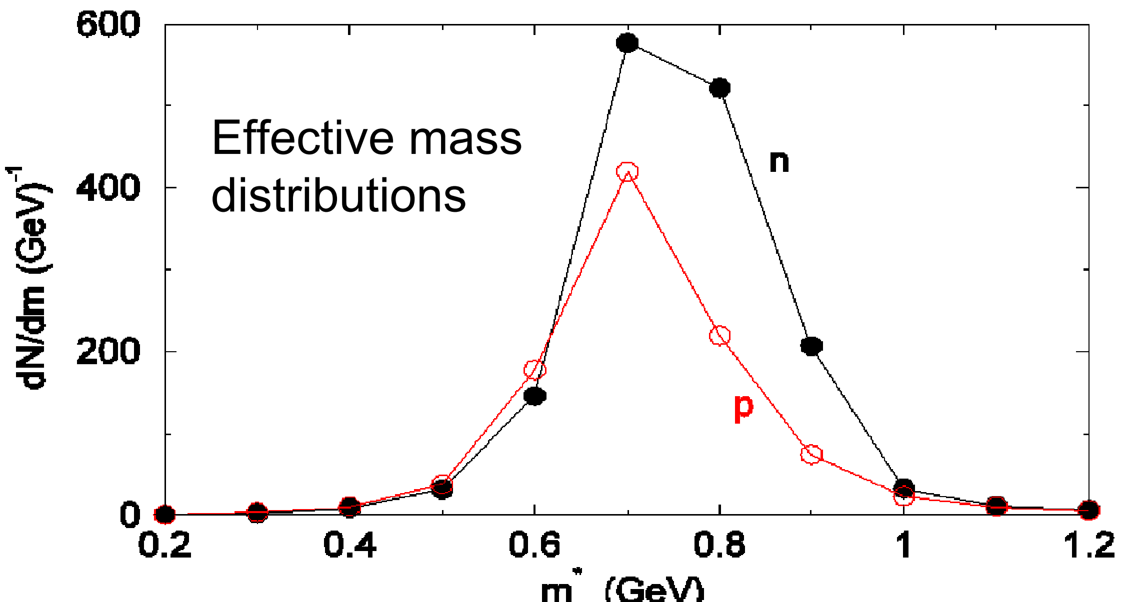
Application in neutron-rich matter:
nn and pp xsections are splitted due to the neutron-proton effective mass slitting

Bao-An Li and Lie-Wen Chen, nucl-th/0508024, Phys. Rev. C (2005) in press.

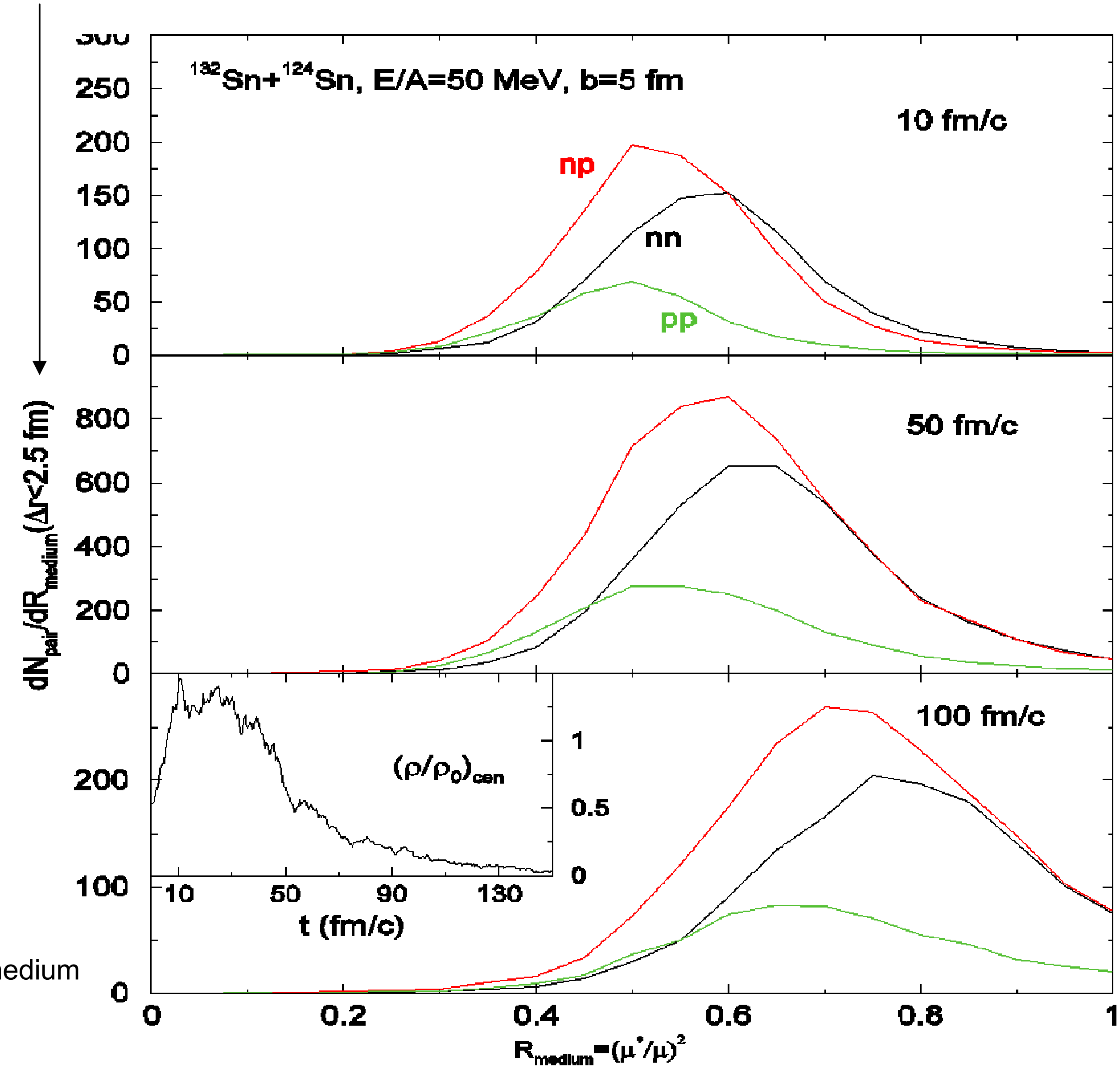
Nucleon effective masses during heavy-ion reactions

B.A. Li and L.W. Chen, nucl-th/0508024, Phys. Rev. C (2005) in press.





No. of potential colliding nucleon-nucleon pairs during heavy-ion collisions



$\sigma_{medium}=\sigma_{free} \times R_{medium}$

Reduction factor of their corresponding cross sections in the medium

Promising Probes of the $E_{sym}(\rho)$ in Nuclear Reactions (an incomplete list !)

At sub-saturation densities

- **Sizes of n-skins of unstable nuclei from total reaction cross sections**
- **Proton-nucleus elastic scattering in inverse kinematics**
- **Parity violating electron scattering studies of the n-skin in ^{208}Pb**
- **n/p ratio of FAST, pre-equilibrium nucleons**
- **Isospin fractionation and isoscaling in nuclear multifragmentation**
- **Isospin diffusion/transport**
- **Neutron-proton differential flow**
- **Neutron-proton correlation functions at low relative momenta**
- **$t/^3He$ ratio**

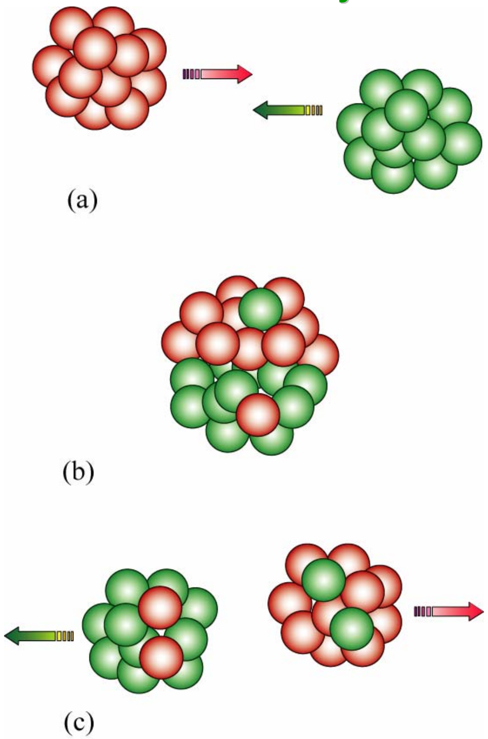
Towards high densities reachable at FAIR/GSI, RIA, RIKEN and CSR/China

- **π^-/π^+ ratio, K^+/K^0 ?**
- **Neutron-proton differential transverse flow**
- **n/p ratio at mid-rapidity**
- **Nucleon elliptical flow at high transverse momenta**

(1) Multi-observable correlations are important

(2) Detecting neutrons simultaneously with charged particles is critical

Extract the $E_{sym}(\rho)$ at subnormal densities from isospin diffusion/transport



A quantitative measure:

$$R_X^{A+B} \equiv \frac{2X^{A+B} - X^{A+A} - X^{B+B}}{X^{A+A} - X^{B+B}}$$

$$R_X^{A+A} = 1 \text{ and } R_X^{B+B} = -1$$

$R_X^{A+B} \approx 0$ for complete isospin mixing

X is an isospin-sensitive obseravble,
F. Rami et al. (FOPI/GSI), PRL, 84, 1120 (2000).

Nucleon flux:

$$\Gamma_i = \rho_i V_i$$

Isospin transport/diffusion:

$$\Gamma_n - \Gamma_p \propto \rho D_I \nabla_r \delta$$

The degree of isospin transport/diffusion depends on both the symmetry potential and the in-medium neutron-proton scattering cross section.

For near-equilibrium systems, the mean-field contributes:

$$D_I^m \propto dt \bullet F_{np} \propto \frac{1}{\sigma_{np}} \bullet \left(\frac{\partial \mu_{np}}{\partial \delta} + \frac{4E_{sym}^{\text{int}}}{m}\right)$$

During heavy-ion reactions, the collisional contribution to D_I is expected to be proportional to σ_{np}

*L. Shi and P. Danielewicz, Phys. Rev. C**68**, 017601 (2003).*

Isospin transport/diffusion experiments at the NSCL/MSU

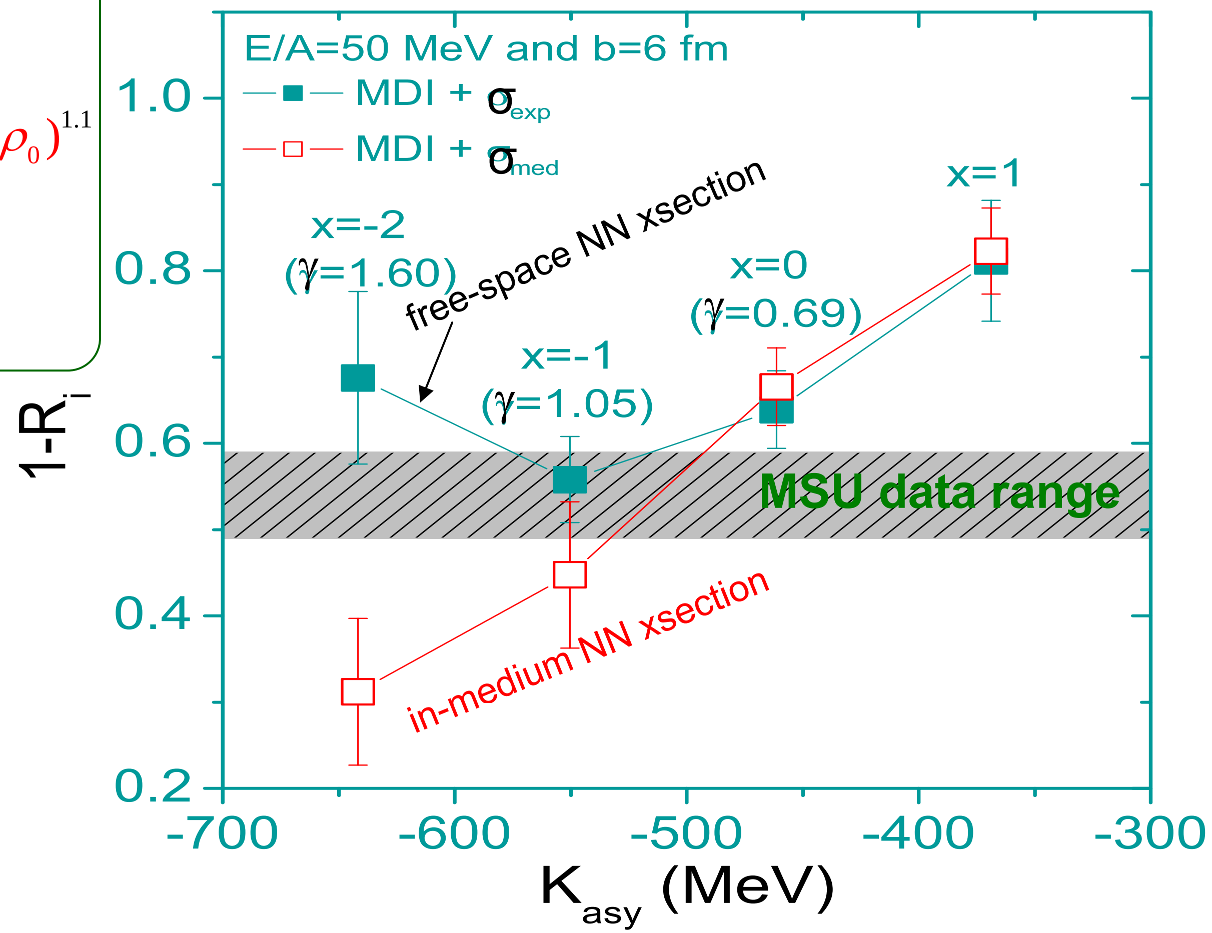
Isospin transport in $^{124}Sn+^{112}Sn$ using $^{112}Sn+^{112}Sn$ and $^{124}Sn+^{124}Sn$ as references
E_{beam}/A=50 MeV, use X=^{7}Li/^{7}Be or isospin-asymmetry of the projectile-like residue.
M.B. Tsang et al., Phys. Rev. Lett. 92, 062701 (2004)

Conservative Conclusions:

$$32(\rho/\rho_0)^{0.7} \le E_{sym}(\rho) \le 32(\rho/\rho_0)^{1.1}$$

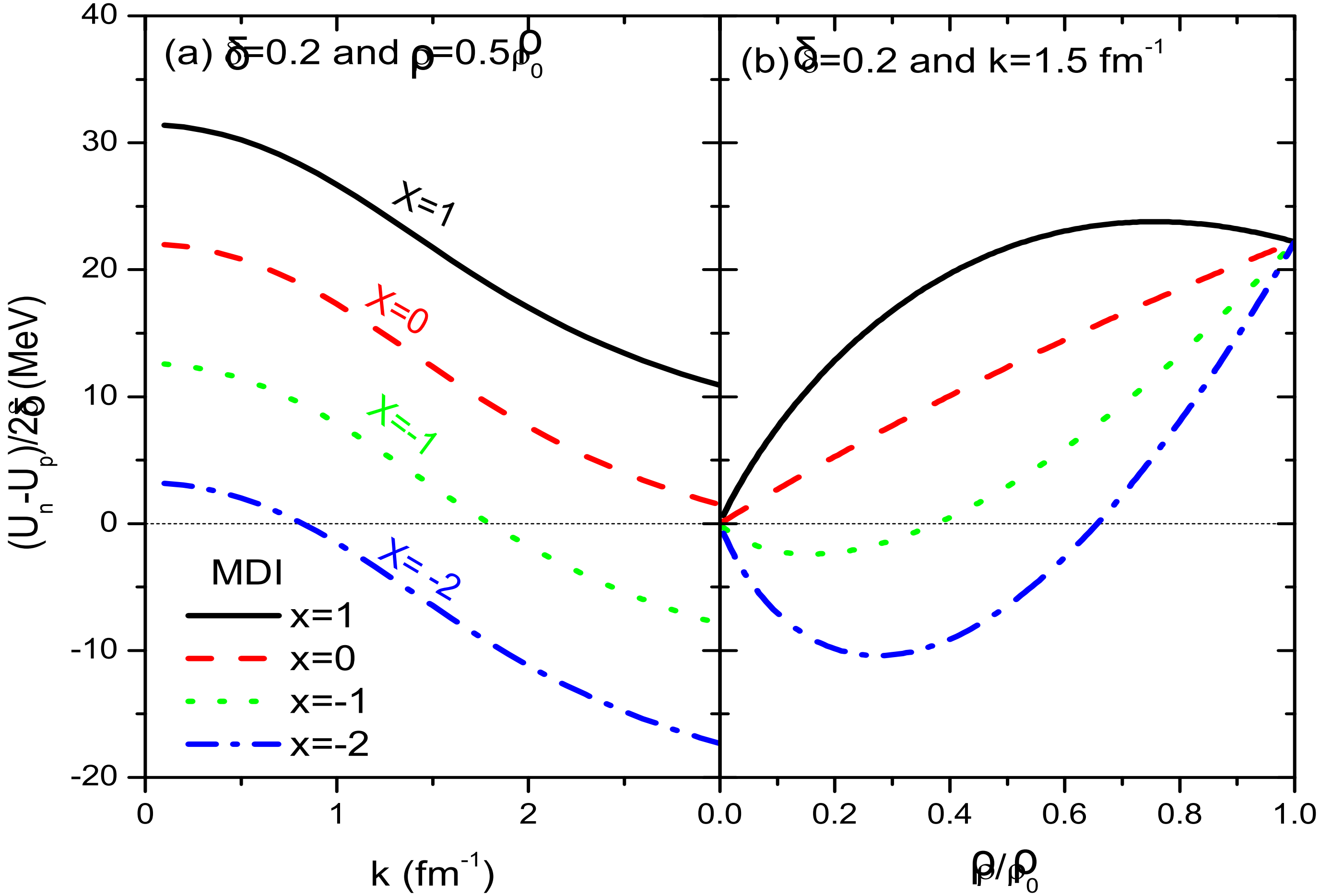
$$K_{asy}(\rho_0) \approx -500 \pm 50 \text{ MeV}$$

L.W. Chen, C.M. Ko and B.A. Li, Phys. Rev. Lett. 94, 32701 (2005);
Bao-An Li and Lie-Wen Chen, Phys. Rev. C (2005) in press.



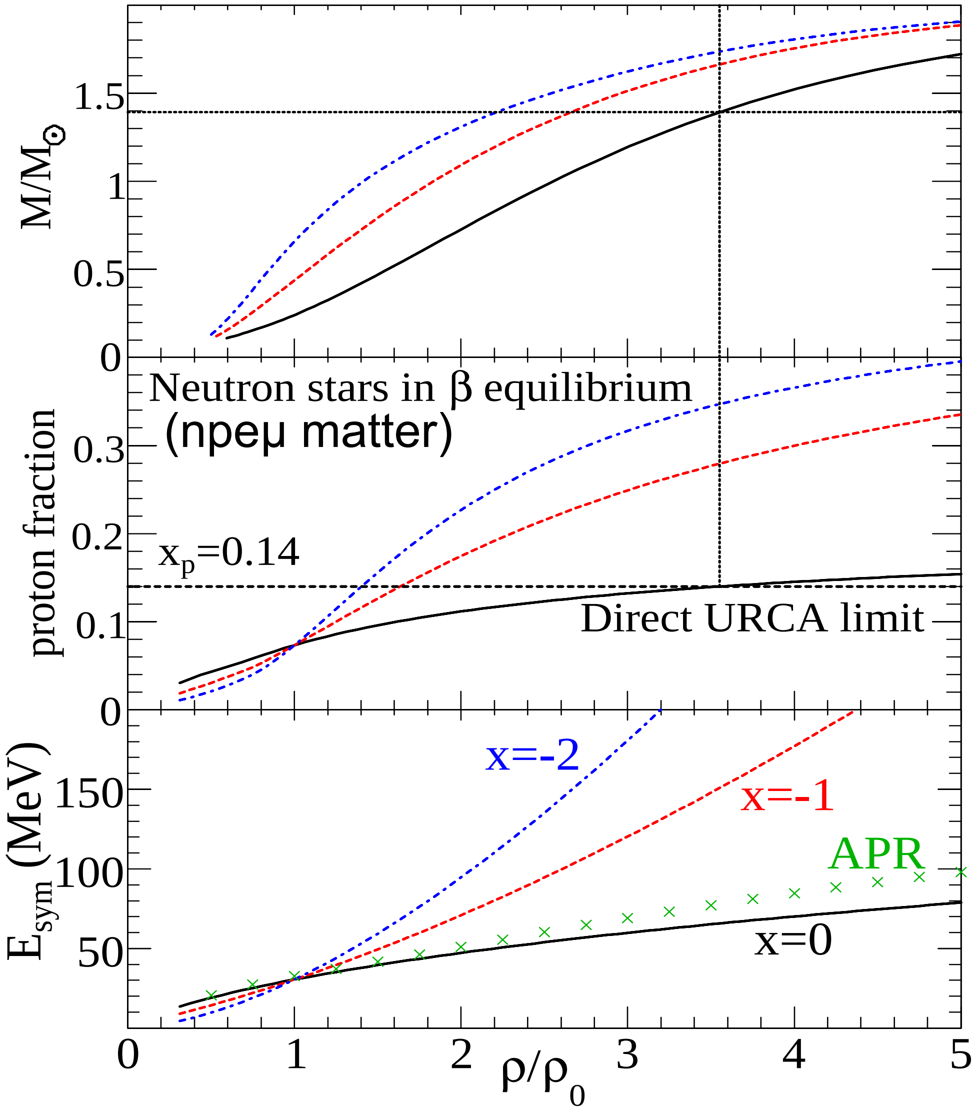
$$K_{asy}(\rho_0) \equiv 9\rho_0^2 (d^2E_{sym}/d\rho^2)_{\rho_0} - 18\rho_0(dE_{sym}/d\rho)_{\rho_0}$$

Strength of the symmetry potential at sub-normal densities



Impacts of the symmetry energy constrained by the isospin diffusion data

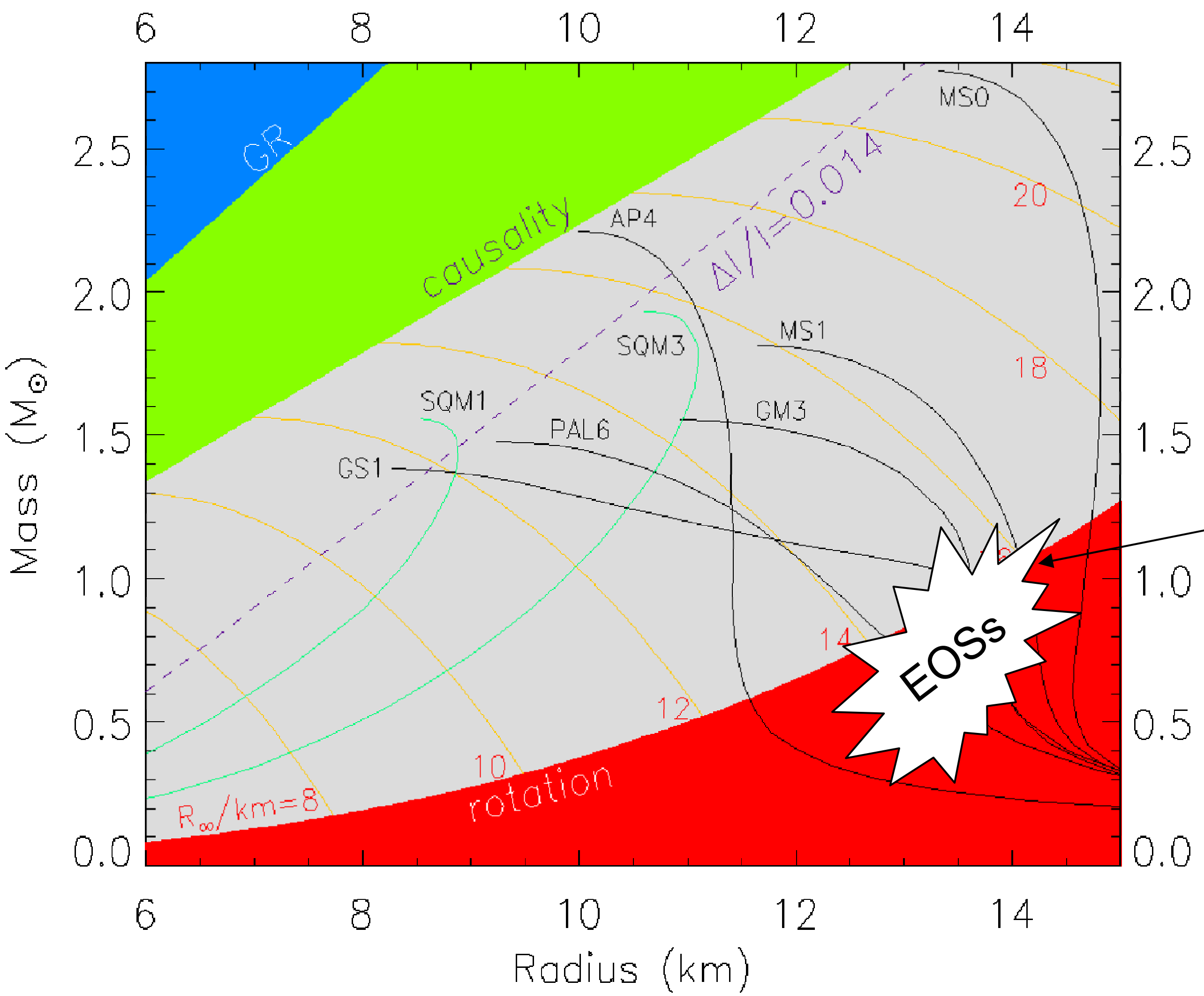
(2) Cooling mechanisms of proto-neutron stars



Direct URCA processes are possible for neutron stars with central densities $\rho_c > 3.5\ \rho_0$ and masses $M > 1.39 M_\odot$

A. Akmal, V.R.Pandharipande and D.G. Ravenhall
Phys. Rev. C58, 1804 (1998)

Mass-radius correlation of neutron stars and their EOS



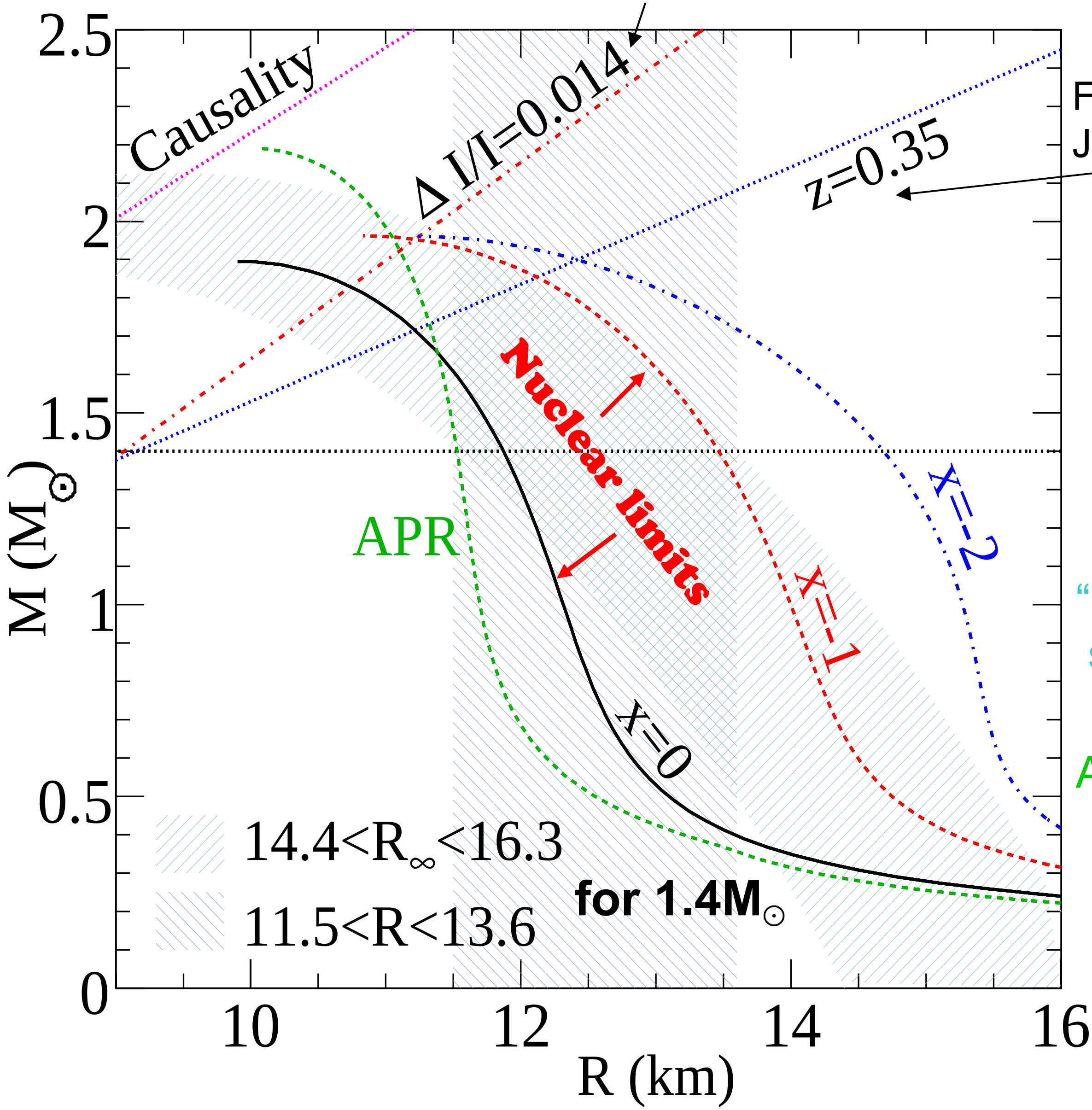
Different EOS predicted by various theories

Essentially, none of them was ever tested against reaction data

J.M. Lattimer and M. Prakash, *Science Vol. 304 (2004) 536-542.*

Constraining the radii of neutron stars with terrestrial nuclear laboratory data

Vela glitch: B. Link, et al, PRL 83, 3362 (1999).



For EXO0748
J. Cottam et al, Nature 420, 51 (2002)

Graviational redshift

$$R_\infty = R(1+z) = R/\sqrt{1-2GM/Rc^2}$$

matter radius where P®=0.

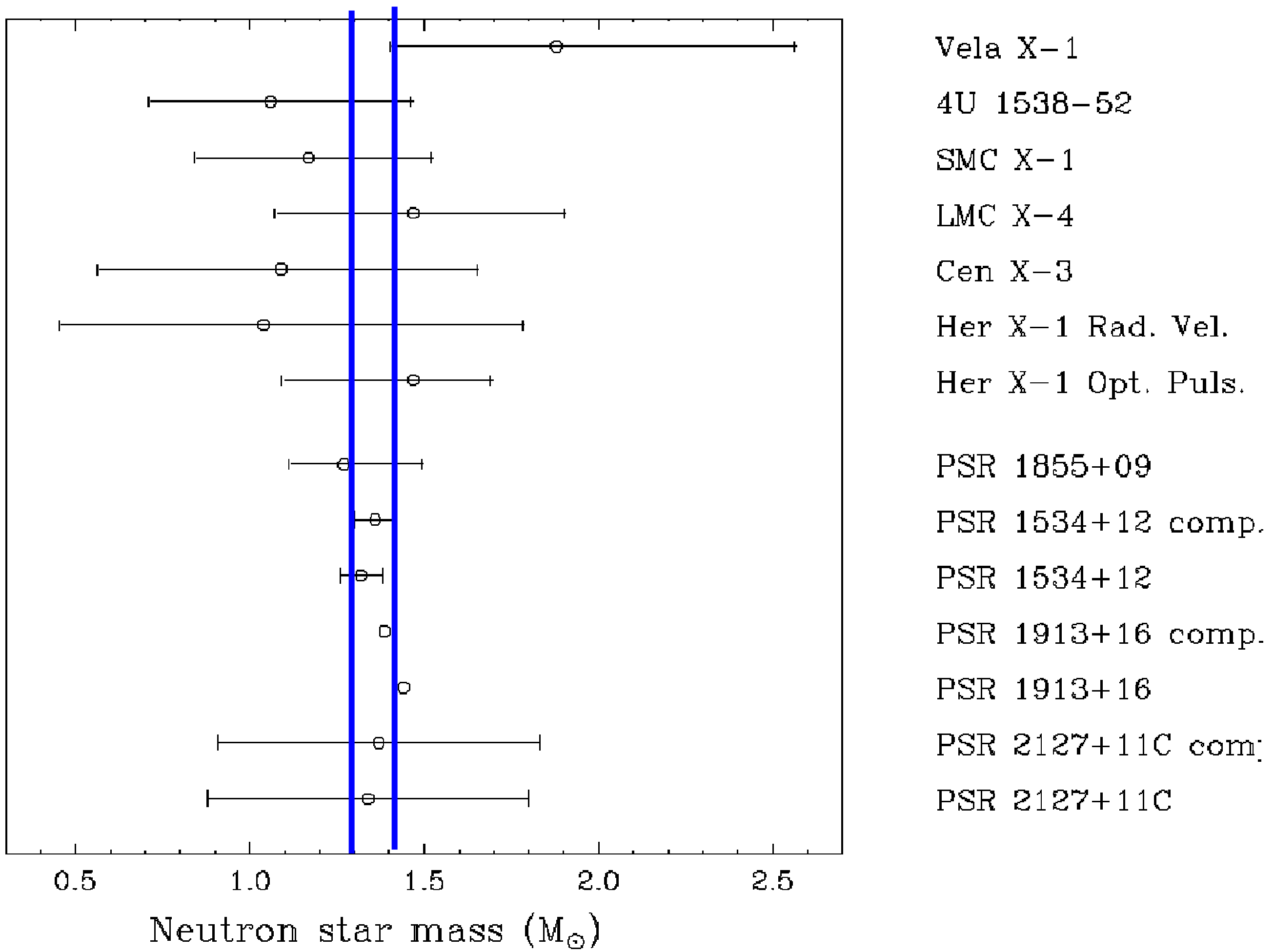
"radiation radius" seen by observer at infinity

APR: A. Akmal, V.R.Pandharipande and D.G. Ravenhall
K_0=269 MeV

K_0=211 MeV for x=0, -1, and -2

Bao-An Li and Andrew W. Steiner, nucl-th/0511064

Masses of canonical neutron stars



$\langle M_{neutron\ star} \rangle = 1.35 \pm 0.04\ M_\odot$

S.E. Thorsett and D. Charkrabarty, Astrophysics J. 512, 288 (1999).

Measuring Neutron Star Radii

- Determine luminosity, temperature and deduce surface area. If black body $L=4\pi R_\infty^2\sigma T^4$.
  - T from X-ray spectrum, such as those from Chandra satellite
  - Need distance to star from parallax to get L.
  - Deduce R from surface area (~30% corrections from curvature of space-time).

  The radiation radius for an observer at infinity:

  $$R_\infty = R(1+z) = R/\sqrt{1-2GM/Rc^2}$$

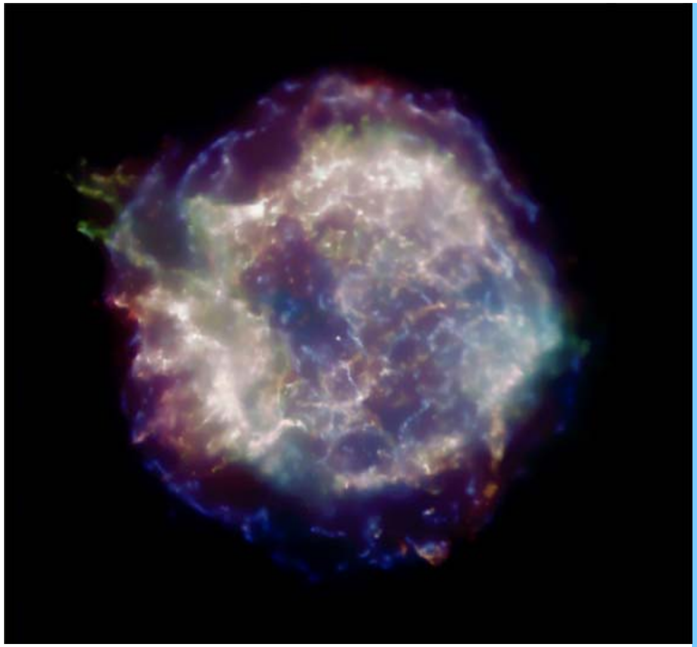
  z is the gravitational redshift and R the matter radius where the pressure vanishes
- Complications
  - Spectrum peaks in UV and this is heavily absorbed by interstellar H.
  - Not a black body: often black body fit to X-ray does not fit visible spectra.
  - Model NS atmospheres (composition uncertain) to correct black body.
- Current status: available estimates give a wide range

  "Although accurate masses of several neutron stars are available, a precise measurement of the radius does not exist yet"……

  Lattimer and Prakash, *Science Vol. 304 (2004) 536*

The Chandra X-Ray Observatory lunched on July 23, 1999

Latest status of the radiation radius R_∞ measured on space x-ray observatories (Chandra and XMM-Newton) --- Bob Rutledge, Oct. 2005



Chandra image of Cas A

The radii are estimated assuming the masses are all $1.4M_\odot$ without actually measuring the masses simultaneously because some of them are isolated neutron stars instead of being in a binary

Name	R_∞ (km/D)	D (kpc)	$kT_{eff,\infty}$ (eV)	N_H (10^{20} cm^{-2})	Ref.
omega Cen (Chandra)	13.5 ± 2.1	5.36 ±6%	66^{+4}_{-5}	(9)	Rutledge et al (2002)
omega Cen (XMM)	13.6 ± 0.3	5.36 ±6%	67 ±2	9 ± 2.5	Gendre et al (2002)
M13 (XMM)	12.6 ± 0.4	7.80 ±2%	76 ±3	(1.1)	Gendre et al (2002)
47 Tuc X7 (Chandra)	$R=14.5_{-1.4}^{+1.6}$ (M=1.4)	5.13 ±4%	kT=105 ±6	$4.2^{+1.8}_{-1.6}$	Rybicki et al (2005)
M28 (Chandra)	$14.5_{-3.8}^{+6.9}$	5.5 ±10%	90_{-10}^{+30}	26 ± 4	Becker et al (2003)

The radii of neutron stars are primarily determined by $\frac{dE_{sym}(\rho)}{d\rho}|_{\rho_0}$

unlike other properties, such as the masses

First found empirically then proven analytically by Prakash and Lattimer, Astro. Phys. Jour. ***550****, 426 (2001)*

Why ?

The radius and mass are determined by the Tolman-Oppenheimer-Volkoff eq. for the gravitational equilibrium

$$\frac{dP}{dr} = -\frac{G(e(r)+P(r)/c^2)(m(r)+4\pi r^3 P(r)/c^2)}{r^2(1-2Gm(r)/rc^2)}, \ \mathrm{m(r)}=\int_0^r 4\pi \mathrm{r}'^2 e(r')dr', \ e(r) \text{ is the energy density at r}$$

the radius is determined by P(R)=0, the pressure P(ρ) at β-equilibrium is obtained from

$$\mathrm{P}(\rho,\delta)=\mathrm{P}_{\text{nuclear}} + \mathrm{P}_{\text{electron}} = \rho_0^2(\frac{\partial E}{\partial \rho})_\delta + \frac{1}{4}\rho_e\mu_e = \rho_0^2(E'_{\text{nuclear matter}}(\rho) + E'_{sym}(\rho)\delta^2) + \frac{1}{2}\delta(1\text{-}\delta)\rho \bullet \mathrm{E}_{\text{sym}}(\rho)$$

with δ determined by the chemical equilibrium condition $\mu_e = \mu_n - \mu_p = 4\delta E_{sym}(\rho)$ and the charge neutrality $\rho_e = \rho_p$

Example: at ρ_0, $\delta \approx 0.86$ with $\mathrm{E}_{\text{sym}}(\rho_0) = 32$ MeV, and $\mathrm{E}'_{\text{nuclear matter}}(\rho_0) = 0$

thus $\mathrm{P}(\rho_0) = \rho_0^2\delta^2 E'_{sym}(\rho_0) + \frac{1}{2}\delta(1\text{-}\delta)\rho \bullet \mathrm{E}_{\text{sym}}(\rho_0) \approx \rho_0^2\delta^2 E'_{sym}(\rho_0)$

Most models predict $\mathrm{E}'_{\text{sym}}(\rho) \sim E'_{sym}(\rho_0)$ for $\rho \leq 5\rho$

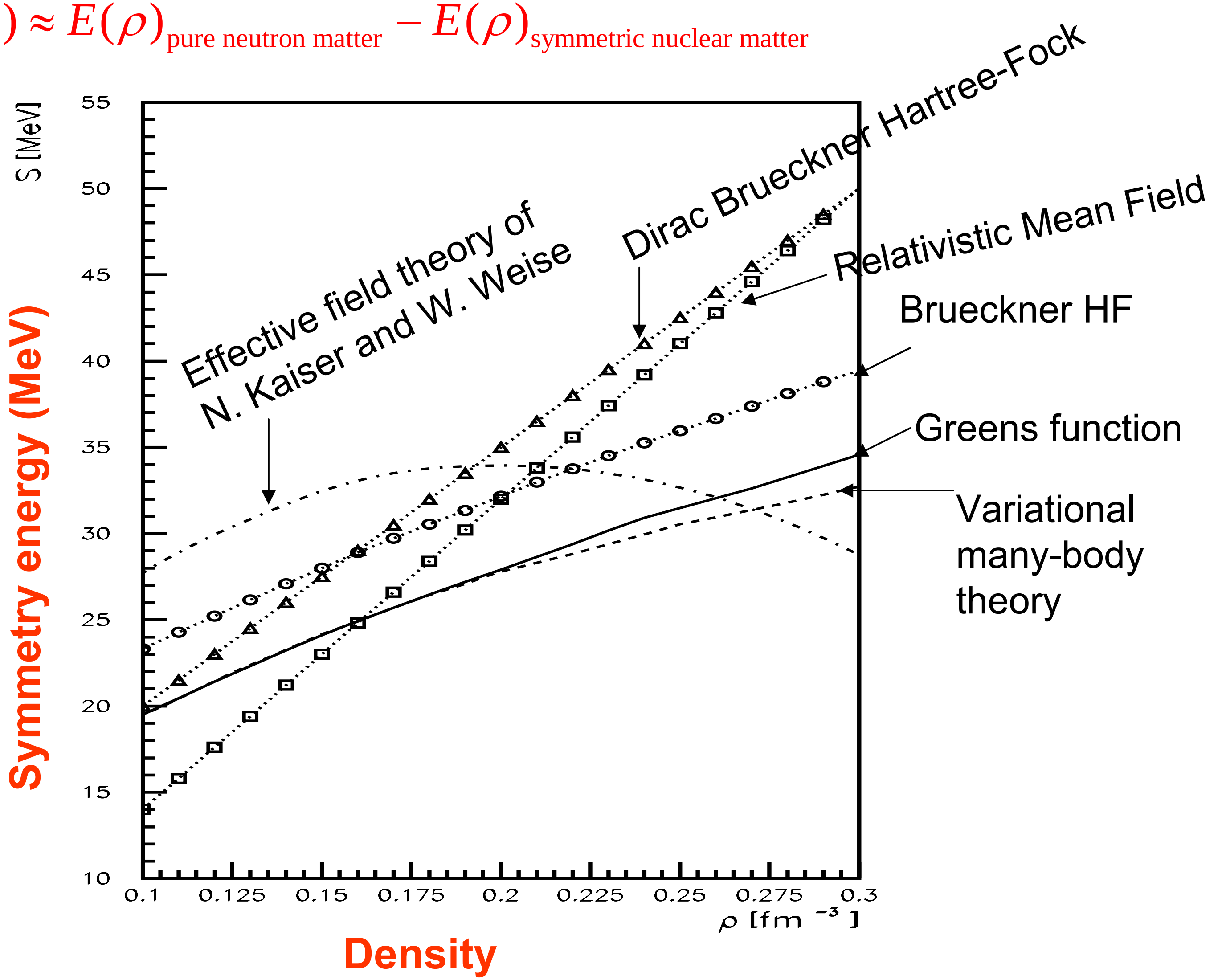
Since the radius is determined by P(R)=0, the R is thus very sensitive to the

behavior of $\mathrm{P}(\rho_0) \propto \mathrm{E}'_{\text{sym}}(\rho_0)$ while the mass $\mathrm{m(r)}=\int_0^r 4\pi \mathrm{r}'^2 e(r')dr'$ is sensitive to the EOS at all densities

E_{sym} (ρ) predicted by microscopic many-body theories

EOS: $E(\rho,\delta) = E(\rho,0) + E_{sym}(\rho)\delta^2 + o(\delta^4)$, where $\delta \equiv (\rho_n - \rho_p)/\rho$

$$E_{sym}(\rho) \approx E(\rho)_{\text{pure neutron matter}} - E(\rho)_{\text{symmetric nuclear matter}}$$



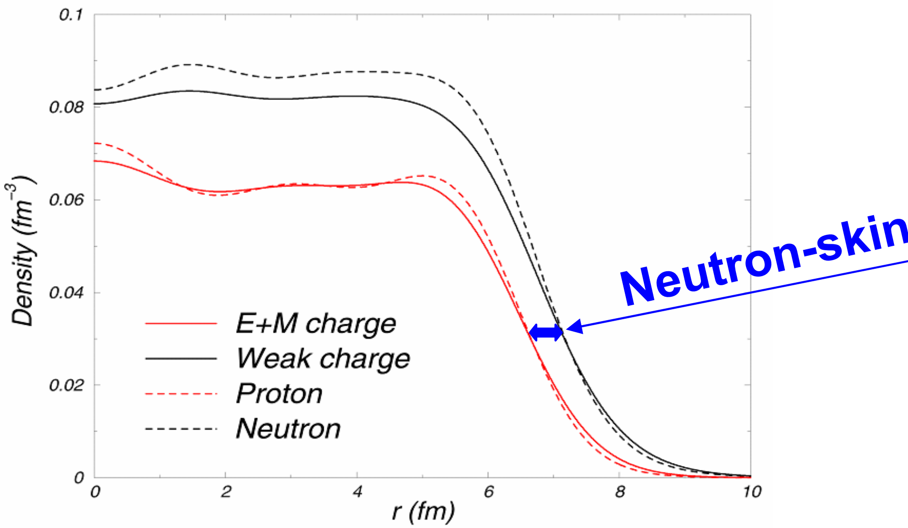
A.E. L. Dieperink, Y. Dewulf, D. Van Neck, M. Waroquier and V. Rodin, Phys. Rev. C68 (2003) 064307

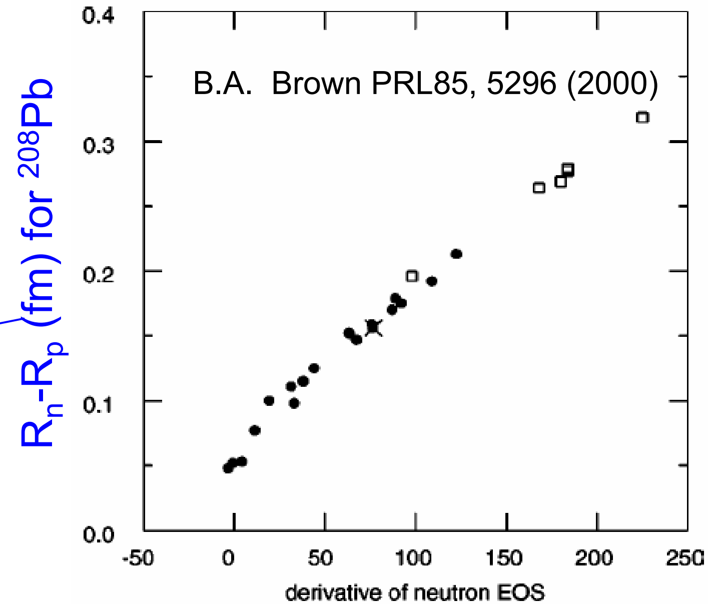
Neutron-skin in ^{208}Pb and $dE_{sym}/d\rho$

B.A. Brown, C. Horowitz, J. Piekarewicz, R.J. Furnstahl, J.R. Stone, et al.

^{208}Pb

C.J. Horowitz and J. Piekarewicz, PRL 86, 5647 (2001)





Pressure forces neutrons out against surface tension. Large pressure gives large neutron skin. **$dE_{sym}/d\rho$ determines the size of n-skin and pressure of neutron matter at ρ_0**

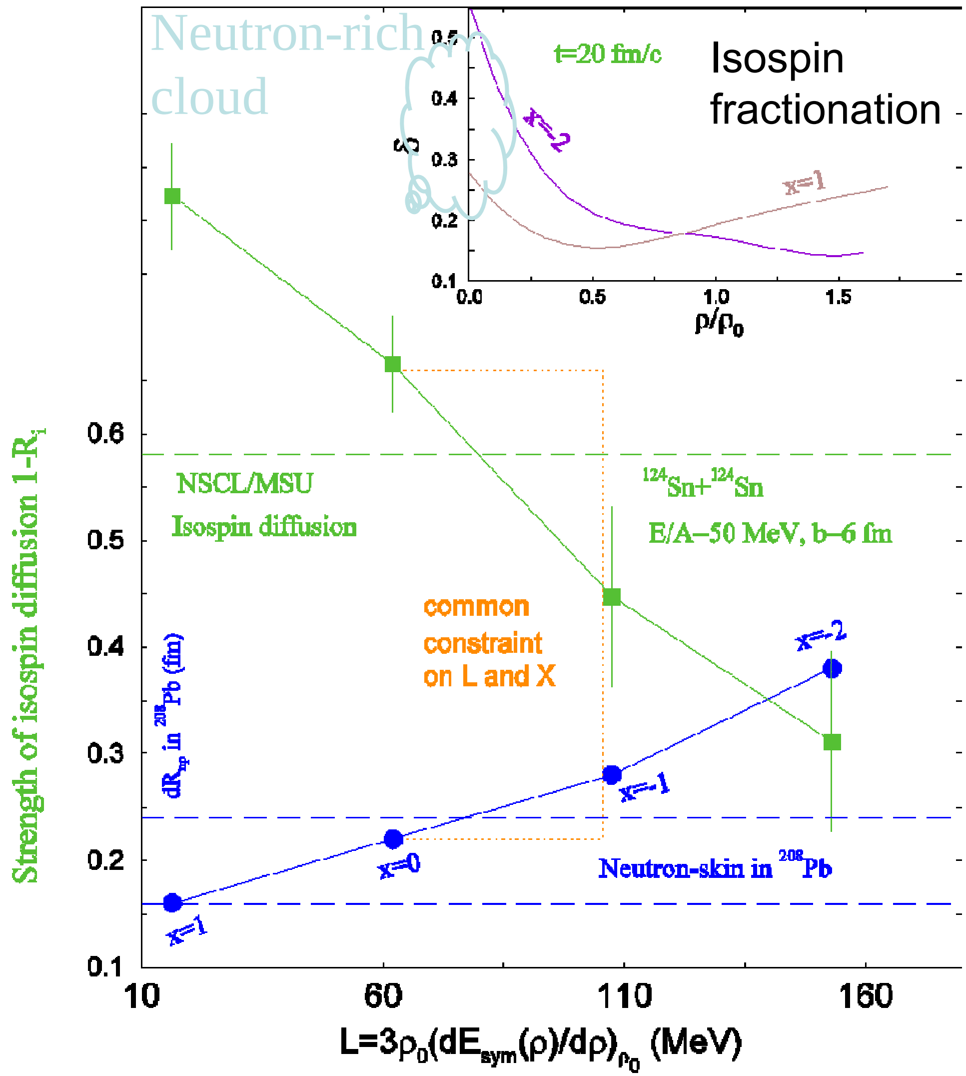
$$E_{neutron} = E_{nuclear} + E_{sym}, \quad R_n - R_p \propto \Delta p_{np} = dE_{nuclear}/d\rho\big|_{\rho_0} + dE_{sym}/d\rho\big|_{\rho_0} = 0 + dE_{sym}/d\rho\big|_{\rho_0}$$

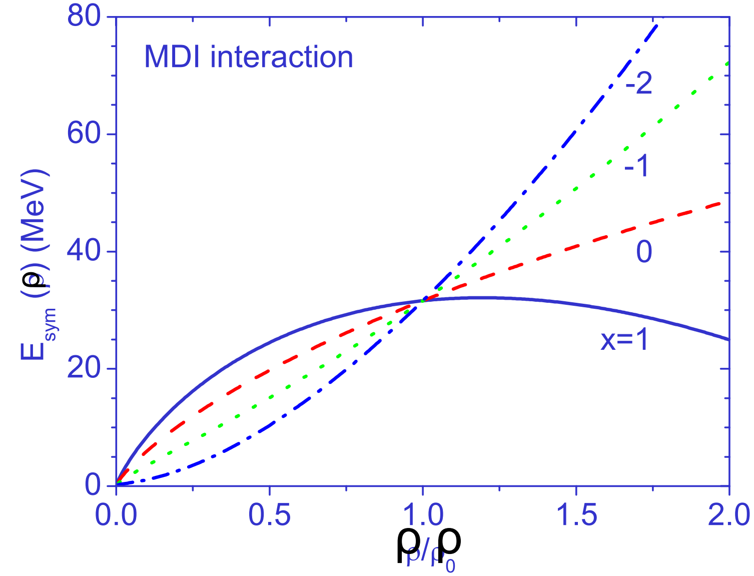
For the same reason, it is harder for neutrons and protons to mix-up with a larger $dE_{sym}/d\rho$, thus a smaller/slower isospin diffusion

→ correlation of neutron-skin and isospin diffusion

Andrew W. Steiner and Bao-An Li, Phys. Rev. C72, 041601 (2005).

Constraining the $dE_{sym}/d\rho$ with data on both isospin diffusion and n-skin in ^{208}Pb





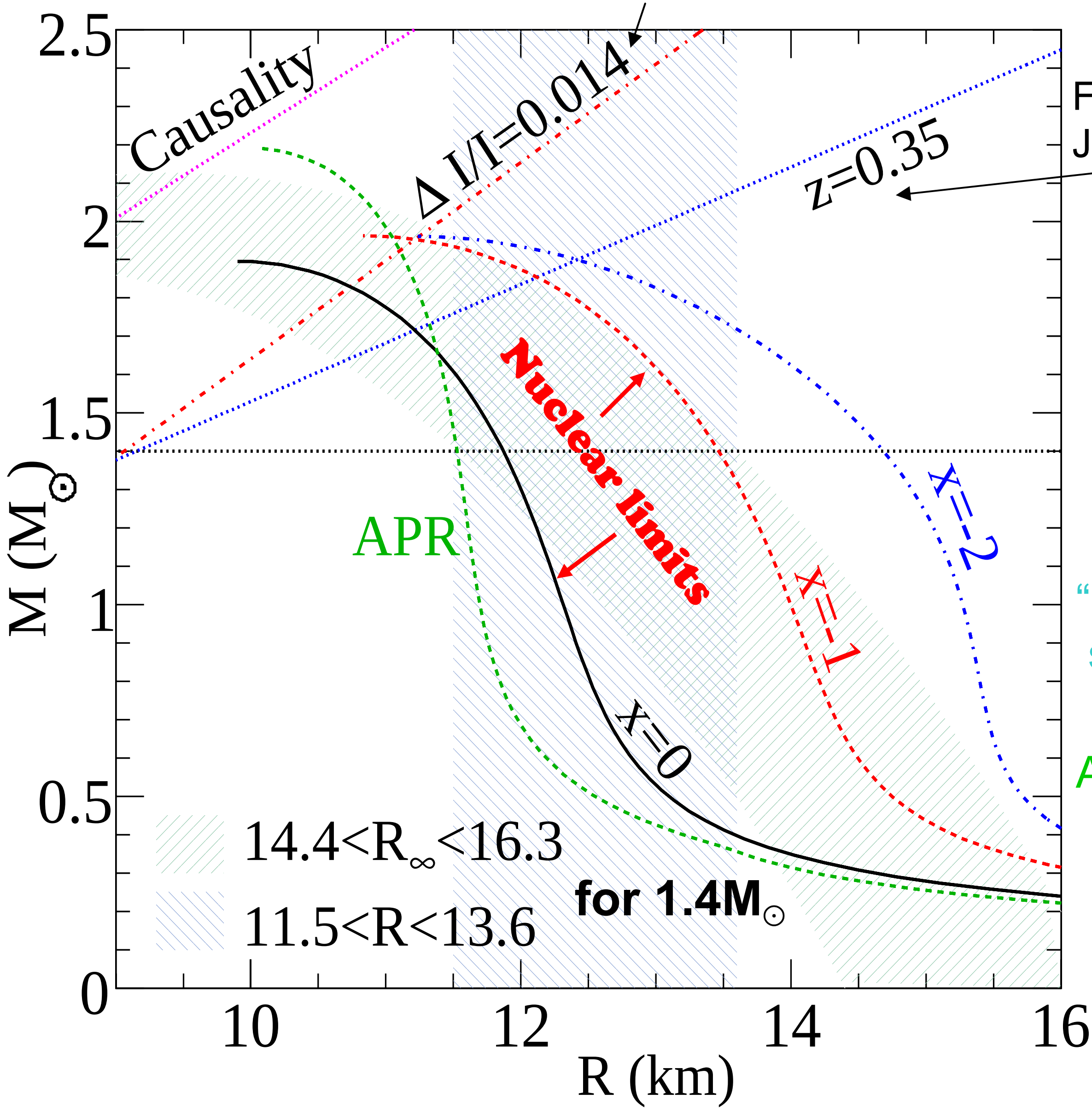
Neutron skin is calculated with Skyrme HF with interactions parameters adjusted such that the same EOS as used in calculating the isospin diffusion is obtained for a given x

Neutron-skin data: V.E. Starodubsky and N.M. Hintz, PRC 49, 2118 (1994);

B.C. Clark, L.J. Kerr and S. Hama, PRC 67, 054605 (2003)

Constraining the radii of neutron stars with terrestrial nuclear laboratory data

Vela glitch: B. Link, et al, PRL 83, 3362 (1999).



For EXO0748
J. Cottam et al, Nature 420, 51 (2002)

Graviational redshift

$$R_\infty = R(1+z) = R/\sqrt{1-2GM/Rc^2}$$

matter radius
where P®=0.

"radiation radius"
seen by observer at infinity

APR: A. Akmal, V.R.Pandharipande
and D.G. Ravenhall
K_0=269 MeV

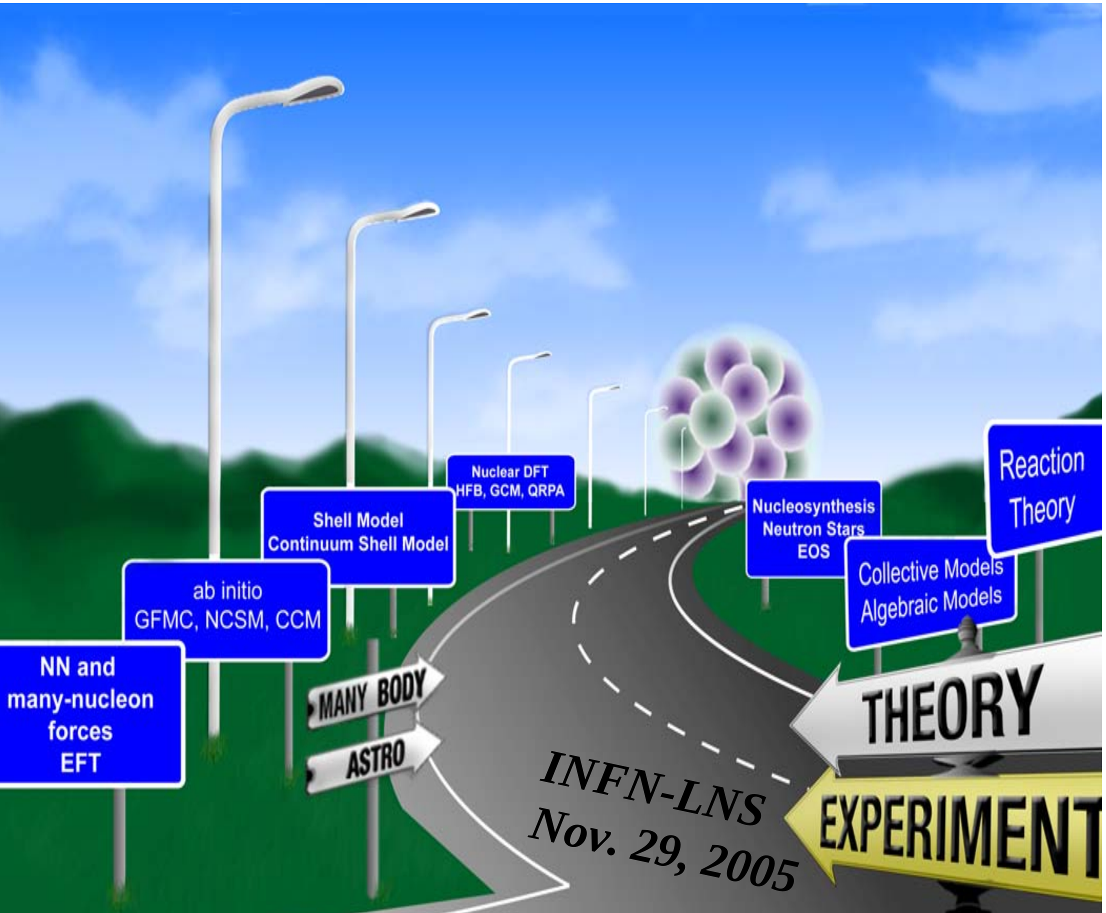
K_0=211 MeV for x=0, -1, and -2

Bao-An Li and Andrew W. Steiner, nucl-th/0511064

Summary

Intermediate energy heavy-ion collisions are a unique tool to study the isospin dependence of strong interactions, it is a fundamental quantity for understanding the nature of neutron-rich matter and has significant ramifications in astrophysics

(Hope the director, Prof. E. Migneco will consider this in making the future plan for the INFN-LNS)



Transport model anslyses of available isospin diffusion data from MSU lead to

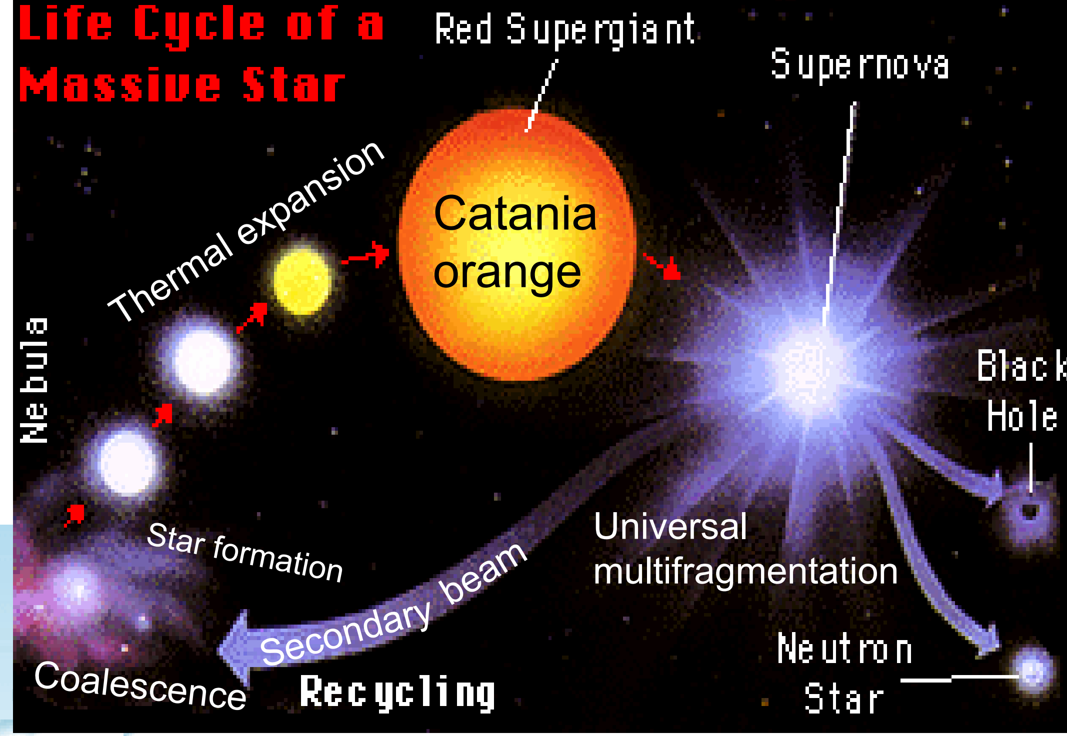
$$32(\rho/\rho_0)^{0.7} \le E_{sym}(\rho) \le 32(\rho/\rho_0)^{1.1}$$

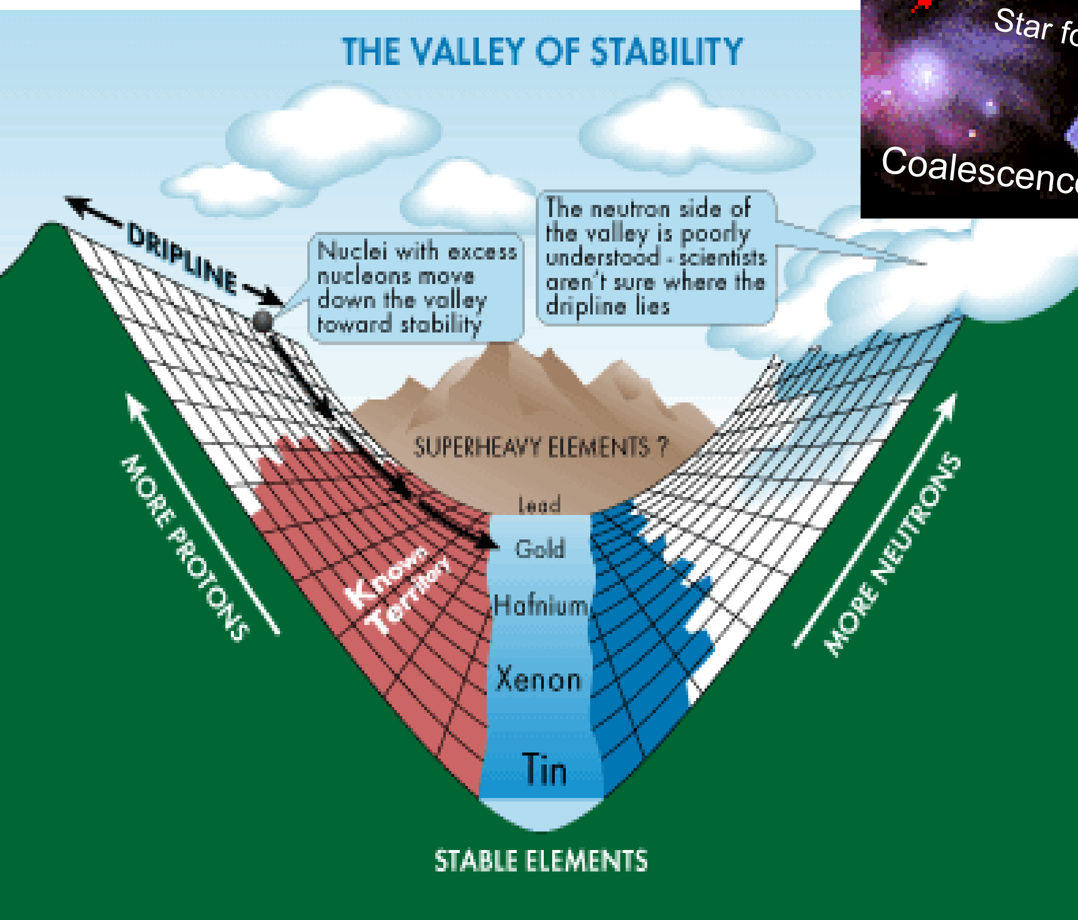
$$K_{asy}(\rho_0) \approx -500 \pm 50 \text{ MeV}$$

Important constraints are put on

- EOS of neutron-rich matter
- Nuclear effective interactions
- Cooling mechanisms of n-stars
- Radii of n-stars

Looking forward and driving away from the valley of stability → EOS of dense n-rich matter





- How supernovae explode
- How heavy elements are formed in the universe
- What are the properties of n-stars
- What is the critical M/R ratio of a neutron star before it becomes a black hole when the neutron degenerate pressure in the star can no longer support its gravity
- Isospin dependence of in-medium nuclear effective interactions