Isospin Asymmetry in Nuclei, Neutron Stars, and Heavy-Ion Collisions

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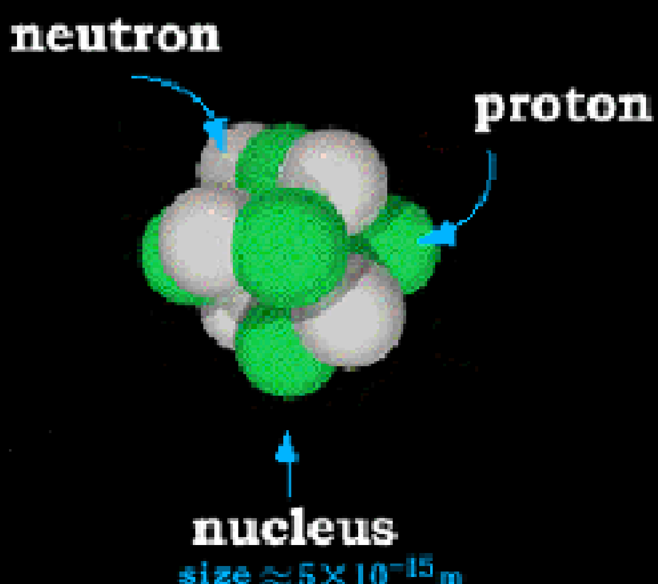
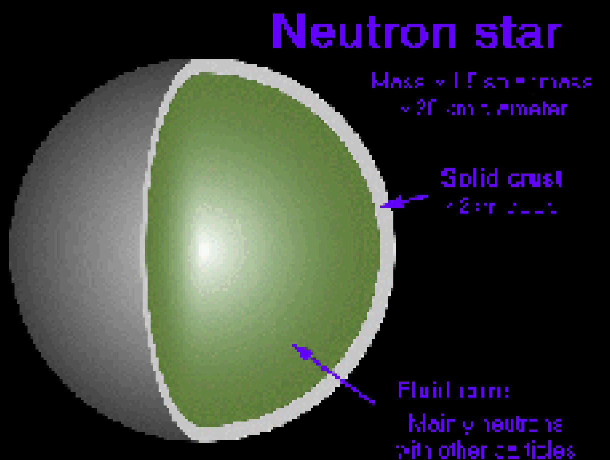
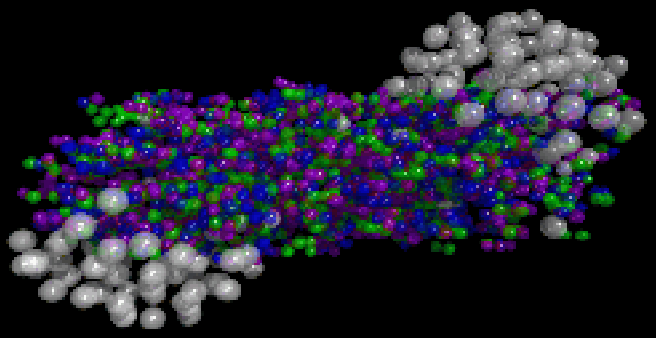




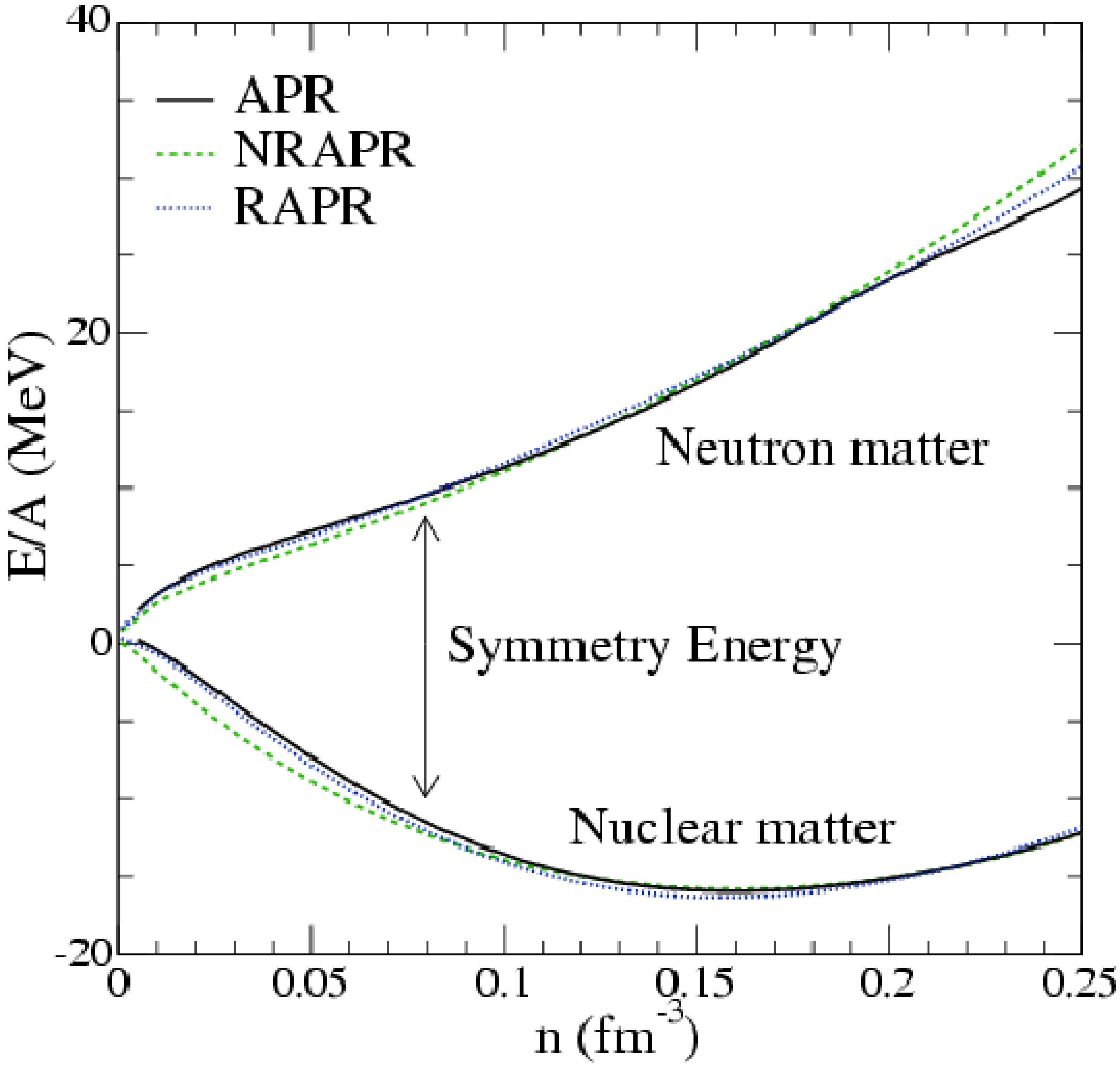


Outline of the Talk

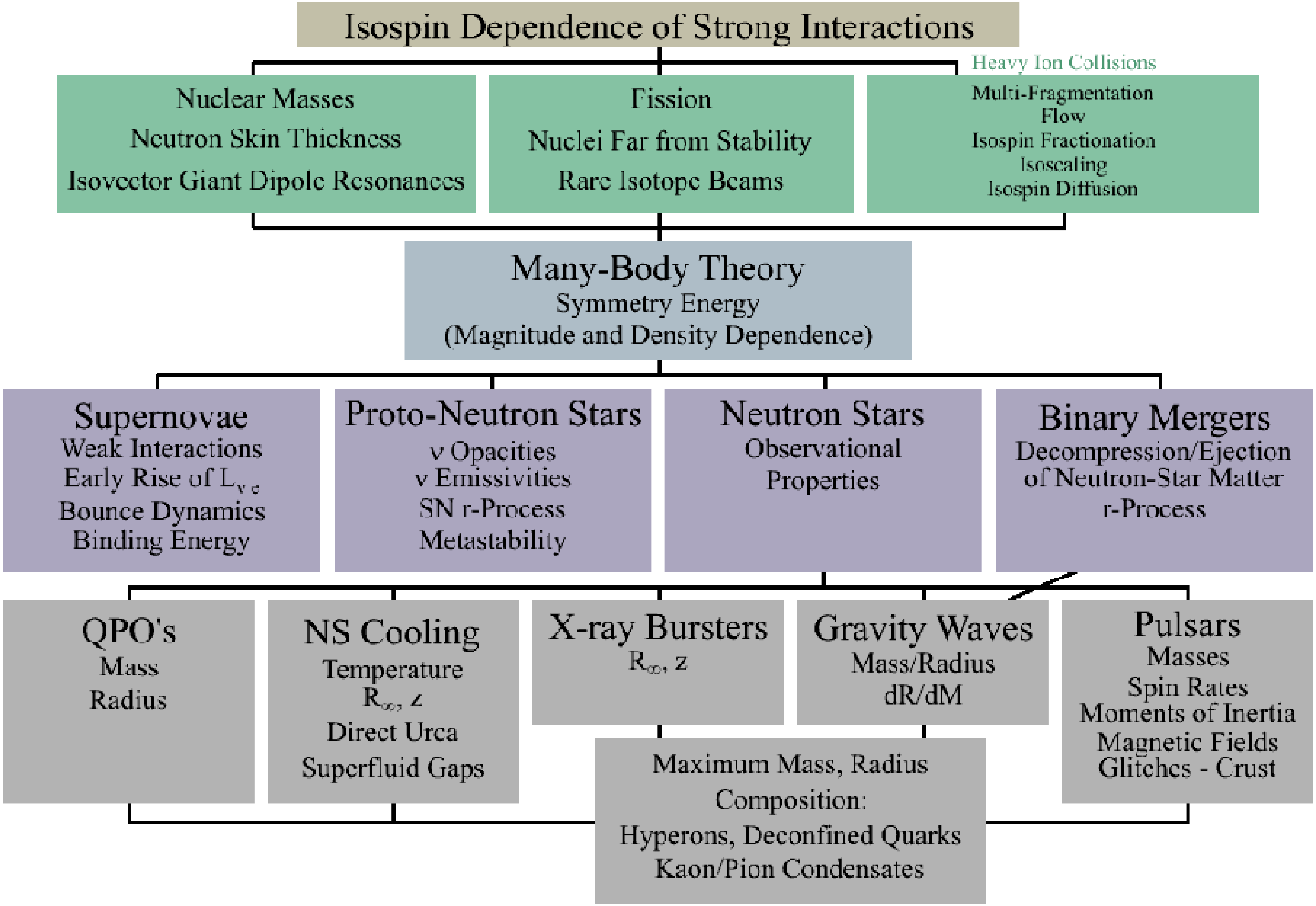
- Symmetry Energy
  - Definition
  - Importance
  - Uncertainty
- Equation of State
- Applications
  - Nuclei
  - Neutron Stars
  - Heavy-Ion Collisions

The Nuclear (A)symmetry Energy

- The symmetry energy is the size of the energy cost in QCD of creating an asymmetry between the number of neutrons and protons
- Note that the pressure (at zero T) is related to the derivative of the energy per baryon (E/A)
- Of concern is the magnitude of the symmetry energy and its density dependence
- The analog of the compressibility for the isospin degree of freedom



Taken from A.S., M. Prakash, J.M. Lattimer, and P.J. Ellis, Phys. Rep. 411 (2005) 325.



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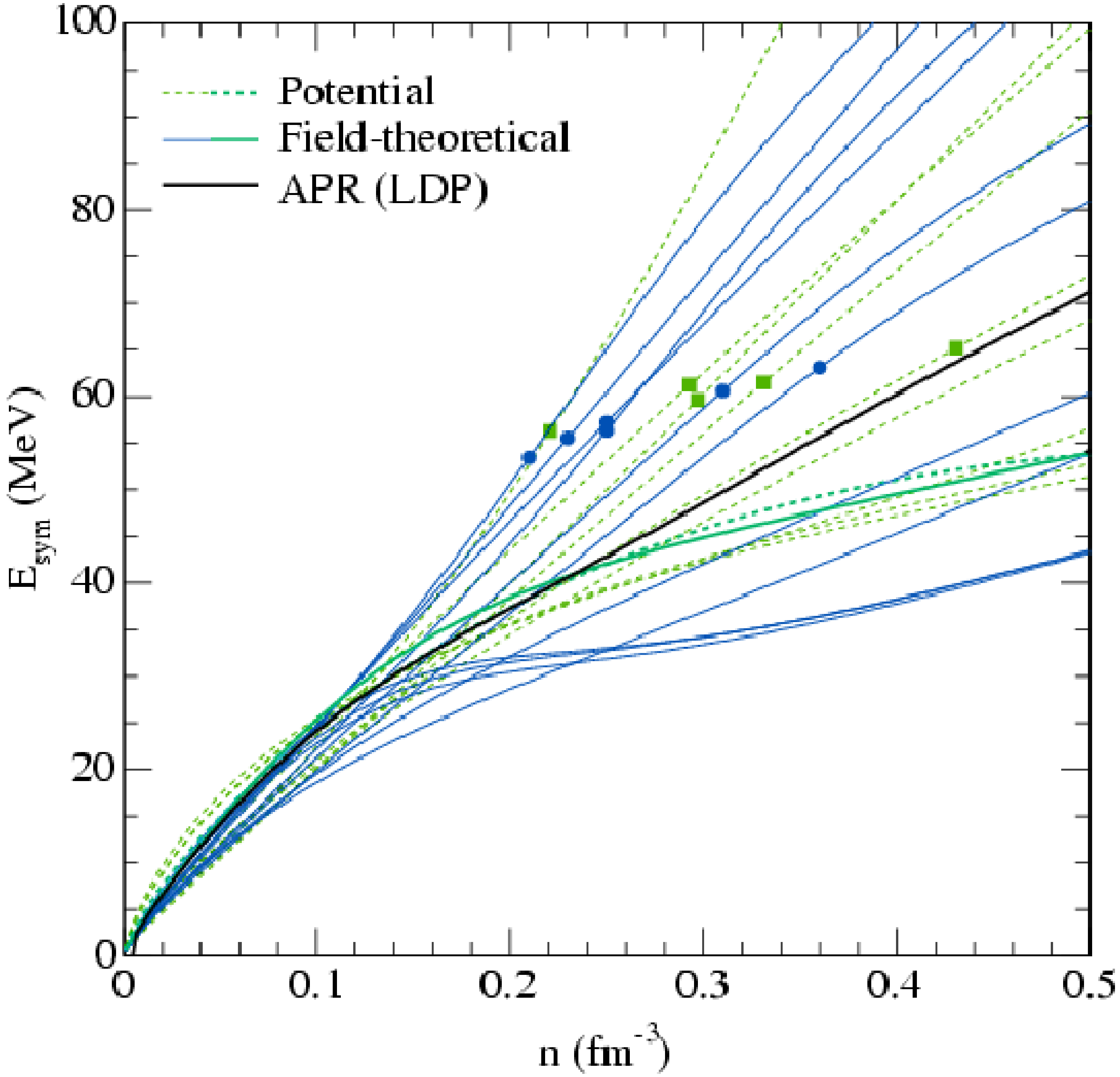
The Nuclear Symmetry Energy

- There is considerable variation among models, both relativistic and non-relativistic
- Relativistic models = Extensions of the Walecka model to include higher order interactions between the isoscalar and isovector mesons
- Non-relativistic models = Skyrme Hamiltonian
- APR = Akmal, et. al. - Ab-initio Monte Carlo calculations of nuclear and neutron matter



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What do we know?

- Properties of saturated nuclear matter: binding energy, saturation density, compressibility, effective mass, symmetry energy (25-35 MeV)
- Nuclear structure: nuclear binding energies and charge density distributions
  - Binding energies and charge radii of doubly-magic nuclei (^{208}Pb, ^{90}Zr, ^{40}Ca) in the Hartree or Hartree-Fock approximations.
- Stability
  - Restrictions on the Landau parameters
  - Pressure should increase with density
  - Chemical potential should increase with concentration
- Neutron stars: Must be able to support a 1.44 solar mass neutron star (This may change soon!)
- These quantities are *easy* to calculate for a given EOS.

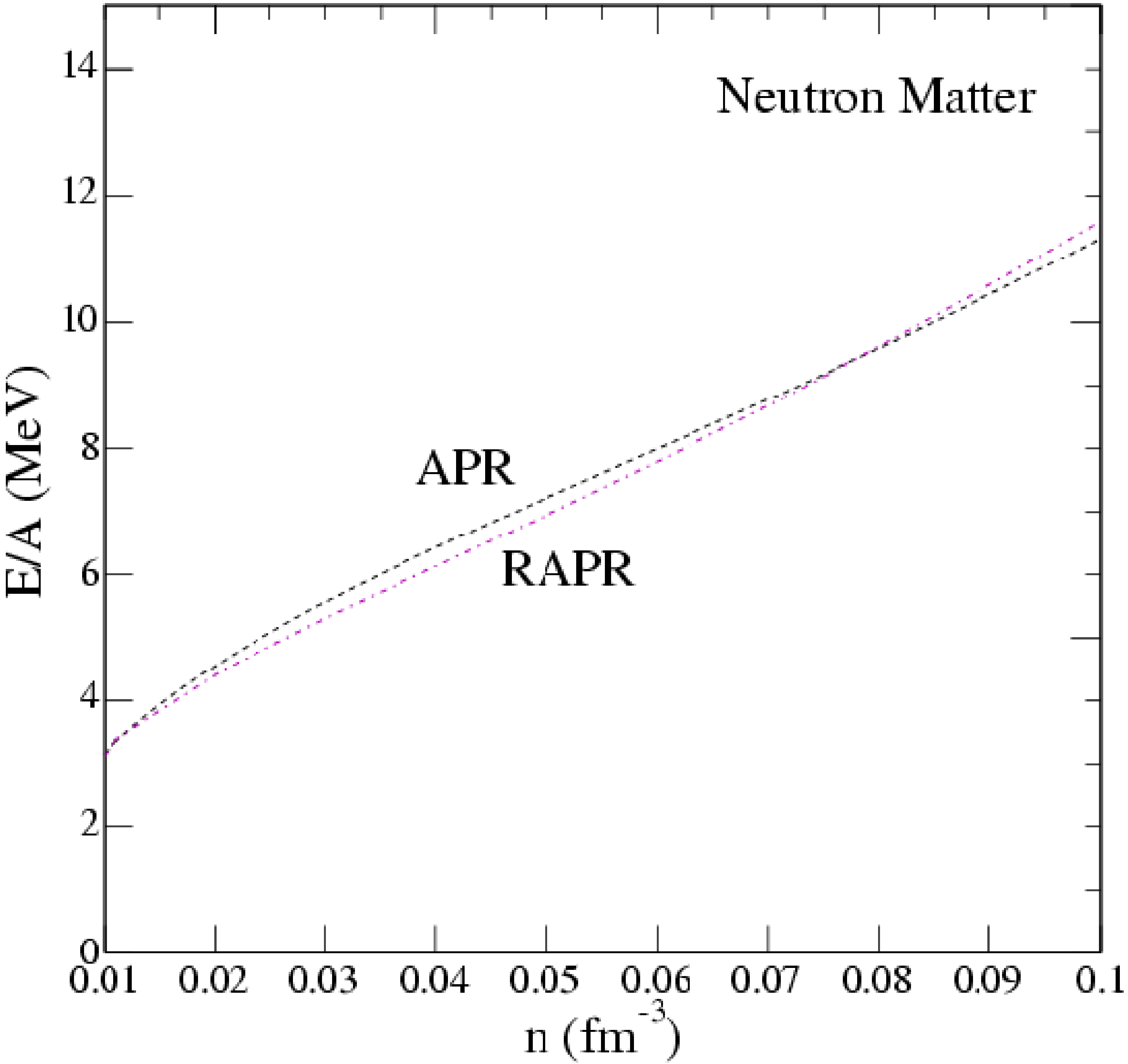
The Akmal, Pandharipande, and Ravenhall EOS

- Original calculations based on exact methods accesible for A<16
- Fit the APR results to both a relativistic and a non-relativistic model
- Now we can calculate large A nuclei!

Nucleus	Property	Experiment	Potential	Field-theoretical
^{208}Pb	Charge radius (fm)	5.50	5.41	5.41
	Binding energy (MeV)	7.87	7.87	7.77
	Skin thickness (fm)	0.12±0.05, 0.20±0.04	0.19	0.20
^{90}Zr	Charge radius (fm)	4.27	4.18	4.17
	Binding energy (MeV)	8.71	8.88	8.65
	Skin thickness (fm)	0.09±0.07	0.075	0.093
^{40}Ca	Charge radius (fm)	3.48	3.40	3.34
	Binding energy (MeV)	8.45	8.89	8.61
	Skin thickness (fm)	-0.06±0.05, -0.05±0.04	-0.044	-0.046

Low-density neutron matter

- Ab-initio calculations (like APR) of neutron matter predicit a fairly precise behavior of the EOS at low densities
- The energy per baryon should be about 1/2 the Fermi gas energy
- Our relativistic fits to APR demonstrate that this is possible to express in a field-theoretical context
- This results in a clear finite-temperature generalization



Taken from A.S., M. Prakash, J.M. Lattimer, and P.J. Ellis, nucl-th/0505062

Correlations

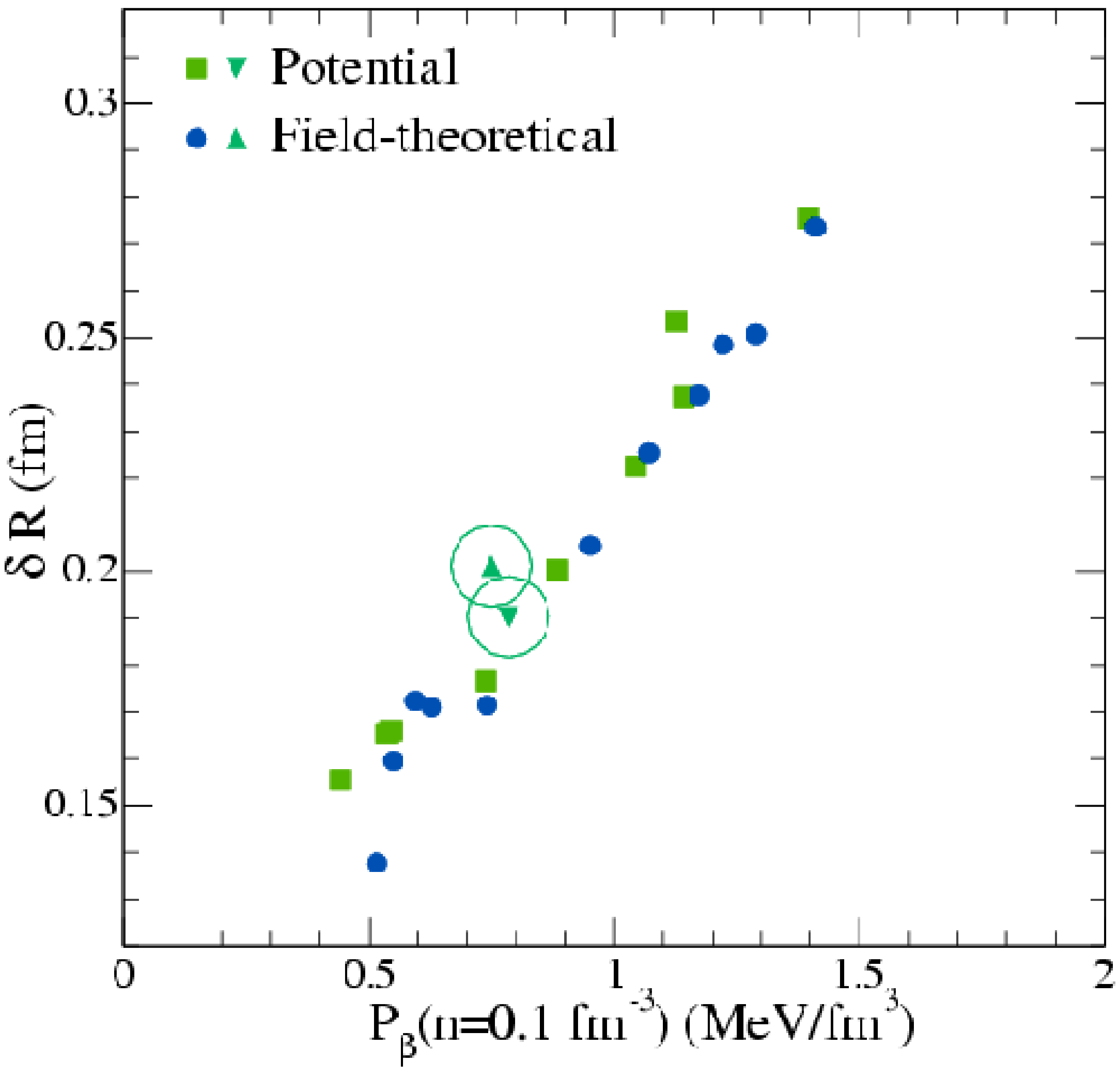
- Correlations provide a paradigm for possible progress: If we have a correlation between two experimental observables - hopefully a measurement of one will offer a prediction of the other
- How accurately can we calculate these observables from a given equation of state? What are the systematic uncertainties?
- Challenge for the Theorists: Understand our calculations
- P. Danielewicz, "Different assumptions can give similar results... we need dedicated observables".
- Our solution: Calculate those observables with as many EOSs as possible...making sure that we restrict ourselves only to EOSs which match what we know.
- We found very few models which matched this criteria, so in some cases, we made our own.

E_{sym} and Nuclei

- The "neutron skin thickness" is the difference between the neutron and proton rms radii: $\sqrt{\langle r_n^2 \rangle} - \sqrt{\langle r_p^2 \rangle}$
- This number is tightly correlated to the pressure of neutron matter at a particular density (Typel and Brown)
- The neutron skin thickness of Pb^{208} will be measured accurately at Jefferson Lab
- Use a liquid-droplet model to understand the connection:

$$\frac{\sigma_\delta}{E_{\rm sym}} \sim \int \left[\frac{E_{sym}}{E_{sym}(n)} - 1\right] \frac{n}{[\mathcal{H} + nB]^{1/2}} dn$$

$$\delta R \sim \frac{2\delta_L}{(1-\delta_L^2)} \frac{\sigma_\delta}{E_{\rm sym}}$$



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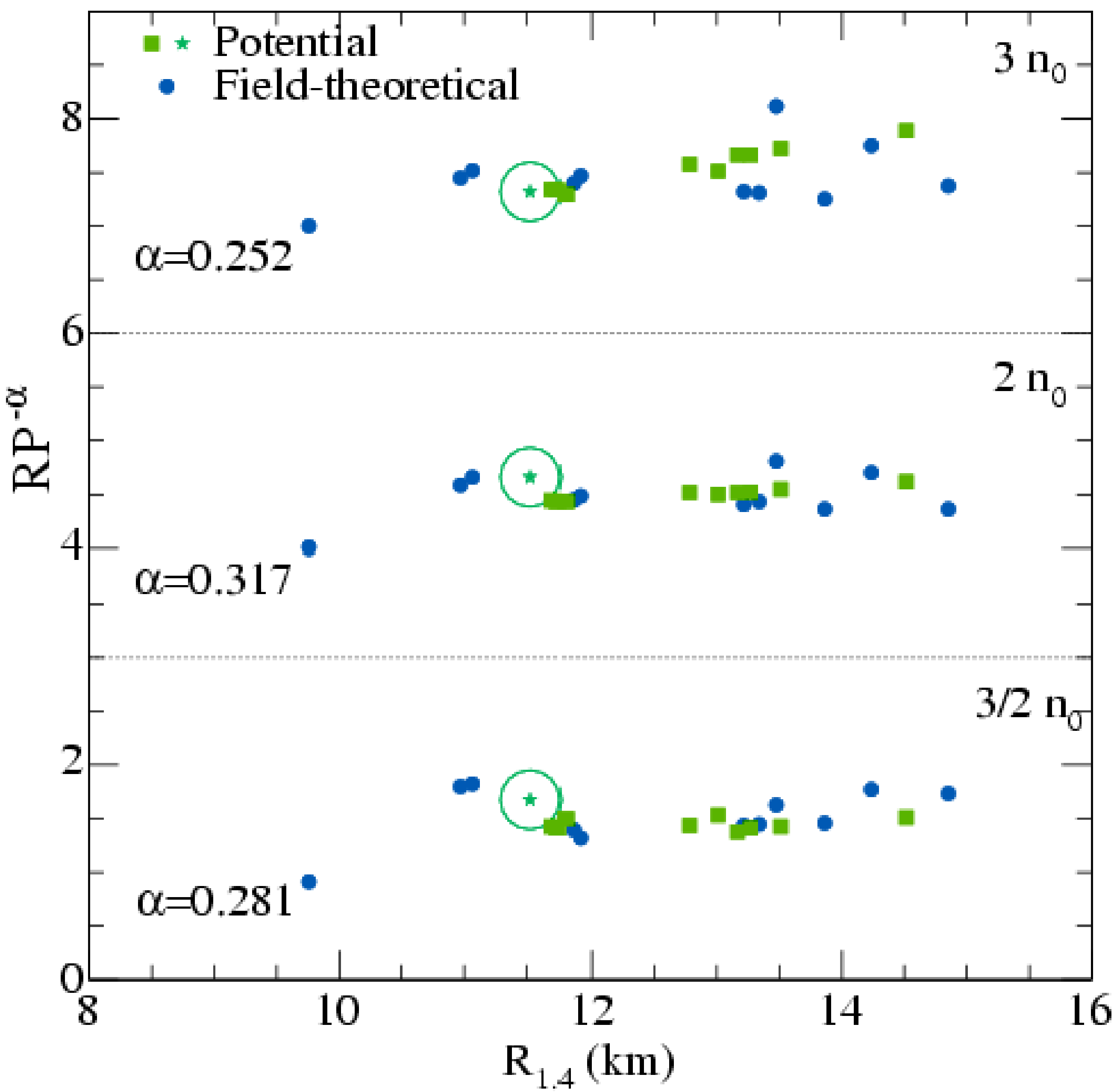
E_{sym} and Neutron Star Radii

- Analytical solutions of the Tolman-Oppenheimer-Volkov equations suggest that $R \sim RP^{-\alpha}$
- Therefore the radius is correlated with the pressure at densities somewhat larger than nuclear matter densities (Lattimer and Prakash)
- Thus neutron star radii are determined, in large part, by the symmetry energy



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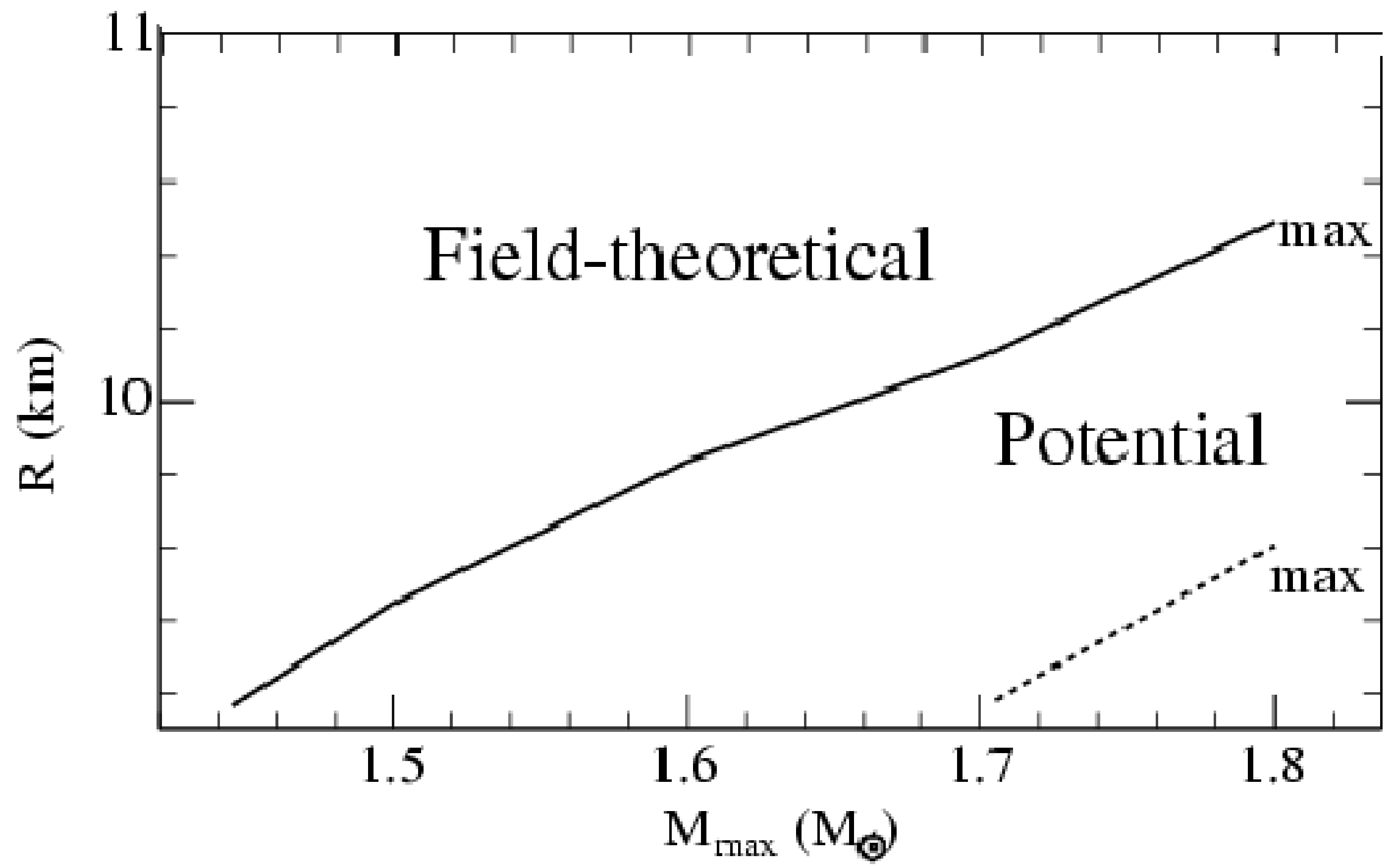
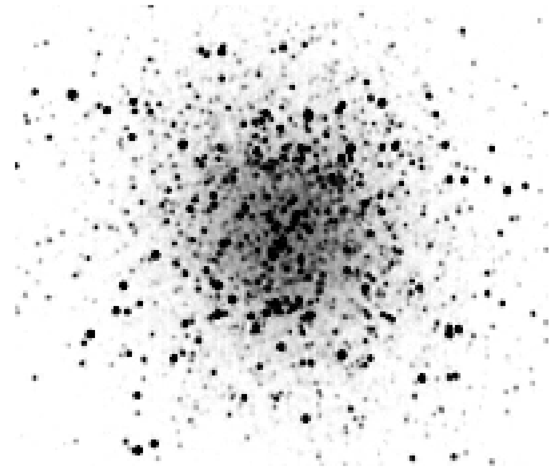
Small Neutron Stars

- What is the smallest possible radius for a neutron star which doesn't contain exotic components?
- Largest accurate mass measurements used to be 1.44 solar masses, now they may be as large as 2.0!
- Neutron star radius measurements are becoming available in globular clusters, where distance and age is easier to determine.

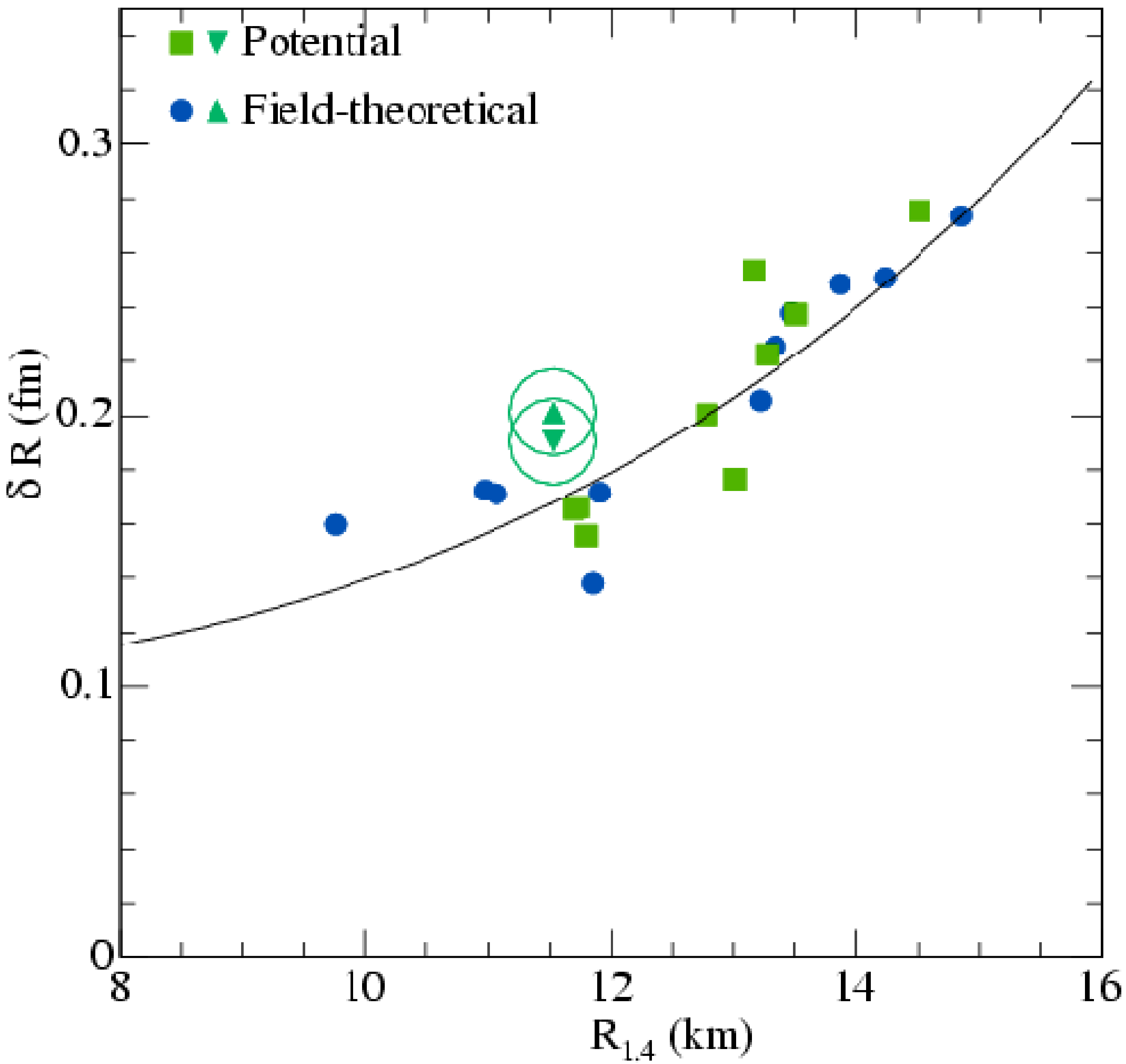




Globular cluster M13

Neutron Stars and Nuclei

- $\delta R \Leftrightarrow P \Leftrightarrow R_{NS}$
  (Horowitz and Piekarewicz)
- This emerges naturally from the two previous correlations if the pressure at the two densities are correlated
- We find that this correlation is not quite linear, but obeys a power law
- A similiar correlation for the radius of the maximum mass star
- So the symmetry energy has provided us with a connection between quantites in two very distinct subfields



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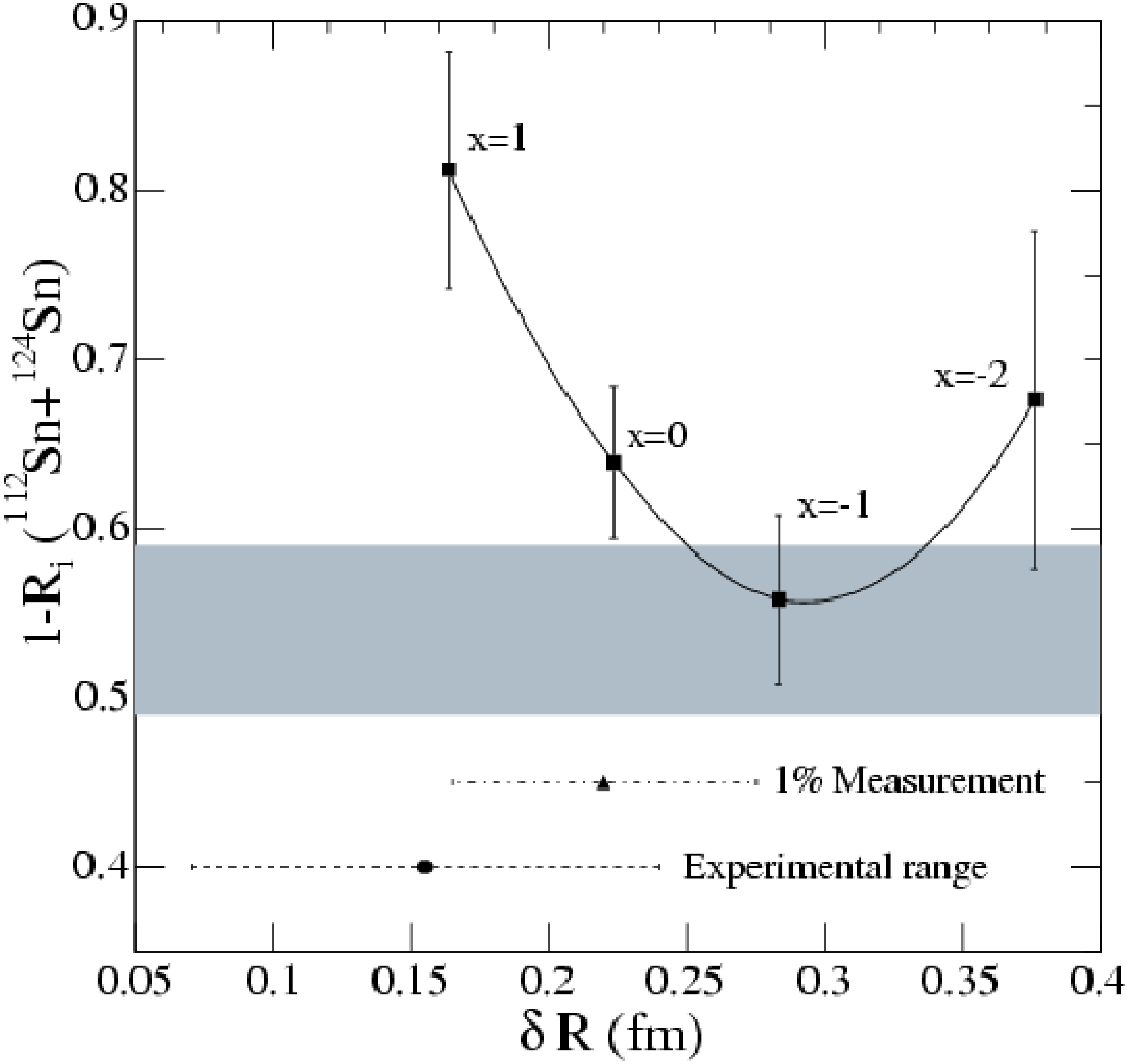
Heavy-Ion Collisions and Nuclei

- Use the symmetry energy to connect nuclear structure with heavy-ion collisions
- MSU data provides us with a measurement of the magnitude of isospin diffusion, R_i, measured in collisions involving Sn^{112} and Sn^{124}
- Use transport codes (B.-A. Li) to calculate $1-R_i$ and Hartree-Fock codes to calculate the skin thickness for the same models
- Vary a parameter which controls the symmetry energy



Taken from A.S. and B.-A. Li, nucl-th/0505051.

Summary

- A paradigm for eliminating the systematic uncertainties which plague us
- A field-theoretical formulation which matches the most modern ab-initio equation of state.
- A prediction of the structure of lead from APR: neutron skin thickness of 0.19-0.20 fm.
- A lower limit on the neutron skin thickness in lead from isospin diffusion in heavy-ion collisions: 0.15 fm.
- A lower limit on the radius of neutron stars *not* containing exotic matter: 9 km.
- Determining the symmetry energy is within our reach, but...
  ...it will likely demand information from nuclear structure, astrophysics, and heavy-ion collisions.