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Neutron Rich Nuclei in Heaven and Earth

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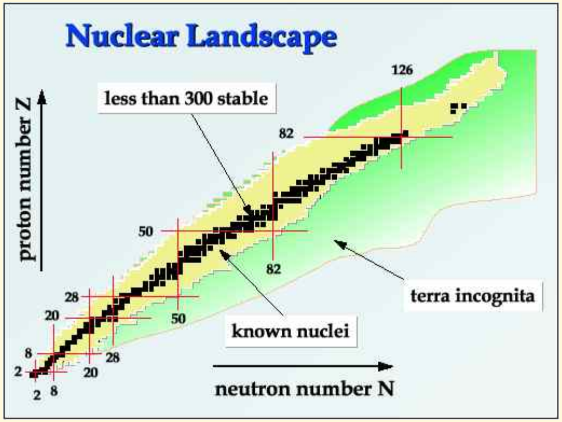

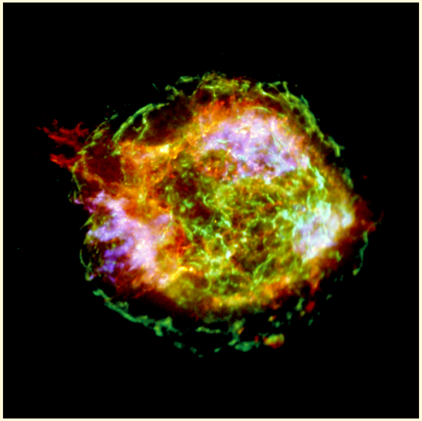

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Neutron Stars at the Crossroads of Fundamental Physics

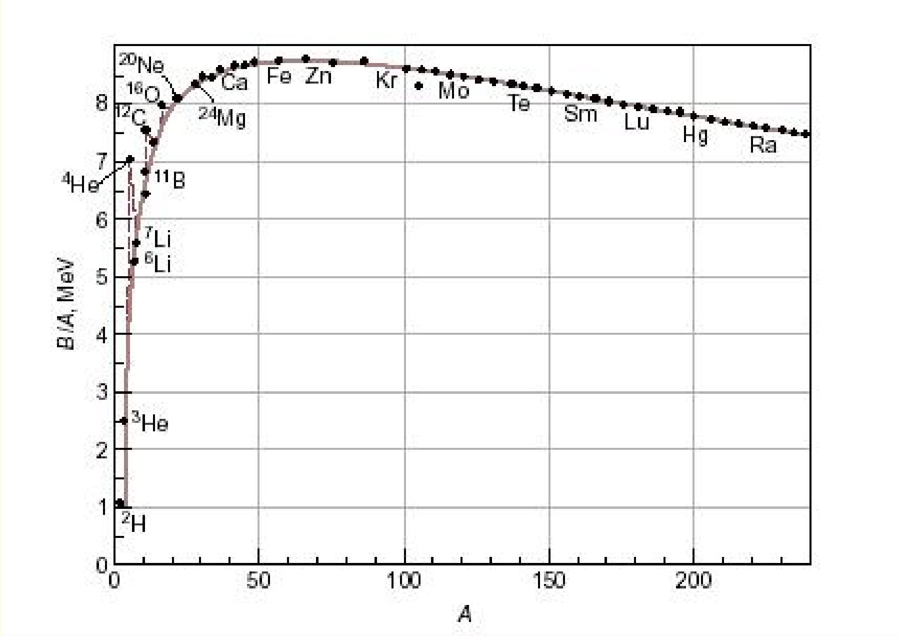
University of British Columbia, Vancouver, Canada
August 10-13, 2005

Equation of State I: Generalities

The Bethe-Weizsäcker (BW) Mass Formula:

$$E(Z,N) = a_{\rm vol}A + a_{\rm surf}A^{2/3} + a_{\rm coul}Z^2/A^{1/3} + a_{\rm symm}(N-Z)^2/A + \dots$$

- Parameters extracted from a fit to thousands of known nuclear masses
- Hidden behind its success is the saturation of the nuclear force
- BW constrains the above parameters at (or near) saturation density:
  $(a_{\rm vol}, a_{\rm surf}, a_{\rm coul}, a_{\rm symm}) \simeq (-16, +18, +1, +26)$ MeV



BW offers little on the density dependence of the parameters!

Equation of State II: Infinite Nuclear Matter

Recipe to make infinite nuclear matter:

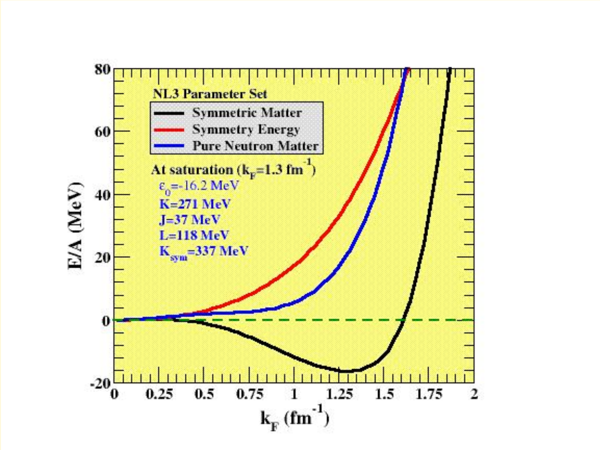
- Turn off the long-range Coulomb force
- Let Z, N and V go to infinity with ratios remaining finite:
  $\rho = A/V,\ Y_p = Z/A,\ b=\delta=(N-Z)/A,\ \ldots$
- Only surviving terms in the thermodynamic limit:
  $E(Z,N)/A = a_{\rm vol} + a_{\rm symm}b^2 = \epsilon_0 + Jb^2$

Symmetric *vs* Asymmetric Matter:

- Expand the total energy per nucleon around $b=0$:

$$E(\rho;b)/A = \underbrace{E(\rho;b{=}0)/A}_{\text{Symmetric Matter}} + \underbrace{b\left(\frac{\partial E/A}{\partial b}\right)_{b=0}}_{0} + \underbrace{b^2\,\frac{1}{2}\left(\frac{\partial^2 E/A}{\partial b^2}\right)_{b=0}}_{\text{Symmetry Energy}} + \ldots$$

Pure neutron matter ≈ Symmetric Matter + Symmetry Energy!



Goal: Study the density dependence of the equation of state

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Density Functional, Kohn-Sham, MF Theory

Improving the Bethe-Weizsäcker (BW) Mass Formula:

$$\mathcal{L}_{\rm int} = g_{\rm s}\bar{\psi}\psi\phi - g_{\rm v}\bar{\psi}\gamma^{\mu}\psi V_{\mu} - \frac{g_{\rho}}{2}\bar{\psi}\gamma^{\mu}\boldsymbol{\tau}\cdot\mathbf{b}_{\mu}\psi - e\bar{\psi}\gamma^{\mu}\tau_{p}\psi A_{\mu}$$
$$-\frac{\kappa}{3!}(g_{\rm s}\phi)^3 - \frac{\lambda}{4!}(g_{\rm s}\phi)^4 + \Lambda_{\rm v}(g_{\rm v}^2 V^{\mu}V_{\mu})(g_{\rho}^2 b^{\mu}b_{\mu}) + \frac{\zeta}{4!}g_{\rm v}^4(V_{\mu}V^{\mu})^2$$

- Parameters fitted to a large body of ground-state properties (mostly binding energies and charge radii of many nuclei)
- Ground-state observables computed at the mean-field level
- Formalism is **NOT** Hartree (Hartree-Fock) theory
- Parameters of the model encode correlations that go beyond two-body (short, long, and pairing correlations in an average way)

Resulting model unlikely to describe correctly NN physics!

Correlating Model Parameters to the Physics:

Parameters	Constrained by
$g_{\rm s}, g_{\rm v}$	Ground state properties of finite nuclei
g_{ρ}	Ground state properties of heavy nuclei
κ, λ	Isoscalar giant monopole resonance
$\Lambda_{\rm v}$	Neutron radius of heavy nuclei
ζ	Neutron star structure

- Existent observables insufficient to constrain all parameters
- Determination of neutron radii of neutron-rich nuclei presses!
- Simultaneous mass-radius measurement of neutron stars presses!

Crucial measurements in Heaven and Earth on the horizon!

Accurately Calibrated Parametrizations

The Program:

- Input binding energy and charge radii of doubly magic nuclei
  Solve in self-consistent mean-field approximation
- Compute the linear response of the mean-field ground state
  Solve in self-consistent MF+RPA approximation
- Without any further adjustment, compare to EoS from nuclear collisions
  Up to five times nuclear-matter saturation density
- Without any further adjustment, predict neutron-star structure
  Only physics that neutron stars are sensitive to — is the EoS of neutron-rich matter ...

A	Observable	Experiment	NL3 Stiff-Stiff	NL3_030 Stiff-Soft	FSUGold_000 Soft-Stiff	FSUGold* Soft-Soft
^{90}Zr	B/A (MeV)	8.71	8.69	8.70	8.68	8.68
	$R_{\rm ch}$ (fm)	4.26	4.26	4.27	4.25	4.25
	$R_n - R_p$ (fm)	—	0.11	0.08	0.09	0.09
	GMR (MeV)	17.89 ± 0.20	18.62	18.75	17.89	17.98
^{208}Pb	B/A (MeV)	7.87	7.88	7.89	7.87	7.89
	$R_{\rm ch}$ (fm)	5.50	5.51	5.52	5.51	5.52
	$R_n - R_p$ (fm)	—	0.28	0.20	0.29	0.21
	GMR (MeV)	14.17 ± 0.28	14.32	14.74	13.73	14.04
	GDR (MeV)	13.30 ± 0.10	12.70	13.07	12.79	13.07

$*$ **Disclaimer: Gold is referred to the color — not the metal!**

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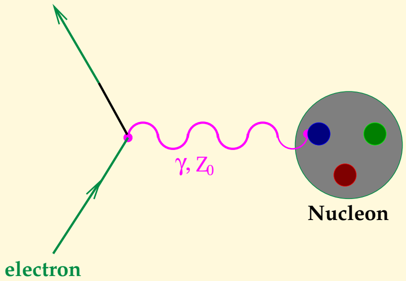
Experimental Extraction of $R_n - R_p$

JLAB Experiment 00-003 (03-011) [Michaels, Souder, Urciuoli]:

- Parity Violating Asymmetry in elastic $e-$Pb scattering
- Electroweak (as opposed to hadronic) probe of neutron density
- Weak-vector boson Z^0 couples strongly to neutrons
- A clean and accurate measurement of the neutron radius

1% or 0.05 fm measurement of the neutron radius of ^{208}Pb



Particle	EM coupling	Weak-Vector coupling
up-quark	$+2/3$	$+1-4\sin^2\theta_{\rm w}(+2/3) \simeq +1/3$
down-quark	$-1/3$	$-1-4\sin^2\theta_{\rm w}(-1/3) \simeq -2/3$
proton	$+1$	$+1-4\sin^2\theta_{\rm w} \simeq 0$
neutron	0	-1

$$g_{\rm v}^{f} = 2T_z^{f} - 4\sin^2\theta_{\rm w} Q^{f}\,, \quad \sin^2\theta_{\rm w} \approx 0.231 \simeq 1/4$$

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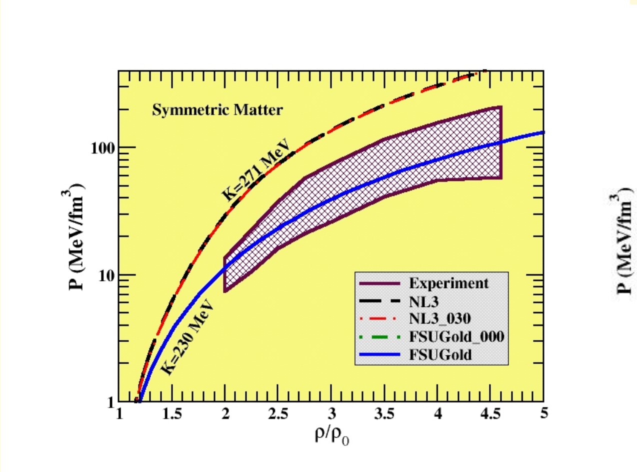
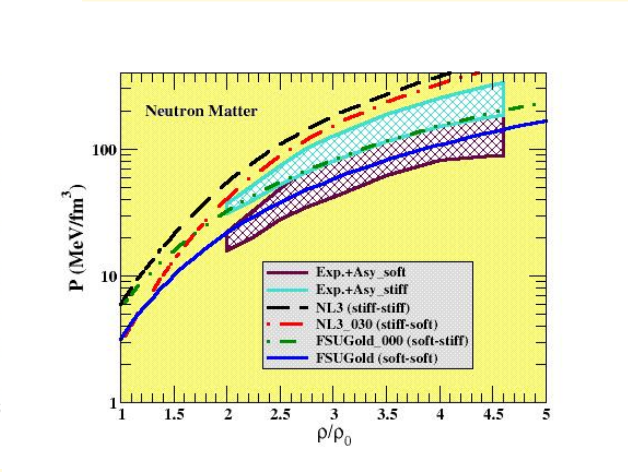
High Densities in Earth

[Danielewicz, Lacey, and Lynch – Science **298**, 1592 (2002)]

Nuclear Collisions: Constraints and Predictions

- Sole earthly tool available to compress nuclear matter
- Compressions up to several (five) times nuclear saturation density
- Imprint of the EoS left in the flow and fragment distribution





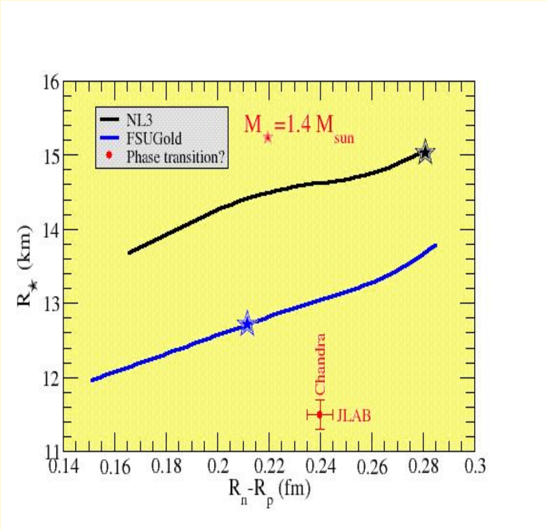
FSUGold provides a reliable extrapolation to high density ...

Neutron Skin and Neutron-Star Radii

Question: Is there a correlation between the neutron skin of ^{208}Pb and the radius of a *"canonical"* $1.4M_\odot$ neutron star?
Answer: Probably yes! Same pressure that pushes neutrons out in ^{208}Pb pushes neutrons out in a neutron star.

- Isolated radio-quiet neutron stars already discovered
- Find good candidates for mass-radius measurement

Interesting Correlation:
The neutron skin of ^{208}Pb depends on the EOS below N.M. saturation density, while the radius of the neutron star is also sensitive to the high-density EOS.
"The thinner the skin of ^{208}Pb, the smaller the radius of the star"



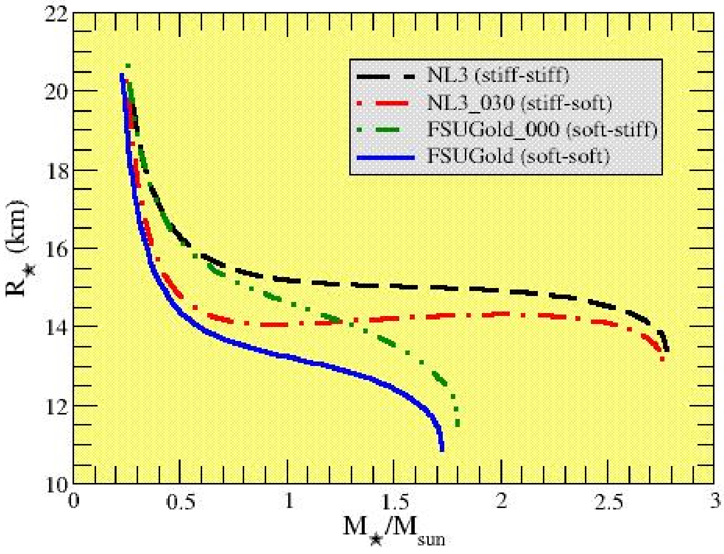
Large neutron skin together with a small neutron-star radius, could provide strong signature in favor of a phase transition ...

Maximum (Limiting) Neutron-Star Mass

- Maximum mass determined by high-density behavior of EOS (ζ)
- Radius of low-mass stars determined by symmetry energy ($\Lambda_{\rm v}$)

At present both parameters are poorly constrained!
However, situation could improve very rapidly ...

- Find a single "heavy" neutron star (PSRJ0751?)
- Measure the neutron radius of ^{208}Pb (JLAB?)



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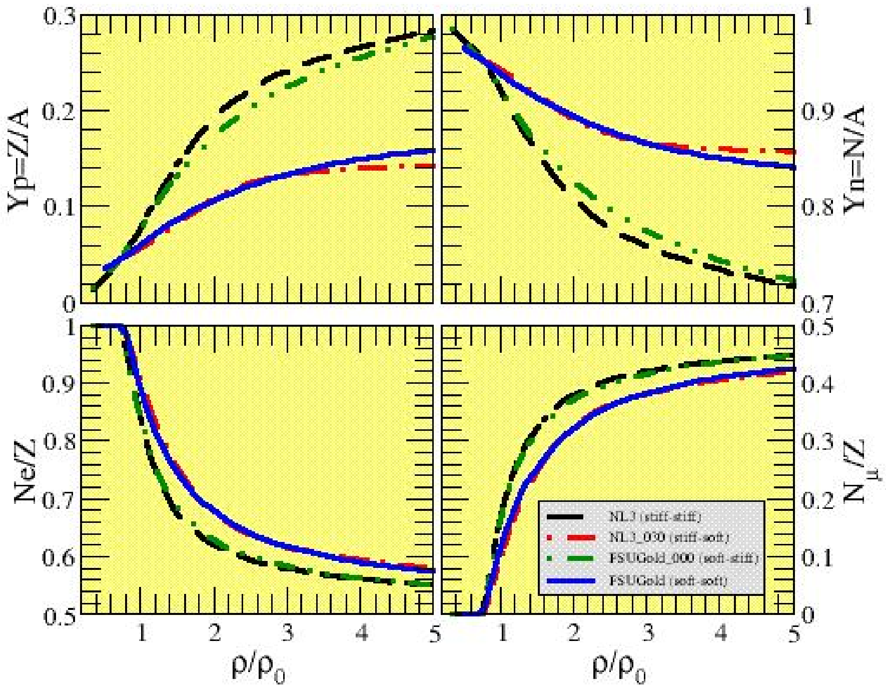
Neutron Star Composition

The composition of non-exotic stars is controlled by the density dependence of the symmetry energy!

- Symmetry energy imposes a penalty for violating $(N=Z)$ balance
- The stiffer the symmetry energy, the higher the price
- The stiffer the symmetry energy, the higher the proton fraction



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Electron Fraction and Neutron-Star Cooling

Enhanced (direct URCA) cooling of non-exotic stars?

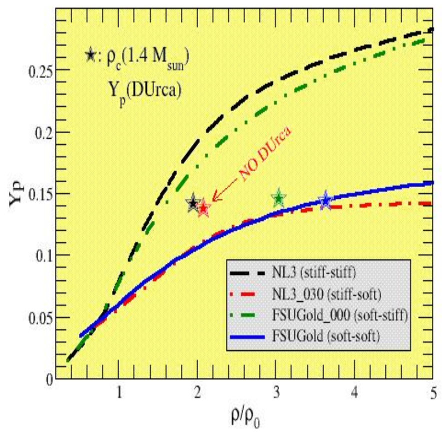
- Core-collapse Supernovae generates proto-neutron star ($T_{\rm core} \simeq 10^{12}$K)
- Direct URCA process cools down the star until ($T_{\rm core} \simeq 10^{9}$K)
- Depending on the EoS direct URCA may continue
  Is Y_p large enough to conserve momentum?
- Best case for DUrca (soft-stiff):
  Soft EoS for symmetric matter $\rightarrow$ large ρ_c
  Stiff symmetry energy $\rightarrow$ large Y_p

Direct URCA process:

a) $n \rightarrow p + e^- + \bar{\nu}_e$

b) $p + e^- \rightarrow n + \nu_e$

may continue cooling the neutron star. FSUGold predicts that the pulsar in 3C58 does NOT need to be an exotic (quark) star.



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High Densities in Heaven

Neutron Stars: Constraints and Predictions

- Sole heavenly tool available to compress nuclear matter
- Compression up to several (ten?) times nuclear saturation density
- Imprint of the EoS left in limiting mass, radius, cooling history, ...

Model	$k_{\rm F}^{0}$ (fm^{-1})	ϵ_0 (MeV)	K (MeV)	J (MeV)	L (MeV)
NL3	1.30	-16.2	271	37.4	118.5
FSUGold	1.30	-16.3	230	32.6	60.5

Observable	NL3	NL3_030	FSUGold_000	FSUGold
ρ_c (fm^{-3})	0.052	0.085	0.051	0.076
R (km)	15.05	14.18	13.80	12.66
$M_{\rm max}(M_\odot)$	2.78	2.75	1.80	1.72
$\rho_{\rm Urca}$ (fm^{-3})	0.21	0.51	0.22	0.47
$M_{\rm Urca}(M_\odot)$	0.84	2.64	0.74	1.30
$\Delta M_{\rm Urca}$	0.38	0.00	0.59	0.06

Some Questions and Answers (FSUGold):

- Is the pulsar in 3C58 an exotic star?

  Not necessarily if $M_* > 1.3\ M_\odot$

- Is the limiting mass of a neutron star $M_{\rm max} \simeq 1.72\ M_\odot$?

  Report suggests $M(PSRJ0751+1807) = 2.1^{+0.4}_{-0.5}$

Fascinating times ahead!