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Neutron Stars: The Richest of the Neutron-Rich Nuclei

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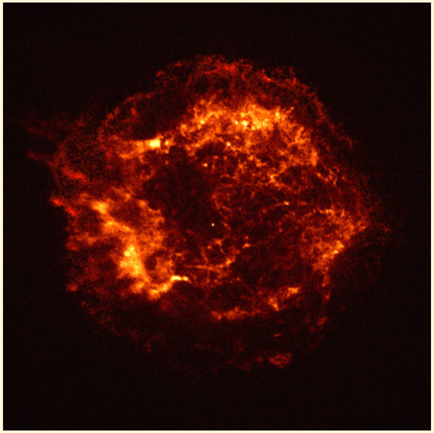
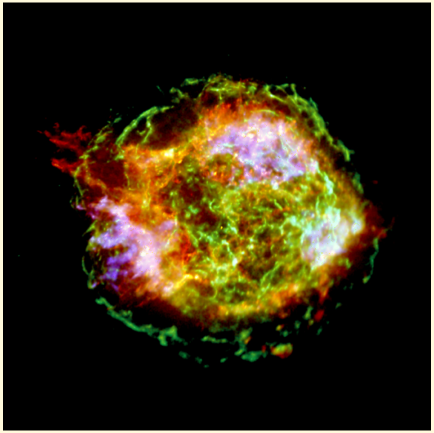
(with C.J. Horowitz)





Cassiopeia A: Chandra 12/21/99 and 08/23/04

Nuclear Equation of State used in Astrophysics Models
A Symposium of the Division of Nuclear Chemistry
Philadelphia, PA (August 22–26, 2004)

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Motivation

(The search for five—or six—nuclear-matter parameters)

Sole feature responsible for neutron-star structure is the equation of state. Combine experimental nuclear physics with observational astronomy to constrain the nuclear-matter EoS.

- Energy systematics of medium to heavy nuclei fix the saturation point (binding energy and density at saturation) of symmetric nuclear matter.

- Energy systematics of heavy nuclei fix the symmetry energy coefficient (a_4 or a_τ or J) of nuclear matter close to—but not at—saturation density.

- Systematics of the isoscalar Giant-Monopole-Resonance in heavy nuclei should fix—but it does not—the compression modulus (K) of symmetric nuclear matter.

- The neutron skin of a heavy nucleus should fix the density dependence of the symmetry energy (p_0 or L). No such (accurate) measurement exists today (although see PREX).

- Neutron star properties should fix the high-density dependence of the EoS. No such (accurate) observation exists today (although see Hubble, Chandra).

Relativistic (Schwarzschild) Stars

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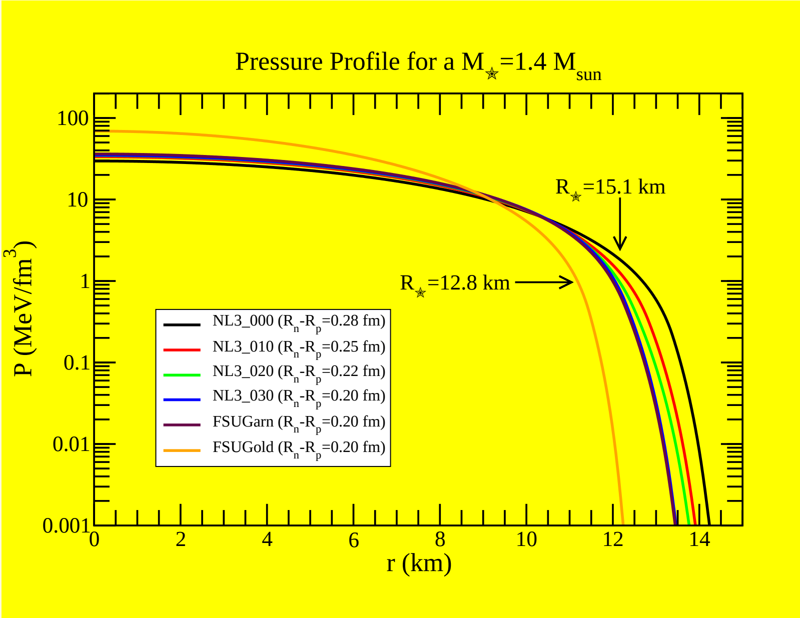
- Spherical and static stars in hydrostatic equilibrium
- Stars obeying the Tolman-Oppenheimer-Volkoff equation

$$\frac{dP}{dr} = -G\frac{\mathcal{E}(r)M(r)}{r^2}\left[1+\frac{P(r)}{\mathcal{E}(r)}\right]\left[1+\frac{4\pi r^3 P(r)}{M(r)}\right]\left[1-\frac{2GM(r)}{r}\right]^{-1}$$

$$\frac{dM}{dr} = 4\pi r^2\mathcal{E}(r)$$

Need an Equation of State: $[\mathcal{E}\ vs\ P]$



Sole feature responsible for neutron-star structure: EoS of neutron-rich matter

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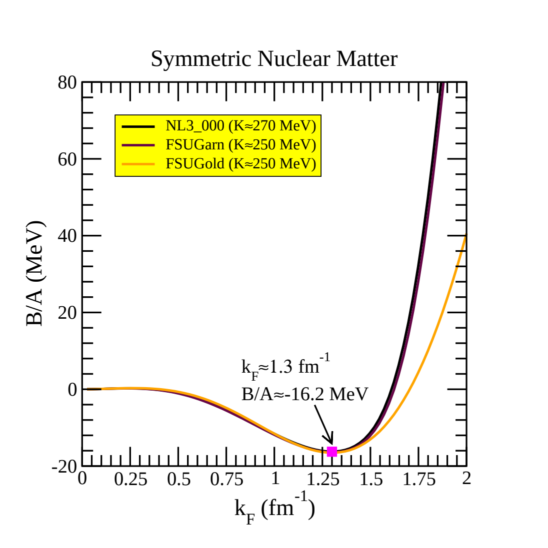
Symmetric Nuclear Matter

Binding energy and density at saturation well constrained by the energy systematics of medium and heavy nuclei; not so the compressibility (curvature at saturation): $k_{\rm F}^{0}\simeq 1.30~{\rm fm}^{-1}$, $\epsilon_0 \equiv B/A \simeq -16$ MeV, $K \simeq 220-280$ MeV

Model	$k_{\rm F}^{0}$ (fm^{-1})	ϵ_0 (MeV)	K (MeV)
SII	1.30	16.0	342
SIII	1.29	15.9	356
SVI	1.29	15.8	364
SkX	1.32	16.1	271
SGII	1.33	15.6	215
SkM*	1.33	15.8	217
Q1	1.30	16.1	242
Q2	1.30	16.1	279
G1	1.31	16.1	215
G2	1.32	16.1	215
NL3	1.30	16.2	271
TM1	1.29	16.3	281
FSUGarn	1.30	16.2	250
FSUGold	1.30	16.2	250



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Symmetry Energy I

Expand the total energy of the system around: $b \equiv (N-Z)/A = 0$

$$E(k_{\rm F}, b) = E(k_{\rm F}, b=0) + b \underbrace{\left(\frac{\partial E}{\partial b}\right)_{b=0}}_{0} + b^2 \underbrace{\frac{1}{2}\left(\frac{\partial^2 E}{\partial b^2}\right)_{b=0}}_{\mathcal{S}} + \ldots$$

$$E(k_{\rm F})_{\rm PNM} \equiv E(k_{\rm F}, b=1) \approx E(k_{\rm F}, b=0) + \mathcal{S}(k_{\rm F})$$

Characterization of the Equation of State: $\xi \equiv (k_{\rm F} - k_{\rm F}^0)/k_{\rm F}^0$

$$E/A(k_{\rm F}, b=0) = \epsilon_0 + \frac{1}{2} K \xi^2 + \ldots$$

$$\mathcal{S}/\mathcal{A}(k_{\rm F}) = J + L\xi + \frac{1}{2} K_{\rm sym} \xi^2 + \ldots$$

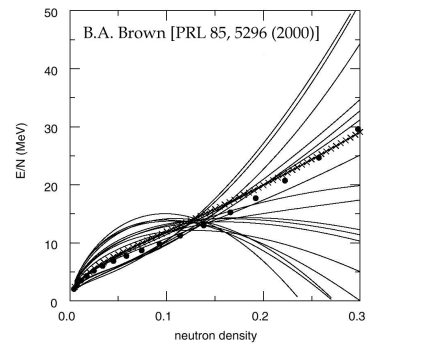
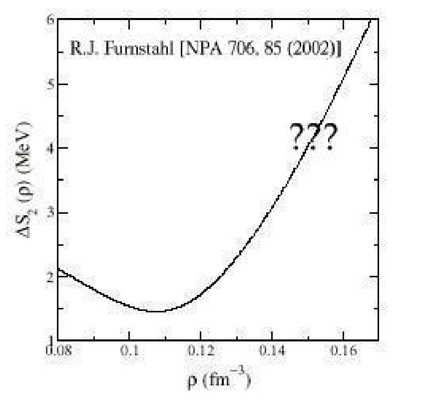


FIG. 2. The neutron EOS for 18 Skyrme parameter sets. The filled circles are the Friedman-Pandharipande (FP) variational calculations and the crosses are SkX. The neutron density is in units of neutron/fm^3.



Symmetry energy well constrained by the energy systematics of medium to heavy nuclei—but **NOT** at saturation density. Rather,

$$\mathcal{S}/\mathcal{A} \simeq (25-26)\ {\rm MeV\ at}\ \rho \simeq (0.10-0.11)\ {\rm fm}^{-3}$$

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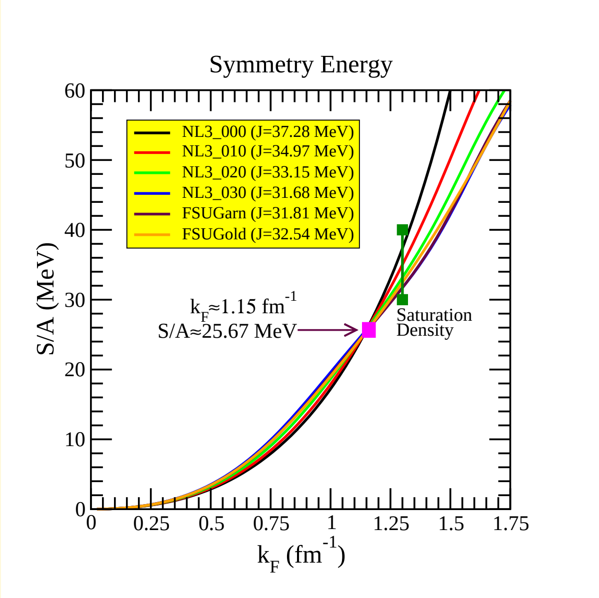
Symmetry Energy II

Symmetry energy and slope at saturation **NOT** well constrained by the energy systematics of medium to heavy nuclei: $J \simeq 25-40$ MeV, $L \simeq -10-120$ MeV. Yet the symmetry energy at $\widetilde{k}_{\rm F}^{0} \simeq 1.15\ {\rm fm}^{-1}$ is well constrained to the value $\widetilde{J} \simeq 25-26$ MeV

Model	J (MeV)	L (MeV)
SII	34.2	50.0
SIII	28.2	9.9
SVI	26.9	−7.4
SkX	31.1	33.2
SGII	26.8	37.6
SkM*	30.0	45.8
QHD	35.0	115.5
Q1	36.4	—
Q2	35.2	—
G1	38.5	—
G2	36.4	—
NL3	37.4	118.5
TM1	37.9	114.0
FSUGarn	31.8	57.4
FSUGold	32.5	64.1



The symmetry energy at saturation is not well known because it consists of two contributions: a symmetry energy at $k_{\rm F}^{0} \simeq 1.15\ {\rm fm}^{-1}$, which is well known, and the slope of the symmetry energy which is unknown.

$$J \equiv a_4 = (25\ {\rm MeV}) + (0.12) \begin{cases} 50 = 31\ {\rm MeV}\ , & \text{NonRelativistic;} \\ 100 = 37\ {\rm MeV}\ , & \text{Relativistic.} \end{cases}$$

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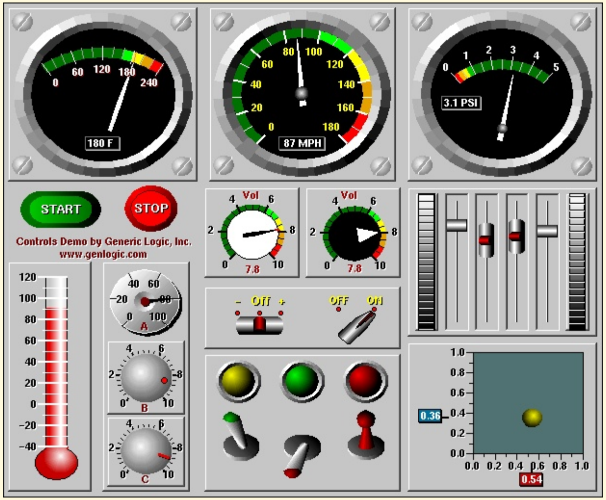
$$\mathcal{L}_{\rm int} = g_{\rm s}\bar\psi\psi\phi - g_{\rm v}\bar\psi\gamma^\mu\psi V_\mu - \frac{g_\rho}{2}\bar\psi\gamma^\mu\boldsymbol{\tau}\cdot\mathbf{b}_\mu\psi - e\bar\psi\gamma^\mu\tau_p\psi A_\mu$$
$$-\frac{\kappa}{3!}(g_{\rm s}\phi)^3 - \frac{\lambda}{4!}(g_{\rm s}\phi)^4 + \Lambda_{\rm v}(g_{\rm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

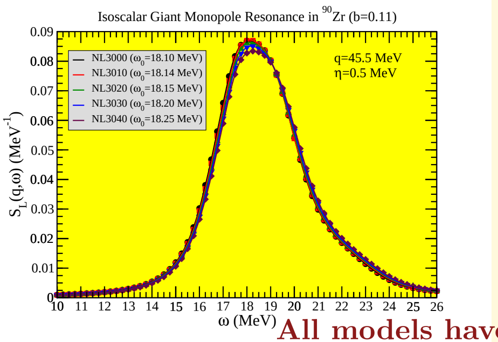


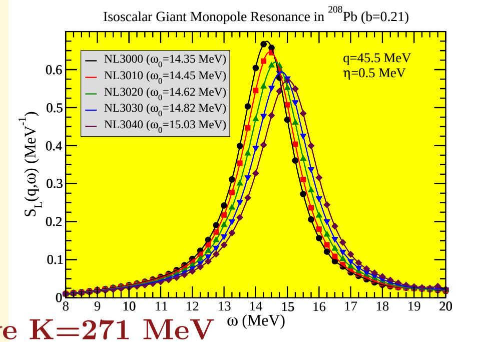
Parameters	EoS	Constrained	Ranking
$g_{\rm s}, g_{\rm v}$	$k_{\rm F}^0, \epsilon_0$	Ground state properties of finite nuclei	$\star\star\star\star$
g_ρ	$\widetilde{k}_{\rm F}^0, \widetilde{J}$	Ground state properties of heavy nuclei	$\star\star\star$
κ, λ	K	Isoscalar giant monopole resonance	$\star\star$
$\Lambda_{\rm v}$	$\widetilde{L}$	Neutron radius of heavy nuclei	$\star$
ζ	???	Neutron star structure	-

Could the discrepancy among "best-fit" non-relativistic and relativistic models in the values of K, L be two different symptoms of the same disease?

K and L: Symptoms of the same Disease?

- Discrepancies in $R_n - R_p$ between NR and Rel. models due to difference in L.
- Discrepancies in K even after both models reproduce the $ISGMR$ in ^{208}Pb.
- The isoscalar Giant Monopole Resonance in heavy "neutron-rich" nuclei measures the *curvature of the EoS in asymmetric nuclear matter*. As such, it should be sensitive to the *density dependence of the symmetry energy …*





All models have K=271 MeV

Model	B/A (MeV)	$r_{\rm ch}$ (fm)	$\tilde{J}$ (MeV)	L (MeV)	$R_n - R_p$ (fm)	K_{90} (MeV)
NL3000	8.69	4.26	25.67	118.19	0.11	263.13
NL3010	8.69	4.26	25.67	87.73	0.10	263.76
NL3020	8.70	4.26	25.67	68.22	0.09	265.23
NL3030	8.70	4.27	25.67	55.31	0.08	266.84
NL3040	8.70	4.27	25.67	46.61	0.07	268.32
Experiment	8.71±0.01	4.26±0.01	—	—	—	—

Model	B/A (MeV)	$r_{\rm ch}$ (fm)	$\tilde{J}$ (MeV)	L (MeV)	$R_n - R_p$ (fm)	K_{208} (MeV)
NL3000	7.87	5.51	25.67	118.19	0.28	242.93
NL3010	7.89	5.51	25.67	87.73	0.25	244.22
NL3020	7.91	5.51	25.67	68.22	0.22	248.88
NL3030	7.91	5.52	25.67	55.31	0.20	254.46
NL3040	7.92	5.53	25.67	46.61	0.17	259.87
Experiment	7.87±0.01	5.50±0.01	—	—	—	—

Use neutron excess $b=(N-Z)/A$ as a lever arm to fix both K and L.

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A Back-of-the-Envelope Calculation

Disclaimer: Properly way to do this is by recalibrating the parameters of the model (almost done!). Nonetheless:

$$E_{\rm GMR} \propto \sqrt{K} \quad (K_{\rm th} = 271 \text{ MeV})$$

- ISGMR in ^{90}Zr:

Experiment: 17.89 ± 0.20 MeV; Theory: 18.70 ± 0.08 MeV

$$K_{\rm exp} = \left(\frac{E_{\rm exp}}{E_{\rm th}}\right)^2 K_{\rm th} = 248 \pm 8 \text{ MeV}$$

Model	L (MeV)	$R_n - R_p$ (fm)	$E_{\rm GMR}$ (MeV)
NL3000	118.19	0.28	14.32 → 13.70
NL3010	87.73	0.25	14.43 → 13.80
NL3020	68.22	0.22	14.57 → 13.94
NL3030	55.31	0.20	14.74 → 14.10
NL3040	46.61	0.17	14.91 → 14.26
Experiment	—	—	14.17 ± 0.28

Back of the envelope calculation yields:

$K \simeq 248$ MeV, $L \leq 55$ MeV, $R_n - R_p \leq 0.20$ fm

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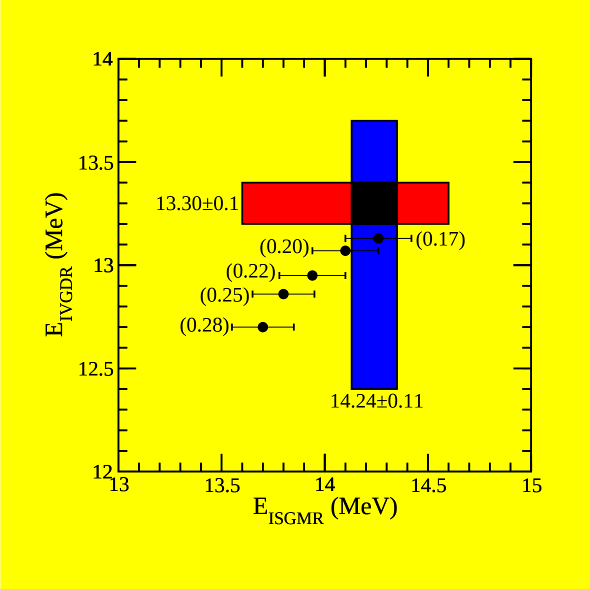
A Consistency Check

- The IVGDR mode is sensitive to the symmetry energy
- Stiff symmetry energy yields lower symmetry energies at low densities
- The stiffer the symmetry energy, the lower the centroid of the IVGDR



Parameters	EoS Parameters	Ranking
$g_{\rm s}, g_{\rm v}$	$k_{\rm F}^0 \simeq 1.30\ {\rm fm}^{-1}$; $\epsilon_0 \simeq -16.20$ MeV	$\star\star\star\star$
g_ρ	$\widetilde{k}_{\rm F}^0 \simeq 1.15\ {\rm fm}^{-1}$; $\widetilde{J} \simeq 25-26$ MeV	$\star\star\star$
κ, λ	$K \simeq 250 \pm 10$ MeV	$\star\star$
$\Lambda_{\rm v}$	$\widetilde{L} \leq 55$ MeV	$\star$

So what if $\widetilde{L} \leq 55$ MeV or equivalently $R_n - R_p \leq 0.20$ fm?

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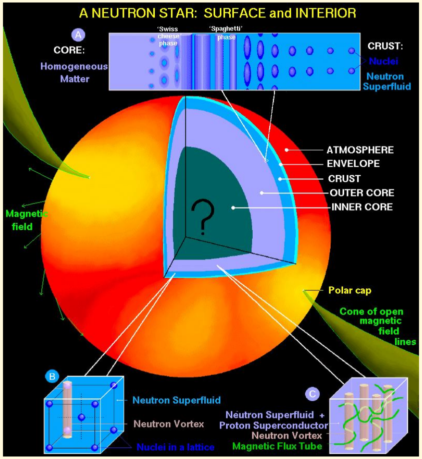
Neutron Skin and Neutron Stars

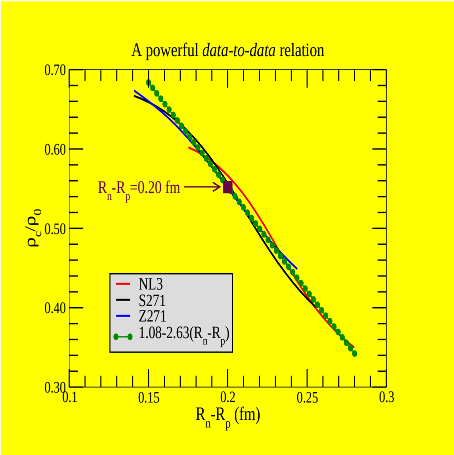
(Nuclear Astrophysics at Jefferson Lab)

^{208}Pb and the crust of a N.S. made up of similar material:

(neutron-rich matter at similar nuclear densities ...)

- Neutron stars contain a solid crust above a uniform liquid mantle
- The stiffer the EoS the lower the transition to non-uniform matter
- Energetically unfavorable to separate into low- and high-density regions
- The stiffer the EoS the larger the neutron skin of a heavy nucleus





A powerful data-to-data relation:

The thicker the neutron skin of a heavy nucleus, the lower the transition density to non-uniform neutron-rich matter ...

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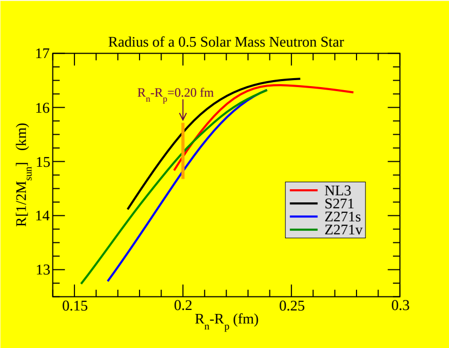
Neutron Skin and Neutron-Star Radii

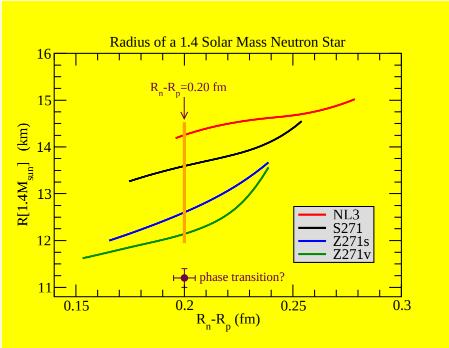
Is there a correlation between the neutron skin of ^{208}Pb and the radius of a *"canonical"* $1.4M_\odot$ neutron star? How about a correlation with a low-mass $0.5M_\odot$ neutron star?

- Isolated radio-quiet neutron stars recently discovered
- Study their black-body spectra and atmospheric data
- Geminga and RX J1856... good candidates for radius measurements

The neutron skin of ^{208}Pb depends on the EoS at and below nuclear matter saturation density, while the radius of a $M_\star = 1.4M_\odot$ neutron star is also sensitive to the high-density EoS. Although no longer a *data to data* relation: the larger the skin of a heavy nucleus the larger the radius of the star.

Model dependence considerably weaker for low-mass ($e.g., M_\star = 0.5M_\odot$) neutron stars, as they are both neutron-rich matter at similar densities.





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

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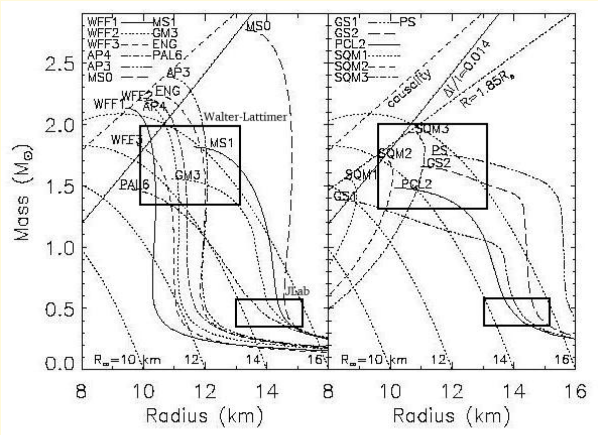
“Making” Low-Mass Neutron Stars

- First ever simultaneous determination of mass and radius of a neutron star RXJ-185635...
- Very low mass ($M_\star \ll 1.4 M_\odot$) neutron stars have never been observed; may never be observed!
- Low-mass neutron stars and ^{208}Pb are made up of similar material: neutron-rich matter at similar densities.
- Use the neutron-skin of ^{208}Pb to constrain the EoS via *Mass-vs-Radius relation of neutron stars.*



Accurate measurement of both the neutron radius of ^{208}Pb and the radius of a $M_\star = 1.4 M_\odot$ neutron star will significantly constrain the nuclear matter equation of state

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Have we Discovered Quark Stars?

- Is 3C58 too cold? Is 3C58 a Quark Star

- 3C58 witnessed by Chinese and Japanese in 1181
- Accurate age of about 823 years
- Neutron stars are born hot
- Cool promptly by ν-emission (URCA)
- Surface temperature today suggests $T \leq 10^6$ K

NASA News Release
NASA National Aeronautics and Space Administration
Marshall Space Flight Center - Huntsville, Ala. 35812
http://www.msfc.nasa.gov/news

For Release: April 10, 2002

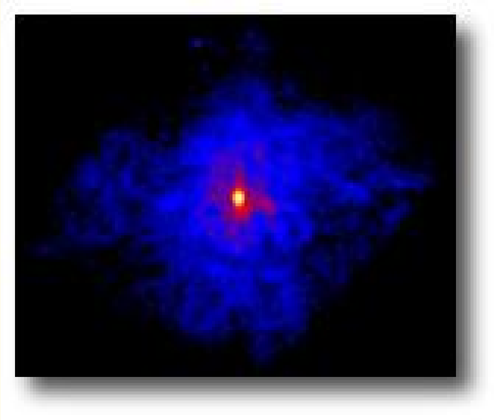
Release: 02-082

Cosmic X-rays reveal evidence for new form of matter

NASA's Chandra X-ray Observatory has found two stars - one too small, one too cold - that reveal cracks in our understanding of the structure of matter. These discoveries open a new window on nuclear physics, offering a link between the vast cosmos and its tiniest constituents.

Chandra?s observations of RXJ1856.5-3754 and 3C58 suggest that the matter in these stars is even denser than nuclear matter found on Earth. This raises the possibility these stars are composed of pure quarks or contain crystals of sub-nuclear particles that normally have only a fleeting existence following high-energy collisions.

By combining Chandra and Hubble Space Telescope data, astronomers found that RXJ 1856 radiates like a solid body with a temperature of 1.2 million degrees Fahrenheit (700,000 degrees Celsius) and has a diameter of about 7 miles (11.3 kilometers). This size is too small to reconcile with standard models for neutron stars - until now the most extreme form of matter known.



Conventional cooling scenarios predict a much hotter star!!

It was named Urca Process for the following: in Rio de Janeiro, we (Schenberg) went gambling at the Urca Casino, and Gamow was impressed by the roulette table where money just disappeared. Very gaily, he said: *"well, the energy disappears in the nucleus of the supernova as quickly as the money disappeared at that roulette table".*

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Electron Fraction and Neutron-Star Cooling

Is 3C58 an exotic star?

Electron fraction $(Y_e = Z/A)$ controls the cooling of the star

Electron fraction controlled by the **symmetry energy**

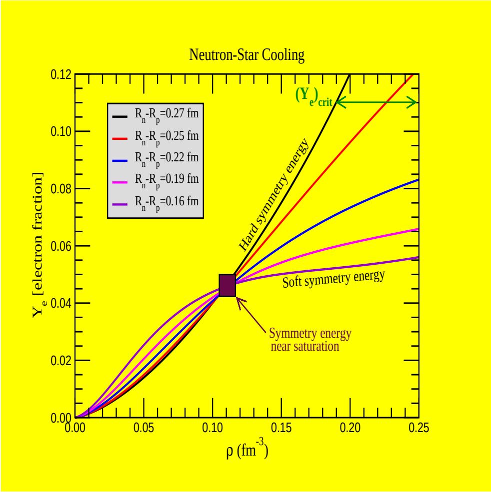
- Core-collapse Supernovae generates proto-neutron star $(T_{\rm core} \simeq 10^{12}{\rm K})$
- Direct URCA process cools down the star until $(T_{\rm core} \simeq 10^{9}{\rm K})$
- Depending on the EoS (symmetry energy) direct URCA may stop

If $R_n - R_p > 0.24$ fm $\rightarrow Y_e > 1/9$
Then the direct URCA process:

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

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

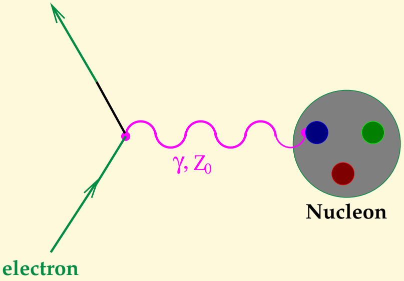
may continue cooling the neutron star.
If $R_n - R_p = 0.20$ fm, 3C58 might indeed be an exotic (quark) star.



The Quest for $R_n - R_p$ in ^{208}Pb

- The binding energy ϵ_0 and density $k_{\rm F}^0$ at saturation well determined.
- The symmetry energy $\widetilde{J}$ at $\tilde{k}_{\rm F}^0 = 1.15\ {\rm fm}^{-1}$ relatively well determined.
- Go after the density dependence of the symmetry energy $\widetilde{L}$, $\widetilde{K}$, ...

JLAB Experiment 00-003 (Michaels, Souder, Urciuoli)
A clean (1%) measurement of the neutron radius of ^{208}Pb
via parity-violating electron scattering



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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Conclusions

- Sole feature responsible for neutron-star structure:
  Equation of state of neutron-rich matter
- Best-fit Relativistic models can fit a host of nuclear observables
  Saturation properties, binding energies, charge densities, ...
- Yet, these theories predict a wide range of neutron radii for ^{208}Pb
  Soon to be measured at JLAB?
- Density dependence of the symmetry energy adjustable
  Through coupling between isoscalar and isovector mesons
- Proposed interesting correlations between:
  The neutron skin of Pb and properties of neutron-rich nuclei, phases, sizes, composition, and cooling of neutron stars
- Systematics of GMR may help extract simultaneously K and L
  ($K \sim 250$ MeV and $R_n - R_p \sim 0.20$ fm)

Tremendous excitement with the operation and commissioning of Chandra, Hubble, Rossi-XTE, XMM-Newton, GSI, GANIL, JLAB, KVI, MSU, RCNP, RIA, RIKEN, ...