Florida State University

The Quest for the Neutron Radius of Lead: How, Why, and When

Jorge Piekarewicz
with B.G. Todd-Rutel and C.J. Horowitz
Florida State University
Tallahassee, Florida, USA

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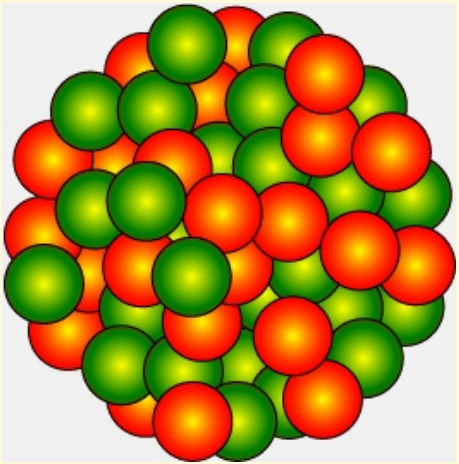
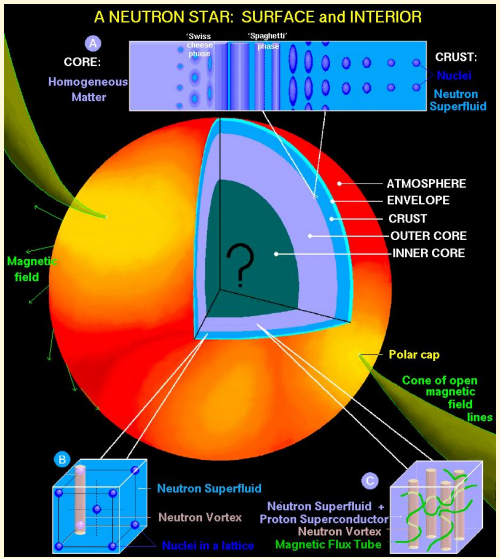
CONCLUSIONS





Jefferson Laboratory (December 6, 2005)

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Motivation

To map the neutron distribution in nuclei ... and much more!

• The distribution of protons in nuclei has been exquisitely mapped via elastic electron scattering; photons are insensitive to the ground-state neutron distribution.

• Mapping the neutron distribution with hadronic probes (protons, neutrons, pions) is possible; yet the model-independent extraction (*i.e., separating the nuclear structure from the reaction dynamics*) is difficult.

• Constraining the neutron distribution from theoretical modeling is hindered by an incomplete nuclear "database". Effective-theory models that reproduce a myriad of bulk properties of finite nuclei (such as binding energies and charge radii) predict neutron skins in ^{208}Pb ranging from $R_n - R_p \approx 0.1$ fm up to $R_n - R_p \approx 0.3$ fm.

• The neutral weak vector boson Z_0 does for neutrons what photons do for protons. Expect a 1% determination of the neutron radius in ^{208}Pb from parity-violating electron scattering at JLAB.

Such a determination will have far reaching consequences in many areas of physics, ranging from nuclear structure to astrophysics ...

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How NOT to: Proton-Nucleus Scattering

Protons are strongly interacting probes!

- Theoretical uncertainties in the reaction mechanism
  - ⋆ No such thing as a one-photon-exchange approximation
- Nucleus provides an *Optical Potential* for the proton
  - ⋆ NN interaction folded with prescribed nuclear densities
- Assume impulse approximation for the NN interaction
  - ⋆ This ignores possible medium-modification to the interaction
- NN interaction mostly isoscalar at medium-energies
  - ⋆ This is the region where impulse approximation is "valid"

$$\begin{aligned} R_0 &= \sqrt{\frac{Z}{A}R_p^2 + \frac{N}{A}R_n^2} \approx R_p\left(1 + \frac{N}{A}\frac{\Delta R}{R_p}\right) \\ &\approx \left[5.46 + 0.23\left(\frac{\Delta R}{0.21}\right)\right]\,\mathrm{fm} \simeq \Big(5.57 - 5.79\Big)\mathrm{fm}\,. \end{aligned}$$

The large (factor of 3) spread in the neutron skin among the various models gets diluted into a mere 3% difference in the (isoscalar) matter radius ...

Theoretical Uncertainties in the Extraction

Unphysical dependence of the neutron skin on beam energy!

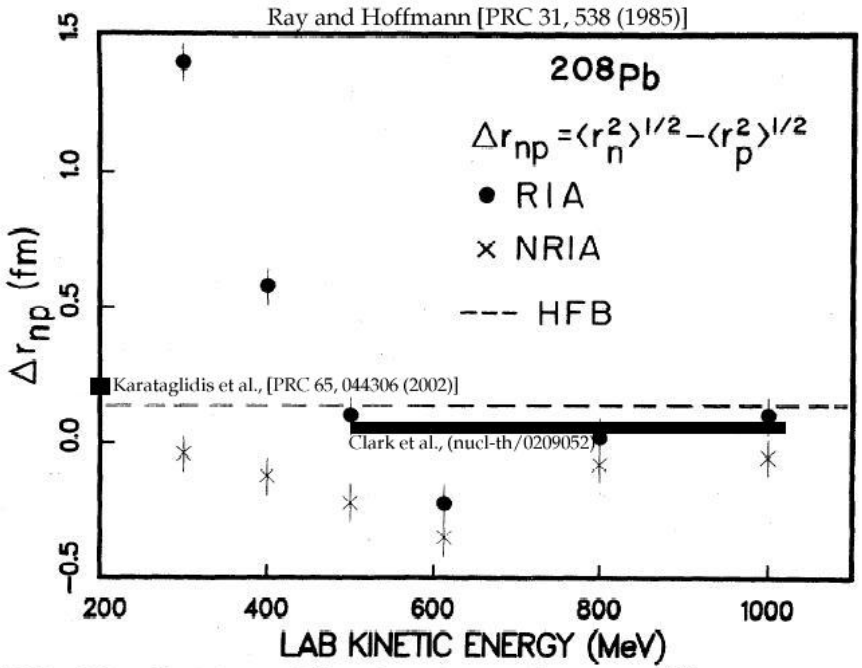

FIG. 10. Same as Fig. 8 except that the ^{208}Pb results are shown. The theoretical value of 0.13 fm (Ref. 39) is indicated by the dashed line.

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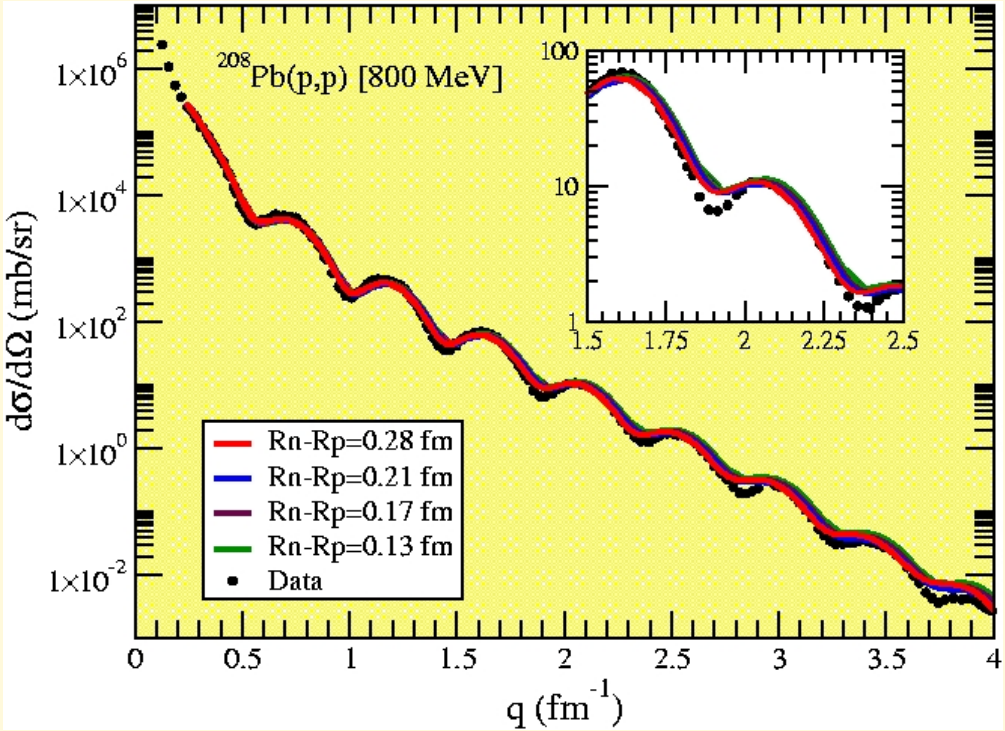
Insensitivity to the Neutron Skin

[J.P. and S.W. Weppner; nucl-th/0509019]

Proton scattering at medium energies probes isoscalar density!



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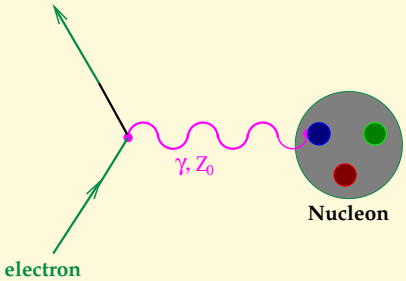
How to: Parity Radius Experiment

[Horowitz, Pollock, Souder, and Michaels; PRC**63**, 025501 (2001)]

JLAB Experiment 00-003 (Michaels, Souder, Urciuoli)
A clean (1%) measurement of the neutron skin of ^{208}Pb through 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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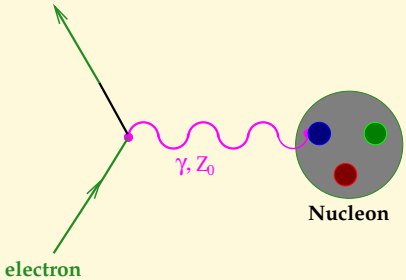
Clean Extraction of the Neutron Radius

[Horowitz, Pollock, Souder, and Michaels; PRC**63**, 025501 (2001)]



- PV asymmetry involves the interference of EM and NC amplitudes:

$$\mathcal{M}_{\rm EM} = \frac{4\pi\alpha}{Q^2} F_{\rm EM}(Q^2) = \frac{4\pi\alpha}{Q^2} F_p(Q^2)$$

$$\mathcal{M}_{\rm NC} = \frac{G_{\rm F}}{\sqrt{2}} F_{\rm NC}(Q^2) = \frac{G_{\rm F}}{\sqrt{2}} \left[(1-4\sin^2\theta_W) F_p(Q^2) - F_n(Q^2) \right]$$

- PV asymmetry provides a clean measurement of the neutron form factor

$$A_{\rm PV} \approx \frac{G_{\rm F} Q^2}{4\pi\alpha\sqrt{2}} \frac{F_n(Q^2)}{F_p(Q^2)} \; ; \quad \frac{1}{N} F_n(Q^2) = \left(1 - \frac{Q^2 R_n^2}{6} + \ldots \right)$$

PV electron scattering may do for neutron structure what electron scattering has done for proton structure!

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WHY?

Nuclear Structure

After more than 70 years, the neutron density of a heavy nucleus is a fundamental nuclear-structure observable that remains elusive!

- As fundamental as the charge density of a heavy nucleus
  - ⋆ *cf.* proton and neutron electromagnetic structure
- Reflects a poor understanding of the symmetry energy of NM
  - ⋆ Symmetry energy penalty imposed for breaking $N = Z$ balance
- Pure neutron matter well constrained at $\rho \approx (2/3)\rho_0$
- Slope is completely unconstrained by available nuclear data!

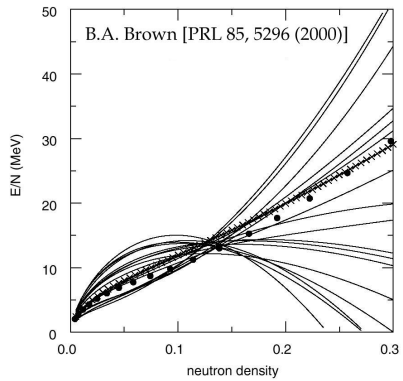

FIG. 2. The neutron EOS for 18 Skyrme parameter sets. The filled circles are the Friedman-Pandharipande (FP) variational calculations and the crosses are SkX. The neutron density is in units of neutron/fm^3.

Adding the neutron radius of a single heavy nucleus to the database will eliminate the large dispersion in the plot!

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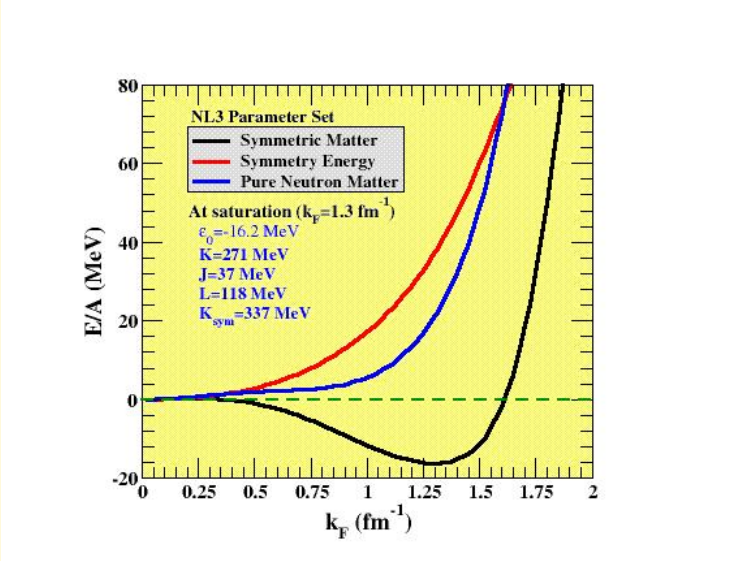
Neutron Skin and the Symmetry Energy

Symmetry energy: penalty levied on the system for upsetting the $N = Z$ balance. Expand the binding energy around $b \equiv (N-Z)/A = 0$:

$$\mathcal{B}/\mathcal{A}(k_F, b) = \mathcal{B}/\mathcal{A}(k_F, b=0) + b \underbrace{\left(\frac{\partial \mathcal{B}/\mathcal{A}}{\partial b}\right)_{b=0}}_{0} + b^2 \underbrace{\frac{1}{2}\left(\frac{\partial^2 \mathcal{B}/\mathcal{A}}{\partial b^2}\right)_{b=0}}_{\mathcal{S}/\mathcal{A}} + \ldots$$

PNM $\approx$ SNM + Symmetry Energy!



Slope of PNM (pressure) pushes neutrons out against surface tension $\Rightarrow$ neutron skin

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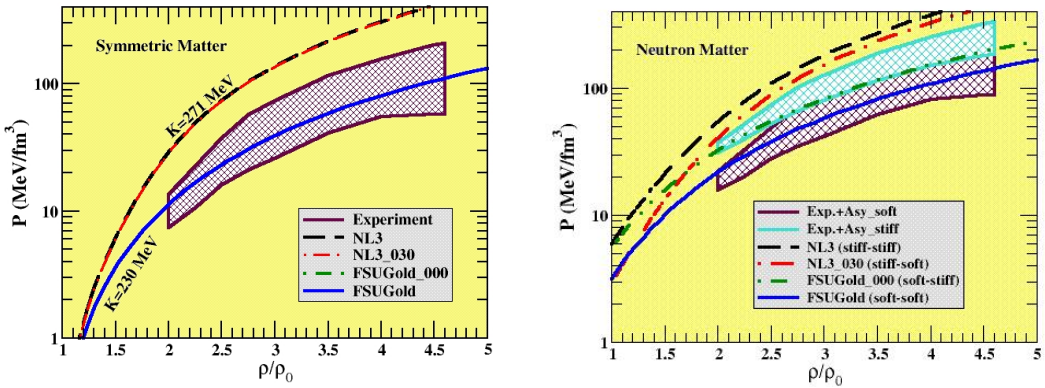
Neutron Skin and Heavy-Ion Collisions

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

Nuclear Collisions: Constraints and Predictions

- Sole terrestrial 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



Knowledge of the neutron radius of a single heavy nucleus will eliminate the dispersion in the plot!

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Neutron Skin and Atomic Parity Violation

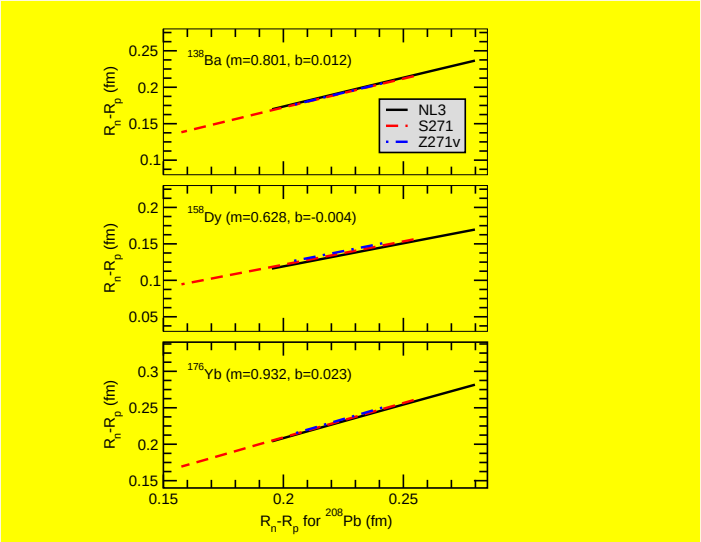
Measure E1 transition among (e.g., 6s and 7s) electronic states

$$A_{\rm PV}(N,Z) = \xi(Z) Q_W(N,Z) \equiv \xi(Z)\left[Q_W^{\rm SM}(N,Z) + \Delta Q_W^{n-p}(N,Z)\right]$$

- $\xi(Z) \Rightarrow$ uncertainty in atomic structure:
  - ⋆ measure amplitude ratios along stable isotopes chains (Ba, Dy, Yb)
- $\Delta Q_W^{n-p}(N,Z) \Rightarrow$ uncertainty in nuclear structure:
  - ⋆ Nuclear structure remains the sole theoretical uncertainty!

$$\Delta Q_W^{n-p}(N,Z) = N\left(1 - \frac{q_n}{q_p}\right)$$

$$q_n = 1 - (Z\alpha)^2\left[\frac{817}{3150} + \frac{232}{525}\frac{(R_n - R_p)}{R_p} + \ldots\right]$$



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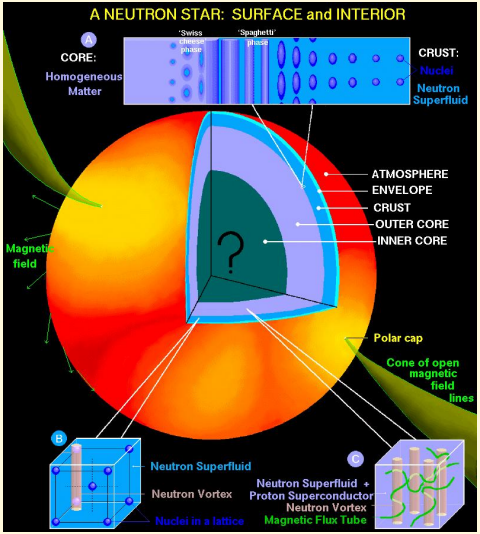
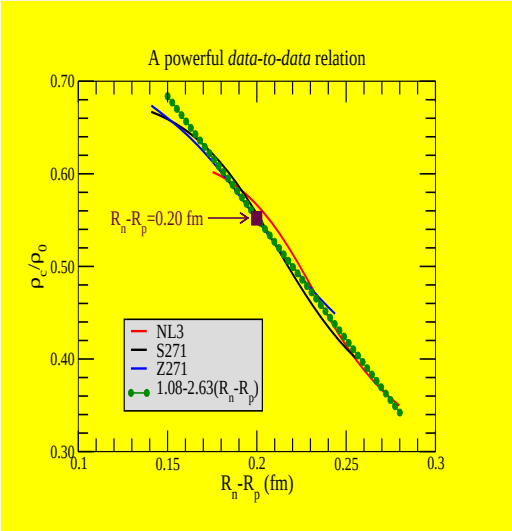
Neutron Skin and Neutron Stars

(Nuclear Astrophysics at Jefferson Lab)

The neutron skin of ^{208}Pb and the crust of a neutron star are made up of similar material: neutron-rich matter at (slightly) subnuclear 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 from uniform to non-uniform neutron-rich matter ...

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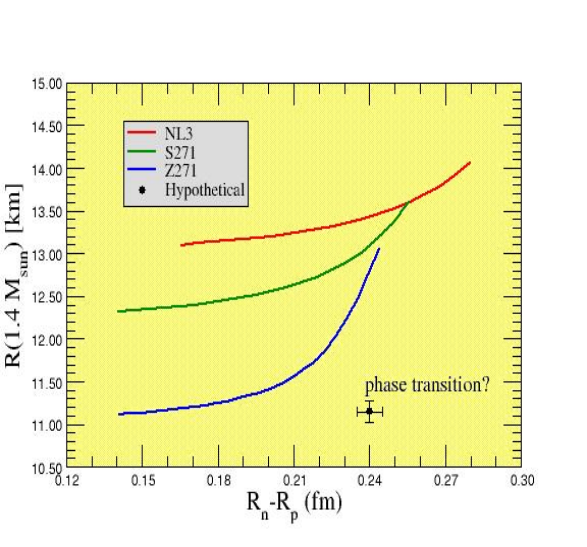
Neutron Skin and Neutron-Star Radii

Is there a correlation between the neutron skin of ^{208}Pb and the radius of a "canonical" $1.4M_{\odot}$ neutron star?

- Study isolated radio-quiet neutron stars
- Study low-mass x-ray binaries in quiescence
- Study their black-body spectra and atmospheric data
- Several good candidates for radius measurements



- However, NOT a data-to-data relation:
  - ⋆ Neutron skin of ^{208}Pb depends on the EOS at subnuclear densities
  - ⋆ Radius of N.S. also sensitive to the high-density EOS
- The thinner the skin of a heavy nucleus, the thinner 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!

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Have we Discovered Quark Stars?

- Is the isolated neutron star RX J1856 too small?
- Is the pulsar in supernova remanent 3C58 too cold?

NASA News Release

National Aeronautics and Space Administration

Marshall Space Flight Center - Huntsville, Ala. 35812
http://www.msfc.nasa.gov/news

For Release: April 10, 2002

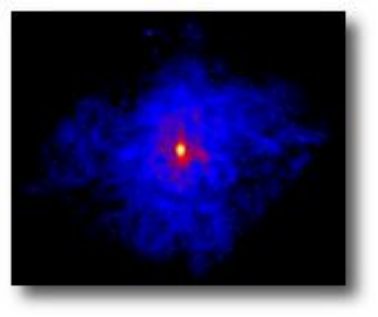
Release: 02-082

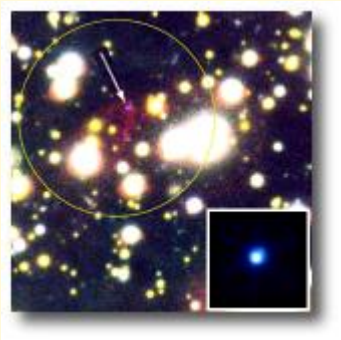
Cosmic X-rays reveal evidence for new form of matter

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.





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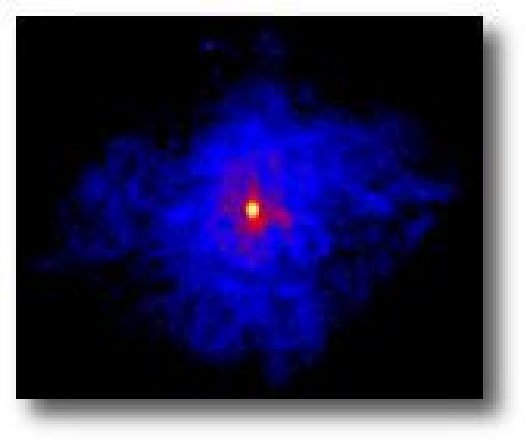
Reports on the Temperature of 3C58

- 3C58 witnessed by Chinese and Japanese in 1181
- Accurate age of about 825 years
- Neutron stars are born hot
- Cool promptly by ν-emission (URCA)
- Surface temperature today suggests $T \leq 10^6$ K



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".*

Neutron Skin and Neutron-Star Cooling

Enhanced (DURCA) cooling of non-exotic stars?

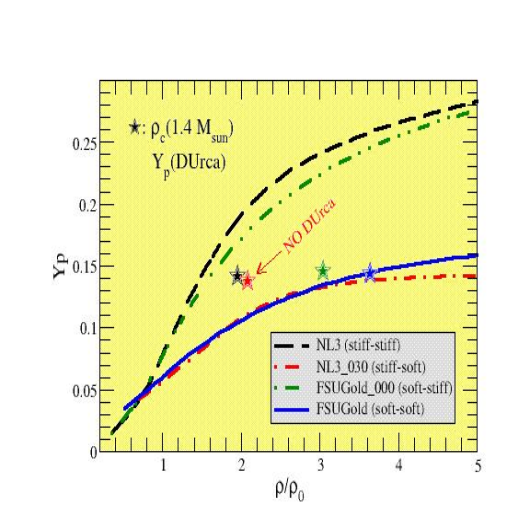
- Core-collapse Supernovae generates proto-neutron star ($T_{\rm core} \simeq 10^{12}$K)
- Direct URCA process cools down the star until ($T_{\rm core} \simeq 10^{9}$K)
- Depending on the EoS [or $R_n(^{208}\mathrm{Pb})$] direct URCA may continue
  - ⋆ Is Y_p large enough to conserve momentum?
- Best case for DUrca (soft-stiff):
  - ⋆ Soft EoS for symmetric matter → large ρ_c
  - ⋆ Stiff symmetry energy → large Y_p

Direct URCA process:

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

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

may continue cooling the neutron star if proton fraction is large enough! FSUGold predicts that the pulsar in 3C58 does NOT need to be an exotic (quark) star provided $R_n - R_p \leq 0.21$ fm.



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Conclusions

The widespread impact of one single number: $R_n(^{208}\mathrm{Pb})$

- On the structure of neutron-rich nuclei
- On the structure of neutron-rich matter
- On the dynamics of heavy-ion collisions
- On the atomic-parity-violating program
- On the EOS of neutron-rich matter
- On the size of neutron stars
- On the cooling of neutron stars
- On the existence of quark stars

Model	K (MeV)	J (MeV)	L (MeV)	$R_n - R_p$ (fm)
NL3	271	37.4	118.5	0.28
FSUGold	230	32.6	60.5	0.21

Neutron-Star Observable	NL3	FSUGold
ρ_c (fm^{-3})	0.052	0.076
R (km)	15.05	12.66
$M_{\mathrm{max}}(M_\odot)$	2.78	1.72
ρ_{Urca} (fm^{-3})	0.21	0.47
$M_{\mathrm{Urca}}(M_\odot)$	0.84	1.30
ΔM_{Urca}	0.38	0.06

JLAB measurement will have strong impact on MSU, RIA, GSI, RIKEN, HST, Chandra, XMM-Newton, etc. Need strong community support (which exists in part) to get this crucial JLAB experiment off the ground!