# **And Now for Something Completely Different ... Probing the Neutron-Star Matter EOS**

## *Neutrino Astrophysics and Fundamental Properties (INT June 2015)*



**The only input required to compute the structure of neutron stars is the equation of state of cold neutron-rich matter:**  $P = P(\mathcal{E}, T = 0)$ 

J. Piekarewicz (FSU) [Neutron-Star Matter Equation of State](#page-14-0) Neutrino Astrophysics and ... 1/15

<span id="page-0-0"></span>

#### **My FSU Collaborators**

- Genaro Toledo-Sanchez
- **Karim Hasnaoui**
- **Bonnie Todd-Rutel**
- **Brad Futch**
- $\bullet$  Jutri Taruna
- **Farrukh Fattoyev**
- **Wei-Chia Chen**
- **Raditya Utama**



### **My Outside Collaborators**

- B. Agrawal (Saha Inst.)
- M. Centelles (U. Barcelona)
- G. Colò (U. Milano)
- C.J. Horowitz (Indiana U.)
- W. Nazarewicz (MSU)
- N. Paar (U. Zagreb)
- M.A. Pérez-Garcia (U. Salamanca)
- P.G.- Reinhard (U. Erlangen-Nürnberg)
- X. Roca-Maza (U. Milano)
- D. Vretenar (U. Zagreb)



#### **Nuclear Charge and Weak-Charge Form Factors (Electroweak )**



- Charge densities known with enormous precision  $R_{ch}^{208}$  = 5.5012(13) fm Started with Hofstadter in the late 1950's and continues to this day in RIBFs
- **•** Provides our most detailed picture of the atomic nucleus
- Weak-charge densities as fundamental as charge densities
- Weak-charge densities are very poorly known *R* 208 *wk* =5.826(181)fm
- **Elastic e-scattering largely insensitive to** the weak-charge distribution
- **Elastic**  $\nu$ **-scattering very sensitive to the** weak-charge distribution

#### **Parity Violation in Elastic e-Nucleus Scattering (JLab and Mainz)**

- Charge (proton) densities known with exquisite precision charge density probed via parity-conserving eA scattering
- Weak-charge (neutron) densities very poorly known weak-charge density probed via parity-violating eA scattering

$$
A_{\text{PV}} = \frac{G_F Q^2}{2\sqrt{2}\pi\alpha} \left[ \underbrace{1 - 4 \sin^2 \theta_W}_{\approx 0} - \frac{F_n(Q^2)}{F_p(Q^2)} \right]
$$

- Use parity violation as  $Z_0$  couples preferentially to neutrons
- PV provides a clean measurement of neutron densities ( $R_n^{208}$ )





#### **CEvNS: From Dark Matter Searches to Neutron Stars**

- $\bullet$  Coherent elastic  $\nu$ -Nucleus scattering has never been observed!
- Predicted shortly after the discovery of weak neutral currents
- **•** Enormously challenging; must detect exceedingly slow recoils
- CEvNS (*pronounced "7s"* ) are backgrounds for DM searches
- CEvNS is coherent ("large") as it scales ∼*N* 2
- "Piggybacking" on the enormous progress in dark-matter searches





*Coherent Elastic* ν*-Nucleus Scattering at the Spallation Neutron Source (ORNL) may become possible in the "not-so-distant" future (see Kate Scholberg's talk)*





### **Neutron Stars: The Role of Nuclear Physics**

- Chandrasekhar shows that massive stars will collapse (1931)
- Chadwick discovers the neutron (1932) ... predicted earlier by Ettore Majorana but never published!
- Baade and Zwicky introduce the concept of neutron stars (1933)
- Oppenheimer-Volkoff compute masses of neutron stars using GR (1939) Predict  $M_{\star} \simeq 0.7 M_{\odot}$  as maximum NS mass or minimum black hole mass
- Demorest/Antoniadis discover massive neutron stars (2010-2013) Observation of  $M_{\star} \simeq 2 M_{\odot}$  in compact relativistic binaries



### Increase from  $(0.7 \rightarrow 2)M_{\odot}$  is all Nuclear Physics!



J. Piekarewicz (FSU) [Neutron-Star Matter Equation of State](#page-0-0) Neutrino Astrophysics and ... 6 / 15

#### **The Anatomy of a Neutron Star (Figures courtesy of Dany Page and Sanjay Reddy)**

- *Atmosphere* (10 cm): Shape of Thermal Radiation (*L*=4πσ*R* 2*T* 4 )
- *Envelope* (100 m): Huge Temperature Gradient (10<sup>8</sup>*K*  $\leftrightarrow$  10<sup>6</sup>*K*)  $\bullet$
- *Outer Crust* (400 m): Coulomb crystal of exotic neutron-rich nuclei  $\bullet$
- *Inner Crust* (1 km): Coulomb frustrated "Nuclear Pasta"  $\bullet$
- *Outer Core* (10 km): Neutron-rich uniform matter (*n*, *p*, *e*, µ)  $\bullet$
- *Inner Core* (?): Exotic matter (Hyperons, condensates, quark matter, . . .)



J. Piekarewicz (FSU) [Neutron-Star Matter Equation of State](#page-0-0) Neutrino Astrophysics and ... 7 / 15

#### **Neutron Stars as Nuclear Physics Gold Mines**

- Neutron Stars are the remnants of massive stellar explosions Are bound by gravity NOT by the strong force Satisfy the Tolman-Oppenheimer-Volkoff equation ( $v_{esc}/c$  ∼ 1/2)
- Only Physics sensitive to: Equation of state of neutron-rich matter EOS must span about 11 orders of magnitude in baryon density
- Increase from 0.7 $\rightarrow$ 2 $M_{\odot}$  must be explained by Nuclear Physics!



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

Need an EOS:  $P = P(\mathcal{E})$  relation distance, a high pulsar mass, and a limit on the variation of Newton's gravitational

**Nuclear Physics Critical** 



#### **The EOS of neutron-rich matter: Where do the extra neutrons go?**

- The EOS of asymmetric matter  $\left[\alpha\!\equiv\!(\mathit{N-}Z)/\mathit{A},\ x\!\equiv\!(\rho\!-\!\rho_{\scriptscriptstyle{0}})/3\rho_{\scriptscriptstyle{0}}\right]$  $\mathcal{E}(\rho,\alpha)\approx\mathcal{E}_{\mathbf{0}}(\rho)+\alpha^2\mathcal{S}(\rho)\approx \biggl(\epsilon_{\mathbf{0}}+\frac{1}{2}\biggr)$  $\left(1 + \frac{1}{2}K_0x^2\right) + \left(1 + \frac{1}{2}x + \frac{1}{2}\right)$  $\frac{1}{2}$ K<sub>sym</sub> $x^2$ ) $\alpha^2$
- **In <sup>208</sup>Pb, 82 protons/neutrons form an isospin symmetric spherical core** Where do the extra 44 neutrons go?
- **Competition between surface tension and density dependence** of  $S(\rho)$ Surface tension favors placing them in the core where  $\mathcal{S}(\rho_{\scriptscriptstyle{\text{0}}})$  is large Symm. energy favors pushing them to the surface where  $\mathcal{S}(\rho_{\text{max}})$  is small
- If difference  $\mathcal{S}(\rho_{_{0}})\!-\!\mathcal{S}(\rho_{_{\mathrm{surf}}})\!\propto\! L$  is large, then neutrons move to the surface **The larger the value of** *L* **the thicker the neutron skin of** <sup>208</sup>**Pb**





#### **Heaven and Earth: Nuclear Physics Informing Neutron Stars**

Maximum neutron-star mass sensitive to EOS at high density

Best—perhaps unique—available constraint at  $\rho\!\gg\!\rho_0$ 

Accurate mass measurements:  $M = (1.97 \pm 0.04) M_{\odot}$  $M = (2.01 + 0.04) M_{\odot}$ 



standard x<sup>2</sup> fit produce similar uncertainties.

- Instead, stellar radii sensitive to EOS at intermediate densities Unique synergy between laboratory experiments and astronomical observations Not possible to adjust EOS at  $\rho{\gtrsim}2\rho_0$  without affecting laboratory observables ່ເ
- Neutron-star radii sensitive to one fundamental parameter of the EOS The slope of the symmetry energy at saturation density *L*∝*P<sub>PNM</sub>*
- Correlation among observables differing by 18 orders of magnitude! Same pressure creates neutron-rich skin and NStar radius LETTER RESEARCH



J. Piekarewicz (FSU) **Meutron-Star Matter Equation of State** Neutrino Astrophysics and ... 10 / 15



amplitude and sharpness of the Shapiro delay increase rapidly with

#### **The Enormous Reach of the Neutron Skin: Covariance Analysis**

- Neutron skin as proxy for neutron-star radii . . . and more!
- Calibration of nuclear functional from optimization of a quality measure
- New era: predictability typical uncertainty quantification demanded
- Neutron skin strongly correlated to a myriad of neutron star properties: Radii, Enhanced Cooling, Moment of Inertia, ...



#### **PREX: The Lead Radius EXperiment Abrahamyan et al., PRL 108, (2012) 112502**

- **Ran for 2 months: April-June 2010**
- **•** First electroweak observation of a neutron-rich skin in <sup>208</sup>Pb
- Promised a 0.06 fm measurement of  $R_n^{\text{208}}$ ; error 3 times as large!



*"One of the main science drivers of FRIB is the study of nuclei with neutron skins 3-4 times thicker than is currently possible ... Studies of neutron skins at JLab and FRIB will help pin down the behavior of nuclear matter at densities below twice typical nuclear density"*



## **A Physics case for PREX-II, CREX, and ... Coherent** ν**-nucleus scattering**



#### **"Heaven and Earth" Guillot** *et al.,* **ApJ, 772:7 (2013)**

- Same pressure creates neutron skin and NS radius Correlation among observables differing by 18 orders of magnitude!
- *"Using conservative assumptions, we found:*  $R_{NS} = 9.1^{+1.3}_{-1.4}$  *km"*<br>*theory of dense nuclear matter may need to be revisited ... theory of dense nuclear matter may need to be revisited*
- Very difficult to reconcile small stellar radii with large *R* 208 skin May be evidence of a softening due to phase transition (quark matter?)
- Very difficult to reconcile small stellar radii with large limiting mass EOS must stiffen again to account for large neutron-star masses



*Tension between theory/experiment/observation*

#### **Addressing the Tension ... W.-C. Chen and JP (arXiv:1505.07436)**

- Guillot *et al.,* assumes all neutron stars have a common radius! Assumption on observable MR rather than on EOS
- One-to-one correspondence between MR and EOS TOV equation +  $EOS \rightarrow MR$
- "Lindblom's inversion algorithm" proves the inverse [APJ 398, 569 (1992)] TOV equation +  $MR \rightarrow EOS$
- Tension in reconciling NS with large masses and small radii Is the resulting EOS causal or superluminal?
- Stellar radius of 1.4 M<sub>o</sub> must exceed 10.7 km! Astrophysical observations are imposing similar upper limits!



#### **Conclusions and Outlook: The Physics of Neutron Stars**

- Astrophysics: What is the minimum mass of a black hole?
- . Atomic Physics: Pure neutron matter as a Unitary Fermi Gas
- $\bullet$ Condensed-Matter Physics: Signatures for the liquid to crystalline transition?
- General Relativity: Rapidly rotating neutrons stars as a source of gravitational waves?
- Nuclear Physics: What are the limits of nuclear existence and the EOS of nuclear matter?
- Particle Physics: QCD made simple the CFL phase of dense quark matter

#### QCD MADE SIMPLE

**Q**uantum chromodynamics, familiarly called QCD, is the modern theory of the strong interaction.1 Historicphysics and the description of ordinary matter—understand-ing what protons and neutrons are and how they inter-act. Nowadays QCD is used to

commonly called "testing QCD." Such is the success of the

to the presence or motion of color charge, very similar to the way photons respond to electric charge. Quarks and gluons One class of particles that carry color charge are the quarks. We know of six different kinds, or "flavors," of quarks—denoted u, d, s, c, b, and t, for: up, down, conceptually simple. Its realization conceptually simple. Its realization in nature, however, is usually very complex. But not always. Frank Wilczek

gluons, and a photons, responding to one one one of the photons, responding to one of the photons, responding

QCD. With regard to this still to things still to be found, search strategies for the Higgs particle and for manifestations of manifestations of manifestations of manifestations of supersymmetry depend on detailed understanding of production mechanisms and backgrounds calculated by gle picture at the box, which represents the box, which represents the box, which represents the box, which represents the box, interaction vertex at which a photon responds to the presence or motion of electric charge.2 This is not just a control of the charge. metaphor. Quite definite and precise algorithms for calculating physical processes are attached to the Feynman graphs of QED, construction inter-In the same pictorial language, QCD appears as an expanded version of QED. Whereas in QED there is just one kind of charge, QCD has the charge of charge, QCD has the charge of charge, QCD has the charge of charges of charge, labeled by "color." Avoiding charge, we might choose red, green, and blue. But, of coloring the coloring terms of coloring the coloring terms of coloring the coloring terms of charges of QCD have not to do with physical colors. Rather, they have properties analogous to electric charge. In particular, the color charges are conserved in all phys-conserved in all phys-conserve ical processes, and there are photon-like massless parti-Aquark of any one of the six flavors can also carry a unit of any of the three color charges. Although the different quark flavors all have different masses, the theory is perfective symmetrical with respect to the three colors. color symmetry is described by the Lie group SU(3). Quarks are spin-1/2 point particles, very much like electrons. But instead of electric charges, they can charge. To be more precise, quarks carry *fractional* electric charge (+ 2*e*/3 for the u, c, and t quarks, and – *e*/3 for the d, s, and b quarks) in addition to the d, s, and For all their similarities, however, there are a few crucial differences between  $\mathcal{L} = \mathcal{L} \mathcal{L}$ the response of gluons to color charges, as measured by the color charges, as measured by the charge of the charges of QCD coupling constant, is much more vigorous than the response of photons to electric charge. Second, as shown in the charge of photons in the charge. Second, as shown in in the box, in addition to just responding to the color charge, in addition to provide the charge, in addition of gluons can also change on color charge into another. possible changes of this kind are allowed, and yet color charge is conserved. So the gluons themselves must be able to carry unbalanced color charges. For example, if  $\alpha$ absorption of a gluon changes a blue quark into a reduced a blue quark into a reduced a reduced a reduced a reduced a reduced as a quark, the gluon itself must have carried one unit of red charge and minus one unit of blue charge. All this would see the seem to require 3  $\sim$  35 different seems to require 3  $\sim$ color gluons. But one particular combination of gluons the color-SU(3) singlet—which responds to all the color-SU(3) singlet—which responds to all the colorcharges, is different from the rest. We must remove it if if  $\alpha$ we are to have a perfect line to have a perfect theory. The next perfect line of the symmetric theory. Then the we are left with only 8 physical gluon states (forming and color-SU(3) octet). Fortunately, this conclusion is vindicat-The third difference between QCD and QCD and QCD and QED, which is a second of the third difference between  $\mathcal{L}_\mathbf{C}$ the most profound, follows from the second. Because gluons respond to the presence and motion of color charge *and* they can recommend color charges that they can be a second color charge of the charge of the charges of

## **Neutron Stars are the natural meeting place for fundamental and interesting Physics**



J. Piekarewicz (FSU) [Neutron-Star Matter Equation of State](#page-0-0) Neutrino Astrophysics and ... 15 / 15

<span id="page-14-0"></span>