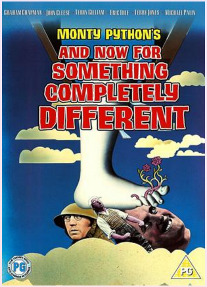
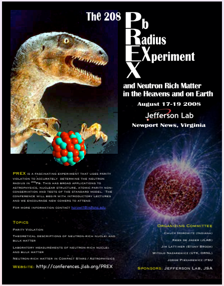
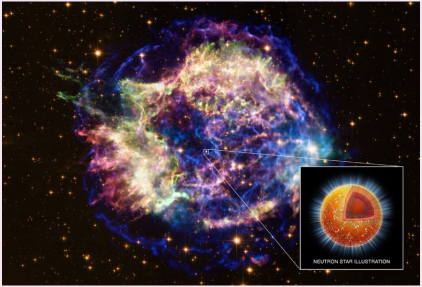
And Now for Something Completely Different ... Probing the Neutron-Star Matter EOS

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: $P = P(\mathcal{E}, T = 0)$

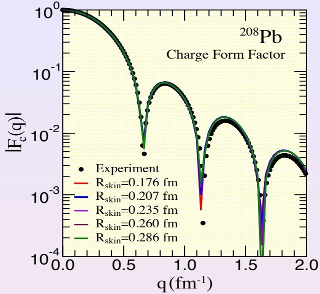
My FSU Collaborators

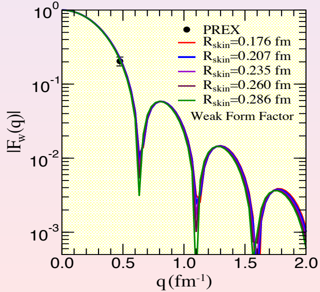
- Genaro Toledo-Sanchez
- Karim Hasnaoui
- Bonnie Todd-Rutel
- Brad Futch
- Jutri Taruna
- **Farrukh Fattoyev**
- **Wei-Chia Chen**
- Raditya Utama

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)



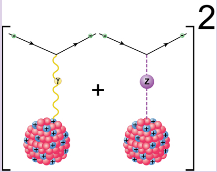


- Charge densities known with enormous precision $R_{ch}^{208} = 5.5012(13)\,\mathrm{fm}$
  Started with Hofstadter in the late 1950's and continues to this day in RIBFs
- Provides our most detailed picture of the atomic nucleus

- Weak-charge densities as fundamental as charge densities
- Weak-charge densities are very poorly known $R_{wk}^{208} = 5.826(181)\,\mathrm{fm}$
- Elastic e-scattering largely insensitive to the weak-charge distribution
- Elastic ν-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



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

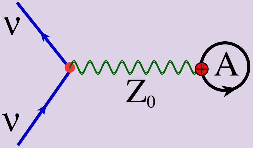
- Use parity violation as Z_0 couples preferentially to neutrons
- PV provides a clean measurement of neutron densities (R_n^{208})

	up-quark	down-quark	proton	neutron
γ-coupling	$+2/3$	$-1/3$	$+1$	0
Z_0-coupling	$\approx +1/3$	$\approx -2/3$	≈ 0	-1

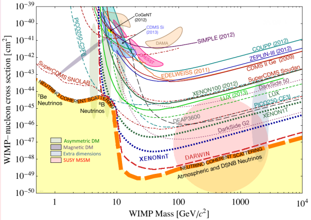
$$g_{\rm v} = 2t_z - 4Q\sin^2\theta_{\rm W} \approx 2t_z - Q$$

CEvNS: From Dark Matter Searches to Neutron Stars

- Coherent elastic ν-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 $\sim N^2$
- "Piggybacking" on the enormous progress in dark-matter searches

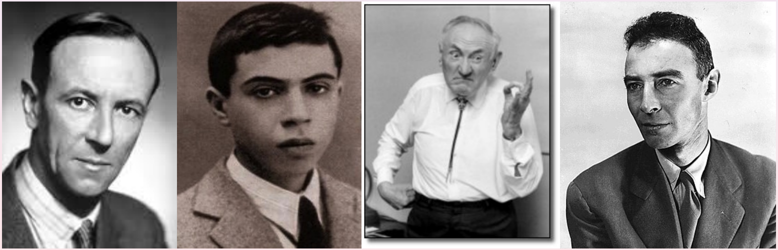


Coherent Elastic ν-Nucleus Scattering at the Spallation Neutron Source (ORNL) may become possible in the "not-so-distant" future (see Kate Scholberg's talk)



Neutron Stars: The Role of Nuclear Physics

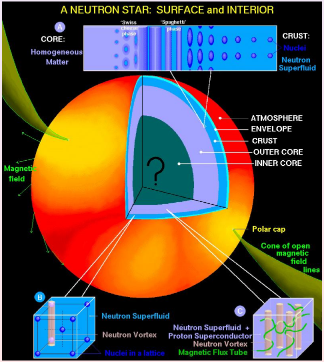
- Chandrasekhar shows that massive stars will collapse (1931)
- Chadwick discovers the neutron (1932)
  ... predicted earlier by Ettore Majorana but never published!
- Baade and Zwicky introduce the concept of neutron stars (1933)
- Oppenheimer-Volkoff compute masses of neutron stars using GR (1939)
  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

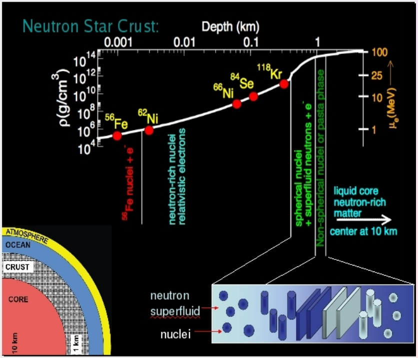


Increase from $(0.7 \rightarrow 2)M_{\odot}$ is all Nuclear Physics!

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

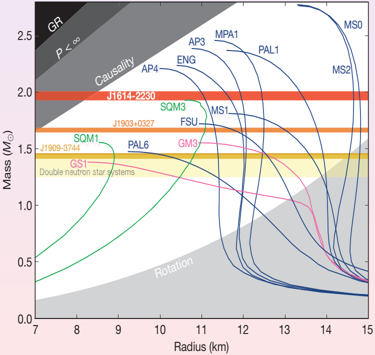
- *Atmosphere* (10 cm): Shape of Thermal Radiation ($L = 4\pi\sigma R^2 T^4$)
- *Envelope* (100 m): Huge Temperature Gradient ($10^8 K \leftrightarrow 10^6 K$)
- *Outer Crust* (400 m): Coulomb crystal of exotic neutron-rich nuclei
- *Inner Crust* (1 km): Coulomb frustrated "Nuclear Pasta"
- *Outer Core*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





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 ($v_{\rm esc}/c \sim 1/2$)
- Only Physics sensitive to: Equation of state of neutron-rich matter
  - EOS must span about 11 orders of magnitude in baryon density
- Increase from $0.7 \rightarrow 2M_{\odot}$ must be explained by Nuclear Physics!



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

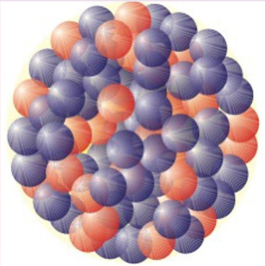
$$\frac{dP}{dr} = -G\frac{\mathcal{E}(r)M(r)}{r^2}\left[1+\frac{P(r)}{\mathcal{E}(r)}\right]\left[1+\frac{4\pi r^3 P(r)}{M(r)}\right]\left[1-\frac{2GM(r)}{r}\right]^{-1}$$

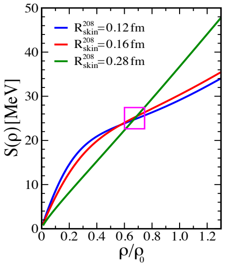
Need an EOS: $P = P(\mathcal{E})$ relation

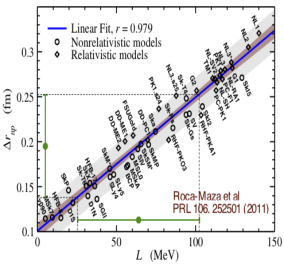
Nuclear Physics Critical

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

- The EOS of asymmetric matter $\left[\alpha \equiv (N-Z)/A,\ x \equiv (\rho-\rho_0)/3\rho_0\right]$
$$\mathcal{E}(\rho,\alpha) \approx \mathcal{E}_0(\rho) + \alpha^2 \mathcal{S}(\rho) \approx \left(\epsilon_0 + \frac{1}{2}K_0 x^2\right) + \left(J + \boxed{L}\, x + \frac{1}{2}K_{\rm sym} x^2\right)\alpha^2$$
- In ^{208}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 $\mathcal{S}(\rho)$
Surface tension favors placing them in the core where $\mathcal{S}(\rho_0)$ is large
Symm. energy favors pushing them to the surface where $\mathcal{S}(\rho_{\rm surf})$ is small
- If difference $\mathcal{S}(\rho_0)-\mathcal{S}(\rho_{\rm surf}) \propto L$ is large, then neutrons move to the surface
The larger the value of L the thicker the neutron skin of ^{208}Pb

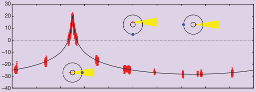




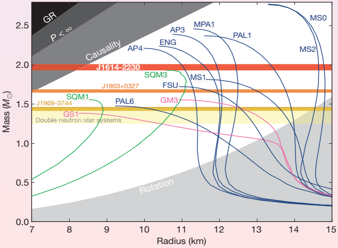


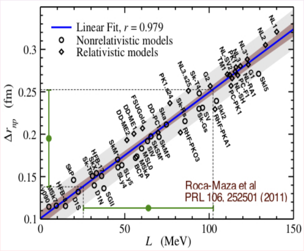
Heaven and Earth: Nuclear Physics Informing Neutron Stars

- Maximum neutron-star mass sensitive to EOS at high density
  - Best—perhaps unique—available constraint at $\rho \gg \rho_0$
  - Accurate mass measurements:
    - $M = (1.97 \pm 0.04)\, M_\odot$
    - $M = (2.01 \pm 0.04)\, M_\odot$



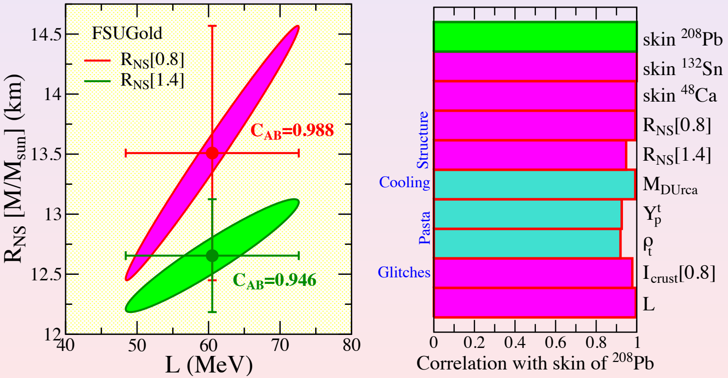
- Instead, stellar radii sensitive to EOS at intermediate densities
  - Not possible to adjust EOS at $\rho \gtrsim 2\rho_0$ without affecting laboratory observables
  - Unique synergy between laboratory experiments and astronomical observations
- Neutron-star radii sensitive to one fundamental parameter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





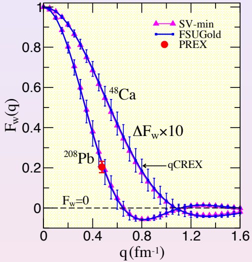
The Enormous Reach of the Neutron Skin: Covariance Analysis

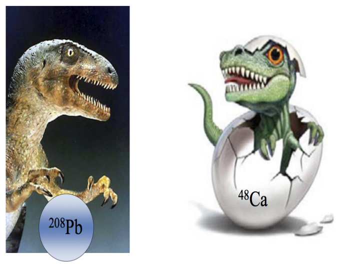
- Neutron skin as proxy for neutron-star radii . . . and more!
- Calibration of nuclear functional from optimization of a quality measure
- New era: predictability typical – uncertainty quantification demanded
- Neutron skin strongly correlated to a myriad of neutron star properties:
  Radii, Enhanced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

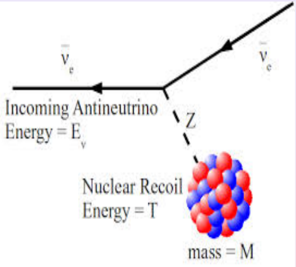


PREX: The Lead Radius EXperiment Abrahamyan et al., PRL 108, (2012) 112502

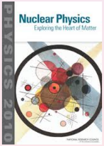
- **Ran for 2 months: April-June 2010**
- First electroweak observation of a neutron-rich skin in ^{208}Pb
- Promised a 0.06 fm measurement of R_n^{208}; error 3 times as large!







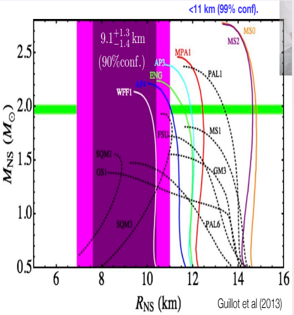
"One of the main science drivers of FRIB is the study of nuclei with neutron skins 3-4 times thicker than is currently possible ... Studies of neutron skins at JLab and FRIB will help pin down the behavior of nuclear matter at densities below twice typical nuclear density"

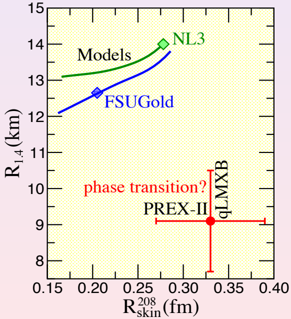


A Physics case for PREX-II, CREX, and ... Coherent ν-nucleus scattering

"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"*
  ... theory of dense nuclear matter may need to be revisited
- Very difficult to reconcile small stellar radii with large $R^{208}_{\rm skin}$
  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

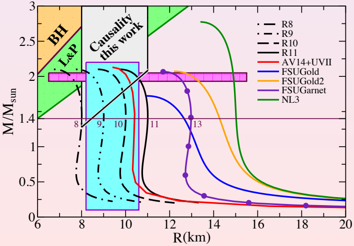


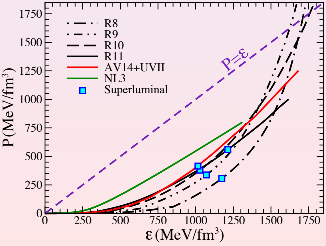


Tension between theory/experiment/observation

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

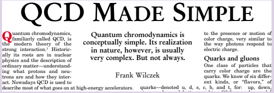
- Guillot *et al.*, assumes all neutron stars have a common radius!
  - Assumption on observable MR rather than on EOS
- One-to-one correspondence between MR and EOS
  - TOV equation + EOS $\rightarrow$ MR
- "Lindblom's inversion algorithm" proves the inverse [APJ 398, 569 (1992)]
  - TOV equation + 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 $M_{\odot}$ 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
- 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

Quantum chromodynamics is conceptually simple. Its realization in nature, however, is usually very complex. But not always.

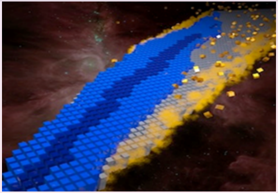
Frank Wilczek

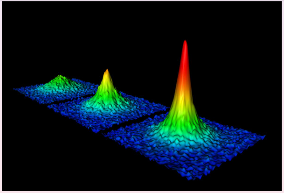
Quantum chromodynamics, familiarly called QCD, is the modern theory of the strong interaction.[1] Historically its roots are in nuclear physics and the description of ordinary matter—understanding what protons and neutrons are and how they interact. Nowadays QCD is used to describe most of what goes on at high-energy accelerators.

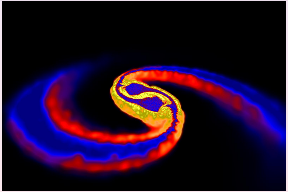
... to the presence or motion of color charge, very similar to the way photons respond to electric charge.

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,







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