Symposium in Honor of Brian Serot
A Mentor, a Colleague, and a Friend
My FSU Collaborators

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

My Outside Collaborators

- B. Agrawal (Saha Inst.)
- M. Centelles (U. Barcelona)
- G. Colò (U. Milano)
- C.J. Horowitz (Indiana U.)
- W. Nazarewicz (U. Tennessee)
- 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)
From Finite Nuclei to Neutron Stars

- B.C. Clark et al., successful Dirac approach to proton-nucleus scattering
  "Dirac equation impulse approximation ...", PRL50,1644(1983) [Clark, Hama, Mercer, Ray, Serot]

- I jumped on the Dirac bandwagon; Prof. R.D. Amado (PhD thesis 1985)


  Second most-cited paper in nuclear theory with about 1,500 citations

- A theory that can describe finite nuclei and neutron stars!

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Fig. 6. Charge density distribution for $^{208}$Pb. The solid curve is from [De87]. Thin results are indicated by the long-dashed curve (set L2) and the dot-dashed curve (s)

Fig. 4. Calculated neutron star mass in units of the solar mass $M_{\odot}$ as a function of the central density. Results are shown for QHD-I (solid, based on Fig. 3) and QHD-II (dashed, see Section 7).
QHD: “The only consistent approach ... which meets these objectives is a local, relativistic, (renormalizable), many-body QFT."
renormalizable to extrapolate away from the empirical calibration without introducing no new unknown parameters

QHD: ... reinterpretation as non-renormalizable EFT
... natural ordering of the infinite-number of couplings that allowed a meaningful truncation

Naturalness: include all terms through a given order of truncation
... generalizations that include quartic self-interactions (\(\zeta\)) for the neutral vector meson have been discussed ...

RMF theory and the high-density EOS [Müller & Serot (1996)]
... models yield same observables at normal densities, but yield maximum NStar masses that differ by more than 1\(M_\odot\)

Incompressibility of nuclear matter from the GMR [Youngblood (1999)]
\(K_{nm}\) is important in the description of nuclei, supernovae explosions, neutrons stars, and heavy-ion collisions

Fig. 7. Maximum neutron star mass as function of \(\xi\) and \(\zeta\). Results for pure neutron matter and for matter in \(\beta\)-equilibrium are displayed. The shaded areas show the mass range obtained when \(\xi\) is varied; the upper boundaries correspond to \(\xi = 0\) and the lower boundaries to \(\xi = 1.5\).
Relativistic DFT: From Finite Nuclei to Stars

- QHD: effective QED-like theory with additional couplings:
  \[ \mathcal{L}_{\text{int}} = \mathcal{L}_{\text{Yukawa}} + \frac{\zeta}{4!} (W_\mu W_\mu)^2 + \Lambda_\nu (W_\mu W_\mu)(B^\nu \cdot B_\nu) + \ldots \]

- Incorporate physical insights into the construction of the functional
- Empirical constants determined from optimization of a quality measure
- Empirical constants directly fitted to many-body observables
- Complicated dynamics encoded in the empirical constants
- Predictions accompanied by meaningful theoretical errors
Neutron-Star Structure

- Neutron Stars satisfy the Tolman-Oppenheimer-Volkoff equation, a General-Relativistic extension of Newtonian gravity ($v_{esc}/c \lesssim 1/2$).
- Only unknown physics is the **Equation of State**.
- EOS must span **10-11 orders of magnitude** in baryon density.
- Enormous uncertainty in the prediction of neutron-star radii.

**Maximum stellar mass may be tuned with** \( \zeta \), **stellar radii with** \( \Lambda_v \).

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

**Need an** \( \mathcal{E} \) **vs** \( P \) **relation!**
Neutron Skins and the Symmetry Energy

- Symmetry energy: Penalty for breaking $N = Z$ symmetry
  - Symmetry Energy $\approx$ PNM - SNM $[B(Z, N) = -a_a(N-Z)^2/A + \ldots]$  
  - Slope (pressure) of pure neutron matter $L$ poorly constrained

- Adjust the pressure of pure neutron matter by tuning $\Lambda_v$

- Neutron skin strongly correlated to the pressure of pure neutron matter

- Pressure of PNM pushes against surface tension $\Rightarrow$ neutron skin
  - Pressure of PNM pushes against gravity $\Rightarrow$ neutron-star radius

- The larger the neutron skin, the larger the neutron-star radius!!
Heaven on Earth: Neutron Skins and Neutron Stars

- Same dynamical origin to neutron skin and NS radius
- Same pressure creates neutron skin and NS radius
- Correlation among observables differing by 18 orders of magnitude!
- NS radius sensitive to the high-density component of the EOS
- Hence the model dependence ...
- Large neutron skin and small neutron radius?
  May be evidence in favor of a phase transition to exotic matter

Synergy between astrophysical and laboratory observables!
PREX: The Lead Radius EXperiment [PRL 108, 112502 (2012)]

- Ran for 2 months on April-June 2010
- First purely electroweak (clean!) measurement of $R_n^{(208\,\text{Pb})}$
- Promised a 1% measurement of $R_n^{(208\,\text{Pb})}$
- Uses parity violation as $Z_0$ couples preferentially to neutrons

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<th>up-quark</th>
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<tr>
<td>$\gamma$-coupling</td>
<td>$+2/3$</td>
<td>$-1/3$</td>
<td>$+1$</td>
<td>$0$</td>
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<tr>
<td>$Z_0$-coupling</td>
<td>$\approx +1/3$</td>
<td>$\approx -2/3$</td>
<td>$\approx 0$</td>
<td>$-1$</td>
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$$g_v = 2t_z - 4Q \sin^2 \theta_W \approx 2t_z - Q$$

We report the first measurement of the parity-violating asymmetry $A_{PV}$ in the elastic scattering of polarized electrons from $^{208}\text{Pb}$. $A_{PV}$ is sensitive to the radius of the neutron distribution ($R_n$). The result $A_{PV} = 0.656 \pm 0.060 \text{(stat)} \pm 0.014 \text{(syst)}$ ppm corresponds to a difference between the radii of the neutron and proton distributions $R_n - R_p = 0.33^{+0.16}_{-0.18}$ fm and provides the first electroweak observation of the neutron skin which is expected in a heavy, neutron-rich nucleus.

A Physics case for PREX-II and beyond!
The Electric Dipole Polarizability as a Proxy for $R_{\text{skin}}$

IVGDR: *Coherent oscillations of protons against neutrons*
Nuclear symmetry energy as the restoring force

RCNP: polarized proton inelastic scattering at very forward angles
Cross sections at very small angles arise purely from CoulEx

High-resolution exp. in excellent agreement with photo-absorption data

Accurate measurement of $E1$ polarizability: $\alpha_D = (20.1 \pm 0.6) \text{ fm}^3$

$E1$ polarizability as a complement/proxy to $R_{\text{skin}}^{208\text{Pb}}$

J. Piekarewicz (FSU)
Covariance Analysis: Neutron Skins and Neutron Stars

- Powerful covariance analysis provides meaningful theoretical errors
- Powerful covariance analysis unravels interesting correlations
- PNM pressure $L$ correlated to a myriad of NS observables
  NS-radii, proton fraction, core-crust transition density, DUrca cooling, ...

$C_{AB} = 0.988$

$C_{AB} = 0.946$

J. Piekarewicz (FSU)
The Stellar Crust: Non-Uniform Nuclear Matter

- Neutron stars contain a non-uniform crust above the liquid core
- Neutron star crust extends for about 1 km out of about 10-12 km
- Uniform neutron-rich matter is unstable against cluster formation
- Exotic states speculated to exist in the stellar crust:
  - Coulomb crystal of neutron-rich nuclei (outer crust)
  - Coulomb frustrated pasta structures (inner crust)
Coulomb Crystal of Neutron-Rich Nuclei

- Neutrons, protons, and a uniform electron Fermi gas
- Composition emerges from relatively simple dynamics:
  \[ \frac{E}{A_{\text{tot}}} = \frac{M(N, Z)}{A} + \frac{3}{4} Y_e^{4/3} \kappa_{\text{Fermi}} + \text{lattice} \]
- bcc Crystal of neutron-rich nuclei immersed in a uniform $e^-$ gas
- As density increases in the outer crust, $^{56}\text{Fe}$, $^{62}\text{Ni}$, ..., $^{118}_{36}\text{Kr}_{82}$ (?)
- Neutron-drip line defines the outer-inner crust interface
The Inner Crust: $10^{-3} \rho_0 \lesssim \rho \lesssim 10^{-1} \rho_0$

"Frustration and Nuclear Pasta"

- Frustration emerges from a dynamical (or geometrical) competition
- Impossibility to simultaneously minimize all elementary interactions
- Emergence of a multitude of competing (quasi) ground states
- Universal in complex systems (nuclei, $e^-$ systems, magnets, proteins, ...)
- Emergence of complex topological shapes driven by long-range Coulomb interaction

"Nuclear Pasta" or "Micro-emulsions"

Coherent neutrino scattering from "warm" nuclear pasta may play an important role in the energetics of core-collapse supernovae
A Celebration of the Life of a *Mensch*

**Brian: the paradigm of a Mensch**
- A person that radiates decency
- A person having admirable characteristics
- A person with the qualities one would hope for in a dear friend
- A person with the qualities one would hope for in a trusted colleague

*Professor Brian D. Serot*  
(February 1, 1955 – March 2, 2012)