Neutron star Equations of State: An ideal to aim towards

- Astrophysical modeling generally requires EOS tables more extensive than traditional pressure versus energy density:
- Chemical potentials, density-derivatives of pressure, chemical potentials...
- Versus individual proton and neutron densities $n_p$, $n_n$ (not just $\beta$-equilibrium)
- Effective masses, superfluid gaps, transport properties...
- Crust properties (composition, shear modulus)
- Consistently calculated, informed by state-of-the-art microscopic nuclear matter calculations, explore symmetry energy variation
- Provided in a form useful for astrophysical codes (community effort)
- Not all or nothing – any progress in way EOSs are prepared is valuable

(e.g. see discussion in Lin, Andersson, Comer, PRD78, 083008 (2008) for the astrophysicist’s perspective)
Neutron star masses

- Over what mass range are we probing primarily properties of nucleonic matter?
- Target low mass stars for unambiguous signatures of nucleonic matter properties?
- What is the minimum mass nature produces?

- How are low mass neutron stars born?
  - e-capture SN scenario believed to produce many neutron stars over a tight mass range at around $1.25M_{\text{SUN}}$
  - Observational evidence only circumstantial (Type Ib/c Sne; properties of certain NS binary systems)
  - Claim: 1D SN simulations are sufficient to model e-capture SN, and little mass loss, but no systematic analysis yet performed
  - If above holds, could place strong constraints on binding energy (thus EOS);
  - Also a very important stellar evolutionary scenario; influences NS initial mass function

Gandolfi, Carlson, Reddy PRC85 (2012)
How thick is a neutron star crust?

- Crust thickness depends on crust-core transition pressure $P_{cc}$
- $P_{cc}$ depends mainly on $E_{\text{sym}}(\rho_0)$, $L(\rho_0)$, $K_{\text{sym}}(\rho_0)$ (alternatively $E_{\text{sym}}(\rho\approx0.1\text{fm}^{-3})$, $L(\rho\approx0.1\text{fm}^{-3})$)
- Measurement of crust thickness gives constrains higher order terms in symmetry energy expansion (and vice versa!)
- Crust thickness probed by glitches, crust thermal relaxation timescale, crust oscillations...

What does the crust-core transition look like?

Pasta phases:
- How extensive? (depends on same symmetry energy quantities as crust thickness)
- Can we perform reliable calculations of their shear modulus, transport properties, entrainment parameters? Are they sensitive to the symmetry energy?
- Can we find unambiguous observational signatures?
Calculating pasta: the state of the art:
- Classical/quantum molecular dynamics, 3D(TD)HF
- How best to combine advantages of these techniques? (3DHF: quantum shell effects, band structure but small volume; C/QMD: larger volumes
- Mesophysics: how do pasta structures organize on larger scales; strong analogy with soft condensed matter systems. Can we learn from soft condensed matter techniques (lattice Boltzmann...)?

What does the crust-core transition look like?
How do pasta layers influence:

- The evolution of the crustal magnetic field?
- The frequencies of crust oscillations?
- The coupling between crust and core oscillation modes?
- Thermal relaxation of the crust?

We have demonstrated that the pasta phases can have a first overtone, is consistent only with low core Alfvén waves (Sotani et al. 2008).

Figure 4. R-mode instability window for different values of the “slip” parameter $S$ (Glampedakis & Andersson 2006; see text). A large slip parameter, corresponding to a nearly completely rigid crust, appears to be necessary to explain the observations. Haskell, Degenaar, Ho, MNRAS 424 (2012)
Effect of short-range correlations, tensor force, and the high-momentum tail

- In asymmetric nuclear matter, large fraction of protons occupy high momentum states due to SRCs
- Effect on proton superfluidity, v-emission processes, transport properties...
- Requires consistent microscopic calculations at supra-saturation densities