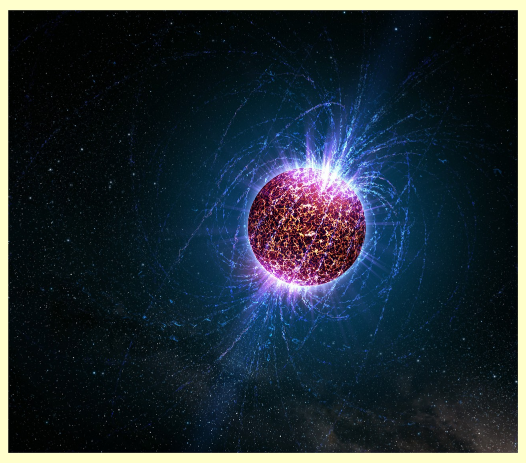
Investigation of Mass/Energy limits of Neutron Stars
by Oliver Hamil

Limiting Energy Densities of Neutron Stars

- Studying energy density limits of compact stars is of key importance because it can tell us about the composition (fundamental building blocks, phase transitions) of ultra-dense matter.
- Limiting energy density also determines a maximum mass for compact stars which is of key importance for estimating the number of low-mass black holes in Galaxies.



Equation of State

- An equation of state (EoS) describes the state of matter in a given physical system.
- An example of a well known EoS is as follows: PV = nRT (ideal gas law)
- So what is the EoS of a Neutron Star?

EoS Ultra-dense matter

- Has form:

$$p(\epsilon)$$

  - where pressure is a function of density
- Determining models for the EoS constitutes a very complicated many-body problem with $\sim 10^{57}$ particles.
- Different competing theoretical frameworks are:
  - Schroedinger-based (non-relativistic) methods
  - Relativistic, quantum-field theoretical methods (Dirac equation)
- Challenges:
  - Do not know the building blocks:
    - Hyperons?
    - Delta particles?
    - Quarks?
    - Superconductivity?

Equation of State for this study

- The equation of state for the low density region up to about nuclear density is known and given by Harrison-Wheeler/Negele-Vautherine.
- The equation of state for the ultra-high density region above nuclear density is only very poorly known. For this reason it is necessary to create equations of state from a variational Ansatz.
- The Ansatz is made with three key assumptions:
  - Einstein's theory of relativity is the correct theory of gravity.
  - Causality is not violated in the high pressure regime; (sound cannot propagate faster than the speed of light).

$$v(\epsilon) = \sqrt{\frac{dp}{d\epsilon}} \leq 1$$

  - The system exhibits microscopic stability as per Le Chatelier's principle;

$$\frac{dp}{d\rho} \geq 0$$

Variational Ansatz

- From the afore mentioned assumptions, the variational Ansatz takes the following form:
  - Low density:
    - Harrison-Wheeler/Negele-Vautherine

$$\epsilon(\rho) = \epsilon_{H-W/N-V} \qquad p(\rho) = p_{H-W/N-V}$$

  - Parameterized Region:

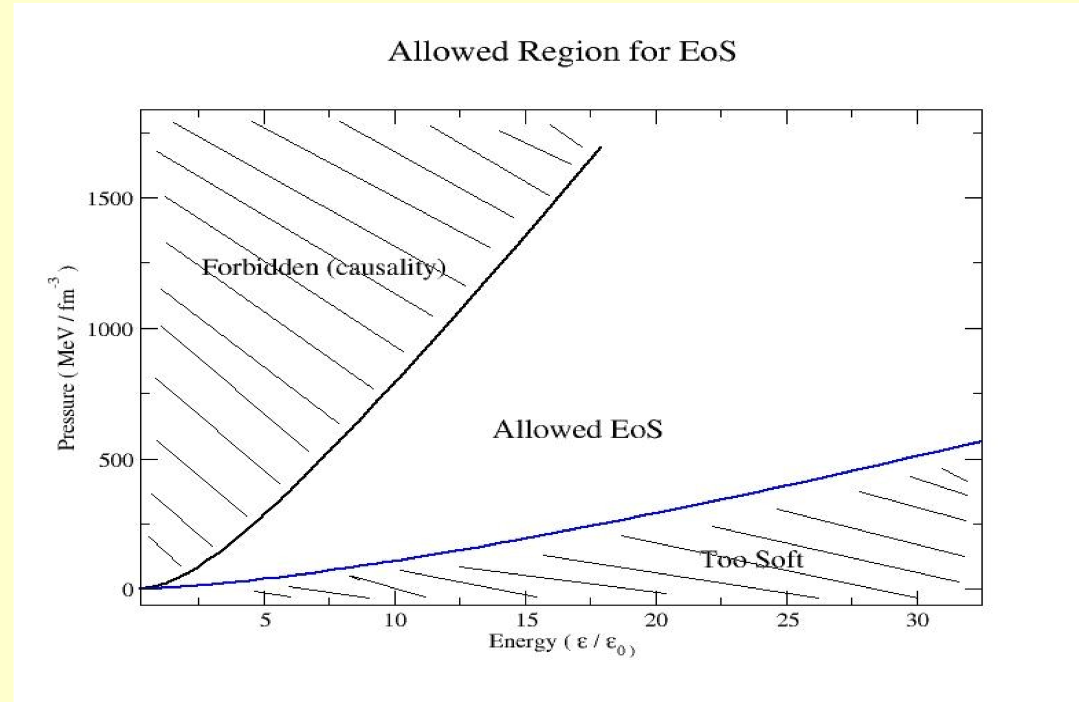
$$\epsilon(\rho) = \frac{A}{\gamma - 1}(u^{\gamma} - u) + u\epsilon_1 + (1 - u)(A - p_0)$$

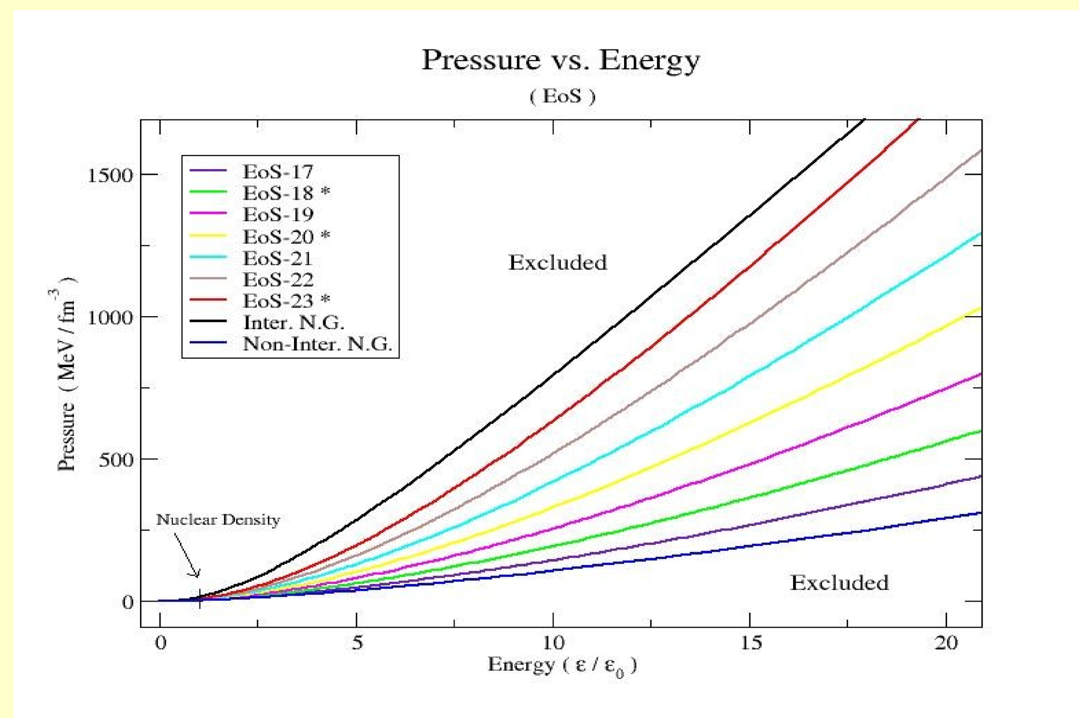
$$p(\rho) = A(u^{\gamma} - 1) + p_0 \qquad u = \frac{\rho}{\rho_1}$$

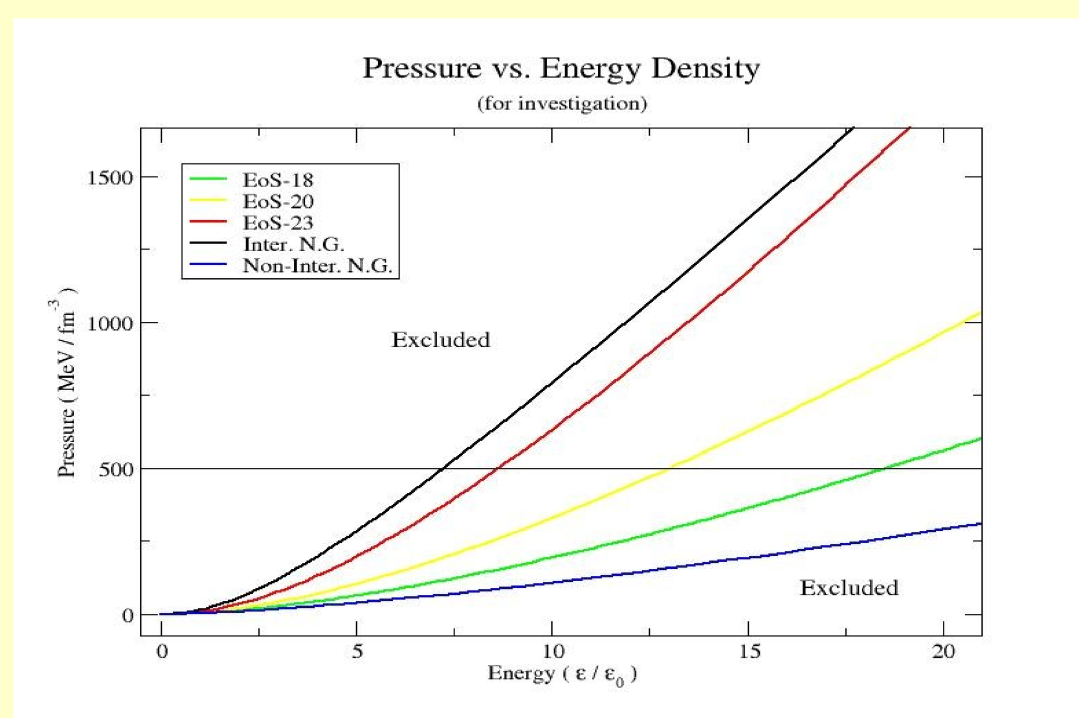
  - Phase Transition Region:

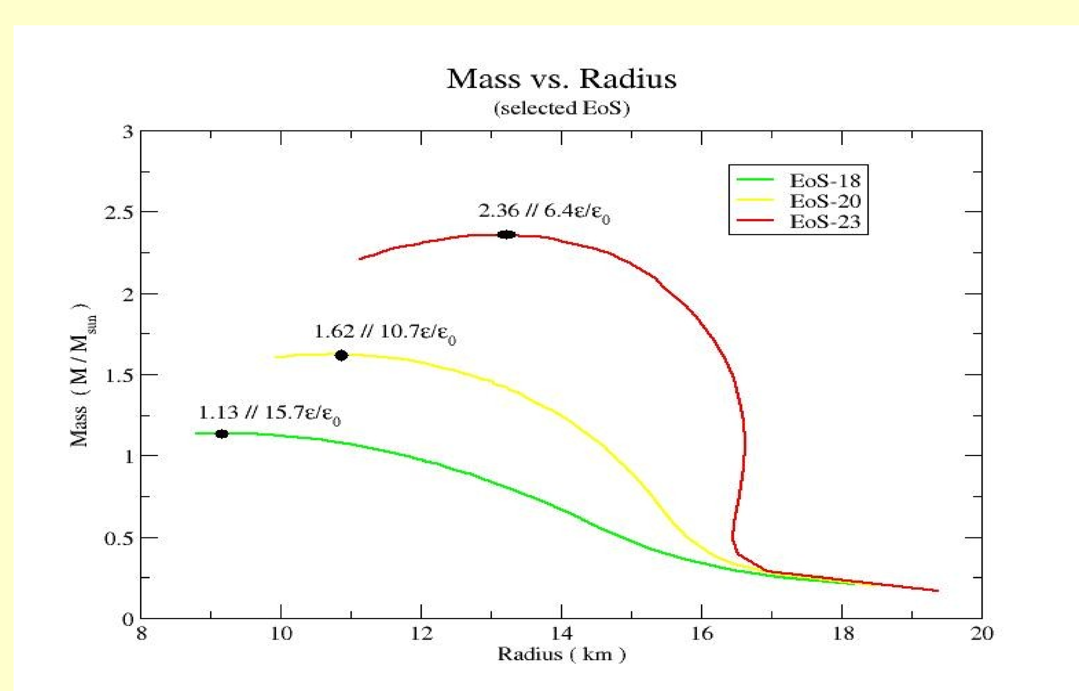
$$\epsilon(\rho) = \frac{\rho}{\rho_0}(\epsilon_0 + p_0) - p_0 \qquad p(\rho) = p_0$$

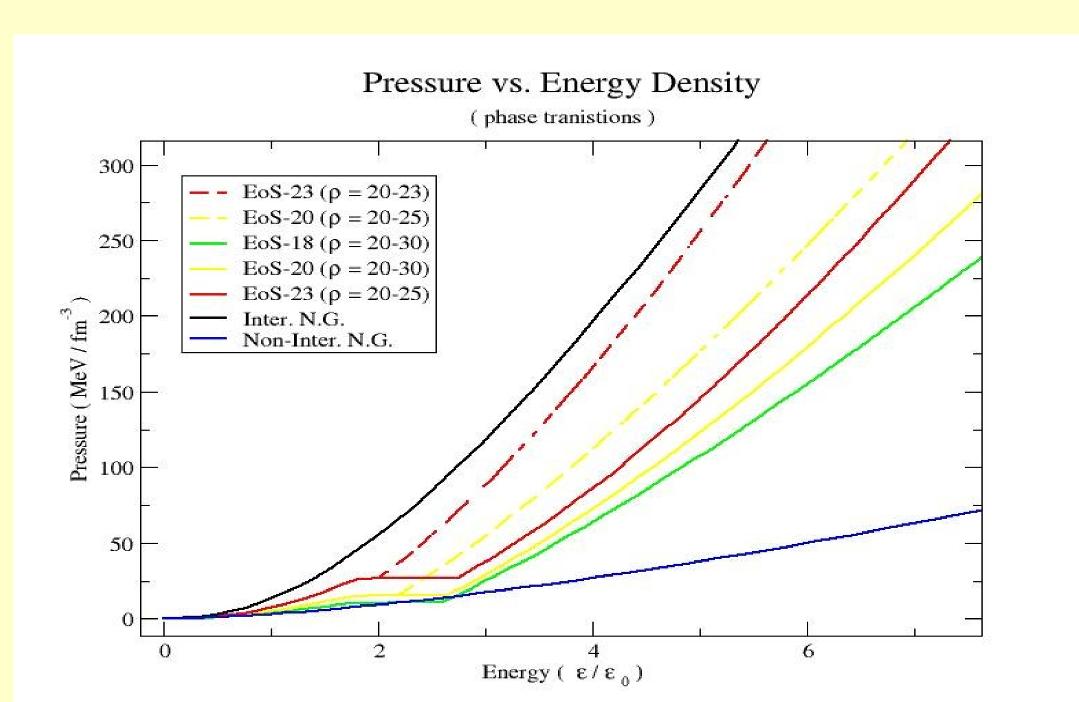
    - (note: A and gamma are varied to control the EoS)

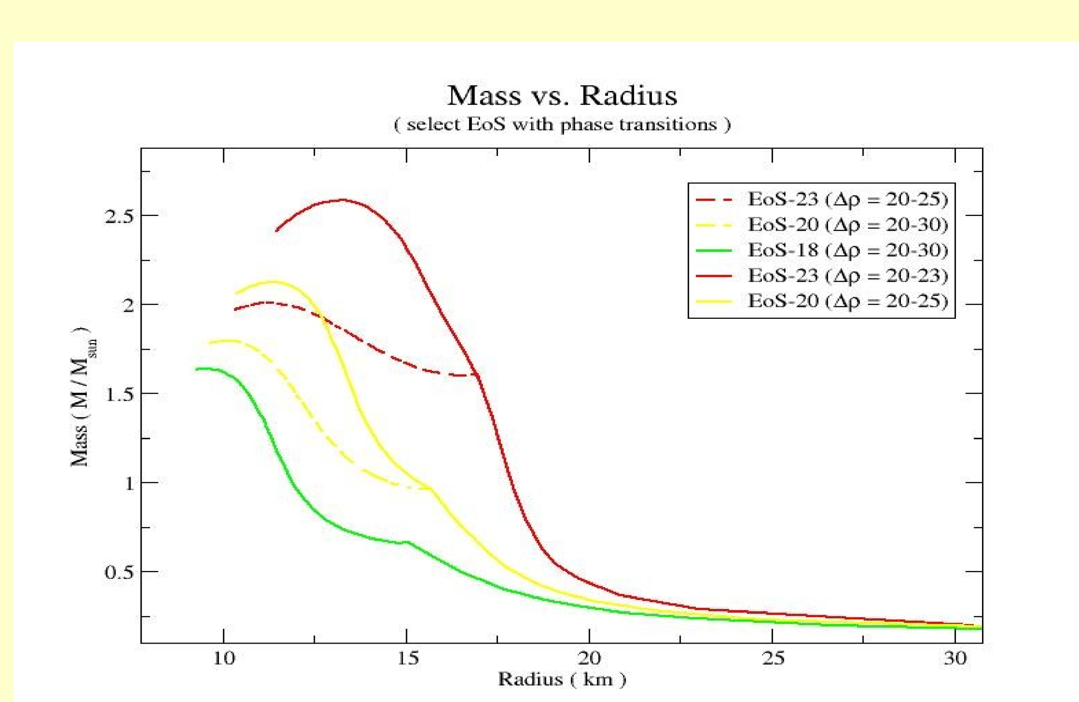


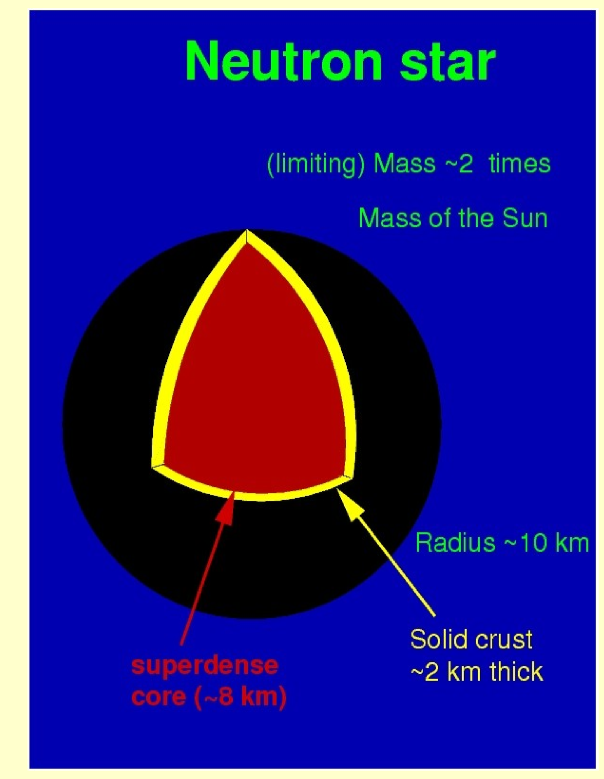


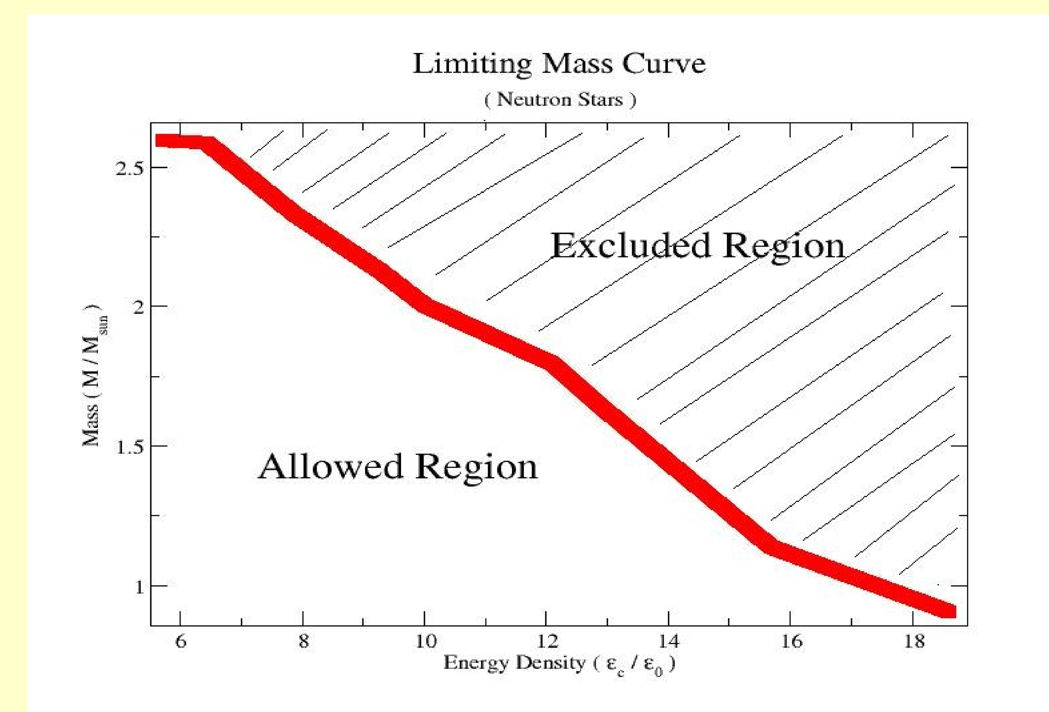












Summary

- Variational study of EoS of ultra-dense matter assuming:
  - Einstein's theory of relativity is the correct theory of gravity
  - Causality is not violated
  - Microscopic stability is guaranteed
- Input variational EoS into existing stellar code to generate stellar sequences for neutron stars.
- Found a firm upper mass limit for neutron stars of around 2.6 solar masses, and consequently a lower limit on low mass black holes.
- Found that heavy neutron stars with masses of around 2 solar masses can have densities up to 10 times nuclear matter density.
  - shows potential for high energy particles (hyperons, quarks, etc.)

Still to come...

- Generalize the limiting mass curve to three dimensions to include rotation from zero out to the keppler (mass shedding) frequency. (or possibly red-shift)
  - Gives a double constraint on limiting mass

- Advising Professor:
  - Dr. Fridolin Weber
- SDSU (physics department)