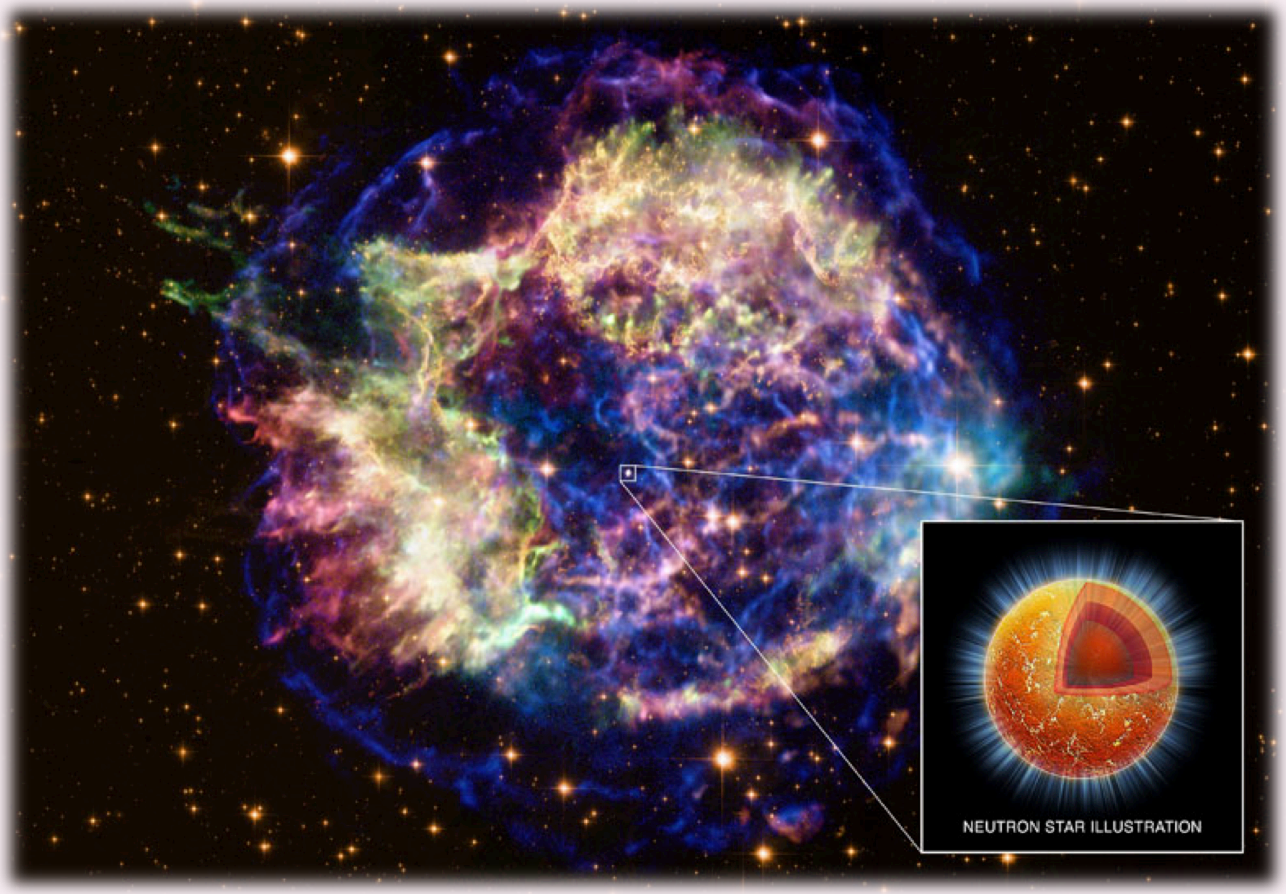
Neutron Star Properties and the Role of the Nuclear Symmetry Energy



Farrukh J. Fattoyev

Department of Physics & Astronomy Colloquium
Texas A&M University-Commerce
January 16, 2014

Outline

- Historical Overview: Some Interesting Facts
- Neutron Star Properties
- The Equation of State as a Sole Ingredient
- Density Dependence of the Nuclear Symmetry Energy
- Role and Impacts of the Symmetry Energy in
  - Mass versus Radius Relation
  - Transition Properties
  - Moments of Inertia
  - Enhanced Cooling: Direct Urca Process
  - Tidal Polarizability
- Concluding Remarks

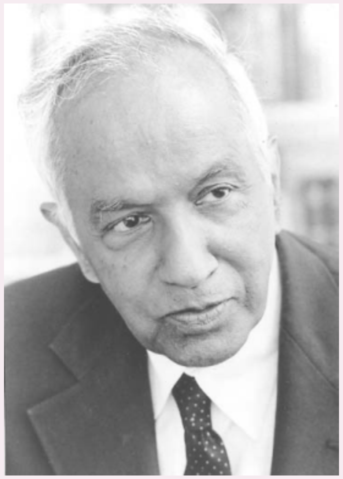
Neutron stars: from ancestors to descendants

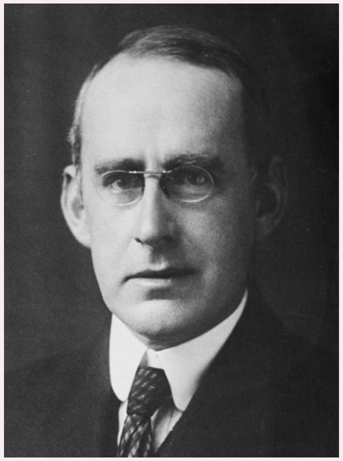
- **13.8 billion years ago** the Universe was created in the Big Bang.
- Within **1 second after the Big Bang** neutrons and protons were formed.
- Between **3-20 minutes after the Big Bang** H, He, and traces of light elements were formed.
- First stars were formed due to the gravitational collapse of gases of H and He **about 1 billion years after** the Big Bang.
- As clouds of gases collapse, the gravitational energy turns into thermal energy. At high T in the core of stars thermonuclear fusion begins.
- In massive stars (8-40 solar mass stars) thermonuclear fusion continues until the formation of the iron ^{56}Fe core.
- *Fusion ends:* if the core is more massive then about 1.44 solar mass (Chandrasekhar's limit) it collapses: → *Core Collapse Supernovae!*
- 99% of the gravitational binding energy is radiated in neutrinos.
- *Every C in our cells, O that we breath, Ca in our bones, Fe in our blood are the result of this Supernovae!*
- An incredibly dense and fascinating object is left behind:

either a neutron star or a black hole

Neutron stars: Some Historical Facts

- 1926 – **Ralph H. Fowler** proposed that white dwarfs must be supported by the electron degeneracy pressure rather than the thermal pressure.
- 1930 – On a trip from India to England *at the age of 19* **Subrahmanyan Chandrasekhar** worked out the statistical physics of a degenerate Fermi gas and applied to white dwarfs. His calculations showed that massive stars cannot go through the white dwarf stage. He has found that for masses above 1.44 $M_\odot$ (originally 0.91 $M_\odot$) the electrons become relativistic and the pressure can no longer support the star!
- 1935 – **Arthur Eddington** publicly criticized his results calling it *absurd*: *"I think there should be a law of Nature to prevent a star from behaving in this absurd way!"*
- 1983 – Chandrasekhar was awarded a *Nobel Prize in Physics* (together with W. A. Fowler – not the same Fowler above)
- 1999 – NASA launched the "Chandra" X-Ray Observatory





Neutron stars: Some Historical Facts

- **1931 – Lev Landau *at the age of 23* anticipated the existence of neutron stars** *"We expect that this must occur when the density of matter becomes so great that atomic nuclei come in close contact, forming one gigantic nucleus."*
- **1932 – James Chadwick discovered the neutron.**
- **1933 – Walter Baade and Fritz Zwickey predicted neutron stars to explain the enormous energy release in Supernovae:** *"With all reserve we advance the view that supernovae represent the transition from ordinary stars into neutron stars, which in their final stages consist of closely packed neutrons."*
- **1939 – Robert Oppenheimer and George Volkoff computed the neutron star mass considering General Relativity. They predicted the maximum mass of $M = 0.71 M_{\odot}$.** "It seems likely that our limit of ~ *0.7M is* near the truth."

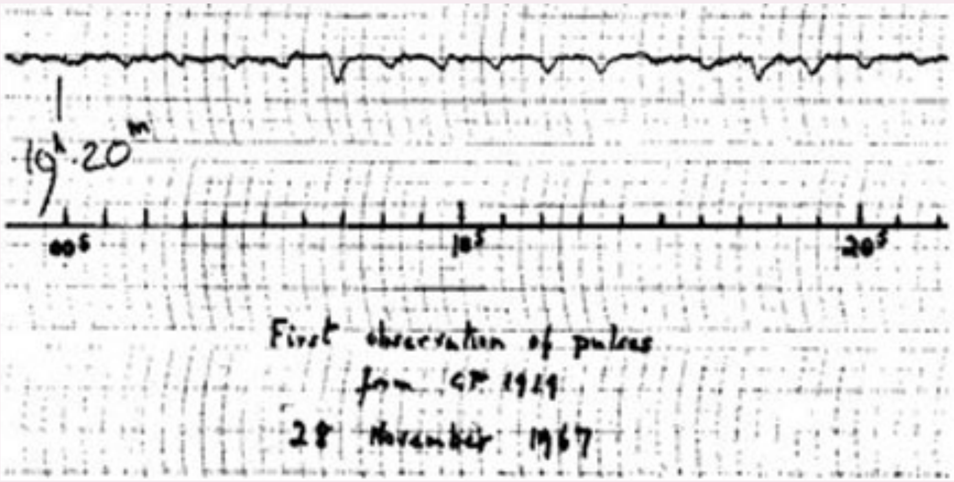
And of course they were later wrong!

- **1967 – Jocelyn Bell *at the age of 24* discovers pulsars.**
- **1968 – Gold and Pacini propose a lighthouse model:**

Pulsars are rapidly spinning neutron stars!

Neutron stars: Some Historical Facts

On August 6, 1967 working under Anthony Hewish Jocelyn Bell discovered a weak variable signal:



First observation of pulses from CP 1919 28 November 1967

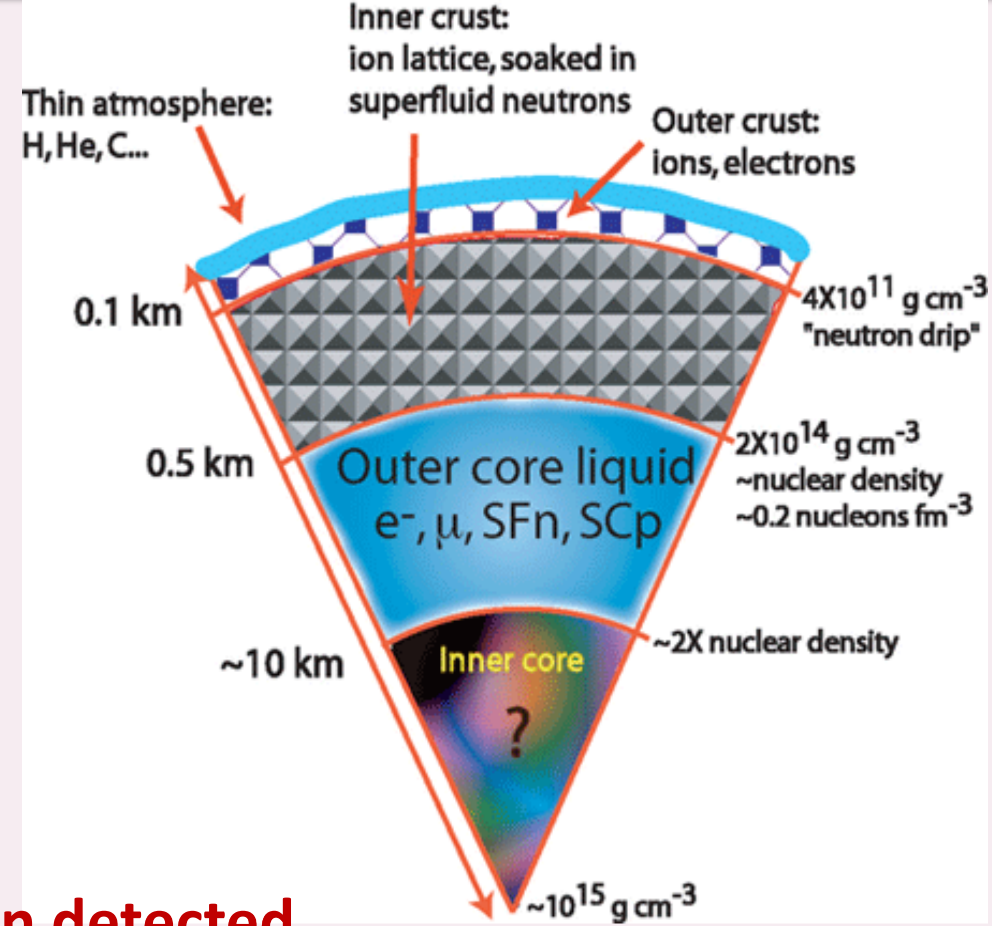
The signal had extreme regularity: *P = 1.337302088331* seconds.

The signal was even referred as "Little Green Men" and the publication delayed until the situation would clarify.

The paper announcing the discovery of the first pulsar, now known as PSR B1919+21, was published in *Nature* 217, 709 (1968) by A. Hewish et al. *A Nobel Prize in Physics was awarded to A. Hewish and Martin Ryle in 1974.*

Properties of Neutron Stars: Current Picture

Mass: 1 – 3 $M_{\odot}$
Radius: 10 – 15 km
Magnetic Field: $10^{10} – 10^{15}$ Gauss
Pressure: ~10^{29} atm
Density: ~10^{17} kg/m^3
Temperature: ~10^6 K
Period: ~(ms to sec)
Surface gravity: ~10^{11} x g



More facts:

- *So far* 2302 neutron stars have been detected.
- The escape velocity from the neutron star is about 100,000 km/s (1/3 c).
- A teaspoon material of a neutron-star matter w times more eat Pyramid of Giza.

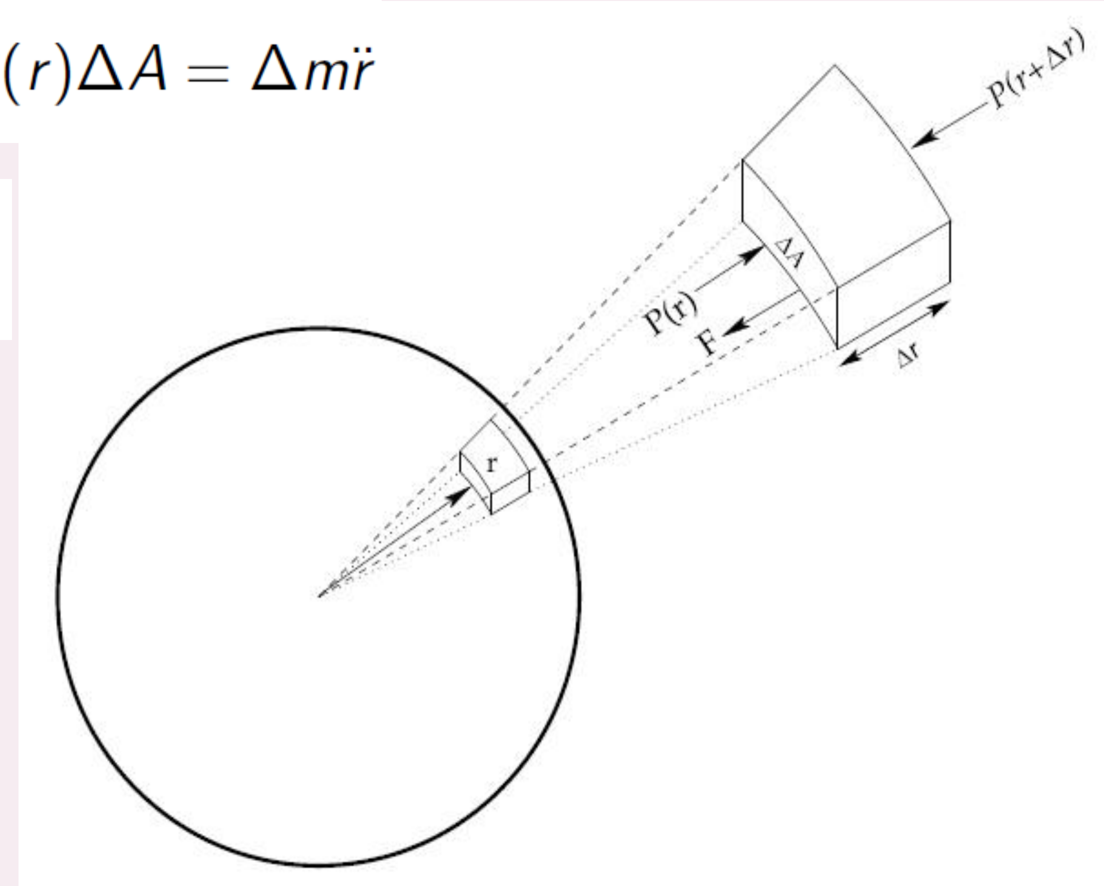
= **900 x**

A Star in Hydrostatic Equilibrium

$$F = -G\frac{M\Delta m}{r^2} - P(r+\Delta r)\Delta A + P(r)\Delta A = \Delta m\ddot{r}$$

$$\frac{dP}{dr} = -G\frac{M(r)\rho(r)}{r^2}\ , \qquad P(0) = P_c\ .$$

$$\frac{dM(r)}{dr} = 4\pi r^2\rho(r)\ , \qquad M(0) = 0\ .$$



The only ingredient required is the *Equation of State:* $P = P(\rho)$

General Relativity

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

TOV Equation

$$I = \frac{8\pi}{3}\int_0^R \frac{(\rho + P/c^2)e^{-\nu}}{\sqrt{1 - \frac{2Gm(r)}{c^2 r}}}\frac{\bar{\omega}}{\Omega}r^4 dr$$

Moment of Inertia

The Equation of State

Bethe-Weizsacker Mass Formula (way back to circa 1935)

$$E(Z,N) = a_{\mathrm{vol}} A + a_{\mathrm{surf}} A^{2/3} + a_{\mathrm{Coul}} Z^2 / A^{1/3} + a_{\mathrm{symm}} (N-Z)^2 / A \ + \ldots$$

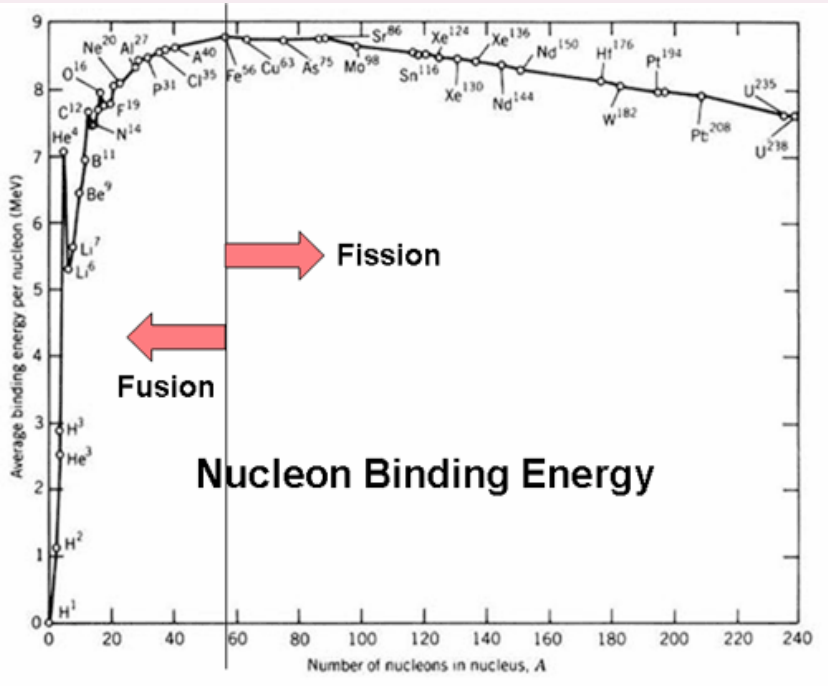
- The parameters of the nuclear droplet model are extracted from a fit to several thousands masses of nuclear isotopes.
- BW constrains these parameters or close to the nuclear saturation density:

$\rho_0 \approx 0.15 \ \mathrm{fm}^{-3}$

$a_{\mathrm{vol}} \approx -15.8\,\mathrm{MeV}$

$a_{\mathrm{symm}} \approx +23.2\,\mathrm{MeV}$

- Gives a very good approximation for most of the nuclear masses (*except for the light nuclei and magic nuclei*)
- Offers very little on the density dependence of these parameters.



The Equation of State: Nuclear Symmetry Energy

Bethe-Weizsacker Mass Formula (thermodynamic limit)

$$E(\rho,\alpha)/A = a_{\mathrm{vol}} + a_{\mathrm{symm}}\alpha^2 + \ldots$$

$$\alpha = \frac{N-Z}{A}$$

isospin asymmetry

- No surface term; Coulomb forces are turned off.
- N, Z, A all go to infinity, but their ratio remains finite:

$$\rho = \frac{A}{V} \qquad Y_{\mathrm{p}} = \frac{Z}{A}$$

However if one Taylor expands…

$$E(\rho,\alpha)/A = E(\rho,0)/A + S(\rho)\alpha^2 + \ldots$$

$E(\rho,0)/A$ – Binding energy per nucleon of symmetric nuclear matter (SNM).

$S(\rho)$ – Nuclear Symmetry Energy is a penalty to break N=Z symmetry

Nuclear masses provide the values of binding energy and the nuclear symmetry energy only at a particular density (usually at the *nuclear saturation density*).

Symmetry Energy ≈ Pure Neutron Matter - Symmetric Nuclear Matter

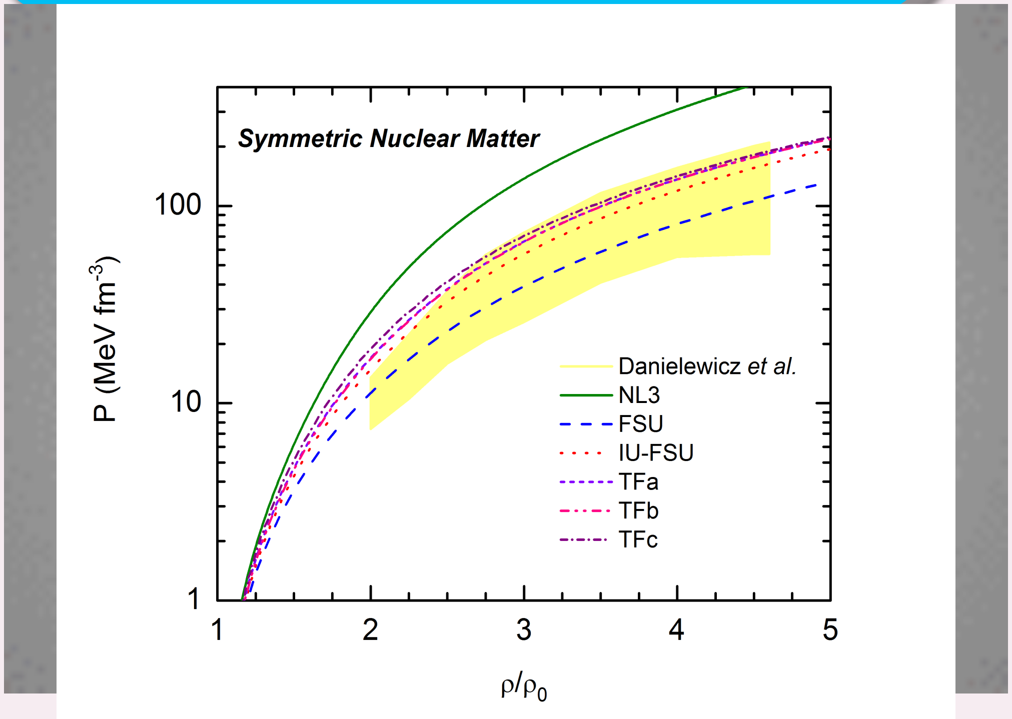
The Equation of State: Nuclear Symmetry Energy

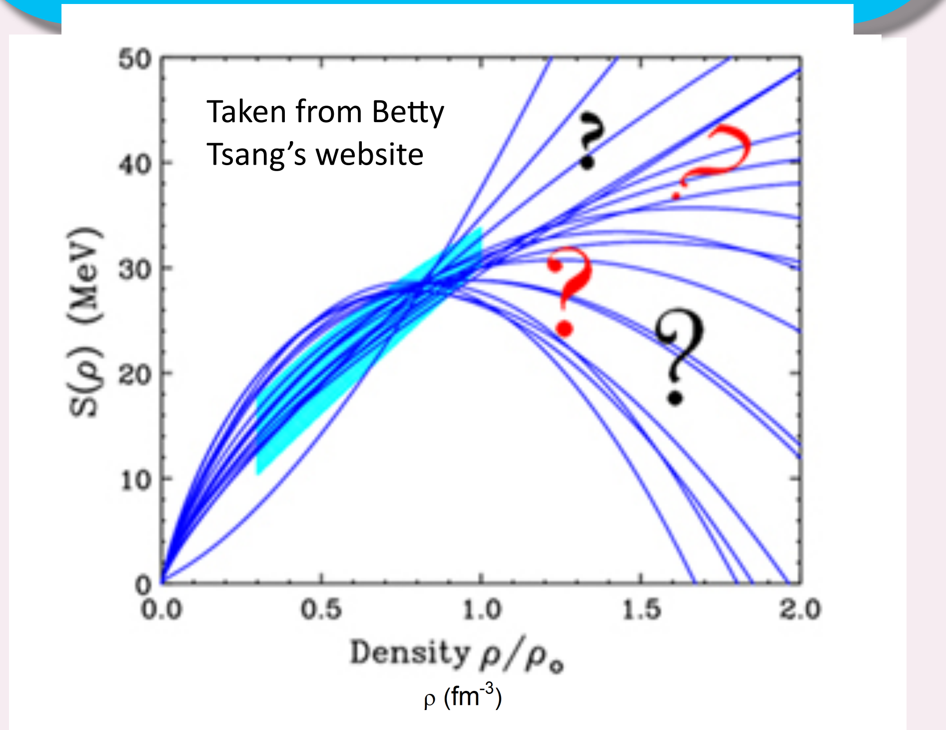
Symmetric Nuclear Matter:

- Binding energy at saturation is constrained at about 5% level;
- Density dependence of SNM around saturation is constrained at about 15% level;
- High density component of the EOS is constrained by the experimental and observational data.

Symmetry Energy:

- Symmetry energy at saturation is constrained at about 20% level;
- Density dependence of the symmetry energy *(denoted by L)* around saturation is totally unconstrained with discrepancy of the order of 100%;
- High density component of the symmetry energy is totally uncertain.





Taken from Betty Tsang's website

Critical Role of Symmetry Energy: Mass vs Radius

- ***Neutron*** **stars are mostly made of neutrons.**
- **In the simplest scenario there also exists protons, electrons, and muons whose fractions are determined by the beta-equilibrium and charge neutrality.**

$$\boxed{n \rightarrow p + e^- + \bar{\nu}_e}$$

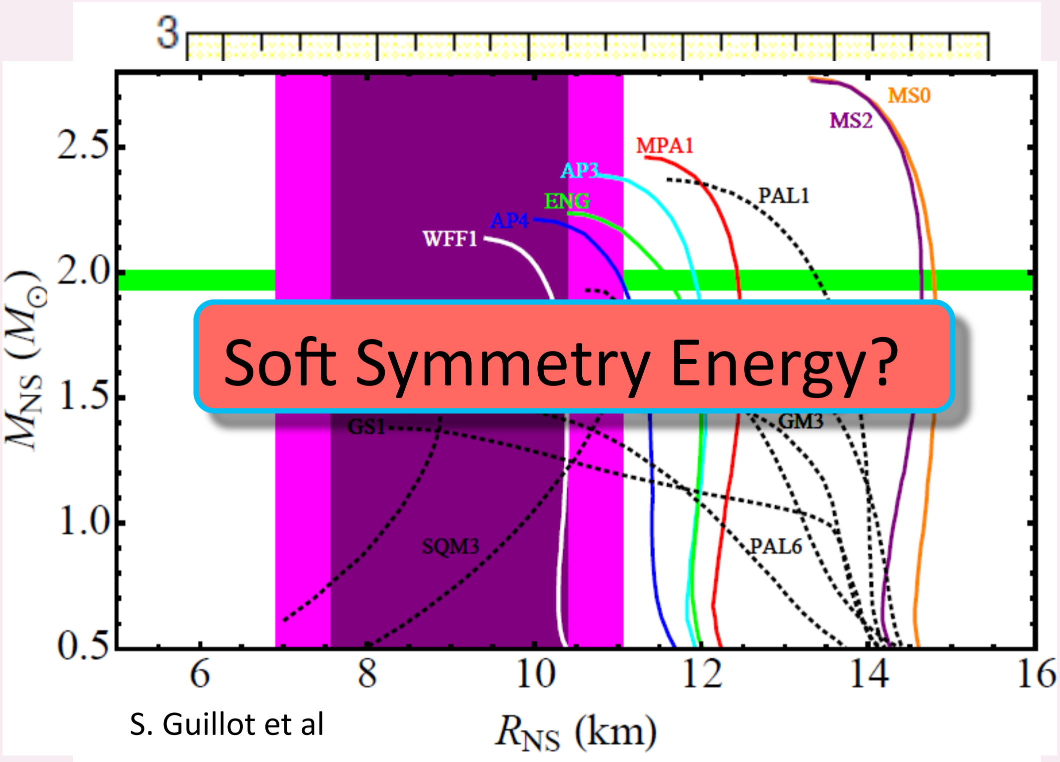
$$\boxed{\mu_n = \mu_p + \mu_{e^-}}$$

$$\boxed{e^- \rightarrow \mu^- + \nu_e + \bar{\nu}_\mu}$$

$$\boxed{\mu_{e^-} = \mu_{\mu^-}}$$

- **The EOS er is sensit ymmetry energy.**
- **Stellar composition is determined fully by the symmetry energy.**

- **Maximum stellar mass is controlled by the high density component of the EOS.**
- **Stellar radii are controlled by the density dependence of the nuclear symmetry energy:**
  - **The smallness (largeness) of the stellar radii is determined by the softness (stiffness) of the nuclear symmetry energy.**

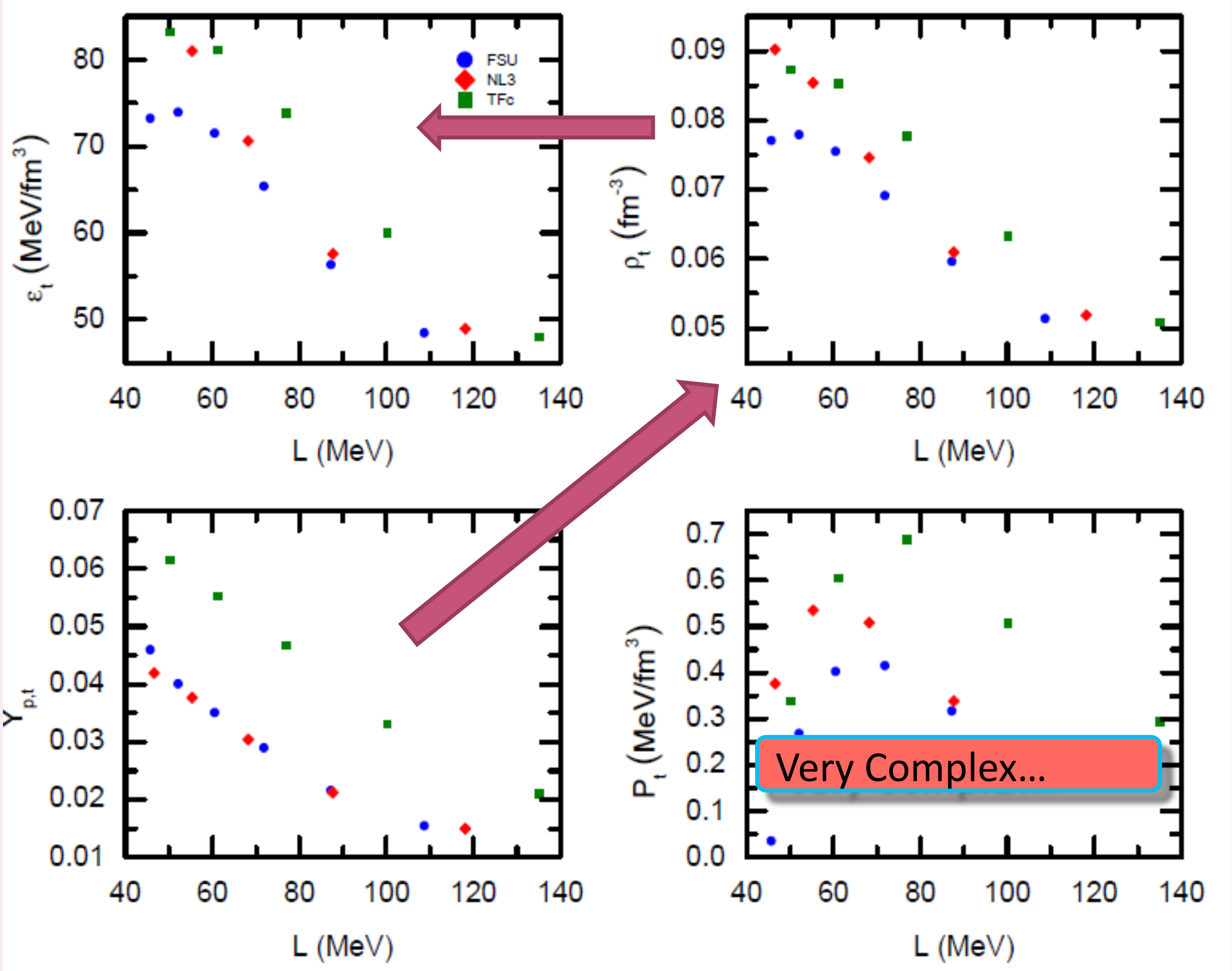


Soft Symmetry Energy?

S. Guillot et al

Crust-Core Transition

- **The core-crust boundary is determined by identifying the highest baryon density at which the uniform ground state becomes unstable against cluster formation.**



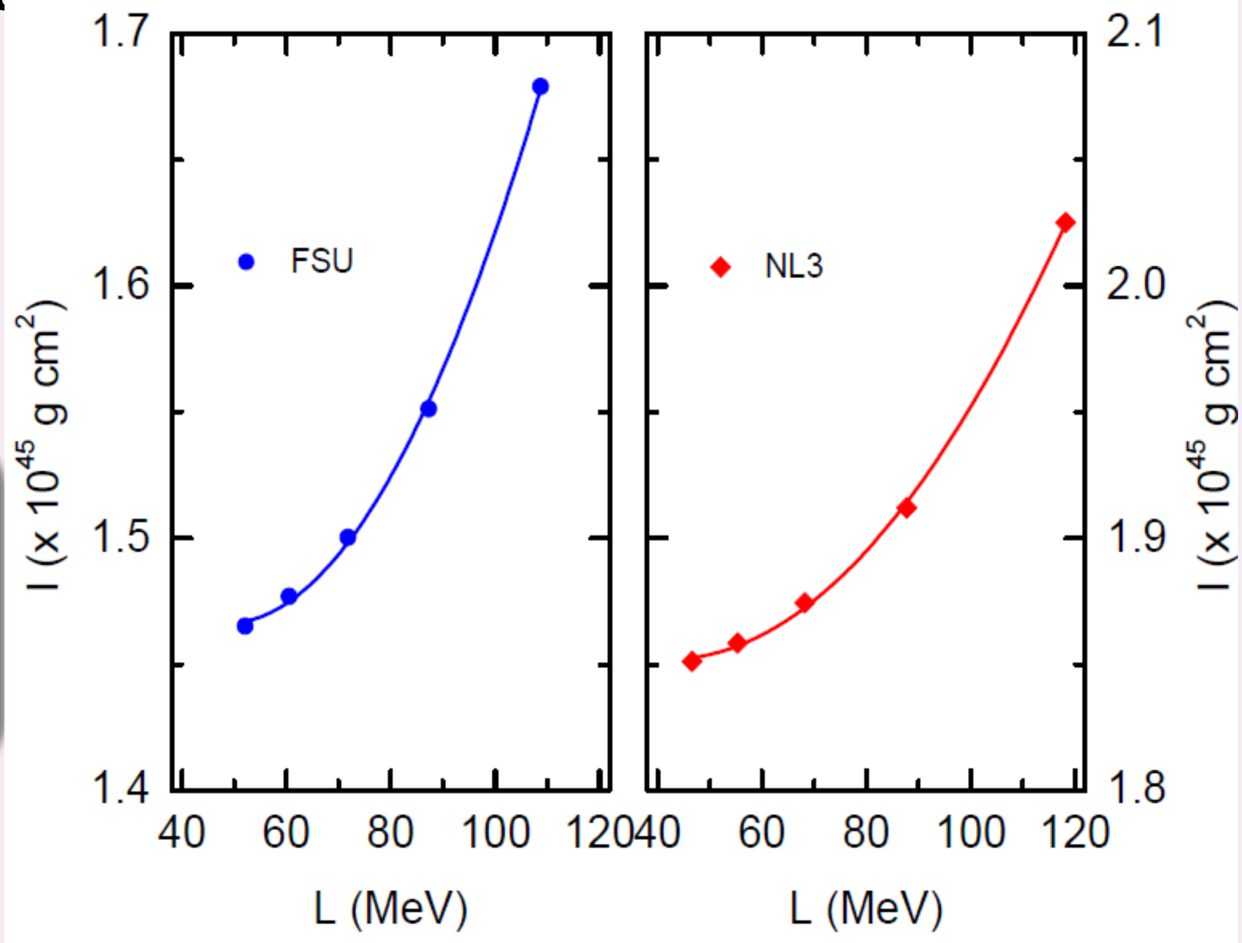
Very Complex…

Moment of Inertia: PSR J0737-3039A

- **In 2003 a double pulsar PSR J0737-3039 was discovered.**
- **The first known double pulsar.**
- **Ten times closer then the celebrated Hulse-Taylor binary (1974) (Nobel Prize, 1993).**
- **Energy loss due Gravitational Waves – precise tests of General Relativity through timing.**
- **Inspiral – the orbit shrinks 7 mm/day – merges in 85 mln years.**
- **Measurement of the spin-orbit coupling → Moment of Inertia!**

$$I = \frac{8\pi}{3}\int_0^R \frac{(\rho + P/c^2)e^{-\nu}}{\sqrt{1-\frac{2Gm(r)}{c^2 r}}}\frac{\bar{\omega}}{\Omega} r^4 dr$$

Moment of Inertia scales as
Radius Squared →
Density dependence squared!

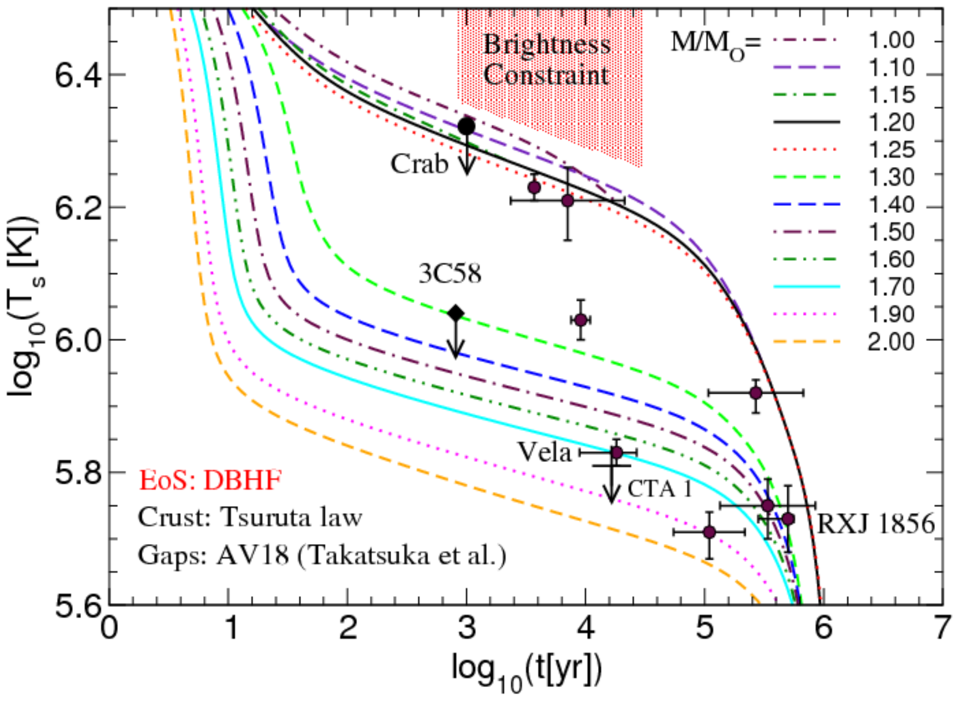


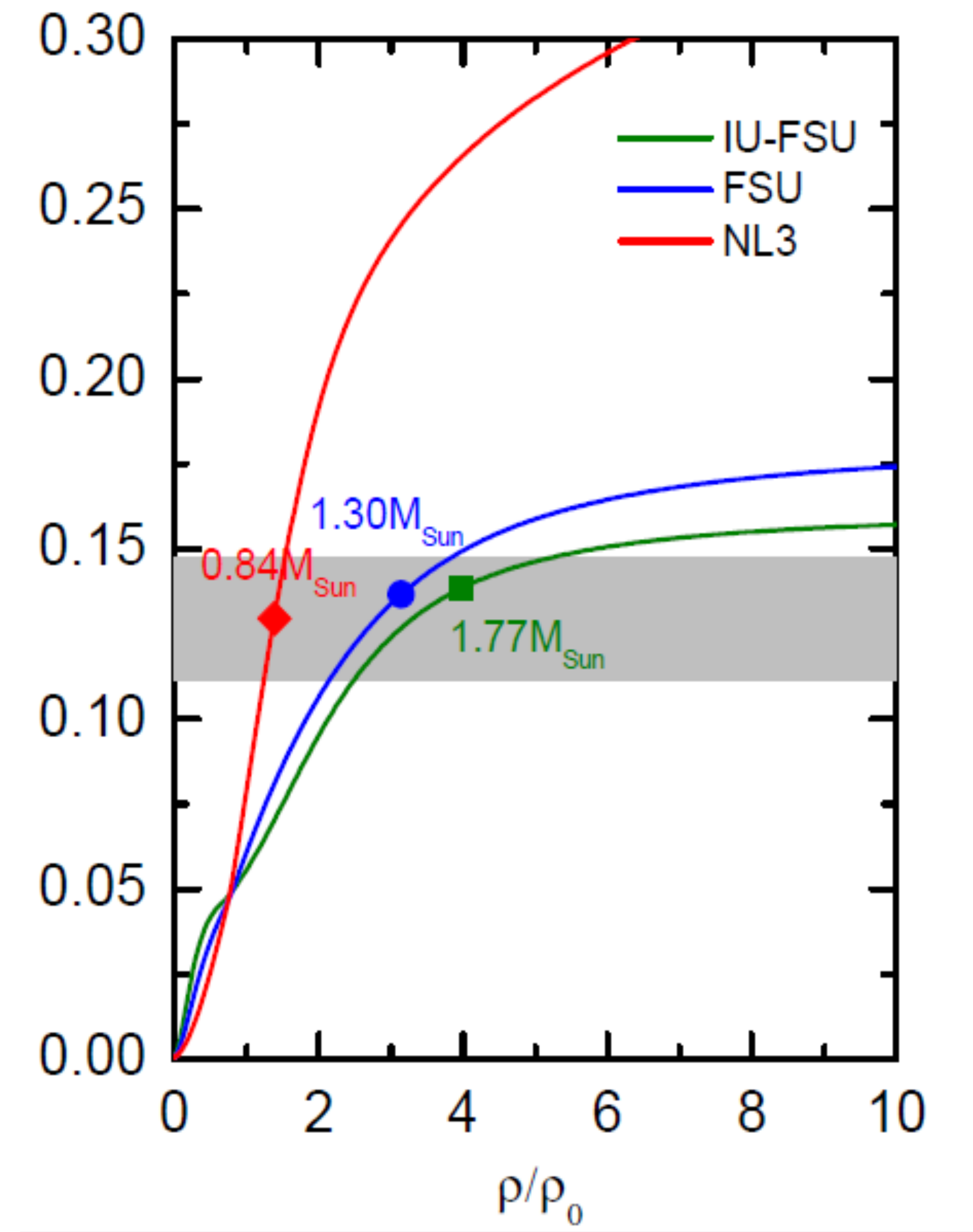
Enhanced Cooling: Direct Urca Process

- **A newly born neutron star is very hot: T = 10^{12} K**
- **There are several cooling scenarios: Direct Urca process is a very fast cooling process**

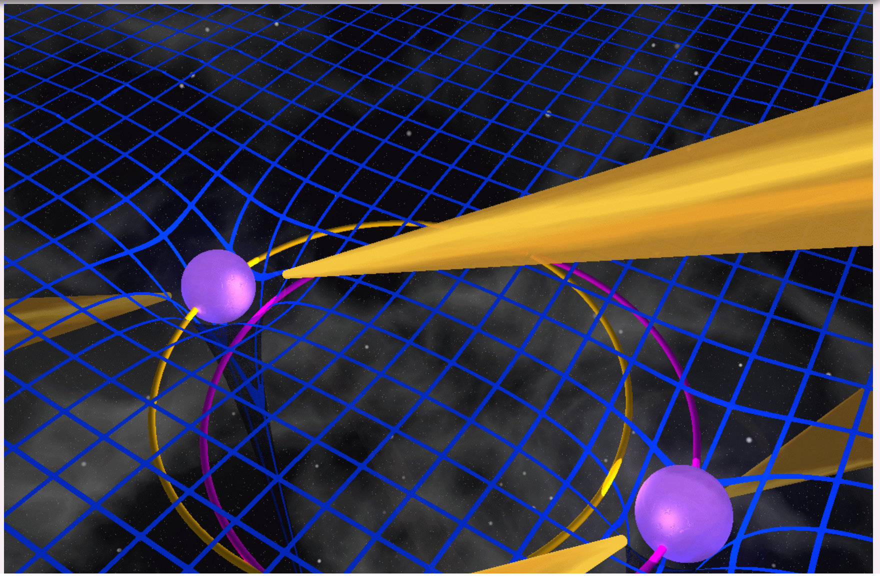
$$\boxed{n \rightarrow p + e^{-} + \overline{\nu}_e}$$

- **Modified cooling process needs a bystander neutron and is much**





Gravitational Waves: Tidal Polarizability



- LIGO II plans to detect inspirals at a rate of ~2/day
- At low frequency, tidal corrections to the GW waveforms phase depends on a single parameter: tidal Love number!

$$Q = -\lambda E$$

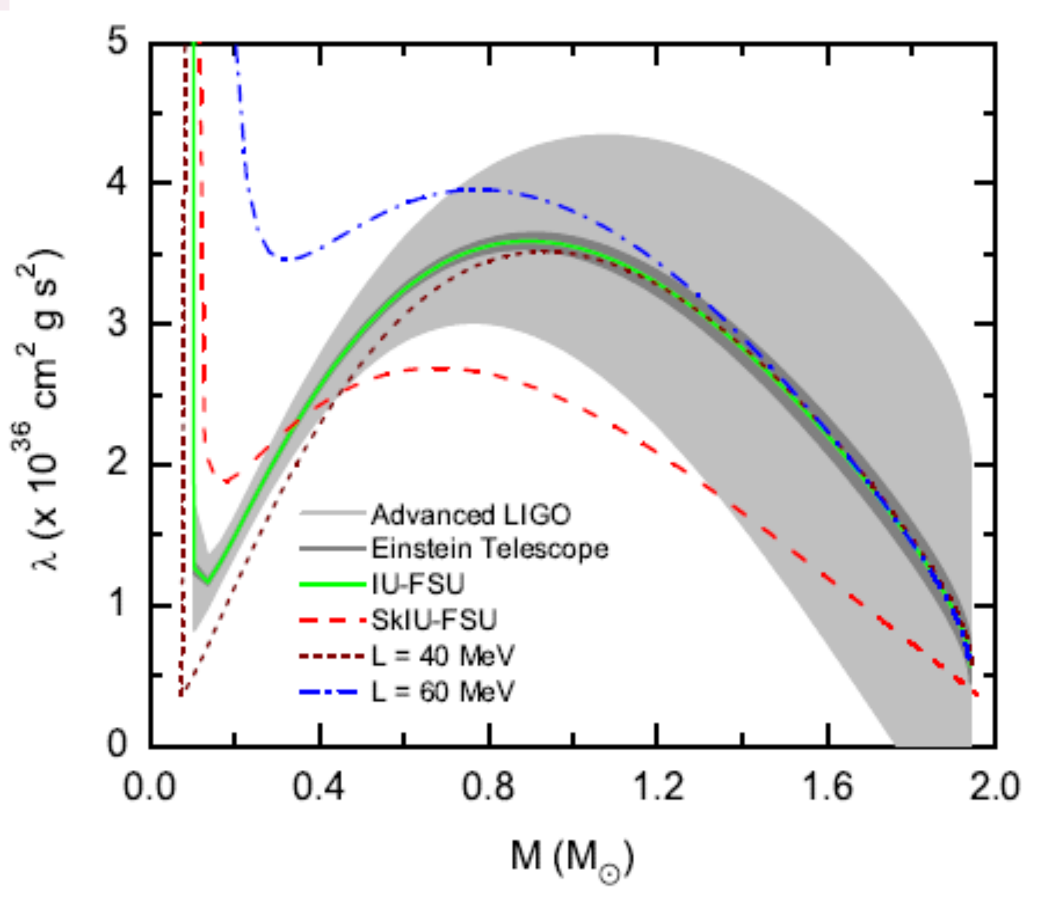
$$\lambda = 2k_2 R^5 / 3G$$

- It can be measured at a 10% lev

Flanagan and Hinderer, Phys. Rev. D, 077, 021502 (2008)

- Very sensitive to the density dependen of symmetry energy through the 5 power of radius. But is actually mo complex.

$$\begin{aligned} k_2 \;=\; & \frac{1}{20}\left(\frac{R_s}{R}\right)^5\left(1-\frac{R_s}{R}\right)^2\left[2-y_R+(y_R-1)\frac{R_s}{R}\right]\times \\ & \times\left\{\frac{R_s}{R}\left(6-3y_R+\frac{3R_s}{2R}(5y_R-8)+\frac{1}{4}\left(\frac{R_s}{R}\right)^2\left[26-\right.\right.\right. \\ & \left.\left.- 22y_R+\left(\frac{R_s}{R}\right)(3y_R-2)+\left(\frac{R_s}{R}\right)^2(1+y_R)\right]\right)+ \\ & + 3\left(1-\frac{R_s}{R}\right)^2\left[2-y_R+(y_R-1)\frac{R_s}{R}\right]\times \\ & \left.\times \log\left(1-\frac{R_s}{R}\right)\right\}^{-1}, \qquad (1) \end{aligned}$$



Concluding Remarks

- **The EOS of neutron-rich matter is the sole ingredient to understand the physics of neutron stars.**
- ***Nuclear symmetry energy plays a critical role*** **in understanding various properties of neutron stars including their structure and composition.**

My Collaborators:

My TAMUC collaborators: B.-A. Li, W. G. Newton

My outside collaborators:
C. J. Horowitz (IU-FSU)
J. Piekarewicz (FSU)
G. Shen (TU Darmstadt)
J. Xu (SINAP)

THANKS