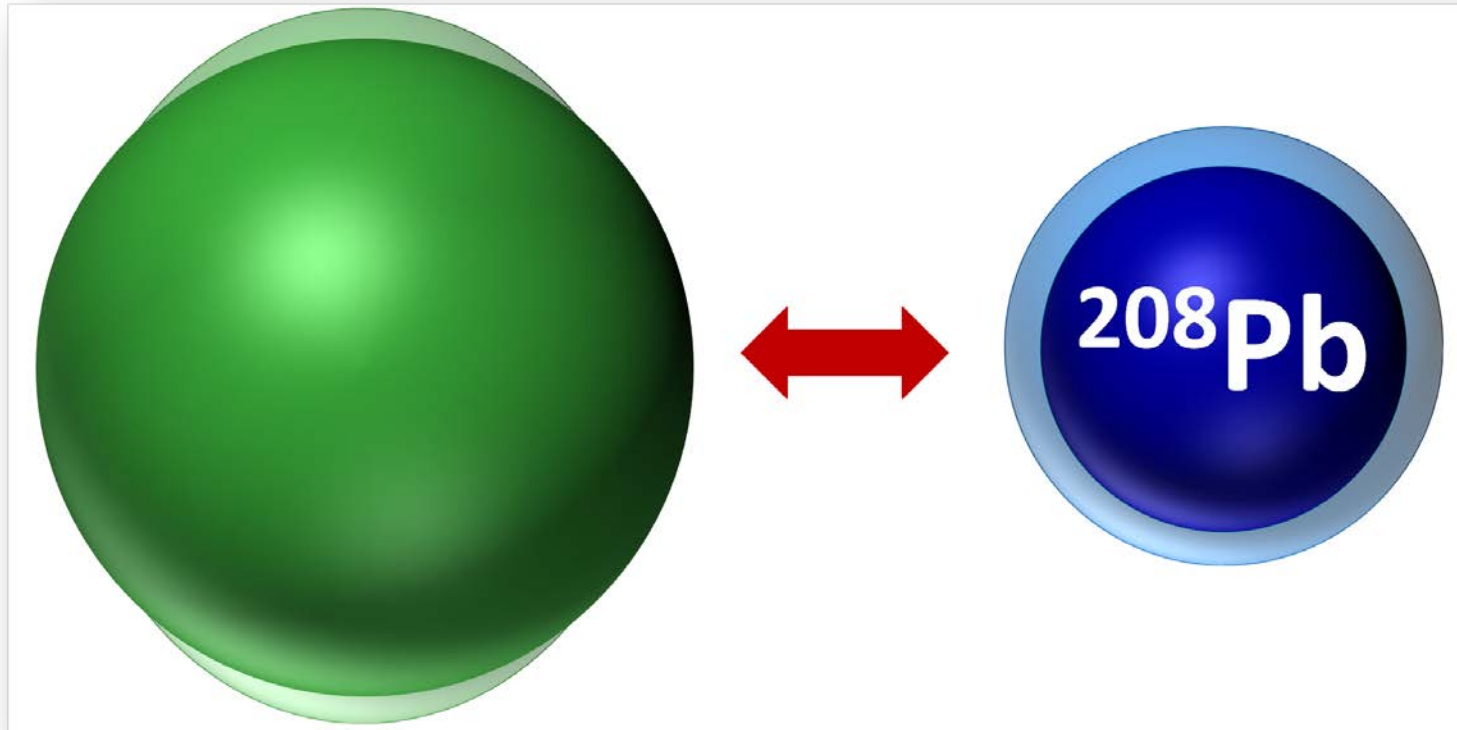


# Neutron Skins and Neutron Star Properties



**Farrukh J. Fattoyev**  
Indiana University

**CIPANP 2018 – Thirteenth Conference on the Intersections of Particle and Nuclear Physics**  
Palm Springs, CA, May 29 – June 3, 2018

# Neutron Star as a Giant Nucleus

1931 – “The density of matter becomes so great that atomic nuclei come in close contact, forming one *gigantic nucleus*.” L. Landau

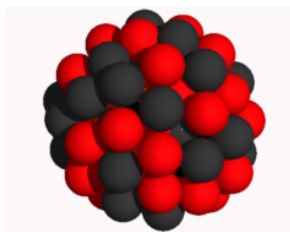
1932 – J. Chadwick discovers *neutrons*.

1934 – “...supernovae represent the transitions from ordinary stars to *neutron stars*...” Baade & Zwicky

1967 – First neutron star is discovered – J. Bell & A. Hewish



## Nucleus of an atom



$$A \simeq 10^2$$

$$\rho_{\text{ave}} \simeq 0.7 \rho_0$$

Supported by surface tension

$$R \simeq 10^{-14} \text{ m}$$

## Neutron Star



$$A \simeq 10^{59}$$

$$\rho_{\text{ave}} \simeq 2.0 \rho_0$$

Supported by gravity

$$R \simeq 10^4 \text{ m}$$



# Neutron Star as a Giant Nucleus

1931 – “The density of matter becomes so great that atomic nuclei come in close contact, forming one *gigantic nucleus*.” L. Landau

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**Nucleus of an atom**



**Neutron Star**



**Yet, they are governed  
by the same Physics  
of Strong Force!**

$$\rho_{\text{ave}} \approx 2.0 \rho_0$$

Supported by surface tension

Supported by gravity

$$R \approx 10^{-14} \text{ m}$$

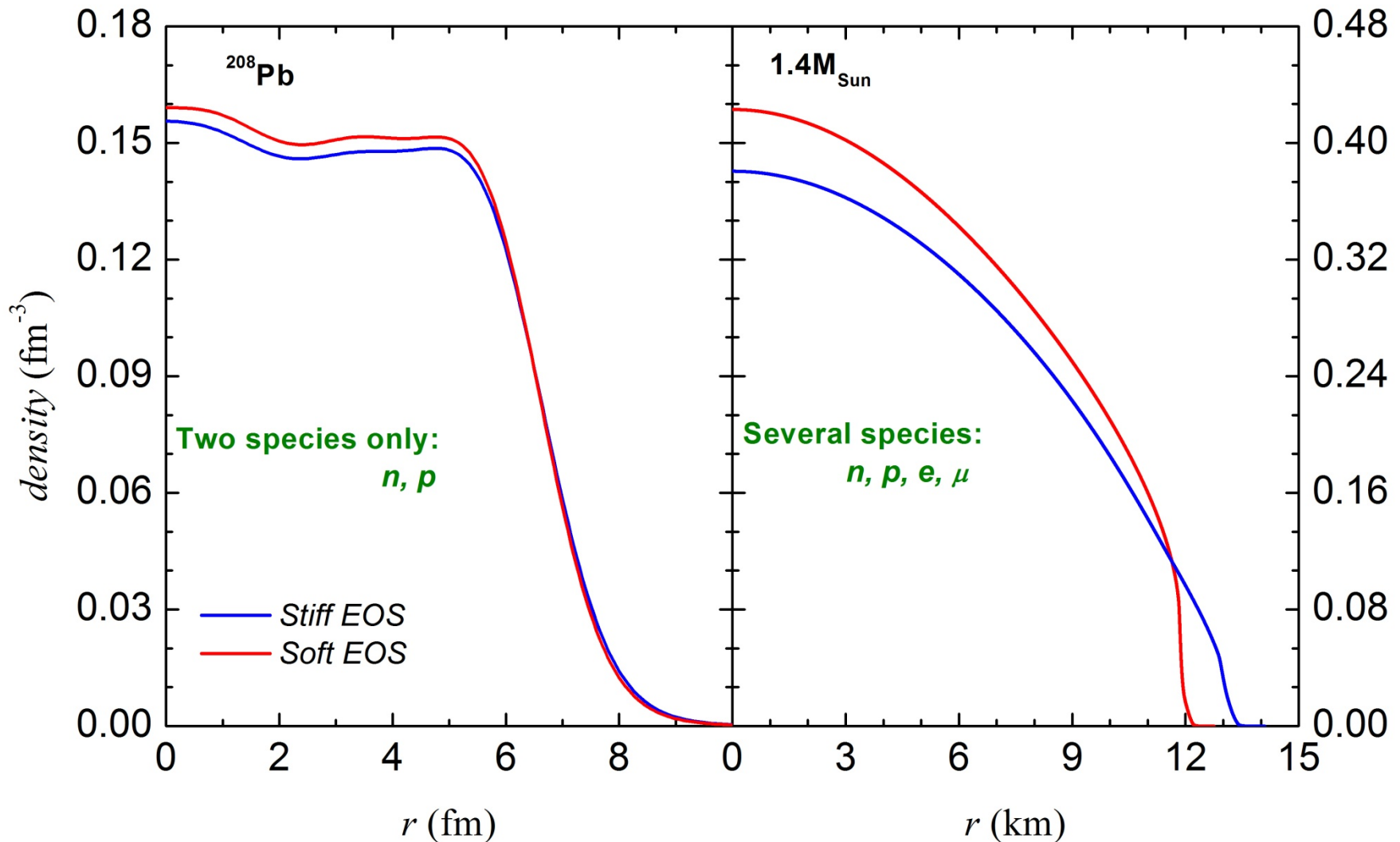
$$R \approx 10^4 \text{ m}$$



# Neutron Star as a Giant Nucleus

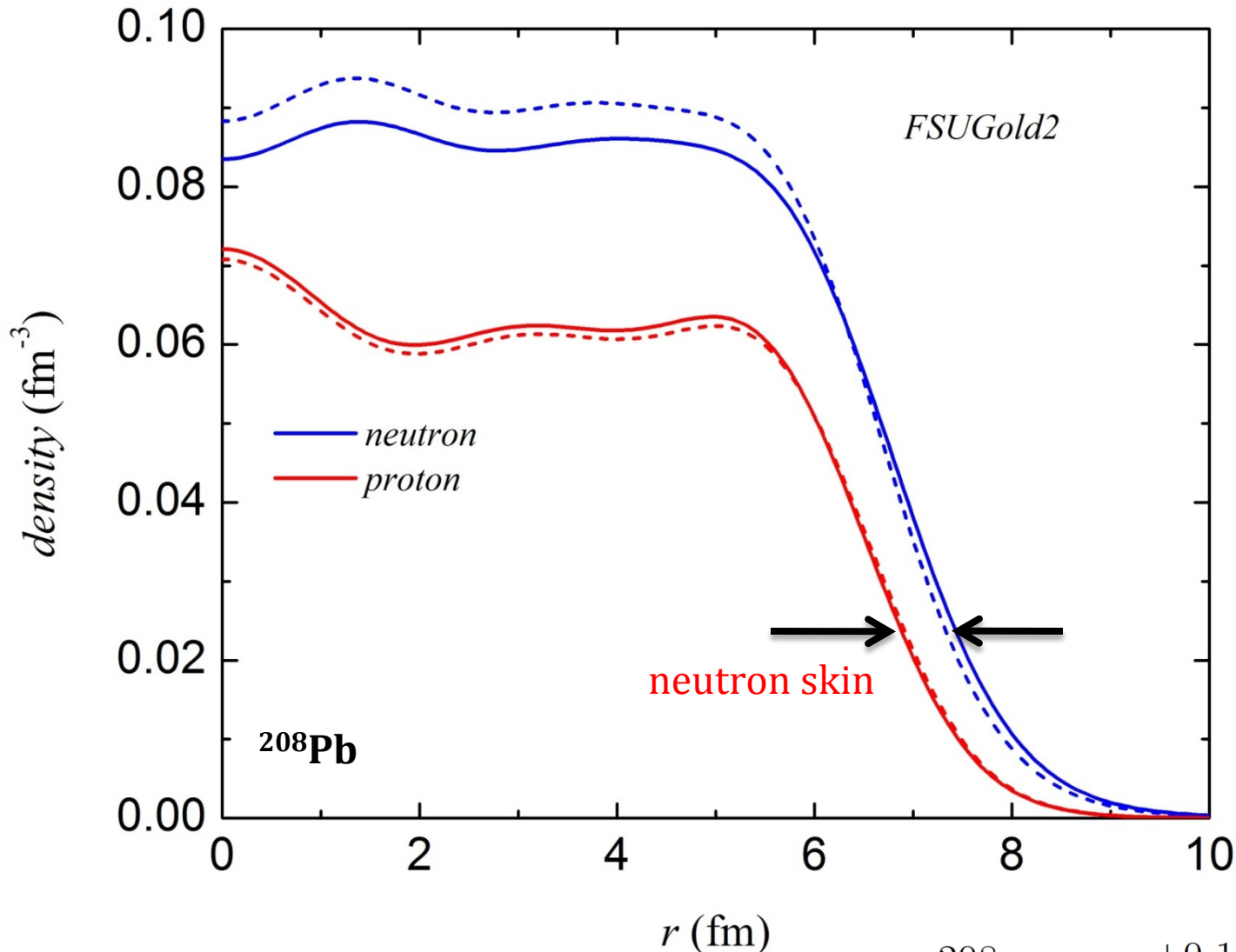
Nucleus of an atom

Neutron Star



The sole ingredient required: The Equation of State of Neutron-Rich Matter!

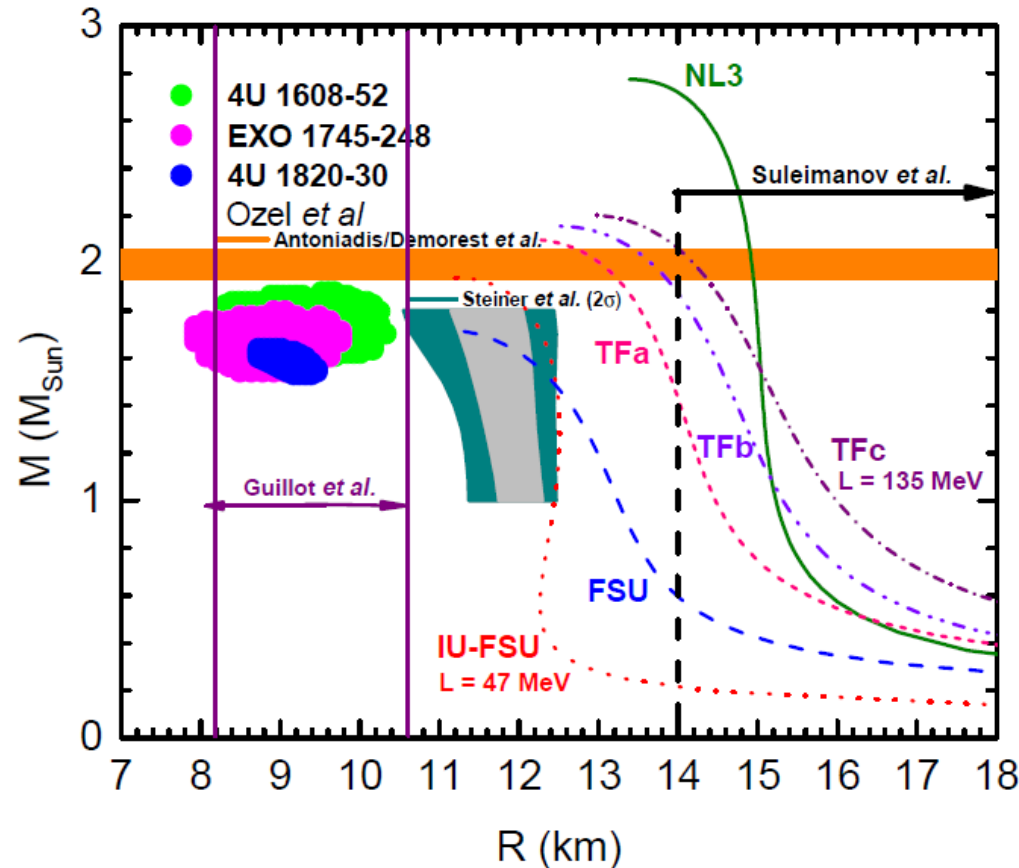
# Neutron Skins and the Equation of State



PREX measured the first model independent neutron skin:  $R_{\text{skin}}^{208} = 0.33^{+0.16}_{-0.18}$  fm  
PREX-II aims to measure with a **higher accuracy** how much neutrons stick out past protons.

# Neutron Stars and the Equation of State

- Neutron stars satisfy the Tolman-Oppenheimer-Volkoff equation  
General relativistic extension of Newtonian gravity ( $v_{\text{esc}}/c \lesssim 0.5$ )
- The only unknown physics is the Equation of State, which must span 10-11 orders of magnitude in baryon density.
- Enormous uncertainty exists in neutron star radii predictions.



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

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

$$\left[ 1 + \frac{4\pi r^3 P(r)}{M(r)} \right] \left[ 1 - \frac{2GM(r)}{r} \right]^{-1}$$

Need an  $\mathcal{E}$  vs  $P$  relation!

Fattoyev and Piekarewicz  
Phys. Rev. Lett. 111, 162501 (2013)

# Uncertainties in the Equation of State: Symmetry Energy

Neutron star properties and neutron skins are both determined by the EOS of neutron-rich matter:

$$P = P(\rho, \alpha) \quad \text{and} \quad \mathcal{E} = \mathcal{E}(\rho, \alpha)$$

$$\alpha = \frac{\rho_n - \rho_p}{\rho_n + \rho_p} \quad \begin{array}{l} \text{isospin} \\ \text{asymmetry} \end{array}$$

$$P = \rho \frac{\partial \mathcal{E}}{\partial \rho} - \mathcal{E} \quad \begin{array}{l} \text{Thermodynamic} \\ \text{consistency} \end{array}$$

For a neutron-rich matter it is useful to expand:

$$\mathcal{E}(\rho, \alpha) = \mathcal{E}(\rho, 0) + \left. \frac{\partial^2 \mathcal{E}(\rho, \alpha)}{\partial \alpha^2} \right|_{\alpha=0} \alpha^2 + \dots$$

$$\mathcal{E}_{\text{SNM}}(\rho) \equiv \mathcal{E}(\rho, 0) = \epsilon_0 + \frac{1}{2} K_0 \chi^2 + \dots$$

Binding energy per nucleon in symmetric nuclear matter (SNM).

$$\mathcal{S}(\rho) \equiv \left. \frac{\partial^2 \mathcal{E}(\rho, \alpha)}{\partial \alpha^2} \right|_{\alpha=0} = J + \boxed{L} \chi + \frac{1}{2} K_{\text{sym}} \chi^2 + \dots$$

Nuclear Symmetry Energy is a penalty to break N=Z symmetry

$$\chi = \frac{\rho - \rho_0}{3\rho_0} \quad \begin{array}{l} \text{a useful expansion} \\ \text{parameter} \end{array}$$

# Uncertainties in the Equation of State: Symmetry Energy

Neutron  
by the E

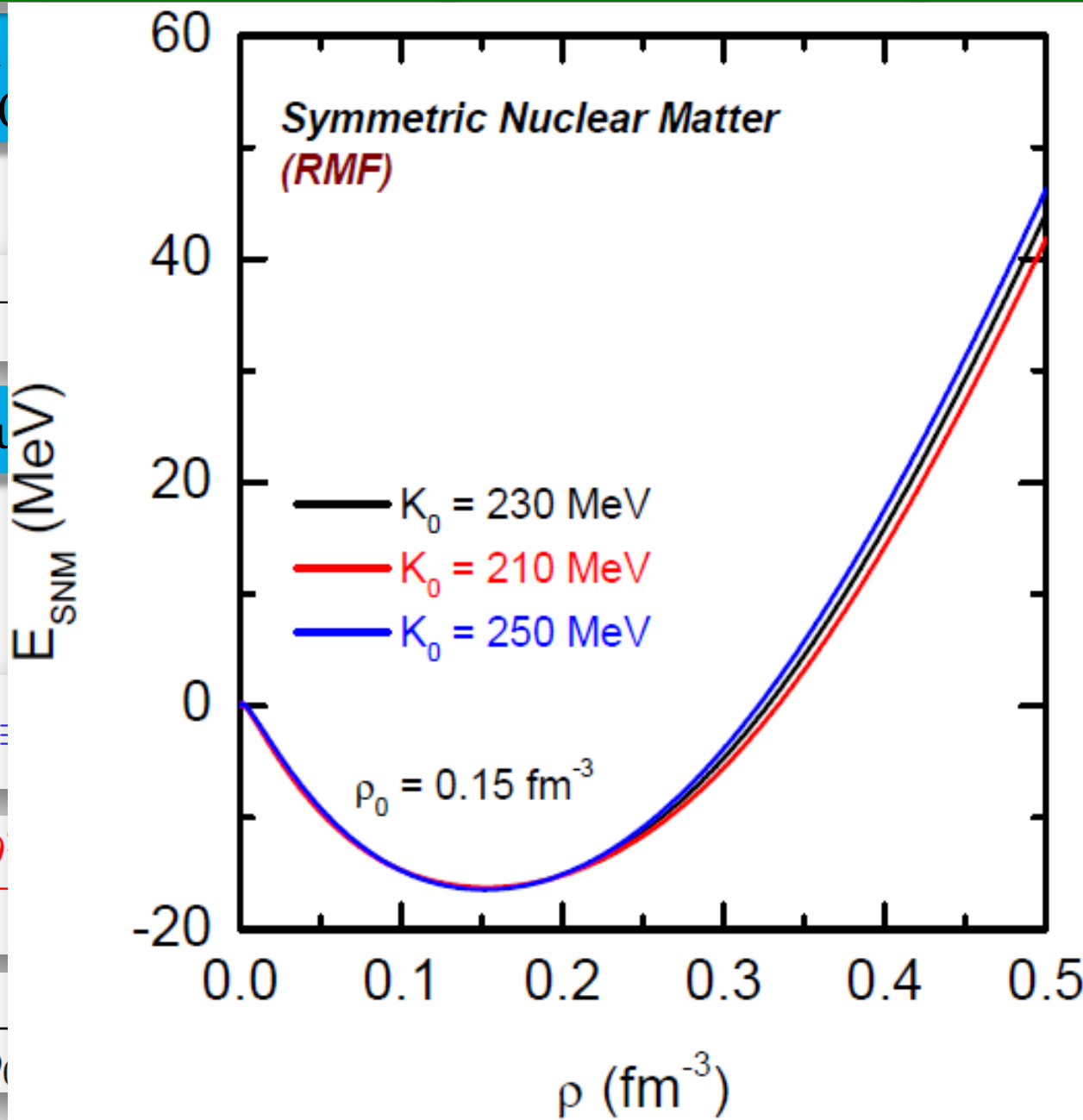
$$\alpha = \frac{\rho_n}{\rho_n}$$

For a neu

$$\mathcal{E}_{\text{SNM}}(\rho) \equiv$$

$$\mathcal{S}(\rho) \equiv \frac{\partial}{\partial \rho}$$

$$\chi = \frac{\rho -}{3\rho}$$



ined

hydrodynamic  
stability

nucleon in  
matter (SNM).

symmetry  
penalty to  
symmetry



# Uncertainties in the Equation of State: Symmetry Energy

Neutrino  
by the

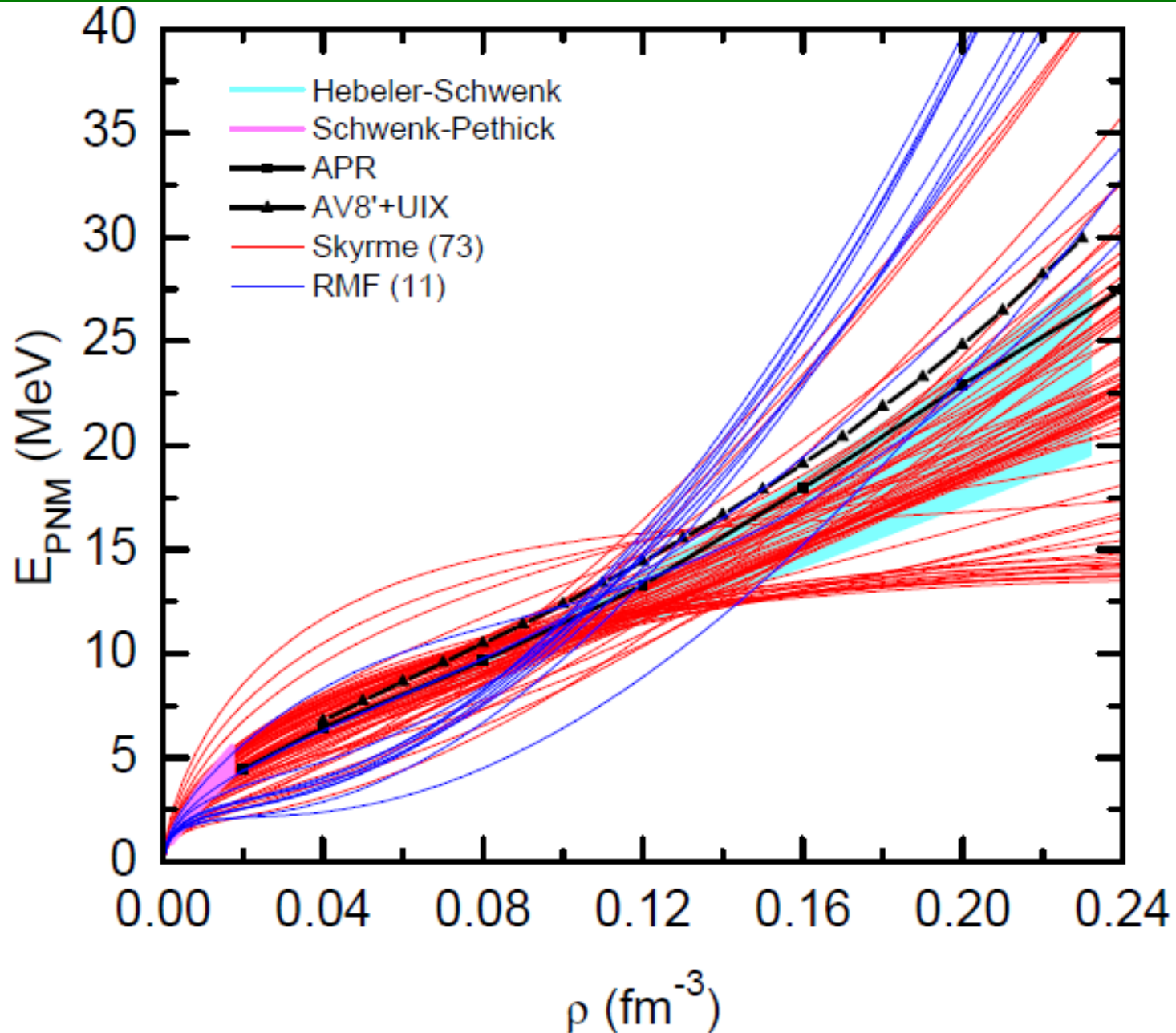
$\alpha =$

For a r

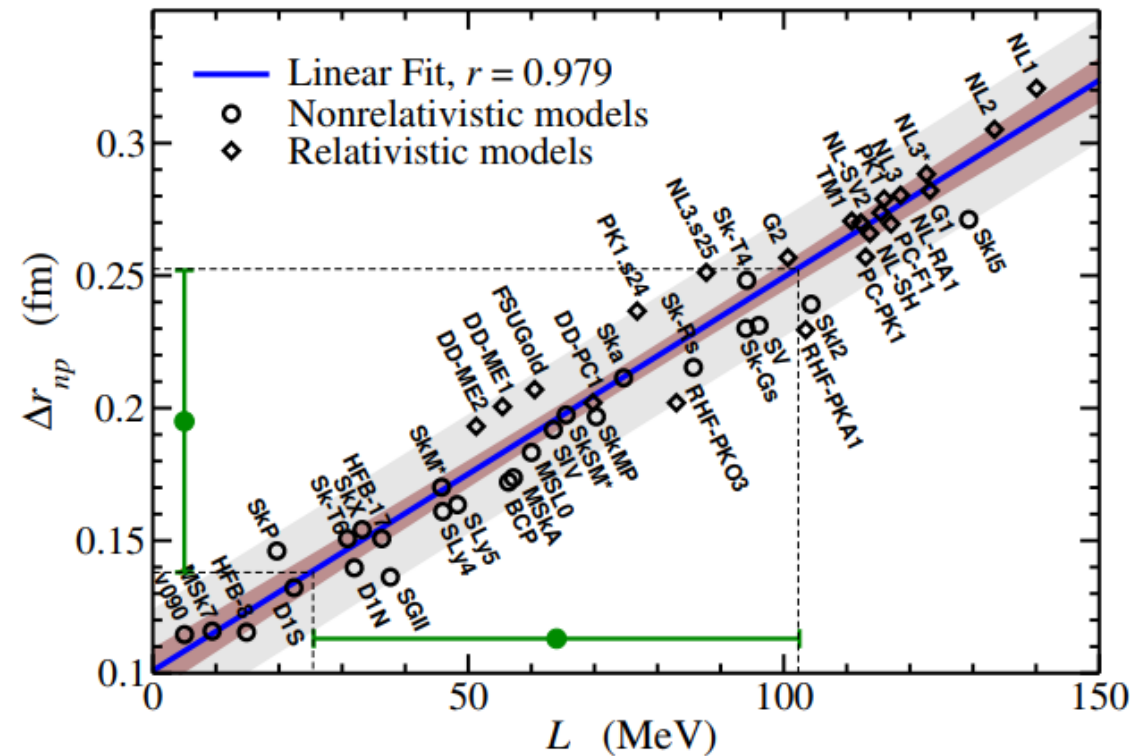
$\mathcal{E}_{\text{SNM}}(\rho)$

$\mathcal{S}(\rho) \equiv$

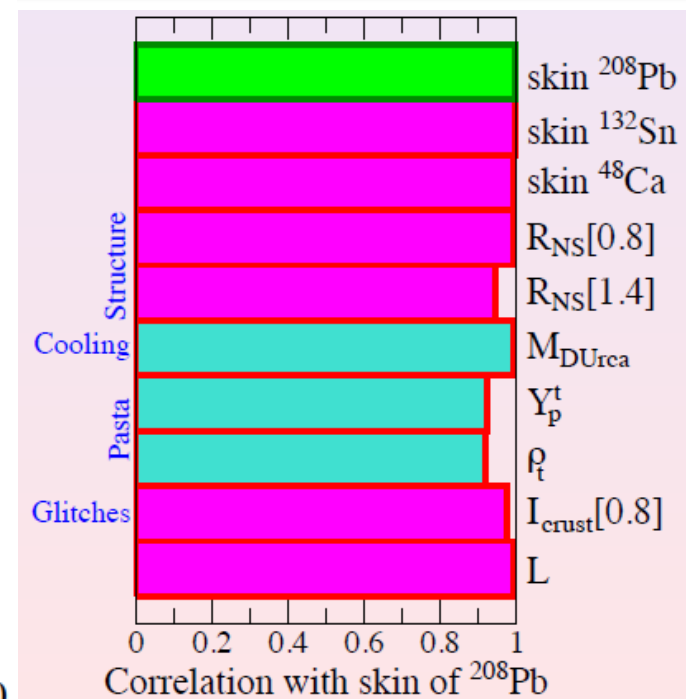
$\chi = \frac{\rho}{\rho_0}$



# Neutron Skins and Neutron Stars



Roca-Maza et al., PRL106,252501(2011)



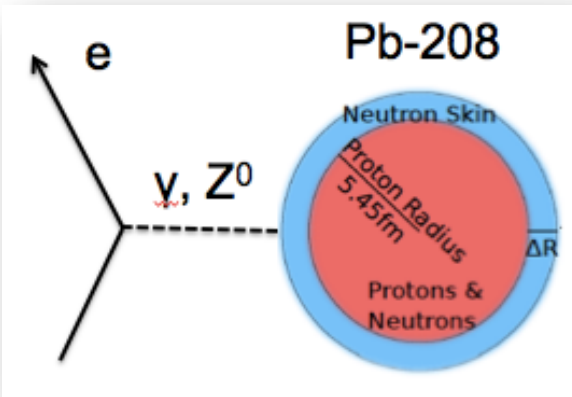
Fattoyev & Piekarewicz, PRC86,015802(2012)

$$P(\rho_0) \approx \rho_0 L / 3$$

Neutron skin thickness is strongly correlated with the pressure of pure neutron matter (PNM):

- Pressure of PNM pushes against surface tension  $\Rightarrow$  neutron skin!
- Pressure of PNM pushes against gravity  $\Rightarrow$  neutron-star radius!
- *The larger is the neutron skin, the larger is the neutron-star radius!*

# Neutron Skins from Parity Violating Experiments



	proton	neutron
Electric charge	1	0
Weak charge	0.07	-0.99

Proton form factor

$$F_P(Q^2) = \frac{1}{4\pi} \int d^3r j_0(qr) \rho_P(r)$$

Neutron form factor

$$F_N(Q^2) = \frac{1}{4\pi} \int d^3r j_0(qr) \rho_N(r)$$

Parity Violating Asymmetry

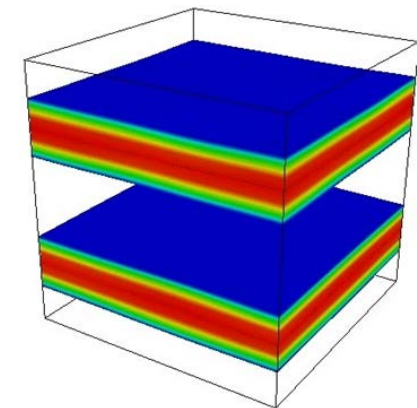
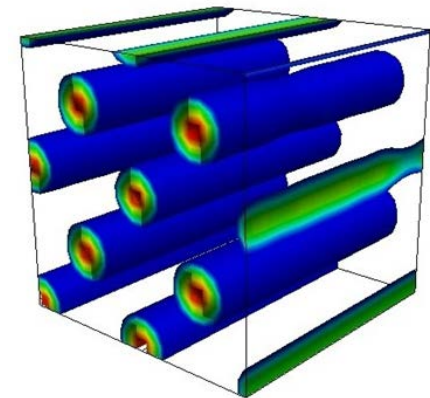
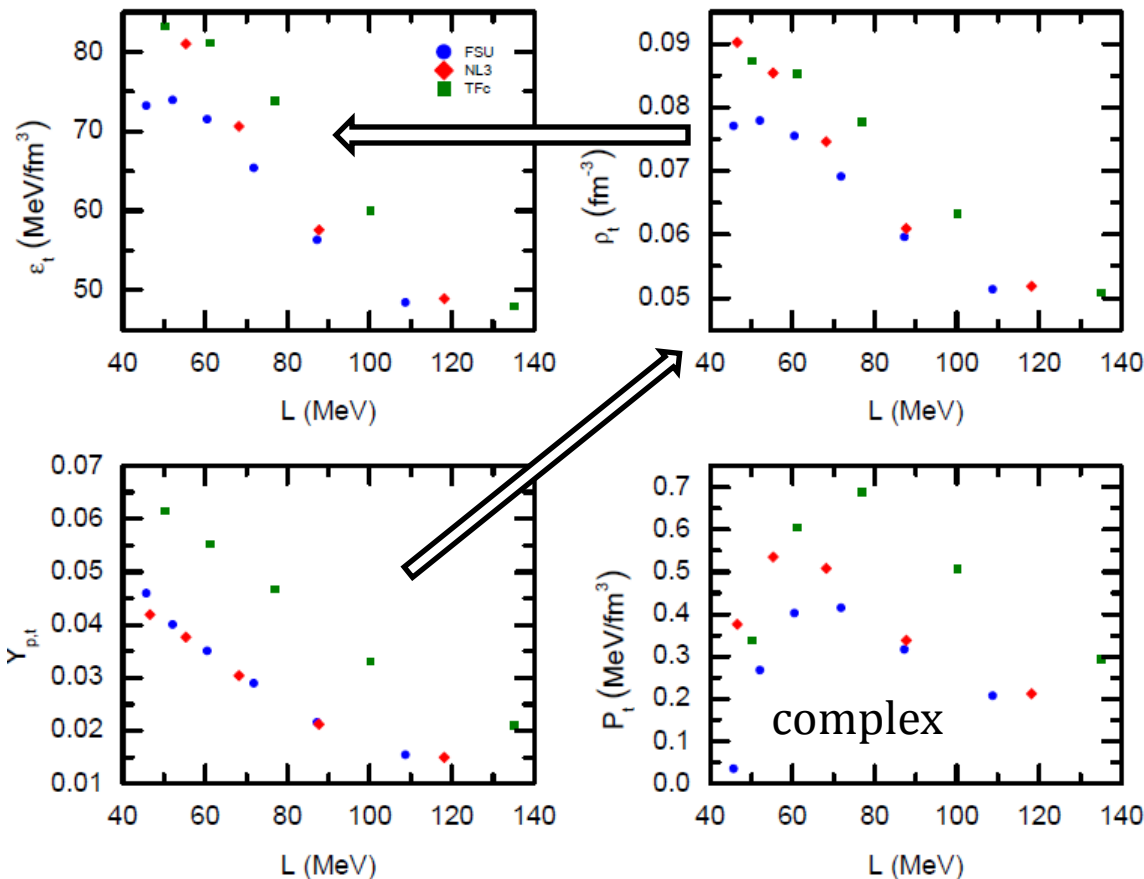
$$A = \frac{\left(\frac{d\sigma}{d\Omega}\right)_R - \left(\frac{d\sigma}{d\Omega}\right)_L}{\left(\frac{d\sigma}{d\Omega}\right)_R + \left(\frac{d\sigma}{d\Omega}\right)_L} = \frac{G_F Q^2}{2\pi\alpha\sqrt{2}} \left[ \underbrace{1 - 4\sin^2\theta_W}_{\approx 0} - \frac{F_N(Q^2)}{F_P(Q^2)} \right]$$

- Proton form factors are known with enormous precision (Hofstadter 1950's - to date).
- Neutron form factors are as fundamental as proton form factors (still elusive after more than 80 years of nuclear physics).
- PREX & CREX at JLAB will measure neutron radii with a 1% accuracy (2019).
- MESA at Mainz also plans to measure neutron radius with a 0.5% accuracy.

# Crust Core Transition: Nuclear Pasta

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

(Right) At densities of the inner crust nuclear attraction and Coulomb repulsion length scales become comparable. The system gets *frustrated*. Complex topological shapes emerge: **nuclear pasta**. *This universal behavior is found in proteins, low-D magnets, etc.*



# Neutron Skin and Moment of Inertia

- In 2003 the first double pulsar PSR J0737-3039 was discovered.
- Ten times closer than the celebrated Hulse-Taylor binary (Nobel Prize, 1993).
- Energy loss due gravitational waves – precise tests of General Relativity.
- Inspiral – the orbit shrinks 7 mm/day – merges in 85 million years.
- Measurement of the spin-orbit coupling → **Moment of Inertia!**

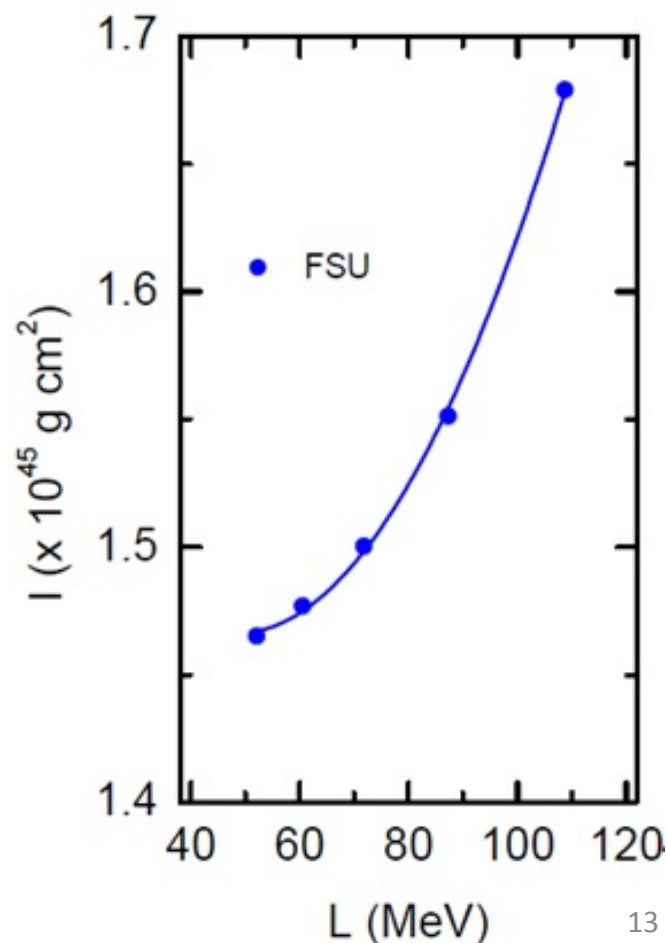
$$I = \frac{8\pi}{3} \int_0^R \frac{(\rho + P/c^2)e^{-\nu}}{\sqrt{1 - \frac{2Gm(r)}{c^2 r}}} \frac{\bar{\omega}}{\Omega} r^4 dr$$

**Moment of Inertia scales as Radius Squared!**

Long time observation of precession will enable a potential measurement of moment of inertia of one of the neutron stars in binary system J0737-3039.

This constrains  $L$ , which in turn, constrains the neutron skin.

Fattoyev and Piekarewicz, Phys. Rev. C 82, 025810 (2010)



# Neutron Skin and Moment of Inertia: Pulsar Glitches

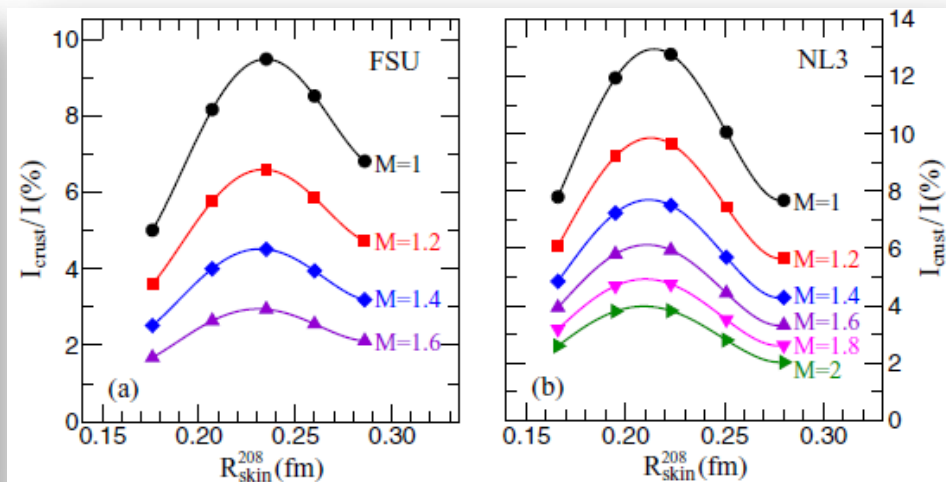
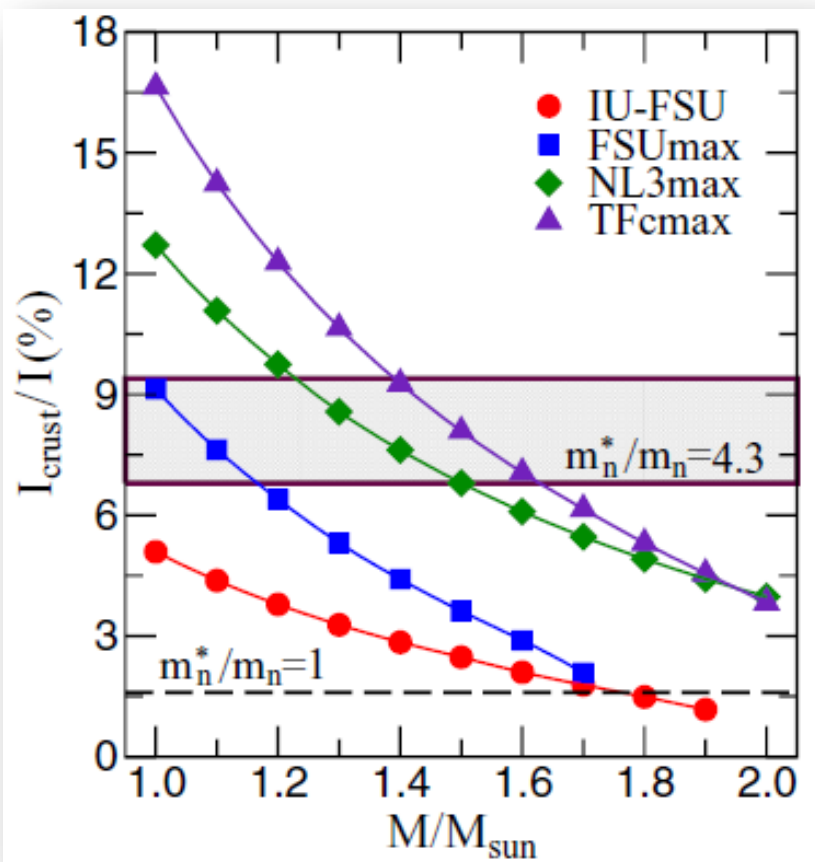
Pulsar glitches are sudden spin-ups in the rotational frequency of a neutron star.

Vela:  $P = 0.541404373627$  s;  $dP/dt = 9.778E-15$  – a very accurate natural clock

So far, **504 glitches** have been observed from a total of **187 pulsars**, and counting...

Glitchers are recurrent: Vela (20 glitches), Crab (27 glitches)...

Standard glitch mechanism: angular momentum transfer from the inner core to the crust.



$$59 \text{ MeV} < L < 74 \text{ MeV}$$

$$0.20 \text{ fm} < R_{\text{skin}} < 0.26 \text{ fm}$$

Piekarewicz, Fattoyev, Horowitz, Phys. Rev. C 90, 015803 (2014)

# Tidal Polarizability and the Equation of State

On August 17 2017, 12:41:04.43 **two neutron stars merged**. The gravitational waves produced by this merger were detected by LIGO and Virgo GW detectors.

Abbott et al. PRL 119, 161101 (2017)

$$Q_{ij} = -\lambda \mathcal{E}_{ij}$$

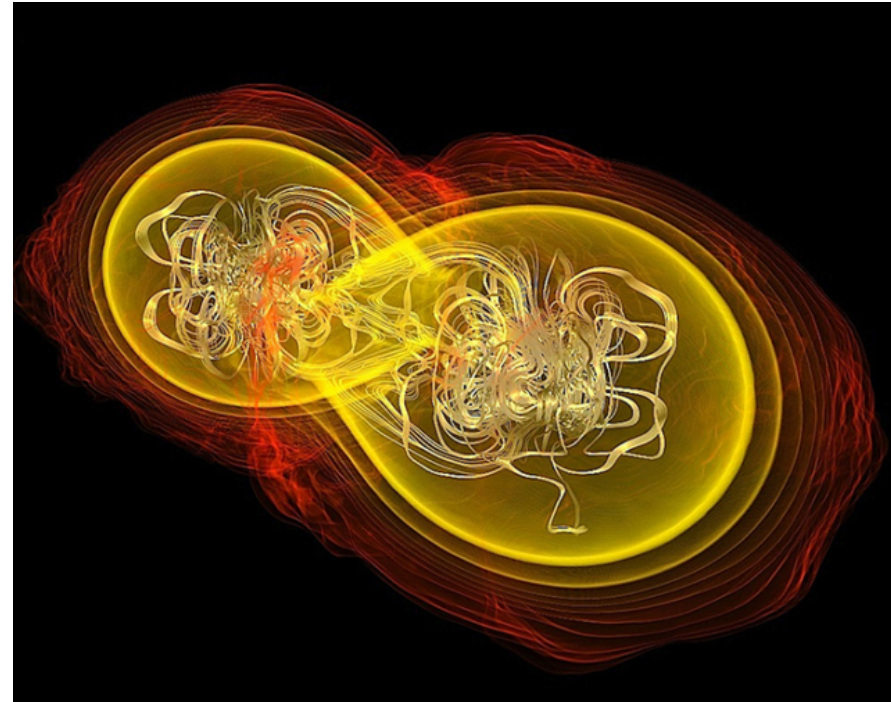
quadrupole deformation

external gravitational field

tidal Love number

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

tidal polarizability



Artist's impression. Taken from Physics World.  
"Distorted neutron stars give up secrets of dense nuclear matter".

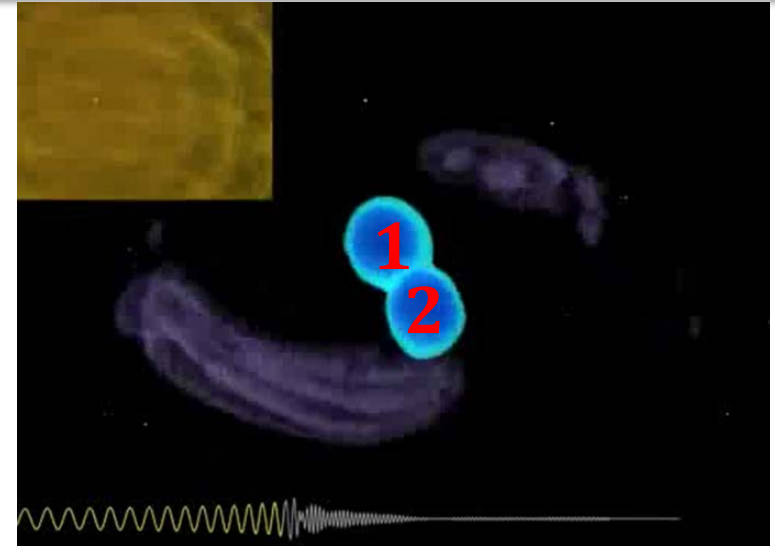
**Quadrupole deformation scales as the 5<sup>th</sup> power of the Radius.**

Fattoyev, Carvajal, Newton, Li, Phys. Rev. C 87, 015806 (2013)  
Steiner, Gandolfi, Fattoyev, Newton, Phys. Rev. C 91, 015804 (2015)  
Fattoyev, Piekarewicz, Horowitz, Phys. Rev. Lett., 172702 (2018)

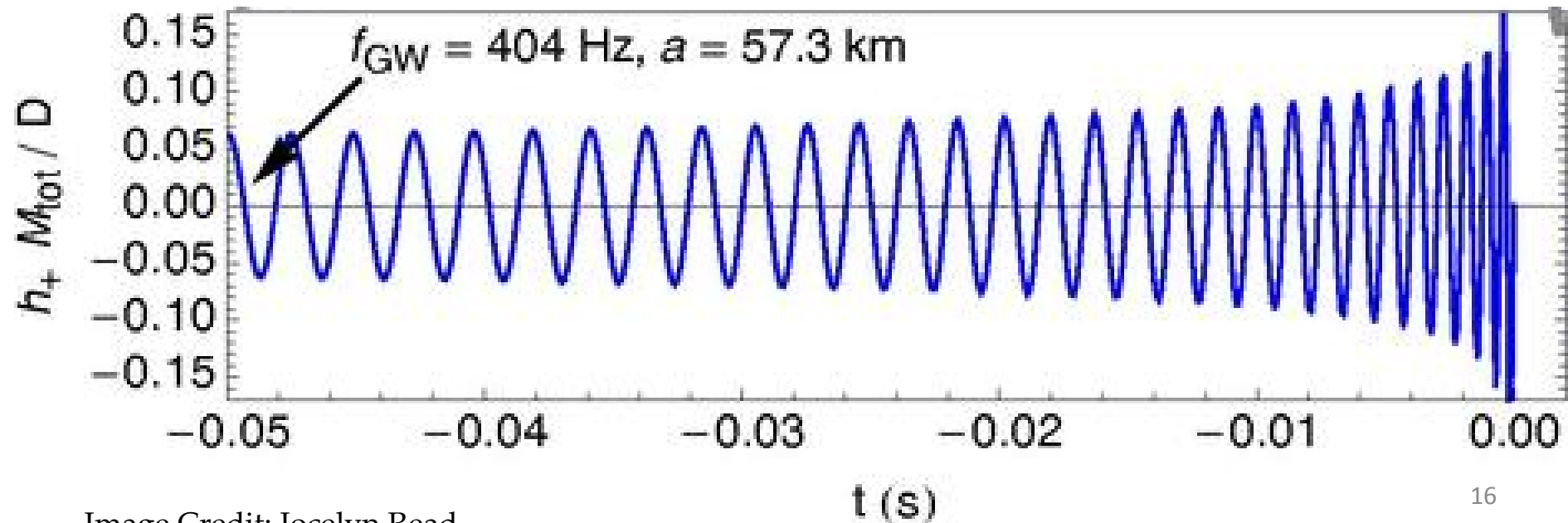
# Tidal Polarizability and the Equation of State

$$V(r) \approx -\frac{GM}{r} - \frac{GQ}{r^3} + \dots$$

The induced quadrupole deformation advances the orbit and changes the rotational phase.



BH-BH merger:

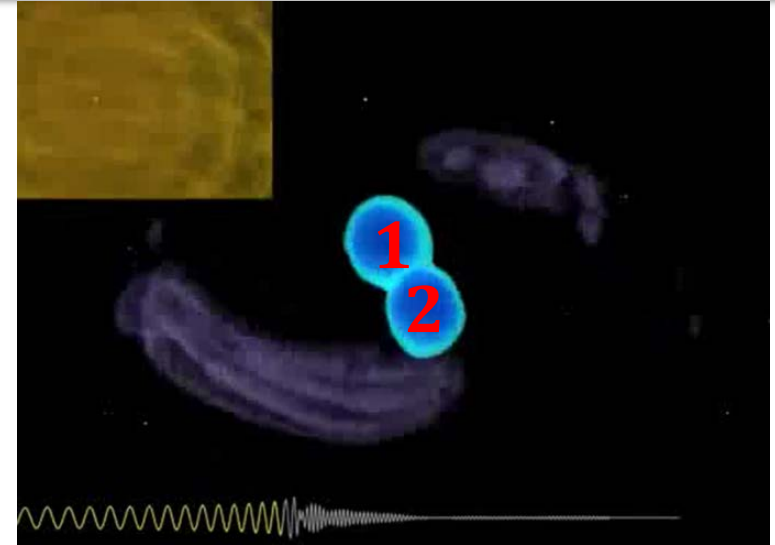




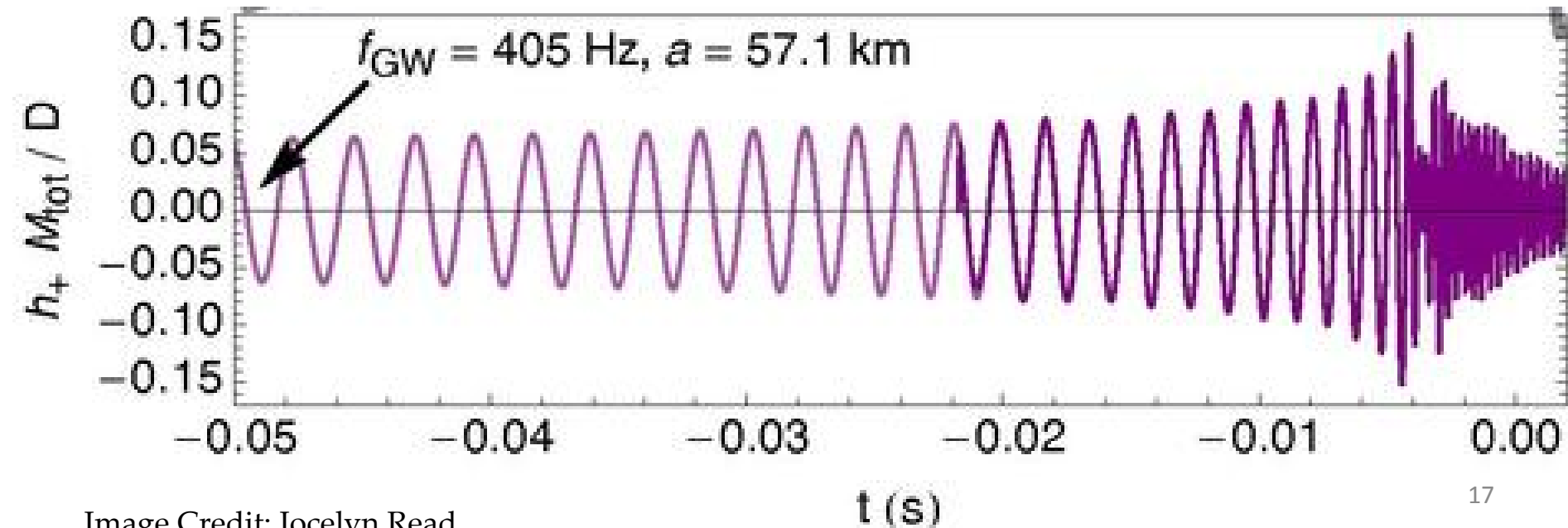
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NS-NS merger:



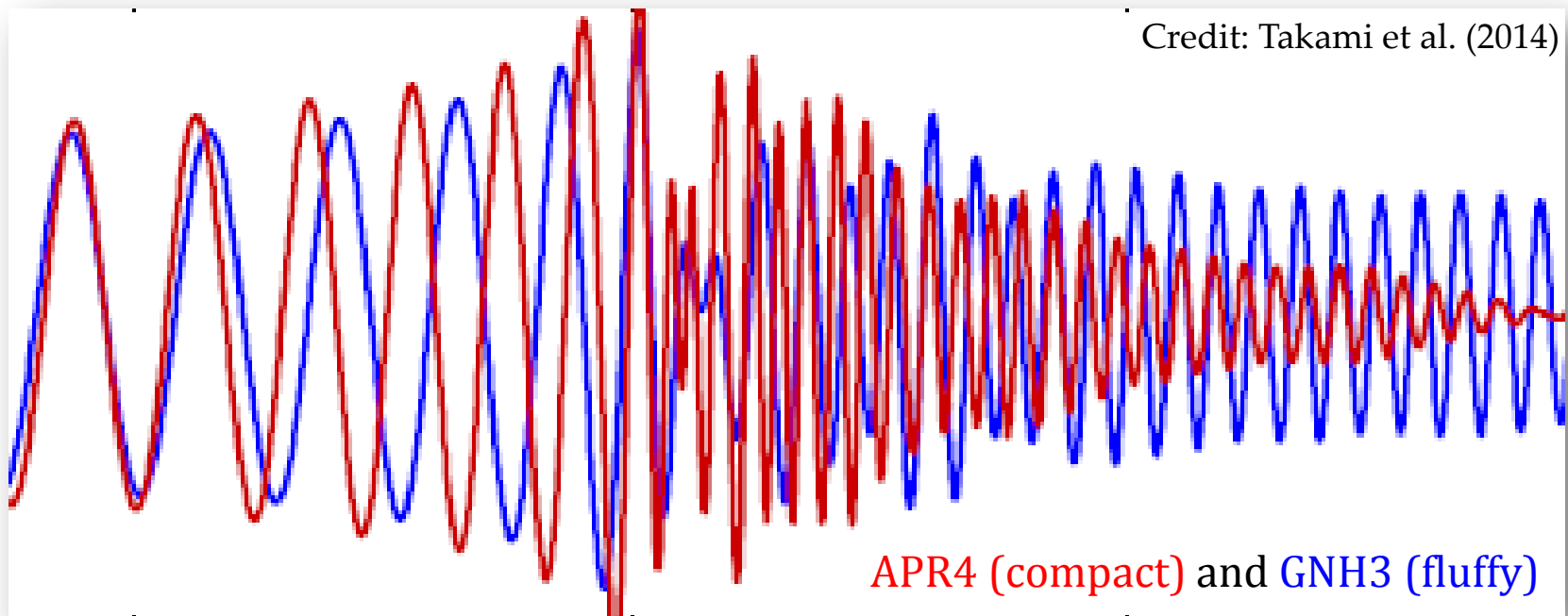
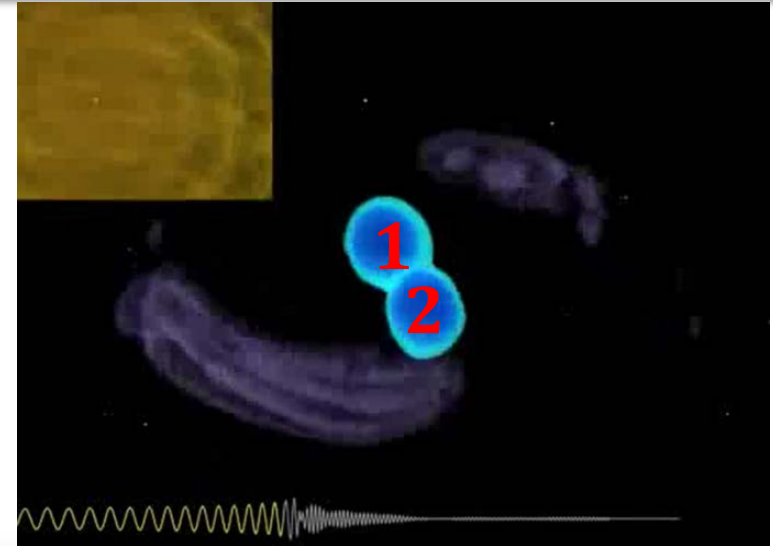
# Tidal Polarizability and the Equation of State

$$V(r) \approx -\frac{GM}{r} - \frac{GQ}{r^3} + \dots$$

Fluffy stars collide earlier, thus merge at a lower frequency.

Compact stars continue to orbit until later time and merge at a higher frequency.

NS-NS merger:



Credit: Takami et al. (2014)

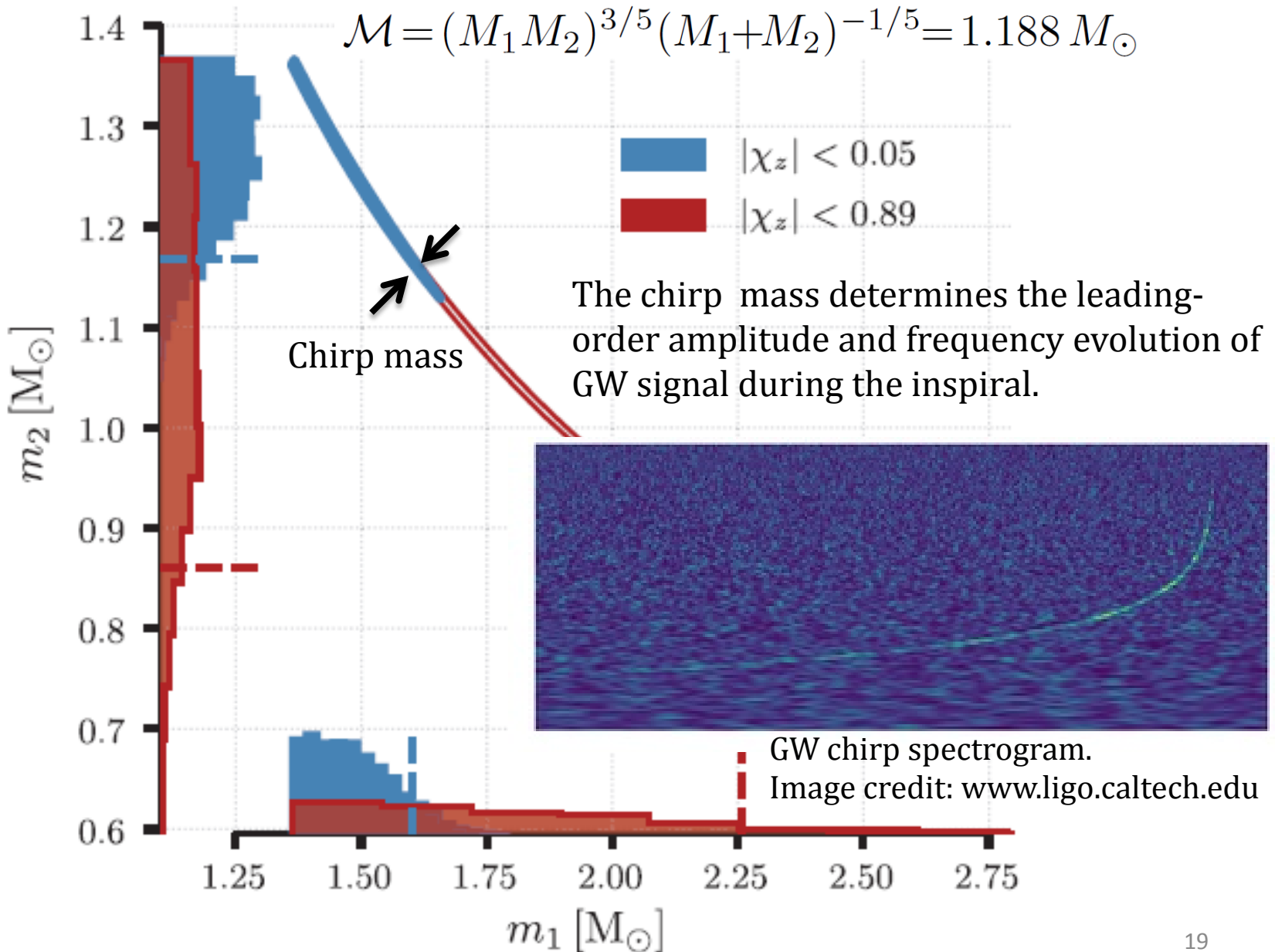
APR4 (compact) and GNH3 (fluffy)

-6.5 ms

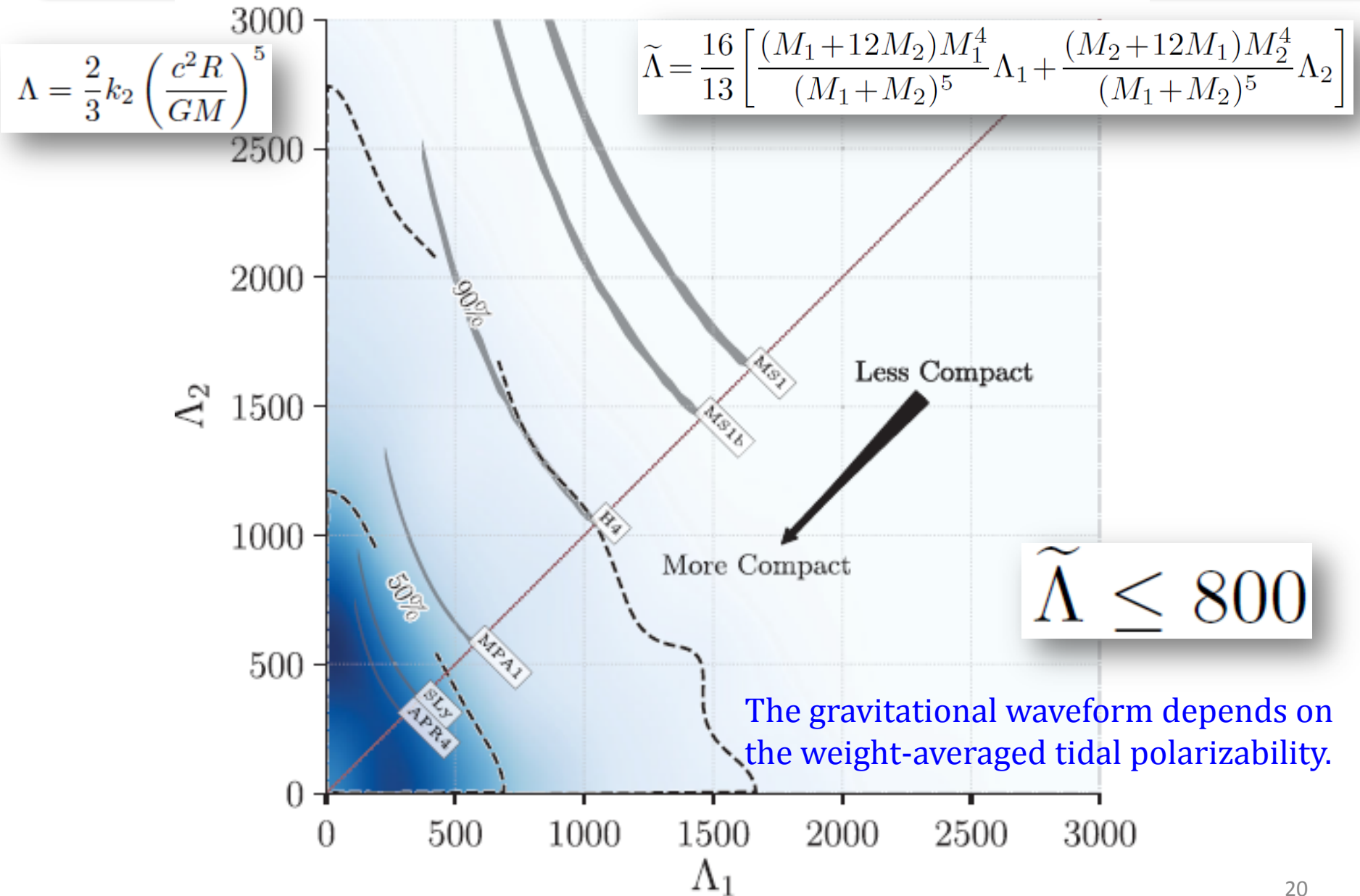
0 ms

6.5 ms

# GW170817: Chirp Mass



# GW170817: Tidal Polarizability



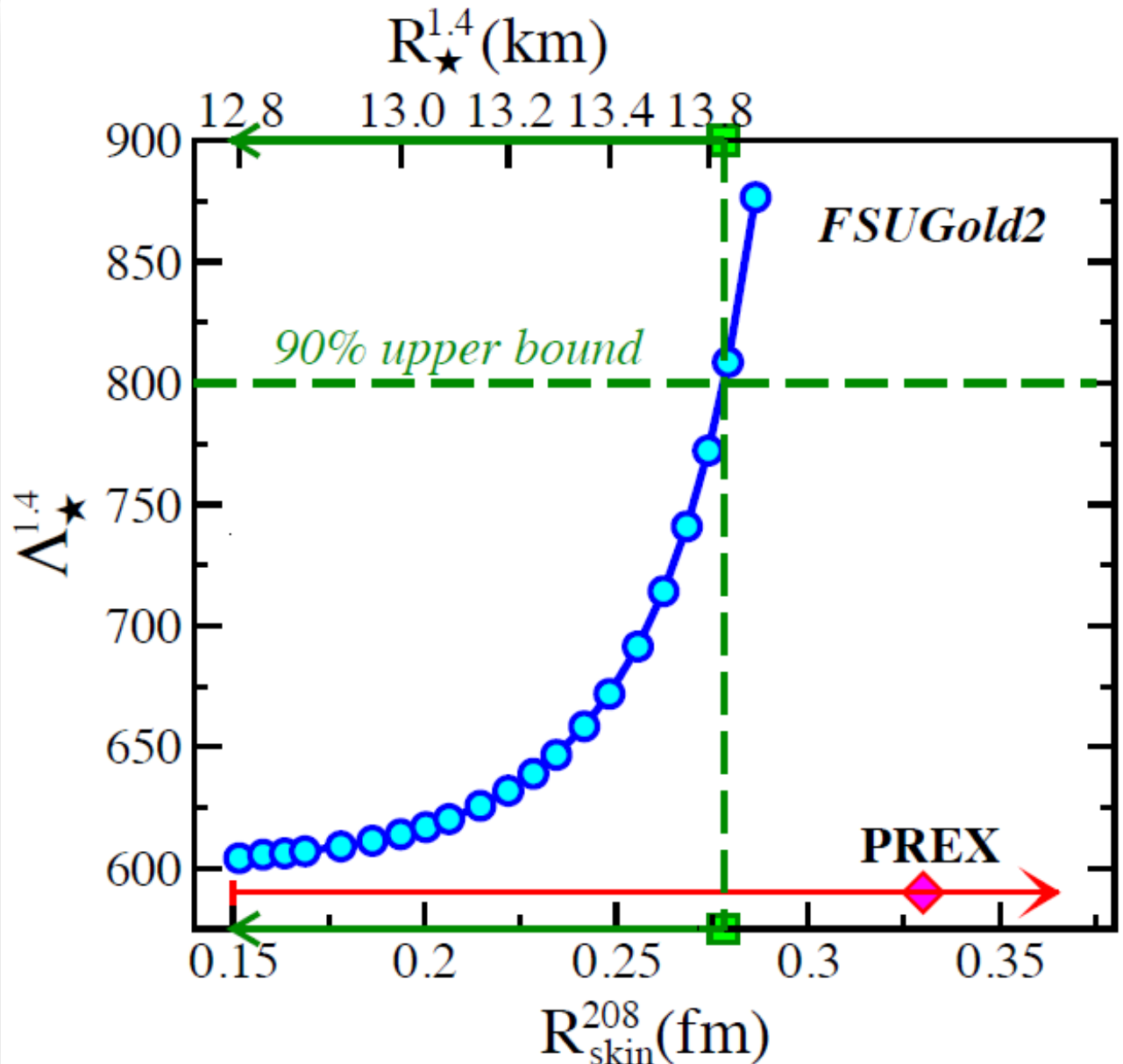
# Connecting Neutron Skins to Tidal Polarizabilities

$$\Lambda = \frac{2}{3} k_2 \left( \frac{c^2 R}{GM} \right)^5$$

**Scales as Radius  
to the 5<sup>th</sup> power!**

$R_{\text{skin}}^{208} \gtrsim 0.28 \text{ fm}$   
**region is ruled out!**

$R_{\star}^{1.4} \leq 13.9 \text{ km}$   
neutron stars are not  
overly fluffy.



# Connecting Neutron Skins to Tidal Polarizabilities

PREX at Jefferson Laboratory had already measured a neutron skin thickness of 0.33 fm (albeit with large error-bars).

- What if the large central value of 0.33 fm is confirmed by the upcoming PREX-II experiment?
- The average nuclear density is about 0.7 saturation density. The average density of neutron star-matter depends on the mass of the star, but is several times nuclear saturation density.
- This may suggest that there is a phase transition at higher densities to an exotic phase of dense matter that makes the EOS soft:  
*For example, QCD phase transition to a quark core!*

# Astrophysics and Nuclear Physics: Neutron Skins to Tidal Polarizabilities

## A More Robust Analysis:

The SNM EOS at high-densities  
now becomes important  
– Heavy Ion Collisions!!  
(NSCL/MSU, TAMU, RHIC)

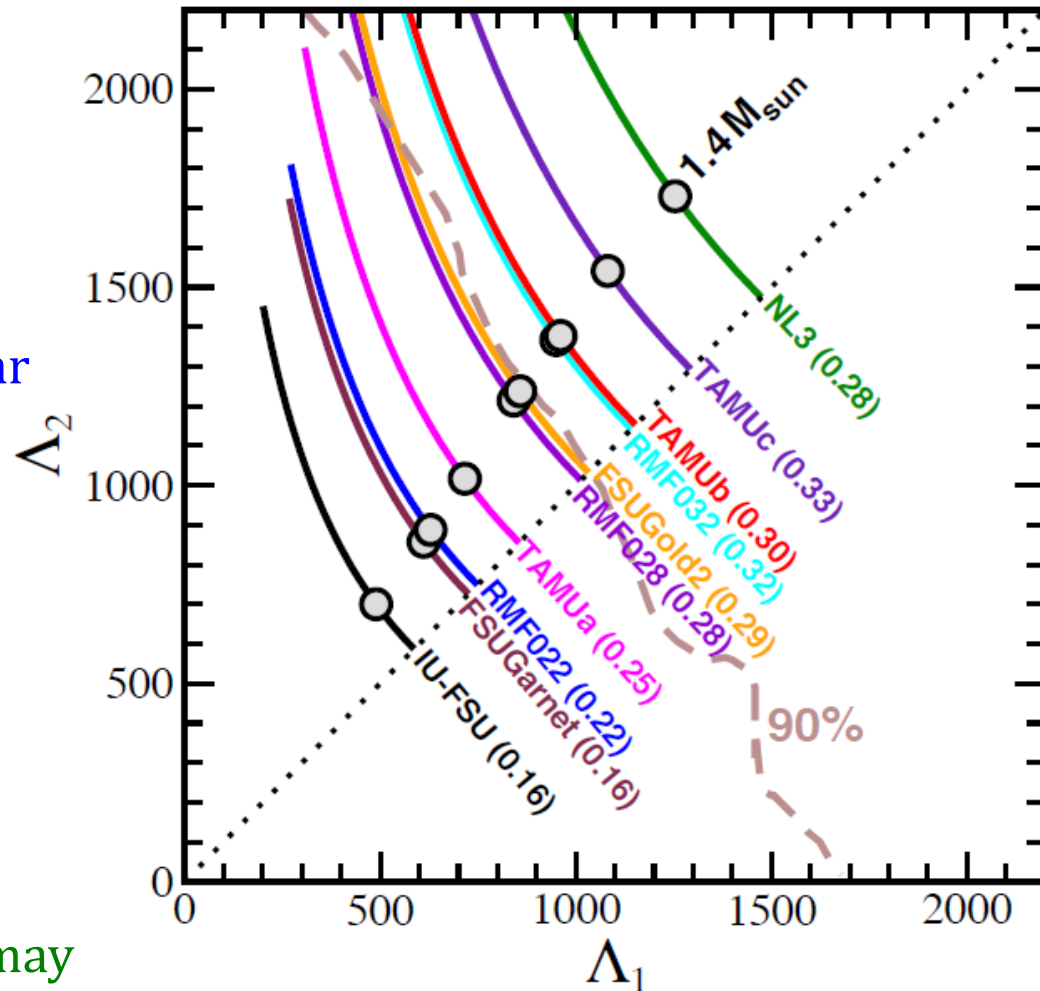
Observation of a massive neutron star  
relieves the tension between various  
Models – Shapiro Delay!!

Demorest et al. Nature 467 (2010)

Some models with stiff SNM EOS,  
Such as NL3, may have already been  
*ruled out*.

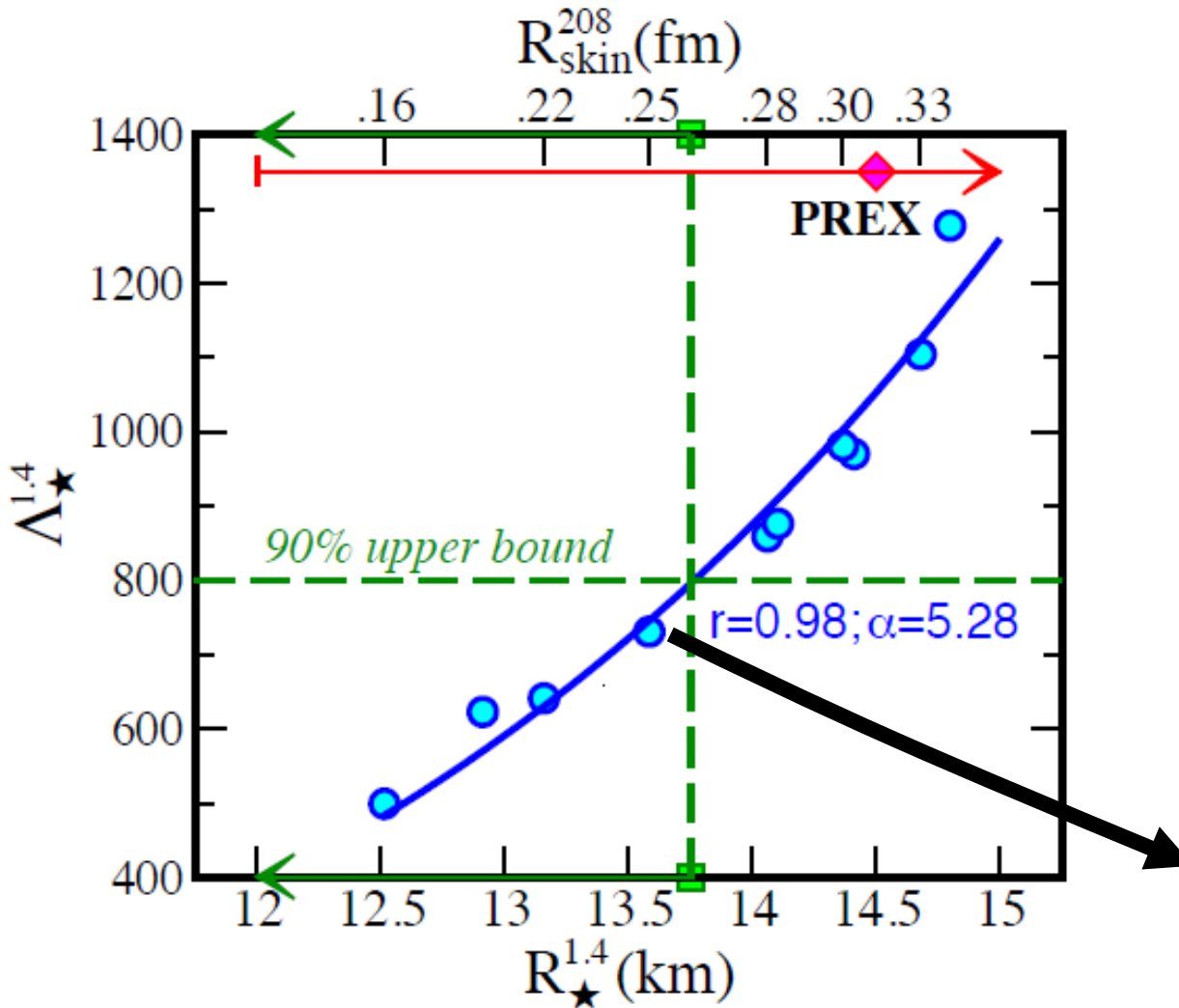
Recent EM analyses show models  
that predict masses below  $2.17 M_{\odot}$  may  
have been ruled out.

(e.g. Margalit & Metzger, ApJL-2017, Rezzolla et al., ApJL-2017).



Fattoyev, Piekarewicz, Horowitz, Phys. Rev. Lett., 172702 (2018)

# Connecting Neutron Skins to Tidal Polarizabilities



Fattoyev, Piekarewicz, Horowitz, Phys. Rev. Lett., 172702 (2018)

$$\Lambda_{\star} = a R_{\star}^{\alpha}$$

$$a \approx 7.76 \times 10^{-4}$$

$$\alpha \approx 5.28$$

$$R_{\star}^{1.4} < 13.76 \text{ km}$$

in perfect agreement with the FSUGold2 family.

$$R_{\text{skin}}^{208} = 0.25 \text{ fm}$$



# Connecting Neutron Skins to Tidal Polarizabilities

Tidal polarizability constrains neutron skins to be  $\lesssim 0.25$  fm.

PREX had already imposed a lower bound to the neutron skin thickness of 0.15 fm.

What does this imply on tidal polarizabilities?

# Connecting Neutron Skins to Tidal Polarizabilities

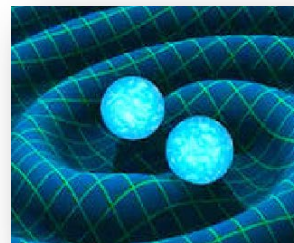
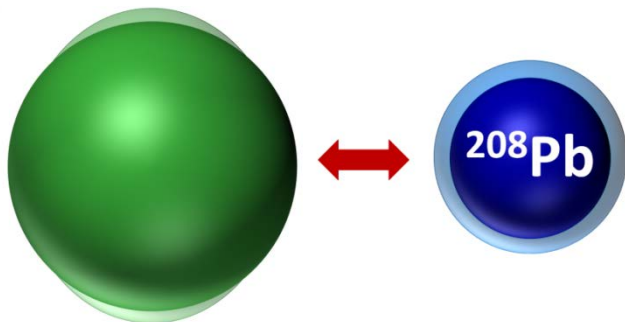
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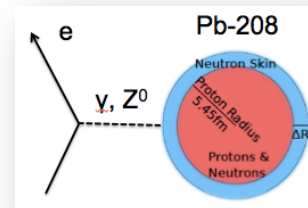
What does this imply on tidal polarizabilities?

$$R_{\text{skin}}^{208} \simeq 0.15 \text{ fm} \longrightarrow R_{\star}^{1.4} \simeq 12.55 \text{ km} \longrightarrow \Lambda_{\star}^{1.4} \simeq 490$$

A strong synergy is being developed among *computational physics*, *nuclear physics*, *astrophysics*, *particle physics*, and *gravitational wave astronomy* that yet to uncover some deepest secrets in neutron stars!!



GW170817



Parity Violating  
Radius Experiment

# Concluding Remarks

- **Nuclear Physics:** Neutron skin measurements inform about the equation of state of neutron-rich matter *below* and slightly above nuclear saturation.
  - **Astrophysics:** Neutron star radii and mass measurements provide information on the equation of state of dense matter *above* saturation.
  - **General Relativity:** Neutron star mergers tell us about neutron star radii.
  - **Particle Physics:** In conjunction with neutron skin measurements and neutron star observables one can probe exotic phases that inhabit in the neutron star core.
  - **Atomic Physics:** Unitary Fermi Gas puts a tighter constraint on the pure neutron matter EOS applicable to neutron star matter.
1. Neutron stars are the natural meeting place for interdisciplinary and fundamental physics.
  2. Neutron skins are intimately connected to the properties of neutron stars.

## In collaboration with:

C. J. Horowitz (IU), J. Piekarewicz (FSU), W. G. Newton (TAMUC), B.-A. Li (TAMUC), A. W. Steiner (UTK/ORNL), S. Gandolfi (Los Alamos), B. Schuetrumpf (MSU)

# Thank You!