Nuclear Astrophysics in the new era of multimessenger astronomy

Workshop on ^{208}Pb(e,e'K) and Neutron Stars

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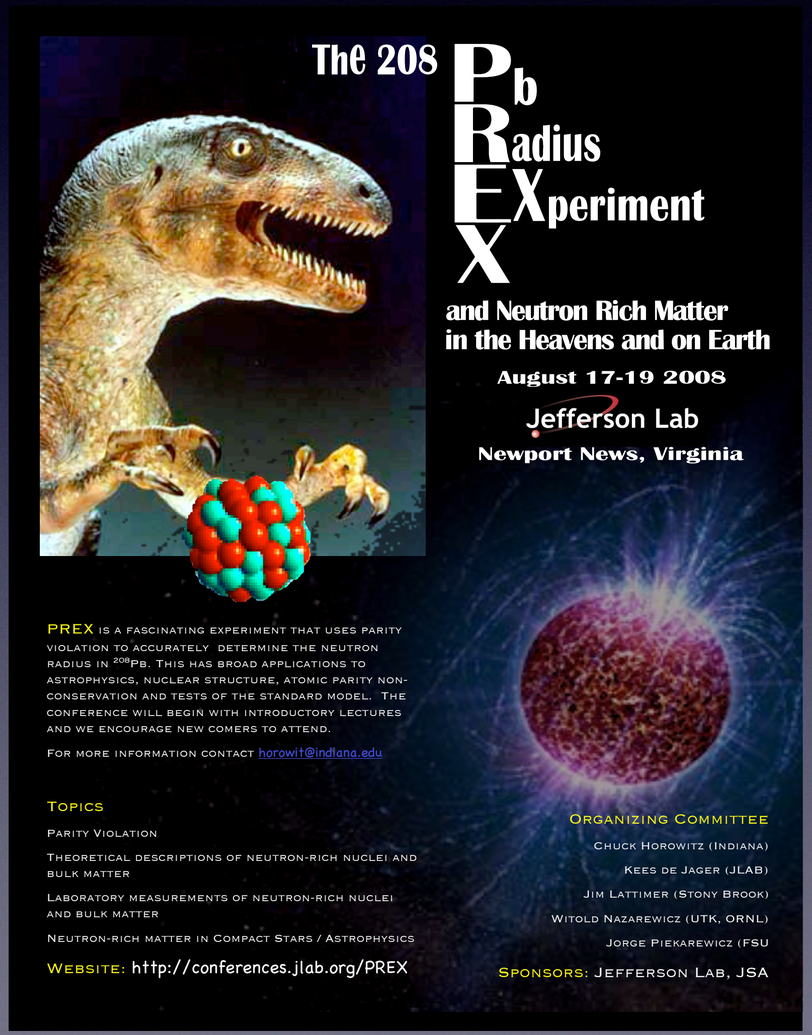
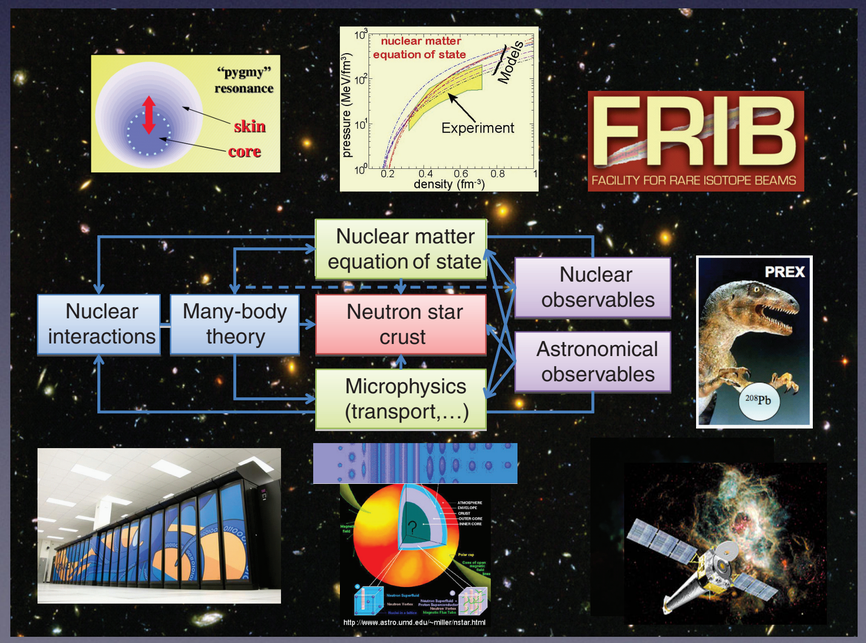
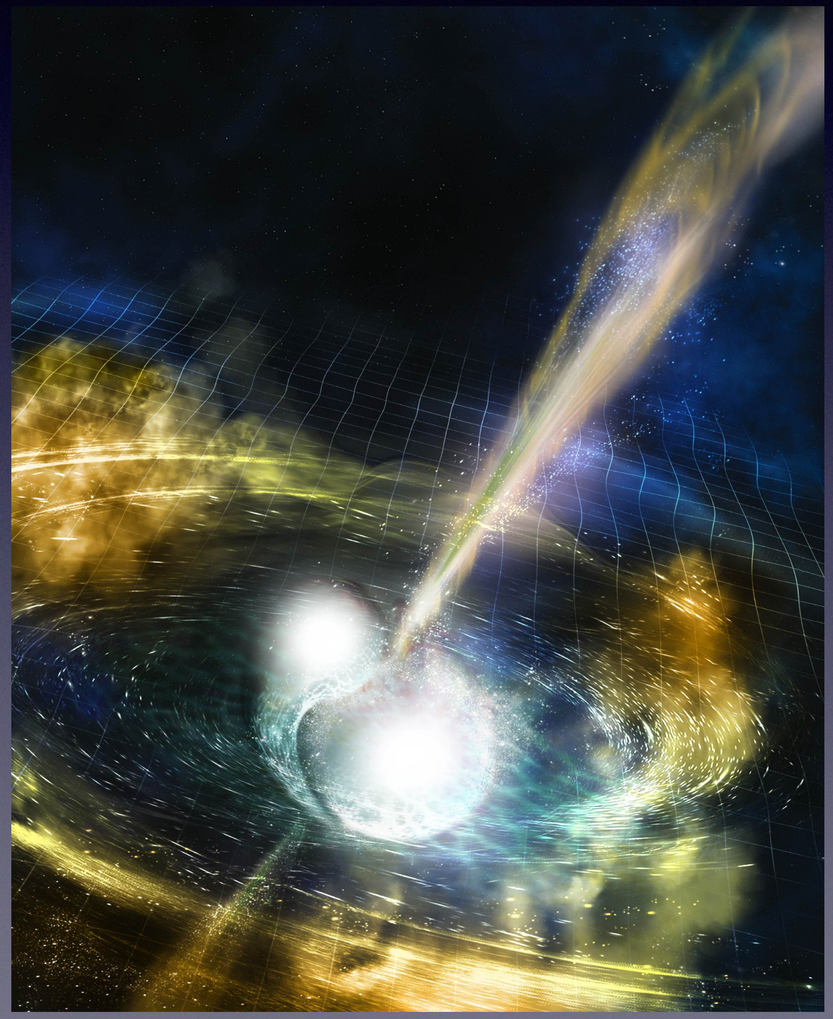






Neutron Rich Matter in Heaven:

The historical first detection of gravitational waves from a binary neutron-star merger

GW170817: places important constraints on the EOS

Imprinted in the GW profile is the “tidal polarizability” an observable sensitive to the stellar compactness (Radius/Mass)
LIGO-Virgo suggest that stars are fairly compact (small radii)

Is there any compelling evidence in favor of hyperons (or other exotica) in the core of neutron stars?

- It is natural to expect hyperons to appear at high density when the neutron Fermi momentum can compensate for the excess mass
- However, enormous uncertainties in the hyperon dynamics (e.g., hyperon-nucleon interaction) severely hinders the argument

My philosophy: Rely exclusively on nucleons-only models informed by both terrestrial experiments and astrophysical observations and see if and how they fail. So far, they have not …

Selected for a Viewpoint in *Physics*
PRL **119,** 161101 (2017) PHYSICAL REVIEW LETTERS week ending 20 OCTOBER 2017

GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspiral

B. P. Abbott *et al.*[*]
(LIGO Scientific Collaboration and Virgo Collaboration)
(Received 26 September 2017; revised manuscript received 2 October 2017; published 16 October 2017)

On August 17, 2017 at 12:41:04 UTC the Advanced LIGO and Advanced Virgo gravitational-wave detectors made their first observation of a binary neutron star inspiral. The signal, GW170817, was detected with a combined signal-to-noise ratio of 32.4 and a false-alarm-rate estimate of less than one per 8.0×10^4 years. We infer the component masses of the binary to be between 0.86 and 2.26 $M_\odot$, in agreement with masses of known neutron stars. Restricting the component spins to the range inferred in binary neutron stars, we find the component masses to be in the range 1.17–1.60 $M_\odot$, with the total mass of the system $2.74^{+0.04}_{-0.01} M_\odot$. The source was localized within a sky region of 28 deg^2 (90% probability) and had a luminosity distance of 40^{+8}_{-14} Mpc, the closest and most precisely localized gravitational-wave signal yet. The association with the γ-ray burst GRB 170817A, detected by Fermi-GBM 1.7 s after the coalescence, corroborates the hypothesis of a neutron star merger and provides the first direct evidence of a link between these mergers and short γ-ray bursts. Subsequent identification of transient counterparts across the electromagnetic spectrum in the same location further supports the interpretation of this event as a neutron star merger. This unprecedented joint gravitational and electromagnetic observation provides insight into astrophysics, dense matter, gravitation, and cosmology.

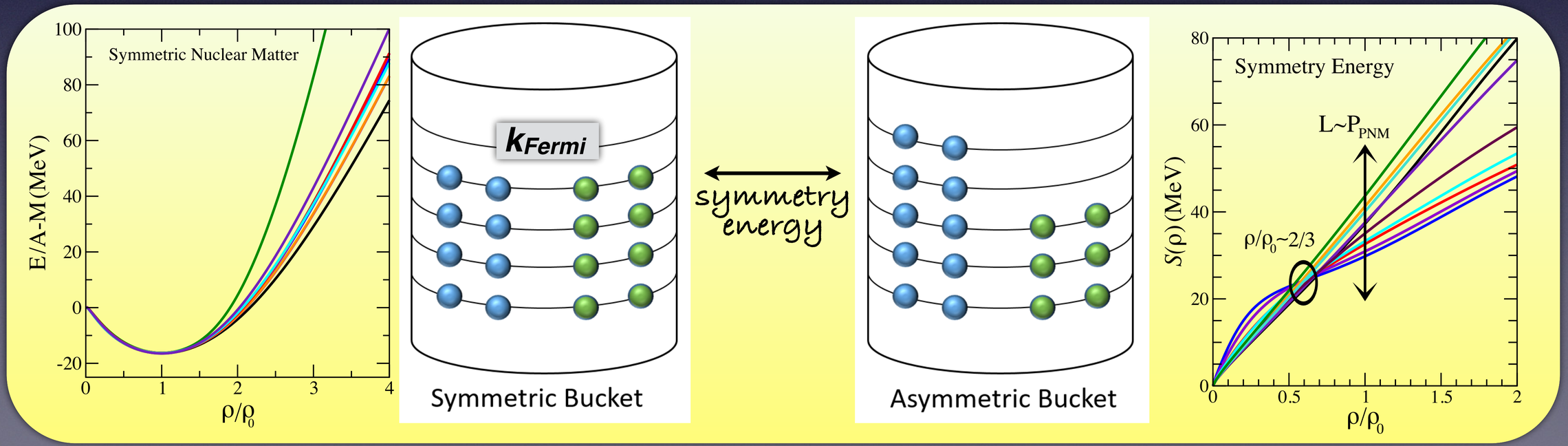
Neutron-star mergers create gravitational waves, light, and gold!

The Equation of State of Neutron-Rich Matter

- Two conserved charges: proton and neutron densities (no weak interactions)
- Equivalently; total nucleon density and asymmetry: ρ and α=(N-Z)/A
- Expand around nuclear equilibrium density: $x=(\rho-\rho_0)/3\rho_0$; $\rho_0 \simeq 0.15$ fm-3

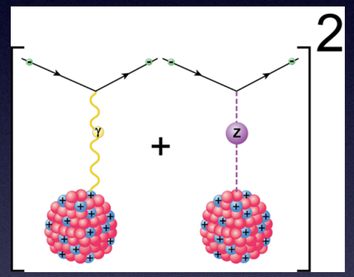
$$\mathcal{E}(\rho,\alpha) \simeq \mathcal{E}_0(\rho) + \alpha^2 \mathcal{S}(\rho) \simeq \left(\epsilon_0 + \frac{1}{2}K_0 x^2\right) + \left(J + Lx + \frac{1}{2}K_{\rm sym} x^2\right)\alpha^2$$

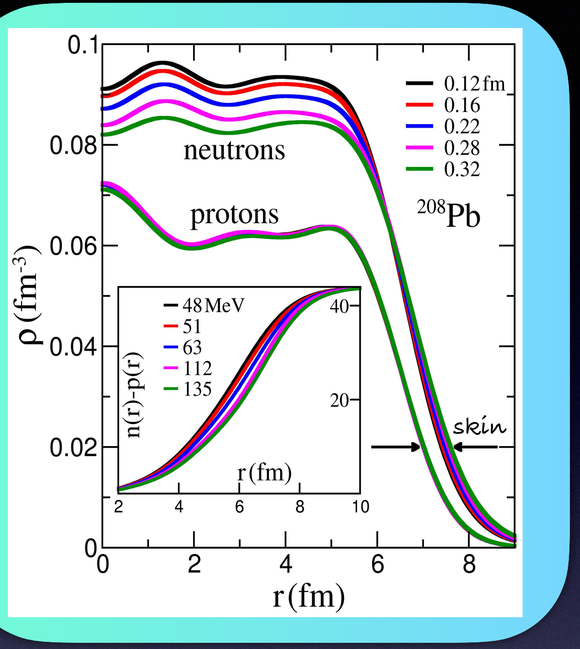
- Density dependence of symmetry energy poorly constrained!!
  "L" symmetry slope ~ pressure of pure neutron matter at saturation



Neutron-Star Structure at JLab: R_{skin} as a proxy for L

- PREX@JLAB: First **Electroweak** (clean!) evidence in favor of Rskin in Pb
- Precision hindered by radiation issues
  - Statistical uncertainties 3 times larger than promised: Rskin=0.33(16)fm
- PREX-II & CREX to run in 2019-20
  - Original goal of 1% in neutron radius

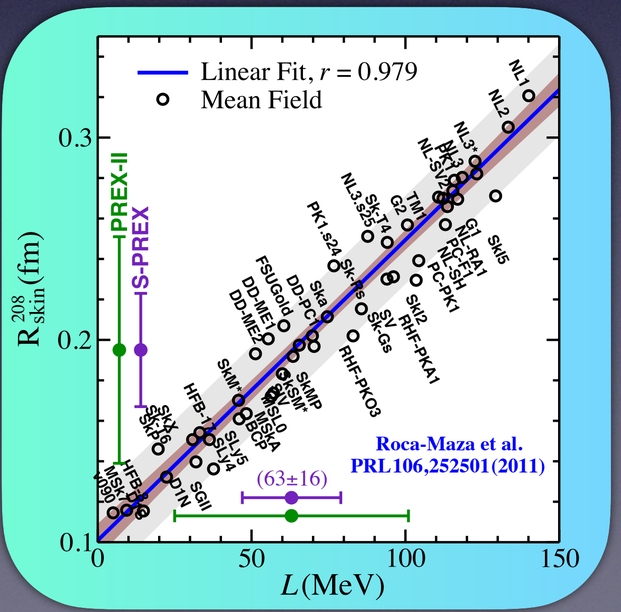




$$A_{\rm PV} \equiv \left[\frac{\left(\frac{d\sigma}{d\Omega}\right)_R - \left(\frac{d\sigma}{d\Omega}\right)_L}{\left(\frac{d\sigma}{d\Omega}\right)_R + \left(\frac{d\sigma}{d\Omega}\right)_L}\right] = \left(\frac{G_{\rm F}Q^2}{4\pi\alpha\sqrt{2}}\right)\frac{F_{wk}(Q^2)}{F_{ch}(Q^2)} \simeq 10^{-6}$$

	up-quark	down-quark	proton	neutron
γ-coupling	$+2/3$	$-1/3$	$+1$	0
Z_0-coupling	$\approx +1/3$	$\approx -2/3$	≈ 0	-1

$$g_{\rm v} = 2t_z - 4Q\sin^2\theta_{\rm W} \approx 2t_z - Q$$

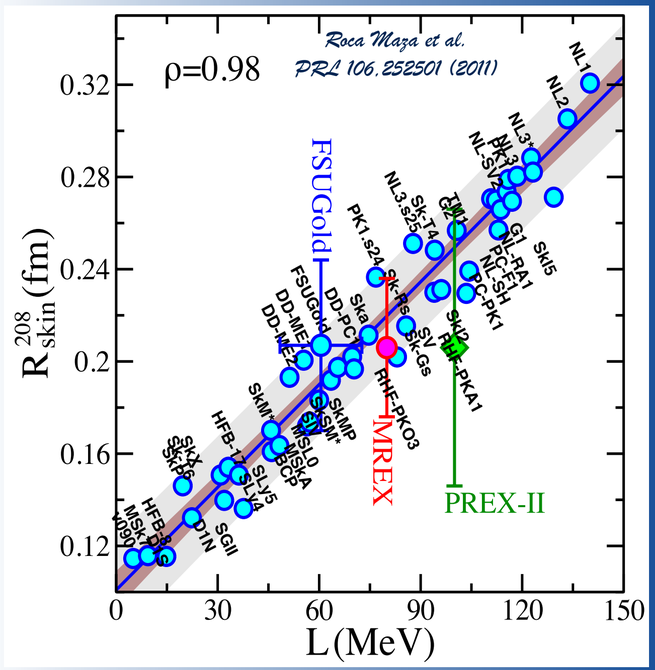


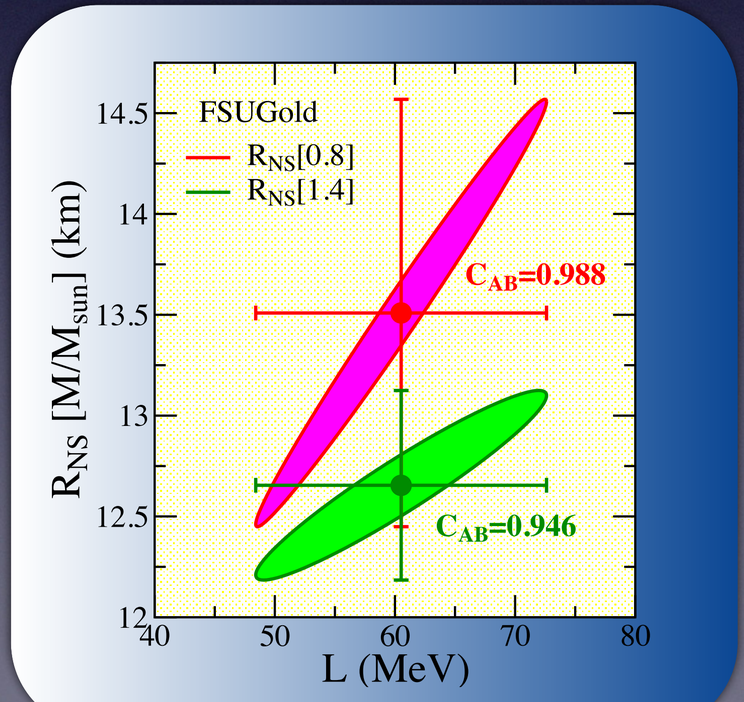
Neutron Rich Matter on Earth:

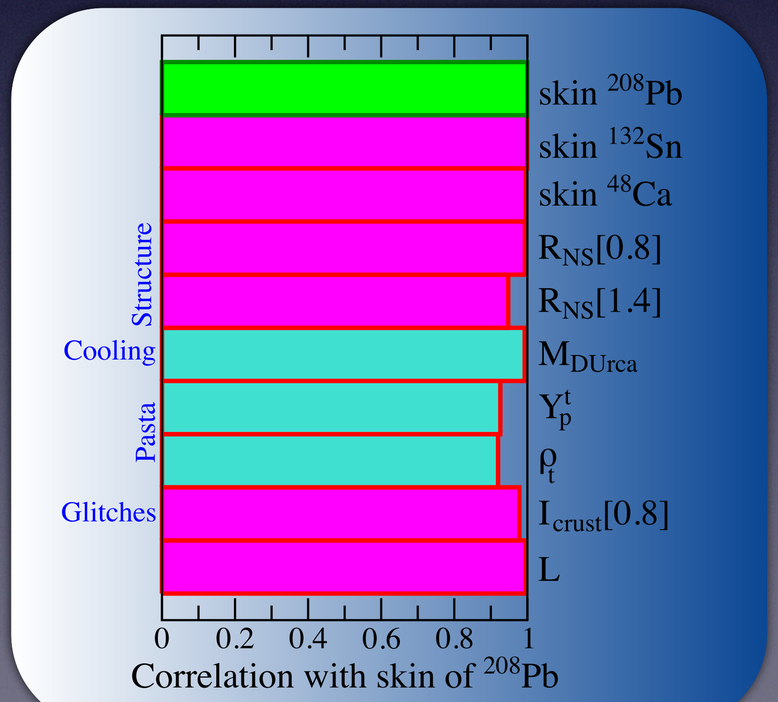
The Quest for "L" at Terrestrial Laboratories

- Although a fundamental parameter of the EOS, L is ***NOT*** a physical observable
- Strong correlation emerges between the neutron skin thickness of ^{208}Pb and L
- L controls both the neutron skin of ^{208}Pb and the radius of a neutron star
- … As well as many other stellar properties sensitive to the symmetry energy

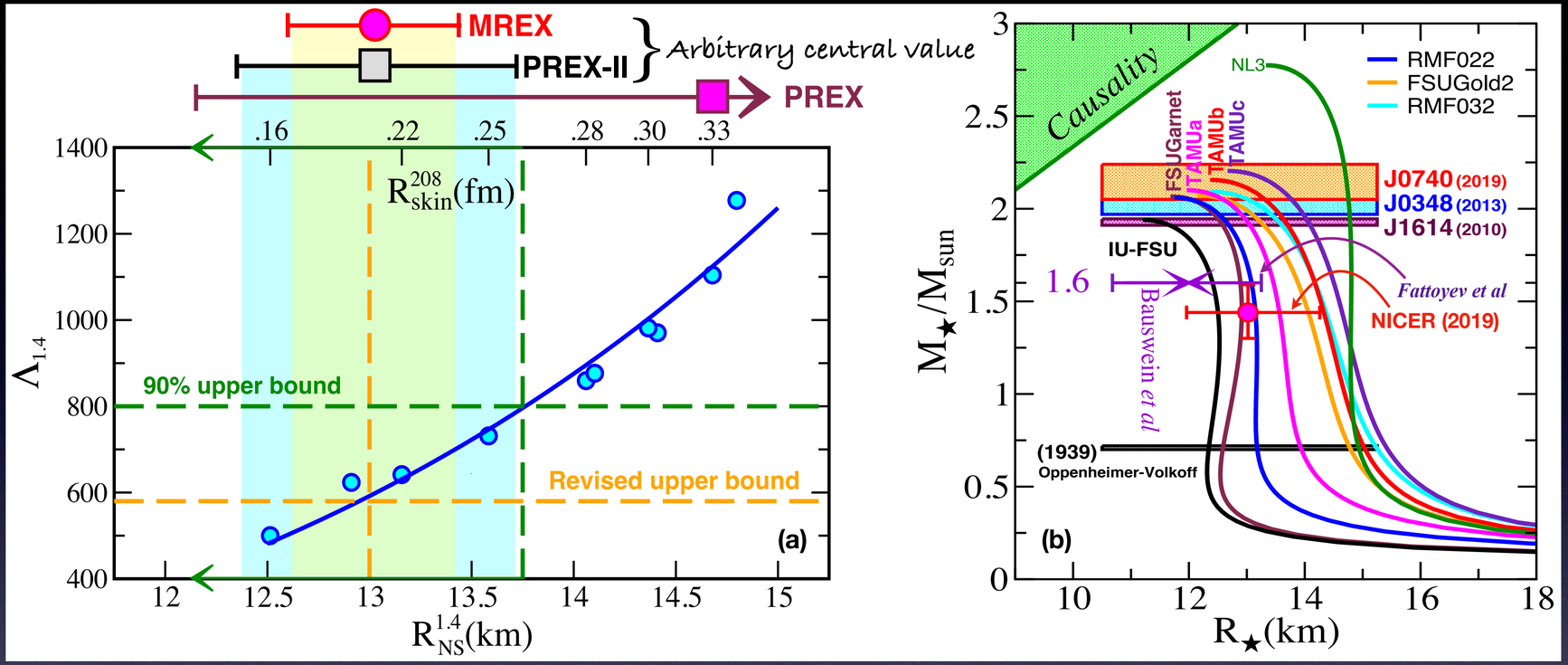
18 orders of magnitude!!

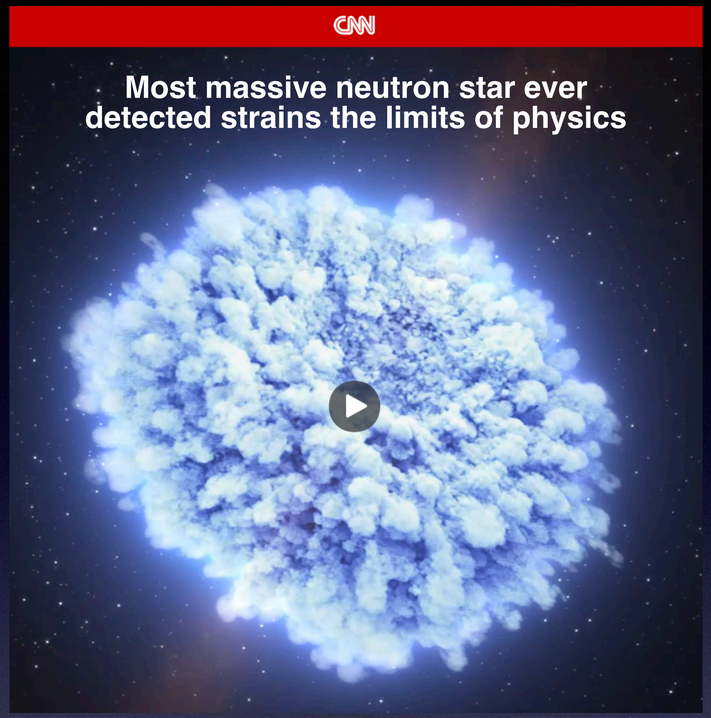


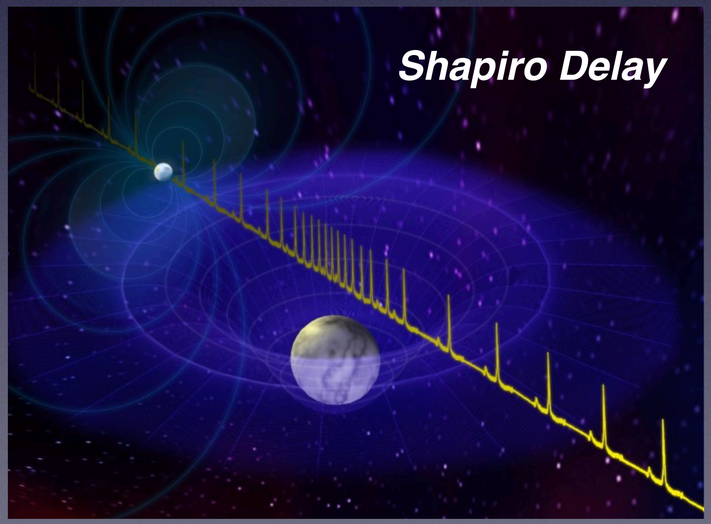




How can we make massive stars with small radii?







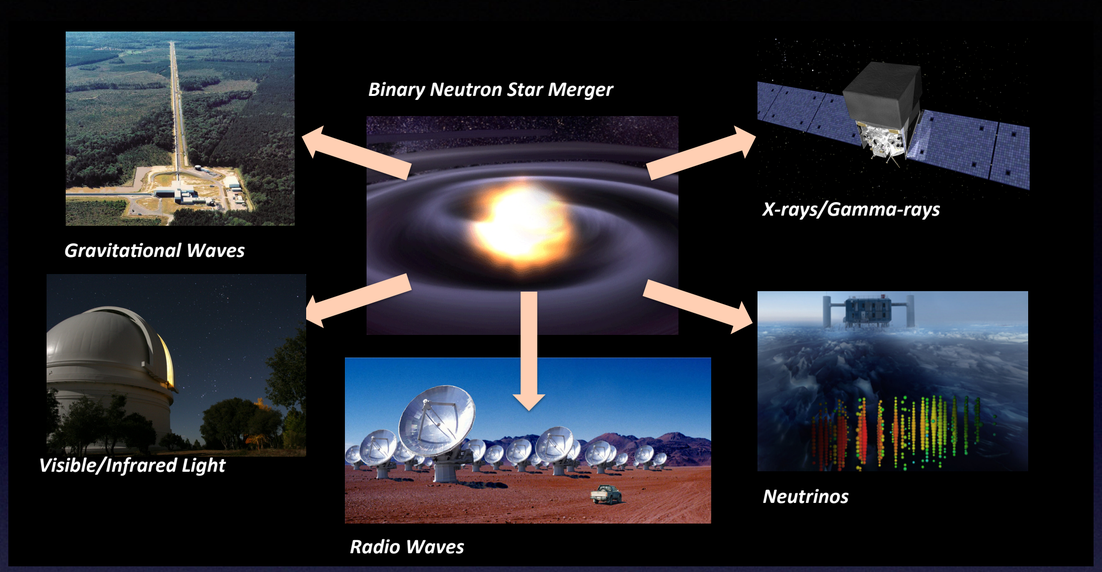
Tantalizing Multi-Messenger Possibility

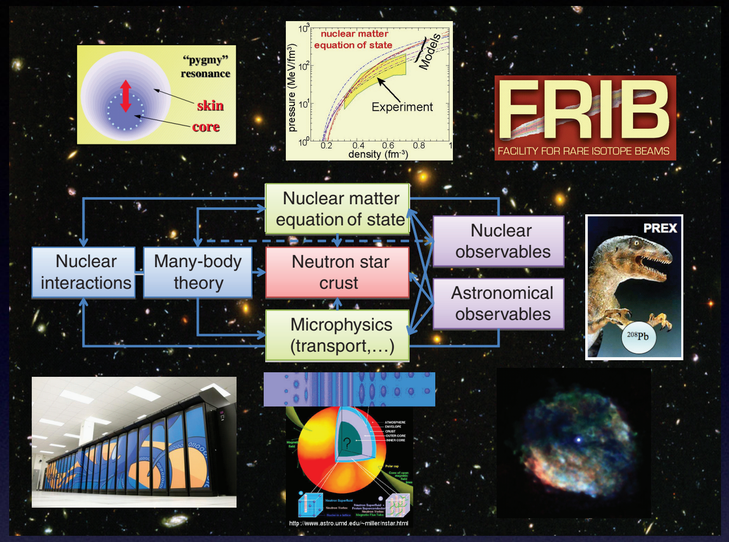
- *Laboratory Experiments suggest large neutron radii for Pb*
- *Gravitational Waves suggest small stellar radii*
- *Electromagnetic Observations suggest large stellar masses*

Exciting possibility: If all are confirmed, this tension may be evidence of a softening/stiffening of the EOS (phase transition?) …

So far, however, nucleons-only models have NOT failed!

It is all Connected!





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- Karim Hasnaoui
- Bonnie Todd-Rutel
- Brad Futch
- Jutri Taruna
- **Farrukh Fattoyev**
- **Wei-Chia Chen**
- **Raditya Utama**

My Outside Collaborators

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- G. Colò (U. Milano)
- C.J. Horowitz (Indiana U.)
- W. Nazarewicz (MSU)
- 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)

The New Generation

- **Pablo Giuliani**
- **Daniel Silva**
- **Junjie Yang**

Gravitational-wave astronomy has opened a new window into the cosmos. New capabilities in heaven and earth will unravel nature's deepest secrets