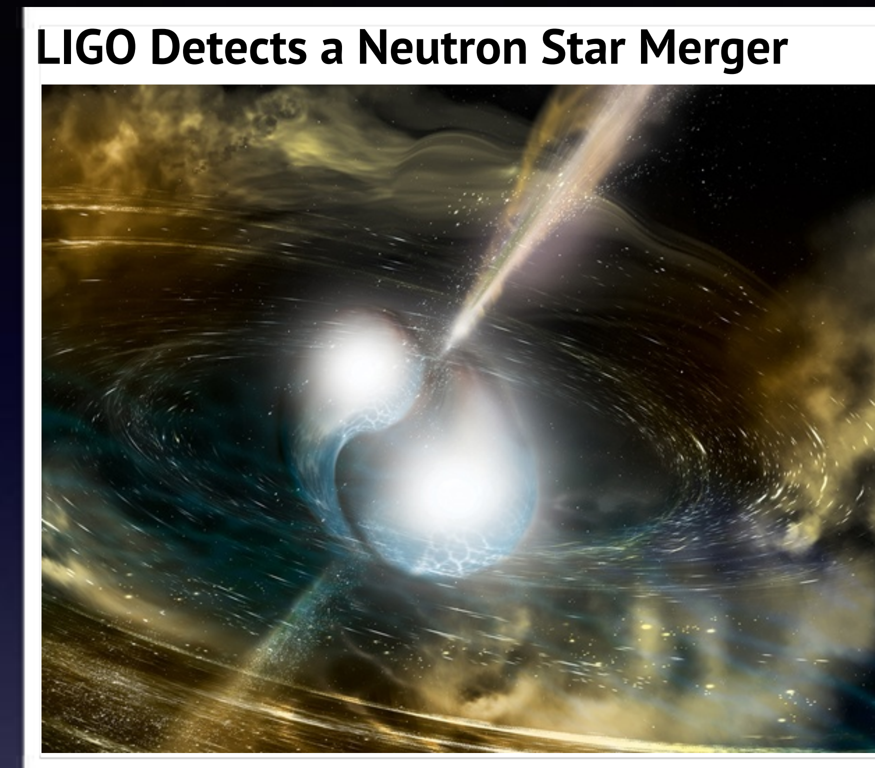
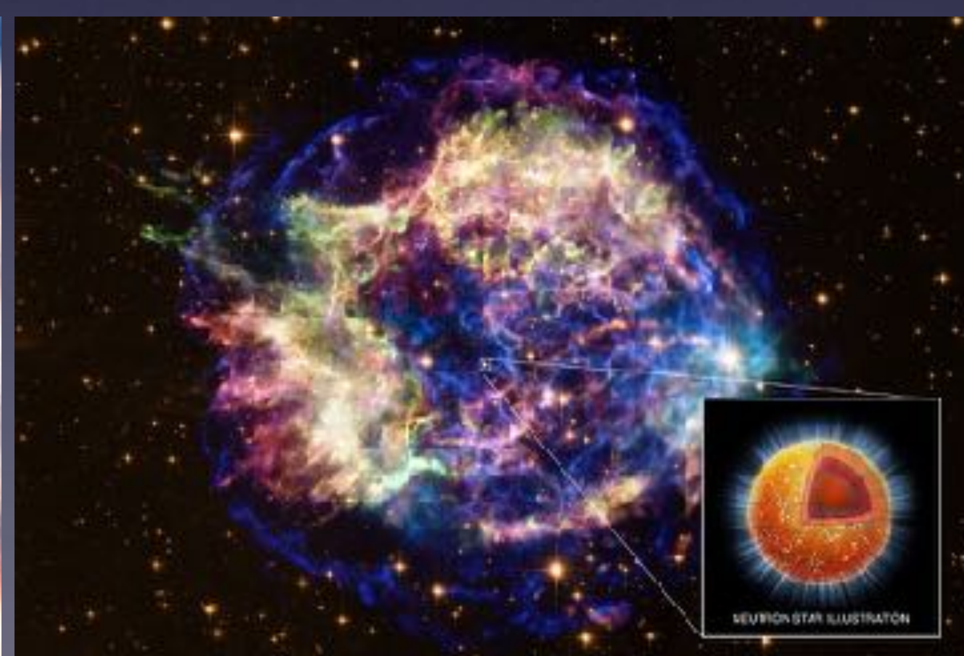
Nuclear Astrophysics in the new era of multi-messenger Astronomy





Two Stars:
Pele'
and
Cassiopeia A

Jorge Piekarewicz
Florida State University

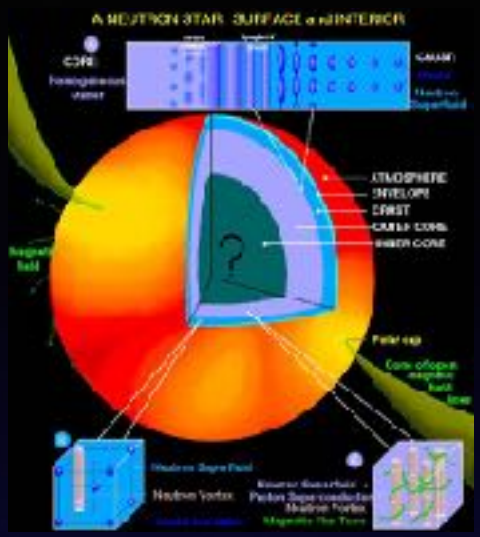
Outline

- ☑ ...
- ☑ Neutron stars as unique cosmic laboratories
- ☑ Heaven and Earth: Laboratory constraints on NS
- Earth and Heaven: NS constrains on laboratory observables

- The ***BIG*** questions?
- The creation of the heavy elements
- New states of matter at low and high densities
- The equation of state of neutron-rich matter

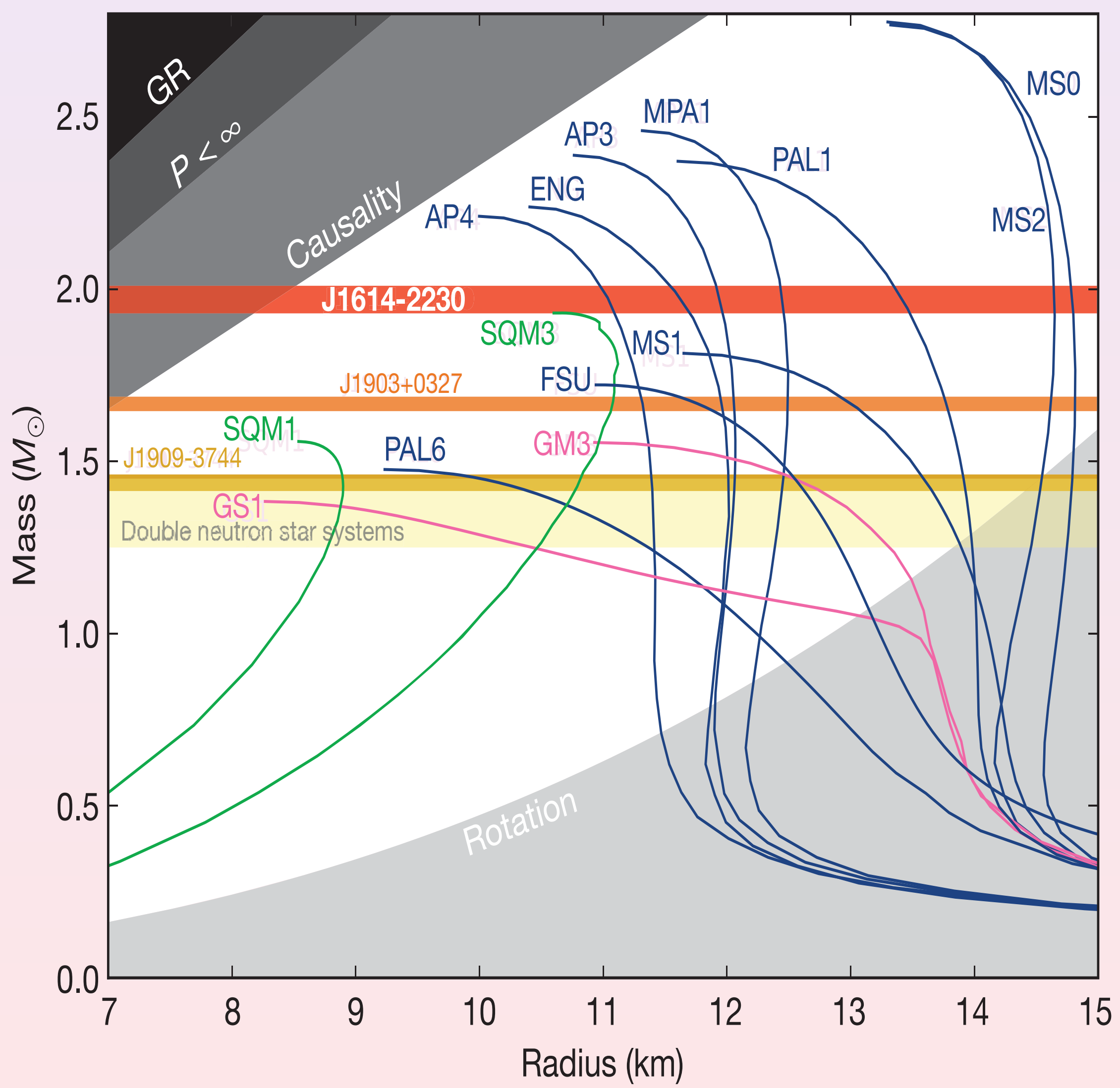
The Anatomy of a Neutron Star

- Atmosphere (10 cm): Shapes Thermal Radiation ($L=4\pi\sigma R^2T^4$)
- Envelope (100 m): Huge Temperature Gradient ($10^8K \leftrightarrow 10^6K$)
- Outer Crust (400 m): Coulomb Crystal (Exotic neutron-rich nuclei)
- Inner Crust (1 km): Coulomb Frustration ("Nuclear Pasta")
- Outer Core (10 km): Uniform Neutron-Rich Matter (n,p,e,μ)
- Inner Core (?): Exotic Matter (Hyperons, condensates, quark matter)



- The composition of the outer crust – as well as the r-process – is extremely sensitive to nuclear masses of exotic, neutron-rich nuclei. RIBFs will help — but only to some extent. Theory (e.g., DFT+BNN) is essential to predict the masses of nuclei that will never be measured in the laboratory
- The unknown EOS of the inner crust (especially in the nuclear pasta phase) is essential to understand the tidal polarizability in BNS mergers
- The neutron skin of lead has been identified as a proxy for the slope of the symmetry energy ("L") which in turn largely determines the size of the neutron star — objects that differ by 18 orders of magnitude!

The Holy Grail: The Equation of State of Neutron-Star Matter



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

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

Need an EOS: $P = P(\mathcal{E})$ relation

Nuclear Physics Critical

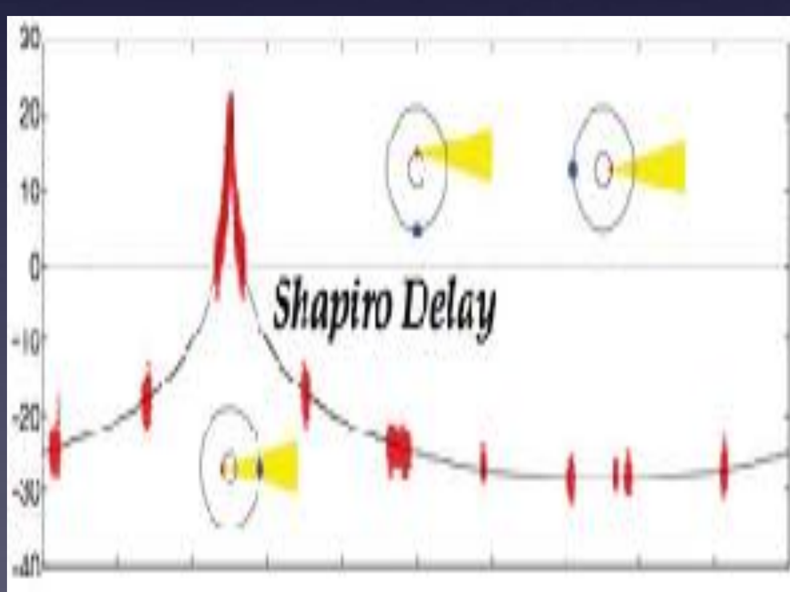
Many nuclear models that accurately predict the properties of finite nuclei yield enormous variations in the prediction of neutron-star radii and maximum mass

What is missing?

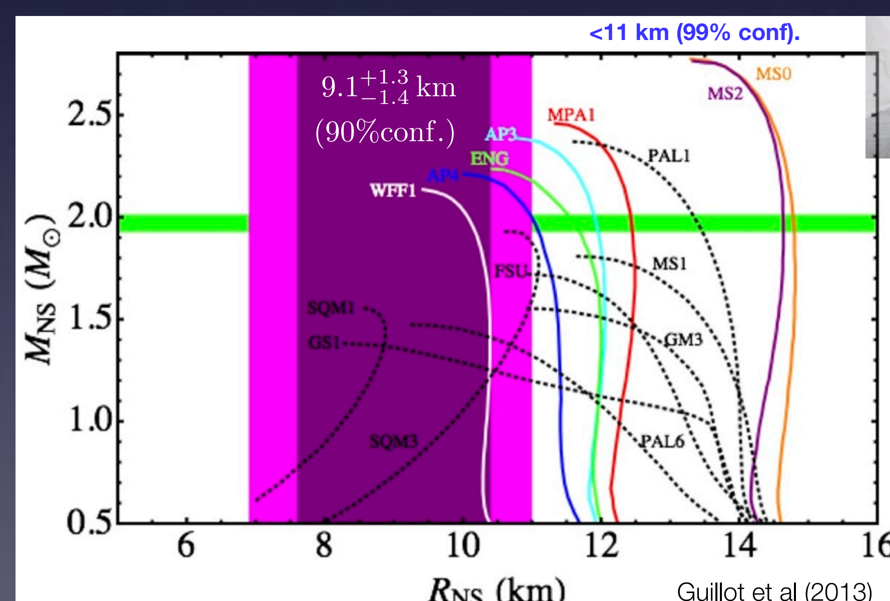
An Interesting Challenge

A significant tension has emerged!

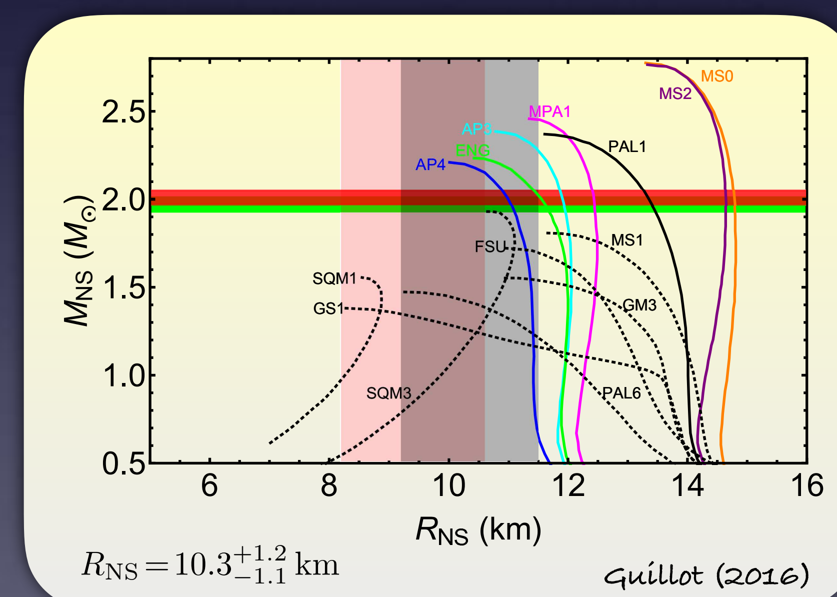
- Stunning observations have established the existence of massive (i.e, 2 solar mass) Neutron stars
- Recent observations has suggested that NS have small radii
- Extremely difficult to reconcile; evidence of a phase transition?



Time delay due to NS emission dipping into the gravitational well of WD!



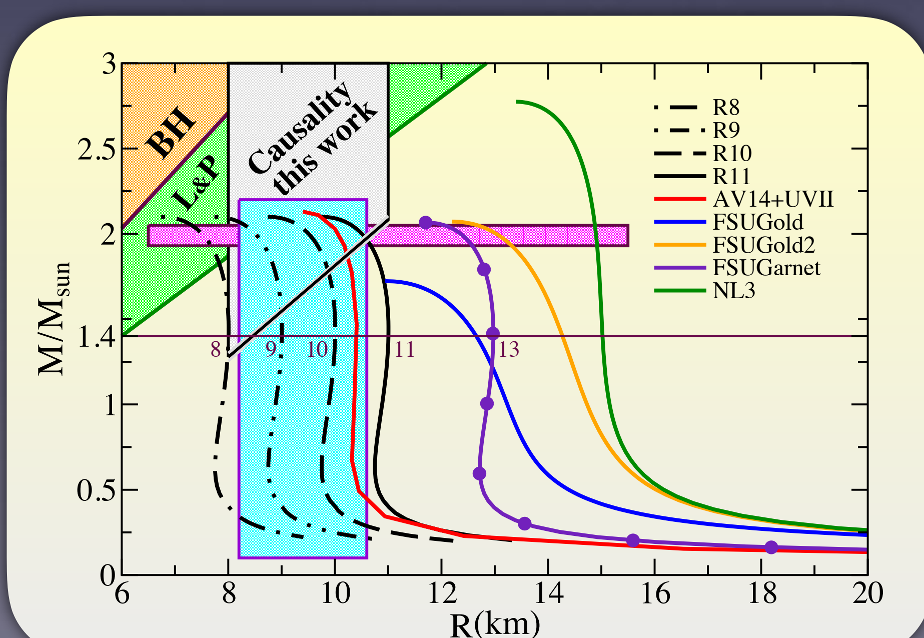
WFF1 violates causality! At high densities speed of sound larger than speed of light

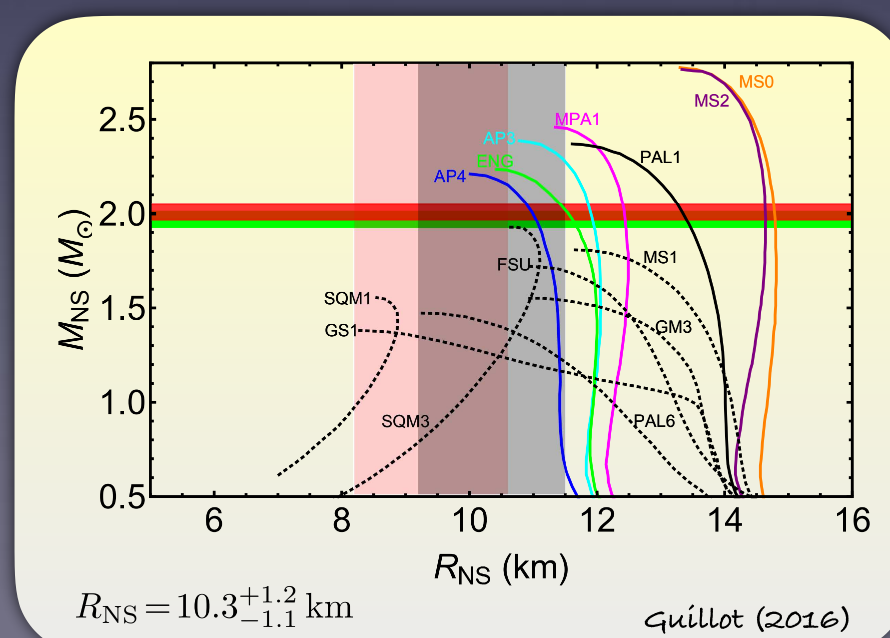


Some tension has been released!

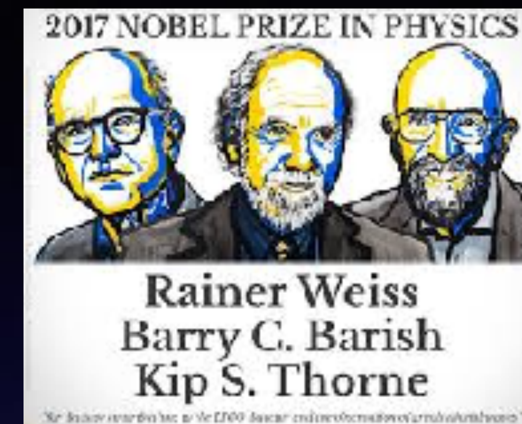
Addressing the Challenge

- Guillot *et al.*, assume all neutron stars have a common radius
  - Assumption on MR observable rather than on EOS
- Remarkable one-to-one correspondence between MR and EOS
  - TOV equation + EOS → MR
- "Lindblom's inversion algorithm" proves the inverse
  - TOV equation + MR → EOS
- Minimum radius such that: (a) EOS is causal and (b) $M_\star \gtrsim 2\,M_\odot$
- Radius of a 1.4 solar-mass NS must be larger than 10.7 km!

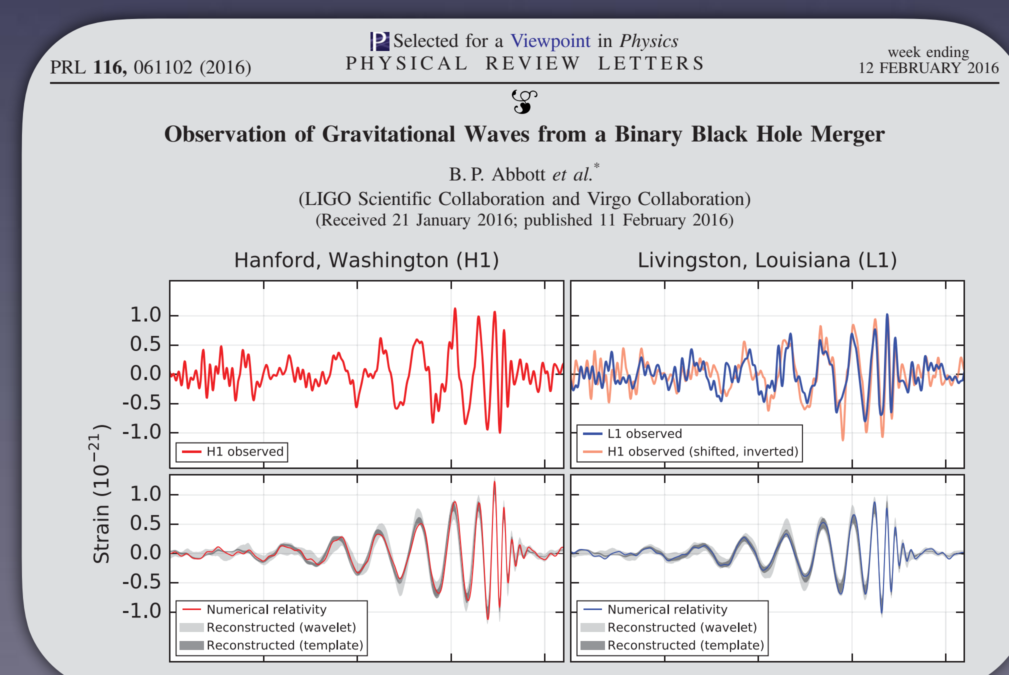




"We have detected gravitational waves; we did it"
David Reitze, February 11, 2016



- ## The dawn of a new era: GW Astronomy
  - Initial black hole masses are 36 and 29 solar masses
  - Final black hole mass is 62 solar masses;
    3 solar masses radiated in Gravitational Waves!



Selected for a Viewpoint in *Physics*

PRL **116,** 061102 (2016) PHYSICAL REVIEW LETTERS week ending 12 FEBRUARY 2016

Observation of Gravitational Waves from a Binary Black Hole Merger

B. P. Abbott *et al.*[*]

(LIGO Scientific Collaboration and Virgo Collaboration)

(Received 21 January 2016; published 11 February 2016)

2017 BREAKTRHOUGH of the YEAR!

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

PRL **119**, 161101 (2017) Selected for a Viewpoint in *Physics* 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.

GW170817: A play in three acts

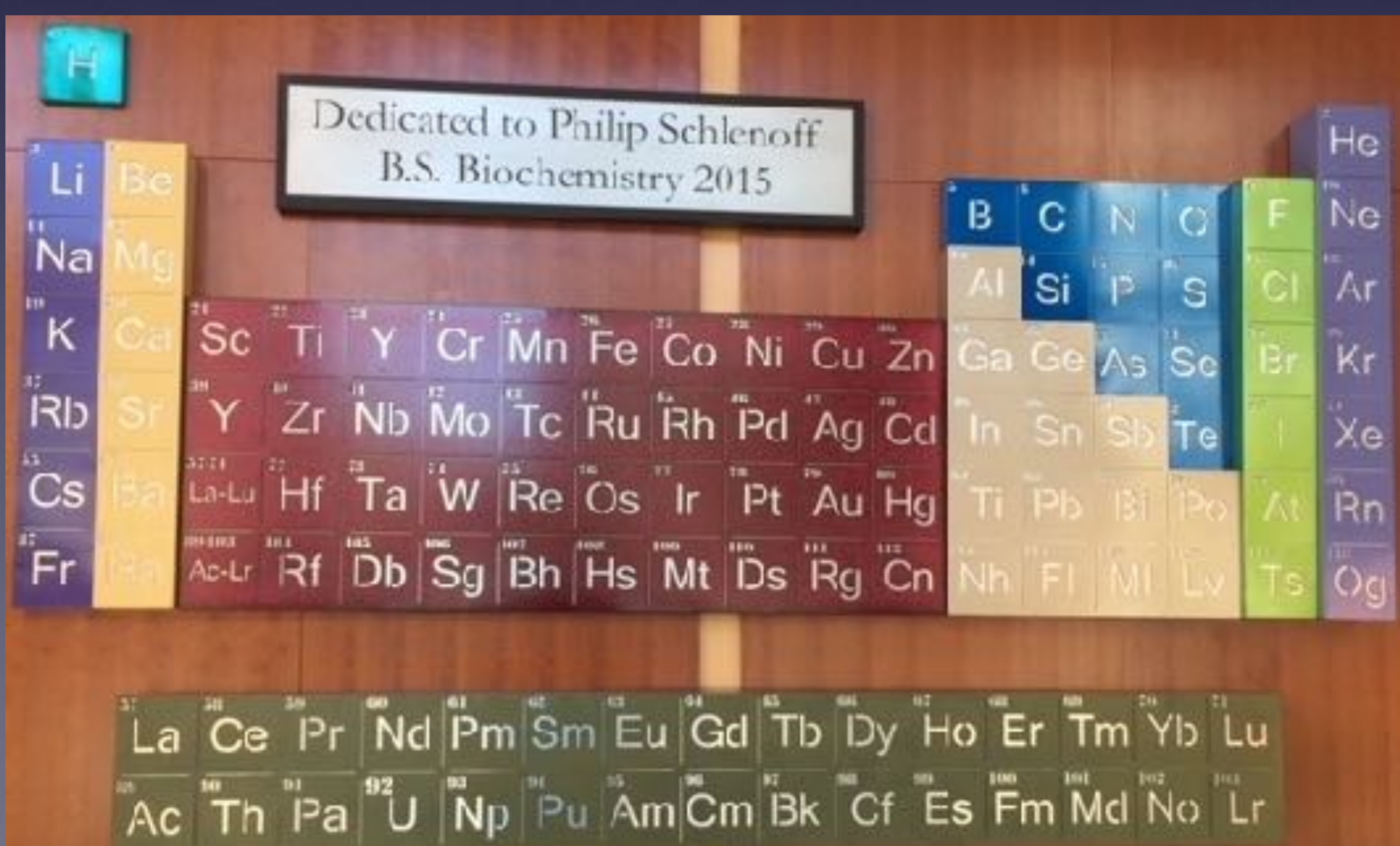
- Act 1: LIGO detects GW from BNS merger
  - Extraction of "tidal polarizability"
    Stringent limits on the EOS of dense matter
- Act 2: Fermi/Integral detect short γ-ray burst
  - detected ~2 seconds after GW signal
  - Confirms long-held belief of the association between BNS merger and γ-ray bursts
- Act 3: ~70 telescopes tracked the "kilonova"
  - Afterglow of the explosive merger ~11 hours later
  - Powered by the radioactive decay of "r-process" elements
    BNS mergers as a critical site for the r-process!

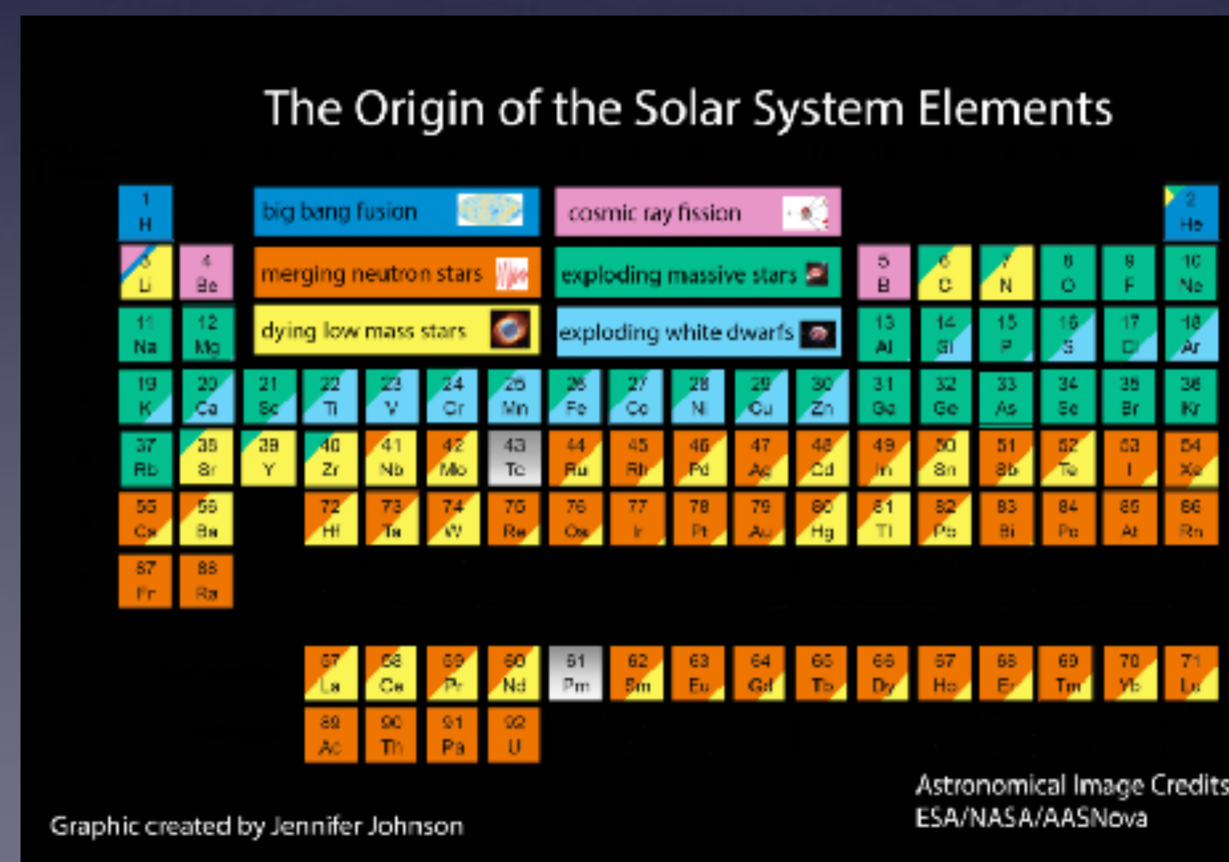
Neutron-star mergers create gravitational waves, light, and gold!

The New Periodic Table of the Elements

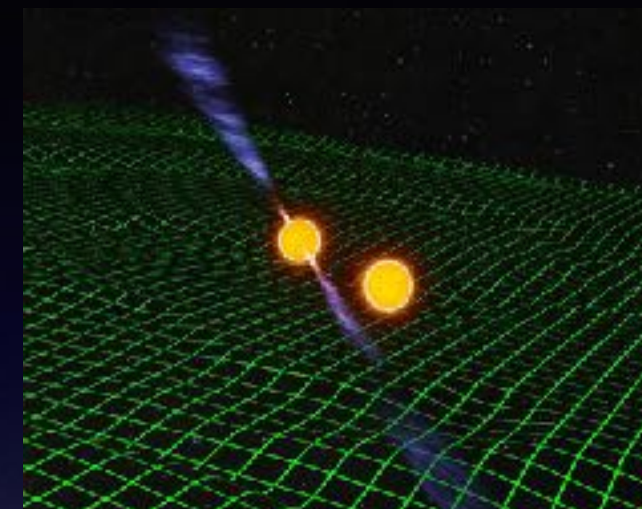
Abstract *MR Drout et al., Science - Dec, 2017*

On 17 August 2017, gravitational waves (GWs) were detected from a binary neutron star merger, GW170817, along with a coincident short gamma-ray burst, GRB 170817A. An optical transient source, Swope Supernova Survey 17a (SSS17a), was subsequently identified as the counterpart of this event. We present ultraviolet, optical, and infrared light curves of SSS17a extending from 10.9 hours to 18 days postmerger. We constrain the radioactively powered transient resulting from the ejection of neutron-rich material. The fast rise of the light curves, subsequent decay, and rapid color evolution are consistent with multiple ejecta components of differing lanthanide abundance. The late-time light curve indicates that SSS17a produced at least ~0.05 solar masses of heavy elements, demonstrating that neutron star mergers play a role in rapid neutron capture (r-process) nucleosynthesis in the universe.

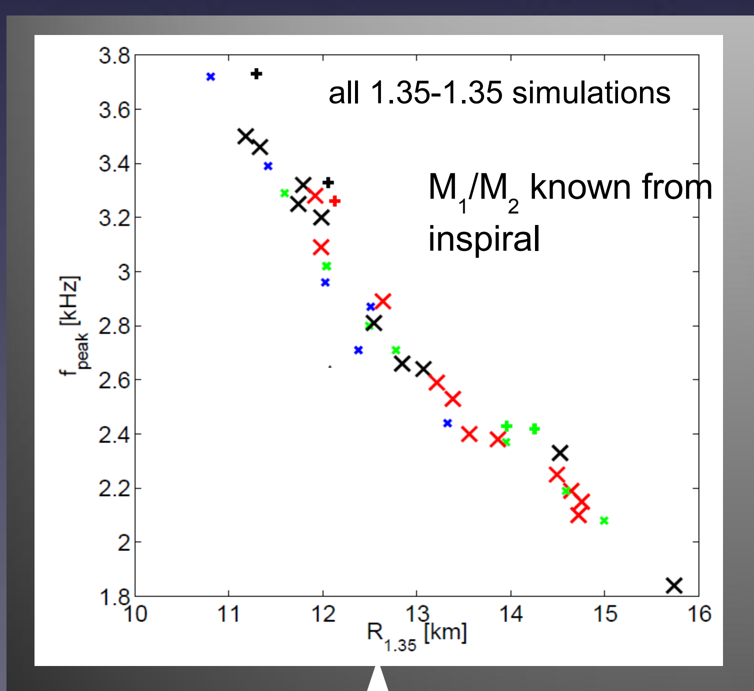


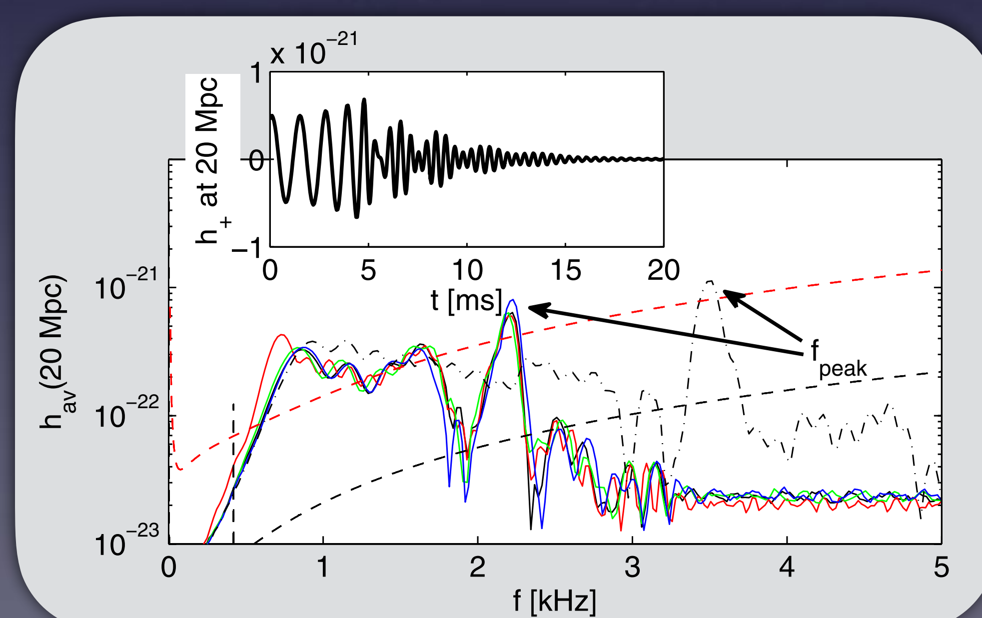


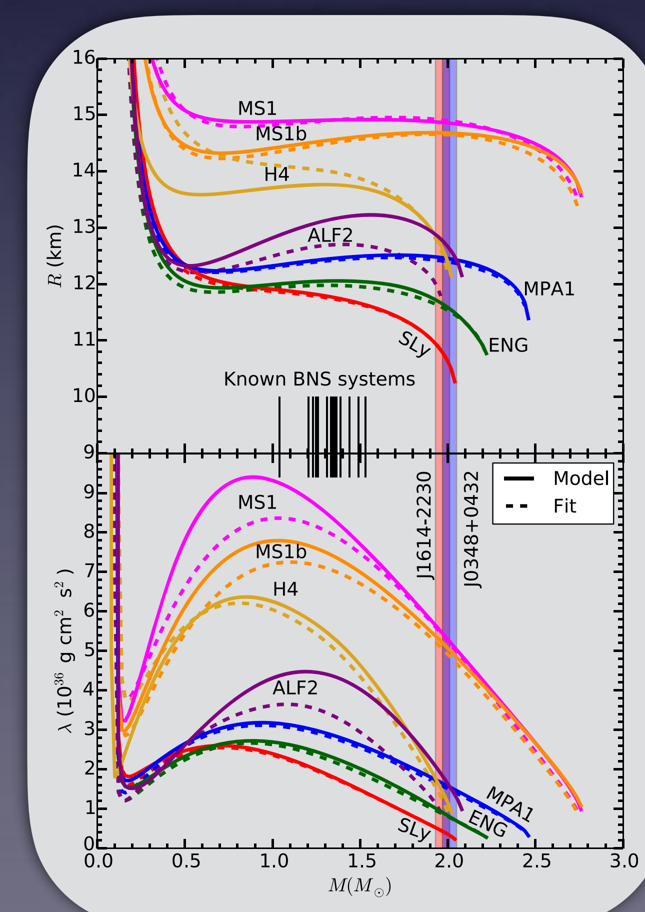
What Will We Learn from Neutron-Star Mergers



Tidal polarizability scales as R^5 …



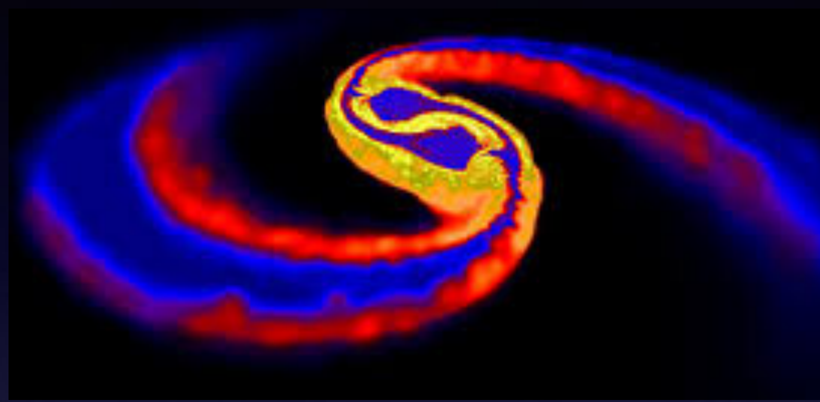




NS radius may be constrained by future BNS mergers to better than 1km!

Tidal Polarizability, Neutron-Star Radii, and the Equation of State

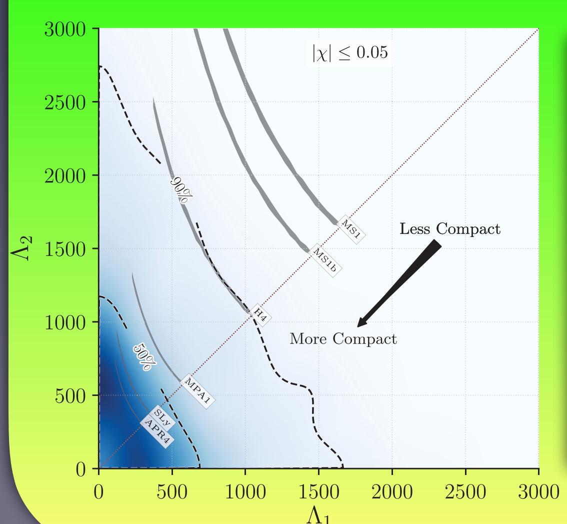
- Electric Polarizability:
  - Electric field induced a polarization of charge
  - A time dependent electric dipole emits electromagnetic waves: $P_i = \chi E_i$



- Tidal Polarizability:
  - Tidal field induces a polarization of mass
  - A time dependent mass quadrupole emits gravitational waves: $Q_{ij} = \Lambda \mathcal{E}_{ij}$

$$\Lambda \approx \left(\frac{c^2 R}{2GM}\right)^5 \simeq \left(\frac{R}{R_s}\right)^5$$

the posterior shown in Fig. 4. We find that our constraints on Λ_1 and Λ_2 disfavor equations of state that predict less compact stars, since the mass range we recover generates Λ values outside the 90% probability region. This is con-



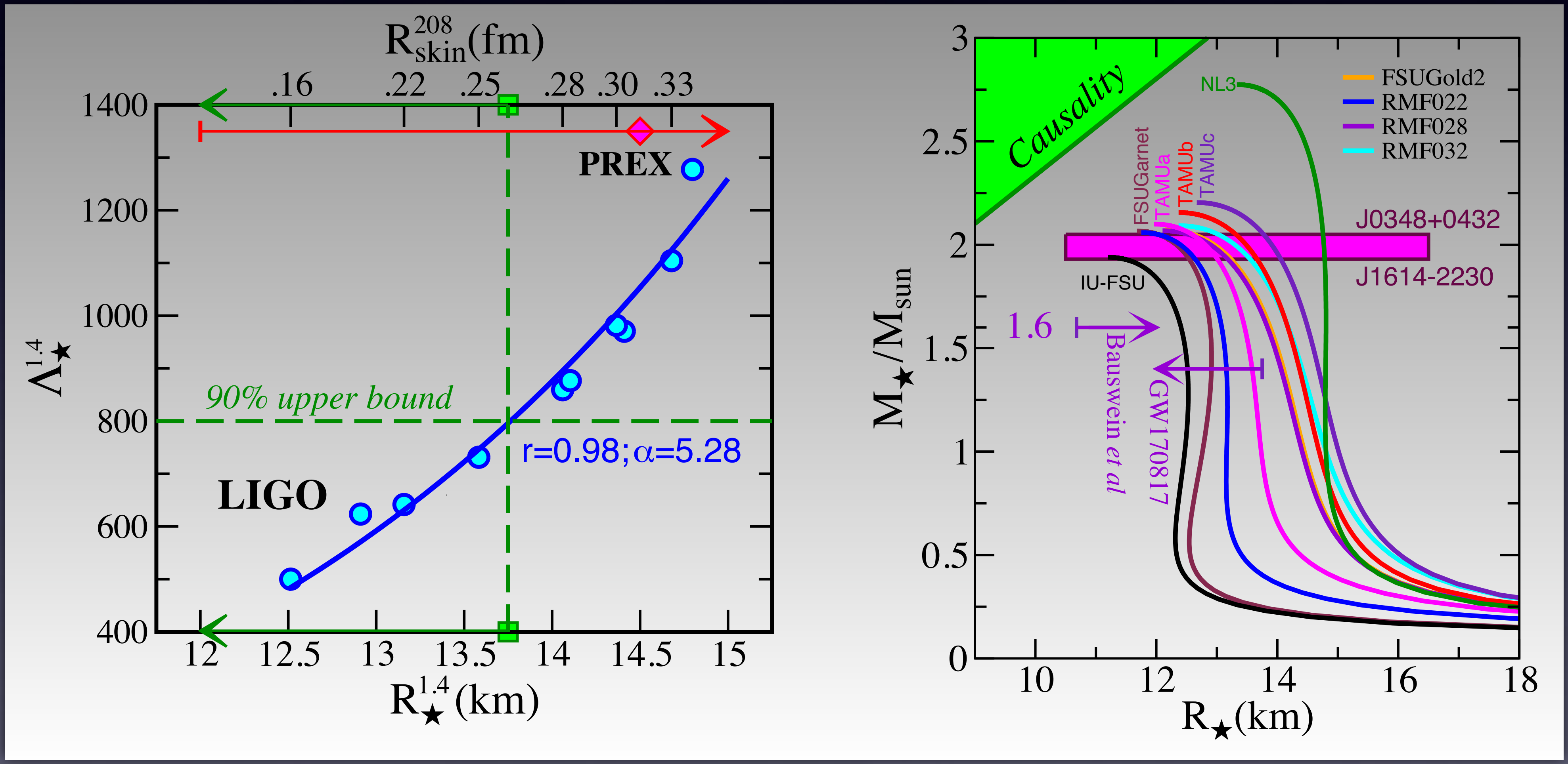
Equations of state with a very stiff symmetry energy (and very larger neutron star radii) are ruled out!

The tidal polarizability measures the "fluffiness" (or stiffness) of a neutron star against deformation

Neutron skins and neutron stars in the multi-messenger era

Neutron skins and neutron stars in the multi-messenger era

F. J. Fattoyev,[1,*] J. Piekarewicz,[2,†] and C. J. Horowitz[1,‡]
[1] *Center for Exploration of Energy and Matter and Department of Physics, Indiana University, Bloomington, IN 47405, USA*
[2] *Department of Physics, Florida State University, Tallahassee, FL 32306, USA*
(Dated: November 16, 2017)



Exciting possibility: If PREX confirms that Rskin is large and LIGO-Virgo that NS-radius is small, this may be evidence of a softening of the EOS at high densities (phase transition?)

The very first observation of a BNS merger already provides a treasure trove of insights into the nature of dense matter!

Color Superconductivity in Quark Matter

QCD Made Simple

Quantum chromodynamics is conceptually simple. Its realization in nature, however, is usually very complex. But not always.

Frank Wilczek

Quantum chromodynamics, familiarly called QCD, is the modern theory of the strong interaction.[1] Historically its roots are in nuclear physics and the description of ordinary matter—understanding what protons and neutrons are and how they interact. Nowadays QCD is used to describe most of what goes on at high-energy accelerators.

to the presence or motion of color charge, very similar to the way photons respond to electric charge.

Quarks and gluons

One class of particles that carry color charge are the quarks. We know of six different kinds, or "flavors," of quarks—denoted u, d, s, c, b, and t, for: up, down,

Frank Wilczek
2004 Nobel Laureate
Herman Feshbach Professor of Physics
Massachusetts Institute of Technology

$$\mathcal{L} = \frac{1}{4g^2} G^a_{\mu\nu} G^a_{\mu\nu} + \sum_j \bar{q}_j (i\gamma^\mu D_\mu + m_j) q_j$$

where $G^a_{\mu\nu} \equiv \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + i f^a_{bc} A^b_\mu A^c_\nu$

and $D_\mu \equiv \partial_\mu + i t^a A^a_\mu$

That's it!

Physics Today - August, 2000

Have We Discovered Quark Stars?


NASA

National Aeronautics and Space Administration

News Release

Marshall Space Flight Center - Huntsville Ala. 35812

http://www.msfc.nasa.gov/news

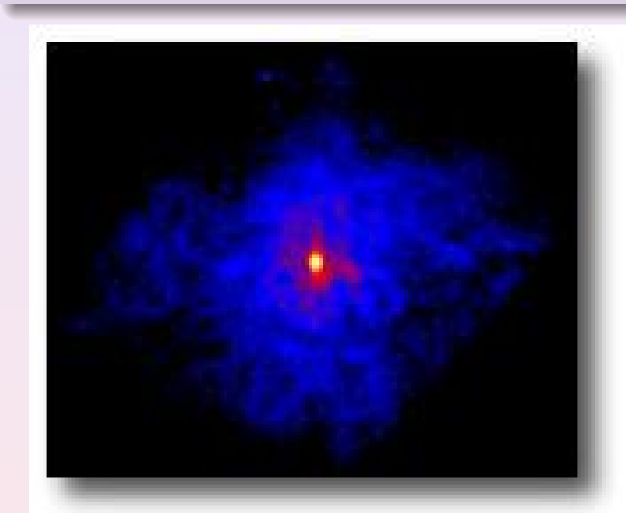
For Release: April 10, 2002

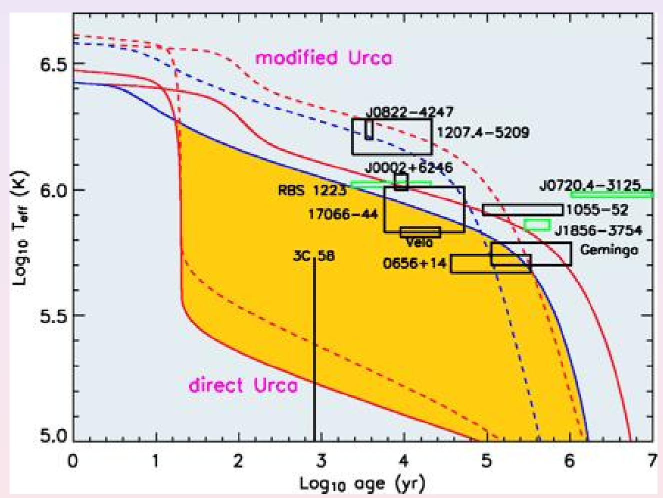
Release: 02 082

Cosmic X-rays reveal evidence for new form of matter

Enhanced vs Minimal Cooling of Neutron Stars: Quark Stars?

- Core-collapse supernovae generates hot (proto) neutron star $T \simeq 10^{12}\mathrm{K}$
- Neutron stars cool promptly by ν-emission (URCA) $n \to p + e^{-} + \bar{\nu}_e \ldots$
- Direct URCA process cools down the star until $T \simeq 10^{9}\mathrm{K}$
- Inefficient modified URCA takes over $(n) + n \to (n) + p + e^{-} + \bar{\nu}_e \ldots$





- Neutrino "enhanced" cooling possible in exotic quark matter
- **Unless ...** symmetry energy is stiff: large $Y_p \Leftrightarrow$ large neutron skin

- Assume $R_n - R_p \lesssim 0.18$ fm and $M(3C58) \lesssim 1.3 M_{\odot}$
- Then the pulsar in 3C58 may indeed be a quark star

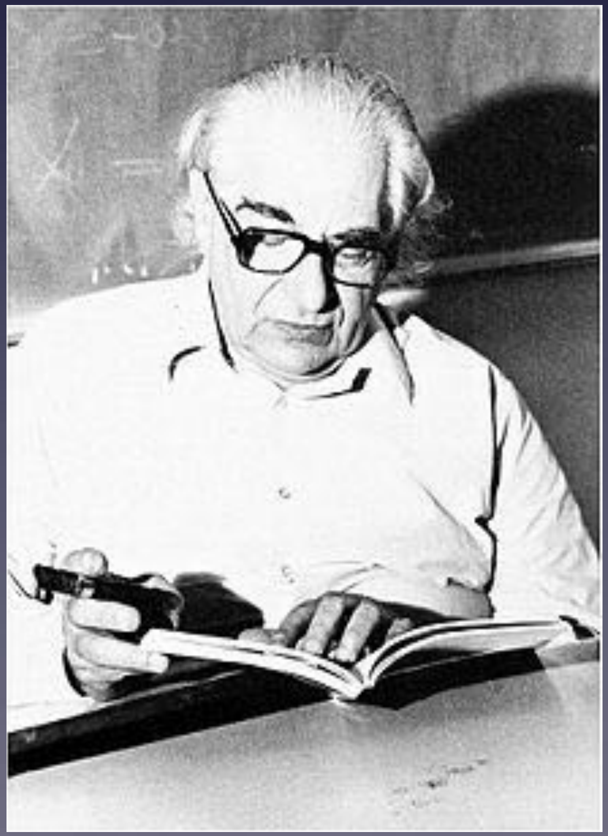
George Gamow and URCA cooling

Gamow, Schenberg, and URCA Cooling?

- URCA is not an acronym but rather, the name of a Casino in Rio de Janeiro where George Gamow commented to the Brazilian astrophysicist Mario Schenberg: *“The energy disappears in the nucleus of the supernova as quickly as the money disappears at the roulette table”*

- In Gamow’s Russian dialect, “urca” also means a *pickpocket*, someone that can steel your money in a matter of seconds!

URCA Casino, Rio de Janeiro

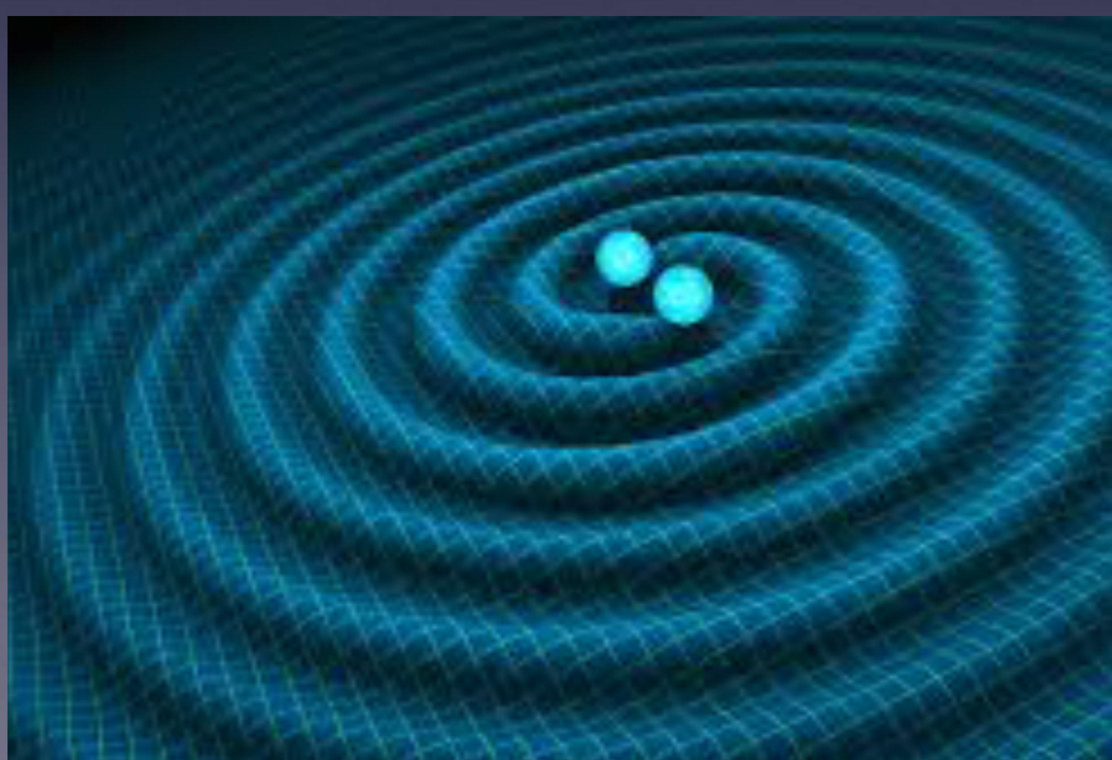


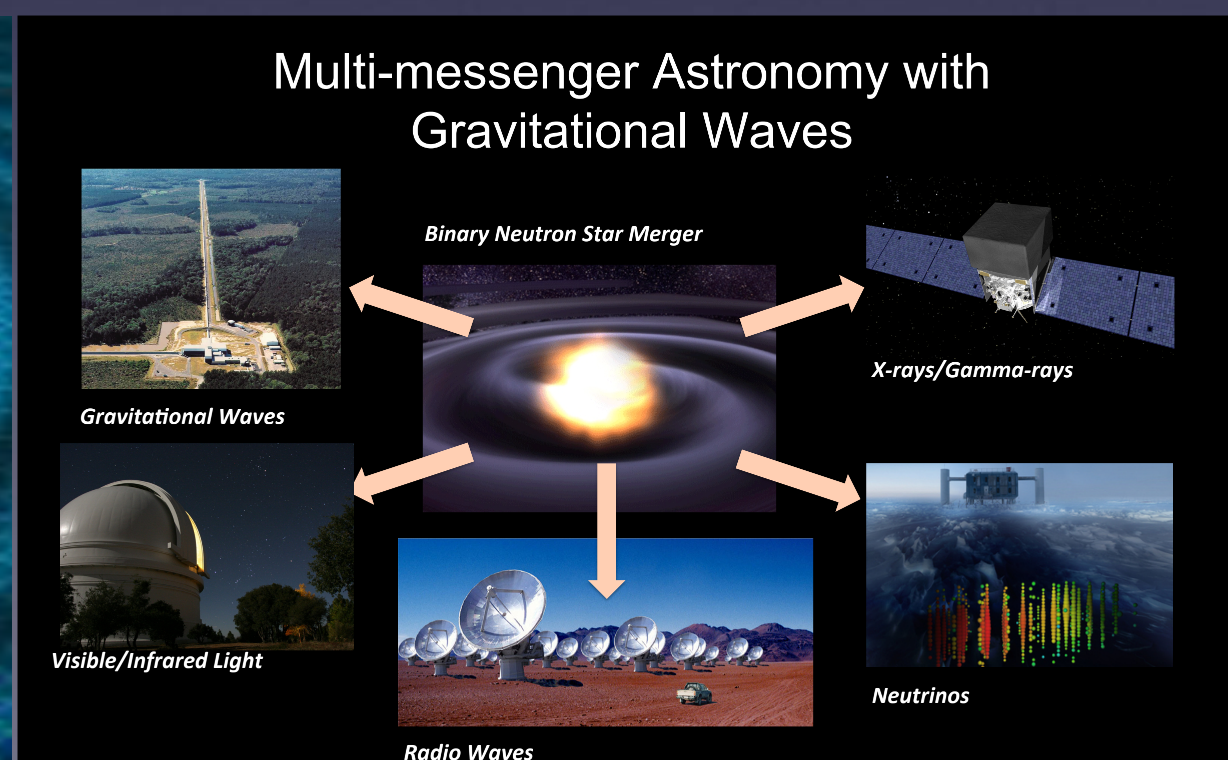
Gamow and Schenberg

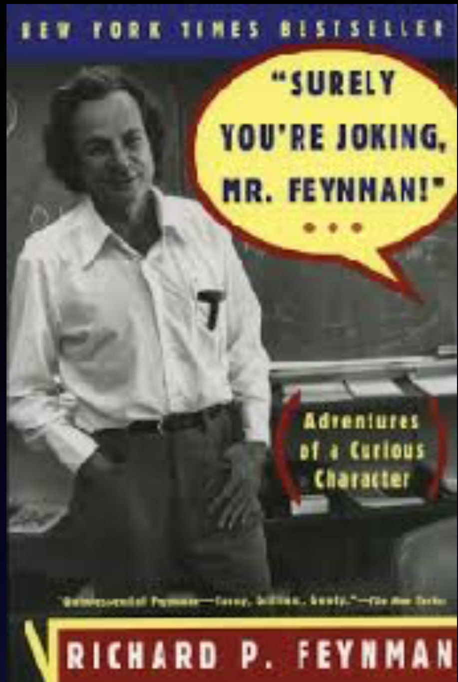
Conclusions: It is all Connected

- Astrophysics: What is the minimum mass of a black hole?
- C.Matter Physics: Existence of Coulomb-Frustrated Nuclear Pasta?
- General Relativity: Can BNS mergers constrain stellar radii?
- Nuclear Physics: What is the EOS of neutron-rich matter?
- Particle Physics: What exotic phases inhabit the dense core?
- Machine Learning: Extrapolation to where no man has gone before?

Neutron Stars are the natural meeting place for interdisciplinary, fundamental, and fascinating physics!







A message from Feynman
to all the students

May 11, 1918

"That night I calculated all kinds of things with this theory
(V-A theory of the weak interactions)
The first thing I calculated was the rate of disintegration of the muon and the neutron. I went on and checked some other things, which fit, and new things fit, new things fit, and I was very excited. It was the first time, and the only time, in my career that I knew a law of nature that nobody else knew."

Until we meet again …
Muito obrigado
Florianópolis!