# Neutron-rich matter in heaven and on Earth

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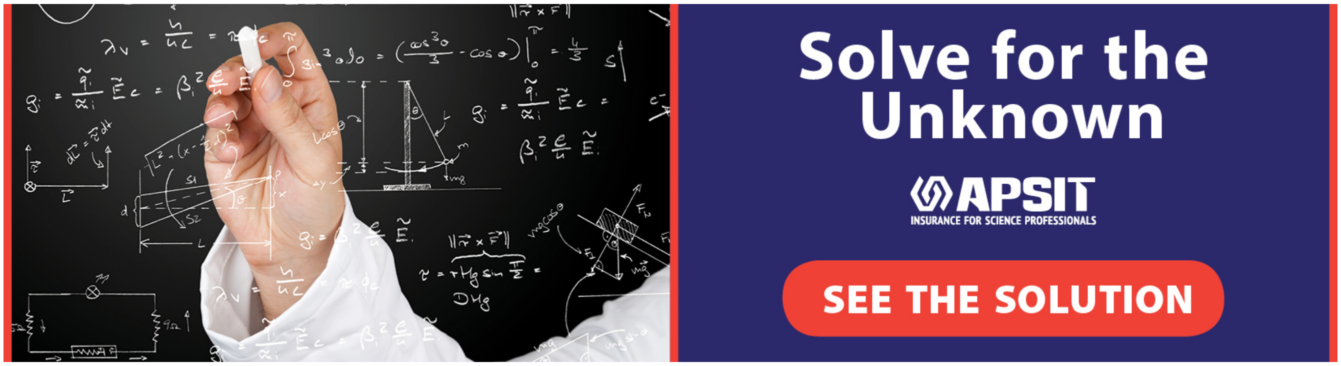
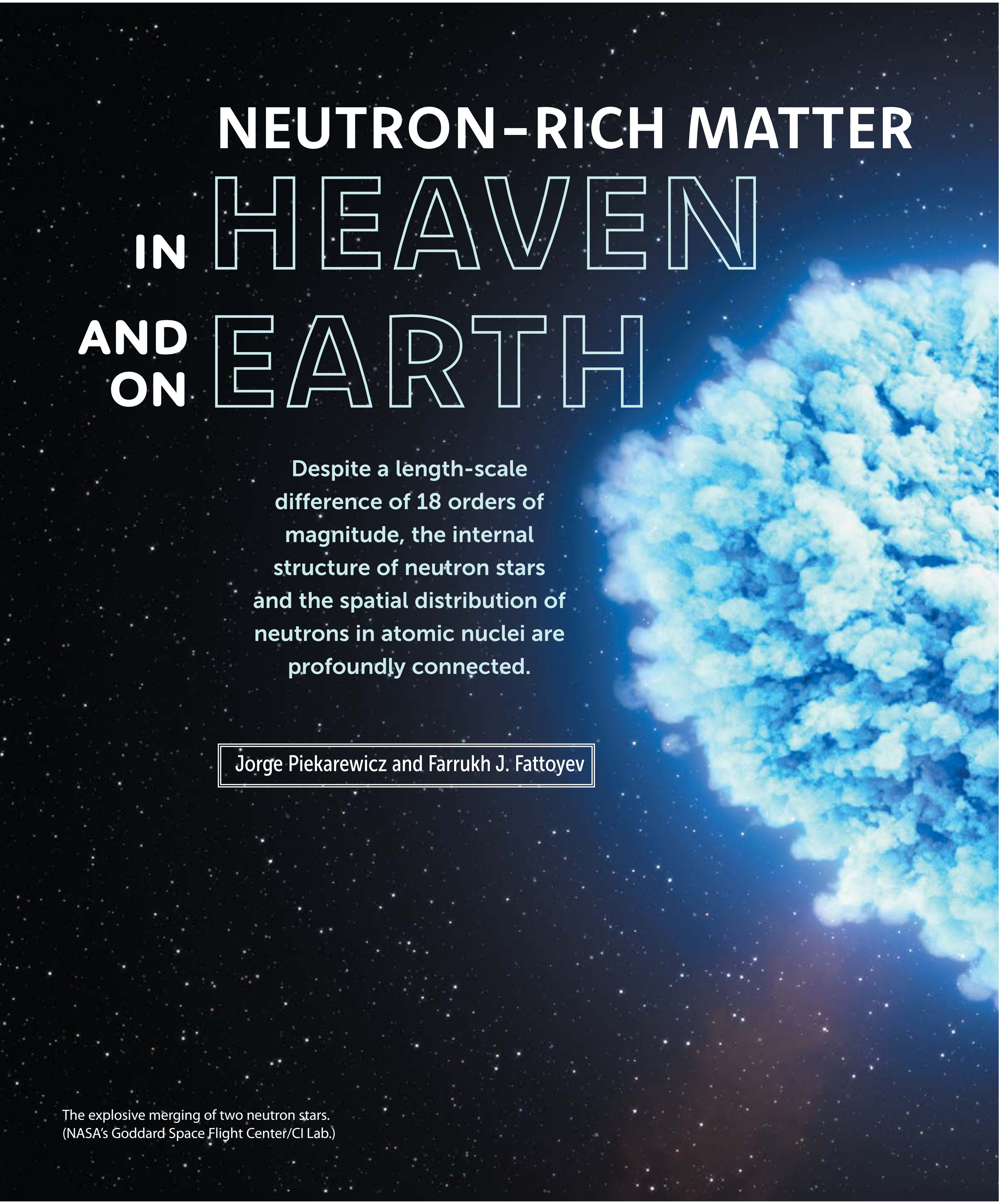


# NEUTRON-RICH MATTER IN HEAVEN AND ON EARTH

Despite a length-scale difference of 18 orders of magnitude, the internal structure of neutron stars and the spatial distribution of neutrons in atomic nuclei are profoundly connected.

**Jorge Piekarewicz and Farrukh J. Fattoyev**



The explosive merging of two neutron stars. (NASA's Goddard Space Flight Center/CI Lab.)

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Where do neutrons go? The elusive answer to such a seemingly simple question provides fundamental new insights into the structure of both atomic nuclei and neutron stars. To place the question in the proper context, consider lead-208, the element's most abundant isotope, which contains 82 protons and 126 neutrons. As the heaviest known doubly magic nucleus, $^{208}$Pb holds a special place in the nuclear-physics community. Just as noble gases with filled electronic shells exhibit low levels of chemical reactivity, doubly magic nuclei with filled proton and neutron shells display great stability. Because $^{208}$Pb is heavy, the Coulomb repulsion among its protons leads to a large neutron excess. The Lead Radius Experiment, or PREX, at the Thomas Jefferson National Accelerator Facility in Virginia was built to measure the location of $^{208}$Pb's 44 excess neutrons.[1] In turn, a detailed knowledge of the neutron distribution in $^{208}$Pb illuminates the structure of a neutron star.

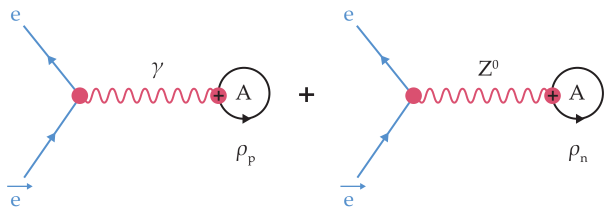


**FIGURE 1. PROBING THE NEUTRON DISTRIBUTION.** The Feynman diagram on the left illustrates the exchange of a photon between an electron and an atomic nucleus, and the one on the right shows the exchange of a neutral weak boson $Z^0$. The quantum mechanical interference of the two generates a difference in the cross section between right- and left-handed polarized electrons. The induced parity-violating asymmetry provides a powerful model-independent tool to probe the neutron distribution of neutron-rich nuclei.

To understand how the challenging measurement was made, consider the liquid-drop model[2,3] of George Gamow, Carl von Weizsäcker, Hans Bethe, and Robert Bacher, which they developed shortly after James Chadwick's discovery of the neutron. In the model, the atomic nucleus is regarded as an incompressible drop consisting of two quantum fluids. One is electrically charged and consists of $Z$ protons; the other is electrically neutral with $N$ neutrons. The radius of the charged drop—indeed, the entire proton distribution—has been accurately mapped since the advent of powerful electron accelerators in the 1950s. In contrast, knowledge of the neutron distribution comes entirely from experiments involving strongly interacting probes, such as pions and protons. Unlike experiments with electromagnetic reactions involving weakly coupled photons, those with strongly interacting probes are difficult to decode because of myriad theoretical uncertainties. PREX took advantage of the flagship parity-violating program at Jefferson Lab to infer the radius of the neutron distribution in $^{208}$Pb.

In some parity-violating experiments, one measures the difference in the cross section between right- and left-handed longitudinally polarized electrons. In a world in which parity is exactly conserved, the parity-violating asymmetry would vanish. However, the weak interaction violates parity, so an asymmetry emerges from a quantum mechanical interference of two Feynman diagrams: a large one involving the exchange of a photon and a much smaller one involving the exchange of a neutral weak vector boson $Z^0$, as shown in figure 1. Whereas photons couple to the electric charge and are therefore insensitive to the neutron distribution, the $Z^0$ boson plays the complementary role. That is, the weak charge of the neutron is large compared with that of the proton,[4] which makes parity-violating electron scattering an ideal tool to determine the neutron distribution. PREX has provided the first model-independent evidence that the rms radius of the neutron distribution in $^{208}$Pb is larger than the corresponding radius of the proton distribution.[1] The difference between those two radii is known as the neutron-skin thickness, a dilute region of the nucleus populated primarily by neutrons.

## Neutron skins

Characterizing the neutron-rich skin in $^{208}$Pb may help constrain nuclear models that aim to describe the nuclear dynamics of both atomic nuclei and neutron stars in a single unified framework. The link between the very small and the very large is particularly compelling given that a strong connection has been established between the thickness of the neutron skin of $^{208}$Pb and the radius of a neutron star.[5] The dynamics behind such a correlation can be revealed by returning to the liquid-drop model, in which the nuclear binding energy is encoded in a handful of empirical parameters that represent volume, surface, Coulomb, and symmetry contributions:

$$B(Z,A) = a_v A - a_s A^{2/3} - a_c Z^2/A^{1/3} - a_a (N - Z)^2/A + \ldots.$$

The volume term $a_v$ scales with the total number of nucleons $A = Z + N$, and that fact underscores both the short-range nature and saturation properties of the underlying nuclear force. A hallmark of nuclear dynamics is the existence of a saturation density of about $\rho_0 \approx 0.15\ \text{fm}^{-3}$, which is close but not equal to the nearly constant central density observed in atomic nuclei. The next two terms represent corrections to the energy that result from the development of a finite nuclear surface $a_s$ and the Coulomb repulsion among protons $a_c$. A quantum correction is applied for asymmetric nuclei because of the Pauli exclusion principle. The last term—the sym-

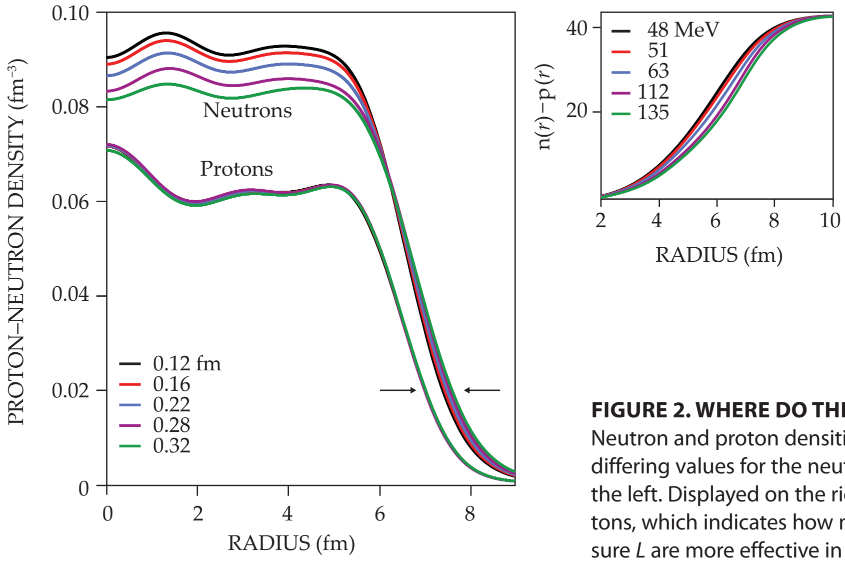
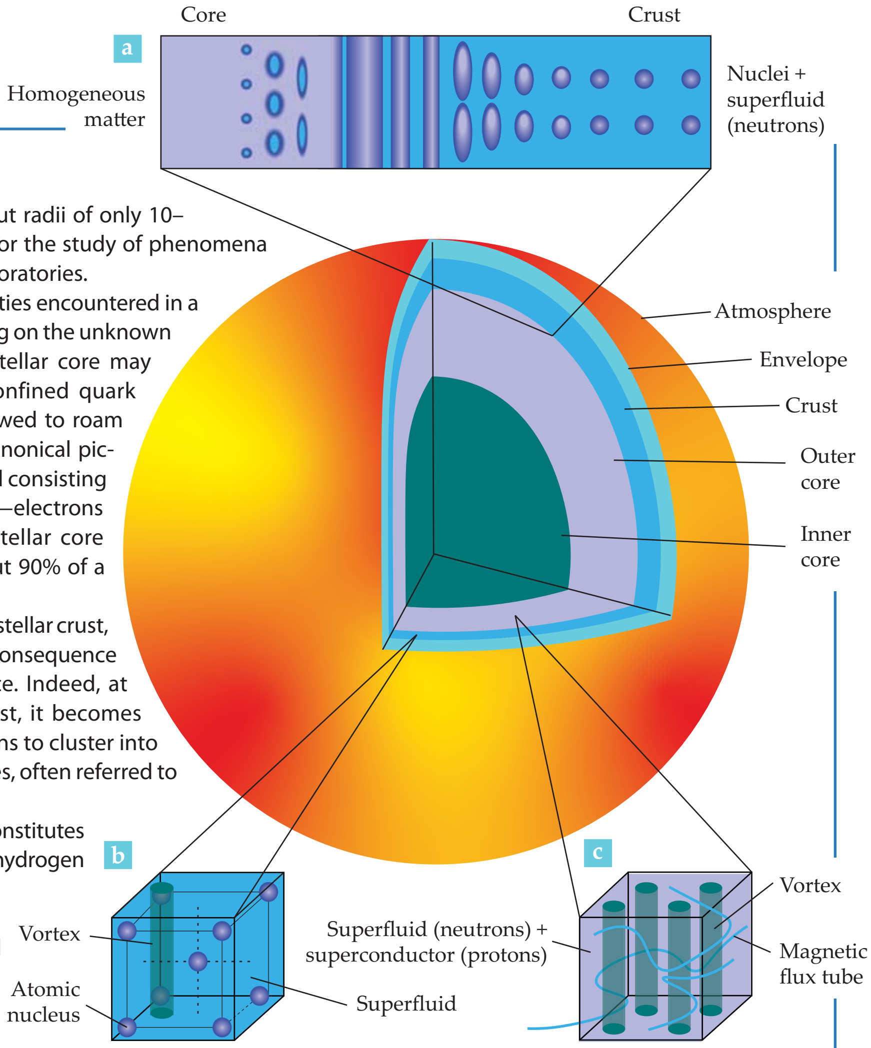


**FIGURE 2. WHERE DO THE EXCESS NEUTRONS OF LEAD-208 GO?** Neutron and proton densities in $^{208}$Pb are predicted by various models with differing values for the neutron-skin thickness, as shown in the legend on the left. Displayed on the right is the running sum of neutrons minus protons, which indicates how models with larger values of the symmetry pressure $L$ are more effective in pushing the 44 excess neutrons to the surface.

# BOX 1. ANATOMY OF A NEUTRON STAR



With masses comparable to that of our sun but radii of only 10–15 km, neutron stars are unique laboratories for the study of phenomena that lie well outside the realm of terrestrial laboratories.

The stellar composition at the highest densities encountered in a neutron star's inner core is unknown. Depending on the unknown compressibility of neutron-rich matter, the stellar core may harbor exotic states of matter, such as deconfined quark matter, a novel state in which quarks are allowed to roam freely at enormously high densities. Yet the canonical picture of the stellar core is that of a uniform liquid consisting of neutrons, protons, and neutralizing leptons—electrons and muons—in chemical equilibrium. The stellar core accounts for practically all the mass and about 90% of a neutron star's size.

Above the uniform core lies the nonuniform stellar crust, a region about 1 km thick that develops as a consequence of the short-range nature of the nuclear force. Indeed, at the subsaturation densities of the stellar crust, it becomes energetically favorable for neutrons and protons to cluster into complex nuclei that display highly exotic shapes, often referred to as nuclear pasta.

The outermost surface of the neutron star constitutes the very thin atmosphere that is composed of hydrogen but may also contain heavier elements such as helium and carbon. To date, most of the information on neutron star radii has been obtained from the thermal emission from its surface, often assumed to be consistent with a blackbody spectrum. Unfortunately, complications due to both distortions to the blackbody spectrum and distance measurements make the determination of stellar radii a challenging task. Yet the discovery of gravitational waves from GW170817 has opened a new window into the study of neutron star properties and will nicely complement electromagnetic observations. (Image adapted from artwork by Dany Page.)

metry energy $a_a$ and especially its density dependence—is crucial in connecting the neutron-skin thickness of atomic nuclei to the radius of a neutron star.

Although the liquid-drop model successfully describes the smooth variation of the nuclear binding energy with $Z$ and $N$, the atomic nucleus is not an incompressible liquid drop. So although highly insightful, the semiempirical mass formula fails to capture the response of the liquid drop to changes in density. That information is embodied in the equation of state, which dictates how the energy depends on the overall density and neutron–proton asymmetry of the system.

In the thermodynamic limit and ignoring the long-range Coulomb interaction, the energy per nucleon at the equilibrium density is given entirely by the terms of volume $a_v$ and symmetry energy $a_a$. The volume term $a_v$ accounts for the dynamics of a symmetric system having equal numbers of protons and neutrons, whereas $a_a$ penalizes the system for breaking the symmetry.

So what happens as the system departs from its equilibrium position? Changes to the energy per nucleon with density are imprinted in the pressure. However, the contribution to the pressure from the symmetric term vanishes at the equilibrium density. Thus the entire contribution to the pressure at saturation density comes from the symmetry pressure. Often denoted in the literature by $L$, the quantity is closely related to the pressure at saturation density of a system made entirely of neutrons; that is, $P_0 \approx L\rho_0 / 3$. The symmetry pressure, therefore, controls both the neutron-skin thickness of atomic nuclei and the radius of a neutron star.[6]

## Connecting the very large to the very small

Where do the 44 excess neutrons in $^{208}$Pb go? Although the liquid-drop model favors the formation of a spherical drop of uniform density, it is unclear what fraction of the excess neutrons should reside at the surface or in the core. Surface tension favors placing them in the core, which tends to minimize the surface area. But the symmetry energy, which is larger at the core than at the surface, disfavors that arrangement. Conversely, moving them to the surface increases the surface tension but reduces the symmetry energy. Thus the thickness of the neutron skin is determined by a tug-of-war between the surface tension and the difference between the symmetry energy at saturation density and at the lower surface density. That difference is nothing more than the symmetry pressure $L$. If the pressure is large, then energy considerations favor the excess neutrons to move to the surface where the low symmetry energy results in a thick neutron skin.[6]

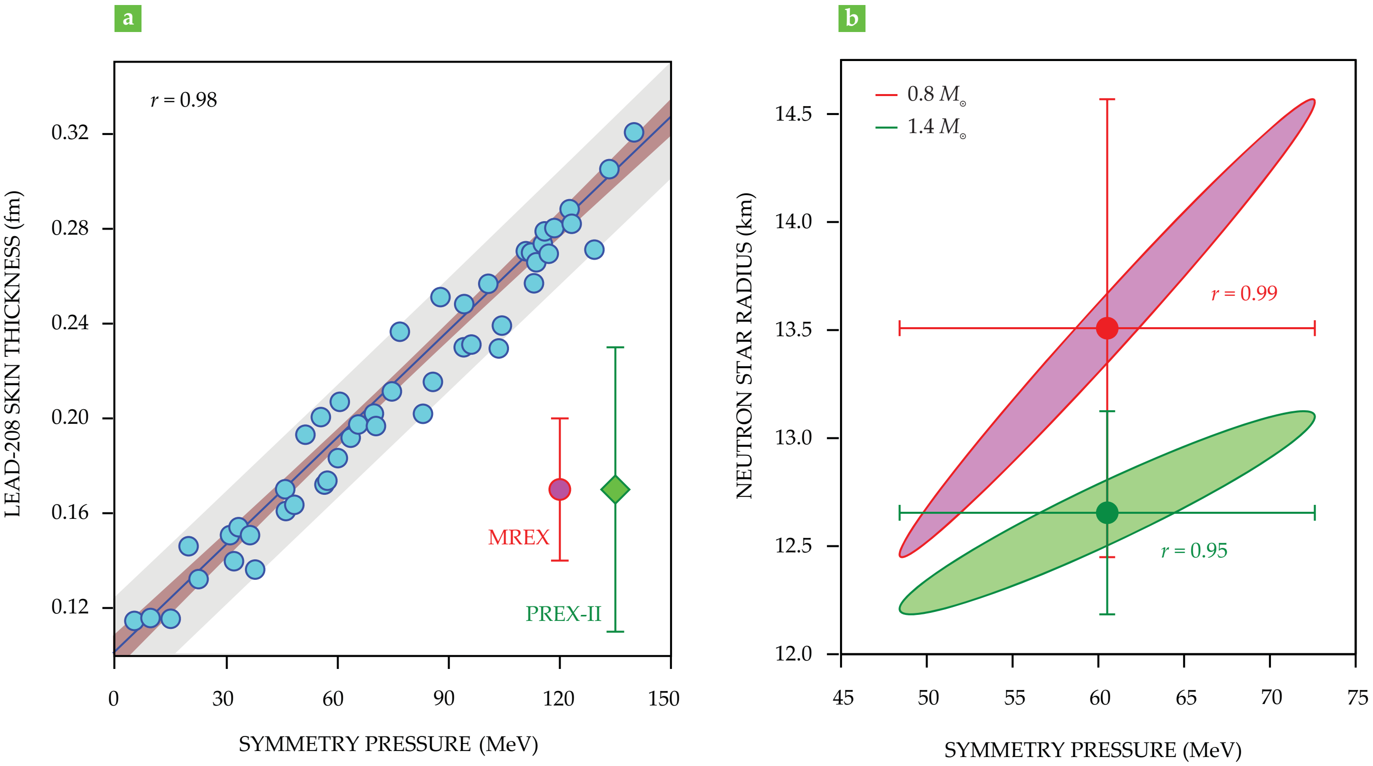


**FIGURE 3. CONNECTING THE VERY SMALL TO THE VERY LARGE.** The symmetry pressure *L* controls both the neutron-skin thickness of lead-208 and the radius of a neutron star despite the difference in size of 18 orders of magnitude. Many successful models illustrate the correlation **(a)** between *L* and the neutron-skin thickness of $^{208}$Pb. (Adapted from ref. 7.) The correlation between *L* and the radii of two neutron stars **(b)** is illustrated for different masses.

Where the neutrons go is nicely illustrated in figure 2, which displays neutron and proton densities for $^{208}$Pb as predicted by various models that successfully reproduce properties of finite nuclei and neutron stars.[7] Given that the proton (or rather the charge) distribution of $^{208}$Pb has been measured with remarkable precision, no significant spread is observed in the model predictions. Instead, challenging parity-violating experiments are required for a clean measurement of neutron densities. And although PREX has provided an important first step, the precision attained was insufficient to distinguish between the various competing models. The result means that a large model spread remains for the neutron densities and consequently for the neutron-skin thickness, whose values are indicated in the figure 2 legend on the left and schematically depicted by the region between the two arrows. The running sum, which naturally terminates at 44, represents the total number of excess neutrons accumulated up to a distance *r*. Models with a large symmetry pressure *L* push the excess neutrons farther out to the surface.

The strong correlation between the neutron-skin thickness of $^{208}$Pb and the symmetry pressure *L* is evident in figure 3a, which shows predictions from a large number of models that utilize density functional theory in the spirit of the models[7] displayed in figure 2. With a Pearson correlation coefficient of nearly 1, the correlation is strong indeed. Such a result indicates how a fundamental parameter of the equation of state of neutron star matter can be measured in a terrestrial laboratory. The error bars in figure 3a indicate the precision anticipated for upcoming campaigns: PREX-II at Jefferson Lab and the Mainz Radius Experiment at the future Mainz Energy-Recovering Superconductor Accelerator at Johannes Gutenberg University.

Remarkably, it is the same symmetry pressure *L* that determines the radius of a neutron star, as shown in figure 3b. In that case, however, the symmetry pressure pushes against the immense gravitational attraction encountered in the stellar interior. Yet regardless of whether the pressure pushes against surface tension or against gravity, both the neutron-skin thickness of $^{208}$Pb and the radius of a neutron star are sensitive to the symmetry pressure in the vicinity of saturation density. Despite a difference in size of 18 orders of magnitude, a powerful data-to-data relation emerges: The thicker the neutron-skin thickness of $^{208}$Pb, the larger the radius of a neutron star. The correlation is particularly strong for low-mass neutron stars in which the interior density is only slightly larger than saturation density. As shown in figure 3b, the correlation coefficient weakens from $r = 0.99$ to $r = 0.95$ in going from a neutron star with solar mass of 0.8 to 1.4.

## Neutron stars

Neutron stars are fascinating systems whose understanding requires a convergence of disciplines. Although the most common perception of a neutron star is that of a uniform assembly of neutrons packed to enormous densities, the reality is far dif-

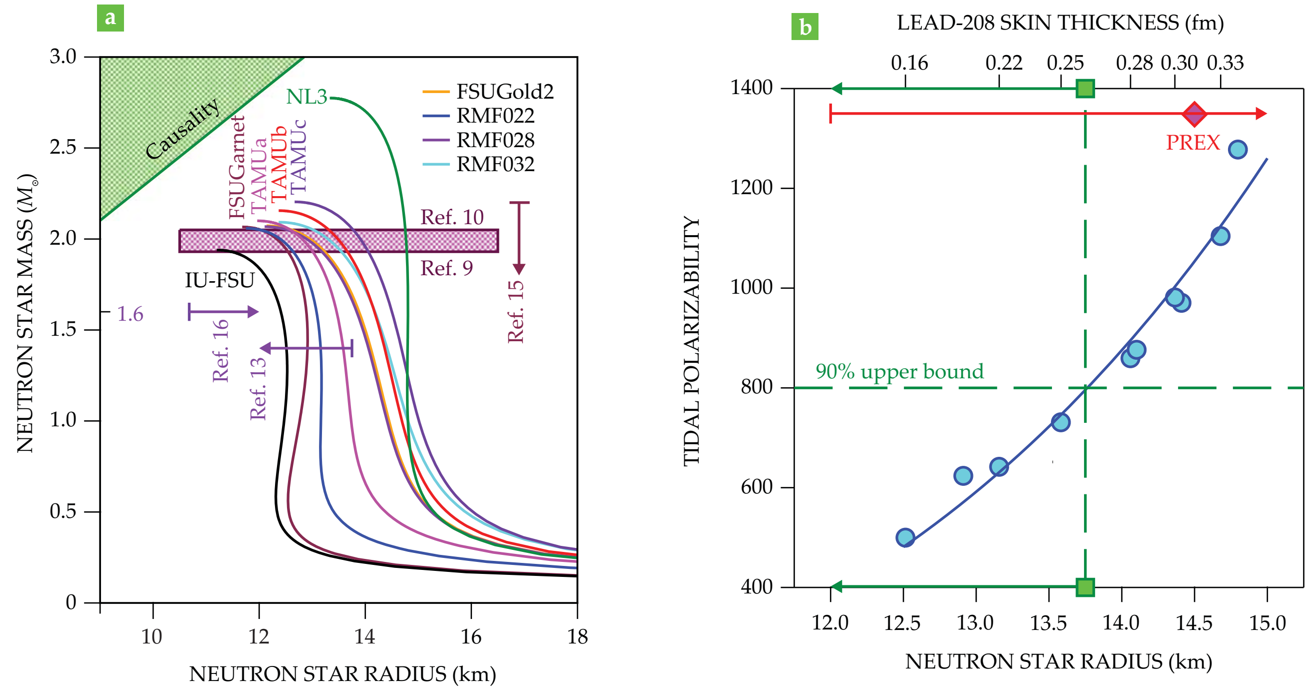


**FIGURE 4. THE MASS-VERSUS-RADIUS RELATION (a)** of neutron stars is reproduced by models (colored lines), which predict different stellar radii. Arrows indicate the limits that were obtained by combining electromagnetic and gravitational-wave observations. The rectangle defines the lower limits of the maximum stellar radius determined by photometry.[9,10] The other limits emerge from electromagnetic and gravitational-wave data from GW170817. Models predicting a maximum mass below the rectangle are inconsistent with observations. The green triangle denotes the forbidden area that violates causality, that is, faster-than-light speed of sound. The same models predict the tidal polarizability and radius **(b)** for a 1.4-solar-mass neutron star and the neutron-skin thickness of lead-208. Limits on the tidal polarizability inferred from GW170817 suggest that both the neutron star radius and the neutron-skin thickness are relatively small. However, the Lead Radius Experiment at the Thomas Jefferson National Accelerator Facility in Virginia reported a large value for the neutron-skin thickness of $^{208}$Pb, albeit with large error bars. (Figures adapted from ref. 13.)

ferent and much more interesting. First theorized in 1933 by Walter Baade and Fritz Zwicky, neutron stars—or more precisely the radio pulses they emit—were detected in 1968 by a talented Cambridge graduate student named Jocelyn Bell Burnell. The achievement famously won her doctoral adviser, but not her, a share of the 1974 Nobel Prize in Physics.[8] Bell Burnell's contributions were honored in 2018 with the Special Breakthrough Prize in Fundamental Physics, and she has announced that she will donate the full $3 million award to programs that support diversity in the field.

Nuclear physics is important for elucidating the structure and composition of neutron stars (see box 1). Unlike white dwarf stars, which are entirely supported against gravitational collapse by the pressure from their degenerate electrons, neutron stars get critical pressure support from nuclear interactions. Indeed, in a 1939 paper, J. Robert Oppenheimer and George Volkoff demonstrated that a neutron star supported exclusively by neutron degeneracy pressure will collapse into a black hole once its mass exceeds 0.7 solar masses ($M_\odot$). Today, however, physicists know of at least two neutron stars with masses[9,10] as large as 2 $M_\odot$.

The surface of a neutron star, though largely insensitive to nuclear dynamics, is of observational importance because it significantly influences estimates of the stellar radius. Assuming that the thermal emission from the surface follows a blackbody spectrum at a uniform temperature, then the stellar radius may be determined from the Stefan–Boltzmann law, which relates the luminosity to the temperature and radius of the star. Unfortunately, the determination of stellar radii by photometric means has been plagued by large systematic uncertainties arising from unreliable distance measurements and from distortions to the blackbody spectrum from a thin stellar atmosphere. In the past, those uncertainties revealed discrepancies in the extraction of stellar radii as large as 5–6 km. (Average neutron star radii are 10–15 km.) Fortunately, the situation has improved significantly through a better understanding of systematic uncertainties, important theoretical developments, and the implementation of robust statistical methods.[11] And while the uncertainty has now been reduced to about a couple of kilometers, a powerful new player has entered the game: gravitational-wave astronomy.

## Multimessenger astronomy

The first direct detection of gravitational waves, from a binary neutron star merger known as GW170817, by the collaboration of the Laser Interferometer Gravitational-Wave Observatory (LIGO) and Virgo has begun a new era of multimessenger astronomy.[12] Besides gravitational waves, electromagnetic counterparts associated with both a short gamma-ray burst and a

## BOX 2. HEAVEN AND EARTH

The neutron-skin thickness of atomic nuclei offers valuable insights into the nature of neutron-rich matter. Parity-violating electron scattering, a sensitive and powerful experimental tool perfected at the Thomas Jefferson National Accelerator Facility in Virginia, has been used to provide the first model-independent evidence in support of a neutron-rich skin in lead-208. Later this year the neutron-skin thickness of $^{208}$Pb and calcium-48 will be measured with enough precision to constrain both nuclear models and the symmetry pressure *L*. To accomplish that ambitious project, state-of-the-art equipment—like the five-story-high spectrometer shown in the top figure—is essential. (Photo courtesy of DOE Jefferson Lab.)

On 17 August 2017, the collaboration of the Laser Interferometer Gravitational-Wave Observatory (LIGO) and Virgo (shown in the second image) detected gravitational waves from the merger of two neutron stars known as GW170817. The detection provided critical insights for the synthesis of the heavy elements and the nature of neutron-rich matter—fundamental questions that scientists hope will be addressed by the mission of the Facility for Rare Isotope Beams (FRIB) currently under construction at Michigan State University. The LIGO–Virgo collaboration began its third operating run in April 2019, and the scientists anticipate detecting many more binary neutron star mergers. (Photo courtesy of Caltech/MIT/LIGO Lab.)

Two of the main science drivers of FRIB are the study of the heaviest elements and the production of exotic nuclei with thick neutron skins. In particular, FRIB will use strongly interacting probes to measure the neutron-skin thickness of short-lived isotopes. To ensure the success of such a challenging program, the upcoming electroweak measurements at Jefferson Lab will be instrumental in supplying critical calibrating anchors. The third image shows the progress on FRIB's high-power superconducting linear accelerator, which will propel heavy ions and produce rare isotopes by in-beam fragmentation. (Photo courtesy of Michigan State University.)

The Neutron Star Interior Composition Explorer (NICER) is part of NASA's first program dedicated specifically to studying the exotic structure and composition of neutron stars. Launched in June 2017 aboard SpaceX's Falcon 9 rocket, NICER was successfully deployed to the International Space Station, as shown in the bottom photo. By measuring radii of neutron stars, NICER will provide some of the most stringent tests of the equation of state of neutron-rich matter. NICER is a powerful complement to LIGO in this brand-new era of multimessenger astronomy. (Photo courtesy of NASA/CI Lab/Walt Feimer.)

long-term kilonova powered by the radioactive decay of *r*-process elements were also detected (see the article by Anna Frebel and Timothy C. Beers, PHYSICS TODAY, January 2018, page 30). GW170817 has also provided fundamental new insights into the nature of dense matter.

Critical properties of the equation of state are encoded in the tidal polarizability, a property that describes the neutron star's tendency to deform in response to the tidal field induced by a companion star. The tidal polarizability is highly sensitive to the stellar structure and scales as the fifth power of the compactness. That quantity is defined as the ratio of the stellar radius to the Schwarzschild radius—that is, the radius at which the star would become a black hole. The Schwarzschild radius is directly proportional to the stellar mass; for our sun it is approximately 3 km. So, as two neutron stars approach each other, the phase of the gravitational wave deviates from its point-mass nature characteristic of black holes, and those deviations are imprinted in the tidal polarizability.

A fluffy or large-radius neutron star is much easier to polarize than a corresponding compact star with the same mass but a smaller radius. Given the sensitivity of the gravitational-wave signal to the neutron star structure, limits on the tidal polarizability inferred from GW170817 rule out overly large stellar radii and thereby provide a powerful complementary approach to the traditional photometric techniques.[13,14] Additional observational limits have been obtained on both the maximum stellar mass and the minimum radius of a 1.6 solar-mass neutron star.[15,16] As shown in figure 4a, the limiting values of stellar radii and maximum masses are now starting to paint a detailed picture of the mass-versus-radius relation.

## A bright future

How do all the new developments illuminate the connection between GW170817 and atomic-scale laboratory experiments? In particular, given their sensitivity to the symmetry pressure, how do the inferred limits on stellar radii reflect on the neutron-skin thickness of $^{208}$Pb? Considering that GW170817 disfavors overly large stellar radii, the inferred neutron-skin thickness is well below the central value measured by the PREX collaboration[13] and is clearly illustrated in figure 4b. To reduce the experimental uncertainty by a factor of three, the follow-up PREX-II experiment is scheduled to run at Jefferson Lab in 2019. After it and its sister campaign on calcium-48 are completed, the lab will pass the baton to the Facility for Rare Isotope Beams (FRIB) at Michigan State University that will study exotic nuclei with thick neutron skins.

**A strong connection has been established between the thickness of the neutron skin of lead-208 and the radius of a neutron star.**

The third observing run by the LIGO–Virgo collaboration began in April 2019 with the promise of many more detections of binary neutron star mergers. A PREX-II confirmation that the neutron-skin thickness of $^{208}$Pb is large would imply that the symmetry pressure is also large or "stiff" at the typical densities found in atomic nuclei. If at the same time the LIGO–Virgo collaboration validates the relatively small stellar radii suggested by GW170817, then it will imply that the symmetry pressure is small or soft at about twice the saturation density. The evolution of the symmetry energy from stiff at typical nuclear densities to soft at slightly higher densities may indicate an exotic phase transition in the neutron star interior. In a recent reanalysis of GW170817 data, the LIGO–Virgo collaboration obtained limits on the tidal polarizability that are even more stringent than reported in the original discovery paper.

The determination of the symmetry pressure $L$—and more generally the density dependence of the symmetry energy—has far-reaching consequences in areas of physics as diverse as precision tests of the standard model using atomic-parity violation, the collision of heavy ions, and nuclear and neutron star structures. However, the search for new physics beyond the standard model is hindered by large uncertainties in the neutron radius, which, as previously discussed, is highly sensitive to $L$. Above saturation density, the symmetry pressure may be determined by means of experiments involving the collision of heavy ions, the only way to probe vast regions of the nuclear equation of state in terrestrial laboratories. Past experiments with energetic heavy ions enabled nuclear matter to be compressed to several times the nuclear saturation density and allowed researchers to extract the equation of state of symmetric nuclear matter. Current uncertainties in the density dependence of the symmetry energy are large, yet ongoing international efforts, such as the RIKEN Nishina Center for Accelerator-Based Science in Japan, FRIB, and the Facility for Antiproton and Ion Research at the GSI Helmholtz Center for Heavy Ion Research in Germany, are poised to probe neutron-rich matter at suprasaturation density and will offer a better understanding of its properties.

Although the multimessenger era is still in its infancy, the first observation of a binary neutron star merger is already providing a treasure trove of insights into the nature of dense matter. In the new era of multimessenger astronomy, the strong synergy between nuclear physics and astrophysics will grow even stronger. As illustrated in box 2, ultrasensitive gravitational-wave observatories, Earth- and space-based telescopes operating at various wavelengths, and new terrestrial facilities probing atomic nuclei at the limits of their existence are poised to answer 2 of the 11 science questions for the next century:[17] What are the new states of matter at exceedingly high density and temperature? How were the elements from iron to uranium made? The future is very bright indeed!

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