Astrophysical Constraints on the Symmetry Energy and the Neutron Skin of ^{208}Pb with Minimal Modeling Assumptions

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The symmetry energy and its density dependence are crucial inputs for many nuclear physics and astrophysics applications, as they determine properties ranging from the neutron-skin thickness of nuclei to the crust thickness and the radius of neutron stars. Recently, PREX-II reported a value of 0.29±0.07 fm for the neutron-skin thickness of ^{208}Pb, implying a slope parameter $L = 110 \pm 37$ MeV, larger than most ranges obtained from microscopic calculations and other nuclear experiments. We use a nonparametric equation of state representation based on Gaussian processes to constrain the symmetry energy S_0, L, and $R_{\rm skin}^{^{208}\rm Pb}$ directly from observations of neutron stars with minimal modeling assumptions. The resulting astrophysical constraints from heavy pulsar masses, LIGO/Virgo, and NICER clearly favor smaller values of the neutron skin and L, as well as negative symmetry incompressibilities. Combining astrophysical data with PREX-II and chiral effective field theory constraints yields $S_0 = 34^{+3}_{-3}$ MeV, $L = 58^{+19}_{-19}$ MeV, and $R_{\rm skin}^{^{208}\rm Pb} = 0.19^{+0.03}_{-0.04}$ fm.

Introduction– The symmetry energy $S(n)$ is a central quantity in nuclear physics and astrophysics. It characterizes the change in the nuclear-matter energy as the ratio of protons to neutrons is varied and thus impacts, e.g., the neutron-skin thickness of nuclei [1–3], their dipole polarizability [4, 5], and the radius of neutron stars (NSs) [6, 7]. This information is encoded in the nuclear equation of state (EOS), described by the nucleonic energy per particle, $E_{\rm nuc}/A$, a function of total baryon density n and proton fraction $x = n_p/n$ for proton density n_p. The energy per particle is connected to the bulk properties of atomic nuclei for proton fractions close to $x = 1/2$, i.e., symmetric nuclear matter (SNM) with $E_{\rm SNM}/A = (E_{\rm nuc}/A)|_{x=1/2}$. As the neutron-proton asymmetry increases (or the proton fraction x decreases) the energy per particle increases, reaching a maximum for $x = 0$, i.e., pure neutron matter (PNM) with $E_{\rm PNM}/A = (E_{\rm nuc}/A)|_{x=0}$. PNM is closely related to NS matter. The symmetry energy characterizes the difference between these two systems:

$$S(n) = \frac{E_{\rm PNM}}{A}(n) - \frac{E_{\rm SNM}}{A}(n)\,. \tag{1}$$

Crucial information is encoded in the density dependence of $S(n)$, which is captured by the slope parameter L and the curvature $K_{\rm sym}$ defined at nuclear saturation density, $n_0 \sim 0.16\,{\rm fm}^{-3}$,

$$L = 3n\,\frac{\partial S(n)}{\partial n}\bigg|_{n_0}\,, \quad K_{\rm sym}(n) = 9n^2\,\frac{\partial^2 S(n)}{\partial n^2}\bigg|_{n_0}\,. \tag{2}$$

As $d(E_{\rm SNM}/A)/dn = 0$ at n_0, L describes the pressure of PNM around n_0. $S_0 = S(n_0)$ and L are of great interest to nuclear physics [5, 8, 9] and astrophysics [10–12]. Experimental [4, 5, 13, 14] and theoretical [15–18] determinations consistently place S_0 in the range of 30–35 MeV and L in the range of 30–70 MeV. Recently, however, the PREX-II experiment reported a new result for the neutron-skin thickness of ^{208}Pb [19], $R_{\rm skin}^{^{208}\rm Pb}$, a quantity strongly correlated with L (see, e.g., [1–3]). The measurement of $R_{\rm skin}^{^{208}\rm Pb} = 0.29 \pm 0.07$ fm (mean ± standard deviation), including PREX-I and PREX-II data, led Ref. [20] to conclude that $L = 110 \pm 34$ MeV. This value is larger than previous determinations, and thus presents a challenge to our understanding of nuclear matter, should a high L value be confirmed precisely.

In this Letter, we address this question by constraining S_0, its density dependence L, and $R_{\rm skin}^{^{208}\rm Pb}$ directly from astrophysical observations. We adopt a nonparametric representation for the EOS [21, 22] to minimize the model dependence of the analysis, in contrast to other astrophysical inferences, e.g., Refs. [23–26]. Nonparametric inference allows us to explore a multitude of EOSs that are informed *only* by a NS crust model at densities $n < 0.3n_0$, where the EOS uncertainty is small, combined with the requirements of causality and thermodynamic stability at higher densities. Following Ref. [27], the possible EOSs are weighted based on their compatibility with gravitational-wave (GW) and electromagnetic observations of NSs (massive pulsars and X-ray timing with NICER). By calculating S_0, L, $K_{\rm sym}$ and $R_{\rm skin}^{^{208}\rm Pb}$ for each of these EOSs, we obtain astrophysically informed posterior distributions for these key nuclear properties. Furthermore, we study how L and $R_{\rm skin}^{^{208}\rm Pb}$ change as constraints from nuclear theory are included up to progres-

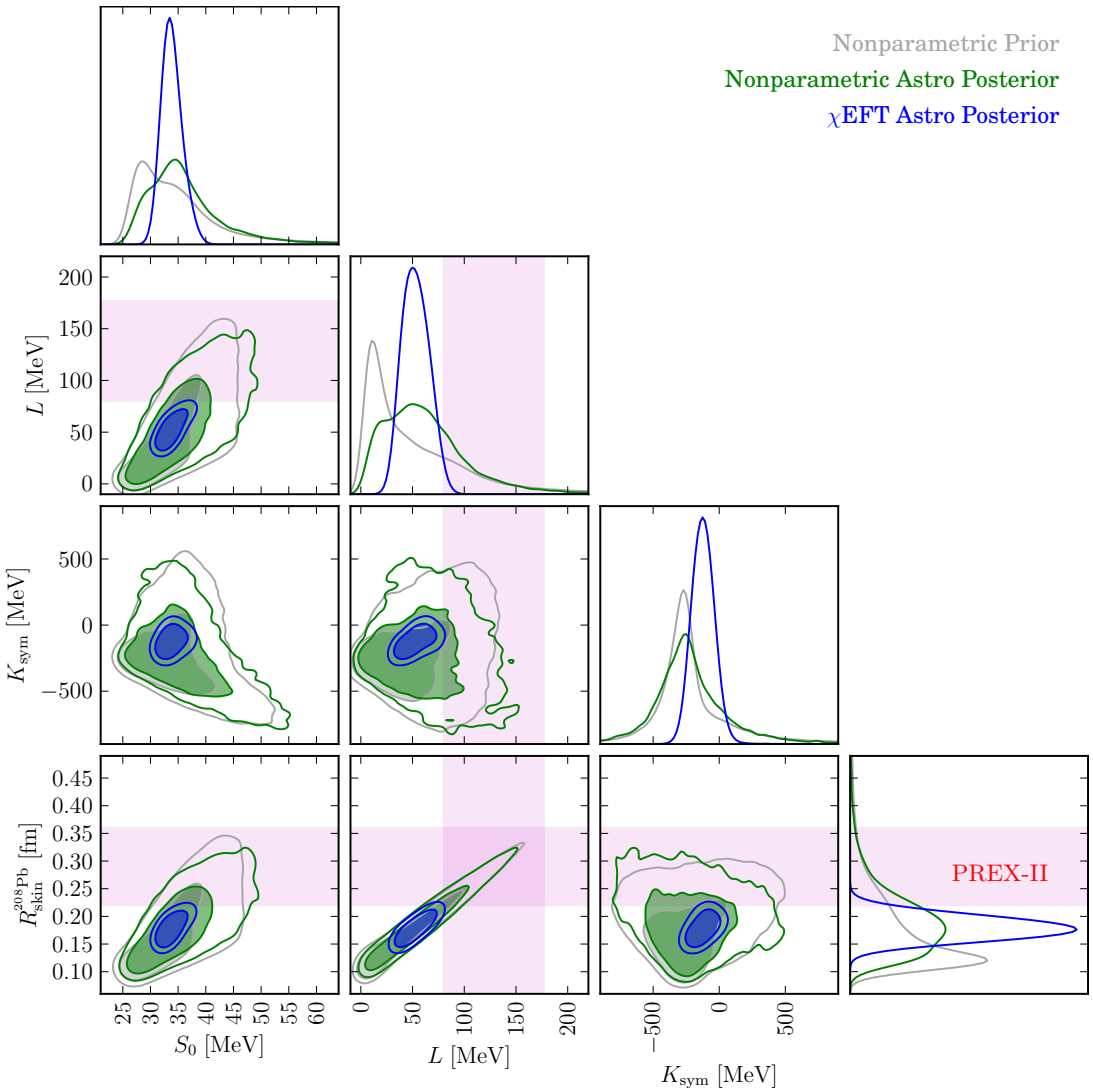

Figure 1. Correlations between the symmetry energy S_0, the slope parameter L, the symmetry incompressibility $K_{\rm sym}$, and the neutron skin thickness of ^{208}Pb: $R_{\rm skin}^{^{208}\rm Pb}$. We show the nonparametric prior (*grey*), the nonparametric posterior conditioned on astrophysical observations (*green*), and the nonparametric posterior conditioned on four χEFT calculations (up to $\sim n_0$) and astrophysical observations (*blue*). Joint distributions show the 68% (*shaded*) and 90% (*solid lines*) credible regions. Shaded bands (*pink*) show the approximate 68% credible region for parameters constrained by PREX-II: $R_{\rm skin}^{^{208}\rm Pb}$ [19] and the resulting constraints on L using the correlation from Ref. [2]. Note how the inclusion of the astrophysical observations shifts the peak in the marginal distributions for S_0, L and $R_{\rm skin}^{^{208}\rm Pb}$, a trend that is reinforced by the addition of χEFT information.

sively higher densities.

Nonparametric inference for the EOS– We connect NS observables to S_0 and L using a nonparametric representation of the EOS based on Gaussian processes (GPs) [21, 22]. The GPs model the uncertainty in the correlations between the sound speed in β-equilibrium at different pressures, but do not specify the exact functional form of the EOS, unlike other parameterizations [28–36]. The nonparametric EOSs consequently exhibit a wider range of behavior than parametric EOSs, mitigating the impact of modeling assumptions.

The nonparametric EOS inference proceeds through Monte-Carlo sampling from a prior constructed as a mixture of GPs to obtain a large set of EOS realizations. Each EOS is then compared to astrophysical observations via optimized kernel density estimates (KDEs) of the likelihoods, resulting in a discrete representation of the posterior EOS process as a list of weighted samples (see [22, 27] for more details). The posterior probability of a given EOS realization ε_β is calculated as

$$P(\varepsilon_\beta|\{d\}) \propto P(\varepsilon_\beta) \prod_i P(d_i|\varepsilon_\beta), \tag{3}$$

where $\{d\} = \{d_1, d_2, \dots\}$ is the set of observations,

	$E_{\rm PNM}/A$ [MeV]	S_0 [MeV]	L [MeV]	$K_{\rm sym}$ [MeV]	$R_{\rm skin}^{^{208}\rm Pb}$ [fm]
Nonparametric Prior	17^{+15}_{-8}	33^{+15}_{-8}	38^{+110}_{-40}	-255^{+847}_{-572}	$0.16^{+0.15}_{-0.07}$
Nonparametric Astro Posterior	19^{+12}_{-9}	35^{+12}_{-9}	57^{+66}_{-53}	-245^{+586}_{-483}	$0.18^{+0.10}_{-0.09}$
Nonparametric Astro+PREX-II Posterior	22^{+12}_{-10}	38^{+12}_{-10}	83^{+66}_{-53}	-246^{+686}_{-557}	$0.22^{+0.10}_{-0.08}$
χEFT Astro Posterior	18^{+3}_{-2}	34^{+3}_{-2}	52^{+20}_{-18}	-124^{+132}_{-135}	$0.18^{+0.04}_{-0.04}$
χEFT Astro+PREX-II Posterior	18^{+3}_{-2}	34^{+3}_{-3}	58^{+19}_{-19}	-107^{+128}_{-138}	$0.19^{+0.03}_{-0.04}$

Table I. Medians and 90% highest-probability-density credible regions. We compute $R_{\rm skin}^{^{208}\rm Pb}$ from L using the linear fit reported in Ref. [2], approximating the uncertainty in the fit as described in the text.

$P(d_i|\varepsilon_\beta)$ are the corresponding likelihood models, and $P(\varepsilon_\beta)$ is the EOS realization's prior probability. The specific likelihoods used in this work are as follows: (a) Pulsar timing measurements of masses for the two heaviest known NSs (PSR J0740+6620 [37], PSR J0348+0432 [38]) modeled as Gaussian distributions with means and standard deviations $2.14 \pm 0.10\,M_\odot$ and $2.01 \pm 0.04\,M_\odot$, respectively; (b) GW measurements of masses and tidal deformabilities in the binary NS merger GW170817 [39] from advanced LIGO [40] and Virgo [41], modeled with an optimized Gaussian KDE [22]; and (c) X-ray pulse-profile measurements of PSR J0030+0451's mass and radius assuming a three-hotspot configuration [42] (see also Ref. [43], which yields comparable results [27]), similarly modeled with an optimized Gaussian KDE [22].

Our basic nonparametric prior can also be conditioned self-consistently on theoretical calculations of the EOS at nuclear densities, while retaining complete model freedom at higher densities [44]. Here we marginalize over the uncertainty bands from four different chiral effective field theory (χEFT) calculations: quantum Monte Carlo calculations using local χEFT interactions up to next-to-next-to-leading order (N^{2}LO) [45], many-body perturbation theory (MBPT) calculations using nonlocal χEFT interactions up to next-to-next-to-next-to-leading order (N^{3}LO) of Refs. [16, 46], and MBPT calculations with two-nucleon interactions at N^{3}LO and three-nucleon interactions at N^{2}LO (based on a broader range of three-nucleon couplings) [31, 47]. This allows us to account for different nuclear interactions and many-body approaches, increasing the robustness of our results.

To translate the EOS posterior process into distributions for the nuclear physics properties, we establish a probabilistic map from ε_β to $E_{\rm PNM}/A$, S_0, L, and $K_{\rm sym}$ (described below). Marginalization over the EOS then yields a posterior

$$P(E_{\rm PNM}/A, S_0, L, K_{\rm sym}|\{d\}) = \int \mathcal{D}\varepsilon_\beta\, P(\varepsilon_\beta|\{d\}) P(E_{\rm PNM}/A, S_0, L, K_{\rm sym}|\varepsilon_\beta) \quad (4)$$

informed by the astrophysical observations. Constraints on $R_{\rm skin}^{^{208}\rm Pb}$ are obtained from empirical correlations with L [2] calculated from a broad range of nonrelativistic Skyrme and relativistic mean-field density functionals; see also Refs. [1, 3]. To account for the theoretical uncertainty in the fit of Ref. [2] and mitigate its model dependence, we adopt a probabilistic mapping: $P(R_{\rm skin}^{^{208}\rm Pb}|L) = \mathcal{N}(\mu_R, \sigma_R)$ with $\mu_R\,[\rm fm] = 0.101 + 0.00147 \times (L\,[\rm MeV])$ and $\sigma_R = 0.0125\,\rm fm$.

Reconstructing the symmetry energy– Because our nonparametric EOS realizations are not formulated in terms of S_0, L, or $K_{\rm sym}$, we discuss how to extract the nuclear parameters near n_0 directly from the EOS. The nonparametric inference provides the individual EOSs in terms of the baryon density n, and pressure p_β and energy density ε_β in β-equilibrium. Each realization is matched to the BPS crust [48] around $0.3n_0$. The EOS quantities are related to $E_{\rm nuc}/A$ through $\varepsilon = n \cdot (E_{\rm nuc}/A + m_{\rm N})$ with the average nucleon mass m_N. To reconstruct $E_{\rm nuc}/A$, we correct ε_β by the electron contribution $\varepsilon_{\rm e}$,

$$\frac{E_{\rm nuc}}{A}(n,x) = \frac{\varepsilon_\beta(n) - \varepsilon_{\rm e}(n,x)}{n} - m_{\rm N}\,. \quad (5)$$

The proton fraction $x(n)$ is unknown and needs to be determined self-consistently for each EOS by enforcing β-equilibrium, $\mu_{\rm n}(n,x) = \mu_{\rm p}(n,x) + \mu_{\rm e}(n,x)$, where $\mu_i(n,x)$ is the chemical potential for particle species i. This leads to the condition for β-equilibrium (see [31] for details),

$$0 = m_{\rm n} - m_{\rm p} - \frac{\partial\,(E_{\rm nuc}/A)}{\partial x} - \mu_{\rm e}(n,x)\,. \quad (6)$$

To extract the symmetry energy from each EOS realization, we need to know the dependence of $E_{\rm nuc}/A$ with proton fraction. Here, we approximate the x dependence using the standard quadratic expansion,

$$\frac{E_{\rm nuc}}{A}(n,x) = \frac{E_{\rm SNM}}{A}(n) + S(n)(1-2x)^2\,. \quad (7)$$

Non-quadratic terms are small at n_0 and can be neglected given current EOS uncertainties [49, 50]. Because we work around n_0, we can characterize the SNM energy using the standard expansion,

$$\frac{E_{\rm SNM}}{A}(n) = E_0 + \frac{1}{2}K_0\left(\frac{n-n_0}{3n_0}\right)^2 + \cdots\,, \quad (8)$$

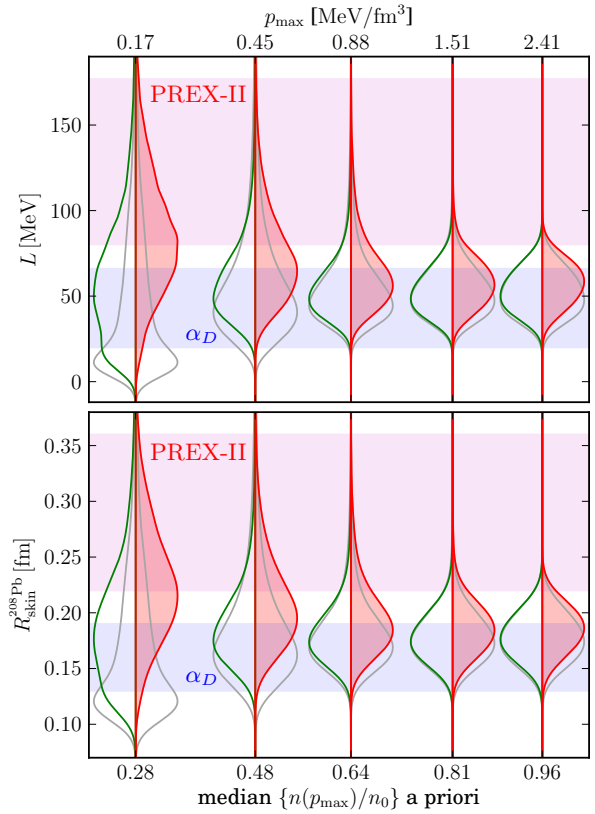

Figure 2. Prior (*gray, unshaded*), Astro posterior (*green, left/unshaded*), and Astro+PREX-II posterior (*red, right/shaded*) distributions for L (*top*) and $R_{\rm skin}^{^{208}{\rm Pb}}$ (*bottom*) as a function of the maximum pressure (*top axis*) or density (*bottom axis*) up to which we trust theoretical nuclear-physics predictions from χEFT (see text for details). Shaded bands show the approximate 68% credible region from PREX-II [19] (*pink*) and of Ref. [13] based on the electric dipole polarizability α_D (*light blue*).

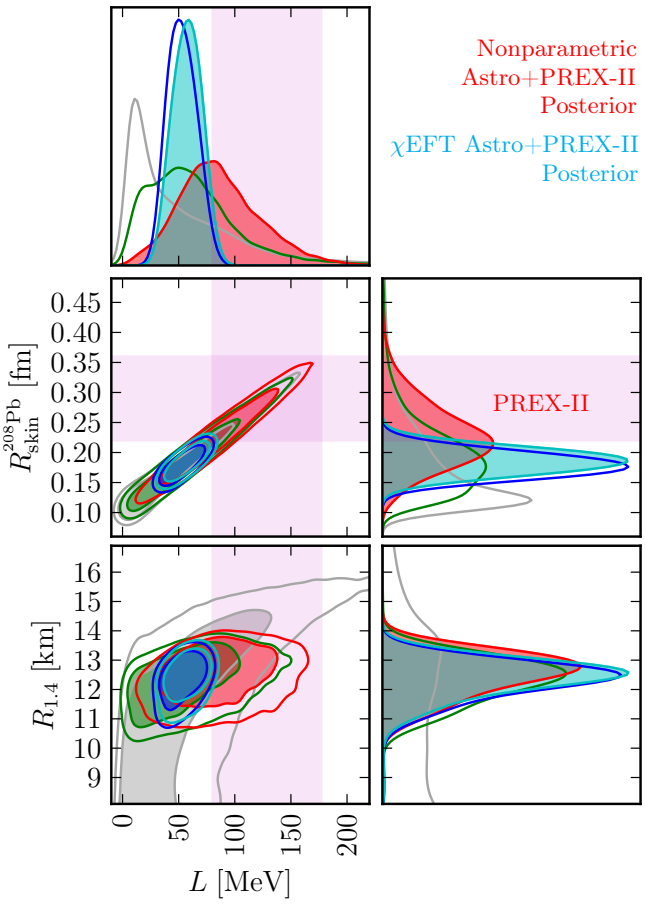

Figure 3. Correlations between $R_{\rm skin}^{^{208}{\rm Pb}}$, L, and the radius of a $1.4M_\odot$ NS, $R_{1.4}$. In addition to the priors and posteriors shown in Fig. 1, we show the nonparametric (*red*) and χEFT (trusted up to n_0; *light blue*) posteriors conditioned on both astrophysical observations and PREX-II. Astro+PREX-II posteriors are shaded in the one-dimensional distributions to distinguish them from the Astro-only posteriors. Joint distributions show the 68% (*shaded*) and 90% (*solid lines*) credible region. Shaded bands (*pink*) show the approximate 68% credible region from PREX-II.

where uncertainty in the saturation energy E_0, n_0, and the incompressibility K_0 is based on the empirical ranges from Ref. [9]. Combining Eqs. (1) and (5)–(8), we find that β-equilibrium must satisfy

$$\frac{1-2x_\beta}{4}\left(m_p - m_n + \mu_{\rm e}(n,x_\beta)\right) = \left(\frac{\varepsilon_\beta - \varepsilon_{\rm e}(n,x_\beta)}{n} - m_{\rm N} - \frac{E_{\rm SNM}}{A}(n)\right) . \quad (9)$$

We use the relations for a relativistic Fermi gas for the electron energy density and chemical potential [51]. To summarize, given a nonparametric EOS realization and a fair draw from the empirical distributions for the parameters E_0, K_0, and n_0, we reconstruct the proton fraction x_β self-consistently at each density around nuclear saturation. We then calculate $E_{\rm PNM}/A$, S_0, L, and $K_{\rm sym}$ as a function of n and report their values at the reference density $n_0^{(\rm ref)} = 0.16\,{\rm fm}^{-3}$. The neutron-skin thickness is estimated via the empirical fit between $R_{\rm skin}^{^{208}{\rm Pb}}$ and L, as discussed above.

Results and discussion– The constraints on S_0, L, $K_{\rm sym}$, and $R_{\rm skin}^{^{208}{\rm Pb}}$ are shown in Fig. 1. We plot the nonparametric prior, the posterior constrained by astrophysical data, and the posterior additionally constrained by the χEFT calculations up to $n \sim n_0$. As our GPs are conditioned on χEFT up to a maximum pressure ($p_{\rm max}$), we report the median density at that pressure (the exact density at $p_{\rm max}$ varies due to uncertainty in the EOS from χEFT). Prior and posterior credible regions are provided in Tb. I. We find that the PREX-II result for $R_{\rm skin}^{^{208}{\rm Pb}}$ and the extracted range for L of Ref. [20], 73–147 MeV at 1σ, are in mild tension with the GP conditioned on χEFT

calculations up to n_0, while the GP conditioned only on astrophysical observations is consistent with both results and cannot resolve any tension due to its large uncertainties. However, the Astro-only and χEFT posteriors peak at similar values for L (50–60 MeV), below the PREX-II result. The astrophysical data does not strongly constrain $K_{\rm sym}$, but suggests it is negative.

In Fig. 2, we show the evolution of our constraints on L and $R_{\rm skin}^{^{208}\rm Pb}$ as a function of the maximum density up to which we condition on χEFT, from no conditioning on χEFT to conditioning on χEFT up to n_0. The more we trust χEFT constraints, the larger the tension with PREX-II results becomes. We estimate a 13% probability (p-value) that the true $R_{\rm skin}^{^{208}\rm Pb}$ differs from the PREX-II mean at least as much as the Astro+χEFT posterior suggest, given the uncertainty in PREX-II's measurement. However, if a hypothetical experiment confirmed the PREX-II mean with half the uncertainty, this p-value would be reduced to 0.7%. We also show the estimate for $R_{\rm skin}^{^{208}\rm Pb}$ obtained from an analysis of dipole polarizability data [13], which finds $R_{\rm skin}^{^{208}\rm Pb} = 0.13$–$0.19\,$fm. The latter agrees very well with both the χEFT results and the nonparametric GP.

In Fig. 3, we present the modeled correlation between L and $R_{\rm skin}^{^{208}\rm Pb}$ as well as the radius of a $1.4M_\odot$ NS, $R_{1.4}$. In addition to Fig. 1, we show posteriors that are also conditioned on the PREX-II result. Even though the results for L and $R_{\rm skin}^{^{208}\rm Pb}$ are very different for the various constraints, $R_{1.4}$ does not significantly change. Indeed, the mapping from L to $R_{1.4}$ is broader than often assumed [6], and we find that $R_{1.4}$ is nearly independent of our range for L. Hence, the findings of Ref. [20], indicating that PREX-II requires large radii, include some model dependence.

Given the mild tension between the PREX-II value of $R_{\rm skin}^{^{208}\rm Pb}$ and that inferred from the astrophysical inference with χEFT information, we investigate what kind of EOS behavior is required to satisfy both the PREX-II and astrophysical constraints. In Fig. 4 we show the speed of sound c_s as a function of density for the nonparametric GP conditioned only on astrophysical data for all values of L, for $30\,{\rm MeV} < L \leq 70\,{\rm MeV}$, and for $L > 100\,$MeV. We find that the speed of sound generally increases with density. However, if we assume $L > 100$ MeV, we find a local maximum in the median $c_s(n)$ just below n_0, although the uncertainties in c_s are large. The reason for this feature is that EOSs that are stiff at low densities (large L) need to soften beyond n_0 to remain consistent with astrophysical data. Should the PREX-II constraints be confirmed with smaller uncertainty in the future, this might favor the existence of a phase transition between 1–2n_0.

In summary, we have used nonparametric GP EOS inference to constrain the symmetry energy, its density dependence, and $R_{\rm skin}^{^{208}\rm Pb}$ directly from astrophysical data, leading to $S_0 = 35^{+12}_{-9}$ MeV, $L = 57^{+66}_{-53}$ MeV, and

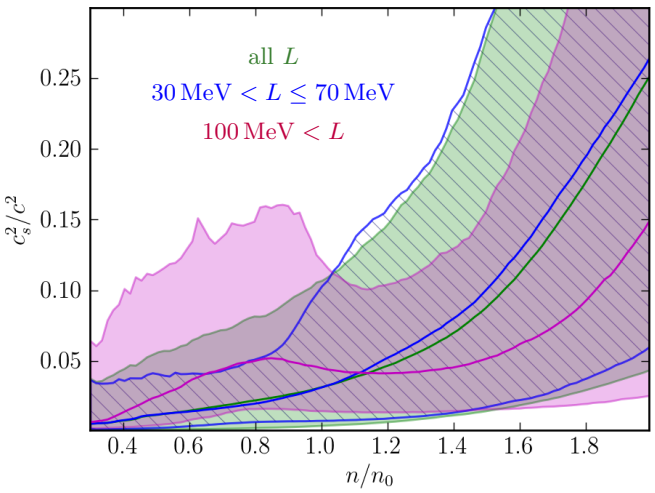

Figure 4. Median and 90% one-dimensional symmetric posterior credible regions for c_s^2 at each density n with astrophysical observations for all L (*shaded green*), $30\,{\rm MeV} < L \leq 70\,{\rm MeV}$ (*unshaded blue hatches*), and $100\,{\rm MeV} < L$ (*shaded purple*).

$R_{\rm skin}^{^{208}\rm Pb} = 0.18^{+0.10}_{-0.09}\,$fm. Folding in χEFT constraints reduces these ranges to $S_0 = 34^{+3}_{-2}$ MeV, $L = 52^{+20}_{-18}$ MeV, and $R_{\rm skin}^{^{208}\rm Pb} = 0.18^{+0.04}_{-0.04}\,$fm. While these results prefer values below the recent PREX-II values [19, 20], in good agreement with other nuclear physics information, the PREX-II uncertainties are still broad and any tension is very mild. Our nonparametric analysis suggests that a $R_{\rm skin}^{^{208}\rm Pb}$ uncertainty of $\pm 0.04\,$fm could challenge astrophysical and χEFT constraints. Finally, our results demonstrate that the correlation between $R_{1.4}$ and L (or $R_{\rm skin}^{^{208}\rm Pb}$) is looser than analyses based on a specific class of EOS models would suggest. Extrapolating neutron-skin thickness measurements to NS scales thus requires a careful treatment of systematic EOS model uncertainties. In particular, the PREX-II result does not require large NS radii. However, if the high L values of PREX-II persist, this may suggest a peak in the sound speed around saturation density.

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