

Equation of state extrapolation systematics: Parametric vs nonparametric inference of neutron star structure

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The equation of state (EOS) of cold dense matter remains one of the central open problems in nuclear astrophysics. Its inference is complicated by the lack of *ab initio* theoretical control above about twice nuclear saturation density, where the EOS must be extrapolated. Parametric schemes such as piecewise polytropes (PP) are computationally efficient but impose restrictive functional forms, while nonparametric approaches such as Gaussian processes (GP) offer greater flexibility at the cost of larger prior volumes. In this work, we extend our hybrid EOS framework by replacing the high-density polytropic extension with a Gaussian process representation of the squared sound speed, anchored at low densities by the SLy crust EOS and a nuclear meta-model constrained by χ EFT and laboratory measurements. Using a hierarchical Bayesian analysis, we jointly constrain the EOS and the neutron star mass distribution with multimessenger data, including NICER radius measurements, GW170817 and GW190425 tidal deformabilities, $2M_{\odot}$ pulsars, and neutron skin experiments. We explore four scenarios defined by the choice of high-density extrapolation (PP vs GP) and hot spot geometry in the NICER modeling of PSR J0030 + 0451 (ST + PDT vs PDT-U). We find that GP extrapolations generally yield softer EOS posteriors with broader uncertainty bands. Hot spot geometry assumptions also play an important role, leading to systematic shifts in the inferred mass-radius relations. Bayesian evidence strongly favors the ST + PDT geometry over PDT-U across both extrapolation schemes, while the GP extension is consistently preferred over PP, with substantial support. Taken together, these results underscore the importance of both observational modeling choices and EOS extrapolation strategies in shaping neutron star EOS inferences, and demonstrate that a GP-based extension provides a robust framework for quantifying systematic uncertainties in high-density matter.

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I. INTRODUCTION

Over the past decade, *multimessenger* observations have revolutionized our understanding of the neutron star (NS) equation of state (EOS). Gravitational-wave (GW) detections of binary neutron star (BNS) mergers (GW170817 [1–3], GW190425 [4]) have constrained tidal deformabilities at intermediate densities, while NICER x-ray timing [5–10] has provided complementary mass–radius measurements. Observations of $\sim 2M_{\odot}$ pulsars [11,12] have ruled out soft EOSs unable to support such high maximum masses. Laboratory measurements of neutron-skin thicknesses (PREX-II [13], CREX [14]) have further refined constraints on the symmetry energy near nuclear saturation density. On the theory side, chiral effective field theory (χ EFT) [see, e.g., Refs. [15–19]] provides a controlled

description of nuclear interactions up to densities of $\sim 1.5\text{--}2n_s$, where $n_s \approx 0.16\text{ fm}^{-3}$ denotes the nuclear saturation density, while perturbative QCD [20–22] is reliable only at extremely high densities ($\sim 40n_s$). This leaves a wide intermediate-density regime that must be bridged phenomenologically.

A central challenge in EOS inference therefore lies in extrapolating the EOS beyond the domain of theoretical control. Parametric representations—such as piecewise polytropes (PP) [23], spectral expansions [24], and speed-of-sound parametrizations [25]—are widely used because they are computationally efficient, but their restrictive functional forms can bias the inferred pressure-density relation [26] and associated neutron star observables. Complementary approaches based on nuclear metamodels [27] or relativistic mean-field (RMF) interactions [28,29] retain an explicit connection to nuclear microphysics, but likewise require assumptions [30] when extrapolated to supranuclear densities relevant for neutron star interiors. By contrast, nonparametric approaches, such as Gaussian process (GP) representations [21,31–33], treat the EOS as a distribution over functions rather than a fixed

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template. These methods allow greater flexibility and broader prior support, but they can require larger datasets for meaningful inference and may obscure direct physical interpretation.

To balance these competing strengths and limitations, hybrid EOS frameworks have been developed [30,34,35], in which the EOS at low densities is anchored by a nuclear meta-model [36] informed by empirical constraints (e.g., PREX/CREX, χ EFT, and symmetry energy parameters), while the high-density regime is extended using a phenomenological extrapolation. This construction enables systematic comparison of modeling assumptions while retaining a firm physics-based foundation near nuclear saturation density.

In this work, we extend our previous EOS inference framework [37] in two important ways. First, we replace the piecewise polytropic high-density extrapolation with a Gaussian process representation of the squared sound speed. This allows us to quantify the systematic errors introduced by restrictive parametric forms and assess their impact on the recovered pressure-density relation and neutron star observables. Second, we modify the crust-core junction procedure: whereas our earlier work imposed continuity of the pressure at a single matching density between the crust and the empirical meta-model, here we adopt a thermodynamically consistent finite-interval blending construction in which only the pressure is interpolated, while the chemical potential and energy density are reconstructed from the fundamental relations for cold barotropic matter. The center of the blending region is set to an empirically estimated crust–core transition density rather than an *ad hoc* fixed value (see Sec. II B). This procedure allows for a smoother transition between crust and core models while preserving the thermodynamic relations across the matching region. By integrating constraints from multimessenger astrophysics (NICER, gravitational waves, pulsar masses), nuclear theory, and laboratory experiments within a hierarchical Bayesian framework, we provide a systematic comparison of parametric and nonparametric EOS inference and establish robust, bias-minimized constraints on the dense matter EOS.

II. EOS MODEL WITH GAUSSIAN PROCESS EXTENSION

Our EOS construction combines three components: (i) a fixed SLy [38] crust at low densities, (ii) a nuclear meta-model (see Sec. II A) anchored near saturation density, characterized by the symmetry energy slope L and curvature K_{sym} , and (iii) a high-density extension governed by a Gaussian process representation of the squared sound speed.

These components are joined in sequence as follows:

- (i) for $n < n_{cc}$, the EOS is given by the fixed SLy crust;

- (ii) for $n_{cc} \leq n \leq n_t$, the EOS is described by the empirical meta-model; and
- (iii) for $n > n_t$, the EOS is extended using the GP representation.

Here n_{cc} denotes the crust–core transition density (treated with a smooth blending construction, see Sec. II B), while n_t is the matching density at which the empirical meta-model is joined to the GP extension.

A. Nuclear meta-model

The empirical meta-model [39] (see also Ref. [40] for a general discussion of the meta-model framework) expresses the energy per nucleon of nuclear matter as a function of baryon density n and isospin asymmetry $\delta = 1 - 2Y_e$,

$$e(n, \delta) = e_0(n) + e_{\text{sym}}(n)\delta^2 + \mathcal{O}(\delta^4), \quad (1)$$

where the isoscalar part $e_0(n)$ and the symmetry energy $e_{\text{sym}}(n)$ are expanded around the saturation density n_0 as

$$e_0(n) = e_0(n_0) + \frac{K_0}{2}\chi^2 + \dots, \quad (2)$$

$$e_{\text{sym}}(n) = e_{\text{sym}}(n_0) + L\chi + \frac{K_{\text{sym}}}{2}\chi^2 + \dots, \quad (3)$$

with $\chi = (n - n_0)/(3n_0)$. The coefficients are the standard nuclear matter parameters (NMPs): $e_0(n_0)$ is the binding energy at saturation, K_0 is the incompressibility, $e_{\text{sym}}(n_0)$ is the symmetry energy, and L and K_{sym} are its slope and curvature. The β -equilibrated EOS is obtained by imposing charge neutrality and the condition of chemical equilibrium under weak interactions, $\mu_n - \mu_p = \mu_e$, which determines the proton fraction Y_e as a function of density. The pressure and energy density are then given by $P = n^2 \partial e / \partial n$ and $\varepsilon = n(m_N + e)$, respectively, where $m_N = 931.494$ MeV is the nucleon mass, evaluated along the β -equilibrium track, yielding the EOS as a function of baryon density n alone.

The lower-order NMPs are well constrained by nuclear experiments and are fixed following our previous work [35]. Specifically, we fix the saturation density $n_0 = 0.16 \text{ fm}^{-3}$ and the energy per nucleon at saturation $e_0(n_0) = -15.9$ MeV. A survey of 53 experimental results [41] found $e_{\text{sym}}(n_0) = 31.7 \pm 3.2$ MeV and $K_0 = 240 \pm 30$ MeV. Previous Bayesian analyses combining gravitational-wave and x-ray observations found that current multimessenger data do not provide significant constraints on these parameters [30,35], so we fix $e_{\text{sym}}(n_0)$ and K_0 at their survey median values of 31.7 MeV and 240 MeV, respectively, rather than unnecessarily increasing the dimensionality of the EOS parametrization. Since the present data do not favor or constrain a particular range of $e_{\text{sym}}(n_0)$ and K_0 , our results remain robust under

TABLE I. Prior ranges of the NS EOS and mass distribution model hyperparameters used in this work. The notation U and $\mathcal{N}$ stands for uniform and normal distribution, respectively.

Model	Parameters	Units	Prior
EOS	L	MeV	$U(0, 150)$
	K_{sym}	MeV	$U(-600, 100)$
	n_t	n_s	$U(1, 2)$
	l	n_s	$\mathcal{N}(1, 0.25)$
	η	$\dots$	$\mathcal{N}(1.25, 0.2)$
	$\tilde{c}_s^2$	$\dots$	$\mathcal{N}(0.5, 0.25)$
Mass	μ_1	$M_\odot$	$U(0.9, \mu_2)$
	σ_1	$M_\odot$	$U(0.01, \sigma_2)$
	μ_2	$M_\odot$	$U(0.9, M_{\text{max}})$
	σ_2	$M_\odot$	$U(0.01, 1.0)$
	w	$\dots$	$U(0.1, 0.9)$

reasonable variations of these parameters. This leaves the slope L and the curvature K_{sym} of the symmetry energy as the two free parameters of the meta-model, both sampled with broad uniform priors as listed in Table I.

B. Crust-core blending

In our earlier work [37,43], the crust-core junction was determined by enforcing continuity of the pressure at a single matching density. While this prescription yields a thermodynamically consistent EOS, it generally leads to a discontinuity in the derivative $dP/d\epsilon$, and hence in the squared speed of sound c_s^2 , at the matching point. A finite-interval connection between crust and core models can provide a smoother transition, but requires care: interpolating multiple thermodynamic quantities with a density-dependent blending function can lead to violations of first-law consistency, including the identity $c_s^2 = dP/d\epsilon$. In the present analysis, we therefore adopt a thermodynamically consistent finite-interval matching procedure in which only the pressure is interpolated across the blending region, while the chemical potential and energy density are reconstructed from the fundamental relations for cold barotropic matter [44].

Instead of performing a single-point match, we connect the SLy crust and the empirical meta-model across a finite density interval centered on the crust-core transition density. Rather than fixing n_{cc} to an *ad hoc* value, we estimate it self-consistently from the symmetry energy parameters using the empirical fit of Ducoin *et al.* [45],

$$n_{cc} = 3.23 \times 10^{-4} (L_{01} + 0.426 K_{\text{sym},01}) + 0.0802 \text{ [fm}^{-3}\text{]}, \quad (4)$$

where L_{01} and $K_{\text{sym},01}$ are the symmetry energy slope and curvature evaluated at $n_{\text{ref}} = 0.1 \text{ fm}^{-3}$. This relation was derived from the crossing of the dynamical spinodal with

the β -equilibrium line across a wide range of Skyrme and relativistic nuclear models [45], and yields transition densities in the physically expected range $0.06\text{--}0.10 \text{ fm}^{-3}$, consistent with more microscopic extended Thomas-Fermi calculations [46]. In our meta-model, where $e_{\text{sym}}(n) = e_{\text{sym},0} + L\chi + \frac{1}{2}K_{\text{sym}}\chi^2$ with $\chi = (n - n_0)/(3n_0)$, these coefficients reduce to

$$L_{01} = L + K_{\text{sym}}\chi_{\text{ref}}, \quad K_{\text{sym},01} = K_{\text{sym}}, \quad (5)$$

where $\chi_{\text{ref}} = (n_{\text{ref}} - n_0)/(3n_0)$. Since L and K_{sym} are free parameters in our inference, n_{cc} varies self-consistently across the posterior rather than being fixed at a single value. The blending half-width is held fixed at $\Delta n = 0.004 \text{ fm}^{-3}$, which is a purely numerical smoothing parameter chosen small enough to have no impact on the inferred EOS. We define the blending region $n_b \in [n_{cc} - \Delta n, n_{cc} + \Delta n]$.

Within this interval, we construct a smooth (C^∞) weight function following the prescription of Ref. [47],

$$w(n_b) = \frac{f(x)}{f(x) + f(1-x)}, \quad x = \frac{n_b - (n_{cc} - \Delta n)}{2\Delta n}, \quad (6)$$

where

$$f(x) = \begin{cases} \exp(-1/x), & x > 0, \\ 0, & x \leq 0. \end{cases} \quad (7)$$

This function satisfies $w = 0$ at $n_{cc} - \Delta n$, $w = 1$ at $n_{cc} + \Delta n$, and is infinitely differentiable inside the interval.

We blend only the pressure,

$$P_{\text{blend}}(n_b) = (1 - w)P_{\text{SLy}}(n_b) + wP_{\text{emp}}(n_b), \quad (8)$$

and reconstruct the remaining thermodynamic quantities from the fundamental relations for cold barotropic matter, as advocated in Ref. [44]. In particular, the chemical potential is obtained from

$$\mu(n_b) = \mu(n_1) + \int_{n_1}^{n_b} \frac{1}{n} \frac{dP_{\text{blend}}}{dn} dn, \quad (9)$$

where $n_1 = n_{cc} - \Delta n$. The energy density then follows from

$$\epsilon(n_b) = n_b \mu(n_b) - P_{\text{blend}}(n_b). \quad (10)$$

To ensure continuity of the chemical potential at $n_{cc} + \Delta n$, we apply a constant shift $\Delta\mu$ to the core-side energy density, following the matching prescription of Ref. [44]. This guarantees continuity of P , μ , and ϵ across the matching region.

The squared speed of sound is subsequently computed consistently from

$$c_s^2 = \frac{dP}{d\epsilon}. \quad (11)$$

This construction preserves thermodynamic consistency by building the EOS from a single interpolated pressure function, while the C^∞ weight ensures a smooth transition between crust and core models. Compared to a single-point matching procedure, it significantly reduces numerical artifacts in the stiffness of the EOS and improves stability when sampling over wide ranges of (L, K_{sym}) .

C. Gaussian process high-density extension

Beyond the matching density n_t , the squared sound speed $c_s^2(n)$ is modeled as a Gaussian process (GP), following Refs. [21,31,48]. To map the causal domain $c_s^2 \in [0, 1]$ to the real line, we introduce an auxiliary variable

$$\phi(n) = -\log\left(\frac{1}{c_s^2(n)} - 1\right). \quad (12)$$

The GP prior is then placed on $\phi(n)$,

$$\phi(n) \sim \mathcal{N}\left(-\ln\left(\frac{1}{\bar{c}_s^2} - 1\right), K(n, n')\right), \quad (13)$$

with a squared-exponential kernel

$$K(n, n') = \eta \exp\left[-\frac{(n - n')^2}{2\ell^2}\right], \quad (14)$$

where η controls the variance of fluctuations and ℓ sets the correlation length in density. The mean function corresponds to the logit transform of a reference sound speed $\bar{c}_s^2$.

The GP hyperparameters are drawn hierarchically from broad normal priors,

$$\begin{aligned} \ell &\sim \mathcal{N}(1.0n_s, (0.25n_s)^2), \\ \eta &\sim \mathcal{N}(1.25, 0.2^2), \\ \bar{c}_s^2 &\sim \mathcal{N}(0.5, 0.25^2), \end{aligned} \quad (15)$$

ensuring that the ensemble of EOSs spans a wide range of plausible supranuclear behaviors. At the matching density n_t , the GP is anchored to the meta-model prediction, ensuring continuity of the EOS.

From each realization of $\phi(n)$ we reconstruct the EOS by inverting to obtain $c_s^2(n)$, integrating the baryon chemical potential, and computing the energy density and pressure

$$\mu(n) = \mu_t \exp\left(\int_{n_t}^n \frac{c_s^2(n')}{n'} dn'\right), \quad (16)$$

$$\epsilon(n) = \epsilon_t + \int_{n_t}^n \mu(n') dn', \quad (17)$$

$$P(n) = n\mu(n) - \epsilon(n). \quad (18)$$

This GP construction automatically enforces causality and thermodynamic stability, while providing much greater flexibility than polytrope-based models. By comparing inferences under the two frameworks, we can directly quantify the systematic errors introduced by parametric versus nonparametric extrapolations of the EOS at high densities.

III. INFERENCE METHODOLOGY

Following our previous work [37], we employ a hierarchical Bayesian framework to jointly constrain the neutron star EOS and the mass distribution. This approach integrates diverse datasets spanning theory, experiment, and observation. The posterior distribution of the model parameters is obtained via Bayes' theorem

$$P(\theta|D) = \frac{P(D|\theta)P(\theta)}{P(D)}, \quad (19)$$

where θ represents the set of model parameters—including EOS parameters (θ_{EOS}) and mass distribution parameters (θ_{pop})—and D denotes the combined dataset. The likelihood $P(D|\theta)$ encodes the agreement between model predictions and data, while $P(\theta)$ represents prior knowledge or theoretical constraints. The evidence $P(D)$ serves as a normalization constant and is not required for parameter estimation. A complete summary of the model parameters and their prior ranges is provided in Table I.

A. EOS model parameters

The EOS hyperparameters considered in this work are

- (i) L : slope of the symmetry energy at saturation density,
- (ii) K_{sym} : curvature of the symmetry energy,
- (iii) n_t : transition density between the empirical meta-model and the GP EOS, and
- (iv) $\ell, \eta, \bar{c}_s^2$: hyperparameters of the GP EOS, corresponding to the correlation length, variance, and reference sound speed squared.

In our Bayesian framework, we additionally treat the random seed used to generate Gaussian process realizations as a parameter. Specifically, we assign a uniform prior over integer values between 1 and 10,000. This choice ensures that the stochasticity inherent to GP draws is explicitly tracked within the inference process. By retaining the seed as part of the posterior, any EOS sample can be uniquely reconstructed, which in turn allows us to evaluate other macroscopic neutron star properties in a consistent and reproducible manner.

B. Mass distribution parameters

We describe the neutron star mass distribution using a two-component Gaussian mixture, capturing the presence of distinct sub-populations. The model is characterized by:

- (i) μ_1, μ_2 : mean masses of the two Gaussian components,
- (ii) σ_1, σ_2 : corresponding standard deviations, and
- (iii) w : mixture weight of the first component, with the second assigned a weight of $1 - w$.

In compact form, the probability density for a neutron star mass M is written as

$$P(M) = [w\mathcal{N}(M|\mu_1, \sigma_1)/B + (1-w)\mathcal{N}(M|\mu_2, \sigma_2)/C] \times U(M|M_{\min}, M_{\max}), \quad (20)$$

where $\mathcal{N}(M|\mu, \sigma^2)$ denotes a normal distribution with mean μ and variance σ^2 and the term $U(M|M_{\min}, M_{\max})$ reads

$$U(M|M_{\min}, M_{\max}) = \begin{cases} \frac{1}{M_{\max} - M_{\min}} & \text{if } M_{\min} \leq M \leq M_{\max}, \\ 0 & \text{else.} \end{cases} \quad (21)$$

C. Likelihood components

The likelihood function is constructed by combining the following datasets and theoretical inputs:

- (i) NICER: Simultaneous mass-radius inferences for PSRs J0030 + 0451 [49,50], J0740 + 6620 [51,52], J0437 – 4715 [9,53], and PSR J0614 – 3329 [10].
- (ii) Gravitational waves: Tidal deformability posteriors from GW170817 [2] and GW190425 [4].
- (iii) Theory priors: Chiral effective field theory (χ EFT) at low densities [54,55], and perturbative QCD (pQCD) at asymptotically high densities [20–22].
- (iv) Laboratory experiments: Neutron skin thickness measurements from PREX-II [56] and CREX [14], which are directly related to the symmetry energy.
- (v) Radio pulsar masses: Three classes of neutron star mass measurements [57,58]. These include precise individual masses (from Shapiro delay or relativistic orbital parameters), as well as binary systems with total mass or mass ratio constraints combined with the mass function, marginalizing over inclination.

We do not include the mass-radius data for PSR J1231 – 1411 to provide a cleaner comparison with earlier works. As shown by [59], the Bayesian analysis of this system is sensitive to radius priors and exhibits convergence issues, motivating its exclusion here.

D. Full likelihood

Combining all ingredients, the full likelihood used in this work can be expressed schematically as

$$\begin{aligned} \mathcal{L}(D|\theta_{\text{EOS}}, \theta_{\text{pop}}) &= \mathcal{L}_{\text{GW}}(D_{\text{GW}}|\theta_{\text{EOS}}, \theta_{\text{pop}}) \\ &\times \mathcal{L}_{\text{NICER}}(D_{\text{NICER}}|\theta_{\text{EOS}}, \theta_{\text{pop}}) \\ &\times \mathcal{L}_{\text{Mass}}(D_{\text{Radio}}|\theta_{\text{EOS}}) \\ &\times \mathcal{L}_{\chi\text{EFT}}(\theta_{\text{EOS}})\mathcal{L}_{\text{pQCD}}(\theta_{\text{EOS}}) \\ &\times \mathcal{L}_{\text{Skin}}(D_{\text{skin}}|\theta_{\text{EOS}}). \end{aligned} \quad (22)$$

We note that both χ EFT calculations and neutron-skin measurements primarily constrain the EOS of isospin-symmetric or pure neutron matter, rather than matter in β -equilibrium. In the present analysis, these inputs are therefore incorporated as approximate likelihoods on the underlying empirical nuclear parameters, which in turn determine the β -equilibrated EOS. As such, their impact on neutron star observables is mediated through the assumed isospin dependence of the EOS near saturation density. Detailed derivations and discussions of each likelihood component can be found in [37]. Posterior samples are drawn using a nested sampling algorithm implemented in PyMultiNest [60].

IV. RESULTS

To quantify the impact of EOS extrapolation strategy and NICER hot spot geometry assumptions, we analyze four scenarios: (i) GP high-density extension with J0030 modeled under the ST + PDT hot spot geometry, (ii) GP extension with the PDT-U geometry, (iii) PP high-density extension with ST + PDT, and (iv) PP extension with PDT-U. In what follows, we use “GP” and “PP” to specifically refer to the choice of high-density extrapolation, while “ST + PDT” and “PDT-U” indicate the assumed hot spot geometry of J0030’s x-ray pulse profile.

A. Impact of modeling assumptions on EOS parameters

Figure 1 shows the posterior distributions of three key EOS parameters that are common across all scenarios: the symmetry energy slope L , the curvature of the symmetry energy K_{sym} , and the transition density n_t at which the empirical meta-model is matched to the high-density extension.

A systematic trend emerges: across both EOS extrapolation strategies, adopting the PDT-U hot spot geometry systematically shifts the inferred values of L and K_{sym} toward higher medians compared to the ST + PDT case. This effect is robust to whether the high-density EOS is modeled with a GP or PP extension, and the two extrapolation schemes provide broadly similar posteriors for L and K_{sym} .

The behavior of the transition density parameter n_t highlights differences between the four scenarios. GP-based models tend to prefer somewhat lower transition densities compared to PP-based models, but the exact posteriors vary with the assumed hot spot geometry. This indicates that both the extrapolation strategy and

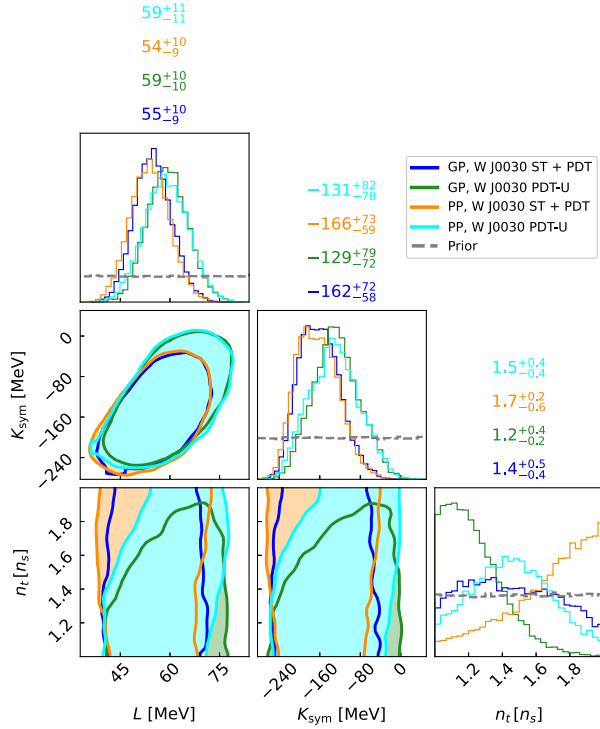


FIG. 1. Posterior distributions for the symmetry energy slope L , curvature K_{sym} , and transition density n_t under four scenarios: GP high-density extrapolation with J0030 ST + PDT (blue), GP with J0030 PDT-U (orange), PP with J0030 ST + PDT (green), and PP with J0030 PDT-U (red). The prior distribution is shown in gray.

the treatment of J0030's pulse profile introduce distinct systematics into the inferred matching density.

B. Constraints on GP hyperparameters

Figure 2 shows the posterior distributions of the GP hyperparameters that regulate the high-density extrapolation of the EOS: the correlation length ℓ , the variance amplitude η , and the reference mean squared sound speed $\bar{c}_s^2$. These are compared to the broad hierarchical priors described in Table I.

The variance amplitude η remains almost completely prior dominated. Its posterior closely follows the prior distribution, demonstrating that the current multimessenger dataset does not meaningfully constrain the typical size of local fluctuations in the squared sound speed.

By contrast, the data strongly inform both ℓ and $\bar{c}_s^2$. The posteriors of $\bar{c}_s^2$ are consistently shifted relative to the prior, reflecting that the dataset places nontrivial constraints on the average stiffness of the EOS at supranuclear densities. Moreover, the two hot spot geometries for PSR J0030 + 0451 yield nearly identical posteriors for $\bar{c}_s^2$, indicating that this parameter is robust against pulse-profile modeling choices.

The correlation length ℓ exhibits more nuanced behavior. In both hot spot geometries, the posterior median of ℓ lies below the prior mean, suggesting that the data

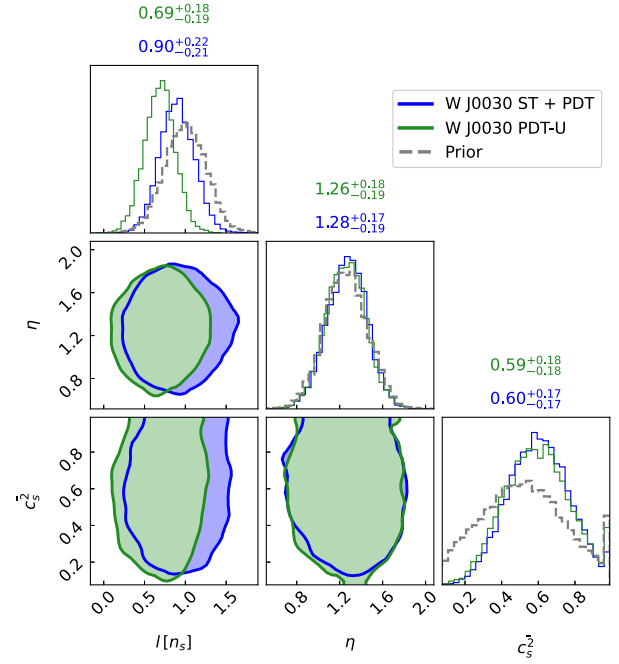


FIG. 2. Posteriors of GP hyperparameters compared with priors. η remains prior dominated, $\bar{c}_s^2$ is robust across hot spot geometries, while ℓ shifts to smaller values in both cases, with PDT-U favoring the shortest correlation lengths.

generally favor shorter correlation lengths than assumed *a priori*—that is, the EOS is allowed to vary less smoothly with density than the prior would indicate. Furthermore, a geometry dependence is evident: the PDT-U solution drives ℓ to even smaller values than the ST + PDT case. This preference can be interpreted as follows: since the PDT-U geometry infers larger neutron star radii, it requires a stiffer EOS at intermediate densities. Reconciling this with the remaining observational and theoretical inputs necessitates more localized adjustments in the sound-speed profile, which are enabled by reducing ℓ . By contrast, the ST + PDT geometry is more compatible with the combined dataset and therefore favors smoother high-density extrapolations with moderately larger ℓ .

C. Reconstructed high-density EOS and stellar structure under different modeling assumptions

Figure 3 presents the inferred pressure-density relations (top), mass-radius curves (middle), and sound-speed profiles (bottom) for the four inference scenarios, comparing GP and PP extrapolations combined with either the ST + PDT or PDT-U hot spot geometry of PSR J0030 + 0451.

With only nuclear-theory and experimental likelihoods applied, the GP extrapolation already behaves differently from the PP case. GP EOSs favor systematically softer posteriors in the density range $1 - 3n_s$, while also spanning a visibly broader envelope across all densities. By contrast,

the PP representation produces narrower credible regions, but at the cost of stronger dependence on its restrictive functional form.

Adding astrophysical data (NICER, GW, and pulsar masses) dramatically improves the constraints. Under the ST + PDT geometry, the GP EOS posteriors are significantly softer than PP, yielding smaller radii, higher maximum masses, and larger central densities. The PDT-U

geometry shifts the posteriors toward stiffer EOSs with correspondingly larger radii, but the differences between GP and PP extrapolations remain evident in the widths of their credible bands.

The sound-speed reconstructions highlight these differences most clearly. For the ST + PDT case, the GP EOS produces somewhat tighter constraints on $c_s^2(n)$ up to $\sim 3.3n_s$, while for PDT-U the informative range extends

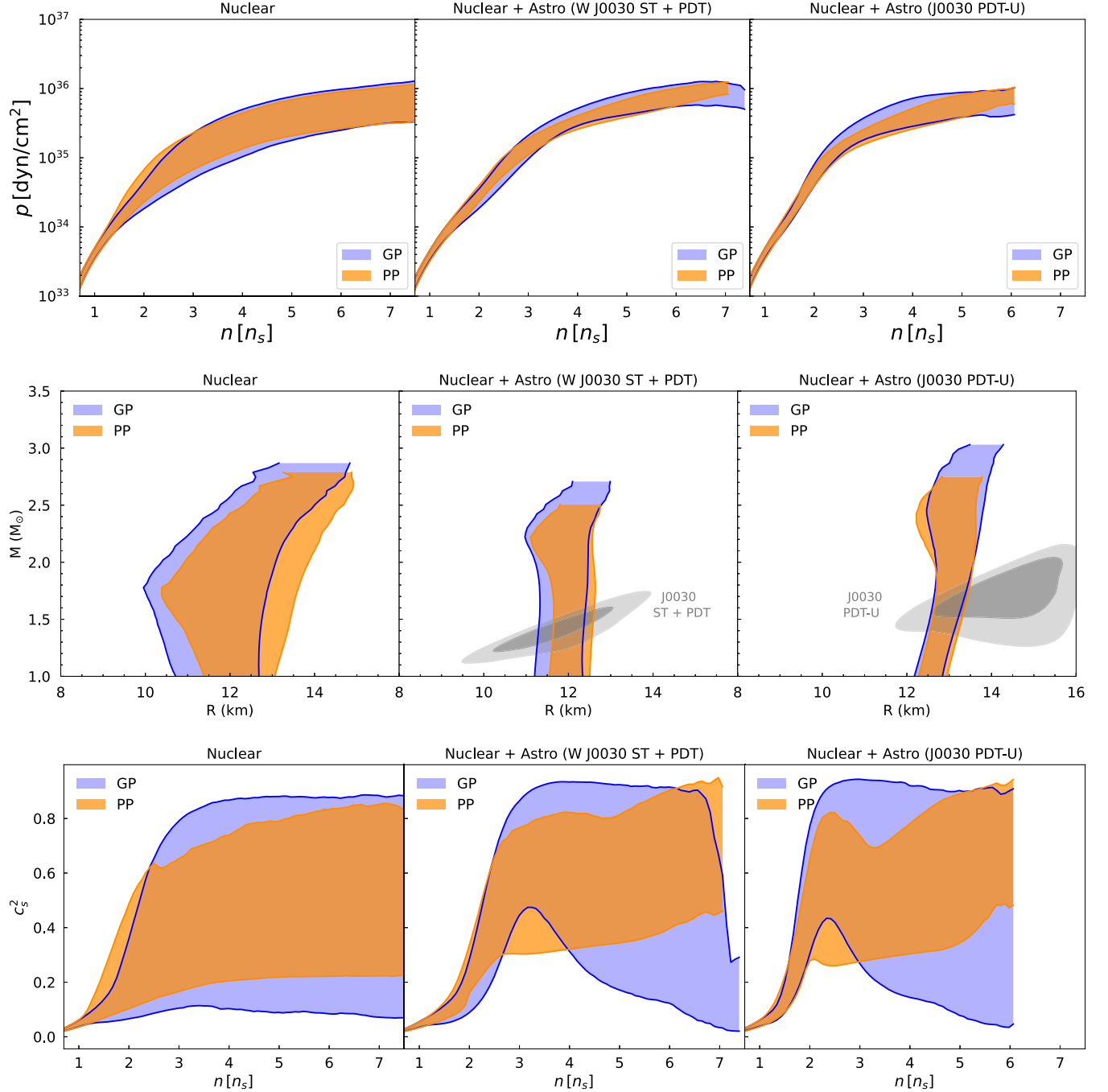


FIG. 3. Posterior distributions of the EOS obtained with GP and PP extrapolations under two hot spot geometries of PSR J0030 + 0451 (ST + PDT and PDT-U). Top: pressure-density relation. Middle: mass-radius curves. Bottom: squared sound speed vs density.

only to $\sim 2.5n_s$. Moreover, the ST + PDT solution admits central densities higher than those of PDT-U, and the GP posteriors reveal a dip in c_s^2 near the central density in this case. Such features are inaccessible in the PP representation, which enforces stepwise continuity.

D. Macroscopic neutron star properties

Figure 4 shows the posterior distributions of macroscopic neutron star properties inferred from our EOS models: the radius $R_{1.4}$ and tidal deformability $\Lambda_{1.4}$ of a $1.4M_\odot$ star, the maximum mass M_{max} , the corresponding

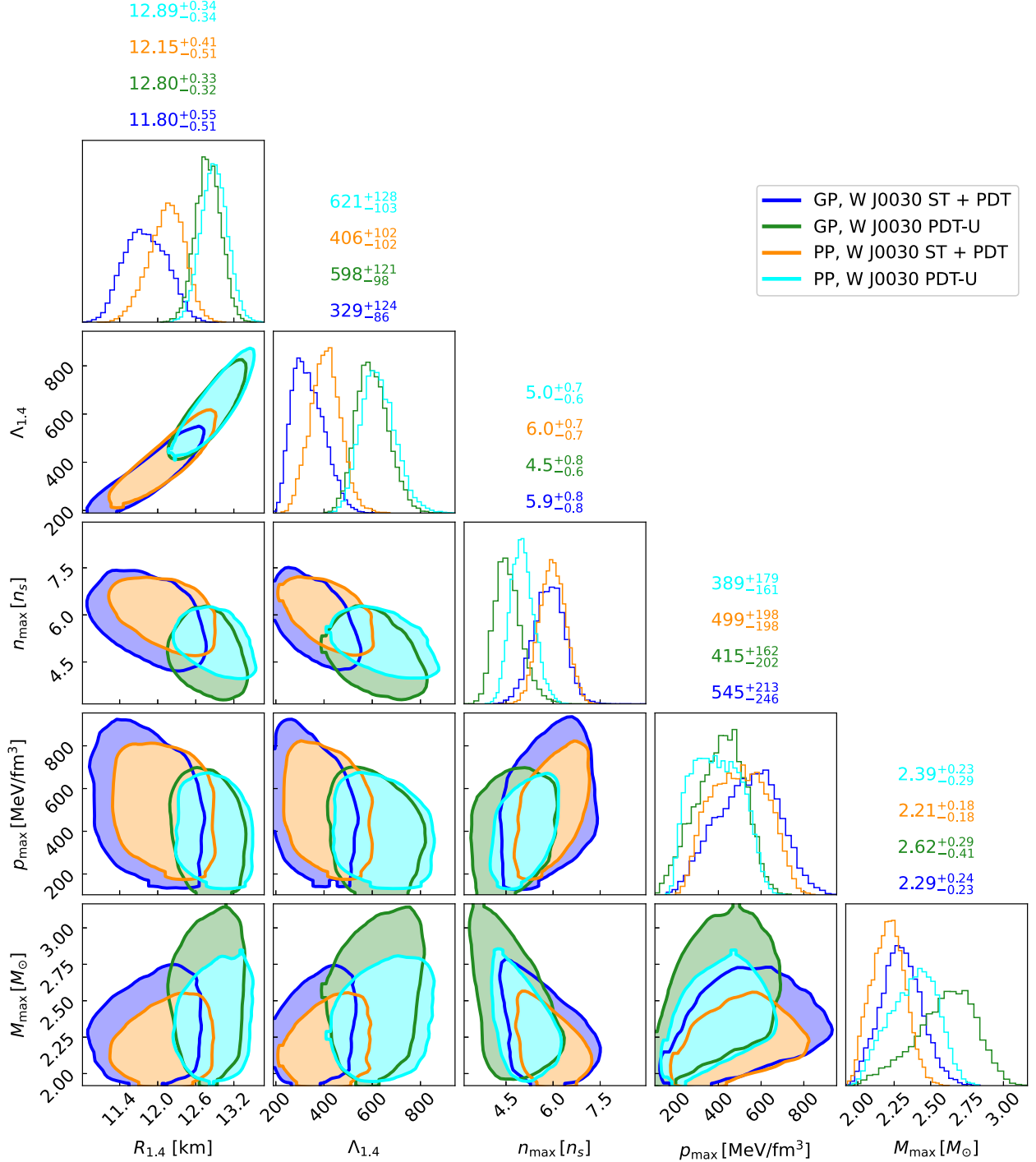


FIG. 4. Correlations between radius ($R_{1.4}$) and tidal deformability ($\Lambda_{1.4}$) of a $1.4M_\odot$ NS, maximum density (n_{max}), maximum pressure (p_{max}), and maximum mass (M_{max}) are shown for each scenario considered in this study, as indicated in the legend of the plot. In the marginalized one-dimensional plots, the median and 90% CIs are shown for each constraint type, with each constraint represented in its respective color.

central density $n_{\max}$, and the central pressure $p_{\max}$. Results are compared across the four scenarios combining GP or PP extrapolations with the ST + PDT or PDT-U hot spot geometry of PSR J0030 + 0451.

For $R_{1.4}$ and $\Lambda_{1.4}$, both the extrapolation strategy and the hot spot geometry play important roles. Within the ST + PDT geometry, GP models predict systematically smaller radii and tidal deformabilities than PP models, with median shifts of about ~ 350 m and ~ 80 , respectively. Changing the hot spot geometry has a larger effect: moving from ST + PDT to PDT-U increases $R_{1.4}$ by roughly ~ 1.1 km and $\Lambda_{1.4}$ by about ~ 270 in the GP case. While the precise values differ for PP, the same trend holds: PDT-U always favors larger radii and tidal deformabilities than ST + PDT.

The maximum mass follows a consistent but distinct set of trends. PDT-U solutions yield larger $M_{\max}$ than ST + PDT in both GP and PP cases, reflecting their preference for stiffer EOSs. In addition, GP extrapolations systematically predict higher $M_{\max}$ than PP under the same geometry. This is in contrast to the behavior of $R_{1.4}$ and $\Lambda_{1.4}$, where GP tends to give smaller values than PP. The pattern highlights the flexibility of the GP representation: it can accommodate large maximum masses while allowing softer intermediate-density behavior.

The corresponding central densities and pressures underscore these differences. ST + PDT models, which favor softer EOSs, are associated with higher $n_{\max}$ and $p_{\max}$ than PDT-U. This outcome is expected: softer EOSs must reach higher central densities and pressures to support massive stars, whereas stiffer EOSs achieve the same or larger $M_{\max}$ at lower central densities and pressures.

Finally, we note that the posterior distributions of the neutron star mass distribution parameters are not shown here, as they are largely insensitive to the choice of hot spot geometry or EOS extrapolation scheme. These results are consistent with our previous analyses [37,43], where the corresponding distributions were presented in detail. For completeness, we simply refer the reader to those earlier works.

E. Model comparison via Bayesian evidence

We assess the relative support for different modeling assumptions using Bayesian evidence, considering both

(i) the hot spot geometry in pulse-profile modeling (ST + PDT vs PDT-U), and (ii) the high-density extrapolation scheme for the EOS (piecewise polytrope vs Gaussian process). Following the interpretation of Kass and Raftery [42], we interpret differences in log-evidence in terms of the strength of model preference. The resulting log-evidence values for all model combinations are summarized in Table II.

For the PP model, the evidence difference between ST + PDT and PDT-U is $\Delta \log Z \approx 3.68$, corresponding to $\log_{10} \text{BF} \approx 1.59$. This constitutes *strong evidence* in favor of ST + PDT. For the GP model, the preference is even stronger: $\Delta \log Z \approx 4.52$, or $\log_{10} \text{BF} \approx 1.96$, which constitutes *very strong evidence*. Thus, under both extrapolation schemes, ST + PDT is favored, with the GP extension providing the sharper distinction.

Comparing the extrapolation strategies themselves, the GP extension is preferred over PP in both hot spot geometries. For ST + PDT, the evidence difference is $\Delta \log Z \approx 2.08$, corresponding to a Bayes factor (BF) of about 8 ($\log_{10} \text{BF} \approx 0.9$), indicating *substantial evidence* for GP. For PDT-U, the difference is smaller, $\Delta \log Z \approx 1.24$, corresponding to a Bayes factor of about 3.5 ($\log_{10} \text{BF} \approx 0.54$), indicating *substantial evidence*.

Overall, the dataset decisively favors the ST + PDT hot spot geometry, and within either geometry, shows a substantial preference for the GP extrapolation. The combination of ST + PDT + GP is the most strongly supported model.

F. Comparison with Ng *et al.* [61]

Our results can be compared directly with the recent work of Ng *et al.* [61], who also adopt a semi-nonparametric EOS framework based on Gaussian processes. Using a comparable set of astrophysical observations, they report $R_{1.4} = 11.4^{+0.98}_{-0.60}$ km and $M_{\max} = 2.31^{+0.35}_{-0.23} M_{\odot}$ (90% CL), whereas our ST + PDT + GP analysis yields $R_{1.4} = 11.8^{+0.55}_{-0.51}$ km and $M_{\max} = 2.29^{+0.24}_{-0.23} M_{\odot}$. Although the median values are consistent, the credible intervals reported by Ng *et al.* [61] are noticeably broader than those obtained in this work.

An important difference lies in the inference methodology. Ng *et al.* [61] do not provide explicit details of their sampling scheme. However, their Gaussian-process

TABLE II. Bayesian evidence comparison for EOS extrapolation models (PP vs GP) and hot spot geometries (ST + PDT vs PDT-U). Quoted values are log-evidences with sampling uncertainties. Evidence differences $\Delta \log Z$ are shown for both hot spot and extrapolation comparisons. Interpretation follows Kass and Raftery [42].

EOS model	Geometry	$\log Z$	$\Delta \log Z$ (Geom.)	$\Delta \log Z$ (EOS)
PP	ST + PDT	-11.838 ± 0.019	$\approx + 3.68$ (favor ST + PDT)	$\approx - 2.08$ (vs GP)
PP	PDT-U	-15.517 ± 0.129		$\approx - 1.24$ (vs GP)
GP	ST + PDT	-9.754 ± 0.015	$\approx + 4.52$ (favor ST + PDT)	$\approx + 2.08$ (vs PP)
GP	PDT-U	-14.276 ± 0.041		$\approx + 1.24$ (vs PP)

framework closely follows Landry *et al.* [31] and Essick *et al.* [48], where posterior distributions are obtained via direct Monte Carlo draws of EOS realizations from the GP prior, reweighted by the likelihood. Convergence in that approach is typically monitored using the effective sample size. While this procedure is formally correct, it is computationally inefficient in high-dimensional problems where the posterior occupies only a small fraction of the prior volume. As a result, many samples carry negligible weight, limiting the effective number of posterior draws and leading to broader credible intervals.

By contrast, our analysis employs nested sampling as implemented in PyMultiNest, which adaptively explores the high-likelihood regions of parameter space and simultaneously yields Bayesian evidence estimates. This strategy achieves a more efficient exploration of the posterior distribution, resulting in tighter constraints on $R_{1.4}$ and M_{max} , while also enabling robust model comparison between different EOS extrapolation strategies and hot spot geometries. We therefore attribute part of the broader uncertainties in Ng *et al.* [61] to the sampling methodology, in addition to possible differences in prior choices and observational inputs.

V. CONCLUSION

In this work, we have extended our earlier hybrid EOS framework [37] by replacing the high-density piecewise-polytropic extrapolation with a Gaussian process representation of the squared sound speed. This allows a systematic comparison between parametric and nonparametric extrapolation strategies while retaining the same physics-informed SLy crust and nuclear meta-model near saturation density.

Using a hierarchical Bayesian framework that incorporates constraints from NICER, gravitational waves, radio pulsar mass measurements, neutron-skin thickness experiments, and theoretical input from χ EFT and pQCD, we performed joint inference of the neutron star EOS and mass distribution under four scenarios: two EOS extrapolations (PP and GP) and two hot spot geometries for PSR J0030 + 0451 (ST + PDT and PDT-U).

Our previous works [37,43] demonstrated that hot spot geometry assumptions strongly influence EOS inferences when using piecewise-polytropic extrapolations, with the PDT-U model favoring larger radii and stiffer EOSs than the ST + PDT configuration. Here we show that the same qualitative behavior persists with the GP extension, confirming that this effect is robust across extrapolation strategies. Quantitatively, GP-based EOSs yield broader posteriors than PP models, but generally predict higher maximum masses and smaller neutron star radii. Bayesian model comparison strongly favors the ST + PDT geometry over PDT-U in both extrapolation schemes, and—while not decisive overall—provides substantial support for the GP extension over the PP model, particularly in the ST + PDT case.

Overall, our results highlight that both astrophysical systematics (hot spot geometry assumptions) and theoretical systematics (EOS extrapolation schemes) continue to play a central role in dense-matter inference. Looking forward, the evidence in favor of the GP framework suggests that nonparametric extrapolations may offer a more reliable path toward robust, bias-minimized EOS constraints in the multimessenger era.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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