Gravitational Laboratories for Nuclear Physics

Nonparametric Astrophysical Inference of the Nuclear Equation of State and Connections to Nuclear Experiment and Theory

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Perimeter Institute for Theoretical Physics

Key References

P. Landry and R. Essick, *Nonparametric Inference of the Neutron Star Equation of State from gravitational Wave Observations*, PRD 99, 084049 (2019)

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Nonparametric Equation of State Inference

getting the EoS right

Comparisons with *ab initio* Chiral Effective Field Theory Calculations

connecting astrophysical observations with terrestrial experiments

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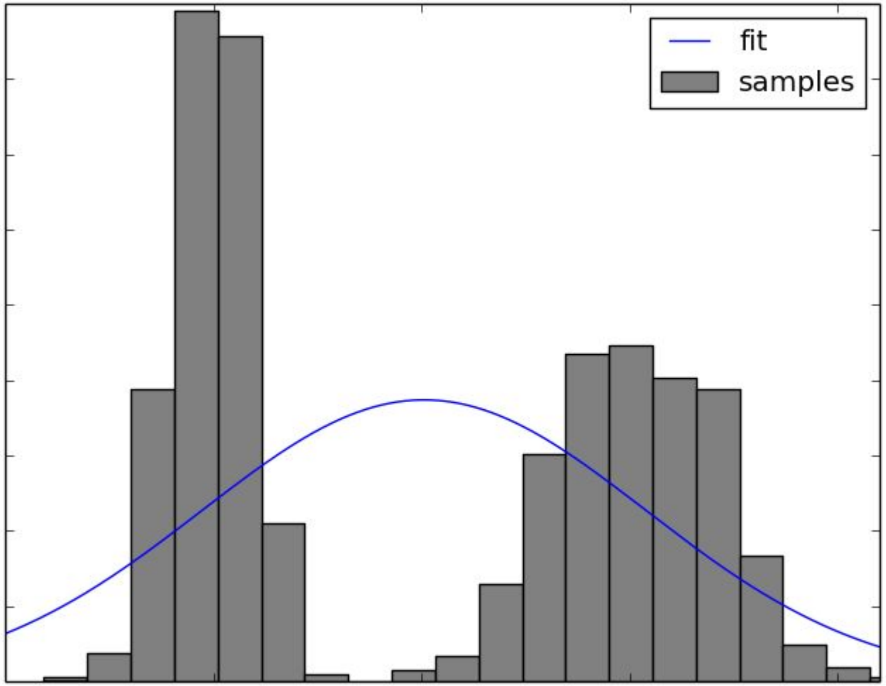
Parametric vs. Nonparametric Inference

Parametric constructions:

- Typically, include a small number of parameters and claim they reproduce proposed EOS reasonably well
- Think of fitting a collection of data with a fixed function

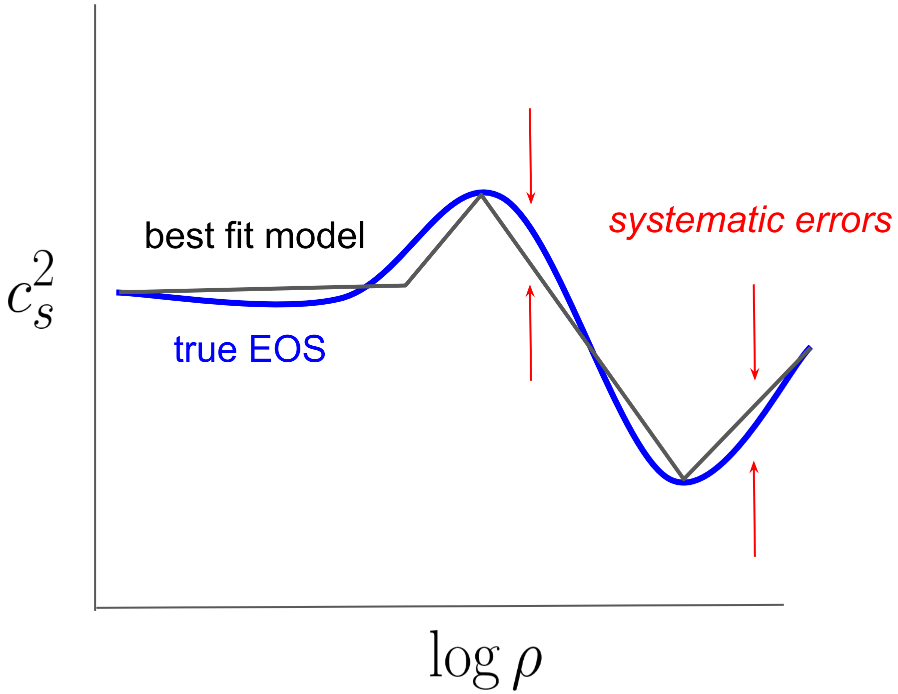
Parametric analyses require the function to be of a specific form which may or may not faithfully represent the data.



Parametric vs. Nonparametric Inference

Parametric constructions

- only allow for certain types of behavior (set of measure zero), and all expected behavior must be built into the model from the start
- If true EOS is not exactly described by the parameterized model, it can never be exactly recovered

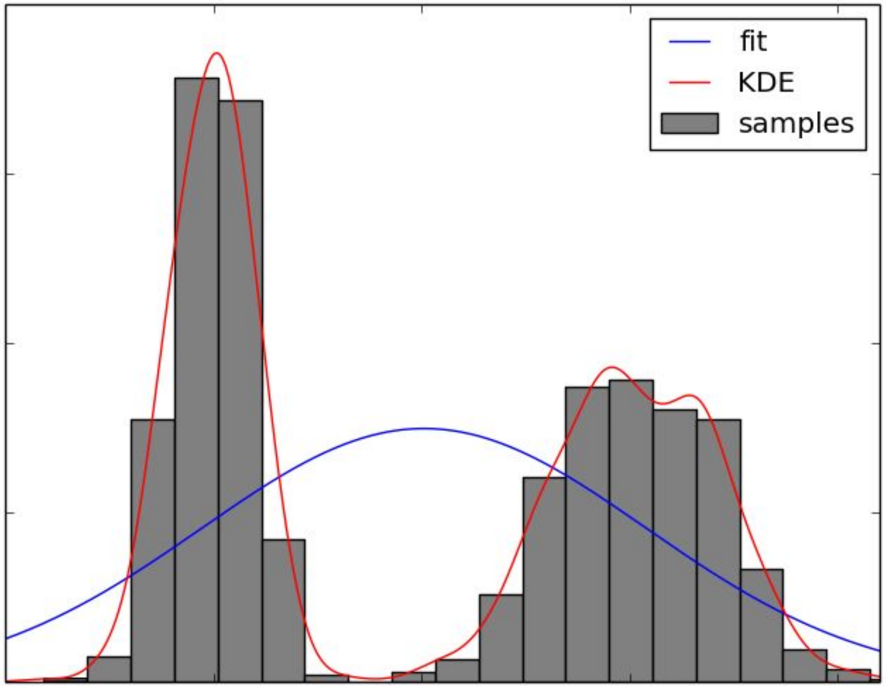


Parametric vs. Nonparametric Inference

Nonparametric constructions:

- Do not assume a functional form for the EOS a prior
- Think of making a histogram or kernel density estimate instead of using a fixed functional form

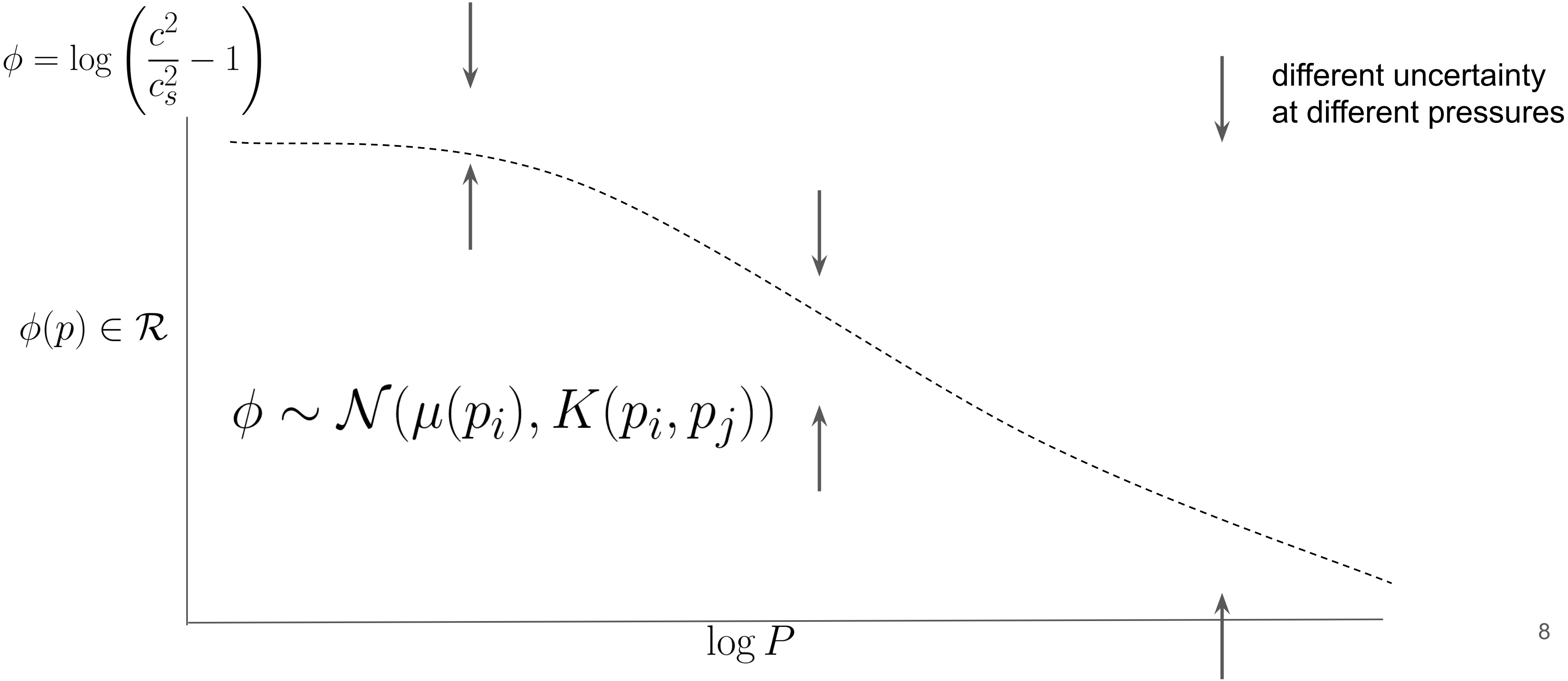
Nonparametric analyses assume things about the type of correlations within a function but do not require the function to have any specific form!



Nonparametric EoS Inference (Gaussian Processes)

Gaussian processes generate functions that have support along the entire real line, so we map the sound speed to an *auxiliary variable* that spans this range

$$\phi = \log\left(\frac{c^2}{c_s^2} - 1\right)$$



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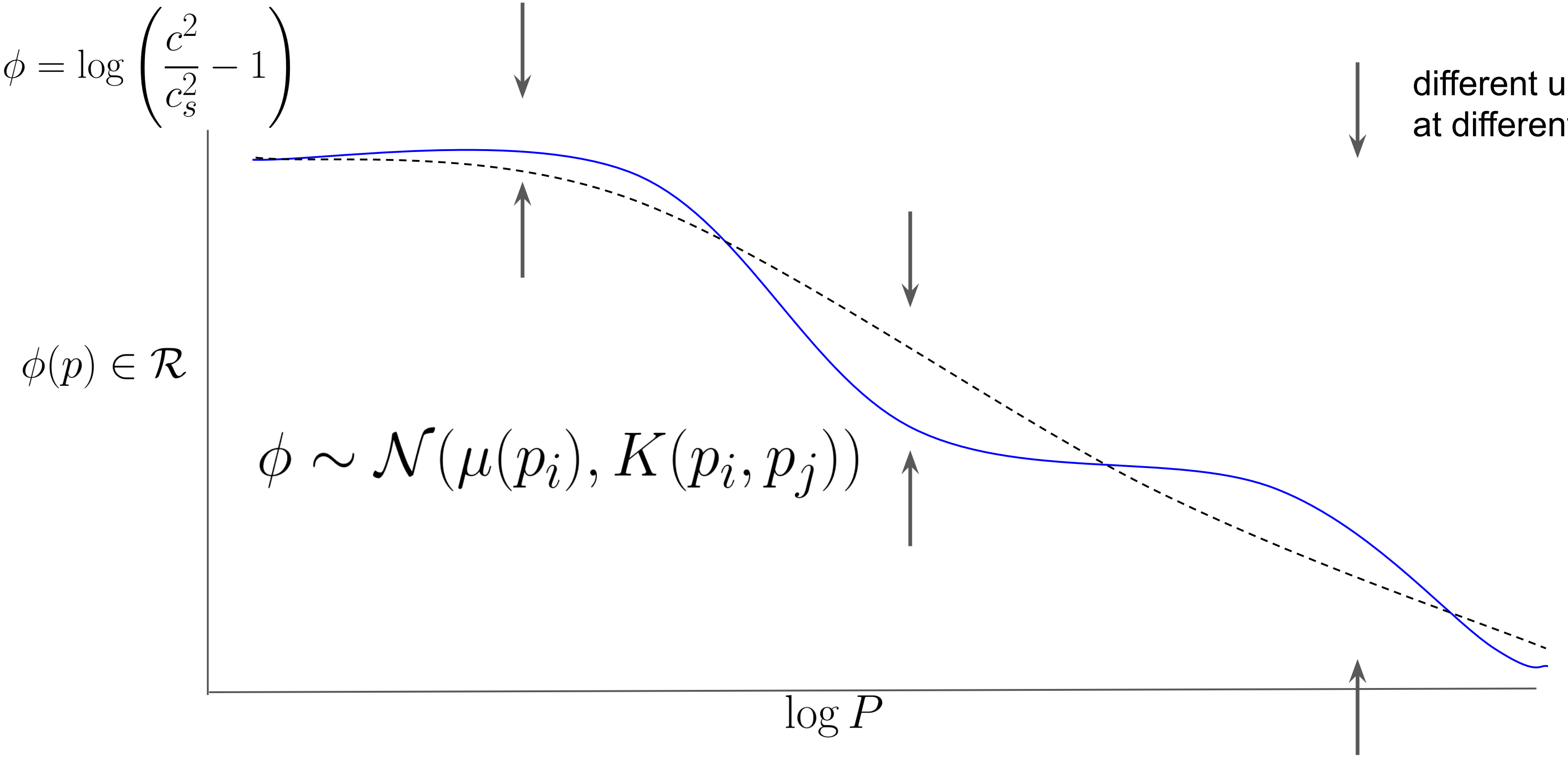

different uncertainty at different pressures

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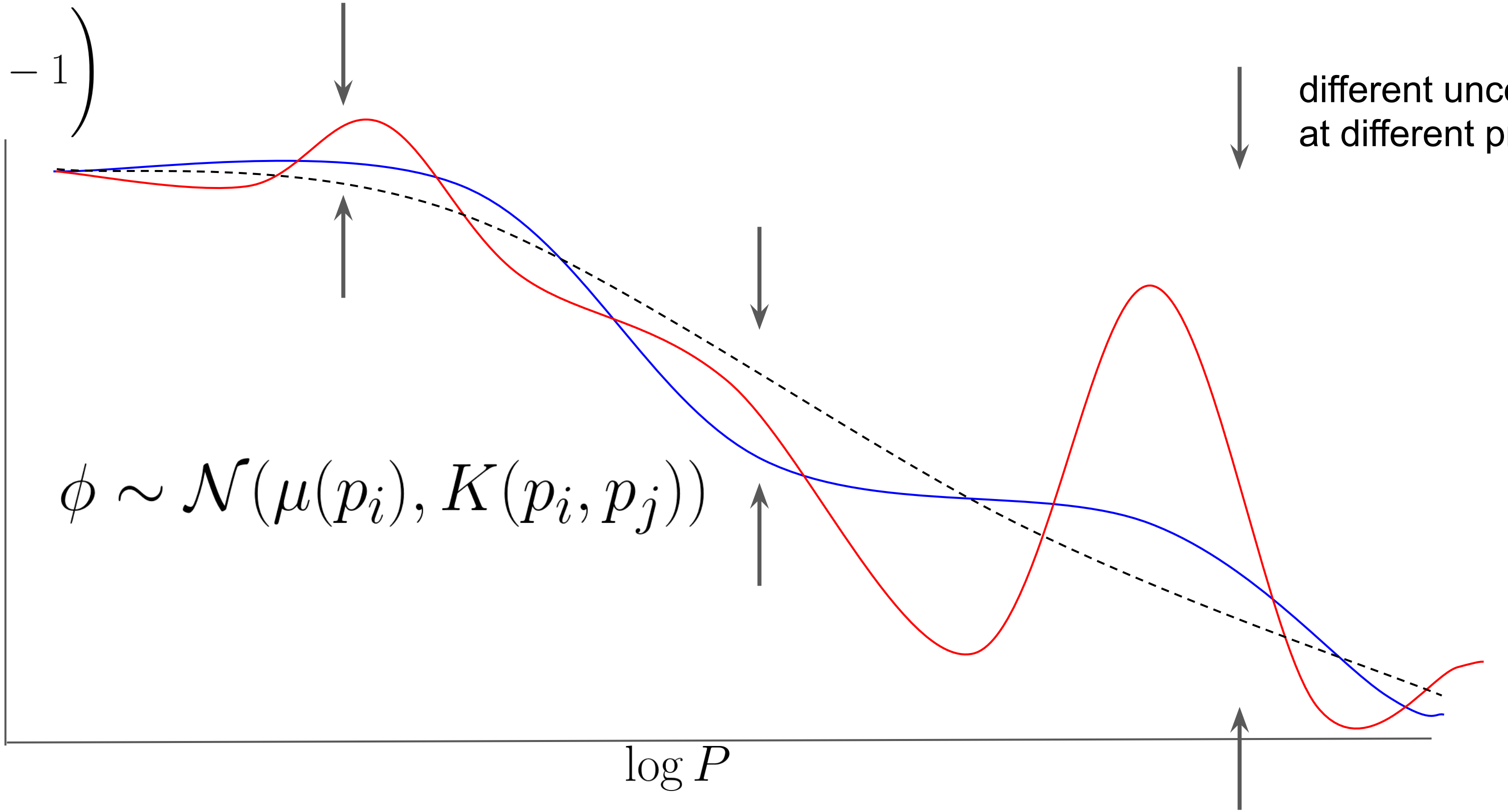
$$\phi(p) \in \mathcal{R}$$



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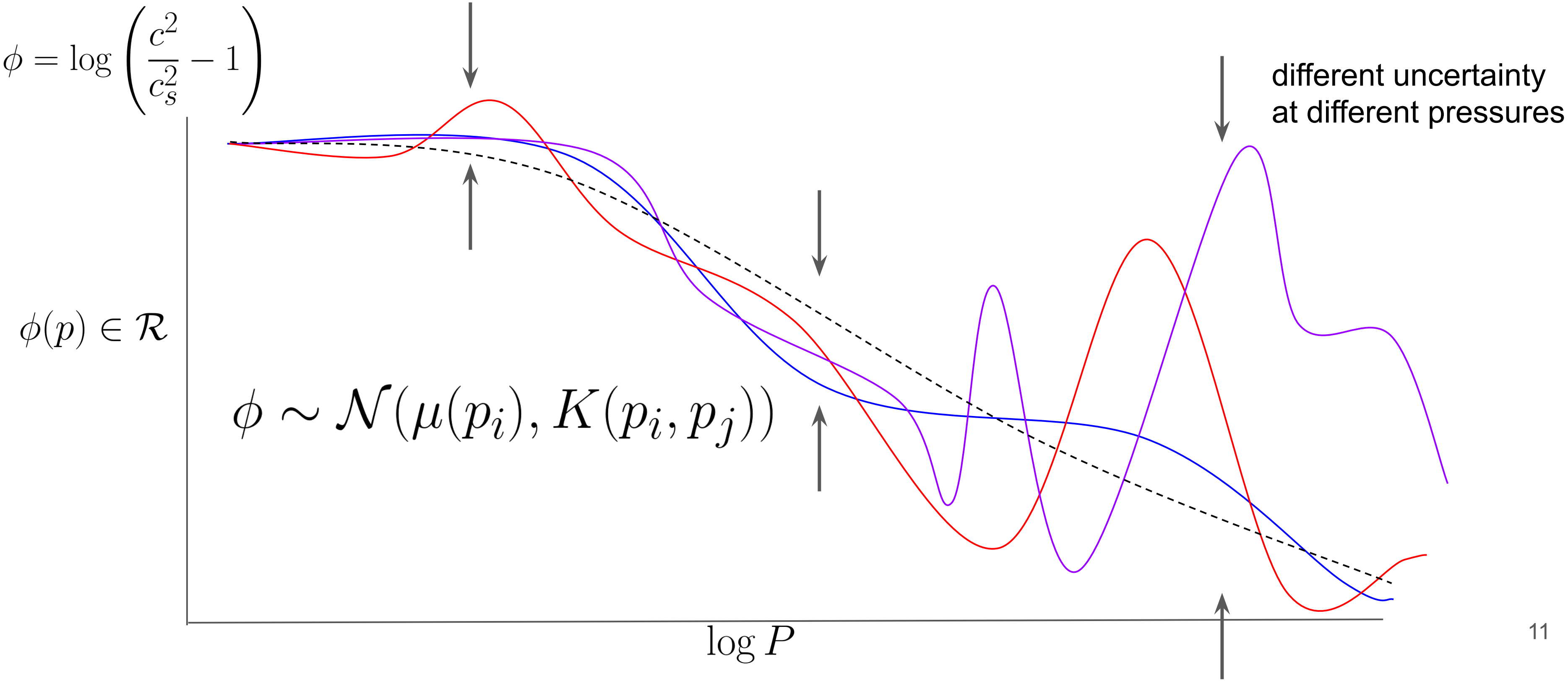

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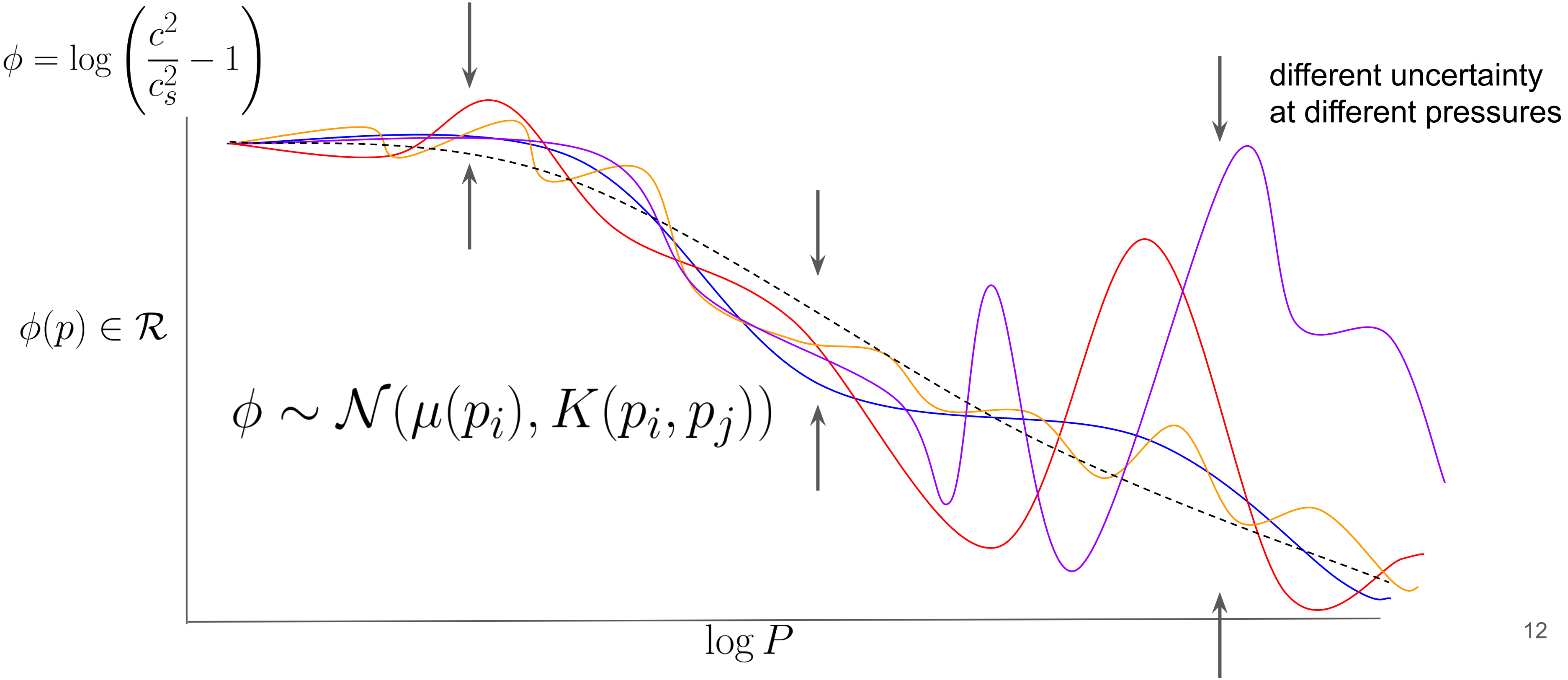

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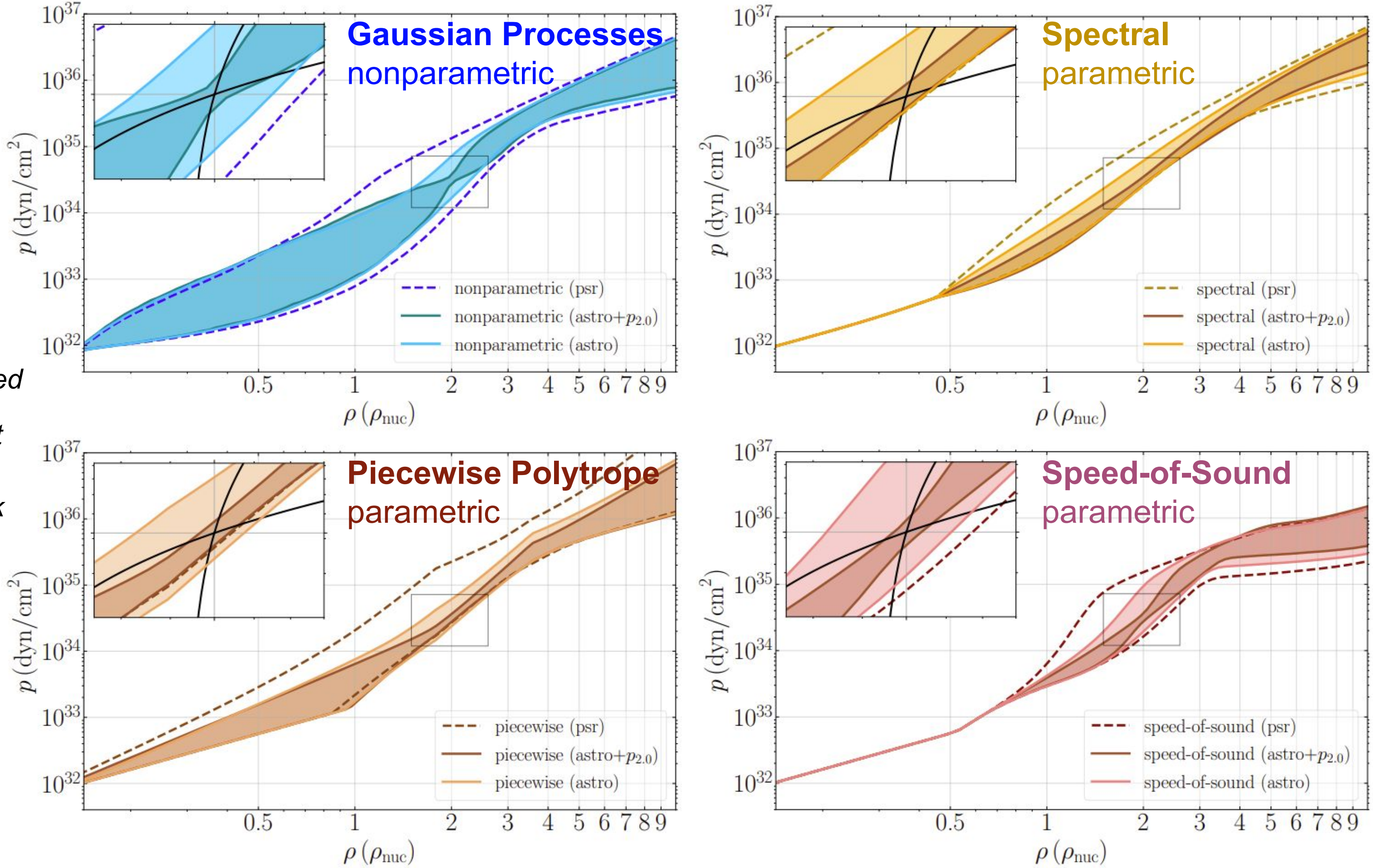
Nonparametric EoS Inference

priors	*dashed*
astro data	*light*
mock obs of $p(2n_{sat})$	*dark*



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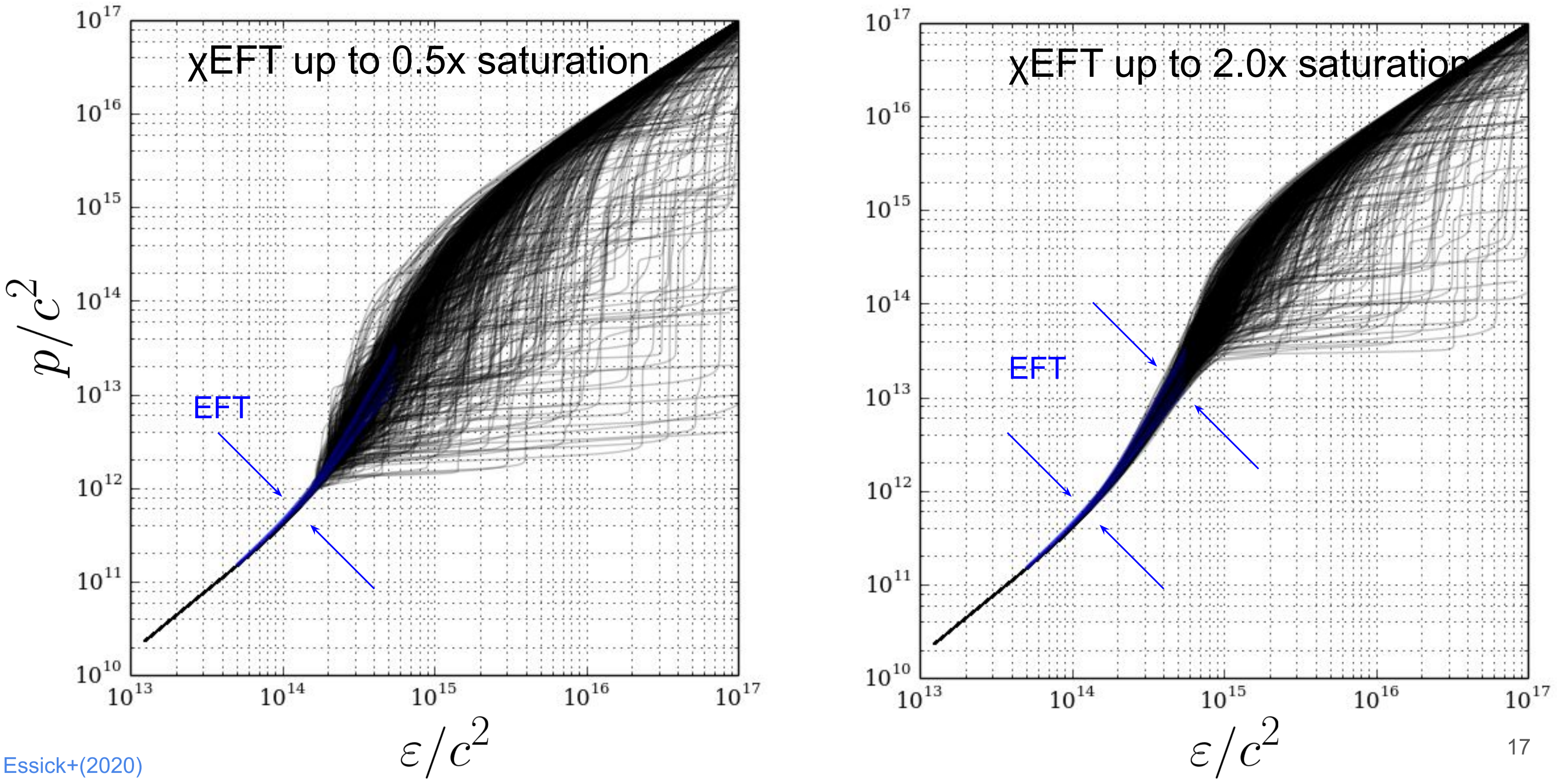

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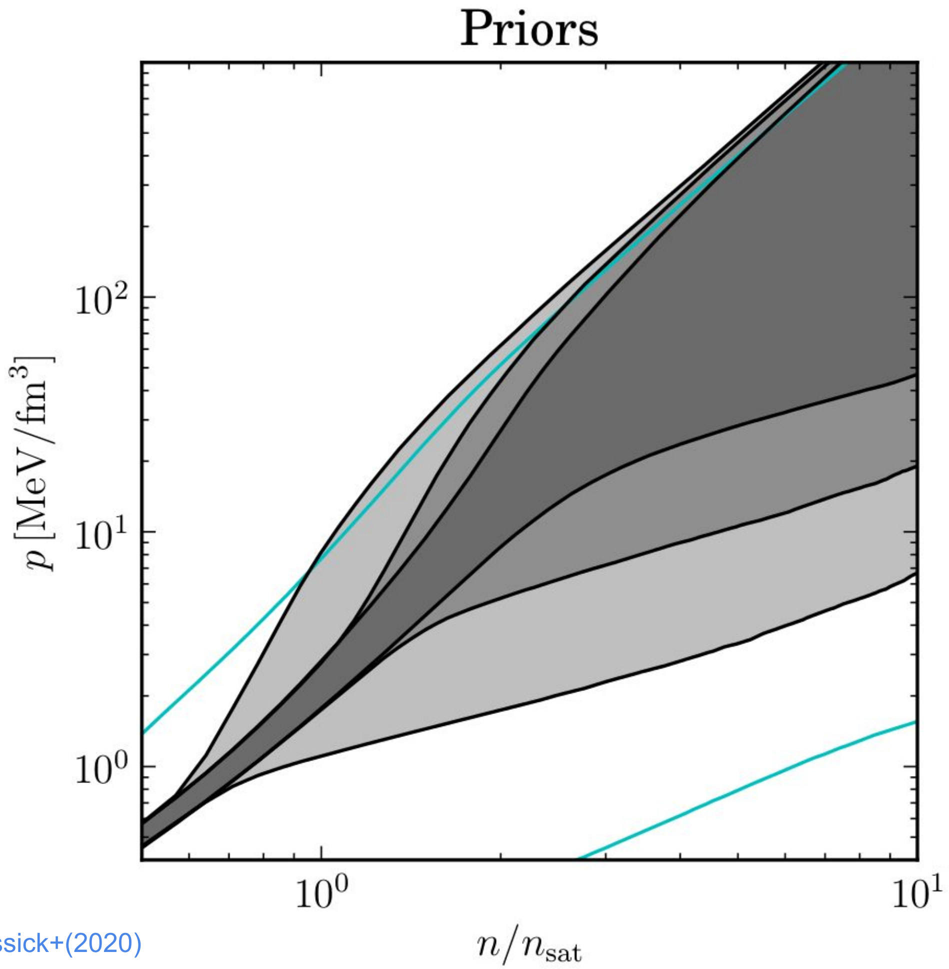

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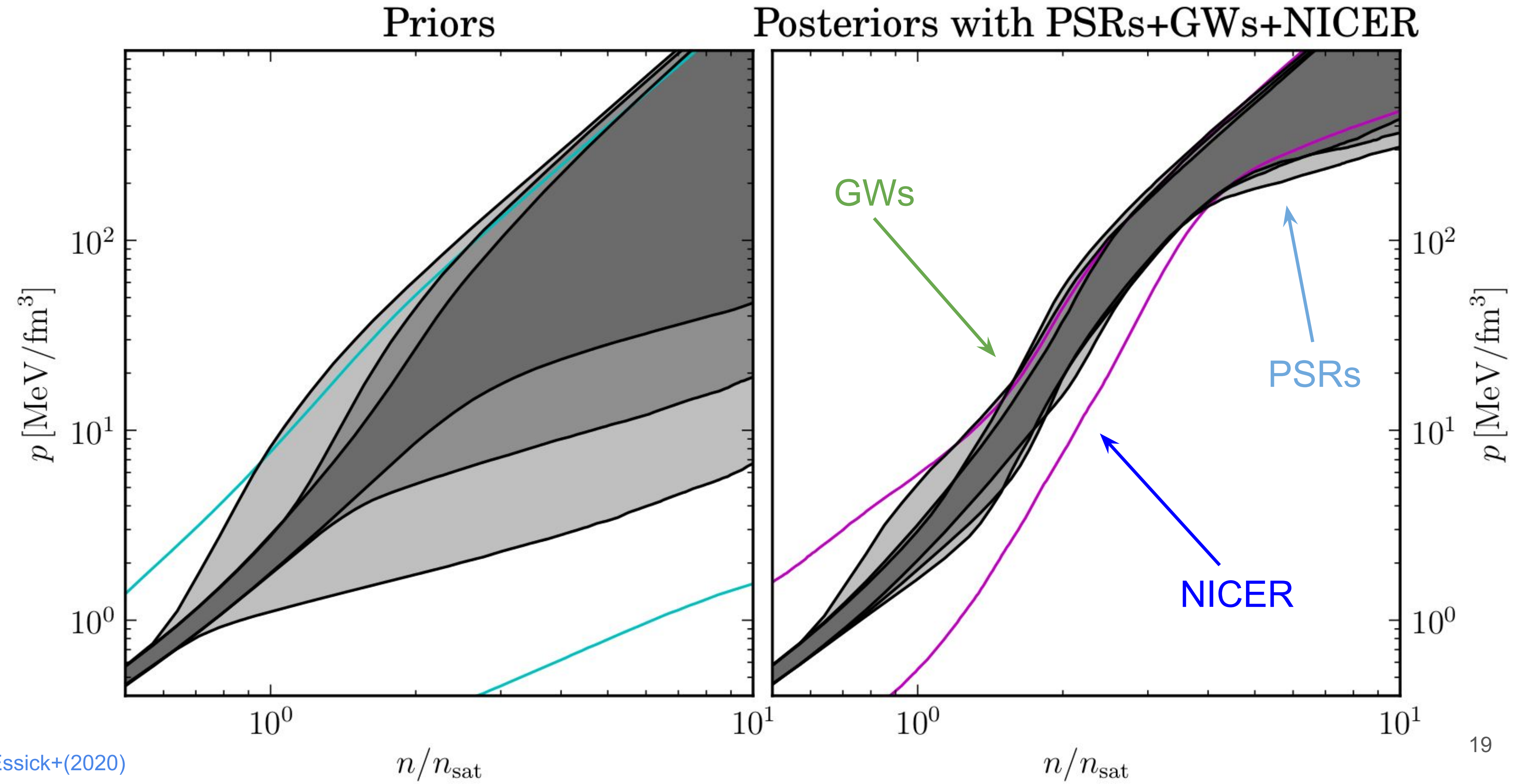

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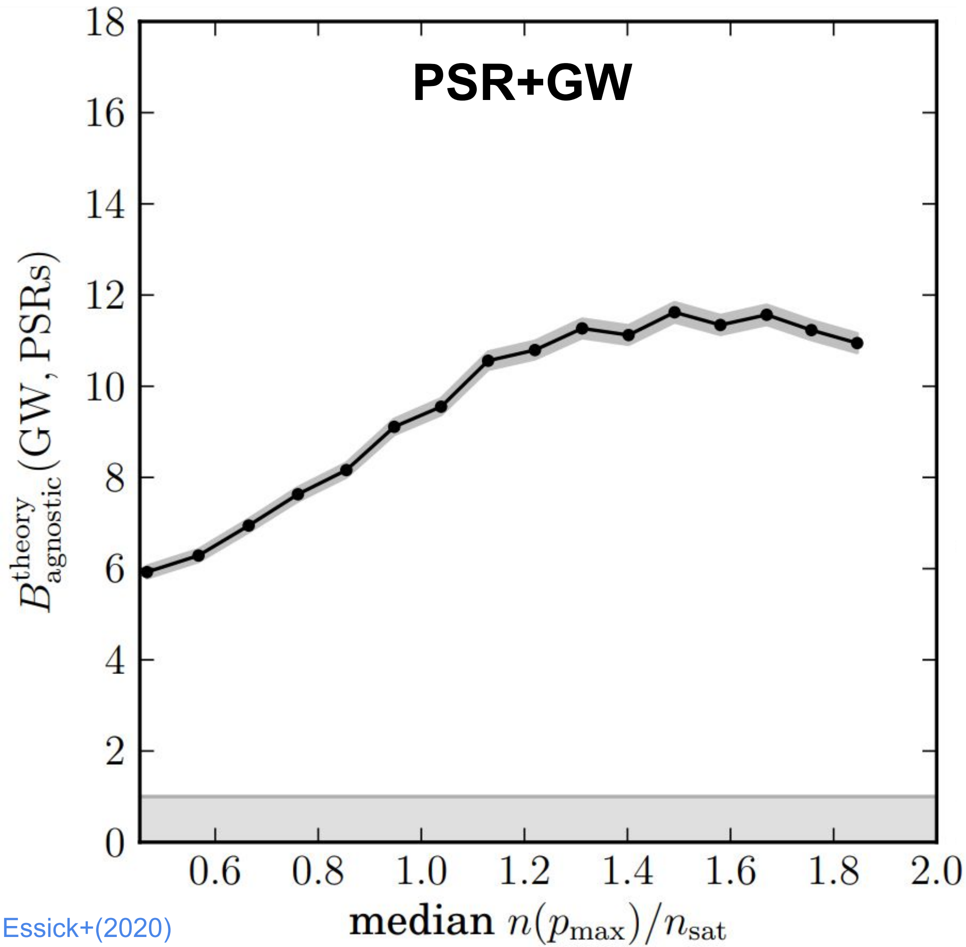

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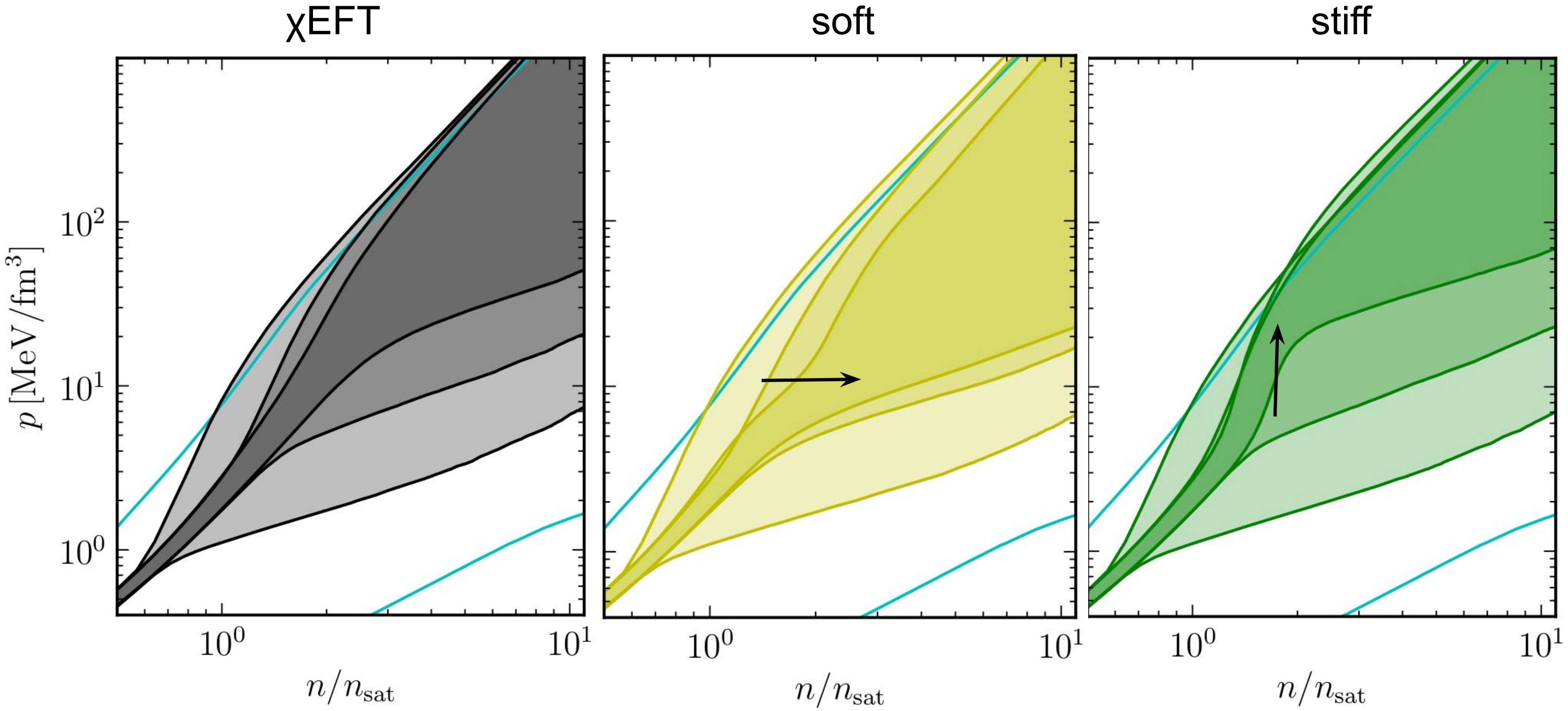

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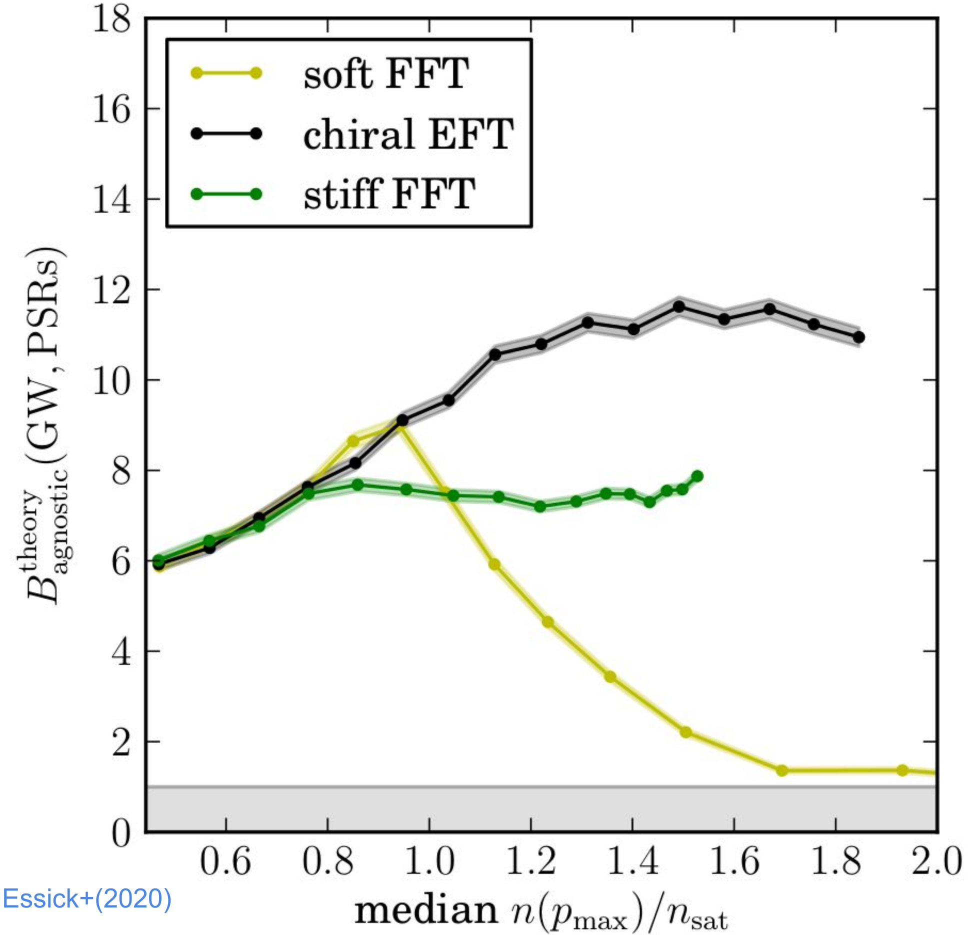
Comparisons with *ab initio* Chiral Effective Field Theory Calculations

PSR+GW



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Comparisons with *ab initio* Chiral Effective Field Theory Calculations

Quantity	$\mathrm{QMC}^{(2018)}_{\mathrm{N^2LO},\mathrm{l}} \lesssim n_{\mathrm{sat}}$		$\mathrm{QMC}^{(2018)}_{\mathrm{N^2LO},\mathrm{l}} \lesssim 2n_{\mathrm{sat}}$		Marginalized $\mathrm{QMC}^{(2018)}_{\mathrm{N^2LO},\mathrm{l}}$		Completely Agnostic	
	PSRs+GWs	+NICER	PSRs+GWs	+NICER	PSRs+GWs	+NICER	PSRs+GWs	+NICER
M_{max} [$M_\odot$]	$2.20^{+0.25}_{-0.20}$	$2.25^{+0.32}_{-0.25}$	$2.18^{+0.20}_{-0.17}$	$2.21^{+0.28}_{-0.22}$	$2.19^{+0.24}_{-0.18}$	$2.24^{+0.31}_{-0.23}$	$2.20^{+0.24}_{-0.18}$	$2.22^{+0.30}_{-0.20}$
$R_{1.4}$ [km]	$11.59^{+1.23}_{-1.19}$	$12.59^{+0.64}_{-0.59}$	$11.21^{+1.23}_{-0.91}$	$12.43^{+0.53}_{-0.77}$	$11.40^{+1.38}_{-1.04}$	$12.54^{+0.71}_{-0.63}$	$10.95^{+2.00}_{-1.37}$	$12.32^{+1.09}_{-1.47}$
$\Lambda_{1.4}$	291^{+264}_{-175}	518^{+208}_{-163}	227^{+218}_{-108}	465^{+125}_{-177}	260^{+270}_{-140}	494^{+201}_{-166}	228^{+319}_{-134}	451^{+241}_{-279}
$p(n_{\mathrm{sat}})$ [MeV/fm^3]	$2.13^{+0.49}_{-0.46}$	$2.27^{+0.58}_{-0.46}$	$2.19^{+0.49}_{-0.47}$	$2.54^{+0.60}_{-0.49}$	$2.15^{+0.64}_{-0.53}$	$2.42^{+0.75}_{-0.66}$	$1.38^{+2.72}_{-1.31}$	$2.68^{+2.37}_{-2.48}$
$p(2n_{\mathrm{sat}})$ [10 MeV/fm^3]	$1.62^{+1.94}_{-0.99}$	$3.12^{+2.03}_{-1.42}$	$1.33^{+0.99}_{-0.51}$	$2.61^{+0.94}_{-1.23}$	$1.42^{+1.81}_{-0.84}$	$2.87^{+1.53}_{-1.50}$	$1.10^{+1.88}_{-1.09}$	$2.38^{+1.66}_{-1.83}$
$p(3n_{\mathrm{sat}})$ [10^2 MeV/fm^3]	$0.86^{+0.61}_{-0.57}$	$1.12^{+0.59}_{-0.40}$	$0.68^{+0.51}_{-0.45}$	$1.05^{+0.49}_{-0.37}$	$0.79^{+0.56}_{-0.55}$	$1.08^{+0.56}_{-0.38}$	$0.71^{+0.60}_{-0.56}$	$0.98^{+0.59}_{-0.56}$
$p(4n_{\mathrm{sat}})$ [10^2 MeV/fm^3]	$2.03^{+0.90}_{-0.74}$	$2.12^{+1.07}_{-0.88}$	$2.00^{+0.78}_{-0.71}$	$2.08^{+0.92}_{-0.64}$	$2.02^{+0.87}_{-0.73}$	$2.11^{+1.08}_{-0.69}$	$2.01^{+0.95}_{-0.84}$	$2.11^{+1.11}_{-0.73}$
$p(6n_{\mathrm{sat}})$ [10^2 MeV/fm^3]	$5.35^{+2.57}_{-2.78}$	$4.95^{+3.05}_{-3.18}$	$5.41^{+2.20}_{-2.15}$	$4.99^{+2.86}_{-2.58}$	$5.36^{+2.39}_{-2.53}$	$4.97^{+2.96}_{-2.98}$	$5.71^{+2.57}_{-2.48}$	$5.38^{+3.30}_{-2.66}$

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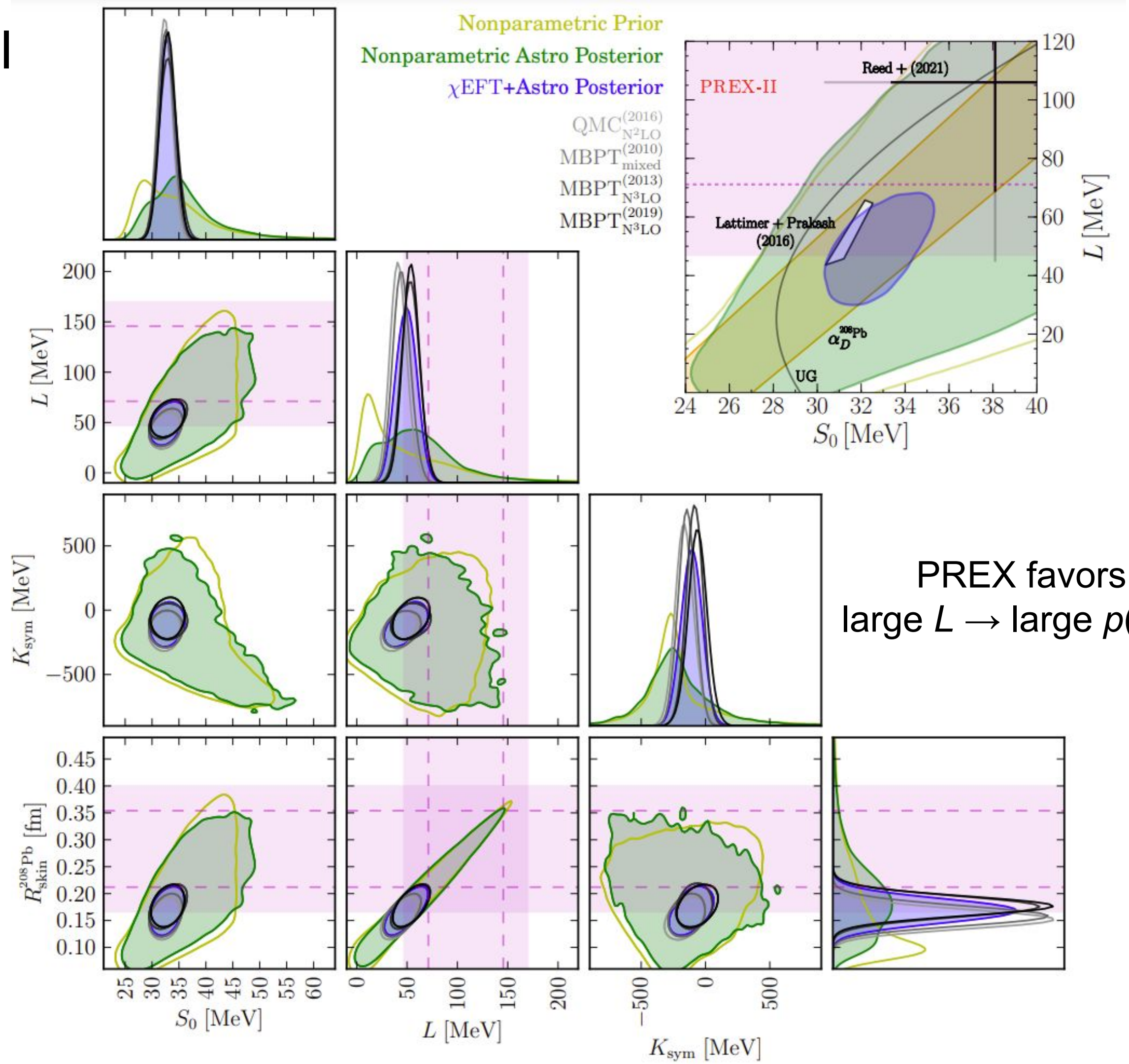


We can also extract "nuclear parameters" directly from nonparametric EoS Without the need for "parametrized EoS models"

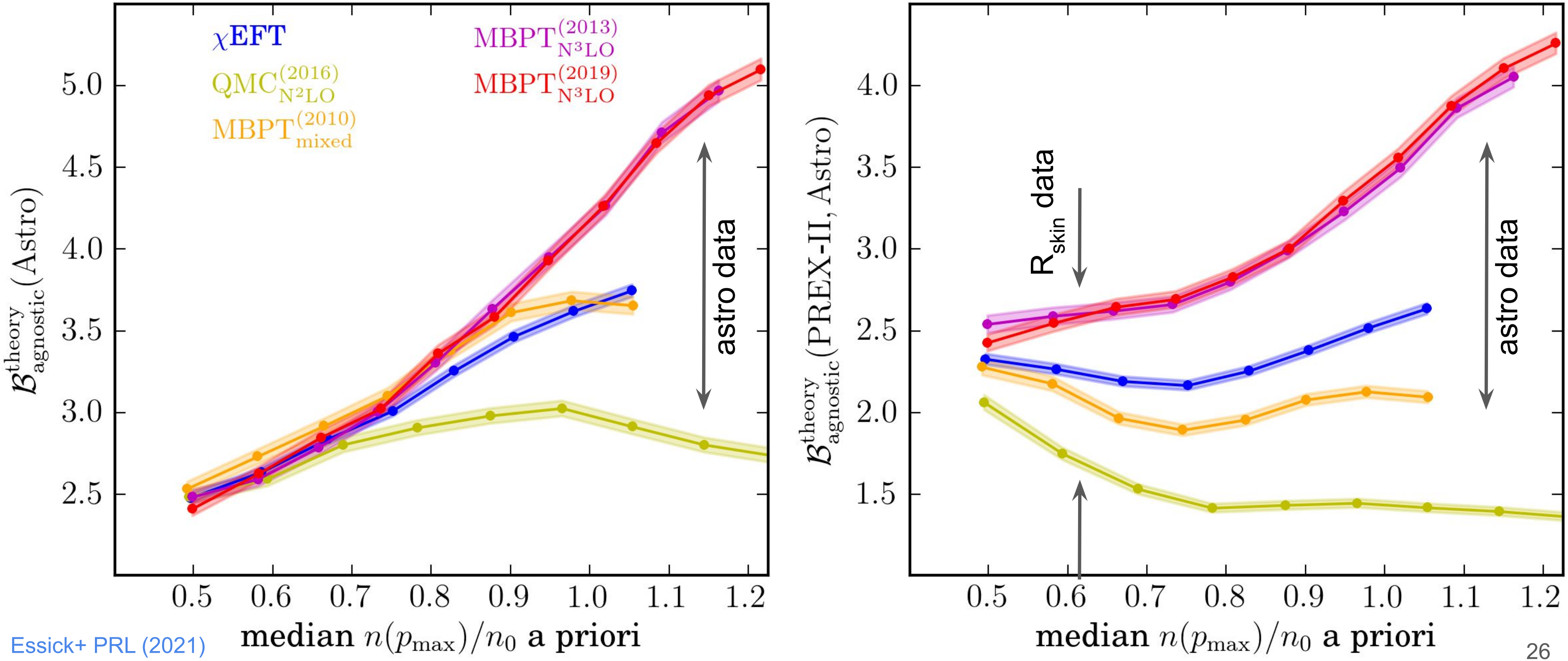
PREX favors large $L \to$ large $p(n_{\rm sat})$

Essick+ PRL (2021)
Essick+ PRC (2021)

Comparisons with Terrestrial Nuclear Experiments

astro data can distinguish between nuclear theories at high densities

nuclear experiments probe lower densities



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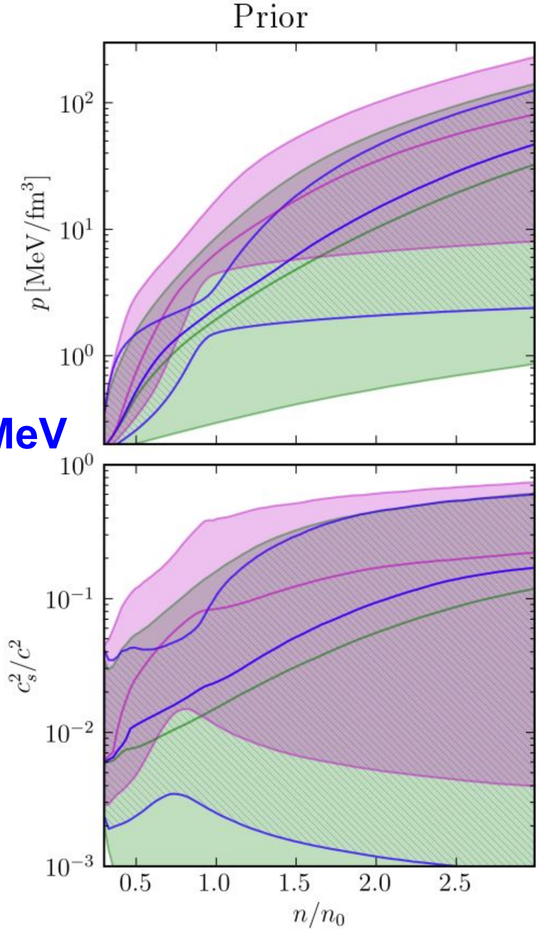

100 MeV < *L*

30 MeV < *L* < 70 MeV

All *L*

Essick+ PRL (2021)
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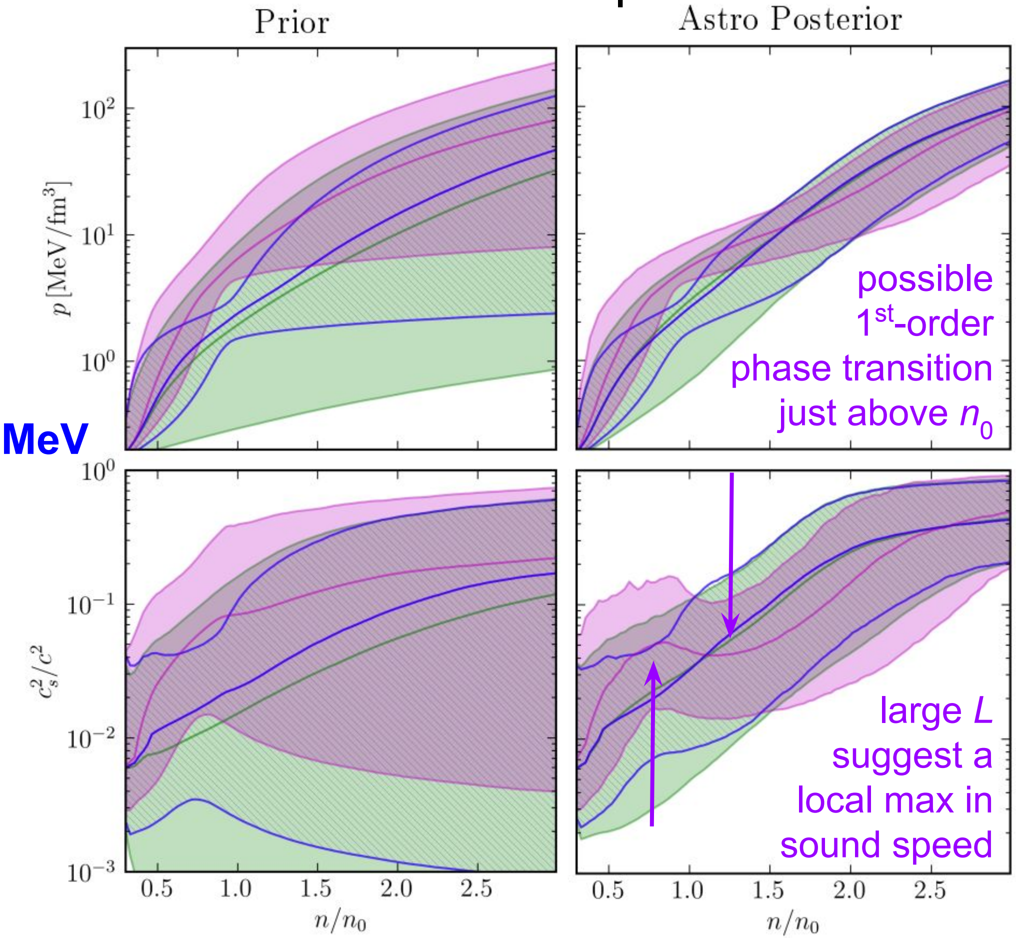

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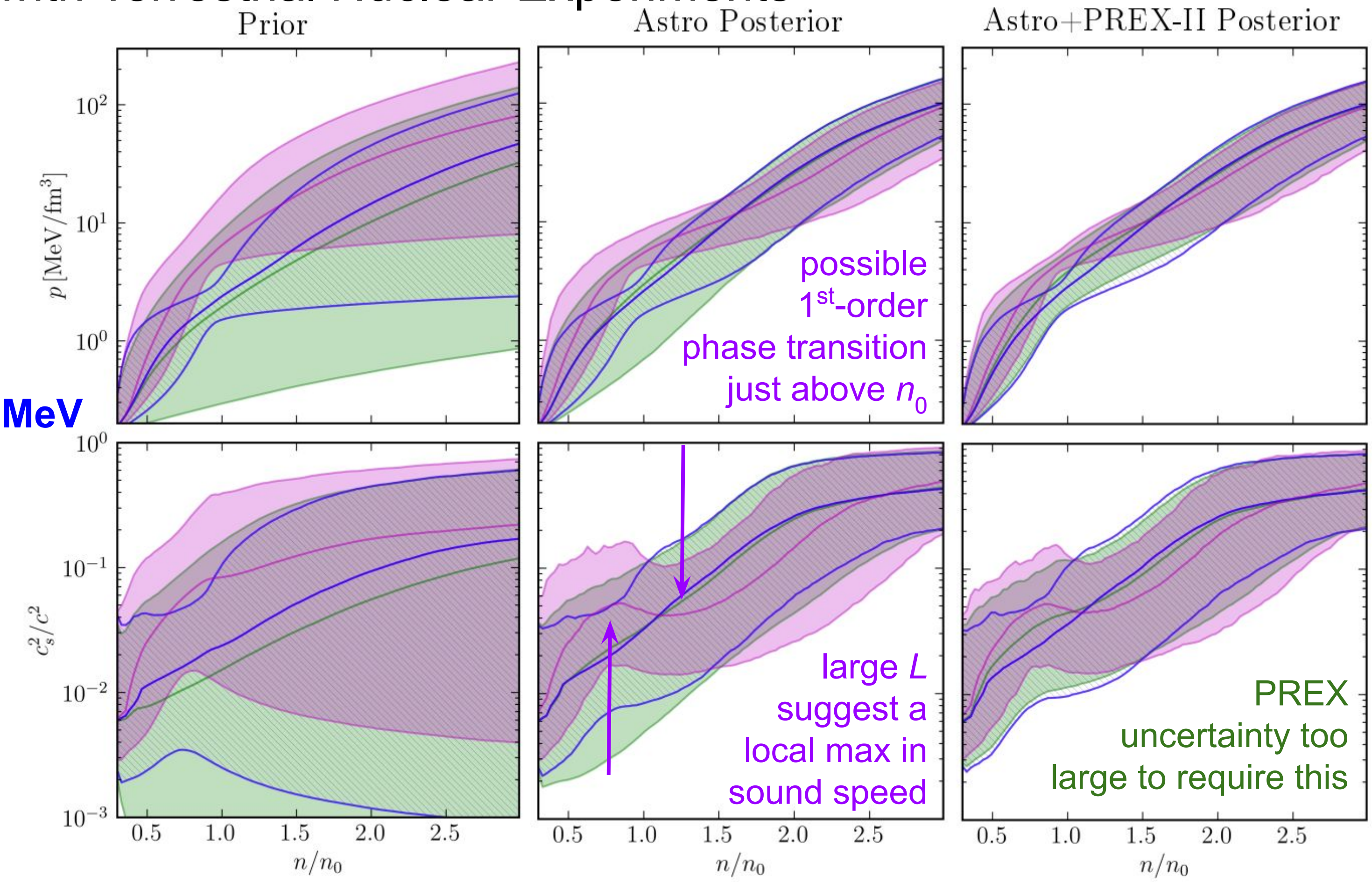

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Extra Slides

Nonparametric EoS Inference

consider a toy model:
→ fitting a 1D function (pressure vs. energy density) without constraints

point+slope

$$p(\varepsilon) = p_a + c_s^2(\varepsilon - \varepsilon_a)$$

two-point

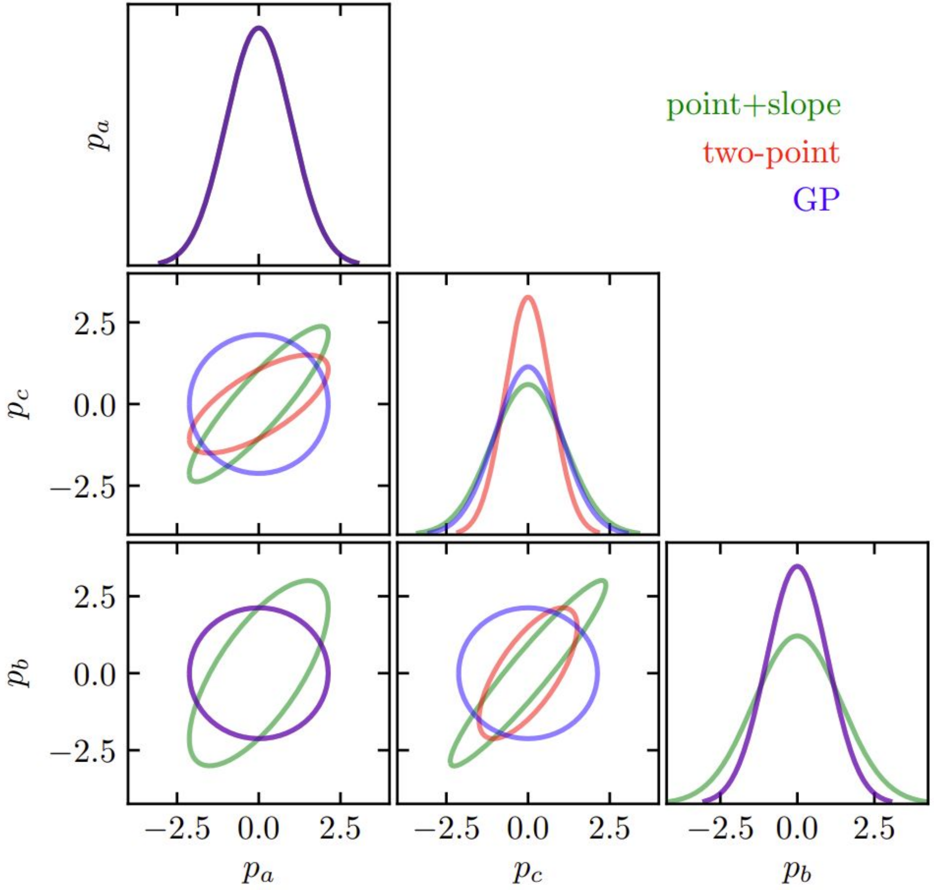
$$p(\varepsilon) = p_a + \frac{p_b - p_a}{\varepsilon_b - \varepsilon_a}(\varepsilon - \varepsilon_a)$$

GP

$$\vec{p} \sim \mathcal{N}(\vec{\mu}, \Sigma)$$

$$\Sigma_{ij} = \mathrm{Cov}(p_i, p_j)$$

$$= K_{\mathrm{se}}(\varepsilon_i, \varepsilon_j) = \sigma^2 \exp\left(-\frac{(\varepsilon_i - \varepsilon_j)^2}{l^2}\right)$$



only the **GP** has ***independent marginal distributions*** for all pressures

Legred+(2022)

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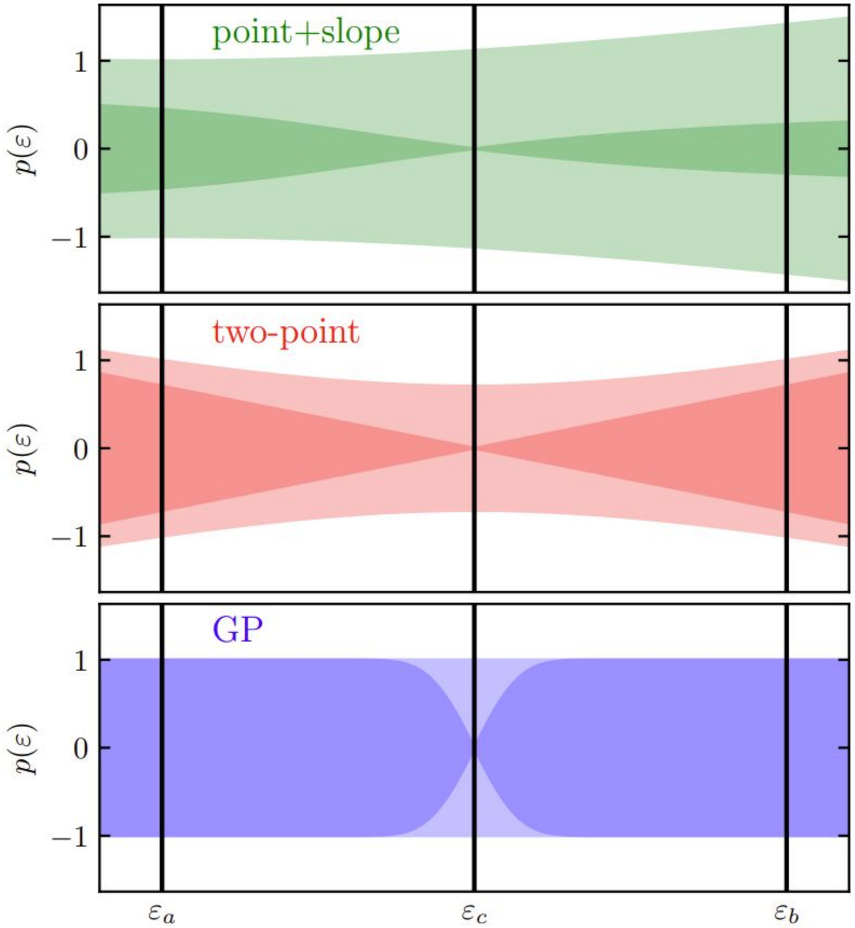

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Comparisons with Terrestrial Nuclear Experiments

Map from nonparametric EoS in β-equilibrium to nuclear params describing the energy per particle near nuclear saturation (n_0: minimum of E_{SNM})

$$x = n_p/n$$

proton fraction

$$E_{\mathrm{nuc}}(n, x) = E_{\mathrm{SNM}}(n) + (1-2x)^2 S_0(n) + \mathcal{O}(x^4)$$

nuclear energy per particle

$$= \frac{\varepsilon_\beta(n) - \varepsilon_e(n, x)}{n} - m_N$$

$$E_{\mathrm{SNM}}(n) = E_0 + \frac{1}{2} K_0 \left(\frac{n - n_0}{3n_0}\right)^2 + \cdots$$

symmetric-nuclear-matter
energy per particle
(local min at n_0)

$$\mu_n = \mu_p + \mu_e$$

condition for β-equilib

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Comparisons with Terrestrial Nuclear Experiments

Map from nonparametric EoS in β-equilibrium to nuclear params describing the energy per particle near nuclear saturation (n_0: minimum of E_{SNM})

$$x = n_p/n$$

proton fraction

$$E_{\mathrm{nuc}}(n,x) = E_{\mathrm{SNM}}(n) + (1-2x)^2 S_0(n) + \mathcal{O}(x^4)$$

$$= \frac{\boxed{\varepsilon_\beta(n)} - \boxed{\varepsilon_e(n,x)}}{n} - \boxed{m_N}$$

nuclear energy per particle

$$E_{\mathrm{SNM}}(n) = \boxed{E_0} + \frac{1}{2}\boxed{K_0}\left(\frac{n-n_0}{3n_0}\right)^2 + \cdots$$

symmetric-nuclear-matter energy per particle (local min at n_0)

$$\boxed{\mu_n = \mu_p} + \boxed{\mu_e}$$

condition for β-equilib

constrained by astro observations (input from nonparametric analysis)
measured in the lab (input from terrestrial experiment)
modeled as degenerate Fermi gas (input from theory)
expressed in terms of derivatives of E_{nuc}

$$\mu_i = \frac{dE}{dN_i}$$

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Comparisons with Terrestrial Nuclear Experiments

Map from nonparametric EoS in β-equilibrium to nuclear params describing the energy per particle near nuclear saturation (n_0: minimum of E_{SNM})

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symmetric-nuclear-matter energy per particle (local min at n_0)

$$\boxed{\mu_n = \mu_p} + \boxed{\mu_e}$$

condition for β-equilib

solve these self-consistently to obtain $S_0(n)$ and then compute

$$L = 3n\left(\frac{dS_0}{dn}\right)$$

$$K_{\mathrm{sym}} = 9n^2\left(\frac{d^2S_0}{dn^2}\right)$$

constrained by astro observations (input from nonparametric analysis)
measured in the lab (input from terrestrial experiment)
modeled as degenerate Fermi gas (input from theory)
expressed in terms of derivatives of E_{nuc}

$$\mu_i = \frac{dE}{dN_i}$$

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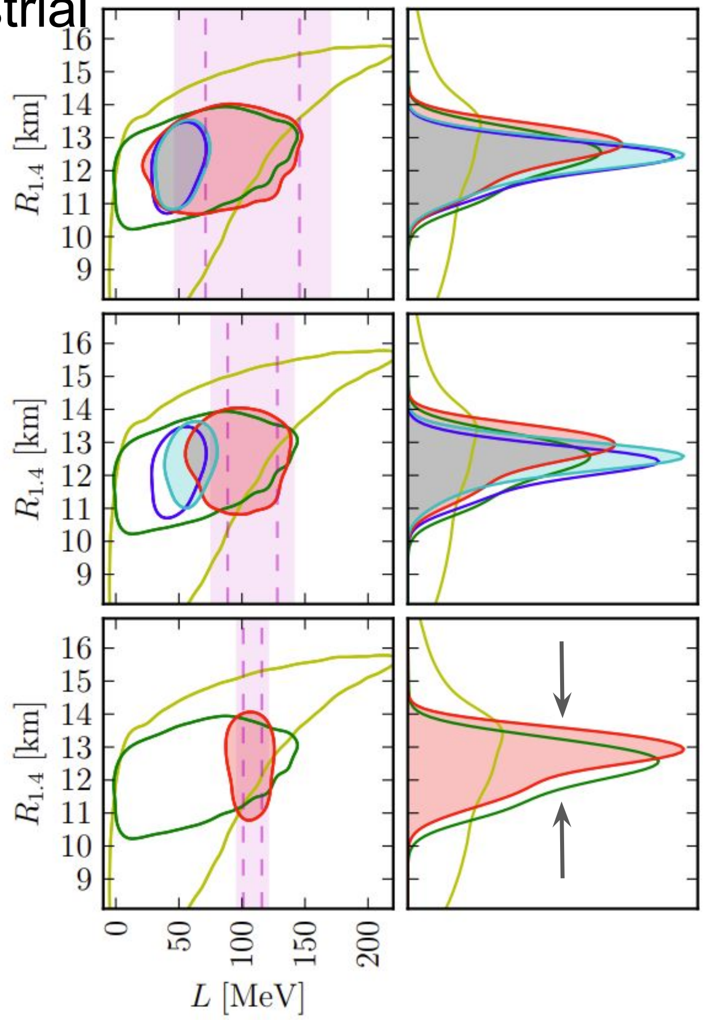
Comparisons with Terrestrial Nuclear Experiments

current R_{skin} uncertainty

R_{skin} uncertainty improved by a factor of 2

hypothetical perfect R_{skin} measurement



nonparametric prior

nonparametric astro-only posterior

χEFT+astro posterior

nonparametric astro+R_{skin} posterior

χEFT+astro+R_{skin} posterior

improved precision in nuclear experiments is unlikely to affect our knowledge of NS radii without improved theoretical calculations

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Essick+ PRC (2021)