Gravitational Laboratories for Nuclear Physics

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2024 CAP Congress
Computational Advances in Astrophysics and Cosmology

Outline

Types of observations → set up the inverse problem

Difficulties with inverse problem PRD 105, 043016 (2022)

- Parametric model → reduce dimensionality, traditional sampling methods
- Nonparametric representation → high dimensionality, novel sampling methods

Incorporating theoretical predictions within the prior PRC 102, 055803 (2020)

Exotic high-density behavior with efficient TOV sequences arXiv:2405.05395 (2024)

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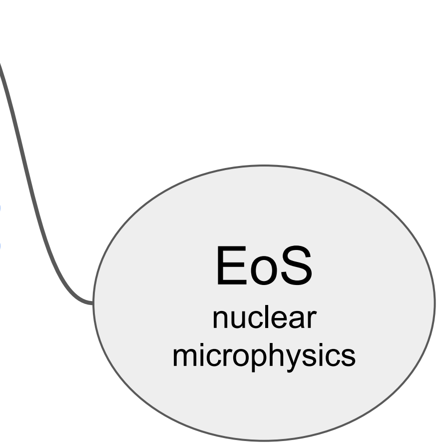
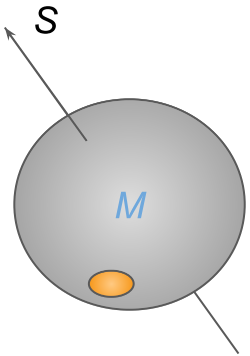
NS Observables: mass

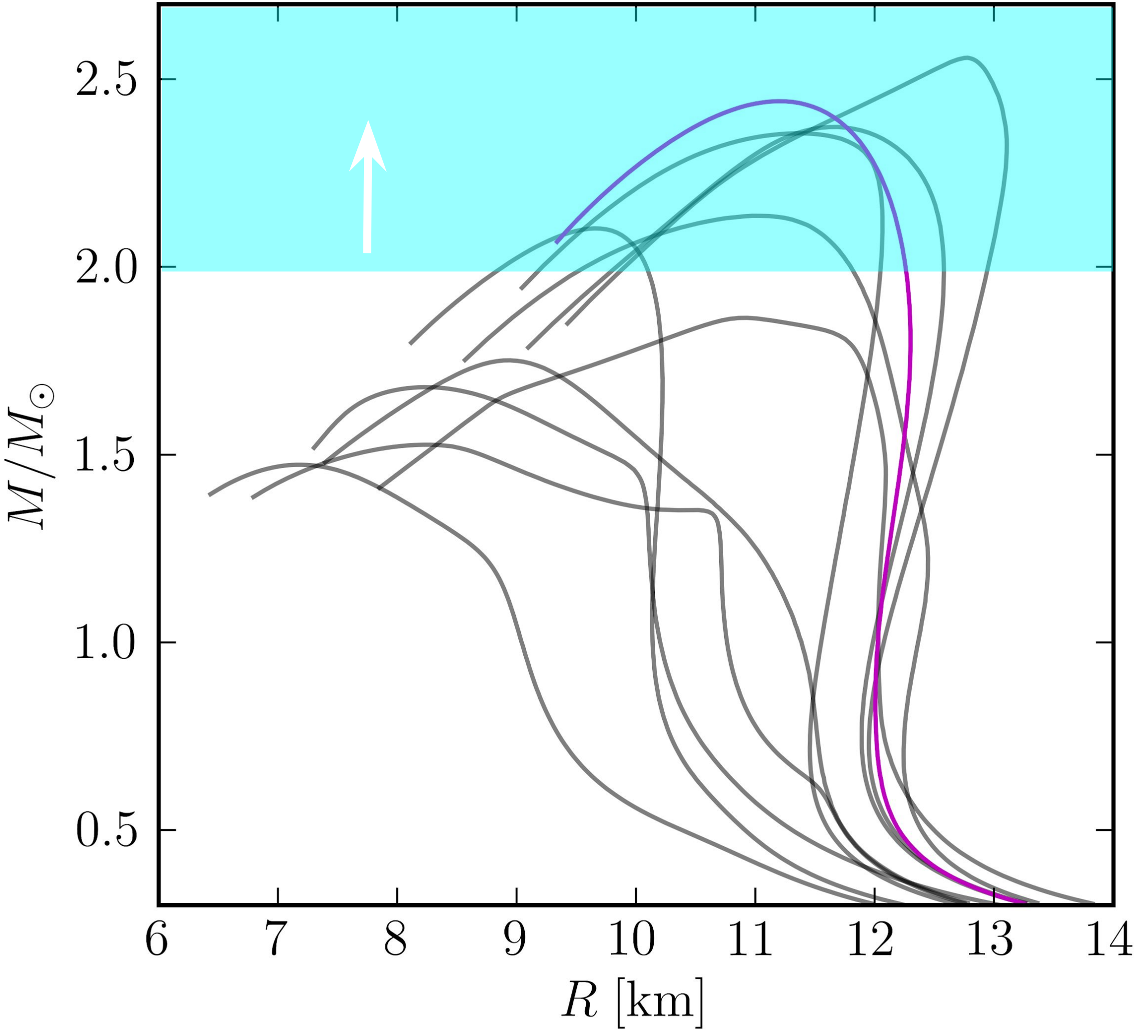
Massive pulsars (PSRs)
J0740+6620 Cromartie+(2019)
Fonseca+(2021)



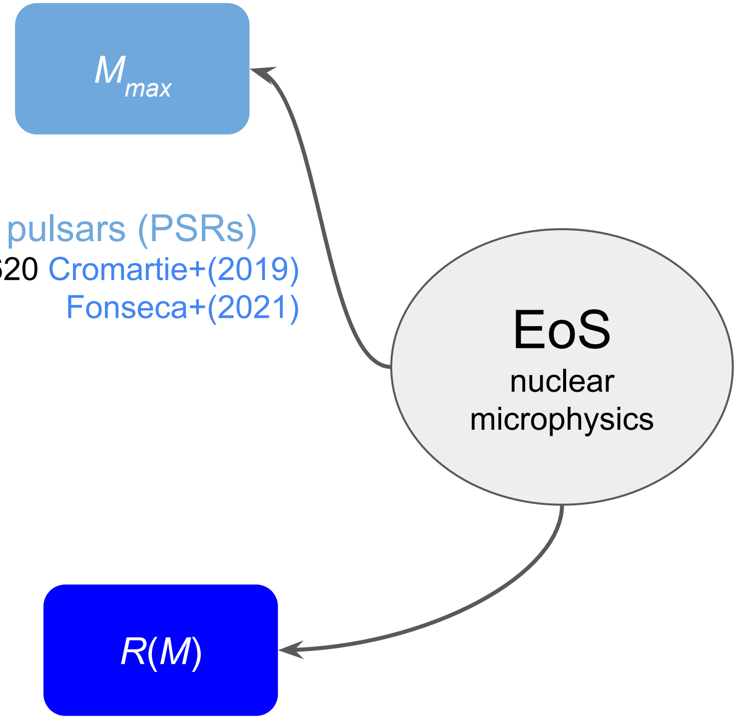


pulsar observations
radial velocity
Shapiro delay

NS Observables

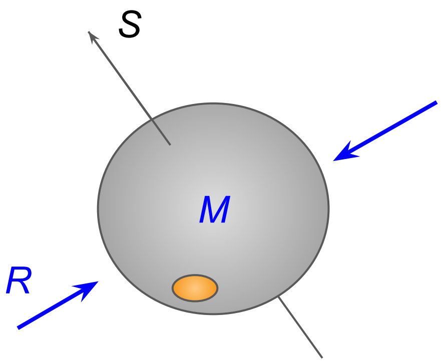


NS Observables: mass and radius



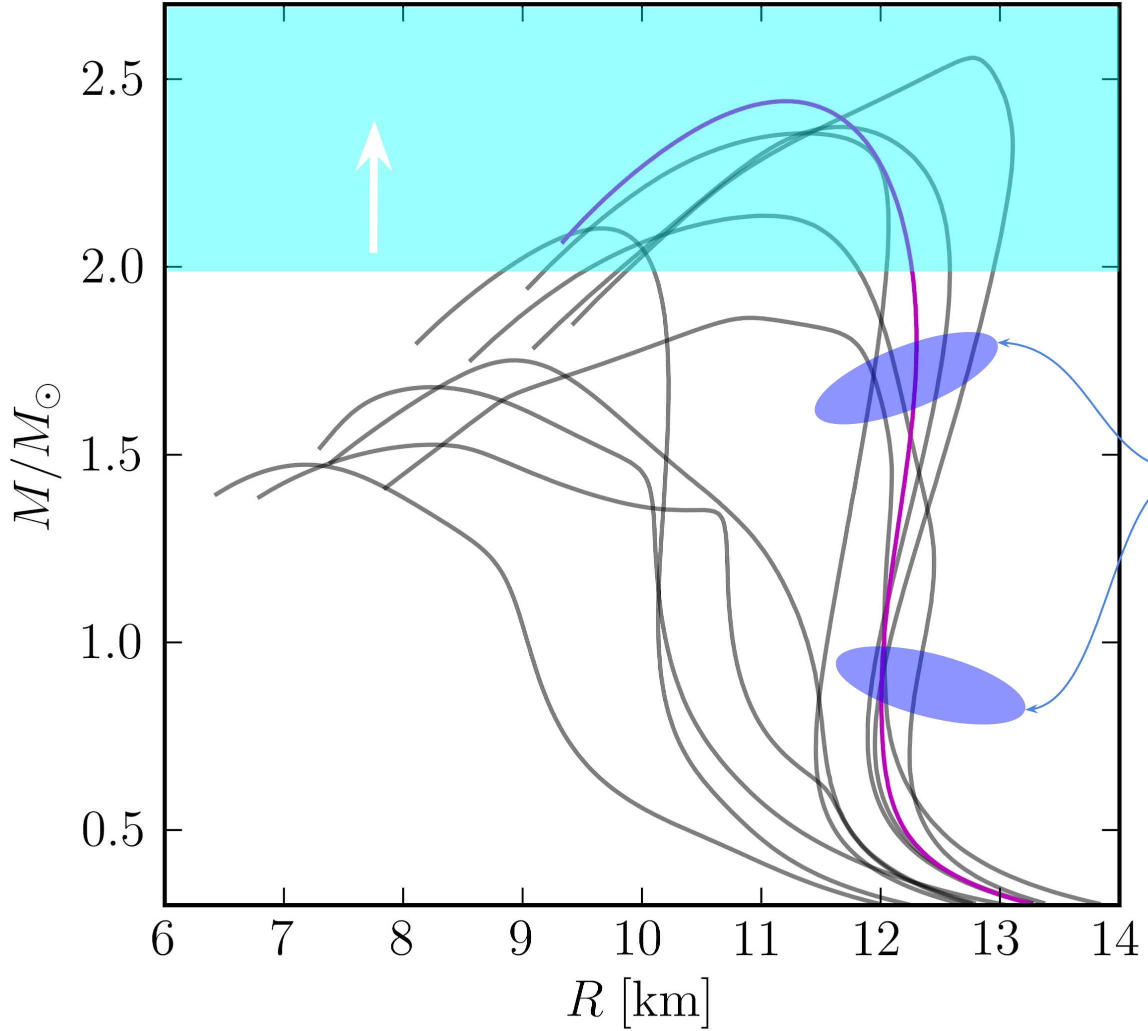
Massive pulsars (PSRs)
J0740+6620 Cromartie+(2019)
Fonseca+(2021)

X-ray pulse timing (NICER)
J0030+0451 Miller+(2019)
J0740+6620 Miller+(2021)



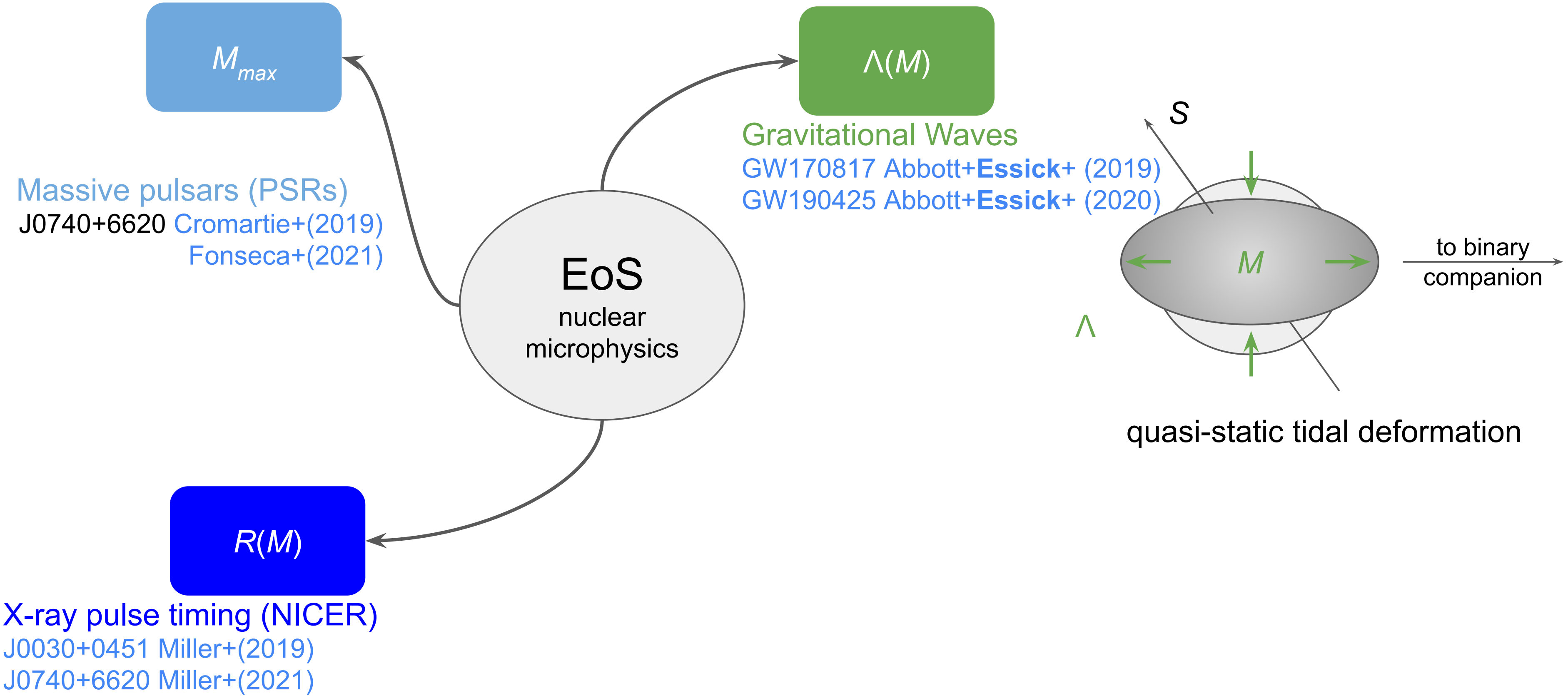
X-ray timing
Pulse profile modeling

NS Observables

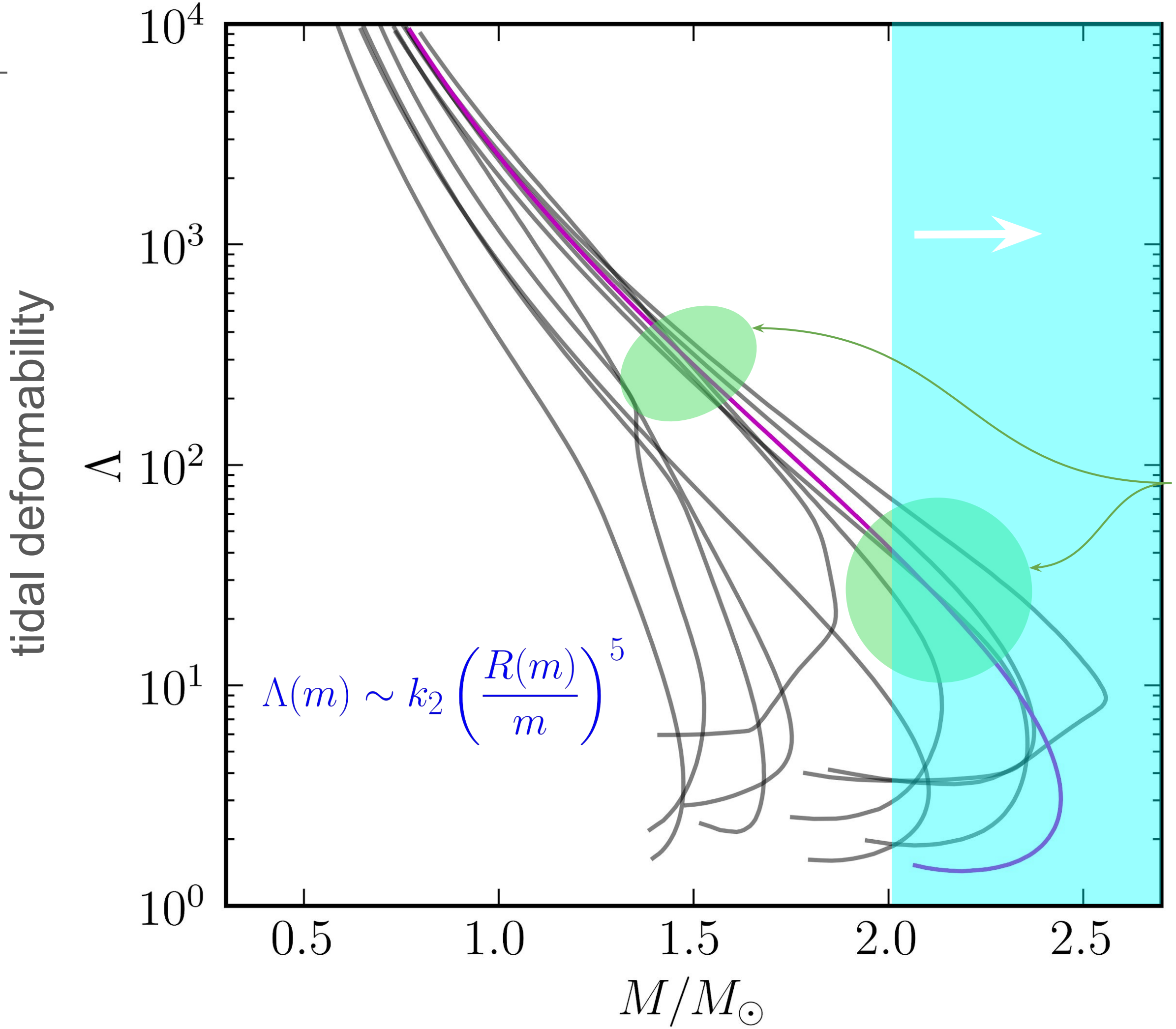


independent measurements from separate systems

NS Observables: mass and tidal deformability



NS Observables



simultaneous measurements from the same system

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Inference of the NS EoS: systematics from parametric models

Legred+**Essick**+ (2022)

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

linear parameterizations

point+slope

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

two-point

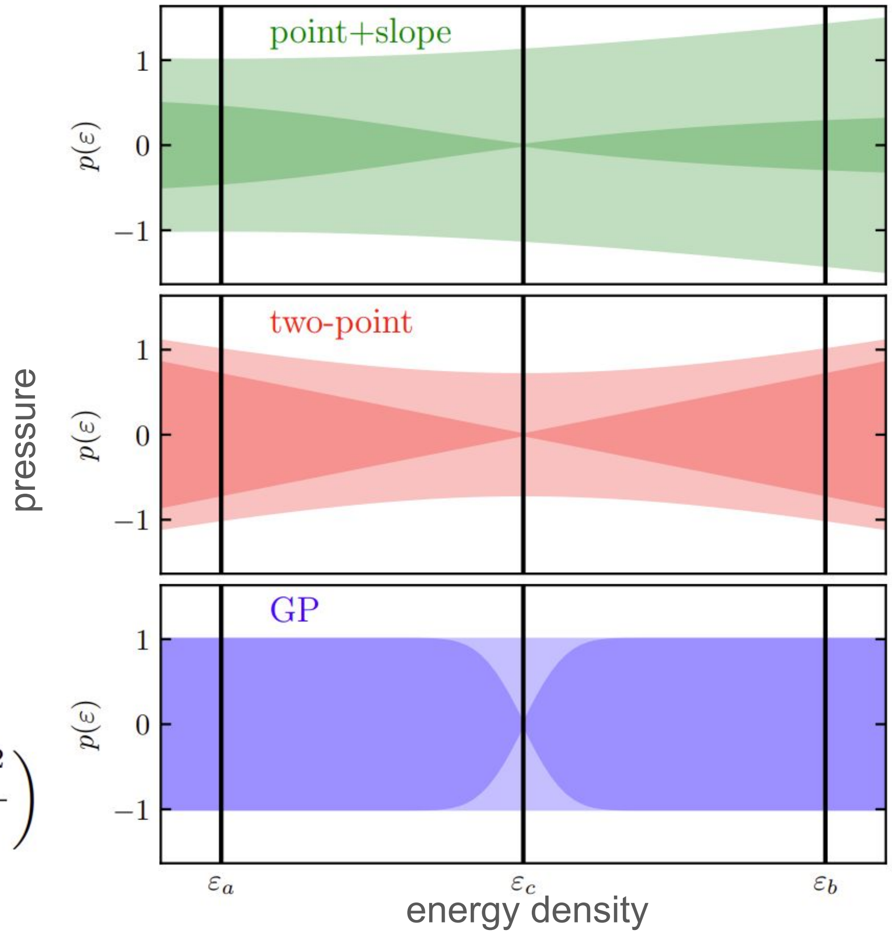
$$p(\varepsilon) = p_a + \frac{p_b - p_a}{\varepsilon_b - \varepsilon_a}(\varepsilon - \varepsilon_a)$$

Gaussian Process

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

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

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



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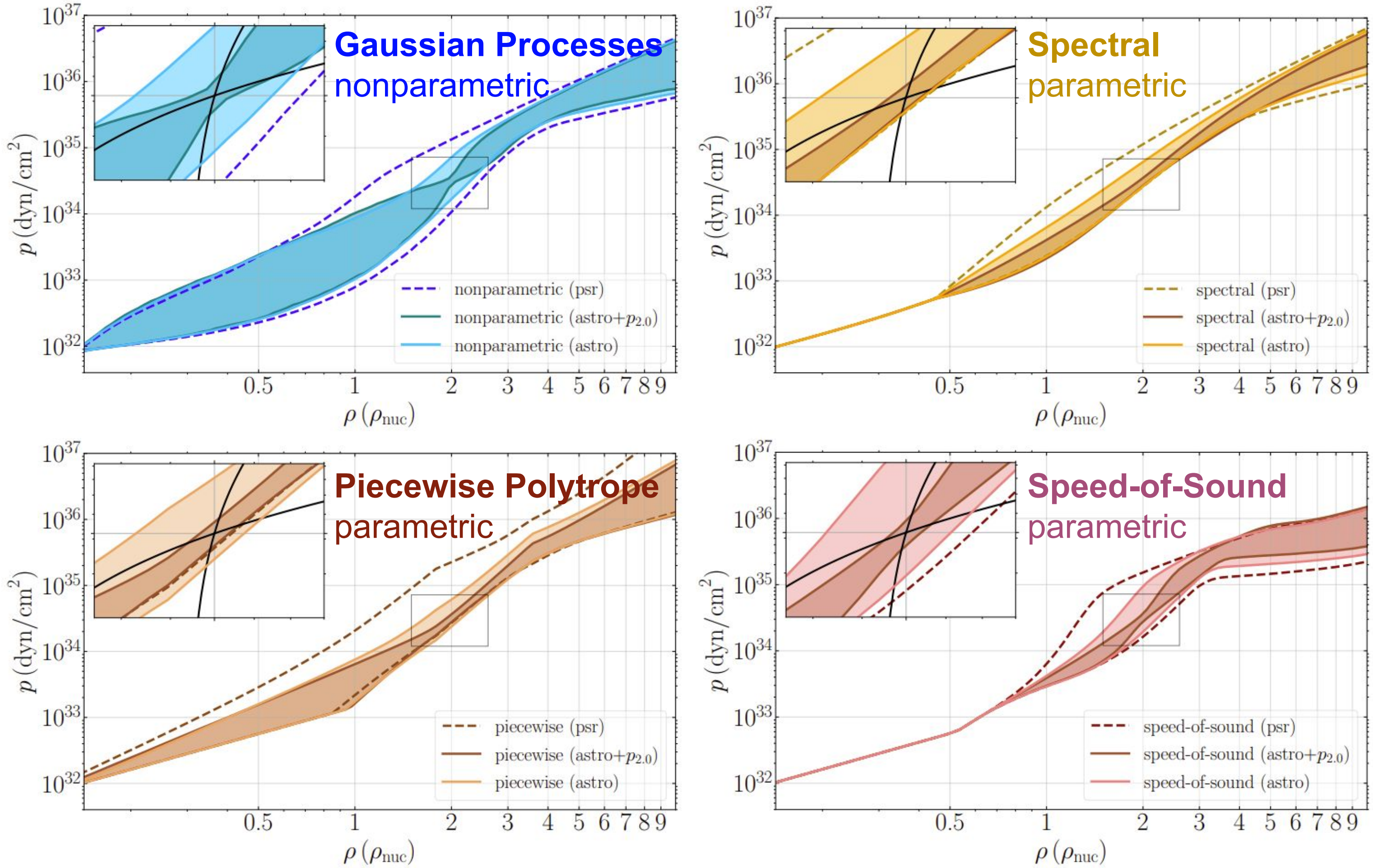

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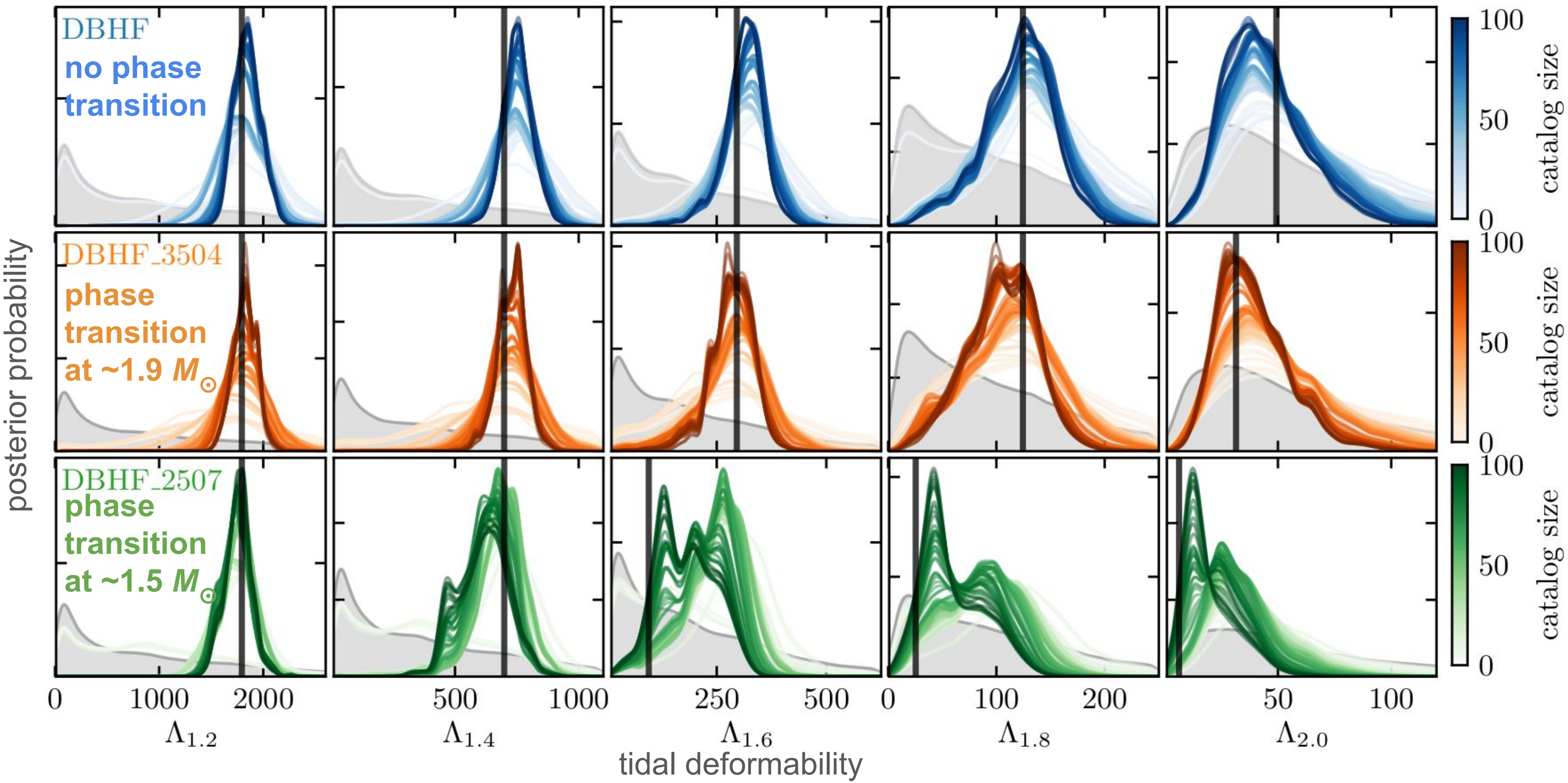
Inference of the NS EoS: no systematics with nonparametrics

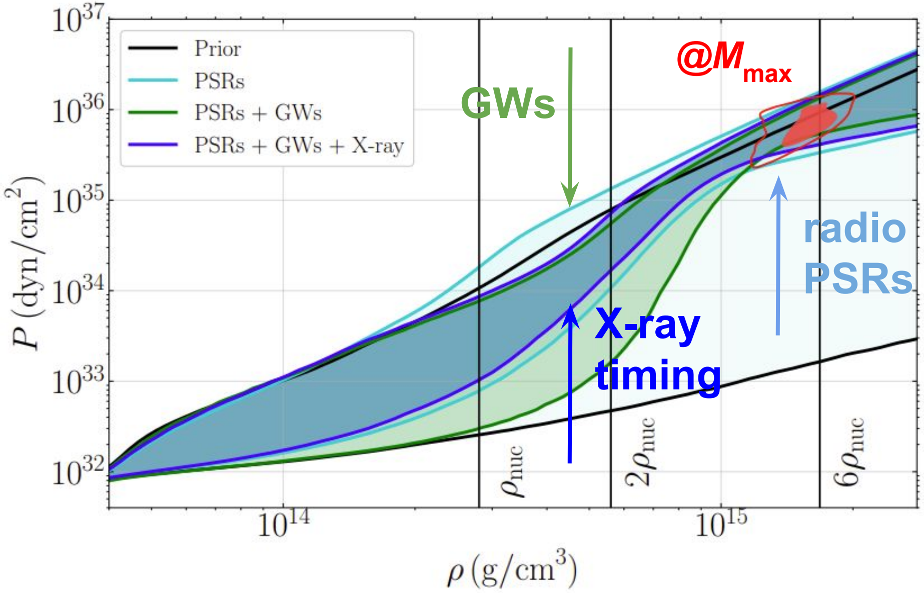
Essick+ (2023)

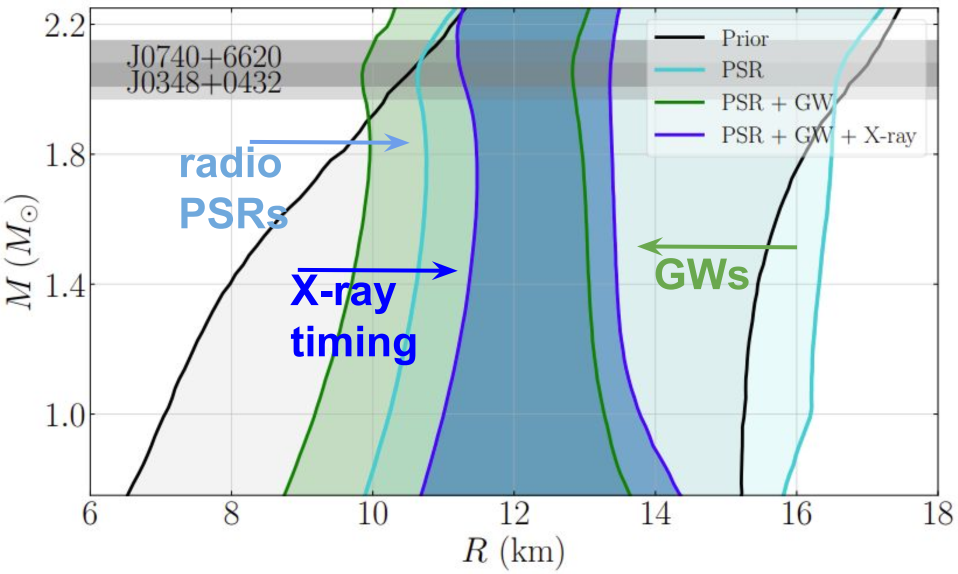


Inference of the NS EoS: nonparametric results

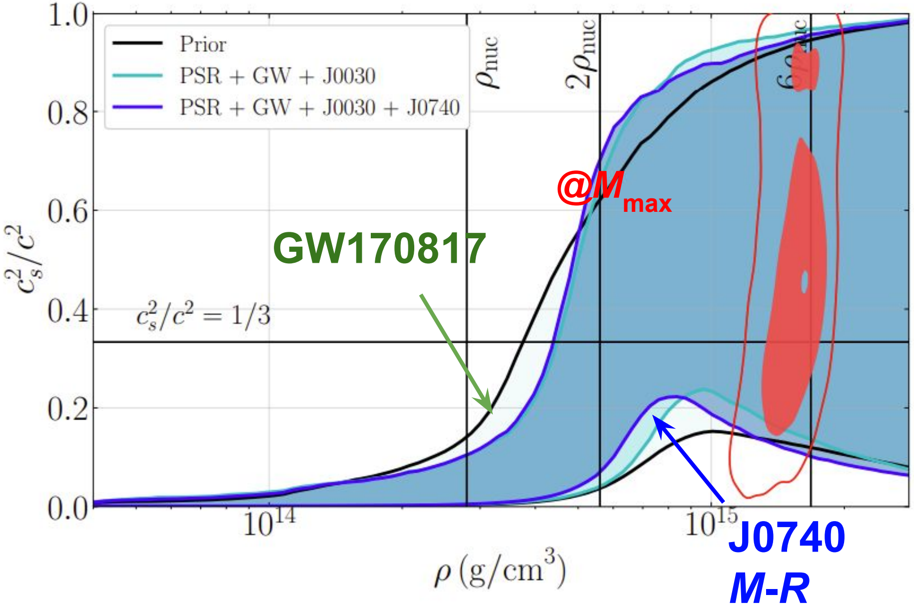
Legred+**Essick**+ (2021)

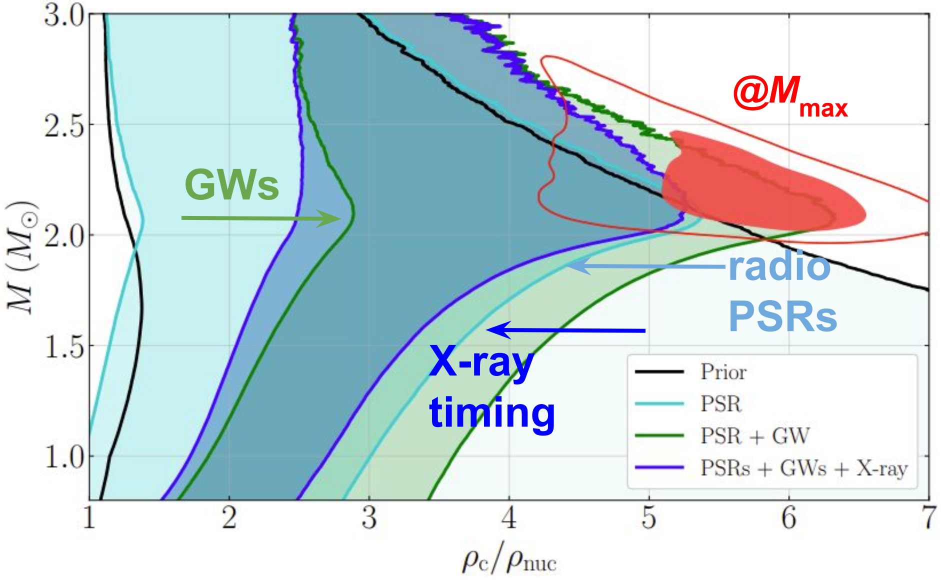
Current *Theory Agnostic* Constraints





Inference of the NS EoS





supranuclear sound speed almost certainly exceeds the conformal limit
→strongly-coupled interactions

maximum central density is likely ~6ρ_{nuc}

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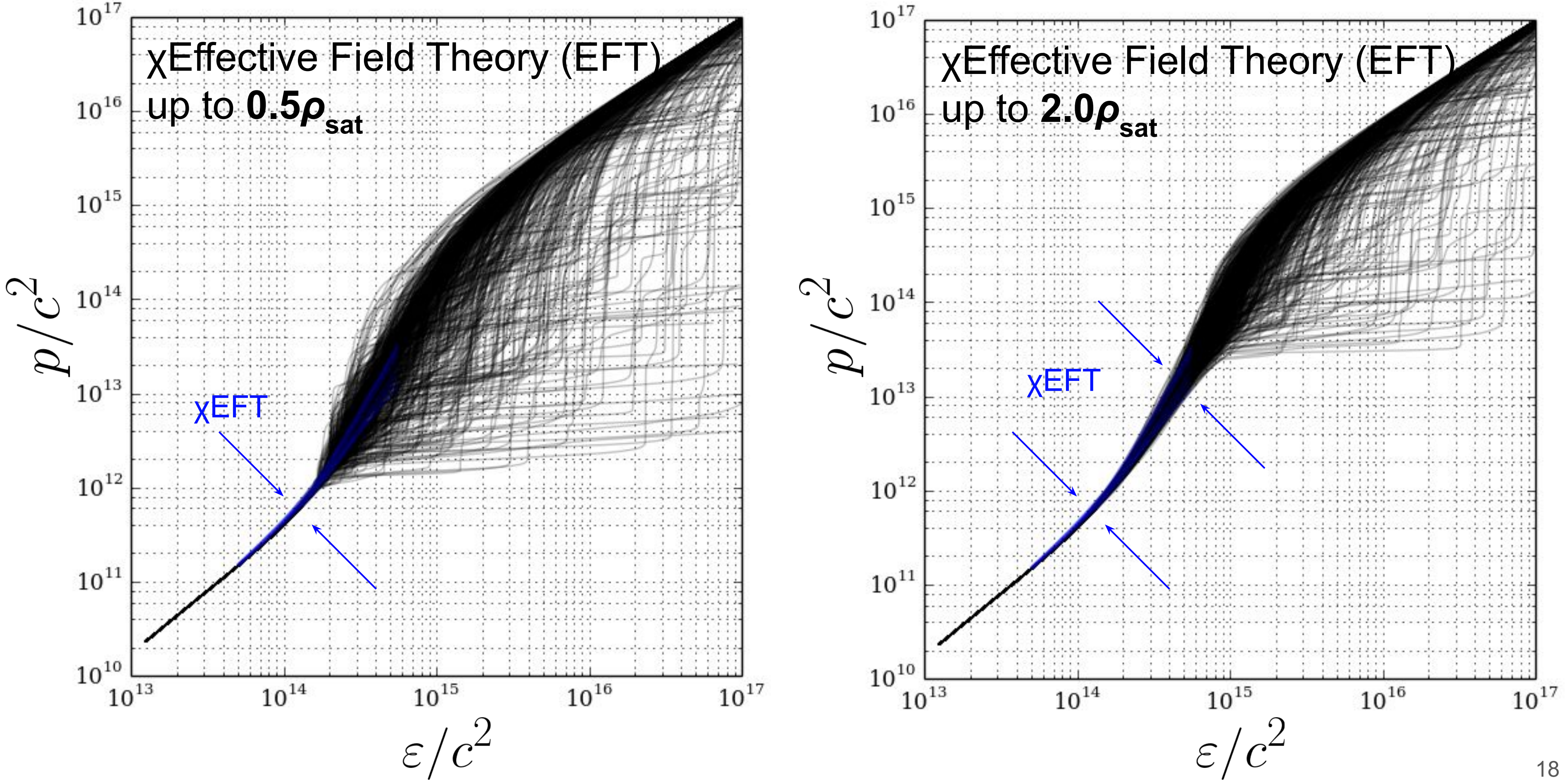
Inference of the NS EoS: incorporating low-density nuclear theory

Essick+ (2020)



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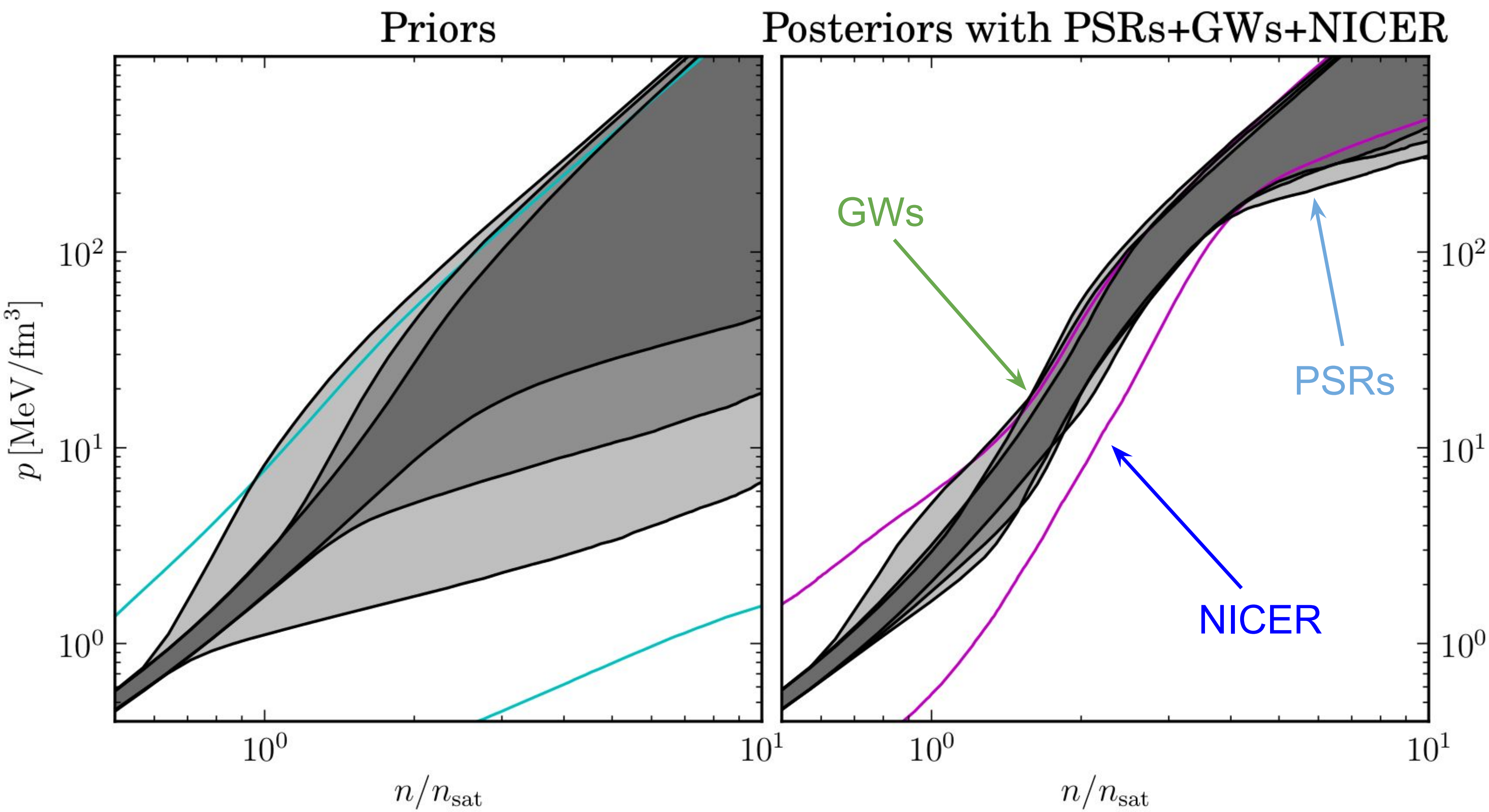

Inference of the NS EoS: comparing low-density theories

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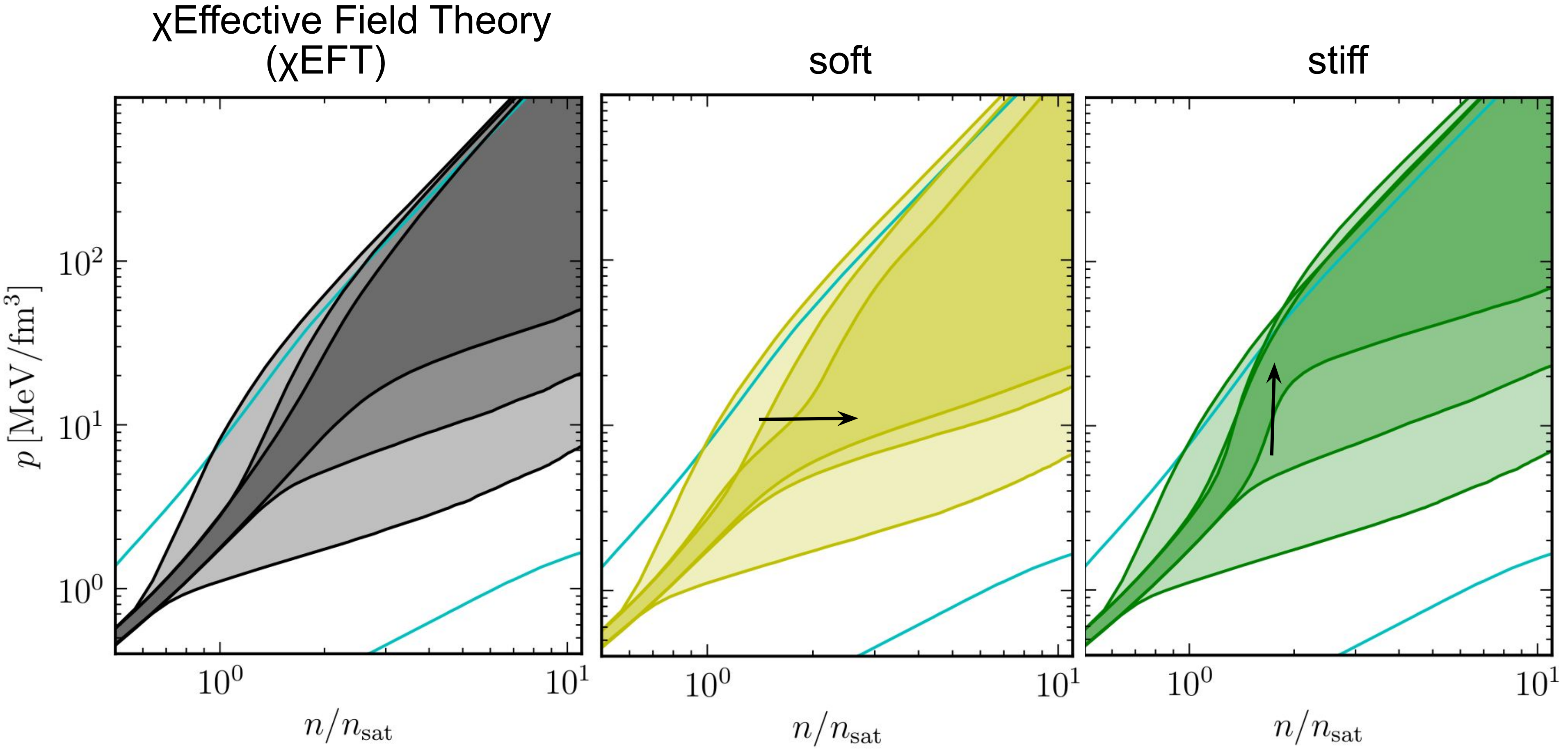

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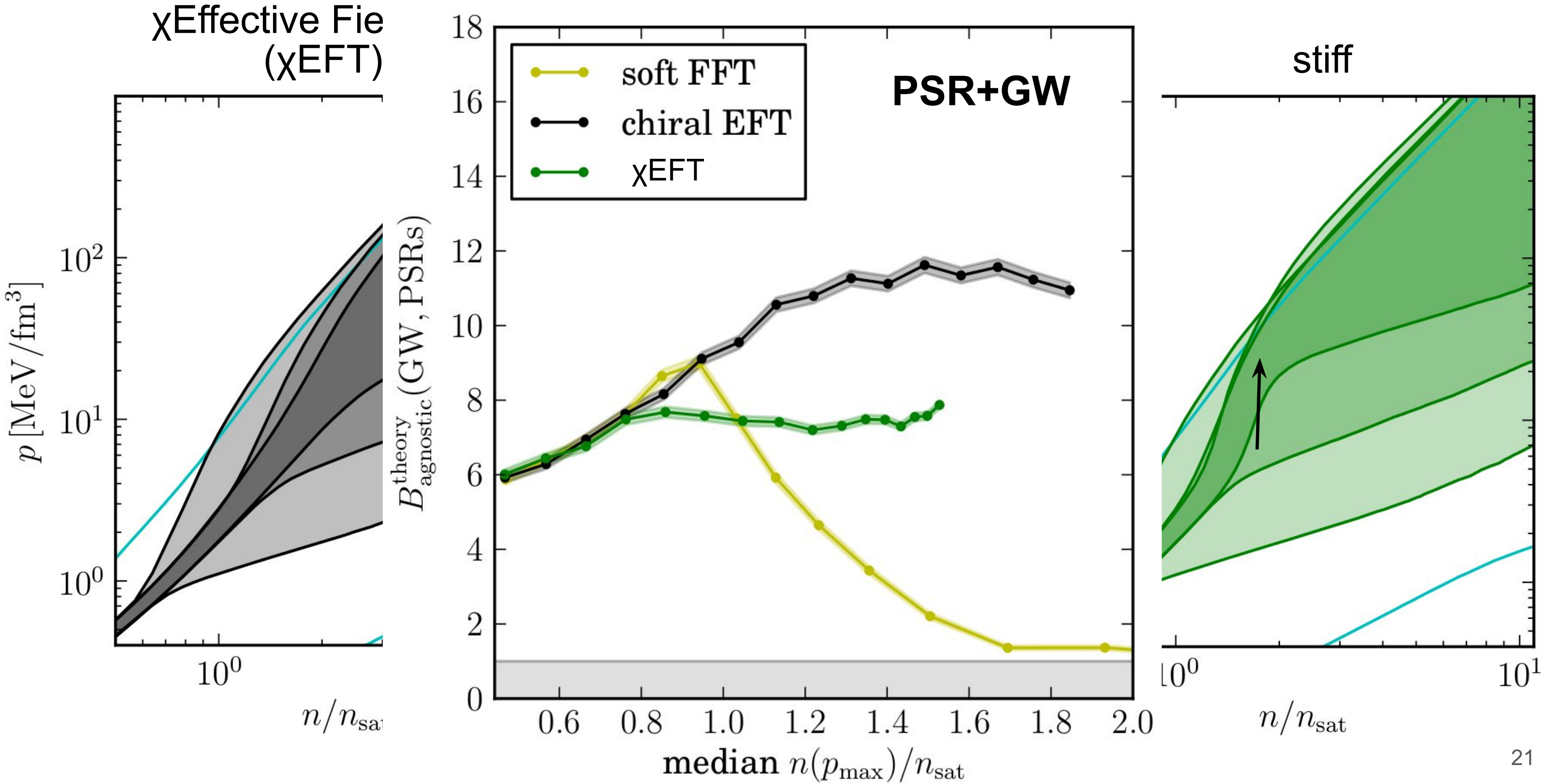


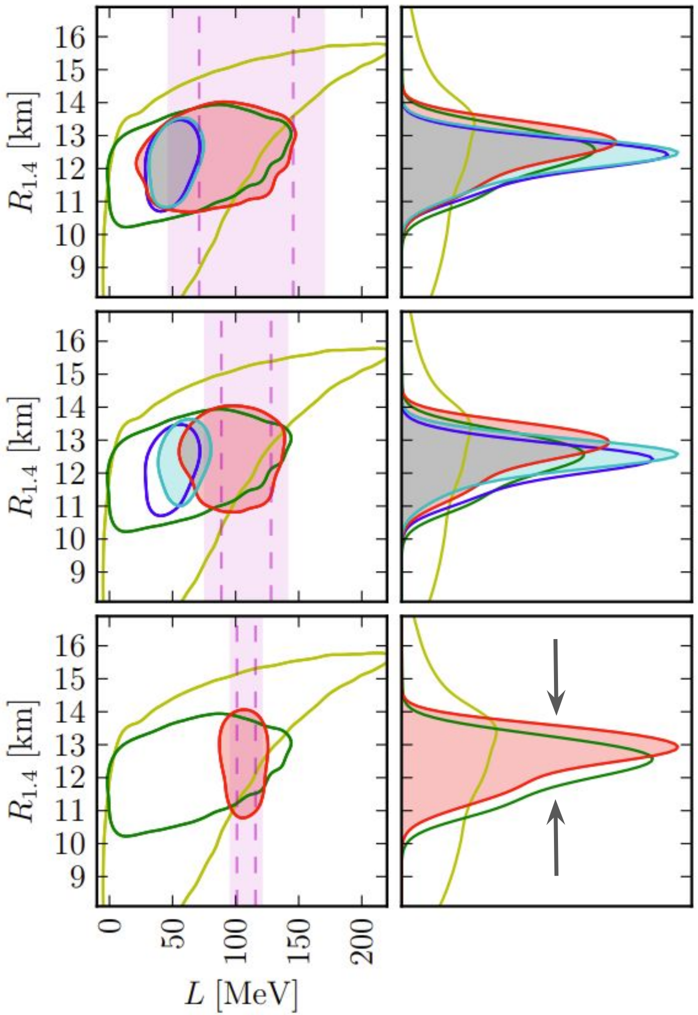
Inference of the NS EoS

Essick+ (2021)
Essick+ (2021)

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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Exotic Behavior with Efficient TOV Sequences

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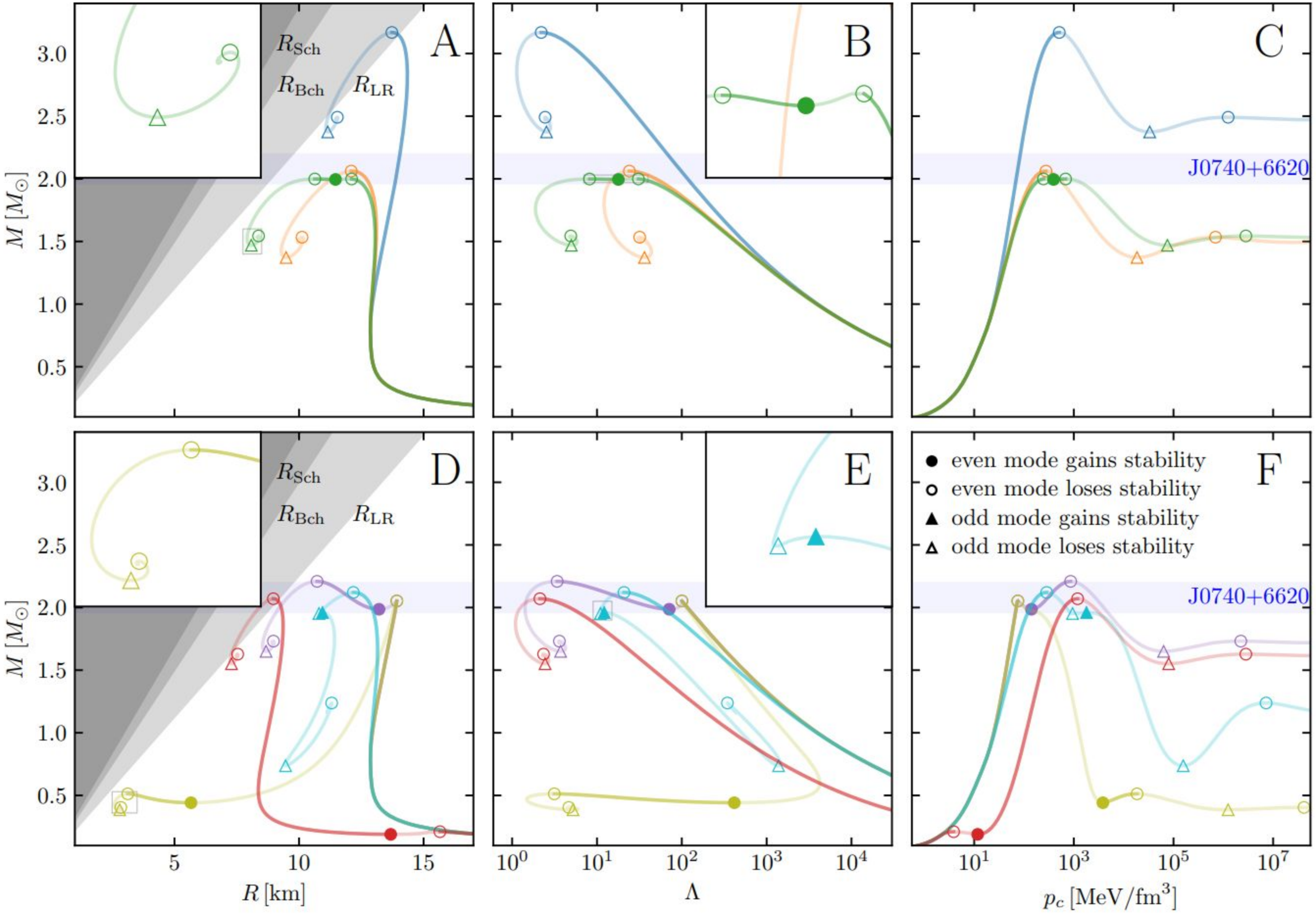

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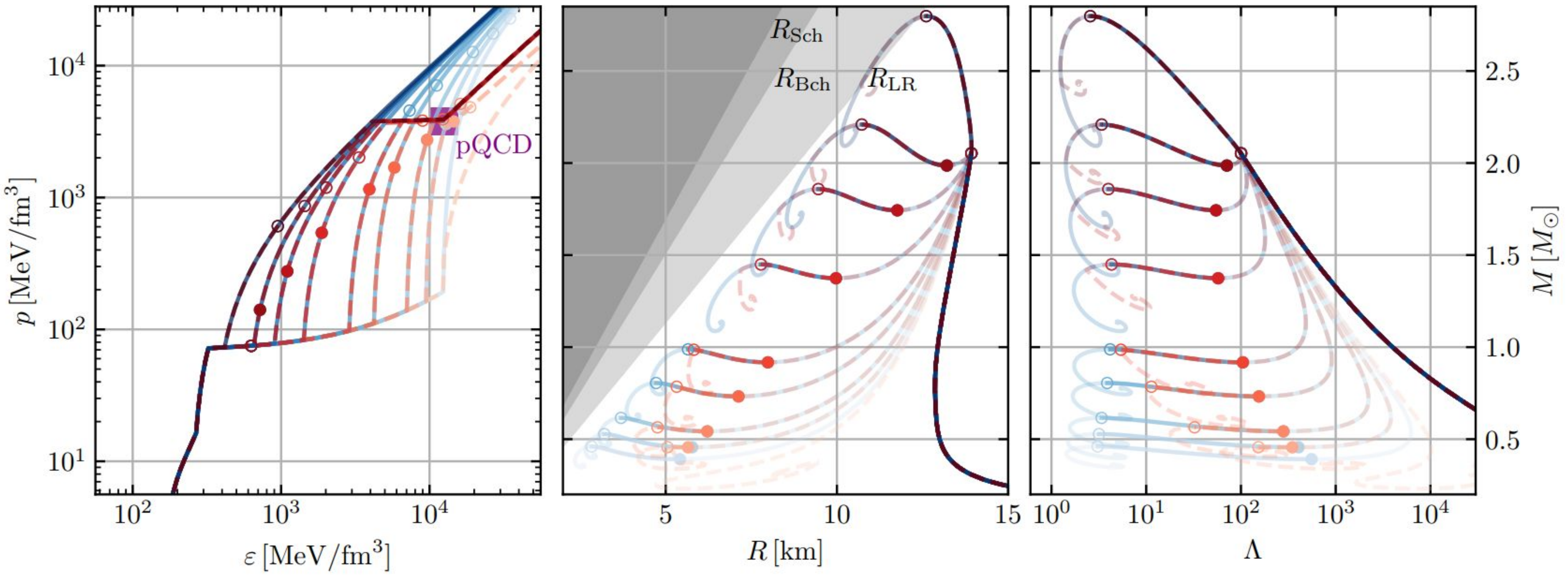

References

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R. Essick, I. Tews, P. Landry, S. Reddy, D. E. Holz, *Direct Astrophysical Tests of Chiral Effective Field Theory at Supranuclear Densities*, PRC 102, 055803 (2020)

R. Essick, I. Tews, P. Landry, A. Schwenk, *Astrophysical Constraints on the Symmetry Energy and the Neutron Skin of ^{208}Pb with Minimal Modeling Assumptions,* PRL 127, 192701 (2021)

R. Essick, P. Landry, A. Schwenk, I. Tews, *Detailed Examination of Astrophysical Constraints on the Symmetry Energy and Neutron Skin of ^{208}Pb with Minimal Modeling Assumptions*, PRC 104, 065804 (2021)

R. Essick, *Exotic Stable Branches and Efficient TOV Sequences*, arXiv:2405.05395 (2024)

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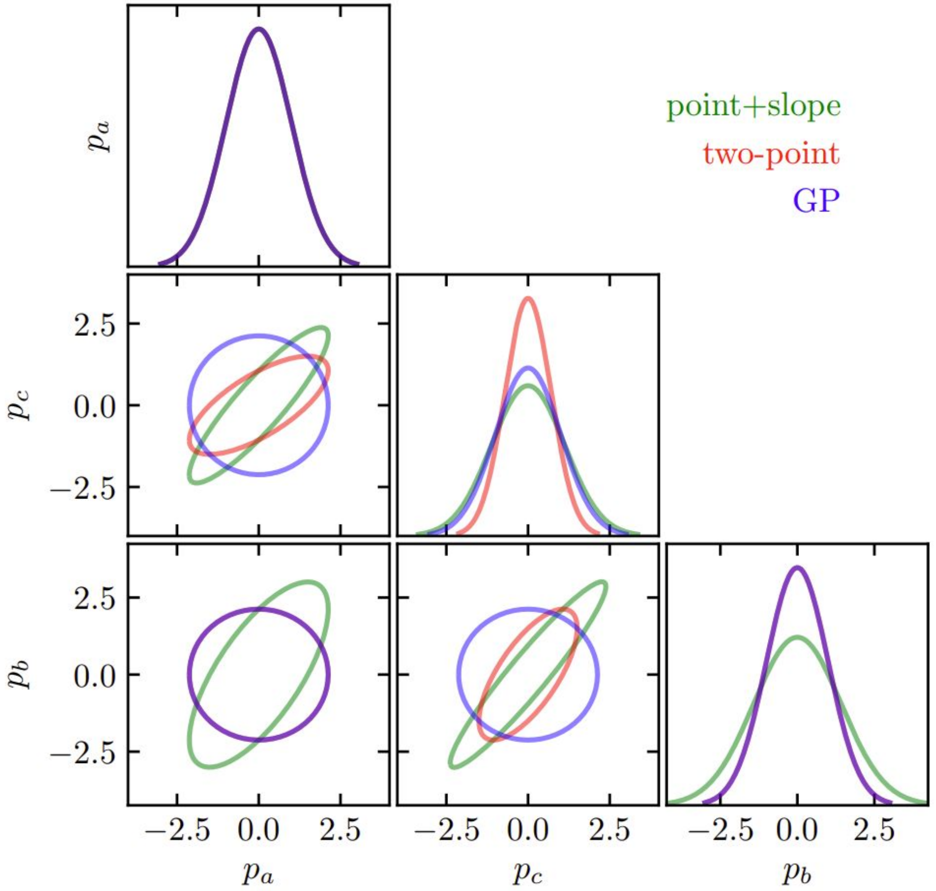
GP

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

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

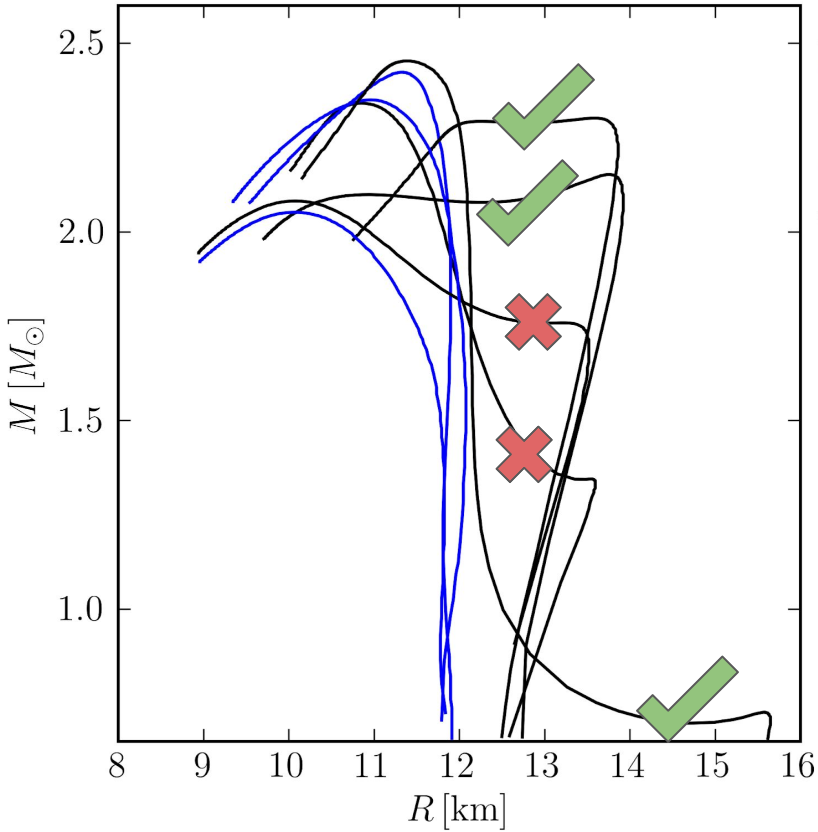
$$= K_{\mathrm{se}}(\varepsilon_i, \varepsilon_j) = \sigma^2 \exp\left(-\frac{(\varepsilon_i - \varepsilon_j)^2}{l^2}\right)$$



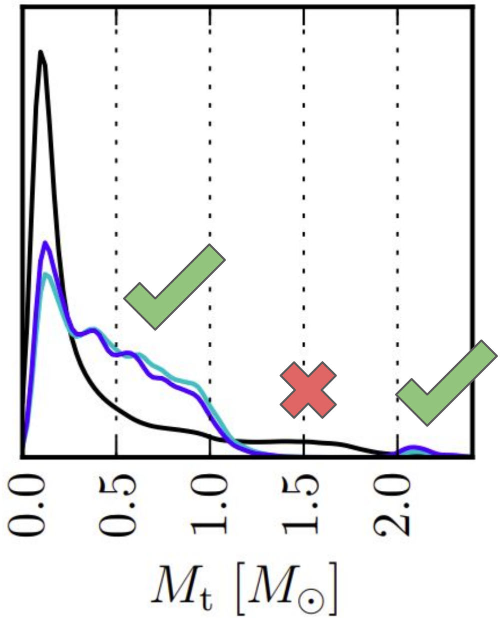
only the **GP** has ***independent marginal distributions*** for all pressures

Inference of the NS EoS: phase transitions

Legred+**Essick**+ (2021)



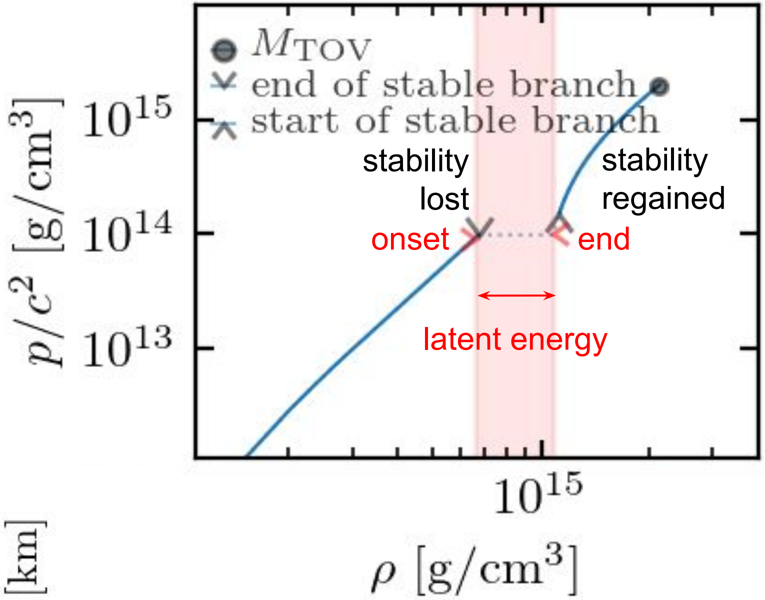
Data		$\max \mathcal{L}^{n>1}_{n=1}$	$\mathcal{B}^{n>1}_{n=1}$	$\max \mathcal{L}^{c_s^2>c^2/3}_{c_s^2\leq c^2/3}$	$\mathcal{B}^{c_s^2>c^2/3}_{c_s^2\leq c^2/3}$
w/PSRs		1.00	0.120 ± 0.002	1.0	10.2 ± 0.5
w/o J0740+6620		0.97	0.220 ± 0.007	50.8	2220 ± 790
w/J0740+6620	Miller+	0.60	0.146 ± 0.005	26.7	1000 ± 340
	Riley+	0.94	0.185 ± 0.006	72.7	2450 ± 1820

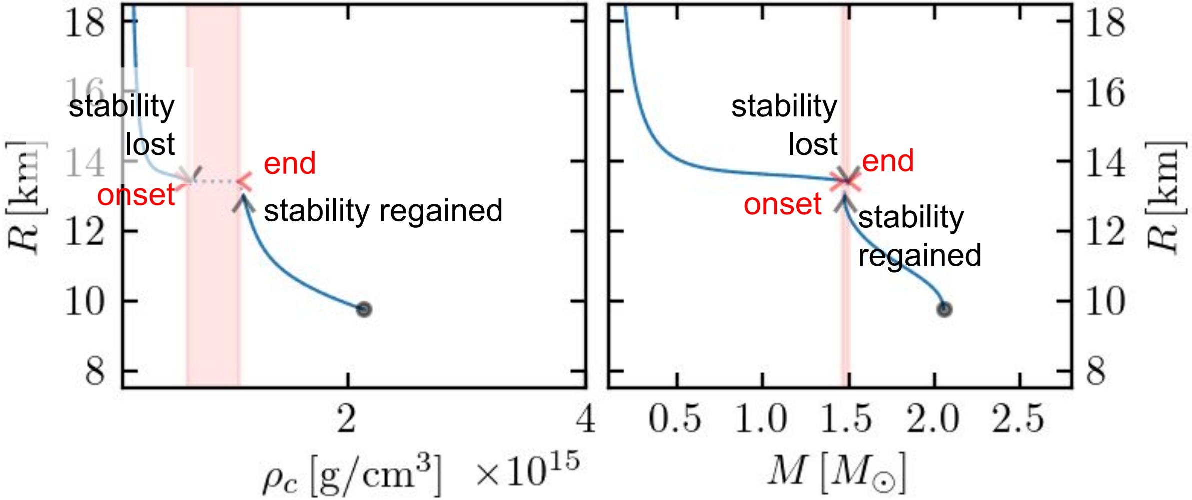


Inference of the NS EoS: phase transitions

Essick+ (2023)

the sudden appearance of new (degenerate) degrees of freedom produces a sharp drop in the sound speed (c_s)
→ *“loss of pressure support”*





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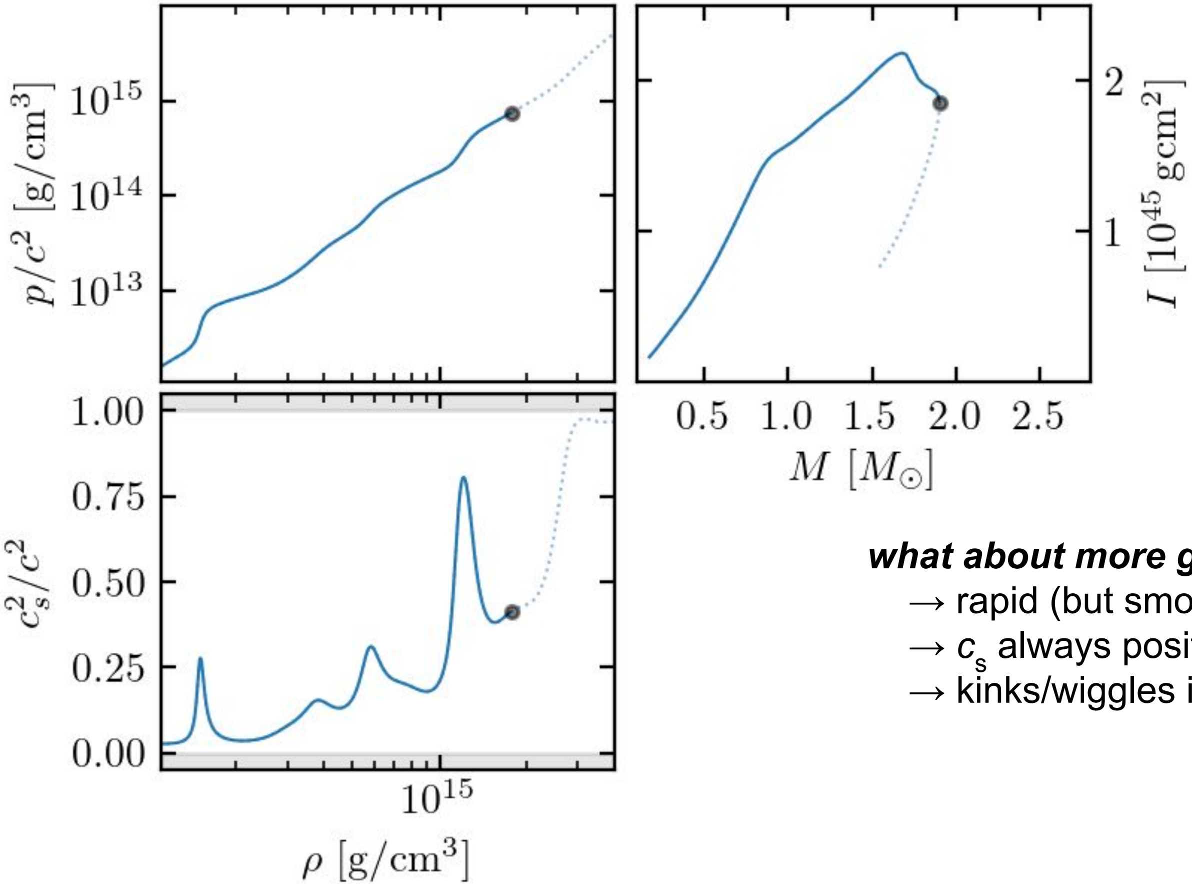


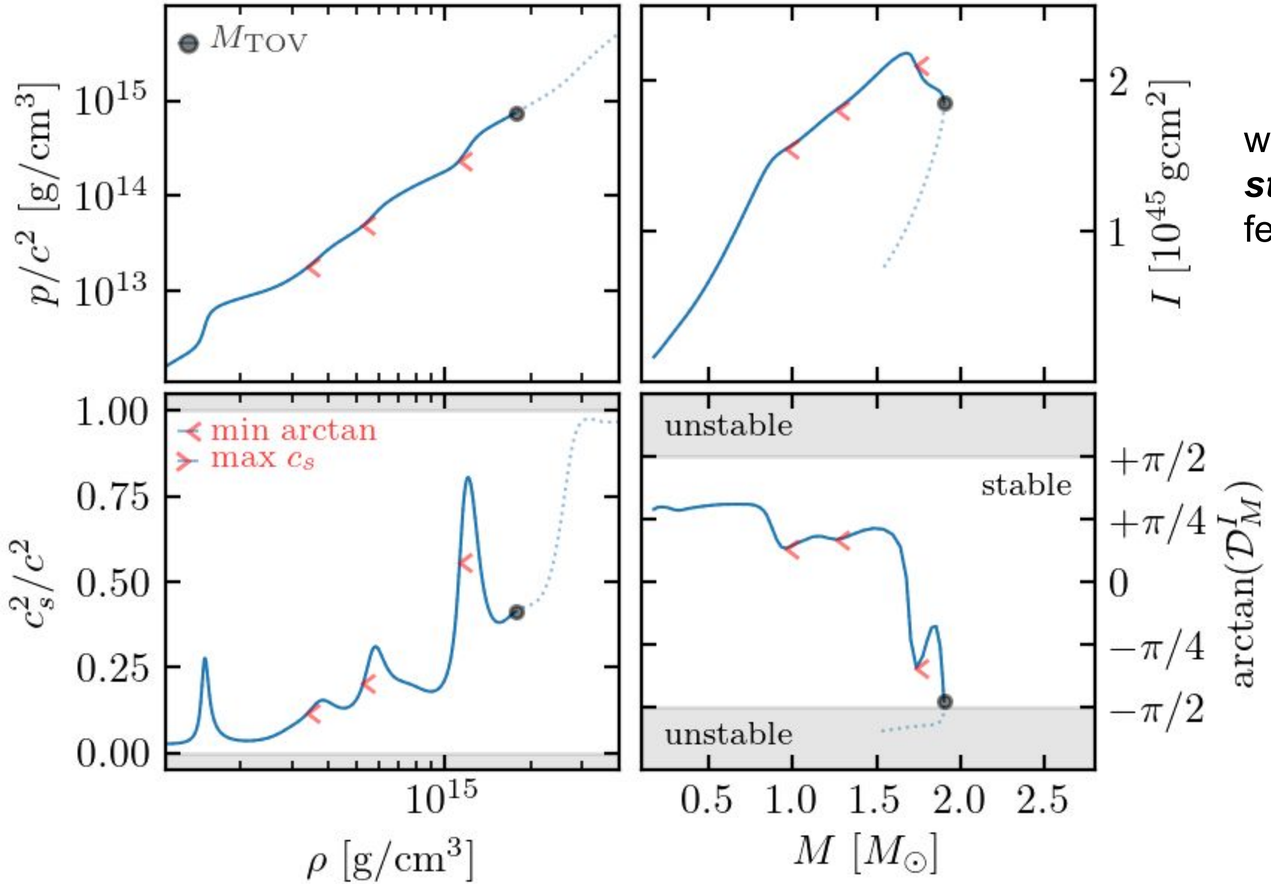
what about more general phenomenology?

→ rapid (but smooth) changes in c_s?

→ c_s always positive definite?

→ kinks/wiggles in stellar sequence but no loss of stability?

Essick+ (2023)



we search for ***features based on stellar properties*** and connect these to features in c_s

$$\mathcal{D}^I_M \equiv \frac{d \log I / d \log p_c}{d \log M / d \log p_c}$$

Inference of the NS EoS: phase transitions

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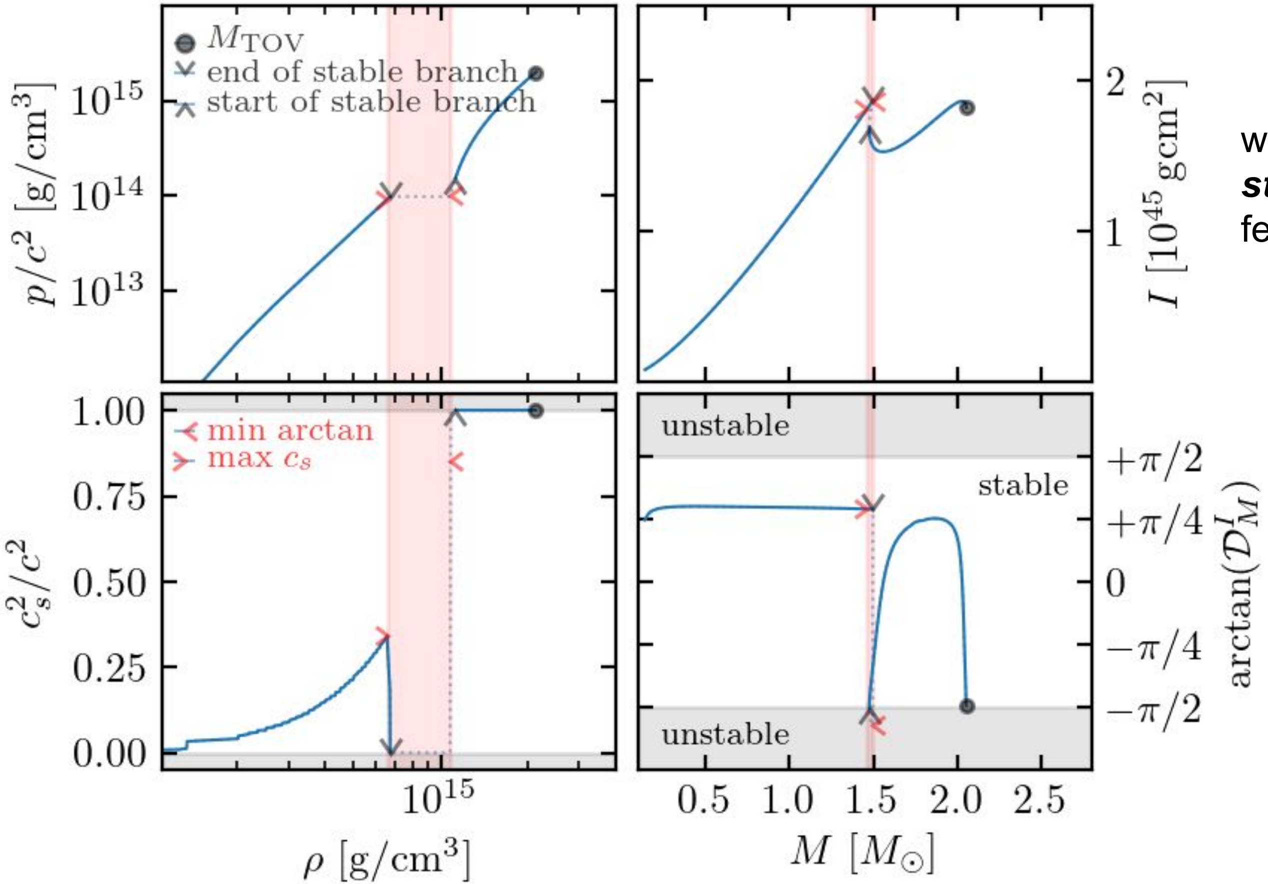

we search for ***features based on stellar properties*** and connect these to features in c_s

local minima → ***end*** of phase trans

and do so more precisely than where stability is regained

Inference of the NS EoS: phase transitions

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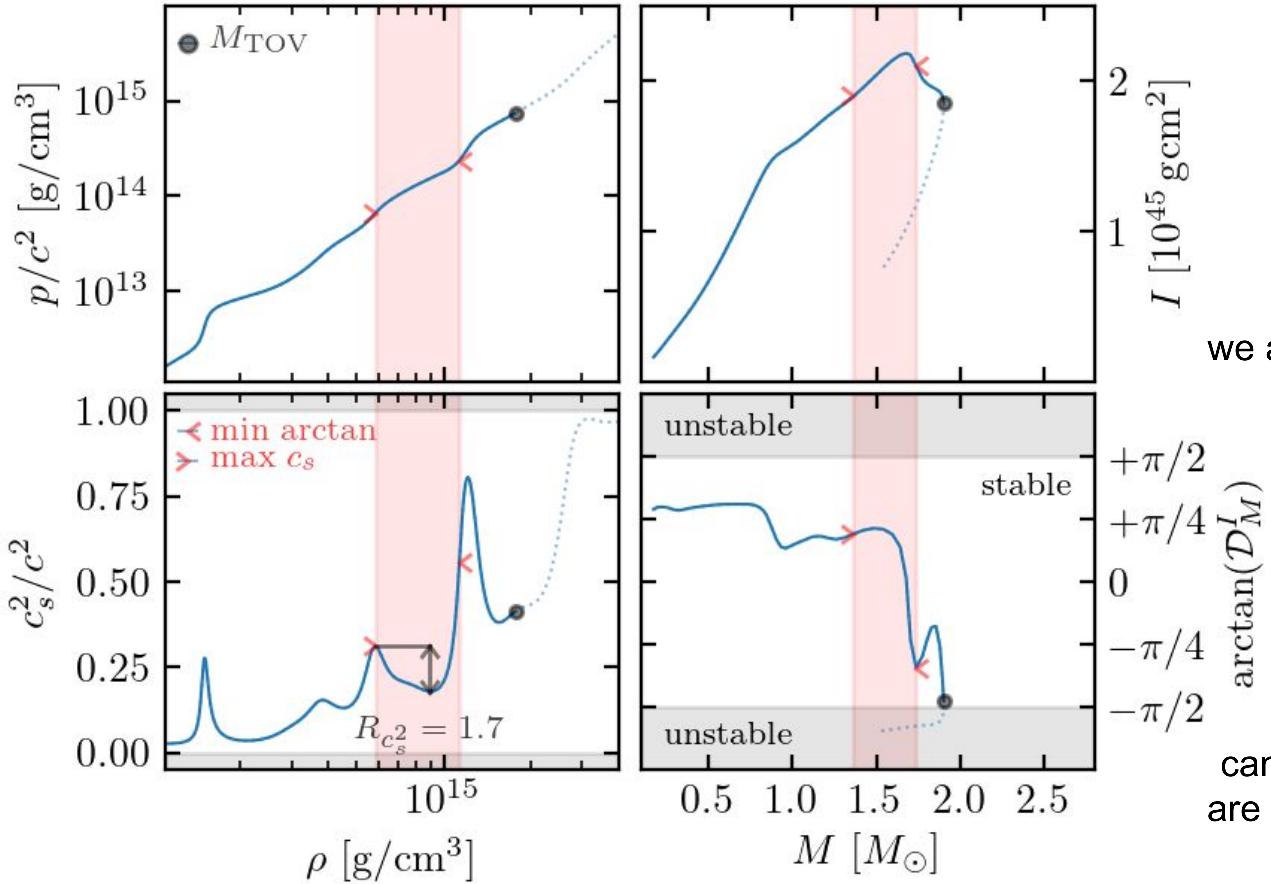
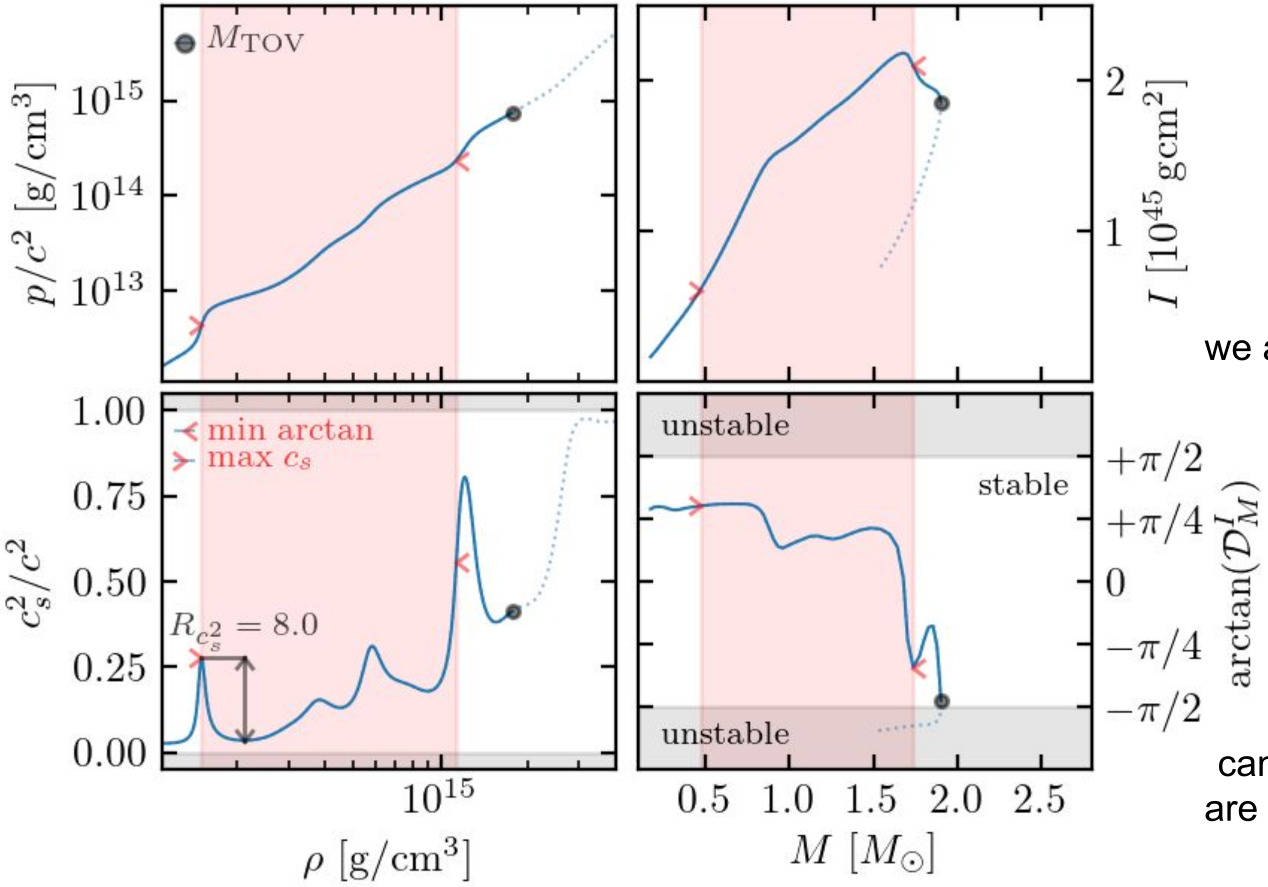


we associate a ***local minimum*** (***end***) with the most recent preceding ***"running maximum" in c_s*** (***onset***)

candidate ***running maxima in c_s*** (***onset***) are accepted only if they are followed by a ***large drop in c_s***

Inference of the NS EoS: phase transitions

Essick+ (2023)



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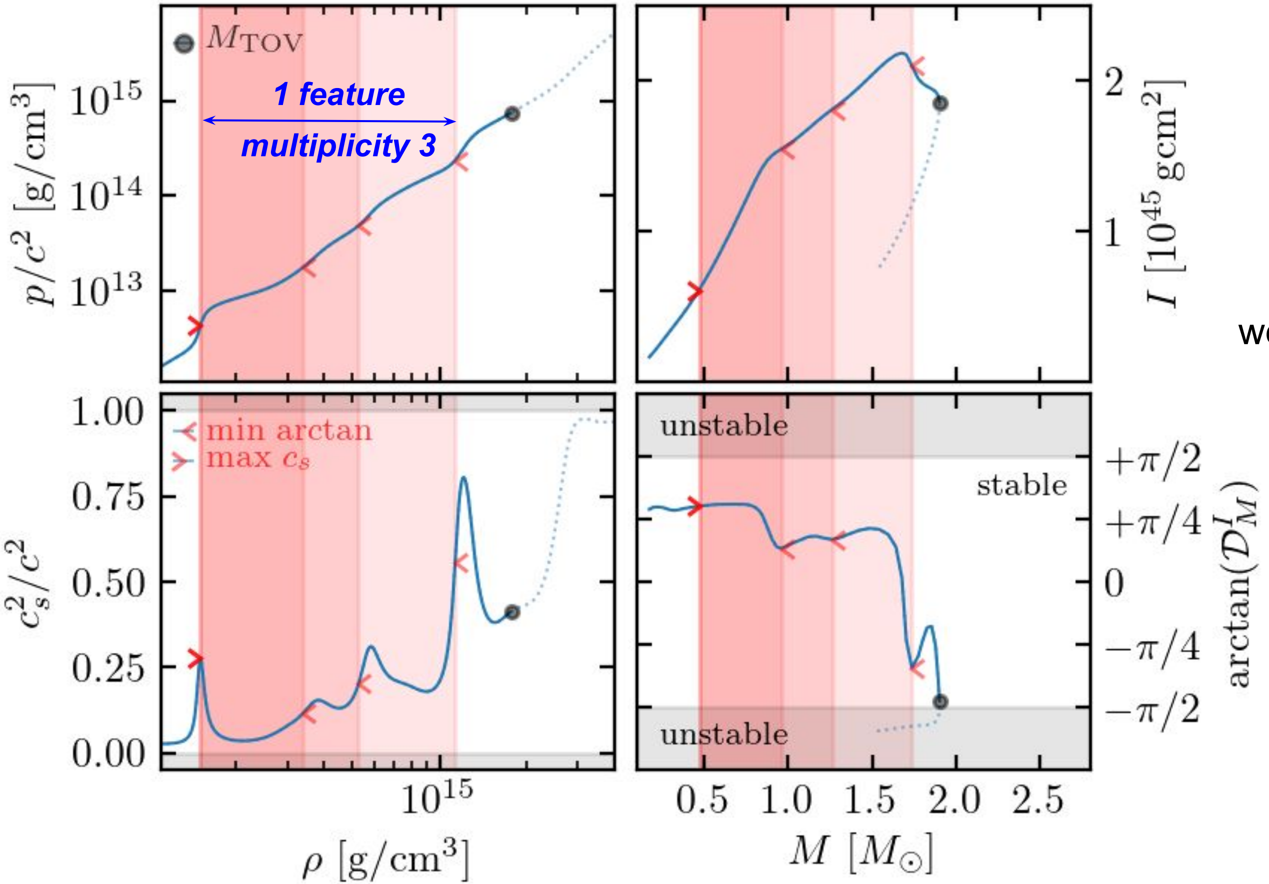


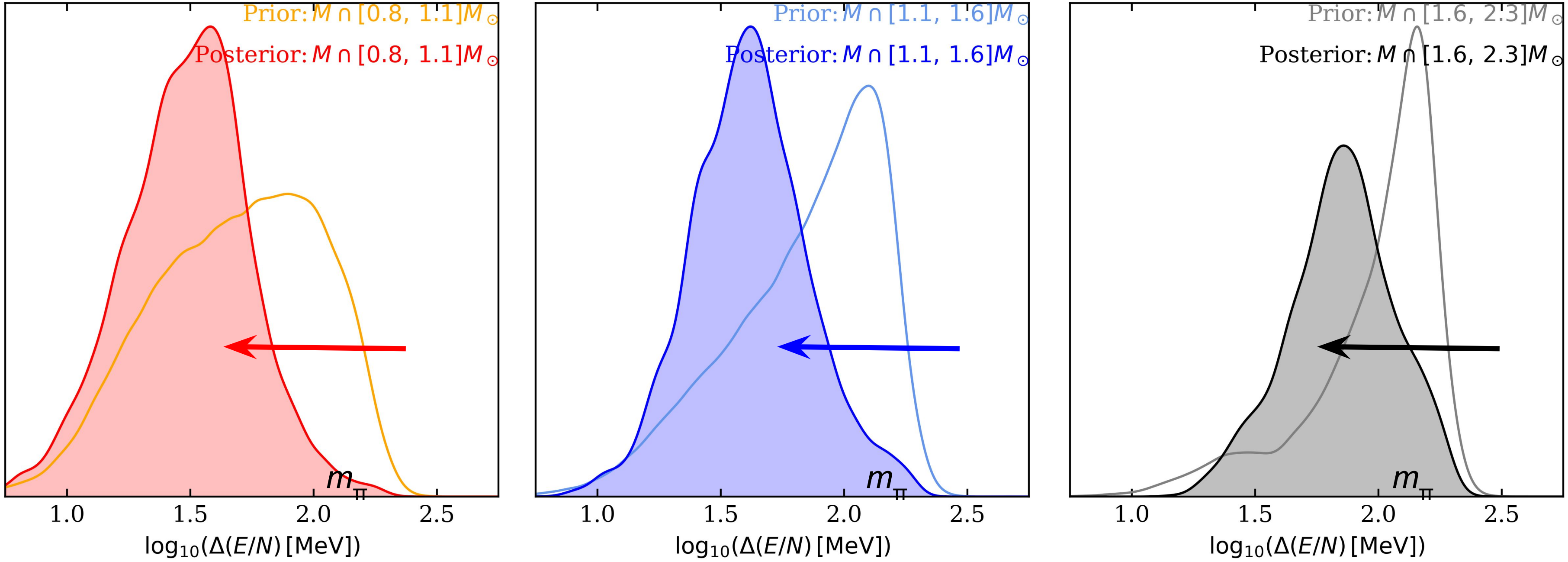
we iterate until all ***local minimum*** (***end***) *have an associated* ***"running maximum" in c_s*** (***onset***)

this EoS has ***1 feature*** with ***multiplicity 3***

Inference of the NS EoS: phase transitions

Essick+ (2023)

masses from J0348, J0740
LIGO-Virgo-KAGRA GWs from GW170817, GW190425
NICER X-ray Timing from J0030, J0740



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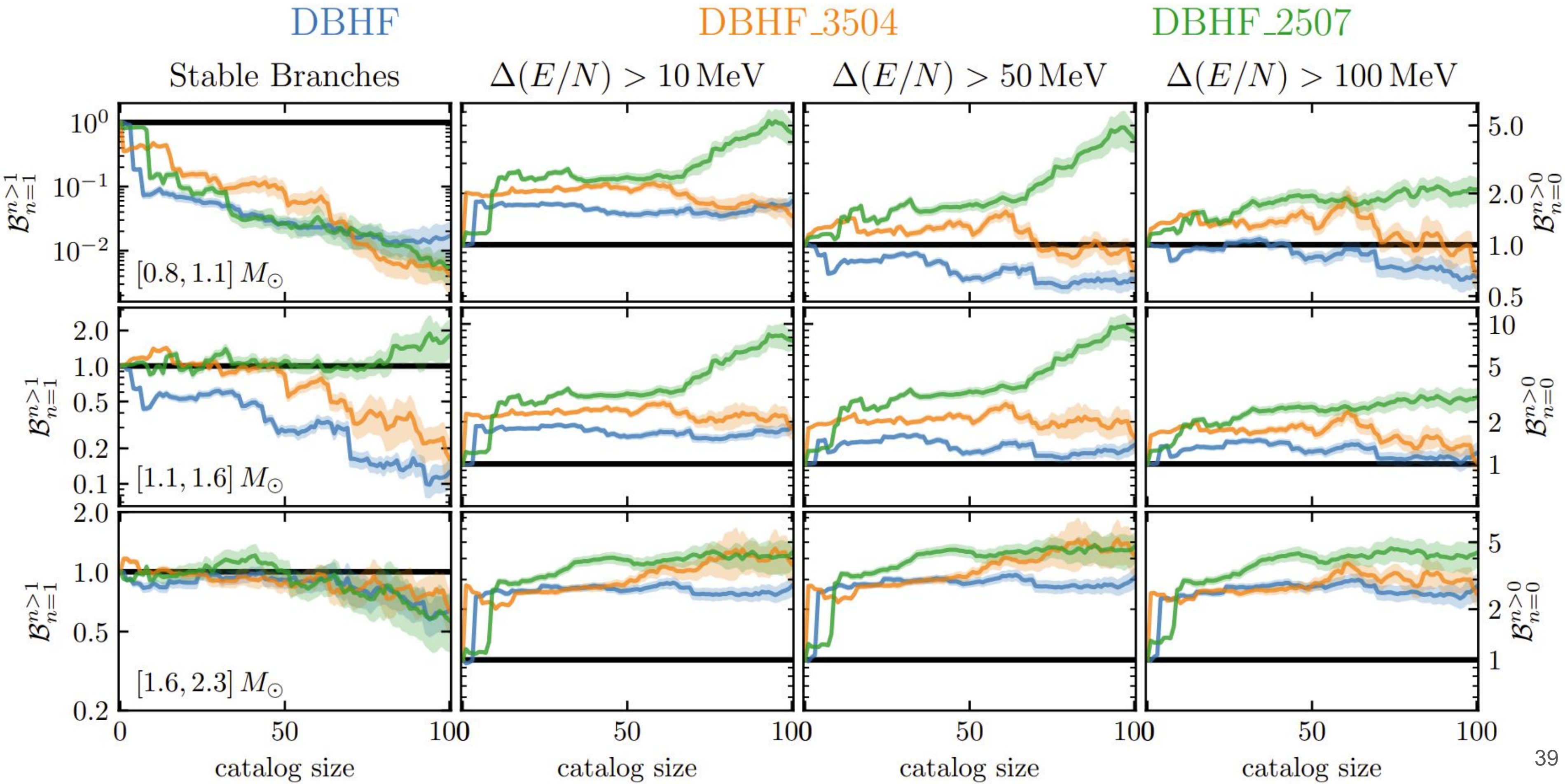
M $[M_\odot]$	Stable Branches			$\min \Delta(E/N)$ [MeV]	$\mathcal{D}_M^I$ Features		
	$\max \mathcal{L}_{n=1}^{n\geq2}(\mathrm{PGX})$	$\mathcal{B}_{n=1}^{n\geq2}(\mathrm{PGX})$	$\mathcal{B}_{n=1}^{n\geq2}(\mathrm{GX}\vert\mathrm{P})$		$\max \mathcal{L}_{n=0}^{n\geq1}(\mathrm{PGX})$	$\mathcal{B}_{n=0}^{n\geq1}(\mathrm{PGX})$	$\mathcal{B}_{n=0}^{n\geq1}(\mathrm{GX}\vert\mathrm{P})$
0.8–1.1	0.47	0.362 ± 0.036	2.219 ± 0.162	10	0.57	1.222 ± 0.020	0.684 ± 0.011
				50	0.49	0.366 ± 0.011	0.588 ± 0.016
				100	0.26	0.117 ± 0.008	0.292 ± 0.021
1.1–1.6	0.14	0.030 ± 0.006	0.291 ± 0.055	10	0.57	1.043 ± 0.020	0.552 ± 0.010
				50	0.49	0.463 ± 0.013	0.552 ± 0.010
				100	0.26	0.152 ± 0.009	0.267 ± 0.017
1.6–2.3	0.20	0.147 ± 0.028	0.120 ± 0.026	10	0.52	1.012 ± 0.035	0.385 ± 0.013
				50	0.49	0.898 ± 0.034	0.385 ± 0.013
				100	0.29	0.383 ± 0.023	0.256 ± 0.016

Future Prospects: phase transitions

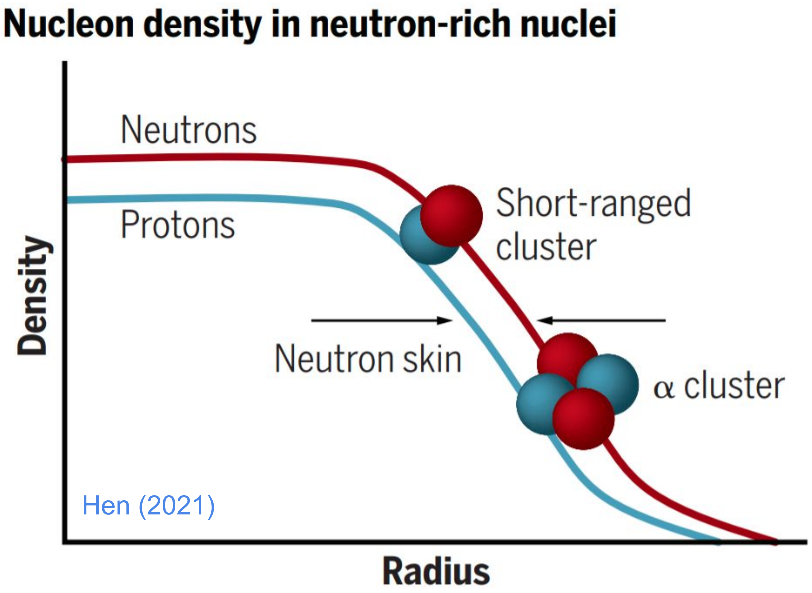
Essick+ (2023)



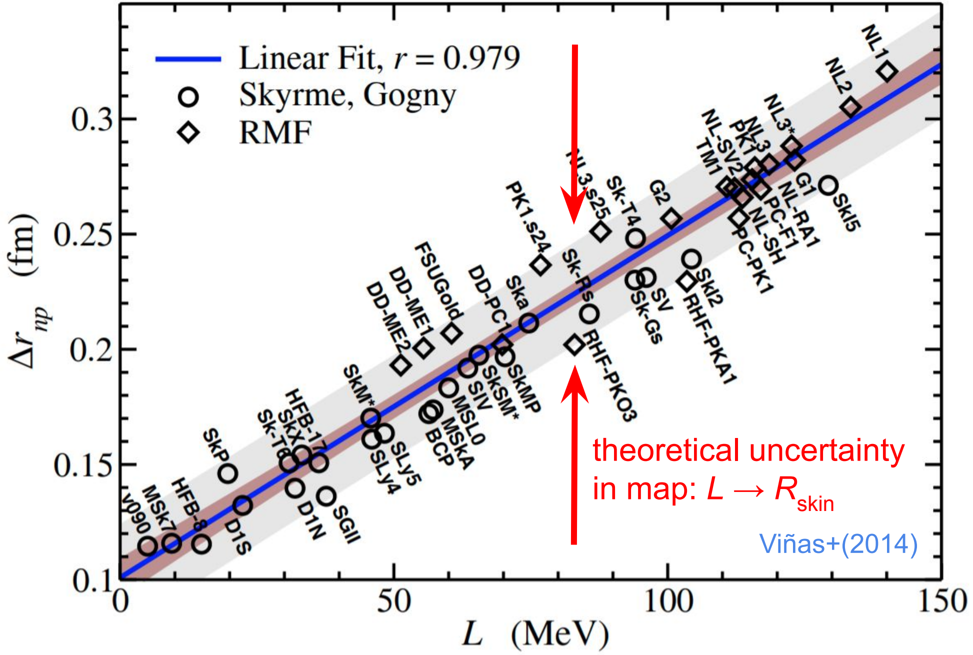
Inference of the NS EoS: low-density nuclear experiment

Connection to “new” experimental probes: Neutron Skin Thickness (R_{skin})

Reed+(2021) infer $L \gtrsim 100$ MeV based on $R_{skin} = 0.29 \pm 0.07$ fm. Suggest this implies $R_{1.4} \gtrsim 14$ km.



Scattering experiments (PREX) measure this



we constrain this with astrophysical observations

Inference of the NS EoS: low-density nuclear experiment

Essick+ (2021)
Essick+ (2021)

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

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

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

nuclear energy per particle

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

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

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

condition for β-equilib

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

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

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

constrained by astro observations (input from nonparametric analysis)

measured in the lab (input from terrestrial experiment)

modeled as degenerate Fermi gas (input from theory)

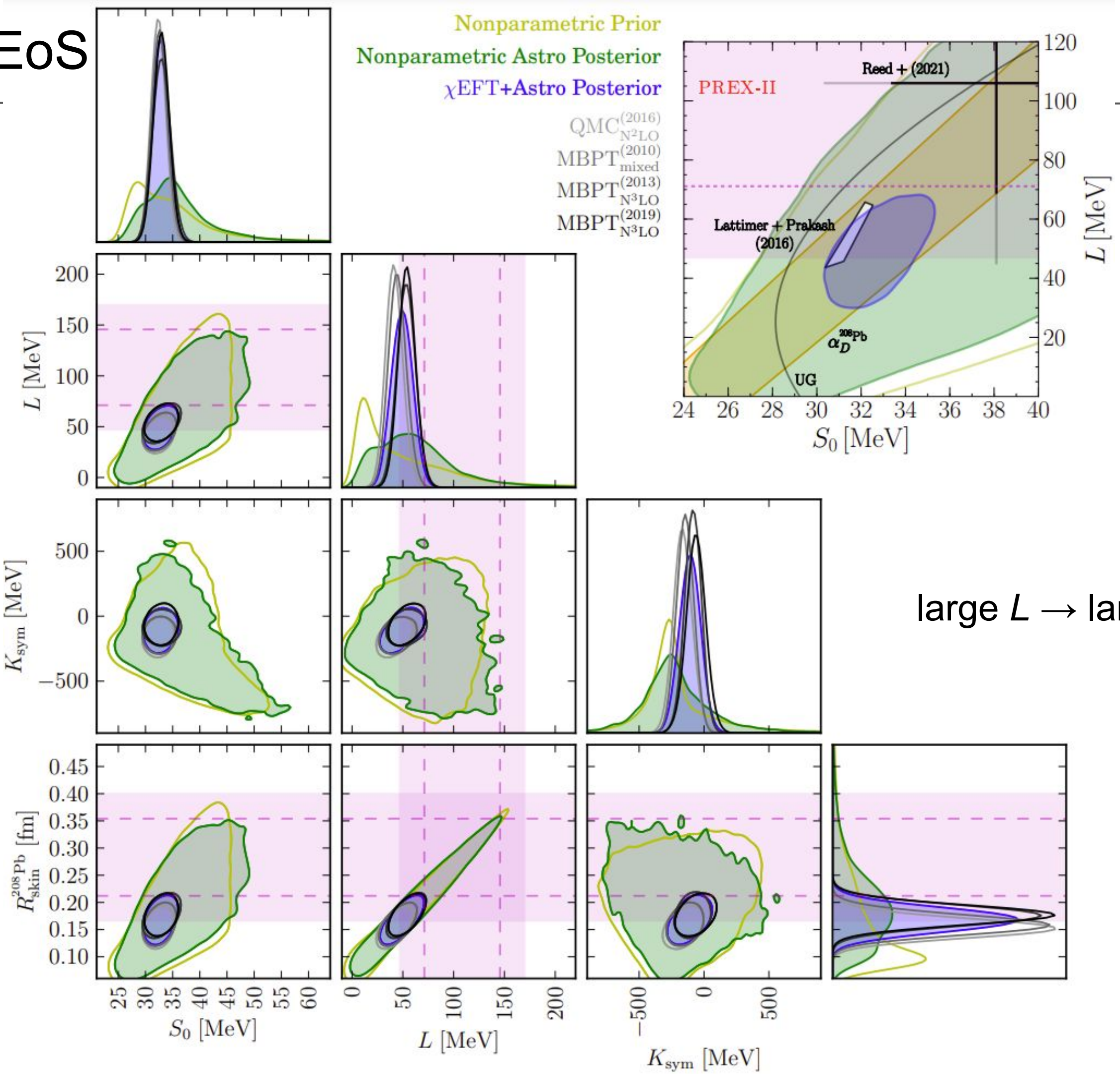
expressed in terms of derivatives of $E_{\rm nuc}$

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

Inference of the NS EoS

Essick+ (2021)
Essick+ (2021)

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



large $L \rightarrow$ large $p(n_{sat})$

Inference of the NS EoS: low-density nuclear experiment

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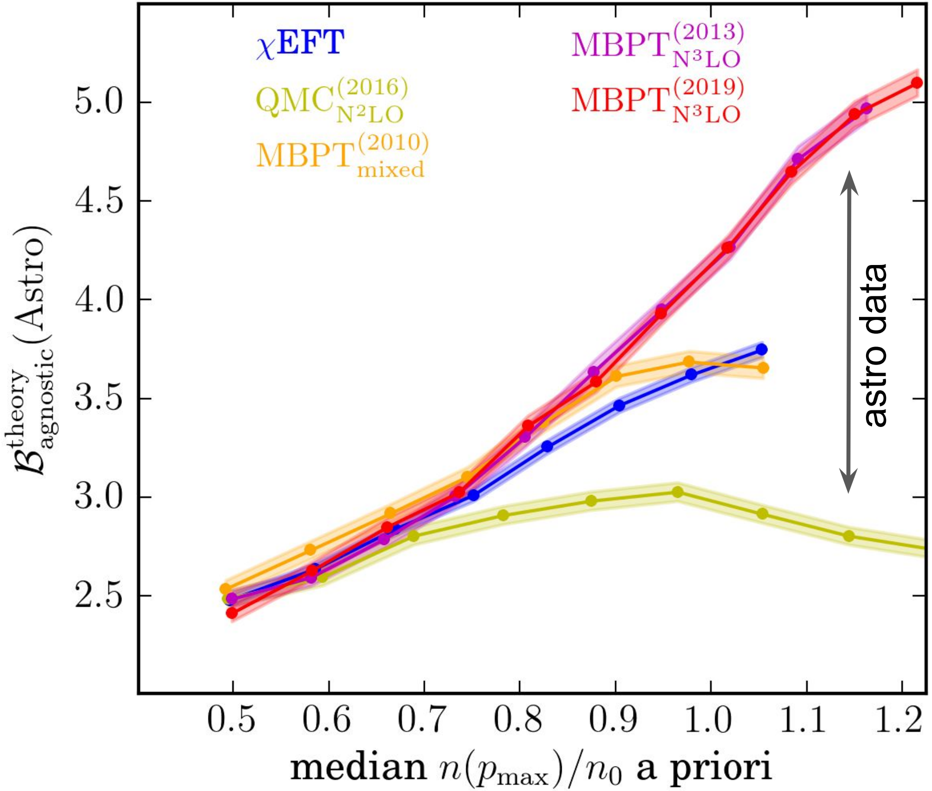
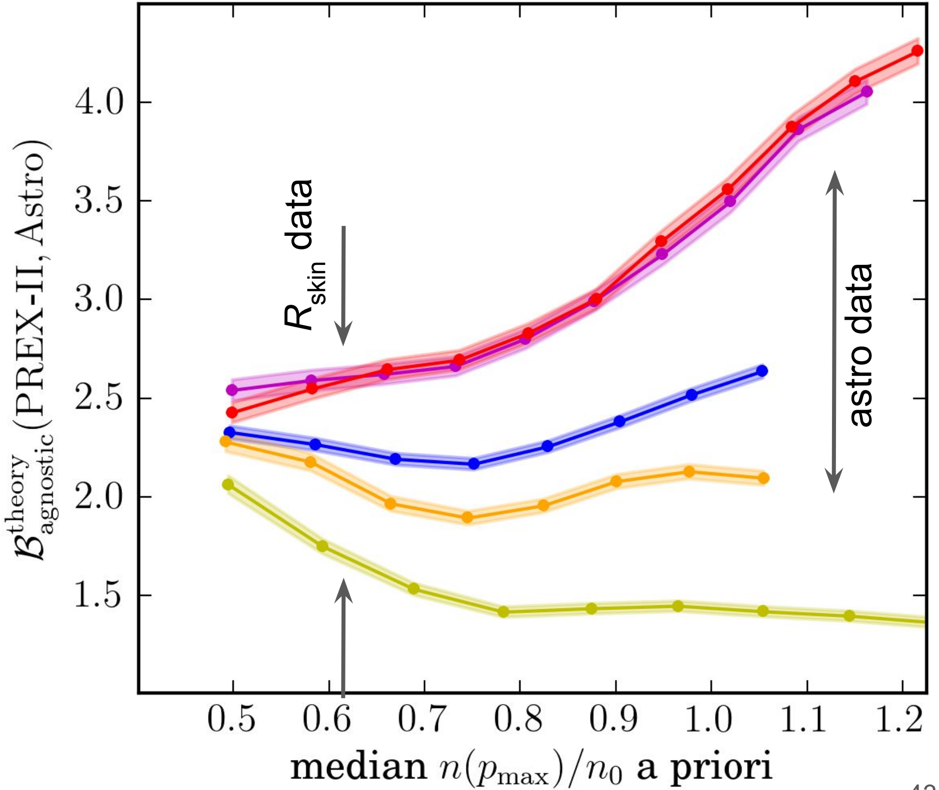
astro data can distinguish between nuclear theories at high densities



nuclear experiments probe lower densities



Inference of the NS EoS: low-density nuclear experiment

Essick+ (2021)
Essick+ (2021)

100 MeV < *L*
30 MeV < *L* < 70 MeV
All *L*