Gravitational Wave Observables (and Observations!) and their Connections to Nuclear Physics

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Basic Physics

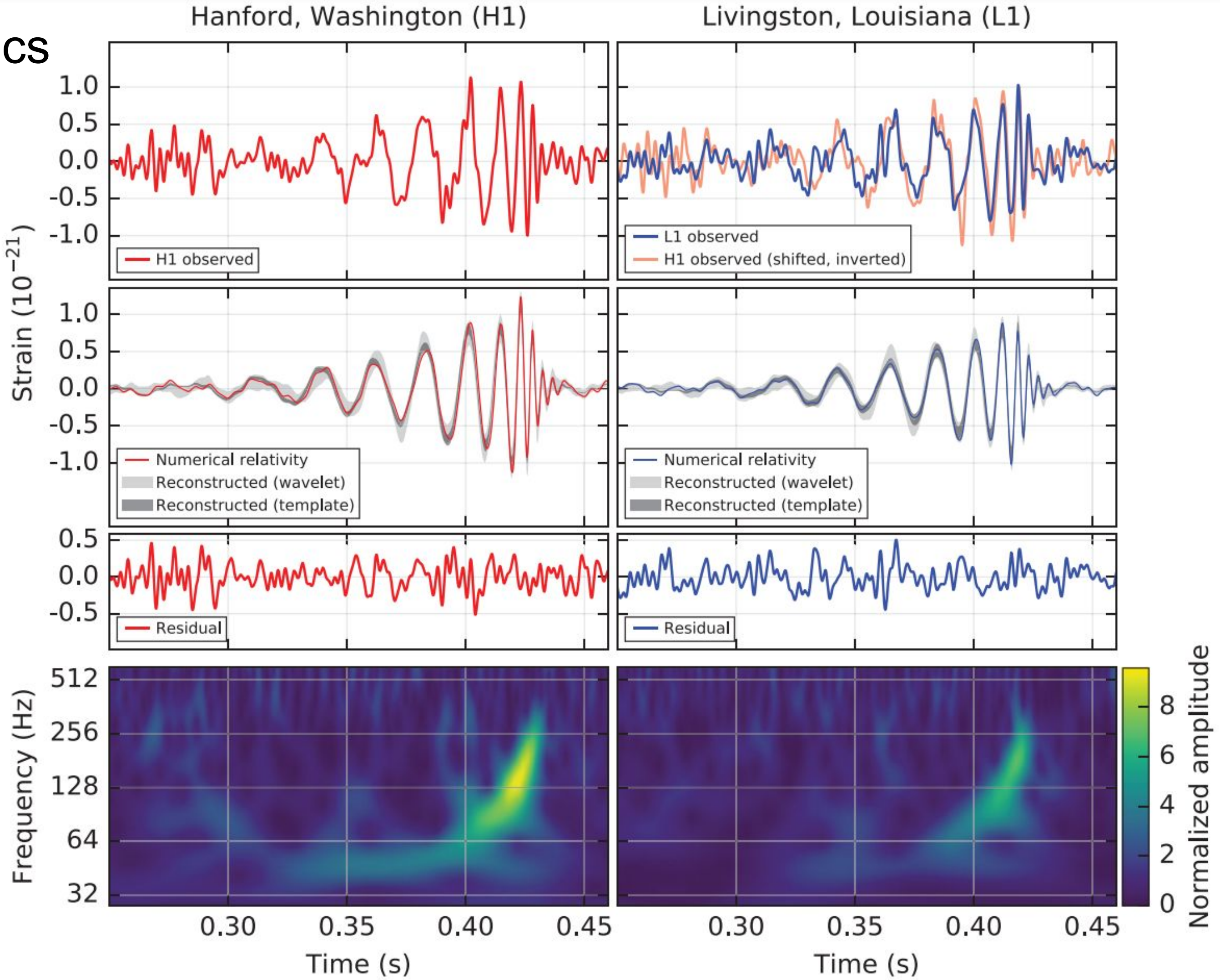
Current Status

- EoS from adiabatic tidal deformabilities
- Connections to other astrophysical observations, nuclear theory and experiment

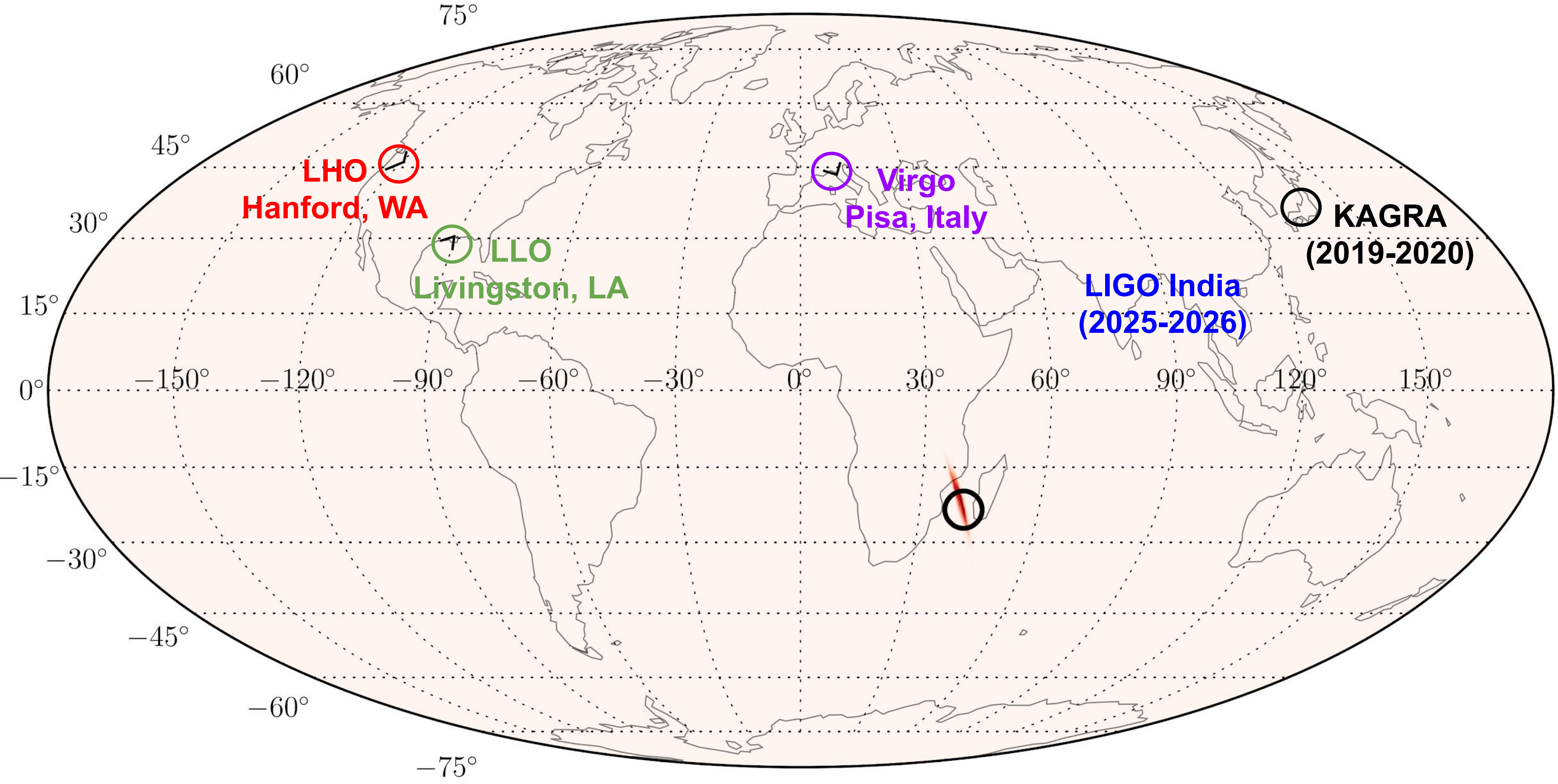
Connections between the Population of Merging Binaries and the EoS

How can we determine whether a GW source contains a NS?

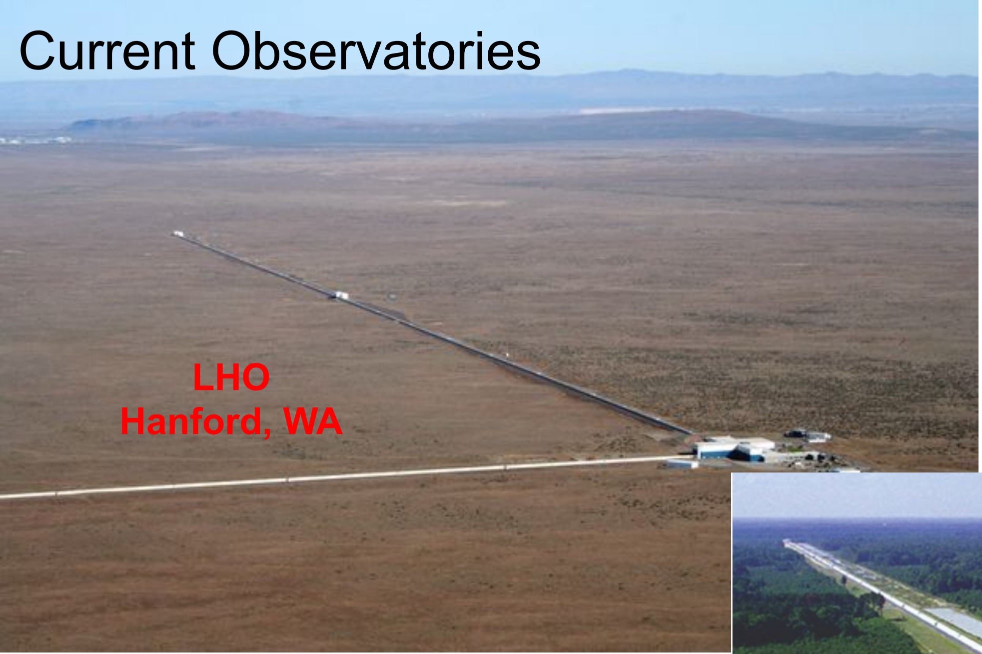
Basic Physics



Current Observatories



Current Observatories



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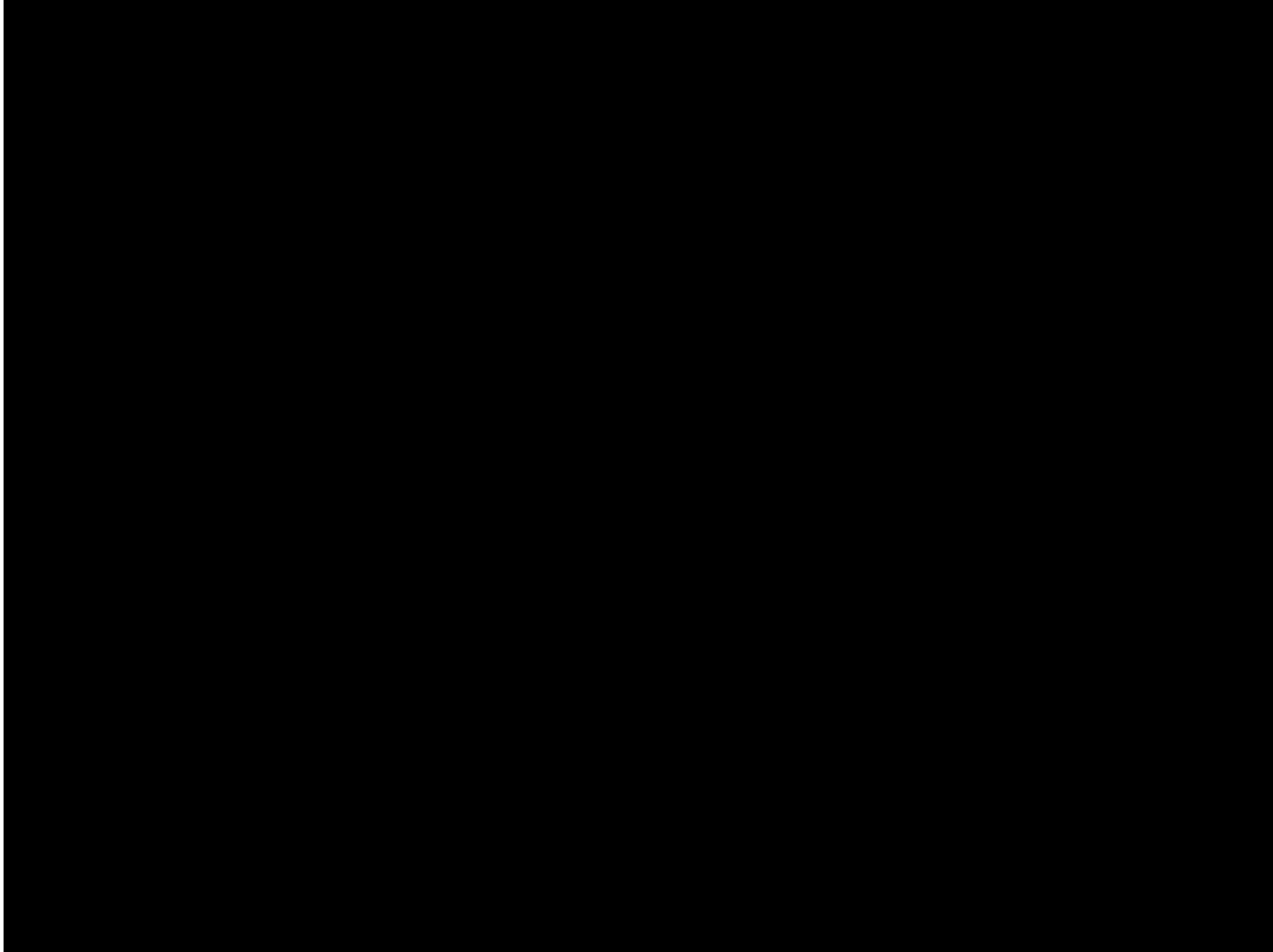
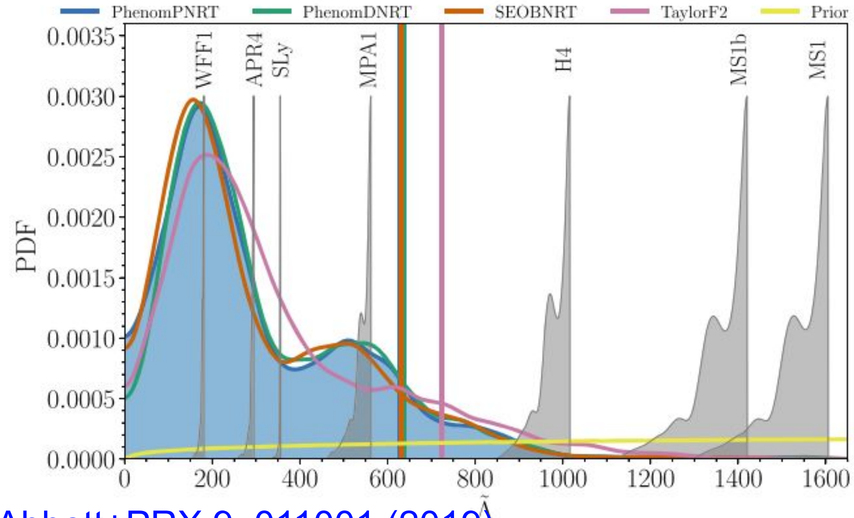
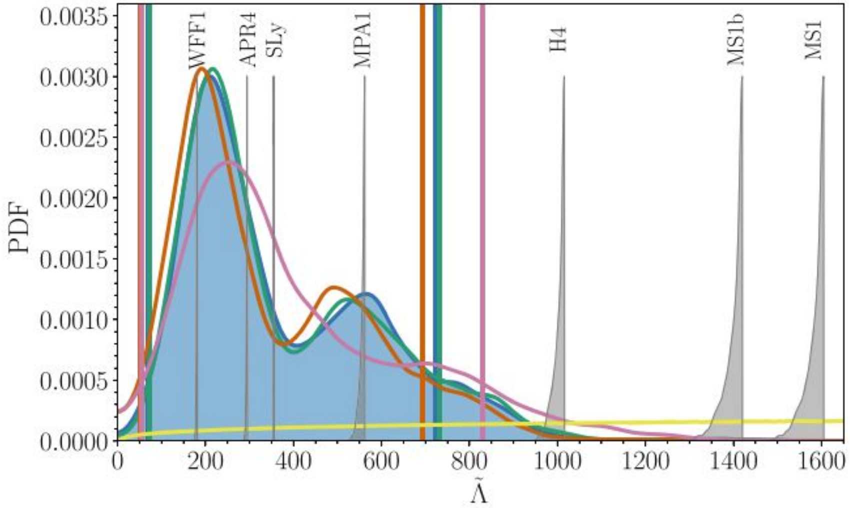
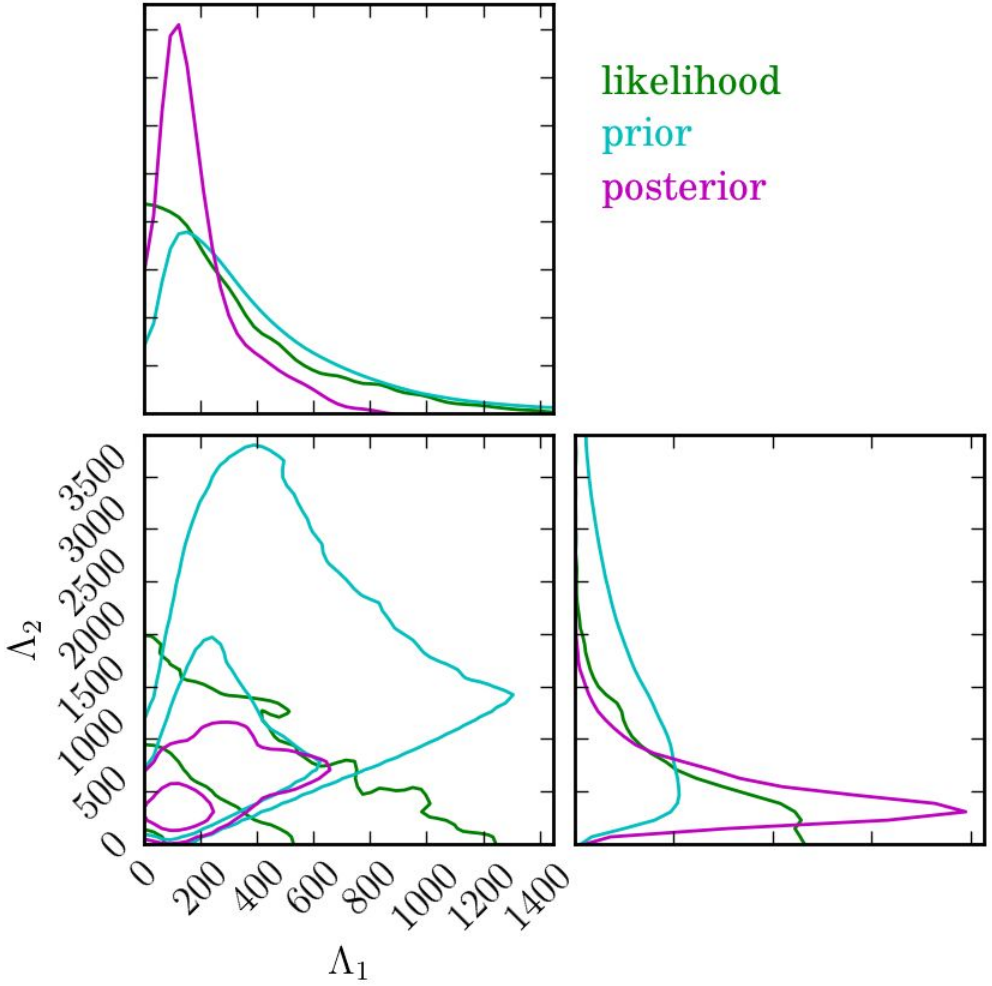


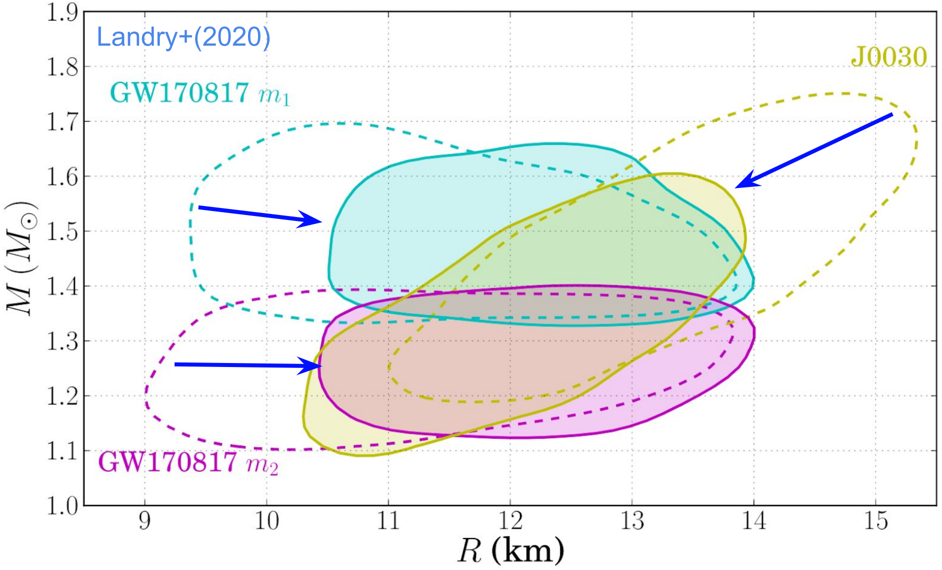


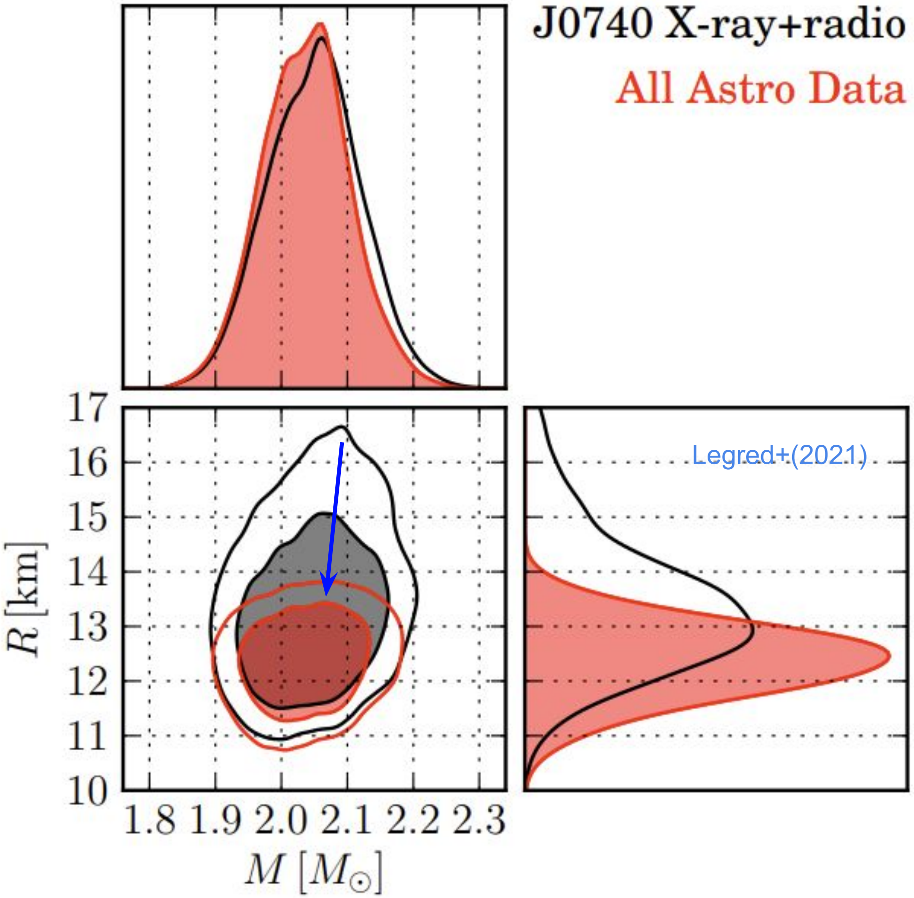
Abbott+PRX 9, 011001 (2019)



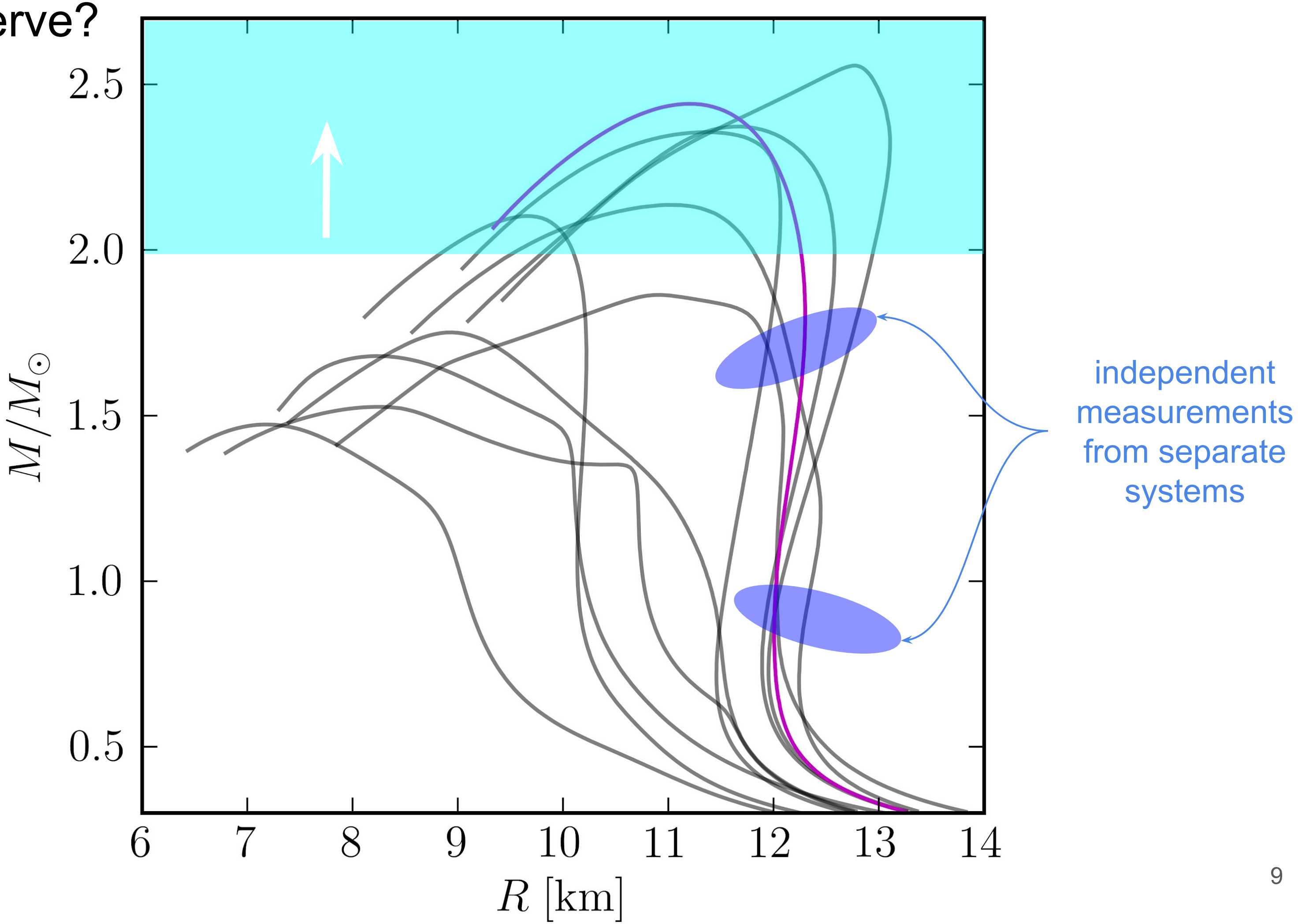


Multi-messenger Hierarchical Bayesian Analysis

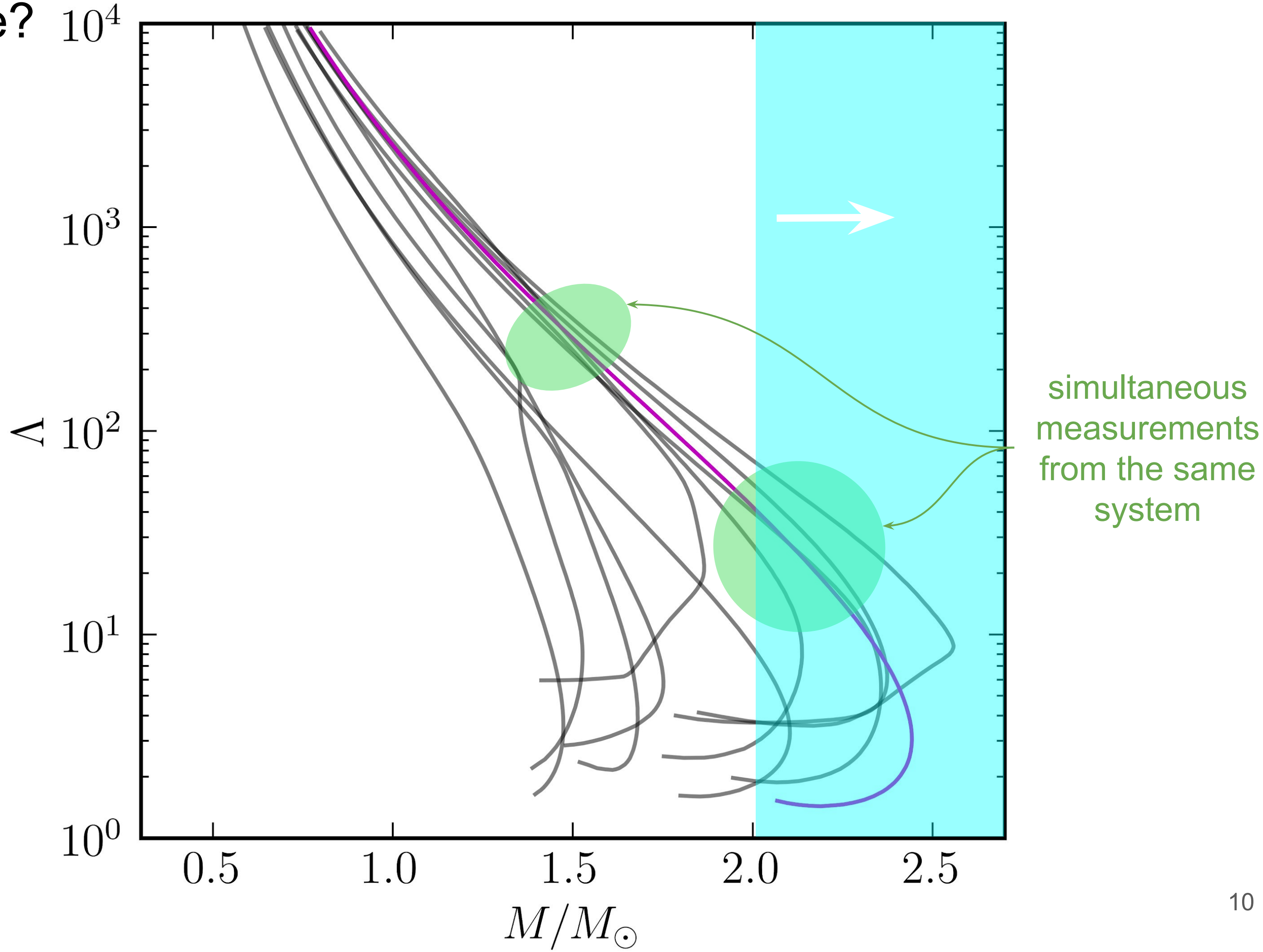


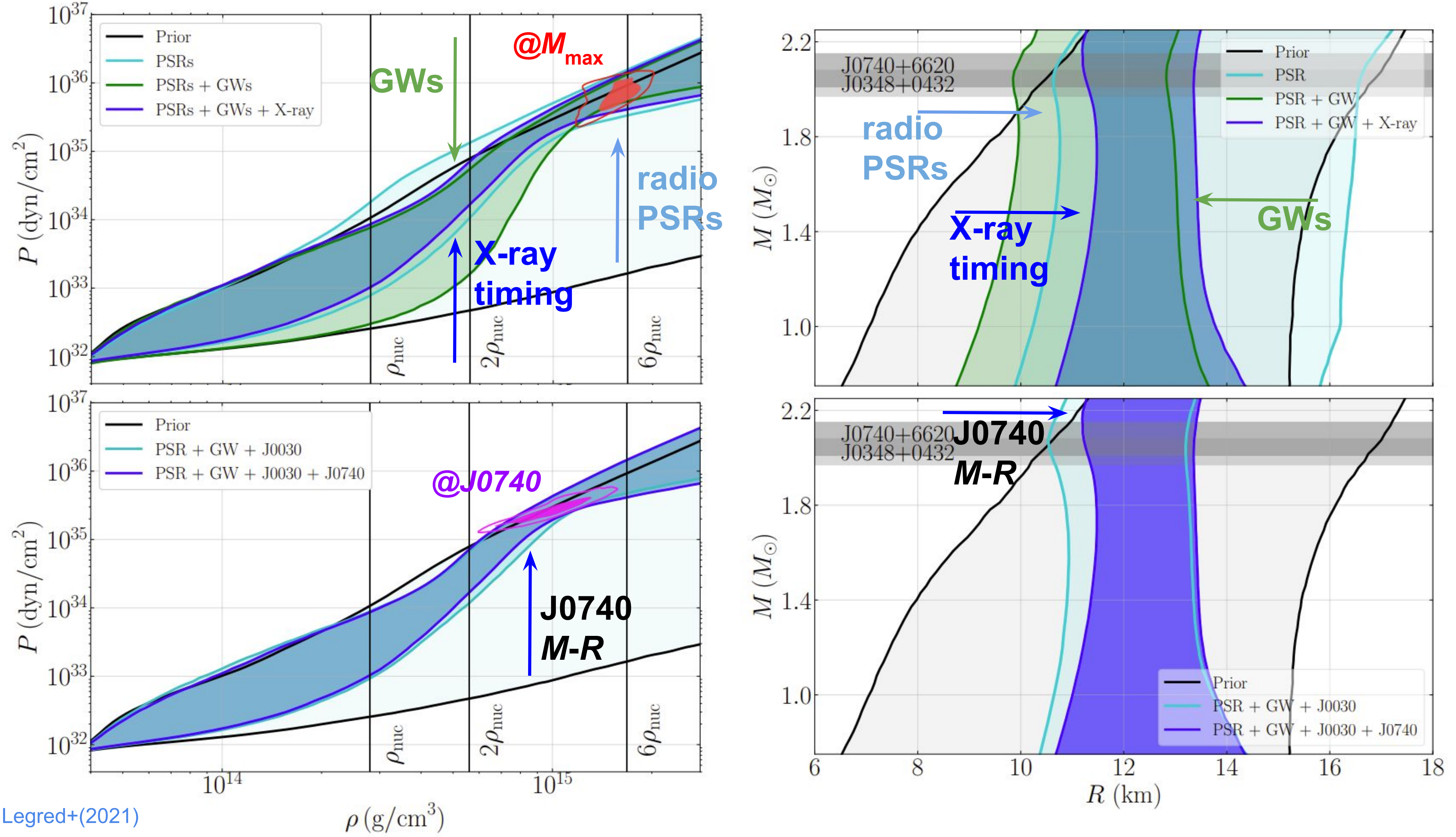


What do we observe?



What do we observe?





Prior
PSRs
PSRs + GWs
PSRs + GWs + X-ray
@M_{max}
GWs
radio PSRs
X-ray timing
ρ_{nuc}
$2\rho_{nuc}$
$6\rho_{nuc}$
P (dyn/cm^2)
PSR + GW + J0030
PSR + GW + J0030 + J0740
@J0740
J0740 M-R
ρ (g/cm^3)
J0740+6620
J0348+0432
PSR
PSR + GW
PSR + GW + X-ray
M ($M_\odot$)
R (km)

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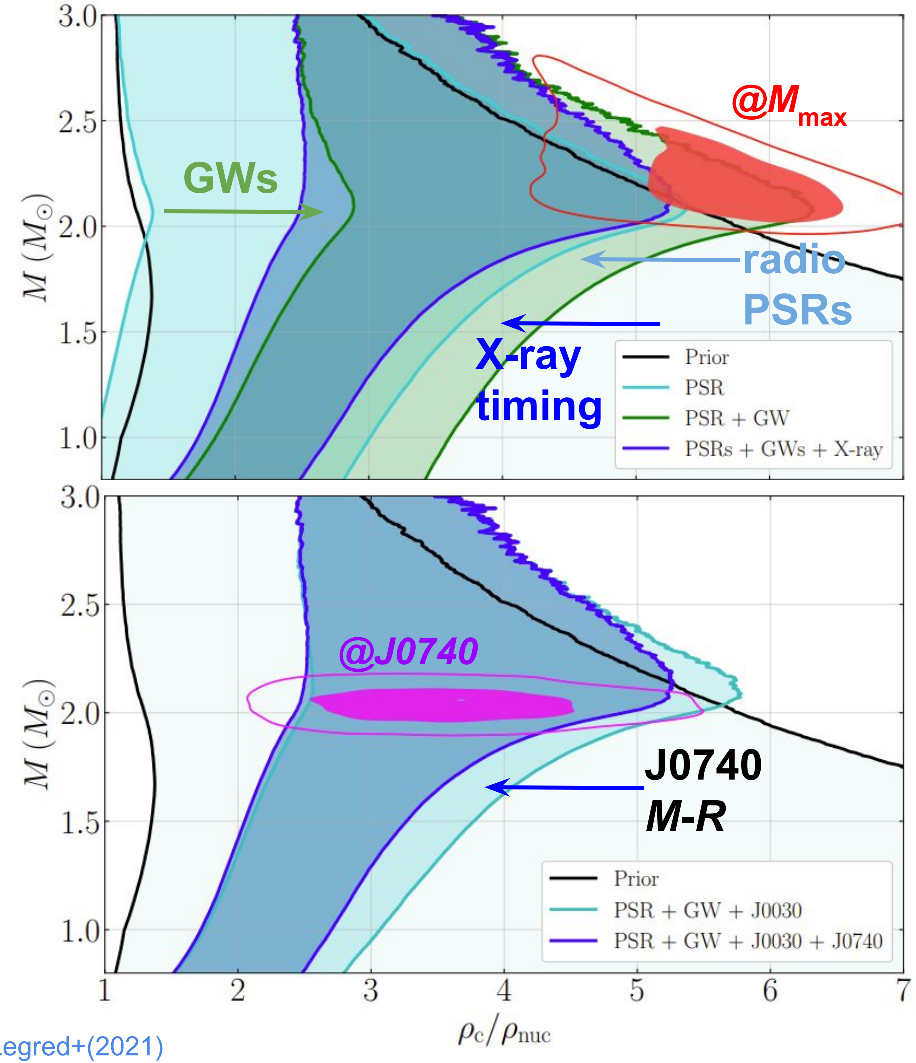
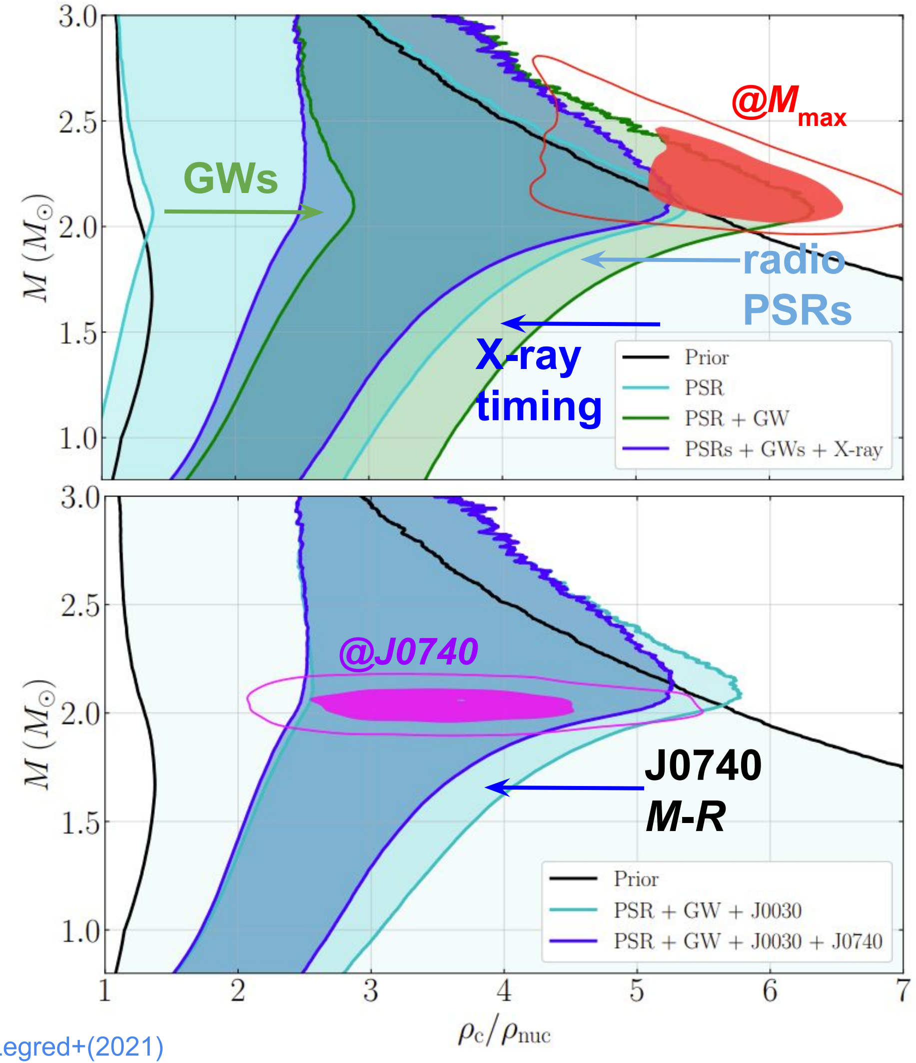
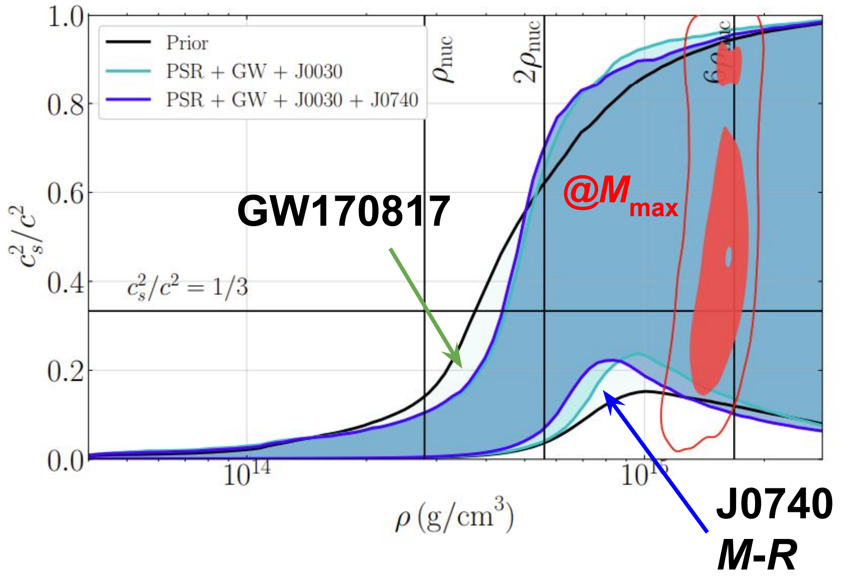


Legred+(2021)

There is a limit to the densities we can probe within NSs

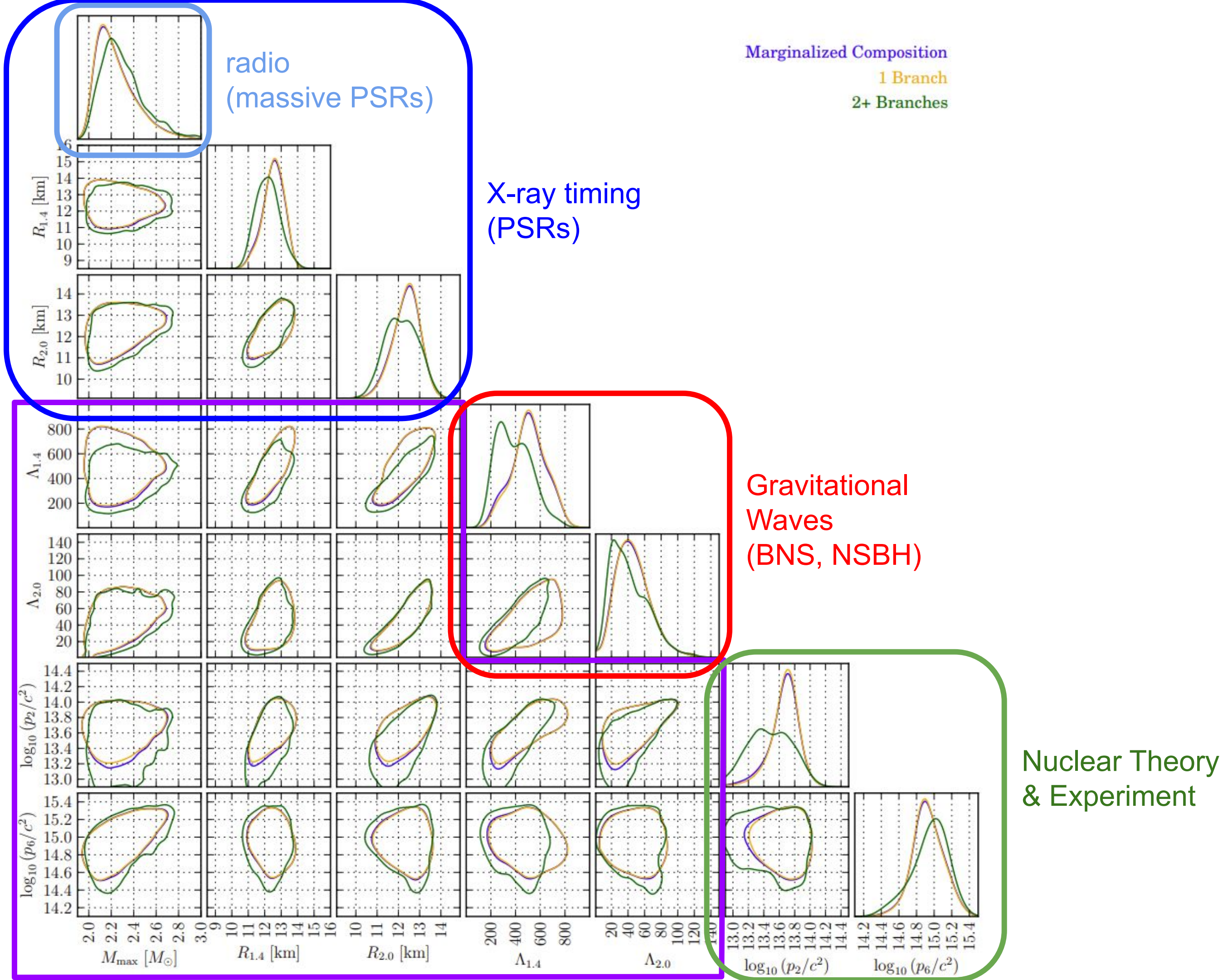




supranuclear sound speed almost certainly exceeds the conformal limit (suggests strongly-coupled interactions)

Legred+(2021)

Nonparametric EoS Inference



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Nonparametric EoS Inference

Current “Theory Agnostic” Constraints

	Observable	Prior	w/ PSRs	w/o J0740+6620	w/J0740+6620	
					Miller+	Riley+
	$M_{\max}$ [$M_{\odot}$]	$1.47^{+0.71}_{-1.37}$	$2.24^{+0.48}_{-0.24}$	$2.20^{+0.30}_{-0.19}$	$2.21^{+0.31}_{-0.21}$	$2.19^{+0.27}_{-0.19}$
Properties of the EoS	$p(\rho_{\rm nuc})$ [10^{33}dyn/cm^2]	$2.25^{+5.81}_{-2.15}$	$6.07^{+7.53}_{-5.93}$	$4.05^{+3.59}_{-3.74}$	$4.30^{+3.37}_{-3.80}$	$4.15^{+3.50}_{-3.76}$
	$p(2\rho_{\rm nuc})$ [10^{34}dyn/cm^2]	$1.22^{+4.86}_{-1.21}$	$6.00^{+4.79}_{-5.99}$	$3.75^{+2.36}_{-2.98}$	$4.38^{+2.46}_{-2.96}$	$3.90^{+2.11}_{-2.88}$
	$p(6\rho_{\rm nuc})$ [10^{35}dyn/cm^2]	$2.43^{+4.70}_{-2.43}$	$7.51^{+6.77}_{-5.15}$	$8.33^{+5.22}_{-4.14}$	$7.41^{+5.87}_{-4.18}$	$7.82^{+5.47}_{-3.53}$
	$\max\{c_s^2/c^2\} \mid \rho \le \rho_c(M_{\max})$	$0.76^{+0.24}_{-0.37}$	$0.72^{+0.28}_{-0.26}$	$0.84^{+0.16}_{-0.28}$	$0.75^{+0.25}_{-0.24}$	$0.80^{+0.20}_{-0.26}$
	$\rho(\max\{c_s^2/c^2\})$ [10^{15}g/cm^3]	$1.38^{+1.65}_{-1.34}$	$0.97^{+0.64}_{-0.70}$	$1.13^{+0.64}_{-0.63}$	$1.01^{+0.63}_{-0.53}$	$1.10^{+0.63}_{-0.58}$
	$p(\max\{c_s^2/c^2\})$ [10^{35}dyn/cm^2]	$1.65^{+8.16}_{-1.65}$	$2.68^{+5.18}_{-2.68}$	$3.52^{+6.90}_{-3.48}$	$2.77^{+5.81}_{-2.70}$	$3.26^{+6.51}_{-3.15}$
Properties defined for both NSs and BHs	$R_{1.4}$ [km]	$8.09^{+5.68}_{-3.96}$	$13.54^{+2.61}_{-3.13}$	$12.25^{+1.13}_{-1.33}$	$\boxed{12.56^{+1.00}_{-1.07}}$	$12.34^{+1.01}_{-1.25}$
	$R_{2.0}$ [km]	$5.90^{+6.97}_{-0.00}$	$13.18^{+3.02}_{-2.90}$	$12.05^{+1.18}_{-1.45}$	$12.41^{+1.00}_{-1.10}$	$12.09^{+1.07}_{-1.17}$
	$\Delta R \equiv R_{2.0} - R_{1.4}$ [km]	$0.48^{+1.28}_{-6.67}$	$-0.07^{+1.00}_{-1.04}$	$-0.17^{+0.85}_{-0.83}$	$-0.12^{+0.83}_{-0.85}$	$-0.20^{+0.82}_{-0.88}$
	$\Lambda_{1.4}$	24^{+841}_{-24}	795^{+1262}_{-708}	442^{+235}_{-274}	507^{+234}_{-242}	457^{+219}_{-256}
	$\Lambda_{2.0}$	0^{+54}_{-0}	66^{+184}_{-66}	34^{+35}_{-27}	44^{+34}_{-30}	35^{+32}_{-24}
Properties defined only for NSs	$\rho_c(1.4\,M_{\odot})$ [10^{14}g/cm^3]	$8.4^{+12.5}_{-6.0}$	$5.7^{+3.2}_{-3.1}$	$7.2^{+2.6}_{-1.7}$	$6.7^{+1.7}_{-1.3}$	$7.1^{+2.1}_{-1.5}$
	$\rho_c(2.0\,M_{\odot})$ [10^{14}g/cm^3]	$9.0^{+5.7}_{-6.3}$	$8.5^{+4.8}_{-5.3}$	$10.5^{+4.1}_{-3.8}$	$9.7^{+3.6}_{-3.1}$	$10.4^{+3.6}_{-3.5}$
	$\rho_c(M_{\max})$ [10^{15}g/cm^3]	$2.4^{+0.9}_{-2.0}$	$1.4^{+0.5}_{-0.6}$	$1.6^{+0.3}_{-0.4}$	$1.5^{+0.3}_{-0.4}$	$1.6^{+0.3}_{-0.3}$

$R(1.4M_{\odot}) \sim 12.5 \pm 1$ km

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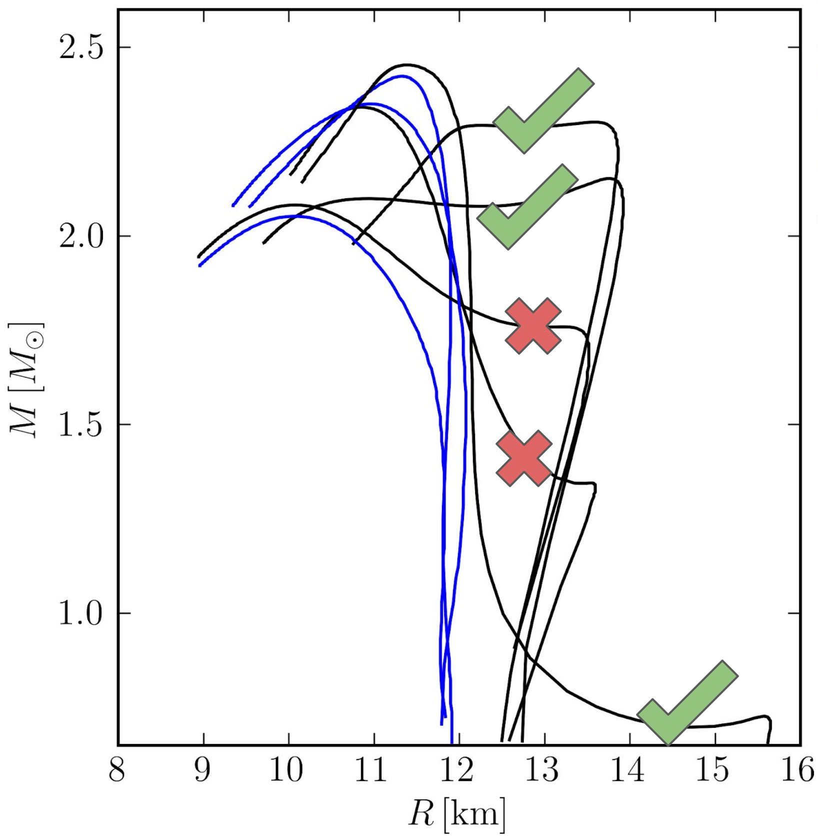
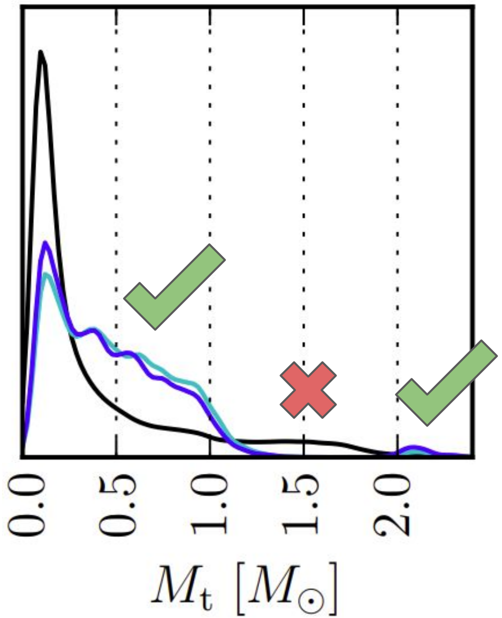
Nonparametric EoS Inference



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

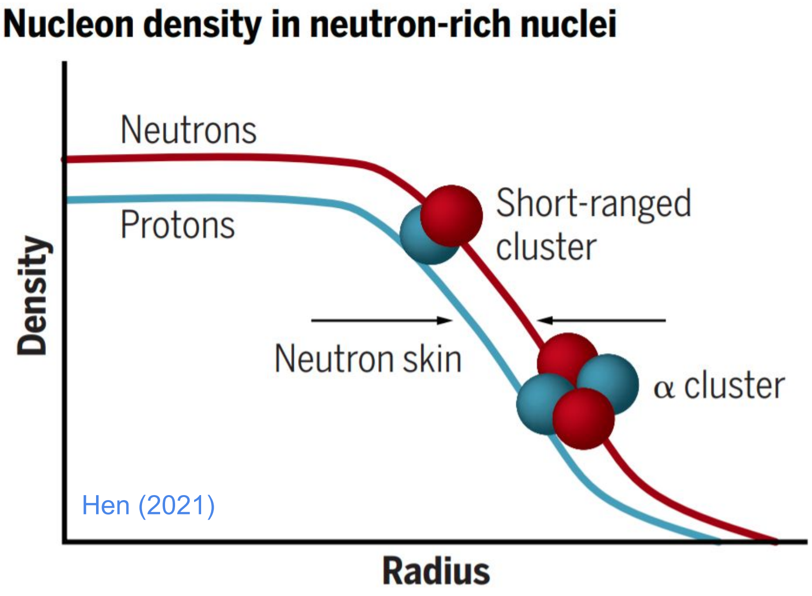


Legred+(2021)

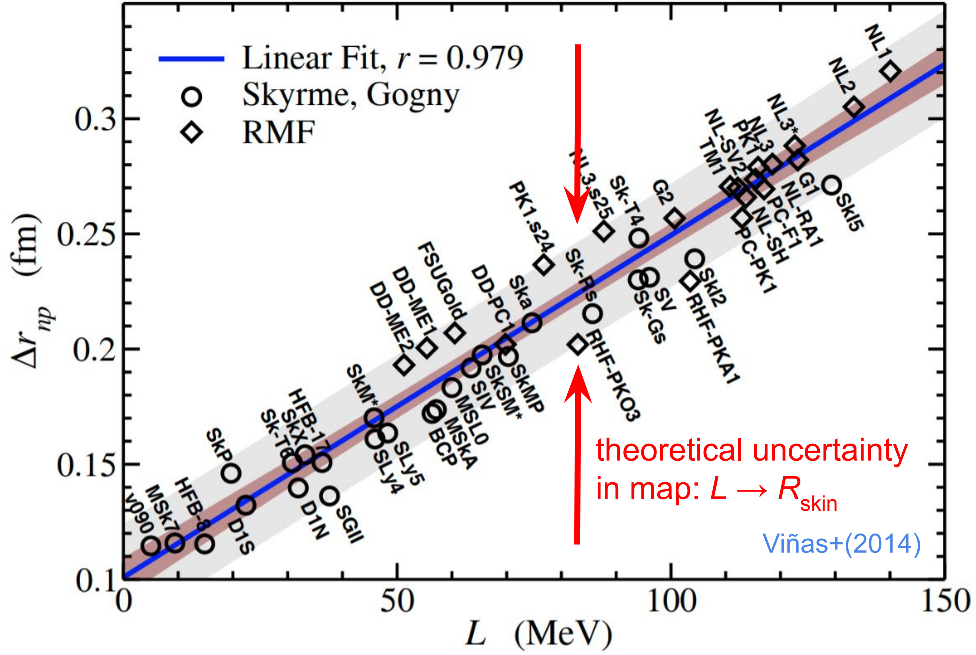
Comparisons with Terrestrial Nuclear Experiments

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

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

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

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

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

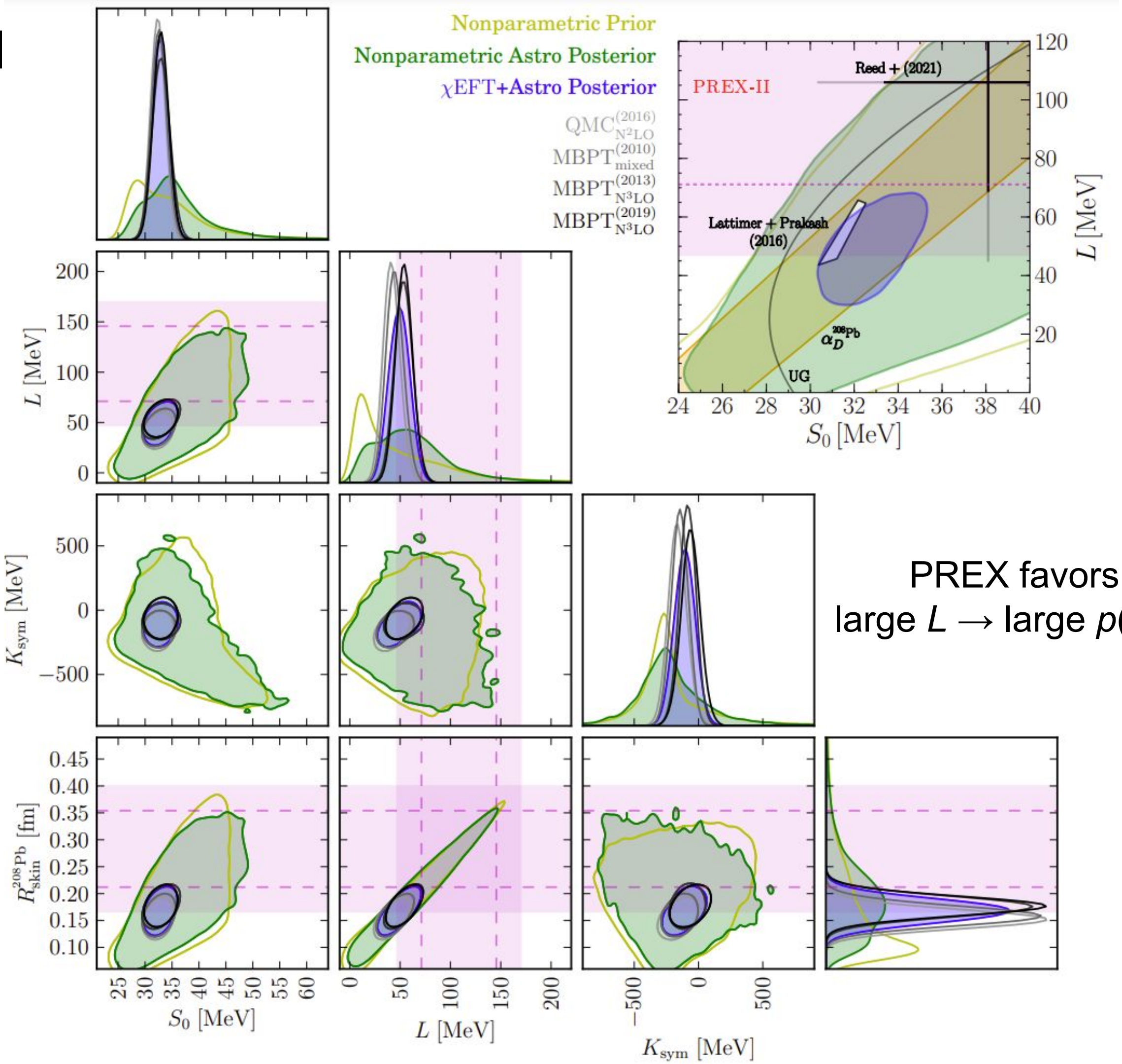
$$K_{\mathrm{sym}} = 9n^2\left(\frac{d^2S_0}{dn^2}\right)$$

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}

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

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

Comparisons with Terrestrial Nuclear Experiments

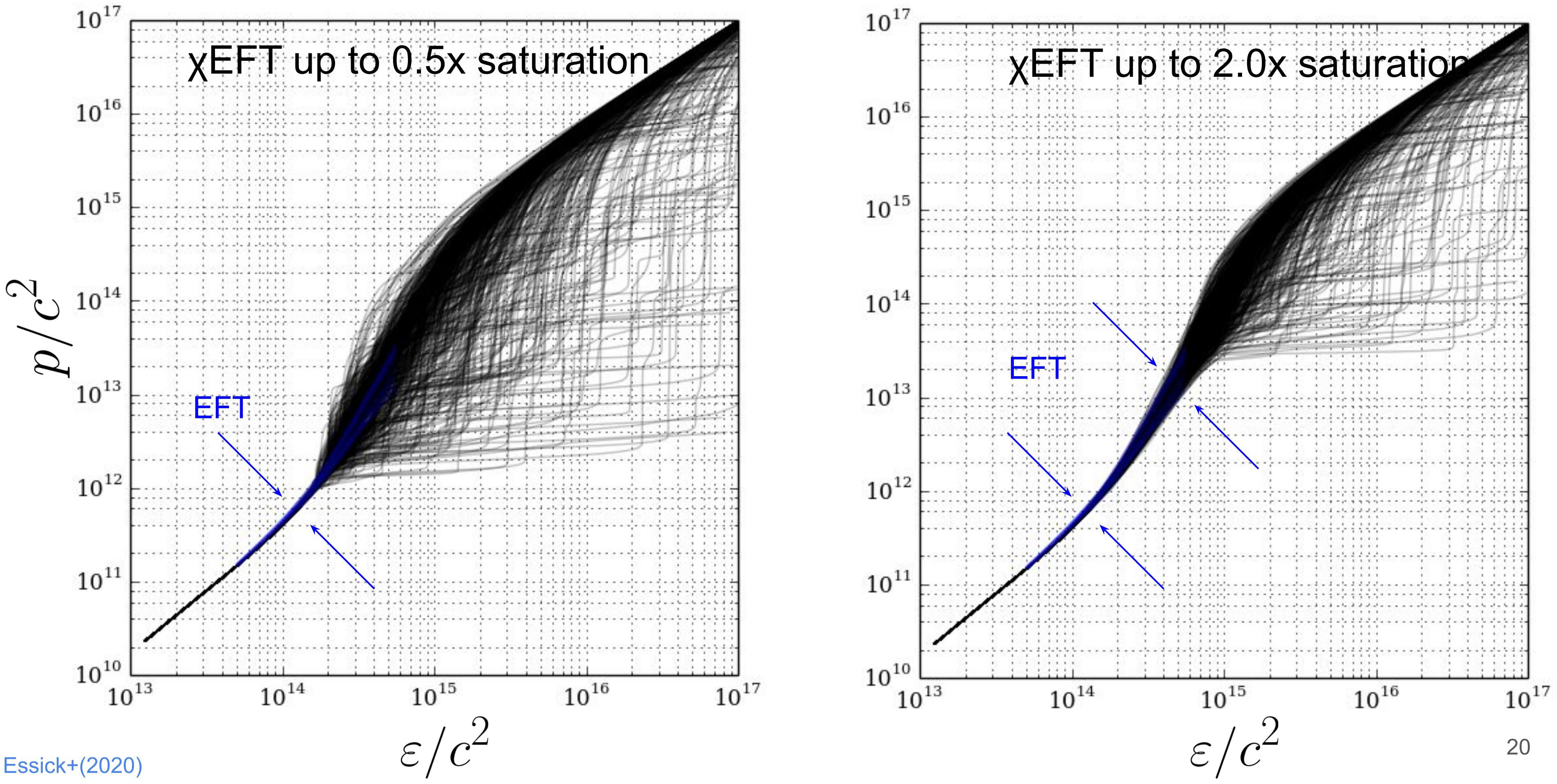


We can also extract "nuclear parameters" directly from nonparametric EoS Without the need for "parametrized EoS models"

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

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

Comparisons with *ab initio* Chiral Effective Field Theory Calculations

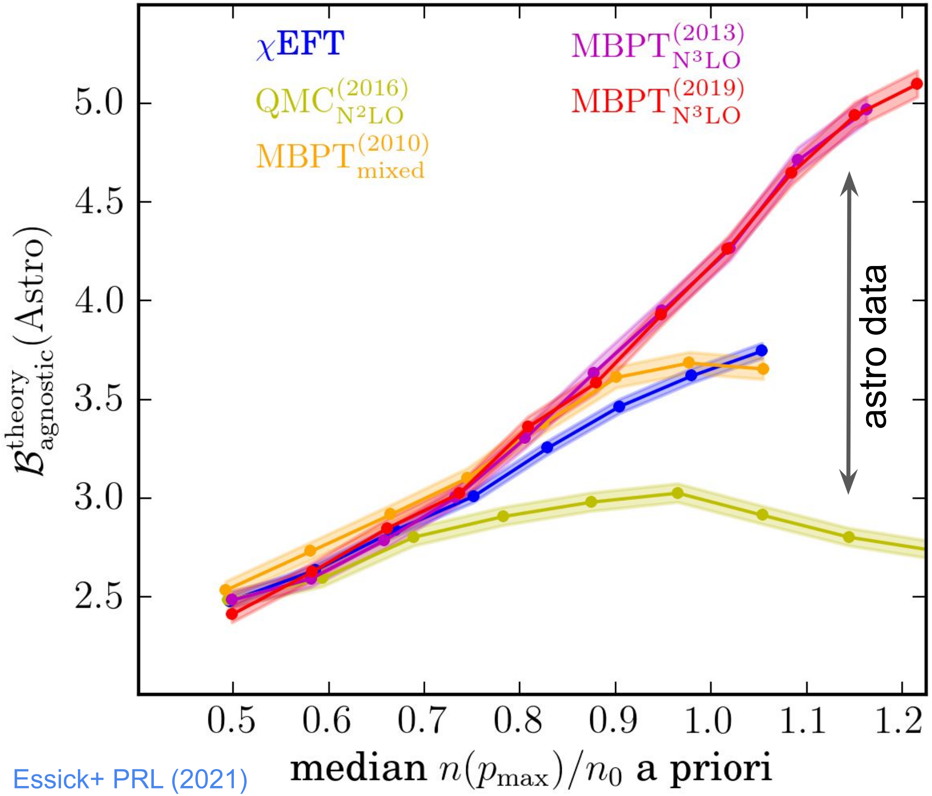


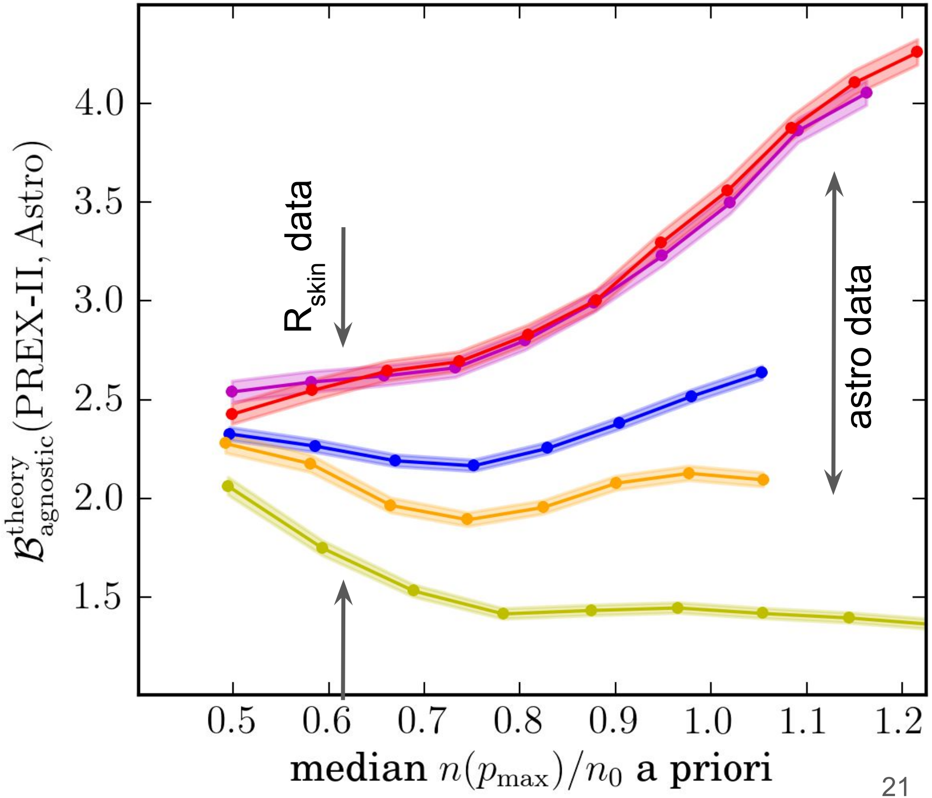
Essick+(2020)

Comparisons with Terrestrial Nuclear Experiments

astro data can distinguish between
nuclear theories at high densities

nuclear experiments probe lower densities





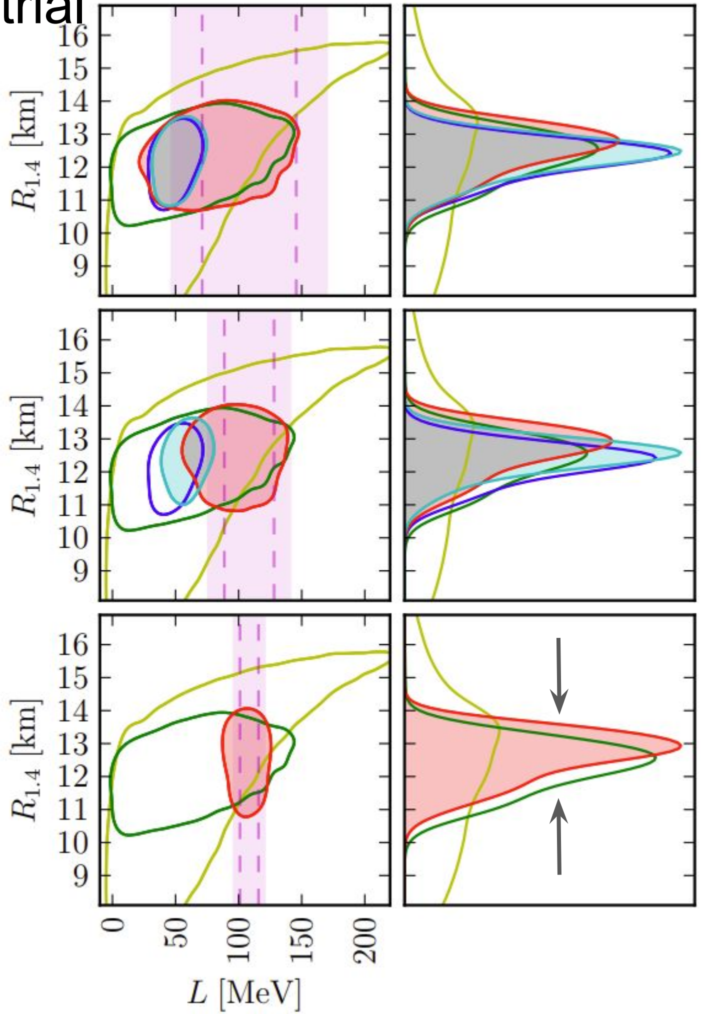
Essick+ PRL (2021)
Essick+ PRC (2021)

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

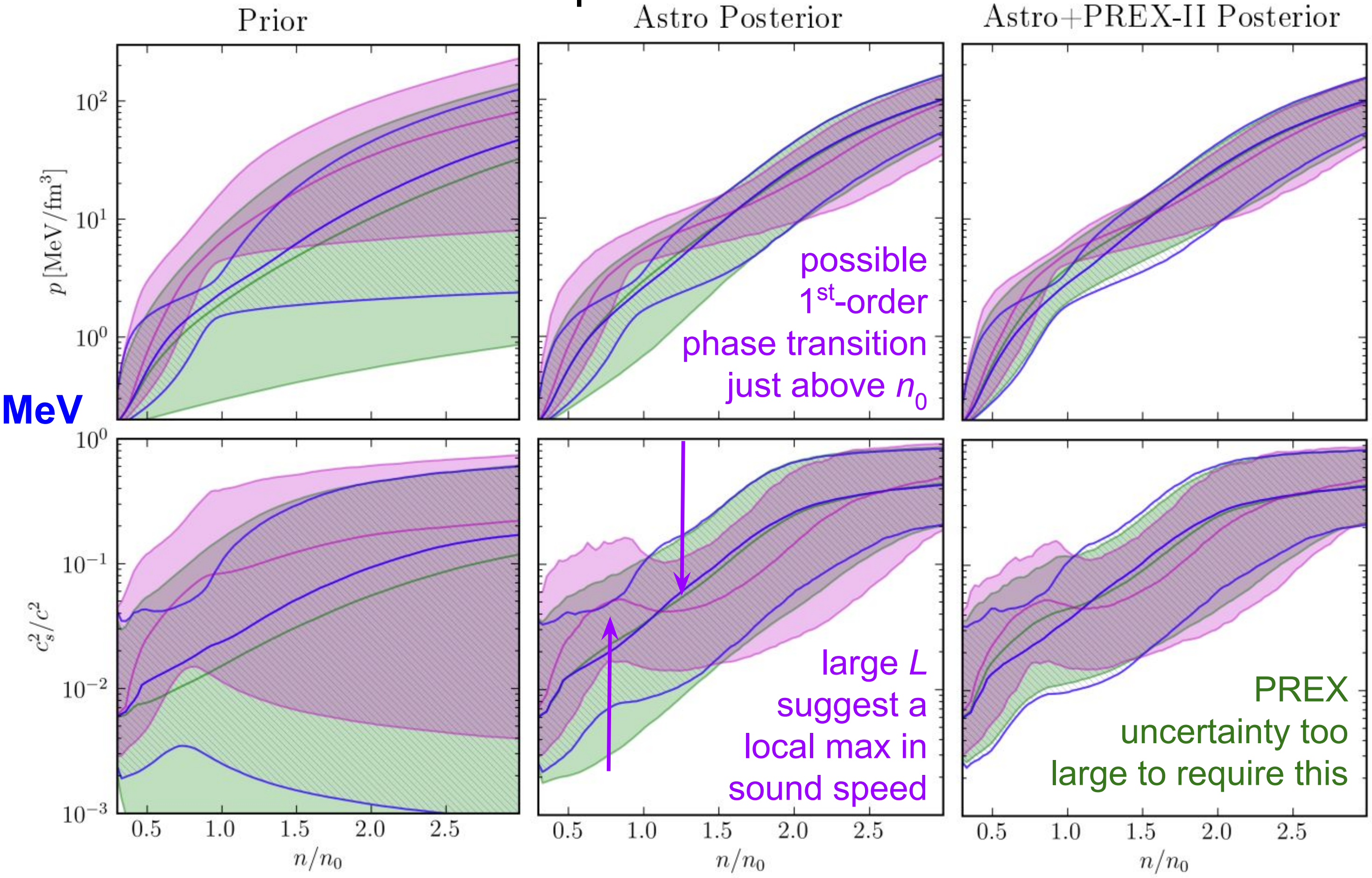
χEFT+astro+R_{skin} posterior

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

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

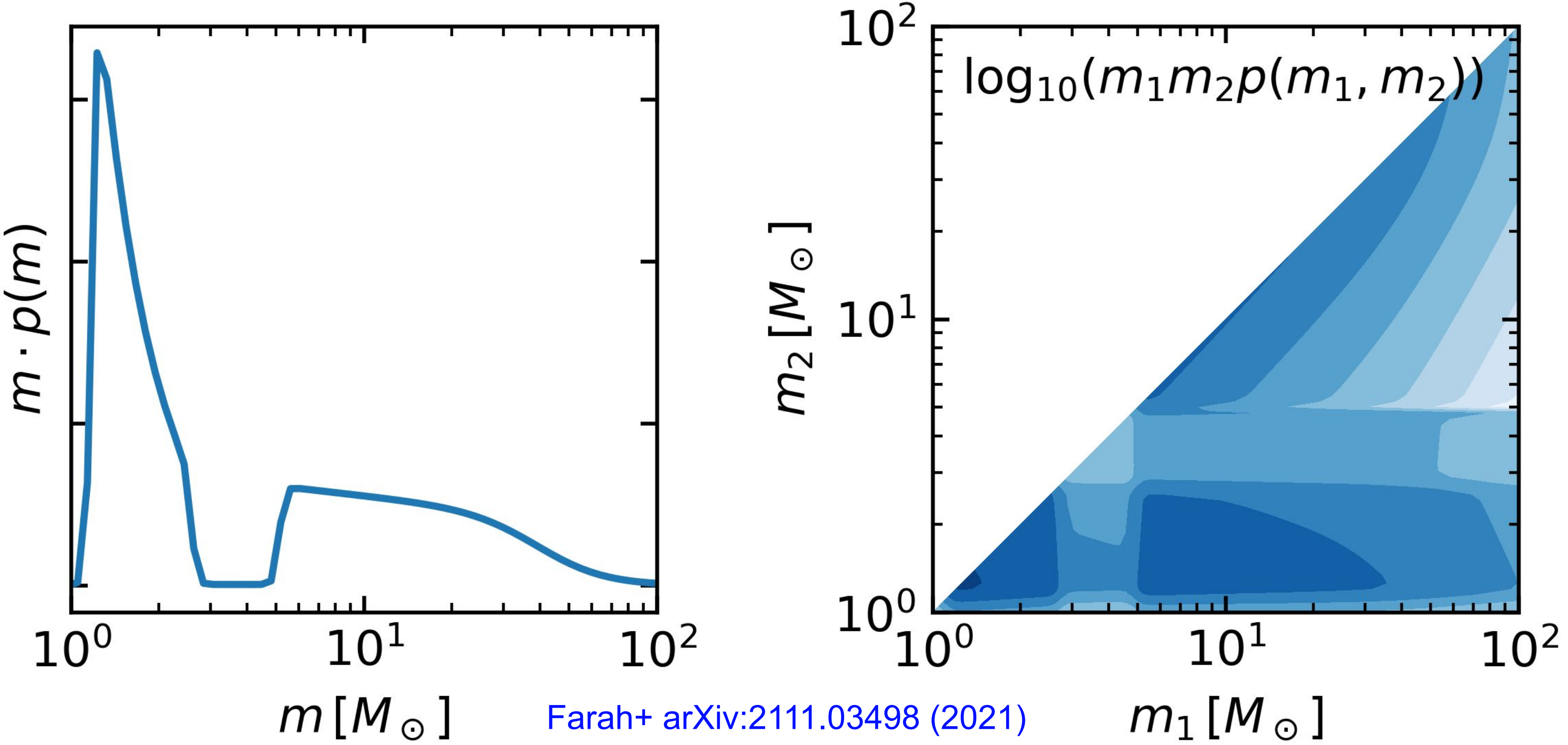
Comparisons with Terrestrial Nuclear Experiments

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

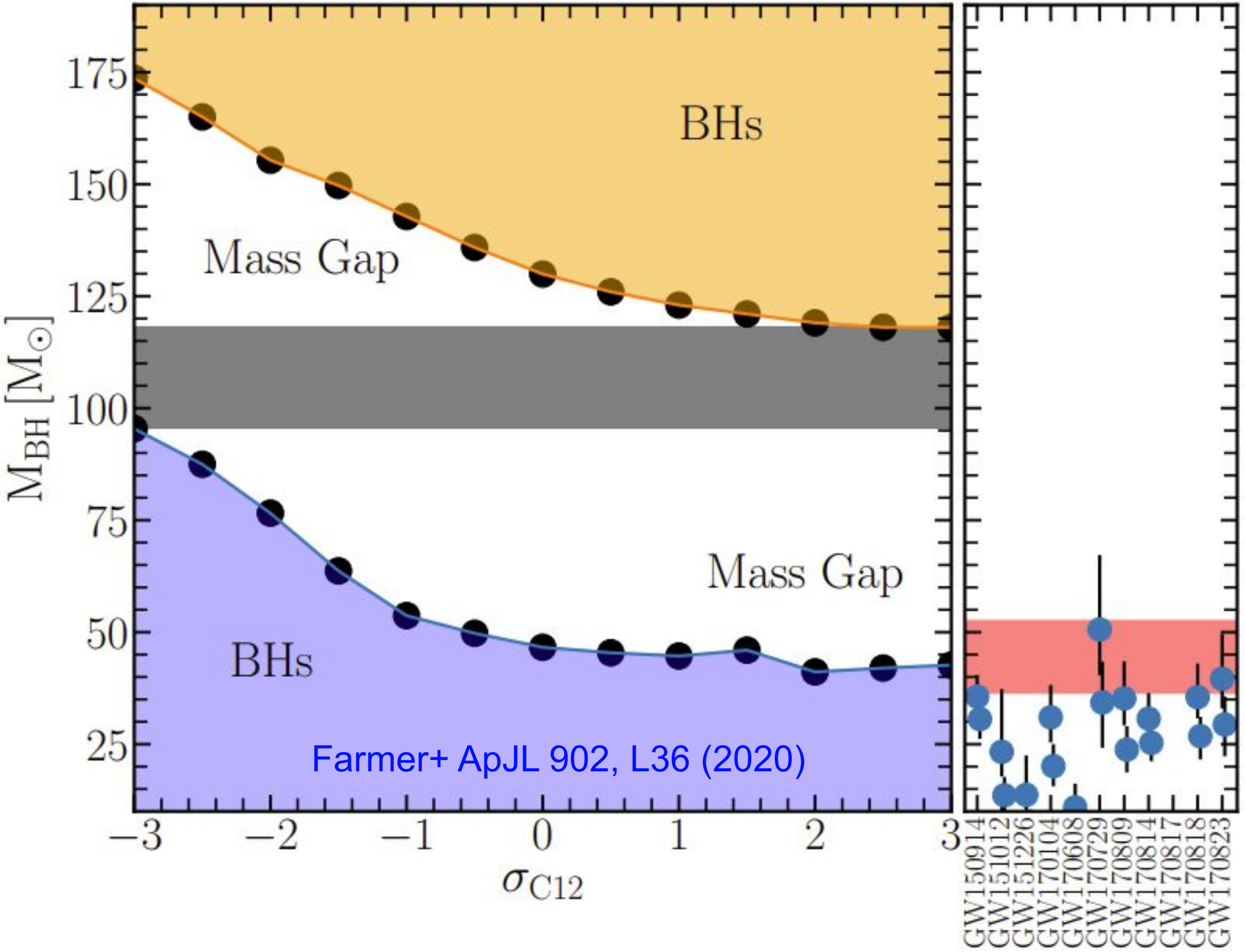


Essick+ PRL (2021)
Essick+ PRC (2021)

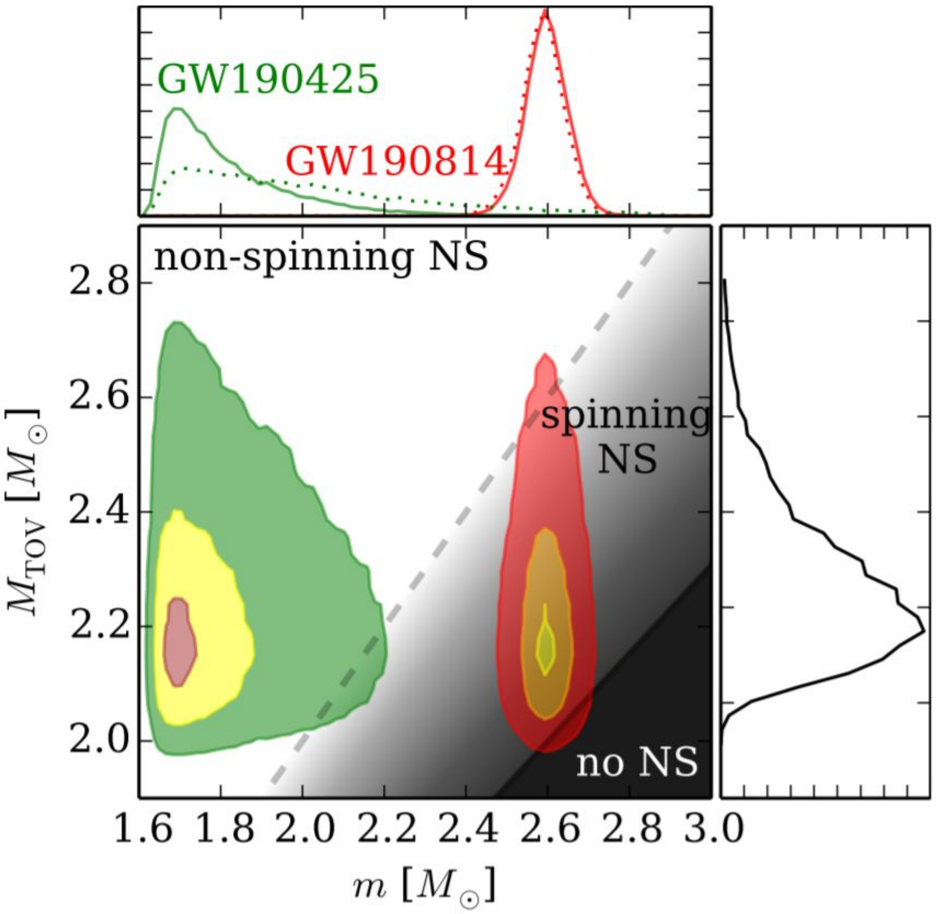
maximum a posteriori population model

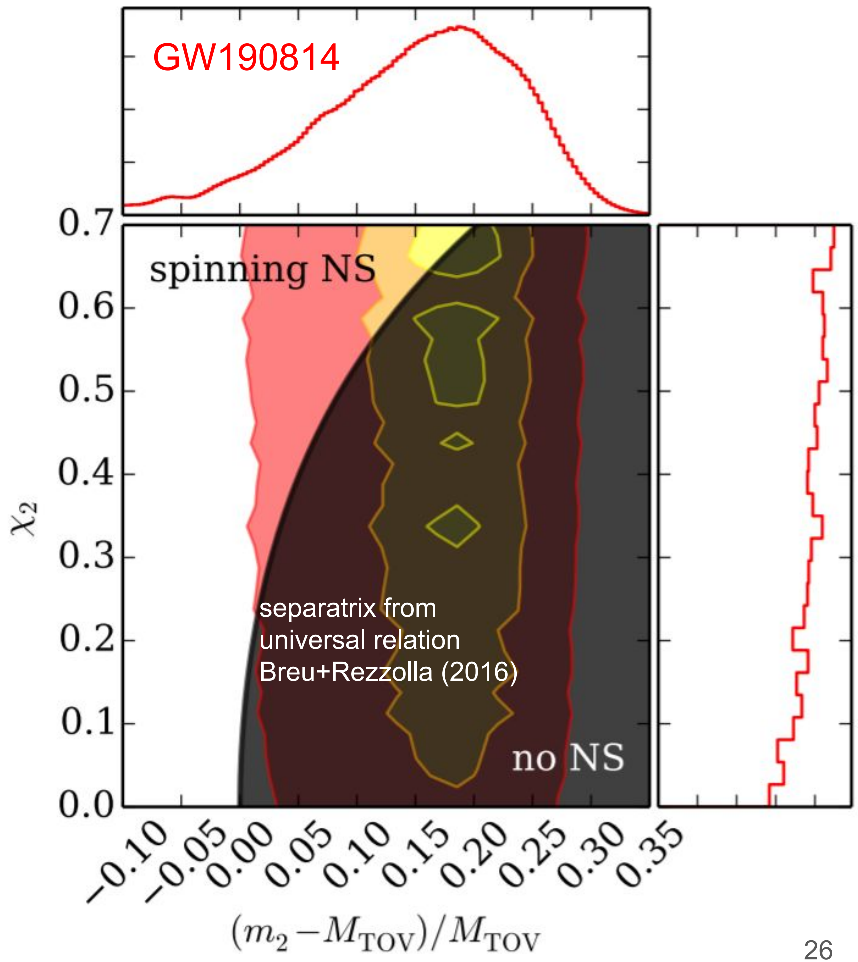


Farah+ arXiv:2111.03498 (2021)



$^{12}C\,(\alpha,\gamma)^{16}O$ reaction rate

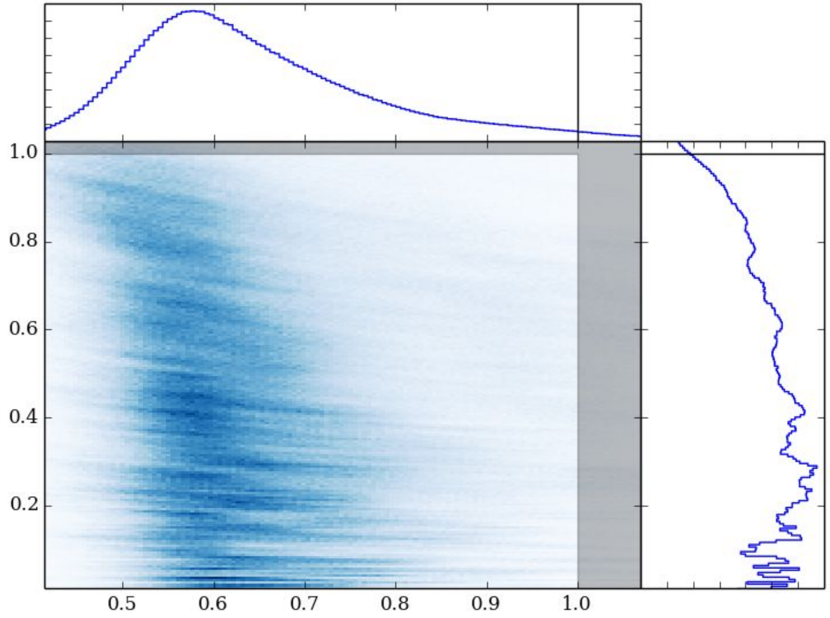




Essick+Landry (2020)

Connecting it all together : GW200115

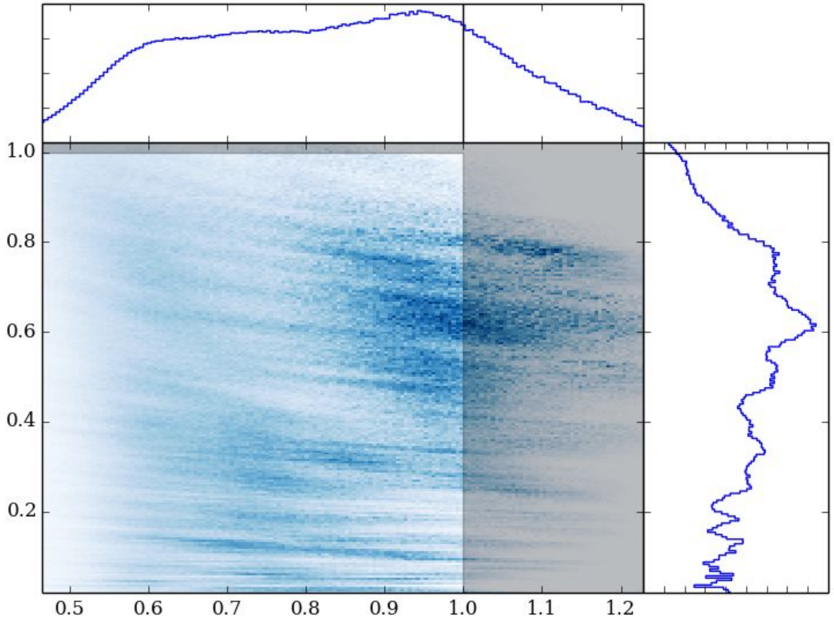
mass distribution disfavors equal-mass binaries



$s / s_{max}(M_{TOV}, R_{TOV})$

$m / M_{max}(M_{TOV}, s)$

mass distribution favors equal-mass binaries



$m / M_{max}(M_{TOV}, s)$

Essick+Landry (2020)