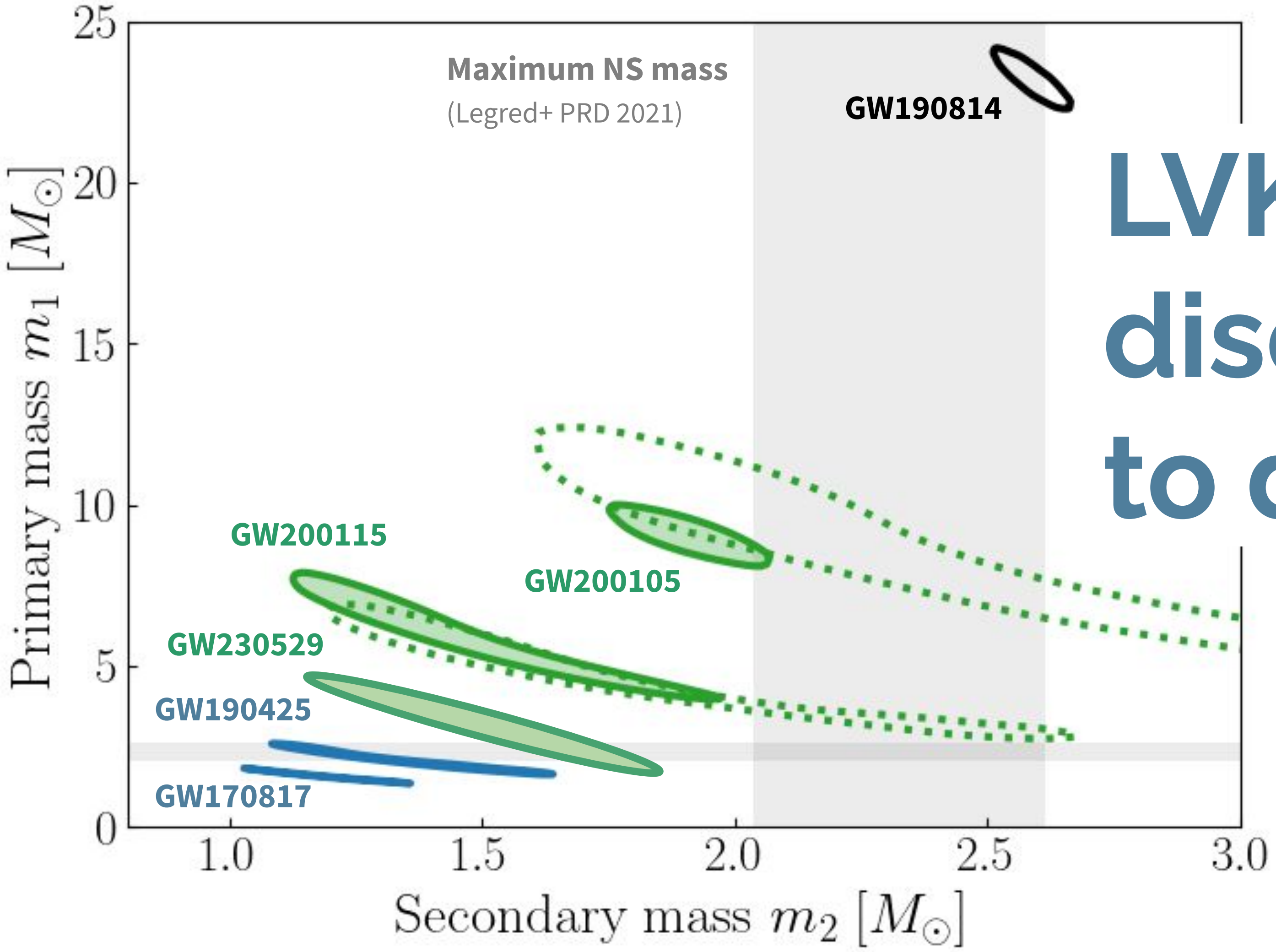
A nonparametric tour of neutron-star matter with gravitational waves

Philippe Landry ⬥ Canadian Institute for Theoretical Astrophysics

based on work with Reed Essick, Katerina Chatziioannou, Isaac Legred,
Sophia Han, Ingo Tews, Sanjay Reddy, and many other collaborators

INT-N3AS 24-89W – 6 Sep 2024

LVK NS discoveries to date



GWTC-3 catalog*

Abbott+ PRX 13 041039 (2023)

*plus GW230529
Abac+ ApJL 970 L34 (2024)

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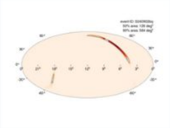
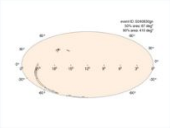
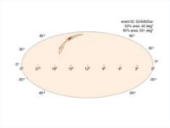
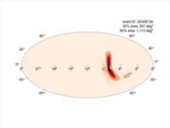
Event ID	Possible Source (Probability)	Significant	UTC	GCN	Location	FAR
S240902bq	BBH (>99%)	Yes	Sept. 2, 2024 14:33:06 UTC	GCN Circular Query Notices | VOE		1 per 12.505 years
S240830gn	BBH (89%), NSBH (11%)	Yes	Aug. 30, 2024 21:11:20 UTC	GCN Circular Query Notices | VOE		1 per 50.02 years
S240825ar	BBH (97%), NSBH (3%)	Yes	Aug. 25, 2024 05:51:46 UTC	GCN Circular Query Notices | VOE		1 per 10.004 years
S240813d	BBH (>99%)	Yes	Aug. 13, 2024 04:39:13 UTC	GCN Circular Query Notices | VOE		1 per 1.7544e+10 years

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Event ID	Possible Source (Probability)	Significant	UTC
S240902bq	BBH (>99%)	Yes	Sept. 2, 2024 14:33:06 UTC
S240830gn	BBH (89%), NSBH (11%)	Yes	Aug. 30, 2024 21:11:20 UTC
S240825ar	BBH (97%), NSBH (3%)	Yes	Aug. 25, 2024 05:51:46 UTC
S240813d	BBH (>99%)	Yes	Aug. 13, 2024 04:39:13 UTC

open data

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GWTC

Name	Version	Release	GPS	Mass 1 ($M_\odot$)	Mass 2 ($M_\odot$)	Network SNR	Distance (Mpc)	χ_{eff}	Total Mass ($M_\odot$)
GW200322_091133	v1	GWTC-3-confident	1268903511.3	38^{+130}_{-22}	$11.3^{+24.3}_{-6.0}$	$4.5^{+2.7}_{-3.0}$	3500^{+12500}_{-2200}	$0.27^{+0.54}_{-0.58}$	50^{+132}_{-22}
GW200316_215756	v1	GWTC-3-confident	1268431094.1	$13.1^{+10.2}_{-2.9}$	$7.8^{+2.0}_{-2.9}$	$10.3^{+0.4}_{-0.7}$	1120^{+480}_{-440}	$0.13^{+0.27}_{-0.10}$	$21.2^{+7.2}_{-2.0}$
GW200311_115853	v1	GWTC-3-confident	1267963151.3	$34.2^{+6.4}_{-3.8}$	$27.7^{+4.1}_{-5.9}$	$17.8^{+0.2}_{-0.2}$	1170^{+280}_{-400}	$-0.02^{+0.16}_{-0.20}$	$61.9^{+5.3}_{-4.2}$
GW200308_173609	v1	GWTC-3-confident	1267724187.7	60^{+166}_{-29}	24^{+36}_{-13}	$4.7^{+2.5}_{-2.9}$	7100^{+13900}_{-4400}	$0.16^{+0.58}_{-0.49}$	$92.0^{+169.0}_{-48.0}$
GW200306_093714	v1	GWTC-3-confident	1267522652.1	$28.3^{+17.1}_{-7.7}$	$14.8^{+6.5}_{-6.4}$	$7.8^{+0.4}_{-0.6}$	2100^{+1700}_{-1100}	$0.32^{+0.28}_{-0.46}$	$43.9^{+11.8}_{-7.5}$
GW200302_015811	v1	GWTC-3-confident	1267149509.5	$37.8^{+8.7}_{-8.5}$	$20.0^{+8.1}_{-5.7}$	$10.8^{+0.3}_{-0.4}$	1480^{+1020}_{-700}	$0.01^{+0.25}_{-0.26}$	$57.8^{+9.6}_{-6.9}$
GW200225_060421	v1	GWTC-3-confident	1266645879.3	$19.3^{+5.0}_{-3.0}$	$14.0^{+2.8}_{-3.5}$	$12.5^{+0.3}_{-0.4}$	1150^{+510}_{-530}	$-0.12^{+0.17}_{-0.28}$	$33.5^{+3.6}_{-3.0}$

real-time public alerts

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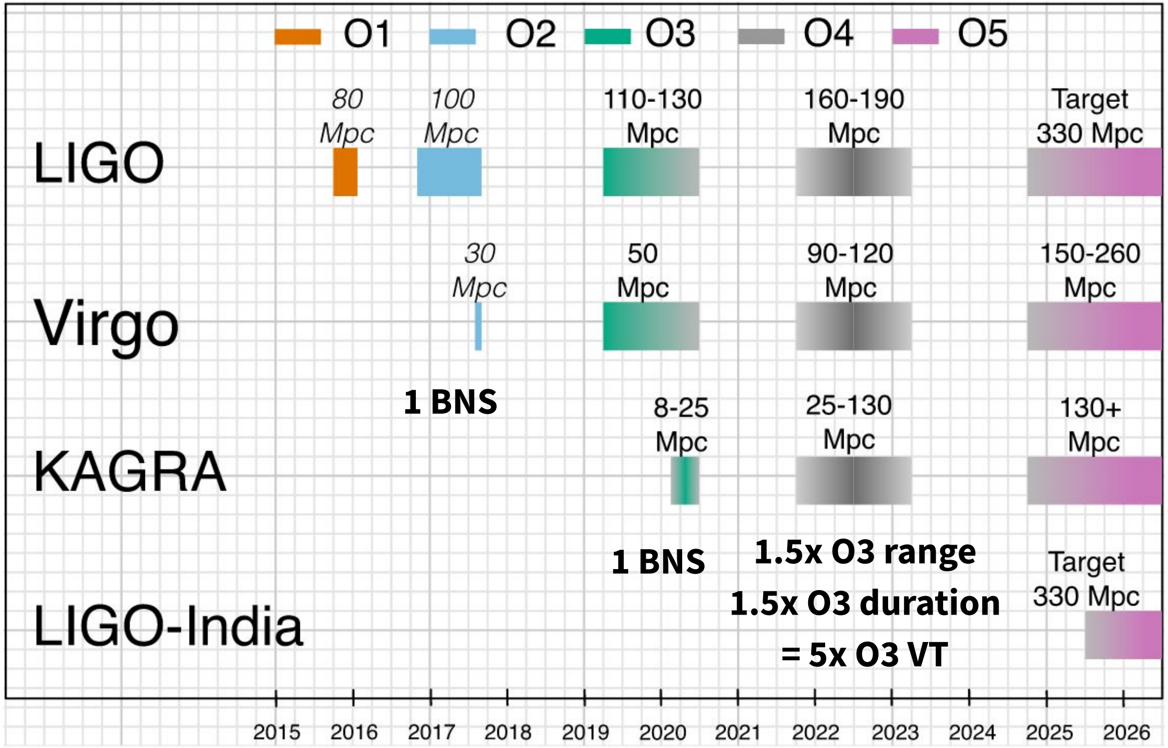
LVK O4 & beyond

observing prospects

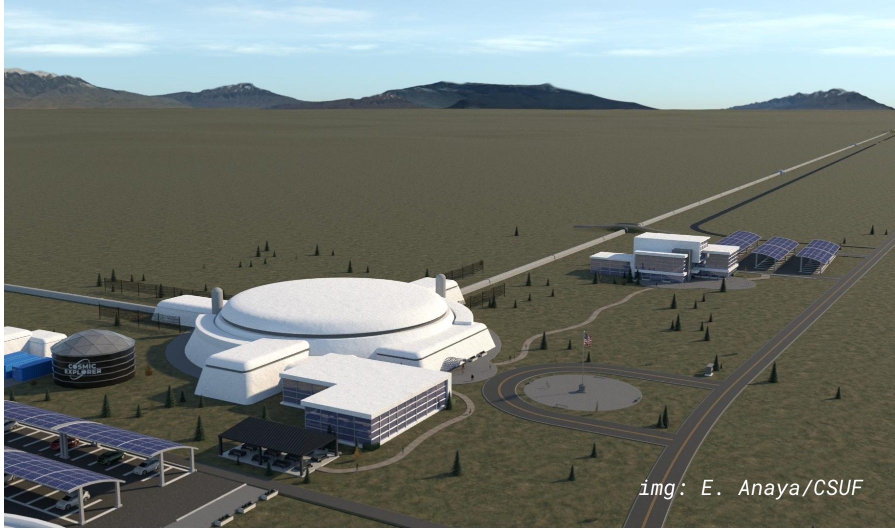
Abbott+ LRR 23 3 (2020)



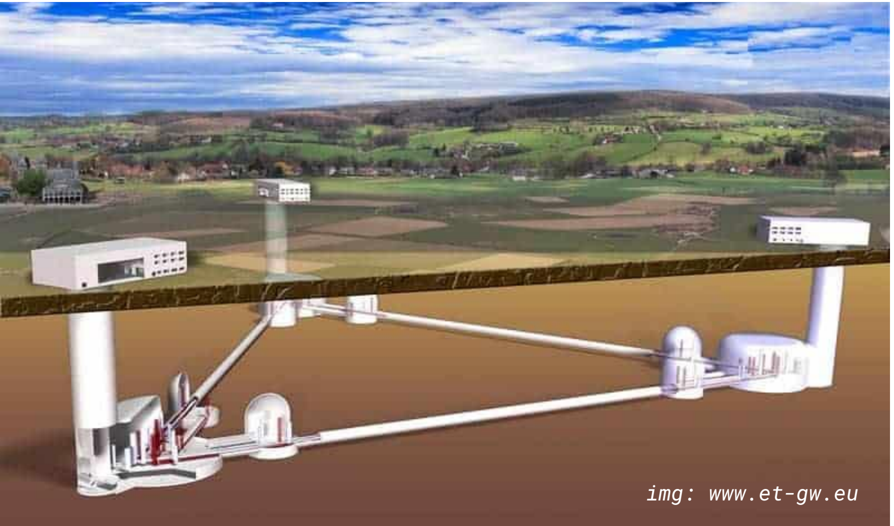
Colombo+ ApJ 937 79 (2022), Patricelli+ MNRAS 513 3 (2022) predict one multimessenger BNS detection during O4

Cosmic Explorer: a US-led next-gen GW observatory project

20 and 40 km L-shaped surface interferometers, 10x LIGO A+ sensitivity



img: E. Anaya/CSUF

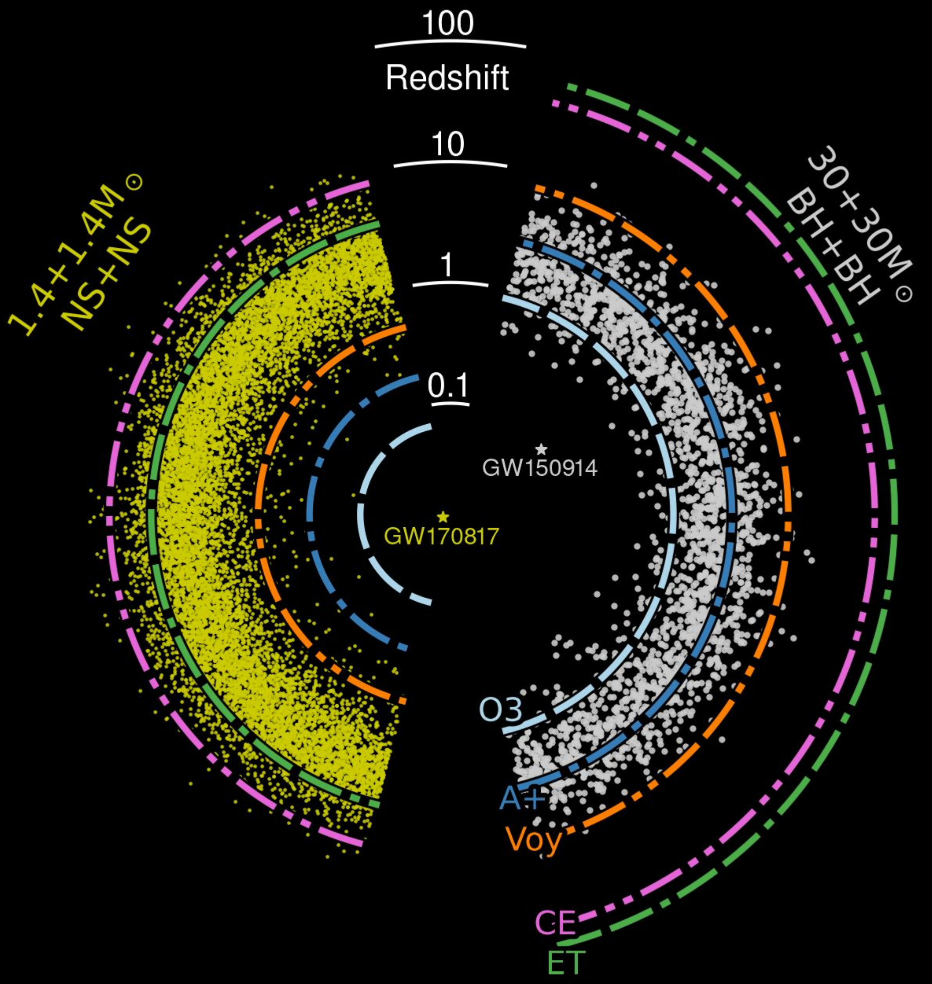


img: www.et-gw.eu

Einstein Telescope: Europe's next-gen GW observatory

3 co-located detectors, each with high- and low-frequency interferometers, in 10 km triangular design, underground

CE+ET BNS survey is complete to z ~ 0.5 and sensitive to entire merging population



Evans+ (incl. PL) arXiv:2109.09882

Bayesian EOS inference

Landry,Essick+Chatziioannou PRD 101 123007 (2020)

GW parameter estimation likelihood

EOS m-Λ relation

$$P(\mathrm{eos}\,|d) \propto P(\mathrm{eos}) \prod_i \int P(d_i|m^i_{1,2}, \Lambda^i_{1,2}) P(m^i_{1,2}, \Lambda^i_{1,2}|\,\mathrm{eos}\,) dm^i_{1,2} d\Lambda^i_{1,2}$$

EOS posterior

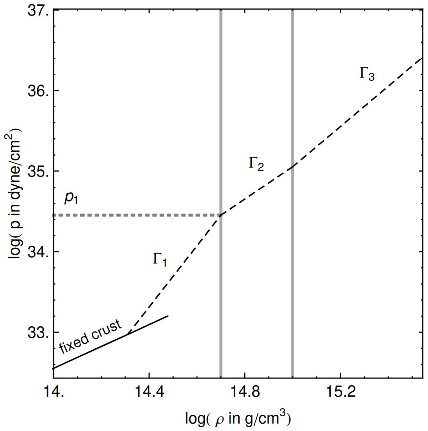
EOS prior

EOS likelihood

Bayesian EOS inference

Landry,Essick+Chatziioannou PRD 101 123007 (2020)

Read+ PRD 79 124032 (2009)



EOS prior

- → EOS model
- → prior support
- → shape of prior

GW parameter estimation likelihood

EOS m-Λ relation

$$P(\text{eos}\,|d) \propto P(\text{eos}) \prod_i \int P(d_i|m^i_{1,2}, \Lambda^i_{1,2}) P(m^i_{1,2}, \Lambda^i_{1,2}|\,\text{eos}\,) dm^i_{1,2} d\Lambda^i_{1,2}$$

EOS posterior

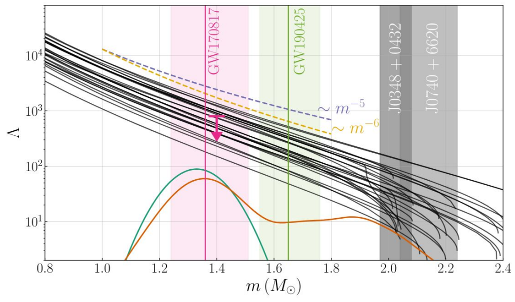
EOS prior

EOS likelihood

Bayesian EOS inference

Landry,Essick+Chatziioannou PRD 101 123007 (2020)

Chatziioannou GRG 52 109 (2020)



m-Λ relation

- → EOS model
- → TOV solver
- → interpolation

GW parameter estimation likelihood

EOS m-Λ relation

$$P(\mathrm{eos}\,|d) \propto P(\mathrm{eos}) \prod_i \int P(d_i|m^i_{1,2}, \Lambda^i_{1,2}) P(m^i_{1,2}, \Lambda^i_{1,2}|\,\mathrm{eos}\,) dm^i_{1,2} d\Lambda^i_{1,2}$$

EOS posterior

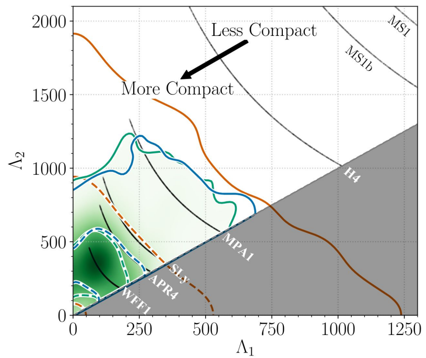
EOS prior

EOS likelihood

Bayesian EOS inference

Landry,Essick+Chatziioannou PRD 101 123007 (2020)

LVC (incl. PL) PRL 2018



GW likelihood

- → waveform model
- → sampling
- → interpolation

GW parameter estimation likelihood

EOS m-Λ relation

$$P(\mathrm{eos}\,|d) \propto P(\mathrm{eos}) \prod_i \int P(d_i|m^i_{1,2}, \Lambda^i_{1,2}) P(m^i_{1,2}, \Lambda^i_{1,2}|\,\mathrm{eos}\,) dm^i_{1,2} d\Lambda^i_{1,2}$$

EOS posterior

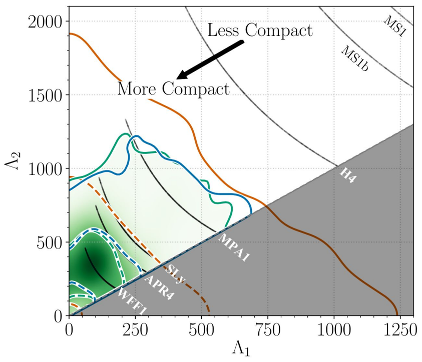
EOS prior

EOS likelihood

Bayesian EOS inference

Landry,Essick+Chatziioannou PRD 101 123007 (2020)

LVC (incl. PL) PRL 2018



EOS likelihood

- → EOS model
- → non-GW data
- → sampling

GW parameter estimation likelihood

EOS m-Λ relation

$$P(\text{eos}\,|d) \propto P(\text{eos}) \prod_i \int P(d_i|m^i_{1,2}, \Lambda^i_{1,2}) P(m^i_{1,2}, \Lambda^i_{1,2}|\,\text{eos}\,) dm^i_{1,2} d\Lambda^i_{1,2}$$

EOS posterior

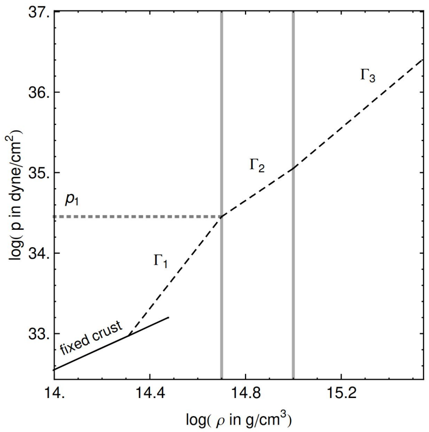
EOS prior

EOS likelihood

Bayesian EOS inference

Landry,Essick+Chatziioannou PRD 101 123007 (2020)

Read+ PRD 79 124032 (2009)



EOS prior

- → EOS model
- → prior support
- → shape of prior

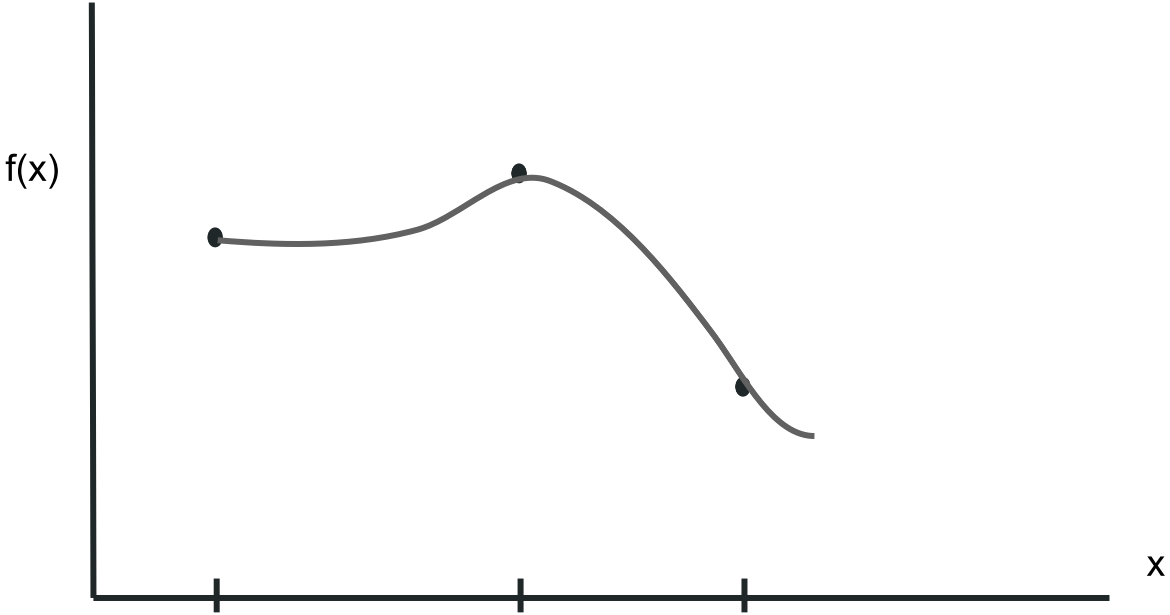
GW parameter estimation likelihood

EOS m-Λ relation

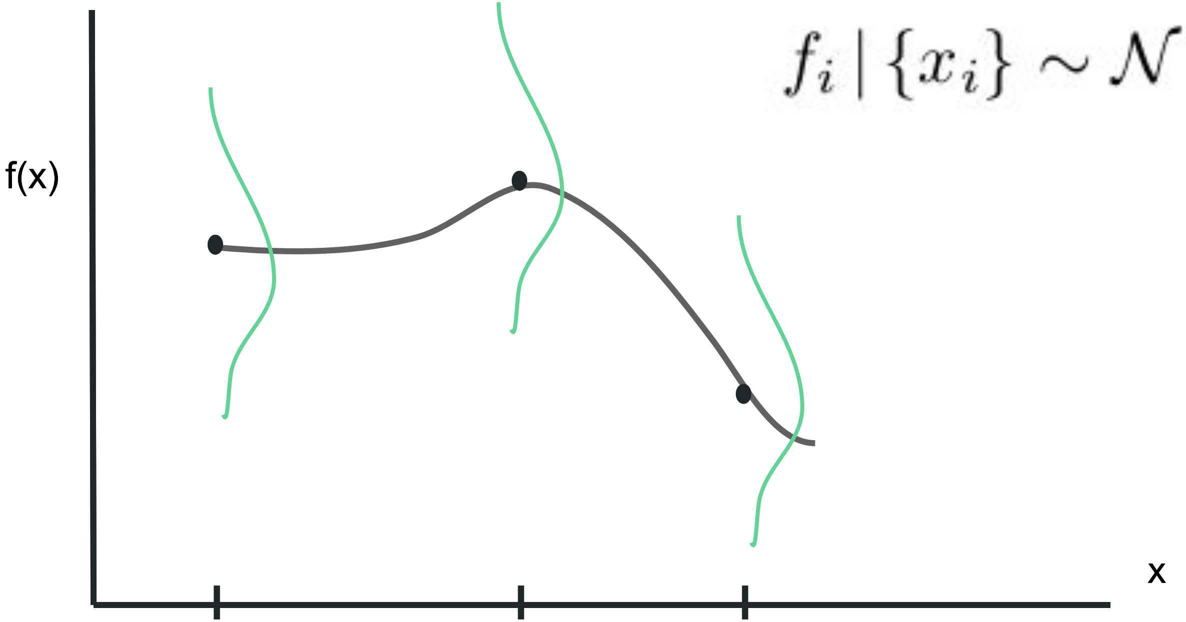
$$P(\text{eos}\,|d) \propto P(\text{eos}) \prod_i \int P(d_i|m^i_{1,2}, \Lambda^i_{1,2}) P(m^i_{1,2}, \Lambda^i_{1,2}|\,\text{eos}\,) dm^i_{1,2} d\Lambda^i_{1,2}$$

EOS posterior — EOS prior — EOS likelihood

Gaussian processes

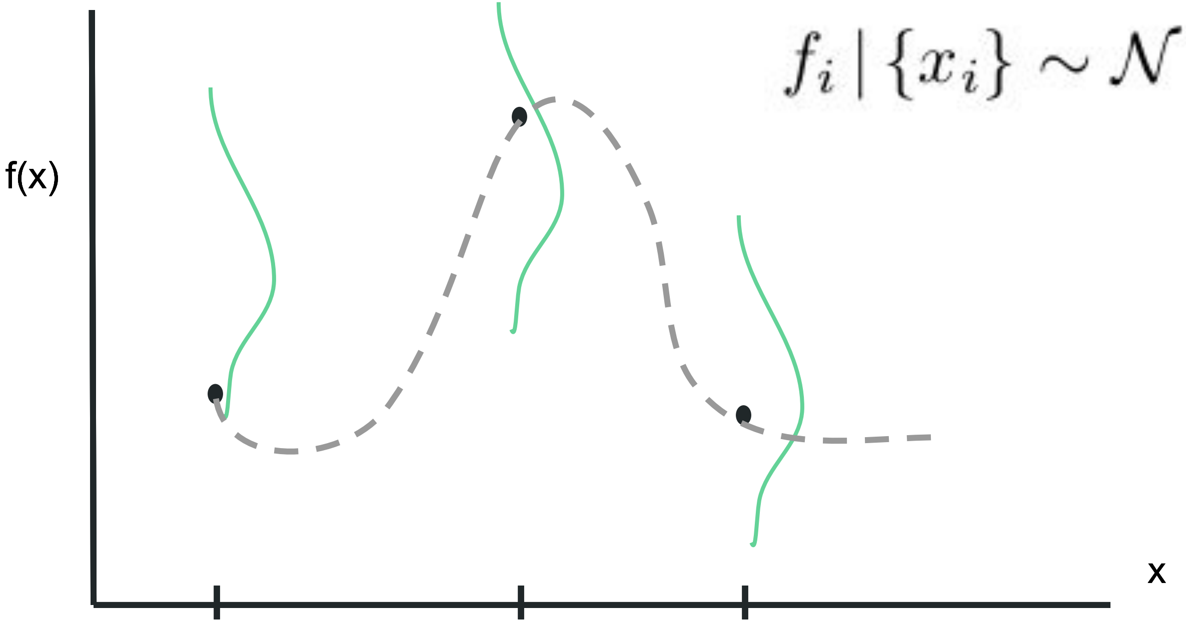


Gaussian processes



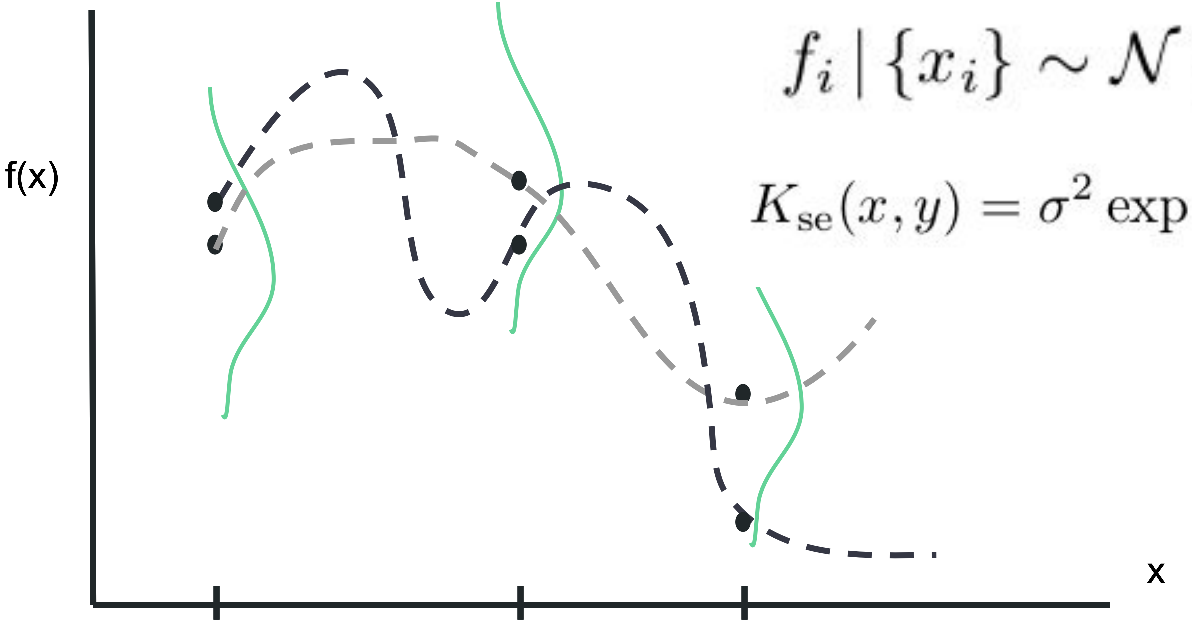
$$f_i \,|\, \{x_i\} \sim \mathcal{N}\left(\langle f_i \rangle, \Sigma_{ij}\right)$$

Gaussian processes



$$f_i \,|\, \{x_i\} \sim \mathcal{N}\left(\langle f_i \rangle, \Sigma_{ij}\right)$$

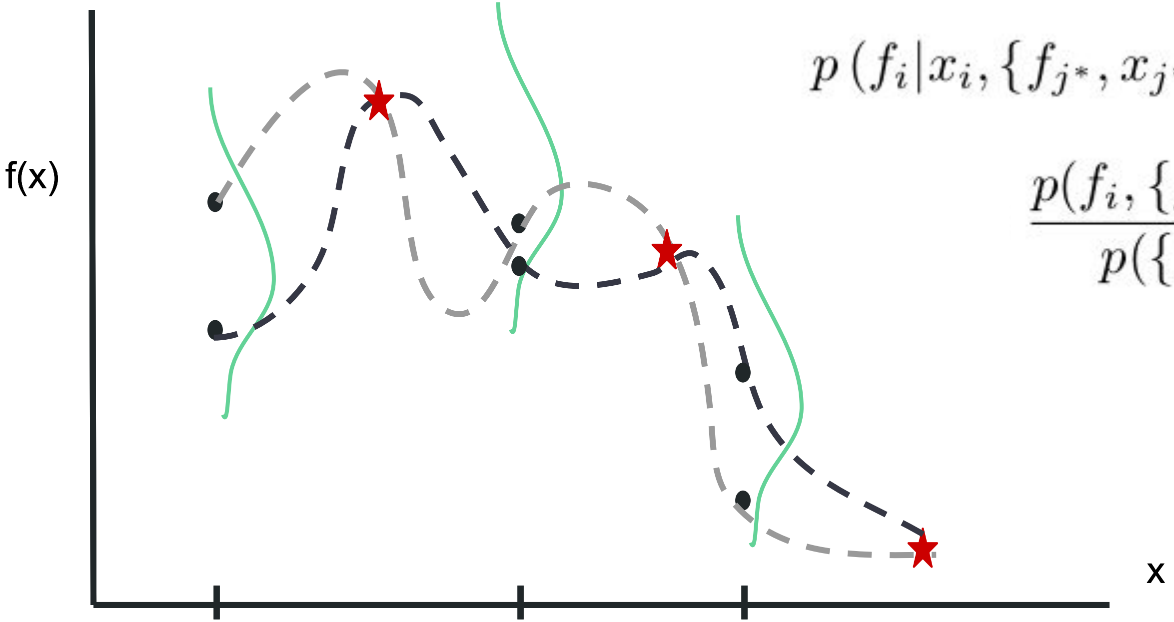
Gaussian processes



$$f_i \,|\, \{x_i\} \sim \mathcal{N}\left(\langle f_i \rangle, \Sigma_{ij}\right)$$

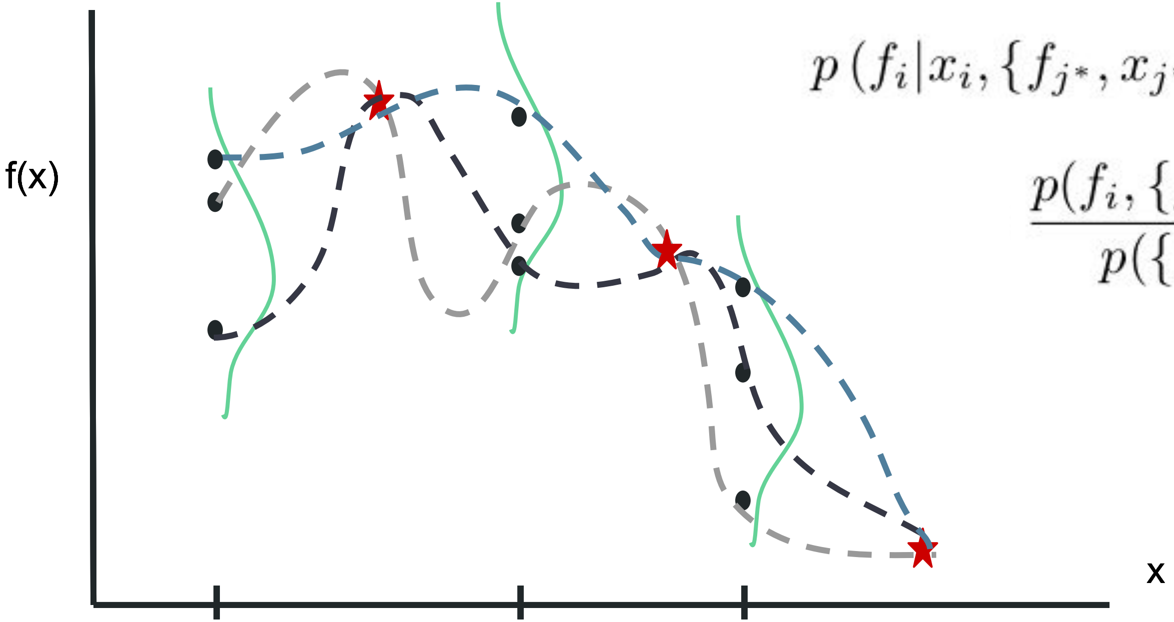
$$K_{\mathrm{se}}(x, y) = \sigma^2 \exp\left(-\frac{(x-y)^2}{2l^2}\right)$$

Gaussian processes



$$p\left(f_i|x_i,\{f_{j^*},x_{j^*}\}\right) = \frac{p(f_i,\{f_{j^*}\}|x_i,\{x_{j^*}\})}{p(\{f_{j^*}\}|\{x_{j^*}\})}$$

Gaussian processes



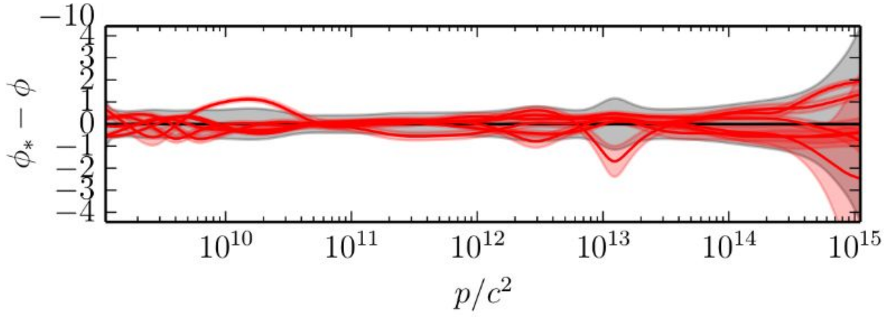
$$p\left(f_i | x_i, \{f_{j^*}, x_{j^*}\}\right) =$$

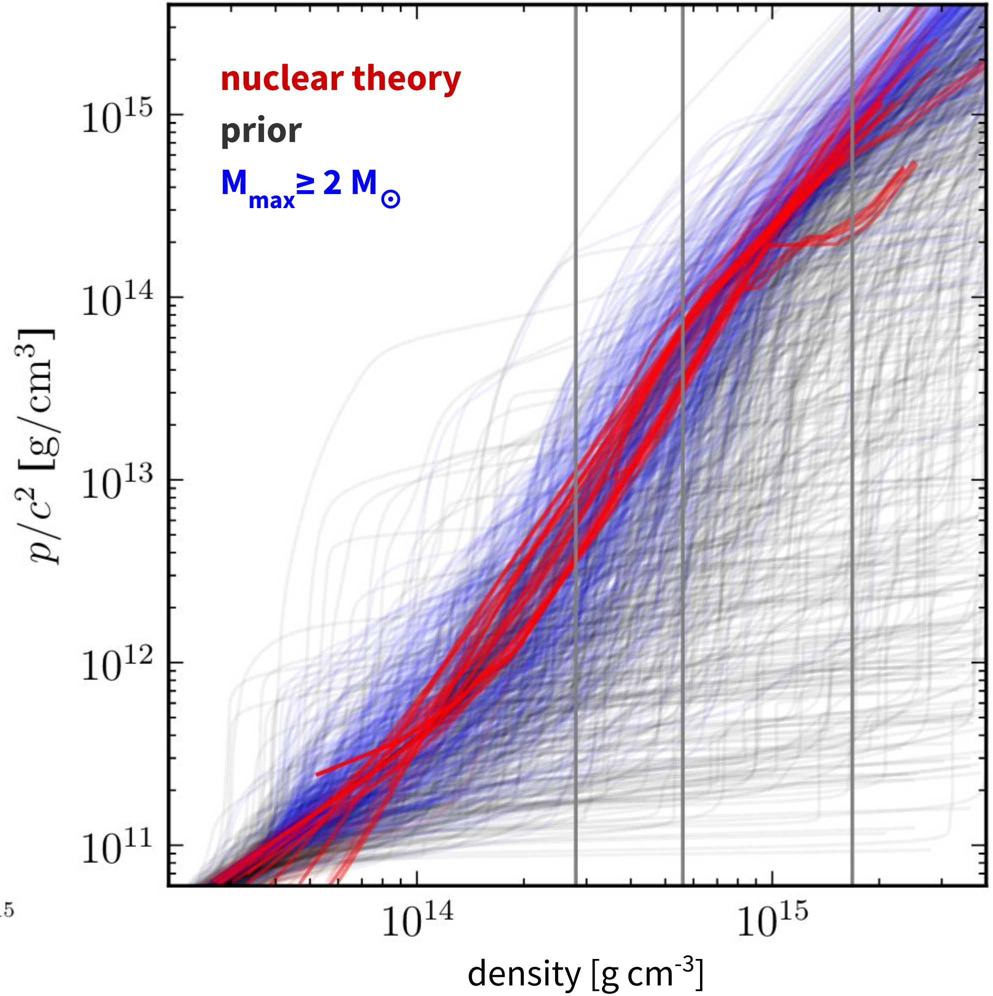
$$\frac{p(f_i, \{f_{j^*}\} | x_i, \{x_{j^*}\})}{p(\{f_{j^*}\} | \{x_{j^*}\})}$$

Landry+Essick PRD 99 084049 (2019), Essick,Landry+Holz PRD 101 063007 (2020)

Gaussian process EOS model

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

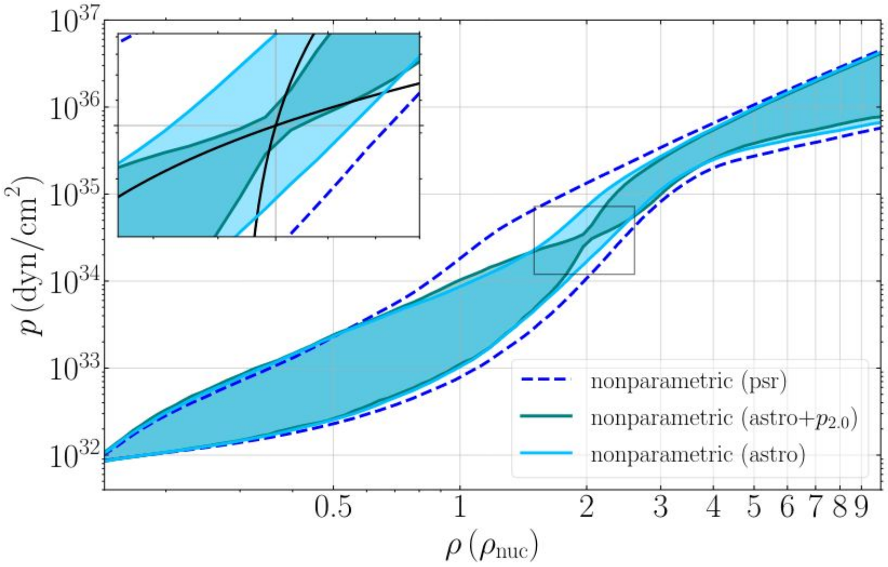




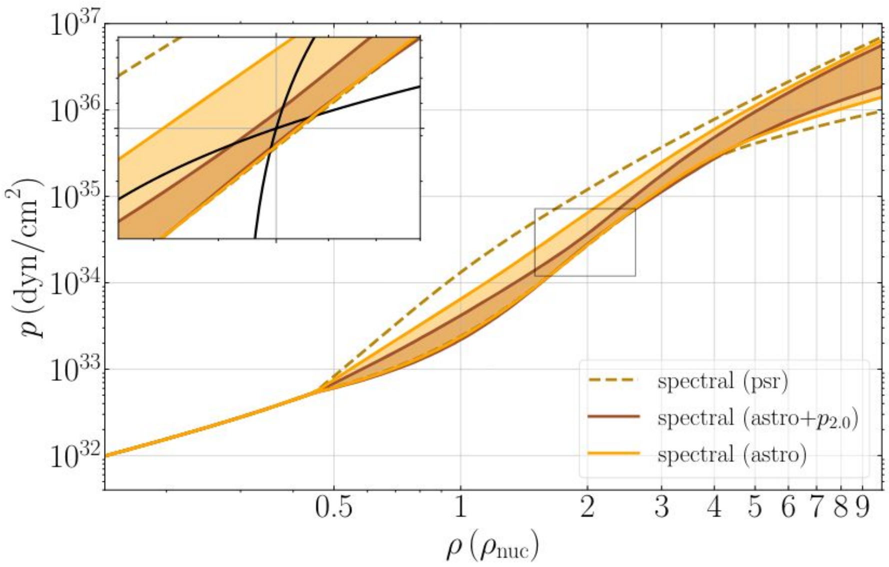
implicit correlations in parametric EOS models

Legred+ (incl. PL)
PRD 105 043016 (2022)

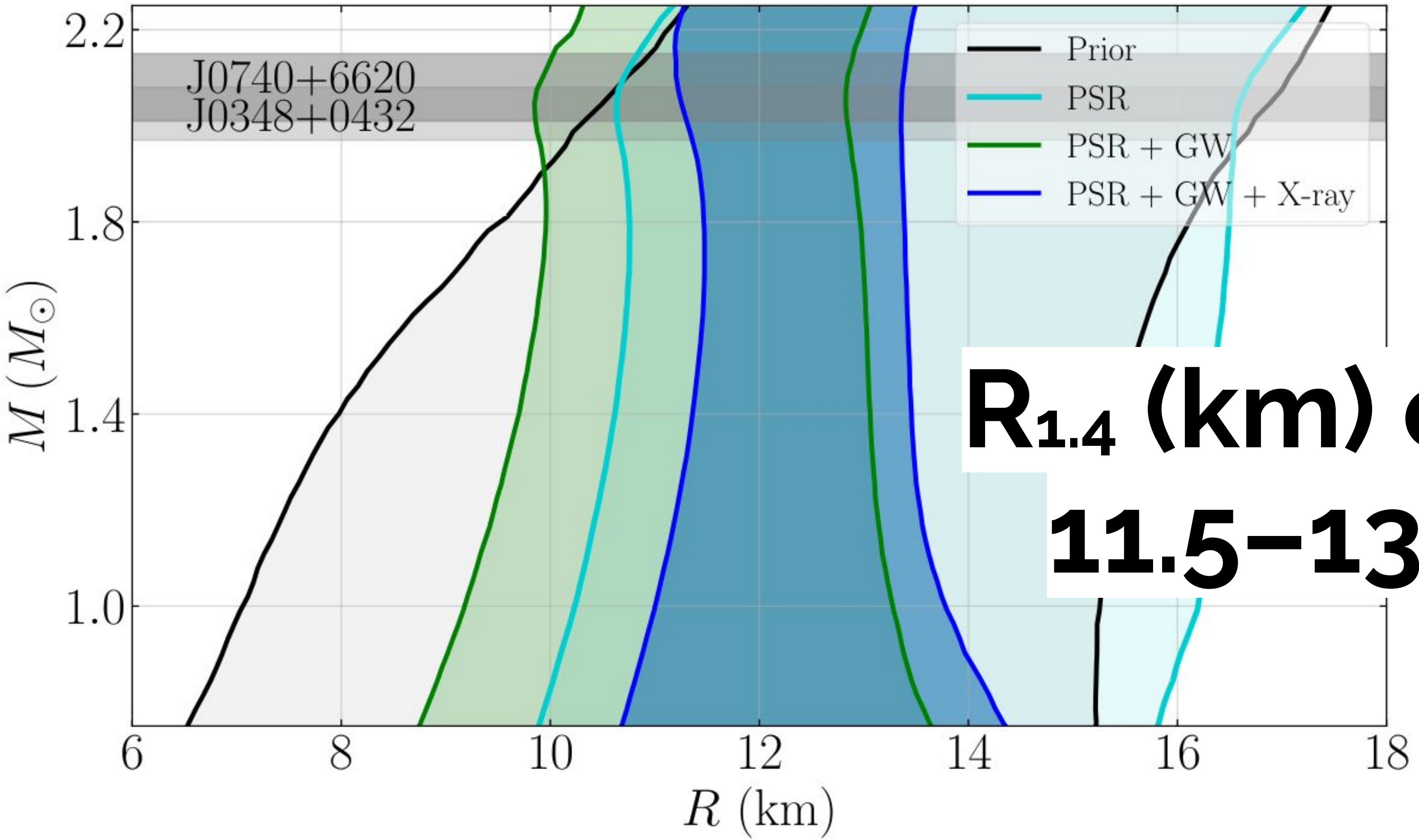
nonparametric



parametric

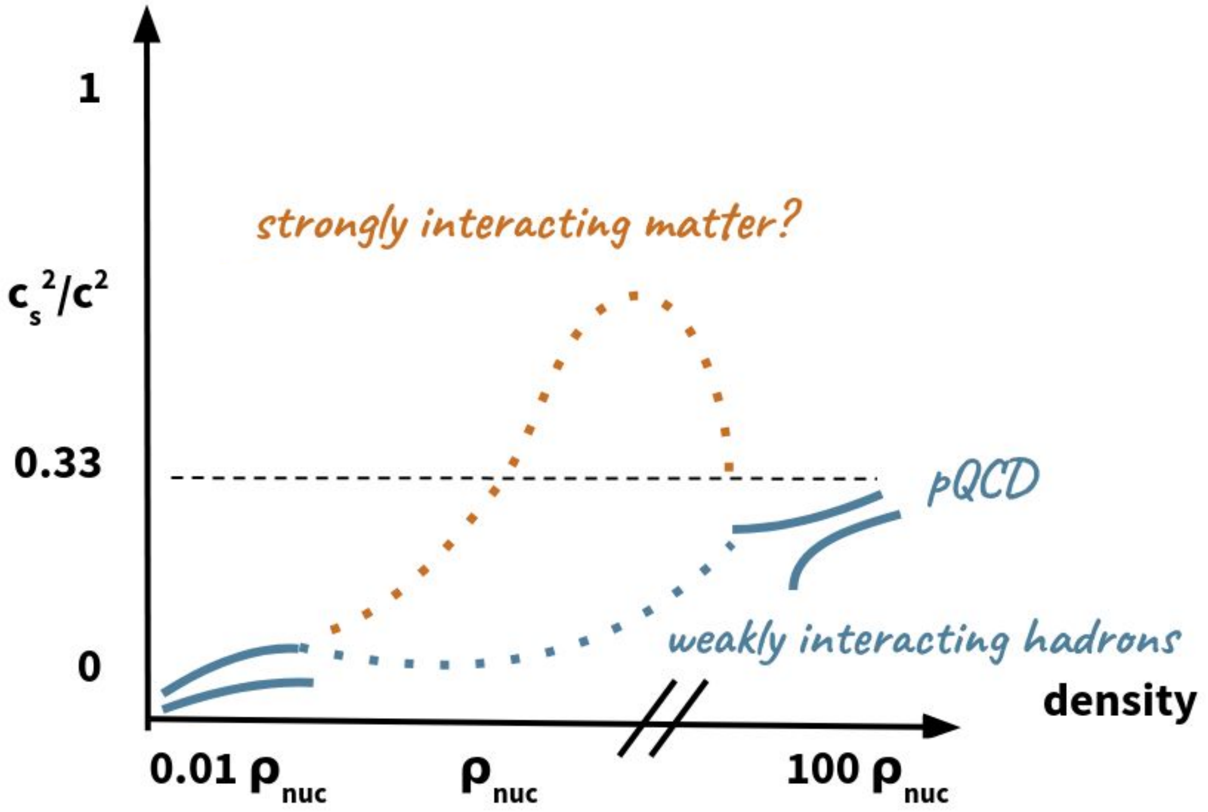


Legred+ (incl. PL) PRD 104 063003 (2021)

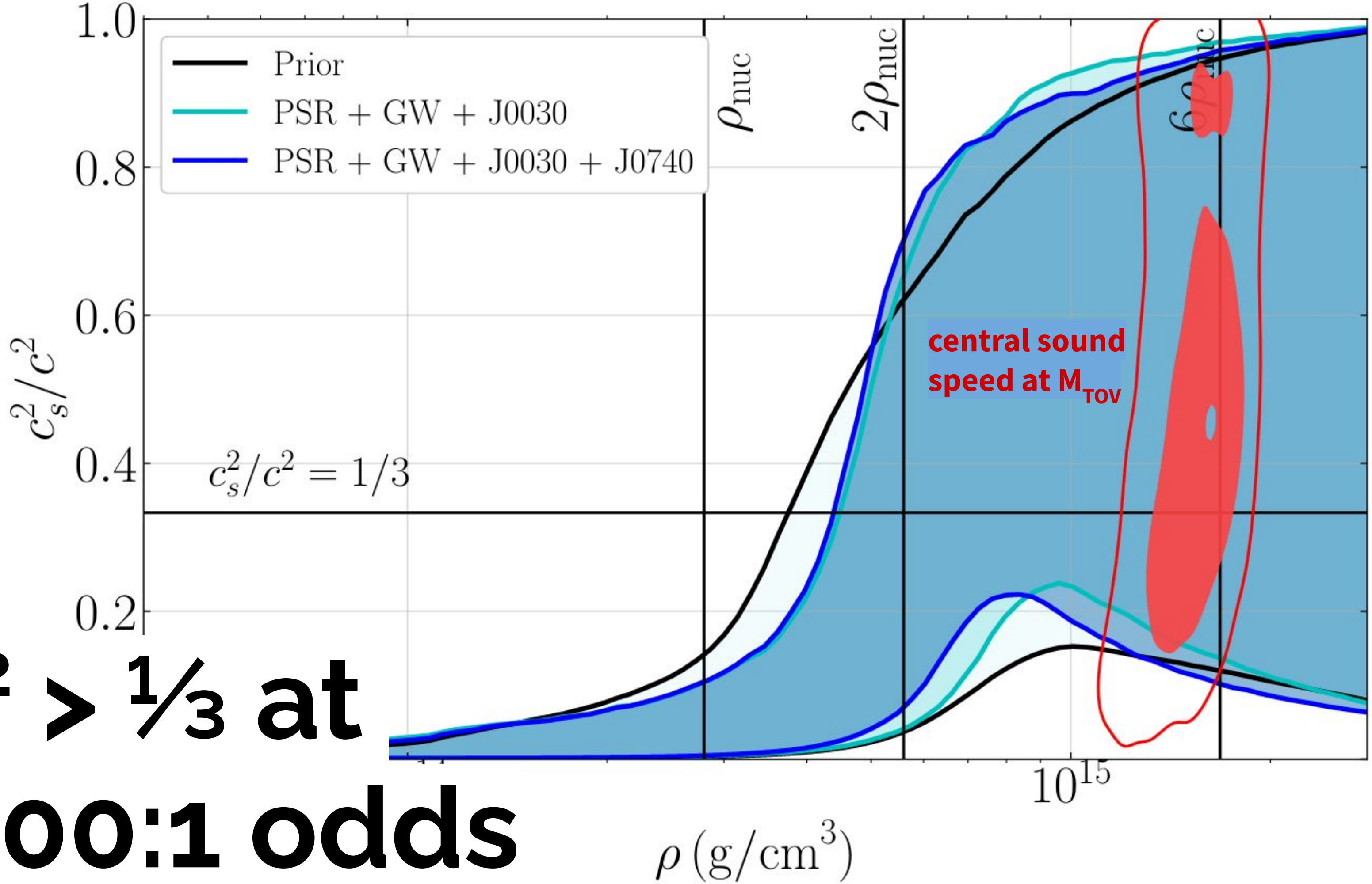


$R_{1.4}$ (km) of 11.5–13.5

Legred+ (incl. PL) PRD 104 063003 (2021)

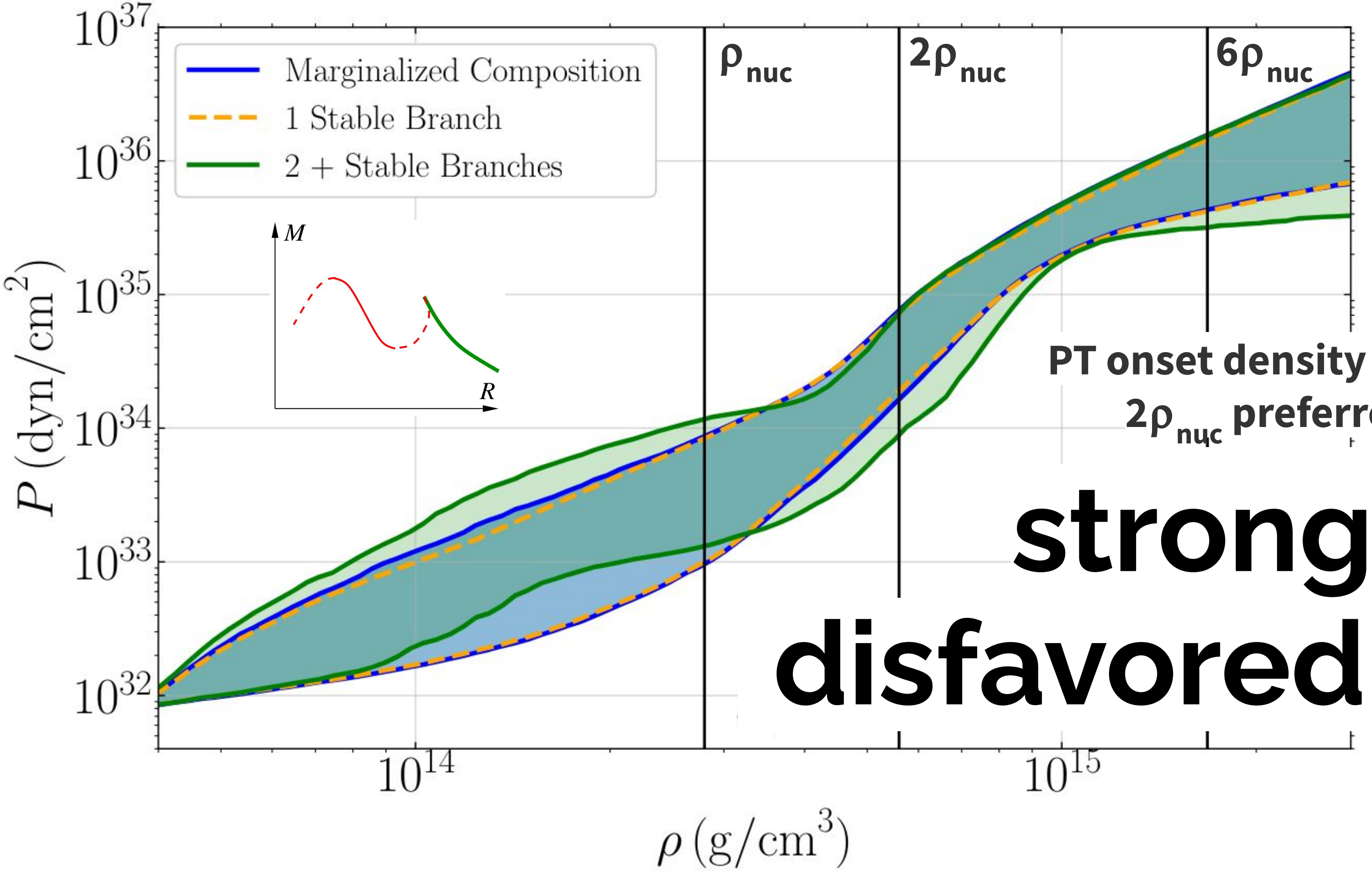


Legred+ (incl. PL) PRD 104 063003 (2021)



$c_s^2 > 1/3$ at 1000:1 odds

Legred+ (incl. PL) PRD 104 063003 (2021)

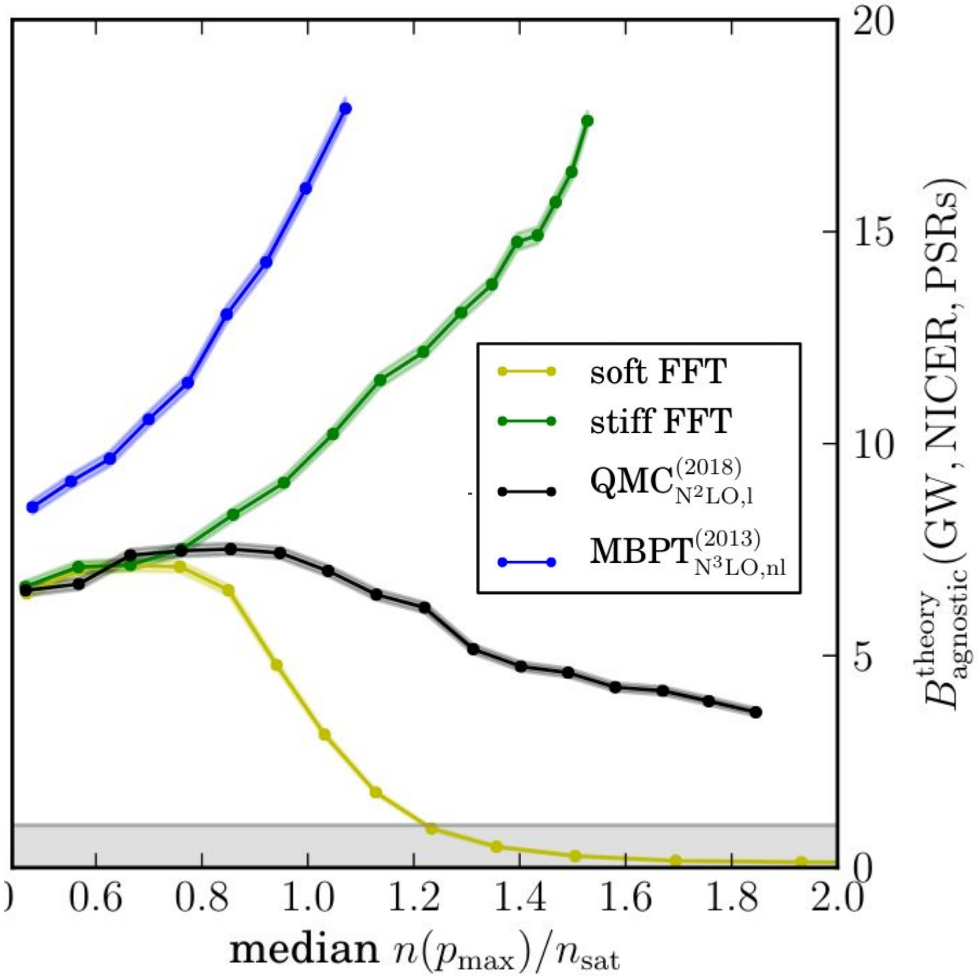


PT onset density below $2\rho_{nuc}$ preferred

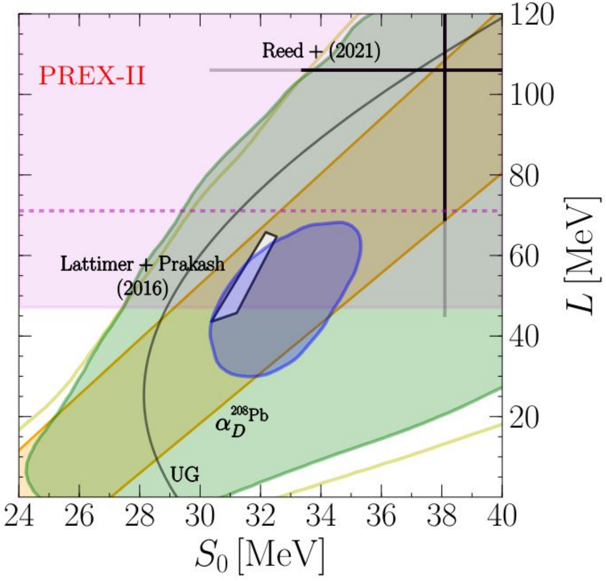
strong PT disfavored 7:1

where does XEFT break down?

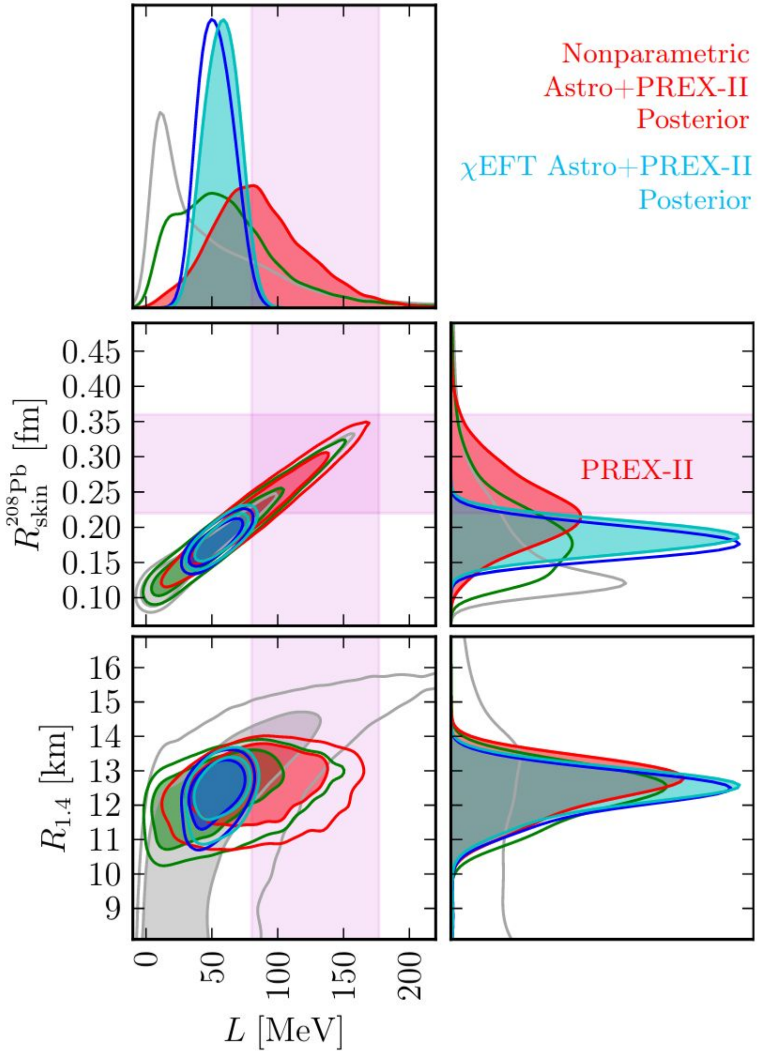
Essick+ (incl. PL) PRC 102 055803 (2020)

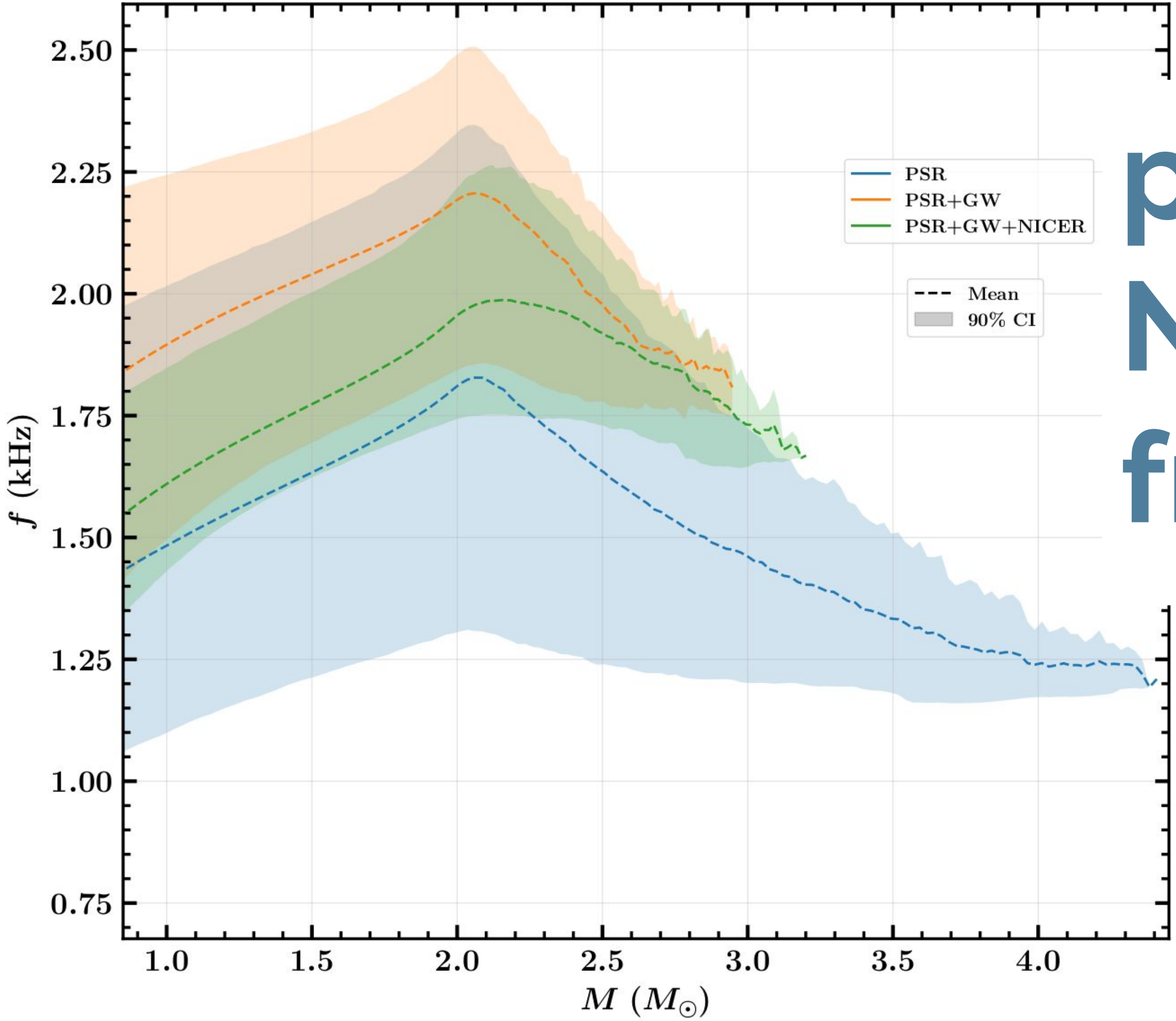


joint nuclear & astro inference



Essick+ (incl. PL)
PRL 127 192701 (2021)
PRC 104 065804 (2021)





predicting NS f-mode frequencies

Mohanty+ (incl. PL) in prep.

public EOS inference code

git.ligo.org/reed.essick/lwp

L lwp

main lwp / + History Find file Edit Code

Merge branch 'User-Priors' into 'main'
Isaac Legred authored 9 months ago
8ebd8f2a

```
result = executables.lwp_pipe(eos_indices = np.array(eos_to_be_used),
                    retrieve_macro_data = lambda index: macro_data[index],
                    gw_posterior_samples = astro_data,
                    likelihood_bandwidth=bandwidth,
                    save_likelihoods=f"./{astro_prefix}_post.csv",
                    save_marginalized_likelihoods=f"./{astro_prefix}_eos.csv",
                    mc_marginalization_range=chirp_mass_range,
                    seed=12345,
                    dump_config="example_nb.ini",
                    dump_config_kwargs={"config_kwargs": {"eos-indices": "eos_indices.csv"},
                                        "lwp_pipe_data_kwargs":{"gw_posterior_samples": "PE190425_low_spin.csv",
                                                                "eos_samples_h5_path":samples_file,
                                                                "eos_samples_h5_macro_subgroup":"ns",
                                                                "outdir":"DefaultOutdir"}})
```

zenodo

Published April 28, 2022 | Version v1
Dataset Open

Impact of the PSR J0740+6620 radius constraint on the properties of high-density matter: Neutron star equation of state posterior samples

Legred, Isaac[1]; Chatziioannou, Katerina[1]; Essick, Reed[2]; Han, Sophia[3]; Landry, Philippe[4]

Show affiliations

Equation of state posterior samples associated with Legred et al., "Impact of the PSR J0740+6620 radius constraint on the properties of high-density matter," Phys. Rev. D 104, 063003 (2021); doi:10.1103/PhysRevD.104.063003

EOS posterior samples

zenodo.org/records/6502467

Bayesian EOS inference

Landry,Essick+Chatziioannou PRD 101 123007 (2020)

population-scale data

- → population model
- → selection function
- → hierarchical inference

GW parameter estimation likelihood

EOS m-Λ relation + pop-informed mass prior

population prior

$$P(\mathrm{eos}\,|d) \propto P(\mathrm{eos}) \prod_i \int \frac{P(d_i|m^i_{1,2},\Lambda^i_{1,2})P(m^i_{1,2},\Lambda^i_{1,2}|\mathrm{eos},\mathrm{pop})\, P(\mathrm{pop})\, d\mathrm{pop}\; dm^i_{1,2}d\Lambda^i_{1,2}}{\zeta(\mathrm{pop})}$$

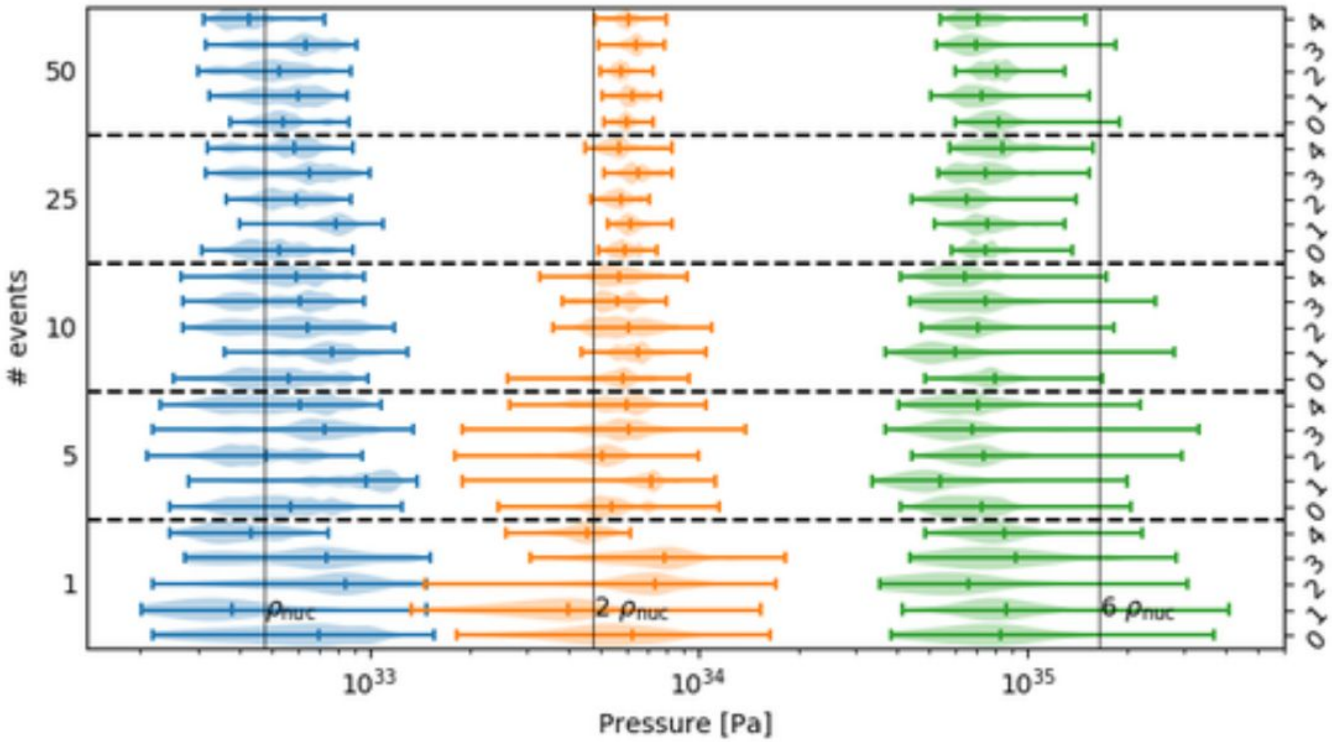
selection effects

EOS posterior — EOS prior — EOS likelihood

Simultaneous population & EOS inference

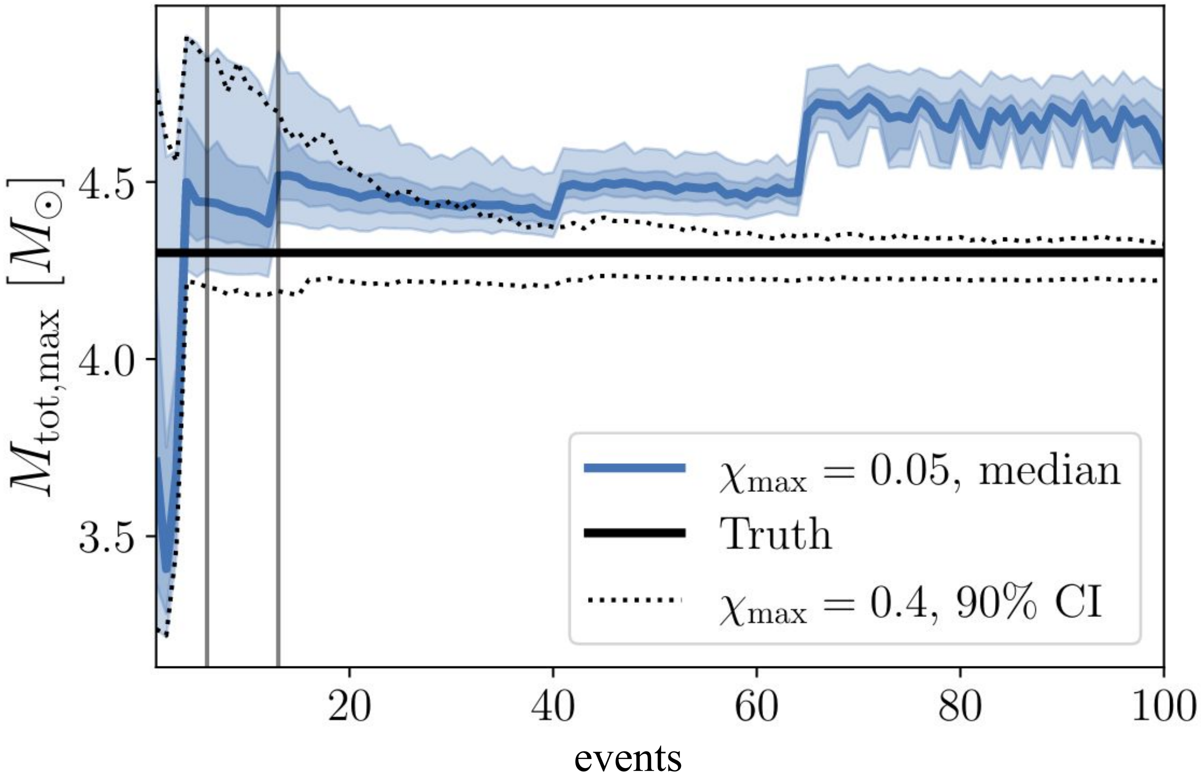
Wysocki+ arXiv:2001.01747

imposing the wrong population -level mass prior can bias the inferred EOS after O(10) BNS observations



Simultaneous population & EOS inference

Biscoveanu+Talbot+Vitale MNRAS 2022



incorrectly assuming NSs spin slowly can bias the inferred maximum mass in the population after O(10) BNS observations

summary and outlook

Existing observations of neutron stars suggest that…

- NSs are small-ish ($R \approx 12$ km): nuclear interactions not so repulsive
- despite near-constant $R(M)$, cores may harbour exotic matter: hints from c_s?

With next-gen observatories like Cosmic Explorer, we can expect…

- $O(100)$ BNSs per yr with SNR > 100 for precise tidal measurements

R&D for next-gen dense matter science is underway

- nonparametric EOS inference is well suited for the opportunities and challenges of population-scale, high-precision BNS observations


join the Cosmic Explorer Consortium!
cosmicexplorer.org
COSMIC EXPLORER

Thanks!

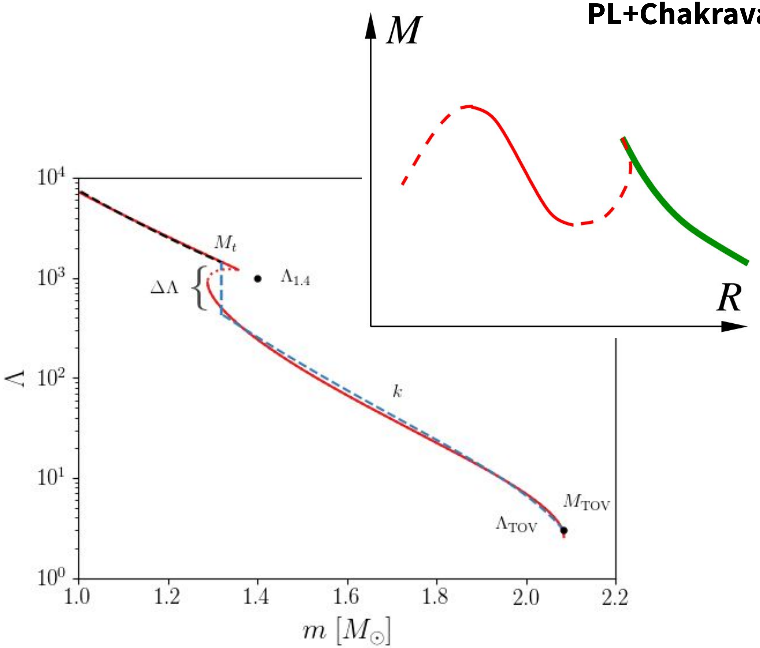
P.L. is supported by the Natural Sciences & Engineering Research Council of Canada (NSERC).

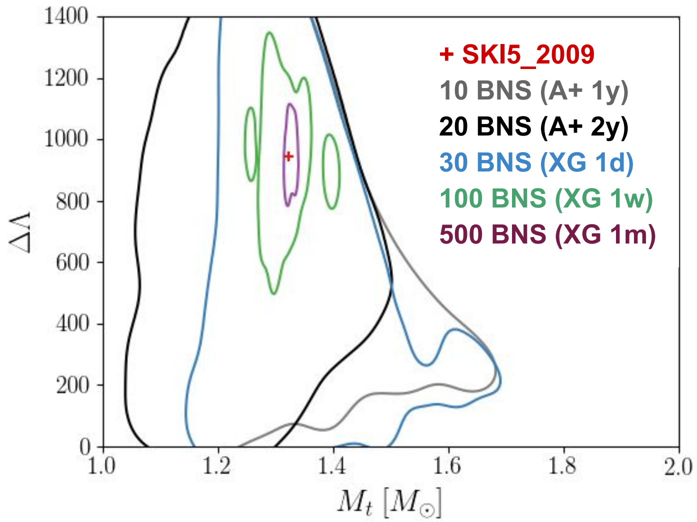
Many collaborators inside and outside the LIGO-Virgo-KAGRA collaboration and the Cosmic Explorer project are acknowledged, especially Reed Essick (CITA), Katerina Chatziioannou and Isaac Legred (Caltech).

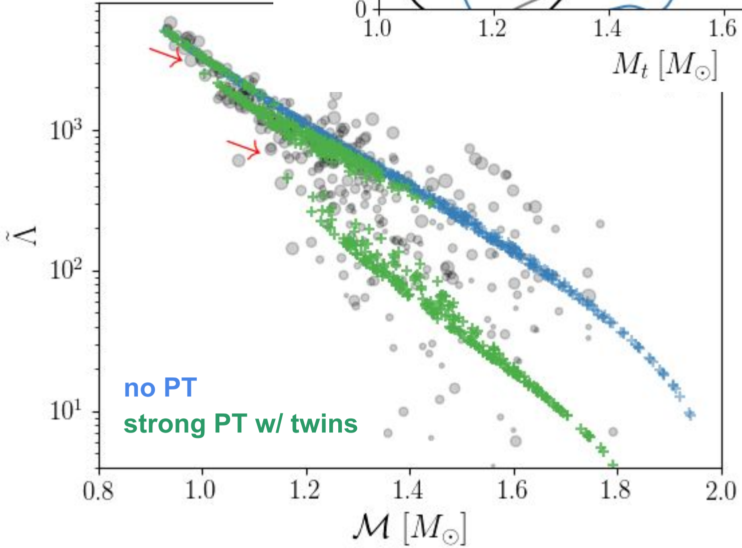
twin stars in CE+ET

strong phase transitions can give rise to hadronic and hybrid twins with the same mass but different R and Λ

PL+Chakravarti arXiv:2212.09733







twins are distinguishable via population