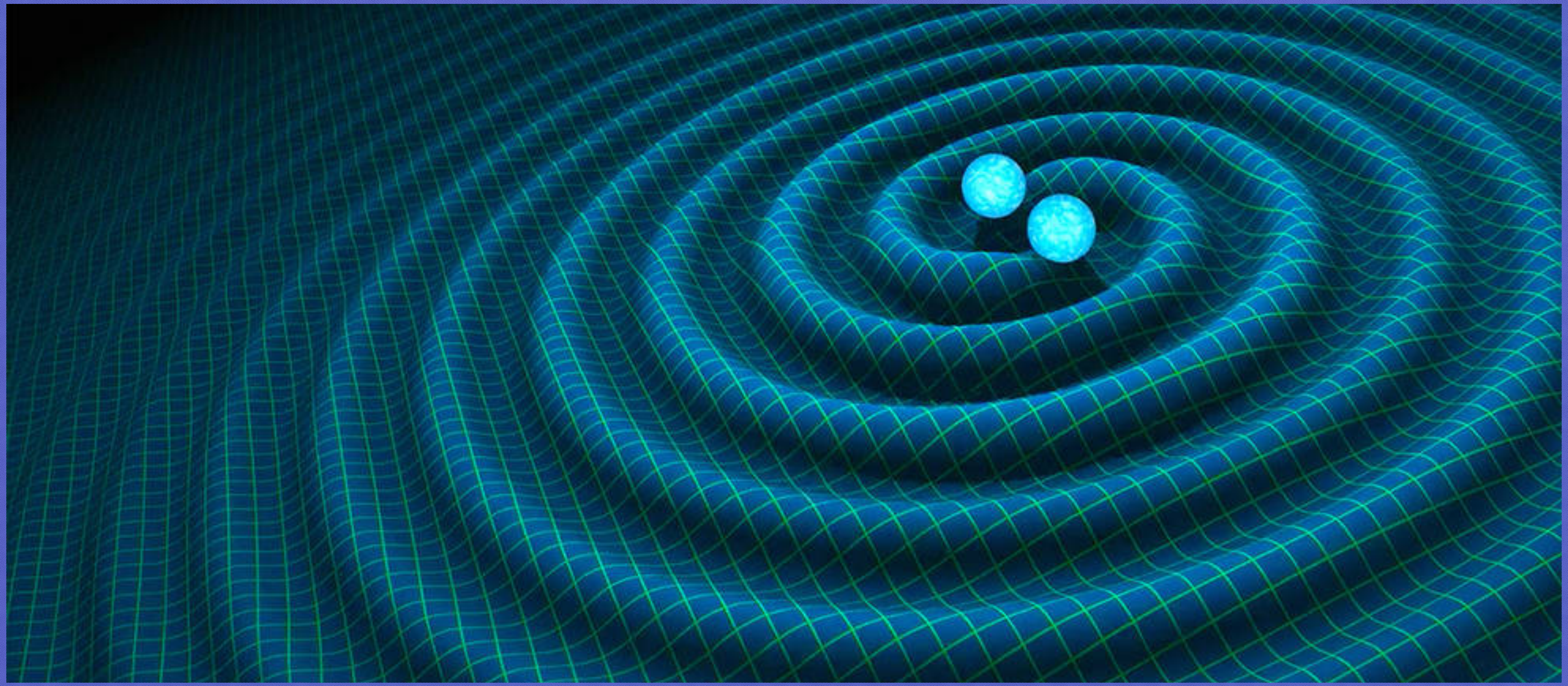
Multimessenger inference of neutron star equation of state and gravity



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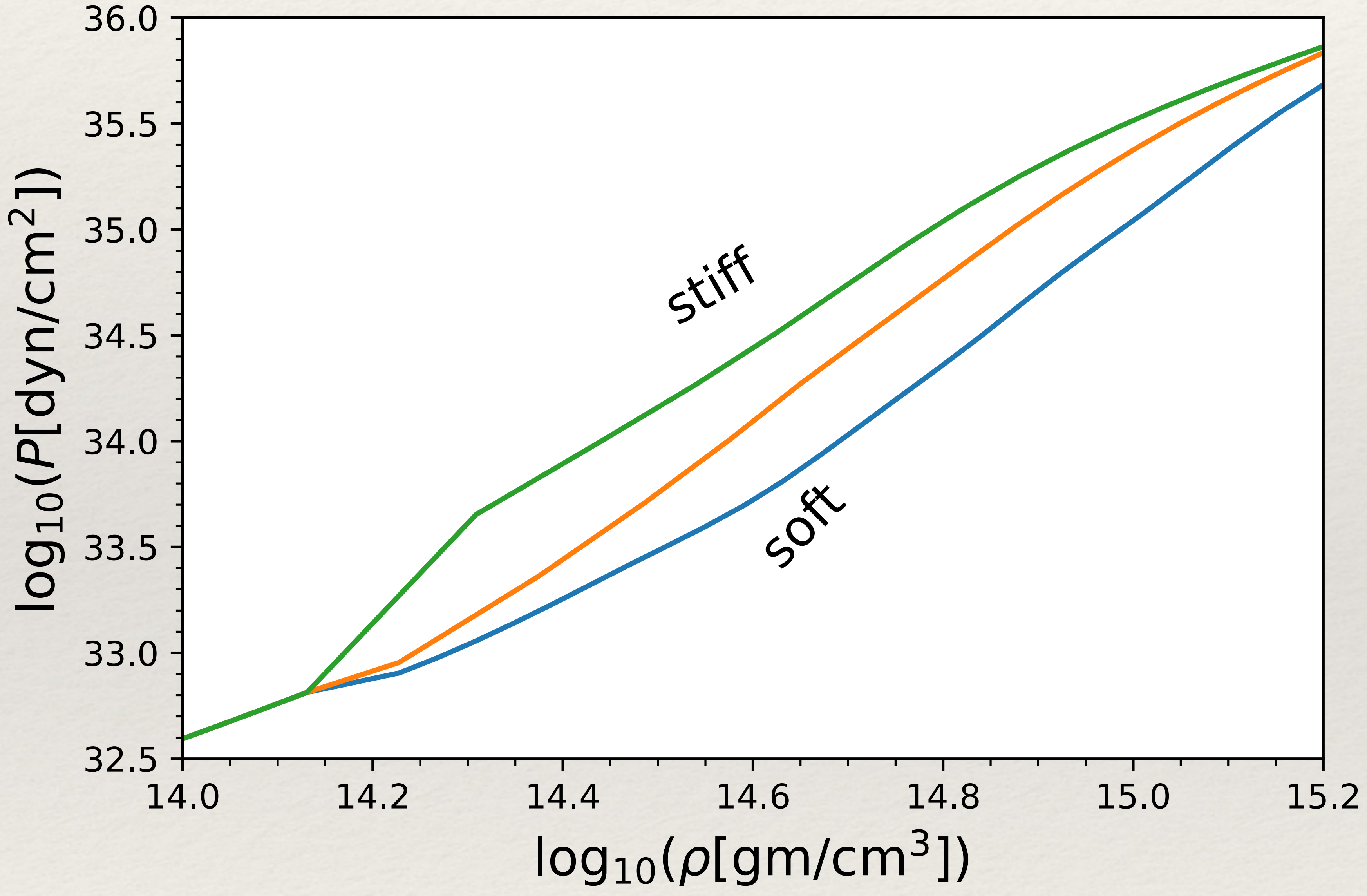
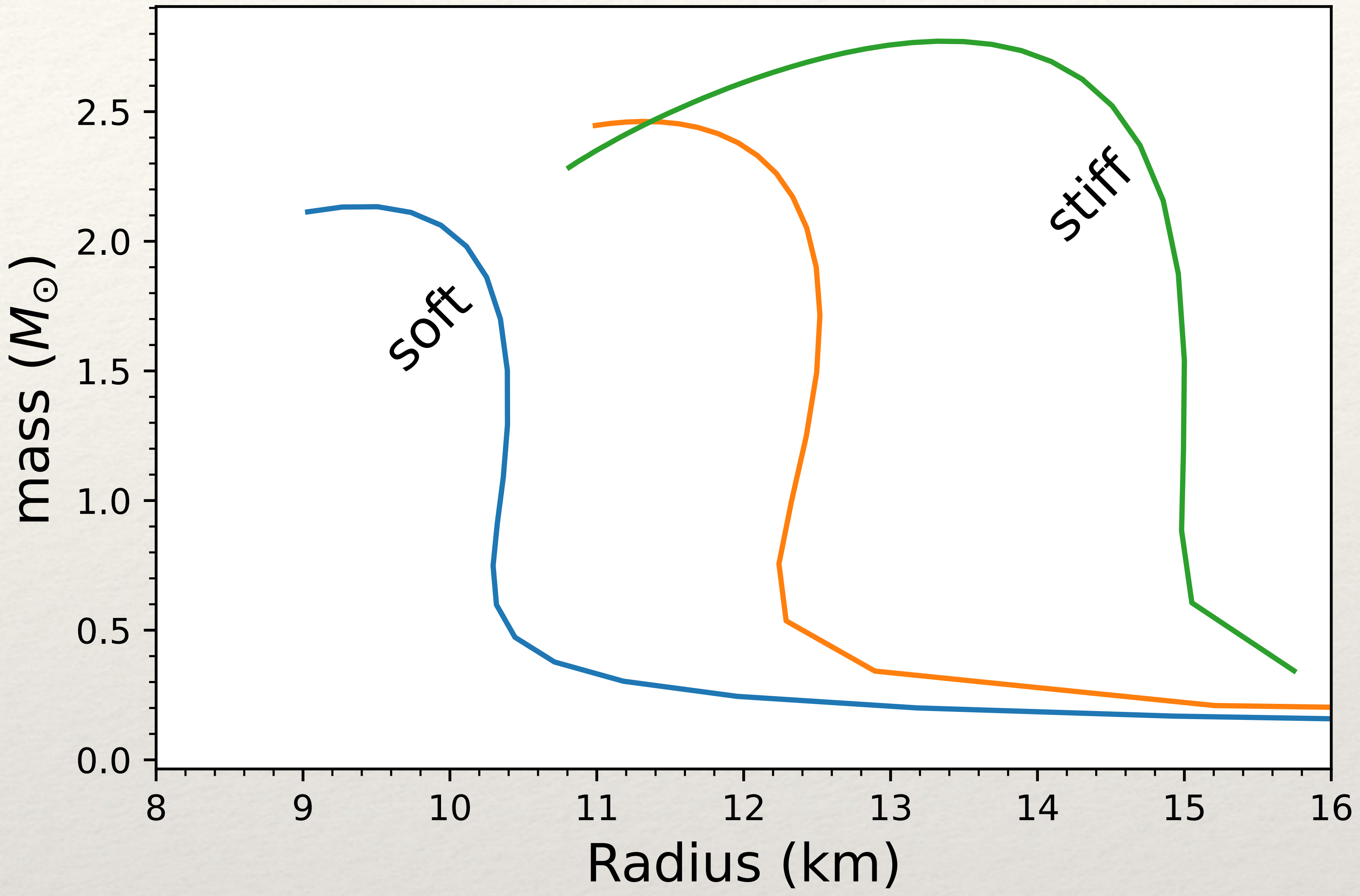
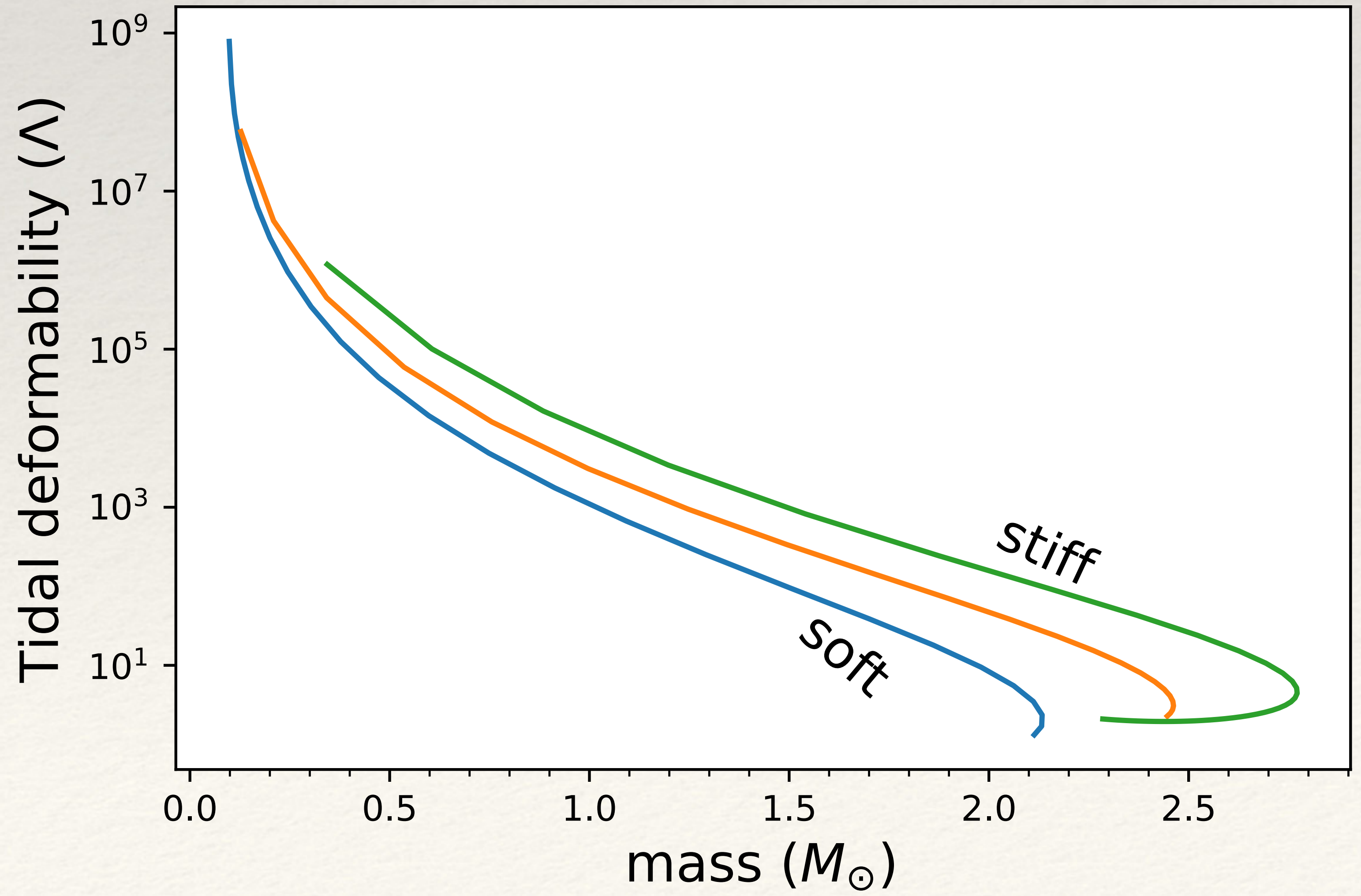
October 17, 2023

EOS & observables

EOS, $P = P(\rho)$

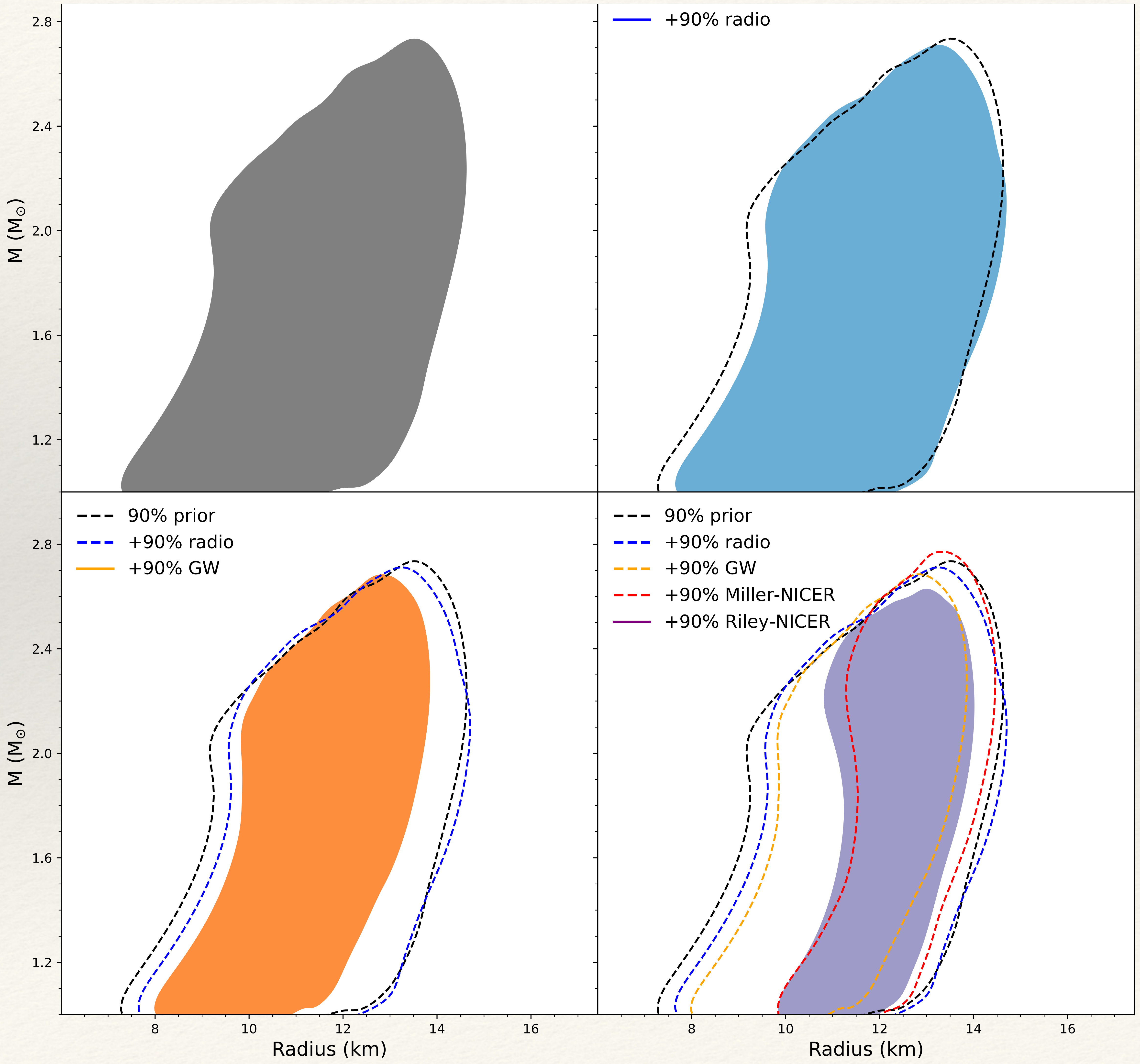






- Radio observables — M
- X-ray observables — M , R
- GW observables — M , Λ

Current mass-radius constraints



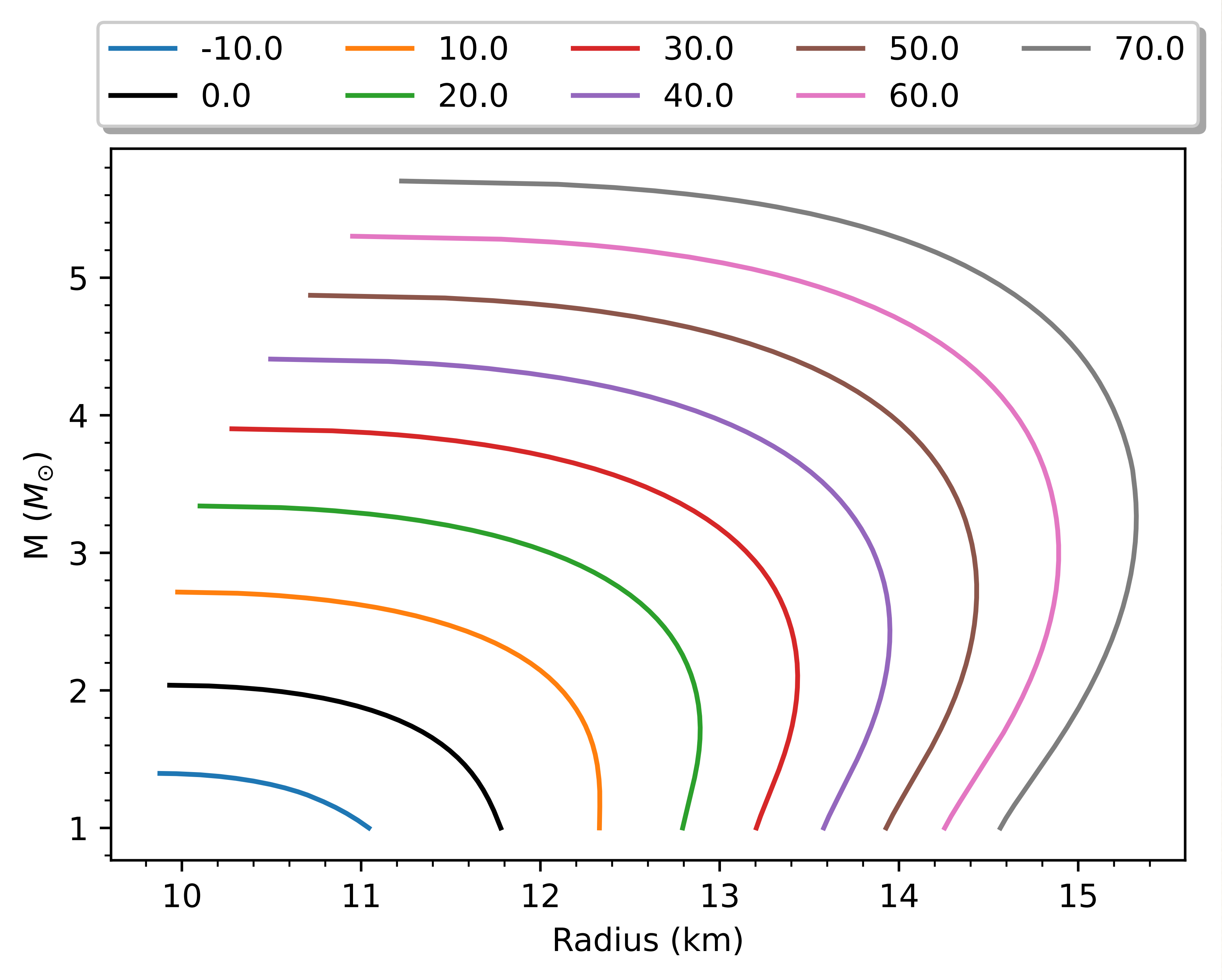
B. Biswas and S. Datta, PRD 2022

EOS-gravity degeneracy

- We consider a particular 4D Horndeski scalar-tensor theory originating from higher-order EGB gravity with action

$$S = \frac{1}{2\kappa}\int \mathrm{d}^4x\sqrt{-g}\{R + \alpha[\phi\mathcal{G} + 4G_{\mu\nu}\nabla^\mu\phi\nabla^\nu\phi - 4(\nabla\phi)^2\Box\phi + 2(\nabla\phi)^4]\} + S_\mathrm{m}$$

- Where $\kappa = 8\pi G/c^4, \mathcal{G} = R^2 - 4R_{\mu\nu}R^{\mu\nu} + R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma}$ is the Gauss-Bonnet scalar and S_m is the matter Lagrangian. The coupling constant α has units of [km^2].



- M-R sequences in 4D EGB gravity with varying couling constant α
- Similar effect to EOS with varying stiffness
- a minimum black hole mass of $M = 5.7 \pm 1.8 M_\odot$ of GW200115, yields $\alpha = 285^{+207}_{-171}$ [km^2].

Charmousis, Lehébel, Smyrniotis & Stergioulas, JCAP **2**, 33 (2022)

Methodology & EOS catalogues

Hierarchical Bayesian statistics

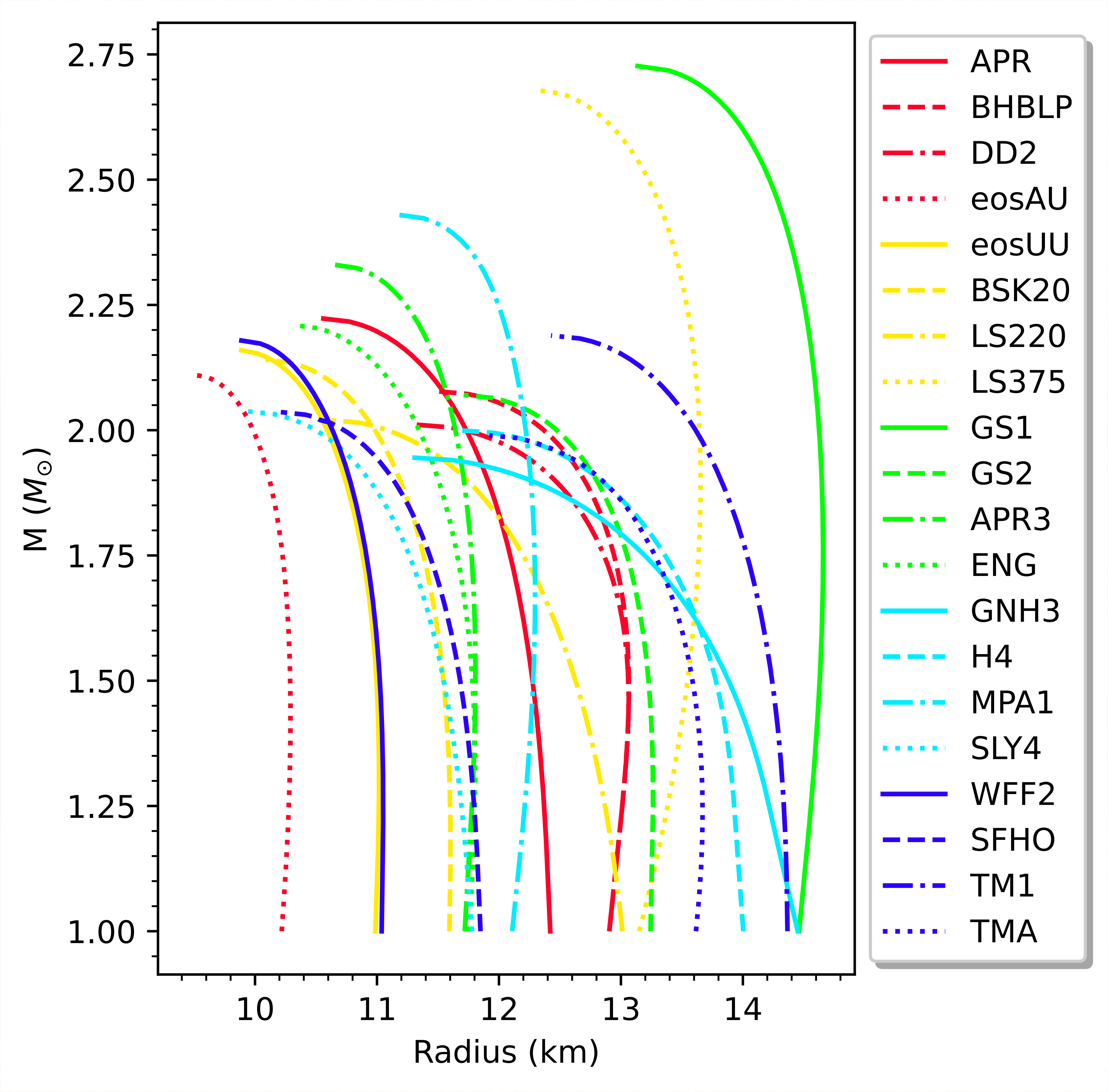
- $P(\theta|d) \propto P(\theta)\Pi_i P(d_i|\theta)$,

  $\theta \in$ (EOS, α, population parameters)

- We have 20 EOSs; each EOSs are assigned with an integer index. A uniform prior on EOS_index is considered between 1 and 20.

- Uniform prior on $\alpha \in (-10,70)\,\mathrm{km}^2$.

- Population parameters: kept fixed for this work.



Constraints using current observations

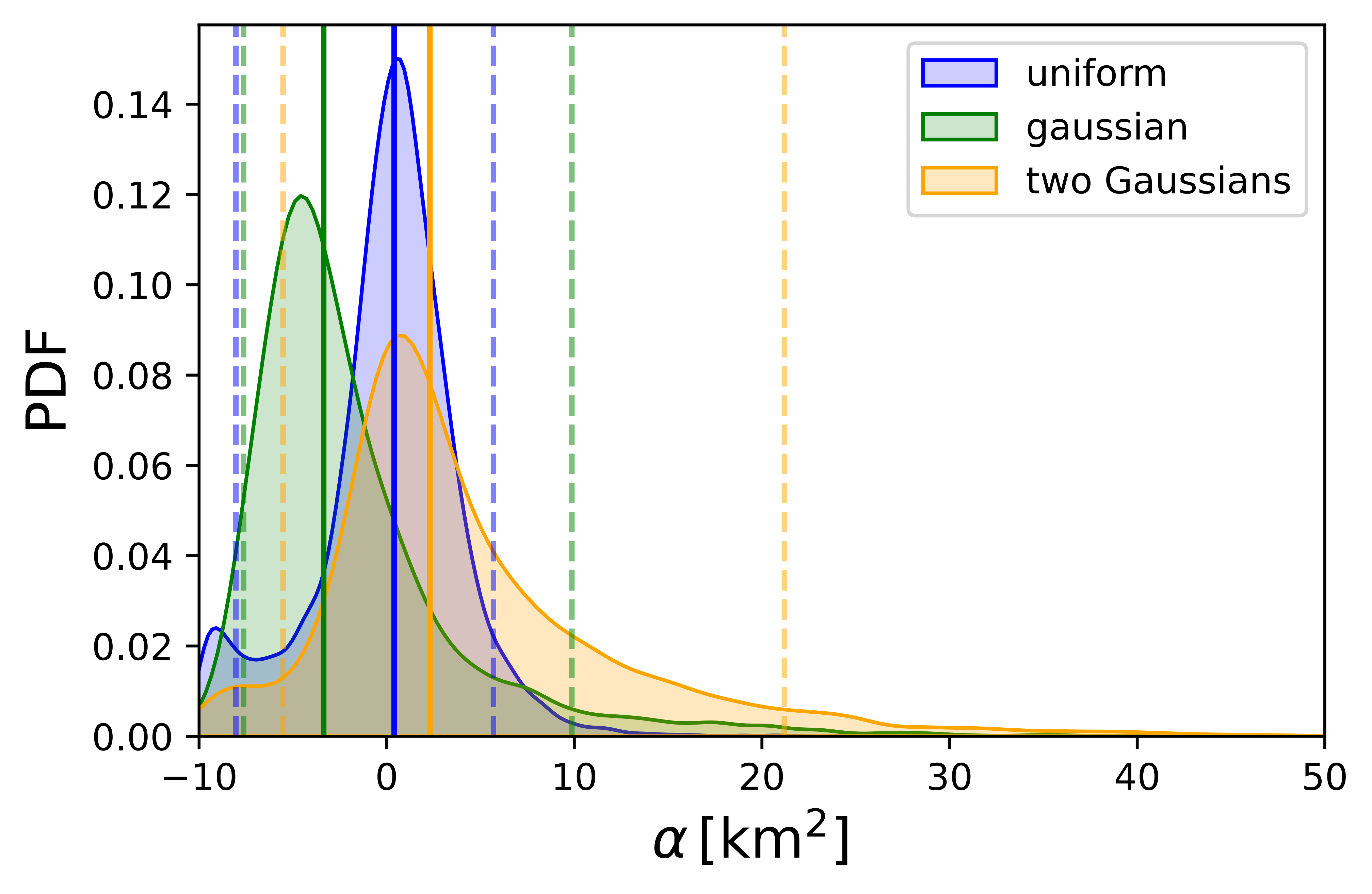
- We consider three models of NS mass distribution:

$$p_{\rm U}(m \mid m_{\rm min}=1, m_{\rm max}) := U(m \mid m_{\rm min}, m_{\rm max})$$
$$p_{\rm N}(m \mid \mu, \sigma, m_{\rm min}, m_{\rm max}) := \mathcal{N}(m \mid \mu, \sigma) U(m \mid m_{\rm min}, m_{\rm max})/A$$
$$p_{\rm NN}\left(m \mid \mu, \sigma, \mu', \sigma', w, m_{\rm min}, m_{\rm max}\right) := \left[w\mathcal{N}(m \mid \mu, \sigma)/B + (1-w)\mathcal{N}\left(m \mid \mu', \sigma'\right)/C\right] U(m \mid m_{\rm min}, m_{\rm max})$$

Datasets used

GWs : GW170817, GW190425
Xrays : PSR J0451, PSR J0740

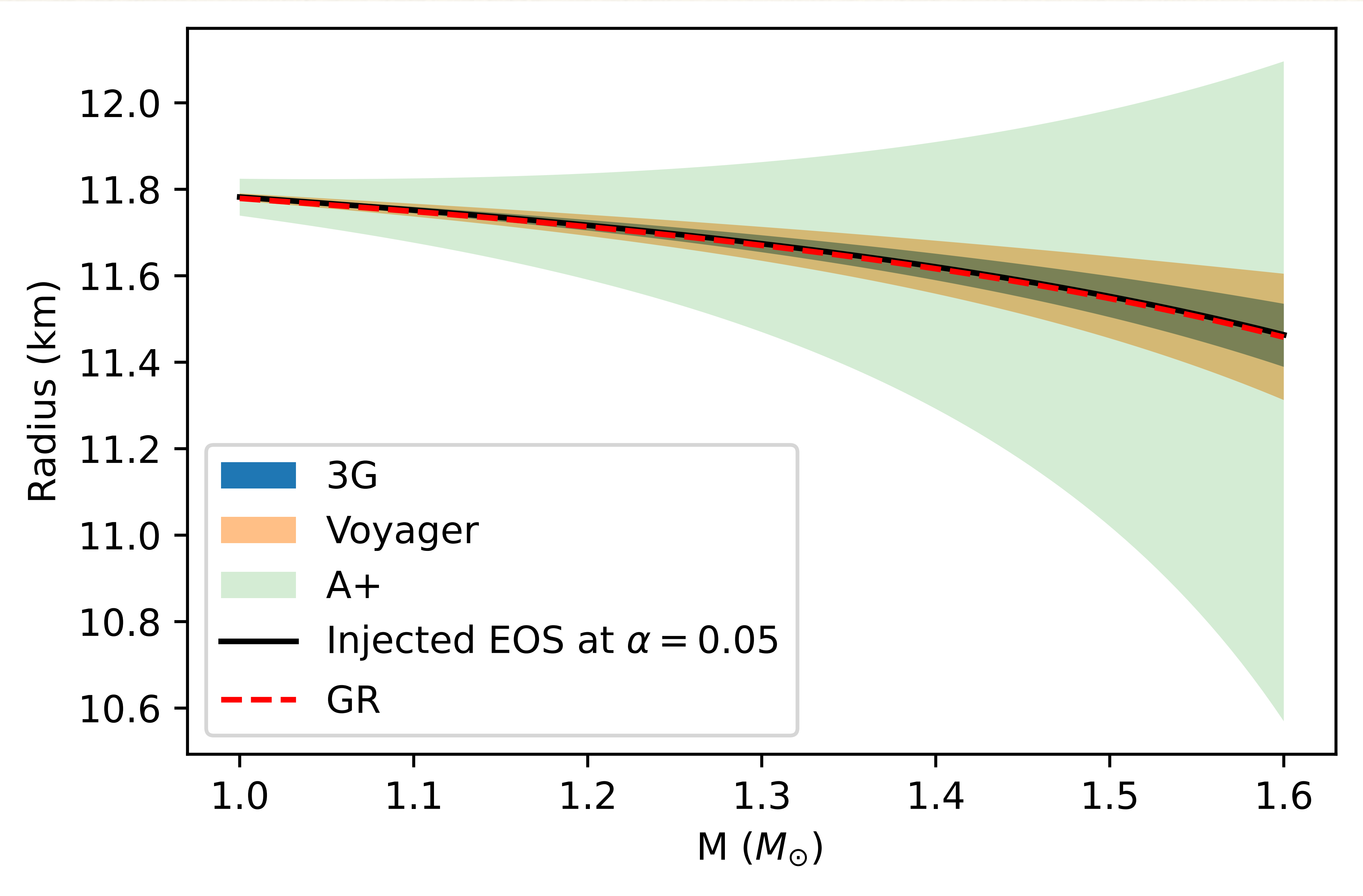
Quantity	uniform	Gaussian	two gaussian
90% CI of α [km^2]	$0.40^{+5.29}_{-8.43}$	$-3.36^{+13.22}_{-4.27}$	$2.30^{+18.90}_{-7.82}$
$\log_{10} Z$	-10.82 ± 0.02	-31.90 ± 0.02	-9.25 ± 0.04



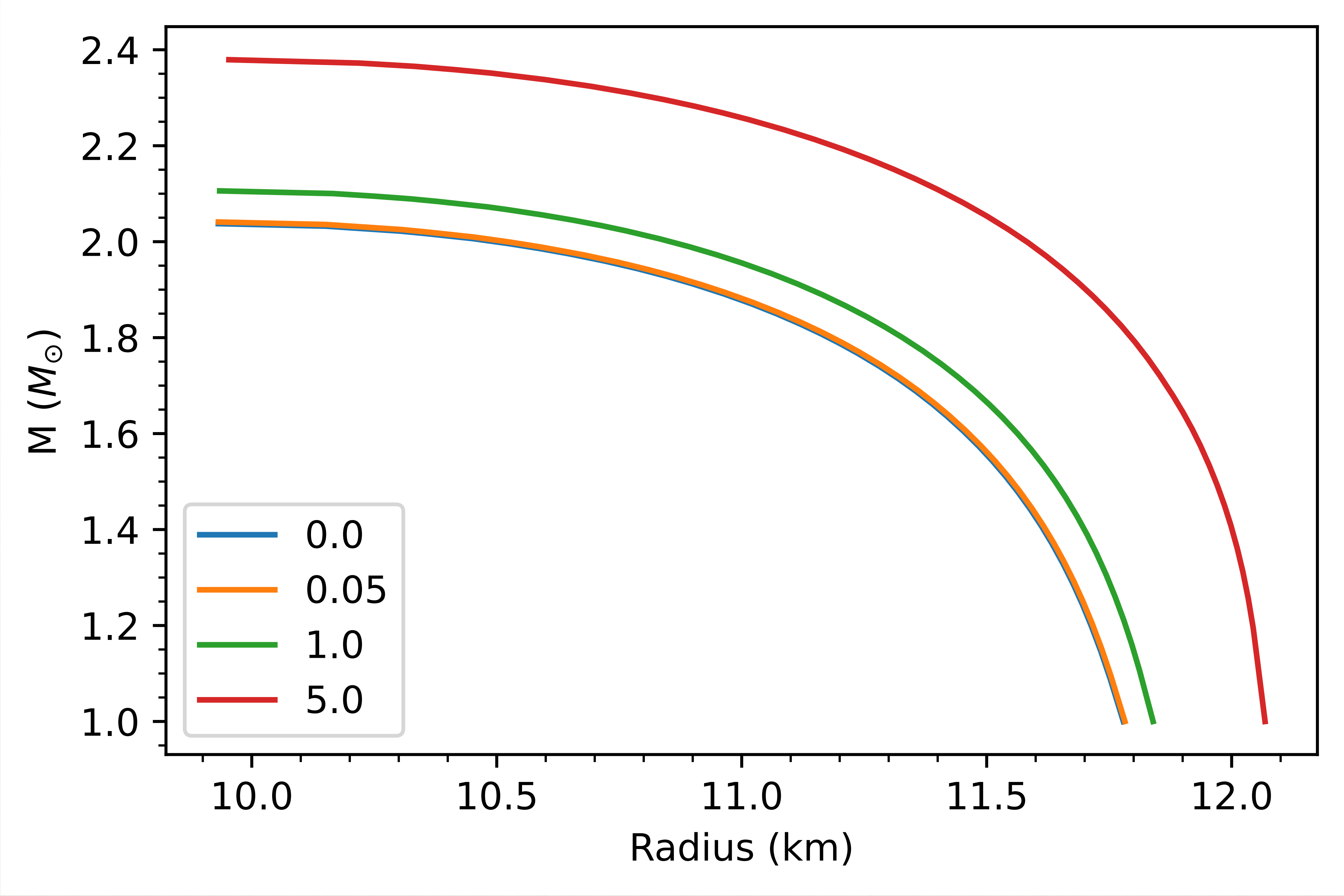
- Posterior of α is consistent with GR and improves previous constraints.
- Need more observations to break EOS-gravity degeneracy

B. Biswas, E. Smyrniotis, I. Liodis, and N. Stergioulas, arXiv: 2309.05420 (2023)

Expected NS radius constraints with future GW detectors



Based on the calculations done by K. Chatziioannou, Phys. Rev. D. 105, 084021 (2022)

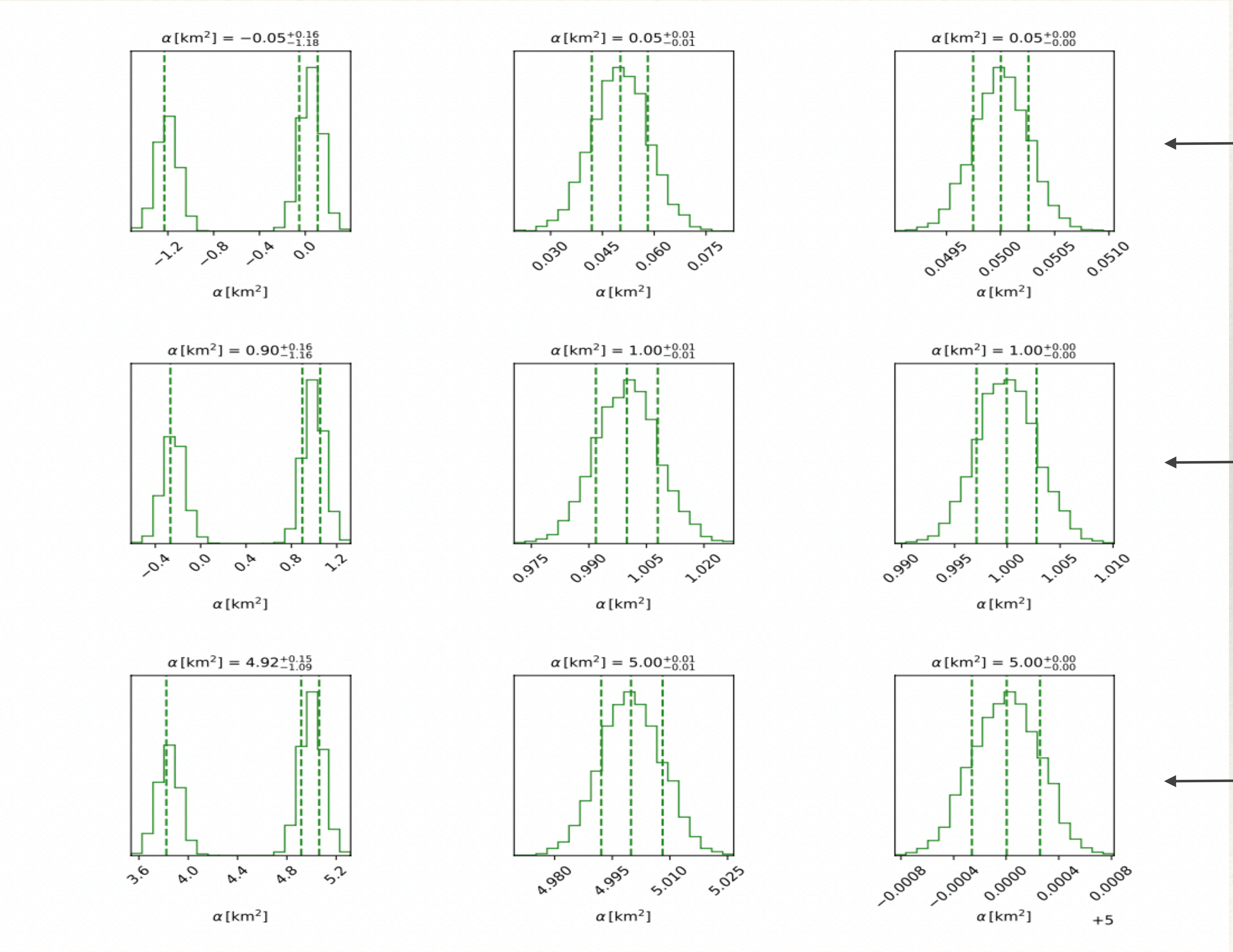


Mass vs. radius sequences for the different injected values of α (the GR case corresponds to $\alpha = 0$).

Constraints with future GW detectors

A+ Voyager 3G

Injected value of coupling constant



$\alpha = 0.05$

$\alpha = 1$

$\alpha = 5$

- A+ does not strictly break EOS-gravity degeneracy; but can place constraints or disfavor GR depending on the value of α

- Voyager or 3G can potentially break the degeneracy, even for small deviations from GR

B. Biswas, E. Smyrniotis, I. Liodis, and N. Stergioulas, arXiv: 2309.05420 (2023)

EOS-gravity degeneracy: future directions

Following improvements needs to be made in the future

- Instead of using a finite number of EOS candidates, a parametrization of NS EOS will be used
- Instead of using an expected radius uncertainty, a proper injection study needs to be performed for future detectors.