# Investigating three-nucleon forces with current and future Gravitational Wave detections

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ECT* workshop: “Neutron Stars as multi-messenger laboratories for dense matter”
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A. Sabatucci, O. Benhar, A. Maselli and C.  Pacilio, arXiv:2206.11286 [astro-ph] (2022)
A. Maselli, A. Sabatucci and O. Benhar, Phys. Rev. C 103, 065804, (2021)

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# Introduction

In this presentation I will report the details of a study aimed at *inferring direct information on the repulsive three-nucleon potential from multimessenger astronomy*[1].

- The baseline of our analysis is the dynamical model used to obtain the APR[2] equation of state.
- We have considered the coupling constant of the repulsive part of three-nucleon interaction -providing the dominant contribution at high density- as a free parameter.
- We have made bayesian inference employing the NICER and LIGO/Virgo datasets in order to constrain this coupling constant.
- We extended our analysis to the next generation of gravitational wave (GW) observatories, in particular we analyzed the potential of the Einstein Telescope (ET).

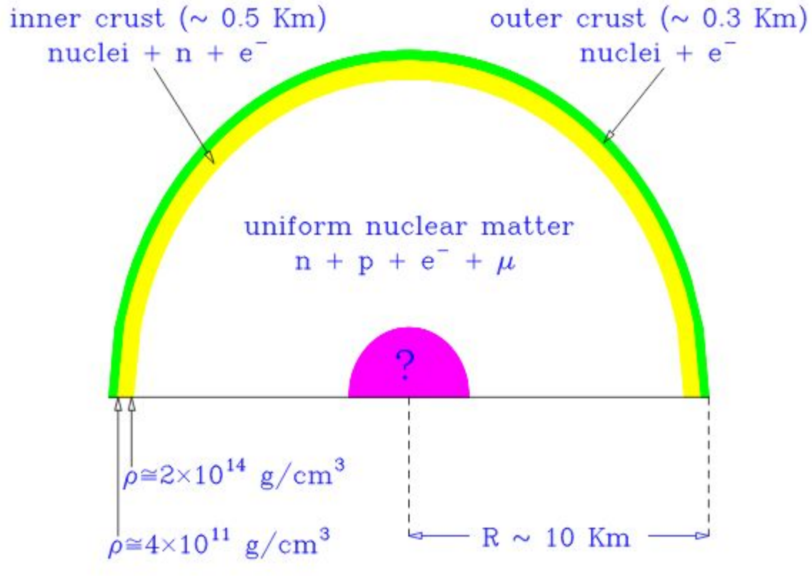
We are **fixing a microscopic model** and then trying to use **astrophysical observations to constrain** one parameter which is directly related to the underlying **microscopic dynamics**.

[1] A. Maselli, A. Sabatucci and O. Benhar, Phys. Rev. C 103, 065804, (2021)
[2] A. Akmal, V. R. Pandharipande, and D. G. Ravenhall, Phys. Rev. C 58, 1804 (1998)

# Neutron Stars

Neutron Stars (NSs) are extremely compact objects, with masses as large as one or two solar masses and with radii of about ten kilometers.

In the NS interior matter can reach very extreme conditions, impossible for Earth-based experiments.



## In the innermost region

$$\rho > \rho_0$$

$$\rho_0 = 2.67 \times 10^{14}\, g/cm^3\; (0.16\, fm^{-3})$$

$$T \sim 10^9\, K << T_F$$

$$T_F \sim 10^{12}\, K$$

**NSs provide a unique opportunity to investigate the properties of nuclear matter at high density and low temperature.**

# Nuclear Dynamics

**Non-relativistic nuclear many body theory (NMBT)**. We have point-like nucleons, interacting through nucleon-nucleon (NN) and three-nucleon (NNN) potentials.

$$\mathcal{H} = \sum_{i=1}^{A} \frac{p_i^2}{2m} + \sum_{i<j} v_{ij} + \sum_{i<j<k} V_{ijk}$$

- For the APR EOS the authors employed the phenomenological **Argonne v18** NN potential and the **Urbana IX** NNN potential.
- The equation of state of cold nuclear matter is carried out by computing the ground state energy by means of variational approaches.

$$E_0 = \langle \psi_0 | \mathcal{H} | \psi_0 \rangle$$

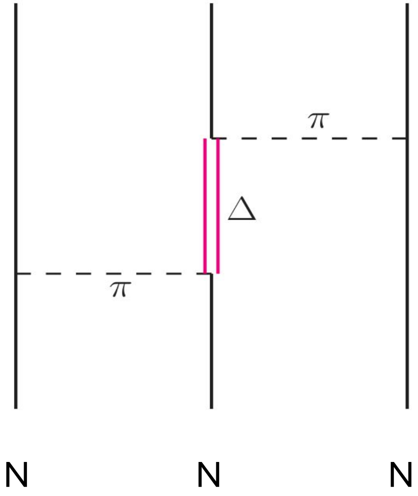
A variational approach is necessary because of the strong repulsive core of NN interaction which cannot be treated in perturbation theory.

# Three-Nucleon Potential

Three-nucleon interactions must be introduced in order to account for processes involving the internal structure of nucleons.

The **Urbana IX** (UIX) model of three-nucleon potential comprises two terms.

$$V_{ijk} = V_{ijk}^{2\pi} + V_{ijk}^{R}$$



This two terms bring **two free parameters** that are adjusted in order to reproduce the binding energy of $^3$He and $^4$He, and the correct value of the nuclear saturation density respectively.

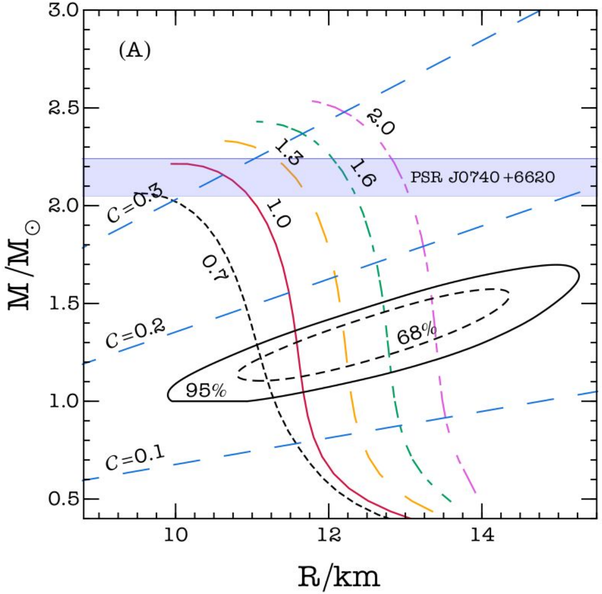
**The repulsive term is purely phenomenological and it’s only constrained to reproduce the correct value of the nuclear saturation density.**

# Resulting Equations of State

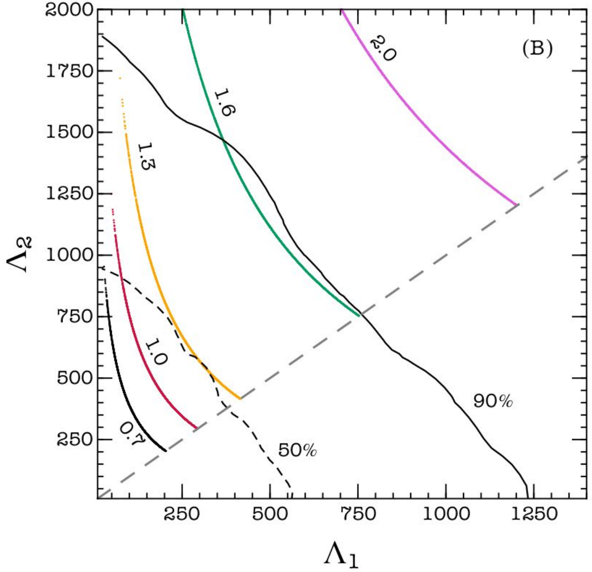
We have generated **a set of APR-like EOSs** computed replacing :

$$\langle V^R_{ijk} \rangle \rightarrow \alpha \langle V^R_{ijk} \rangle$$

NICER PSR J0030+0451



LIGO/Virgo GW170817



# Bayesian Inference Framework

We have made Bayesian inference on $\alpha$ employing the following dataset:

- Gravitational Wave (GW) observation of the binary system GW170817 made by the LIGO-Virgo collaboration (LVC)
- The spectroscopic observation of the millisecond pulsars PSR J0030+0451 performed by the NICER satellite.
- The maximum mass constraint provided by the high-precision radio pulsars timing of the binary PSR J0740+6620

The posterior distribution defined through Bayes Theorem

$$\mathcal{P}(\theta|O) \propto \mathcal{P}_0(\theta) \prod_{i=1}^{n} \mathcal{L}(O^{(i)}|D(\theta))$$

Is sampled with Markov Chain Monte Carlo (MCMC) simulations with the *emcee* algorithm[3].

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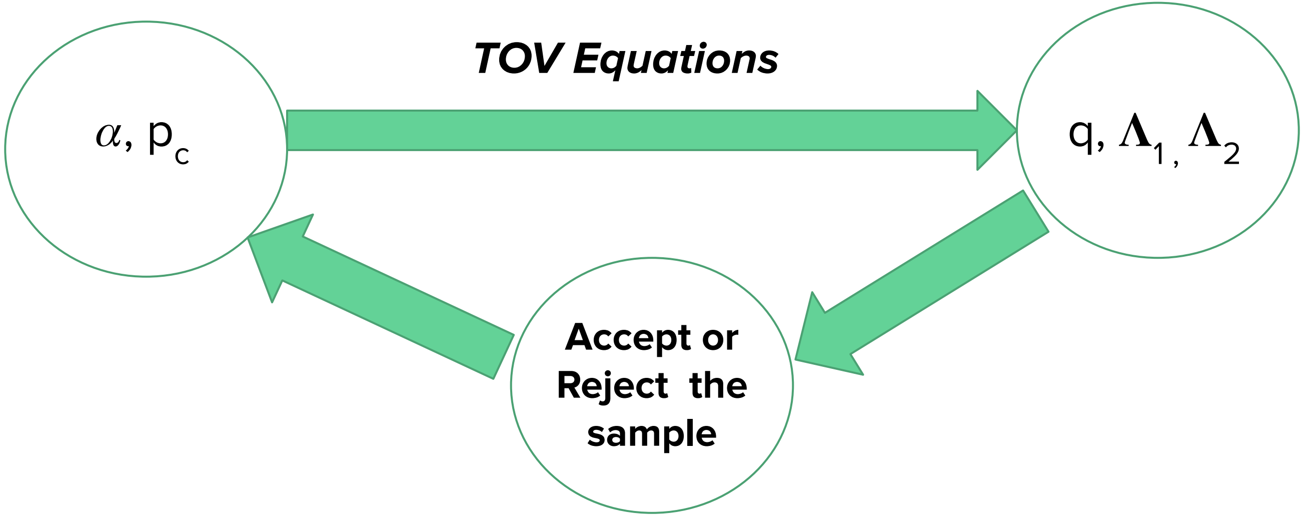
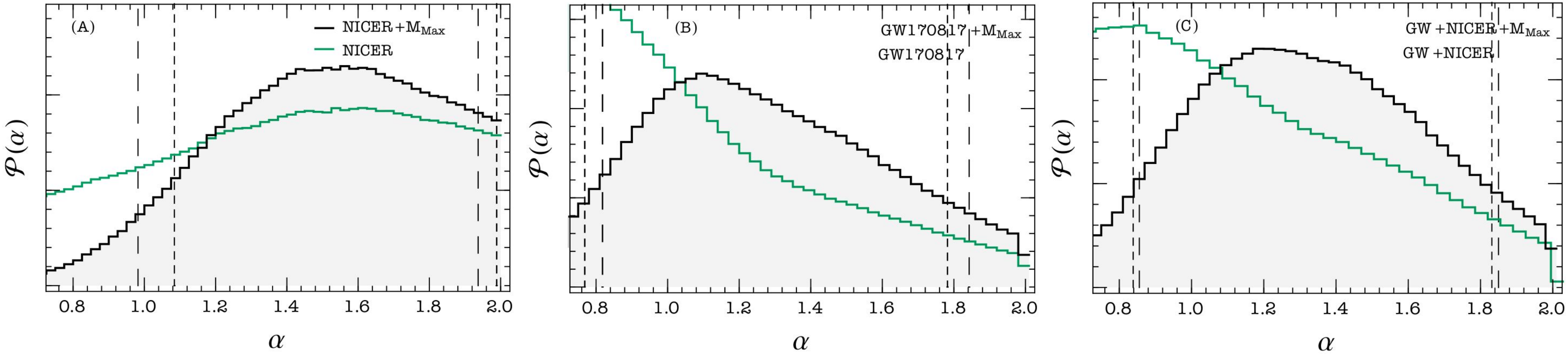
[3] D. Foreman-Mackey, D. W. Hogg, D. Lang, and J. Goodman, Astron. Soc. Pac. 125, 306 (2013)

# Sampling The Posterior

$$\mathcal{P}(\alpha, p_c^{(1)} | O_{\mathrm{GW}}) \propto \mathcal{P}_0(\alpha, p_c^{(1)}, p_c^{(2)}) \mathcal{L}_{\mathrm{GW}}(q, \Lambda_1, \Lambda_2)$$



# Posterior Distributions



The GWs alone turn out to be not enough to extract relevant information about the strength of NNN repulsion and the shape of the PDF appears to be dominated by the maximum mass requirement.

However this analysis, yielding $\alpha_{\mathrm{GW+EM}} = 1.32^{+0.48}_{-0.51}$ has shown that there is sensitivity of NS observables with respect to the considered microscopic parameter.

A. Maselli, A. Sabatucci and O. Benhar, Phys. Rev. C 103, 065804, 2021

# Extension to Future GW detections

We extended our study by repeating the **same analysis** but with a set of **simulated data** in order to investigate the following scenarios

- Increasing number of observations
- New generation detectors

We simulate **30 binary neutron star events** for two different observatories:

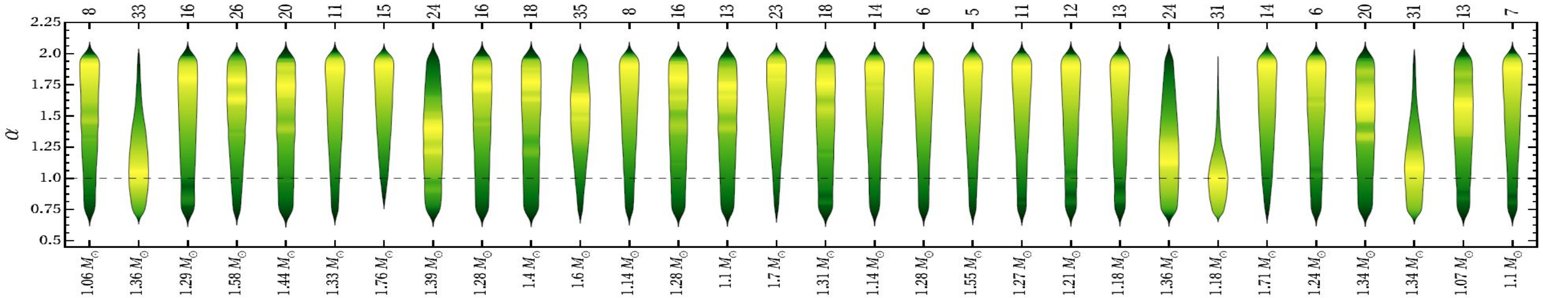
- **LIGO Hanford, LIGO Livingston, and Virgo detectors** at design sensitivity
- The future third-generation interferometer **Einstein Telescope**

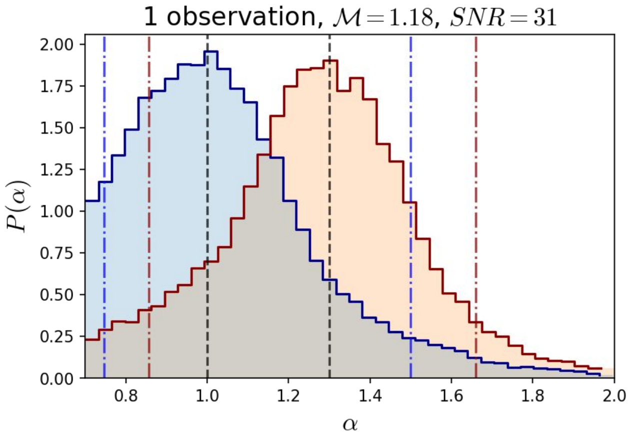
We have generated two different set of 30 binaries by using EOSs associated with two different values of $\alpha$ for each observatory.

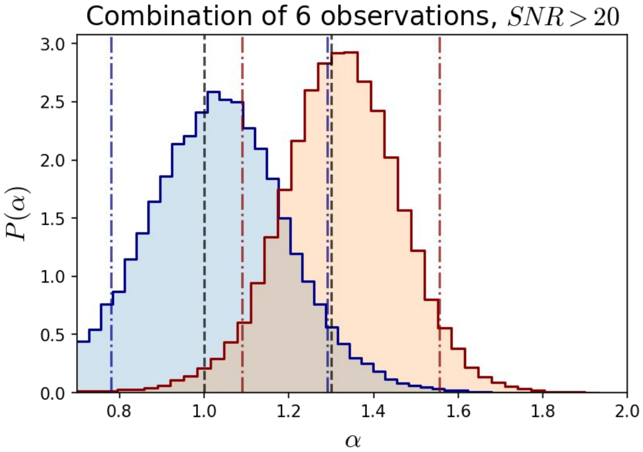
- The injected values of $\alpha$ are $\alpha$=1.0 and $\alpha$=1.3
- Sky location and inclination uniformly distributed over the sky.
- We assumed the chirp mass of each event to be measured with infinitesimal precision.

A. Sabatucci, O. Benhar, A. Maselli and C. Pacilio (paper in preparation)

# Mocked Data: LIGO/Virgo

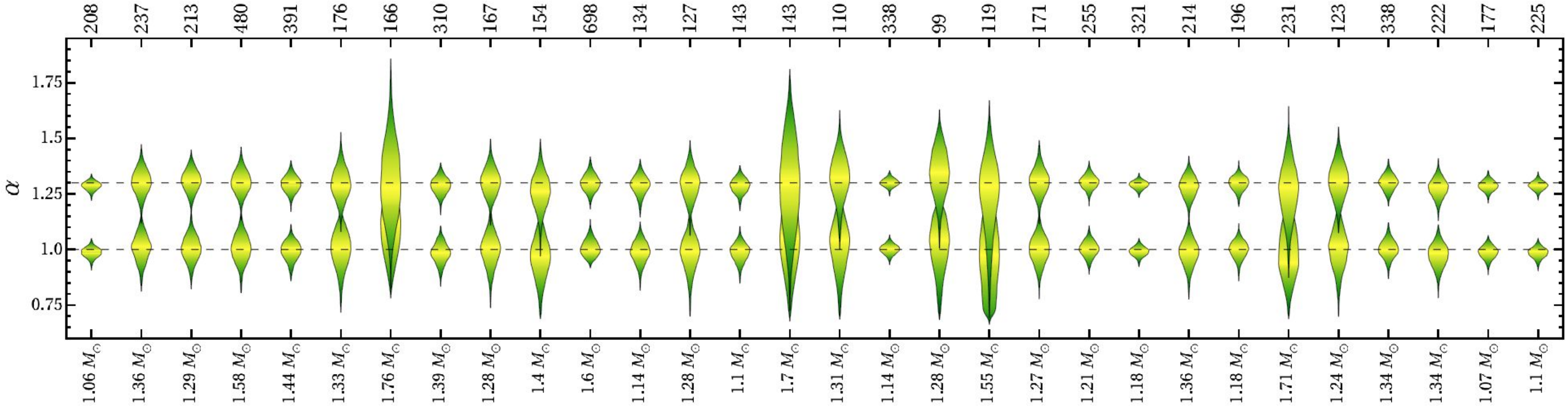



1 observation, $\mathcal{M}=1.18$, $SNR=31$

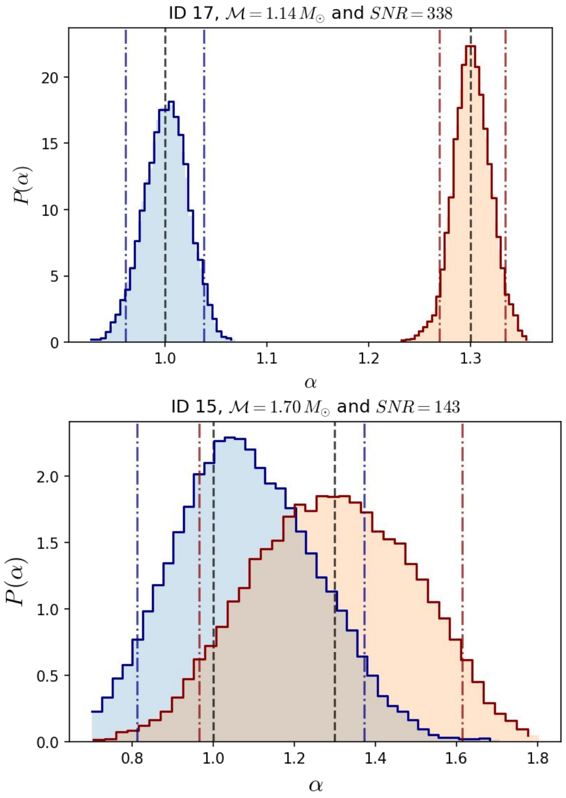

Combination of 6 observations, $SNR>20$

# Mocked Data: Einstein Telescope

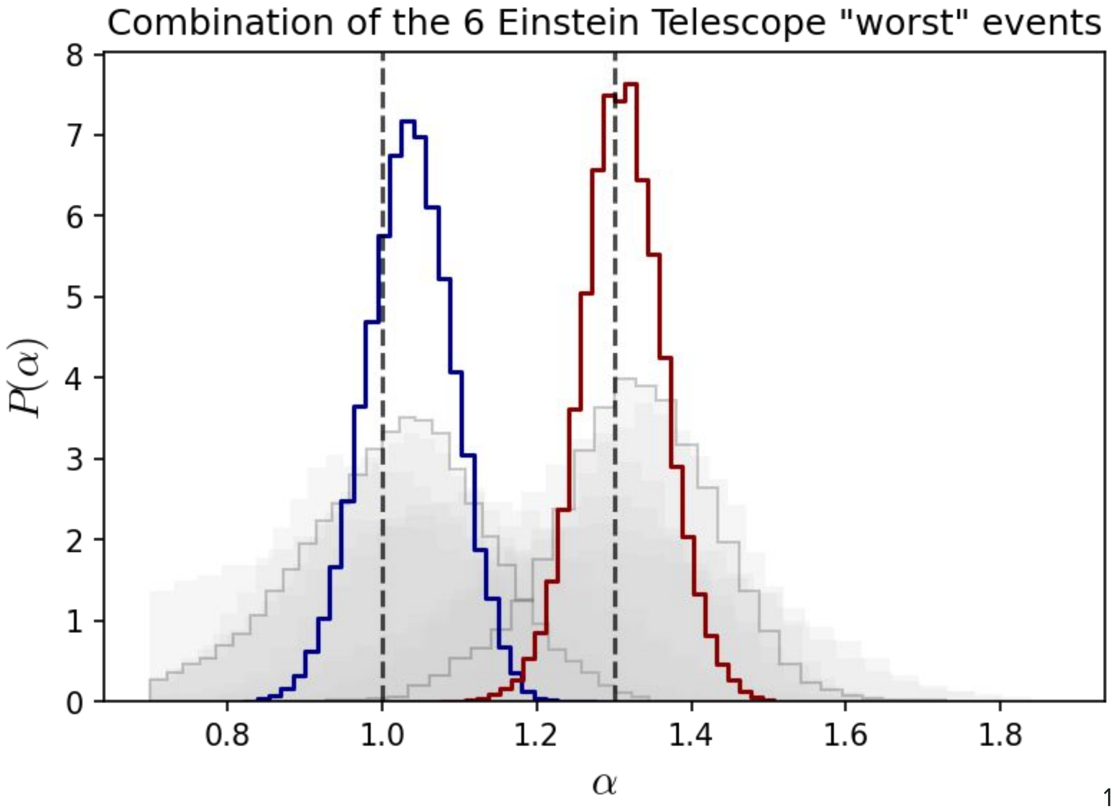
Violin plot of the marginal posterior of $\alpha$ for the 30 ET events. On the bottom and top axis are reported the chirp mass and the signal-to-noise ratio (SNR) for each event respectively.



# Mocked Data: Einstein Telescope

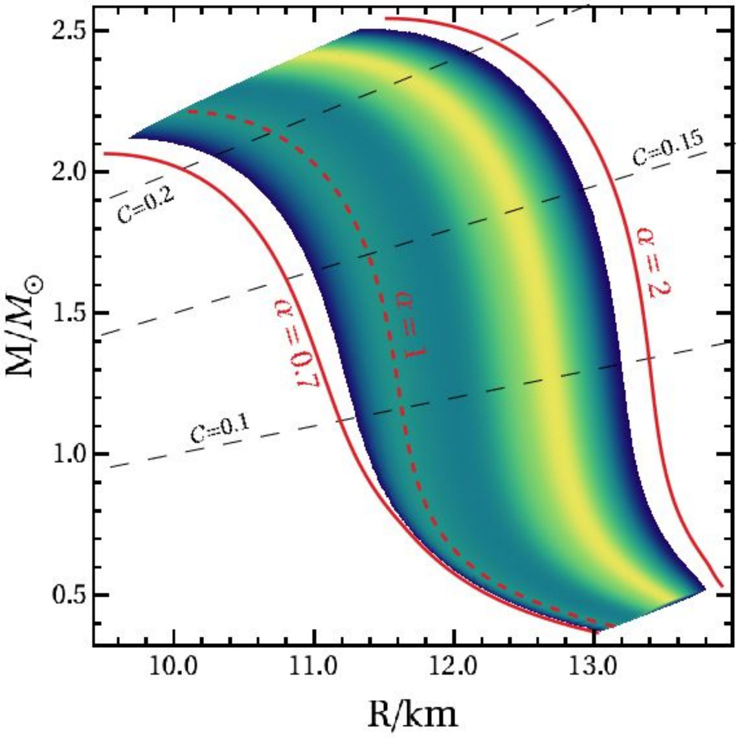

ID 17, $\mathcal{M} = 1.14\,M_\odot$ and $SNR = 338$

ID 15, $\mathcal{M} = 1.70\,M_\odot$ and $SNR = 143$

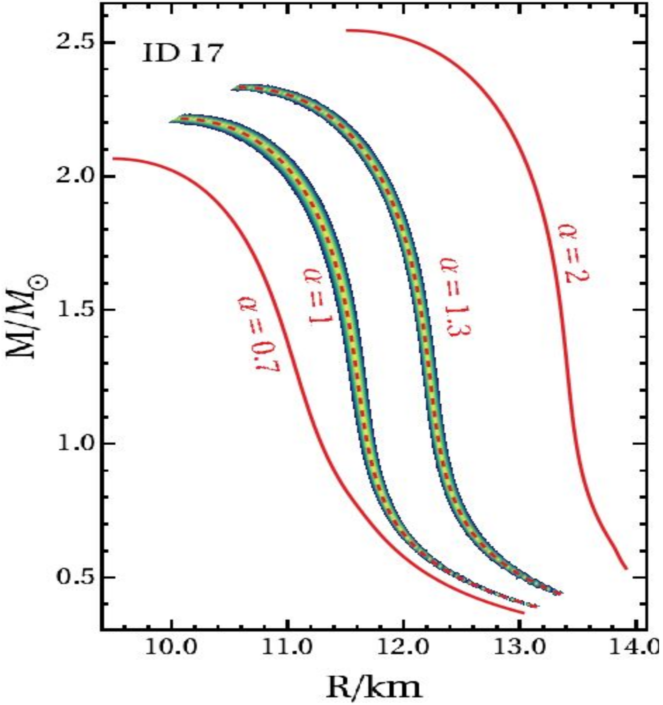

Combination of the 6 Einstein Telescope "worst" events

# Comparison between current and future constraints

Current multimessenger data
(LIGO/Virgo + NICER)



Expected Einstein Telescope constraints



# Summary and Outlook

- We have **investigated the constraints** that recent observations of GW170817 and the NICER pulsar PSR J0030+0451 can impose **on the NNN potential**.
- We have explored **both single and multimessenger constraints**, including also the bound on the maximum mass given by PSR J0740+6620.
- The results appears to be dominated by the maximum mass requirement, whereas the **GW170817** appears to be **not enough to infer relevant information**.
- However **there is sensitivity of neutron star observables with respect to $\alpha$**, suggesting that future observations will definitely improve our understanding.
- The analysis with the **Einstein Telescope** appears to confirm this picture. For small values of the chirp mass we **can distinguish between two different values of $\alpha$ with just one observation**!

# Thank you for the attention!

# Backup

# Resulting EOSs