Multimessenger constraints on the neutron star equation of state and the Hubble constant

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Introduction

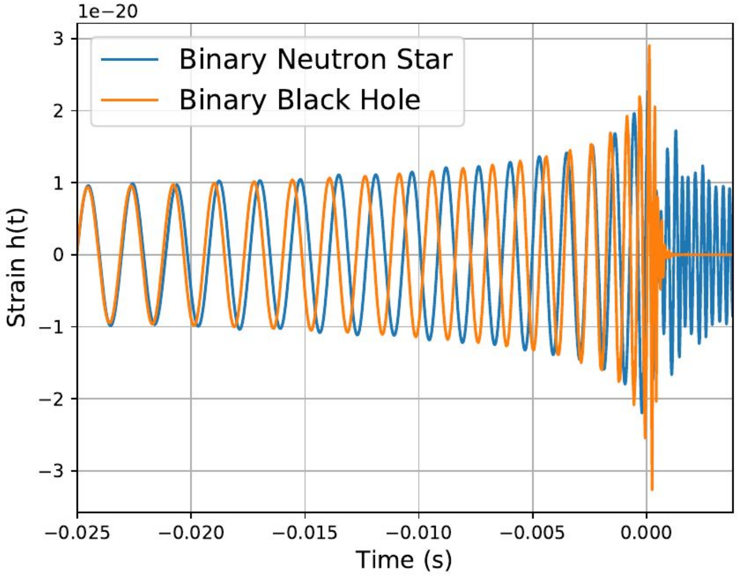
- The nature of supranuclear matter is not fully understood
  - Theoretical calculation (QCD) at density of a few times saturation density become difficult
  - Such a density is not achievable at terrestrial lab
  - A neutron star is the perfect lab for probing such a density

Introduction

- Isolated neutron star
  - Mass estimation of heavy pulsars
  - X-ray observation of pulsars (e.g. NICER)
- A binary neutron star merger
  - Gravitational waves
  - Electromagnetic radiations
    - From radio waves to Gamma-ray
    - Kilonova, GRB, GRB afterglow

Gravitational waves

- During the inspiral of the compact stars
  - Matter tidal effect deviate the orbit from a point-particle orbit
  - Determined by the **Tidal deformability** $\Lambda = \frac{2}{3} k_2 C^{-5}$
  - k_2 is the second tidal Love number and C is the compactness



Kilonova

- Electromagnetic signal (mostly optical) generated by various ejecta
- The physical properties of the ejecta components
  - The exact dependence is kilonova model-dependent
  - The ejecta mass of the two components
    - The dynamic eject mass
    - The wind eject mass
  - The ejecta mass depends on the EoS and the binary masses

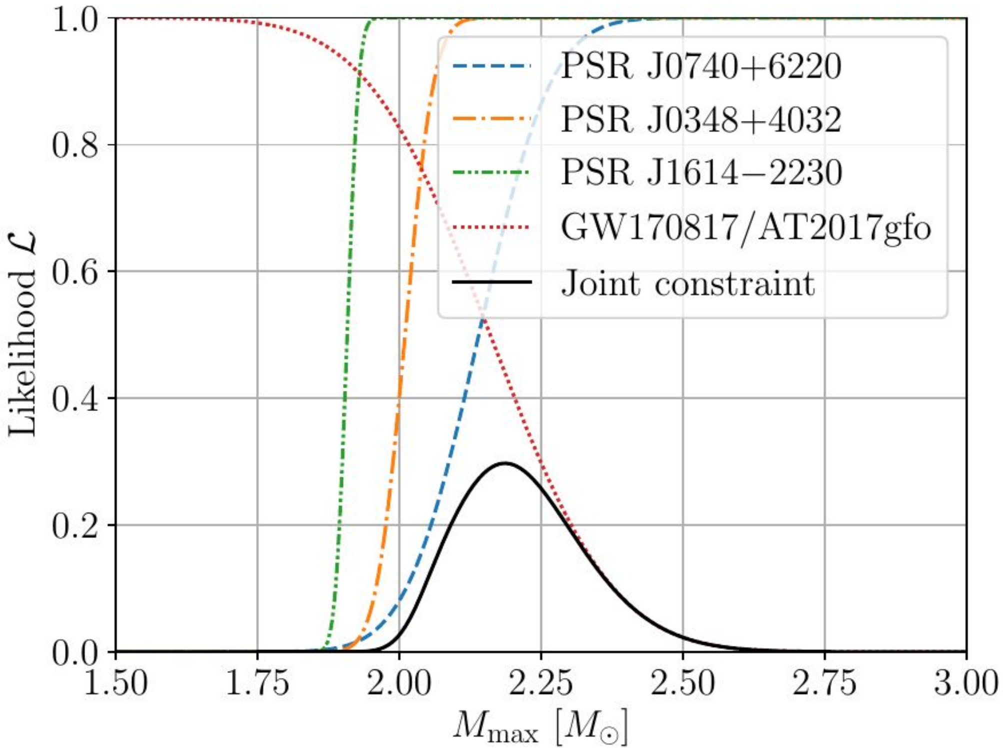
A multi-messenger approach

- Nuclear Physics Multi-Messenger Astronomy framework is based on
  - Chiral effective field theory
  - $M_{\max}$ lower bound from heavy pulsars
  - $M_{\max}$ upper bound from Rezzolla et. al
  - NICER observation on PSR J0030+0451
  - GW170817, GW190425
  - AT2017gfo

Chiral effective theory

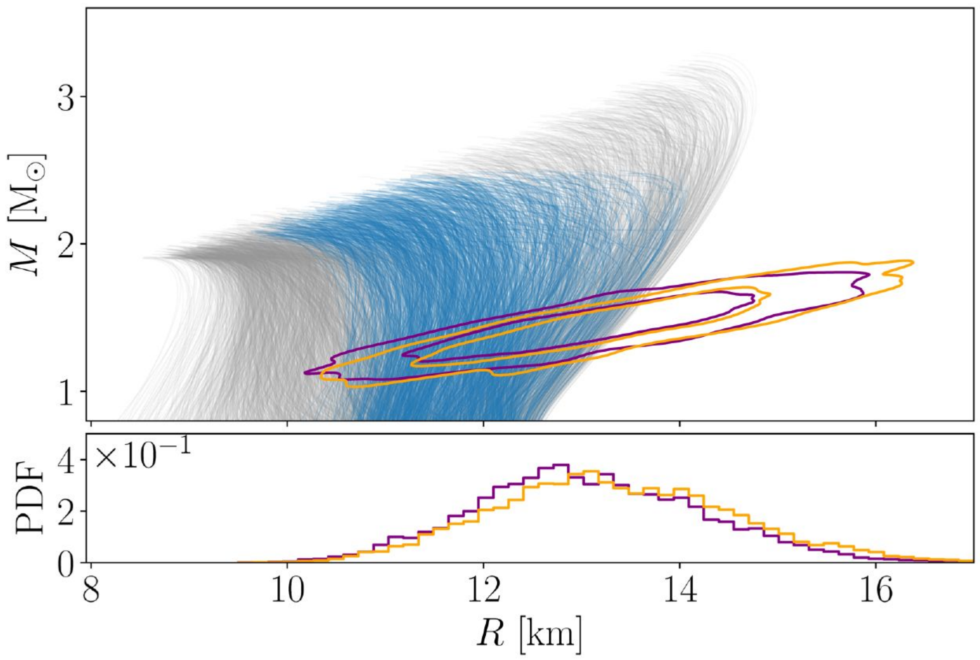
- The Lagrangian is written in
  - nucleon and pion degrees of freedom
  - Pion exchange (long range) and nucleon contact (short range)
- The Lagrangian is expanded in terms of $\frac{p}{\Lambda_b}, \Lambda_b \approx 600\text{MeV}$
- The EOS is then obtained with quantum Monte Carlo
- The resulting EOS are taken up to $1.5n_{\text{sat}}$
- The density above is extended with speed-of-sound interpolation

Constraint on maximum mass



- The heavy pulsar measurement is modelled as a Gaussian
- The upper bound on $M_{\rm max}$ is estimated by assuming GW170817 results in a BH and use of quasi-universal relation

NICER observation

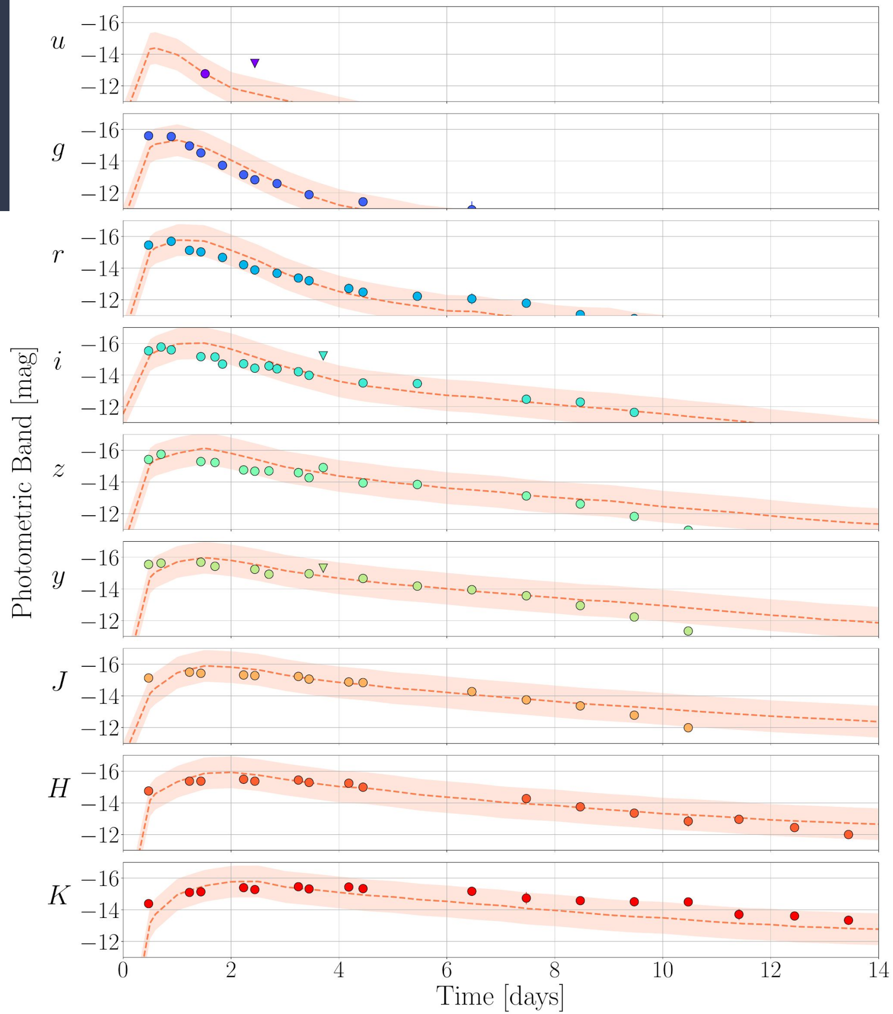


- The NICER observation results in a posterior on M-R plane

$$\begin{aligned}
&\mathcal{L}_{\mathrm{NICER}}(\mathrm{EOS}) \\
&= \int dM\,dR\, p_{\mathrm{NICER}}(M,R)\pi(M,R|\mathrm{EOS}) \\
&= \int dM\,dR\, p_{\mathrm{NICER}}(M,R)\delta(R - R(M,\mathrm{EOS})) \\
&= \int dM\, p_{\mathrm{NICER}}(M, R = R(M,\mathrm{EOS})),
\end{aligned}$$

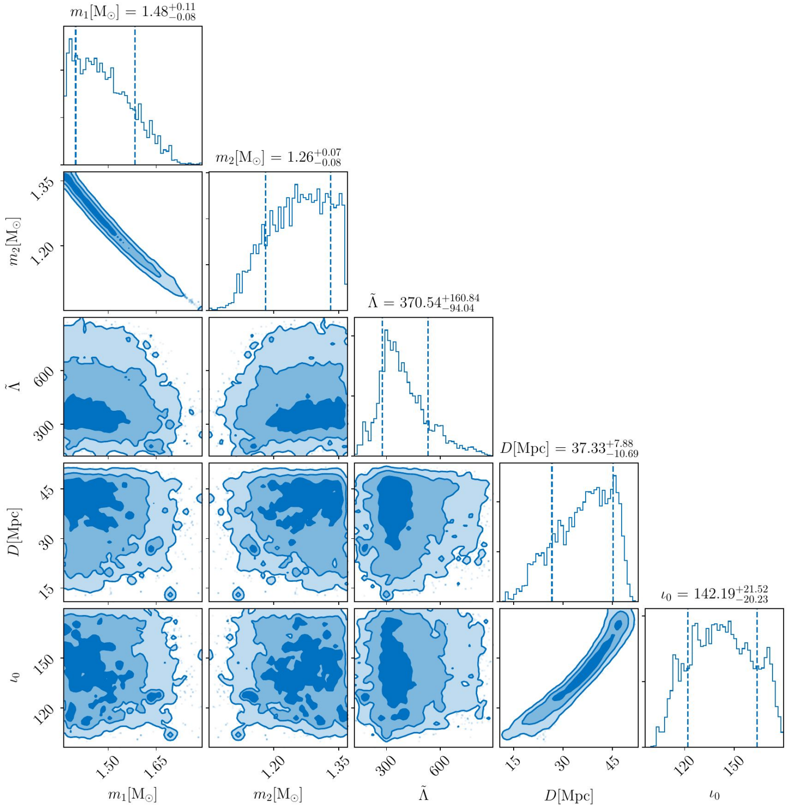
Light curve analysis

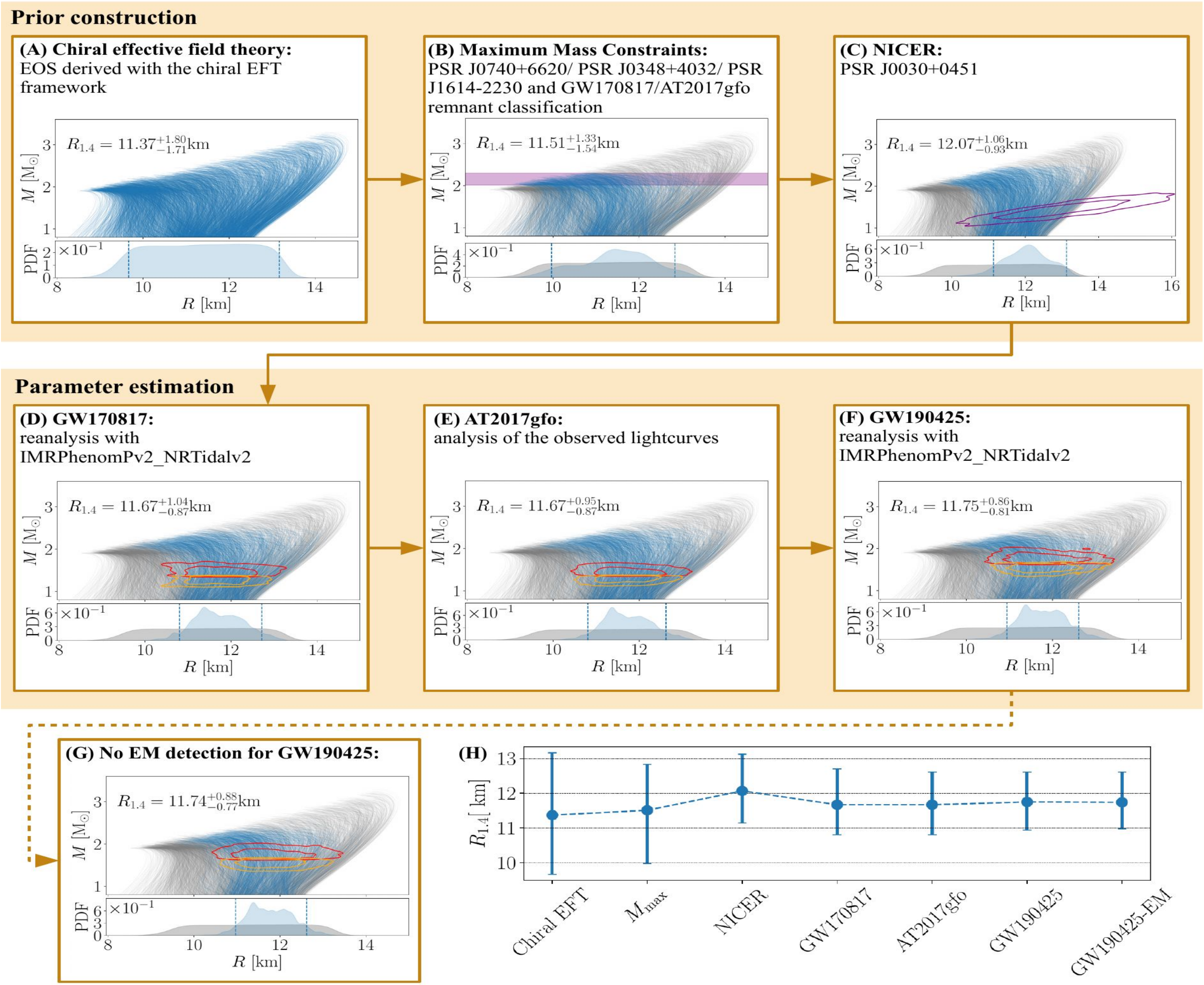
- A χ^2 fitting likelihood between the data and the estimated light curve
- The ejecta properties are being measured
- Connected to EoS via quasi-universal relation



Gravitational-wave analysis

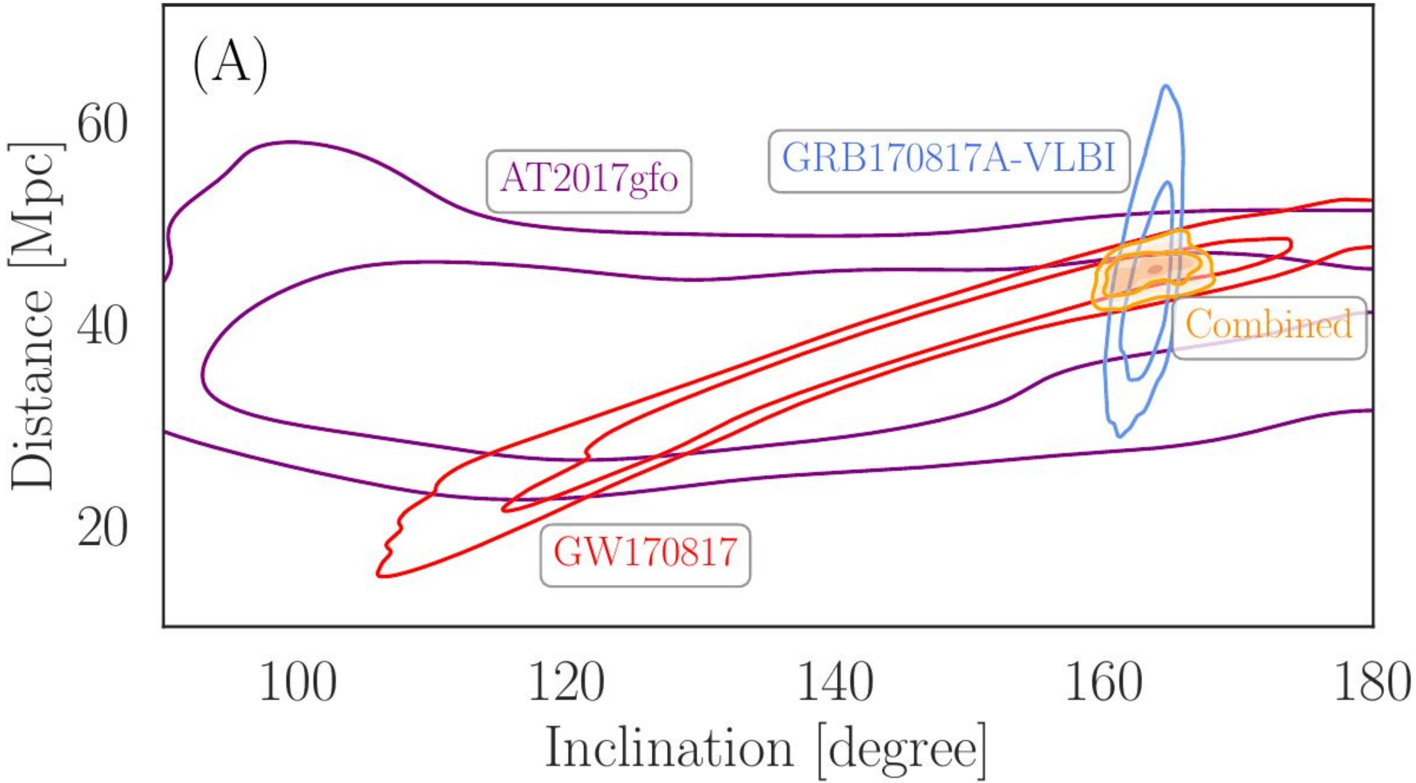
- Billions of waveforms are compared with the data
- The posterior of the source parameters are estimated





Prior construction
(A) Chiral effective field theory:
EOS derived with the chiral EFT framework
$R_{1.4} = 11.37^{+1.80}_{-1.71}$km
(B) Maximum Mass Constraints:
PSR J0740+6620/ PSR J0348+4032/ PSR J1614-2230 and GW170817/AT2017gfo remnant classification
$R_{1.4} = 11.51^{+1.33}_{-1.54}$km
(C) NICER:
PSR J0030+0451
$R_{1.4} = 12.07^{+1.06}_{-0.93}$km
Parameter estimation
(D) GW170817:
reanalysis with IMRPhenomPv2_NRTidalv2
$R_{1.4} = 11.67^{+1.04}_{-0.87}$km
(E) AT2017gfo:
analysis of the observed lightcurves
$R_{1.4} = 11.67^{+0.95}_{-0.87}$km
(F) GW190425:
reanalysis with IMRPhenomPv2_NRTidalv2
$R_{1.4} = 11.75^{+0.86}_{-0.81}$km
(G) No EM detection for GW190425:
$R_{1.4} = 11.74^{+0.88}_{-0.77}$km
M [$M_\odot$]
PDF
$\times 10^{-1}$
R [km]
(H)
$R_{1.4}$ [km]
Chiral EFT
$M_{\max}$
NICER
GW170817
AT2017gfo
GW190425
GW190425-EM

Estimation of Hubble constant



Estimation of Hubble constant

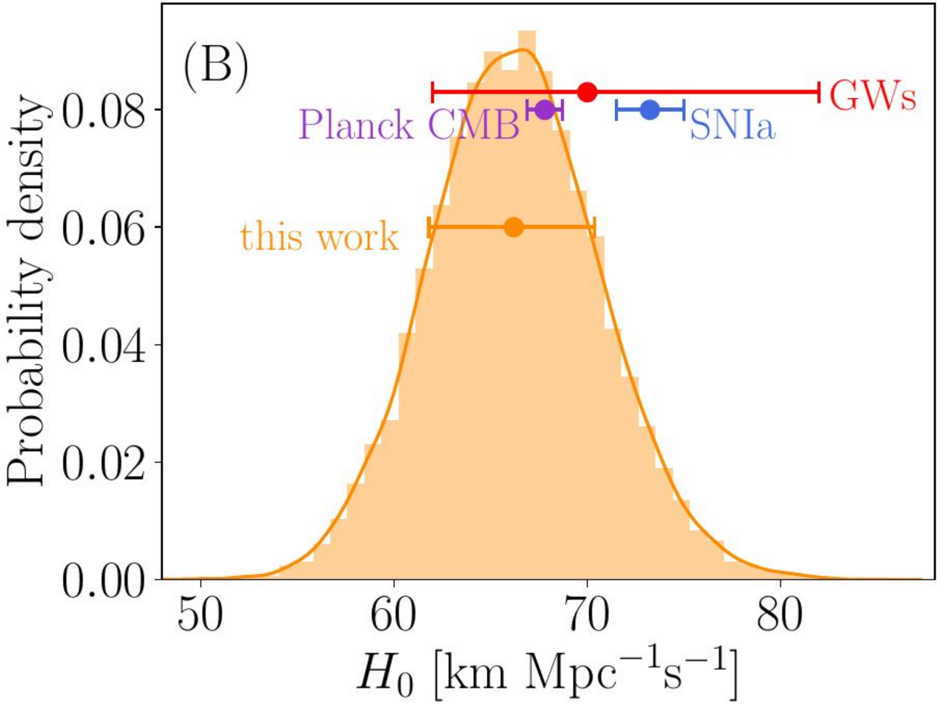
$$v_r = H_0 D + v_p$$

v_r := CoM recession velocity relative to CMB

v_p := peculiar velocity

$v_r = 3327 \pm 72\,\mathrm{km\,s^{-1}}$

$v_p = 310 \pm 150\,\mathrm{km\,s^{-1}}$



Conclusion

- Nuclear Physics Multi-Messenger Astronomy framework includes a vast majority of information on the supranuclear matter
- The radius of a neutron star with $1.4 M_{\odot} = 11.75^{+0.86}_{-0.81}\ \mathrm{km}$
- The Hubble constant is estimated to be $66.2^{+4.4}_{-4.2}\ \mathrm{km\,Mpc^{-1}\ s^{-1}}$
  - Our result is favouring the Planck estimation

Reference

- T. Dietrich, M. W. Coughlin, P. T. H. Pang, M. Bulla, J. Heinzel, L. Issa, I. Tews, and S. Antier, “Multimessenger constraints on the neutron-star equation of state and the Hubble constant,” Science, vol. 370, no. 6523, pp. 1450–1453, 2020