QUARK MATTER KRAKÓW 2022

Constraining Neutron-Star Matter with Microscopic and Macroscopic Collisions

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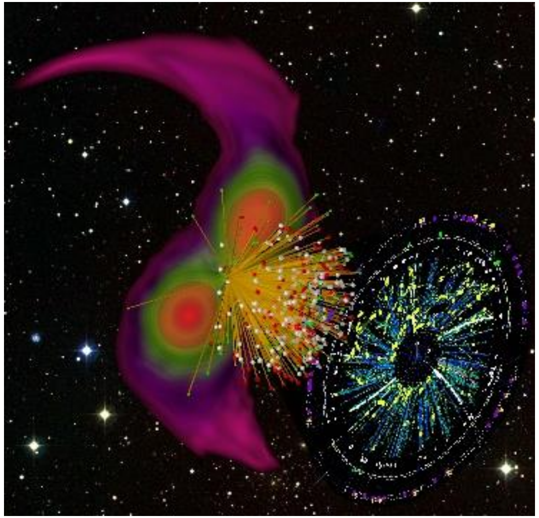
arXiv: 2107.06229

MOTIVATION: To combine information from heavy-ion collisions with astrophysical observations →
New frontier of Multi-Messenger Physics



METHOD – BAYESIAN INFERENCE

Bayesian Inference is used to combine the information from microscopic nuclear theory (χEFT), astrophysical observations and terrestrial heavy-ion collision experiments

Methodology based on:
T. Dietrich et al., Science 370 (2020) 6523
P. Pang et al., Astrophys.J. 922 (2021) 1, 14

The posterior distribution of the combined Pure Neutron Matter Equation of State (EOS) is dependent on the prior from Astro and likelihood of the HIC measurements for a given EOS

$$
\begin{aligned}
p(\mathrm{EOS}|\mathrm{MMA},\mathrm{HIC}) &\propto p(\mathrm{HIC}|\mathrm{EOS}) \\
&\times p(\mathrm{MMA}|\mathrm{EOS})p(\mathrm{EOS}) \\
&= p(\mathrm{HIC}|\mathrm{EOS})p(\mathrm{EOS}|\mathrm{MMA}) \\
&\equiv \mathcal{L}_{\mathrm{HIC}}(\mathrm{EOS})\mathcal{P}_{\mathrm{MMA}}(\mathrm{EOS})
\end{aligned}
$$

For the likelihood function, pressure is a function of density for a given EOS and the relative accuracy of experimental results at various densities is accounted for

$$
\mathcal{L}_{\mathrm{HIC}}(\mathrm{EOS}) = \int dn\, P(n, P = P(n;\mathrm{EOS})|\mathrm{HIC})
$$

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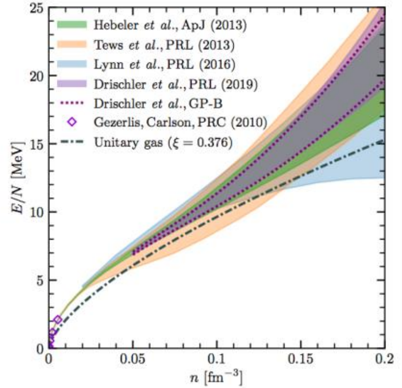
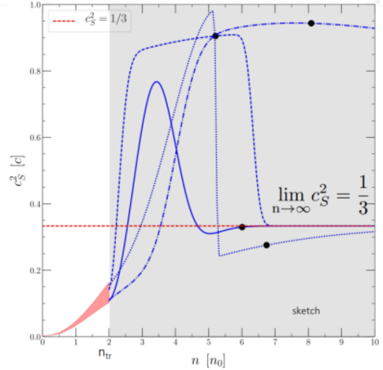
CHIRAL EFFECTIVE FIELD THEORY (χEFT) INGREDIENTS TO BUILD A PRIOR

S. Huth et al., Phys.Rev.C 103 (2021) 2, 025803



I. Tews et al., Astrophys.J. 860 (2018) 2, 149



χEFT – BRIEF INTRODUCTION

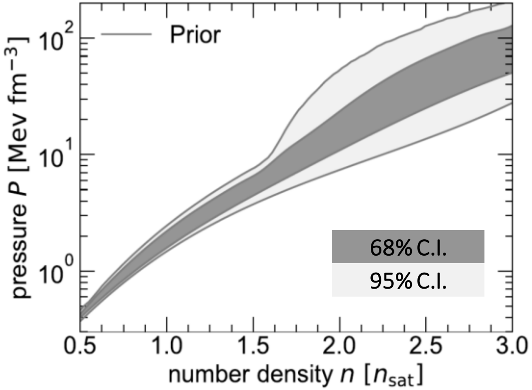
- Effective theory of QCD that describes strong interactions in terms of nucleon and pion degrees of freedom using a systematic momentum expansion of nuclear forces
- EFT order-by-order expansion enables estimates of theoretical uncertainties
- Systematic expansion of nuclear forces in Q over breakdown scale Λ_b ~500-600 MeV/c, i.e., limited applicability to $2n_{sat}$

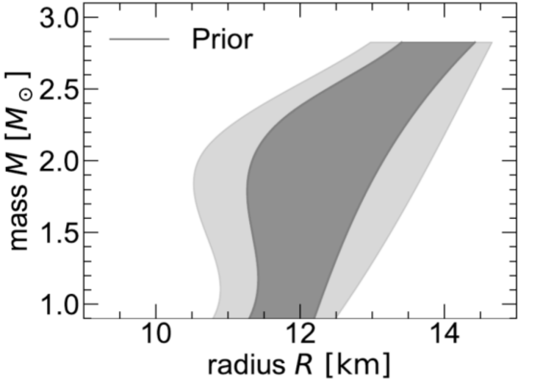
EXTRAPOLATION TO HIGHER DENSITIES

- Speed-of-sound (c_s) extrapolation to extend EOS ≥ $1.5n_{sat}$
- Extrapolation only constrained by causality ($c_s \leq c$) and stability of neutron-star matter ($c_s \geq 0$). No information at asymptotically high densities from pQCD
- Resulting prior to support neutron stars with masses of ≥ 1.9M (lower limit from the combined observations of heavy pulsars)
- First-order phase transition explicitly included ($c_s = 0$)

Set of 15,000 EOSs generated

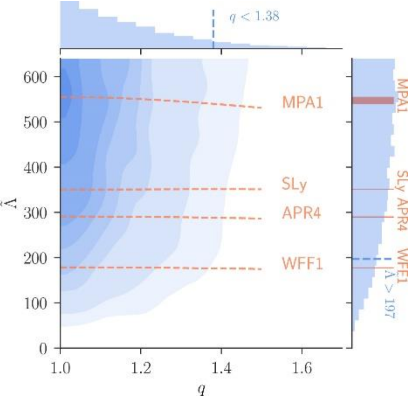
PRIOR WITH χEFT



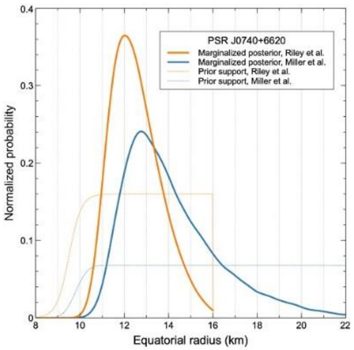


ASTROPHYSICAL OBSERVATIONS (ASTRO)
MACROSCOPIC COLLISIONS

M. Coughlin et al., Mon. Not. Roy. Astron. Soc. 480 (2018) 3, 3871-3878



Astrophys.J.Lett. 918 (2021) 2, L28
Astrophys.J.Lett. 918 (2021) 2, L27



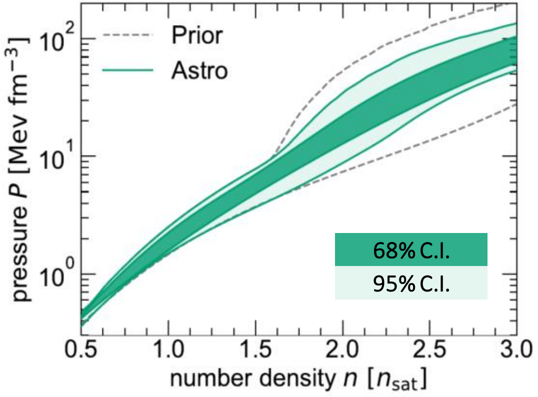
BINARY NEUTRON STAR MERGERS, GRAVITATIONAL WAVES AND KILONOVA

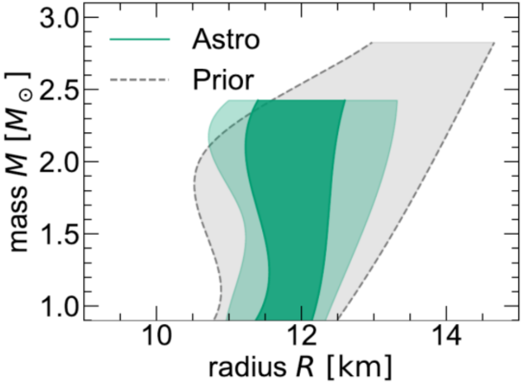
- Upper bound on neutron-star maximum mass: Information from remnant classification of GW170817/AT2017gfo, where black hole was formed after the coalescence
- GW Constraints: Reanalysis of GW170817 and GW190425 by using Bayesian inference (IMRPhenomPv2_NRTidalv2) by matching the observed GW data with theoretical GW models
- Kilonova Constraints: Analysis of AT2017gfo light-curves with full radiative transfer simulations

PULSAR OBSERVATIONS

- Lower bound on neutron-star maximum mass: Information from heavy radio pulsars' mass measurements (PSR J0348+0432 & PSR J1614-2230)
- Mass-Radius Constraints: X-ray pulse-profile modeling using data from NICER and XMM-Newton (PSR J0030+0451 & PSR J0740+6620)

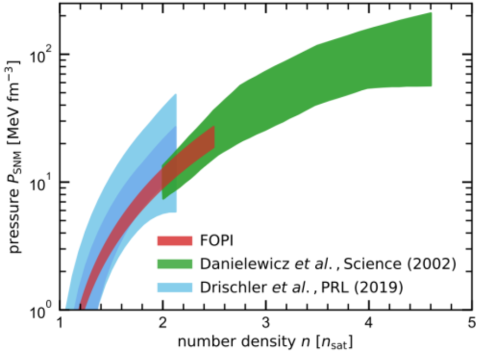
POSTERIOR WITH ASTRO

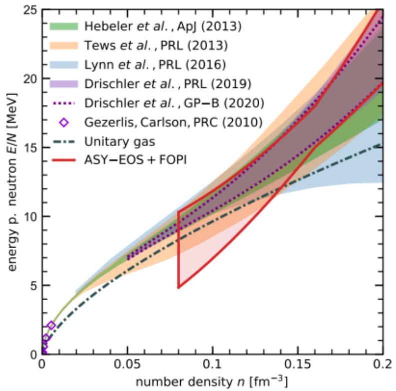




Constraints strongest above 1.5n_{sat} and high-mass region → Exclude the stiffest EOSs

HEAVY-ION COLLISIONS (HIC) MICROSCOPIC COLLISIONS





S. Huth, P.T.H. Pang et al., arXiv:2107.06229 [nucl-th]

$$\frac{E}{A}(n,\delta) \approx \frac{E}{A}(n,0) + S(n)\delta^2$$

Transport codes used to extract the EOS information

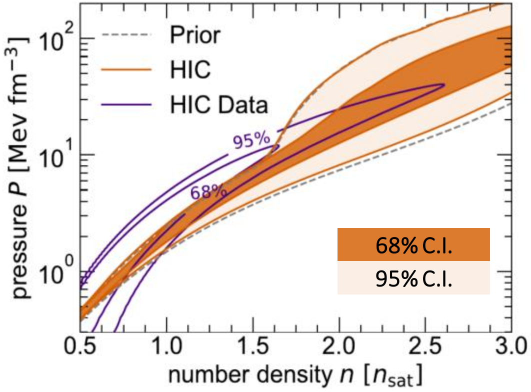
SYMMETRIC NUCLEAR MATTER ($\lesssim 4.5n_{sat}$)

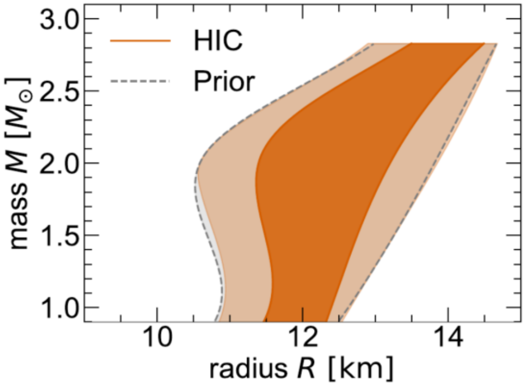
- Collective Flow: Nuclear incompressibility by FOPI-SIS18 (K = 175-225; IQMD, UrQMD; up) and HIC experiments at Bevalac and AGS (K > 260 MeV; BUU)
- Sub-threshold Strangeness Production: Nuclear incompressibility from the production of K^+ mesons produced in multi-step secondary collisions below production threshold by KaoS-SIS18 (K = 200 ; IQMD)

SYMMETRY ENERGY ($\lesssim 2n_{sat}$)

- Elliptic Flow Ratio of Isospin Partners: The slope parameter is deduced by ASY-EOS-SIS18 (L = 52-74 MeV; UrQMD, IQMD, TüQMD)
- Sub-Threshold Yield Ratios of Isospin Partners: The slope parameter is deduced by SπRIT-RIKEN (L = 42-117 MeV)

POSTERIOR WITH HIC





HIC tend to prefer EOSs stiffer than the ones favored by astro observations (up to $2n_{sat}$)

COMBINED BAYESIAN ANALYSIS
MICROSCOPIC + MACROSCOPIC COLLISIONS

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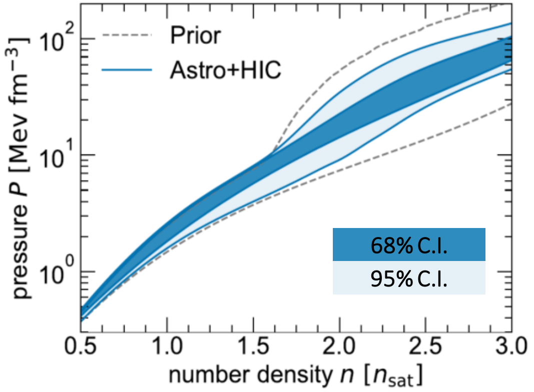
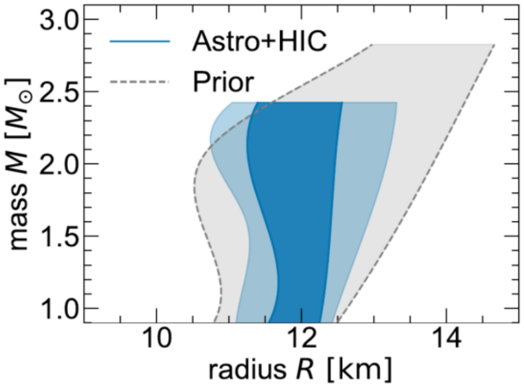
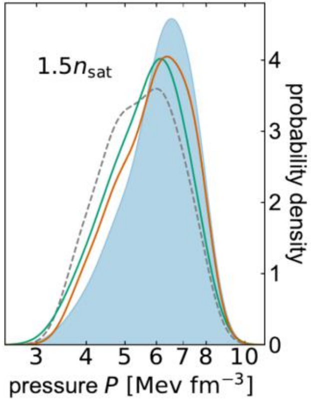
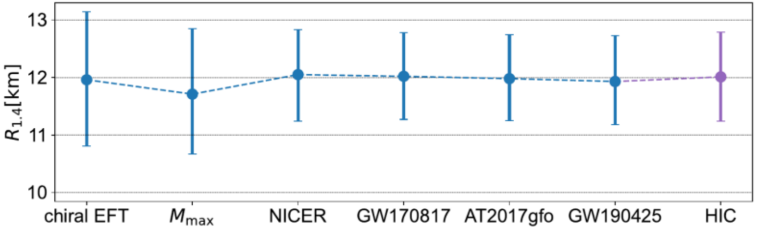
POSTERIOR WITH ASTRO+HIC

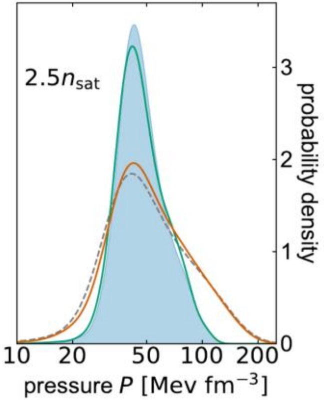






HIC experiments show remarkable agreement with astrophysical observations at 'lower' densities ($\sim 1.5n_{sat}$), i.e., where HIC data is available





FUTURE AT HIGHER DENSITIES

- Pressure PDF at $\geq 2.5n_{sat}$ is driven completely by Astro because existing HIC data loses sensitivity because of no data for symmetry energy and no precise data for symmetric nuclear matter
- Symmetry Energy: ASY-EOS-II, HADES, BM@N, CBM, …
- Symmetric Nuclear Matter: HADES, STAR-FXT, BM@N, CBM, …

Future HIC experiments probing higher densities can contribute significantly to constraint the properties of pure neutron matter under this Bayesian framework