Constraining neutron-star matter with microscopic and macroscopic collisions

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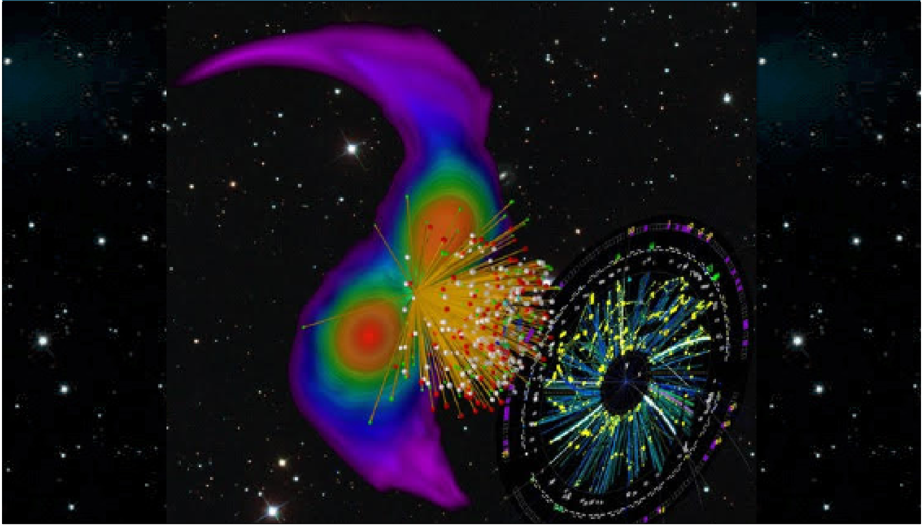

Equation of state (EOS) for neutron stars

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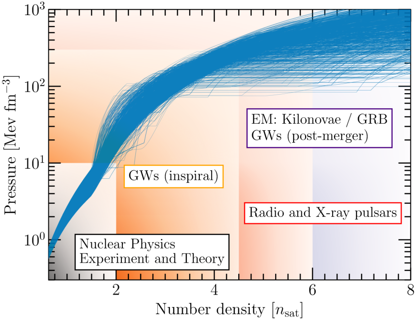
- EOS is well constrained at low (chiral EFT) and high densities (pQCD)
- Intermediate densities are sensitive to observations
  $\Rightarrow$ No tight constraints so far
- Heavy-ion collision (HIC) experiment offer complementary information
- Also promising: fRG calculations
  Leonhardt *et al.*, PRL (2020); Braun & Schallmo, arXiv:2204.00358

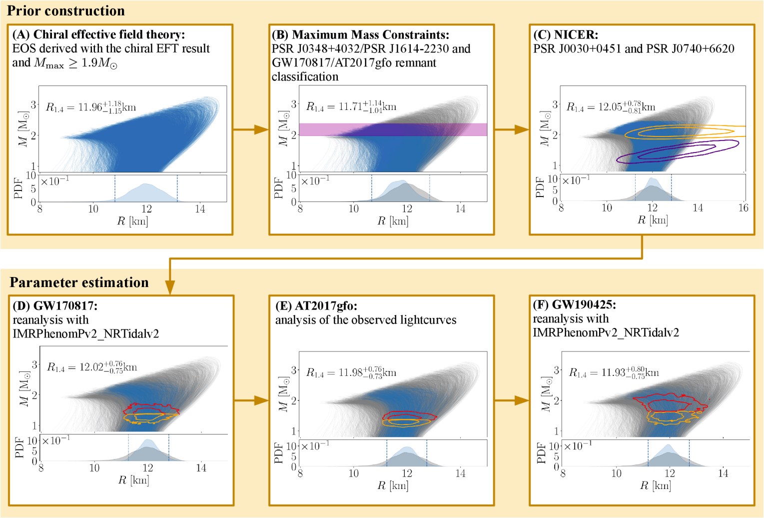
Constrain EOS with combined information from HICs and observations



Pang *et al.*, arXiv:2205.08513 (2022)

Bayesian multi-messenger framework

Dietrich *et al.*, Science (2020)



Prior construction

Tews *et al.*, PRC (2018)

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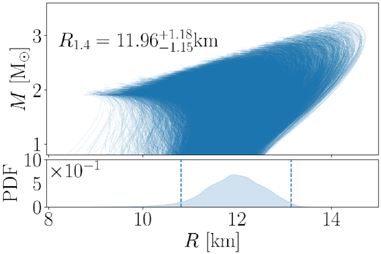
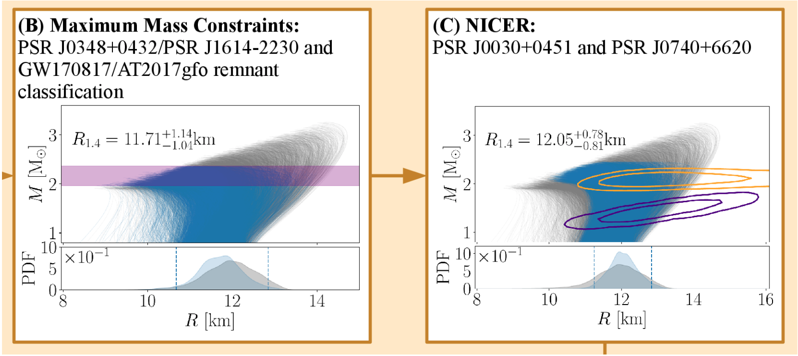
- Set of 15000 EOS
- Chiral EFT for $n \leq 1.5 n_{\text{sat}}$
- Speed of sound extension for higher densities
- General assumptions:
  - $M_{\max} \geq 1.9 M_{\odot}$
  - Causality $c_s \leq c$

(A) Chiral effective field theory:
EOS derived with the chiral EFT result and $M_{\max} \geq 1.9 M_{\odot}$



$M_{\max}$ and NICER

- $M_{\max}$ constraint from heavy pulsar masses and GW170817 estimates
- Results for mass and radius for two pulsars from NICER



Gravitational wave (GW) data

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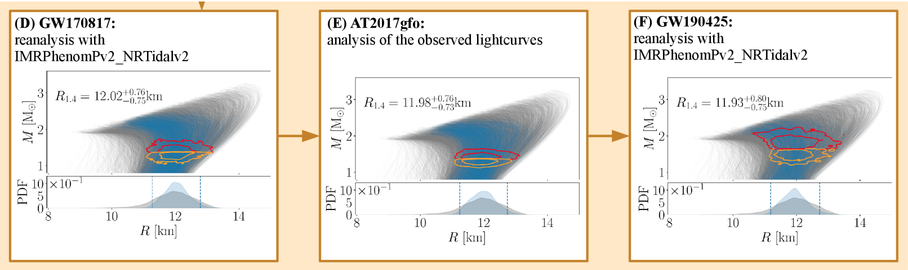
- Evaluation of GW170817 and GW190425 with improved waveform model
- Information of observed kilonova lightcurves from GW170817



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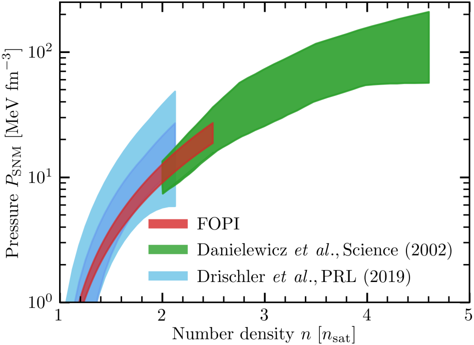
Heavy-ion collision constraints

Danielewicz *et al.*, Science (2002); Le Fèvre *et al.*, Nucl. Phys. A (2016)

- FOPI experiment: elliptic flow measurement from ^{197}Au $+^{197}$Au at GSI
- Constraint for $n \sim 1$–$3n_0$ for symmetric nuclear matter
- Result for incompressibility:
  $K = 220 \pm 25\,\mathrm{MeV}$
- consistent with chiral EFT
- Danielewicz *et al.*:
  - Consistent with FOPI
  - Used in density range where constraint for neutron-star matter is sensitive



SH, Pang *et al.*, Nature (2022)

Heavy-ion collision constraints

Russotto *et al.*, PRC (2016)

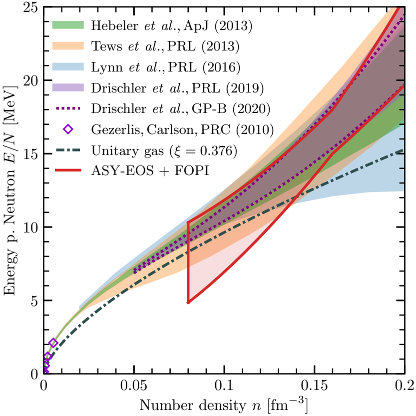
- ASY-EOS experiment: elliptic flow ratio for ^{197}Au $+ ^{197}$Au collision at GSI

- Constraint for $n \sim 1$–$2n_0$ for symmetry energy

$$S(n) = E_{\text{kin},0}\left(\frac{n}{n_0}\right)^{2/3} + E_{\text{pot},0}\left(\frac{n}{n_0}\right)^{\gamma_{\text{asy}}}$$

- γ_{asy} fitted to experimental data for $E_{\text{sym}} = 31\,\text{MeV}$ and $34\,\text{MeV}$

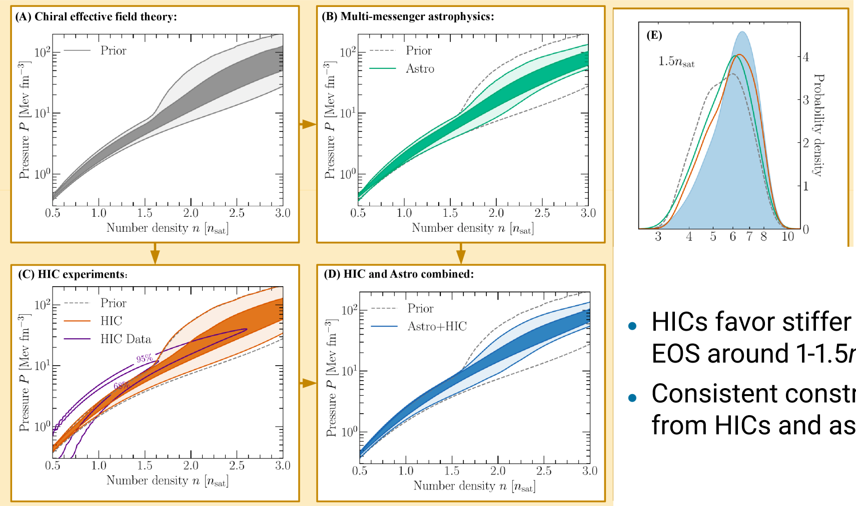
- Combination of FOPI and ASY-EOS yields constraint for neutron-star matter



SH, Pang *et al.*, Nature (2022)

Constraints on the EOS

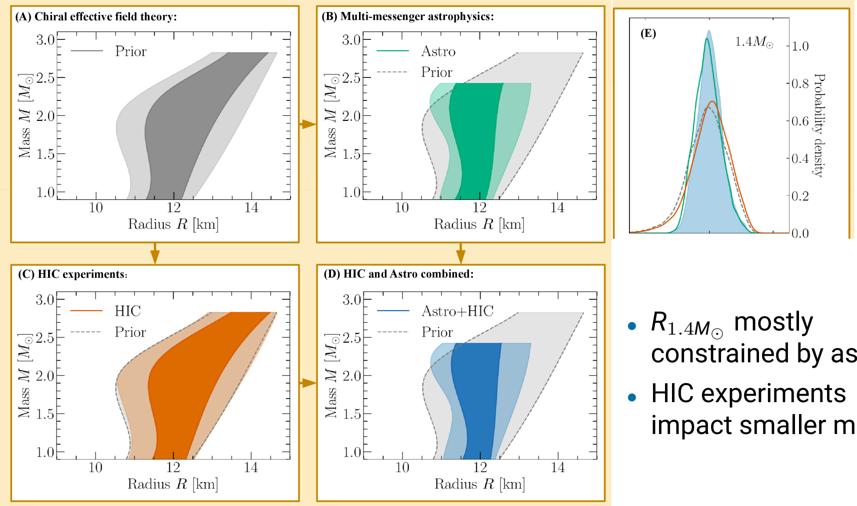
SH, Pang *et al.*, Nature (2022)



- HICs favor stiffer EOS around 1-1.5n_0
- Consistent constraints from HICs and astro

Constraints on neutron star mass and radius

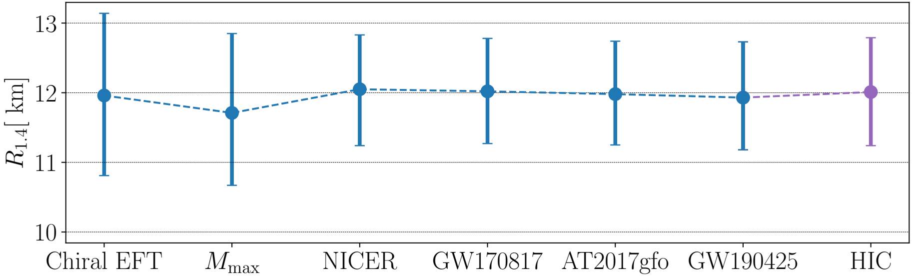
SH, Pang *et al.*, Nature (2022)



- $R_{1.4M_\odot}$ mostly constrained by astro
- HIC experiments impact smaller masses

Bayesian multi-messenger framework

- NICER prefers stiffer EOS while GW data point to smaller radii
- HIC shifts $R_{1.4}$ towards larger radii, similar to NICER



SH, Pang *et al.*, Nature (2022)

Summary

- Systematic and interdisciplinary study that combines nuclear theory, nuclear experiment, and observations
- Remarkable consistency between HIC experiments and constraints from nuclear theory and astrophysics

  → Future HIC constraints to pin down EOS uncertainty need:
  - intermediate densities where chiral EFT and observations are less sensitive
  - smaller uncertainties

Summary

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  → Future HIC constraints to pin down EOS uncertainty need:
  - intermediate densities where chiral EFT and observations are less sensitive
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Thank you for your attention!

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