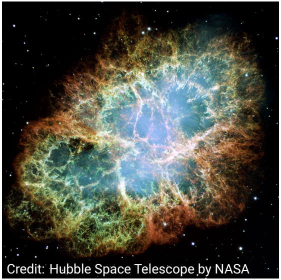
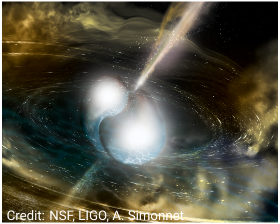
Nuclear equation of state constrained by nuclear physics, microscopic and macroscopic collisions

Sabrina Huth

Equation of state for astrophysical applications





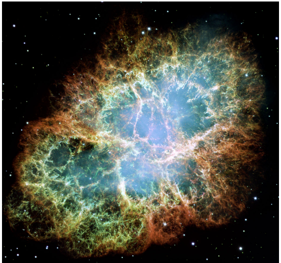
EOS is key microphysics input in

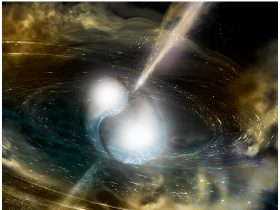
→ Core-collapse supernovae (CCSN) simulations

→ Neutron star merger (NSM) simulations

Overall Goal:
EOS for simulations consistent with nuclear physics and observations

Equation of state for astrophysical applications


Credit: Hubble Space Telescope by NASA


Credit: NSF, LIGO, A. Simonnet

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1. New EOS functional and EOS for astro applications
   Yasin, SH, Arcones, Schwenk, PRL (2020); SH, Wellenhofer, Schwenk, PRC (2021)
2. Constraints on EOS using heavy-ion collisions
   SH, Pang *et al.*, Nature (2022)

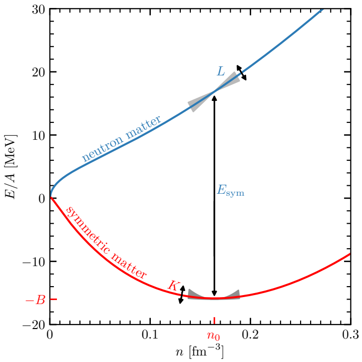
Starting point for building new EOS: Nuclear theory up to around saturation density

Expansion of energy per particle around n_0 and $\beta = (n_\mathrm{n} - n_\mathrm{p})/n$

$$\frac{E}{A}(n,\beta) = -B + \frac{K}{18}\left(\frac{n-n_0}{n_0}\right)^2 + S(n)\beta^2 + \ldots$$

Saturation density n_0 and energy B, incompressibility K

Symmetry energy $E_\mathrm{sym} \simeq S(n_0)$, slope $L \sim \partial_n E_\mathrm{sym}|_{n_0}$



Starting point for building new EOS: Nuclear theory up to around saturation density

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Expansion of energy per particle around n_0 and $\beta = (n_\mathrm{n} - n_\mathrm{p})/n$

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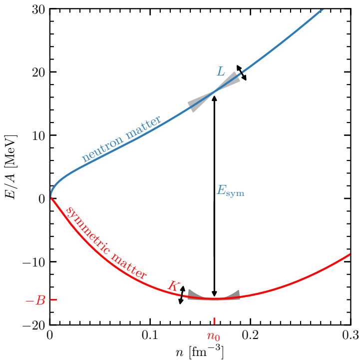
		Nucl. Theory	LS220	Shen
n_0	$[\mathrm{fm}^{-3}]$	0.164(7)	0.155	0.145
B	$[\mathrm{MeV}]$	15.86(57)	16.0	16.3
E_sym	$[\mathrm{MeV}]$	32(4)	29.3	36.9
L	$[\mathrm{MeV}]$	51(19)	73.7	110.8
K	$[\mathrm{MeV}]$	215(40)	220	281
$m^*/m\ (n_0)$		$\sim$ 0.9(2)	1.0	0.634



Hebeler *et al.*, PRC (2011); Hebeler *et al.*, APJ (2013); Drischler *et al.*, PRC (2016, 2017); Drischler *et al.*, PRL (2019)

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Energy density functional

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- Construct new energy density functional depending on density, proton fraction, and temperature:

$$\frac{E}{V}(n,x,T) = \sum_t \frac{\tau_t}{2m_t^*} + \sum_i \left[\frac{a_i}{d + n^{(\delta_i - 2)/3}} + \frac{4b_i x(1-x)}{d + n^{(\delta_i - 2)/3}} \right] n^{\delta_i/3+1} - xn\Delta\ ,$$

SH, Wellenhofer, Schwenk, PRC (2021)

with isospin $t = (n,p)$

kinetic energy density τ

nucleon effective mass m^*

- Choose δ, d to ensure good fit performance
- Fit parameters a_i, b_i to reproduce available EOS constraints

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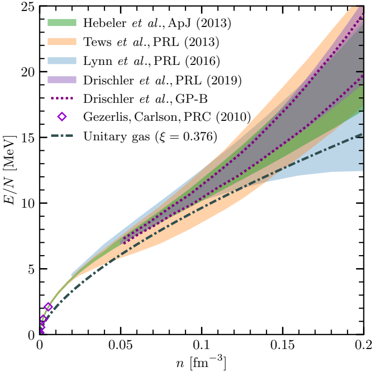
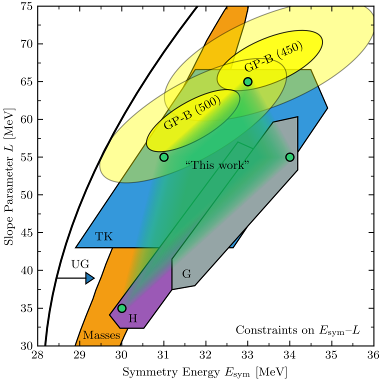
$\boxed{\text{Strategy: vary parameters to obtain broad EOS band}}$

Constraints from nuclear physics

Zero–temperature properties

- 4 E_{sym} - L pairs cover broad range of theoretical uncertainty
- Unitary gas serves as lower bound for PNM energy



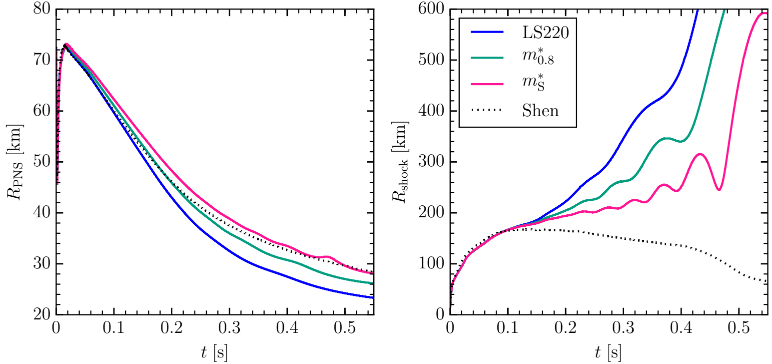


SH, Wellenhofer, Schwenk, PRC (2021); Lattimer & Lim, APJ (2013); Drischler, PRL (2020)

Constraints from nuclear physics

Nucleon effective mass and thermal effects

- Effective mass governs proto-neutron star contraction in CCSNe through thermal effects $\rightarrow$ Accurate implementation of m^* is crucial



Yasin, SH, Arcones, Schwenk, PRL (2020), cf. Schneider *et al.*, PRC (2019)

Constraints from nuclear physics

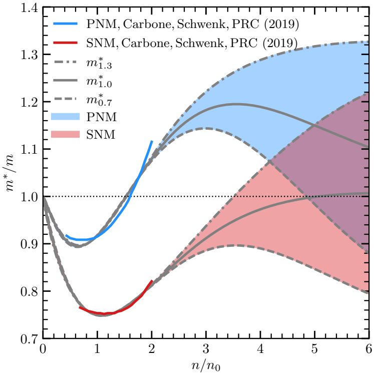
Nucleon effective mass and thermal effects

- Effective mass governs proto-neutron star contraction in CCSNe through thermal effects $\rightarrow$ Accurate implementation of m^* is crucial

- *Ab initio* calculations at finite temperature from chiral EFT
  Carbone & Schwenk, PRC (2019); Keller *et al.*, PRC (2021)

- m^* increases after saturation density due to 3N forces

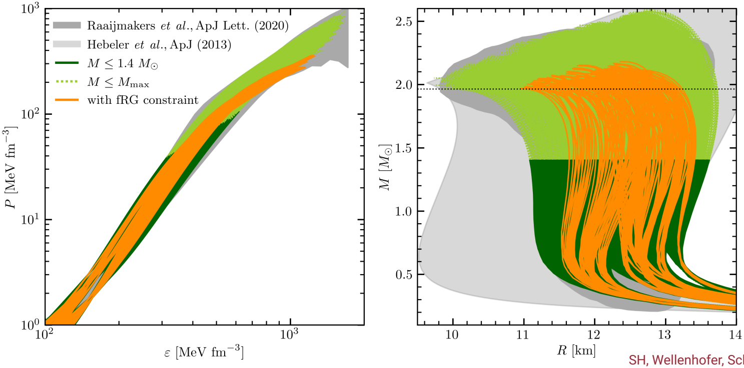
- Important impact on thermal index!



SH, Wellenhofer, Schwenk, PRC (2021)

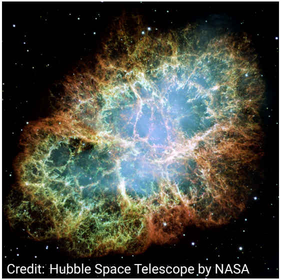
Neutron star properties

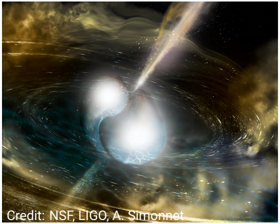
- Constraint from observations: 2σ bands from joint analysis of $2.14\ M_\odot$ + GW170817 + NICER from Raaijmakers *et al.*, APJ Lett. (2020)
- Additional high-density constraint for EOS of SNM based on QCD using functional Renormalization Group from Leonhardt *et al.*, PRL (2020)



SH, Wellenhofer, Schwenk, PRC (2021)

Equation of state for astrophysical applications


Credit: Hubble Space Telescope by NASA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Heavy-ion collision constraints

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

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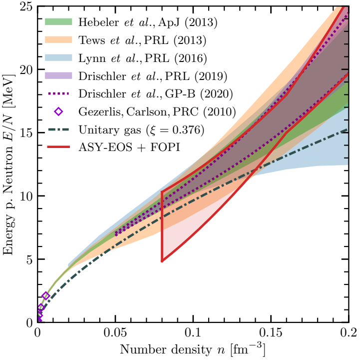
- FOPI and ASY-EOS experiments: ^{197}Au $+^{197}$Au collisions at GSI
  $\rightarrow$ Constraint for $\sim$ 1–2n_0
- Symmetric nuclear matter from FOPI:
  - incompressibility $K = 220 \pm 25\,\mathrm{MeV}$
- Symmetry energy from ASY-EOS:

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

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



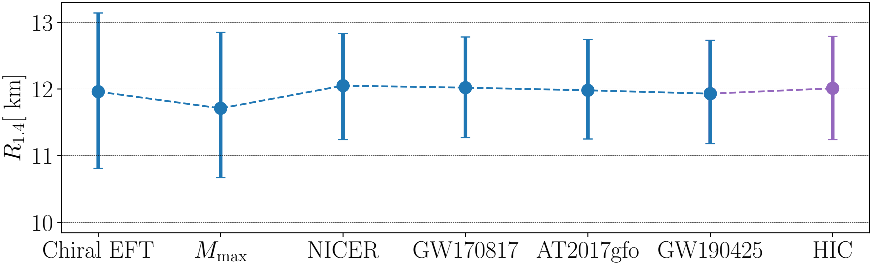
SH, Pang *et al.*, Nature (2022)

- Danielewicz *et al.*:
  - Constraint at higher densities consistent with FOPI
  - Used here in density range where ASY-EOS is sensitive

Bayesian multi-messenger framework

Dietrich *et al.*, Science (2020)

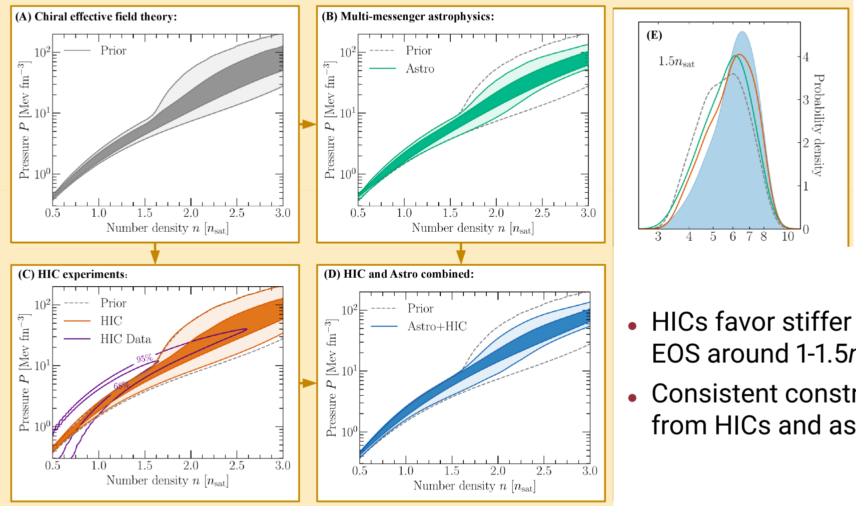
- EOS prior based on chiral EFT for $n \leq 1.5\, n_{\text{sat}}$ with speed of sound extension to higher densities by Tews *et al.*, PRC (2018)
- Observations: mass measurements, GW data, NICER data
- HIC shifts $R_{1.4}$ towards larger radii, similar to NICER



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

Constraints on the EOS

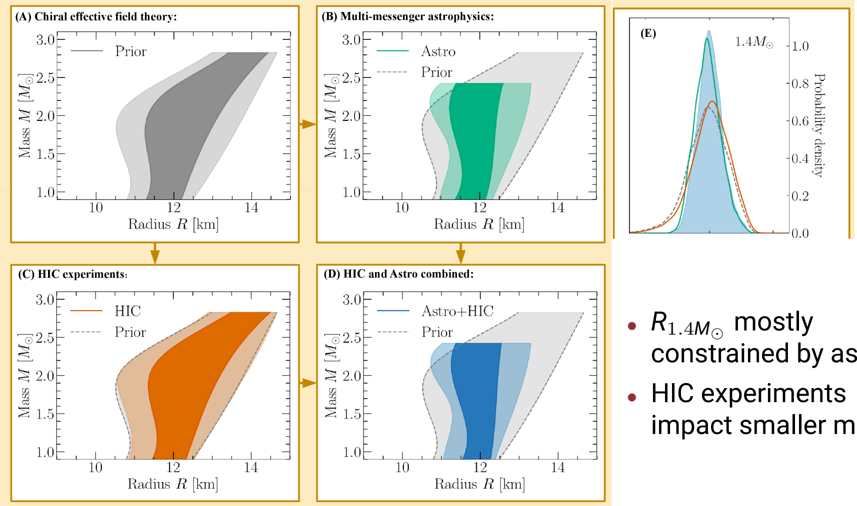
SH, Pang *et al.*, Nature (2022)



- 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

Summary

- Effective mass m^* mainly determines PNS contraction!
  $\rightarrow$ New m^* parametrization based on *ab initio* calculations
- New EOS functional interpolates flexibly and stable between low and high densities
- Systematic and interdisciplinary study that combines nuclear theory, nuclear experiment, and observations
- Remarkable consistency between HIC experiments and constraints from nuclear theory and astrophysics
  $\rightarrow$ Future HIC constraints with smaller uncertainties at intermediate densities can pin down uncertainties of the EOS and neutron star radii

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