New equations of state constrained by nuclear physics, observations & high-density QCD calculations

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with Corbinian Wellenhofer, Hannah Yasin, Almudena Arcones, and Achim Schwenk

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Picture credit: NASA/ESA Hubble Space Telescope

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Equation of state for astrophysical applications

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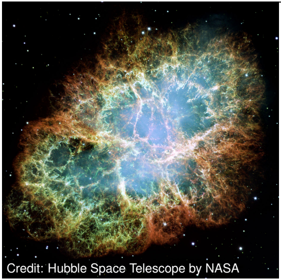
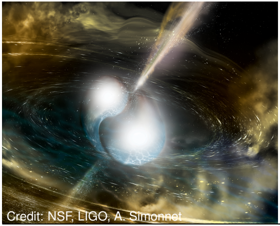

Credit: Hubble Space Telescope by NASA


Credit: NSF, LIGO, A. Simonnet

Microphysics inputs in core-collapse supernovae (CCSN) and neutron star merger (NSM) simulations are

1. Equation of state (EOS)
2. Neutrino interactions

Overall Goal: EOS and neutrino interactions for simulations consistent with each other and with nuclear physics and observations

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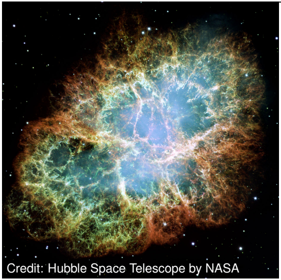

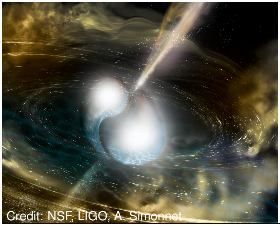

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Here: New EOS functional and EOS for astro applications

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Proto–neutron star (PNS) evolution

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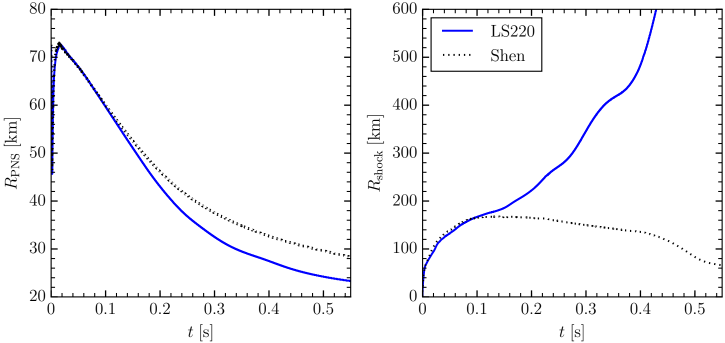
Sim: 1*D* with heating factor, FLASH code, M1 ν–transport, 15 $M_\odot$ progenitor

Fryxell *et al.*, APJ Suppl. Ser. (2000); O'Connor, Couch, APJ (2018); Woosley *et al.*, RMP (2002)

PNS evolution is sensitive to EOS → Faster contraction favors explosion



Yasin, SH, Arcones, Schwenk, PRL (2020)

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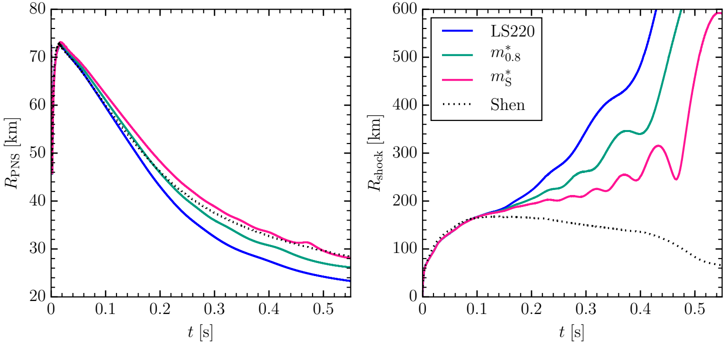

Key finding: effective mass m^* mainly determines PNS contraction!

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

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Constraints from nuclear physics

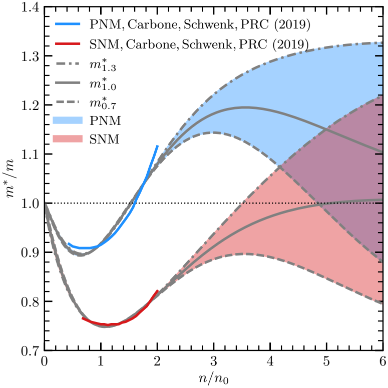
Nucleon effective mass and thermal effects

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

- *Ab initio* calculations at finite temperature from chiral EFT
  Carbone & Schwenk, PRC (2019)

- m^* increases after saturation density due to 3N forces
  → Need new parametrization $m^*(n, x)$

- Behavior at densities above $2n_0$ unknown
  → Investigate different scenarios



SH, Wellenhofer, Schwenk, PRC (2021)

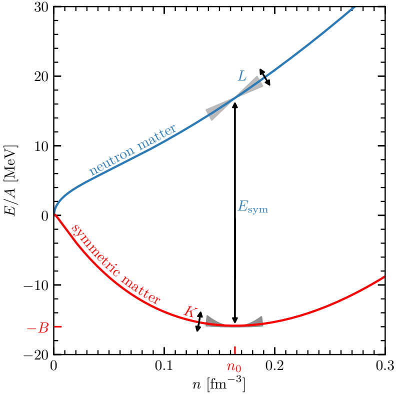
Starting point for building new EOS: Nuclear theory up to around saturation density

Expansion of energy per particle around n_0 and $\beta = (n_n - n_p)/n$

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

Saturation density n_0 and energy B, incompressibility K

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



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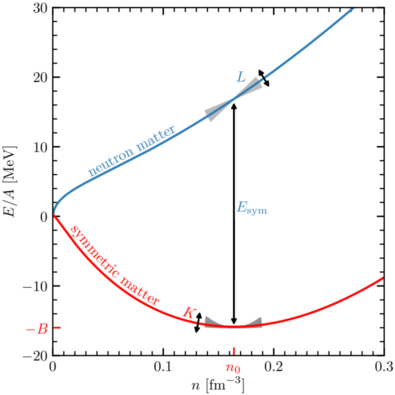
		Nucl. Theory	LS220	Shen
n_0	[fm^{-3}]	0.164(7)	0.155	0.145
B	[MeV]	15.86(57)	16.0	16.3
E_{sym}	[MeV]	32(4)	29.6	36.9
L	[MeV]	51(19)	73.7	110.8
K	[MeV]	215(40)	220	281
$m^*/m\,(n_0)$		$\sim$ 0.9(2)	1.0	0.634



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

Energy density functional

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

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

with isospin $t = (n, p)$

kinetic energy density τ

nucleon effective mass m^*

SH, Wellenhofer, Schwenk, PRC (2021)

- Choose δ, d to ensure good fit performance:
  - $\delta_{i,k_\mathrm{F}} = \{3, 4, 5, 6\}$ with d fixed to 1, 3, 5, or 7
  - $\delta_{i,n} = \{3, 6, 9, 12\}$ with d fixed to 0.2, 0.4, 0.6, or 0.8

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kinetic energy density τ

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SH, Wellenhofer, Schwenk, PRC (2021)

- Fit parameters a_i, b_i to reproduce available EOS constraints:
  - Nuclear matter properties: $n_0, B, K, E_{\mathrm{sym}}, L$
  - Neutron matter at low density from QMC calculations
    Gezerlis & Carlson, PRC (2010)
  - Pressure of PNM and SNM at high densities

Constraints from nuclear physics

Zero temperature properties

Expansion of energy per particle around n_0 and $\beta = (n_n - n_p)/n$

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

- Symmetric nuclear matter (SNM):

  Saturation density $n_0 = 0.164(7)\ \mathrm{fm}^{-3}$

  Binding energy $B = 15.86(57)$ MeV

  Incompressibility $K = 215(40)$ MeV

  Hebeler *et al.*, PRC (2011); Drischler *et al.*, PRC (2016) & PRL (2019)

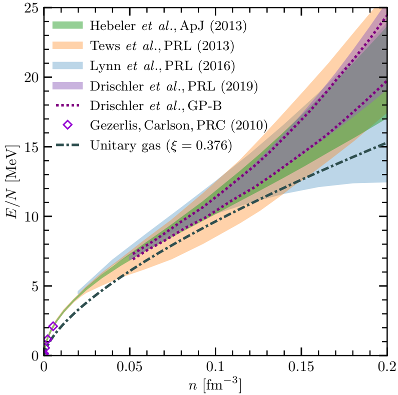
  $\rightarrow$ 3 (n_0, B, K) triples to cover ranges

- Pure neutron matter (PNM):

  Symmetry energy $E_{sym} \simeq S(n_0)$

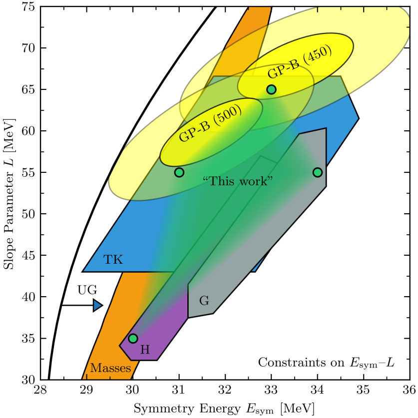
  Slope parameter $L \sim \partial_n E_{sym}|_{n_0}$

  $\rightarrow$ PNM uncertainty band



Variations of nuclear matter properties

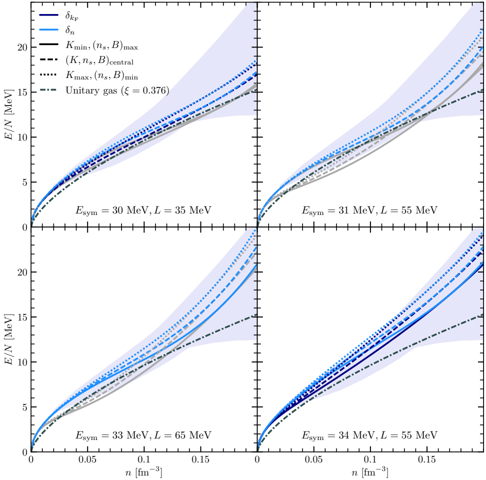
$E_{sym} - L$ correlation



- Microscopic calculations with various many-body methods:
  - H Hebeler, Schwenk, PRC (2010)
  - G Gandolfi *et al.*, PRC (2012)
  - TK Tews, Krüger *et al.*, PRL (2013)
  - GP-B Drischler *et al.*, arXiv:2004.07232
- Calculations consistent with unitary gas conjecture
  Tews *et al.*, APJ (2017)
- 4 E_{sym}, L pairs cover broad range of theoretical uncertainty and agree with dipole polarizability experiments (B04)
  SH, Wellenhofer, Schwenk, PRC (2021)

Lattimer & Lim, APJ (2013); Drischler *et al.*, PRL (2020)

Variations of nuclear matter properties



- 4 E_{sym}, L panels cover PNM uncertainty band
- Unitary gas serves as lower bound for PNM

  Tews *et al.*, APJ (2017)

SH, Wellenhofer, Schwenk, PRC (2021)

Constraints from observations

Greif *et al.*, MNRAS (2019)

Raaijmakers *et al.*, APJ Lett. (2020)

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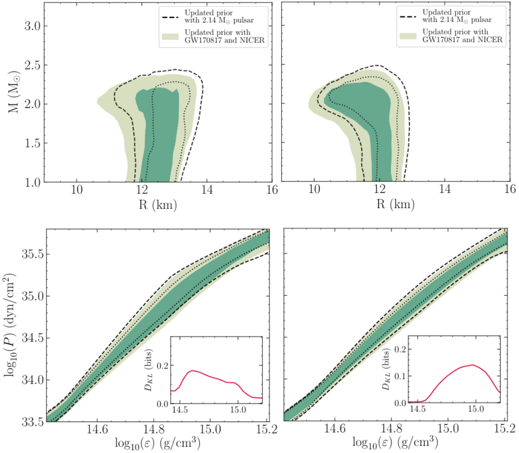
PP model

CS model



- 2σ bands from joint analysis of $2.14\ M_\odot$ + GW170817 + NICER
- Based on general EOS extensions:
  - Piecewise polytropes (PP)
  - Speed of sound model (CS)

$\rightarrow$ Additional constraint for functional: EOS needs to support $\sim 2\ M_\odot$

Antoniadis *et al.*, Science (2013)
Cromartie *et al.*, Nature Astron. (2020)

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Neutron star matter

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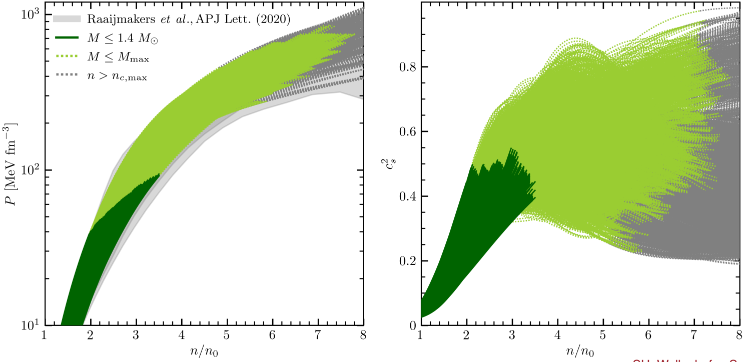
- Restrict pressure to lie within 2σ bands of Raaijmakers *et al.*, APJ Lett. (2020) $\rightarrow$ EOS span almost entire band

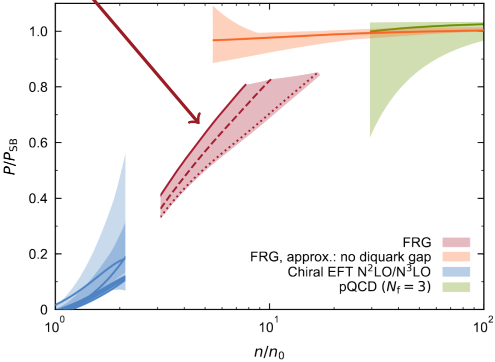


SH, Wellenhofer, Schwenk, PRC (2021)

Constraints from high-density QCD calculations

Leonhardt *et al.*, PRL (2020)

- First high-density calculations for EOS of SNM based on QCD using functional Renormalization Group (fRG)
- Remarkable consistency with chiral EFT results
- Results imply maximum for speed of sound

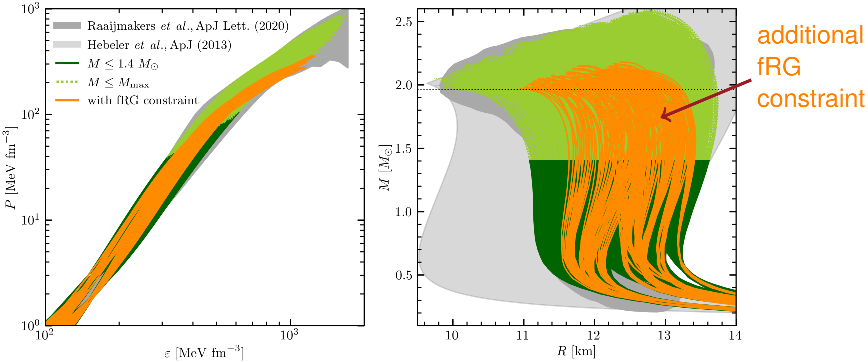


Neutron star properties

Mass-radius relation

- Compute mass–radius relations via Tolman–Oppenheimer–Volkoff equations

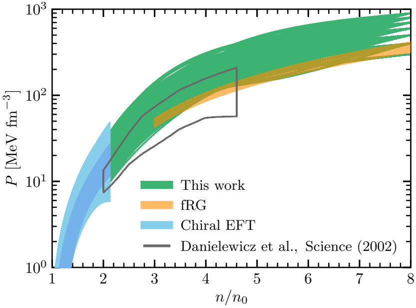
$R_{1.4M_\odot}$ = 11.1 – 13.6 km



SH, Wellenhofer, Schwenk, PRC (2021)

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 density
- SNM: Promising consistency between different dense-matter constraints



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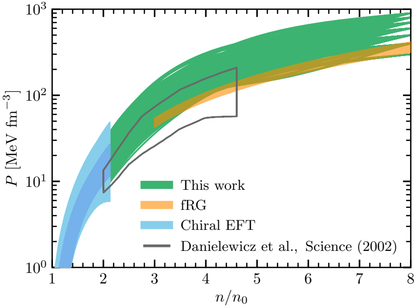

Collaborators:

C. Wellenhofer, H. Yasin, A. Arcones, A. Schwenk

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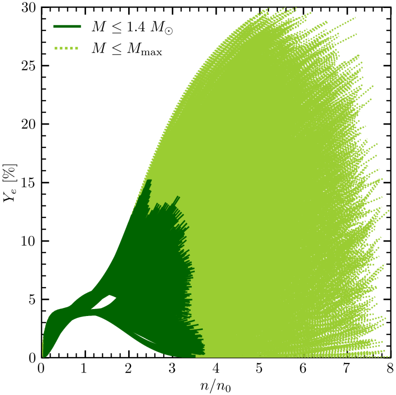
Thank you!

Back-up: Electron fraction

- Electron fraction for canonical neutron stars mostly satisfy

  $Y_{e,1.4M_\odot} \lesssim 11\%$

  → Consistent with observations of neutron star cooling



Back-up: Maximum mass

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- Maximum masses mostly consistent with boundary inferred from GW170817: $M_{\text{max}} \lesssim 2.3 - 2.4\ M_\odot$

e.g., Margalit, Metzger, APJ (2017)
Shibata *et al.*, PRD (2017)
Rezzolla *et al.*, APJ (2018)