Equation of state effects in core-collapse supernovae

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

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Picture credit: NASA/ESA Hubble Space Telescope

Proto–neutron star evolution

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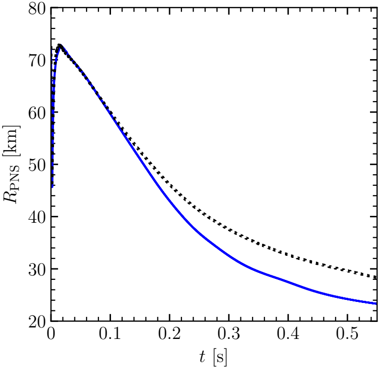
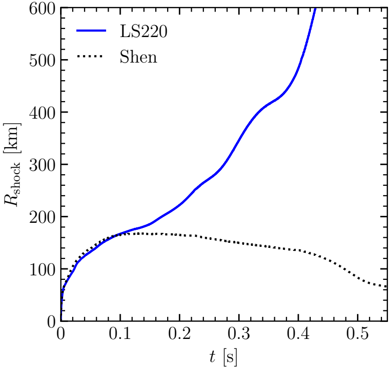
Proto–neutron star (PNS) evolution is sensitive to equation of state (EOS)

$\rightarrow$ faster contraction favors explosion





Yasin, SS, Arcones, Schwenk, arXiv:1802.02002; cf. Janka, ARNPS (2012)

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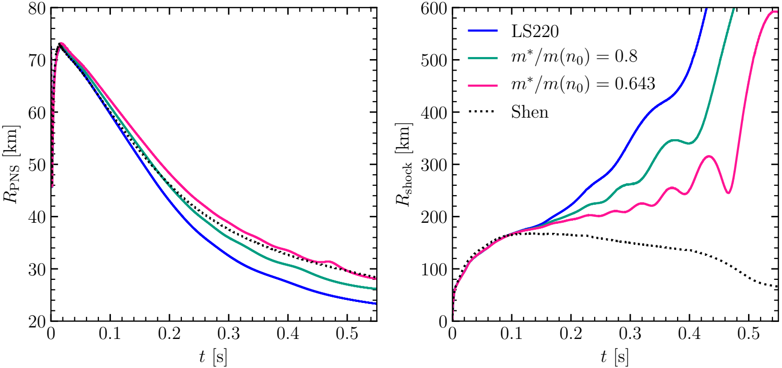

key finding: effective mass m^* mainly determines PNS contraction!

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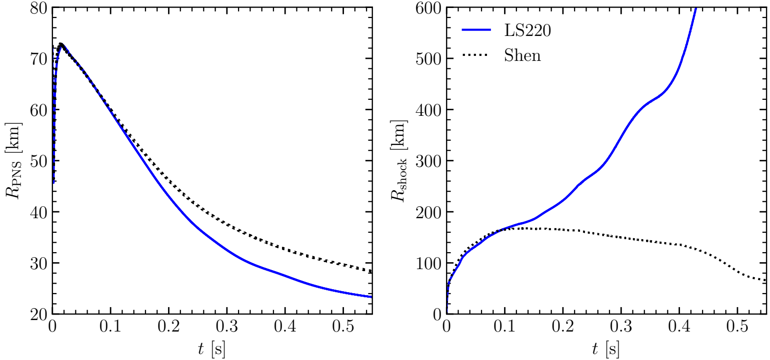
Equations of state for supernova simulations

EOS differ in underlying theory and nuclear matter properties

- LS EOS: based on Skyrme energy density functional
- Shen EOS: Relativistic mean–field theory



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Equation of state of nuclear matter

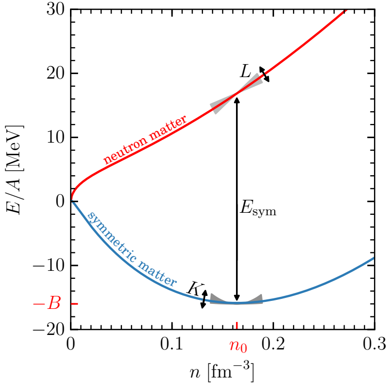
$T = 0$ **properties**

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

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

saturation density n_0, binding energy B,
incompressibility K, symmetry energy $S(n_0) \simeq E_{sym}$

		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); Wellenhofer *et al.*, PRC (2014); Drischler *et al.*, PRC (2016, 2017); Drischler *et al.*, PRL (2019)

Skyrme parameters and nuclear matter properties

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LS EOS: simplified Skyrme energy density functional for nucleons

$$\frac{E}{V}(n,x,T) = \sum_t \frac{\tau_t}{2m_t^*} + [a + 4bx(1-x)]\,n^2 + cn^{1+\delta} - xn\Delta$$

Lattimer, Swesty, Nucl. Phys. A (1991)

with density–dependent $m^*(n)$: $\frac{1}{2m_t^*} = \frac{1}{2m} + \alpha n$

Skyrme parameters depend on nuclear matter properties m^*, K, E_{sym}, B, n_0

systematically vary nuclear matter properties one by one

Skyrme parameters and nuclear matter properties

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generated with SRO Code, Schneider, Roberts, Ott, PRC (2017)

LS EOS: simplifi

$\frac{E}{V}(r$

with density–deper

model	$m^*/m\,(n_0)$	K [MeV]	E_{sym} [MeV]	n_0 [fm^{-3}]	B [MeV]
LS220	1.0	220	29.3	0.155	16
$m^*_{0.8}$	0.8	220	29.3	0.155	16
m^*_S	0.634	220	29.3	0.155	16
$(m^*, K)_S$	0.634	281	29.3	0.155	16
$(m^*, E_{sym})_S$	0.634	220	36.9	0.155	16
$(m^*, K, E_{sym})_S$	0.634	281	36.9	0.155	16
SkShen	0.634	281	36.9	0.145	16.3

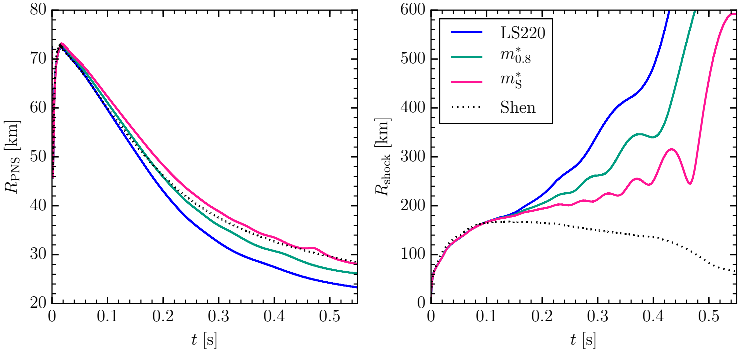
Skyrme parameters depend on nuclear matter properties m^*, K, E_{sym}, B, n_0

systematically vary nuclear matter properties one by one

Proto–neutron star contraction and shock behavior

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

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



- PNS contraction mainly governed by effective mass

Yasin, SS, Arcones, Schwenk, arXiv:1802.02002;
cf. Schneider *et al.*, PRC (2019)

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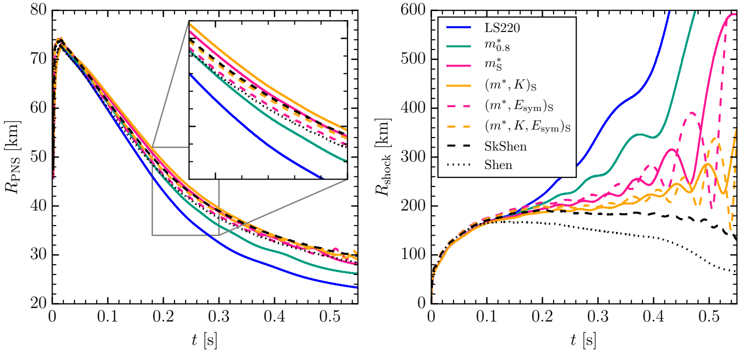
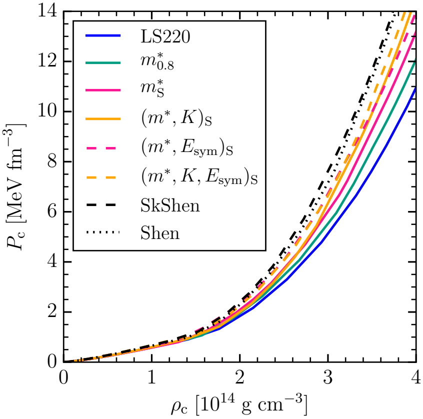


- PNS contraction mainly governed by effective mass
- incompressibility and symmetry energy only small impact
- important effect from saturation point $\rightarrow$ SkShen

Yasin, SS, Arcones, Schwenk, arXiv:1802.02002; cf. Schneider *et al.*, PRC (2019)

Impact on central pressure and density



- $P \sim 1/m^*$
  $\rightarrow$ smaller m^* leads to larger pressure
- larger incompressibility of Shen stiffens EOS further
- SkShen model yields similar pressure as Shen EOS
  ($\rightarrow$ nuclear matter properties more important than theoretical framework)

Yasin, SS, Arcones, Schwenk, arXiv:1802.02002

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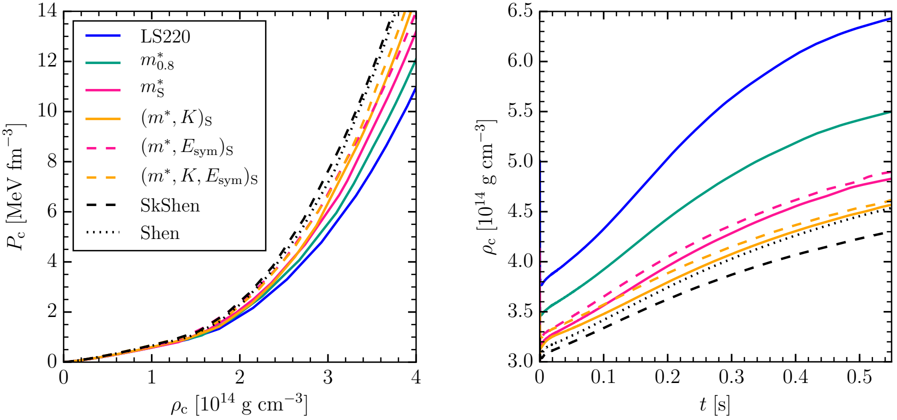

- larger pressures result in smaller densities

Yasin, SS, Arcones, Schwenk, arXiv:1802.02002

Characterizing thermal effects

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- separate pressure and energy density into cold and thermal part

$\rightarrow$ thermal index $\Gamma_{\text{th}} = 1 + \frac{P_{\text{th}}}{\epsilon_{\text{th}}} = 1 + \frac{P - P_{\text{cold}}}{\epsilon - \epsilon_{\text{cold}}}$

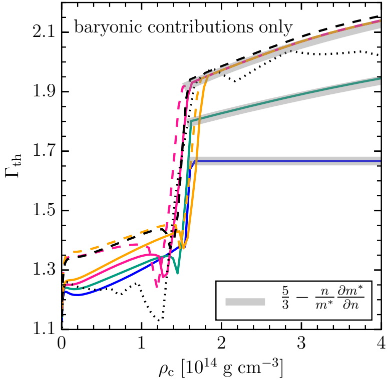
e.g., Bauswein *et al.*, PRD (2010)

- analytical limits:

non–relativistic free or unitary Fermi gas: $\Gamma_{\text{th}} = \frac{5}{3}$

ideal Fermi gas with $m^*(n)$: $\Gamma_{\text{th}} = \frac{5}{3} - \frac{n}{m^*}\frac{\partial m^*}{\partial n}$

- Γ_{th} solely depends on m^* at high ρ where matter is homogeneous



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Central entropy, electron fraction, and temperature

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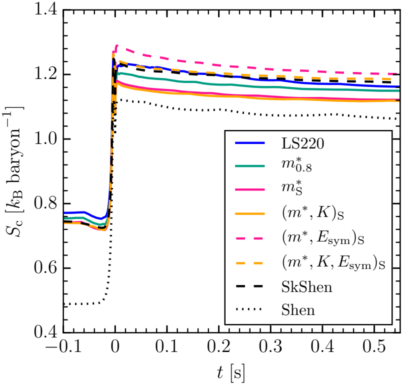

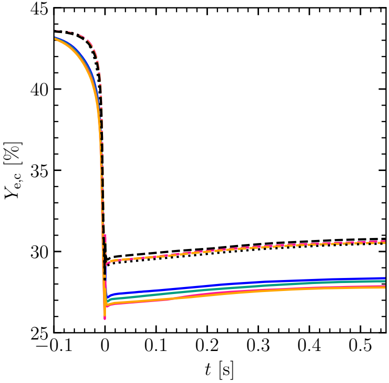

- larger E_{sym} increases electron fractions → larger entropies
- temperatures increase for $m^* < m$ due to similar entropies and $S \sim m^* T$

Yasin, SS, Arcones, Schwenk, arXiv:1802.02002

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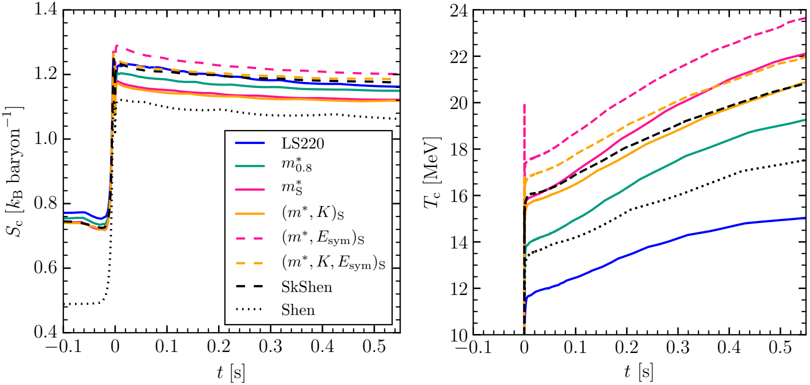

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Mass–radius relation of cold neutron stars

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

  cold neutron stars: $T = 0$

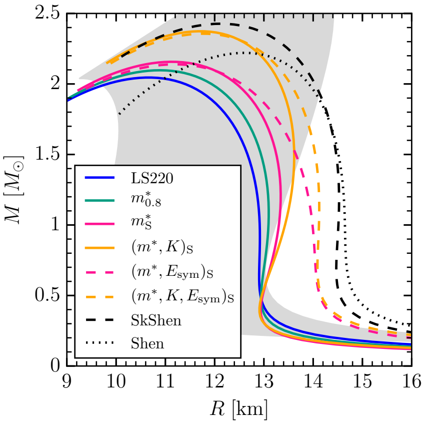
  beta equilibrium: $\mu_\nu = 0$

- gray band: radius uncertainty band
  Hebeler *et al.*, APJ (2013)

- all new parametrizations fulfill mass constraint of a $\sim 2\ M_\odot$ neutron star
  Demorest *et al.*, Nature (2010)
  Antoniadis *et al.*, Science (2013)

- radius mostly affected by E_{sym}/L

- maximal masses and radii increase for smaller m^* and larger K



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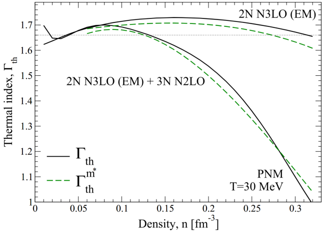
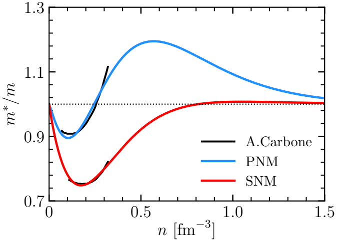
Constraints from *ab initio* calculations and observations

Nucleon effective mass and thermal effects

- *ab initio* calculations at finite temperature
  Carbone, Schwenk, PRC(2019)
- thermal index approximation with m^* fits thermal index from chiral EFT very well
- m^* increases after saturation density again
  $\rightarrow$ need new parametrization
- behavior at densities above $2n_0$ unknown
- important impact on thermal index
  $\rightarrow$ simulation!



Carbone, Schwenk, PRC(2019)



Constraints from *ab initio* calculations

Nuclear matter properties

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- extend LS Skyrme functional to incorporate more constraints
- use estimates for nuclear matter properties from chiral effective field theory

K	E_{sym}	L	n_0	B
215(40)	32(4)	51(19)	0.164(7)	15.86(57)

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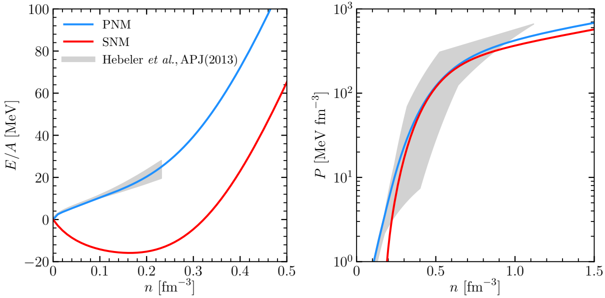
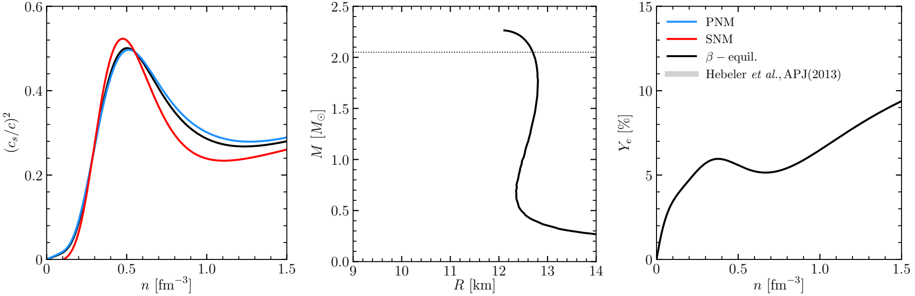


High-density constraints

Work in progress!

- causality: speed of sound $c_s \leq c$
- maximum mass $M_{\max} \gtrsim 2\ M_\odot$
  Cromartie *et al.*, Nature Astronomy (2020)
- electron fraction $Y_e \lesssim 0.1$ up to $10n_0$



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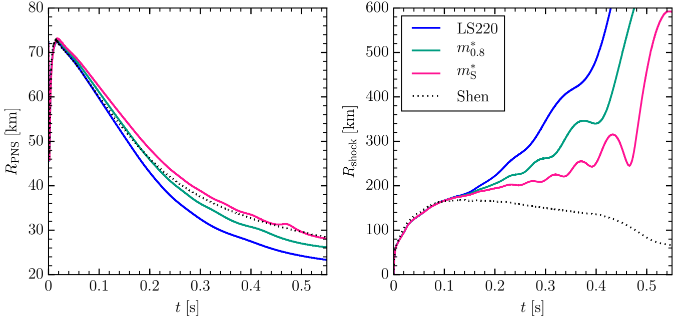

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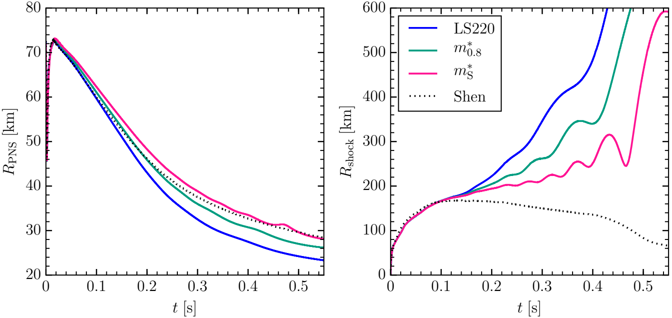

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Thank you!

Collaborators: A. Carbone, C. Wellenhofer, H. Yasin, A. Arcones, A. Schwenk