Equation of State for Astrophysical Applications

DTP/TALENT 2024 — Nuclear Theory for Astrophysics

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EOS Effects on the Core-collapse of a 20-$\mathrm{M}_\odot$ star

Codes/data used on the paper:

- SROEOS (Schneider *et al.* 2017)
- NuLib (O'Connor 2015)
- GR1D (O'Connor & Ott 2010, 2011)
- Zelmani (Roberts *et al.* 2016, Löffler *et al.* 2012, Mösta *et al.* 2014)
- 20 $\mathrm{M}_\odot$ pre-SN progenitor star of Woosley & Heger (2007).

Published on *Physical Review C*

SRO EOSs

Schneider *et al.* (2019). See also Yasin *et al.* (2020).

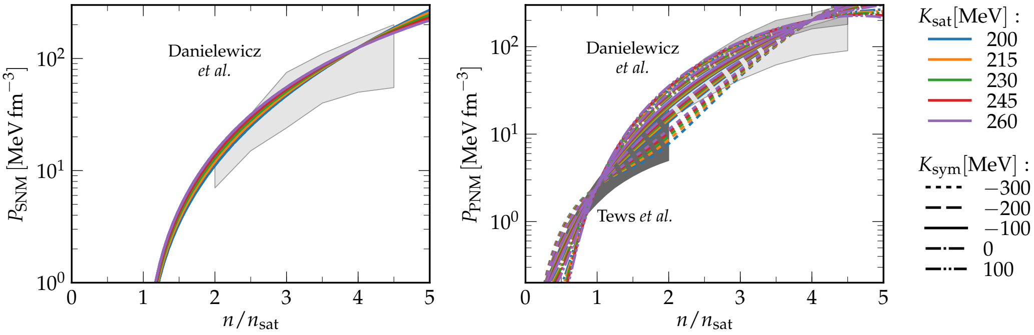
Study EOS effects in 4 sets of 25 EOSs:

Analyze $\pm 1\sigma$ and $\pm 2\sigma$ changes in two quantities at a time.

Set	Quantity	x	Exp/Theory	Schneider+2019	Units
s_M	$m_n^\star(n_{\text{sat}},1/2)$	0	0.75 ± 0.10	0.75 ± 0.10	m_n
	$\Delta m^\star(n_{\text{sat}},0)$	0	0.10 ± 0.10	0.10 ± 0.10	m_n
-	n_{sat}	0	0.155 ± 0.005	0.155	fm^{-3}
	ϵ_{sat}	0	-15.8 ± 0.3	-15.8	MeV baryon^{-1}
s_S	ϵ_{sym}	0	32 ± 2	32 ± 2	MeV baryon^{-1}
	L_{sym}	0	60 ± 15	45 ± 7.5	MeV baryon^{-1}
s_K	K_{sat}	0	230 ± 20	230 ± 15	MeV baryon^{-1}
	K_{sym}	0	-100 ± 100	-100 ± 100	MeV baryon^{-1}
s_P	$P_{SNM}^{(4)}$	1	100 ± 50	125 ± 12.5	MeV fm^{-3}
	$P_{PNM}^{(4)}$	1	160 ± 80	200 ± 20	MeV fm^{-3}

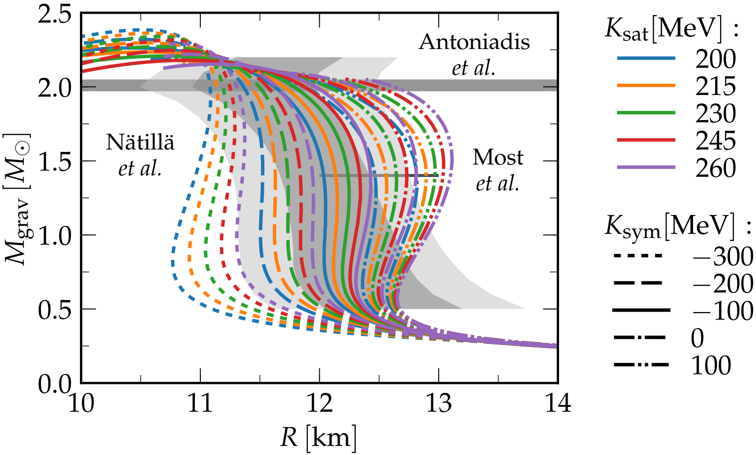
EOS constraints from Margueron *et al.* (2018) and Danielewicz *et al.* (2002).

Nuclear Incompressibility Effect in Nuclear Matter Pressure



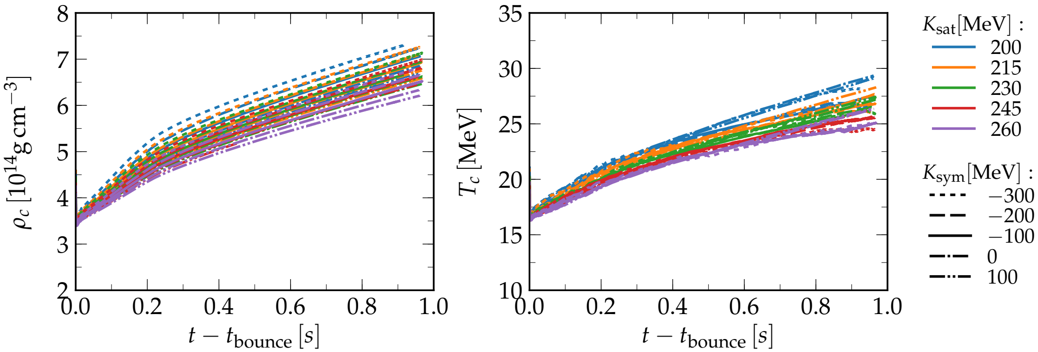
Effect of changing K_{sat} e K_{sym} in the pressure os SNM (left) and PNM (right).

Nuclear Incompressibility Effect in Cold NSs



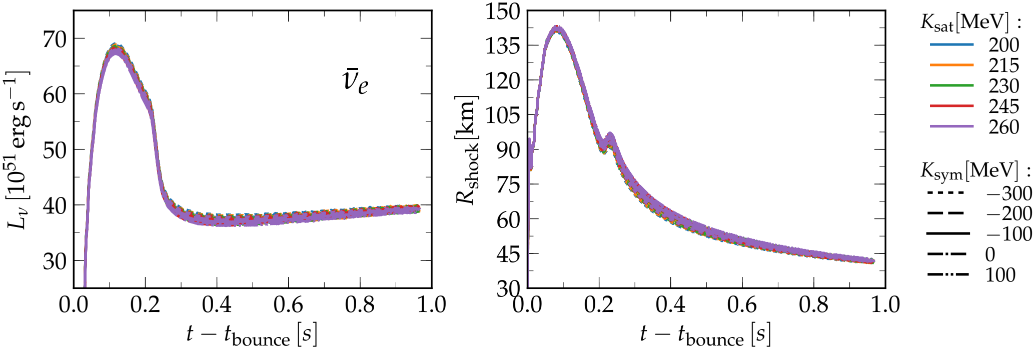
Effect of changing K_{sat} e K_{sym} in the mass-radius relationships of neutron stars.

Nuclear Incompressibility Effect in CCSNe



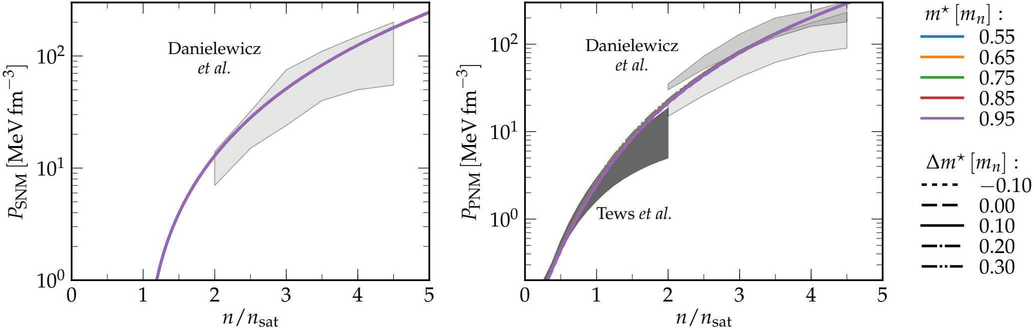
Effect of changing K_{sat} e K_{sym} in the central density and central temperature of a PNS formed in the core-collapse of a 20 $M_{\odot}$ star simulated with GR1D.

Nuclear Incompressibility Effect in CCSNe



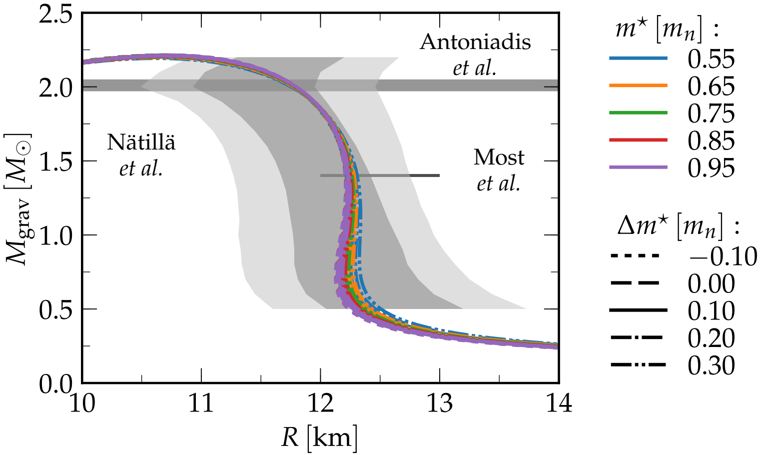
Effect of changing K_{sat} e K_{sym} in the $\bar{\nu}_e$ neutrino signal and the shock radius from the core-collapse of a 20 $M_\odot$ star simulated with GR1D.

Effective Mass Effect in Nuclear Matter Pressure



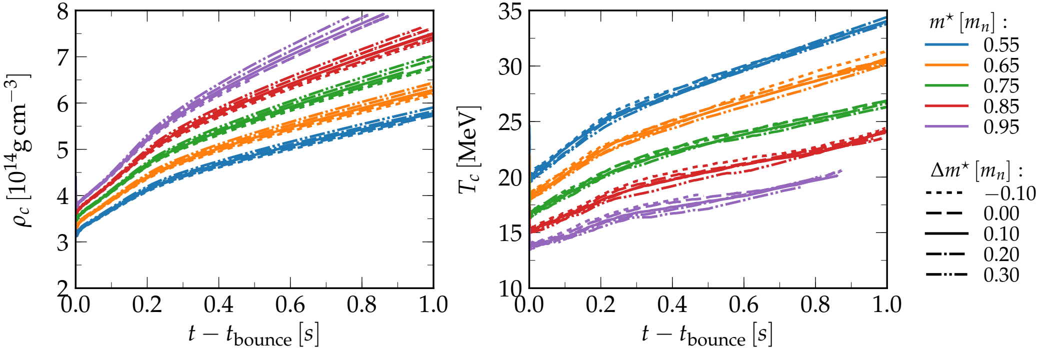
Effect of changing the $m^\star$ e $\Delta m_\star$ on the pressure os SNM (left) and PNM (right).

Effective Mass Effect in Cold NSs



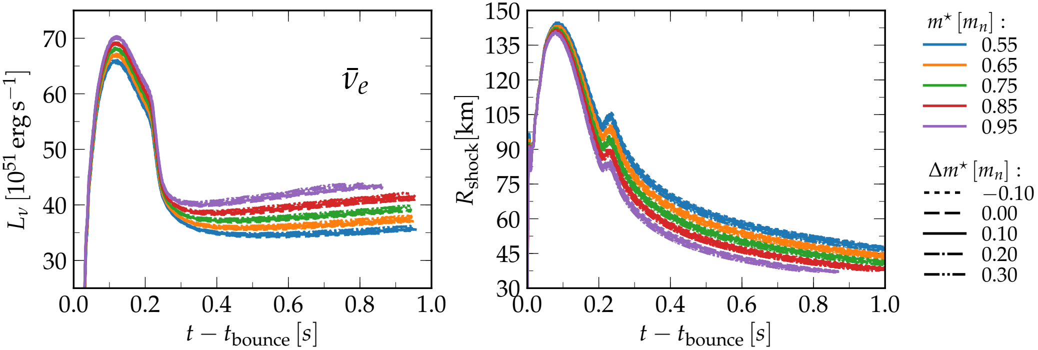
Effect of changing $m^\star$ e $\Delta m_\star$ on the mass-radius relationships of neutron stars.

Nuclear Incompressibility Effect in CCSNe



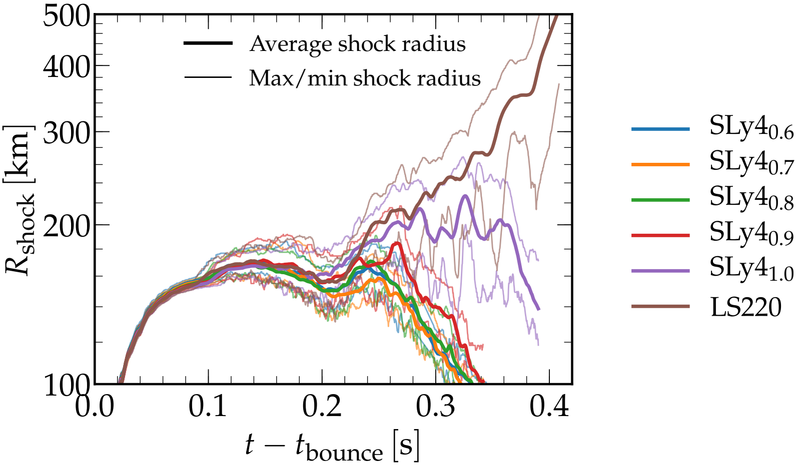
Effect of changing $\mathrm{m}^\star$ e $\Delta \mathrm{m}_\star$ on the central density and central temperature of a PNS formed in the core-collapse of a $20\,\mathrm{M}_\odot$ star simulated with GR1D.

Nuclear Incompressibility Effect in CCSNe



Effect of changing $m^\star$ e $\Delta m_\star$ on the $\bar{\nu}_e$ neutrino signal and the shock radius from the core-collapse of a 20 $M_\odot$ star simulated with GR1D.

Efective Mass Effect in 3D CCSNe



Effect of changing $m^\star$ e $\Delta m^\star$ in the shock radius expansion during the core-collapse of a $M_{\rm ZAMS} = 20\,M_\odot$ from Woosley & Heger (2007) for an octant 3D simulation using Zelmani.

Effective Mass in the EOS

Why does the effective mass have such a strong effect in CCSNe?

Change in $m^\star$ affects **specific heat capacity** c_v:

$$\boxed{c_v \simeq \left(\frac{\pi}{3}\right)^{2/3} \frac{T}{n} \left(n_p^{1/3} m_p^\star + n_n^{1/3} m_n^\star\right)}$$

A **larger** heat capacity (larger $m^\star$) causes:

- lower thermal pressure during core-collapse;
- PNS core is colder and more compact;
- PNS surface is hotter:

  ⇒ more neutrinos emitted;

  ⇒ neutrinos have higher energy.
- More neutrinos deposit energy behind the stalled shock

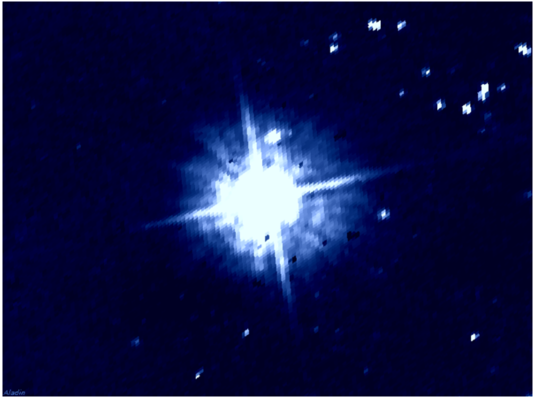
  ⇒ explosion more likely!

Schneider *et al.* (2019) e Yasin *et al.* (2020).

Birth of Stellar Mass BHs

If PNS M_{grav} larger than supported by EOS:

- Second collapse takes place and BH forms
  - After shock revival: successful SN.
  - Before shock revival: failed supernova.
  - Even failed SN may eject matter!
- BH quickly swallows the PNS;
- Neutrino emission ceases abruptly;
- No rotation: external shells freefall into BH.
- Rotation: disk forms around BH.



9 $M_\odot$ stellar Mass BH VFTS 243 around a star of 25 $M_\odot$. Image by HST.

Birth os Stellar Mass BHs

O'Connor & Ott (2011)

GR1D simulations of

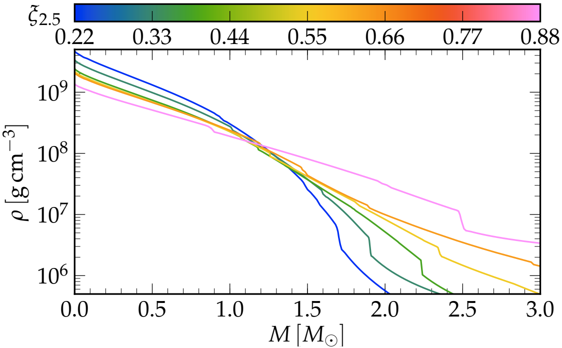
- 106 pre-SN progenitors
- 4 EOSs

Found that time to BH formation

$$t_{\rm BH} \simeq A\xi_{2.5}^{B}$$

depends on core-compactness

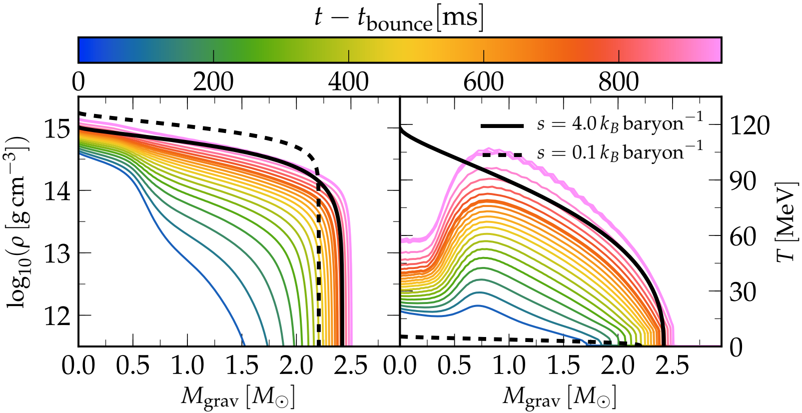
$$\xi_M = \frac{M/M_\odot}{R(M_{\rm baryon} = M)/1000{\rm km}} \, .$$



Example of CCSNe progenitor density structures.

Core-collapse of a $40\,M_\odot$ Star

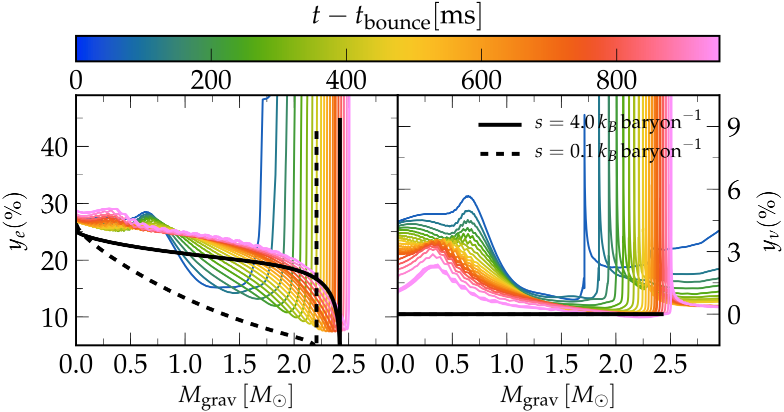
High-compactness CCSN progenitor ⇒ BH forms quickly.



Density and temperature during BH formation of a $M_{\mathrm{ZAMS}} = 40\,M_\odot$ from Woosley & Heger (2007) compared with most massive PNS with $s = 0.1$ and $4.0\,\mathrm{k_B}\,\mathrm{baryon}^{-1}$.

Core-collapse of a $40\,M_\odot$ Star

High-compactness CCSN progenitor ⇒ BH forms quickly.



Proton fraction and neutrinos per baryon during BH formation of a $M_{\rm ZAMS} = 40\,M_\odot$ from Woosley & Heger (2007) compared with most massive PNS with $s = 0.1$ and $4.0\,{\rm k_B\,baryon^{-1}}$.

Core-collapse of a $40\,M_\odot$ Star

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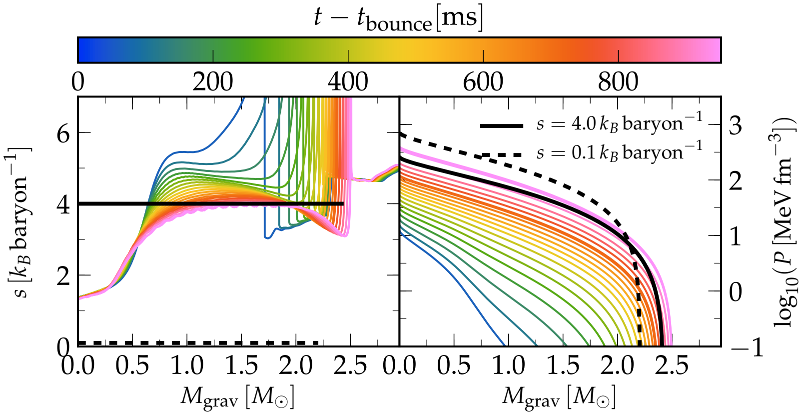
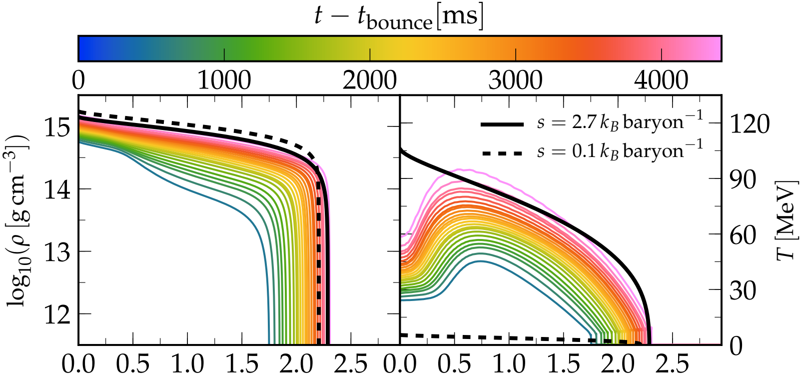


Entropy and pressure during BH formation of a $M_{\mathrm{ZAMS}} = 40\,M_\odot$ from Woosley & Heger (2007) compared with most massive PNS with $s = 0.1$ and $4.0\,k_B\,\mathrm{baryon}^{-1}$.

Core-collapse of a $50\,M_\odot$ Star

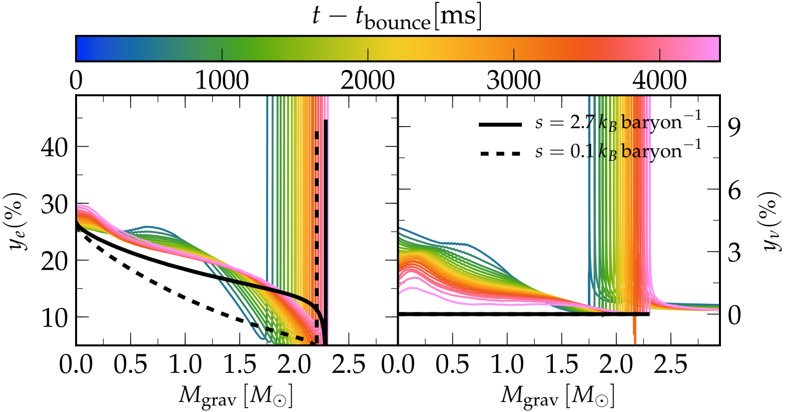
Low-compactness CCSN progenitor ⇒ forms BH slowly.



Density and temperature during BH formation of a $M_{\mathrm{ZAMS}} = 50\,M_\odot$ from Woosley & Heger (2007) compared with most massive PNS with $s = 0.1$ and $2.7\,k_{\mathrm{B}}\,\mathrm{baryon}^{-1}$.

Core-collapse of a $50\,M_\odot$ Star

Low-compactness CCSN progenitor ⇒ forms BH slowly.



Proton fraction and neutrinos per baryon during BH formation of a $M_{\text{ZAMS}} = 50\,M_\odot$ from Woosley & Heger (2007) compared with most massive PNS with $s = 0.1$ and $2.7\,k_B\,\text{baryon}^{-1}$.

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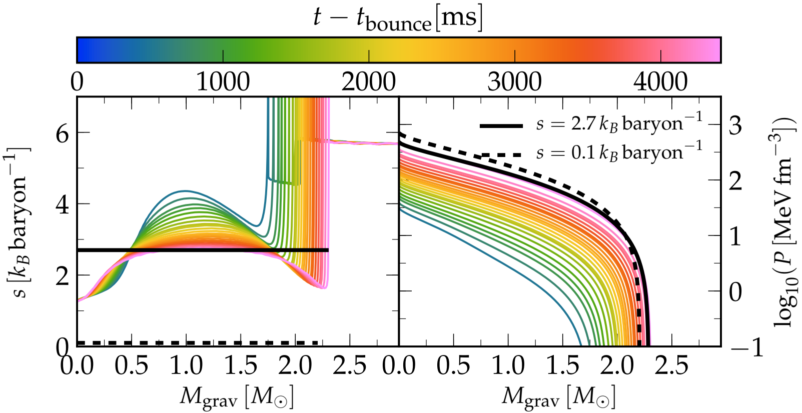
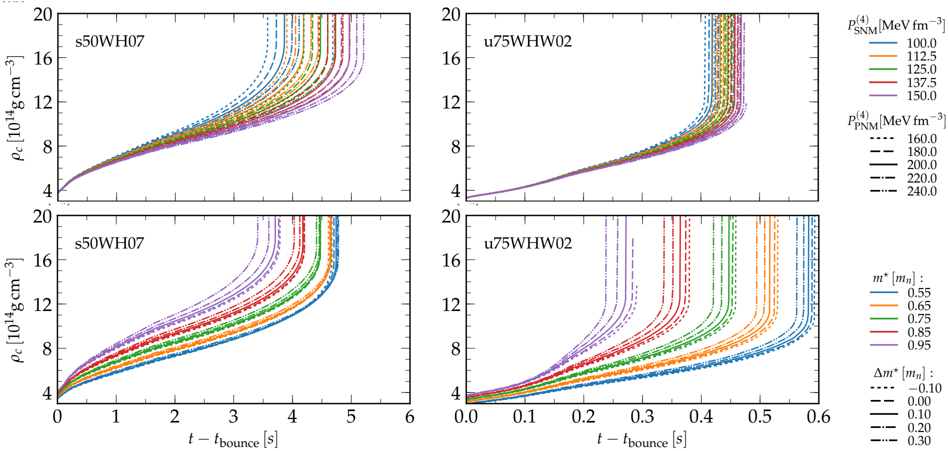


Entropy and pressure during BH formation of a $M_{\mathrm{ZAMS}} = 50\,M_\odot$ from Woosley & Heger (2007) compared with most massive PNS with $s = 0.1$ and $2.7\,k_B\,\mathrm{baryon}^{-1}$.

Time to Form a BH



Central density evolution during CCSNe for a low (left) and high (right) compactness progenitor stars for EOSs that differ in their $T = 0$ component (top, s_P set from SRO EOSs) and $T \neq 0$ component (bottom, s_M set from SRO EOSs).

BH Formation

Black line: Maximum mass supported by the SRO EOS as a function of constant star entropy.

Colored lines: gravitational mass-entropy evolution for progenitor from Sukhbold *et al.* (2018) with different compactness $\xi_M = (M/M_\odot)/(R(M)/1000)$.

BH forms once PNS overcomes maximum gravitational mass it can support!

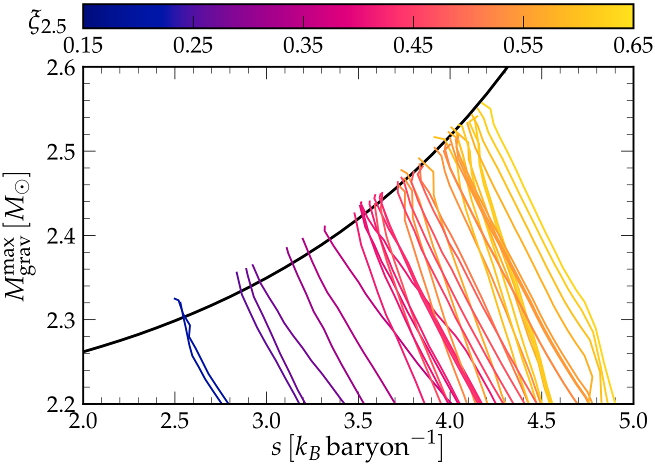
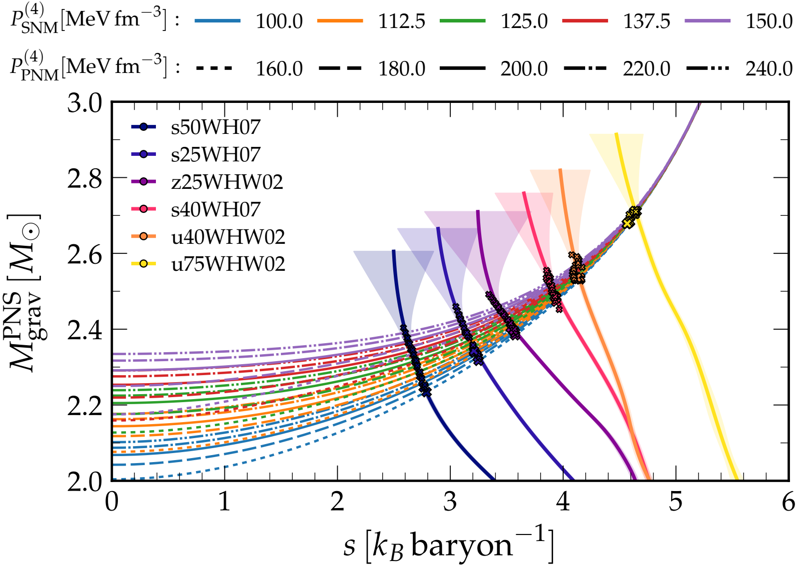
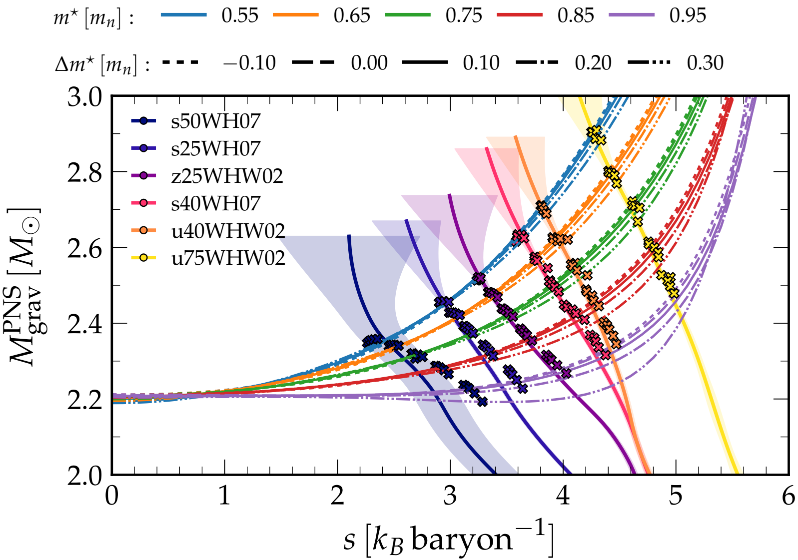


Figure from Schneider *et al.* (2020).

High Density Pressure Effect on PNS Entropy at BH formation.



Effective mass Effect on PNS Entropy at BH formation.



BH Formation

Maximum mass supported by different EOSs found in the literature as a function of entropy and mass-entropy evolution for progenitor from Woosley *et al.* (2002) and Woosley & Heger (2007).

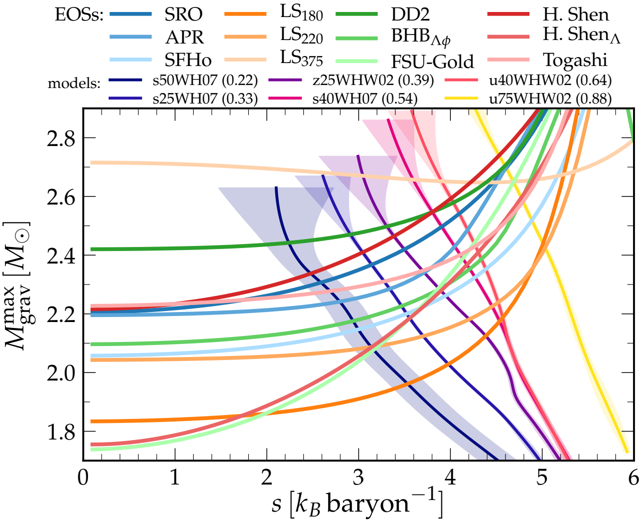
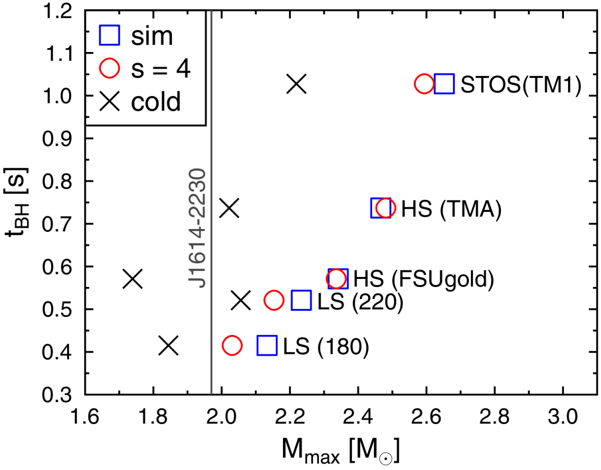


Figure from Schneider *et al.* (2020).

BH Formation

BH forms once PNS overcomes maximum gravitational mass it can support.

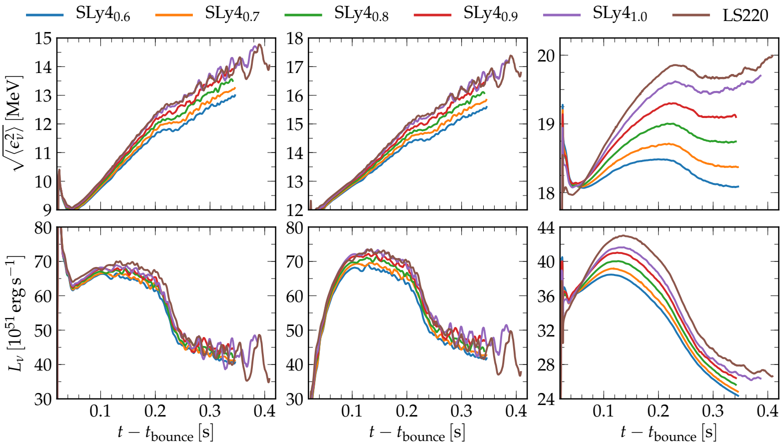
PNS mass at BH formation time for a $40\,\mathrm{M}_\odot$ progenitor from Woosley & Heger (2007) compared to the maximum mass supported by a cold and a $s = 4\,\mathrm{k_B}/\mathrm{baryon}^{-1}$.



NS. Figure from Hempel *et al.* (2012).

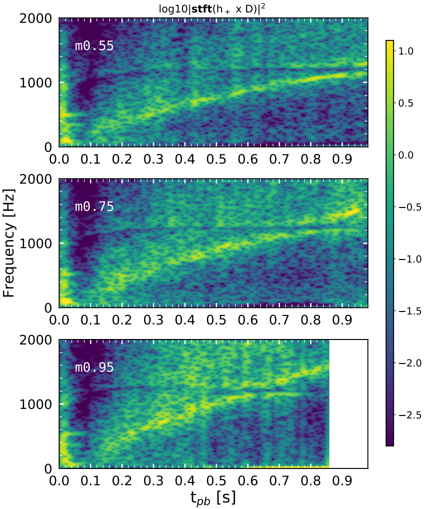
EOS effects on Neutrino Emission

Neutrinos carry information from PNS surface.



EOS effects on neutrinos emitted from a PNS formed in the core-collapse of a 20 $M_\odot$ star.

EOS effects on Gravitational Waves

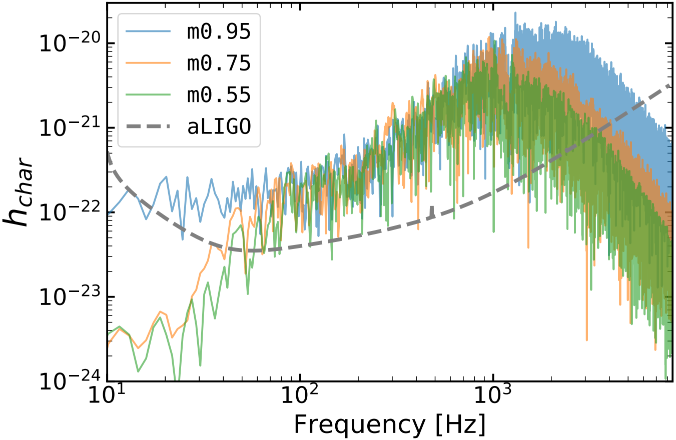


GWs carry information from motion of matter in the PNS interior.

- Lower thermal pressure
  $\Rightarrow$ more compact PNS.
  $\Rightarrow$ GW signal louder &
  with higher frequency.

GW signal from the core-collapse of a $M_{\mathrm{ZAMS}} = 20\,M_{\odot}$ progenitor from Woosley & Heger (2007) simulated in 2D with FLASH. Figure from Eggenberger Andersen *et al.* (2021).

EOS effects on Gravitational Waves



GW signal from the core-collapse of a $M_{\mathrm{ZAMS}} = 20\,M_\odot$ progenitor from Woosley & Heger (2007) simulated in 2D with FLASH at 10 kpc. Figure from Eggenberger Andersen *et al.* (2021)

EOS effects on BH Supernova

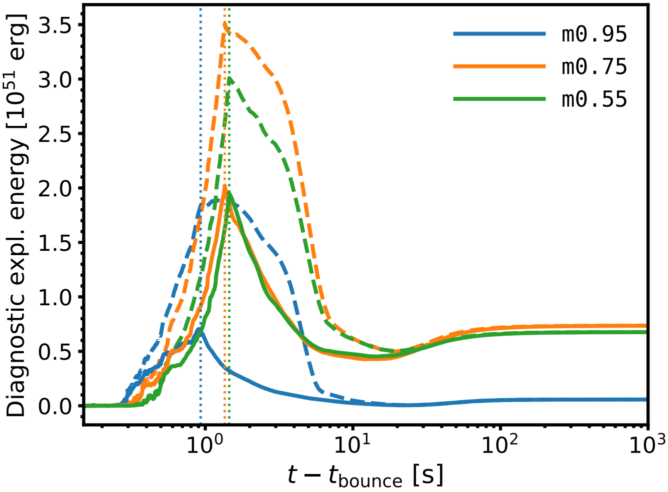
BH Supernovae ejecta are also affected by the EOS.

Eggenberger Andersen *et al.* (in preparation): axisymmetric core-collapse of a $M_{\mathrm{ZAMS}} = 60\,M_{\odot}$ progenitor of Sukhbold *et al.* (2018) using FLASH.

$m^{\star}$ $[m_n]$	T_{BHF} [s]	E_{expl} $[10^{50}\,\mathrm{erg}]$	M_{BH} $[M_{\odot}]$	M_{ej} $[M_{\odot}]$	$M_{\mathrm{Ni^{56}}}$ $[M_{\odot}]$
0.95	0.93	0.57	25.48	21.67	0.000
0.75	1.36	7.23	24.02	23.09	0.0157
0.55	1.45	6.68	24.30	22.80	0.0182

Time to BH-formation from bounce (T_{BHF}), final explosion energy (E_{expl}), final BH mass (M_{BH}), the ejected mass (M_{ej}), and Ni^{56} ejecta mass ($M_{\mathrm{Ni^{56}}}$).

EOS effects on BH Supernova



Explosion energy for the core-collapse of a $M_{\mathrm{ZAMS}} = 60\,M_\odot$ progenitor of Sukhbold *et al.* (2018) using FLASH in axisymmetry.

EOS Properties from NS Mergers

- In ~ 20 years: cold-NS EOS will be well constrained.
- Detection of NS merger by CE and ET ⇒ EOS constraints for T > 0.

Simulated GW signal for a NS merger detected by Cosmic Explorer with SNR 15 for EOSs that differ in their thermal component.

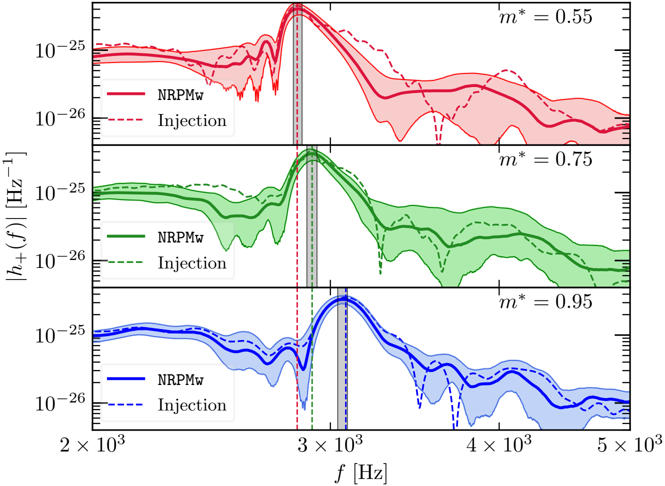


Figura 1: Figure by Fields *et al.* (2023).

Prospects for the Future

- New/better EOS constraints from astrophysical events
  - mass-radius measurements from NICER;
  - NS merger GW detections and kilonovae observations.
- Galactic SN observation (if we are lucky) and
  - with known/identified progenitor star;
  - GW detection (if we are very lucky);
  - telescope observations over many frequencies;
  - up to 10^5 to 10^6 neutrinos;
  - remnant determined.

Prospects for the Future

In parallel:

- Neutrino mass hierarchy and oscillation matrix.
- Neutron rich nuclei properties from FRIB, FAIR, ...
- High density constraints from LHC, RHIC, ...
- Increase in computational power.
- Better theory/codes/simulations ($\Leftarrow$ Our contribution!)
- Improved EOS code:
  - Relativistic Model;
  - Include other particles:
    (pions, muons, hyperons, quarks);
  - Include nuclei consistently;
  - ...