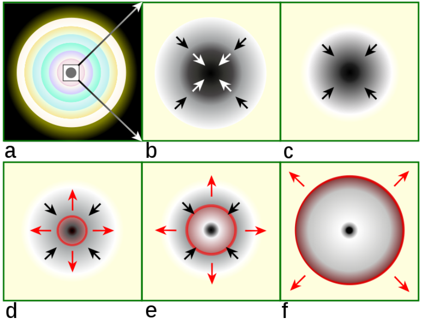
Equation of State Effects on Core-Collapse Supernovae

A. S. Schneider, L. F. Roberts, C. D. Ott

NuSYM18 September 2018

Core-Collapse Supernovae



Wiki

(a) Massive star ($\gtrsim 8M_\odot$) near end of its life.

(b) Nickel/Iron core becomes unstable against gravitational collapse. Also, $p+e^- \to n+\nu_e$.

(c) Core density reaches $\sim 3\cdot 10^{14}\,\mathrm{g\,cm^{-3}}$: collapse stops.

(d) Infalling material hits degenerate core and bounces.

(e) Shock stalls due to breaking up of heavy nuclei.

(f) Shock reinvigorated by ν heating and outer material is ejected.

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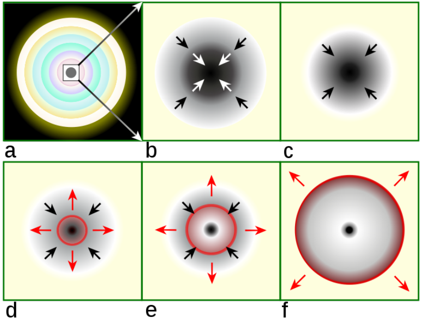

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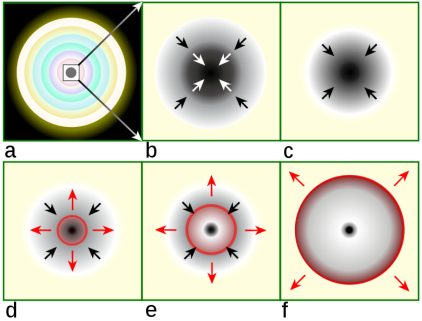

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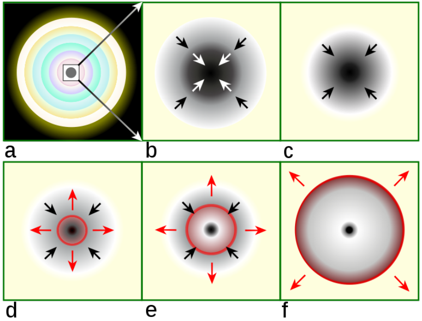

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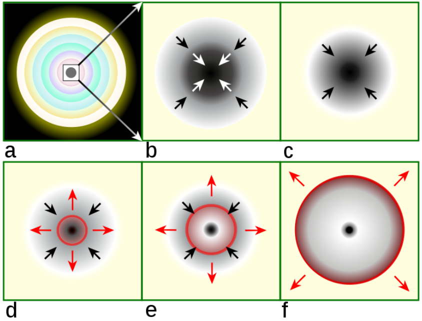

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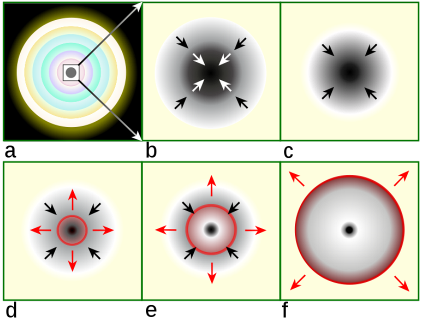

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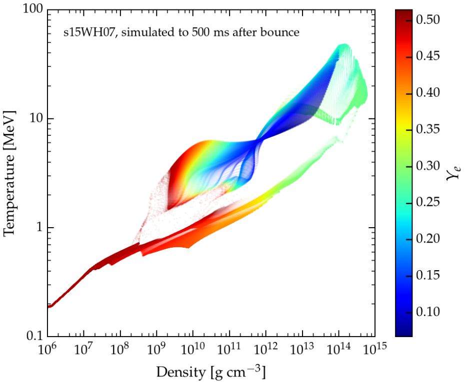
Equation of state (EOS):
$\varepsilon(n, y, T)$, $P(n, y, T)$, $s(n, y, T)$, ...

Astrophysical relevance

- Core-collapse supernovae;
- NS structure and evolution;
- Compact star mergers;
- ...

CCSNe



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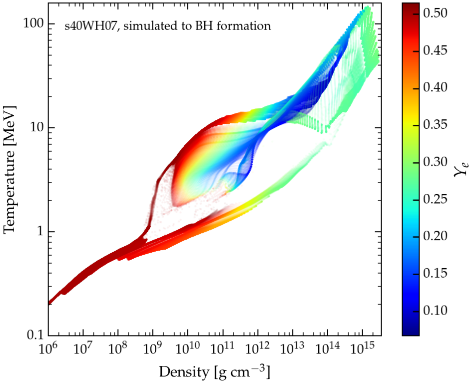

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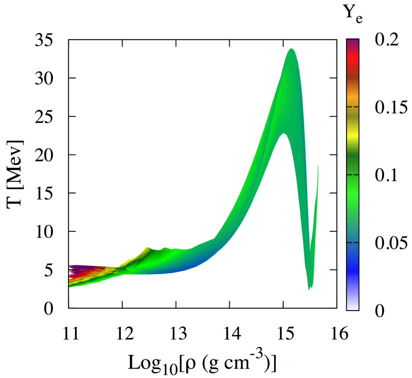
NS merger



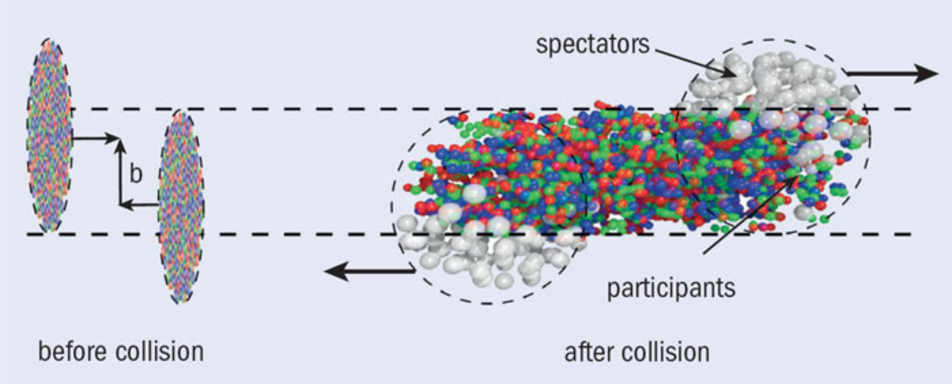
K. Kiuchi

The EOS determines

- How many p are converted into n.
- Density which collapse halts.
- Heat produced during collapse.
- Mass/size of the core.
- Momentum transferred to the shock.
- Rate νs are produced in the core.
- Shock heating and expansion rate.
- Gravitational wave signal.
- Proto-neutron star properties and cooling rate.
- Final neutron star mass, radius and composition.

Information about EOS comes from many sources.

- heavy ion collision experiments;
- nuclear reactions and nuclei properties;
- observations of astrophysical phenomena;



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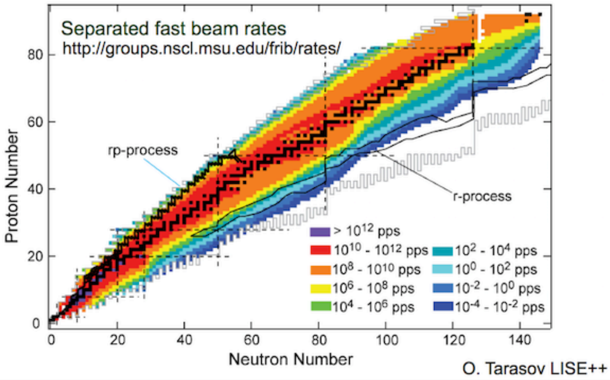

O. Tarasov LISE++

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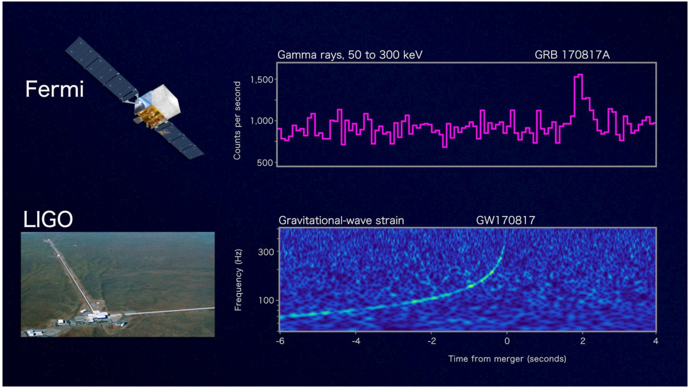

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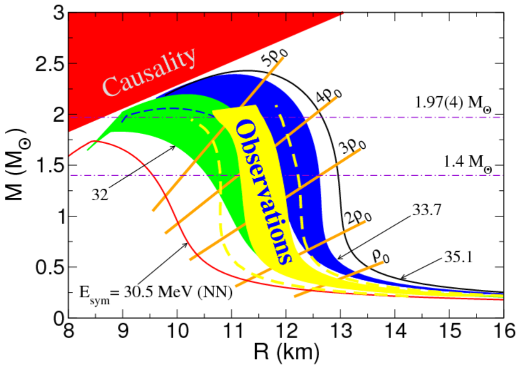
- observations of astrophysical phenomena;
- simulations of dense matter;
- many-body calculations;



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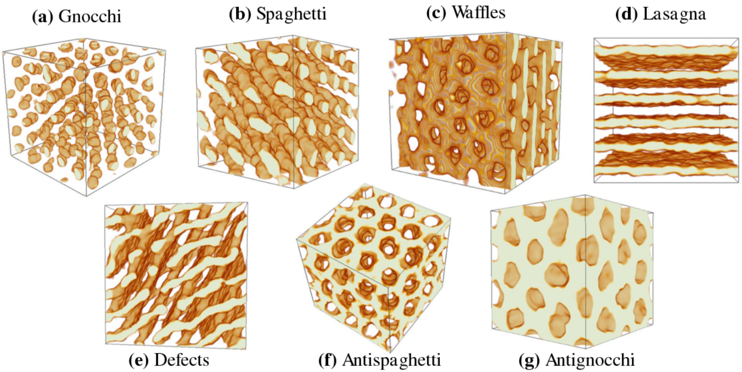
(a) Gnocchi (b) Spaghetti (c) Waffles (d) Lasagna (e) Defects (f) Antispaghetti (g) Antignocchi

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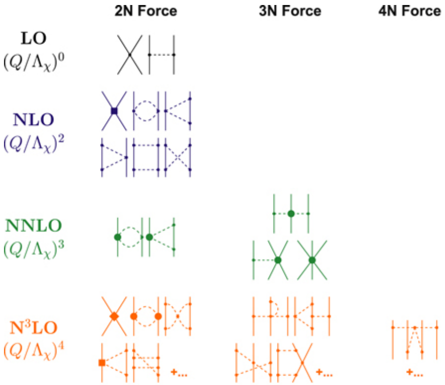


There is still plenty of uncertainty in the EOS:

- $n \gtrsim 3n_{\mathrm{sat}} \sim 10^{15}\,\mathrm{g\,cm^{-3}}$;
  - What are the phases of very dense matter?
  - Are there hyperons?
  - Is there a transition to a quark-gluon plasma?
  - ...
- $n_{\mathrm{sat}}/10 \lesssim n \lesssim 2n_{\mathrm{sat}}/3$;
  - What are the phases of nuclear pasta?
  - How much do they affect neutrino transport?
  - ...
- $y \lesssim 0.30$;
  - What are the properties of neutron rich nuclei?
  - Where is the neutron drip line?
  - ...
- ...

How to obtain hot-dense EOS?

1. Relativistic vs Non-relativistic.
2. Realistic potentials vs Effective potentials.
3. SNA vs NSE vs reaction networks.
4. Include muons, pions, hyperons, quarks, ...

EOS available:

1. Lattimer & Swesty
2. H. Shen *et al.*
3. G. Shen *et al.*
4. Hempel *et al.*
5. Steiner *et al.*
6. Banik *et al.*
7. Furusawa *et al.*
8. Togashi *et al.*
9. Schneider *et al.*
10. ...

The Lattimer & Swesty EOS:

- Published on Nucl. Phys. A **535**, 331 (1991)
- Uses a phenomenological Skyrme parametrization of nuclear forces.
- Non-relativistic compressible liquid-drop description of nuclei.
- Widely used in simulations of CCSNe and NS mergers.
- Contains:
    1. protons and neutrons;
    2. alpha particles;
    3. electrons and positrons;
    4. photons.
- Leptons and photons form background gas.
- Nucleons may cluster to form nuclei in the single nucleus approximation (SNA).

The SROEOS code.

- Based on the Lattimer & Swesty EOS.
- Constructs EOS tables for astrophysical simulations for Skyrme parametrizations of the nuclear force.
- "Easy" to update/extend as new nuclear matter constraints become available.
- Code is open-source. See `https://stellarcollapse.org/SROEOS`
- Published on Phys Rev C **96** 065802 (2017)

How to compute an EOS?

At $T = 0$:

$$\varepsilon(n, y) = \varepsilon_{\mathrm{is}}(x) + \delta^2 \varepsilon_{\mathrm{iv}}(x)$$

where $\delta = 1 - 2y$ and $x = (n - n_{\mathrm{sat}})/3n_{\mathrm{sat}}$.

$$\varepsilon_{\mathrm{is}}(x) = \varepsilon_{\mathrm{sat}} + \frac{1}{2} K_{\mathrm{sat}} x^2 + \frac{1}{3!} Q_{\mathrm{sat}} x^3 + \ldots,$$

$$\varepsilon_{\mathrm{iv}}(x) = \varepsilon_{\mathrm{sym}} + L_{\mathrm{sym}} x + \frac{1}{2} K_{\mathrm{sym}} x^2 + \frac{1}{3!} Q_{\mathrm{sym}} x^3 + \ldots,$$

Empirical parameters are constrained experimentally and/or theoretically and/or observationally.

Finite T:

$$\varepsilon(n, y, T) = \varepsilon_{\text{kin}}(n, y, T) + \varepsilon_{\text{pot}}(n, y) .$$

The kinetic energy term

$$\varepsilon_{\text{kin}}(n, y, T) = \frac{1}{n}\left(\frac{\hbar^2 \tau_n}{2 m_n^\star} + \frac{\hbar^2 \tau_p}{2 m_p^\star}\right)$$

Nucleon kinetic energy density τ_t

$$\tau_t = \frac{1}{2\pi^2}\left(\frac{2 m_t^\star T}{\hbar^2}\right)^{\frac{5}{2}} F_{3/2}(\eta_t(n, y)),$$

and of density dependent effective nucleon masses $m_t^\star$

$$\frac{\hbar^2}{2 m_t^\star} = \frac{\hbar^2}{2 m_t} + \alpha_1 n_t + \alpha_2 n_{-t} .$$

In Skyrme-type models expand

$$\varepsilon_{\mathrm{pot}}(n, y) = \sum_{i=0}^{N} \left[a_i + 4 b_i y(1-y)\right] n^{\delta_i} .$$

Lattimer & Swesty EOS:;

- Set $\alpha_1 = \alpha_2 = 0$, $N = 1$, $\delta_0 = 1$, $b_1 = 0$.
- Compute a_0, b_0, a_1, δ_1 from nuclear properties.

SRO EOS:

- Use Skyrme parametrizations from the literature. (Dutra+ 2012)
- Make new parametrization that satisfies known nuclear physics constraints.

This work:

- Set $\delta_0 = 1$, $\delta_1 = 4/3$, $\delta_2 = 2$, $\delta_3 = 8/3$.
- Compute α_1, α_2, a_i, b_i from known nuclear physics constraints.

Set values for *empirical parameters*

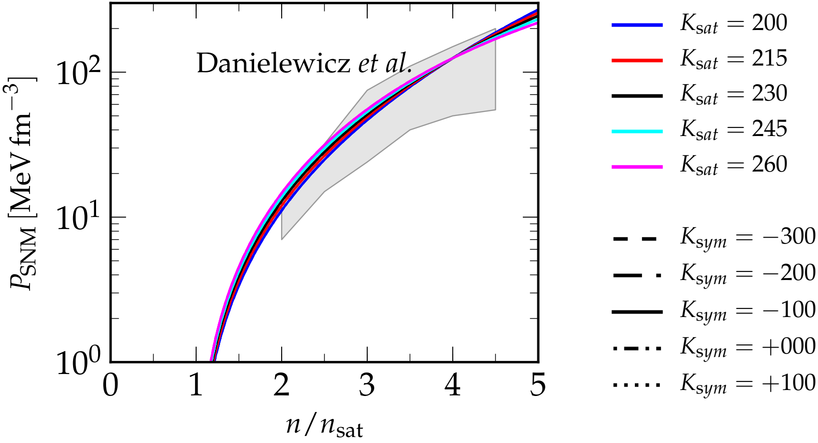
Quantity	Exp./Theor. Range			This work			Units
$m_n^\star(n_{\rm sat}, 1/2)$	0.75	±	0.10	0.75	±	0.10	m_n
$\Delta m^\star(n_{\rm sat}, 0)$	0.10	±	0.10	0.10	±	0.10	m_n
$n_{\rm sat}$	0.155	±	0.005	0.155			fm^{-3}
$\varepsilon_{\rm sat}$	−15.8	±	0.3	−15.8			$\mathrm{MeV\,baryon}^{-1}$
$\varepsilon_{\rm sym}$	32	±	2	32	±	2	$\mathrm{MeV\,baryon}^{-1}$
$L_{\rm sym}$	60	±	15	45	±	7.5	$\mathrm{MeV\,baryon}^{-1}$
$K_{\rm sat}$	230	±	20	230	±	15	$\mathrm{MeV\,baryon}^{-1}$
$K_{\rm sym}$	−100	±	100	−100	±	100	$\mathrm{MeV\,baryon}^{-1}$
$P^{(4)}_{SNM}$	100	±	50	125	±	12.5	$\mathrm{MeV\,fm}^{-3}$
$P^{(4)}_{PNM}$	160	±	80	200	±	20	$\mathrm{MeV\,fm}^{-3}$

Use SROEOS code to compute hot-dense EOSs:

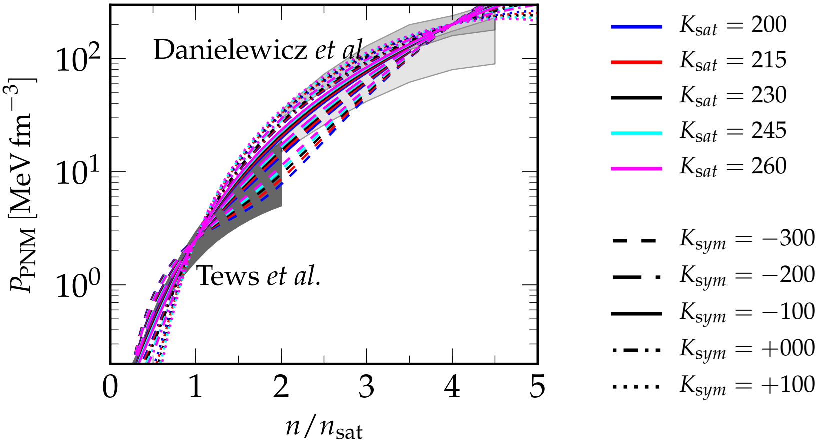
- Modular Fortran 90 code.
- Computes EOSs based on the liquid-drop model of Lattimer and Swesty.
- Uses Skyrme interactions for nucleon-nucleon interactions.
- Code is open-source: `https://stellarcollapse.org/SROEOS`
- Code details: *Physical Review C* **96** 065802 (2017)
- Allows computations of hot-dense EOS with independent variation of nuclear properties.

Use GR1D/NuLib codes to simulate spherically symmetric CCSN of a $20M_\odot$ star.

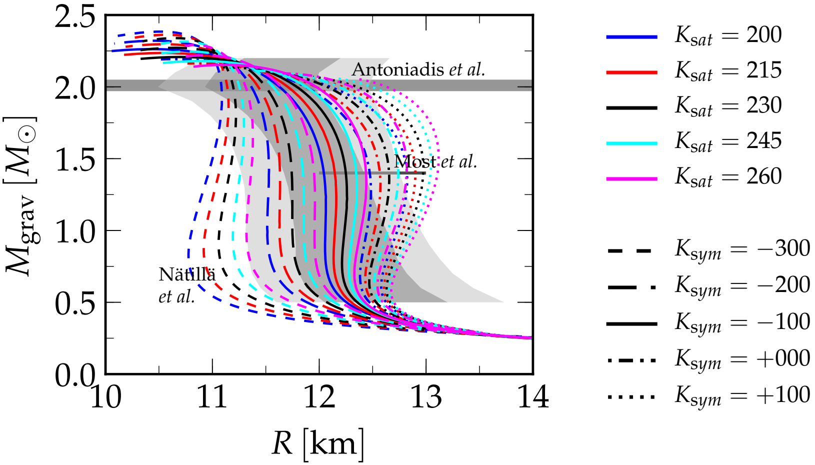
Effect due to incompressibility changes in SNM EOS.



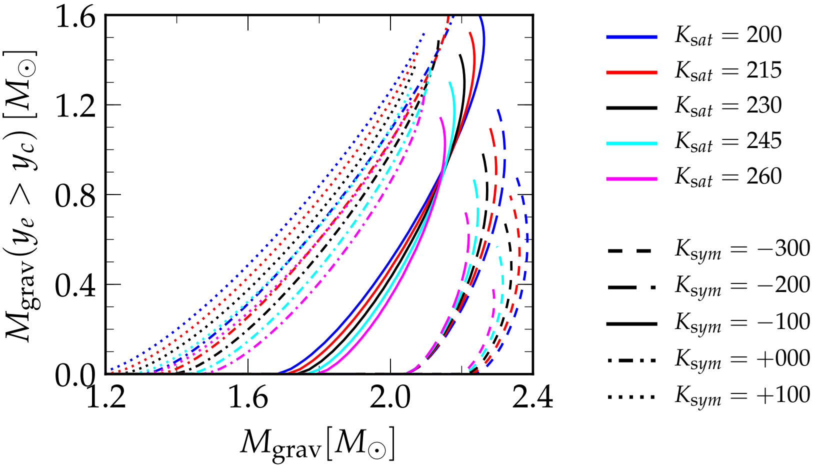
Effect due to incompressibility changes in PNM EOS.



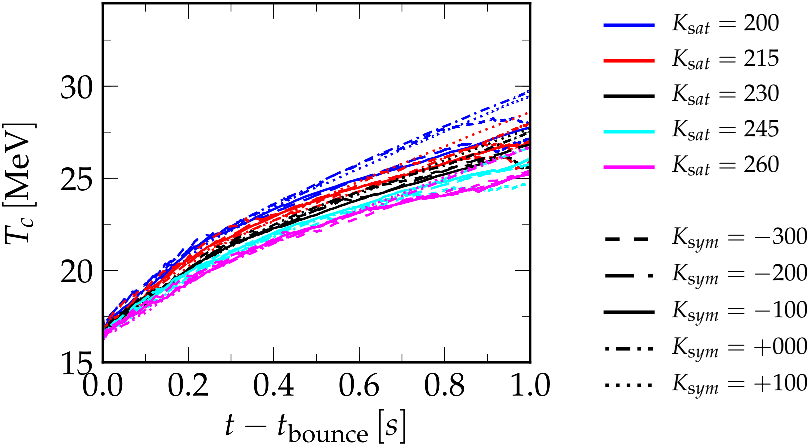
Effect due to incompressibility changes in cold NS mass-radius curve.



Effect due to incompressibility changes in NS proton fraction.



Effect due to incompressibility changes in 1D CCSNe of $20M_\odot$ star.



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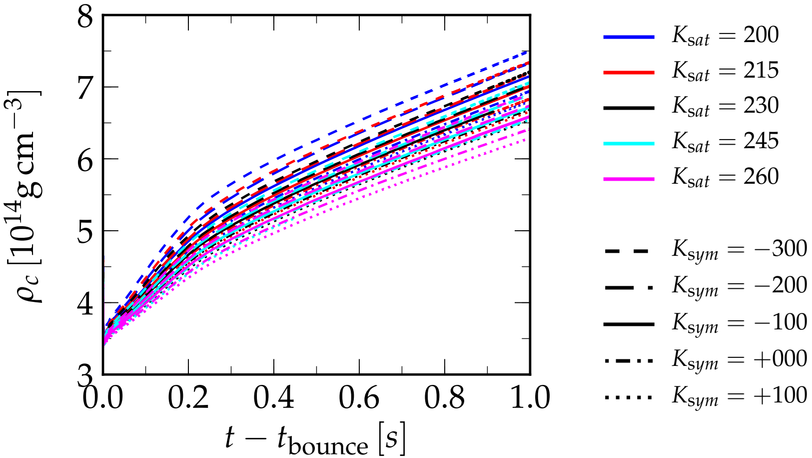

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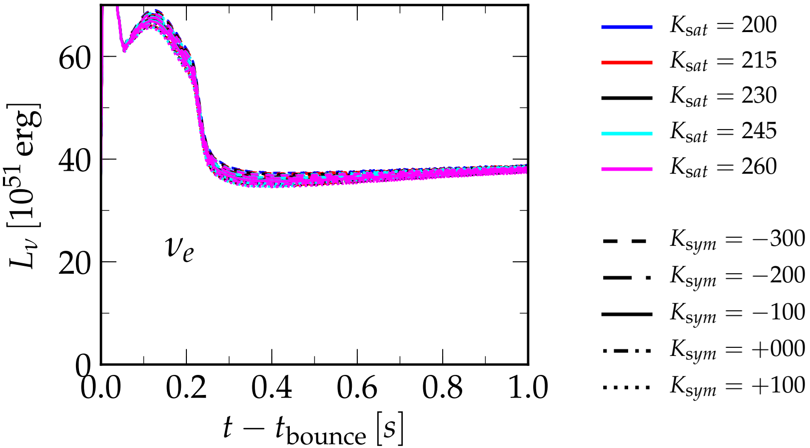

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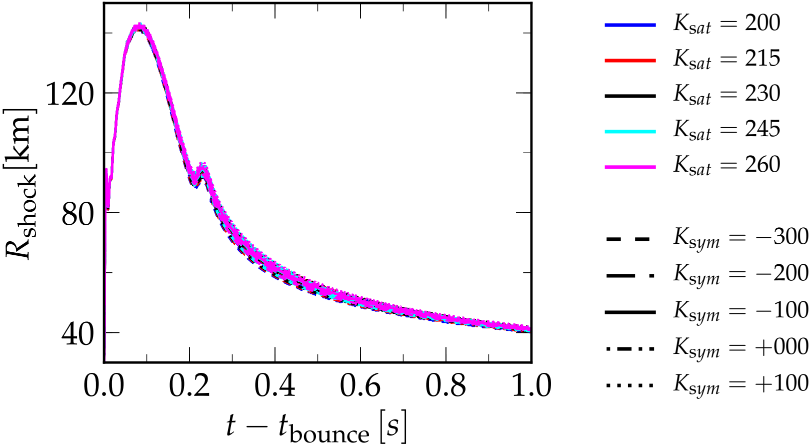
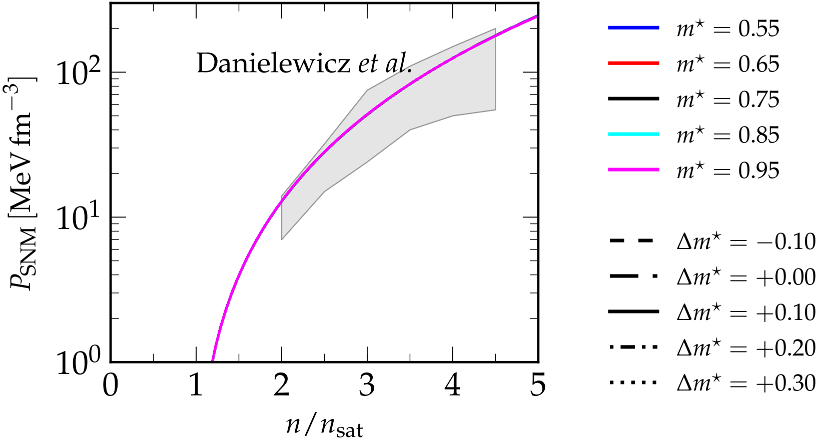


Effect due to effective mass changes in SNM EOS.



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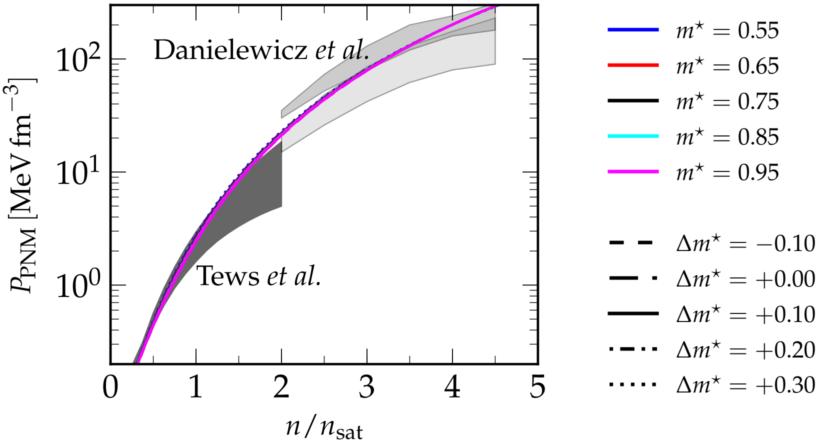

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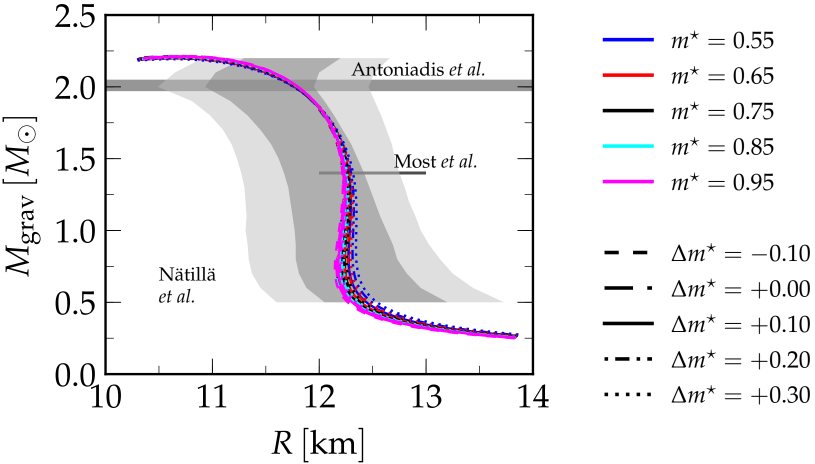

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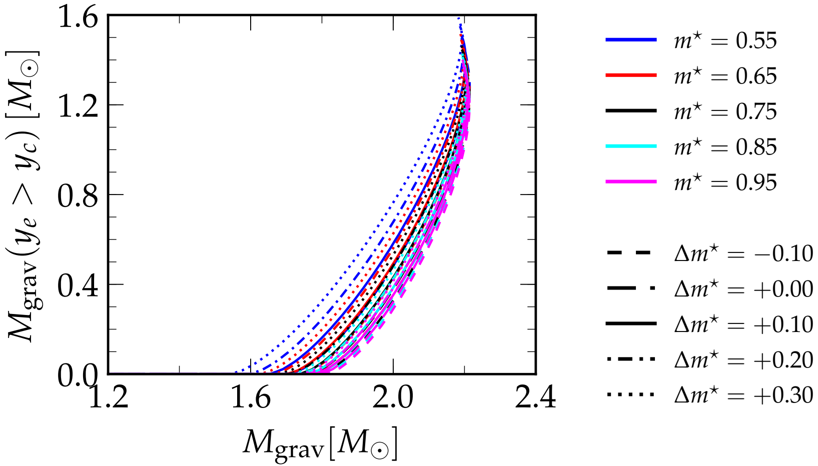

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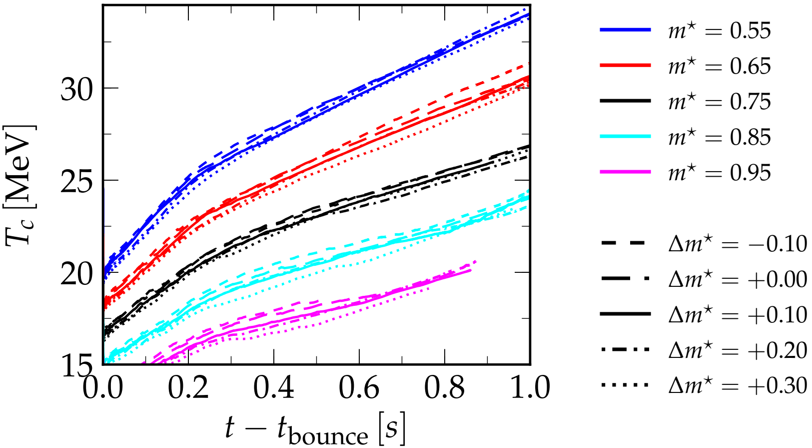

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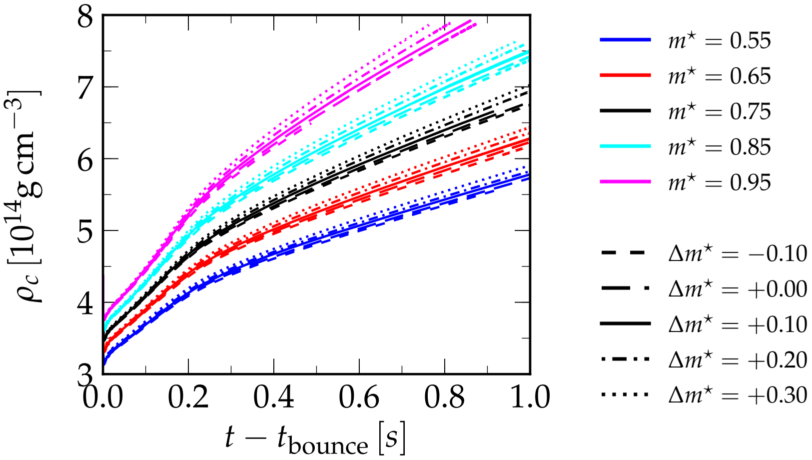

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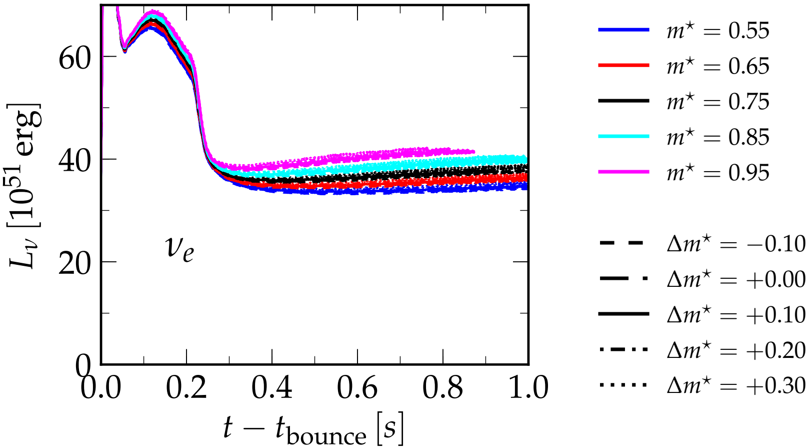

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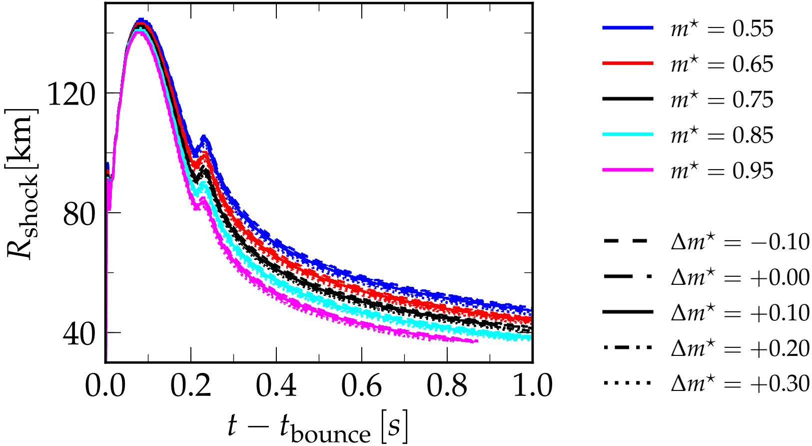
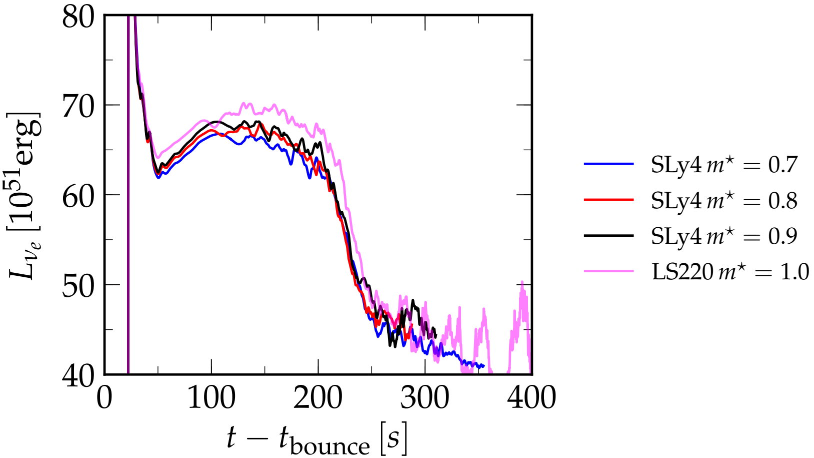


Effect due to effective mass changes in octant 3D CCSNe of $20M_{\odot}$ star.



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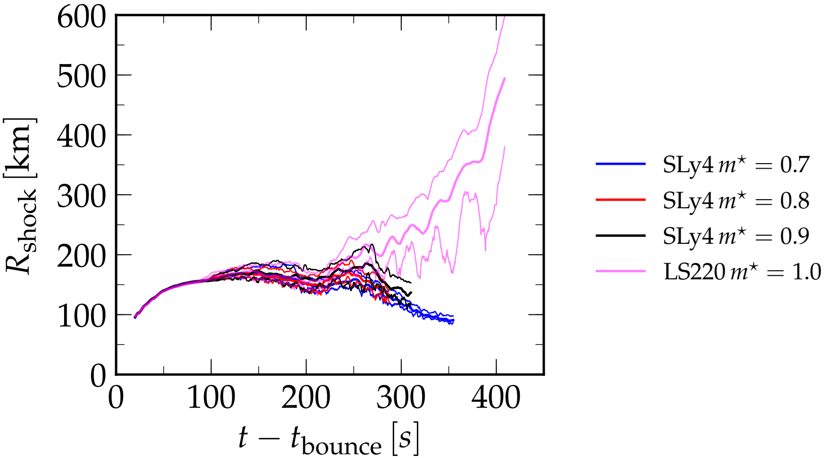

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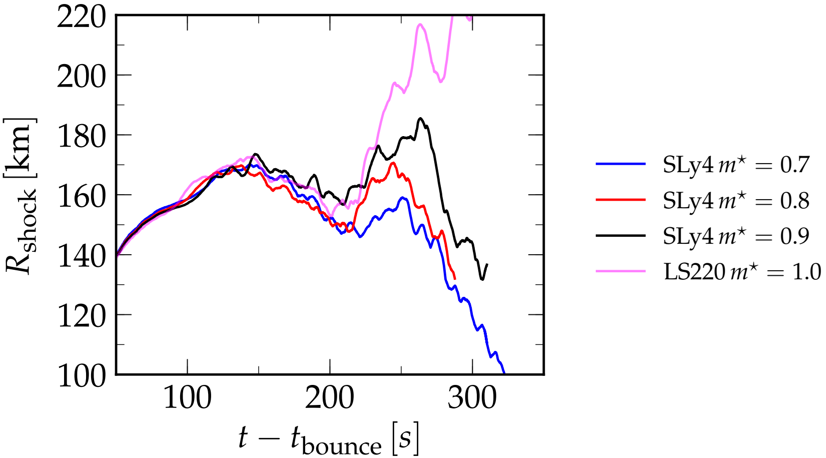

Summary

- For CCSNe *empirical parameters* at $T = 0$ are well constrained.
- Except for effective mass, changes in *empirical parameters* do not seem to significantly affect CCSNe observables.
- For Skyrme-type models effective mass increase correlates with how easy it is to make a supernovae explode.
- Supernovae are hot! Temperature dependence of the EOS should be better explored.

Future

Near future:

- Finish 3D data analysis.
- Repeat study for 2D CCSNe.
- More 3D octant runs, full 3D runs, other progenitors, ...
- What is the role of temperature/effective mass on NS mergers?
- Study EOSs with more complex effective mass behavior, *e.g.* APR-type parametrizations.
- Add muons and pions at high densities/temperatures.