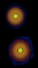
Nuclear Matter Properties in Neutron-Star Mergers

Max Jacobi



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Characterizing EOS effects in mergers

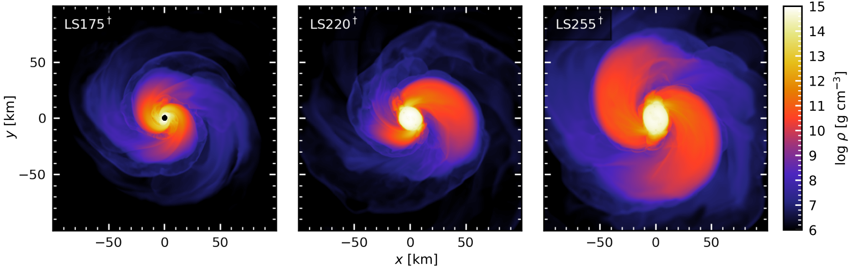
Usually: study EOS effects in mergers with selection of EOSs from literature

- Vary in many aspects and underlying microphysics

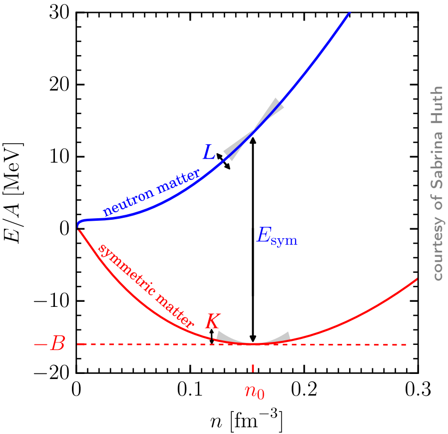
This work: use EOSs based on the same Skyrme EDF parametrization

Lattimer & Swesty, NuPhA 535 (1991), Schneider, Roberts, Ott, PRC 96 (2017)

- Consistent microphysics
- Systematically vary parameters one by one



The properties of nuclear matter



Expansion in density and proton fraction:

$$\chi = \frac{(n - n_0)}{3n_0} \qquad \beta = \frac{n_n - n_p}{n}$$

$$\frac{E}{A}(\chi, \beta) \approx -B + \frac{1}{2}K\chi^2 + S(\chi)\beta^2 + \mathcal{O}(\chi^3)$$

$$S(\chi) = E_{\mathrm{sym}} + L\chi + K_{\mathrm{sym}}\chi^2 + \mathcal{O}(\chi^3)$$

$$P(n = n_0) \propto L\beta^2 \qquad \frac{\partial P}{\partial n}(n = n_0) \propto K + K_{\mathrm{sym}}\beta^2$$

Change model parameters to vary expansion parameters

Skyrme parametrization

Parametrization of bulk energy density

Lattimer & Swesty, NuPhA 535 (1991)

$$\epsilon(n, Y_e, T) = \sum_t \frac{\tau_t(n, Y_e, T)}{2m^*(n)} - Y_e n \Delta + \left[a + 4bY_e(1 - Y_e)\right] n^2 + cn^{1+\delta}$$

- Fix n_0, B, E_{sym}, K

$\rightarrow$ 4 free parameters: a, b, c, δ

SROEOS code $\rightarrow$ add non-uniform nuclear matter, electrons, positrons, photons

Schneider, Roberts, Ott, PRC 96 (2017)

Schneider+, PRC 100 (2019) ; Yasin+, PRL 124 (2020) ; Andersen+, PRC 923 (2021) ; Fields+ APJ 952 (2023)

BNS simulations with the Einstein Toolkit

- One simulation per EOS
- Total mass $2.73 M_\odot$, mass ratio $= 1$
- $M_{\rm chirp} = 1.188 M_\odot$ (GW170817)

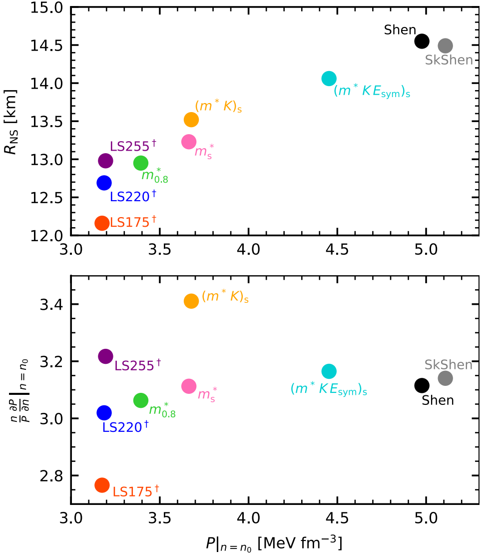
  Abbott+ PRL 119 (2017)
- Einstein Toolkit + WhiskyTHC

  einsteintoolkit.org; Radice+, CQGra 31, (2014)
- Neutrino transport:
  - Emission: local leakage scheme

    Galeazzi+, PRD 88 (2013)
  - Absorption: ray-by-ray "M0" scheme

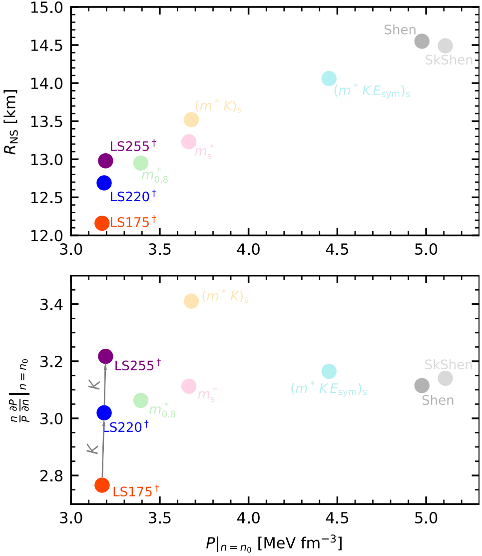
    Radice+, MNRAS 460 (2016)

Remnant dynamics



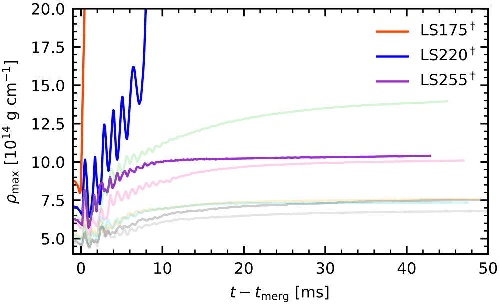
Variations based on LS220 Yasin+, PRL 124 (2020)

Remnant dynamics

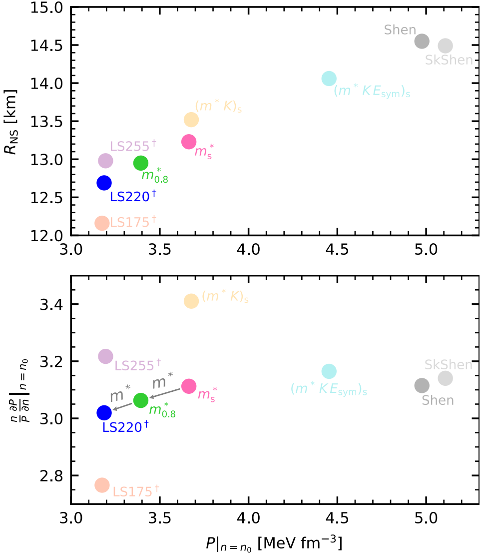


Variations based on LS220 Yasin+, PRL 124 (2020)

1. $K = (175\,, 220\,, 255)\,\mathrm{MeV}$
   - $\uparrow K \to \uparrow$ slope of $P_{cold}(\rho = \rho_0)$
   - $\uparrow P$ at high ρ
   - Collapse outcome

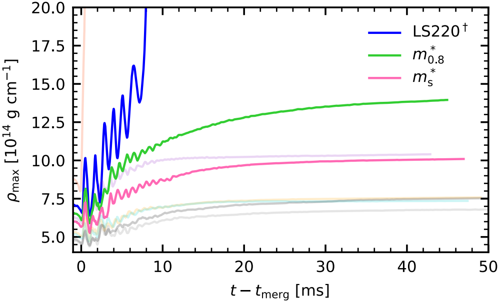


Remnant dynamics

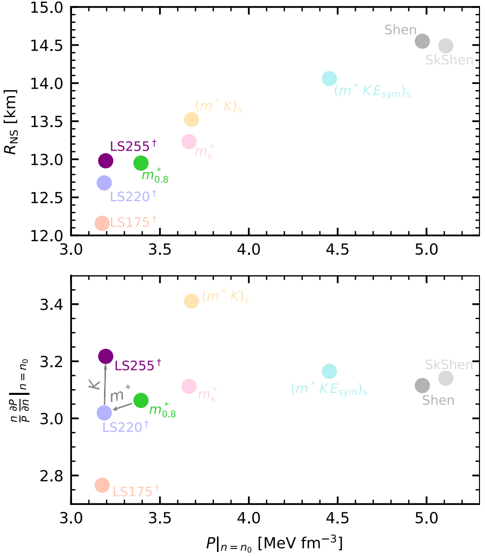


Variations based on LS220 Yasin+, PRL 124 (2020)

2. $m^*/m_n = (1\,, 0.8\,, 0.634)$
   - $\downarrow m^*$
   - $\uparrow L, K_{sym} \rightarrow P_{cold}$



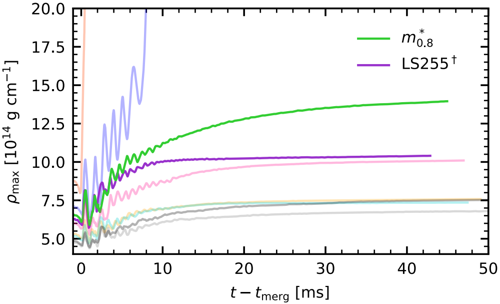
Remnant dynamics



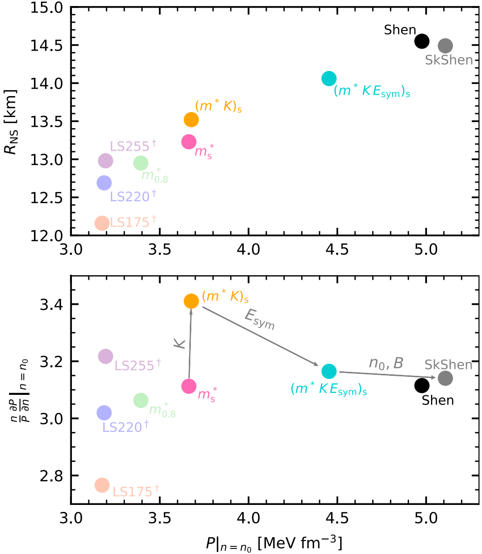
Variations based on LS220 Yasin+, PRL 124 (2020)

2. $m^*/m_n = (1\,, 0.8\,, 0.634)$
   - $\downarrow m^*$
   - $\uparrow L, K_{\mathrm{sym}} \rightarrow P_{\mathrm{cold}}$

   Slope of P → timescale of contraction



Remnant dynamics

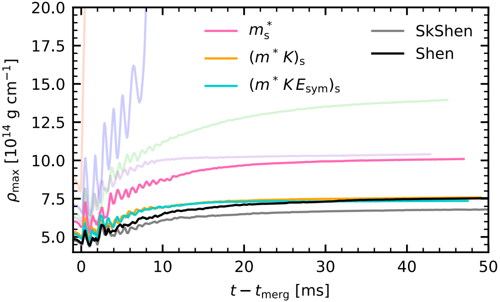


Variations based on LS220 Yasin+, PRL 124 (2020)

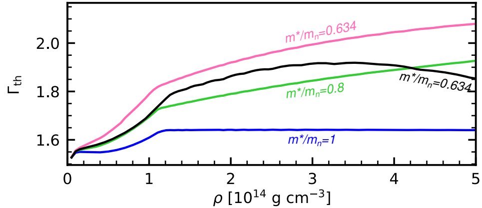
3. Systematically match Shen EOS

Shen+, PThP 100 (1998)

- $\rho \approx \rho_0 \rightarrow$ similar
- $\rho > \rho_0 \rightarrow$ diverge



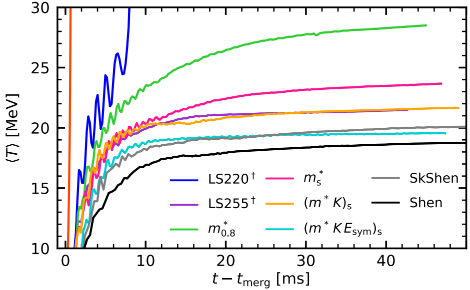
Remnant dynamics

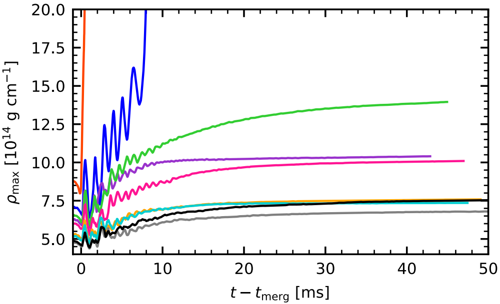


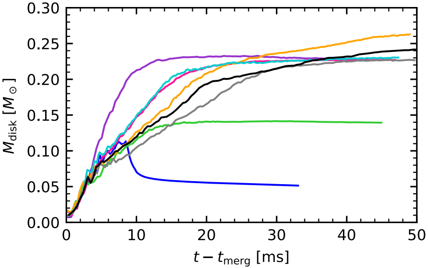
Variations based on LS220 Yasin+, PRL 124 (2020)

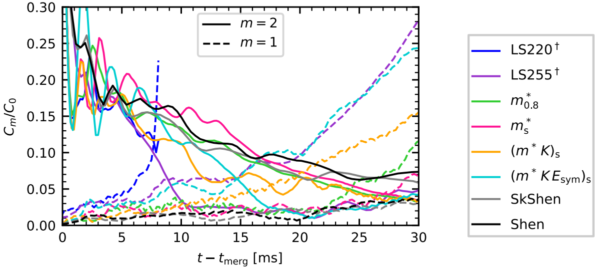
- softer EOS $\rightarrow \uparrow$ shock heating
- $\uparrow \Gamma_{th} \rightarrow \uparrow$ shock heating

$$\Gamma_{th} := 1 + \frac{P_{th}}{\epsilon_{th}} \approx \frac{5}{3} - \frac{n}{m^*}\frac{\partial m^*}{\partial n}$$

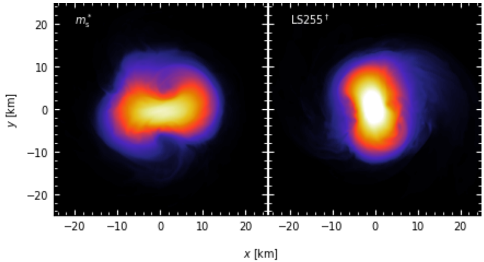




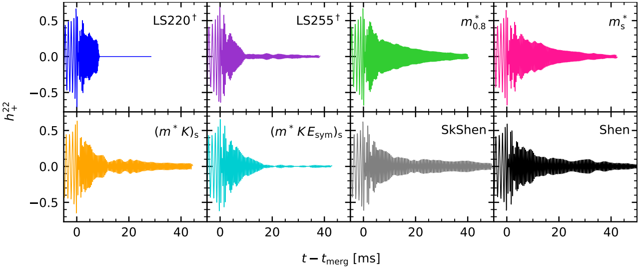




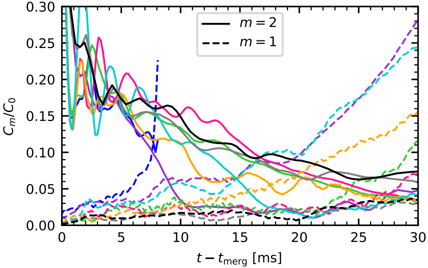
- Higher K, lower m^* $\rightarrow$ heavier disk
- Disk definition is ambiguous
- NS deformation linked to incompressibility?



Gravitational waves



- Post-merger GW amplitude decay
  $\rightarrow m = 2$ deformation



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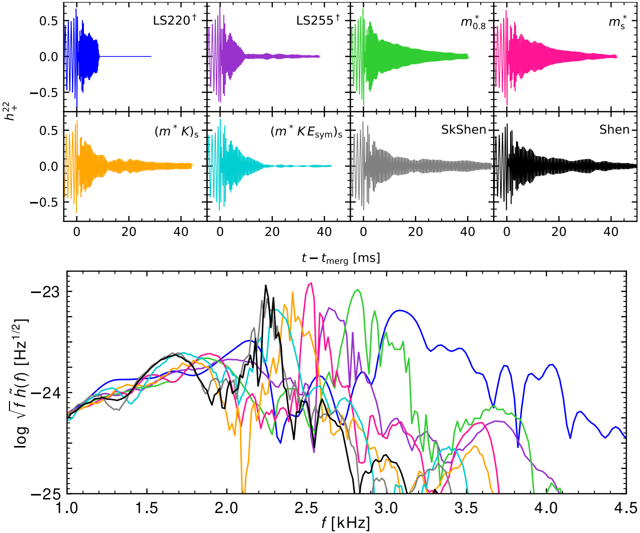


- Post-merger GW amplitude decay $\rightarrow m = 2$ deformation
- Peak frequency correlated with compactness

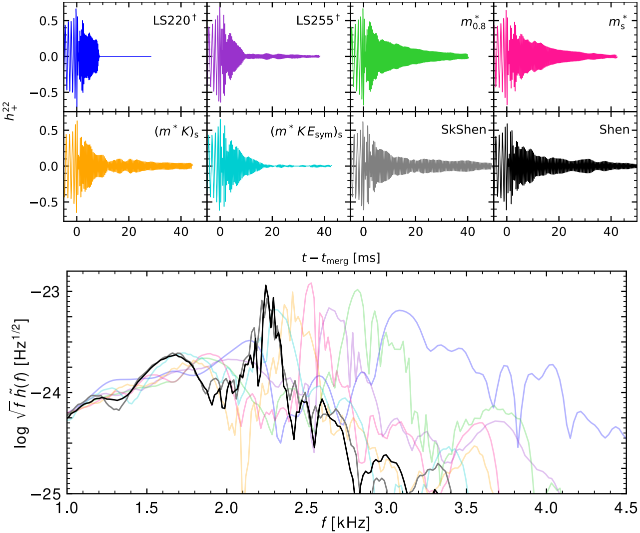
$\Rightarrow$ Results match universal relations ($\pm 10\%$)

Rezzolla & Takami, PRD 93 (2016),

Bauswein+, EPJA 52 (2016),

Kiuchi+, PRD 101 (2020)

Gravitational waves



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Rezzolla & Takami, PRD 93 (2016),

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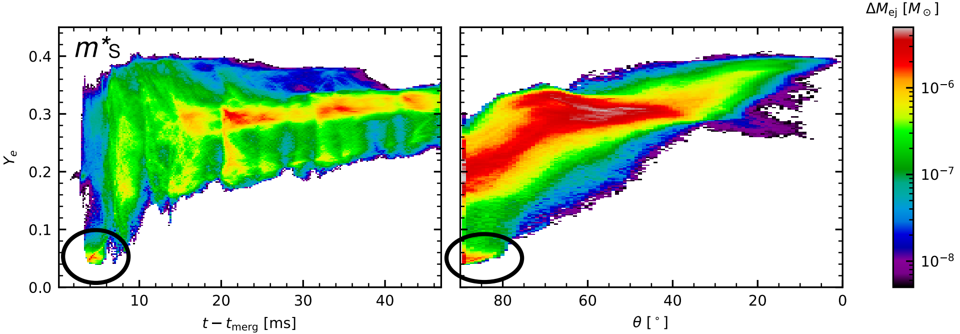
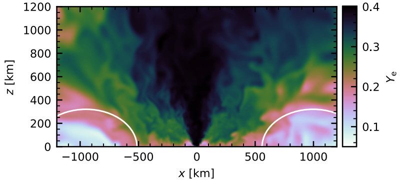
- Shen and SkShen **very** similar

$\Rightarrow$ GW spectrum depends on EOS at n_0

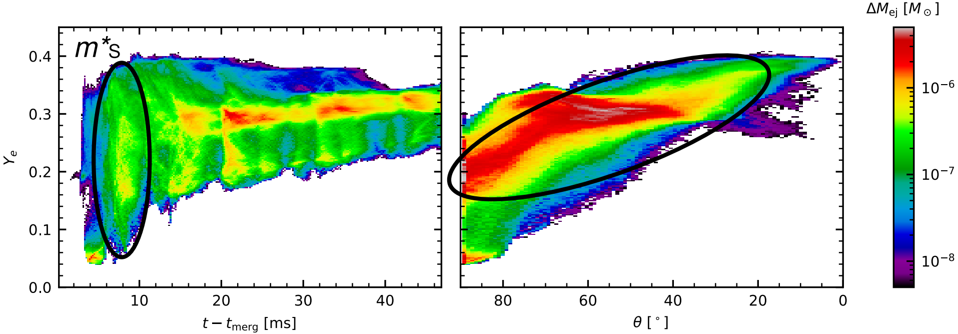
Mass ejection



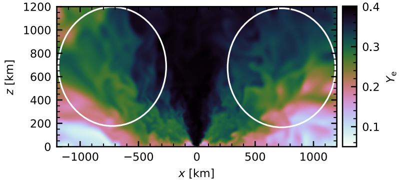
- Tidal ejecta: low Y_e, equatorial



Mass ejection



- Tidal ejecta: low Y_e, equatorial
- Shock heated ejecta: broad Y_e, θ



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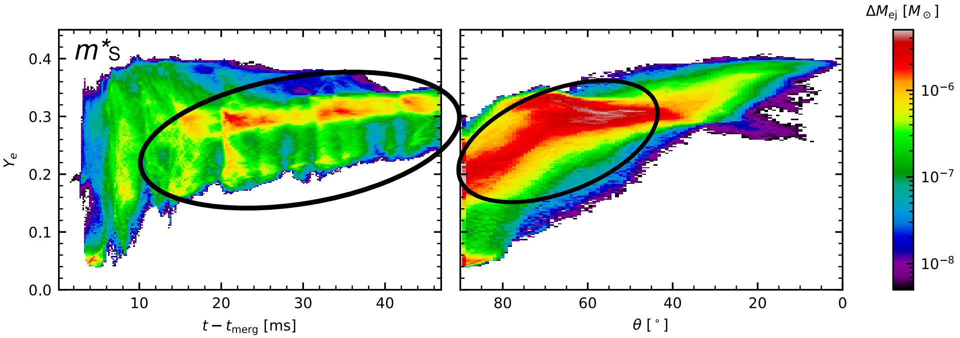
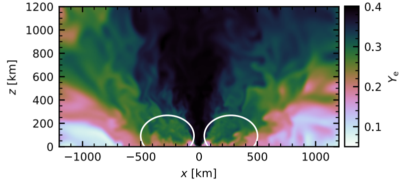


- Tidal ejecta: low Y_e, equatorial
- Shock heated ejecta: broad Y_e, θ
- Disk ejecta: spiral wave + ν-driven wind



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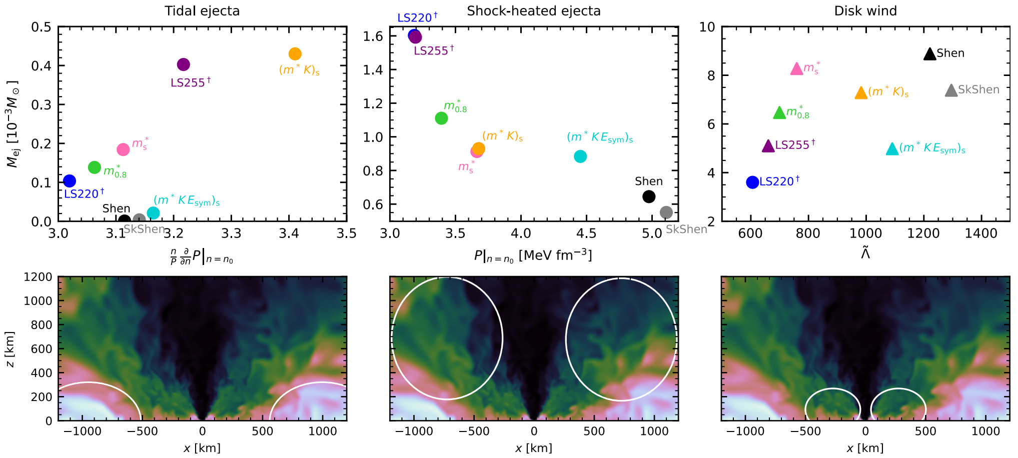

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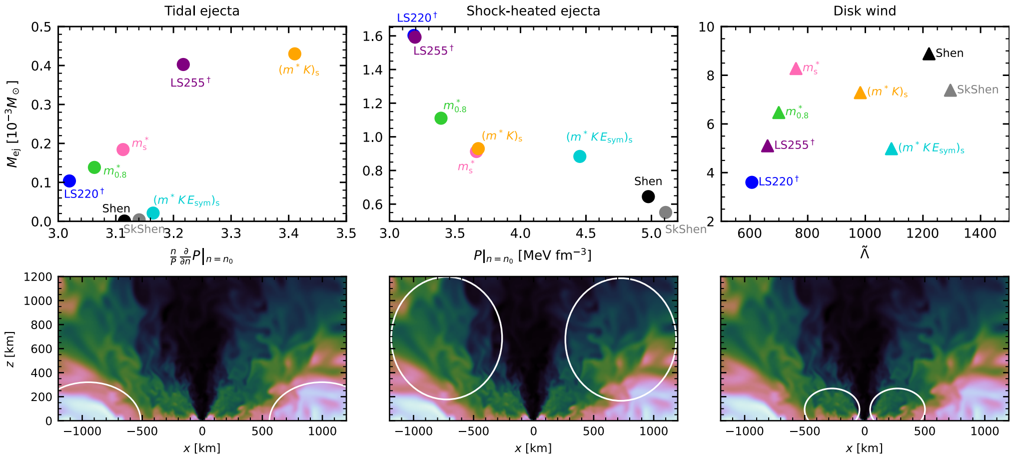
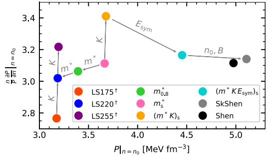
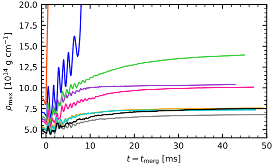


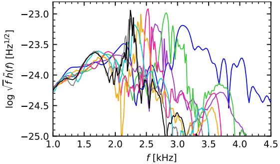
Talk by Giacomo Ricigliano tomorrow ⇒ Nucleosynthesis and lightcurves

Summary

- BNS simulations with systematic EOS variations
- Investigated dependence of
  - Remnant contraction, heating, & deformation
  - GW amplitude & frequencies
  - Ejection of matter
- Differentiate stiffness of EOS at nuclear & supranuclear densities







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Thank you for the attention