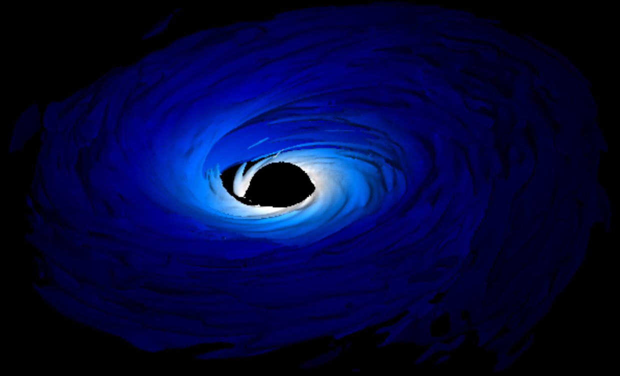
Nuclear Matter Properties in Neutron-Star Mergers



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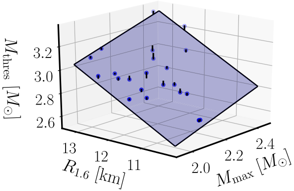
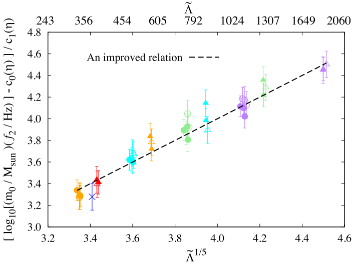
EOS effects in mergers

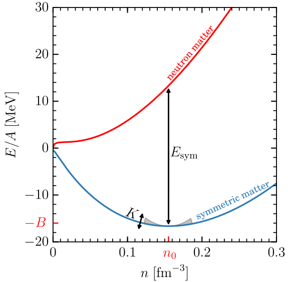


Bauswein *et al.* 2021



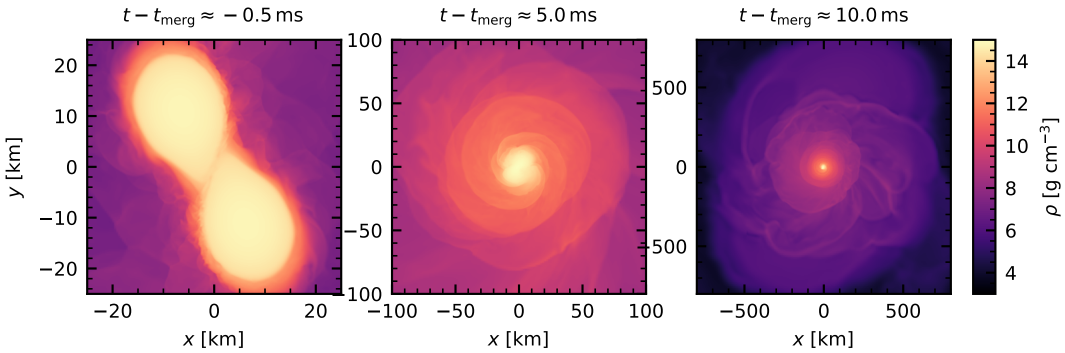
Kiuchi *et al.* 2020

- Multi-messenger observables effected by EOS
  - Inspiral/chirp GW signal (GW170817)
  - Collapse
  - Post-merger GW signal
  - Ejecta properties → Kilonova
- Use nuclear matter properties instead of TOV-related parameters



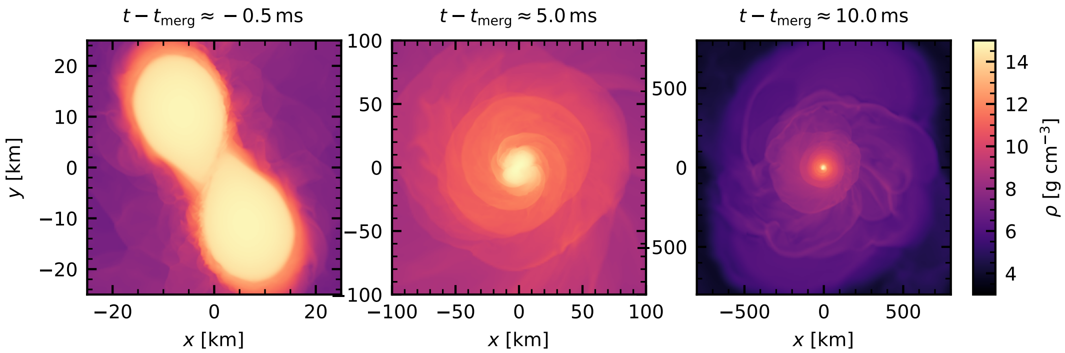
courtesy of Sabrina Huth

EOS effects in merger simulations



- Larger NS radii $\rightarrow$ Less violent plunge
- Tidal disruption of star depends on structure of BNSs
- Prompt / delayed / no collapse $\rightarrow$ P at high density

EOS effects in merger simulations

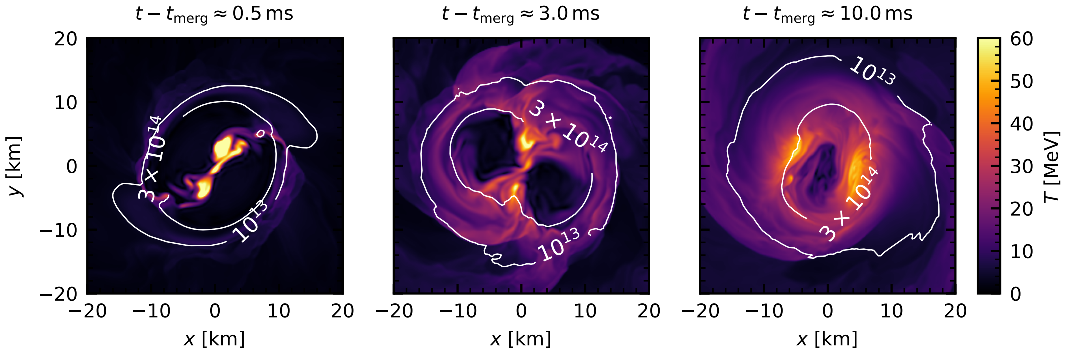


- Remnant deformation / oscillation:

→ Post-merger GW emission

→ Disk formation + mass ejection

EOS effects in merger simulations



- Shock heating depends on thermal effects → Effective mass
- Neutrinos emission + absorption

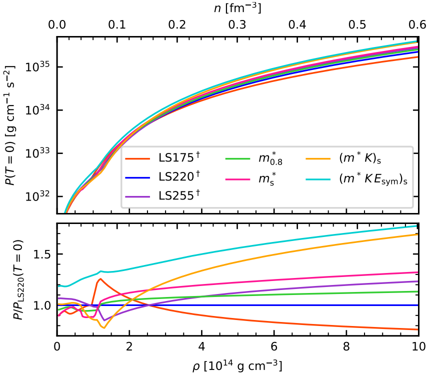
EOS Models

EOS	$\frac{m^*}{m_N}$	B	K	E_{sym}	L	ρ_0
LS220[†]	1.0	16.0	220	29.3	73.7	2.59
LS175[†]	.	.	175	.	.	.
LS255[†]	.	.	255	.	.	.
$m^*_{0.8}$	0.8	.	220	.	79.3	.
m^*_{S}	0.634	.	.	.	86.5	.
$(m^* K)_{\mathrm{S}}$	.	.	281	.	.	.
$(m^* K E_{\mathrm{sym}})_{\mathrm{S}}$	.	.	.	36.9	109.3	.
SkShen	.	16.3	.	.	.	2.43
Shen	.	.	.	.	110.8	.

- Study impact of individual nuclear matter properties following Yasin *et al.* 2020

  (Schneider *et al.* 2017, 2018)
- Fiducial model LS220 EOS (Lattimer & Swesty 1991)
- Vary effective nucleon mass m^* and incompressibility K
- Match nuclear matter properties to Shen EOS (Shen *et al.* 1998)

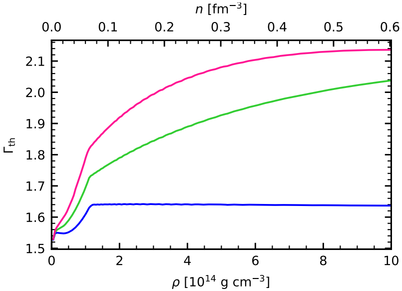
Nuclear matter properties



$$\Gamma_{\rm th} = 1 + \frac{P_{\rm th}}{\epsilon_{\rm th}} = 1 + \frac{P - P_{\rm cold}}{\rho\left(\varepsilon - \varepsilon_{\rm cold}\right)}$$

$$\approx \frac{5}{3} - \frac{n}{m^*}\frac{\partial m^*}{\partial n}$$

- $K \rightarrow$ slope of cold $P(\rho = \rho_0)$
- $m^* \rightarrow$ cold and thermal P
- $E_{\rm sym} \rightarrow L \rightarrow$ cold P + composition



Carbone & Schwenk 2019, Yasin *et al.* 2020, Keller *et al.* 2021, Huth, Wellenhofer, Schwenk 2021

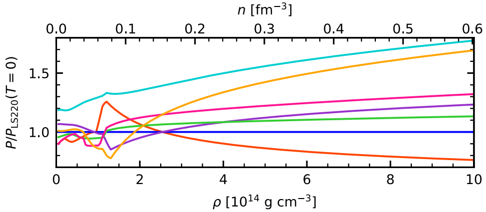
BNS simulations with the Einstein Toolkit

- Full GR simulations
- Einstein Toolkit + WhiskyTHC (Radice *et al.* 2014)
- Neutrino transport:
  - Emission: local leakage scheme (Galeazzi *et al.* 2013)
  - Absorption: ray-by-ray "M0" scheme (Radice *et al.* 2016)
- Initial data with `Lorene` library (Gourgoulhon *et al.* 2001)
- One simulation per EOS
- Total mass $2.73_{\odot}$, mass ratio $= 1$
- $M_{\mathrm{chirp}} = 1.188 M_{\odot}$ (GW170817)

einsteintoolkit.org

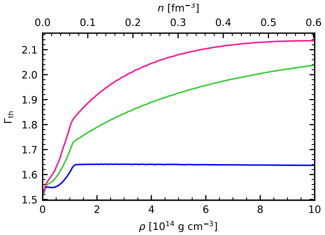
Remnant properties

- Pressure at high $\rho \to \rho_{\max}$
  - LS175[†]: instant collapse
  - LS220[†]: delayed collapse
  - Others: no collapse
- Shen and SkShen similar

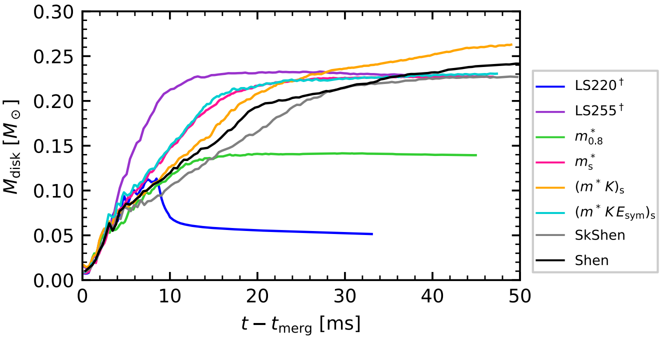


Remnant properties

- Pressure at high $\rho \to \rho_{\max}$
  - LS175†: instant collapse
  - LS220†: delayed collapse
  - Others: no collapse
- Shen and SkShen similar
- Softer EOS $\to$ more shock heating
- Lower m^* $\to$ more shock heating

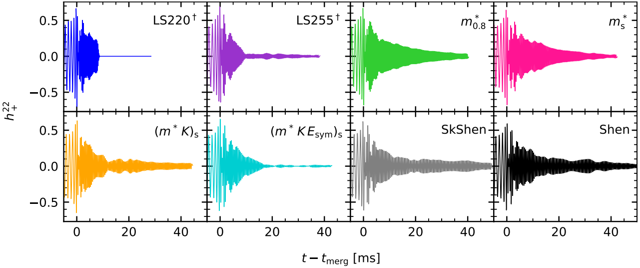


Disk properties



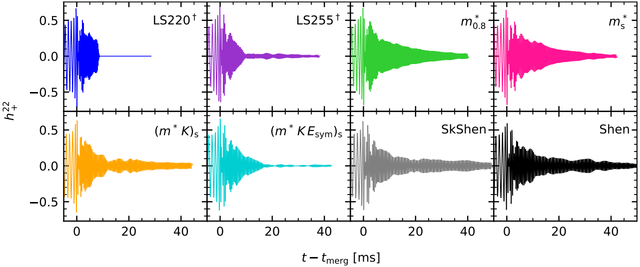
- Disk definition is ambiguous for NS remnants
- Higher K, lower m^* $\rightarrow$ heavier disk
- Remnant deformation important $\Rightarrow$ dependence on EOS complecated

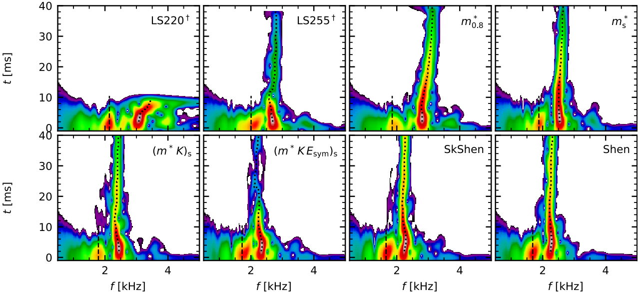
Gravitational waves



- Post-merger GW amplitude decay varies

Gravitational waves

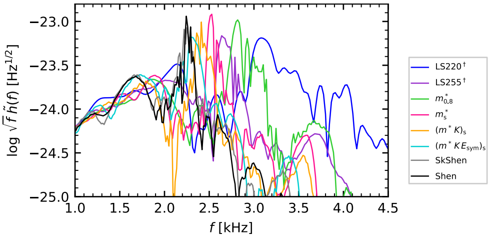




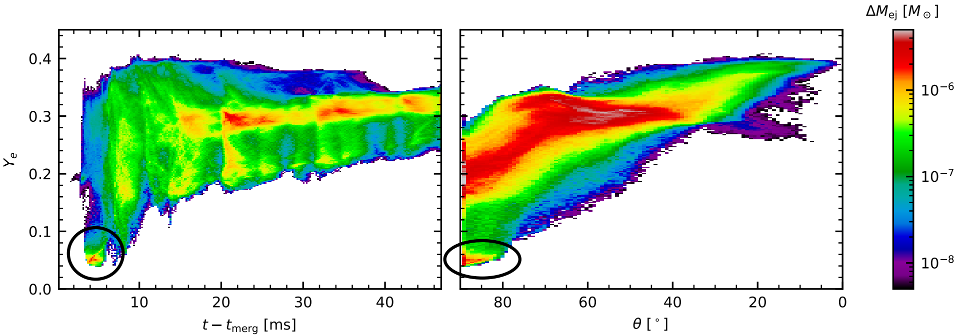
- Post-merger GW amplitude decay varies
- Peak frequency correlated with compactness
- Fit universal relations ($\pm 10\%$)

(Rezzolla & Takami, Bauswein *et al.* 2016, Kiuchi *et al.* 2020)

- Shen and SkShen **very** similar

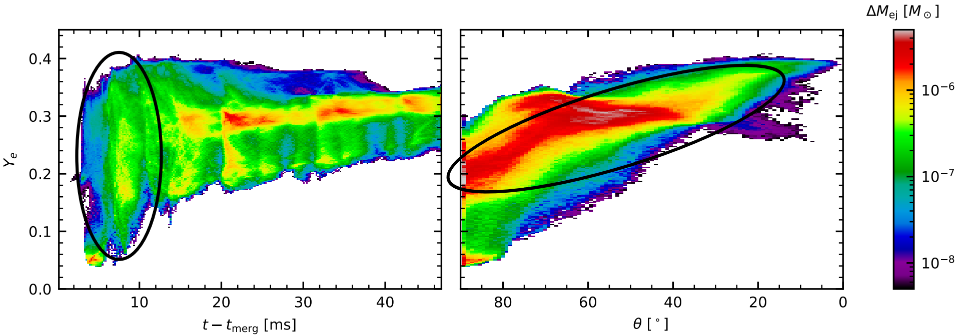


Mass ejection



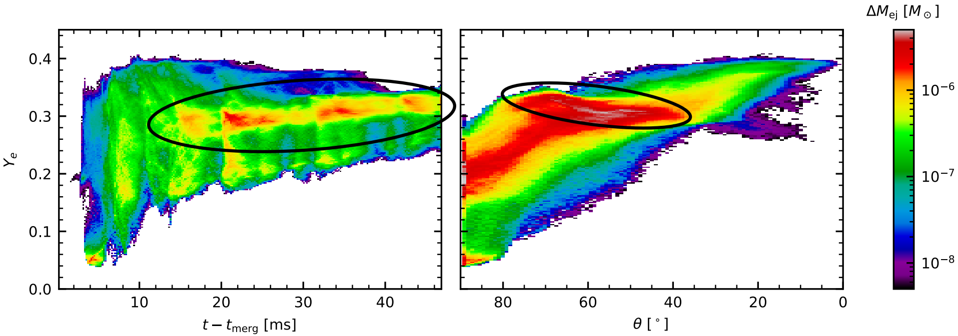
- Tidal ejecta: Low ye, equatorial

Mass ejection



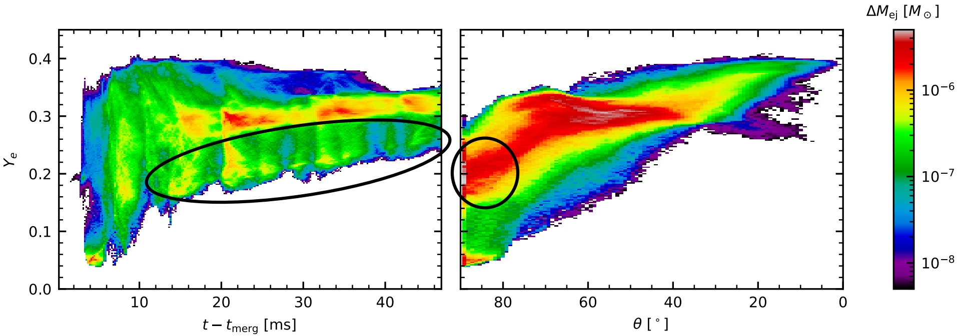
- Tidal ejecta: Low ye, equatorial
- Shock heated ejecta: Broad ye, broad angular distribution

Mass ejection



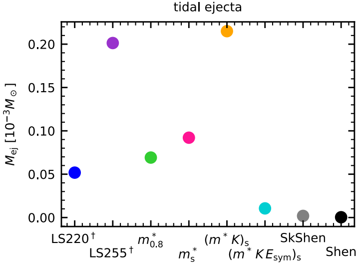
- Tidal ejecta: Low ye, equatorial
- Shock heated ejecta: Broad ye, broad angular distribution
- Neutrino wind: ν absorption above disk

Mass ejection



- Tidal ejecta: Low ye, equatorial
- Shock heated ejecta: Broad ye, broad angular distribution
- Neutrino wind: ν absorption above disk
- Equatorial wind: Disk shields from ν absorption $\rightarrow$ lower Y_e

Mass ejection



- Dependent on K
- Minor dependence on m^*
- No tidal ejecta for stiffest EOSs

- Dependent on m^*
- SkShen and Shen even lower

- Correlates with remnant deformation
- Not saturated

Summary

- K and m^* most important for
  - Remnant dynamics
  - Post-merger GW spectrum
- K $\rightarrow$ larger effect for high ρ
- m^* $\rightarrow$ thermal effects secondary to cold pressure
- SkShen very similar to Shen (especially GW spectrum)
- Tidal ejecta correlated to K
- Shock heated ejecta correlated to m^*