UNIVERSITÀ DI TRENTO

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TIFPA

Effects of nuclear matter properties in neutron star mergers

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M. Jacobi, F.M. Guercilena, S. Huth, G. Ricigliano, A. Arcones, A. Schwenk, MNRAS, 527, 3, 2023

Sesto Incontro Nazionale di Fisica Nucleare, Trento - 26/02/2024

BACKGROUND: NEUTRON STARS

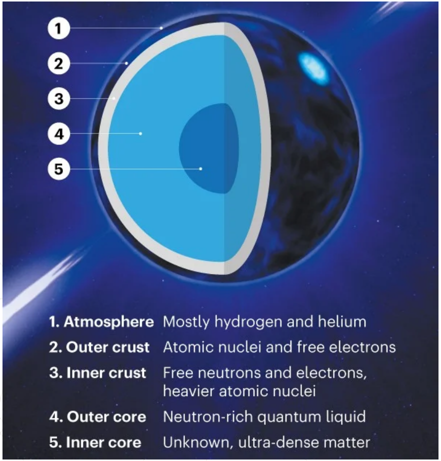


Image from *[Mann, 2020]*

- Mass: ~ 1 to $\sim 2.3\ M_\odot$
- Density: ~ 1 to $\sim 10\ n_0$
- Radius: ~ 12 km
- Composition: mostly neutrons

The core is well modeled as nuclear matter.

👉 Details of nuclear interaction in these conditions aren't well constrained → Neither is high-density EOS

Note: "isolated" NS too can give us precious information (e.g. $M_{\max}$)

$M_{\max} \simeq 1.97\ M_\odot$ *[Demorest et al., 2010]*

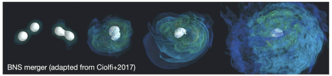
$M_{\max} \simeq 2.01\ M_\odot$ *[Antoniadis et al., 2013]*

$M_{\max} \simeq 2.08\ M_\odot$ *[Fonseca et al., 2021]*

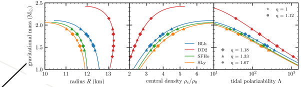
$M_{\max} \simeq 2.35\ M_\odot$ *[Romani et al., 2022]*

BACKGROUND: BINARY NEUTRON STARS

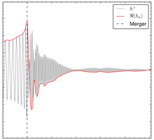
BNS mergers


BNS merger (adapted from Ciolfi+2017)

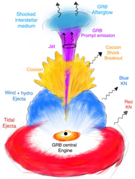
EOS of dense matter



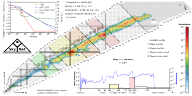
Gravitational waves



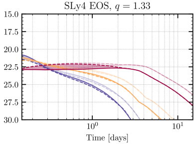
sGRB



r-process nucleosynthesis



Kilonovae



BACKGROUND: BINARY NEUTRON STARS

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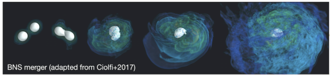
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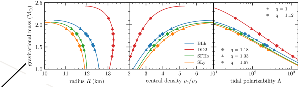

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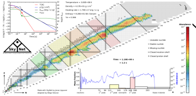
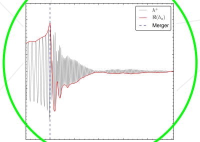


Gravitational waves



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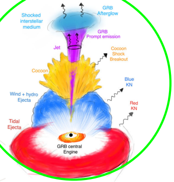

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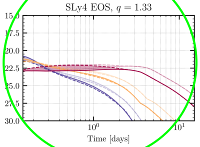


A spectacular confirmation from the events GW170817 (GW signal), GRB170817A (sGRB) and AT2017gfo (kilonova), the first multimessenger detection of a BNS merger

↓

The start of multimessenger astronomy

METHODS: SELECTING NUCLEAR PROPERTIES

The problem in a nutshell: can we pinpoint nuclear properties starting from BNS observables? Our approach:

Construct an EOS from a Skyrme parametrization of the energy per nucleon...

$$\frac{E}{A}|_{T=0} = \frac{3\hbar}{10m^*}(3\pi^2 n)^{2/3}[(1-x)^{5/3}+x^{5/3}] + [a+4bx(1-x)]n + cn^{\delta} - x\Delta$$

$$x = \frac{n_{\mathrm{p}}}{n}$$

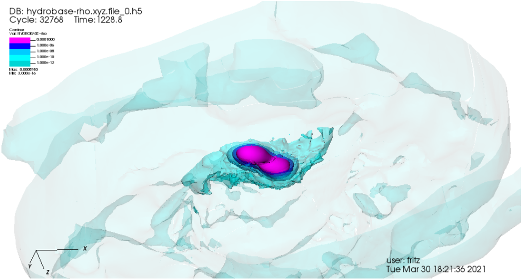
$$\hbar^2/(2m^*) = \hbar^2/(2m) + \alpha n$$

and fix coefficients a, b, c and δ to target specific values of B, K, E_{sym} and n_0. m^* is varied directly, we cannot control L.

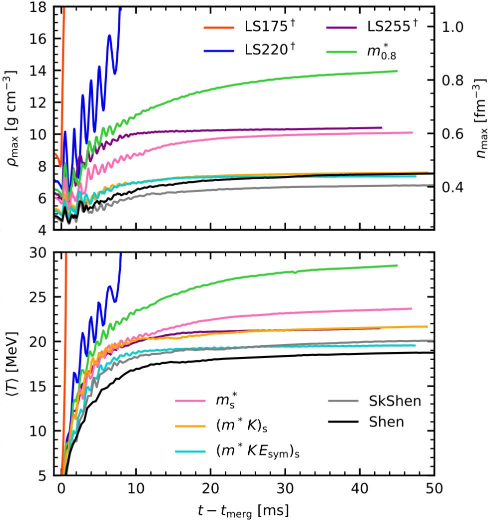
EOS	m^*	B	K	E_{sym}	L	n_0
LS175	1.0	16.0	175	29.3	73.7	0.155
LS220	1.0	16.0	220	29.3	73.7	0.155
LS255	1.0	16.0	255	29.3	73.7	0.155
$m^*_{0.8}$	0.8	16.0	220	29.3	79.3	0.155
m^*_S	0.634	16.0	220	29.3	86.5	0.155
$(m^*K)_S$	0.634	16.0	281	29.3	86.5	0.155
$(m^*KE)_S$	0.634	16.0	281	36.9	109.3	0.155
SkShen	0.634	16.3	281	36.9	109.4	0.145
Shen	0.634	16.3	281	36.9	110.8	0.145

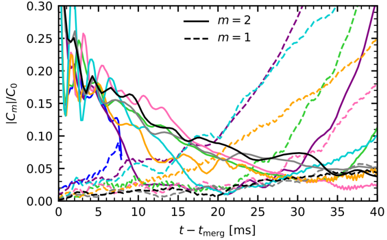
METHODS: SIMULATING BNS MERGERS

- One 1.365 $M_\odot$ equal mass simulation for each EOS
- BNS merger simulations performed with the `EinsteinToolkit` *[Zlochower et al., 2022]*
- Full GR (`BSSNOK` formulation of the EfE)
- Valencia formulation of Euler equations (`WhiskyTHC` code) *[Radice and Rezzolla, 2012]*
- Leakage (emission) + M0 (absorption) neutrino transport module *[Galeazzi et al., 2013, Radice et al., 2016]*



RESULTS: STRUCTURE OF THE MERGER REMNANT

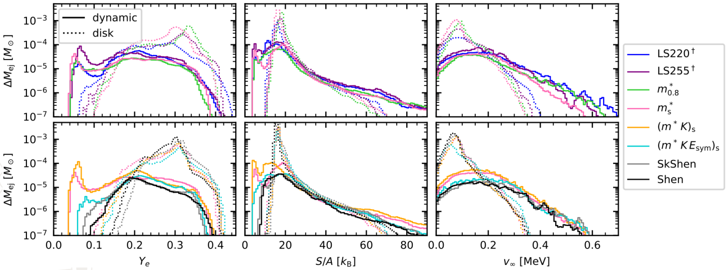




$$C_m = \int e^{-im\phi} \rho \mathrm{d}x\mathrm{d}y$$

- merger remnant structure and fate are tied to $P|_{n_0}$ and $dP/dn|_{n_0}$
- the incompressibility K has particular influence
- the final density correlates tightly with pressure at $(6 \sim 7 \cdot 10^{14}\ g/cm^3)$
- the crossover from the $m = 2$ to $m = 1$ mode is also influenced by the incompressibility

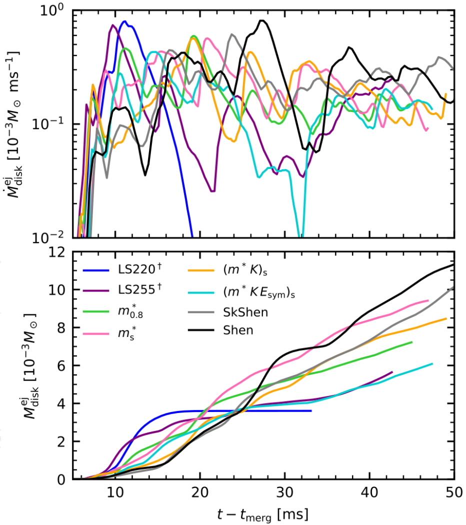
RESULTS: EJECTA PROPERTIES



- ejecta are divided in dynamical (satisfying the Geodesic criterion) and disk ejecta (satisfying the Bernoulli criterion)
- dynamical ejecta are further divided in tidal ($Y_{\rm e} < 0.1$) and shock-heated ($Y_{\rm e} \geq 0.1$)

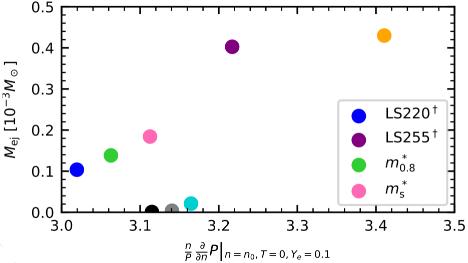
- ejecta properties are different between dynamical (lower $Y_{\rm e}$, higher v_∞ and broader s) and disk
- not much difference between EOS (no visible trend)
- cf. *[Bovard et al., 2017]*

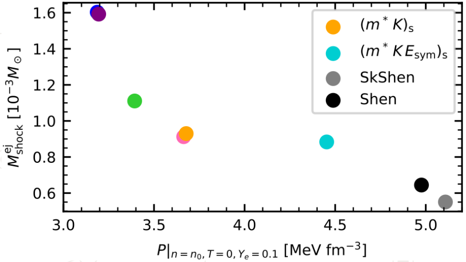
RESULTS: DISK EJECTA MASSES



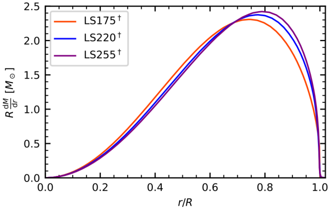
- of course collapse plays a dominant role
- dominance of the $m = 2$ bar mode leads to efficient mass ejection - so called spiral wave wind {see *[Nedora et al., 2019]*}
- besides very general observations (e.g. softer EOSs lead to enhanced neutrino winds), no clear trends with EOS

RESULTS: DYNAMICAL EJECTA MASS VS. NUCLEAR PROPERTIES

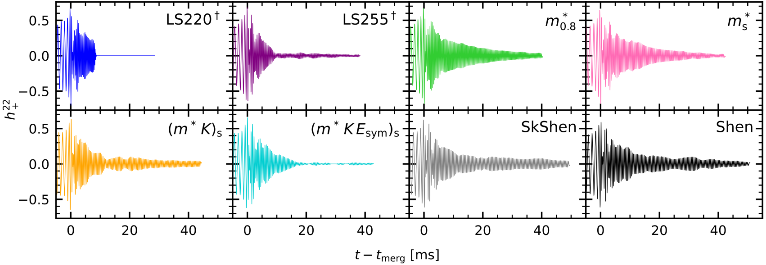




- tidal and shock-heated components have different ejection mechanisms, so they correlate to different nuclear properties
- shocked ejecta correlate with $P|_{n_0}$ (therefore m^* or $E_{\rm sym}$) 👉 almost no dependence on K
- for very stiff EOS, shock-heating dominates and there is no tidal ejecta
- otherwise, clear correlation between $M^{\rm tid}_{\rm ej}$ and K (possibly due to radial matter pile-up)

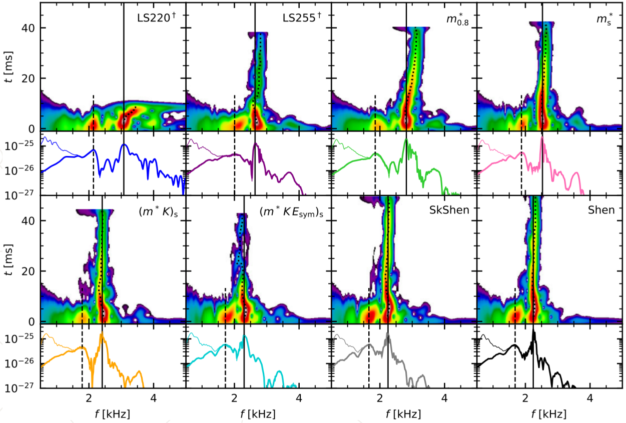


RESULTS: GRAVITATIONAL WAVES



- $+$ polarization of the $(2,2)$-mode of the GW strain h
- collapse induced shut-down for models LS175 and LS220
- "two phases" behaviour in amplitude reduction slope post-merger
  - 👉 linked to transition from $= 2$ to $m = 1$ mode in the remnant

RESULTS: GRAVITATIONAL WAVES



- model LS220 shows a “chirp-like” behaviour of the peak frequency before collapse, due to increased rotational velocity as the star contracts
- same effects is seen in other models (e.g. $m^*_{0.8}$ and m^*_S), but less dramatic
- decreasing m^*, increasing K and $E_{\rm sym}$ increases the central pressure and decreases the density, reducing f_2
- the sequence of models m^*_S, $(m^*K)_S$, $(m^*KE_{\rm sym})_S$ and SkShen tends toward the Shen EOS spectrum. In particular SkShen and Shen are almost indistinguishable
- computed GW properties are therefore independent of the EOS microphysical model and mostly sensitive to the EOS around saturation density

CONCLUSIONS

- K has a large impact at high density, i.e. in the core of the merger remnant. Increasing K decreases the compactness of the remnant and lowers the dominant GW frequency. It also quickly halts the remnant contraction, dampening its oscillations
- m^* is important for both P_{cold} and P_{th}. Lowering it increases the P_{cold} at all densities, with a similar influence as K. But: the pressure density dependence is less steep, leading longer oscillations. Decreasing m^* increases Γ_{th}, while reducing shock-heating via reduced compactness. So P_{th} actually drops
- The mass of tidal ejecta correlates with K and the mass of shock-heated ejecta correlates with m^*. Mass ejection from the disk is more complex and hard to correlate with the EOS.
- The SkShen EOS is very similar to the original Shen (larger high density P and a slightly lower Γ_{th}. They lead to a similar evolution, and the GW spectra are remarkably similar

  👉 nuclear matter properties are a useful measure to quantify EOS effects in BNS mergers

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Future work: run many more models, try to perform actual fits as function of m^*, K, etc.

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Thank you

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