Accretion discs from binary neutron star mergers

Geometrical, Dynamical and Thermodynamical properties

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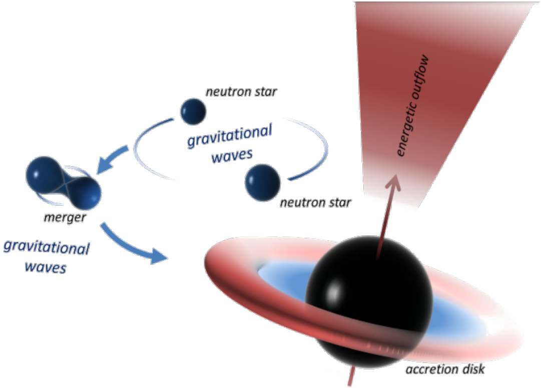
EUROPEAN CENTRE
FOR THEORETICAL STUDIES
IN NUCLEAR PHYSICS AND RELATED AREAS

Accretion discs from binary neutron star (BNS) mergers

- Formation: tidal interaction and shocks
- Timescale:
  - formation timescale $\sim 10\ \mathrm{ms}$
  - viscous timescale $\sim 1\ \mathrm{s}$



Credits: K. H. Lee et al 2020 ApJL 902 L23

Importance of accretion discs

Accretion discs formed during the merger of binary neutron stars:

- accrete into the central object: SGRBs (Berger 2014) , induce collapse (Bernuzzi 2020)
- source of ejected matter: neutrino driven (Perego 2014) winds, viscous effects (Metzger 2010) , magnetic stresses (Siegel 2017)

Properties of ejected matter are important for:

- r-process nucleosynthesis
- kilonova light-curves

Accretion discs simulations

- Used to investigate the effects of different mechanisms on the ejecta properties
- Idealized initial condition of disc:
  - constant specific angular momentum
  - constant entropy per baryon ($\sim 8k_B \ \mathrm{baryon}^{-1}$)
  - constant electron fraction (~ 0.3)

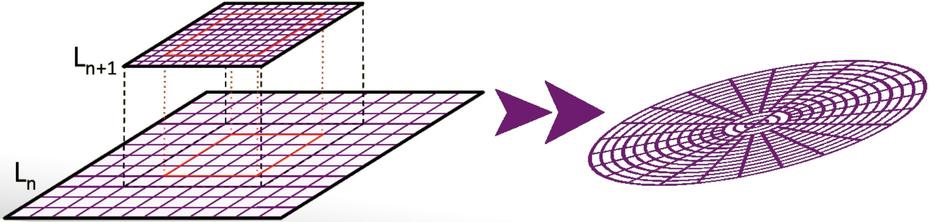
Aim:

- Characterization of accretion discs from BNS
- Improve/clarify the initial conditions

BNS merger simulations: numerical setup

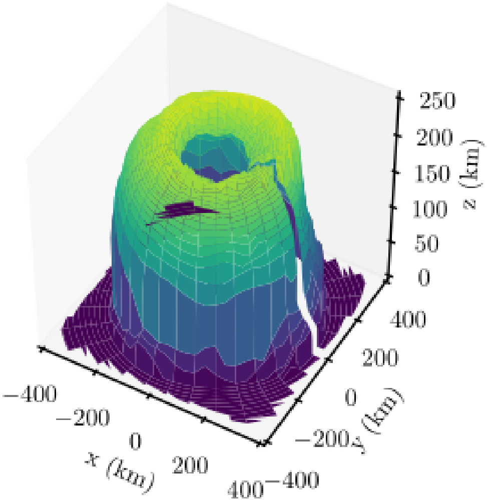
- EinsteinToolkit
- Full General Relativity
- Hydro: `WhiskyTHC`
- Neutrino: `Leakeage + M0`

- Grid: `Carpet`, 7 nested refinement level
- Resolutions: HR (123m), SR (185m), LR (246m)
- Interpolation to a cylindrical grid



Disc extraction

- maximum density: 10^{13} g cm^{-3}
- minimum lapse: 0.3
- minimum density: such that $M_{\rm disc} = 0.95 M_{\rm tot}$
- Unbound matter removed: $|u_t| \geq c$



Simulation sample

- 5 equation of state (EOS): LS220, DD2, SFHo, SLy, BLh.
- $q = M_1/M_2 \in [1, 1.67]$

Classification:

- prompt: immediate black hole (BH) formation
- short-lived: collapse before simulations end
- long-lived: no BH

class	sim	q	longest (ms)
long-lived	20	$1 - 1.66$	103
short-lived	9	$1 - 1.43$	36
prompt	9	$1.12 - 1.66$	25

Total of 44 simulations.

- 38 with $M_{\text{chirp}} = 1.18\ M_\odot$ ($M_{\text{tot}} \sim 2.6\ M_\odot$)
- 6 simulations $M_{\text{chirp}} = 1.44\ M_\odot$ ($M_{\text{tot}} \sim 3.3\ M_\odot$)

Results

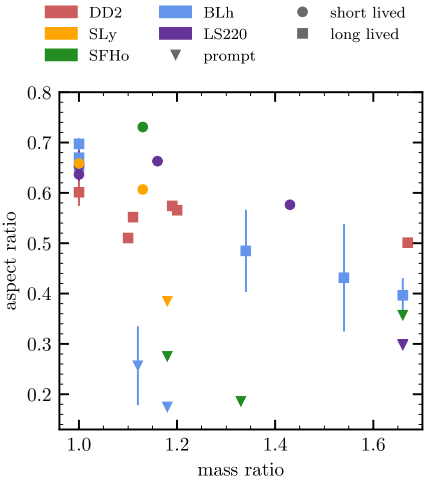
Aspect ratio

$$\text{aspect ratio} = \left\langle \frac{\mathrm{H}(\phi)}{\mathrm{R}(\phi)} \right\rangle_{\phi}$$

- long/short-lived: decreases with the mass ratio and softness of the EOS $(0.7 - 0.4)$
- prompt/high mass: lower values and flatter $\sim 0.3 - 0.2$

Remark

Discs from BNS mergers are **thick**

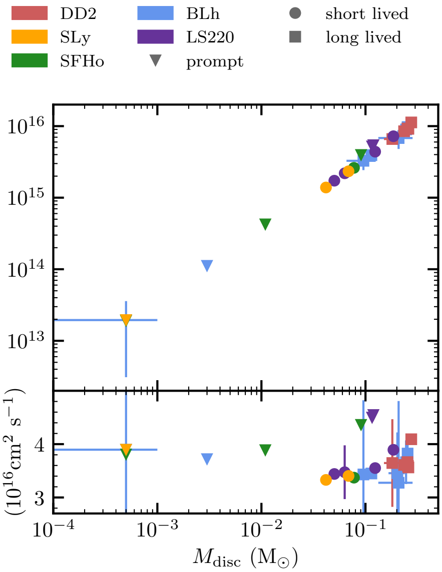


Mass and angular momentum

$$M_{\mathrm{disc}} = \int_{\mathrm{disc}} \sqrt{\gamma}\rho W \; r dr d\phi dz$$

$$J_{\mathrm{disc}} = \int_{\mathrm{disc}} \sqrt{\gamma}\rho h W^2 v_\phi \; r dr d\phi dz$$

- Trend independent from EOS, total mass, mass ratio, ...
- Why $J_{\mathrm{disc}}/M_{\mathrm{disc}} \approx \mathrm{const}$?

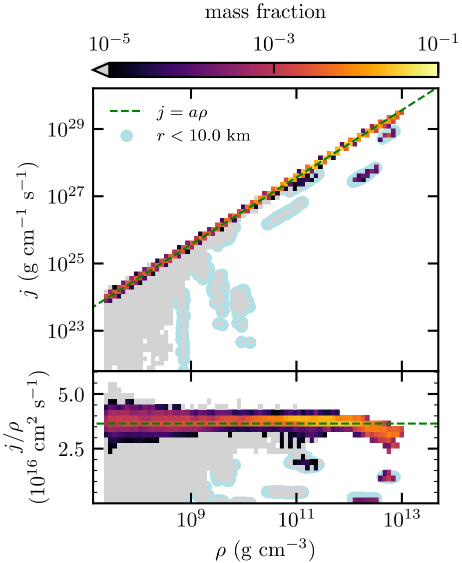


Specific angular momentum

Remark

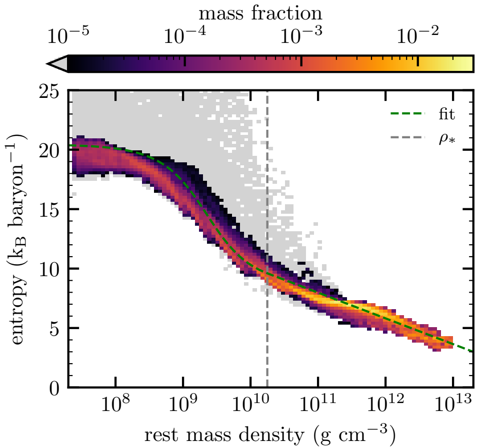
Specific angular momentum is almost constant: discs are **non Keplerian**

Disc specific angular momentum is in the range $3 - 5\ \times 10^{16}\ \mathrm{cm}^2\ \mathrm{s}^{-1}$.

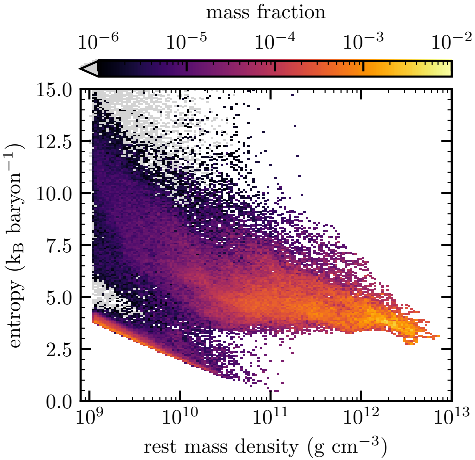


Entropy per baryon

Small mass ratio ($q \lesssim 1.3$)

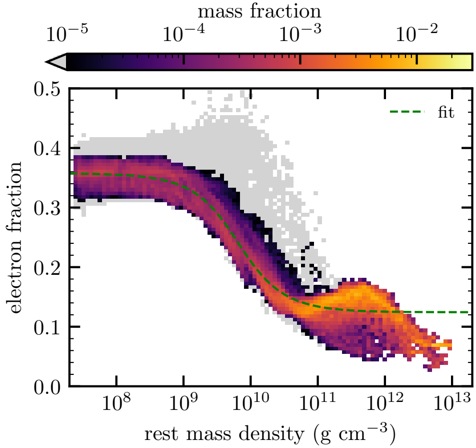


Higher mass ratio ($q \gtrsim 1.3$)



Electron fraction

- Different trend between low-high mass ratio
- Sigmoidal distribution with ρ at $q \lessapprox 1.3$
- Transient between $\rho \sim 10^{11} - 10^{13}\mathrm{g\ cm}^{-3}$: neutrino decoupling



Conclusions

Aspect ratio

Discs from BNS mergers are **thick**

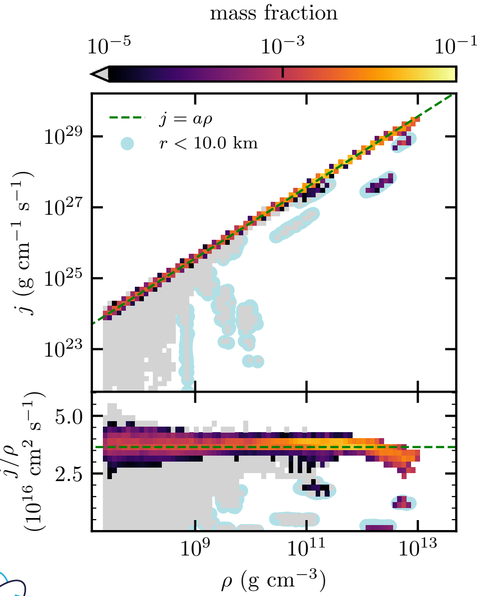
Constant specific angular momentum

Non Keplerian discs

Entropy & electrion fraction

Not isentropic.

Sigmoidal distribution with ρ at low mass ratio $q \lesssim 1.3$



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