3D BNS merger ejecta evolution up to second timescales

Dynamics, Element Distribution, and Light Curves

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Multi-Messenger Astrophysics in the Dynamic Universe

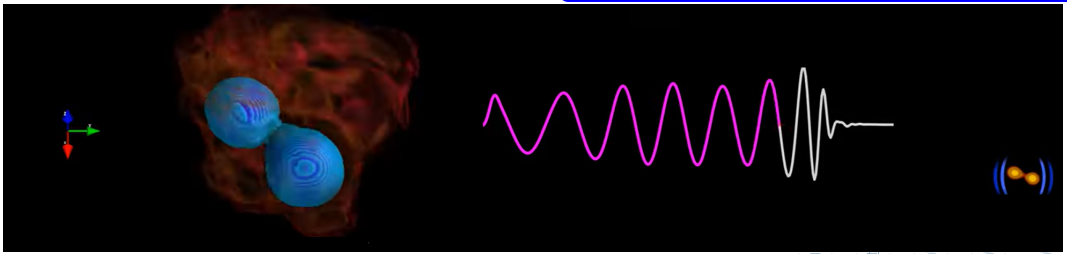
Introduction

Astrophysical Relevance of BNS

- Gravitational Waves
- Electromagnetic Radiation
- Neutrino Emission
- Nucleosynthesis

Motivations and Goals

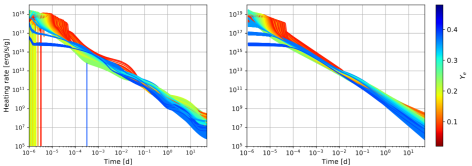
- Multiple Scales guiding the problem
- High costs of long NR simulations
- Large d.o.f. of nuclear networks
- Goal : bridge the gap between these different regimes



Methods

NR simulations

- Original THC Simulations full GRhydro + M1 (Radice & Benuzzi 2023, Benuzzi et al. 2025; Gutierrez et al. 2024)
- Athena++ extensions (Stone et al. 2020)
  - Time-dependent BC in Schwarzschild
  - $q = wq_{\mathrm{nuclear}} + (1-w)q_{Helmholtz}$
  - Nuclear heating tabulated as Wu et al. 2021



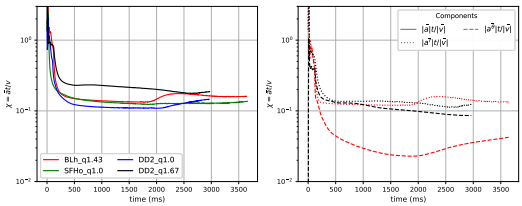
Post-processing

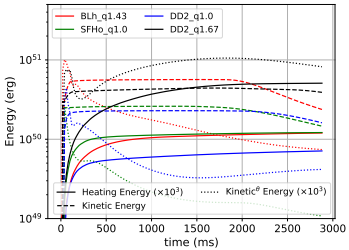
- KNEC code for light curves
  - Magistrelli et al. 2025
- WinNet for nucleosynthesis
  - fed with backwards time integrated tracers
  - enough tracers to resolve the total mass $\sim 4.2 \times 10^4$
  - Reichert et al. 2023

Models

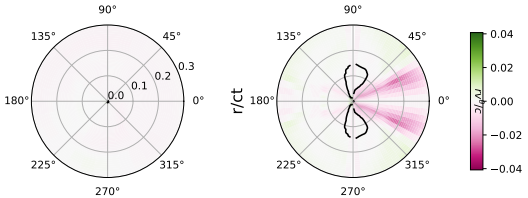
Model	EOS	$M_1[M_\odot]$	$M_2[M_\odot]$	Remnant	$t_{\rm collapse}$ [ms]	$M_{\rm ej}[M_\odot]$
BLh_q1.43	BLh	1.635	1.146	BH	114	$8.37(8.31)\times10^{-3}$
SFHo_q1.0	SFHo	1.35	1.35	BH	8.3	$4.58(4.57)\times10^{-3}$
DD2_q1.0	DD2	1.35	1.35	NS	-	$4.63(4.61)\times10^{-3}$
DD2_q1.67	DD2	1.80	1.08	NS	-	$1.38(1.40)\times10^{-2}$

Dynamics

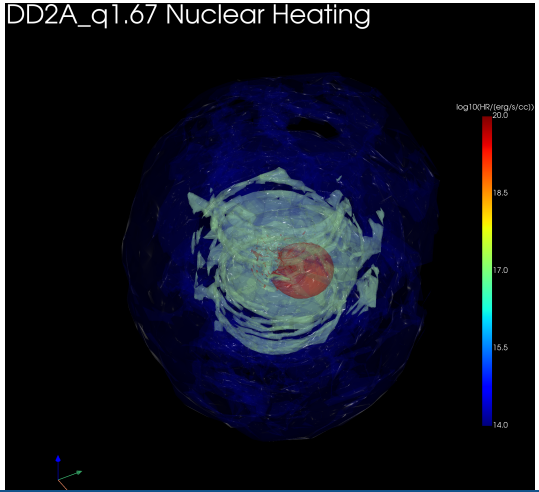




- $\chi \equiv \bar{a}t/v$
- All models show decaying χ after the end of injection
- Models show increasing χ at $t \sim 2\,\mathrm{s}$
  - Due to mass exiting the grid
- DD2_q1.67 has significant non-radial motion
  - Due to elevated nuclear heating



Dynamics



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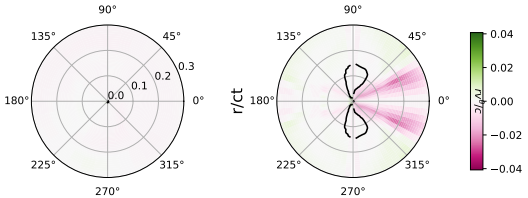
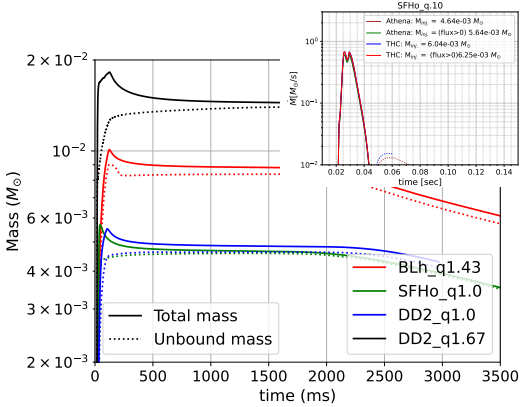


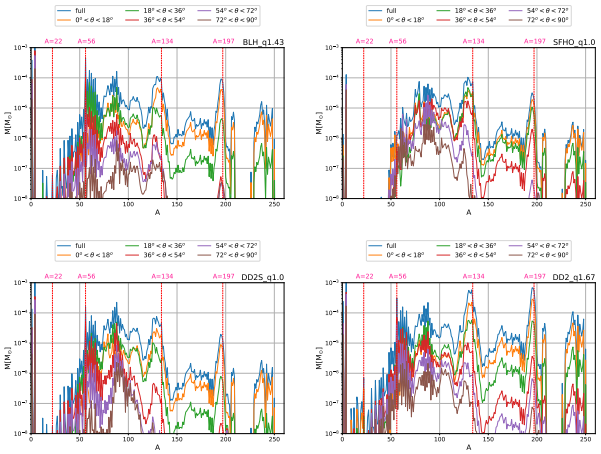
Fallback material

- Estimated fallback mass
- Only SFHo_q1.0 includes ejection in NR
- SFHo_q1.0 has a disk mass $M \sim 0.011\,M_\odot$ (Gutiérrez et al. 2025)
- Viscous disk ejecta $\sim 30\%$ of disk mass (Fujibayashi et al. 2020)
- Possible interaction between these components

Model	$M_{\rm fall}\,[M_\odot]$	$M_{\rm ej}\,[M_\odot]$
BLh_q1.43	1.24×10^{-3}	8.37×10^{-3}
SFHo_q1.0	1.01×10^{-3}	4.58×10^{-3}
DD2_q1.0	6.62×10^{-4}	4.63×10^{-3}
DD2_q1.67	3.66×10^{-3}	1.38×10^{-2}

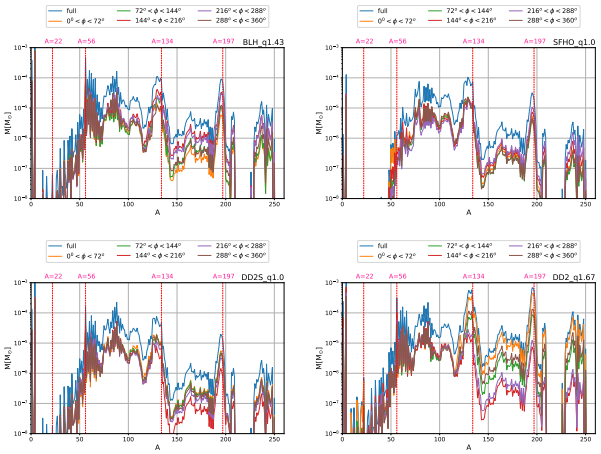


Elements distribution's dependence on θ



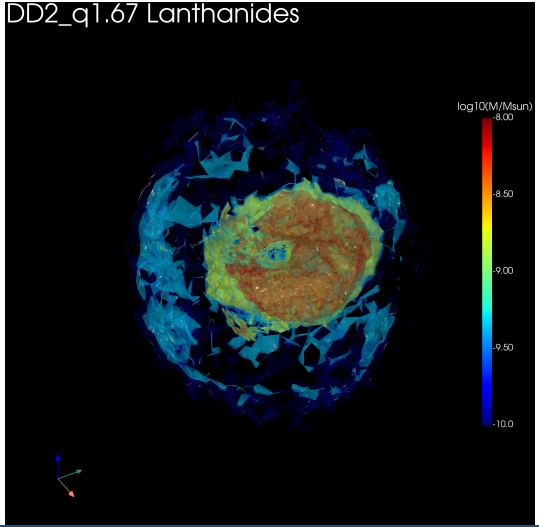
- Bulk of heavy elements for $\theta \lesssim 36°$
- Largest mass of heavy *r*-process elements for DD2_q1.67
- SFHo_q1.0 has the smallest production of H and He and light *r*-process elements

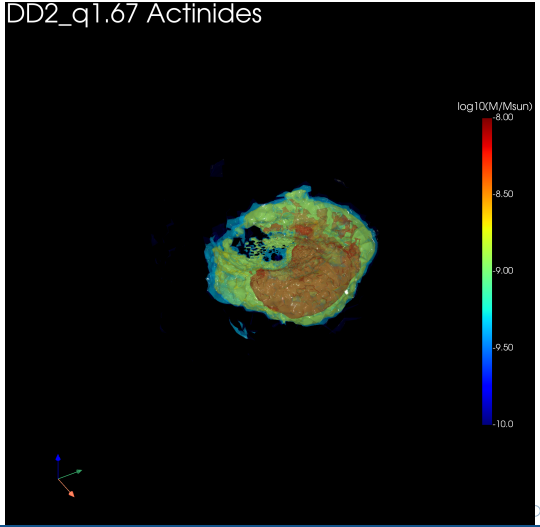
Elements distribution's dependence on ϕ



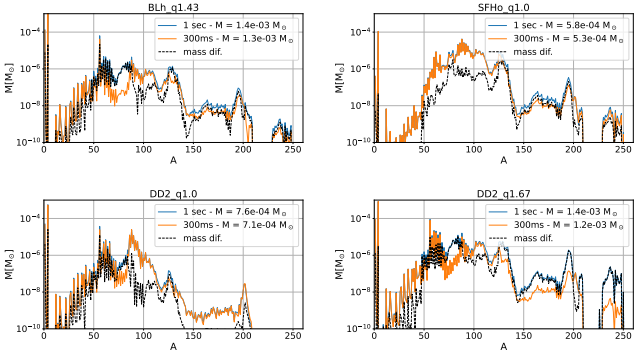
- SFHo_q1.0 and DD2_q1.0 show stronger ϕ dependence for elements such as $^{134}_{54}\mathrm{Xe}$
- SFHo_q1.0 and DD2_q1.0 production varies by less than a factor $\lesssim 2$
- Largest variations for BLh_q1.43 and DD2_q1.67 occur for $A \gtrsim 134$
- Variations can reach factors of $\sim$ 5–10

Lanthanides and Actinides DD2_q1.67



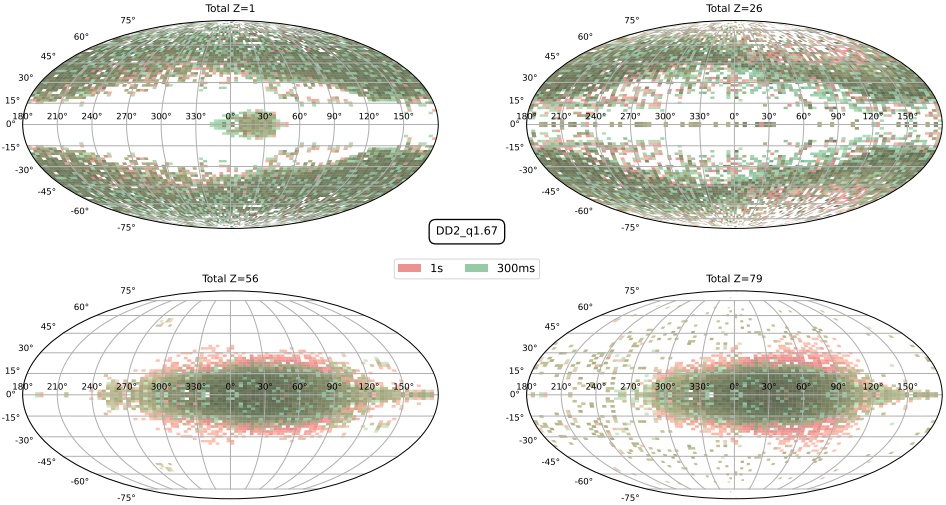


Temporal Dependence

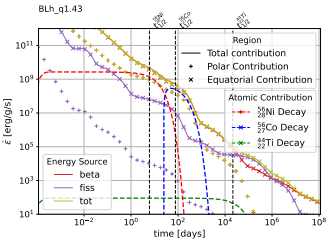


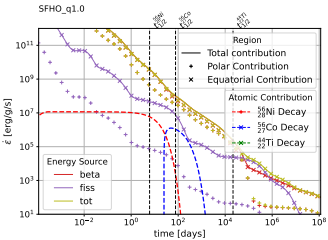
- WinNet fed with datasets evolved for 300 ms and 1 s
- Symmetric binaries show limited sensitivity
- BLh_q1.43 polar regions affected near the first r-process peak
- DD2_q1.67 polar regions affected for $A \gtrsim 130$
- Lanthanide and actinide expansion (?)

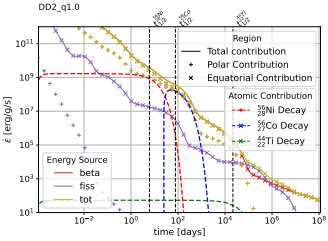
Temporal Dependence

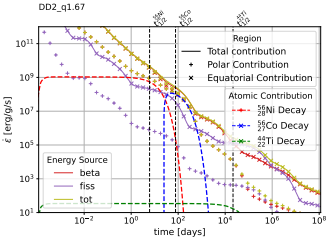


$^{56}_{28}$Ni impact









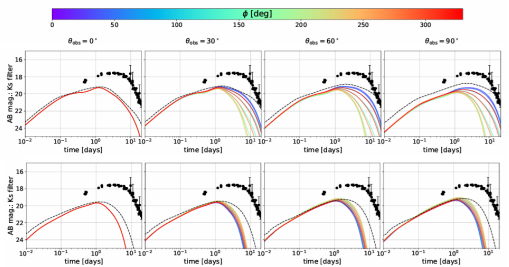
Ejecta masses

Model	$M_{\rm ej}$ $[M_\odot]$
BLh_q1.43	8.37×10^{-3}
SFHo_q1.0	4.58×10^{-3}
DD2_q1.0	4.63×10^{-3}
DD2_q1.67	1.38×10^{-2}

Nickel masses

Model	$M_{^{56}\rm Ni}$ $[M_\odot]$
BLh_q1.43	4.60×10^{-4}
SFHo_q1.0	1.10×10^{-6}
DD2_q1.0	1.59×10^{-4}
DD2_q1.67	3.10×10^{-4}

AB magnitudes at 40Mpc for DD2_q1.67 and BLh_q1.43



Discussion

- Comparison with 2D simulations
- Comparison with AT2017gfo data
- Extra ϕ-dependence does not bridge the gap
- Can actually work the other way around
- Bigger difference in the Ks filter
- Effect of the "lack" of a lanthanide curtain at $\theta \sim 200^o$ for DD2_q1.67

Conclusions and Future Work

Conclusion

- New set-up for long term ejecta: Athena++, Transition EOS, KNEC, WinNet
- $\dot{\epsilon}$ is responsible for expansion of lanthanides curtain
- $^{56}_{28}$Ni decay route is the main source of $\dot{\epsilon}$ at $t \sim 100$days
- Larger effects of $^{56}_{28}$Ni at $\theta > 45^o$ regions
- Extra ϕ dependence does not bridge the gapes on the KN's light curves

Future Work

- Extend the study for larger times
- Study interaction of ISM
- Inclusion of B-fields

Thanks for your attention!