The astrophysical robustness of the r-process in neutron star mergers

Oleg Korobkin

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March 12, 2013

This talk is based on:
O. Korobkin, S. Rosswog, A. Arcones, C. Winteler,
"On the astrophysical robustness of the neutron star merger r-process"
MNRAS 2013

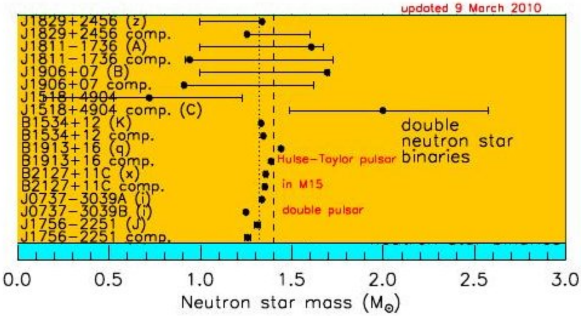
Outline

- Introduction
- Simulating merging neutron stars
- Properties of the ejecta
- The r-process nucleosynthesis
- Results
- Conclusion

Introduction

Binary neutron stars

- handful of binary ns systems are known to exist;
- decay due to emission of gravitational waves;
- will eventually merge.



[from Lattimer (2010)]

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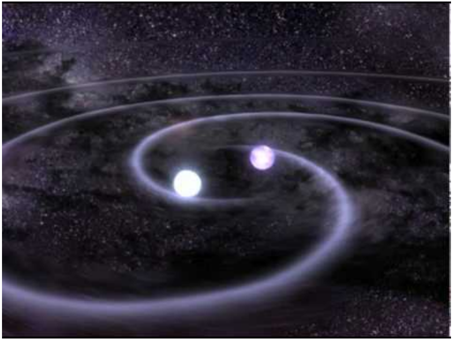
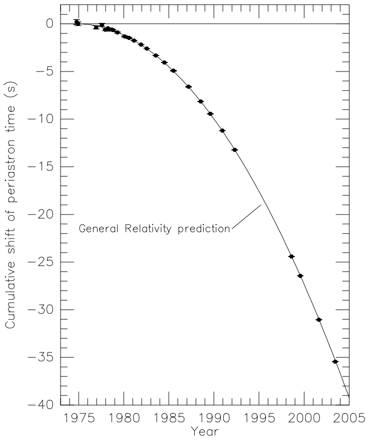


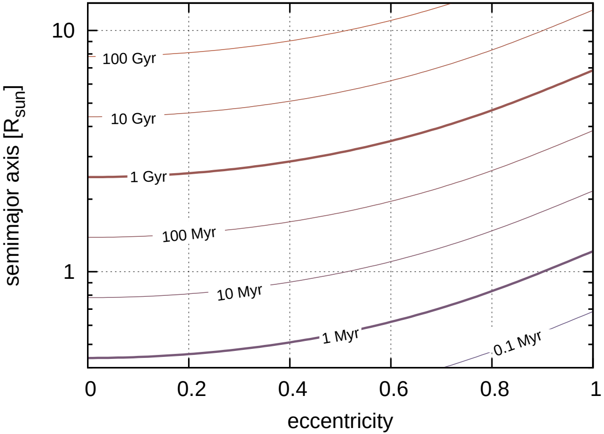
Binary neutron stars



PSR B1913+16:
The Hulse-Taylor binary pulsar
(to merge in $\sim 3 \times 10^8$ years).

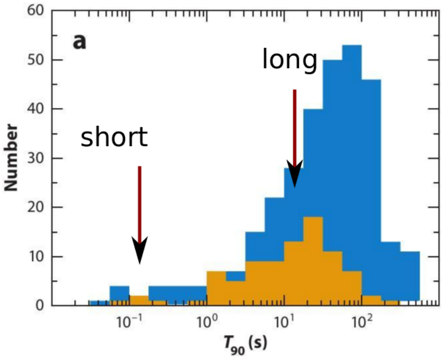
[from Weisberg & Taylor (2004)]

Orbital lifetime of an eccentric binary system:



The origin of short GRBs

Bimodal distribution:



[from Gehrels, Ramirez-Ruiz & Fox (2009)]

The origin of short GRBs

Short GRBs most likely result from mergers of two neutron stars or a neutron star and a black hole.

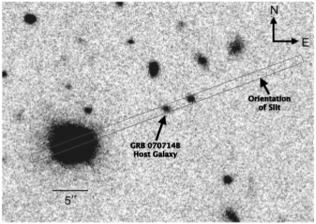


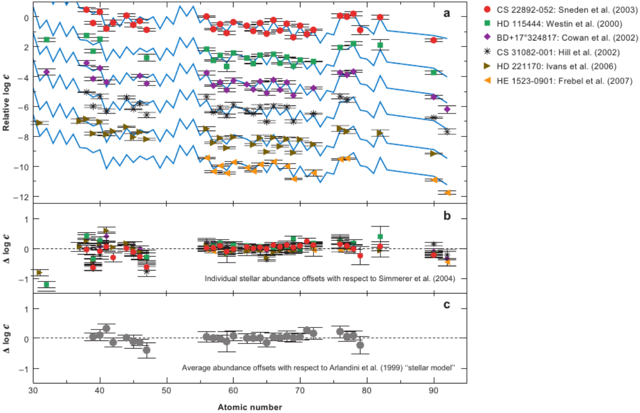
Figure 1. Combined *i*-band image of the GRB 070714B host and the surrounding field. The host and the slit orientation used in the spectroscopy are annotated.

[from Graham et al.(2007)]

Example GRB (070714B):

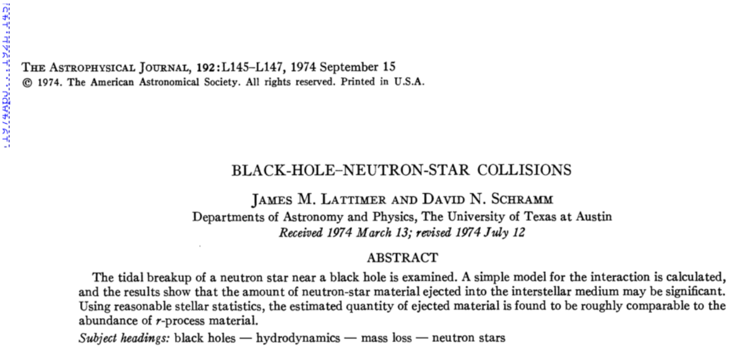
- energetics: $E_{\text{iso}} = 1.2 \times 10^{51}\,\text{erg}$;
- duration: $\tau \sim 3$ s;
- spectroscopic redshift: $z = 0.923$;
- distance: $D = 7.4 \times 10^{9}$ light years.

Metal-poor r-process stars



[from Sneden et al. (2008)]

Connection with the r-process



THE ASTROPHYSICAL JOURNAL, **192**:L145–L147, 1974 September 15

BLACK-HOLE–NEUTRON-STAR COLLISIONS

JAMES M. LATTIMER AND DAVID N. SCHRAMM
Departments of Astronomy and Physics, The University of Texas at Austin
Received 1974 March 13; revised 1974 July 12

ABSTRACT

The tidal breakup of a neutron star near a black hole is examined. A simple model for the interaction is calculated, and the results show that the amount of neutron-star material ejected into the interstellar medium may be significant. Using reasonable stellar statistics, the estimated quantity of ejected material is found to be roughly comparable to the abundance of *r*-process material.

Subject headings: black holes — hydrodynamics — mass loss — neutron stars

Neutron star mergers

Simulation method

- Smooth Particle Hydrodynamics (SPH) – *Rosswog (2009)*;
- Shen equation of state – *Shen et al. (1998a,b)*;
- Opacity-dependent multi-flavour neutrino leakage scheme – *Rosswog & Liebendörfer (2003)*;
- State of the art artificial viscosity prescription – *Rosswog (2008)*;
- Newtonian gravity.

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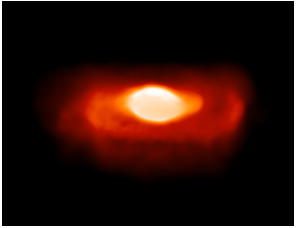
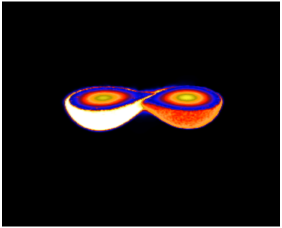
Animations

Coalescence of two neutron stars with masses 1.4 and 1.3 $\mathcal{M}_\odot$, with no spin (the most likely case).

temperature

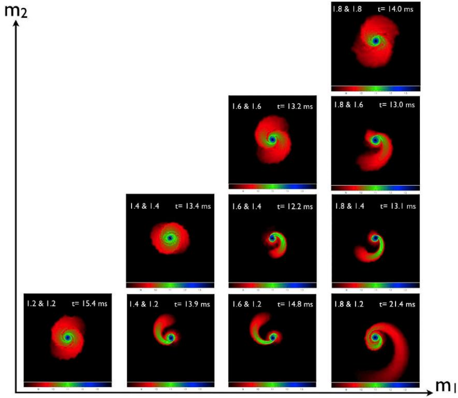


electron fraction



[see Rosswog, Piran&Nakar (2012)]

Parameter space



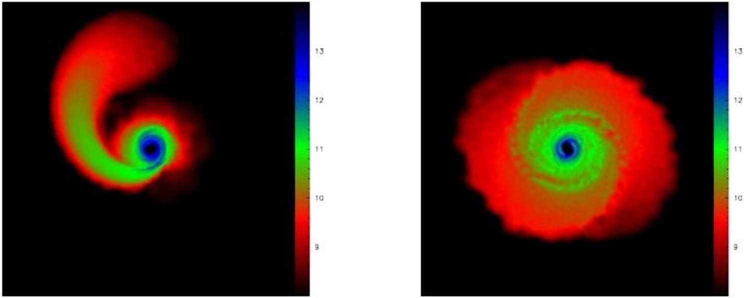
[from Piran, Nakar & Rosswog 2012]

Explored parameter space:

- neutron stars masses: $1.0, 1.2, ..., 2.0\mathcal{M}_\odot$;
- black hole - neutron star mergers: $m_{bh} = 5, 10\mathcal{M}_\odot$, $m_{ns} = 1.4\mathcal{M}_\odot$.

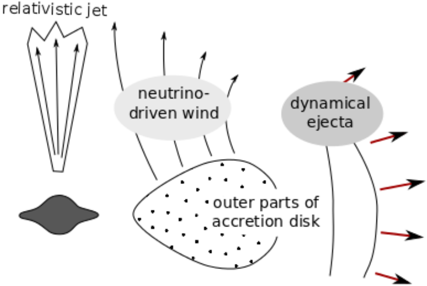
Morphology of the mergers

Density cuts of the 1.2-1.4 $\mathcal{M}_\odot$ and the 1.4-1.4 $\mathcal{M}_\odot$ cases:



Dynamical ejecta

We are interested in the nucleosynthesis in all regions of the merger where the matter becomes unbound and contributes to the galaxy:



- neutrino-driven winds;
- outer parts of accretion disk;
- dynamical ejecta;

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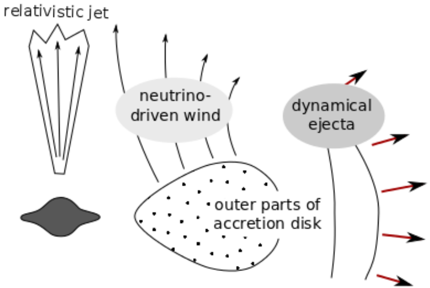
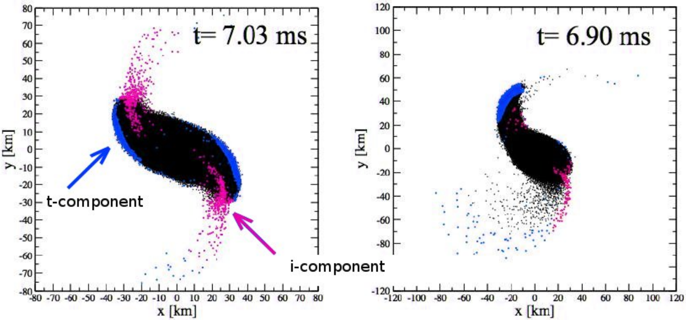


- neutrino-driven winds;
- outer parts of accretion disk;
- **dynamical ejecta.**

Where does the dynamical ejecta come from?

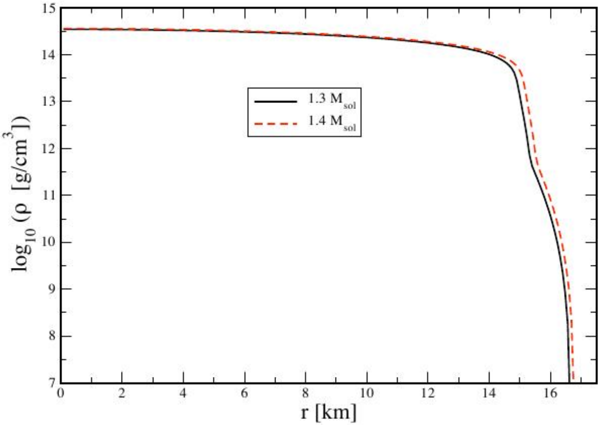
Two components can be identified:

- tidal component;
- interaction region component.



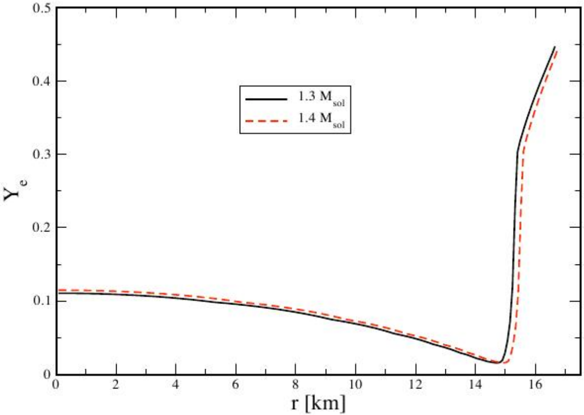
Location of the ejecta prior to merger

Density profile inside of a neutron star:



Location of the ejecta prior to merger

Profile of the electron fraction:



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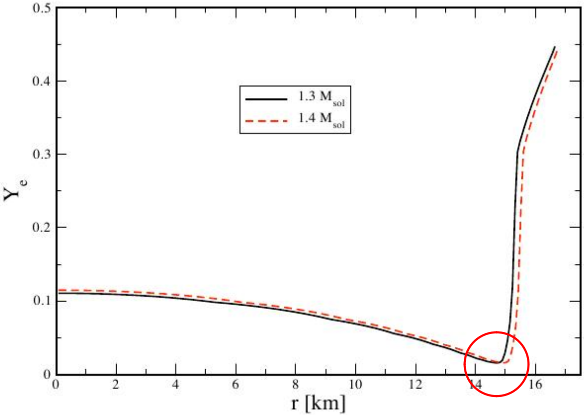

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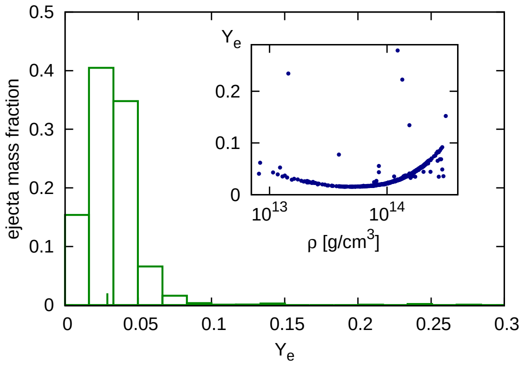


Distribution is clustered around $\langle Y_e \rangle \approx 0.03$

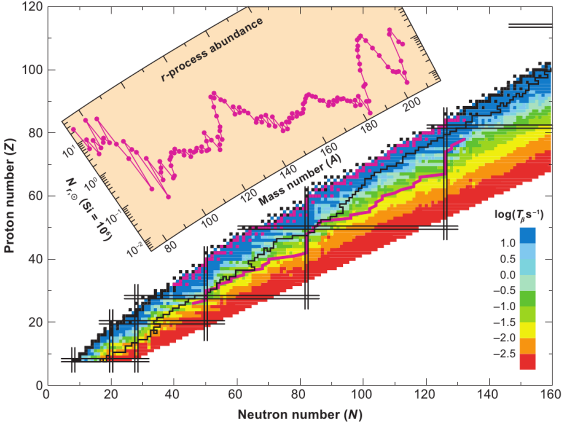
Properties of the ejecta

Summary:

- masses: $M_{\mathrm{ej}} = (7.6 \times 10^{-3} - 3.9 \times 10^{-2})\ \mathcal{M}_{\odot}$;
- velocities: $v_{\mathrm{ej}} \sim 0.11$ c;
- electron fraction: $Y_e = 0.04 \pm 0.02$;
- starting densities: $\rho = (1.4 \pm 0.5) \times 10^{14}$ g cm^{-3};
- will continue to expand adiabatically and without shocks;
- densities when the temperature drops to 10GK:
  $\rho = (10^9 - 10^{12})$ g cm^{-3}.

Nucleosynthesis

The r-process path



[Möller, Nix & Kratz (1997)]

Method

- use thermodynamic conditions from merger simulations for calculating r-process network nucleosynthesis;
- large reaction network (*Winteler 2012, Winteler et al. 2012*), based on the BasNet network (*Thielemann et al. 2011*);
- includes more than 5800 isotopes up to Z = 111;
- reaction rates from *Rauscher & Thielemann (2000)*;
- $e^{\pm}$-captures, β-decays (*Arcones & Martinez-Piñedo 2011*);
- neutron capture and neutron-induced fission rates (*Panov 2010*);
- β-delayed fission (*Panov 2005*);

Individual trajectories of the SPH particles

To calculate nucleosynthetic yields, we follow thermodynamical histories of individual SPH particles.

- 30 representative SPH particles from each merger simulation;
- because merger simulations only cover $10 - 20$ ms, we extrapolate densities using a free expansion fit: $\rho(t) = \rho_{\rm fin} \left(\frac{t}{t_{\rm fin}}\right)^{-3}$;
- we calculate the temperature by taking into account nuclear heating: $T(t) = T_{\rm EoS}[S(t), \rho(t), Y_e(t), \langle A\rangle]$, where nuclear heating increases the entropy $S(t)$.
- at each timestep, we increment the entropy by $\Delta S = \epsilon_{\rm th}\delta Q/T$
- $\epsilon_{\rm th}$ is the heating efficiency (Metzger, 2010).

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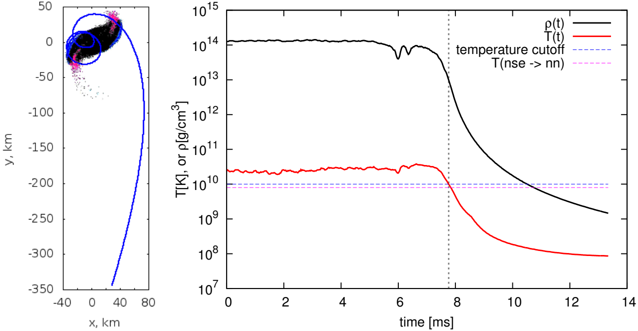
Individual trajectories of the SPH particles

Typical thermodynamic trajectory:

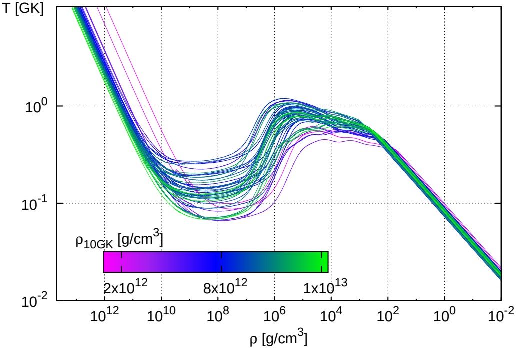


Database of thermodynamic trajectories:

http://compact-merger.astro.su.se/downloads.html

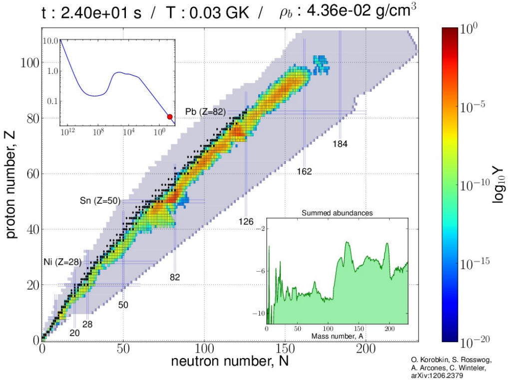
Individual trajectories of the SPH particles

Bundle of postprocessed thermodynamic trajectories:



Results

Animation of the r-process

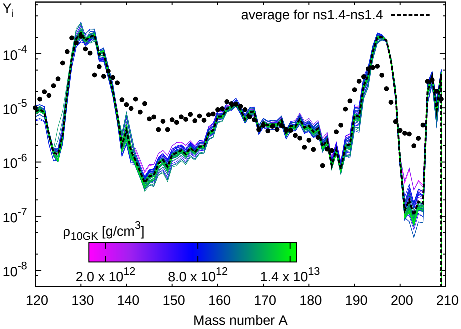


O. Korobkin, S. Rosswog, A. Arcones, C. Winteler, arXiv:1206.2379

[produced using modified python script of C. Winteler]

Main result

Robust pattern of main r-process final abundances, independent from the trajectories or simulations:



(confirmed in *Bauswein et al. 2013* for a wide range of EoS)

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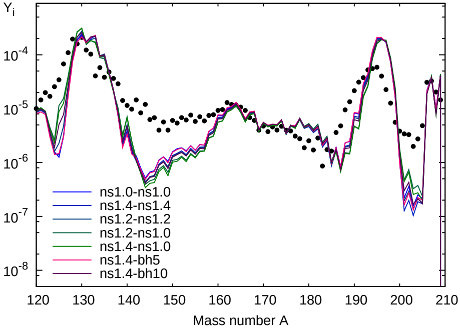

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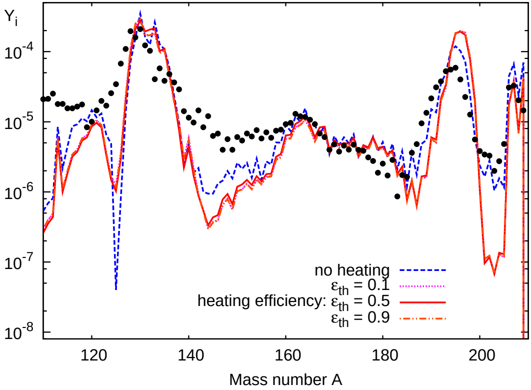
Dependence on the heating efficiency (in $\Delta S = \epsilon_{\mathrm{th}} \delta Q / T$):



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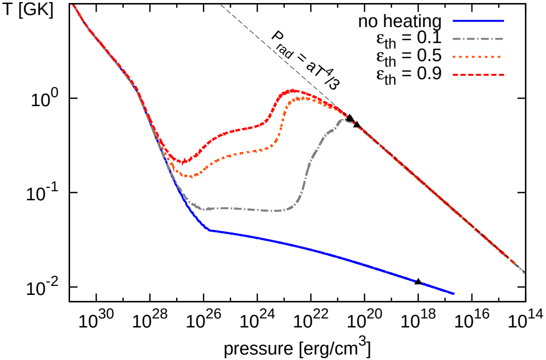

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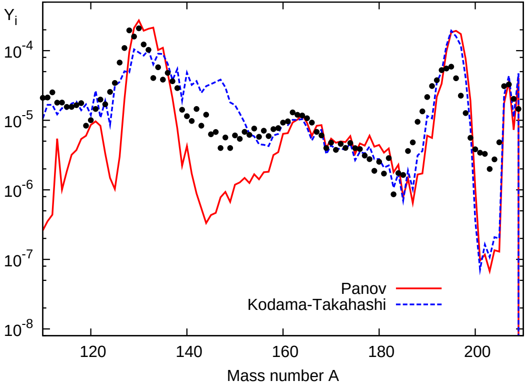
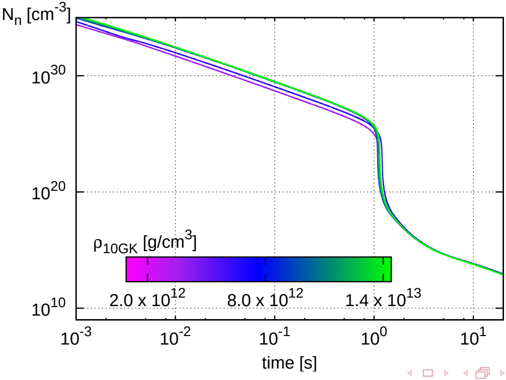
Main result

There is much more substantial variation due to the nuclear input, such as fission products mass distribution:



Interpretation

The ejected matter is extremely neutron-rich. As a result, the r-process path lies very close to the neutron drip line and leads to several fission cycles:



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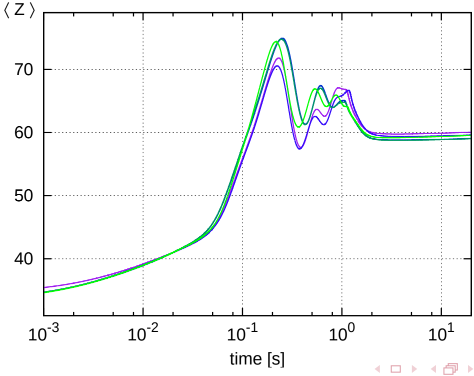
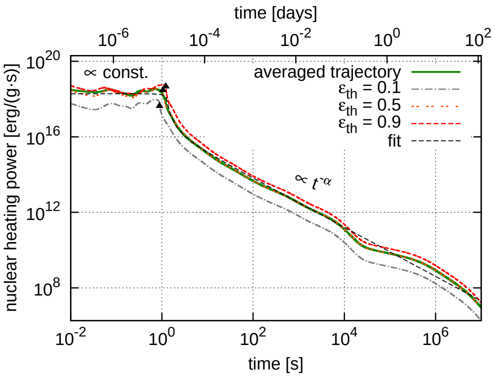


Fit formula for the nuclear heating power



$$\dot{\epsilon}(t) = \epsilon_0 \left(\frac{1}{2} - \frac{1}{\pi} \arctan \frac{t - t_0}{\sigma} \right)^{\alpha} \times \left(\frac{\epsilon_{th}}{0.5} \right) \tag{1}$$

with $\epsilon_0 = 2 \times 10^{18}$ erg/(g s), $t_0 = 1.3$ s, $\sigma = 0.11$ s, and $\alpha = 1.3$.

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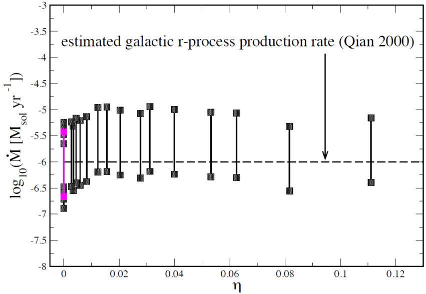
Galactic r-process production rate estimates



(ns merger rate/galaxy) × (total mass ejected per event) =

$$(83.0^{+209.1}_{-66.1}\ \mathrm{Myr}^{-1}) \times (0.012\ \mathcal{M}_\odot) \approx 10^{-6}\mathcal{M}_\odot \cdot \mathrm{yr}^{-1}$$

Conclusion

1. We systematically cover the plausible ns binary parameter space with masses from 1.0 to 2.0 $\mathcal{M}_\odot$ in 21 ns^2 + 2 nsbh simulations.
2. Nucleosynthesis in neutron star merger ejecta is *robust*.
3. The amount of ejected material is consistent with the observed quantity of the r-process in the galaxy.
4. The pattern of nucleosynthetic yields for the heavy elements roughly reproduces solar abundances, as well as similar abundances in the r-process enriched stars. Discrepancy mostly due to unknown nuclear physics near the neutron drip line.

Database of ns^2 and nsbh merger trajectories:

`http://compact-merger.astro.su.se/downloads.html`

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Weak and main r-process in metal-poor stars

From *H. Li, X. Sheng, S. Liang, W. Cui, B. Zhang (2013)*:

$$N_i([Fe/H]^*) =$$

$$(C_{r,m}N_{i,r,m} + C_{r,w}N_{i,r,w}) \times 10^{[Fe/H]}$$