r-process nucleosynthesis in neutron star mergers and associated macronovae events

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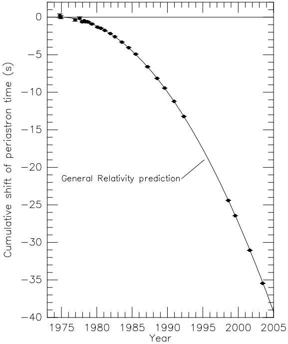
Outline

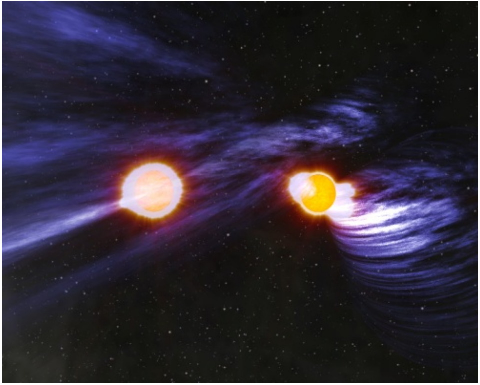
- Introduction
- Binary neutron stars
- Merger dynamics
- r-process nucleosynthesis
- Electromagnetic transient: macronova (kilonova)
- Neutrino-driven winds
- Macronova detection
- Conclusions

Introduction

Binary neutron stars

- several (10) binary ns systems are known in our Galaxy;
- decay due to emission of gravitational waves;
- 7 out of 10 will merge in $\lesssim 3$ Gyr.





[Weisberg & Taylor (2004)]

Binary neutron stars

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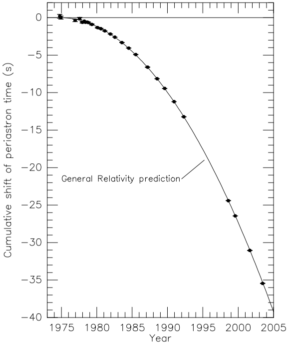
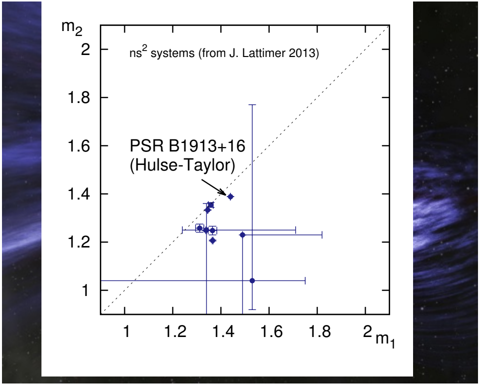
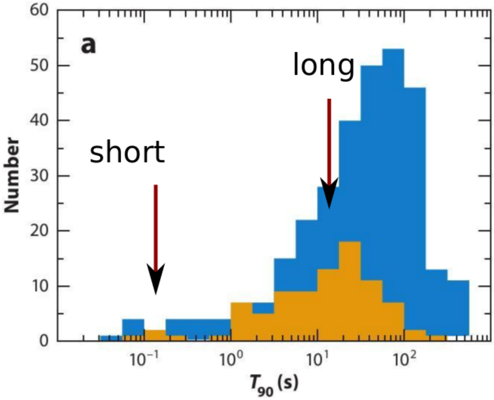


[Weisberg & Taylor (2004)]



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.

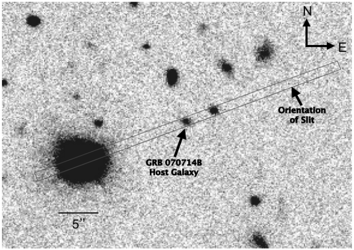


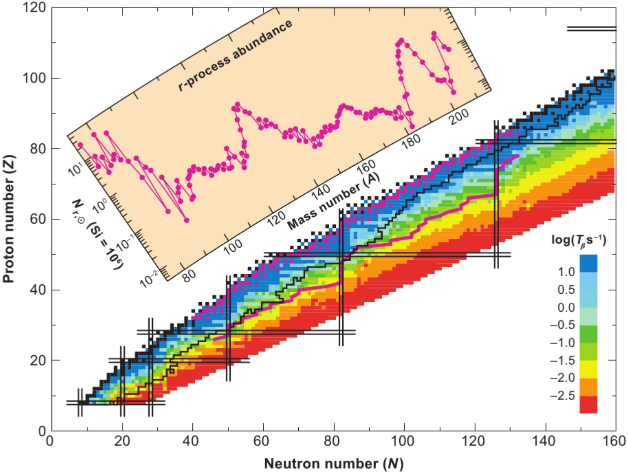
Figure 1. Combined *i*-band image of the GRB 070714B host and the surrounding field. The host and the slit orientation used in the spectroscopy are annotated.

[from Graham et al.(2007)]

Example GRB (070714B):

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

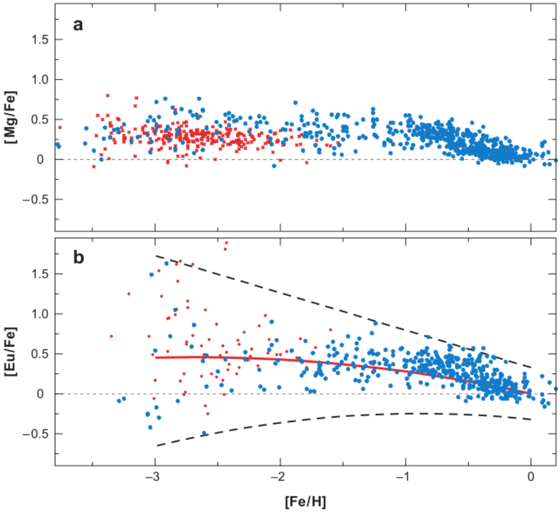
The r-process



[Möller, Nix & Kratz (1997)]

Absence of Eu-Fe correlation in old stars

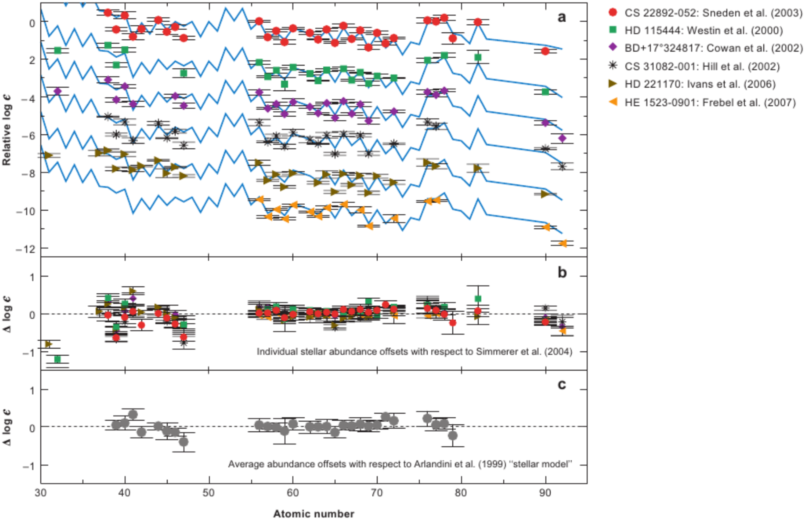
Very old stars exhibit large scatter in $[Eu/Fe]$ ratio:



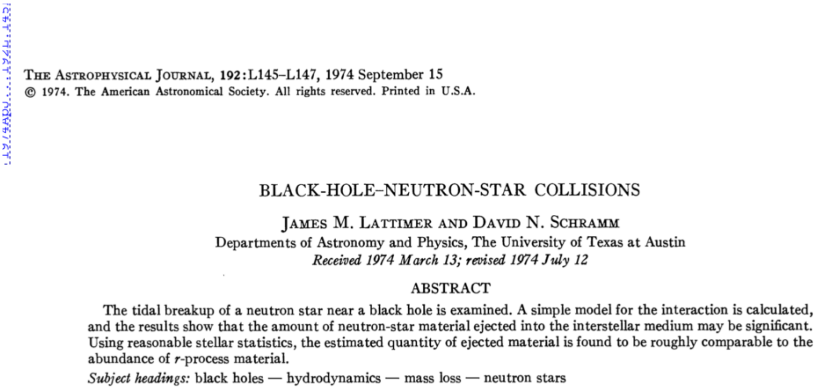
[Sneden et al. (2008)]

Metal-poor r-process stars

Robust strong r-process pattern in metal-poor r-process enriched stars:



Are merging neutron stars the main source of r-process?



1974ApJ...192L.145L

The Astrophysical Journal, 192:L145–L147, 1974 September 15
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BLACK-HOLE–NEUTRON-STAR COLLISIONS

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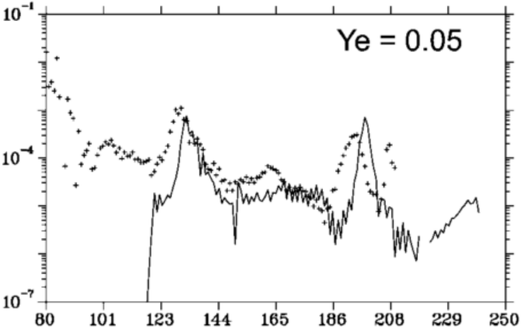
Received 1974 March 13; revised 1974 July 12

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.

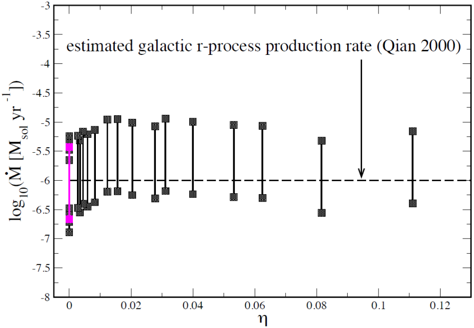
Subject headings: black holes — hydrodynamics — mass loss — neutron stars

Are merging neutron stars the main source of r-process?



[from Freiburghaus, Rosswog & Thielemann (1999)]

Galactic r-process production rate estimates



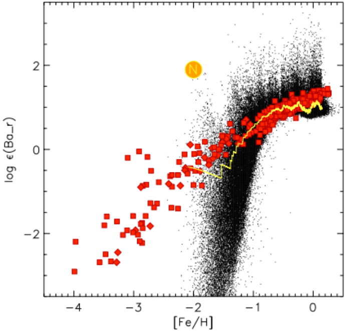
(ns merger rate/galaxy) × (total mass ejected per event) =

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

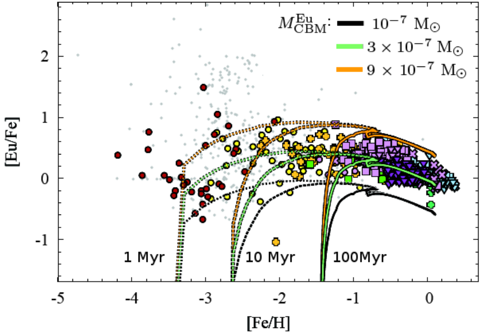
† [from Kalogera+ 2004]

Chemical evolution case: CCSNe vs NSM

Updated chemical evolution studies do not rule out NSMs as major sites for the r-process:



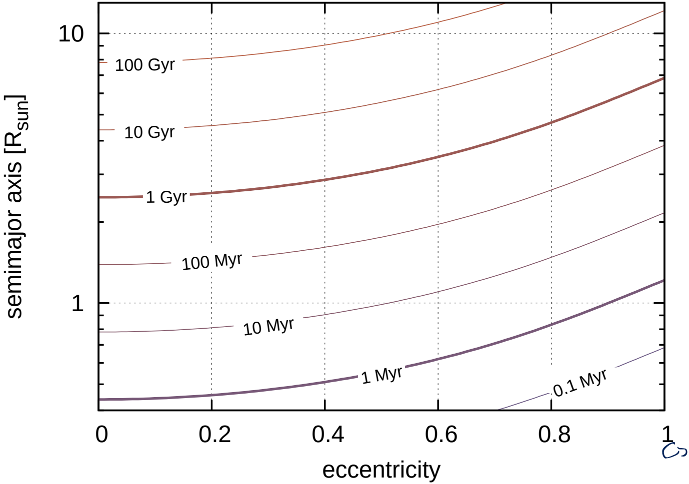
[Argast et al. (2004)]



[Matteucci et al. (2014)]

Orbital lifetime of an eccentric binary system

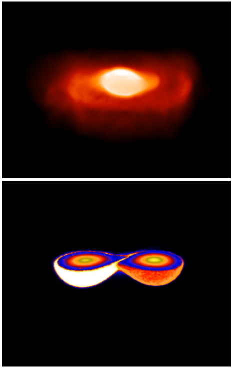
If formed with large initial eccentricity, binary neutron star system could merge in less than a million years.



Merger dynamics

Hydrodynamical simulations

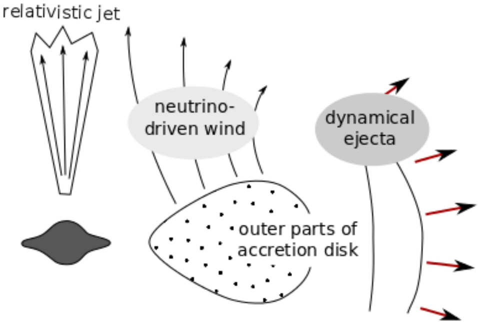
In [Korobkin et al. (2012)] we revisit the problem of r-process nucleosynthesis based on the updated set of hydrodynamic simulations from *Rosswog, Piran & Nakar (2013)*.



- Smooth Particle Hydrodynamics (SPH) – *Rosswog (2009)*;
- Microphysical equation of state;
- Opacity-dependent multi-flavour neutrino leakage scheme – *Rosswog & Liebendörfer (2003)*;
- Explored range of neutron stars masses: $1.0, 1.2, ..., 2.0\mathcal{M}_{\odot}$;
- Black hole - neutron star mergers: $m_{bh} = 5, 10\mathcal{M}_{\odot}$, $m_{ns} = 1.4\mathcal{M}_{\odot}$.
- Newtonian gravity (Paczyński-Wiita potential for BH).

Merger dynamics and the variety of outflows

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



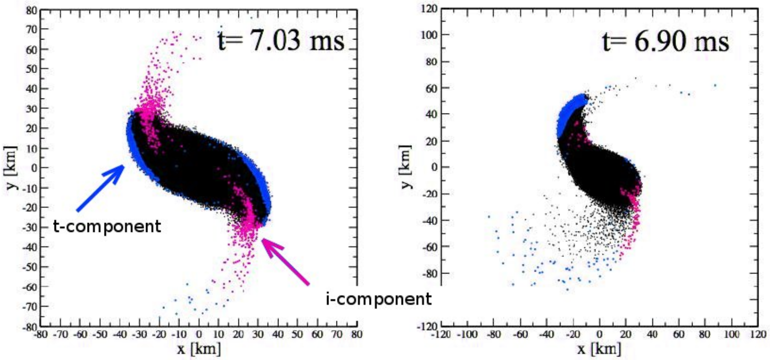
- neutrino-driven winds;
- outer parts of accretion disk;
- dynamical ejecta;

[see also: Metzger & Fernandez (2014)]

Where does the dynamical ejecta come from?

Two components can be identified:

- tidal component;
- interaction region component.



Nucleosynthesis

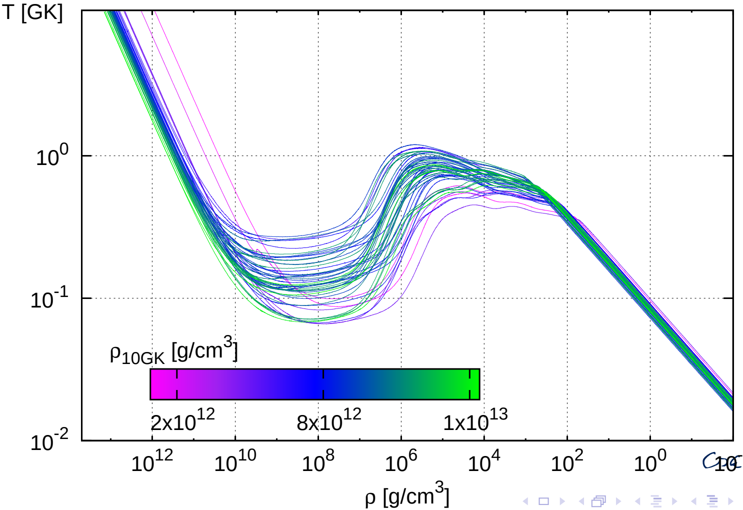
O.K., S. Rosswog, A. Arcones & C. Winteler, "On the astrophysical robustness of the neutron star merger r-process", arXiv:1206.2379, MNRAS (2012)

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*);

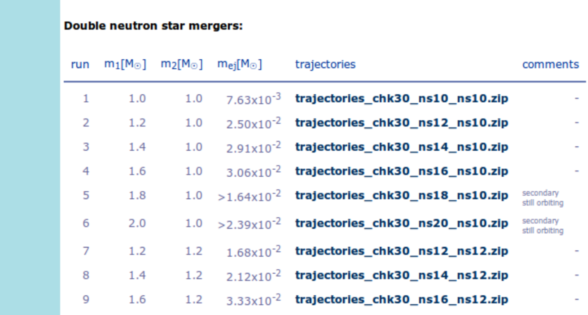
Individual trajectories of the SPH particles

Thermodynamic trajectories of individual particles, modified to include nuclear heating:



Database of thermodynamic trajectories

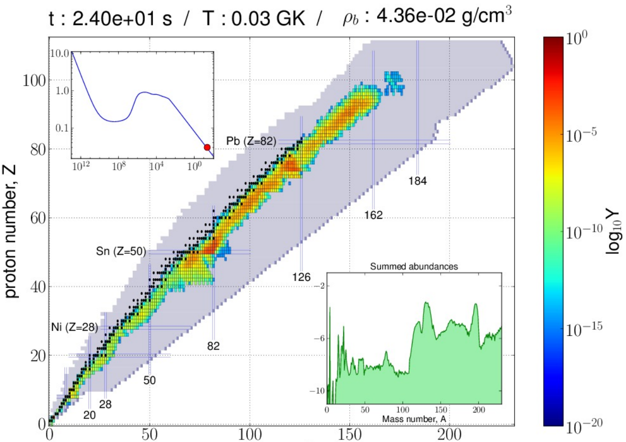
http://compact-merger.astro.su.se/downloads.html



Double neutron star mergers:

run	$m_1[M_\odot]$	$m_2[M_\odot]$	$m_{ej}[M_\odot]$	trajectories	comments
1	1.0	1.0	7.63×10^{-3}	**trajectories_chk30_ns10_ns10.zip**	-
2	1.2	1.0	2.50×10^{-2}	**trajectories_chk30_ns12_ns10.zip**	-
3	1.4	1.0	2.91×10^{-2}	**trajectories_chk30_ns14_ns10.zip**	-
4	1.6	1.0	3.06×10^{-2}	**trajectories_chk30_ns16_ns10.zip**	-
5	1.8	1.0	$>1.64\times10^{-2}$	**trajectories_chk30_ns18_ns10.zip**	secondary still orbiting
6	2.0	1.0	$>2.39\times10^{-2}$	**trajectories_chk30_ns20_ns10.zip**	secondary still orbiting
7	1.2	1.2	1.68×10^{-2}	**trajectories_chk30_ns12_ns12.zip**	-
8	1.4	1.2	2.12×10^{-2}	**trajectories_chk30_ns14_ns12.zip**	-
9	1.6	1.2	3.33×10^{-2}	**trajectories_chk30_ns16_ns12.zip**	-

Animation of the r-process

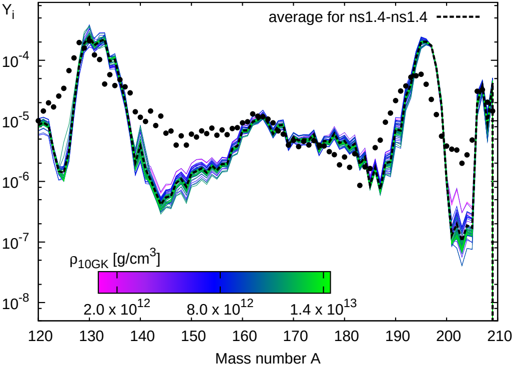


O. Korobkin, S. Rosswog,
A. Arcones, C. Winteler,
arXiv:1206.2379

[made with the script by C. Winteler]

Main result

Robust pattern of main r-process final abundances, independent from the trajectories or simulations [O.K., Arcones, Rosswog & Winteler (2012)]:



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

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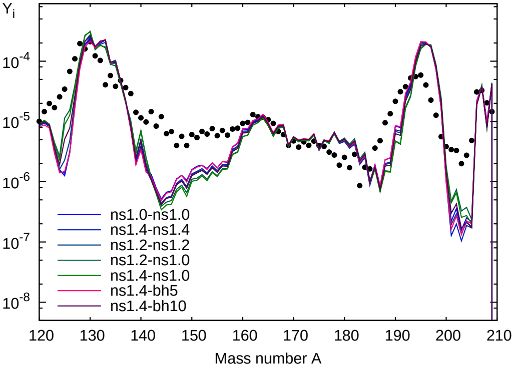
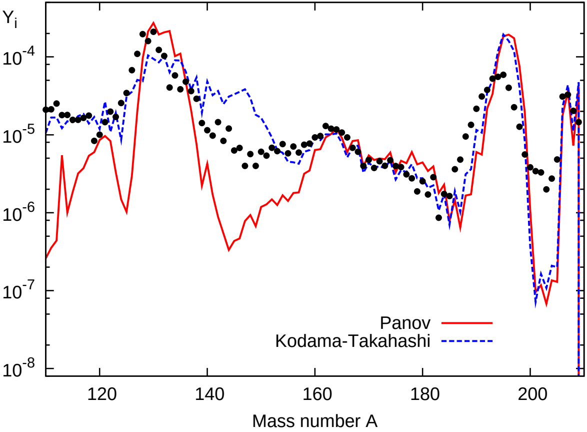


(confirmed in *Bauswein et al. 2013* for a wide range of EoS)

Main result

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



Electromagnetic transient: macronova (kilonova)

S. Rosswog, O.K., A. Arcones, F.-K. Thielemann,
"The longterm evolution of neutron star merger remnants I:
the impact of r-process nucleosynthesis", arXiv:1307.2943,
MNRAS (2014)

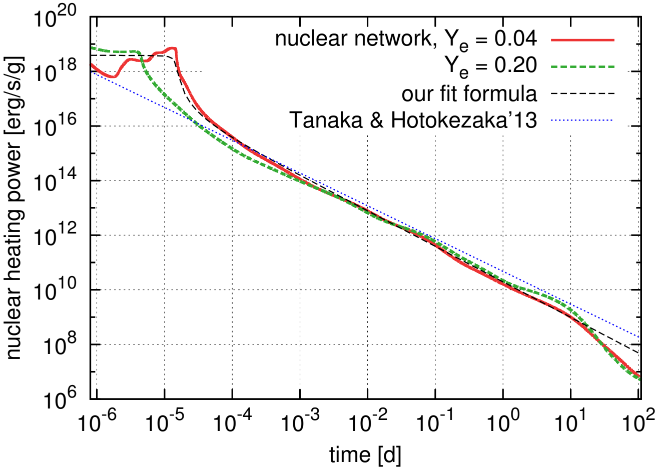
D. Grossmann, O.K., S. Rosswog, T. Piran
"The longterm evolution of neutron star merger remnants II:
radioactively powered transients", arXiv:1307.2943,
MNRAS (2014)

Electromagnetic r-process transients

Previous studies:

- Li & Paczyński (1998)
- Kulkarni (2005)
- Metzger, Martínez-Pinedo et al. (2010)
- Metzger, Arcones et al. (2010)
- Roberts, Kasen & Lee (2011)
- Goriely, Bauswein & Janka (2011)
- Wanajo & Janka (2012)
- Kasen, Badnell & Barnes (2013)
- Barnes & Kasen (2013)
- Tanaka & Hotokezaka (2013)
- Tanvir et al., *Nature* (2013)

Radioactive heating power



$$\dot{\epsilon}(t) = 9.8 \times 10^9 \ \mathrm{erg/(g \cdot s)} \left(\frac{t}{1 \ \mathrm{day}} \right)^{-1.3}$$

Simple analytic estimates

Peak times:

$$\tilde{t}_p \approx \sqrt{\frac{\kappa m_{\rm ej}}{4\pi c \bar{v}}} = \mathbf{4.9\ days} \left(\frac{\kappa_{10} m_{\rm ej,-2}}{\bar{v}_{-1}}\right)^{1/2},$$

$$\tilde{L}_p \approx \dot{\epsilon}_0 m_{\rm ej} \left(\frac{\kappa m_{\rm ej}}{4\pi c \bar{v} t_0^2}\right)^{-\alpha/2} = \mathbf{2.5 \times 10^{40}} \frac{\rm erg}{\rm s} \left(\frac{\bar{v}_{-1}}{\kappa_{10}}\right)^{\alpha/2} m_{\rm ej,-2}^{1-\alpha/2},$$

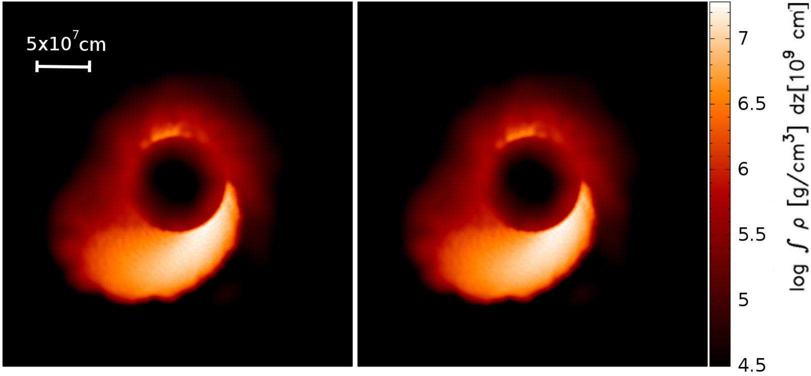
$$\tilde{T}_{\rm eff} \approx \left(\frac{\dot{\epsilon}_0 c}{\sigma_{SB}}\right)^{1/4} \left(\frac{m_{ej}}{4\pi c t_0}\right)^{-\alpha/8} \kappa^{-(\alpha+2)/8} \bar{v}^{(\alpha-2)/8}$$

$$= \mathbf{2200}\ \mathrm{K}\ \kappa_{10}^{-(\alpha+2)/8} \bar{v}_{-1}^{(\alpha-2)/8} m_{\rm ej,-2}^{-\alpha/8}.$$

where $\kappa_{10} = (\kappa/10\,{\rm cm^2 g^{-1}})$, $m_{\rm ej,-2} = (m_{\rm ej}/0.01\,\mathcal{M}_\odot)$, $\bar{v}_{-1} = (\bar{v}/0.1\,c)$.
Very high opacities! (*Kasen (2013)*, *Tanaka&Hotokezaka (2013)*).

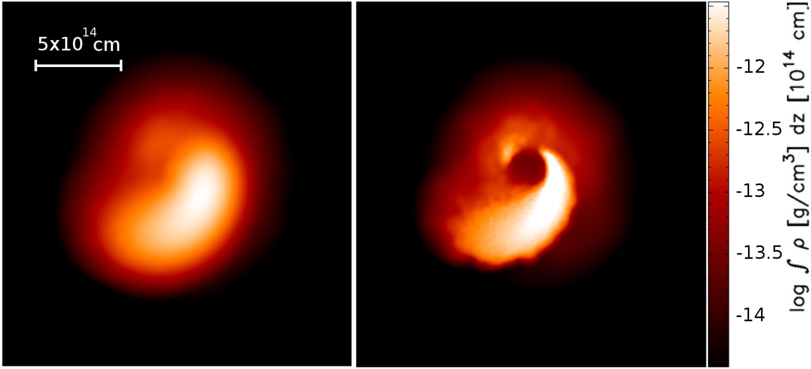
Effect of the r-process heating on the morphology

At the time of merger:



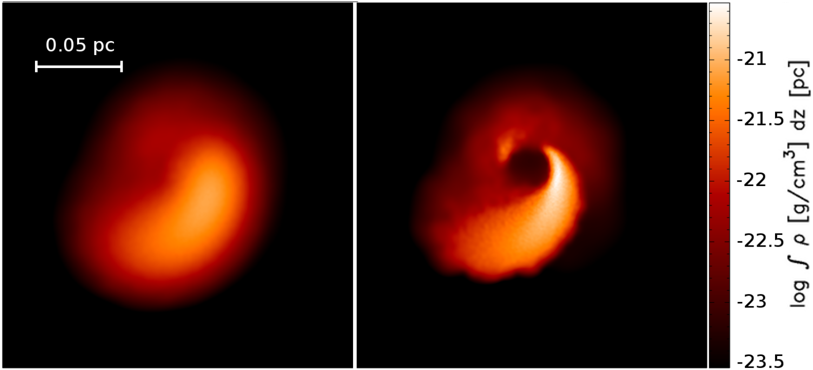
Effect of the r-process heating on the morphology

After one day:



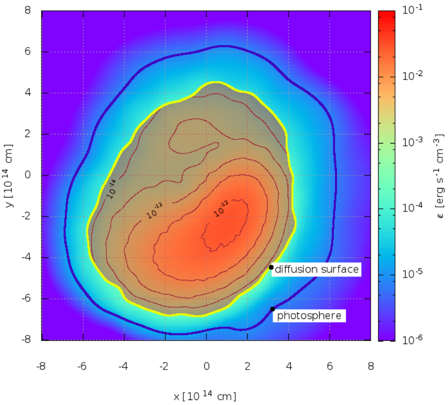
Effect of the r-process heating on the morphology

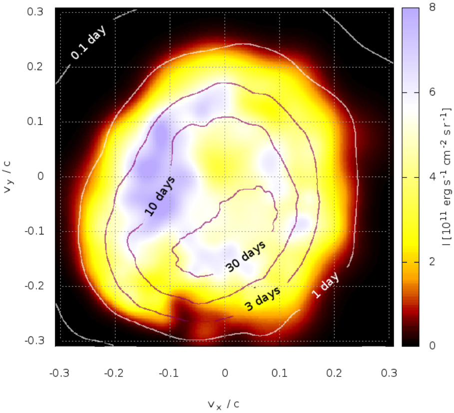
After one year:



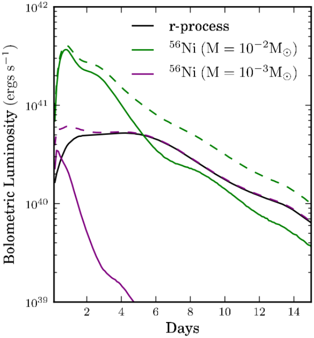
Radiative structure of the remnant

Luminosity is produced due to radioactive heating in the layer between the photosphere $\tau_{\rm ph} = \frac{2}{3}$ and the diffusion surface $\tau_{\rm diff} = \frac{ct}{\zeta}$: $L = \sum_{\tau_b>\tau_{\rm ph}}^{\tau_b<\tau_{\rm diff}} \dot{\epsilon}(t) m_b$

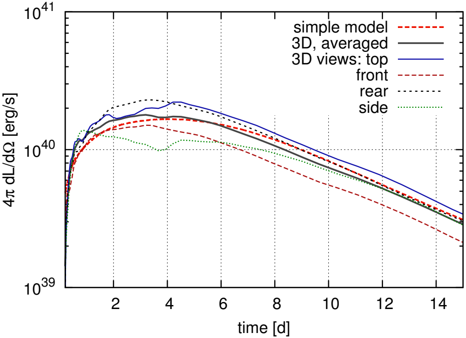




Synthetic macronova lightcurves



[Barnes & Kasen (2013)]



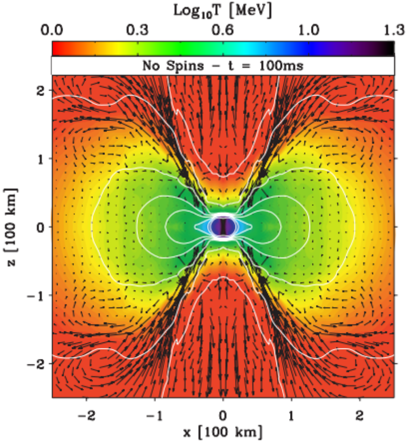
[Grossman et al. (2013)]

- transient peaks in near infrared;
- very weak signal;
- extremely hard to detect in modern surveys.
- how about an additional blue component?

Neutrino-driven winds

Neutrino-driven wind model

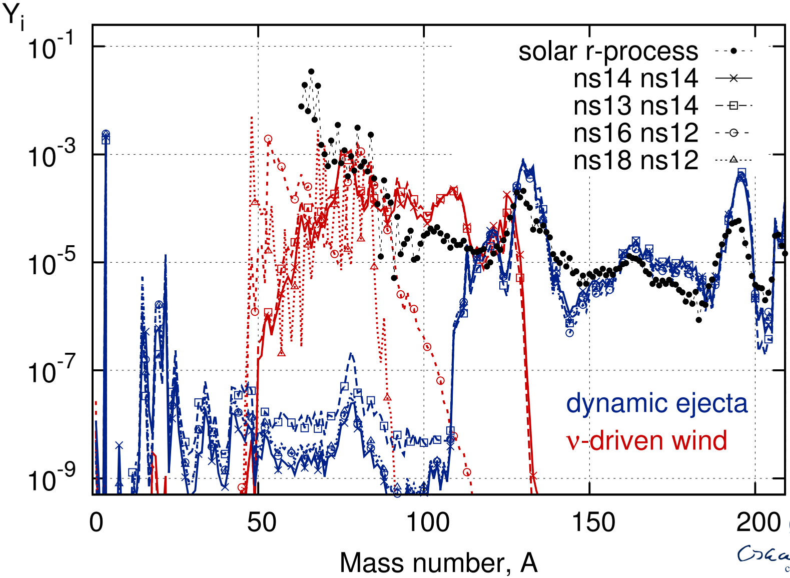
Dessart+ 2009:



Assumptions:

- linear expansion: $\rho(t) = \rho_0(1 + vt/R_0)^{-3}$;
- characteristic radius: $R_0 = 200$ km;
- expansion velocity: $v = 0.11c$;
- initial density: $\rho_0 = 5 \times 10^7$ gcm^{-3};
- typical entropy for our merger simulations: 8 k_B/baryon;
- electron fraction (*Qian&Woosley 1996*): $0.28 \leq Y_e \leq 0.40$.
- we parameterize the wind mass: 10^{-4} - $10^{-2}\mathcal{M}_\odot$.

ν-driven wind nucleosynthesis and lightcurves



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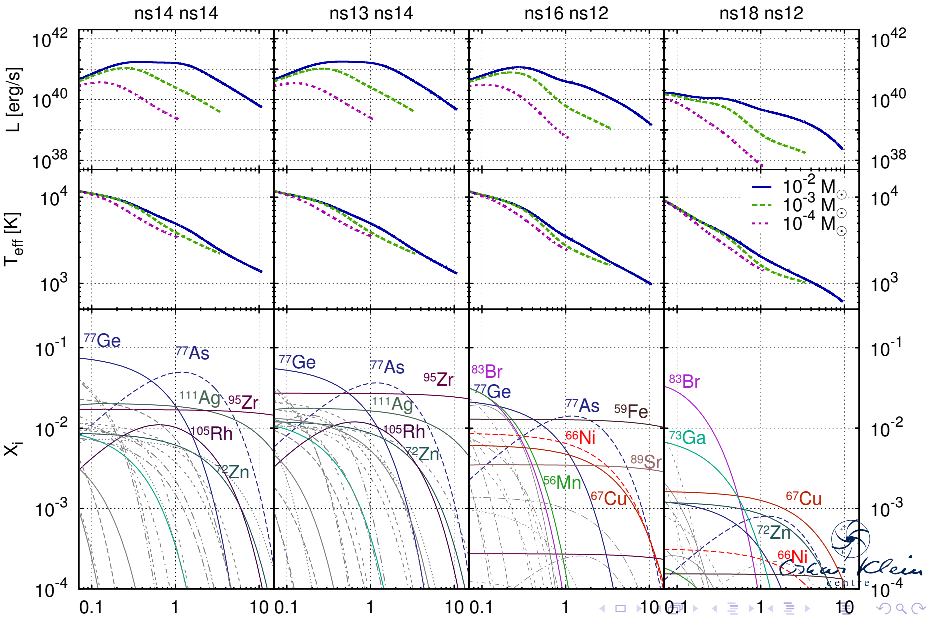
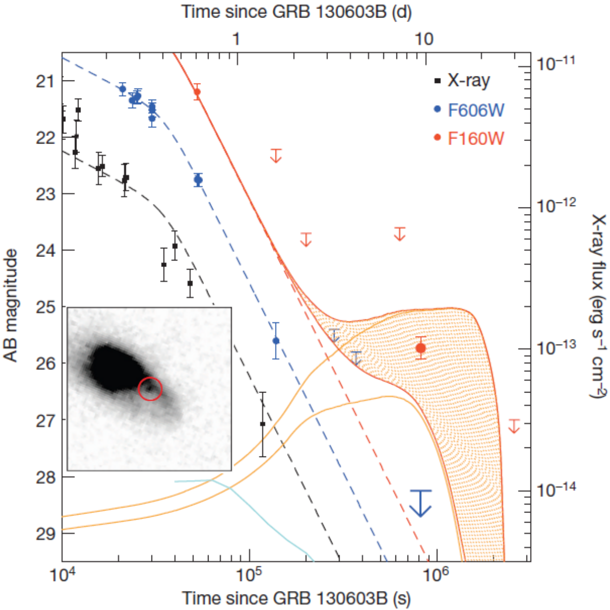


Macronova detection

GRB130603B *(Tanvir+ 13, de Ugarte Postigo+ 13)*:



Lower mass limit for GRB130603B

Assuming that the infrared source was produced by the r-process macronova, we can estimate an absolute lower limit on the mass of the radioactive material:

- measured magnitude: $M(J)_{AB} = -15.35$ in the J-band at $t = 6.6$ days;
- spectral flux: $F_\nu = 5.0 \times 10^{-14} \frac{\mathrm{erg}}{\mathrm{s \cdot cm^2 \cdot Hz}}$;
- luminosity: $L = \pi F_\nu \, \Delta\nu_J \cdot 4\pi D^2 = 3.2 \times 10^{40} \ \mathrm{erg \cdot s^{-1}}$,
- heating rate: $h(6.6 \ \mathrm{d}) = 8.4 \times 10^{8} \ \mathrm{erg \cdot (g \cdot s)^{-1}}$;

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- heating rate: $h(6.6\,\mathrm{d}) = 8.4 \times 10^8 \, \mathrm{erg \cdot (g \cdot s)^{-1}}$;
- **ejecta mass**: $m_{\mathrm{ej}} \geq L/h = \mathbf{0.02\ M_\odot}$.

[Piran, O.K. & Rosswog (2014)]

Conclusions

Conclusions

- Neutron star mergers seem to be a plausible candidate for the main source of r-process in the galaxy.
- The astrophysical robustness of r-process in neutron star mergers naturally explains the abundances in the old r-process stars.
- Radioactive heating produced in merger ejecta leads to an infrared transient, similar to a supernova (a macronova, or kilonova), peaking around ~ 6 days.
- Nuclear heating in the ejecta imprints on the lightcurve of the transient.
- Radioactive heating smears the morphology of the ejecta, but preserves some memory about its original shape; in particular, it fails to render the ejecta spherically symmetric.
- Variety of additional outflows, such as neutrino-driven winds, could produce an additional, early blue signal, that may be easier to detect.
- The infrared transient in the afterglow of the GRB 130603B is consistent with the model, provided that the mass of the ejected material is $\mathbf{0.02\ M_\odot}$.