Macronovae from Neutron Star Mergers

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Stockholm University

Oskar Klein centre

Physics of neutron star mergers

NSMs link together and explain several phenomena:

- shrinking orbits of galactic binary neutron stars;
- short GRBs;
- robust pattern of r-process in MP stars;
- abundance of live ^{244}Pu in deep-sea reservoirs on Earth.

Predictions:

- gravitational waves;
- electromagnetic signals (macronovae / kilonovae);
- neutrino signals.

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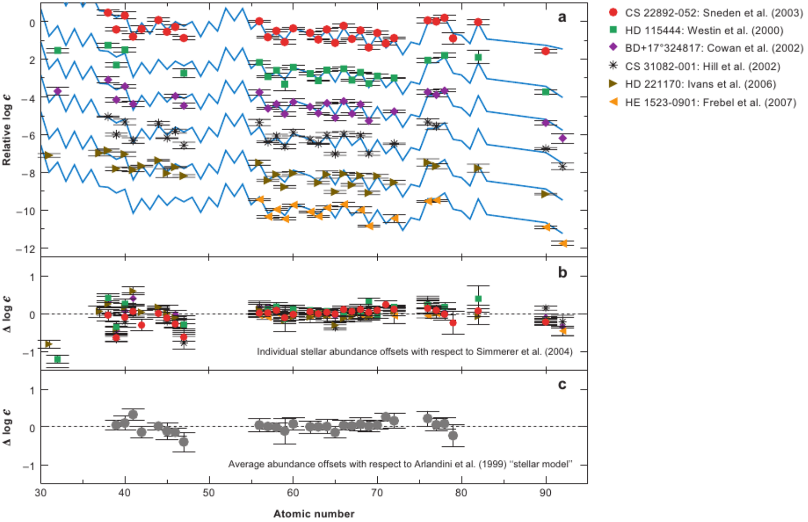
Astrophysical robustness of r-process

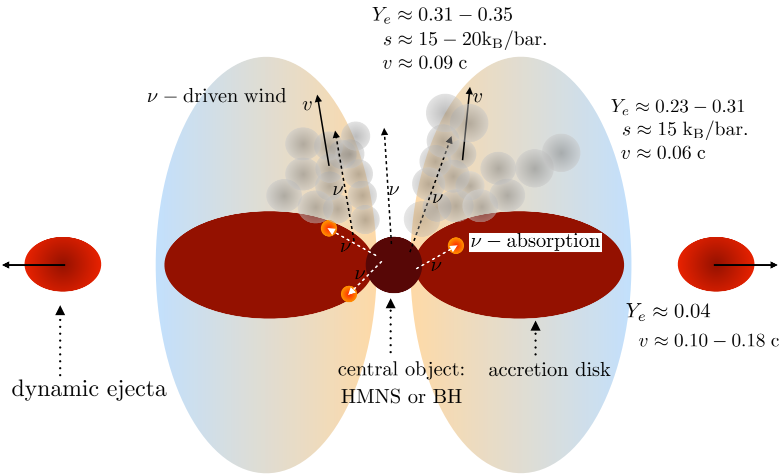
Robustness of r-process in metal-poor stars



[Sneden et al. (2008)]

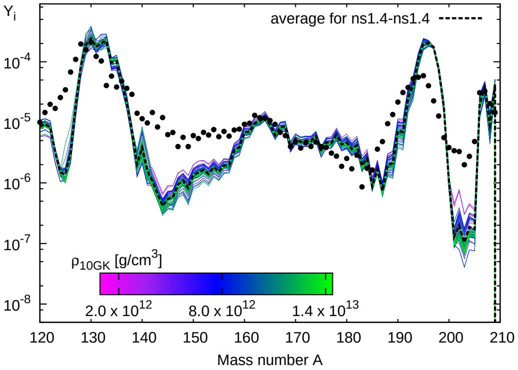
Different components of the merger remnant

[From Rosswog (2015):]



Robustness of the "strong" r-process in simulations

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



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

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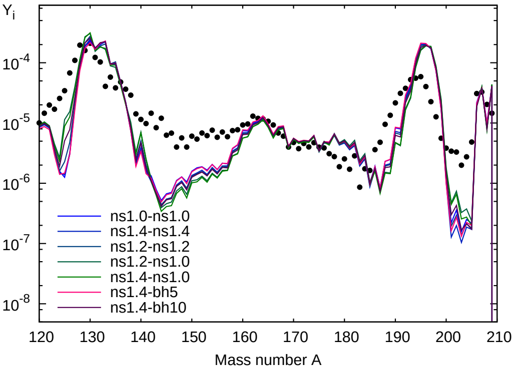
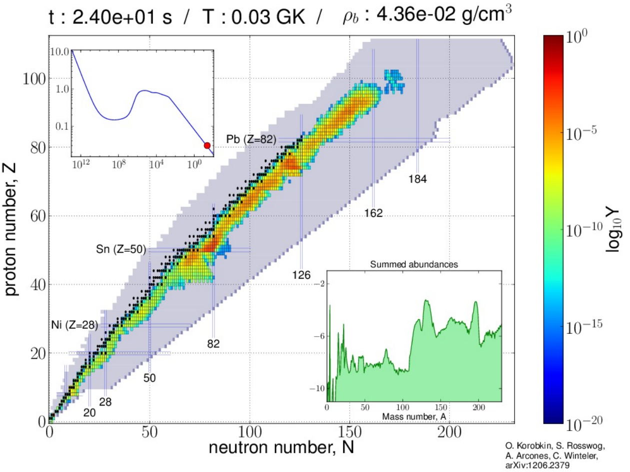


(confirmed in *Bauswein et al. 2013* for a wide range of EoS)

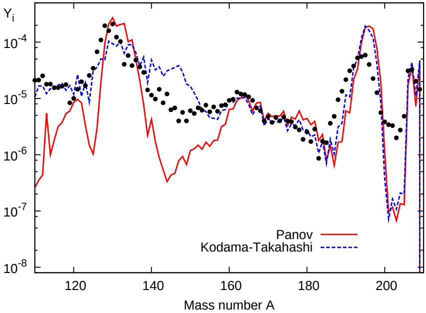
Multiple fission cycles in the r-process



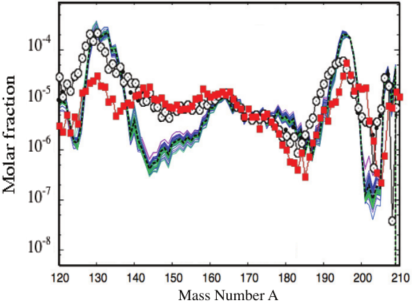
[made with the script by C. Winteler]

Improved nuclear physics

There is much more substantial variation due to the nuclear input, (e.g., fission products distribution):



Dependence on fission model



[S. Goriely et al. (2014)]

Improved nuclear physics

- → see talk by Shota Shibagaki;
- *From M. Eichler et al. (2014):* impact of fission model and beta decay rates on the r-process abundances:

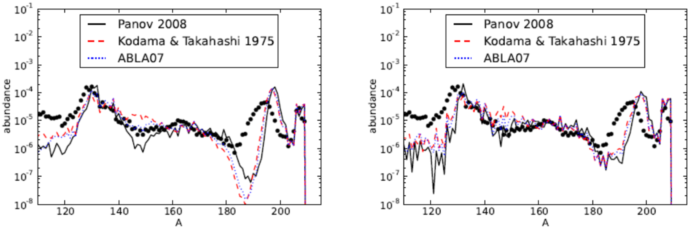
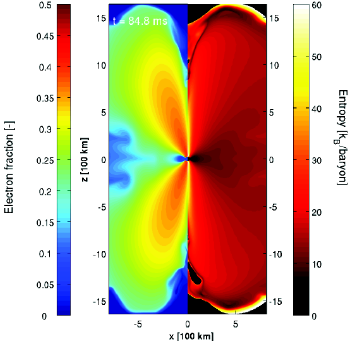
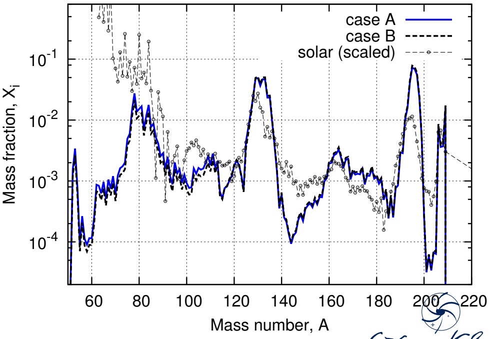



Fig. 4.— Similar to Fig. 1, several fission fragment distributions are tested for the mass models ETFSI-Q (left) and HFB-14 (right). It can be realized that in both cases the ABLA07 fragment distribution leads to the best fit to solar r-abundances in the mass region A=140-170. In addition, these mass models also avoid the still (to some extent) existing underproduction due to FRDM,

Nucleosynthesis in neutrino-driven winds

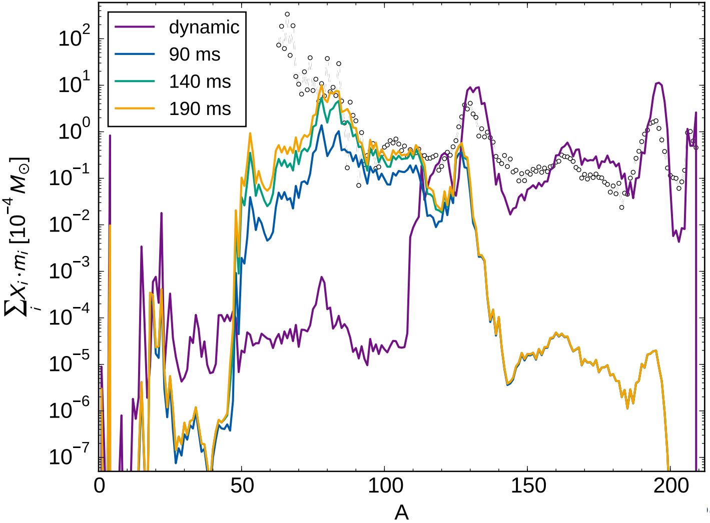
- $\rightarrow$ see talk by Albino Perego;
- *From A. Perego et al. (2014):* detailed 3D hydrodynamical study of ν-driven winds with Neutonian gravity and spectral leakage scheme which is adjusted to account for ν-heating.





Combined picture of r-process

[From D. Martin i in. (2015):]



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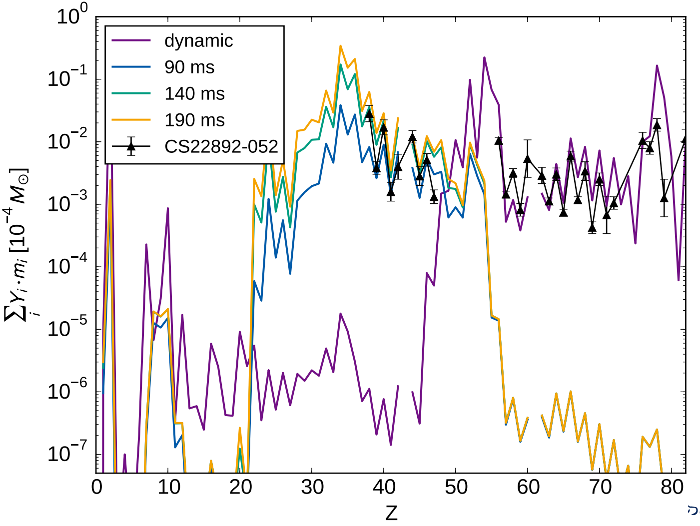


Alternative explanation of robustness

- → see talk by Yuichiro Sekiguchi;
- [From Wanajo et al. (2014):]

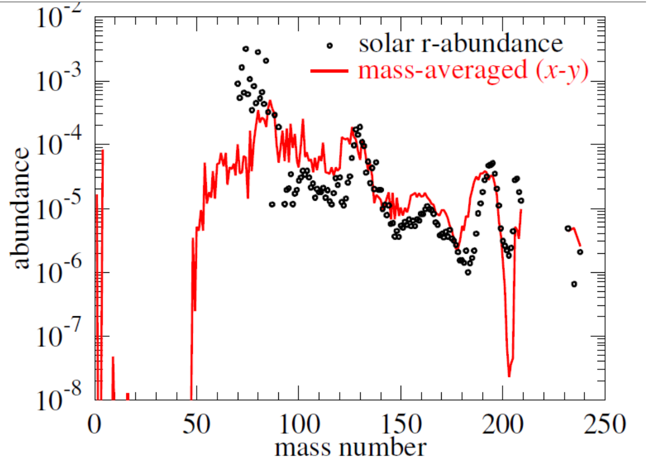
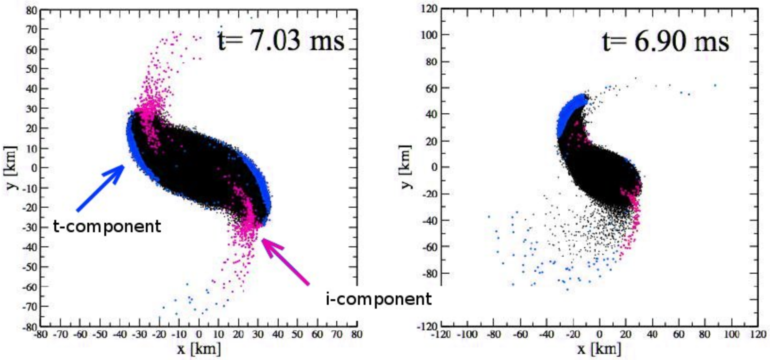


Figure 4. Final nuclear abundances for selected trajectories (top) and that mass-averaged (bottom; compared with the solar *r*-process abundances).

Where does the dynamical ejecta come from?

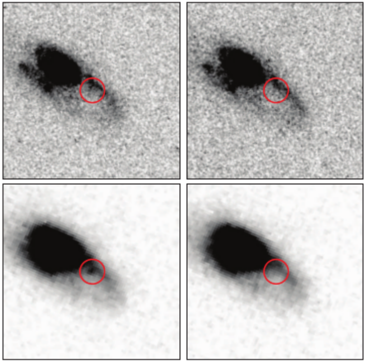
Two components can be identified:

- tidal component;
- interaction region component.



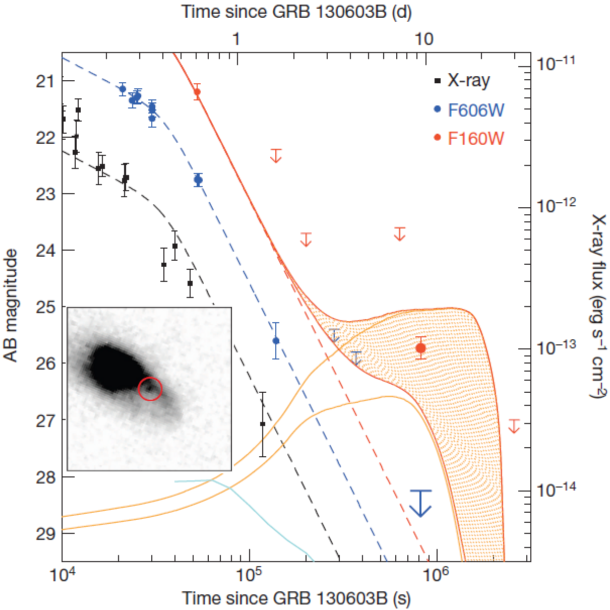
Macronovae

Early studies of the r-process-powered transients

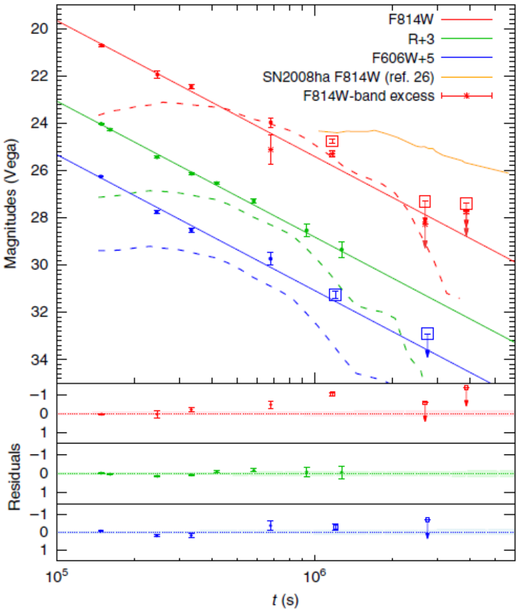


- Li & Paczyński (1998)
- Kulkarni (2005)
- Metzger, Martínez-Pinedo et al. (2010)
- Metzger, Arcones et al. (2010)
- Roberts, Kasen & Lee (2011)
- Goriely, Bauswein & Janka (2011)
- Wanajo & Janka (2012)
- Kasen, Badnell & Barnes (2013)
- Barnes & Kasen (2013)
- Tanaka & Hotokezaka (2013)
- Tanvir et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

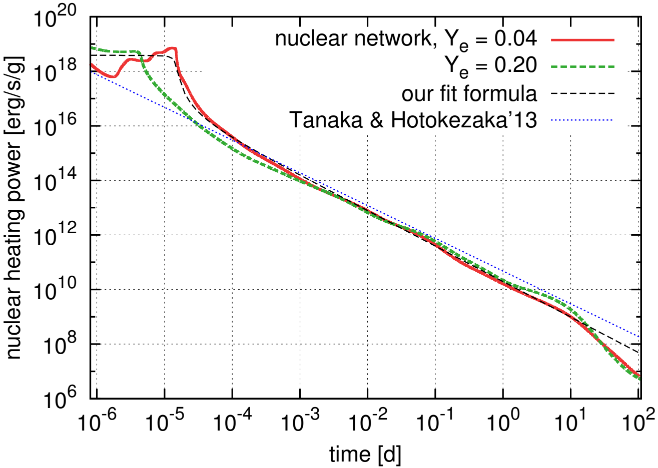
Candidate #1: GRB130603B *(Tanvir+ 13, de Ugarte Postigo+ 13)*



Candidate #2: GRB060614 *(Yang+ 15)*



Radioactive heating power



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

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: $h(6.6\ \mathrm{d}) = 8.4 \times 10^8\ \mathrm{erg \cdot (g \cdot s)^{-1}}$;

[Piran, Korobkin & Rosswog (2014)]

(→ see also review by Tsvi Piran)

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- **ejecta mass**: $m_{\text{ej}} \geq L/h = \mathbf{0.02\ M_\odot}$.

[Piran, Korobkin & Rosswog (2014)]
($\rightarrow$ see also review by Tsvi Piran)

Simple analytic estimates

Peak times:

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

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

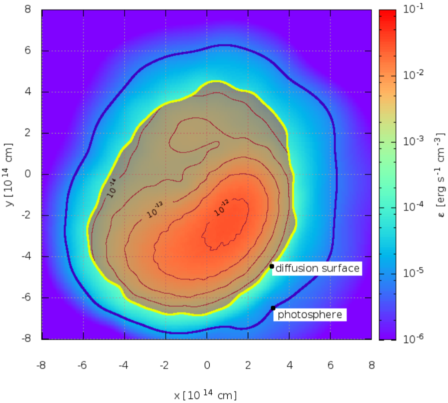
$$\tilde{T}_{\rm eff} \approx \left(\frac{\dot{\epsilon}_0 c}{\sigma_{SB}}\right)^{1/4}\left(\frac{m_{ej}}{4\pi c t_0}\right)^{-\alpha/8}\kappa^{-(\alpha+2)/8}\bar{v}^{(\alpha-2)/8}$$

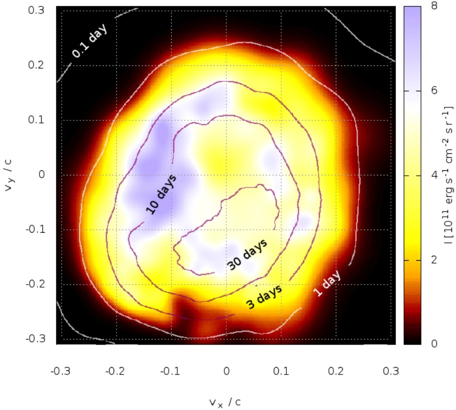
$$= \mathbf{2200}\ \text{K}\ \kappa_{10}^{-(\alpha+2)/8}\bar{v}_{-1}^{(\alpha-2)/8} m_{\rm ej,-2}^{-\alpha/8}.$$

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

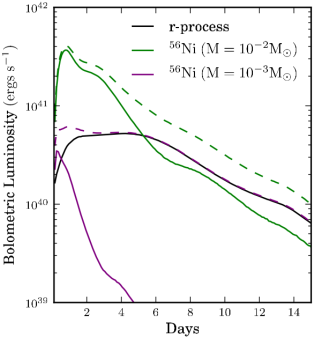
Radiative structure of the remnant

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

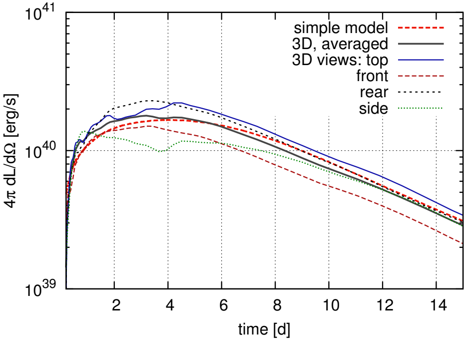




Synthetic macronova lightcurves



[Barnes & Kasen (2013)]

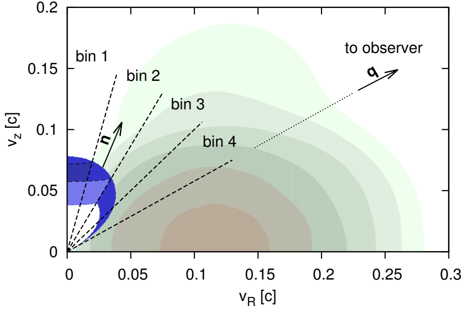


[Grossman et al. (2013)]

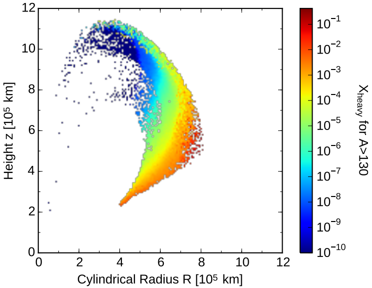
- transient peaks in near infrared;
- very weak signal;
- extremely hard to detect in modern surveys.
- how about an additional blue component?

Lanthanides in the neutrino-driven wind

- $\rightarrow$ see talk by Jonas Lippuner;
- *From D. Martin et al. (2015):* nucleosynthesis in neutrino-driven winds after neutron star mergers



wind + dyn.ejecta

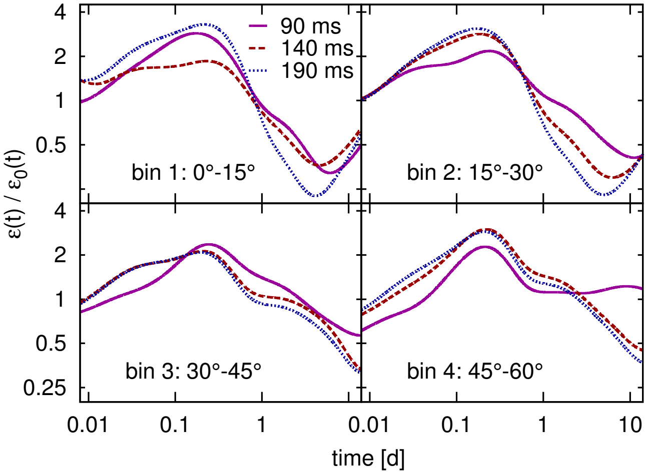


fraction of heavy isotopes

See also: [Lippuner et al. (2015)]

Heating rates in the neutrino-driven wind

- → see talk by Jonas Lippuner;
- *From D. Martin et al. (2015):*



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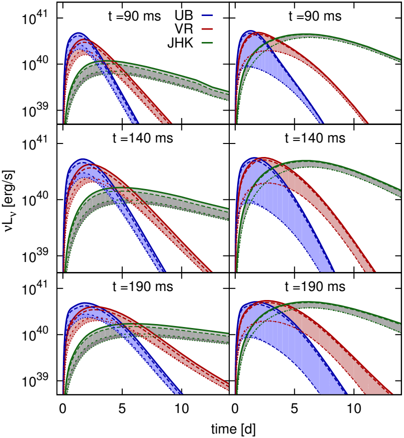
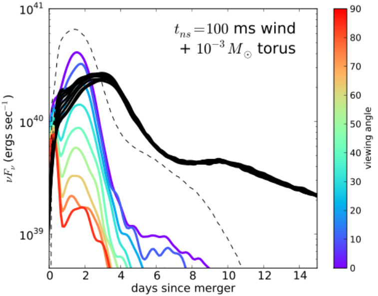
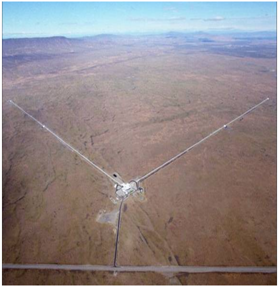




Left: *From D. Martin et al. (2015)*: combined blue (U+V bands), red (V+R) and infrared (J+H+K) contributions.
Right: from [Kasen, Fernandez & Metzger (2014)].

Detecting gravitational wave bursts



- NSMs are the primary targets for the advanced GW detectors (LIGO, VIRGO), coming into operation in the next few years;
- estimated rates: several events per year;
- due to poor directional sensitivity of GW detectors, we will remain blind to the location of the mergers, unless they also produce sGRB;
- which only happens for a small fraction of all events.
- Detection of isotropic component of NSM would be desirable! [Nissanke +13]
- → see review by Stephen Fairhurst.

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Conclusions

Conclusions

- Neutron star mergers are plausible candidates for the main producers of the r-process.
- The astrophysical robustness of main r-process in neutron star mergers naturally explains the robust pattern of abundances in the old metal-poor stars.
- Weak r-process can be explained by nucleosynthesis in the neutrino-driven wind ejecta.
- Radioactive heating produced in merger ejecta leads to an infrared transient, (macronova / kilonova), peaking around ~ 6 days.
- Additional neutrino-driven wind outflow could produce an early blue signal, that may be easier to detect.
- Detected infrared transients in the afterglow of the GRB 130603B and GRB 060614 are consistent with the model, but give high mass estimates.

Open questions

- What is the correct morphology of the dynamical ejecta?
- How much matter is ejected, depending on the merging system?
- What are the opacities of the hot freshly produced r-process plasma?
- Can we detect macronovae from radioactively decaying freshly synthesized r-process elements?
- Can we detect blue transients from the viscously driven / ν-driven winds? What is the level of "lanthanide / actinide pollution"?
- Does neutrino irradiation of the dynamical ejecta significantly affect its electron fraction and subsequent nucleosynthesis (as in [Wanajo et al. 2014])?
- Is fast neutron burst from shock interface a numerical artifact, or is it a detectable phenomena (as in [Metzger et al. 2014])?
- etc.