Overview: Kilonova

1. Basics
2. Prospects for EM observations
3. Signatures of r-process nucleosynthesis

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References (Reviews)

- **Rosswog, S. 2015**
  “The multi-messenger picture of compact binary mergers”
  International Journal of Modern Physics D, 24, 1530012-52

- **Fernandez, R. & Metzger, B. D. 2016**
  “Electromagnetic Signatures of Neutron Star Mergers in the Advanced LIGO Era”
  Annual Review of Nuclear and Particle Science, 66, 23

- **Tanaka, M. 2016**
  “Kilonova/Macronova Emission from Compact Binary Mergers”
  Advances in Astronomy, 634197

- **Metzger, B. D. 2017**
  “Kilonovae”
  Living Reviews in Relativity, 20, 3
Merger
Francois’s talk (Monday)
Masaru’s talk (Thursday)
r-process nucleosynthesis
Radioactive decay => kilonova

Timeline
Merger -> r-process nucleosynthesis -> Radioactive decay
Dynamical Wind
< 10 ms ~< 100 ms < 1 sec ~ days

Tsunami
energy deposition

Diffusing out

Masaru’s talk (Thursday)
Francois’s talk (Monday)
My talk (today)
Merger => see Masaru’s talk

Dynamical ejecta (~< 10 ms)
- \( \text{Mej} \sim 10^{-3} - 10^{-2} \) Msun
- \( v \sim 0.1-0.2 \) c
- wide Ye
- \( n + \nu_e \rightarrow p + e^- \)
- \( n + e^+ \rightarrow \overline{\nu}_e + p \)

Post-dynamical ejecta (~< 100 ms)
- \( \text{Mej} > 10^{-3} \) Msun
- \( v \sim 0.05 \) c
- relatively high Ye
Nucleosynthesis (< 1 sec) => see Francois’s talk

=> Solar abundance? (Discussion yesterday)  (from Wanajo+14)
Radioactive heating (decay of many r-process nuclei)

For our fiducial model, we assume before the initial temperature dissociations, as explained by Petermann et al. 2008 that includes neutron captures, photonuclear reactions, and spontaneous fission. The change of temperature during the initial expansion is determined using the statistical code of Martoller et al. (1999). All heating is self-consistently added to the ejecta. We use a dynamical Finite Range Droplet Model (FRDM; Moller et al. 1995) and the NS–NS merger product nuclei obtained by Freiburghaus et al. (1999) due to an improved treatment of delayed fission yields and freeze-out effects.

In this section, we present calculations of the radioactive heating of the radioactive heating (decay of many r-process nuclei). In Fig. 1, we show for comparison the heating rate per unit mass produced by the decay chain of the r-process product nuclei. Note: Above, the equilibrium photon energy produced in the decay.

\[ \text{Average photon energy produced in the decay.} \]

Although we assume that the r-process begins (Meyer 1989; Freiburghaus et al. 1999). Our results for the total radioactive power are determined using the statistical code of Martoller et al. (1999).

\[ E_{\text{avg}} = \frac{1}{N} \sum_{i} E_{i} \]

\[ M = 0.01 \text{ Msun} \]

\[ T_{\text{r}} \text{ -process heat-} \]

\[ T_{\text{r}} \text{-process, which ends when } Z/\bar{A} \text{ denotes by dashed and dotted lines, respectively. The large heating in Fig. 1. On time-scales of interest the radioactive power can be estimated using the statistical code of Martoller et al. (1999). The change of temperature during the initial expansion is determined using the statistical code of Martoller et al. (1999). All heating is self-consistently added to the ejecta. We use a dynamical Finite Range Droplet Model (FRDM; Moller et al. 1995) and the NS–NS merger product nuclei obtained by Freiburghaus et al. (1999) due to an improved treatment of delayed fission yields and freeze-out effects.

\[ T_{\text{r}} \text{-process peaks at } Z/\bar{A} \text{ due to the decay of }^{56}\text{Ni} \text{ and its }^{56}\text{Co.} \]

\[ T_{\text{r}} \text{-process heating, and that the NS–merger product nuclei, calculated for the }^{56}\text{Ni and its }^{56}\text{Co.} \]

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\[ T_{\text{r}} \text{-process peaks at } Z/\bar{A} \text{ due to the decay of }^{56}\text{Ni} \text{ and its }^{56}\text{Co.} \]
Physical properties of NS merger ejecta at ~1 day
"Kilonova/Macronova"

**Initial works:** Li & Paczynski 98, Kulkarni 05, Metzger+10, Goriely+11, ...

**High opacity:** Kasen+13, Barnes & Kasen 13, MT & Hotokezaka 13, ...

### Timescale

\[ t_{\text{peak}} = \left( \frac{3\kappa M_{\text{ej}}}{4\pi c v} \right)^{1/2} \]

\[ \approx 8.4 \text{ days} \left( \frac{M_{\text{ej}}}{0.01M_{\odot}} \right)^{1/2} \left( \frac{v}{0.1c} \right)^{-1/2} \left( \frac{\kappa}{10 \text{ cm}^2 \text{ g}^{-1}} \right)^{1/2} \]

### Luminosity

\[ L_{\text{peak}} = L_{\text{dep}}(t_{\text{peak}}) \]

\[ \approx 1.3 \times 10^{40} \text{ erg s}^{-1} \left( \frac{M_{\text{ej}}}{0.01M_{\odot}} \right)^{0.35} \left( \frac{v}{0.1c} \right)^{0.65} \left( \frac{\kappa}{10 \text{ cm}^2 \text{ g}^{-1}} \right)^{-0.65} \]
Opacity

Atomic structure calculation with HULLAC code (relativistic, local radial potential, Bar-Shalom+99) and GRASP code (relativistic, e-e interaction, Jonsson+07)

\[
\kappa \text{ (p shell)} < \kappa \text{ (d shell)} < \kappa \text{ (f shell)}
\]

\[
\kappa \text{ (Lanthanide)} \sim 10 \text{ cm}^2 \text{ g}^{-1}
\]

MT+ in prep.

Kasen+13, MT & Hotokezaka 13
Light curve

- **Type Ia SN**
- **NS merger**
- **Luminosity (erg/s)**
  - $10^{43}$
  - $10^{42}$
  - $10^{41}$
  - $10^{40}$
  - $10^{39}$

**Days after the merger**

- $1$
- $10$

**Mej = 0.01 Msun**

- **Decay energy**

- **a few x $10^{40}$ erg/s @ ~1 week**

MT 16
Spectra

Extremely red spectra (peaks at near infrared wavelengths)

Fe opacity

r-process

Kasen+13

Extremely red spectra (peaks at near infrared wavelengths)
If post-dynamical ejecta is Lanthanide-free (Ye >~ 0.25)
=> low opacity => “blue kilonova”

(Metzger+14, Kasen+15)
“Blue kilonova”

L ~ $10^{41}$ erg/s, $t$ ~ a few days, Optical
Summary
Overview: Kilonova

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Optical light curves in observed magnitudes

FIG. 2: Expected observed magnitudes of kilonova models at 200 Mpc distance [70, 71]. The red, blue, and green lines show the models of NS-NS merger (APR4-1215), BH-NS merger (APR4Q3a75), and a wind model, respectively. The ejecta mass is $M_{\text{ej}} = 0.01 M_{\odot}$ for these models. For comparison, light curve models of Type Ia SN are shown in gray. The corresponding absolute magnitudes are indicated in the right axis.

B. NS-NS mergers

When two NSs merge with each other, a small part of the NSs is tidally disrupted and ejected to the interstellar medium (e.g., [36, 42]). This ejecta component is mainly distributed in the orbital plane of the NSs. In addition to this, the collision drives a strong shock, and shock-heated material is also ejected in a nearly spherical manner (e.g., [48, 84]). As a result, NS-NS mergers have quasi-spherical ejecta. The mass of the ejecta depends on the mass ratio and the eccentricity of the orbit of the binary, as well as the radius of the NS or equation of state (EOS, e.g., [48, 84–88]): a more uneven mass ratio and more eccentric orbit leads to a larger amount of tidally-disrupted ejecta and a smaller NS radius leads to a larger amount of shock-driven ejecta.

The red line in Figure 1 shows the expected luminosity of a NS-NS merger model (APR4-1215 from Hotokezaka et al. 2013 [48]). This model adopts a “soft” EOS APR4 [89], which gives the radius of 11.1 km for a 1.35 $M_{\odot}$ NS. The gravitational masses of two NSs are 1.2 $M_{\odot} + 1.55 M_{\odot}$ and the ejecta mass is 0.01 $M_{\odot}$. The light curve does not have a clear peak since the energy deposited in the outer layer can escape earlier. Since photons kept in the ejecta by the earlier effect effectively escape from the ejecta at the characteristic timescale (Eq. 2), the luminosity exceeds the energy deposition rate at $\sim 5 - 8$ days after the merger.

Figure 2 shows multi-color light curves of the same NS-NS merger model (red line, see the right axis for the absolute magnitudes). As a result of the high opacity and the low temperature [77], the optical emission is greatly suppressed, resulting in an extremely “red” color of the emission. The red color is more clearly shown in Figure 3, where the spectral evolution of the NS-NS merger model is compared with the spectra of a Type Ia SN and a broad-line Type Ic SN. In fact, the peak of the spectrum is further displaced to longer wavelengths due to the higher opacity.
Constraints from short GRBs (1/2)

**GRB 130603B**

- June 13, 2013
- 75,000 light-years
- 23 kiloparsecs
- 3\"9

Tanvir+2013, Berger+2013

1 + 1(?) more cases
GRB 060614 & GRB 050709

Ejection of \(~0.06\) Msun

Hotokezaka+13, Barnes+16

GRB 160821B: \(~0.01\) Msun?

(Troja+16)
Constraints from short GRBs (2/2)

@ 200 Mpc
21 mag
24 mag

Can be brighter at t < 1 day

200 Mpc shallow
deep
Field of view (deg²) vs Limiting magnitude

- Kiso
- La Silla
- PTF
- CRTS
- ZTF
- LSST
- HST
- CRTS
- PTF

- VISTA (NIR)
- DECam
- CFHT

- typical 8-10m
- typical 4m
- typical 1-2m
- ~ 8-10m
- ~ 4m
- ~ 1-2m

- t >~ 1 day
DECam observations of GW151226
Cowperthwaite+16

2015 December 28, at 1.8 hours UT

5σ point source limiting magnitude

21.9
22.2
22.5
22.8
23.1
23.4
23.7
24.0
24.3

RA (degrees)
Dec (degrees)

=> see Philip’s talk
J–GEM observations of GW151226

Yoshida, Utsumi, Tominaga, Morokuma, MT et al. 2017
Utsumi, Tominaga, MT in prep.

=> see Nozomu’s talk (next week)

987 deg²
Subaru/HSC: 64 deg²
Kiso: 778 deg²
MOA: 145 deg²
Heavy contamination of supernovae, AGNs, and variable stars => How to select NS mergers?

- Association with nearby galaxies
- Faintness
- Rapid evolution
- Red color

Δmag (in 3 days)

Fast rise

Slow

Fast decline

Blue

i - z

Red

MT+14, MT 16
Candidate selection for Subaru/HSC survey (~ 23-24 mag)

- Association with nearby galaxies
- Faintness
- Rapid evolution
- Red color

0 remaining candidate

Utsumi, Tominaga, MT+ in prep.
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### Supernova vs NS merger

<table>
<thead>
<tr>
<th></th>
<th>Supernova</th>
<th>NS merger</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>M (r-process)</strong></td>
<td>$10^{-2}$ Msun (?)</td>
<td>$10^{-2}$ Msun</td>
</tr>
<tr>
<td><strong>M (total)</strong></td>
<td>$\sim 10$ Msun</td>
<td>$10^{-2}$ Msun</td>
</tr>
<tr>
<td><strong>Heating source</strong></td>
<td>$^{56}$Ni</td>
<td>r-process</td>
</tr>
<tr>
<td><strong>Spectra</strong></td>
<td>H, He, $\alpha$ elements, Iron group</td>
<td>r-process (w/ heavy blend)</td>
</tr>
</tbody>
</table>

We can “measure” r-process mass with kilonova

\[
L_{\text{peak}} = L_{\text{dep}}(t_{\text{peak}}) \\
\approx 1.3 \times 10^{40} \text{ erg s}^{-1} \left( \frac{M_{\text{ej}}}{0.01 M_\odot} \right)^{0.35} \left( \frac{v}{0.1 c} \right)^{0.65} \left( \frac{\kappa}{10 \text{ cm}^2 \text{ g}^{-1}} \right)^{-0.65}
\]
NS merger as a possible origin of r-process elements

Event rate

\( R_{NSM} \sim 10^2-10^3 \text{ Gpc}^{-3} \text{ yr}^{-1} \)
\( \sim 3-30 \text{ GW events yr}^{-1} \)
\( (\text{w/ Adv. detectors, } < 200 \text{ Mpc}) \)

\[ \uparrow \quad \text{LIGO O1} \quad \text{GW} \quad R_{NSM} < 10^4 \text{ Gpc}^{-3} \text{ yr}^{-1} \]

Ejection per event

\( M_{ej}(r\text{-process}) \sim 10^{-2} \text{ Msun} \)

\[ \uparrow \quad \text{EM} \]

Enough to explain the r-process abundance in our Galaxy

\( M(\text{Galaxy, r-process}) \sim M_{ej}(r) \times (R_{NSM} \times t_G) \)
\( \sim 10^{-2} \times 10^{-4} \times 10^{10} \sim 10^4 \text{ Msun} \)
Simulations for dynamic NSNS ejecta, for other cases we use a parametrized treatment with numerical values based on existing hydrodynamic studies.

2.1. NSNS merger simulations

The NSNS simulations of this paper make use of the Smooth Particle Hydrodynamics (SPH) method, see \[72–75\] for recent reviews. Our code is an updated version of the one that was used in earlier studies \[11, 76–78\]. We solve the Newtonian, ideal hydrodynamics equations for each particle:

\[
\sum \rho \rho = -\Pi \nabla \cdot V
\]

Figure 2. Summary of various rate constraints. The lines from the upper left to lower right indicate the typical ejecta mass required to explain all r-process/all r-process with \(A > 80\)/all r-process with \(A > 130\) for a given event rate (lower panel per year and Milky Way-type galaxy, upper panel per year and Gpc\(^3\)). Also marked is the compiled rate range from Abadie et al. (2010) for both double neutron stars and neutron star black hole systems and (expected) LIGO upper limits for O1 to O3 (Abbott et al. 2016b).

The dynamic ejecta results from some hydrodynamic simulations are also indicated: the double arrow denoted 'nsns Bauswein+13' indicates the ejecta mass range found in \[23\], 'nsns Rosswog 13' refers to \[24\], 'nsns Hotokezaka+13' to \[25\], 'nsbh Foucart+14' to \[26\] and 'nsbh Kyutoku+13' to \[27\].

Rosswog+17, see also Hotokezaka+15
Constraints on the NS-NS merger rate

Expected event rates

- BH-BH
- O3:
- O2:
- O1:

- Dominik et al. pop syn
- de Mink & Belczynski pop syn
- Vangioni et al. r-process
- Jin et al. kilonova
- Petrillo et al. GRB
- Coward et al. GRB
- Siellez et al. GRB
- Fong et al. GRB
- Kim et al. pulsar
- aLIGO 2010 rate compendium

BNS Rate (Gpc\(^{-3}\)yr\(^{-1}\))

arXiv:1607.07456
How good we can estimate ejected mass?

Mej = 0.01 Msun

We need (1) multi-color observations, and (2) good theoretical models for spectra

- mergers and nucleosynthesis (long-term simulations)
- heating rate (nuclear physics)
- radiative transfer (atomic data, opacity)
The observed value of $J_{0453+1559}$ is $q = 0.75 \pm 0.124$ and the recently discovered PSR $J_{1913+1102}$ could have an even lower mass ratio $\pm 0.125$. The left panel of Figure 9 shows the results for the macronova model 1, the middle panel shows MNmodel2 with the FRDM mass formula and the right panel refers to MNmodel2 with DZ31. The general trends with a fainter and faster lightcurve in the bluer bands is apparent, while the near-infrared (NIR) lightcurves can stay bright for several weeks. We typically have $-11.5$ at peak in the $g$ band versus $-13.8$ in the $K$ band. The MNmodel2 results are about 0.7 magnitudes brighter at peak, but decay faster at later times. Both effects are mainly due to the time variation of the thermalization efficiency, see Figure 8. As expected from the enhanced net heating rate at late times (see Figure 7) the DZ31 mass model yields peak magnitudes that are another 0.8 magnitudes brighter than for the FRDM case. At the same time, both runs using MNmodel2 are significantly redder in the optical, being about one magnitude fainter at peak in the $g$ band. Additionally, their $g$-band lightcurves peak much earlier—only half a day after the merger versus about three days for MNmodel1.

Figure 10 shows the predictions for run B3 ($1.2 \odot M_{\text{NS}}$ and a $7.0 \odot M_{\text{BH}}$ with a dimensionless spin parameter $\chi = 0.9$). The BH mass of $7 \odot M_{\text{BH}}$ is close to the expected peak of the BH mass distribution $\pm 0.126$, but the spin is admittedly high. However, if we are interested in NSBH systems that are able to launch a short GRB, we need a large BH spin ($\chi \approx 0.9$).

We need (1) multi-color observations, and (2) good theoretical models for spectra: mergers and nucleosynthesis (long-term simulations), heating rate (nuclear physics), radiative transfer (atomic data, opacity).

FRDM: Finite range droplet model
DZ31: 31-parameter mass model (Duflo and Zuker 95)

Rosswog+17
Summary

- **Kilonova**
  - **Dynamical ejecta** (Lanthanide-rich)
    => $L \sim 10^{40-41}$ erg s$^{-1}$ for a week, red spectrum
  - **Post-dynamical ejecta** (IF Lanthanide-free)
    => $L \sim 10^{41}$ erg s$^{-1}$ for a few days, blue spectrum

- **For EM follow-up observations**
  - **At $>\sim 1$ day**: Likely to be fainter than 22 mag @ 200 Mpc
    => $>4$m-class telescopes
  - **At $\sim< 1$ day**: Can be brighter than 21 mag @ 200 Mpc
    => 1-2m-class telescopes

- **Measurements of r-process mass**
  - Need multi-color observations
  - Need good theoretical models to predict spectra/color