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 => see Masaru's talk

Dynamical ejecta (~< 10 ms)

Dynamical ejecta (~< 10 ms) Post-dynamical ejecta (~< 100 ms)

- Mej [~] 10^{−3} 10^{−2} Msun in *x*-*y* (lower in each panel) and *x*-*z* (upper in each panel) planes. The top three panels show the results for SFHo-135-135h
- \overline{a} above the disc, to a typical asymptotic expansion velocity of \overline{a} $-v \sim 0.1$ -0.2 c $v \sim 0.1$ ₂ c $v \sim 0.05$ c merger.
- **- wide Ye**

 $v \cdot L^-\,v \cdot L \cdot C$
n + v_e -> $p + e^-$ To characterize the matter properties, we plot in Fig. 15 2D λ **e** (to re+ couples of row), n + e⁺ -> \overline{v}_e + p binaries, the typical ejecta mass would approach 10²*M*

- Mej >~ 10⁻³ Msun \sim at a certain time. $-v \sim 0.05 c$ FIG. 2. Profiles of the electron number per baryon, *Ye*, (left in each panel) and the specific entropy, *s*, (right in each panel) (left), SFHo-130-140h (middle), and SFHo-125-145h (right) at ⇡ 13 ms after the onset of the merger. The lower three panels
	-
	- **relatively high Ye -**

Nucleosynthesis (< 1 sec) => see Francois's talk

=> Solar abundance? (Discussion yesterday) (from Wanajo+14)

eating (decay of many r-process nuclei) Radioactive heating (decay of many r-process nuclei)

 \int iol IVI – (**Figure 1.** Radioactive heating rate per unit mass $\mathsf{Metzger+10}$ **(for M = 0.01 Μsun)**

Physical properties of NS merger ejecta at ~1 day

(Blackboard)

"Kilonova/Macronova"

Initial works: Li & Paczynski 98, Kulkarni 05, Metzger+10, Goriely+11, ... **High opacity**: Kasen+13, Barnes & Kasen 13, MT & Hotokezaka 13, ...

> $t_{\rm peak}$ = $\left(\frac{3\kappa M_{\rm ej}}{4\pi cv}\right)^{1/2}$ \approx 8.4 days $\left(\frac{M_{\rm ej}}{0.01\,\mathrm{M}}\right)$ $0.01M_{\odot}$ $\bigwedge^{1/2}$ *(v* 0*.*1*c* $\bigwedge \frac{-1/2}{\pi}$ \bigwedge $10 \text{ cm}^2 \text{ g}^{-1}$ $\sqrt{1/2}$

Luminosity

Timescale

$$
L_{\text{peak}}
$$
 = $L_{\text{dep}}(t_{\text{peak}})$
\n $\simeq 1.3 \times 10^{40} \text{ erg s}^{-1} \left(\frac{M_{\text{ej}}}{0.01 M_{\odot}} \right)^{0.35} \left(\frac{v}{0.1 c} \right)^{0.65} \left(\frac{\kappa}{10 \text{ cm}^2 \text{ g}^{-1}} \right)^{-0.65}$

Opacity

Atomic structure calculation

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

κ (p shell) < **κ** (d shell) < **κ** (f shell) MT+ in prep. **κ** (Lanthanide) ~ 10 cm² g⁻¹ Kasen+13, MT & Hotokezaka 13

Light curve ◆◆ 研究奨励賞

Spectra

moly rod snoctra (noaks at noar infrarod wavelengthe (black line) or our Autostructure-derived *r*-process opacities (red line). For **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"

red optical $\mathsf{L} \sim 10^{41}$ erg/s, t ~ a few days, Optical

2013 Tanvir et al., Berger et al.: NIR kilonova candidate following GRB 130603B 2013 Yu, Zhang, Gao: magnetar-boosted kilonova ("merger-nova") **Summary**

peak timescale. The wavelength of the predicted spectral peak are indicated spectral peak are indicated by color as

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Optical light curves in observed magnitudes

RESEARCH LETTER **Constraints from short GRBs (1/2)**

this field. The redshifts of the afterglow21 and the host galaxy22 were both found to be z 5 0.356. **GRB 130603B**

Tanvir+2013, Berger+2013 filter (0.6 mm) and the NIR F160Wfilter (1.6 mm) (full details of the imag-

 $1 + 1(?)$ more cases \overline{CDP} \overline{O} \overline SIND OOOD THREE CIND ODD TO SHARE GRB 060614 & GRB 050709

optical and NIR; right axis, X-ray. Upper limits are 2s and 2 **Ejection of ~0.06 Msun** Hotoke: the NIR data have been interpolated to the F160W band using an average

Hotokezaka+13, Barnes+16

 $CDD1$ $CDD1$ CQ ^{$D1$} $D. ~N$ $D1$ N CQ _{DQ} T_{rel} **GRB 160821B: ~ 0.01 Msun?** (Troja+16)

Constraints from short GRBs (2/2)

DECam observations of GW151226

=> see Philip's talk

Cowperthwaite+16

J-GEM observations of GW151226

Yoshida, Utsumi, Tominaga, Morokuma, MT et al. 2017 Utsumi, Tominaga, MT in prep. *Publications of the Astronomical Society of Japan*, (2014), Vol. 00, No. 0 **3**

=> 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**

Candidate selection for Subaru/HSC survey (~ 23-24 mag)

- **Association with nearby galaxies**
- iness survives survives in the number of candidates survives if \mathcal{C} **- Faintness**
- **Rapid evolution**
- $\hbox{\bf color} \qquad \qquad \qquad \qquad \qquad \qquad \qquad$ **- Red color**

dividually. For example, the number of candidates satisfying (*i* − *z*)1st *>* 0*.*5 and ∆*i >* 1*.*0 mag is 16. **0 remaining candidate**

well to supernova contaminations the number of supernova contact of supernova contact of supernova contact of

cause they do not exhibit such rapid variability, and the num-

ber of survived candidates becomes feasible to be inspected in-

Fig. 5. Transient candidates on the plane of ∆*i* vs *i* − *z* with kilonovae and Supernovae. Candidates survived with Processing the Superior 3 and 3 and 3 are shown in the shown in this Figure. Utsumi, Tominaga, MT+ in prep.

Overview: Kilonova

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Supernova vs NS merger

We can "measure" r-process mass with kilonova

$$
L_{\text{peak}}
$$
 = $L_{\text{dep}}(t_{\text{peak}})$
\n $\simeq 1.3 \times 10^{40} \text{ erg s}^{-1} \left(\frac{M_{\text{ej}}}{0.01 M_{\odot}} \right)^{0.35} \left(\frac{v}{0.1 c} \right)^{0.65} \left(\frac{\kappa}{10 \text{ cm}^2 \text{ g}^{-1}} \right)^{-0.65}$

NS merger as a possible origin of r-process elements

Event rate

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

LIGO O1

Ejection per event

 $M_{\text{ei}}(r\text{-process}) \approx 10^{-2}$ Msun

T GW R_{NSM} < 10^4 Gpc⁻³ yr⁻¹ **EM**

Enough to explain the r-process abundance in our Galaxy $M(Galaxy, r-process) \sim M_{ej}(r) \times (R_{NSM} \times t_G)$ \sim 10⁻² x 10⁻⁴ x 10¹⁰ \sim 10⁴ Msun

Figure 2. Summary of various rate constraints. The lines from the upper left to lower left to l

Table 2. Sensitive space-time volume h*V T*i and 90% confidence upper limit *R*90% for NSBH systems with isotropic and aligned Constraints on the NS-NS merger rate

 10^0 10^1 10^2 10^3 10^4 BNS Rate $(Gpc^{-3}yr^{-1})$ aLIGO 2010 rate compendium Kim et al. pulsar Fong et al. GRB Siellez et al. GRB Coward et al. GRB Petrillo et al. GRB Jin et al. kilonova -Vangioni et al. r-process de Mink & Belczynski pop syn Dominik et al. pop syn O3 O2 O1 **O1: 2015-2016 O2: 2016-2017 O3: 2018 BH-BH**

are shown for both the pycbc and gstlal pipelines. ^h*V T*ⁱ is calculated using a FAR threshold of 0.01 yr1. The rate upper **limit is calculated using a uniform prior** $\frac{1}{2}$ **Fxpected event rates**

Figure 6. A comparison of the O1 90% upper limit on the arXiv:1607.07456

How good we can estimate ejected mass? , *T* = 5*,* 000 K, and *t* = 1 day after the merger. For doubly ionized ions (Nd iii and **How good we can estimate ejecte Observed magnitude (200 Mpc)**

$Mej = 0.01$ Msun **1 = 0.03 Msun 15 20**

Figure 4. Comparison of line expansion opacities between HULLAC and GRASP2K calculations. For singly ionized ions (Nd ii and

Nuclear mass model => heating rate

FRDM: Finite range droplet model

DZ31:

31-parameter mass model (Duflo and Zuker 95)

Rosswog+17

We need (1) multi-color observations, and

Figure 7. Left: Compare 7. Left: Compare 12) and the original models for spectral rates between the second rates between t (2) **good theoretical models for spectra**

- network of Wintels of Windows Constant Constant and Mendoza-Temperature *et*ails *etails* FRD mass model. The overall and model over many property is good over many contract the state of the state over many contract the state of the s - mergers and nucleosynthesis (long-term simulations)
- orders of magnitude. Rights of magnitude in the FRDM and DZ31 net nuclear heating rates for the FRDM and DZ31 n
Page 1986 net nuclear for the FRDM and DZ31 nuclear for the FRDM and DZ31 nuclear for the FRDM and DZ31 nuclea a a set of the ating rate (nuclear physics)
- mass model (all runs N15 and B1–15 and B1–B3; Mendoza-Temis and B1–B3; Department of the DZ315; Mendoza-Temis i
Experimental property in the DZ315; Mendoza-Temis in the DZ315; Mendoza-Temis in the DZ315; Mendoza-Temis in t a and the stransfer (atomic data, opacity)

Summary

- **• Kilonova**
	- **Dynamical ejecta** (Lanthanide-rich) $=$ \geq L \sim 10⁴⁰⁻⁴¹ erg s⁻¹ for a week, red spectrum
	- **Post-dynamical ejecta** (IF Lanthanide-free) $=$ L \sim 10⁴¹ erg s⁻¹ for a few days, blue spectrum
- **•** For EM follow-up observations
	- At $>$ 1 day: Likely to be fainter than 22 mag @ 200 Mpc => >4m-class telescopes
	- At ~< 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