Kilonovae

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Abstract

- Mergers of double neutron star (NS–NS) and black hole (BH)–NS binaries are promising gravitational wave (GW) sources for Advanced LIGO and future GW detectors.
- Rapid neutron capture (r-process) nucleosynthesis, enriching our Galaxy with rare heavy elements like gold and platinum.
- The radioactive decay of these unstable nuclei also powers a rapidly evolving, supernova-like transient known as a “kilonova” (approximately isotropic electromagnetic counterpart to the GW signal.
- History and physics of kilonovae, using a simple light curve model to illustrate the basic physics, and introducing potentially important variations on this canonical picture, including: ∼day-long optical (“blue”) emission from lanthanide-free components of the ejecta; ∼hour-long precursor UV/blue emission, powered by the decay of free neutrons in the outermost ejecta layers; and enhanced emission due to energy input from a long-lived central engine, such as an accreting BH or millisecond magnetar.
- Prospects of kilonova detection following future GW detections of NS–NS/BH– NS mergers in light of the recent follow-up campaign of the LIGO binary BH–BH mergers.

Structure

- Introduction
- Historical background
- NS mergers as sources of the r-process
- A brief history of kilonovae
- Basic ingredients
- Sources of ejecta in binary NS mergers
- Opacity
- Unified toy model
- R-process heating
- Red kilonova: lanthanide-bearing ejecta
- Blue kilonova: lanthanide-free ejecta
- Free neutron precursor
- Engine power
- Kilonova candidates following short GRBs
- GW follow-up: prospects and strategies
- The GW/EM horizon ahead
- Final thoughts

Introduction

- Information from merging events: GW data + EM counterpart

Needed to locate the merging system

Same process used for GRBs!

Measure redshift of host galaxy

With redshift GW can be used as cosmological standard rulers

Parameters of the system (ex. Inclination angle)

Introduction

- Problems with BH-BH merger: no luminous EM emission -> study NS-NS or NS-BH systems
- Expected detection rate from Advanced LIGO/Virgo 0.3-300 events/yr
- Obs + theoretical evidence already support connection between compact star merger and short GRBs (< 2s)

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- Possibly powered by accretion disks onto BH or NS remnant (timescale of seconds)
- After GW chirp -> follow-up detection by X-ray telescopes pointed at burst location (Swift) -> good angular resolution -> identification of host galaxy

Problem for GRB detection

- Expected detection rates for short GRBs after merging < 1 event/yr
- GRBs subjected to relativistic beaming effect -> radiation concentrated into narrow solid angle
- Observation depends on position

Kilonovae

- More isotropic counterparts -> easier detection
- Day to week long thermal supernova-like transient
- Probably powered by radioactive decay of neutron rich elements synthetized in expanding ejecta
- **Possible probe of unknown astrophysical origin of heavy elements**

R-process elements

- Rapid neutron capture elements
- Free neutrons density very high -> neutron captures on nuclei is faster than β-decay
- Low electron fraction $Y_e = \frac{n_p}{n_p+n_n}$ needed
- If $Y_e < 0.5$ there is neutron abundance

First hypothesis: Core collapse supernovae

- Promising r-process sources
- They would be formed in wind heated by neutrino emission
- Unlikely necessary conditions

Second hypothesis: merger of compact binaries

- More probable source
- Elements possibly formed during decompression of highly neutron rich ejecta
- Nature and geometry of the system allows $Y_e \leq 0.2$

Kilonovae – historical background

- 1998 Li and Paczyński -> radioactive ejecta from NS/BH merger source of transient supernova–like emission
- Luminosity peak predicted at day timescale
- Low mass, high velocity ejecta becomes transparent earlier

Kilonovae – historical background

- Luminosity at peak ~ 1000 L novae
- 2010 Metzger et al. introduced term «Kilonova»
- Predicted connection between GWs of binary mergers, GRBs and

r-processes

- 2013: if heavy elements are produced -> peak of light curves pushed forward in time and wavelength

Kilonovae – hystorical background

- 2013: if heavy elements are produced -> peak of light curves pushed forward in time and wavelenght
- Timescale from 1 day to 1 week
- Peak from UV/optical to NIR
- Important impications for EM follow-up of future GW events

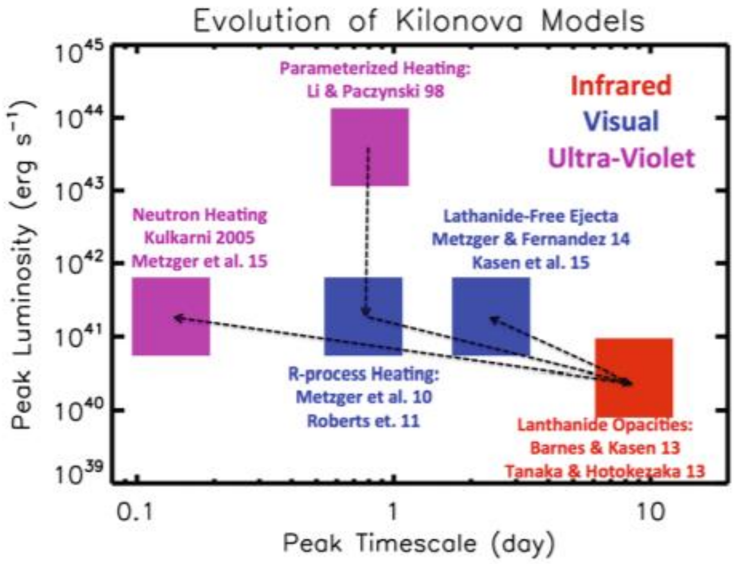


Fig. 1 Timeline of the development kilonova models in the space of peak luminosity and peak timescale. The wavelength of the predicted spectral peak are indicated by *color* as marked in the figure

All images used belong to Metzger et al.

Kilonovae - physics

- Initial phase: hot -> thermal radiation can’t escape
- Initial high optical depth
- $\tau \propto t^{-1}$
- After day/week light curve peak
- $L_{peak} \approx \dot{Q}\,(t_{peak})$
- Merger calculations expect lighter r-process elements 90 $\leq A \leq$130 produced in spherically symmetric ejecta
- Lower electron fraction matter $A \geq$130 closer to equatorial plane -> different kilonova types

Heating rate

- Radioactive heating rate of the ejecta
- Important to predict luminosity curve
- 1998: $\dot{Q}_{pl} \propto \frac{1}{t}$
- Today: $\dot{Q} \propto t^{-\alpha}$ $with\ \alpha = 1.1 - 1.4$

Key elements of kilonovae

- Timescale and luminosity at peak, temperature
- Need to study:

1) mass and velocity of ejecta

2) opacity of expanding matter

3) sources that contribute to $\dot{Q}$

1) Sources of ejecta

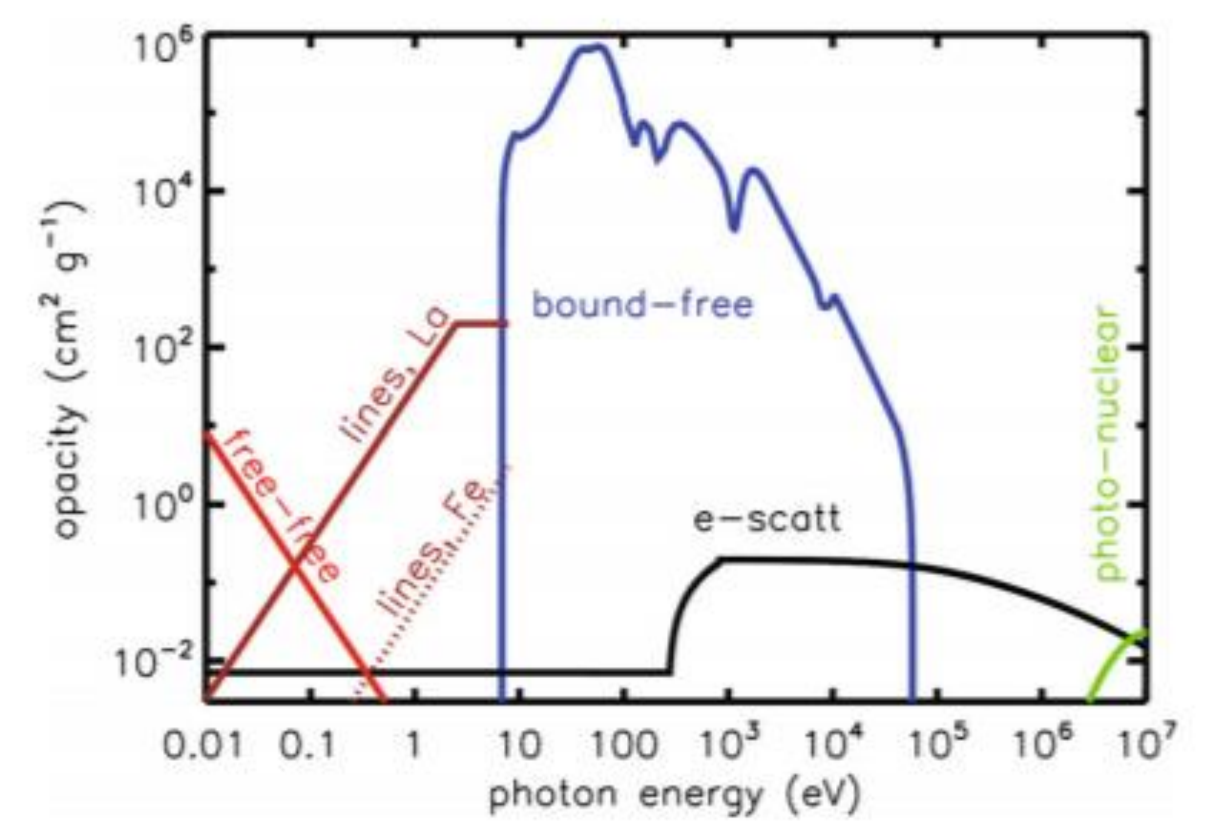
- <u>Dynamical ejecta</u>: <1ms, tidal forces at the heating interface between merging bodies
- Different processes for different systems: for NS-NS up to $10^{-4} - 10^{-2}\, M_{\odot}$ for BH-NS $\sim 0.1\, M_{\odot}$
- <u>Outflows</u> from central remnant accretion disk, if present. Timescale of seconds

Ejecta dependance on properties of the system

- **BH-NS merger:** a lot of mass ejected if BH mass is low and it’s rapidly spinning -> NS tidally disrupted
- **NS-NS merger:** ejecta depends on type of remnant which depends on binary system mass
  - $M > M_{crit} \sim 2.6 - 3.9\, M_{\odot}$ -> immediate collapse to black hole
  - $M \leq M_{crit}$ -> massive NS remnant supported by differential rotation (HMNS)
  - $M \ll M_{crit}$ -> indefinitely stable remnant

2) Opacity

- Kilonova emission peaks in opt/NIR
- Expanding merger ejecta becomes transparent in these wavelenght first
- In figure, effects that contribute to opacity at various wavelength and relative importance



3) Energy sources

- Power kilonova emission
- 3.1) **Radioactivity:** ejecta powered by radioactive decay of heavy nuclei synthetized in ejecta by r-processes

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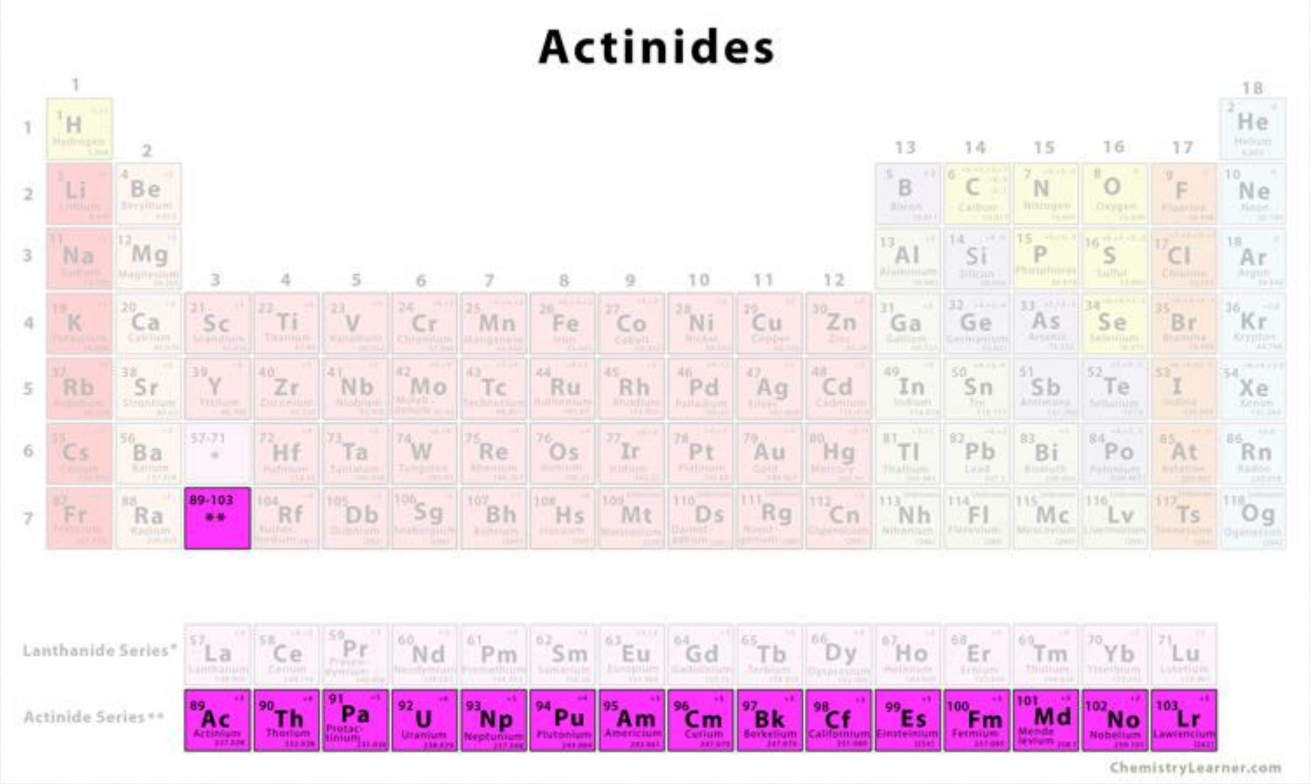
$$\dot{Q} = \underbrace{dM_v}_{\text{Infinitesimal mass layer}} \; \underbrace{X_{r,v}}_{\text{R-process mass fraction}} \; \underbrace{\dot{e}_r(t)}_{\text{Specific heating rate}}$$

3.1) Radioactivity

- Process involved: combination of β-decay, α-decay, and fission
- Quantity of actanides produced varies a lot with mass of the system



Actinides

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1 H																	2 He
2	3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
3	11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
4	19 K	20 Ca	21 Sc	22 Ti	23 V	24 Cr	25 Mn	26 Fe	27 Co	28 Ni	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
5	37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
6	55 Cs	56 Ba	57-71 *	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
7	87 Fr	88 Ra	89-103 **	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt	110 Ds	111 Rg	112 Cn	113 Nh	114 Fl	115 Mc	116 Lv	117 Ts	118 Og
Lanthanide Series*			57 La	58 Ce	59 Pr	60 Nd	61 Pm	62 Sm	63 Eu	64 Gd	65 Tb	66 Dy	67 Ho	68 Er	69 Tm	70 Yb	71 Lu	
Actinide Series**			89 Ac	90 Th	91 Pa	92 U	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr	

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3.2) Central engine

- Ejecta powered by activity of compact remnant of the merger
- Evidence: 15-25% of short GRB detected by Swift followed by «hump» of X-ray emission
- Other GRBs show a «plateau» in X-ray afterglows (100-1000 s)
- CE activity could dominate radioactivity contribution
- Process involved: fall back accretion -> matter that remains bound falls back on the remnant after seconds/days
- $$\dot{Q}_{fb} = \varepsilon_j \dot{M}_{fb} c^2$$

Jet/disk efficiency factor

Fall back mass rate

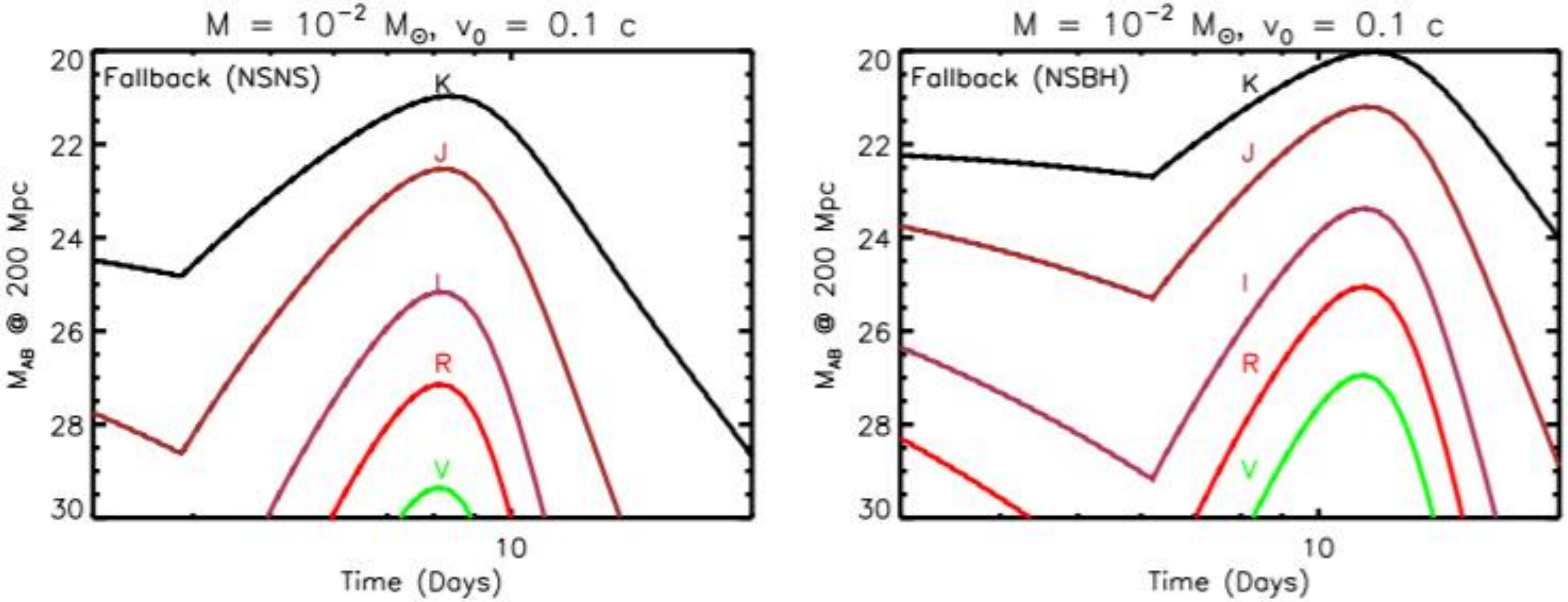
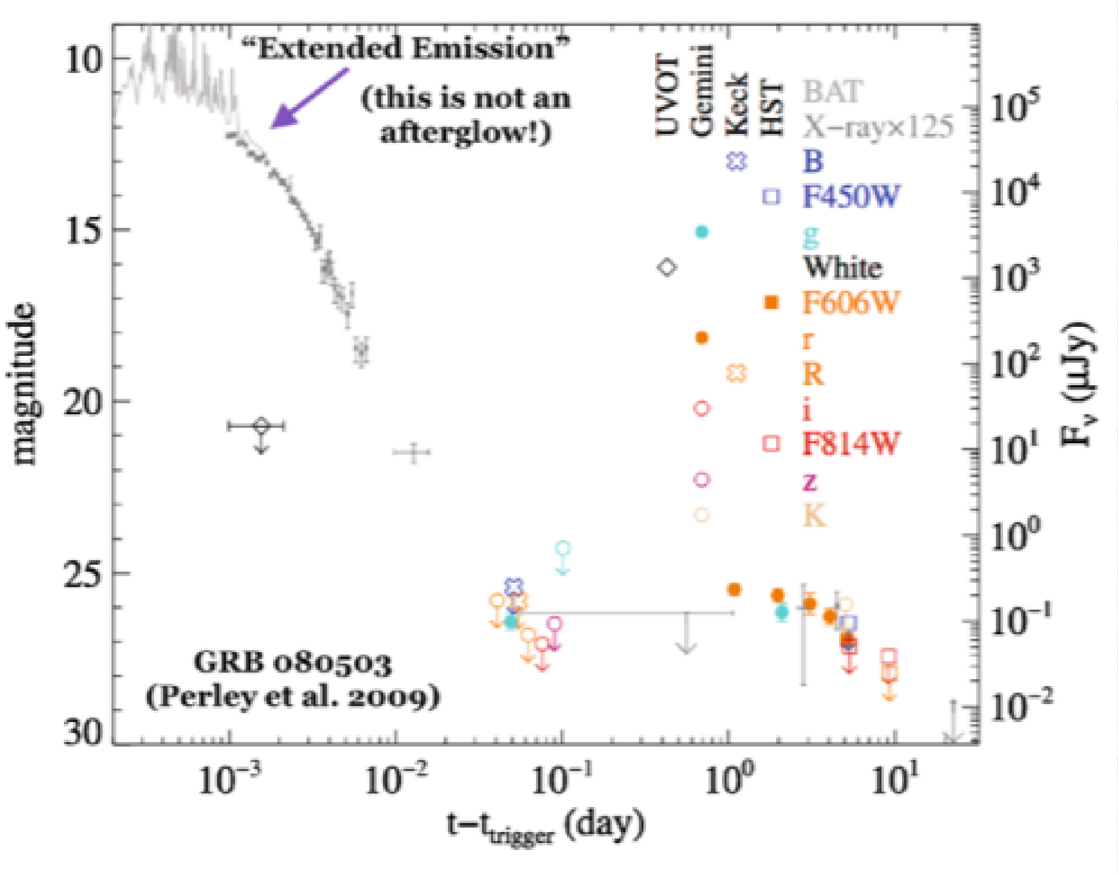


Fig. 7 Kilonova light curves powered by fall-back accretion, calculated for the same parameters of total ejecta mass $M = 10^{-2}$ and velocity $v_0 = 0.1$ c used in Fig. 5, and for an opacity appropriate to lanthanide-bearing nuclei. We adopt an ejecta heating rate from Eq. (30) for a fixed efficiency $\epsilon_{\rm j} = 0.1$. We normalize the mass fall-back rate to a value of $\dot{M}_{\rm fb}(t = 0.1) = 10^{-3} M_\odot\ {\rm s}^{-1}$ in the case of NS–NS mergers (*top panel*), and to a value 10 times higher in BH–NS mergers (*bottom panel*), based on Rosswog (2007)

3.3) Magnetar

- Typical remnants: BH, HMNS, SMNS, stable NS
- Possibility that the merger remnant is a NS with dipole magnetic field $B \sim 10^{15} - 10^{16}\ G$ typical of galactic magnetars
- Energy emission from this objects could explain extended X-ray emission following short GRBs



X-ray and optical light curves of GRB 080503

3.3) Magnetar

- Spin-down contribution to ejecta heating:
- $$\dot{Q}_{sd} = \underbrace{\varepsilon_{th}}_{\text{Thermal efficiency}} \overbrace{L_{sd}}^{\text{Spin down luminosity}}$$

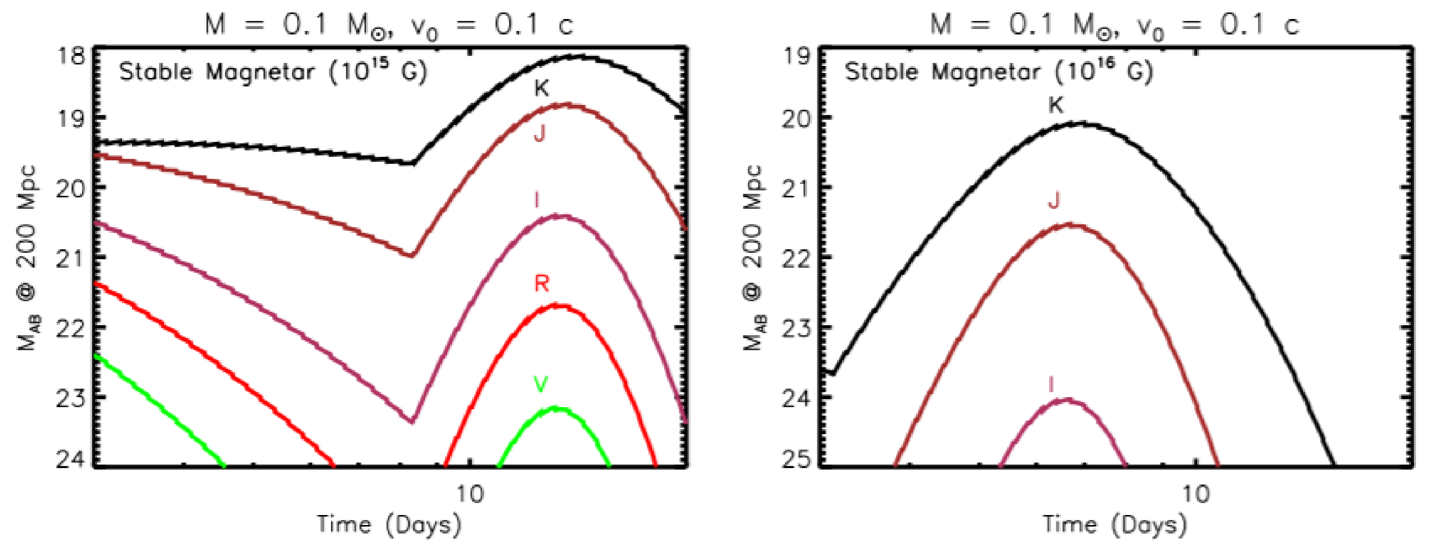
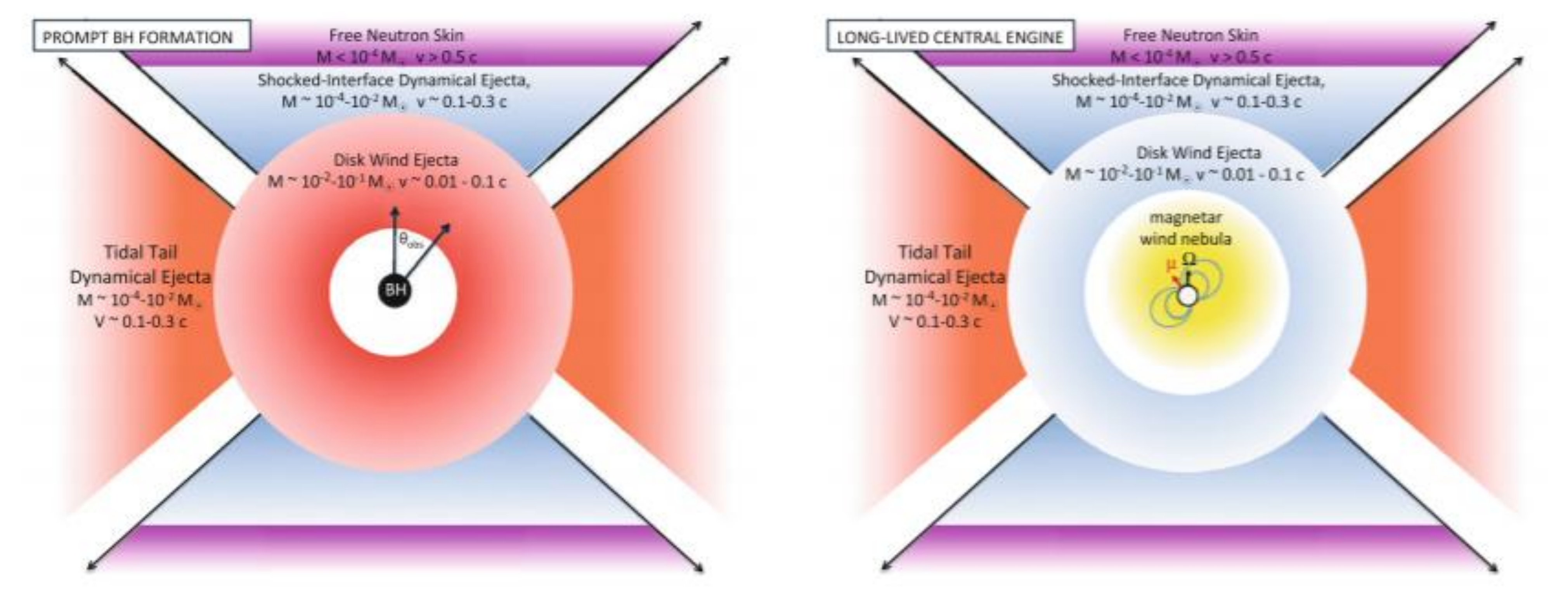


Fig. 10 Kilonova light curves, boosted by spin-down energy from an indefinitely stable magnetar ($t_{\rm collapse} = \infty$). We assume an ejecta mass $M = 0.1 M_\odot$ (Metzger and Fernández 2014), initial magnetar spin period $P_0 = 0.7$ ms, thermalization efficiency $\epsilon_{\rm th} = 1$ and magnetic dipole field strength of 10^{15} G (*left panel*) or 10^{16} G (*right panel*)

Components of kilonova emission



Types of kilonova emission

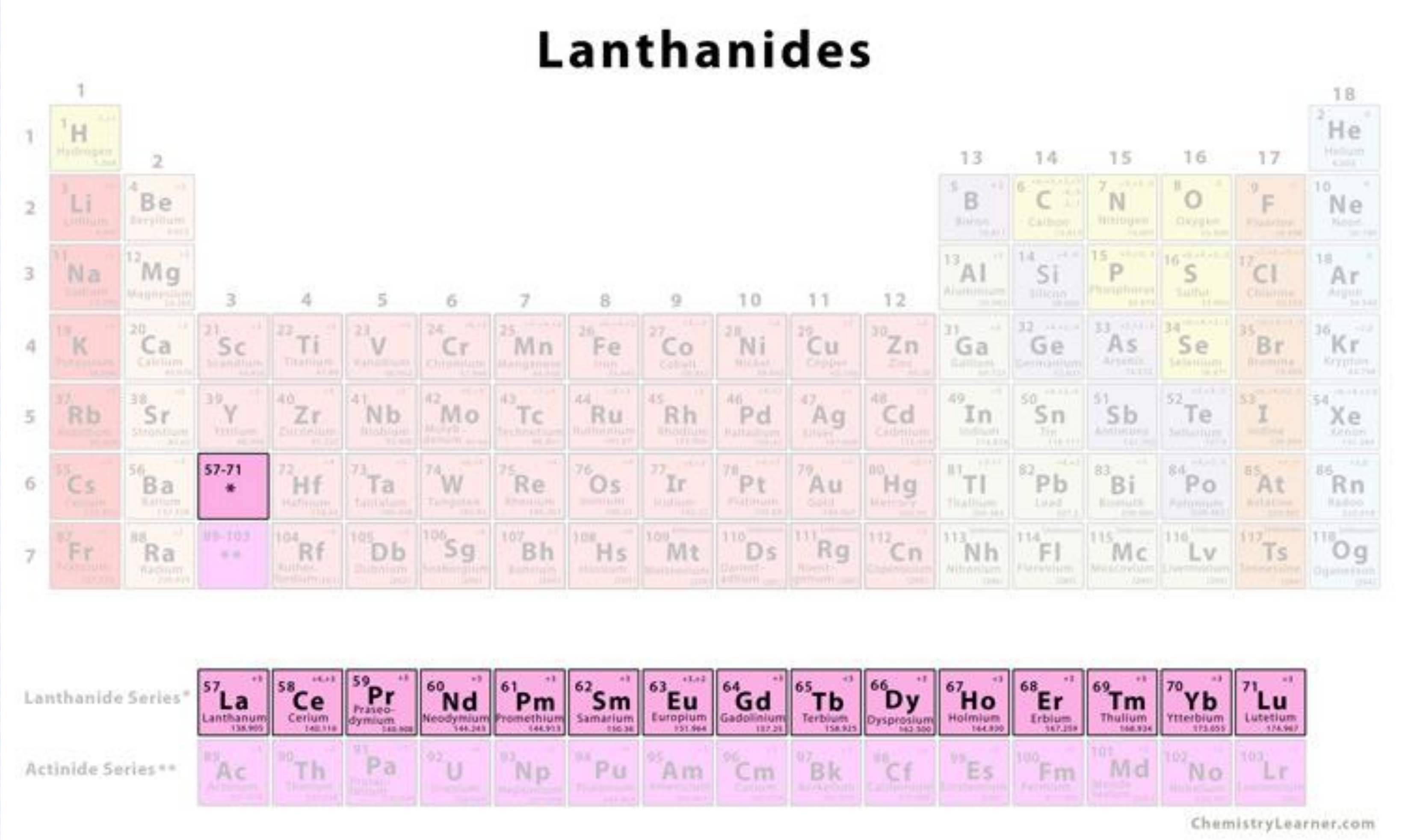
Red

- If highly neutron matter -> heavy r-process nuclei are formed
- Lanthanide bearing matter
- Usually in equatorial plane
- Peak in NIR -> red kilonova
- Timescale of days/week
- Optical emission (R V I bands) suppressed -> problem for follow-up programs!

Blue

- Unbound matter from merger is less neutron rich ($Y_e > 0.30$)
- No Lanthanides group elements
- Lower opacity
- Peak in visual band R,I
- Timescale 1 day
- Usually in polar regions
- Expelled during dynamical ejecta or outflow of accretion disk
- Brighter than Lanthanide rich matter -> best candidate for follow-up!

Lanthanides



Types of kilonova emission

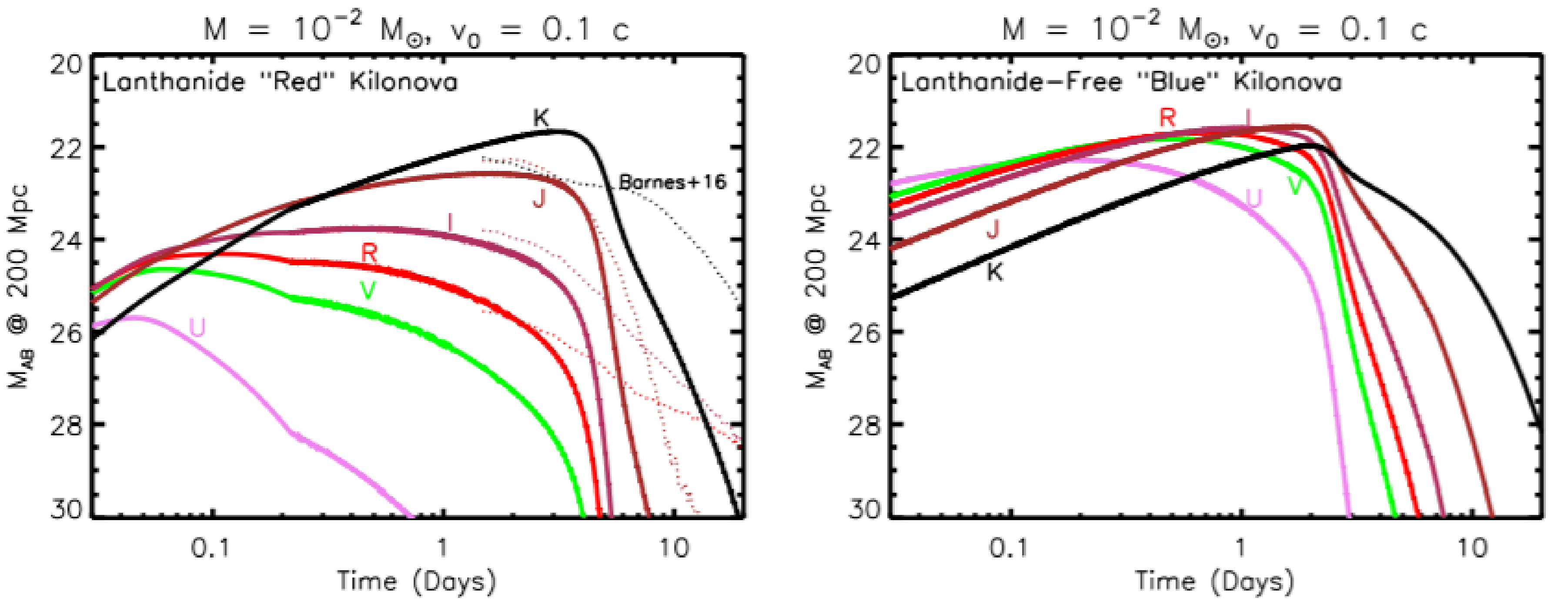
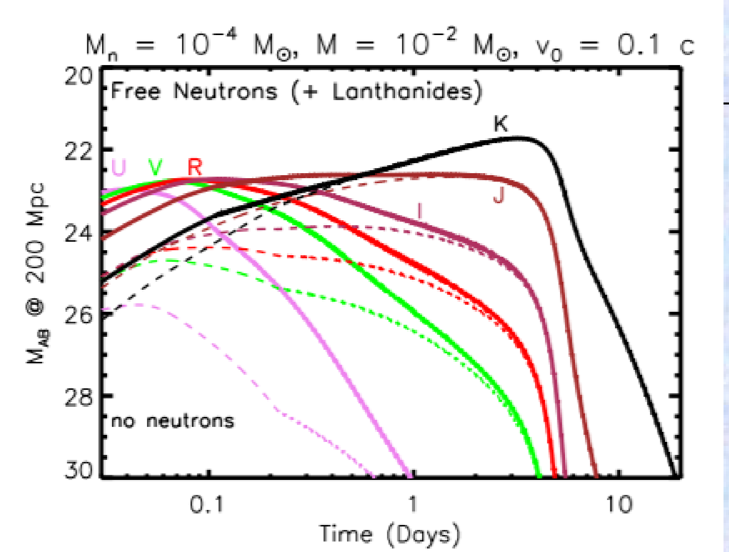
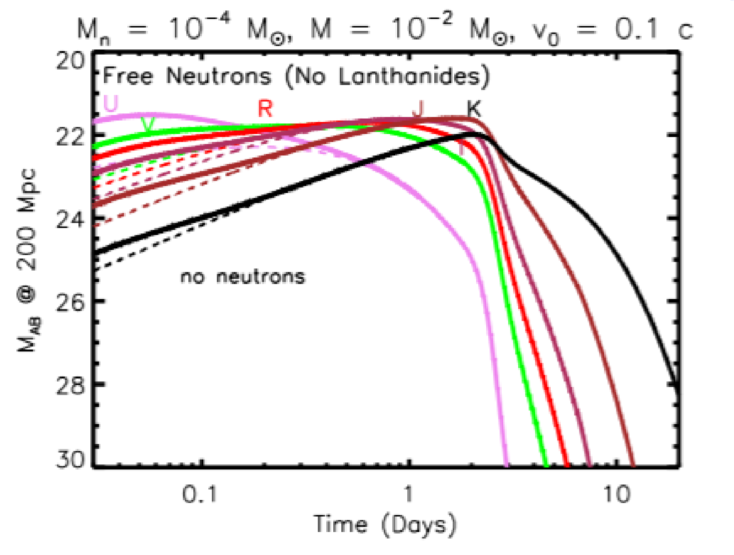


Fig. 5 Kilonova light curves in AB magnitudes for a source at 200 Mpc, calculated using the toy model presented in Sect. 4, assuming a total ejecta mass $M = 10^{-2}$ and minimum velocity $v_0 = 0.1$ c. The *top panel* shows a standard "*red*" kilonova, corresponding to very neutron-rich ejecta with Lanthanide elements, while the *bottom panel* shows a "*blue*" kilonova produced by ejecta without Lanthanides. Shown for comparison in the red kilonova case with dashed lines are models from Barnes et al. (2016) for $v = 0.1$ c and $M = 10^{-2} M_\odot$. Depending on the viewing angle of the observer, both *red* and *blue* emission components may be present in a single merger, if they originate from different locations in the ejecta (Fig. 3)

Types of kilonova emission – free neutrons layer

- Simulations -> small fraction of dynamical ejecta expands very fast
- Neutrons don’t have time to be captured in nuclei
- Neutron heating increases U V R luminosity
- Timescale of hours





Kilonova following short GRBs

- If confirmed that sGRB originate from compact object merger -> constrain kilonova model by opt/NIR follow-ups of nearby bursts with timescale of hours/week

Examples:

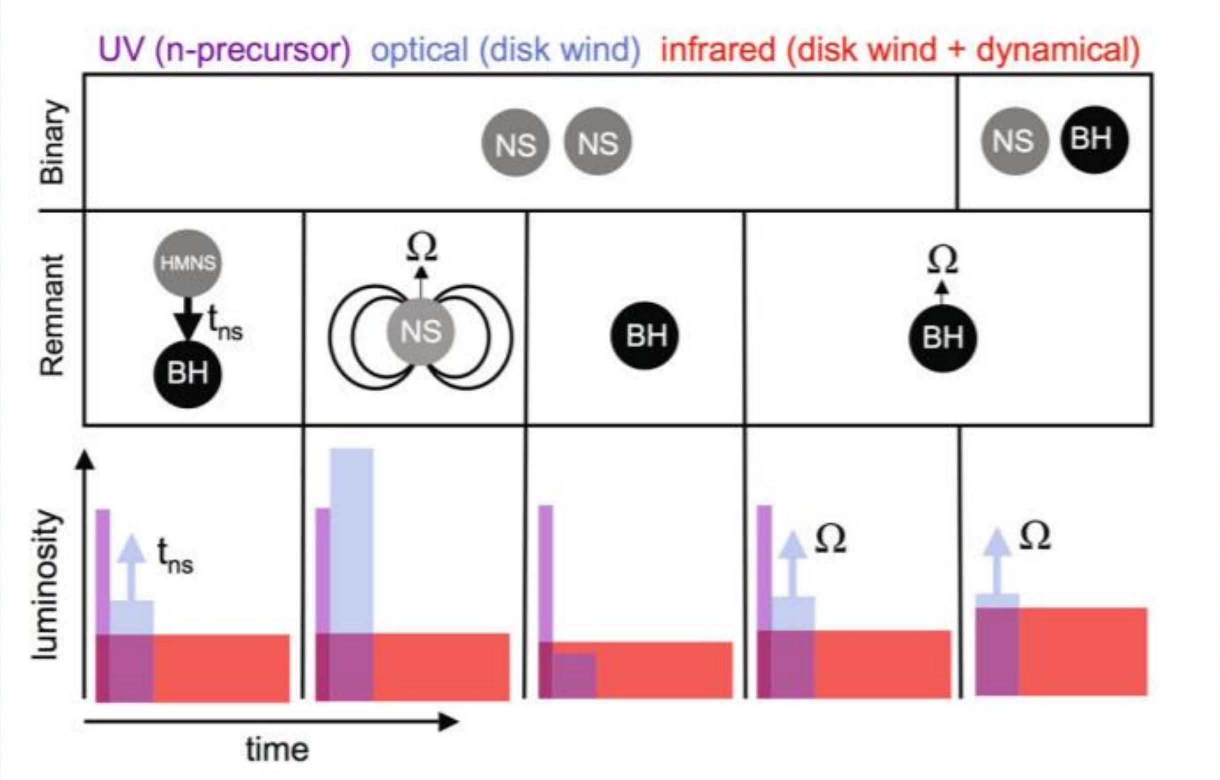
- 2009: GRB 080503 optical peak, timescale of day -> potentially consistent with blue kilonova
- 2015-2016: detected NIR emission in excess in afterglows following GRBs 050709 and 080614 -> possible kilonova emission

Kilonova following short GRBs

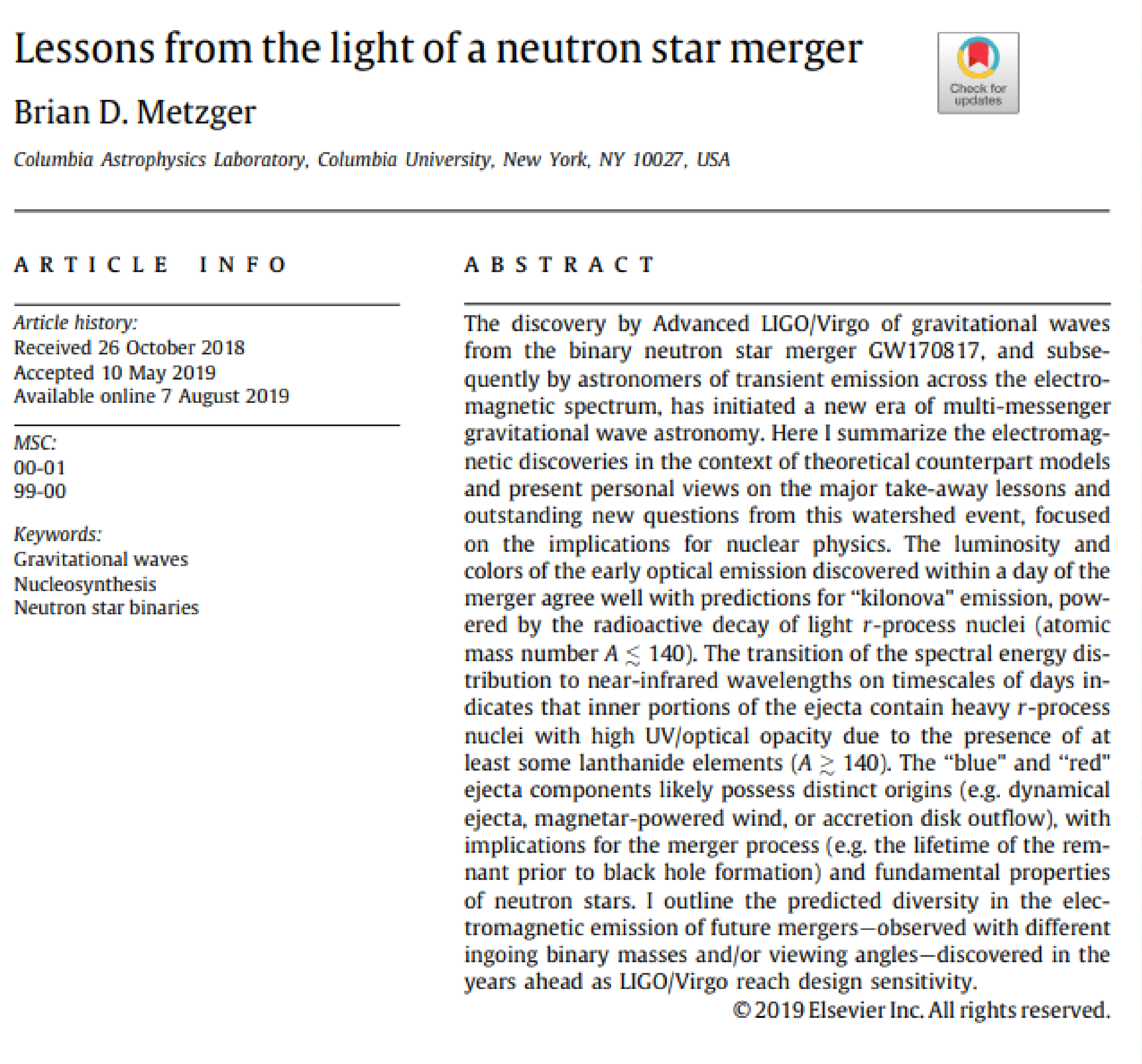
- Host galaxies were not identified
- Unconstrained luminosity
- We can’t identify the kilonova powering process
- Wide field radio surveys -> detect stable magnetars, independent of GRB formation
- Possibility that GRBs are only formed if prompt BH formation
- Ground follow-ups to constrain kilonovae are difficult -> importance of space telescopes (Hubble and in future James Webb, Wide Field Infrared Survey Telescope)

Kilonova following gravitational waves

- Necessity of optical follow-ups of GW trigger events (chirp)
- Useful to constrain kilonova model by observation of NS-NS or BH-NS merger



GW170817



Lessons from the light of a neutron star merger

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ABSTRACT

The discovery by Advanced LIGO/Virgo of gravitational waves from the binary neutron star merger GW170817, and subsequently by astronomers of transient emission across the electromagnetic spectrum, has initiated a new era of multi-messenger gravitational wave astronomy. Here I summarize the electromagnetic discoveries in the context of theoretical counterpart models and present personal views on the major take-away lessons and outstanding new questions from this watershed event, focused on the implications for nuclear physics. The luminosity and colors of the early optical emission discovered within a day of the merger agree well with predictions for "kilonova" emission, powered by the radioactive decay of light *r*-process nuclei (atomic mass number $A \lesssim 140$). The transition of the spectral energy distribution to near-infrared wavelengths on timescales of days indicates that inner portions of the ejecta contain heavy *r*-process nuclei with high UV/optical opacity due to the presence of at least some lanthanide elements ($A \gtrsim 140$). The "blue" and "red" ejecta components likely possess distinct origins (e.g. dynamical ejecta, magnetar-powered wind, or accretion disk outflow), with implications for the merger process (e.g. the lifetime of the remnant prior to black hole formation) and fundamental properties of neutron stars. I outline the predicted diversity in the electromagnetic emission of future mergers—observed with different ingoing binary masses and/or viewing angles—discovered in the years ahead as LIGO/Virgo reach design sensitivity.

GW170817

- First detection of GW chirp of NS merger with subsequent localization to host galaxy -> opportunity to test predictions
- Obs consistent with previous predictions -> most direct evidence that NS merger are source of short GRBs at cosmological distance
- Detection of transient event
- Spectrum of optical counterpart of GW170817 strongly supports kilonova model

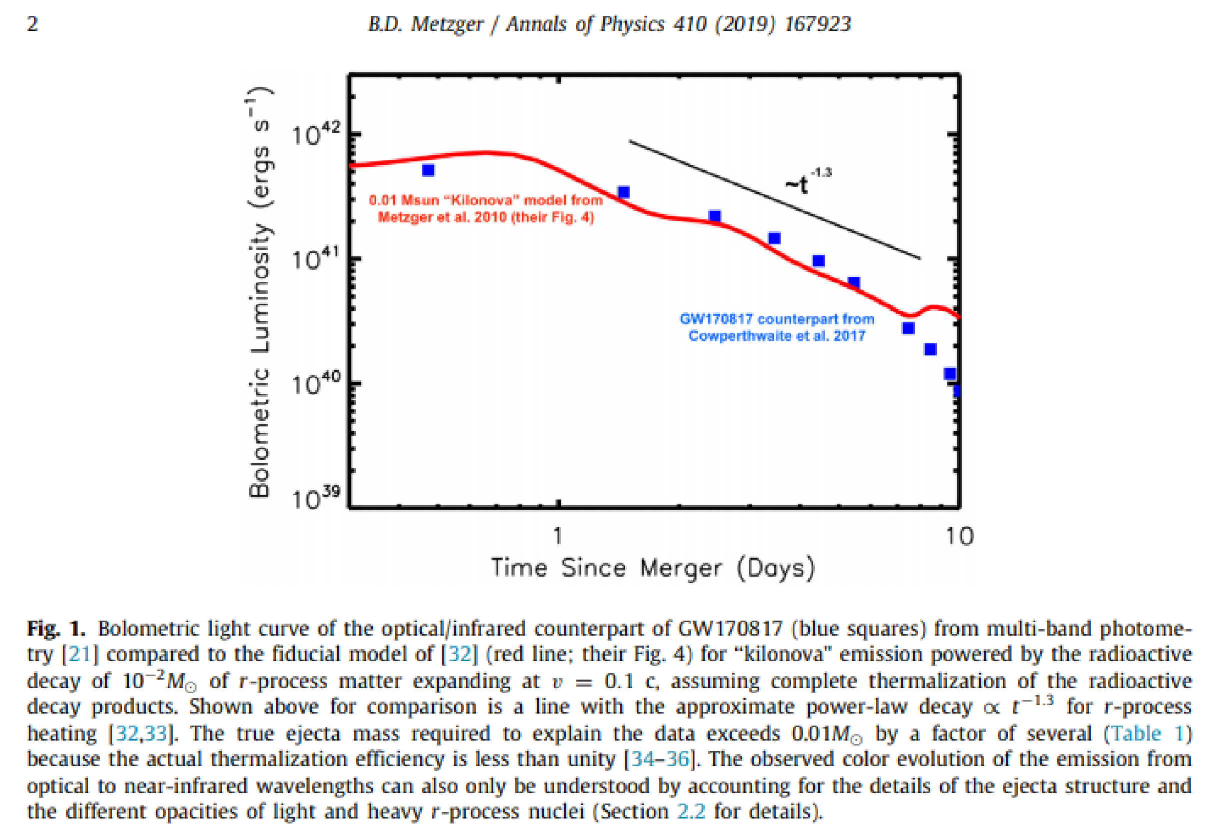

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Fig. 1. Bolometric light curve of the optical/infrared counterpart of GW170817 (blue squares) from multi-band photometry [21] compared to the fiducial model of [32] (red line; their Fig. 4) for "kilonova" emission powered by the radioactive decay of $10^{-2}M_{\odot}$ of *r*-process matter expanding at $v = 0.1$ c, assuming complete thermalization of the radioactive decay products. Shown above for comparison is a line with the approximate power-law decay $\propto t^{-1.3}$ for *r*-process heating [32,33]. The true ejecta mass required to explain the data exceeds $0.01M_{\odot}$ by a factor of several (Table 1) because the actual thermalization efficiency is less than unity [34–36]. The observed color evolution of the emission from optical to near-infrared wavelengths can also only be understood by accounting for the details of the ejecta structure and the different opacities of light and heavy *r*-process nuclei (Section 2.2 for details).

GW170817

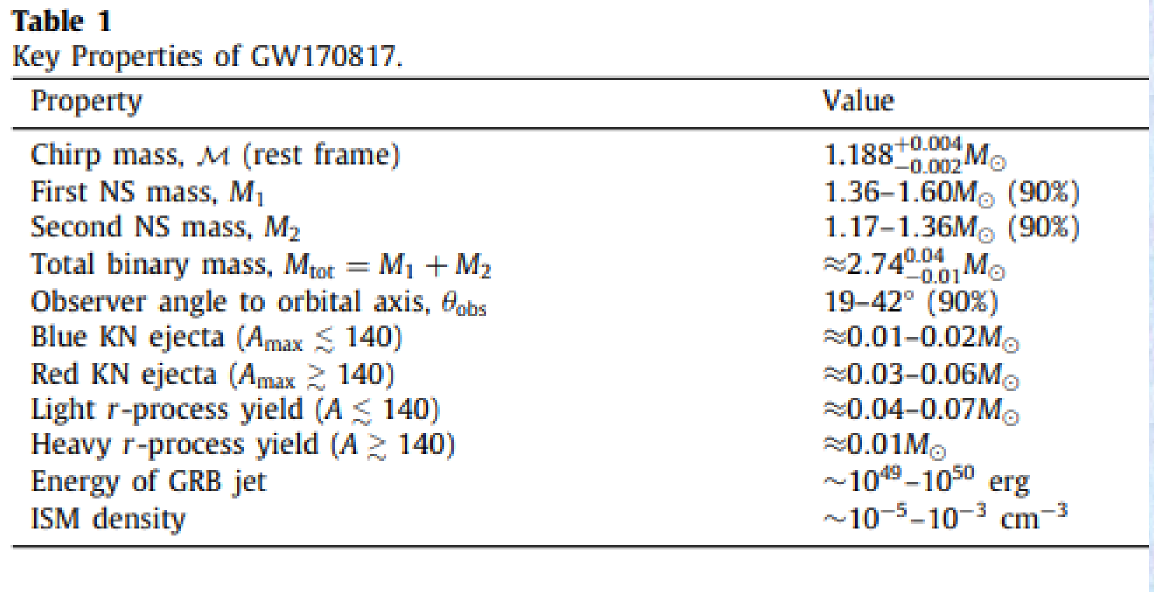
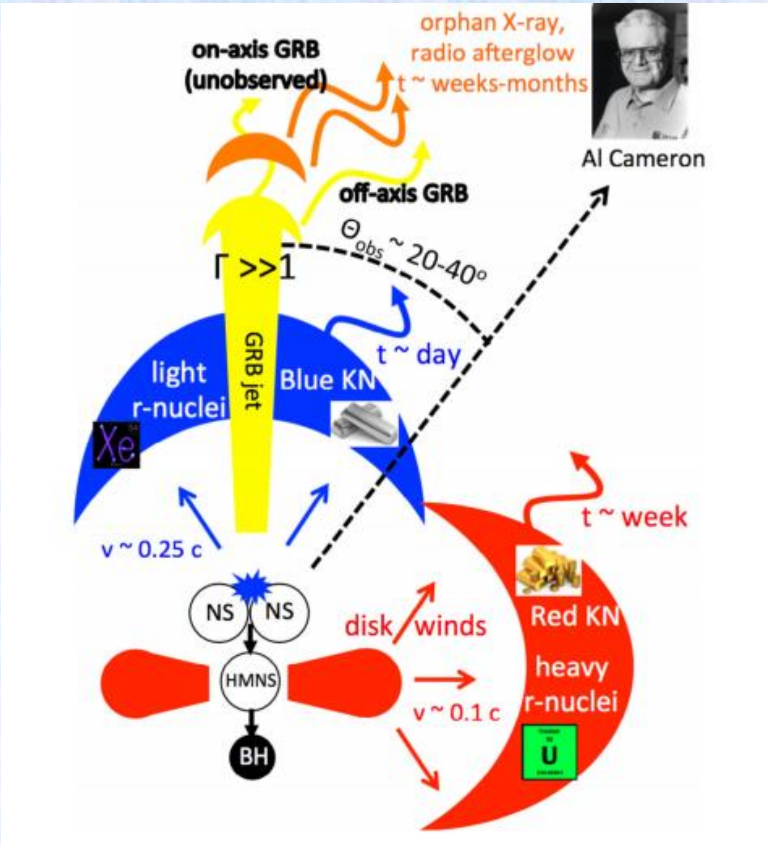


Table 1
Key Properties of GW170817.

Property	Value
Chirp mass, $\mathcal{M}$ (rest frame)	$1.188^{+0.004}_{-0.002} M_\odot$
First NS mass, M_1	$1.36–1.60 M_\odot$ (90%)
Second NS mass, M_2	$1.17–1.36 M_\odot$ (90%)
Total binary mass, $M_{\rm tot} = M_1 + M_2$	$\approx 2.74^{0.04}_{-0.01} M_\odot$
Observer angle to orbital axis, $\theta_{\rm obs}$	19–42° (90%)
Blue KN ejecta ($A_{\rm max} \lesssim 140$)	$\approx 0.01–0.02 M_\odot$
Red KN ejecta ($A_{\rm max} \gtrsim 140$)	$\approx 0.03–0.06 M_\odot$
Light r-process yield ($A \lesssim 140$)	$\approx 0.04–0.07 M_\odot$
Heavy r-process yield ($A \gtrsim 140$)	$\approx 0.01 M_\odot$
Energy of GRB jet	$\sim 10^{49}–10^{50}$ erg
ISM density	$\sim 10^{-5}–10^{-3}$ cm^{-3}



Scenario for EM counterparts of GW170817 as viewed by observer

It's likely that NS merger are important if not dominant sites for r-process nuclei, but not the only one!

GW follow-up: prospects and strategies

- <u>Follow up strategies</u>:
- Optical telescopes have greater sensitivity-> first use this to identify target (days after merger)
- Follow up with spectroscopy or photometry in NIR (weeks after merger) ->IRIS

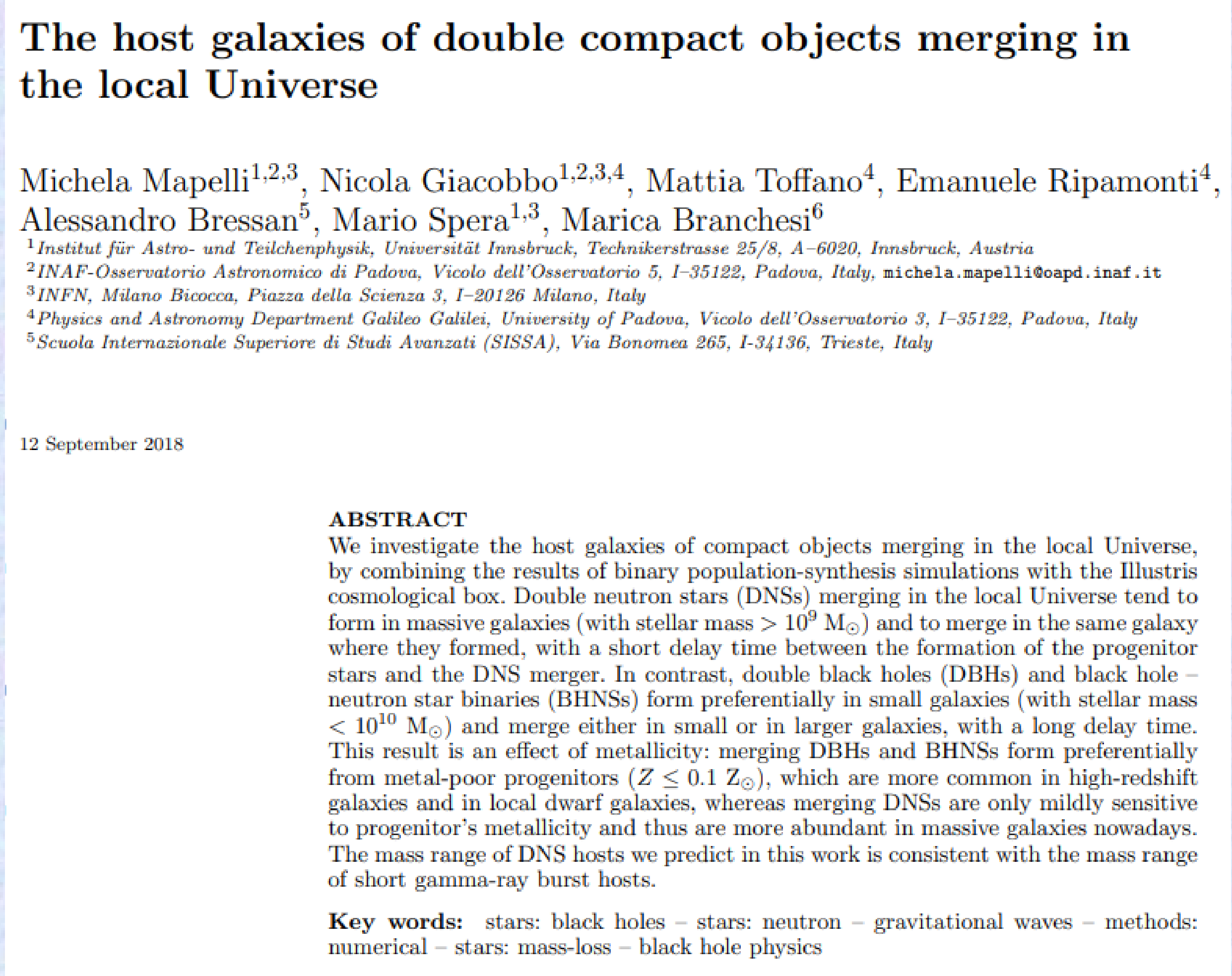
- <u>Ultimate confirmation of kilonova model</u>:
- Spectroscopic measure of absoption lines from r-process elements
- Hard to identify individual lines -> look for strange spectrum
- (Spectrum of EM counterpart of GW170817 consistent with kilonova predictions)

Future prospects

- Combination of data from GRB emission and GW signal (EM emission, inclination of the souce)
- Detailed info about angular structure of luminosity of ejecta
- Comparison of relative strength of blue and red components for different inclination
- Information about total contribution of compact object merger to production of r-process elements

Identification of host galaxy

- Studying the properties of host galaxies from simulations -> astrophysically motivated criteria to localize host galaxy of a GW event even if electromagnetic counterpart not observed
- Metallicity of progenitor stars is a key property for DBHs and BHNSs, while it is much less important for DNSs



The host galaxies of double compact objects merging in the local Universe

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ABSTRACT

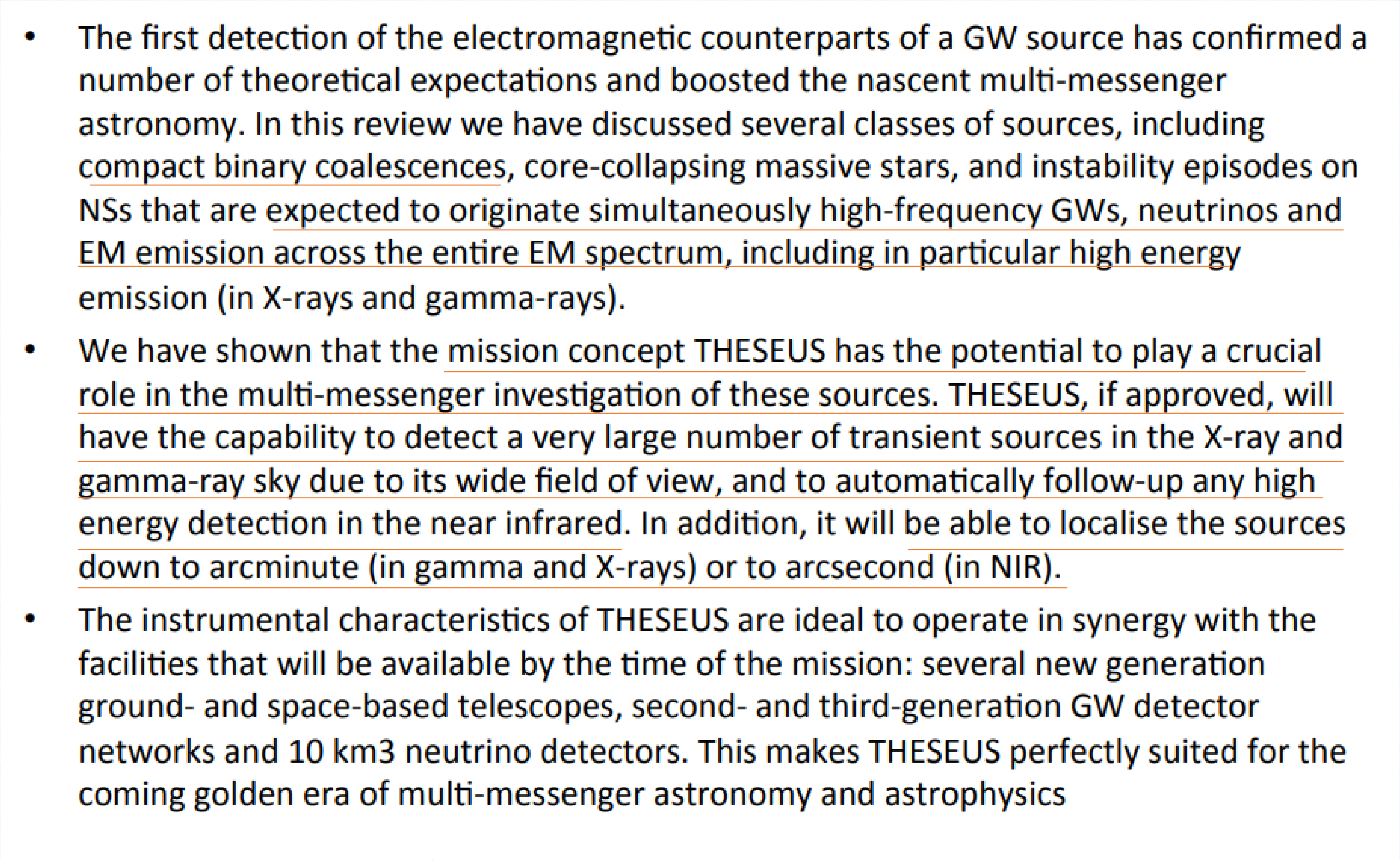
We investigate the host galaxies of compact objects merging in the local Universe, by combining the results of binary population-synthesis simulations with the Illustris cosmological box. Double neutron stars (DNSs) merging in the local Universe tend to form in massive galaxies (with stellar mass $> 10^9$ M$_\odot$) and to merge in the same galaxy where they formed, with a short delay time between the formation of the progenitor stars and the DNS merger. In contrast, double black holes (DBHs) and black hole – neutron star binaries (BHNSs) form preferentially in small galaxies (with stellar mass $< 10^{10}$ M$_\odot$) and merge either in small or in larger galaxies, with a long delay time. This result is an effect of metallicity: merging DBHs and BHNSs form preferentially from metal-poor progenitors ($Z \leq 0.1$ Z$_\odot$), which are more common in high-redshift galaxies and in local dwarf galaxies, whereas merging DNSs are only mildly sensitive to progenitor's metallicity and thus are more abundant in massive galaxies nowadays. The mass range of DNS hosts we predict in this work is consistent with the mass range of short gamma-ray burst hosts.

Key words: stars: black holes – stars: neutron – gravitational waves – methods: numerical – stars: mass-loss – black hole physics

Final thoughs

- Connection between optical transients and r-process nuclei
- Important and open field with rapid evolution
- Largest uncertainties:
- Dependence on wavelength of the ejecta opacity
- Presence of free neutron layer

THESEUS



- The first detection of the electromagnetic counterparts of a GW source has confirmed a number of theoretical expectations and boosted the nascent multi-messenger astronomy. In this review we have discussed several classes of sources, including compact binary coalescences, core-collapsing massive stars, and instability episodes on NSs that are expected to originate simultaneously high-frequency GWs, neutrinos and EM emission across the entire EM spectrum, including in particular high energy emission (in X-rays and gamma-rays).
- We have shown that the mission concept THESEUS has the potential to play a crucial role in the multi-messenger investigation of these sources. THESEUS, if approved, will have the capability to detect a very large number of transient sources in the X-ray and gamma-ray sky due to its wide field of view, and to automatically follow-up any high energy detection in the near infrared. In addition, it will be able to localise the sources down to arcminute (in gamma and X-rays) or to arcsecond (in NIR).
- The instrumental characteristics of THESEUS are ideal to operate in synergy with the facilities that will be available by the time of the mission: several new generation ground- and space-based telescopes, second- and third-generation GW detector networks and 10 km3 neutrino detectors. This makes THESEUS perfectly suited for the coming golden era of multi-messenger astronomy and astrophysics

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