

The multi-component and anisotropic character of kilonovae/macronovae

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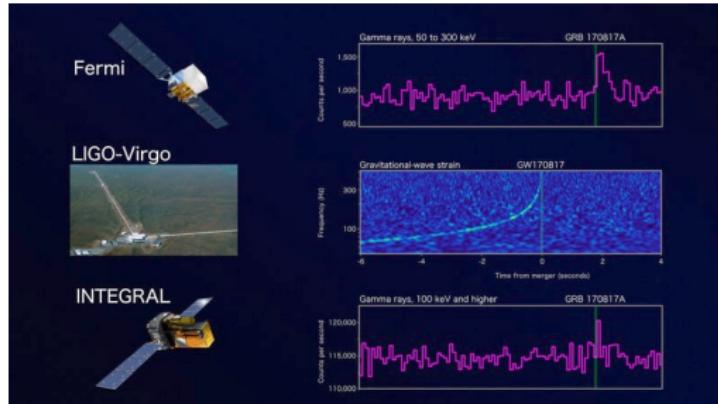
16 July 2018

Talk at “FRIB and the GW170817 kilonova” workshop
FRIB, Michigan State University, East Lansing

in collaboration with A. Arcones, S. Bernuzzi, O. Korobkin, D. Martin, D. Radice, S. Rosswog, F.-K. Thielemann, ...

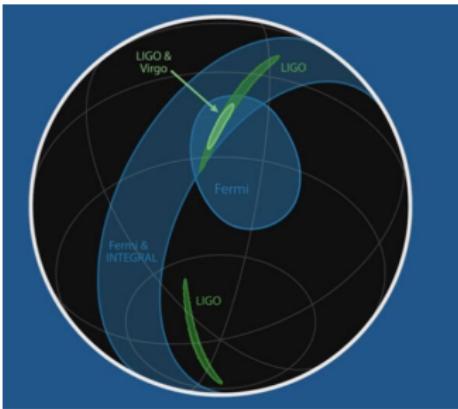


GW170817 and GRB170817a



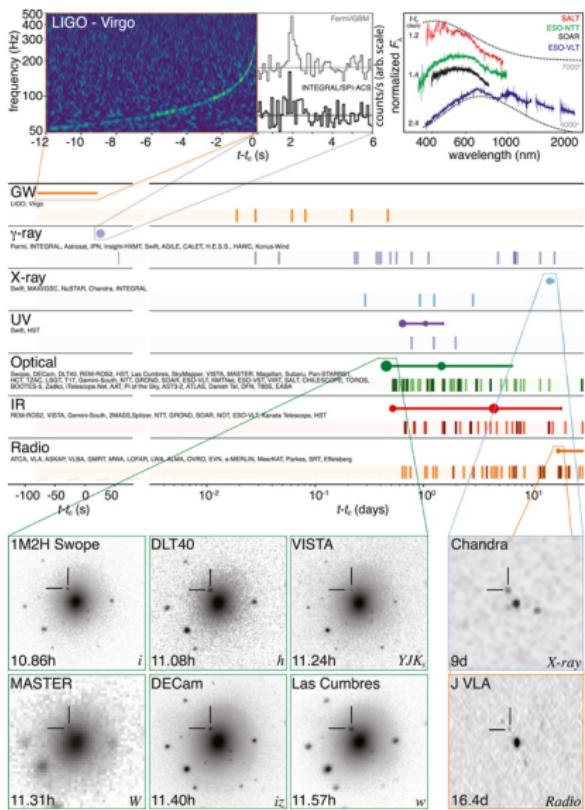
- ▶ On August, 17th 2017, LVC reported GW detection of an event (GW170817) compatible with BNS merger LVC PRL 2017
- ▶ 1.8 seconds after, γ -ray satellites detected signal compatible with GRB signal (short, ~ 1 sec) LVC PRL, ApJL 2017
- ▶ GW detector network + γ -ray detection: good sky localization LVC PRL, ApJL 2017

GW170817 and GRB170817a



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GW170817 and AT2017gfo

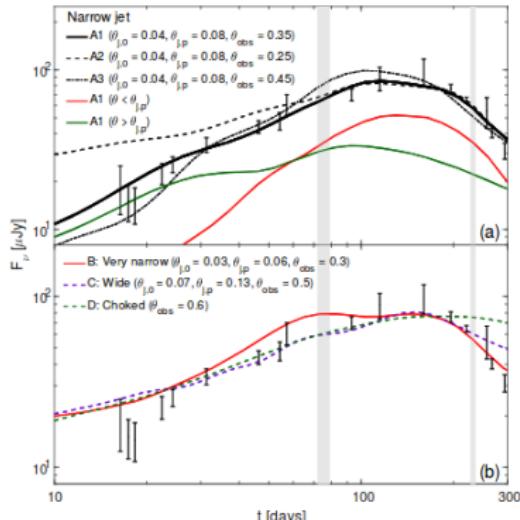
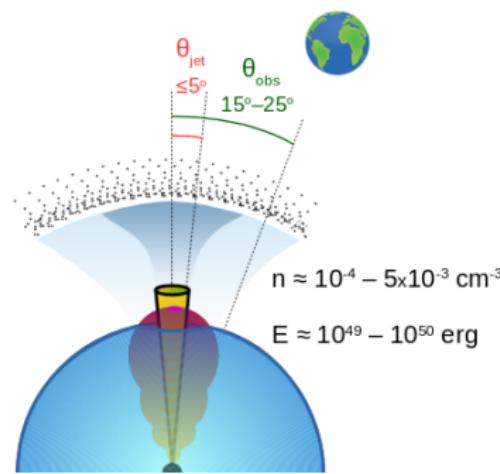


- ▶ EM follow-up campaign
 - ▶ UV/Opt/IR emission detection after 10 hrs in NGC 4993 (40 Mpc)
 - ▶ EM emission compatible with kilonova signal (AT2017gfo)
 - ▶ radio and X-ray emission after 10 days: afterglow of an off-axis GRB?
 - ▶ beginning of the multimessenger astronomy era led by GW observations

LVC ApJL 2017

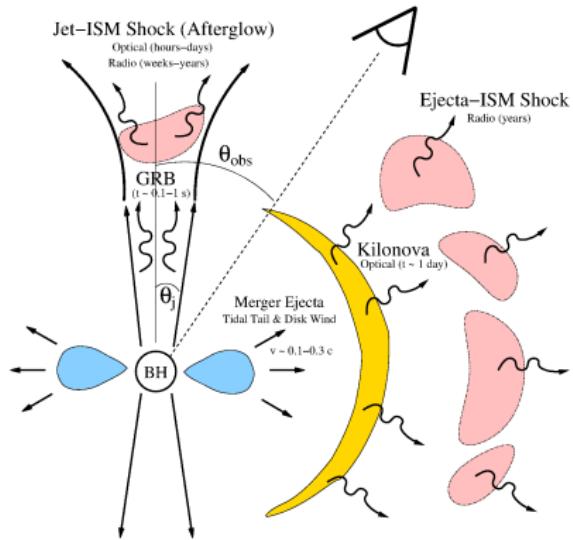
Possible interpretation of the event chain

- ▶ collision and merger of two NSs
- ▶ ejection of matter
- ▶ r -process nucleosynthesis and powering of a kilonova transient
- ▶ production of a relativistic jet and non-trivial jet-ejecta interaction



Kilonova emission

- decay of freshly synthesized r -process element: release of nuclear energy



Berger & Metzger 12

$$\left(\frac{dE}{dt dm} \right)_{r-\text{proc}} \propto t^{-1.3}$$

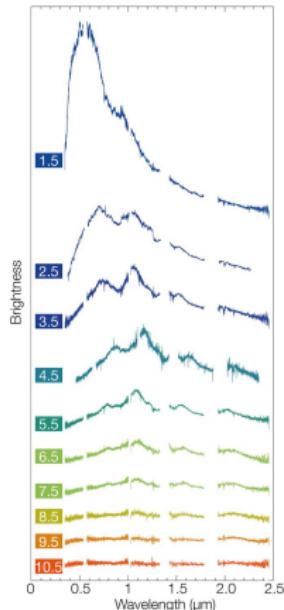
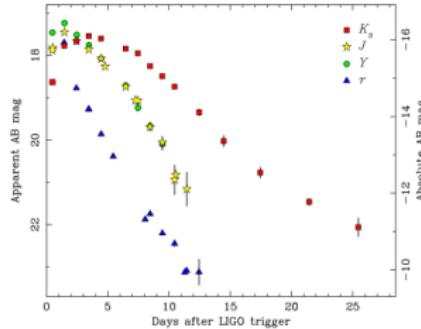
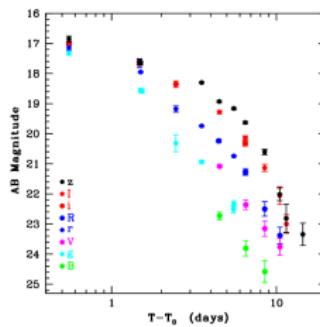
Metzger+10, Korobkin+12

- high energy γ themalize (with a certain efficiency)
Barnes+16
- when $t_{\text{diff}} \sim t_{\text{dyn}}$, thermal photons diffuse and are emitted at photosphere
- crucial parameter: m_{ej} , v_{ej} and κ_{ej}

Properties of AT2017gfo

AT2017gfo, EM counterpart of GW170817

- ▶ light curve properties:
 - ▶ bright, UV/O component, with a peak @ $\sim 1\text{ day}$
 - ▶ rather bright, IR component, with a peak @ $\sim 4\text{ day}$
- ▶ light curve properties depends on the properties of the ejecta (e.g., mass, velocity, composition \rightarrow photon opacity)



Xshooter spectra

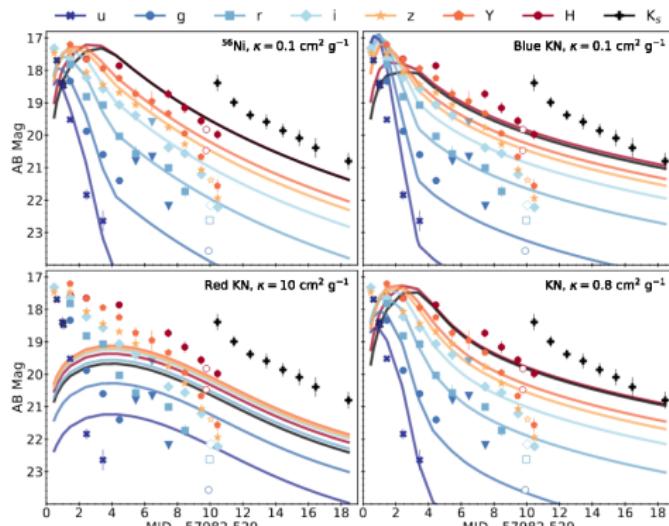
VLT@EOS;

Pian, D'Avanzo+2017

Light curves; Pian, D'Avanzo+2017 (left); Tanvir+2017 (right)

The need for multicomponent models

- ▶ failure of model with a single component in reproducing AT2017gfo key features
- ▶ “component”: spherically symmetric KN model labelled by $(M_{\text{ej}}, v_{\text{ej}}, \kappa)$
- ▶ “model”: different levels of approximations ranging from semi-analytical to radiative transmittt approaches



← Cowperthwaite+ 2017, ApJL

see also, e.g.,

Chornock+17, Drout+17, Nicholl+17, Tanaka+17,

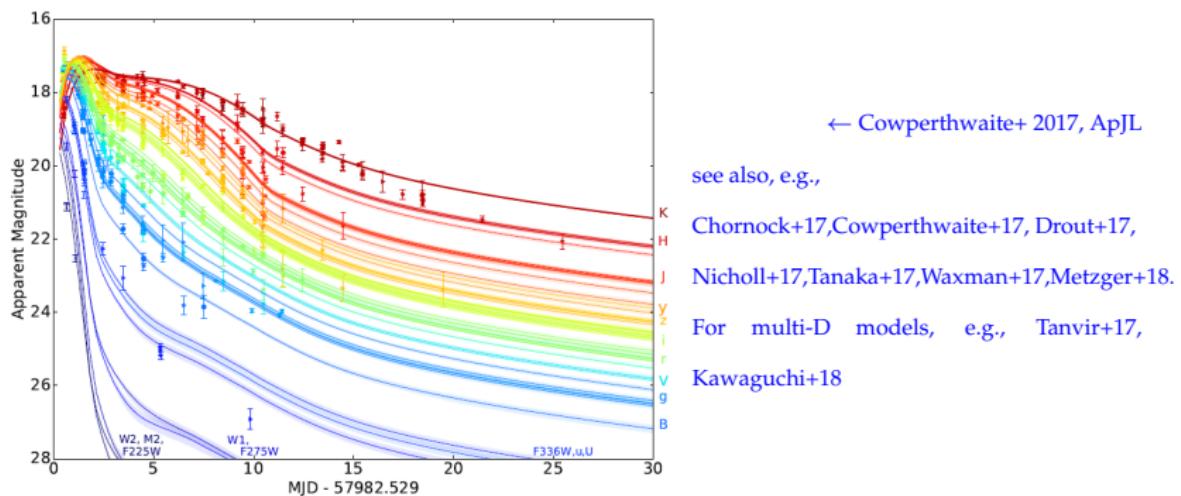
Villar+17, Waxman+17, Metzger+18.

For multi-D models, e.g., Tanvir+17,

Kawaguchi+18

Results from multicomponent models

- ▶ reasonable agreement of multicomponent models in reproducing AT2017gfo key features
- ▶ often, $(M_{\text{ej}}, v_{\text{ej}}, \kappa)$ still correlate in each component
- ▶ usually, multicomponent = combination of spherically symmetric single component models



Let's take a step back...

multicomponent models are valuable approaches, however ...

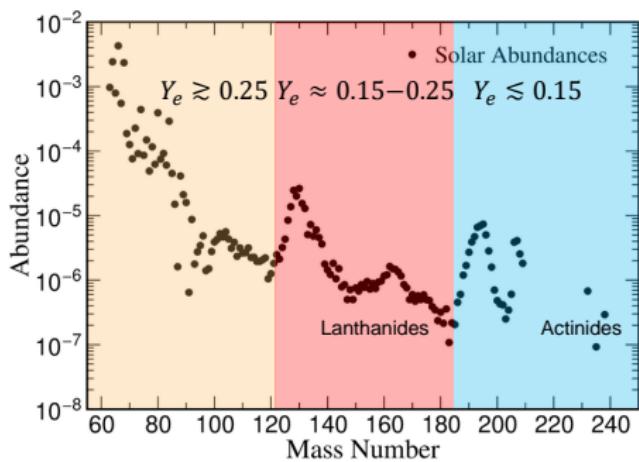
- ▶ they are not conclusive: several models fit the data
e.g. Villar+17, Shibata+17
- ▶ how reasonable is the assumption of correlated ejecta properties?
- ▶ how good is a spherically symmetric description of the ejecta?
- ▶ is it enough to combine independent single component models to get multicomponent models?

in other words,

can we explain the observed light curve properties in terms of the ejecta properties provided by the best current knowledge that we have from BNS modelling?

Matter Ejection Channels

- ▶ why different ejection channels?
 - ▶ different physical origins and timescales
- ▶ which implications from different channels?
 - ▶ different amount of mass and expansion velocity
 - ▶ different Y_e, s, t_{dyn} → composition (*r*-process nucleosynthesis) → photon opacity, κ_γ
- ▶ low entropy ejecta: Y_e leading parameter



- ▶ no lanthanides: low opacity ($\kappa \lesssim 1 \text{ cm}^2/\text{g}$)
- ▶ presence of lanthanides: increased opacity ($\kappa \sim 10 \text{ cm}^2/\text{g}$)

Courtesy of G. Martinez-Pinedo

Basic ν features in BNS mergers

Role of ν 's

- ▶ exchange energy and momentum with matter
- ▶ set n -to- p ratio (i.e. Y_e)
 $p + e^- \rightarrow n + \nu_e$ (EC)
 $n + e^+ \rightarrow p + \bar{\nu}_e$ (PC)
- ▶ influence nucleosynthesis

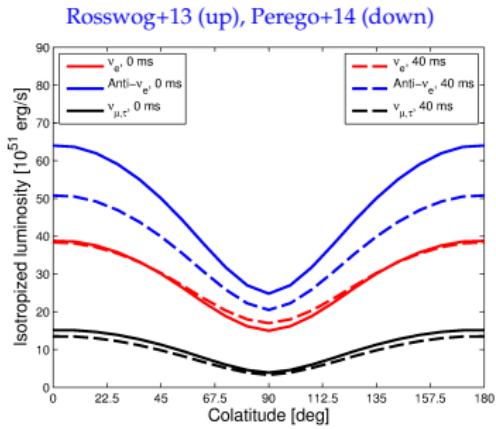
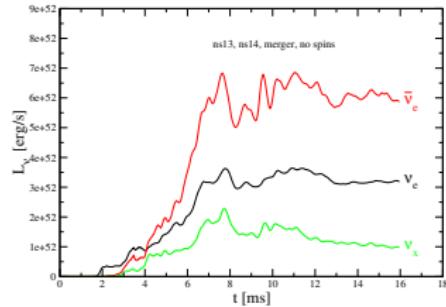
ν luminosities

- ▶ ν gas formation and diffusion
- ▶ n -richness $\rightarrow L_{\bar{\nu}_e} \gtrsim L_{\nu_e}$

anisotropic ν emission, due to the presence of the disk:

- ▶ $F_{\nu, \text{equator}} \approx (1/3)F_{\nu, \text{pole}}$

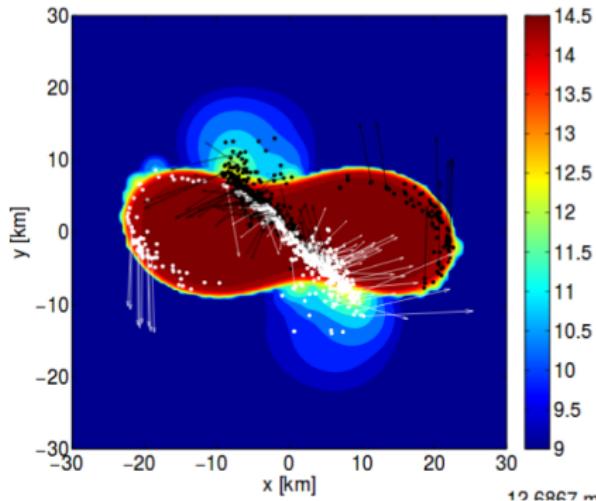
Dessart+09; Perego+14, Just+15, ...



Dynamical ejecta from BNS merger

- ▶ $t_{\text{ej,dyn}} \sim \text{few ms}$
- ▶ $v_{\text{ej,dyn}} \sim \text{few } 0.2 - 0.3 c$
- ▶ $M_{\text{ej,dyn}} \sim 10^{-4} - 10^{-2} M_{\odot}$, depending on q and EOS

Korobkin+12, Hotokezaka+13, Bauswein+13, Wanajo+14, Sekiguchi+15, Radice+16, Bovard+17, ...

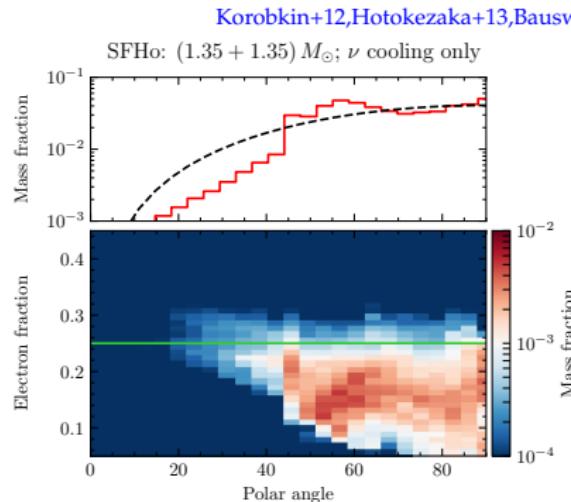


Bauswein+13

- ▶ tidal component
 - ▶ equatorial
 - ▶ low Y_e
- ▶ shocked component
 - ▶ equatorial & polar
 - ▶ higher entropy
 - ▶ larger Y_e at high latitudes

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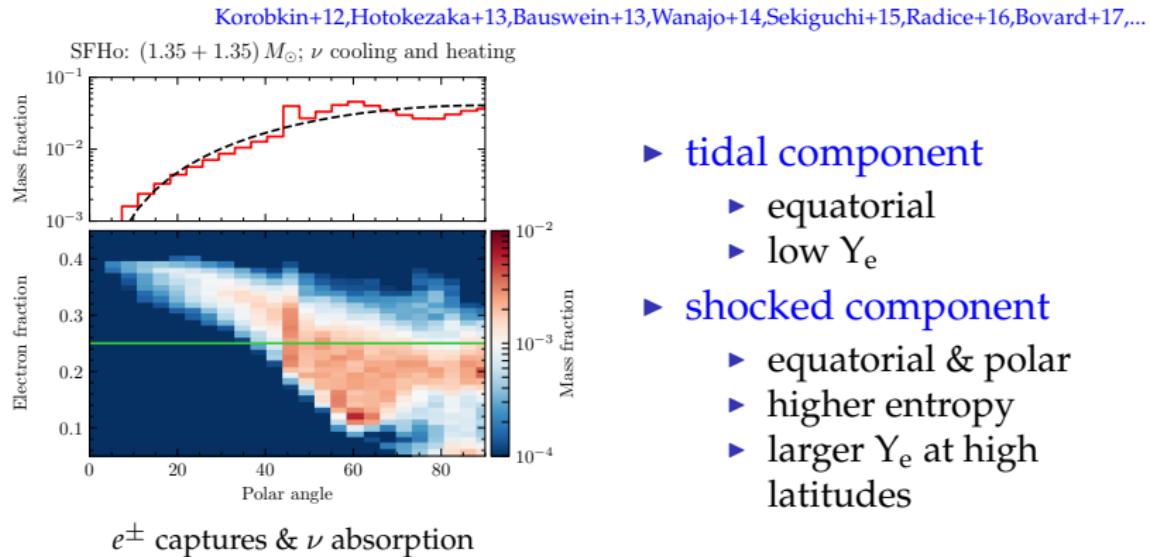
e^{\pm} captures but no ν absorption

Radice+ in prep; Perego, Radice, Bernuzzi ApJL 17

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Radice+ in prep.; Perego,Radice,Bernuzzi ApJL 17

How robust are dynamic ejecta properties?

Martin, Perego, Kastaun, Arcones CQG 2018; cf. Goriely+2015

- shock heated dynamic ejecta from GR simulation Kastaun+17
- postprocessing of tracer particles to include ν 's feedback

$$\begin{aligned}\frac{dY_e}{dt} &= (\lambda_{\nu_e} + \lambda_{e^+}) Y_n - (\lambda_{\bar{\nu}_e} + \lambda_{e^-}) Y_p \\ \frac{ds}{dt} &= \left(\frac{ds}{dt} \right)_{\text{hydro}} + \frac{1}{T} \left[\left(\frac{dQ}{dt} \right)_\nu - (\mu_e - \mu_n + \mu_p) \left(\frac{dY_e}{dt} \right)_\nu \right]\end{aligned}$$

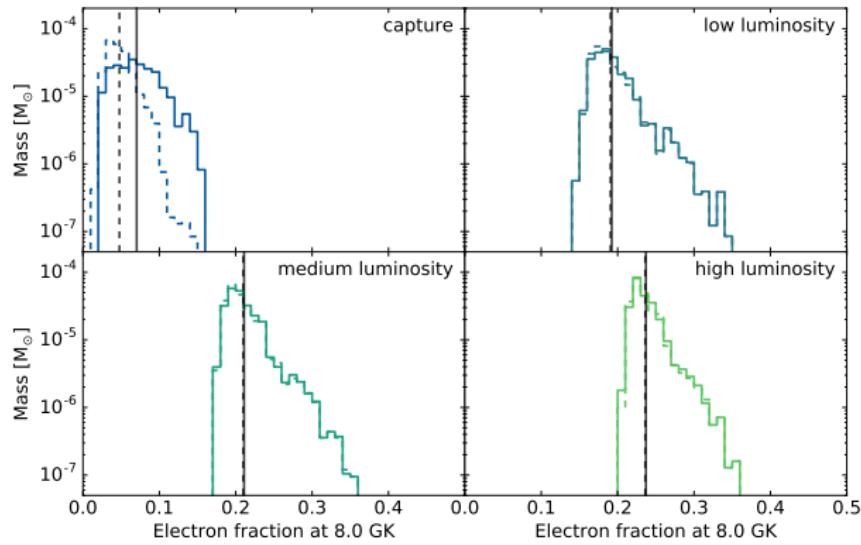
- optically thin conditions ($\rho < 10^{12} \text{ g/cm}^3$)
- consistent ν emission, λ_{e^\pm} Bruenn 1985 + Horowitz 2002
- parametrized ν flux for ν absorption, $F_\nu \propto L_\nu / (\langle E_\nu \rangle R^2)$

Name	$L_{\nu_e, \text{max}}$ [10^{53} erg/s]	$L_{\bar{\nu}_e, \text{max}}$ [10^{53} erg/s]	$E_{\nu_e, \text{max}}$ [MeV]	$E_{\bar{\nu}_e, \text{max}}$ [MeV]
capture	0.0	0.0	0.0	0.0
low	0.86	1.0	11.5	16.2
medium	1.0	1.5	12.0	16.3
high	1.2	2.4	13.0	16.7

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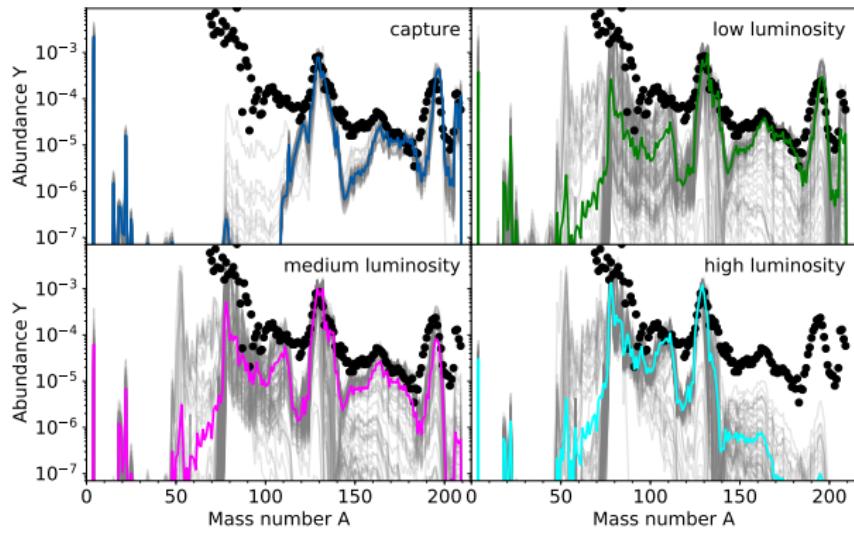
Martin+ 18, CQG

[increasing ν flux: higher total luminosity or anisotropic emission:
smaller along the equator, larger along the poles]

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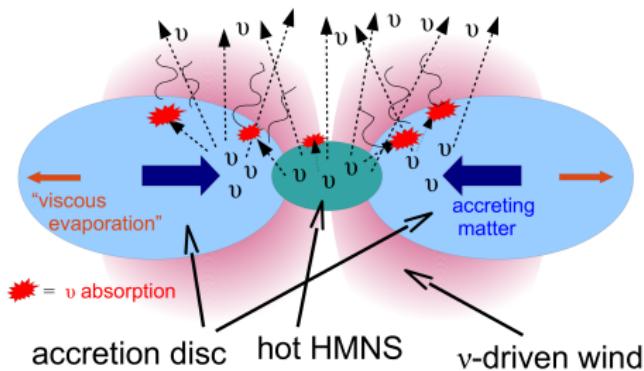


Martin+ 18, CQG

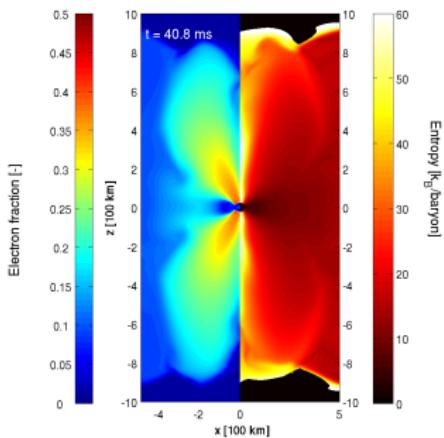
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Wind ejecta from BNS merger

- ▶ due to neutrino absorption or magnetic processes inside the remnant
- ▶ enhanced by the presence of central MNS
- ▶ $t_{\text{ej,wind}} \sim \text{few 10's ms}$ and $v_{\text{ej,wind}} \lesssim 0.1 c$
- ▶ $M_{\text{ej,wind}} \lesssim 0.05 M_{\text{disk}}$
- ▶ polar character, with low opacity ($\lesssim 1 \text{ cm}^2 \text{g}^{-1}$)



Perego,Rosswog,Cabezon+14, MNRAS

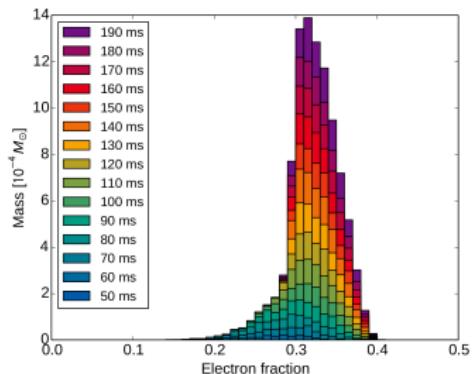
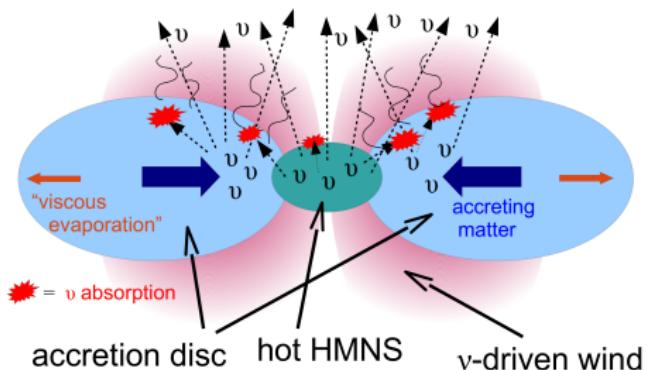


see also Dessart+2009, Metzger & Fernandez 14, Fujibayashi+18

Martin,AP,Arcones+ 15, ApJ

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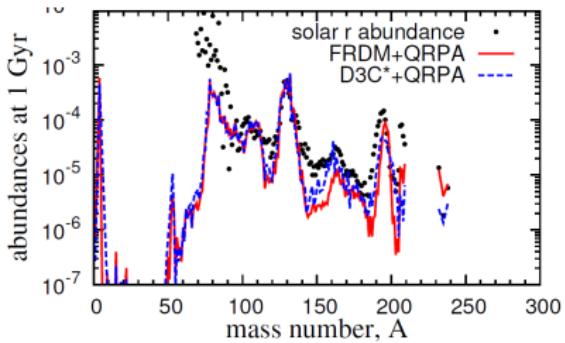
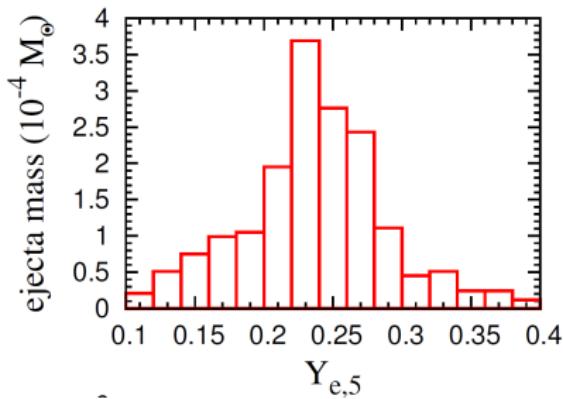


Perego,Rosswog,Cabezon+14, MNRAS; Martin,AP,Arcones+ 15, ApJ

see also Dessart+2009, Metzger & Fernandez 14, Fujibayashi+18

Viscous ejecta from BNS merger

- ▶ due to viscosity and nuclear recombination in the disk
- ▶ $t_{\text{ej,sec}} \sim \text{few 100's ms}$ and $v_{\text{ej,sec}} \lesssim 0.1c$
- ▶ broad distribution of n-rich matter ($0.1 \lesssim Y_e \lesssim 0.4$)
- ▶ $M_{\text{ej,sec}} \sim (0.2 - 0.4) M_{\text{disk}}$
- ▶ all solid angle ejection, intermediate opacity $1 - 10 \text{ cm}^2 \text{g}^{-1}$

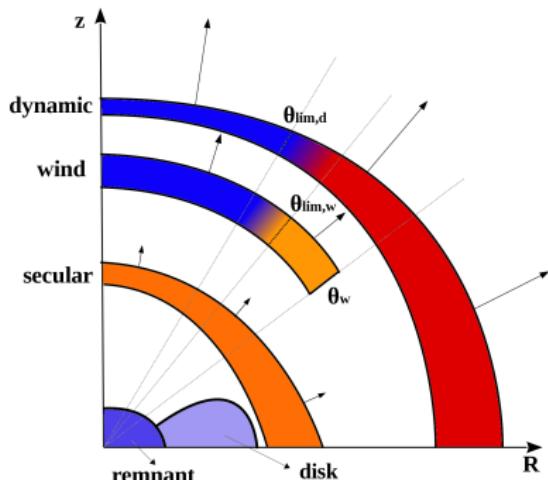


Figures from Wu+16, see e.g. Metzger+2010, Fernandez & Metzger 2013, Just+15, Lippuner+17, Siegel & Metzger 17, Fujibayashi+18, ...

Multi-Component Anisotropic Kilonova Model

- ▶ kilonova model that includes our present knowledge about ejecta
- ▶ different ejection channels → multi-component
- ▶ explicit dependency on polar angle → anisotropic
 - ▶ multi-angle (polar angle discretization)
 - ▶ explicit dependence on observer viewing angle

Perego, Radice, Bernuzzi 17, ApJL



- ▶ $M_{\text{ej}}(\theta), v_{\text{ej}}(\theta), \kappa_{\text{ej}}(\theta)$
- ▶ 1D models along each ray
- ▶ extension of previous semi-analytical models

Korobkin+2014, Martin+2015

Kilonova model I

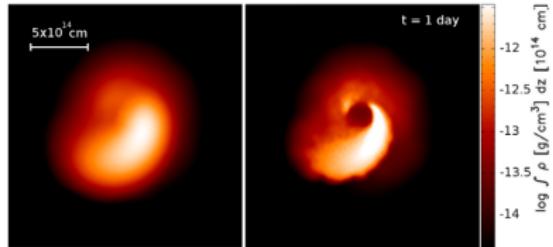
see Grossman+ 14, Martin+ 15

- ▶ homologous expansion (from long term simulations)

$$M_{\text{ej}} = \int_0^{\pi} \left(\int_0^{v_{\max}} \xi(v, \theta) dv \right) d\theta$$
$$\xi(v, \theta) = \xi_0 \left(1 - \left(\frac{v}{v_{\max}(\theta)} \right)^2 \right)^3$$

- ▶ composition-dependent opacity: effective gray opacity inspired by detailed atomic transition calculations

e.g., Roberts+2012, Tanaka+13, Kasen+13, Wollaeger+17



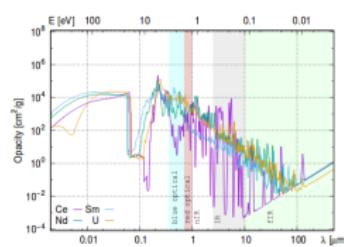
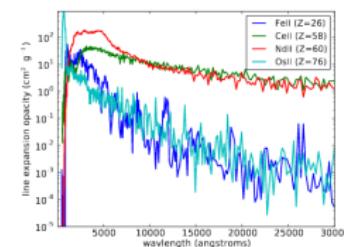
Rosswog+14

Albino Perego

Kasen+13, Wollaeger+17

Talk at FRIB, MSU, East Lansing, 16/06/2018

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Kilonova model II

see Grossman+ 14, Martin+ 15

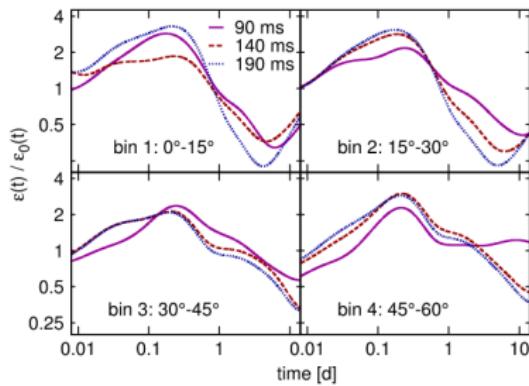
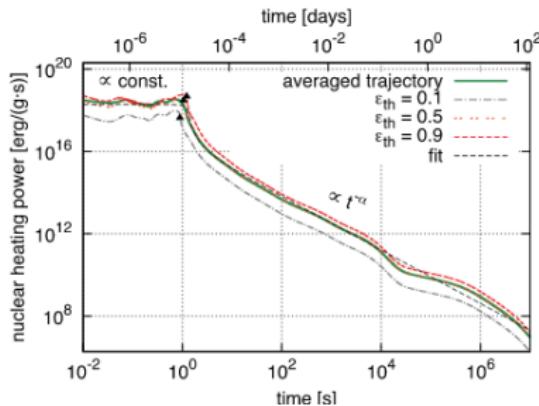
- ▶ nuclear heat

$$Q_{\text{heat}} \approx Q_0(t, Y_e) (t_{\text{days}})^{-1.3}$$

- ▶ impact of weak r-process nucleosynthesis:
shorter β decays lifetimes
- ▶ time-dependent thermalization fraction
- ▶ irradiation effect: inner photospheres irradiate outer matter & outer photosphere determine emission properties

Barnes+2016

cfr. Kawaguchi+18



Korobkin+ 12; see also Metzger+ 10

Martin+ 15

Model parameter exploration

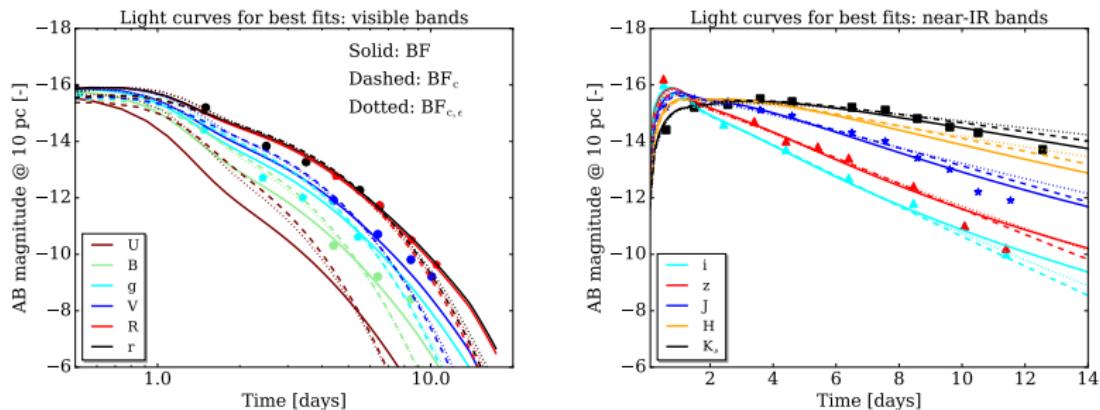
Main parameter ranges	
$M_{\text{disk}} [M_{\odot}]$	{0.01; 0.08; 0.1; 0.12; 0.15; 0.2}
$m_{\text{ej,dyn}} [10^{-2}M_{\odot}]$	{0.05; 0.5; 1.0; 2.0; 5.0}
ξ_{wind}	{0.001; 0.05; 0.1; 0.15; 0.2}
ξ_{sec}	{0.001; 0.1; 0.2; 0.3; 0.4}
$v_{\text{rms,dyn}} [c]$	{0.1; 0.13; 0.17; 0.2; 0.23}
$v_{\text{rms,wind}} [c]$	{0.033; 0.05; 0.067}
$v_{\text{rms,sec}} [c]$	{0.017; 0.027; 0.033; 0.04}
$\kappa_{\text{dyn}} [\text{cm g}^{-1}]$	{(0.5, 30); (1, 30)}
$\kappa_{\text{wind}} [\text{cm g}^{-1}]$	{(0.5, 5); (0.1, 1)}
$\kappa_{\text{sec}} [\text{cm g}^{-1}]$	{1; 5; 10; 30}
θ_{obs}	$n \pi / 36$ for $n = 0 \dots 11$
$\epsilon_o [10^{18} \text{erg g}^{-1} \text{s}^{-1}]$	{2; 6; 12; 16; 20}

Our procedure:

- ▶ fix a parameter set
- ▶ produce a model (lightcurves in different filters)
- ▶ compare with observations

Pian, D'Avanzo +17, Tanvir+17

Best-fit models



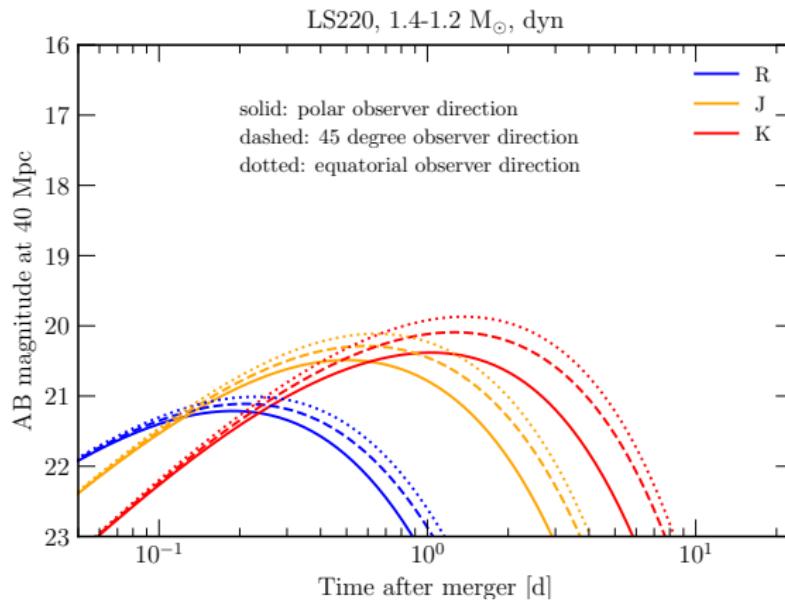
- ▶ multi-components (2 or 3) models reproduce major observed features of AT2017gfo
- ▶ fast ($v \sim 0.3c$), low opacity ($\kappa \sim 1 \text{ cm}^2 \text{g}^{-1}$) material essential
- ▶ global properties for AT2017gfo
 - ▶ anisotropic and multicomponent ejecta
 - ▶ $M_{\text{ej,tot}} \sim 0.05M_{\odot}$, $\theta_{\text{obs}} \approx 30^\circ$, $M_{\text{disk}} \sim 0.1M_{\odot}$
 - ▶ low-opacity material at high latitude: neutrinos @ work

Builting up the light curves

how do different components enter the light curves?

- ▶ $M_{\text{ej,dyn}} \approx 1.9 \times 10^{-3} M_{\odot}$
- ▶ NR distributions as input for dynamical ejecta

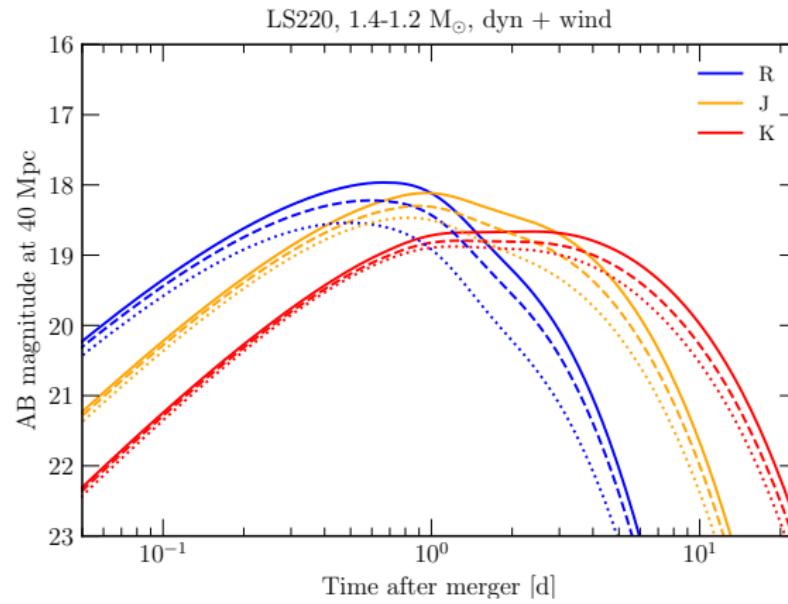
Radice+, in prep



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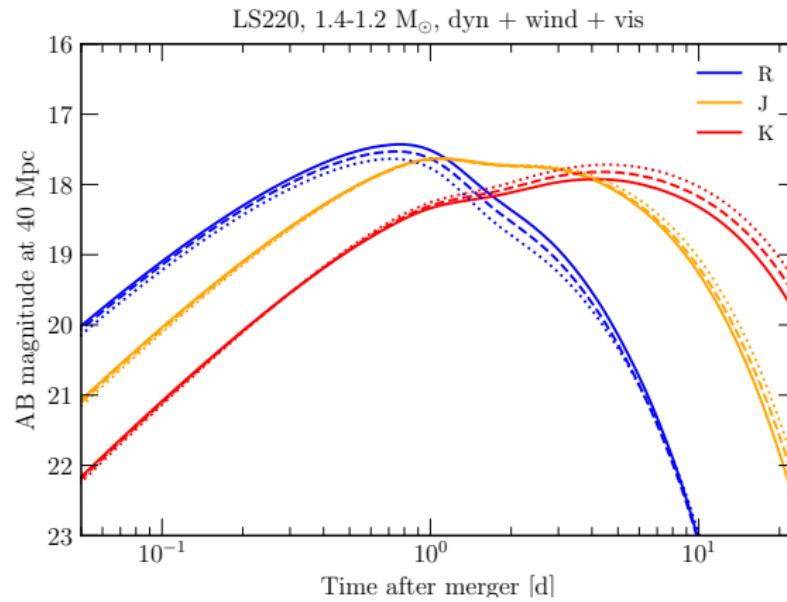
- ▶ $M_{\text{disk}} \approx 0.23M_{\odot}$
- ▶ $M_{\text{ej,wind}} \approx 0.03 \times M_{\text{disk}}, \kappa = 1 \text{ cm}^2/\text{g}$



Builting up the light curves

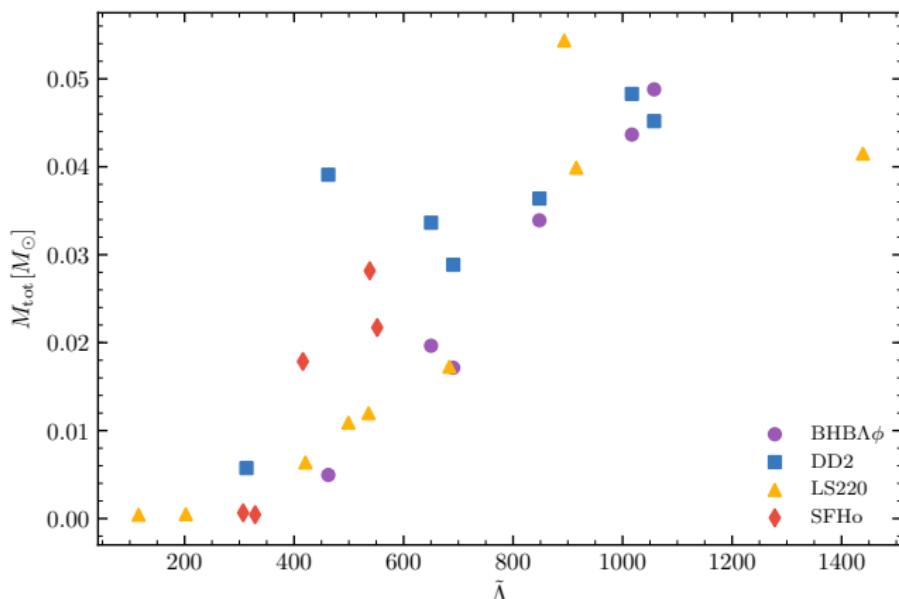
how do different components enter the light curves?

- ▶ $M_{\text{disk}} \approx 0.23M_{\odot}$
- ▶ $M_{\text{ej,vis}} \approx 0.20 \times M_{\text{disk}}, \kappa = 5 \text{ cm}^2/\text{g}$



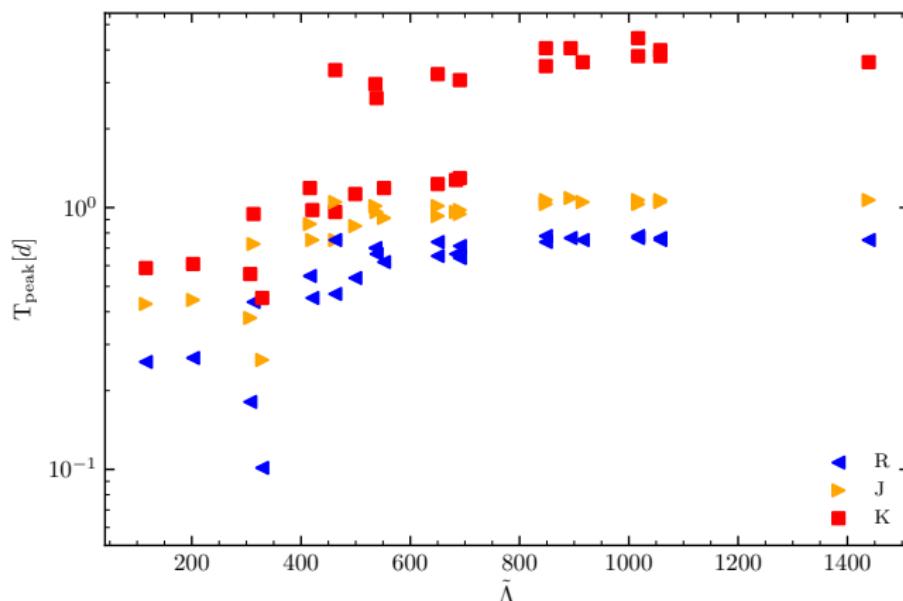
Intrinsic variability: ejected mass

- ▶ large sample of NR BNS simulations to compute $M_{\text{ej,dyn}}$ and M_{disk}
- ▶ $M_{\text{ej}} \sim M_{\text{ej,dyn}} + 0.03(0.005) \times M_{\text{disk}} + 0.2 \times M_{\text{disk}}$



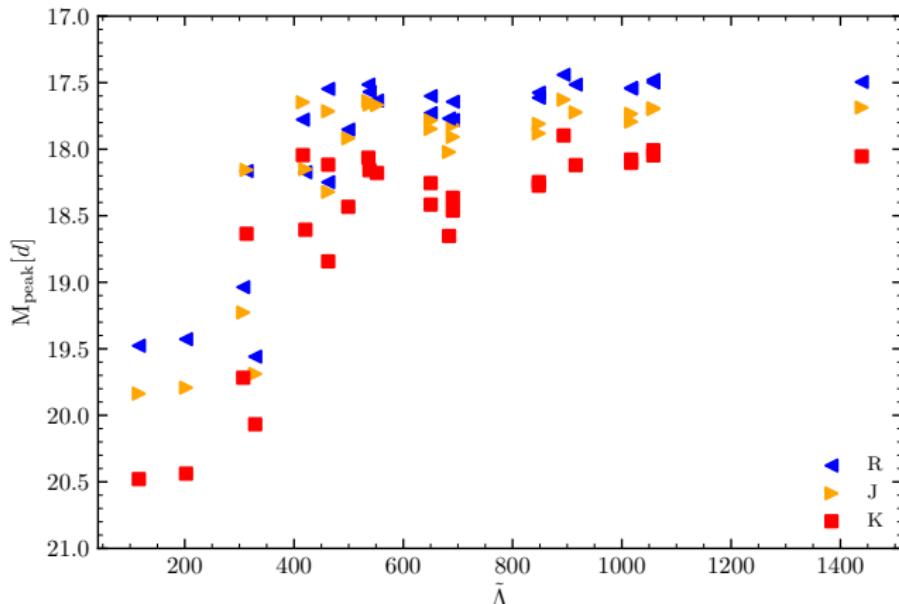
Intrinsic variability: peak time

- ▶ large sample of NR BNS simulations to compute $M_{\text{ej,dyn}}$, dynamical ejecta distributions, and M_{disk}
- ▶ time fo the peak for three different bands



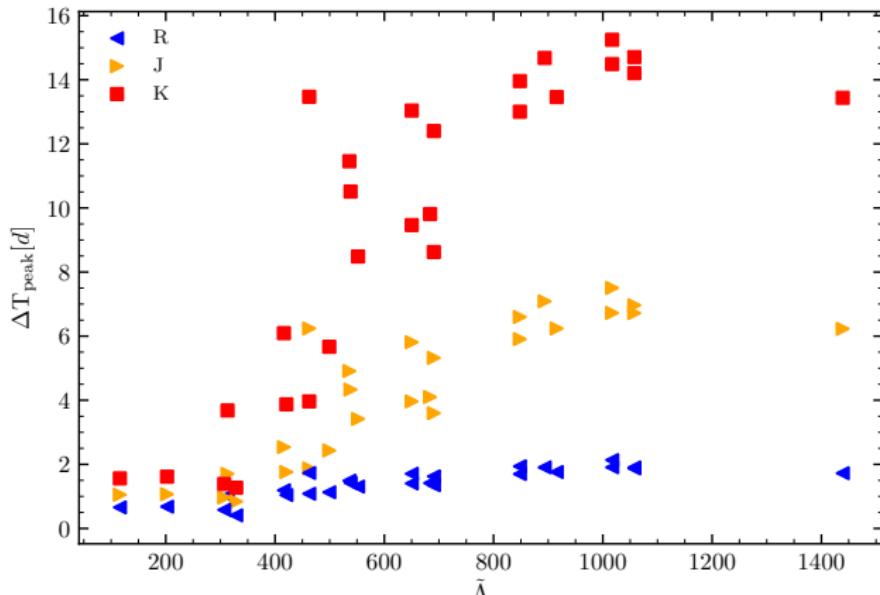
Intrinsic variability: peak magnitude

- ▶ large sample of NR BNS simulations to compute $M_{\text{ej,dyn}}$, dynamical ejecta distributions, and M_{disk}
- ▶ minimum magnitude at peak for three different bands



Intrinsic variability: peak width

- ▶ large sample of NR BNS simulations to compute $M_{\text{ej,dyn}}$, dynamical ejecta distributions, and M_{disk}
- ▶ peak width (time interval for $\Delta M = 1$ around maximum) for three different bands



Conclusion & Discussion

- ▶ multi-component and anisotropic nature of kilonovae emerges from BNS modelling
 - ▶ compatible with what we have observed so far
 - ▶ non-trivial coupling with intrinsic BNS variabilities, but trends can be found
 - ▶ more cases necessary to improve our present understanding
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- ▶ impact on light curve properties?
 - ▶ impact on nucleosynthesis yields?
 - ▶ how can radiative transfer models help improving semi-analytical models?
 - ▶ how can semi-analytical models guide radiative transfer studies?