A Neutrinosphere Model for the Photometry of Kilonovae

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Introduction

In a binary neutron star merger (BNS), the rapid inspiral produces a gravitational wave signal. The collision ejects matter, where nuclei are synthesized through the r-process (rapid neutron capture) and then decay, producing an electromagnetic transient known as a kilonova. In 2017, LIGO/VIRGO made the first GW detection of a BNS, GW170817 [1], which was followed by many EM observations (e.g. [2]).

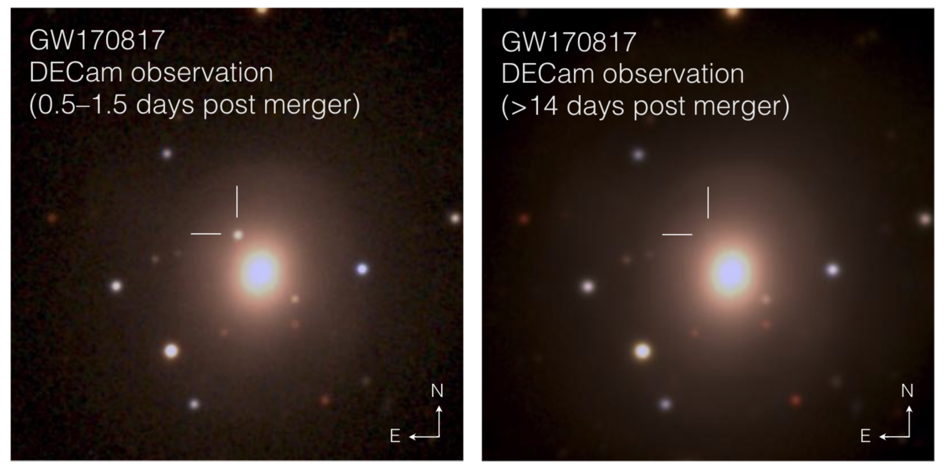


Figure: The EM counterpart of GW170817 [2].

Models of kilonova observables, when fitted to data, can deduce properties such as

- the contribution of kilonovae to the universe's heavy elements
- the neutron star equation of state.

We devise a unified, physically-motivated kilonova model, which we use to constrain the properties of GW170817 by fitting its lightcurves.

Ejecta Model

Within a few ms post-merger, matter is ejected "dynamically," in the form of equatorial tidal arms and spherical shocks from the oscillating remnant. Other "wind" processes produce ejecta, but these may be obscured by the dynamical ejecta so we exclude them.

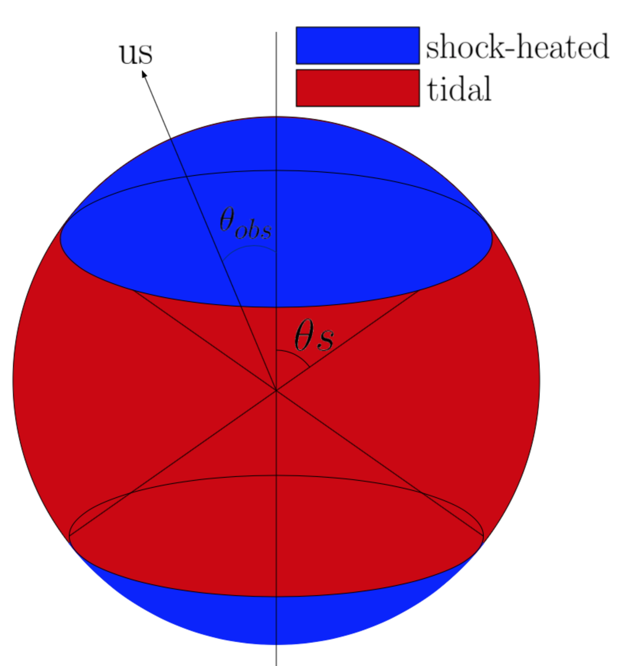


Figure: Our anisotropic two-component ejecta model.

Neutrinosphere model

We develop a method to determine the ejecta composition "from scratch." After the merger, the hypermassive neutron star remnant and accretion disk emit neutrinos and antineutrinos from a streaming surface known as the neutrinosphere. We treat this surface as a cylindrical blackbody, scaling the luminosity by literature values.

The dynamical ejecta's electron fraction (Y_e; proton to nucleon count ratio) is initially very low, but is driven up by neutrino irradiation for a few ms as it escapes. We use the neutrino luminosities to calculate the Y_e by integrating the equation

$$\dot{Y}_e = \lambda_{\nu_e}(1 - Y_e) - \lambda_{\bar{\nu}_e} Y_e. \qquad (1)$$

It exhibits dependence on velocity, polar angle, and ejection time.

More neutron-rich (low-Y_e) ejecta synthesize heavier r-process elements (e.g. lanthanides), which due to their high opacities produce a dimmer, redder, and slower-evolving signal. We use each component's Y_e to determine its lanthanide fraction, which we use to determine its SED (spectral energy distribution) by interpolating two parametrized grids [3, 4]. We weight the two SEDs by their projected areas to produce a total observed SED, which we use to calculate lightcurves.

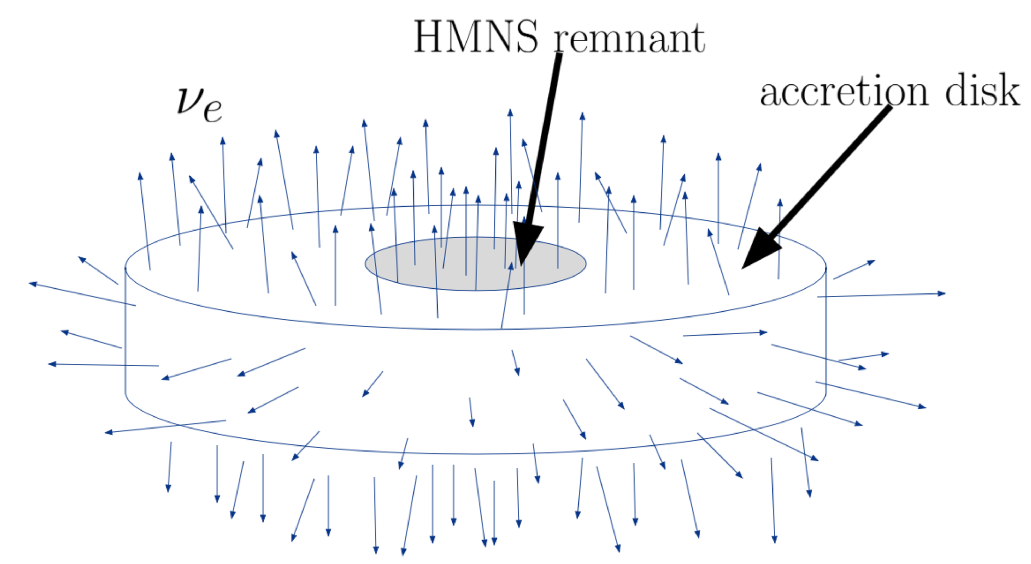


Figure: The neutrinosphere

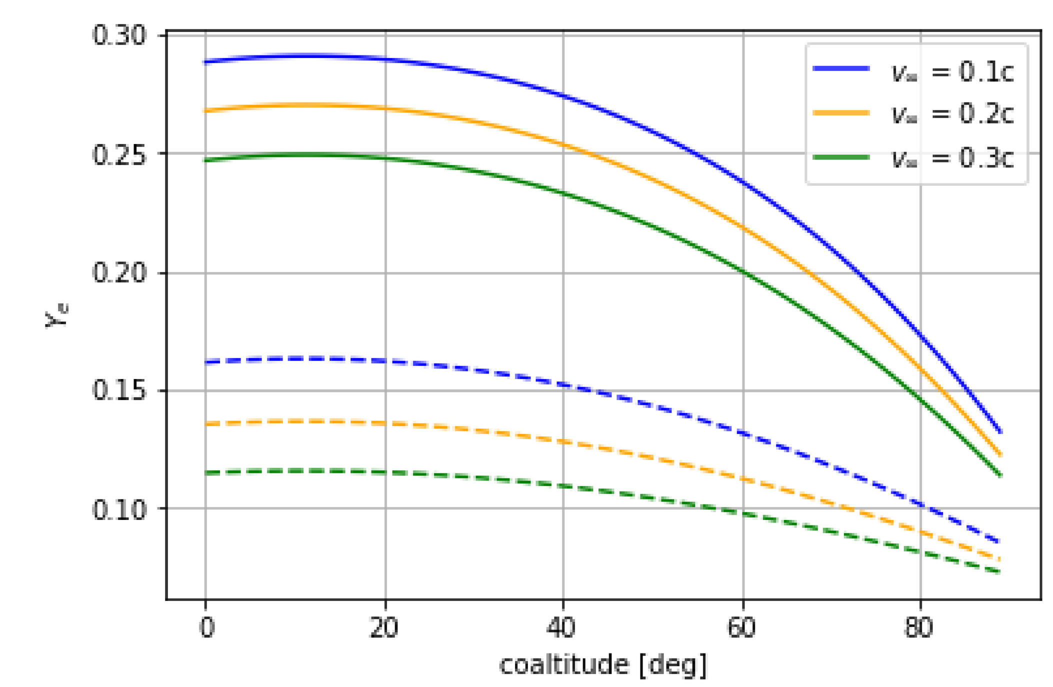
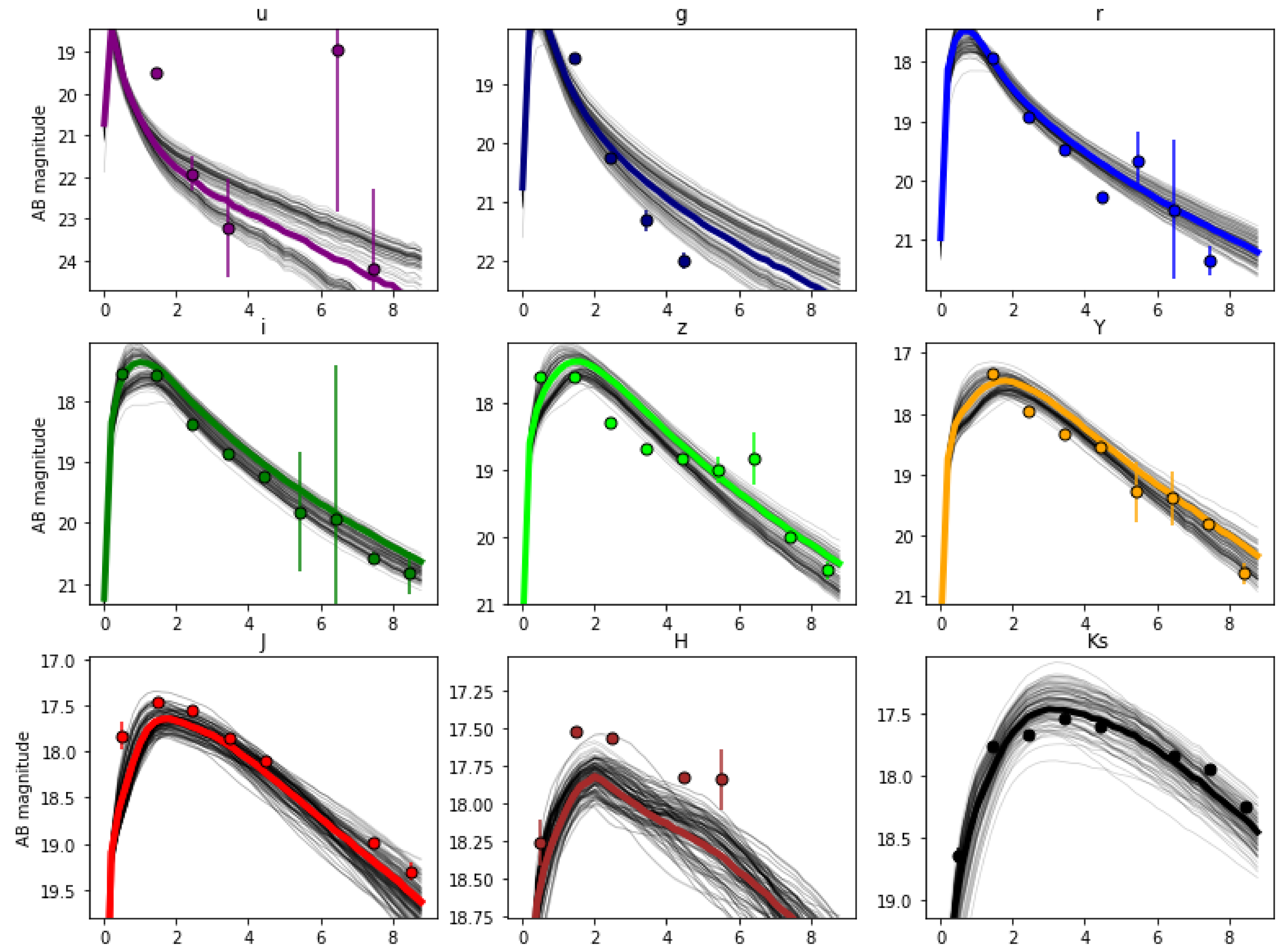


Figure: Example Y_e values for the shock-heated (solid) and tidal (dashed) ejecta. The tidal arms escape when the neutrino luminosity is low, allowing their Y_e to remain low.

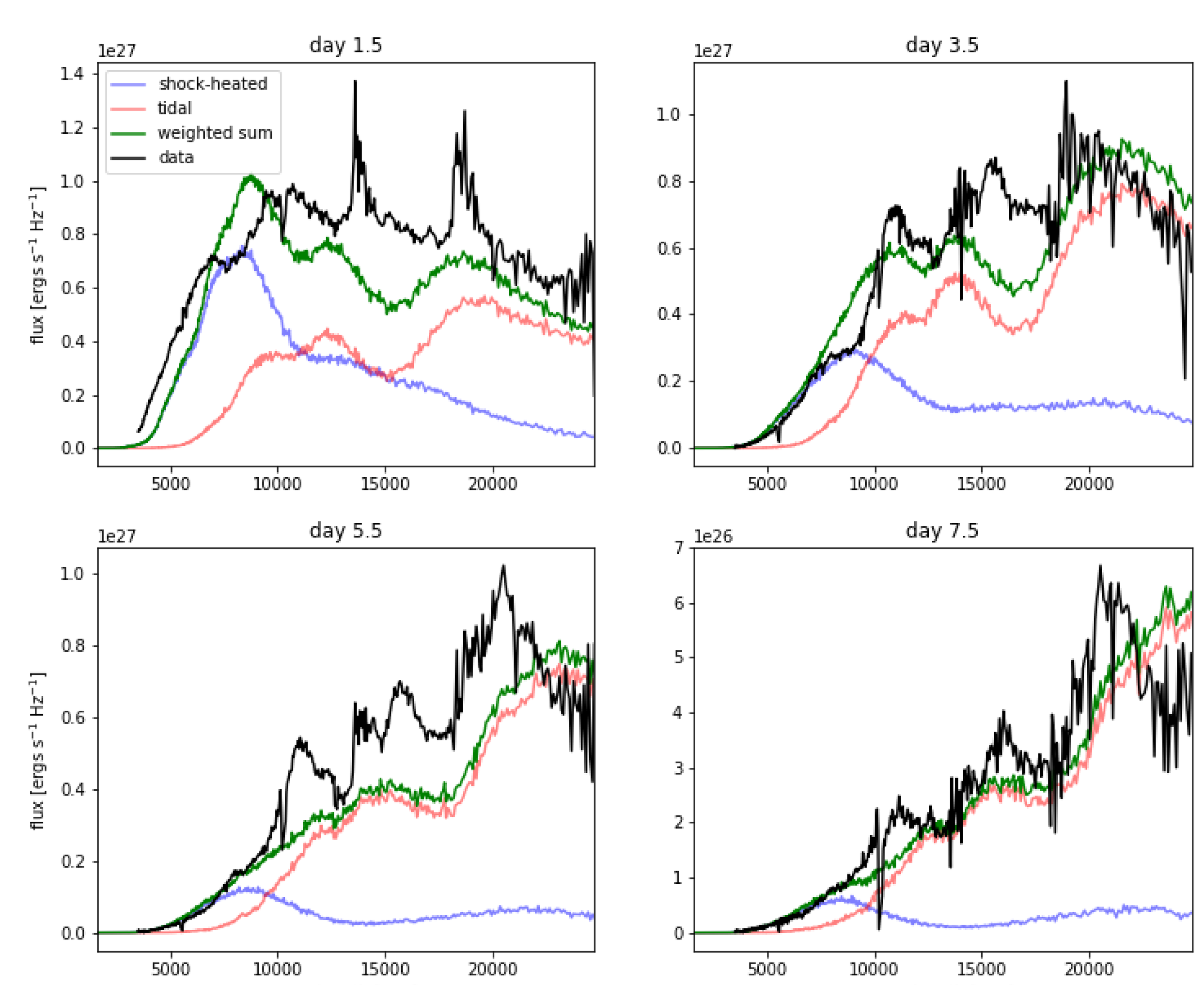
Results

M_{shock} $[M_\odot]$	v_{shock} $[c]$	M_{tidal} $[M_\odot]$	v_{tidal} $[c]$	θ_{obs} $[°]$	θ_{shock} $[°]$	σ $[mag]$
$0.016^{+0.004}_{-0.002}$	$0.293^{+0.003}_{-0.011}$	$0.049^{+0.003}_{-0.007}$	$0.242^{+0.022}_{-0.047}$	$35.12^{+6.06}_{-7.05}$	$45.58^{+10.21}_{-8.76}$	$0.361^{+0.048}_{-0.043}$

Table: Best-fit parameters for GW170817.



(a) We perform MCMC fitting to DECam and other near-IR photometry [2, 5, 6], resulting in these best fit lightcurves.



(b) Best-fit model SEDs over calibrated X-Shooter spectra [7].

Discussion

- Our neutrinosphere model appears able to well describe the data in most bands. However, the best-fit reduced chi square is ~ 150, due to the data's small errors and high scatter.
- Other 2-component model fits agree, roughly, with our masses and lanthanide fractions; however, most predict the tidal component to be much slower [4, 8].
- Based on our ejecta masses and the accepted BNS rate, BNS's can more than account for the universe's light and heavy r-process elements.
- We find evidence for highly massive tidal arms and a much lower-mass shock-heated component. This could support a stiffer neutron star equation of state.
- The inner disk wind component may affect the observables. We hope to include this component in the future.

References

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