Breaking the Viewing Angle-Distance Degeneracy for Binary Neutron Star Events Using Optical Measurements

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Breaking the Viewing Angle-Distance Degeneracy for Binary Neutron Star Events Using Optical Measurements

Kamile Lukosiute

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Abstract

1 Introduction

1.1 Binary Neutron Star Cosmology

1.2 GW170817

1.3 Work Presented

2 Binary Neutron Star Merger Emissions

2.1 Gravitational Wave Emission

2.2 Electromagnetic Emission

2.2.1 Optical Emission

2.2.2 Gamma-Ray, X-Ray, and Radio Emission

3 Gravitational Wave Follow-Up With DECam

3.1 The Trigger System

3.2 Search and Discovery Using the Dark Energy Camera

4 Methods

4.1 Model of Kilonova Emission

4.1.1 Spectral Energy Distributions

4.1.2 Geometric Model

4.2 MOSFiT

5 Results and Discussion

5.1 Theoretical Predictions

5.1.1 Results

5.1.2 Discussion

5.2 Recovery Using MCMC Methods
5.2.1 Results ................................................................. 33
5.2.2 Discussion ........................................................... 37

6 Conclusion ................................................................. 38

6.1 Recommendations for Observational Strategy ................. 38

6.2 Future Work ........................................................... 39

Appendices ................................................................. 40

A Simulated Light Curves and Corner Plots for Full Simulation Set 40

References

List of Figures

1 DECam grz band color composites of the host galaxy NGC4993 of the optical
counterpart GW170817. Left: GW170817, with the first image taken on 2017
18 00:05:23 UT Right: The same area two weeks later [29] ....................... 4

2 Comparison of the GW170817 measurement of $H_0$ with the Planck, SHOES,
and GW170817 measurements. The dashed and dotted lines represent the 1σ
and 2σ intervals for the GW170817 measurement [1]. ........................... 5

3 Illustration of the meaning of inclination angle. The red vector represents the
vector total angular momentum of the system, while the green vector points
towards the viewer. $\theta_{JN}$ is then the angle defined by these two vectors. .... 7

4 Comparison of the GW170817 measurement of $H_0$ with the Planck, SHOES,
and GW170817 measurements as correlated with $\iota$. The dashed and dot-
ted lines represent the 1σ and 2σ intervals for the GW170817 measurement
Graphic Credit: Abbott et al. 2017 [1]. ............................................. 8
Illustration of a plausible explanation for the observations from GW170817, starting with two massive stars orbiting each other and ending with a black hole and the emission of GWs and light. Graphic: J.S. Bloom, S. Sigurdsson, and G. Grullon, *Science*, 2017.

Components of matter ejected from neutron star mergers, depending on the constituents and remnant. Red colors indicate regions of heavy r-process materials, which radiate red/infrared light. Blue colors indicate light r-process products, which radiate blue optical light. **a.** If the remnant survives into a neutron star for at least tens of milliseconds, fewer neutrinos irradiate the disk ejecta and produces a blue wind. **b.** If the remnant collapses into a black hole quickly, the disk wind may be more red. **c.** In the merger of a neutron star and black hole (not discussed in this work), only a single, red, tidal tail is ejected. Graphic: Kasen et al. *Nature*, 2017.

Sky localization map for GW170817 constructed from the two LIGO detectors (light blue contours) and from the three LIGO and Virgo detectors (dark blue contours). A higher latency analysis that further reduced the area of the probability map is shown in green. In the inset, the location of NGC 4993, which is now believed to be the host galaxy of GW170817. The bottom right panel shows the calculated luminosity distance distribution from the three analyses, as well as the distance of NGC 4993. Graphic: B.P. Abbott et al., *Phys. Rev. Lett.*, 2017.

The DECam search exposures (in red hexagons) for GW170817 overlaid with the LIGO-Virgo probability maps (white solid: initial, cyan dashed: revised). The inner and outer contours show the 50% and 90% probability. The orange dot is the final determined location of the host galaxy. The transient is located at R.A., decl. = 197.450374, -23.381495 (degrees). Graphic Credit: Soares-Santos et al., *ApJ*, 2017.
9. The DECam u,g,r,i,z and Y bandpasses. Graphic Credit: Cerro Tololo Inter-American Observatory.


12. Left: A side view of the two main ejecta components, as well as the obscured inner disk wind component. Right: The geometry of the photosphere model. Labelled are the viewing angle, $\theta_{JN}$, and $\phi$, the half-opening angle. Graphic Credit: J. Metzger.

13. Left: The area weight $A_{blue}$ for the blue component as defined for all $\theta_{JN}$ and $\phi$. Right: The area weight $A_{red}$.

14. A 3D view of the photosphere model with changing viewing angles for a blue component with $\phi = 40^\circ$. There are two primary states: when only one ‘blue patch’ is visible (as in $\theta_{JN} = 0^\circ$ and $25^\circ$) and when both are visible (as in $\theta_{JN} = 50^\circ$ and $90^\circ$). The angle at which the second patch becomes visible depends on the size of the blue patches (determined by the half-opening angle $\phi$).

15. A schematic explanation of the role of each weight ($w_m$ and $A_{blue}$) in transforming the geometry from the Kasen et al. 2017 simulations to our model geometry.

16. Left: The mass weight on the blue ejecta as a function of half opening angle $\phi$. Right: The mass weight on the red ejecta.
Left: The total weight for the blue component (the product of the mass and area weights) as defined for all $\theta_JN$ and $\phi$. Right: The total weight for the red component.

Comparison of predicted lightcurves for the same physical parameters but differing viewing and opening angles ($\theta, \phi \in \{10, 40, 80\}$ degrees). Each subplot shows a different band.

(a-c) Absolute value of differences in magnitude for $\theta_JN = 80^\circ$ and $\theta_JN = 10^\circ$ versus $\phi$ for simulations with the parameters given in Table 1 for $t = 1, 3, and 8$ days. (d-f) Average differences in magnitude for $\Delta\theta_JN = 10^\circ$ for $t = 1, 3, and 8$ days.

Comparison of predicted lightcurves all parameters fixed except for $M_{red}$ and $M_{blue}$. Each subplot shows a different band.

Comparison of predicted lightcurves all parameters fixed except for $X_{red}$ and $X_{blue}$. Each subplot shows a different band.

Comparison of predicted lightcurves all parameters fixed except for $v_{red}$ and $v_{blue}$. Each subplot shows a different band.

Lightcurves (input data and all walker models) as well as the distribution of parameters for two representative parameter combinations for the first ejecta parameter set.

$\theta_JN$ measured by MOSFiT versus the true $\theta_JN$ for five values of $\phi$ using the values described in Table 1 for the ejecta parameters. The error bars represent the $1\sigma$ spread of all the values determined by all 128 walkers.

$1\sigma$ ranges for $\theta_JN$ for all sets of simulations.

$1\sigma$ ranges for $\theta_JN$, averaged over all $\theta_JN$ in each set for a given $\phi$.

Light curve and corner plot for $\phi = 15^\circ$ and $\theta_JN = 15^\circ$.

Light curve and corner plot for $\phi = 25^\circ$ and $\theta_JN = 15^\circ$.

Light curve and corner plot for $\phi = 35^\circ$ and $\theta_JN = 15^\circ$. 

Light curve and corner plot for $\phi = 15^\circ$ and $\theta_JN = 15^\circ$. 

Light curve and corner plot for $\phi = 25^\circ$ and $\theta_JN = 15^\circ$. 

Light curve and corner plot for $\phi = 35^\circ$ and $\theta_JN = 15^\circ$. 

Light curve and corner plot for $\phi = 15^\circ$ and $\theta_JN = 15^\circ$. 

Light curve and corner plot for $\phi = 25^\circ$ and $\theta_JN = 15^\circ$. 

Light curve and corner plot for $\phi = 35^\circ$ and $\theta_JN = 15^\circ$. 

Light curve and corner plot for $\phi = 15^\circ$ and $\theta_JN = 15^\circ$. 

Light curve and corner plot for $\phi = 25^\circ$ and $\theta_JN = 15^\circ$. 

Light curve and corner plot for $\phi = 35^\circ$ and $\theta_JN = 15^\circ$. 

Light curve and corner plot for $\phi = 15^\circ$ and $\theta_JN = 15^\circ$. 

Light curve and corner plot for $\phi = 25^\circ$ and $\theta_JN = 15^\circ$. 

Light curve and corner plot for $\phi = 35^\circ$ and $\theta_JN = 15^\circ$. 

Light curve and corner plot for $\phi = 15^\circ$ and $\theta_JN = 15^\circ$. 

Light curve and corner plot for $\phi = 25^\circ$ and $\theta_JN = 15^\circ$. 

Light curve and corner plot for $\phi = 35^\circ$ and $\theta_JN = 15^\circ$. 

Light curve and corner plot for $\phi = 15^\circ$ and $\theta_JN = 15^\circ$. 

Light curve and corner plot for $\phi = 25^\circ$ and $\theta_JN = 15^\circ$. 

Light curve and corner plot for $\phi = 35^\circ$ and $\theta_JN = 15^\circ$.
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>30</td>
<td>Light curve and corner plot for $\phi = 45^\circ$ and $\theta_{JN} = 15^\circ$</td>
</tr>
<tr>
<td>31</td>
<td>Light curve and corner plot for $\phi = 55^\circ$ and $\theta_{JN} = 15^\circ$</td>
</tr>
<tr>
<td>32</td>
<td>Light curve and corner plot for $\phi = 65^\circ$ and $\theta_{JN} = 15^\circ$</td>
</tr>
<tr>
<td>33</td>
<td>Light curve and corner plot for $\phi = 75^\circ$ and $\theta_{JN} = 15^\circ$</td>
</tr>
<tr>
<td>34</td>
<td>Light curve and corner plot for $\phi = 15^\circ$ and $\theta_{JN} = 30^\circ$</td>
</tr>
<tr>
<td>35</td>
<td>Light curve and corner plot for $\phi = 25^\circ$ and $\theta_{JN} = 30^\circ$</td>
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<td>36</td>
<td>Light curve and corner plot for $\phi = 35^\circ$ and $\theta_{JN} = 30^\circ$</td>
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<td>37</td>
<td>Light curve and corner plot for $\phi = 45^\circ$ and $\theta_{JN} = 30^\circ$</td>
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<td>Light curve and corner plot for $\phi = 55^\circ$ and $\theta_{JN} = 30^\circ$</td>
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<td>Light curve and corner plot for $\phi = 65^\circ$ and $\theta_{JN} = 30^\circ$</td>
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<td>40</td>
<td>Light curve and corner plot for $\phi = 75^\circ$ and $\theta_{JN} = 30^\circ$</td>
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<tr>
<td>41</td>
<td>Light curve and corner plot for $\phi = 15^\circ$ and $\theta_{JN} = 30^\circ$</td>
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<td>42</td>
<td>Light curve and corner plot for $\phi = 25^\circ$ and $\theta_{JN} = 30^\circ$</td>
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<td>43</td>
<td>Light curve and corner plot for $\phi = 35^\circ$ and $\theta_{JN} = 30^\circ$</td>
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<td>Light curve and corner plot for $\phi = 45^\circ$ and $\theta_{JN} = 30^\circ$</td>
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<td>45</td>
<td>Light curve and corner plot for $\phi = 55^\circ$ and $\theta_{JN} = 30^\circ$</td>
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<td>46</td>
<td>Light curve and corner plot for $\phi = 65^\circ$ and $\theta_{JN} = 30^\circ$</td>
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<td>47</td>
<td>Light curve and corner plot for $\phi = 75^\circ$ and $\theta_{JN} = 30^\circ$</td>
</tr>
<tr>
<td>48</td>
<td>Light curve and corner plot for $\phi = 15^\circ$ and $\theta_{JN} = 45^\circ$</td>
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<tr>
<td>49</td>
<td>Light curve and corner plot for $\phi = 25^\circ$ and $\theta_{JN} = 45^\circ$</td>
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<td>50</td>
<td>Light curve and corner plot for $\phi = 35^\circ$ and $\theta_{JN} = 45^\circ$</td>
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<td>51</td>
<td>Light curve and corner plot for $\phi = 45^\circ$ and $\theta_{JN} = 45^\circ$</td>
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<td>52</td>
<td>Light curve and corner plot for $\phi = 55^\circ$ and $\theta_{JN} = 45^\circ$</td>
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<td>53</td>
<td>Light curve and corner plot for $\phi = 65^\circ$ and $\theta_{JN} = 45^\circ$</td>
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<td>54</td>
<td>Light curve and corner plot for $\phi = 75^\circ$ and $\theta_{JN} = 45^\circ$</td>
</tr>
<tr>
<td>55</td>
<td>Light curve and corner plot for $\phi = 15^\circ$ and $\theta_{JN} = 60^\circ$</td>
</tr>
<tr>
<td>56</td>
<td>Light curve and corner plot for $\phi = 25^\circ$ and $\theta_{JN} = 60^\circ$</td>
</tr>
</tbody>
</table>
57  Light curve and corner plot for \( \phi = 35^\circ \) and \( \theta_{IN} = 60^\circ \)  
58  Light curve and corner plot for \( \phi = 45^\circ \) and \( \theta_{IN} = 60^\circ \)  
59  Light curve and corner plot for \( \phi = 55^\circ \) and \( \theta_{IN} = 60^\circ \)  
60  Light curve and corner plot for \( \phi = 65^\circ \) and \( \theta_{IN} = 60^\circ \)  
61  Light curve and corner plot for \( \phi = 75^\circ \) and \( \theta_{IN} = 60^\circ \)  
62  Light curve and corner plot for \( \phi = 15^\circ \) and \( \theta_{IN} = 75^\circ \)  
63  Light curve and corner plot for \( \phi = 25^\circ \) and \( \theta_{IN} = 75^\circ \)  
64  Light curve and corner plot for \( \phi = 35^\circ \) and \( \theta_{IN} = 75^\circ \)  
65  Light curve and corner plot for \( \phi = 45^\circ \) and \( \theta_{IN} = 75^\circ \)  
66  Light curve and corner plot for \( \phi = 55^\circ \) and \( \theta_{IN} = 75^\circ \)  
67  Light curve and corner plot for \( \phi = 65^\circ \) and \( \theta_{IN} = 75^\circ \)  
68  Light curve and corner plot for \( \phi = 75^\circ \) and \( \theta_{IN} = 75^\circ \)
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Abstract

In 2017, the LIGO/Virgo collaboration made history by detecting the ripples in space and time—gravitational waves (GW)—emitted by the merger of two neutron stars. Twelve hours later, telescopes detected the bright light produced by the merger—a kilonova. This joint detection marked the beginning of a new era in cosmology. Kilonova GW detections can provide the next generation of cosmological distance measurements, and when combined with redshift from an optical detection, these systems can be used to study the origin and evolution of the universe. Over the next 10 years, we expect LIGO/Virgo detectors to accumulate several times the current number of GW detections. Therefore, accurately measuring the distance is essential to maximize science gains. One problem is that the distance measurement from the GW waveform is degenerate with the inclination angle of the system. In this study, we explore the possibility of measuring the viewing angle solely from the optical signal by building an angle-dependent model of kilonova emission. We generate mock observations and use Markov Chain Monte Carlo methods to study the model’s ability to recover the parameters of the data. The results of this thesis indicate that the model can be used to recover the viewing angle parameter.
1 Introduction

In 1927, the Belgian cosmologist and priest Georges Lemaître published a cosmological study based on a study of 43 galaxies whose radial velocities had been calculated from the measurement of wavelength shift \[16\]. By studying the emission spectra of galaxies and comparing these spectra to the those of the common elements, Gustaf Strömberg had determined that the observed spectra of galaxies were systematically shifted by a small amount, on the order of \(\Delta \lambda / \lambda \approx 0.002\); he used this information to calculate the radial velocity of the galaxies \[30\]. Thirty seven of the 43 galaxies had a radial velocity away from us, which Lemaître interpreted as a Doppler shift caused by the expansion of the universe \[16\] \[27\].

His research was largely ignored at the time. Two years later, in 1929, the astronomer Edwin Hubble published his distance estimates to 20 additional galaxies, as well as their velocities, and scientists’ understanding of the nature of the universe fundamentally changed. Hubble found that the galaxies were moving away from the Earth at a speed proportional to their distance \[13\]. He quantified this with the now-famous Hubble law,

\[ v = H_0 r, \tag{1} \]

where \(H_0\) is the Hubble constant. This value is typically reported in the units of km s\(^{-1}\) Mpc\(^{-1}\) \[27\].

Hubble’s results shattered the scientific community’s understanding of the universe. Hubble not only showed that the blurry objects we now call galaxies are outside of our own galaxy, but also that the universe is not static as previously thought but rather expanding. Since 1929, cosmologists have been trying to study the exact nature of our mysterious expanding universe \[27\].

One method used to measure \(H_0\) and other important cosmological parameters is called the method of “standard candles.” For most astrophysical objects, it is difficult to tell if the object is distant and therefore dim, or if the object is inherently dim. However, “standard
candles” have a known brightness, and so we can measure the distance to them from their brightness alone. Type Ia supernovae, a type of exploding star often used as a standard candle, have a predictable intrinsic luminosity, which we can use to measure the distance. If we observe many of these events, we can combine the distance measures with measures of velocity from the redshift in order to determine \( H_0 \). The most recent measurement of \( H_0 \) using this method comes from the SH0ES (Supernovae \( H_0 \) for the Equation of State of Dark Energy) collaboration. They found \( H_0 = 73.24 \pm 1.74 \text{ km s}^{-1} \text{ Mpc}^{-1} \) [26].

Another modern method of performing cosmological measurements involves observations of the cosmic microwave background (CMB). The CMB is radiation left over from the first few minutes of the universe. The radiation is approximately uniform, present in the sky in all directions, and has a blackbody temperature of approximately \( T = 2.73 \text{ K} \), which puts the radiation in the microwave region of the spectrum. The early universe was filled with many particles, including photons, electrons, and protons. As the universe expanded and cooled, the protons and electrons combined to form hydrogen atoms. Photons easily scatter off of electrons, but once the electrons are combined into atoms, electrons interact very weakly with the atoms. The photons then ”decoupled” from the matter and have been travelling freely ever since. Because the universe is expanding, the wavelength of these photons is stretched. Therefore, the photons that we observe now from the CMB are much less energetic than when they decoupled.

Although the CMB temperature is approximately uniform and is consistent with blackbody emission, there are some small anisotropies, or directional dependencies. Measuring these anisotropies allows CMB cosmologists to extract various cosmological parameters, including the expansion rate of the universe, \( H_0 \). The most advanced all-sky CMB experiment is called Planck, a spacecraft observatory that observed the CMB from 2009 to 2013. The most recent Planck measurement of \( H_0 \) from the 2018 data release is \( 67.4 \pm 0.5 \text{ km s}^{-1} \text{ Mpc}^{-1} \) [7].

There is a tension of 3.4 standard deviations between the SH0ES and Planck measure-
ments. This poses a problem for cosmologists because precise knowledge of these parameters allows them to deduce information about the nature of the universe. A different, independent measurement of \( H_0 \), with entirely different sources of systematic errors, could resolve this discrepancy. Joint gravitational wave and electromagnetic emission could be used to resolve this disparity.

1.1 Binary Neutron Star Cosmology

In 1986, Schutz first proposed that information from the merger of two neutron stars could be used to measure \( H_0 \) \cite{28}. Neutron stars are thought to be produced after the collapse of a star in a supernova, and they are predominantly composed of tightly packed neutrons. A gravitationally bound pair of orbiting binary neutron stars will eventually merge. As the stars orbit, they create ripples in space and time. As they approach each other, the frequency of their orbit increases so does the intensity of the gravitational waves. Using ground-based gravitational wave (GW) detectors, we can now detect these ripples. The GW signal contains information about the masses of the stars and, importantly, about the distance to the stars. Intuitively, a detector will observe stronger GWs from a nearby collision, while a more distant collision will have a fainter signal. Schutz proposed that if an electromagnetic (EM) counterpart is detected, then we could use the distance measurement from the GW signal, combined with a redshift from the EM signal to measure \( H_0 \).

A few decades later, Li and Paczynski determined that during a neutron star merger, a small amount of mass would be ejected at mildly relativistic velocities, and as the matter decompressed it would form radioactive nuclei. This radioactive matter could provide a heating source and therefore produce light, predominantly in the optical part of the EM spectrum, which would last for a few days \cite{17}. Since then, much more research has been done to model binary neutron star (BNS) merger optical counterparts - now referred to as kilonovae \cite{14}. The first of these events, however, was not detected until 2017.
1.2 GW170817

On August 17th, 2017, the advanced Laser Interferometer Gravitational-Wave Observatory (LIGO) in the US and the Virgo Observatory in Italy detected the GW signal from a BNS merger, GW170817 [18]. The signal was followed 1.7 seconds later by a short gamma-ray burst detection by the Fermi and INTEGRAL satellites [10]. Four hours after detection, LIGO released a sky localization map of the event. Several telescopes, including the Dark Energy Survey’s Camera (DECam) and the Swope Telescope, began imaging the area after darkness fell. About 11 hours after the GW detection, an optical counterpart was detected (see Fig. 1). After the optical discovery, observations were obtained with a variety of telescopes, spanning X-rays to radio waves [29].

Using the redshift obtained from the follow-up observations and the distance measurement from the GW signal, a measurement of $H_0$ was made and determined to be $70.0^{±12.0}_{±8.0}$ km s$^{-1}$ Mpc$^{-1}$. This independent measurement of $H_0$ is consistent with the two other state-of-the-art determinations from Planck and SH0ES, but it does have large uncertainties. The
uncertainty is due to the fact that the measurement is based on a single event, detector noise and calibration uncertainties, and a geometrical factor that depends on the correlation of distance with the viewing angle of the system.

LIGO detectors have been shut down for upgrades since August 2017, and detector sensitivity has increased. As a new observing run began in March 2019 and has already started to detect events at a significantly higher rate than in the last observing season, the issue of small sample size of events will be naturally solved. However, the last cause of uncertainty, the viewing angle-distance degeneracy, in the GW-EM $H_0$ measurement remains and will prove to be the biggest barrier in using this method for cosmology.

1.3 Work Presented

Because the viewing angle-distance measurement degeneracy is proving to be an important barrier to overcome in using the GW-EM method for cosmology, this thesis explores the possibility of using solely the optical data to measure the viewing angle for future improvements of the distance measurement. In Chapter 2, I describe the emissions from the merger of neutron stars, including GW and EM. In Chapter 3, I describe the tools and processes used in optical follow-up observations of gravitational wave events. In Chapter 4, I describe
the tools I will be using to model the optical emission from BNS mergers. In Chapter 5, I present the results, and in Chapter 6, I discuss observing strategies in order to maximize the ability to measure the viewing angle from the optical data.
2 Binary Neutron Star Merger Emissions

2.1 Gravitational Wave Emission

BNS mergers have the possibility of resolving the modern $H_0$ problem. The measure of distance from the GW signal has completely different systematic errors and, when combined with a measure of redshift from an optical counterpart, can be used to determine $H_0$. However, because the viewing angle and the distance measurement are degenerate in the GW signal, there is additional error on the distance measurement. Therefore, in this work, I explore the possibility of measuring the viewing angle solely with the optical emission, which will be reliably present in all BNS mergers. In this chapter, I discuss the various sources of GW and EM emission and formally define the viewing angle, $\theta_{JN}$.

Under general relativity, two objects in orbit will slowly spiral and eventually merge. This merger happens because angular momentum and energy is carried away as gravitational radiation in the form of gravitational waves (GWs). The amplitude of these waves is remarkably small – gravitational waves will change the 4 km long LIGO arms by only about $10^{-22}$m – but as the radius of the orbit shrinks, the frequency and amplitude of the waves increases [20]. With current instruments, such as the LIGO interferometers in the US and the Virgo interferometer in Italy, these GWs can be detected for a few seconds before the merger. Currently, these detectors can only detect the mergers of the heaviest, most dense objects in our universe - black holes and neutron stars [2].

Figure 3: Illustration of the meaning of inclination angle. The red vector represents the vector total angular momentum of the system, while the green vector points towards the viewer. $\theta_{JN}$ is then the angle defined by these two vectors.
Figure 4: Comparison of the GW170817 measurement of $H_0$ with the Planck, SHOES, and GW170817 measurements as correlated with $\iota$. The dashed and dotted lines represent the $1\sigma$ and $2\sigma$ intervals for the GW170817 measurement Graphic Credit: Abbott et al. 2017 [1].

In this work, we will focus on BNS mergers because in addition to the GW emission, there are several predicted mechanisms of EM emission. For cosmology, the most useful objects are those with both GW and EM emission. EM emission will be discussed in Section 2.2.

Using general relativity, the equations for the waveforms due to mergers can be predicted. The amplitude of the GW signal depends on $d \cos(\iota)$, where $d$ is the luminosity distance to the event and $\iota$ is the inclination angle of the system. The viewing is defined as the angle between the total angular momentum of the system and the position vector of the Earth relative to the system. This is illustrated in Fig. 3. The viewing angle, $\theta_{JN}$ is defined as $\min(\iota, 180 - \iota)$. In the discussion of mass ejection mechanisms below, the term “polar” is used to describe emission in a cone centered on the vector of total angular momentum.

If the members of the binary system have a large difference in mass, higher order harmonic terms in the GW equations can be used to determine $\theta_{JN}$. However, because neutron star masses typically fall in the narrow range of 1.04 to 1.52$M_\odot$ (solar masses), the measurement of inclination angle is strongly correlated with distance and they can’t be measured using GW methods alone [23]. Fig. 4 illustrates how the GW170817 $H_0$ measurement depends on the inclination angle. Constraining the inclination angle to a range smaller than the current $2\sigma$ range (approx. 40 degrees) would greatly improve the $H_0$ measurement.

Since the viewing angle information is key to constraining the $H_0$ measurement, we
explore other non-GW methods. A BNS merger also emits electromagnetic (EM) radiation in addition to GWs, so we investigate the possibility of using EM emission to measure the viewing angle.

2.2 Electromagnetic Emission

Electromagnetic emission from BNS mergers comes from multiple physical mechanisms, corresponding to different wavelengths. The life history of neutron stars and the resulting emission from their merger is summarized in Fig. 5.

2.2.1 Optical Emission

The ultraviolet, optical, and near-infrared signals are thought to be powered by the radioactive decay of heavy elements formed in the merger; this signal is dubbed a kilonova. Neutron star mergers eject matter through two main types of process: “dynamical” and “wind” processes.

Within a few milliseconds (ms) of the merger ($t = 0$; time of first surface contact), matter
Figure 6: Components of matter ejected from neutron star mergers, depending on the constituents and remnant. Red colors indicate regions of heavy r-process materials, which radiate red/infrared light. Blue colors indicate light r-process products, which radiate blue optical light. **a.** If the remnant survives into a neutron star for at least tens of milliseconds, fewer neutrinos irradiate the disk ejecta and produces a blue wind. **b.** If the remnant collapses into a black hole quickly, the disk wind may be more red. **c.** In the merger of a neutron star and black hole (not discussed in this work), only a single, red, tidal tail is ejected. Graphic: Kasen et al. *Nature*, 2017.

is thrown off the surfaces of the stars in violent processes. There are two main mechanisms to this dynamical ejecta: tidal and shock-heated. As the stars inspiral, tidal forces peel matter from the surfaces of the approaching stars, flinging out tails of debris. The tidal tails are expected to be cold and neutron-rich. Next, at around 2 ms, if the remnant of the merger is a hypermassive neutron star (HMNS), the oscillating remnant will send shocks through the surroundings, ejecting matter quasi-isotropically. This shock-heated ejecta will likely be hotter, higher-entropy, and less neutron-rich. The dynamical ejecta travels at mildly relativistic velocities of 0.1 – 0.3c.

Lastly, on a much longer timescale of around 100 ms, neutrino winds and viscous heating drive matter away in high temperature winds in velocities of 0.01 – 0.1c. The HMNS remnant and the accretion disk emit neutrinos, a fraction of which can interact with the surrounding matter and lift it out of the gravitational potential of the remnant. If the HMNS survives for a relatively long period of time (tens of milliseconds), the neutrino irradiation lasts longer. Later, matter moving as a fluid in the accretion disk unbinds a fraction of the disk (viscous heating). This matter has an uncertain composition.

The matter ejected through each of these mechanisms is neutron-rich and moving at
mildly relativistic velocities. As the ejected matter decompresses, it undergoes rapid neutron capture (r-process) nucleosynthesis. In this type of nucleosynthesis, a seed proton captures neutrons, which quickly undergo beta decay, leaving behind a proton, an electron, and an anti-neutrino. This process happens continuously and creates the heaviest elements of the periodic table. If the matter is very neutron-rich (neutron mass fraction \( \eta \geq 0.75 \)), it forms into heavy r-process elements \( (58 \leq Z \leq 90, \text{ where } Z \text{ is the atomic number}) \), and if the matter is only moderately neutron-rich \( (0.6 \leq \eta \leq 0.75) \), lighter r-process material is formed \( (28 \leq Z \leq 58) \). Each component will have slightly different but distinguishable characteristics. Tidal tail ejecta is expected to be neutron-rich, which forms heavy r-process material and in turn radiates red/infrared light. The ‘squeezed’ polar and disk wind ejecta is expected to be neutron-poor because it experiences additional neutrino irradiation which converts neutrons into protons; this therefore produces light r-process materials and blue light \[14\]. As shown in Fig. \[6\], the material is ejected in different directions.

### 2.2.2 Gamma-Ray, X-Ray, and Radio Emission

GW170817 also confirmed the long-held belief that BNS mergers could be the source of extra-galactic gamma-ray bursts. As the stars merge, their magnetic fields align and are pointed towards the poles. A small amount of mass is then launched along the magnetic field lines, creating a jet, which has a narrow opening angle \( \approx 10^\circ \). The ejected mildly relativistic mass can produce photons through synchrotron radiation, which occurs when photons are emitted when charged particles are accelerated in a curved path. The charged particles can also further increase the energy of already present photons by transferring part of their energy to the photons through inverse Compton scattering. \[15\].

The X-ray and radio emissions are also associated with the gamma-ray burst. As the charged particles move away from the location of the merger, they are tightly collimated in the jet. However, when the jet has moved outside the immediate stellar environment, it will hit the interstellar medium. The interaction disrupts the flow of the particles in the jet.
and violently disperses them, changing their straight paths into curved ones, again emitting synchrotron radiation. This radiation is less energetic and is thus emitted in the form of radio waves and X-rays. [22].

The gamma-ray burst emission is polar, and the direction of the gamma-rays determined the areas of emission of the radio waves as well. Therefore, the viewing angle of the system can be determined from observations for radio waves and gamma-rays. Using these methods the viewing angle for GW170817 was found $\approx 30^\circ$ [15][12].

Although research suggests that we should expect gamma-ray and radio emission for every binary neutron star event, these methods produce measurements of the viewing angle with high uncertainties [15]. Therefore, in this work, we consider the possibility of using the optical emission, which is also angle dependent, to determine the viewing angle parameter to add to the possible methods. In Chapter 4, I describe the model of optical emission we use to determine how the optical signal will change with viewing angle.
3 Gravitational Wave Follow-Up With DECam

In order to make a measurement of $H_0$ using BNS events, we first need to detect the optical counterparts. In this chapter, I will describe the process of GW follow-up with telescopes, as well as the specifics of the instrument I will be focusing on: The Dark Energy Camera.

3.1 The Trigger System

When the LIGO and Virgo detectors are operational, they are constantly taking and automatically analyzing data. If the data analysis reveals a probable event, a trigger is sent out to telescope partners, such as the Dark Energy Survey (DES). In addition to the trigger, LIGO sends out a probably sky location map. The sky location map for GW170817 is shown in Fig. 7 [18].

After the telescope operators receive the LIGO alert, they have to determine whether it will be possible to observe the event. For example, the event could be in the northern sky,
while the telescope may be located in the southern hemisphere. If it is nighttime and the
telescope will be able to observe the event’s sky map, then the telescope operators begin the
process of attempting to find the counterpart. Before describing this process, I will describe
the telescope the DES GW group uses.

3.2 Search and Discovery Using the Dark Energy Camera

The Dark Energy Survey (DES) is a large optical survey focusing on better understanding the
role of dark energy in the cosmos by imaging a large section of the southern sky in optical
to near-infrared wavelengths. DES uses the wide-field Dark Energy Camera (DECam), a
wide-field-of-view (3 deg²) 570 Megapixel camera mounted on the Blanco 4-meter telescope
at the Cerro Tololo Inter-American Observatory (CTIO) in northern Chile [21].

For the DES-GW team, the process of locating an optical counterpart to a GW event
is now almost fully automated. After receiving a LIGO trigger and sky localization map, a
plan is automatically for taking images that will most efficiently cover the entire area. This
plan is then sent to the Blanco telescope observers, where they begin the process of imaging.
DECam’s wide field of view, it can quickly image the entire area. The LIGO probability
map, overlaid with the locations of the DECam exposures, for GW170817 is shown in Fig. 8.

For search purposes, exposures are only taken in only two telescope filters. Telescope
filters (also known as passbands or simply, bands) only allow certain wavelengths of light to
pass through to the detector. The DECam filters used most often are $g, r, i$ and $z$. There
are two additional filters, $u$ and $Y$, which are used less frequently because $u$ has a low
transmission and is in the ultraviolet range, and $Y$ largely overlaps with $z$ [21]. The fraction
of transmission with respect to wavelength for the DECam filters is shown in Fig. 9. For
GW170817, search exposures were taken in $i$ and $z$ bands [29].

As the search exposures are taken, they are processed and compared to archival exposures
of the same area. If an object that was not present before is located, it is evaluated for
Figure 8: The DECam search exposures (in red hexagons) for GW170817 overlaid with the LIGO-Virgo probability maps (white solid: initial, cyan dashed: revised). The inner and outer contours show the 50% and 90% probability. The orange dot is the final determined location of the host galaxy. The transient is located at R.A., decl. = 197.450374, -23.381495 (degrees). Graphic Credit: Soares-Santos et al., ApJ, 2017.

Figure 9: The DECam $u, g, r, i, z$ and $Y$ bandpasses. Graphic Credit: Cerro Tololo Inter-American Observatory
probability of being the counterpart. Only one object should remain at the end of the selection process. After a counterpart is discovered, the telescope can observe the object in all the bands.

After an object is observed in a given band, the magnitude of the object in a given band can be calculated from the flux in that band ($F_{\text{band}}$) using the formula

$$m_{\text{band}} = -2.5 \times \log_{10} \left( \frac{F_{\text{band}}}{F_{0,\text{band}}} \right)$$  \hspace{1cm} (2)$$

where $F_{0,\text{band}}$ defines the zero-point magnitude in a given band. Because of this system, the larger the magnitude, the dimmer the object is. Therefore, in plots of magnitude versus time, the y-axis scale is inverted. Lightcurve data will be the primary type of data discussed throughout this thesis, and an example lightcurve for GW170817 as observed by DECam is shown in Fig. 10.
4 Methods

In this chapter, I describe the tools and methods used to explore the sensitivity of optical emission to the viewing angle. Since there has been only one observed kilonova event, the most appropriate methodology for this project is to create a parameterized model of kilonova emission, simulate data using the model, evaluate the effect of changing physical parameters on the optical signal, and evaluate attempts to recover the original parameters through curve-fitting methods.

4.1 Model of Kilonova Emission

4.1.1 Spectral Energy Distributions

Kasen et al. [14] have performed radiative transfer simulations to create models of the radioactive aftermath of a BNS merger. The parameters of their models are the mass of the ejecta $M$, characteristic expansion ‘kinetic’ velocity $v_k$ (defined as $v_k = (2E/M)^{0.5}$ where $E$ is the kinetic energy of the ejecta), and the composition of the ejected matter, quantified as fraction of lanthanides present $X_{lan}$. In their model, the ejecta is expanding freely in a spherical distribution. They have released the observables of the simulations, or the spectral energy distributions (SEDs; spectra over time) to the public. Kasen et al. 2017 created spectra for the set of parameters $M \in \{0.001, 0.0025, 0.005, 0.01, 0.02, 0.025, 0.03, 0.04, 0.05, 0.075, 0.1\} \text{M}_\odot$ (solar masses), $v_k \in \{0.03, 0.05, 0.1, 0.2, 0.3\} c$, and $X_{lan} \in \{10^{-1}, 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5}, 10^{-9}\}$. Each simulation is assigned one of each of the three parameters. Kasen et al. 2017 did not calculate the combination $v = 0.3c$, $X_{lan} = 10^{-1}$, and $M = 0.1M_\odot$, so there are a total of 329 simulations. Examples of these spectra are given in Fig. 11. For each of the light-emitting areas in our model, we choose a set of parameters $M$, $v_k$, and $X_{lan}$ and apply the corresponding SED to each component. I describe the components in Section 4.1.2.
4.1.2 Geometric Model

We developed a two-component model of the ejecta from a BNS merger. While there are truly three or four ejection mechanisms (as discussed in Section 2.2.1), the inner winds travel more slowly, so they are obscured by the dynamical ejecta. While their photons will diffuse through the outer component and increase the total energy output, the effect is degenerate with increasing the mass of the outer component. Therefore, we use a two component model, considering the tidal tails and the shock-heated ejecta alone. We predict that the total best-fit masses will be an overestimate for the dynamical ejecta alone but accurate for the total ejecta mass.

Since the tidal tails are ejected near the equatorial plane, they partly obstruct the shock-heated ejecta. All the ejecta expands homologously, keeping the same relative position though changing in size. Therefore, the tidal tails will always obstruct the shock-heated ejecta as all the matter expands. We consider a spherical photosphere (surface from which photons are streaming towards the observer) model. This model is illustrated in Fig. 12. Our model states that each visible area emits light according to the SEDs as described in Section 4.1.1. However, since the Kasen et al. SEDs were created for a spherical geometry,
we modify the signal with weights to account for our aspherical geometry.

The first weight applied is the projected area weight. The projected area of the surface that is facing the observer determines the optical signal that we will observe. Assuming a spherical photosphere (which will have a circular projected area towards the observer), the sum of both area weights will be equal to one. Depending on the viewing angle $\theta_{JN}$ and half-opening angle of the polar ejecta $\phi$, we calculate the geometric weight on the shock-heated ejecta (more likely to be blue, so hereafter referred to as the ‘blue’ component) as fraction of a circle that is visible, $A_{\text{blue}}$:

$$A_{\text{blue}} = \pi \sin(\phi)^2 \cos(\theta_{JN}) + 2(1 - \cos(\theta_{JN})) \arcsin(x) - \frac{x \sqrt{1 - x^2}}{\pi}$$

where

$$x = \begin{cases} 
\frac{\sqrt{\sin(\phi)^2 - \cos(\theta_{JN})^2}}{\sin(\theta_{JN})}, & \text{if } \phi + \theta_{JN} > \pi/2 \\
0, & \text{otherwise}
\end{cases}$$

$A_{\text{red}}$, the fraction of a circle of which the red component is visible, is simply $1 - A_{\text{blue}}$. 

Figure 12: Left: A side view of the two main ejecta components, as well as the obscured inner disk wind component. Right: The geometry of the photosphere model. Labelled are the viewing angle, $\theta_{JN}$, and $\phi$, the half-opening angle. Graphic Credit: J. Metzger.
Figure 13: Left: The area weight $A_{\text{blue}}$ for the blue component as defined for all $\theta_{JN}$ and $\phi$. Right: The area weight $A_{\text{red}}$.

Fig. 13 shows the distribution of this weight for all $\phi$ and $\theta_{JN}$ for both the blue and red components. Figure 14 shows how the photosphere appearance changes with differing viewing angles in our model.

In addition to the projected area weight, we also apply a mass weight to account for the differing distributions of mass in our model. The Kasen et al. simulations were performed for spheres, and when a conversion from the Kasen et al. SEDs to a luminosity in our model is done, it assumes a spherical distribution. However, our model assumes cones for the blue ejecta and spheres with removed cones for the red. Therefore, we introduce an additional mass weight to account for the difference to convert to a different shape. The mass weight models compressing the matter distributed in spheres into cones. The matter then emits light with the same properties as the SED, but through a different surface. The total energy emitted will be the same, since only the parameters $X_{\text{lan}}$, $v_k$, and $M$ control the total energy, but the flux of photons will be higher because they will be streaming through the smaller surface of the new shape.

To explain the mass weight of the blue ejecta, we first start with the solid angle starting
Figure 14: A 3D view of the photosphere model with changing viewing angles for a blue component with $\phi = 40^\circ$. There are two primary states: when only one ‘blue patch’ is visible (as in $\theta_{JN} = 0^\circ$ and $25^\circ$) and when both are visible (as in $\theta_{JN} = 50^\circ$ and $90^\circ$). The angle at which the second patch becomes visible depends on the size of the blue patches (determined by the half-opening angle $\phi$).

Figure 15: A schematic explanation of the role of each weight ($w_m$ and $A_{\text{blue}}$ in transforming the geometry from the Kasen et al. 2017 simulations to our model geometry.
Figure 16: Left: The mass weight on the blue ejecta as a function of half opening angle $\phi$. Right: The mass weight on the red ejecta.

at the center of a sphere and subtending an angle $2\phi$. The solid angle of this cone is

$$\Omega = 2\pi(1 - \cos \phi)$$

(5)

and the volume of the cone is given by $\frac{1}{3}\Omega R^3$. Since there are two cones, we multiply this by 2. Dividing the volume of a sphere by this volume, we obtain

$$w_{m,\text{blue}} = \frac{1}{1 - \cos \phi}$$

(6)

as the weight for the blue ejecta. The weight the red ejecta is

$$w_{m,\text{red}} = \frac{V_{\text{sphere}}}{V_{\text{sphere}} - V_{\text{cones}}} = \frac{1}{\cos \phi}$$

(7)

Fig. 16 shows how $w_{m,\text{blue}}$ and $w_{m,\text{red}}$ behave, depending on different values of $\phi$. $w_{m,\text{blue}}$ approaches infinity as $\phi$ approaches 0, which represents all of the blue ejecta being squeezed into a cone of infinitely small opening angle, while as $\phi$ approaches 0, $w_{m,\text{red}}$ approaches 1, since the entire sphere is essentially composed of red ejecta. The opposite effect happens as $\phi$ approaches 90.
Figure 17: Left: The total weight for the blue component (the product of the mass and area weights) as defined for all $\theta_{JN}$ and $\phi$. Right: The total weight for the red component.

The total weight is calculated as $w_m * A$ for each component. The net weights for all $\phi$ and $\theta_{JN}$ are shown in Fig. 17. Fig. 15 shows the role of each weight in transforming the geometry of the Kasen et al. 2017 SEDs into our geometry for the blue component. First, we apply a mass weight that “compresses” the mass of a sphere into the shape of two cones. Since the surface area of these two cones is smaller than the surface area of the sphere, the flux of photons is greater than the flux through the surface of the sphere even though the total energy output is the same. Then, because only a certain fraction of the sphere is visible, the area weight works to “block out” the part of the cones that is hidden behind the red ejecta. For the red ejecta, the matter is “compressed” by the mass weight into a sphere with two cones removed.

4.2 MOSFiT

I combined the geometrical models described in Section 4.1.2 with the Kasen et al. SEDs for use with the Python program MOSFiT, the Modular Open Source Fitter for Transients. MOSFiT is designed specifically to perform Markov Chain Monte Carlo (MCMC) parameter determination from astrophysical transient lightcurves, such as those from supernovae and
kilonovae [11]. MOSFiT has two modes: generative and determinative. In generative mode, MOSFiT creates exact light curves for a model with a given set of parameters ($M$, $X_{\text{lan}}$, $v_k$, $\phi$, and $\theta_{JN}$). In determinative mode, MOSFiT performs MCMC parameter determination using a model.

When attempting to find best fit parameters for data with a model with more than one or two parameters, it quickly becomes computationally prohibitive to sample the entire space evenly. For example, in a model with eight parameters, if we were to sample 100 points along each dimension, we would have to make a total of $100^8$ samples. To avoid this problem, we use algorithms that can explore the parameter space more efficiently. MCMC methods are a class of algorithms that use a chain of steps to explore the parameter space. Monte Carlo methods use random sampling to make estimations of unknown parameters, and Markov chain methods refers to models where the probability of the next event depends entirely on the state attained from the last event.

For each ‘walker’ walking in a parameter space, the MCMC algorithm first picks a random location for the initial position. Then, the algorithm proposes a new location for that walker, the model is evaluated and scored at that location. If that location is ‘good’ and the new location’s parameters make the residuals of the data and model smaller, that location is added to the chain and the process repeats. If that location is deemed not good enough, the algorithm proposes a different new location, and the process repeats until a location is accepted. However, even if the point is deemed ‘bad,’ there is some probability that the walker will accept that location anyway. This makes sure that the walkers explore the entire parameter space and do not get stuck in local optima. The methods used to determine whether to accept or reject a location vary but generally involve some probabilistic favoring of certain combinations of parameters. Because of this favoring, the walkers spend more time in the region of the parameter space where the parameters fit the data best and can provide us with an inference of the most likely value for the parameters as well as the uncertainty of the parameters [9].

24
In Python, the package emcee is commonly used to perform MCMC parameter determination. emcee uses a set of independent walkers that can explore the parameter space efficiently [9]. MOSFiT is a ‘wrapper’ for emcee that allows for user-friendly fitting of astrophysical transient models and data using MCMC tools [11].

We use both the generative and determinative modes to first, explore the differences in the theoretical predictions of light curves, and second, evaluate the model’s ability to determine $\phi$ and $\theta_{JN}$. 
Table 1: Physical parameter values used in the creation of the lightcurves in Fig. 18.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{\text{blue}}$</td>
<td>0.025$M_{\odot}$</td>
<td>$M_{\text{red}}$</td>
<td>0.04$M_{\odot}$</td>
</tr>
<tr>
<td>$v_{\text{blue}}$</td>
<td>0.3$c$</td>
<td>$v_{\text{red}}$</td>
<td>0.1$c$</td>
</tr>
<tr>
<td>$X_{\text{blue}}$</td>
<td>$1 \times 10^{-4}$</td>
<td>$X_{\text{red}}$</td>
<td>$1 \times 10^{-2}$</td>
</tr>
</tbody>
</table>

5 Results and Discussion

In this chapter, I present the results of various studies done using MOSFiT in both generative and determinative mode. I will also discuss what the results tell us about the ability of this model to constrain the viewing angle.

5.1 Theoretical Predictions

5.1.1 Results

In this section, I discuss the results of studying the exact model predictions of the model I have built. I focus on evaluating the differences in lightcurves between different viewing angles. Fig. 18 provides an intuition for how the lightcurve in each band changes with viewing angle and opening angle. For each lightcurve, I generated data with the physical parameters listed in Table 1. These parameters were chosen because they were closest to those determined to be the best fit parameters for GW170817 using the Kasen et al. 2017 model.

To quantify these results, we plot in each band the change in magnitude of the $\theta_{JN} = 10^\circ$ and $\theta_{JN} = 80^\circ$ versus $\phi$ at three different times: $t \in \{1, 3, 8\}$ days after merger. For example, for u-band (shown in Fig. 18a), and for $\phi = 80^\circ$, this amounts to the difference between the orange line ($\theta_{JN} = 80^\circ$) and the dark green line ($\theta_{JN} = 10^\circ$). The results are shown in Fig. 19a-c.

The results of 19 a-c only communicate the most extreme differences, showing only the difference in magnitude between the most extreme viewing angles of 10° and 80°. To see if the viewing angle could potentially be measured to a level of $\pm 10^\circ$, I plot the average.
Figure 18: Comparison of predicted lightcurves for the same physical parameters but differing viewing and opening angles ($\theta, \phi \in \{10, 40, 80\}$ degrees). Each subplot shows a different band.
difference in magnitude for a $\Delta \theta_{JN}$ of $10^\circ$. For example, for $\phi = 10^\circ$, I compute the average $\Delta m$ for $\theta_{JN} = 0^\circ$ and $10^\circ$, $\theta_{JN} = 10^\circ$ and $20^\circ$, $\theta_{JN} = 20^\circ$ and $30^\circ$, etc., up to $\theta_{JN} = 80^\circ$ and $90^\circ$. The results are shown in Fig. 19 d-f. The error bars represent the spread of the data, indicating the 16th and 84th quantiles and do not represent any measurement errors, since these data are theoretical predictions.

To determine whether changes in other parameters would be degenerate with changes in $\phi$ and $\theta_{JN}$, I created simulated data with varying masses, velocities, and lanthanide fractions. In order to match the relative properties of the blue and red ejecta, I plot only the simulations where $M_{\text{red}} > M_{\text{blue}}$, $X_{\text{red}} > X_{\text{blue}}$, and $v_{\text{red}} < v_{\text{blue}}$. For the parameters not varied in a given study, I fixed them to the parameters in Table 1, and $\phi = 40^\circ$ and $\theta_{JN} = 30$. For example, in Fig. 20, $v_{\text{blue}}$, $v_{\text{red}}$, $X_{\text{blue}}$, and $X_{\text{red}}$ are given by 1 and and $\phi = 40^\circ$ and $\theta_{JN} = 30$. The values for mass are shown in the legend.

5.1.2 Discussion

Overall, the raw results indicate that there is a difference in the lightcurves depending on the viewing angle and the opening angle. It may therefore be possible to recover the viewing angle using this model. For each band in Fig. 18, for a given opening angle, the overall brightness increases as the half-opening angle is decreased. This is because squeezing the ‘blue’ mass into a cone, which corresponds to reducing the half-opening angle, significantly increases the overall flux of photons through the decreasing blue cone surface. Squeezing the red component into a thin disk does not have the same effect because the red component is overall less energetic than the blue and the blue component, although in a larger cone, still outshines the red component.

Furthermore, while the differences in Fig. 19 a-c are large and quite detectable (an error of $\pm 0.1$ magnitudes is readily achievable for observations using DECam), the average differences for a $\Delta \theta_{JN}$ of $10^\circ$ (Fig. 19d-f) are only on the order of a few tenths of a magnitude. However, even if a telescope has limited observing time and bands, using a combination of
Figure 19: (a-c) Absolute value of differences in magnitude for $\theta_{JN} = 80^\circ$ and $\theta_{JN} = 10^\circ$ versus $\phi$ for simulations with the parameters given in Table 1 for $t = 1, 3, \text{ and } 8$ days. (d-f) Average differences in magnitude for $\Delta \theta_{JN} = 10^\circ$ for $t = 1, 3, \text{ and } 8$ days.
Figure 20: Comparison of predicted lightcurves all parameters fixed except for $M_{\text{red}}$ and $M_{\text{blue}}$. Each subplot shows a different band.
Figure 21: Comparison of predicted lightcurves all parameters fixed except for $X_{\text{red}}$ and $X_{\text{blue}}$. Each subplot shows a different band.
Figure 22: Comparison of predicted lightcurves all parameters fixed except for $v_{\text{red}}$ and $v_{\text{blue}}$. Each subplot shows a different band.
u-band or g-band within the first three days after trigger and z-band at later times, and extending the observations out to eight days, may still allow for recovery of the viewing and opening angles.

Lastly, from Figures 20, 21, and 22 it seems that the effects of changing the other parameters are different from the effects of changing the opening and viewing angles. The effect of changing mass, like changing the opening angle viewing angles, is that the entire lightcurve is translated vertically. However, the lightcurve also slightly changes shape. For lower mass, in the red bands, the light curve is more ‘flat,’ having a longer time at constant brightness. Changing lanthanide fraction also significantly changes the position and shape of the lightcurve. Lastly, changing velocity moves the peak of the light curve, with smaller total velocities producing a kilonova that peaks later.

5.2 Recovery Using MCMC Methods

Guided by the positive results from the model predictions, I created a set of mock data files and attempted to recover the viewing and opening angles using MOSFiT in determinative mode. I explored twenty five simulations, with \( \phi \in \{15, 25, 35, 45, 55, 65\} \) degrees and \( \theta_{JN} \in \{15, 30, 45, 60, 75\} \) degrees. The other physical parameters constant were fixed at the values in Table 1.

5.2.1 Results

Using a simulated observational error \( \pm 0.02 \) magnitudes for each data point, I ran MOSFiT with the two free parameters (\( \phi \) and \( \theta_{JN} \)), with 128 walkers for 500 steps each.

Each walker determines its own final position independently of other walkers. For two representative simulations, the final distribution of these parameters is shown in the triangle histogram plots of Fig. 23. The solid line represents the true, known values of the two parameters \( \phi \) and \( \theta_{JN} \). The dashed lines represent the 16th, 50th (the mean), and 84th quantiles of the final walker distribution, and the difference between the 84th and 16th
Figure 23: Lightcurves (input data and all walker models) as well as the distribution of parameters for two representative parameter combinations for the first ejecta parameter set.
a) $\phi=15^\circ$

b) $\phi=25^\circ$

c) $\phi=35^\circ$

d) $\phi=45^\circ$

e) $\phi=55^\circ$

f) $\phi=65^\circ$

Figure 24: $\theta_{JN}$ measured by MOSFiT versus the true $\theta_{JN}$ for five values of $\phi$ using the values described in Table I for the ejecta parameters. The error bars represent the 1$\sigma$ spread of all the values determined by all 128 walkers.
Figure 25: $1\sigma$ ranges for $\theta_{JN}$ for all sets of simulations.

Figure 26: $1\sigma$ ranges for $\theta_{JN}$, averaged over all $\theta_{JN}$ in each set for a given $\phi$. 
quantile represents the 68th percentile, or the 1σ level. Fig. 23 also shows the final model light curves, with each of the 128 final model light curves plotted. Each line represents a model as determined by a given combination of parameters as determined by each of the 128 walkers. All final position distribution and light curve plots are given in Appendix A.

Fig. 24 summarizes the results by showing the 1σ level for each simulation, including the line that would correspond to a perfect measurement of the true θ_JN.

For each simulation, Fig. 25 shows the 1σ level for θ_JN. Fig. 26 shows the 1σ level averaged over all θ_JN for a given φ.

### 5.2.2 Discussion

From these results, the geometrical model seems to be effective at differentiating between different combinations of viewing angles and opening angles. From Fig. 25 it seems that the model is most efficient at small φ and large θ_JN, since the 1σ ranges are smallest. However, simulation studies suggest that the half-opening angle for typical BNS events should be around 60° [24]. Around this φ, we can only expect the model to constrain the viewing angle with an error of 25°. Referring back to Fig. 4 the 1σ area for H_0 versus iota spans approximately 35°. Constraining the viewing angle even with an uncertainty of 25° would reduce the area of the distribution of H_0 versus viewing angle.

However, in this work, I have only presented the results of fitting for only for φ and θ_JN and kept all the other parameters fixed. In real event BNS analyses, all the parameters will be allowed to vary since the signature of the ejected mass comes in the form UVOIR light, and we have no other way to constrain these parameters. Allowing all parameters to vary will most certainly decrease the model’s constraining power.
6 Conclusion

6.1 Recommendations for Observational Strategy

The optimal strategy for observing an event is of course to observe in as many bands, as often as possible. However, there are practical limitations that prevent this. For example, telescopes can often only observe to a maximum magnitude in a reasonable amount of time. For DECam, this limiting magnitude is about 23. From a telescope operation perspective, it is better to observe in the redder bands at later times. While results from Section 5.1 suggest that the greatest differences in light curves between different sets of parameters will be most apparent in bluer ($u$ and $g$) bands at early times, at later times, the differences are also significant in redder ($z$ and $Y$) bands. Therefore, the optimal strategy from a telescope perspective as well as a parameter determination perspective is to observe first in bluer bands, then after a few days, in redder bands.

Another limitation is that the event may not be found right after trigger. If the trigger comes in during the nighttime, or the first night is cloudy, the next event may not be observed until a few days later. The blue component fades much more quickly than the red component, as seen in the different shape of the lightcurves in Fig. 18a and e. If the event is not identified until a few days after initial trigger, it is more helpful to observe in the redder bands because they will hold more useful information.

Lastly, telescopes operate on tight schedule, with certain amount of hours in a night being dedicated to a certain project. Therefore, an unplanned yet opportunistic event like a BNS merger may interrupt regularly scheduled observations but only be given a certain amount of observing time. In this case, decisions must be made about the optimal strategy for the limited amount of time. Since switching bands may take up more time, the decision will have to be made about which bands are best to observe in.
6.2 Future Work

The results from Section 5.2.1 seem promising. The model seems to be able to differentiate among different viewing and opening angles, and this model may be able to do the same for data from real events. However, this work was completed with only two free parameters: $\theta_{JN}$ and $\phi$. For a real event, all parameters would have to be free. The results from Figures 20, 21, and 22 make us hopeful about the model’s ability to constrain the other parameters since changing the other parameters seem to produce changes in lightcurves that are distinguishable, at least to the human eye, to changes in $\phi$ and $\theta_{JN}$.

Another natural addition to the model currently implemented in MOSFiT would be to build an SED interpolator. As the model currently stands, only a discrete set of parameter combinations are allowed (as defined by the simulations performed by Kasen et al. 2017). In total, determining a single mock data point observation requires determining the SED with three physical parameters ($X_{lan}, v_k, M$), then pulling the correct times and wavelengths from the SED. At the beginning of this project, we attempted to build an interpolator, both using numerical interpolation methods and through a function that approximates the entire parameters space. Both of these methods failed simply because of the large amount of data involved. However, building an interpolator would allow for more precise parameter fitting of real event data.

While the methods presented in this thesis have only been shown to work in the case of two free parameters, the work presented will serve as solid groundwork for building inclination angle dependency into kilonova models within the MOSFiT framework. As more BNS events are observed, we will learn more about this system. Other models may rely on different physical parameters, study different geometries, or add more kilonova components. Since the code is freely available online, future studies can investigate new models much more quickly.
Appendices

A  Simulated Light Curves and Corner Plots for Full Simulation Set

Figure 27: Light curve and corner plot for $\phi = 15^\circ$ and $\theta_{JN} = 15^\circ$
Figure 28: Light curve and corner plot for $\phi = 25^\circ$ and $\theta_{JN} = 15^\circ$

Figure 29: Light curve and corner plot for $\phi = 35^\circ$ and $\theta_{JN} = 15^\circ$
Figure 30: Light curve and corner plot for $\phi = 45^\circ$ and $\theta_{JN} = 15^\circ$

Figure 31: Light curve and corner plot for $\phi = 55^\circ$ and $\theta_{JN} = 15^\circ$
Figure 32: Light curve and corner plot for $\phi = 65^\circ$ and $\theta_{JN} = 15^\circ$

Figure 33: Light curve and corner plot for $\phi = 75^\circ$ and $\theta_{JN} = 15^\circ$
Figure 34: Light curve and corner plot for $\phi = 15^\circ$ and $\theta_{JN} = 30^\circ$

Figure 35: Light curve and corner plot for $\phi = 25^\circ$ and $\theta_{JN} = 30^\circ$
Figure 36: Light curve and corner plot for $\phi = 35^\circ$ and $\theta_{JN} = 30^\circ$

Figure 37: Light curve and corner plot for $\phi = 45^\circ$ and $\theta_{JN} = 30^\circ$
Figure 38: Light curve and corner plot for $\phi = 55^\circ$ and $\theta_{JN} = 30^\circ$

Figure 39: Light curve and corner plot for $\phi = 65^\circ$ and $\theta_{JN} = 30^\circ$
Figure 40: Light curve and corner plot for $\phi = 75^\circ$ and $\theta_{JN} = 30^\circ$

Figure 41: Light curve and corner plot for $\phi = 15^\circ$ and $\theta_{JN} = 30^\circ$
Figure 42: Light curve and corner plot for $\phi = 25^\circ$ and $\theta_{JN} = 30^\circ$

Figure 43: Light curve and corner plot for $\phi = 35^\circ$ and $\theta_{JN} = 30^\circ$
Figure 44: Light curve and corner plot for $\phi = 45^\circ$ and $\theta_{JN} = 30^\circ$

Figure 45: Light curve and corner plot for $\phi = 55^\circ$ and $\theta_{JN} = 30^\circ$
Figure 46: Light curve and corner plot for $\phi = 65^\circ$ and $\theta_{JN} = 30^\circ$

Figure 47: Light curve and corner plot for $\phi = 75^\circ$ and $\theta_{JN} = 30^\circ$
Figure 48: Light curve and corner plot for $\phi = 15^\circ$ and $\theta_{JN} = 45^\circ$

Figure 49: Light curve and corner plot for $\phi = 25^\circ$ and $\theta_{JN} = 45^\circ$
Figure 50: Light curve and corner plot for $\phi = 35^\circ$ and $\theta_{JN} = 45^\circ$

Figure 51: Light curve and corner plot for $\phi = 45^\circ$ and $\theta_{JN} = 45^\circ$
Figure 52: Light curve and corner plot for \( \phi = 55^\circ \) and \( \theta_{JN} = 45^\circ \)

Figure 53: Light curve and corner plot for \( \phi = 65^\circ \) and \( \theta_{JN} = 45^\circ \)
Figure 54: Light curve and corner plot for $\phi = 75^\circ$ and $\theta_{JN} = 45^\circ$

Figure 55: Light curve and corner plot for $\phi = 15^\circ$ and $\theta_{JN} = 60^\circ$
Figure 56: Light curve and corner plot for $\phi = 25^\circ$ and $\theta_{JN} = 60^\circ$

Figure 57: Light curve and corner plot for $\phi = 35^\circ$ and $\theta_{JN} = 60^\circ$
Figure 58: Light curve and corner plot for $\phi = 45^\circ$ and $\theta_{JN} = 60^\circ$

Figure 59: Light curve and corner plot for $\phi = 55^\circ$ and $\theta_{JN} = 60^\circ$
Figure 60: Light curve and corner plot for $\phi = 65^\circ$ and $\theta_{JN} = 60^\circ$

Figure 61: Light curve and corner plot for $\phi = 75^\circ$ and $\theta_{JN} = 60^\circ$
Figure 62: Light curve and corner plot for $\phi = 15^\circ$ and $\theta_{JN} = 75^\circ$

Figure 63: Light curve and corner plot for $\phi = 25^\circ$ and $\theta_{JN} = 75^\circ$
Figure 64: Light curve and corner plot for $\phi = 35^\circ$ and $\theta_{JN} = 75^\circ$

Figure 65: Light curve and corner plot for $\phi = 45^\circ$ and $\theta_{JN} = 75^\circ$
Figure 66: Light curve and corner plot for $\phi = 55^\circ$ and $\theta_{JN} = 75^\circ$

Figure 67: Light curve and corner plot for $\phi = 65^\circ$ and $\theta_{JN} = 75^\circ$
Figure 68: Light curve and corner plot for $\phi = 75^\circ$ and $\theta_{JN} = 75^\circ$
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