



Distinguishing KNe from NSBH and BNS Mergers

CONTRIBUTORS

Yugesh Bhoge
IIT Bombay

Dr. Ish Gupta
UC, Berkeley

Dr. Rahul Kashyap
IIT Bombay

Dr. Mukul Bhattacharya
IIT Indore

Roadmap

"A goal without a plan is just a wish."
- Antoine de Saint-Exupéry

1

Motivation

2

Core Problem

3

Methodology

4

Results

5

Caveats

6

Conclusion

Motivation

Multi-Messenger

Great Potential

CBC mergers with at least one Neutron Star (NS) are premier sources for multi-messenger astronomy.

Proof of Concept

GW170817

The BNS event GW170817 established the first joint GW and EM observations.

The Gap

NSBH Missing Link

Despite BNS success, no EM counterpart for NSBH mergers has been detected to date.

Core Problem

"Nature uses only the longest threads to weave her patterns."

- Richard Feynman

"Unfortunately, she also knots them so we can't tell HMNS from LMBH."

Mass Degeneracy

2.5 – 5 M_{\odot} Range

Estimations are often degenerate, making it hard to distinguish HMNS from LMBH.

Detection Limits

Sub-threshold Events

LMBH binaries produce weaker GW signals, often detected by only a single interferometer.

The Key Challenge

KN Signature Alone

Can a Kilonova (KN) observation alone identify a BNS vs. NSBH progenitor without GW data?

Methodology

1. Input Physics

Population Synthesis
Uniform BNS & NSBH distribution

2. Binary Sampling & Ejecta

NR Fitting Formulae to calculate
ejecta masses (dynamical and disk)

$m_1, m_2, \chi_{\text{BH}}, \Lambda_{\text{NS}}$

3. Disruption Check

Condition: $R_{\text{tidal}} > R_{\text{ISCO}}$
Else: Dark Merger

4. Light Curve Modeling

Lightcurve calculation via ACV LC Model

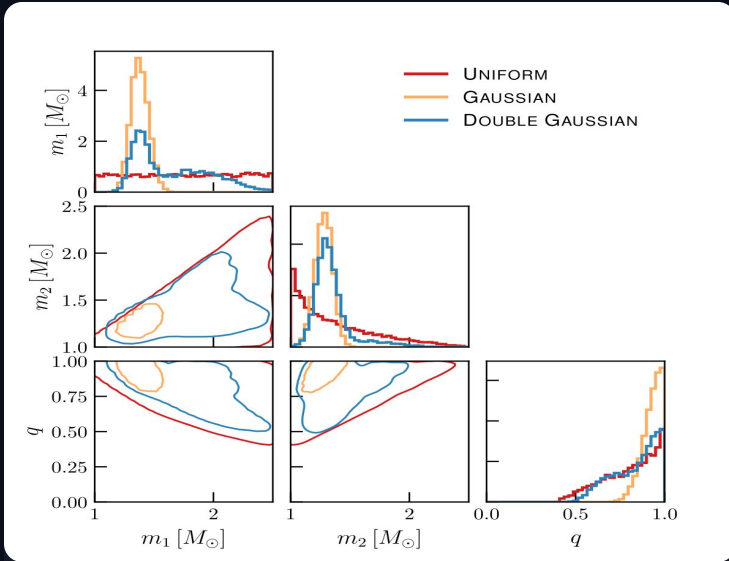
$d\varepsilon/dt \propto t^{-\alpha}$

5. Resultant Observables

Synthetic Kilonova Parameters

$t_{\text{peak}}, M_{\text{peak}}, \Delta m$

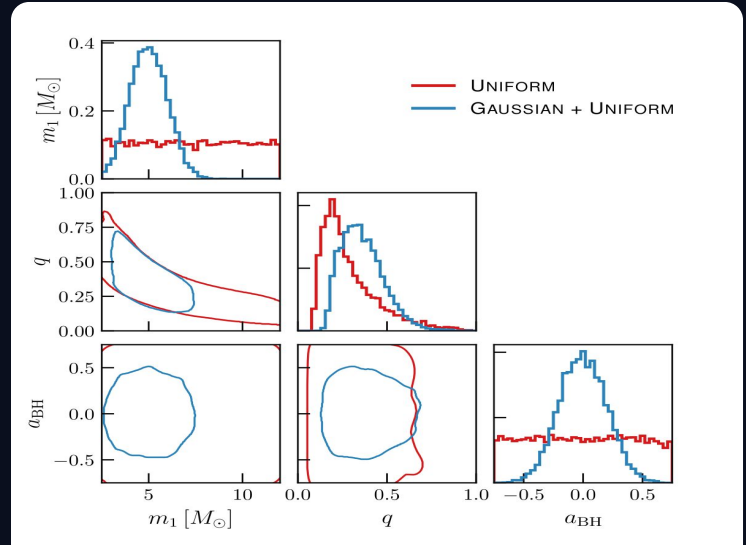
Methodology: Population Synthesis



BNS Populations

Mass priors: Uniform, Gaussian, and Double Gaussian.

Statistical Priors



NSBH Populations

Mass priors: Uniform and "Gaussian + Uniform" prescription.

Methodology: Modeling Ejecta

BNS Merger

Ejecta Mass

Disk (winds + viscous heating) + Dynamical (Shock heated + Tidal tails)

Colors & Opacities

Blue, Purple, Red | κ : [0.5, 3, 10]

Component Fraction

[0.2, 0.6, 0.2]

NSBH Merger

Ejecta Mass

Disk + Dynamical components

Colors & Opacities

Blue, Red | κ : [4, 36]

Component Fraction

Variable distribution

Kilonova Light Curve Generation

01. Energy Source & Efficiency

Powered by radioactive decay of r-process nuclei, governed by thermalization efficiency $\epsilon_{th}(t)$. **Barnes et al. (2016)**

$$\epsilon_{th}(t) = 0.36 \left[e^{-at} + \frac{\ln(1 + 2bt^d)}{2bt^d} \right]$$

02. Ejecta Component Evolution

Independent diffusion zones modeled via expansion (τ_{exp}) and diffusion (τ_{diff}) timescales.

$$\tau_{exp} = \frac{R}{v}, \quad \tau_{diff} = \frac{\kappa M}{\beta c R}$$

03. Peak Luminosity Approximation

The time of peak luminosity (t_{peak}) is determined as a geometric mean of the primary timescales.

$$t_{peak} \approx \sqrt{\tau_{exp} \tau_{diff}}$$

Defining Photometric Observables

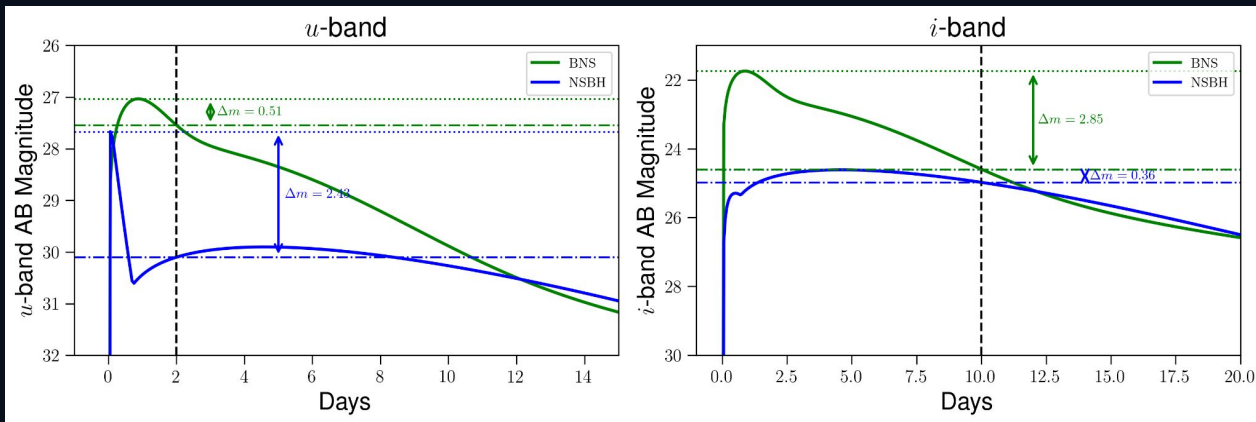
1. Characterization

Light curves are characterized by post-peak

decline: $\Delta\text{mag} = m_{\text{peak}} - m_{\text{peak}+\Delta t}$

2. Evaluation Matrix

Measured at fixed delay times $\Delta t = [1, 2, 5, 10, 15]$ days across u, g, r, i, z, y bands.



Results:

1. OPTIMAL SEPARATION WINDOWS

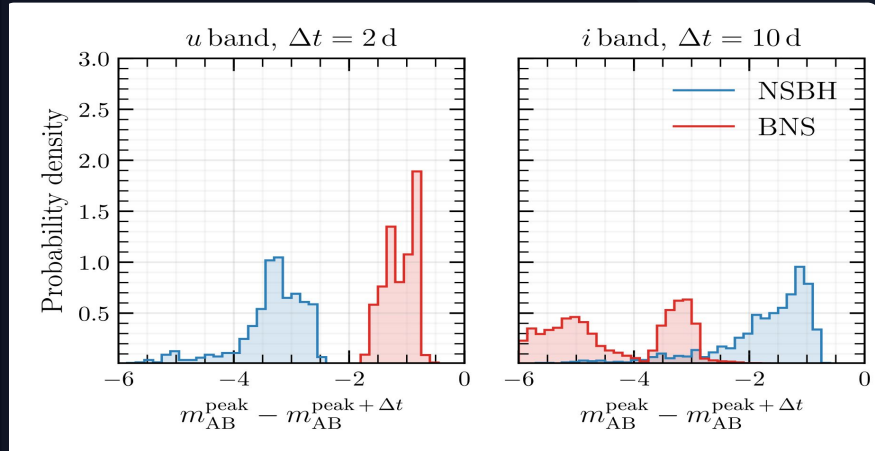
Maximum distinction occurs in the **u-band** at 2 days and the **i-band** at 10 days.

2. U-BAND DYNAMICS (EARLY)

NSBH KNe dim rapidly ($\gtrsim 3$ mag) compared to BNS KNe (~ 1 mag) over the first 48 hours.

3. I-BAND REVERSAL (LATE)

The trend reverses at late times: NSBH KNe exhibit slower decay rates than BNS KNe.



Post-peak decline for fiducial populations showing probability density across u and i bands.

Robustness Analysis

Test 1: Astrophysical Populations

- **Methodology**

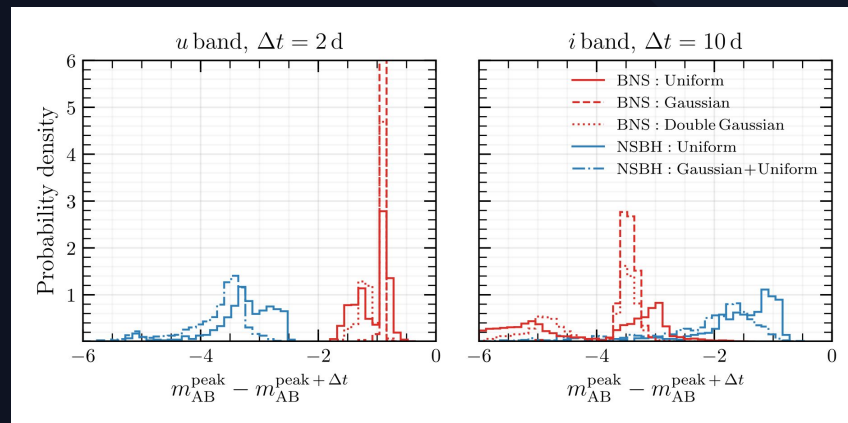
Analysis repeated using restrictive, observation-motivated mass priors.

- **BNS vs NSBH Separation**

Morphological distinction remains robust, particularly within the u-band.

- **Key Observation**

NSBH systems occupy the rapidly declining u-band region with minimal overlap.



Comparative Probability Density: u-band (left) vs i-band (right)

Robustness Analysis

Test 2: Equation of State (EOS) Impact

- **Compactness Control**

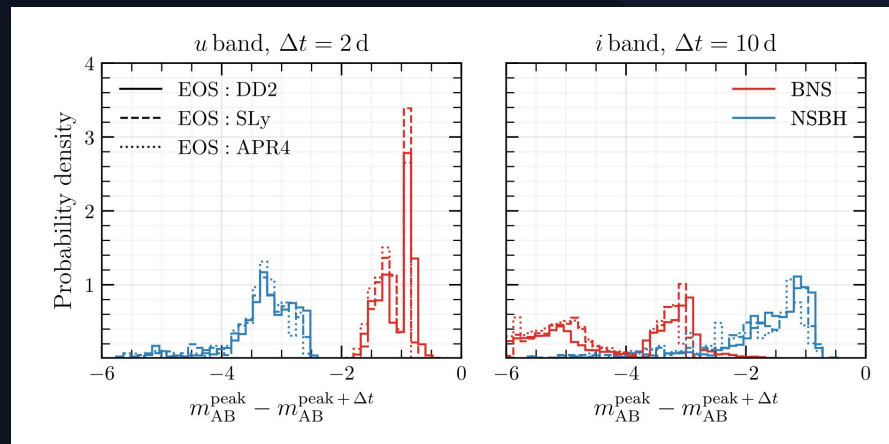
EOS dictates NS compactness, directly controlling tidal disruption and ejecta mass scales.

- **EOS Range Tested**

Evaluation spanning DD2 (stiffest), SLy, and APR4 (softest) to ensure model stability.

- **Key Conclusion**

Softer EOS yields smaller ejecta and faster decay, yet BNS/NSBH separability is preserved.



Post-peak decline variations across tested NS Equations of State

Robustness Analysis

Test 3: Composition and Model Parameters

- **Color Evolution**

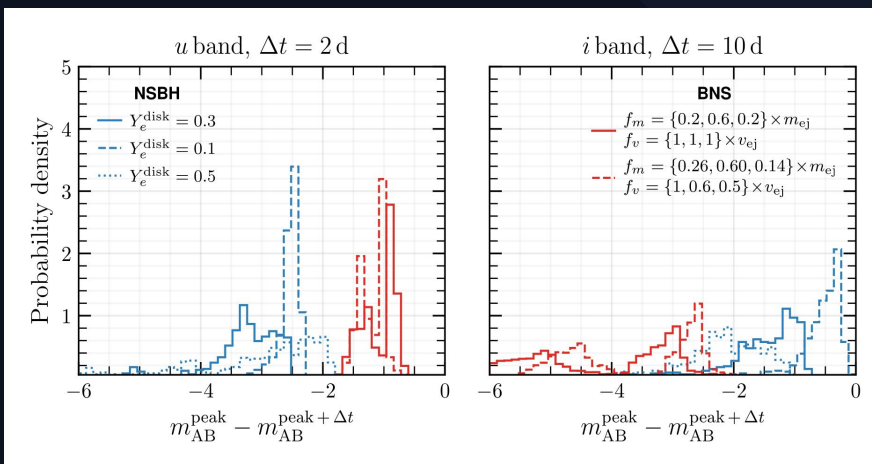
Varying NSBH disk wind electron fraction (Y_e) significantly alters photometric color tracks.

- **Disk Opacity**

Lower opacity ($Y_e = 0.5$) increases i-band overlap; however, source classes remain distinguishable.

- **Ejecta Kinematics**

Shifts in mass and velocity alter distributions, but qualitative separations between BNS/NSBH persist.



Distribution shifts relative to ejecta-model parameter variations.

Robustness Analysis

Test 4: Impact of Numerical Relativity Fitting Formulae

- **Bimodality**

Old BNS fits from *Nedora et al* can introduce artificial bimodality via hyperbolic tangent function saturation.

$$\log_{10} \left(\frac{M_{\text{disk}}^{\text{BNS}}}{M_{\odot}} \right) = \max \left[-3.0, \log_{10} \left(\alpha + \beta \tanh \left(\frac{\tilde{\lambda} - \gamma}{\delta} \right) \right) \right], \quad (\text{A2})$$

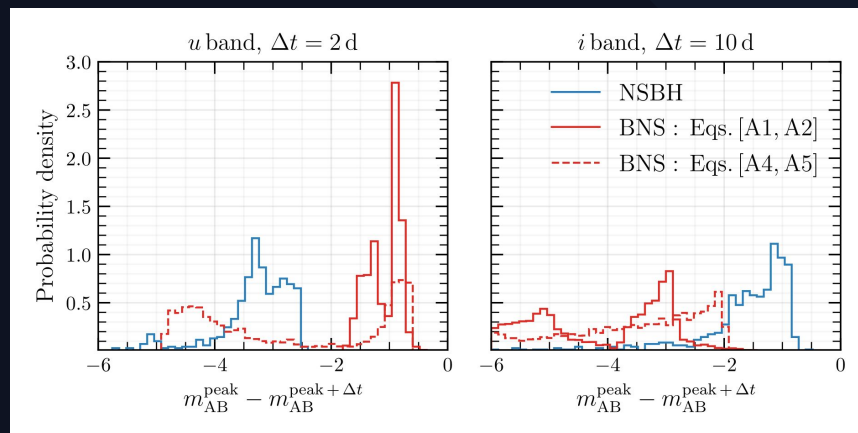
- **Alternative Fitting**

New *Nedora et al* eq ensure smooth distributions but require numerical floors.

$$\log_{10} \left(\frac{M_{\text{disk}}^{\text{BNS}}}{M_{\odot}} \right) = \log_{10} M_1 + \max(-3.3, \gamma \log_{10}(\alpha C_{\text{NS},1} + \beta)), \quad (\text{A5})$$

- **Classification Viability**

BNS/NSBH separation remains viable despite fit-dependent quantitative overlaps.



Comparison of BNS ejecta mass fit prescriptions across observed bands.

Correlation with Binary Parameters

Results: BNS and NSBH System Evolution

- **BNS Evolution**

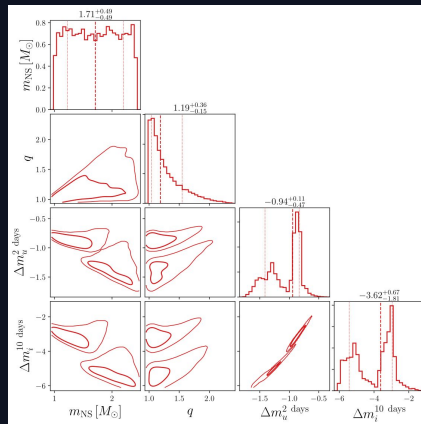
Lower mass Neutron Stars yield larger ejecta and slower post-peak evolution tracks.

- **NSBH Dynamics**

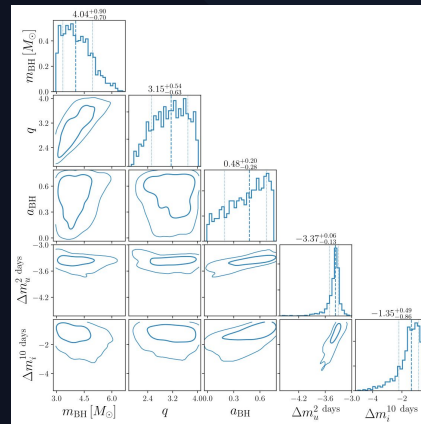
Lower BH mass and higher spin are strongly associated with a significantly slower decline.

- **Comparable mass regime**

Around $2.5M_{\odot}$ both system shows distinction.



BNS: Parameters vs. Decline



NSBH: Parameters vs. Decline

Modeling Caveats

Systematic uncertainties in synthetic kilonova light curve generation

- **Analytical Fits**

Inherit roughly 10% errors from numerical relativity calibration. Old BNS fits introduces artificial bimodality.

- **Heating Rates**

Standard functional forms used, but isotopic abundances vary significantly between merger classes.

- **Geometry**

Assumption of isotropic emission neglects viewing-angle effects and internal composition gradients.

- **Radiative Transfer**

Complex opacity variations are simplified using semi-analytic floors, impacting color tracks.

Summary & Conclusions

Post-peak photometric decline as a robust classification probe

Overcoming GW Ambiguity

Distinguishing BNS from NSBH is critical but challenging via GW data alone due to low-mass ambiguity. Photometry provides a robust tie-breaker.

u-band: Early Diagnostic

NSBH decays rapidly (≥ 3 mag) over 2 days.
BNS decays slowly (~ 1 mag).

i-band: Late Diagnostic

NSBH decays more slowly than BNS over 10 days.
Trend reversal allows for high-confidence classification.

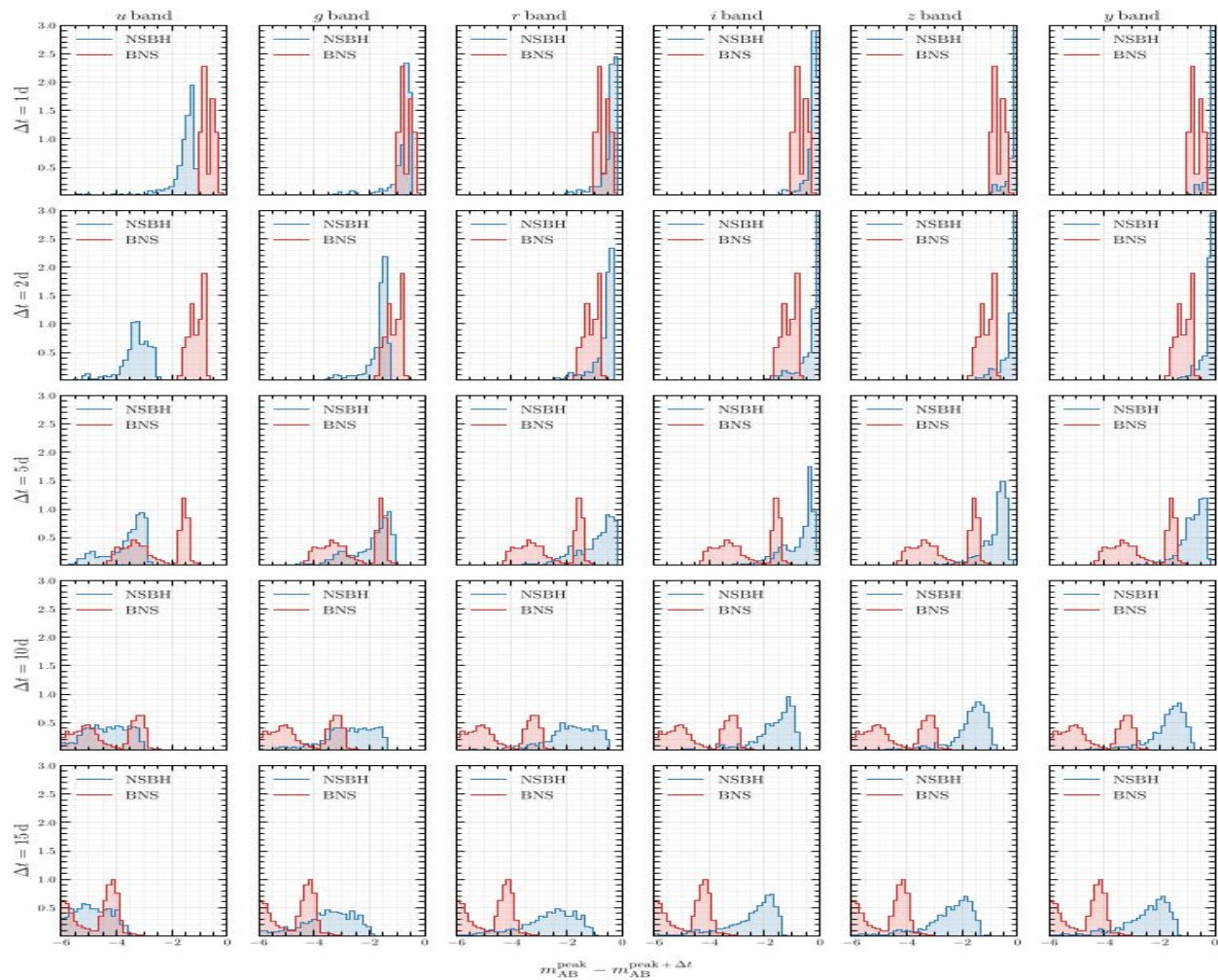
Future Outlook

These diagnostics are vital for classifying orphan kilonovae in next-generation optical surveys where GW counterparts may be absent.

Population	$m_1 (M_\odot)$	$m_2 (M_\odot)$
BNS		
Uniform	$\mathcal{U}(1, 2.5)$	$\mathcal{U}(1, m_1)$
Gaussian	$\mathcal{N}(1.33, 0.9)$	
Double Gaussian	$0.64 \times \mathcal{N}(1.33, 0.9) + 0.36 \times \mathcal{N}(1.8, 0.3)$	
NSBH		
Uniform	$\mathcal{U}(2.5, 12)$	$\mathcal{U}(1, 2.5)$
Gaussian+Uniform	$\mathcal{N}(5, 1)$	$\mathcal{U}(1, 2.5)$

For the *ugrizy* bands, we use the following wavelengths: $\lambda_u = 3.546 \times 10^{-7}$ m, $\lambda_g = 4.670 \times 10^{-7}$ m, $\lambda_r = 6.156 \times 10^{-7}$ m, $\lambda_i = 7.472 \times 10^{-7}$ m, $\lambda_z = 8.917 \times 10^{-7}$ m, and $\lambda_y = 1.0305 \times 10^{-6}$ m.

$$L_{bol}(t) = 2 \exp\left(-\frac{t^2}{\tau^2}\right) \int_{t_i}^t \dot{Q}(t') \times \epsilon_{th}(t') \times \frac{t'}{\tau^2} \times \exp\left(\frac{t'^2}{\tau^2}\right) dt'$$



In the u band, the effect is more pronounced. With the alternative fits, one branch of the BNS distribution moves closer to negligible ($\lesssim 0.5$ mag) decline, corresponding to very slowly evolving blue emission, while a second branch peaks near -5 , indicating much more rapid fading. This rapidly declining branch comprises systems with $M_1 \gtrsim 1.6 M_\odot$, for which the inferred disk mass is driven to the floor value of $\sim 5 \times 10^{-4} M_\odot$. Consequently, although these systems appear to overlap with NSBH mergers in the post-peak decline distribution, this overlap is an artifact of the fit reaching its calibration floor rather than a robust physical prediction.