Evaluating Neutron Star Mergers Using Multi-Messenger Astrophysics and ZTF Transients

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Introduction

Kilonovae are the electromagnetic transients created by the radioactive decay of synthesized elements surrounding a neutron star merger (NSM). Kilonovae from NSMs are difficult to detect because of their inherent short-lived behavior and infrared nature. Much work needs to be done to improve detection procedures in this field. Currently, the best data available on this topic are from the gravitational wave signal GW170817 and its accompanying kilonova AT2017gfo. Measures are currently being taken to produce a more reliable detection framework. Faster kilonova identification pipelines will allow for a rapid slew of the telescopes for subsequent follow-up observations. The LANL-ZTF Summer School addresses multiple aspects of this problem.

M. Tousif Reza - Equation of State and Structural Properties of Neutron Star

Neutron stars are the most compact material objects in the universe. They represent unique systems of matter under extreme conditions of pressure and density, exhibiting a variety of fascinating properties that can be inferred from astronomical observations. We explore MIT Bag Model with density dependent bag pressure to model neutron star's matter. We construct the Equation of State using purely quark matter in Bodmer & Witten conjecture. Solving Tolman-Oppenheimer-Volkoff Equations we study mass-radius, compactness parameter and surface gravitational redshifts etc. In addition, we extend our work to incorporate GR effects to compute tidal Love number and tidal deformability [1] which are the crucial parameters for neutron stars merger. Our preliminary work shows good agreement for mass-radius and tidal deformability measurements of GW170817. Combined observations of GW and Kilonova are necessarily required for better understanding of Neutron stars Equation of State.

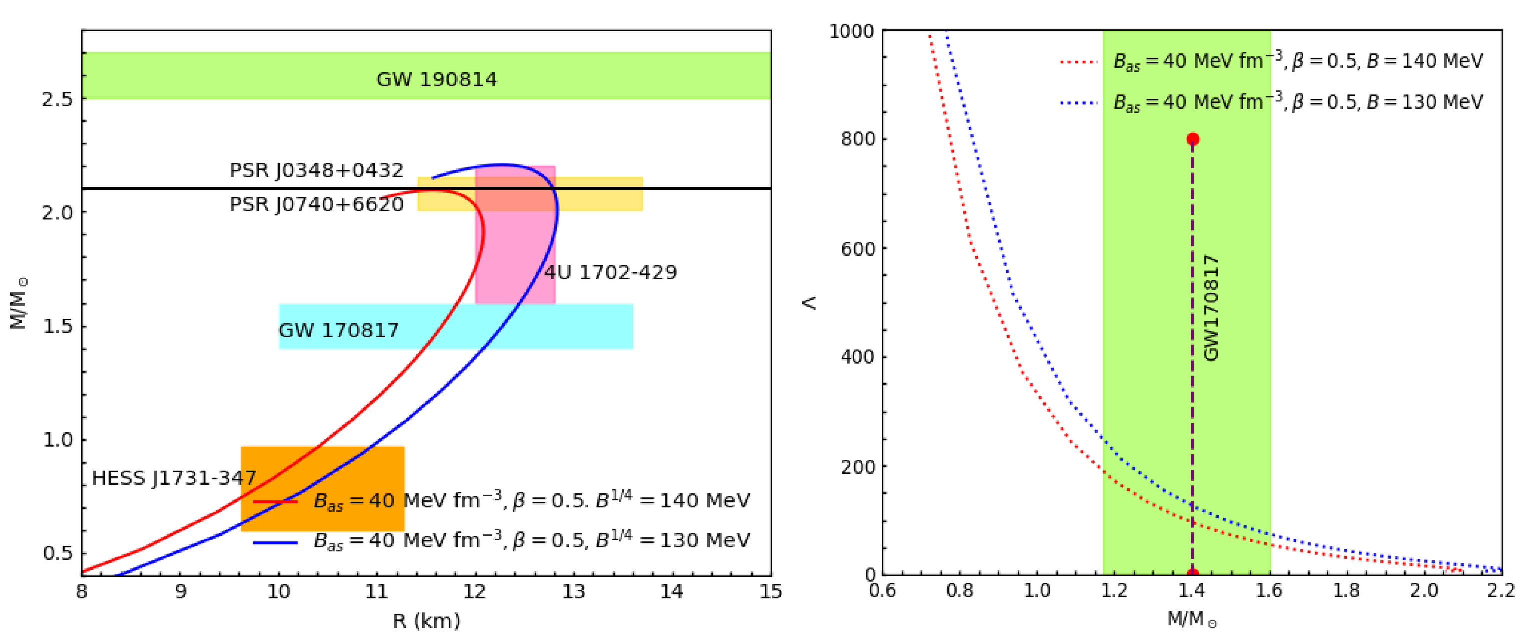

Chart 1. Left fig: Mass vs Radius plot. Right fig: Mass vs Tidal deformability plot.

Yuan Feng – Modeling Superfluidity with FlecSPH

Here we try to model superfluid in neutron stars using two-fluid approach within the FlecSPH [2a] framework. By using the mesh-free Lagrangian method, we solve the partial differential equations for fluid elements of normal fluid and superfluid [2b]. The total number density current and energy-momentum tensor are defined as below. Baryon number conservation is given by the coupled equations of each component. We considered the pinned limit of superfluid case. Our goal is to simulate mergers of two neutron stars with superfluid cores.

$$\mathcal{N}^\mu = n u^\mu + f^2 \xi^\mu$$

$$T^{\mu\nu} = e u^\mu u^\nu + P\Delta^{\mu\nu} + f^2 \xi^\mu \xi^\nu$$

$$\rho h \Gamma \frac{du^\mu}{dt} + f^2 e_S \Gamma_S \frac{d\xi^\mu}{dt} = -\nabla_\mu P\left(g^{\mu\nu} + u^\mu u^\nu\right),$$

$$\frac{d\xi^i}{dt} = \epsilon^i_{jk} v^j B^k - \partial_i \xi^0 + v^\ell_S \partial_\ell \xi^i$$

Felipe Fontinele Nunes - New Composition-Dependent LANL Kilonovae Grid

To explore the effect of ejecta properties on the kilonovae light curves, we design a new grid of two-component, 2D axisymmetric kilonovae simulations to study the impact of ejecta properties on the light curves. These simulations vary in mass, velocity, morphology, and composition, and improve on the previous one [3a] by employing realistic ejecta composition and incorporating stochastic elements to quantify the impact of parameter space variance on the modelled spectra.

Using the Monte Carlo radiative transfer code SuperNu [3b] using a full suite of lanthanide and fourth-row element opacities, we will simulate a total of 2560 models, consisting of a toroidal neutron-rich ejecta and robust r-process composition, sampled from the interval $Y_{e,dyn}\in[0.05,0.2]$, and either spherical or lobed neutron-poor ejecta with $Y_{e,wind}\in\{0.1,0.2,0.3,0.4\}$, both with relative randomization in the mass fractions of individual elements at each point. Each component's mass and velocity will range from 0.001 to 0.1 $M_{\odot}$ and 0.05 to 0.3c, respectively. We plan to incorporate this robust grid in NMMA to improve the comparison of model light curves and spectra with future multi-messenger observations of neutron star mergers.

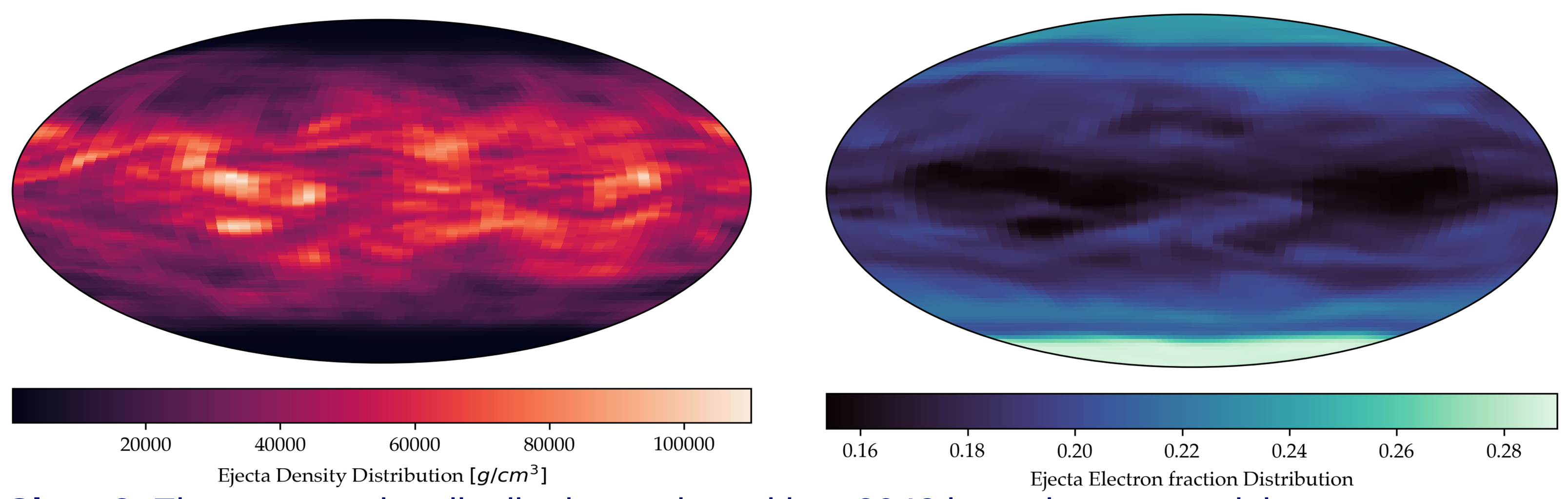

Chart 2. Ejecta properties distribution projected in a 2948 km sphere around the merger. Left fig: Density. Right fig: Electron fraction.

Michael C. Davis & Madison Reuter - NMMA Preliminary Results

The Nuclear-physics Multi-Messenger Astronomy (NMMA) framework is a Bayesian pipeline used to analyze gravitational wave and electromagnetic data. Photometric and spectroscopic data from the Zwicky Transient Facility (ZTF) have been identified as possible kilonovae. Michael is analyzing ZTF transients with NMMA to create a kilonovae classifier.

For Madison's project, a set of simulated kilonova spectra was ran through a variety of visual filters, resulting in a single magnitude value per filter and timestep. These models will be input into the NMMA framework to compare against the observed light curves. The new models are spherically-symmetric and cover a range of electron fractions [4]. Implementing a test for composition does not yet exist within NMMA: the current models do not account for the electron fraction.

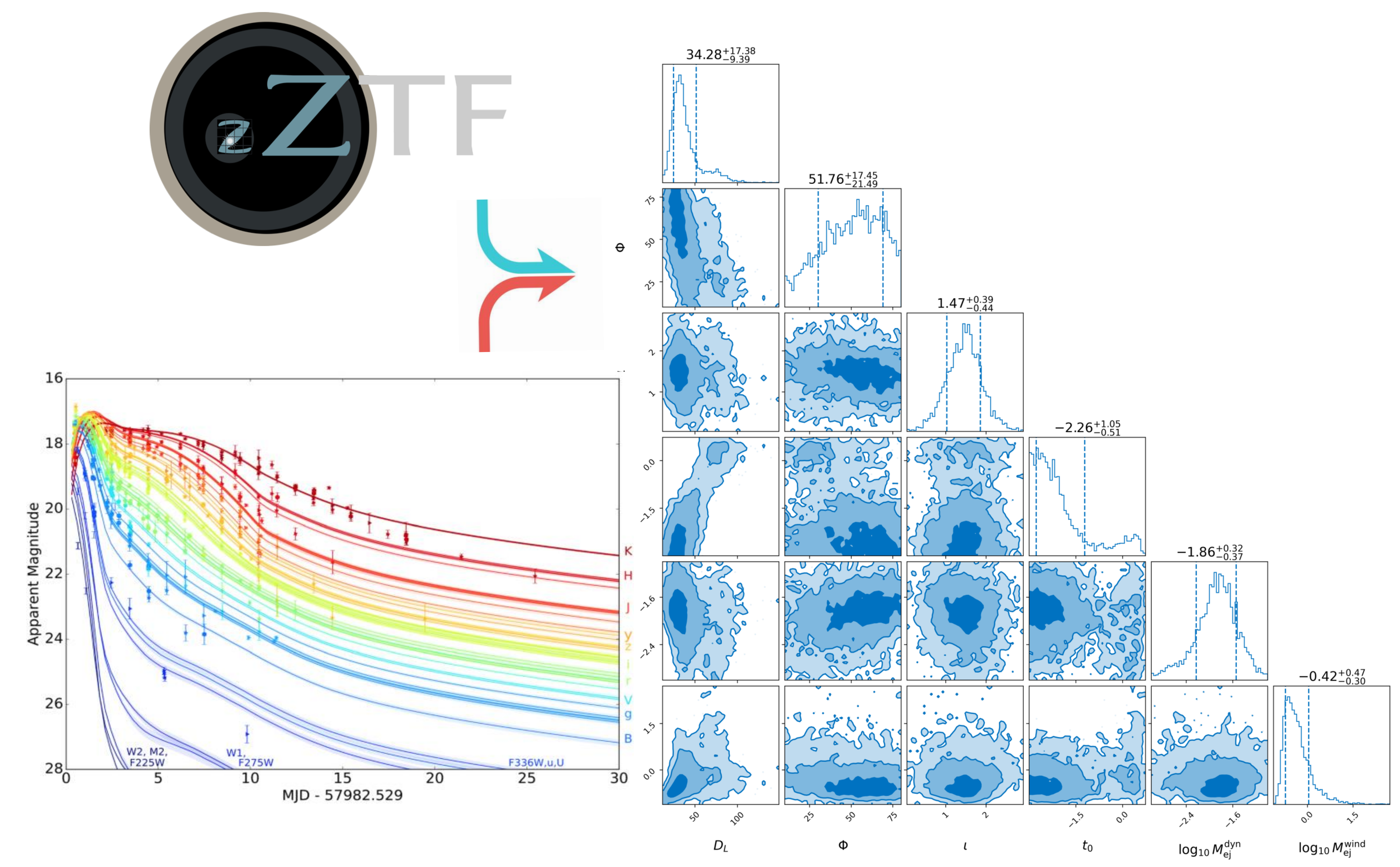

Chart 3. Comparison of ZTF observations and a set of models (left), and Bayesian inference of kilonova parameters with NMMA (right)

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References

[1] Hinderer et al. PRD 81(2010); **[2a]** Loiseau et al. SoftwareX (2020); **[2b]** Carter et al. Phys.Rev.D (1995); **[3a]** R. T. Wollaeger et al. ApJ (2021); **[3b]** R. T. Wollaeger et al. ApJ (2013); **[4]** Peng et al. Nat.Comm (2023); **[5]** S. Rosswog & O. Korobkin Ann.Phys (2022)