Synthetic Source Injection for the LSST Kilonova Data Challenge

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ABSTRACT

In this project we worked to finish the Kilonova Data Challenge (KDC) for the Legacy Survey of Space and Time (LSST). LSST is a major astrophysics experiment supported by DOE and NSF that seeks to learn more about the nature of dark energy, to take a census of solar system objects, to further understand the Milky Way and much more. It plans to begin survey operations in 2025. Much of our work was done within the LSST Dark Energy Science Collaboration (DESC). Our goal was to constrain how well kilonovae can be found in LSST data. Kilonovae are rare events associated with neutron star-neutron star or neutron star-black hole collisions that are often found based on their gravitational wave signatures but that also produce electromagnetic waves. We worked in the Rubin Science Platform (RSP) in order to use synthetic source injection to add simulated kilonovae to simulated LSST images in the RSP. We modified an existing Jupyter notebook to complete the source injection. We also further investigated how many kilonovae would be visible at various redshifts and found that the number rapidly decreases to zero. Finally, we developed several useful notebooks, including one to display multiple single chip images at once in a mosaic. Our final step after this summer will be to assemble the set of images containing kilonovae, find all transients in those images and make a conclusion about how many of the kilonovae can be found during LSST.

I. INTRODUCTION

Dark energy, the cause of the increasing rate of expansion of the universe, is a critical topic of research. Both the Legacy Survey of Space and Time Dark Energy Science Collaboration (LSST-DESC) and gravitational wave experiments such as the Laser Interferometer Gravitational Wave Observatory (LIGO) provide means for further constraining the nature of dark energy. DESC plans an ambitious scientific program including joint analysis of five dark energy probes (weak and strong gravitational lensing, large-scale structure, galaxy clusters, and supernovae) that are complementary in constraining power. These probes taken together result in Stage IV-level constraints on dark energy [1]. Gravitational wave projects such as the Dark Energy Survey Gravitational Wave (DESGW) collaboration [6] do cosmology with standard siren measurements, using compact object collisions such as kilonovae as distance indicators in order to measure the Hubble constant. Kilonovae are emissions of electromagnetic waves from neutron star-neutron star or neutron star-black hole collisions; they are typically found based on their gravitational wave signature. The Kilonova Data Challenge where we test how well DESGW and LSST-DESC can find kilonovae in LSST data, is of interest to both LSST-DESC and DESGW. M. Wiesner makes regular reports on the KDC in DESGW meetings; in the LSST-DESC, he has reported on it in the Time Domain Working Group and in the Cosmological and Survey Simulations Working Group. It was approved as LSST-DESC project number 211 during the 2021-2022 academic year.

LSST is an effort to advance astrophysics in multiple domains, including cosmology, transient astrophysics, Milky Way astronomy, gravitational lensing, solar system astronomy and more. It includes the construction of the 8.4-meter Simonyi telescope at the Vera C. Rubin Observatory as well as the development of the 3.2 gigapixel LSST camera, the largest camera yet made. Eight science collaborations collaborate with the LSST project, including the DESC, formed in 2012. Fermilab is a leader in LSST and the Rubin Observatory and work with the DESC is currently a high priority for the lab as it advances efforts in the Cosmic Frontier.

Efforts in the LSST-DESC have focused on preparations for data, as the survey is expected to begin in 2025. Part of these preparations has been data challenges, the development of highly realistic simulated data on which to test scientific analyses and codes. The first data challenge (DC1) covered ten years of data taking over an area of about 40 deg^2 but in r-band only [5]. The LSST second data challenge (DC2) is a similar but much larger project to produce 300 deg^2 of simulated images over 10 years in all 6 LSST filters [1]. M. Wiesner was involved in work on the deep drilling field (DDF) of DC2, working on lensed hosts of quasars and supernovae using what was referred to as the Sprinkler [8], a code package that sprinkled lensed objects throughout DC2. He was also involved with efforts to add a large amount of lensed objects to early simulated images in the Twinkles [3] project.

In our previous work on this project, we had developed code [7] to predict magnitude as a function of time in all 6 LSST filter bands and to produce spectral energy distributions as a function of time. The magnitude predictions were based on the Kasen et al. (2017) [2] kilonova models. We verified previously that our code using these models reproduced the observed magnitude as a function of time (light curves) for the first kilonova, GW170817. We then chose host galaxies for the kilonovae by matching galaxies in DC2 to real galaxies that hosted short gamma ray bursts using r-i color. (Short gamma ray bursts are thought to be associated with colliding neutron stars, events that can produce kilonovae.) We concluded previously by producing full simulations for seven observing visits and 1 square degree of sky.

The goal this summer was to build on and finish our previous work to add simulated kilonovae to DC2 images. Last year we worked on adding kilonovae by rerunning the image simulations using PhoSim [4], adding the kilonovae to raw images. This year we complemented that work by adding the kilonovae to reduced and processed single visit images using synthetic source injection. We chose a series of visits in r-band that were sequential within several days, allowing the transients in the images, including kilonovae, to change only a small amount in magnitude. We ran the source injection using a Jupyter notebook on the notebook aspect of the Rubin Science Platform. We also built a new notebook that can display multiple single chip images as a mosaic and added that to the delegate contributions on Github. We also considered how many kilonova models would be visible at a series of increasing redshifts; we found that the number of visible kilonovae rapidly decreases with increasing redshift.

II. PROGRESS

1: Learning to Do Synthetic Source Injection in the Rubin Science Platform

Our first goal was learning to do synthetic source injection of objects into DC2 images served through the Rubin Science Platform (RSP). I tried several Jupyter notebooks, and found places where code was still being developed. I ultimately found a notebook developed by a member of the Community Science Team for the first Data Preview on the RSP, Data Preview 0.1, although now the primary data release is DP0.2. As it was developed for DP0.1, some modifications in the code were needed for it to fully run.

We spent much of the second week of the program attending the DP0.2 Summer School; this program involved going through each of the tutorial notebooks developed to teach users how to utilize the Rubin Science Platform. This was extremely helpful in teaching us how to better use all the capabilities of the RSP. This especially taught us how to access the API aspect of the RSP using the program TopCat. We used this tool throughout the rest of the summer.

2: Galaxy Viewer and Mosaic

One of our goals was to produce Jupyter notebooks that could visualize the galaxies in DC2 into which we were inserting kilonovae. We previously chose galaxies to host kilonovae and wanted to be able to view them in either coadds or single visit images. Single visit images would be most useful since we would use these to insert kilonovae, as they vary in time. We also wanted to be able to view cutouts of the coadds so we could view galaxies of interest up close. We put all of these tasks together in a single notebook which we entitled *galaxy_viewer.ipynb*. In addition we wrote a function to find the tract and patch for a particular right ascension and declination and then to use the LSST Butler to make available the coadd image for that location.

We also wrote a new notebook called *mosaic.ipynb* that produces a mosaic image of a series of single visit detector images (that is, single CCDs on the focal plane of LSSTCam). This was useful for us as it would allow us to visualize the full square degree region of interest at once. This capability had not been previously produced in the RSP. Both notebooks were added to the delegate contributions Github [9] via a pull request and were integrated into that repository, in the *view_mosaic* folder. An image of the view produced by the mosaic notebook is provided in Figure 1. This is full zoomable and is an interactive display. These two notebooks were presented at a DP0 Delegate Assembly in late July.

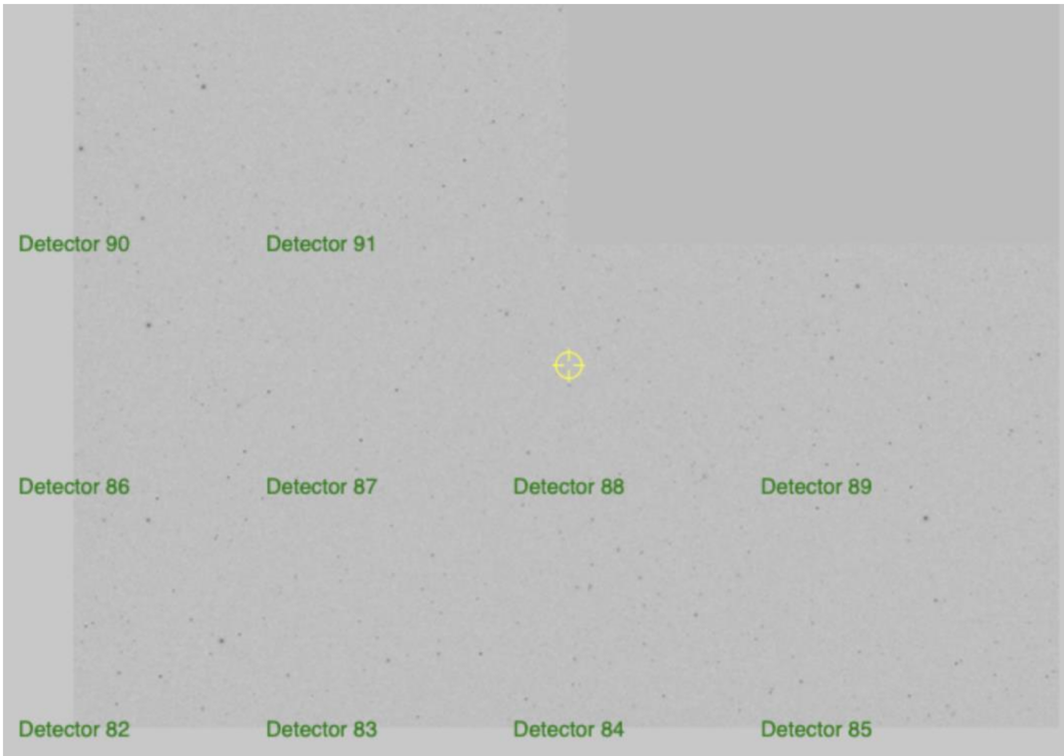

Figure 1. A mosaic view of detectors 82-91 using the mosaic notebook. (There are 189 detectors in the camera.) It is possible to zoom in to any of the individual detectors to view objects more closely.

3: Study of How Many Kasen Kilonova Models Would Be Visible

We spent time investigating how many of the 329 Kasen kilonova models would be visible in LSST. We calculated the brightest magnitude for each model at low redshift. We found that the brightest kilonova was at close to 21st magnitude in r-band, while the dimmest was at close to magnitude 30, well below LSST limits. The three variables in the models were ejecta mass, ejecta velocity and lanthanide fraction. We quote from the Kasen et al. (2017) [2] paper: "A larger ejecta mass produces a brighter and longer-lasting kilonova; a higher velocity gives a brighter and briefer kilonova." The brightest model thus was the highest mass, highest velocity, lowest fraction of lanthanides.

We further made light curves for each of the kilonova models and plotted each against the single visit limiting magnitude for LSST. We ultimately did this for each of the six LSST filter bands *ugrizy*. We did this for a series of redshifts starting at z=0.0099 (the redshift of kilonova GW170817) and continuing to z=0.5. We then counted in each case how many of the kilonova models could be observed at some point in its evolution in single visit images in LSST. The results are shown in Figure 2.

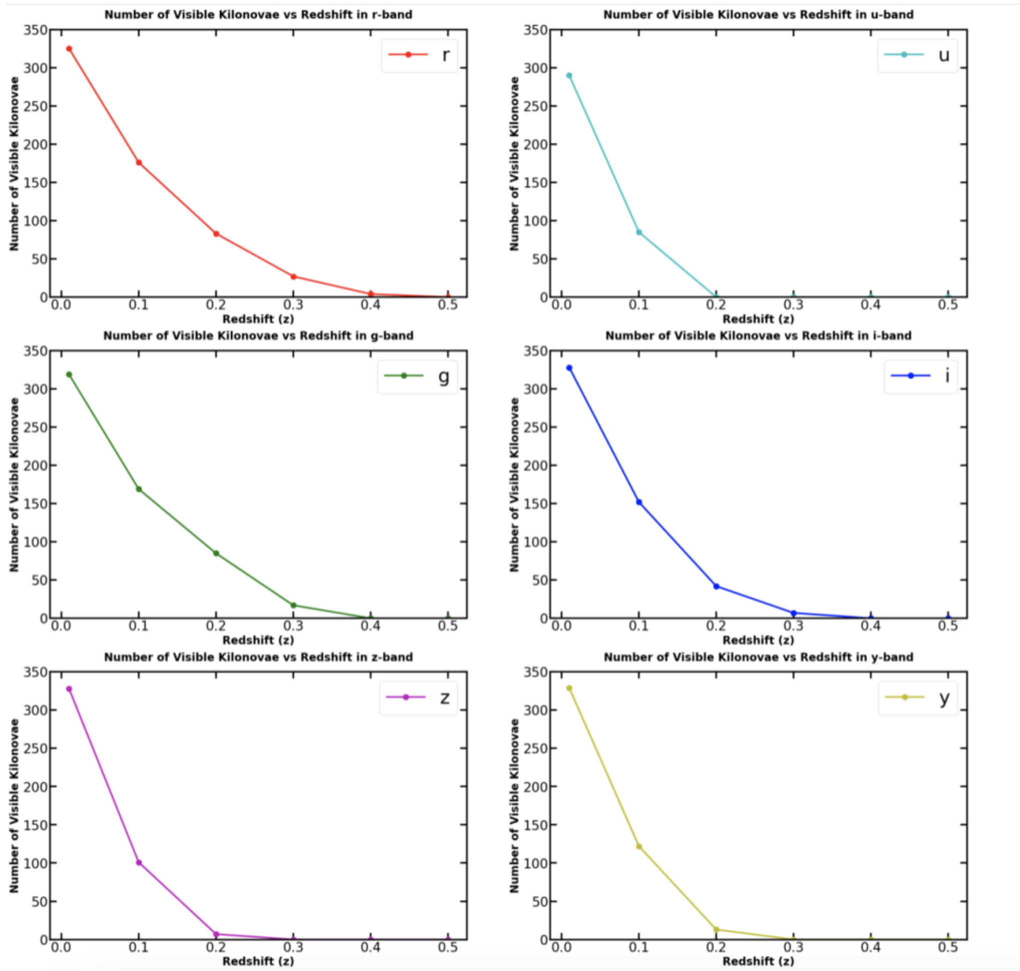

Figure 2. Number of Kasen et al. (2017) kilonova models visible in LSST as a function of redshift for all six LSST filters. The filter band used is shown in the upper right of each plot.

4: Verifying the Results Produced by Synthetic Source Injection

Part of the synthetic source injection notebook involves remeasuring all sources in the image, including the injected sources. We tested adding point sources of varying magnitudes, from magnitude 14.5 to 24 in r-band. We did this to verify that the sources were visible and also to test magnitude errors as a function of magnitude. We found that measurement errors were several millimags at brighter magnitudes but then grew to around 20 millimags by magnitude 24. We repeated this process with the actual simulated kilonovae. We used the predicted initial magnitudes from our light curve code and found that most of the kilonovae were not detectable in single visit images, as their initial magnitudes were less than the limiting magnitude (24.03 in r-band). Note that the 20 kilonova models were chosen randomly to be a representative sample of kilonovae, with varying ejecta mass, ejecta velocity and lanthanide fraction.

5: Producing Final Light Curves for the Simulated Kilonovae

As part of the synthetic source injection program, we used our previously produced code to determine magnitude as a function of time for each kilonova model in *u*, *g*, *r* and *i*-filters. These light curves are shown in Figure 3. The horizontal line shows *r*-band limiting magnitude for single visit LSST images. One of the conclusions reached from this figure is that only 9 of the 20 kilonovae are at any point observable in LSST. After also inserting the 20 simulated kilonovae into images and remeasuring the flux from each object, we further found that only 2 of the 20 were ultimately detected in single visit images.

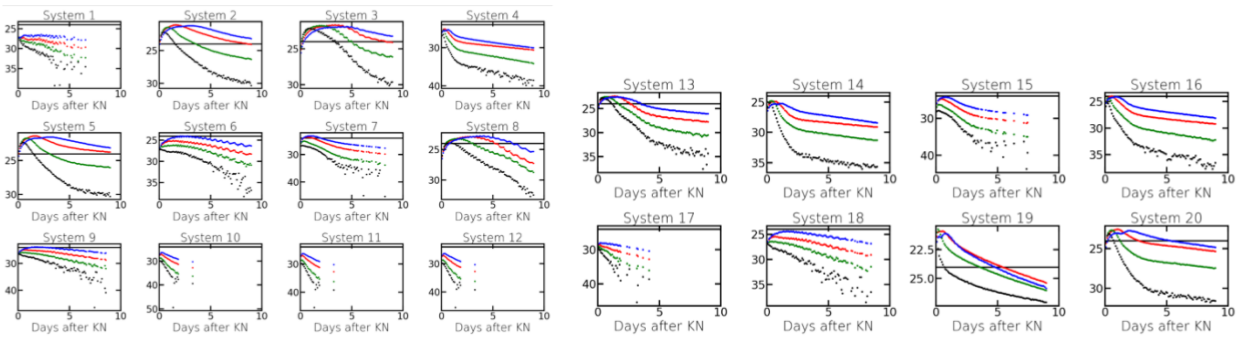

Figure 3. Light curves for all 20 kilonovae. In all cases we also show r-band limiting magnitudes for LSST single visit images with a horizontal line. The blue line is i-band, red is r, green is g and black is u-band.

III. FUTURE WORK

The final steps for this project involve producing all images with injected kilonovae as well as the catalogs of objects including the inserted objects. We will then identify all transients in the one square degree region, including supernovae and variable stars. (This step can be done through ADQL queries in the RSP.) The final step will be determining how many of the kilonovae could be identified and whether they would be differentiable from other transients. We plan to complete this over the Fall and Spring semesters.

We will be presenting our work over the summer and throughout the academic year at the Rubin Observatory Project and Community Workshop and at the LSST-DESC Time Domain and Cosmological and Survey Simulations Working Groups. Finally we plan to submit a paper on this work to internal review within DESC; we worked on the draft of this paper over the summer and will continue working on it this fall.

IV. IMPACT ON LABORATORY OR NATIONAL MISSIONS

Fermilab is a leader in dark energy research, in the LSST Dark Energy Science Collaboration and in the Rubin Observatory. The Department of Energy supports the DESC. This project is interesting to the DESC as kilonova searches will be done during LSST operations; Rubin Observatory is developing a plan for Target of Opportunity observations such as would be done when a neutron star-neutron star merger is found by LIGO. Kilonovae, as likely sources of gravitational waves, can provide an independent measure of the expansion rate of the universe (H_0) by constraining the distance-redshift relation, and so understanding how well kilonovae will be found in LSST is a relevant and timely topic. My group recently was accepted for funding from the LSST Discovery Alliance Catalyst Fellowship Expansion mentors program and we have also submitted a proposal for the DOE RENEW-HEP grant. These grants will involve the Rubin RSP in addition to other observing and research opportunities; our experience with this project in the VFP has positioned us well for the next phase in our research with Rubin Observatory, LSST-DESC, DESGW and other projects.

V. CONCLUSIONS

Based on our work this summer, we conclude that only 9 of the 20 simulated kilonovae at any point reach magnitudes above LSST limiting magnitudes in single visit images. (We focused on single visit images as these are where transients will be identified.) We ultimately found that only 2 of these are bright enough to be distinguished from background in the images. So we conclude that about 10% of existing kilonovae will be observed, assuming our distribution of ejecta mass and velocity, location and redshift is somewhat realistic. We will further investigate this conclusion over the upcoming year and in the final paper, but hopefully this conclusion can help to inform survey strategy considerations as plans are developed for Target of Opportunity observations in LSST.

VI. REFERENCES

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[2] Kasen, D., Metzger, B., Barnes, J. et al 2017. "Origin of the heavy elements in binary neutron-star mergers from a gravitational-wave event," *Nature* 551, 80–84 (2017). https://doi.org/10.1038/nature24453. Code for kilonova models available here: https://github.com/dnkasen/Kasen_Kilonova_Models_2017

[3] Marshall, P., Wood-Vasey, M., et al. https://github.com/LSSTDESC/Twinkles

[4] Peterson, J., et al. 2015, "Simulation of Astronomical Images from Optical Survey Telescopes Using a Comprehensive Photon Monte Carlo Approach," *The Astrophysical Journal Supplement*, 2015, 218, 14.

[5] Sánchez, J., Walter, C. W., Awan, H., et al. 2020, "The LSST DESC data challenge 1: generation and analysis of synthetic images for next-generation surveys", *Monthly Notices of the Royal Astronomical Society*, 497, 210.

[6] Soares-Santos, M., Holz, D. E., Annis, J., et al. 2017, "The Electromagnetic Counterpart of the Binary Neutron Star Merger LIGO/Virgo GW170817. I. Dark Energy Camera Discovery of the Optical Counterpart," *The Astrophysical Journal*, 848, L16, 981, arXiv:1710.05459.

[7] Codebase for this project available at: https://github.com/mpwiesner/KDC

[8] Codebase for the Sprinkler: https://github.com/LSSTDESC/SLSprinkler

[9] DP0.2 Delegate Contributions: https://github.com/rubin-dp0/delegate-contributions-dp02

APPENDIX

Participants-

Name	Institution	Email	Role
Prof. Matthew P. Wiesner	Benedictine University	mwiesner@ben.edu	Dr. Wiesner led the design of the project, implemented software, ran simulations.
Dr. Douglas L. Tucker	Fermi National Accelerator Laboratory	dtucker@fnal.gov	Dr. Tucker provided constant support and software design advice. He also provided software for the project.
Dr. Huan Lin	Fermi National Accelerator Laboratory	hlin@fnal.gov	Dr. Lin was available for support.
Dr. Brian Yanny	Fermi National Accelerator Laboratory	yanny@fnal.gov	Dr. Yanny helped us to solve some computing problems.
Ms. Anna Khalid	Benedictine University	anna_khalid@ben.edu	Ms. Khalid developed software and plots for the project and did several analyses.
Mr. Arman Svoboda	Benedictine University	arman_svoboda@ben.edu	Mr. Svoboda worked especially on several Jupyter notebooks important to the project.

Scientific Facilities – We regularly used Fermilab computing resources as well as NERSC and Rubin Observatory computing resources.

Notable Outcomes –This project is project #211 in the LSST-DESC Document Database. I presented on the Jupyter notebooks we wrote for this project at a DP0 Delegate Assembly in July 2023 as well as at the 2023 Rubin Observatory Project and Community Workshop.

Research Vibrancy – We plan to finish this project over the academic year. We plan to continue collaboration with Dr. Tucker and others at Fermilab and across the Rubin, DESC and DESGW collaborations. We will be giving periodic updates in DESC working groups on this project.

Connection to Programs at Home Academic Institution – This program has had a major impact on my students Arman Svoboda and Anna Khalid. It has introduced them to physics and astronomy projects they previously were unaware of and has enabled them to experience the culture of a National Lab. I will be finishing the paper on this project over the academic year; Arman will likely continue to work on this project and other undergraduates may also become involved with it.