ABSTRACT
Synthetic Source Injection for the LSST Kilonova Data Challenge
Matthew P. Wiesner

In summer 2021, our group began the Kilonova Data Challenge (KDC) during the Visiting Faculty Program at Fermilab. This was a project to add simulated kilonovae (optical emission from neutron star collisions) to the Legacy Survey of Space and Time Dark Energy Science Collaboration (LSST-DESC) second data challenge (DC2). (DESC is one of the science collaborations associated with the Rubin Observatory.) This summer, we focused on synthetic source injection, adding simulated kilonovae directly to processed DC2 images in the Rubin Science Platform. We have also further analyzed the kilonova models and found that many of them would not be observable in LSST single exposure images. We plan to finish adding the kilonovae, download the catalogs and images and then make a conclusion about the number of kilonovae that would be observable in a small area of LSST.

Synthetic Source Injection for the LSST Kilonova Data Challenge

Summer 2023

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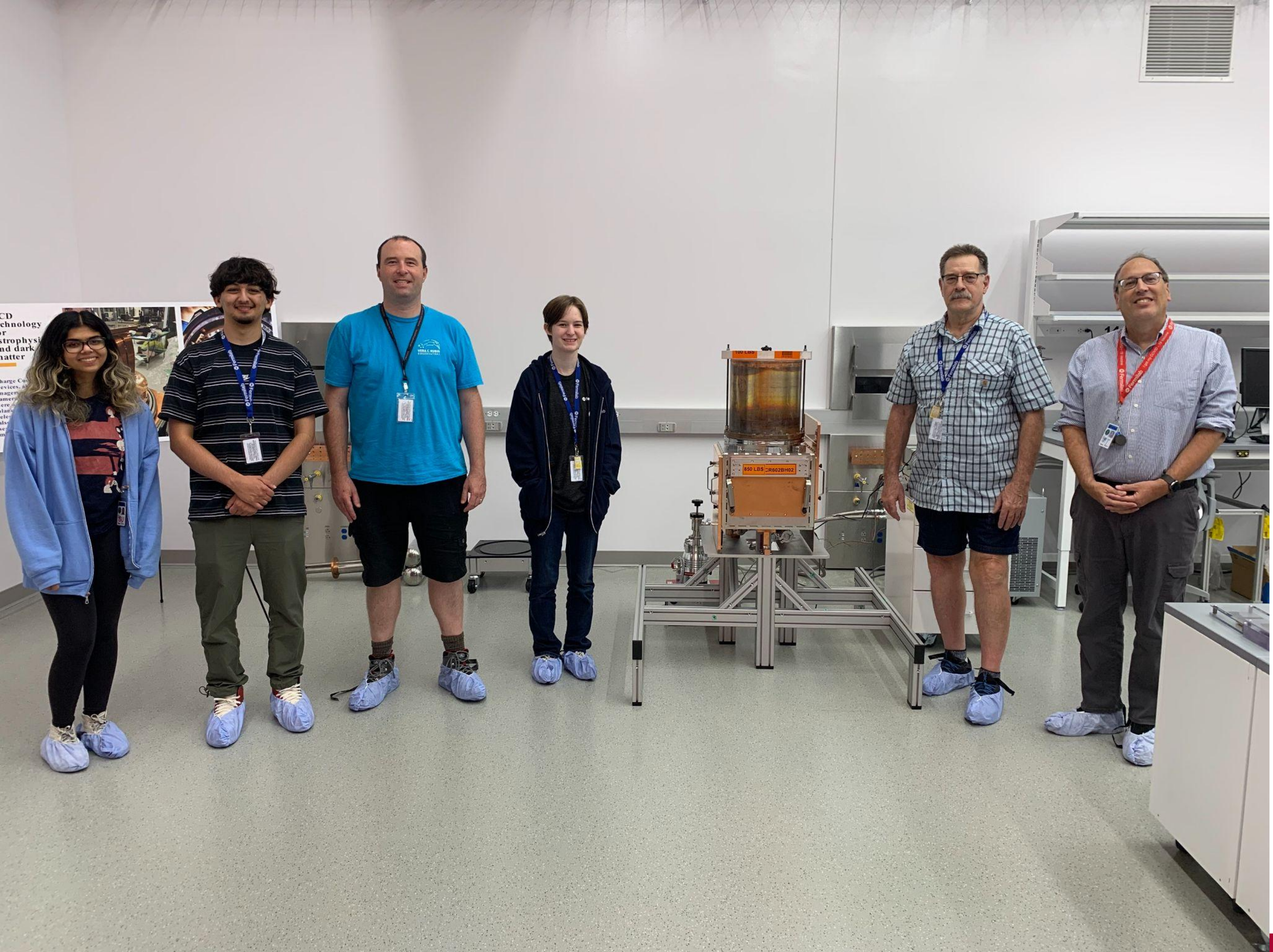
Douglas Tucker (Fermilab)

Thank you especially

- Fermilab and the astrophysics group for hosting us
- Douglas Tucker for mentoring our group
- Brian Yanny for computing support
- Huan Lin, Jim Annis and my chair Andrew Wig for support in applying for the VFP



Our group

Summary and Outline

- Background information
- What is the Kilonova Data Challenge?
- What has been done previously on this project?
- What was done this summer?
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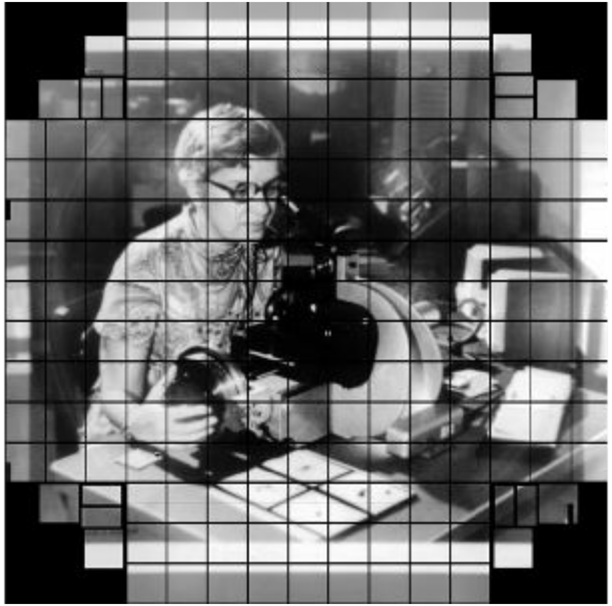
The Legacy Survey of Space and Time at the Vera C. Rubin Observatory

LSST DESC
Dark Energy Science Collaboration

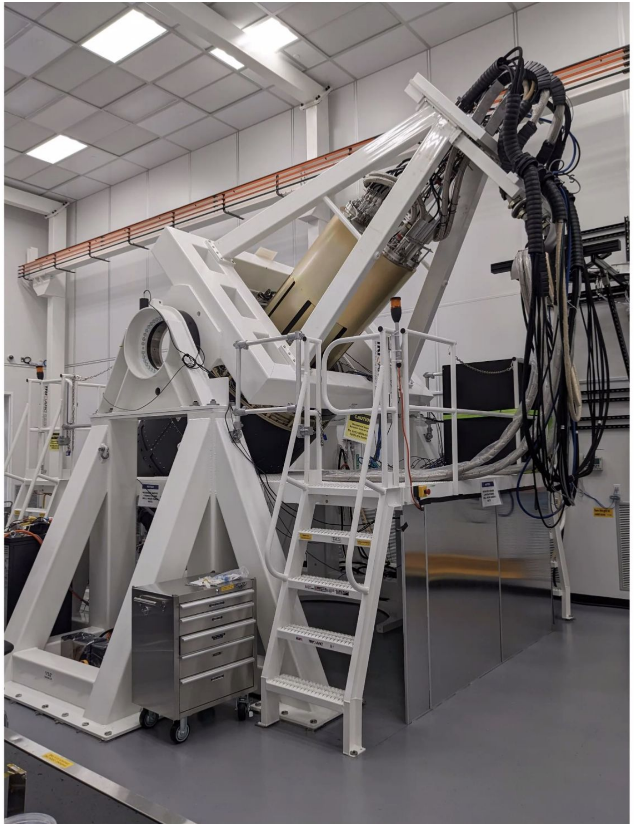


LSST

The Legacy Survey of Space and Time will be conducted by the Vera C. Rubin Observatory using the 8.4-meter Simonyi Survey Telescope. The Rubin Observatory is nearing completion on Cerro Pachón in Chile.

RubinObs/NSF/AURA/L. Guy

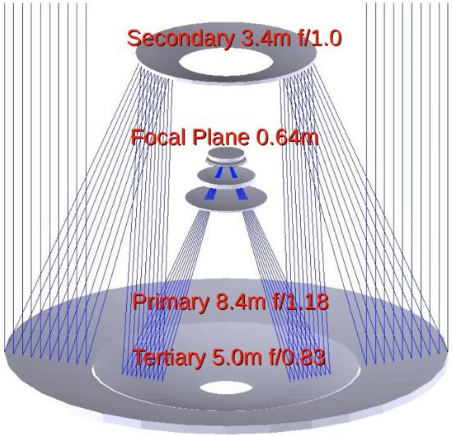
SITCom Update Photos



LSSTCam being tested at SLAC

Telescope System:

- Etendue (AΩ) : 319 meter^{2}degrees^2
- Field of View : 3.5 degrees (9.6 square degrees)
- Primary mirror diameter : 8.4 m
- Mean effective aperture : 6.423 m (area weighted over FOV)
- Final f-ratio : f/1.234
- Camera weight : 6,746 lbs (3,060 kg)
- Mirror (M1+M3 glass mirror only) weight : 35,900 pounds (16,284 kg)



M1M3 Assembly Testing at summit

The DESC Second Data Challenge

- 300 deg^2 of data in all six bands u, g, r, i, z, y in WFD field
- 1 deg^2 in DDF
- Based on cosmological (N-body) simulation
- Realistic observing cadences over 10 years, data processed by LSST pipelines
- Contains realistic galaxies, stars, supernovae, AGN, lensing

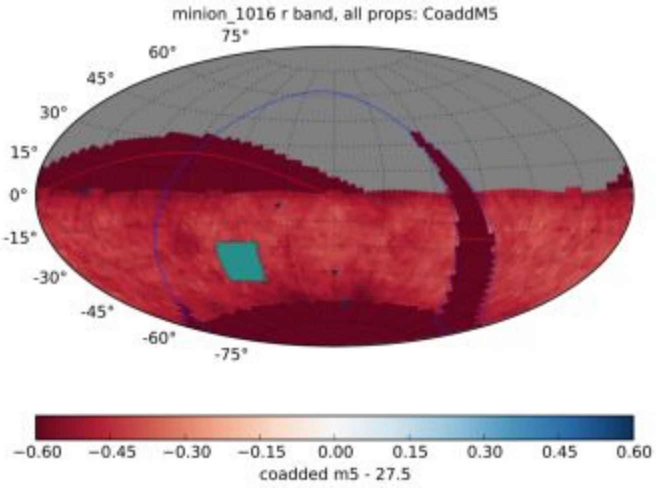


Figure 1. Image of the sky along with possible coverage by LSST observations (red, Jones et al. 2015) from the minion_1016 survey simulation shown in Aitoff projection. The blue line marks the Galactic equator and the red line the Ecliptic. More details are provided in Section 3. The green region shows the area on the sky that is covered by DC2 and is simply overlaid on the coadded depth skymap.

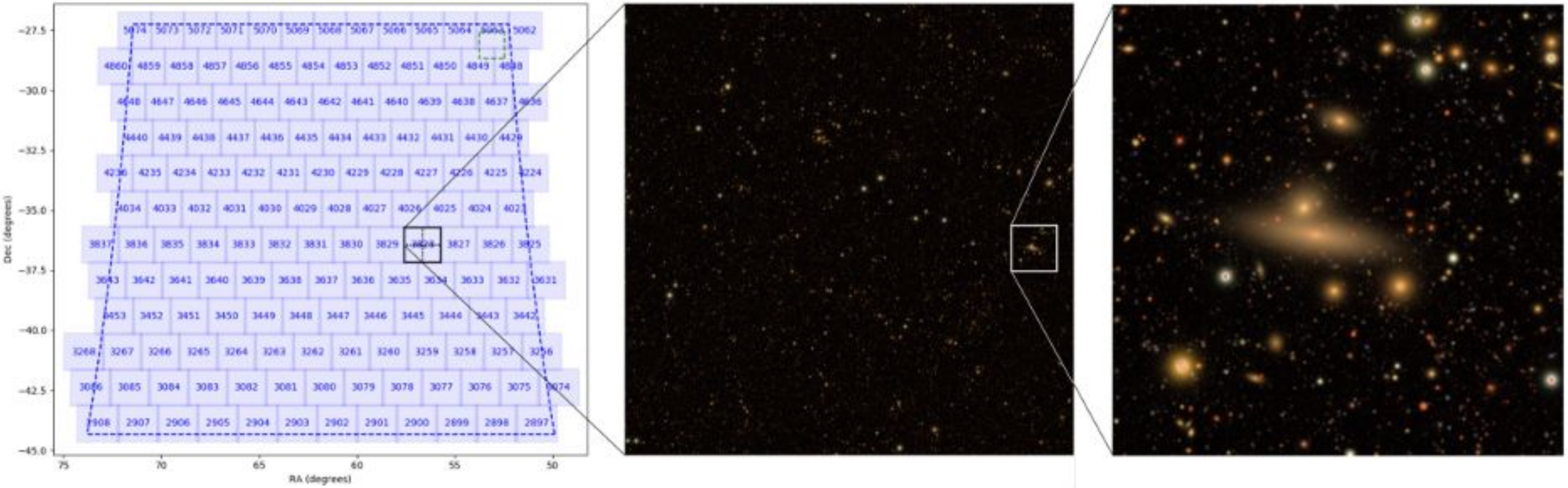


Figure 15. Illustration of the detailed image simulations available in DC2. The left image shows the tracts in the DC2 area. The middle panel shows the upper quadrant of tract 3828 in *gri*. The right panel shows a further zoom-in to the image simulations.

DP0.2

- DP0 is a release of DC2 images and catalogs processed with the LSST DM Stack.
- DP0 is data served through the Rubin Science Platform (RSP) to test user access to Rubin data products and train users on use of the platform.

- Data Preview 0 (DP0) is based on simulated LSST-like data and is being released in three phases (most recently, DP0.2), with DP0.3 expected by Sep 2023.
- Data Preview 1 (DP1) will be based on data from the LSSTCam obtained during a period of a few days after System First Light and is expected by Apr 2025.
- Data Preview 2 (DP2) will serve a full consistent reprocessing of all science-grade LSSTCam images obtained before survey operations, and is expected by Mar 2026.
- Data Release 1 (DR1) will be based on the first 6 months of survey operations and is expected by Nov 2026.

https://www.lsst.org/scientists/early-science

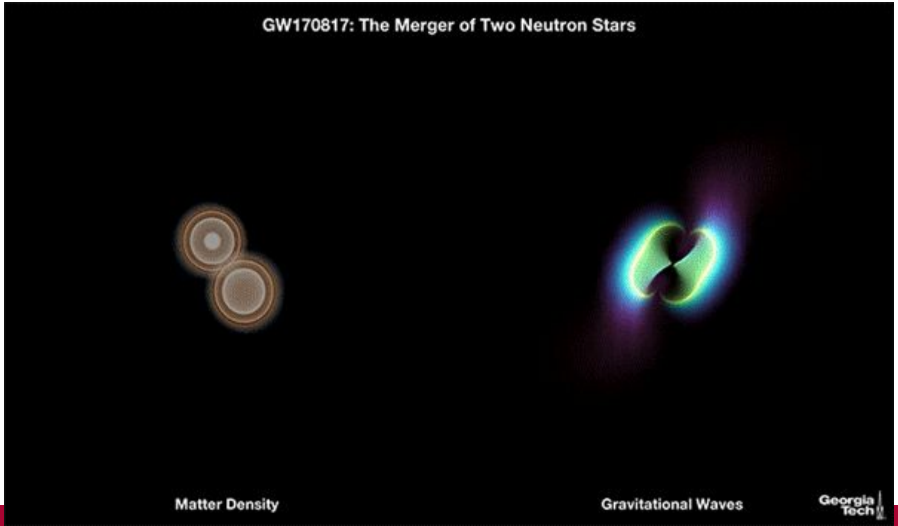
What is a Kilonova?

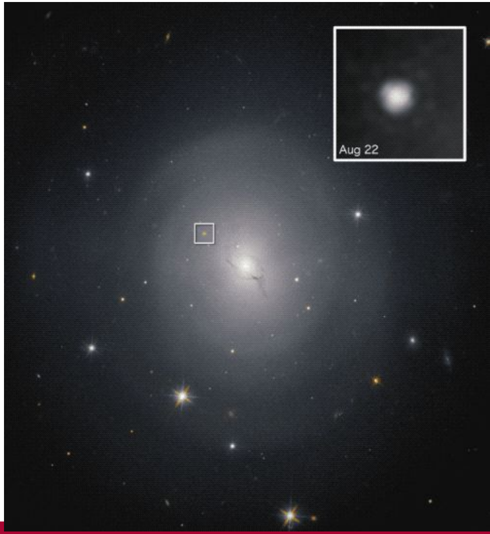
•A kilonova is a cosmic event that occurs when two neutron stars or a neutron star and a black hole collide

•Search usually based on gravitational wave signals

•As standard sirens can constrain H_0 (they can calibrate the distance-redshift relation)

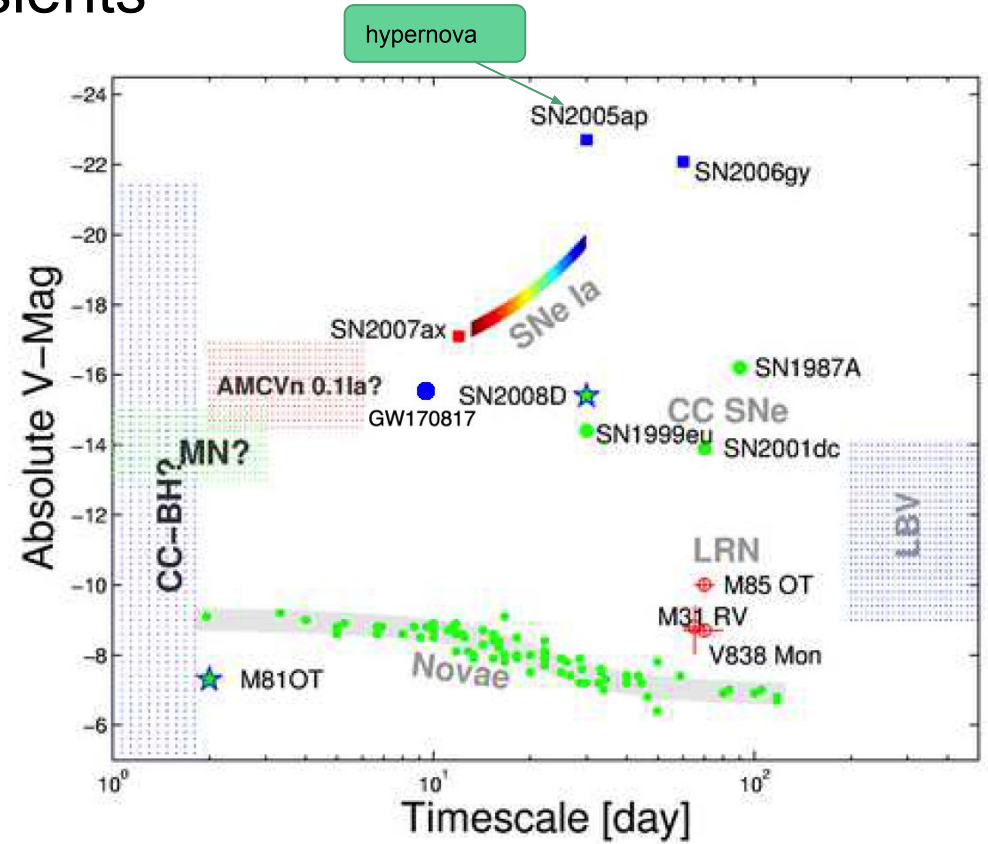
•Luminosity between a nova and a supernova





Hubble/STScI

The phase space of cosmic explosive and eruptive transients



Modified from Ivezic et al. 2008

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The Idea:

Make a tiny version of DC2 images that are overpopulated with kilonovae.

Do this for 1 square degree (about 21 of the 189 chips) centered around (59.65688129, -36.75083078).

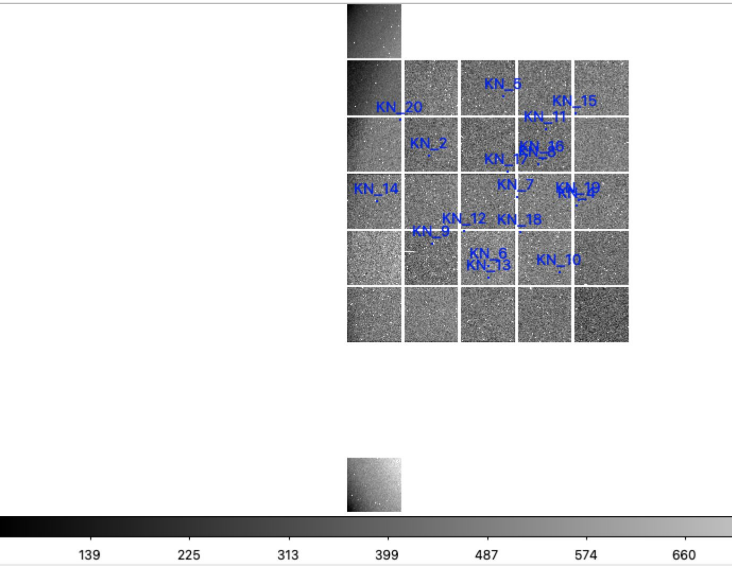
Add point sources that follow light curves and SEDs as expected for a kilonova.

Initially we planned to do this by rerunning the simulations using PhoSim.

We had to choose sequential observations.

This summer, we are doing this with synthetic source injection.

This was finished in 2022



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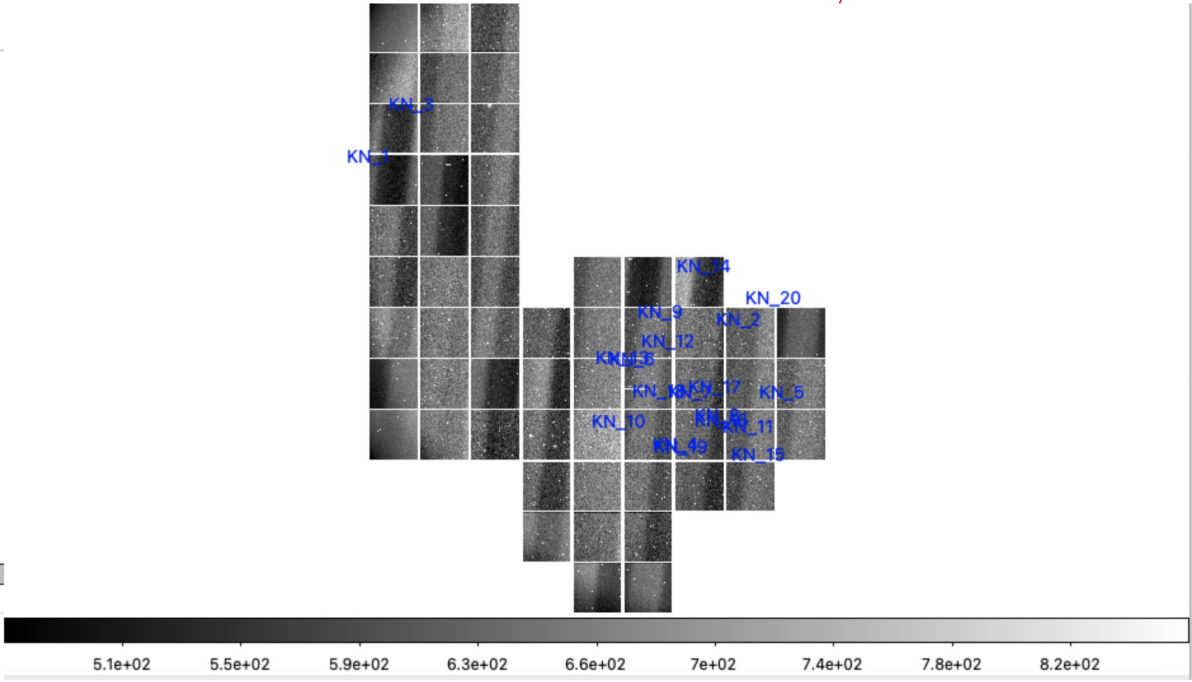

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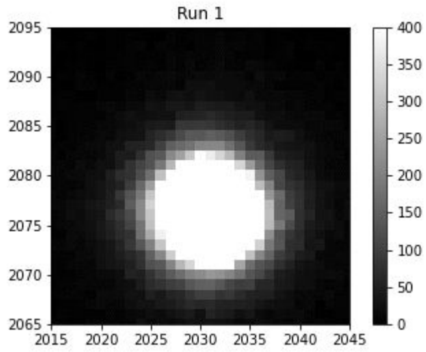
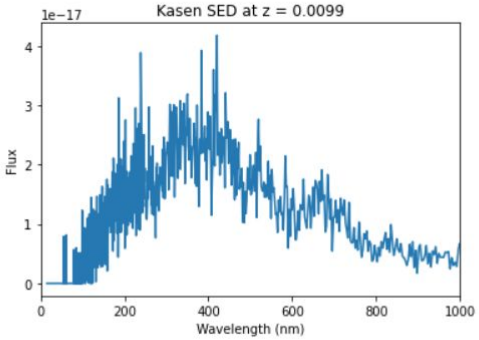
What we did before:

- We previously developed the tools necessary to simulate kilonovae using DC2.
    - Build code to produce kilonova SEDs that evolve with time following Kasen kilonova models (https://github.com/dnkasen/Kasen_Kilonova_Models_2017).
    - Predict magnitude as a function of time to produce lightcurves.
    - Develop method to choose host galaxies.
    - Repository: https://github.com/mpwiesner/KDC

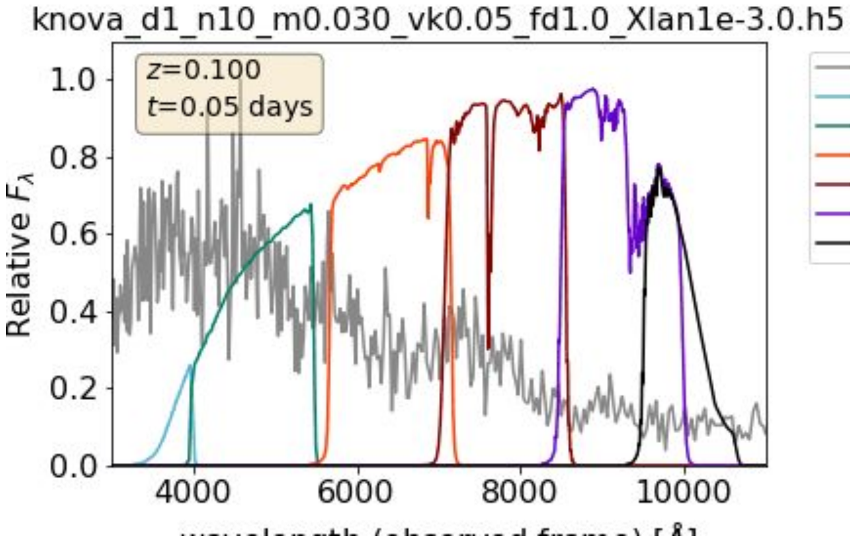


Sequential simulated images of a kilonova produced by PhoSim.

SEDs

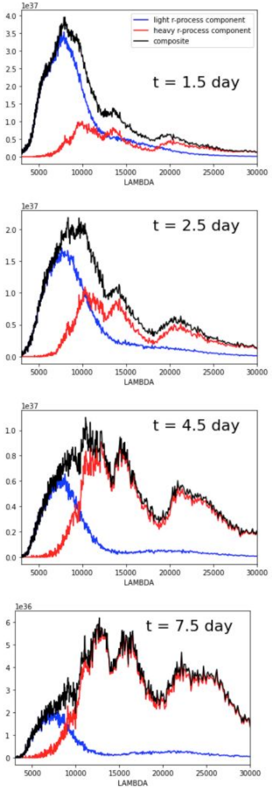


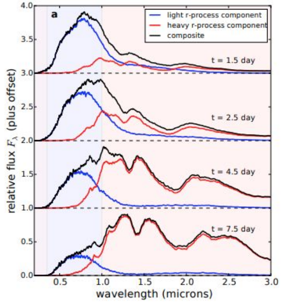
A single kilonova SED for z =0.0099 (early attempt).



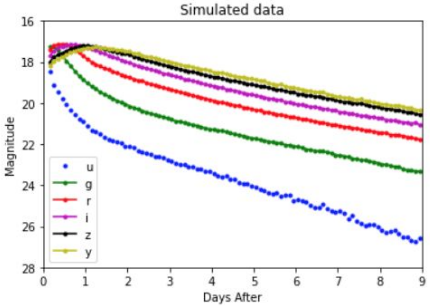
Evolution of the SEDs with time, plotted against DES filters.

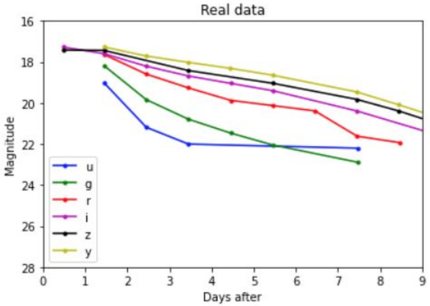
Validation





The figure on the right is Figure 5 from Kasen et al (2017) (https://arxiv.org/pdf/1710.05463.pdf) where he shows how he uses two models to reproduce spectrum of GW170817. On the left is our reproduction of it.





This is a light curve for GW170817 predicted by our code (top) and the light curve of this object measured by DES.

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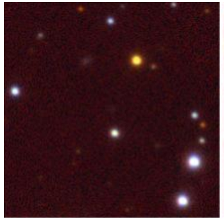
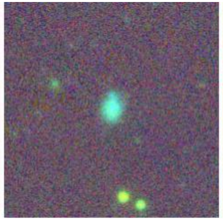
The Pan-STARRS galaxies

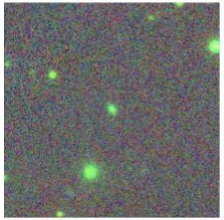

297.110651, -29.181865, 0.80408227

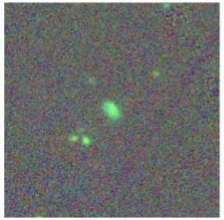

93.5111645, -28.316378, 0.09295455

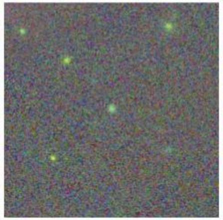

0.68982158, -28.271429, 0.07214077

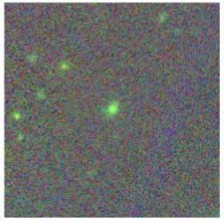

89.5298012, -27.747887, 0.25206122

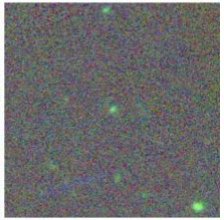

33.5875779, -27.580026, 0.22870549

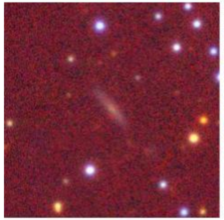

81.3019541, -27.258943, 0.4725188

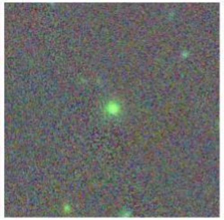

16.0011975, -27.198812, 0.18787424


57.1870523, -26.870315, 0.43715359

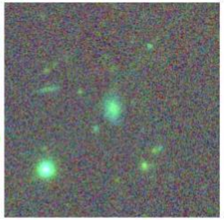

333.601593, -26.59909, 0.38513805


27.1229388, -26.122447, 0.57396317

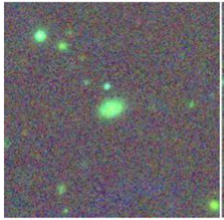

122.096109, -25.306582, 0.08214666

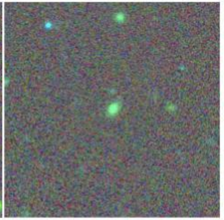

15.8015744, -24.502737, 0.31332508


200.286174, -24.201016, 0.10776384

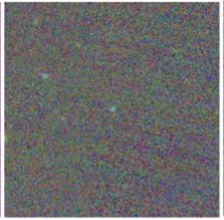

0.87165067, -23.713008, 0.25007637


197.448745, -23.383945, -0.0367164


225.147174, -10.391344, 0.18688171

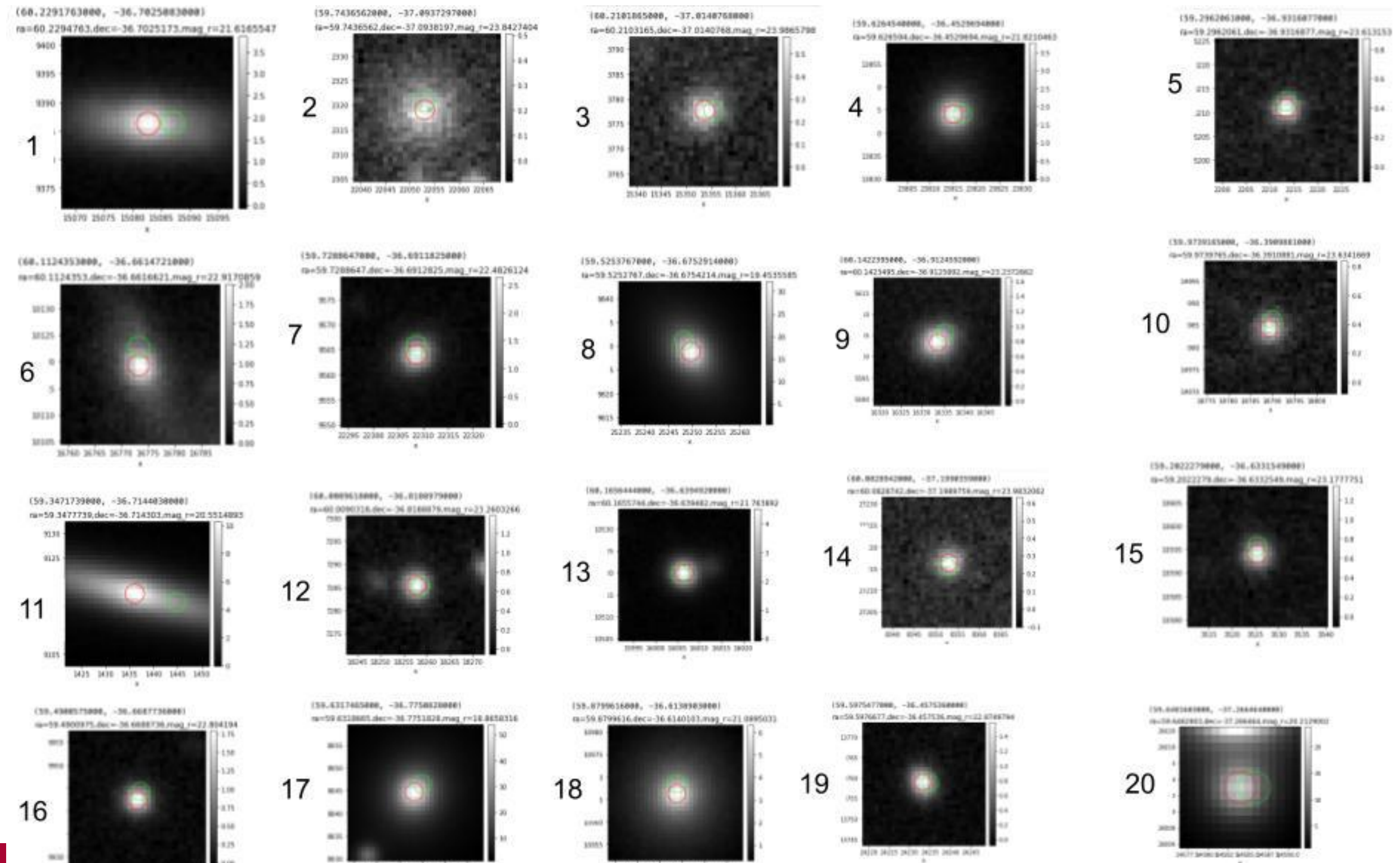

19.1808092, -0.1323831, 0.24589061


198.794314, 4.32563312, 0.33203274


348.207611, 8.34072441, 0.64954364


251.833429, 27.2759694, 0.08925837

The galaxies in DP0



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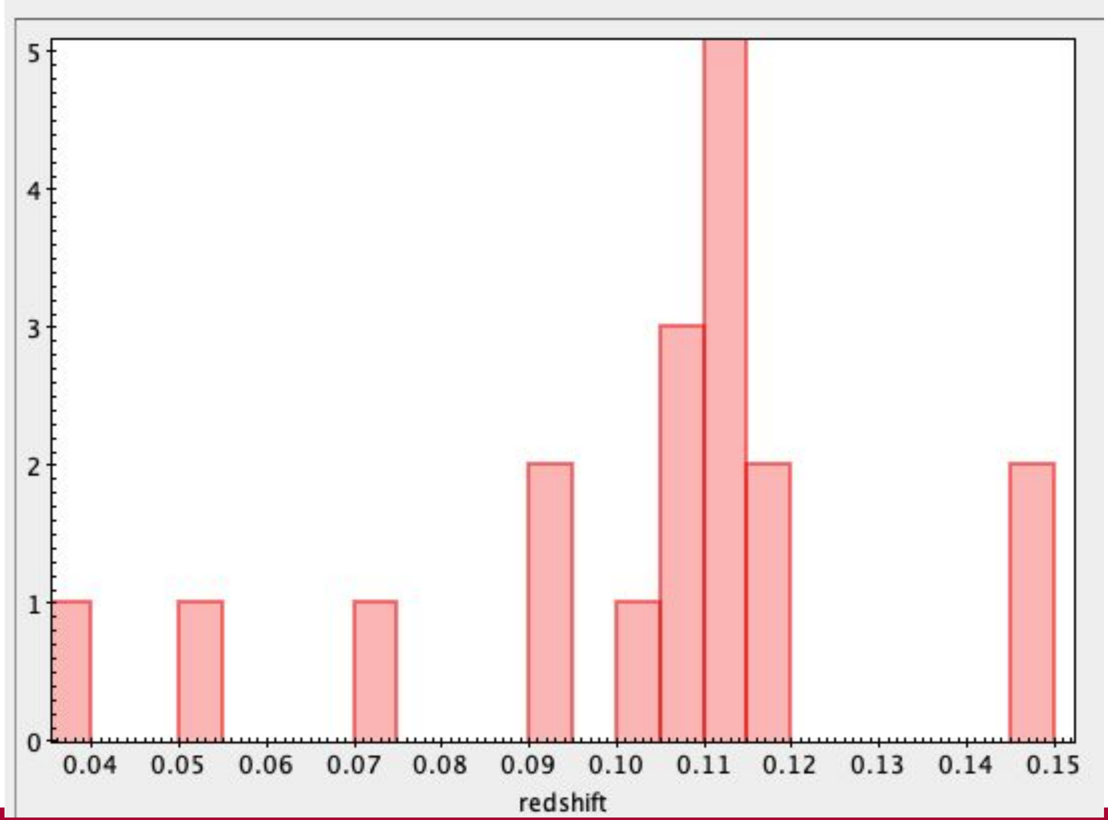
Histogram of DP0 galaxy redshifts



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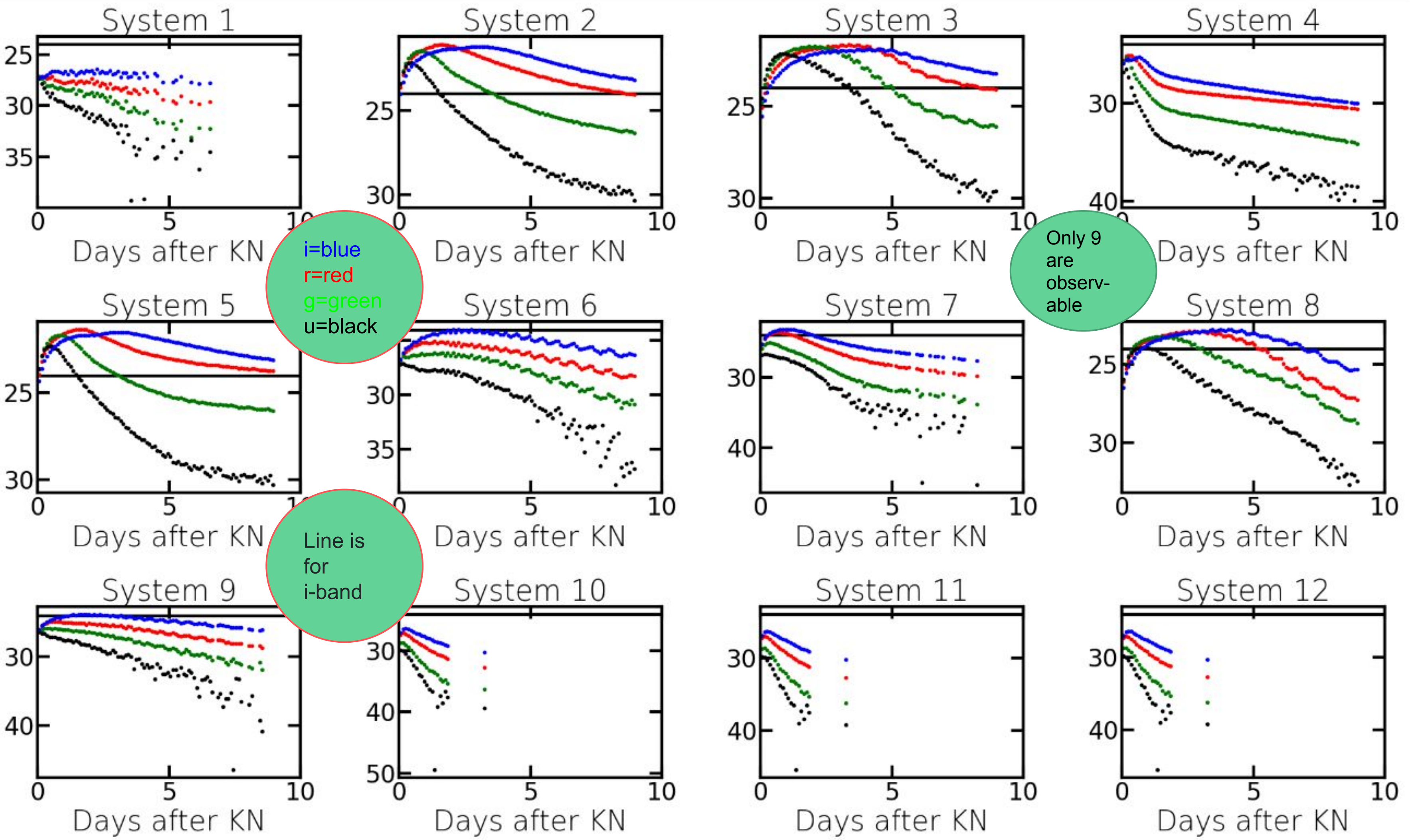
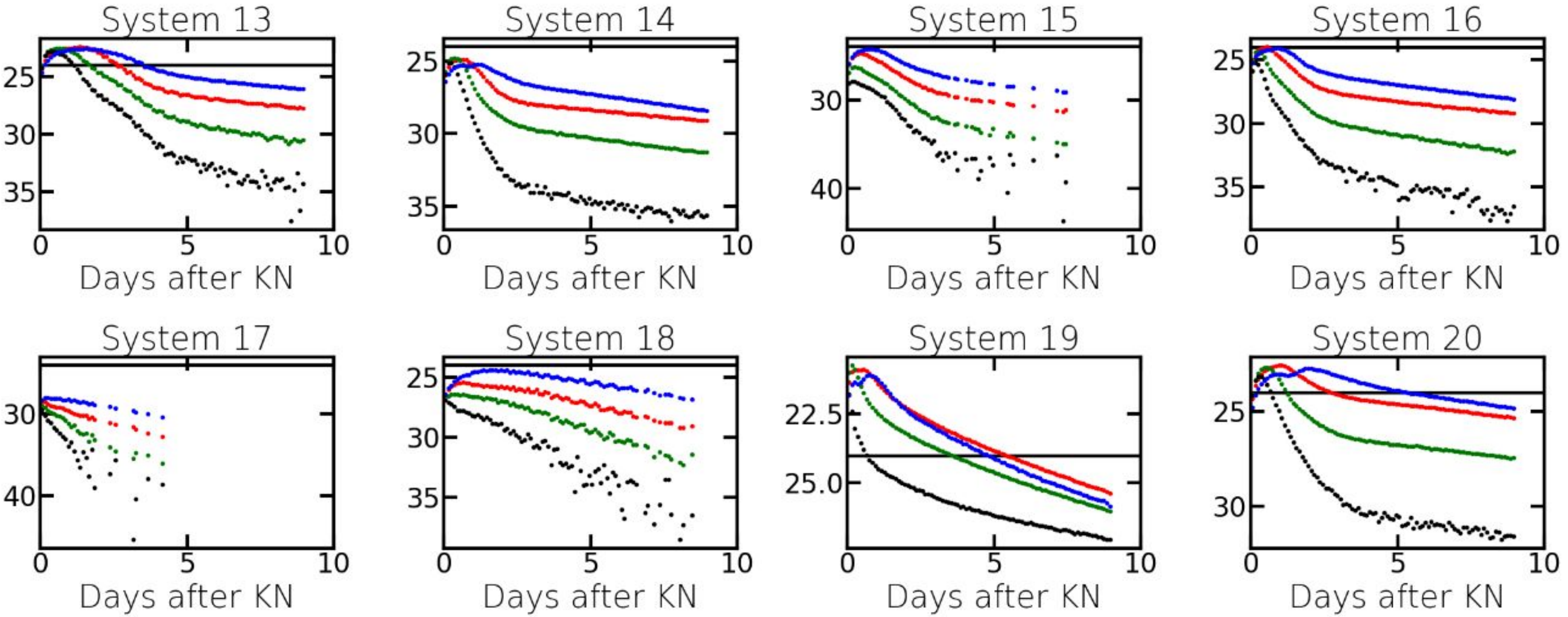


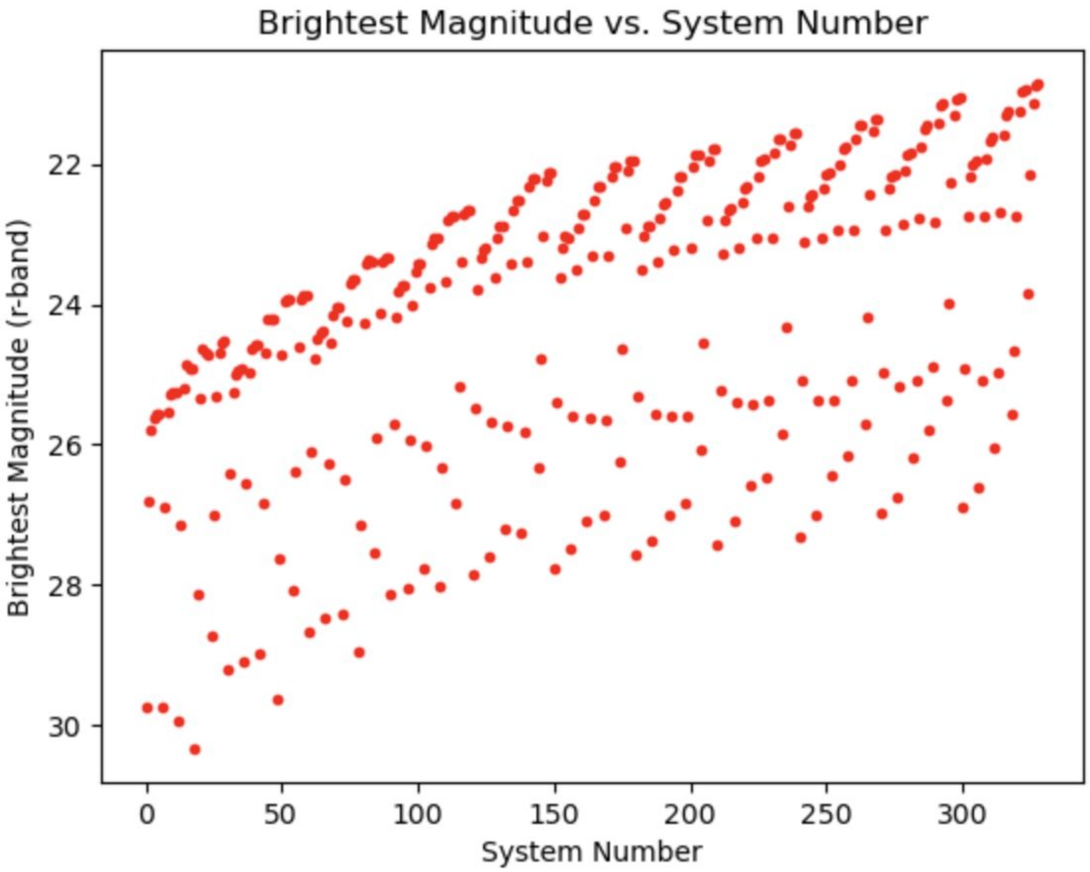
i=blue
r=red
g=green
u=black

Only 9 are observable

Line is for i-band


System 13
System 14
System 15
System 16
System 17
System 18
System 19
System 20
Days after KN

Exploring the Kasen kilonova models



A larger ejecta mass produces a brighter and longer-lasting kilonova; a higher velocity gives a brighter and briefer kilonova. Lower lanthanide fraction is associated with brighter kilonova.

Mass continually increases from 0.001 to 0.1 M_{sun}.

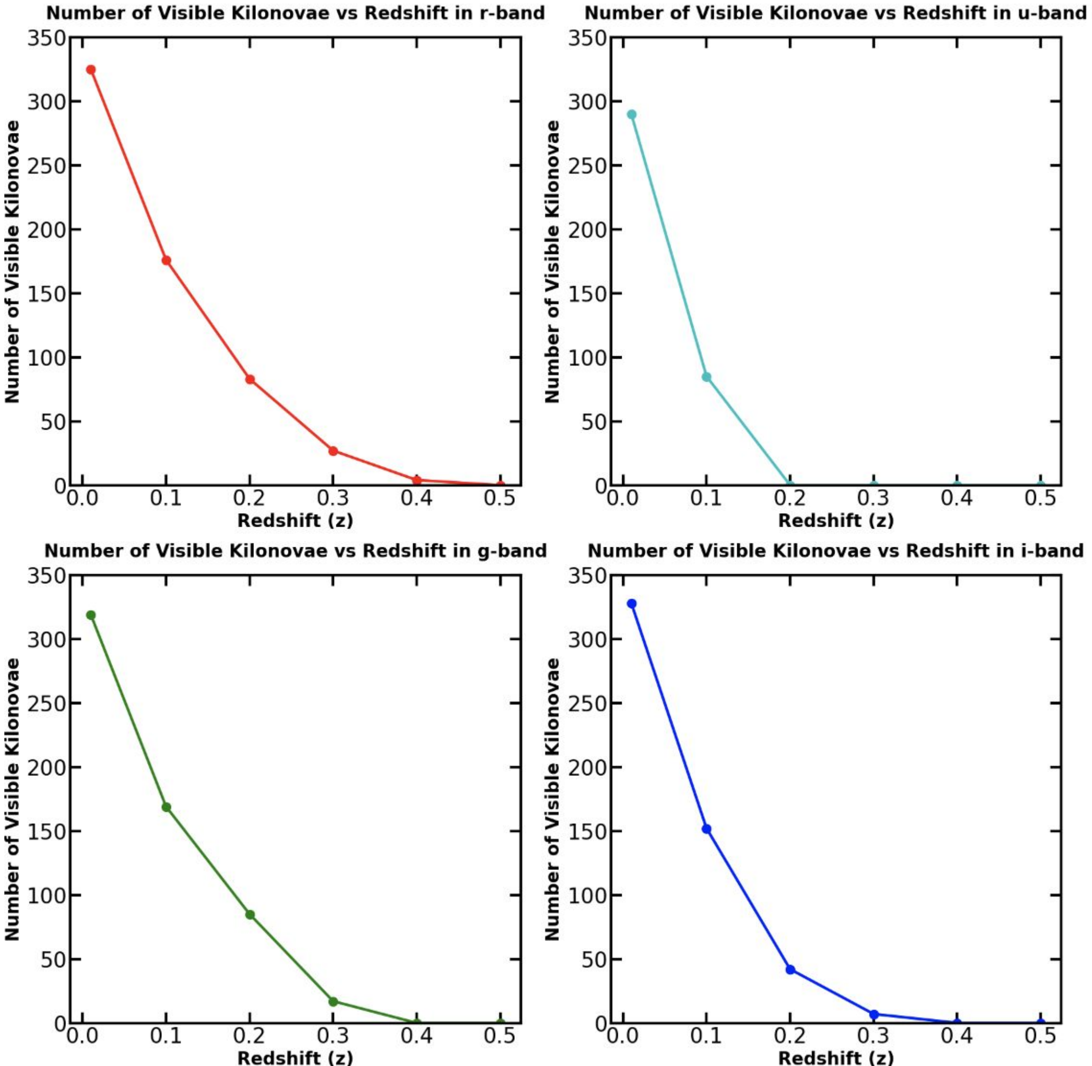
Velocity cycles from 0.03c to 0.3c.

Lanthanide fraction cycles from 0.01 to 1×10^{-9}.

For each 30 systems with 1 mass, lanthanide fraction goes from high to low, then there is a higher velocity, repeat lanthanide fraction cycle.

First system is lowest mass, lowest velocity, highest Xlan.

Last system is highest mass, highest velocity, lowest Xlan.



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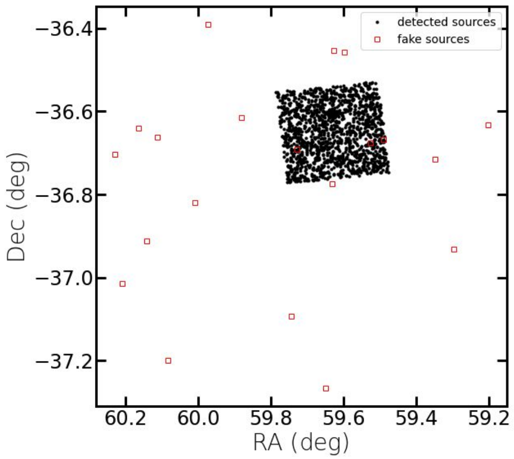
We took each of the 329 Kasen kilonova models and made light curves for each

We then determined how many would be observable by LSST at several redshifts (starting at 0.0099) in 4 different bands (u=23.8, g=24.5, r=24.03, i=23.41)

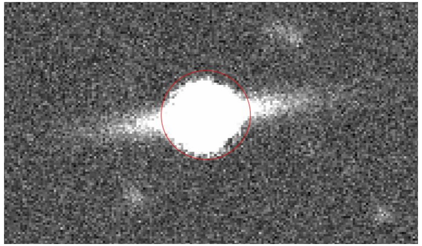
Synthetic Source Injection

- Using a Jupyter notebook written for DP0.1 by Jeff Carlin, I have been working on modifying it to take in positions and magnitudes for our simulated kilonovae.
- I will do this for a series of visits 0.05, 1.05, 5.05, 6.85 and 8.85 days past the kilonova.
- I will download the catalog of objects and the images themselves.
- I can access catalogs of all objects in this area also (I have been using DP0.2 data access through Topcat).

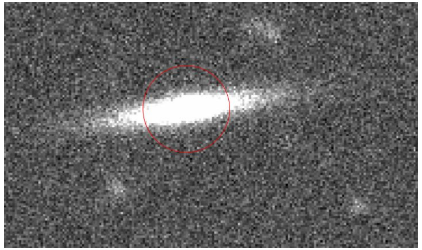


A plot from the notebook showing how many injected objects overlap with the current detector.

Here we show a series of point sources of varying magnitudes injected into a DC2 calibrated exposure

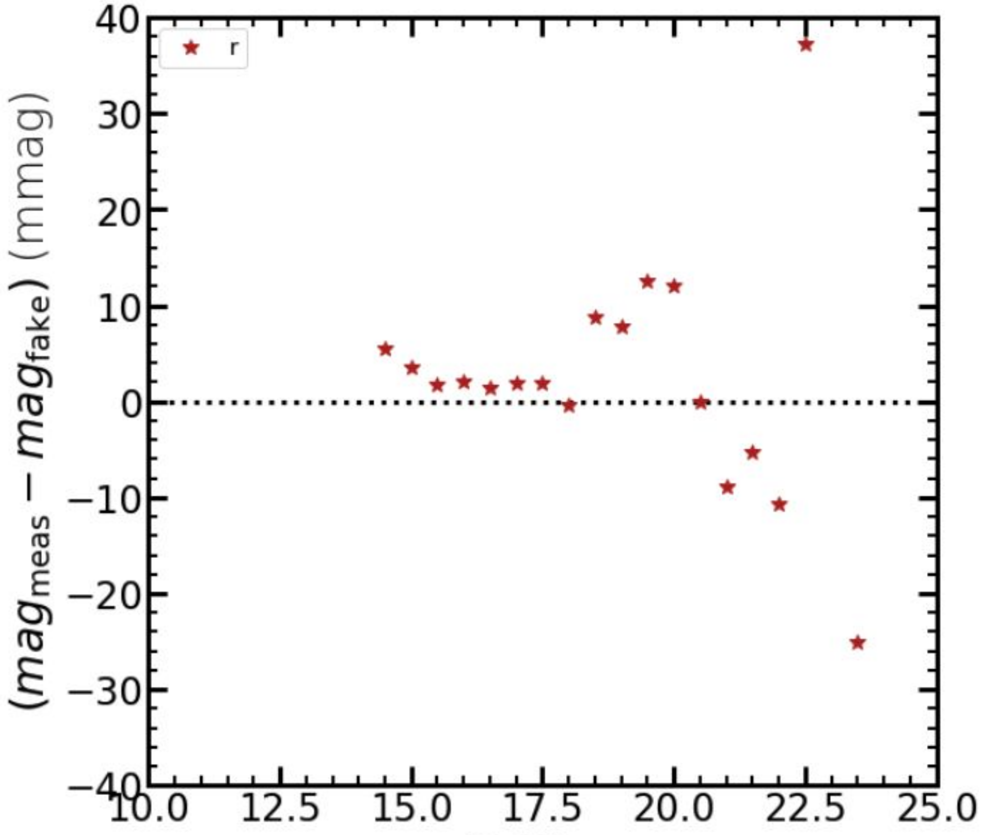


With magnitude 15 star



Without

Magnitude errors for point sources



ra	dec	r_fake	r_meas	rerr_meas	sep_r
deg	deg	mag	mag	mag	arcsec
float64	float64	float64	float64	float64	float64
59.7	-36.8	14.5	14.506	0.00045022	0.20008
59.72	-36.7	15	15.004	0.00050255	0.20028
59.63	-36.81	15.5	15.502	0.00086664	0.20124
59.645	-36.82	16	16.002	0.00065464	0.28232
59.66	-36.83	16.5	16.501	0.00095613	0.0015169
59.675	-36.84	17	17.002	0.001051	0.0010313
59.69	-36.85	17.5	17.502	0.001331	0.20017
59.705	-36.84	18	18	0.0022328	0.19973
59.72	-36.83	18.5	18.509	0.0022998	0.2001
59.735	-36.82	19	19.008	0.0029724	0.2848
59.75	-36.81	19.5	19.513	0.0049666	0.0015528
59.765	-36.8	20	20.012	0.0050374	0.2006
59.78	-36.79	20.5	20.5	0.0073692	0.20289
59.795	-36.78	21	20.991	0.011223	0.19513
59.81	-36.77	21.5	21.495	0.015317	0.27198
59.825	-36.76	22	21.989	0.020892	0.0092895
59.84	-36.75	22.5	22.537	0.035228	0.21932
59.855	-36.74	23	23.066	0.052887	0.027954
59.87	-36.73	23.5	23.475	0.077263	0.24837
59.8	-36.72	24	23.805	0.10355	0.076953

ra	dec	r_fake	r_meas	rerr_meas	sep_r
deg	deg	mag	mag	mag	arcsec
float64	float64	float64	float64	float64	float64
59.75	-36.8	27.169	-99.9	99.9	2.7356
59.76	-36.7	23.641	23.575	0.083598	0.011678
59.63	-36.81	25.11	-99.9	99.9	10.228
59.645	-36.82	25.632	-99.9	99.9	10.506
59.66	-36.83	23.949	-99.9	99.9	5.231
59.675	-36.84	26.895	-99.9	99.9	5.9486
59.69	-36.85	25.289	-99.9	99.9	3.6002
59.705	-36.84	26.12	-99.9	99.9	16.057
59.72	-36.83	26.044	-99.9	99.9	12.138
59.735	-36.82	27.341	-99.9	99.9	10.375
59.75	-36.81	27.301	-99.9	99.9	23.029
59.765	-36.8	27.302	-99.9	99.9	5.2729
59.78	-36.79	24.331	-99.9	99.9	2.0151
59.795	-36.78	25.959	-99.9	99.9	12.309
59.81	-36.77	26.042	-99.9	99.9	14.378
59.825	-36.76	24.972	-99.9	99.9	1.5436
59.84	-36.75	28.48	-99.9	99.9	8.7676
59.855	-36.74	26.552	-99.9	99.9	6.7217
59.87	-36.73	21.364	21.37	0.011943	0.27911
59.82	-36.72	24.327	-99.9	99.9	18.93

Magnitude errors

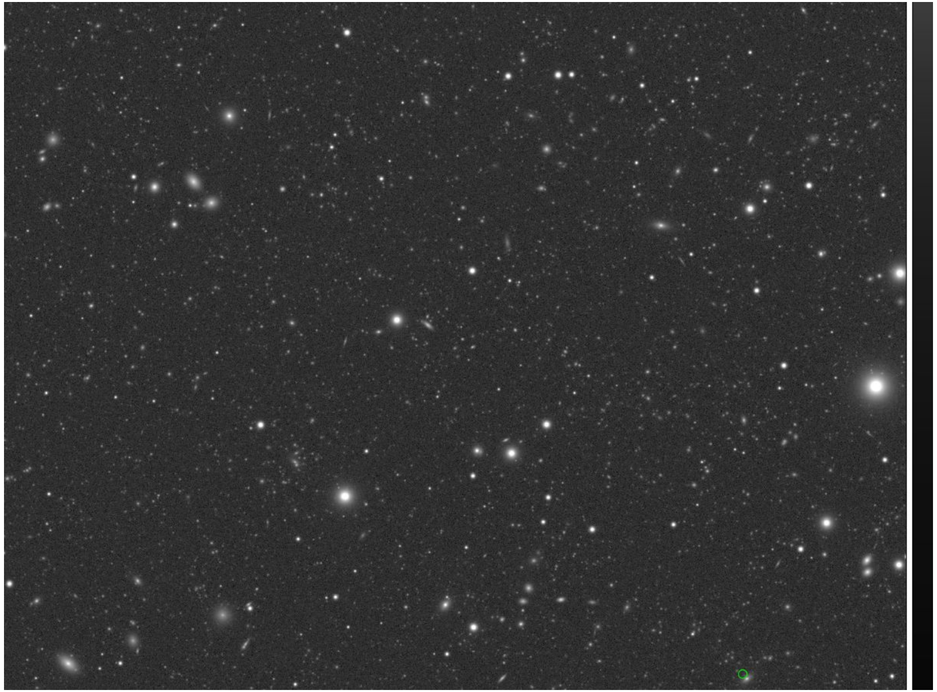
LSST DESC Dark Energy Science Collaboration

Replaced the bright magnitudes with the kilonova magnitudes.

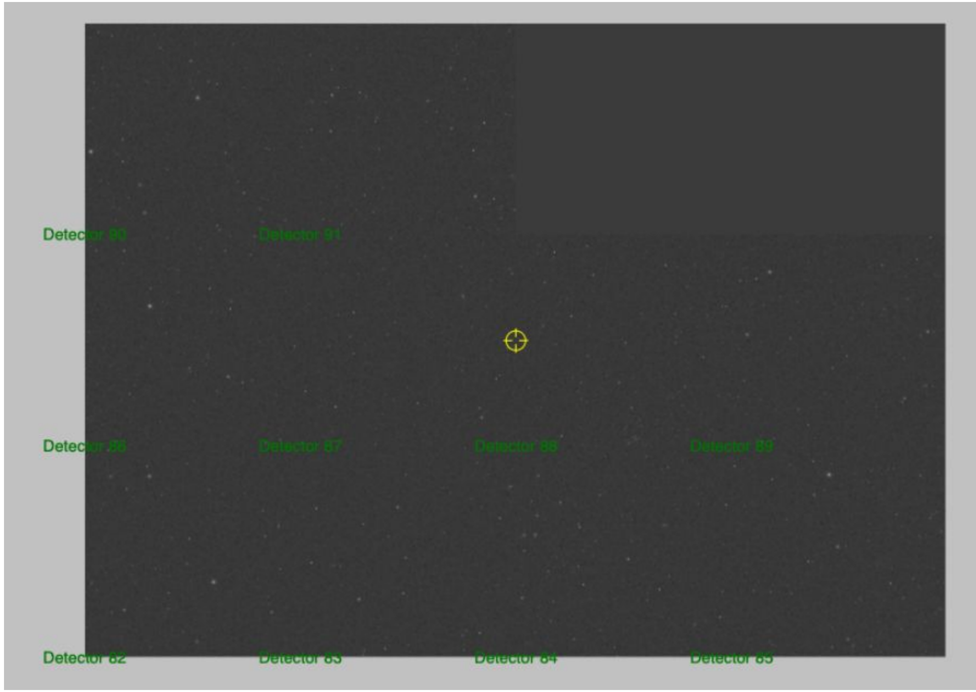
This suggests that only 10% (2) of the input kilonovae are observable in LSST single exposure images.

Contributions to delegate notebooks: view_mosaic

Galaxy_viewer displays multiple calexps, a single coadd or a cutout



Mosaic shows multiple chips as a mosaic



Summary and Outline

LSST DESC
Dark Energy Science Collaboration

- Background information
- What is the Kilonova Data Challenge?
- What has been done previously on this project?
- What was done this summer?
- What are the final steps?

Final steps

- Report in the CSS and TD Working Groups in DESC.
- What are all the transients in the 1 square degree region of interest?
- Of the 9 visible kilonovae, would all of them be detected by difference imaging?
- Could they be differentiated from the supernovae?
- Make the images and catalogs available, possibly in a DP0 delegate-contributed notebook.

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EXTRA SLIDES