The GuRu (GRAWITA using Rubin) project

Hunting for gravitational wave events counterparts and transients in the Vera Rubin Observatory (LSST) era inside the INAF GRAWITA collaboration

Silvia Piranomonte - Second GraviGamma Workshop - June 25th, 2021

Outline Talk

- Rubin-LSST intro
- Why LSST for GW counterparts search?
- The GuRu (GRAWITA using Rubin) project inside RUBIN-TVS Group
- Multi-wavelength and GW follow-up with Rubin
- Kilonovae serendipitous search with Rubin

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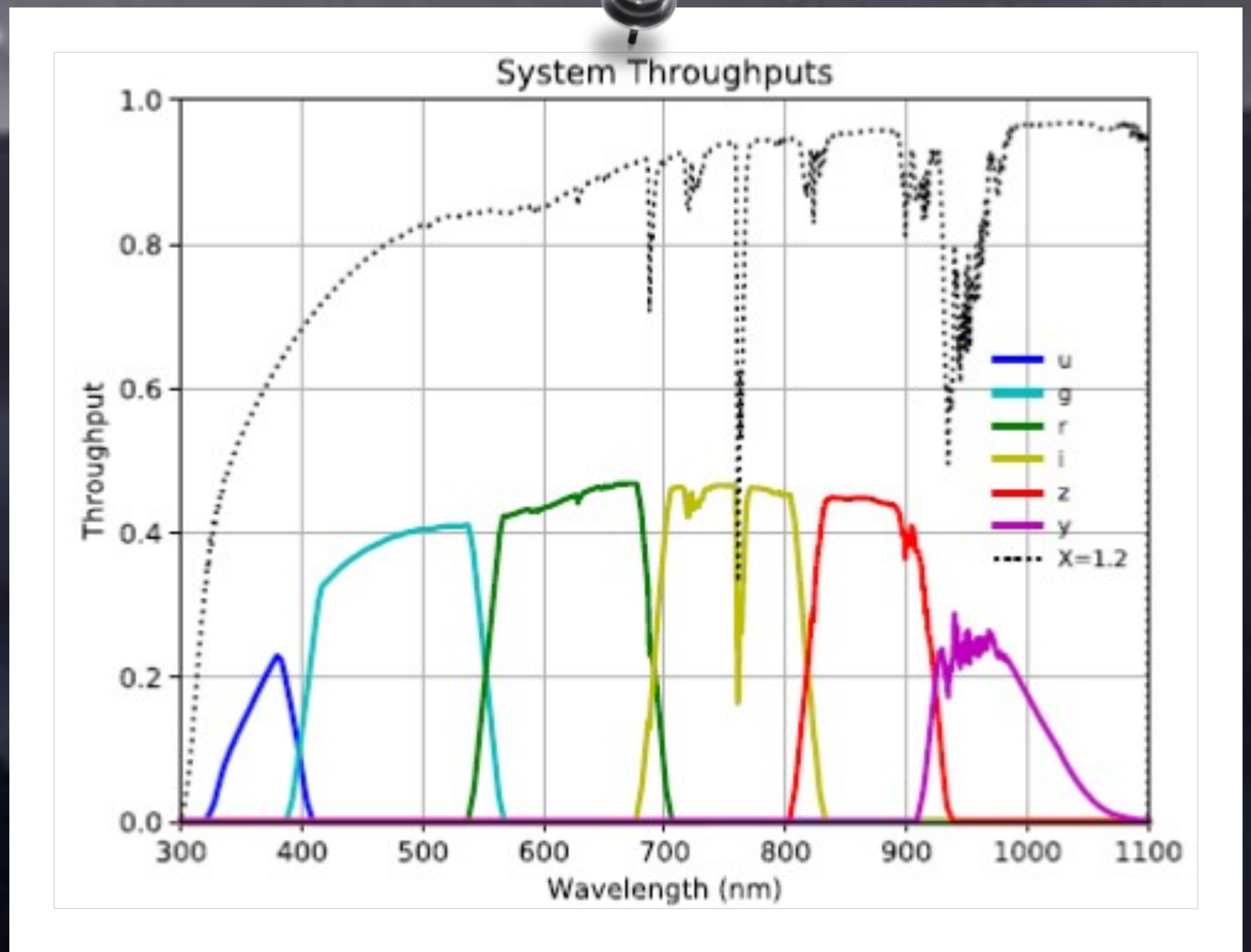
Opening a Window of Discovery on the Dynamic Universe

5σ point source depth - Single exposure idealized for stationary sources after 10 years

u	23.9	26.1
g	25.0	27.4
r	24.7	27.5
i	24.0	26.8
z	23.3	26.1
y	22.1	24.9



Ivezić et al. 2019

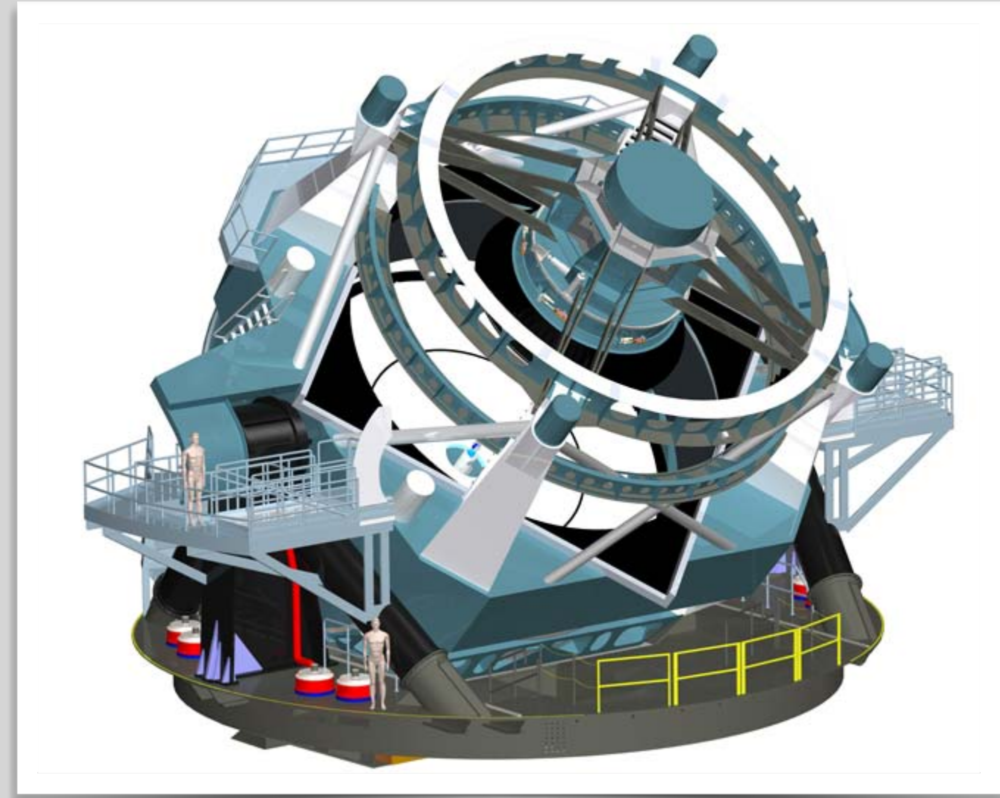
- ✓ 6-band (0.3-1.1 micron) wide-field deep astronomical survey of over 20,000 square degrees of the southern sky.
- ✓ Each patch of sky will be visited about 1000 times in ten years.

FoV 9.6 deg^2
0.2”/pixel pitch
3.2 Gpixel camera
8.4m primary mirror
10 year survey of the sky
37 billion stars and galaxies
Site El Penon, Cerro Pachon, Chile
Each image has size of 40 full moons
Up to 10 million alerts, 20 TB of data ... **every night!**

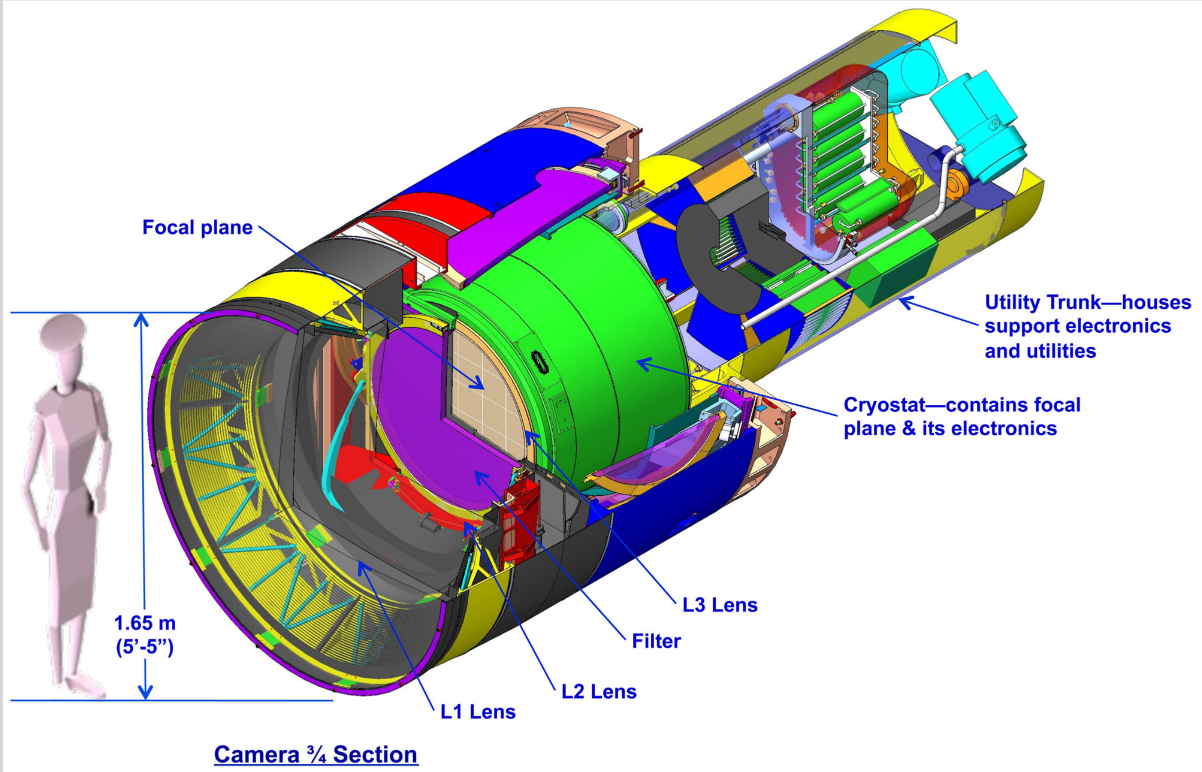
- ✓ Survey speed (~ Etendue) ≈ 319 m^{2}deg^2
- ✓ Standard visit exposures (expected) : 2 x 15 sec
- ✓ Median (Mean) visit time : 39s (42.2s)
- ✓ Photometric accuracy : 10 mmag
- ✓ Astrometric accuracy : 50 mas
- ✓ Astrometric precision : 10 mas
- ✓ image quality dominated by seeing (median ~0.67”)

Telescope Progress Summary

Cerro Pachón (Chile)



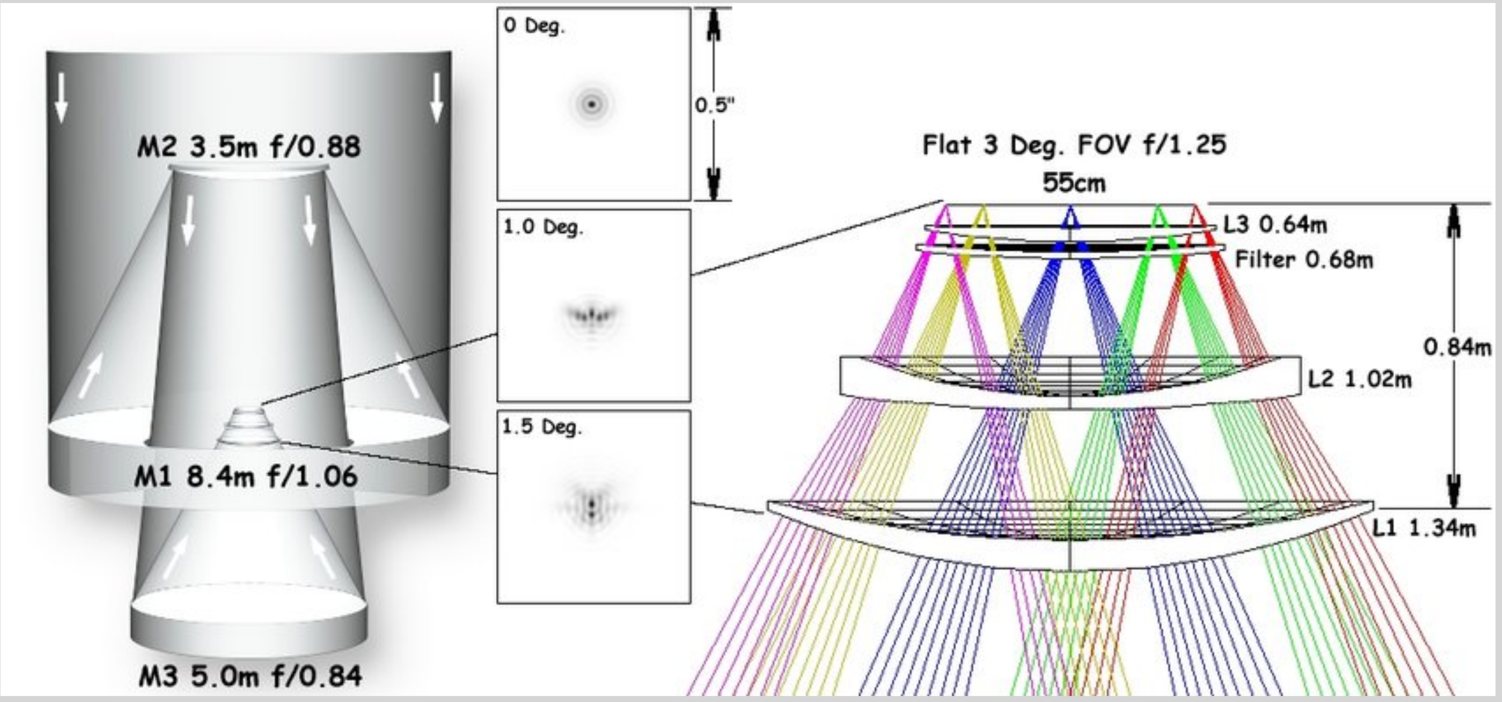
Countdown to Data Preview Zero (the first simulated data using the Rubin Science Platform (RSP))! From June 29th 2021 !!



Select Milestones

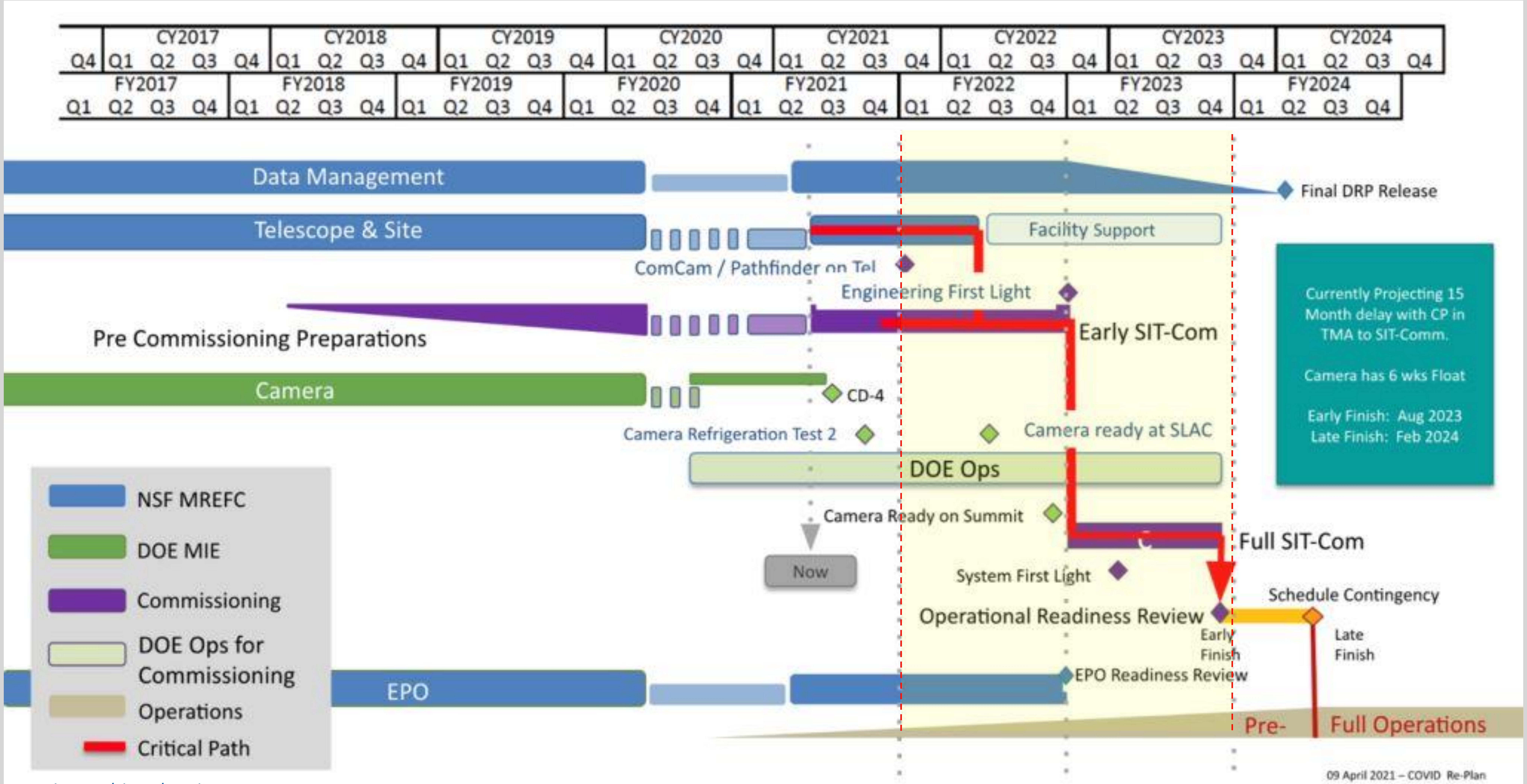
Updated with post Covid replan dates

Activity Name	Baseline Finish
Camera at SLAC ready to ship	May 2022
Engineering First Light w/ComCam	October 2022
System First Light	January 2023
Start of Operations	Not earlier than October 2023



More news: https://www.lsst.org/

Very likely 15 months of time shift due to pandemic



www.lsst.org/about/timeline

TIMELINE

LSST Operations: Sites & Data FLows

- Final volume of raw image data =60 PB
- Final image collection (DR11) =0.5 Exabytes
- Final catalog size (DR11) = 15 PB
- Final disk storage = 0.4 Exabytes
- Peak number of nodes = 1750 nodes
- Peak compute power in LSST data centers = about 2 TFLOPS

The total data volume after processing will be several hundred PB, processed using about 150 TFLOPS (trillion floating point operations per second) of computing power for the first DR, increasing to 950 TFLOPS by DR 11

The Rubin-LSST ecosystem & data production

23 World Countries (13 in Europe)
38 Research/Academic Institutes (24 in Europe)

Community Working Groups (CWGs)

- ❑ Data Q&A
- ❑ Statistics Q&A
- ❑ Survey Cadence Strategy
- ❑ Alerts & Brokers
- ❑ Independent Data Access Centers
- ❑ Photometric Redshifts
- ❑ Crowded Fields
- ❑ Milky Way
- ❑ Science Platform
- ❑ Commissioning
- ❑ Simulations

Science Collaborations (SCs)

- ❖ Galaxies
- ❖ Stars, Milky Way & Local Volume
- ❖ Solar System
- ❖ Dark Energy
- ❖ Active Galactic Nuclei
- ❖ Transient/Variable Stars
- ❖ Strong Lensing
- ❖ Informatics & Statistics

Prompt Data Products

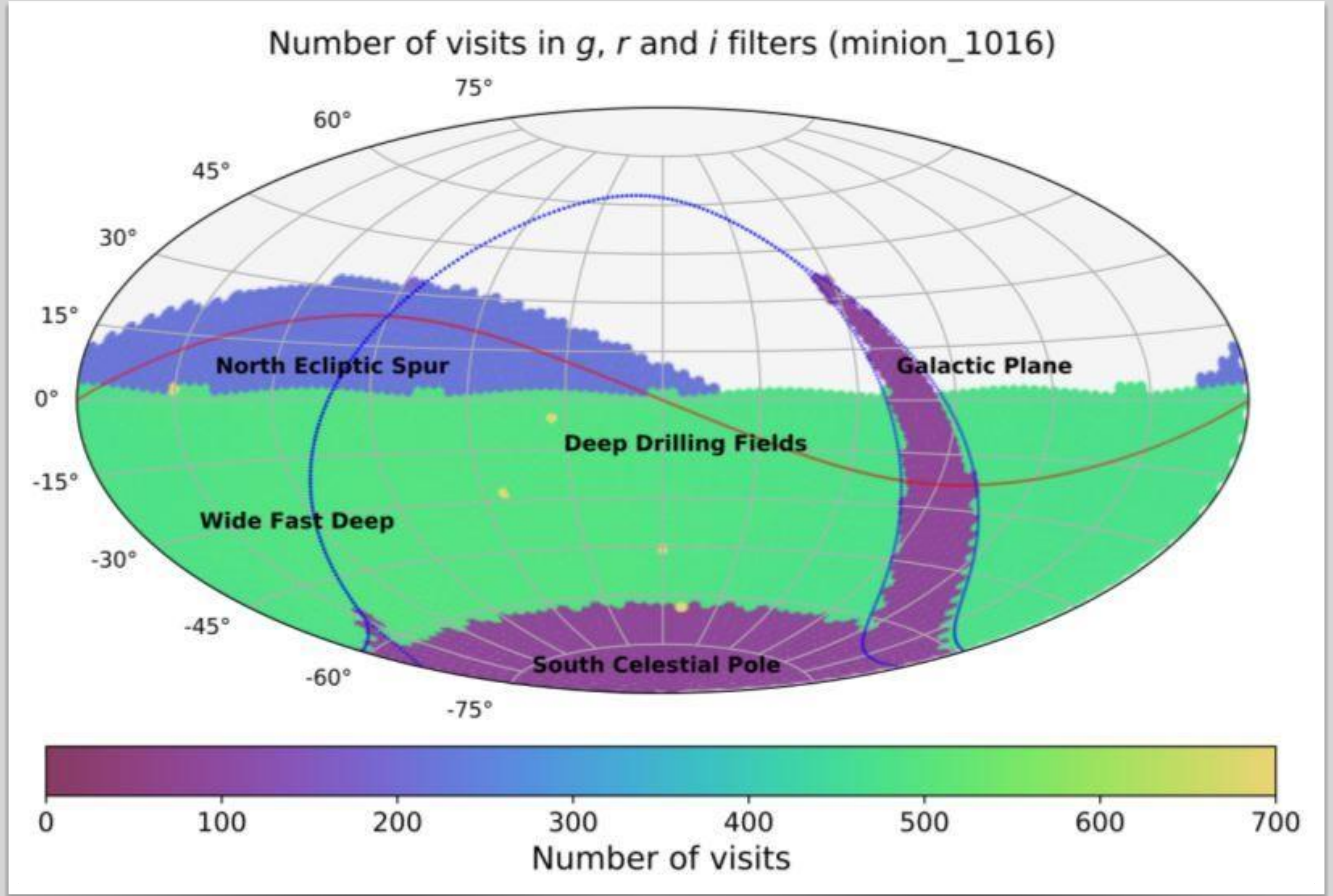
Alerts: up to 10 million per night — 60s via nightly alert streams

Results of Difference Image Analysis (DIA): transient and variable sources
Solar System Objects: ~ 6 million — 24h via Prompt Products Database

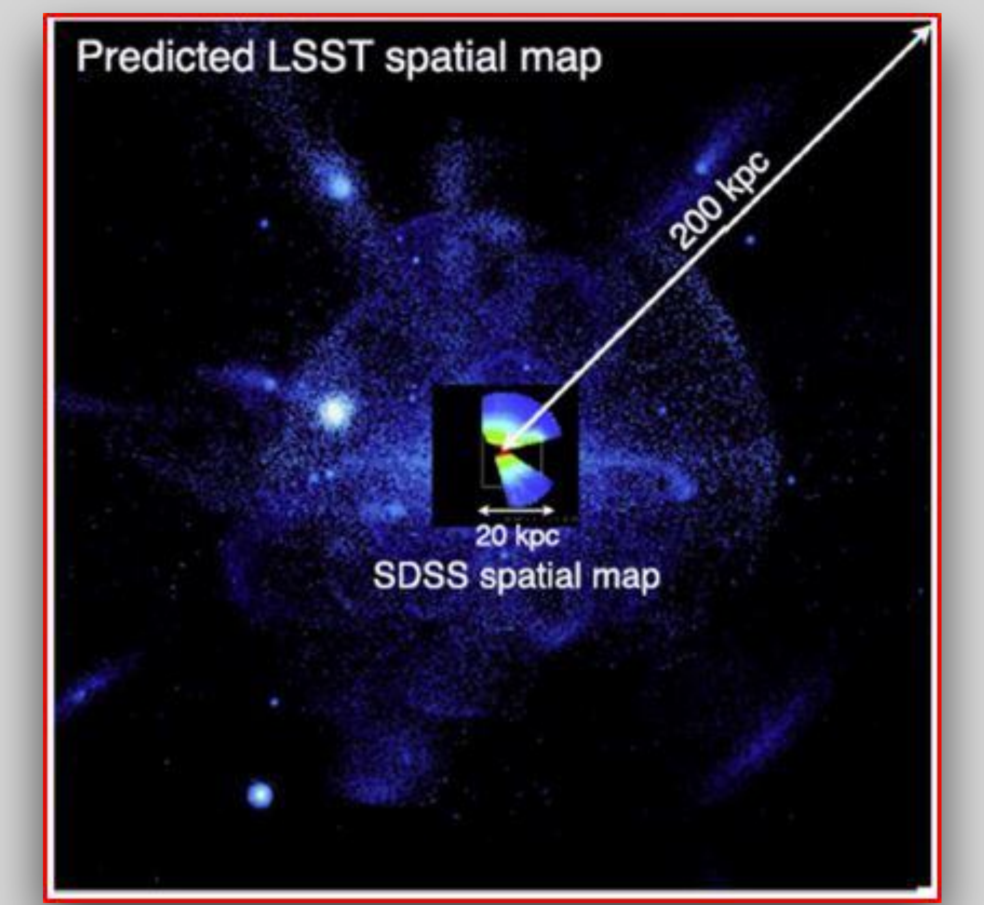
Data Release Data Products

Final 10yr Data Release: Michitaro Koike
- Images: 5.5 million x 3.2 Gpx
- Catalog: 15PB, 37 billion objects

via Data Releases



- Wide-Fast-Deep area of 18,000 deg^2
- 825 visits per field over 10 years, and same night & field re-visit "pairs"
- At least four Deep Drilling Fields
- North Ecliptic Spur, Galactic Plane and South Celestial Pole



Ivezić et al. 2019

Main Modes of Operation Discussed:

Wide-Deep-Fast (WFD) 85%-95% of time

The median single-visit depths for WFD fields are (23.14, 24.47, 24.16, 23.40, 22.23, 21.57) ugrizy

Deep Drilling Fields (5, DDF) 4.5% of time

4 DDF selected and announced,
~5 times more exposures in all filters

Rolling Cadence

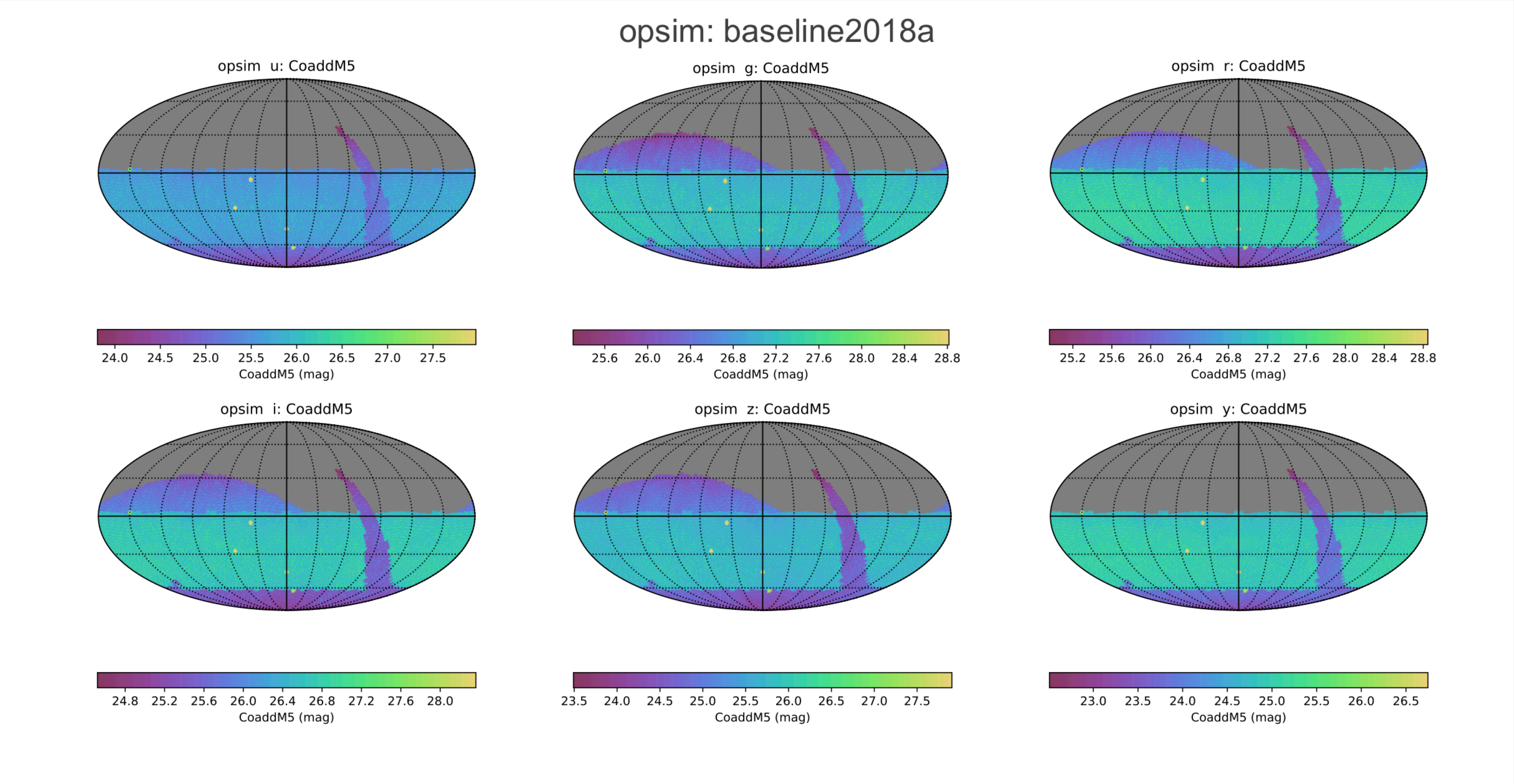
(i.e. "re-allocate" visits in some parts the sky)

Mini Surveys (~few % of time)

Target of Opportunity

Now 1% of time **BUT** it will be 3-4%
(in discussion after O4)

Main Survey coadded 5-sigma depth according to the Baseline2018a OpSim run



Special (additional) Projects

- Deep Drilling Fields

Small areas where higher cadence and deeper coverage are needed
Some fields already selected:

- ELAIS S1
- XMM-LS
- Extended Chandra DFS
- COSMOS

	ELAIS S1	XMM-LSS	Extended Chandra Deep Field-South	COSMOS
RA 2000	00 37 48	02 22 50	03 32 30	10 00 24
DEC 2000	-44 00 00	-04 45 00	-28 06 00	+02 10 55

- Mini surveys

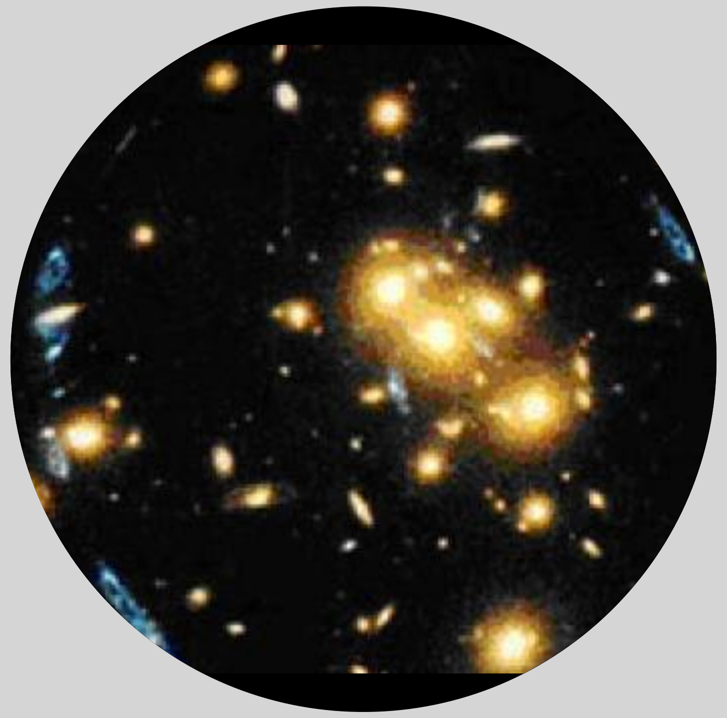
Projects devoted to special environments not covered by WFD survey or projects in need of a different observational strategy (special cadences):

- The Galactic disk
- The Galactic bulge
- The Magellanic Clouds

LSST Science Drivers

Four science programs as the key drivers of the science requirements

Dark Matter, Dark Energy



- Weak Lensing
- Baryon acoustic oscillations
- Supernovae, Quasars

Cataloging the Solar System

- Potentially Hazardous Asteroids
- Near Earth Objects
- Object inventory of the Solar System

Milky Way Structure & Formation

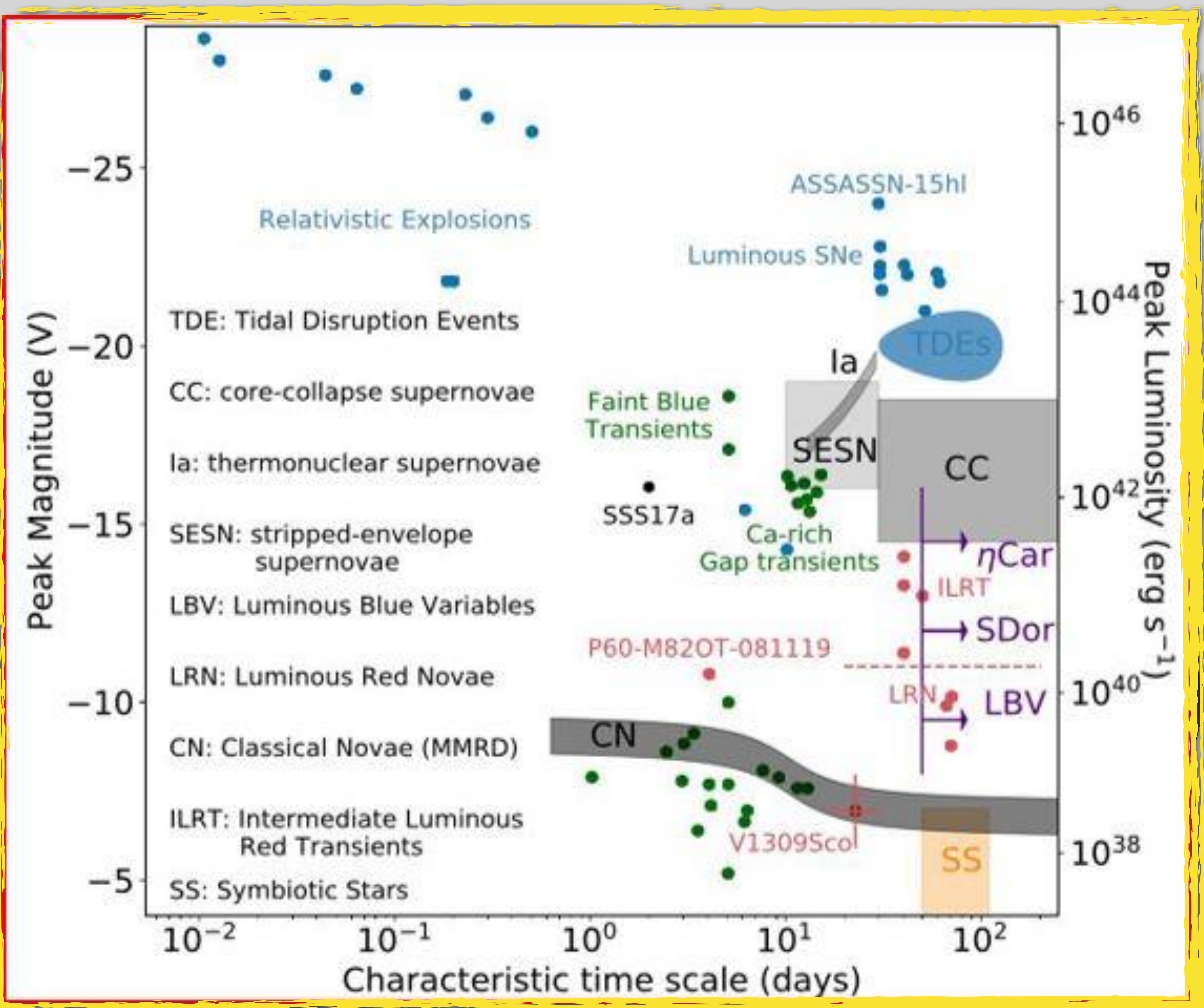
- Structure and evolutionary history
- Spatial maps of stellar characteristics
- Reach well into the halo

Exploring the Transient sky

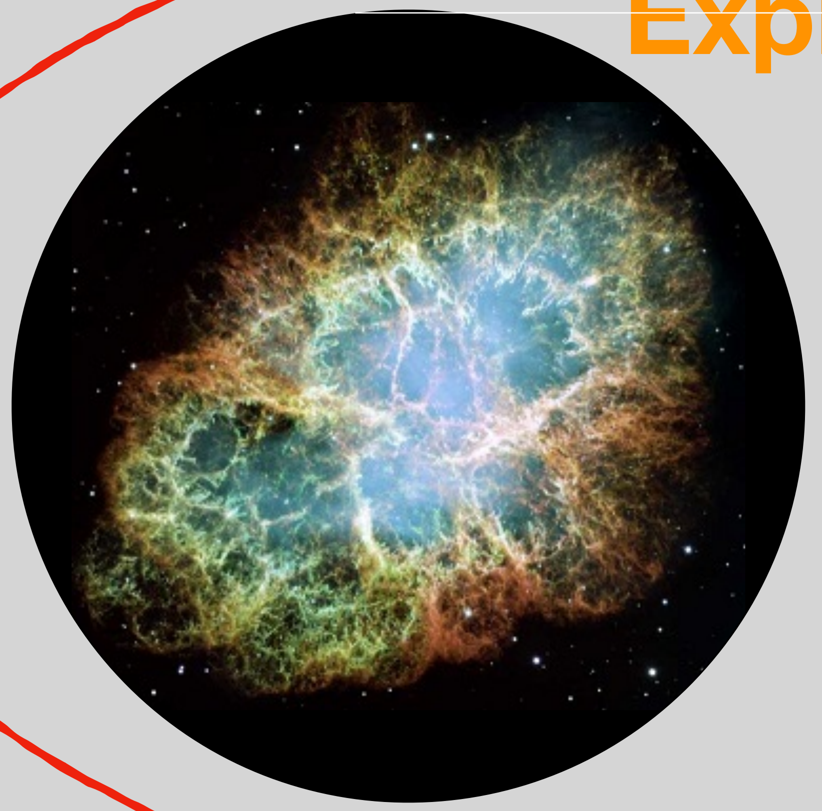
- Variable stars, Supernovae, GRBs, KN…
- Fill in the variability phase-space
- Discovery of new classes of transients

LSST Science Drivers

Four science programs as the key drivers of the science requirements



Exploring the Transient sky



- Variable stars, Supernovae, GRBs, KN…
- Fill in the variability phase-space
- Discovery of new classes of transients

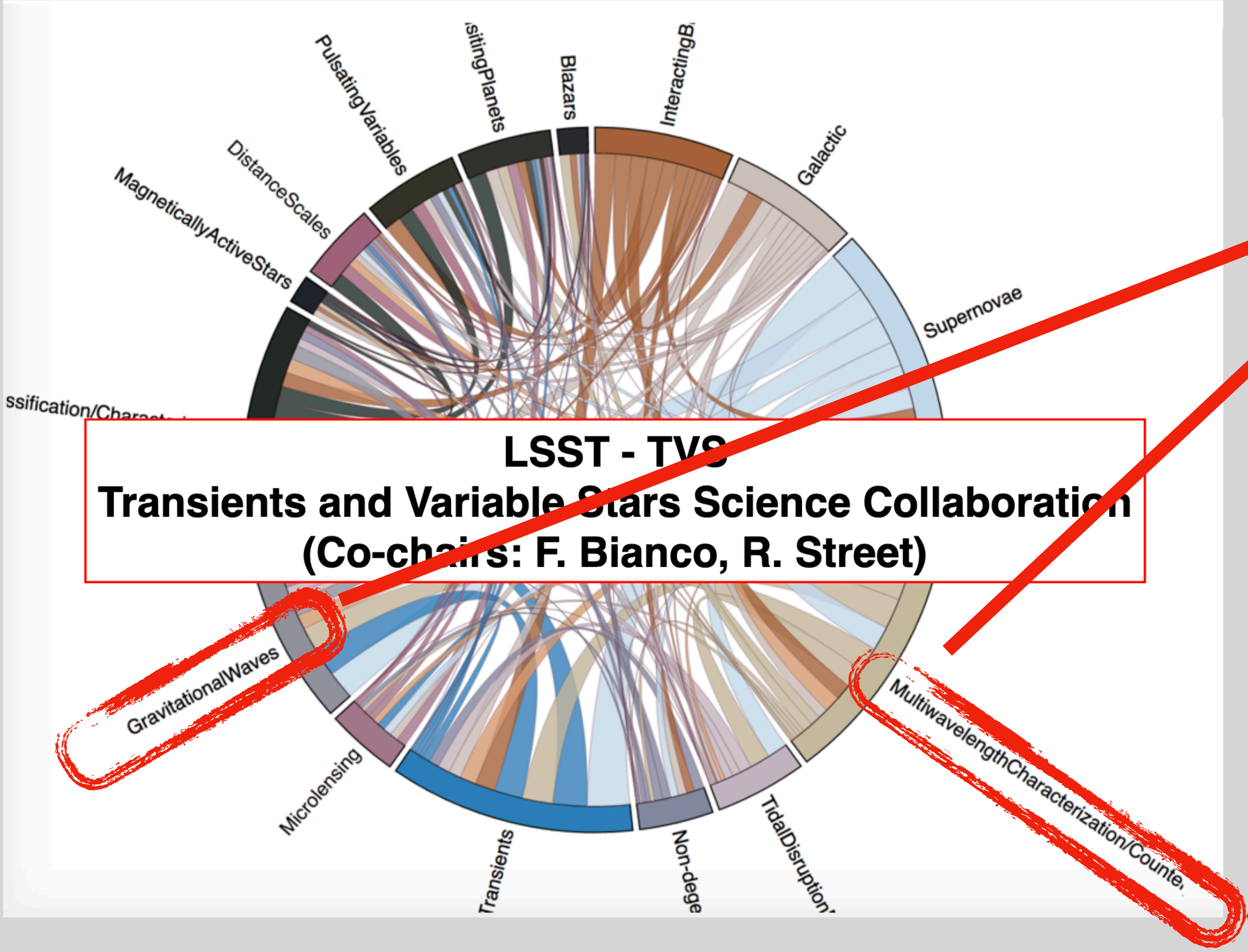
Why Rubin-LSST for GW counterparts search?

- Rubin-LSST horizon increased —> fainter sources.
- The strategy of targeting galaxies is unlikely to often succeed succeed.

How much time?

- We are “competing” with other scientific cases for the remaining few % of time —> realistic estimate ~1-3%

- Allocation of time can/will be revised during LSST life based on performance



Multiwavelength Characterization and Counterparts SUBGROUP

coordinator: Raffaella Margutti, NorthWestern University

Members

Members that collaborated to generate this roadmap:

- Edo Berger - Harvard Smithsonian Center for Astrophysics
- Raffaella Margutti - Northwestern University
- Wen-fai Fong - CfA Harvard
- Derek Fox - Pennsylvania State University
- Virginia Trimble - University of California Irvine

Primary subgroup contact:

Raffaella Margutti (Northwestern University - rafmargutti@gmail.com)

Subgroup MAF engineer:

Zoheyr Doctor (Northwestern University - zdoctor@uchicago.edu)

+ European Collaborators!

Subgroup Primary members

- Edo Berger
- Wen-fai Fong
- Derek Fox
- Raffaella Margutti
- Virginia Trimble

ITALY
The INAF GuRu (GRAWITA using Rubin) project

PI: Silvia Piranomonte

The INAF GuRu (GRAWITA using Rubin) project

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WHAT WE NEED:

1) **Transient alerts: position, timing, magnitude, preliminary classification**
2) **Follow-up: Images and photometric multiband data to construct long-term light curves in different filters**

OBJECTIVES:

I) Exploit the **direct availability of full LSST data to select specific EM counterparts candidates of transient GW events for spectroscopic multi-wavelength campaigns with optical facilities** (LBT, VLT, SRT, E-ELT, etc). This will lead to new fundamental steps on several science goals like final source identification, nature of GW events, host galaxy properties and source physics.

II) AGILE and Fermi have provided a wealth of data for several classes of sources, but the simultaneous optical data are only rarely available, due to the late follow-up observations and the difficulty to match the wide sky coverage currently available in γ-rays. **LSST,** operating in the timeframe of present or future gamma-ray missions, **will allow us to overcome these issues** for a variety of classes of sources, including: Galactic transients and binaries; blazars (optical flares and long-term monitoring); GRBs; GW source counterparts; exotic transients (e.g. TDE).

Multi-wavelength and GW follow-up sub-group

Mode A

Rubin-LSST = discovery machine

Other facilities do follow-up of LSST transients

Mode B

Rubin-LSST = follow-up machine

GW detectors find sources

↓

Rubin Deep Drilling Fields + mini surveys + WDF + ToO(?)

Multi-wavelength and GW follow-up sub-group

Mode A

Rubin-LSST = discovery machine

Oth… SST
trar…

Key Challenge: Limited resources for multi-wave follow-up vs. number of LSST transients

Mode B

Rubin-LSST = follow-up machine

GW detectors find sources

Rubin Deep Drilling Fields + mini surveys + WDF + ToO(?)

Multi-wavelength and GW follow-up sub-group

Mode A

Rubin-LSST = discovery machine

Oth SST
trar

Key Challenge: Limited resources for multi-wave follow-up vs. number of LSST transients

MISSION 1: Conversations with current and future facilities in X-ray/radio/UV AND Interface with brokers to make sure that the relevant info is shared, which will allow us to make informed decisions about which LSST sources to follow up.

Mode B

Rubin-LSST = follow-up machine

GW detectors find sources

Rubin Deep Drilling Fields + mini surveys + WDF + ToO(?)

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Mode A

Multi-wave Observations

Follow up

Identify the nature of the source

LSST transients classification

Key Problem: Prompt Identification of Targets-of-Interest within the LSST data stream **without** spectroscopic info

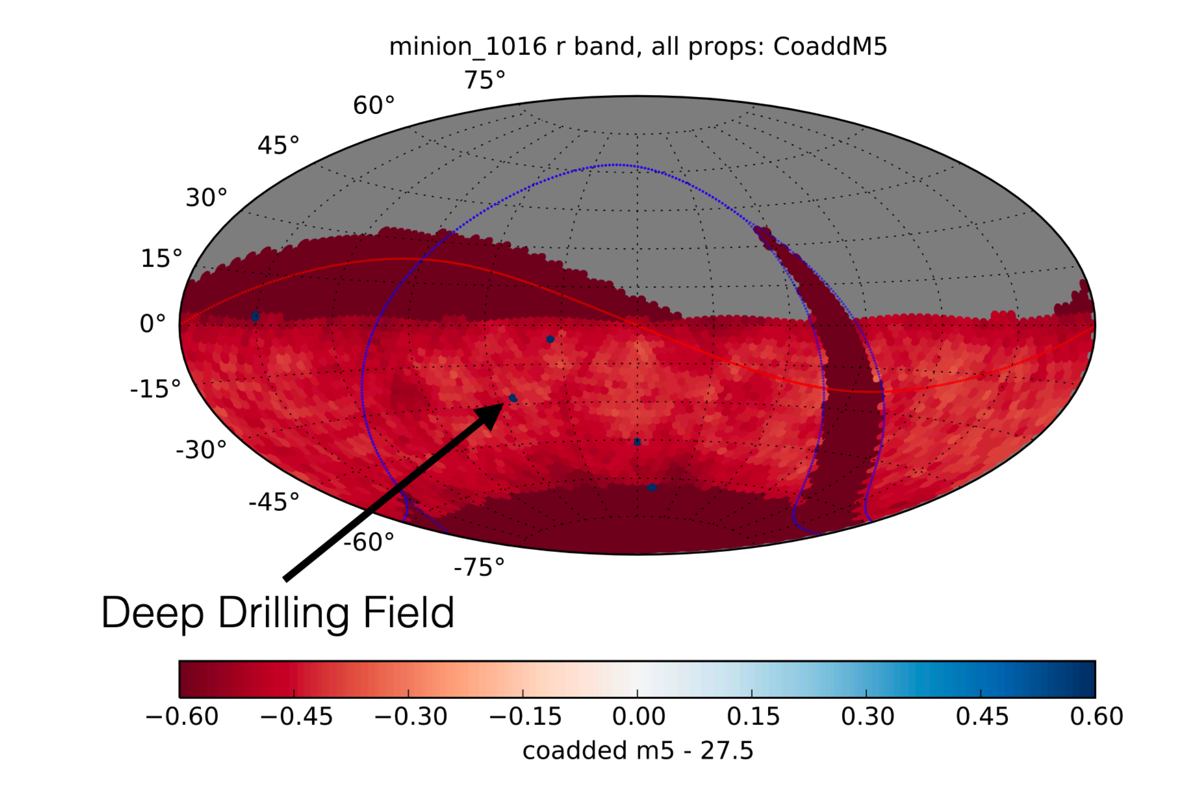
Interface with Brokers (e.g. ANTARES) to best filter out "undesired transients"

Exploit already existing multi-wave info

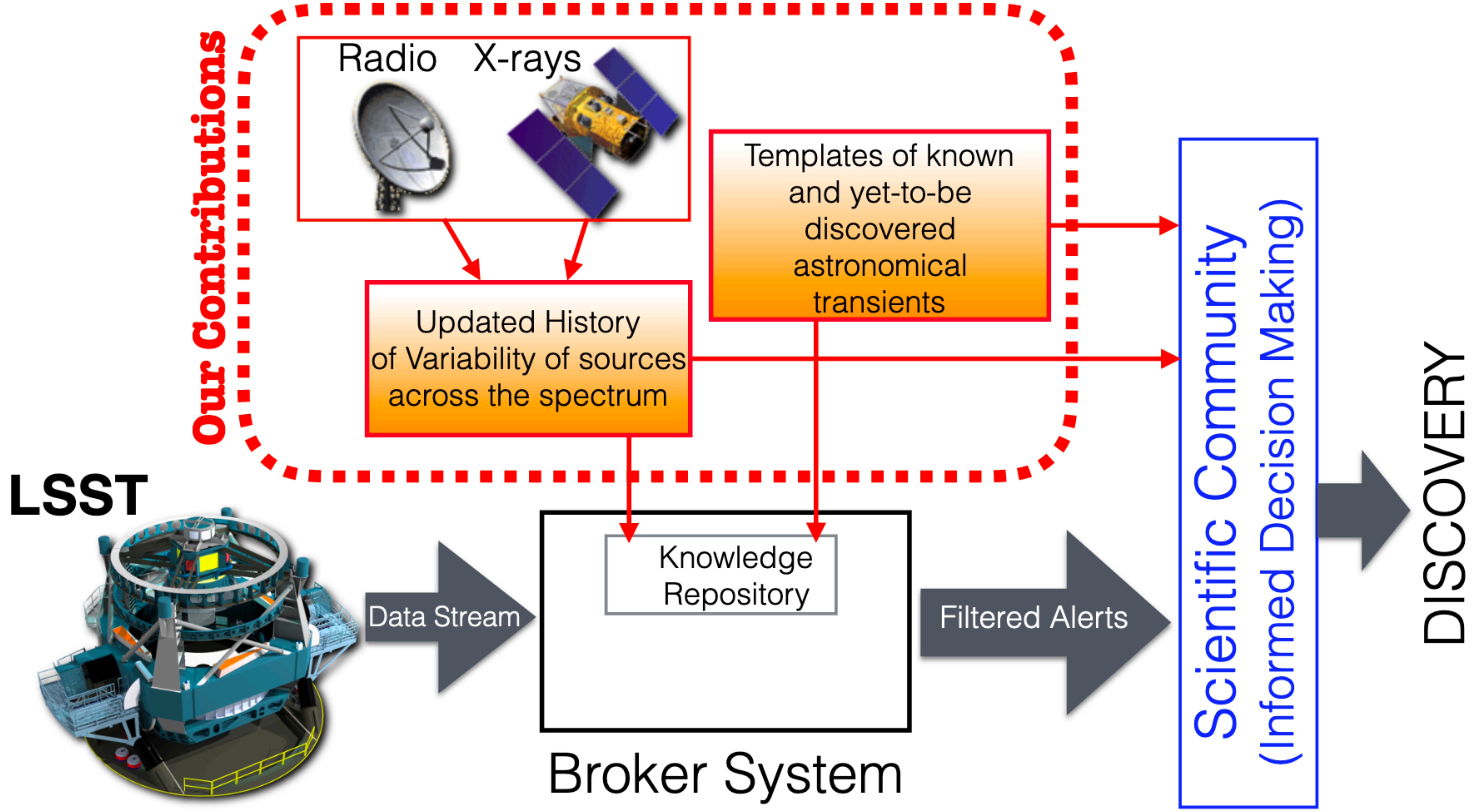
Co-observing

Prioritize the fields to cover

LSST Deep Drilling Fields/ Mini-surveys



Mode A



From Margutti et al., LSST Science Support Proposal

Mode B

Rubin-LSST = follow-up machine

- WDF ALONE will yield a **small number of kilonova detections**, with poor light curves and marginal information content
- Sky area covered by the DDFs **is not large enough** to rely on chance alignment with GW localizations.

↓

Target-of-opportunity follow-up of gravitational wave triggers much more effective approach for kilonova studies —>
ToO highly recommended!

Target of Opportunity Observations of Gravitational Wave Events with LSST

The TVS Multiwavelength Characterization/GW Counterparts subgroup,

Margutti et al. 2018 - arxiv:1812.04051

DRAFT VERSION NOVEMBER 9, 2018
Typeset using LaTeX **twocolumn** style in AASTeX62

LSST Target-of-Opportunity Observations of Gravitational Wave Events: Essential and Efficient

P. S. COWPERTHWAITE,[1] V. A. VILLAR,[2] D. M. SCOLNIC,[3] AND E. BERGER[2]

[1]*The Observatories of the Carnegie Institution for Science, 813 Santa Barbara St., Pasadena, CA 91101, USA*
[2]*Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, Massachusetts 02138, USA*
[3]*Kavli Institute for Cosmological Physics, The University of Chicago, Chicago, IL 60637*

Coperthwaite et al. 2018 - arxiv:1811.0309

Mode B

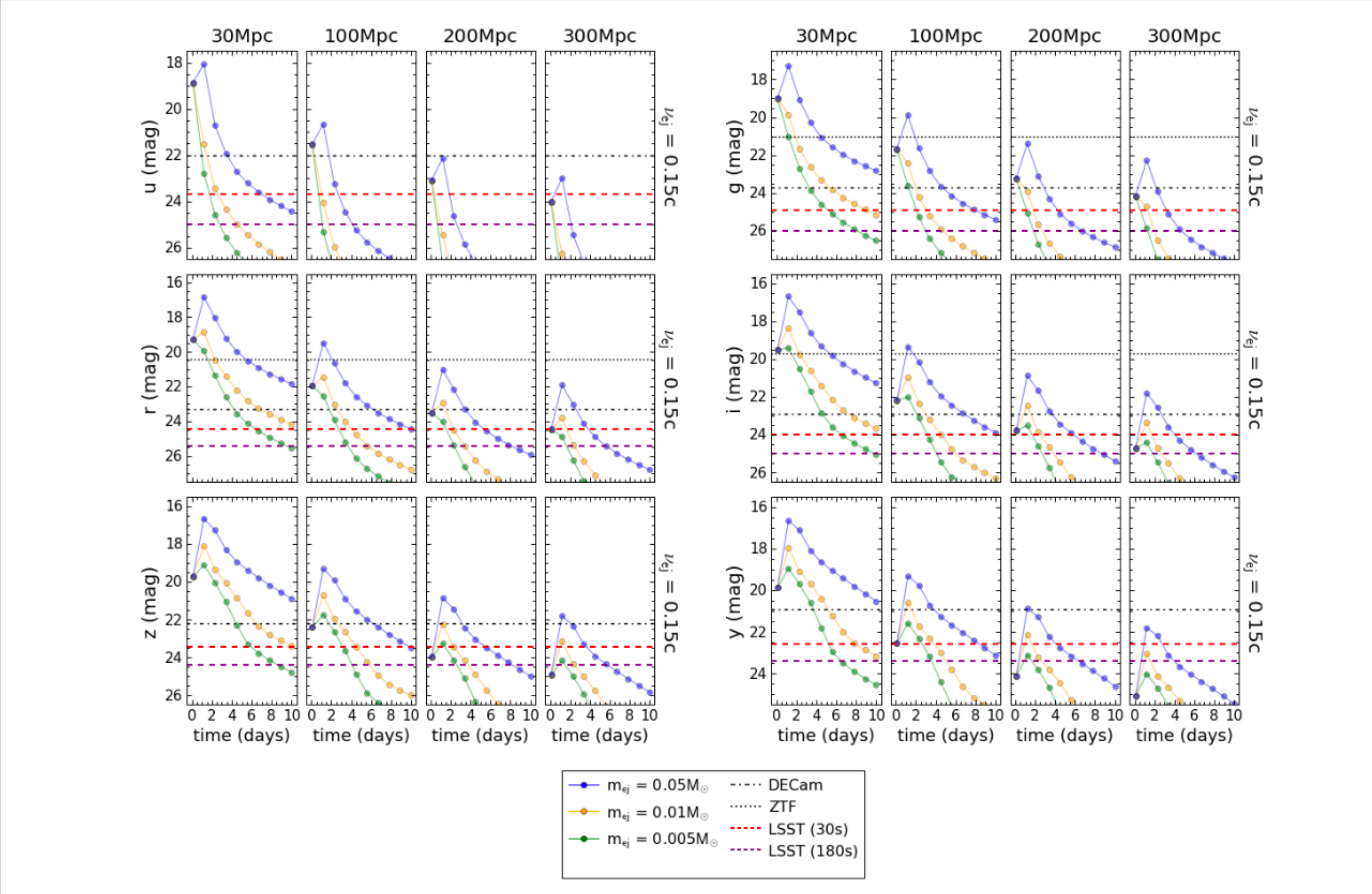


Figure 1: Simulated kilonova (KN) light-curves in the six LSST filters for different properties of the ejecta (mass and velocity) at four representative distances (30, 100, 200 and 300 Mpc). The models include a "red" and "blue" KN component. We explore three values of the red KN ejecta mass $M_{ej,R} = 0.005, 0.01, 0.05\,M_\odot$ and velocity $v_{ej,R} = 0.15\,c$ (the KN luminosity is not a strong function of $v_{ej,R}$ and values within 0.1–0.2 c give comparable results). For each combination of these parameters the blue ejecta component is $M_{ej,B} = 0.5 \times M_{ej,R}$ and $v_{ej,B} = 1.5 \times v_{ej,R}$. Dotted and dot-dashed horizontal lines mark the 5σ threshold of detection of ZTF and DECam, respectively. Red and purple dashed lines: 5σ LSST threshold of detection for exposure times of 30 s and 180 s under ideal observing conditions. Adapted from Mortensen et al., in prep., to include the results from [6].

Margutti et al. 2018 - Arxiv 1812.04051

ToO afraid?

Target of Opportunity Observations ofGravitational Wave Events with LSST, Margutti et al. 2018
(The TVS Multiwavelength Characterization/GW Counterparts subgroup)
Arxiv 1812.04051

MINIMAL STRATEGY: multiple u+g+r+I+z+y visits (30 s for each filter) of well-localized NS-NS mergers with $\Omega_{90\%}\leq$20 deg2 (sky position and time favorable for prompt follow up and continued follow up during the first night). ~2.17hrs and ~2.28hrs per NS-NS merger with $\Omega_{90\%}\leq$20 deg2 and 20 deg2<$\Omega_{90\%}\leq$100 deg2, respectively.

Number of LSST accessible mergers with $\Omega_{90\%}\leq$20 deg2 is N≤(1–2) yr^(–1), while for 20 deg2<$\Omega_{90\%}\leq$100 deg2 N= (1–10) yr^(–1), —> **yearly LSST average time** request for NS-NS follow-up of ~**18 hrs**.

OPTIMAL STRATEGY: multiple u+g+r+I+z+y visits (30 s for each filter) of well-localized NS-NS mergers with $\Omega_{90\%}\leq$ 100 deg2 (sky position and time favorable for prompt follow up) + g+z monitoring (180 sec) at δt ≥ 1 days, reaching m_lim(g) ~ 26mag and m_lim(z) ~ 24.4mag.

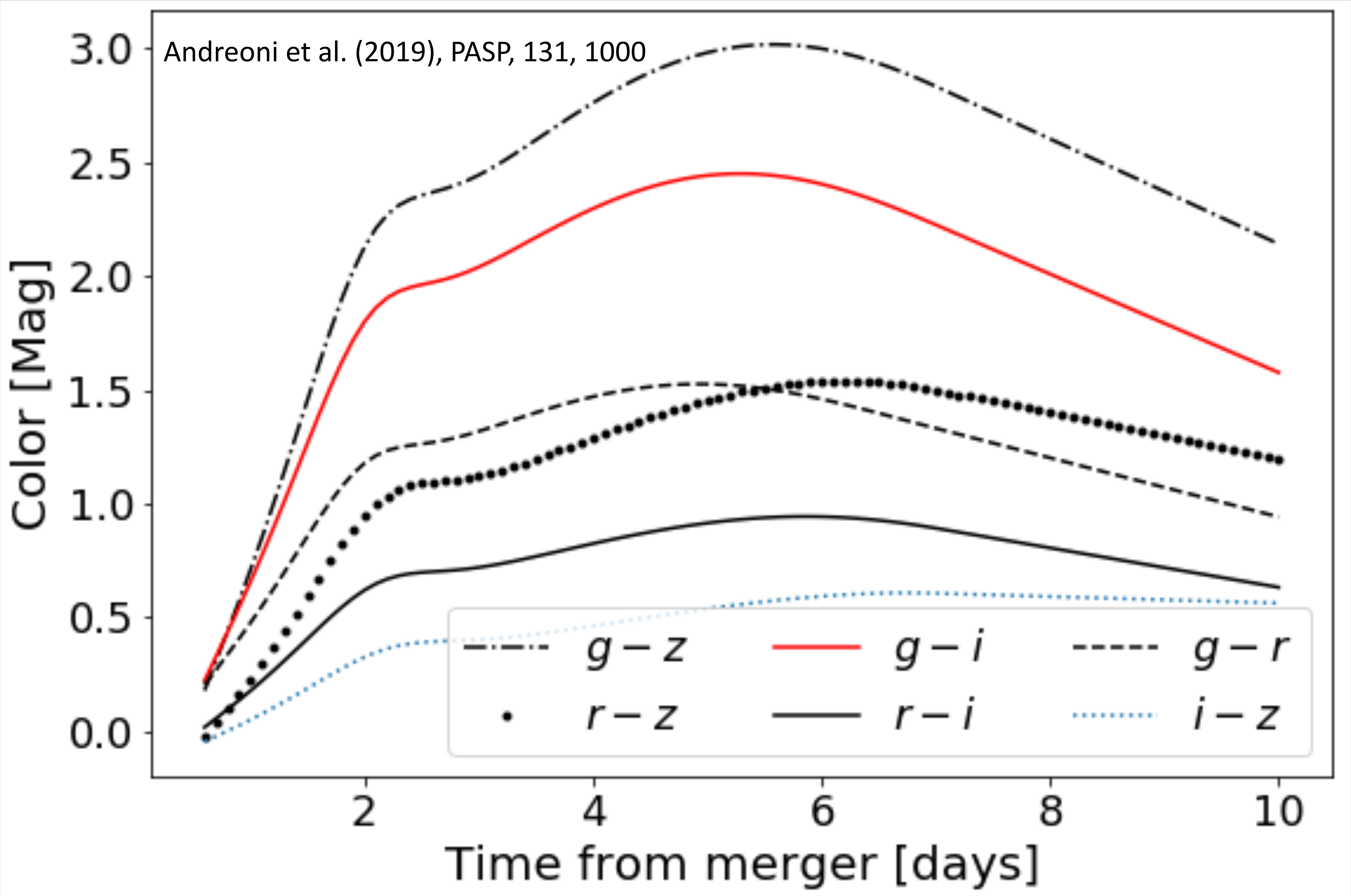
~2.17hrs and~2.28hrs per NS-NS merger with $\Omega_{90\%}\leq$ 20 deg2 and 20 deg2 < $\Omega_{90\%}\leq$ 100 deg2, respectively.

—> **yearly LSST average time** request for NS-NS follow-up of ~**47 hrs**.

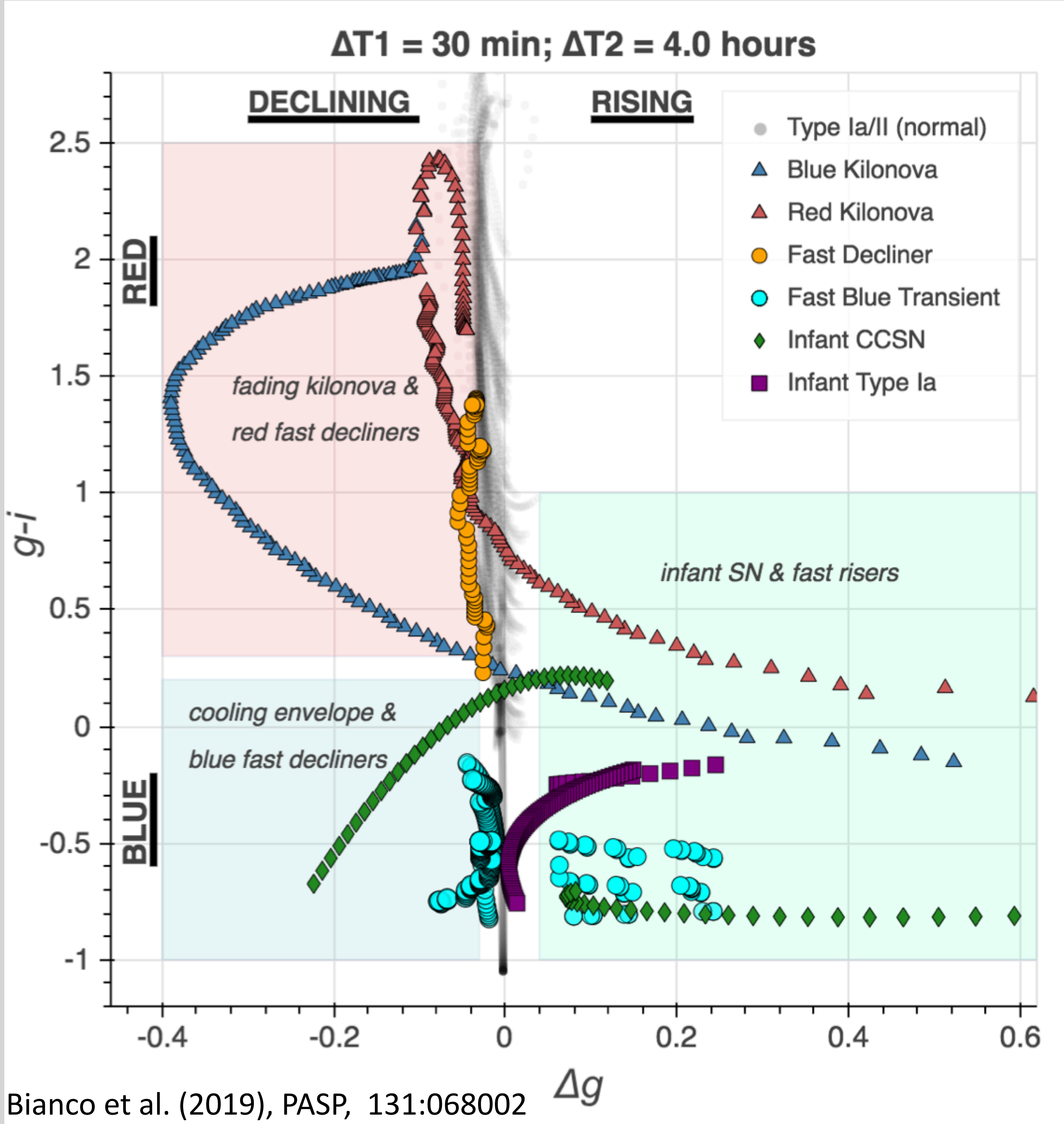
Kilonovae expected to be found serendipitously by Rubin

Kilonovae are expected to be rapidly reddening and fast evolving transients. Obtaining g+i or g+z colors in the first couple of days from a merger is crucial to identify kilonovae

Recommendation: nightly multi-band observations with Rubin

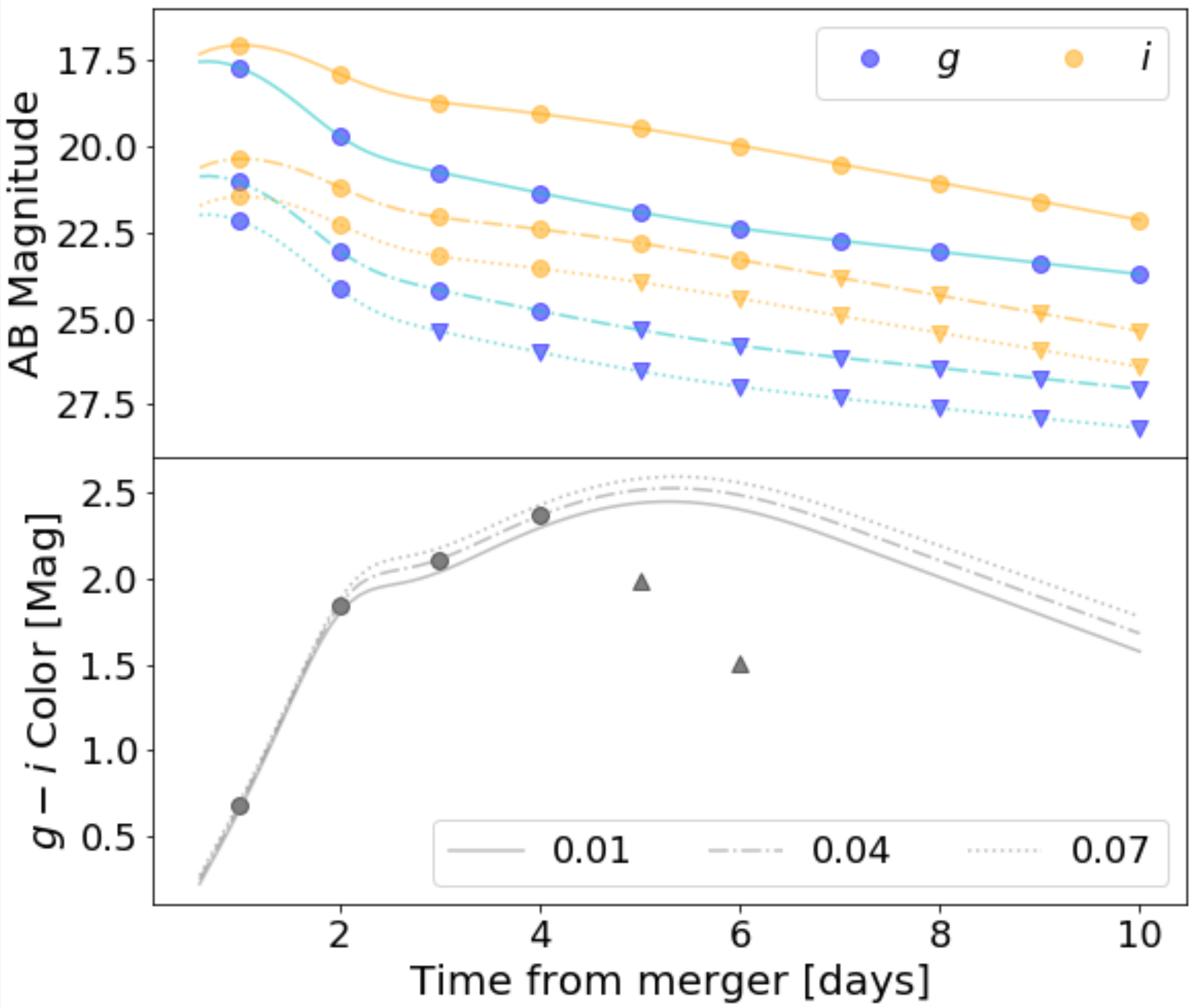


Kilonova color evolution



Courtesy of Andreoni I.

GW170817-like kilonova observed with Rubin, nightly g+i band cadence



GW170817 as it would be observed by Rubin if observations are performed in consecutive nights in *g* and *i* filters, at redshift z=0.01 (40 Mpc, the GW170817 distance, z=0.04 (190 Mpc, the AdLIGO design horizon), and z=0.07 (325 Mpc, A+LIGO upgrade design horizon)

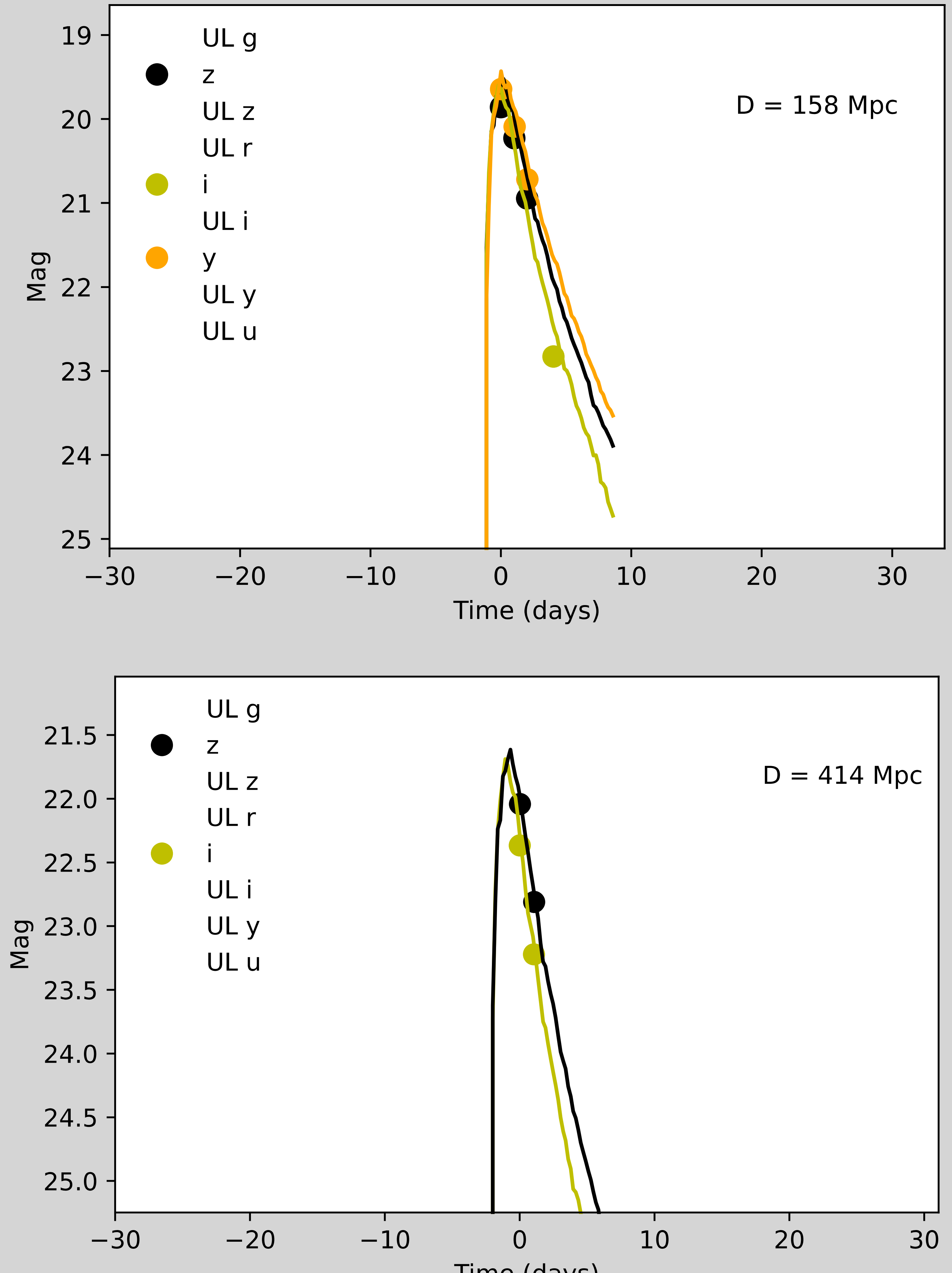
***

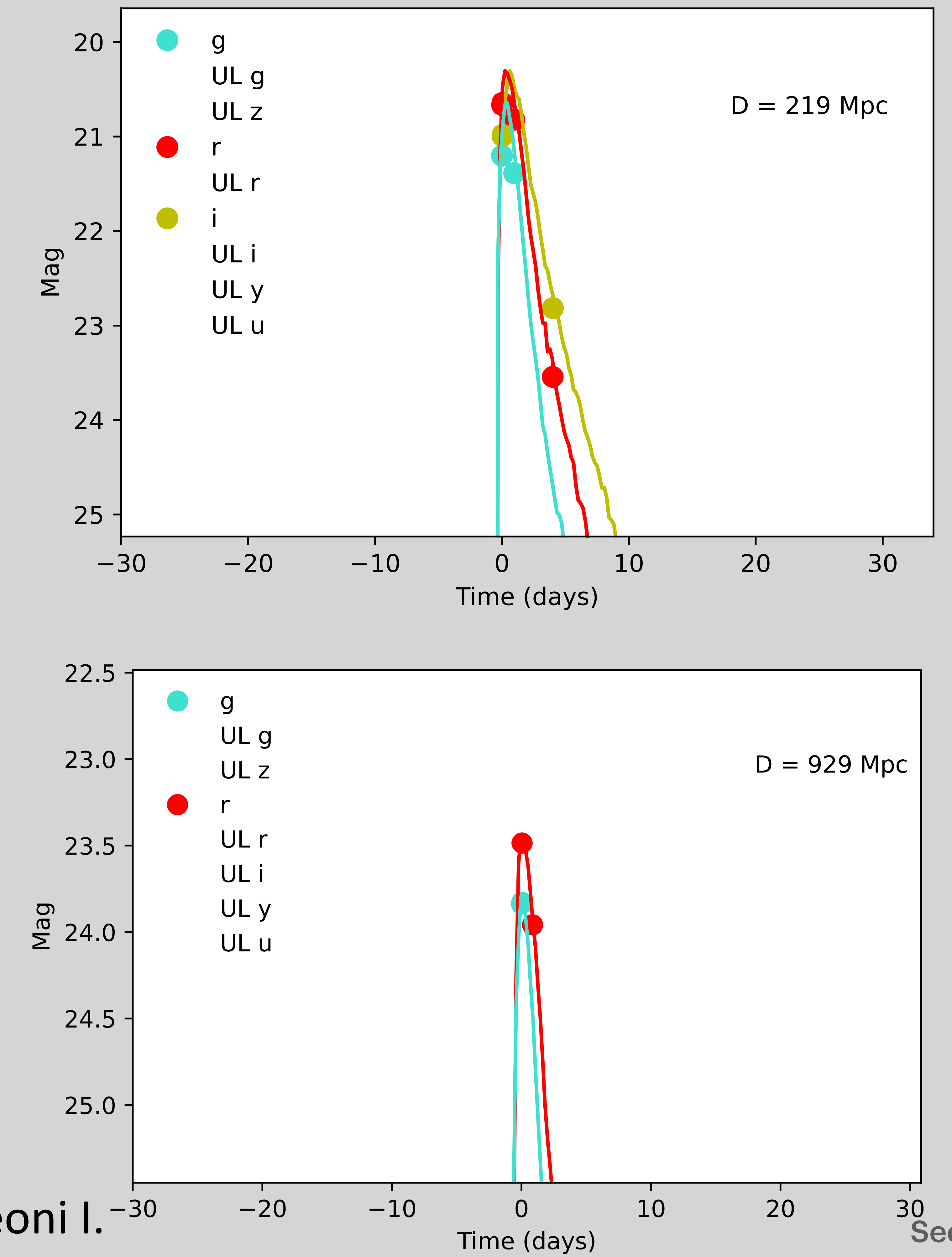
Recommendation (2019): explore the possibility to use a rolling cadence for LSST/WFD survey

Andreoni et al. (2019), PASP, 131, 1000

Courtesy of Andreoni I.

Examples of synthetic GW170817-like kilonovae found serendipitously in the simulated baseline cadence

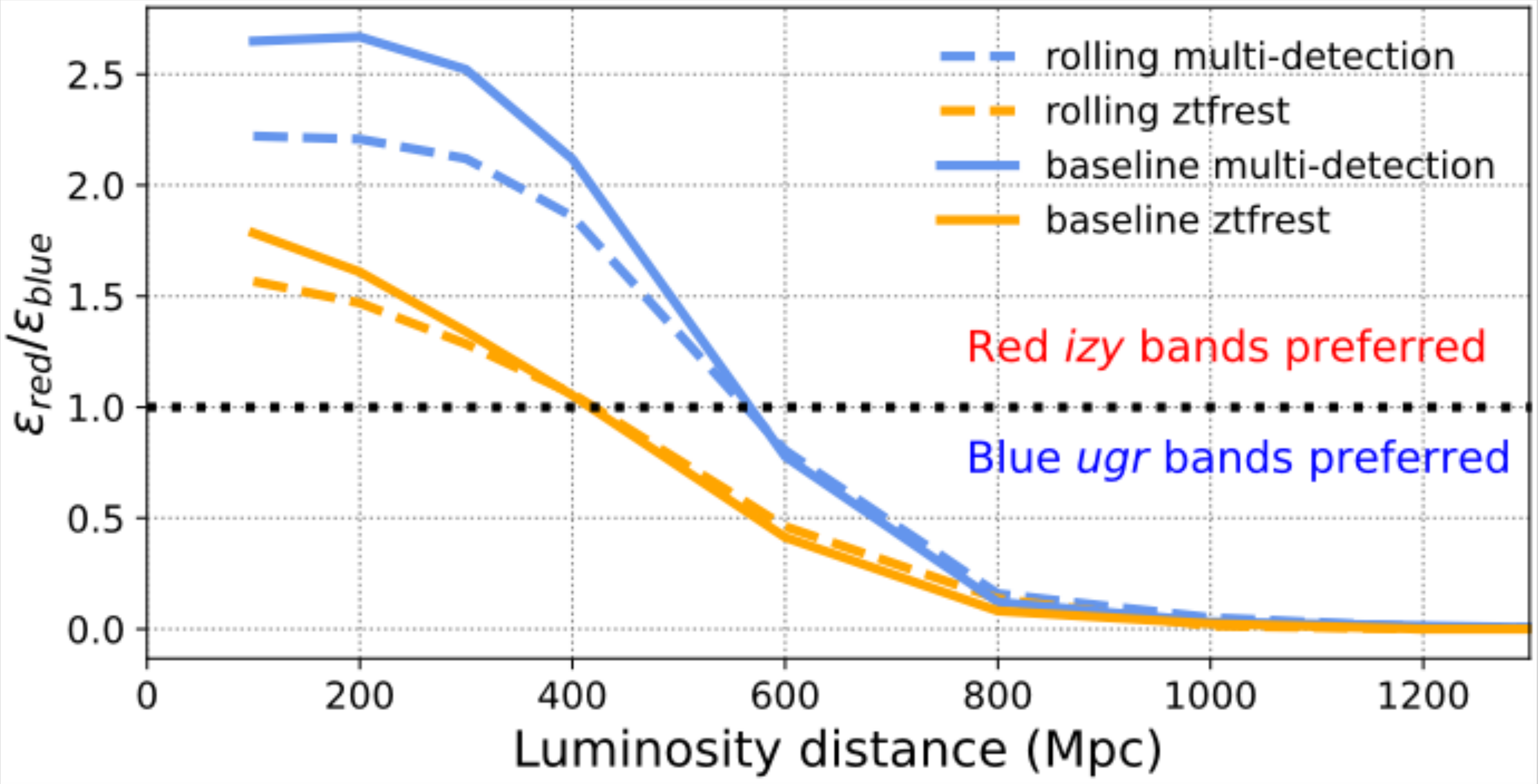




Andreoni et al. (2021), arxiv:2106.06820

Courtesy of Andreoni I.

Red vs Blue bands

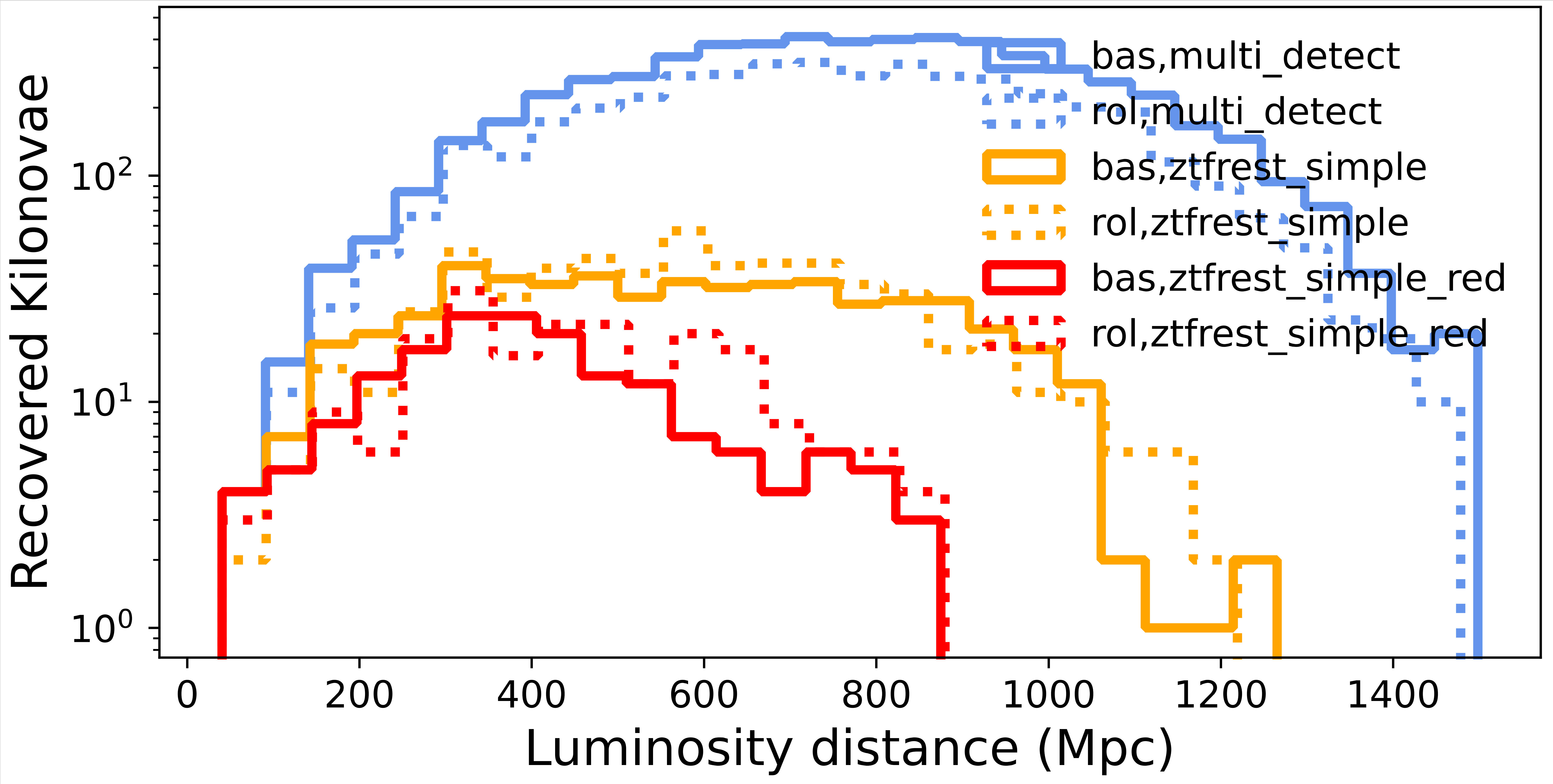


Andreoni et al. (2021), arxiv:2106.06820

For both rolling and baseline cadences, adding more exposures in *i-z-y* filters (as opposed to *u-g-r* filters) can enable the identification of significantly more kilonovae at low redshift, which is better for multi-wavelength follow-up

Courtesy of Andreoni I.

Distance distribution



Andreoni et al. (2021), arxiv:2106.06820

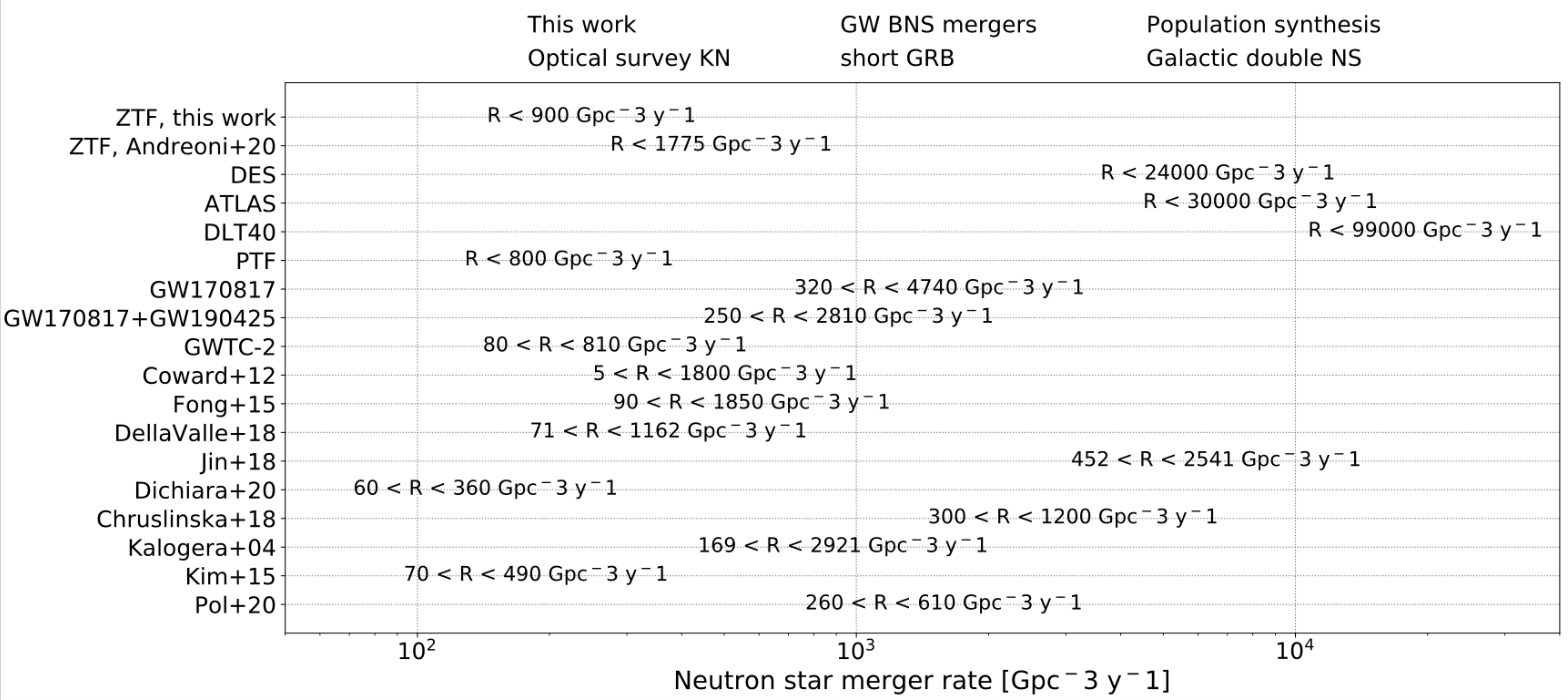
One million GW170817-like kilonovae were injected uniformly distributed in volume

Although many kilonovae could be detected out to > 1Gpc (blue lines), only a handful can be identified to be fast-evolving transients (orange lines)

Courtesy of Andreoni I.

Binary neutron star merger rate and kilonova searches

What will we learn from future LIGO-Virgo-KAGRA observing runs and from Rubin Observatory?!



Andreoni & Coughlin et al. (2021), ApJ, accepted; arxiv:2104.06352

Courtesy of Andreoni I.

Open questions

- Are neutron star mergers the dominant sites for heavy element nucleosynthesis?
- What is the kilonova luminosity function?
- What more Physics can we learn?
- How does matter behave in the interior of extreme compact objects?
- How can we use kilonovae for cosmology?
- What is the rate of binary neutron star and neutron star-black hole mergers?

We need to unveil a population of counterparts to address ALL these questions and **LSST will be of great help!**

THANKS!!!

“Still more mysteries of the universe remain hidden. Their discovery awaits the adventurous scientists of the future!” - Vera Rubin

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Key Numbers

Rubin Observatory System & LSST Survey Key Numbers

This page lists Key Numbers that describe the Rubin Observatory system and LSST survey.

More details are available in the LSST Knowledge Base Confluence page (rendered here), the LSST Overview Paper and Science Requirements Document.

Telescope System:

- Etendue (AΩ) : 319 meter²degrees²
- 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)

Imaging System:

- Pixel count : 3.2 Gpixels
- Focal plane : 189 4kx4k science CCD chips
- Pixel pitch : 0.2 arcsec/pixel
- Pixel size : 10 microns
- Filling factor : >90%
- Minimum exposure time : 1 sec

Throughput:

- 5-sigma point source depth: Single exposure and idealized for stationary sources after 10 years,
  - u : 23.9, 26.1
  - g : 25.0, 27.4
  - r : 24.7, 27.5
  - i : 24.0 , 26.8
  - z : 23.3, 26.1
  - y : 22.1, 24.9

(https://smtn-002.lsst.io : Calculating Rubin Observatory limiting magnitudes and SNR)

Site Stats:

- Median Atmospheric PSF with outer scale of 30m: 0.67" (Tokovinin)
- Site: El Penon, Cerro Pachon, Chile
- Site coordinates: latitude -30:14:40.68 longitude -70:44:57.90
- Altitude: 2647m
- Site observatory code: TBD
- Photometric time: 53% of night time (estimated)

Observation Properties:

- Standard visit exposures (expected) : 2 x 15 sec.
- Median (Mean) visit time : 39s (42.2s)
- Photometric accuracy : 10 mmag
- Astrometric accuracy : 50 mas
- Astrometric precision : 10 mas

Dataset properties:

- Nightly data size: 20TB/night
- Final database size (DR11) : 15 PB
- Real-time alert latency : 60 seconds

Data Releases:

- Survey duration : 10 years
- Number of Data Releases : 11
- Number of objects (full survey, DR11):
  - 20B galaxies
  - 17B resolved stars
  - 6M orbits of solar system bodies
  - Average number of alerts per night: about 10 million