Science with LSST and the Dark Energy Science Collaboration

Michael Wood-Vasey (on behalf of DESC)

University of Pittsburgh

Subaru 20th Anniversary. Nov 2019
By the end of this talk you will be able to...

➢ Describe the LSST telescope and survey

➢ Explain the key science themes for LSST

➢ Describe the Dark Energy Science Collaboration

➢ Explain how Japan can contribute to LSST and DESC.
LSST Project, Facility, and Science
LSST

6.5-m mirror effective

10 sq. deg FoV
3.2 Gpix camera

Cerro Pachon, Chile: -30:15 lat.

18,000 sq. degrees
Over 10 years
Plus ~5 deep fields.

Will cover visible sky every 3 nights
LSST Sky Coverage
LSST Overview:
Key Numbers of Telescope + Survey

- 8.4 diameter -- 6.4m equivalent collecting area @ f/ 1.2
- Site: El Penon, Cerro Pachon, Chile (2647 m, -30:15 latitude)
- 3.2 Gigapixel camera. 189 science chips @ 0.2”/10 um pixel
- 10 square degree field of view.
- Photometric accuracy : 10 mmag
- Astrometric accuracy : 50 mas
- Astrometric precision : 10 mas

<table>
<thead>
<tr>
<th>5-sigma mag limit</th>
<th>u</th>
<th>g</th>
<th>r</th>
<th>i</th>
<th>z</th>
<th>y</th>
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<tbody>
<tr>
<td>1 visit</td>
<td>23.9</td>
<td>25.0</td>
<td>24.7</td>
<td>24.0</td>
<td>23.3</td>
<td>22.1</td>
</tr>
<tr>
<td>10-year</td>
<td>26.1</td>
<td>27.4</td>
<td>27.5</td>
<td>26.8</td>
<td>26.1</td>
<td>24.9</td>
</tr>
</tbody>
</table>
- 3.2 Gigapixel camera
- 189 science chips @ 0.2"/10 um pixel
- 10 square degree field of view.
HSC SCP

300 nights, grizy. +4 narrow filters for Deep, Ultradeep

<table>
<thead>
<tr>
<th>Layer</th>
<th>Area [deg²]</th>
<th># fields</th>
<th># epochs</th>
<th>Depth [mag]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide</td>
<td>1400</td>
<td>916</td>
<td>25</td>
<td>26</td>
</tr>
<tr>
<td>Deep</td>
<td>27</td>
<td>15</td>
<td>40</td>
<td>27</td>
</tr>
<tr>
<td>Ultradeep</td>
<td>3.5</td>
<td>2</td>
<td>80</td>
<td>28</td>
</tr>
</tbody>
</table>
LSST

3650 nights, ugrizy

<table>
<thead>
<tr>
<th>Layer</th>
<th>Area [deg$^2$]</th>
<th># fields</th>
<th># epochs</th>
<th>Depth [mag]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wide</td>
<td>18,000</td>
<td>1,800</td>
<td>800</td>
<td>27</td>
</tr>
<tr>
<td>Deep</td>
<td>50</td>
<td>5</td>
<td>1,000</td>
<td>28-29</td>
</tr>
</tbody>
</table>


Full-depth LSST image simulation => 18,000 deg$^2$ of this...

20 billion galaxies
17 billion stars
6 million Solar System Objects
60 second alerts
On 10 million events/night.
100 million AGN
1 million SNe

with exquisite photometry, image quality, and astrometry in $u$ $g$ $r$ $i$ $z$ $y$
Camera raft integration. 9/21 science rafts 4 corner rafts.
Filter changer will fit inside Camera

Completed in France

In transit to SLAC
LSST Has Four Main Science Themes

- Solar System
- Cosmology
- Milky Way
- Transients
LSST has 8 Active Science Collaborations

- **Solar System** -- Meg Schwamb, David Trilling
  [https://milkyway.science.lsst.org](https://milkyway.science.lsst.org)

- **Galaxies** -- Manda Banerji, Sugata Kaviraj

- **Active Galactic Nucleus** -- Triana Almeyda, Niel Brandt
  [https://agn.science.lsst.org](https://agn.science.lsst.org)

- **Transients and Variables** -- Federica Bianco, Rachel Street

- **Informatics and Statistics** -- Tom Loredo, Chad Schafer

- **Stars, Milky Way, and Local Volume**
  -- John Bochanski, John Gizis, Peregrine McGehee

- **Strong Lensing** -- Timo Anguita, Aprajita Verma

- **Dark Energy Science Collaboration (DESC)**
  -- Rachel Mandelbaum, Pat Burchat [https://lsstdesc.org](https://lsstdesc.org)

[https://www.lsstcorporation.org/science-collaborations](https://www.lsstcorporation.org/science-collaborations)
## LSST for the Solar System

<table>
<thead>
<tr>
<th></th>
<th>Currently known</th>
<th>LSST</th>
<th>Minimum Size</th>
<th>Median Number of Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Near-Earth Objects</td>
<td>14,500</td>
<td>100,000</td>
<td>250 m</td>
<td>60</td>
</tr>
<tr>
<td>Main Belt Asteroids</td>
<td>650,000</td>
<td>5,500,000</td>
<td>500 m</td>
<td>200</td>
</tr>
<tr>
<td>Jupiter Trojans</td>
<td>6,000</td>
<td>28,000</td>
<td>2,000 m</td>
<td>300</td>
</tr>
<tr>
<td>TNOs</td>
<td>2,000</td>
<td>40,000</td>
<td>200,000 m</td>
<td>450</td>
</tr>
<tr>
<td>Interstellar</td>
<td>2</td>
<td>10 (?)</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>

### Main Belt comets and active asteroids Jewitt (2012)

### SSSC RoadMap and Whitepaper

- Schwamb et al. (2019): RNAAS, 3, 3 Software Roadmap.
LSST for Galaxy Science

- The evolution of galaxies, AGN, groups/clusters across 95% of cosmic time
- Low surface brightness.
- Provide optical counterparts for all future surveys at other wavelengths (e.g. the SKA)
- “LSST Galaxy Science Roadmap” Robertson et al. arXiv: 1708.0161
Multi-color selection in *ugrizy* from $z = 0-7.5$
- Ultraviolet excess below $z \approx 2.5$
- Lyman-a forest at high redshifts
- Works best when $L_{\text{AGN}} > L_{\text{Host}}$

Multi-$\lambda$ (radio-to-X-ray) selection
- LSST + MeerKAT/ASKAP + WISE + Euclid/WFIRST + eROSITA/XMM + …

**Variability**
- 55-185 samplings per band over 10 yr
- Highly effective complement to color selection
- Works best when $L_{\text{AGN}} > L_{\text{Host}}$

**Astrometry (Lack of proper motion and differential chromatic refraction)**
- Can reach $\sim 1$ mas yr$^{-1}$ at $r \sim 24$ over 10 yr
- Will help minimize confusion with stars
- Strong emission lines will induce astrometric offsets at high airmass

*Color, variability, multi-$\lambda$ provide different/unique slices through AGN population.*
LSST for Transients and Variables

Phenomena that evolve in time:
- Galactic, Extragalactic,
- Geometric, Physical,
- all energy scales
- all time scales

Increase size of known classes:
- SN subclasses

Rare->Statistical samples:
- TDE, Kilonova

Precursors of transients:
- e.g. LBV

Ivezic+ 2019 [http://ls.st/lop](http://ls.st/lop)
Informatics and Statistics in the Era of LSST

The shift from the variance-dominated era to the bias-dominated era requires careful thought about new methods, not just the scaling of current approaches—root-N is not enough!

The gap from method to application is larger, and requires

- Significant adaptation of existing tools, and new tools
- Deep knowledge of applications
- Expert knowledge on both data science and astronomy sides

The ISSC aims to connect data science expertise to science problems, both across disciplines (astro/data science consulting & collaboration) and across SCs
LSST for Stars, the Milky Way, and the Local Volume
Understanding the accretion history and structure of the Milky Way and the Local Volume,
And the fundamental properties of stars within 300 pc of the Sun...

Streams in Halo
Gaia map from Ibata, Malhan, Martin (2019)

The LSST SMWLV Science Collaboration:
https://milkyway.science.lsst.org
Strong Lensing with LSST

- SL rare. Only $\sim 10^3$ known to date
- Expectations with LSST (OM10; Goldstein+17,18)
  - 1000s lensed AGN
  - $10^{4-5}$ galaxy- & group-scale lenses
  - 1000s of lensing clusters
  - 100s of lensed SNe…
  - 100 double source plane lenses
SL: Wide-ranging Science Goals

**Galaxy Mass & structure:**
Most direct measure of total (stellar & dark) mass in galaxies

**DM Substructure**

**Cosmography:**
Constraints on the cosmic equation of state
Time delays (QSOs, SNe,Refsdal 1964) & double source plane lenses

**Cosmic telescopes:**
structure & properties of high-z galaxies

Linder et al. 2011
Tanaka+ 2016
Goobar+ 2017
Kelly+ 2015,16
Strigari et al. 2007
Kelly & Koppens 2007
International Participation in LSST
I am the DESC Data Coordinator; I speak for the DESC.

I do not speak for any of the following entities:

- LSST Project
- LSST Operations
- US Department of Energy (DOE) or SLAC

My familiarity with this material means I can describe it to you. I personally would like to encourage and help a wide community participate in LSST science, particularly the Japanese community and Subaru.

I encourage you to collect questions and coordinate with Satoshi Miyazaki and Masahiro Takada.
The LSST Enterprise

● LSST Project  [https://project.lsst.org](https://project.lsst.org)
  ○ Construction of Telescope, Site, Data Management, and Camera.
  ○ Ends at end of construction (2022).

● LSST Facility + Operations
  ○ US NSF and US DOE through AURA and SLAC. Begins in 2022.
  ○ Operating the Facility and delivering data to LSST data rights holders.
  ○ Main point for negotiation of international participation agreements

● LSST Science Collaborations  [https://www.lsstcorporation.org/science-collaborations](https://www.lsstcorporation.org/science-collaborations)
  ○ Self-organized groups that are planning for doing science with LSST

● LSST Corporation  [https://lsstcorporation.org](https://lsstcorporation.org)
  ○ Raising money through private philanthropy to support LSST science
    ■ From the original donations for the mirror, to supporting Science Collaborations,
      to funding LSST science through the 2030s
  ○ Interested in working on philanthropic opportunities internationally.
LSST Framework in the Operational Era

science, follow-up, more science

Discovering our Universe Together

KEY

- **DOE and NSF will require that only AURA and SLAC have unambiguous control of all raw data**
- **Interior: base-line operations funded by DOE and NSF, who will hold AURA and SLAC accountable for performance**
- **The larger LSST enterprise supported & funded through other programs and partnerships**
LSST International Participation


- LSST welcomes international participation through in-kind contributions to:
  - “LSST construction project, facility operations, and/or related astrophysical resources”
  - “Examples: dedicated software development staff or computing resources that offset LSST operational costs, or access to complementary data sets or follow-up facilities.”

- Timeline
  - Invitation to current MOA holders and interested groups, October 31
  - Letters of Intent due November 22
  - Proposals due March 31
  - Evaluation feedback provided by May 31
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Dark Energy Science Collaboration
Why is LSST Amazing for Cosmology?

Bigger is Better

Credit: LSST Project OpSim Team
Why is LSST Amazing for Cosmology?

Faster is Better

Credit: Anglo-Australian Observatory/David Malin Images
Science goals

Collaboration ethos

What we are doing to achieve our goals

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Accurate Cosmology
We research new methods for obtaining state-of-the-art, robust cosmology constraints that will realize the full statistical precision of the LSST data.

A Vibrant and Inclusive Scientific Community
We work hard to create a positive and respectful collaborative working environment.

Meeting LSST’s Big Data Challenge
Together we build robust, high-throughput software pipelines to simulate, re-process and analyze images and catalogs at LSST scale.
DESC’s Five Complementary Probes

Supernovae

Credit: https://www.youtube.com/watch?v=alAQQzlB-O8
DESC’s Five Complementary Probes

Supernovae

Credit: High-z Supernova Search Team

Credit: https://www.youtube.com/watch?v=alAQqzIB-O8
DESC’s Five Complementary Probes

Strong lensing
DESC’s Five Complementary Probes

Strong lensing

Credit: H0LiCOW Collaboration

Credit: Chien-Hsiu Lee/Subaru Telescope
DESC’s Five Complementary Probes

Large scale structure

Credit: Chris Blake & Sam Moorfield (SDSS)
DESC’s Five Complementary Probes

Large scale structure

Credit: Blake & Sam Moorfield (SDSS)

Credit: Adapted from Huterer & Shafer 2017
DESC’s Five Complementary Probes

Galaxy clusters

Credit: HST
DESC’s Five Complementary Probes

Galaxy clusters

Credit: HST

Credit: Huterer & Shafer 2017
DESC’s Five Complementary Probes

Weak lensing

Credit: Smoot lensing subgroup
DESC’s Five Complementary Probes

Weak lensing

Credit: Huterer & Shafer 2017
Special mention

Kilonovae

Credit: NASA

Credit: LIGO
Special mention

Photometric redshifts

Credit: Padmanabhan 2007
Precise and accurate cosmology

DESC’s early science goals involve optimal use of early LSST data to minimize the combined statistical + systematic error budget in a joint probe analysis - on our way to …

LSST full survey: %-level dark energy constraints from LSST.

*Note: fundamental cosmological physics is about a lot more than just the dark energy equation of state (EoS)!

Focus on...

Red = current state of the art
Black = LSST with all dark energy probes

Deviation of dark energy EoS from -1 at the present time.

The LSST DESC Science Requirements Document (SRD) v1 (arXiv, Zenodo)
Who is the Dark Energy Science Collaboration?
DESC is organized into Working Groups
We are a large community of scientists getting ready to do cosmology with LSST.

DESC has 1,000 Members, of which ~200 are “Full Members”
DESC is Preparing Now for LSST
The Science Roadmap describes how we will get ready for the LSST data

https://lsstdesc.org/assets/pdf/docs/DESC_SRM_latest.pdf (v2.0)
The data challenges are simulation and analysis products to get us ready for LSST operations.

- **FY19Q1** is in the DC2 production and analysis.
DC2: A virtual LSST sky survey

- **Static sky** (WL, CL, LSS, PZ) with images: **300 sq deg** “main survey” area, 3+ years *ugrizy* Wide-Fast-Deep (WFD) cadence - cf. the *LSSTCam 10-yr depth* SV survey

- **Time domain** (SN, SL) analyses: **1 sq deg** “ultra Deep Drilling Field (DDF)” overlapping with WFD, 10 years *ugrizy* WFD + DDF visits
DC2: Simulated LSST Images


- CosmoDC2 - Extragalactic catalogue based on N-body simulations & semi-analytic models
- ImSim - LSST DESC Image Simulator
- The LSST DM Pipeline
Example Pipeline: TXPipe

Input: DC2 Shear and Photometry Catalogs

TXPipe

TwoPoint Data and Summary Statistics

Fire Crown

Cosmological Parameters!

Shear-Shear
Shear-Galaxy
Galaxy-Galaxy

= 3pt

Credit: Emily Philips Longley & the TXPipe Team
Example Pipeline: TXPipe

$g_1$ component of the shear map

Shear Correlation functions Calculated from DC2

Credit: Joe Zunz & the TXPipe Team
Resources DESC provides to the world

- All collaboration policies are publicly available on our webpage under a Creative Commons license. Please adapt & reuse with attribution!

- Pedagogical resources: 20 LSST-related lessons (slides, videos, notebooks, ...) are available on our Dark Energy school webpage.

- We produce and release software & data products that benefit the community. See…
  - Our Zenodo community.
  - GitHub repositories in the LSSTDESC organization that are public & released; e.g., the Core Cosmology Library.
  - Dataset release papers; e.g., the cosmoDC2 paper.
  - New analysis methods.

- DESC is already writing papers: https://lsstdesc.org/pages/publications.html

- We are early adopters of the LSST DM Science Pipelines who try to provide meaningful feedback to DM via our liaisons.
LSST Observing Strategy
1. “... DESC Recommendations for the Wide-Fast-Deep Survey” (Lochner et al 2018)

2. “...DESC Recommendations for the Deep Drilling Fields and other Special Programs” (Scolnic et al 2018)
DESC External Synergies Working Group

➢ Make DESC science better with data beyond LSST
  ○ Help in developing inter-collaboration agreements
  ○ Coordinate proposals for telescope time
  ○ Inventories science cases that would benefit from in-kind contributions of observing resources, and potential resources that can fill those gaps

➢ Led by Mark Sullivan + Jeff Newman
1. **Deep Multi-object Spectroscopy to Enhance Dark Energy Science from LSST** (Newman et al. 2019): Describes cases for PFS-like capabilities; e.g., photo-z training/calibration

2. **Wide-field Multi-object Spectroscopy to Enhance Dark Energy Science from LSST** (Mandelbaum et al 2019): Focuses mostly on DESI-like data, but some cases are well-suited for PFS: e.g., spectroscopy of SN hosts in LSST deep-drilling fields

3. **Single-object Imaging and Spectroscopy to Enhance Dark Energy Science from LSST** (Hlozek et al. 2019): Describes single-object applications (less synergy with Subaru)

For more ideas of LSST complementarities, including projects beyond DESC, see the Kavli/NOAO/LSST report (Najita, Willman et al. 2016), [Maximizing Science in the Era of LSST](#)
Example: a photo-z training sample of ~20k faint galaxies would greatly enhance LSST + WFIRST, and be a great galaxy evolution survey too - see Jeff Newman’s talk Wed.!

SDSS showed the power of matched imaging and spectroscopic capabilities. LSST has no spectrograph - but **Subaru/PFS could fill the gap!**

Credit: Rongpu Zhou, from Newman et al. 2019 (1903.09325)
HSC could potentially play a role in photo-z training via medium-band surveys

- Could get better photo-z’s in limited areas (bootstrap training, like COSMOS30)

- Basic scaling: $z$ error $\propto (\text{etendue} \times (\text{total time}) \times R)^{(-\frac{1}{2})}$, where R is effective spectral resolution

- ~60 hours (~8 nights) on HSC per 10 square degrees needed to reduce LSST+WFIRST photo-z errors by 2x if ~20 filters total

- Powerful in conjunction with WFIRST grism/prism IR observations of same fields
Conclusions: You should now be able to

➢ Describe the LSST telescope and survey
   6.5-m effective area. 10 sq. FoV. 18,000 sq. degrees over 10 years. 800 visits/field.

➢ Describe the key science themes for LSST
   Cosmology, Milky Way, Solar System, and Transients

➢ Describe the Dark Energy Science Collaboration
   A large, international collaboration dedicated to getting the best cosmology with LSST.
   Activities include data challenges, pipelines, observing strategy, and external synergies

➢ Explain how Japan can contribute to LSST and DESC.
   PFS can play a vital role in making LSST realize its science
   Japanese expertise in deep surveys is valuable for LSST era.
Extra Slides
How do I join LSST?
LSST International Participation

● LSST welcomes international participation through in-kind contributions to:
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From the 2019 Oct LSST Communication

● “...”We’ll also be looking for in-kind contributions that expand the resources available to the US science community. Examples of the type of in-kind contribution that are likely to be acceptable following a positive CEC evaluation include:

● Observing time, dedicated to proposals led by US PIs, at key non-US facilities. (Observing time contributed only to subsets of the US community will not be accepted by the US agencies.)

● Access to surveys or proprietary datasets of high value to the US community, including (but not restricted to) datasets complementary to the LSST survey and which enable high priority LSST science. Dedicated software development effort, to be either embedded in one or more LSST Science Collaborations and assigned to a needed analysis pipeline, or focused on a particular enhancement to the LSST system.
1 FTE year of dedicated effort (at the appropriate skill level) will be approximately sufficient to obtain data rights for 1 PI for the duration of the survey (13 years, US FY22 through FY34). The equivalent cost of the US agencies providing the same 1 FTE year of effort is about $300k; we can use that number as a rough guide when considering the value of other resources, including observing time, again using US prices. For example, computing resources purchased in the US cost roughly $10k per million CPU hours, and $200k per Pb of disk storage, and so 30M CPU hrs, or 1.5 PB of disk space, would be approximately sufficient to obtain data rights for 1 PI for the duration of the survey (modulo CEC evaluation of their location and distribution in time). All these "exchange rates" are only approximate""
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science, follow-up, more science
How do I join DESC?
Becoming an LSST DESC Member

➢ Once you have LSST data rights:

➢ Fill out the web form at http://lsstdesc.org/

➢ Make sure to read the collaboration’s policies

➢ You’ll get a helpful email from SLAC

➢ Login to confluence and slack to join the conversation

➢ Join one of our many collaboration meetings and sprint weeks!

➢ Make sure to become a full member if you are active in the collaboration in