LSST Science

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OUTLINE

• Brief overview of LSST science drivers
• LSST science-driven design
• Examples of LSST science programs
cosmology, extragalactic and Galactic astronomy, solar system studies
**LSST Science Themes**

- **Dark matter, dark energy, cosmology**
  (spatial distribution of galaxies, gravitational lensing, supernovae, quasars)

- **Time domain**
  (cosmic explosions, variable stars, proper motions)

- **The Solar System structure** (asteroids)

- **The Milky Way structure** (stars)

**LSST Science Book: arXiv:0912.0201**

Summarizes LSST hardware, software, and observing plans, science enabled by LSST, and educational and outreach opportunities

245 authors, 15 chapters, 600 pages
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• The Solar System structure (asteroids)

• The Milky Way structure (stars, ISM)

These drivers not only require similar hardware and software systems, but also motivate a universal cadence: about 90% of time will be spent on a uniform survey.
Basic idea behind LSST: **a uniform sky survey**

- 90% of time will be spent on a uniform survey: every 3-4 nights, the whole observable sky will be scanned twice per night.

- After 10 years, half of the sky will be imaged about 1000 times (in 6 bandpasses, ugrizy): a digital color movie of the sky.

- ~100 PB of data: about a billion 16 Mpix images, enabling measurements for 20 billion objects!

**Visit**: basic unit for data taking; baseline assumes a total exposure time per visit of 30 sec, split into two back-to-back exposures of 15 sec each.

**LSST in one sentence**: An optical/near-IR survey of half the sky in ugrizy bands to $r \sim 27.5$ (36 nJy) based on 825 visits over a 10-year period: **deep wide fast**.
Basic idea behind LSST: **a uniform sky survey**

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**LSST in one sentence:**
An optical/near-IR survey of half the sky in ugrizy bands to r~27.5 (36 nJy) based on 825 visits over a 10-year period: deep wide fast.

**Left:** a 10-year simulation of LSST survey: the number of visits in the r band (Aitoff projection of eq. coordinates)

Cadence details still open to optimization
SDSS-LSST comparison: \( \text{LSST} = \frac{d(\text{SDSS})}{dt}, \text{LSST} = \text{SuperSDSS} \)

3x3 arcmin, gri

20x20 arcsec; lensed SDSS quasar (SDSS J1332+0347, Morokuma et al. 2007)

(Deep Lens Survey)
Required system characteristics

- Large primary mirror (at least 6m) to go faint and to enable short exposures (30 s)
- Agile telescope (5 sec for slew and settle)
- Large field of view to enable fast surveying
- Impeccable image quality (weak lensing)
- Camera with 3200 Mpix
- Sophisticated software (20,000 GB/night, 20 billion objects, 20 trillion measurements)
Basic idea behind LSST: a uniform sky survey

**LSST in one sentence:**
An optical/near-IR survey of half the sky in ugrizy bands to $r \sim 27.5$ based on 1000 visits over a 10-year period

- The sky coverage of 20,000 sq. deg. to a depth of $r \sim 27.5$ requires integrated etendue $= (\text{aperture} \times \text{FOV size} \times \text{duration})$ of $\sim 3000 \text{ m}^2 \text{ deg}^2 \text{ year}$ (all losses and down time accounted for)

- Equivalently: $(D/6.7\text{m})^2 (\text{FOV}/10 \text{ sq.deg.}) (\text{duration}/10 \text{ years}) \sim 1$

- 1000 visits implies that a single-visit depth is $r \sim 24.5$, which is consistent with the coadded depth constraint of $r \sim 27.5$

- The most fundamental constraint is the sky coverage of $\sim 20,000 \text{ sq. deg. to a depth of } r \sim 27.5$ (these constraints are directly connected to DETF FoM)
Why 20,000 sq.deg?

**LSST in one sentence:**
An optical/near-IR survey of half the sky in ugrizy bands to $r \sim 27.5$ based on 1000 visits over a 10-year period

- The anticipated science outcome scales with the number of detected sources.
- Source counts increase with magnitude: $\log(N/N_0) = k*(m-m_0)$
- Limiting magnitude: $m = m_0 + 1.25*\log(\text{time}) - k*(X-1)$
- A factor of 2 increase in observing time gives $\sim 0.4$ mag deeper data: for $k<0.8$, less than a factor of 2 increase in source counts
- To maximize the number of sources, maximize the sky area first! (“wide beats deep”)
Galaxies:

- **Photometric redshifts**: random errors smaller than 0.02, bias below 0.003, fewer than 10% $>3\sigma$ outliers

- These photo-z requirements are one of the primary drivers for the photometric depth and accuracy of the main LSST survey (and the definition of filter complement)

![Diagram showing throughput vs wavelength with air mass 1.2 and filter bands u, g, r, i, z, y]

**Photo-z requirements correspond to $r \sim 27.5$**

with the following per band time allocations:

- $u$: 8%; $g$: 10%
- $r$: 22%; $i$: 22%
- $z$: 19%; $y$: 19%

Consistent with other science themes (stars)
The Milky Way Structure (stars)

Main Goals:

- **Stellar counts** to presumed halo edge at 100 kpc
- **Metallicity** to beyond inner/outer halo boundary
- **Kinematics** to beyond thick disk/halo boundary
- **Dwarf detections** to thin disk scale height (300 pc)

Translates to limits on: (consistent with galaxies/SNe)

- **Depth**: halo turn-off stars in blue bands and LTY dwarfs in red bands
- **Photometric calibration**: 1%
- **Astrometry**: 10 mas with about 1000 visits
The main system requirement:

\[(D/6.7m)^2 \times (FOV/10 \text{ sq.deg.}) \times (\text{survey duration/10 years}) \sim 1\]

How to break degeneracy between D, FOV and T?

Survey duration (T) is driven by sociological and economic considerations, and is also limited from below by long-term astrophysical measurements (proper motions, variability):

\[T = 10 \text{ years}\]

Given \(T=10\) years, the FOV is maximized to its practical limit:

\[\text{FOV} = 9.6 \text{ sq.deg.} \text{ which yields } D \sim 6.7m\]
Assumes a field-of-view size of \(\sim 10 \text{ sq.deg.}\)
LSST is designed as a flexible system, informed by diverse community needs and with well-defined goals. Science drivers are consistent across multiple science themes and provide robust quantitative justification for our design decisions.
LSST Deployment Parameters

Given the main system requirement:

\[(D/6.7m)^2 \ (FOV/10 \text{ sq.deg.}) \ (\text{survey duration/10 years}) \sim 1\]

How to optimize the main deployment parameters: exposure time and depth per visit, the mean revisit time, and the number of visits?

While each of these four parameters has its own drivers, they are not independent:

\[m_5 = 24.7 + 1.25 \times \log(t_{vis} / 30 \text{ sec})\]
\[n = 3 \times (t_{vis} / 30 \text{ sec})\]
\[N_{vis} = 1000 \times (30 \text{ sec} / t_{vis}) \times (T / 10 \text{ years})\]

Direct and indirect constraints on the shortest and longest acceptable exposure time per visit span a remarkably narrow range: 20 sec < \(t_{vis}\) < 40 sec for the main survey
LSST Deployment Parameters

Shortest acceptable exposure time:
The single visit depth \((r \sim 24.5)\); driven by SNe, NEOs, RR Lyrae stars, proper motion and trigonometric parallax measurements for stars; also observing efficiency): \(t_{\text{vis}} > 20\) sec

Longest acceptable exposure time:
Revisit time, \(n < 4\) days (SNe and asteroids): \(t_{\text{vis}} < 40\) sec
The number of visits, \(N_{\text{vis}} > 800\) (all bands); driven by control of systematics for WL science, sampling of light curves for time domain science, and by proper motion and trigonometric parallax measurements): \(t_{\text{vis}} < 40\) sec

Baseline: \(t_{\text{vis}} = 30\) sec; a much shorter exposure time does not reach deep enough in single visits, and a much longer exposure time does not obtain enough visits.
Basic idea behind LSST: a uniform sky survey

**LSST in one sentence:**
An optical/near-IR survey of half the sky in ugrizy bands to $r \sim 27.5$ based on 1000 visits over a 10-year period

- The sky coverage of 20,000 sq. deg. to a depth of $r \sim 27.5$, with 1000 visits per sky patch and a single-visit depth is $r \sim 24.5$,
- Equivalently: $D = 6.7 \text{m}, \ FOV = 9.6 \text{ sq.deg.}, \ T=10 \text{ years}, \ t_{\text{vis}}=30 \text{ sec}$
- How will LSST approach the final measurement errors as a function of survey duration?
The Dependence of Science Deliverables on Survey Duration (t)

Co-added survey depth:

\[ m_5(t) = m_5^{\text{Final}} + 1.25 \times \log(t / 10 \text{ yr}) \]

Photometric errors at \( i=25 \) (4 billion galaxy sample):

\[ \sigma_{\text{ph}}(t) = 0.04 \text{ mag} \times (t / 10 \text{ yr})^{-1/2} \]

Trigonometric parallax errors at \( r=24 \):

\[ \sigma_\pi(t) = 3.0 \text{ mas} \times (t / 10 \text{ yr})^{-1/2} \]

Proper motion errors at \( r=24 \):

\[ \sigma_\mu(t) = 1.0 \text{ mas/yr} \times (t / 10 \text{ yr})^{-3/2} \]

DETF FOM:

\[ FOM(t) = FOM^{\text{Final}} \times (t / 10 \text{ yr})^{-1} \]

And other, often very complex (e.g., the faint limit for period recovery of short-period variables, NEO completeness)...
Fig. 3.— The DETF figure of merit error product for simple 2-D dark energy models is plotted as a function of integrated étendue (the value of 3200 m² deg² yr corresponds to a 10-year survey). The width of the bands reflects the assumed range of systematic errors.

Fig. 4.— The sample completeness for simulated RR Lyrae stars with successfully recovered periods using LSST universal cadence observations in the $g$ band (averaged over many fields), as a function of the mean $g$ band magnitude (Oluseyi et al. 2011). The five curves correspond to different survey duration, according to the inset. The sample faint limit improves by $\sim 0.3$ mag between years 8 and 10 both at the 50% and 90% completeness level.
### The Dependence of Science Deliverables on Survey Duration

While unprecedented science outcome will definitely be possible even with a first few years of LSST data, **the complete planned and designed for science deliverables will require 10-years of data**, with a tolerance of at most about 1-2 years.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Year 1</th>
<th>Y3</th>
<th>Y5</th>
<th>Y8</th>
<th>Year 10</th>
<th>Y12</th>
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<tbody>
<tr>
<td>$r_5$ coadd$^a$</td>
<td>26.3</td>
<td>26.8</td>
<td>27.1</td>
<td>27.4</td>
<td>27.5</td>
<td>27.6</td>
</tr>
<tr>
<td>$\sigma(i=25)^b$</td>
<td>0.12</td>
<td>0.07</td>
<td>0.06</td>
<td>0.05</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>color vol.$^c$</td>
<td>316</td>
<td>20</td>
<td>6</td>
<td>1.7</td>
<td>1</td>
<td>0.6</td>
</tr>
<tr>
<td># of visits$^d$</td>
<td>83</td>
<td>248</td>
<td>412</td>
<td>660</td>
<td>825</td>
<td>990</td>
</tr>
<tr>
<td>$\sigma\pi (r=24)^e$</td>
<td>9.5</td>
<td>5.5</td>
<td>4.2</td>
<td>3.3</td>
<td>3.0</td>
<td>2.7</td>
</tr>
<tr>
<td>$\sigma\mu (r=24)^f$</td>
<td>32</td>
<td>6.1</td>
<td>2.8</td>
<td>1.4</td>
<td>1.0</td>
<td>0.8</td>
</tr>
</tbody>
</table>
Modern Cosmological Probes

- Cosmic Microwave Background (the state of the Universe at the recombination epoch, at redshift $\sim 1000$)
- Weak Lensing: growth of structure
- Galaxy Clustering: growth of structure
- Baryon Acoustic Oscillations: standard ruler
- Supernovae: standard candle

Except for CMB, measuring $H(z)$ and growth of structure ($z$)

The Next Generation of Measurements: the Planck satellite for CMB, large optical/IR sky surveys for other methods: Dark Energy Survey, Pan-STARRS, HSC, LSST, WFIRST
Cosmology with LSST

- Derived from 4 billion galaxies with accurate photo-z and shape measurements
- Measuring distances and growth of structure with a percent accuracy for $0.5 < z < 3$
- SNe will provide a high angular resolution probe of homogeneity and isotropy of the Universe

By simultaneously measuring growth of structure and curvature, LSST data will tell us whether the recent acceleration is due to dark energy or modified gravity.
Extragalactic astronomy: 10 billion galaxies

- About 10 billion galaxies, with 4 billion in a "gold" sample defined by $i<25.3$
- The "gold" sample extends to redshifts of $>2.5$: evolution

SDSS: snapshot at $z\sim0$

LSST: a galaxy evolution movie to $z\sim2.5$
Extragalactic astronomy: 10 billion galaxies

[Images of galaxy clusters or clusters with labeled redshifts]
Extragalactic astronomy: quasars

- About 10 million quasars will be discovered using variability, colors, and the lack of proper motions.
- The sample will include $M_i = -23$ objects even at redshifts beyond 3.
- Quasar variability studies will be based on millions of light curves with close to 1000 observations over 10 years.

Top: absolute magnitude vs. redshift diagram for quasars.

LSST will detect $\sim 10,000$ quasars with $6 < z < 7.5$.
The Milky Way structure: 10 billion stars, time domain massive statistical studies!

Compared to SDSS: LSST can “see” about 40 times more stars, 10 times further away and over twice as large sky area

Main sequence stars

Distance and [Fe/H]:

SDSS RR Lyrae

100 kpc

Sesar et al. (2009)
Gaia vs. LSST comparison

- **Gaia**: excellent astrometry (and photometry), but only to $r < 20$
- **LSST**: photometry to $r < 27.5$ and time resolved measurements to $r < 24.5$
- Complementarity of the two surveys: photometric, proper motion and trigonometric parallax errors are similar around $r=20$

The Milky Way disk “belongs” to Gaia, and the halo to LSST (plus very faint and/or very red sources, such as white dwarfs and LT(Y) dwarfs).

The large blue circle: the $\sim$400 kpc limit of future LSST studies based on RR Lyrae

The large red circle: the $\sim$100 kpc limit of future LSST studies based on main-sequence stars (and the current limit for RR Lyrae studies)

The small insert: $\sim$10 kpc limit of SDSS and future Gaia studies for kinematic & $[Fe/H]$ mapping with MS stars
SDSS: main sequence to 10 kpc, RR Lyr to 100 kpc
LSST: 100 kpc & 400 kpc (half way to Andromeda)
Time Domain: objects changing in time positions: asteroids and stellar proper motions brightness: cosmic explosions and variable stars
Time Domain: objects changing in time
positions: asteroids and stellar proper motions
brightness: cosmic explosions and variable stars

For example: SDSS demonstrated that asteroid families have distinct colors: chemical composition
LSST will turn this diagram into a movie (millions of asteroids)
**Killer asteroids:** the impact probability is not 0

The Barringer Crater, Arizona: a 40m object 50,000 yr. ago

Shoemaker-Levy 9 (1994)

Tunguska (1908)

LSST is the only survey capable of delivering completeness specified in the 2005 Congressional NEO mandate to NASA (to find 90% NEOs larger than 140m)
Time Domain: objects changing in time positions: stellar proper motions

Kinematics of halo stars based on SDSS-POSS proper motions: velocity ellipsoid is nearly invariant in spherical coordinate system, which implies that the gravitational potential must be nearly spherical! (c/a < 1)
Time Domain: objects changing in time
brightness: cosmic explosions and variable stars

Not only point sources - echo of a supernova explosion:

As many variable stars from LSST, as all stars from SDSS
Web stream with data for transients within 60 seconds
The impact of LSST on other wavelengths, and vice versa:
1) Science Results (e.g. galaxy/AGN evolution)
2) Tools and Methods (e.g. massive databases [radio])
3) Supplemental data (coeval, identification, physical processes)
   Also non-EM: e.g. Advanced LIGO
Statistical analysis of a massive LSST dataset

- A large (100 PB) database and sophisticated analysis tools: for each of 20 billion objects there will be about 1000 measurements (each with a few dozen measured parameters)

Data mining and knowledge discovery

- 10,000-D space with 20 billion points
- Characterization of known objects
- Classification of new populations
- Discoveries of unusual objects

Clustering, classification, outliers
LSST in one sentence:
An optical/near-IR survey of half the sky in ugrizy bands to $r \sim 27.5$ based on 1000 visits over a 10-year period:
a catalog of 10 billion stars and 10 billion galaxies with exquisite photometry, astrometry and image quality.

Q&A slides