LSST Overview and Science Requirements

Željko Ivezić, LSST Project Scientist, University of Washington

Spectroscopy in the Era of LSST, Tucson, April 11-12, 2013
Outline

0) Main Points

1) Introduction to LSST
   - science themes and science drivers
   - brief system overview
   - baseline cadence and expected data products

2) Spectroscopy and LSST
   - two flavors: calibration and value-added followup
   - a proposal for quantitative summary of needs

3) Brief examples of spectroscopic needs
Main Points:

1) LSST key science deliverables do not require massive spectroscopic followup

   - calibration of photometrically derived quantities needs spectroscopic training samples (e.g. photo-z, photometric parallax and metallicity for stars)

2) LSST can and should be viewed as one of the central pieces of an integrated optical/IR system

   - a fact: it will be possible to get spectra only for a very small fraction of >20 billion LSST sources

   - finding “most interesting” spectroscopic targets will become an (astroinformatics) industry (color and morphology selection, time domain, co-observing)
LSST Science Themes

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

- Time domain (cosmic explosions, variable stars)

- 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
A catalog of 10 billion stars and 10 billion galaxies with exquisite photometry, astrometry and image quality!


LSST in one sentence:
An optical/near-IR survey of half the sky in ugrizy bands to r~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!
LSST Science Themes

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

- Time domain
  (cosmic explosions, variable stars)

- The Solar System structure (asteroids)

- The Milky Way structure (stars)

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!**

**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.

**Left:** a 10-year simulation of LSST survey: the number of visits in the r band (Aitoff projection of eq. coordinates).
SDSS-LSST comparison: $\text{LSST} = d(\text{SDSS})/dt$, $\text{LSST} = \text{SuperSDSS}$

7x7 arcmin, gri

(Deep Lens Survey)
SDSS-LSST comparison: $\text{LSST} = \frac{d(\text{SDSS})}{dt}$, $\text{LSST} = \text{SuperSDSS}$

7x7 arcmin, gri

SDSS: one US Library of Congress worth of data
LSST: one SDSS per night, or all the words ever printed!

(Deep Lens Survey)

(Subaru)
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)
LSST system
Telescope
Camera
Software
Telescope and Site

1,380 m² service and maintenance facility

30 m diameter dome

1.2 m diameter atmospheric telescope

Control room and heat producing equipment (lower level)

350 ton telescope

Base Facility

Stray light and Wind Screen

Calibration Screen

Includes the facilities, and hardware to collect the light, control the survey, calibrate conditions, and support all LSST summit and base operations.
LSST Telescope

8.4m, 6.7m effective
5 sec slew & settle
The field-of-view comparison: Gemini vs. LSST

- **Primary Mirror Diameter**
  - Gemini South Telescope: 8 m
  - LSST: 8.4 m

- **Field of View**
  - Gemini South Telescope: 3.5 degrees
  - LSST: 0.2 degrees

*(Full moon is 0.5 degrees)*
Optical Design for LSST

Three-mirror design (Paul-Baker system) enables large field of view with excellent image quality: delivered image quality is dominated by atmospheric seeing.
Mirror fabrication is advanced - Private funding enabled early start of both reflective optics

- Primary-Tertiary was cast in 2008
- Fabrication completed in 2013
- Secondary substrate fabricated by Corning in 2009.
The largest astronomical camera: 2800 kg, 3.2 Gpix
Modular design: 3200 Megapix = 189 x 16 Megapix CCD
9 CCDs share electronics: raft (=camera)
Problematic rafts can be replaced relatively easily
Software: the subsystem with the highest risk

- 20 TB of data to process every day (~one SDSS/day)
- 1000 measurements for 20 billion objects during 10 years
- Existing tools and methods (e.g. SDSS) do not scale up to LSST data volume and rate (100 PB!)
LSST Observing Cadence

MAIN SURVEY (deep-wide-fast):
Deep Wide Survey: 18,000 square degrees to a uniform depth of
  $u$: 26.1  $g$: 27.4  $r$: 27.5  $i$: 26.8  $z$: 26.1  $y$: 24.9
- pairs of 15 second exposures (to $r$$\sim$24.5 mag) per visit
- visit the same position again within ~1 hour with another pair of exposures
- number of visits per night: 850 (~8,000 sq. deg)

MINI SURVEYS (deep drilling)
10% of time: ~30 selected fields (~300 sq. deg)
  Continuous 15 sec exposures: ~1 hour/night
LSST “guaranteed” fields: CDFS, COSMOS, ES1 and XMM-LSS
  Co-observing?

Detection of transients announced within 60 seconds.
  Expect: 1-2 million alerts per night,
  “thousands worthy of followup!”
Three main classes of LSST data products:

**Level 1 data products** are generated continuously every observing night, including alerts for objects that have changed flux or position, that will be released within 60 seconds (and will include measurements of positions and fluxes, as well as images).

**Level 2 data products** will be made available as annual Data Releases and will include images and catalogs with measurements of positions, fluxes, and shapes, as well as variability information such as orbital parameters for moving objects and light curve parametrization.

Based on about 1000 observations of each position, \( \alpha(t), \delta(t), u(t), g(t), r(t), i(t), z(y), y(t) \) for 20 billion objects!
Three main classes of LSST data products:

**Level 3 data products** will be created by science teams external to the project using suitable Applications Programming Interfaces (APIs) that will be provided by the LSST Data Management System. The Data Management System will also provide about 50 teraflops of user-dedicated processing capability and 12 PB of user-dedicated storage. The key aspect of these capabilities is that they will reside “next to” the LSST data, avoiding the latency associated with downloads.
### LSST: approximate expected data volume (1 billion 16 Mpix images)

<table>
<thead>
<tr>
<th>Dataset</th>
<th>Size</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Final Image Archive</td>
<td>345 PB</td>
<td>All Data Releases</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Includes Virtual Data (315 PB)</td>
</tr>
<tr>
<td>Final Image Collection</td>
<td>75 PB</td>
<td>Data Release 11 (Year 10)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Includes Virtual Data (57 PB)</td>
</tr>
<tr>
<td>Final Catalog Archive</td>
<td>46 PB</td>
<td>All Data Releases</td>
</tr>
<tr>
<td>Final Database</td>
<td>9 PB 32 trillion rows</td>
<td>Data Release 11 (Year 10)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Includes Data, Indexes, and DB Swap</td>
</tr>
<tr>
<td>Final Disk Storage</td>
<td>228 PB 3700 drives</td>
<td>Archive Site Only</td>
</tr>
<tr>
<td>Final Tape Storage</td>
<td>83 PB 3800 tapes</td>
<td>Single Copy Only</td>
</tr>
<tr>
<td>Number of Nodes</td>
<td>1800</td>
<td>Archive Site</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Compute and Database Nodes</td>
</tr>
<tr>
<td>Number of Alerts Generated</td>
<td>6 billion</td>
<td>Life of survey</td>
</tr>
</tbody>
</table>

- Virtual Data is data that is dynamically recreated on-demand from provenance information
Outline

0) Main Points

1) Introduction to LSST
   - science themes and science drivers
   - brief system overview
   - baseline cadence and expected data products

2) Spectroscopy and LSST
   - two flavors: calibration and value-added followup
   - a proposal for quantitative summary of needs

3) Brief examples of spectroscopic needs
Two main classes of LSST-related spectroscopy

1. Calibration samples
   for quantities that can be derived from photometric data: photometric redshifts for galaxies, photometric metallicity for stars

2. Value-added follow-up
   a) supplemental information that cannot be obtained from LSST data: radial velocity, emission and absorption line strengths
   b) identification spectra for transient and/or very unusual objects (SNe, GRB followup, high-z quasars, brown dwarfs)

These differ by the needed sample size, sample depth, required spectral resolution, and the time delay relative to imaging data.

What do we need? How does it compare to what we have?
SPECTROSCOPY OF THE NEXT-GENERATION PHOTOMETRIC SURVEYS

THE BRIGHT END

190 sq deg
Area observed
by LSST in
~10 minutes
to 24.5

Spectroscopic
field of view and
depth in ~1 hour

DESpec on Blanco*
KAOS on Subaru*

LAMOST

AAΩ

WFMOS on Gemini*

*proposed

Adam Myers

IJCAI-09, Pasadena
A proposal for 4-D quantitative summary of needs

1) Sample depth

- shallow: $r < 20$
- medium: $20 < r < 22.5$
- deep: $22.5 < r < 25$

2) Sample size

- small: $< 10,000$
- medium: $> 10,000$
- large: $> 100,000$

3) Resolution

- lowR: for redshifts and stellar $[\text{Fe/H}]$ and radial velocity
- highR: stellar abundances, solar system objects, ...

4) Co-eval or rapid followup? “!”
A proposal for 4-D quantitative summary of needs

<table>
<thead>
<tr>
<th>Program/depth:</th>
<th>bright</th>
<th>medium</th>
<th>faint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibrate photo-z</td>
<td>(exists?)</td>
<td>large lowR</td>
<td>large lowR</td>
</tr>
<tr>
<td>Calibrate photo-FeH</td>
<td>Gaia?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stellar [Fe/H]</td>
<td>(exists?)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stellar radial vel.</td>
<td>(exists?)</td>
<td>medium lowR</td>
<td>small lowR</td>
</tr>
<tr>
<td>Stellar abundances</td>
<td>small midR</td>
<td>small midR</td>
<td></td>
</tr>
<tr>
<td>Galaxy evolution</td>
<td></td>
<td>small midR</td>
<td>small midR</td>
</tr>
<tr>
<td>Brown dwarfs</td>
<td></td>
<td></td>
<td>small lowR</td>
</tr>
<tr>
<td>High-z quasars</td>
<td></td>
<td></td>
<td>small lowR</td>
</tr>
<tr>
<td>Type Ia SNe</td>
<td>small lowR!</td>
<td>small lowR!</td>
<td>small lowR!</td>
</tr>
<tr>
<td>comets</td>
<td>small lowR!</td>
<td>small lowR!</td>
<td>small lowR!</td>
</tr>
</tbody>
</table>

After identifying major programs, we can map them to required resources.
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 ($z$)
Modern Cosmological Probes

- Cosmic Microwave Background
  (the state of the Universe at the recombination epoch, at redshift $\sim1000$)

- Weak Lensing: growth of structure

- Galaxy Clustering: growth of structure

- Baryon Acoustic Oscillations: standard ruler

- Supernovae: standard candle

The Next Generation of Measurements: the Planck satellite for CMB, large optical/IR sky surveys for other methods: Dark Energy Survey, Pan-STARRS, LSST, Euclid, 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
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**.
Galaxies:

- **Photometric redshifts**: random errors smaller than 0.02, bias below 0.003, fewer than 10% >3σ 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 for different bands](image)

**Photo-z requirements correspond to r~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)**
Extragalactic astronomy: 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: galaxies

3x3 arcmin, gri

Gawiser et al

SDSS

MUSYC r \sim 26
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 1000 observations over 10 yrs.

Top: absolute magnitude vs. redshift diagram for quasars

LSST will detect $\sim 10,000$ quasars with $6<z<7.5$!
Time Domain with LSST
"objects changing in time"

1) positions:
   a) fast: asteroids
   b) slow: stellar proper motions

2) brightness: cosmic explosions, variable stars (or periodic vs. irregular, etc.) and everything else

---

Kulkarni et al. 2007
Eyer & Mowlavi 2007
Time Domain: objects changing in time positions: asteroids and stellar proper motions 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.
Real time alerts for microlensing events!
Must have fast classification with low false-positive rate!
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)
Comets and Jovian Trojans have similar albedos: connection?
The Milky Way structure: 10 billion stars, time domain

Compared to SDSS: LSST can “see” 10 times further away and over twice as large an area.
What can we learn from this diagram with time-resolved data?

A Primer on Dissecting the Milky Way with SDSS

- Stars on the main stellar locus are dominated (≈98%) by main sequence stars (for r > 14).
- The position of main-sequence stars on the locus is controlled by their effective temperature/luminosity/[Fe/H], and thus can be used to estimate distance: photometric parallax method for ≈100 million stars (with LSST several billion!)
- Accurate u − g color enables photometric metallicity estimates for 6 million SDSS F/G stars to 10 kpc; (with LSST 200 million to 100 kpc!)
Velocity distribution for halo stars

Proper motions constrain dark matter!

Kinematics of halo stars based on SDSS-POSS proper motions: velocity ellipsoid is nearly invariant in spherical coordinate system, which implies that the DM halo is oblate! (Loebman et al. 2012; arXiv:1209.2708)

To get 3D stellar velocities, time-resolved data are mandatory!
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).

White dwarfs: LF is age probe

~400,000 halo white dwarfs from LSST (10 million total):

L / T dwarfs: L dwarfs are dime a dozen: 200,000 in LSST with proper motion and trigonometric parallax measurements

Simulations predict 2400 T dwarfs with >5σ proper motion and parallax measurements

Compared to UKIDSS, 5 times larger sample of T dwarfs, with parallaxes and 10-20 times more accurate proper motions

(~100 Y dwarfs [model based])
<table>
<thead>
<tr>
<th>Program/depth:</th>
<th>bright</th>
<th>medium</th>
<th>faint</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibrate photo-z</td>
<td>(exists?)</td>
<td>large lowR</td>
<td>large lowR</td>
</tr>
<tr>
<td>Calibrate photo-FeH</td>
<td>Gaia?</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stellar [Fe/H]</td>
<td>(exists?)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stellar radial vel.</td>
<td>(exists?)</td>
<td>medium lowR</td>
<td>small lowR</td>
</tr>
<tr>
<td>Stellar abundances</td>
<td>small midR</td>
<td>small midR</td>
<td></td>
</tr>
<tr>
<td>Galaxy evolution</td>
<td></td>
<td>small midR</td>
<td>small midR</td>
</tr>
<tr>
<td>Brown dwarfs</td>
<td></td>
<td></td>
<td>small lowR</td>
</tr>
<tr>
<td>High-z quasars</td>
<td></td>
<td></td>
<td>small lowR</td>
</tr>
<tr>
<td>Type Ia SNe</td>
<td>small lowR !</td>
<td>small lowR !</td>
<td>small lowR !</td>
</tr>
<tr>
<td>comets</td>
<td>small lowR !</td>
<td>small lowR !</td>
<td>small lowR !</td>
</tr>
</tbody>
</table>

After identifying major programs, we can map them to required resources.