Niel Brandt (Penn State)
Quick Overview, Current Status, and Comparison to Other Variability Surveys
A public optical/NIR survey of ~ half the sky in the $ugrizy$ bands to $r \sim 27.5$ based on ~ 820 visits over a 10-year period.

**Wide**
The observable southern sky. Each exposure covers 50 full Moons.

**Deep**
10-100 times deeper than other very wide-field surveys.

**Fast**
Rapidly scans the sky with 15 sec exposures, providing a color movie of objects that change or move. Whole observable sky scanned every 3-4 nights.

Main Survey - Brief Details

Operations Simulation of $r$-Band Visits

Main survey optimized for homogeneity of depth and number of visits.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Baseline Design Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optical Config.</td>
<td>3-mirror modified Paul-Baker</td>
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<tr>
<td>Mount Config.</td>
<td>Alt-azimuth</td>
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<tr>
<td>Final f-ratio, aperture</td>
<td>f/1.234, 8.4 m</td>
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<tr>
<td>Field of view, étendue</td>
<td>9.6 deg$^2$, 319 m$^2$deg$^2$</td>
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<tr>
<td>Plate Scale</td>
<td>50.9 µm/arcsec (0.2'' pix)</td>
</tr>
<tr>
<td>Pixel count</td>
<td>3.2 Gigapix</td>
</tr>
<tr>
<td>Wavelength Coverage</td>
<td>320 – 1050 nm, ugrizy</td>
</tr>
<tr>
<td>Single visit depths, design a</td>
<td>23.9, 25.0, 24.7, 24.0, 23.3, 22.1</td>
</tr>
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<td>Single visit depths, min. b</td>
<td>23.4, 24.6, 24.3, 23.6, 22.9, 21.7</td>
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<tr>
<td>Mean number of visits c</td>
<td>56, 80, 184, 184, 160, 160</td>
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<tr>
<td>Final (coadded) depths d</td>
<td>26.1, 27.4, 27.5, 26.8, 26.1, 24.9</td>
</tr>
</tbody>
</table>
Image Comparison

Current wide-field surveys

LSST

20 billion galaxies and
20 billion stars with exquisite photometry, image quality, and astrometry.

Many millions of quasars, supernovae, asteroids, etc.
Other Cadence Programs

About 90% of the time will be spent on the main survey.

Remaining ~ 10% will be used for other cadence programs.

Deep-Drilling Fields
- Blank fields (e.g., E-CDF-S, XMM-LSS, COSMOS, ELAIS-S1)
- Nearby clusters of galaxies (e.g., Fornax)
- Local Group and the Galaxy (e.g., LMC, SMC, open clusters)
- Solar System (e.g., TNOs, Neptune Trojans, Jupiter Trojans)

Blank fields aim for 5300-14000 visits per band reaching $urgi = 28.5, z = 28.0, y = 27.0$.

Details under discussion by the Deep-Drilling Interest Group.

Other possible cadence programs include improved Galactic-plane coverage, denser sampling of ~ 600 deg$^2$, rotating “focus” fields, TOO?
LSST Science Themes

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

Time-domain astrophysics
(e.g., SMBHs, compact objects, cosmic explosions, variable stars)

Solar System structure
(e.g., near-Earth asteroids, trans-Neptunian objects)

Milky Way structure
(e.g., stars, star-formation regions, tidal streams)
Project Status and a Few Updates

Received Federal construction start in 2014 Aug as NSF/DOE project.

Primary/tertiary mirror polishing completed in 2015 Feb. Secondary mirror at Exelis for processing to finished polished state.

Plans for camera construction at SLAC received “Critical Decision 2” approval from DOE. Fabrication can begin after “Critical Decision 3” review in 2015 Summer.

Dome contract initiated.

Site leveled and preparation in progress.

LSST Project actively hiring engineering and science staff.

Onset of science operations planned for late 2022 (2019 first light).
Current Project Status

M1M3 after polishing - moved to storage at Tucson International Airport

M2 at Exelis for processing

Site bedrock testing in 2015 June

Cerro Pachón, Chile
2662 m
El Peñón
Future site of the LSST
Some Basic Comparisons to Other Facilities

Étendue Comparison

Above an étendue of 200-300 m$^2$ deg$^2$ it becomes possible to undertake a single comprehensive multi-band survey of the entire visible sky serving most science opportunities, rather than multiple special surveys in series.
Owing to delays in funding for LSST construction, smaller projects are picking off the bright-source science in specific areas; e.g., transients.

Most of the “new discovery volume” for LSST transients in 2022 will be at faint magnitudes. Large telescopes needed for follow-up!
Some SMBH Variability Science with LSST

See, e.g., the LSST Science Book for lots of additional science on other classes of variable objects.
Nightly LSST SMBH Science

Monitoring of \( \sim 3 \) million AGNs (\( \sim 10+ \) million total).

Discovery of \( \sim 50 \) large AGN flares
(e.g., blazars and accretion-disk instabilities).

Discovery of \( \sim 3 \) stellar tidal disruption events.

Discovery of \( \sim 0.1 \) strong quasar microlensing events.

Binary SMBH inspirals and mergers?

Aim to select 20-40 million, or more, AGNs with LSST plus multiwavelength data.

Also \( \sim 2500 \) supernovae and \( \sim 5 \) “orphan” GRB afterglows.
Massive AGN Variability Studies

Millions of well-sampled, accurate, multicolor AGN light curves, spanning minutes-to-years (billions of photometric measurements).

Even better sampling and depth for $\sim 10^5$ AGNs in the DDFs.

Can combine with DES, HSC, Pan-STARRS, SDSS for longer baselines.

Can powerfully study general luminosity and spectral variability as a function of $L, z, \lambda, \Delta t$, color, radio properties, line properties, $M_{\text{BH}}, L/L_{\text{Edd}}$ (some require one-epoch spectra).

Rare but important events - large disk instabilities, strong jet flares, swan-song events, QPOs.
Triggered Spectroscopic Follow-Up: RM

Strong Quasar Continuum Variations Can Trigger Reverberation Mapping Follow-Up

Kaspi et al. (2007)

HET RM light curves for luminous quasar

Shen et al. (2015)

Multi-Object AGN Reverberation Mapping with SDSS

Potentially also photometric RM (Chelouche et al. 2012, 2014).
 Triggered Spectroscopic Follow-Up: BALs

Color Changes Will Trigger Spectroscopic Follow-Up of Strong BAL Variations

Also other absorption changes; e.g., variable dust reddening.

Grier et al. (2015)

Hall et al. (2011)
Microlensing of Accretion Disks

LSST will find and monitor ~ 4000 AGNs lensed into multiple images.

LSST cadence well-suited to rapid identification of microlensing events by stars in lensing galaxy - these give effective \( \mu \)as resolution.

Can trigger dense targeted multicolor and UV/X-ray monitoring, aiming to constrain the accretion-disk temperature profile.

With a large sample, can examine \( L, L/L_{\text{Edd}}, M_{\text{BH}}, z \) effects.
Small-Separation Binary SMBH

For SMBHs to move from pc to $10^{-3}$ pc separations, likely need gas accretion to remove binary angular momentum.

Accretion rate onto both SMBHs may vary on timescales of the binary period.

Month-to-year timescales at $\sim 10^{-2}$ pc, well-suited to LSST monitoring and hard to find in other ways.

Massive LSST variability survey can find or usefully constrain the uncertain frequency of $10^{-2}$ pc binary SMBHs.

Already some candidates being found, but detailed interpretation still unclear.

e.g., Cuadra et al. (2009)

PG 1302-102
Graham et al. (2015)

Also OJ287, PSO J334.2028+01.4075
Transient Fueling of Dormant SMBH

A dormant SMBH can flare to AGN luminosities for months-years via tidal disruption and partial accretion of stars, planets, or gas clouds.

Originally found in the X-ray band with ROSAT with sparsely sampled light curves.

Now possible to identify in wide-field optical/UV (GALEX, SDSS, PTF, Pan-STARRS) and X-ray (Swift) monitoring surveys.

Expect to detect several thousand events per year with LSST, but will likely need to enforce selection cuts for unambiguous detections (confusion with SNe, AGNs).
LSST and Transient SMBH Fueling

Measure outburst rates as a function of galaxy type, redshift, and level of nuclear activity.

Assess the contribution of tidal disruptions to the AGN luminosity function.

Determine fraction with jets via radio follow-up and comparison with radio transient surveys (e.g., VAST, ThunderKAT, LOFAR transients).

Understand diversity of these events ($L_{\text{Bol}}, kT, \text{jet power}$)

Find remarkable events - e.g., white dwarf disruptions by IMBH, giant planet disruptions, gas cloud captures, binary SMBH disruptions.
LSST Synergy with Multiwavelength Satellite Missions
Very Wide-Field Missions for X-ray Transients Being Pursued

Several missions put forward, and hopefully will succeed. Need something post-Swift!

Utilize coded-mask and/or lobster-eye optics for up to ~ 5 sr coverage – some with fast pointing of narrow-field instruments.

Generally cannot match LSST depths, but great for bright transients.

Adding other wavelengths tough on NASA SMEX budget (e.g., X-ray + UV/IR).
Wide-Field X-ray Imaging Missions with Transients Capabilities

eROSITA and Athena moving forward, and other great mission concepts put forward.

Utilize grazing-incidence optics to cover 0.4-1 deg$^2$.

Do a much better job at matching LSST depths over limited area; e.g., could do a great job on LSST DDF transients.

Some have fairly good agility.

New mission concepts require a large NASA Explorer or probe-class mission.
UV Satellite Prospects

Would provide complementary UV data to LSST from 220-280 nm.

Continuous data streaming and real-time analysis, covering 210 deg$^2$ patches in NEP and SEP.

Aiming to investigate

- Supernova shock breakouts
- AGNs (RM and disk tomography)
- Tidal disruption events
- Stellar activity
- Relativistic explosions
- Exoplanets
The End
Extra Slides
LSST AGN Selection

Multicolor selection in $ugrizy$ from $z = 0$-7.5

- Ultraviolet excess below $z \sim 2.5$
- Lyman-$\alpha$ forest at high redshifts
- Works best when $L_{\text{AGN}} > L_{\text{Host}}$

Variability

- 55-185 samplings per band over 10 yr
- Highly effective complement to color selection
- Still need effectiveness assessments when $L_{\text{AGN}} \sim L_{\text{host}}$

Astrometry - Lack of proper motion and differential chromatic refraction

- Will reach $\sim 1$ mas yr$^{-1}$ at $r \sim 24$
- Minimizes confusion with stars
Multiwavelength Selection

$L_R, T_b, \text{morphology}$

ASKAP

$\Gamma_X, L_X$

eROSITA

Infrared-optical colors

Euclid

MeerKAT

$L_X$ and $\Gamma_X$

Chandra

VISTA

$XMM-\text{Newton}$

$L_R, T_b, \text{morphology}$
Plausible AGN Yields

Will have detections for 150 million AGNs in 10000 deg$^2$ primary LSST survey area.

Obscuration and host-galaxy dilution will hinder AGN selection.

Confidently can select 10 million.

Hope to select 20-40 million, and likely more - especially as multiwavelength data accumulate.

Overwhelming statistics to investigate AGN evolution as a function of environment - voids to superclusters.

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Chandra Deep Field-South Number Counts

Lehmer et al. (2012) 14900 deg$^2$
### Plausible AGN Yields

**Variability Selected Quasar Predictions from Palanque-Delabrouille et al. (2013)**

Table 8. Predicted number of quasars over $15.5 < g < 25$ and $0 < z < 6$ for a survey covering 10,000 deg$^2$, based on our best-fit luminosity function.

<table>
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<th>$g/z$</th>
<th>0.5</th>
<th>1.5</th>
<th>2.5</th>
<th>3.5</th>
<th>4.5</th>
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<td>76</td>
<td>15</td>
<td>0</td>
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<td>174</td>
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</table>

**Total** | 571169 | 2789734 | 1368583 | 578092 | 206489 | 31444 | 5545510

**Notes.** Bins are centered on the indicated magnitude and redshift values. The ranges in each bin are $\Delta g = 0.5$ and $\Delta z = 1$. Where we call “quasar” an object with a luminosity $M_l[z = 2] < -20.5$ and either displaying at least one emission line with FWHM greater than 500 km s$^{-1}$ or, if not, having interesting/complex absorption features.