Solar System Science with LSST

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for the

LSST Collaboration

Planetary Science Decadal Survey

October 28, 2009

Main Points

1. LSST will have a major impact on the studies of small Solar System bodies: NEOs, main-belt asteroids, Trojans, KBOs, comets...

2. LSST will use 90% of its observing time for the main "deep-wide-fast" survey – which is **explicitly designed to enable Solar System science:** two visits per night, with revisits on average after every three nights, over the whole visible sky.

3. **A strong team of Solar System scientists is part of LSST effort, and participates in design and decision making process.**

4. LSST is already well underway and is nearing construction readiness – but your support will be invaluable!

Outline

1. The Congressional mandate to catalog 90% of 140m and larger NEOs: quantitative driver for

    - Telescope Aperture, System Etendue, Data Rate

2. Large Synoptic Survey Telescope:

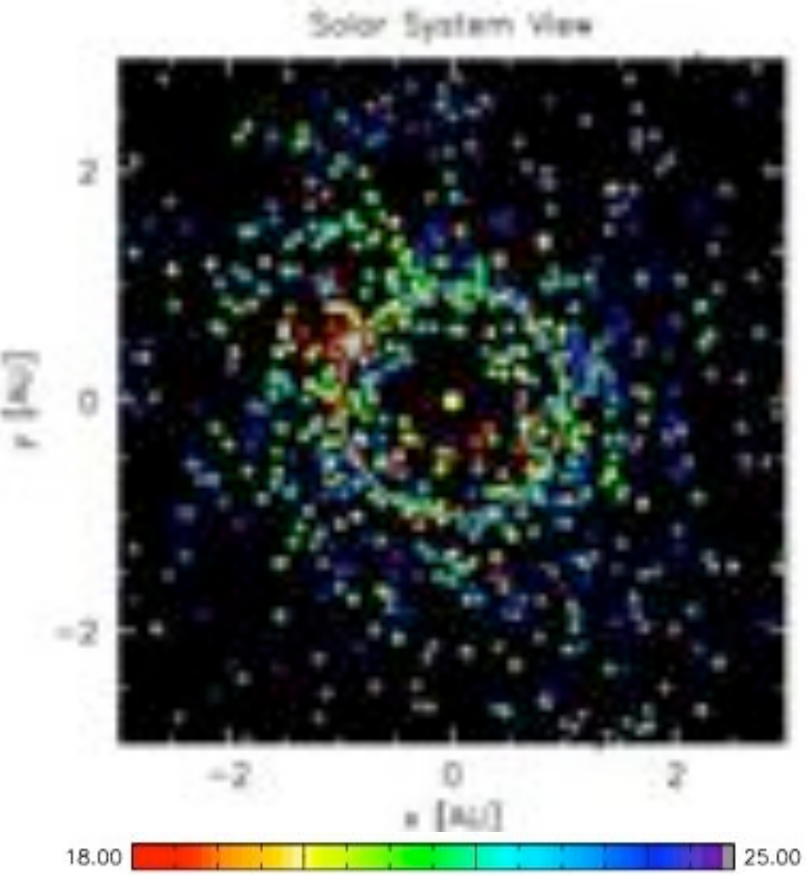
    - The LSST System: telescope, camera, data management
    - Other Science Drivers and Status Report

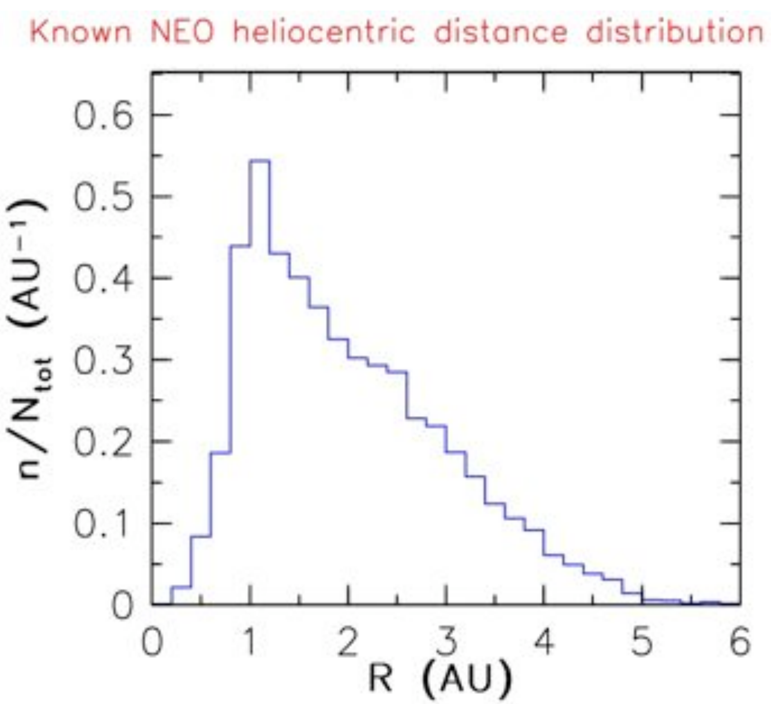
3. LSST Solar System Survey:

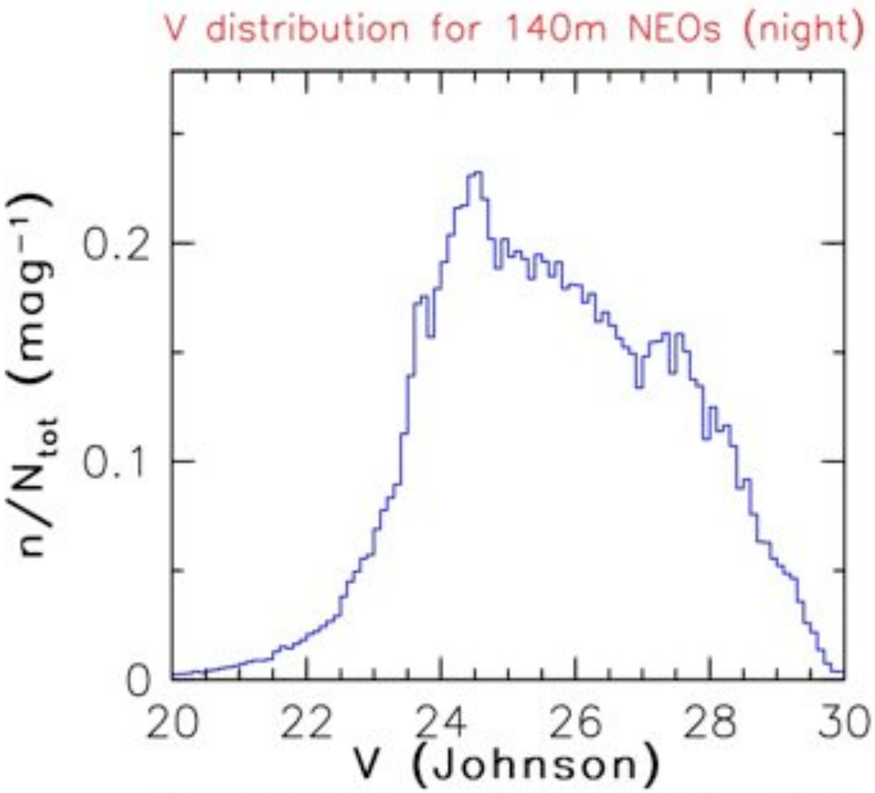
    - The Completeness of the LSST PHA survey
    - Science: Main-belt asteroids, Jovian Trojans, KBOs, Comets

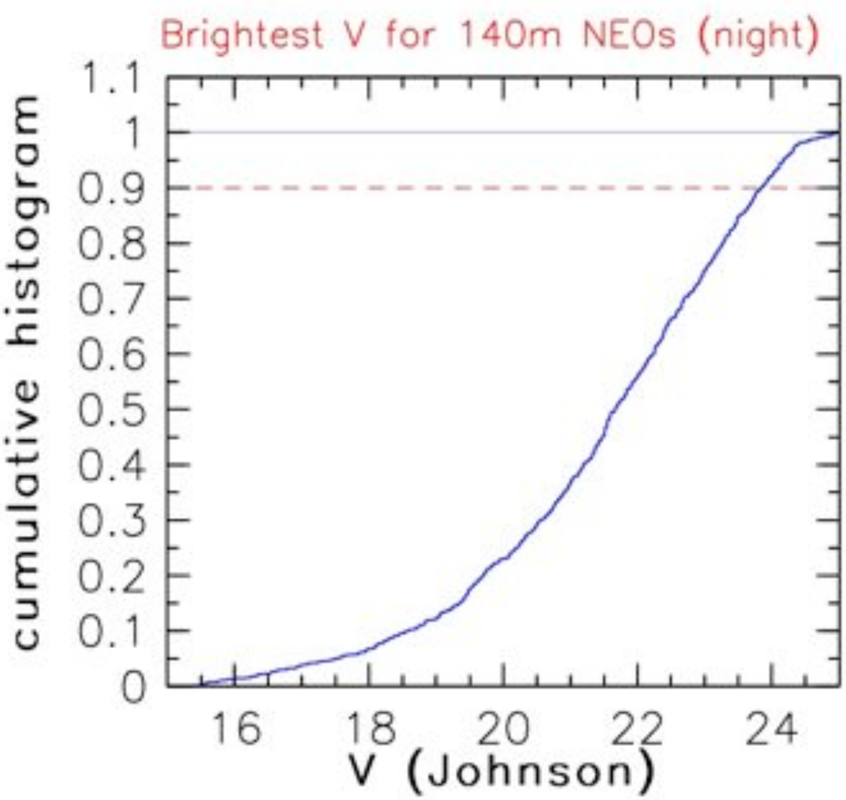
Where are 140m NEOs?

- The Congressional Mandate: 90% of NEOs with >140m diameter
- Assume:
  1. 140m is equivalent to H=22,
  2. the NEO orbital distribution doesn't depend on NEO's size,
  3. it's PHAs, not NEAs
- Compute: Positions and mags of the known PHA/NEO sample for the period 2015-2025
- **Top Left:** Positions of ∼800 known PHAs taken from MPC, coded by V mag (red:bright, blue: faint)
- **Bottom Left:** The distribution of heliocentric distances averaged over 10 years; 14% at $R < 1$, median $\bar{R} \sim 2$ AU, but median $\bar{D} \sim 2.1$ AU!



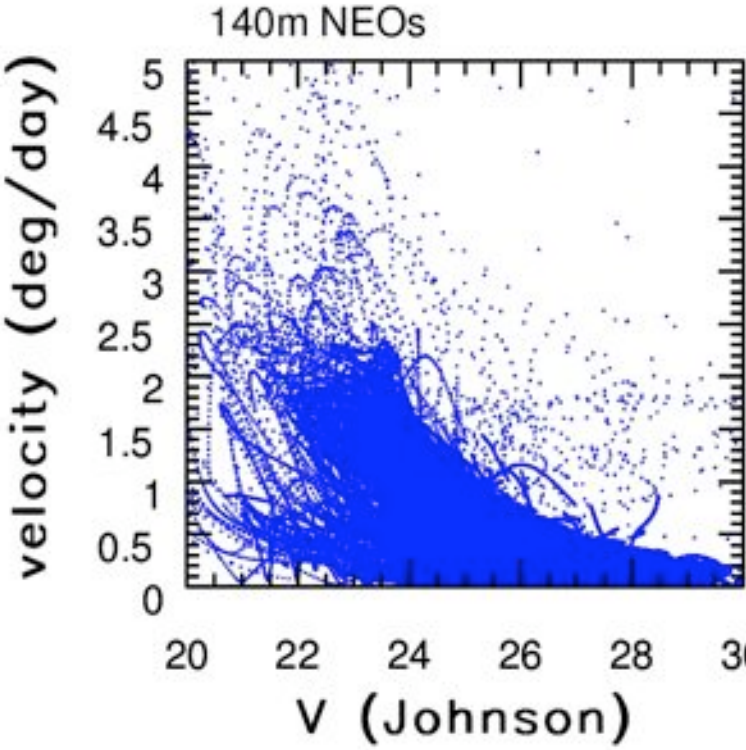


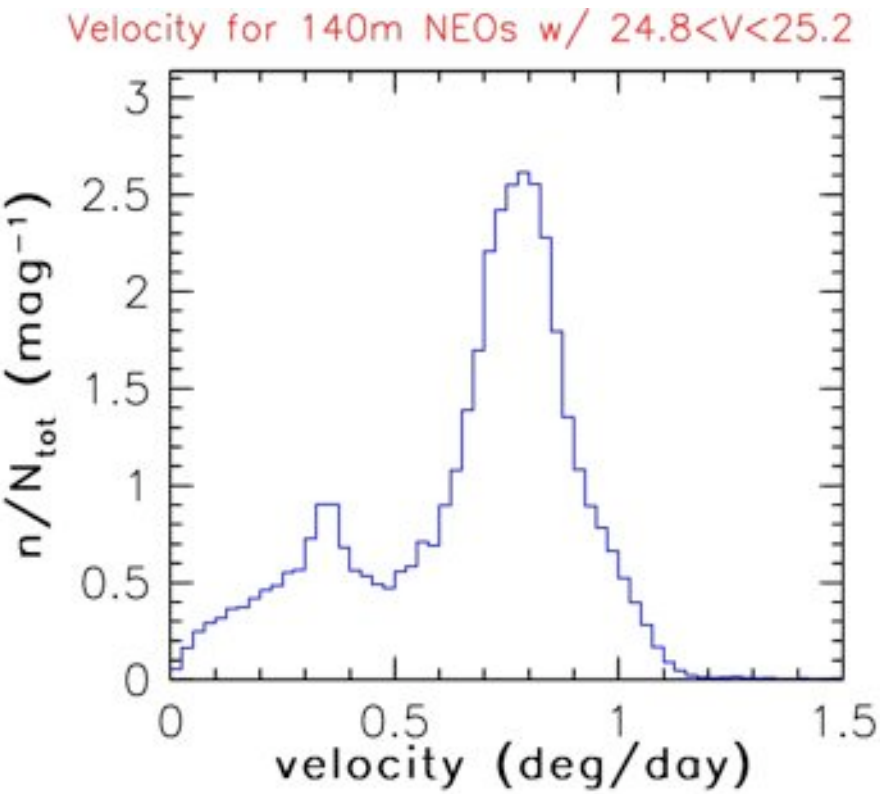




How bright are 140m NEOs?

- Median Values: $\bar{R}\sim 2$ AU and $\bar{D}\sim 2.1$ AU, implies $V\sim 25$
- Full Analysis: R, D, phase effects, etc.
- **Top Left:** the distribution of the Johnson V band apparent magnitudes for 140m NEOs observed during night time, median $\bar{V} = 25.5$
- **Bottom Left:** the cumulative distribution of the brightest V magnitude over 10 years: **10% of 140m NEOs are NEVER brighter than $V = 23.8$**
- Conclusion: **It is impossible to fulfill the NASA goal unless $V > 24$.** Need to reach the equivalent of $V\sim 25$ in **each** observation.
- Question: moving objects suffer from trailing losses (effective sky area increases with time) – what is the longest acceptable exposure time?





How fast are 140m NEOs?

- Requirement: need to reach $V \sim 25$ in each observation, but **how fast?**
- **Top Left:** the angular velocity vs. V magnitude for 140m NEOs, sampled over 1 year
- **Bottom Left:** the angular velocity distribution for 140m NEOs with $24.8 < V < 25.2$
- Conclusion: Need to prevent trailing losses for objects as fast as $\sim$1 deg/day
- Implications: assuming a seeing of 0.7 arcsec, an object moving at 1 deg/day will cross the seeing disk in $\sim$**15 sec; the exposure time shouldn't be much longer than this limit!**

Direct implications of the Congressional mandate:

1. **Telescope Aperture:** 140m object size implies $V \sim 25$ imaging, to reach $V \sim 25$ in 15 sec **need a 10m-class telescope**

2. **Field of view:** in order to cover the sky frequently enough, **need a ~5-10 deg^2 large field of view**, therefore $A\Omega$ product (etendue) needs to be at least several hundred m^{2}deg^2 (also, a large FOV implies a gigapixel-class camera)

3. **Data Rate:** frequent coverage of the whole sky at subarcsec resolution implies **enormous data rates** (e.g. for LSST ~30 TB/night, >100 PB over 10 years)

Inescapable conclusions: **A system** with an etendue of several hundred m^{2}deg^2 and a sophisticated and robust data processing system, **is required to fulfill the Congressional mandate.** **Lots of Solar System science "for free"!**

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   - Telescope Aperture, System Etendue, Data Rate
2. **Large Synoptic Survey Telescope:**
   - The LSST System: telescope, camera, data management
   - Other Science Drivers and Status Report
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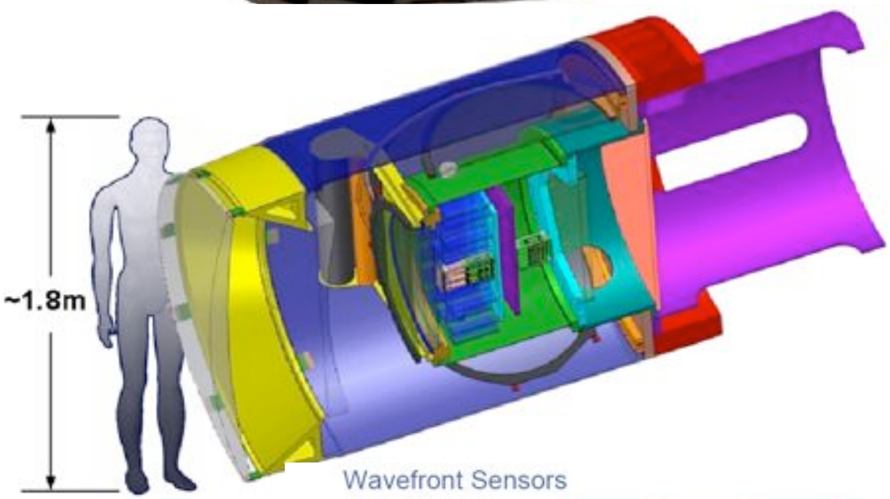
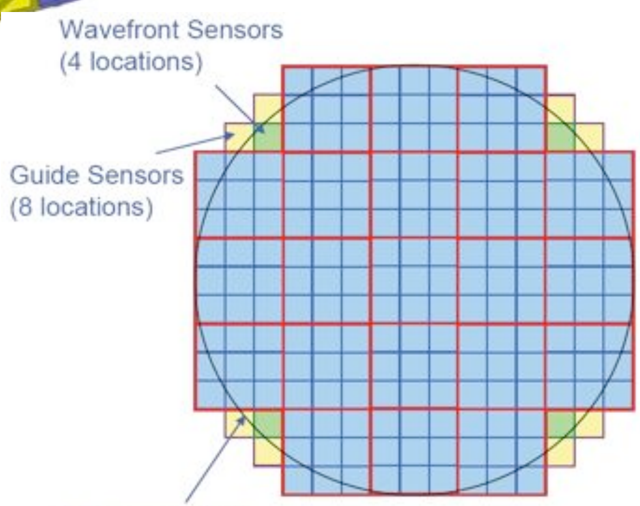
   - The Completeness of the LSST PHA survey
   - Science: Main-belt asteroids, Jovian Trojans, KBOs, Comets

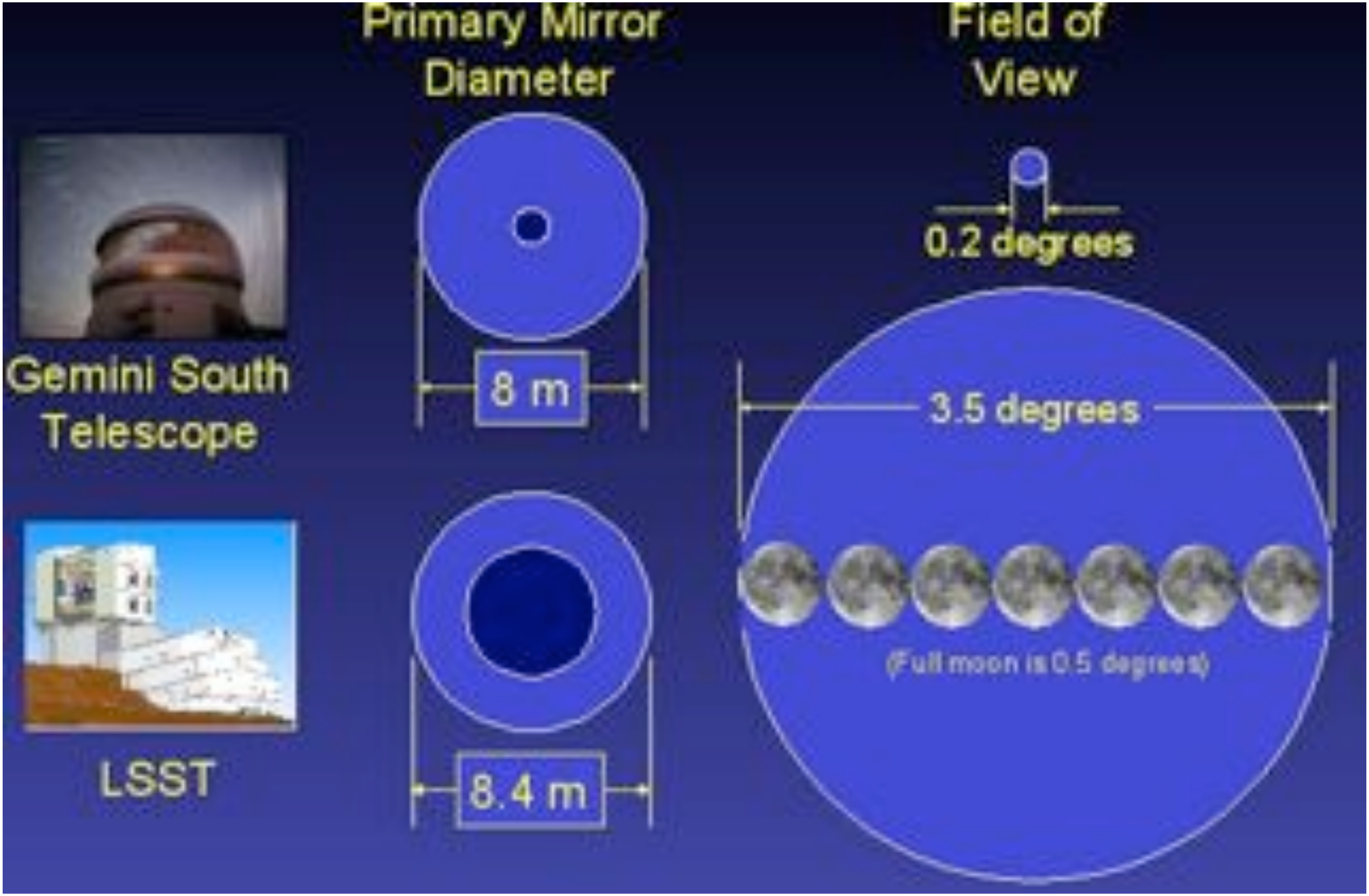


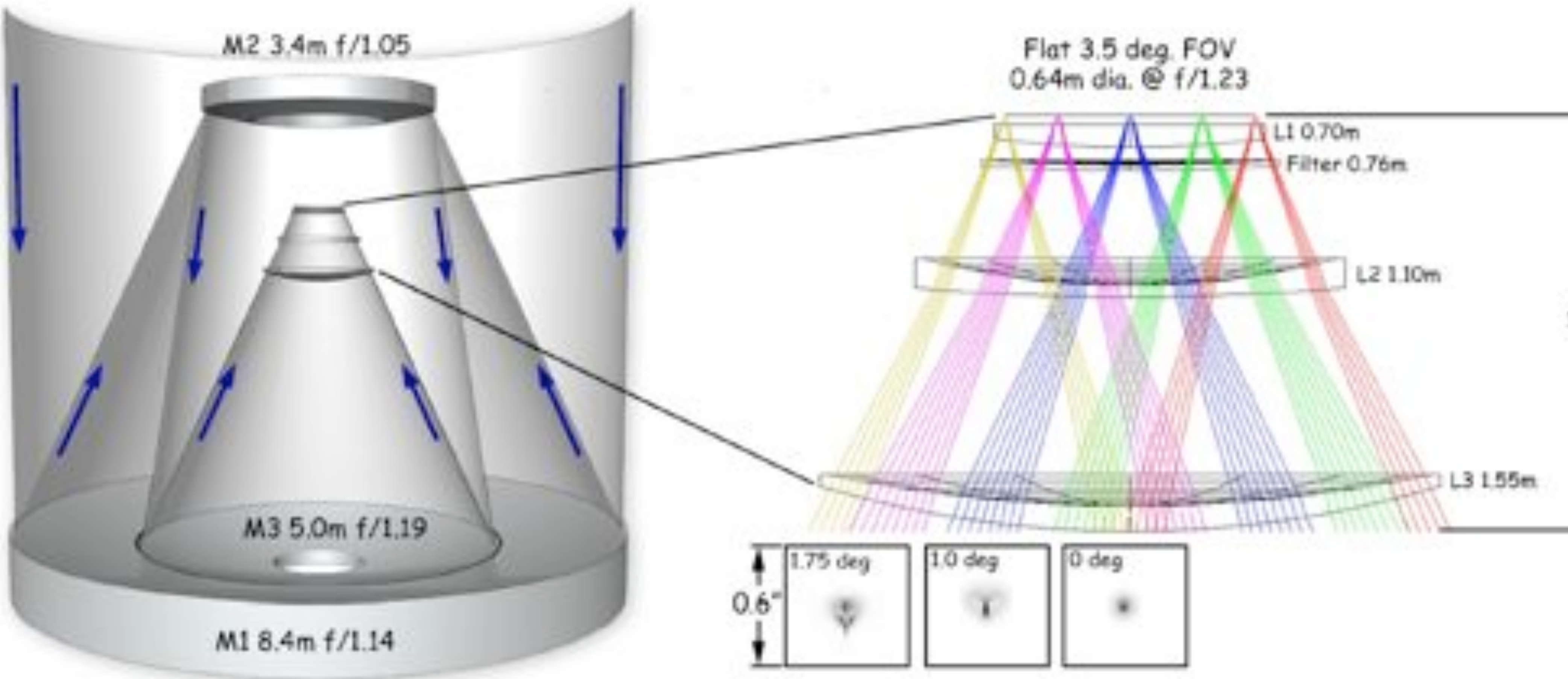


The LSST System

- **Site:** Cerro Pachon, Chile
- **Telescope:** 8.4 m (6.7m effective) diameter primary mirror, a novel three-mirror design (modified Paul-Baker) with a very fast f/1.2 beam, the field of view of 9.6 deg^2
- **Camera:** 3,200 Megapixel with 189 4kx4k science sensors
- **Data Management:** $\sim$30 TB/day, $>$100 PB over 10 years, transient alerts within 30 seconds; astrometry accurate to 10 milliarcsec relative and 50 milliarcsec absolute

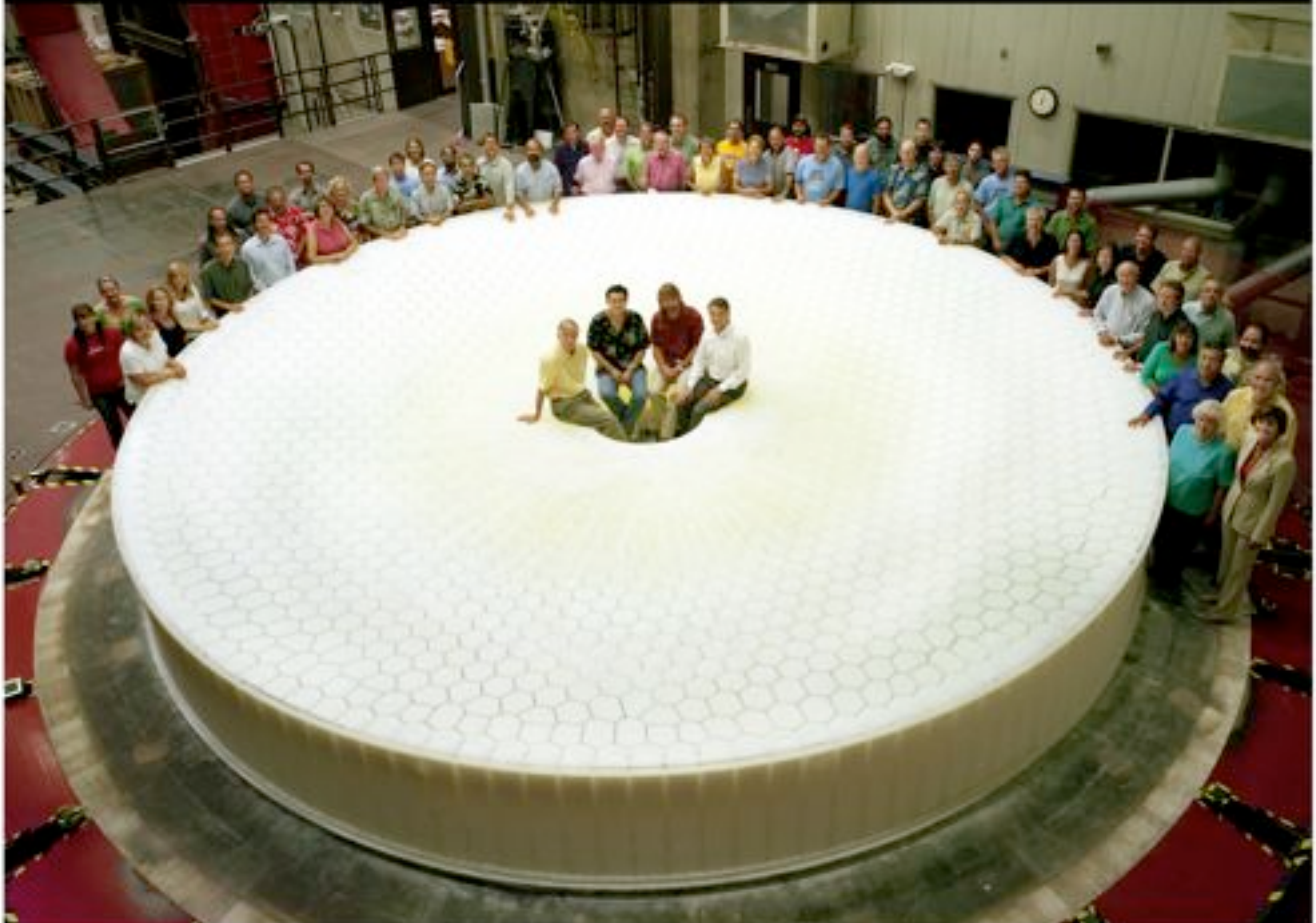
- **LSST system will reach $V =$ 24.5–25.0 in two back-to-back 15 sec exposures; repeated twice a night, every several nights, over half the sky, for 10 years!**


Primary Mirror Diameter
Field of View
Gemini South Telescope
8 m
0.2 degrees
LSST
8.4 m
3.5 degrees
(Full moon is 0.5 degrees)



The primary/tertiary mirror has already been cast, and is now undergoing polishing at the Steward Observatory Mirror Lab.

Large Synoptic Survey Telescope



LSST Primary/Tertiary Mirror Blank

August 11, 2008, Steward Observatory Mirror Lab, Tucson, Arizona

LSST Management, Timeline, and Funding

- **LSST is a collaboration** of numerous (>30) US institutions and Chile (host country), together with a few European collaborating institutions; over 200 collaborators

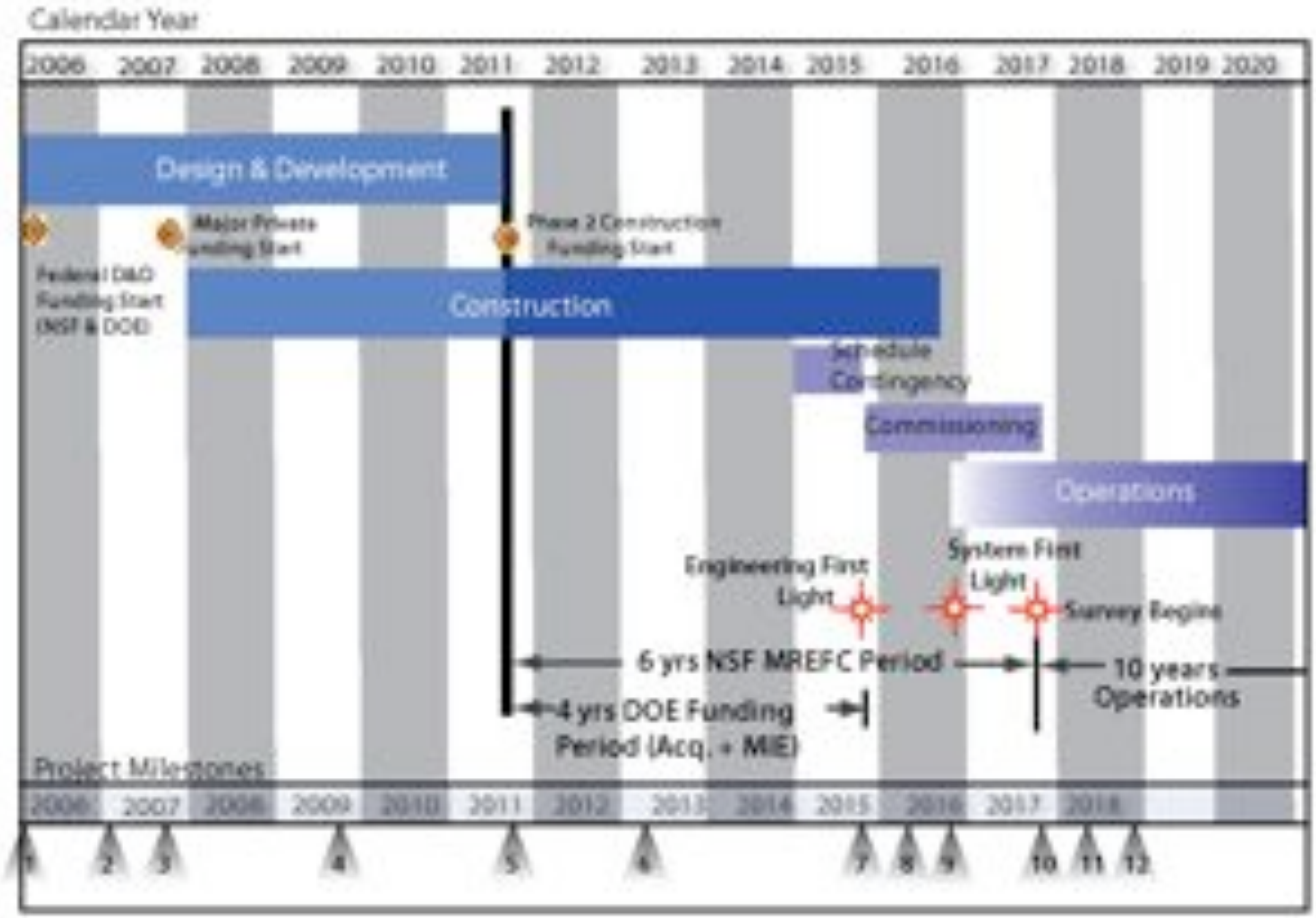
- **The Solar System Science Collaboration** includes about 30 members (chaired by Steve Chesley); one of the main duties of the LSST Performance Scientist (Lynne Jones) is to ensure successful deployment of Moving Object Processing System (developed in collaboration with Pan-STARRS)

- **Management:** solid structure mandated by numerous institutions and participants, following best business practices (Board of Directors, Project Director and Manager, Science Council and Advisory Council, Change Control Board, WBS)

- **Funding:** the construction budget is \$455M (in 2009 \$) and will come from the NSF (∼2/3) and the DOE (∼1/3), with \$50M from private and other sources. Operations budget is \$37M/year

- **Timeline:** if funding stream according to plan, construction begins in 2011 (FY2012), first light in 2015.

Proposed LSST timeline



Major Project Milestones:

1. Sep 2005 NSF D&D Funding Start
2. Feb 2007 NSF MREFC Proposal Submitted
3. Sep 2007 NSF Conceptual Design Review
4. Oct 2009 NSF Preliminary Design Review
5. Oct 2011 NSF Critical Design Review; Construction Funding Start
   DOE Critical Decision 2a Review; DOE Acquisition Funding Start
6. Apr 2013 First Camera Raft Complete
7. Aug 2017 First Engineering Light with Eng Camera
   System Integration and Test Begins
8. Mar 2016 Archive Center Complete
9. Sep 2016 System First Light with 3.2 GP Camera
   System Science Validation Begins
10. Oct 2017 Full Science Operations Begins
11. Apr 2018 First LSST Data Release
12. Oct 2018 Second LSST Data Release

LSST Science Drivers

1. **The Fate of the Universe: Dark Energy and Dark Matter** (weak lensing, supernovae, baryon accoustic oscillations, galaxy clusters with 10 billion galaxies, millions of Type Ia SNe)
2. **Taking an Inventory of the Solar System** (NEOs to a small size limit, several million main-belt asteroids, ∼100,000 TNOs and Jovian Trojans)
3. **Exploring the Unknown: Time Domain** (gamma-ray bursts, variable stars, quasars, unknown phenomena)
4. **Deciphering the Past: mapping the Milky Way** (10 billion stars, from solar neighborhood to the edge of halo)

Different science drivers lead to similar system requirements (NEOs, main-sequence stars to 100 kpc, weak lensing, SNe,...):

And also to the same observing strategy (cadence): a homogeneuos dataset will utilize 90% of observing time and serve the majority of science programs (with a high system efficiency)

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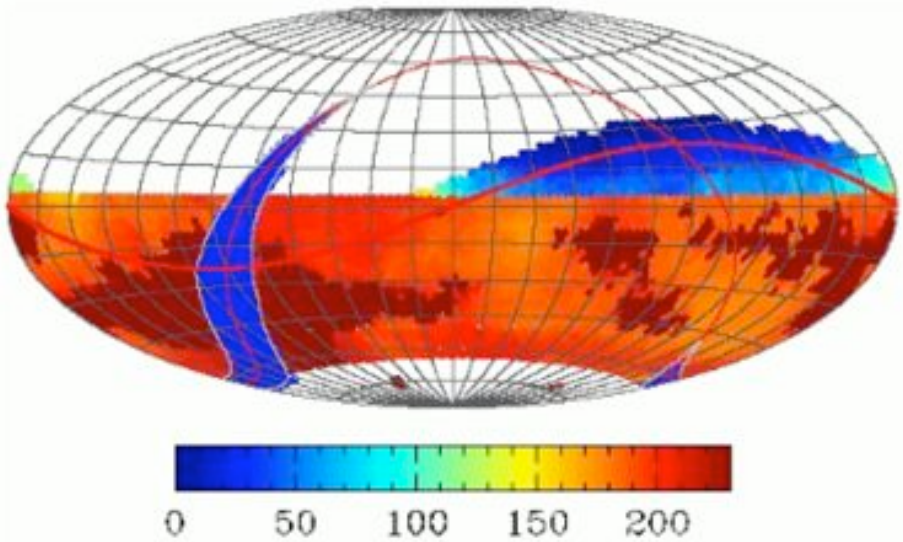
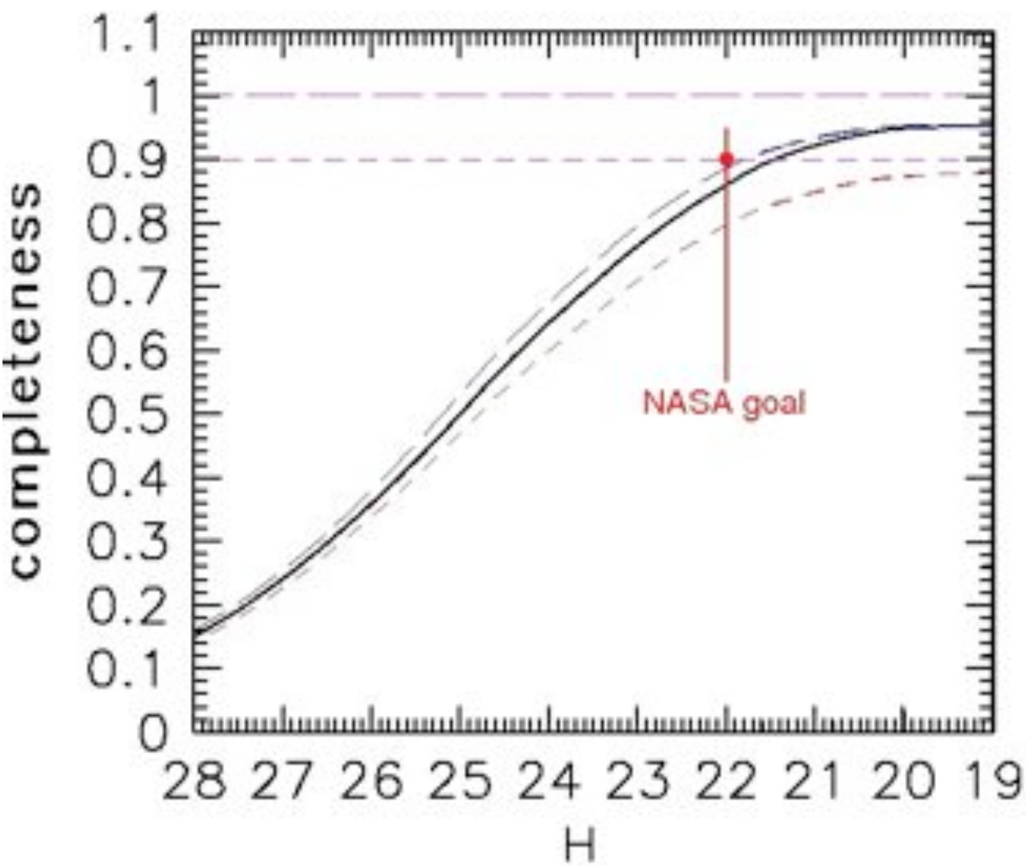
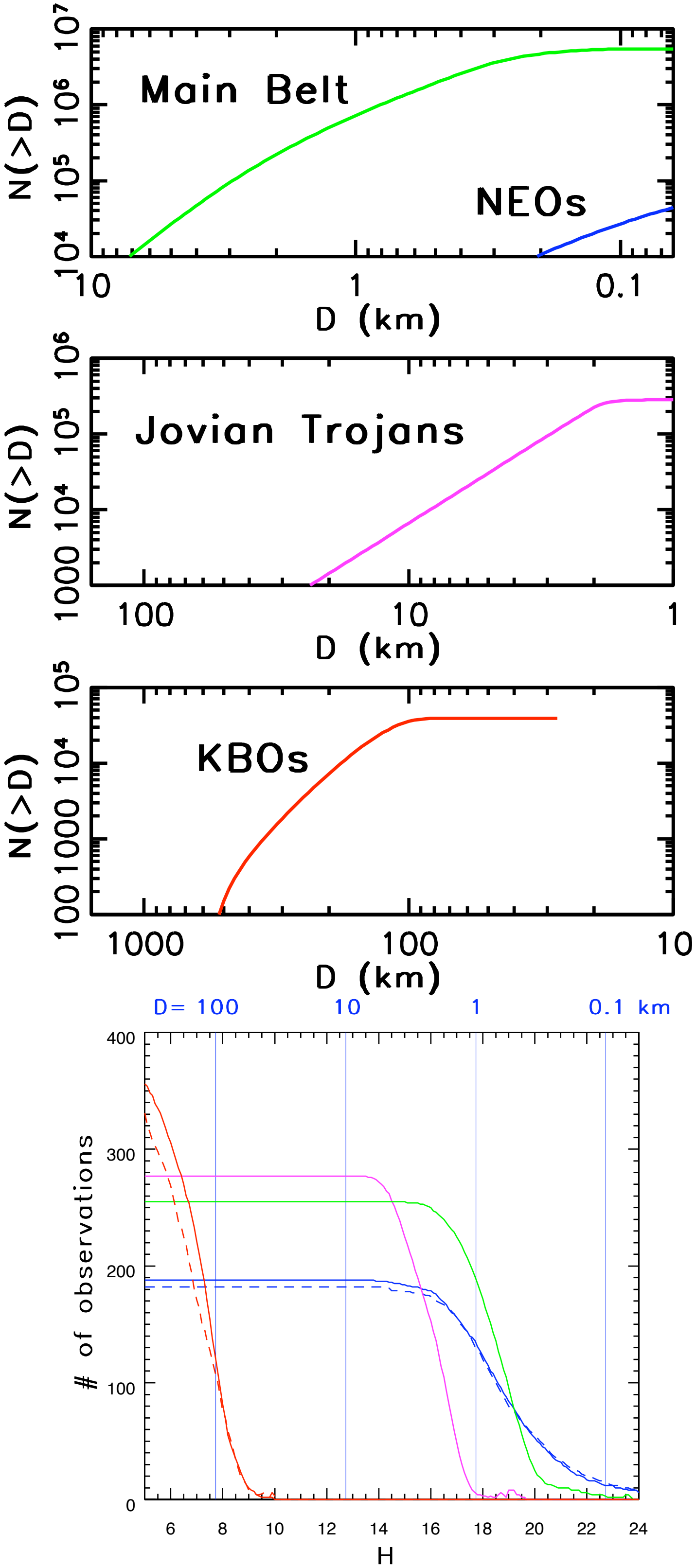




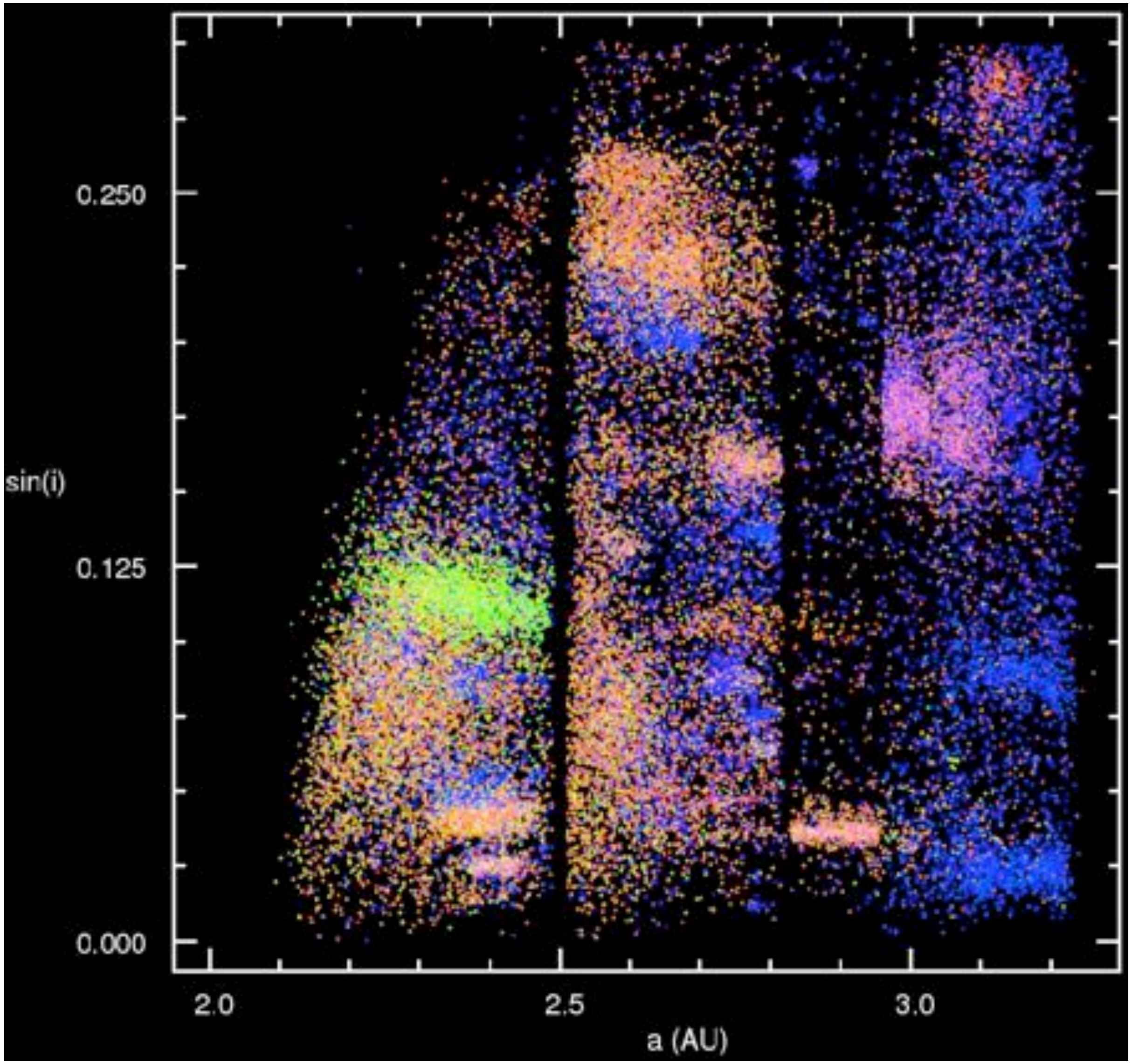
LSST Operations Simulations

- Baseline Cadence: two visits closely separated in time (15-60 min), each visit reaching $V \sim 24.8$, revisiting every few days
- Simulations: **real historical weather and seeing data, exquisite modeling of observational effects**
- Results: The LSST baseline design cadence can achieve, over 10 years, a completeness of 90% for objects larger than ∼250 m diameter, and 80% completeness for >140 m.
- PHA optimization: short-dashed: baseline cadence (10 yrs; 5% of time specialized for NEOs); solid: 15%; long-dashed: 15% of time specialized for PHAs: reaches 90% completeness (>140m) in 12 yrs.



LSST Yields of Primitive Bodies

- **Simulations** (collaboration with Pan-STARRS): 100,000 NEOs (>0.1 km); 5.5 million MBAs (>0.3 km); 300,000 Jovian Trojans (>1 km); 40,000 KBOs (>100 km); about 10,000 comets; **with well-understood selection functions**
- The majority of these objects will have multiple observations: 200-300 per object above the size completeness limit
- Time-resolved multi-epoch photometry will deliver accurate colors and six-band light curves (light curve inversion!).
- **Specialized deep observations for KBOs** (with "shift and stack" technique)
- **LSST will extend the completeness limit of current samples by factors 10-100, and deliver much more diverse and accurate data than currently available: a major impact on Solar System science!**

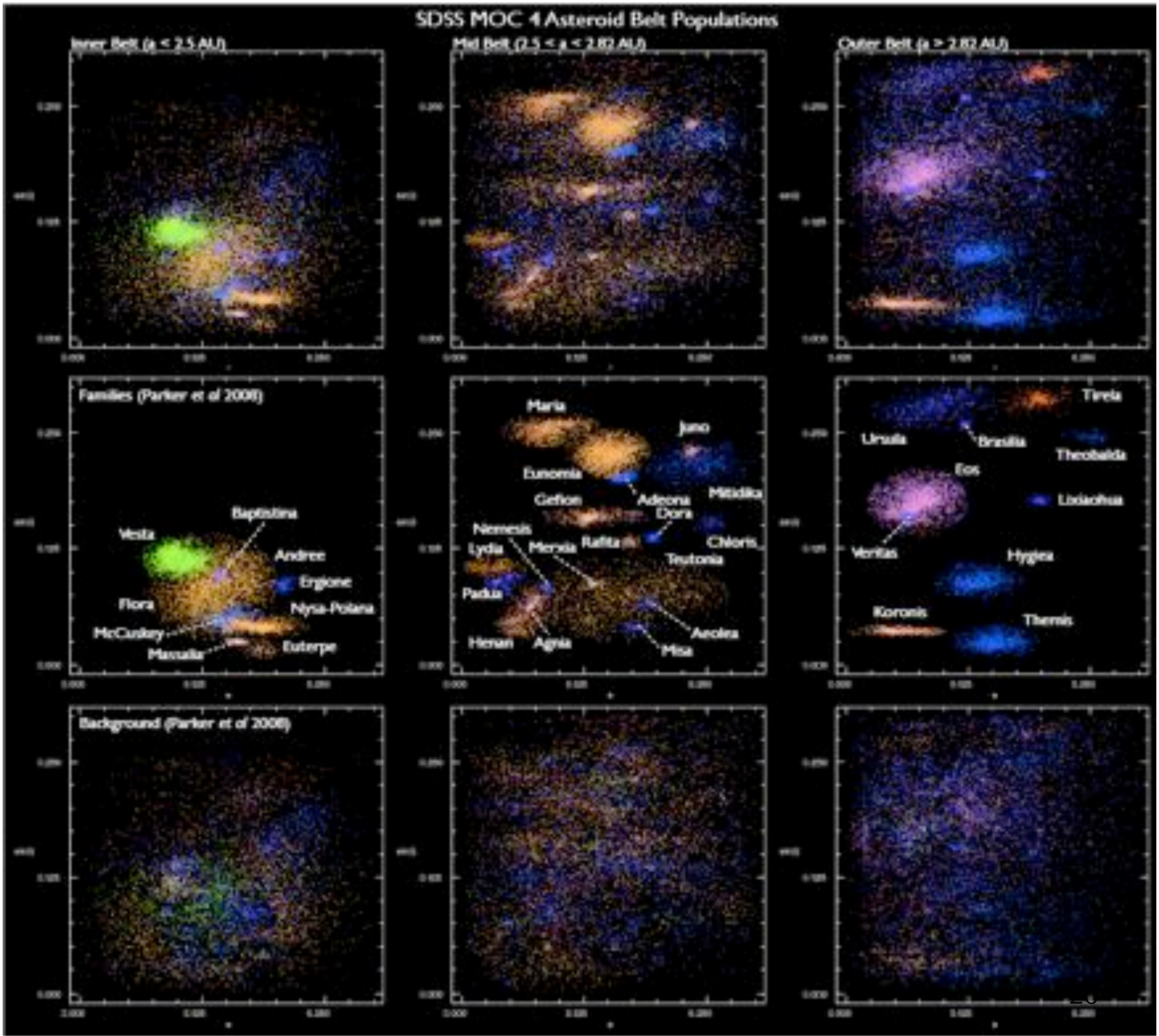


The correlation between color and albedo can be used to estimate object size to within 30%, and with gaussian error distribution.

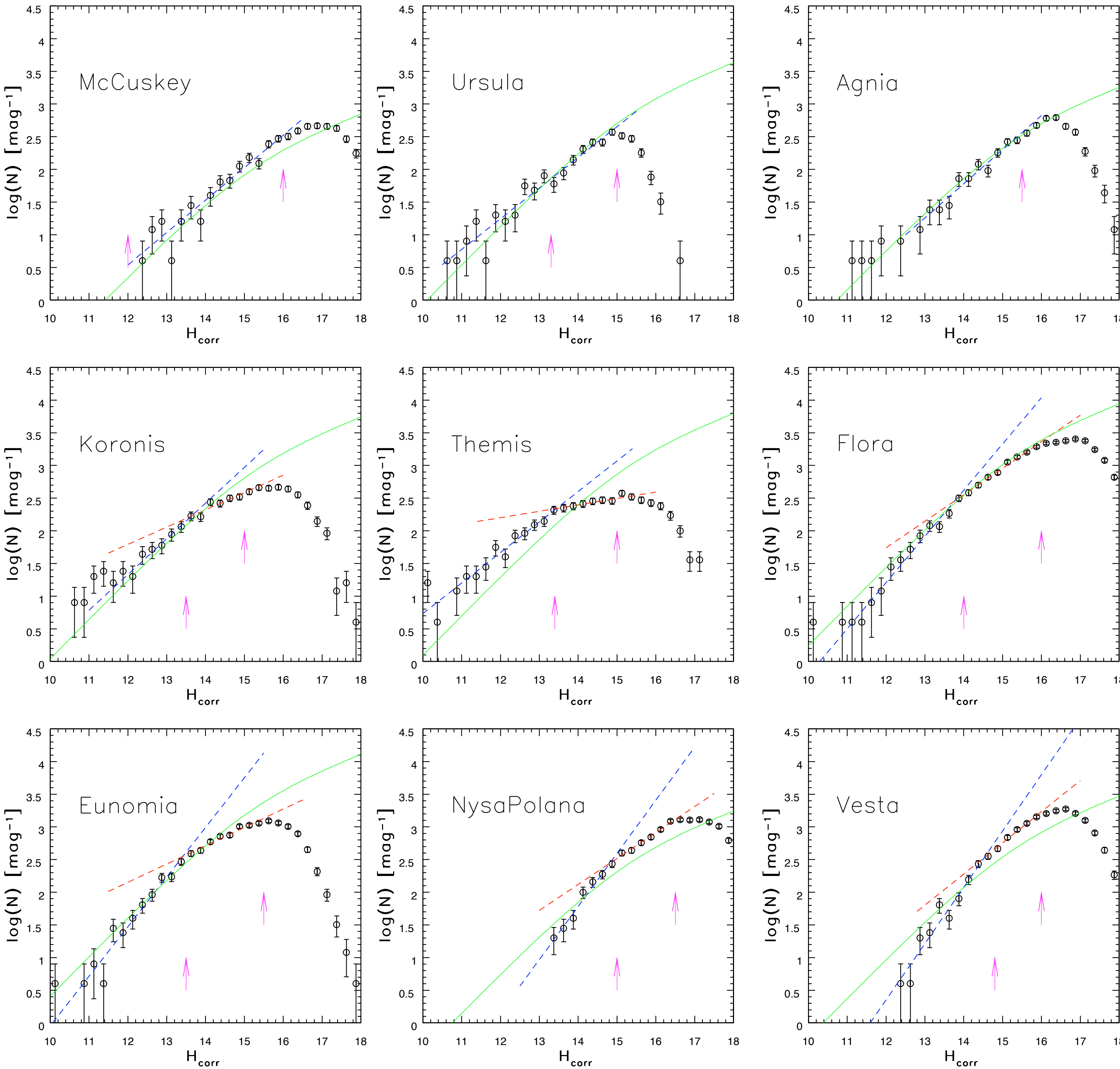
Object Characterization

- **LSST will not only obtain orbits, but will also provide valuable data on objects' physical and chemical characteristics** (e.g. correlations between colors, variability, taxonomy, age, size distribution)
- **Left:** a recent example obtained by a modern large-area multi-color survey: a correlation between orbital elements and optical colors for ∼30,000 main-belt asteroids measured by the Sloan Digital Sky Survey
- **Large Samples:** truly "typical" or "weird" objects (e.g. for NASA rendezvous missions)

Detailed population studies: Parker et al. (2008, Icarus 198, 138)



Size distributions of main-belt families: LSST will go 5 mag deeper!



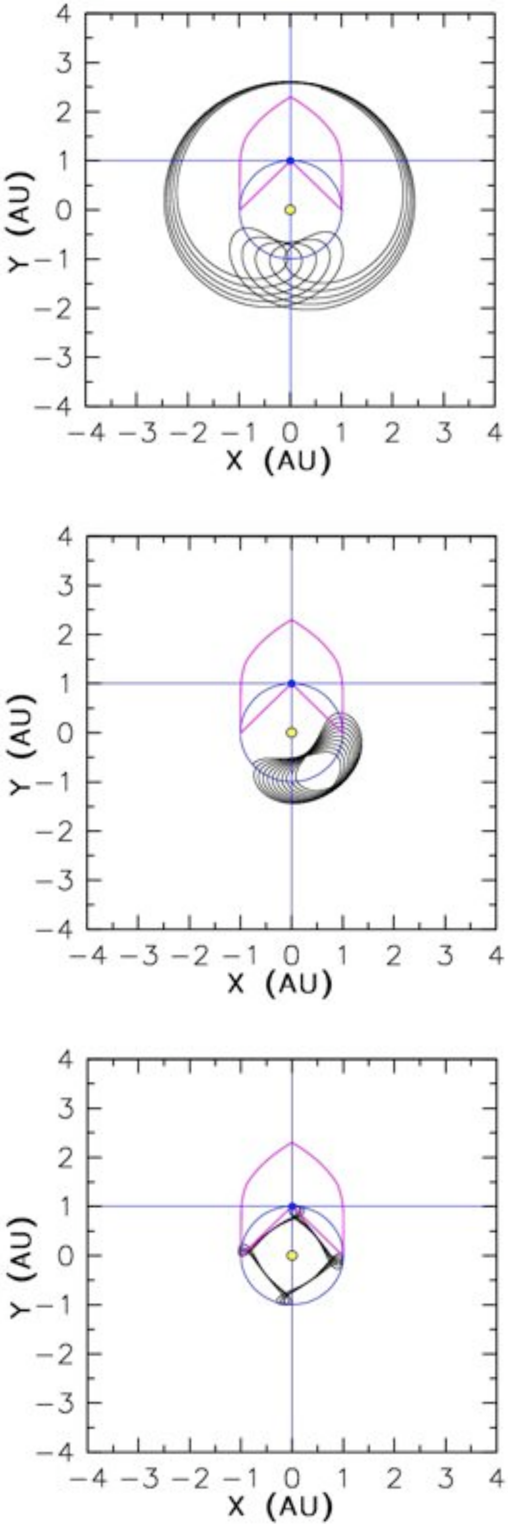
Summary

- The Congressional mandate to discover 140m objects directly and unavoidably leads to a requirement for a 10m-class telescope with a large field of view, gigapixel-class camera and a sophisticated and robust data management system: LSST can reach 90% completeness for >140m PHAs in 12 years.

- The same hardware, software and cadence requirements are driven by science unrelated to Solar System objects: **one dataset fits all!** (no need to fight with TAC for solar system observations; uniform calibrations)

- **LSST will have a major impact on the studies of Solar System objects: NEOs, main-belt asteroids, Trojans, KBOs, comets**

- LSST is already well underway and is nearing construction readiness – **but your support will be invaluable!**



Survey Optimization

- A large number of simulations confirms expectations: to achieve a high completeness must have two visits per night, need to revisit large area fairly often (a few days), and need to go deep ($V \sim 24.5$)
- **Left: examples of undiscovered objects** in a rotating heliocentric coordinate system (blue dot: Earth; yellow dot: Sun); the cross section of the ecliptic plane and the LSST NEO detectability volume for a 140m object is shown by the magenta line.
- Analysis of Undiscovered Objects: need to have a long survey, and need to, at least sometimes, observe at small solar elongation angles (i.e. large airmass).
- **LSST NEO survey optimization is a work in progress, but existing simulations already represent a robust proof of concept, and a detailed demonstration of its capability.**