1998 → 2016

A Guided 'Tour' Through the LSST Science Book

Salman Habib

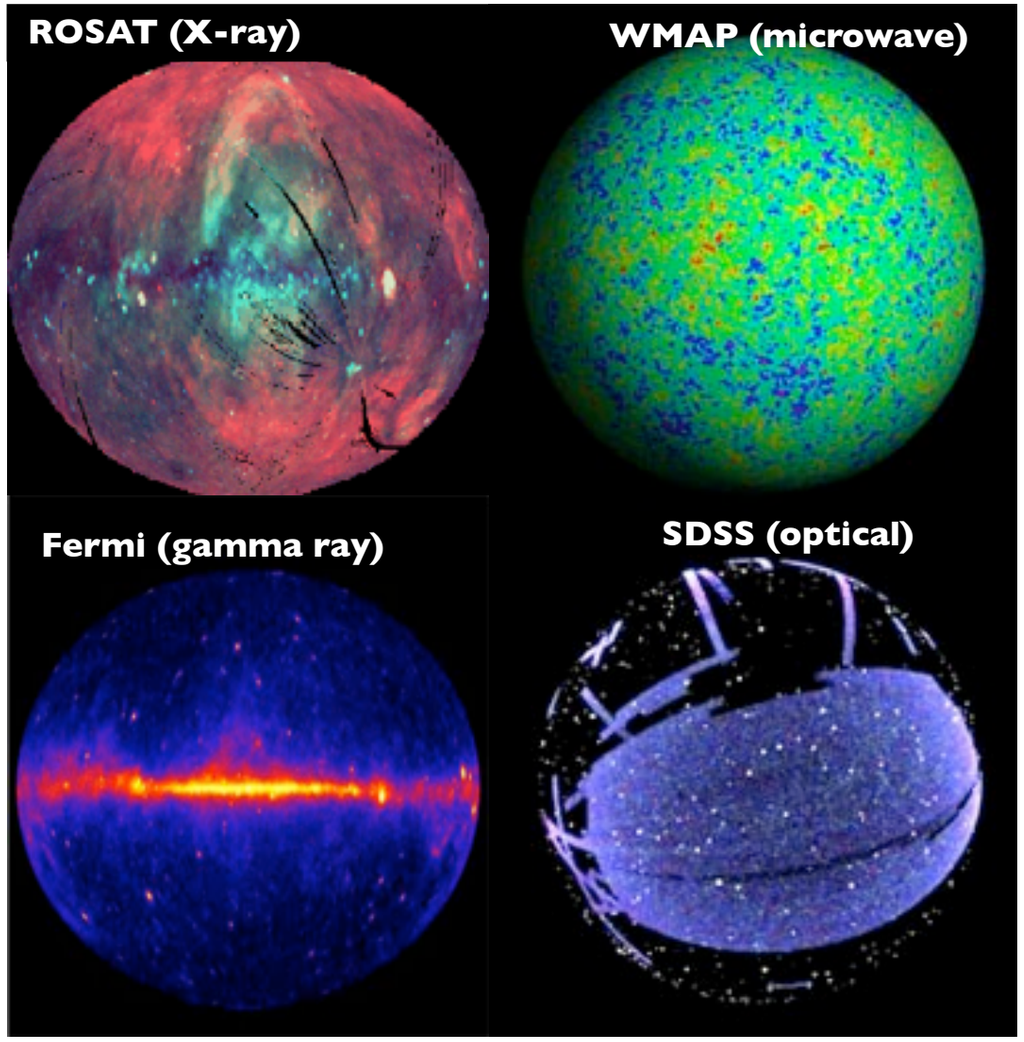
ANL Astro Seminar, November 3, 2011

SDSS, First Light in 1998

Visualization: Pat McCormick, CCS-7, LANL

Deep Lens Survey/LSST

Mapping the Sky --



The Sky Map

1. Detected Objects: Galaxies, stars, comets, --
2. Object Measurements: Colors, distance, brightness, shape, size, --

Uses of Sky Maps

1. Object Classification: What is it? (star, galaxy, comet, asteroid, --)
2. Statistical Analysis: How many specific objects, how are they distributed?
3. Discovery: New objects/phenomena

History of Sky Maps

Hipparchos: catalogs ~850 fixed stars in 129BC, key source for astronomical observations for ~2000 years!

Tycho Brahe: 16th century -- significant improvements in accuracy, Kepler's laws of motion (no telescope! but better instruments and mathematics)

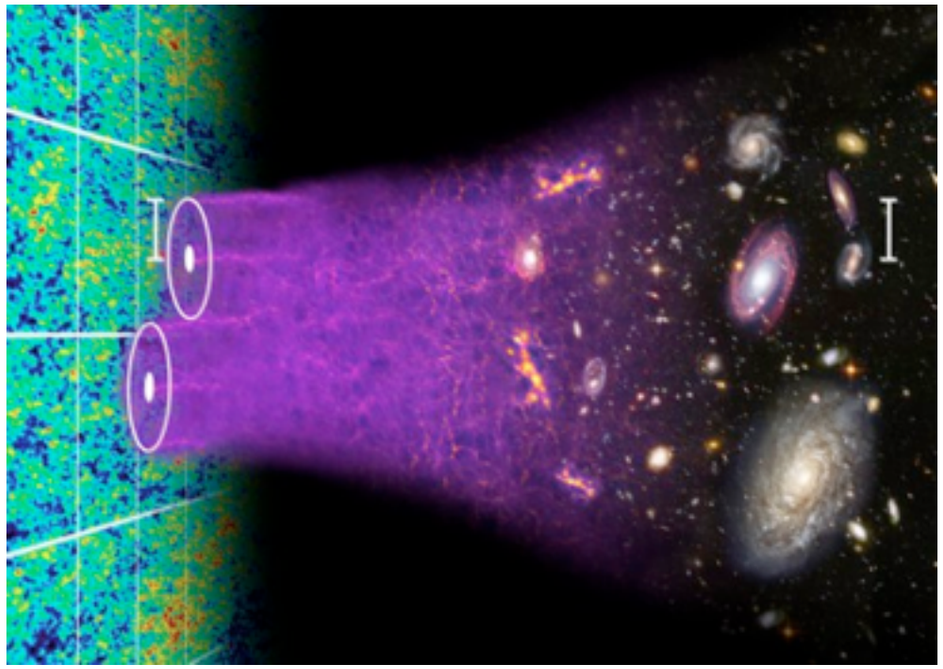
Palomar Sky Survey: 1950's, 48 inch Schmidt (4 sq. deg. FOV) at Palomar Observatory (now doing PTF), photographic plates -- roughly billion objects

Digital Surveys (Optical): 2dF, Sloan Digital Sky Survey, etc. (factor of ten more accurate than POSS, 200 million stars/200 million galaxies, spectra for a million galaxies, ~30TB of data) late '90s -- physics and astronomy come closer together, space and ground-based missions

Whats' New --

SDSS-III/BOSS

1. 2009-2014: Baryon Acoustic Oscillations on 1000 fiber spectrograph on APO 2.5m
2. Statistics: 10,000 sq. degs., 1.5 million redshifts to z~0.7, 160,000 quasar Ly-alpha forest spectra



BAO with BOSS

DES

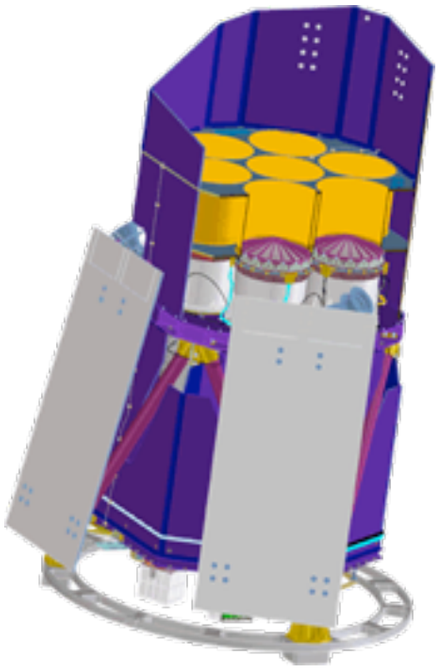
1. 2012-2017: Imaging survey with DECam (570 Megapixels) on the Blanco 4m at CTIO (Sn, BAO, Weak Lensing, Clusters)
2. Statistics: 300 million galaxies, 3000 supernovae

eROSITA

1. 2013(?)-20XX: All-sky cluster survey from space, medium energy X-ray to 10 keV
2. Statistics: 100,000 galaxy clusters

Euclid

1. 2019(?)-2025: Weak lensing and BAO from space, 1.2m telescope, 0.2 arcsec resolution
2. Statistics: More than a billion galaxies to z>2



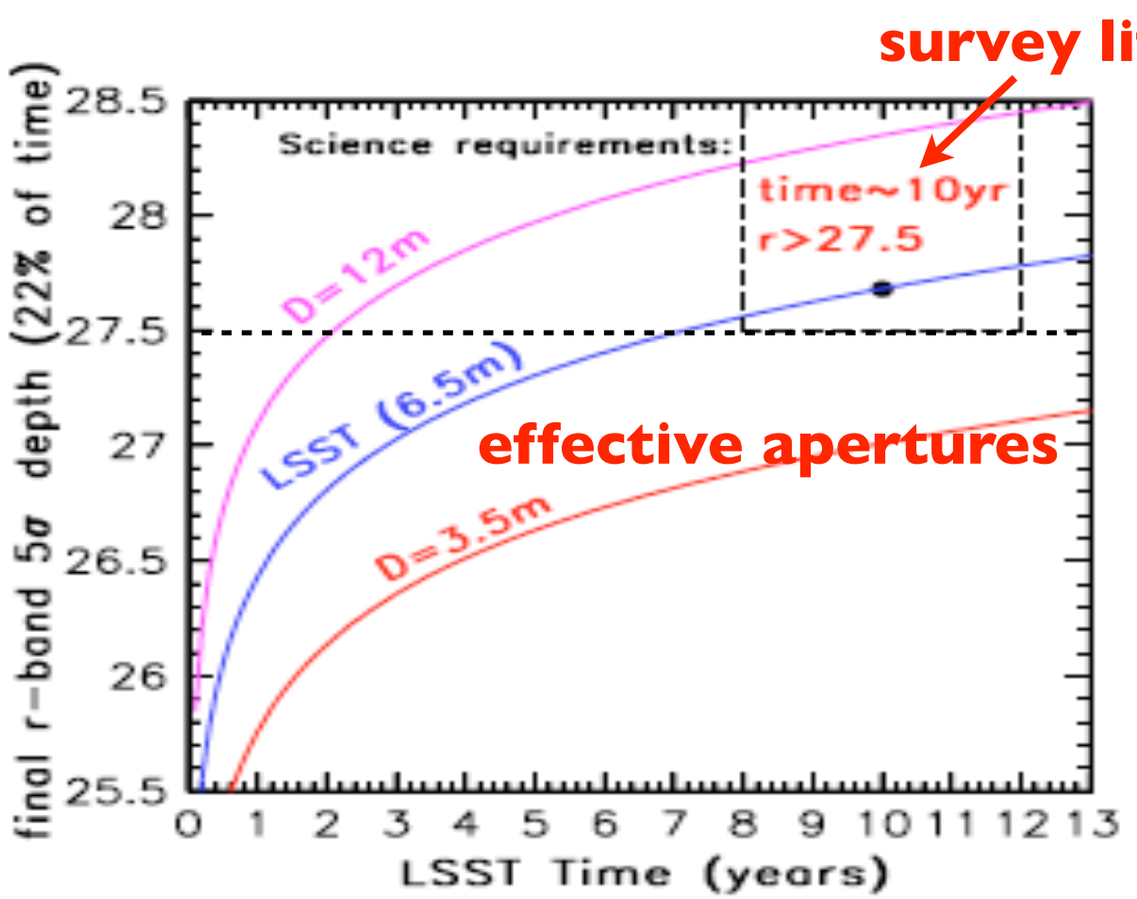
eROSITA

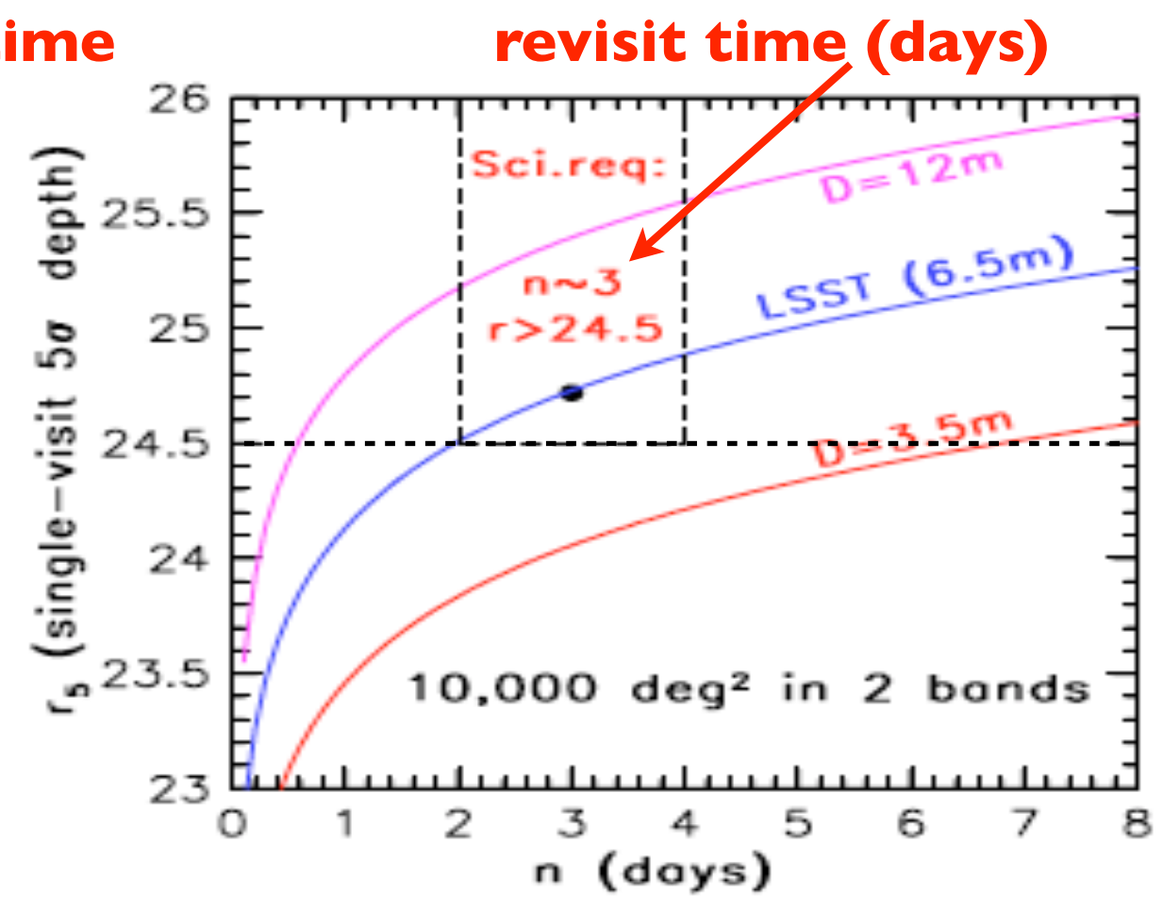
LSST Survey Requirements: 'One Size Fits All'

- LSST is part of a new direction in 'Big Science' as astro/physics communities come together (example: cosmology as a probe of fundamental physics)
- Community-led development of main LSST themes:
  [1] Inventory of the Solar System (SB Ch. V)
  [2] Mapping the Milky Way (SB Chs. VI & VII)
  [3] The Transient/Variable Optical Sky (SB Ch. VIII)
  [4] Galaxy Evolution (SB Chs. IX & X)
  [5] Cosmology, Dark Energy and Dark Matter (Chs. XI - XV)
- Key role of statistical precision, billions of objects, will lead to world's largest non-proprietary database (~200 PB)
- Many exposures in multiple bands to control systematics
- History: mid-late 90's various preliminary ideas and new CCD cameras pioneered by Tony Tyson (e.g., BTC) leading to Roger Angel's 3-mirror design (DMT for solar system plus weak lensing), 2000 Decadal Review names LSST, 2002 LSST Corporation founded, 2008 mirrors cast, 2010 Decadal Review ranks LSST #1, --
- Single telescope enables wide, fast, deep survey

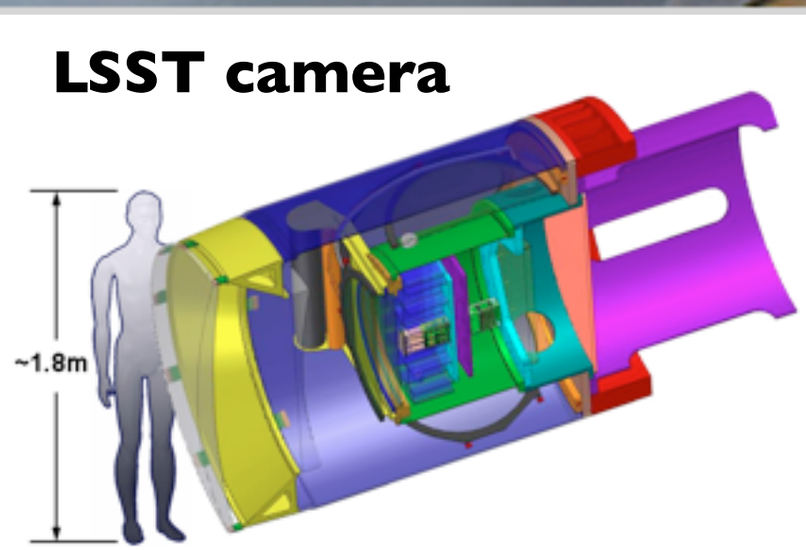
LSST Science Requirements

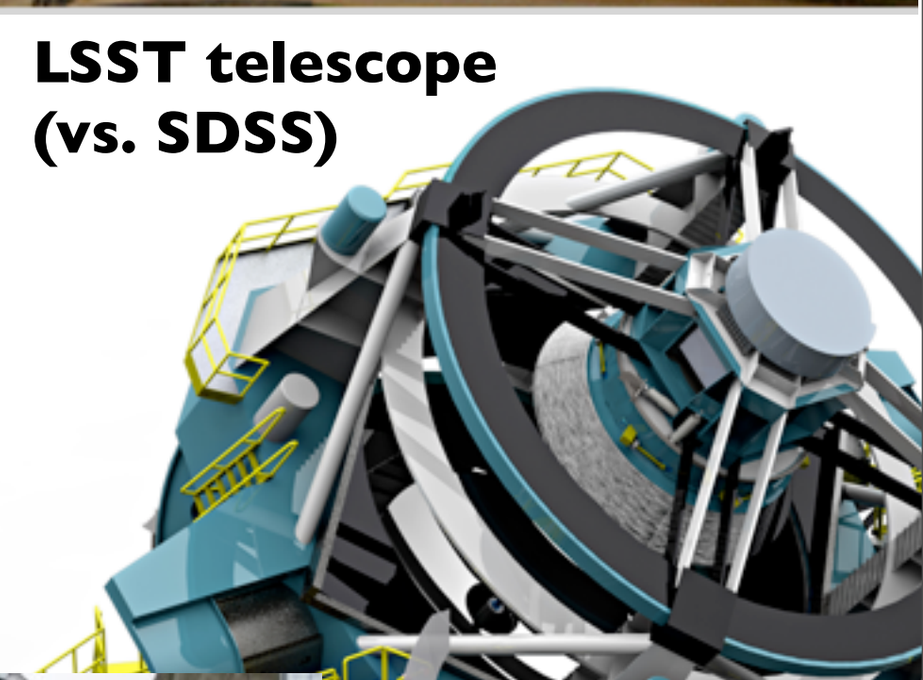
- **Single visit depth** r~24.5 (fast asteroids, transients, stars, weak lensing, --)
- **Photometric repeatability** ~0.005 mag (photo-z, stellar population separation, --)
- **Single visit exposure time** <1min (prevent trailing, control atmosphere, --)
- **Filters**, six from 320-1050 nm (photo-z, stellar typing, obscuration, --)
- **Revisit time distribution** (solar system orbits, SN light curves, --)
- **Total number of visits to one area** ~1000 (weak lensing, asteroids, stars, --)
- **Coadded survey depth** r~27.5 (weak lensing, --)
- **Visit distribution per filter**, r/i preferred (photo-z, stellar populations, --)
- **Distribution of visits on the sky** ~20,000 sq. degs. (weak lensing, LSS, --)
- **Data systems** should enable efficient scientific analysis

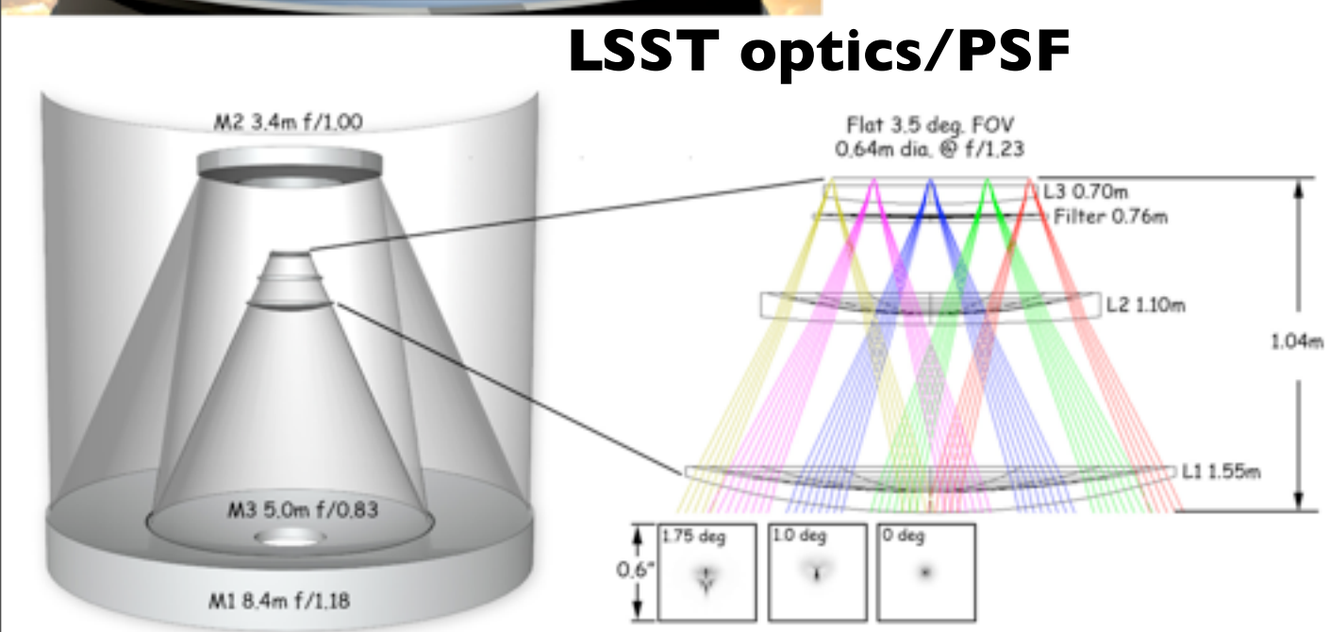


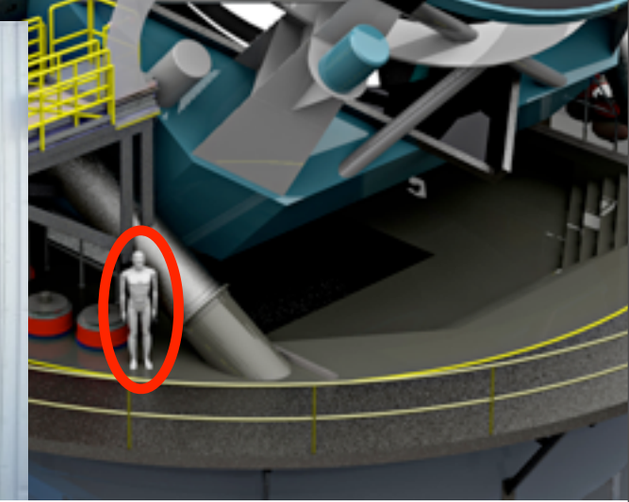


An Informal View of LSST

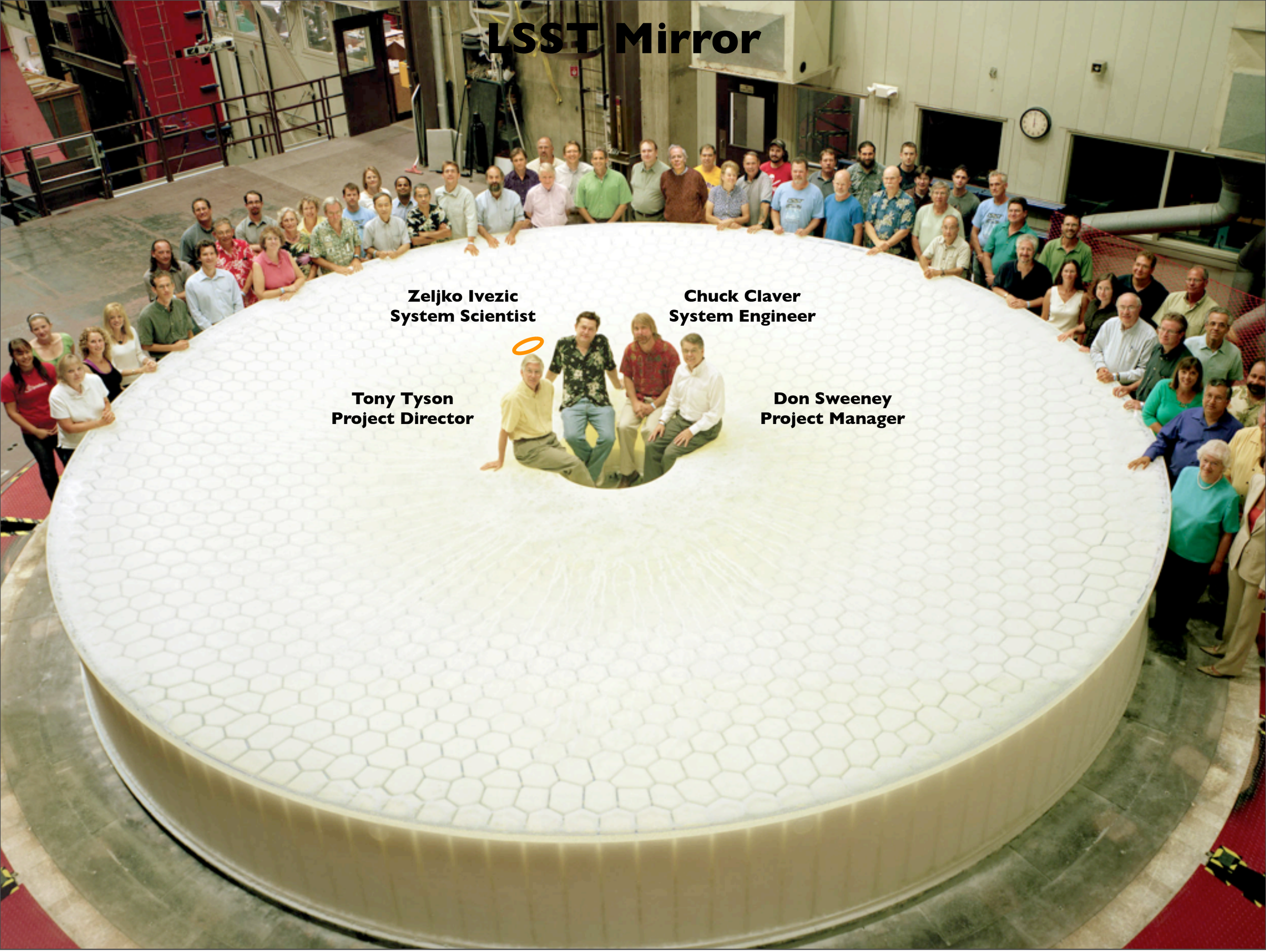








LSST Mirror

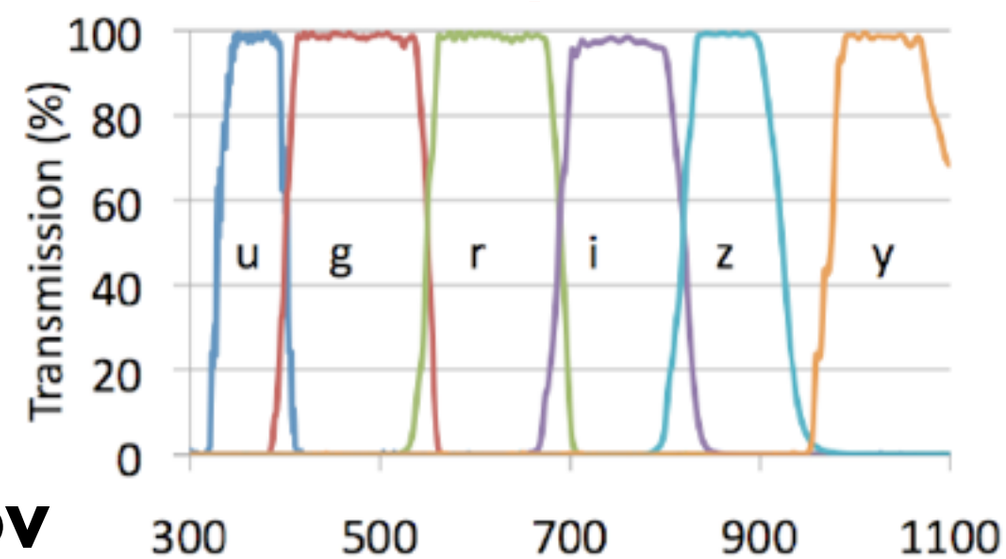

Zeljko Ivezic
System Scientist
Chuck Claver
System Engineer
Tony Tyson
Project Director
Don Sweeney
Project Manager

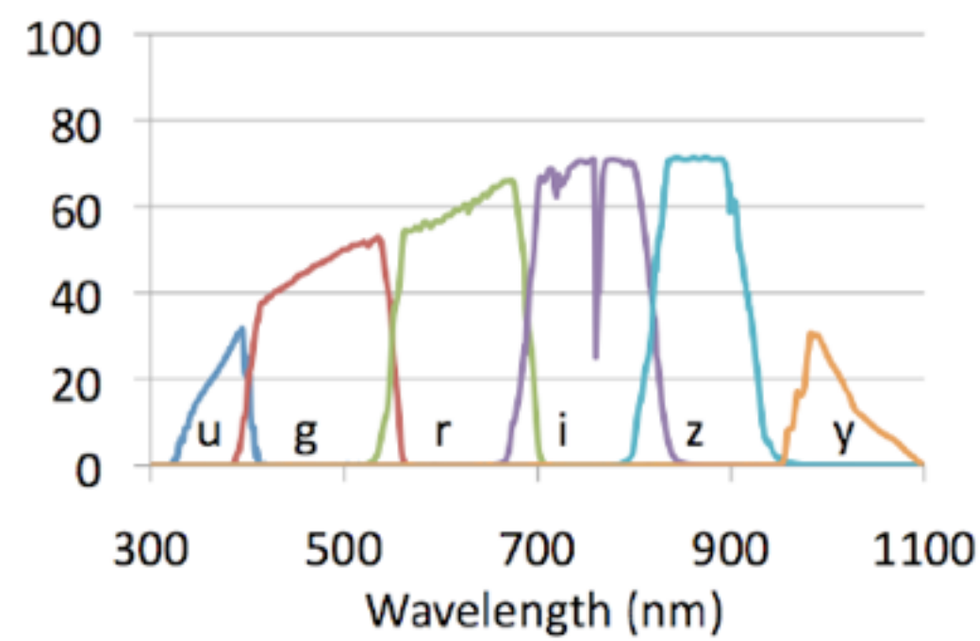
Blasting the Mountain

LSST by the Numbers

- Effective aperture, on-axis, 6.7 m (physical diameter, 8.4 m), area, 35 sq. m
- Field of View, 9.6 sq. deg. (3.5 deg diameter)
- Entendue, 319 sq. m sq. deg. (prim. area X FOV)
- wavelength coverage, 320-1080 nm
- Filters, u,g,r,i,z,y, 5 at a time
- Visits, u:70, g:100, r:230, i:230, z:200,y:200
- Sky coverage, 20000 sq. deg.
- Focal length, 10.3 m
- f/ratio, f/1.23 (needed for good FOV)
- Geometric scale distortion, <0.1% over FOV
- Pixel size, 10 micron (0.2 arcsec)
- Camera pixel count, 3.2 Gpixels
- Focal plane flatness, <10 micron
- Photometric calibration goal, 1%
- Readout time, 2 sec
- Raw pixel data/night, 15 TB
- Final dataset, 200 PB
- Construction cost, $500M
- Operations, $40M/yr

raw filter performance



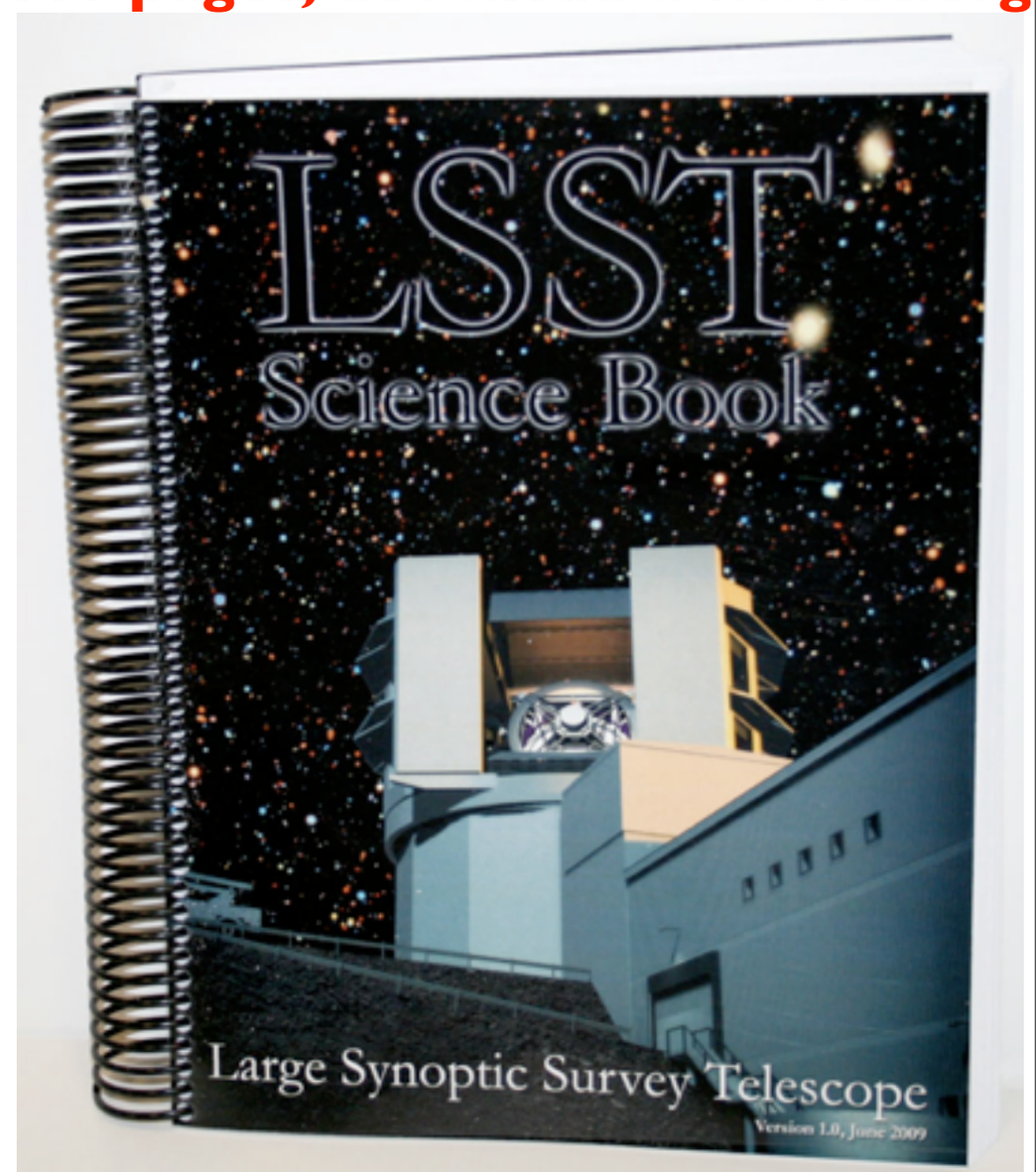


actual throughput

The LSST Collaboration and Science Book

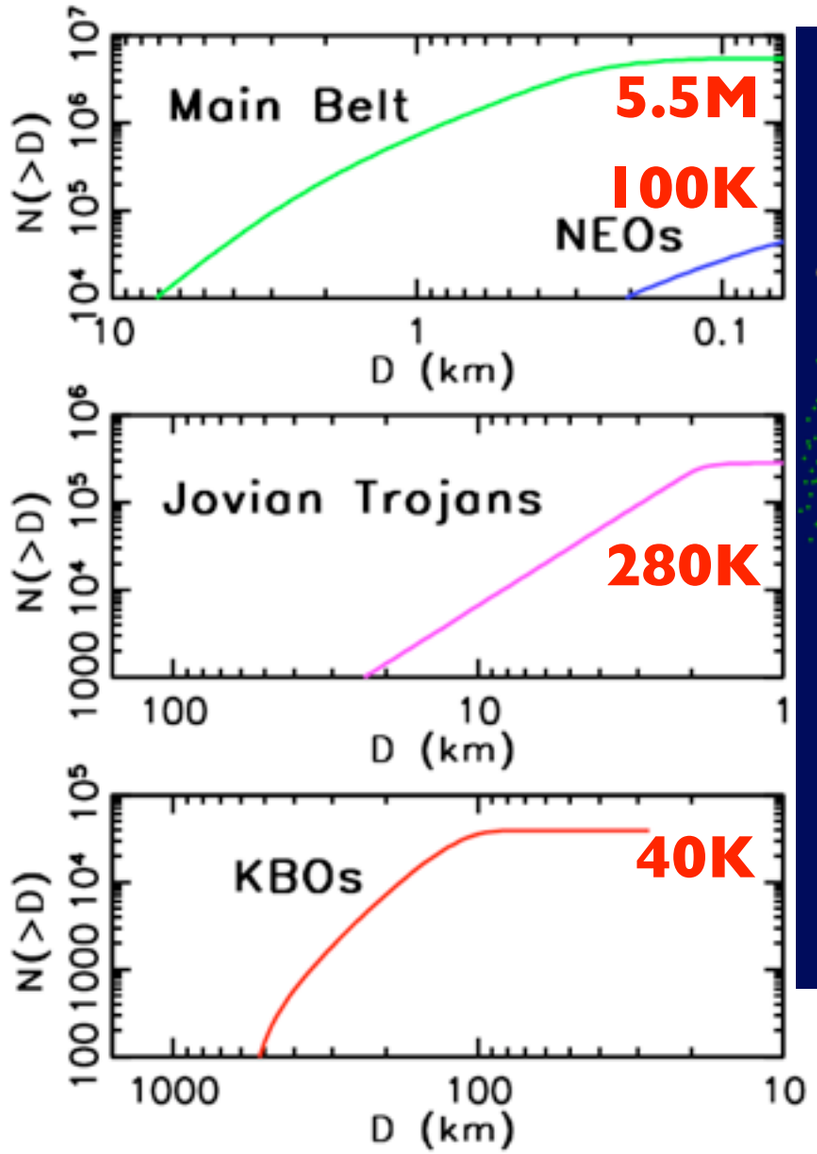
- **Private/public (NSF/DOE) partnership**
- **Project Director: Tony Tyson**
- **Deputy Director: Steve Kahn**
- **Science Groups Chair: Michael Strauss**
- **LSST Science Collaborations: Active Galactic Nuclei, Galaxies, Informatics & Statistics, Large-Scale Structure/ Baryon Oscillations, Milky Way and Local Volume Structure, Solar System, Stellar Populations, Strong Lensing, Supernovae, Transients/Variable Stars, Weak Lensing**
- **Member Institutions: Adler Planetarium, BNL, Caltech, CMU, Chile, Cornell, Drexel, GMU, Google, CfA, IN2P3, JHU, KIPAC, Las Cumbres, LANL, LLNL, Michigan, NOAO, Pitt, Princeton, Purdue, Research Corp., Rutgers, SLAC, STScI, Texas A&M, Penn State, UoA, UC Davis, UC Irvine, UIUC, UPenn, Washington, Vanderbilt**
- **Science Book 2.0: 245 authors, LSST overview, living document**

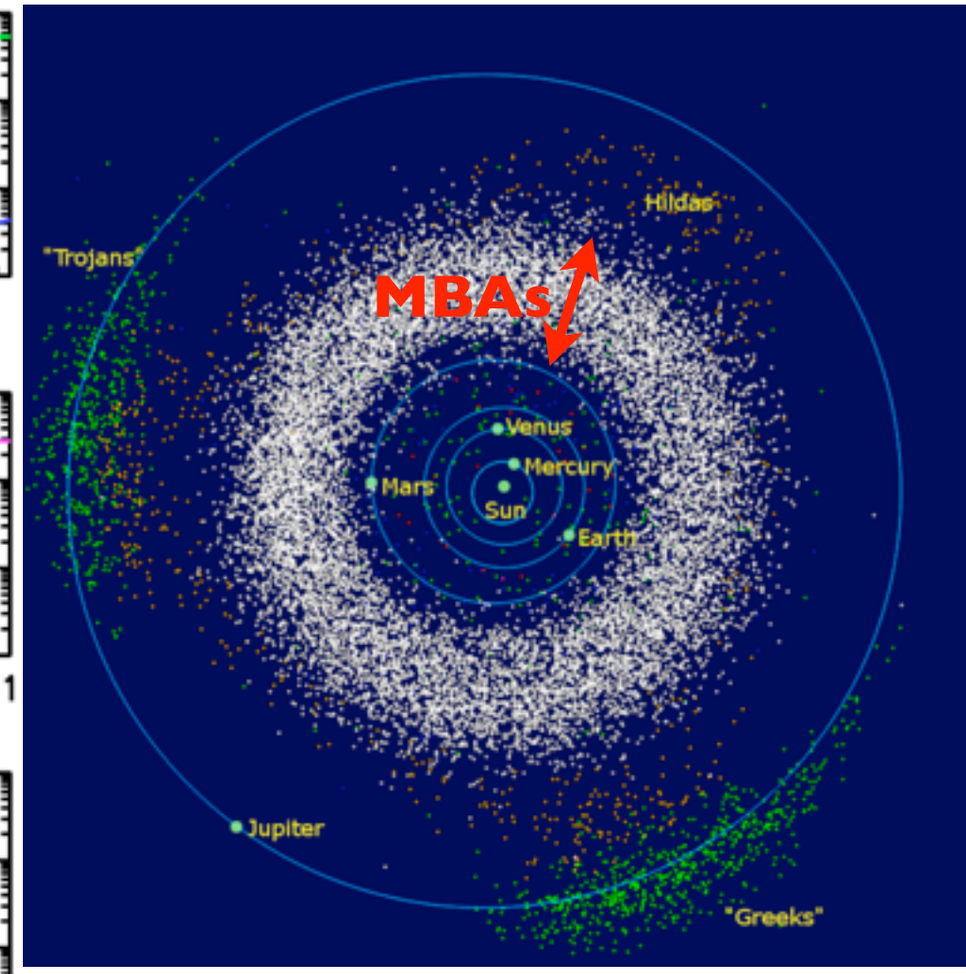
600 pages, download from lsst.org



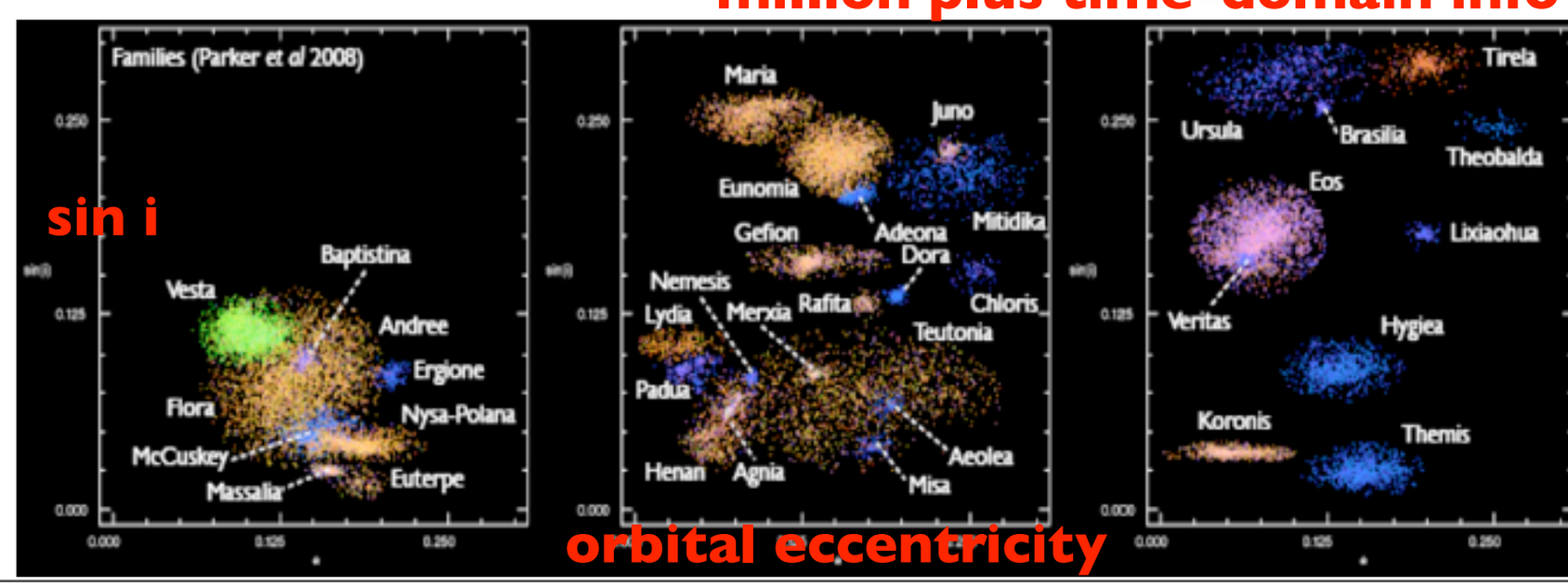
The Solar System: "Small Bodies"

- 90% of Near Earth Asteroids (NEAs) down to sizes of ~150 m
- Census of Main Belt Asteroids (MBAs) along with size distribution (will find 5.5 million)
- Orbital distribution of small bodies probes dynamical history of giant planets (migration), LSST's Trans-Neptunian Objects (TNOs, ~40K) particularly suited for this (since only <2000 known currently)
- Color (not simultaneous) information helps to tag asteroid families
- Time variability information from LSST photometry useful as probe of rotation, shape, composition, --



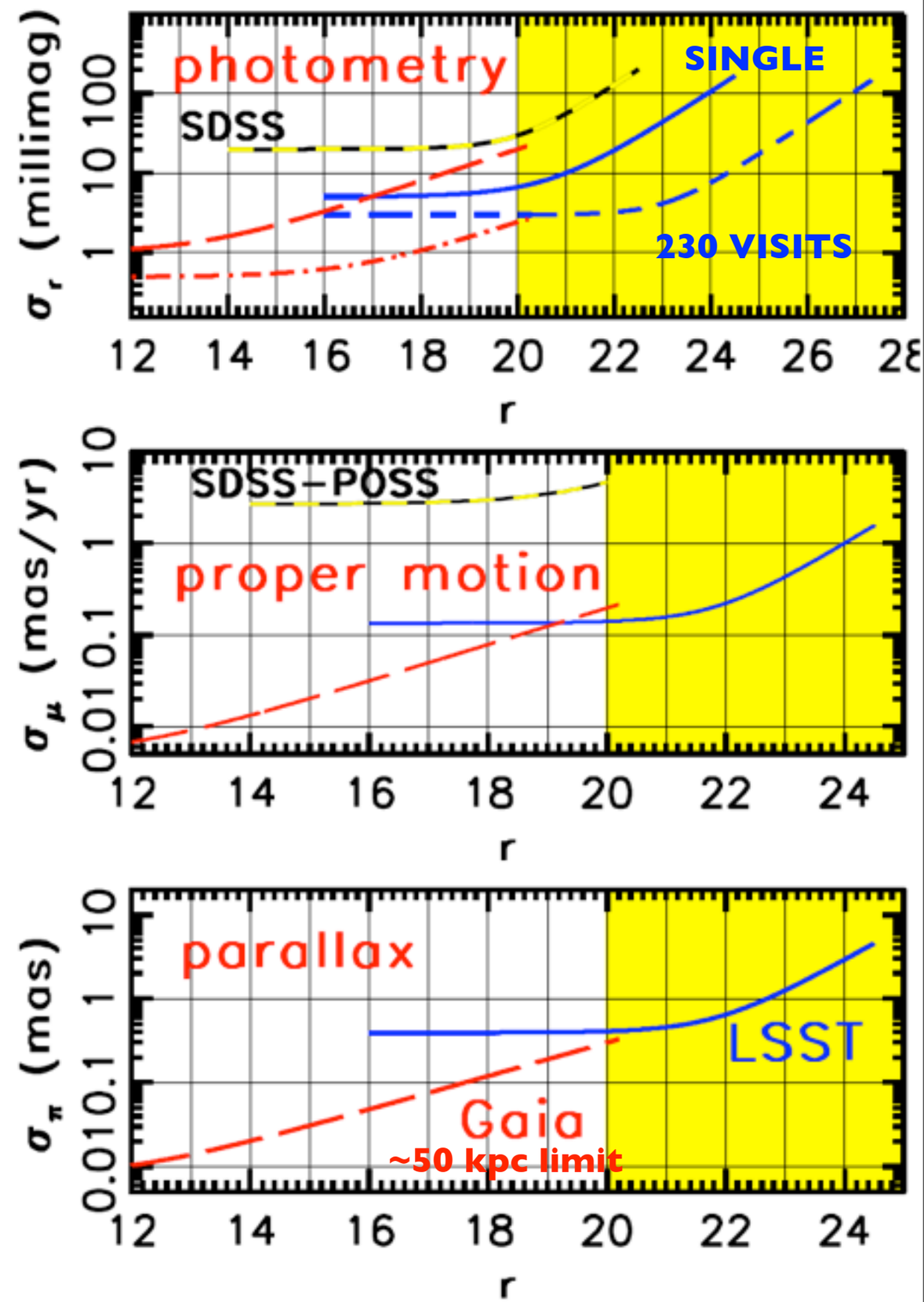


SDSS: 88000 objects; several million plus time-domain info



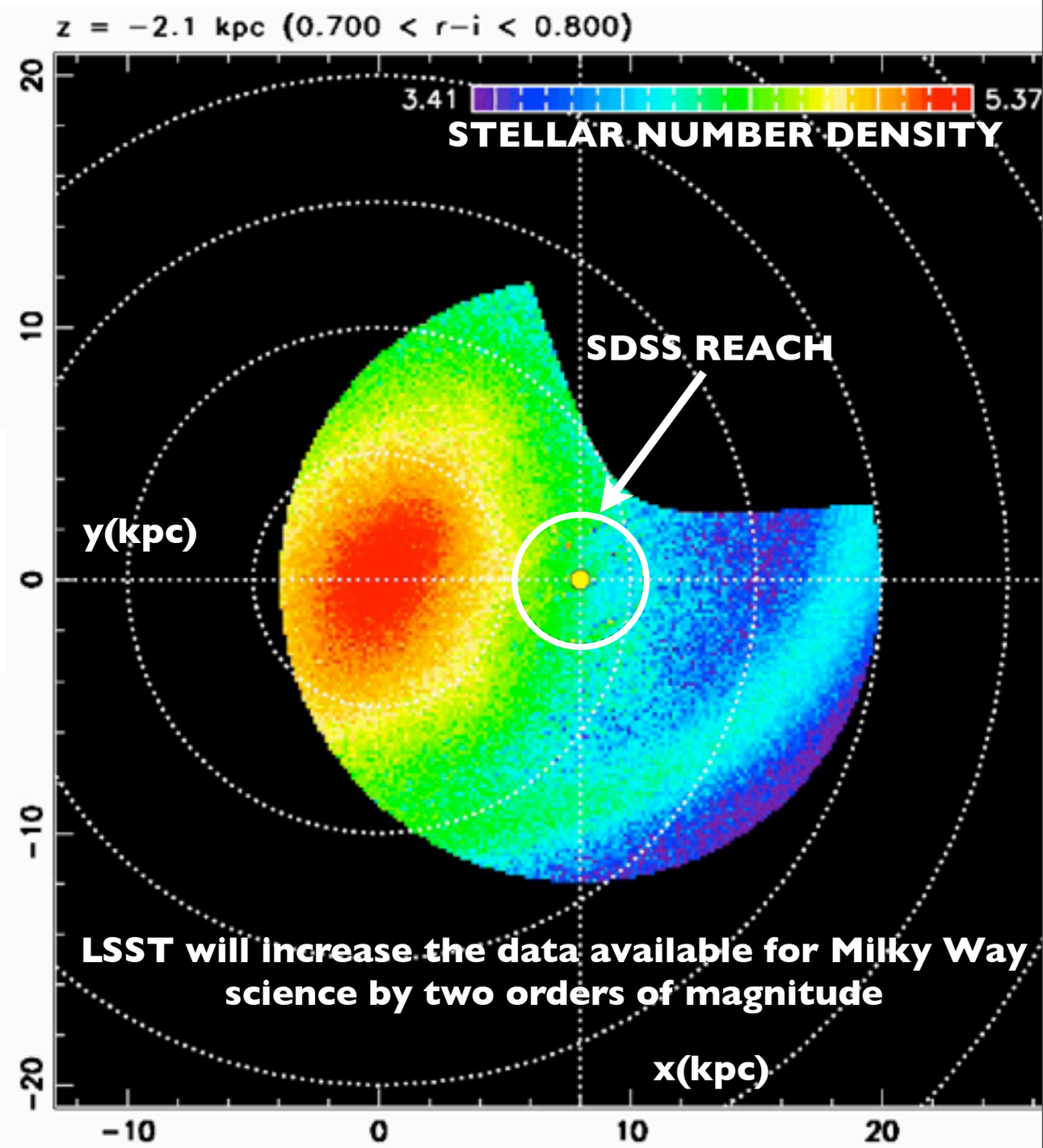
Stellar Populations: Milky Way and Nearby Galaxies

- Smooth extension of Gaia capability (Gaia launch in 2012/13), get billions of stars
- ~6M Eclipsing Binaries (EBs) with ~1.6M at S/N>10, short-period EBs complete to r~22, 80K EBs in LMC/SMC
- SDSS improved White Dwarf sample by a factor of 10, to >10000 (disk only), LSST will get ~400K halo WDs to r<24.5
- VLM Stars and Brown Dwarfs, will get ~40K BDs out to 200 pc (vs. 750 known), >350K M dwarfs
- Photometric search for metal-poor stars will reach ~100 kpc (via SDSS approach)
- Stellar astrophysics in the LMC & SMC, 100K new RR Lyraes, search for stars in the Magellanic Stream
- In nearby galaxies, brightest RGB stars visible to LSST out to ~10 Mpc, crowding limits this to ~4 Mpc
- Distance ladder improvements via study of Cepheid systematics, investigate LPVs as robust distance indicators (since HST search for Cepheids limited to ~40 Mpc), aim to improve H_0 to better than 3%



Milky Way and Local Volume Structure

- Mapping ~10 billion main sequence stars to 100 kpc over 20000 sq. degs.
- Metallicity indicators for ~200 M stars
- More luminous tracers (e.g., RR Lyrae) to 400 kpc, the virial radius, 3-D velocities enable new mass measurements of the dark halo
- Complexity of Milky Way disk as a test of theories of galaxy formation
- M dwarfs to ~30 kpc, with parallaxes to ~300 pc (vs. Gaia ~10 pc), ~7 billion stars
- 3-D dust map of the Milky Way using M dwarf photometry (to ~15 kpc)
- Debris streams, ~100 out to 50 kpc, and ~100 beyond (vs. 11 known)
- Correlate Local Group dwarf galaxy orbits with star formation history
- Search for UFDs, LSST can find ~500 out to the Milky Way virial radius
- Photometric characterization of the globular clusters of every accessible galaxy within ~30 Mpc



LSST will increase the data available for Milky Way science by two orders of magnitude

Transients and Variable Stars I

- **Transients in the Local Universe (d<200 Mpc), novae/SN gap, correlation with new observational windows (cosmic rays, GWs, neutrino detectors, --)**
- **Local Universe, a-LIGO follow-ups with negligible false positives, assumed 12 sq. deg. localization and follow-up depth of r<24**
- **Need to eliminate foreground and background events (asteroids, M dwarf flares, --)**

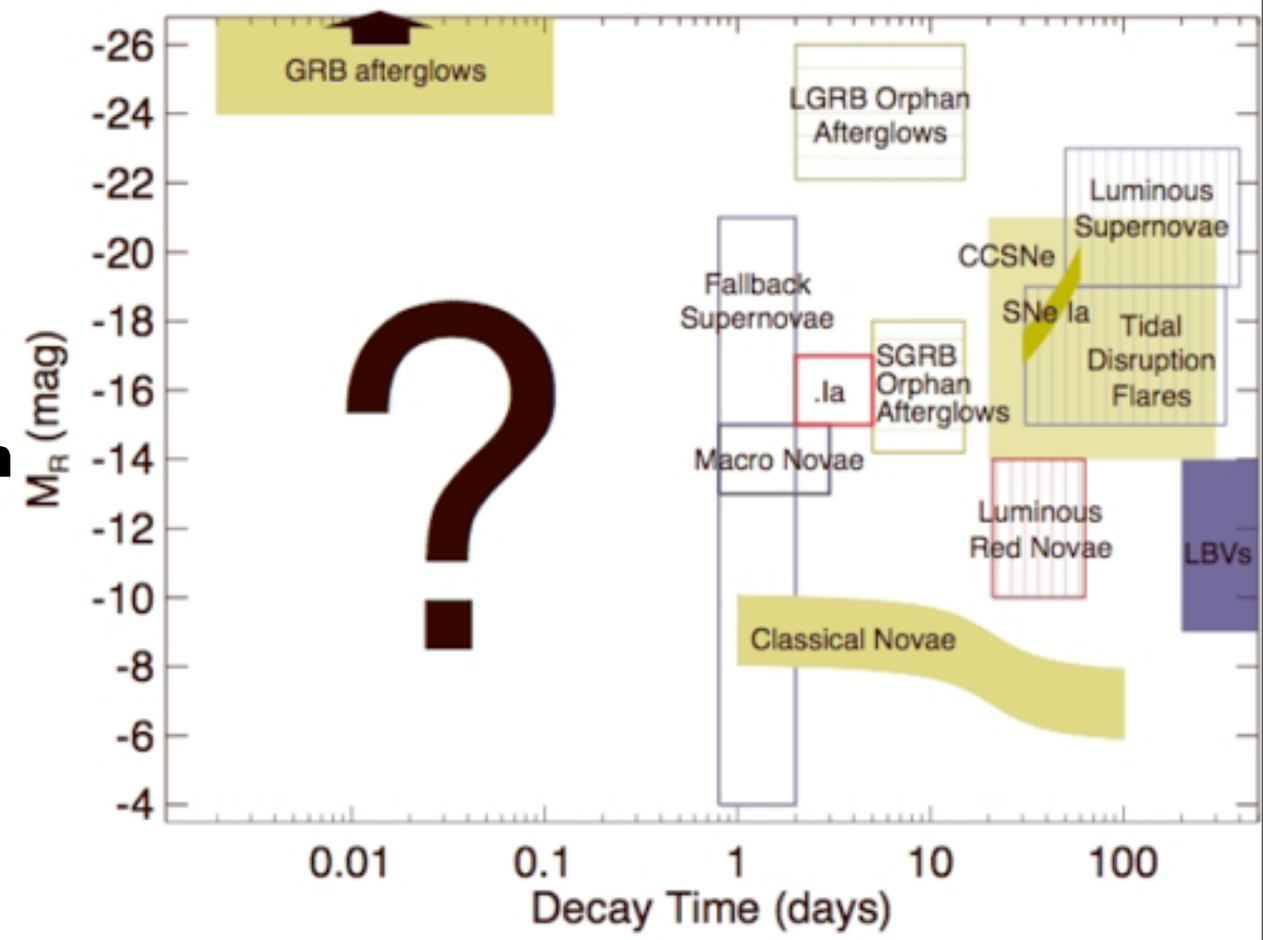


Table 8.2: Properties and Rates for Optical Transients[a]

Class	M_v [mag]	τ^b [days]	Universal Rate (UR)	PTF Rate [yr^{-1}]	LSST Rate [yr^{-1}]
Luminous red novae	$-9..-13$	20..60	$(1..10)\times10^{-13}\,yr^{-1}\,L^{-1}_{\odot,K}$	0.5..8	80..3400
Fallback SNe	$-4..-21$	0.5..2	$<5\times10^{-6}\,Mpc^{-3}\,yr^{-1}$	<3	<800
Macronovae	$-13..-15$	0.3..3	$10^{-4..-8}\,Mpc^{-3}\,yr^{-1}$	0.3..3	120..1200
SNe .Ia	$-15..-17$	2..5	$(0.6..2)\times10^{-6}\,Mpc^{-3}\,yr^{-1}$	4..25	1400..8000
SNe Ia	$-17..-19.5$	30..70	$^c\,3\times10^{-5}\,Mpc^{-3}\,yr^{-1}$	700	200000[d]
SNe II	$-15..-20$	20..300	$(3..8)\times10^{-5}\,Mpc^{-3}\,yr^{-1}$	300	100000[d]

Transients and Variable Stars II

- **Transients in the Distant Universe, 'long' orphan GRB afterglows can be used to determine beaming fraction and universal associated rate**
- **Hybrid GRBs, anomalous supernovae, tidal disruption flares --**
- **LSST micro/mesolensing (MACHO census, planets, solar neighborhood, --)**
- **LSST will discover ~135 million variable stars (~60M pulsating, ~60M eclipsing/ellipsoidal, ~2M flaring, ~1M planetary transits)**

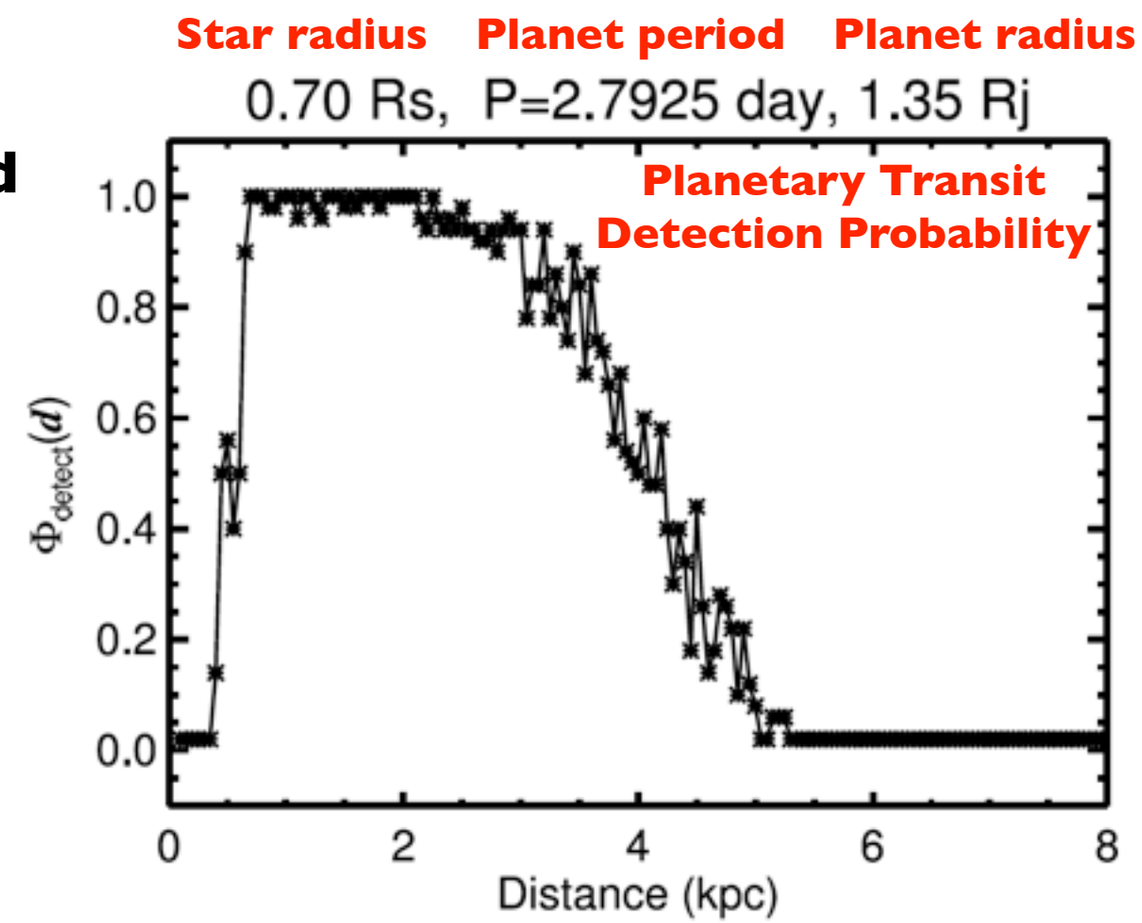
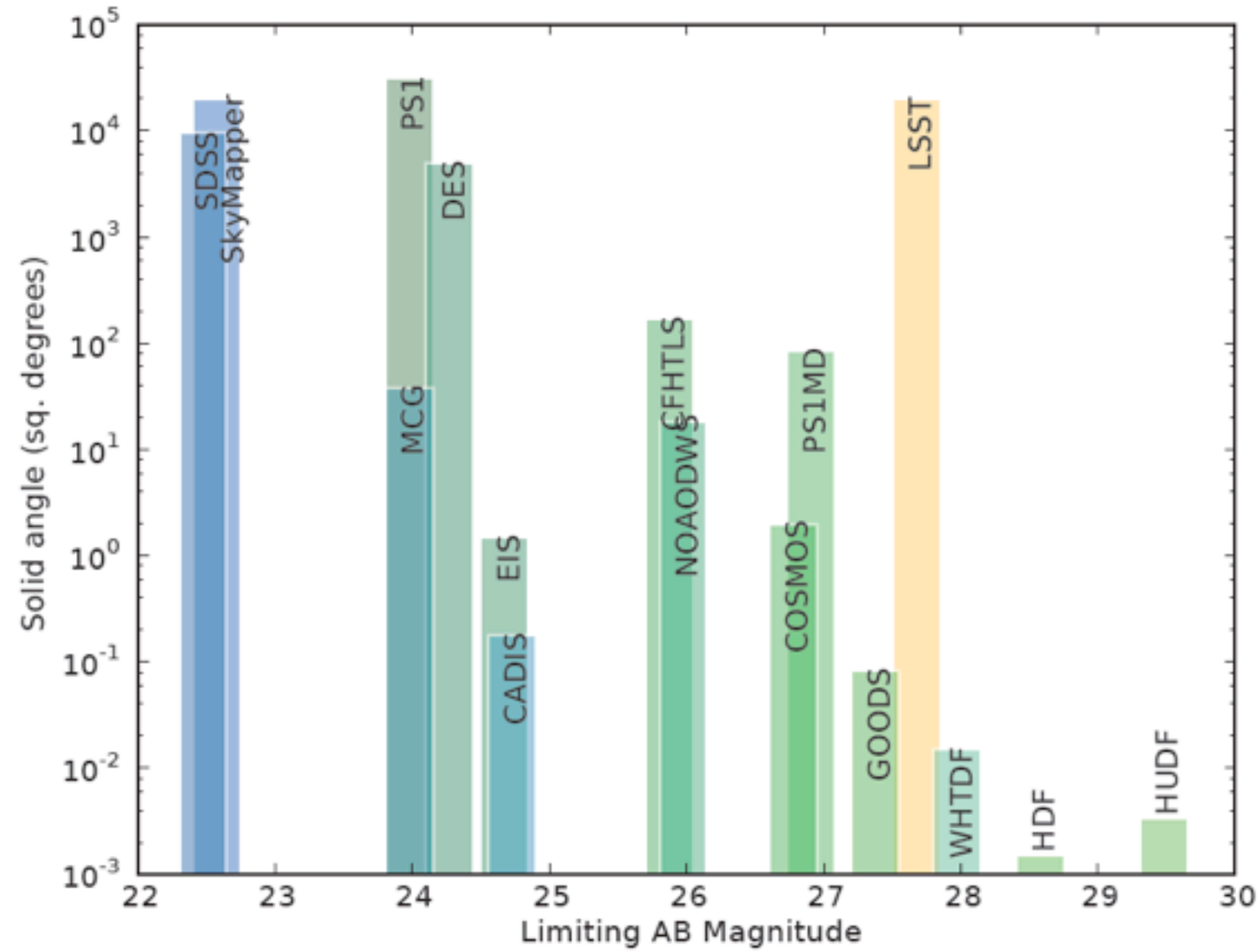


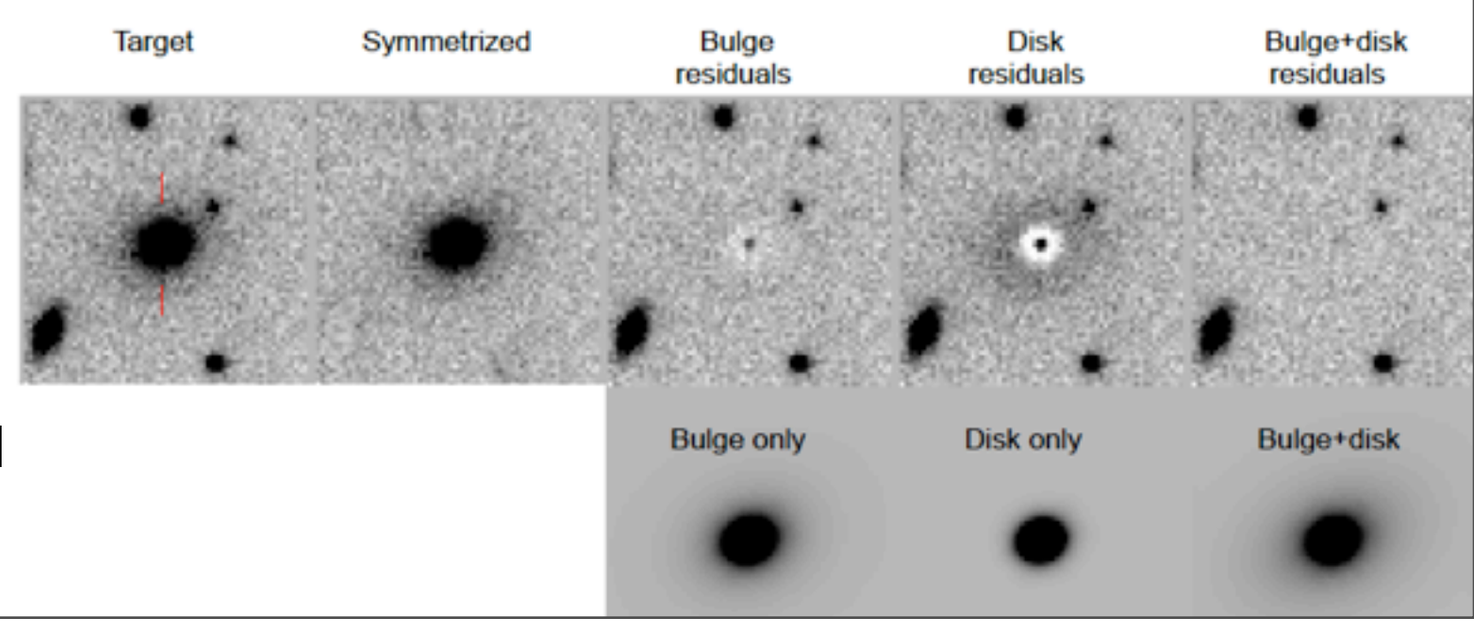
Table 8.3: Properties and Rates for Optical Cosmological Transients[a]

Class	M_v [mag]	τ^b [days]	Universal Rate (UR)	LSST Rate [yr^{-1}]
Tidal disruption flares (TDF)	$-15.. -19$	30..350	10^{-6} Mpc^{-3} yr^{-1}	6,000
Luminous SNe	$-19.. -23$	50..400	10^{-7} Mpc^{-3} yr^{-1}	20,000
Orphan afterglows (SHB)	$-14.. -18$	5..15	$3 \times 10^{-7..-9}$ Mpc^{-3} yr^{-1}	~10–100
Orphan afterglows (LSB)	$-22.. -26$	2..15	$3 \times 10^{-10..-11}$ Mpc^{-3} yr^{-1}	1,000
On-axis GRB afterglows	$.. -37$	1..15	10^{-11} Mpc^{-3} yr^{-1}	~50

Galaxies

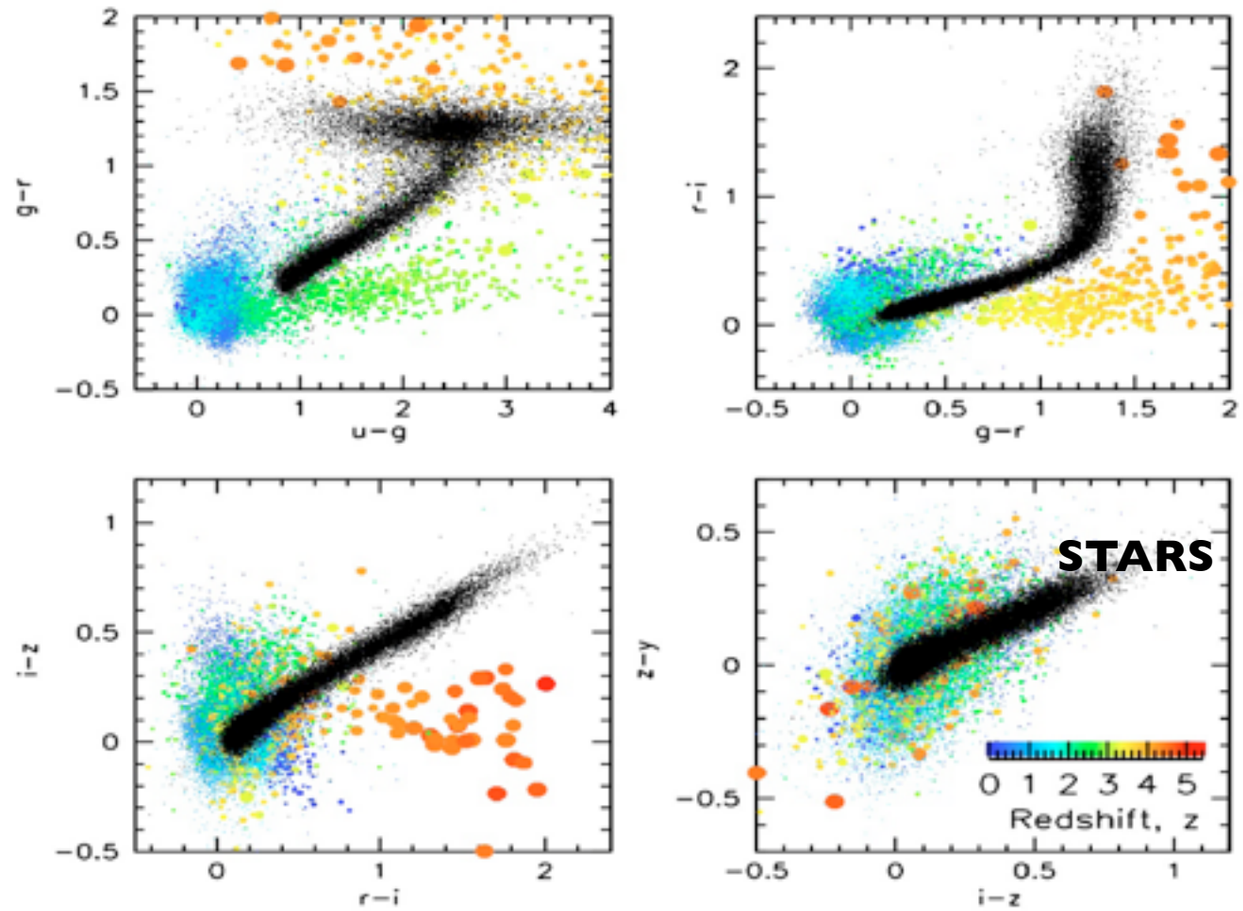
- Measurements for billions of galaxies
- Morphology for L* galaxies out to z~0.5 (res~4 kpc)
- Passively evolving L* galaxies captured to z~2 (and z~3 in deep-drilling fields)
- High-z star-forming galaxies, ~1 billion (z>2), 10 million (z>4.5)
- LSST should be good for LSB dwarfs, but more work needed
- Galaxy color-magnitude diagram
- Galaxy and host DM halo properties, not clear?
- Optical clusters, ~100K at z>1 (since red sequence in place by z~1.5)
- Evolution of galaxy properties using angular correlations in photo-z bins
- Merger rates from morphological disturbances



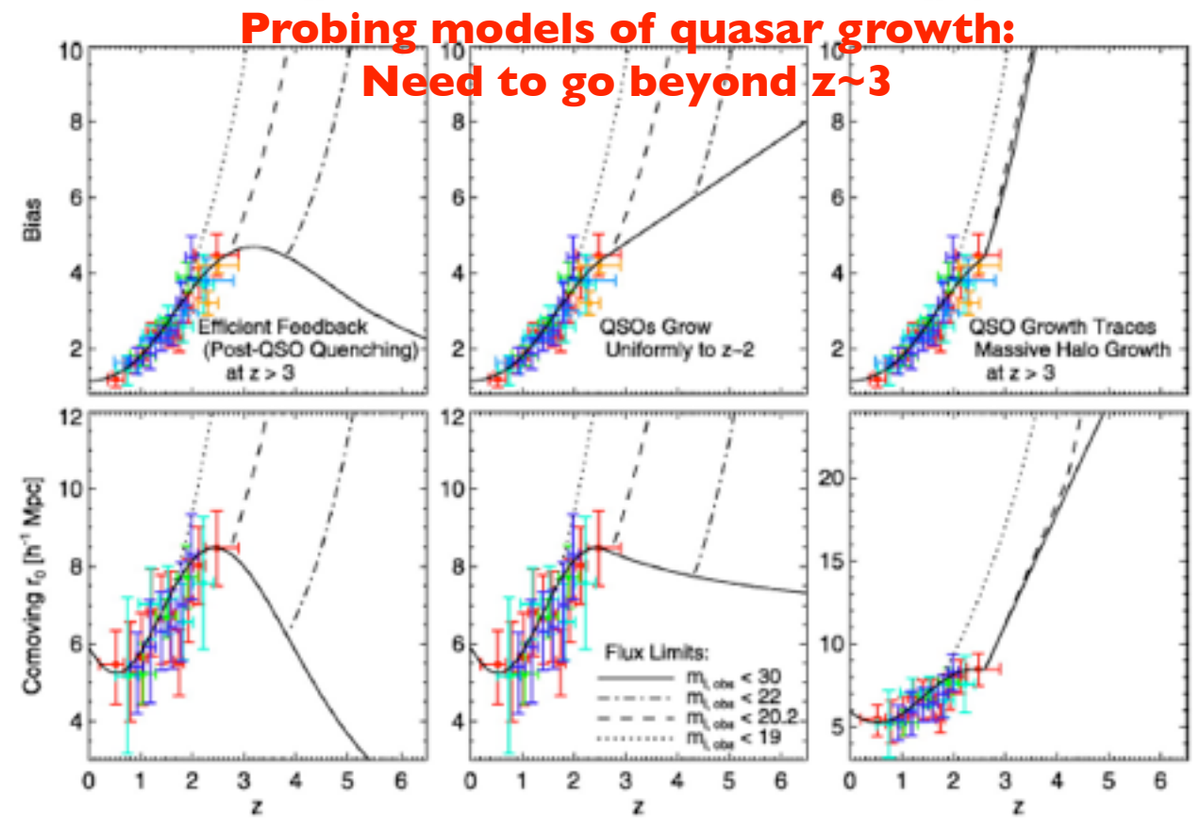


Active Galactic Nuclei

- Find quasars using color selection, lack of proper motion, and variability (LSST's cadence will provide 200 epochs for each candidate)
- photo-z's to dz=+/-0.3 at least (following SDSS)
- ~10 million photometric quasars (SDSSX10)
- LSST census of quasars at z~7 important to understand the end of the reionization epoch and on SMBH accretion history
- Trace SMBH evolution through AGN luminosity function (systematics limited)
- Use AGN clustering to understand SMBH and host halo relationships
- Observations at other wavelengths needed
- LSST will enable variability studies to constrain models for origins of AGN emission (instabilities, jet evolution, --)
- Tidal disruption events, ~130/year



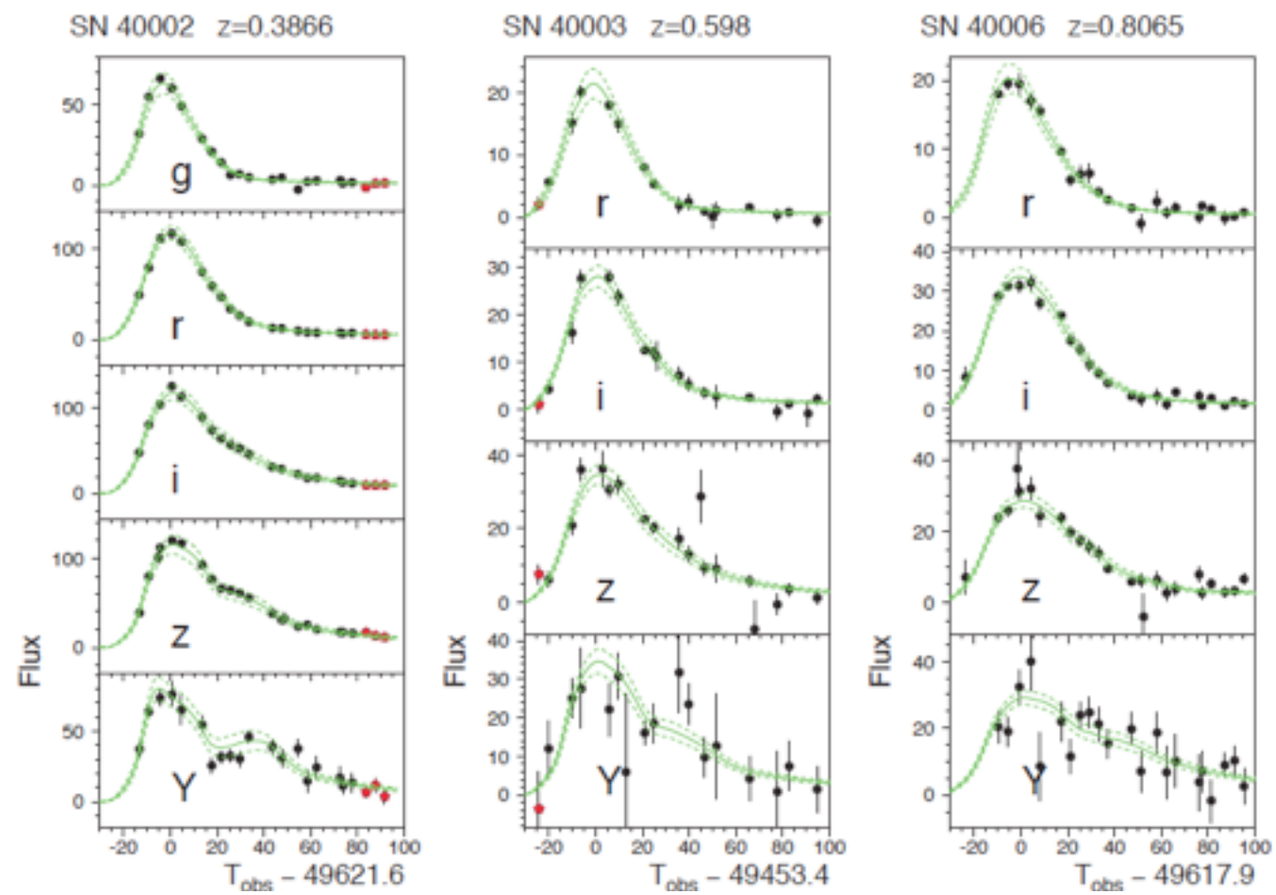
Probing models of quasar growth:
Need to go beyond z~3

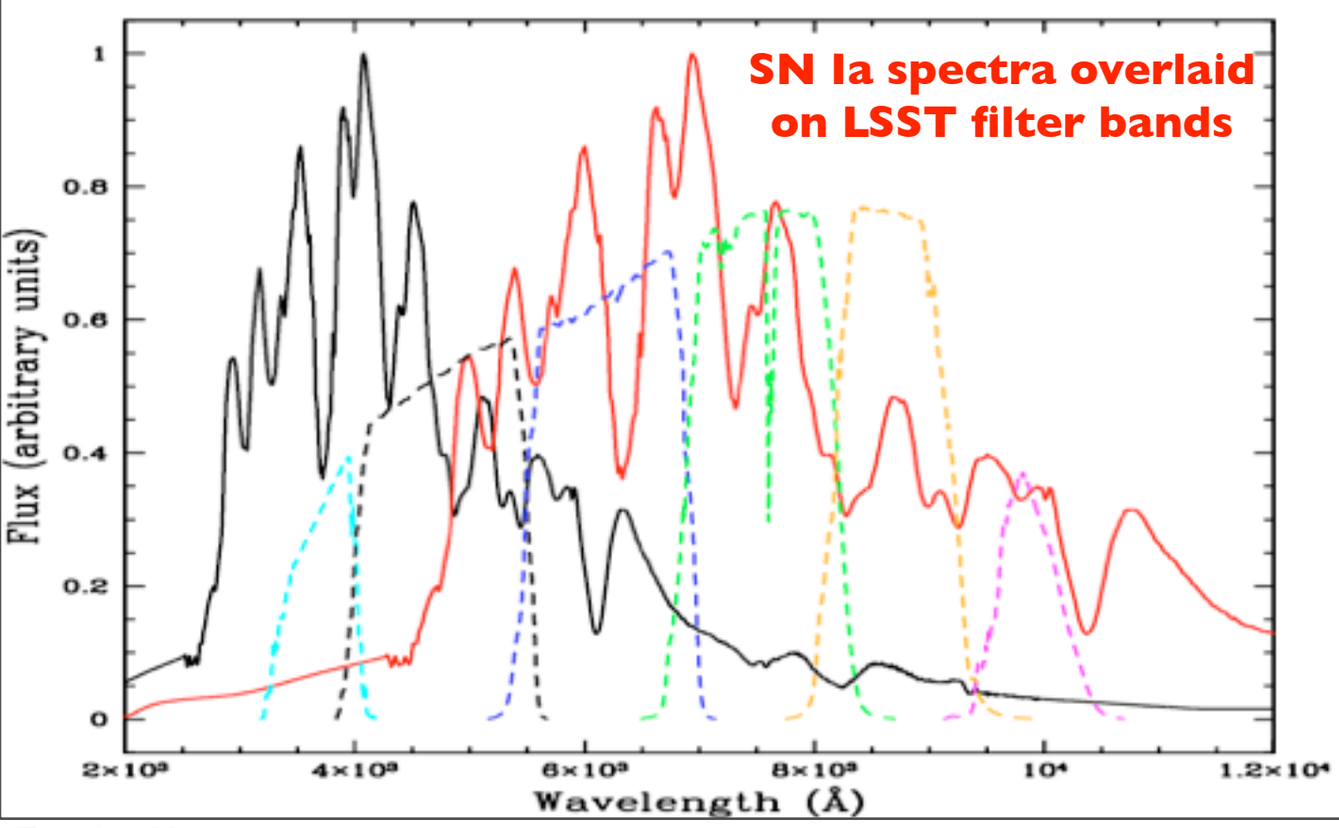


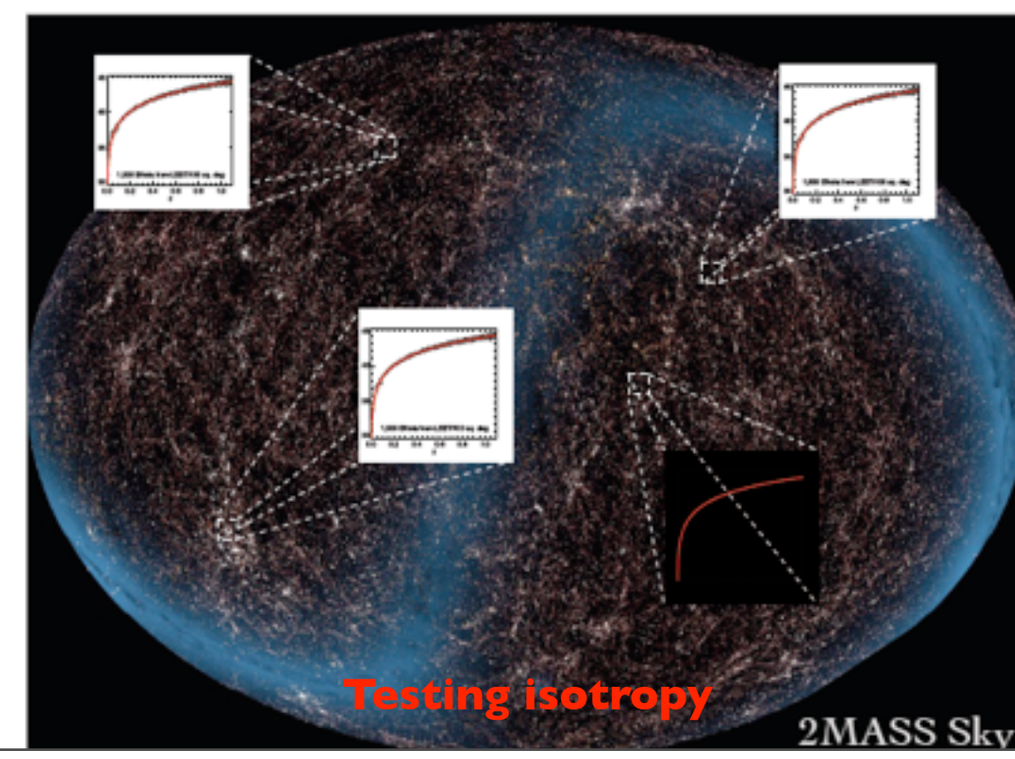
Supernovae

- Compared to ~1000 SN found so far, LSST will deliver 10 million
- ~100K SN Ia (use this to test homogeneity/isotropy), ~10K (deep survey)
- Need to see how well SN photo-z will work
- SN Ia properties as function of host galaxy type
- SN Ia baryon acoustic oscillations
- Many Type II --

Simulated SN Ia light curves for LSST deep drilling survey

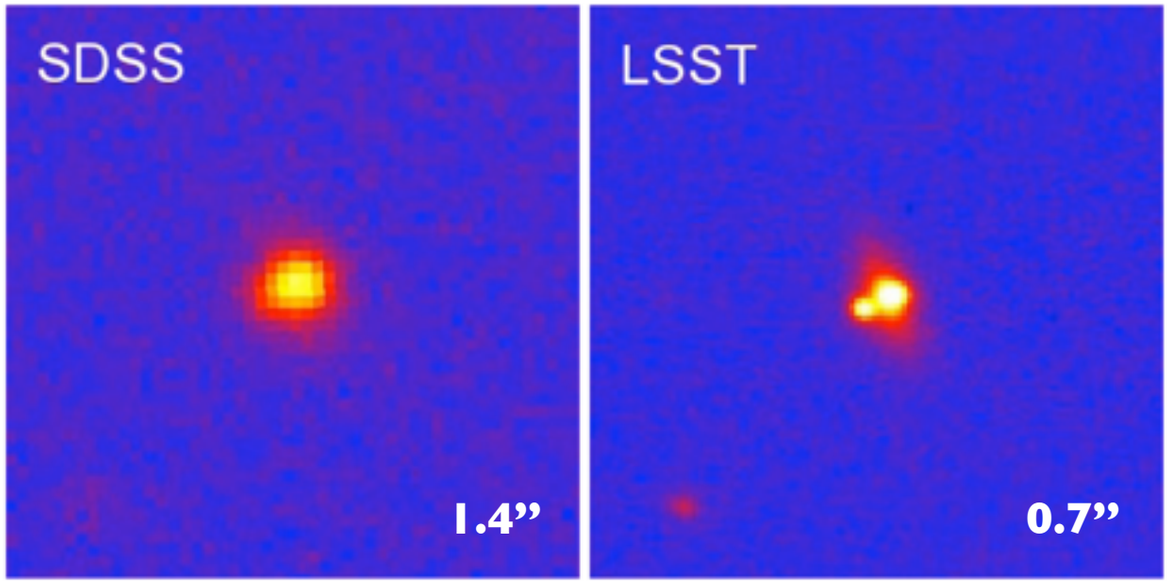


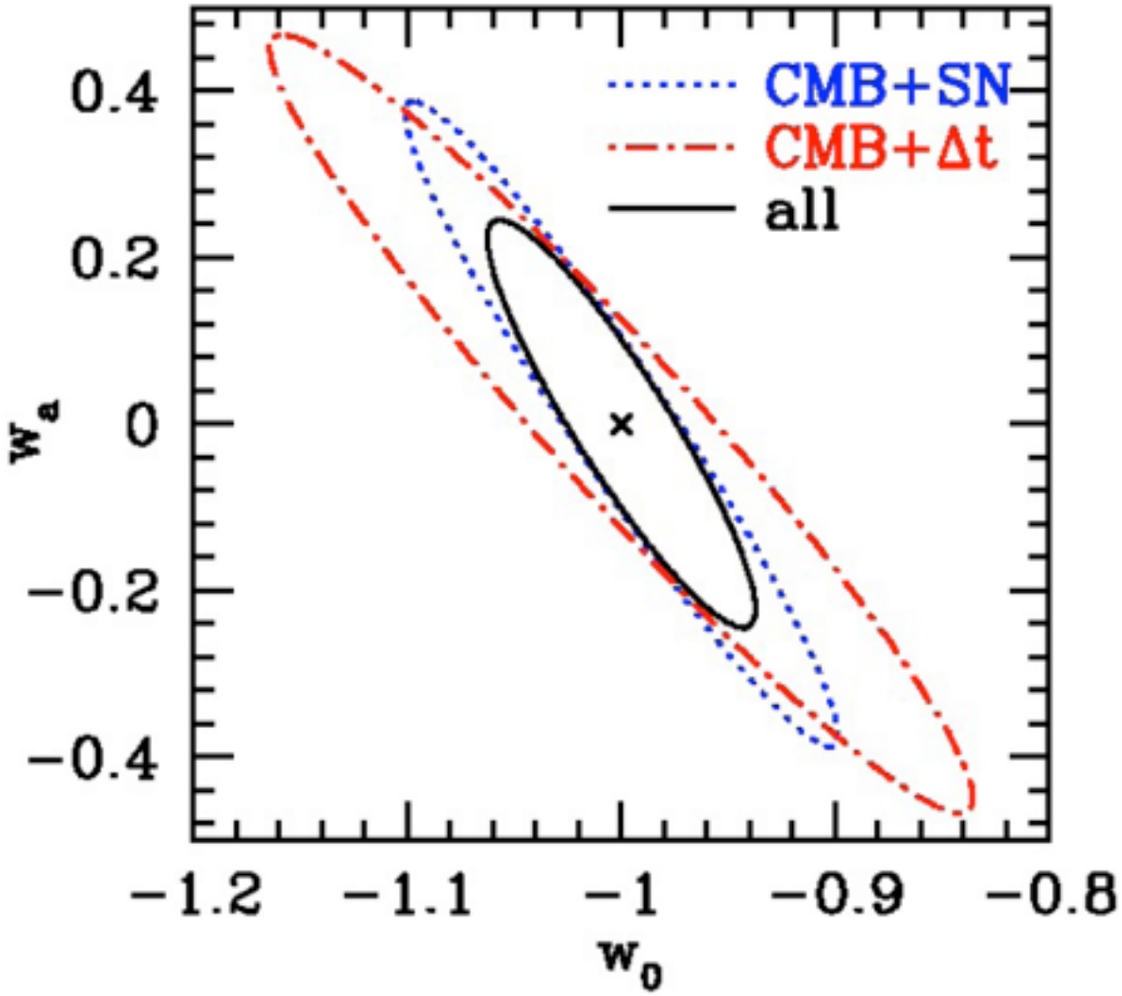




Strong Lensing

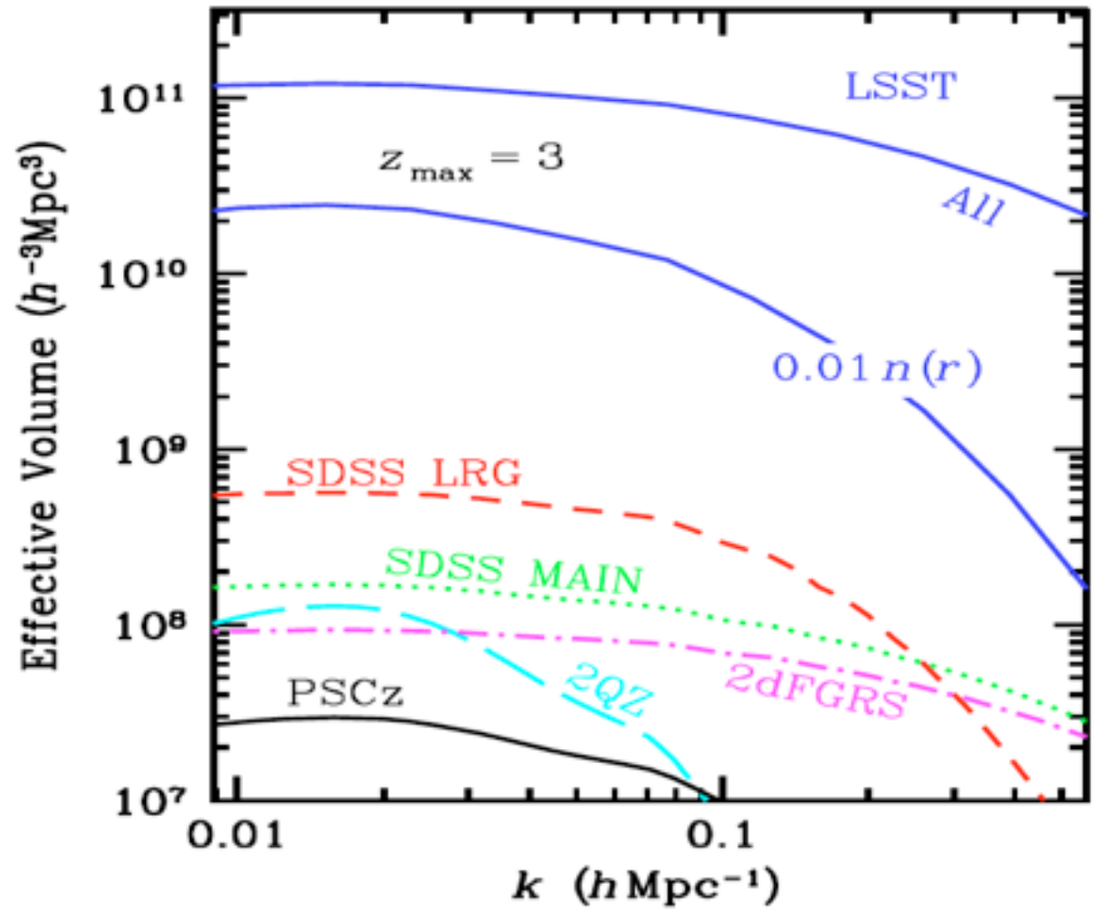
- Most strong lensing events due to massive ellipticals
- ~10000 galaxy-galaxy strong lenses over LSST lifetime (~300 for DES)
- ~2600 lensed quasars (temporal information useful here)
- ~330 lensed supernovae at typical z~0.8 (90 Ia)
- Cluster strong lenses ~1000
- Study mass function of lens galaxies
- Measurements of galaxy mass density profiles to z~1
- Usefulness of time delay measurements for cosmography not fully clear
- Increase of strong lensing dataset for substructure studies (X100)
- Lensing studies of LSST masive cluster sample (~1000 clusters)

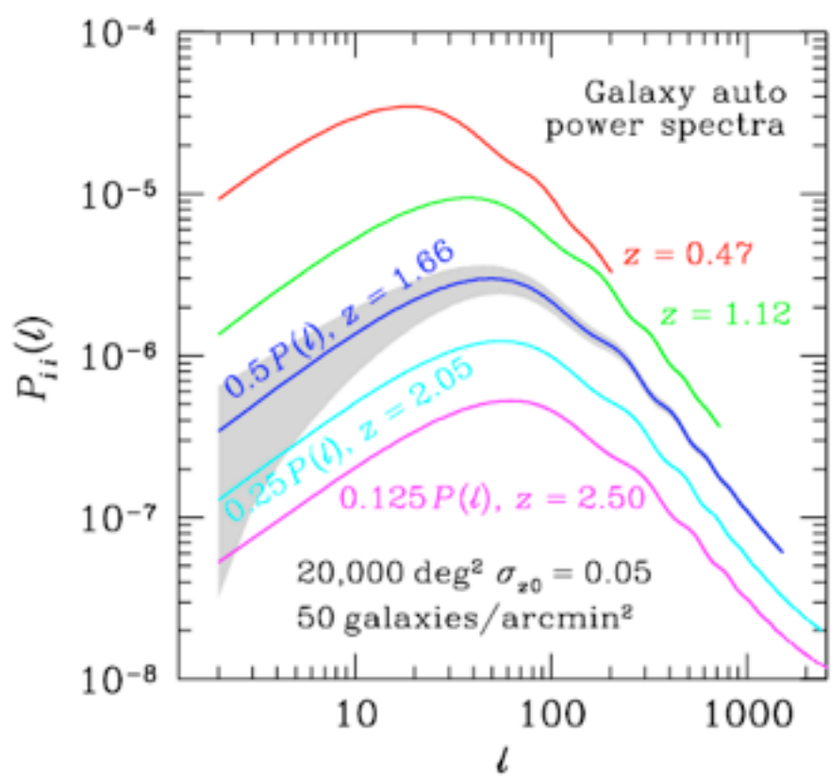


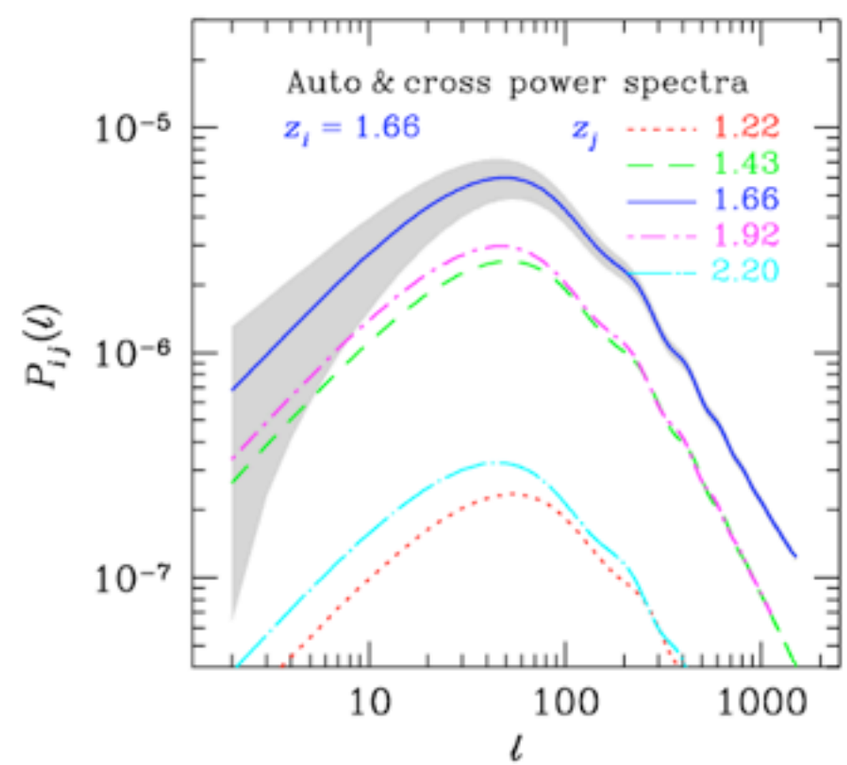


Large-Scale Structure

- Very large effective survey volume although statistical power reduced due to use of photo-z's (factor of ~20)
- Can measure P(k) turn-over at k~0.02 h/Mpc
- BAO via angular power spectra (linear scales here) in 30 redshift bins, improves over current situation by order of magnitude but not competitive alone with a large redshift survey (e.g., BigBOSS)

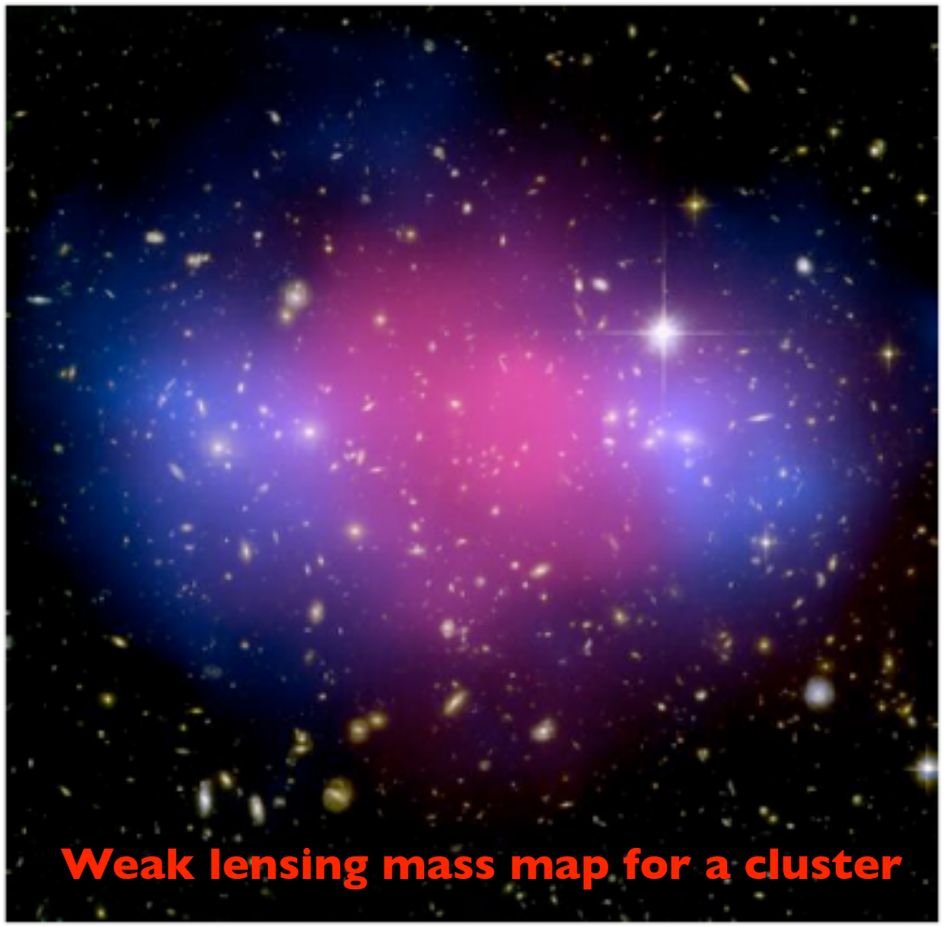


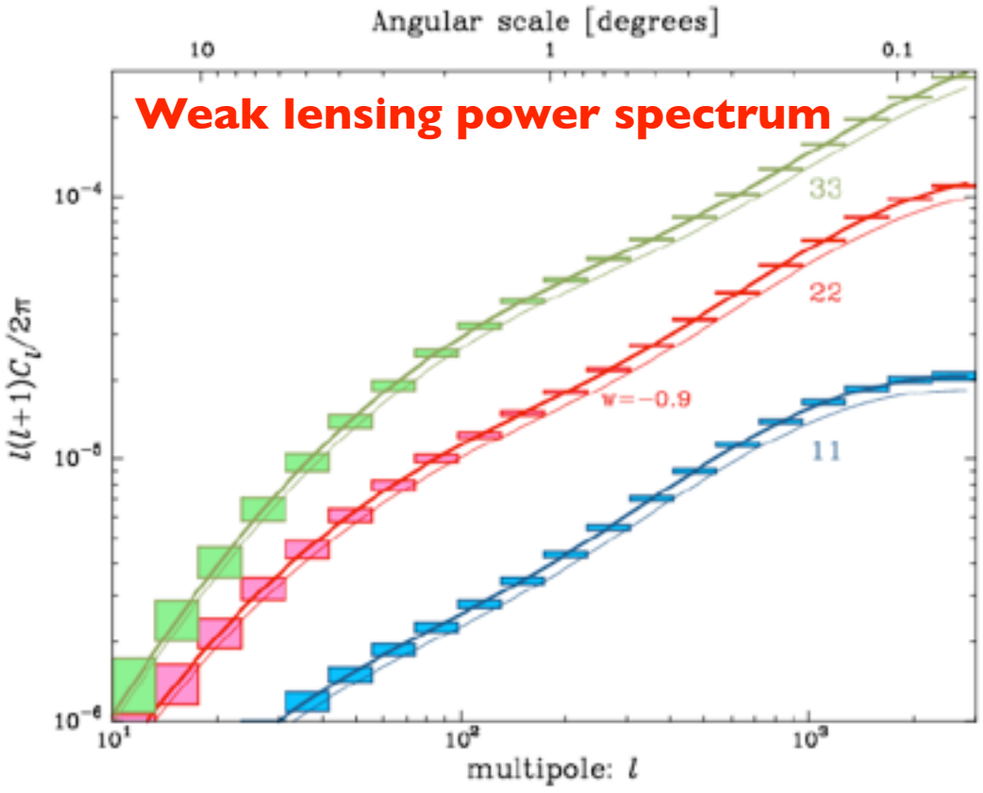




Weak Lensing

- Most direct method for mass mapping
- Key variables are (i) shear from galaxy shapes, and (ii) source redshifts from photo-z observations
- Galaxy-galaxy lensing with stacked sample of lenses (halo mass as function of stellar mass, halo ellipticity, combine with galaxy clustering to get matter correlation function)
- Measure 10% accurate masses for 20000 clusters with mass >1.510^14 M_sun (~40 background galaxies/(am)^2)
- Constrain cosmology from shear peaks, needs more work
- Weak lensing shear is a very powerful probe of cosmology, but systematics will have to be controlled (e.g., intrinsic alignments, PSF, baryonic effects, --)
- Measure mean magnification by (stacked) clusters to calibrate masses -- must have good measurements of galaxy density (e.g., from deep drilling fields)





Interlude: What is Modern Cosmology?

Cosmology: The study of the Universe as a dynamical system

LSST as a driver for this --

- **Propose and test laws governing the dynamics of the large-scale Universe (matter and geometry)**
- **Propose and test theories of initial conditions**
- **Develop rigorous methodology for 'cosmological experiments'**
- **Sharpen cosmology as a tool for fundamental discoveries**

Lev Landau .....

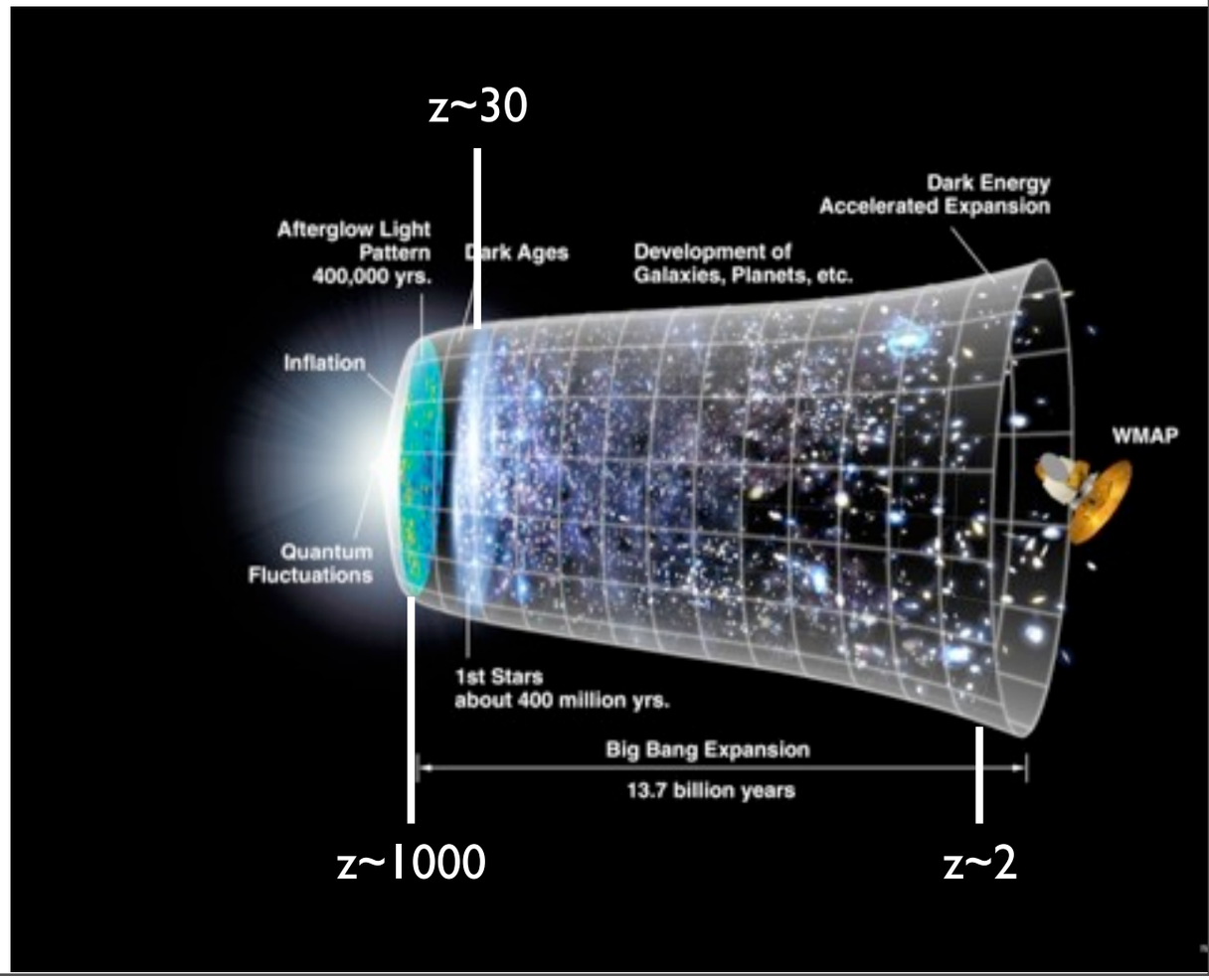
The Cosmological 'Standard Model'

Nuts and Bolts

- Expansion history of the Universe known reasonably well (but still spotty)
- Initial conditions -- Gaussian random field with power-law primordial spectrum
- Cross-validated constraints on ~10 cosmological parameters, including primordial fluctuation amplitude and spectral index, optical depth, Hubble constant, spatial flatness, --
- Accuracy of parameter determination ~10% (some better, some worse)
- For comparison, the particle physics Standard Model has parameters measured to the 0.1% level

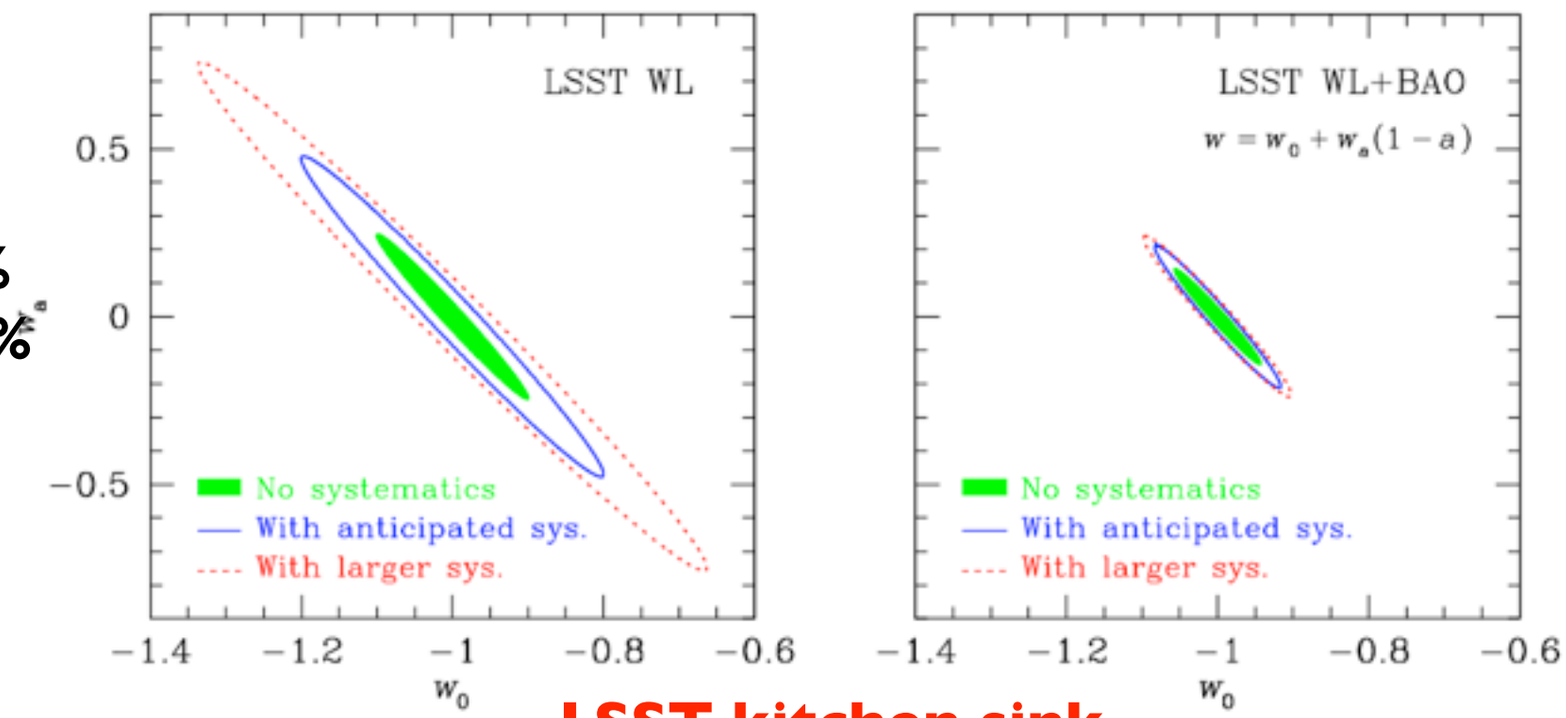
However,

- Late-time acceleration ('Dark Energy') not understood, dark matter also mysterious
- Theory of initial conditions not very satisfactory (inflation or something else?)
- Is GR valid on large length scales?
- Theory and observations must work together to understand the unknowns of the Standard Model

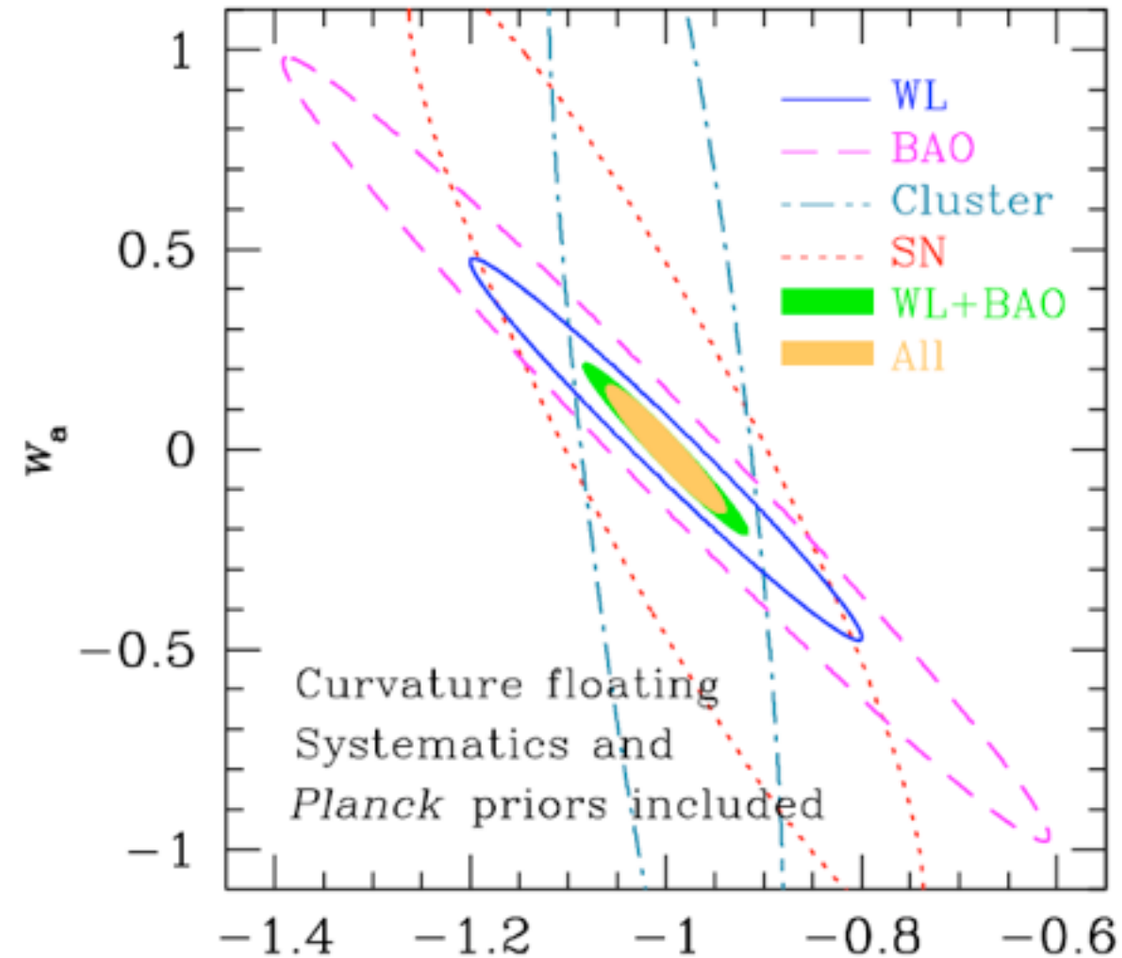


Cosmological Physics

- Power of joint analyses, e.g., weak lensing + BAO, adds immunity to photo-z errors
- WL + BAO can achieve ~0.5% precision on distance and ~2% on the growth factor from z=0.5-3 in bins of dz~0.3 -- can use this to distinguish between dark energy and modified gravity
- WL + BAO can measure the spatial curvature to <.001
- WL + Planck gives strong constraints on sum of neutrino masses, dm~0.03 eV, and on N_v, dN_v~0.08
- Clustering on the largest scales, dark energy anisotropy?
- Next-generation simulations needed to work the theory out --



LSST kitchen sink



Coming (Relatively) Soon --