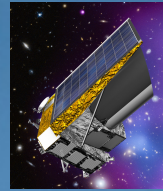


The Synergies between WFIRST and LSST (and Euclid)



Željko Ivezić

Department of Astronomy
University of Washington
LSST Project Scientist



Astronomy in the 2020s: Synergies with WFIRST, Baltimore, June 26, 2017

Outline

- Rapid tour of LSST
 - multi-color time-resolved **faint** sky map
 - 20 billion stars and 20 billion galaxies
- WFIRST-LSST-Euclid complementarity
 - 2,200 sq.deg. of three-way overlap
 - 7,000+ sq.deg. of LSST-Euclid overlap
- And what to do about it
 - cadence coordination
 - enabling matched-catalog-based analysis
 - joint pixel-level processing



LSST: a digital color movie of the Universe...

3.6×10^{-31} erg/s/cm²/Hz
36 nJy
100x fainter than SDSS

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 20 billion stars and 20 billion galaxies with exquisite photometry, astrometry₃ and image quality.

More information at
www.lsst.org
and arXiv:0805.2366

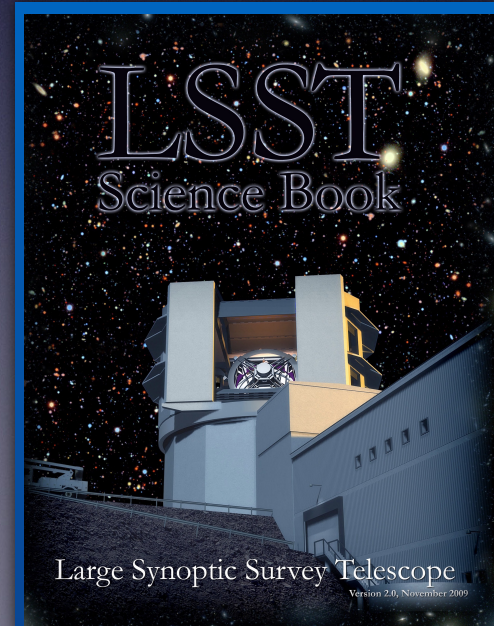
LSST Science Themes

- 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](https://arxiv.org/abs/0912.0201)

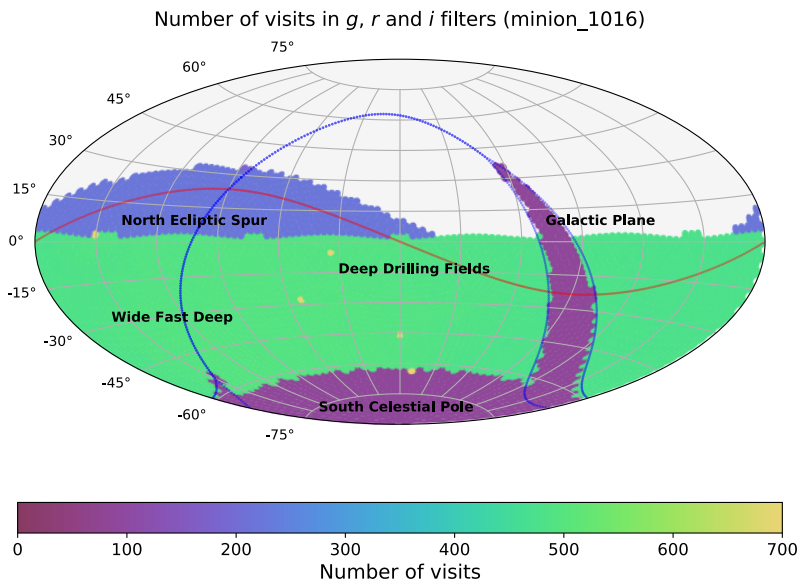
Summarizes LSST hardware, software, and observing plans, science enabled by LSST, and educational and outreach opportunities

245 authors, 15 chapters, 600 pages



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 40 billion objects



LSST in one sentence:

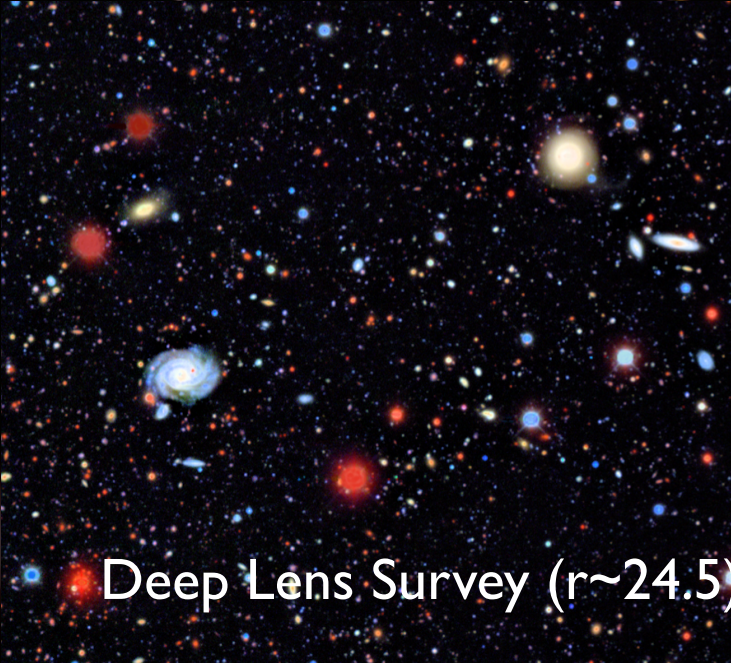
An optical/near-IR survey of half the sky in ugrizy bands to $r \sim 27.5$ (36 nJy) based on 825 visits over a 10-year period: **deep wide fast.**

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

SDSS vs. LSST comparison: LSST=d(SDSS)/dt, LSST=SuperSDSS

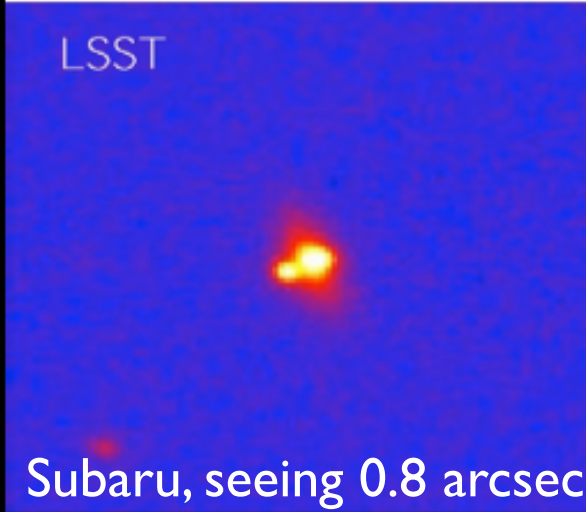
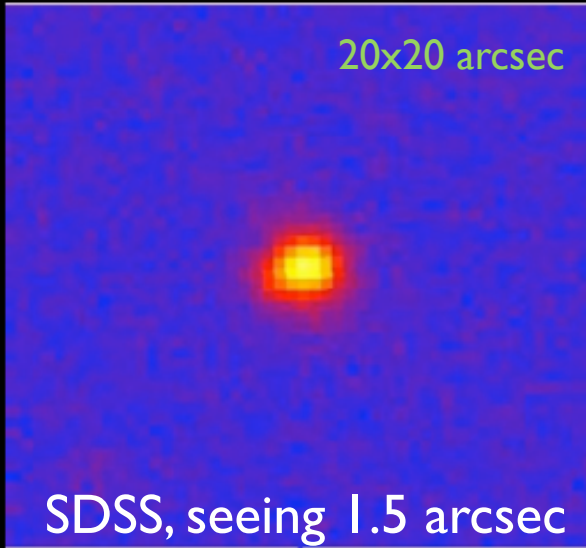
7.5x7.5 arcmin, gri

7.5 arcmin
is 1/4 of
the full
Moon's
diameter



→
single-visit
LSST depth
(10⁻⁶ area)
LSST: x10⁸

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



SDSS

gri

3.5'x3.5'

r~22.5



HSC
gri
3.5'x3.5'
r~27

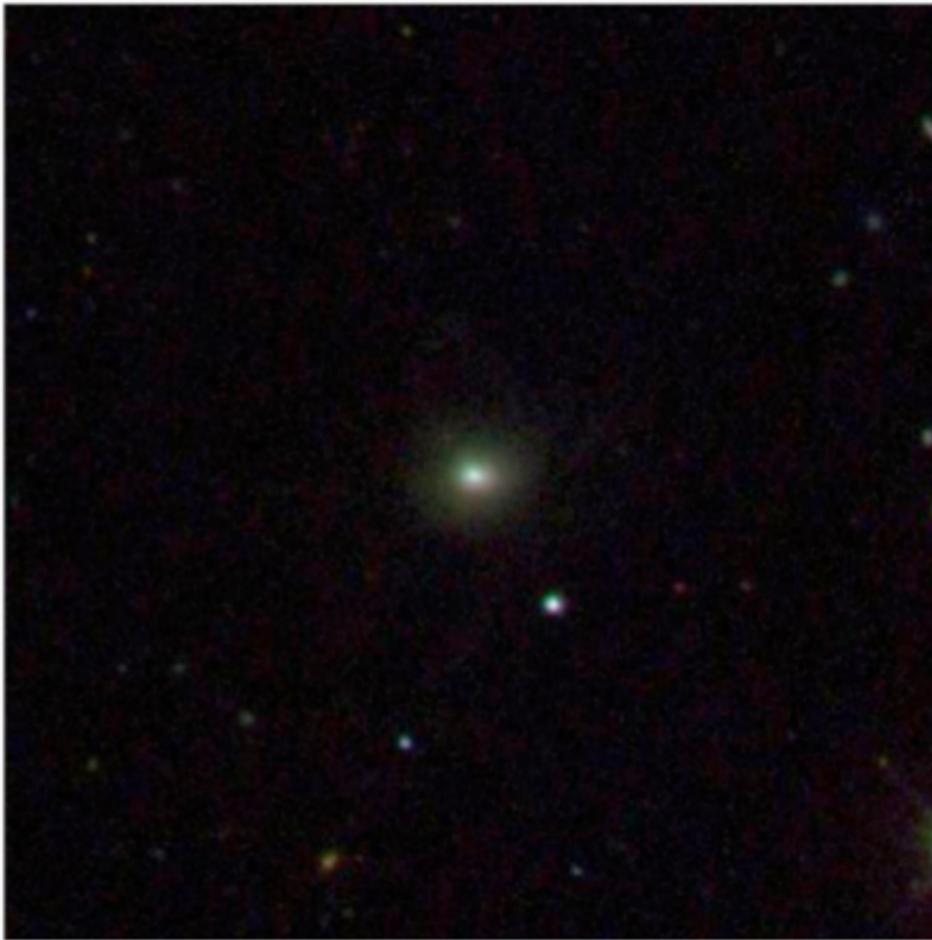


Thanks to
Robert
Lupton

Not just point source depth: faint surface brightness limit

SDSS

3x3 arcmin, gri



MUSYC $r \sim 26$

(almost) like LSST depth
(but tiny area)



Gawiser et al

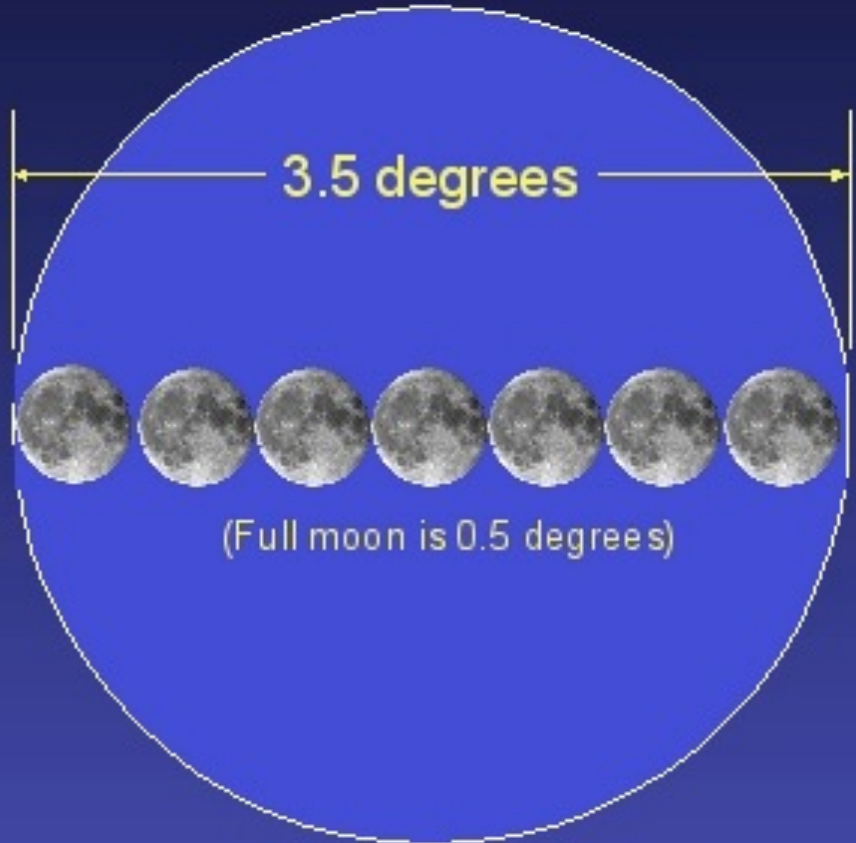
The field-of-view comparison: Gemini vs. LSST

Primary Mirror Diameter

Field of View

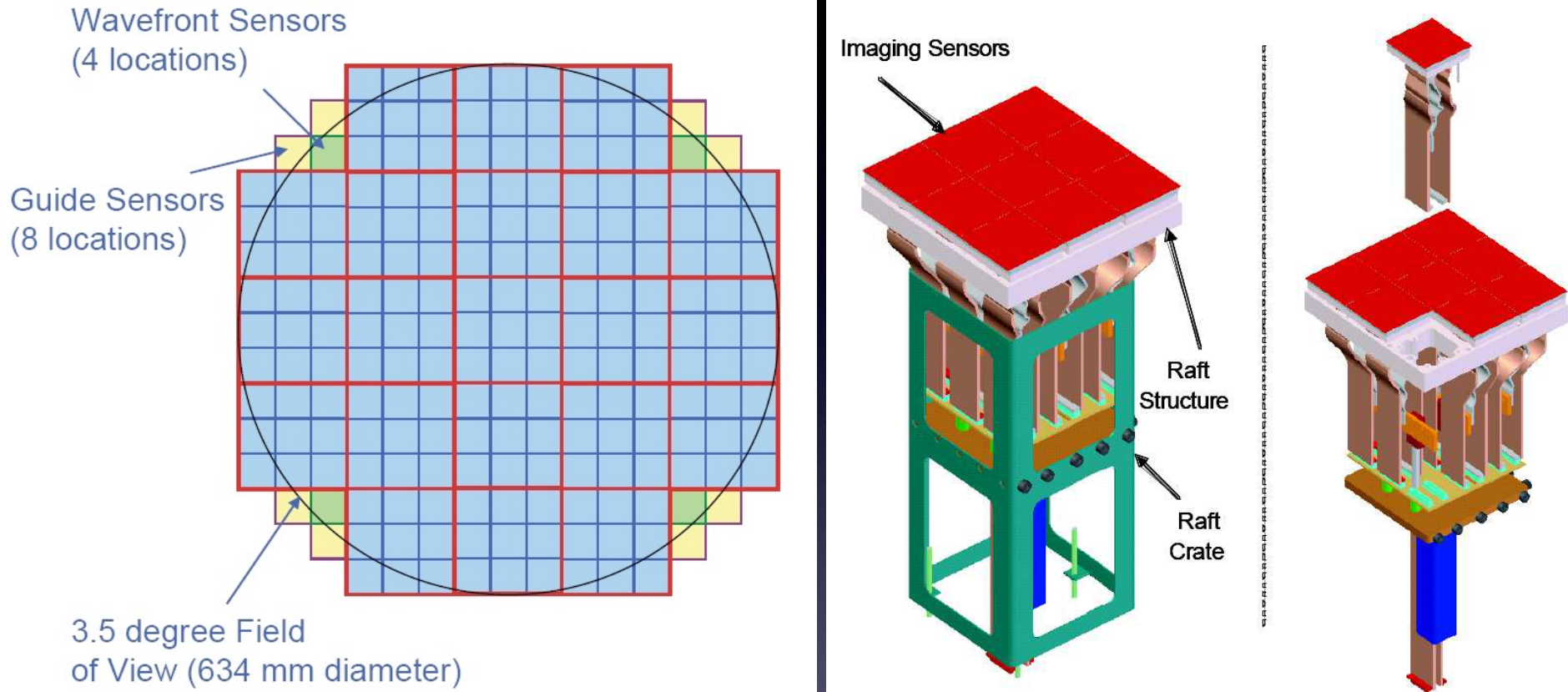


Gemini South Telescope



LSST

LSST camera



Modular design: 3200 Megapix = 189 x 16 Megapix CCD
9 CCDs share electronics: raft (=camera)
Problematic rafts can be replaced relatively easily

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)

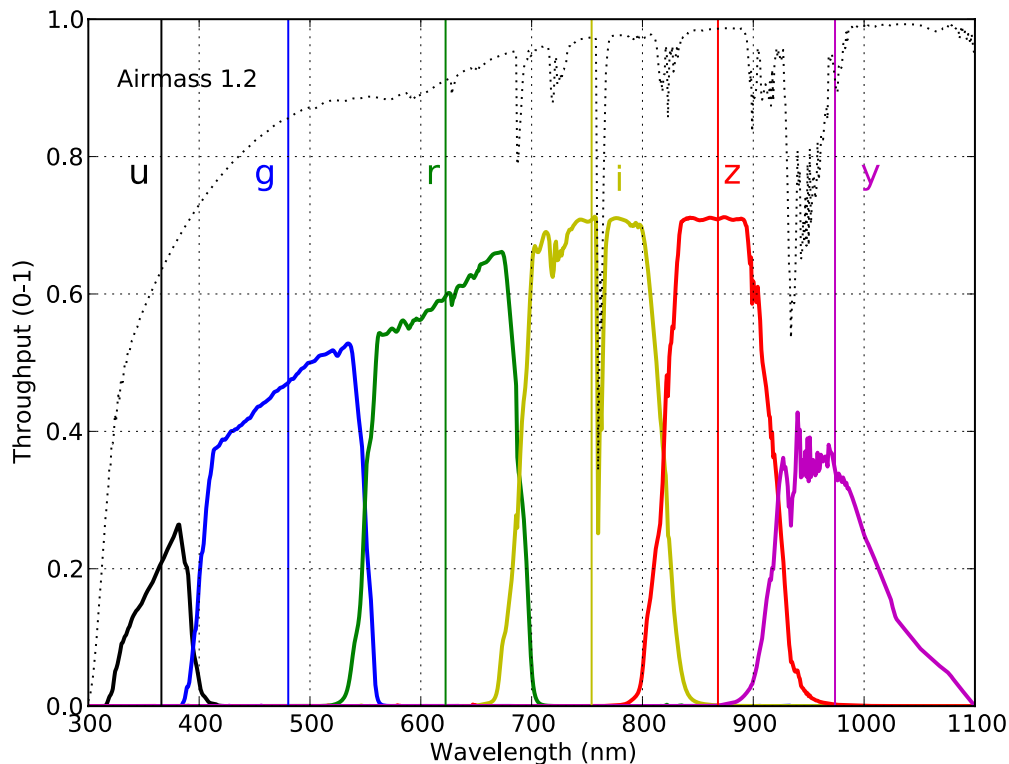


Photo-z requirements correspond to $r \sim 27.5$ with the following per band time allocations:

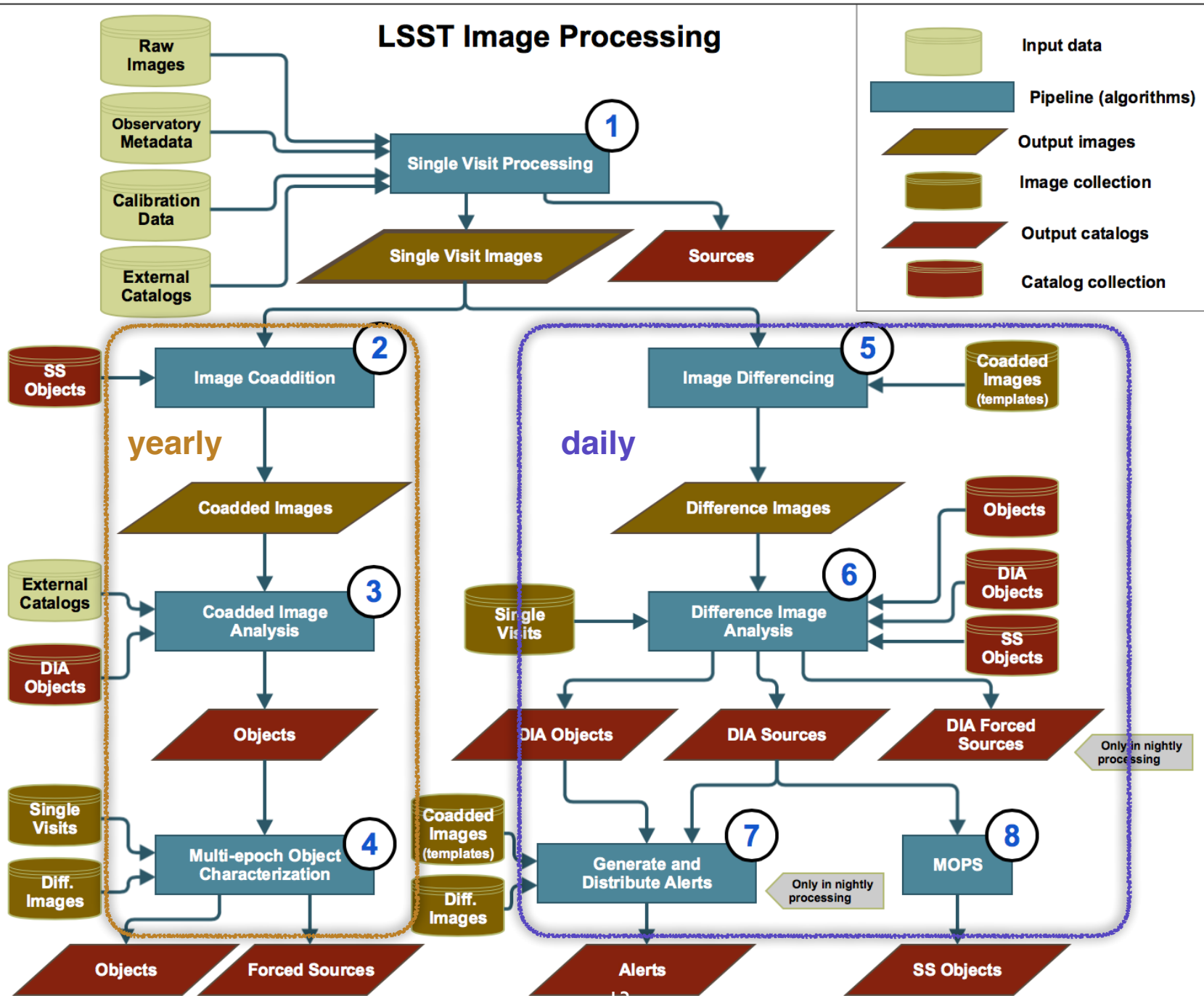
u: 8%; g: 10%

r: 22%; i: 22%

z: 19%; y: 19%

Consistent with other science themes (stars)

LSST Image Processing



LSST From the User's Perspective: A Data Stream, a Database, and a (small) Cloud



Nightly Alert Stream

- A stream of ~10 million time-domain events per night, detected and transmitted to event distribution networks within 60 seconds of observation.
- A catalog of orbits for ~6 million bodies in the Solar System.

Level 1

Yearly Data Releases

- A catalog of ~37 billion objects (20B galaxies, 17B stars), ~7 trillion single-epoch detections (“sources”), and ~30 trillion forced sources, produced annually, accessible through online databases.
- Deep co-added images.

Level 2

Community Services

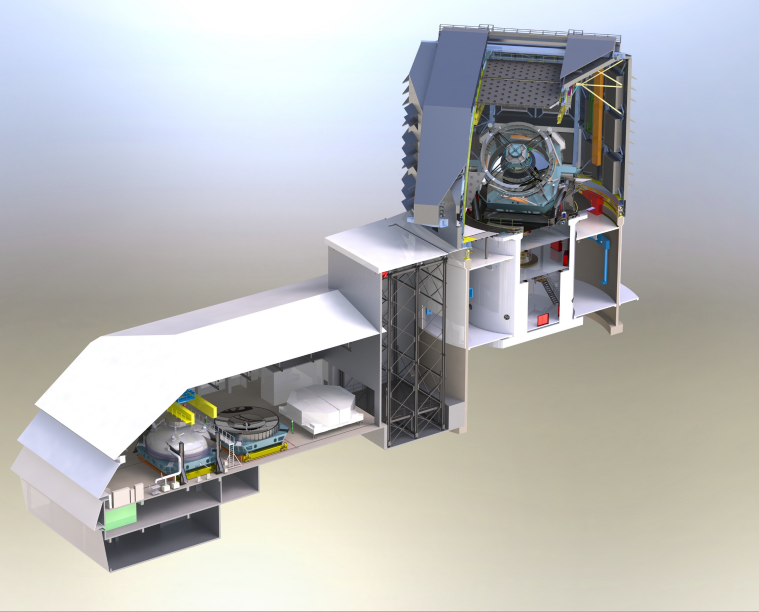
- Services and computing resources at the Data Access Centers to enable user-specified custom processing and analysis.
- Software and APIs enabling development of analysis codes.

Level 3

LSST Construction Schedule

- First light with the commissioning camera: 2020
- First light with the main camera: late 2020
- Science commissioning: 2021
- The start of regular survey operations: 2022

First light: 2020



WFIRST, LSST and Euclid are highly complementary missions.

WFIRST, LSST and Euclid are highly complementary missions.

WFIRST:

2,200 sq.deg

$m_5 \sim 27$

$r_{1/2} \sim 0.12$ arcsec

2025-2031

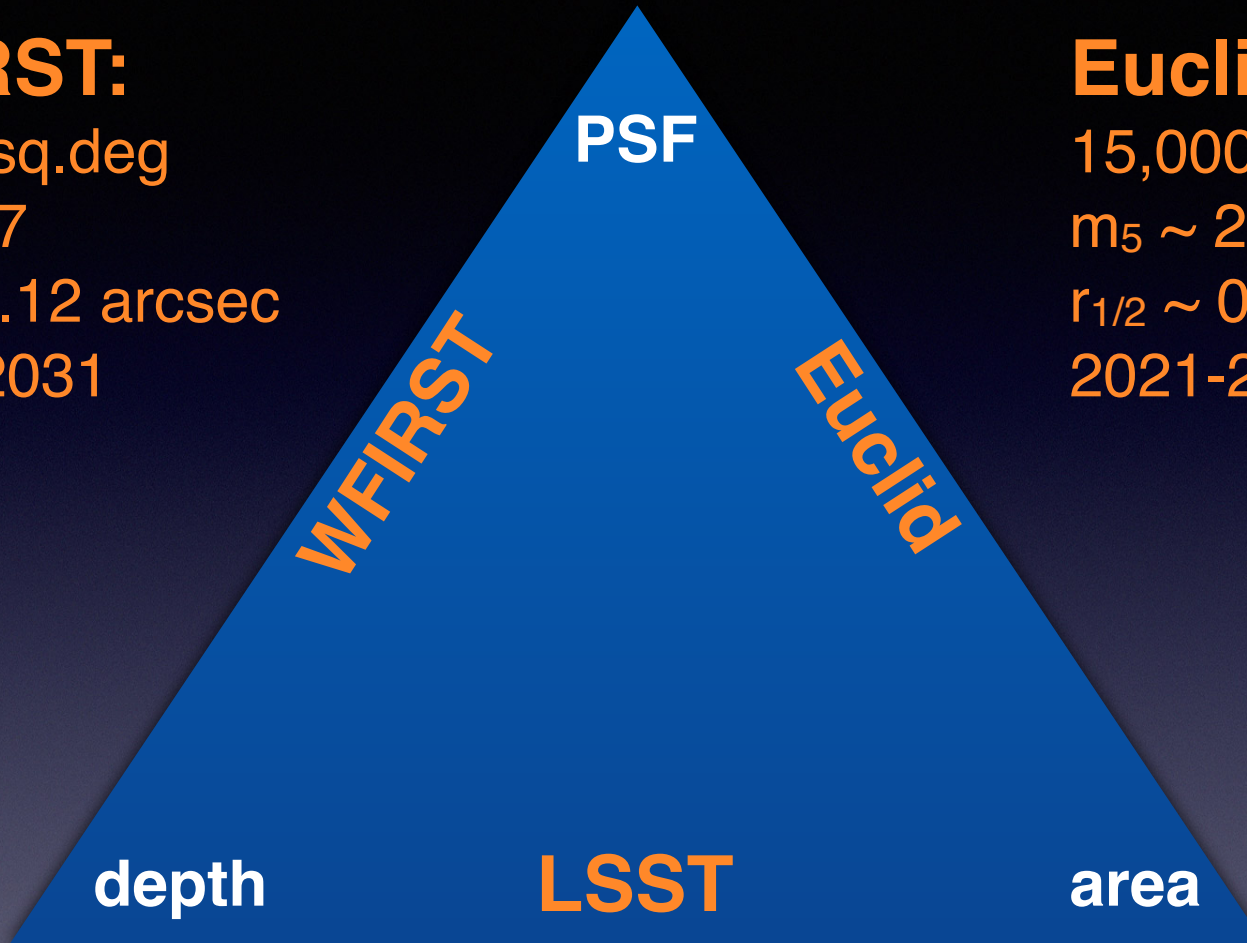
Euclid:

15,000 sq.deg

$m_5 \sim 25$

$r_{1/2} \sim 0.13$ arcsec

2021-2027



18,000 sq.deg

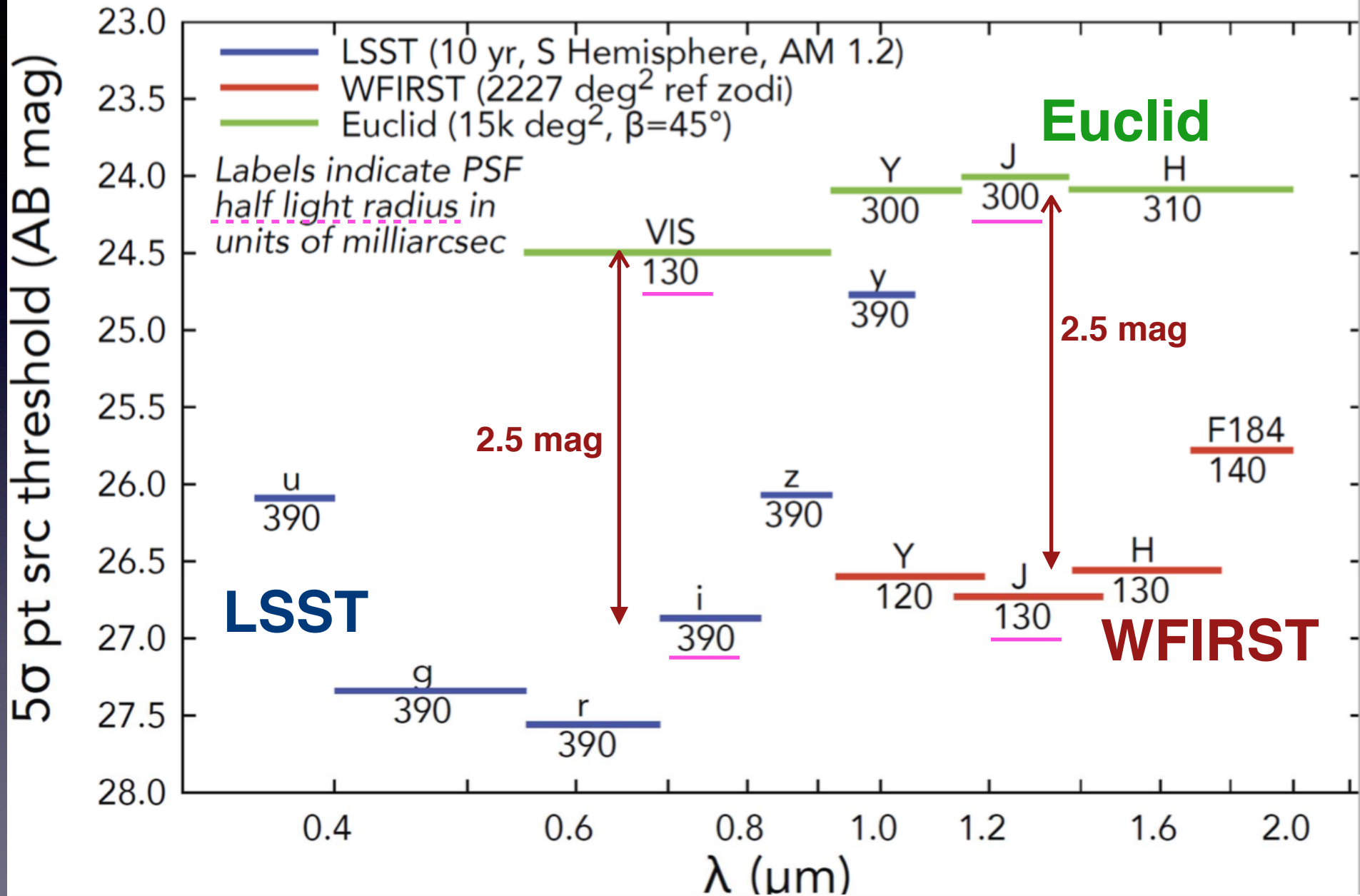
$m_5 \sim 27$

$r_{1/2} \sim 0.4$ arcsec

2022-2032

	LSST	WFIRST <small>SPACE!</small>	Euclid <small>SPACE!</small>
Start	2022 (2020)	~2024	2021
Area	18,000	2,300*	15,000
Location	~south	Overlap LSST	Best
Time	10 years	2 of 6 years	6 years
Passes	Many	~5	1
Depth	25-28 optical	27 NIR	24.5 optical and NIR
Bands	ugrizy	4 NIR	1 wide optical, 3 NIR
Spectra	No	Grism & IFC	Grism

Sensitivities of LSST, WFIRST, and Euclid



Stage IV	DESI	LSST	Euclid	WFIRST
Starts, duration	~2018, 5 yr	2020, 10yr	2020 Q2, 6.25yr	~2025, 5-6 yr
Area (deg ²)	14,000 (N)	20,000 (S)	15,000 (N + S)	2,400 (S)
FoV (deg ²)	7.9	10	0.53	0.281
Diameter (m)	4 (less 1.8+)	6.7	1.3	2.4
Spectroscopic	Y (fibers)		Y (grism)	Y (grism)
	LRGs+ELGs z~0.6-1.7 (20-30m), QSOs/Lya 1.9<z<4 (1m)		ELGs: z~0.7-2.1 (~20m)	ELGs: z =1-2 (20m), 2-3 (2m)
Photometric		Y	Y	Y
Galaxies (per sq arcmin)		~30 over 6 bands (ugrizy)	~30-35, in one broad optical + IR band	68, in 3 bands into near IR
SN1a		10 ⁴ -10 ⁵ SN1a/yr z = 0.-0.7 photometric		2700 SN1a z = 0.1-1.7 IFU spectroscopy

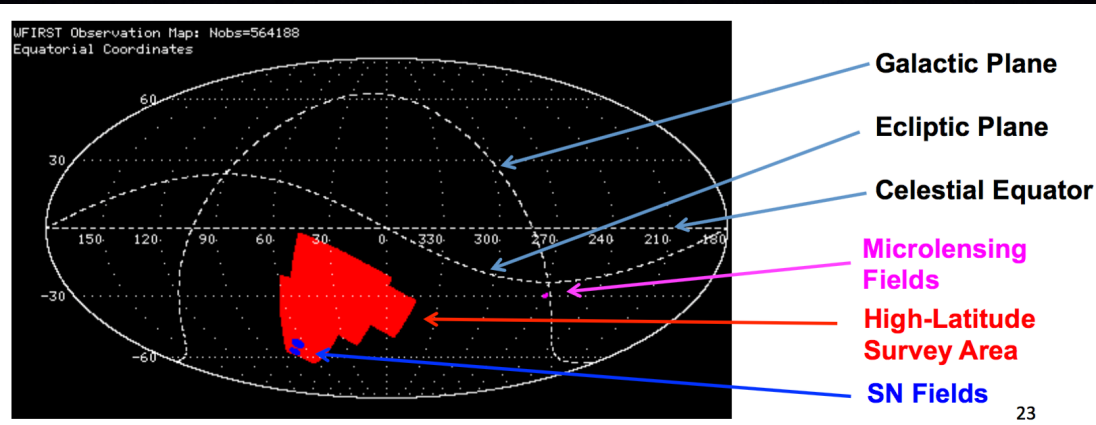
Rachel Bean, BNL, May 2016

LSST estimates for the galaxy count density:

- 55 / sq. arcmin for the total count to $i < 25.3$ ("gold sample")
- 40 / sq. arcmin (+20%) for the WL sample

WFIRST, LSST and Euclid are highly complementary missions.

WFIRST



About 2,200 sq.deg. will be covered by all three surveys: 0.12 arcsec in VIS and YJH and photometry in ugrizyYJH

At least about 7,000 sq.deg. of Euclid-LSST overlap: VIS and photometry in ugrizyYJH

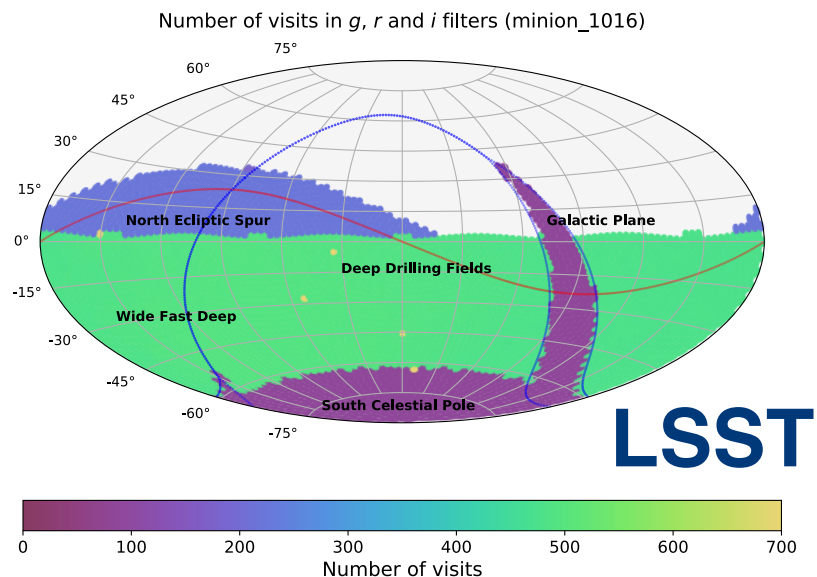
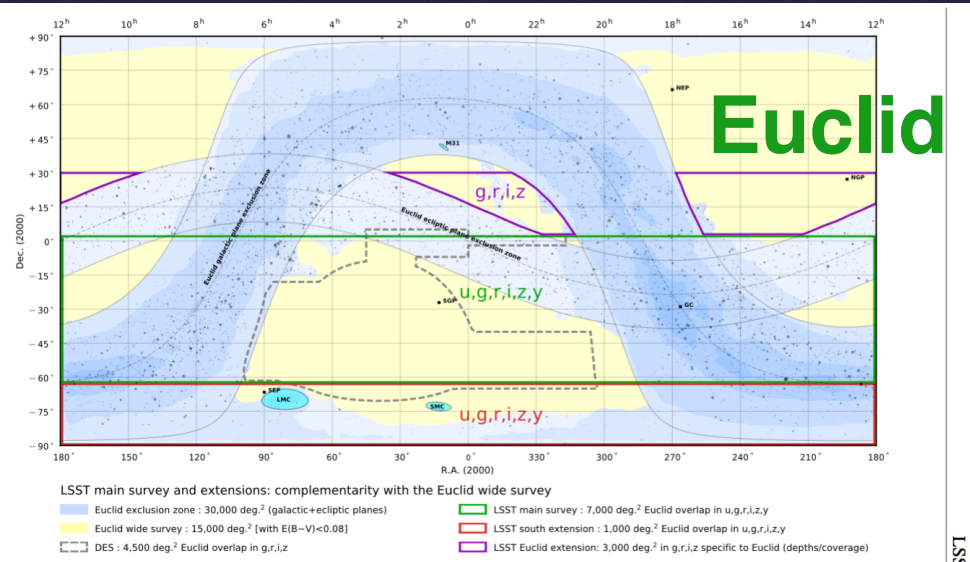
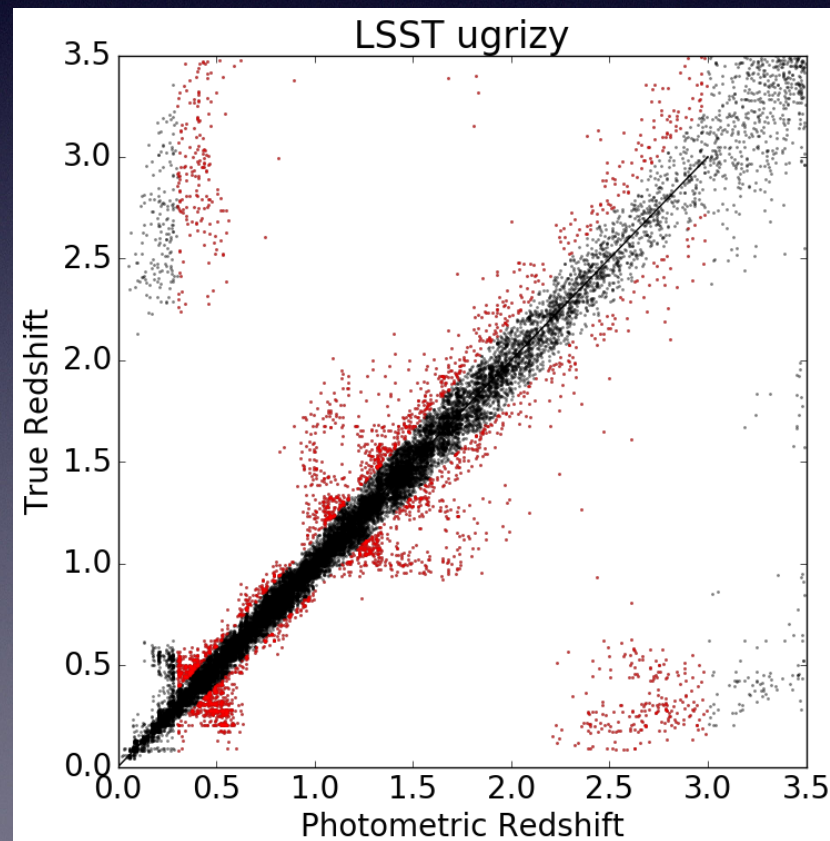


Figure 4.3.1: LSST survey areas (boxes) and the Euclid wide survey (yellow) with its exclusion zones (blue: galactic plane + ecliptic plane + reddening). We indicate the number of square degrees from the LSST surveys that overlap the Euclid wide survey along the relevant photometric bands. The points of interest indicated on this equatorial coordinate projection centered on the south galactic cap are: North&South Ecliptic&Galactic Poles (NEP/SEP/NGP/SGP), the Galactic Center (GC), the Magellanic Clouds (LMC/SMC), and the Andromeda galaxy (M31).

1) WFIRST-LSST-Euclid: about 2,200 sq.deg. will be covered by all three surveys: 0.12 arcsec in VIS and YJH and photometry in ugrizYJH
- with 68 gals/arcmin²: 0.5B galaxies

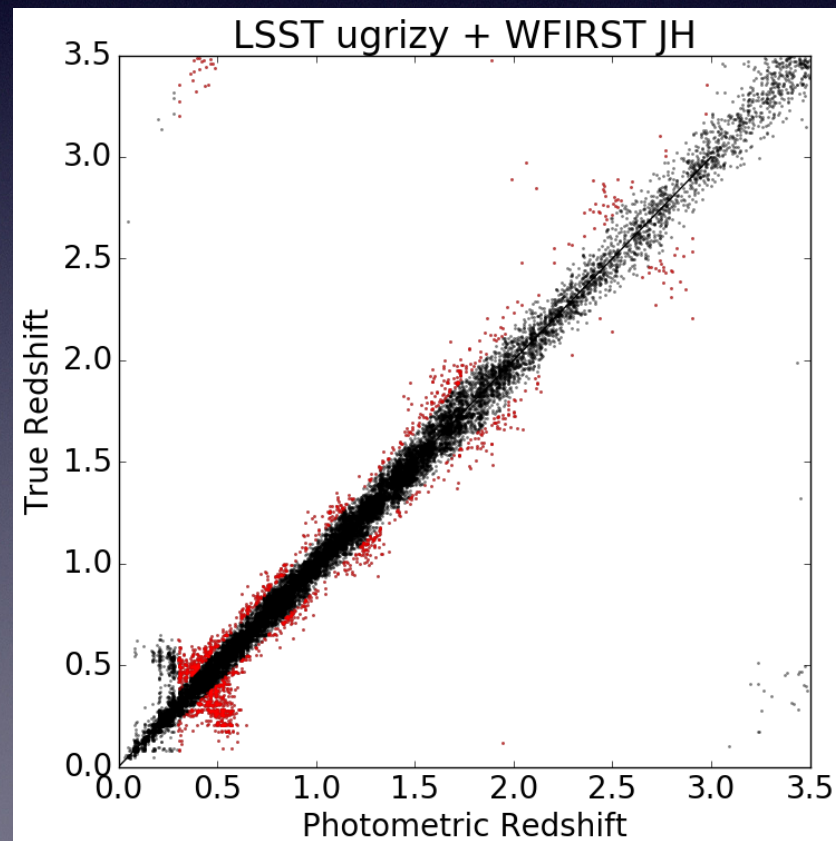
Addition of WIFRST photometry significantly improves photometric redshifts at $z > 2$



Thanks to Melissa Graham

1) **WFIRST-LSST-Euclid: about 2,200 sq.deg. will be covered by all three surveys: 0.12 arcsec in VIS and YJH and photometry in ugrizYJH**
- with 68 gals/arcmin²: 0.5B galaxies

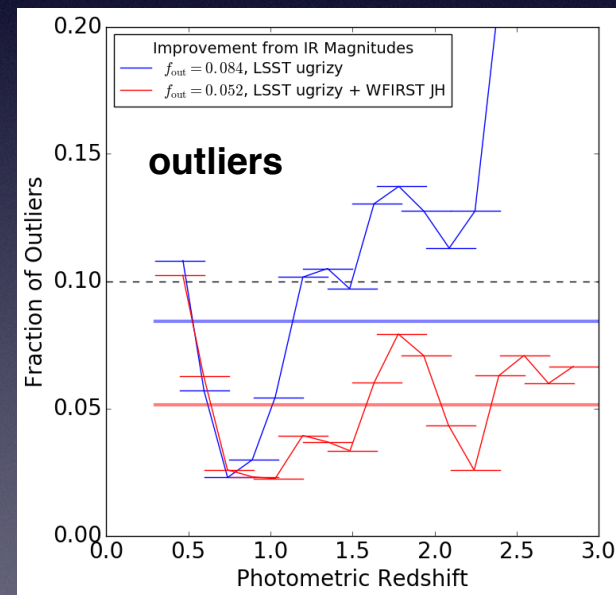
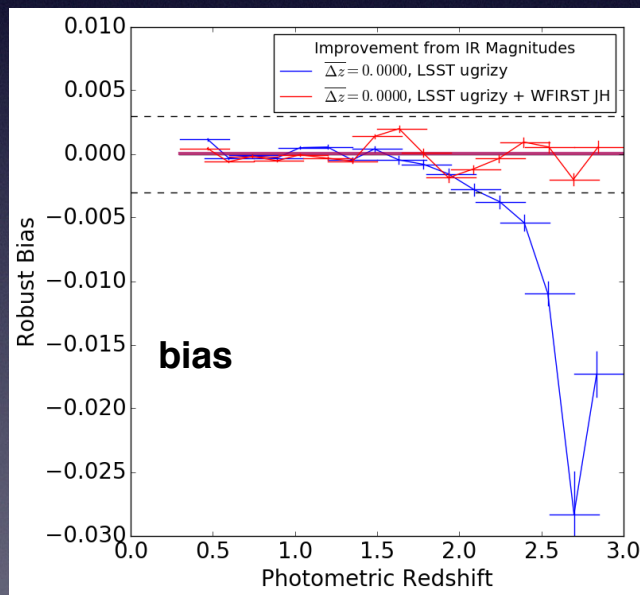
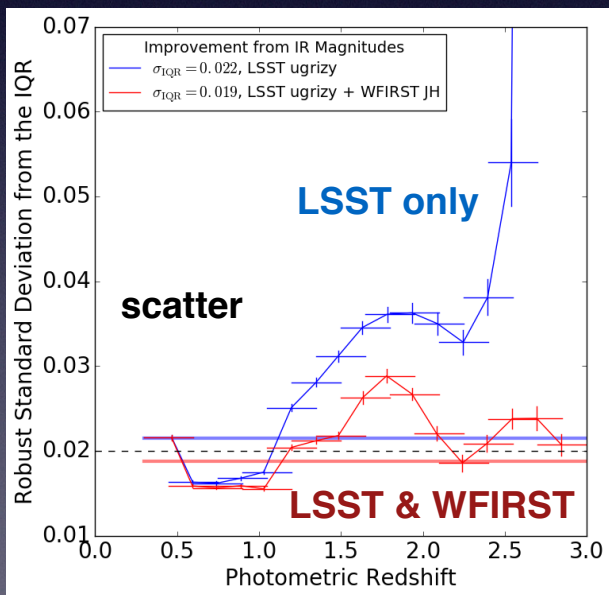
Addition of WFIRST photometry significantly improves photometric redshifts at $z > 2$



Thanks to Melissa Graham

1) WFIRST-LSST-Euclid: about 2,200 sq.deg. will be covered by all three surveys: 0.12 arcsec in VIS and YJH and photometry in ugrizYJH - with 68 gals/arcmin²: 0.5B galaxies

Addition of WFIRST photometry significantly improves photometric redshifts at $z > 2$



Thanks to Melissa Graham

- 1) WFIRST-LSST-Euclid: about 2,200 sq.deg. will be covered by all three surveys: 0.12 arcsec in VIS and YJH and photometry in ugrizYJH**
 - with 68 gals/arcmin²: 0.5B galaxies

- 2) At least about 7,000 sq.deg. of Euclid-LSST overlap: VIS (0.13 arcsec) and photometry in ugrizyYJH (it could be increased to 10,000 sq.deg.)**
 - with 40 gals/arcmin²: 1.0B galaxies

- 3) LSST alone, compared to 1):**
 - ~8 times larger area
 - ~5 times more well-resolved galaxies (~2.6B at 40 gals/arcmin²)
 - but no JH photometry and
 - ~3 times larger PSF

1) WFIRST-LSST-Euclid: about 2,200 sq.deg. will be covered by all three surveys: 0.12 arcsec in VIS and YJH and photometry in ugrizYJH
- with 68 gals/arcmin²: 0.5B galaxies

2) At least about 7,000 sq.deg. of Euclid-LSST overlap: VIS (0.13 arcsec) and photometry in ugrizyYJH (it could be increased to 10,000 sq.deg.)
- with 40 gals/arcmin²: 1.0B galaxies

3) LSST alone, compared to 1):

~8 times larger area

~5 times more well-resolved galaxies (~2.6B at 40 gals/arcmin²)

but no JH photometry and

~3 times larger PSF

How to best utilize these overlapping samples?

- see white paper “The Whole is Greater than the Sum of the Parts: Optimizing the Joint Science Return from LSST, Euclid and WFIRST” by Jain et al. (2015, arXiv:150107897)
- upcoming white paper “Scientific Synergy between LSST and Euclid” by Rhodes et al. (LSST DESC, in prep.)
- “Enabling Cosmological Resonances Between WFIRST and LSST” workshop, Sep 13-15, 2016, the KISS center, Caltech

Synergies between WFIRST, LSST and Euclid:

- photometric calibration
- shear calibration (additive and multiplicative biases)
- photo-z improvements (spec. & due to extended wavelength range)
- non-cosmological benefits from extended wavelength range
- high-resolution space data for deblending and crowded fields
- spectroscopy from Euclid and WFIRST, time domain from LSST
- cross-calibration of systematics ("The whole is greater than the sum...")

Sources of systematics:

- blending
- chromatic PSFs
- imperfect galaxy models
- astrophysical systematics (intrinsic alignments, evolution)

Coordination needs between WFIRST, LSST and Euclid:

- cadence coordination (deep fields, coeval observations)
- for WFIRST-HLS, it would be good if LSST obtained the full depth early
- for Euclid, it would be good if LSST covered more northern sky
- coordinated data releases (with cross-correlated data products)
- joint pixel-level processing
- cosmological simulations

These needs differ greatly in urgency, complexity and uniqueness.

Most are outside the current scope of all three projects.

Political and other issues are being addressed by Euclid/DESC/LSST discussions and a Tri-Agency/Tri-Project group in the US.

Steven M. Kahn

LSST Director

Stanford/SLAC/AURA

Astronomy and Astrophysics Advisory Committee Meeting

NASA/Goddard Space Flight Center

January 29, 2016

Joint Pixel Level Processing Between LSST, Euclid, and WFIRST

- * Cooperation with Euclid requires special consideration, because, at present, most Euclid Consortium members will not have access to LSST data, and most Americans will not have access to Euclid data during the proprietary periods.
- * Draft agreements between the Euclid Consortium, the LSST Project, and the LSST DESC have been generated on both sides of the Atlantic, but, to date, none has been found acceptable to all sides.
- * We are now reforming a Euclid/LSST discussion group to try to work this, first by cooperatively developing the science case, and then an implementation plan.
- * But this process will be drawn out, and we do not expect an agreement on a very short timescale.

Coordination needs between WFIRST, LSST and Euclid:

- cadence coordination (deep fields, coeval observations)
- for WFIRST-HLS, it would be good if LSST obtained the full depth early
- for Euclid, it would be good if LSST covered more northern sky
- coordinated data releases (with cross-correlated data products)
- joint pixel-level processing
- cosmological simulations

What is the worst case scenario if no convergence on coordination?

What science would be lost if no coordination?

What must be done to avoid significant shortcomings?

Coordination needs between WFIRST, LSST and Euclid:

- cadence coordination (deep fields, coeval observations)
- for WFIRST-HLS, it would be good if LSST obtained the full depth early
- for Euclid, it would be good if LSST covered more northern sky
- coordinated data releases (with cross-correlated data products)
- joint pixel-level processing
- cosmological simulations

What is the worst case scenario if no convergence on coordination?

What science would be lost if no coordination?

What must be done to avoid significant shortcomings?

Coordination needs between WFIRST, LSST and Euclid:

1) cadence coordination (deep fields, coeval observations)

- not super urgent, but should be accomplished on time scales of a few years at most for maximum effects

2) joint pixel-level processing

- it would help with deblending, galaxy photometry, sky subtraction...
- not super urgent, but if postponed for too long, there may be missed opportunities in data processing systems
- we should start planning and designing essentially now, even if the “construction” will commence a few years later
- an important consideration here is human resources (institutional knowledge, retaining talent)

Summary

WFIRST, LSST and Euclid are highly complementary missions.

Coordination needs between WFIRST, LSST and Euclid:

- cadence coordination
- coordinated data releases
- joint pixel-level processing
- cosmological simulations

