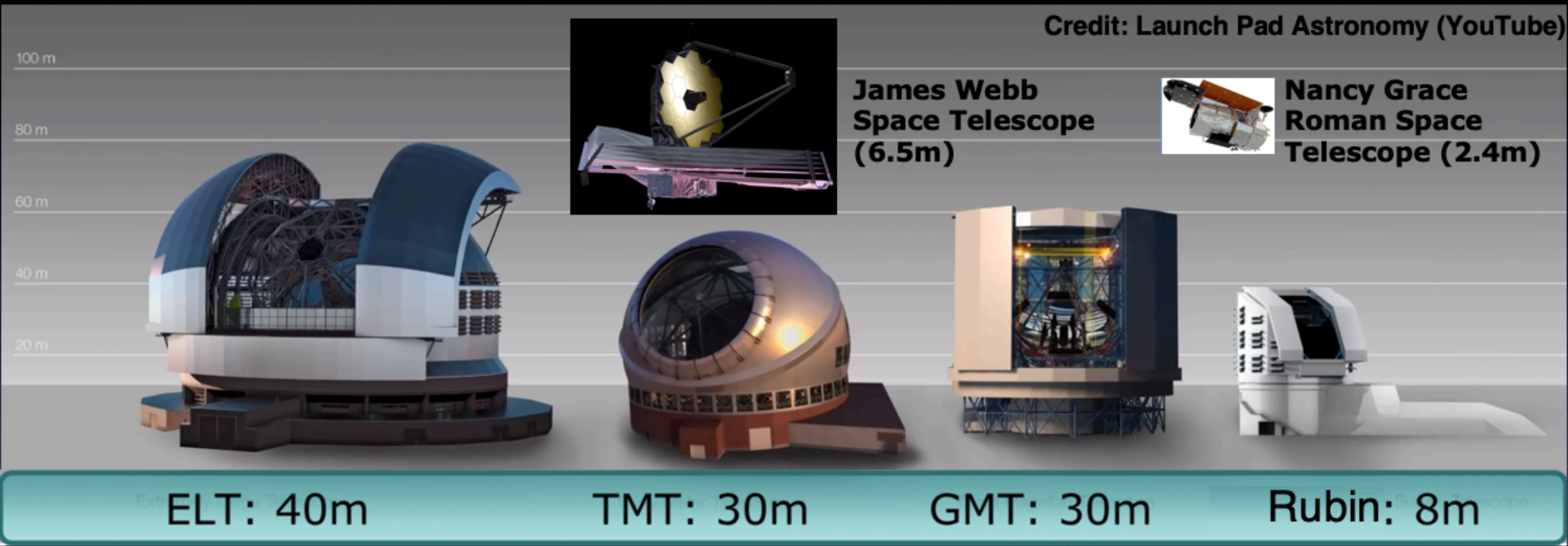
LSST: the Greatest Movie of All Time

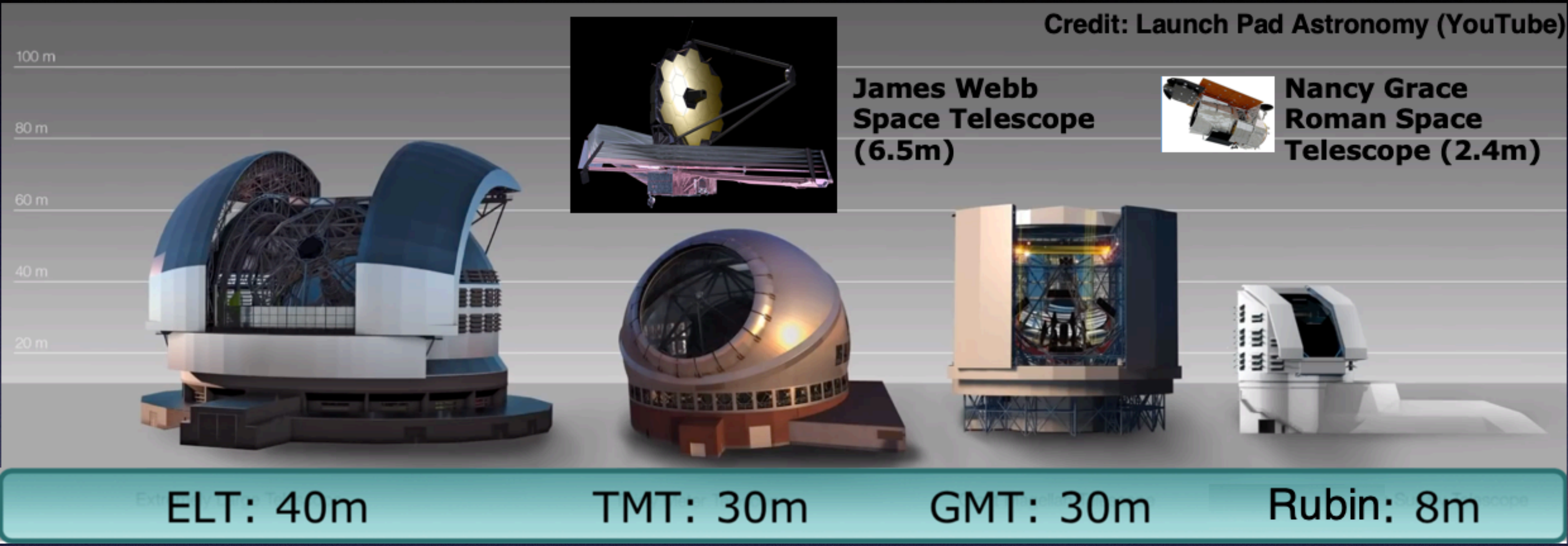
Željko Ivezić (pronounced as Bill)
University of Washington
RubinObs Deputy Director
LSST Project Scientist

VERA C. RUBIN OBSERVATORY

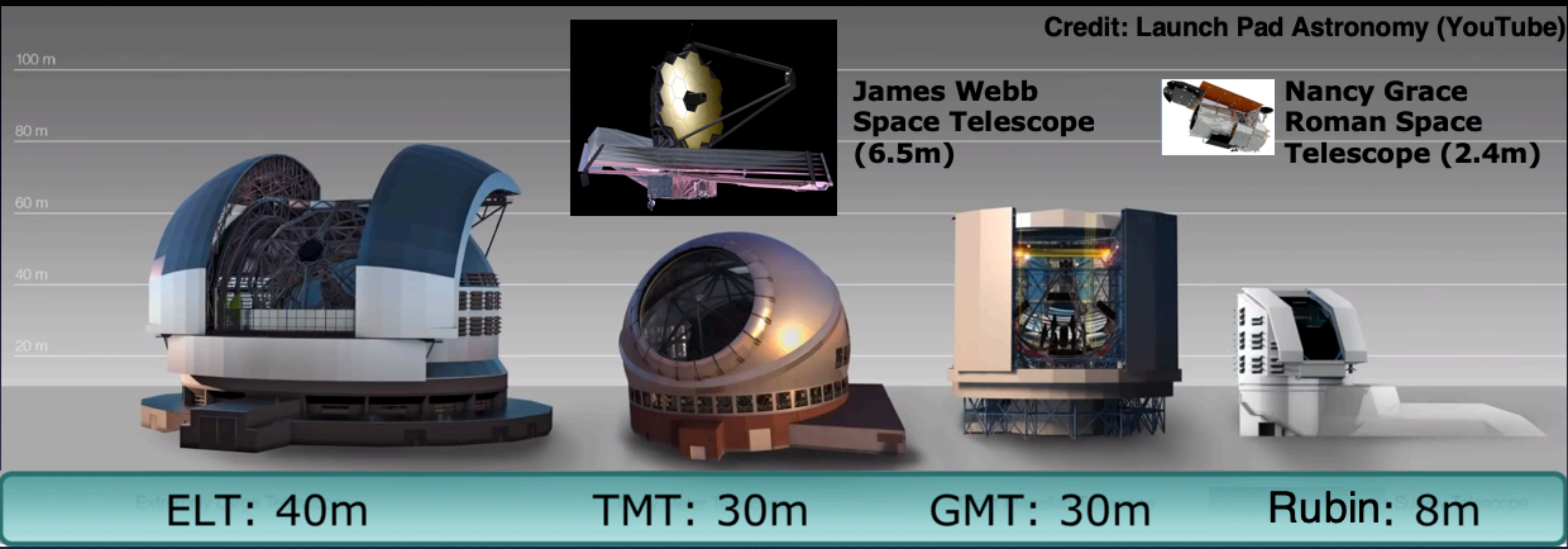
This talk available as:
http://ls.st/ny0

Minnesota Institute for Astrophysics Colloquium, April 16, 2021


Credit: Launch Pad Astronomy (YouTube)
100 m
80 m
60 m
40 m
20 m
James Webb Space Telescope (6.5m)
Nancy Grace Roman Space Telescope (2.4m)
ELT: 40m
TMT: 30m
GMT: 30m
Rubin: 8m



Rubin Obs. will not have the largest mirror but will have by far the largest product of the mirror area and the field-of-view size (etendue or throughput)



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LSST will be delivered by the Vera C. Rubin Observatory, as its first, 10-year, project

Outline

- Rubin Observatory construction status report
  - multi-color time-resolved faint sky map
  - 20 billion stars and 20 billion galaxies
- A tour of anticipated LSST science programs
  - cosmology (dark matter and dark energy)
  - time domain
  - the Milky Way structure
  - the Solar System structure
- Data analysis challenges ahead of us
  - large data sets
  - complex analysis
  - aiming for small systematics

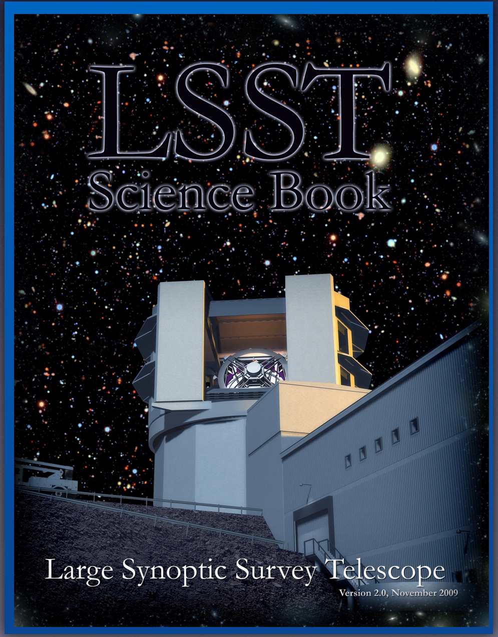
LSST Science Themes

- **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



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

3.6×10^{-31} erg/s/cm^2/Hz
36 nJy

LSST in one sentence:

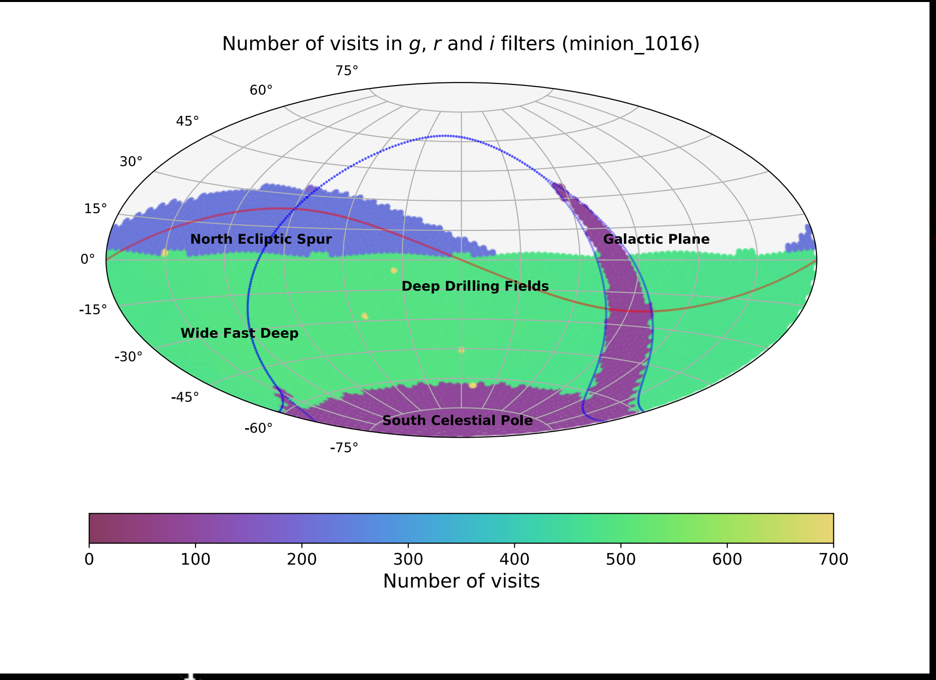
An optical/near-IR survey of half the sky in ugrizy bands to r~27.5 based on ~1000 visits over a 10-year period:

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

A catalog of 20 billion stars and 20 billion galaxies with exquisite photometry, astrometry and image quality!

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~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
gri
3.5’x3.5’
r~22.5

3 arcmin is 1/10 of the full Moon’s diameter

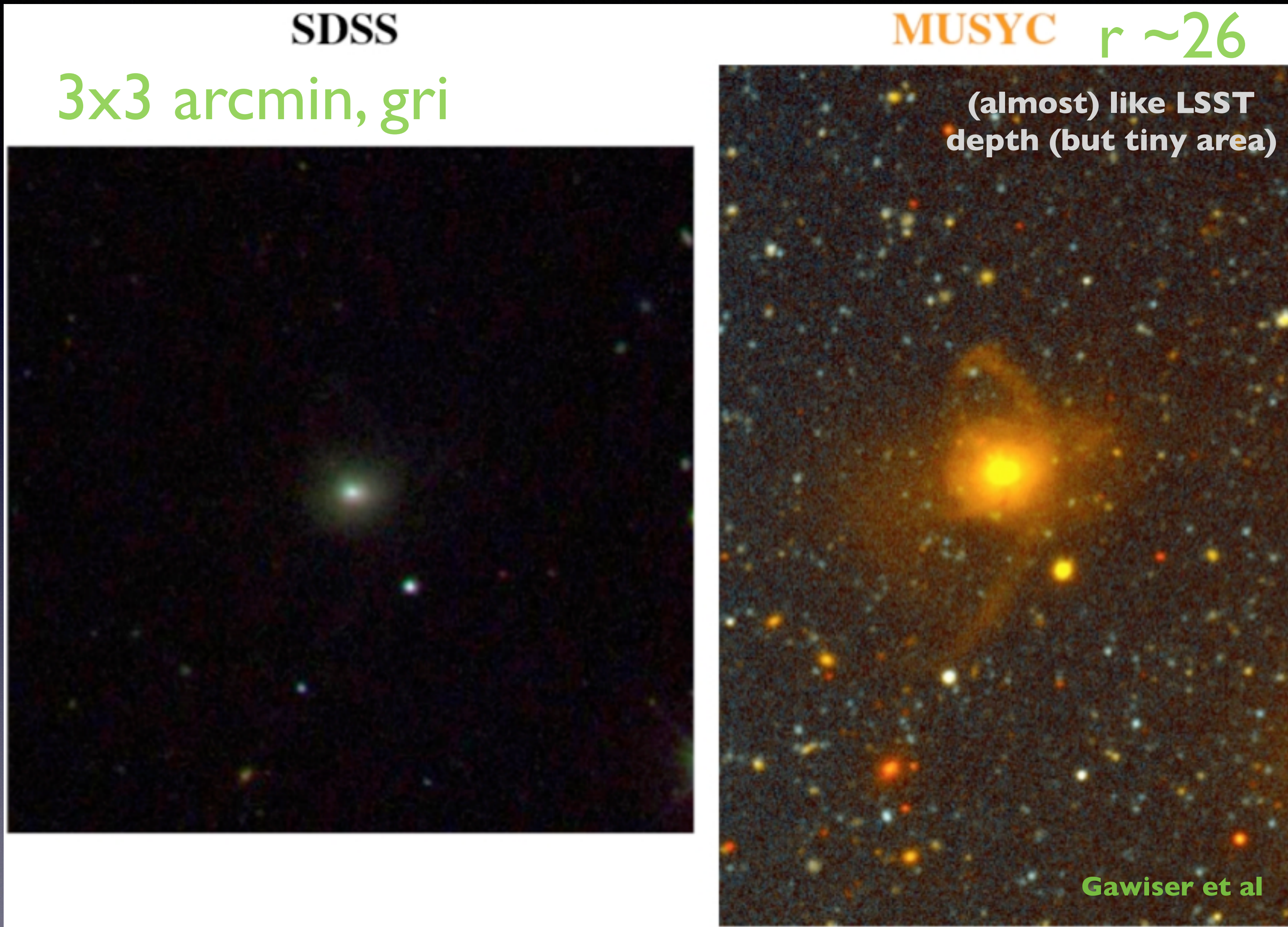
HSC
gri
3.5'x3.5'
r~27

3 arcmin is 1/10 of the full Moon's diameter

like LSST depth (but tiny area)

LSST will deliver 5 million such images

Extragalactic astronomy: faint surface brightness limit

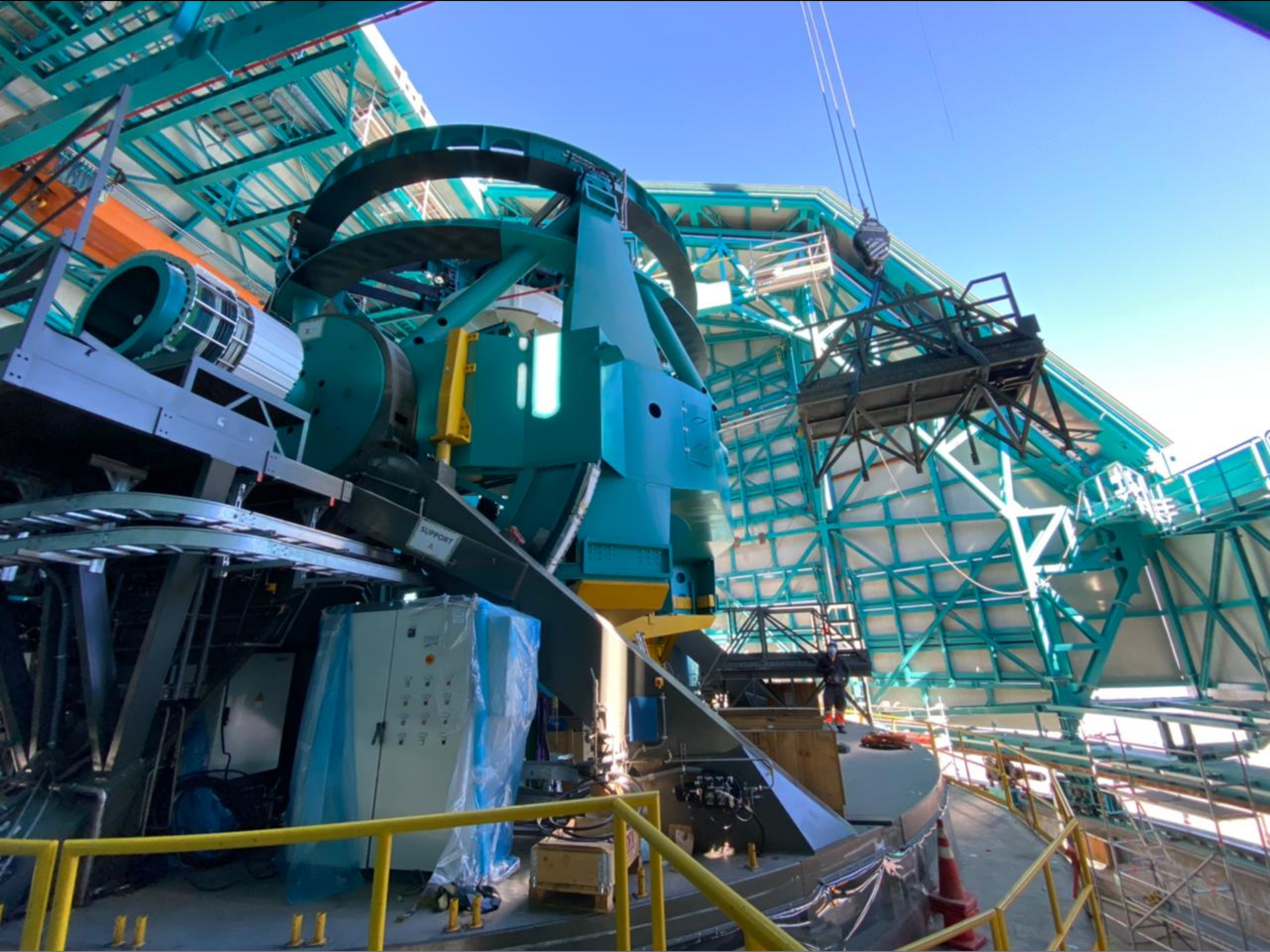


The rise of Vera C. Rubin Observatory: 2011-2021

8.4m, 6.7m effective

5 sec slew & settle

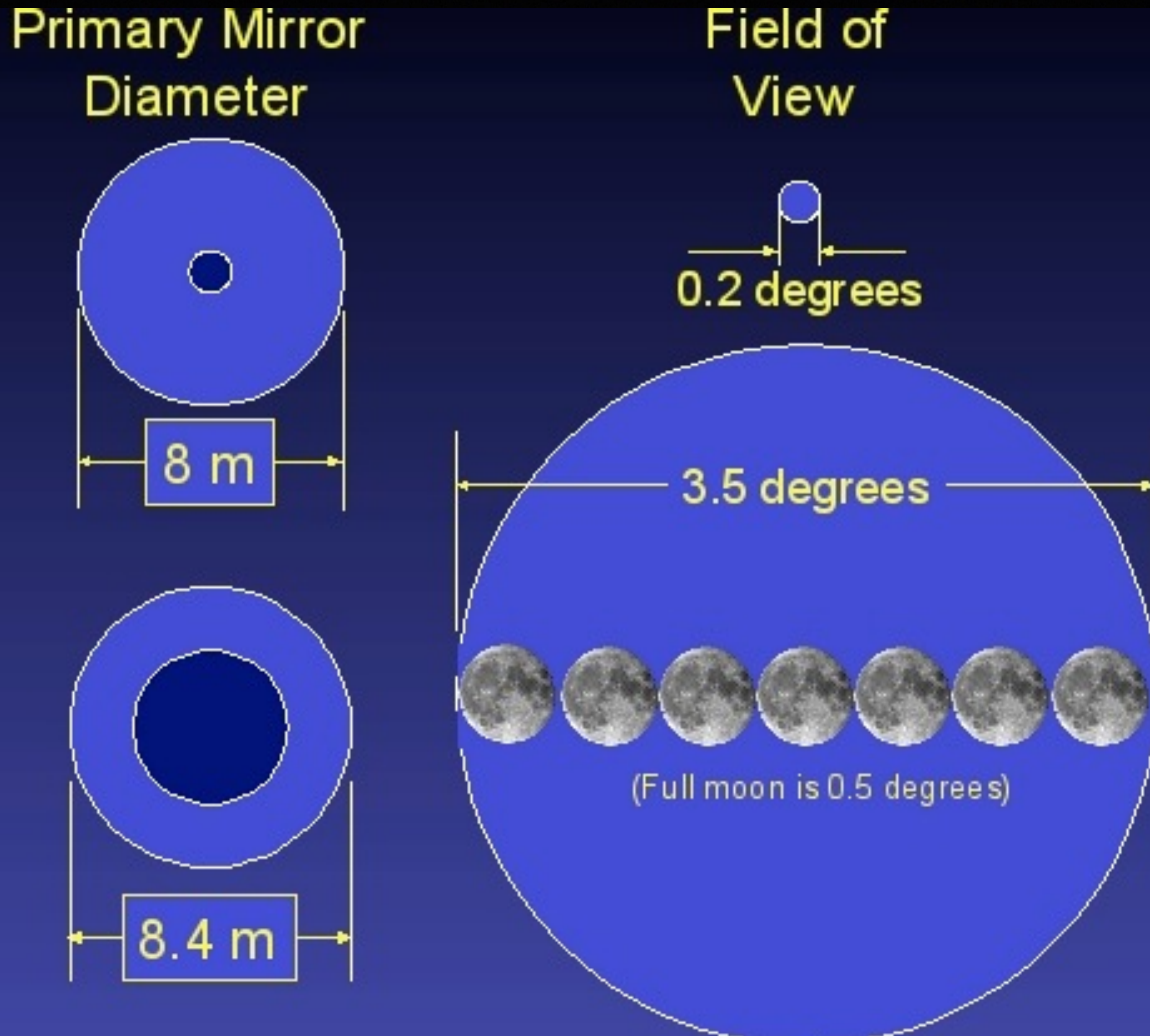
Telescope Mount Assembly before going from Spain to Chile


SUPPORT
A

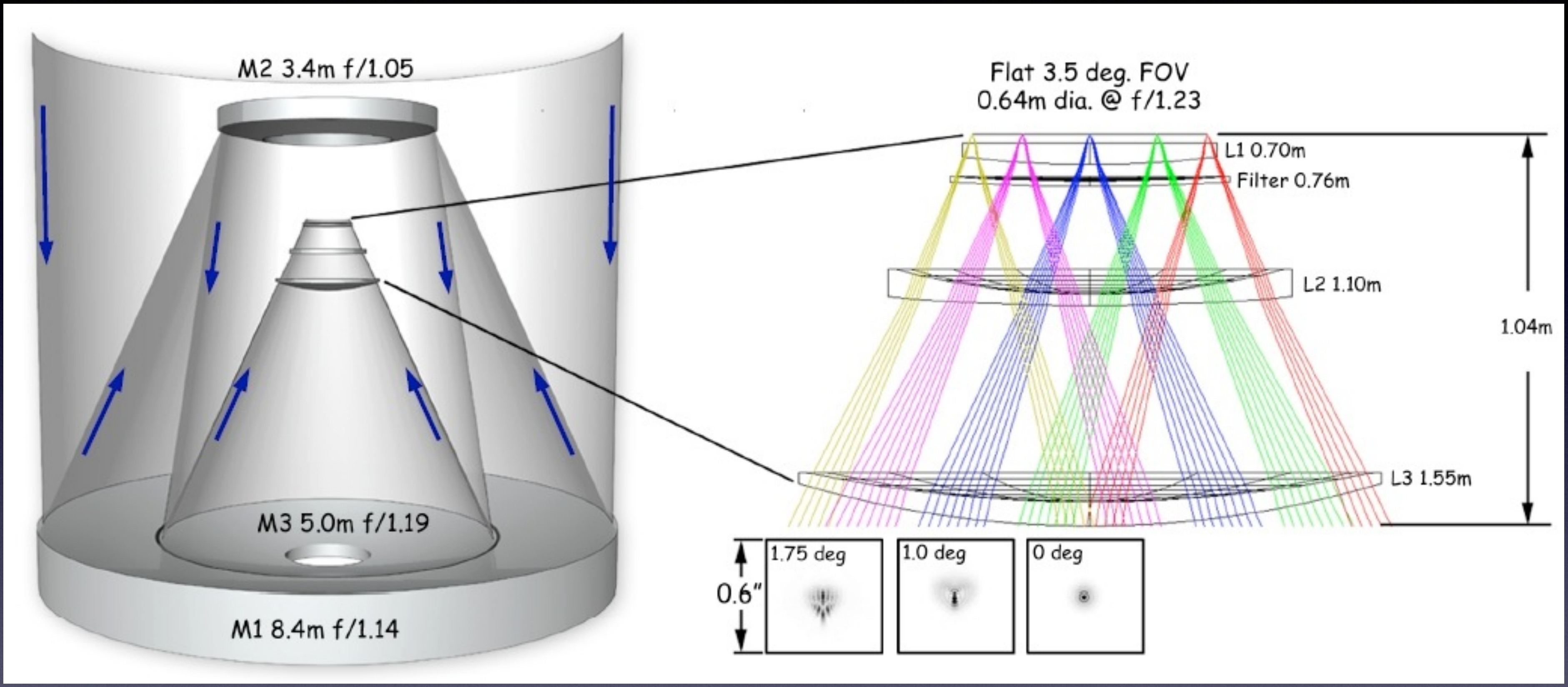
The field-of-view comparison: Gemini vs. LSST

Gemini South Telescope

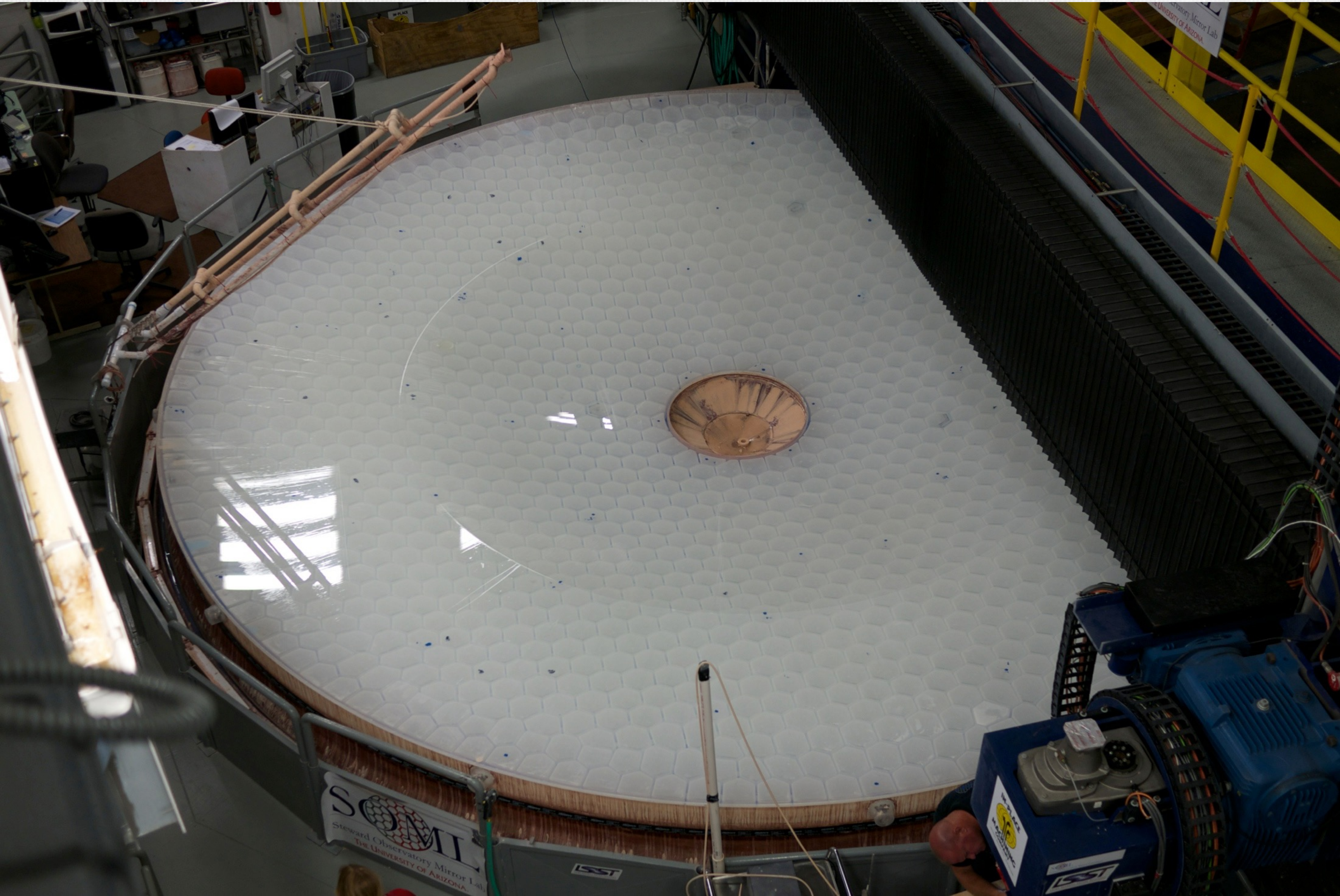
LSST



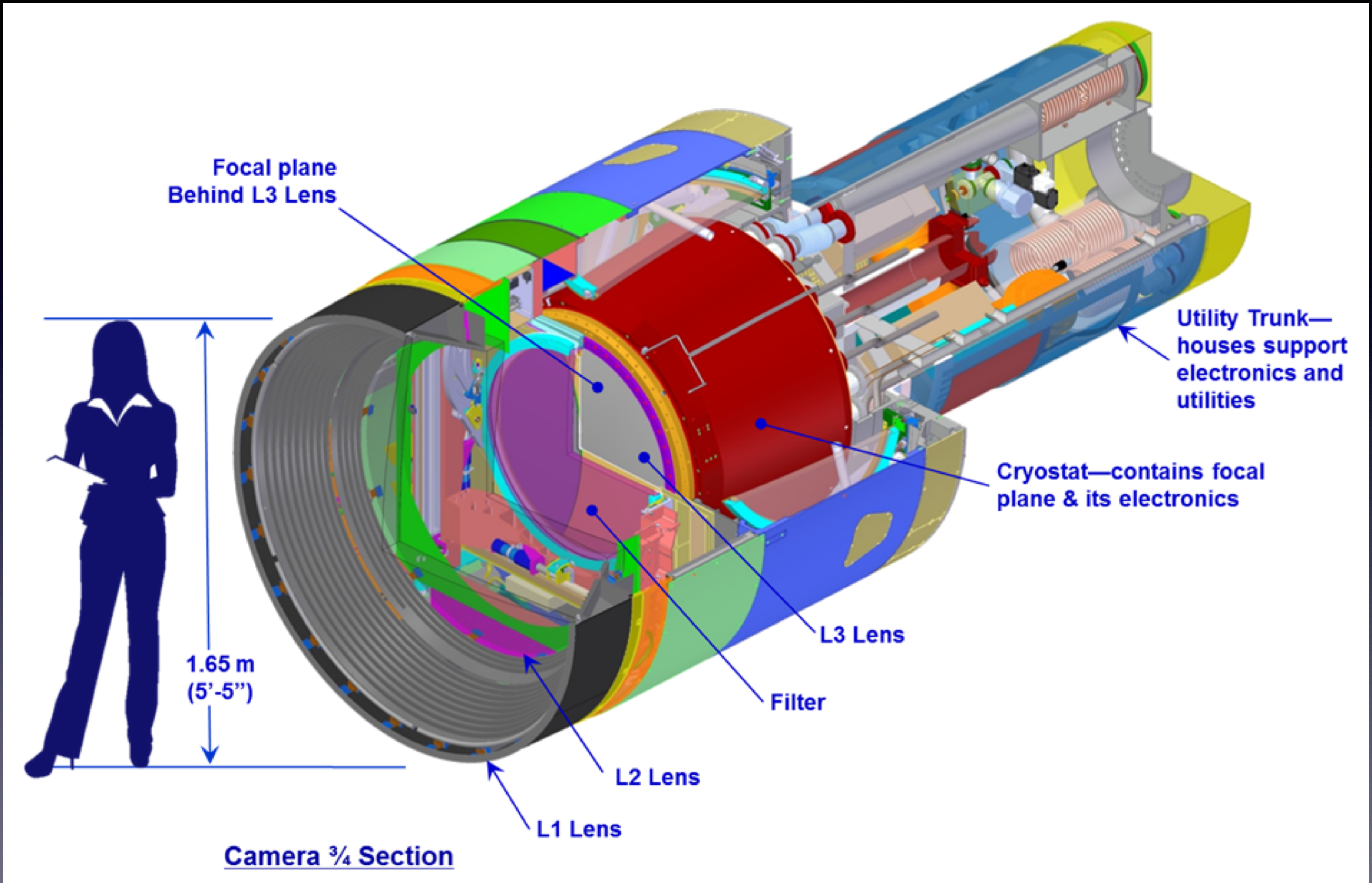
Optical Design for LSST



Three-mirror design (Paul-Baker system)
enables large field of view with excellent image quality:
delivered image quality is dominated by atmospheric seeing

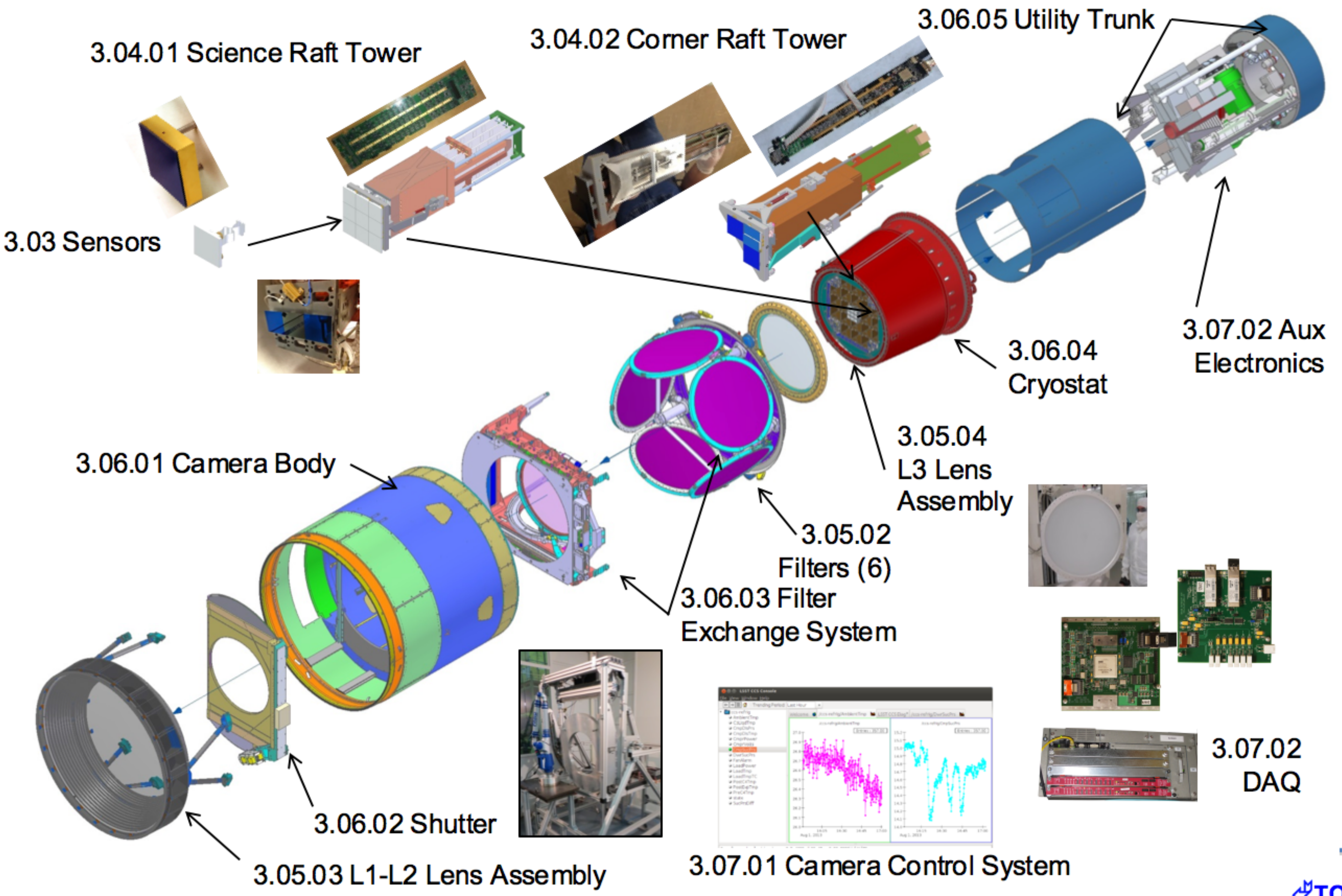

SOML
Steward Observatory Mirror Lab

LSST camera

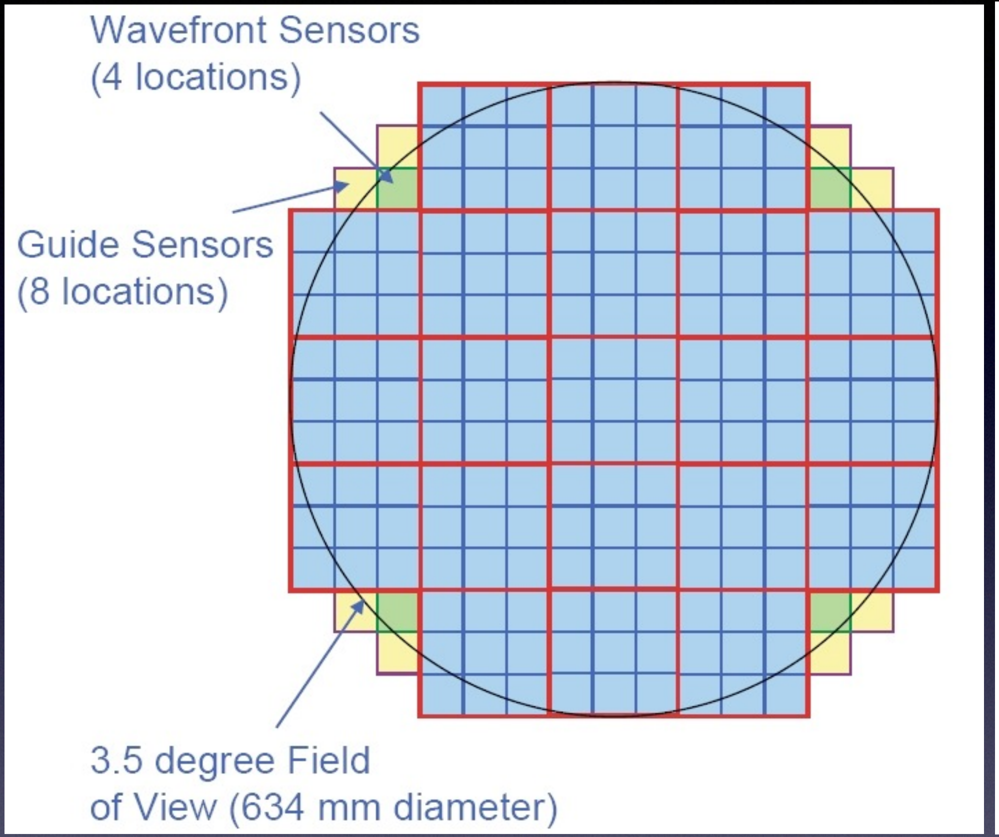


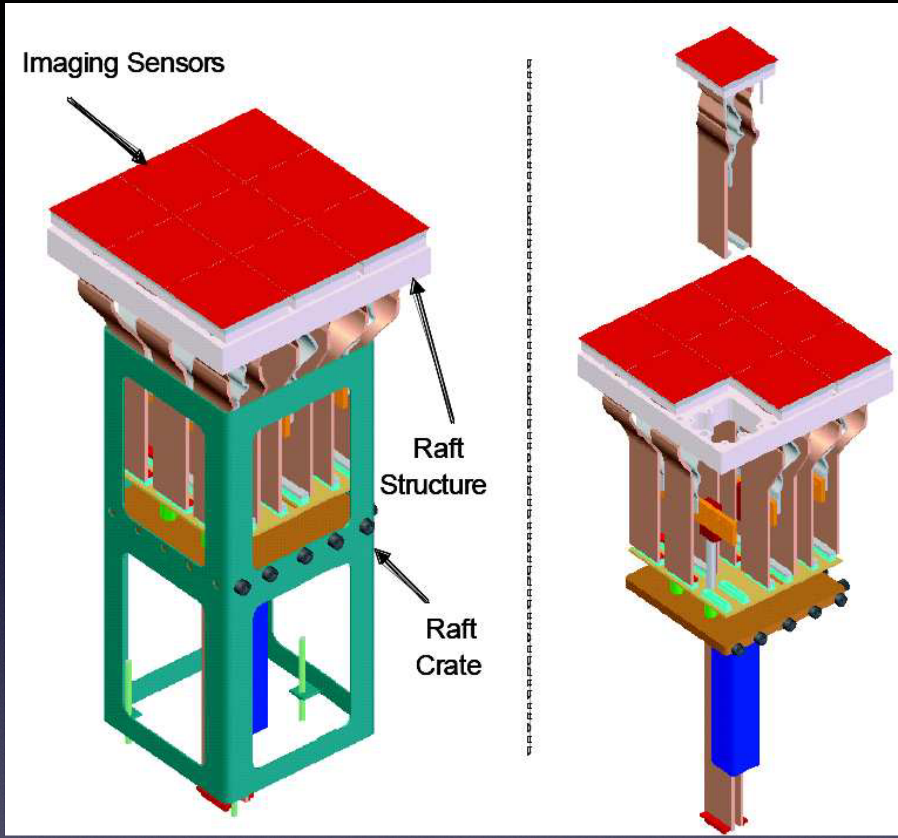
The largest astronomical camera: 2800 kg, 3200 Megapix

Major Camera Elements



LSST camera





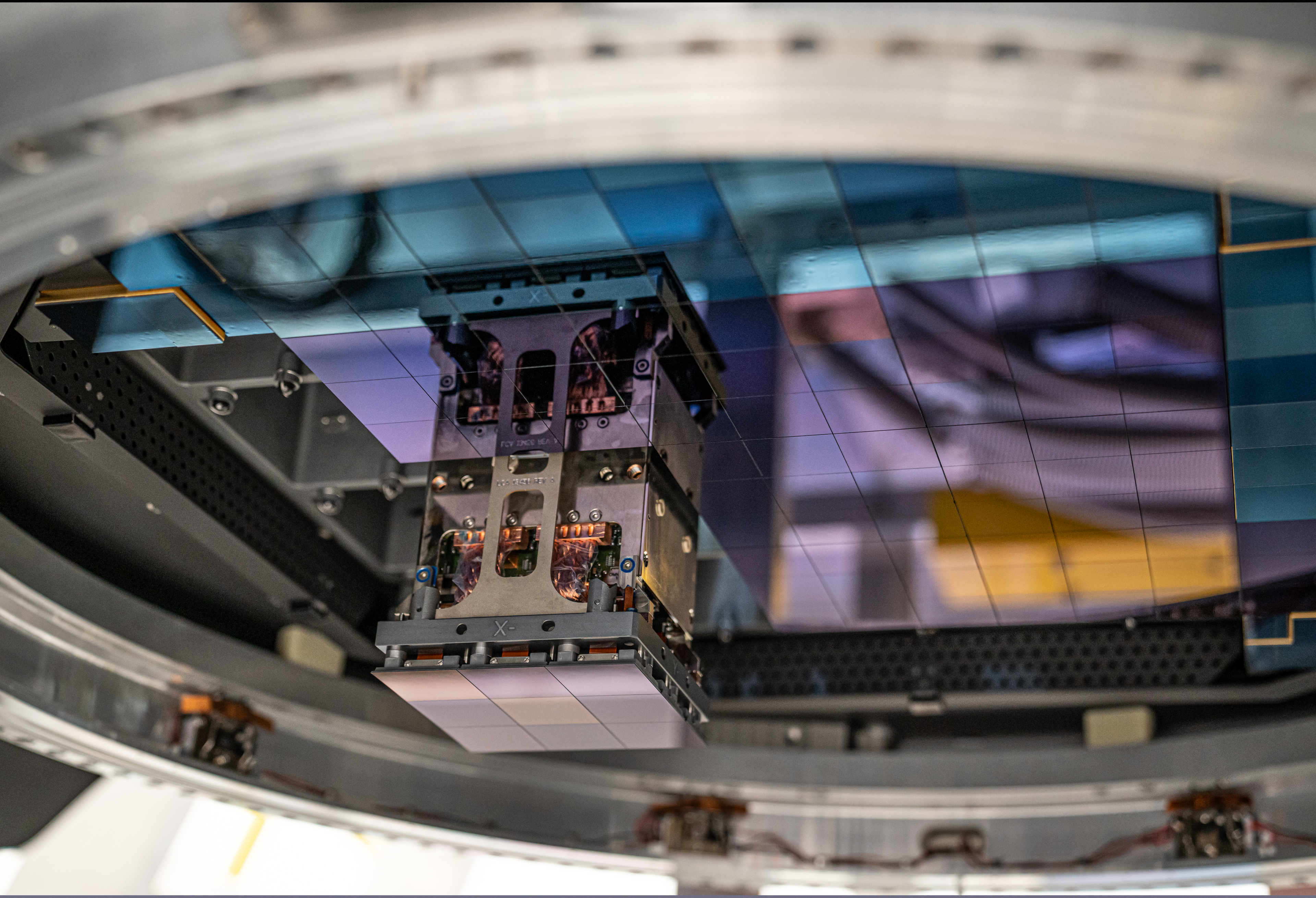
Modular design: 3200 Megapix = 189 x16 Megapix CCD

9 CCDs share electronics: raft (=camera)

Problematic rafts can be replaced relatively easily

LSST Science Sensor procurement (~200 CCDs) is complete!


OPTO ENGINEERING



Filter complement

- **Photometric redshifts for galaxies:** 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)

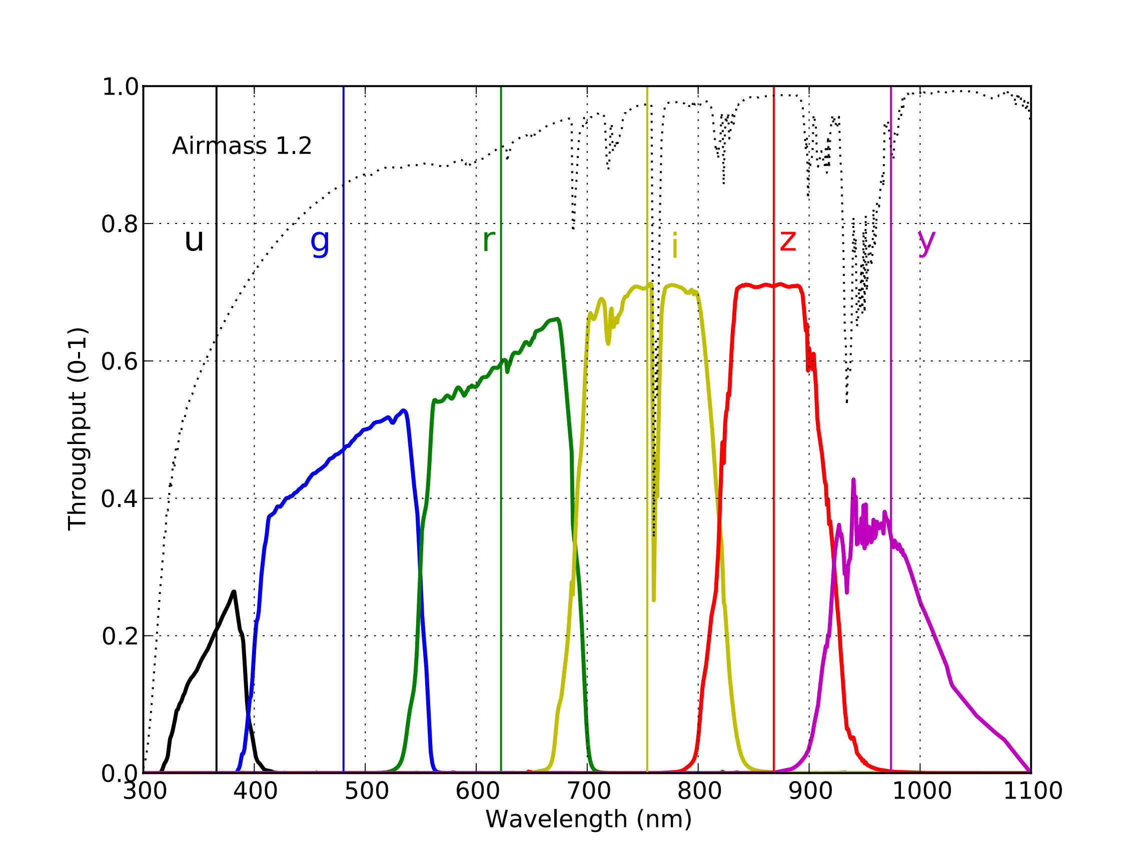


Photo-z requirements correspond to r~27.5 with the following per band time allocations:

u: 8%; g: 10%

r: 22%; i: 22%

z: 19%; y: 19%

Consistent with other science themes (stars)

LSST Large Synoptic Survey Telescope

LSST Operations: Sites & Data Flows

French Site
Satellite Processing Center
Data Release Production
Long-term Storage (copy 3)

HQ Site
Science Operations
Observatory Management
Education & Public Outreach

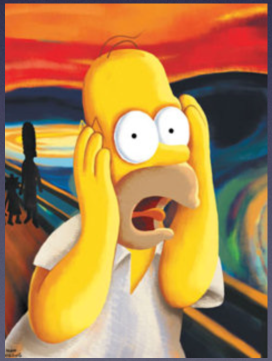
Archive Site
Archive Center
Alert Production
Data Release Production
Calibration Products Production
EPO Infrastructure
Long-term Storage (copy 2)
Data Access Center
Data Access and User Services

Base Site
Base Center
Long-term storage (copy 1)
Data Access Center
Data Access & User Services

Summit Site
Telescope & Camera
Data Acquisition
Crosstalk Correction

LSST Data Management System ("software")

- 20 TB of data to process every day (~one SDSS/day)
- 1000 measurements for 40 billion objects during 10 years
- Existing tools and methods (e.g. SDSS) do not scale up to LSST data volume and rate (100 PB!)



- About 5-10 million lines of code (C++/python)

At the highest level, LSST objectives are:

1) Obtain about 5.5 million images, with 189 CCDs (4k x 4k) in the focal plane; this is about **a billion 16 Megapixel images of the sky**

2) Calibrate these images (and provide other metadata)

3) Produce catalogs ("model parameters") of detected objects (37 billion)

4) **Serve** images, catalogs and all other metadata, that is, **LSST data products to LSST users**

The ultimate deliverable of LSST is not just the telescope, nor the camera, but **the fully reduced science-ready data** as well. **Software!**

LSST data products are organized into three main categories:

Prompt Data Products

Real Time Difference Image Analysis (DIA)

- A stream of ~10 million time-domain events per night (Alerts), transmitted to event distribution networks within 60s of camera readout.
- Images, Object and Source catalogs derived from DIA, and an orbit catalog for ~6 million Solar System bodies within 24h.
- Enables discovery and rapid follow-up of time domain events

Data Release Data Products

Reduced single-epoch & deep co-added images, catalogs, reprocessed DIA products

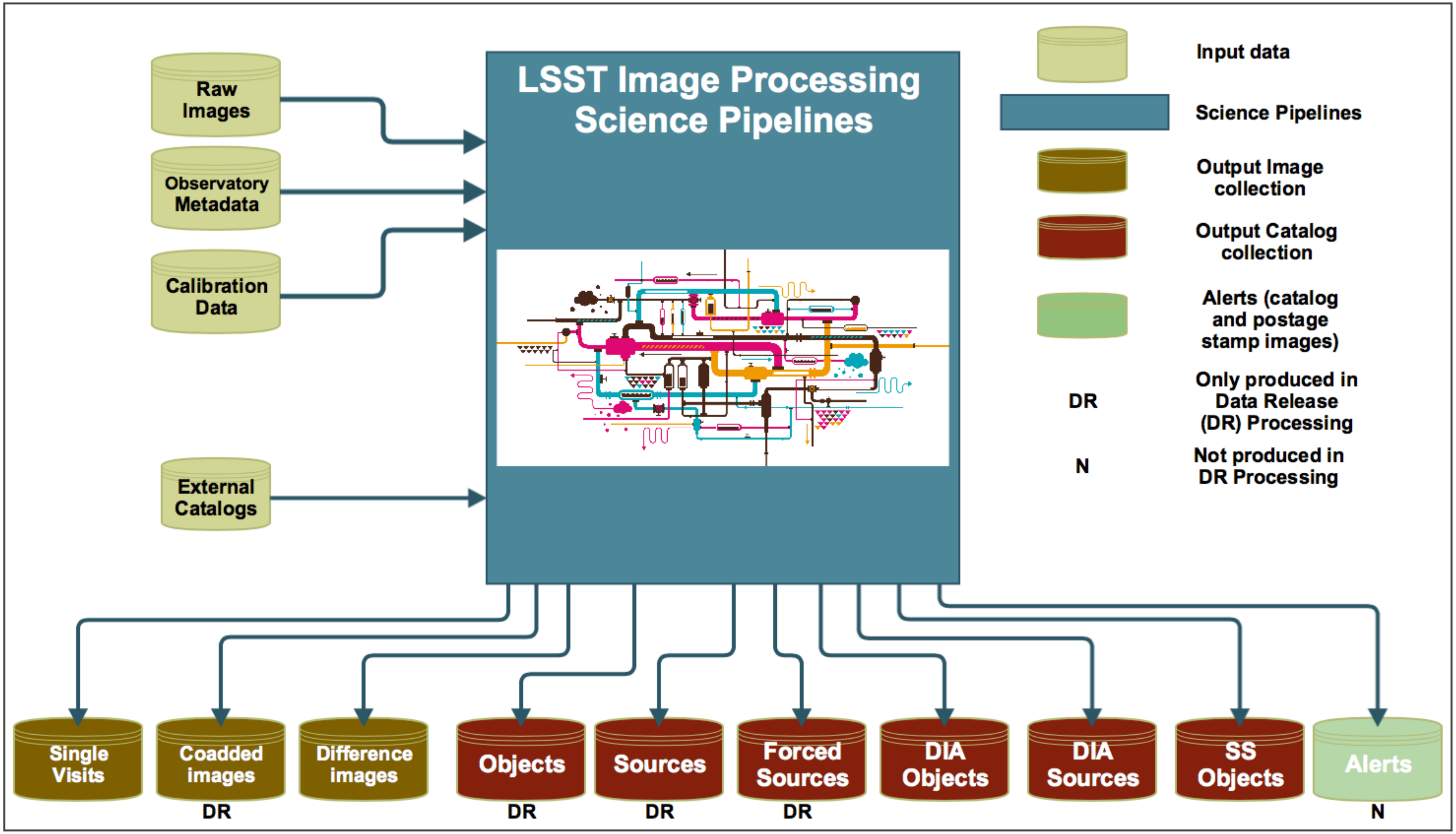
- Catalogs of ~37 billion objects (20 billion galaxies, 17 billion stars), ~7 trillion sources and ~30 trillion forced source measurements.
- 11 Data Releases, produced ~annually over 10 years of operation
- Accessible via the LSST Science Platform & LSST Data Access Centers.

User Generated Data Products

User-produced derived, added-value data products

- Deep KBO/NEO, variable star classifications, shear maps, etc …
- Enabled by services & computing resources at the LSST DACs and via the LSST Science Platform (LSP).
- 10% of LSST computing resources will be allocated for User Generated data product storage & processing.

LSST Data Products: see http://ls.st/dpdd

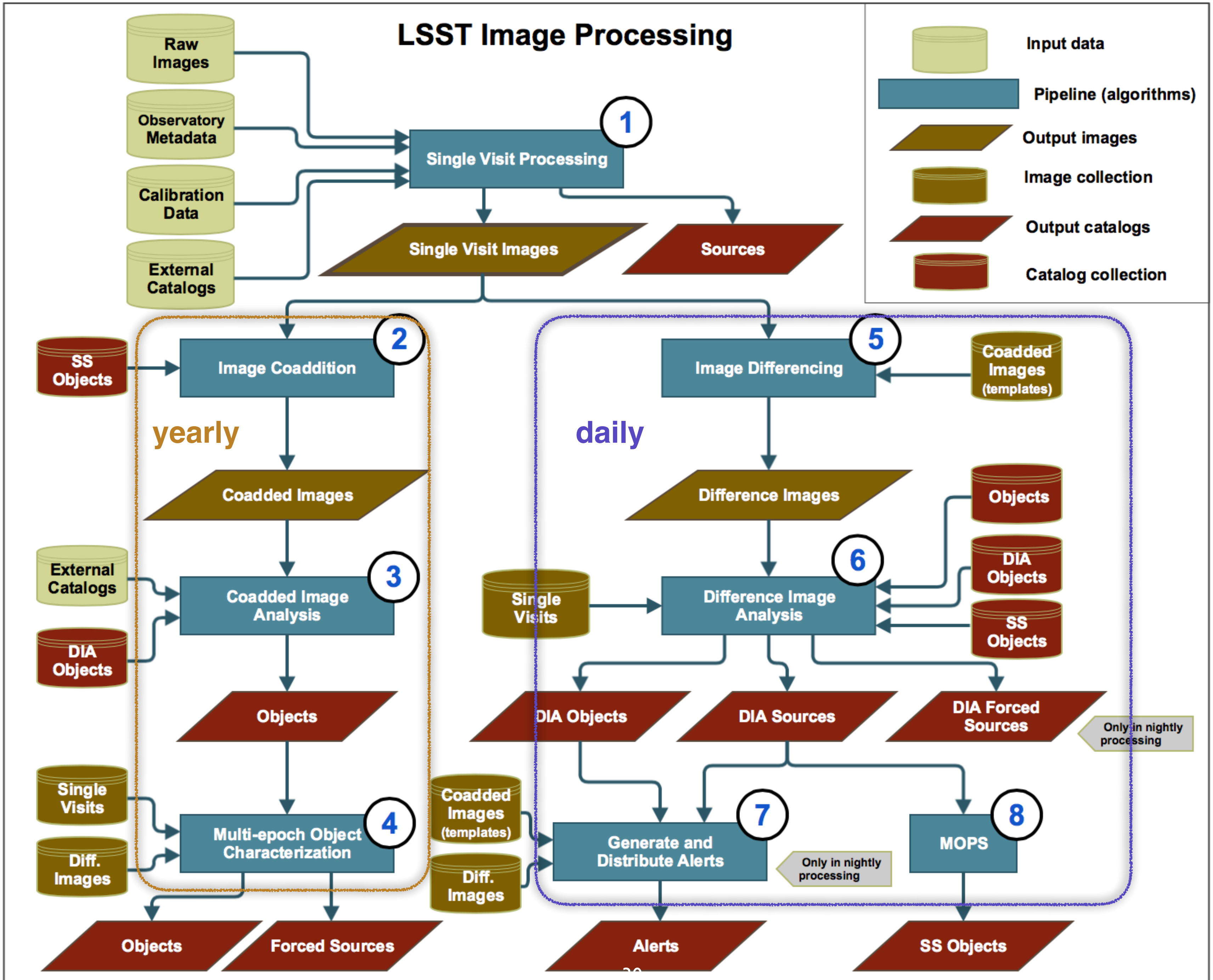


The main classes of LSST data products:

1) **Images**: single visit, coadded images, difference images
2) **Catalogs**:

Nightly Alert stream: DIA Sources, DIA Objects, SS Objects, Alerts

Yearly Data Releases: Sources, Forced Sources, Objects



LSST Image Processing
Raw Images
Observatory Metadata
Calibration Data
External Catalogs
1
Single Visit Processing
Single Visit Images
Sources
Input data
Pipeline (algorithms)
Output images
Image collection
Output catalogs
Catalog collection
2
Image Coaddition
SS Objects
yearly
Coadded Images
3
Coadded Image Analysis
External Catalogs
DIA Objects
Objects
4
Multi-epoch Object Characterization
Single Visits
Diff. Images
Objects
Forced Sources
5
Image Differencing
Coadded Images (templates)
daily
Difference Images
Objects
6
Difference Image Analysis
DIA Objects
SS Objects
Single Visits
DIA Objects
DIA Sources
DIA Forced Sources
Only in nightly processing
Coadded Images (templates)
Diff. Images
7
Generate and Distribute Alerts
Only in nightly processing
8
MOPS
Alerts
SS Objects

LSST all-hands meeting, Aug 2019

LSST all-hands meeting, Aug 2020

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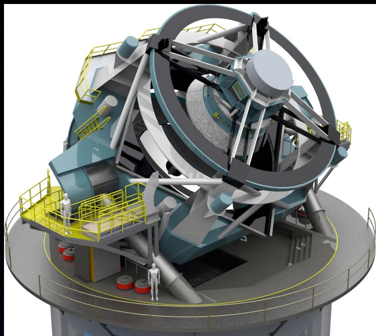
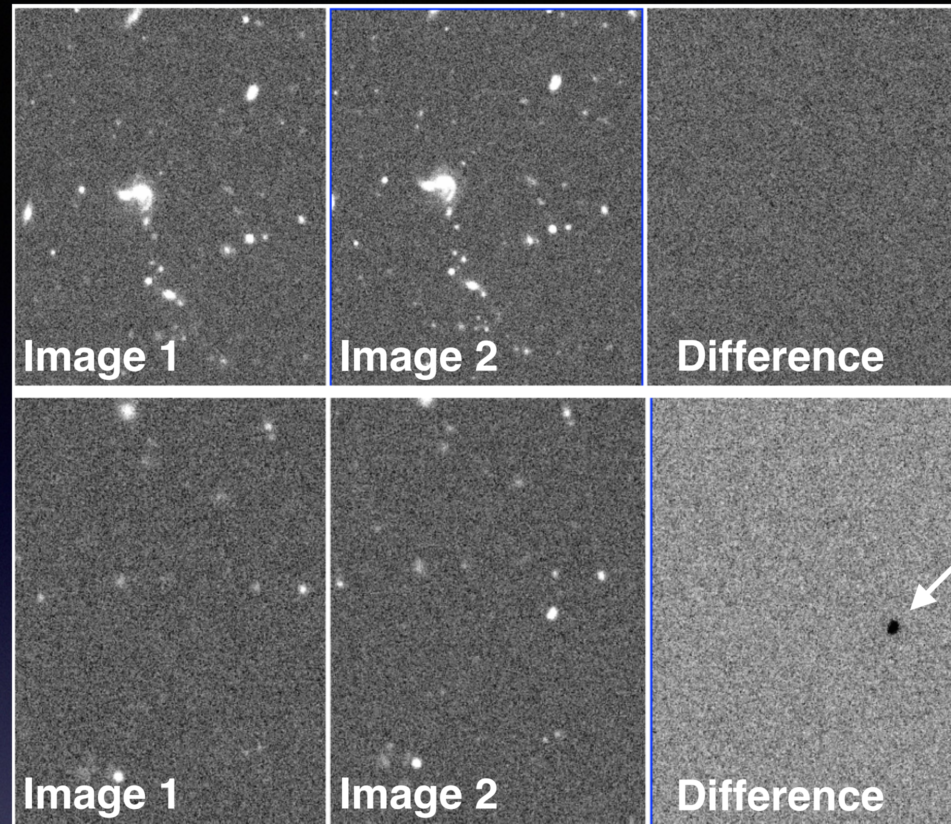




Alert!

Additional “followup” data obtained to:
- confirmation and classification
- provide better temporal resolution
- use different filters/wavelengths
- obtain spectra (distance!)
- other measurements (e.g. polarimetry)

~10 billion alerts

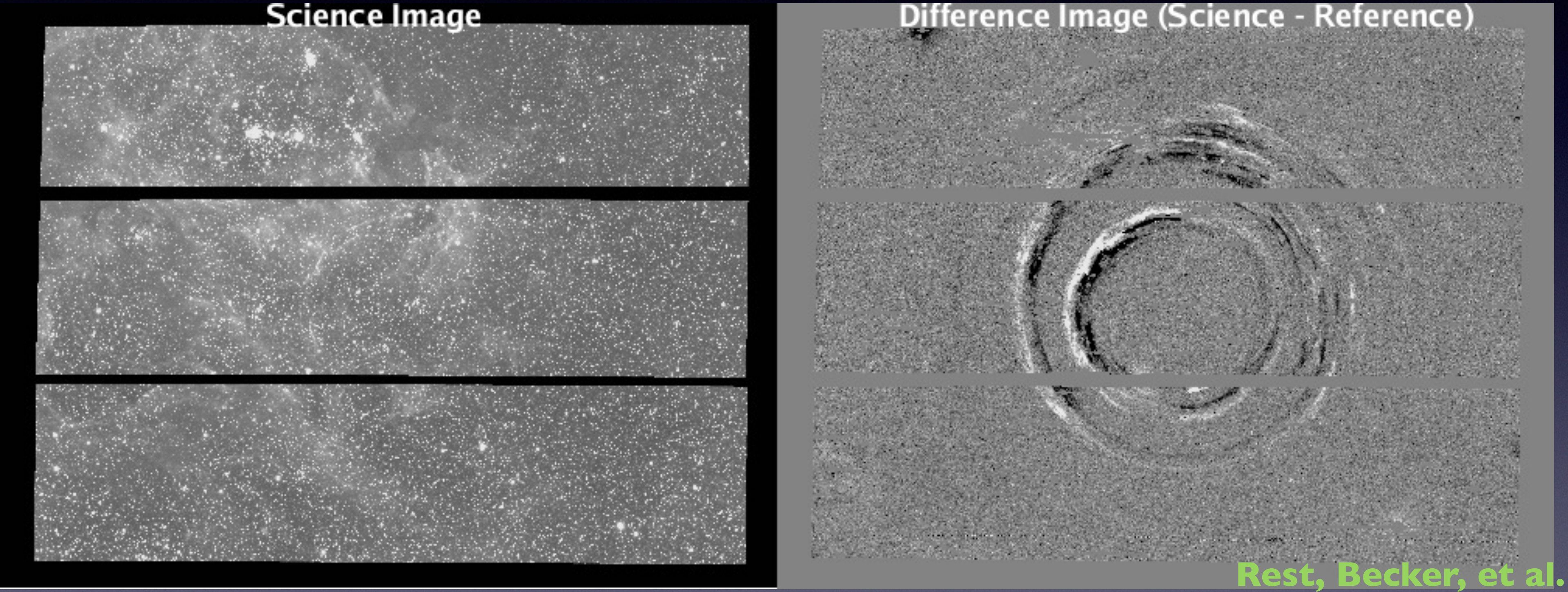
Alerts can trigger “Followup” observations:

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:



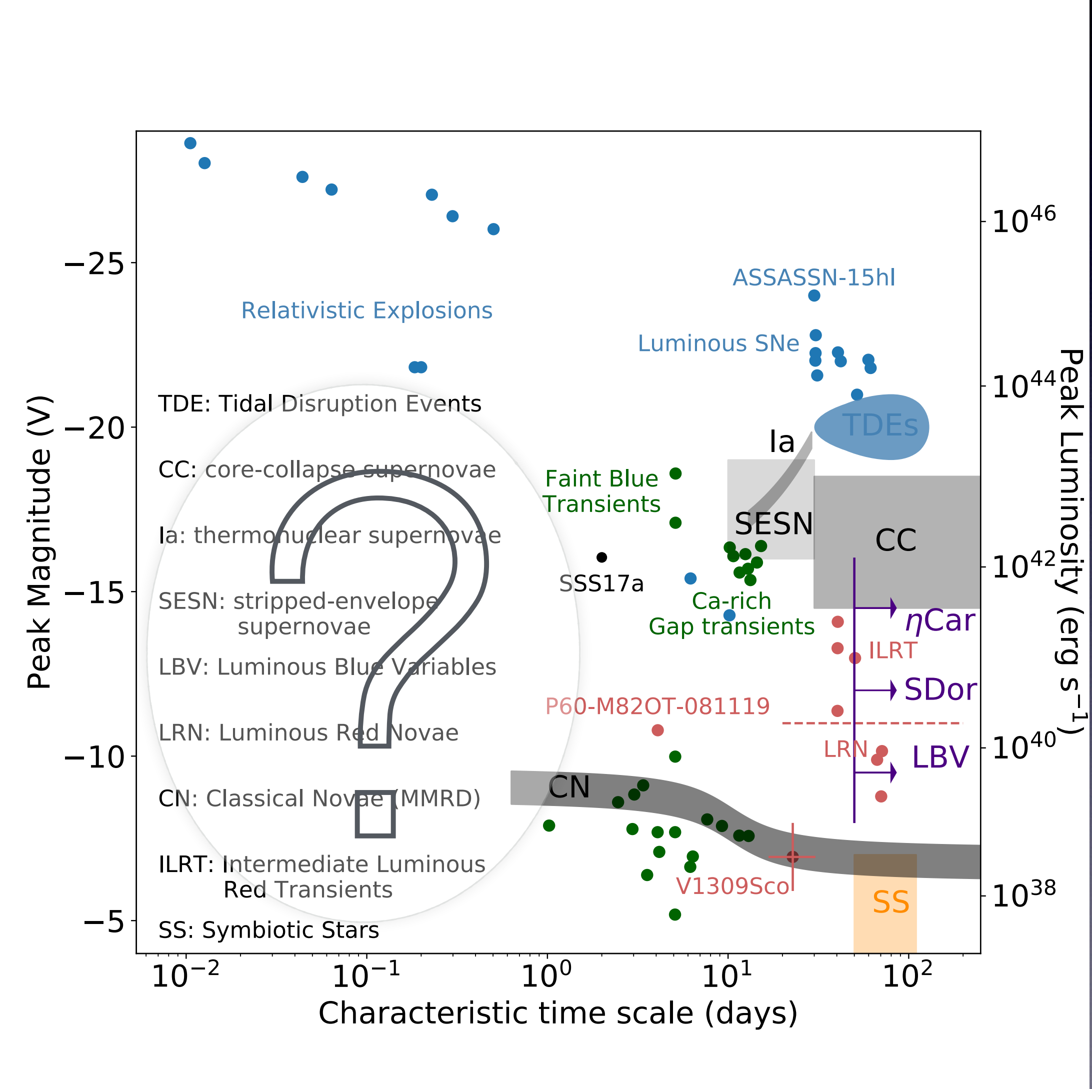
As many variable stars from LSST, as all stars from SDSS

Web stream with data for transients within 60 seconds.

Time Domain: objects changing in time

positions: asteroids and stellar proper motions

brightness: cosmic explosions and variable stars



LSST will extend time-volume space a hundred times over current surveys (new classes of object?):

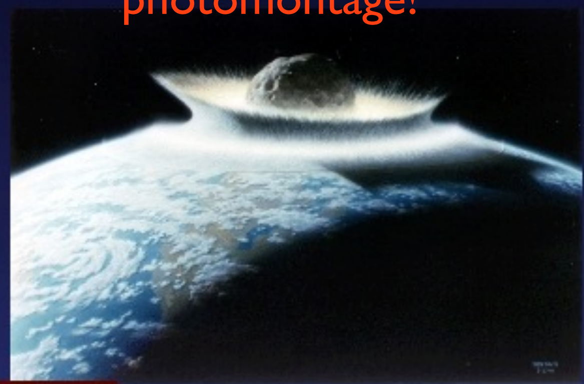
multi-messenger astrophysics

known unknowns

unknown unknowns

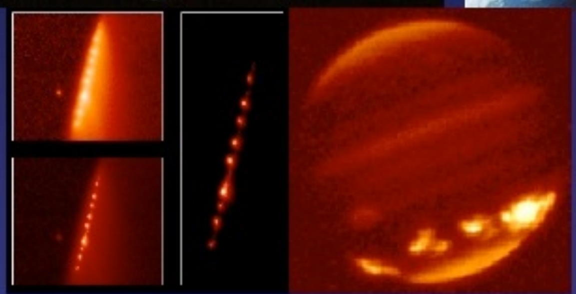
Killer asteroids: the impact probability is not 0!

photomontage!



Asteroids larger than 140m collide with Earth every 20,000 years on average. Typical impact energy of such a collision is 500 Megaton TNT (50x largest bomb)

LSST is the only survey capable of delivering completeness specified in the 2005 USA Congressional NEO mandate to NASA (to find 90% NEOs larger than 140m)

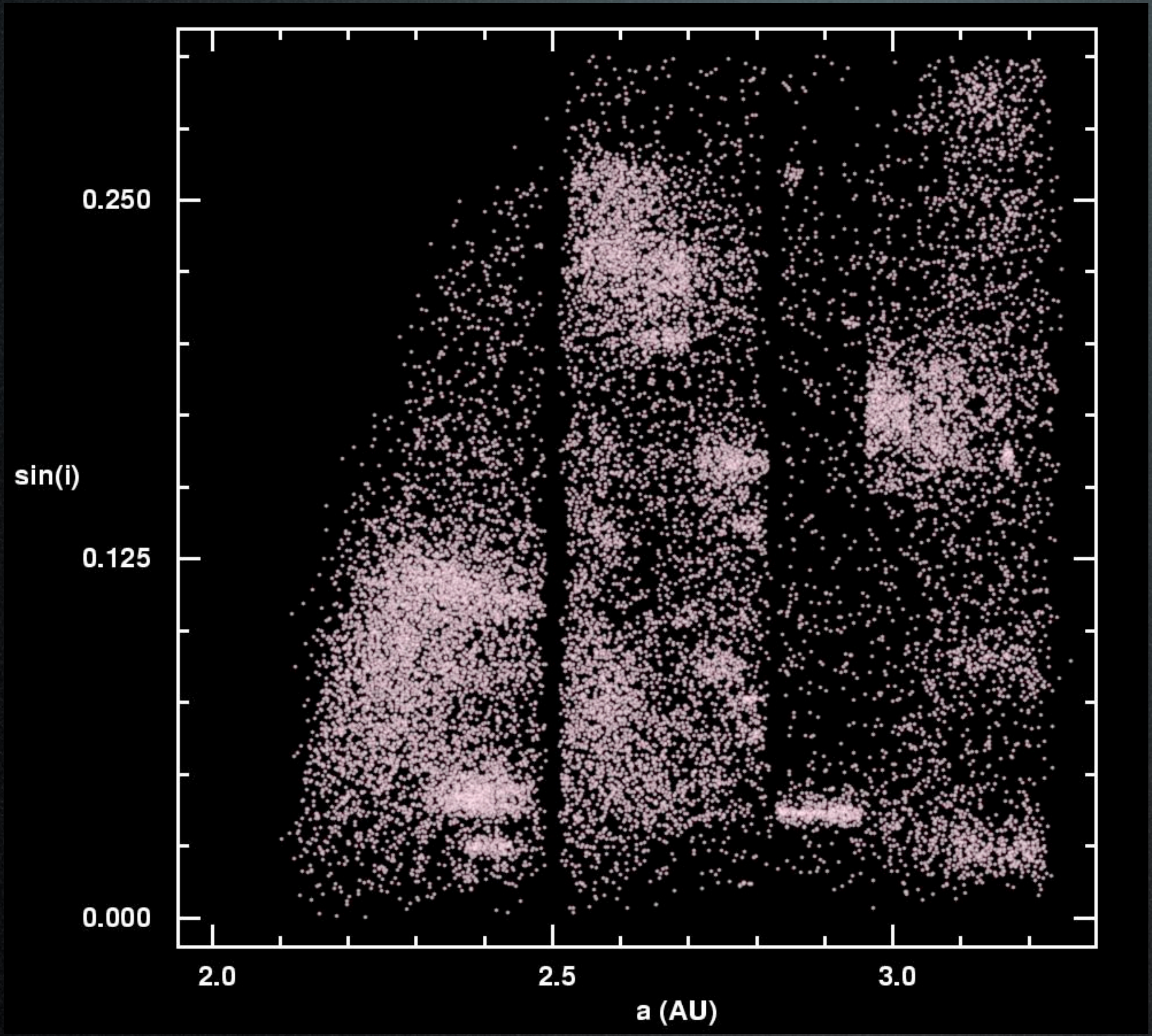


Shoemaker-Levy 9 (1994)

Tunguska (1908)

The Barringer Crater, Arizona: about 40m object 50,000 yr. ago

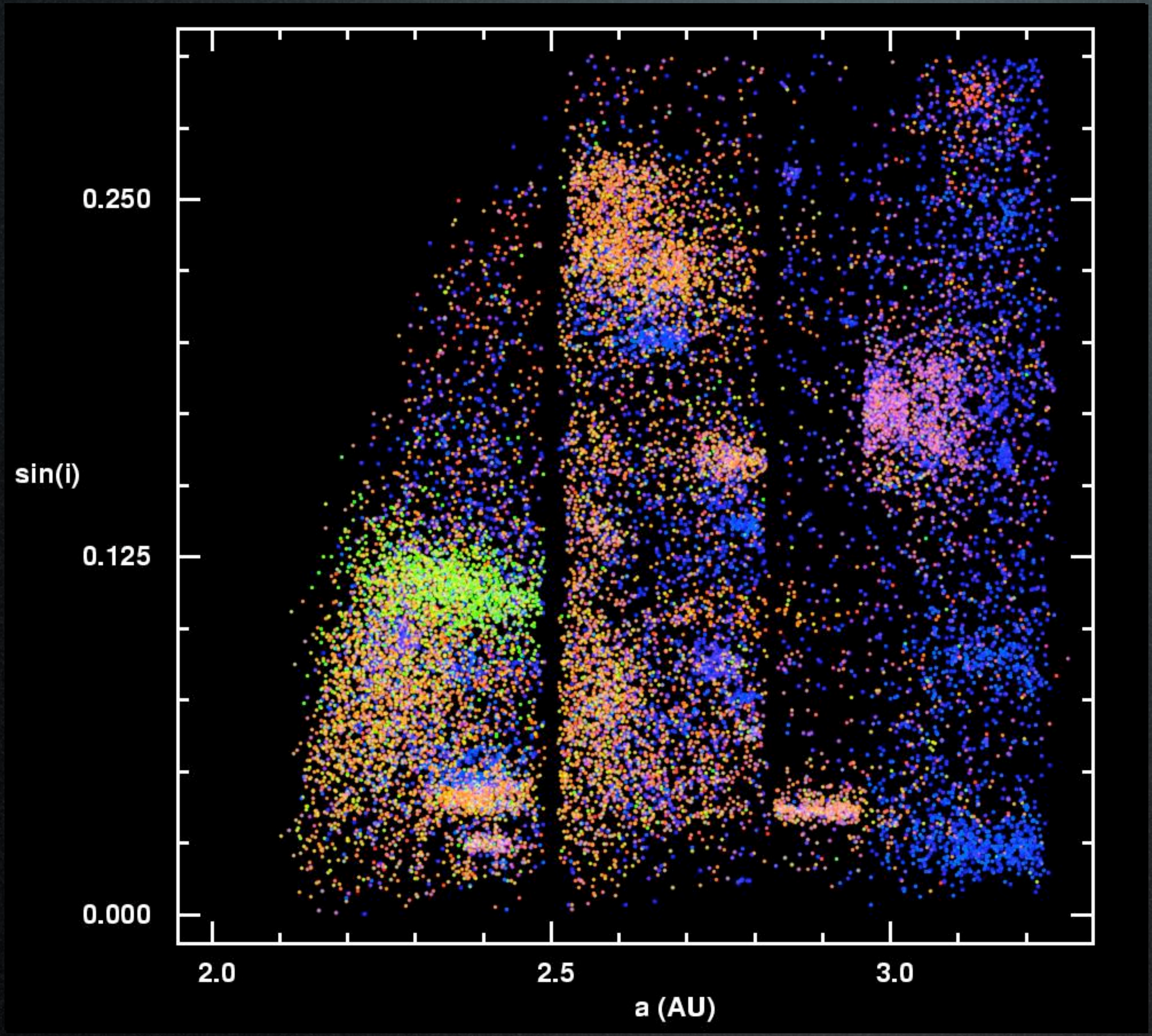
Main-belt Inventory



30,000
Asteroids with
SDSS colors and
proper
orbital elements

(Ivezic, Juric, Lupton 2002)

Main-belt Inventory



30,000
Asteroids with
SDSS colors and
proper
orbital elements

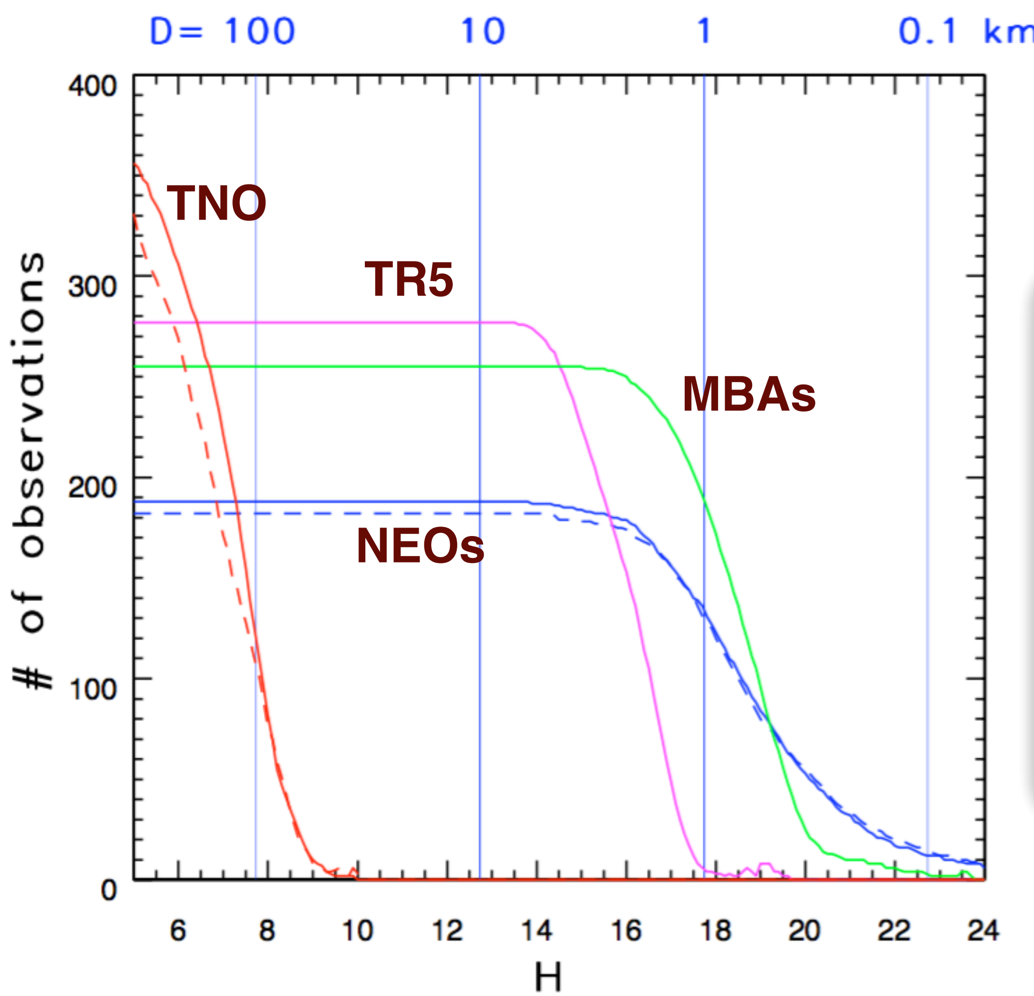
(Ivezic, Juric, Lupton 2002)

Color-coded with
SDSS colors

Colors help with the definition of asteroid families.
LSST will also provide color light curves!

From Chapter 5 in the LSST Science Book: Solar System science

- **MBAs: 5.5 million**
- **TR5: 280,000**
- **NEAs: 100,000**
- **TNOs: 40,000**

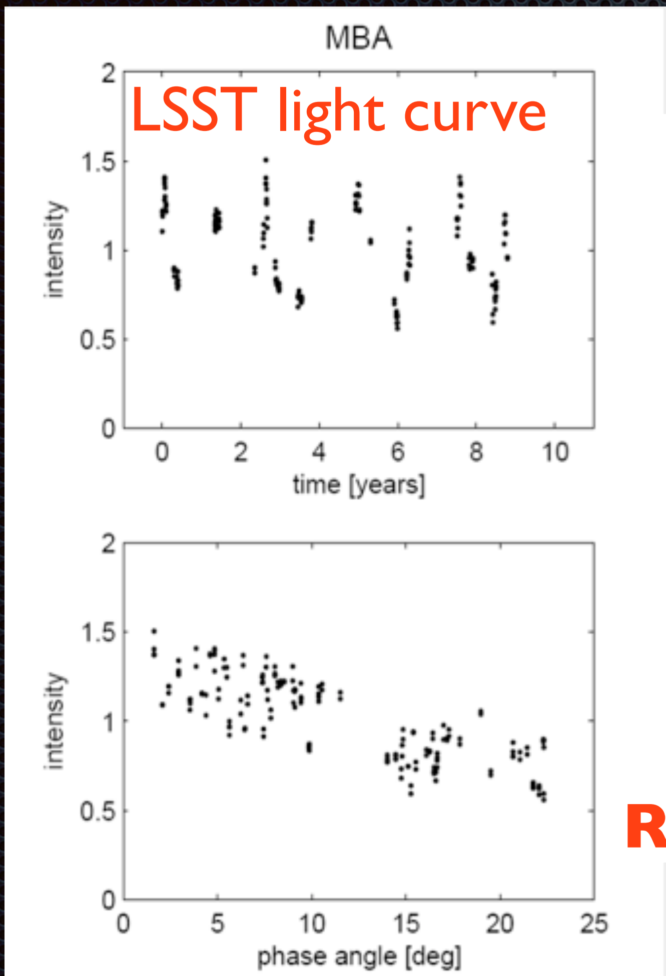


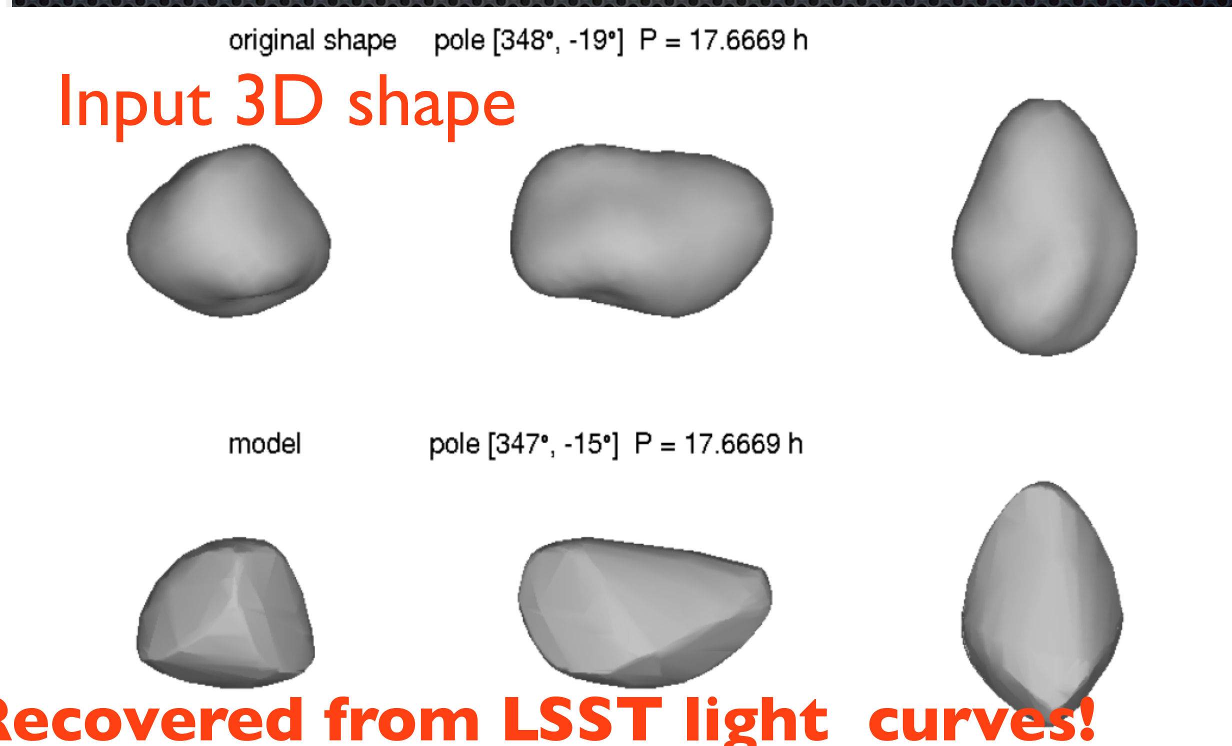
It's not just the number of newly discovered asteroids (5-6 million) but LSST observations will be unprecendented: hundreds of detections per object!

Figure 5.4: The median number of expected LSST detections of a given object as a function of *H* for dominant populations of Solar System bodies. Solid lines correspond to classical TNOs (red), Jovian Trojans (magenta), MBAs (green), and NEAs (blue). The red dashed line corresponds to Scattered Disk Objects, and the blue dashed line to PHAs. Nights with only one detection are not counted.

Sparse Lightcurve Inversion to determine asteroid shapes

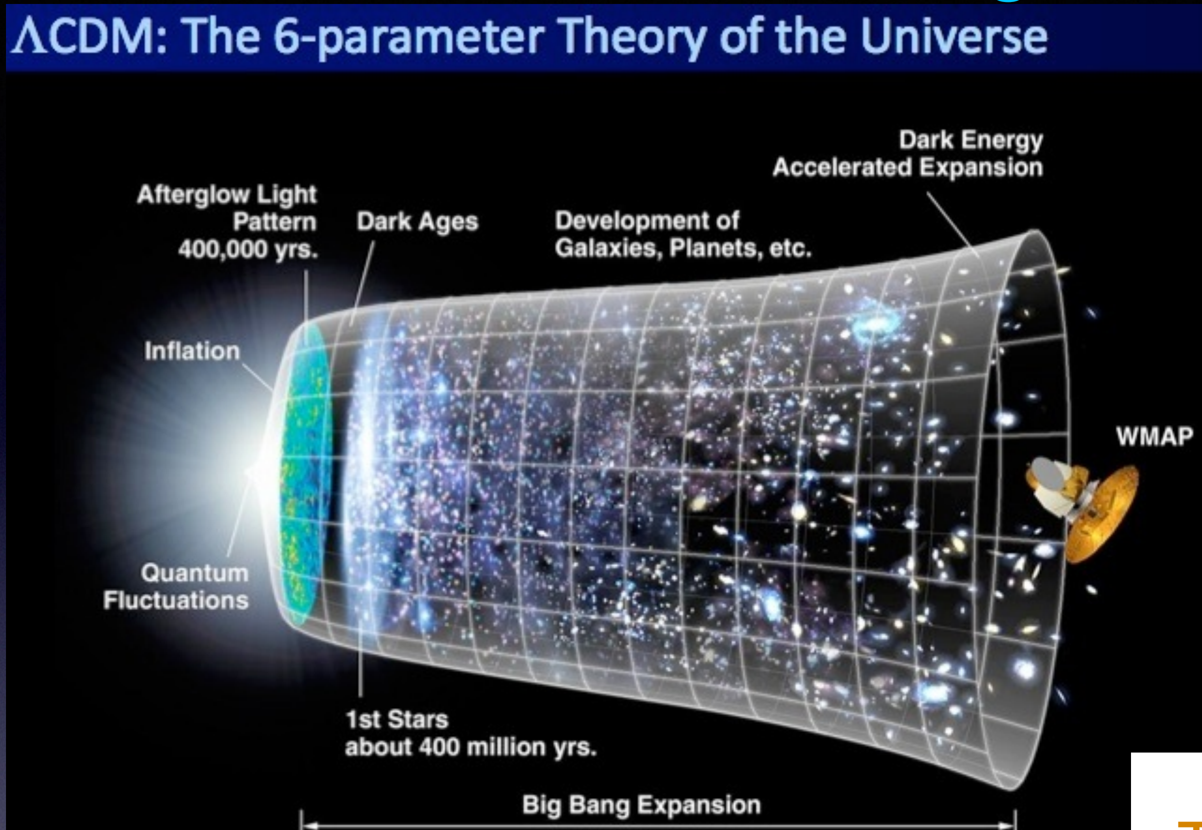
Durech et al. (2007)

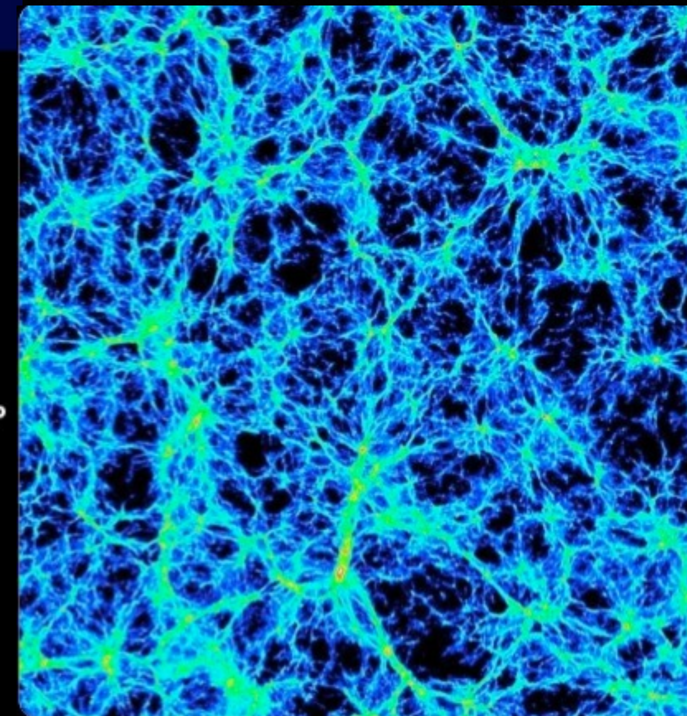


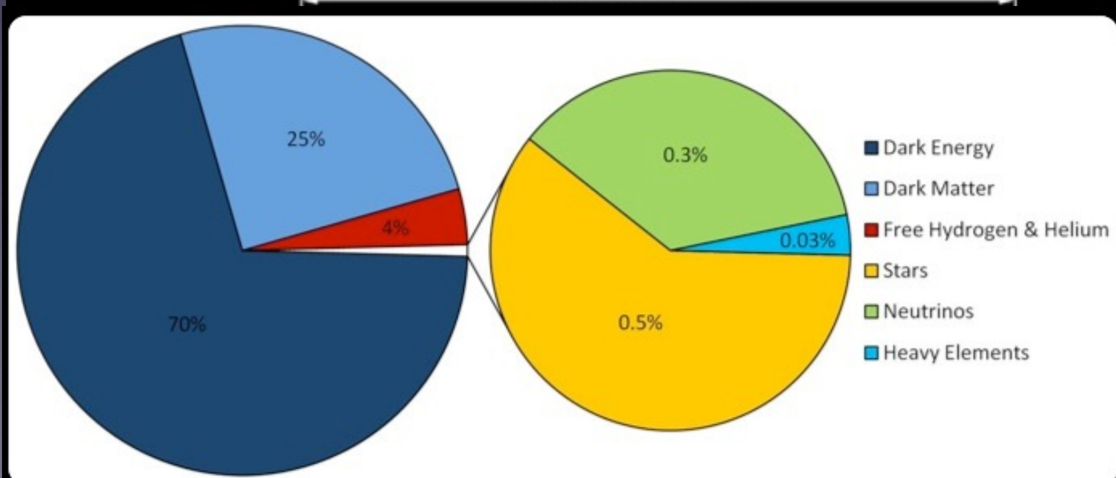


About 100 observations over >5 years are needed

New Cosmological Puzzles







The modern cosmological models can explain all observations, but need to **postulate** dark matter and dark energy (though gravity model could be wrong, too)

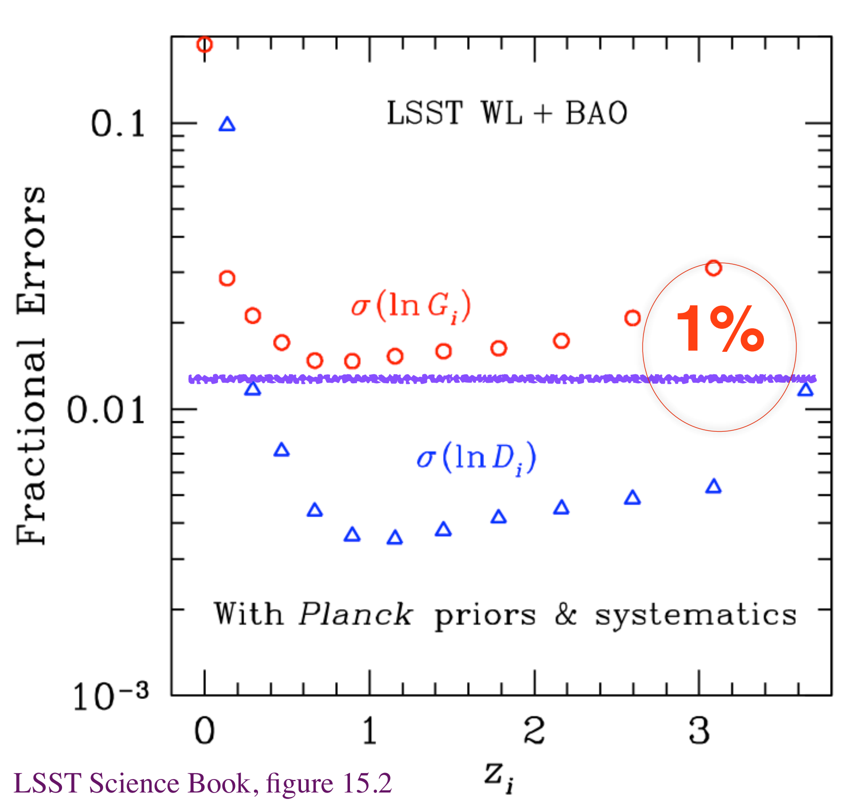
Modern Cosmological Probes

- Cosmic Microwave Background
  (the state of the Universe at the recombination epoch, at redshift ~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 G(z)

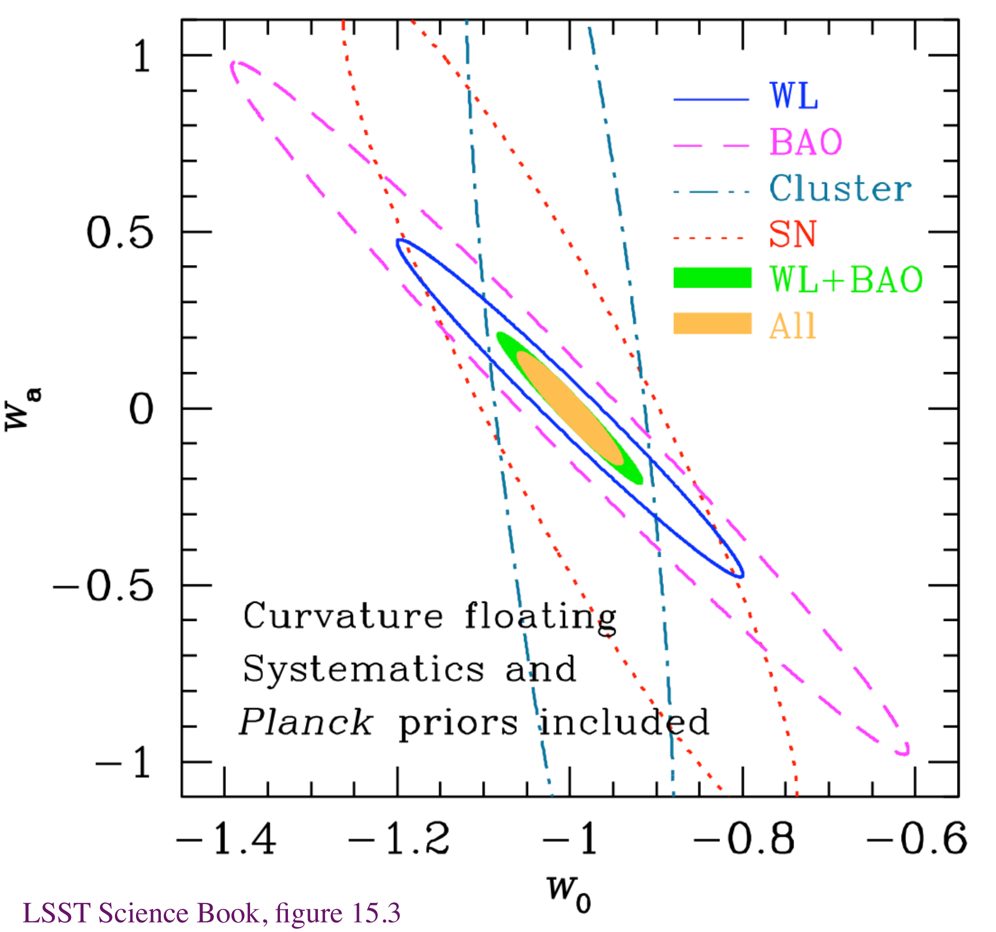
$H(z) \sim d[\ln(a)]/dt$, $G(z) = a^{-1}\delta\rho_m/\rho_m$, with $a(z) = (1+z)^{-1}$

Cosmology with LSST: high precision measurements



LSST Science Book, figure 15.2

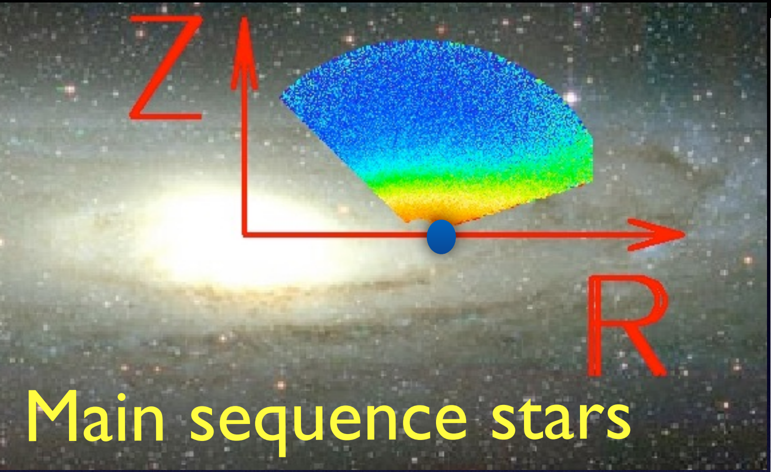
- Measuring distances, H(z), and growth of structure, G(z), with a percent accuracy for 0.5 < z < 3
- Multiple probes is the key!



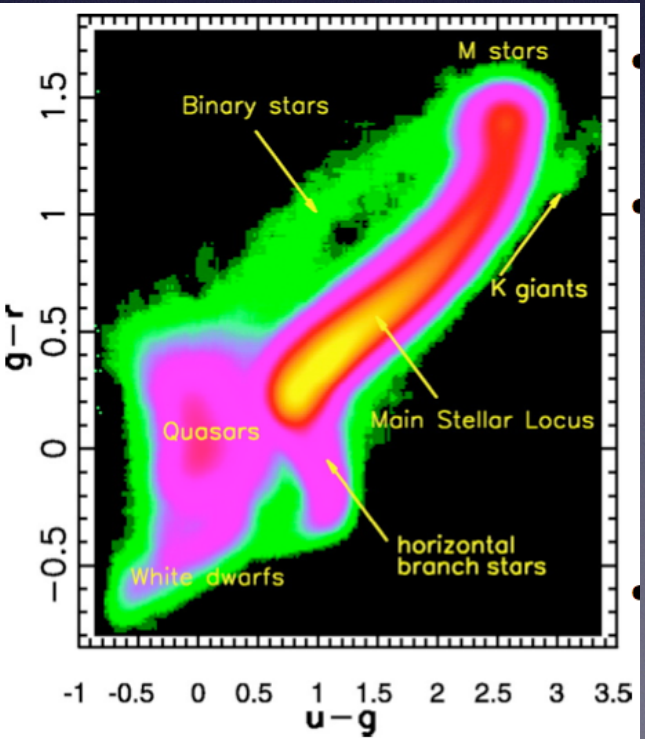
LSST Science Book, figure 15.3

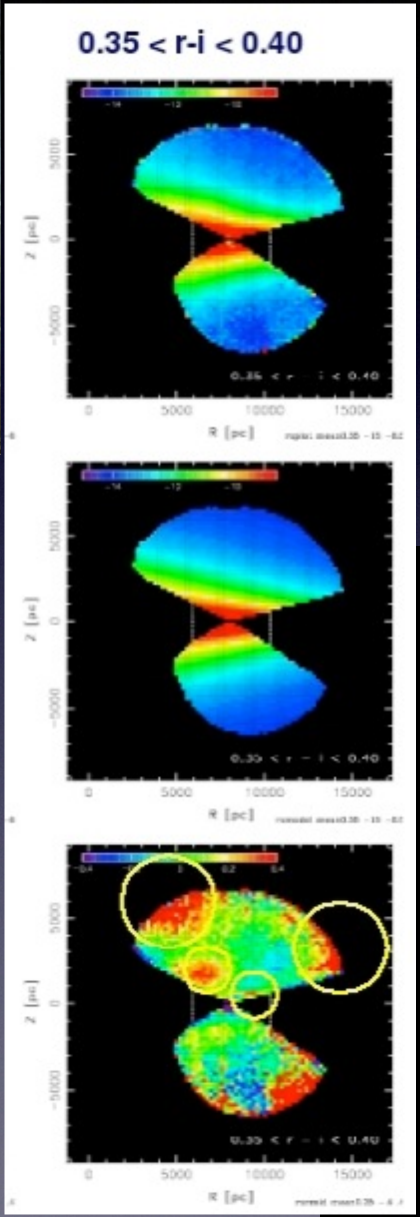
By simultaneously measuring growth of structure and curvature, LSST data will tell us whether the recent acceleration is due to **dark energy or modified gravity.**

The Milky Way structure: 20 billion stars, time domain massive statistical studies!

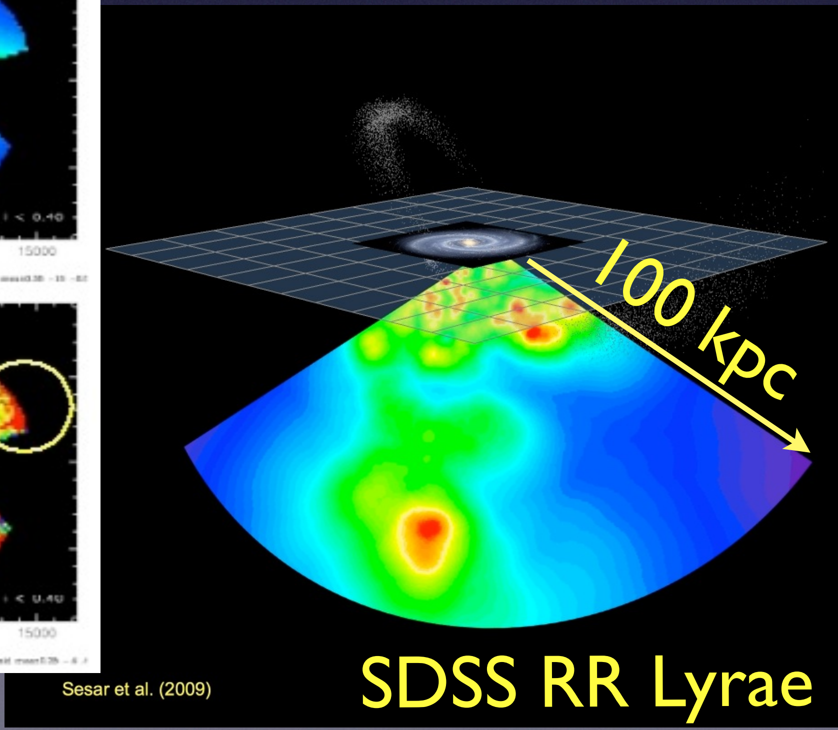


Distance and [Fe/H]:

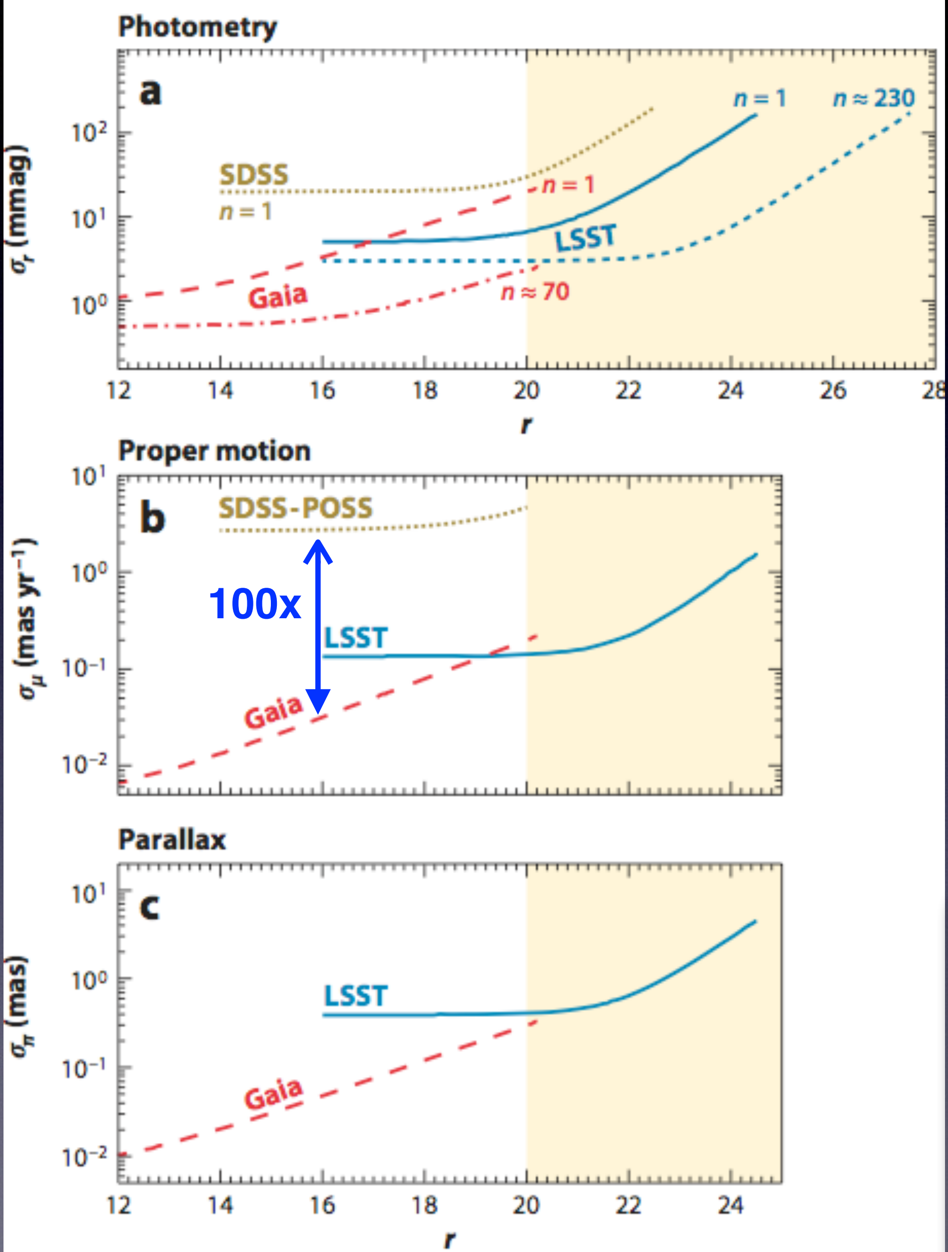




Compared to SDSS: LSST can "see" about 40 times more stars, 10 times further away and over twice as large sky area



Gaia vs. LSST comparison

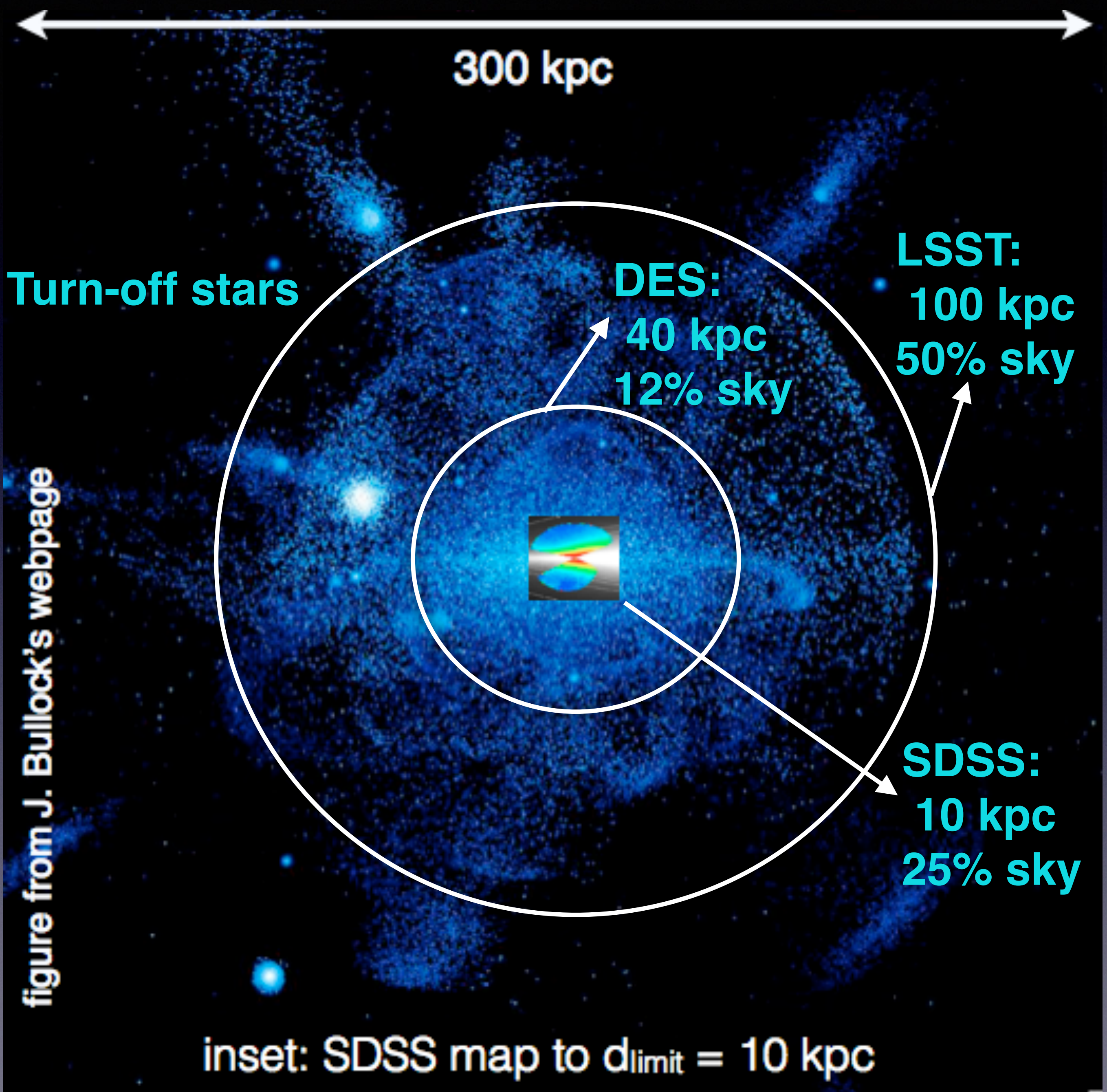


Ivezić, Beers, Jurić 2012, ARA&A, 50, 251

- **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).

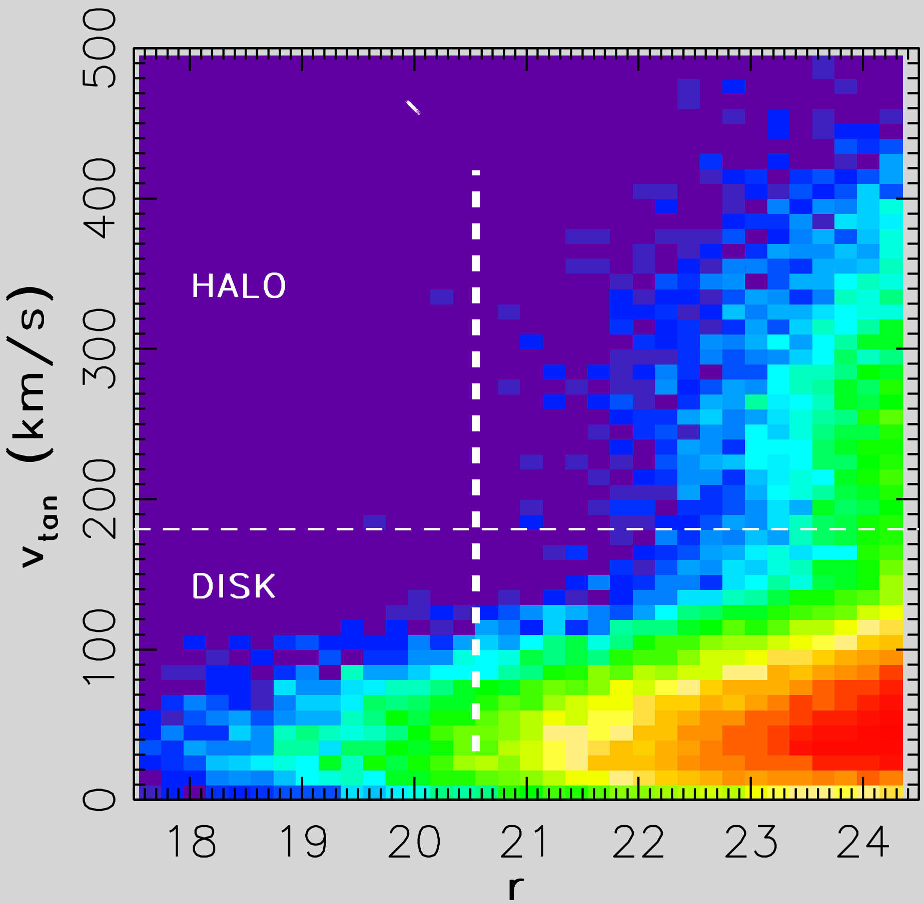
Milky Way science with coadded LSST data



Dwarfs in LSST

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])

"Ask Not What Data You Need To Do Your Science, Ask What Science You Can Do With Your Data."

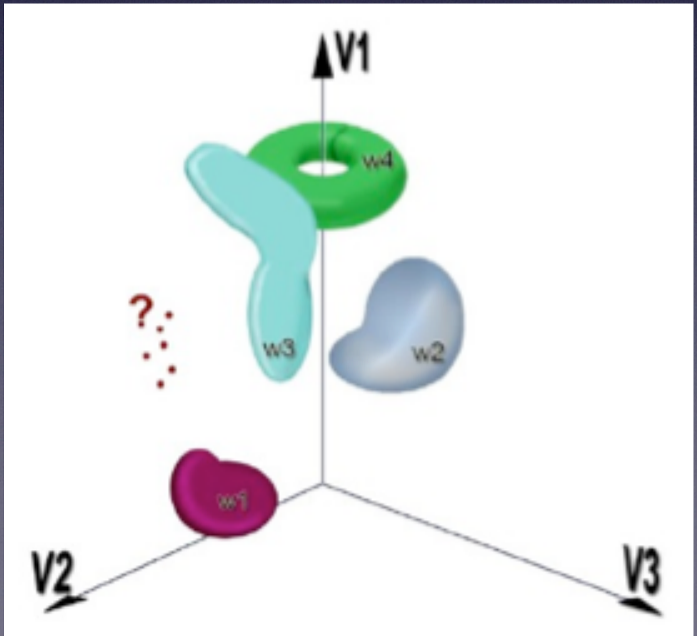
The era of surveys...

- Standard: "What data do I have to collect to (dis)prove a hypothesis"?
- Data-driven: "What theories can I test given the data I already have?"

Statistical analysis of a massive LSST dataset

- A large (100 PB) database and sophisticated analysis tools: for each of 40 billion objects there will be about 1000 measurements (each with a few dozen measured parameters)

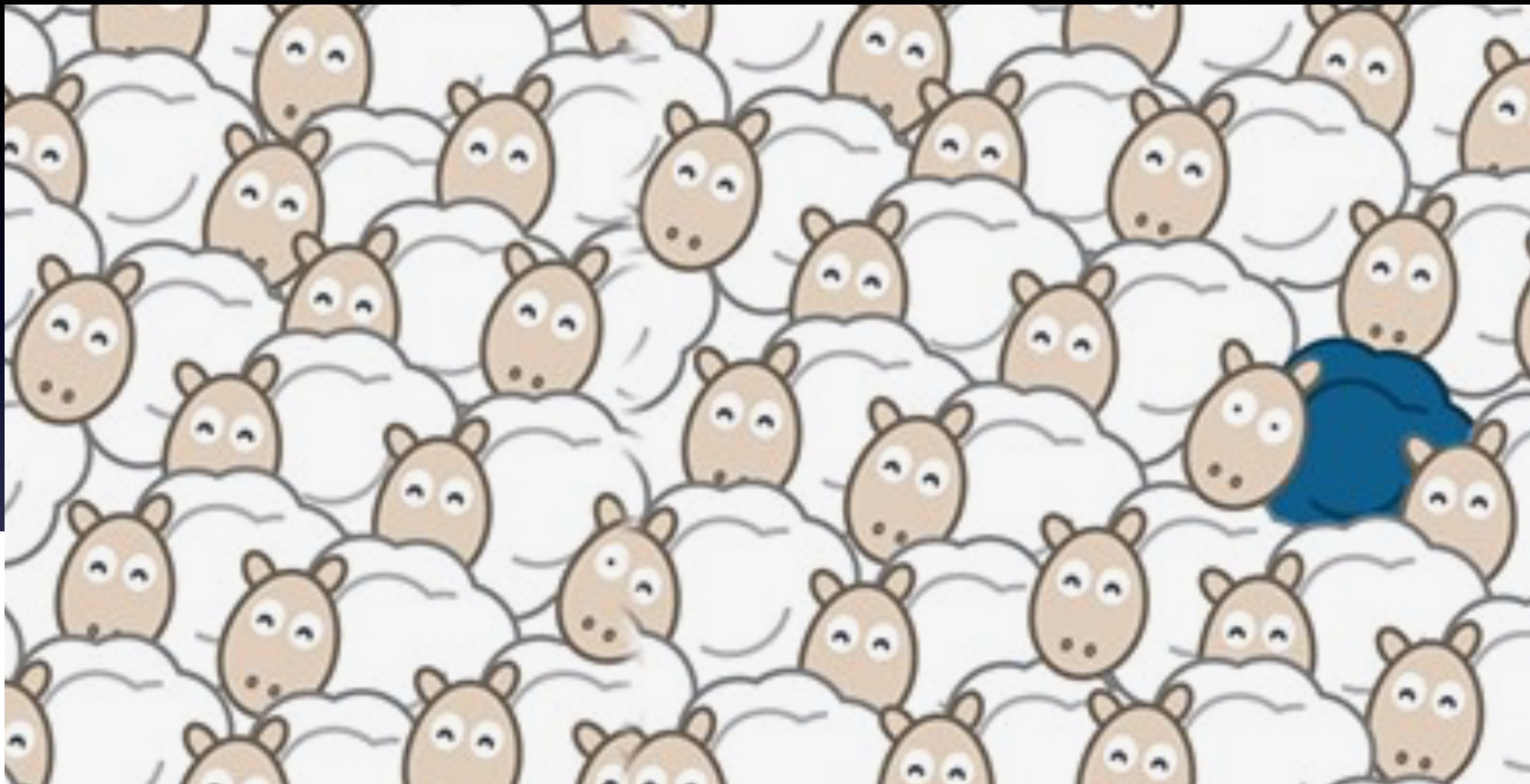
Data mining and knowledge discovery

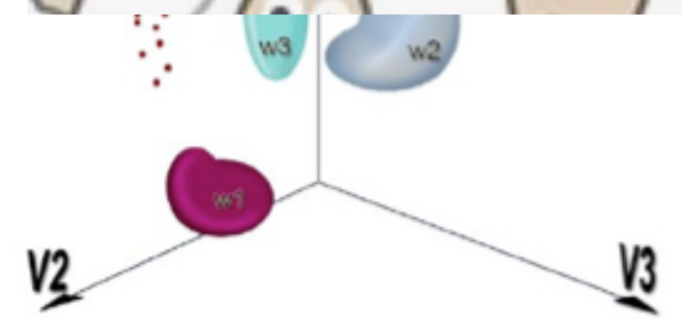


- 10,000-D space with 40 billion points
- Characterization of known objects
- Classification of new populations
- Discoveries of unusual objects

Clustering, classification, outliers

Statistical analysis of a massive LSST dataset





- Classification of new populations
- Discoveries of unusual objects

Clustering, classification, outliers

Data analysis challenges in the era of Big Data

1) Large data volume (petabytes)

2) Large numbers of objects (billions)

3) Highly multi-dimensional spaces (thousands)

4) Unknown statistical distributions

5) Time-series data (irregular sampling)

6) Heteroscedastic errors, truncated, censored and missing data

7) Unreliable quantities (e.g. unknown systematics and random errors)

The bottleneck will not be data availability but instead our ability to extract useful and reliable information from data.

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AstroML: Machine Learning and Data Mining for Astronomy

News

October 2012: astroML 0.1 has been released! Get the source on Github

Our Introduction to astroML paper received the CIDU 2012 best paper award.

Links

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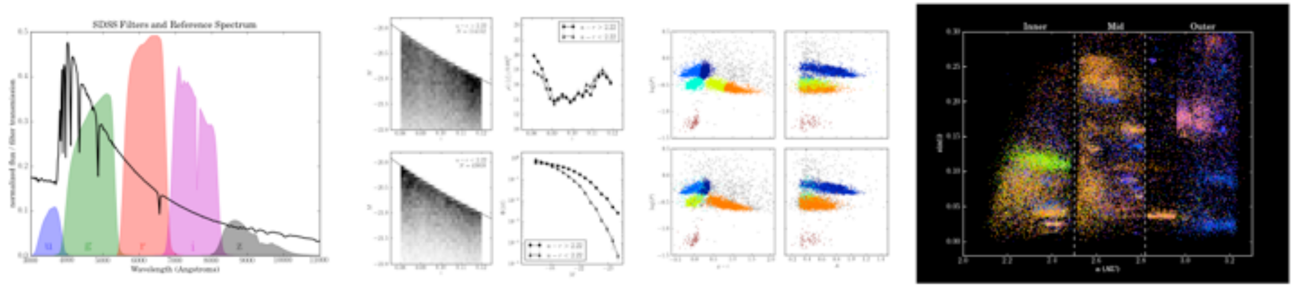


AstroML is a Python module for machine learning and data mining built on numpy, scipy, scikit-learn, and matplotlib, and distributed under the 3-clause BSD license. It contains a growing library of statistical and machine learning routines for analyzing astronomical data in python, loaders for several open astronomical datasets, and a large suite of examples of analyzing and visualizing astronomical datasets.

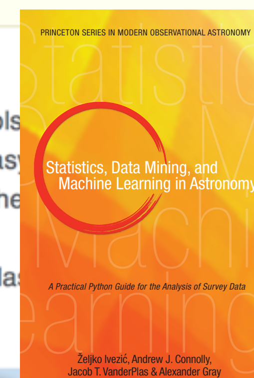
Downloads

- Released Versions: Python Package Index
- Bleeding-edge Source: github

How can we efficiently adopt sophisticated methods from statistics, data mining and machine learning?

...mon tools ... and eas... researche... tistics, **Data Mining, and Machine Learning in Astronomy** by Zeljko Ivezic, Andrew Connolly, Jacob VanderPla... and Alex Gray, to be published in late 2013. The table of contents is available here: `here(pdf)`.

please consider citing astroML.



User Guide

1. Introduction

- 1.1. Philosophy

Open source!
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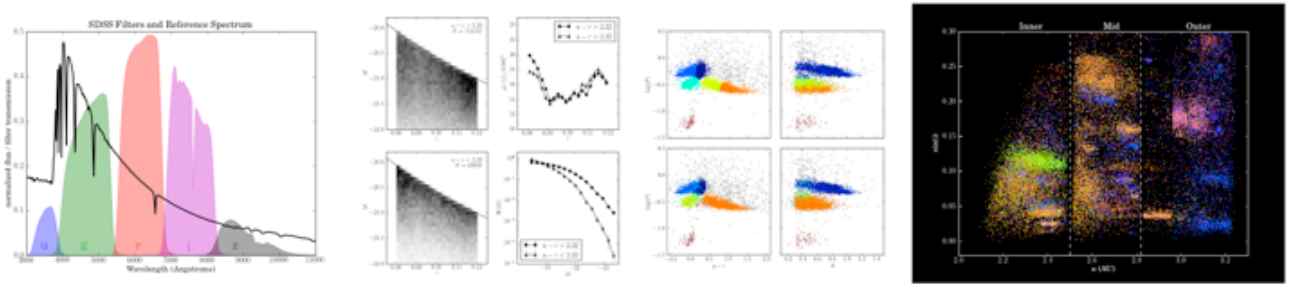

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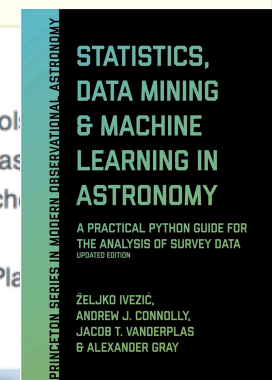


User Guide

1. Introduction

- 1.1. Philosophy

How can we efficiently adopt sophisticated methods from statistics, data mining and machine learning?

Open source!

www.astroML.org

Textbook Figures

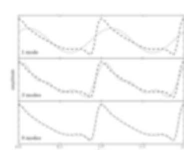
This section makes available the source code used to generate every figure in the book *Statistics, Data Mining, and Machine Learning in Astronomy*. Many of the figures are fairly self-explanatory, though some will be less so without the book as a reference. The table of contents of the book can be seen **`here(pdf)`**.

Figure Contents

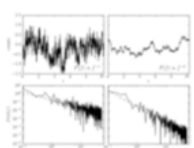
Each chapter links to a page with thumbnails of the figures from the chapter.

Chapter 10: Time Series Analysis

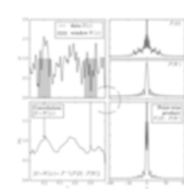
This chapter covers the analysis of both periodic and non-periodic time series, for both regularly and irregularly spaced data.



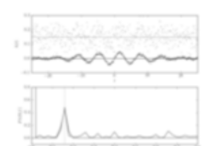
Fourier Reconstruction of RR-Lyrae Templates



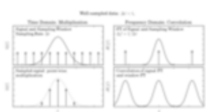
Generating Power-law Light Curves



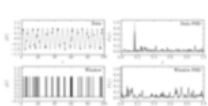
Plot a Diagram explaining a Convolution



Fast Fourier Transform Example



The effect of Sampling



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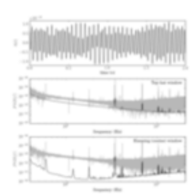
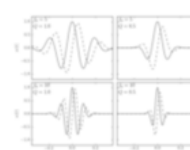


Plot the power spectrum of the LIGO big dog event



Examples of Wavelets

Summary

This talk:
[ls.st/ny0](ls.st/ny0)

- LSST: a 10-year survey starting in Oct 2022
- multi-color time-resolved faint sky map
  - 20 billion galaxies (median redshift ~1)
  - 20 billion stars (to the edge of the Milky Way)
  - 10 billion alerts (across the Universe)
  - "millions and millions" of SNe, quasars, asteroids…
- data analysis challenges: waiting for you!

More details:
LSST overview paper: arXiv:0805.2366
LSST Data Products Definition Document: ls.st/dpdd
LSST Science Requirements Document: ls.st/srd

Total Solar Eclipse over
Cerro Pachon, July 2, 2019
Photo: Kevin Reil

Backup:

Cosmology with LSST: dark energy vs. modified gravity

- Even for a model with modified gravity, it is possible to assume that GR is correct and always find DE with suitable w(z) to explain data for H(z). 😱

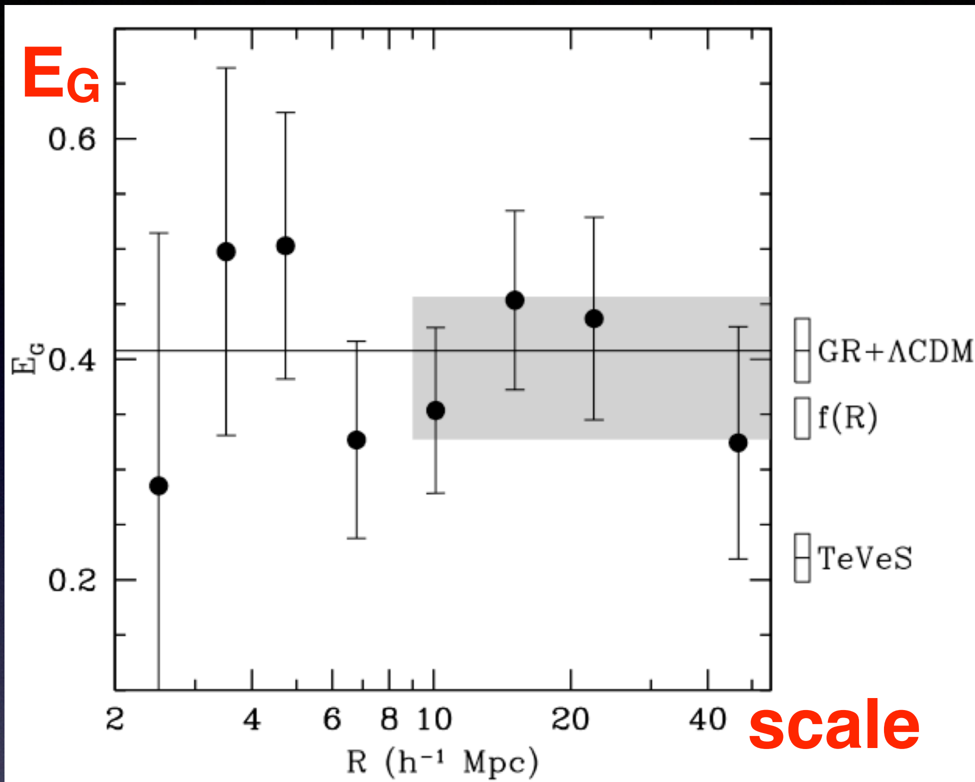
- However, the growth of structure will be different and thus when both H(z) and G(z) are measured, the degeneracy can be broken and DE vs. modified gravity models distinguished (Jain & Zhu 2008, PhysRevD 78, 063503)

$$ds^2 = -(1 + 2\psi)\ dt^2 + (1 - 2\phi)\ a^2(t)\ d\vec{x}^2$$

- φ is the curvature perturbation and ψ is the potential pertur.

- In General Relativity φ = ψ in the absence of anisotropic stresses. A metric theory of gravity relates the two potentials above to the perturbed energy-momentum tensor. 😄
φ and ψ can be constrained with astronomical observations.

Cosmology with LSST: dark energy vs. modified gravity

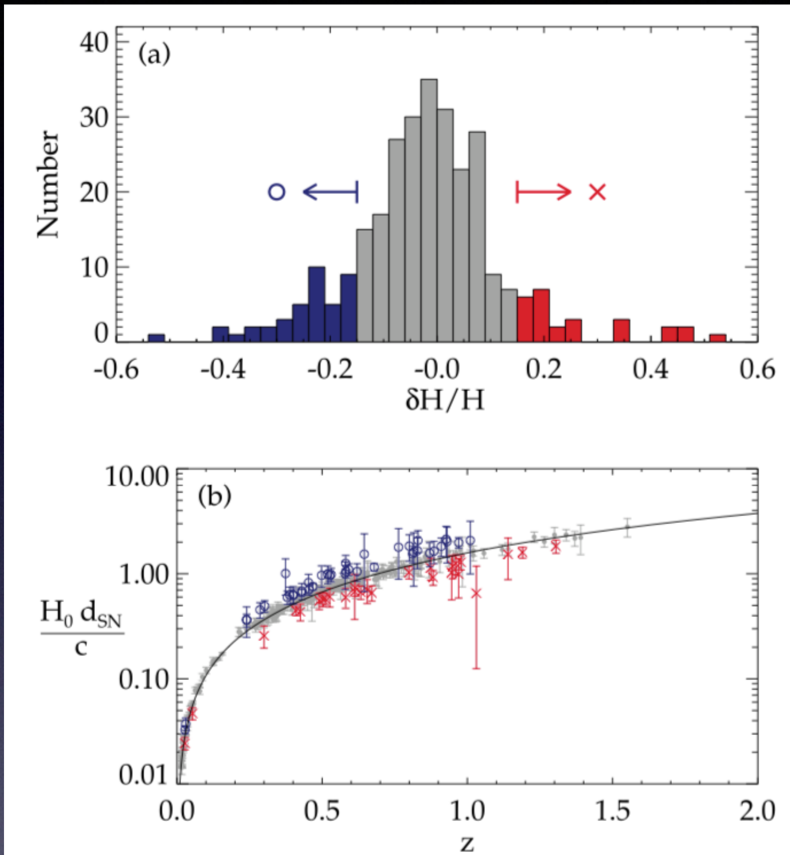


Reyes et al. (2010, Nature 464, 256)

- E_G combines 3 measures of large-scale structure: galaxy-galaxy lensing (φ+ψ), galaxy clustering (φ) and galaxy velocities (from galaxy redshifts; measures G(z))
- SDSS data enabled a test of GR at 15% level: it passed!
- SDSS data already excludes a model within the tensor-vector-scalar gravity theory, which modifies both Newtonian and Einstein gravity.
- Five times better precision needed to rule out f(R)

LSST will measure E_G about 10 times more precisely and will be able to rule out a large class of modified gravity theories (or GR!)

Cosmology with LSST SNe: is the cosmic acceleration the same in all directions?



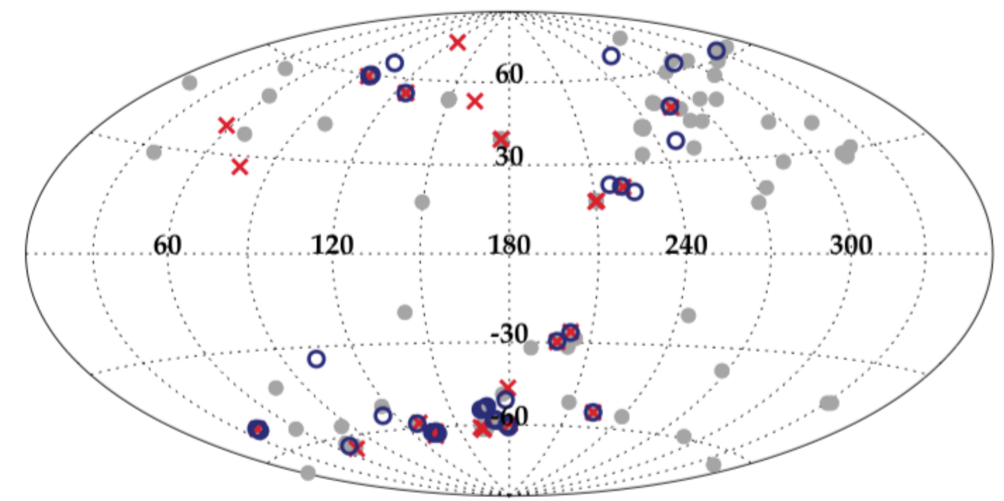


Figure 1. A projection of the spatial distribution of the Union SNe Ia sample in Galactic coordinates. Note the relative uniformity of the points, except around the Galactic plane. The symbols correspond to those in Fig. 2, and are explained in Section 3.1.

Cooke & Lynden-Bell (2009, MNRAS 401, 1409)

Is there spatial structure in the SNe distance modulus residuals for the concordance model?

- Even a single supernova represents a cosmological measurement!
- LSST will obtain light curves for several million Type Ia supernovae!

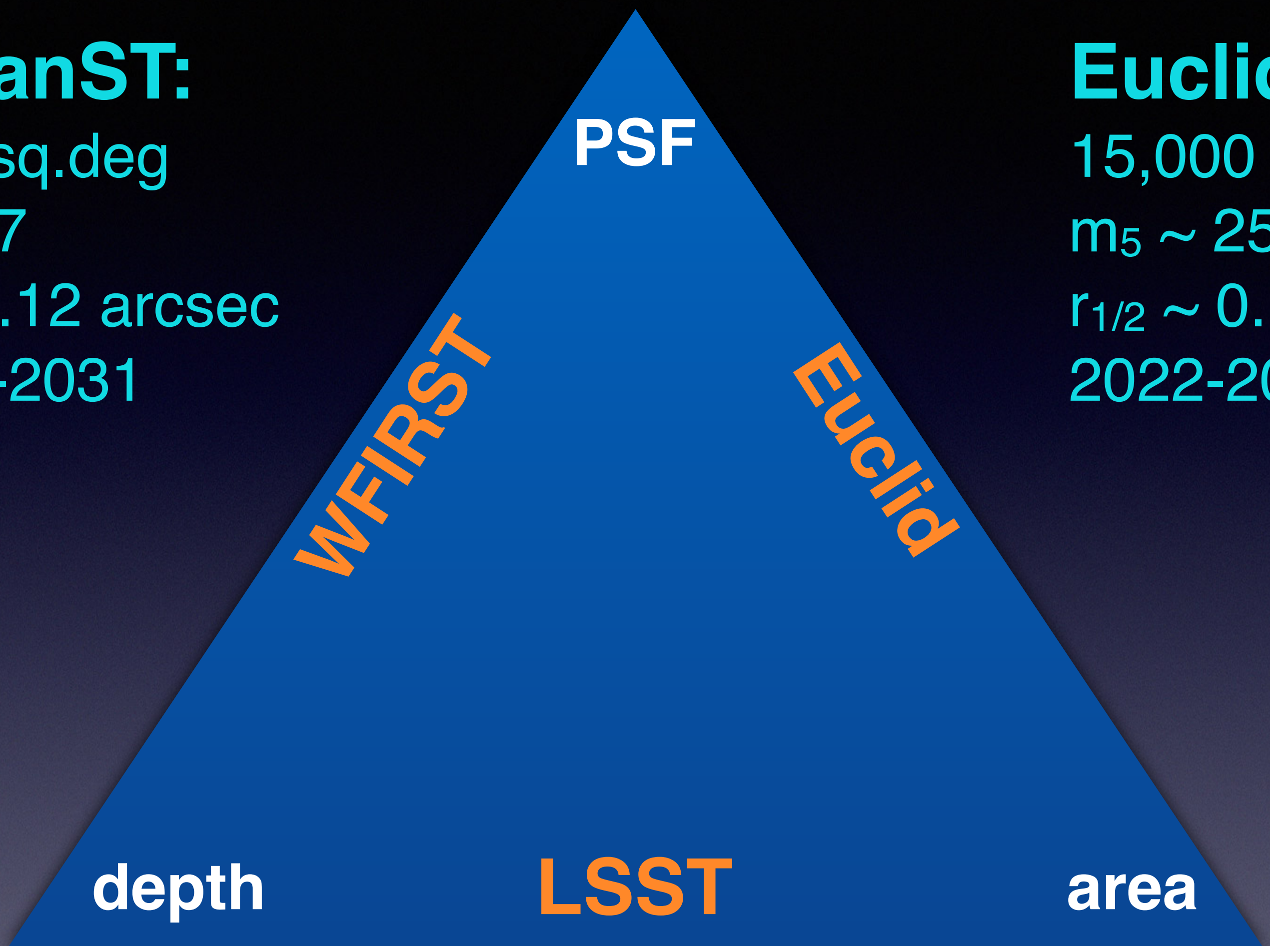
LSST, WFIRST and Euclid are highly complementary missions.

RomanST:

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
2022-2028



18,000 sq.deg
$m_5 \sim 27$
$r_{1/2} \sim 0.4$ arcsec
2022-2032

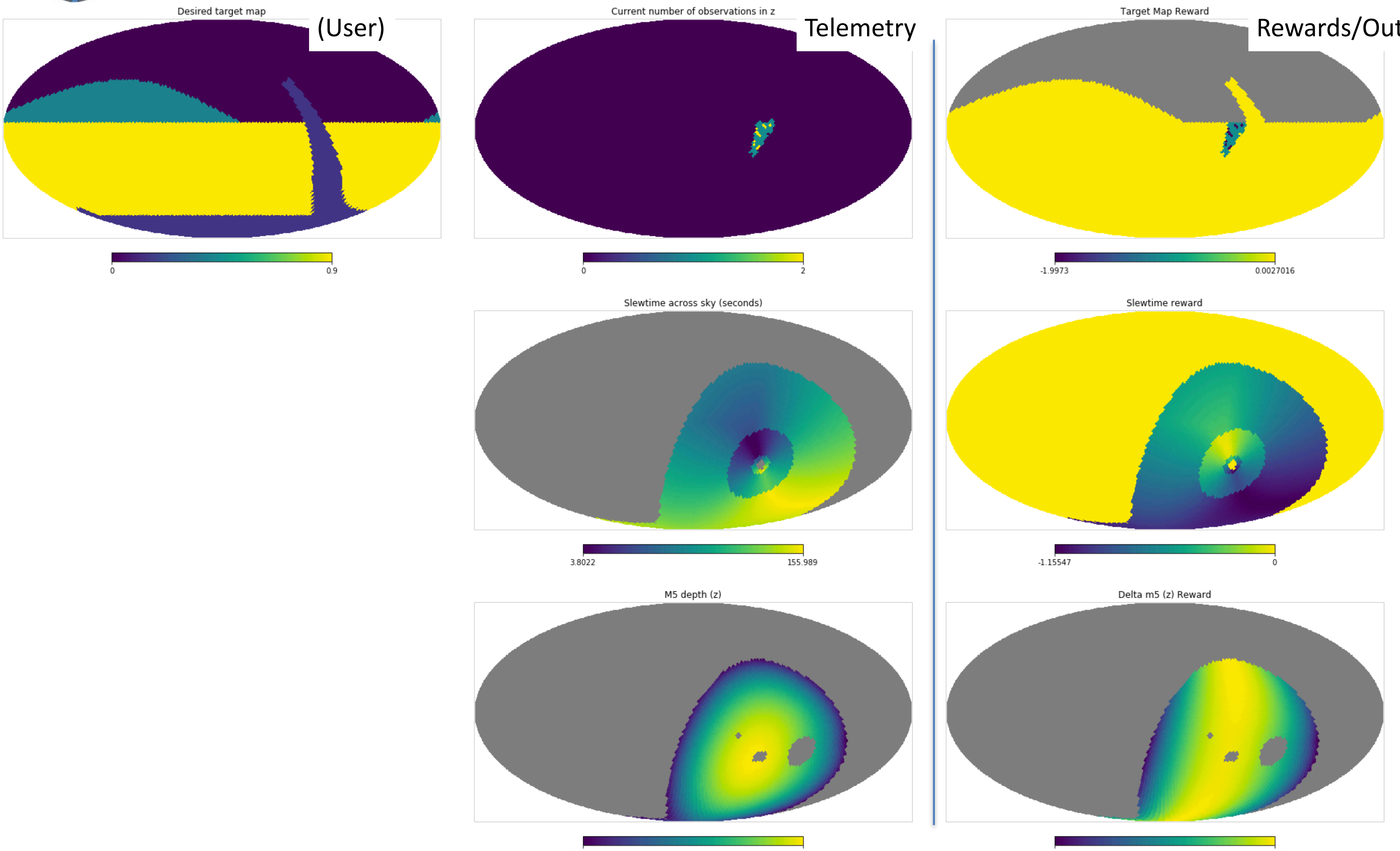
Automated scheduling of LSST observations

- LSST will have to make about 2.5 million decisions about where to point the telescope (2 sky coordinates), what filter to use and how long to keep the shutter open (exposure time); even with a fixed exposure time, each time there are about 100,000 options.

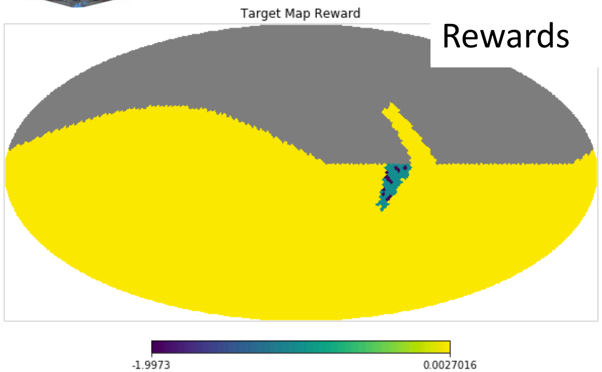
- optimal decision depends on observing conditions (sky brightness, including lunar contribution, atmospheric “seeing”), the system properties (imaging sensitivity as a function of filter and exposure time), as well as survey progress (number of images, their time sampling and achieved signal-to-noise ratio as functions of sky position and filter)

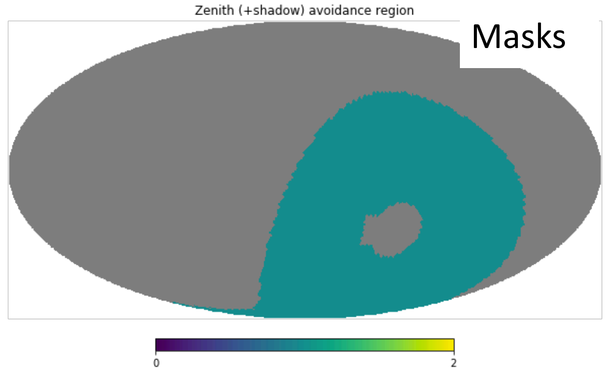
- too complicated for an astronomer to handle: instead, an algorithm will autonomously schedule observations by performing cost-benefit analysis. Astronomers will track the performance and modify this algorithm as needed (and sometimes override it for other reasons)

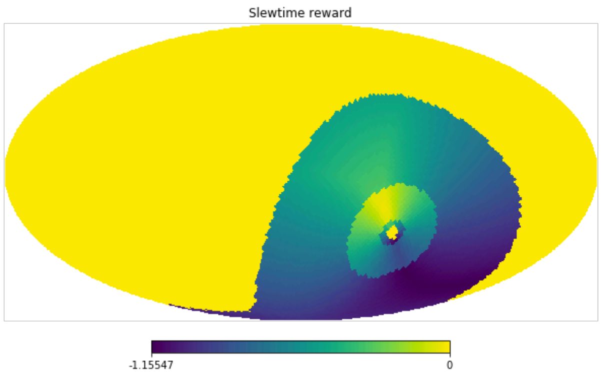
Examples of "Basis Functions"

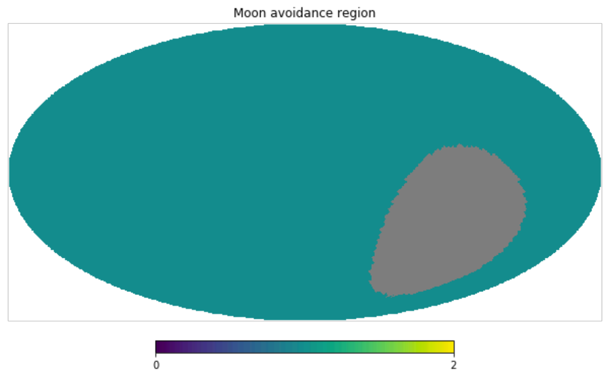


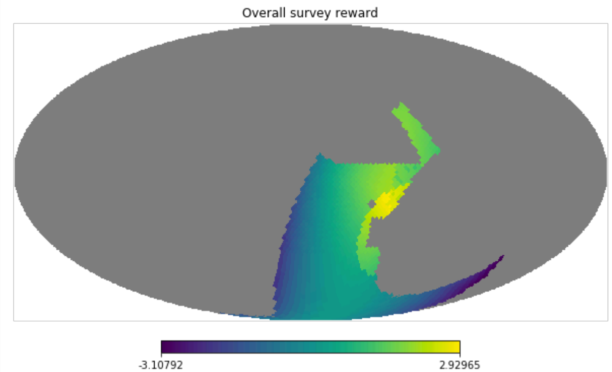
Examples of "Basis Functions"

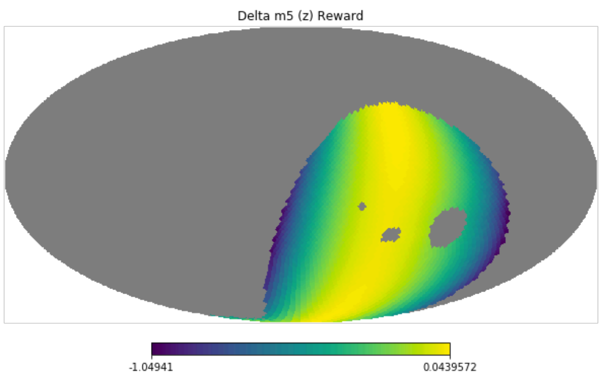




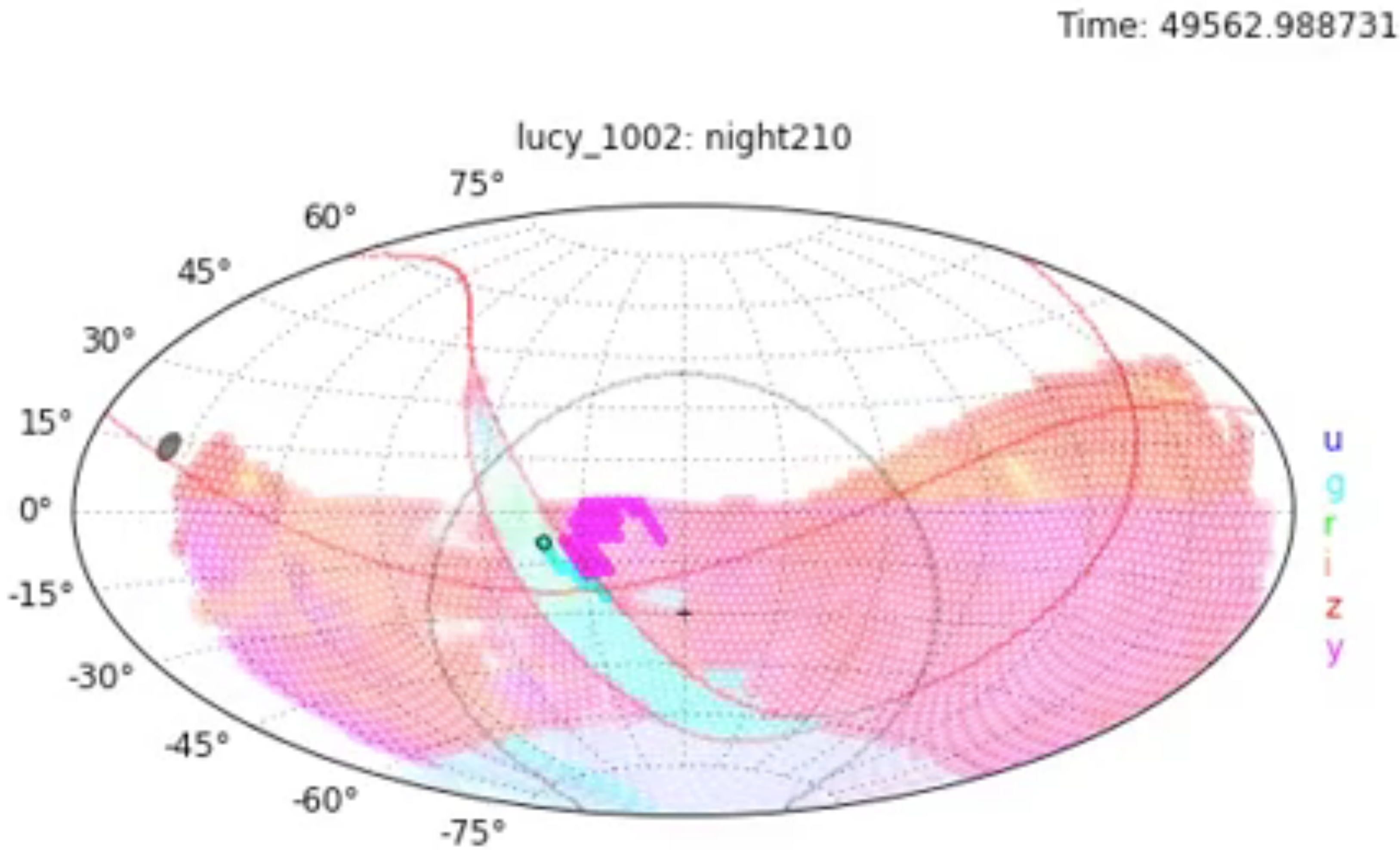






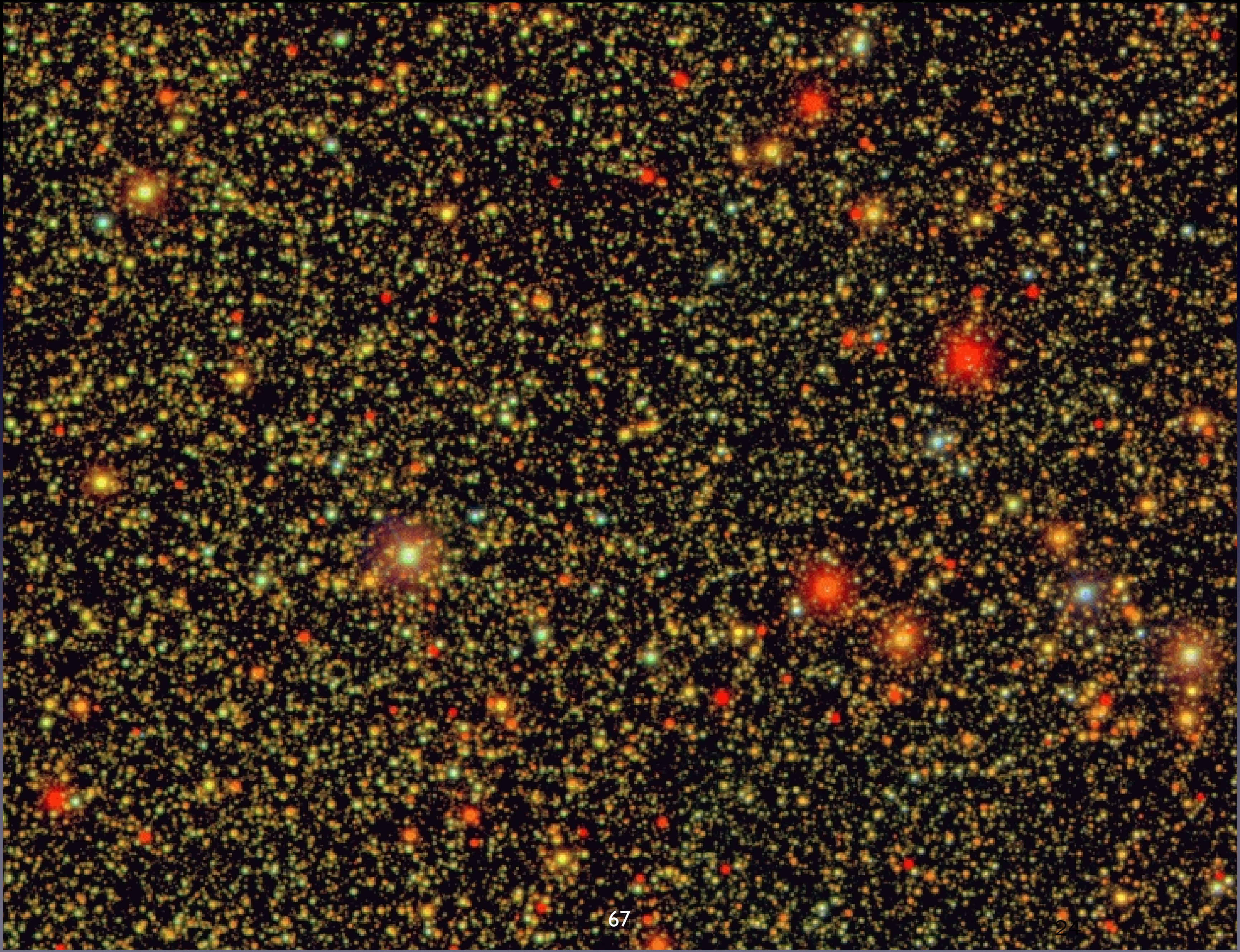


Next pointing @ position with highest reward



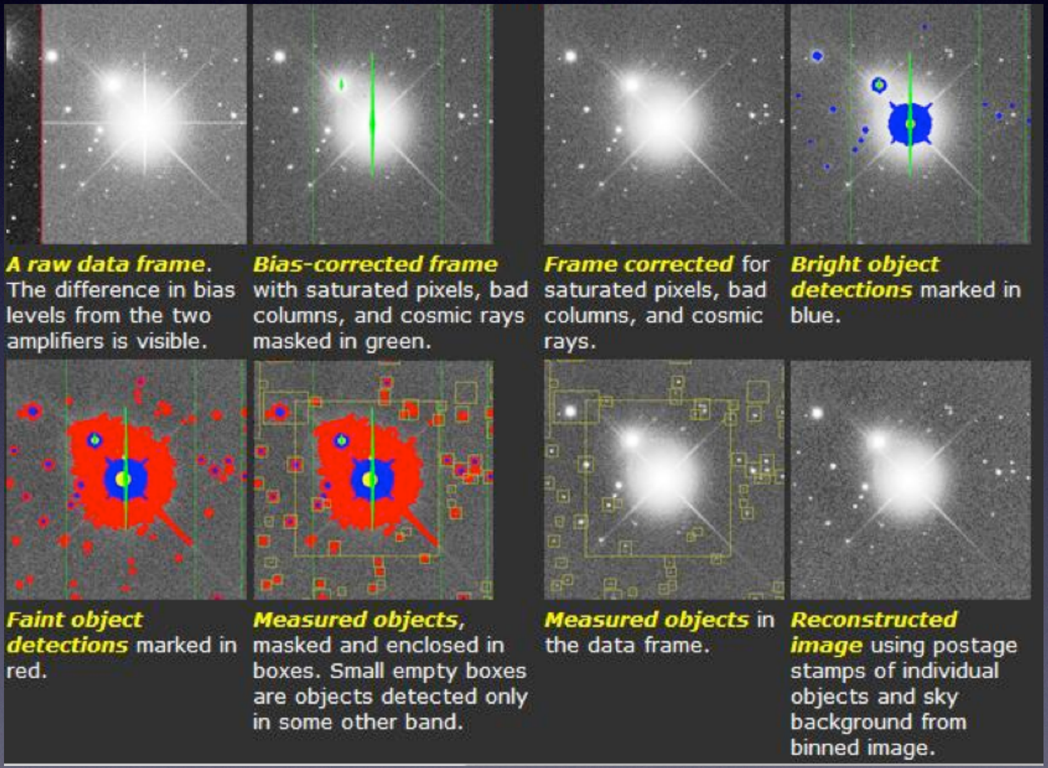
Time: 49562.988731
lucy_1002: night210
75°
60°
45°
30°
15°
0°
-15°
-30°
-45°
-60°
-75°
u
g
r
i
z
y

SDSS view along the Milky Way Disk



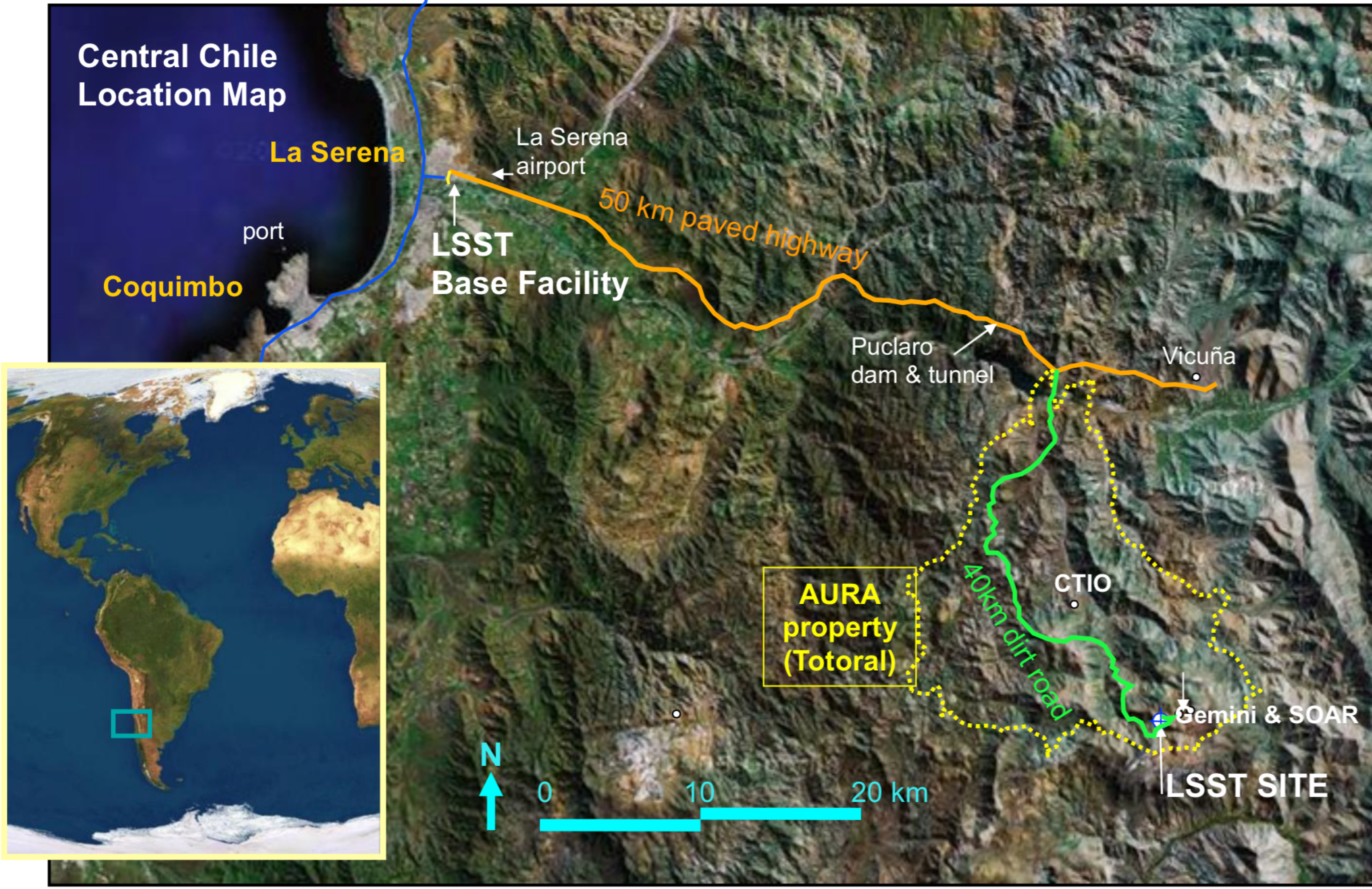
- Astronomical catalogs:
  - a list of all detected objects (stars, galaxies, ...)
  - measured parameters (size, color, brightness,...)

Basic steps in astronomical image processing (example: Sloan Digital Sky Survey):

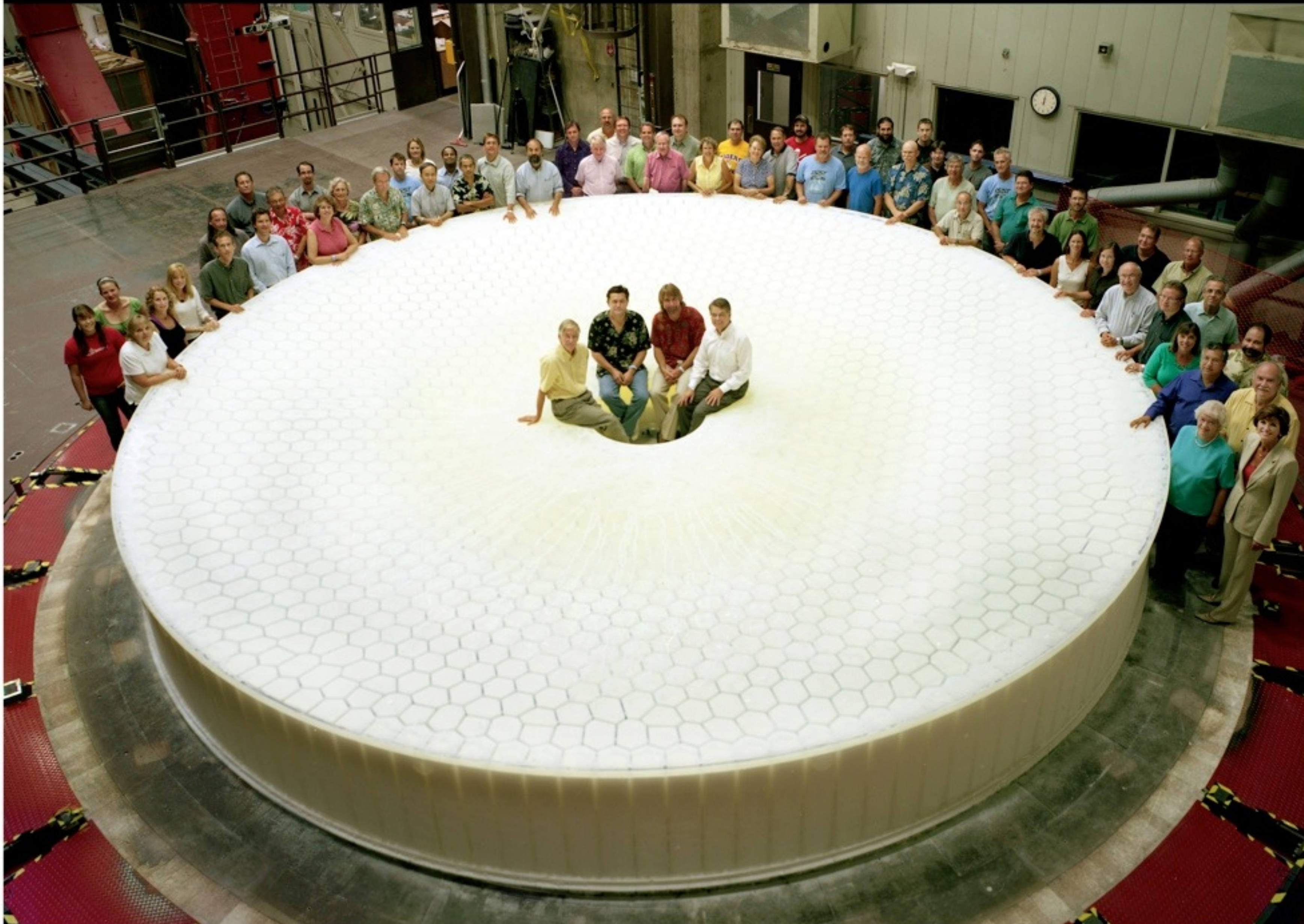


All these (complicated) steps are already done: "science-ready database"

LSST will be sited in Central Chile - Cerro Pachon



Large Synoptic Survey Telescope



The University of Arizona
Tucson Arizona

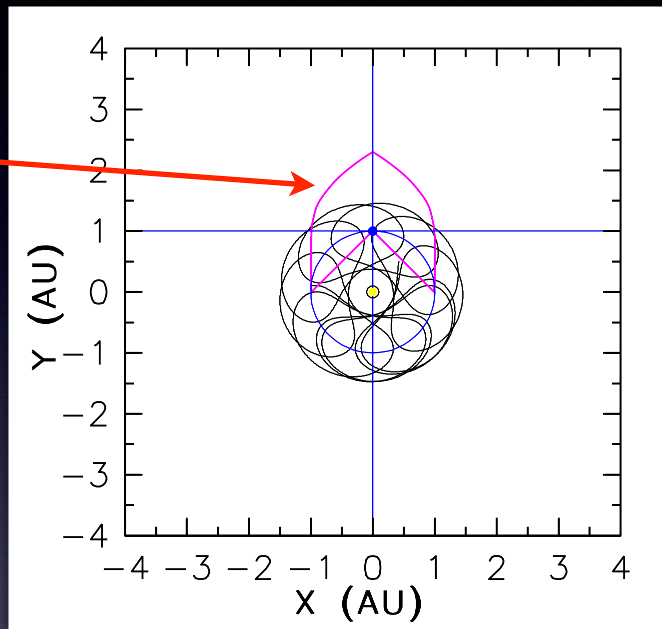
SOML

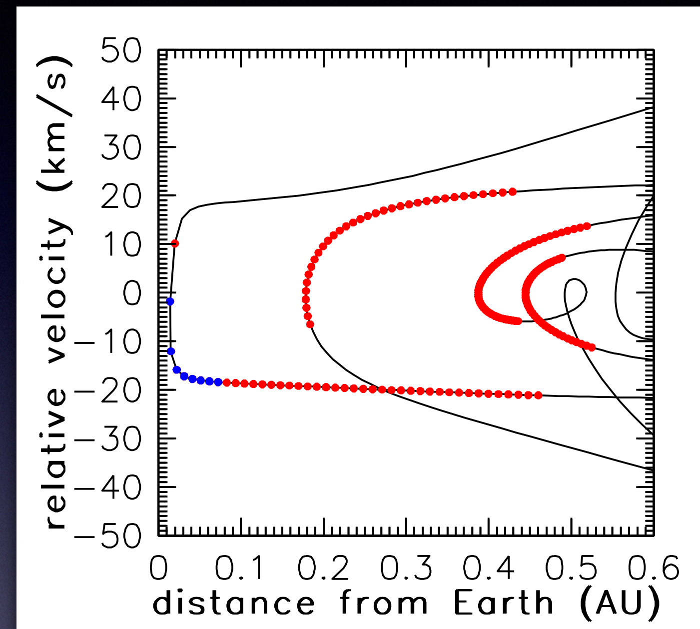
LSST Primary/Tertiary Mirror Blank
August 11, 2008, Steward Observatory Mirror Lab, Tucson, Arizona

LSST
Large Synoptic Survey Telescope

NEO Impact Warning Time

Detection volume for 140m objects





- **For 45m objects, LSST's warning time would be between 1-3 months depending on the orbit.**
- This model PHA is detected 39 days before 'impact' (vs. 5 days for systems with V<20), as well as during its 3 prior close approaches.
- Red dots indicate where the object could be detected by LSST (r=24.5) vs Blue dots, where V<20.

Extreme Deconvolution in high-D (XD)

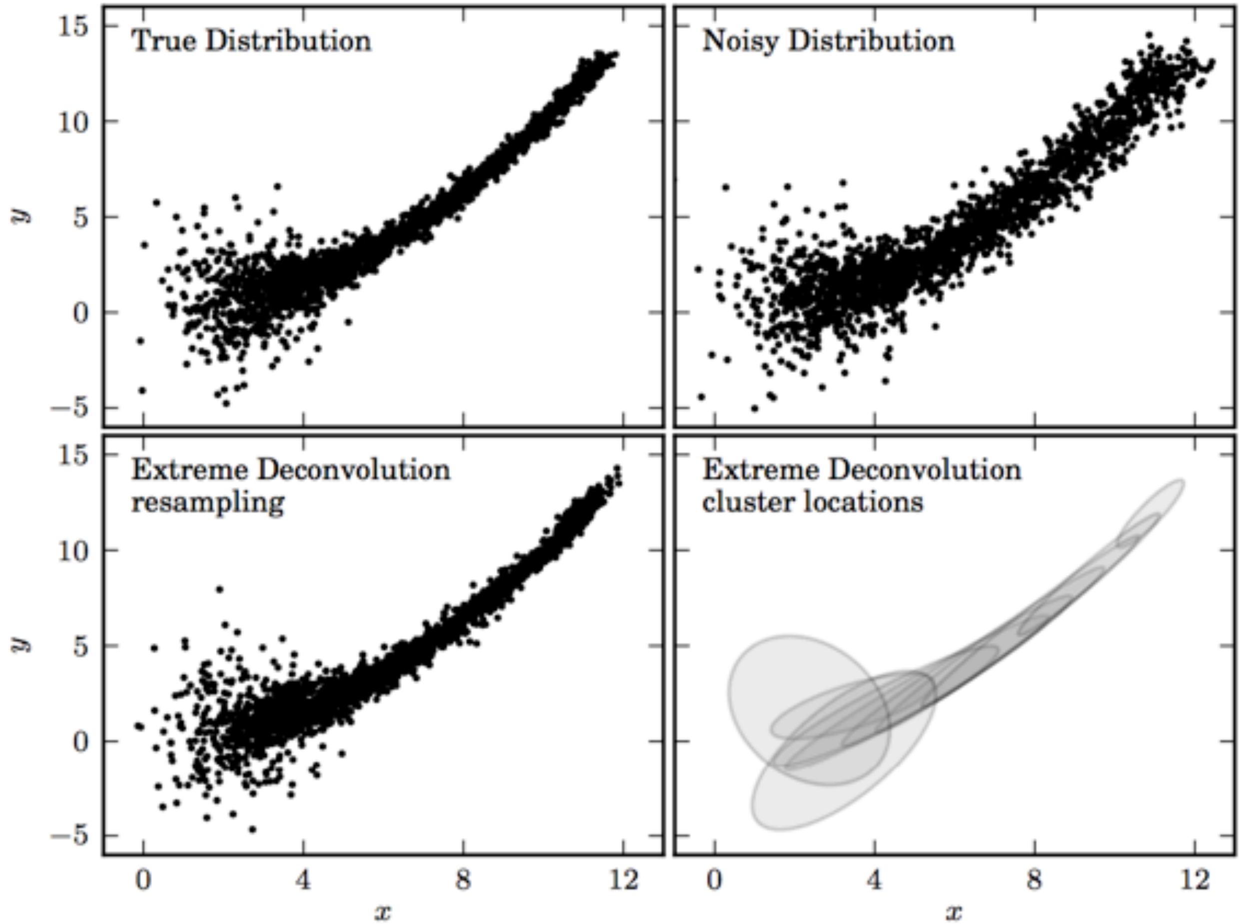


Figure 6.11.: An example of extreme deconvolution showing a simulated two-dimensional distribution of points, where the positions are subject to errors. The top two panels show the distributions with small (left) and large (right) errors. The bottom panels show the densities derived from the noisy sample (top-right panel) using extreme deconvolution; the resulting distribution closely matches that shown in the top-left panel.

Everything we'd like to do with LSST data, but don't know (yet) how

(Ivezić, Connolly, Jurić: arXiv:1612.04772)

1) Interpretation of spectral energy distributions (SEDs)
2) Spatial correlations
3) Moving objects
4) Variable objects
5) Systematic measurement uncertainties
6) Astrophysical simulations and astrophysical systematics
7) LSST System Enhancements
8) New algorithms in LSST

1) Interpretation of spectral energy distributions (SEDs)

- efficient and robust interpretation of time-resolved multi-band photometry for “billions and billions” of objects

Because of integration over broad bandpasses, forward modeling using a trial SED is superior to “correcting data" (fluxes, positions, sizes):

a) photo-z algorithms: observed SED depends on the redshift of an intrinsic SED (expansion of the universe, source evolution, intergalactic extinction)

b) photometric parallax for stars (will greatly benefit from Gaia parallaxes)

c) photometric metallicity for stars (trained using spectroscopic metallicities)

d) interstellar extinction along the line of sight for stars in the Milky Way disk

e) astrometric effects due to atmosphere (point-spread-function effects, image differencing, finding quasars)

LSST Deployment Parameters

Given the main system parameters:

$(D/6.7m)^2$ (FOV/10 sq.deg.) (survey duration/10 years) ~ 1

How to optimize the main deployment parameters:
exposure time and depth per visit, the mean revisit time, and the number of visits?

While each of these four parameters has its own drivers, they are not independent:

$$m_5 = 24.7 + 1.25 * \log(t_{vis} / 30 \text{ sec})$$

$$n = 3 * (t_{vis} / 30 \text{ sec})$$

$$N_{vis} = 1000 * (30 \text{ sec} / t_{vis}) * (T / 10 \text{ years})$$

Direct and indirect constraints on the shortest and longest acceptable exposure time per visit span a remarkably narrow range: 20 sec $< t_{vis} <$ 40 sec for the main survey

LSST Deployment Parameters

Shortest acceptable exposure time:

The single visit depth (r~24.5; driven by SNe, NEOs, RR Lyrae stars, proper motion and trigonometric parallax measurements for stars; also observing efficiency): $t_{vis} > 20$ sec

Longest acceptable exposure time:

Revisit time, n < 4 days (SNe and asteroids): $t_{vis} < 40$ sec

The number of visits, $N_{vis} > 800$ (all bands); driven by control of systematics for WL science, sampling of light curves for time domain science, and by proper motion and trigonometric parallax measurements): $t_{vis} < 40$ sec

Baseline: $t_{vis} = 30$ **sec;** a much shorter exposure time does not reach deep enough in single visits, and a much longer exposure time does not obtain enough visits.

The Dependence of Science Deliverables on Survey Duration (t)

Co-added survey depth:

$$m_5(t) = m_5^{Final} + 1.25 * \log(t / 10\ yr)$$

Photometric errors at i=25 (4 billion galaxy sample):

$$\sigma_{ph}(t) = 0.04\ mag * (t / 10\ yr)^{(-1/2)}$$

Trigonometric parallax errors at r=24:

$$\sigma_{\pi}(t) = 3.0\ mas * (t / 10\ yr)^{(-1/2)}$$

Proper motion errors at r=24:

$$\sigma_{\mu}(t) = 1.0\ mas/yr * (t / 10\ yr)^{(-3/2)}$$

DETF FOM:

$$FOM(t) = FOM^{Final} * (t / 10\ yr)$$

And other, often very complex (e.g., the faint limit for period recovery of short-period variables, NEO completeness)...

The Dependence of Science Deliverables on Survey Duration (t)

Dark Energy Task Force FOM

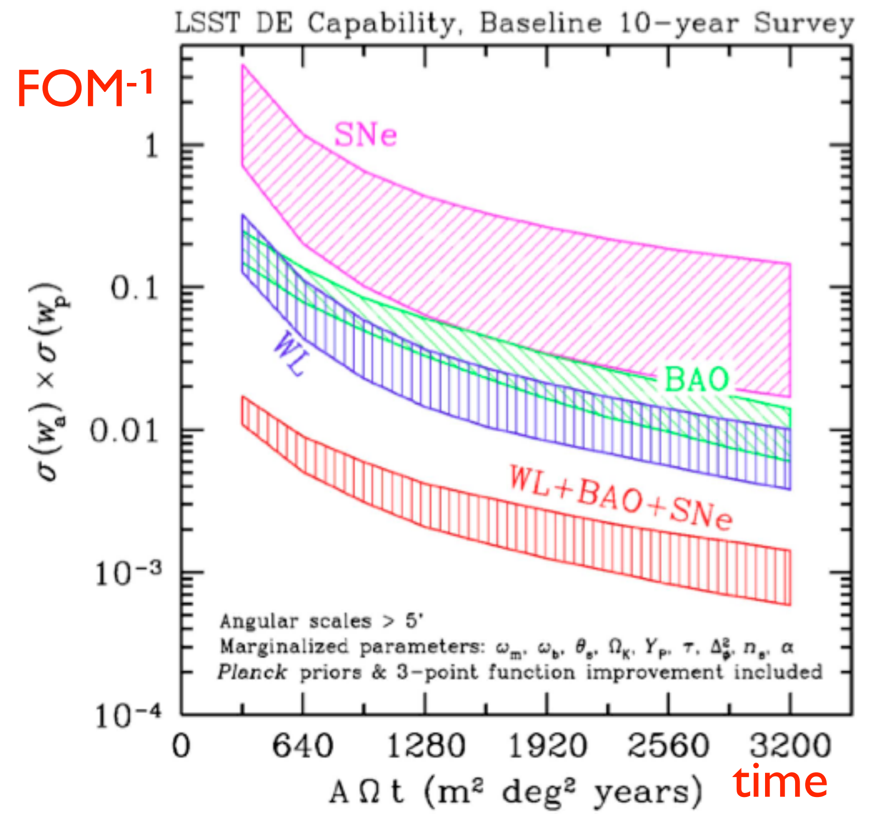


FIG. 3.— The DETF figure of merit error product for simple 2-D dark energy models is plotted as a function of integrated étendue (the value of 3200 $m^2 deg^2 yr$ corresponds to a 10-year survey). The width of the bands reflects the assumed range of systematic errors.

Sample completeness for RR Lyr

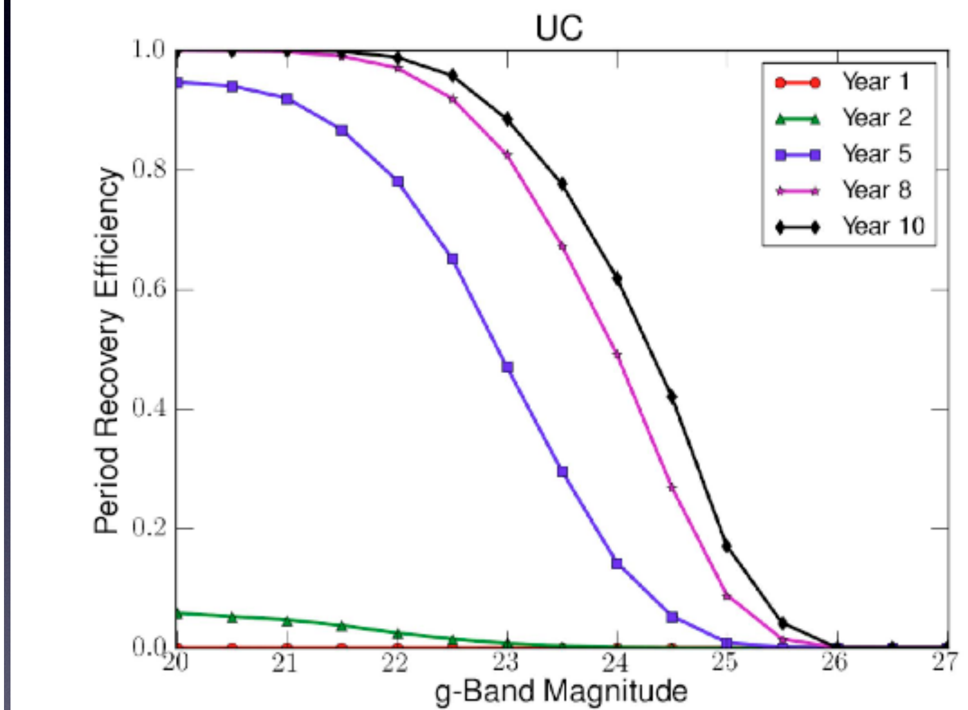


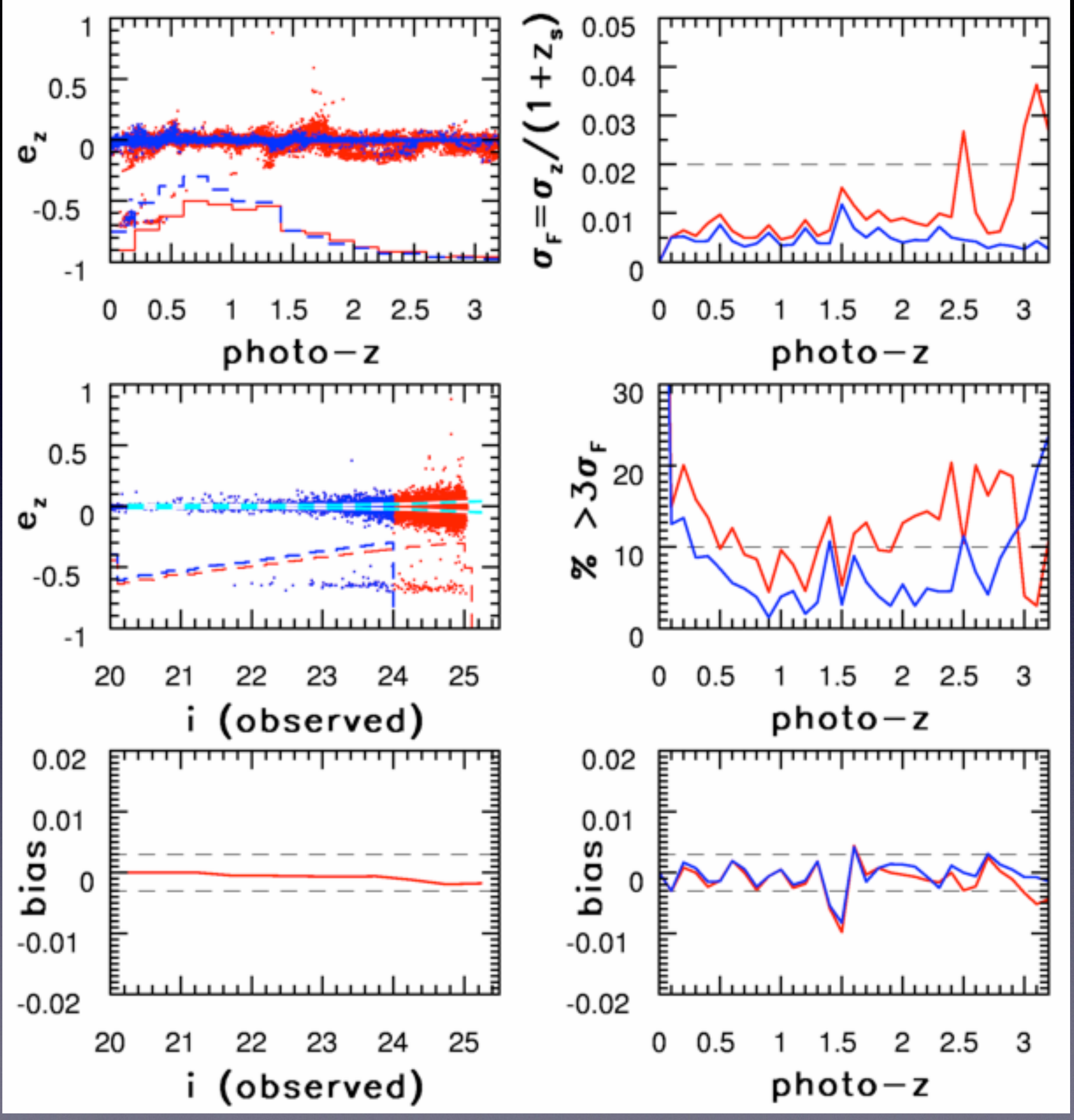
FIG. 4.— The sample completeness for simulated RR Lyrae stars with successfully recovered periods using LSST universal cadence observations in the g band (averaged over many fields), as a function of the mean g band magnitude (Oluseyi et al. 2011). The five curves correspond to different survey duration, according to the inset. The sample faint limit improves by ∼0.3 mag between years 8 and 10 both at the 50% and 90% completeness level.

The Dependence of Science Deliverables on Survey Duration (t)

VARIOUS SCIENCE METRICS AS FUNCTIONS OF SURVEY DURATION.

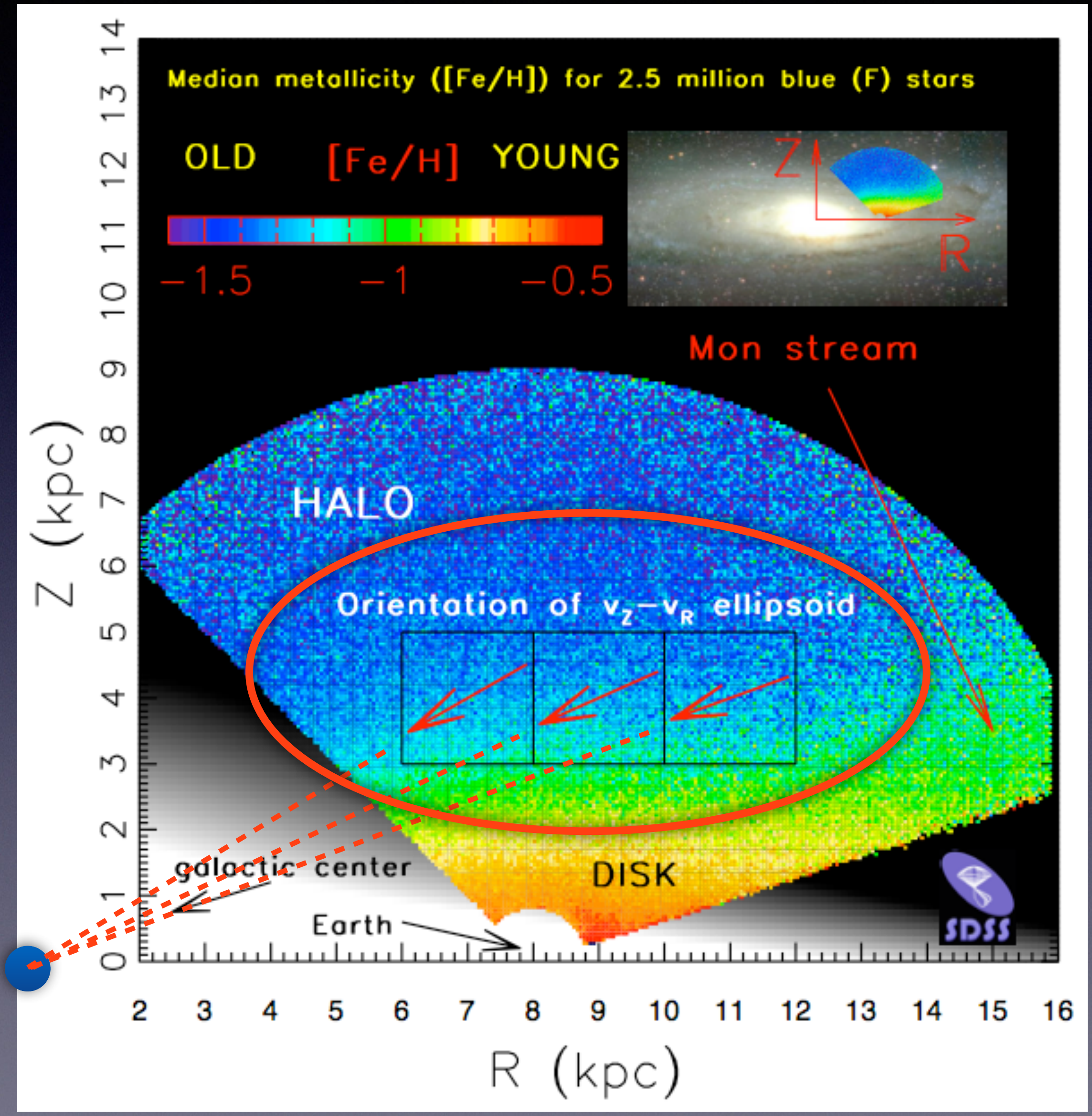
Quantity	Year 1	Y3	Y5	Y8	Year 10	Y12
r_5 coadd[a]	26.3	26.8	27.1	27.4	27.5	27.6
$\sigma(i{=}25)$[b]	0.12	0.07	0.06	0.05	0.04	0.04
color vol.[c]	316	20	6	1.7	1	0.6
# of visits[d]	83	248	412	660	825	990
σ_π $(r{=}24)$[e]	9.5	5.5	4.2	3.3	3.0	2.7
σ_μ $(r{=}24)$[f]	32	6.1	2.8	1.4	1.0	0.8

While unprecedented science outcome will definitely be possible even with a first few years of LSST data, **the complete planned and designed for science deliverables will require 10-years of data,** with a tolerance of at most about 1-2 years.



e_z
photo−z
σ_F=σ_z/(1+z_s)
photo−z
e_z
i (observed)
% >3σ_F
photo−z
bias
i (observed)
bias
photo−z

Velocity distribution for (nearby) halo stars



Kinematics of halo stars based on SDSS-POSS proper motions:

velocity ellipsoid is nearly invariant in spherical coordinate system

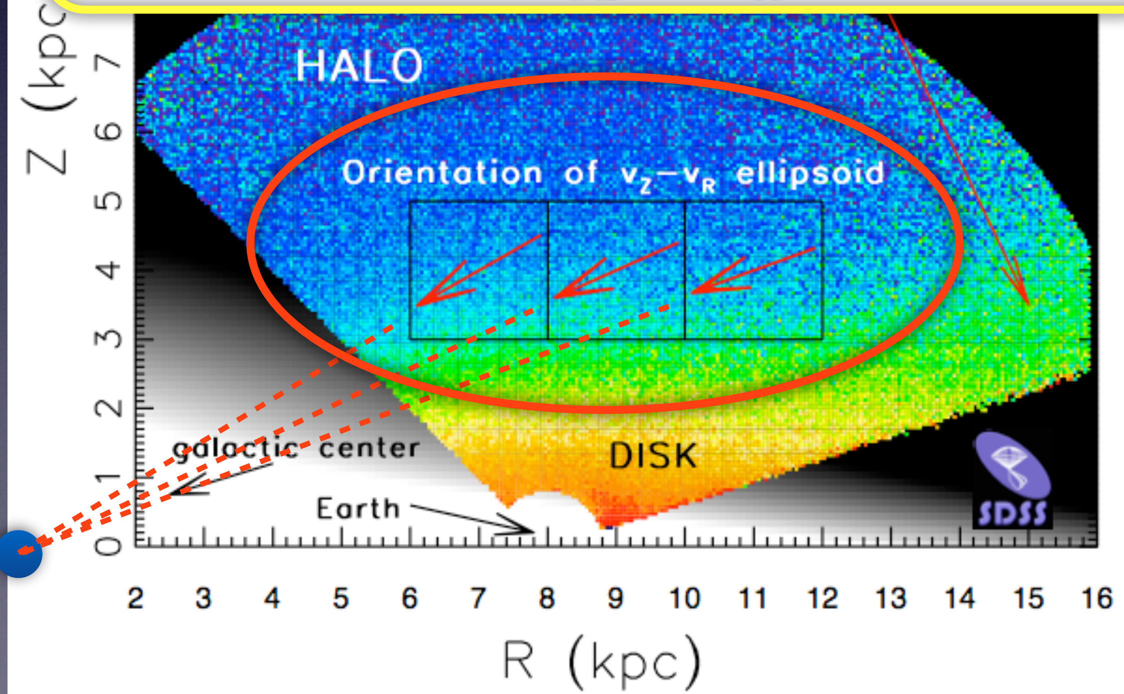
Bond et al. (2010, ApJ, 716, 1)

Velocity distribution for (nearby) halo stars

Kinematic data constrain dark matter via Jeans equations

$$a_R = \sigma^2_{RR} \times \frac{\partial(\ln \nu)}{\partial R} + \frac{\partial \sigma^2_{RR}}{\partial R} + \sigma^2_{RZ} \times \frac{\partial(\ln \nu)}{\partial Z} + \frac{\partial \sigma^2_{RZ}}{\partial Z} + \frac{\sigma^2_{RR}}{R} - \frac{\sigma^2_{\phi\phi}}{R} - \frac{\overline{v_\phi}^2}{R},$$

$$a_Z = \sigma^2_{RZ} \times \frac{\partial(\ln \nu)}{\partial R} + \frac{\partial \sigma^2_{RZ}}{\partial R} + \sigma^2_{ZZ} \times \frac{\partial(\ln \nu)}{\partial Z} + \frac{\partial \sigma^2_{ZZ}}{\partial Z} + \frac{\sigma^2_{RZ}}{R}.$$



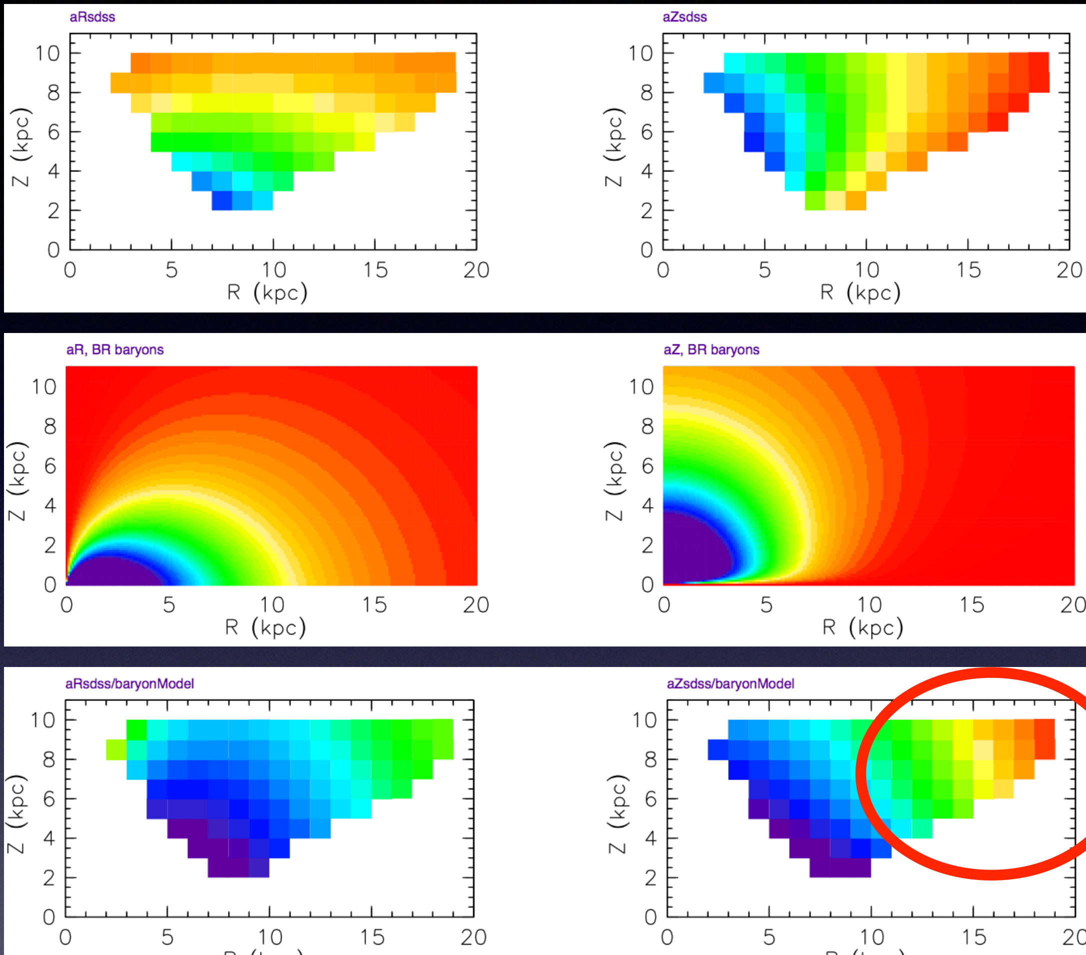
Kinematics of halo stars based on SDSS-POSS proper motions:

velocity ellipsoid is nearly invariant in spherical coordinate system

Bond et al. (2010, ApJ, 716, 1)

Given stellar distribution from Juric+2008 and stellar kinematics from Bond+2010, we can apply **Jeans equations** and infer the gravitational potential, and ultimately the distribution of dark matter!

aR aZ



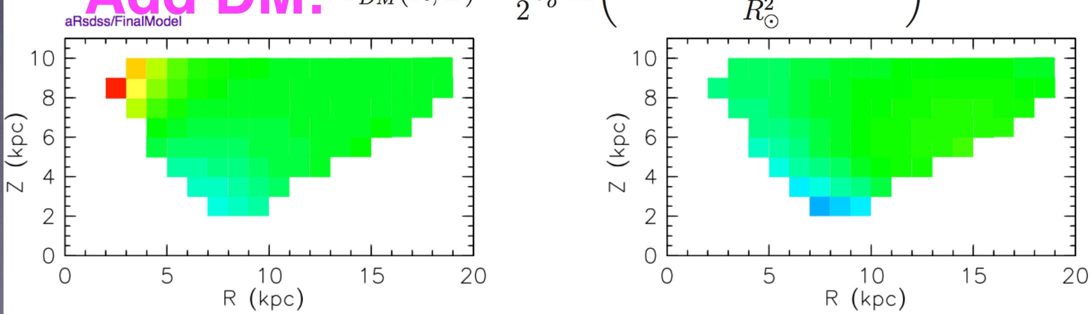
SDSS, halo, total
(Loebman et al. 2012)

Baryons (SDSS, disk)
(Bovy & Rix, 2013)

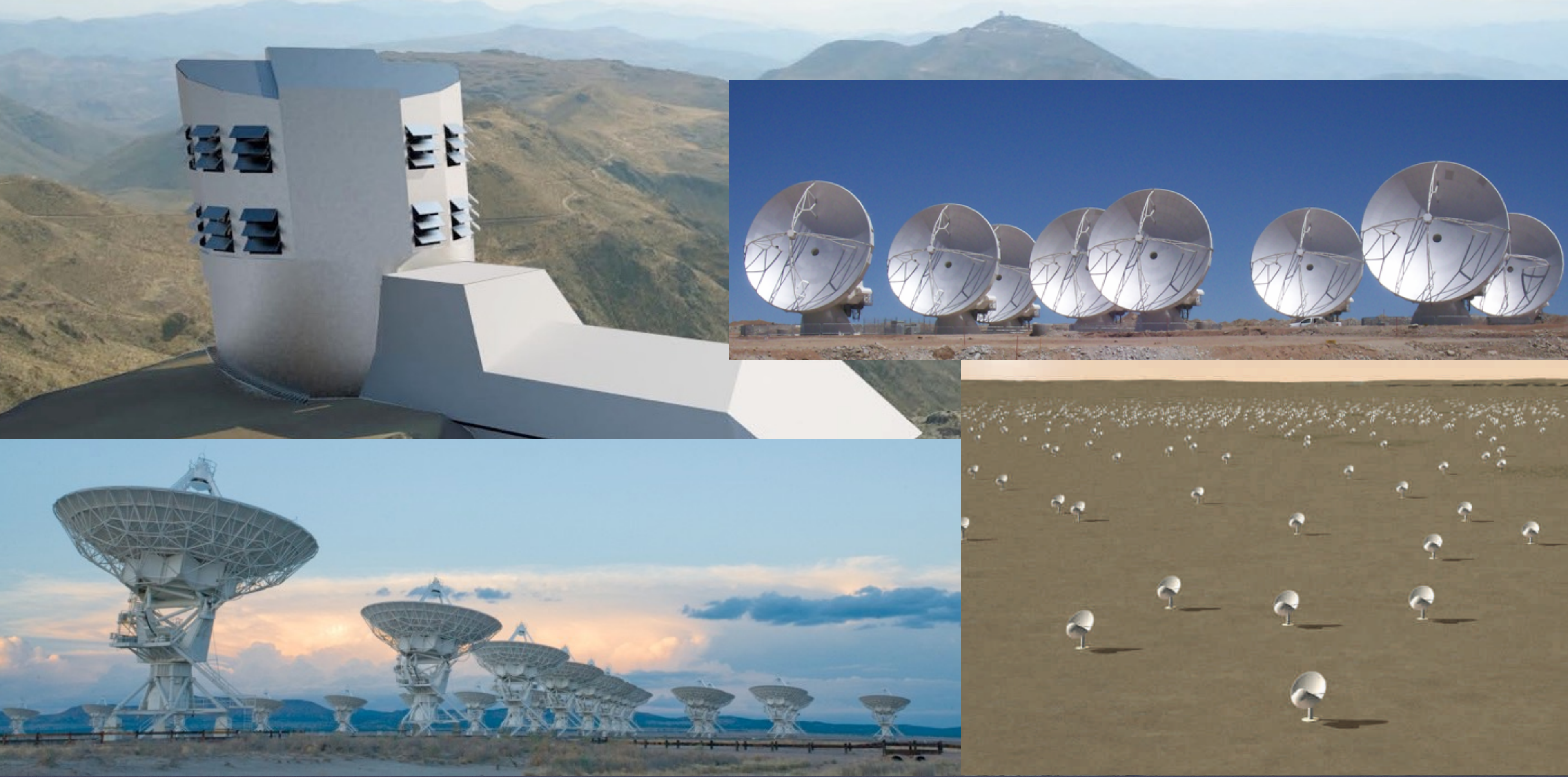
Up to 3 times stronger acc.!

SDSS measured over baryon model

Add DM: $\Phi_{DM}(R,Z) = \frac{1}{2} v_o^2 \ln\left(\frac{R^2 + (Z/q_{DM})^2 + R_{core}^2}{R_\odot^2}\right)$



DM halo is oblate!
qPot=0.7±0.1
qRho=0.4±0.1
(Loebman et al. 2014)



The connections between optical and radio regimes:

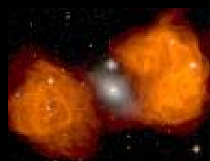
1) Science Results (asking similar and often same questions; e.g. stellar and galaxy formation and evolution, dark energy)

2) Tools and Methods (e.g. massive databases)

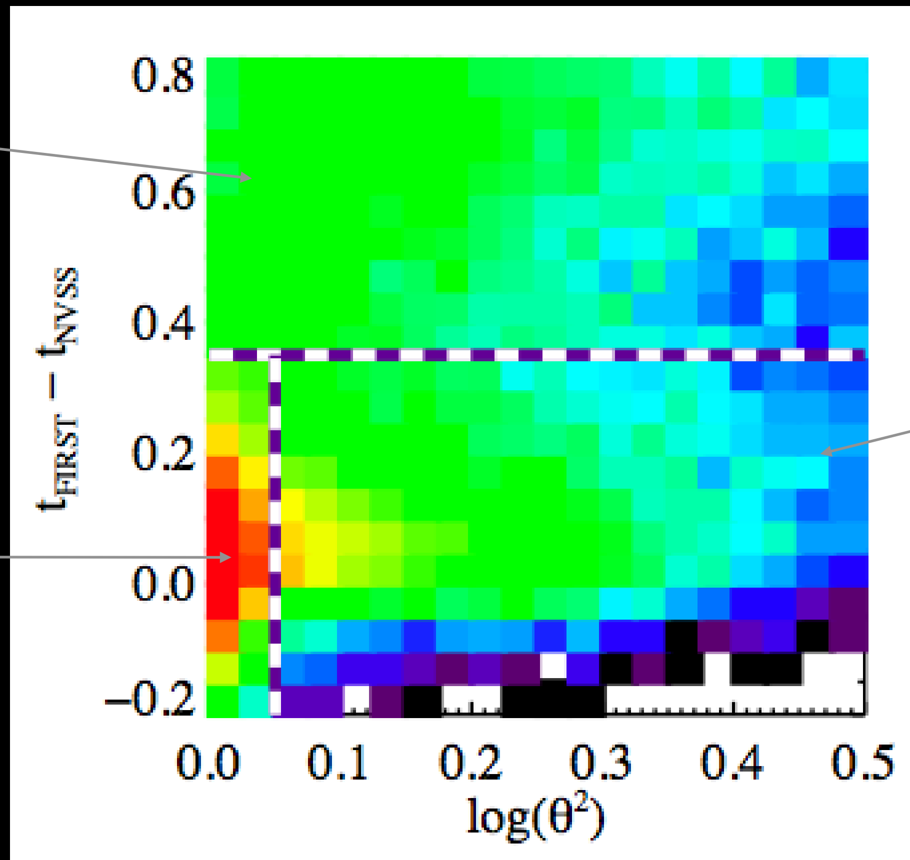
3) Supplemental data (identification, physical processes, HI)

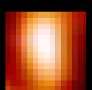
AUTOMATED radio morphology classification for over 100,000 radio sources

FIRST vs. NVSS flux, and FIRST peak vs. integrated flux:

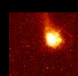


"Complex"





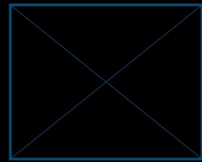
"Resolved"



"Compact" (unresolved)

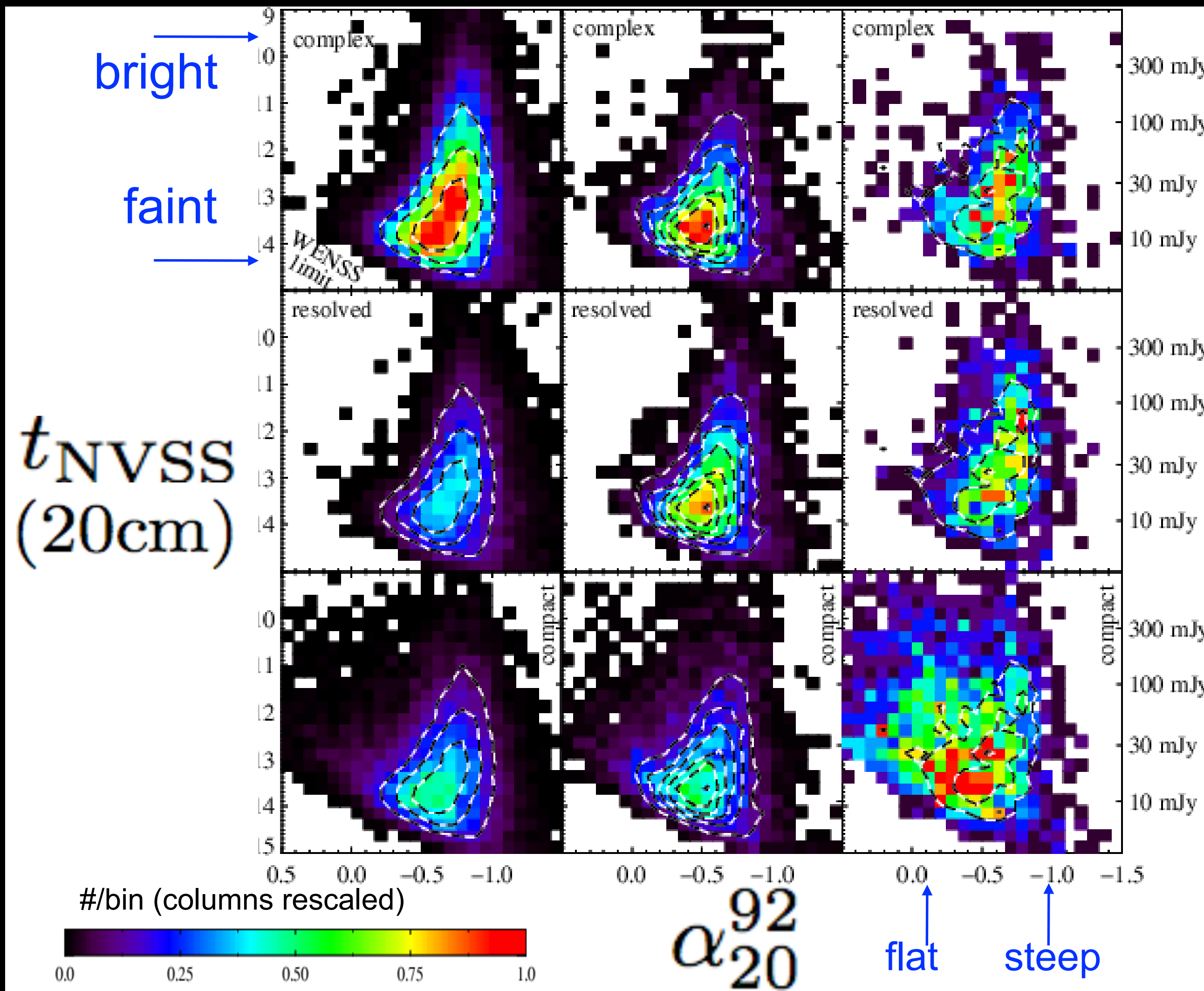
Kimball & Ivezić 2008

Radio "color"-mag. diagrams



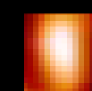
71% | 22% | 7%

Optical: No SDSS | Galaxies | Point sources

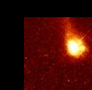


Complex 45%

Resolved 25%



Compact 30%



massive statistical studies!