# LSST Data Management: Building the Data System for the Era of Petascale Optical Astronomy

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ADASS XXV

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- Large Survey and Why They’re Different

***Hipparchus of Rhodes (180-125 BC)***

Discovered the precession of the equinoxes.

Measured the length of the year to ~6 minutes.

**In 129 BC, constructed one of the first star catalogs, containing about 850 stars.**

*n.b.: also the one to blame for the magnitude system ...*

***Galileo Galilei (1564-1642)***

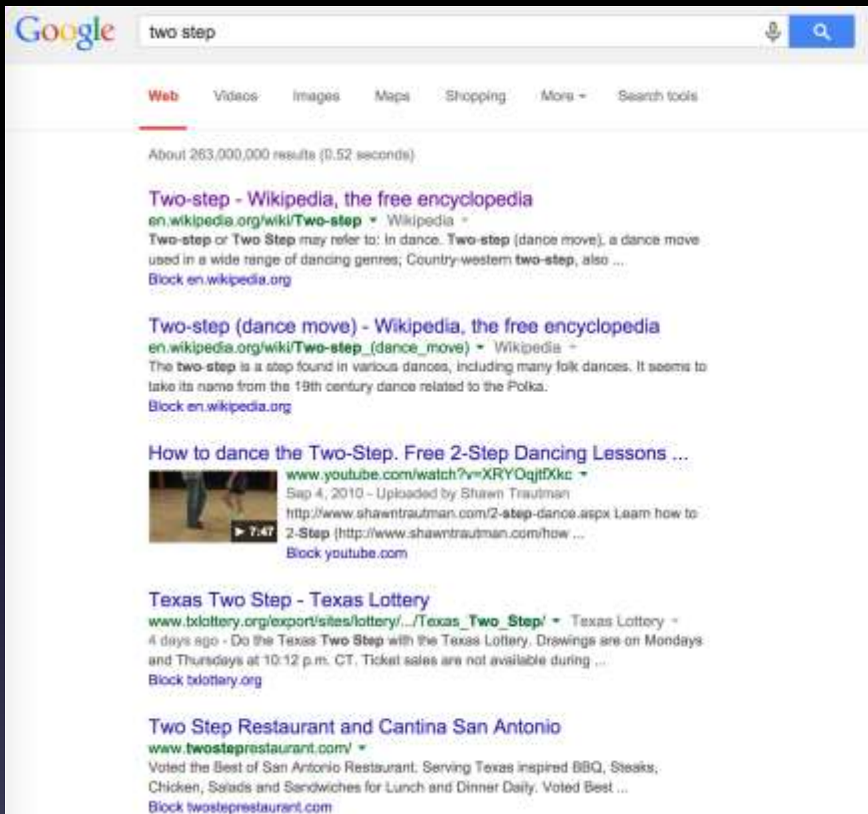
Researched a variety of topics in physics, but called out here for the introduction of the *Galilean telescope*.

Galileo's telescope allowed us for the first time to *zoom in* on the cosmos, and study the individual objects in great detail.

# The Astrophysics Two-Step

- Surveys
  - Construct catalogs  and maps of objects in the sky. Focus on coarse classification and discovering targets for further follow-up.
- Large telescopes
  - Acquire detailed observations of a **few** representative objects. Understand the details of astrophysical processes that govern them, and **extrapolate that understanding to the entire class**.

# Analogy: Google Search






Google's index is a catalog of the Web. We use it to "zoom in" on individual entries to find out more.


But, it’s more than just a catalog of pointers – more and more, Google itself collects, processes, indexes, visualizes, and serves the actual information we need.

More and more often, our “research” begins and ends with Google!

# Entering the Era of Massive Sky Surveys

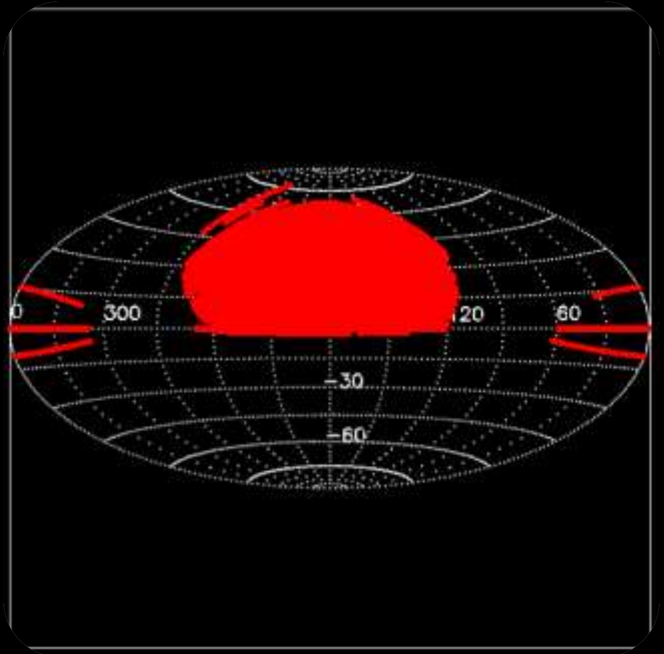
- There's a close parallel with large surveys in astronomy, in scale, quality, and richness of the collected information
  - Scale: We're entering the era when we can image and catalog the entire sky
  - Quality: The measurements can be as precise as those taken with "pointed" observations (used to be ~5-10x worse)
  - Richness: Those catalogs contain not only positions and magnitudes, but also shapes, profiles, and temporal behavior of the objects.

- Quite often, the research can begin and end with the survey.
- This is what makes large surveys of today **not just bigger, but better, more information rich, and therefore different.** **Big data is now about complexity and optimal knowledge extraction, not PBs (IMHO).**

# Sloan Digital Sky Survey

2.5m telescope | >10000 $deg^2$ | 0.1" astrometry | r<22.5 flux limit

5 band, 2%, photometry for >50M stars
>300k R=2000 stellar spectra



# Panoramic Survey Telescope and Rapid Response System

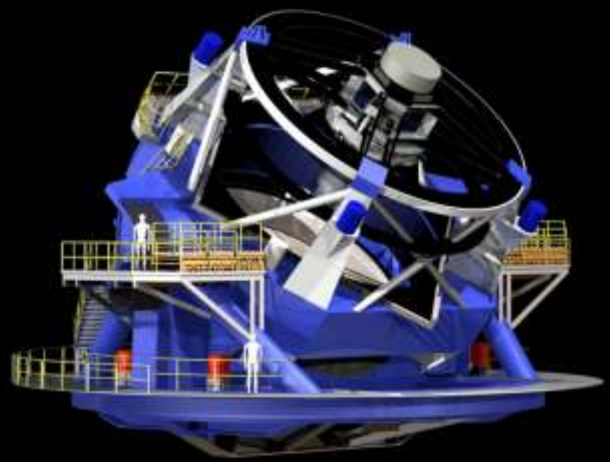
1.8m telescope    30000 $deg^2$    50mas astrometry    r<23 flux limit

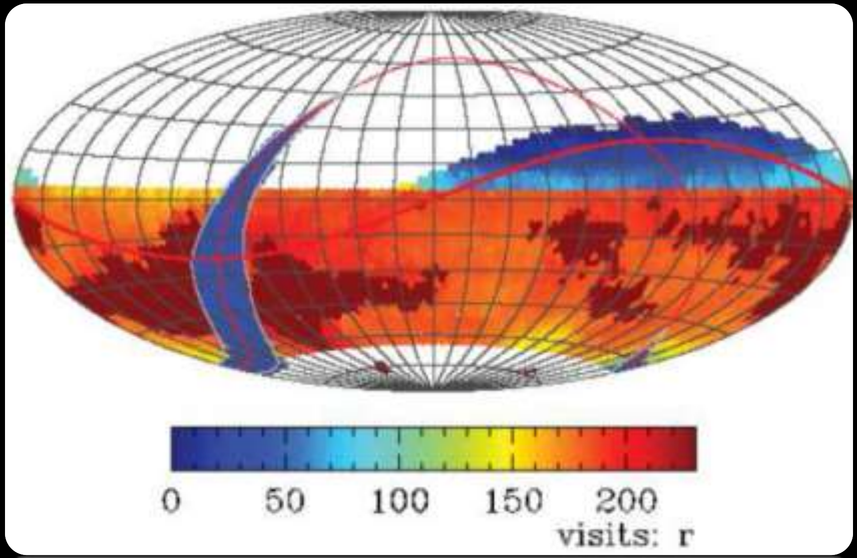
5 band, better than 1% photometry (goal)

# LSST: A Deep, Wide, Fast, Optical Sky Survey

8.4m telescope | 18000+ deg$^2$ | 10mas astrom. | r<24.5 (<27.5@10yr)

ugrizy | 0.5-1% photometry






3.2Gpix camera | 30sec exp/4sec rd | 15TB/night | 37 B objects

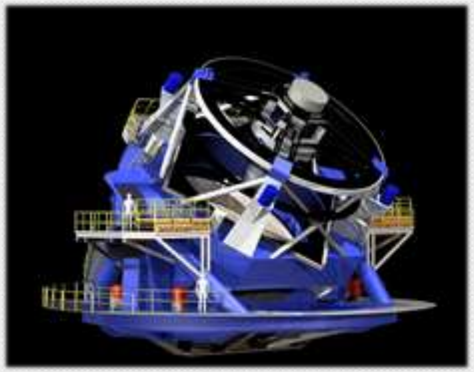
Imaging the visible sky, once every 3 days, for 10 years (825 revisits)

# LSST: Turning the Sky into a Database

- **A wide (half the sky), deep (24.5/27.5 mag), fast (image the sky once every 3 days) survey telescope. Beginning in 2022, it will repeatedly image the sky for 10 years.**

- The LSST will be an automated survey system. In nighttime, the observatory and the data system will operate with minimum human intervention.

- **The ultimate deliverable of LSST is not the telescope, nor the instruments; it is the fully reduced data.**
  - All science will be come from survey catalogs and images



Telescope ➔

Images ➔

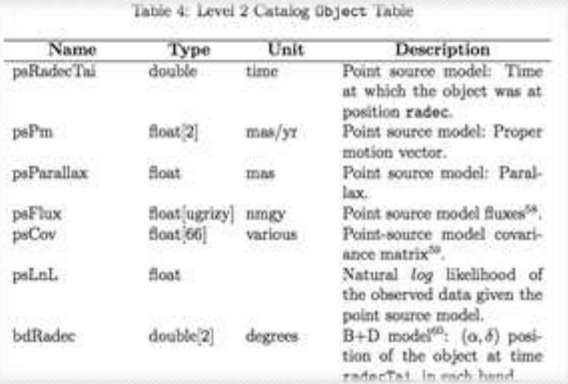


Table 4: Level 2 Catalog Object Table

| Name | Type | Unit | Description |
|---|---|---|---|
| psRadecTai | double | time | Point source model: Time at which the object was at position radec. |
| psPm | float[2] | mas/yr | Point source model: Proper motion vector. |
| psParallax | float | mas | Point source model: Parallax. |
| psFlux | float[ugrizy] | nmgy | Point source model fluxes[58]. |
| psCov | float[66] | various | Point-source model covariance matrix[59]. |
| psLnL | float | | Natural *log* likelihood of the observed data given the point source model. |
| bdRadec | double[2] | degrees | B+D model[60]: $(\alpha, \delta)$ position of the object at time radecTai, in each band. |

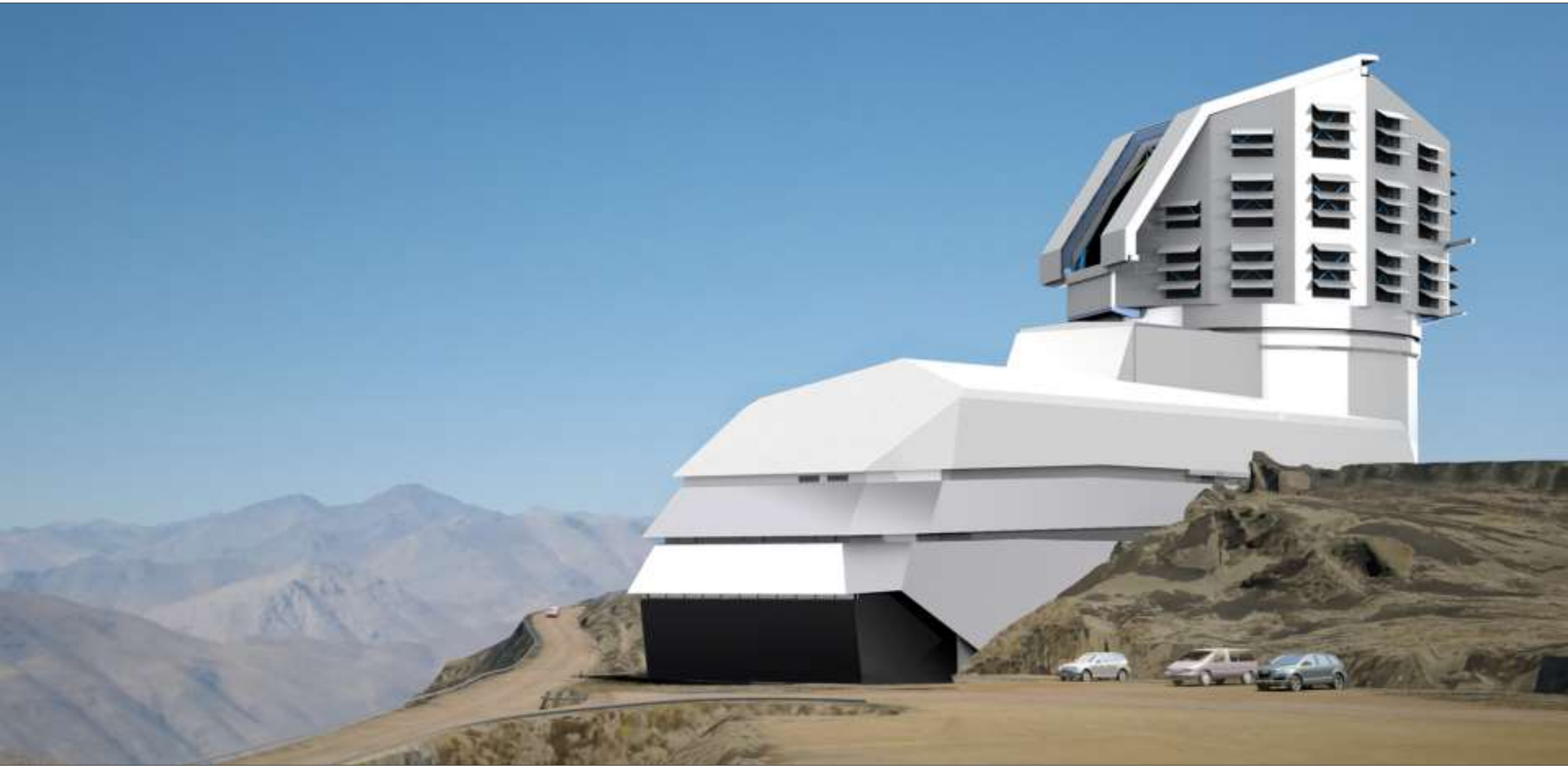
Catalogs

# Location: Cerro Pachon, Chile

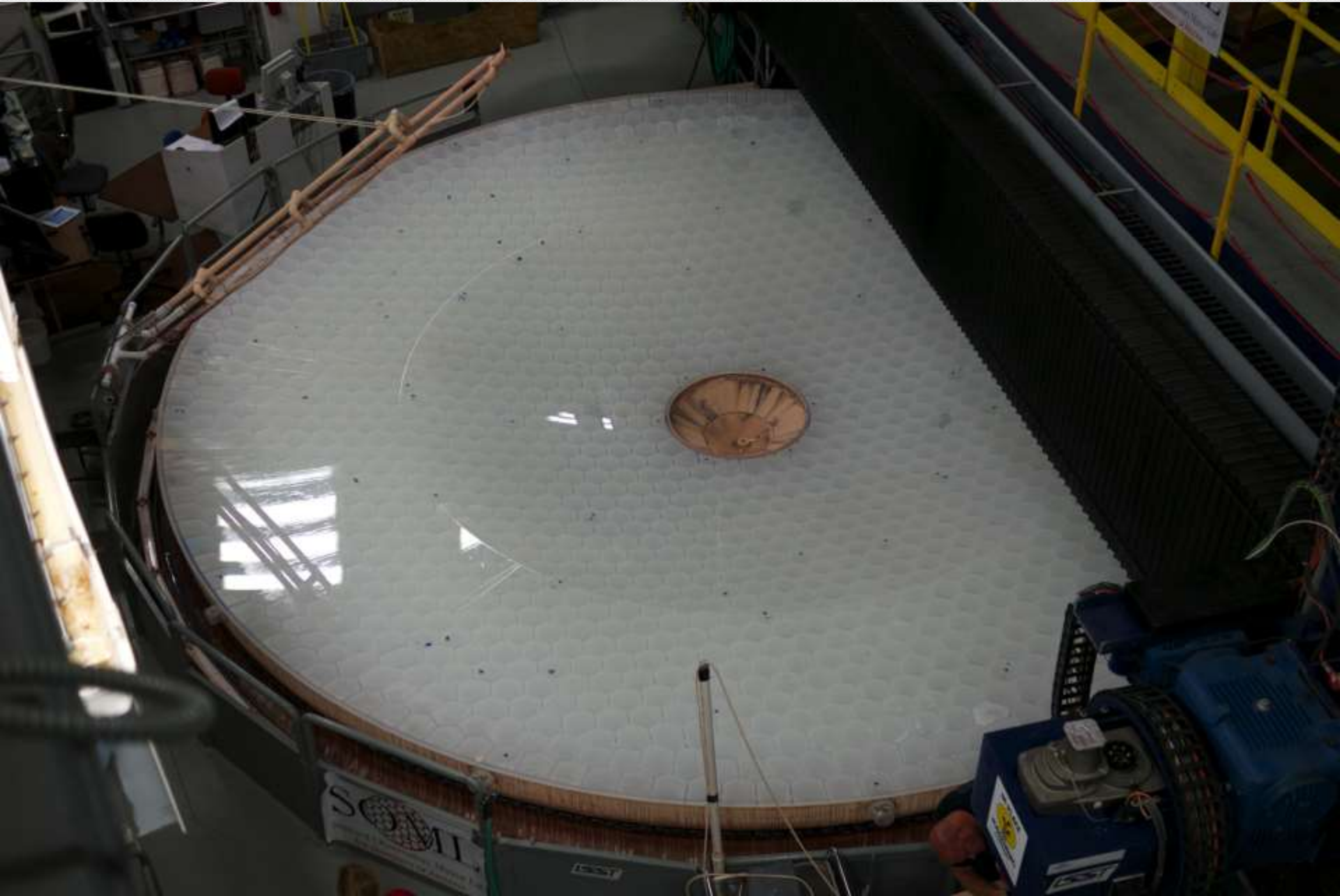


# LSST Site (April 14th, 2015)

# LSST Observatory (cca. late ~2018)

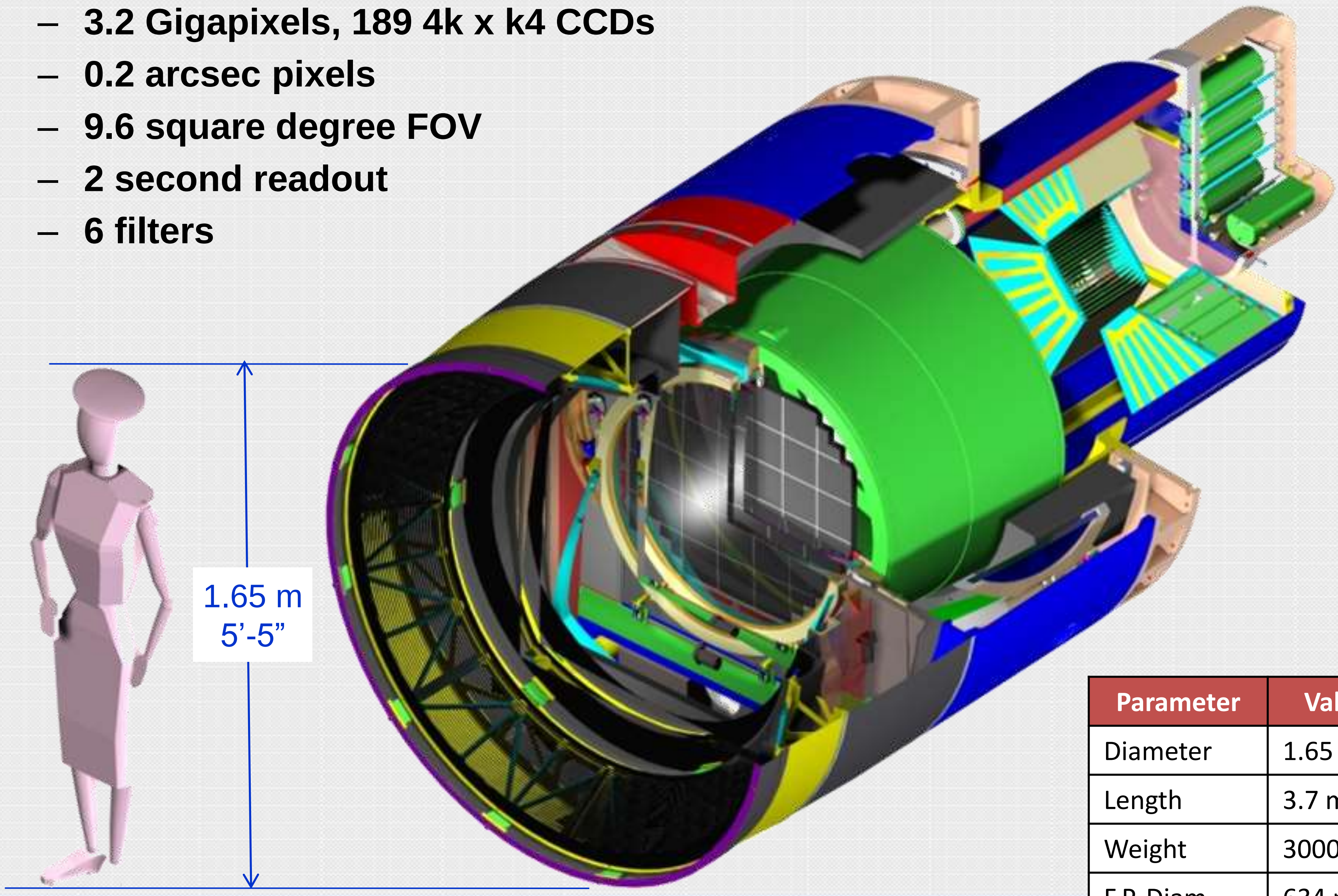


# Done!



# LSST Camera

– **3.2 Gigapixels, 189 4k x k4 CCDs**
– **0.2 arcsec pixels**
– **9.6 square degree FOV**
– **2 second readout**
– **6 filters**




| Parameter | Value |
|---|---|
| Diameter | 1.65 m |
| Length | 3.7 m |
| Weight | 3000 kg |
| F.P. Diam | 634 mm |

# *LSST Imaging: ~5 PB/yr*

*(~5 **expensive, information rich** PB/yr)*

# LSST Operations: Sites and Data Flows

## Satellite Processing Center

***(CC-IN2P3, Lyon, France)***

*Data Release Production (50%)*
*French DAC*

## Archive Site

### Archive Center

Alert Production
Data Release Production (50%)
EPO Infrastructure
Long-term Storage (copy 2)

### Data Access Center

Data Access and User Services

## Summit and Base Sites

Telescope and Camera
Data Acquisition
Crosstalk Correction
Long-term storage (copy 1)
Chilean Data Access Center

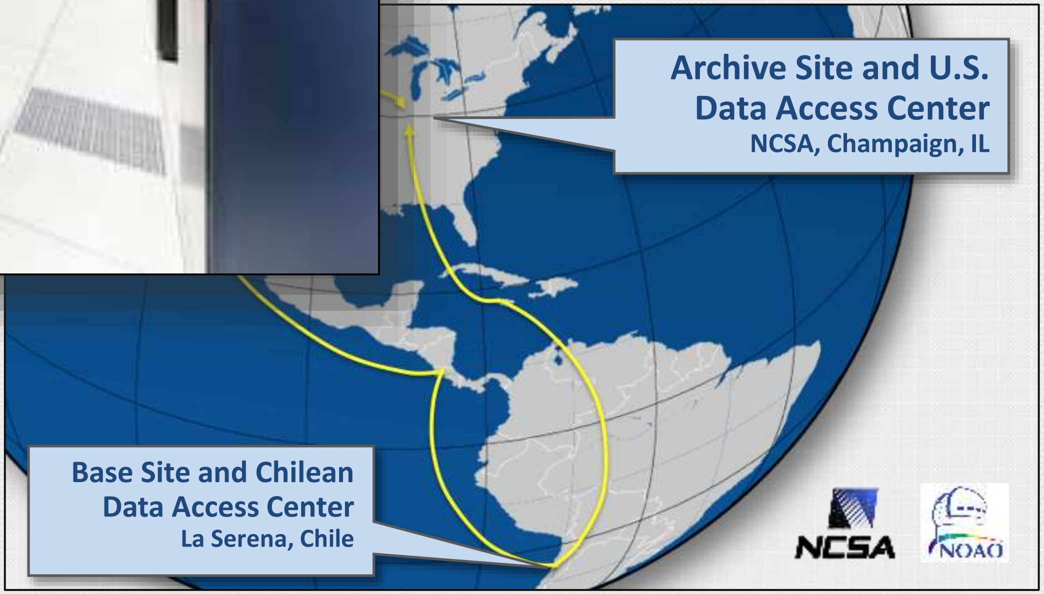
## HQ Site

Science Operations
Observatory Management
Education and Public Outreach

# Infrastructure: Petascale Computing, Gbit Networks

*The computing cluster at the* ***LSST Archive*** *(at NCSA) will run the processing pipelines.*

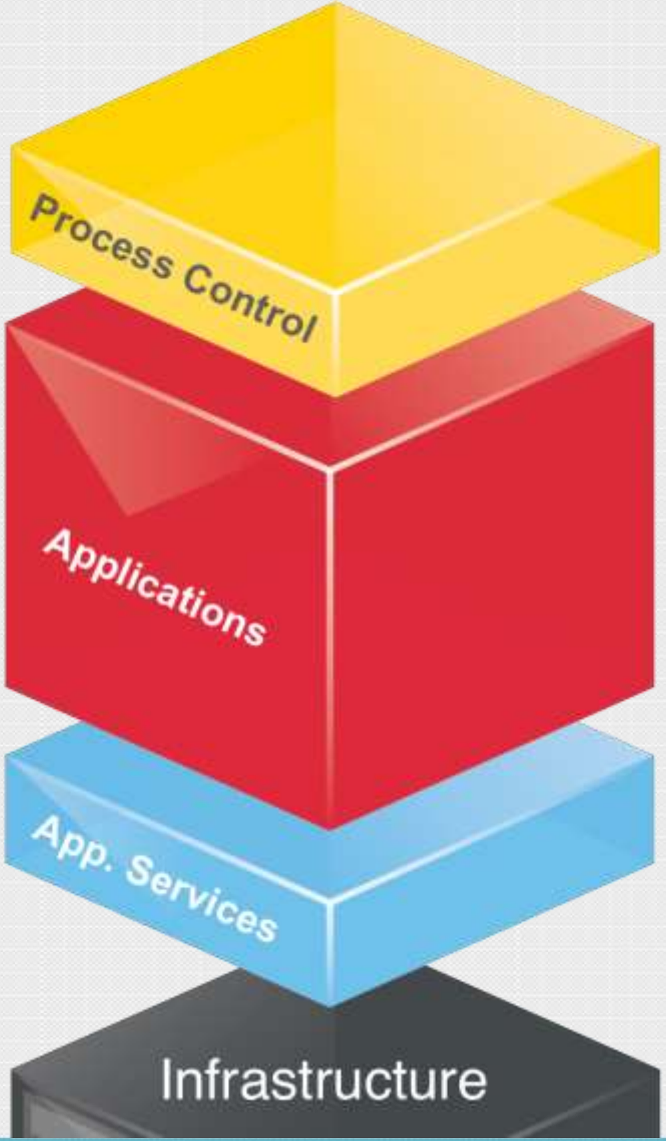
- *Single-user, single-application, dedicated data center*
- *Process images in real-time to detect changes in the sky*
- *Produce annual data releases*




***Long Haul Networks*** to transport data from Chile to the U.S.

- *200 Gbps from Summit to La Serena (new fiber)*
- *2x40 Gbit (minimum) for La Serena to Champaign, IL (protected, existing fiber)*

# "Applications": Scientific Core of LSST DM

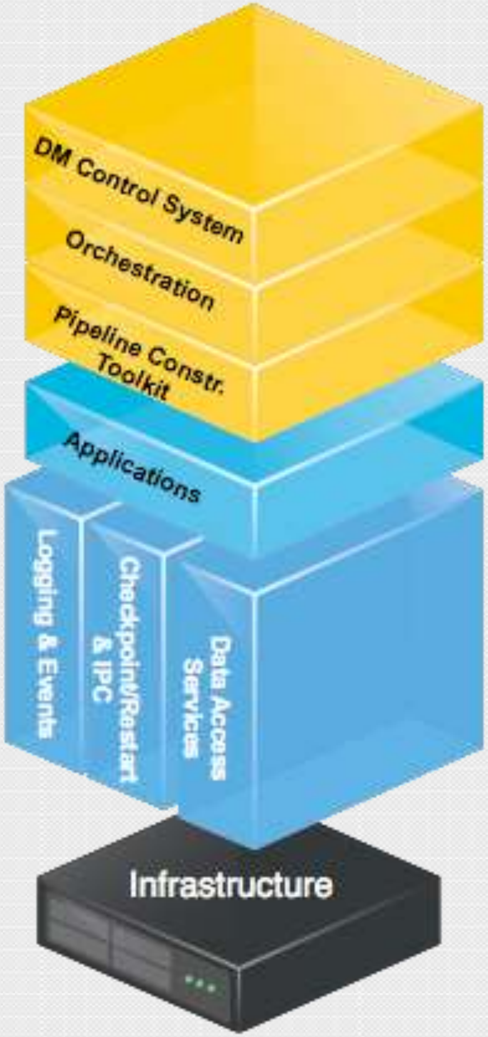



- *Applications* carry core scientific algorithms that process or analyze raw LSST data to generate output Data Products

- Variety of processing
  - Image processing
  - Measurement of source properties
  - Associating sources across space and time, e.g. for tracking solar system objects

- *Applications framework* layer (*afw*; not shown) allows them to be written in a high-level language

# Middleware Layer: Isolating Hardware, Orchestrating Software



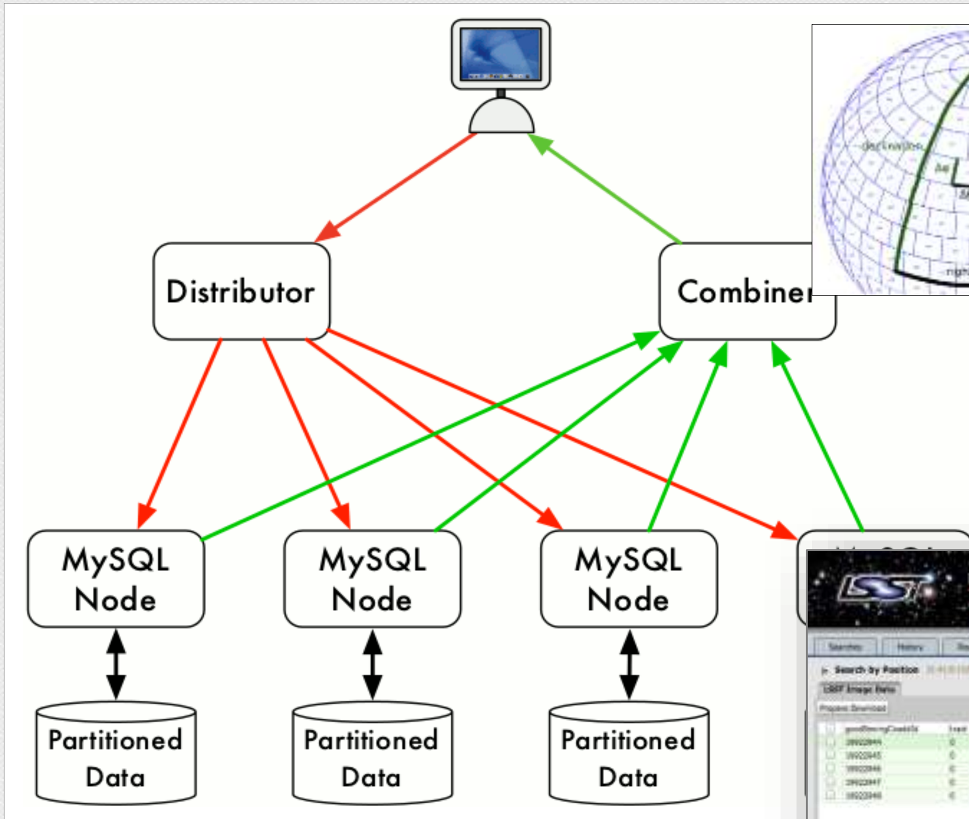

*Enabling execution of science pipelines on hundreds of thousands of cores.*

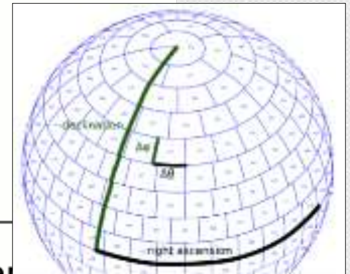
- Frameworks to construct pipelines out of basic algorithmic components
- Orchestration of execution on thousands of cores
- Control and monitoring of the whole DM System

*Isolating the science pipelines from details of underlying hardware*

- Services used by applications to access/produce data and communicate
- "Common denominator" interfaces handle changing underlying technologies

# Database and Science UI: Delivering to Users

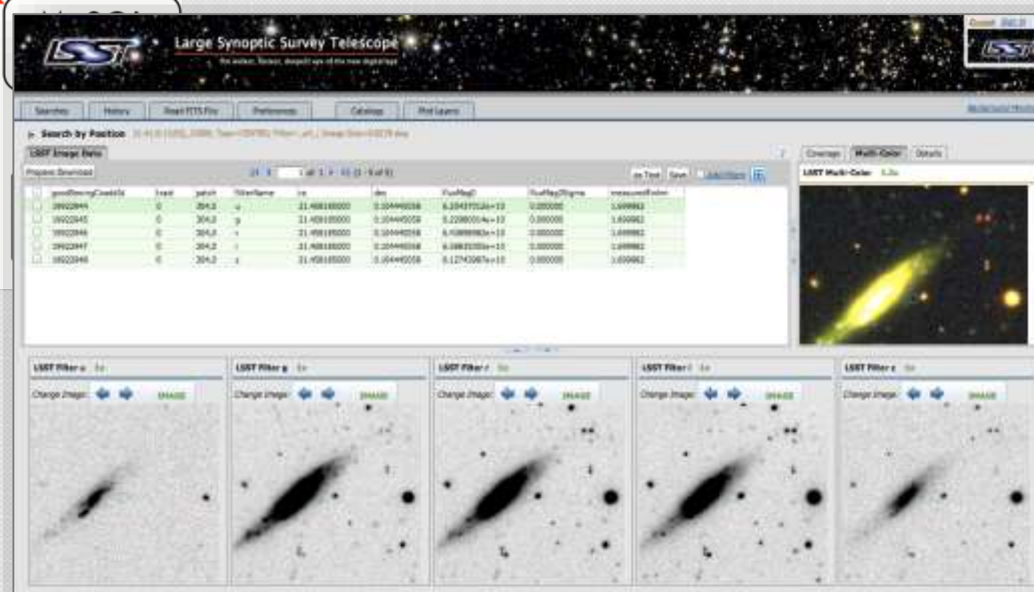


*Massively parallel, distributed, fault-tolerant **relational database**.*

- To be built on existing, robust, well-understood, technologies (MySQL and xrootd)
- Commodity hardware, open source
- Advanced prototype in existence (qserv)

SLAC

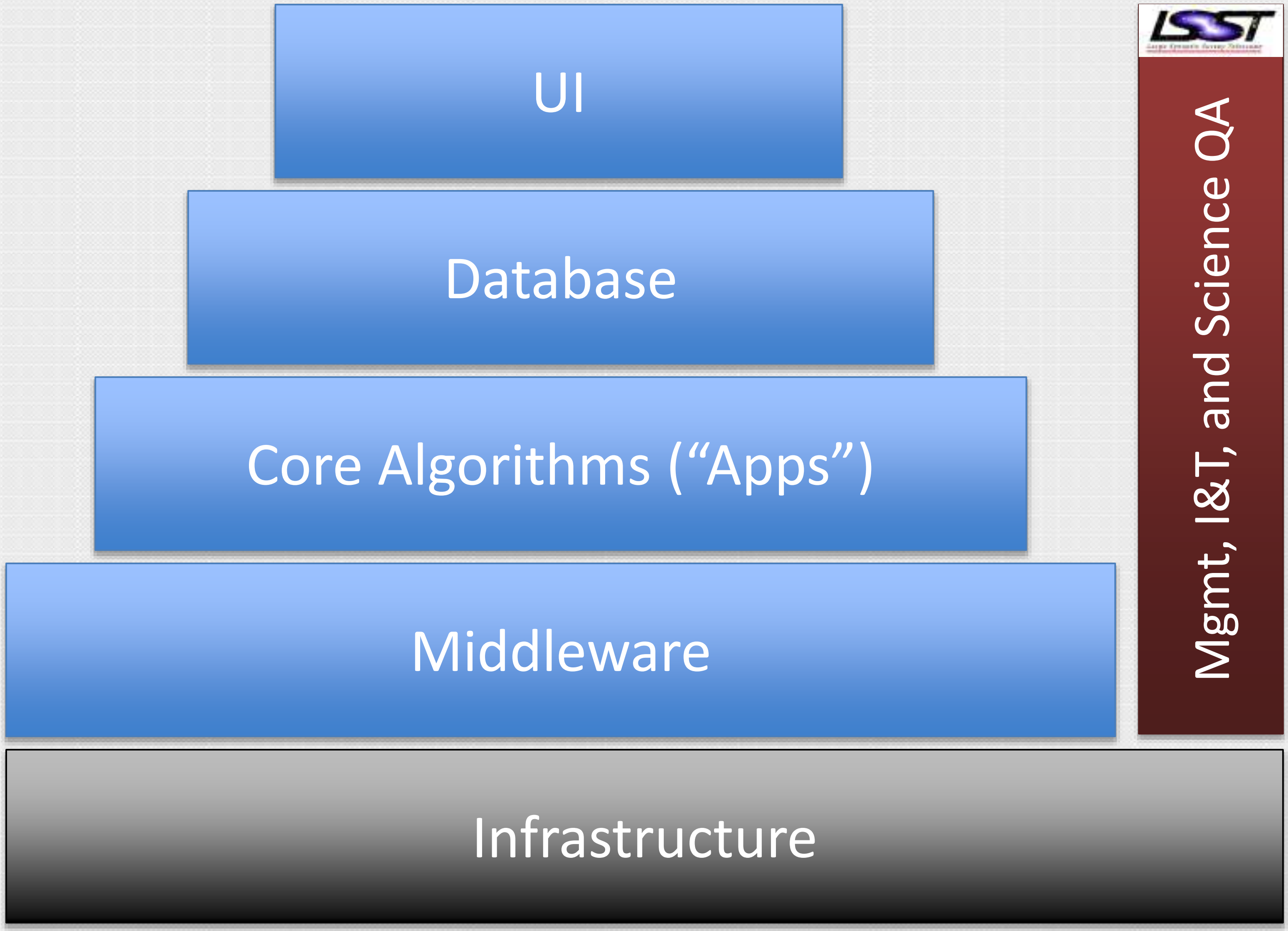



***Science User Interface** to enable the access to and analysis of LSST data*

- Web and machine interfaces to LSST databases
- Visualization and analysis capabilities

ipac

# LSST DM: A Distributed Development Team

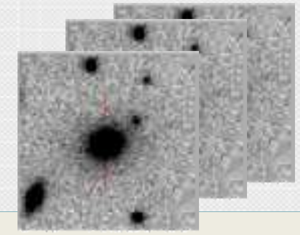


# *LSST's #1 Challenge:*

*General purpose processing while minimizing information loss.*

# From Data to Knowledge

Computationally (and cognitively) expensive, science-case speciific



And metadata!

*Scientists*

*Scientists* **Model** ← *inference* – **Data** *Project*

Scientists **Model** ← Scientists *inference* – Project **Catalog** ← Project Data Processing – Project **Data**

Computationally cheaper,
Easier to understand,
Science-case speciific

- Computationally expensive, general
- Reprojection; may or may not involve compression
- Almost always introduces some information loss
- Data Processing == Instrumental Calibration + Measurement

# Guiding Principles for LSST Data Products

- There are virtually infinite options on what quantities (features) one can measure on images. But if catalog generation is understood as a *(generalized) cost reduction tool*, the guiding principles become easier to define:

1. **Maximize science enabled by the catalogs**
   - Working with images takes time and resources; a large fraction of LSST science cases should be enabled by just the catalog.
   - Be considerate to the user: provide even sub-optimal measurements if they will enable leveraging of existing experience and tools
2. **Minimize information loss**
   - Provide (as much as possible) estimates of likelihood surfaces, not just single point estimators
3. **Provide and document the transformation (the software)**
   - Measurements are becoming increasingly complex and systematics limited; need to be maximally transparent about *how* they're done

# What LSST will Deliver:
# A Data Stream, a Database, and a (small) Cloud

- 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

- 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

- 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 Science Pipelines

- 02C.01.02.01/02. **Data Quality Assessment Pipelines** *(slides by Juric)*
- 02C.01.[02.01.04,04.01,04.02] **Calibration Pipelines** *(slides by Axelrod, Yoachim)*

Level 1

- 02C.03.01. **Single-Frame Processing Pipeline** *(slides by Krughoff, Lupton)*
- 02C.03.02. **Association pipeline** *(slides by Lupton)*
- 02C.03.03. **Alert Generation Pipeline** *(slides by Becker)*
- 02C.03.04. **Image Differencing Pipeline** *(slides by Becker)*
- 02C.03.06. **Moving Object Pipeline** *(slides by Jones)*

Level 2

- 02C.04.03. **PSF Estimation Pipeline** *(slides by Lupton)*
- 02C.04.04. **Image Coaddition Pipeline** *(slides by AlSayyad)*
- 02C.04.05. **Deep Detection Pipeline** *(slides by Lupton)*
- 02C.04.06. **Object Characterization Pipeline** *(slides by Lupton, Bosch)*

L3

- 02C.01.02.03. **Science Pipeline Toolkit** *(slides by Dubois-Felsmann)*
- 02C.03.05/04.07 **Application Framework** *(slides by Lupton)*

*Data Management Applications Design (LDM-151)*

# Implementation Strategy: Transfer Applicable Know-How, Rewrite Code

- **Difficulty adapting existing public codes to LSST requirements (AstroMatic suite, PHOTO, Elixir, IRAF-based pipelines, etc.)**
  - Need to run efficiently at scale
  - Need to be flexible (plugging/unplugging of algorithms at runtime)
  - Need to have it developed by a large team (50+ scientists and programmers)
  - Need to be maintainable over ~25 years of R&D, Construction, and Survey Operations
  - Need to run on a variety of hardware and software platforms
  - Need to have logging and provenance built into the design
  - Need to be able to travel back in time, find Sarah Connor, stop Terminator 3, Salvation, and Genisys from ever being made.

- LSST software stack is largely being written from scratch (transferring the algorithmic knowledge!), in Python 2.7 (w. Python 3 compatible syntax), unless computational demands require the use of C++

# Example: Toy SExtractor with lsst primitives (1/2)

```
exposure = afwImage.ExposureF(fileName)
mi = exposure.getMaskedImage()
im = mi.getImage()

#
# Subtract background
#
back_size = 64
bctrl = afwMath.BackgroundControl(im.getWidth()//back_size  + 1,
                                  im.getHeight()//back_size + 1)
backobj = afwMath.makeBackground(im, bctrl)

im -= backobj.getImageF("LINEAR")

#
# Smooth image with a
#    1 2 1
#    2 4 2
#    1 2 1
# filter
oneD = afwMath.PolynomialFunction1D([2, 0, -1])
kernel = afwMath.SeparableKernel(3, 3, oneD, oneD)

smoothedIm = im.Factory(im.getDimensions())
afwMath.convolve(smoothedIm, im, kernel)

threshold = afwDetection.Threshold(threshold)
fs = afwDetection.FootprintSet(smoothedIm, threshold, npixMin)

if grow > 0:
    isotropic = False
    fs = afwDetection.FootprintSet(fs, grow, isotropic)
```

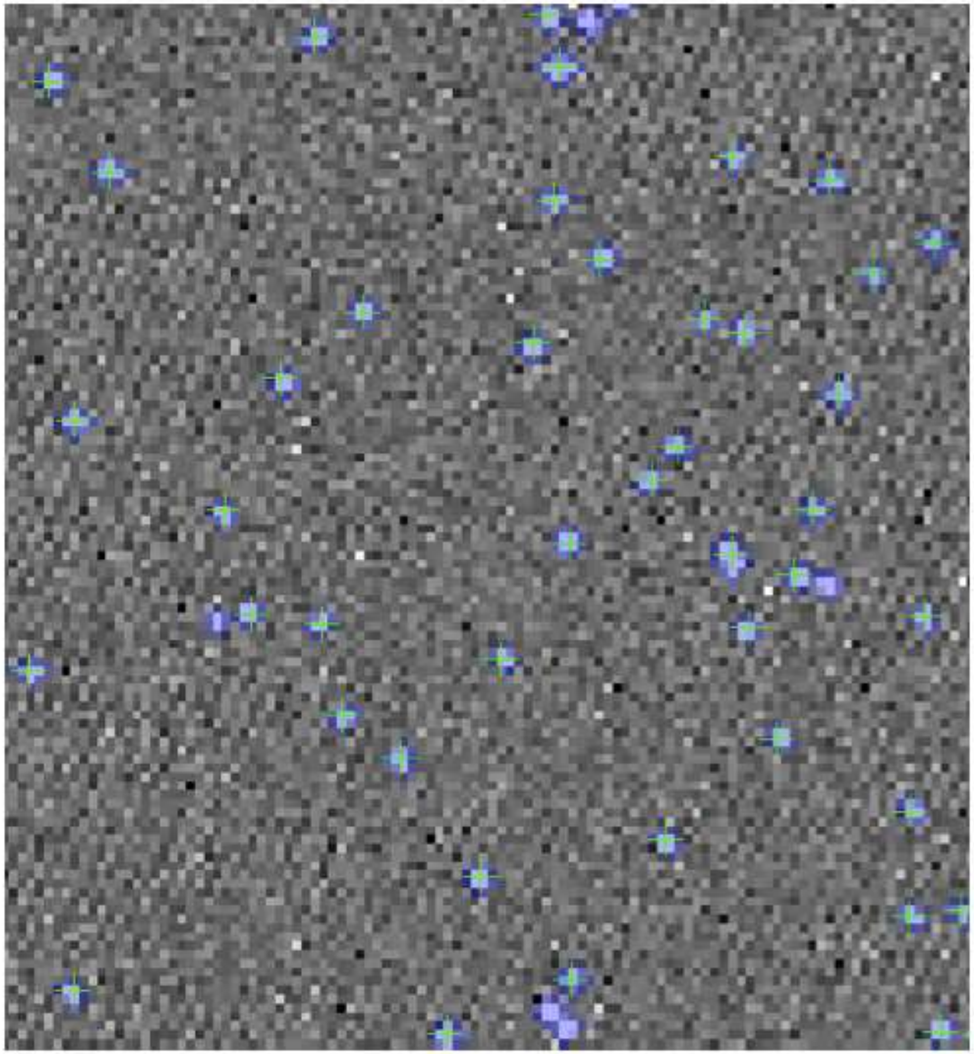
# Example: Toy SExtractor with lsst primitives (2/2)

```
fs.setMask(mi.getMask(), "DETECTED")

# Define the measurements we want to make
ctrlCentroid = measAlg.SdssCentroidControl()
ctrlAperture = measAlg.SincFluxControl()
ctrlAperture.radius2 = apRad

schema = afwTable.SourceTable.makeMinimalSchema()
algorithms = [
    measAlg.MeasureSourcesBuilder().addAlgorithm(ctrlCentroid).build(schema),
    measAlg.MeasureSourcesBuilder().addAlgorithm(ctrlAperture).build(schema)]

cat = afwTable.SourceCatalog(schema)

table = cat.table
table.defineCentroid("centroid.sdss")
table.defineApFlux("flux.sinc")

# Measure sources
fs.makeSources(cat)
print "Measuring %d objects" % (len(cat))

for source in cat:
    for alg in algorithms:
        alg.apply(source, exposure)

if display:
    ds9.mtv(mi, frame=1, title="Detection")
    with ds9.Buffering():
        for source in cat:
            ds9.dot("+", *source.getCentroid(), frame=1)

return mi, cat
```

*For more, see the poster by Tim Jenness et al (P056):*

"The LSST Data Processing Software Stack: Summer 2015 Release"

```
$ main.py C0_20090717-214738-141.fits.gz --display
Measuring 1502 objects
Elapsed time = 1.39s
```

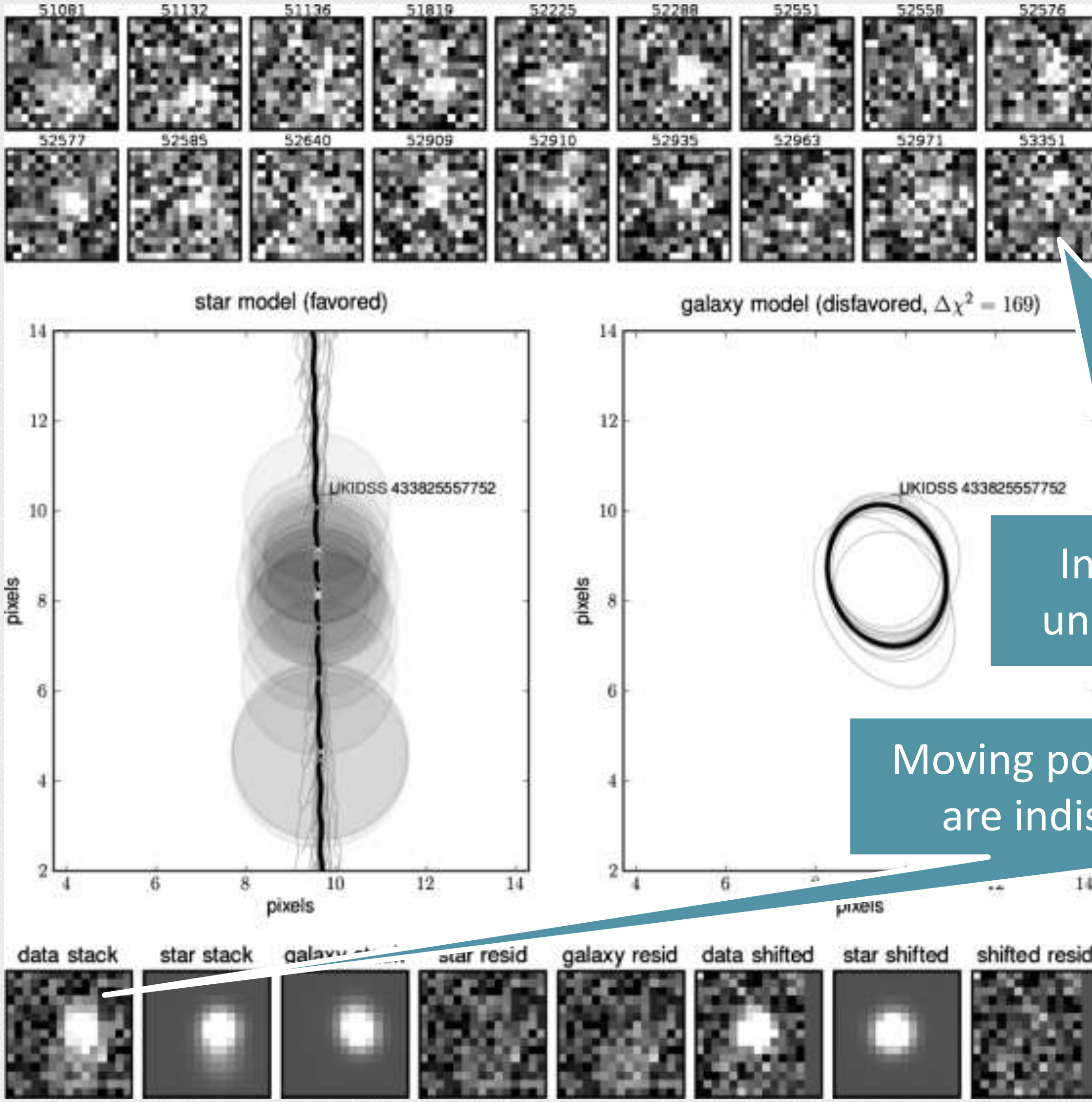


Right: Detection of $^{56}$Fe hits (lab characterization of LSST CCDs)

*For more, see the poster by Tim Jenness et al (P056):*

"The LSST Data Processing Software Stack: Summer 2015 Release"

# Detecting and Estimating Proper Motions Below the Single-Epoch Flux Limit

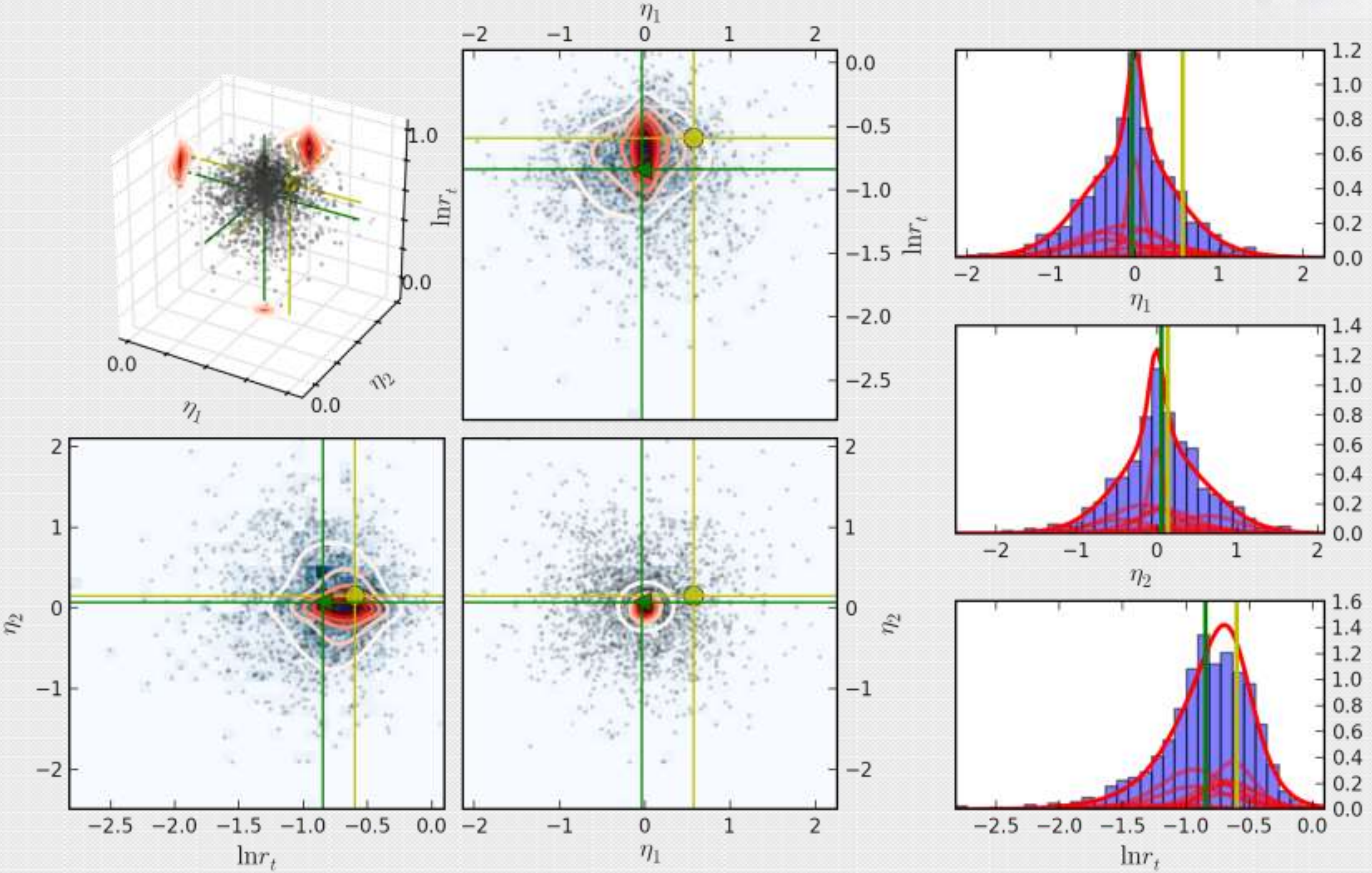



Optimal measurement of properties of objects imaged in multiple epoch. Left: extraction of a moving point source (Lang 2009).

Individual exposures: objects are undetected or marginally detected

Moving point-source and galaxy models are indistinguishable on the coadd

# Example: Sampling and retaining the Likelihoods




*Perform importance sampling from a proposal distribution determined on the coadd. Plan to characterize (and keep!) the full posterior for each object.* ***(Unexplored) possibilities for compression.***

*Improved Algorithms: Background-matched co-add of SDSS Stripe 82 in the vicinity of M2.*

*Background matching preserves diffuse structures.*

*Generated with LSST pipeline prototypes.*

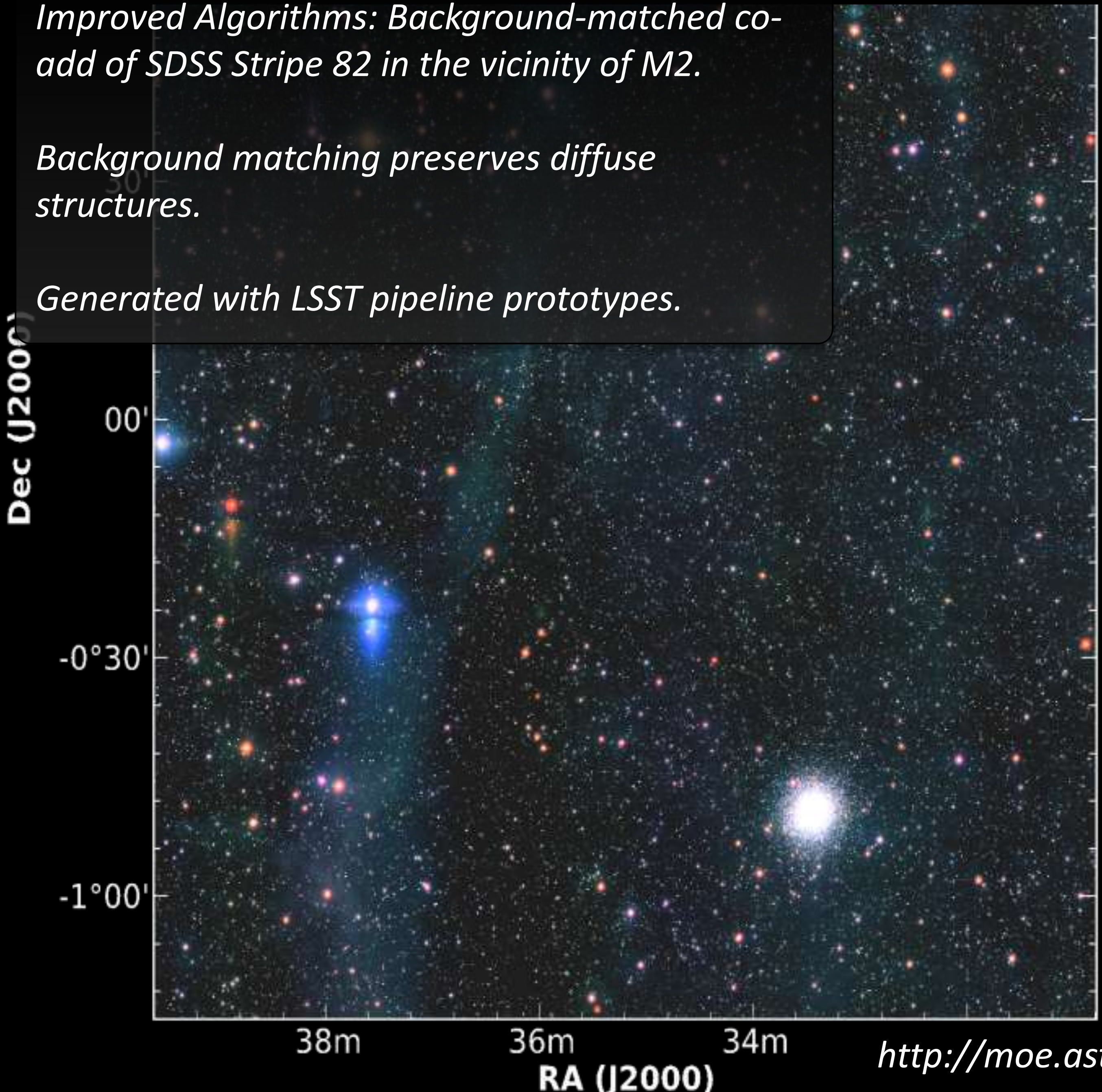



Figure:
5 sq. deg.
background-matched
coadd composite

(g,r,i)
~55 epochs

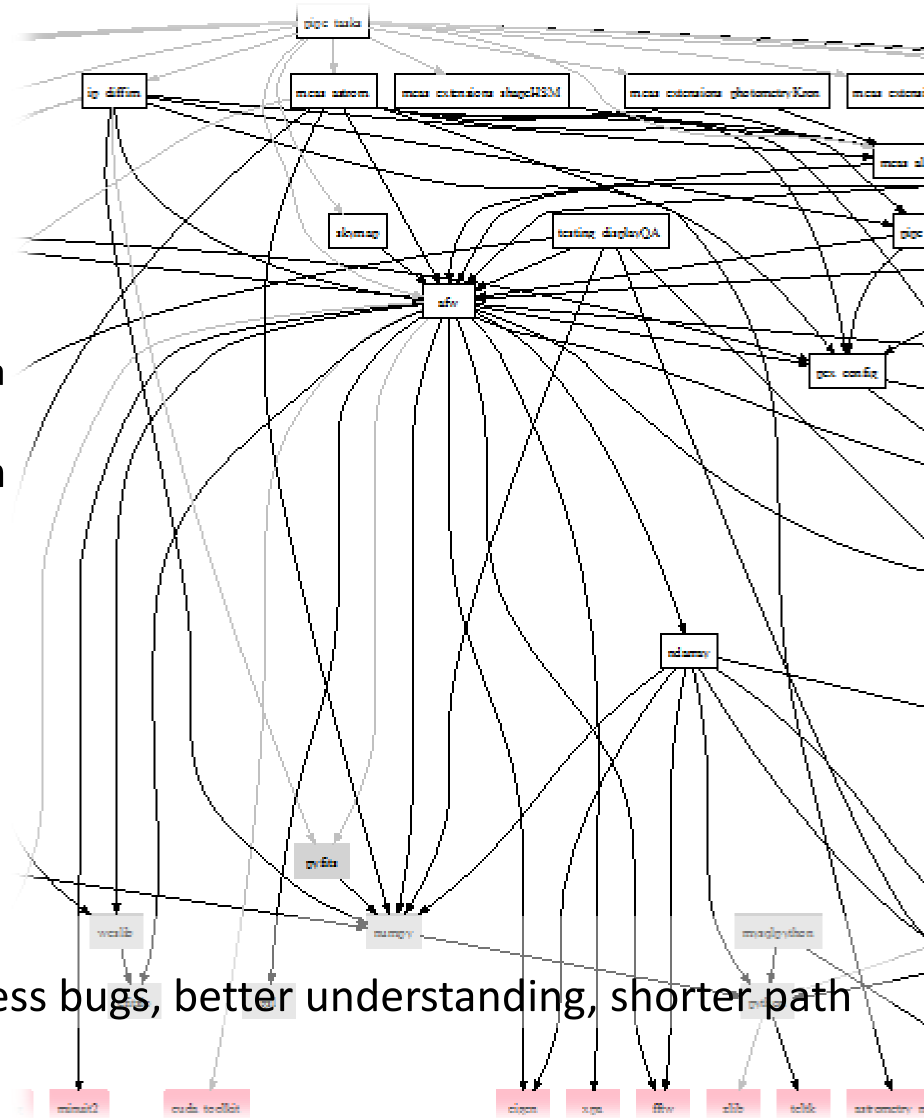
Region: Aqr
Galactic lat = -35.0

*Slide: Yusra AlSayyad*

*http://moe.astro.washington.edu/sdss/*

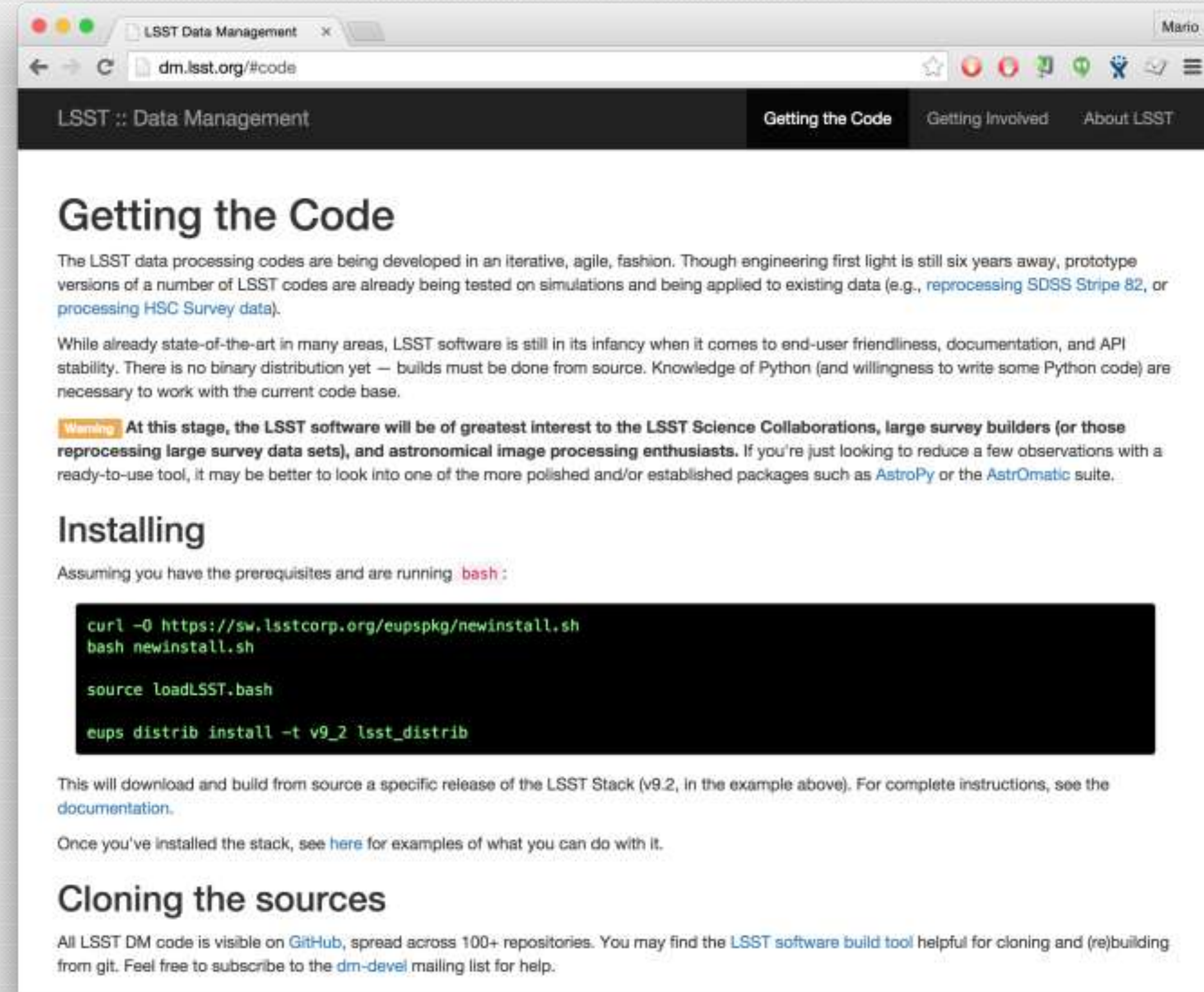
# LSST Vision: Reusable and Open Code and Development

- LSST software is designed to be ***general purpose*** and highly ***reusable***.
  - Necessary to enable “Level 3” use cases (user-driven processing)
  - Necessary to deal with real-world hardware
  - Necessary to be able to process precursor data
- **Opportunities for using LSST-derived code on other data sets**
  - **Used to reprocess SDSS Stripe 82 data**
  - **Used in production for HSC Survey**
  - CFHT and DECam coming this year
  - Possibilities: PS1, HSC, DES, WFIRST, Euclid, …
  - Good basis for analysis frameworks (LSST DESC)



- **The benefits feed back to LSST:** more users, less bugs, better understanding, shorter path to science.

# LSST Software is Freely Available



LSST Data Management × Mario

dm.lsst.org/#code

LSST :: Data Management — Getting the Code | Getting Involved | About LSST

## Getting the Code

The LSST data processing codes are being developed in an iterative, agile, fashion. Though engineering first light is still six years away, prototype versions of a number of LSST codes are already being tested on simulations and being applied to existing data (e.g., reprocessing SDSS Stripe 82, or processing HSC Survey data).

While already state-of-the-art in many areas, LSST software is still in its infancy when it comes to end-user friendliness, documentation, and API stability. There is no binary distribution yet — builds must be done from source. Knowledge of Python (and willingness to write some Python code) are necessary to work with the current code base.

Warning **At this stage, the LSST software will be of greatest interest to the LSST Science Collaborations, large survey builders (or those reprocessing large survey data sets), and astronomical image processing enthusiasts.** If you're just looking to reduce a few observations with a ready-to-use tool, it may be better to look into one of the more polished and/or established packages such as AstroPy or the AstrOmatic suite.

## Installing

Assuming you have the prerequisites and are running `bash` :

```
curl -O https://sw.lsstcorp.org/eupspkg/newinstall.sh
bash newinstall.sh

source loadLSST.bash

eups distrib install -t v9_2 lsst_distrib
```

This will download and build from source a specific release of the LSST Stack (v9.2, in the example above). For complete instructions, see the documentation.

Once you've installed the stack, see here for examples of what you can do with it.

## Cloning the sources

All LSST DM code is visible on GitHub, spread across 100+ repositories. You may find the LSST software build tool helpful for cloning and (re)building from git. Feel free to subscribe to the dm-devel mailing list for help.

***http://dm.lsst.org***

***and***

***http://github.com/LSST***

***#1 Outstanding Issue: Incomplete documentation & insufficient end-user friendliness***

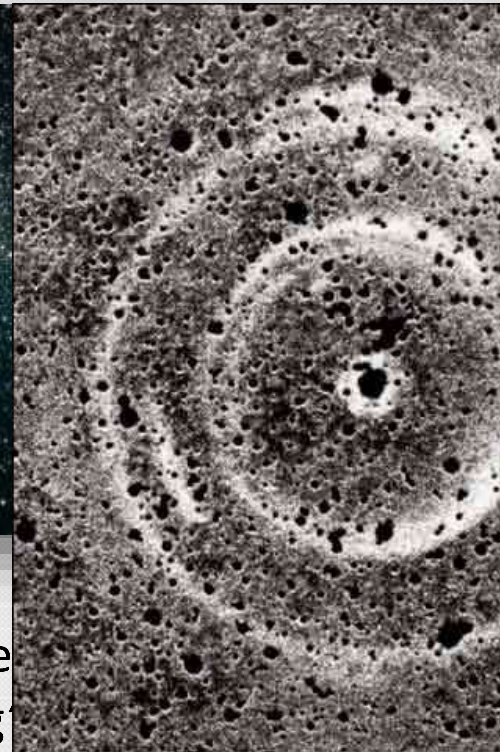
*Planning to address that over the next ~year.*

***WARNING:***

***Still under HEAVY development; don't use unless you have a real need (e.g., want to reprocess an existing or are building a new survey).***

# *Looking Ahead: Astrophysical Inference in the 2020s*

*(or why software and services are even more important than we think)*



- As our measurements become
  occurs in the “Data Processing

- Sometimes, an assumption or an algorithmic choice that's been made th
  may introduce a systematic that drowns out the signal (or eliminates it).

- For optimal inference, one wants to design measurements that directly probe the relevant aspects of the *original (imaging data)*, and not the (lossy-compressed) catalog.
  - Or derive more appropriate catalogs/feature sets/etc.

# Pushing the Boundaries of Optimal Inference

**Model** ← *inference* – **Data**

**Model** ← *inference* – **Catalog** ← Data Processing – **Data**

- **Reasons we don't do this today:**
  1. Computationally (and I/O) intensive
  2. Sociologically difficult
     - Expertize in statistics, applied math, and software engineering is often not there
     - Catalogs are too often taken as "God given", fundamental, result of a survey

- **Things are changing**
  - Big data problems are becoming increasingly computationally tractable
  - Average astronomer in the 2020s will grow up with an expectation of being well versed in Stats, SE, Appl. Math.
  - A concerted effort is under way, primarily driven by people in large survey and telescope projects, to create the necessary software to make this possible.

# Astronomy 2025: Personalized Medicine

- LSST "Level 3" concept our first step in that direction: Enabling the community to create new products using LSST's software, services (APIs), and/or computing resources. This means:
  - **Providing the software primitives to construct custom measurement/inference codes**
  - **Enabling the users to run those codes at the LSST data center, leveraging the investment in I/O (piggyback onto LSST's data trains).**

- Looking ahead: Right now, we see the data releases as the key product of a survey. By the end of LSST, I wouldn't be surprised if we saw **the software as the key product**, with hundreds specialized (and likely ephemeral) catalogs being generated by it.
- LSST "data releases" will just be some of those catalogs, designed to be more broadly useful than others, and retained for a longer period of time.

- **LSST software software and hardware is being engineered to make this possible.**

# Astronomy in the Age of Large Surveys

- Traditionally, astronomy was a data-starved science. Our methods and approach to research were shaped by this environment. Surveys are altering it; data is becoming abundant, well characterized, and rich.

- LSST is a poster-child of this transformation: it will deliver the positions, magnitudes and variability information for virtually *everything* in the southern sky to 24$^{th}$-27$^{th}$ magnitude.

- To enable science, we're building a new data processing system, with software written in Python and C++. Our pipelines are designed to be maintainable and reusable for other cameras.

- As the costs of new surveys and telescopes are entering ~Bn$1 range, the importance of software and optimal data processing is growing as well. **Reusability at every level will be crucial.** Collaboratively developed, open, extensible toolkits (e.g., AstroPy, LSST) and "Data Center in a Box" concepts (like some aspects of LSST Level 3) are beginning to address this.

# Continuing the discussion…

## BoF Session 2

4:15pm – 5:45pm

Sarah Brough
BoF2: LSST and Australia
*Ballroom 1*

# LSST IS HIRING

Large Synoptic Survey Telescope
LSST.ORG

WE'RE SEEKING TOP TALENT TO WORK IN A TEAM ENVIRONMENT THAT INSPIRES EXCELLENCE.

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