# Vera C. Rubin Observatory: Ushering a New Era of TDA

[redacted]

# what's in a name?

VERA C. RUBIN

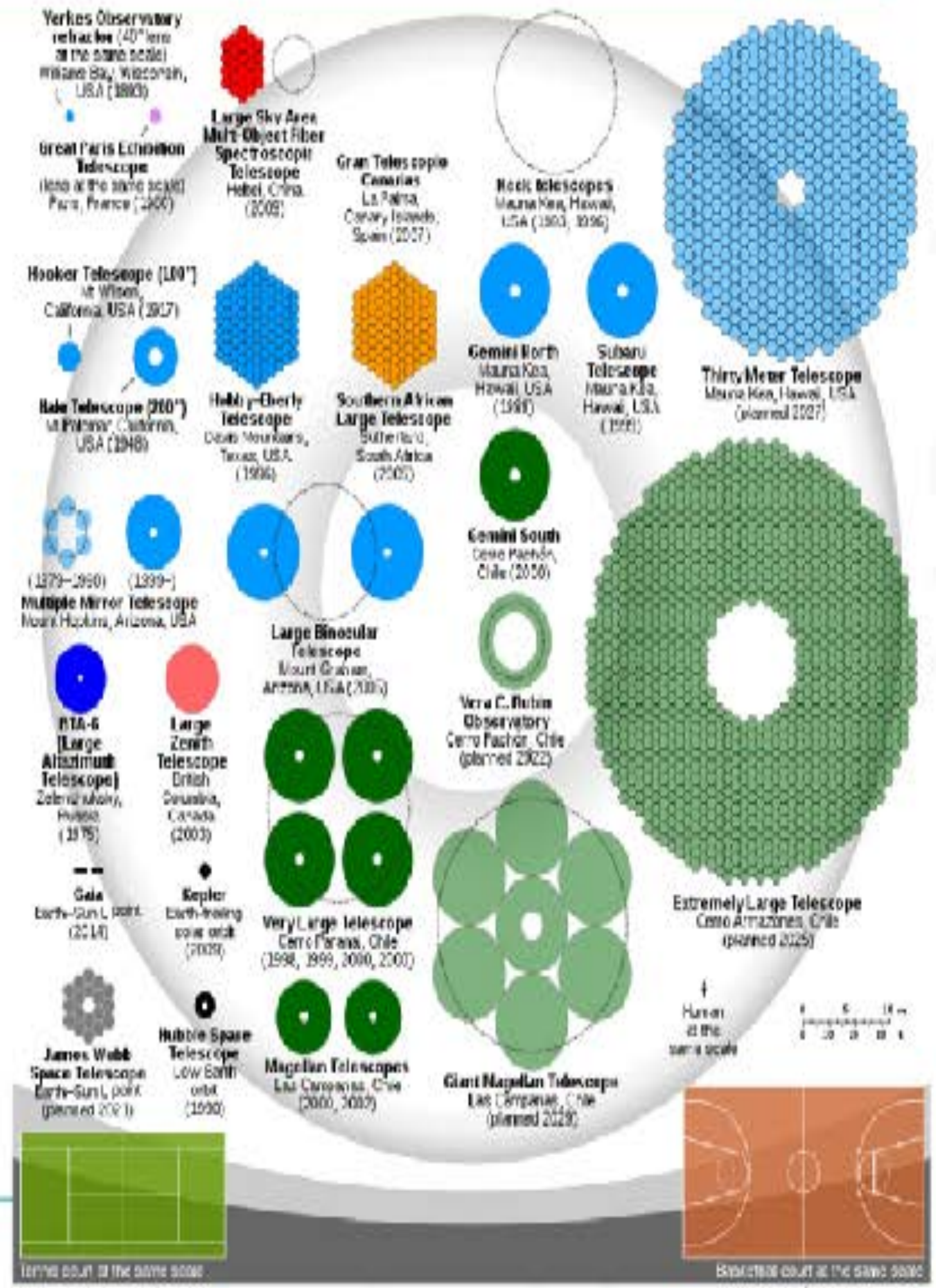
The first ground-based national US observatory named after a woman, Dr. Vera C. Rubin

VRO

In the first 10 years of its life Rubin will conduct the Legacy Survey of Space and Time or LSST

# Rubin Observatory LSST

Legacy Survey of Space and Time

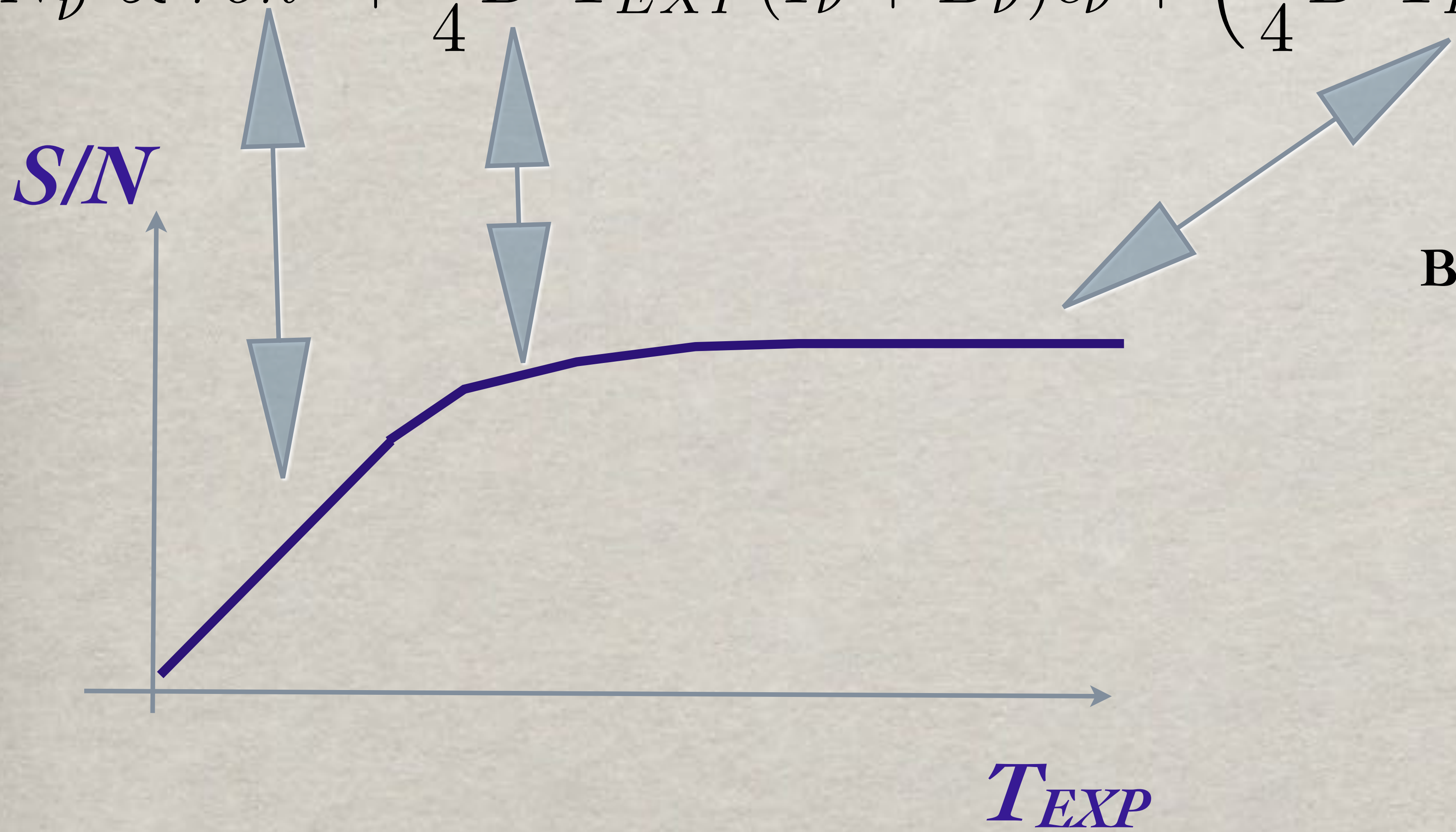


# Signal/Noise from a typical telescope

$$S_\nu \propto \frac{\pi}{4} D^2 T_{EXP} I_\nu \epsilon_\nu$$

**D: Telescope Diameter**
**$T_{EXP}$ Exposure time**
**$I_\nu$ Source Intensity**
**$\epsilon_\nu$ Efficiency**

$$N_\nu^2 \propto ron^2 + \frac{\pi}{4} D^2 T_{EXP} (I_\nu + B_\nu)\epsilon_\nu + \left(\frac{\pi}{4} D^2 T_{EXP} (I_\nu + B_\nu)\epsilon_\nu\right)^2 \times f_{FF}$$

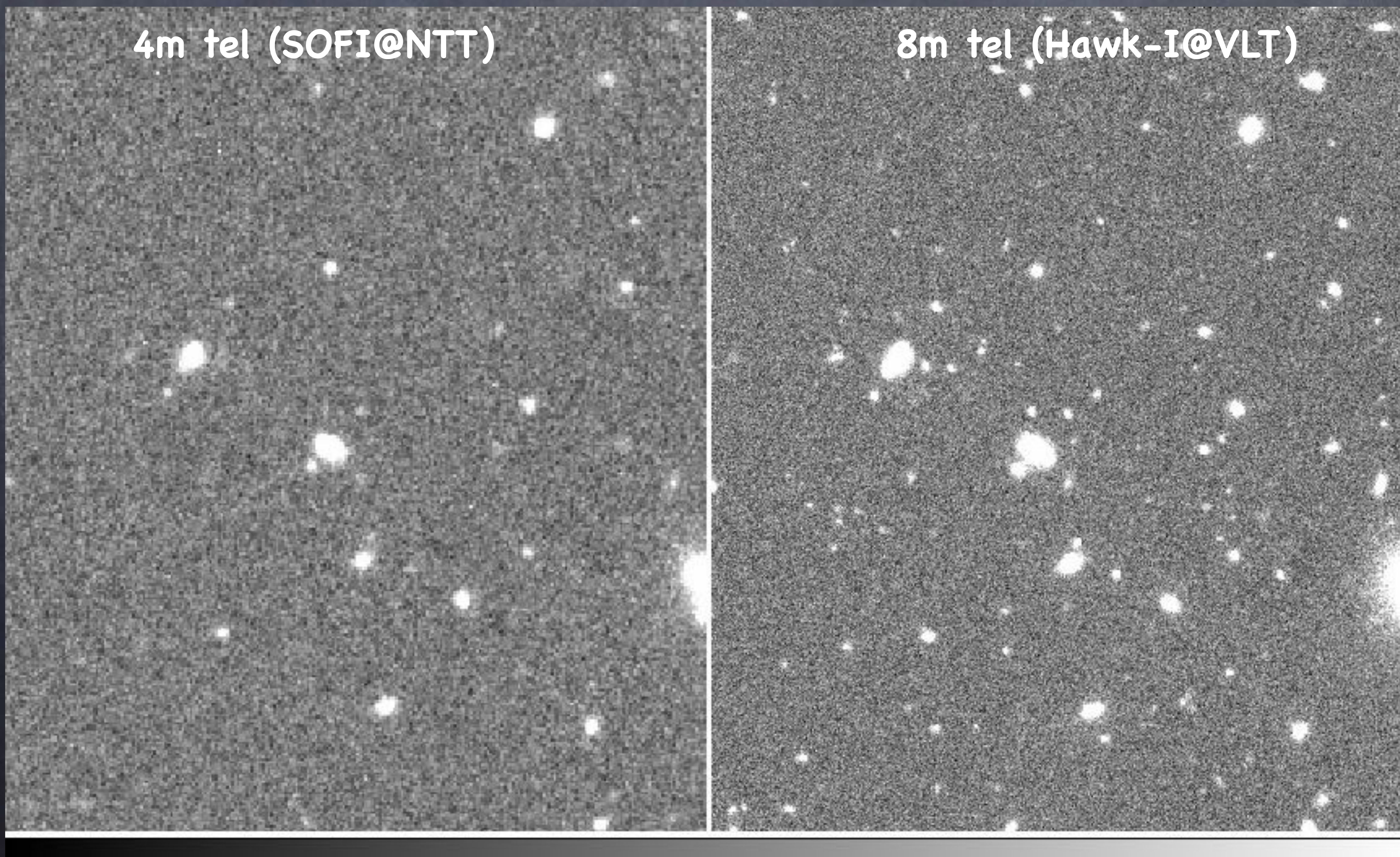



**ron: read out noise**
**$B_\nu$: Background Intensity**
**$f_{FF}$ "Flat Field" noise**

# Why do we need larger telescopes?

1) To get more photons!

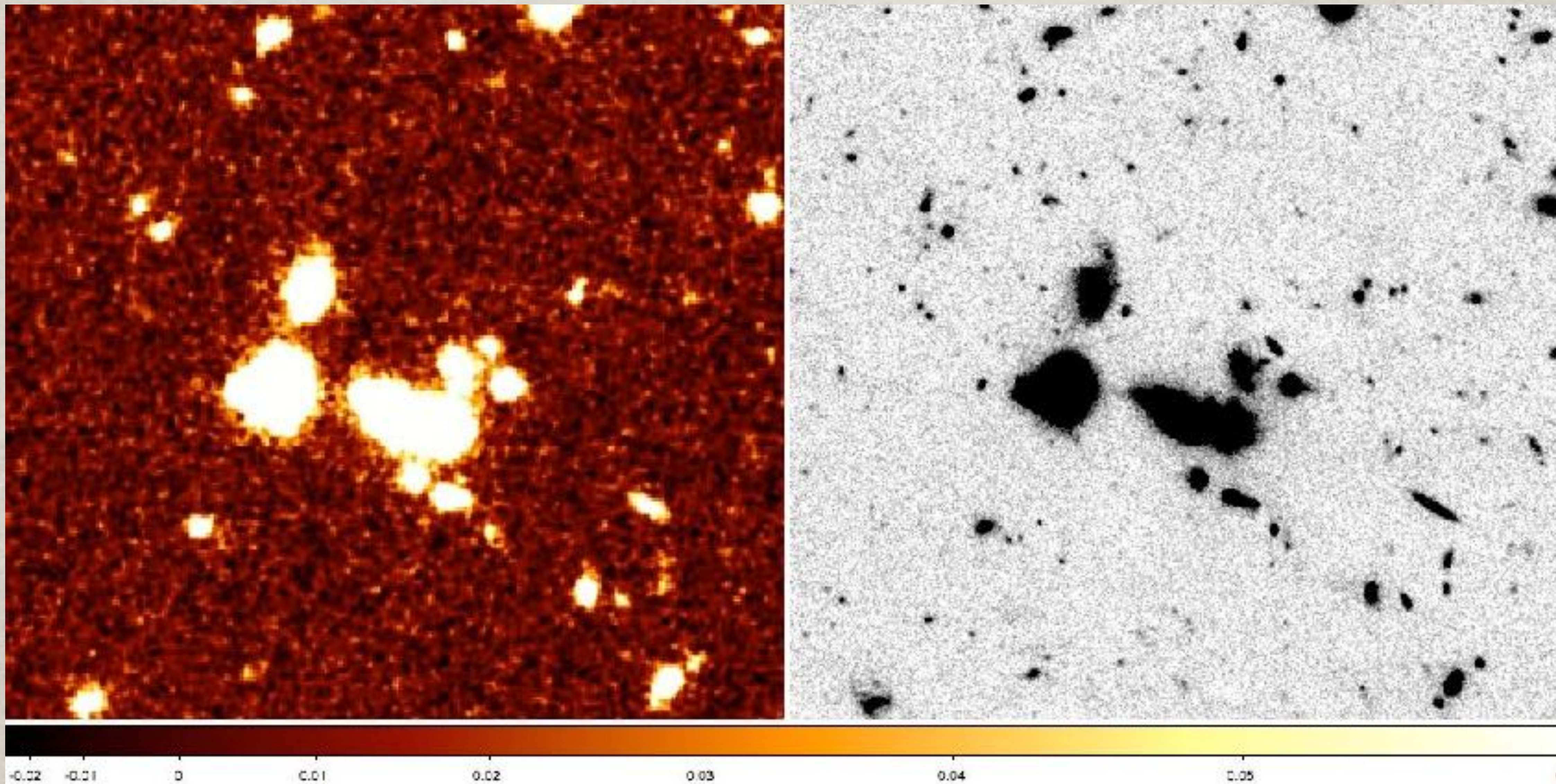
$n_\gamma \propto D^2$



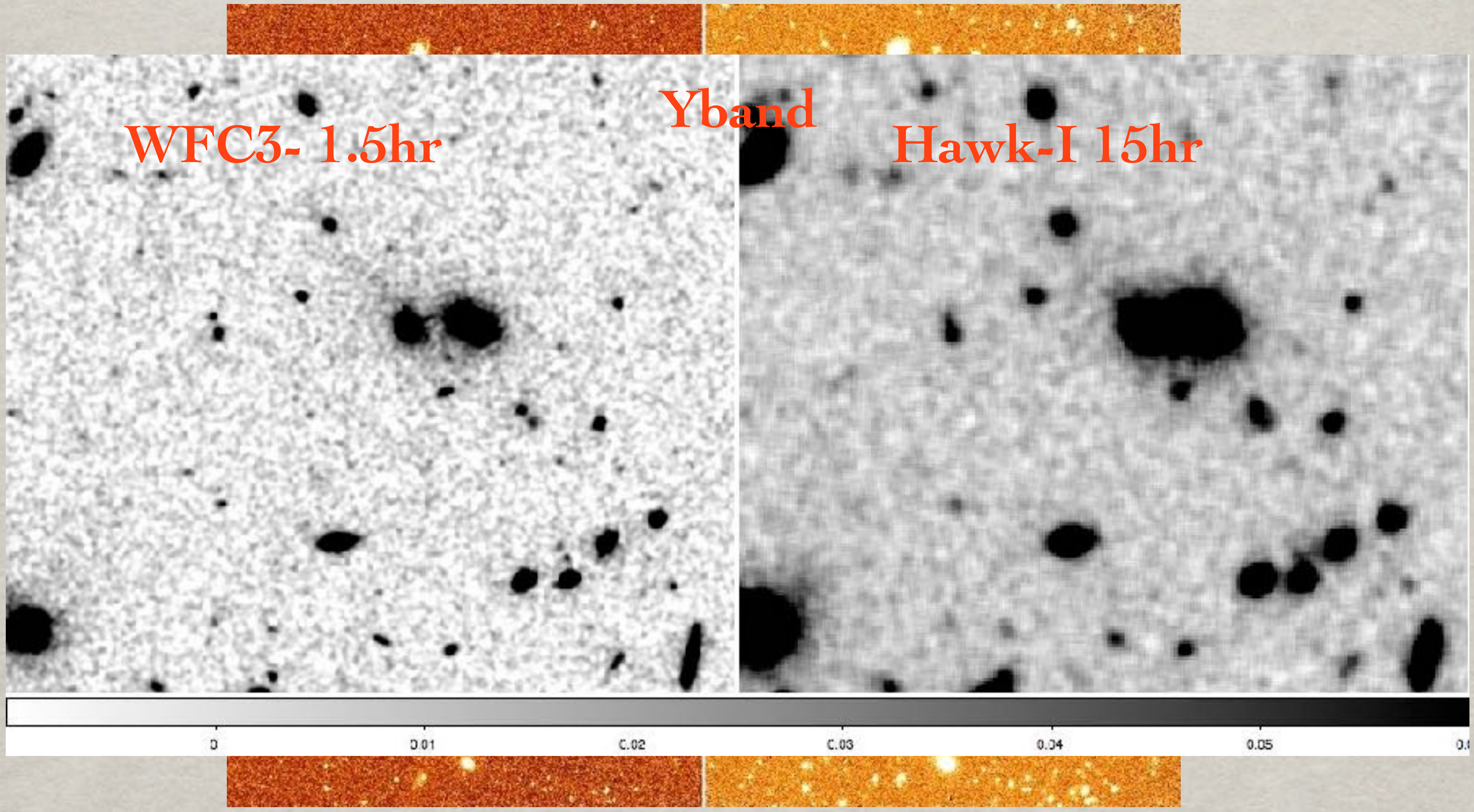
In the IR, observations from the ground are limited by the higher background --> HST wins.

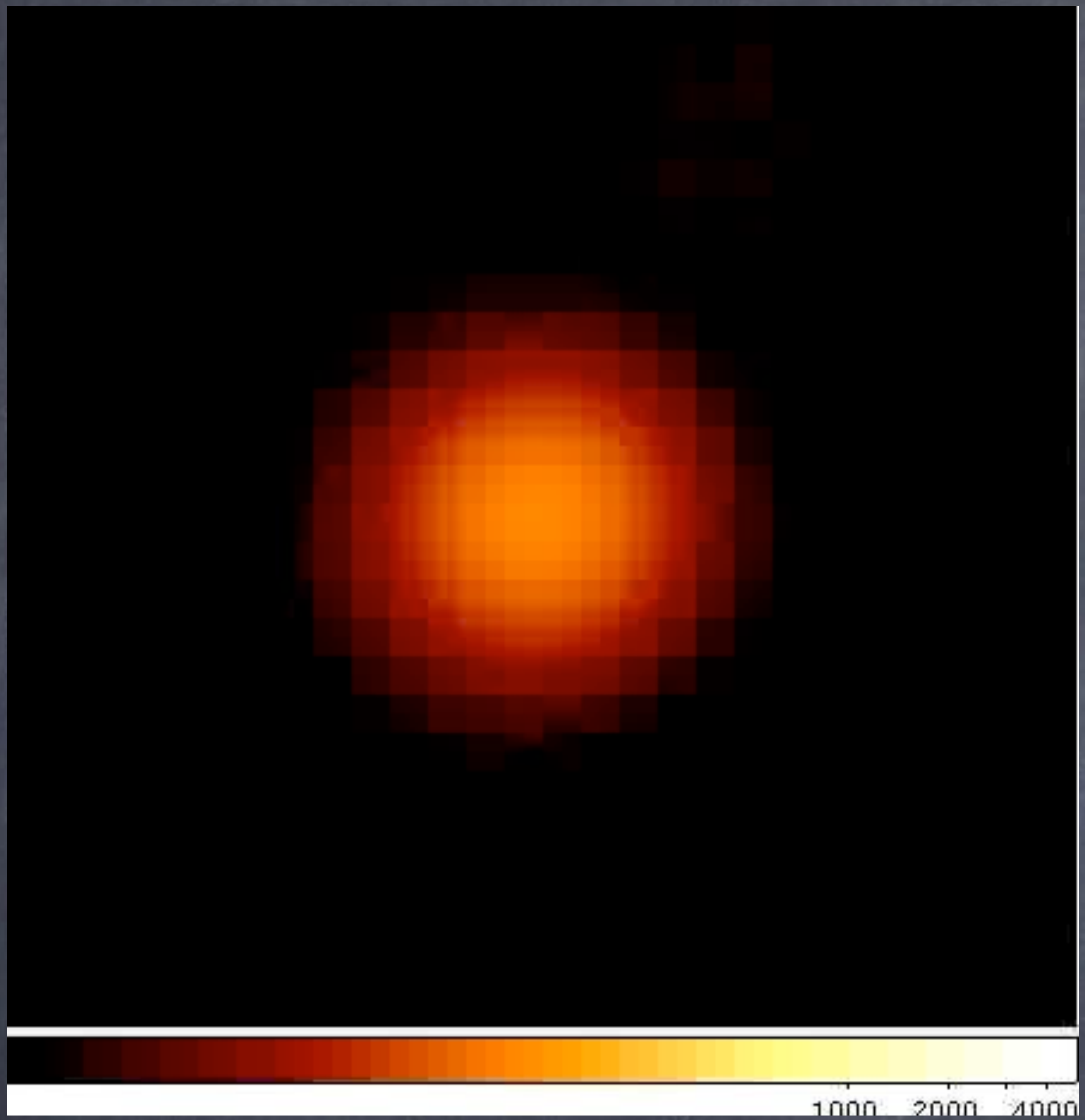
**VLT (8m ground)**
***Y 15hr***

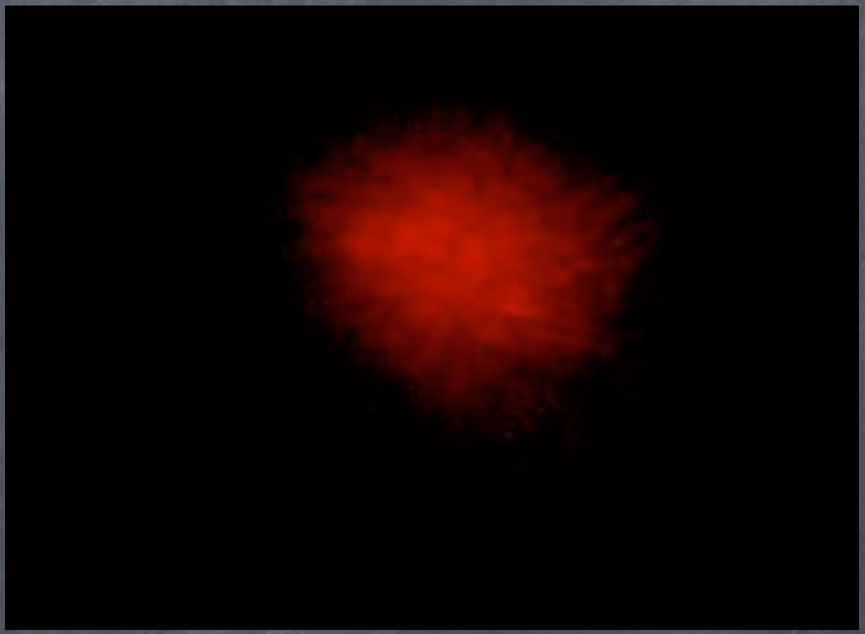
**WFC3@HST-*J 22hr***



Ground-based telescopes are powerful survey machine, even in HST era.

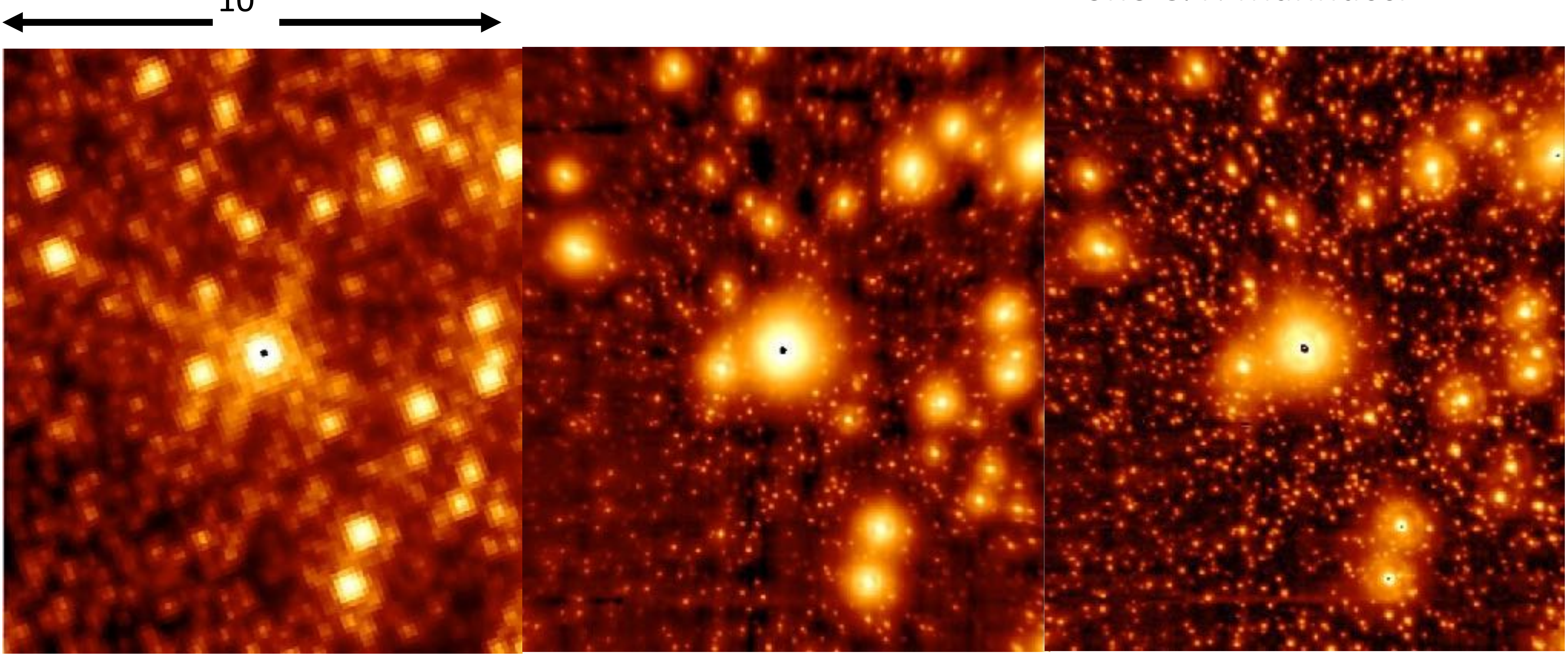



1000 2000 4000



# The Globular cluster M92

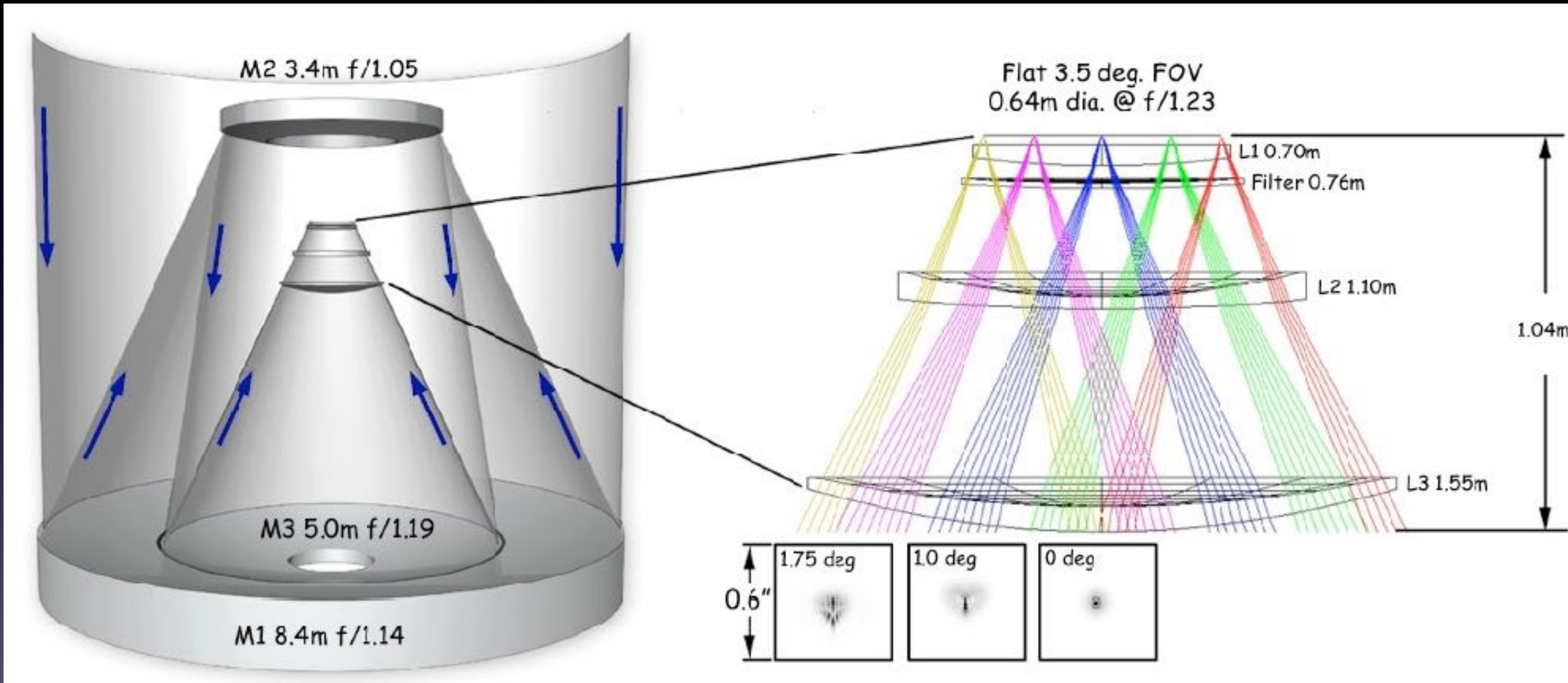
Data reduction G. Bono & F. Mannucci




**HST/WFPC3, H band 21min** **LBT J band, 6min** **LBT K band, 3min**

**Main data:** Rmag 12.0, 0.9'' seeing
**AO settings**: 0.5KHz, 15x15 subaps, 153 corrected modes

# Optical Design for LSST



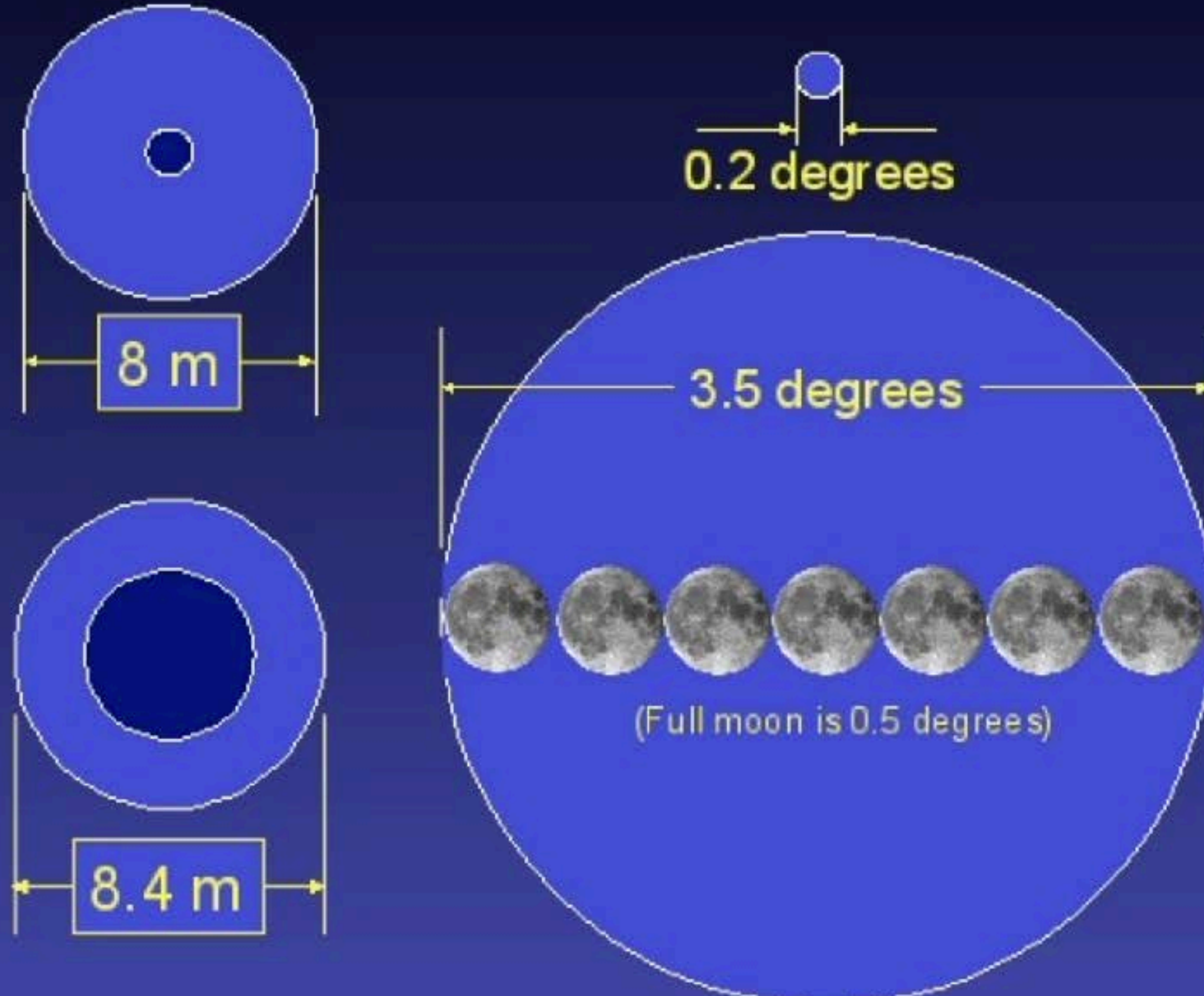

Three-mirror design (Paul-Baker system)
enables large field of view with excellent image quality:
delivered image quality is dominated by atmospheric seeing

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

Primary Mirror Diameter | Field of View

Gemini South Telescope

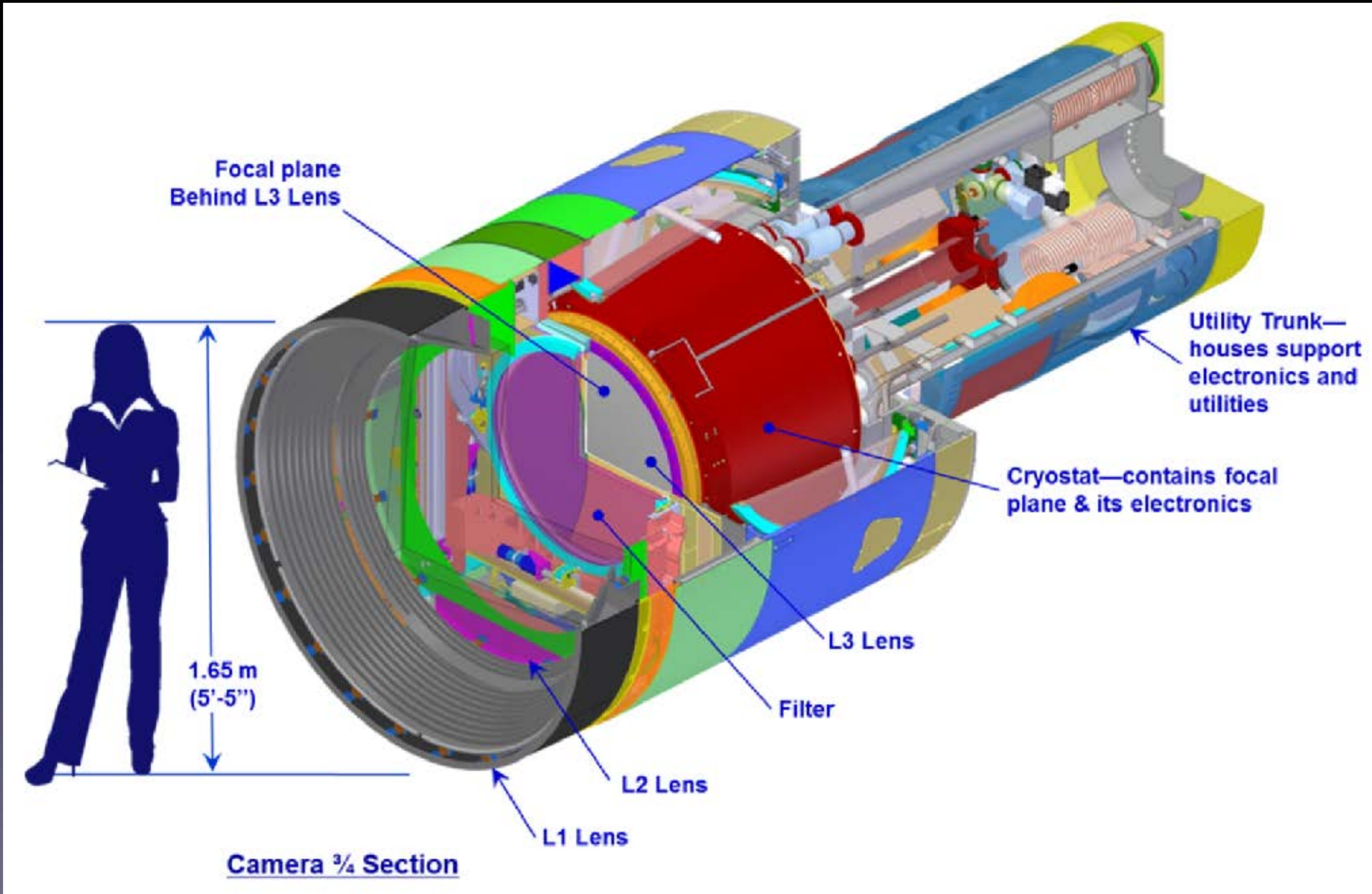
LSST



# Optical design

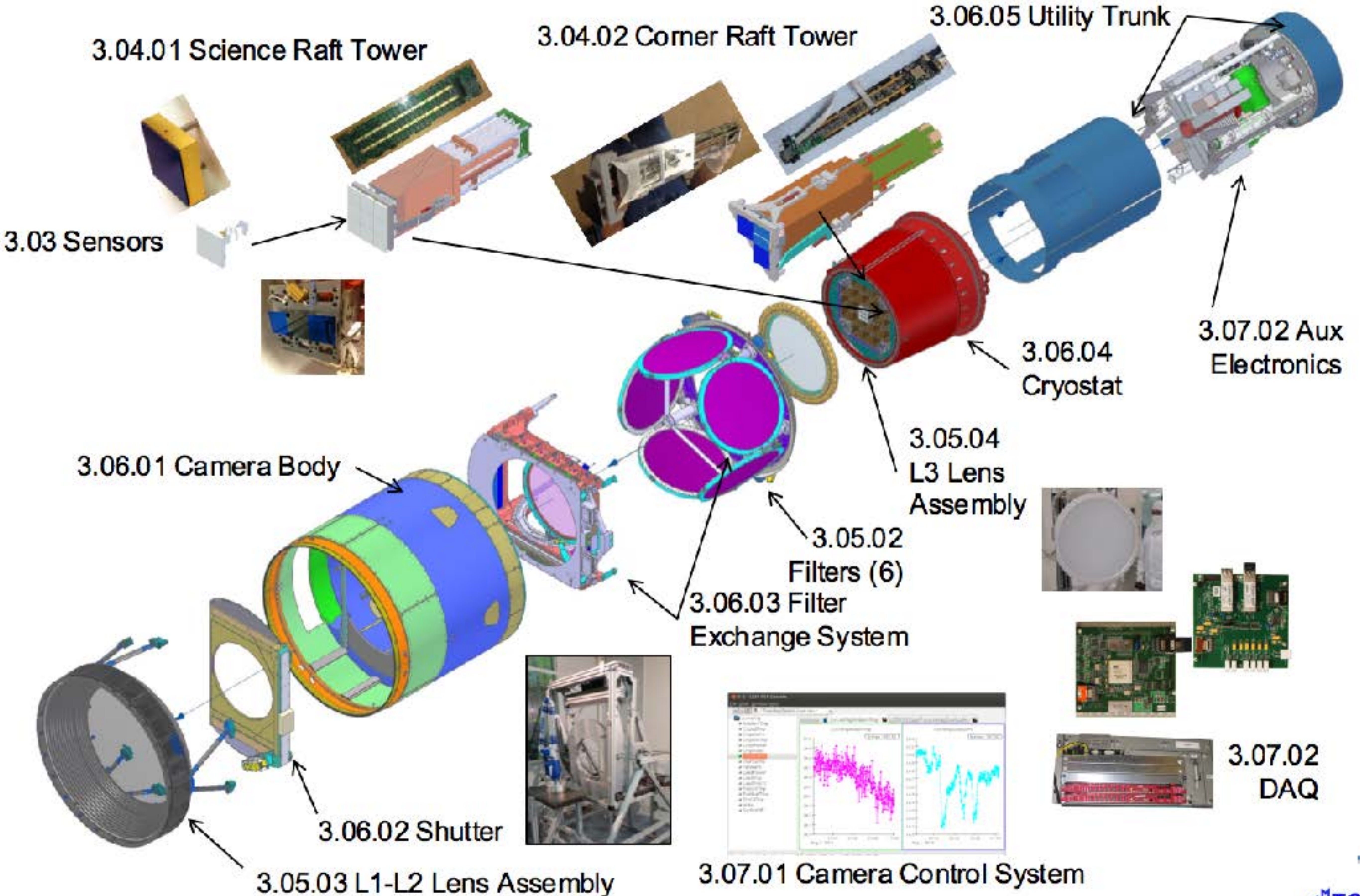
- Primary mirror 8.4m (6.6m effective)
- New optical design with three reflections
- FOV  9.6 sq. degrees
- 3.2 gigapixel instrument (189 CCDs) with a pixel scale of 0.2 arcsec/pixels

# LSST camera

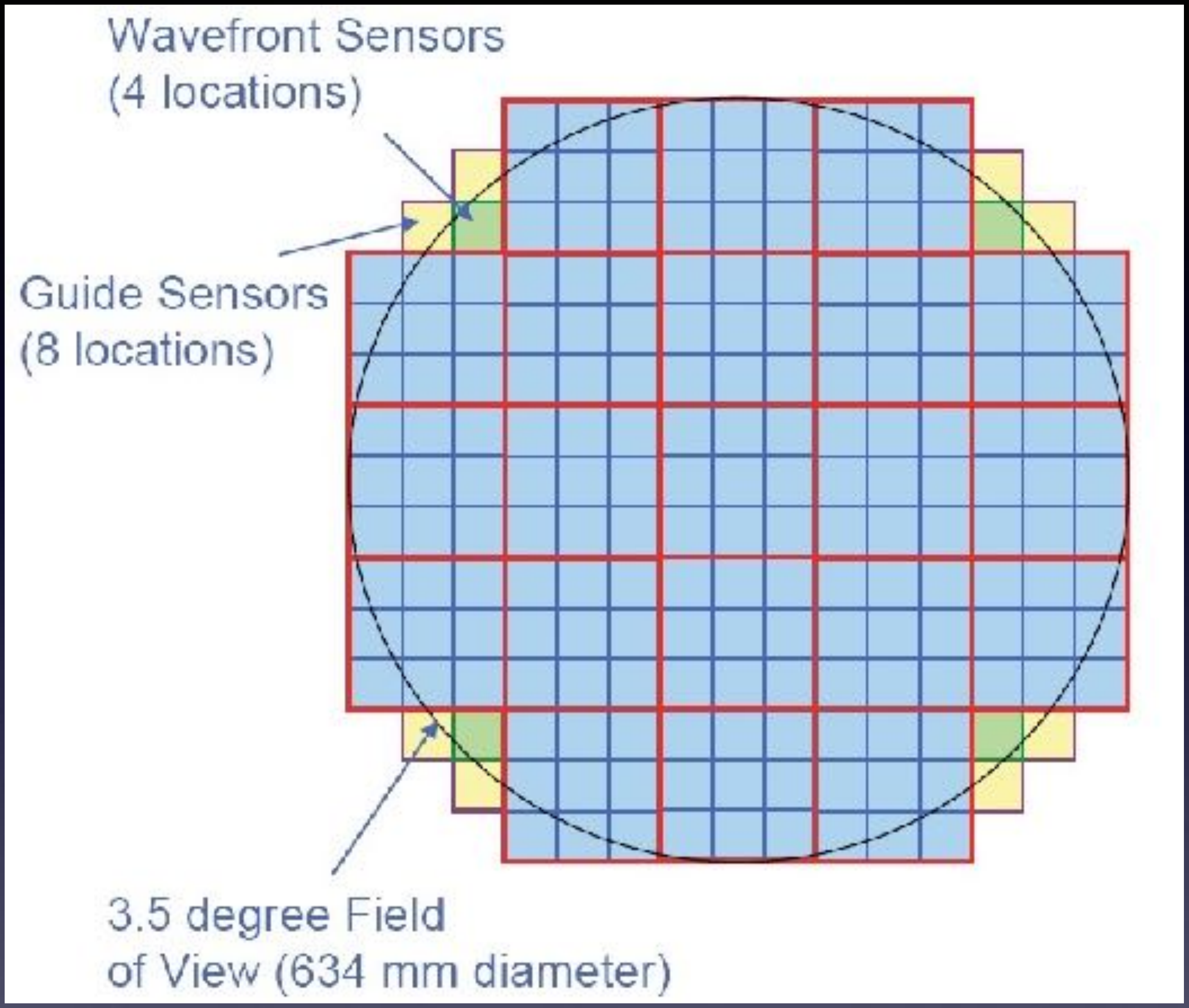


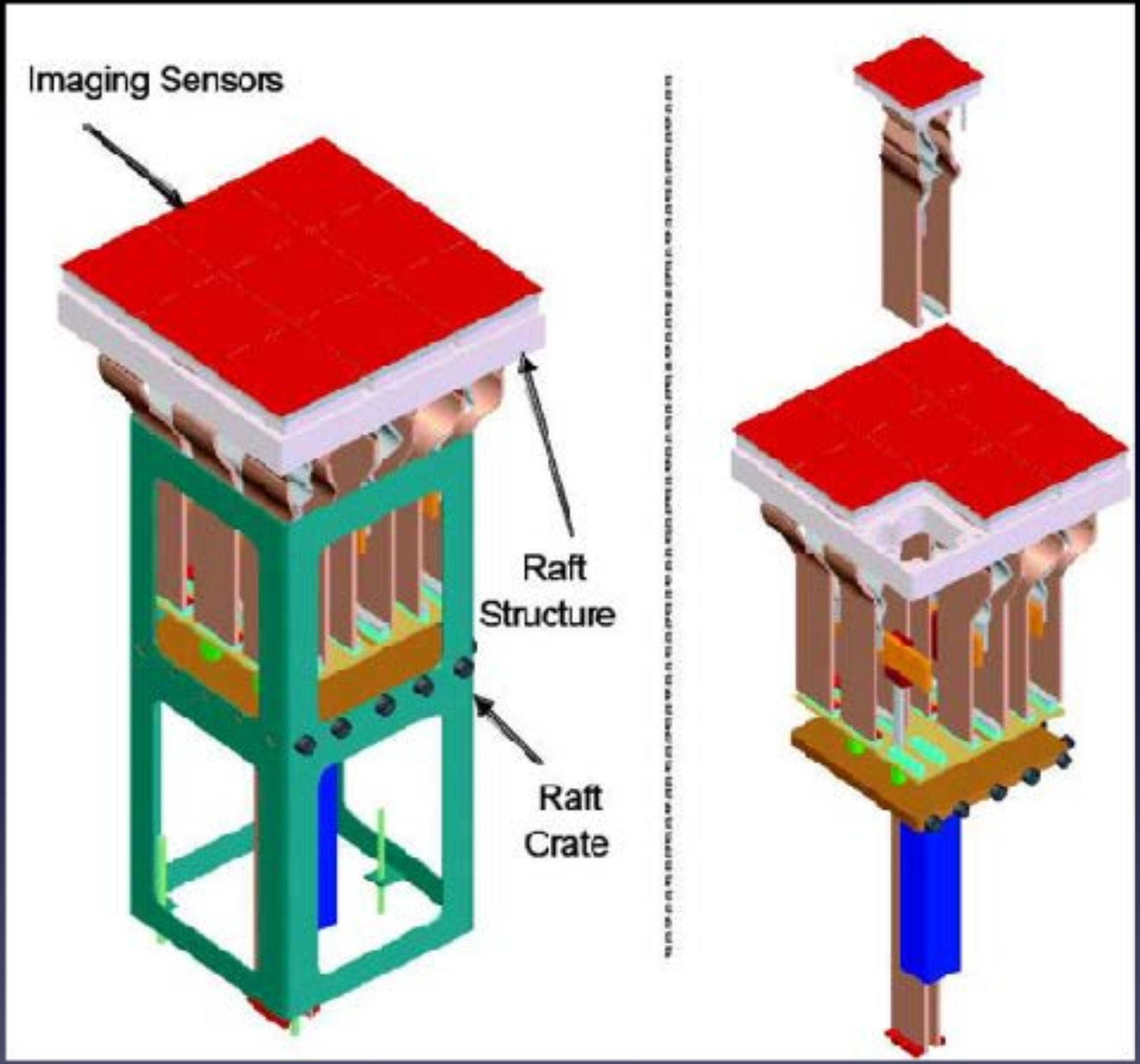

The largest astronomical camera: 2800 kg, 3200 Megapix

# 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!**

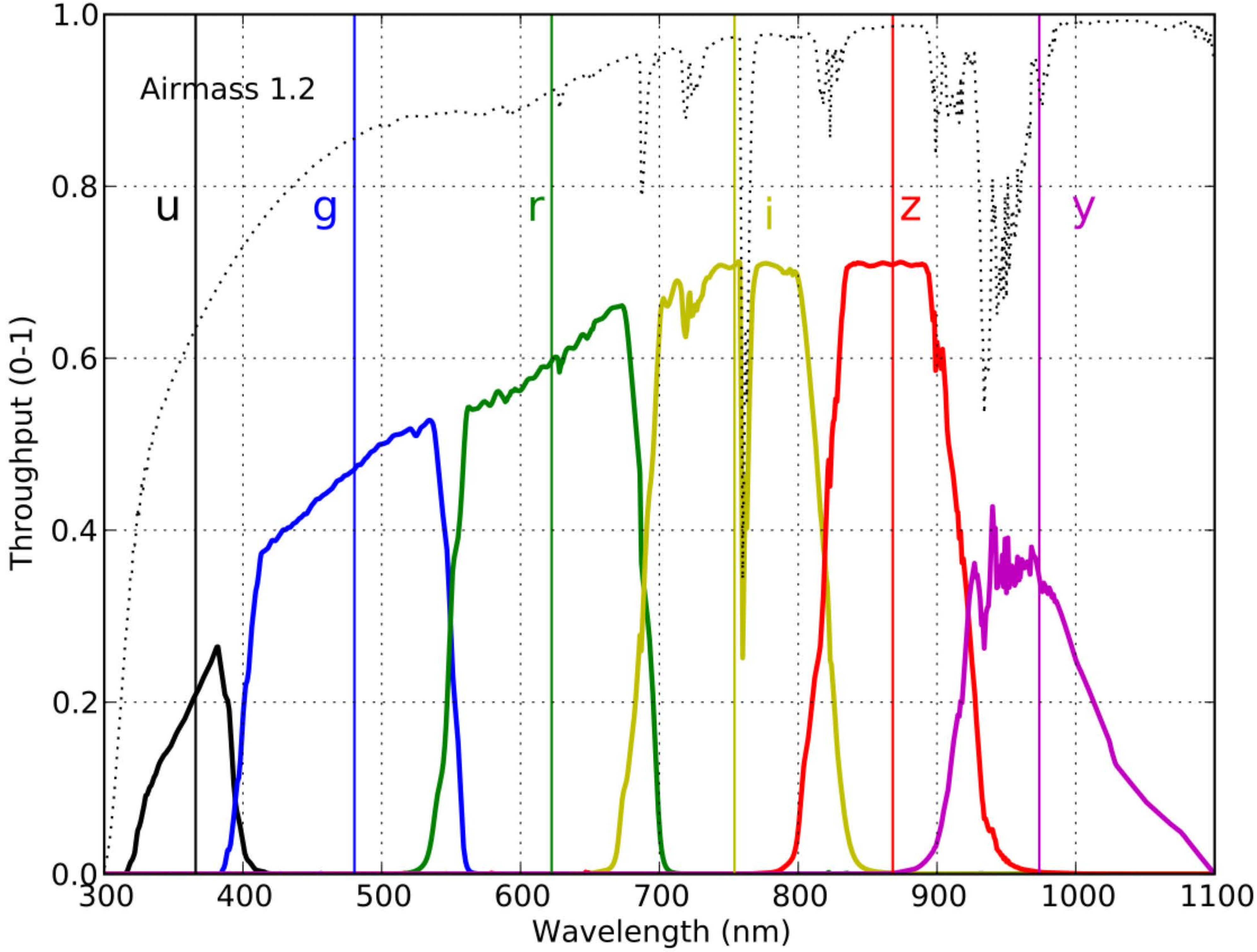
It would take about 1,500 HDTVs to display one image from LSST camera.

**Disclaimer**: I am unaware of any building with 1,500 HDTVs on its walls so we had to do this in PowerPoint…

To view all images one a HDTV with 30 frames per second, it would take 11 months!

**The greatest movie of all time!**

# Filter Set



Airmass 1.2
u
g
r
i
z
y
Throughput (0-1)
Wavelength (nm)
0.0
0.2
0.4
0.6
0.8
1.0
300
400
500
600
700
800
900
1000
1100

# Rubin Observatory LSST

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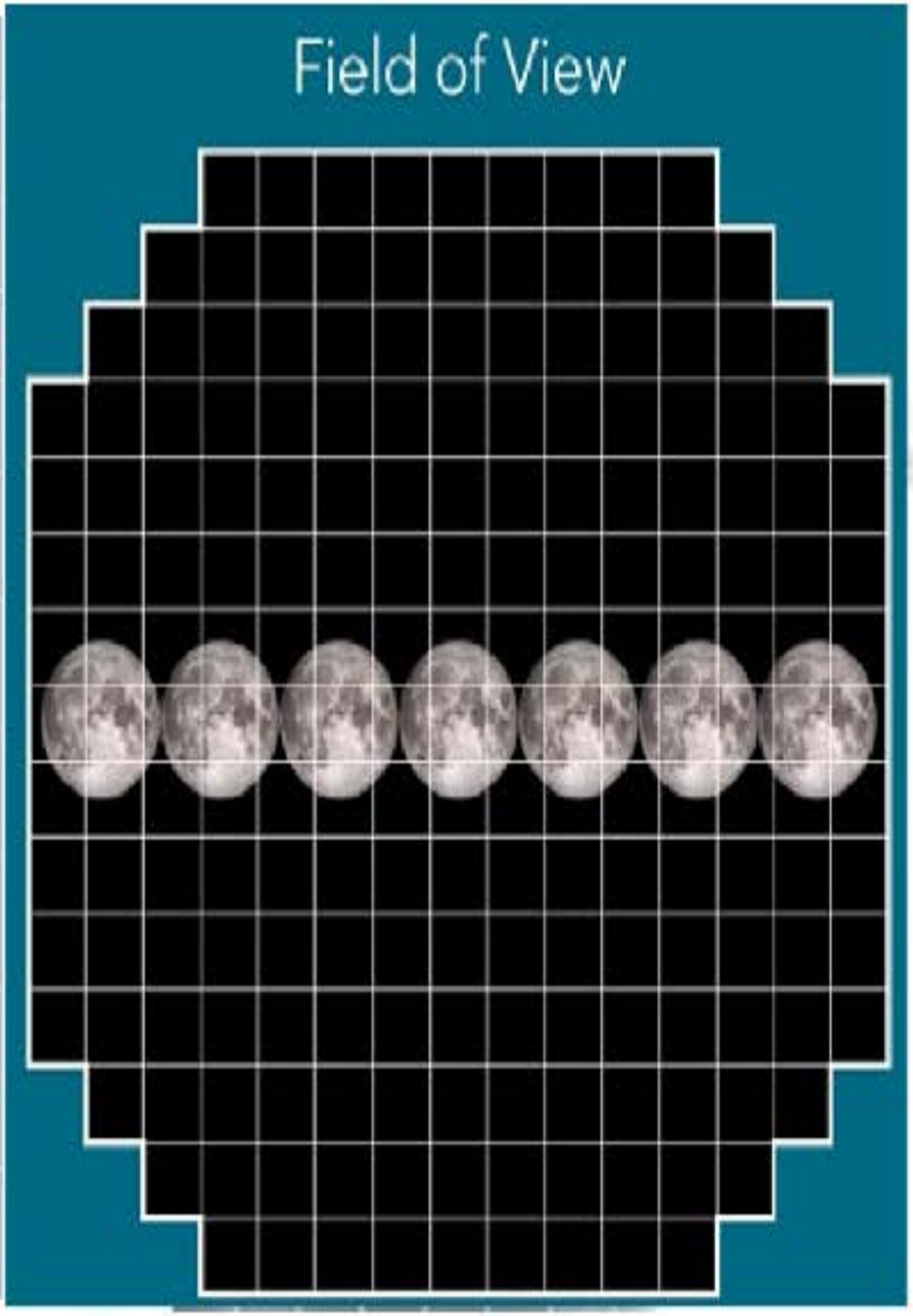
| | |
|---|---|
| field of view | 9.6 deg² |
| camera fill factor | >90 % |
| filters | *u g r i z y* |
| standard visit exposure | 30s (2x15s) |
| standard visit depth | ~ 24, 25, 24.7, 24, 23, 22 |
| saturation | ~ 15, 16, 16, 16, 15, 14 |
| survey visits/field | 56,80,184,184,160,160 (824) |
| survey full depth | ~ 26, 27, 27.5, 27, 26, 25 |
| survey full area | ~18000°² |
| max filter change | 90 sec |
| max slew (180° az) | <120 sec |
| standard visit processing time | 60 sec |




LSST

# SDSS

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One quarter the diameter of the moon

LSST

Legacy Survey of Space and Time

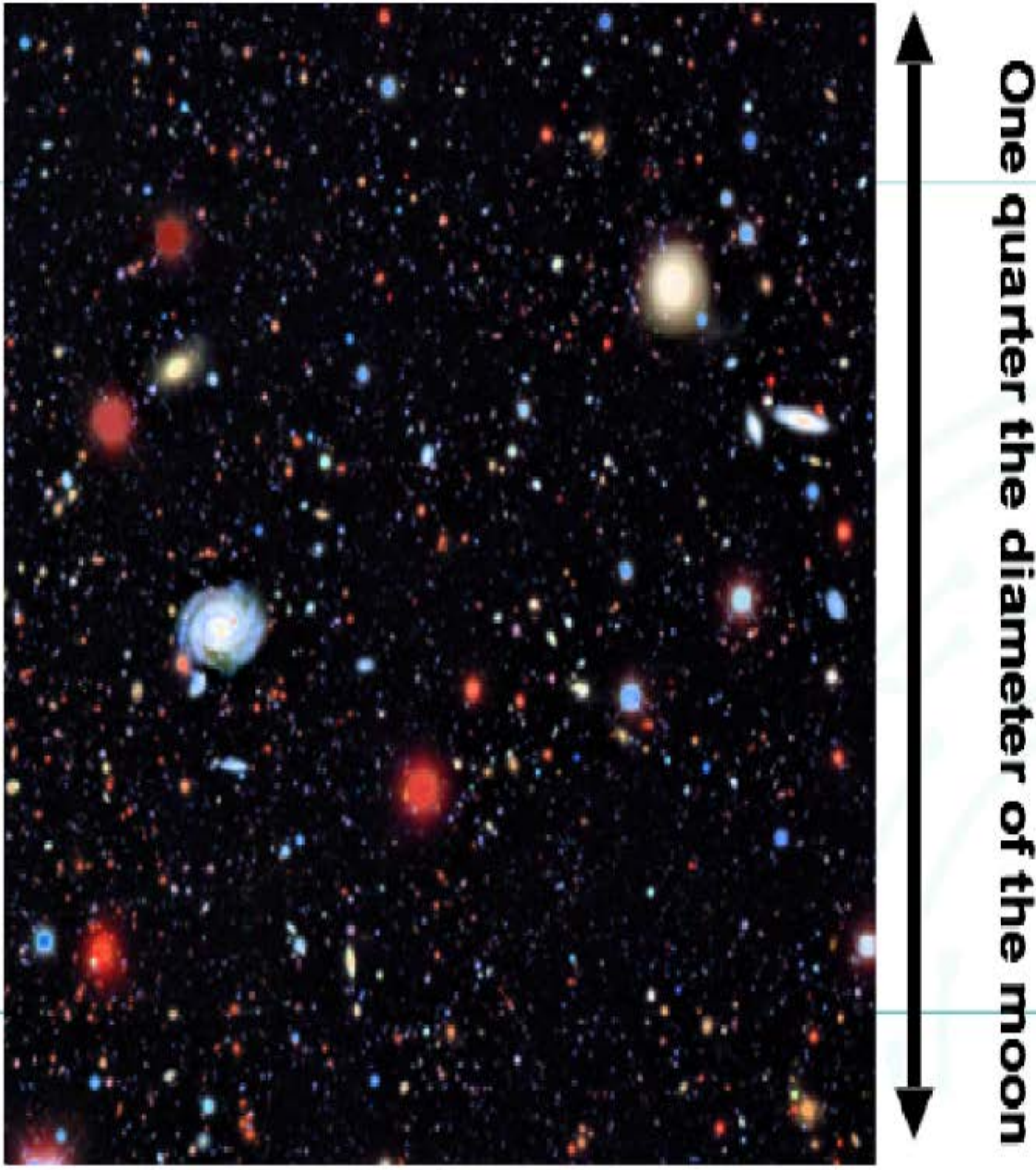
@fedhere

Rubin

VERA C. RUBIN OBSERVATORY

LSST

(simulated)





LSST

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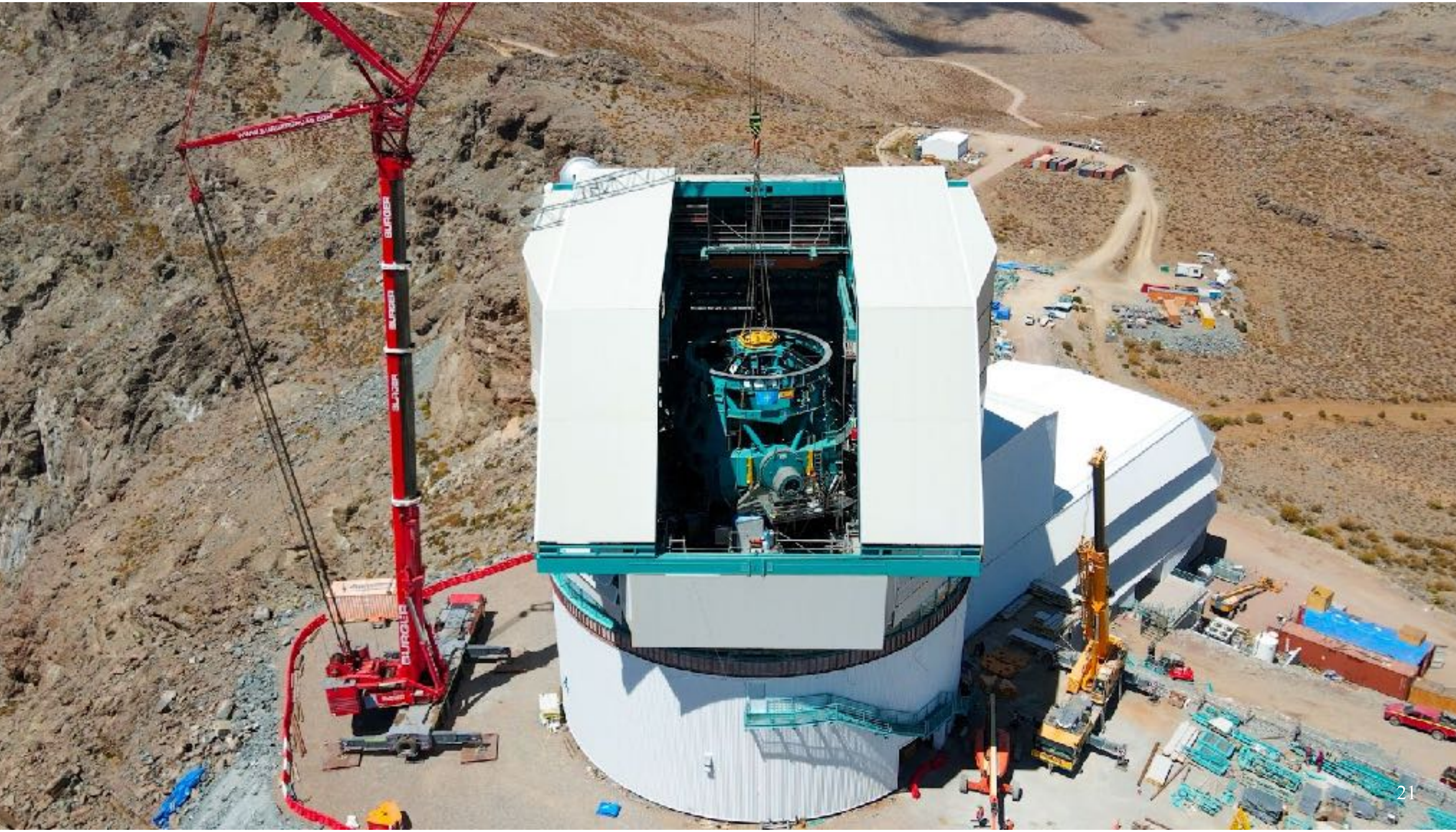
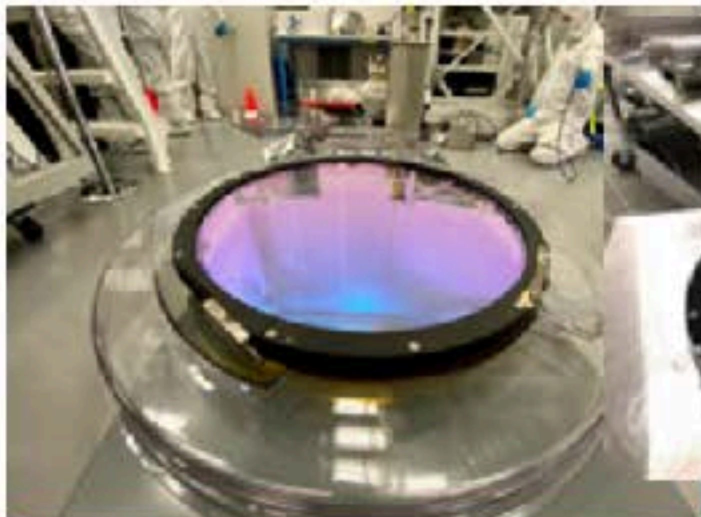

BURGER

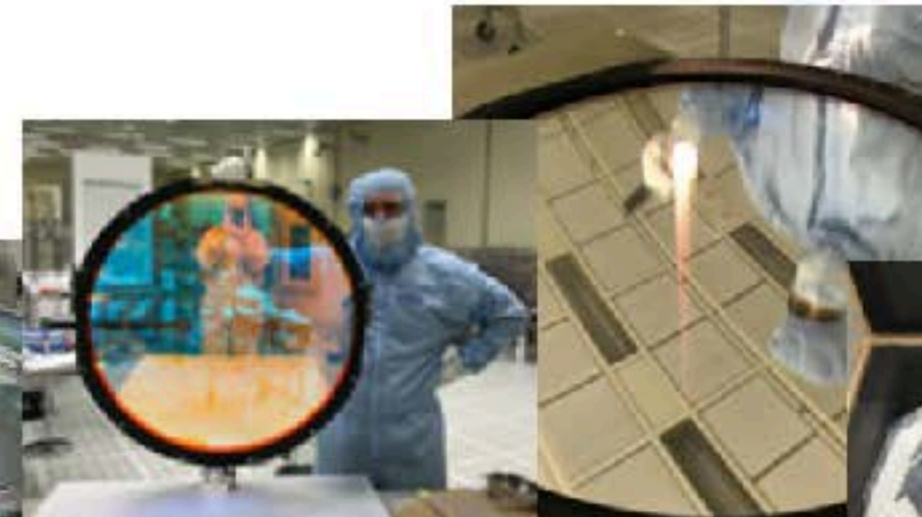
Video of telescope motion: **ls.st/-dt**

# Camera progress



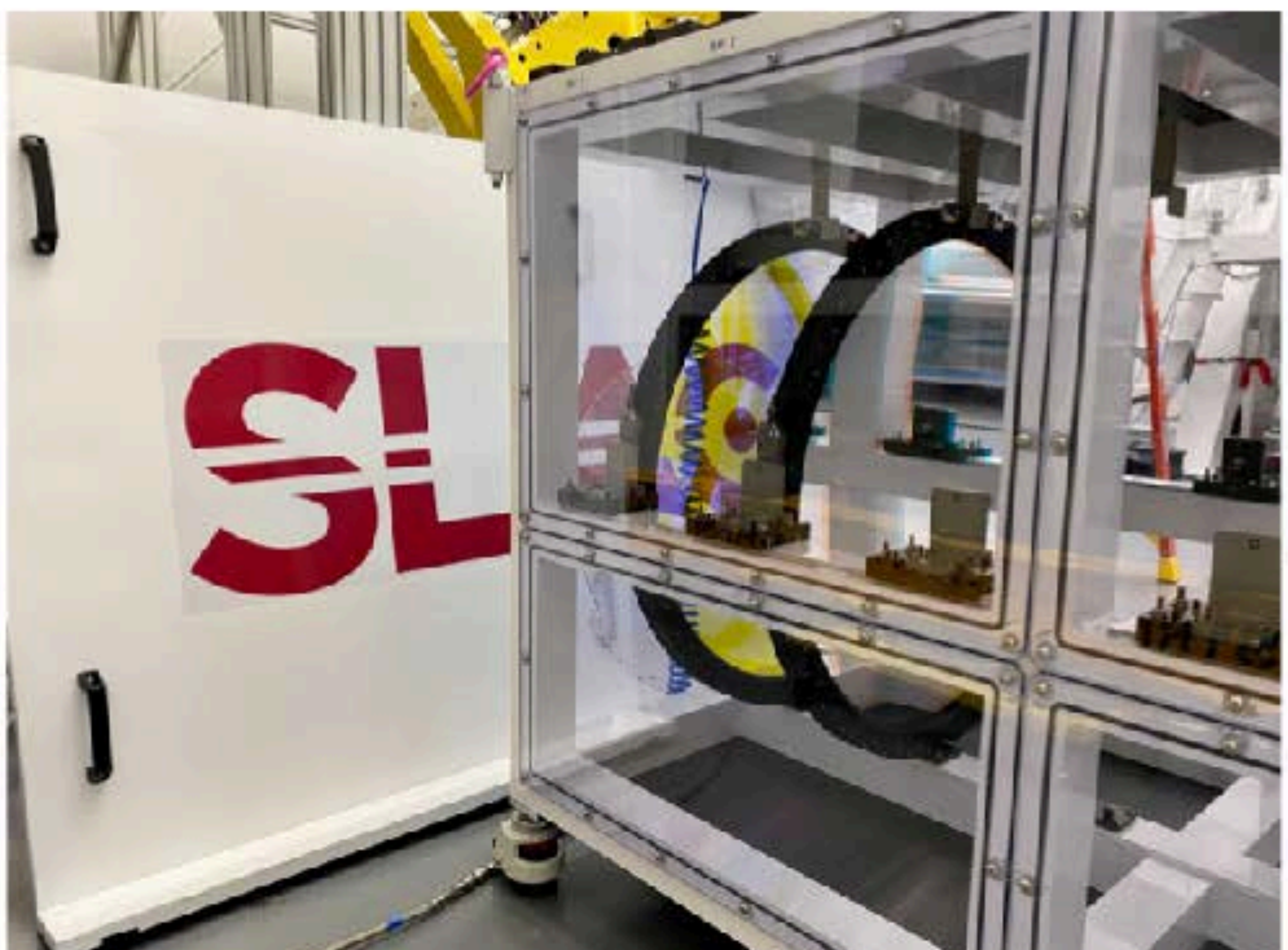
r-band filter in its frame during inspection at SLAC after delivery (March 2021)

z-band (left) filter inspection under bright light at LLNL prior to packing in its shipping container (April 2021) and i-band (right after installation (August 2021)



g-band (left) and y-band (right) filter in their frame during inspection at LLNL prior to packing in their shipping container (May 2021/July 2021)

u-band filter received at




**LSST will observe about half of the sky close to 1000 times over 10 years.**

# *Science*

# Rubin Observatory LSST

VERA C. RUBIN OBSERVATORY

***Probing Dark Energy and Dark Matter***

Exquisite measurements of strong and weak lensing, large-scale structure, clusters of galaxies, and supernovae

*LSST Science Drivers*

# Rubin Observatory LSST

## *Mapping the Milky Way and Local Volume via resolved stellar population*

*17B stars characterized in shape, color, and variability.*

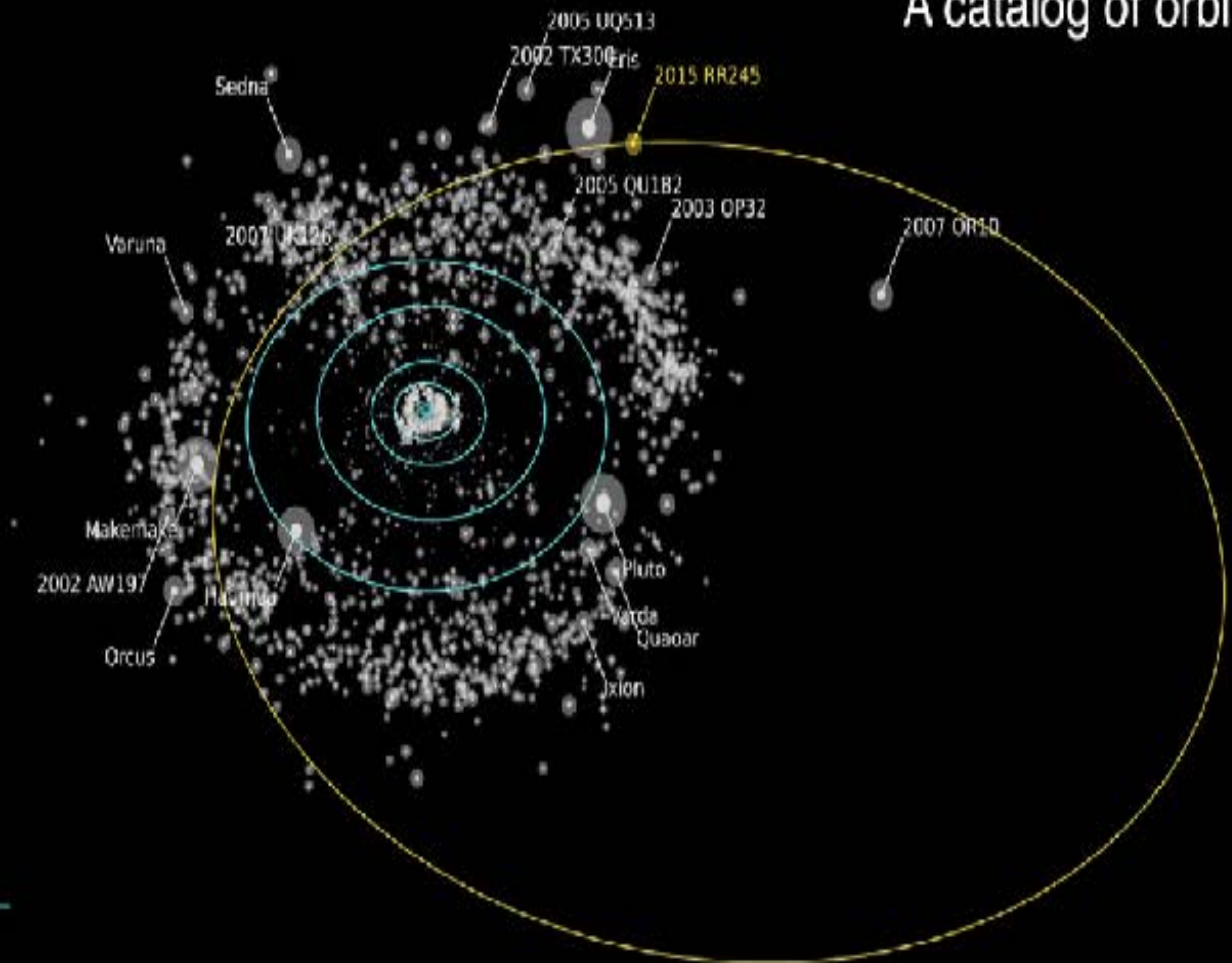
image credit ESO-Gaia

*LSST Science Drivers*

# Rubin Observatory LSST

***An unprecedented inventory of the Solar System from potentially hazardous asteroid to the distant Oort Cloud***

A catalog of orbits for 6 million bodies




*LSST Science Drivers*

federica bianco - fbianco@udel.edu

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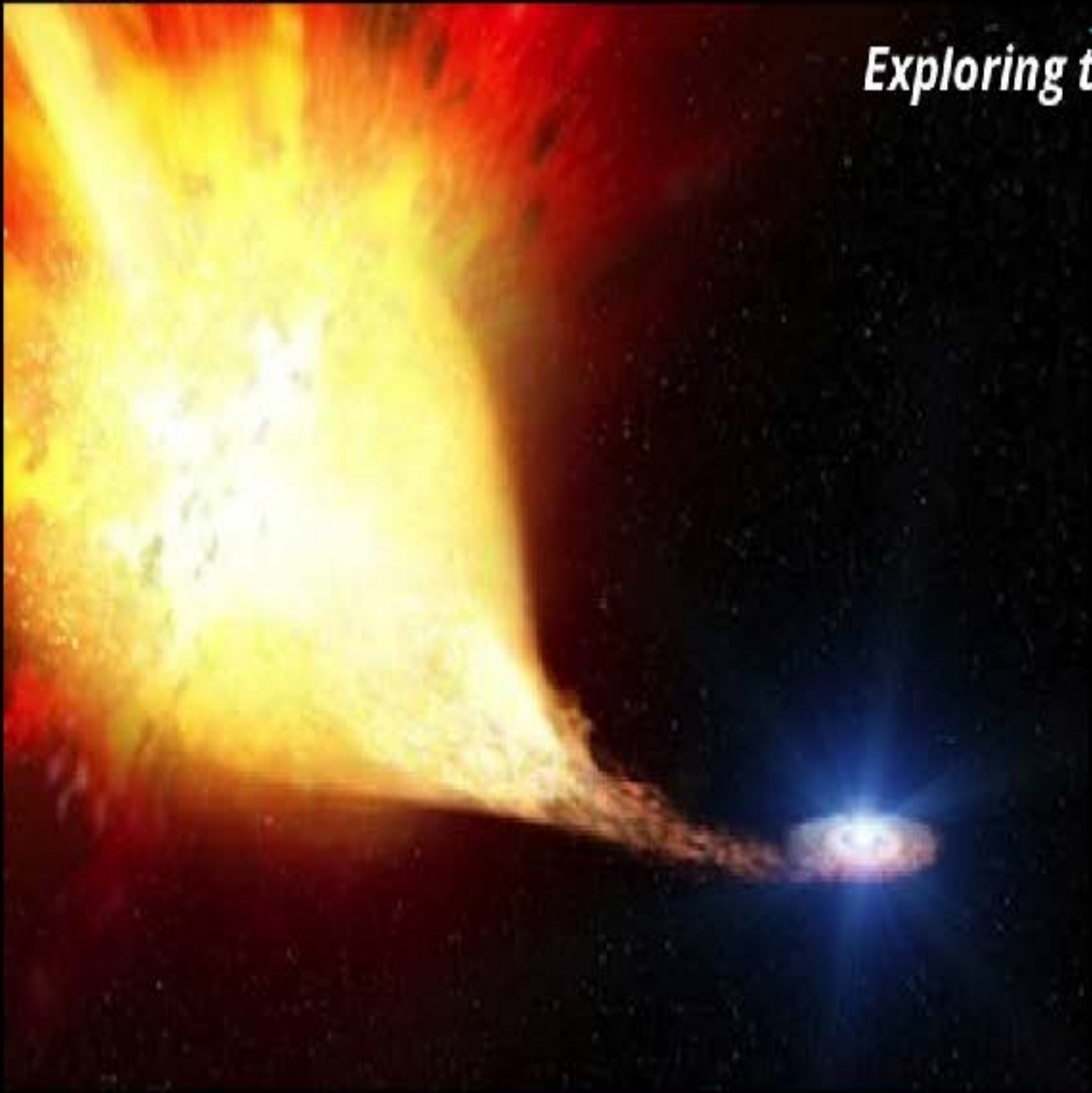
# Rubin Observatory LSST



## *Exploring the Transients and Variable Universe*

*LSST Science Drivers*

image credit: ESA-Justyn R. Maund

*federica bianco - fbianco@udel.edu*

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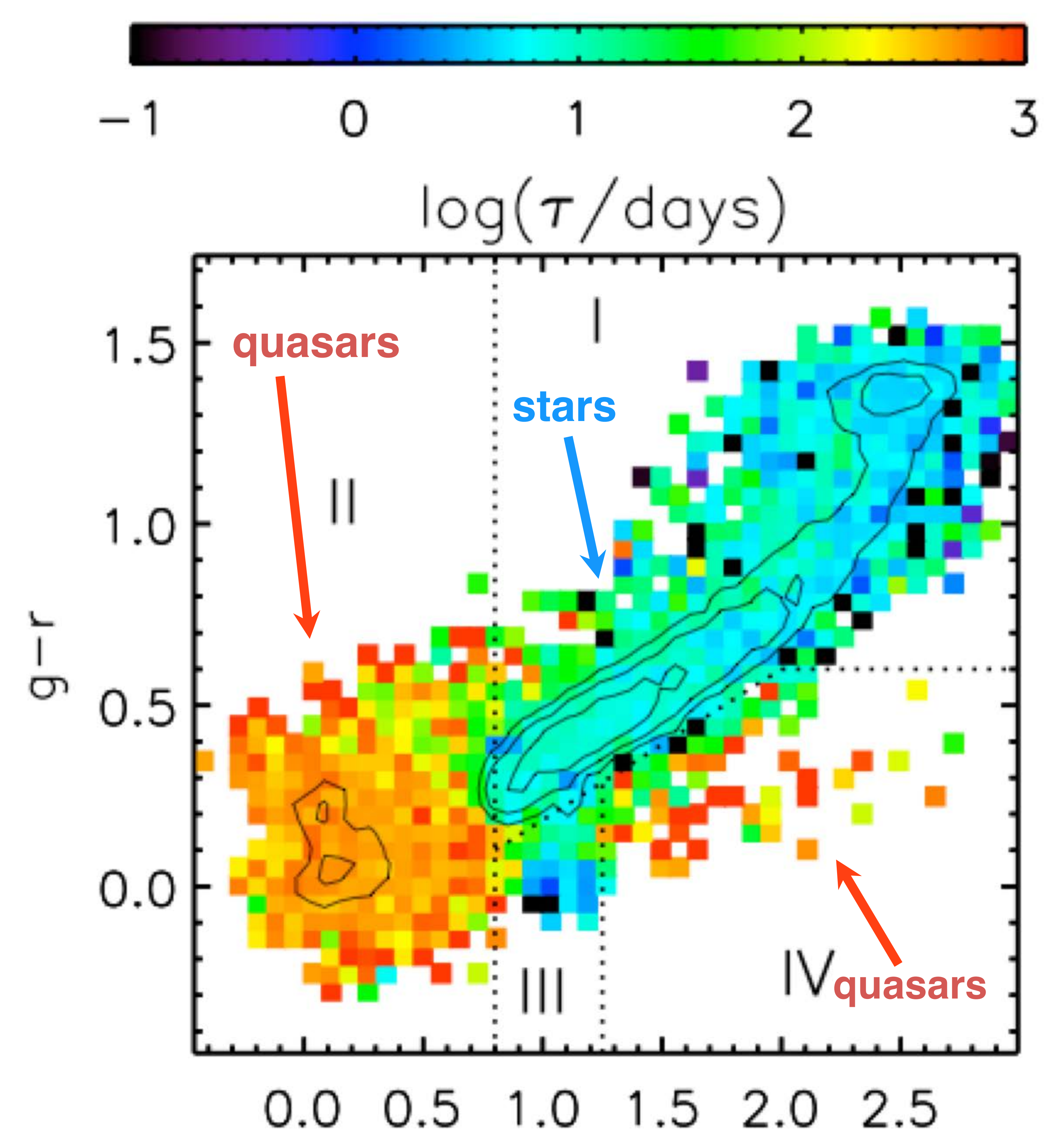
# Special Projects

- Mini surveys are special projects devoted to special environments, where the WFD survey would not be completely effective:
  - The Galactic disk
  - The Galactic bulge
  - The Magellanic Clouds
- They have special cadences and observing strategies

- Deep Drilling Fields are small areas where higher cadence and deeper coverage are needed
- Some examples:
  - XMM-LS
  - Extended Chandra DFS
  - COSMOS

# The variability time scales




McLeod et al. 2011

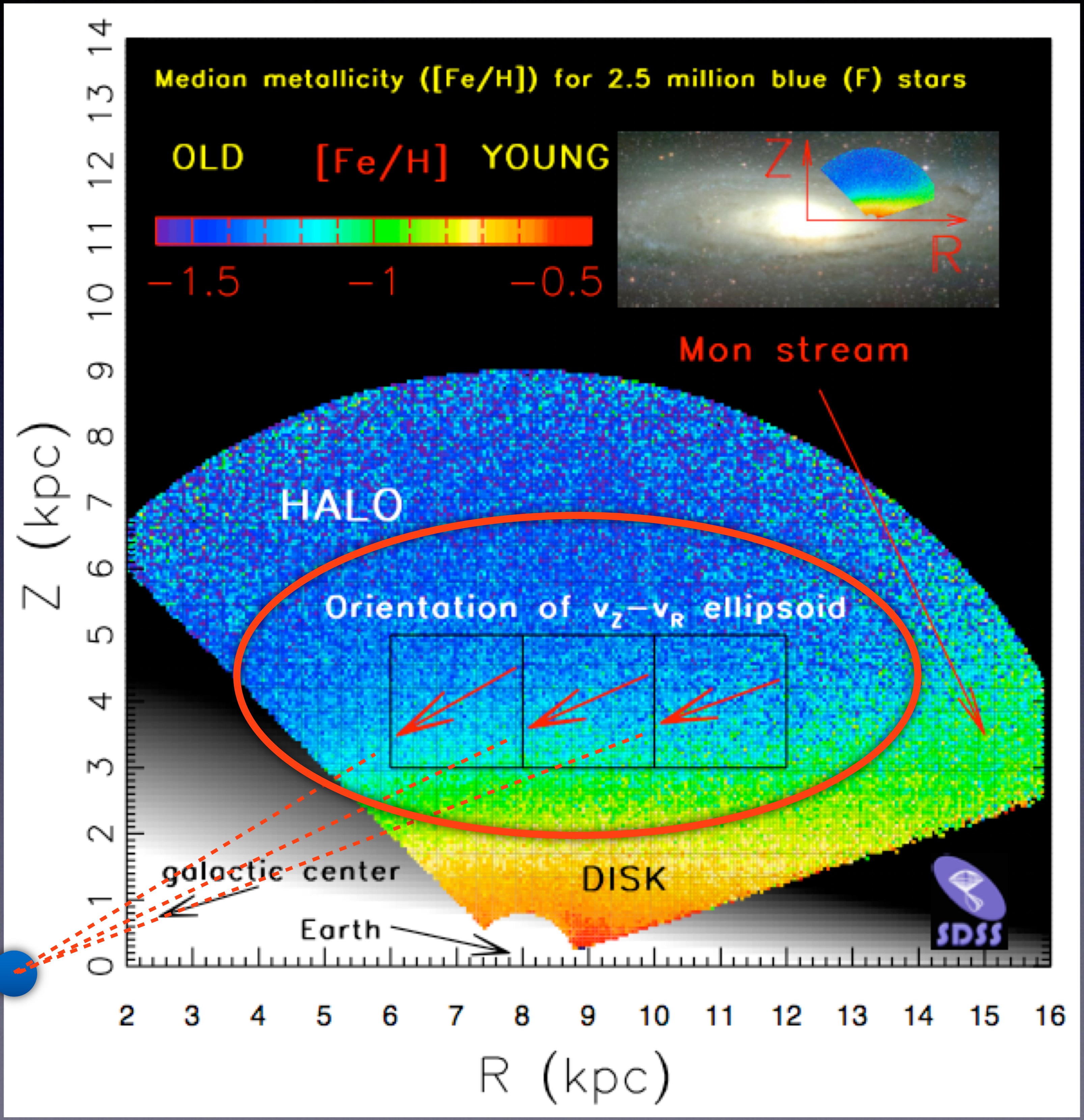
Time scale τ is defined via **damped random walk** (because not all variable sources are periodic)

Quasars are easily distinguished from stars by their long time scales.

**Variability is even better than color selection!**

**Case study:** light curve data and proper motion data for over 1 million sources from SDSS Stripe 82 (all are publicly available)

# Velocity distribution for halo stars (SDSS)



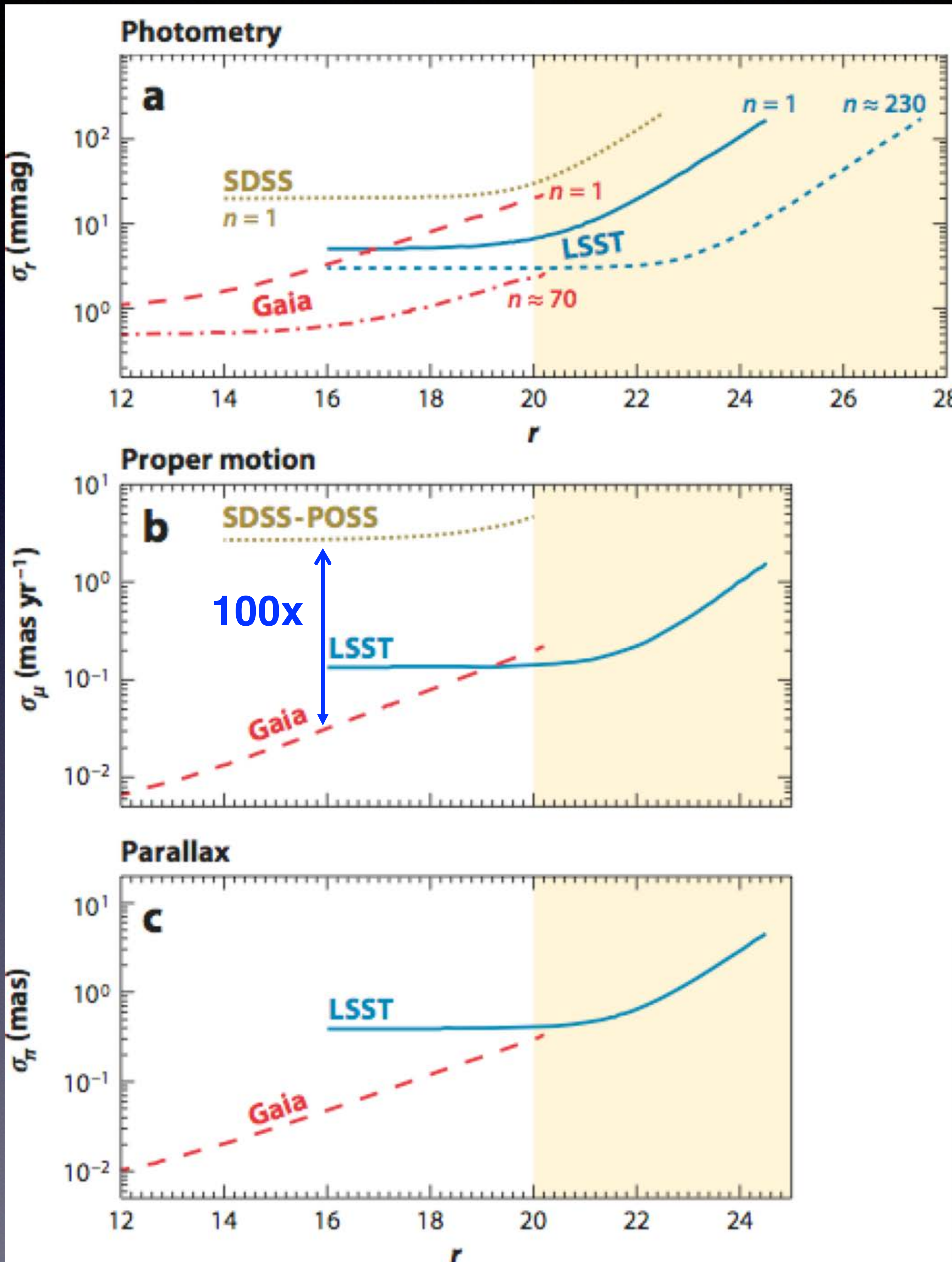

Kinematics of halo stars based on SDSS-POSS proper motions: velocity ellipsoid is nearly invariant in spherical coordinate system

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

Given measured stellar spatial distribution and stellar kinematics from proper motions, we can use **Jeans equations** to infer the gravitational potential, and ultimately the distribution of dark matter!

Loebman et al. (2014, ApJ, 794, 115)

# Gaia vs. LSST comparison

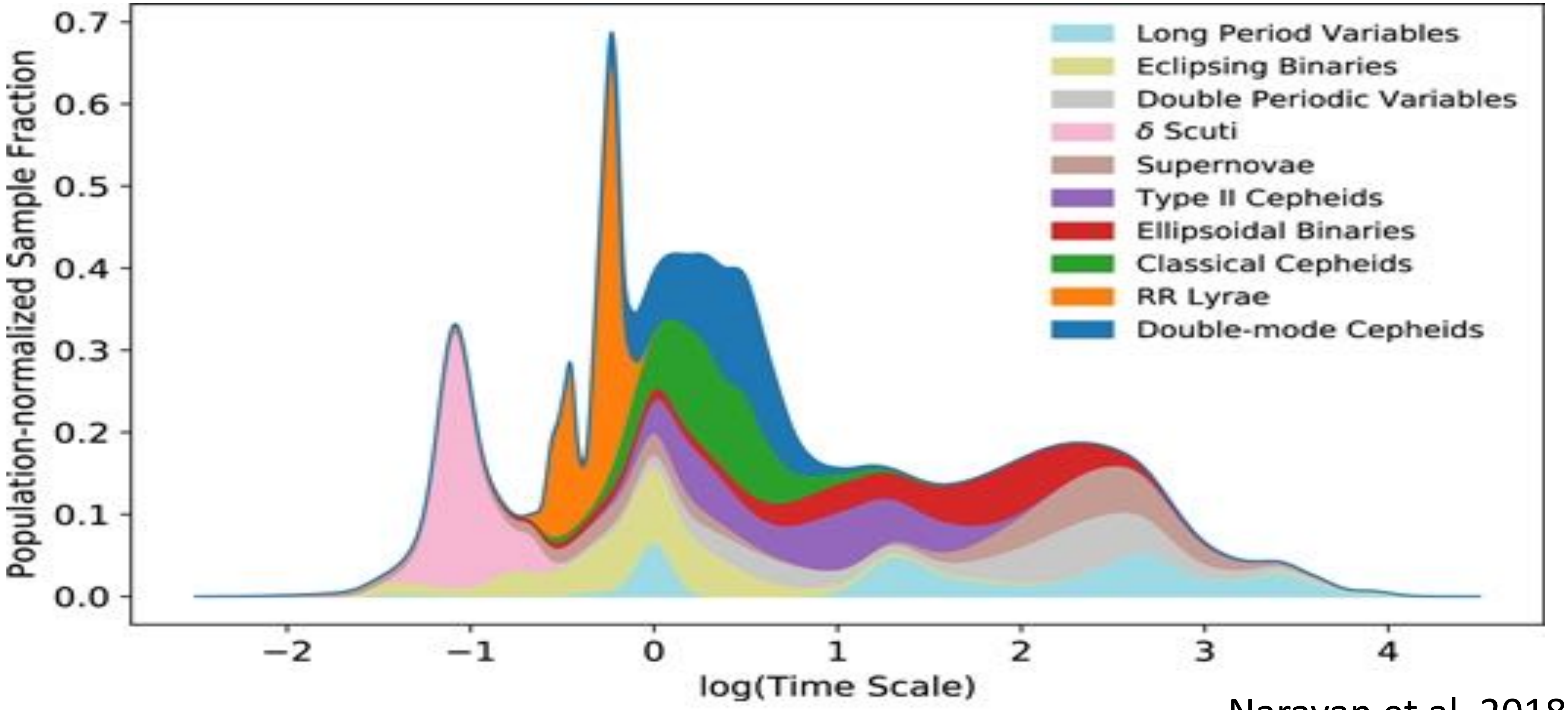



Ivezić, Beers, Jurić 2012, ARA&A, 50, 251

- **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

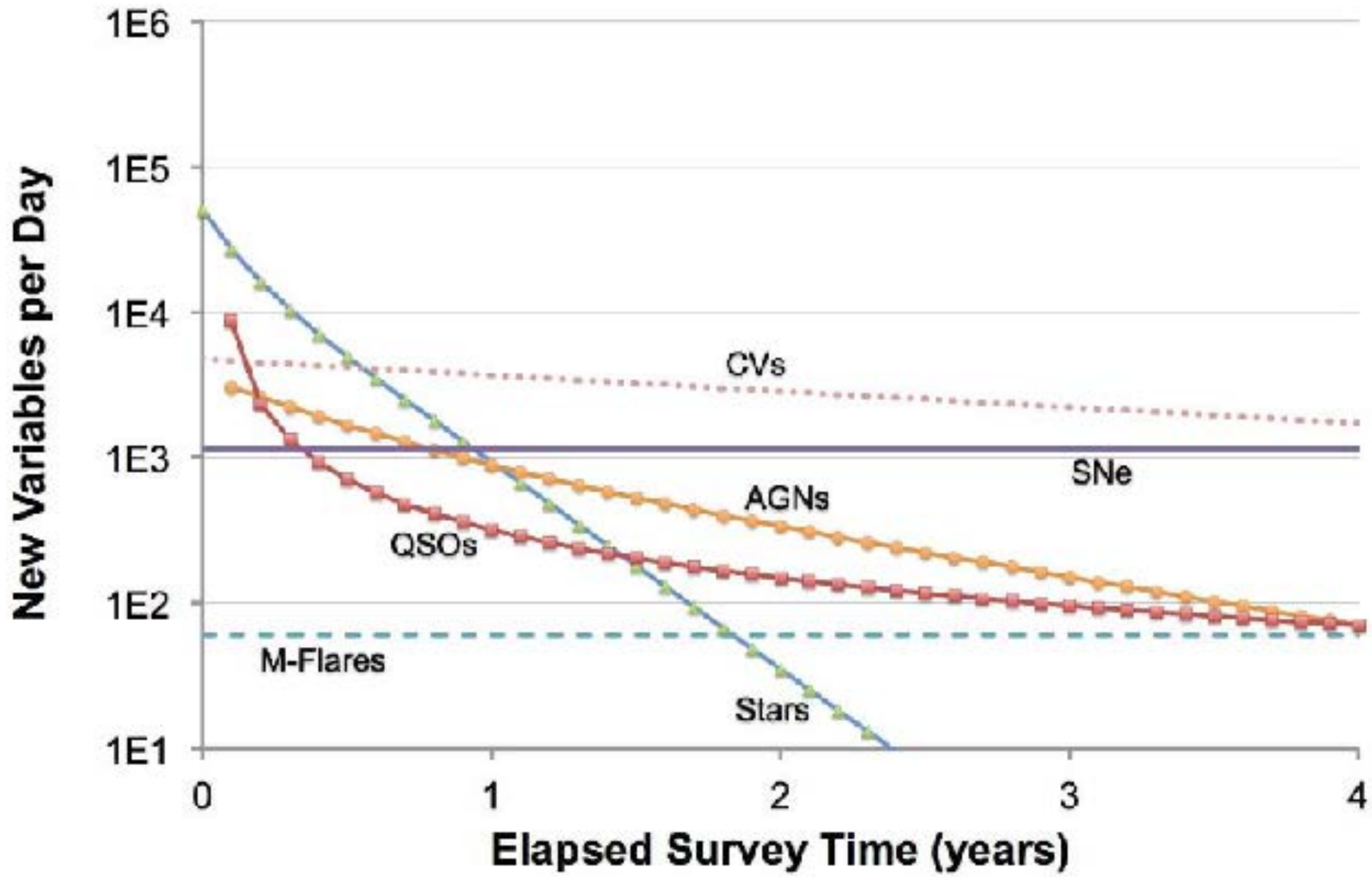
**The Milky Way disk "belongs" to Gaia, and the halo to LSST** (plus very faint and/or very red sources, such as white dwarfs and LT(Y) dwarfs).

# Typical time-scales




Narayan et al. 2018

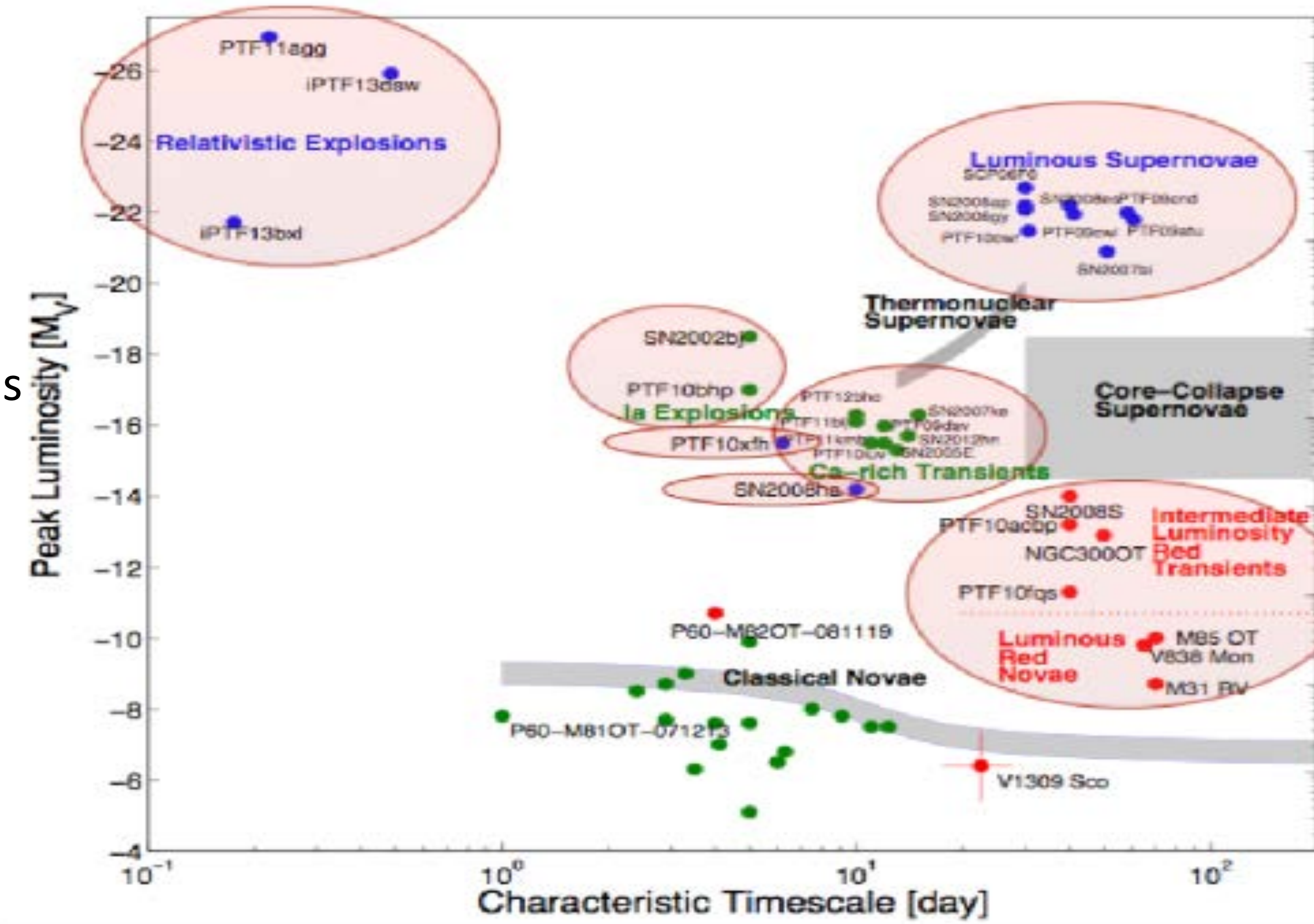
# New variables per night




Middleton et al. 2017
adapted from
Ridgway et al. 2014

# Filling the transients time-energy plane

- Unbiased and statistically significant sample of SNe
- Sample of different classes of transients
- Trained machine-learning classification




E. Bellm

Updated from Kasliwal 2011 (PhDT)

# The LSST Science Book

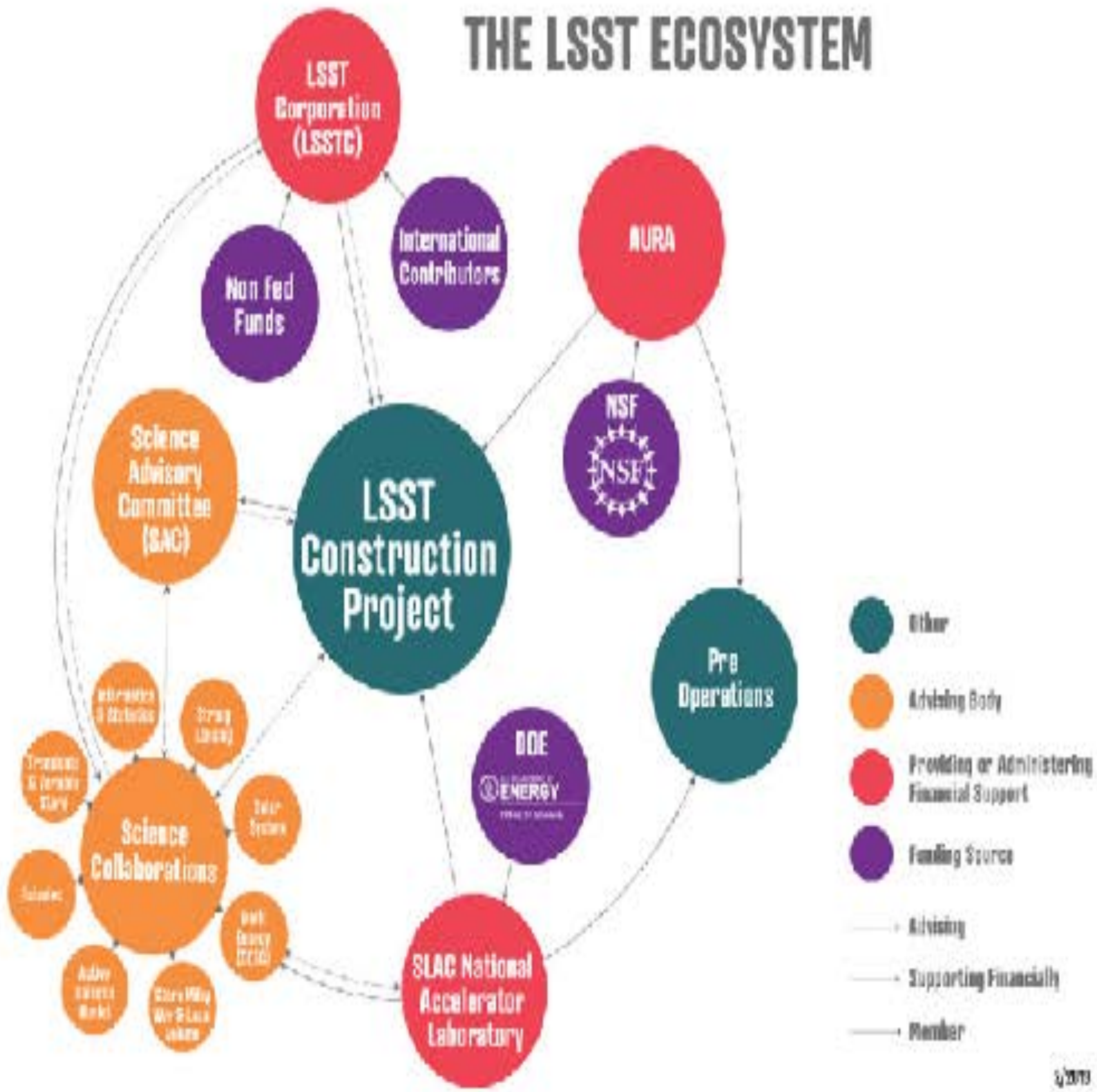
- **Contents:**
  - Introduction
  - LSST System Design
  - System Performance
  - Education and Public Outreach
  - The Solar System
  - Stellar Populations
  - Milky Way and Local Volume Structure
  - The Transient and Variable Universe
  - Galaxies
  - Active Galactic Nuclei
  - Supernovae
  - Strong Lenses
  - Large-Scale Structure
  - Weak Lensing
  - Cosmological Physics

Dark Energy

# the Rubin LSST Science Collaborations

# Rubin Observatory LSST

The Rubin Organization is almost as complex as the Universe it will explore!



# Rubin LSST Science Collaborations

VERA C. RUBIN OBSERVATORY

TVS

DESC

Galaxies SC

SLSC

8 Science Collaborations

think about us as an army of volunteers that thinks Rubin LSST will be amazing and transformational and are investing in preparing to use its data and helping optimize the Observatory choices

SMWLV

SSSC

AGN

ISSC

LSST

8 SCs - 5 continents - 1500 people - 25 countries

federica bianco - fbianco@udel.edu

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# Rubin LSST Science Collaborations

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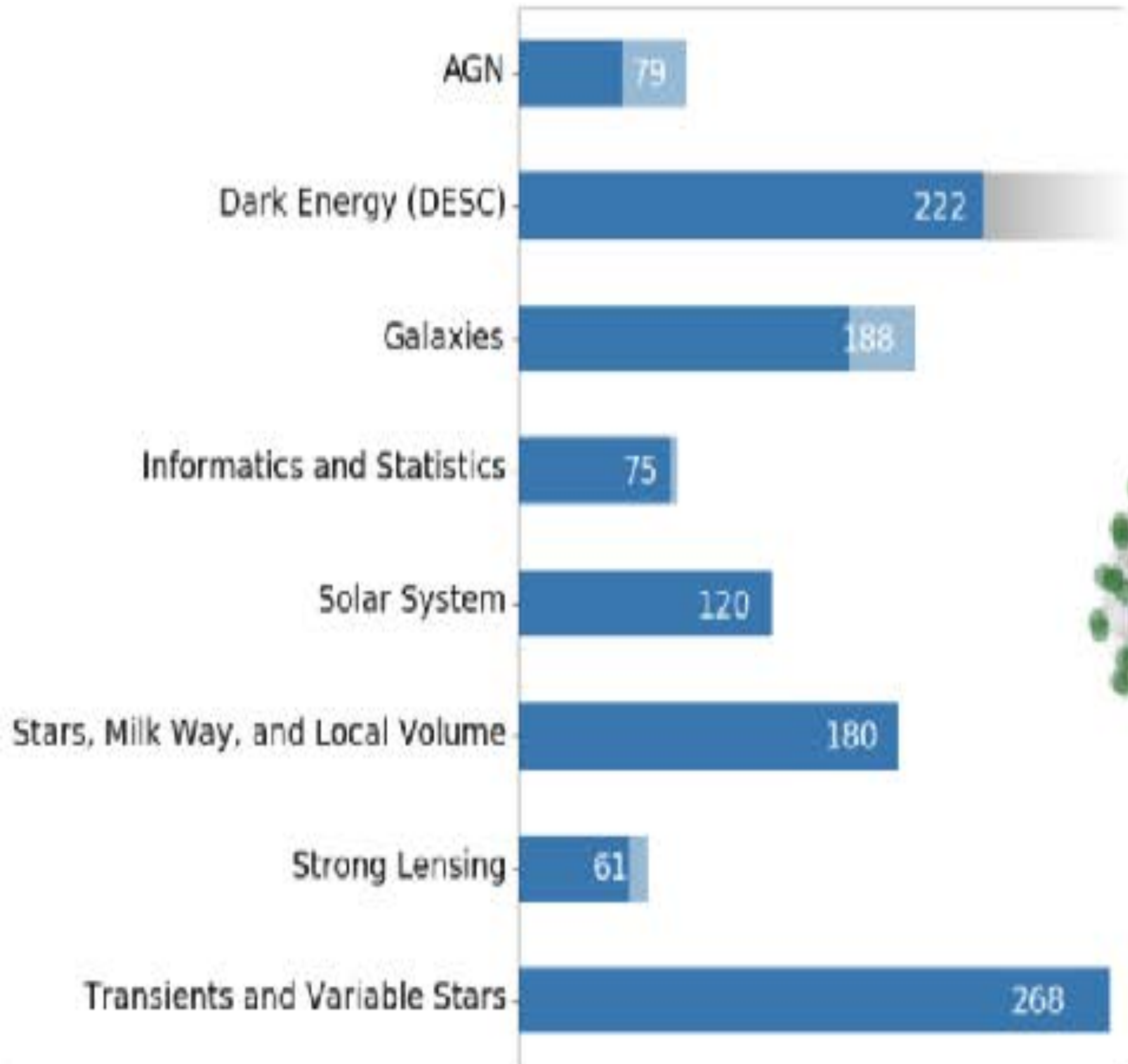


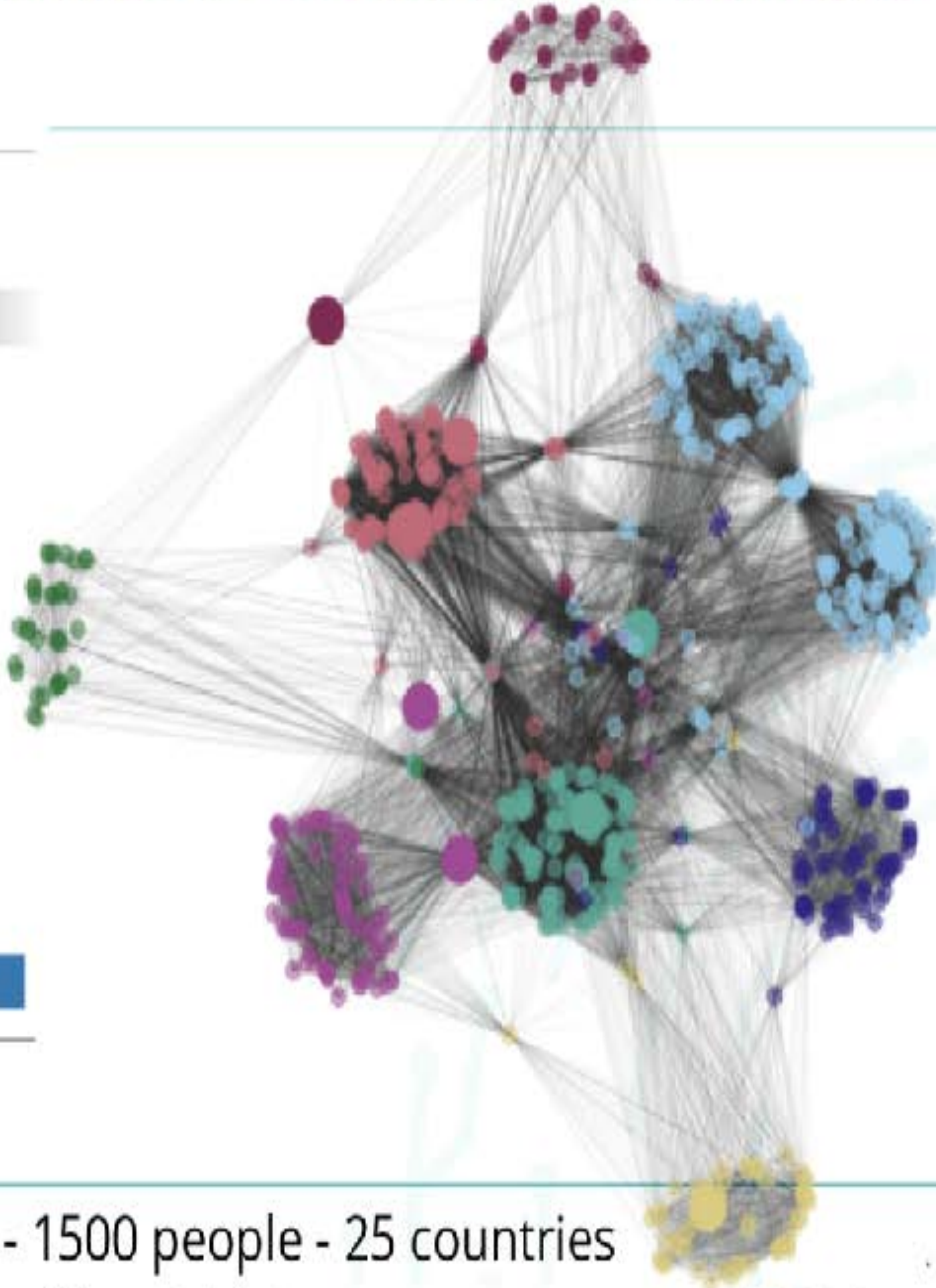

LSST

8 SCs - 5 continents - 1500 people - 25 countries

*federica bianco - fbianco@udel.edu*

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# Rubin LSST Science Collaborations

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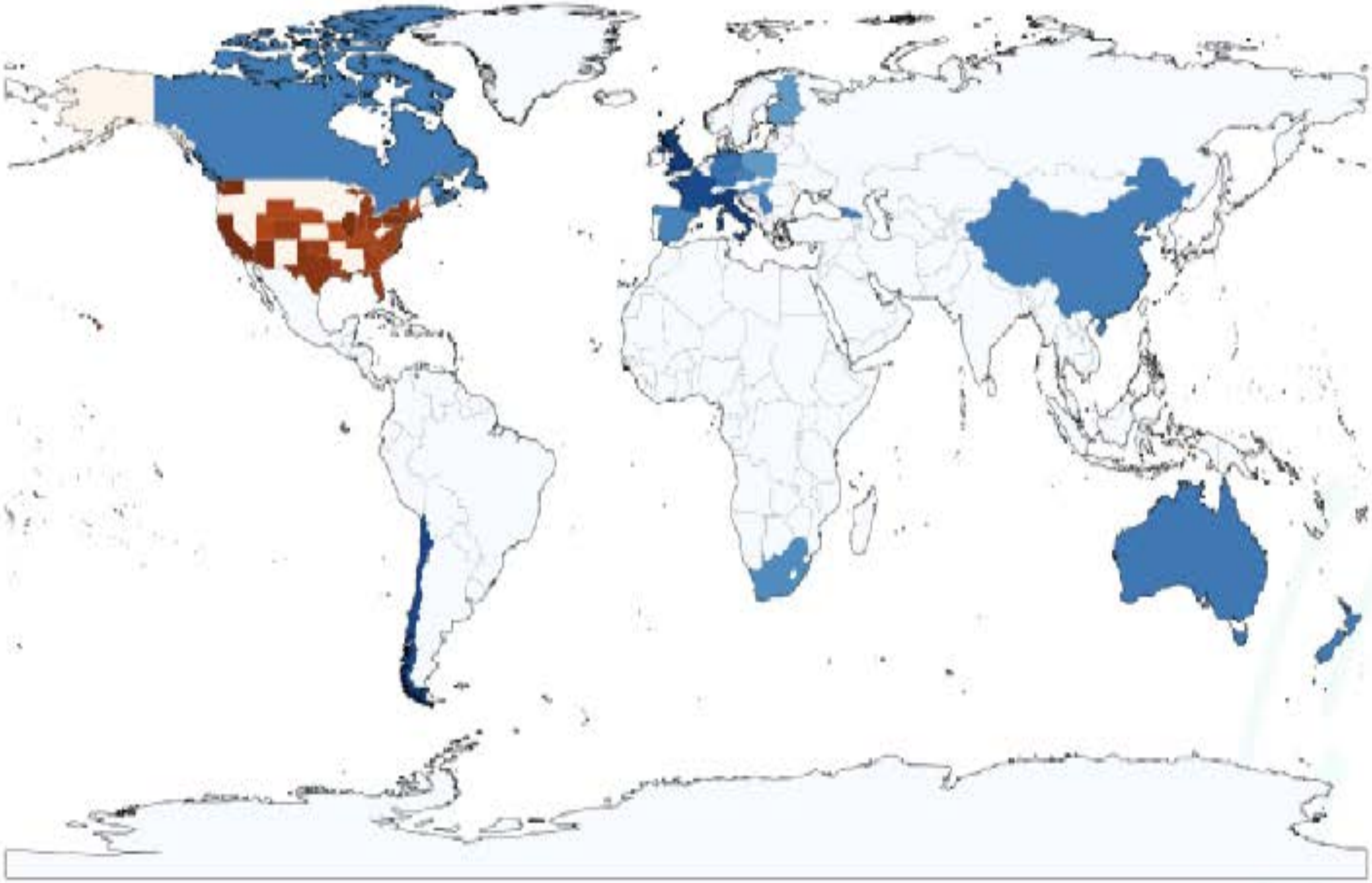

https://community.lsst.org/t/international-in-kind-contribution-evaluation-committee-cec-update-charge-and-science-collaboration-representation/3998

8 SCs - 5 continents - 1500 people - 25 countries

federica bianco - fbianco@udel.edu

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# Diversity
# Equity
# Inclusion

# Rubin LSST Science Collaborations

TVS

DESC

GalaxiesSC

SLSC

*We aspire to be an inclusive, equitable, and ultimately just group and we are working with renewed vigor in the wake of the recent event that exposed inequity and racism in our society to turning this aspiration into action.*

https://lsst-tvssc.github.io/calltoaction.html

SMWLV

SSSC

AGN

ISSC

**#desc-for-black-lives**

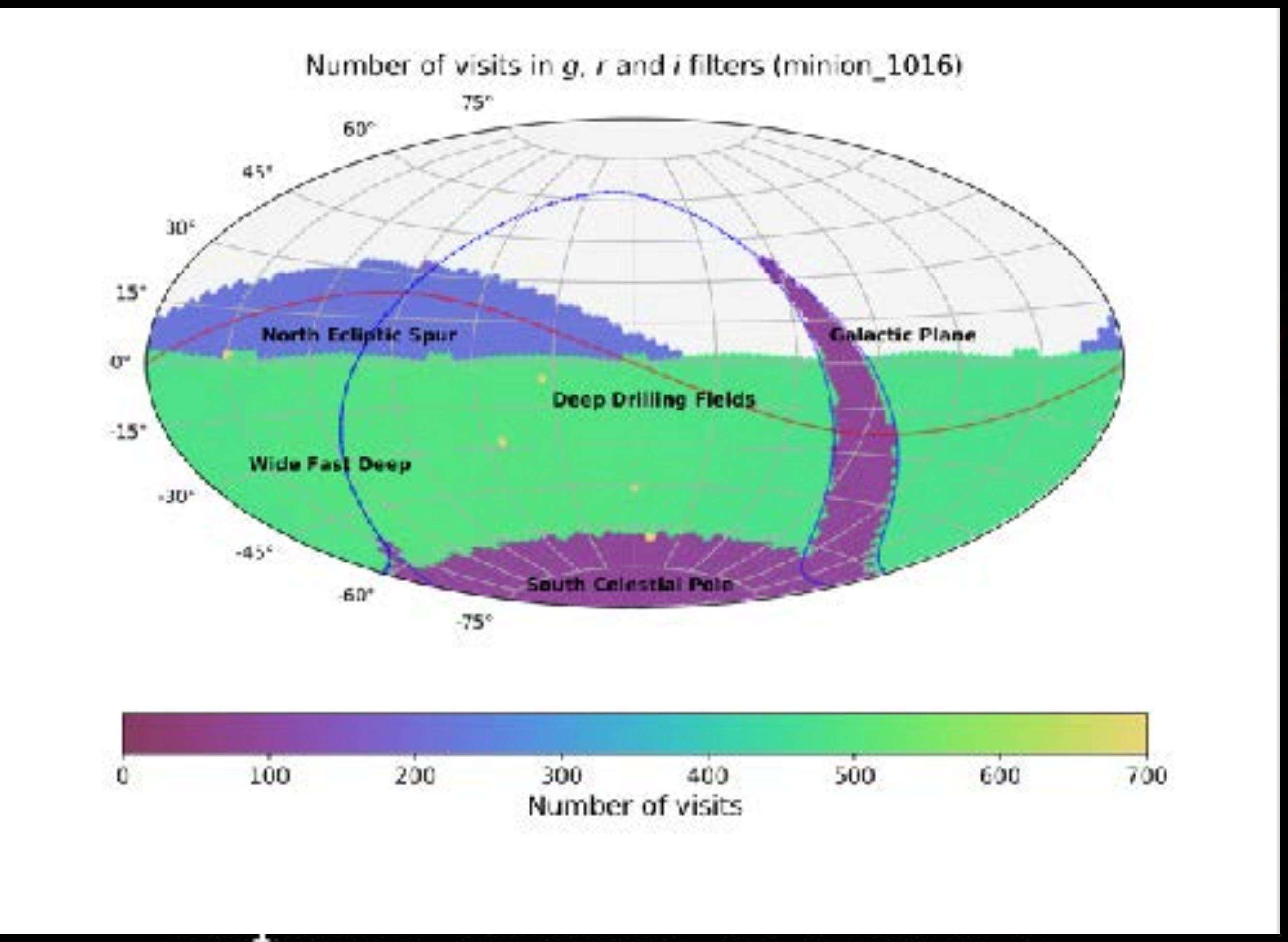
@heather999 created this channel on June 9th. This is the very beginning of the **#desc-for-black-lives** channel. Description: Dialogues about how each of us as individual DESC members and our collaboration as a whole can help eradicate anti-Black racism. (edit)

Diversity Equity and Inclusion council of the SCs

# *Survey*

# 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 imaging 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, $3.6 \times 10^{-31}$ erg/s/cm$^2$/Hz) based on 825 visits over 10 years: deep wide fast.

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

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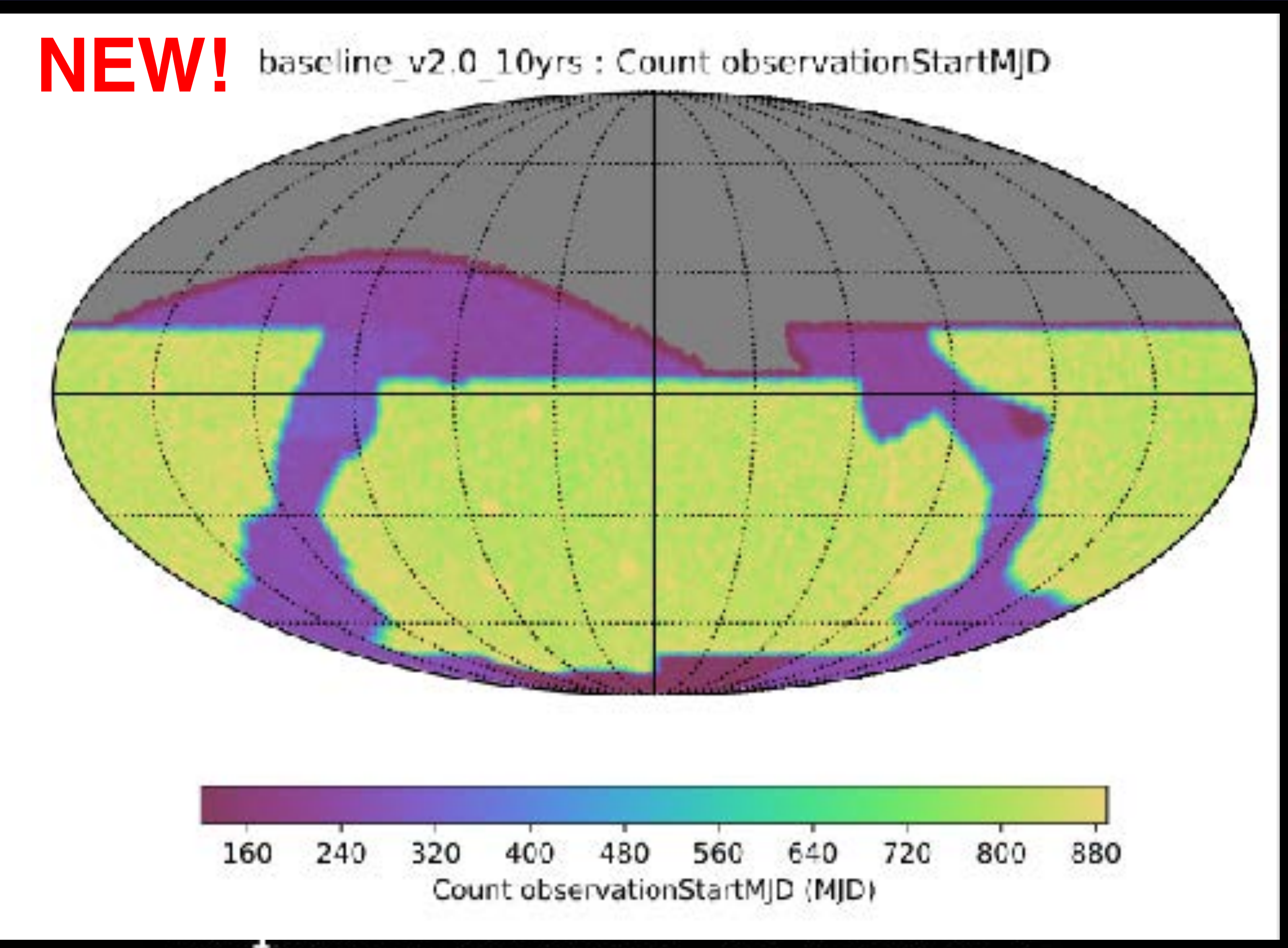


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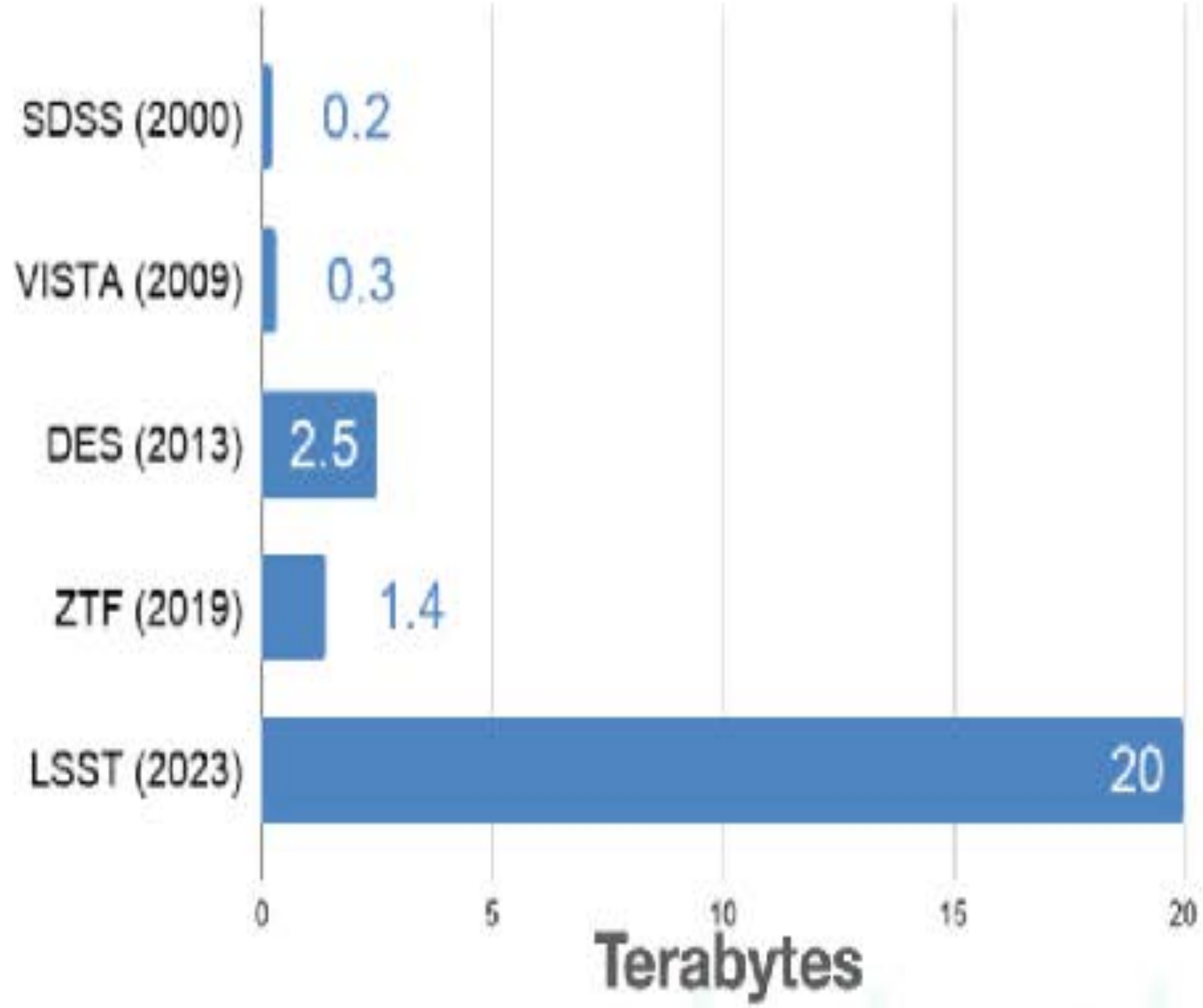
**Left:** a 10-year simulation of LSST survey: the number of visits in the r band (Aitoff projection of eq. coordinates)

# Rubin LSST survey design

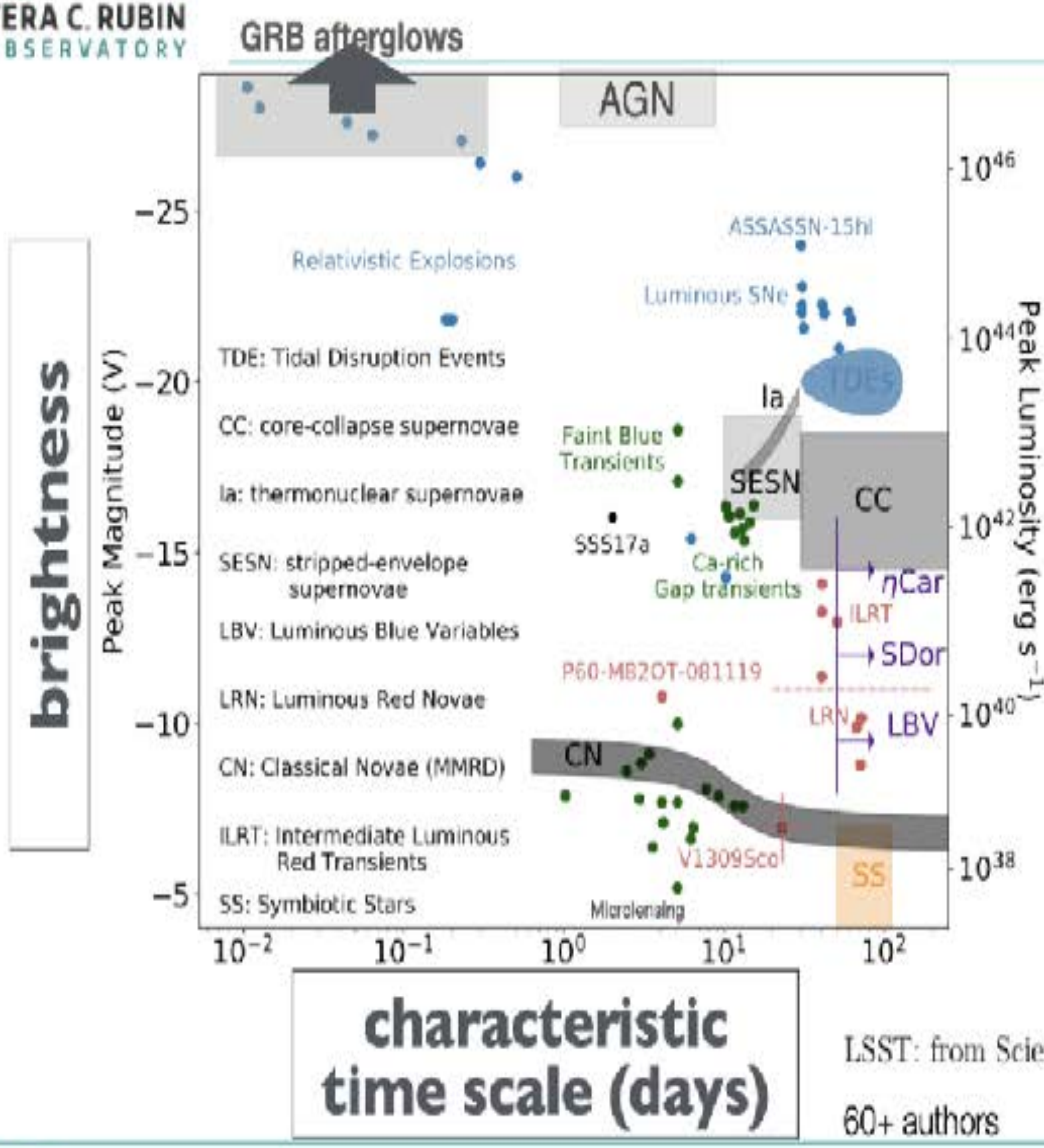
VERA C. RUBIN OBSERVATORY

## Rubin LSST = Astro + DataScience

x10 increase in data volume



# Rubin LSST survey design

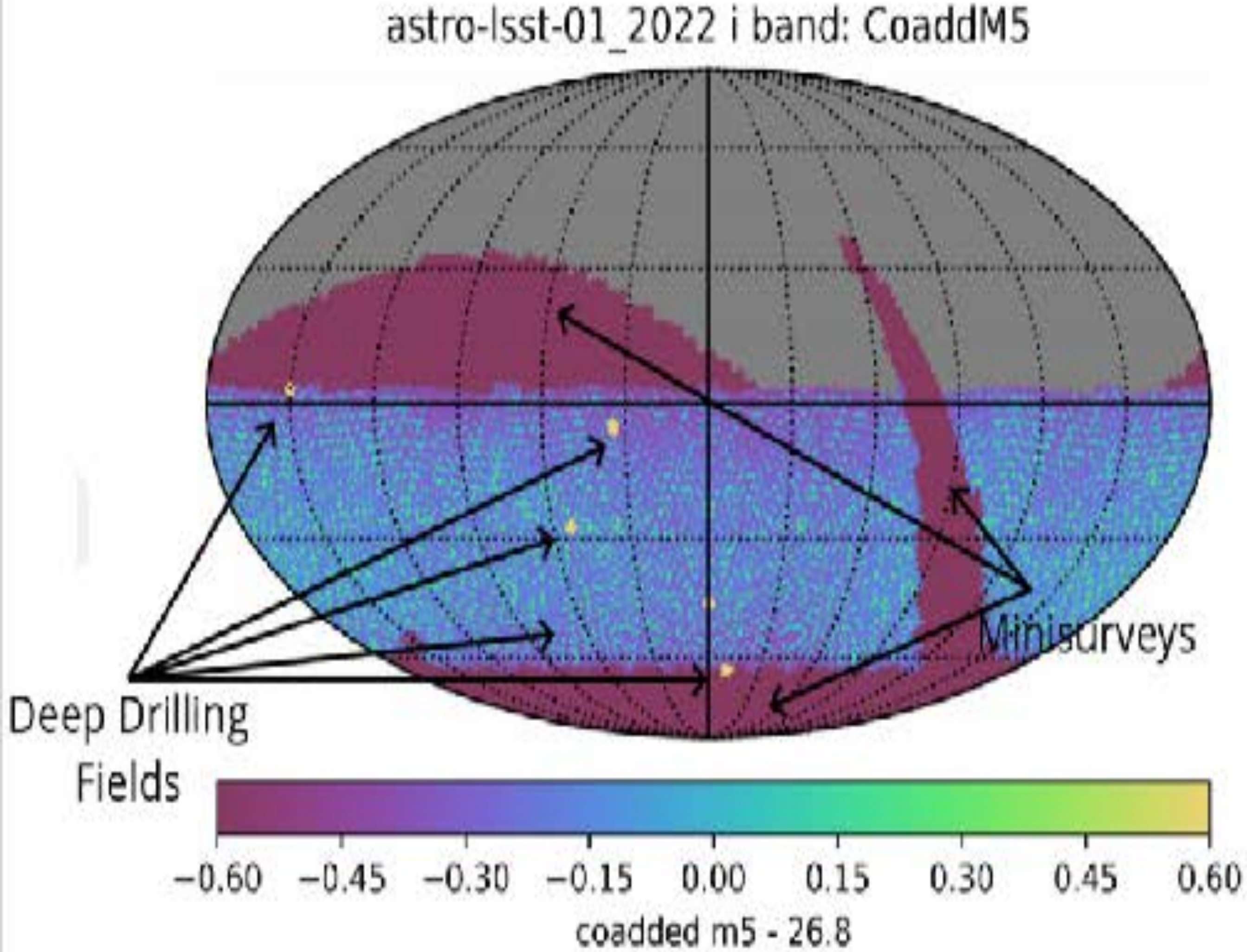



***What time scales can LSST probe?***

LSST: from Science Drivers to Reference Design and Anticipated Data Products

60+ authors Ivezic et al 2019 (2008)

# Rubin LSST survey design




Rothchild+ 2019

https://arxiv.org/abs/1903.00531

***Many surveys in one***

Wide Fast Deep

8oo img over 18,000 sq deg

pairs of observations in <1hour to track asteroid (and get transient colors)

80% of the sky time

Minisurveys

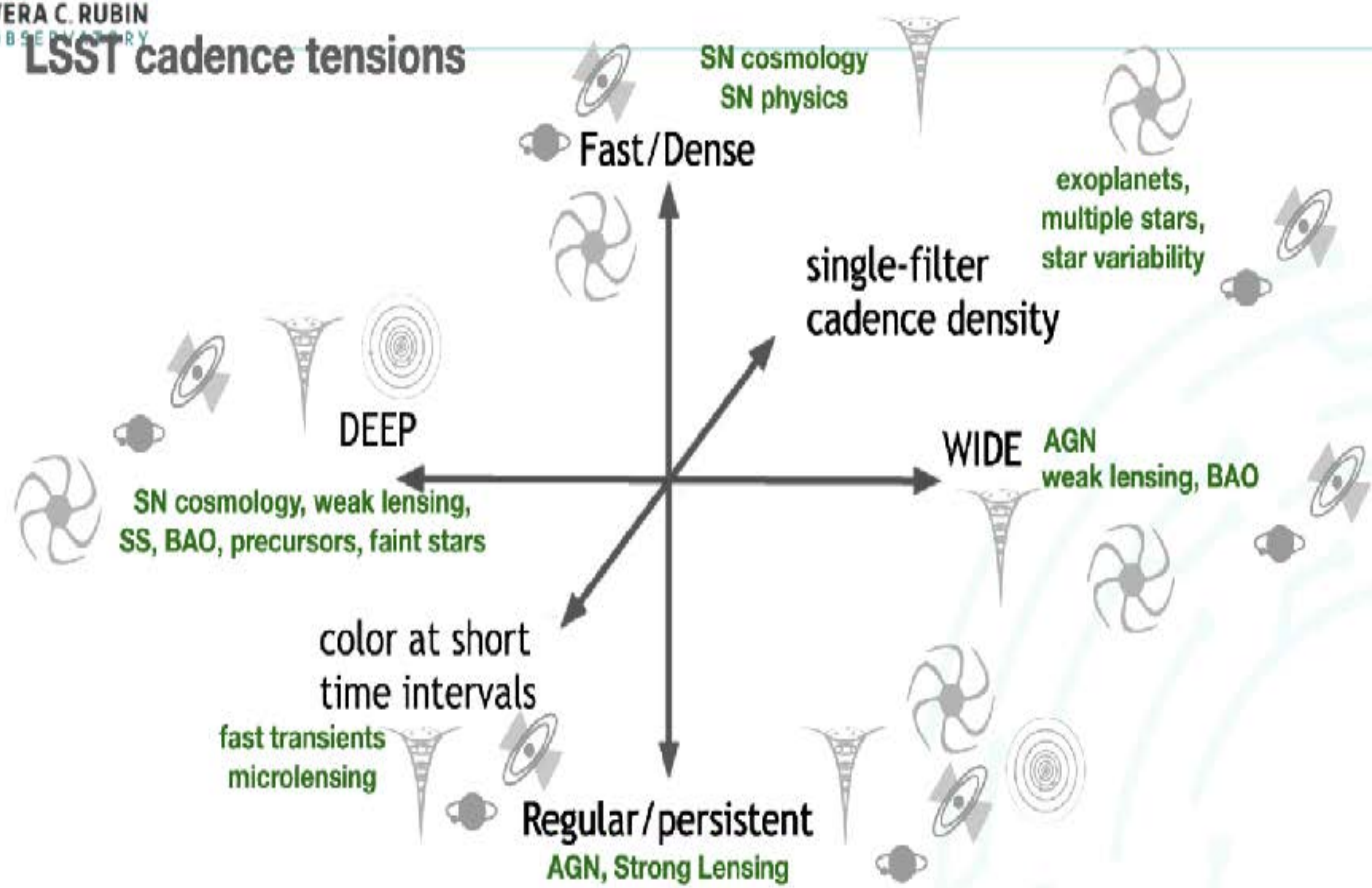
Deep Drilling Fields

Targets of Opportunity

} 20%

# Rubin LSST survey design

## LSST cadence tensions

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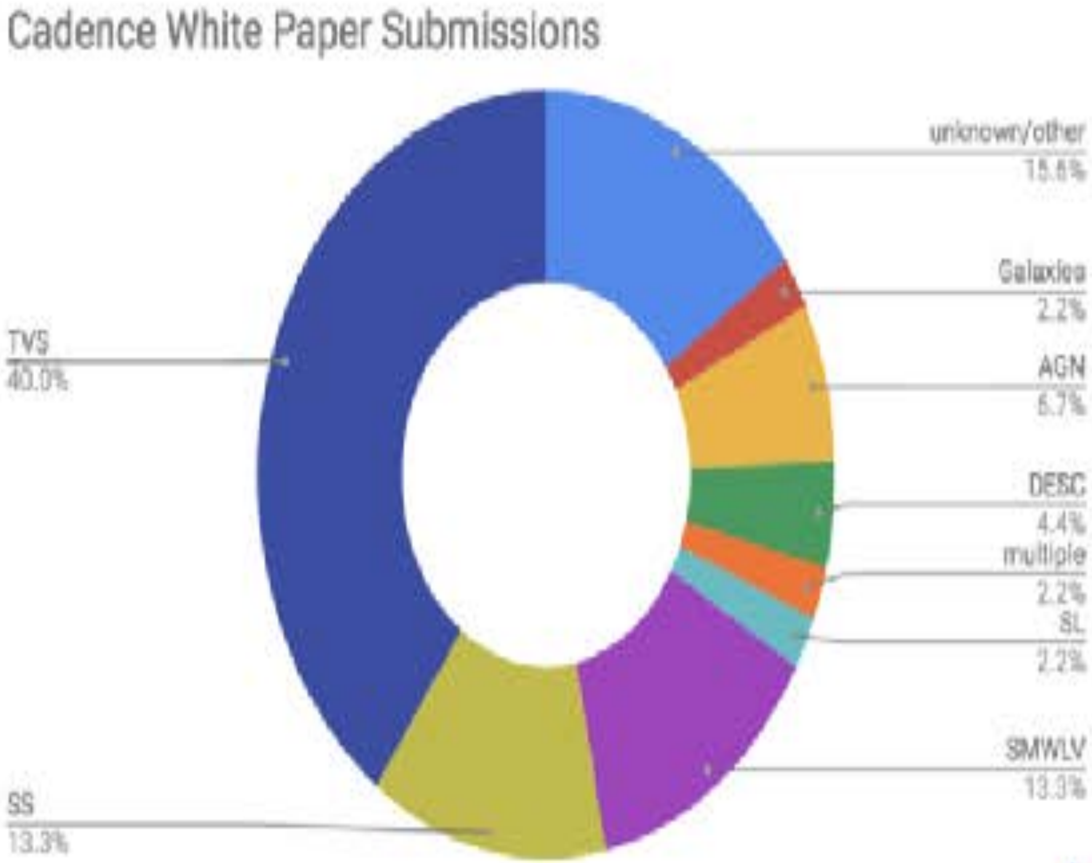
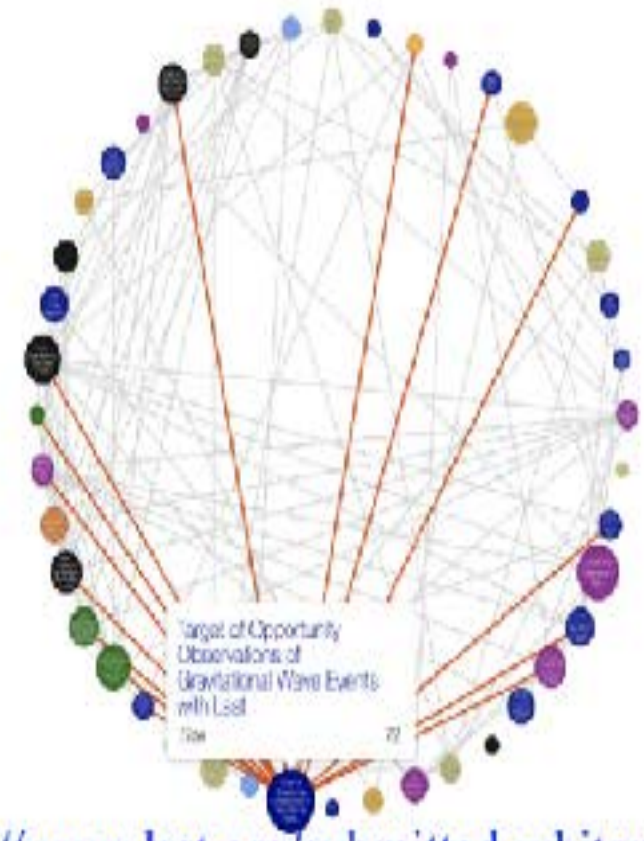
# Rubin LSST survey design

Rubin asked the community how to design the survey

40+ submissions




https://www.lsst.org/submitted-whitepaper-2018

*Helping define the LSST Survey*

http://fbb.space//LSSTWP/LSSTwhitePapers.html

# Rubin data and data products

# Rubin Observatory LSST

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## Data Management System Overview

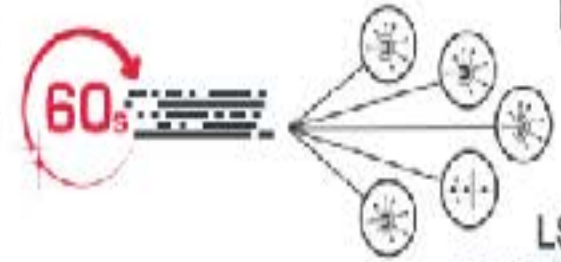
**Raw Data: 20TB/night**

Sequential 30s images that cover the entire visible sky every few days.

**Prompt Data Products**

Alerts: up to 10M/night

via nightly alert streams




Community Brokers

LSST Alert Filtering Service

Results of Difference Image Analysis (DIA): transient and variable sources

Solar System Objects: ~6M by year 10

24h via Prompt Products Database

**Data Release Data Products**

Final 10 year Data Release images: 5.5M x 3.2 Gpx catalogs: 37M objects, 15PB

via Data Releases

LSST DACs (Chile & NCSA)

Independent DACs (iDACs)

Data Products Definition Document http://ls.st/dpdd

LSST

# Rubin Observatory LSST

VERA C. RUBIN OBSERVATORY

## Data Management System Overview

**Raw Data: 20TB/night**

Sequential 30s images that cover the entire visible sky every few days.

Data Products Definition Document
http://ls.st/dpdd

LSST

# Rubin Observatory LSST

VERA C. RUBIN OBSERVATORY

**world public!**

## Data Management System Overview

**Raw Data: 20TB/night**

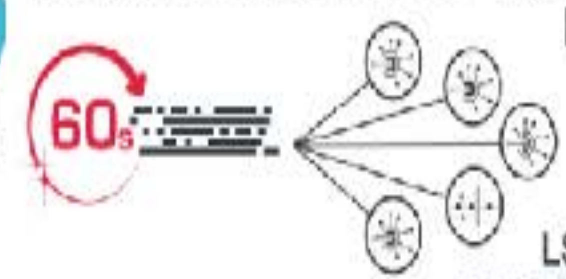
Sequential 30s images that cover the entire visible sky every few days.

**Prompt Data Products**

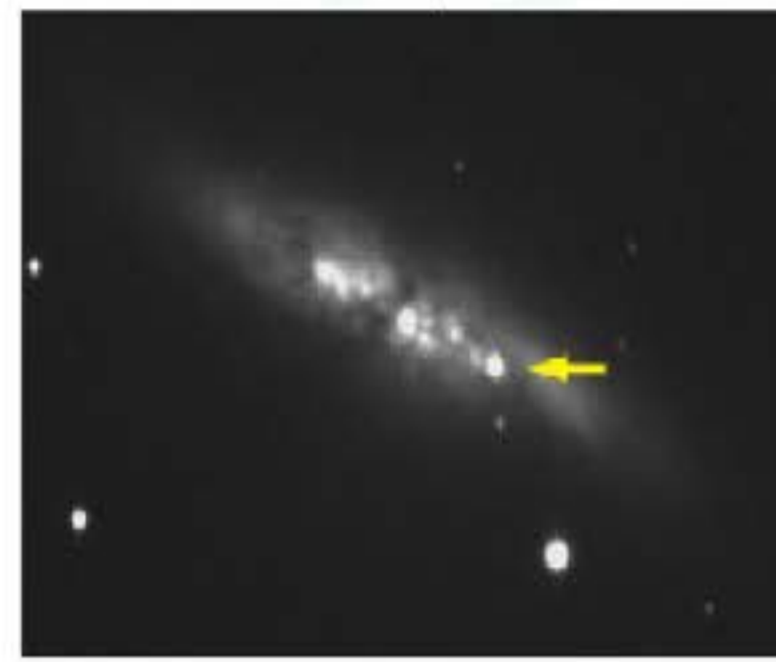
- Alerts: up to 10M/night

**via nightly alert streams**

**Community Brokers**




**LSST Alert Filtering Service**

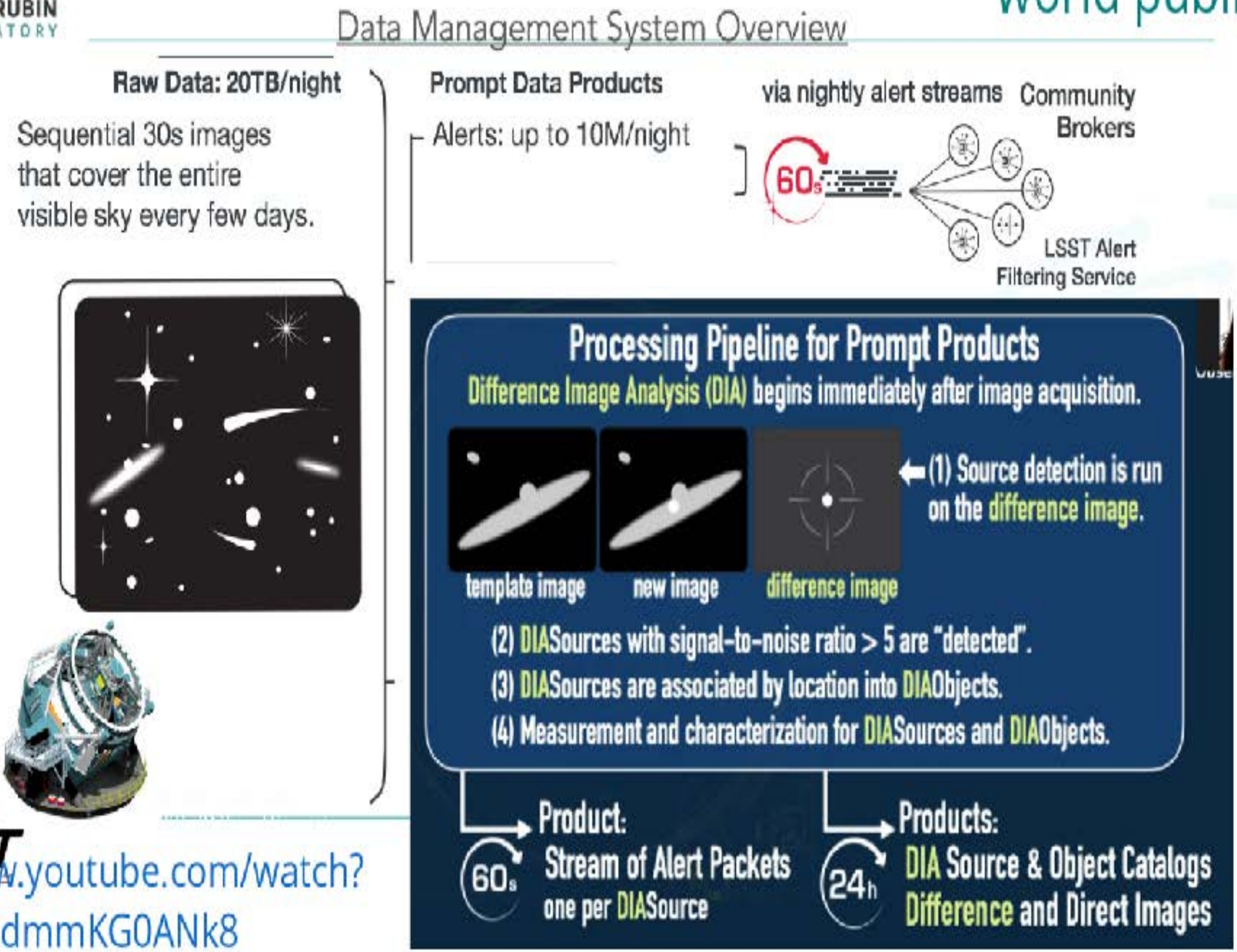


**Data Products Definition Document**
http://ls.st/dpdd

LSST

# Rubin Observatory LSST

world public




https://www.youtube.com/watch?v=6dmmKG0ANk8

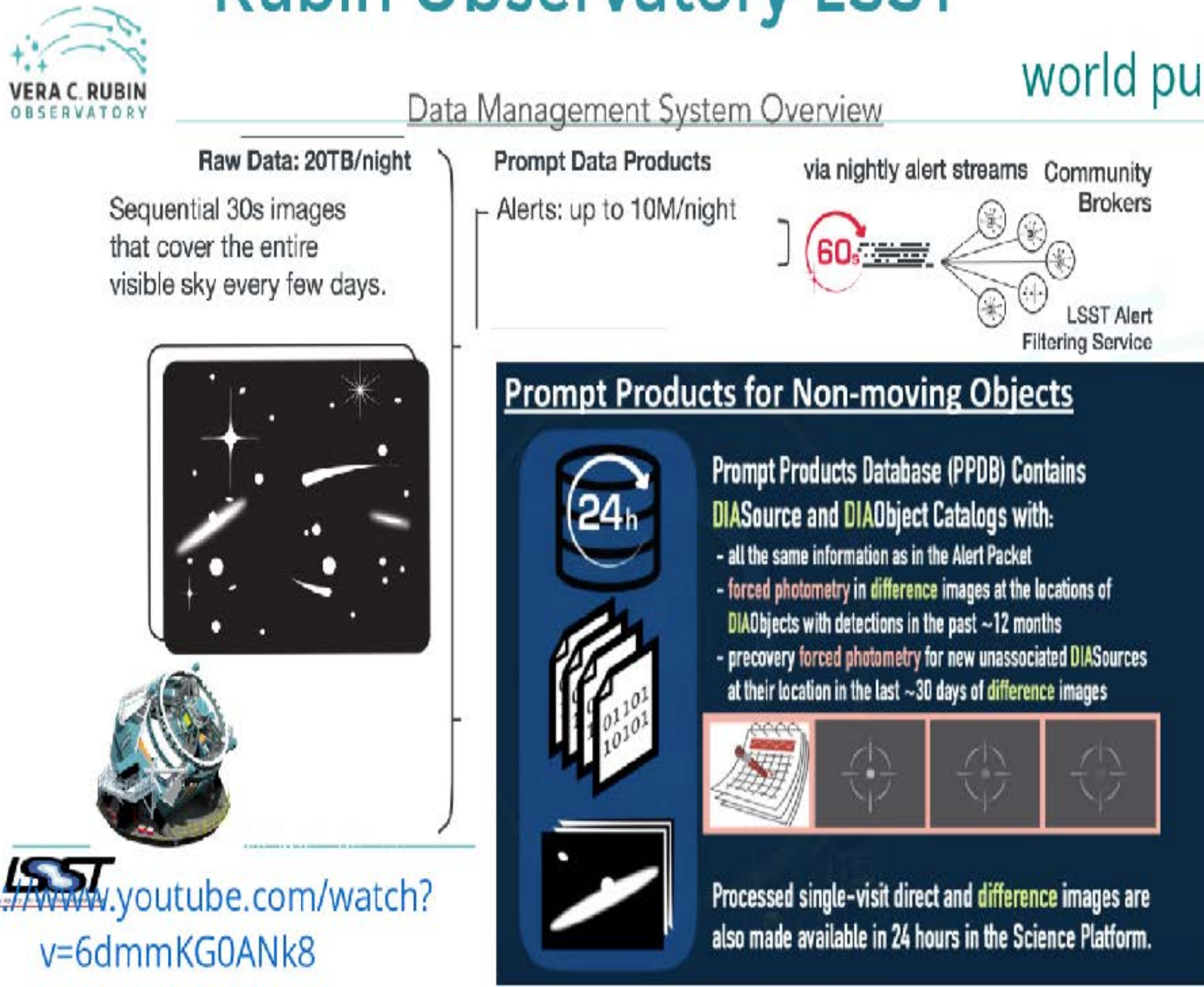
# Rubin Observatory LSST

world public


https://www.youtube.com/watch?v=6dmmKG0ANk8

# Rubin Observatory LSST

world public



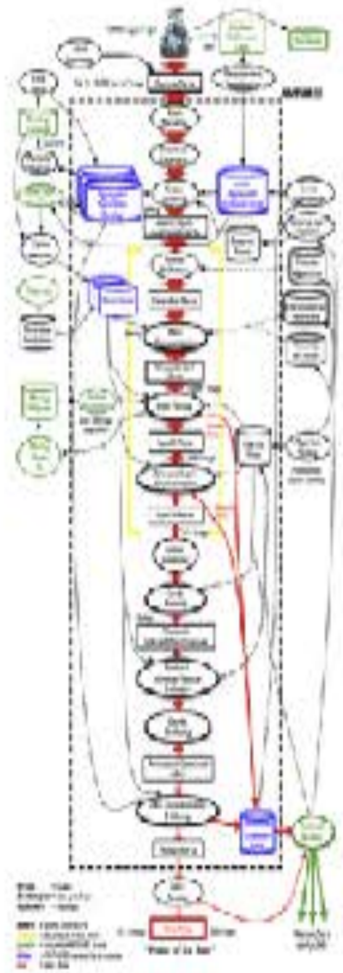

https://www.youtube.com/watch?v=6dmmKG0ANk8

# Big data and time domain astrophysics

## Astronomy's Discovery Chain

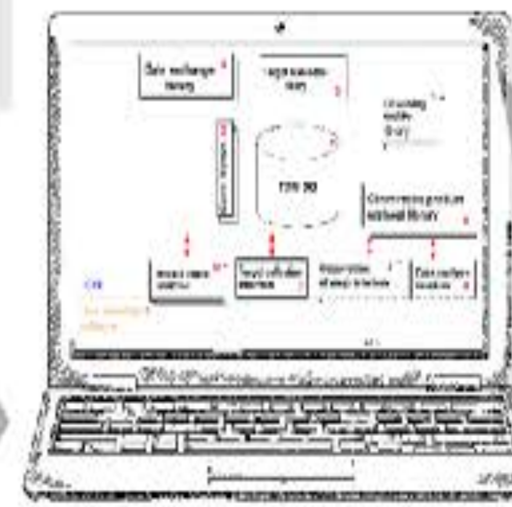
Discovery Engine

10M alerts/night



Community Brokers

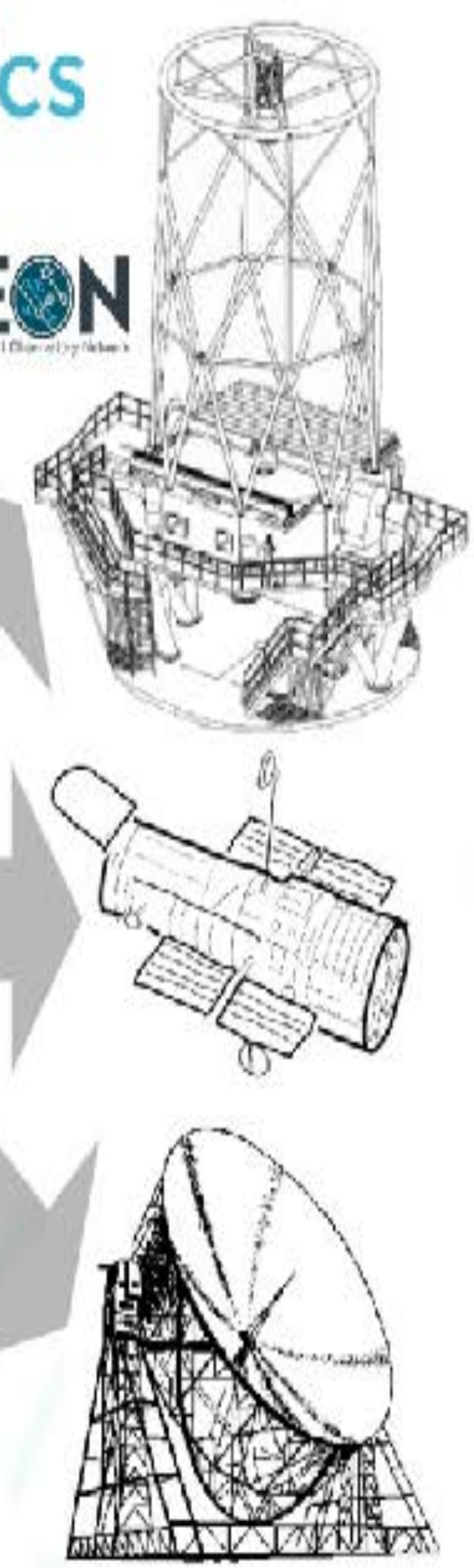
ALeRCE ANTARES beta LASAIR



target observation managers

TOM

TOM TOOLKIT

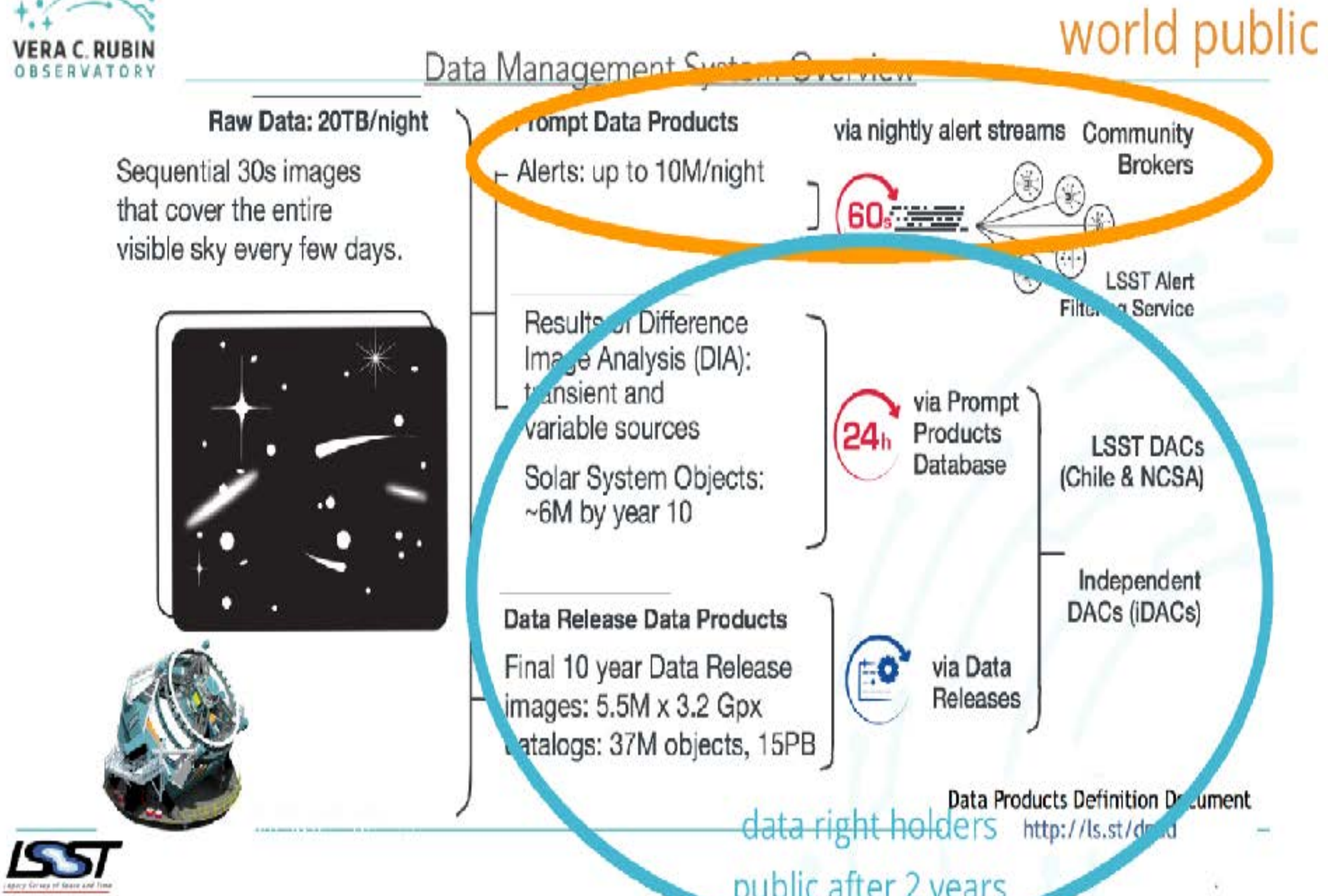


## the astronomy discovery chain

federica bianco - fbianco@udel.edu

@fedhere

# Rubin Observatory LSST



# Rubin Observatory LSST

LIGO/VIRGO area of localization ~100deg square

Ursa Minor contains 255.86 square degrees

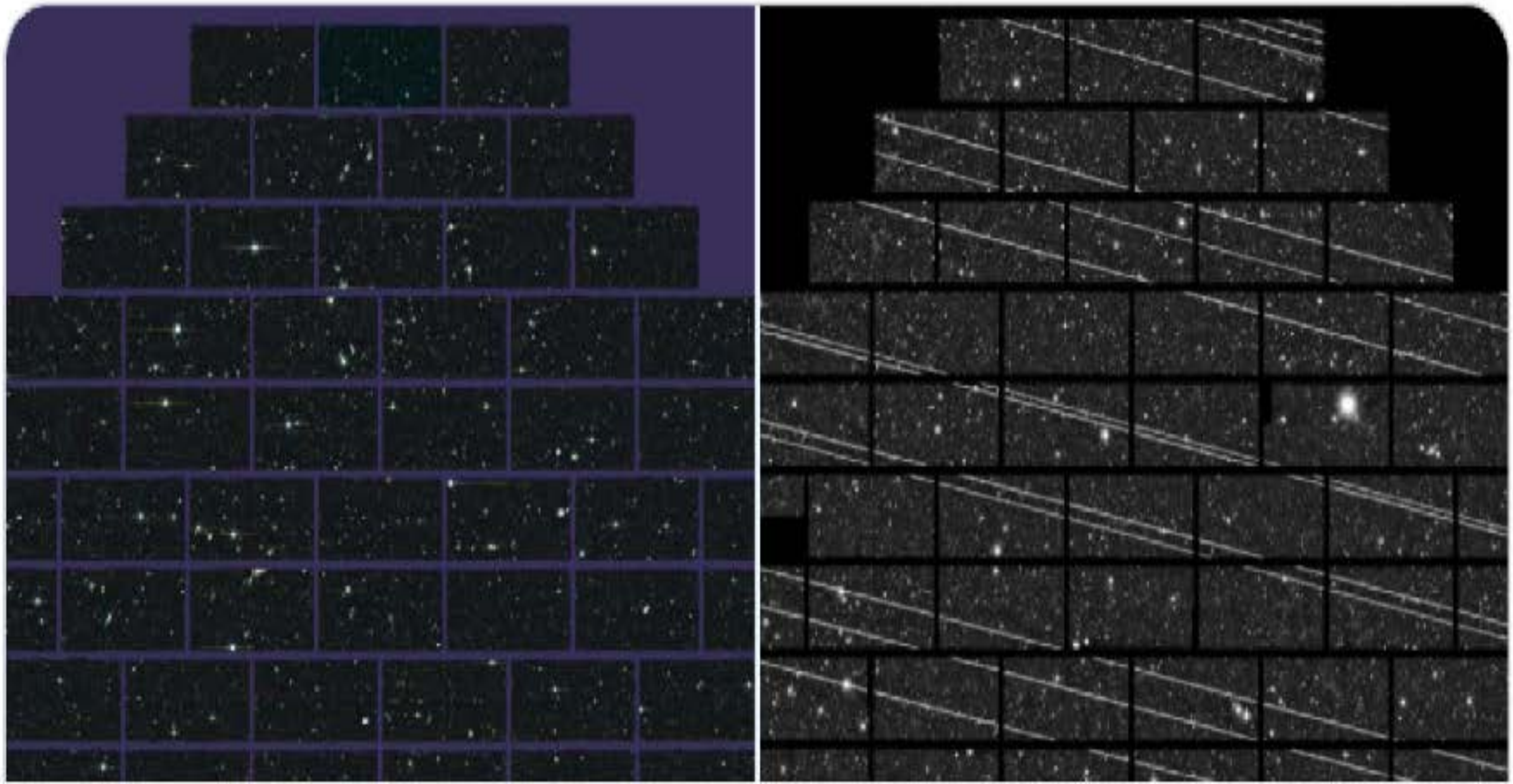

S190425z 18% of the sky localization

# Rubin and LEOsats

# Rubin Observatory LSST

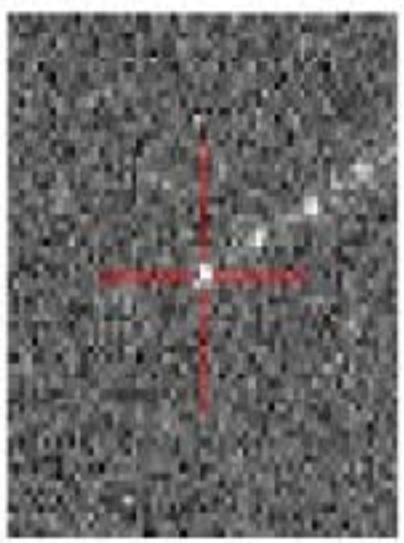
**Meredith Rawls**
@merrdiff

How it started: How it's going:



# Time domain Rubin LSST science

Iridium satellite number 35 lit up the predawn sky west of Boston at 5 a.m. EST on February 1, 1998, *Sky & Telescope*



***Satellite flares***

can be mitigated:

- orientation of satellite,
- directing flares away from observer
- knowing coordinates to associate them to alerts

if not mitigate there would be bogus alerts and images ruined by saturating flares

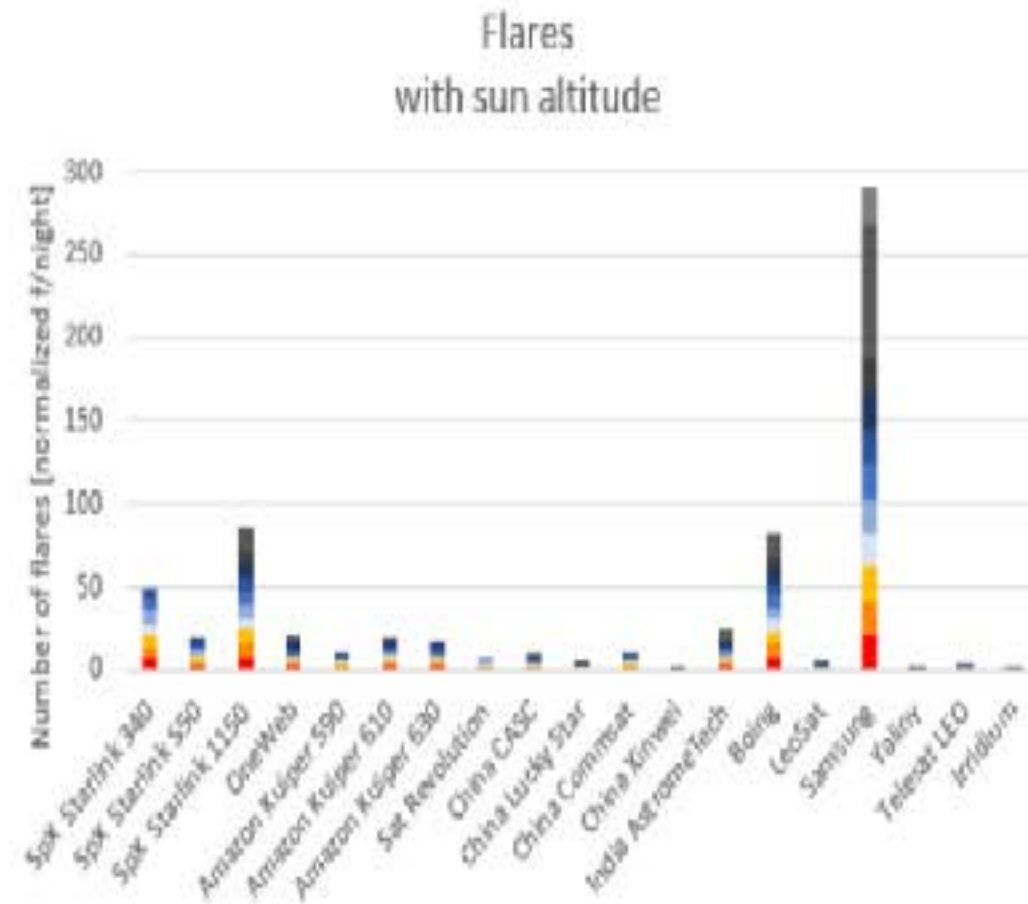


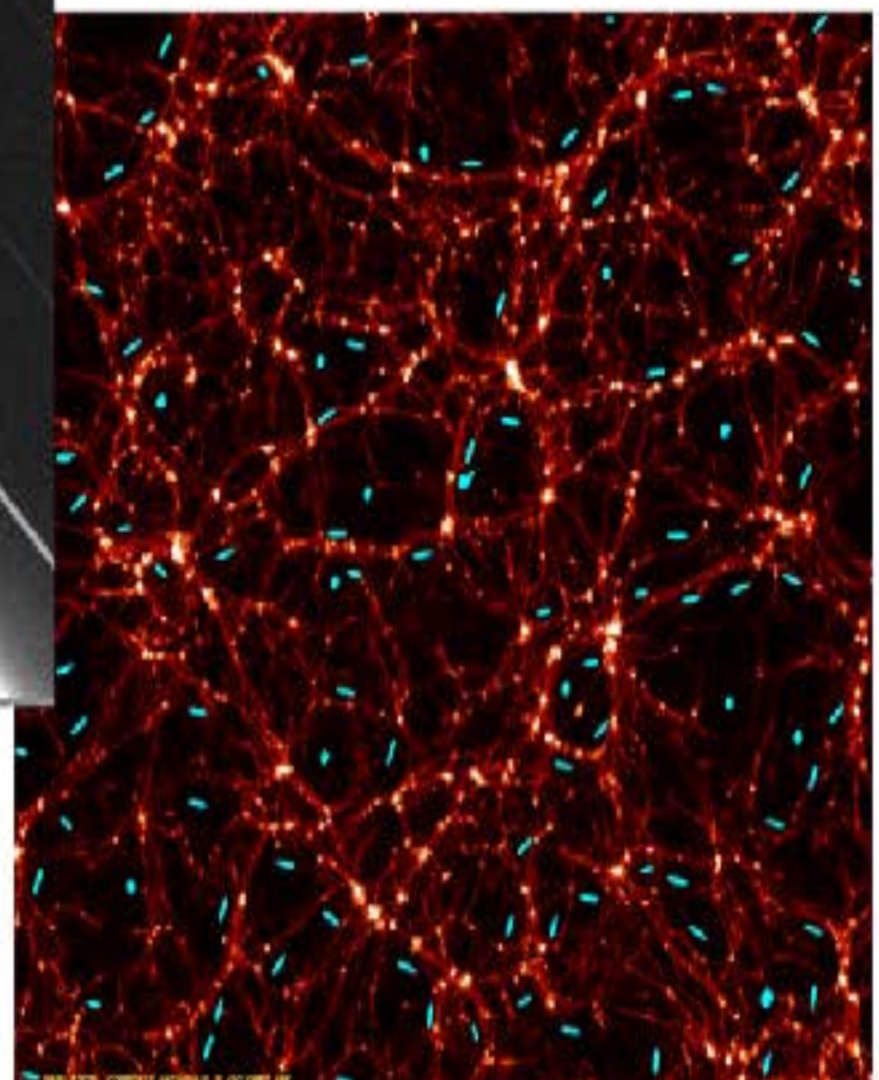

**Fig. 9.** Number of flares for each constellation, simply scaling them to one-third of the flares caused by the original Iridium satellites (which had three large antennas) and to the number of satellites. This is the number of observable flares per night, or the number of flares per week brighter than −5 mag for a mid-latitude site. The colour encodes the sun elevation below the horizon, from 0° (red), −18° (pale blue), and into the night (darker blue to greys).

Hainaut & Williams 2020

https://arxiv.org/abs/2003.01992

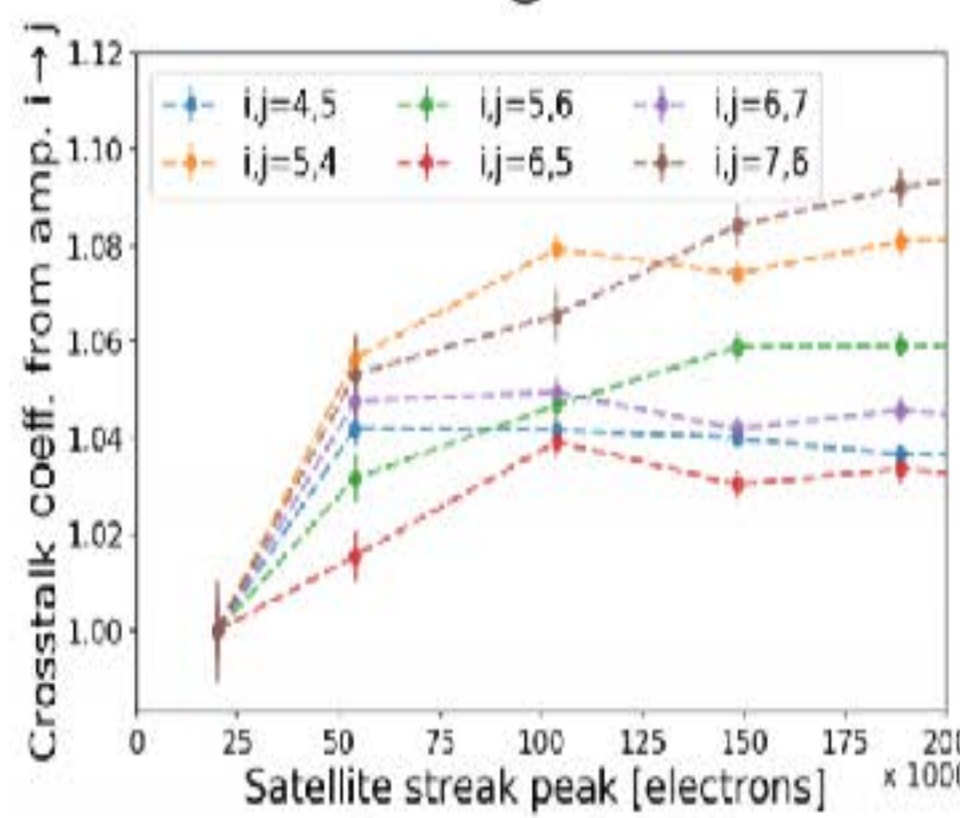
# Static Sky: correlated noise and cross talk

Cosmology probes are systematic dominated



(image credit: Canada-France Hawaii Telescope)

mitigation: simulation of the non-linear crosstalk to measure the effect on precision cosmology and effectiveness of removal algorithms




Tyson et al. 2020

https://arxiv.org/abs/2006.12417

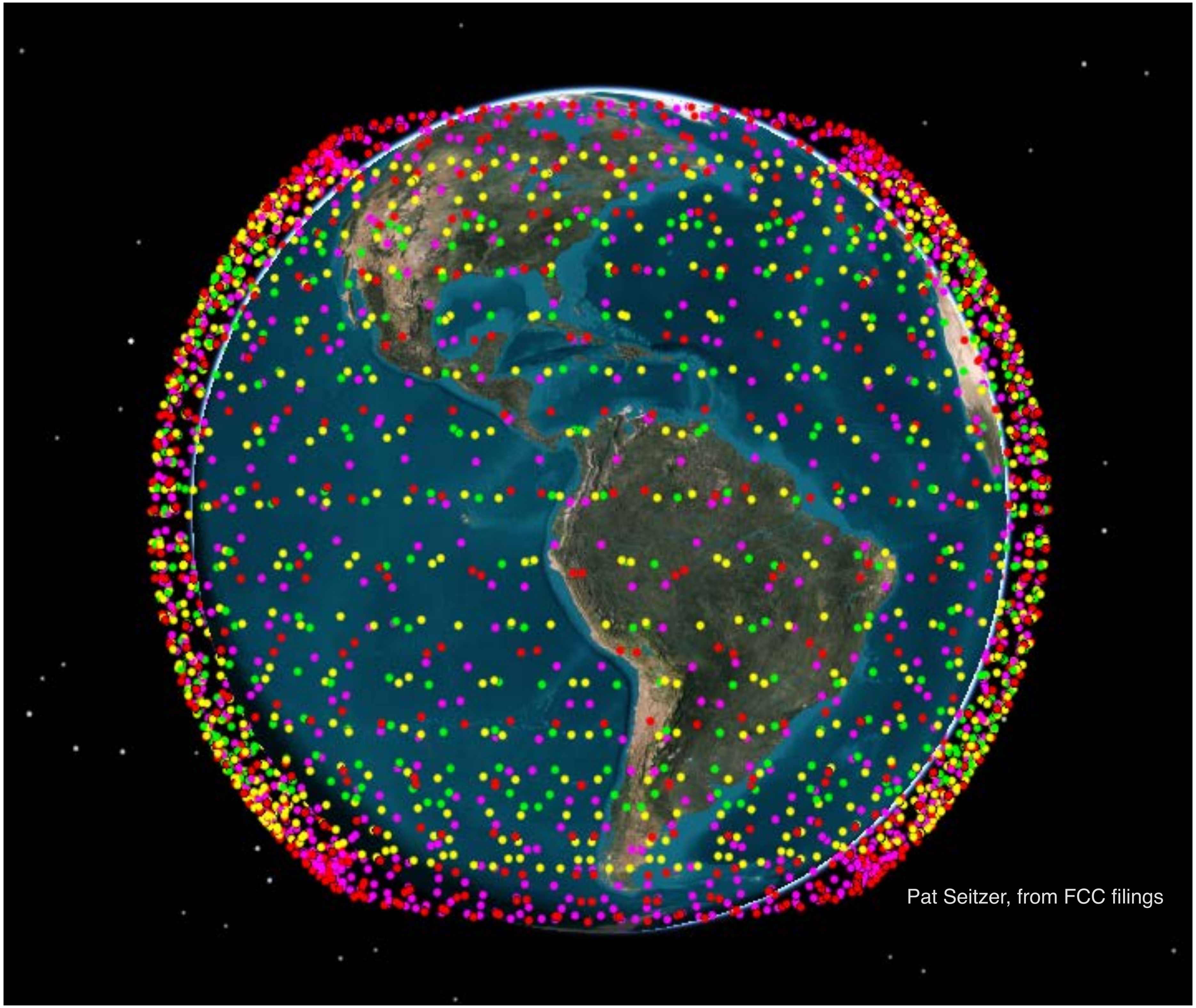
Rubin Observatory

*Science Collaborations*

federica bianco fbianco@udel.edu @fedhere

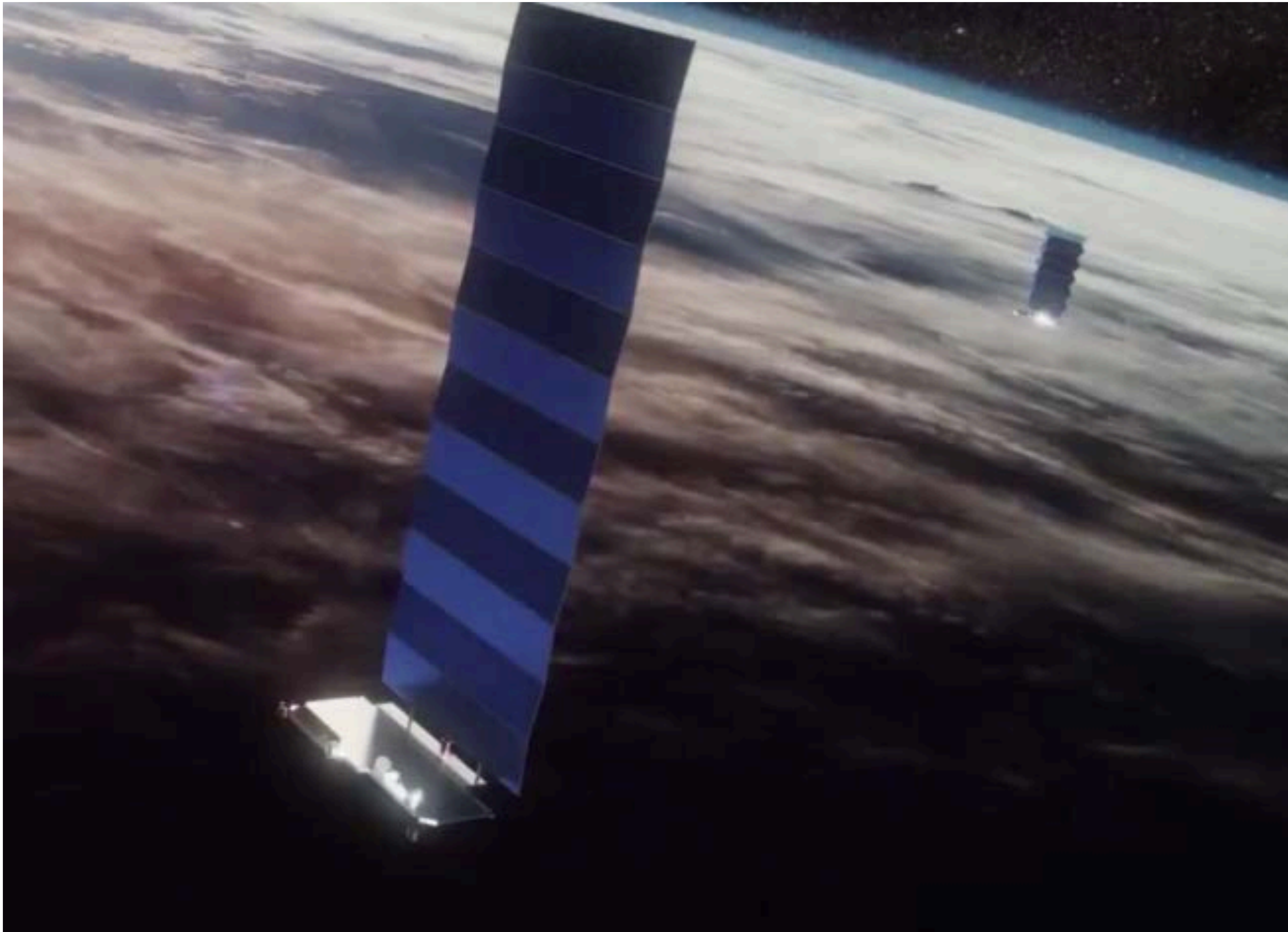
LSST Legacy Survey of Space and Time

# Starlink and Kuiper constellations:



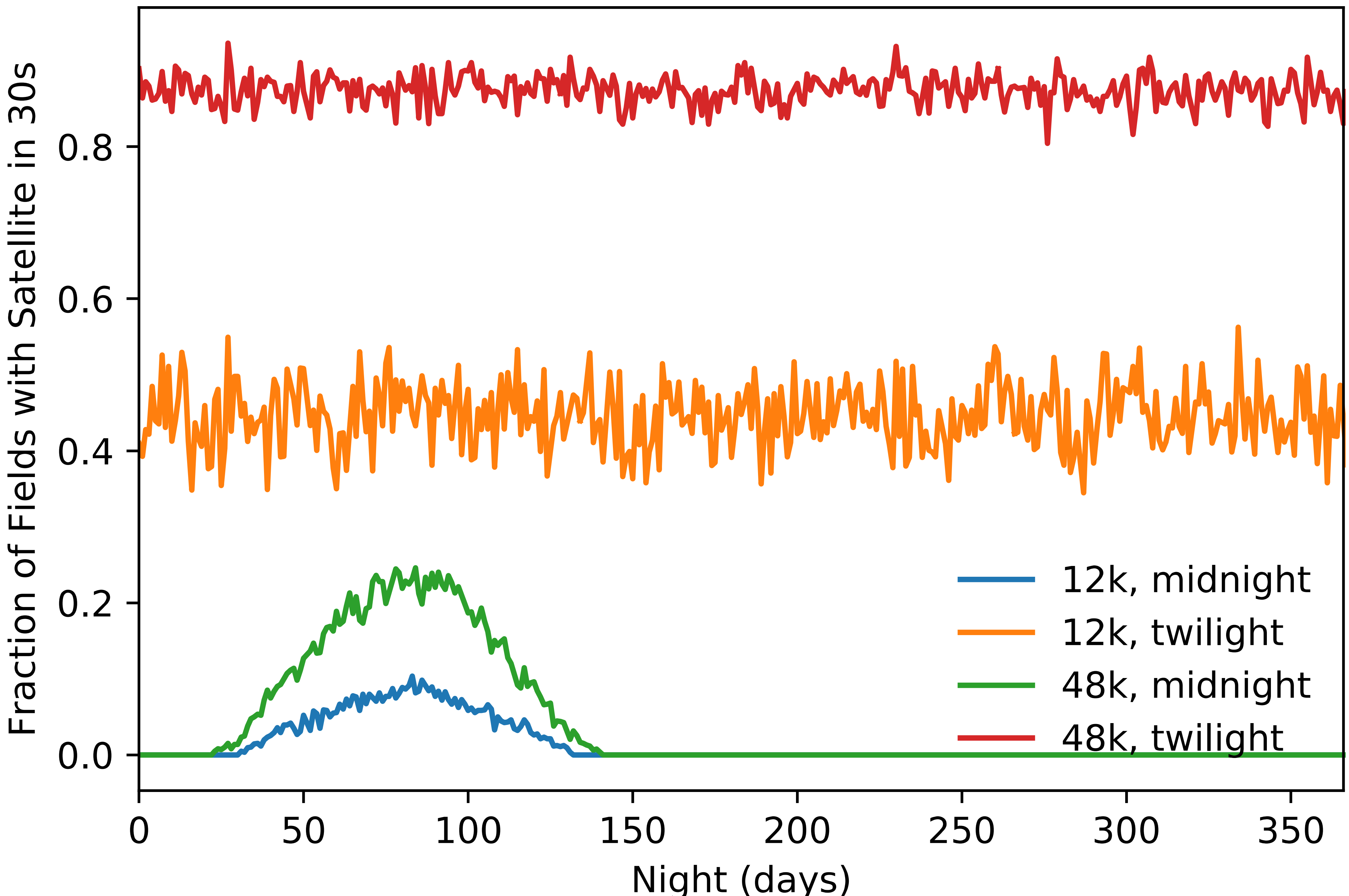

Purpose: direct broad-band internet delivery 24/7

# Starlink satellites



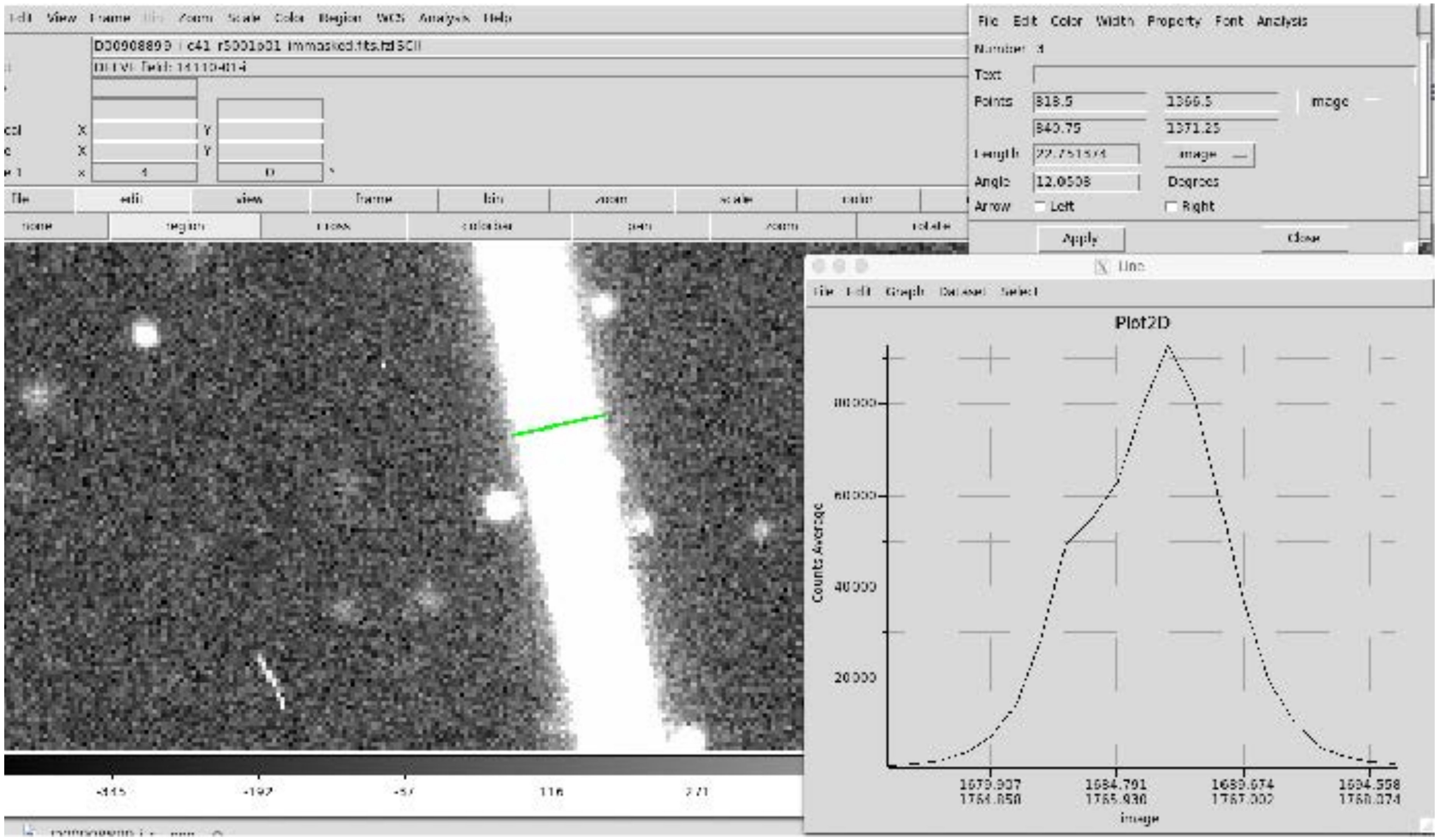
Starlink.com

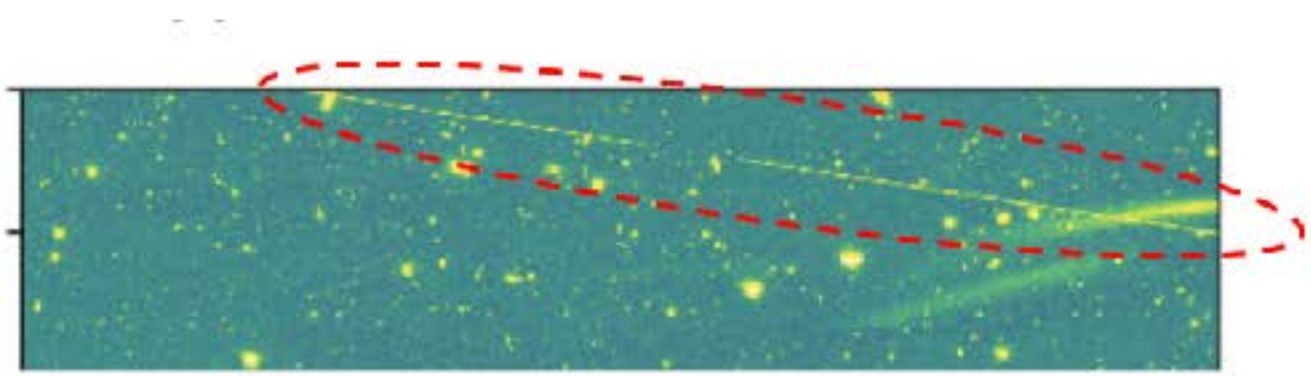
Simulations of 12K, 48K LEO Sats in baseline LSST cadence: about 1% of all LSST pixels affected by satellite trails!



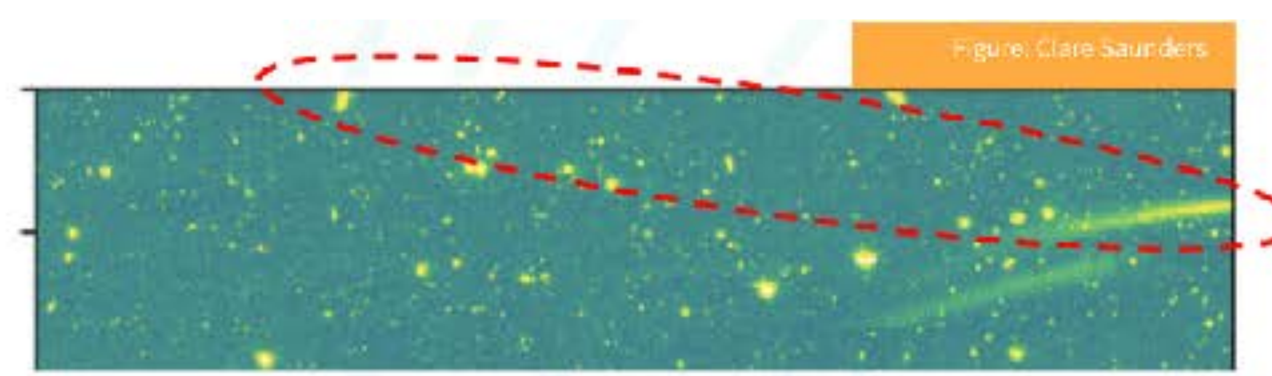

Peter Yoachim

# Starlink detection trail:



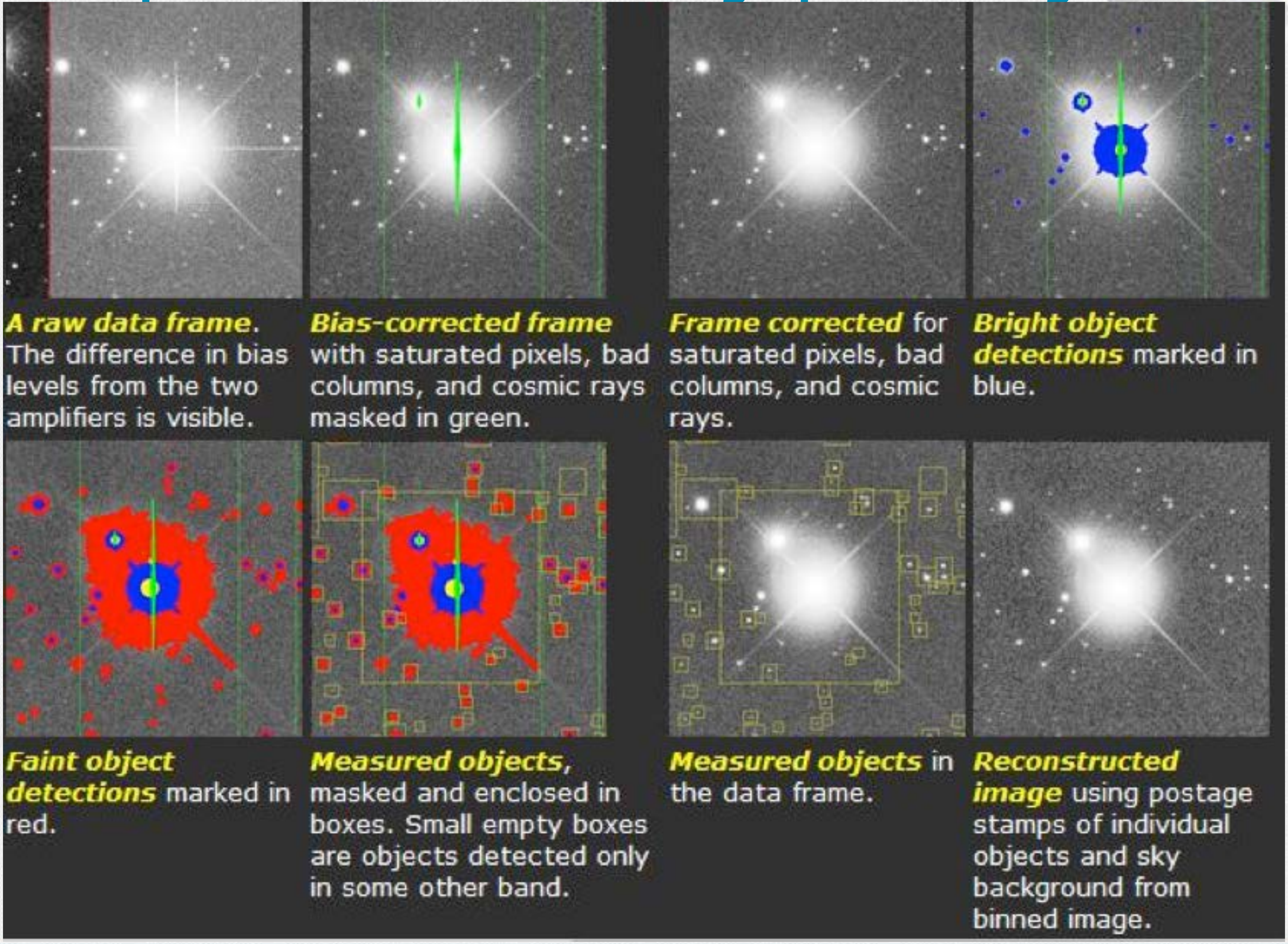



Coadded image without masking




Coadded image with trails masked

# Basic steps in astronomical image processing



***A raw data frame***. The difference in bias levels from the two amplifiers is visible.

***Bias-corrected frame*** with saturated pixels, bad columns, and cosmic rays masked in green.

***Frame corrected*** for saturated pixels, bad columns, and cosmic rays.

***Bright object detections*** marked in blue.

***Faint object detections*** marked in red.

***Measured objects***, masked and enclosed in boxes. Small empty boxes are objects detected only in some other band.

***Measured objects*** in the data frame.

***Reconstructed image*** using postage stamps of individual objects and sky background from binned image.

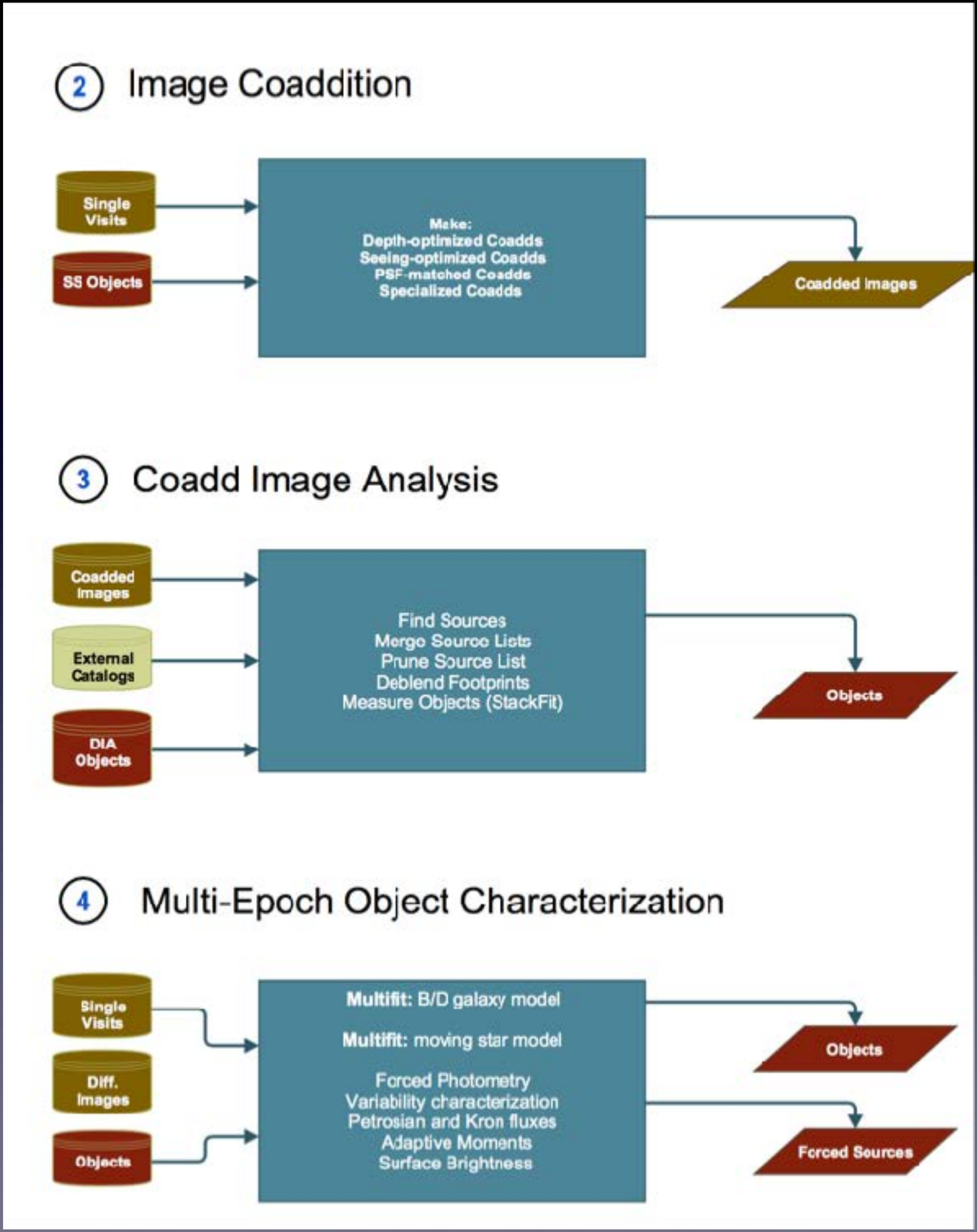



**Image Coaddition**

- more complex than might be expected: need to account for different PSF and background

**Detect and deblend sources**

- deblending is a complex problem and it gets worse as data are deeper as there are more objects per unit angular area

**Multifit**

- a modeling approach based on Bayesian statistics (hard in practice)

## How bright is this star? How do we estimate that from an image?

- let us assume that the stellar profile, or point spread function (PSF) is known
- we will also assume that we know the centroid (position) of our star; both PSF and centroid are determined in “pre-processing”
- then we fit the PSF to the observed image (pixel counts) of our star, with the PSF normalization (overall brightness) as a free model parameter
- in its simplest form, the fitting is done by chi2 minimization
- we can also fit for an intrinsic profile width; that is, we can assume that the observed profile is **wider** than the PSF; this allows us to recognize (barely) resolved galaxies

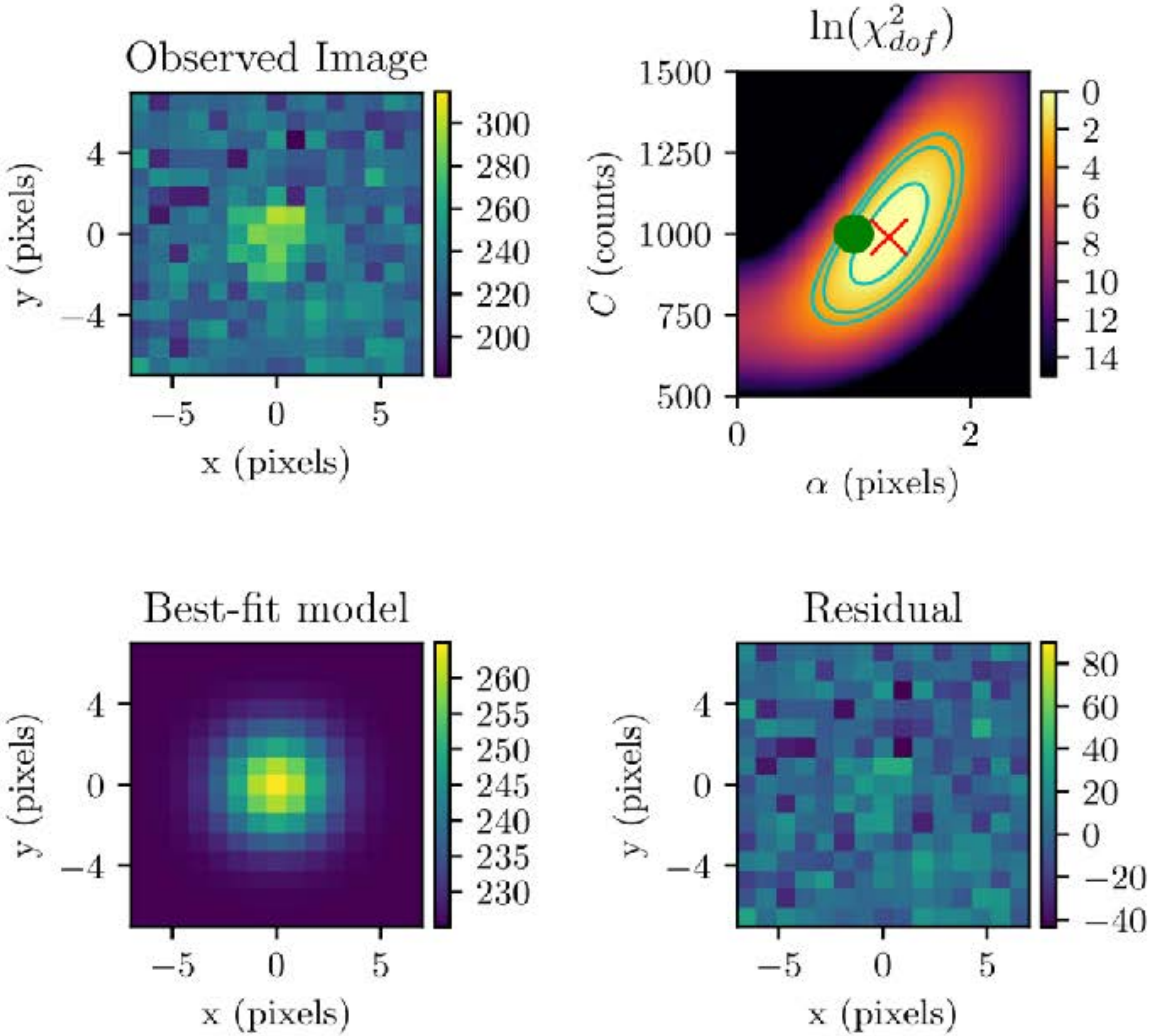



**Figure 2.** Illustration of fitting an image generated with noise per pixel of $\sigma_0 = 15$ counts, PSF with $\alpha_{psf} = 1.5$ pix, the intrinsic profile width $\alpha_g = 1.0$ pix, and a source with $C = 1000$ counts. With an effective number of pixels of ~40, the S/N is ~10. The top left panel shows a data image, and the top right panel shows the $\chi^2$ image as a function of two free parameters, $\alpha_g$ and $C$. The standard $1\sigma$, $2\sigma$, and $3\sigma$ contours are shown by the lines; the maximum-likelihood best-fit values of the free parameters by the ×symbol; and the input values of fitted parameters by the dot. The best-fit model is shown in the bottom left panel, and the data-model residuals are shown in the bottom right panel.

The data likelihood given model for the PSF profile:

$$p(D|S, C_{\rm psf}, I) = (2\pi)^{-N/2} \prod_{i=1}^{N} \sigma_i^{-1} \exp\left( - \frac{(f_i - C_{\rm psf}\,\phi_i)^2}{2\sigma_i^2} \right)$$

The maximum likelihood value of $C_{\rm psf}$, denoted as $\hat{C}_{\rm psf}$, can be found by maximizing the log-likelihood $\ln L$,

$$\ln L(C_{\rm psf}) \equiv \ln(p(D|S, C_{\rm psf}, I)) = {\rm const.} - \frac{1}{2} \sum_{i=1}^{N} \frac{(f_i - C_{\rm psf}\,\phi_i)^2}{\sigma_i^2}, \quad (6)$$

that is, using the condition $d(\ln L)/dC_{\rm psf} = 0$. The associated uncertainty of $\hat{C}_{\rm psf}$ could be estimated from $\sigma_C = (d^2(\ln L)/dC_{\rm psf}^2)^{-1/2}$, evaluated at $C_{\rm psf} = \hat{C}_{\rm psf}$.

The solution for the best-fit normalization, also known as the PSF photometry:

Assuming homoscedastic noise (i.e., $\sigma_i \sim \sigma_0 =$ constant, as is the case when the noise is dominated by the background contribution) yields the maximum likelihood estimate

$$\hat{C}_{\rm psf} = \frac{\sum_{i=1}^{N} f_i \, \phi_i}{\sum_{i=1}^{N} \phi_i^2} \tag{7}$$

and its uncertainty (which implies a Gaussian PDF)

$$\sigma_C = \sigma_0 \left( \sum_{i=1}^{N} \phi_i^2 \right)^{-1/2} = \sigma_0 \, (n_{\rm eff}^{\rm psf})^{1/2}. \tag{8}$$

If the PSF profile is estimated correctly, the PSF photometry is optimal for unresolved sources (stars)

## How bright is this star?   But: is it a star at all?

- we can always assume that the observed profile is well-described by PSF as compute PSF flux (eq. 7)
- since there is no guarantee that the source is unresolved, we also fit for an intrinsic profile width;   when we use this “widened” profile instead of PSF profile in eq. 7, we compute the so-called “model” flux
- if the model flux is statistically larger than the PSF flux, we have evidence that the source is “resolved” (i.e wider than the PSF profile)
- note that the PSF flux can be thought of as the model flux conditioned on the intrinsic profile width being zero

For more details: http://faculty.washington.edu/ivezic/Teaching/Astr511/LSST_SNRdoc.pdf
http://faculty.washington.edu/ivezic/Publications/Slater_2020_AJ_159_65.pdf

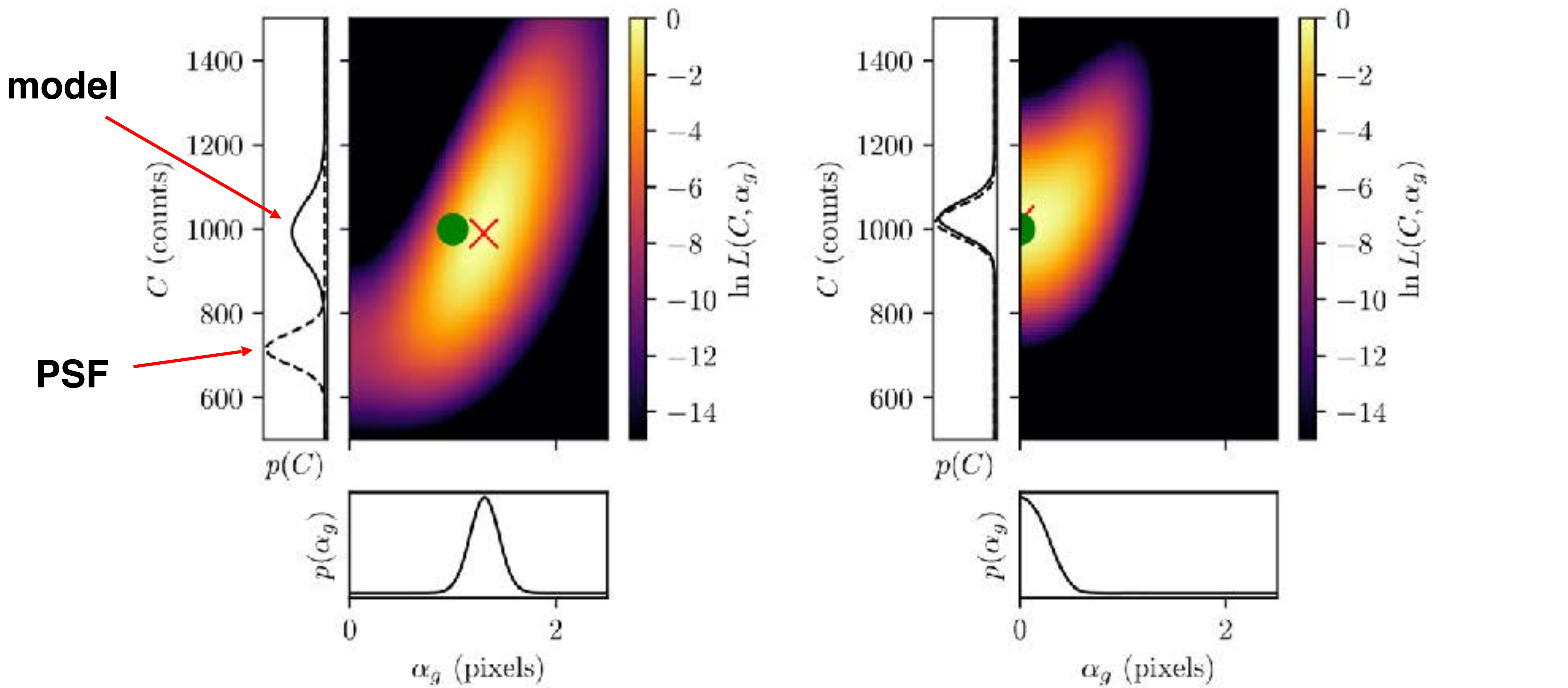


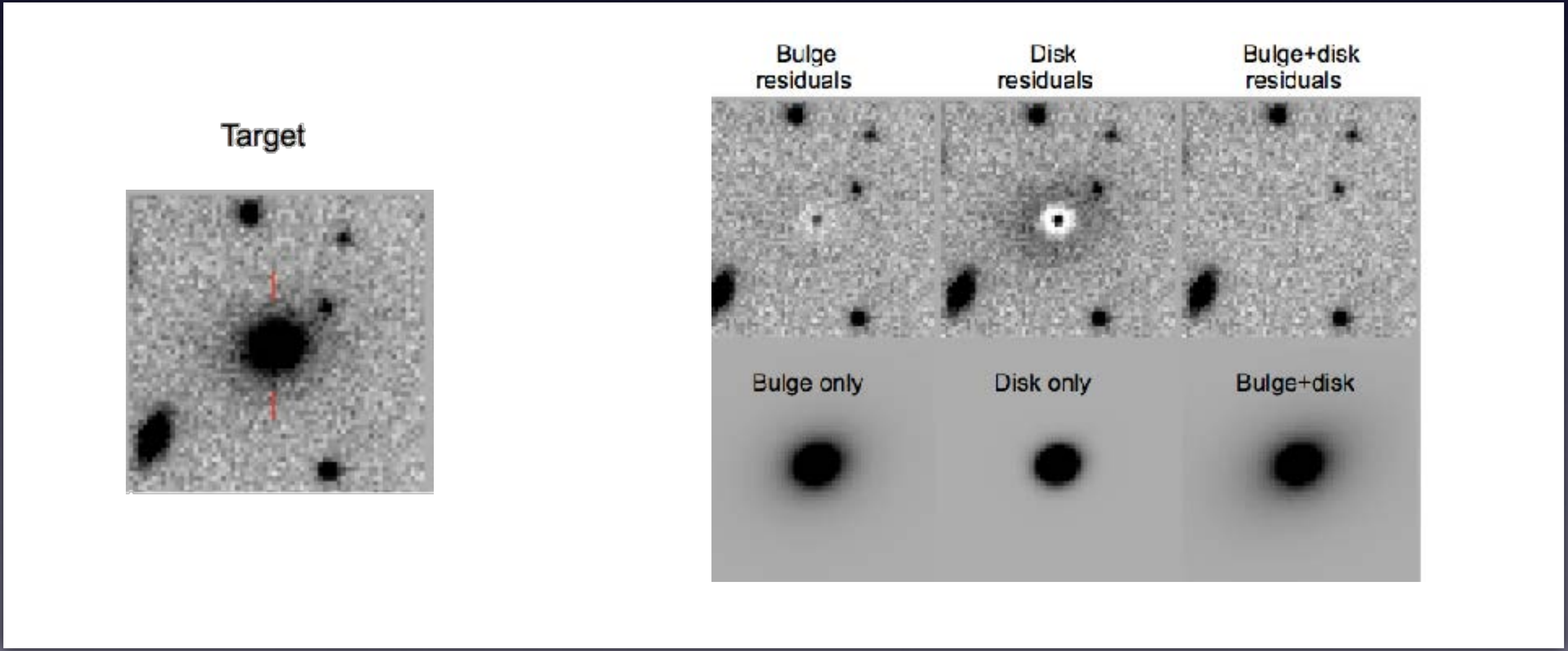

**Figure 3.** Left panel shows the two-dimensional log-likelihood surface ($\ln(L)=-\chi^2/2$) for fitting the intrinsic profile width ($\alpha_g$) and normalization ($C$, see Equation (33)) of an image generated with noise per pixel of $\sigma_0 = 15$ counts, PSF width $\alpha_{psf} = 1.5$ pixels, and $\alpha_g = 1.0$ pixels (same image as shown in the top left panel in Figure 2). The circle marks the true values, and the × symbol marks the maximum likelihood point. Marginal probability distributions for each parameter are shown to the left and below the panel with solid lines. The dashed line in the panel to the left is the conditional distribution of the normalization $C$ given $\alpha_g = 0$. (Note that its peak corresponds to the maximum likelihood value of PSF counts, $C_{psf}$.) The right panel is analogous, except for a profile with $\alpha_g = 0$ (a noisy realization of the PSF profile). Note that the marginal distributions for $\alpha_g$ deviate from a Gaussian shape, especially in the right panel.

**Left: a resolved source, the model flux is larger than the PSF flux**

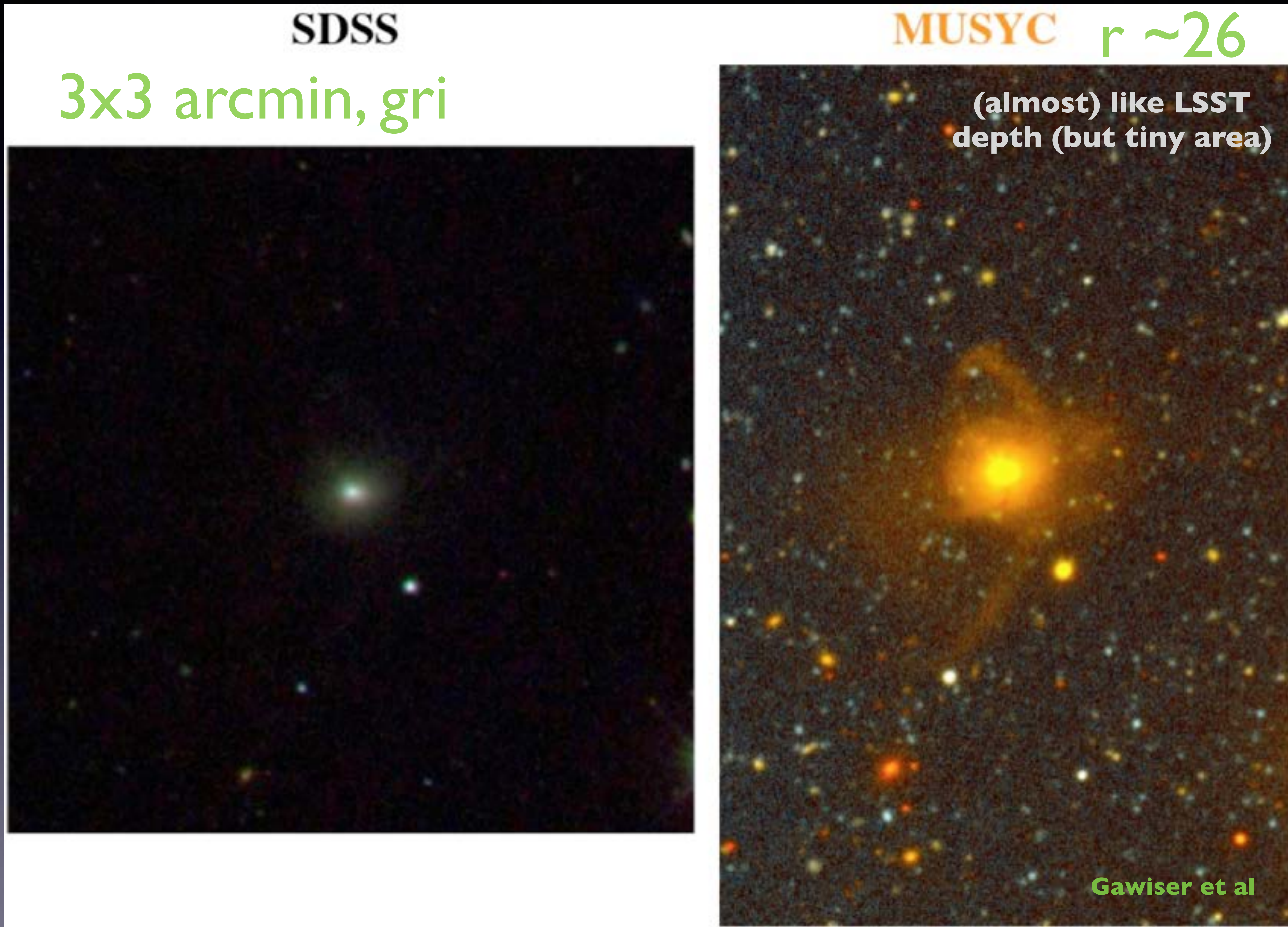
**Right: unresolved source (star, or PSF), the model flux is statistically the same as the PSF flux**

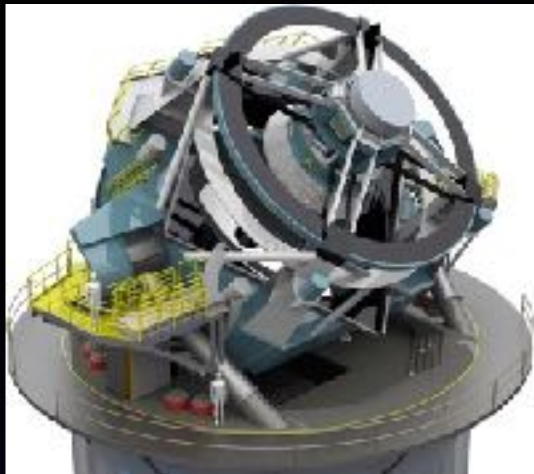
# How bright is this galaxy (resolved) source?

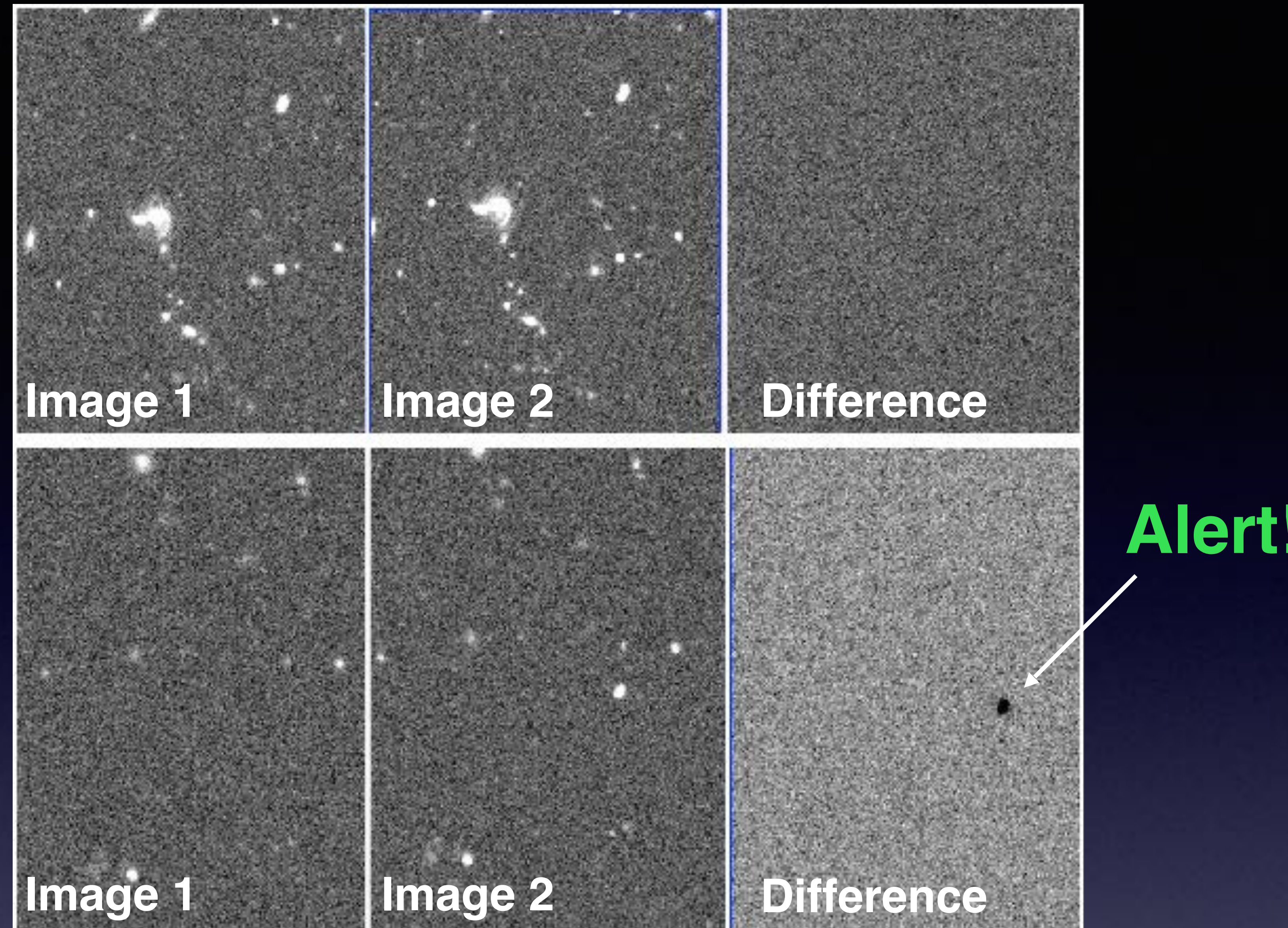
- this is a much harder question since we do not know the galaxy profile a priori (many morphological types of galaxies, inclination effects, distance effects, mergers, galaxy evolution)
- a short answer: need much more complicated models than just the PSF profile (below: “bulge+disk” model)



# Faint surface brightness limit reveals more detail:







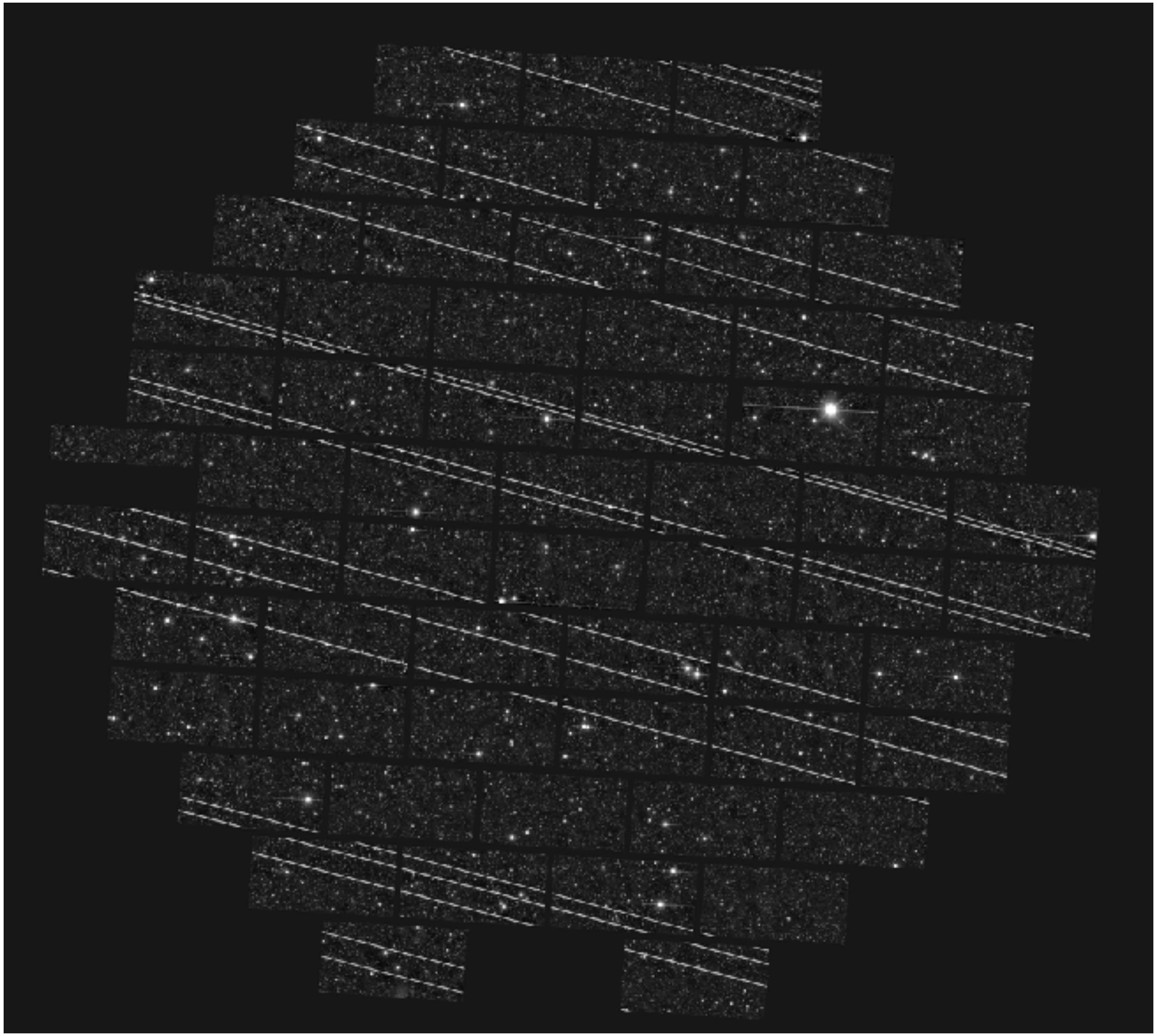

**Additional “followup” data obtained to:**

- confirm and classify
- provide better temporal resolution
- use different filters/wavelengths
- obtain spectra (distance!)
- get other measurements (e.g. polarimetry)

## ~10 billion alerts

**Alerts can trigger “Followup” observations:**

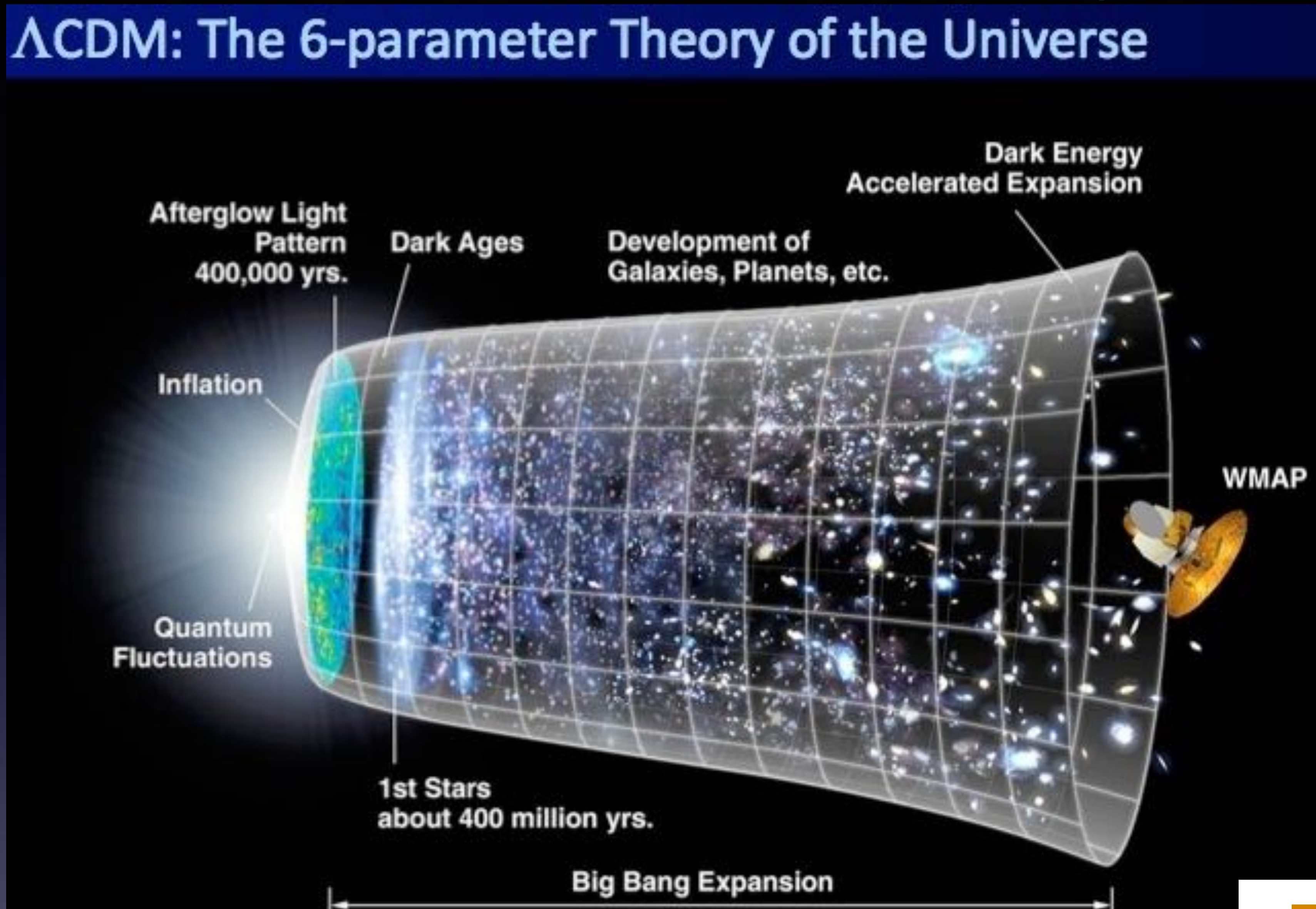
We are expecting tens of thousands of new LEO (~550 km) satellites over the next few years (now about a thousand)

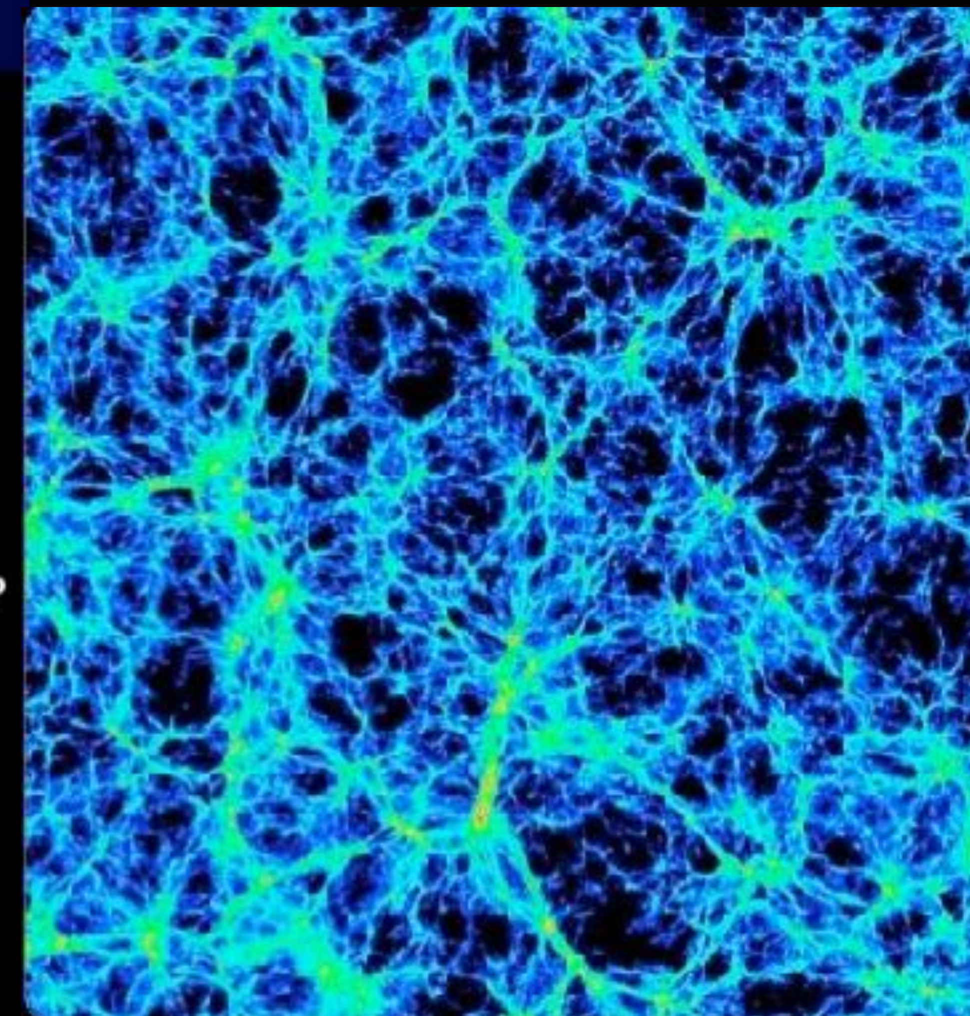


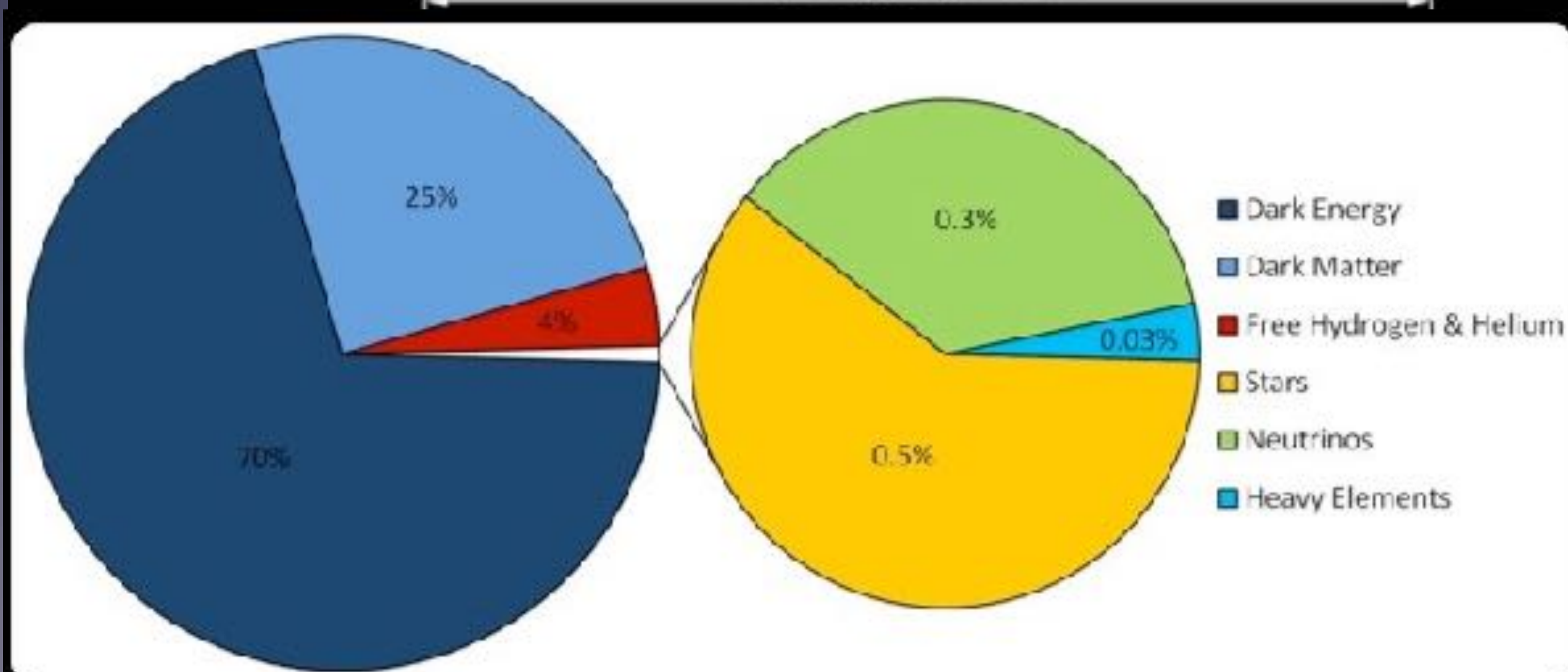
Alex Drlica-Wagner
CTIO, AURA

https://noirlab.edu/public/images/iotw1946a/

# New Cosmological Puzzles





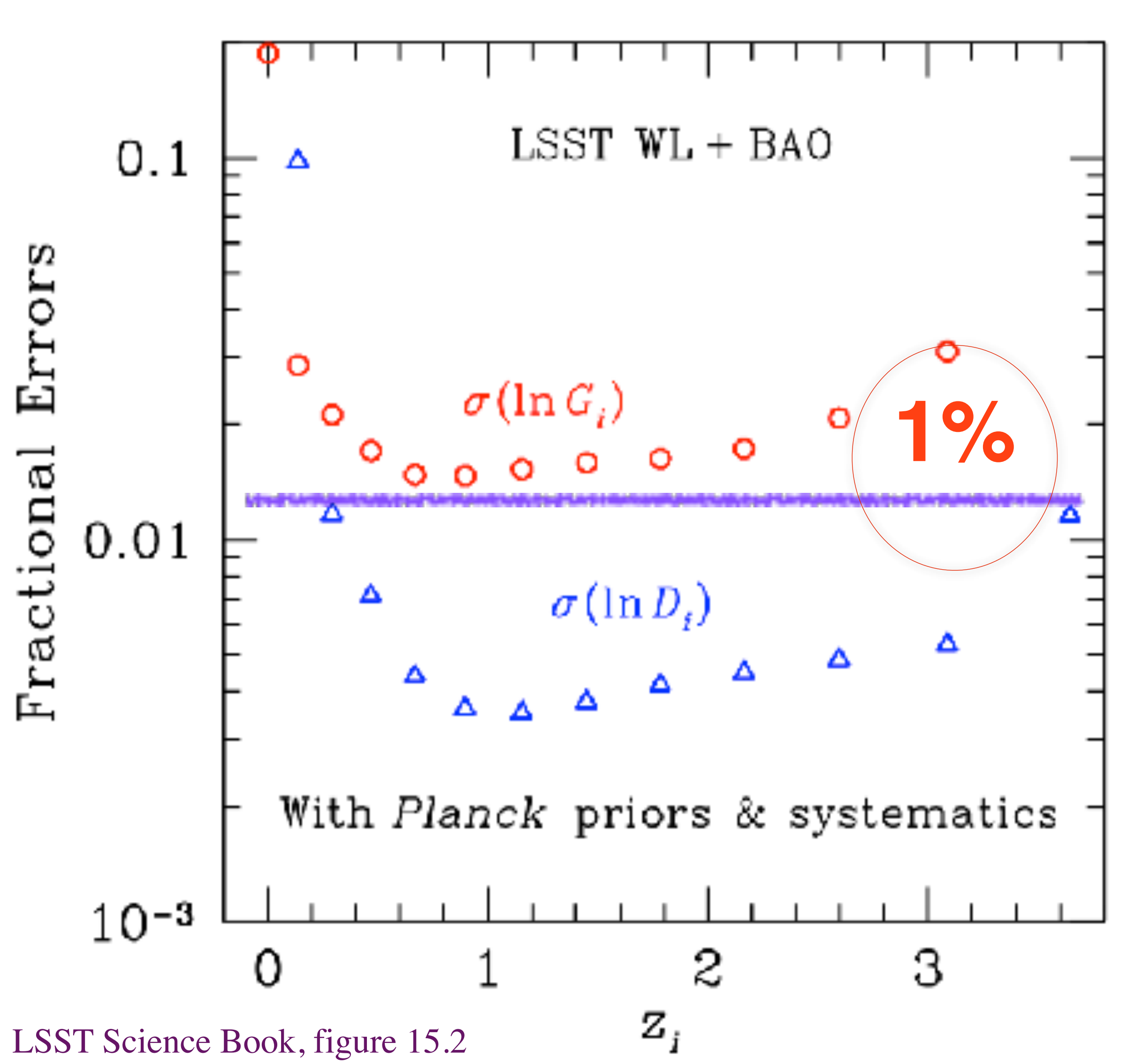

The modern cosmological models can explain all observations, but need to **postulate** dark matter and dark energy (though gravity model could be wrong, too)

# 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

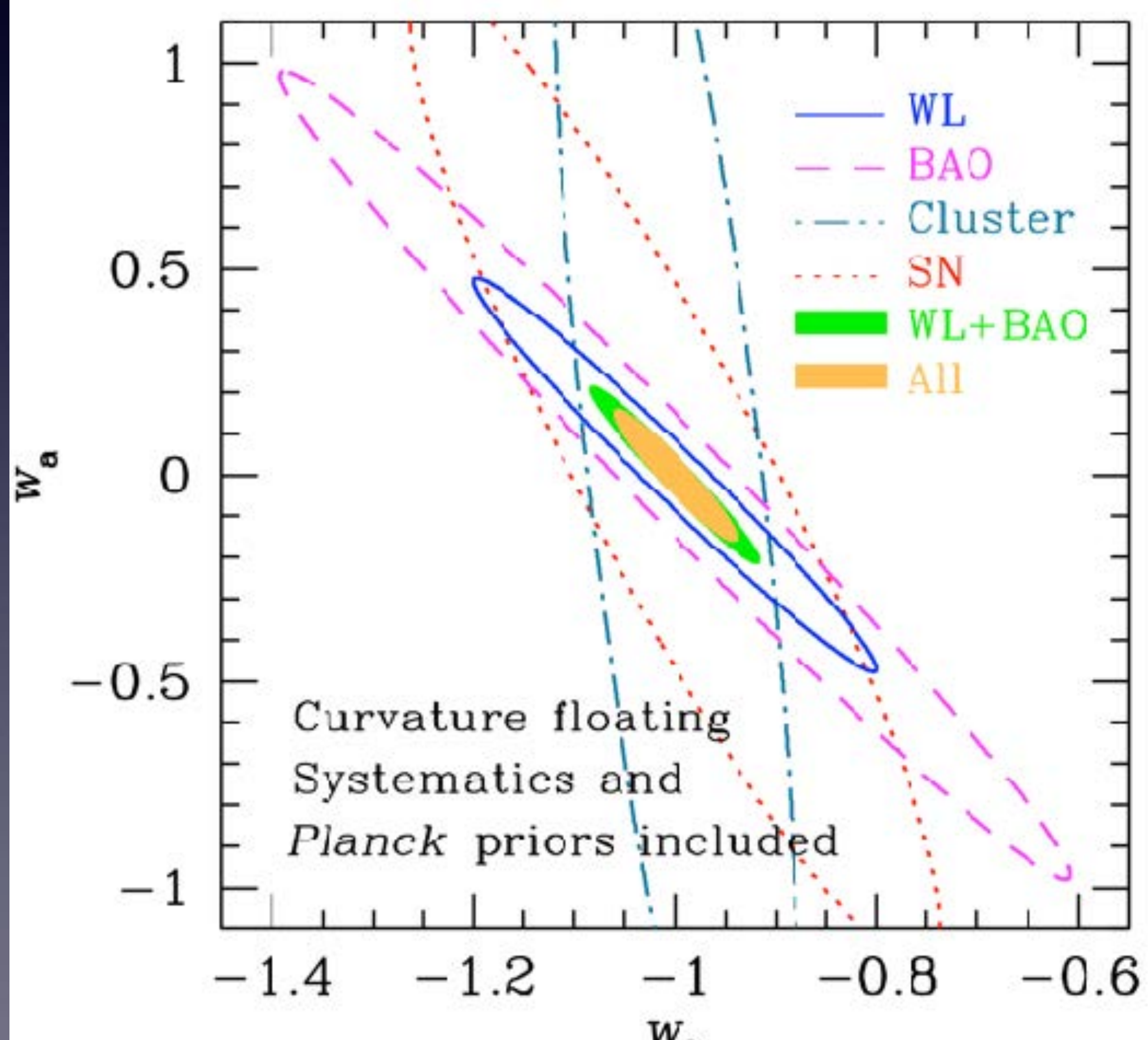
**Except for CMB, measuring H(z) and growth of structure G(z)**
**$H(z) \sim d[\ln(a)]/dt$, $G(z) = a^{-1}\delta\rho_m/\rho_m$, with $a(z) = (1+z)^{-1}$**

# 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.**