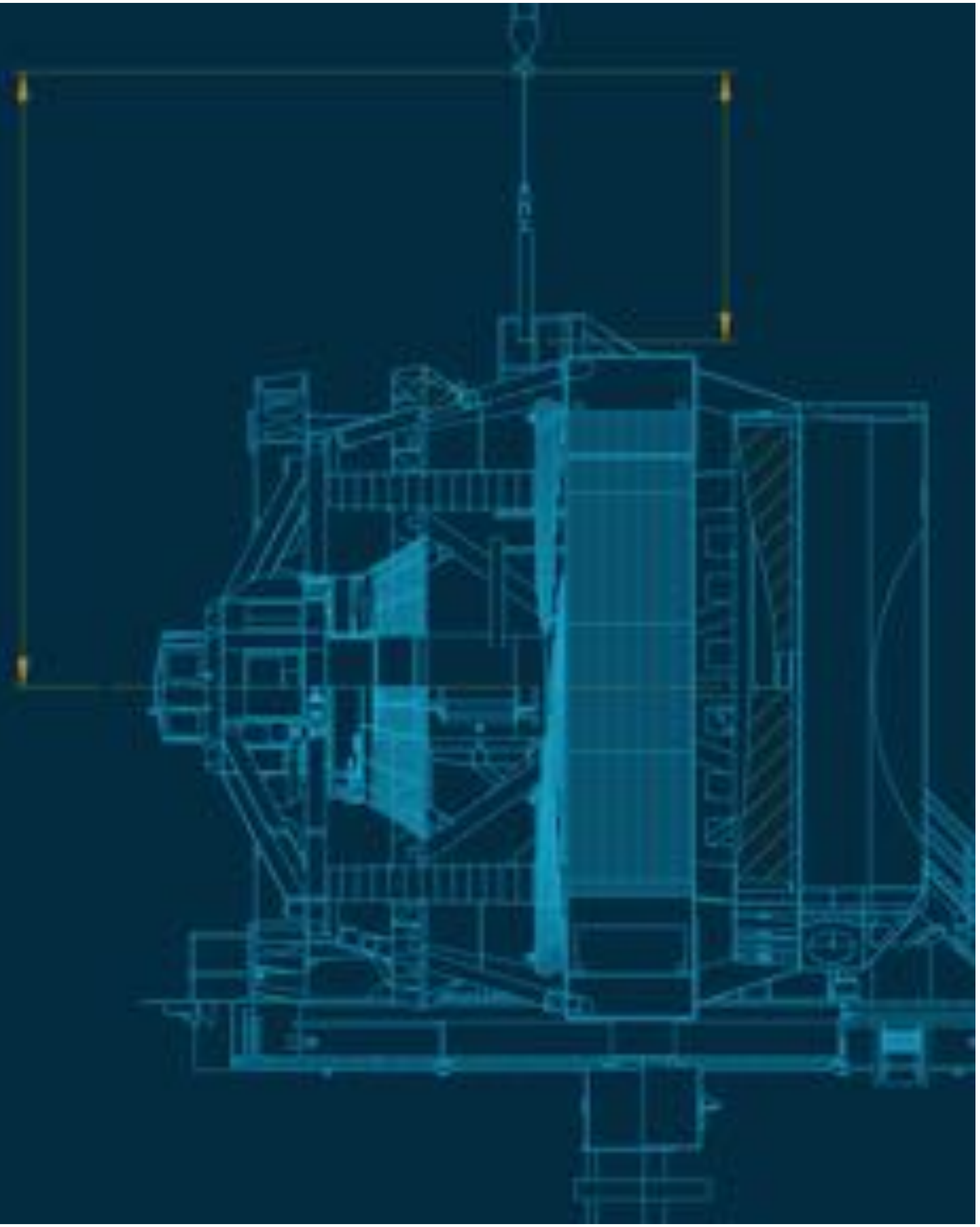
Rubin Observatory

Sky Background Estimation and Source Detection

Yusra AlSayyad

LSSTC-DSFP Session 11 August 2020

Source Detection



Problem: How do we find all the stars/galaxies in this image?

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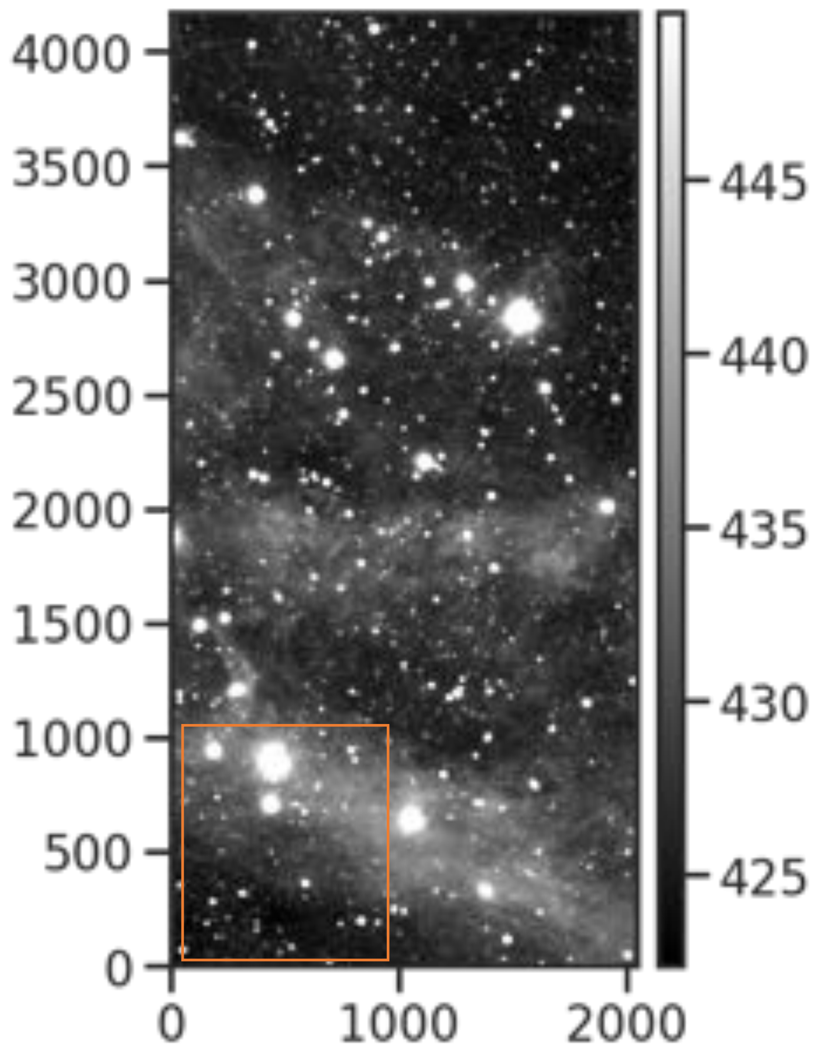


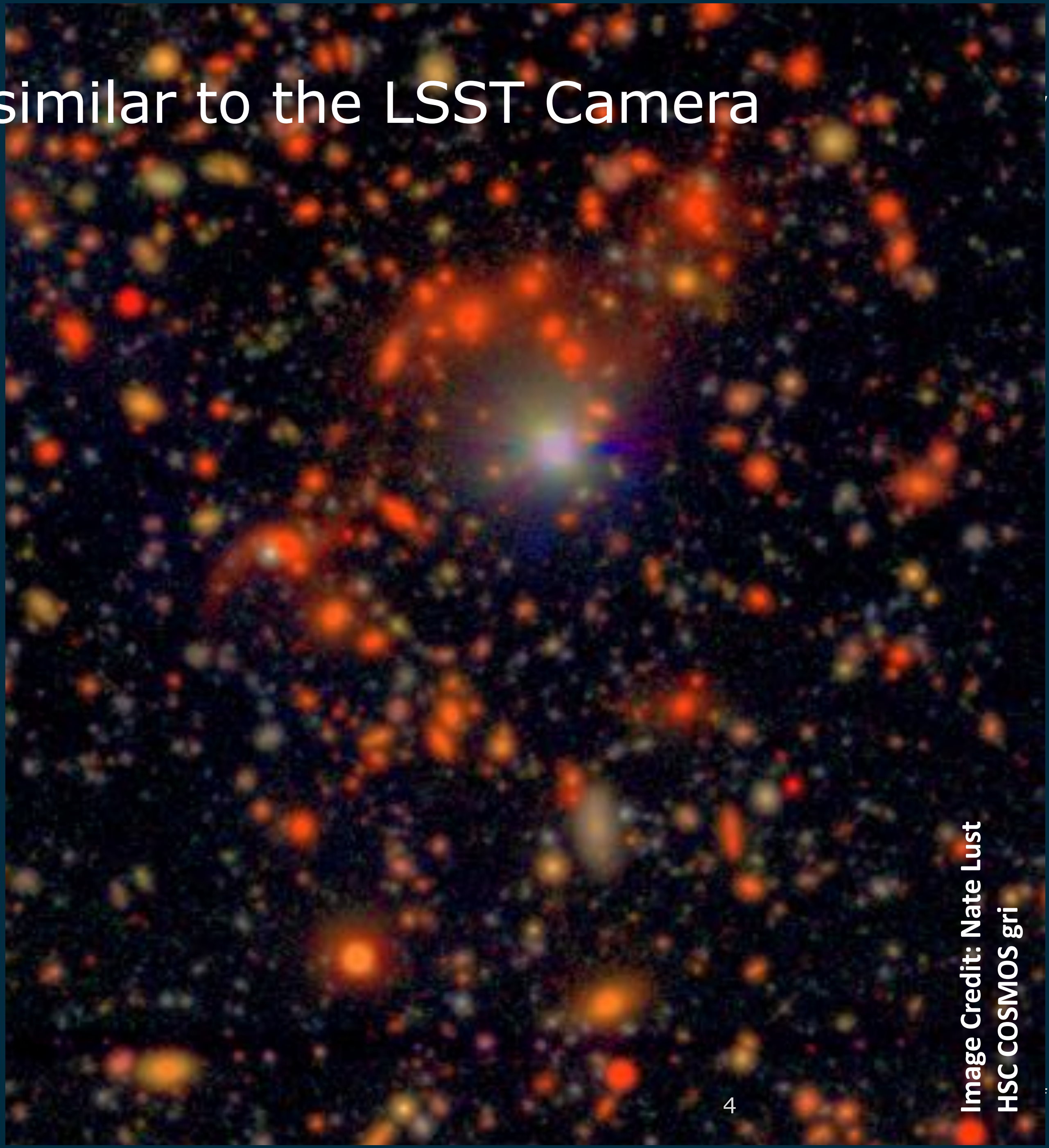
In this image:

- Sources (stars, galaxies, asteroids etc…)
- Noise (see Colin's previous talk)
- [Sky] Background (more on this later)

Hyper Suprime Cam
VISIT = 34464
CCD = 81
Smoothed to make background structure visible

Hyper Suprime-Cam (HSC) is very similar to the LSST Camera

Survey Comparison	LSST	HSC (Subaru Strategic Program)
Effective Aperture of primary mirror	6.5m	8.2m
Filters	ugrizy	grizy + narrow
Exposure time per visit	~30s	~240s
Field of View	10 deg^2 3.5 deg diam	1.8 deg^2 1.5 deg diam
Num CCDs	189 (4k x 4k)	103 (4k x 2k)



Problem: How do we find all the stars/galaxies in this image?

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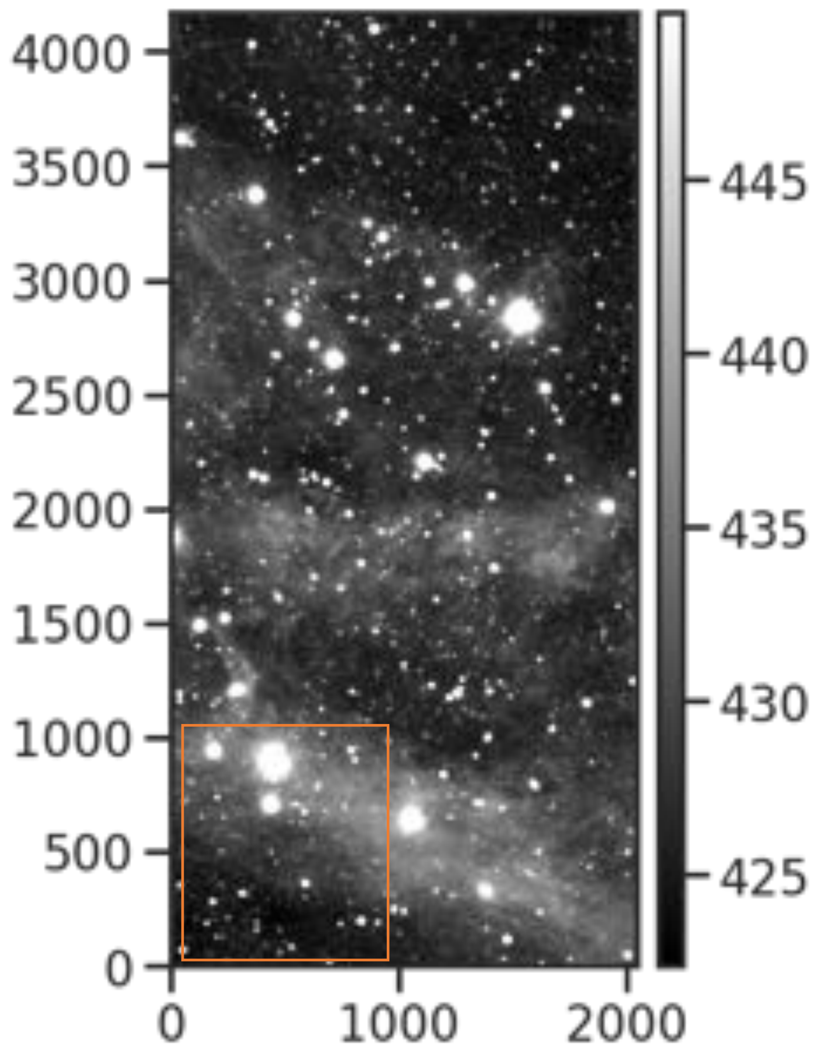


ɔids etc…)
k)
is later)

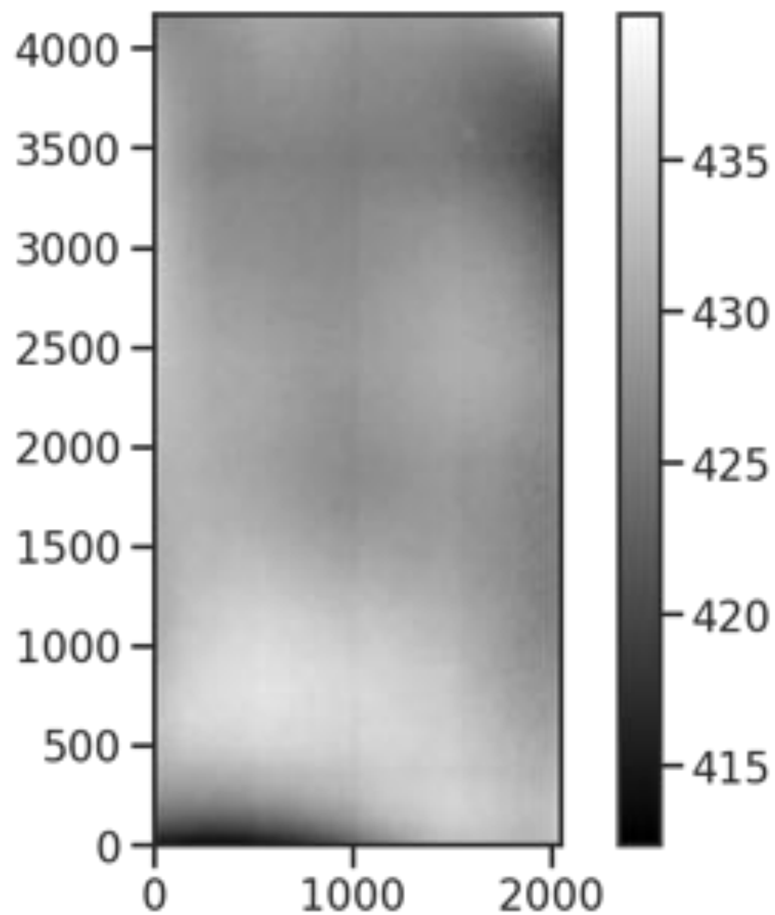
Can we just threshold?

Not yet

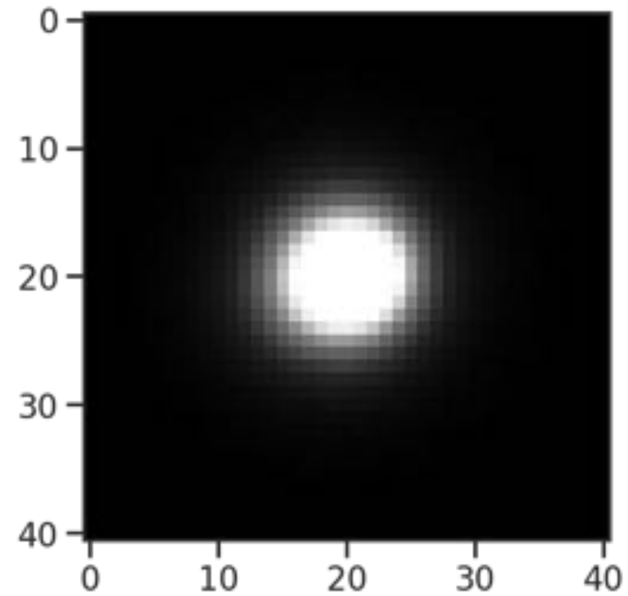
Hyper Suprime Cam
VISIT = 34464
CCD = 81
Smoothed to make background structure visible

What's available:

- A background model



- A PSF model



What's available:

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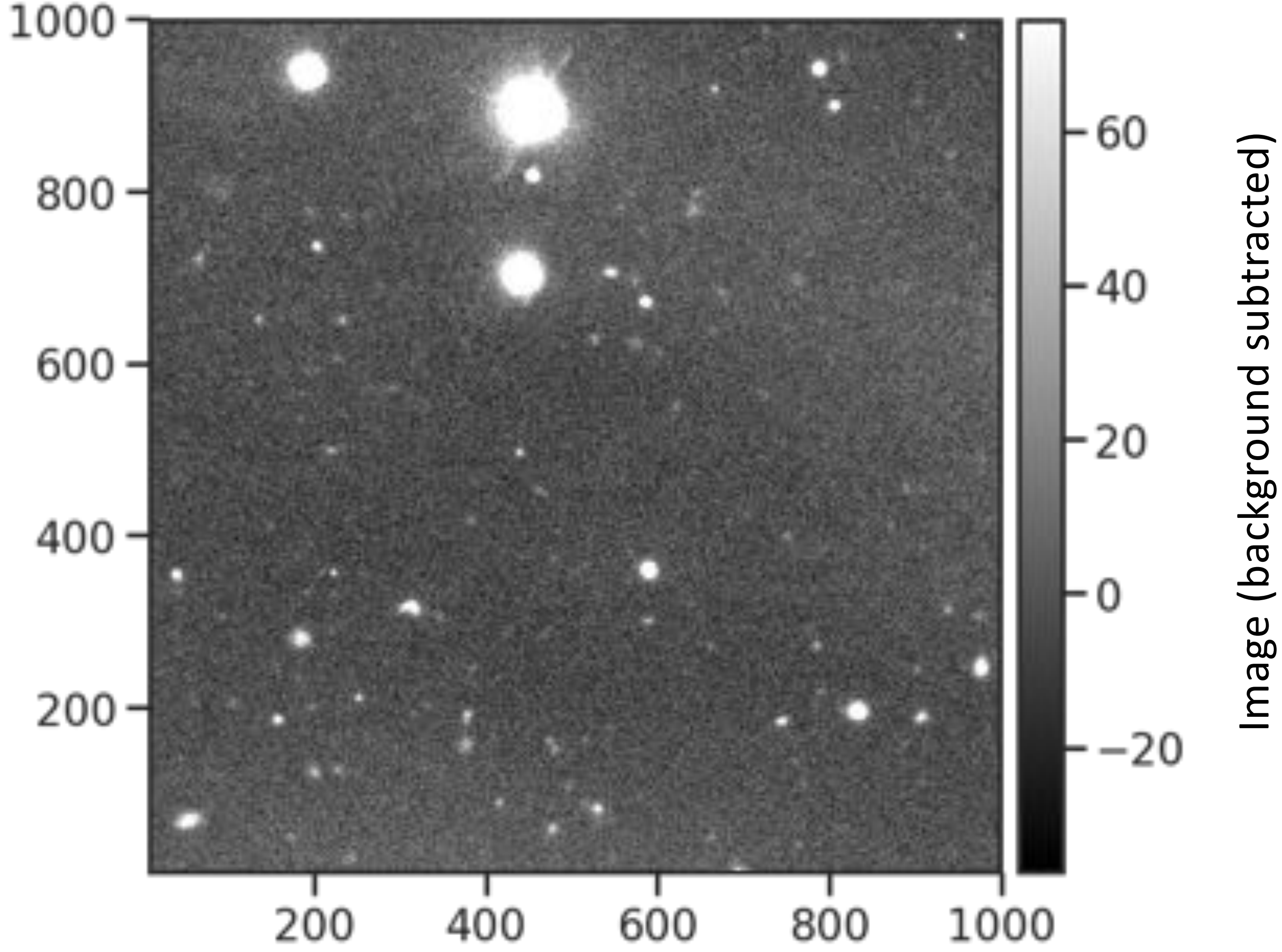
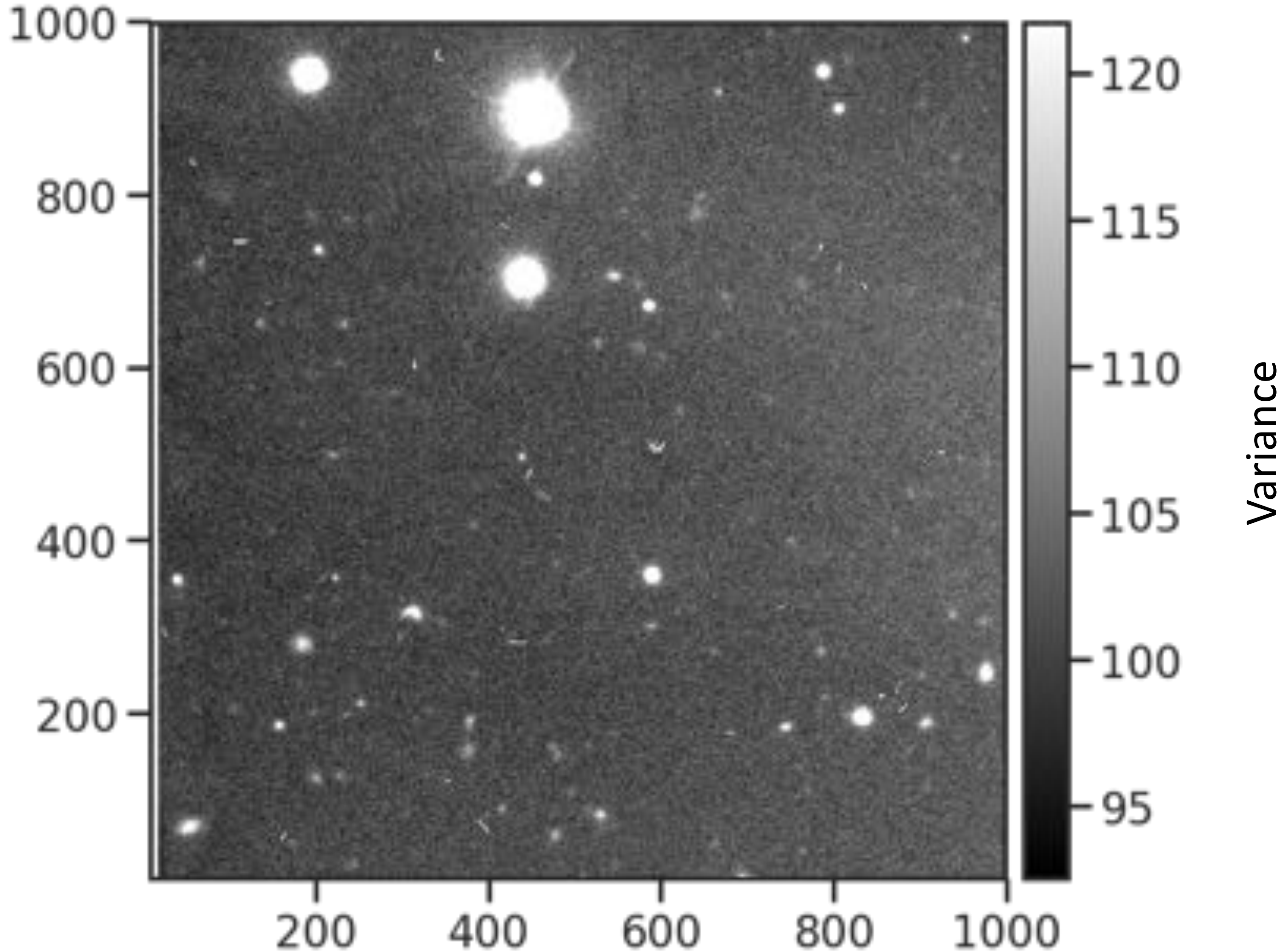
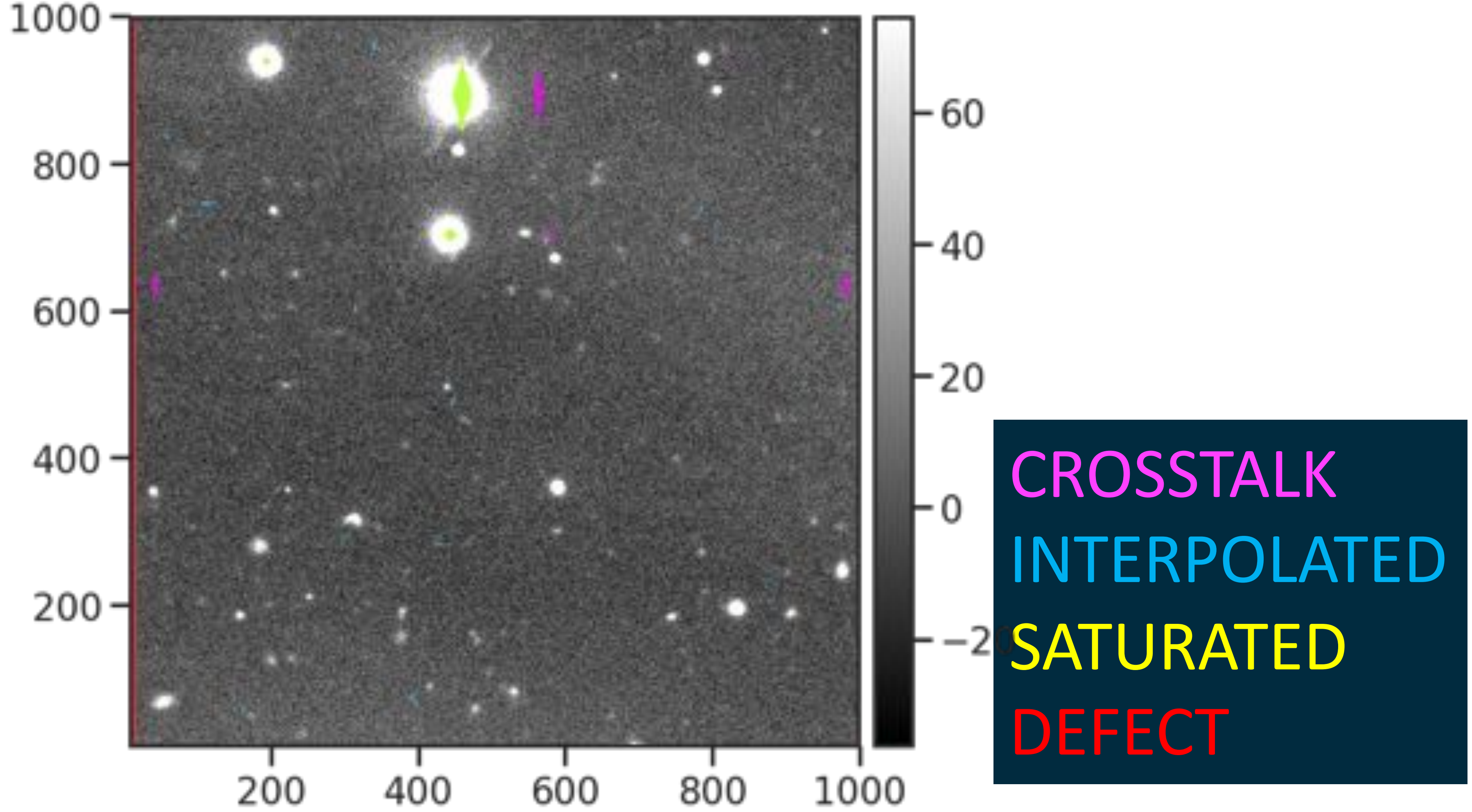


What's available: Noise estimate per pixel



What's available: Masked pixels



What’s available: Masked pixels

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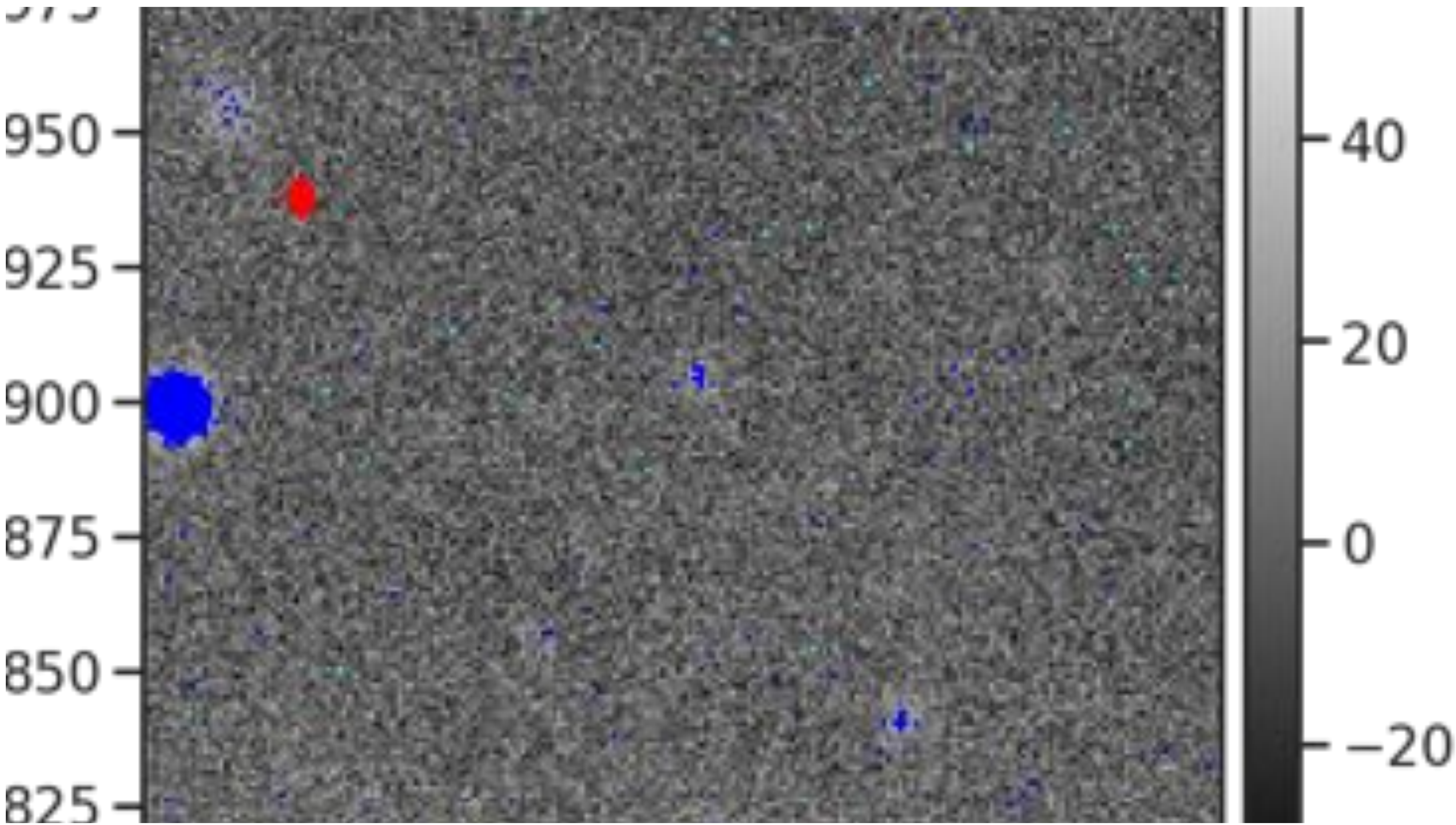
NOW can we just threshold?

Not yet



950
925
900
875
850
825
40
20
0
−20

There is a optimal solution for point source detection

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- Assuming:
  - The source is isolated
  - The noise is known
  - The PSF is known

Test the hypothesis that there is a point source centered at a given pixel.

See problem in notebook

Solution: Need to correlate (convolve image) with the PSF first

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- There are three different ways to understand this:
  - *The image correlated with the PSF IS*
    - (1) A **matched filter (**from signal processing) where the PSF is the template
    - (2)The precomputed PSF-Flux centered at every pixel
    - (3) The **maximum likelihood** estimate per pixel

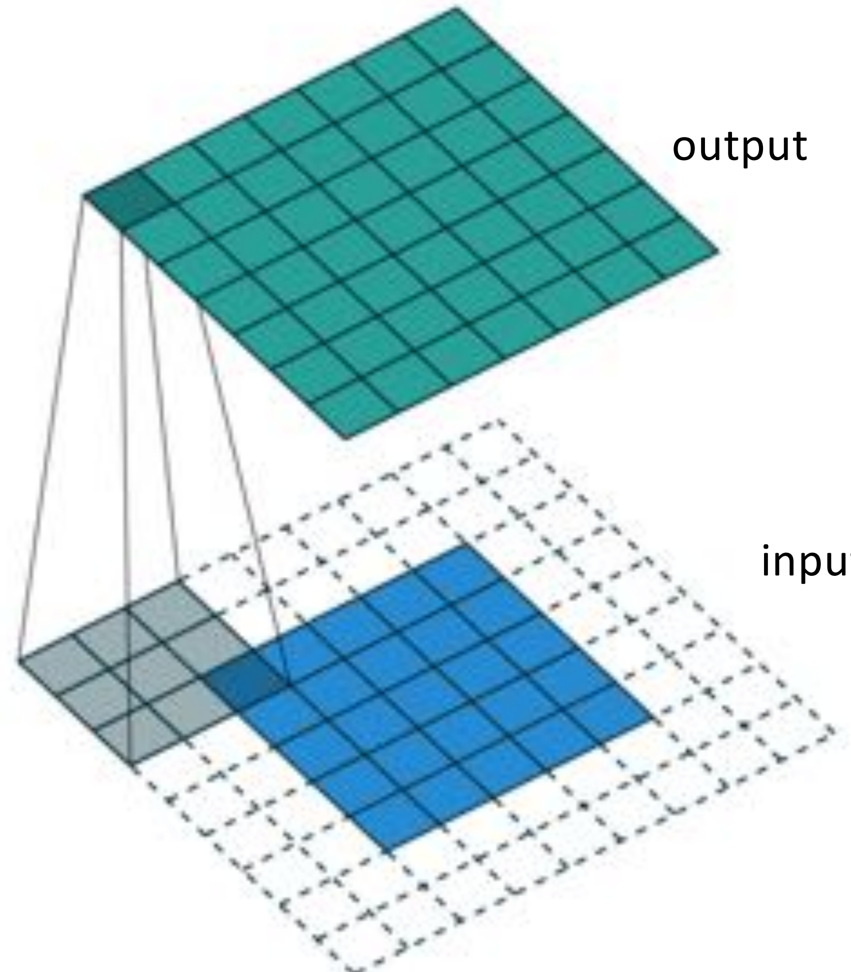

Image credit:

In signal processing, a “matched filter” is correlating a template with a signal to detect the presence of the template.

Cross-correlate the input signal with a kernel/template/known-signal to detect template in the input.

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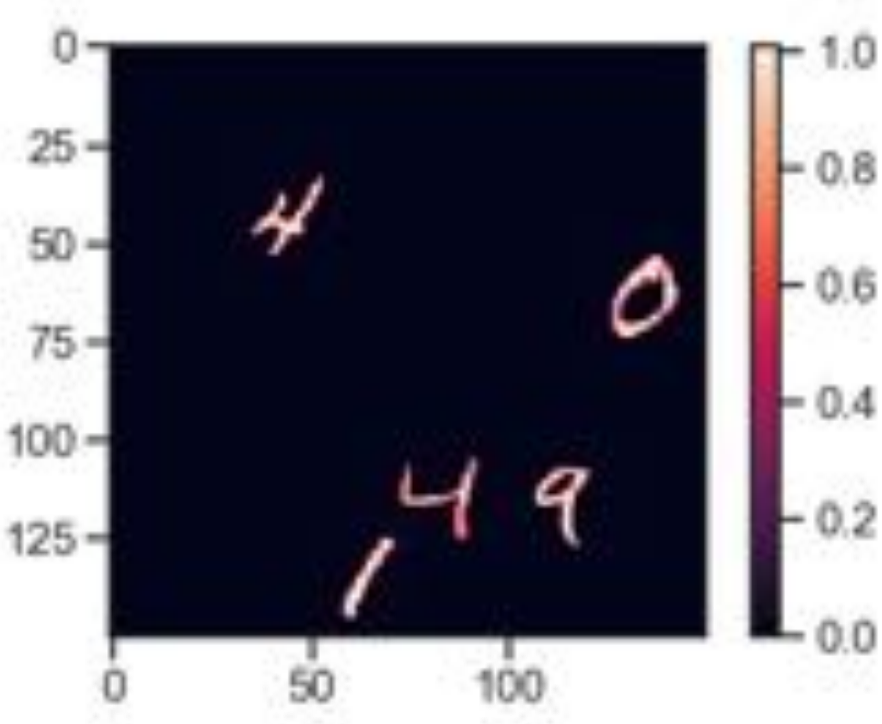
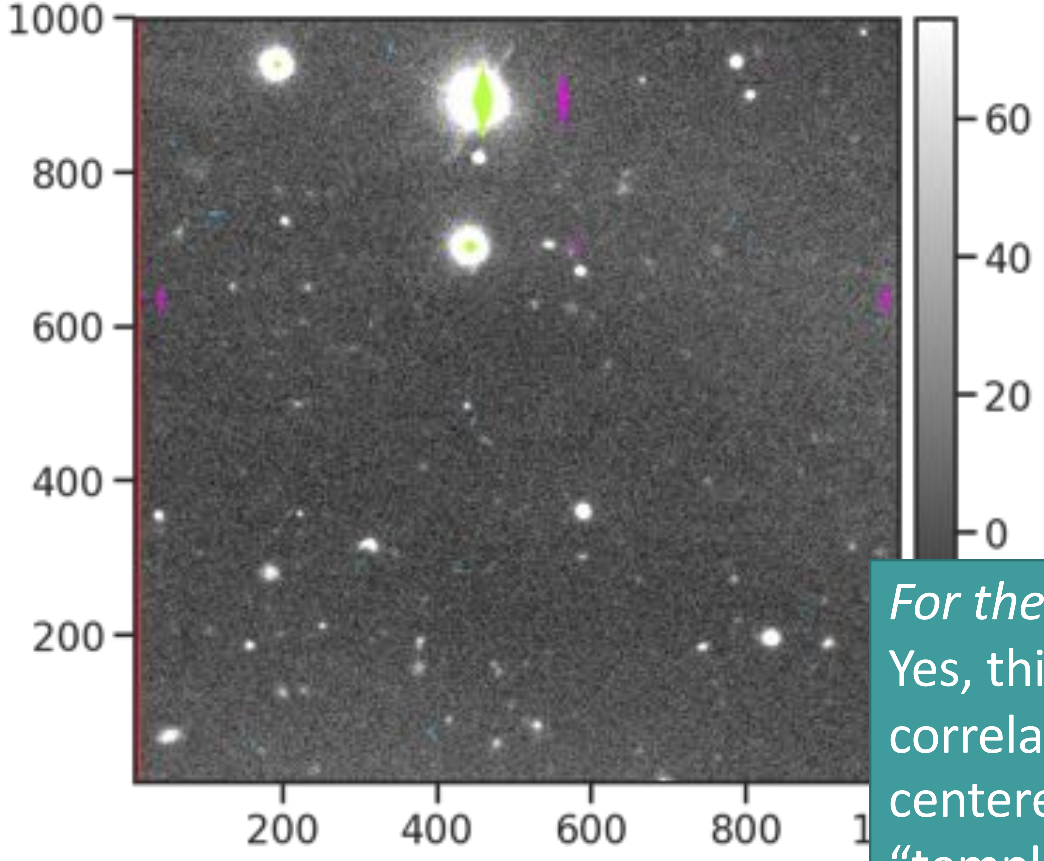


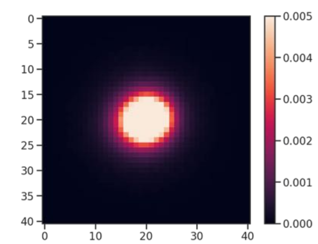
Cross-correlate the input signal with a kernel/template/known-signal to detect template in the input.

Cross-correlate the input signal with a kernel/template/known-signal to detect template in the input.

Correlating with the PSF produces a “detection map” a.k.a a ”likelihood image”



*



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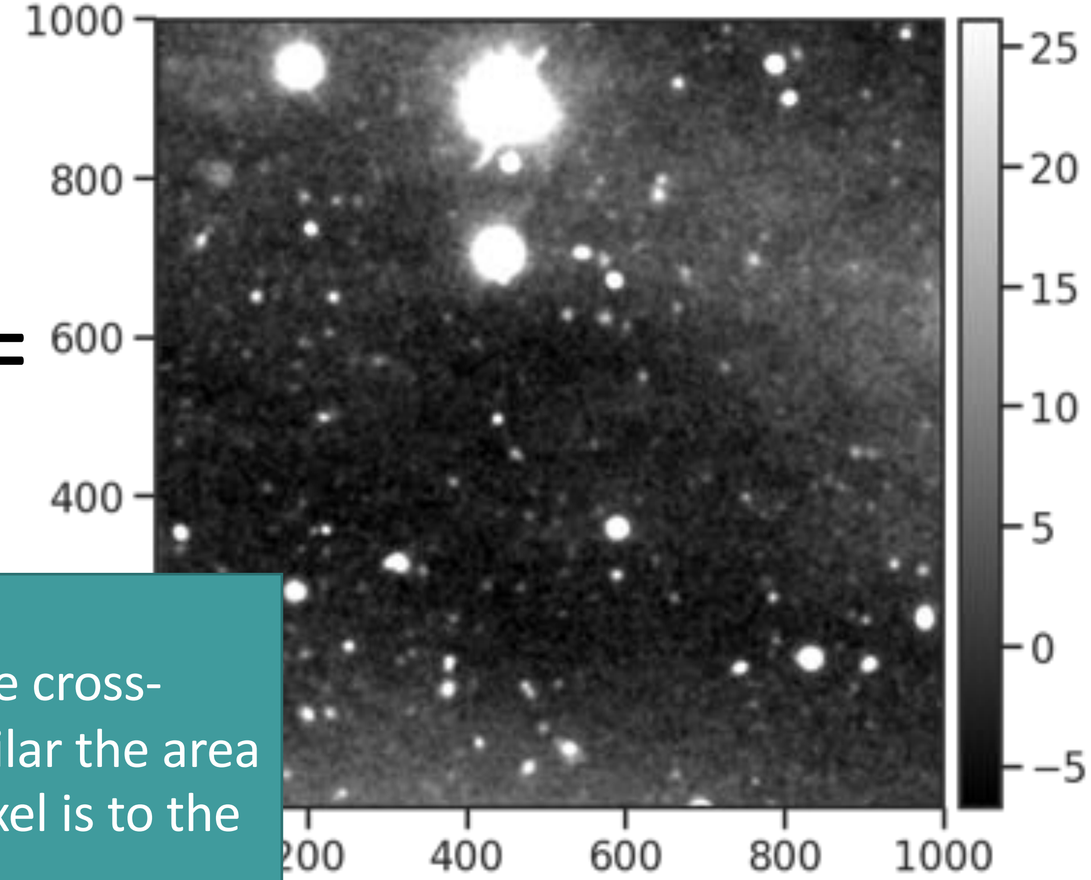

For the spectroscopists:
Yes, this is exactly template cross-correlation. Tests how similar the area centered on the output pixel is to the “template,” the PSF.

Each pixel in the detection map is the pre-computed PSF-Flux if there were a source centered at that pixel!

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- If we just computed the PSF-Flux on every pixel why do we have to compute it again?
  - Because the centers of the stars rarely land exactly in the center of a pixel

Why do we correlate with the PSF even though not everything is a Point Source?

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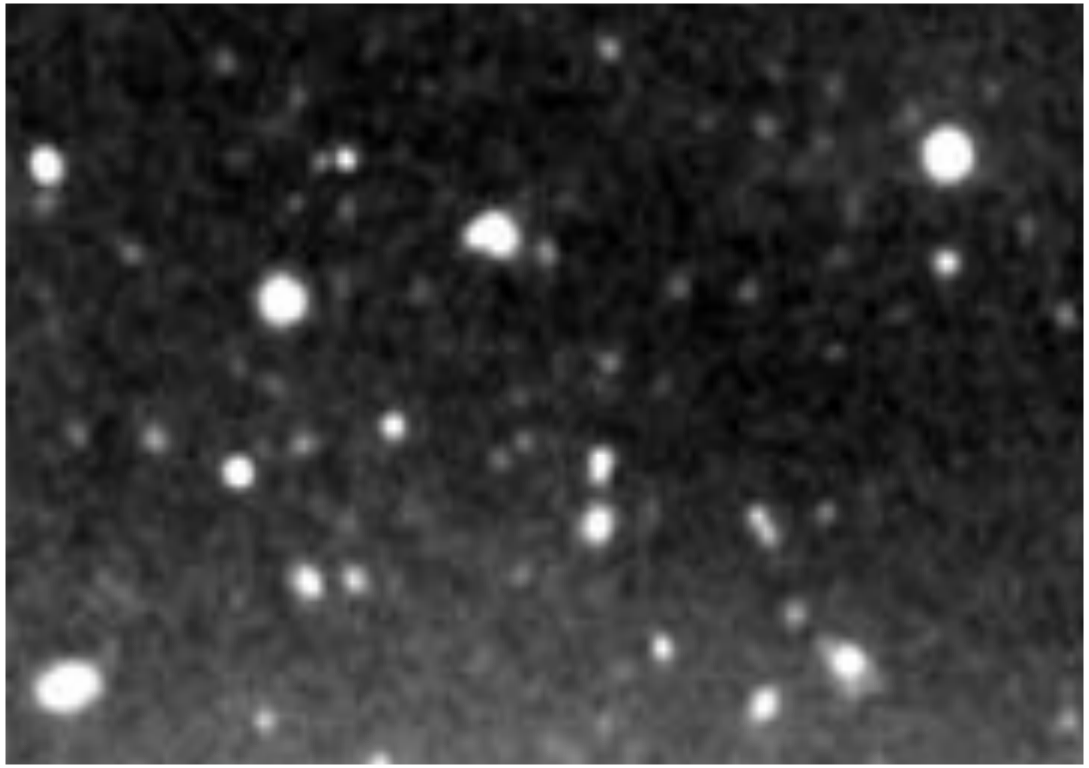
- This detection procedure is optimal for detecting point sources. Not for extended sources.
  - This is why we quote detection efficiencies like “5σ limiting magnitude for point sources = 24.5”
  - The more extended the source, the less efficient the detection.
- However, from the ground everything **is at least** as large as a point source.



Can we just threshold on the likelihood image? Yes, but what value do we pick?

We need an estimate for sigma:

- Empirical standard deviation of the image?
  - More robust, but assumes that noise is constant across image
- Variance plane? (sometimes called "weight map")
  - Beware of: Correlated noise. The variance plane does not necessarily match the empirical variance in the image!

Variance estimation is the step where detection has likely gone wrong. We will revisit this when we discuss detection on image differences.

Threshold = 3 * robust_stdev(detection_map)

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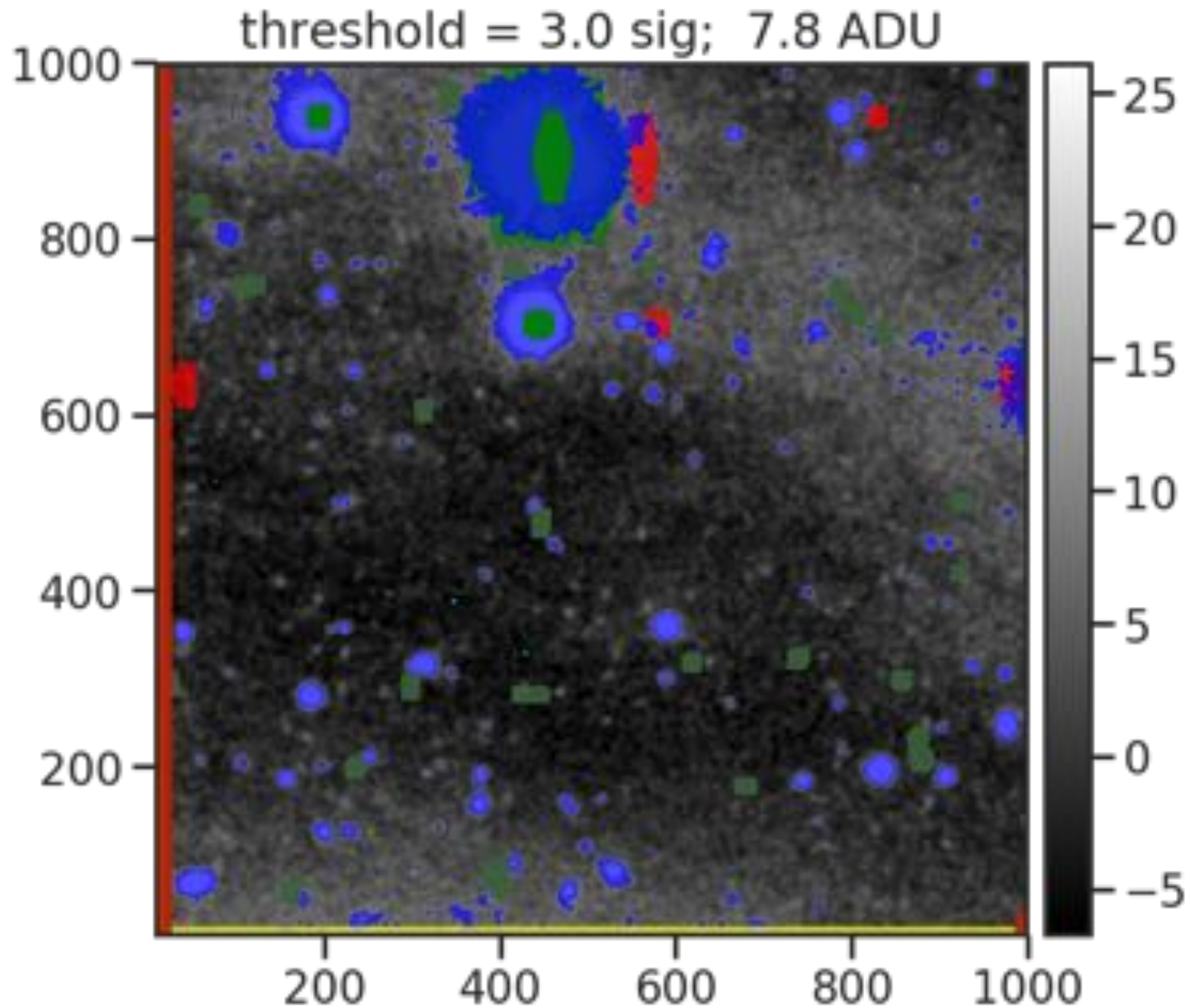

DETECTED
SATURATED
DEFECT/CROSS TALK

Threshold = 4 * robust_stdev(detection_map)

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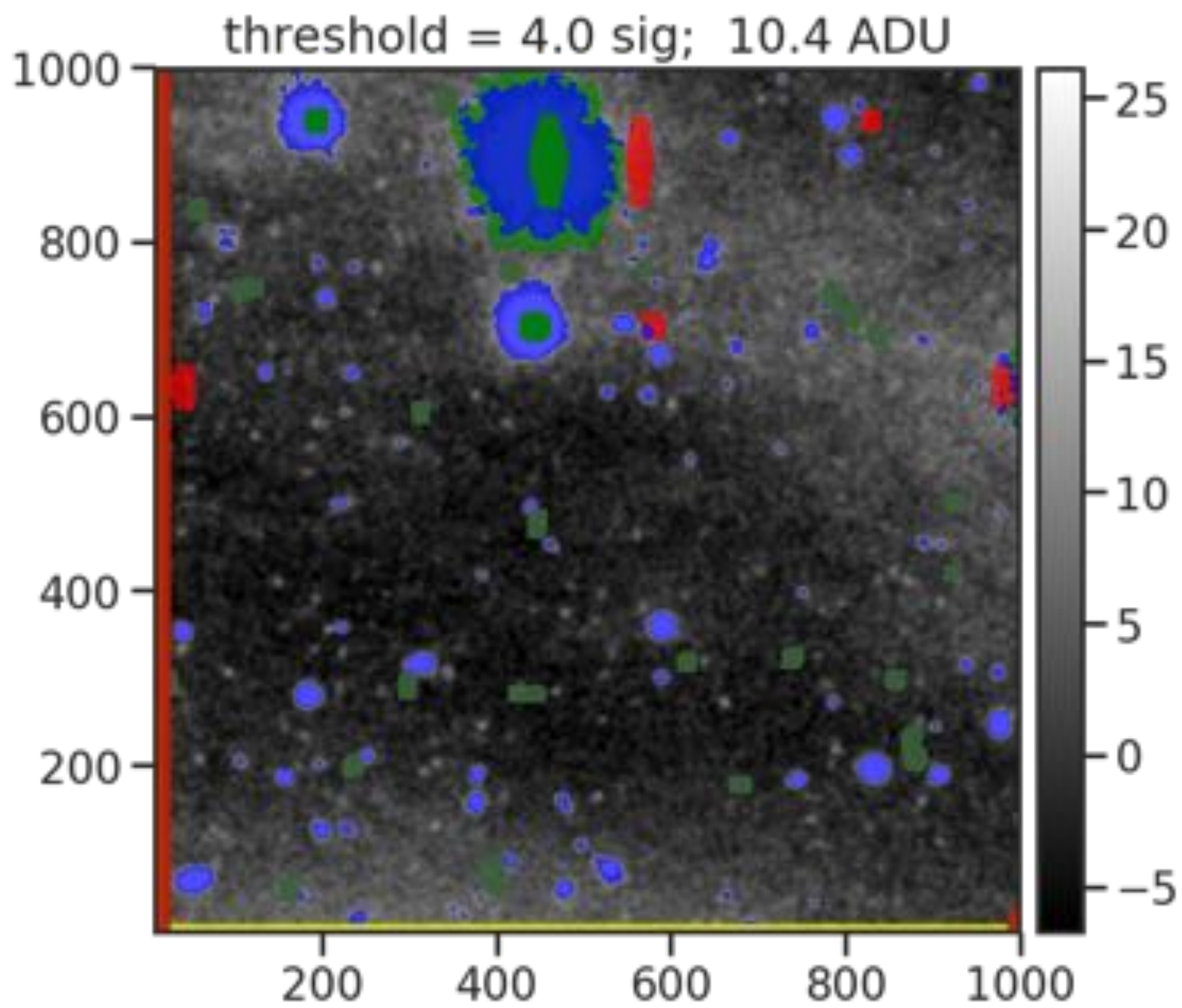
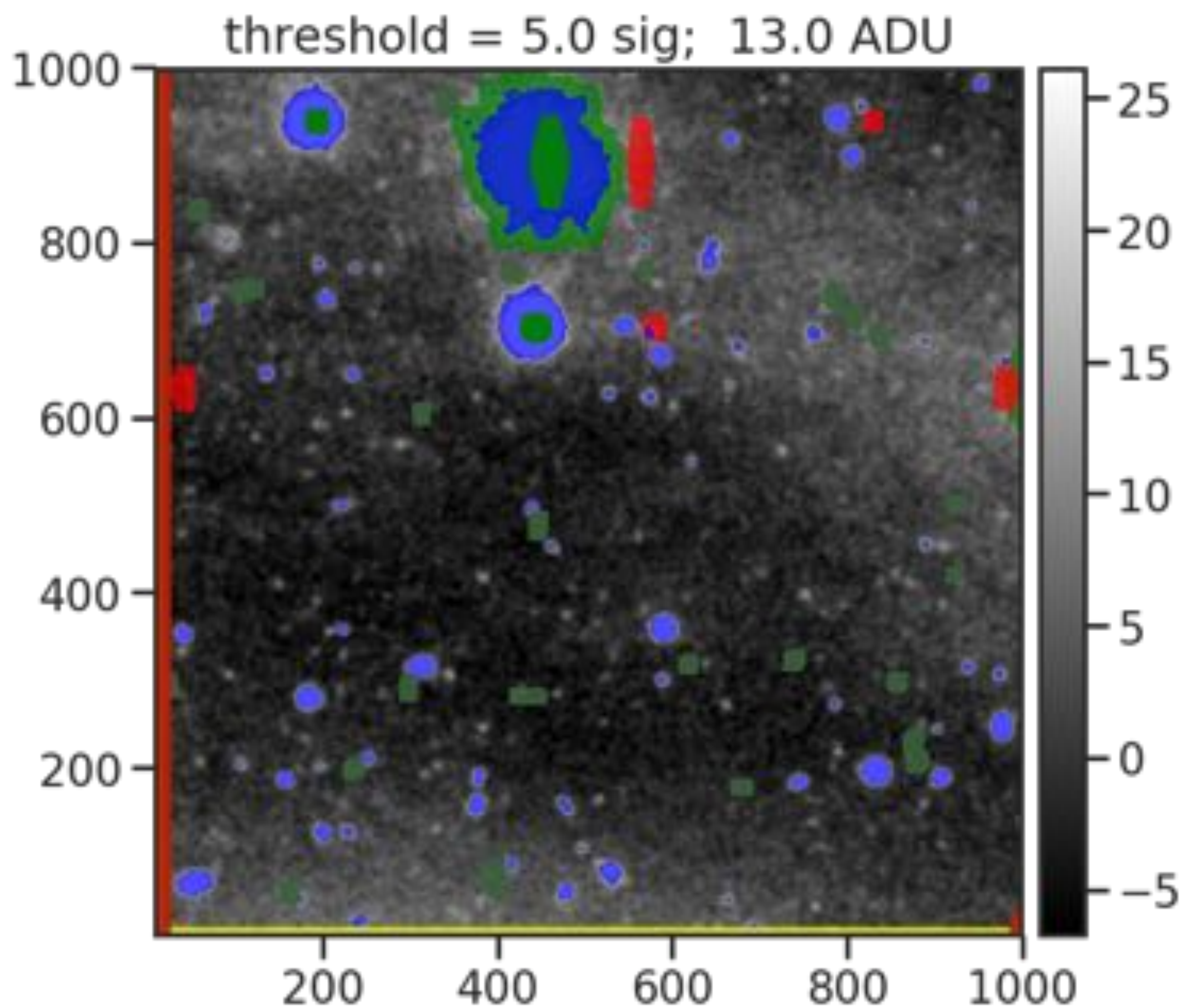


DETECTED
SATURATED
DEFECT/CROSS TALK

Threshold = 5 * robust_stdev(detection_map)



DETECTED
SATURATED
DEFECT/CROSS TALK

Final step, grow/dilate the "footprints" to produce a region/window to measure

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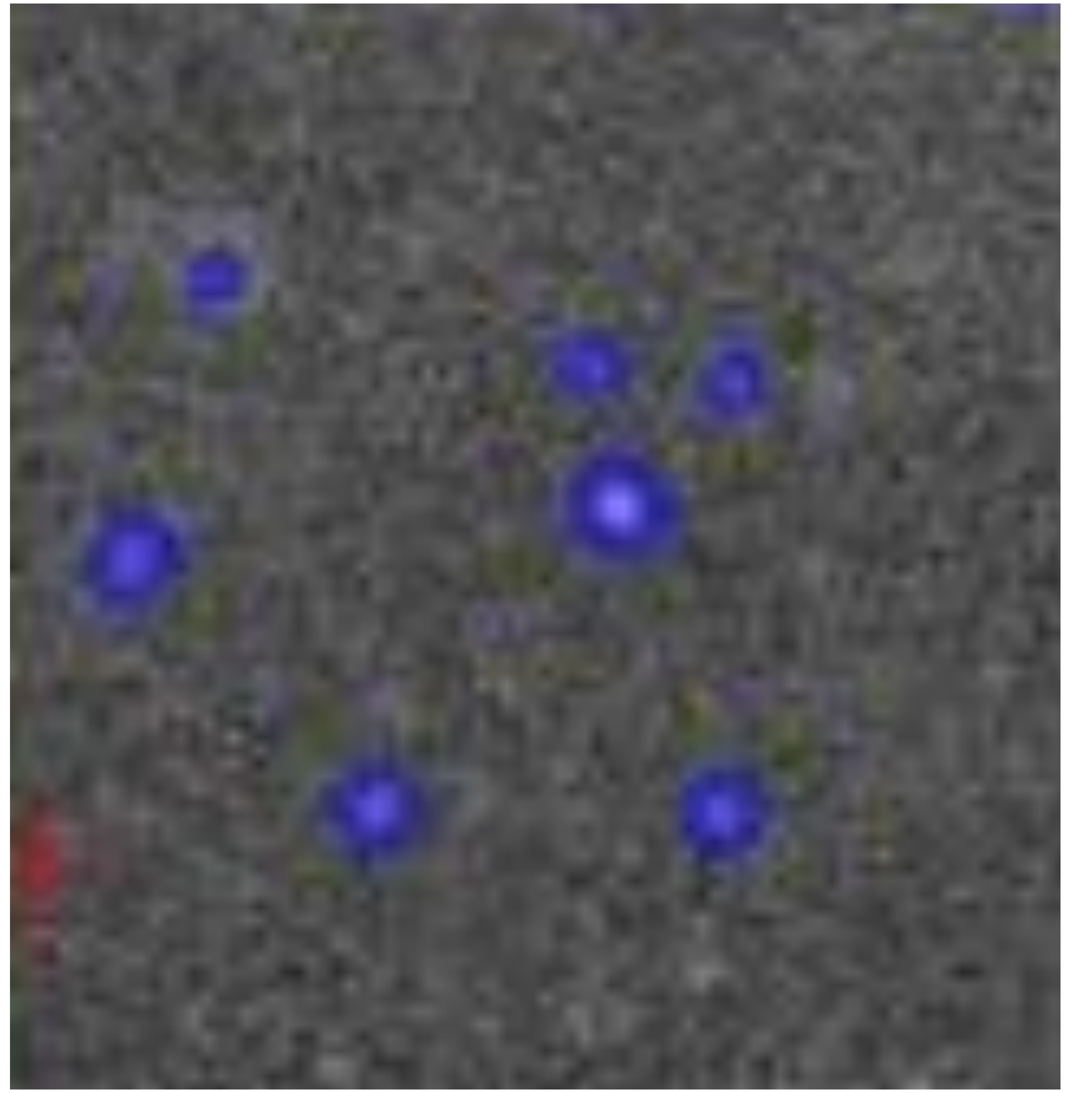

Returning to the chicken and egg problem: Where did we really get that background and PSF model?

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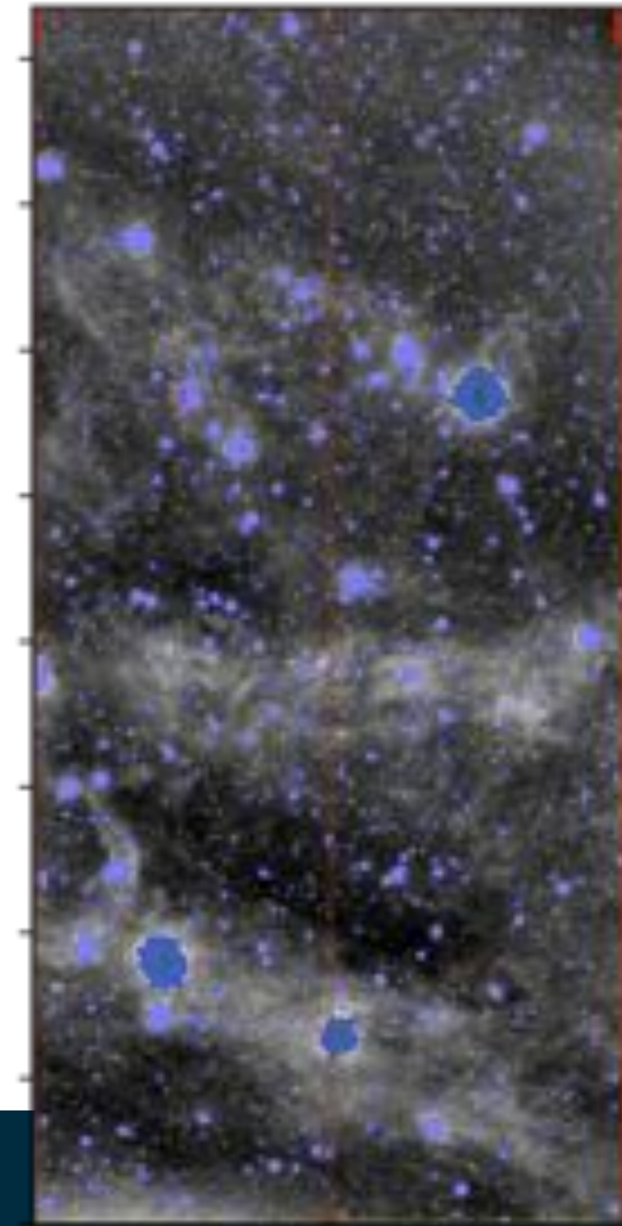
- In practice we iterate:
  1. Estimate background (like you do in exercise 1).
  2. Detect Sources with bright threshold (~50sigma) using a **Gaussian PSF approximation!**
  3. We re-estimate and subtract the background, ignoring pixels marked as belonging to detections in previous step
  4. PSF estimation + (centroiding (see next lecture on astrometry), astrometric calibration, photometric calibration using aperture photometry)
  5. Detect Sources using real PSF model
  6. Re-estimate and subtract background
  7. Measure PSF Flux



For more information:

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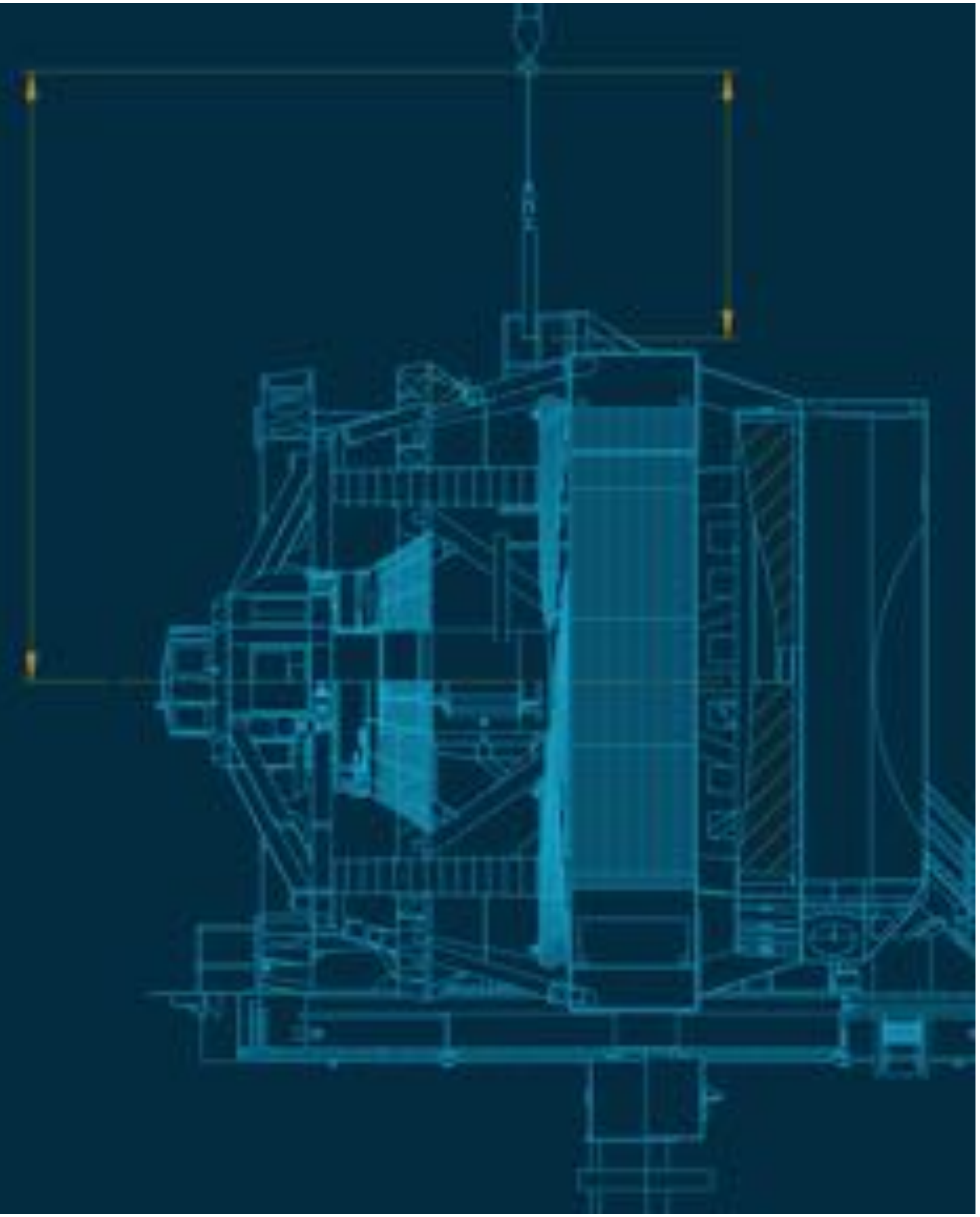
- Details on the LSST science pipelines that produced the HSC data releases: Bosch+17 https://arxiv.org/pdf/1705.06766.pdf
- Review article on source detection: Masias+12 https://doi.org/10.1111/j.1365-2966.2012.20742.x

Sky Background Estimation and Subtraction



Problem: How do we find all the stars/galaxies in this image?

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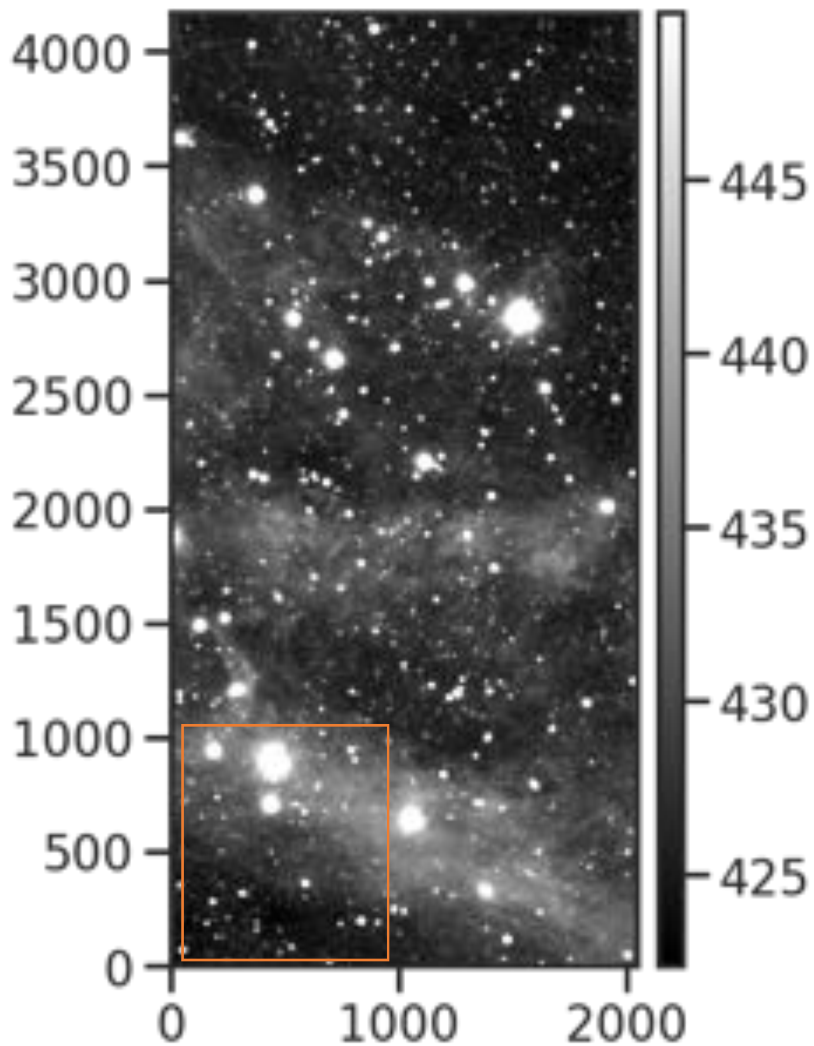
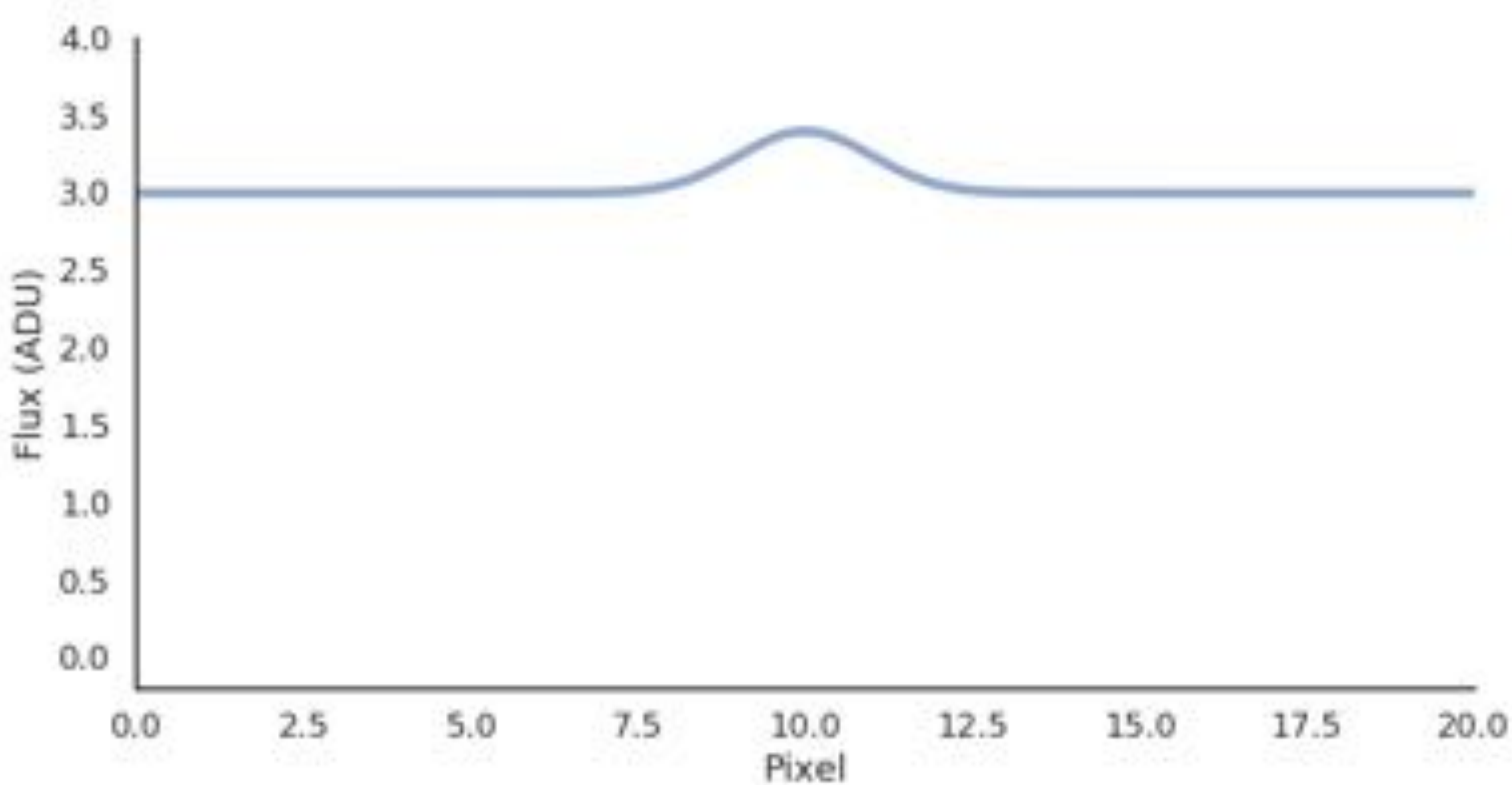


In this image:

- Sources (stars, galaxies, asteroids etc…)
- Noise (see Colin's previous talk)
- [Sky] Backgrounds **NOW!**

Hyper Suprime Cam
VISIT = 34464
CCD = 81
Smoothed to make background structure visible

If sources were isolated and backgrounds were constant offsets, background estimation would be easy



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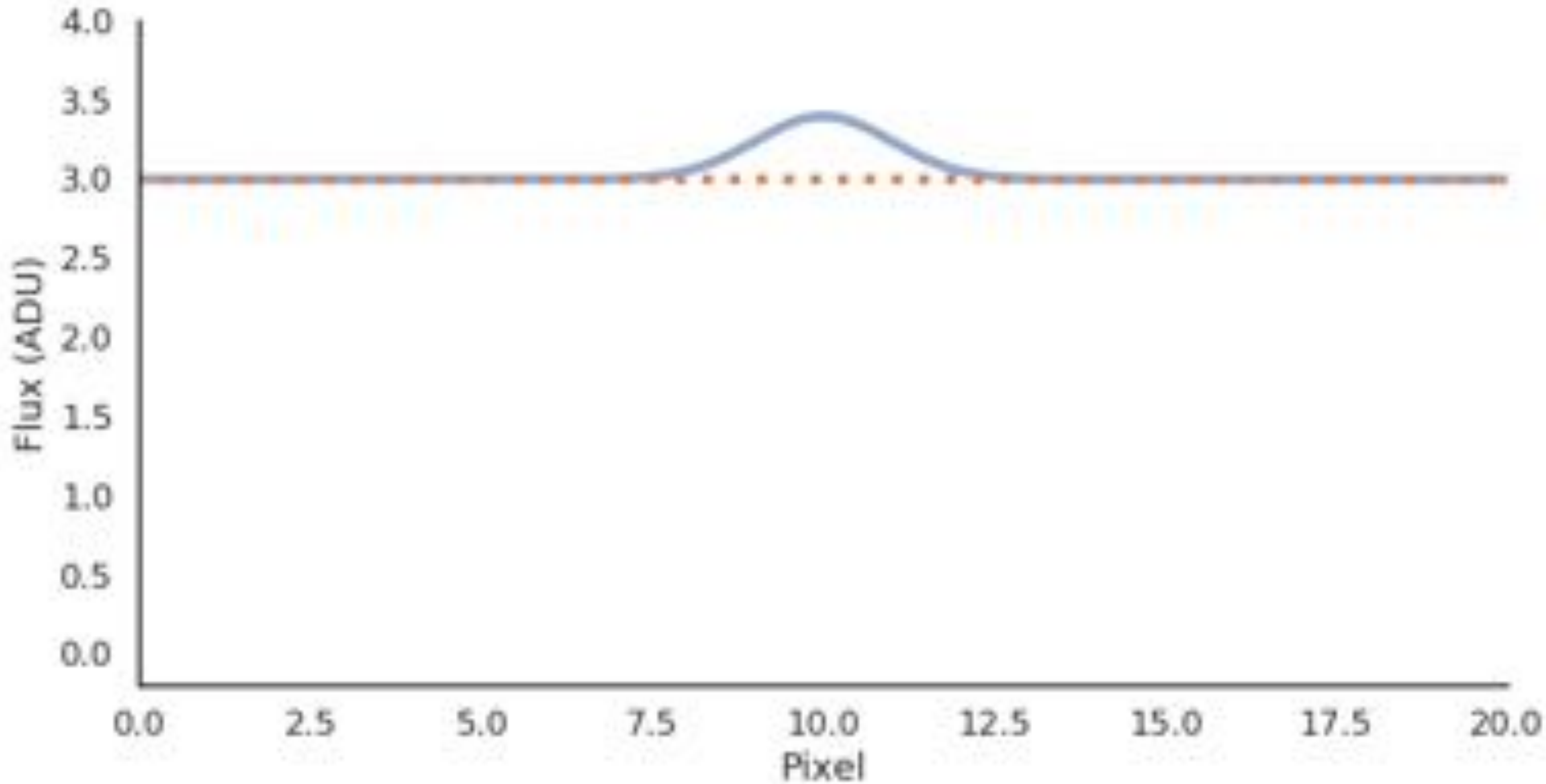

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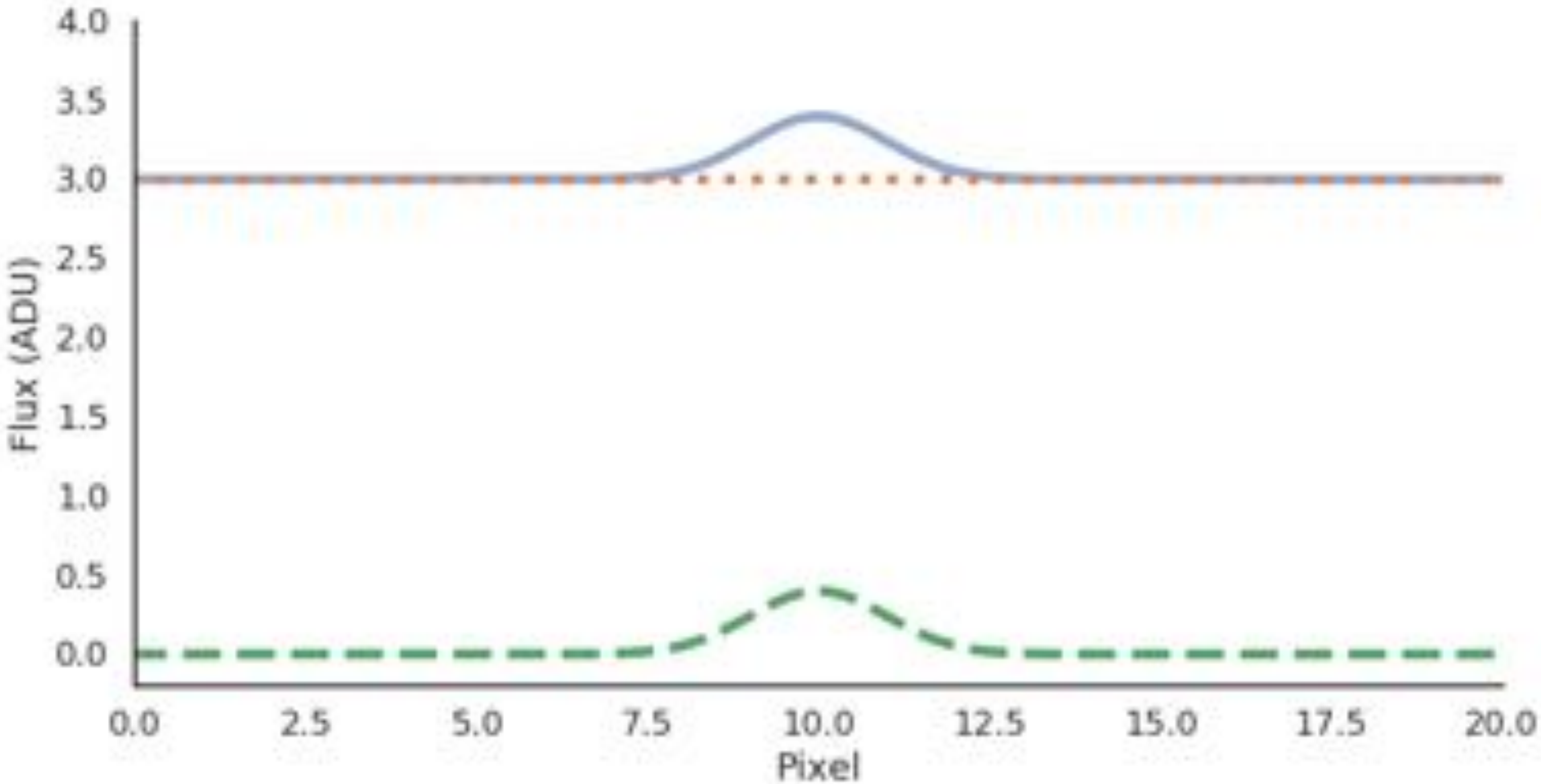

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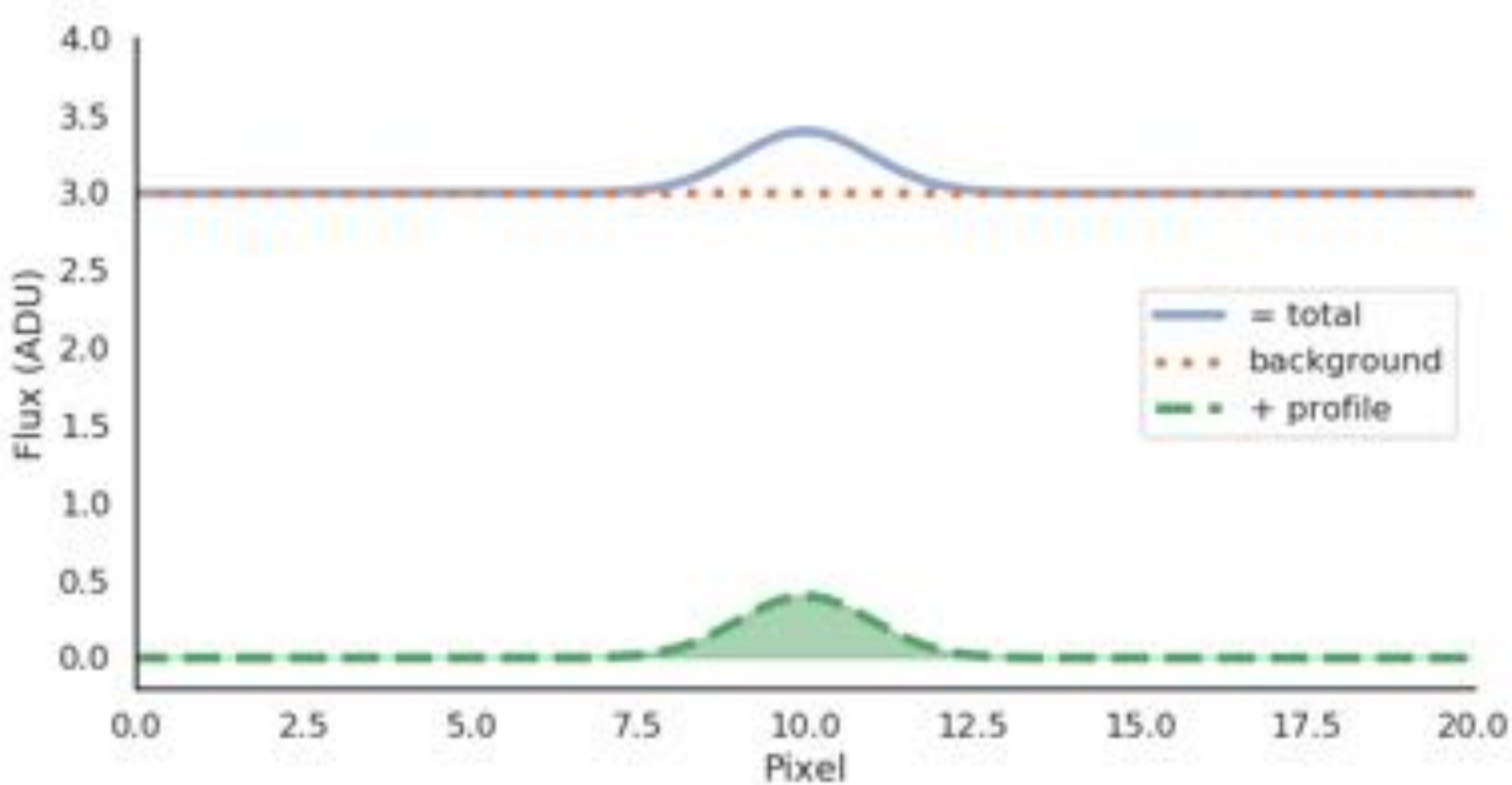
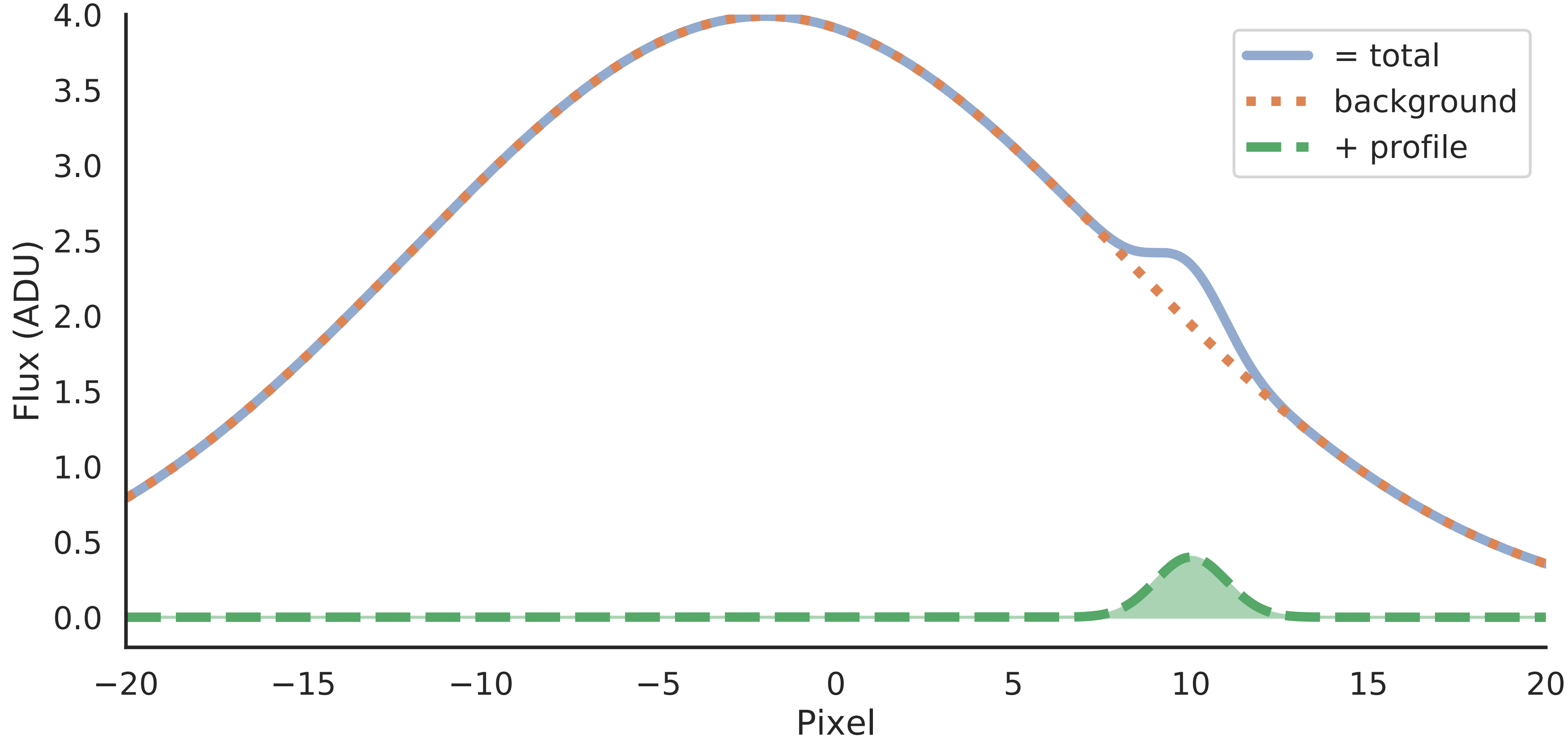


U.S. DEPARTMENT OF ENERGY | Office of Science

But in practice the images look more like this



Backgrounds are any additive flux component not from the source you want to measure RIGHT NOW

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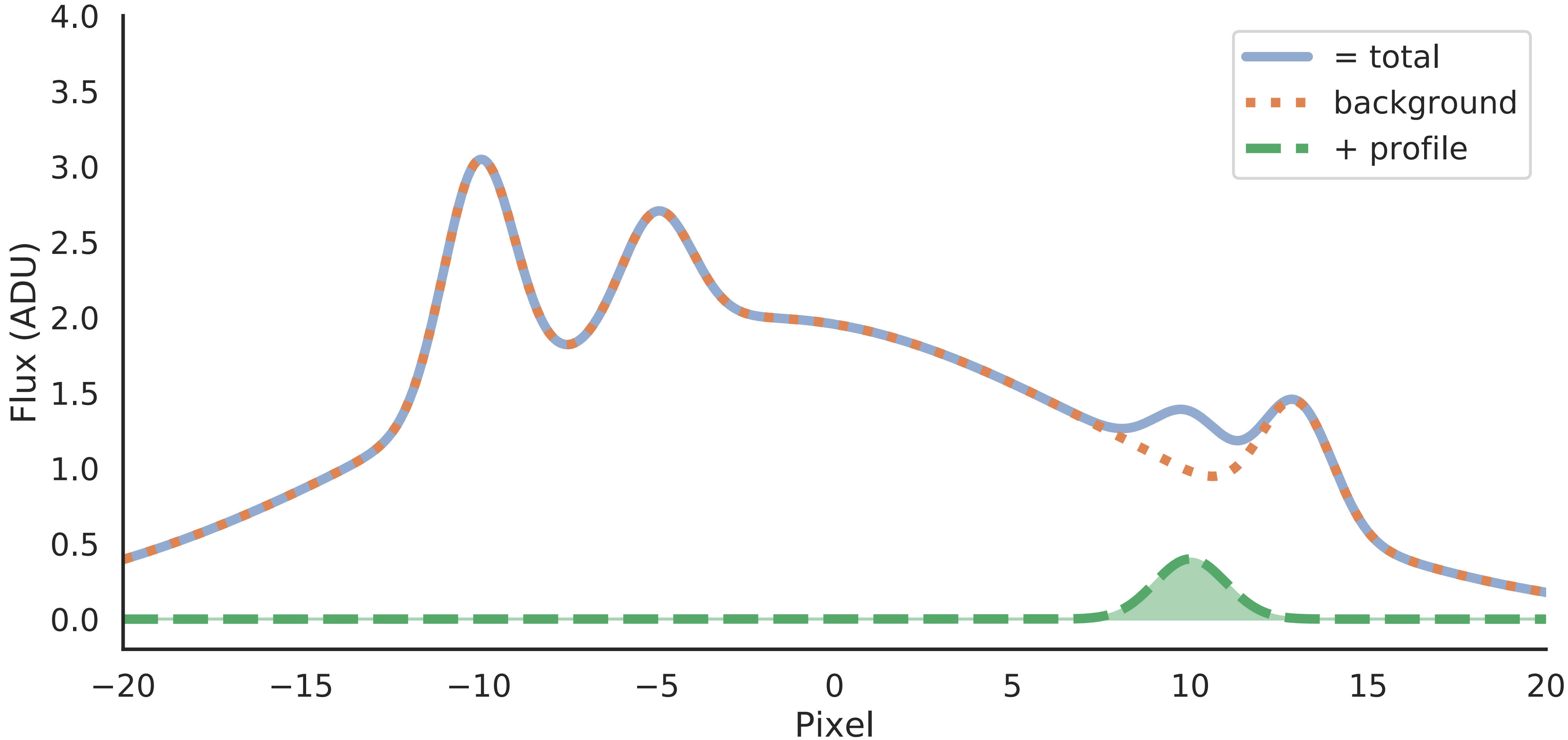

Where does background come from?

Backgrounds have 3 categories of origins: Instrumental, Astrophysical, Neither

- Distinction is important for where in the pipeline we remove each component

Instrumental background has temporally coherent spatial structure over **ccd and focal plane coordinates**

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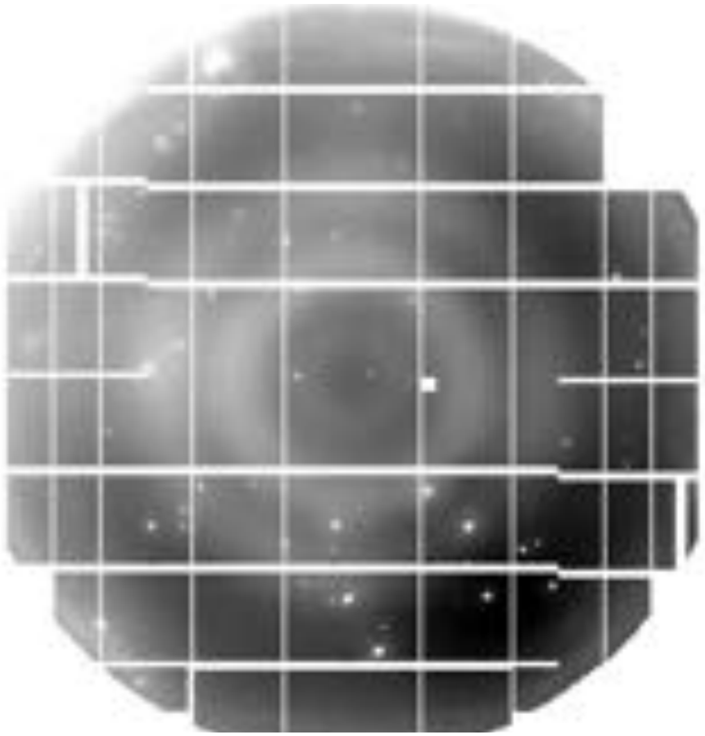
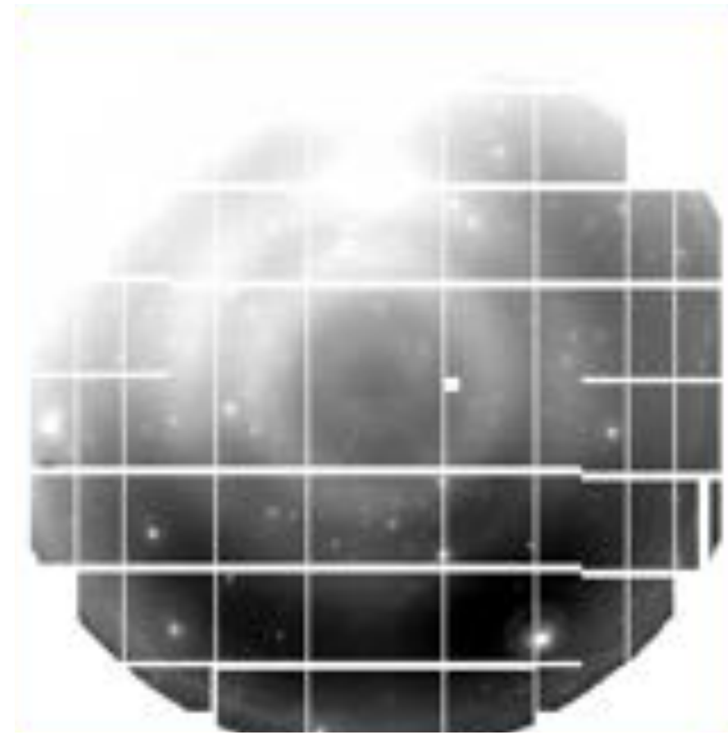
CCDs after Instrument Signature Removal (bias, dark, flat-fielding etc)
Detections removed and binned 128x128pix

e.g. Filter transmission variations



Visit 19500

Visit 7364



Visit 30686

HSC-I

Instrumental background has temporally coherent spatial structure over **ccd and focal plane coordinates**

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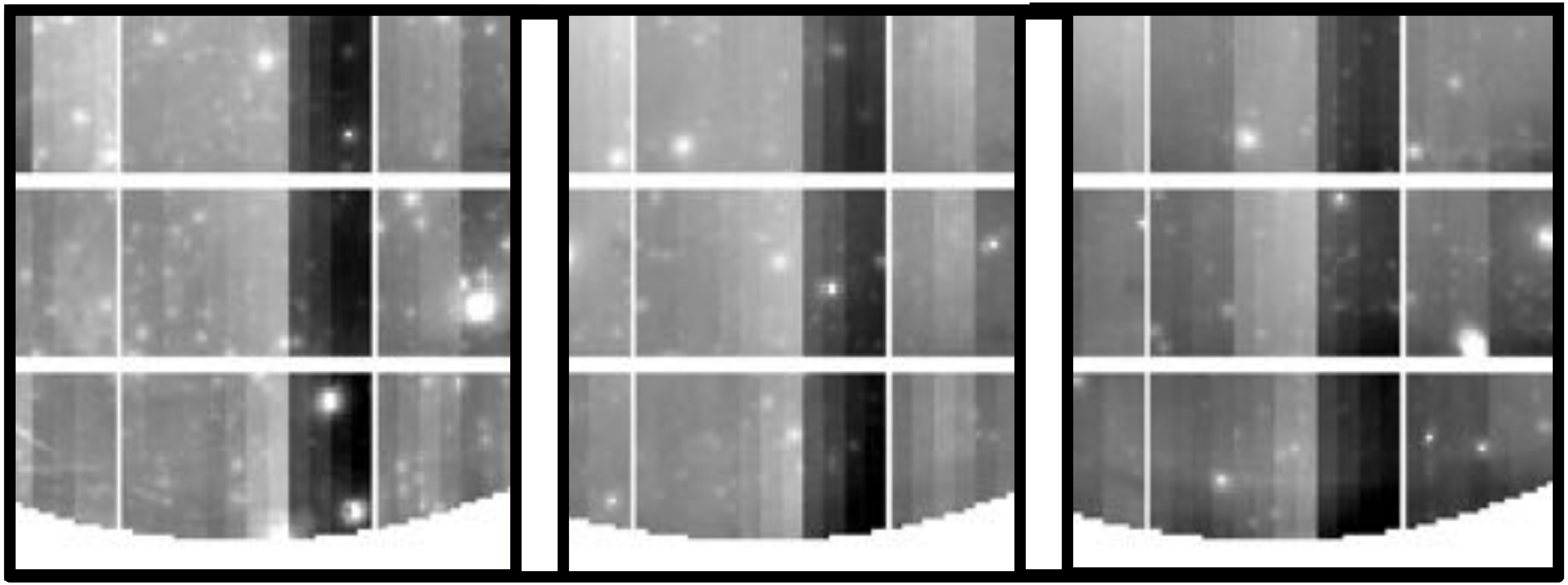
e.g. residual ccd and amp offsets



Visit 15308 Visit 29408 Visit 26098

HSC-G

Astrophysical Background has temporally coherent structure over **Sky Coordinates**

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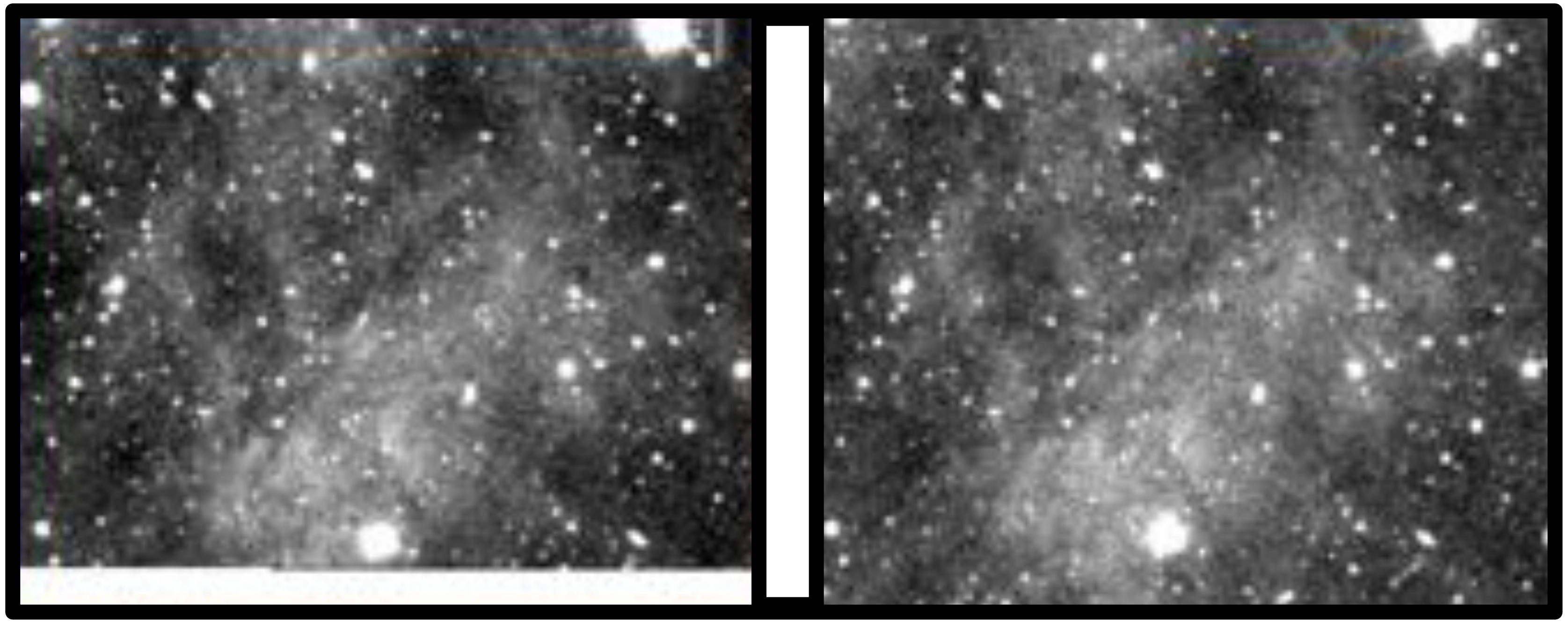
e.g. Galactic IR Cirrus



Visit 34448 Visit 34422

HSC-G

Astrophysical Background has temporally coherent structure over **Sky Coordinates**

The extended PSF **-- diffuse scattering halos** from the atmosphere seen especially around bright stars

Outer regions of large galaxies

Diffuse sources such as cluster ICL and the ISM

Unresolved stars or galaxies

Neighboring stars and galaxies?

https://hscmap.mtk.nao.ac.jp/hscMap4/app

HSC Field=COSMOS, HSC-G, HSC-R, HSC-I PDR2

Distinction is important for where in the pipeline we remove each component

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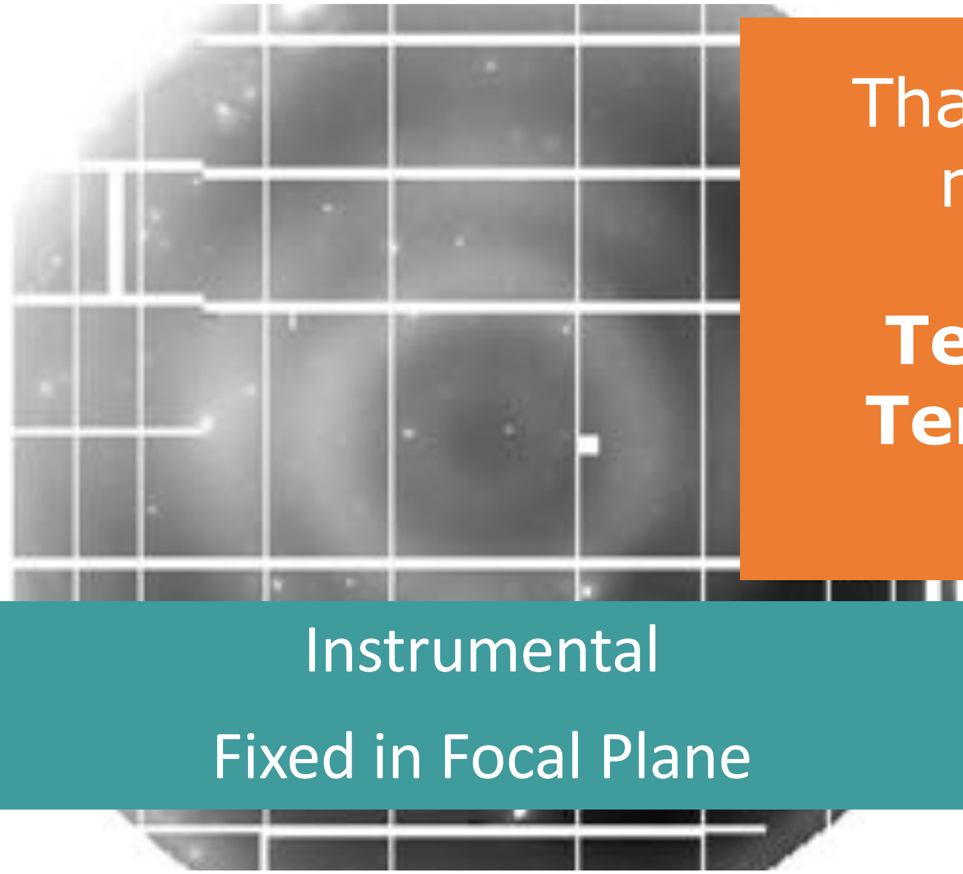


That which is neither:

Temporal, Terrestrial, Solar

Instrumental

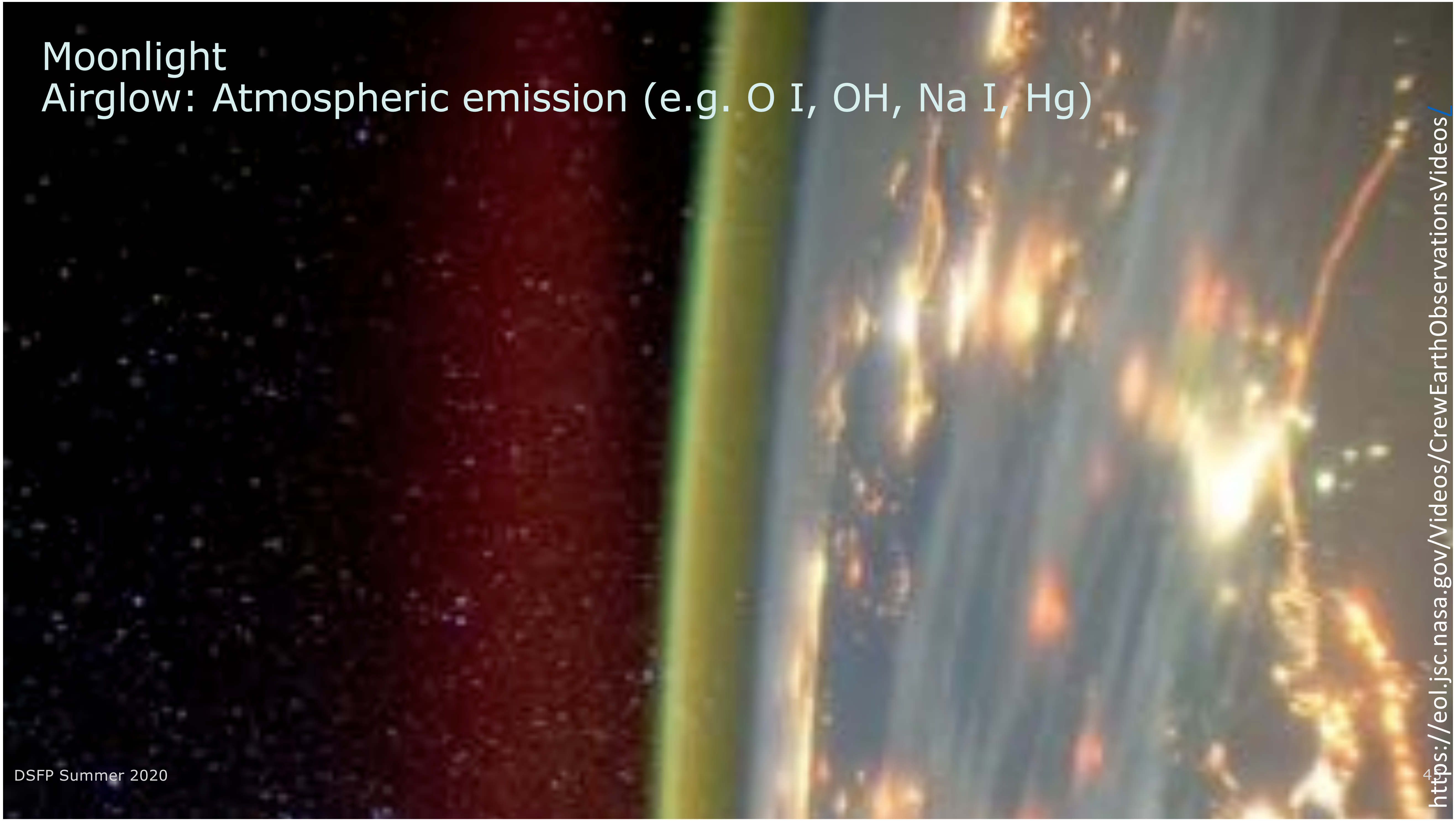
Fixed in Focal Plane

Astrophysical

Fixed in Sky Coords

Moonlight

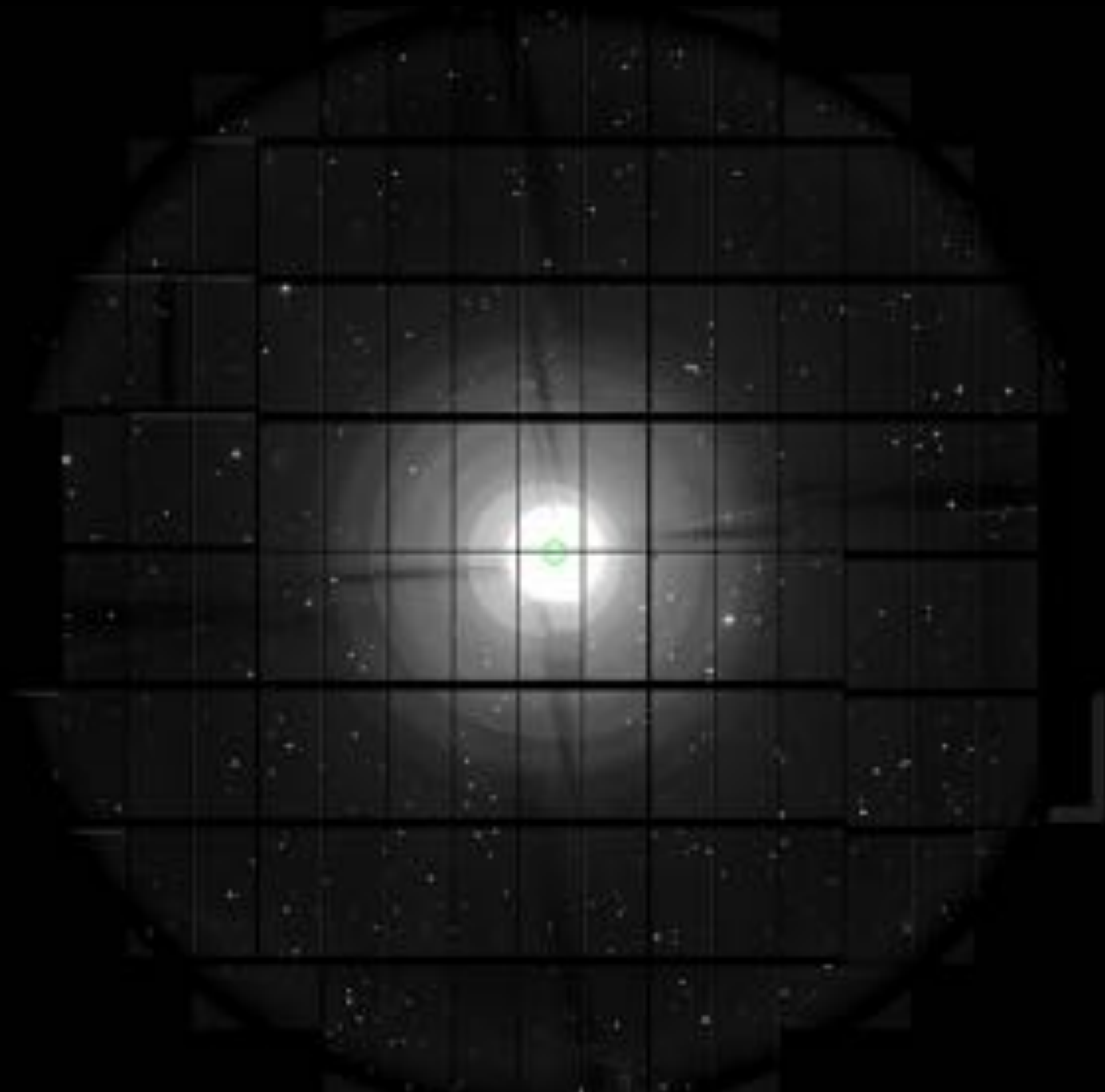
Airglow: Atmospheric emission (e.g. O I, OH, Na I, Hg)



https://eol.jsc.nasa.gov/Videos/CrewEarthObservationsVideos/

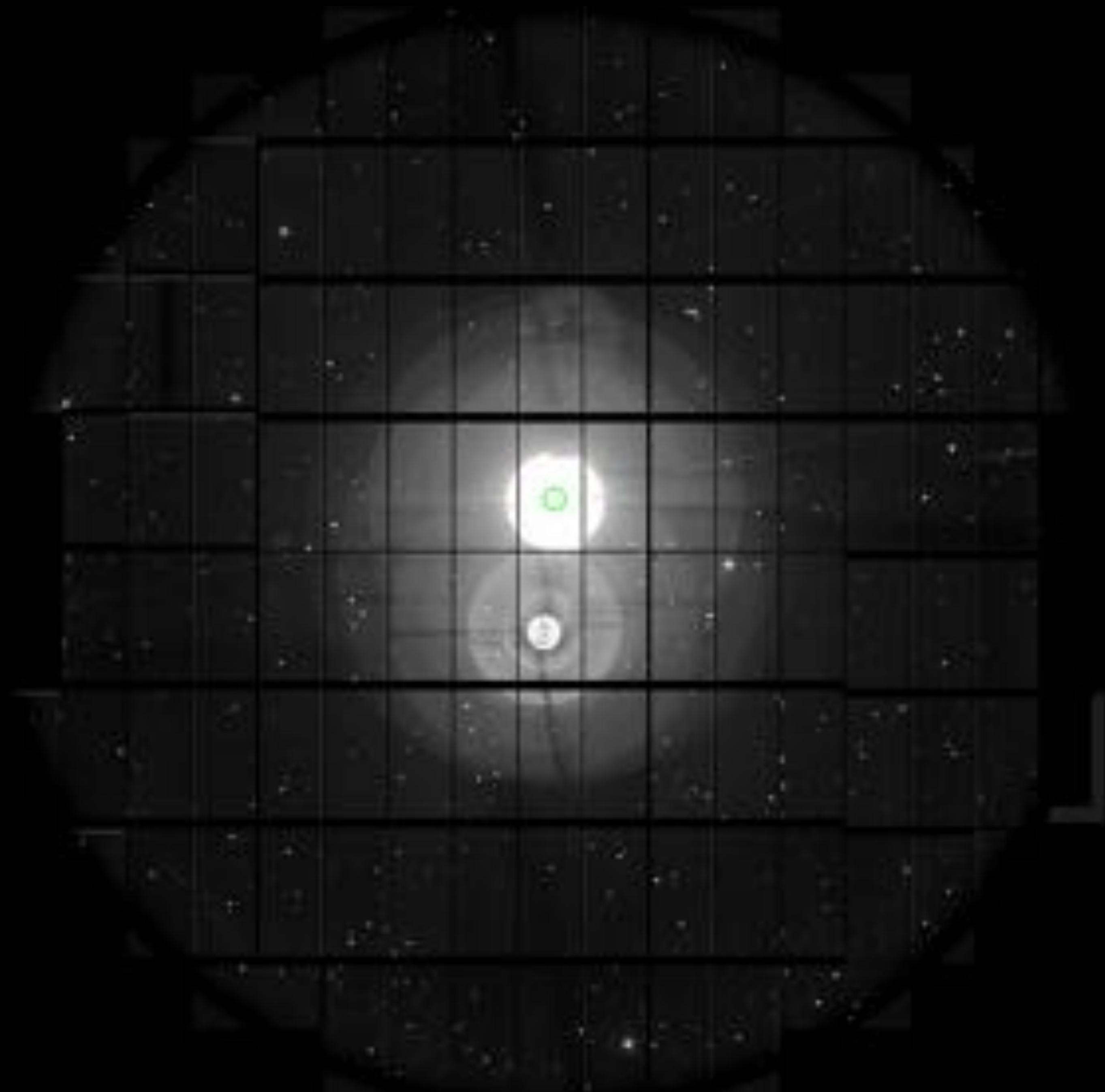

Zodiacal Light
Credit:ESO/Y. Beletsky

Ghosts

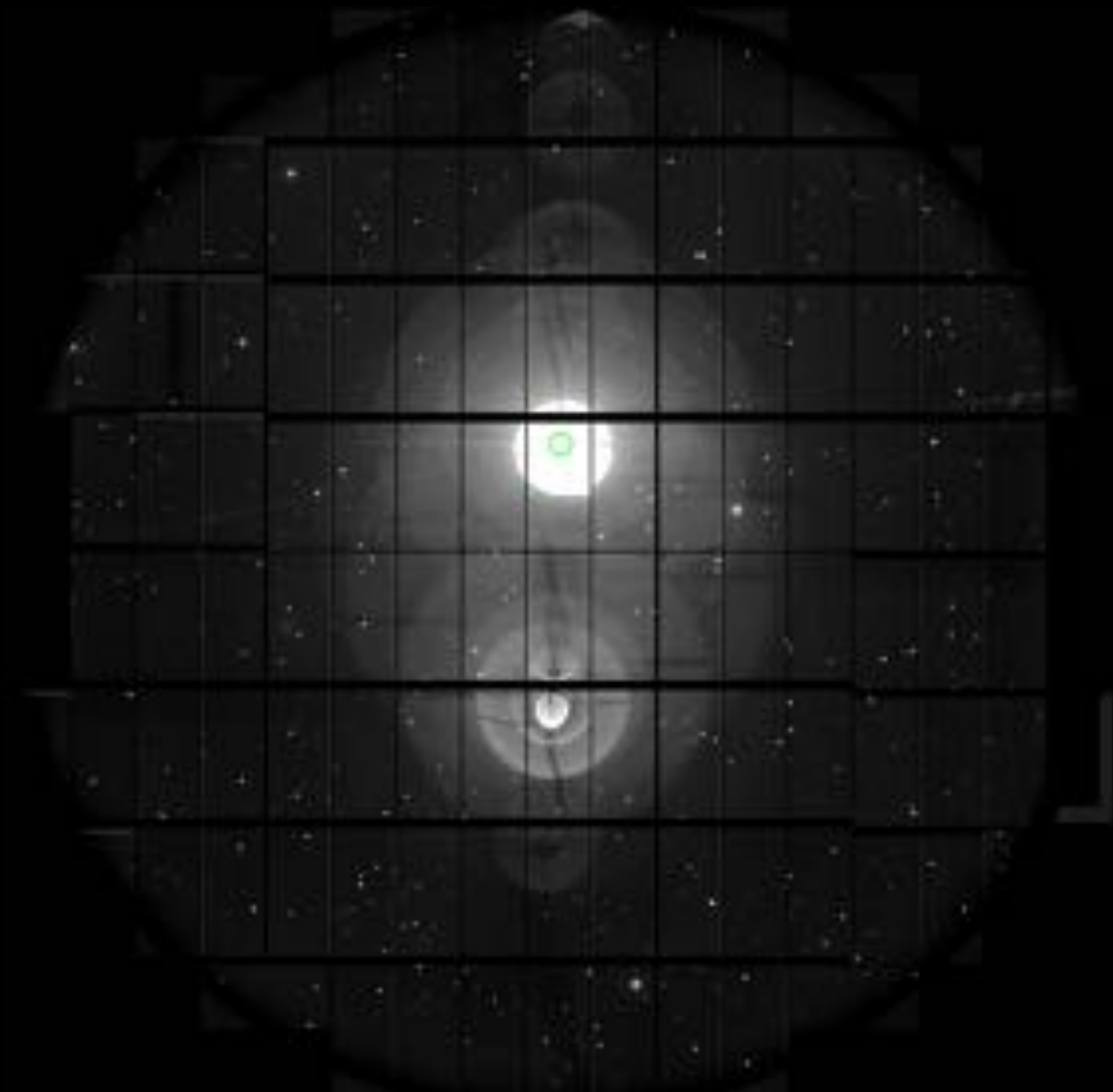


Arcturus (Hokule`a)
Robert Lupton, Jim Gunn
Time courtesy of
Satoshi Miyazaki and the HSC collaboration

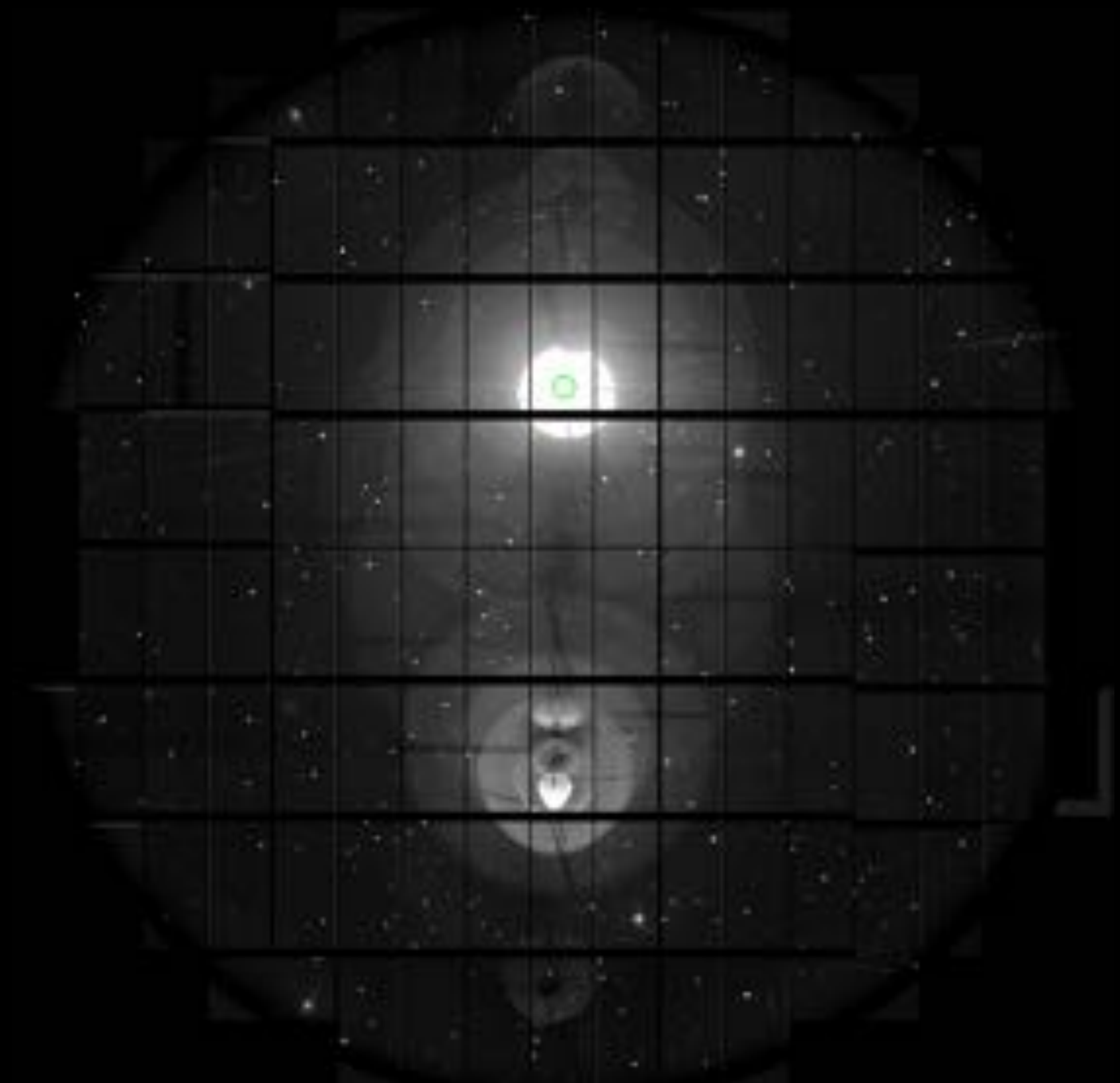
Ghosts



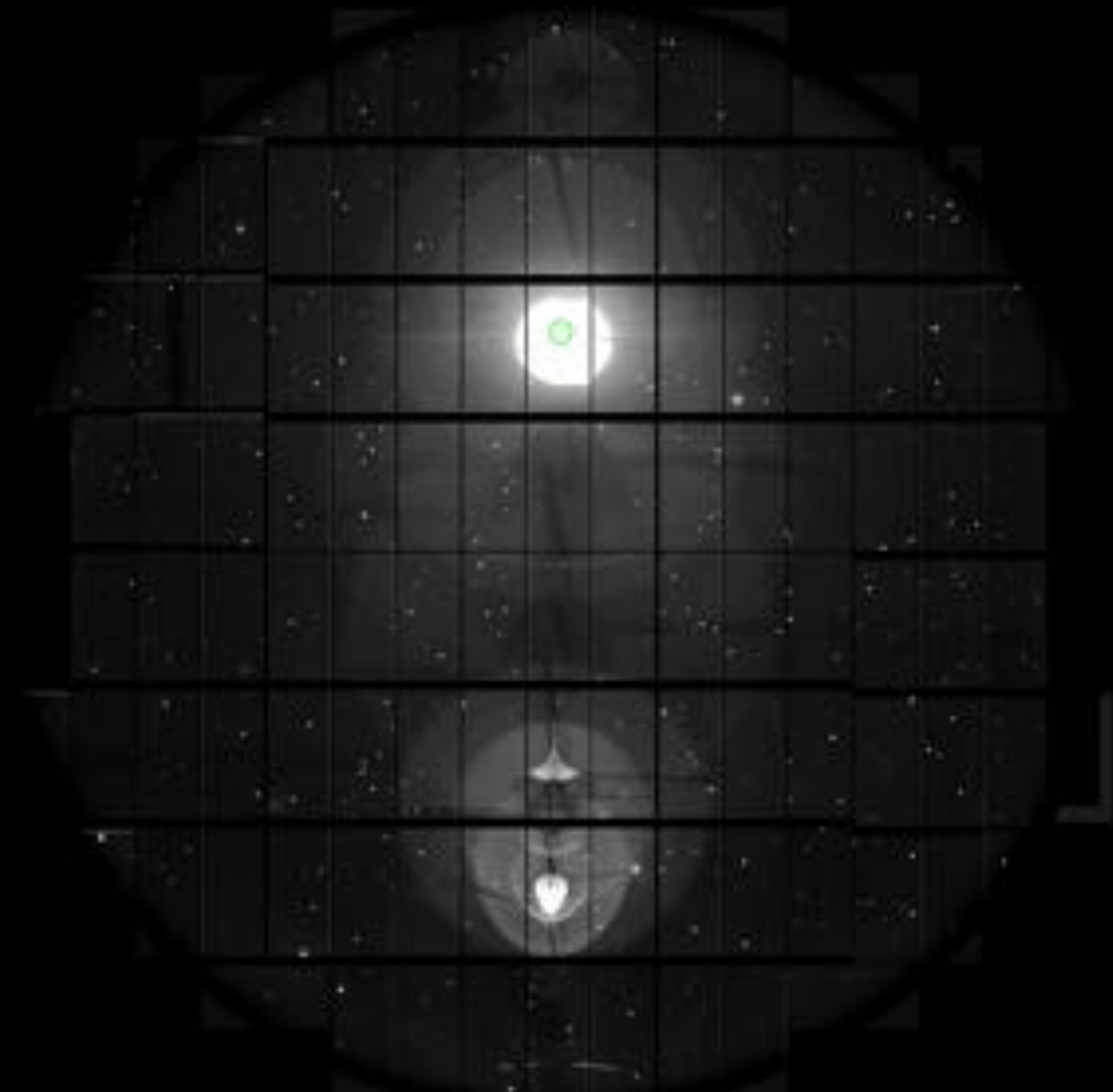
Ghosts



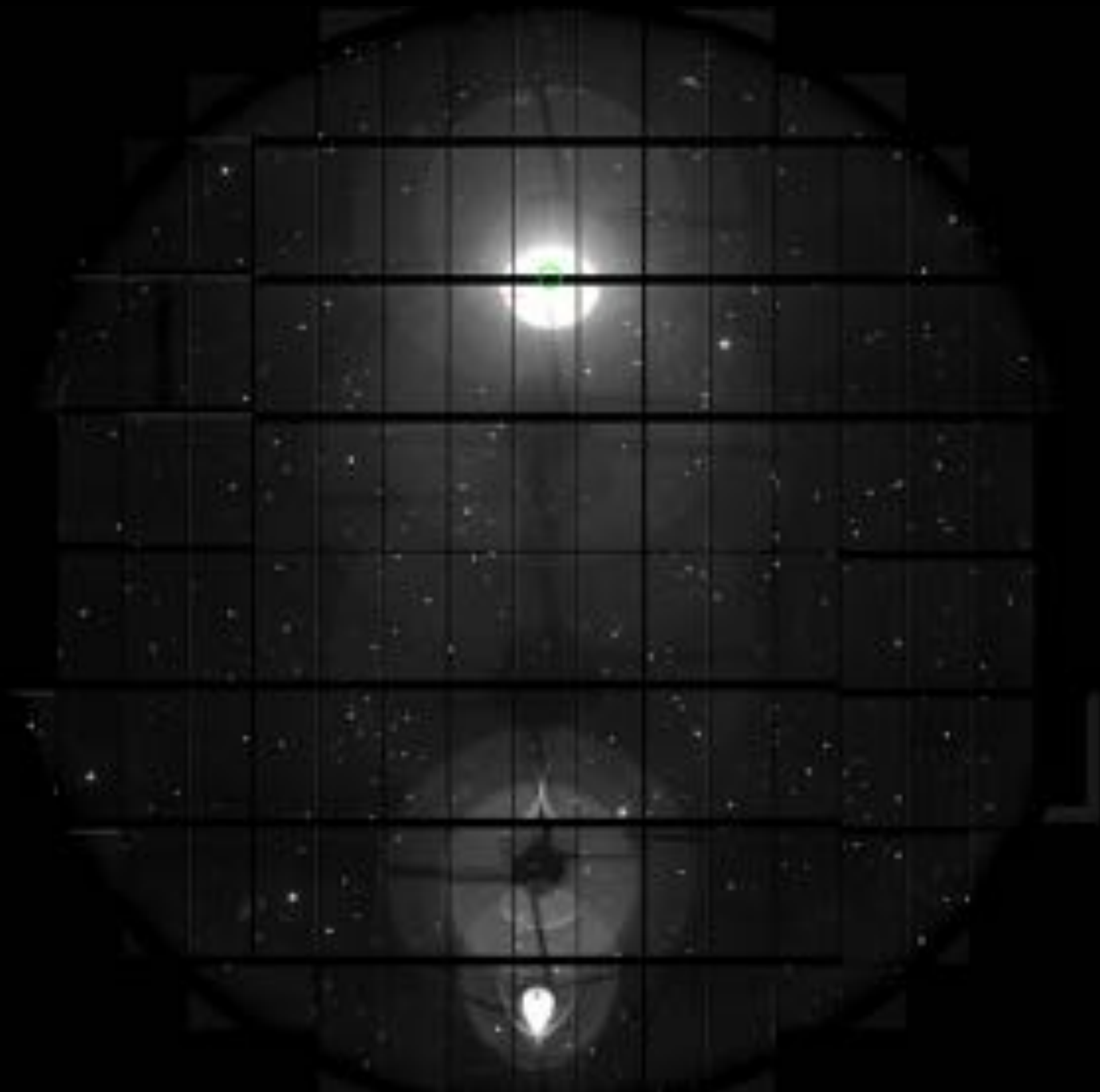
Ghosts



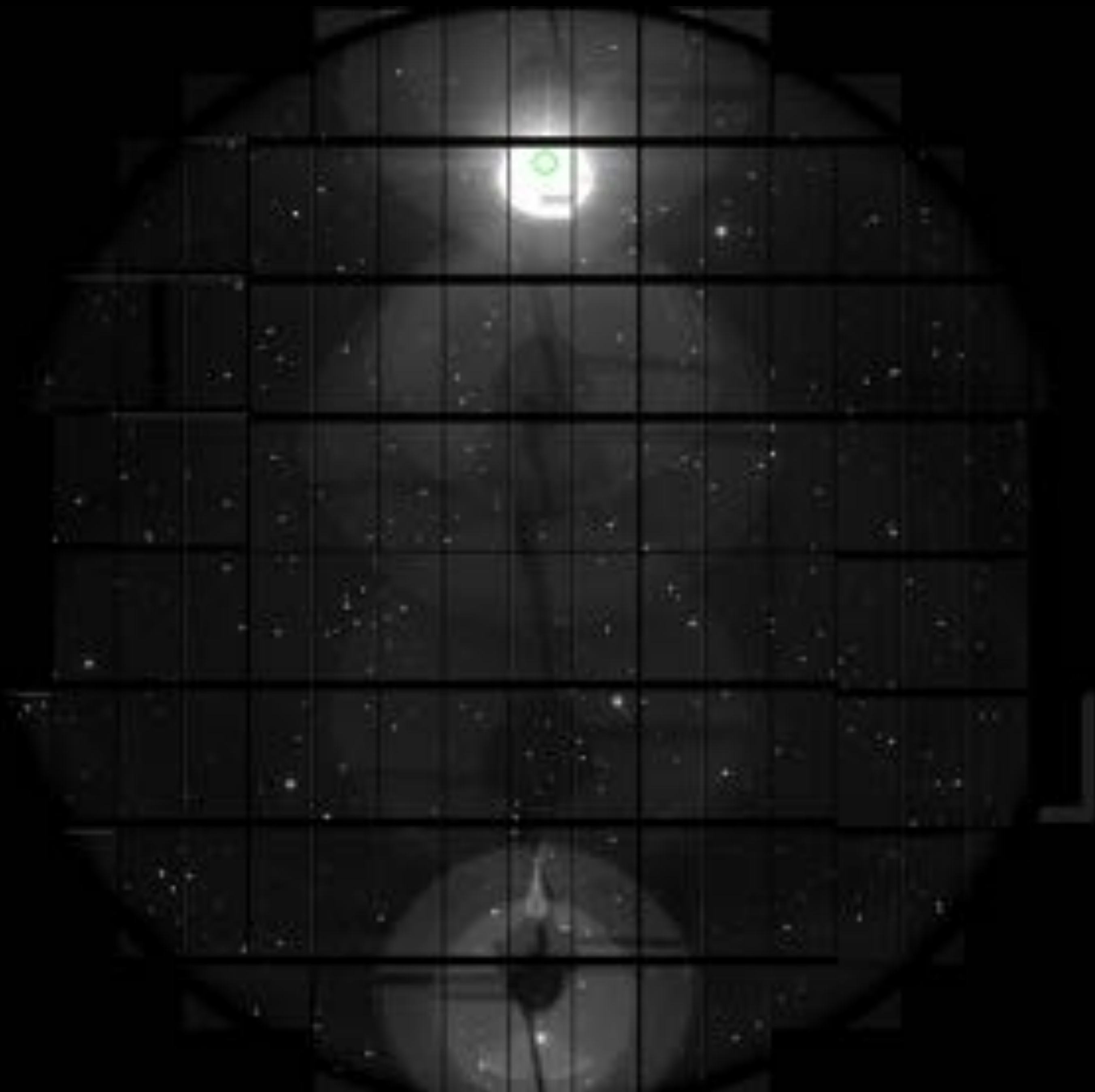
Ghosts



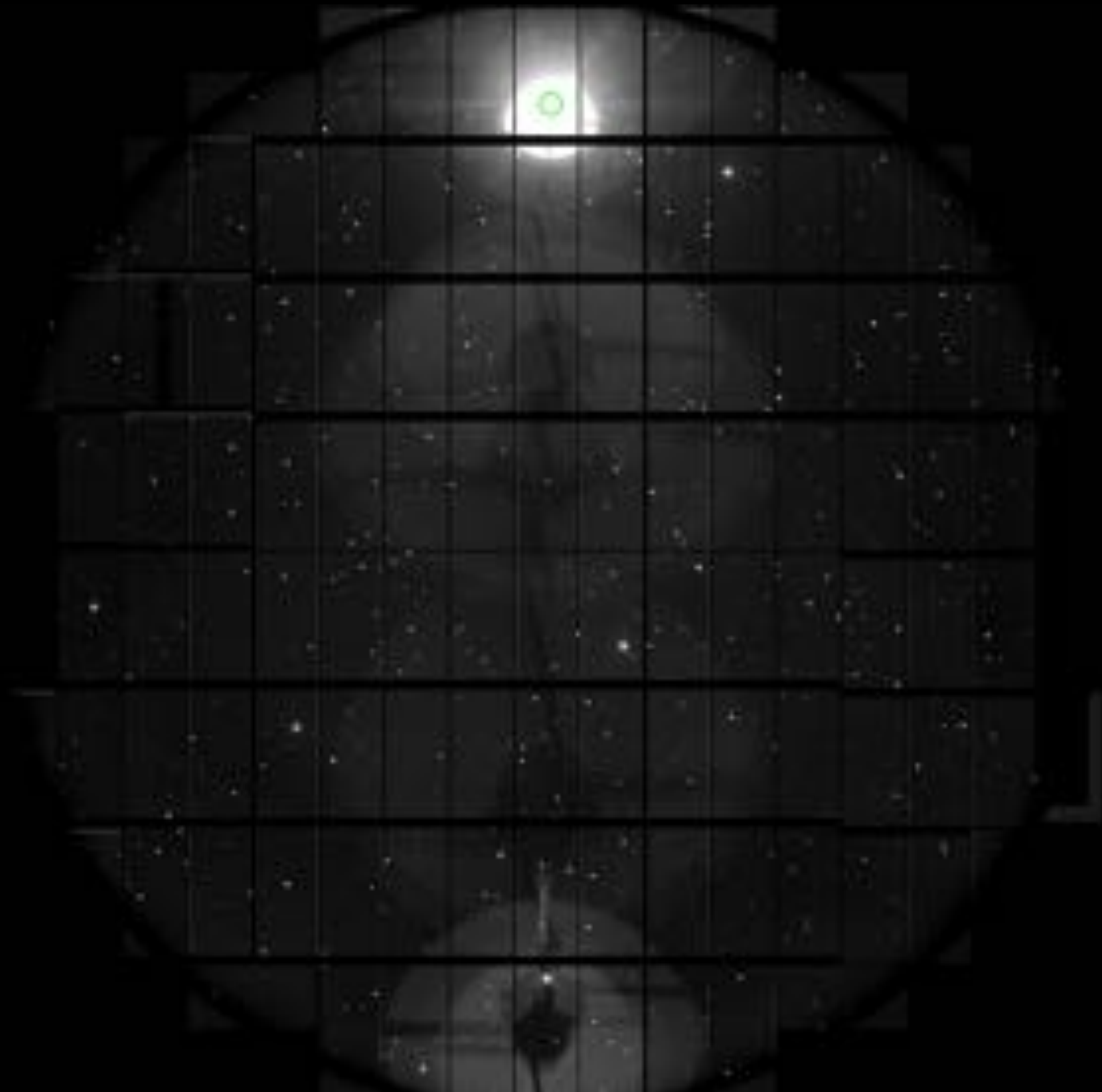
Ghosts



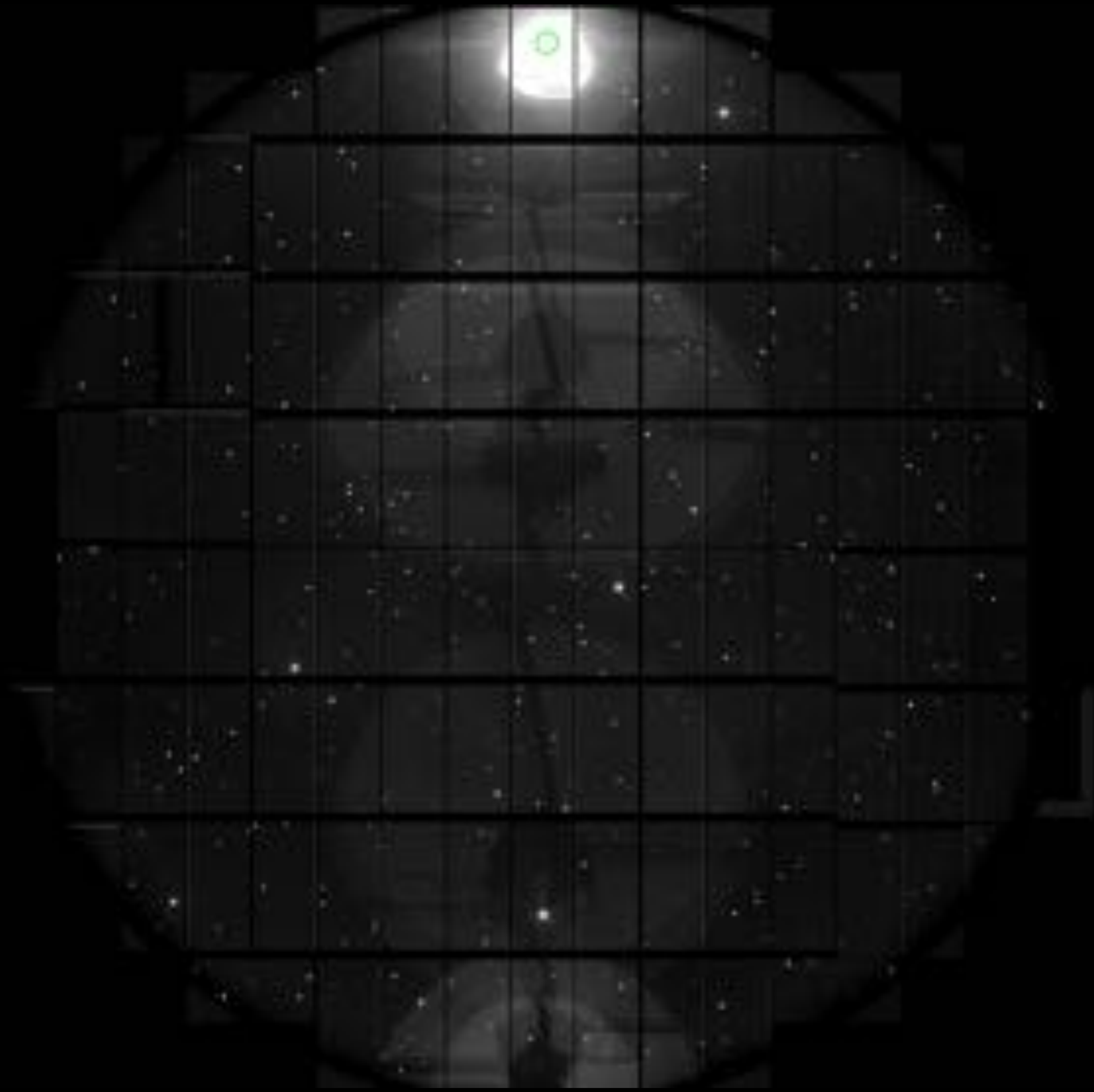
Ghosts



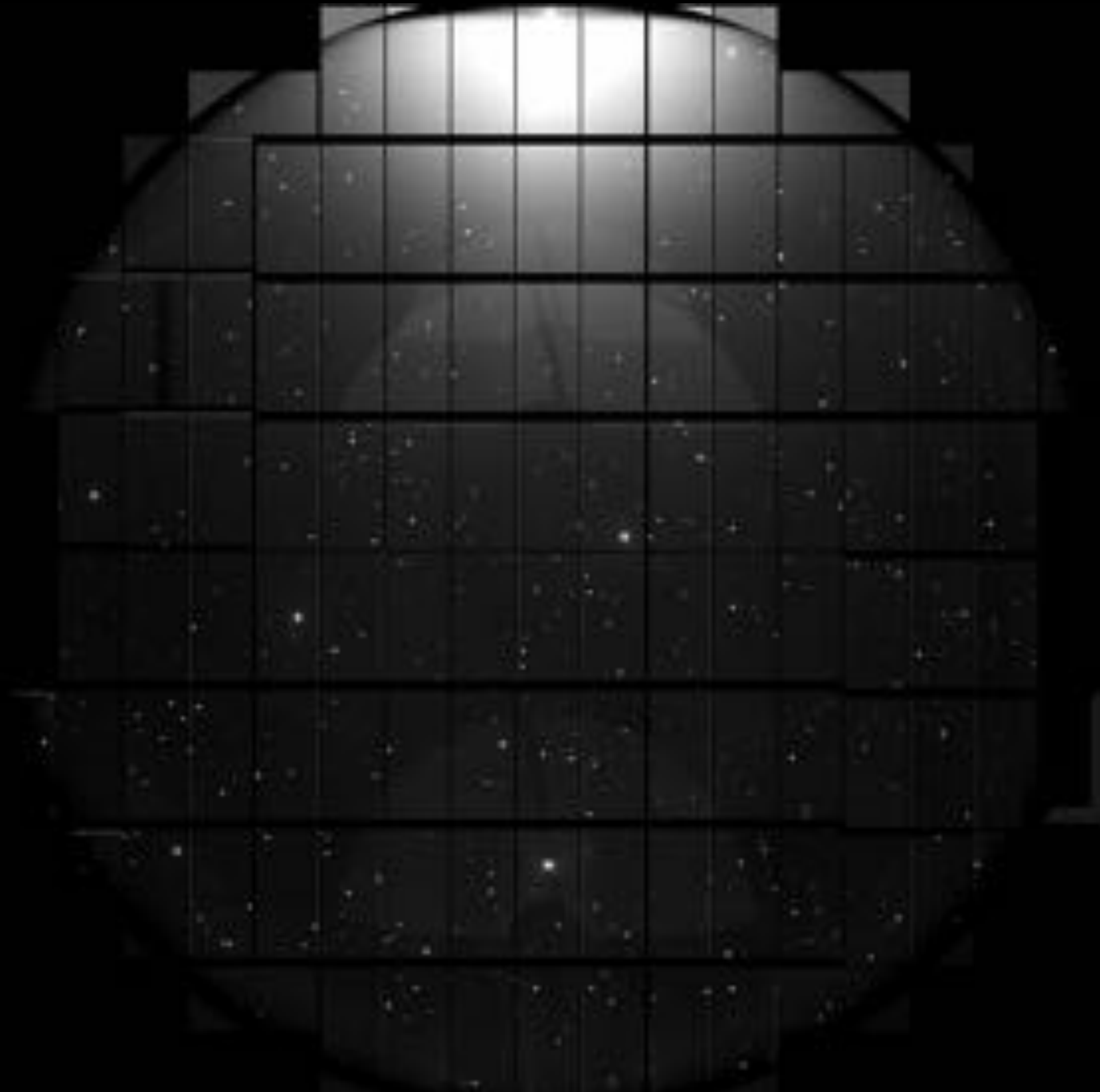
Ghosts



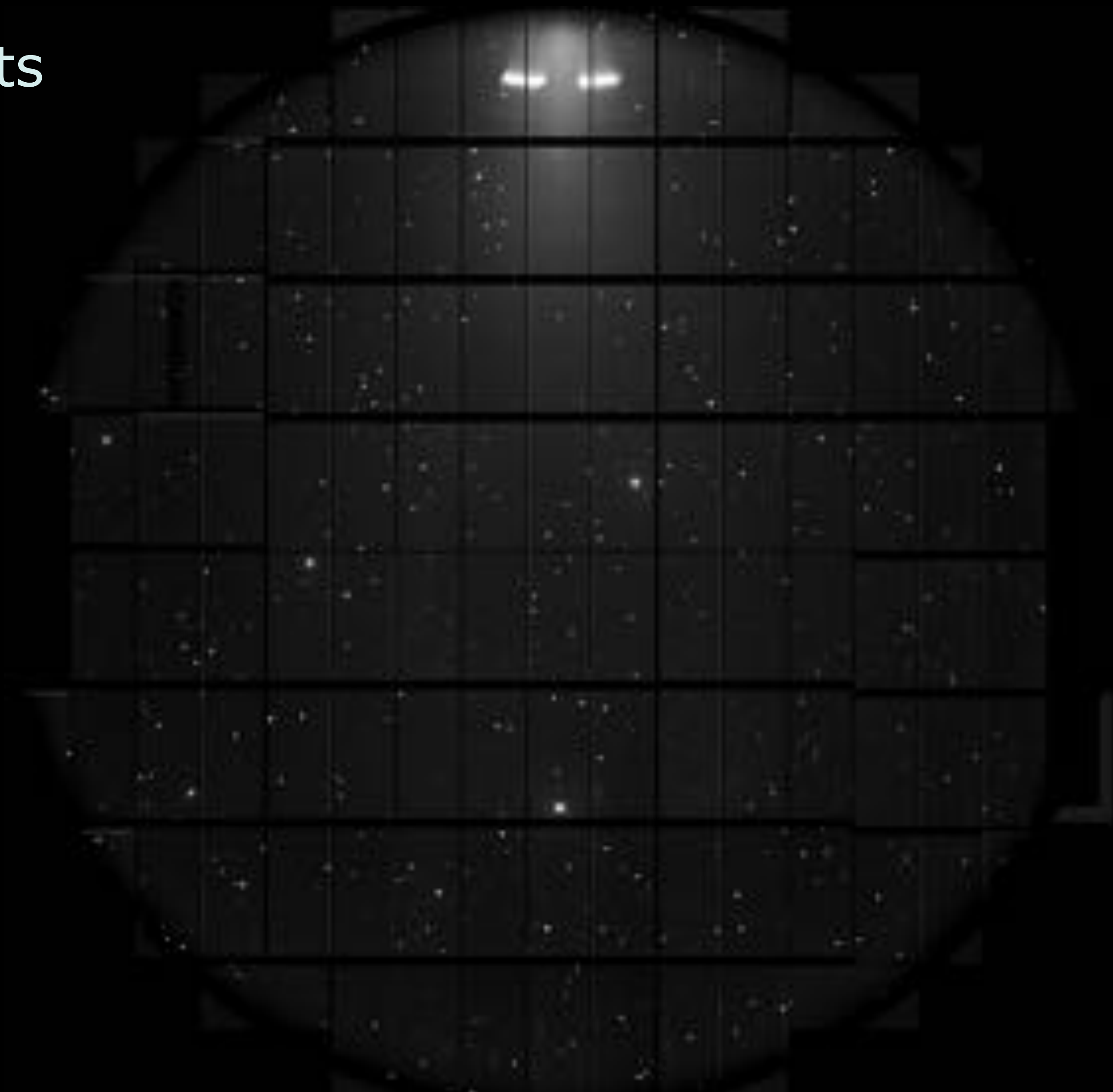
Ghosts



Ghosts



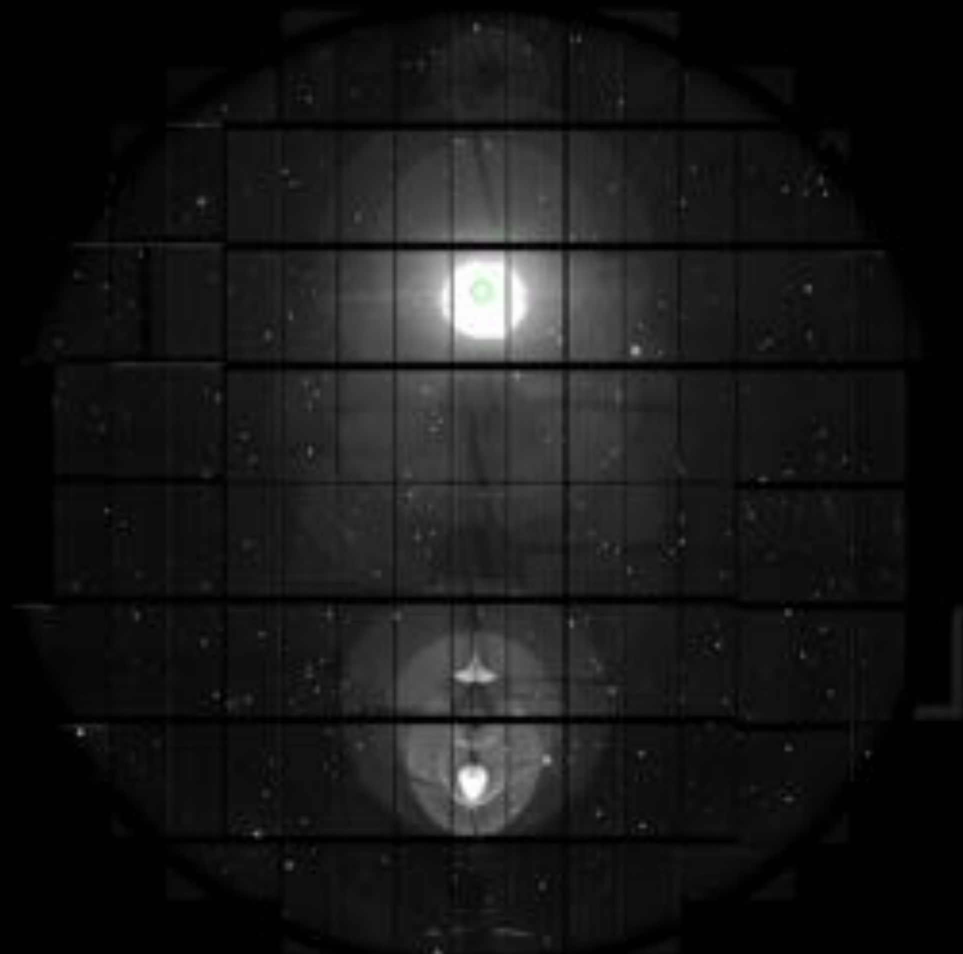
Unimaged ghosts
glints



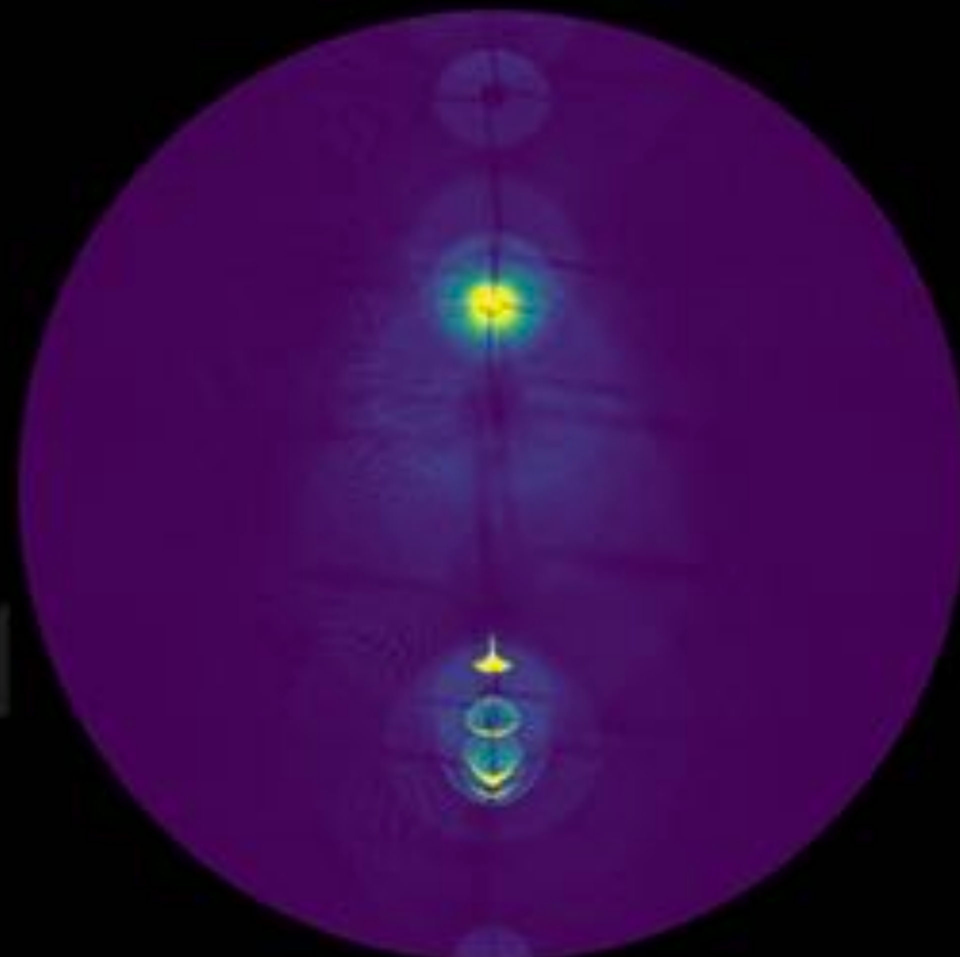
Unimaged ghost glints

Unimaged ghost glints

Ghosts can---in theory---be predicted and subtracted off
Glints cannot



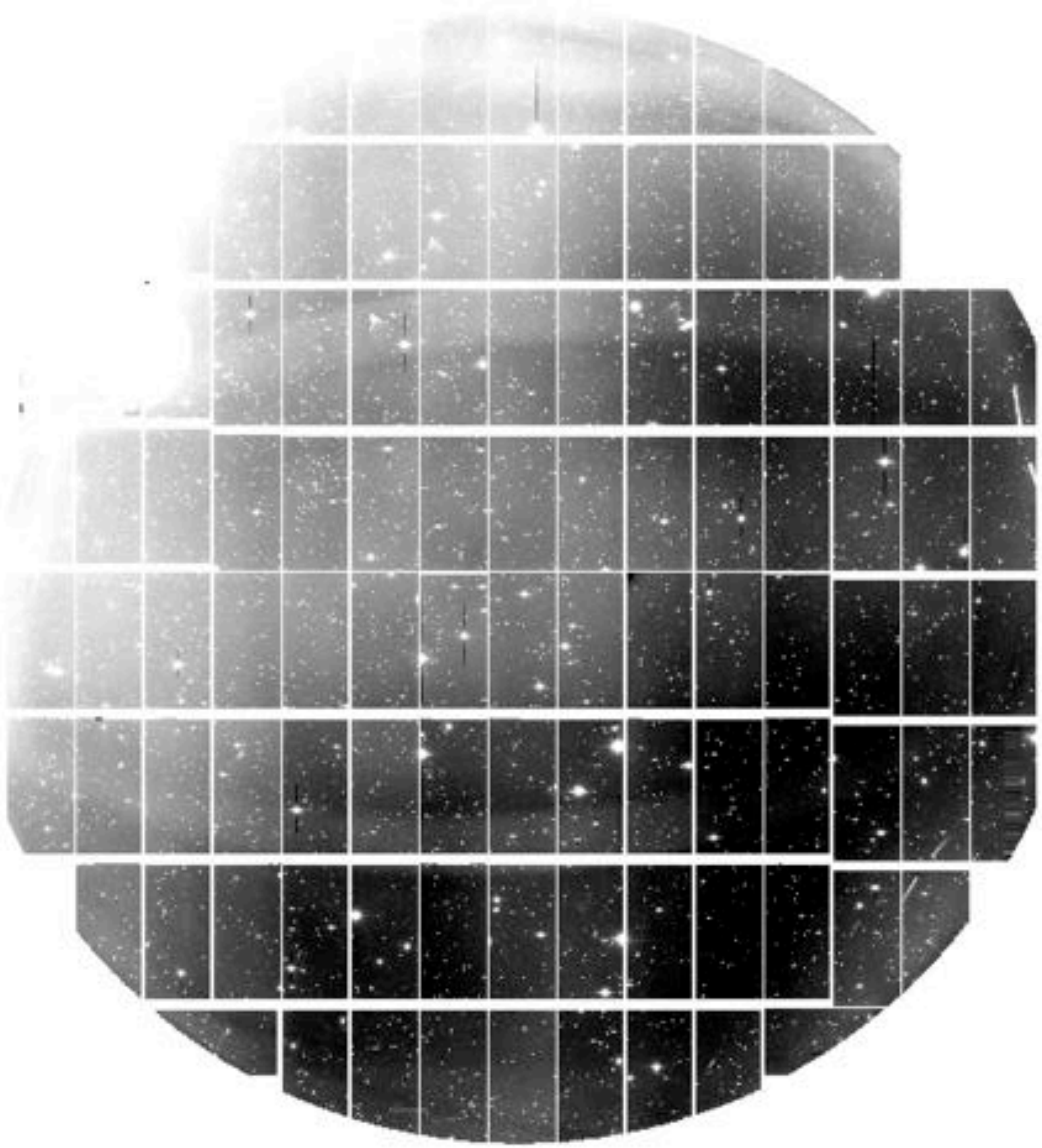
HSC Arcturus
Actual



Batoid Arcturus
Prediction

Image: Josh Meyers
https://github.com/jmeyers314/batoid

MISC



16 HSC-Y visits taken in 20215

Reflected light from an IR LED encoder

Background Estimation bridges flat fielding and deblending

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Flat fielding → Background Subtraction → Deblending

Approaches to background estimation in practice

Per-CCD background estimation

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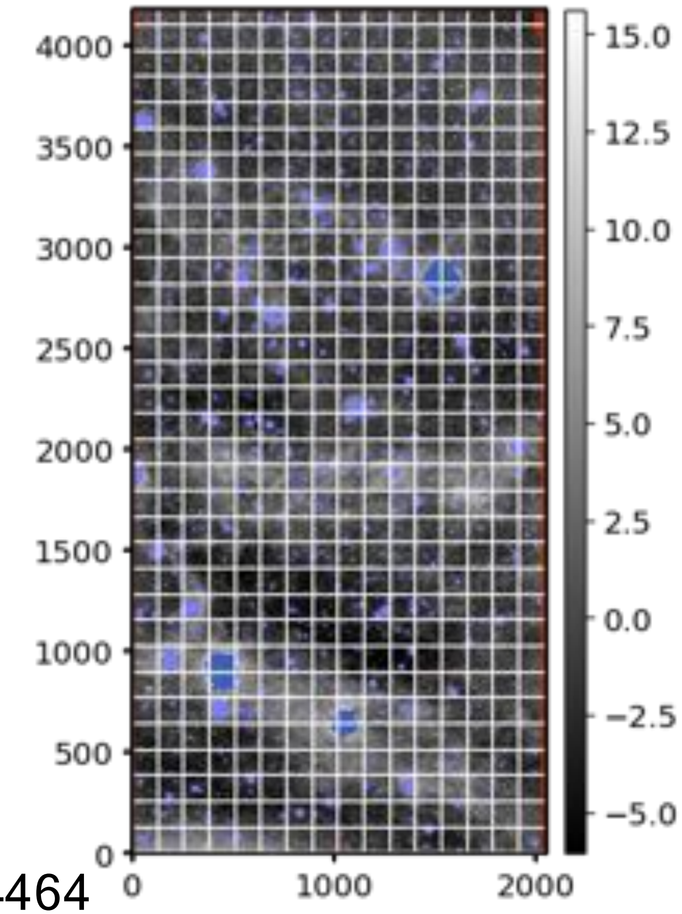
post-ISR CCD (after detrending)

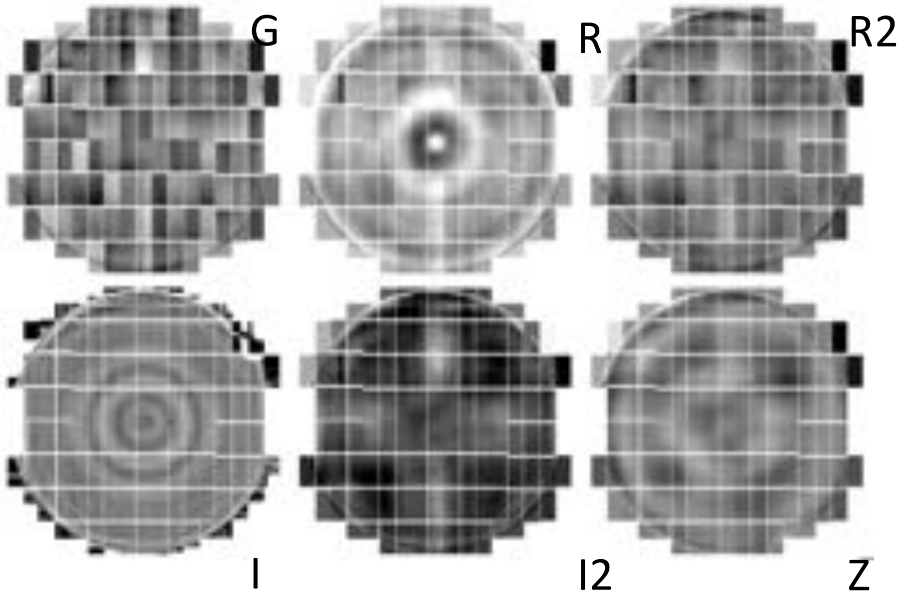


HSC
VISIT = 34464
CCD = 81

Local Background

Background-subtracted

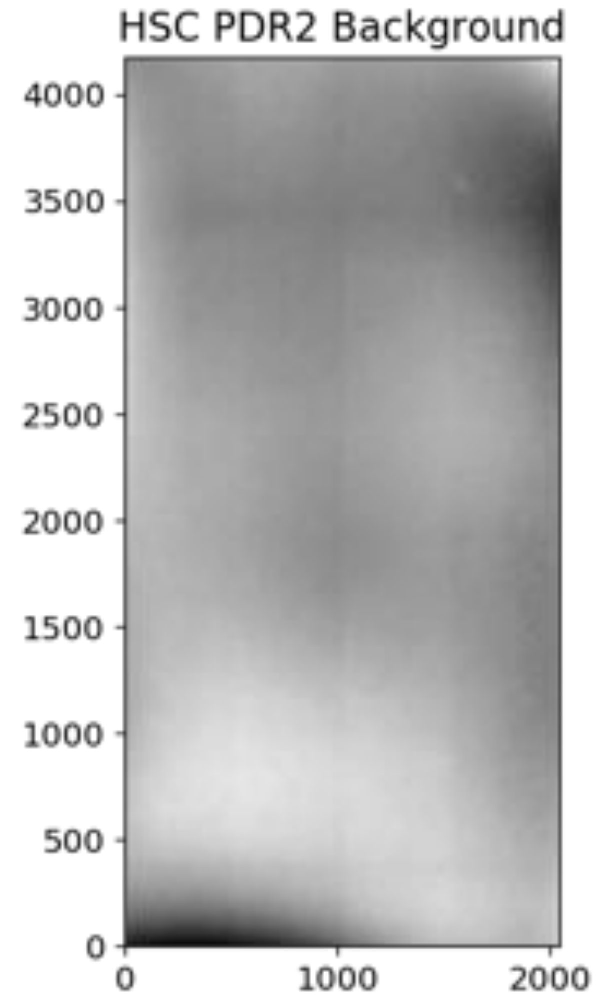
Full focal Plane background model



Median HSC background
Figure: Paul Price

Model full focal plane background (aka. SkyCorr, PDR2 background):

1. Subtract a large-scale 8192-pix background (coordinated across the entire focal plane). Picks up large-scale features that vary from exposure to exposure.
2. Subtract a sky frame from the exposure (with the normalization of the sky frame coordinated across CCDs within the exposure). Picks up small-scale features that are constant between exposures.



Full focal Plane background model
Robust PCA

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- Inspired by DES, Bernstein+17: apply the Robust PCA algorithm from Candes+11:

$$X = L + S$$

It reduces the residual background relative to ”SkyCorr,” however not perfect

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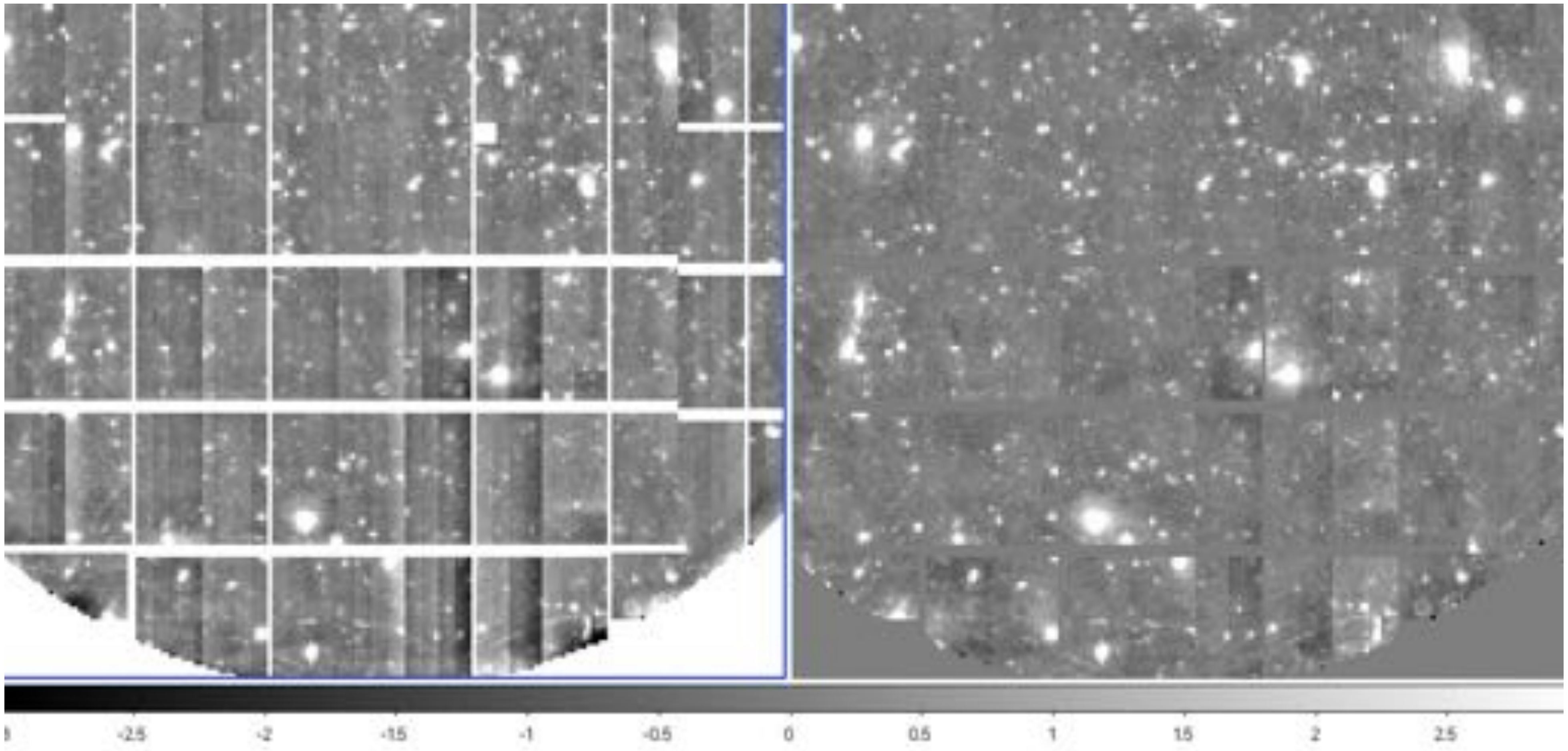
8192pix bins + A * median sky frame

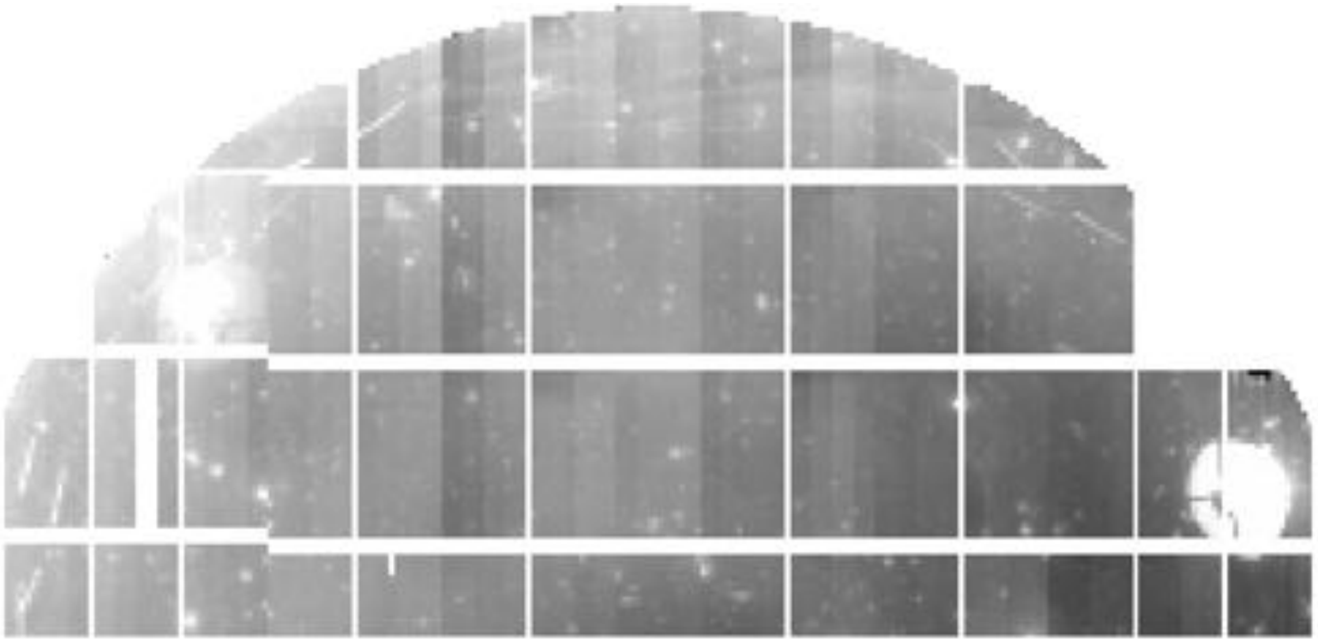
Robust PCA prototype



What can go wrong?

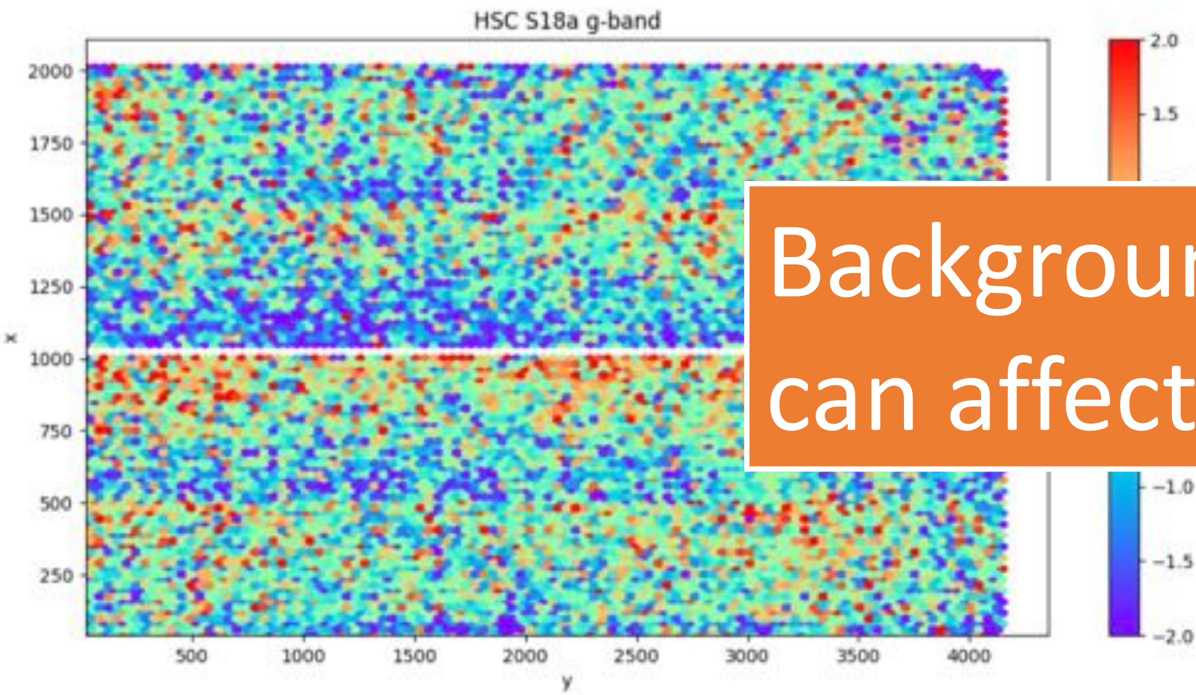
Image Credit: Nate Lust
HSC COSMOS gri

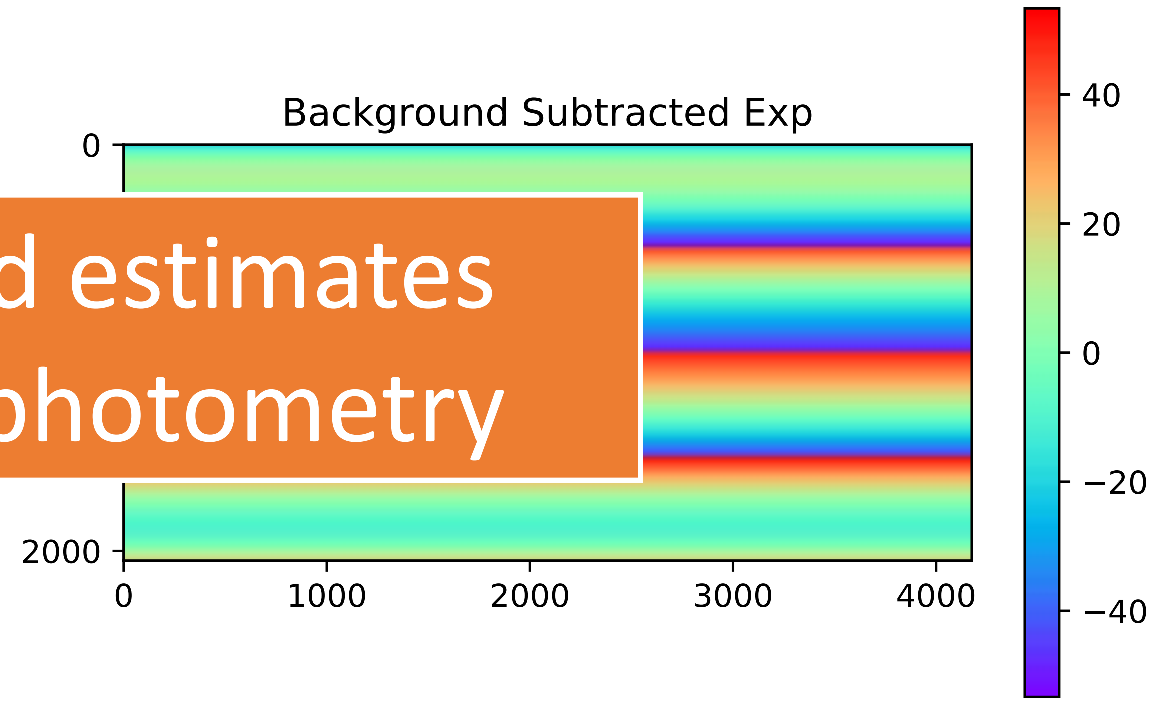
1) Modeling sharp features (instrumental) with a smooth model



1) Modeling sharp features (instrumental) with a smooth model

Rubin Observatory



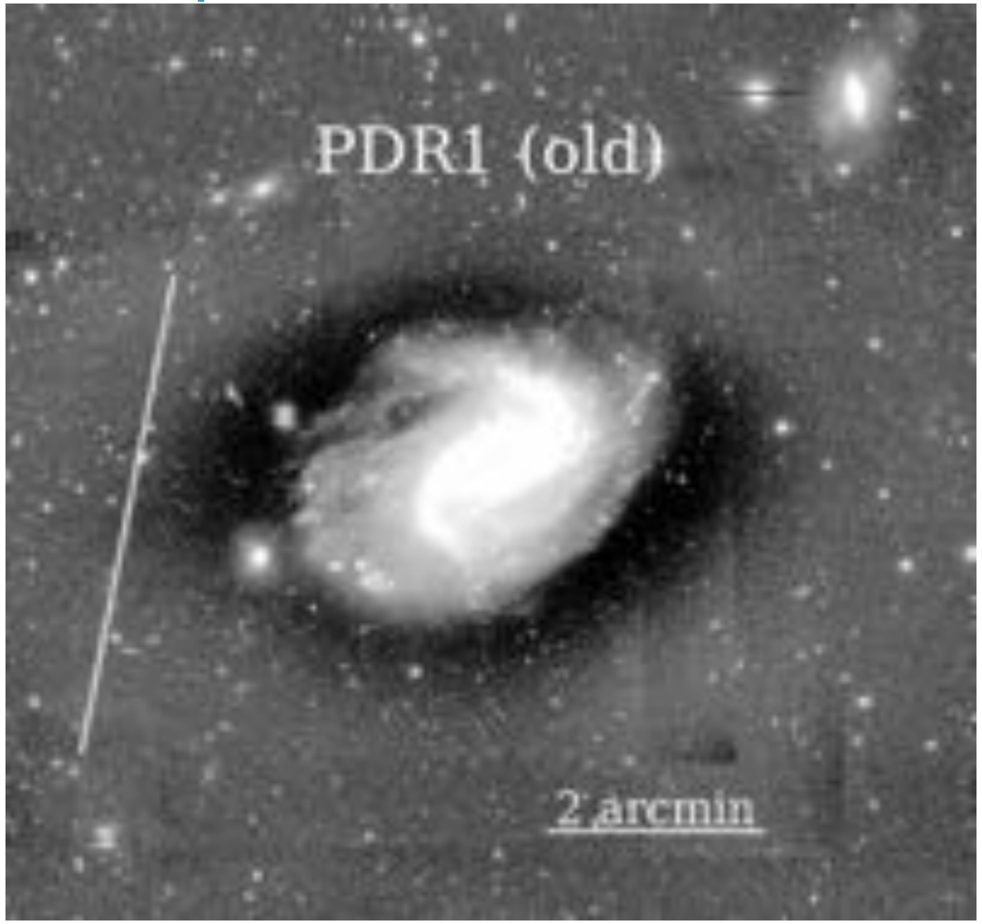


Background estimates can affect photometry

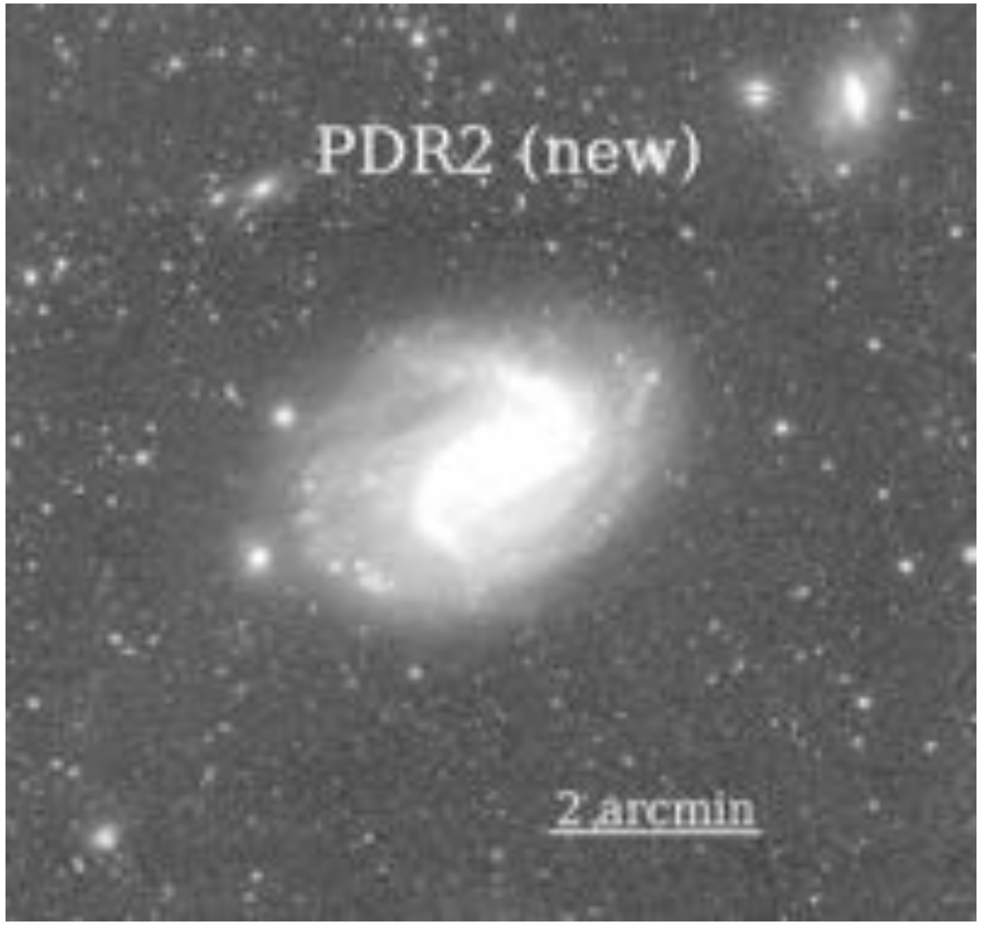
g-band photometric residuals stacked by CCD
Figure: Eli Rykoff

Low Surface Brightness community was happy with PDR2 full focal plane model but it left too much to the deblender

Rubin Observatory



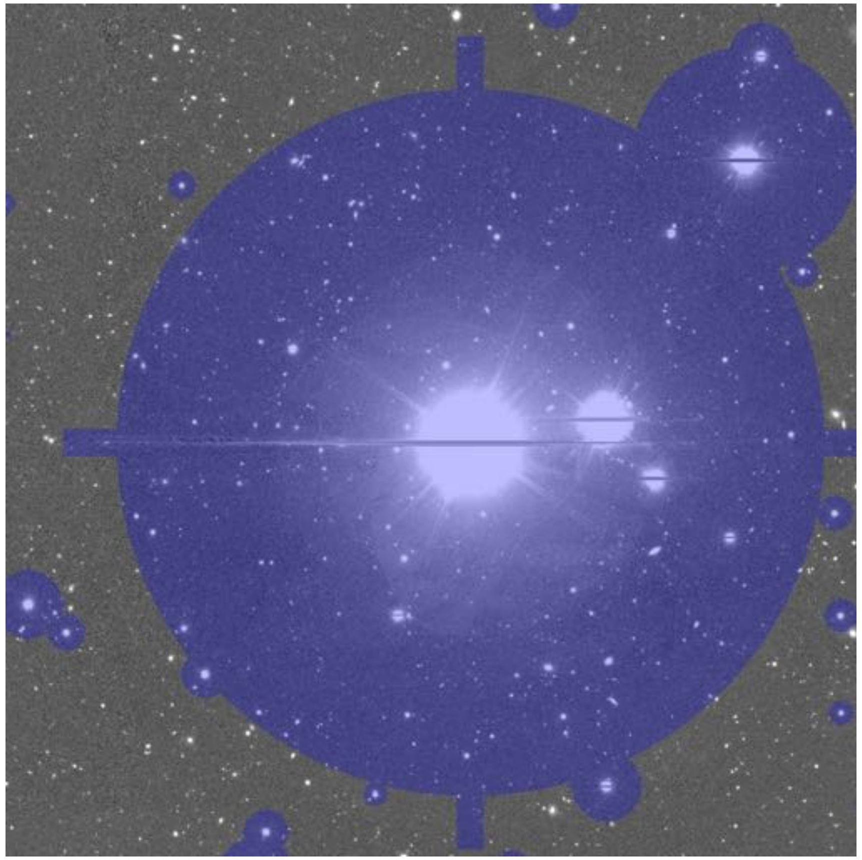
Coadd with
PDR1 Local Background subtraction

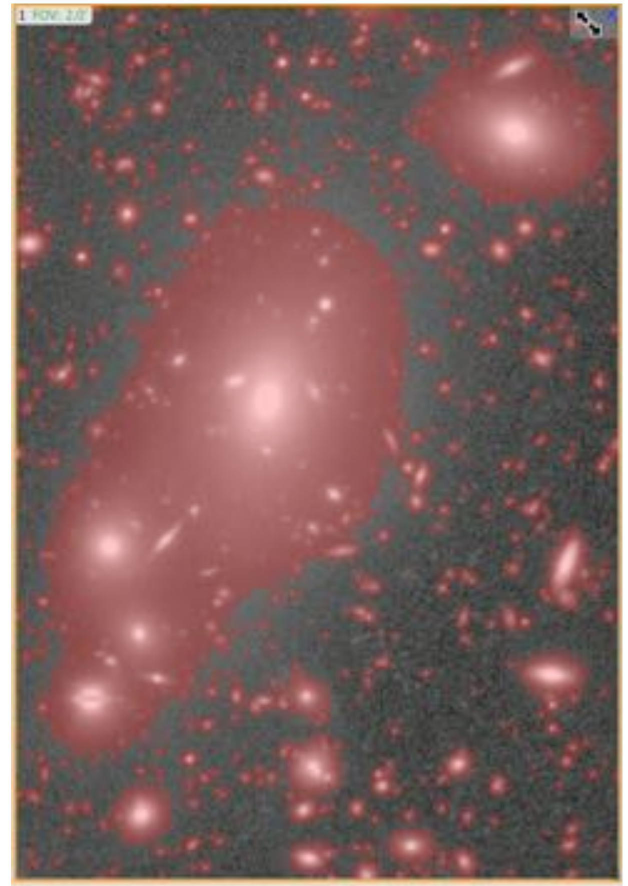


Coadd with
PDR2 Focal Plane Background subtraction

Aihara+19 (PDR2 release paper)

But everyone else was unhappy





As an aside: backgrounds due to bright stars are sufficiently problematic that we work to model and subtract them

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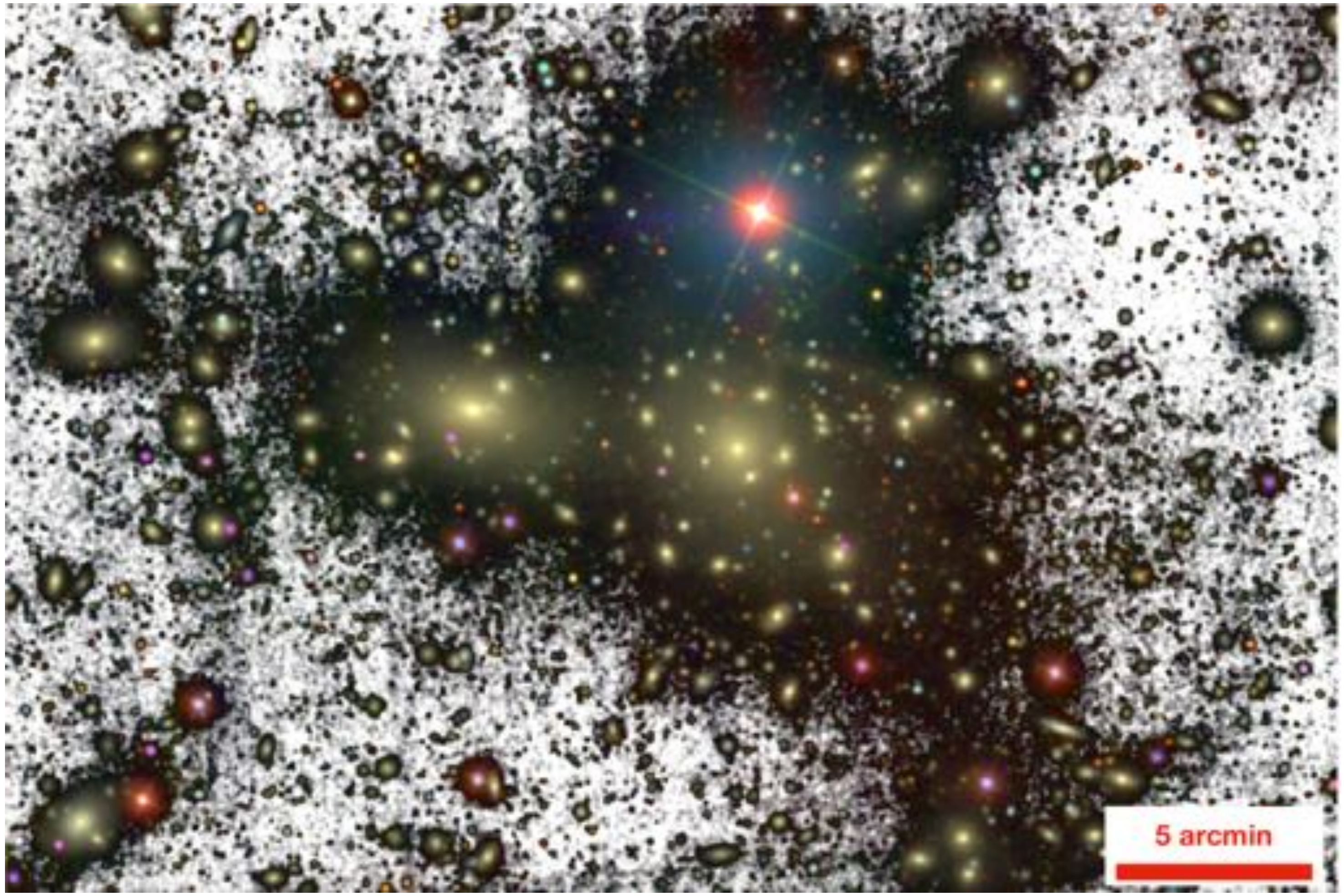

Figure:
Coma Cluster
SDSS Stripe82
Infante-Sainz+19

Recover area in wings of bright stars by modeling and subtracting

Rubin Observatory

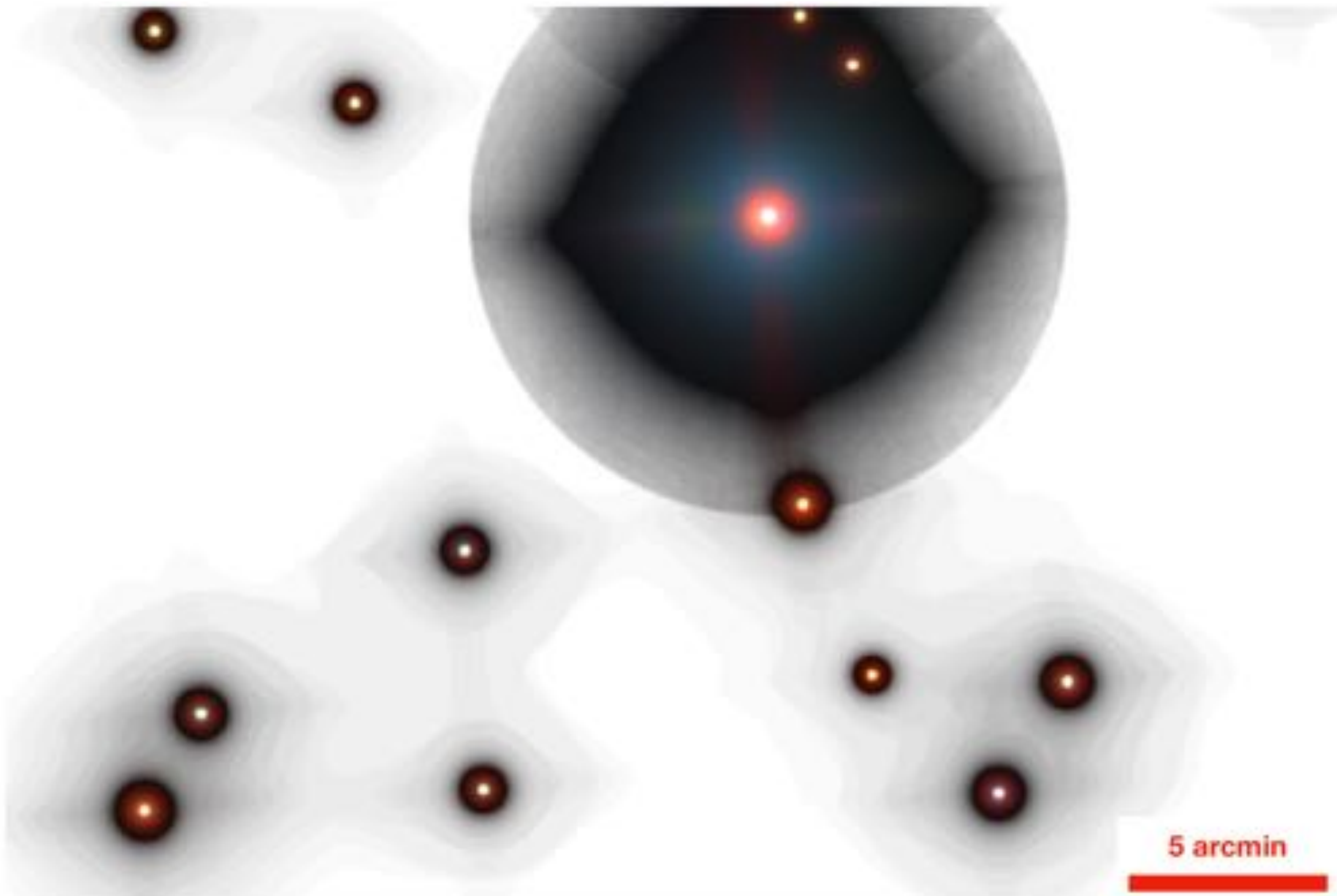

Figure:
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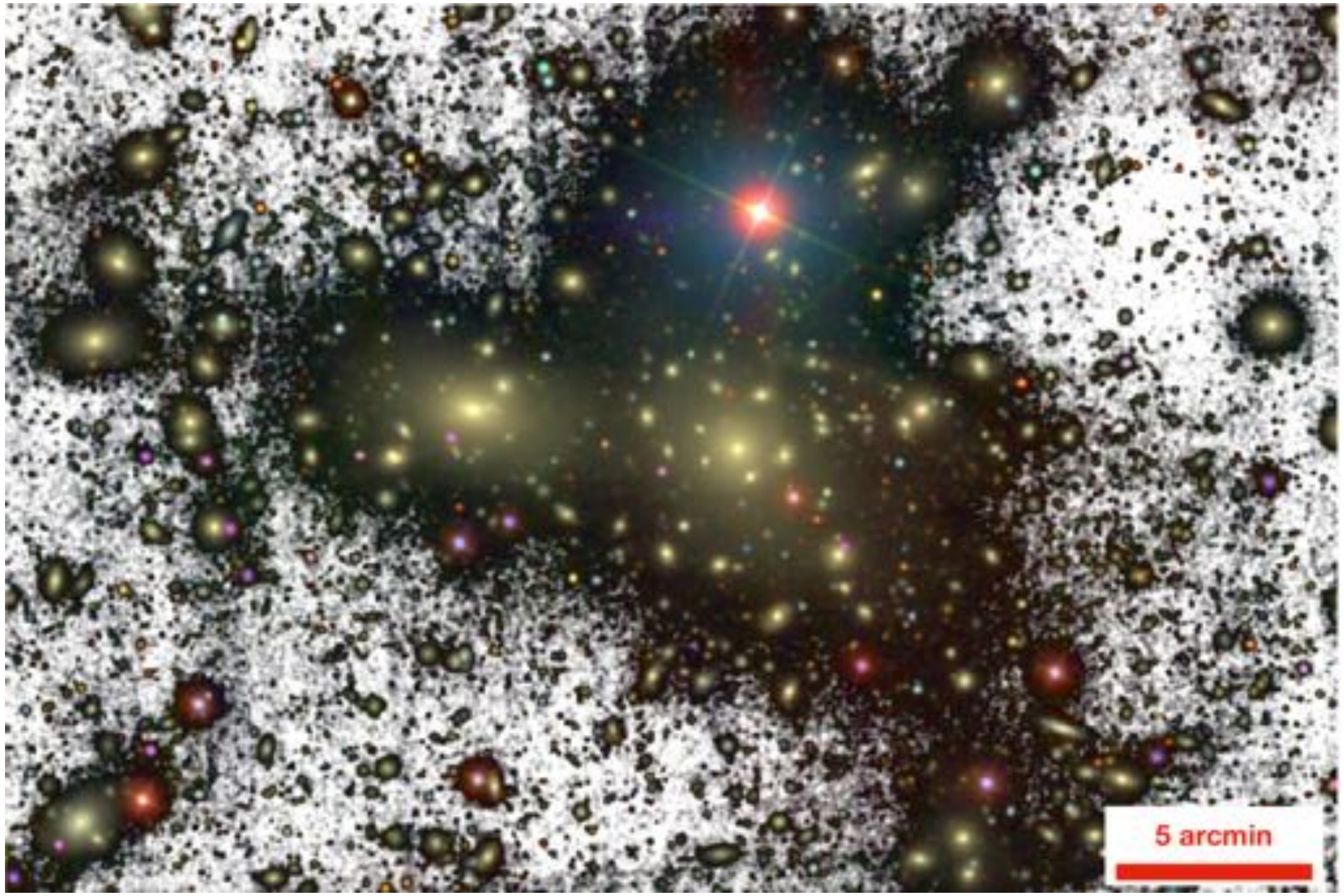

Figure:
Coma Cluster
SDSS Stripe82
Infante-Sainz+19

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Recover area in wings of bright stars by modeling and subtracting

Rubin Observatory

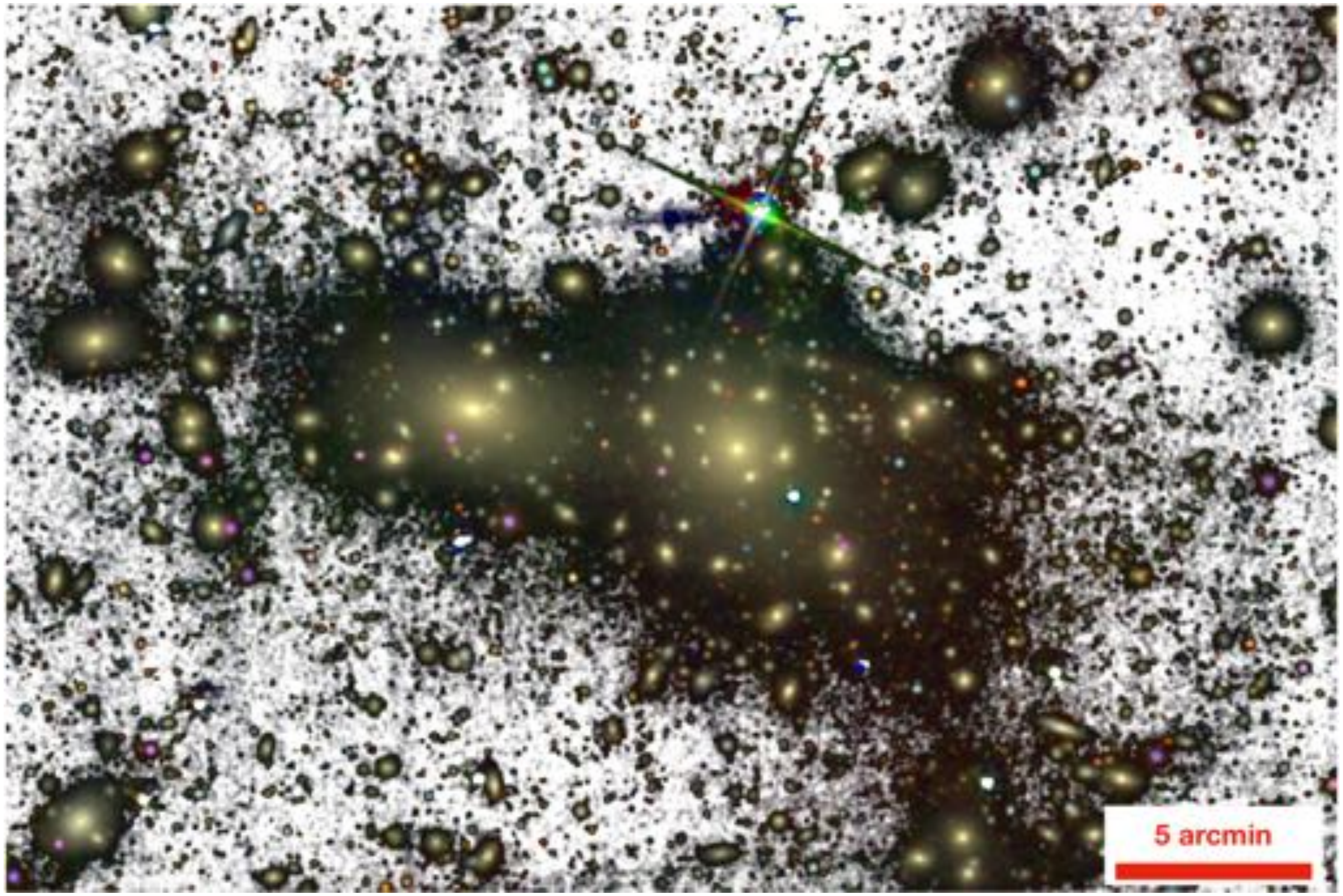
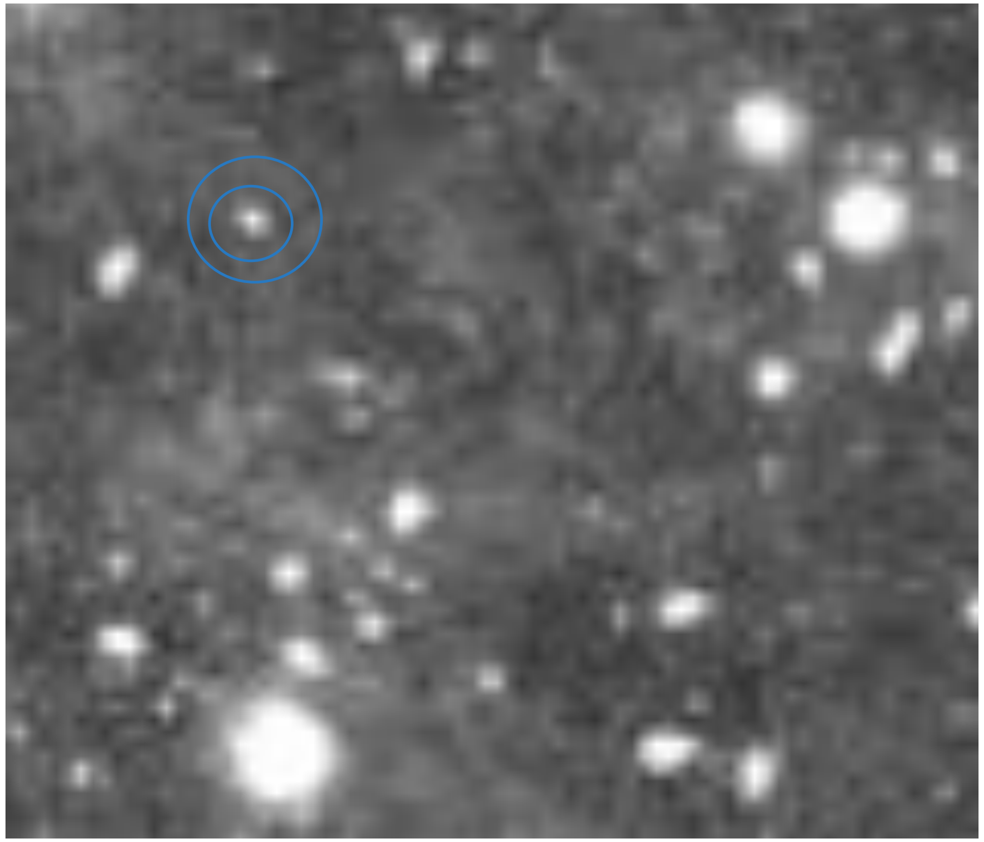


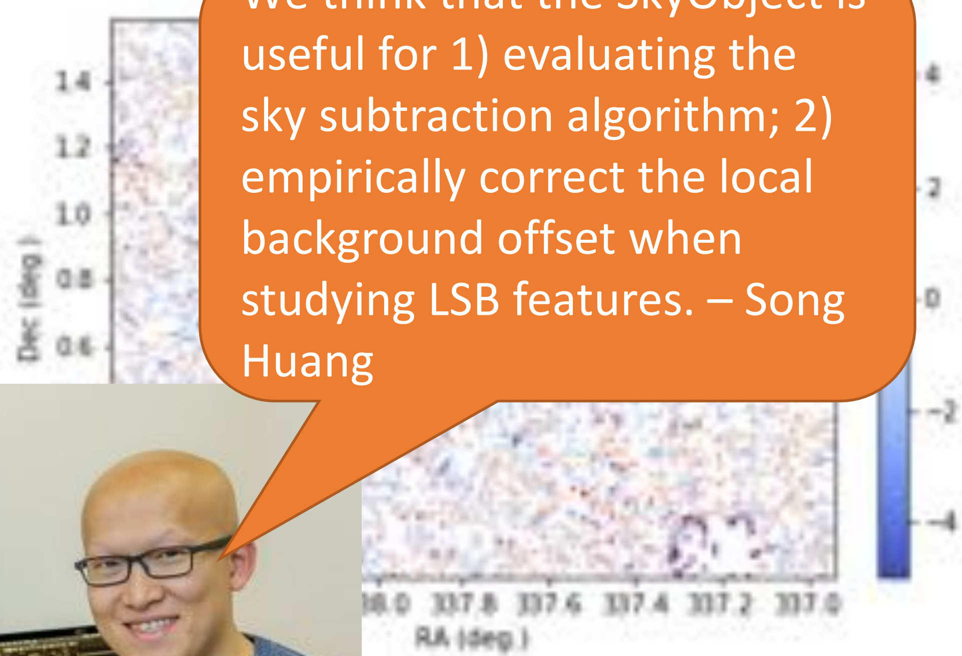
Figure:
Coma Cluster
SDSS Stripe82
Infante-Sainz+19

Catalogs have breadcrumbs that may be useful: **extra columns** as **Sky Annuli**



Rubin Catalogs will contain **extra rows** such as **Sky Objects**

Rubin Observatory



We think that the SkyObject is useful for 1) evaluating the sky subtraction algorithm; 2) empirically correct the local background offset when studying LSB features. – Song Huang

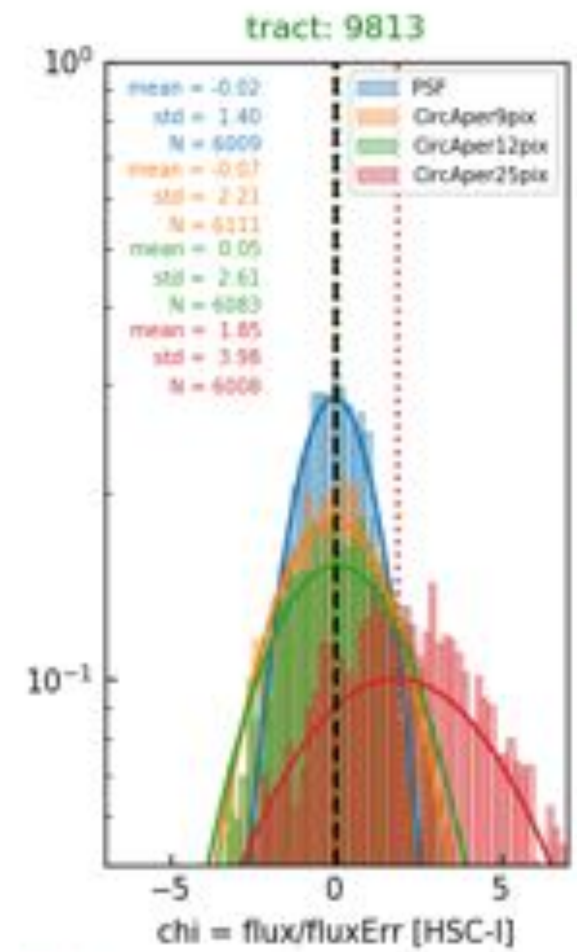


Image Credit: Lauren MacArthur

"The distinction between signal and background is in the eyes of the beholder"
– Bernstein+17

One woman's garbage is another's treasure

- Before you subtract a background, ask yourself what spatial scales are background vs. signal
- You can do this iteratively, subtract off largest scales first, then increasingly smaller. You can add layers add back in to measure objects of various scales.
- Asking the deblender to deblend images with a 8192 pixel scale background shrunk our clean photometric sample of regular, non-diffuse galaxies.
- Background estimates affect photometry
- When using catalogs check for Sky Objects and Sky Annuli to get insight into backgrounds.
- If you're curious about Rubin's plans for background subtraction, I'm happy to answer during the Q&A.