Rubin Observatory

Background Estimation

Yusra AlSayyad and the DRP team

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SLAC

CHARLES AND LISA SIMONYI FUND FOR ARTS AND SCIENCES

LSST CORPORATION

Look, background subtraction is easy, right?!
Just remove the additive offset

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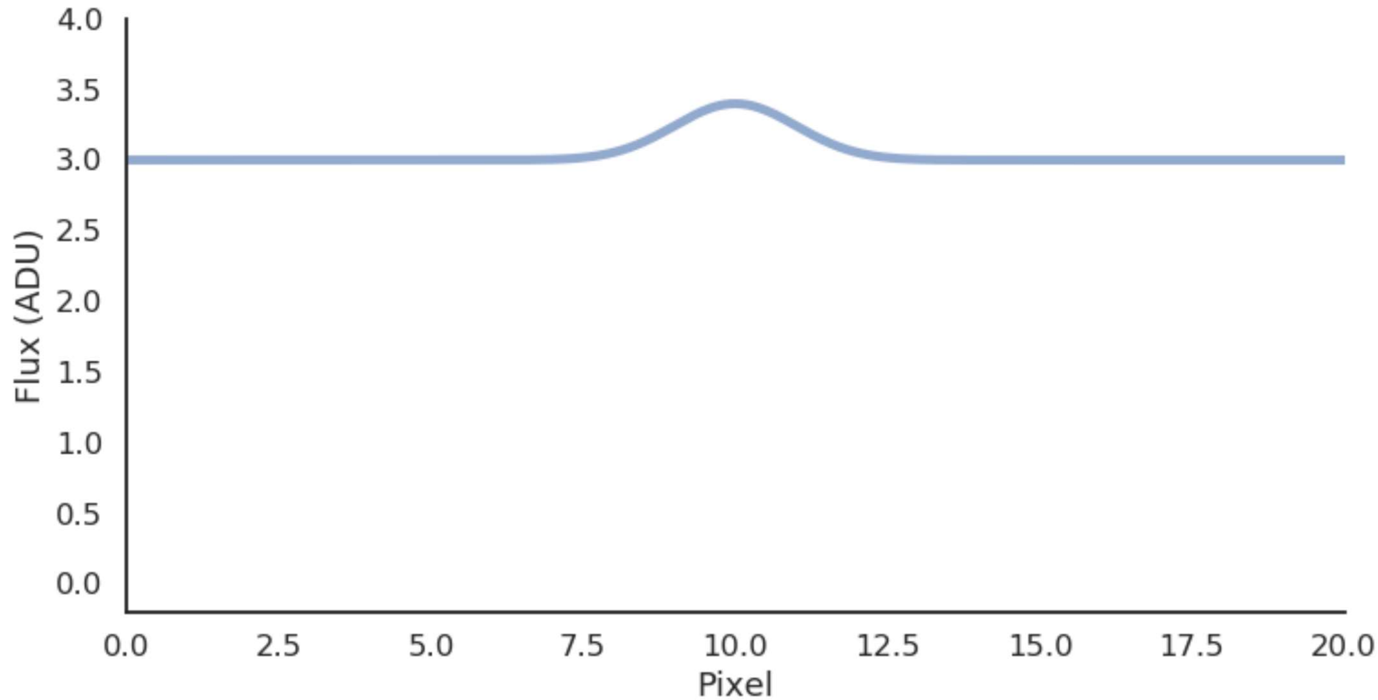

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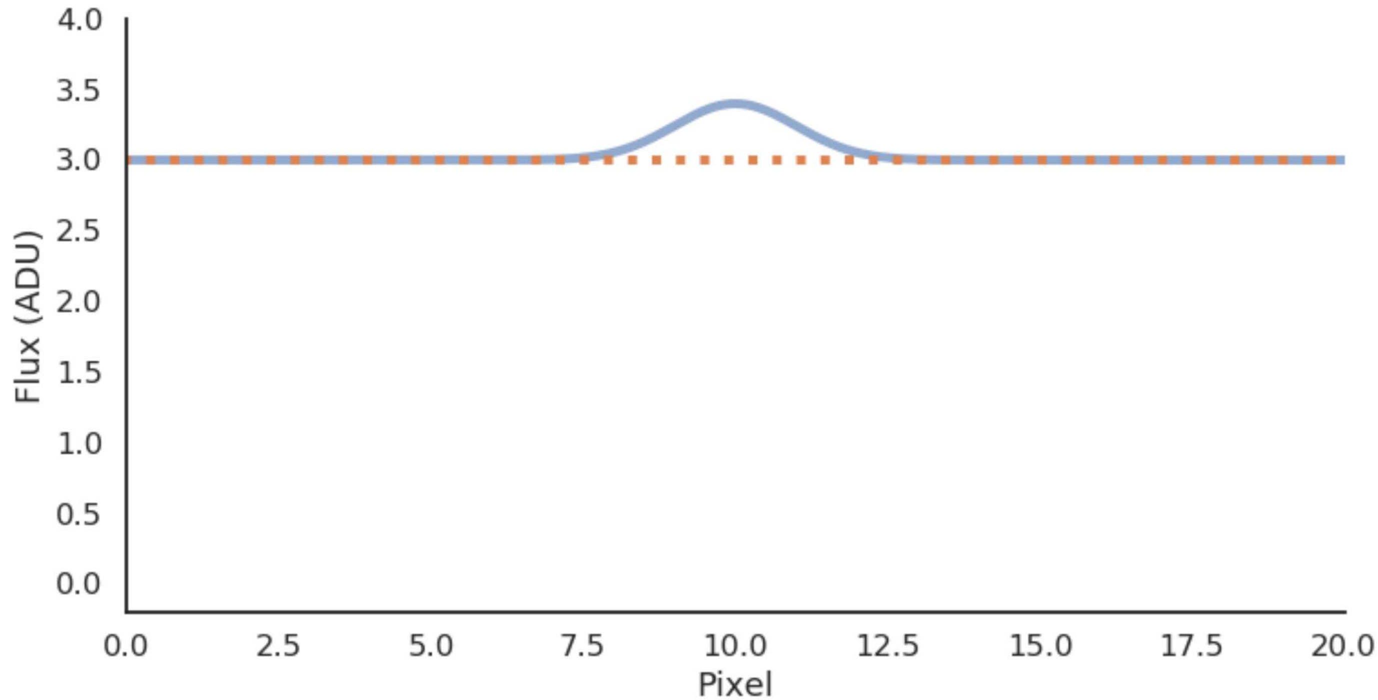

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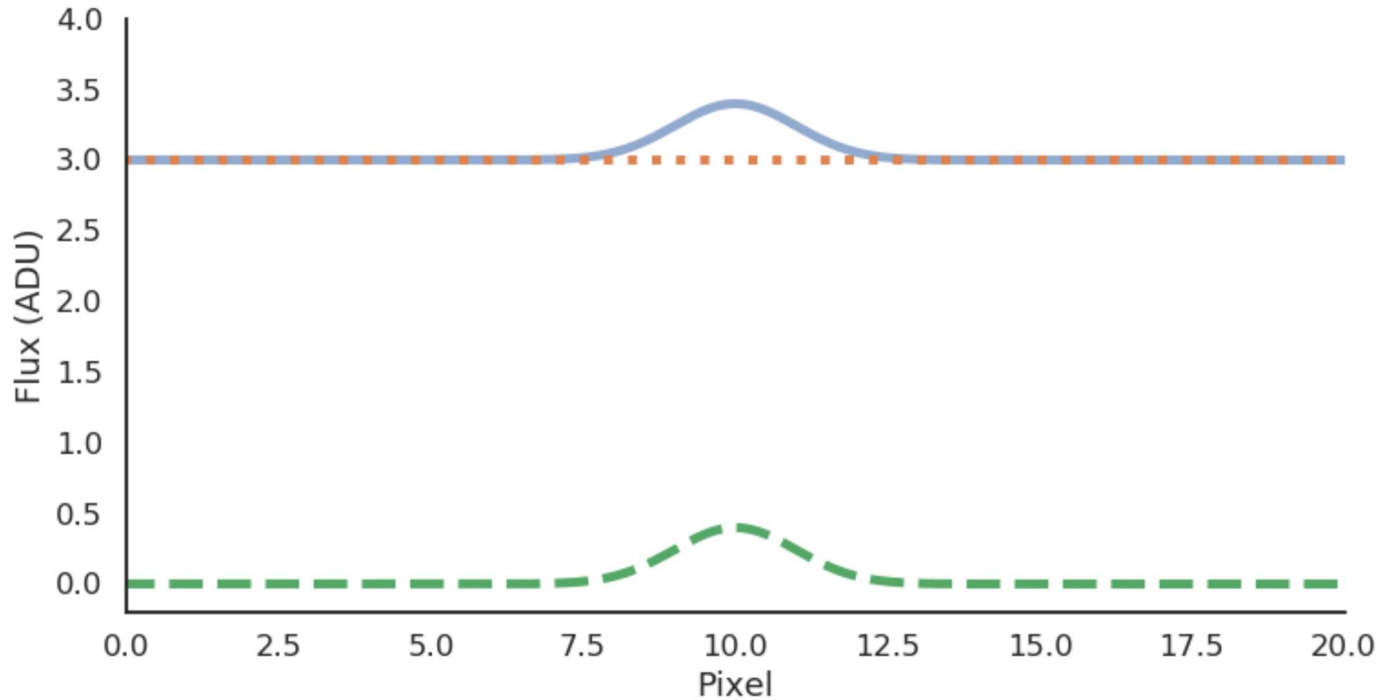

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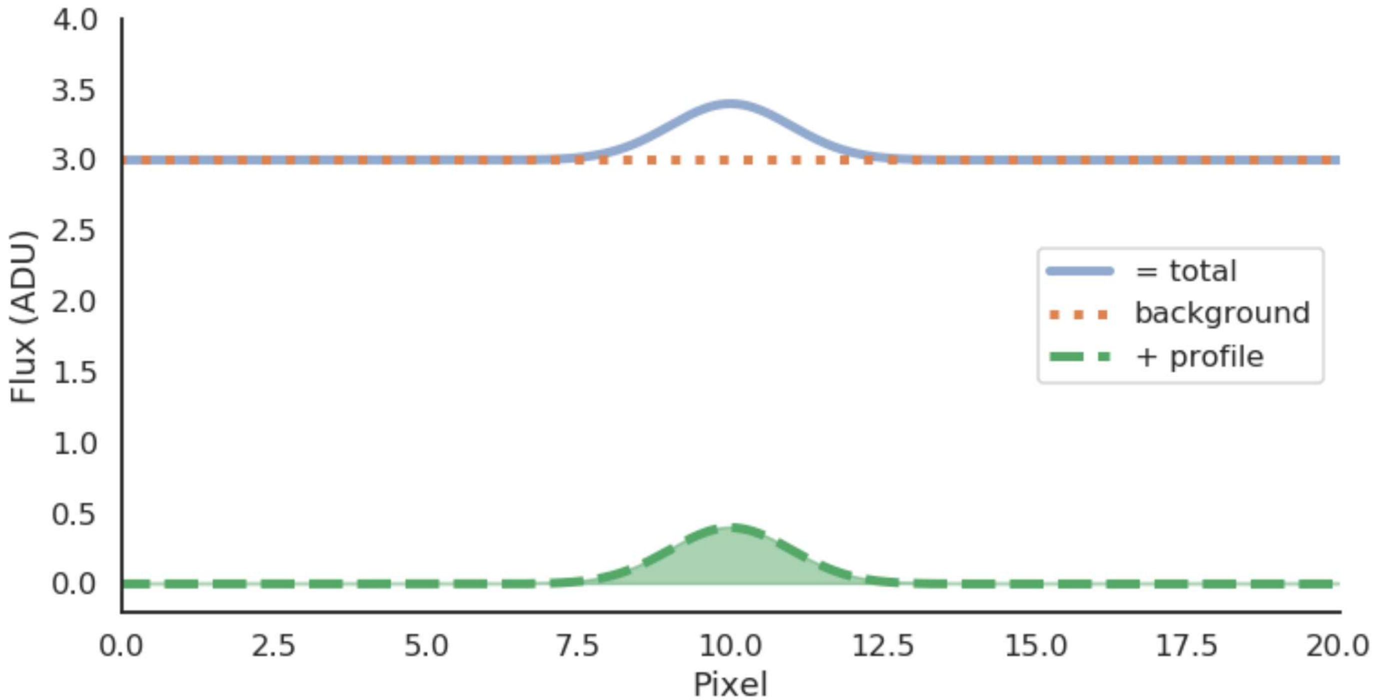

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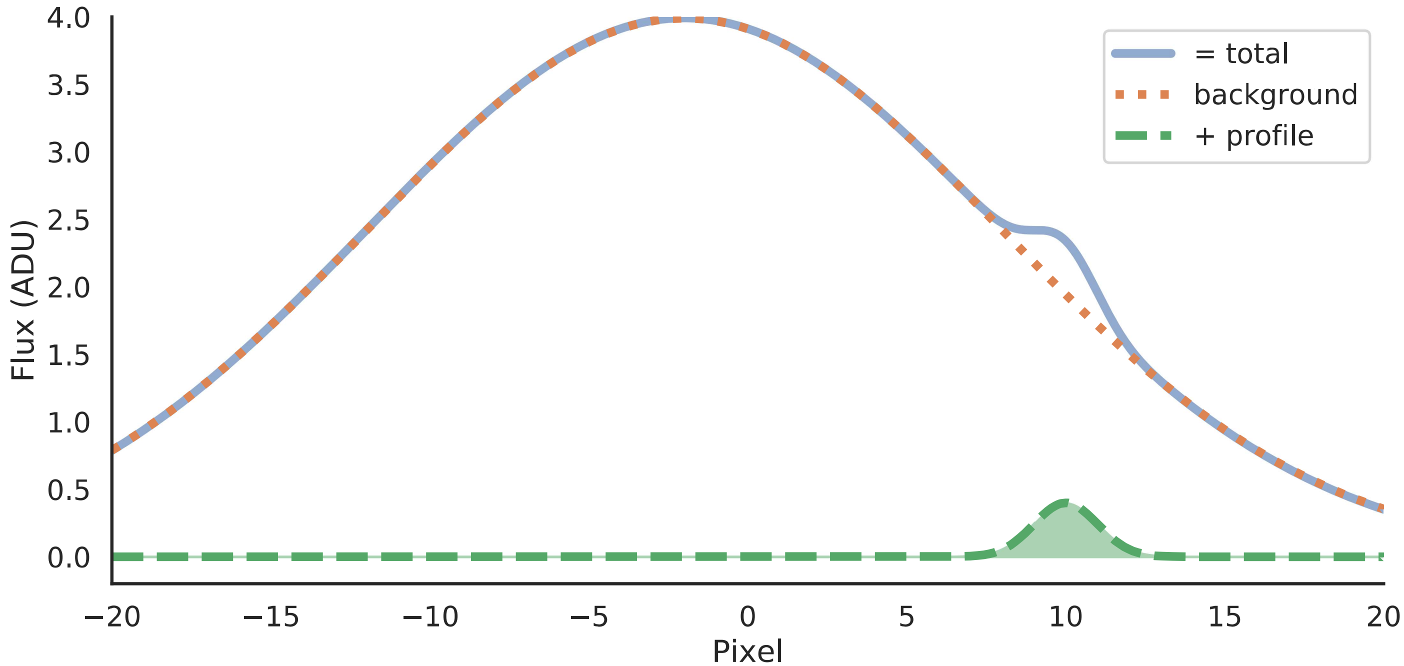

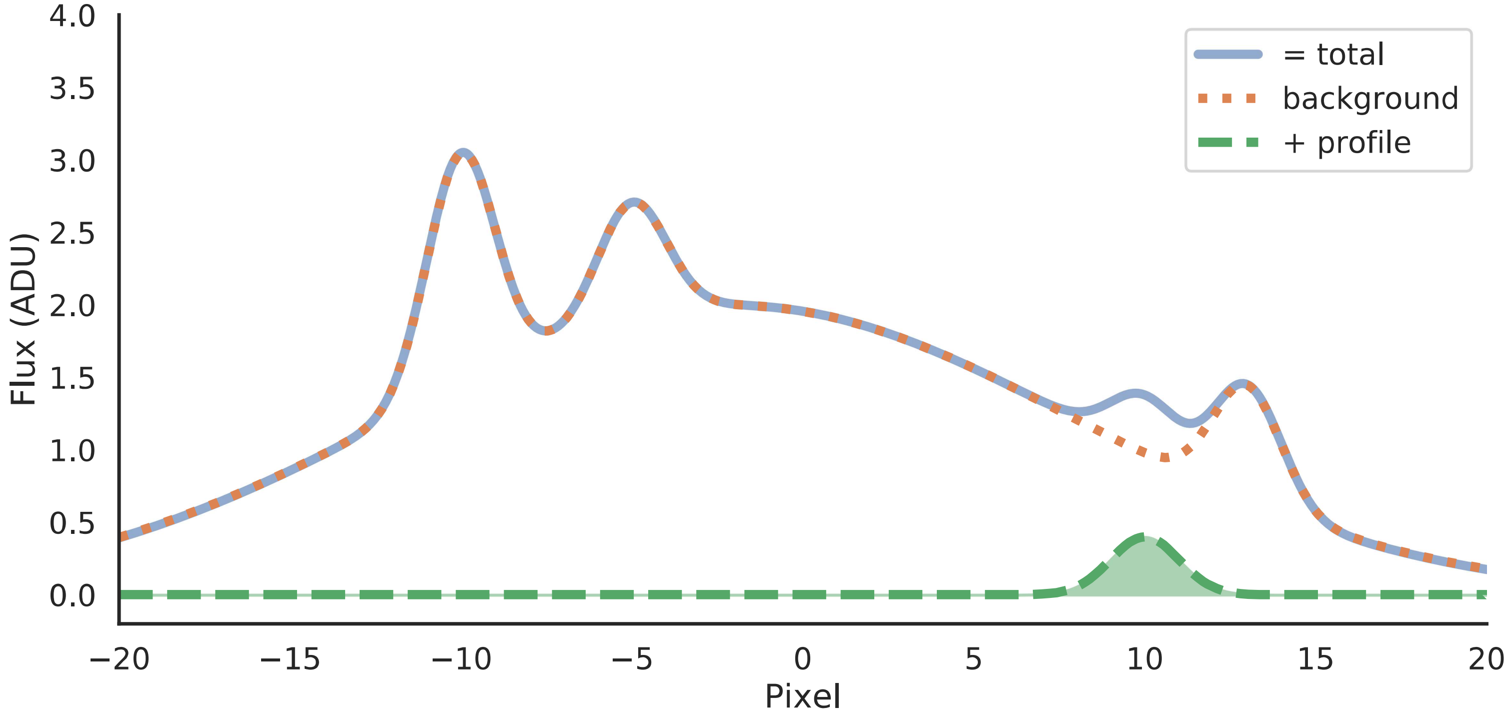
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Flux (ADU)
−20
−15
−10
−5
0
5
10
15
20
Pixel
= total
background
+ profile

There are many ways to do this wrong, with effects on science

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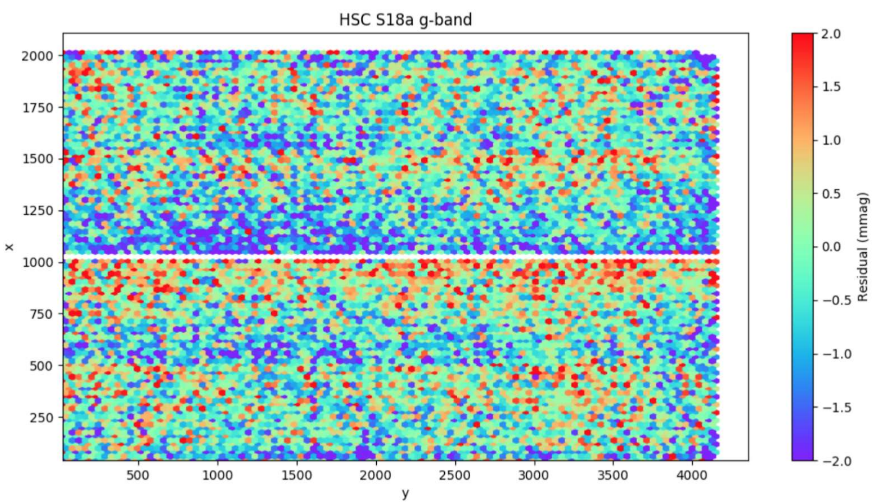

g-band photometric residuals stacked by CCD
Figure: Eli Rykoff (see photometric calibration talk later!)

Backgrounds come from 3 different sources

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- Instrumental
- --------------
- Astrophysical

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

Backgrounds come from 3 different sources

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

Recall from yesterday:

An Ideal Universe

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In Utopia our extra-terrestrial photons would be superimposed on a uniform background. How would that background appear in our data?

- Larger pixels would be brighter than small ones
  - random variations in the mask set
  - tree rings, edge (and median) distortions
  - the Jacobian of the optical distortions (and tangent plane projection)
- More sensitive pixels will be brighter
  - spatial variations in pixel QE
  - spatial variations in the filters'
    - bandpass
    - central wavelength
- ghosts deliver extra light to some pixels

You may be thinking, "That's what a flatfield is for!"

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

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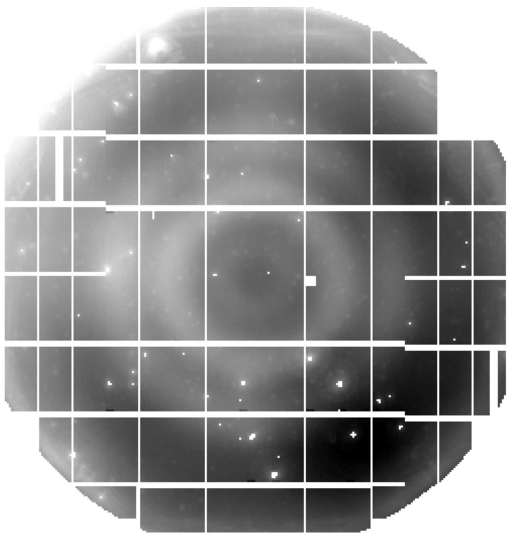
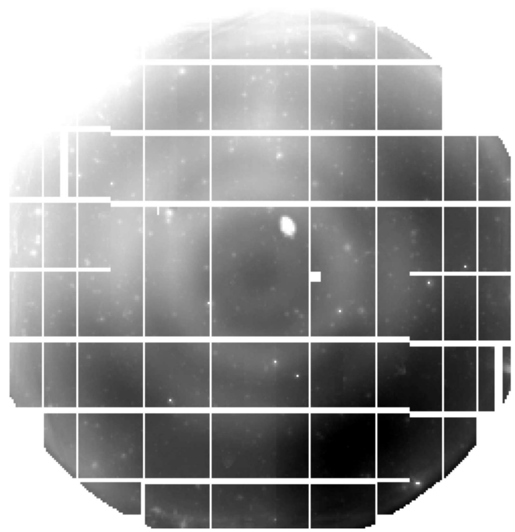
PostISR-CCDs = Calexp + background
Detections removed and binned 128x128pix

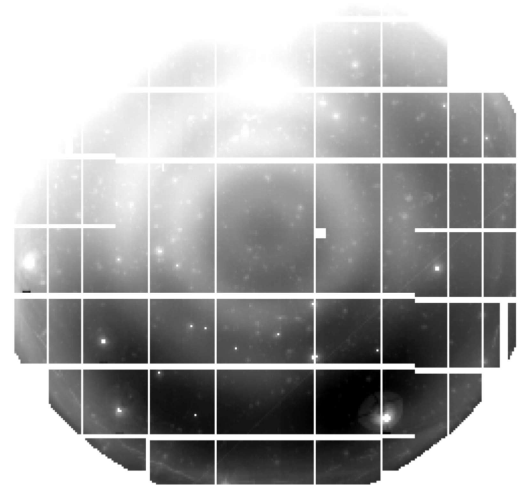
e.g. Filter transmission variations



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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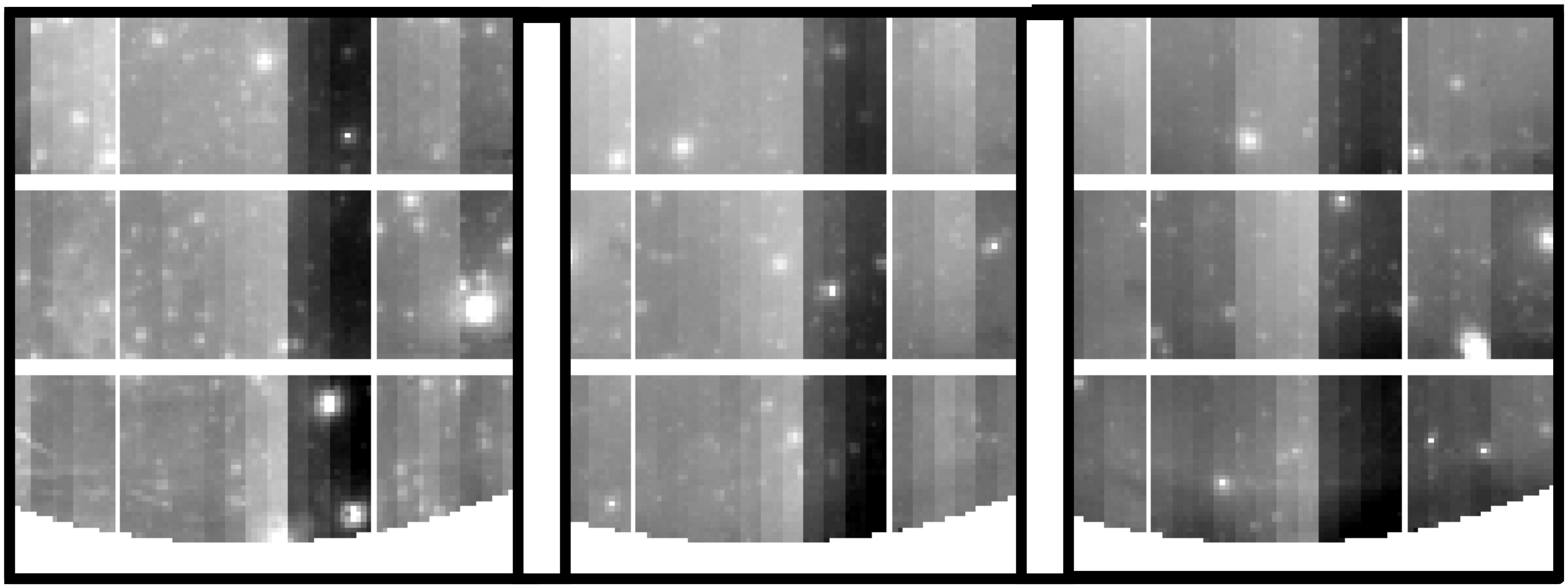
e.g. residual ccd and amp offsets



Visit 15308 Visit 29408 Visit 26098

HSC-G

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

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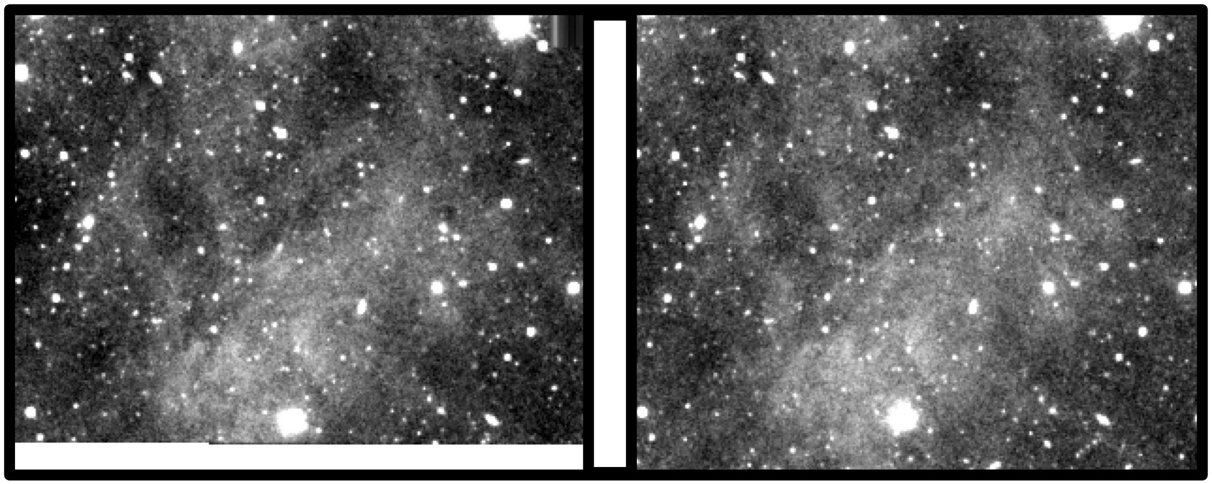
e.g. Galactic IR Cirrus



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?

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

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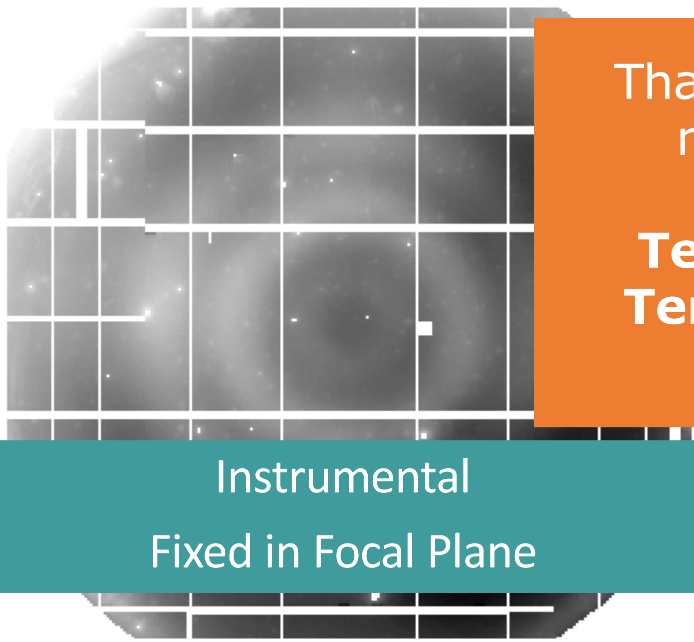
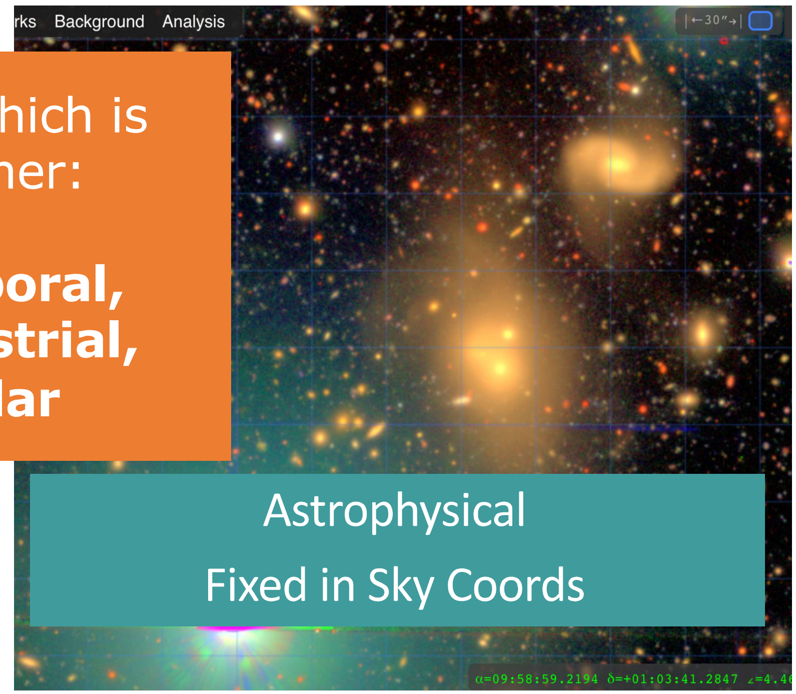


Instrumental

Fixed in Focal Plane

That which is neither:

Temporal, Terrestrial, Solar

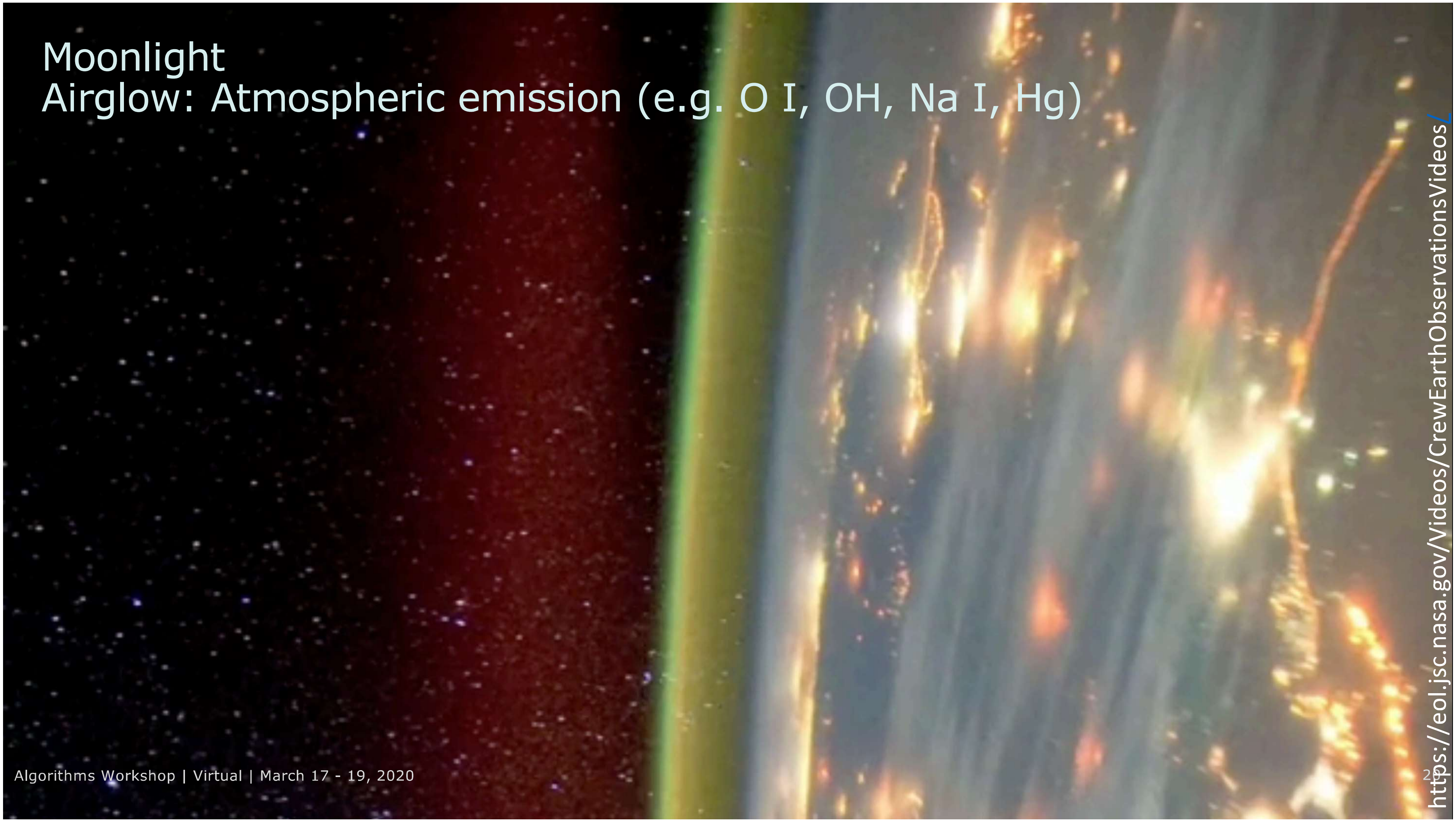


Astrophysical

Fixed in Sky Coords

Moonlight

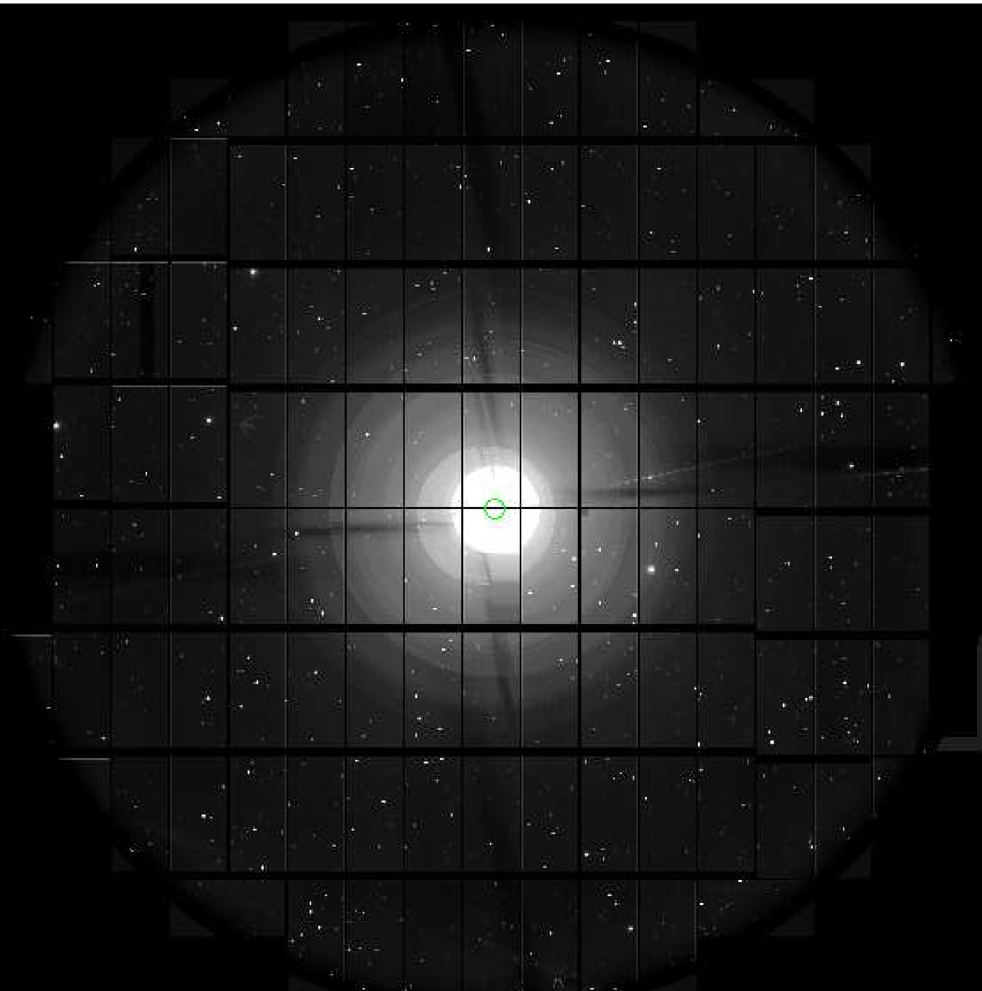
Airglow: Atmospheric emission (e.g. O I, OH, Na I, Hg)



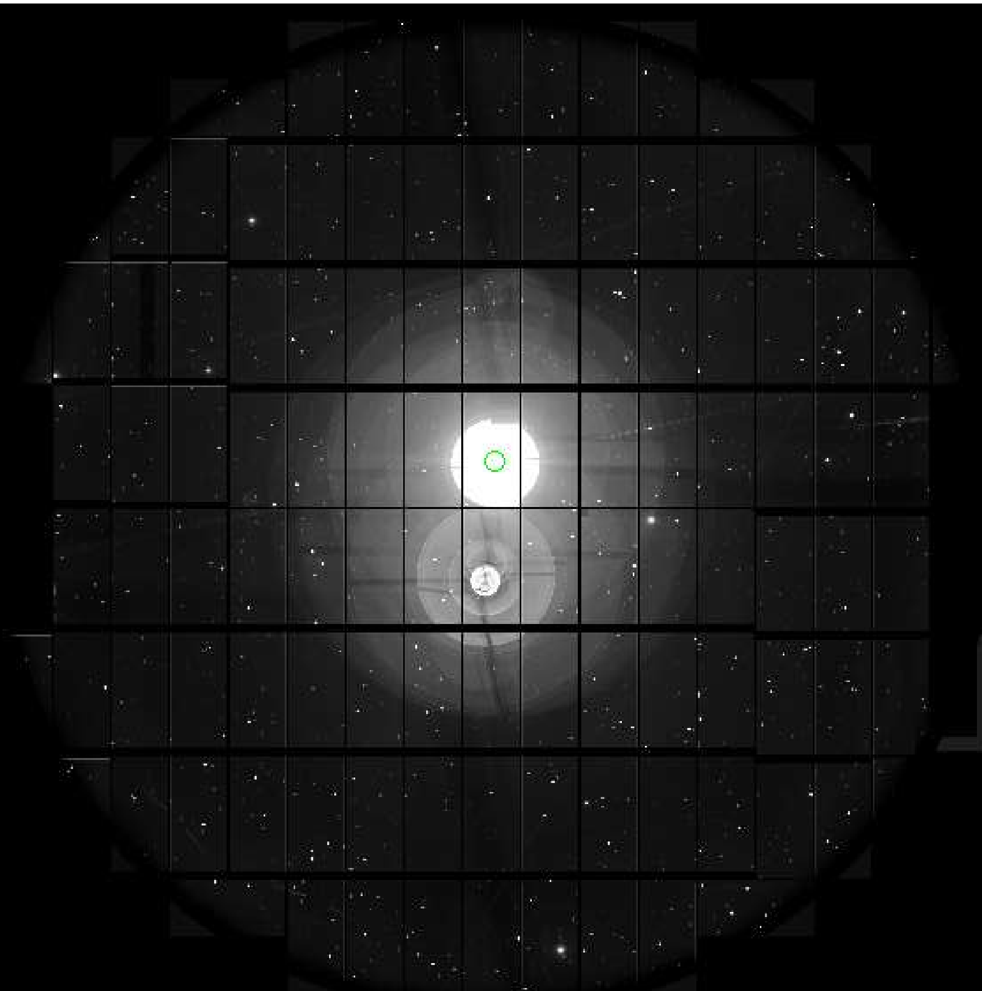
https://eol.jsc.nasa.gov/Videos/CrewEarthObservationsVideos/


Zodiacal Light
Credit: ESO/Y. Beletsky

Ghosts



Ghosts



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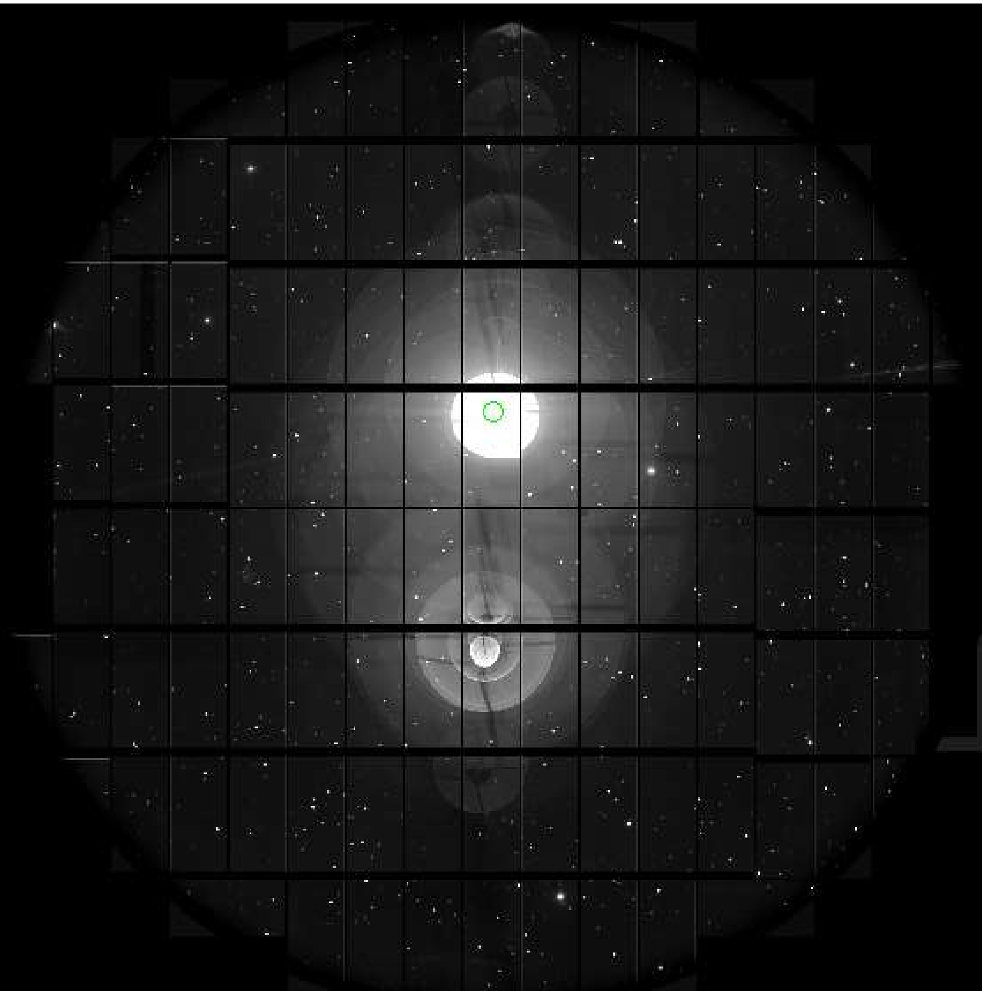

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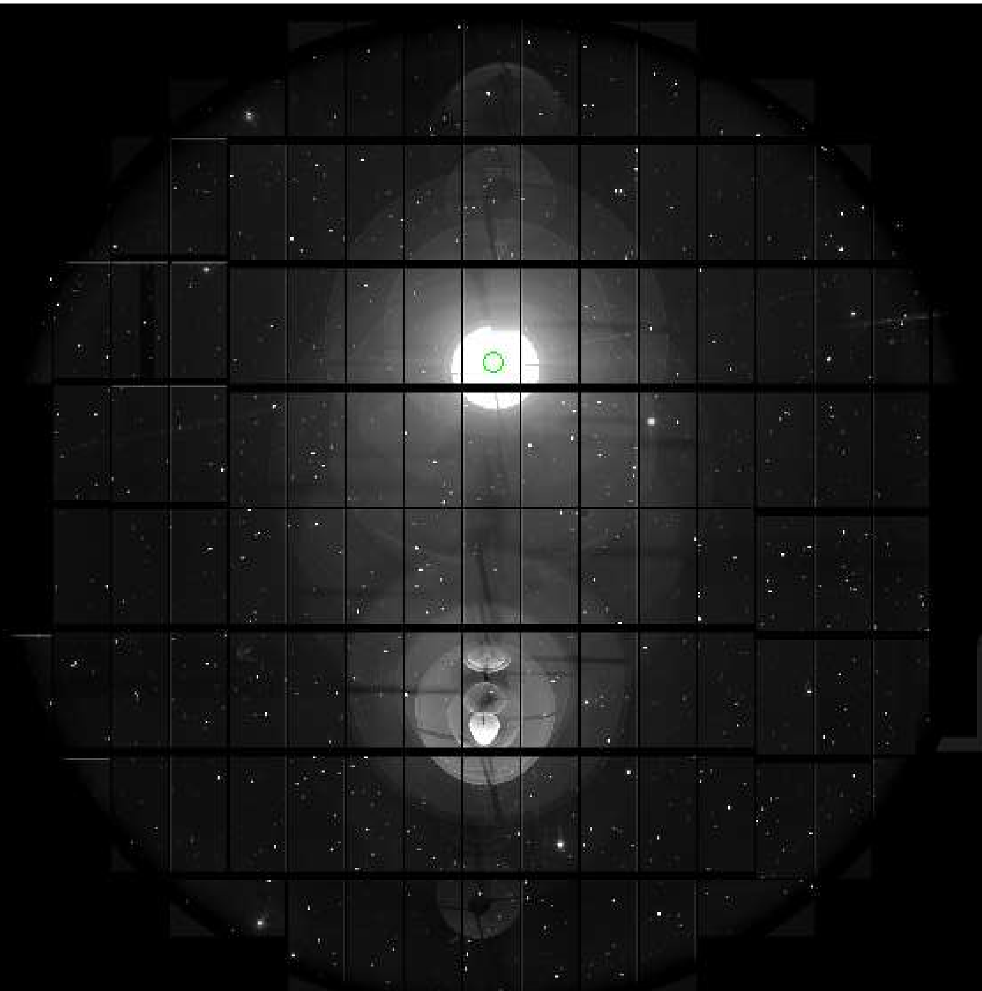

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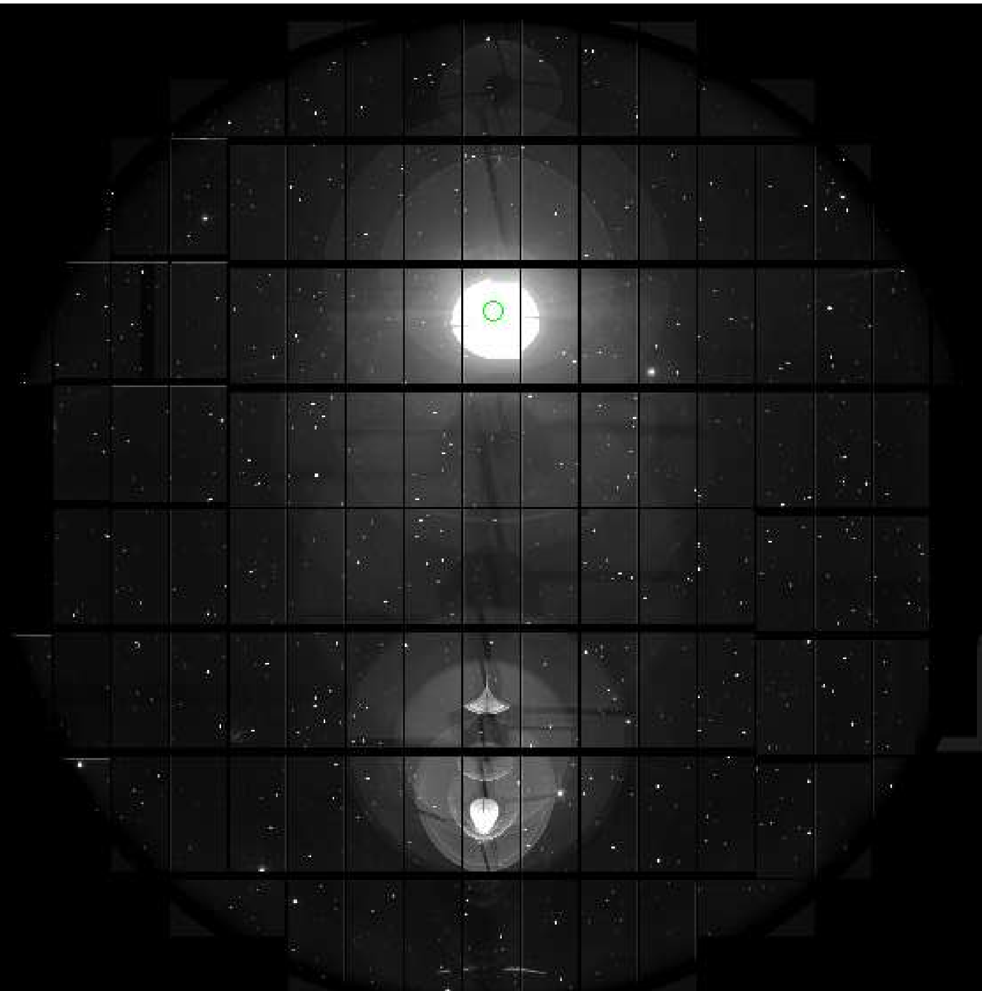

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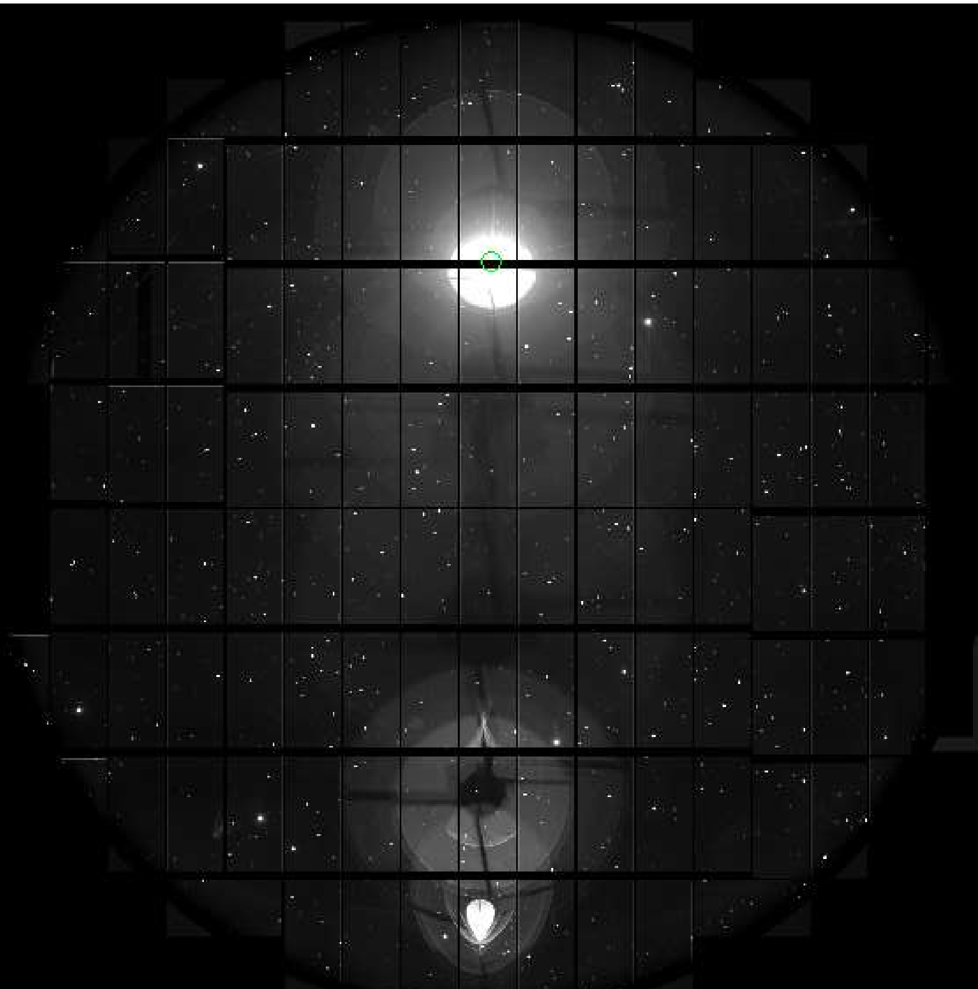

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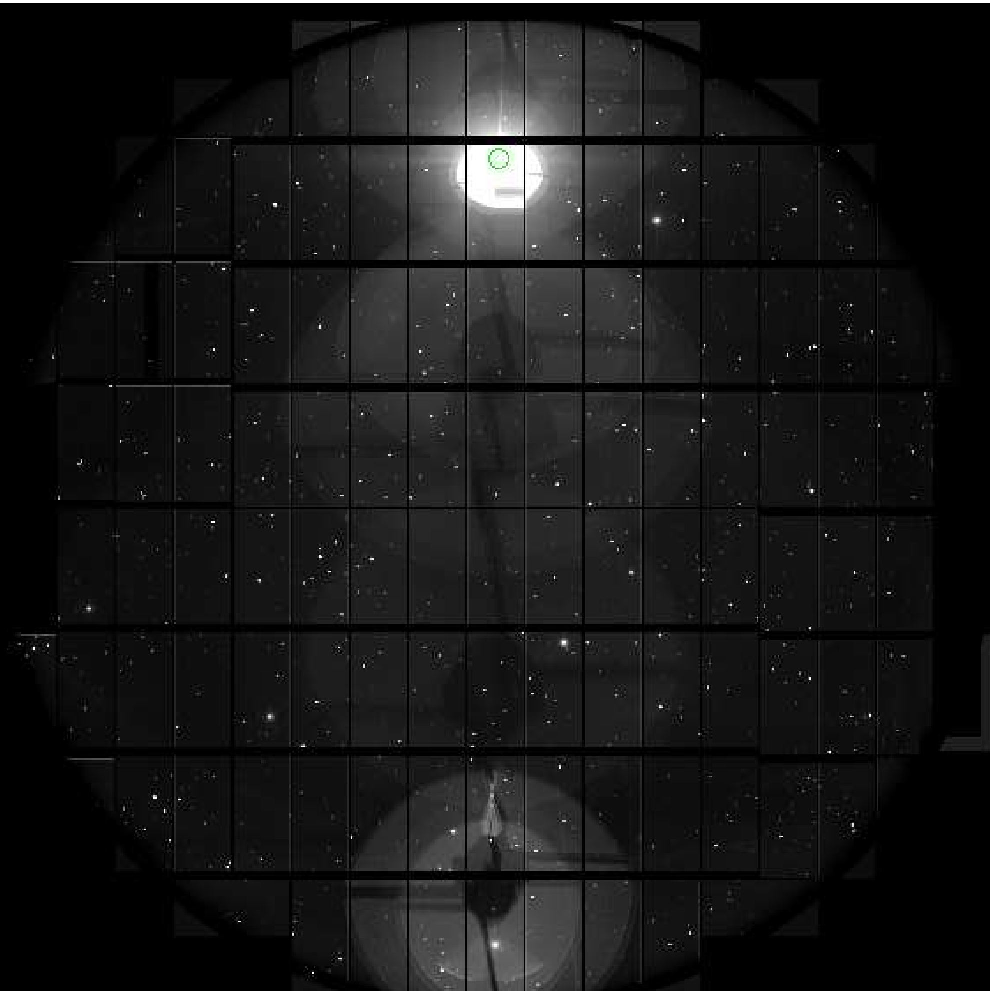
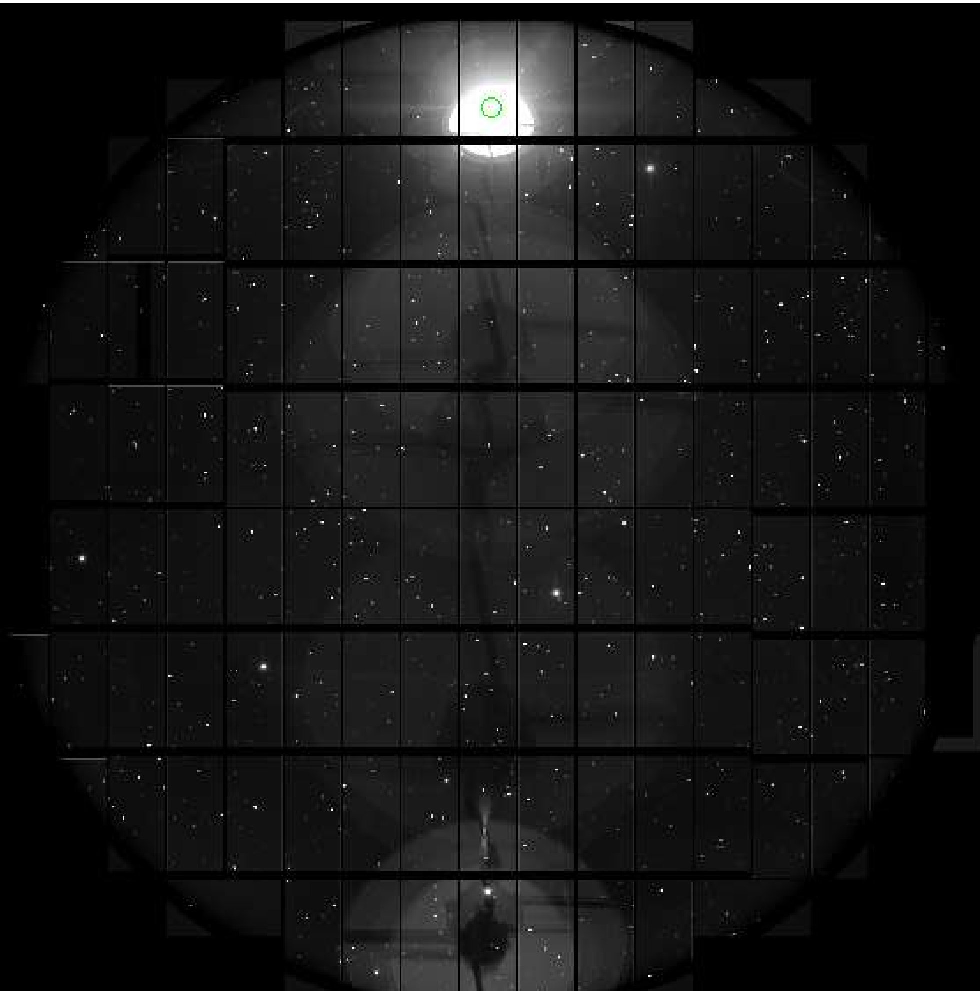
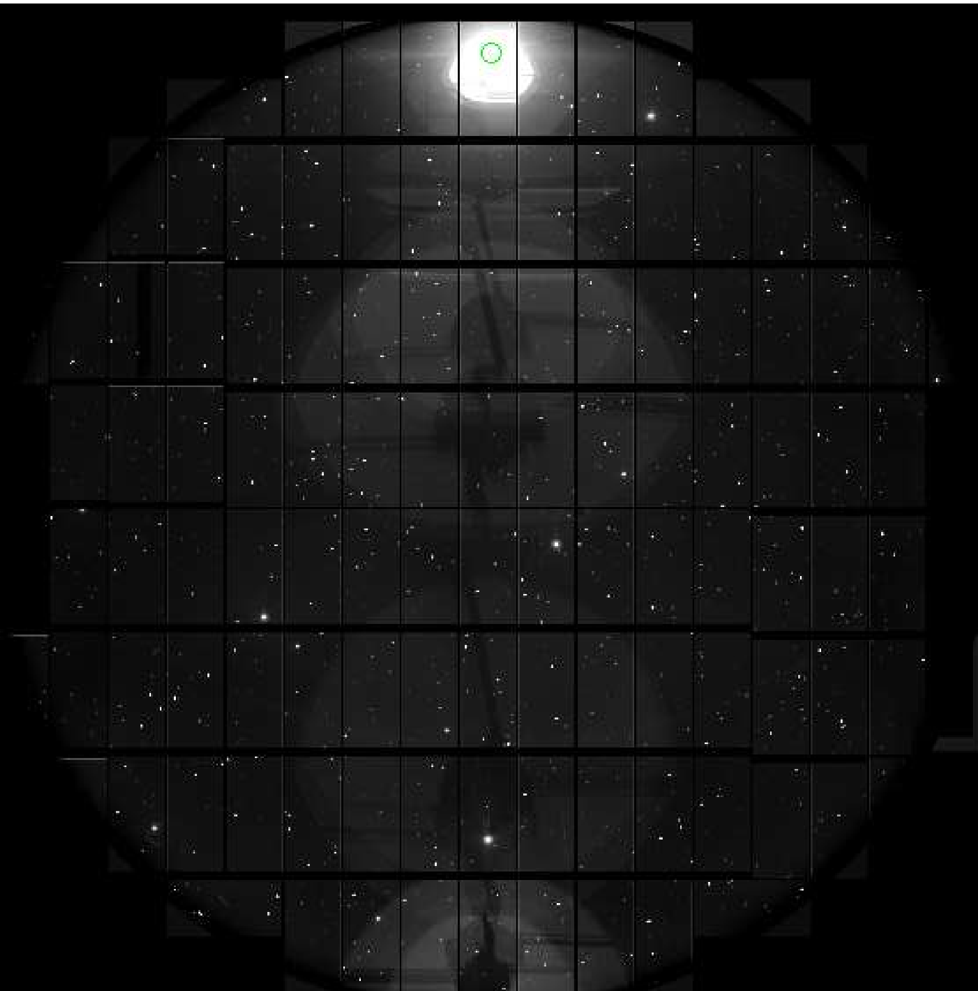


Ghosts



Ghosts



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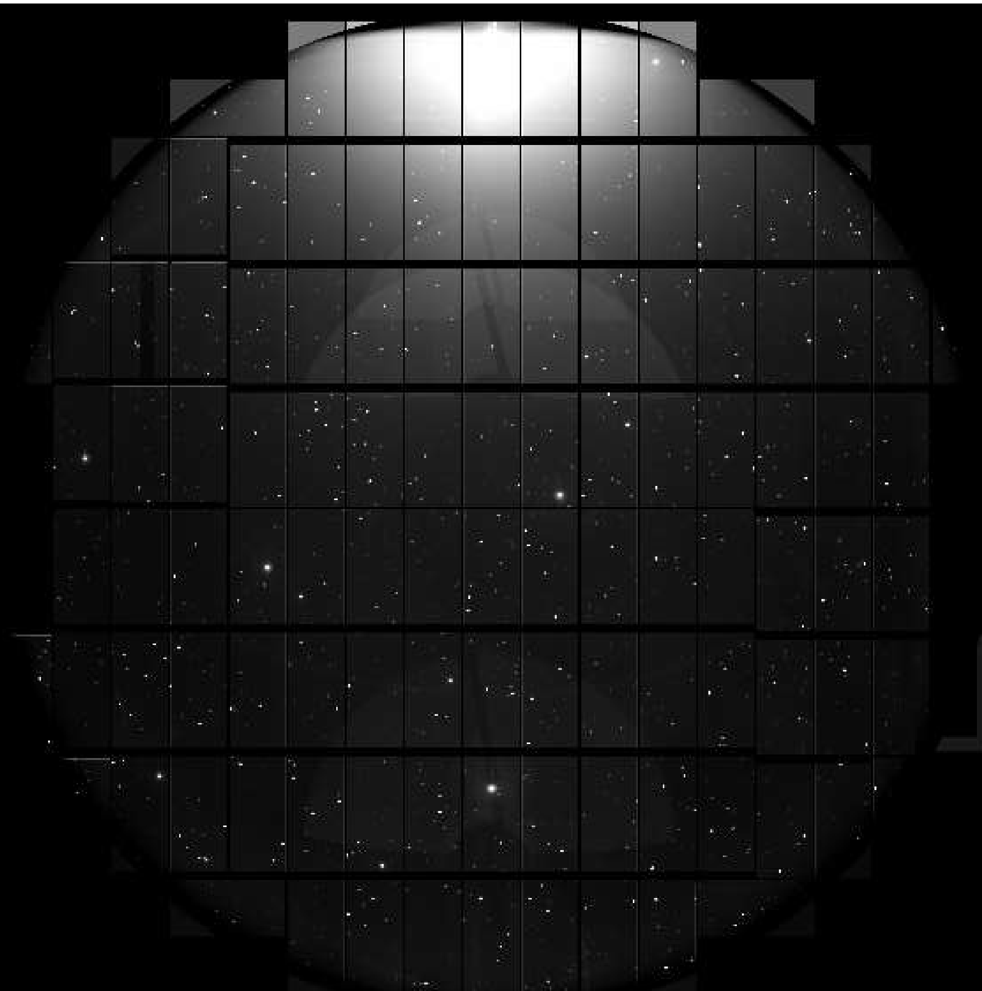
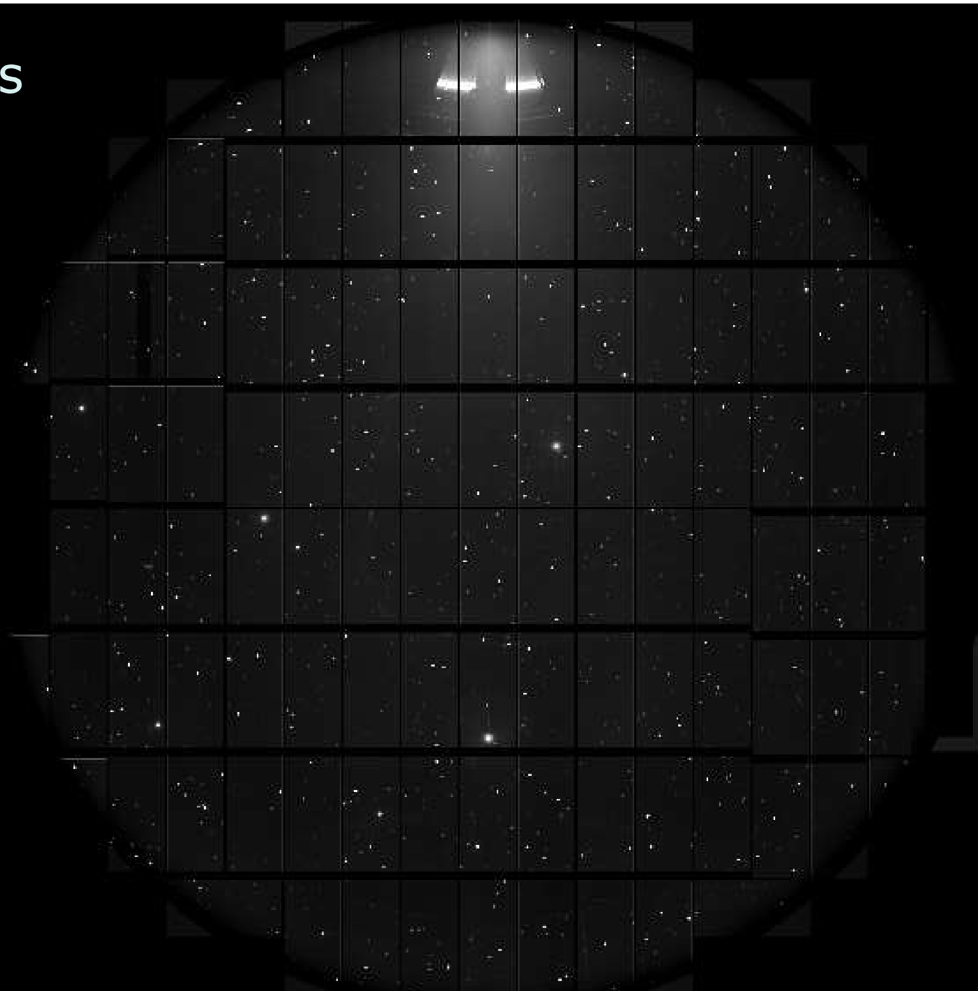


Unimaged ghosts aka “ghoulies”



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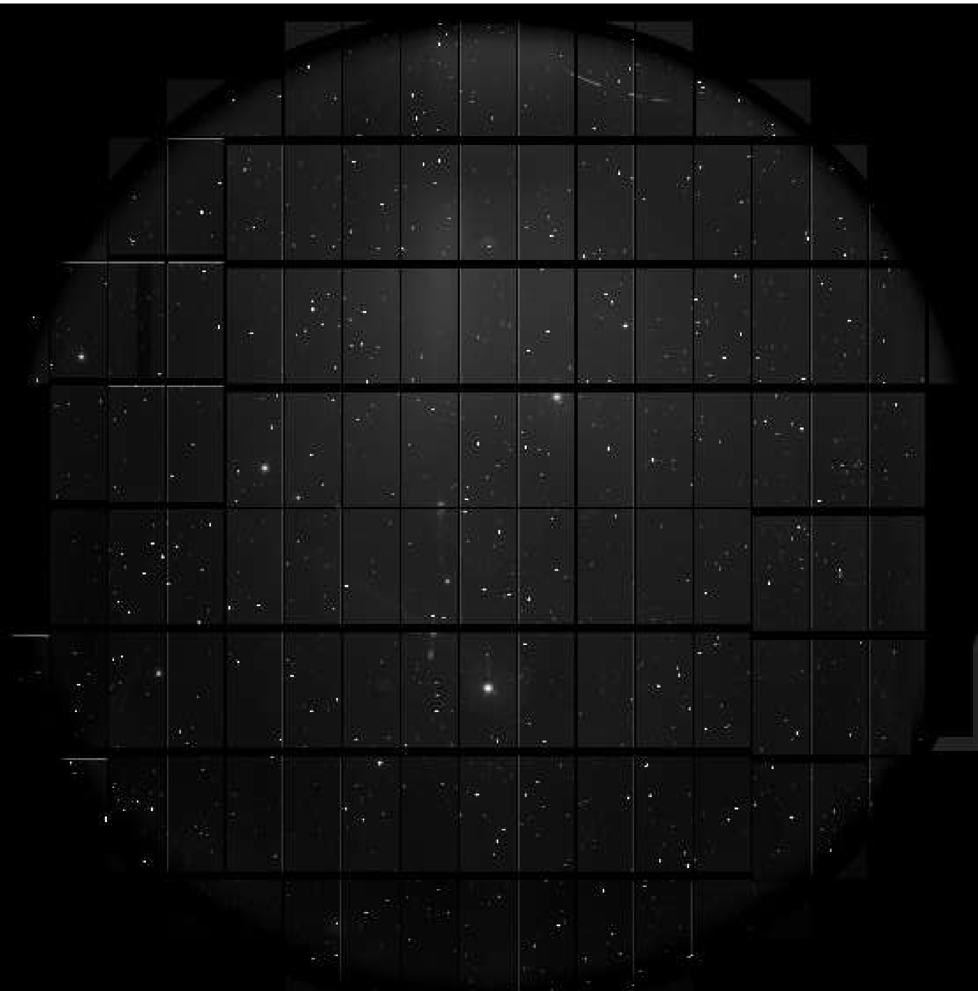

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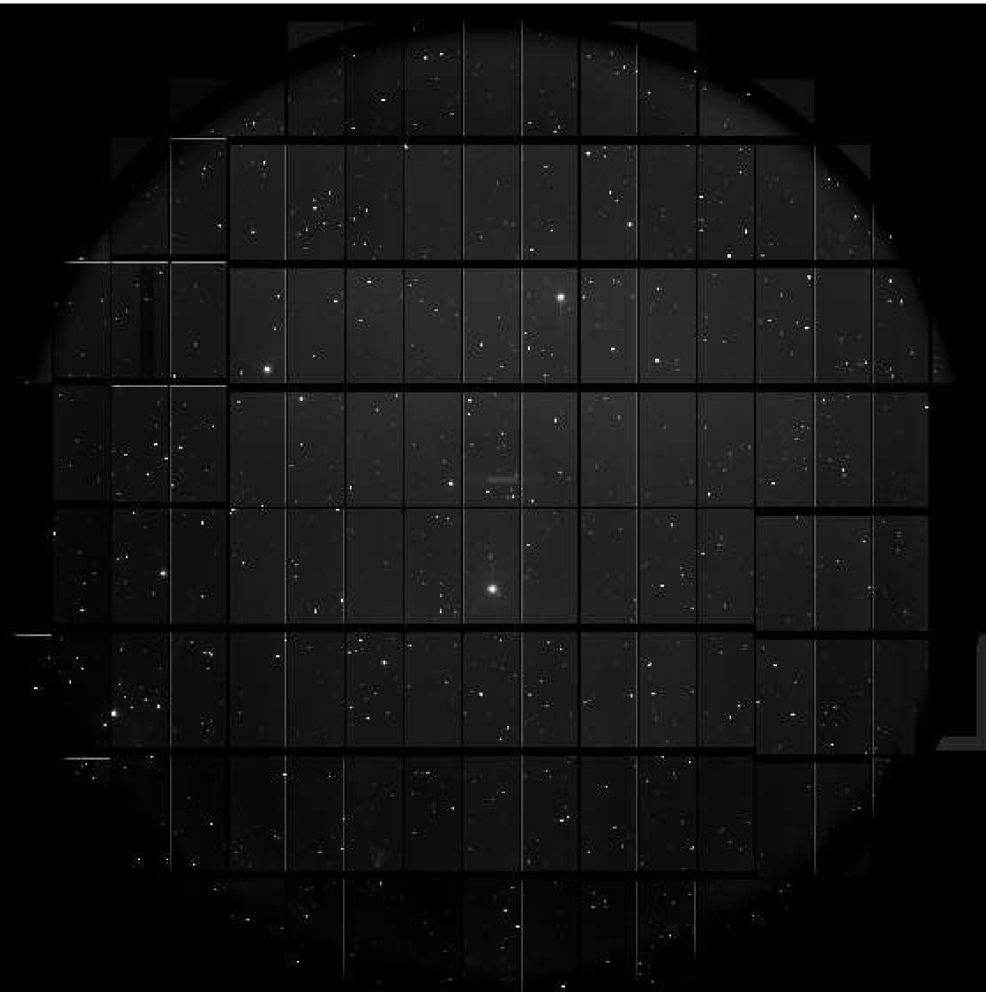
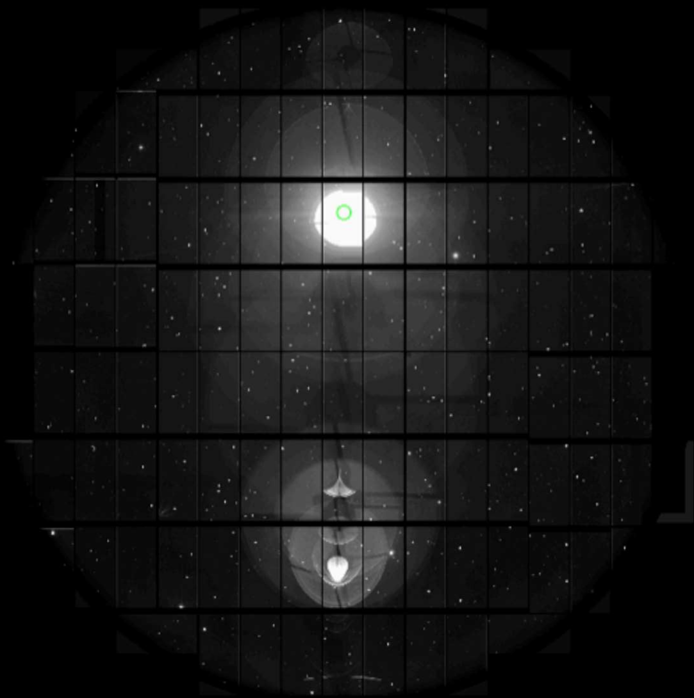
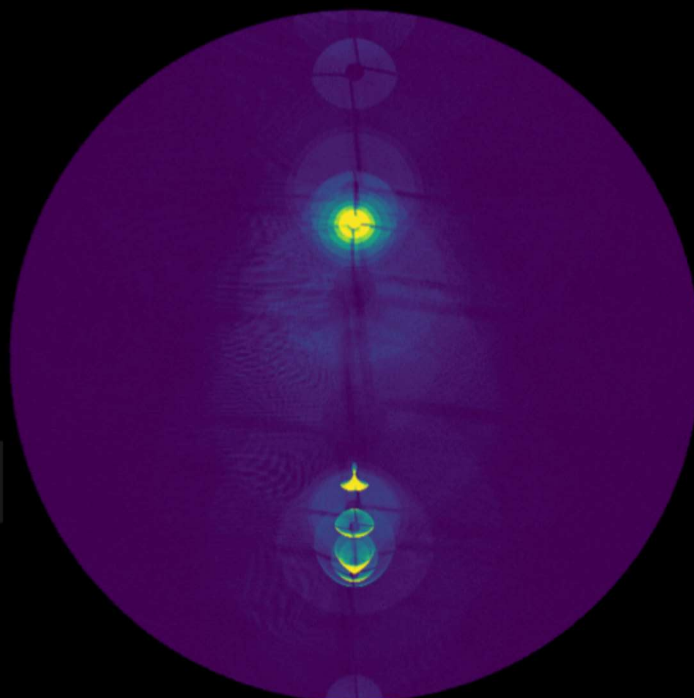
aka “ghoulies”



Ghosts can---in theory---be predicted and subtracted off
“Ghoulies,” Glints cannot



HSC Arcturus
Actual



Batoid Arcturus
Prediction

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

Background Estimation bridges flat fielding and deblending

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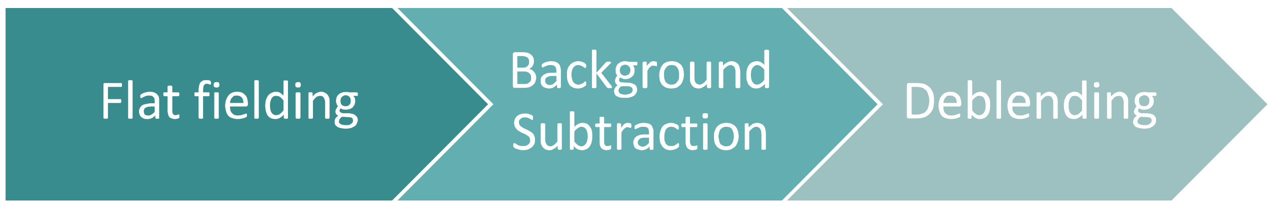

What do the pipelines do now?

Procedure as of HSC Public Data Release 2 (PDR2)
Recall the "Single Visit Processing" stage

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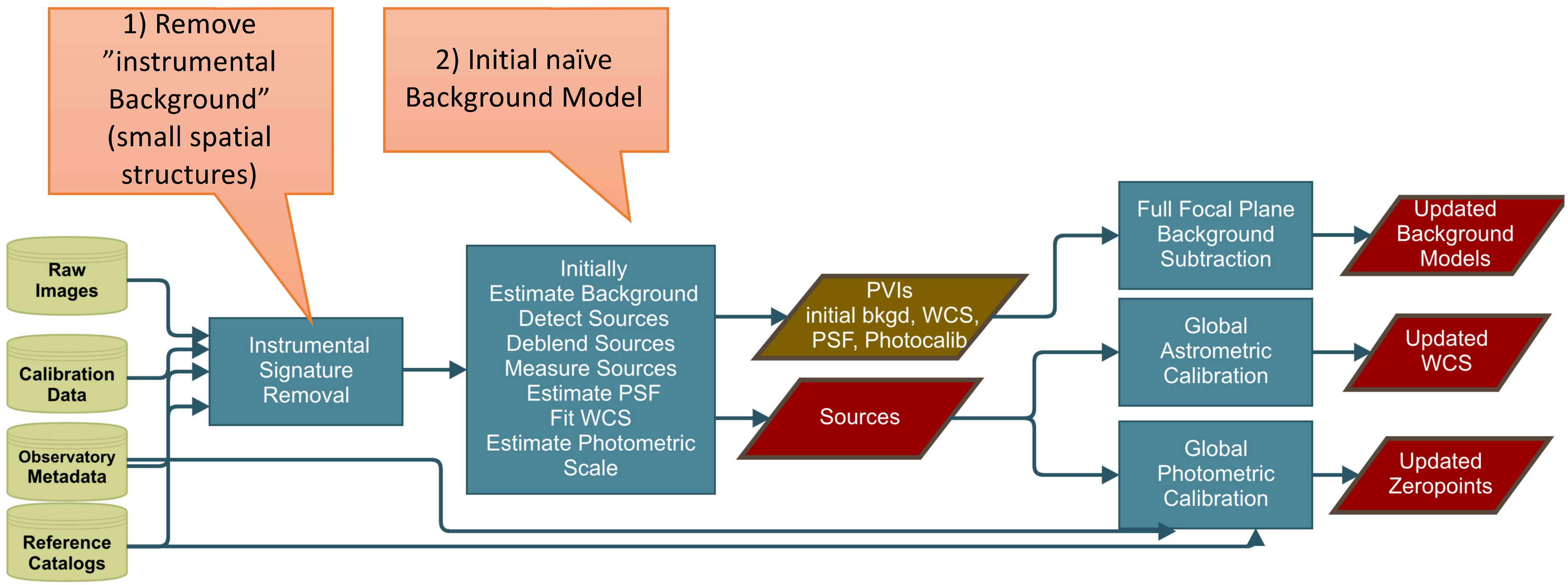

2) Initial Naïve Background Model
Detect initial sources, bin, fit w/ 6^{th} order Chebyshev polynomial.

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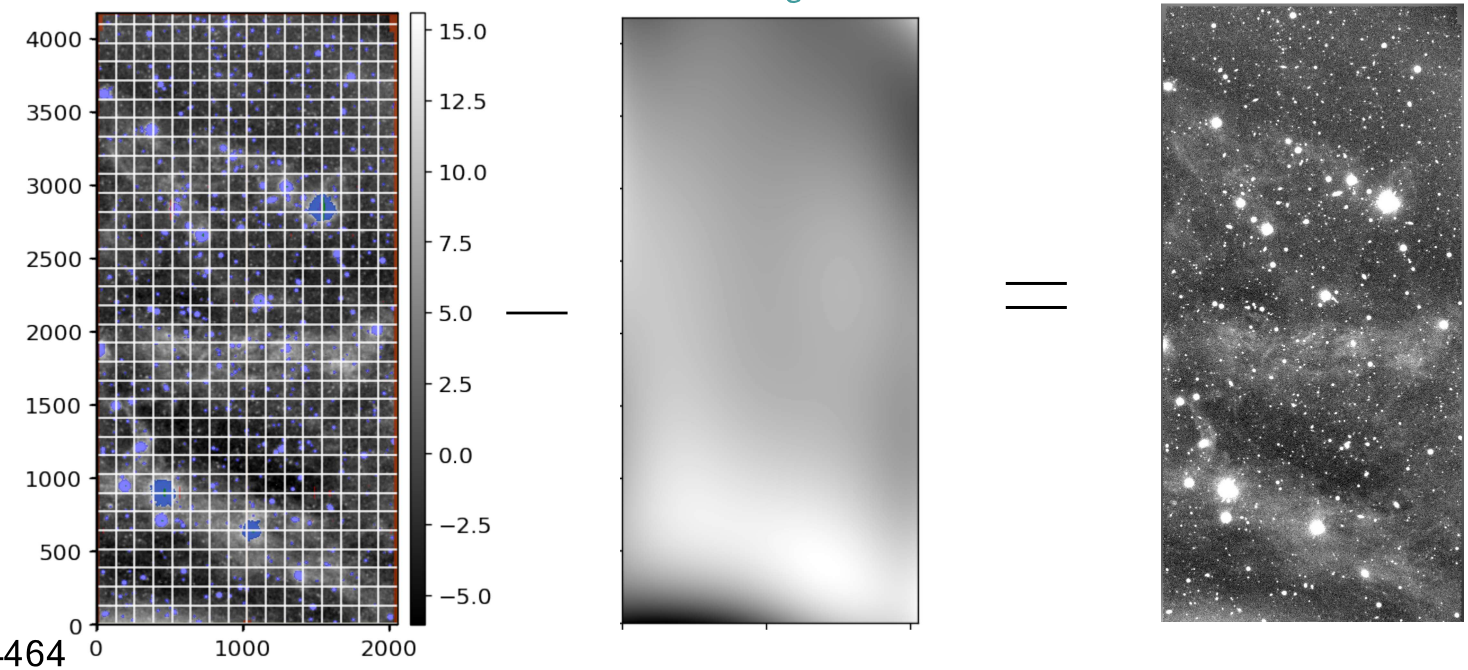
post-ISR CCD (after detrending)

Local Background

PVI



HSC
VISIT = 34464
CCD = 81

Procedure as of HSC Public Data Release 2 (PDR2):

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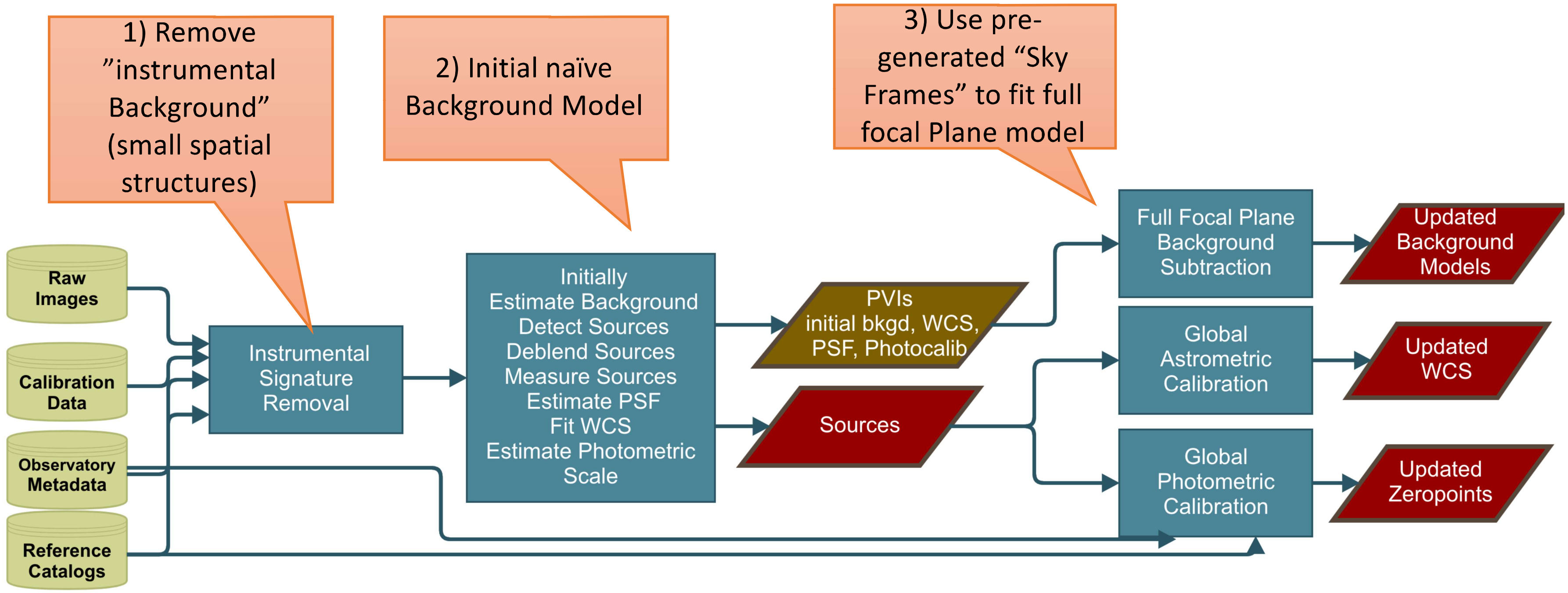

3) Use pre-generated "Sky Frames" to fit full focal Plane model

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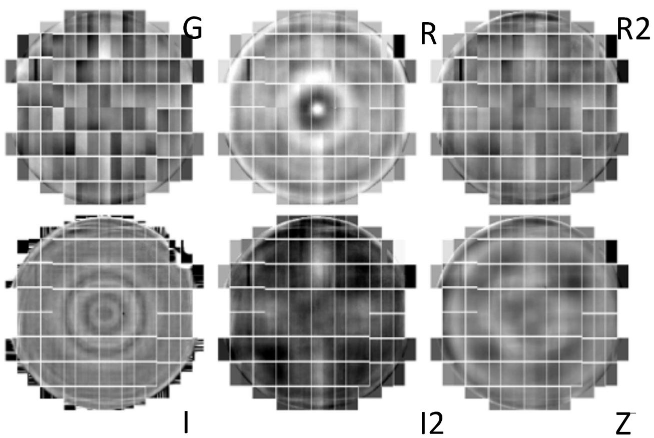
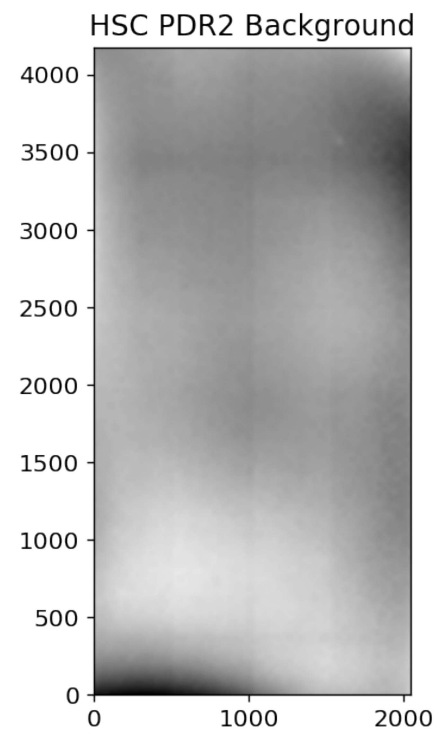


Median HSC background
Figure: Paul Price

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.



How well is it working and project plans

1) Improve instrumental background modeling

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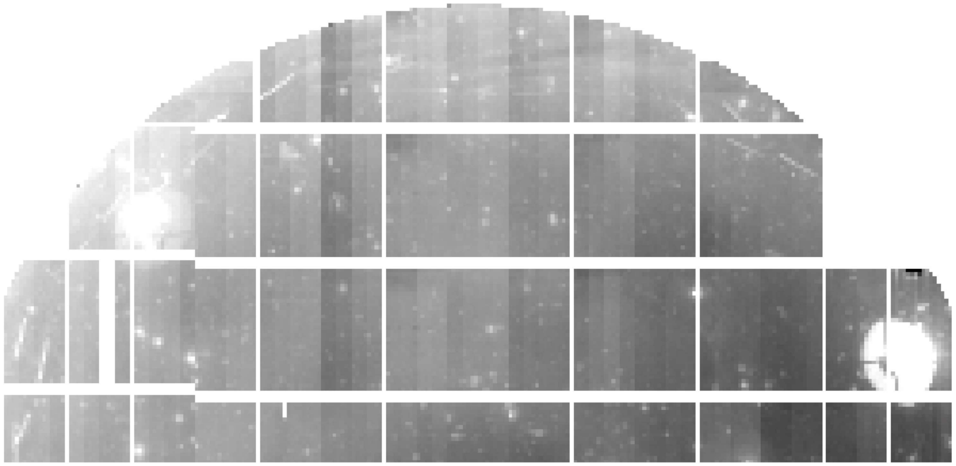

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Improve instrumental background modeling

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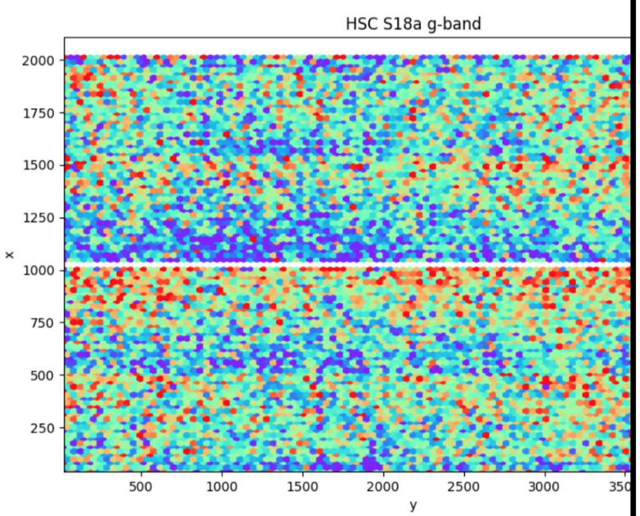

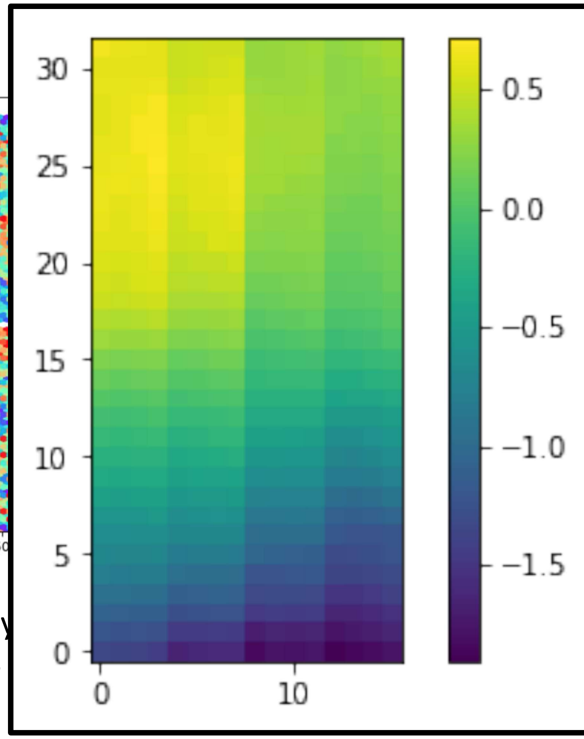

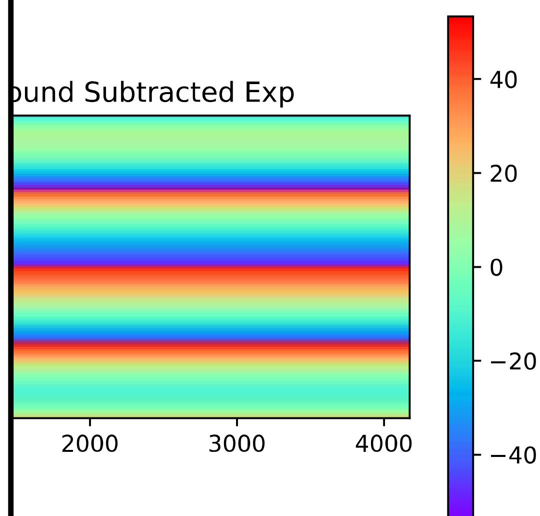

g-band photometric residuals stacked by
Figure: Eli Rykoff (see photometric calib

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Improve instrumental background modeling to handle ccd-to-ccd and amp-to-amp offsets

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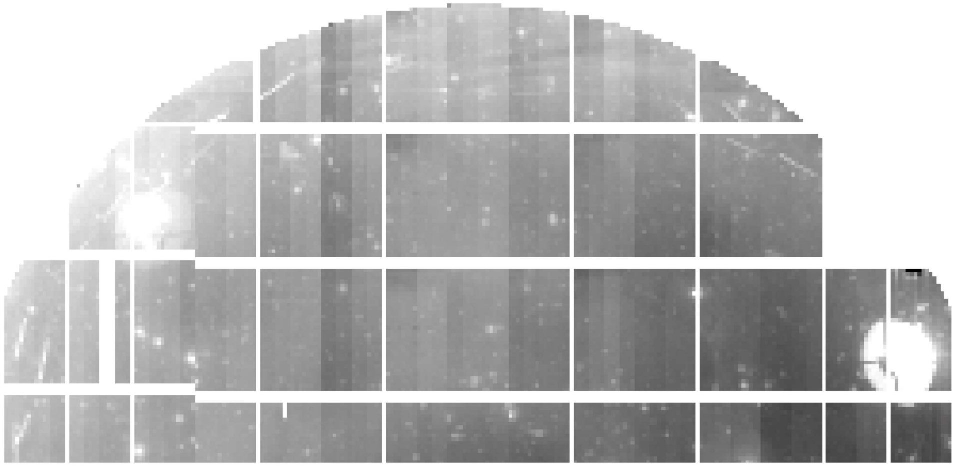
- Three works in progress:
  - **Improving ISR**. Taking more flats varying exposure time to find hidden (non-linearity?) variable
  - **Robust PCA** Inspired by DES, Bernstein+17: apply the Robust PCA algorithm from Candes+11
  - **Amp-to-amp continuity/offset correction** inspired by Pan-STARRS



Low Surface Brightness community was happy with PDR2 full focal plane "SkyCorrection"

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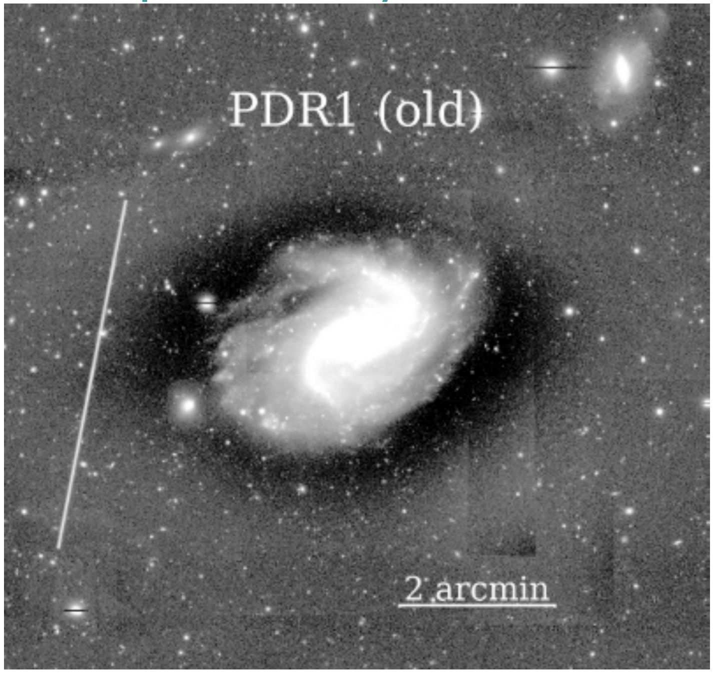
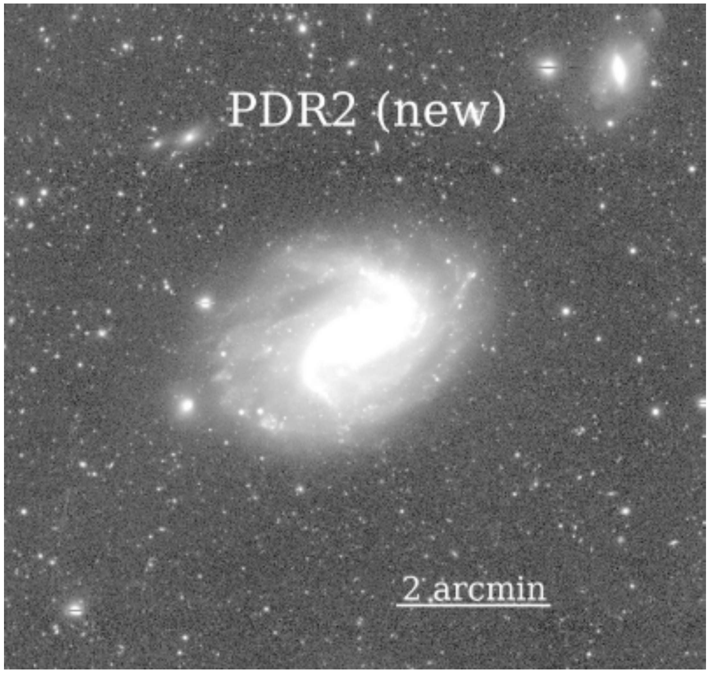


Coadd with
PDR1 Local Background subtraction



Coadd with
PDR2 Focal Plane Background subtraction

Aihara+19 (PDR2 release paper)

But everyone else was unhappy

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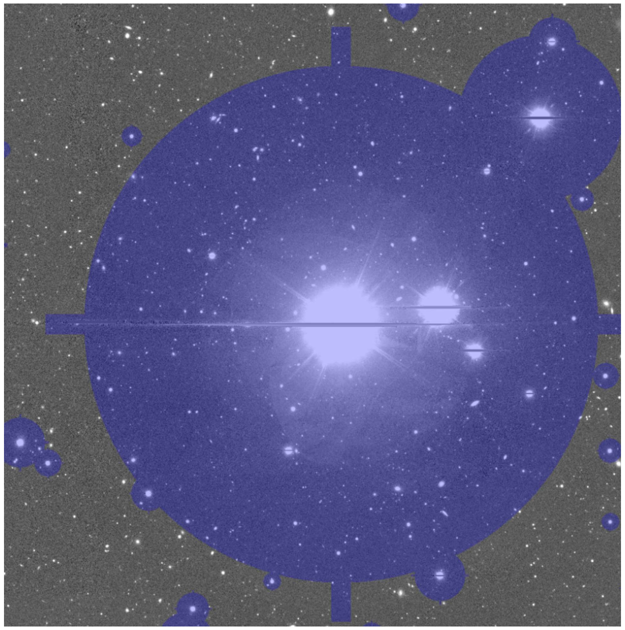

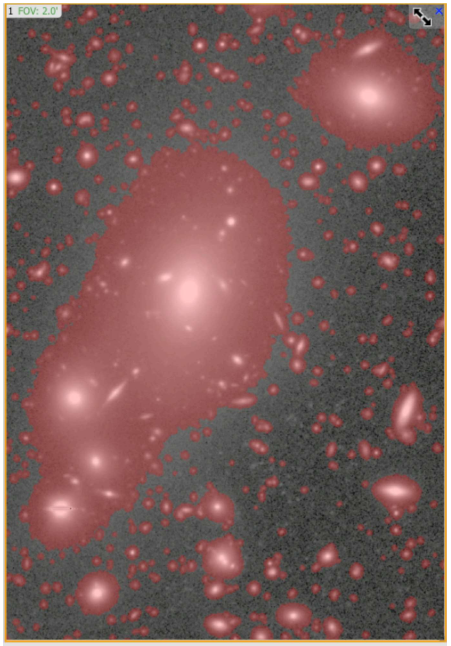

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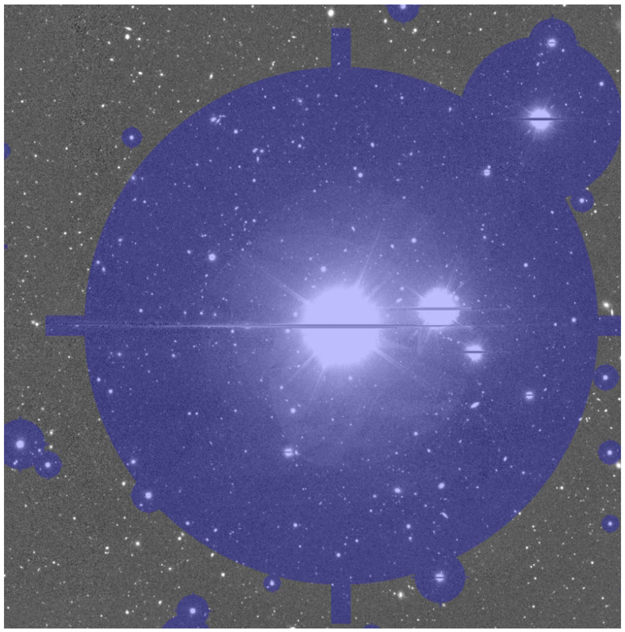

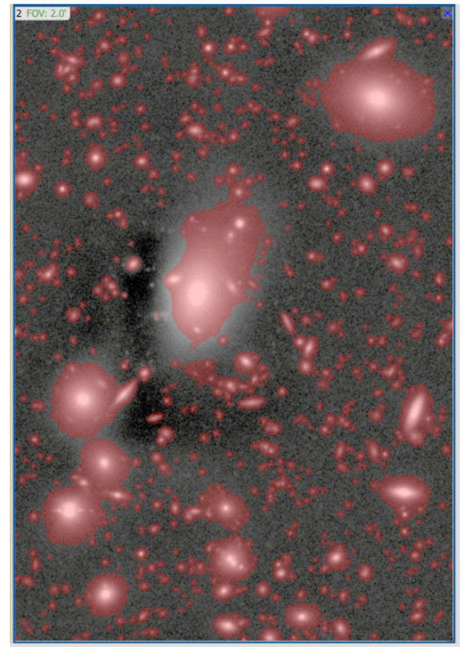

HSC Internal Data Release S19A adds a very aggressive 128x128 binned spline background subtraction to the coadds.

This is what is on the master branch of the stack today.

Put a pin in this over subtraction problem and talk about bright stars first

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2) Wings of bright stars

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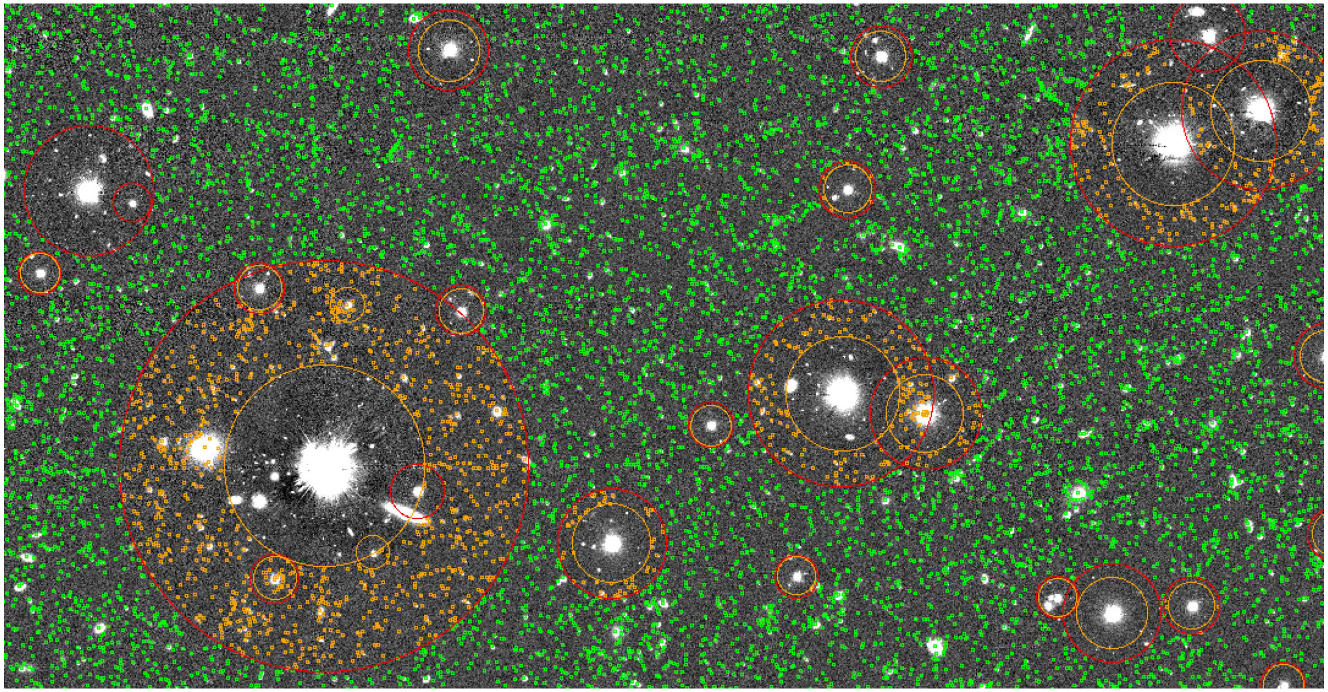
Orange Sources were lost to the the full focal plane backgrounds

Figure: Morgan Schmitz

PDR1 Mask Boundaries

PDR2 Mask Boundaries

Image = Master/current



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Recover area in wings of bright stars by modeling and subtracting

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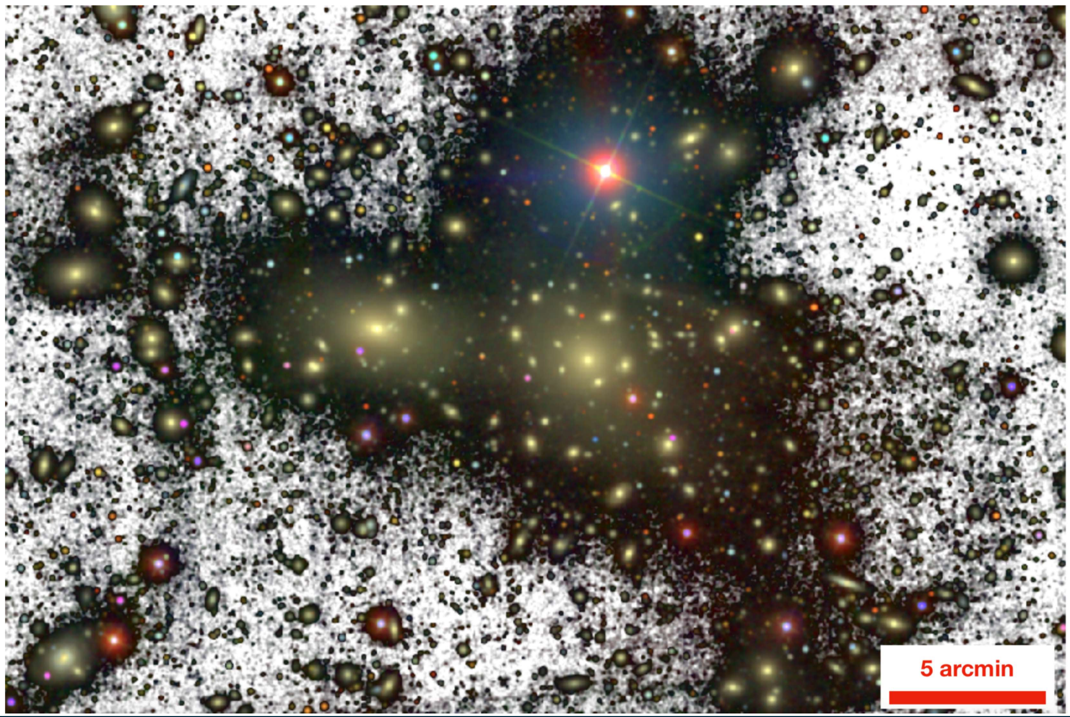
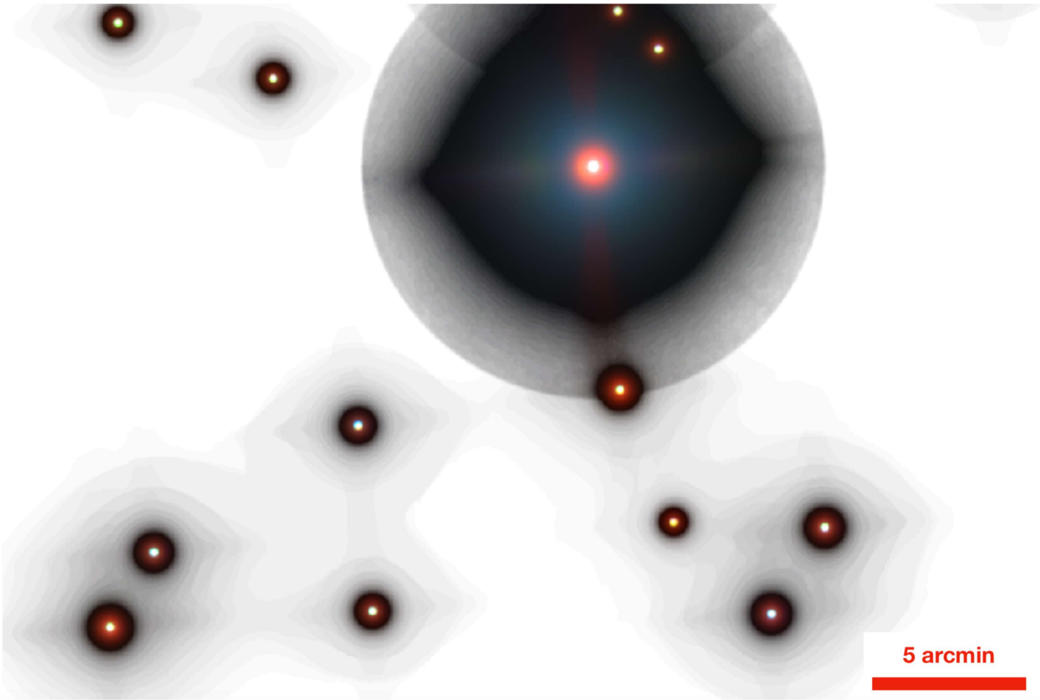


Work in Progress:
Morgan Schmitz
in collaboration
with Raul Infante-Sainz

Figure:
Coma Cluster
SDSS Stripe82
Infante-Sainz+19

Recover area in wings of bright stars by modeling and subtracting

Rubin Observatory



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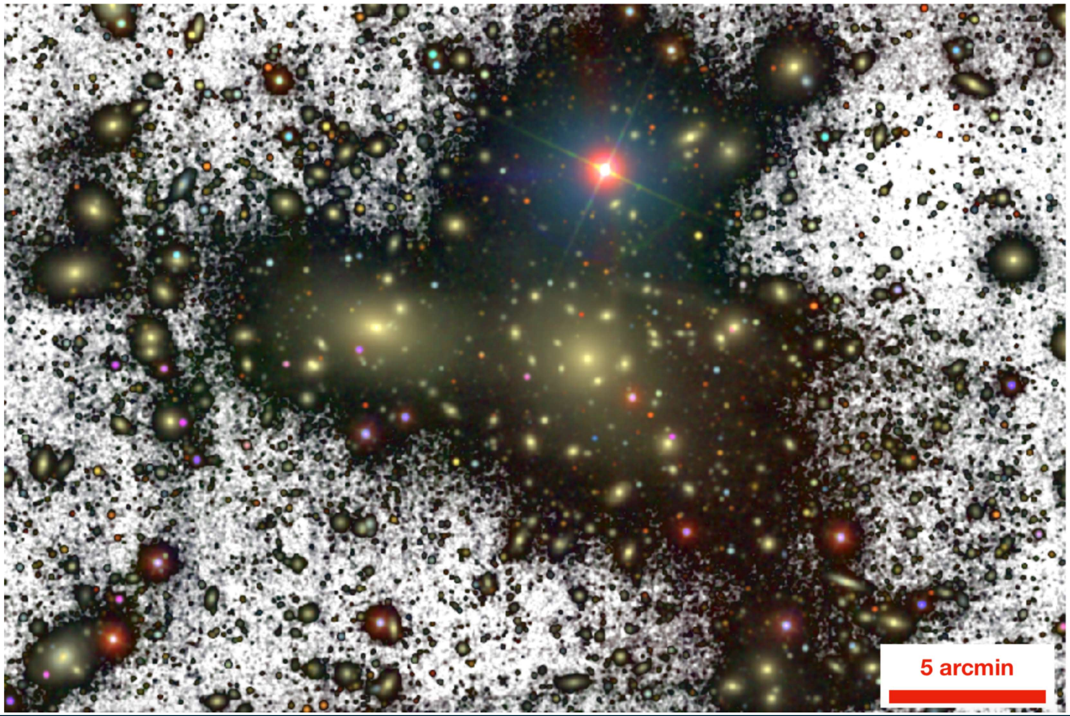

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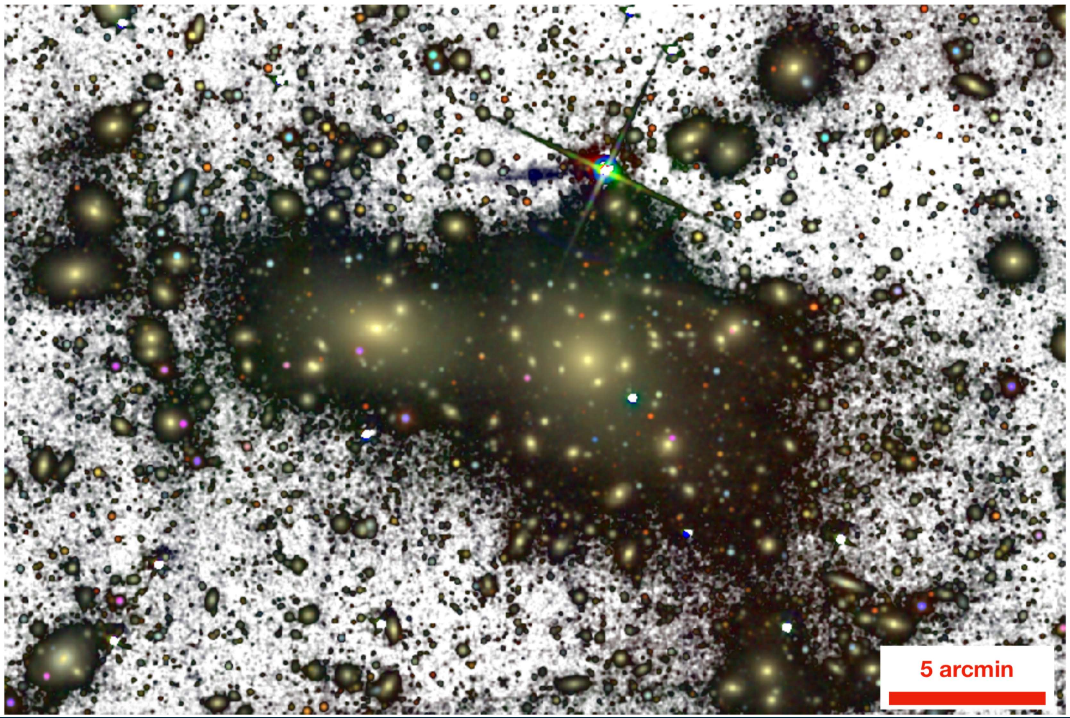

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SDSS Stripe82
Infante-Sainz+19

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Project Plans for Background Estimation

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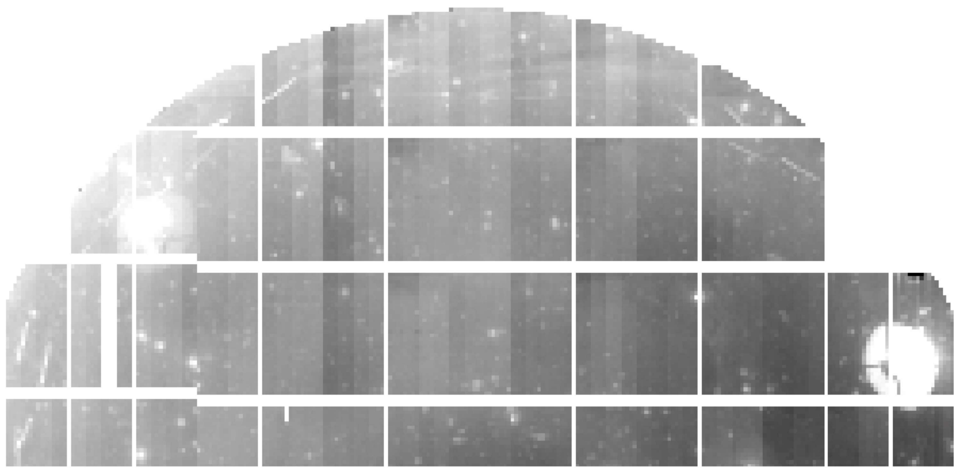
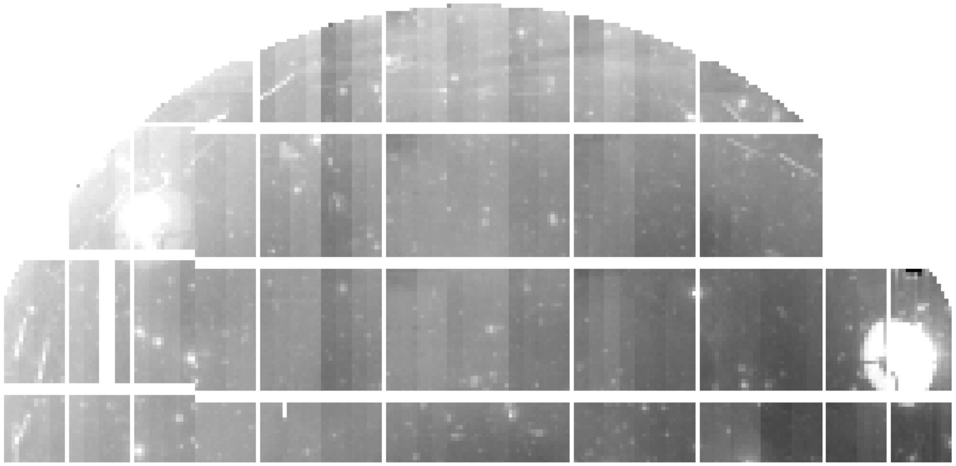
- Step 1) Remove discontinuities and other high frequency structure due to **instrumental background** when still in CCD/Focal plane coordinates.



Project Plans for Background Estimation

Rubin Observatory

- Step 1) Remove discontinuities and other high frequency structure due to **instrumental background** when still in CCD/Focal plane coordinates.
- Step 2) Continue using a local per-ccd background for measuring Sources, then throw it away.



Project Plans for Background Estimation

Rubin Observatory

- Step 1) Remove discontinuities and other high frequency structure due to **instrumental background** when still in CCD/Focal plane coordinates.
- Step 2) Continue using a local per-ccd background for measuring Sources, then throw it away.
- Step 3) **Remove "temporal" background** (that which is neither astrophysical nor instrumental) **by Background Matching**.

3. Background Matching

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- Goal: Estimate the difference in sky level between successive exposures
  - Leave in common-mode (astrophysical) background
    - Wings of galaxies, diffuse nebulosity
  - Remove time-dependent backgrounds
    - Atmospheric: changes airglow, moonlight. Ghosts, glints,
- One realization of the sky survives, but we can subtract this at higher S/N

3. Background Matching

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- Start with a reference image the size of a tract.
  - Locks the sky-level of a coadd patch to that of its neighbors
  - Ensures the coadd will be seamless at patch boundaries

  - On FOV scale: a reference image can be one visit.

Reference Image for example patch

Figures from Stripe 82 S13 Data Challenge

3. Background Matching

For each input Image:

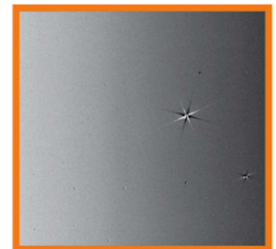
1) Take the difference Image

Reference

−

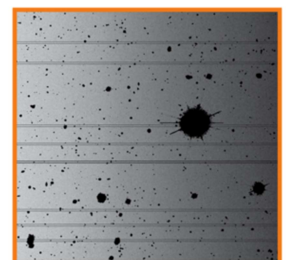
Input

=



Difference

2) Mask out detections and bad pixels in difference image



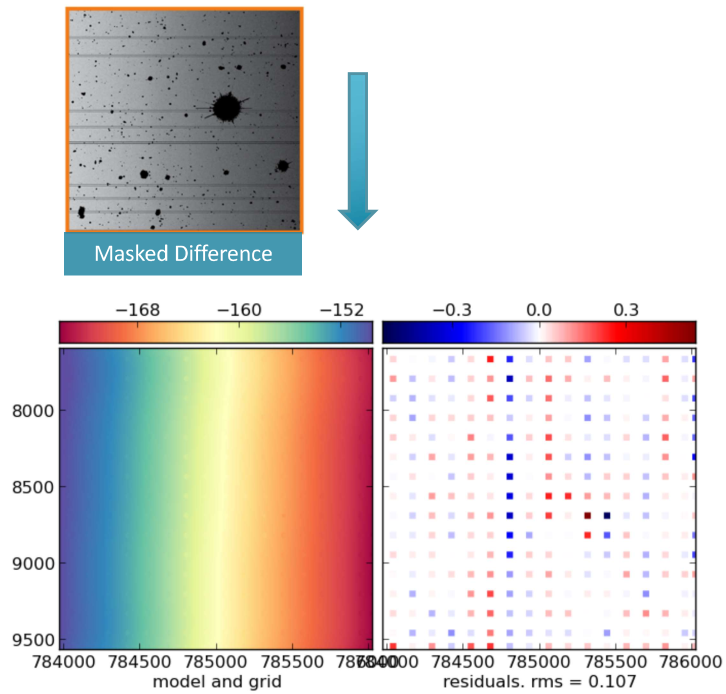
Masked Difference

3: Background Matching

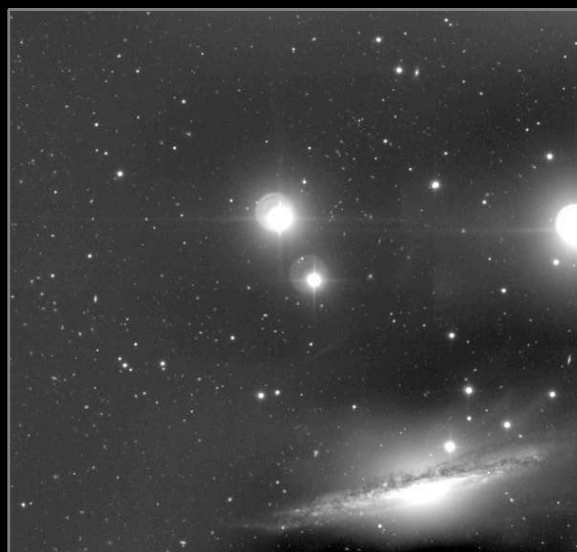
3) Fit a 2D model to the masked difference image to generate an offset image.

4) Add the offset image to the input image, matching the background level to that of the reference image.

5) Check quality of match: (RMS of residuals, MSE/Variance. Leave out if matching failed

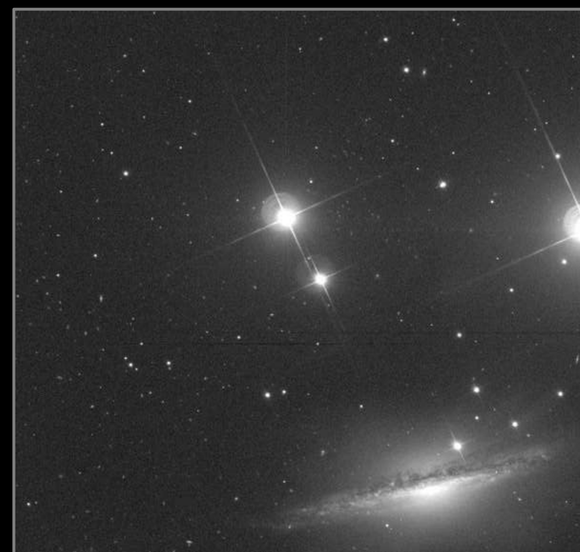


Background-subtracted coadd



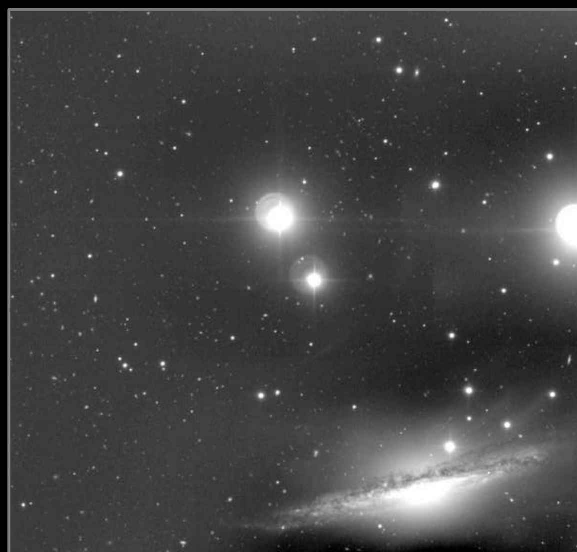
5 arcmin

Single-epoch visit



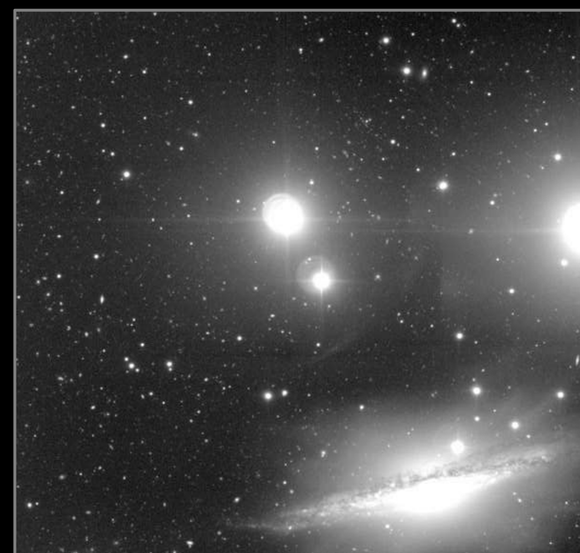
1 patch Stripe 82 SDSS, r-band

Background-subtracted coadd



5 arcmin

Background-matched coadd

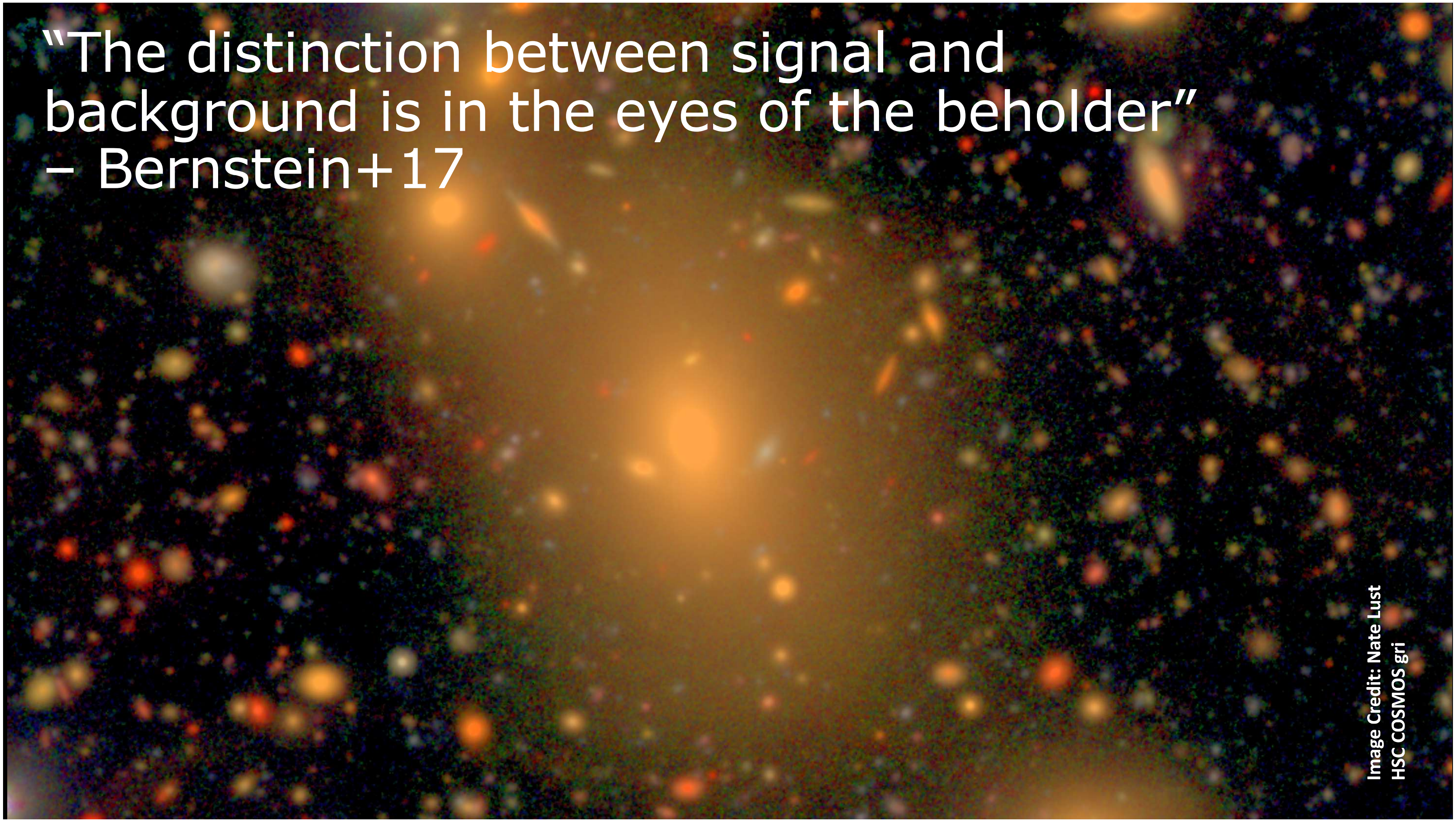


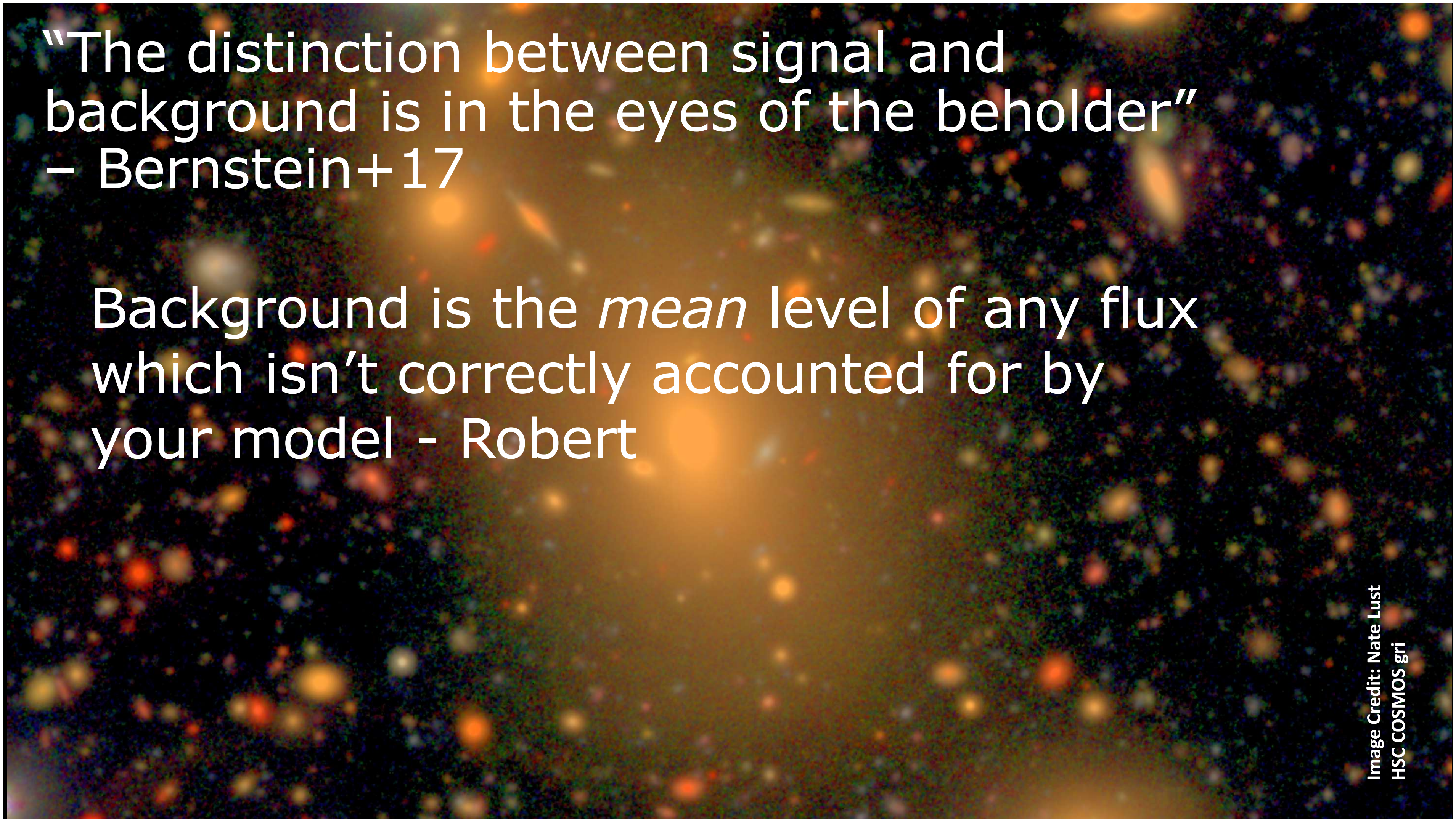
1 patch Stripe 82 SDSS, r-band

Project Plans for Background Estimation

Rubin Observatory

- Step 1) Remove discontinuities and other high frequency structure due to **instrumental background** when still in CCD/Focal plane coordinates.
- Step 2) Continue using a local per-ccd background for measuring Sources, then throw it away.
- Step 3) **Remove "temporal" background** (that which is neither astrophysical nor instrumental) **by Background Matching**.
- Step 4) Model the **astrophysical background** in the higher SNR coadd.


"The distinction between signal and background is in the eyes of the beholder"
– Bernstein+17
Image Credit: Nate Lust
HSC COSMOS gri

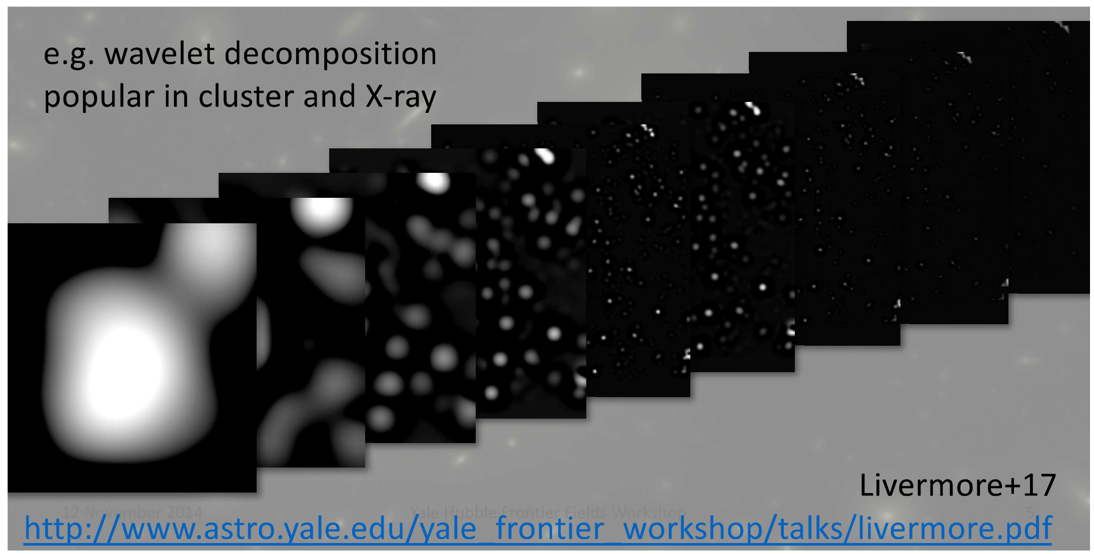

"The distinction between signal and background is in the eyes of the beholder" – Bernstein+17
Background is the *mean* level of any flux which isn't correctly accounted for by your model - Robert
Image Credit: Nate Lust
HSC COSMOS gri

One woman's garbage is another's treasure

- Asking the deblender to deblend images with a 8192 pixel scale background shrunk our clean sample by >30% ☹
- We need to do some astrophysical background subtraction, (though aggressive 128 pixel scale background we're currently subtracting is not ideal)
- You will always be able to add this background back in and look for ultra diffuse galaxies with the pixels. Help us help you by making this background model as useful as possible…

Future ponderings about astrophysical background models

- The scales of interest are varied
- We can store a hierarchical model of the background at many scales:



Plan Summary

Rubin Observatory

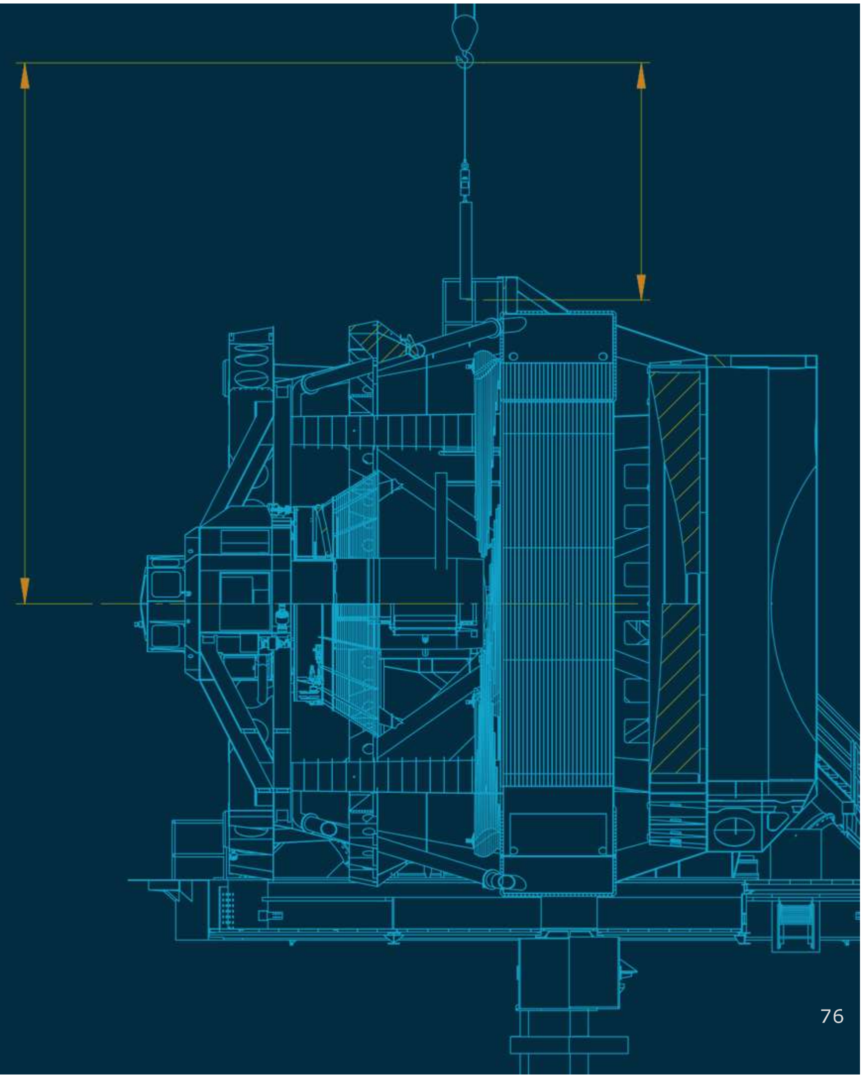
- Instrumental
  - We commit to getting ISR right, and building ability to handle amp-to-amp and ccd-to-ccd discontinuities in background. This will enable either full focal plane background estimation or background matching at coadd stage.
- Temporal (everything that is not fixed in focal plane or sky coords)
  - Background matched coadds: utilize temporal nature to separate astrophysical from
  - Subtracting wings of bright stars
  - Background matched coadds (I am more convinced that we need it now)
- Astrophysical
  - We detect, deblend and measure on a background subtracted image.
  - However, the background model subtracted is available to add back in. The in the future, it should be hierarchical/multi-component so that users can apply spatial scale of their choosing.

Outstanding problems
Potential Unconference discussions

Rubin Observatory

- What do we do about the edges of the ghosts and/or goulies?
- What have you learned about the instrumental background? Will the robust PCA work?
- What do we do about the final astrophysical background?

Appendix



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

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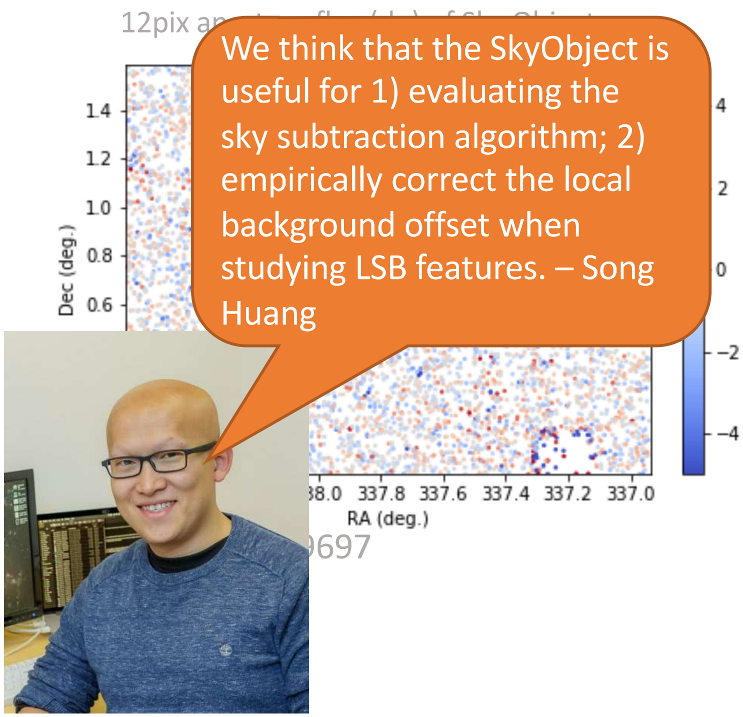

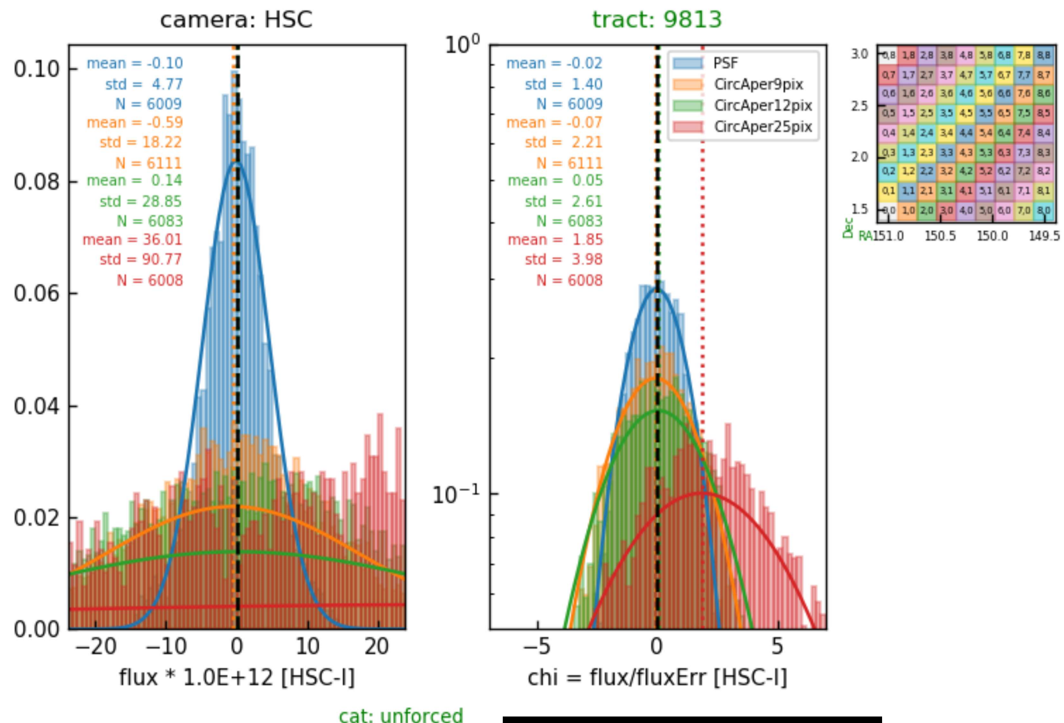

Image Credit: Lauren MacArthur

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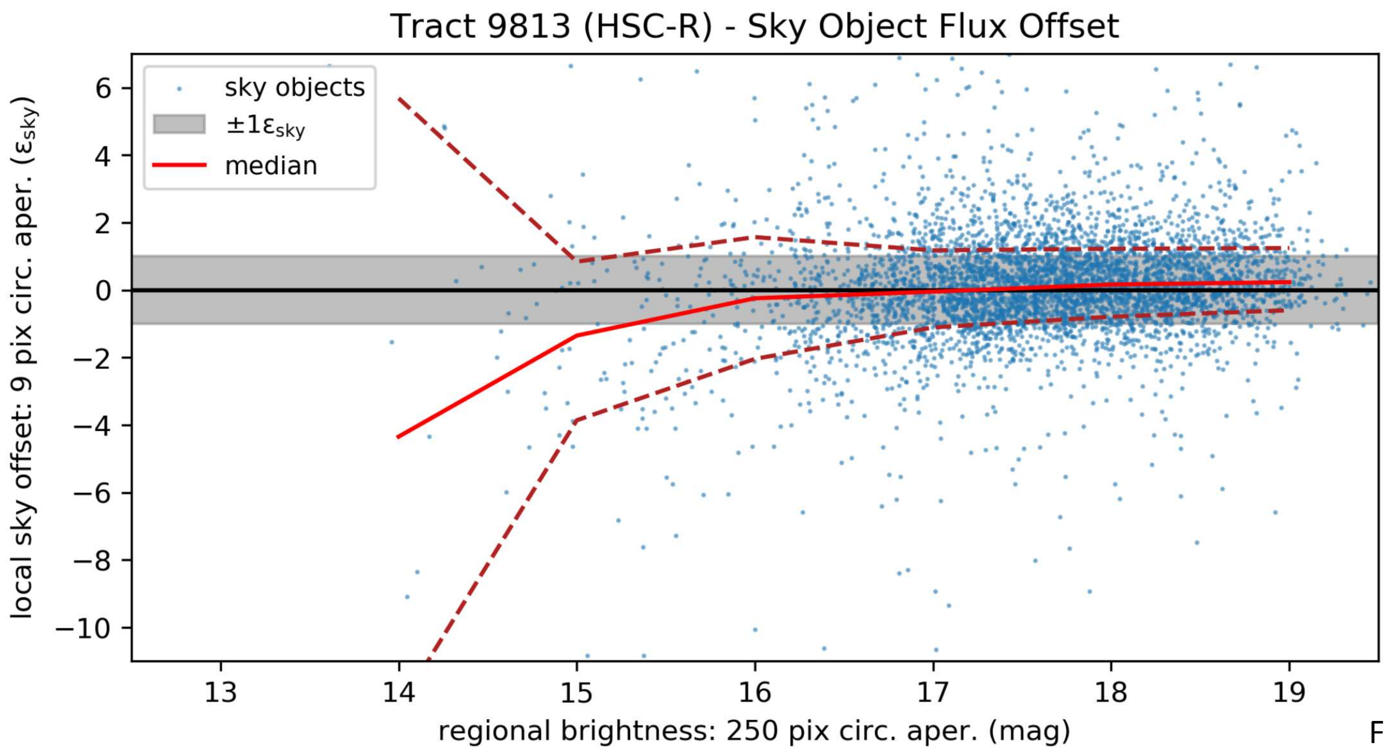

Figure: Lee Kelvin