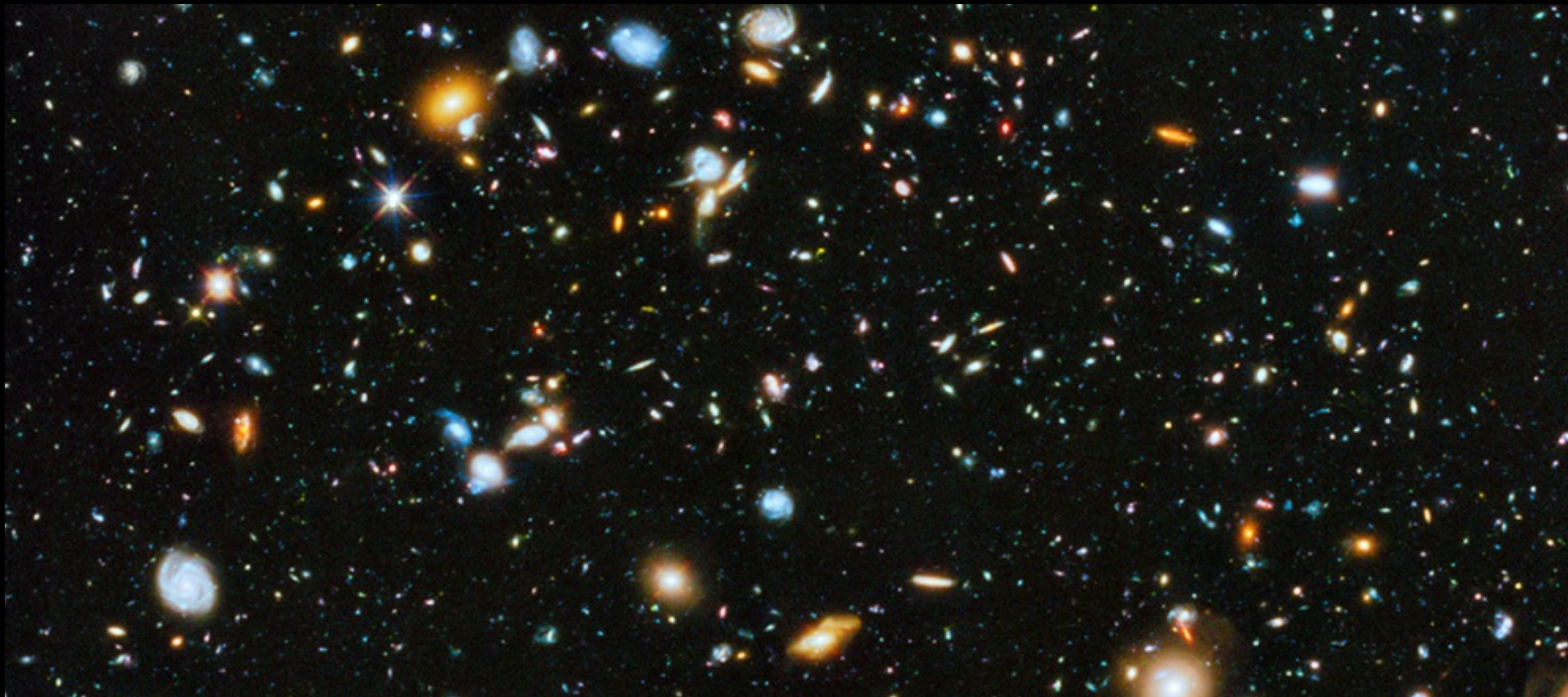


IMAGE STACKING AND DIFFERENCING

GAUTHAM NARAYAN
STSCI

HUDF 2014: NASA, ESA, H.Teplitz and M.Rafelski (IPAC/Caltech), A. Koekemoer (STScI), R. Windhorst(ASU), Z. Levay (STScI)

Image Processing

Astronomical image processing is an enormous topic, and one that we'll return to in future Schools. For example, I worry about:

- Correcting for the effects of CCD electronics on the data
- Estimating the contamination due to moonlight and optical ghosts
- Finding the PSF given an image
- Looking for what has changed between pairs of images
- Measuring the fluxes and colours of faint galaxies
- Disentangling sets of overlapping images
- Subtracting the OH lines from faint spectra
- …

I'm only going to talk about an easier problem today.

THROWBACK!

FROM ROBERT LUPTON'S DSFP #1 PRESENTATION ON PHOTOMETRY

Image Processing

Astronomical image processing is an enormous topic, and one that we'll return to in future Schools. For example, I worry about:

- Correcting for the effects of CCD electronics on the data
- Estimating the contamination due to moonlight and optical ghosts
- Finding the PSF given an image
- Looking for what has changed between pairs of images
- Measuring the fluxes and colours of faint galaxies
- Disentangling sets of overlapping images
- Subtracting the OH lines from faint spectra
- …

I'm only going to talk about an easier problem today.

THROWBACK!

FROM ROBERT LUPTON'S DSFP #1 PRESENTATION ON PHOTOMETRY

Image Processing

Astronomical image processing is an enormous topic, and one that we'll return to in future Schools. For example, I worry about:

- Correcting for the effects of CCD electronics on the data
- Estimating the contamination due to moonlight and optical ghosts
- Finding the PSF given an image
- Looking for what has changed between pairs of images
- Measuring the fluxes and colours of faint galaxies
- Disentangling sets of overlapping images
- Subtracting the OH lines from faint spectra
- …

I'm only going to talk about an easier problem today.

THROWBACK!

FROM ROBERT LUPTON'S DSFP #1 PRESENTATION ON PHOTOMETRY

IMAGE STACKING: PRINCIPLE

IMAGE STACKING: PRINCIPLE

- Combine* several different images of the same region of sky

IMAGE STACKING: PRINCIPLE

- Combine* several different images of the same region of sky
- The shot noise is random

IMAGE STACKING: PRINCIPLE

- Combine* several different images of the same region of sky
- The shot noise is random
- Photons from sources are not random

IMAGE STACKING: PRINCIPLE

- Combine* several different images of the same region of sky
- The shot noise is random
- Photons from sources are not random
- Averaging several images together should improve the S/N as the square root of the number of the images

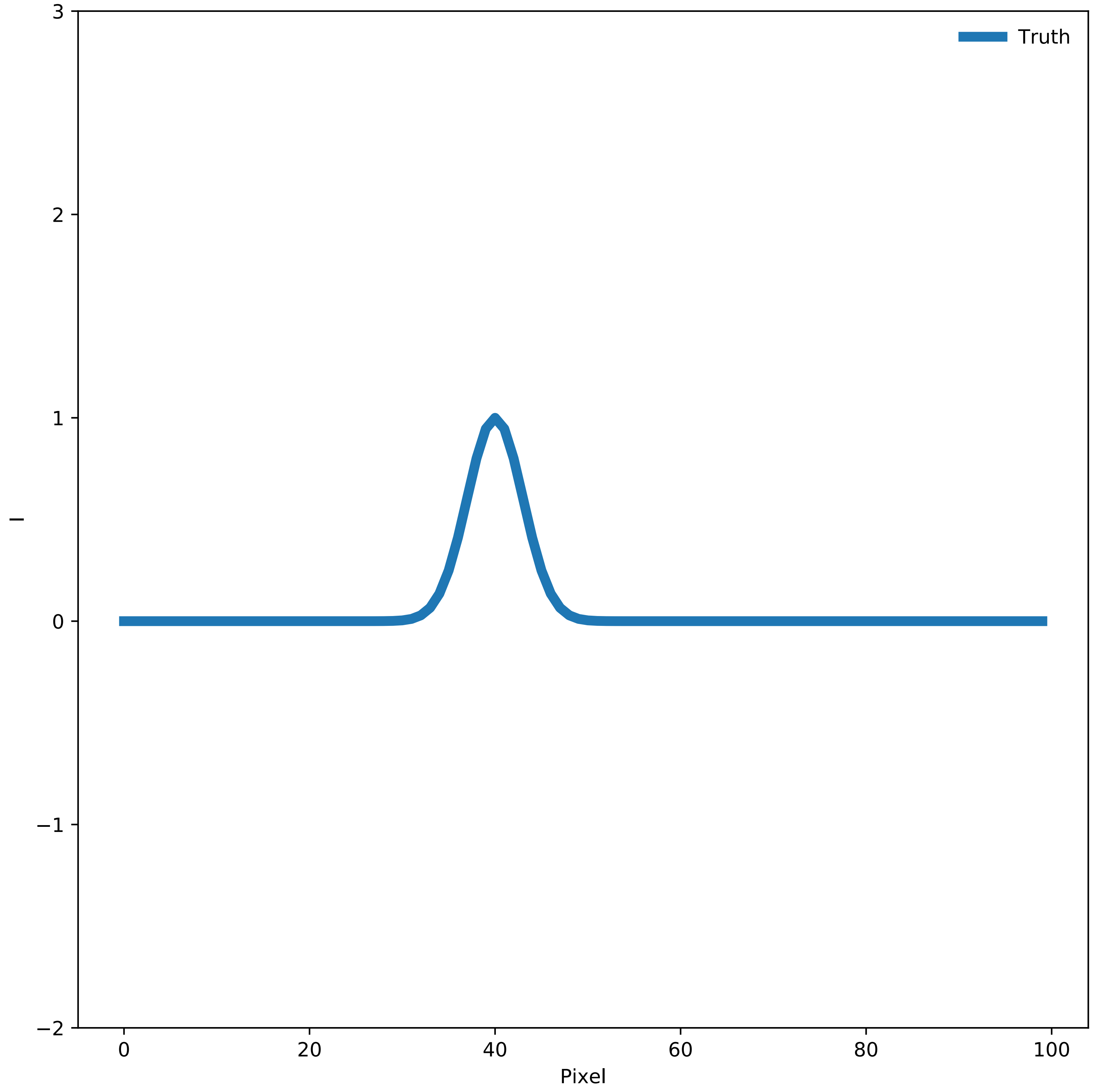


IMAGE STACKING: TOY EXAMPLE

GAUSSIAN WITH THE SAME PARAMETERS FROM RL'S DSFP#1 TALK

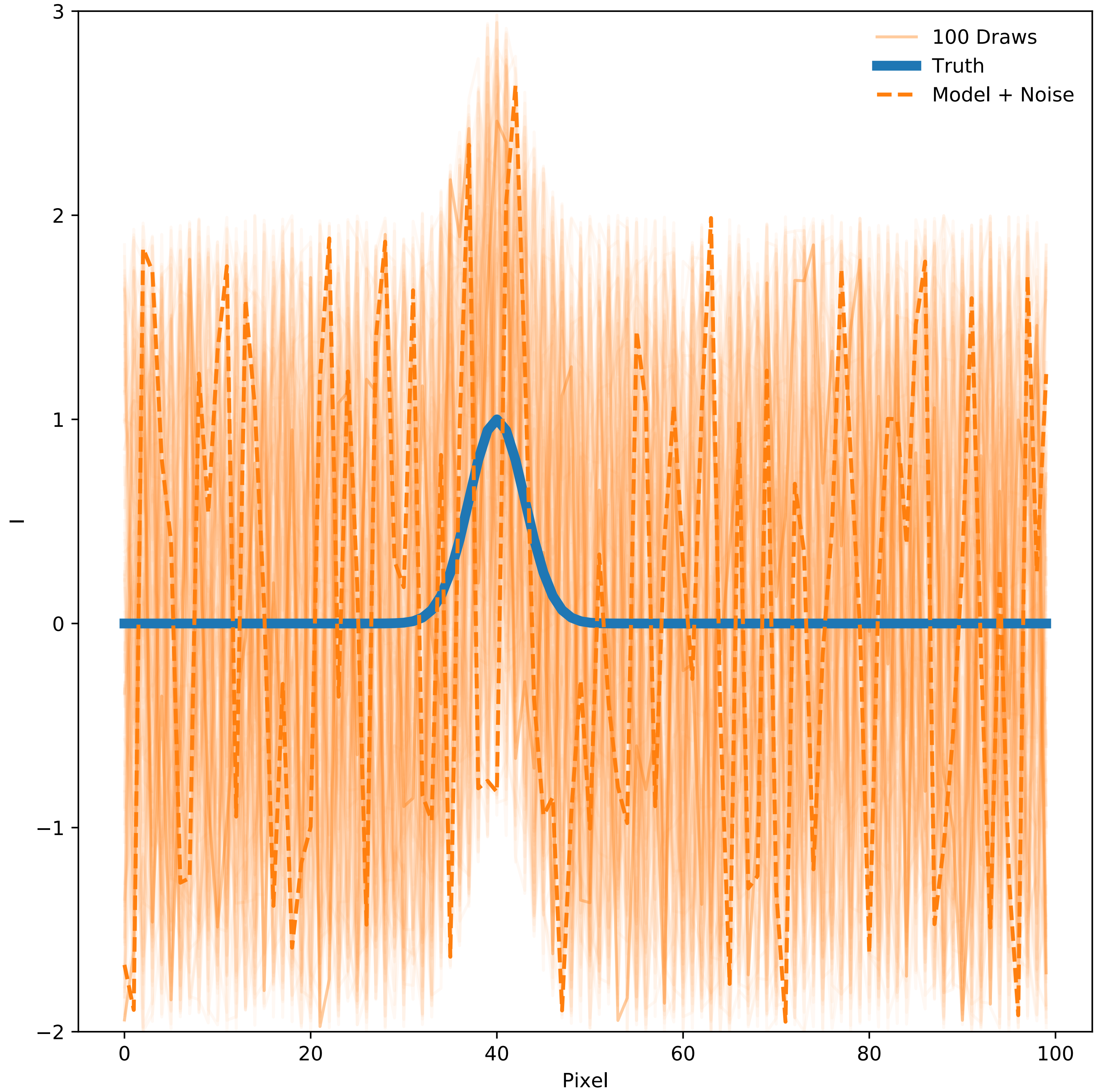


IMAGE STACKING: TOY EXAMPLE

GAUSSIAN BURIED IN NOISE

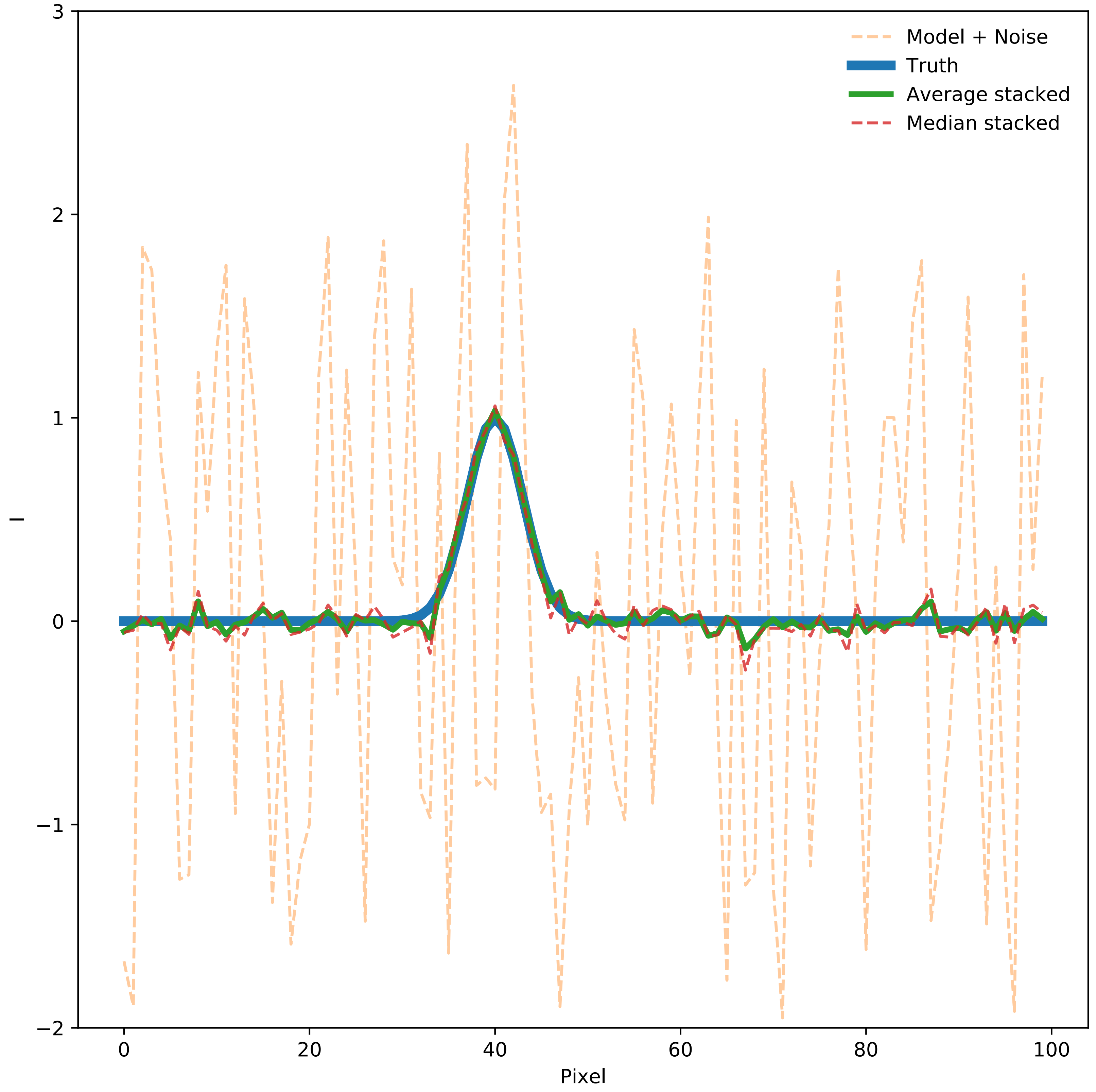


IMAGE STACKING: TOY EXAMPLE

STACKING BEATS DOWN THE NOISE

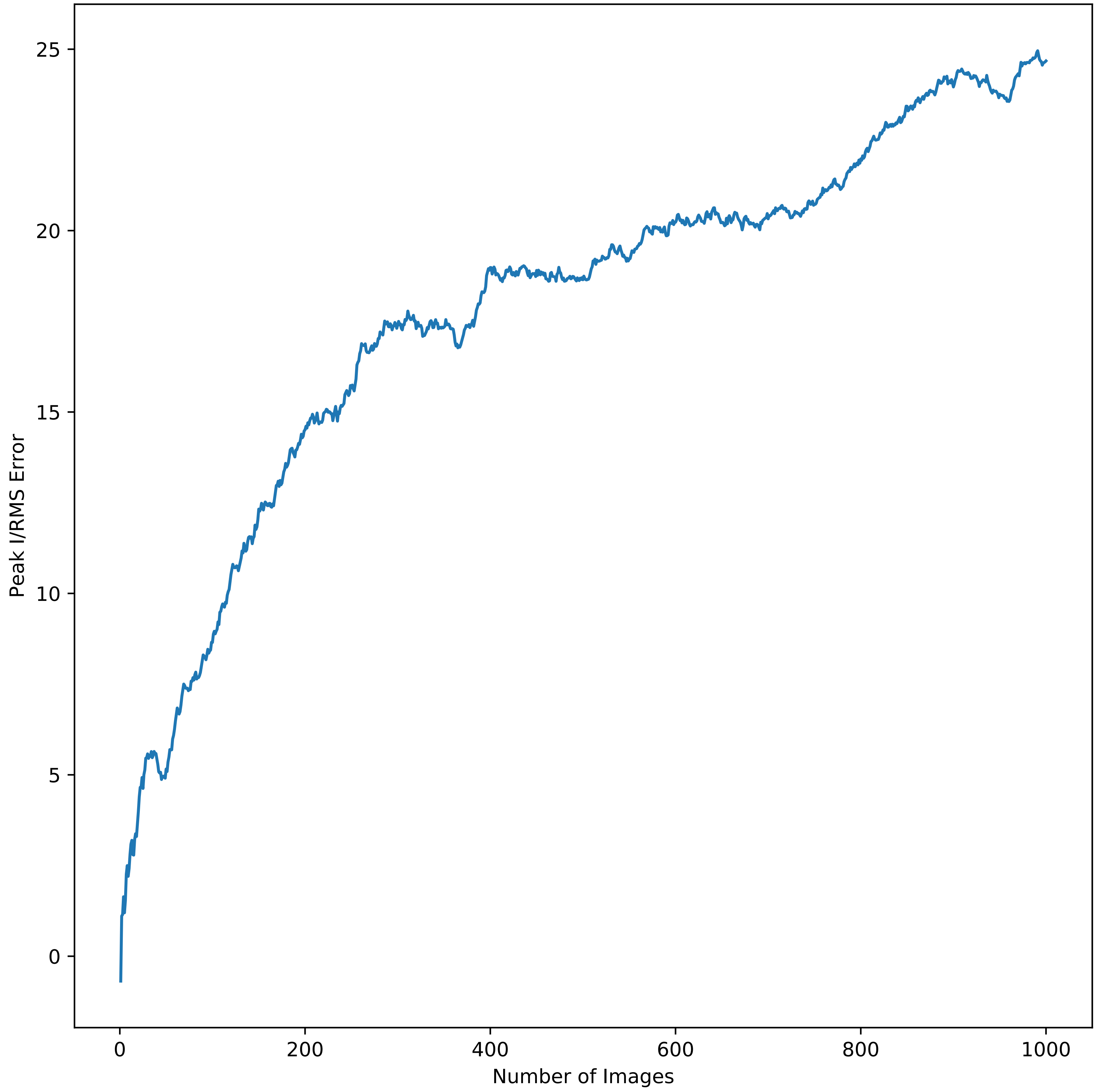


IMAGE STACKING: TOY EXAMPLE

STACKING BEATS DOWN THE NOISE

IMAGE STACKING: WHY NOT JUST INTEGRATE LONGER?

IMAGE STACKING: WHY NOT JUST INTEGRATE LONGER?

* Saturation

IMAGE STACKING: WHY NOT JUST INTEGRATE LONGER?

- Saturation
- Cosmic rays*

IMAGE STACKING: WHY NOT JUST INTEGRATE LONGER?

- Saturation
- Cosmic rays*
- Asteroids/satellites buzzing your science target*

IMAGE STACKING: WHY NOT JUST INTEGRATE LONGER?

- Saturation
- Cosmic rays*
- Asteroids/satellites buzzing your science target*
- Murphy is right (software, instrument, telescope, dome, weather)

IMAGE STACKING: COMPLICATIONS

IMAGE STACKING: COMPLICATIONS

- We don’t want images that are flat in pixel coordinates but rather flat* on the sky: **image registration/WCS**

IMAGE STACKING: COMPLICATIONS

- We don’t want images that are flat in pixel coordinates but rather flat* on the sky: **image registration/WCS**
- Images aren’t aligned with respect to each other: **resampling/reprojection**

IMAGE STACKING: COMPLICATIONS

- We don’t want images that are flat in pixel coordinates but rather flat* on the sky: **image registration/WCS**
- Images aren’t aligned with respect to each other: **resampling/reprojection**
- Sources don’t have the same PSF properties: **convolution**

IMAGE STACKING: COMPLICATIONS

- We don't want images that are flat in pixel coordinates but rather flat* on the sky: **image registration/WCS**
- Images aren't aligned with respect to each other: **resampling/reprojection**
- Sources don't have the same PSF properties: **convolution**
- Images don't have the same noise properties: **image combination**

IMAGE STACKING: COMPLICATIONS

- We don't want images that are flat in pixel coordinates but rather flat* on the sky: **image registration/WCS**
- Images aren't aligned with respect to each other: **resampling/reprojection**
- Sources don't have the same PSF properties: **convolution**
- Images don't have the same noise properties: **image combination**
- **Any of these subjects could be a DSFP lecture on its own.**

IMAGE STACKING: COMPLICATIONS

- We don't want images that are flat in pixel coordinates but rather flat* on the sky: **image registration/WCS**
- Images aren't aligned with respect to each other: **resampling/reprojection**
- Sources don't have the same PSF properties: **convolution**
- Images don't have the same noise properties: **image combination**
- **Any of these subjects could be a DSFP lecture on its own.**
- **You'll have examples of all of these tasks in the interactive session**

IMAGE REGISTRATION

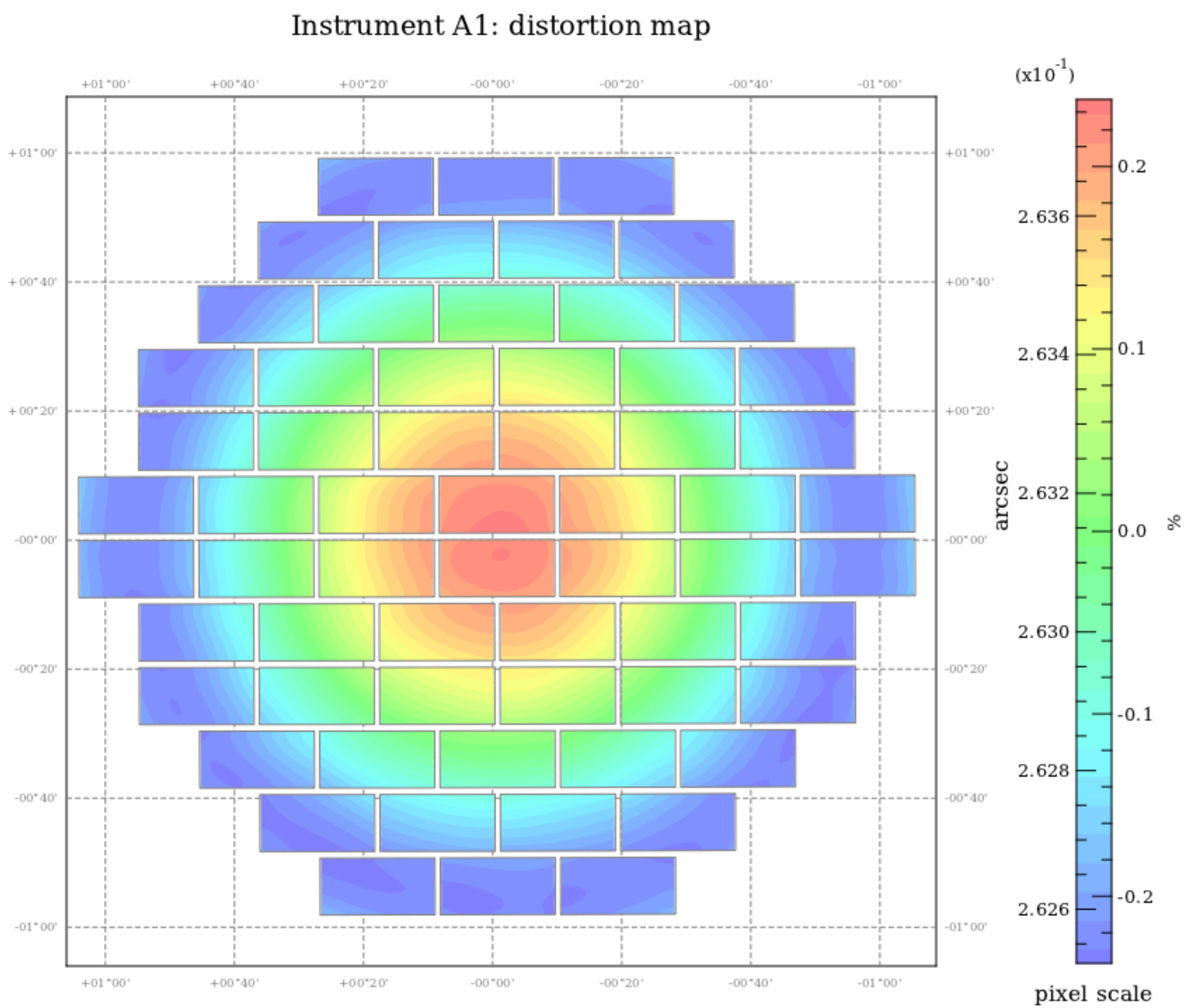


IMAGE REGISTRATION

FROM X, Y TO SKY

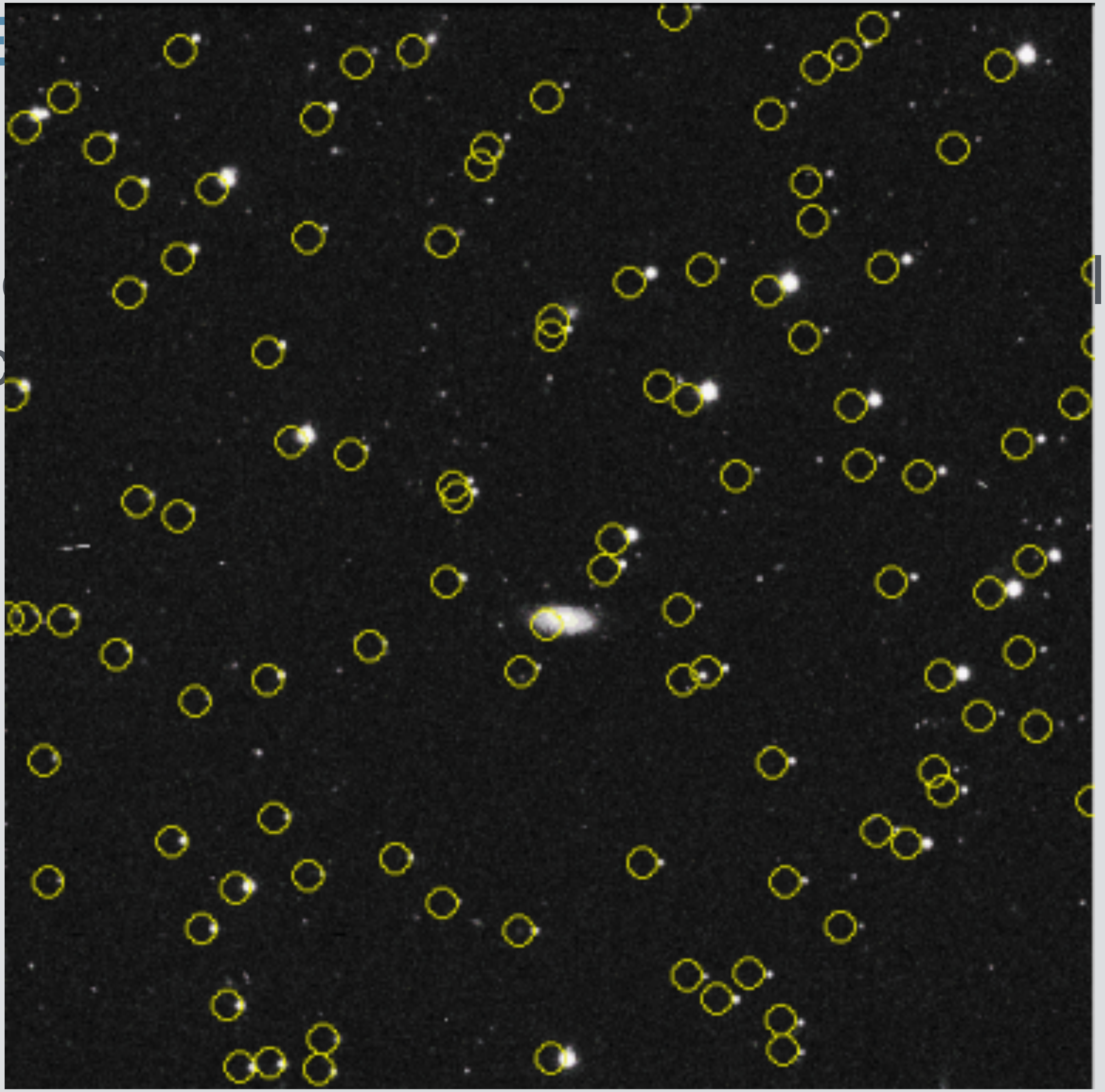
IMAGE REGISTRATION

IMAGE REGISTRATION

- Telescopes having a low-accuracy (typically few arcsec)

IMAGE RE

- Telesc ly few arcsec



Images via Jessica Mink, SAO - author of WCSTools

IMAGE REGISTRATION

- Telescopes having a low-accuracy (typically few arcsec)
- Recorded in FITS headers with non-standard TNX keywords

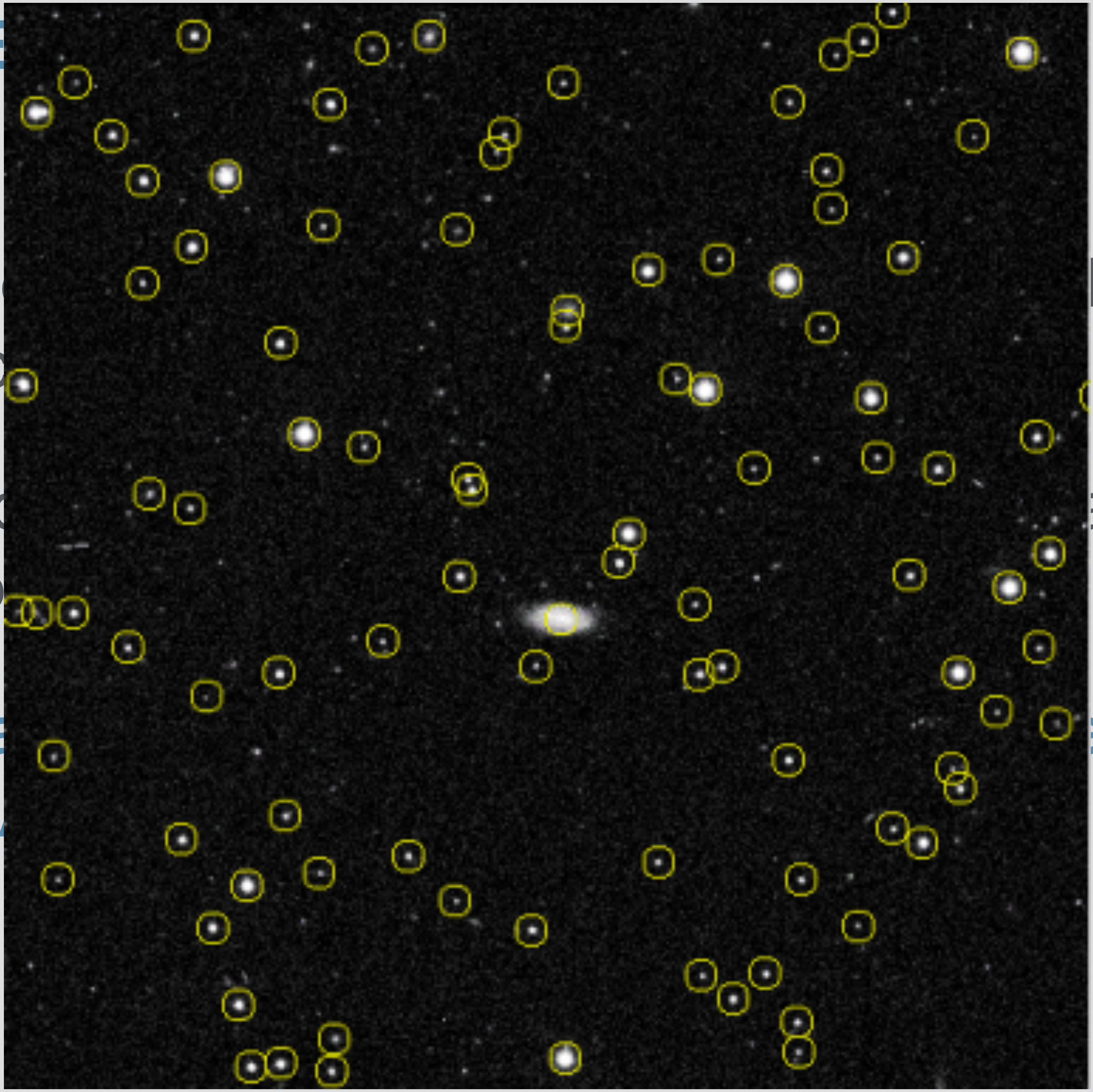
Images via Jessica Mink, SAO - author of WCSTools

IMAGE REGISTRATION

- Telescopes having a low-accuracy (typically few arcsec)
- Recorded in FITS headers with non-standard TNX keywords
- **We want accurate transformation between x, y and RA, Dec**

Images via Jessica Mink, SAO - author of WCSTools

IMAGE RE



- Telesc   ly few arcsec
- Record   ard TNX keywo
- **We wa   een x, y and R**

Images via Jessica Mink, SAO - author of WCSTools

IMAGE REGISTRATION

- Telescopes having a low-accuracy (typically few arcsec)
- Recorded in FITS headers with non-standard TNX keywords
- **We want accurate transformation between x, y and RA, Dec**
- Corrects for optical distortion and maps relative positions of CCDs in mosaics

Images via Jessica Mink, SAO - author of WCSTools

STEPS TO REGISTER AN IMAGE

STEPS TO REGISTER AN IMAGE

- Use a photometry package to identify sources in the image and determine centroids in pixel coordinates

STEPS TO REGISTER AN IMAGE

- Use a photometry package to identify sources in the image and determine centroids in pixel coordinates
  - **Python: Photutils module**,
    Standalone: **Sourceextractor, DOPHOT, DAOPhot (also in IRAF and IDL), IRAF: apphot**

STEPS TO REGISTER AN IMAGE

- Use a photometry package to identify sources in the image and determine centroids in pixel coordinates
  - **Python: Photutils module**,
    Standalone: **Sourceextractor, DOPHOT, DAOPhot (also in IRAF and IDL), IRAF: apphot**
- Find sources in the astrometric reference that are present in the image

STEPS TO REGISTER AN IMAGE

- Use a photometry package to identify sources in the image and determine centroids in pixel coordinates
  - **Python: Photutils module**,
    Standalone: **Sourceextractor, DOPHOT, DAOPhot (also in IRAF and IDL), IRAF: apphot**
- Find sources in the astrometric reference that are present in the image
- Parametrize the mapping from pixel coordinates to sky coordinates (**SIP/STScI or SWarp**)

STEPS TO REGISTER AN IMAGE

- Use a photometry package to identify sources in the image and determine centroids in pixel coordinates
  - **Python: Photutils module**,
    Standalone: **Sourceextractor, DOPHOT, DAOPhot (also in IRAF and IDL), IRAF: apphot**
- Find sources in the astrometric reference that are present in the image
- Parametrize the mapping from pixel coordinates to sky coordinates (**SIP/STScI or SWarp**)
- Does all of the above: ***astrometry.net*** - creates hashes of asterisms found the in the image (quads) - matches them against index files. Also **casutools: wcsfit**

STEPS TO REGISTER AN IMAGE

- Use a photometry package to identify sources in the image and determine centroids in pixel coordinates
  - **Python: Photutils module**,
    Standalone: **Sourceextractor, DOPHOT, DAOPhot (also in IRAF and IDL),**
    IRAF: apphot
- Find sources in the astrometric reference that are present in the image
- Parametrize the mapping from pixel coordinates to sky coordinates (**SIP/STScI or SWarp**)
- Does all of the above: ***astrometry.net*** - creates hashes of asterisms found the in the image (quads) - matches them against index files. Also **casutools: wcsfit**
- Other useful routines: **WCSTools: imstar, imwcs**

```
 xi = a + b * x + c * y
eta = d + e * x + f * y
  b = CD1_1
  c = CD1_2
  e = CD2_1
  f = CD2_2
  a = - b * CRPIX1 - c * CRPIX2
  d = - e * CRPIX1 - f * CRPIX2
lng = CRVAL1 + PROJ (xi, eta)
lat = CRVAL2 + PROJ (xi, eta)
```

COORDINATE TRANSFORMATION EQUATIONS

NOTICE THERE'S NO PROPAGATION OF ERRORS…

```
 xi = a + b * x + c * y
eta = d + e * x + f * y
  b = CD1_1
  c = CD1_2
  e = CD2_1
  f = CD2_2
  a = - b * CRPIX1 - c * CRPIX2
  d = - e * CRPIX1 - f * CRPIX2
lng = CRVAL1 + PROJ (xi, eta)
lat = CRVAL2 + PROJ (xi, eta)
```

Scale * Rotation Matrix
[* linear distortion terms]

Coordinates of reference pixel

Reference position on sky
Coordinate & Projection

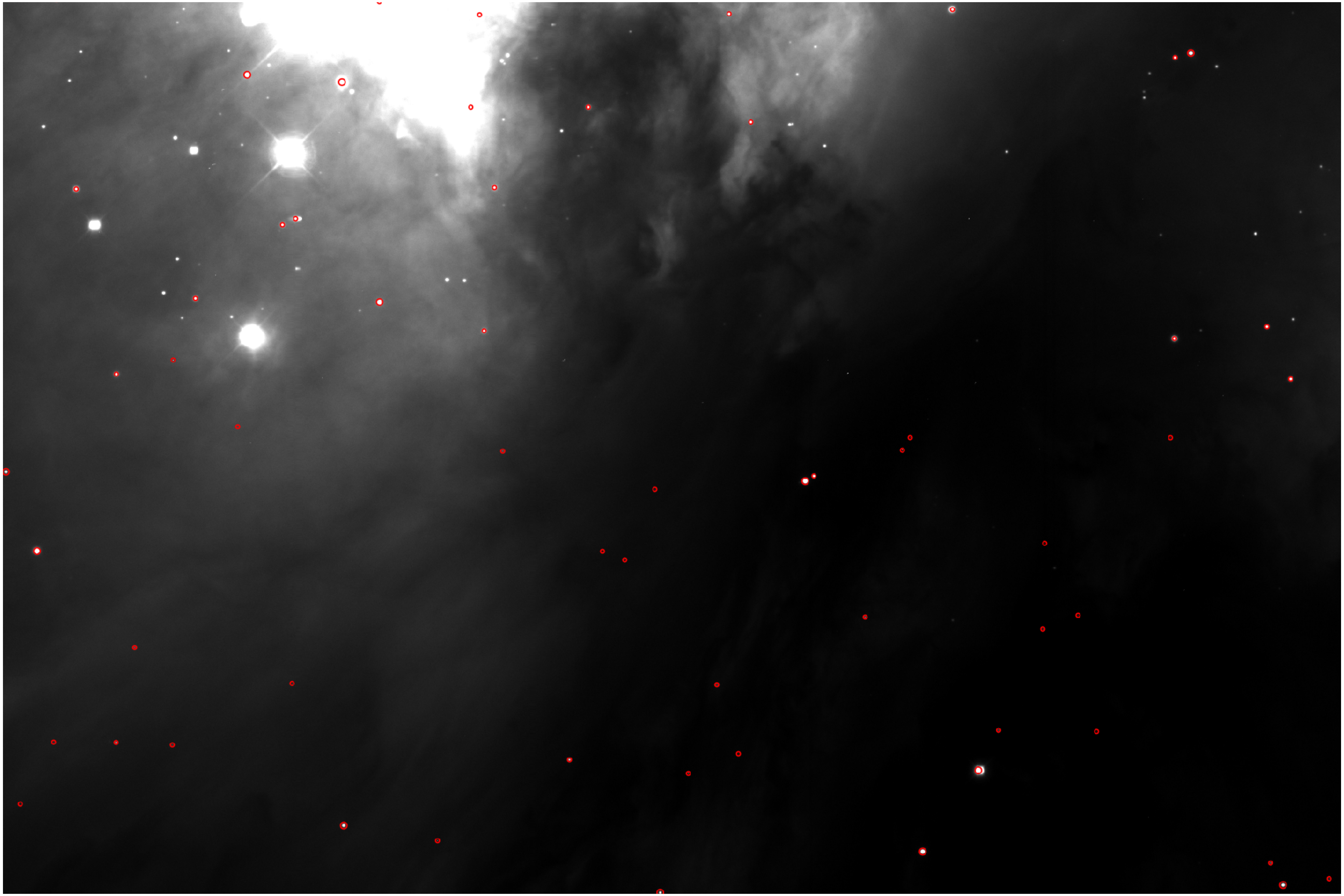
COORDINATE TRANSFORMATION EQUATIONS

NOTICE THERE'S NO PROPAGATION OF ERRORS…

```
EQUINOX =                  2000. / Equinox of WCS
CTYPE1  = 'RA---ZPX'             / Coordinate type
CTYPE2  = 'DEC--ZPX'             / Coordinate type
CRVAL1  =       83.766916666667 / Coordinate reference value
CRVAL2  =      -5.3006944444444 / Coordinate reference value
CRPIX1  =      4152.03773168348 / Coordinate reference pixel
CRPIX2  =      4195.42375738031 / Coordinate reference pixel
CD1_1   =   -9.6821837575595E-7 / Coordinate matrix
CD2_1   =    7.47818380307748E-5 / Coordinate matrix
CD1_2   =    7.48773483089652E-5 / Coordinate matrix
CD2_2   =    8.98167539029998E-7 / Coordinate matrix
WAT0_001= 'system=image'         / Coordinate system
WAT1_002= 'p4=0. projp5=632052. lngcor = "3. 3. 3. 2. -0.31203016064166 -0.003'
WAT1_003= '425476301279112 -0.314189526574204 -0.157433108052880 6.9776357940'
WAT1_004= '06173E-5 0.00167295981742452 0.00142823895913115 -3.98760299129999'
WAT1_005= '0E-4 0.00533155361412972 -0.00253968218235148 "'
WAT2_002= 'jp4=0. projp5=632052. latcor = "3. 3. 3. 2. -0.31203016064166 -0.00'
WAT2_003= '342547630127911 -0.314189526574204 -0.157433108052880 9.439895254'
WAT2_004= '708380E-5 6.53103830617125E-4 0.00158999057475731 5.10627353256451'
WAT2_005= '3E-4 6.37924988908974E-4 9.23317440577101E-4 "'
```

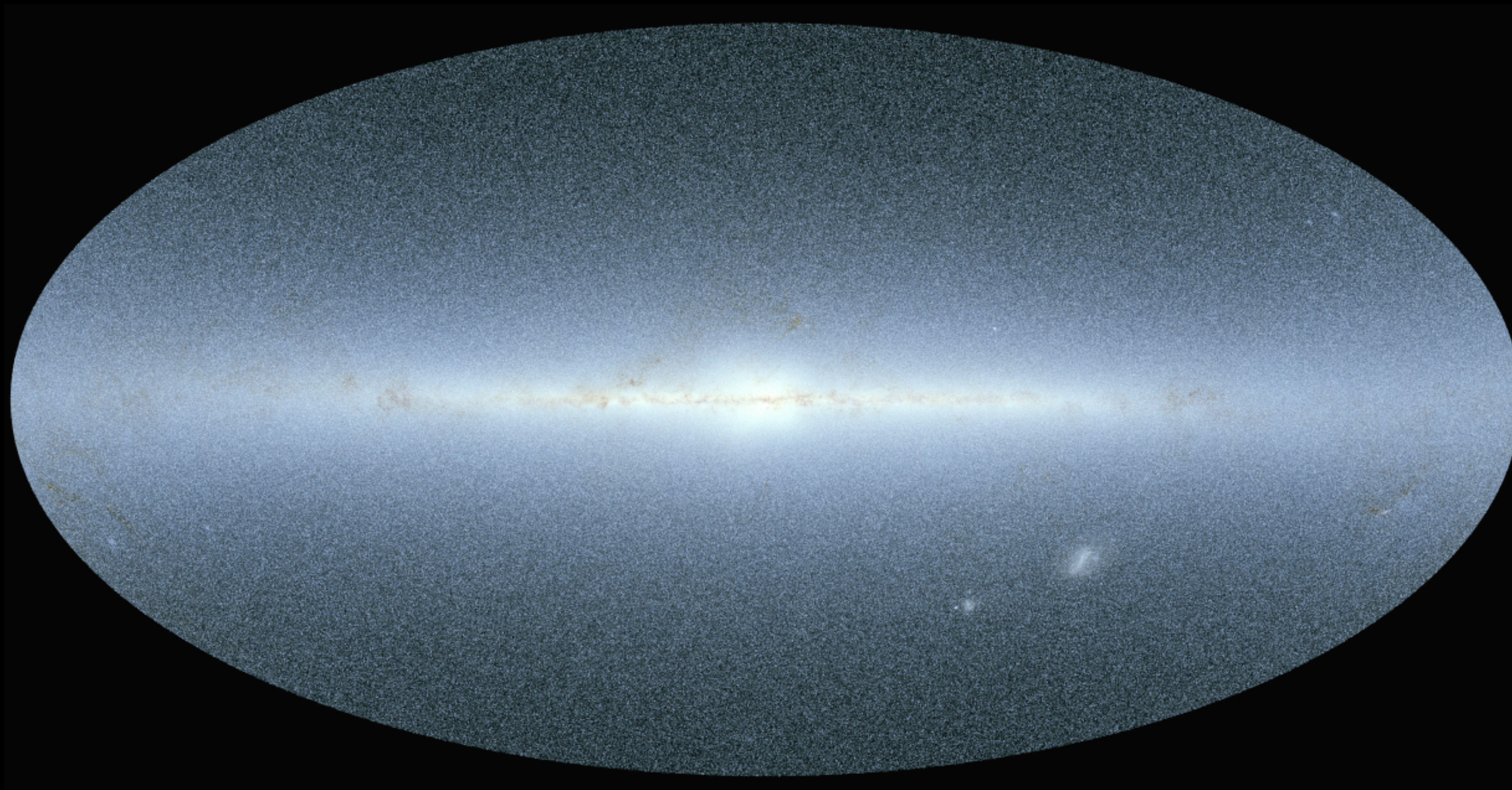
COORDINATE TRANSFORMATION EQUATIONS

WHAT YOU SEE IN THE FITS HEADER - NOTE THAT SOME PROJECTIONS SPECIFY ADDITIONAL FITS HEADER KEYS



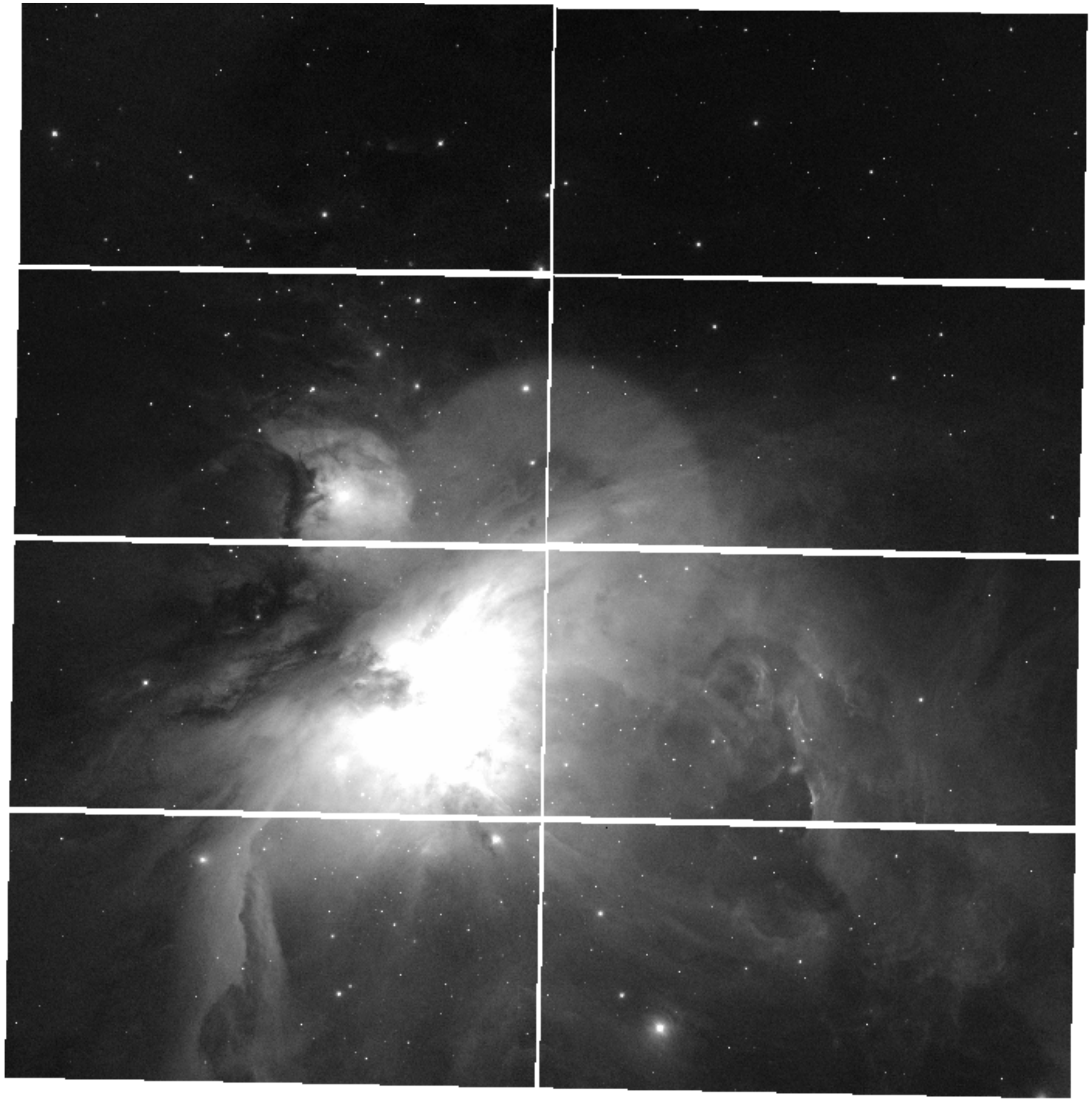
SOURCE DETECTION

YOU CAN EVEN USE LSST-DSFP-SESSION1 CODE TO DO THIS!



ASTROMETRIC REFERENCE CATALOGS

GAIA DR2 (ALL SKY, SOON!), PAN-STARRS (TIED TO GAIA DR1) 2MASS (ALL SKY), USNO-B1 (ALL SKY)



AFTER WCS REGISTRATION!!

THE ASTROMETRY.NET CODE WORKS REALLY WELL EVEN WITH A COMPLICATED BACKGROUND

THE WCS STANDARD ACCOMMODATES SOME REALLY COMPLEX TRANSFORMATIONS

The glass plate scanner of Harvard's DASCH project (@DASCHDesk)

THE WCS STANDARD ACCOMMODATES SOME REALLY COMPLEX TRANSFORMATIONS

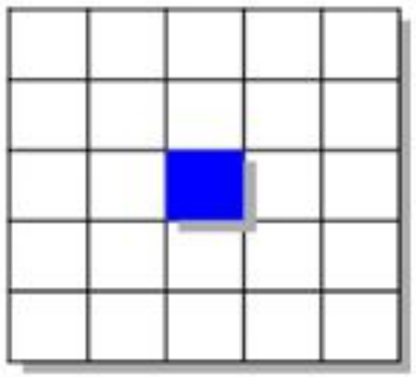
The glass plate scanner of Harvard's DASCH project (@DASCHDesk)

IMAGE RESAMPLING

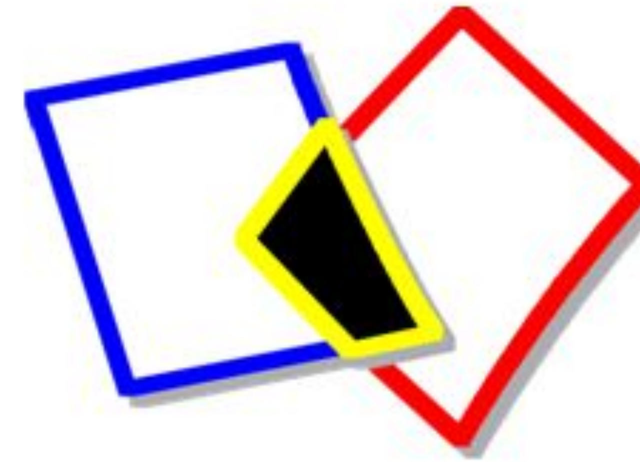
Montage v1.7 Reprojection:

mProject module

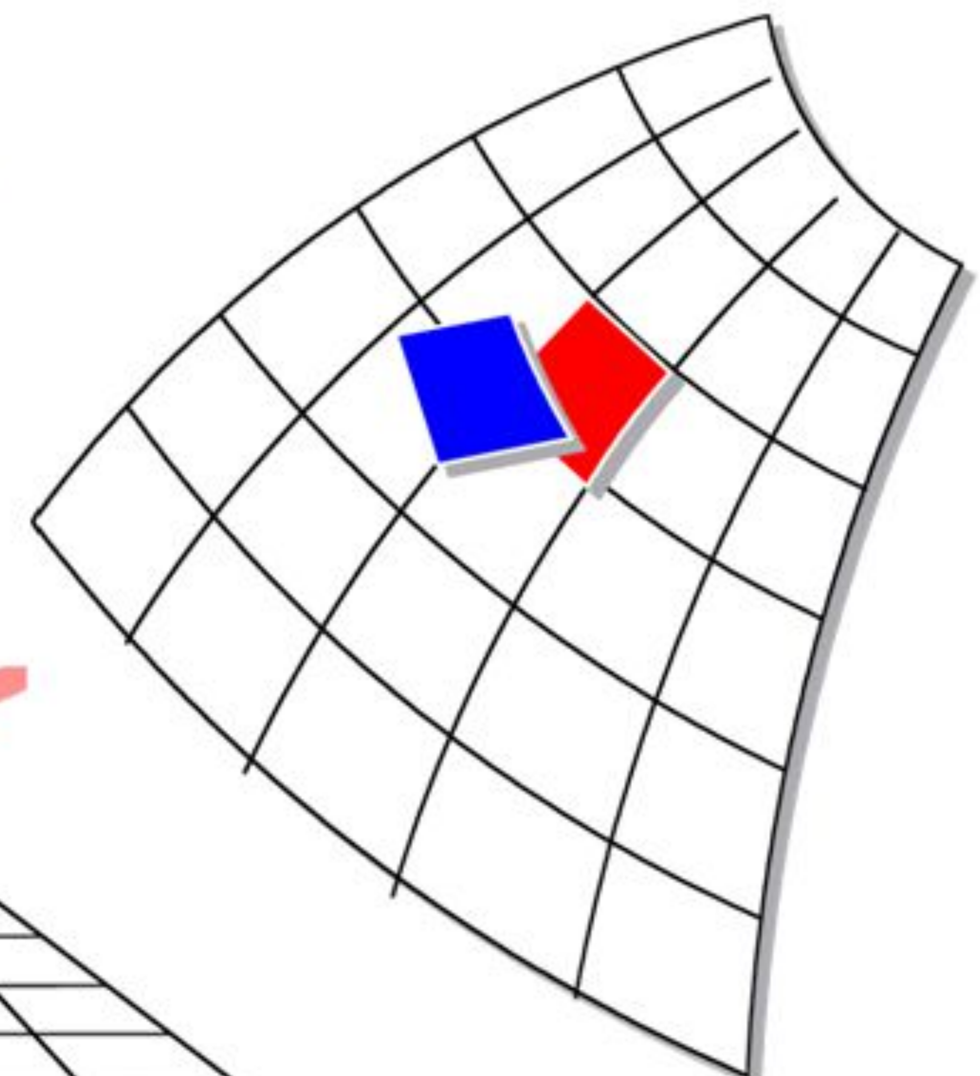
Arbitrary Input Image



Central to the algorithm is accurate calculation of the area of spherical polygon intersection between two pixels (assumes great circle segments are adequate between pixel vertices)



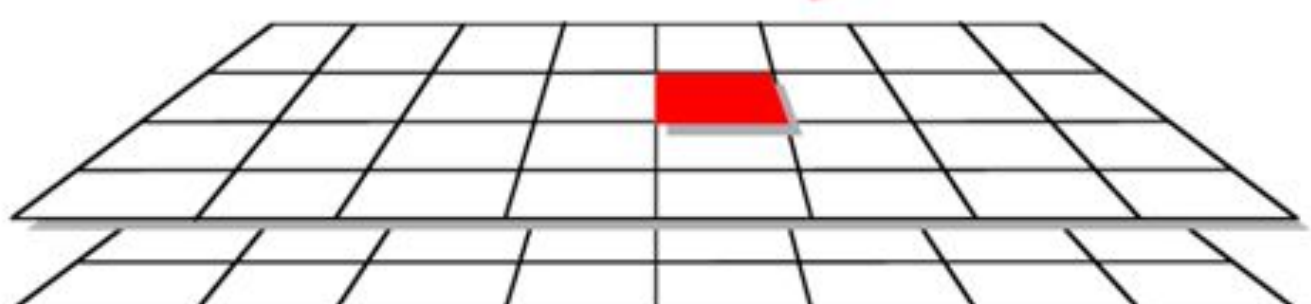
Input pixels projected on celestial sphere



```
SIMPLE  =                T /
BITPIX=          -64 /
NAXIS =            2 /
NAXIS1=         3000 /
NAXIS2=         3000 /
CDELT1=      -   3.333333E-4 /
CDELT2=      -   3.333333E-4 /
CRPIX1=        1500.5 /
CRPIX2=        1500.5 /
CTYPE1='RA---TAN'
CTYPE2='DEC--TAN'
CRVAL1=       265.91334 /
CRVAL2=       -29.35778 /
CROTA2=            0. /
END
```

FITS header defines output projection

Output pixels projected on celestial sphere



Reprojected Image

Montage v1.7 Reprojection:

mProject module

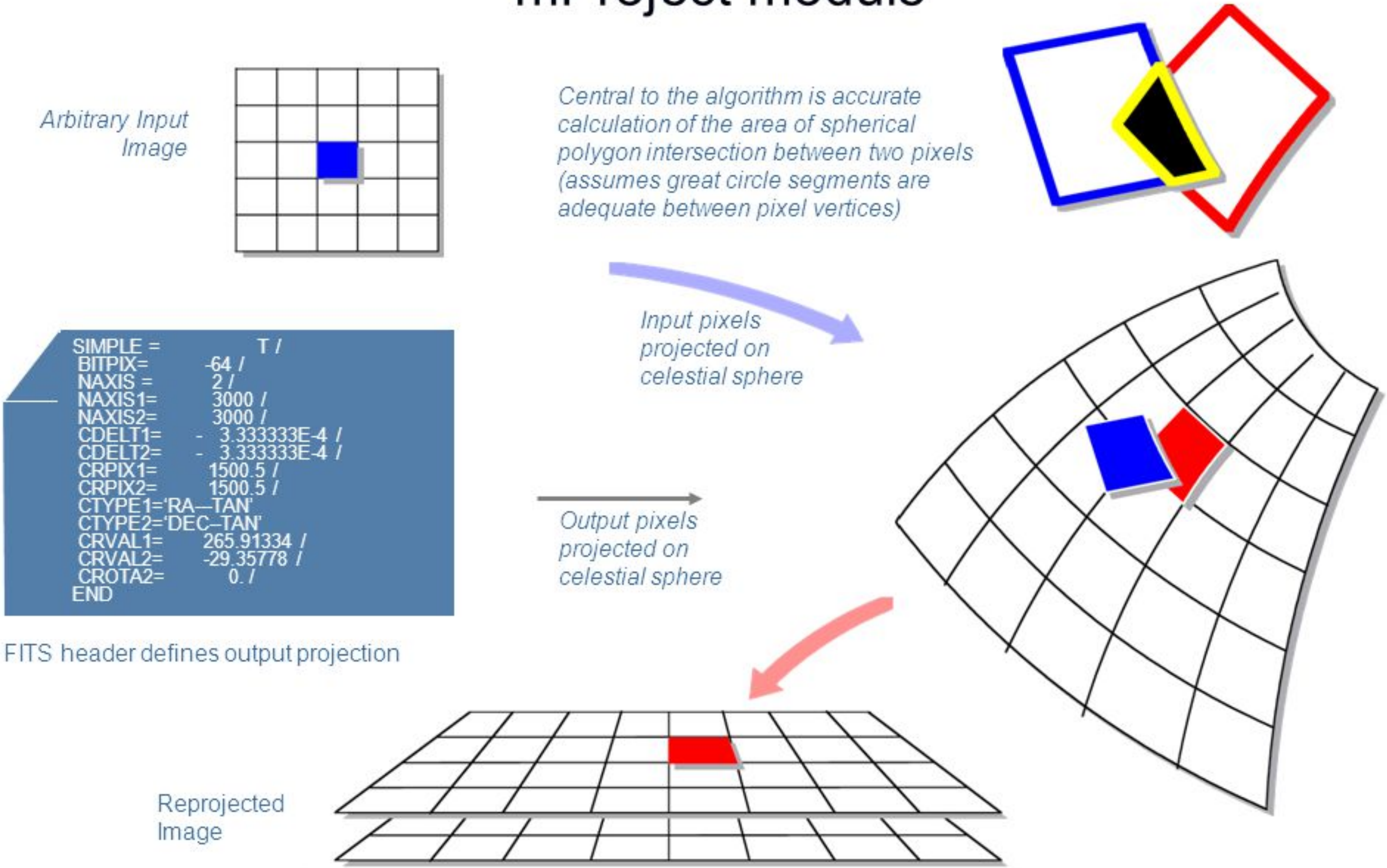
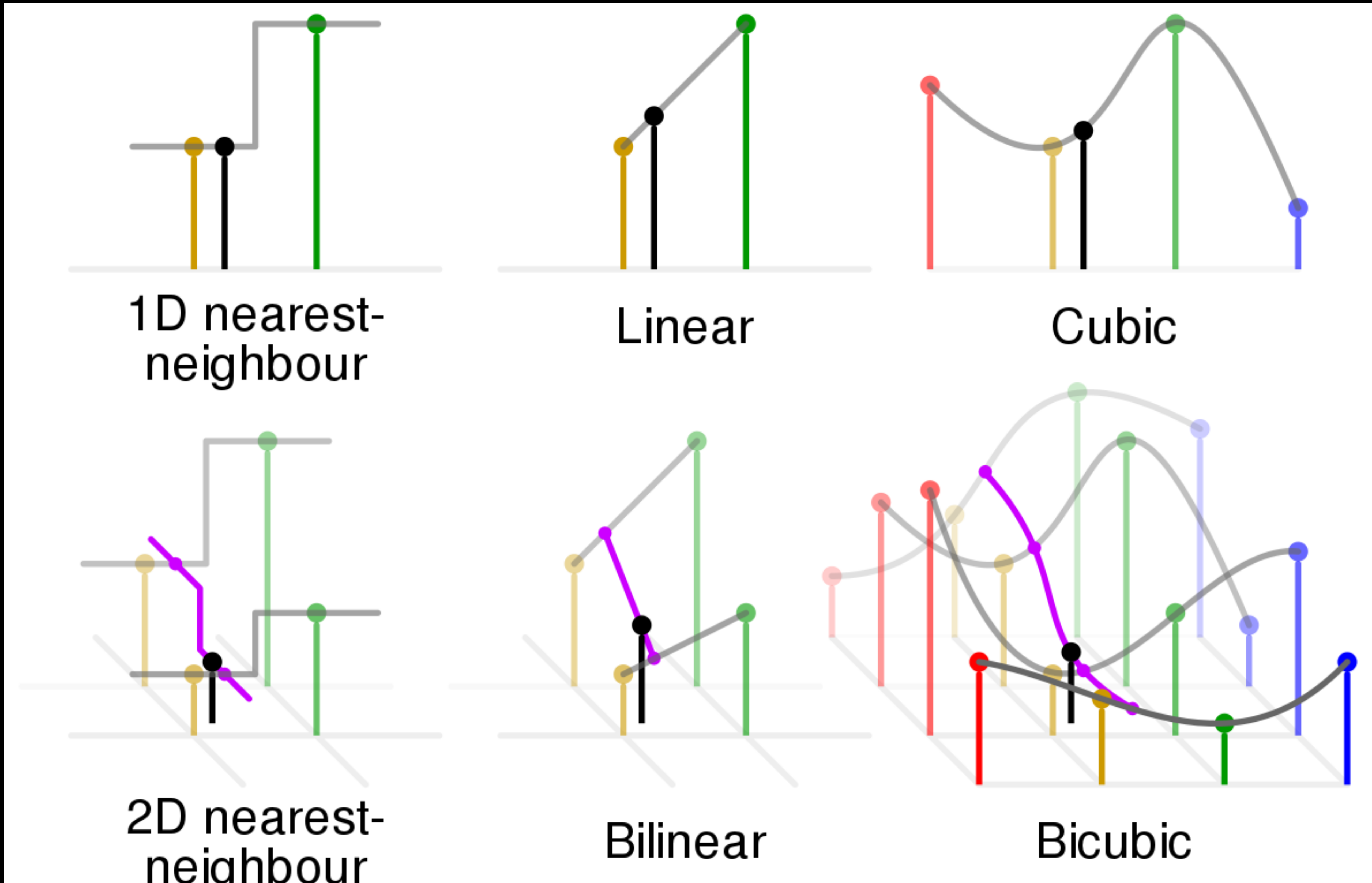
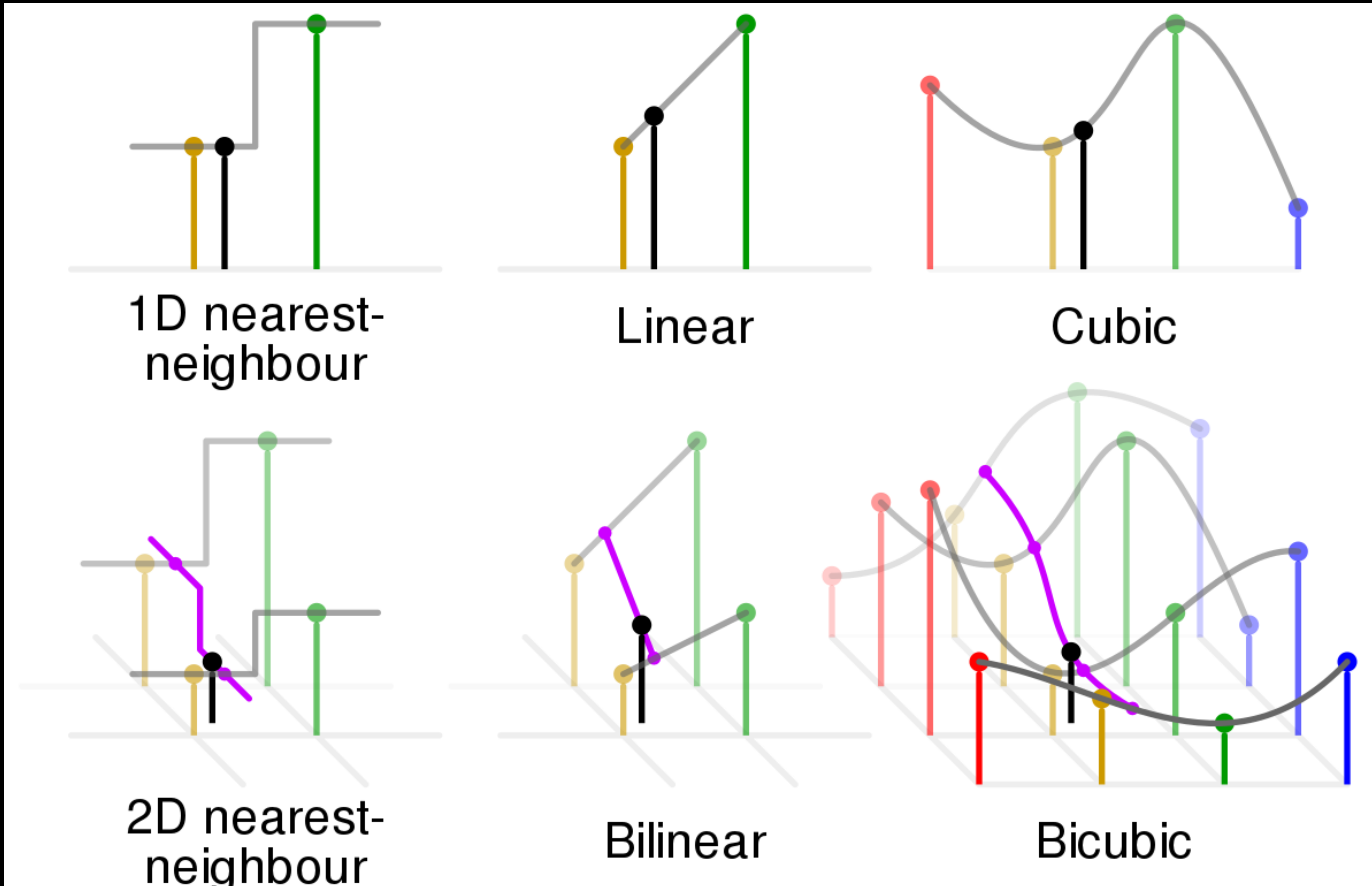


Image from the Montage documentation - http://montage.ipac.caltech.edu/docs/algorithms.html



INTERPOLATION SCHEMES

AND THEIR TRADEOFFS



INTERPOLATION SCHEMES

AND THEIR TRADEOFFS

Occasionally, wiki has a perfectly good image

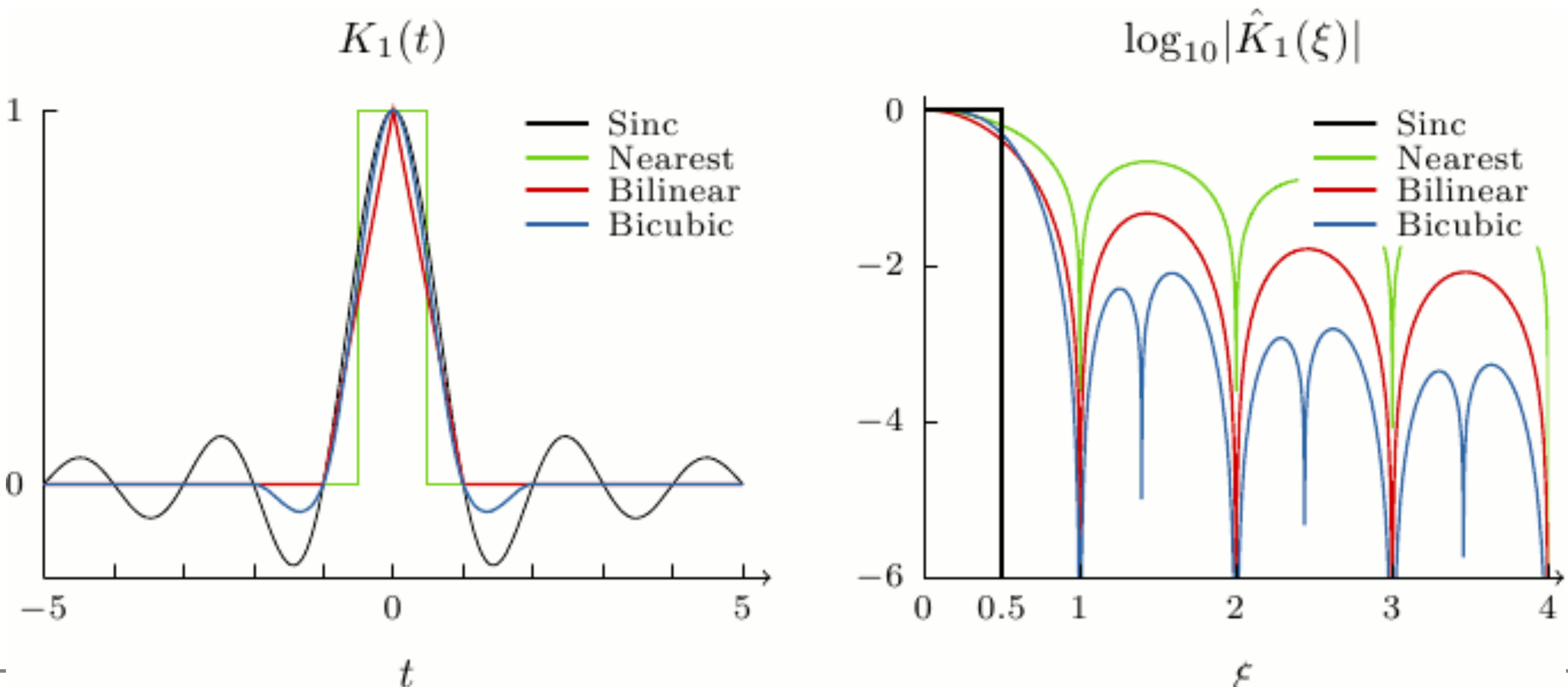
$$\widetilde{f}(\boldsymbol{x}) = K(\boldsymbol{x} - \boldsymbol{x_i}).\boldsymbol{f}$$

$$\widetilde{f}(\boldsymbol{x}) = K(\boldsymbol{x} - \boldsymbol{x}_i).\boldsymbol{f}$$

Interpolated flux

Interpolating function

Input flux array

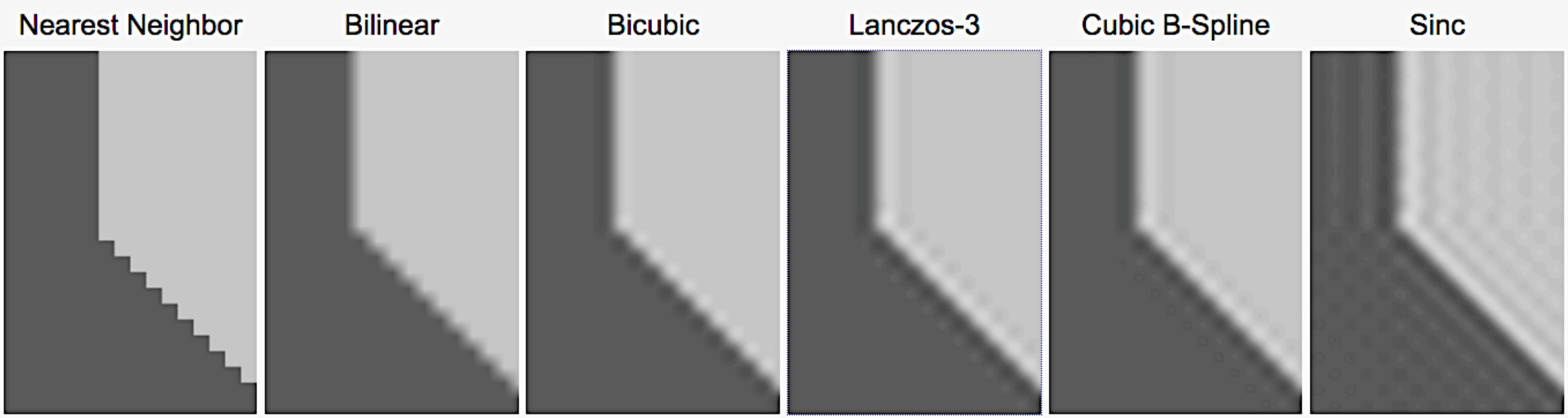


$$\widetilde{f}(\boldsymbol{x}) = K(\boldsymbol{x} - \boldsymbol{x}_i).\boldsymbol{f}$$

Interpolated flux

Interpolating function

Input flux array



Linear interpolation of a step edge: a balance between staircase artifacts and ripples.

P. Getreuer, Linear Methods for Image Interpolation (http://dx.doi.org/10.5201/ipol.2011.g_lmii)

FLUX CONSERVATION: CAVEAT EMPTOR

FLUX CONSERVATION: CAVEAT EMPTOR

- Many algorithms conserve flux density - i.e. surface brightness

FLUX CONSERVATION: CAVEAT EMPTOR

- Many algorithms conserve flux density - i.e. surface brightness
- Consistent photometry requires that you conserve the total flux

$$\text{Ideal}: \quad F_I \equiv \int_S f(\boldsymbol{x}) d^2 x$$

$$\text{Ideal}: \quad F_I \equiv \int_S f(\boldsymbol{x}) d^2x$$

Total flux

Flux distribution

$$\text{Ideal}: \quad F_I \equiv \int_S f(\boldsymbol{x}) d^2x$$

$$\text{Real}: \quad F_R = \int_S q(\boldsymbol{x}).f(\boldsymbol{x}) d^2x$$

$$\text{Ideal}: \quad F_I \equiv \int_S f(\boldsymbol{x}) d^2x$$

$$\text{Real}: \quad F_R = \int_S q(\boldsymbol{x}) . f(\boldsymbol{x}) d^2x$$

QE

$$\text{Ideal}: \quad F_I \equiv \int_S f(\boldsymbol{x}) d^2x$$

$$\text{Real}: \quad F_R = \int_S q(\boldsymbol{x}).f(\boldsymbol{x}) d^2x$$

$$\text{Flat}: \quad F_F = \int_S \frac{q(\boldsymbol{x}).f(\boldsymbol{x})}{f_0.q(\boldsymbol{x}).\delta\Omega(\boldsymbol{x})} d^2x = \int_S \frac{f(\boldsymbol{x})}{f_0.\delta\Omega(\boldsymbol{x})} d^2x$$

$$\text{Ideal}: \quad F_I \equiv \int_S f(\boldsymbol{x}) d^2x$$

$$\text{Real}: \quad F_R = \int_S q(\boldsymbol{x}).f(\boldsymbol{x}) d^2x$$

Area of sky per pixel

$$\text{Flat}: \quad F_F = \int_S \frac{q(\boldsymbol{x}).f(\boldsymbol{x})}{f_0.q(\boldsymbol{x})\,\delta\Omega(\boldsymbol{x})} d^2x = \int_S \frac{f(\boldsymbol{x})}{f_0.\delta\Omega(\boldsymbol{x})} d^2x$$

Flat

$$\text{Ideal}: \quad F_I \equiv \int_S f(\boldsymbol{x}) d^2x$$

$$\text{Real}: \quad F_R = \int_S q(\boldsymbol{x}).f(\boldsymbol{x}) d^2x$$

$$\text{Flat}: \quad F_F = \int_S \frac{q(\boldsymbol{x}).f(\boldsymbol{x})}{f_0.q(\boldsymbol{x}).\delta\Omega(\boldsymbol{x})} d^2x = \int_S \frac{f(\boldsymbol{x})}{f_0.\delta\Omega(\boldsymbol{x})} d^2x$$

$$\text{Warped}: \quad F_w = \int_S \frac{f(\boldsymbol{x})}{\delta\Omega(\boldsymbol{x})} d^2x' = \int_S \frac{f(\boldsymbol{x})}{\delta\Omega(\boldsymbol{x})} \left| \frac{\partial x'}{\partial x} \right| d^2x$$

$$\text{Ideal}: \quad F_I \equiv \int_S f(\boldsymbol{x}) d^2 x$$

$$\text{Real}: \quad F_R = \int_S q(\boldsymbol{x}).f(\boldsymbol{x}) d^2 x$$

$$\text{Flat}: \quad F_F = \int_S \frac{q(\boldsymbol{x}).f(\boldsymbol{x})}{f_0.q(\boldsymbol{x}).\delta\Omega(\boldsymbol{x})} d^2 x = \int_S \frac{f(\boldsymbol{x})}{f_0.\delta\Omega(\boldsymbol{x})} d^2 x$$

$$\text{Warped}: \quad F_w = \int_S \frac{f(\boldsymbol{x})}{\delta\Omega(\boldsymbol{x})} d^2 x' = \int_S \frac{f(\boldsymbol{x})}{\delta\Omega(\boldsymbol{x})} \left| \frac{\partial x'}{\partial x} \right| d^2 x$$

Change of coordinates - i.e. reprojection

Jacobian of transformation

$$\text{Ideal}: \quad F_I \equiv \int_S f(\boldsymbol{x}) d^2 x$$

$$\text{Real}: \quad F_R = \int_S q(\boldsymbol{x}).f(\boldsymbol{x}) d^2 x$$

$$\text{Flat}: \quad F_F = \int_S \frac{q(\boldsymbol{x}).f(\boldsymbol{x})}{f_0.q(\boldsymbol{x}).\delta\Omega(\boldsymbol{x})} d^2 x = \int_S \frac{f(\boldsymbol{x})}{f_0.\delta\Omega(\boldsymbol{x})} d^2 x$$

$$\text{Warped}: \quad F_w = \int_S \frac{f(\boldsymbol{x})}{\delta\Omega(\boldsymbol{x})} d^2 x' = \int_S \frac{f(\boldsymbol{x})}{\delta\Omega(\boldsymbol{x})} \left| \frac{\partial x'}{\partial x} \right| d^2 x$$

$$F_w = \int_S f(\boldsymbol{x}) \left| \frac{\partial x'}{\partial \xi} \right| d^2 x \propto F \text{ (for equal area projections)}$$

$$\text{Ideal}: \quad F_I \equiv \int_S f(\boldsymbol{x}) d^2 x$$

$$\text{Real}: \quad F_R = \int_S q(\boldsymbol{x}).f(\boldsymbol{x}) d^2 x$$

$$\text{Flat}: \quad F_F = \int_S \frac{q(\boldsymbol{x}).f(\boldsymbol{x})}{f_0.q(\boldsymbol{x}).\delta\Omega(\boldsymbol{x})} d^2 x = \int_S \frac{f(\boldsymbol{x})}{f_0.\delta\Omega(\boldsymbol{x})} d^2 x$$

$$\text{Warped}: \quad F_w = \int_S \frac{f(\boldsymbol{x})}{\delta\Omega(\boldsymbol{x})} d^2 x' = \int_S \frac{f(\boldsymbol{x})}{\delta\Omega(\boldsymbol{x})} \left| \frac{\partial x'}{\partial x} \right| d^2 x$$

Change to sky coordinates. Valid if pixel scale varies slowly

$$F_w = \int_S f(\boldsymbol{x}) \left| \frac{\partial x'}{\partial \xi} \right| d^2 x \propto F \ \text{(for equal area projections)}$$

FLUX CONSERVATION: CAVEAT EMPTOR

- Many algorithms conserve flux density - i.e. surface brightness
- Consistent photometry requires that you conserve the total flux

FLUX CONSERVATION: CAVEAT EMPTOR

- Many algorithms conserve flux density - i.e. surface brightness
- Consistent photometry requires that you conserve the total flux
- This is harder to do because it involves a lot more geometry than just interpolation

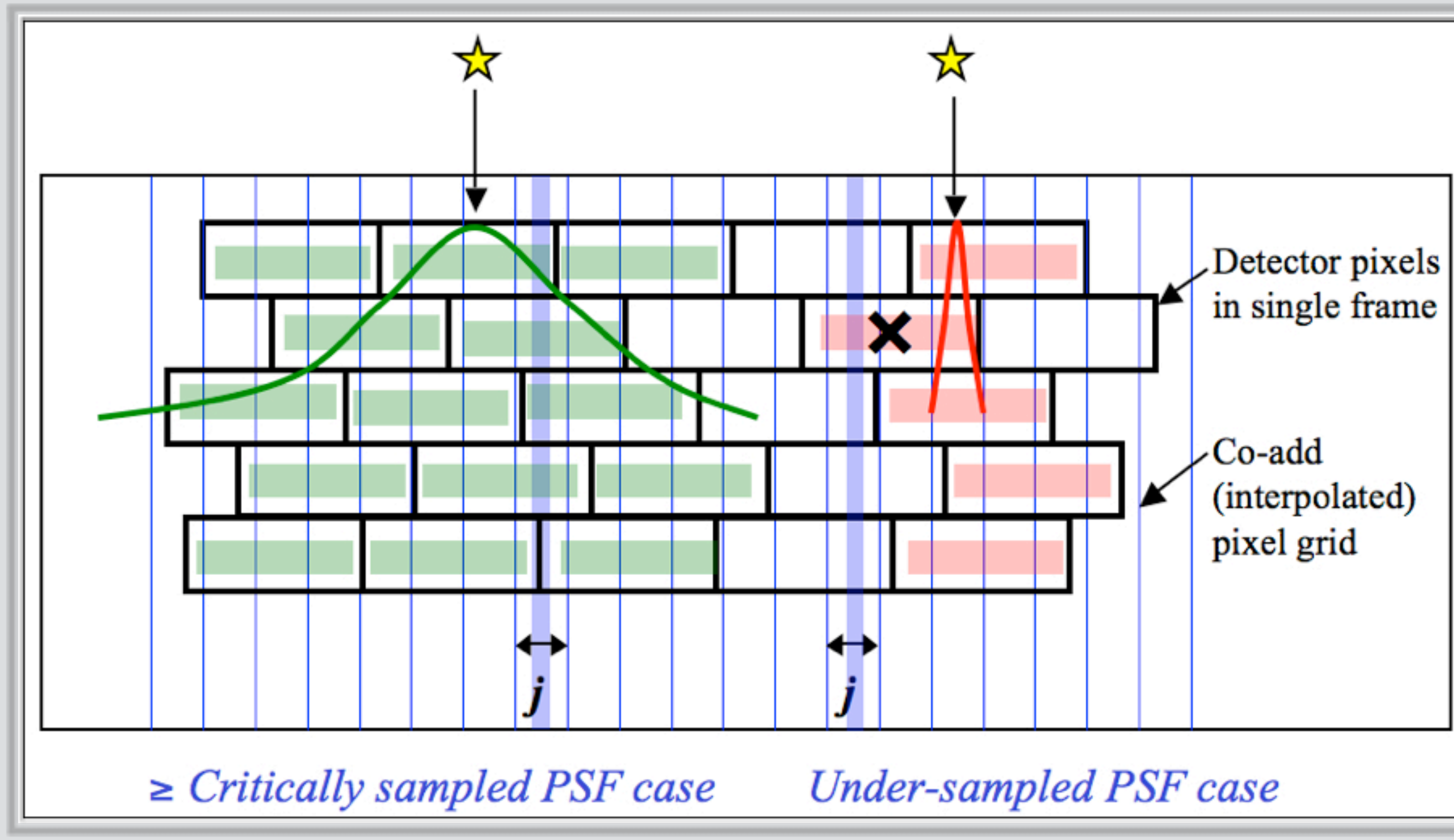
DRIZZLE VS REPROJECT

DRIZZLE VS REPROJECT

- Ground-based observatories typically oversample the PSF
  - small robotic telescopes with commercial cameras are a notable exception

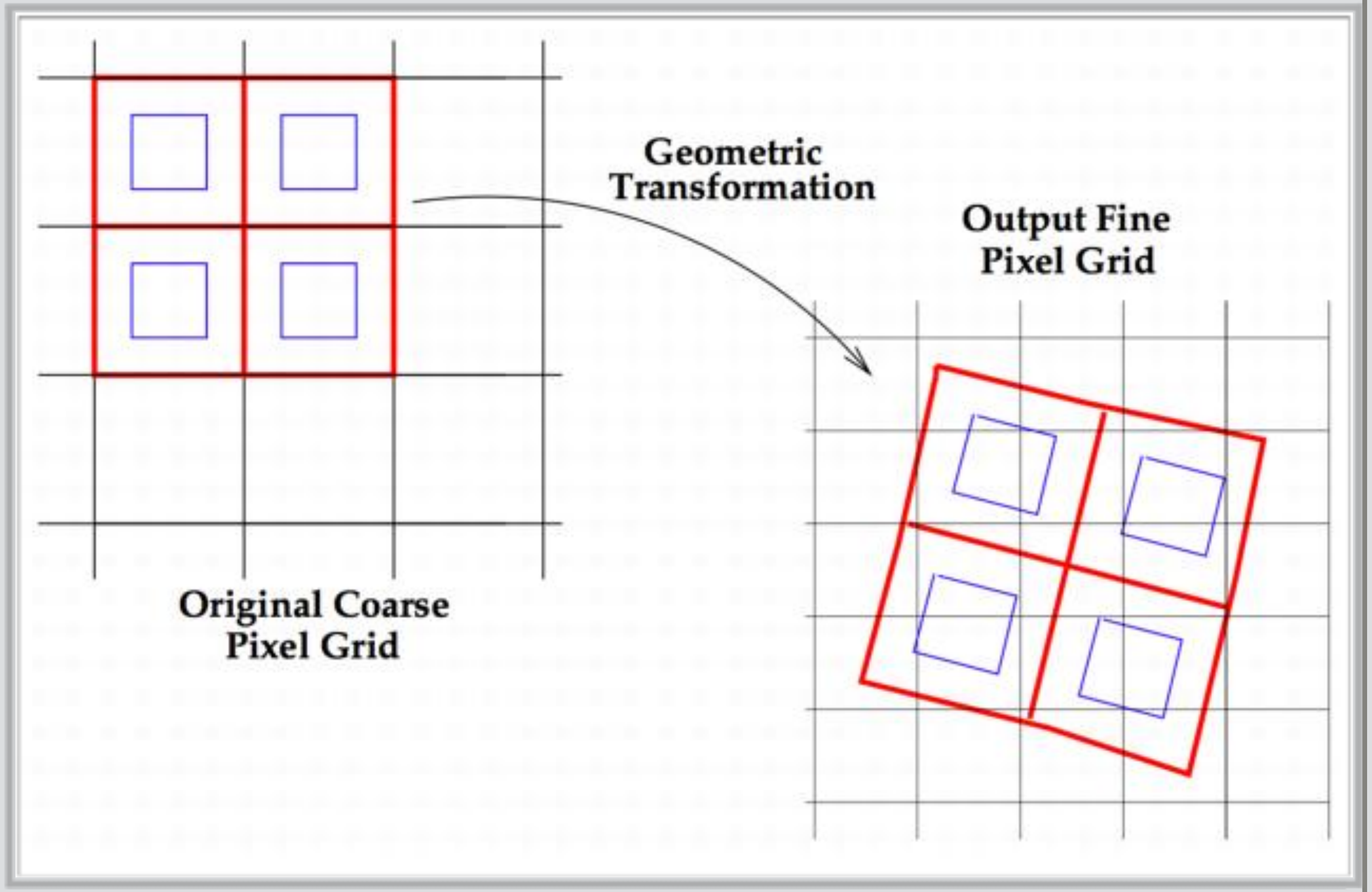
DRIZZLE VS REPROJECT

- Ground-based observatories typically oversample the PSF
  - small robotic telescopes with commercial cameras are a notable exception
- Space-based facilities have optics that provide really great PSFs, but have fat pixels



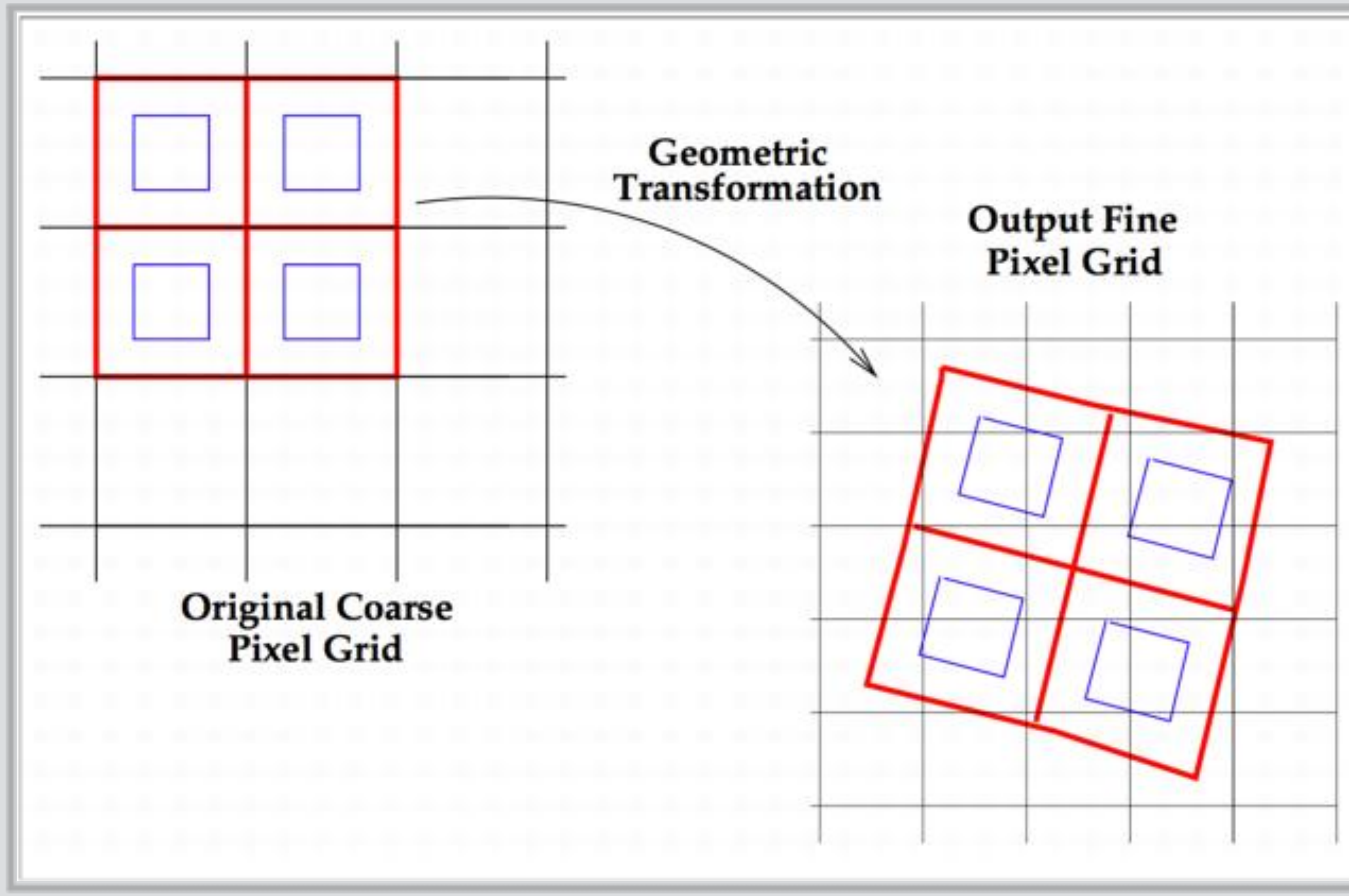
DRIZZLE VS REPROJECT

- Ground-based observatories typically oversample the PSF
    - small robotic telescopes with commercial cameras are a notable exception
- Space-based facilities have optics that provide really great PSFs, but have fat pixels
- Pixels are treated as light buckets with a finite size - “drops” (equal or smaller than the pixel area)



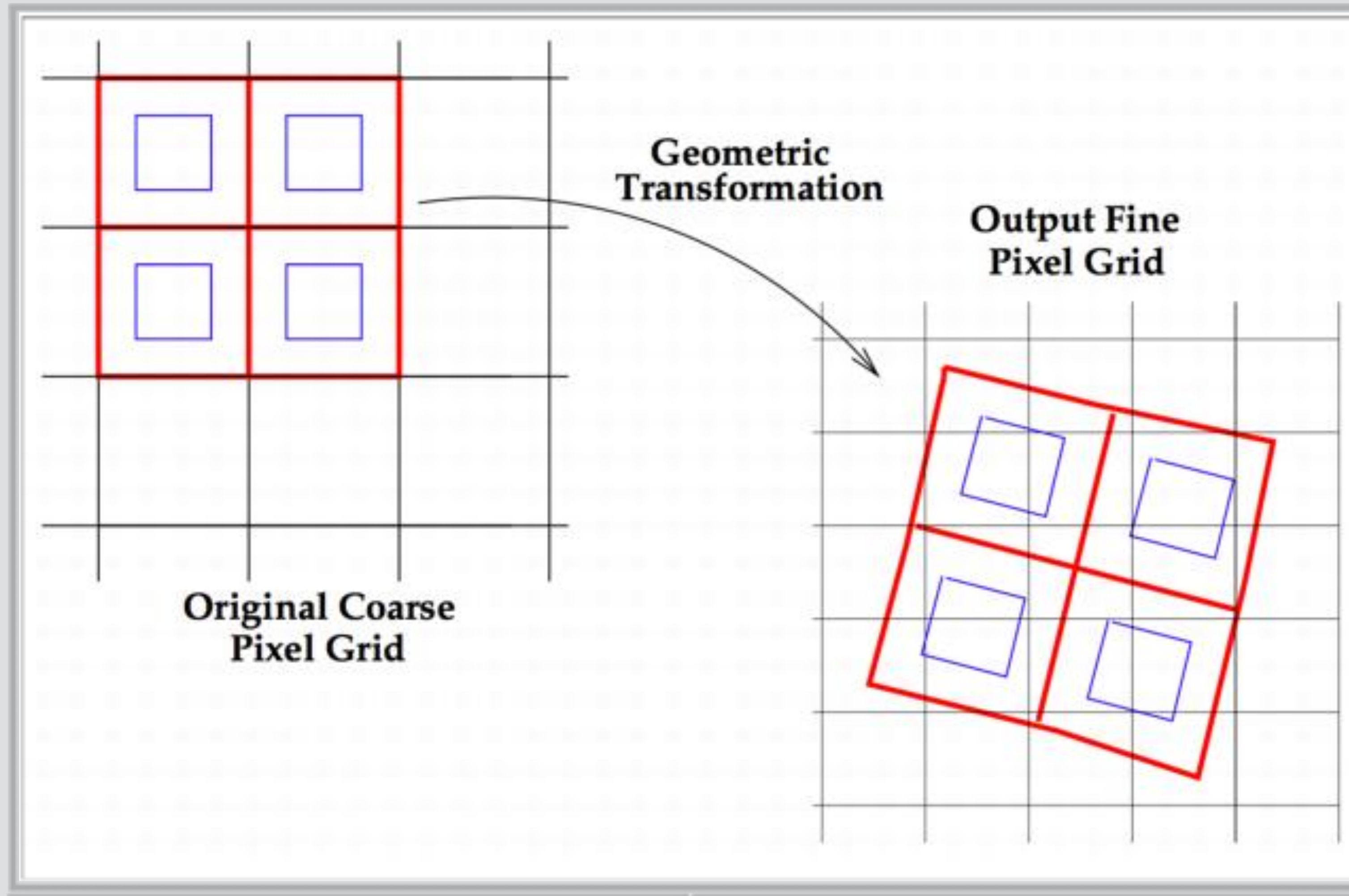
DRIZZLE VS REPROJECT

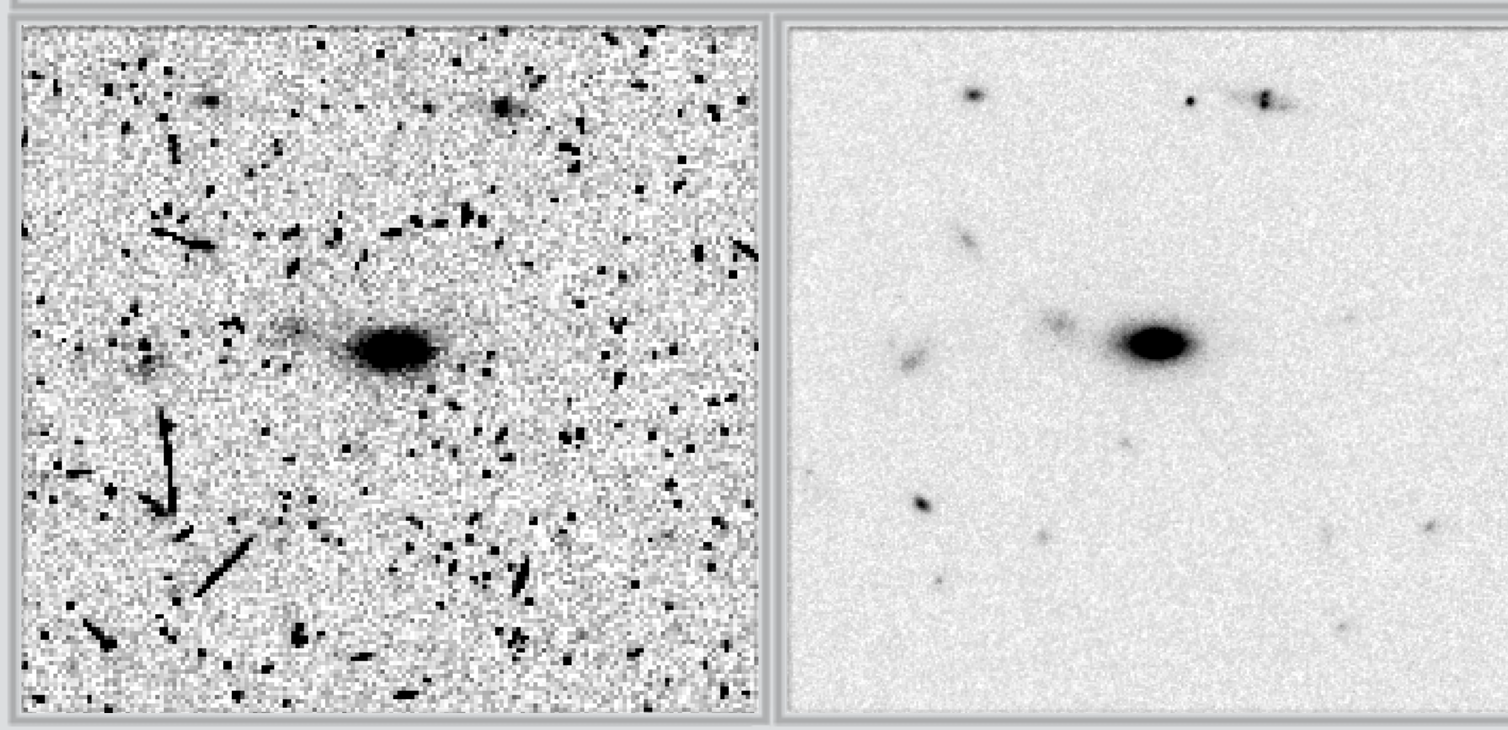
- Ground-based observatories typically oversample the PSF
  - small robotic telescopes with commercial cameras are a notable exception
- Space-based facilities have optics that provide really great PSFs, but have fat pixels
- Pixels are treated as light buckets with a finite size - “drops” (equal or smaller than the pixel area)
- Drops are subdivided into sub pixels - “droplets”



DRIZZLE VS REPROJECT

- Ground-based observatories typically oversample the PSF
    - small robotic telescopes with commercial cameras are a notable exception
- Space-based facilities have optics that provide really great PSFs, but have fat pixels
- Pixels are treated as light buckets with a finite size - “drops” (equal or smaller than the pixel area)
- Drops are subdivided into sub pixels - “droplets”
- Each droplet’s value is averaged into the output pixel

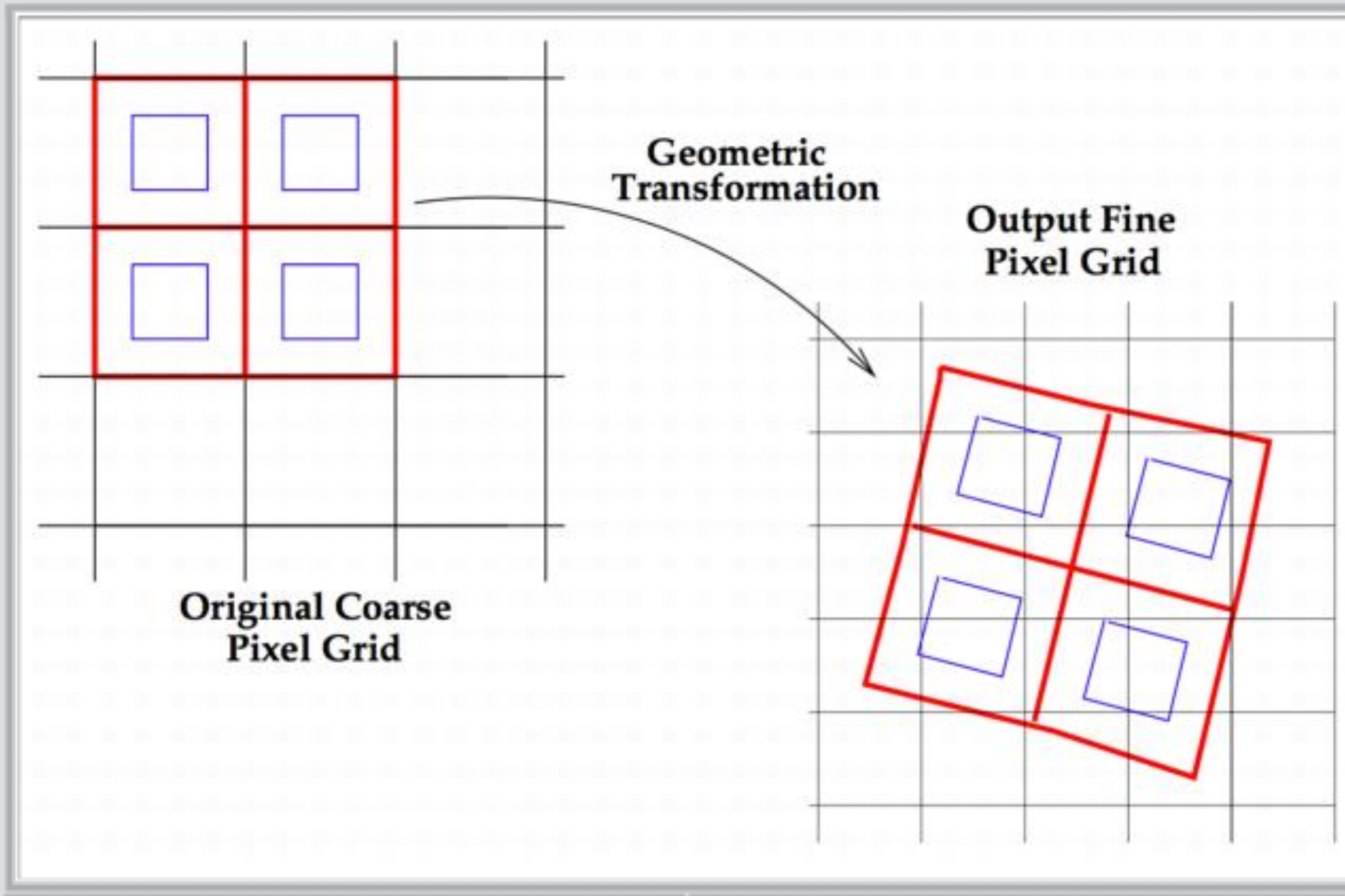


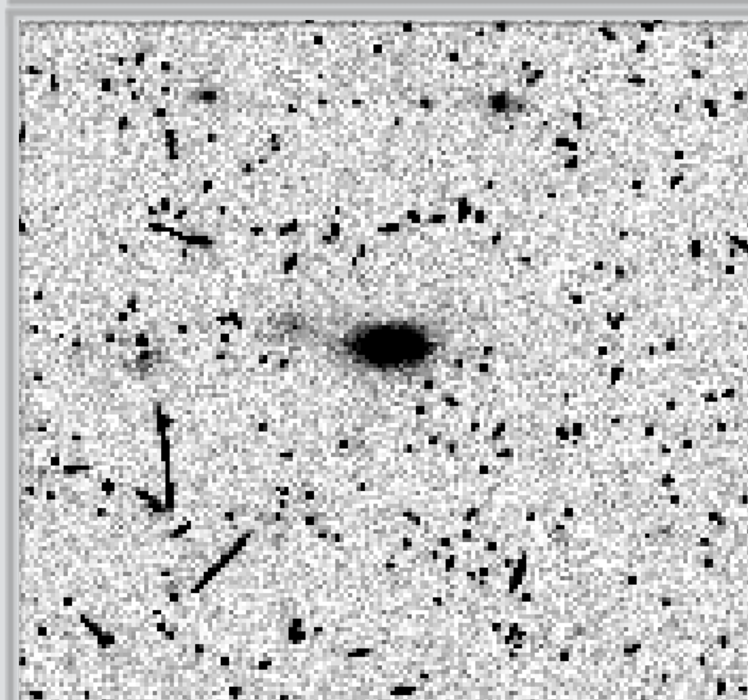


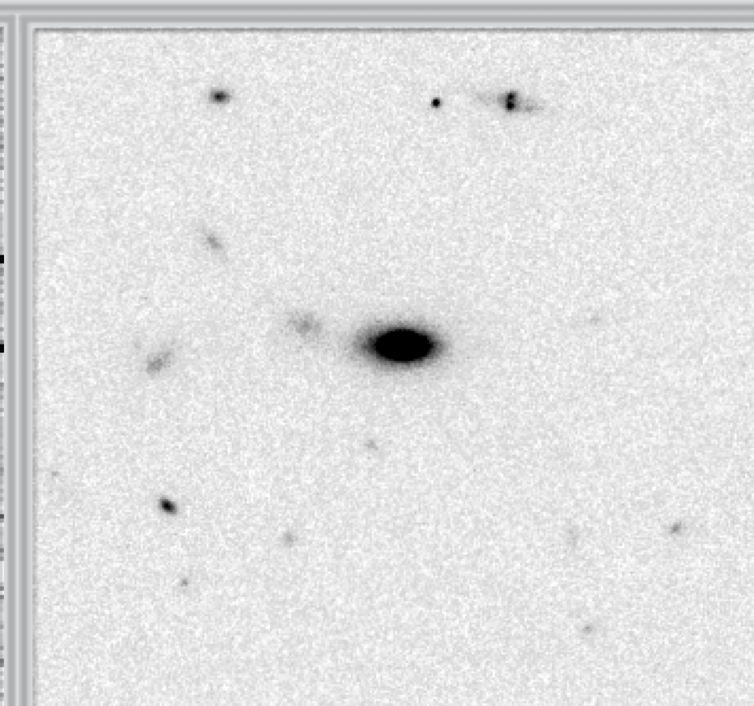
From WISE, STScI’s Astrodrizzle Handbook & Andy Fruchter (STScI) in order of appearance

DRIZZLE VS REPROJECT

- Ground-based observatories typically oversample the PSF
  - small robotic telescopes with commercial cameras are a notable exception
- Space-based facilities have optics that provide really great PSFs, but have fat pixels
- Pixels are treated as light buckets with a finite size - “drops” (equal or smaller than the pixel area)
- Drops are subdivided into sub pixels - “droplets”
- Each droplet’s value is averaged into the output pixel
  - Weighting depends on both input pixel and output pixel

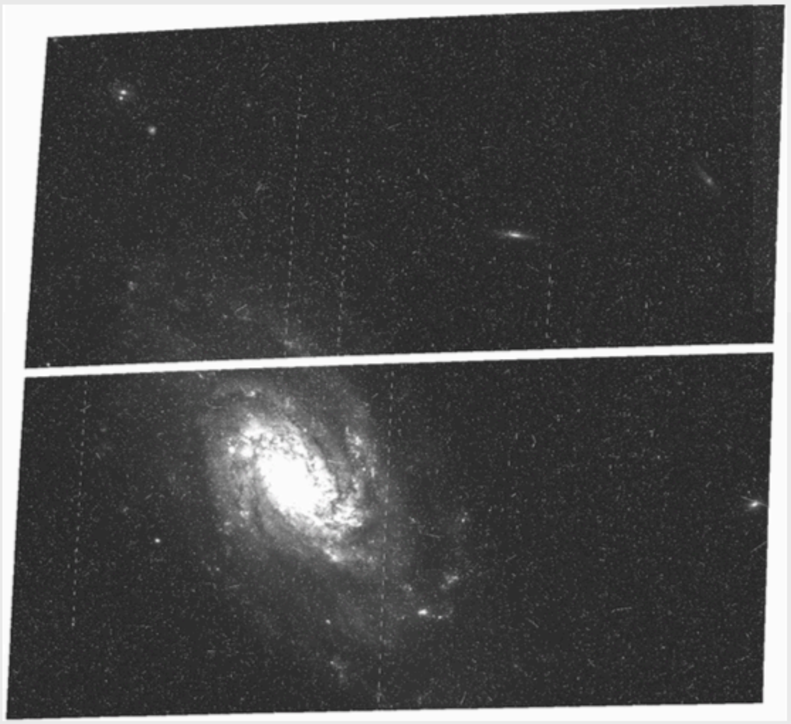




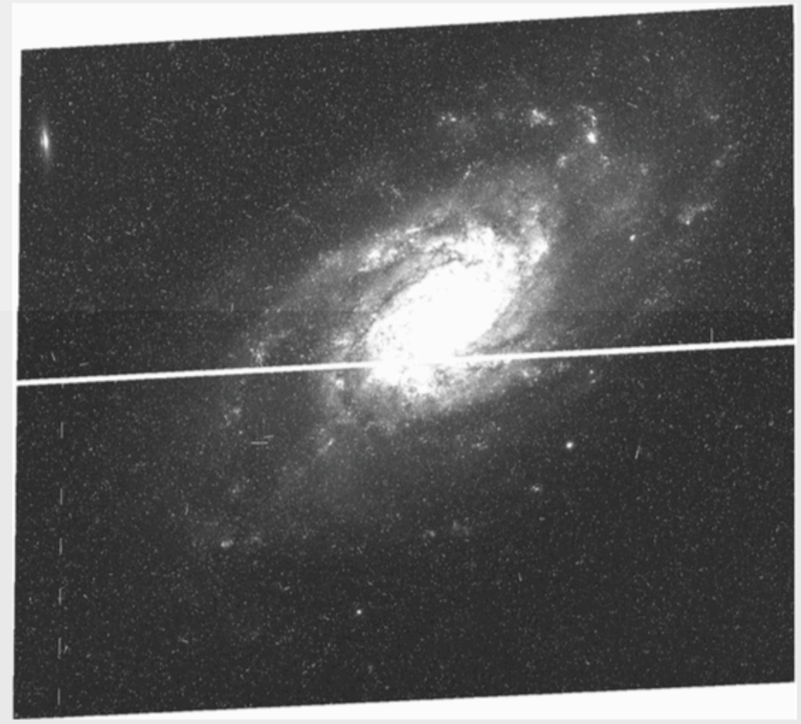


From WISE, STScI’s Astrodrizzle Handbook & Andy Fruchter (STScI) in order of appearance

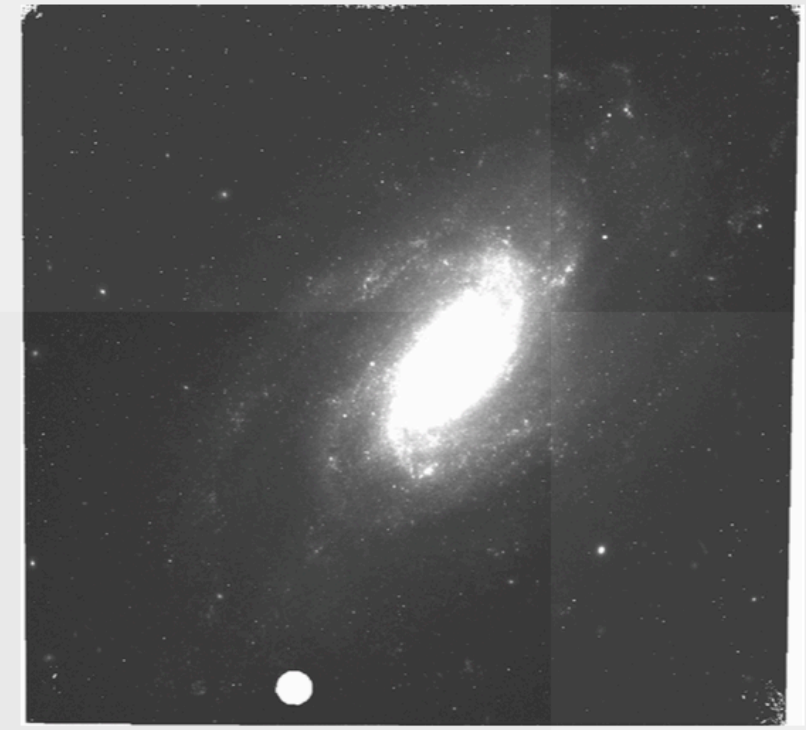
Single Drizzled Images



ACS/WFC F555W (0.049”)

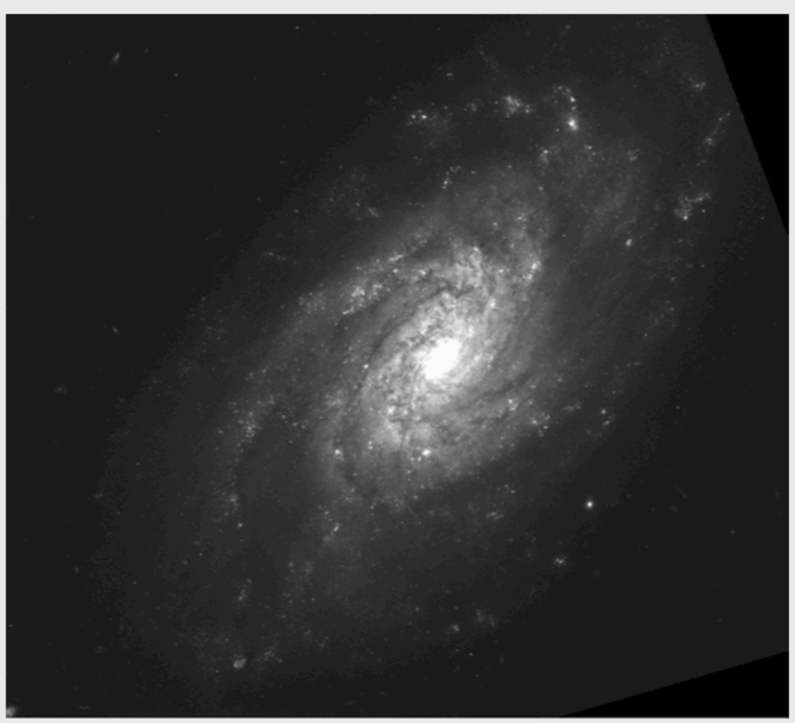


WFC3/UVIS F555W (0.039”)

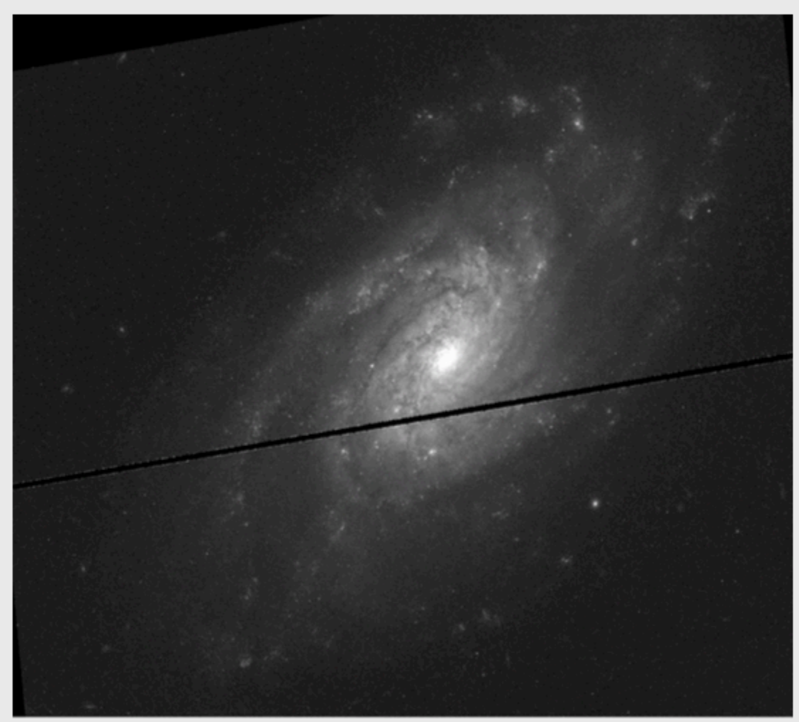


WFC3/IR F160W (0.128”)

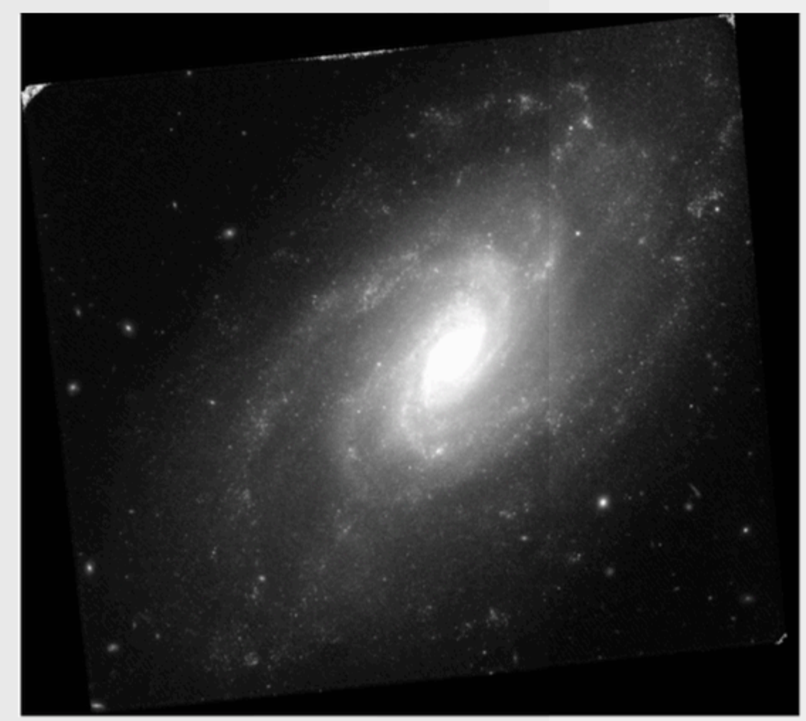
Final Drizzled Stack



ACS/WFC F555W (0.049”)

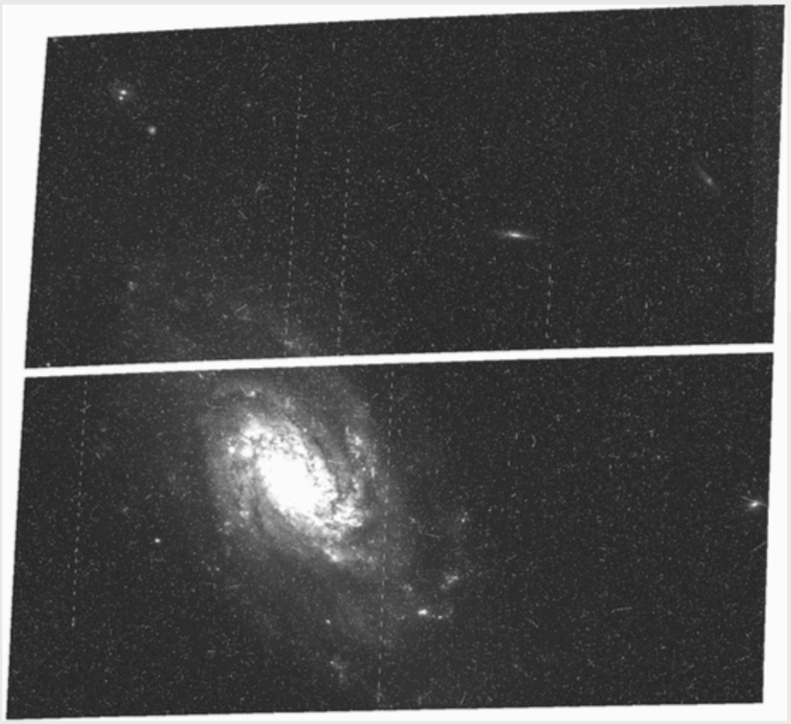


WFC3/UVIS F555W (0.049”)

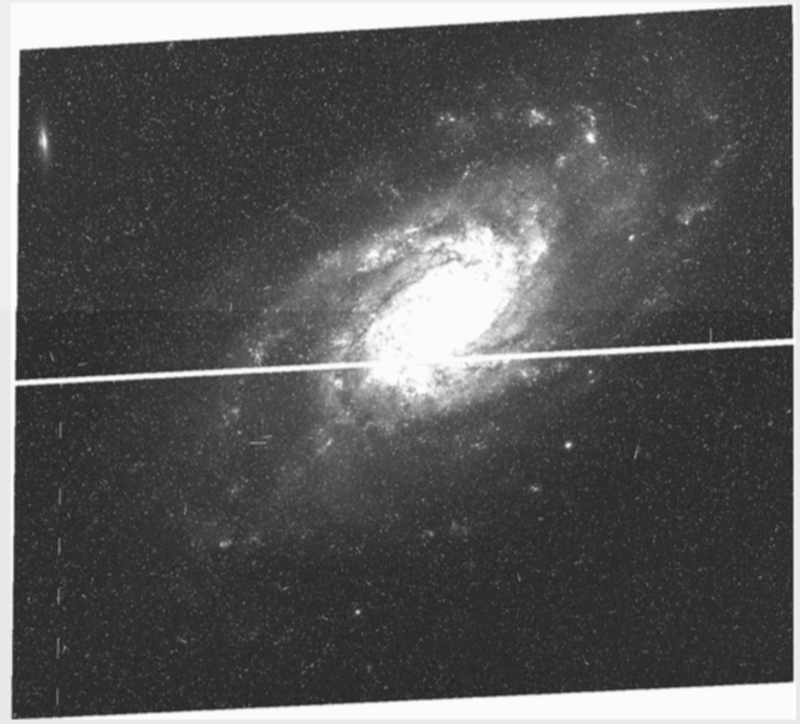


WFC3/IR F160W (0.049”)

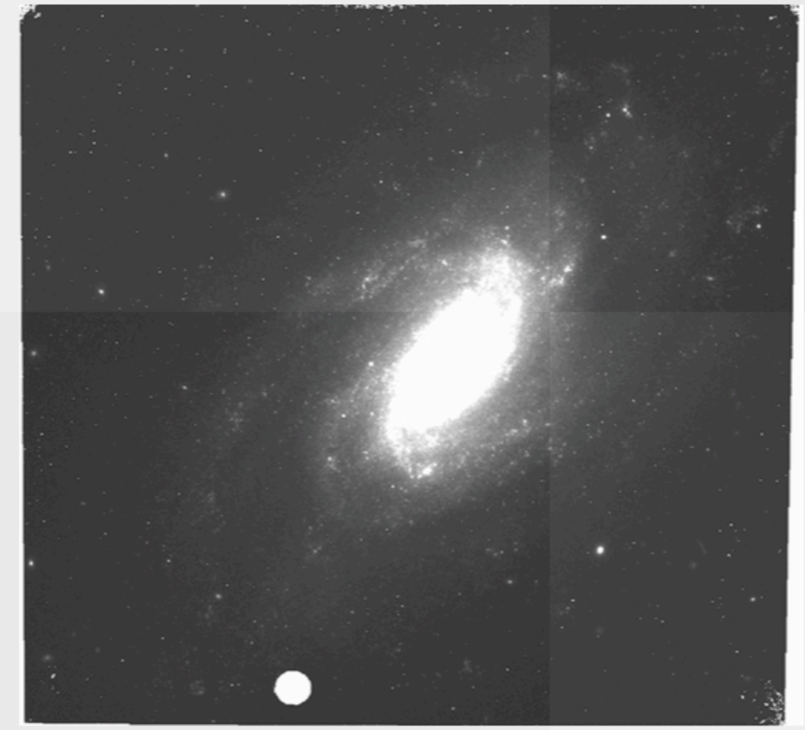
Single Drizzled Images



ACS/WFC F555W (0.049")

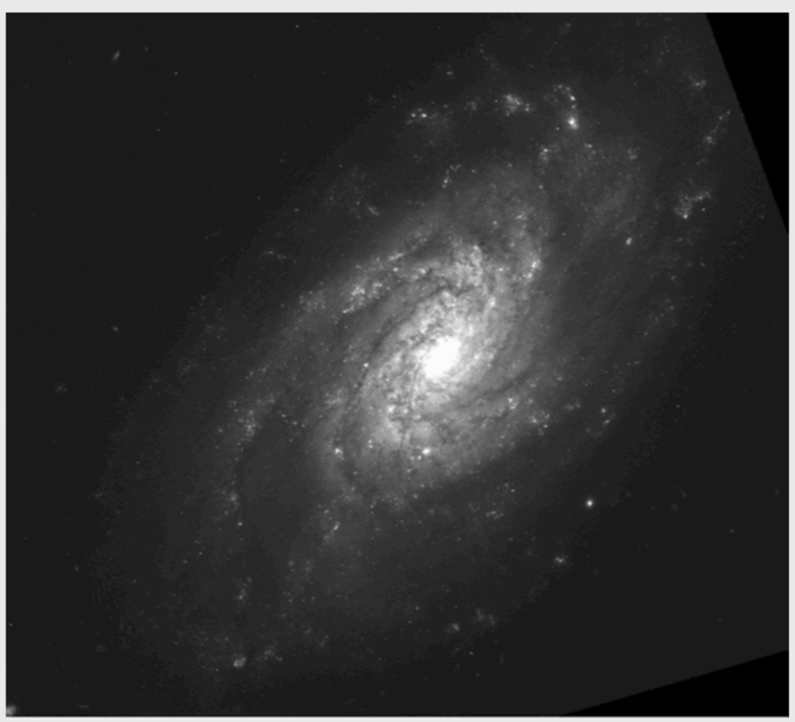


WFC3/UVIS F555W (0.039")

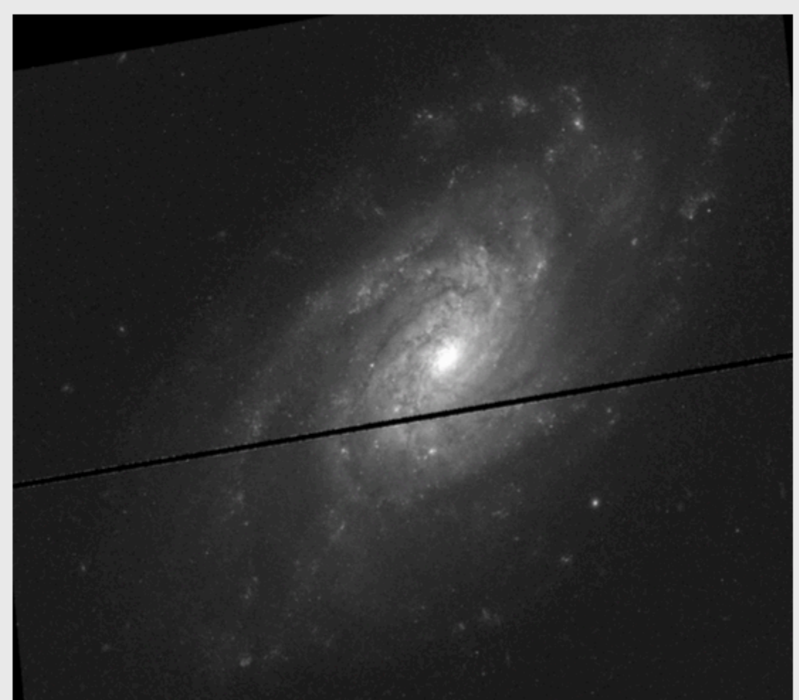


WFC3/IR F160W (0.128")

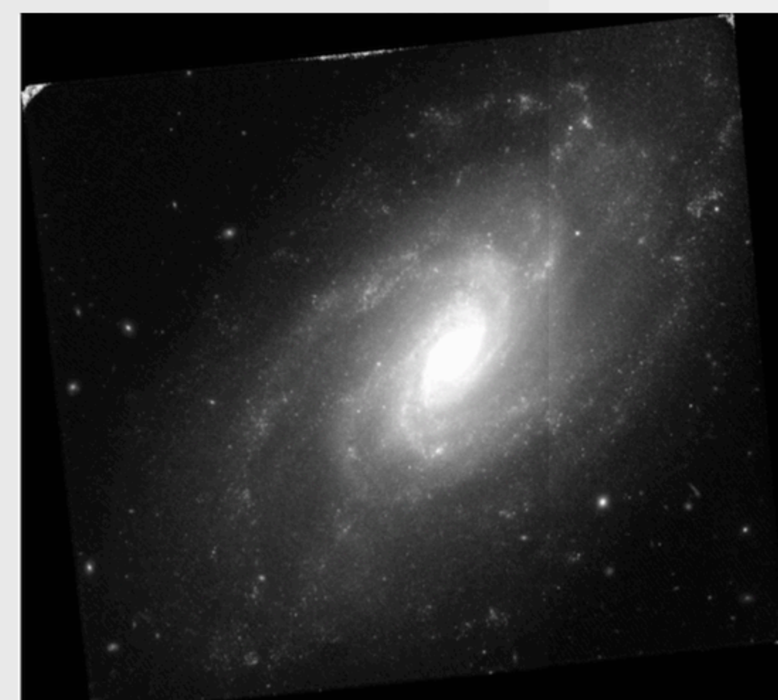
Final Drizzled Stack



ACS/WFC F555W (0.049")



WFC3/UVIS F555W (0.049")



WFC3/IR F160W (0.049")

STEPS TO REPROJECT AN IMAGE

STEPS TO REPROJECT AN IMAGE

- Specify the input grid and output grid. Both are implicitly specified by the WCS (which is why we registered the image in the first place!)

STEPS TO REPROJECT AN IMAGE

- Specify the input grid and output grid. Both are implicitly specified by the WCS (which is why we registered the image in the first place!)
- Specify the interpolation scheme you'd like to use (nearest neighbor, bicubic, Lanczos3) - tradeoff between speed/aliasing effects/photometric accuracy

STEPS TO REPROJECT AN IMAGE

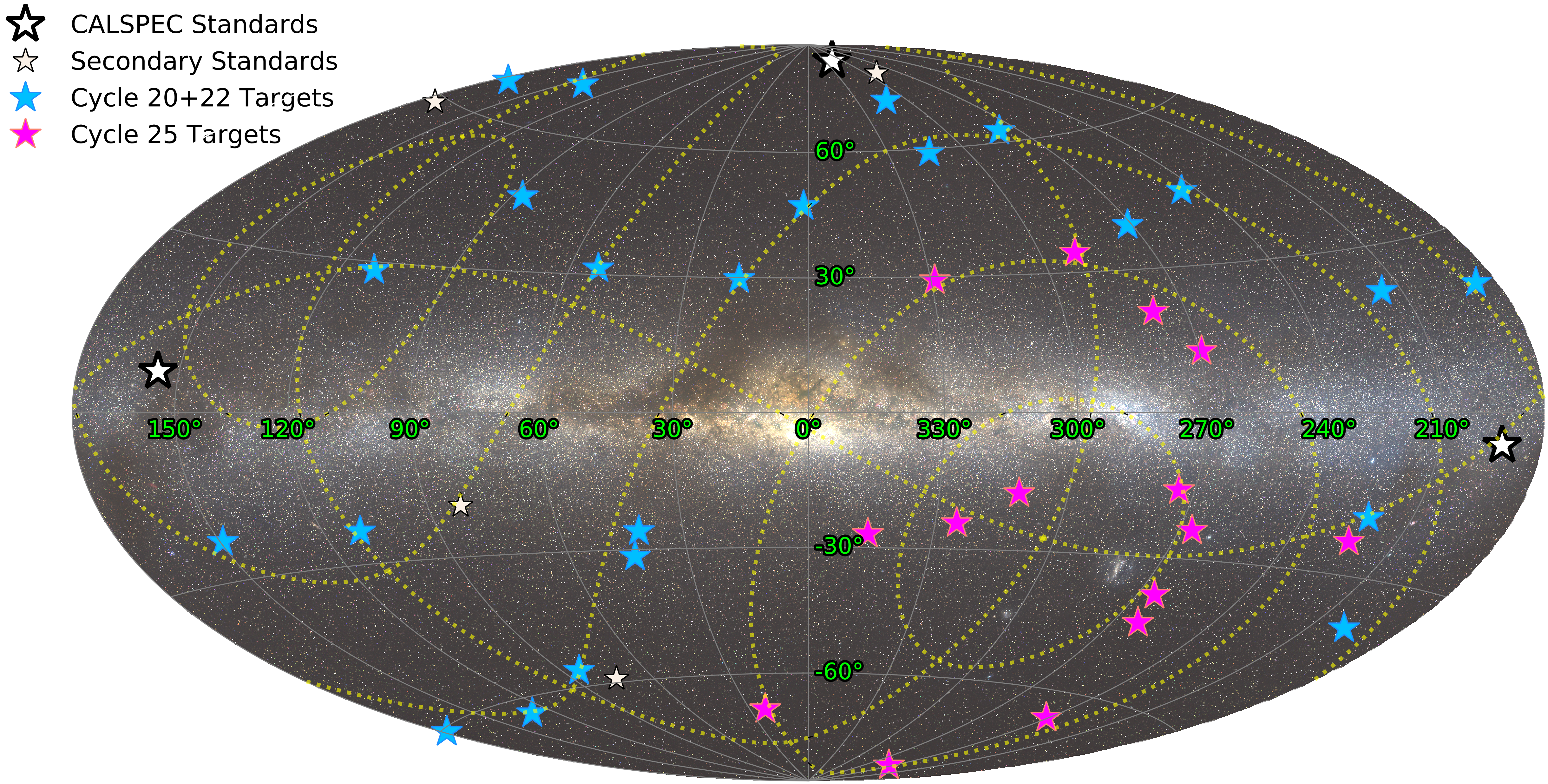
- Specify the input grid and output grid. Both are implicitly specified by the WCS (which is why we registered the image in the first place!)
- Specify the interpolation scheme you'd like to use (nearest neighbor, bicubic, Lanczos3) - tradeoff between speed/aliasing effects/photometric accuracy
    - You can see this if you have a Sony/Samsung TV with automatic uprezzing of video. They use fast algorithms that aren't good so you get "jaggies" and really awkward motion!

STEPS TO REPROJECT AN IMAGE

- Specify the input grid and output grid. Both are implicitly specified by the WCS (which is why we registered the image in the first place!)
- Specify the interpolation scheme you'd like to use (nearest neighbor, bicubic, Lanczos3) - tradeoff between speed/aliasing effects/photometric accuracy
  - You can see this if you have a Sony/Samsung TV with automatic uprezzing of video. They use fast algorithms that aren't good so you get "jaggies" and really awkward motion!
- ***Python: Reproject module*** Standalone: **SWarp, Montage, IDL: HREBIN**

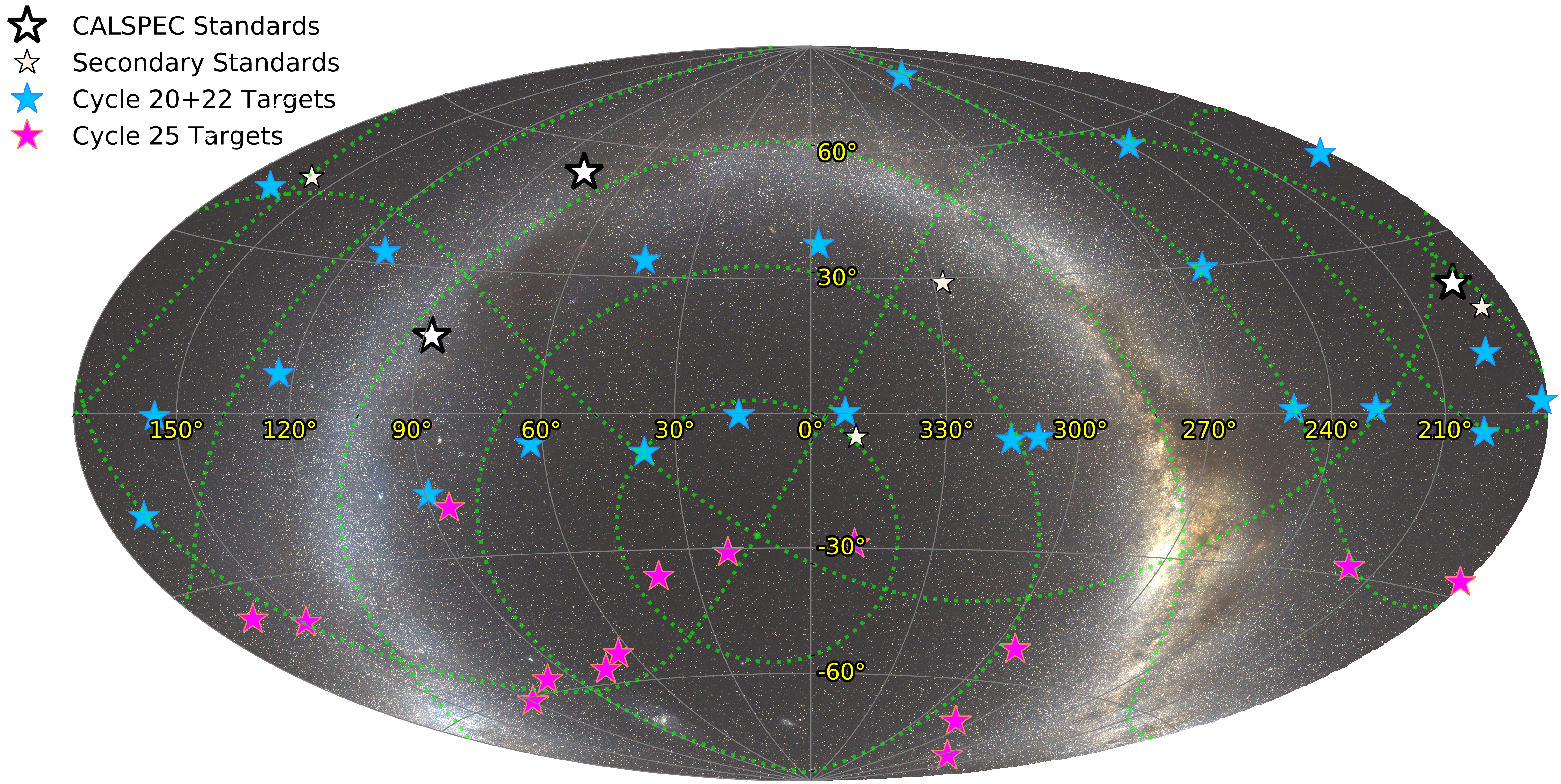
STEPS TO REPROJECT AN IMAGE

- Specify the input grid and output grid. Both are implicitly specified by the WCS (which is why we registered the image in the first place!)
- Specify the interpolation scheme you'd like to use (nearest neighbor, bicubic, Lanczos3) - tradeoff between speed/aliasing effects/photometric accuracy
  - You can see this if you have a Sony/Samsung TV with automatic uprezzing of video. They use fast algorithms that aren't good so you get "jaggies" and really awkward motion!
- ***Python: Reproject module*** Standalone: **SWarp, Montage, IDL: HREBIN**
  - The **drizzlepac module** is used by MAST for Space Telescope data products



CAN ALSO REPROJECT BETWEEN DIFFERENT COORDINATE SYSTEMS

OR ANY VALID SOURCE WCS TO TARGET WAS



CAN ALSO REPROJECT BETWEEN DIFFERENT COORDINATE SYSTEMS

OR ANY VALID SOURCE WCS TO TARGET WAS

TAKEAWAYS ABOUT RESAMPLING/REPROJECTION

TAKEAWAYS ABOUT RESAMPLING/REPROJECTION

- There is no one “best” resampling algorithm

TAKEAWAYS ABOUT RESAMPLING/REPROJECTION

- There is no one “best” resampling algorithm
  - There’s not one definition of “best”…

TAKEAWAYS ABOUT RESAMPLING/REPROJECTION

- There is no one “best” resampling algorithm
    - There’s not one definition of “best”…
    - All “optimal” stacking/subtraction algorithms don’t consider their input i.e. ignore everything about resampling.

TAKEAWAYS ABOUT RESAMPLING/REPROJECTION

- There is no one “best” resampling algorithm
  - There’s not one definition of “best”…
  - All “optimal” stacking/subtraction algorithms don’t consider their input i.e. ignore everything about resampling.
  - There is at least what everyone else does.

TAKEAWAYS ABOUT RESAMPLING/REPROJECTION

- There is no one “best” resampling algorithm
  - There’s not one definition of “best”…
  - All “optimal” stacking/subtraction algorithms don’t consider their input i.e. ignore everything about resampling.
  - There is at least what everyone else does.
- Several metrics we care about - depth, photometric accuracy, resolution, speed…

TAKEAWAYS ABOUT RESAMPLING/REPROJECTION

- There is no one "best" resampling algorithm
  - There's not one definition of "best"…
  - All "optimal" stacking/subtraction algorithms don't consider their input i.e. ignore everything about resampling.
  - There is at least what everyone else does.
- Several metrics we care about - depth, photometric accuracy, resolution, speed…
- Harder to define for extended sources

TAKEAWAYS ABOUT RESAMPLING/REPROJECTION

- There is no one “best” resampling algorithm
  - There’s not one definition of “best”…
  - All “optimal” stacking/subtraction algorithms don’t consider their input i.e. ignore everything about resampling.
  - There is at least what everyone else does.
- Several metrics we care about - depth, photometric accuracy, resolution, speed…
- Harder to define for extended sources
- Undersampled vs oversampled

TAKEAWAYS ABOUT RESAMPLING/REPROJECTION

- There is no one “best” resampling algorithm
  - There’s not one definition of “best”…
  - All “optimal” stacking/subtraction algorithms don’t consider their input i.e. ignore everything about resampling.
  - There is at least what everyone else does.
- Several metrics we care about - depth, photometric accuracy, resolution, speed…
- Harder to define for extended sources
- Undersampled vs oversampled
- Try out a few options out on your dataset

PSF CONVOLUTION AND IMAGE SUBTRACTION

- Thus far, the process is the same whether stacking or subtracting

- Thus far, the process is the same whether stacking or subtracting
- With stacking, we don't want to homogenize the PSF of all the images (Zackay and Ofek, 2017, http://adsabs.harvard.edu/abs/2017ApJ...836..187Z)

- Thus far, the process is the same whether stacking or subtracting
- With stacking, we don't want to homogenize the PSF of all the images (Zackay and Ofek, 2017, http://adsabs.harvard.edu/abs/2017ApJ...836..187Z)
- Subtraction is an operation between only two images though, and should be symmetric

- Thus far, the process is the same whether stacking or subtracting
- With stacking, we don't want to homogenize the PSF of all the images (Zackay and Ofek, 2017, http://adsabs.harvard.edu/abs/2017ApJ...836..187Z)
- Subtraction is an operation between only two images though, and should be symmetric
- The convolution kernel matches the PSF of the two images being subtracted

The AL Formulation : $N - k \bigotimes R \cong 0.$

The AL Formulation : $N - k \otimes R \cong 0.$

New image

Kernel

Reference image

The AL Formulation : $N - k \otimes R \cong 0.$

New image

Kernel

Reference image

- **Alard and Lupton formulations represents the kernel as a sum of basis functions**

$$\text{The AL Formulation}: \underbrace{N}_{\text{New image}} - \underbrace{k}_{\text{Kernel}} \otimes \underbrace{R}_{\text{Reference image}} \cong 0.$$

- Alard and Lupton formulations represents the kernel as a sum of basis functions
- Solve for kernel basis coefficients using linear least squares

$$\text{The AL Formulation}: \; N - k \otimes R \cong 0.$$

New image

Kernel

Reference image

- Alard and Lupton formulations represents the kernel as a sum of basis functions
- Solve for kernel basis coefficients using linear least squares
- Bramich (2008) modification solves for a pixelated kernel

The AL Formulation : $N - k \otimes R \cong 0.$

New image

Kernel

Reference image

- Alard and Lupton formulations represents the kernel as a sum of basis functions
- Solve for kernel basis coefficients using linear least squares
- Bramich (2008) modification solves for a pixelated kernel
- Not symmetric, unstable if N has PSF narrower than R, correlated noise

The AL Formulation : $N - k \otimes R \cong 0.$

New image

Kernel

Reference image

- Alard and Lupton formulations represents the kernel as a sum of basis functions
- Solve for kernel basis coefficients using linear least squares
- Bramich (2008) modification solves for a pixelated kernel
- Not symmetric, unstable if N has PSF narrower than R, correlated noise
- Codes like HOTPANTS use fairly arbitrary image heuristics to pick a convolution direction

The GY Formulation : $k_R \otimes N - k_N \otimes R \cong 0.$

$$\text{The GY Formulation : } k_R \otimes N - k_N \otimes R \cong 0.$$

Convolve new image with reference PSF

Convolve reference image with new PSF

$$\text{The GY Formulation : } k_R \otimes N - k_N \otimes R \cong 0.$$

Convolve new image with reference PSF

Convolve reference image with new PSF

- Gal-Yam+ ’08 solution is symmetric, numerically stable

$$\text{The GY Formulation}: k_R \otimes N - k_N \otimes R \cong 0.$$

Convolve new image with reference PSF

Convolve reference image with new PSF

- Gal-Yam+ '08 solution is symmetric, numerically stable
- Kernel is chosen to be the PSF of each image

$$\text{The GY Formulation}: \; k_R \otimes N - k_N \otimes R \cong 0.$$

Convolve new image with reference PSF

Convolve reference image with new PSF

- Gal-Yam+ ’08 solution is symmetric, numerically stable
- Kernel is chosen to be the PSF of each image
- Leaves no subtraction artifacts

$$\text{The GY Formulation}: \; k_R \otimes N - k_N \otimes R \cong 0.$$

Convolve new image with reference PSF

Convolve reference image with new PSF

- Gal-Yam+ ’08 solution is symmetric, numerically stable
- Kernel is chosen to be the PSF of each image
- Leaves no subtraction artifacts
- Formally has an infinite number of solutions - choice of PSF as kernel is an arbitrary choice

The ZOGY Formulation :

$$\frac{F_R \widehat{k_R} \widehat{N} - F_N \widehat{k_N} \widehat{R}}{\sqrt{\sigma_N^2 F_R^2 |\widehat{k_R}|^2 + \sigma_R^2 F_N^2 |\widehat{k_N}|^2}} \cong \widehat{D}$$

The ZOGY Formulation :

Extra flux normalization term

$$\frac{F_R\widehat{k_R}\widehat{N} - F_N\widehat{k_N}\widehat{R}}{\sqrt{\sigma_N^2F_R^2|\widehat{k_R}|^2 + \sigma_R^2F_N^2|\widehat{k_N}|^2}} \cong \widehat{D}$$

Variance map, flux normalization and PSF appear in denominator

The ZOGY Formulation :

$$\frac{F_R \widehat{k_R} \widehat{N} - F_N \widehat{k_N} \widehat{R}}{\sqrt{\sigma_N^2 F_R^2 |\widehat{k_R}|^2 + \sigma_R^2 F_N^2 |\widehat{k_N}|^2}} \cong \widehat{D}$$

Extra flux normalization term

Hats denote Fourier transform

Variance map, flux normalization and PSF appear in denominator

The ZOGY Formulation :

Extra flux normalization term

Hats denote Fourier transform

$$\frac{F_R\widehat{k_R}\widehat{N} - F_N\widehat{k_N}\widehat{R}}{\sqrt{\sigma_N^2 F_R^2|\widehat{k_R}|^2 + \sigma_R^2 F_N^2|\widehat{k_N}|^2}} \cong \widehat{D}$$

Variance map, flux normalization and PSF appear in denominator

- ZOGY solution is statistically motivated, symmetric, numerically stable

$$\text{The ZOGY Formulation :}$$

Extra flux normalization term

Hats denote Fourier transform

$$\frac{F_R \widehat{k_R} \widehat{N} - F_N \widehat{k_N} \widehat{R}}{\sqrt{\sigma_N^2 F_R^2 |\widehat{k_R}|^2 + \sigma_R^2 F_N^2 |\widehat{k_N}|^2}} \cong \widehat{D}$$

Variance map, flux normalization and PSF appear in denominator

- ZOGY solution is statistically motivated, symmetric, numerically stable
- Expressions for diffim flux normalization, PSF for detection

$$\text{The ZOGY Formulation :}$$

Extra flux normalization term

Hats denote Fourier transform

$$\frac{F_R \widehat{k_R} \widehat{N} - F_N \widehat{k_N} \widehat{R}}{\sqrt{\sigma_N^2 F_R^2 |\widehat{k_R}|^2 + \sigma_R^2 F_N^2 |\widehat{k_N}|^2}} \cong \widehat{D}$$

Variance map, flux normalization and PSF appear in denominator

- ZOGY solution is statistically motivated, symmetric, numerically stable
- Expressions for diffim flux normalization, PSF for detection
- You aren't going to get fired for using what LSST uses

$$\text{The ZOGY Formulation :}$$

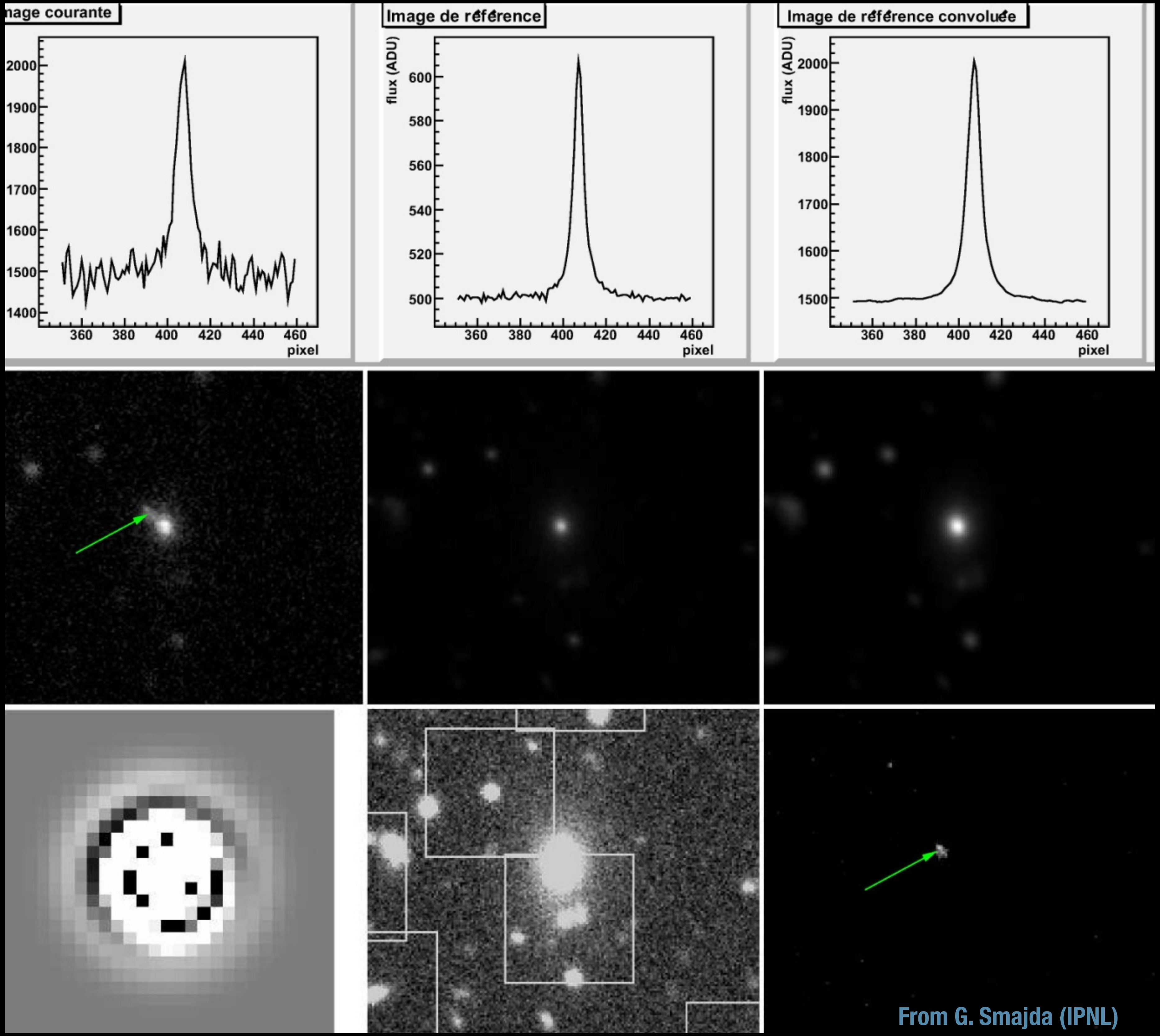
Extra flux normalization term

Hats denote Fourier transform

$$\frac{F_R \widehat{k_R} \widehat{N} - F_N \widehat{k_N} \widehat{R}}{\sqrt{\sigma_N^2 F_R^2 |\widehat{k_R}|^2 + \sigma_R^2 F_N^2 |\widehat{k_N}|^2}} \cong \widehat{D}$$

Variance map, flux normalization and PSF appear in denominator

- ZOGY solution is statistically motivated, symmetric, numerically stable
- Expressions for diffim flux normalization, PSF for detection
- You aren't going to get fired for using what LSST uses
- Extra terms decorrelate output - remember than resampling still introduces correlations



From G. Smajda (IPNL)

SO WHAT DOES THIS ACTUALLY LOOK LIKE

I.E. GAUTHAM, YOU SHOWED ME THREE PAGES OF EQUATIONS… I HATE YOU… I WANT PRETTY PICTURES

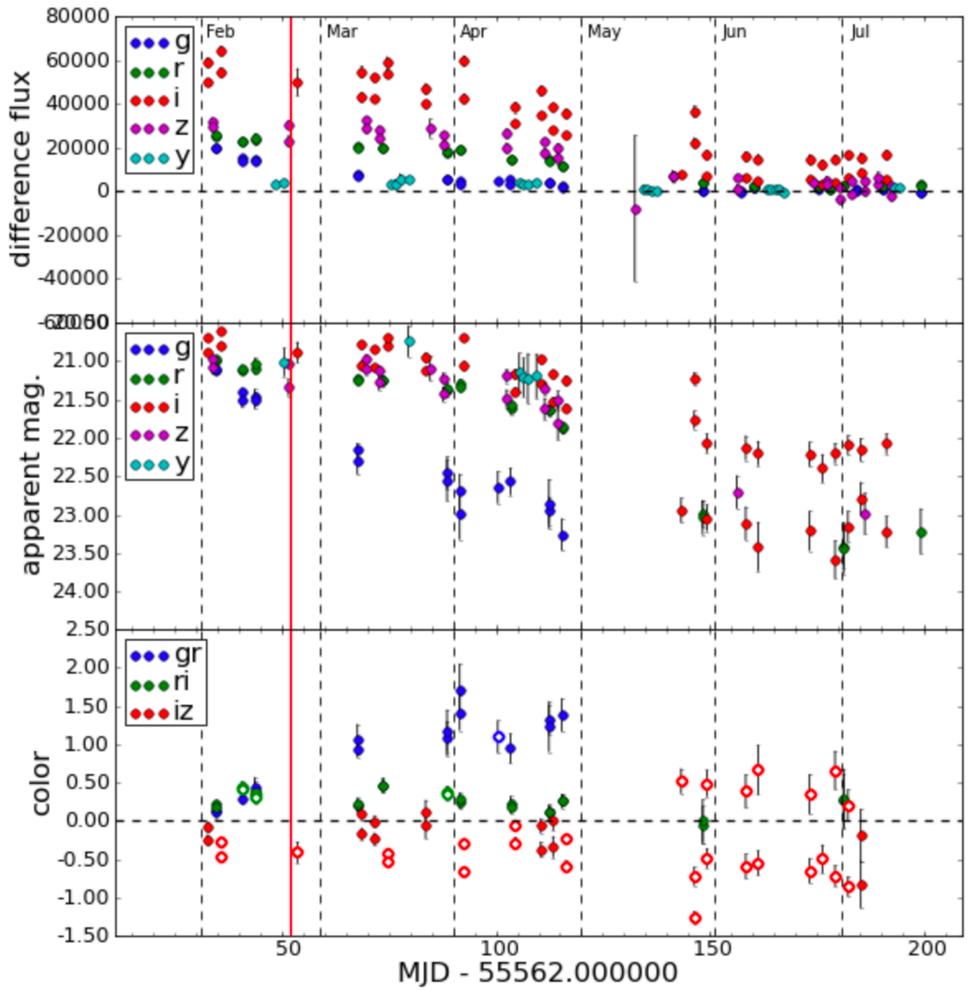
HTTP://TELESCOPES.RC.FAS.HARVARD.EDU/PS1/ALERTS2010/

HTTP://TELESCOPES.RC.FAS.HARVARD.EDU/PS1/ALERTS2010/2011-B-130327/2011-B-130327.HTML

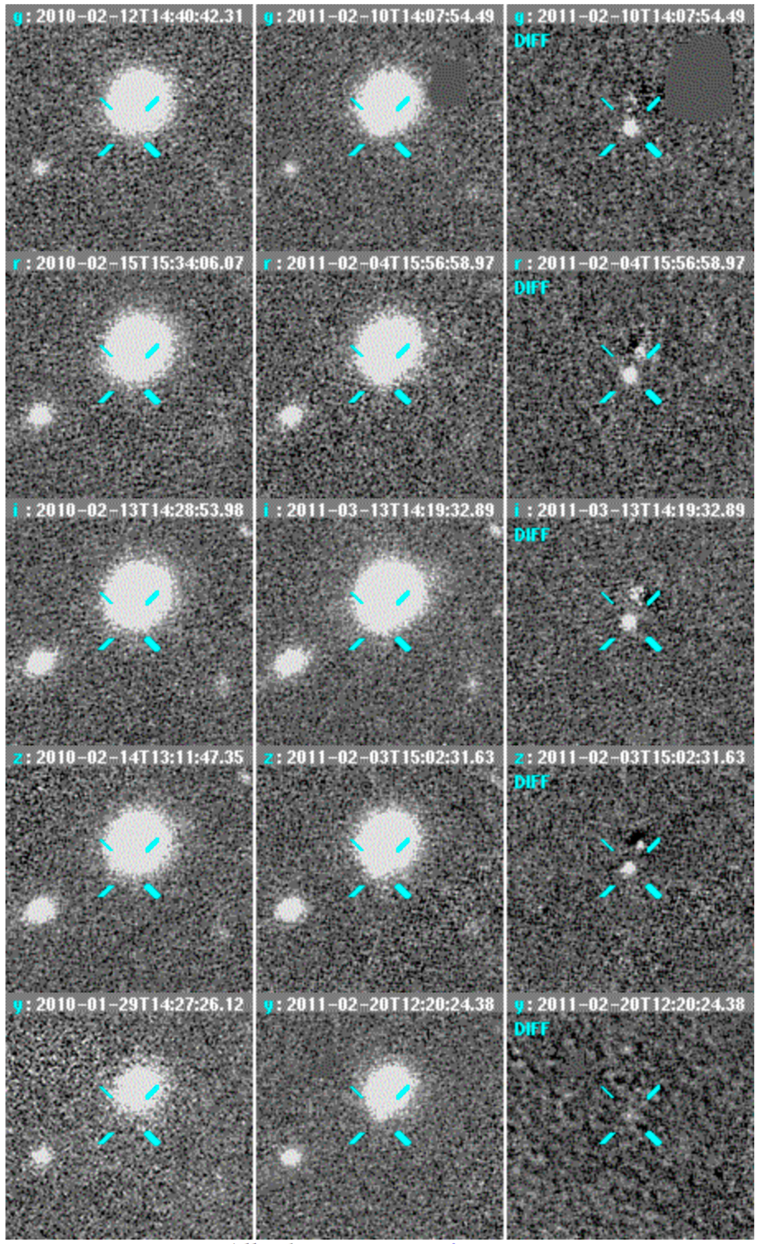
YOU'LL NEED A PASSWORD TO GET TO THESE - SORRY!

PS1-11fl (2011-B-130327)

RA Dec (J2000)	Field/Cut/Disc. Date	status	spec: specprio/queuetele, specstatus, spectel, spectype, specz	g0	r0	i0	z0	g	r	i	z
14:05:19.148 +53:07:24.25	md07s062 / 72 / ut110205g	confirmed	queue -,-,observed,Berger,MMTblue,SNIIp,0.096	21.10	20.97	20.61	20.96	23.26	23.22	22.08	22.99
SUMMARY: SDSS z=0.096; M=-17.7	VisualType: -										



Extra lightcurve plots: mag lc zoomed , all t lc

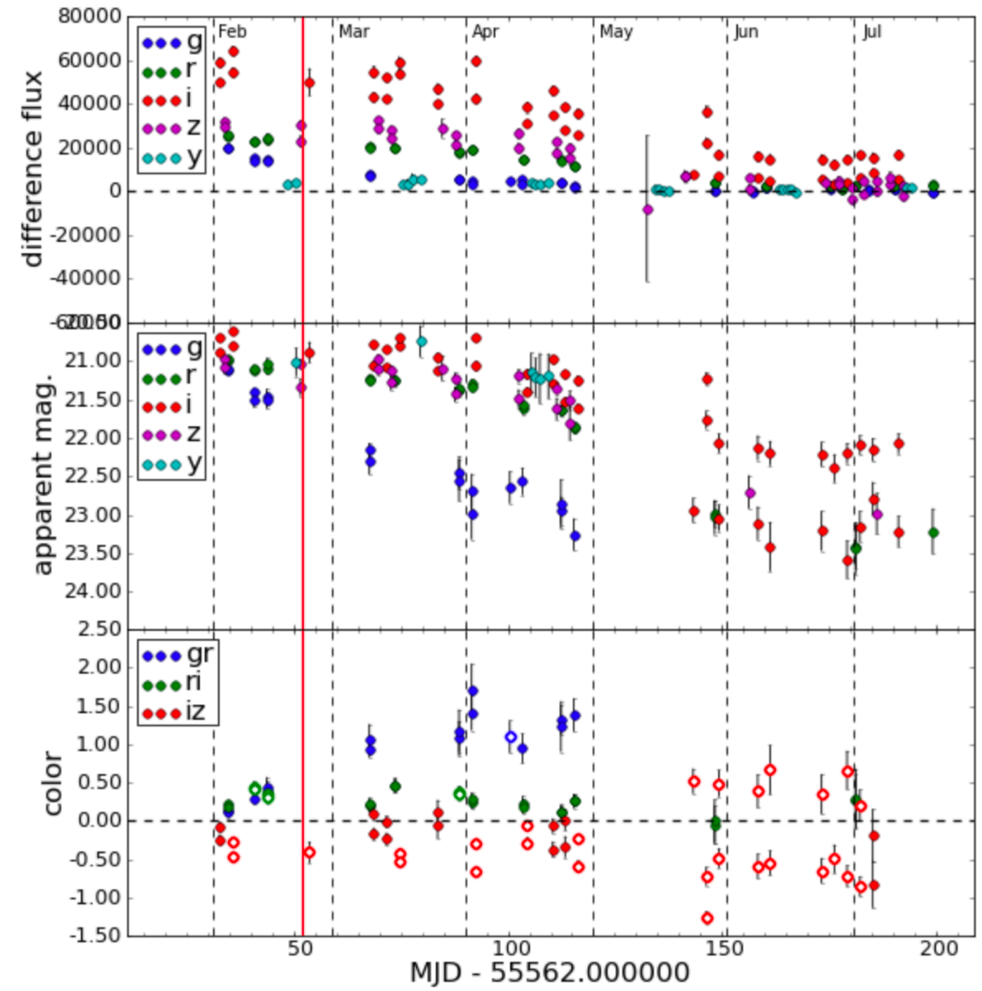


All substamps: g , r , i , z , y ,

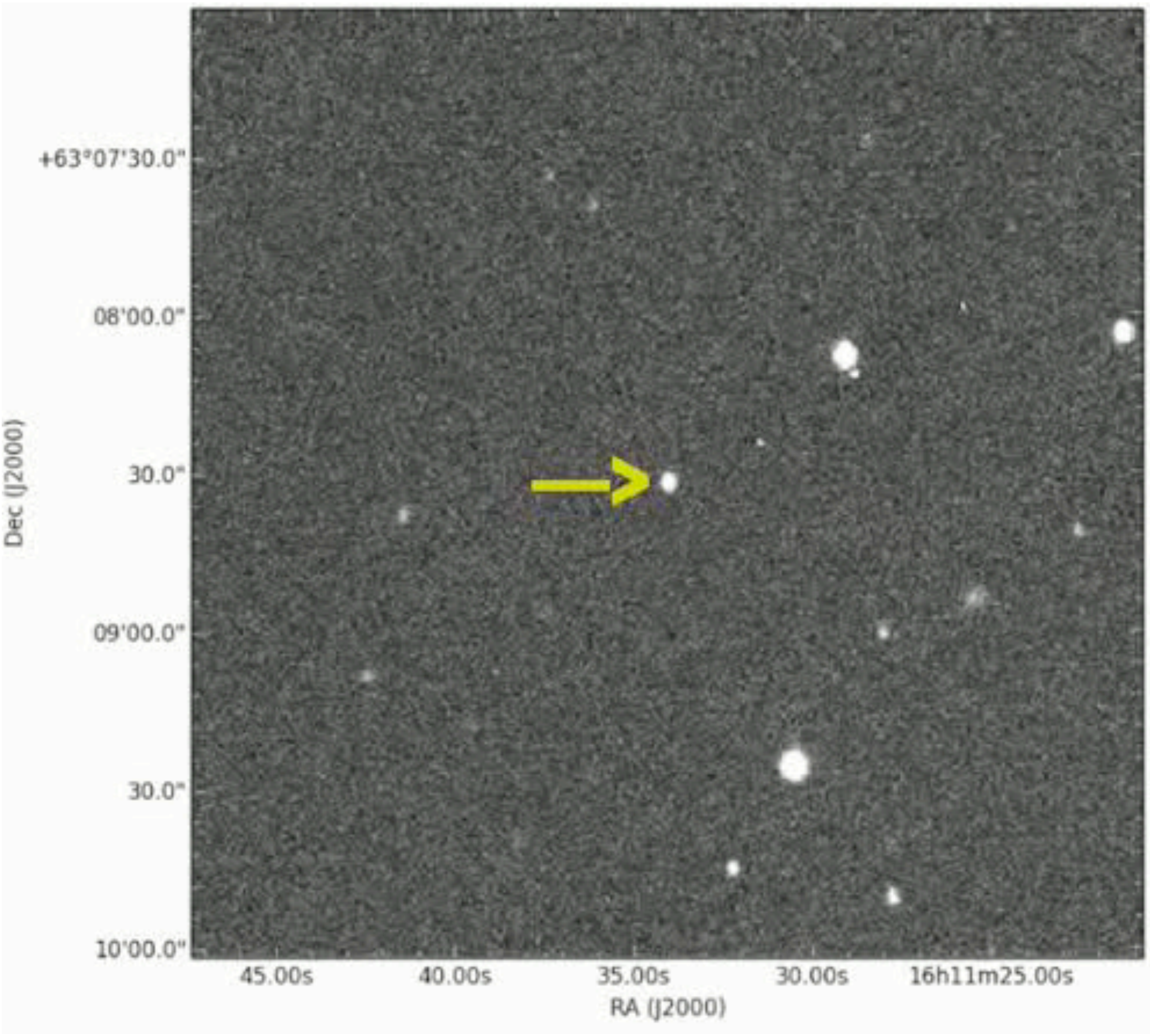
PS1-11fl (2011-B-130327)

RA Dec (J2000)	Field/Cut/Disc. Date	status	spec: specprio/queuetele, specstatus, spectel, spectype, specz	g0	r0	i0	z0	g	r	i	z
14:05:19.148 +53:07:24.25	md07s062 / 72 / ut110205g	confirmed	queue -,-,observed,Berger,MMTblue,SNIIp,0.096	21.10	20.97	20.61	20.96	23.26	23.22	22.08	22.99
SUMMARY: SDSS z=0.096; M=-17.7	VisualType: -										

previous event: 2011-B-130755 next event: 2011-B-130308 Alert Page Spectroscopy Page Finding Chart (event image): ps pdf Difference Image Lightcurve forced unforced



Extra lightcurve plots: mag lc zoomed , all t lc



SURVEY OF TOOLS FOR PSF CONVOLUTION

- ISIS (the original AL implementation)
- HOTPANTS (Andrew Becker's circa 2002 code that refuses to go quiet into the night)
- ***Python ois module*** (Bramich, 2010 - modified AL) http://optimal-image-subtraction.readthedocs.io/en/stable/
- ZOGY (Zackay, Ofek and Gal-Yam, 2016) https://github.com/pmvreeswijk/ZOGY
- ConvNet (Sedaghat and Mahabal, 2017 - kernels? We don't need no stinkin' kernels)

TAKEAWAYS ABOUT PSF CONVOLUTION

TAKEAWAYS ABOUT PSF CONVOLUTION

- Almost all references have “optimal” in the title, yet claim to improve on previous work

TAKEAWAYS ABOUT PSF CONVOLUTION

- Almost all references have “optimal” in the title, yet claim to improve on previous work
- Many of these references are in the last two years

TAKEAWAYS ABOUT PSF CONVOLUTION

- Almost all references have “optimal” in the title, yet claim to improve on previous work
- Many of these references are in the last two years
- Even the current front-runner, ZOGY, may have issues - particularly with relative flux scaling in its case

TAKEAWAYS ABOUT PSF CONVOLUTION

- Almost all references have “optimal” in the title, yet claim to improve on previous work
- Many of these references are in the last two years
- Even the current front-runner, ZOGY, may have issues - particularly with relative flux scaling in its case
- The number of artifacts exceeds the number of real detections by more than an order of magnitude

TAKEAWAYS ABOUT PSF CONVOLUTION

- Almost all references have “optimal” in the title, yet claim to improve on previous work
- Many of these references are in the last two years
- Even the current front-runner, ZOGY, may have issues - particularly with relative flux scaling in its case
- The number of artifacts exceeds the number of real detections by more than an order of magnitude
    - There’s a cottage industry of adapting ML algorithms to distinguish between “real” transients and “bogus” artifacts

TAKEAWAYS ABOUT PSF CONVOLUTION

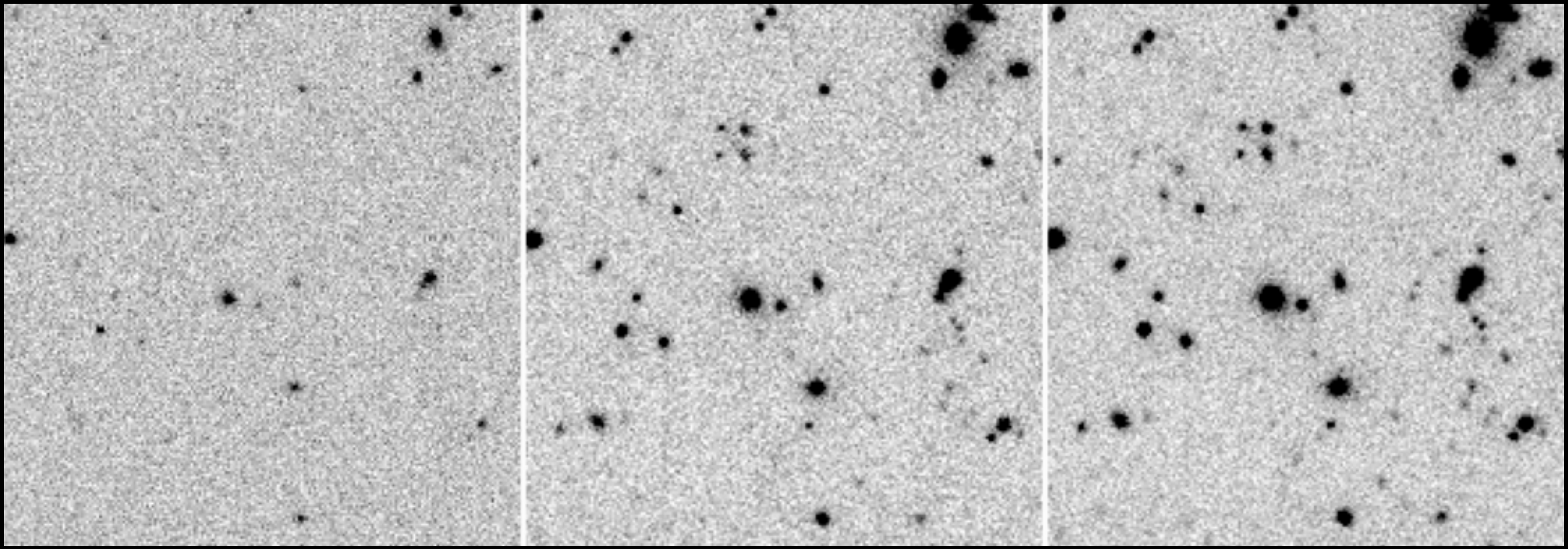
- Almost all references have "optimal" in the title, yet claim to improve on previous work
- Many of these references are in the last two years
- Even the current front-runner, ZOGY, may have issues - particularly with relative flux scaling in its case
- The number of artifacts exceeds the number of real detections by more than an order of magnitude
    - There's a cottage industry of adapting ML algorithms to distinguish between "real" transients and "bogus" artifacts
    - There's also a cottage industry adapting ML algorithms to characterize and classify real transients (and you can work through those techniques if you look at LSST DSFP #3)

IMAGE STACKING

HOW DO YOU STACK THE REGISTERED, REPROJECTED IMAGES: WEIGHTING

- Median: sub-optimal for Gaussian noise, but used to reject image gunk (which may include your rare signal…)
- (Weighted) averages:
- Clipped average:
- “Chi-squared” images: “Optimal” for source detection but not linear for flux measurement.
- ZO weights:

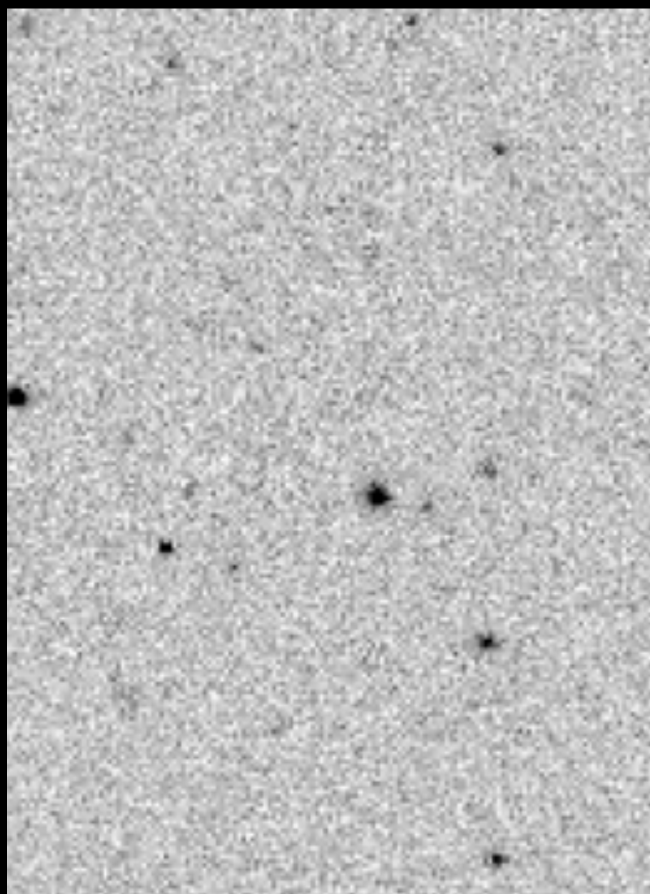
SDSS Stripe 82 Single Frame, Annis et al., 2011 stack and Jian et al., 2014 stack of the same data.
From Jian et al., 2014

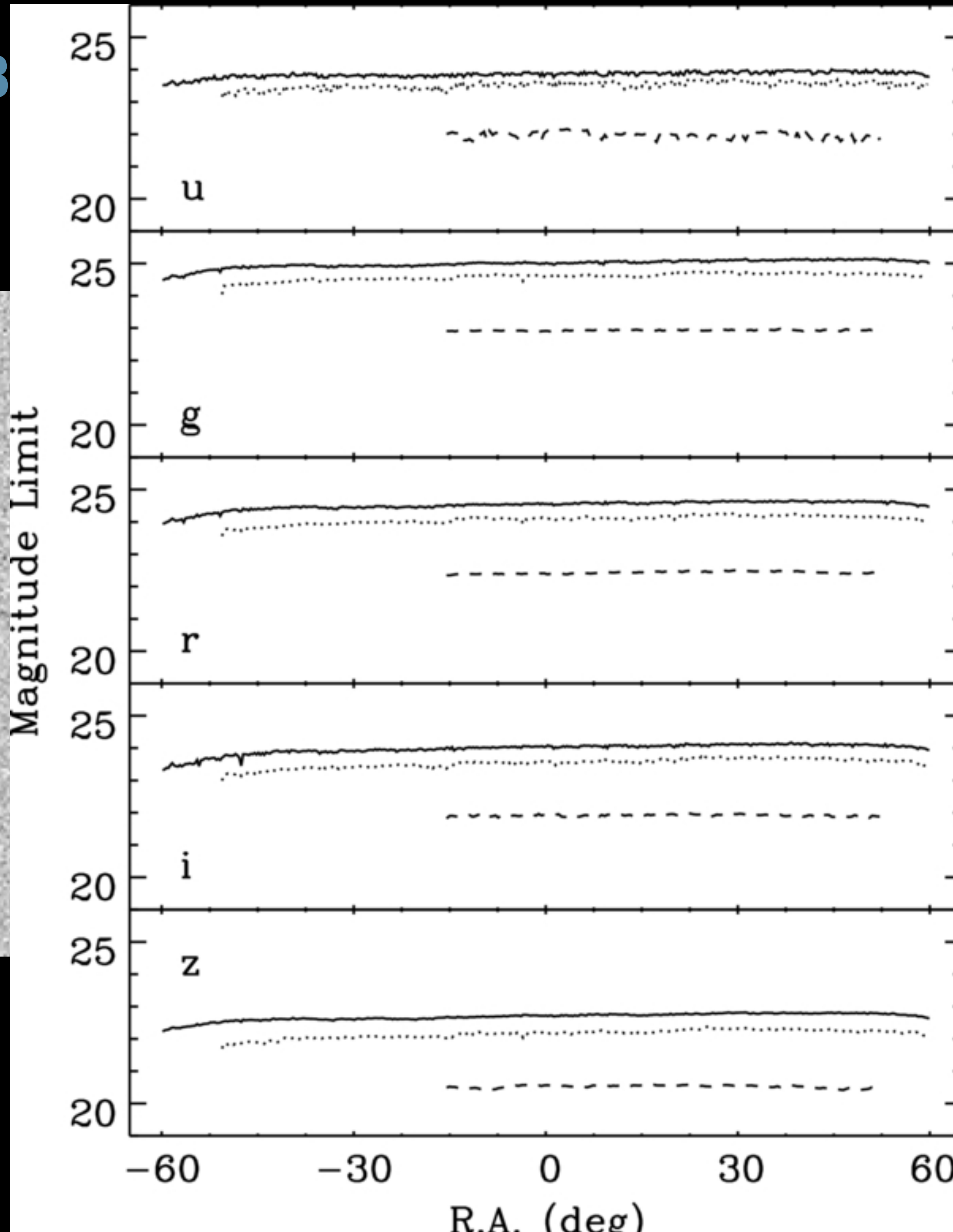


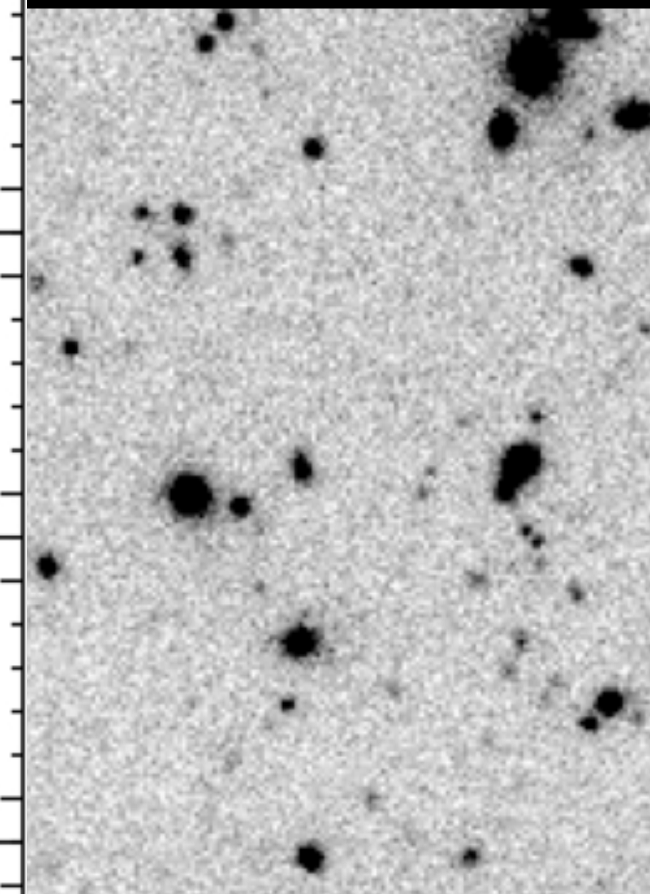
WEIGHTING CHOICE CAN HAVE STRIKING EFFECTS ON FINAL STACK

SIMILAR PSF SIZE, VISIBLY DIFFERENT DEPTHS AND BACKGROUND NOISE PROPERTIES

SDSS Stripe 8 … nd Jian et al.,







WEIGHTING CHOICE CAN HAVE STRIKING EFFECTS ON FINAL STACK

SIMILAR PSF SIZE, VISIBLY DIFFERENT DEPTHS AND BACKGROUND NOISE PROPERTIES

- Caveat about background subtraction

SURVEY OF TOOLS

- **SWarp**, **Montage**, almost anything you like with the ***(numpy, scipy, pyfftw, astropy)*** toolchain
    - e.g. Federica Bianco's coaddfitim - align in pixel space with cross correlation in Fourier space https://github.com/fedhere/coaddfitim
- There's no existing python implementation of Zackay and Ofek's optimal COAAD algorithm - hack project idea?
- If you are trying to produce a nice color image for an article or poster, the amateur/astrophotographer community has much nicer tools

TAKEAWAYS ABOUT STACKING

- As with resampling, there’s several knobs that you can turn
- “Optimal” depends on what your goal is (deepest image, most accurate photometry, highest resolution)

“SO WHAT’S THE BEST THING TO USE?”

“SO WHAT’S THE BEST THING TO USE?”

- When I started in grad school, if a package didn’t do everything I wanted, I’d write something that did

"SO WHAT'S THE BEST THING TO USE?"

- When I started in grad school, if a package didn't do everything I wanted, I'd write something that did
- By the end of grad school, I preferred modifying packages that exist and did most of what I want

"SO WHAT'S THE BEST THING TO USE?"

- When I started in grad school, if a package didn't do everything I wanted, I'd write something that did
- By the end of grad school, I preferred modifying packages that exist and did most of what I want
- Much the same now, except I pick packages that have active developers and users

“SO WHAT’S THE BEST THING TO USE?”

- When I started in grad school, if a package didn’t do everything I wanted, I’d write something that did
- By the end of grad school, I preferred modifying packages that exist and did most of what I want
- Much the same now, except I pick packages that have active developers and users
  - Even if it’s not optimal but does most of the job - your data ages faster than software

“SO WHAT’S THE BEST THING TO USE?”

- When I started in grad school, if a package didn’t do everything I wanted, I’d write something that did
- By the end of grad school, I preferred modifying packages that exist and did most of what I want
- Much the same now, except I pick packages that have active developers and users
  - Even if it’s not optimal but does most of the job - your data ages faster than software
  - It’s better to get papers out the door, even if there’s things you could do better.

USEFUL RESOURCES

SOME USEFUL RESOURCES: IMAGE REGISTRATION

- **The WCS reference page:**
  https://fits.gsfc.nasa.gov/fits_wcs.html
- **Jessica Mink's WCSTools page:**
  http://tdc-www.harvard.edu/wcstools/
- **The astrometry.net paper - Lang et al, 2010:**
  http://adsabs.harvard.edu/abs/2010AJ....139.1782L
- **Interactive walkthrough to establish the WCS of an image:**
  http://iraf.noao.edu/projects/ccdmosaic/astrometry/astrom.html
- **WCS for Dummies guide:**
  http://sun.stanford.edu/~beck/JSOC/HMI_WCS_Dummies.pdf

SOME USEFUL RESOURCES: IMAGE REPROJECTION

- **Montage:**
  http://montage.ipac.caltech.edu/docs/index.html
- **HEALPix:**
  https://healpix.jpl.nasa.gov/index.shtml
- **Drizzle - Fruchter and Hook, 2002:**
  http://adsabs.harvard.edu/abs/2002PASP..114..144F
- **SWarp:**
  https://www.astromatic.net/software/swarp
- **Tom McGlynn (GSFC) on resampling techniques in astronomy:**
  http://www.ipam.ucla.edu/abstract/?tid=4475&pcode=AI2004

SOME USEFUL RESOURCES: PSF CONVOLUTION

- **Alard and Lupton (1998):**
  http://adsabs.harvard.edu/abs/1998ApJ...503..325A
- **Brammich (2008):**
  http://adsabs.harvard.edu/abs/2008MNRAS.386L..77B
- **Zackay, Ofek and Gal-Yam (2016):**
  http://adsabs.harvard.edu/abs/2016ApJ...830...27Z
  also see notes on the LSST pipeline implementation https://dmtn-021.lsst.io/
- **Sedaghat and Mahabal (2017):**
  http://adsabs.harvard.edu/abs/2017arXiv171001422S
- **The nitty gritty on assessing difference imaging performance in the DES pipeline - Kessler et al (2015):**
  http://adsabs.harvard.edu/abs/2015AJ....150..172K
- **David Reiss' state of difference imaging in the LSST stack writeup:**
  https://dmtn-061.lsst.io/

SOME USEFUL RESOURCES: IMAGE STACKING

- **Swarp, Montage and drizzlepac would go here again**
- **Clipped mean stacking for artifact removal** - Gruen, Seitz, Bernstein, 2014
  http://adsabs.harvard.edu/abs/2014PASP..126..158G
- **Zackay and Ofek, COAAD (p1 and p2):**
  http://adsabs.harvard.edu/abs/2017ApJ...836..187Z
  http://iopscience.iop.org/article/10.3847/1538-4357/836/2/188/meta
- **Waters et al., 2016 on what Pan-STARRS is actually doing:**
  http://adsabs.harvard.edu/abs/2016arXiv161205245W
- **Coadding images with MapReduce and Hadoop in the cloud - i.e. really big stacks - Wiley et al, 2011:**
  http://adsabs.harvard.edu/abs/2011PASP..123..366W

“From our home on the Earth, we look out into the distances and strive to imagine the sort of world into which we are born… But with increasing distance our knowledge fades, and fades rapidly, until at the last dim horizon we search among the ghostly errors of observations for landmarks that are scarcely more substantial.

The search will continue. The urge is older than history. It is not satisfied and it will not be suppressed.”

–Edwin P. Hubble, The George Darwin Lecture