

IMAGE STACKING AND DIFFERENCING

GAUTHAM NARAYAN
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

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- * 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

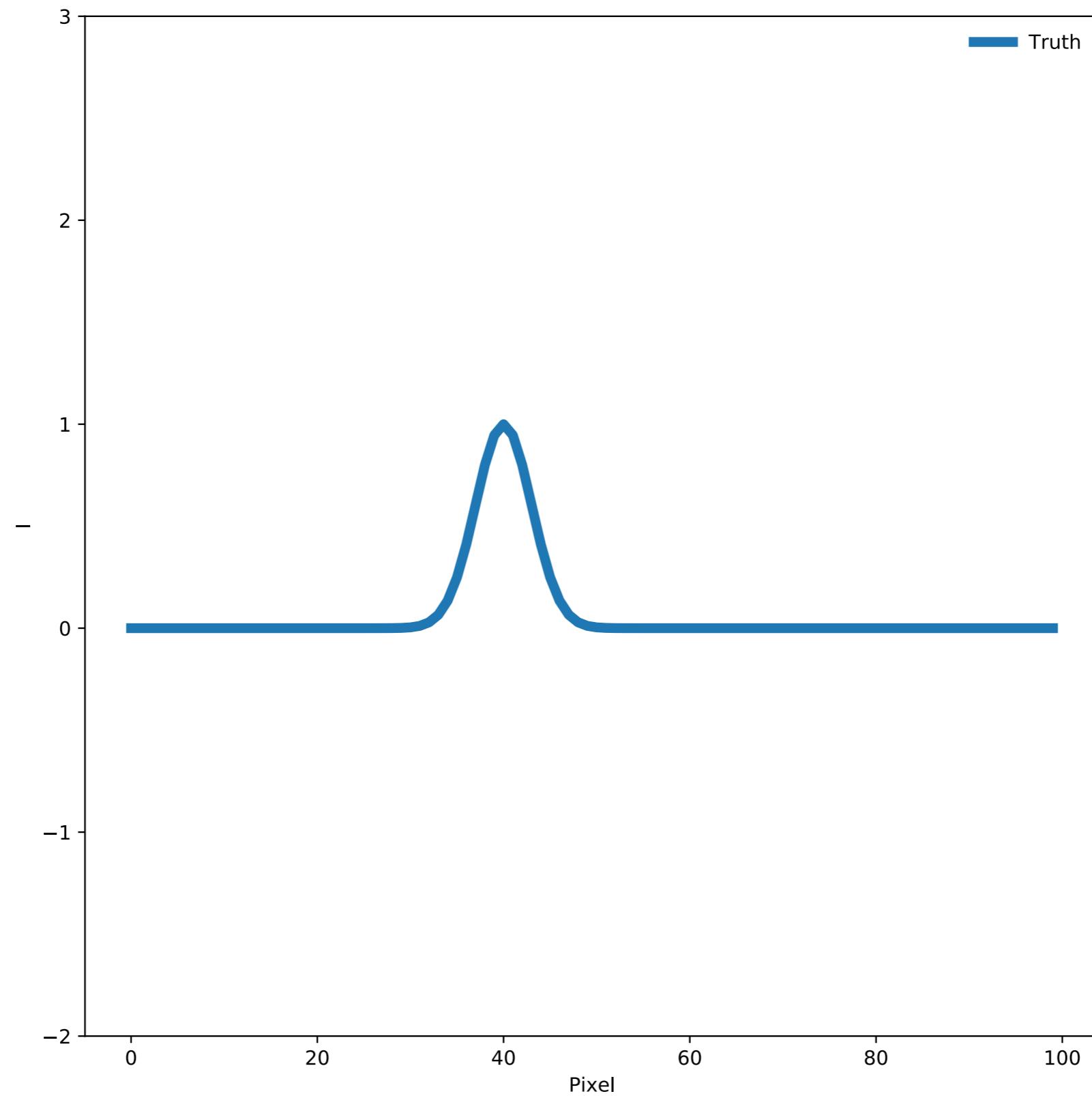


IMAGE STACKING: TOY EXAMPLE

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

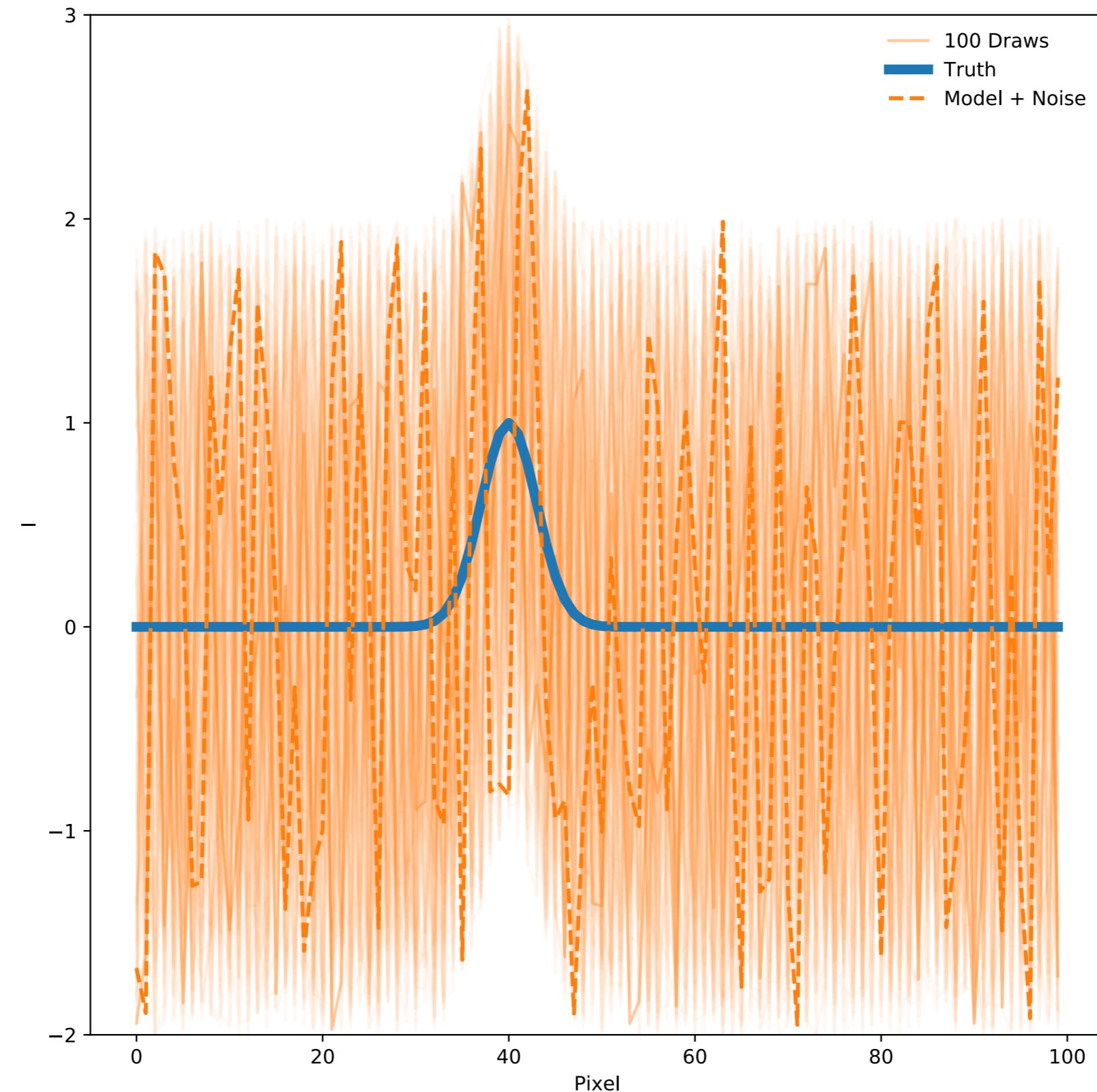


IMAGE STACKING: TOY EXAMPLE

GAUSSIAN BURIED IN NOISE

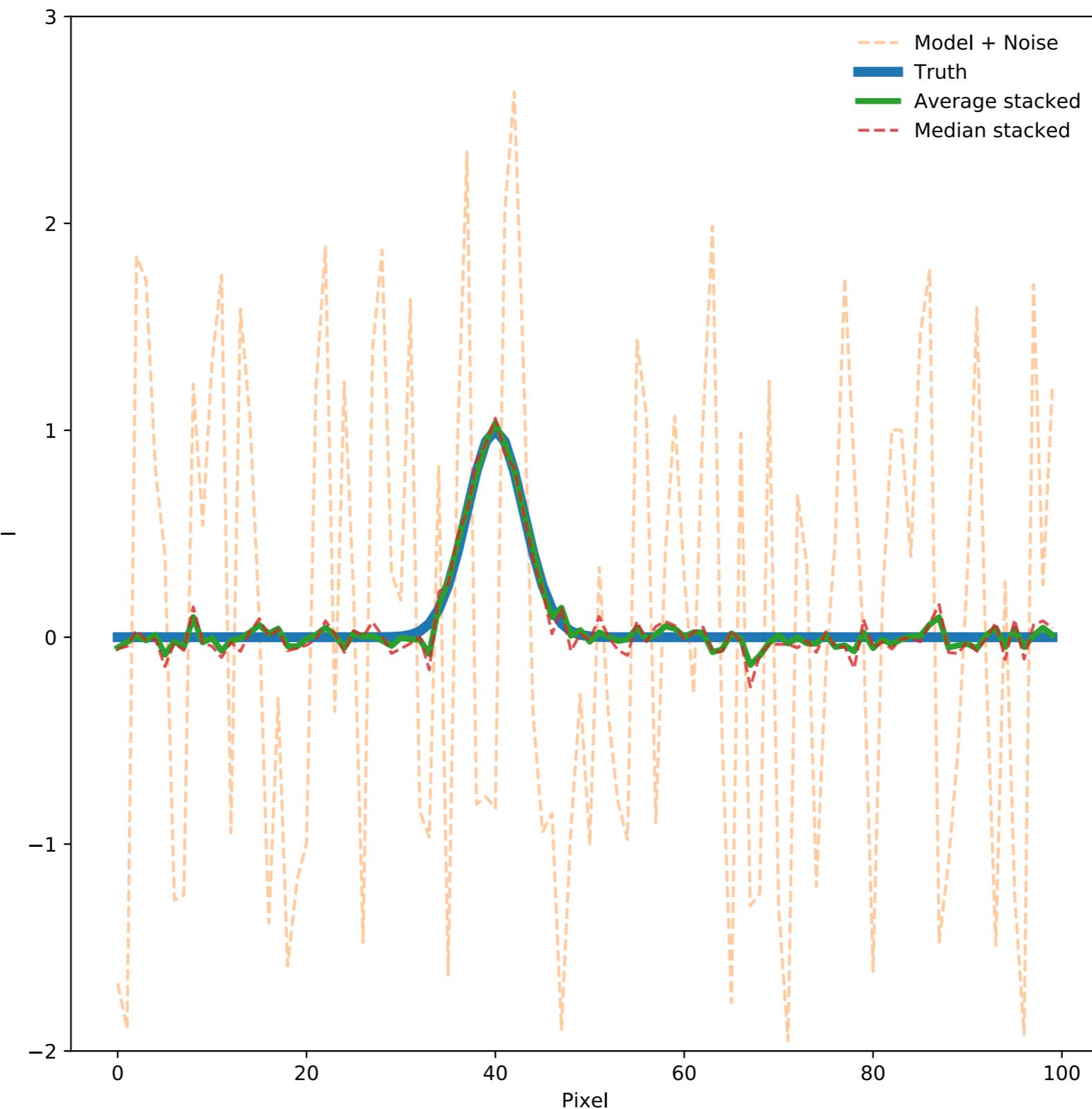


IMAGE STACKING: TOY EXAMPLE

STACKING BEATS DOWN THE NOISE

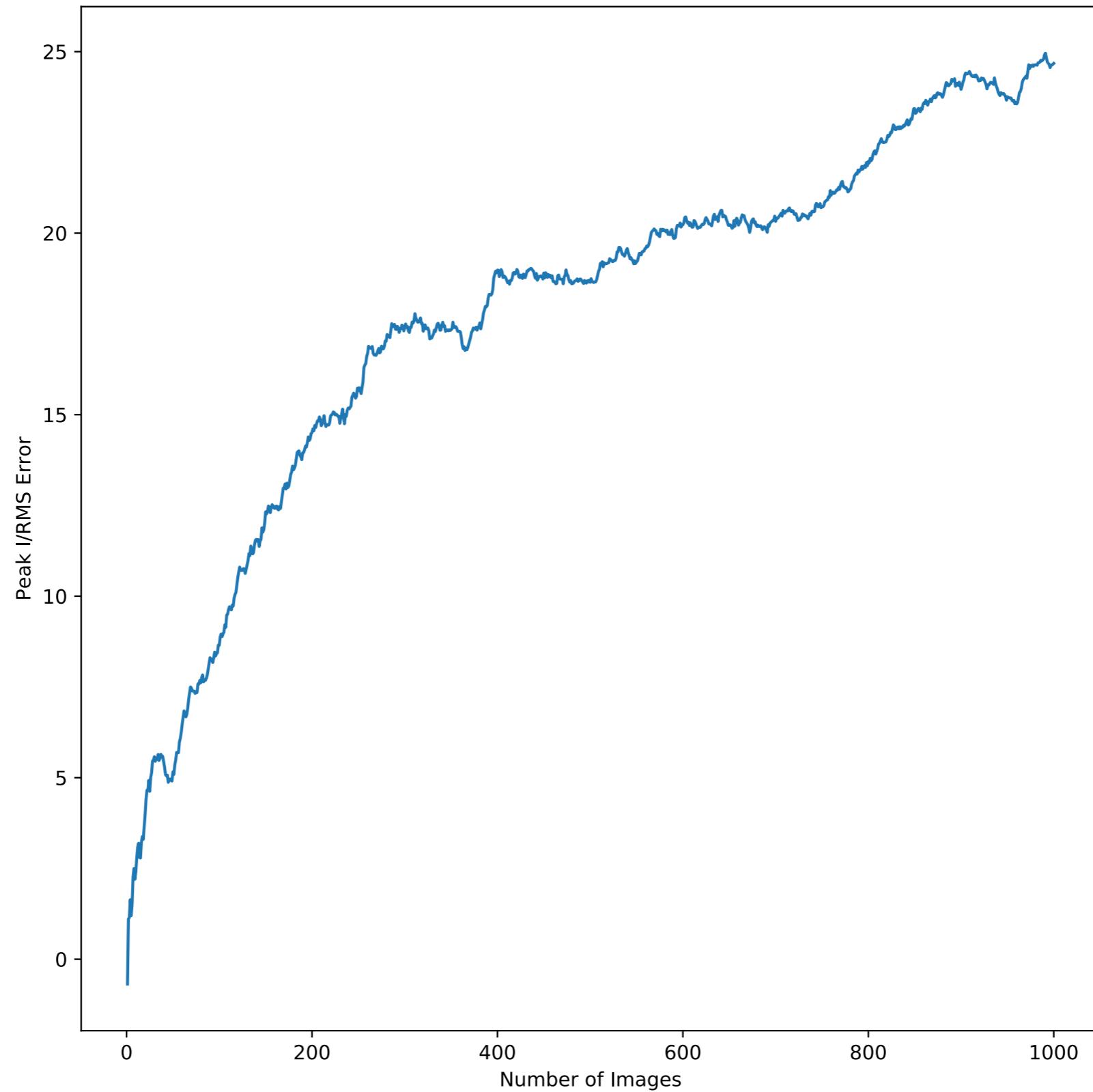


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- * Saturation
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- * Murphy is right (software, instrument, telescope, dome, weather)

IMAGE STACKING: COMPLICATIONS

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- * **You'll have examples of all of these tasks in the interactive session**

IMAGE REGISTRATION

Instrument A1: distortion map

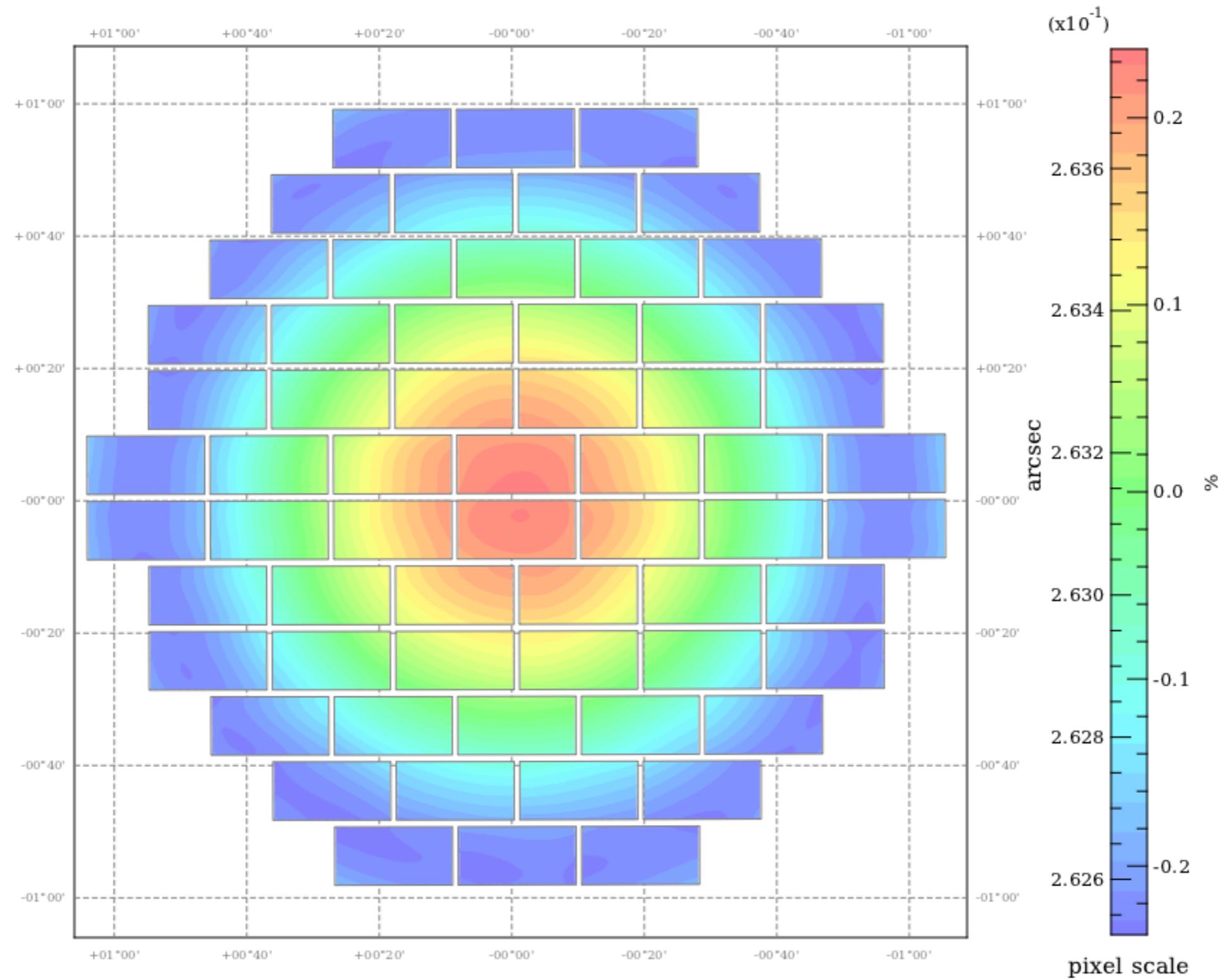


IMAGE REGISTRATION FROM X, Y TO SKY

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IMAGE RE

- * Telescopes arcsec

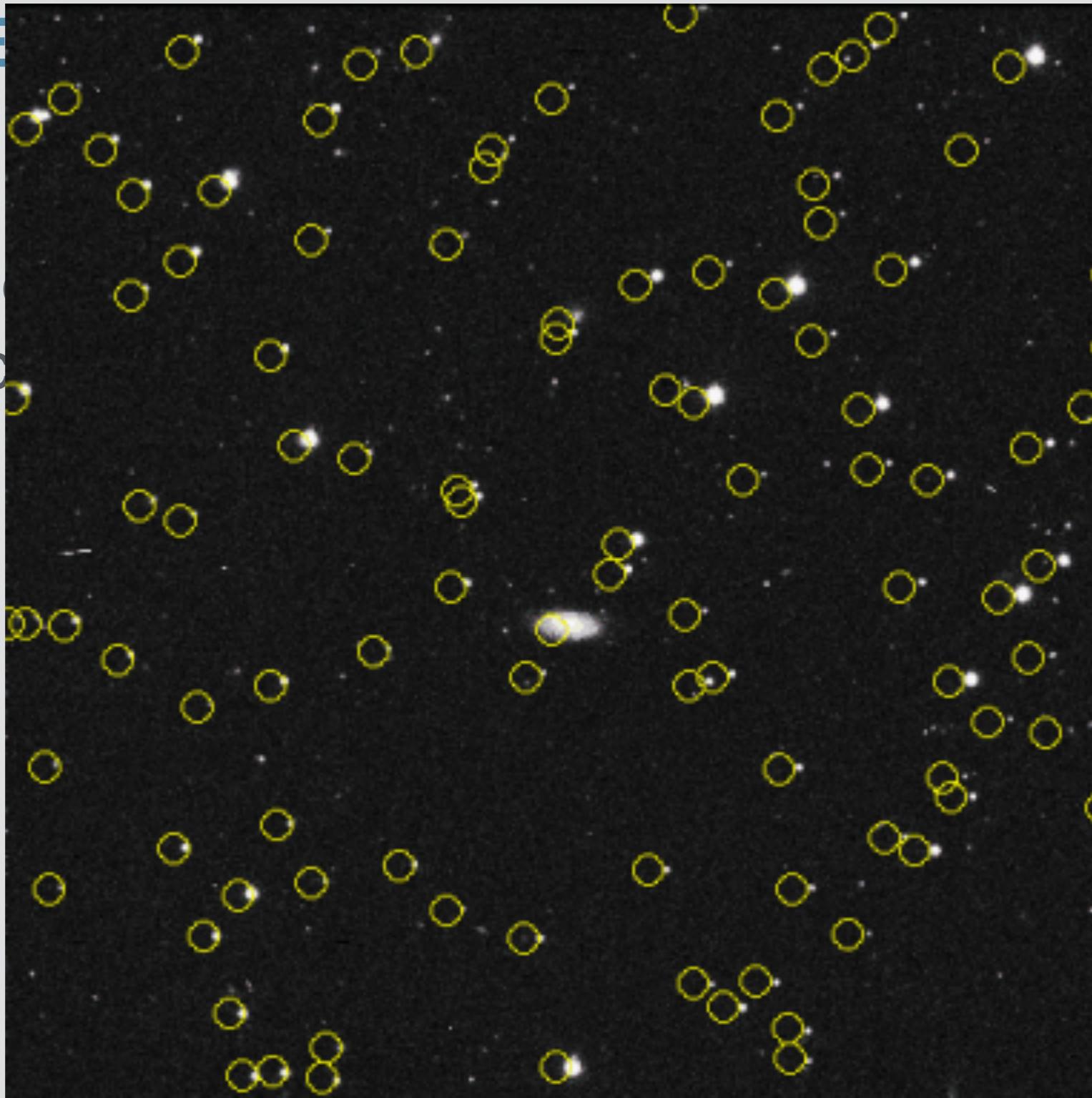


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- * Telescopes arcseconds
- * Records keyword
- * **We want to see x, y and RA, Dec**

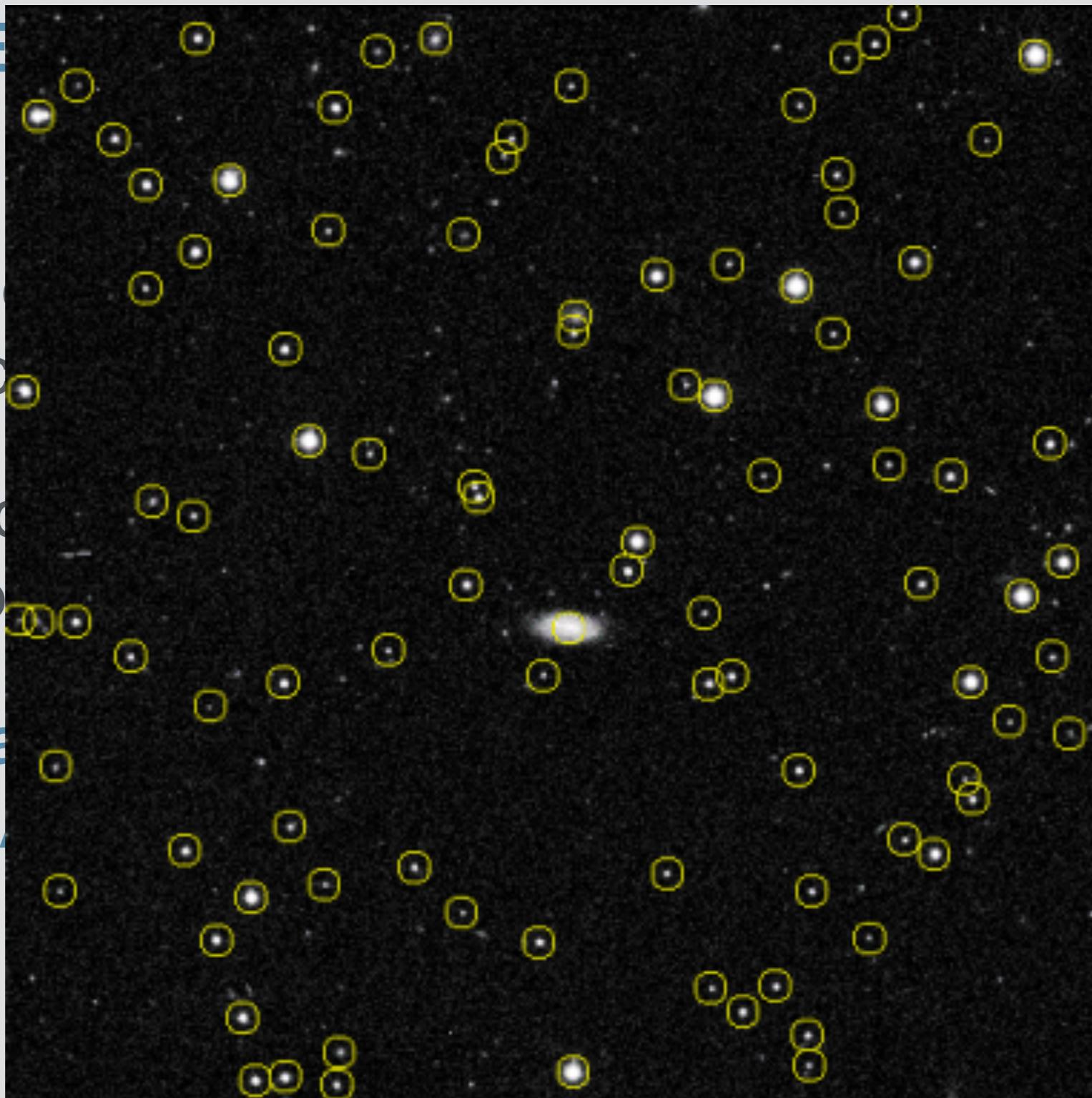


IMAGE REGISTRATION

- * 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

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in the image (quads) - matches them against index files. Also **casutools: wcsfit**

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 - * 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...

$$xi = a + b * x + c * y$$

$$\eta = d + e * x + f * y$$

$$b = CD1_1$$

$$c = CD1_2$$

$$e = CD2_1$$

$$f = CD2_2$$

$$a = -b * CRPIX1 - c * CRPIX2$$

$$d = -e * CRPIX1 - f * CRPIX2$$

$$l_{\text{ng}} = CRVAL1 + \text{PROJ}(xi, \eta)$$

$$l_{\text{lat}} = CRVAL2 + \text{PROJ}(xi, \eta)$$

Scale * Rotation Matrix
 [* linear distortion terms]

Coordinates of reference pixel

COORDINATE TRANSFORMATION EQUATIONS

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Reference position on sky
 Coordinate & Projection

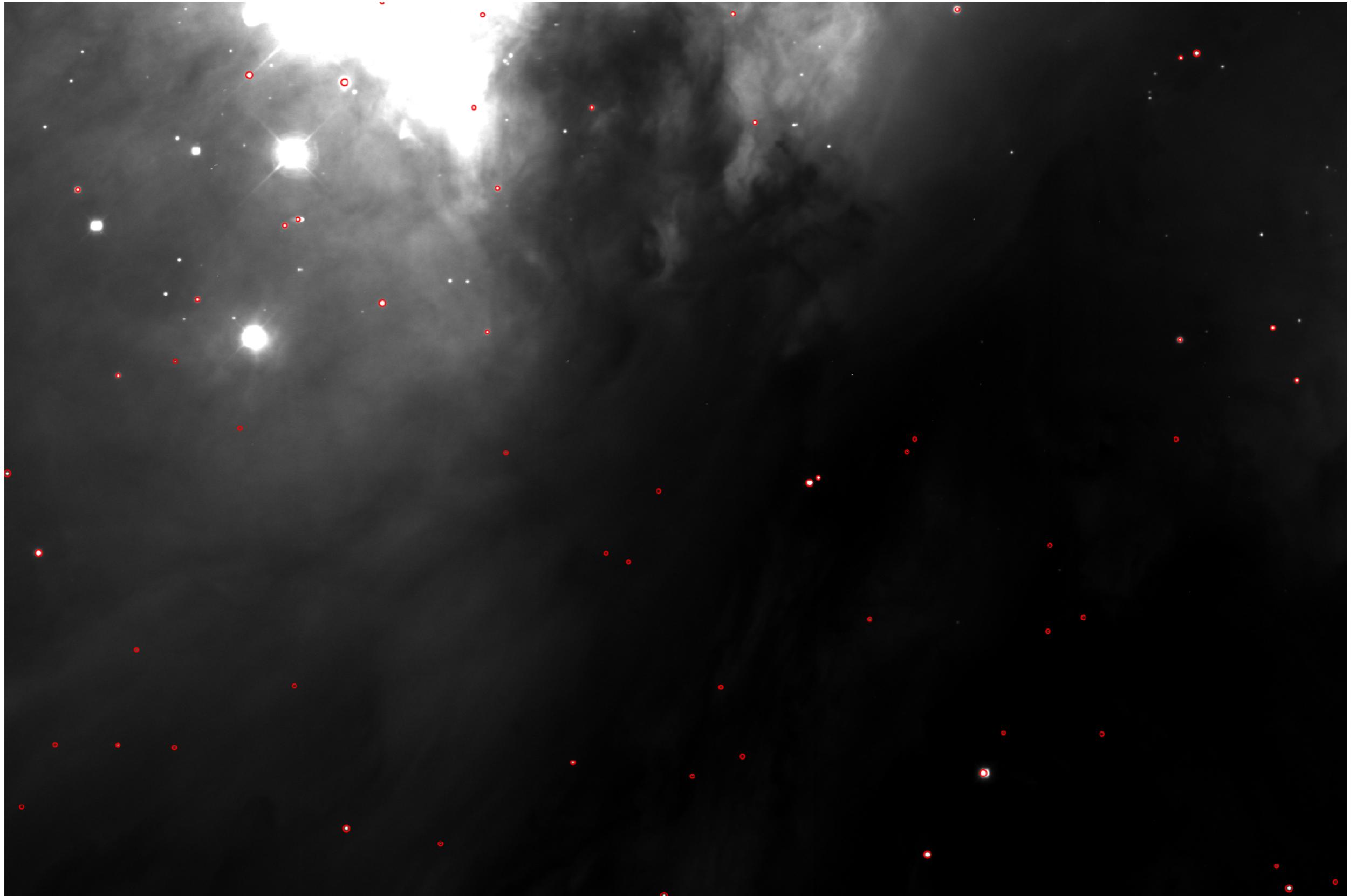
```

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. lncor = "3. 3. 3. 2. -0.312030160641664 -0.003'
WAT1_003= '425476301279112 -0.3141895265742044 -0.1574331080528804 6.9776357940'
WAT1_004= '06173E-5 0.001672959817424523 0.001428238959131151 -3.98760299129999'
WAT1_005= '0E-4 0.005331553614129722 -0.002539682182351483 ""
WAT2_002= 'jp4=0. projp5=632052. latcor = "3. 3. 3. 2. -0.312030160641664 -0.00'
WAT2_003= '3425476301279112 -0.3141895265742044 -0.1574331080528804 9.439895254'
WAT2_004= '708380E-5 6.531038306171254E-4 0.001589990574757316 5.10627353256451'
WAT2_005= '3E-4 6.379249889089745E-4 9.233174405771017E-4 ""

```

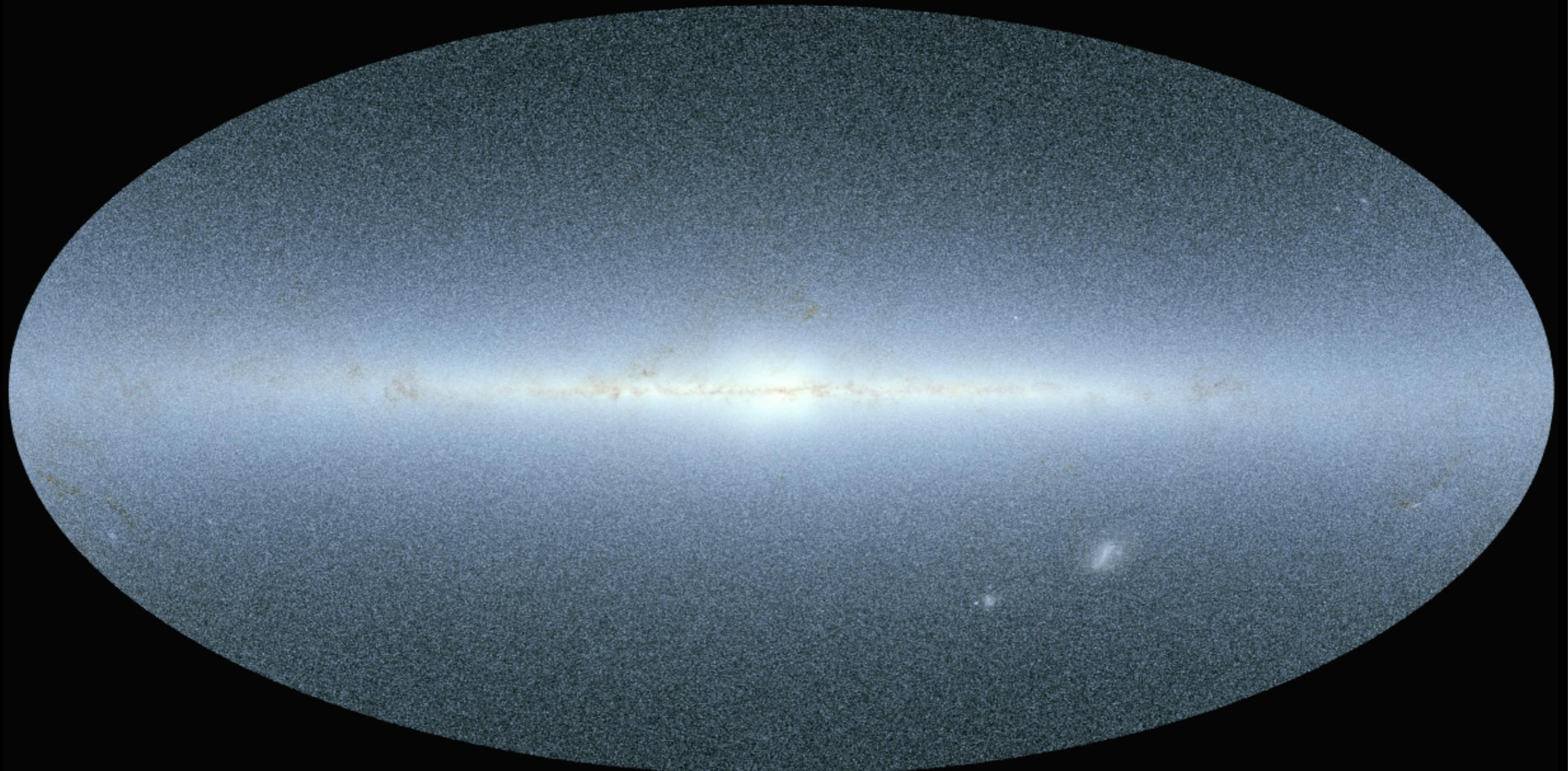
COORDINATE TRANSFORMATION EQUATIONS

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



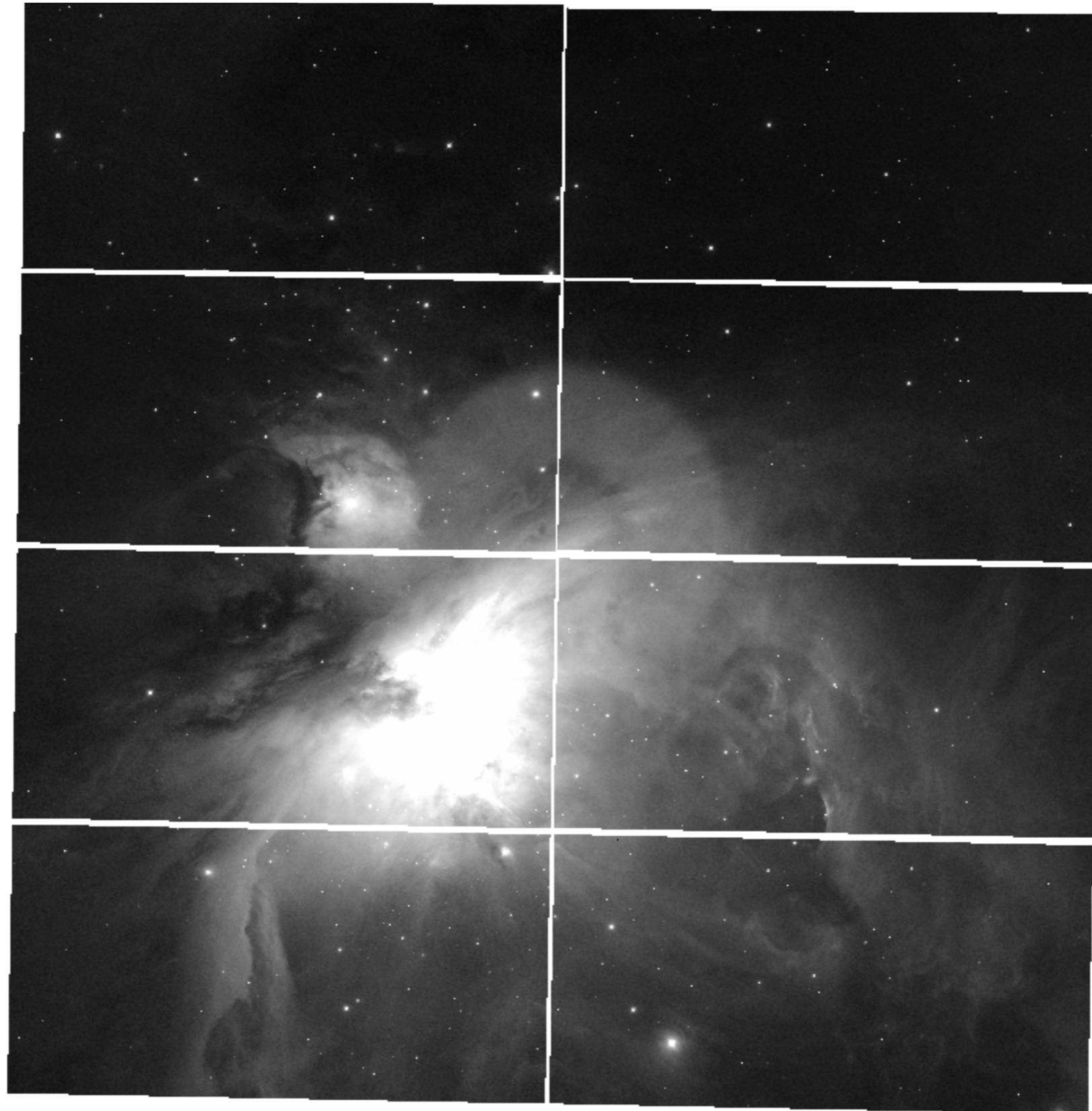
SOURCE DETECTION

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



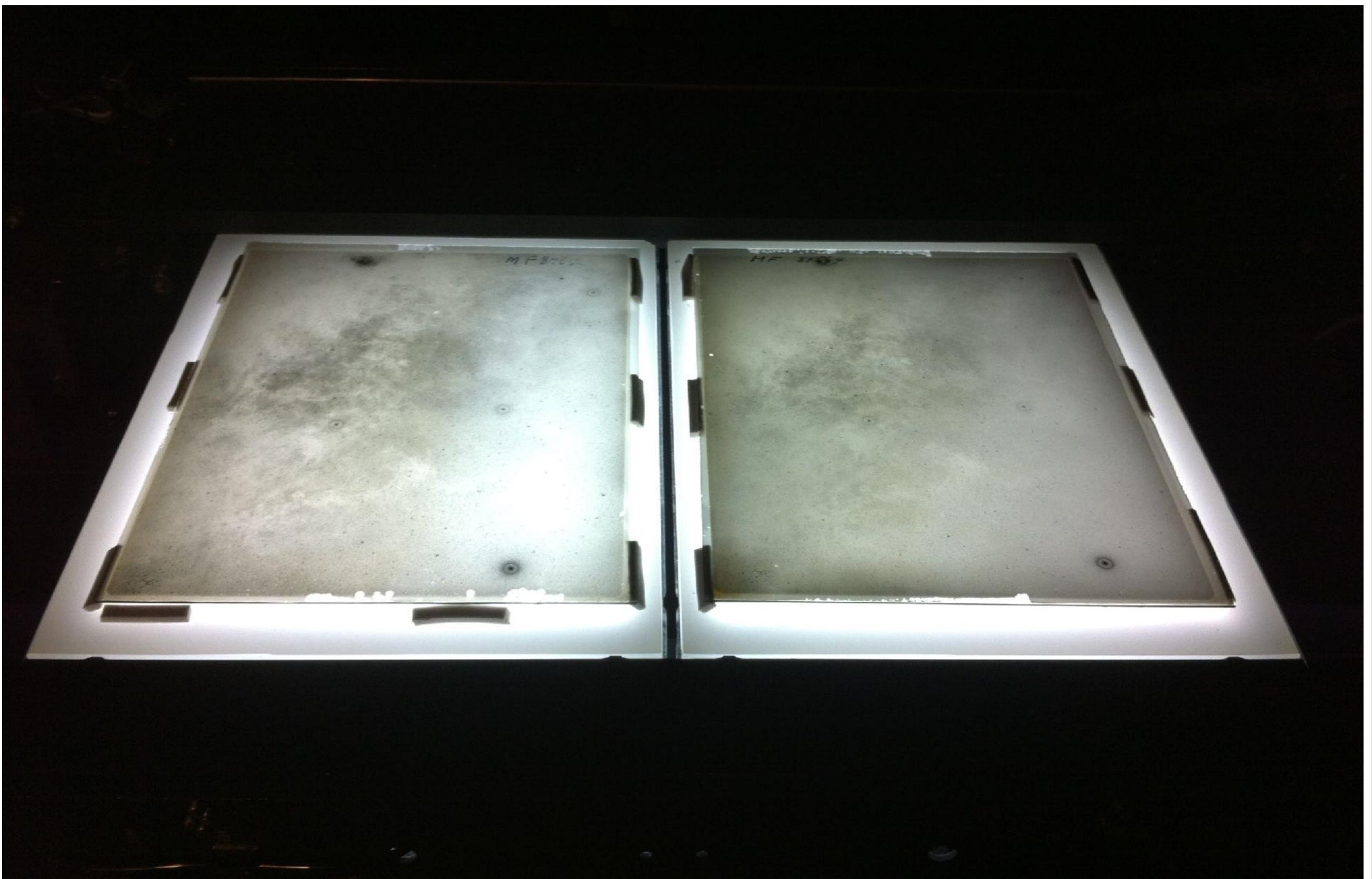
ASTROMETRIC REFERENCE CATALOGS

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)



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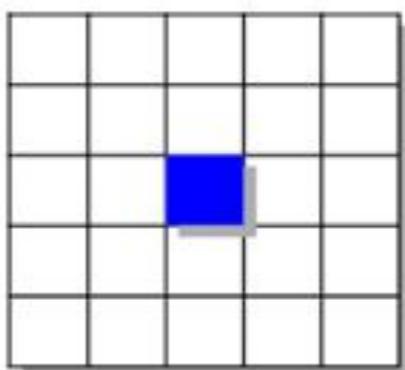
The glass plate scanner of Harvard's DASCH project (@DASCHDesk)

IMAGE RESAMPLING



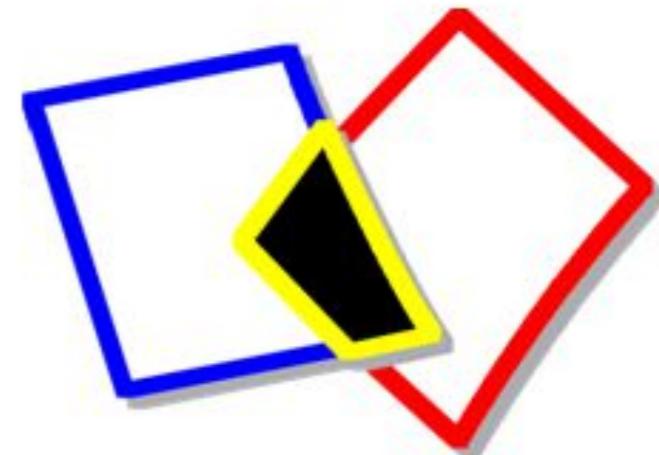
Montage v1.7 Reprojection: mProject module

Arbitrary Input
Image



```
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
```

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)

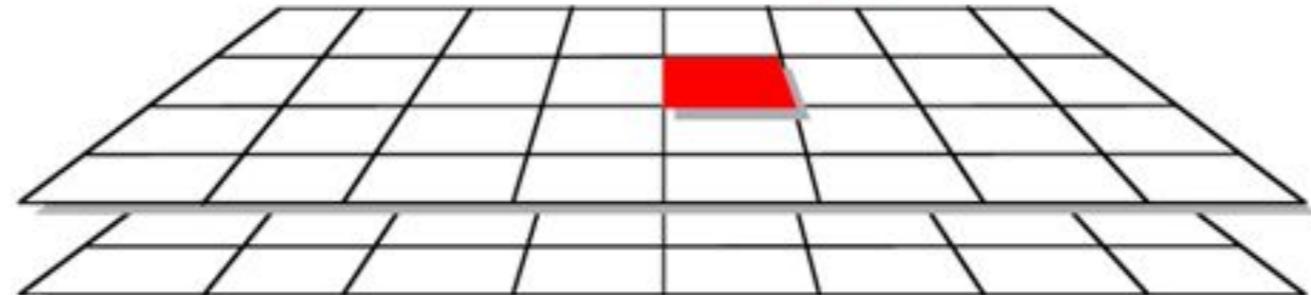


*Input pixels
projected on
celestial sphere*

*Output pixels
projected on
celestial sphere*

FITS header defines output projection

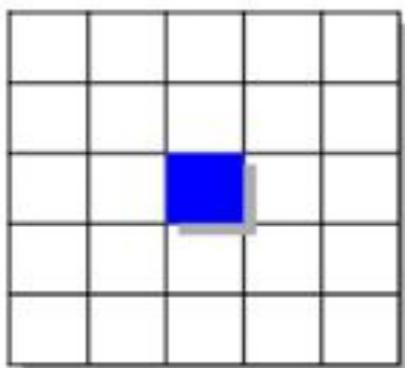
Reprojected
Image





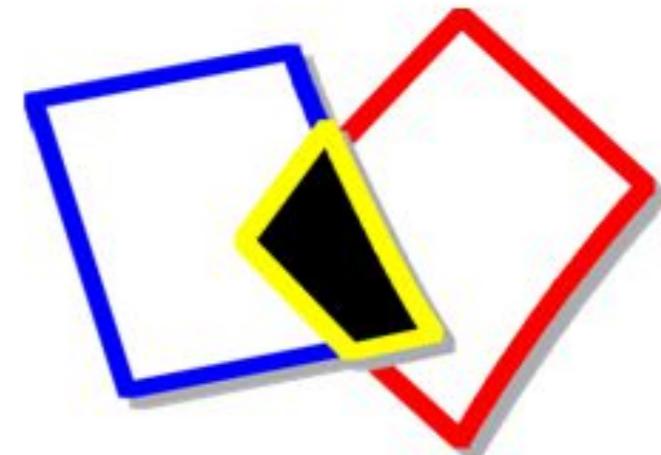
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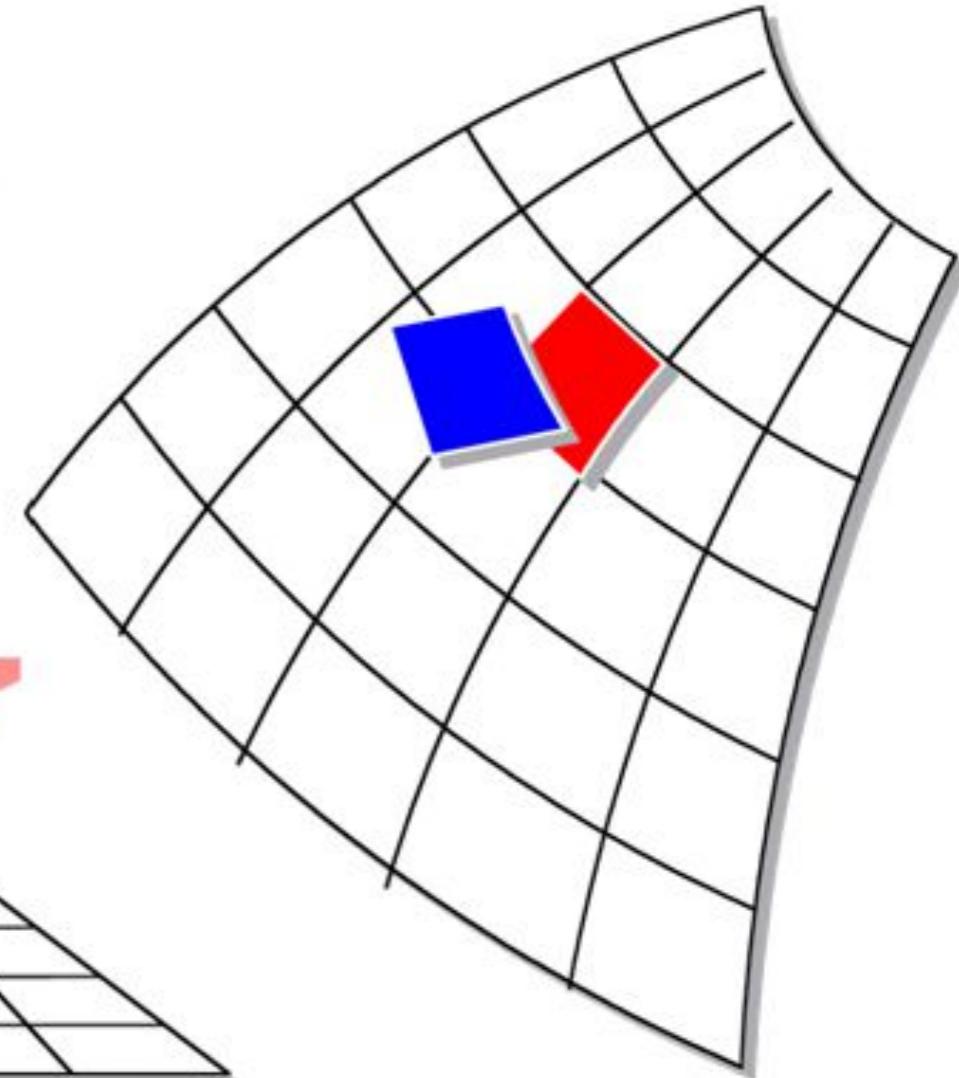
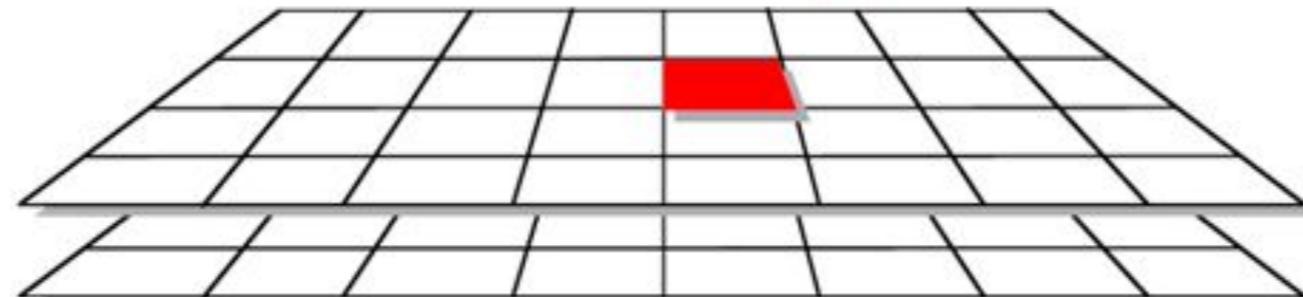


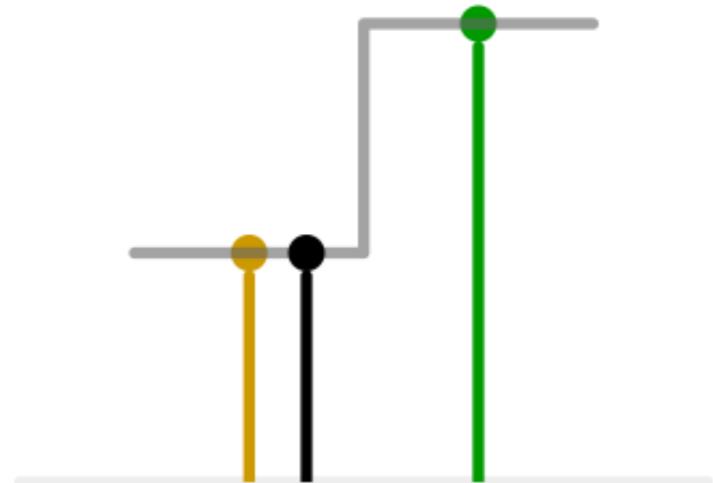
*Input pixels
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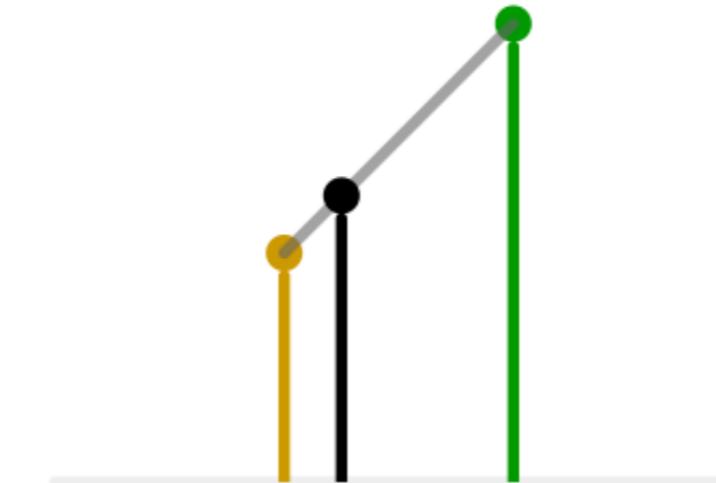
FITS header defines output projection

Reprojected
Image

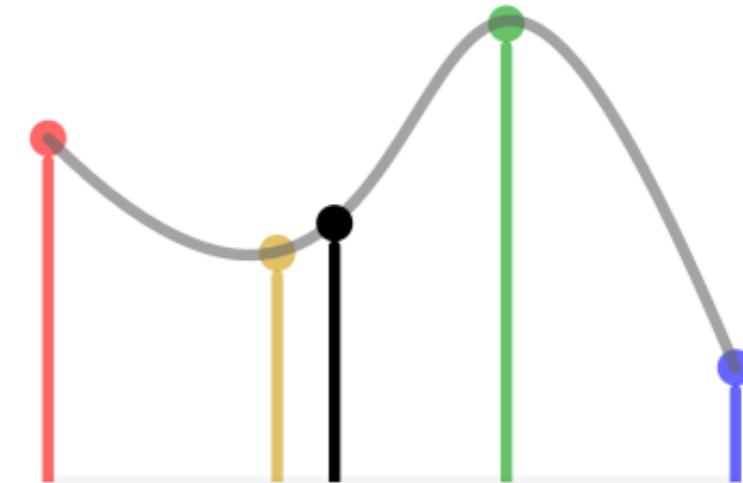




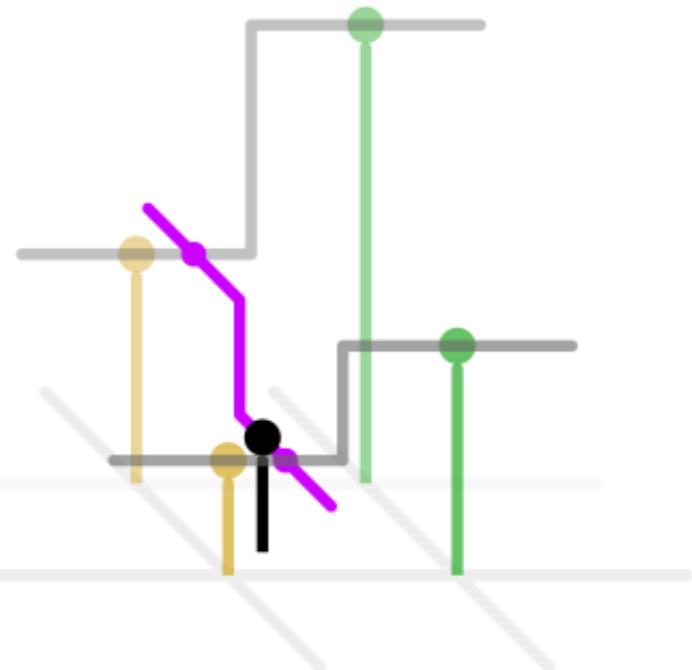
1D nearest-
neighbour



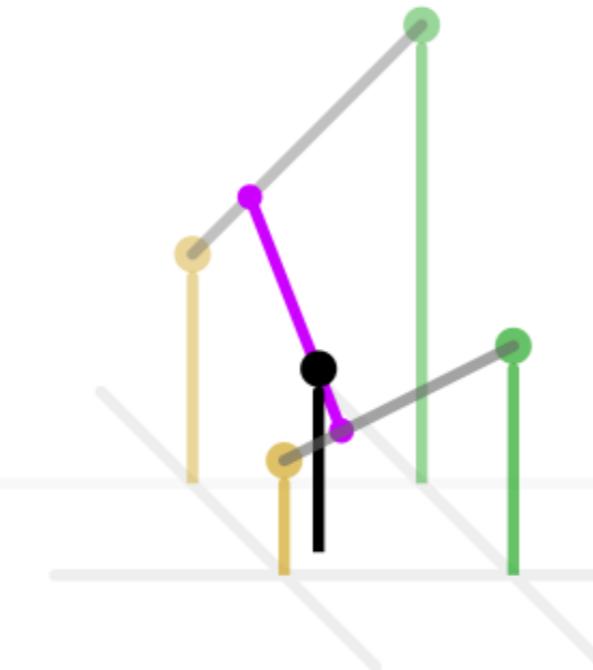
Linear



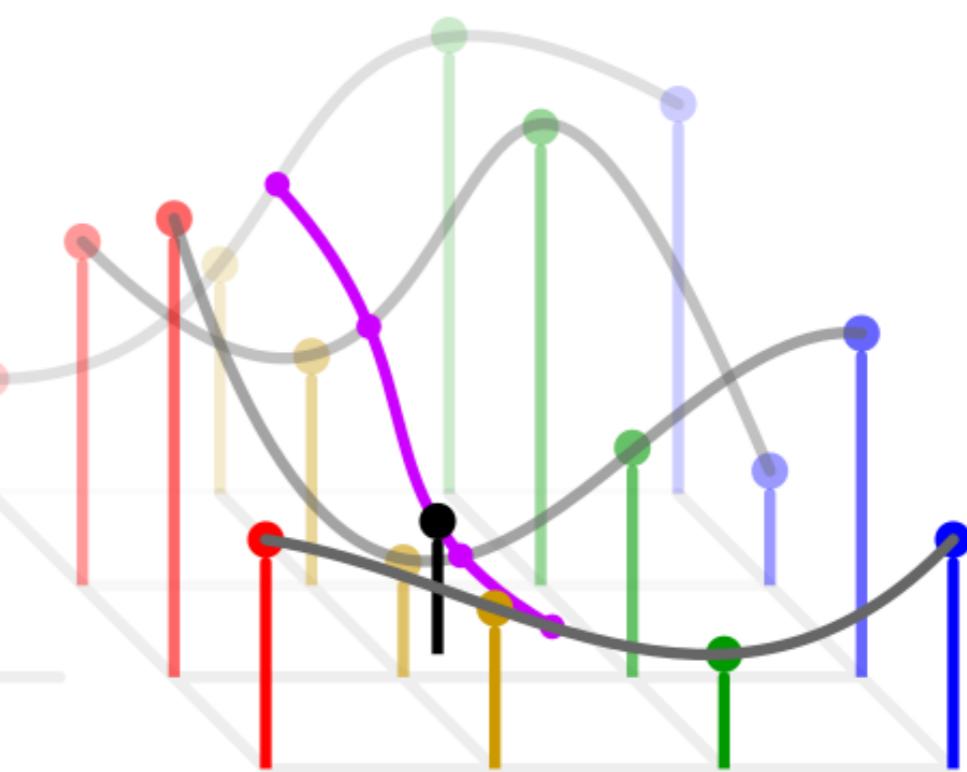
Cubic



2D nearest-
neighbour



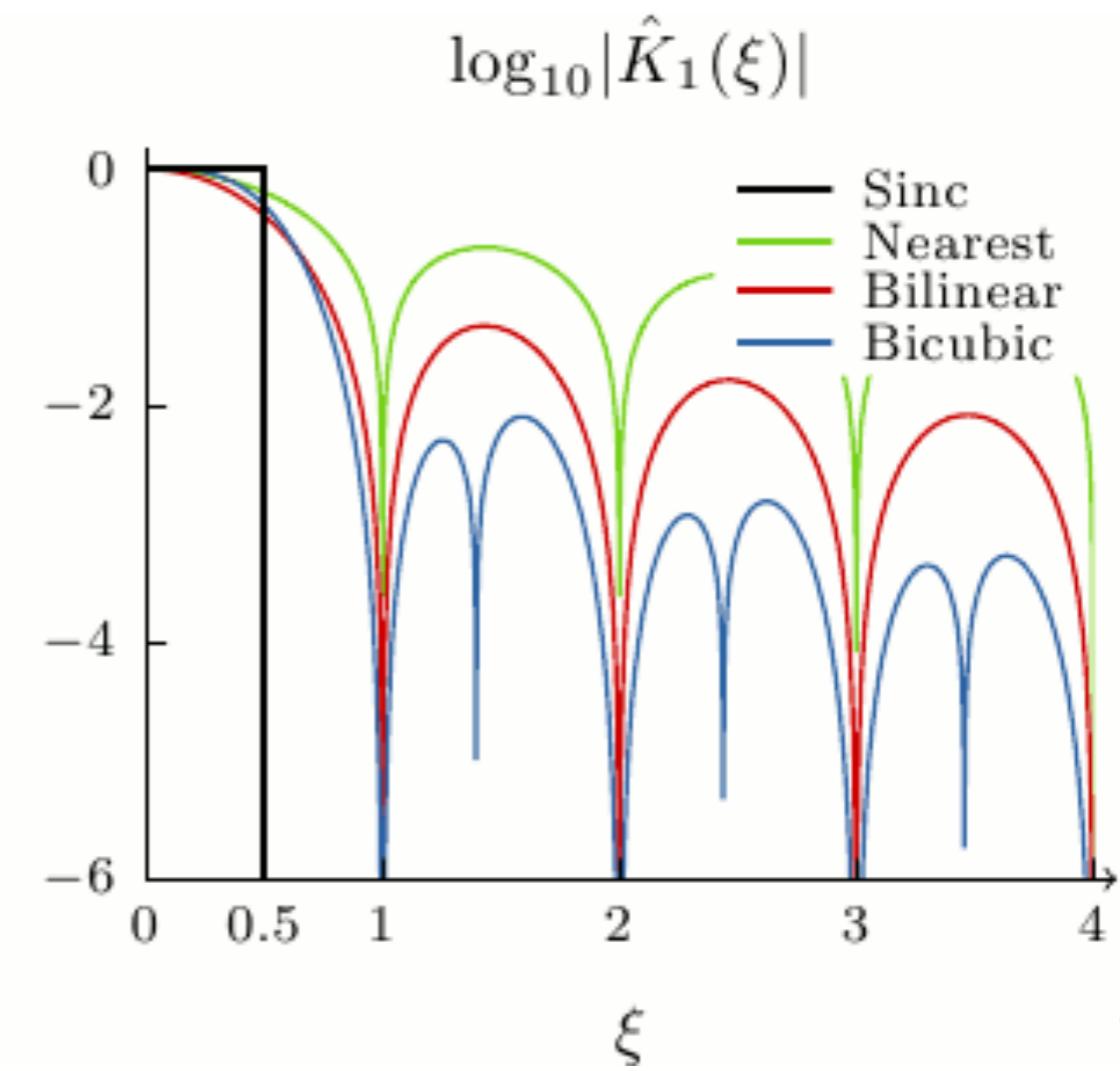
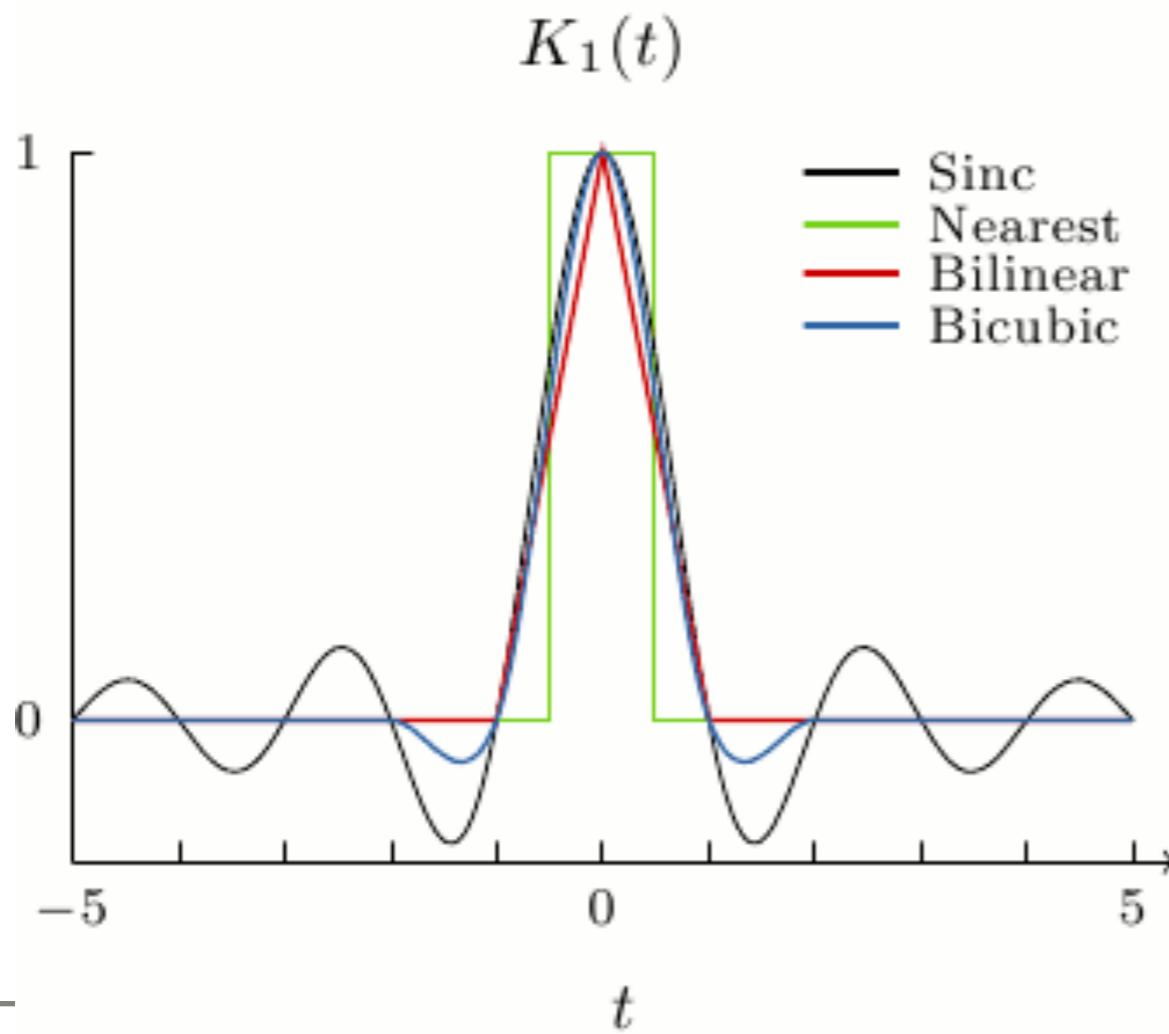
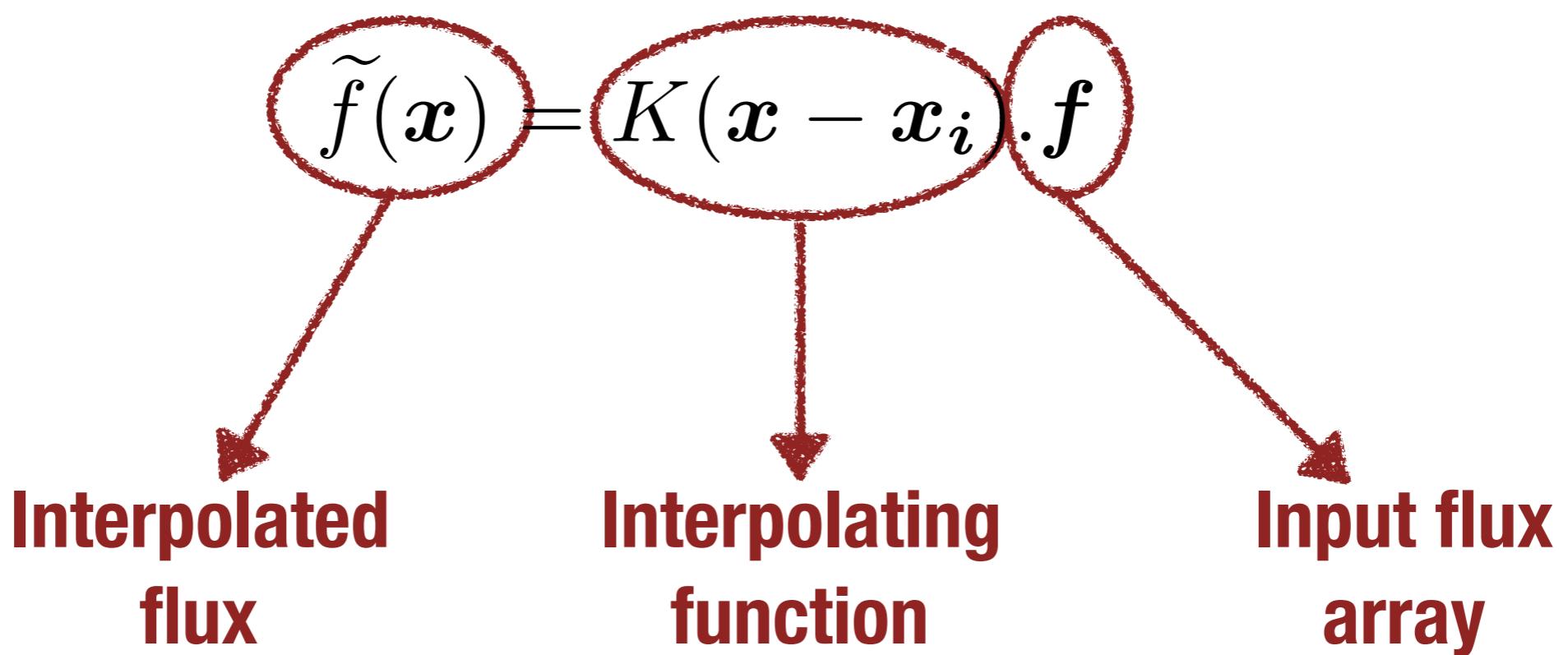
Bilinear

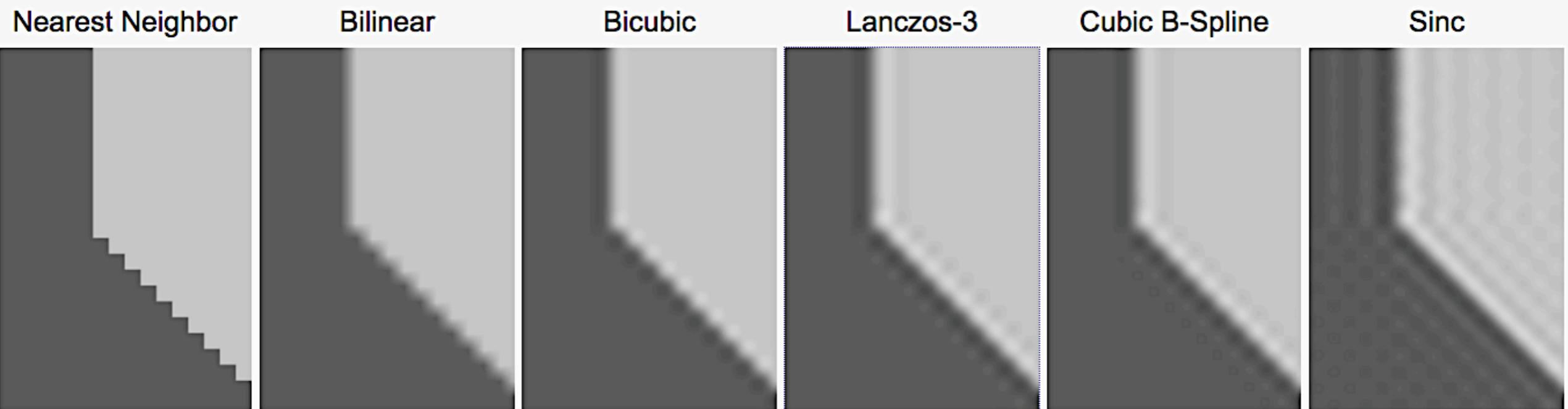
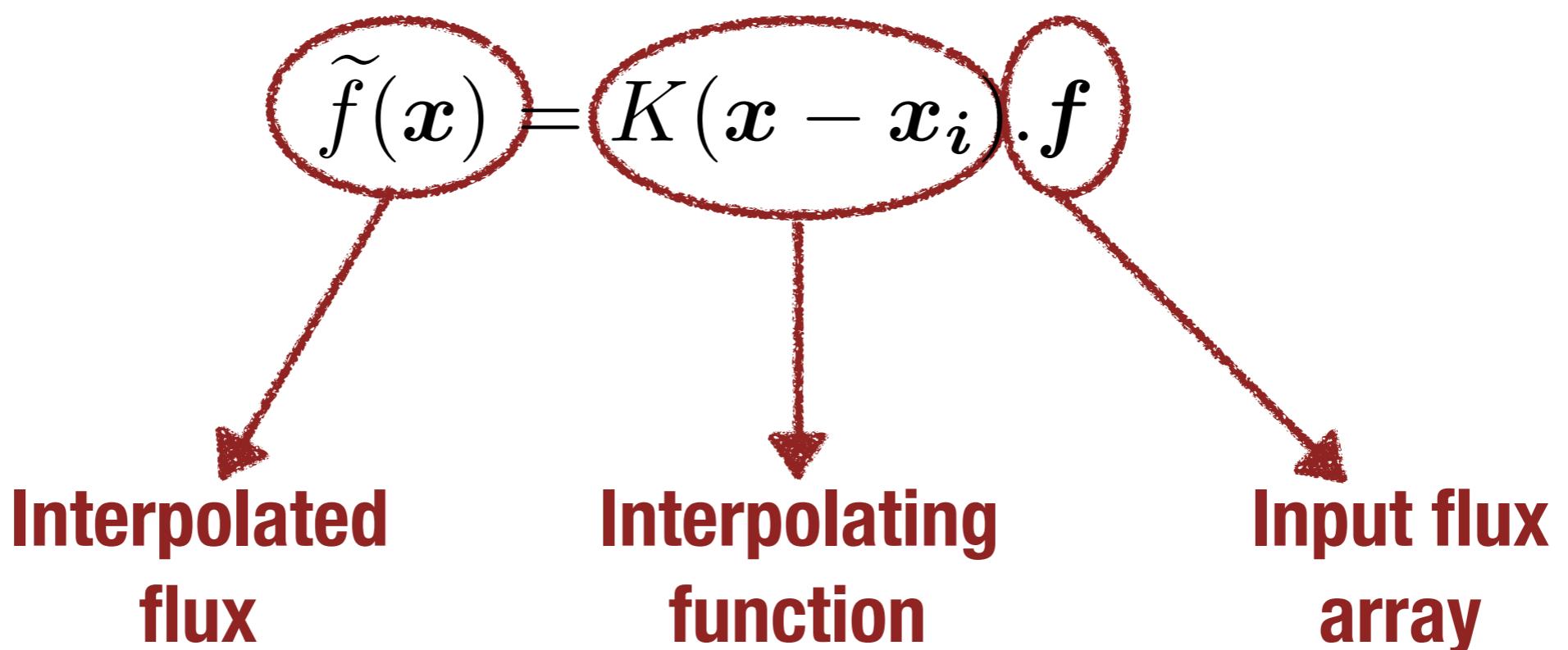


Bicubic

INTERPOLATION SCHEMES AND THEIR TRADEOFFS

$$\tilde{f}(\boldsymbol{x}) = K(\boldsymbol{x} - \boldsymbol{x}_i) \cdot \boldsymbol{f}$$





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

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

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

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

Ideal : $F_I \equiv \int_S f(x) d^2x$

The diagram illustrates the relationship between total flux and flux distribution. On the left, the text "Total flux" is written in red, with a blue arrow pointing towards the right. On the right, the text "Flux distribution" is written in red, with a blue arrow pointing towards the left. In the center, the mathematical definition of ideal flux is given: $F_I \equiv \int_S f(x) d^2x$. The term $f(x)$ is circled in red, and the integral symbol \int_S is also circled in red, indicating that these are the key components being highlighted or defined.

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

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

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QE

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

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

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

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Area of sky per pixel

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

Flat ↗

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

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Change of coordinates
- i.e. reprojection

**Jacobian of
transformation**

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

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Change to sky coordinates. Valid if pixel scale varies slowly

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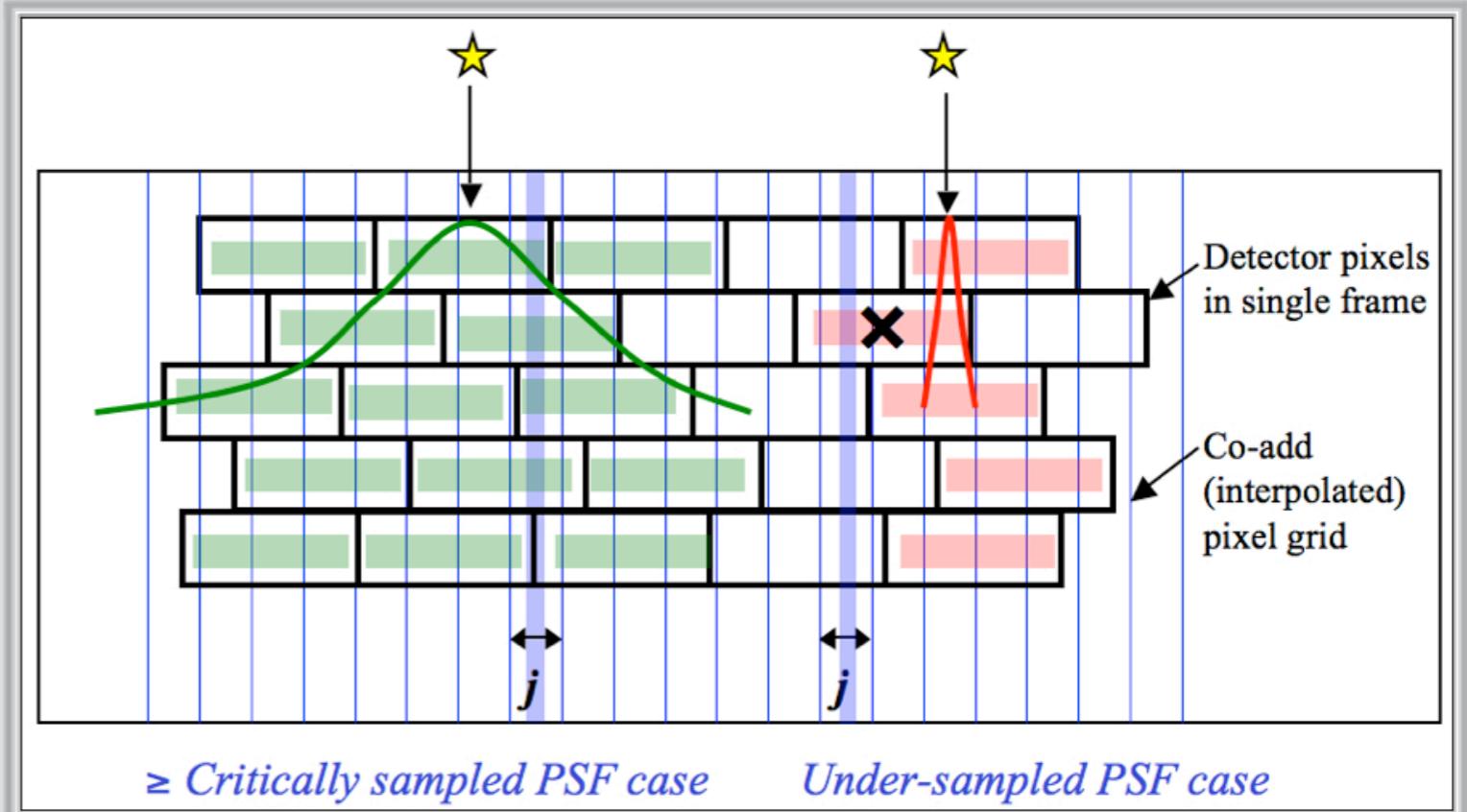
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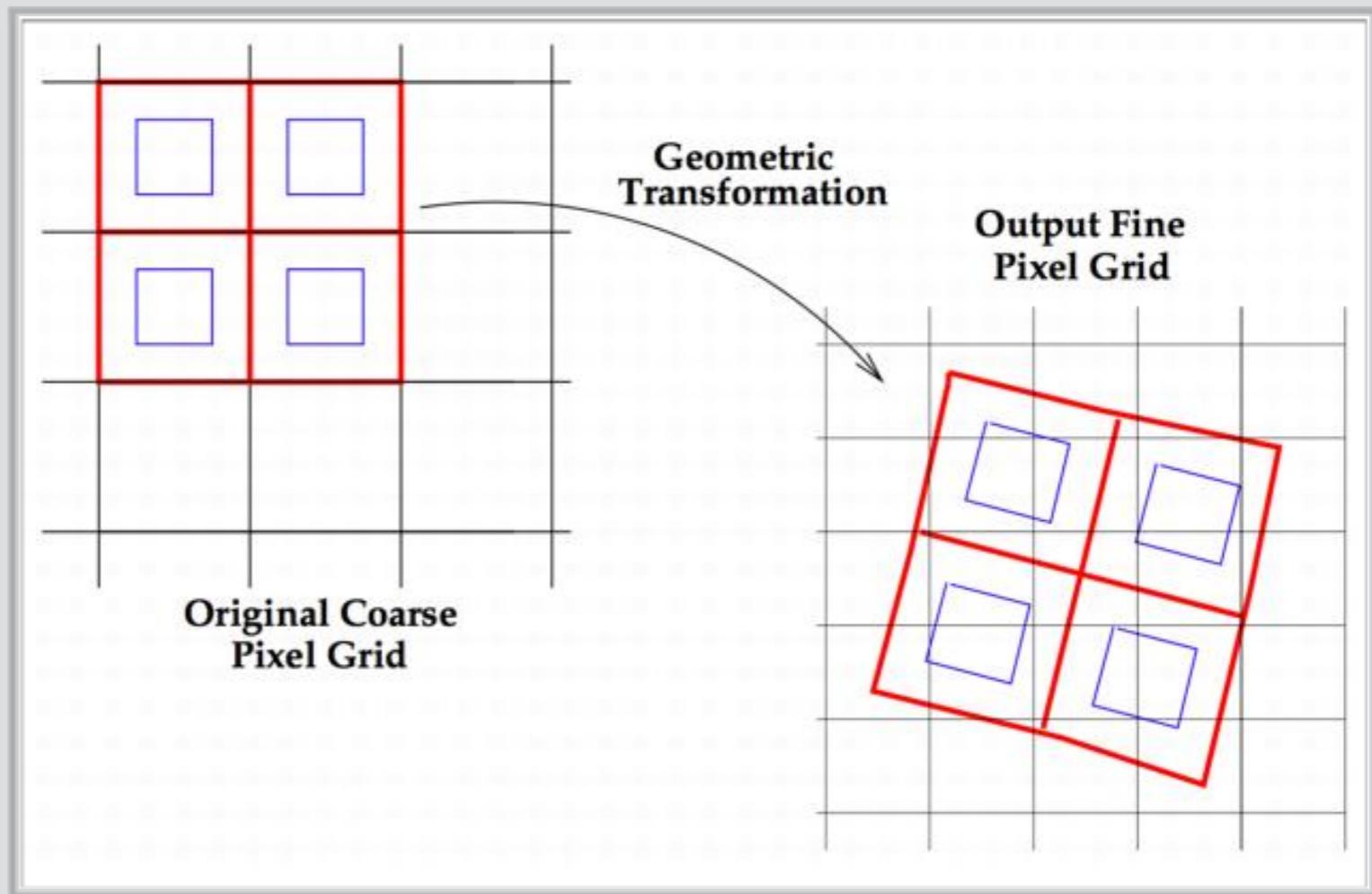
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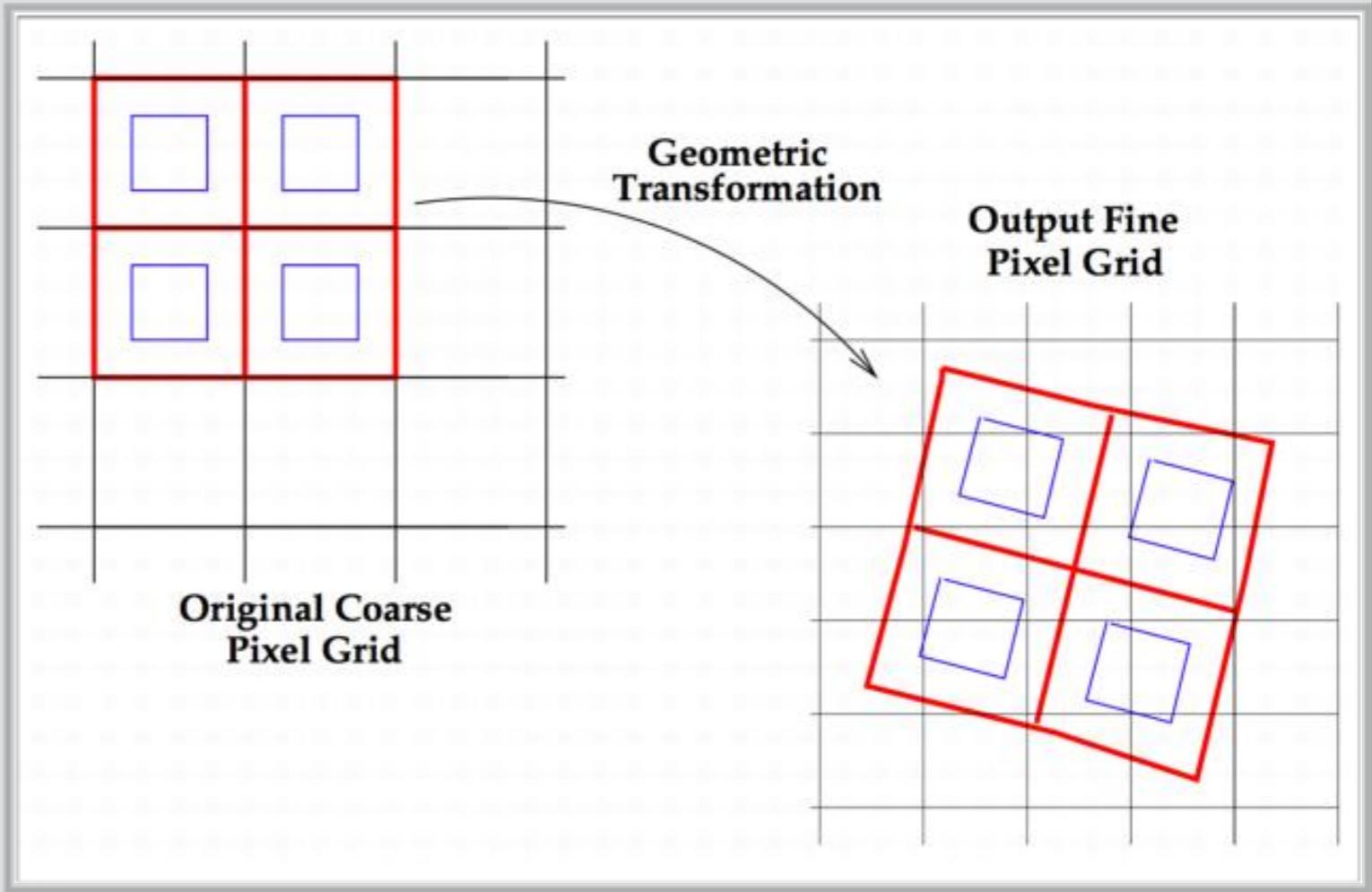
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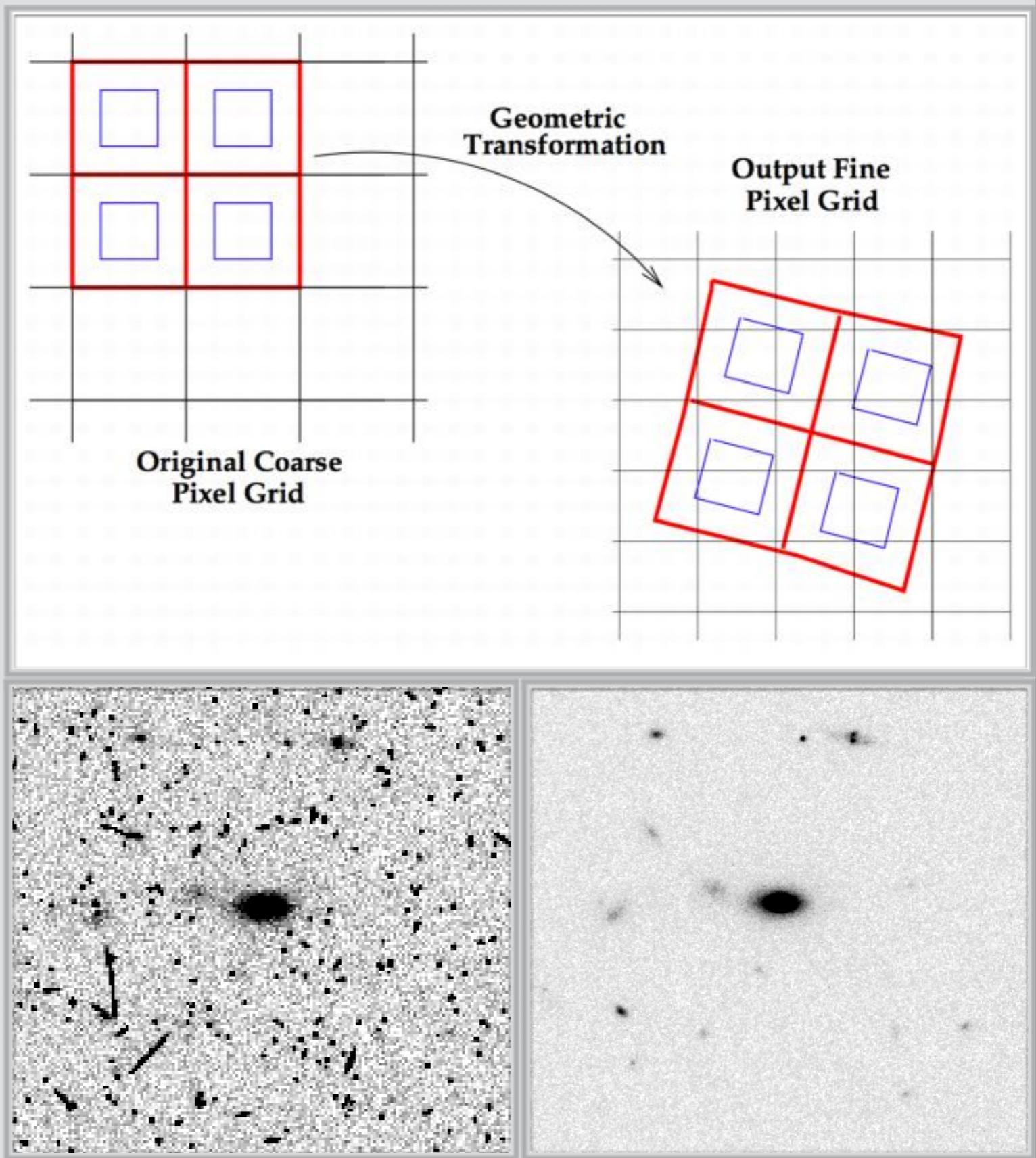
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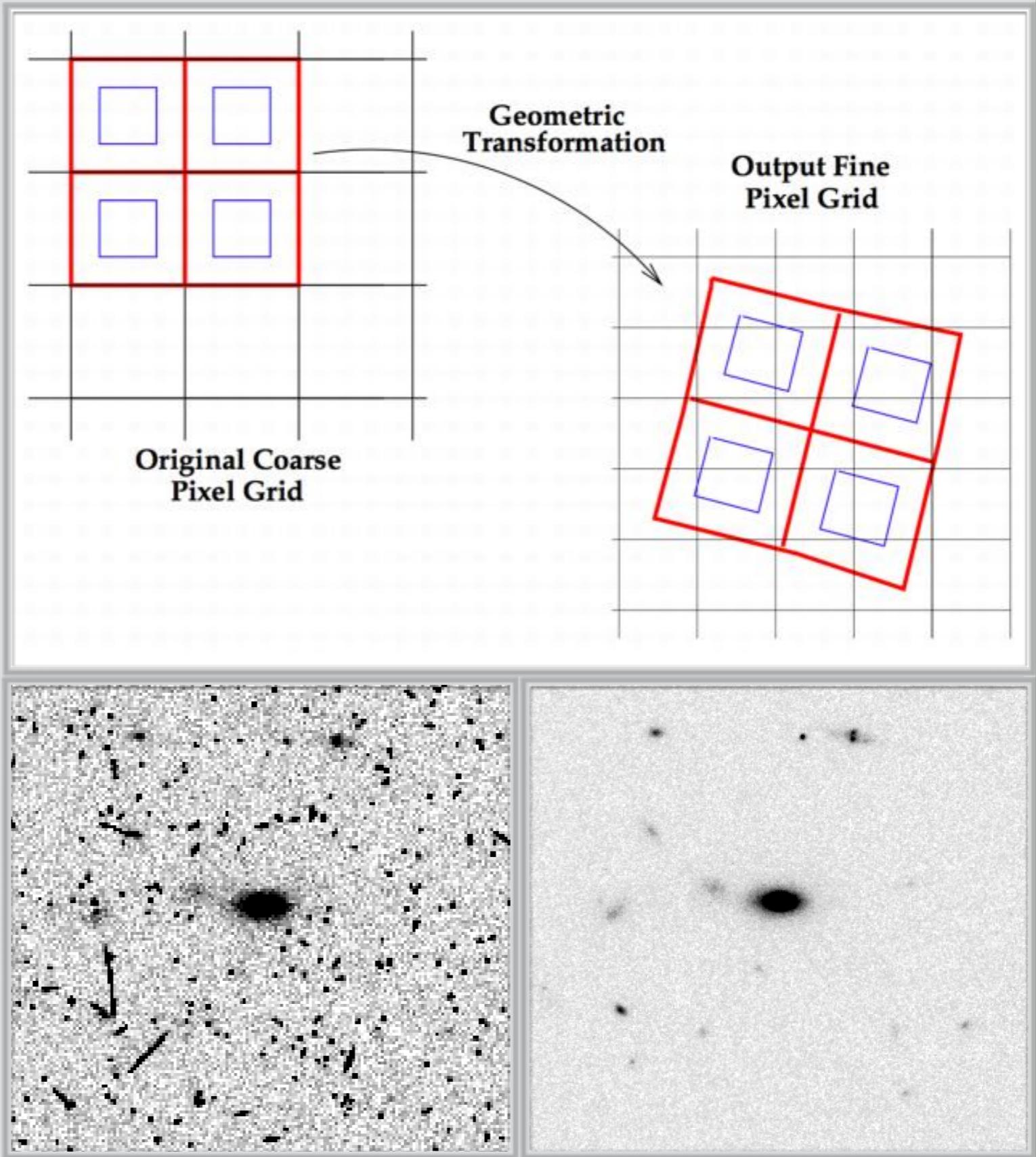
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From WISE, STScI's Astrodrizzle Handbook & Andy Fruchter (STScI) in order of appearance

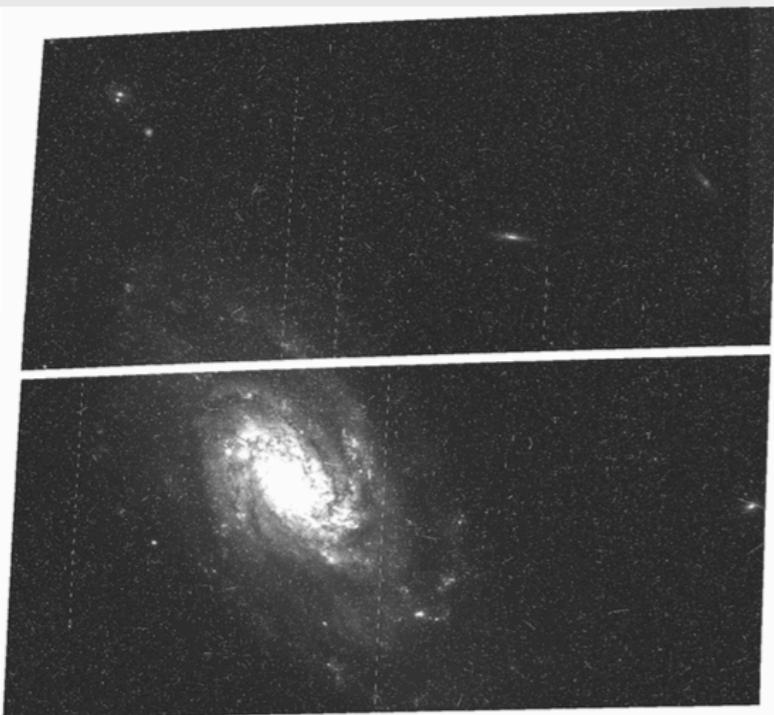
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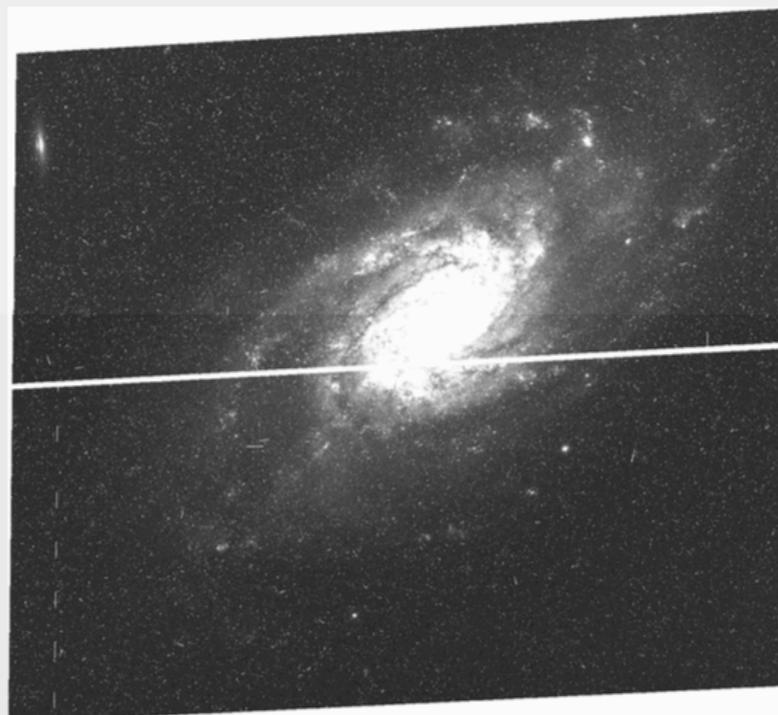


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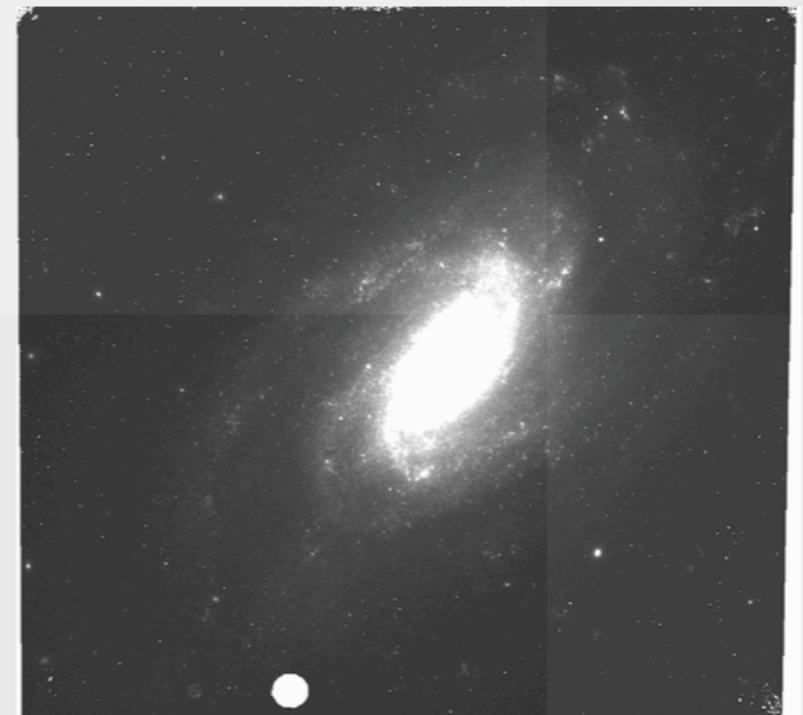
SINGLE DRIZZLED IMAGES



ACS/WFC F555W (0.049")

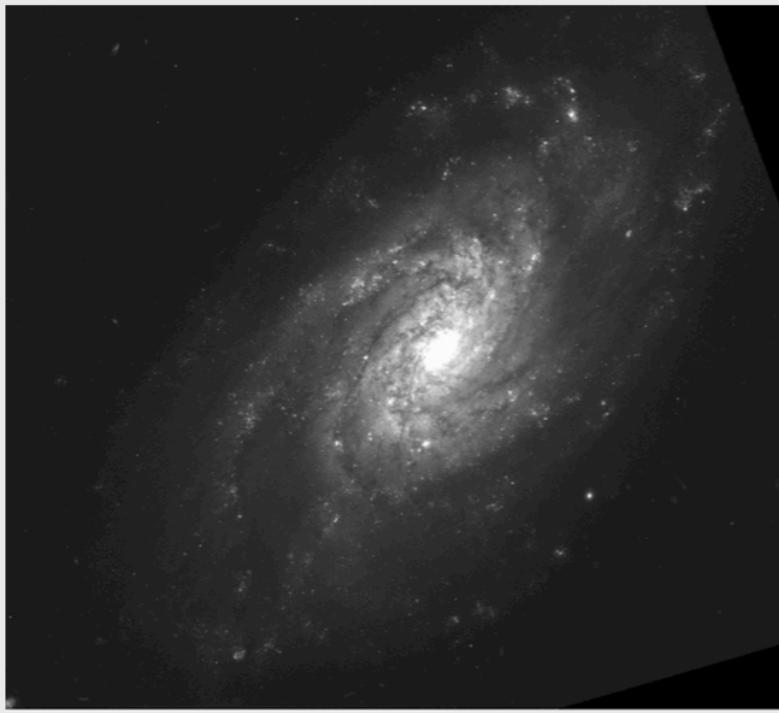


WFC3/UVIS F555W (0.039")

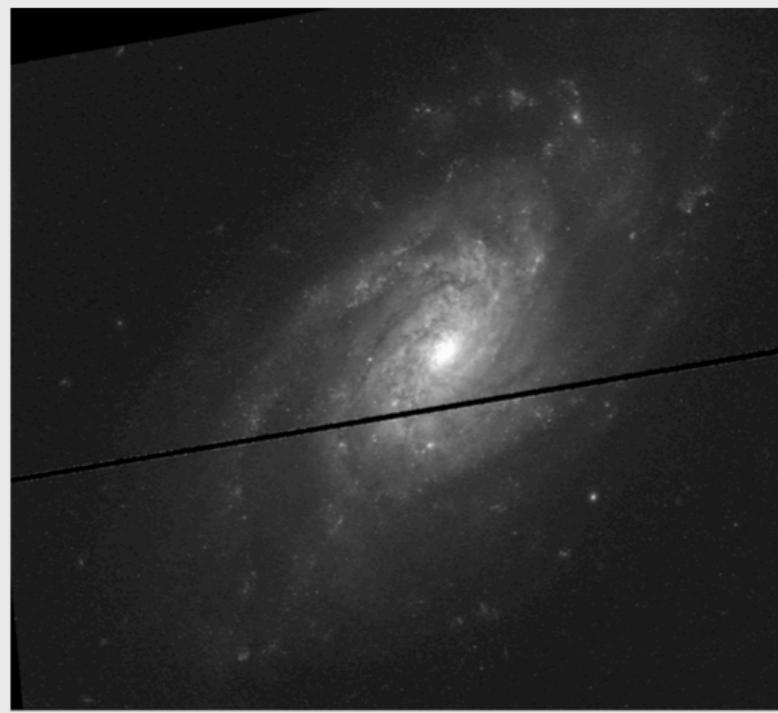


WFC3/IR F160W (0.128")

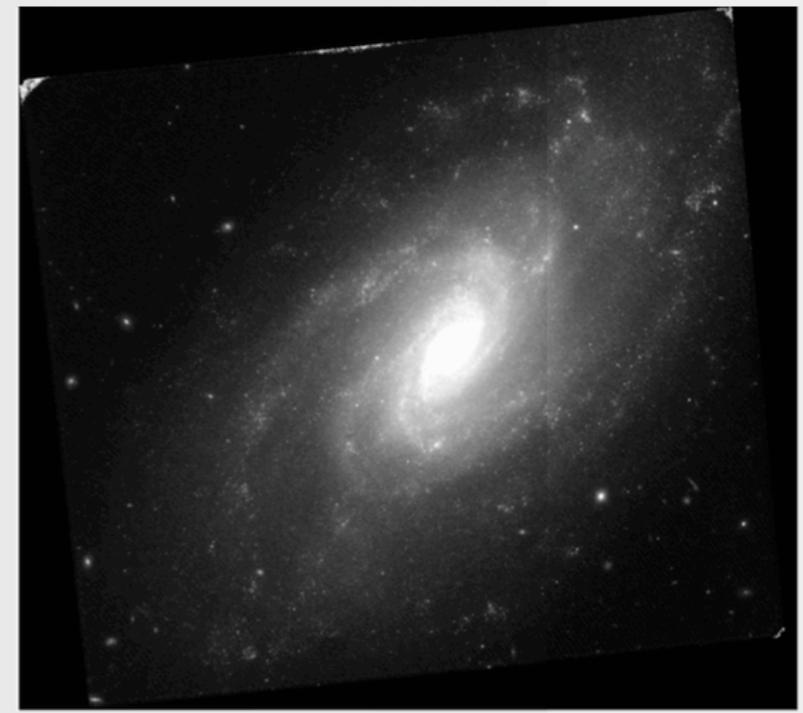
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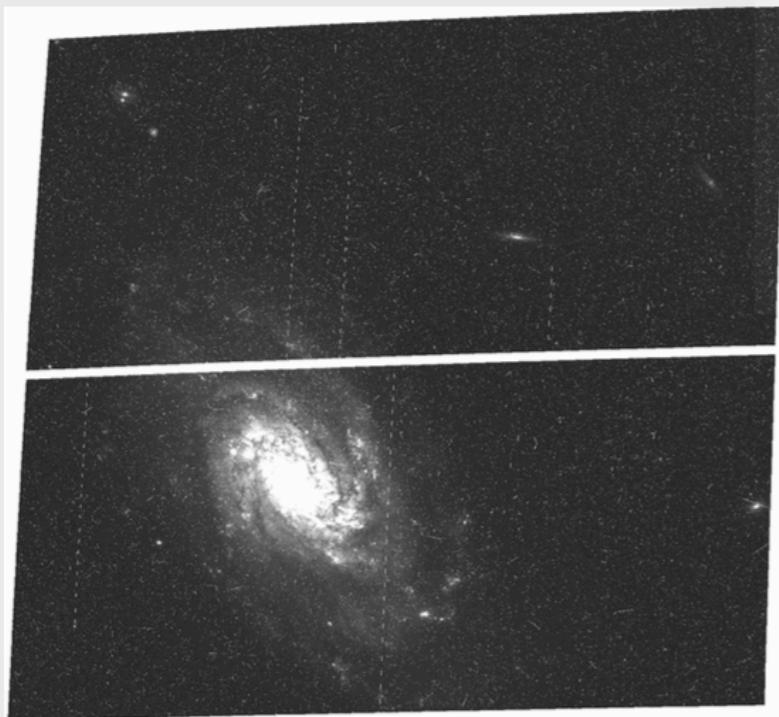


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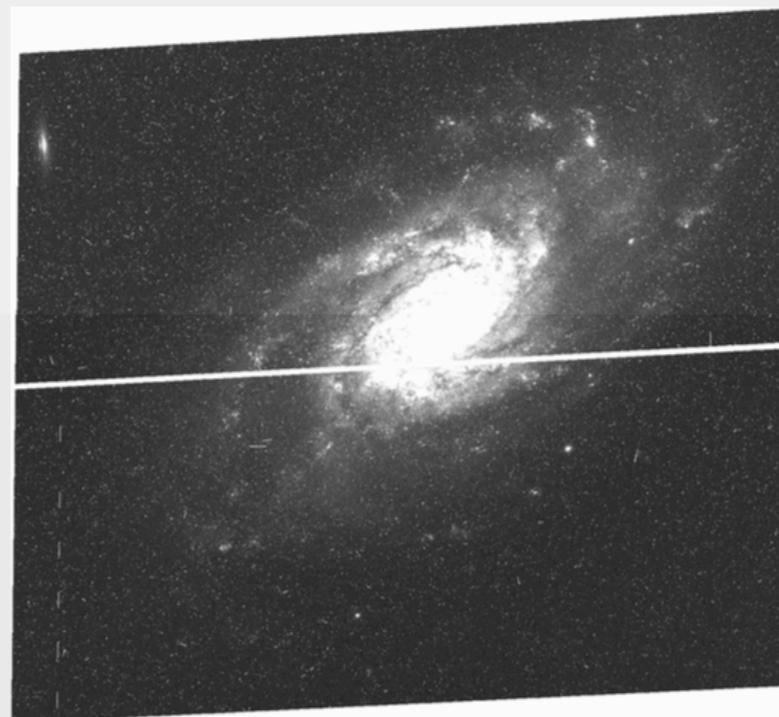


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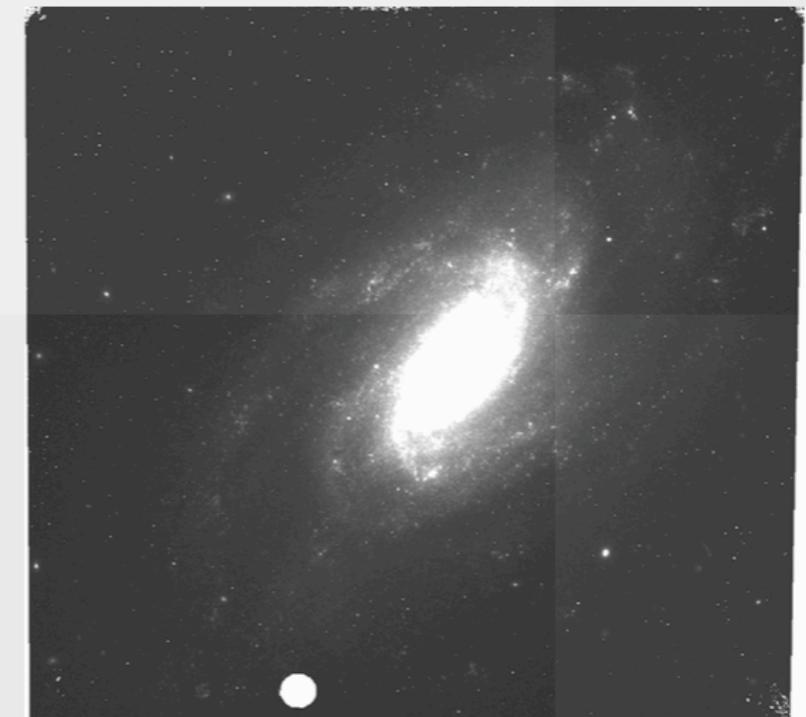
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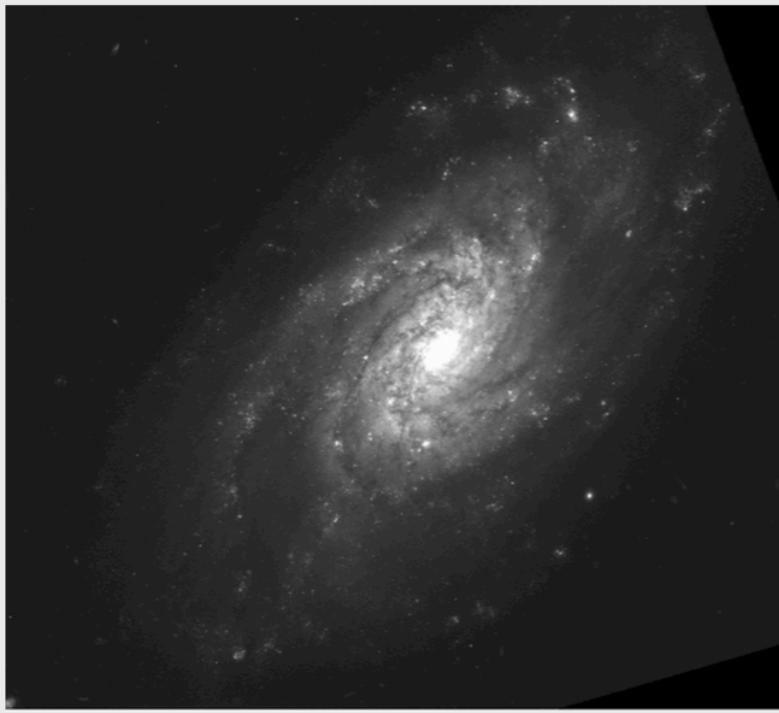


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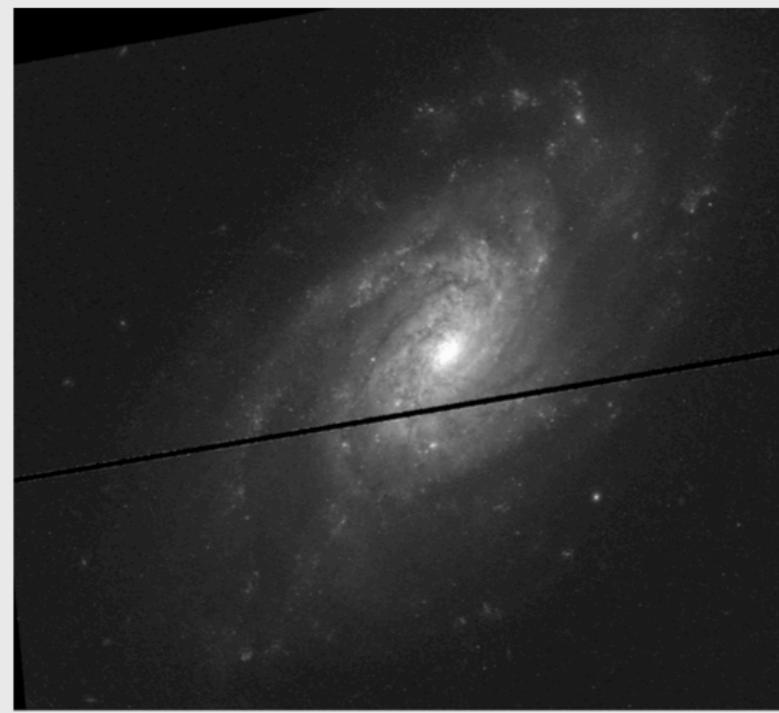


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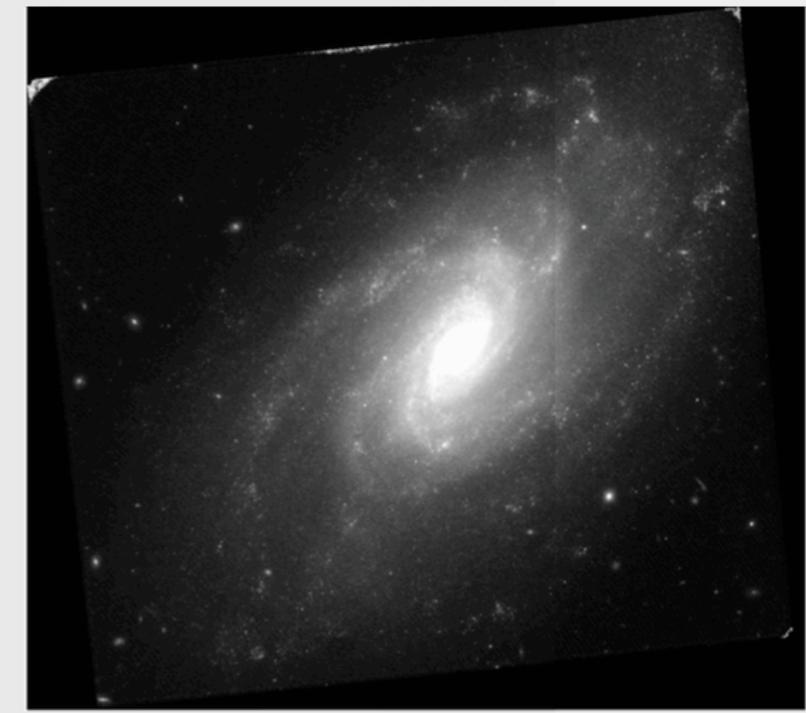
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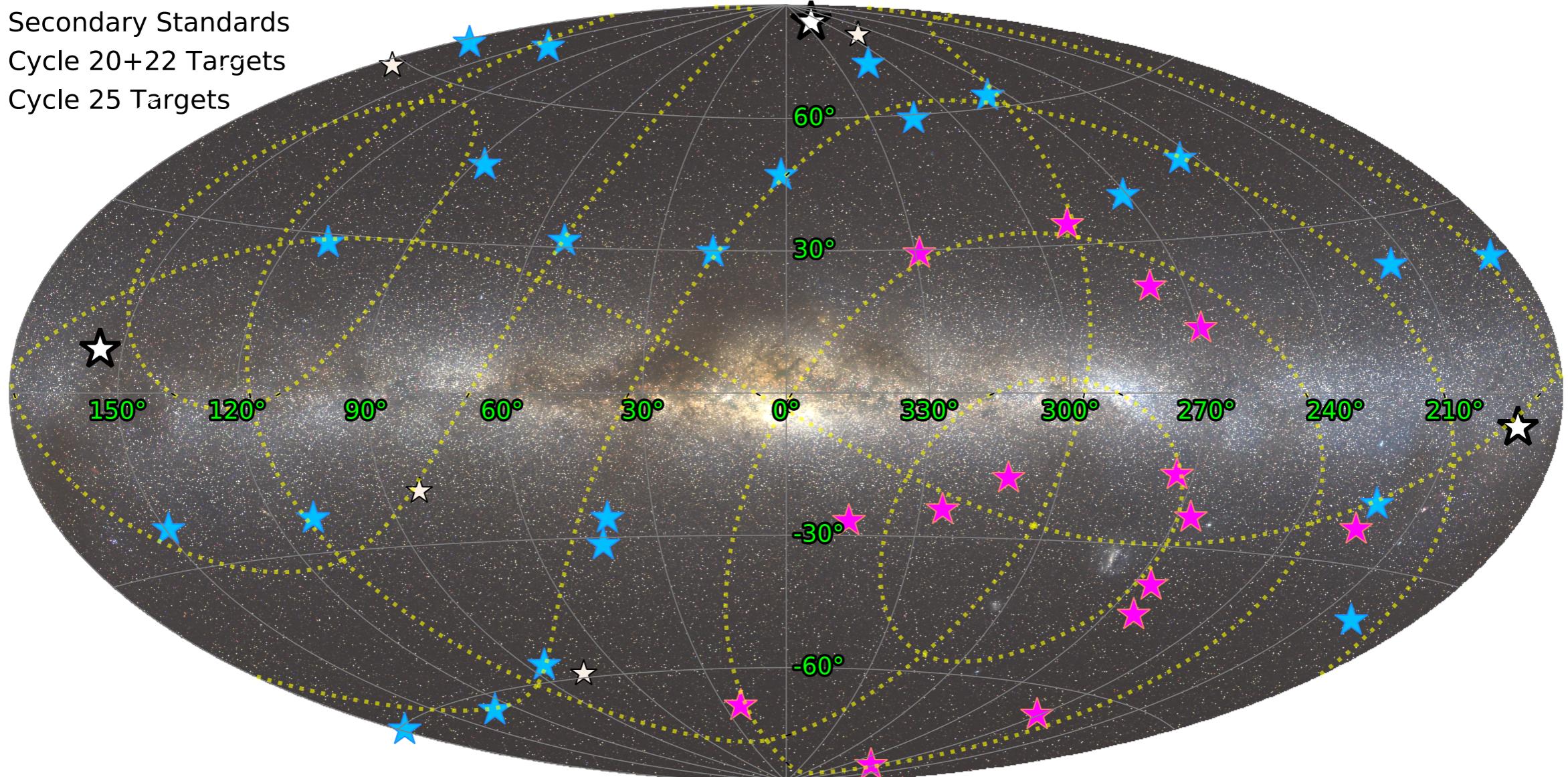
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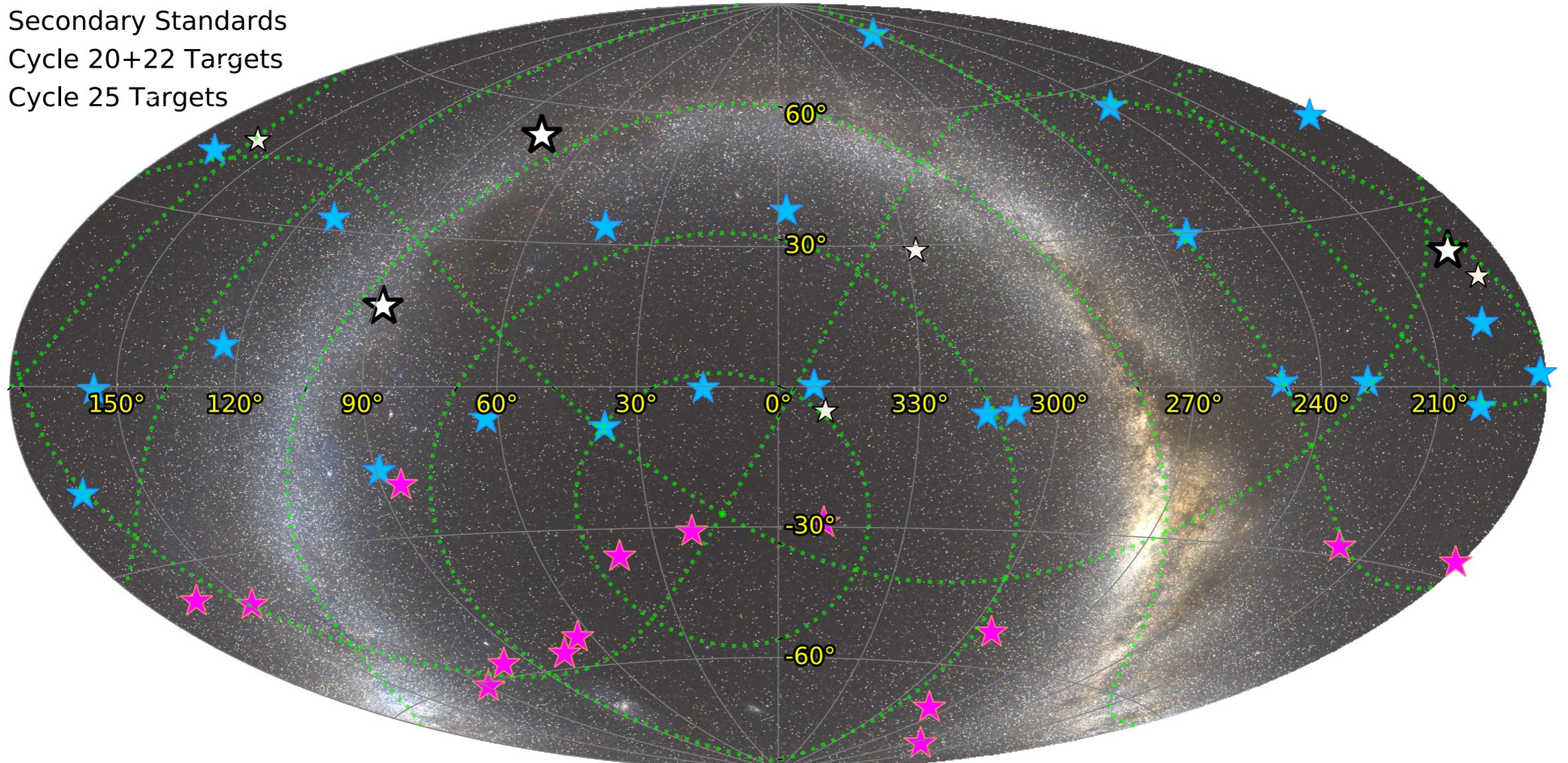
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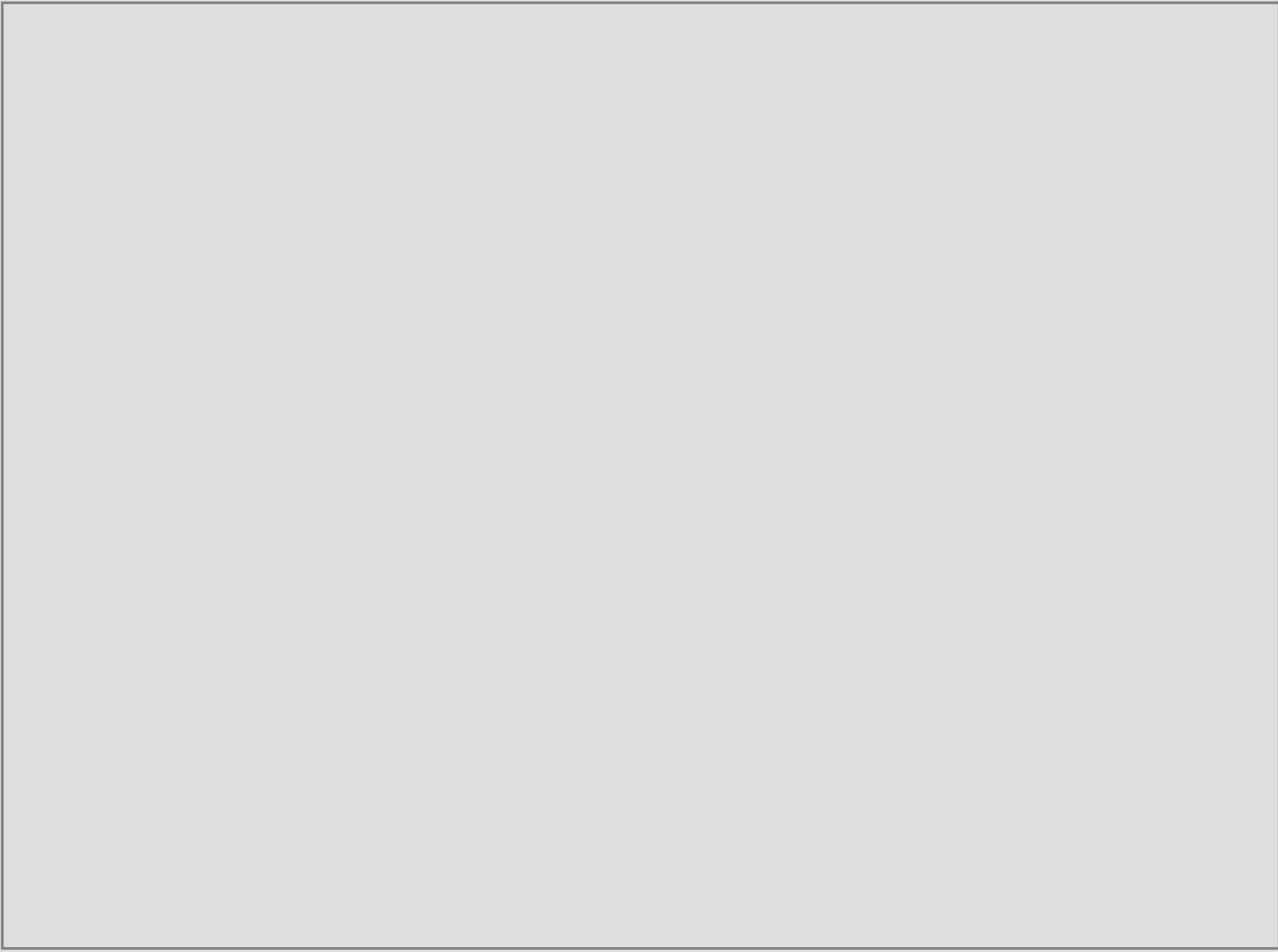
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PSF CONVOLUTION AND IMAGE SUBTRACTION



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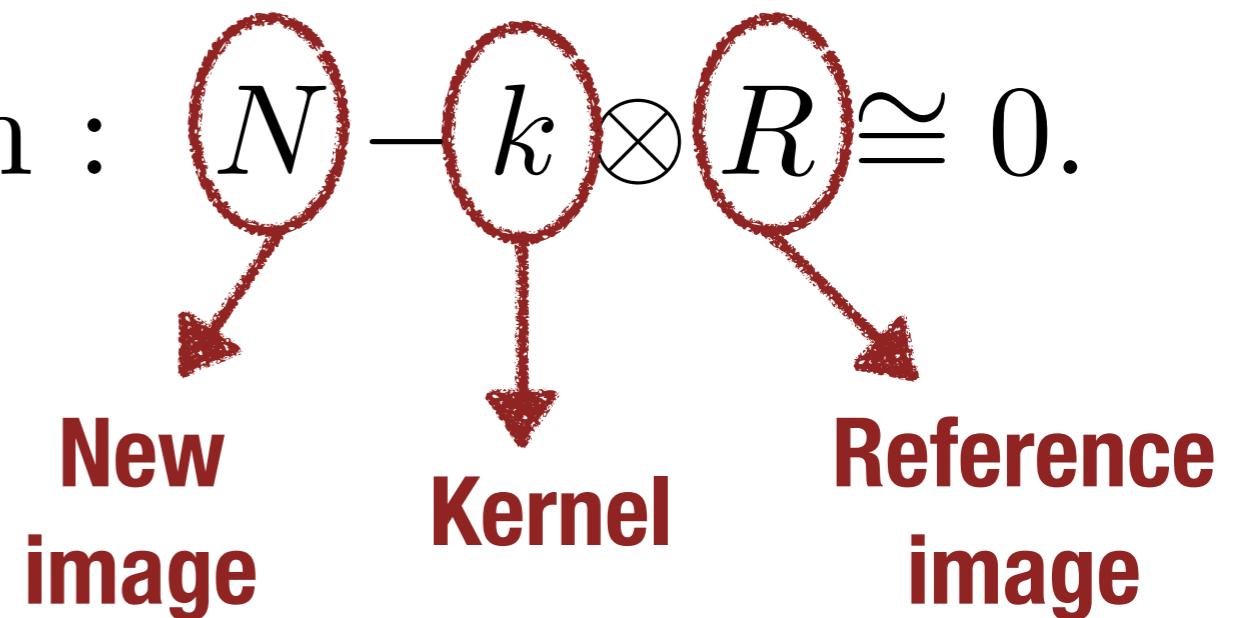
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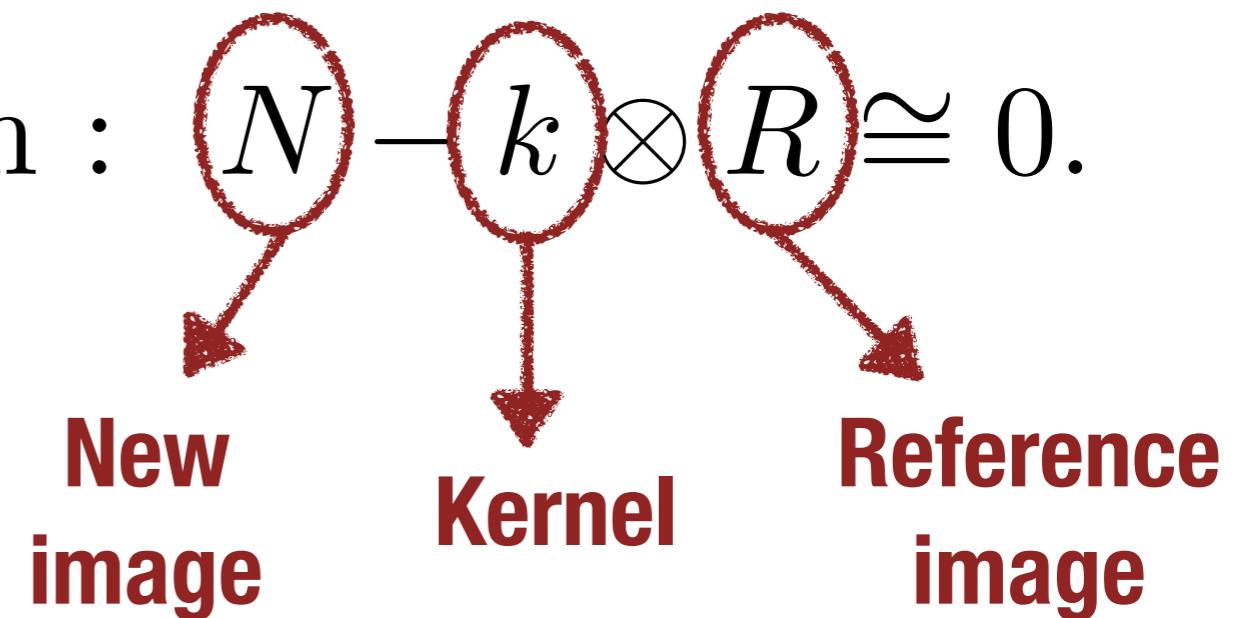
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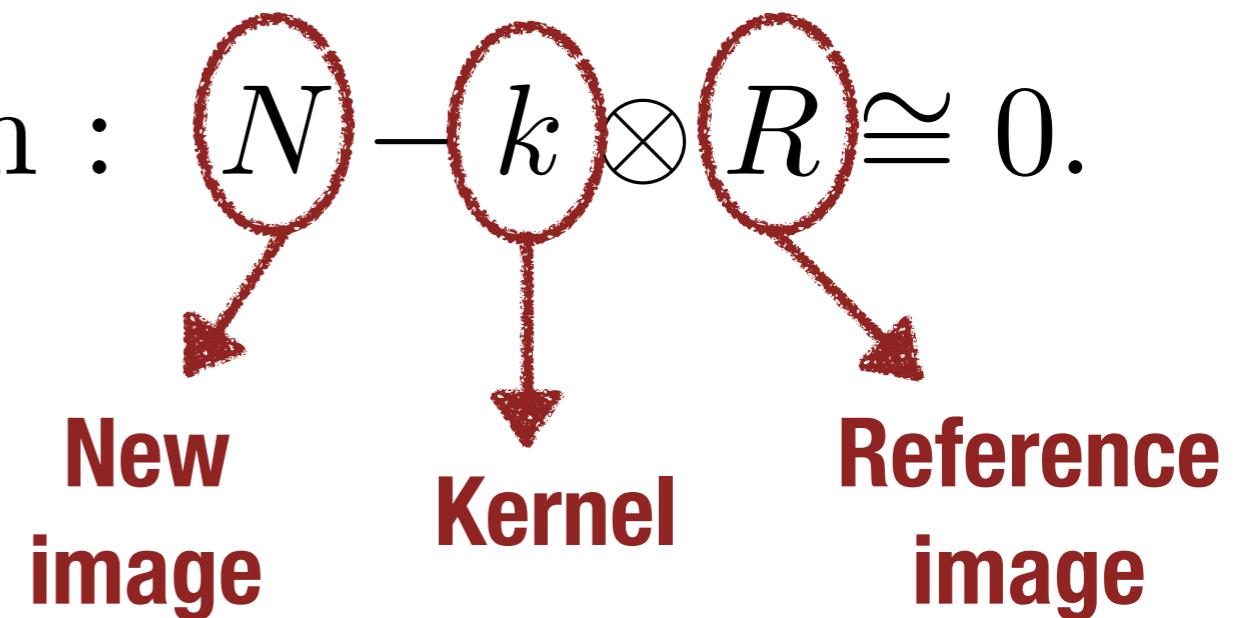


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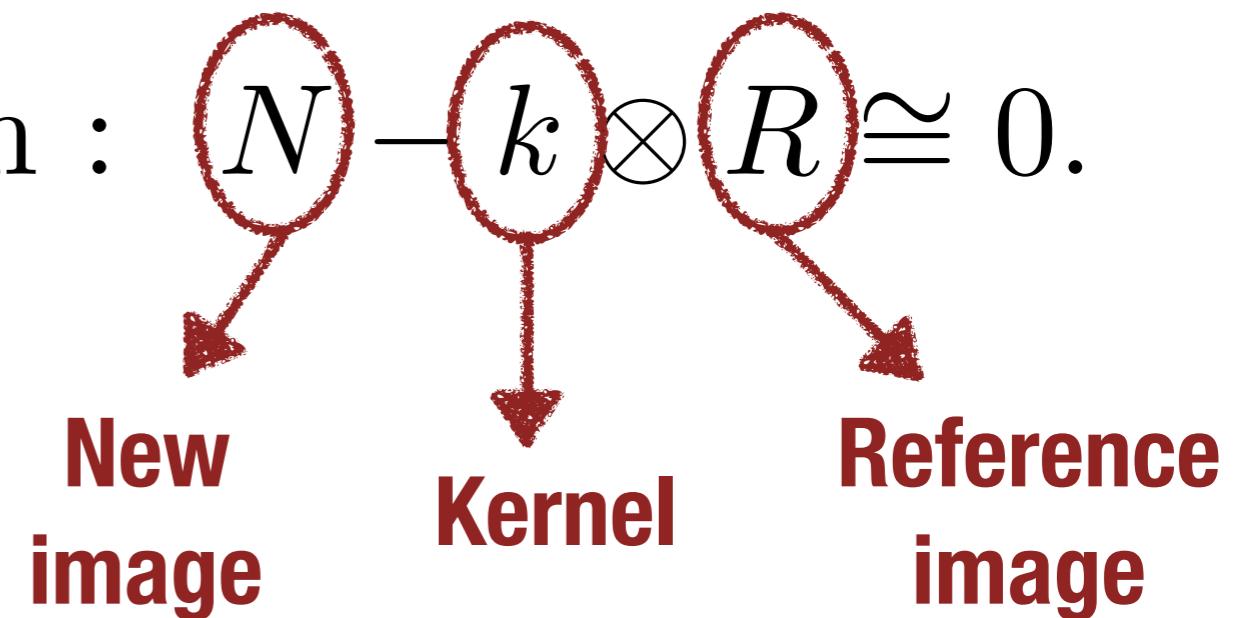
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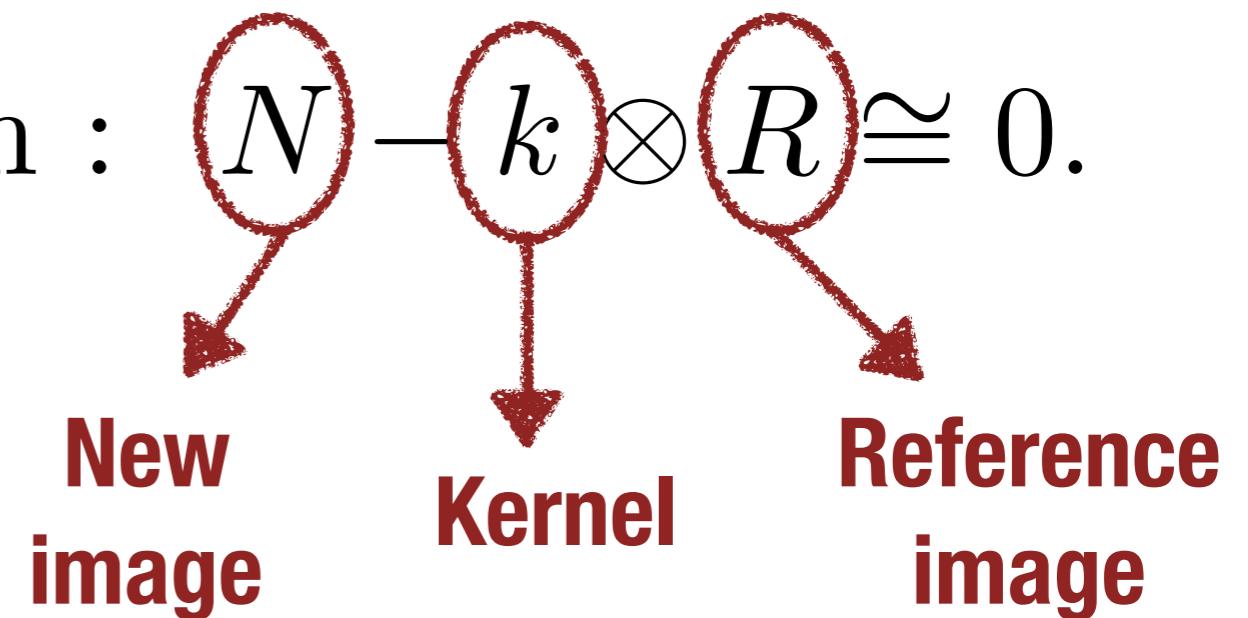
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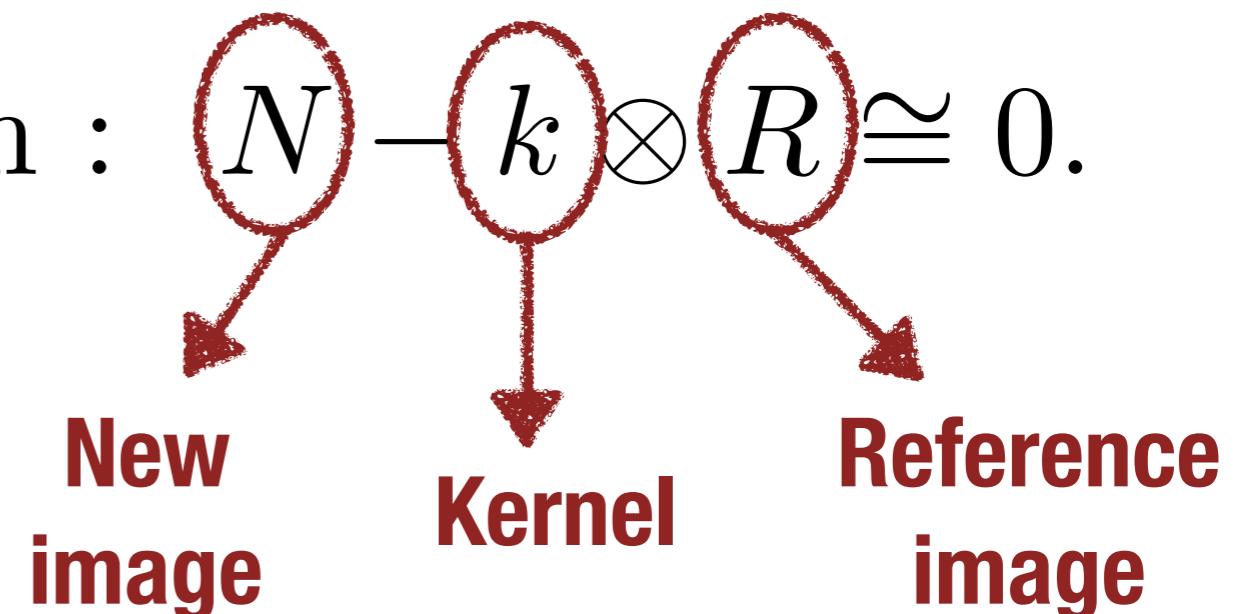
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The ZOGY Formulation :

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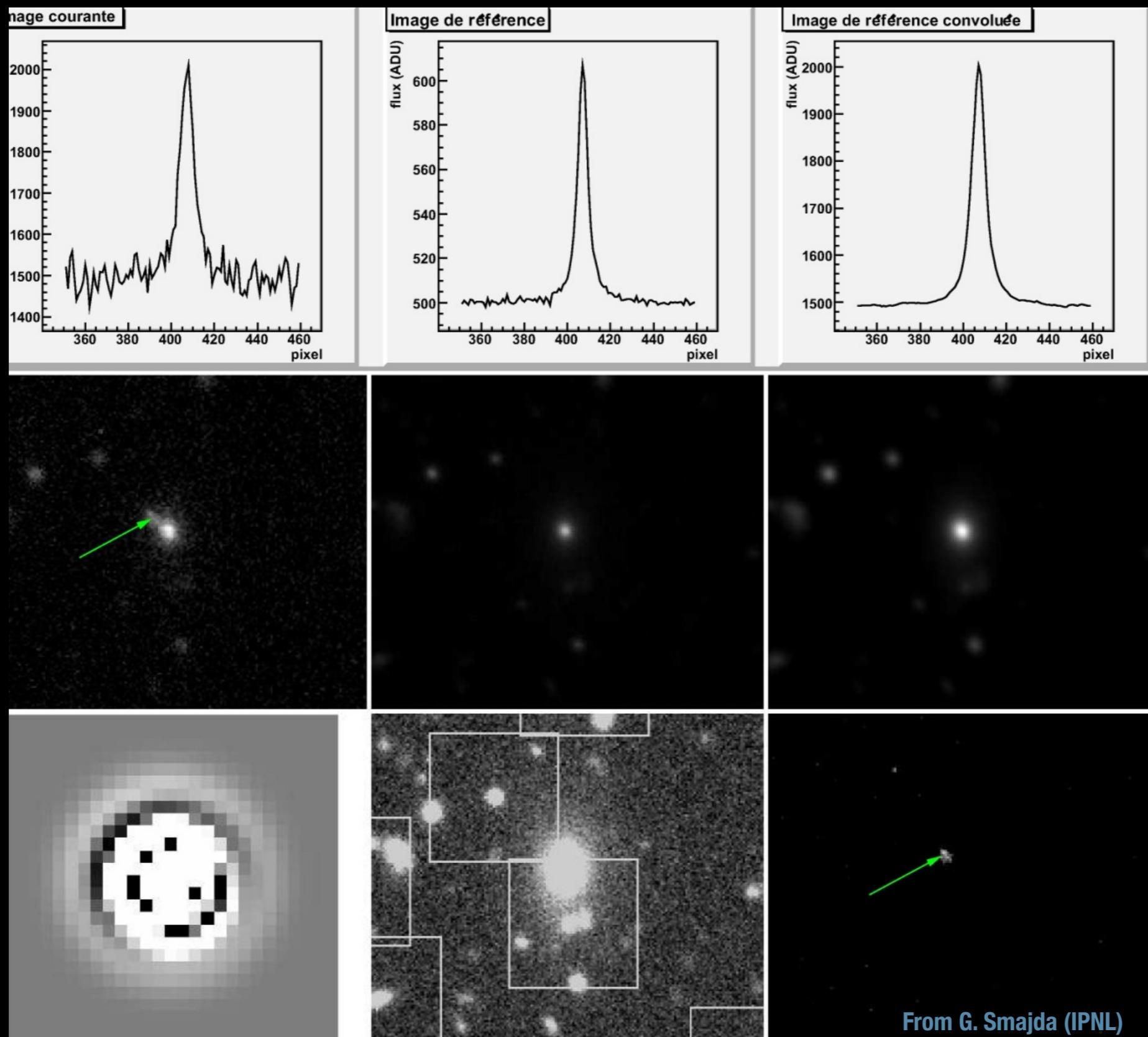
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- Extra terms decorrelate output - remember than resampling still introduces correlations



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/

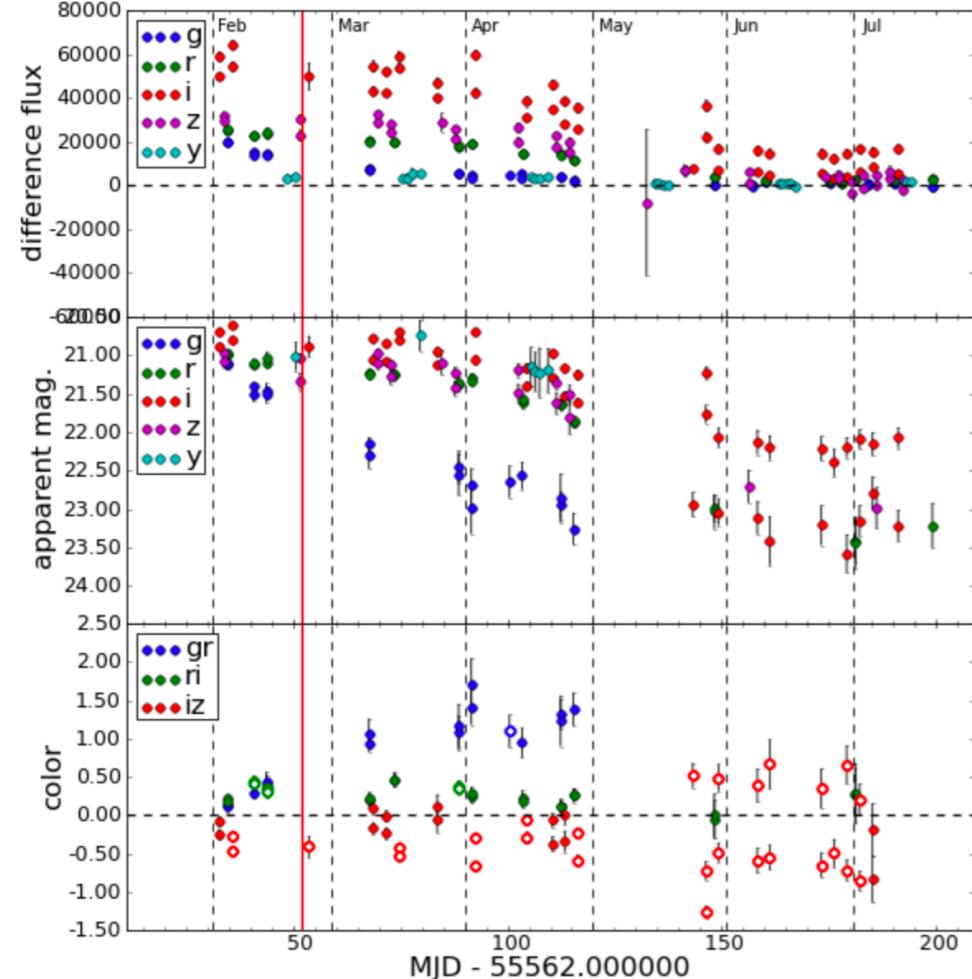
HTTP://TELESCOPES.RC.FAS.HARVARD.EDU/PS1/ALERTS2010/2011-
B-130327/2011-B-130327.HTML

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

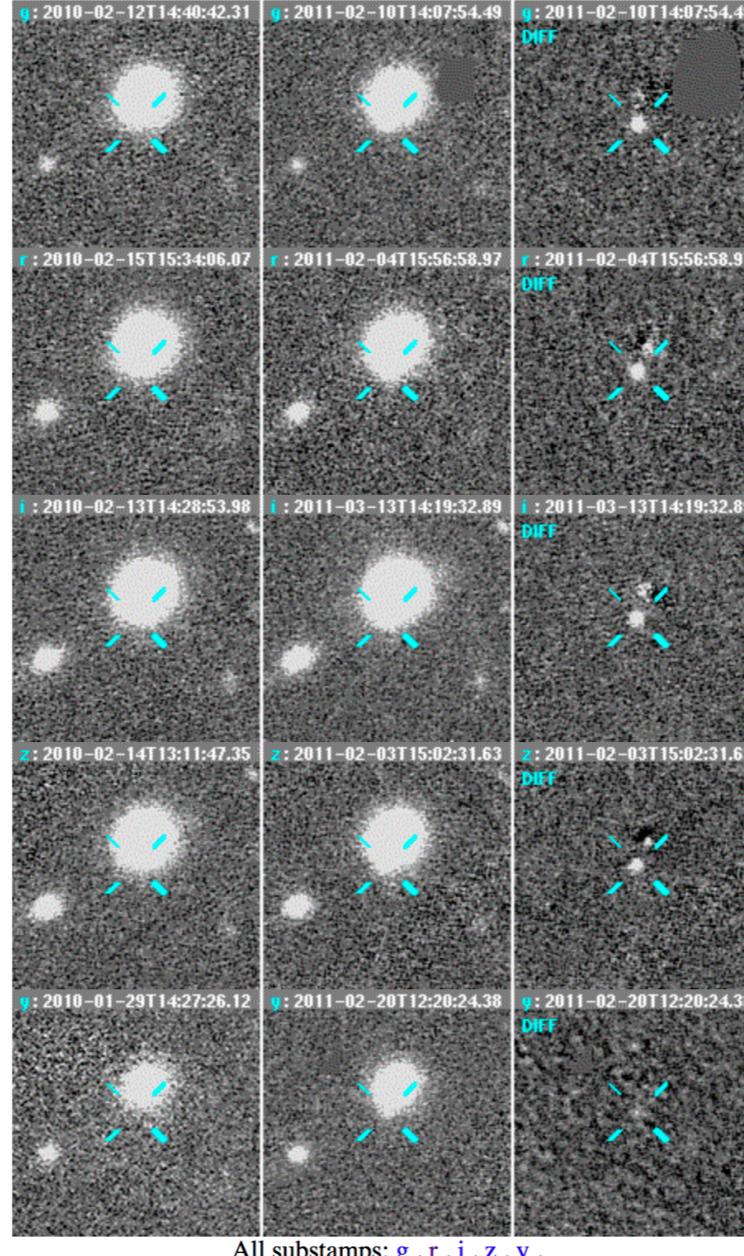
PS1-11fl (2011-B-130327)

RA Dec (J2000)	Field/Cut/Disc. Date	status	spec: specrprio/queue,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](#)



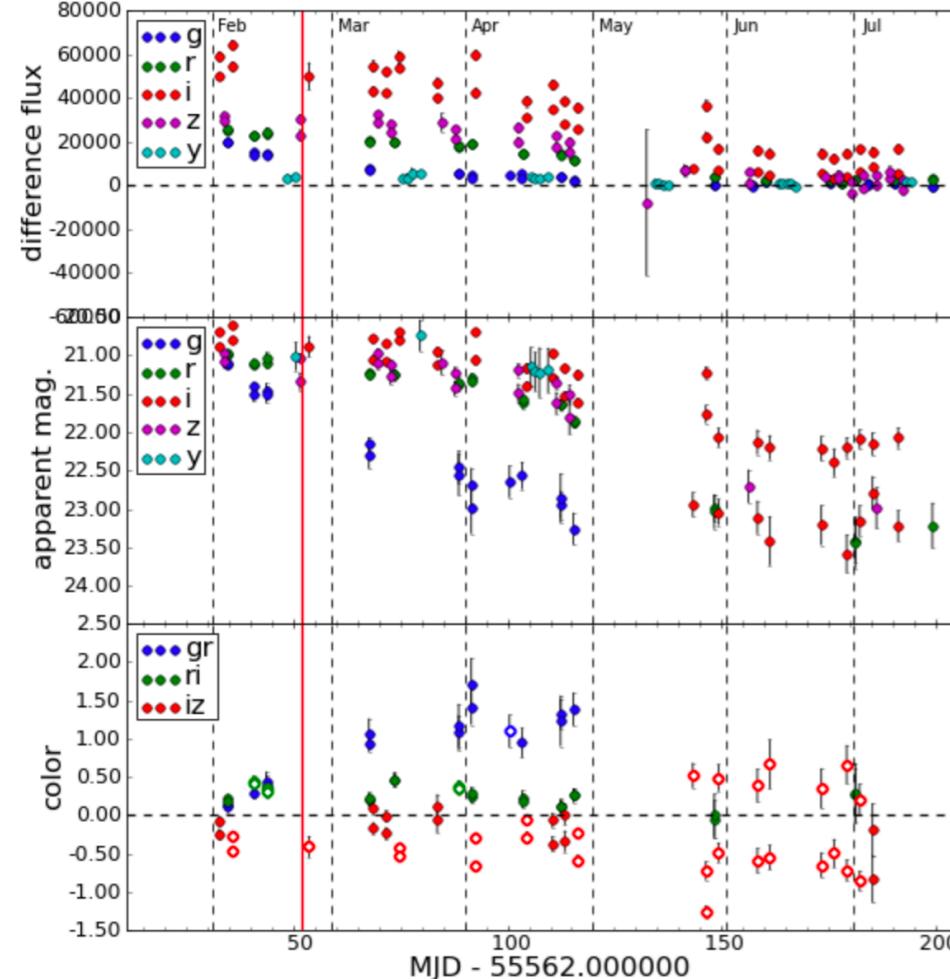
Extra lightcurve plots: [mag lc zoomed](#), [all t lc](#)



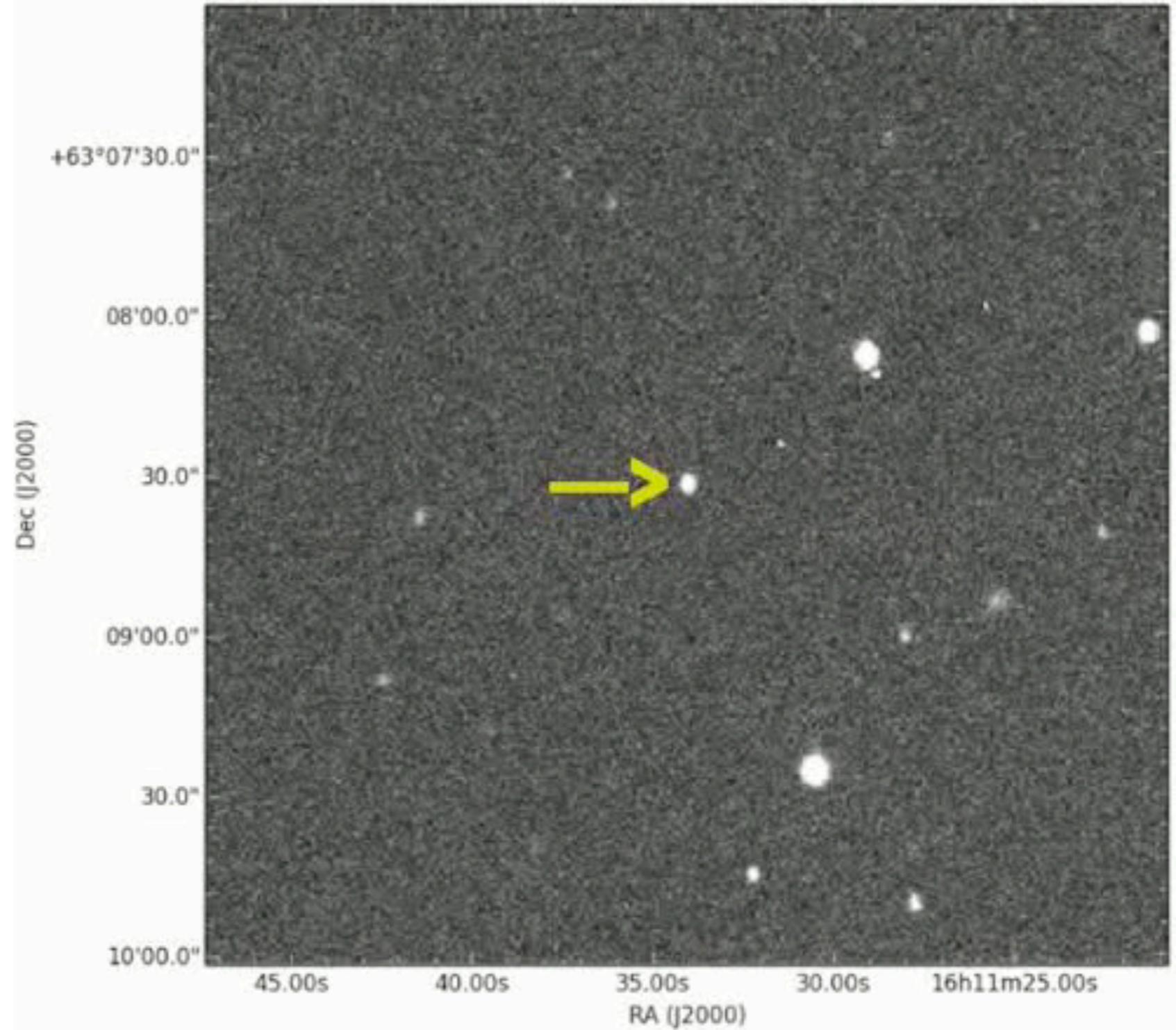
PS1-11fl (2011-B-130327)

RA Dec (J2000)	Field/Cut/Disc. Date	status	spec: specprop/queue, 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: -										

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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)

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 - * 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)

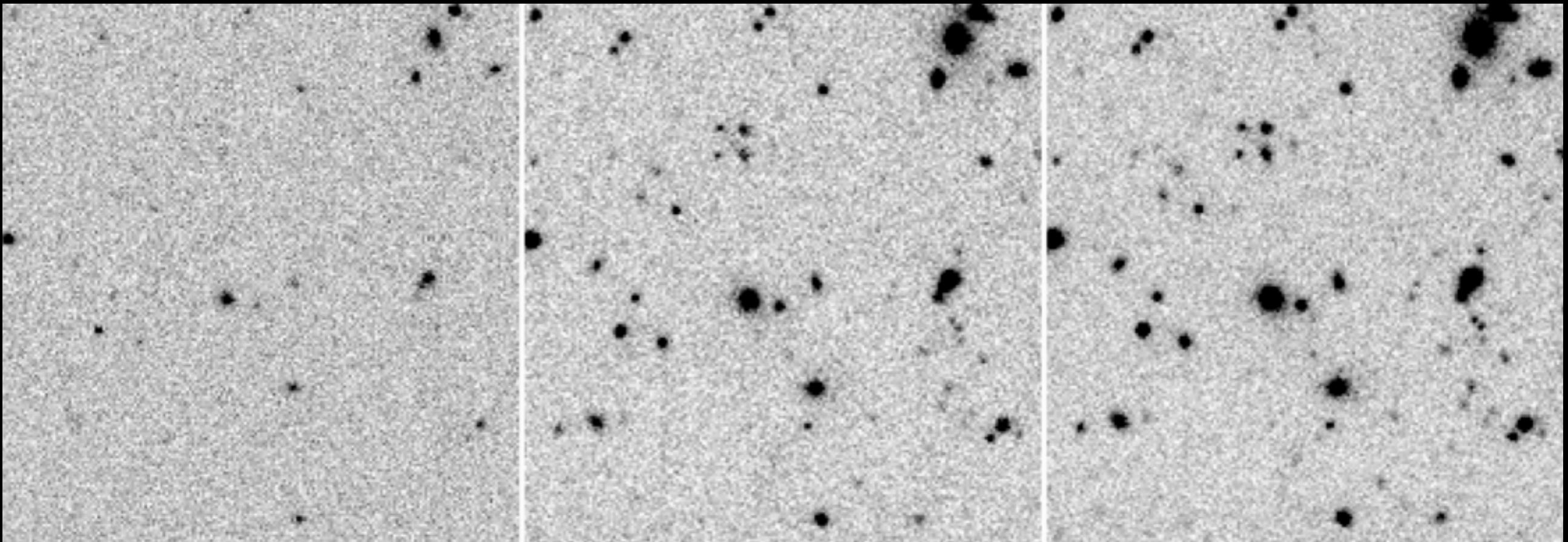
IMAGE STACKING

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: Most common procedure - typically ad hoc weights
- * Clipped average: Above + iterated sigma-clipping to reject outliers, but not valid if PSF is different
- * “Chi-squared” images: “Optimal” for source detection but not linear for flux measurement.

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

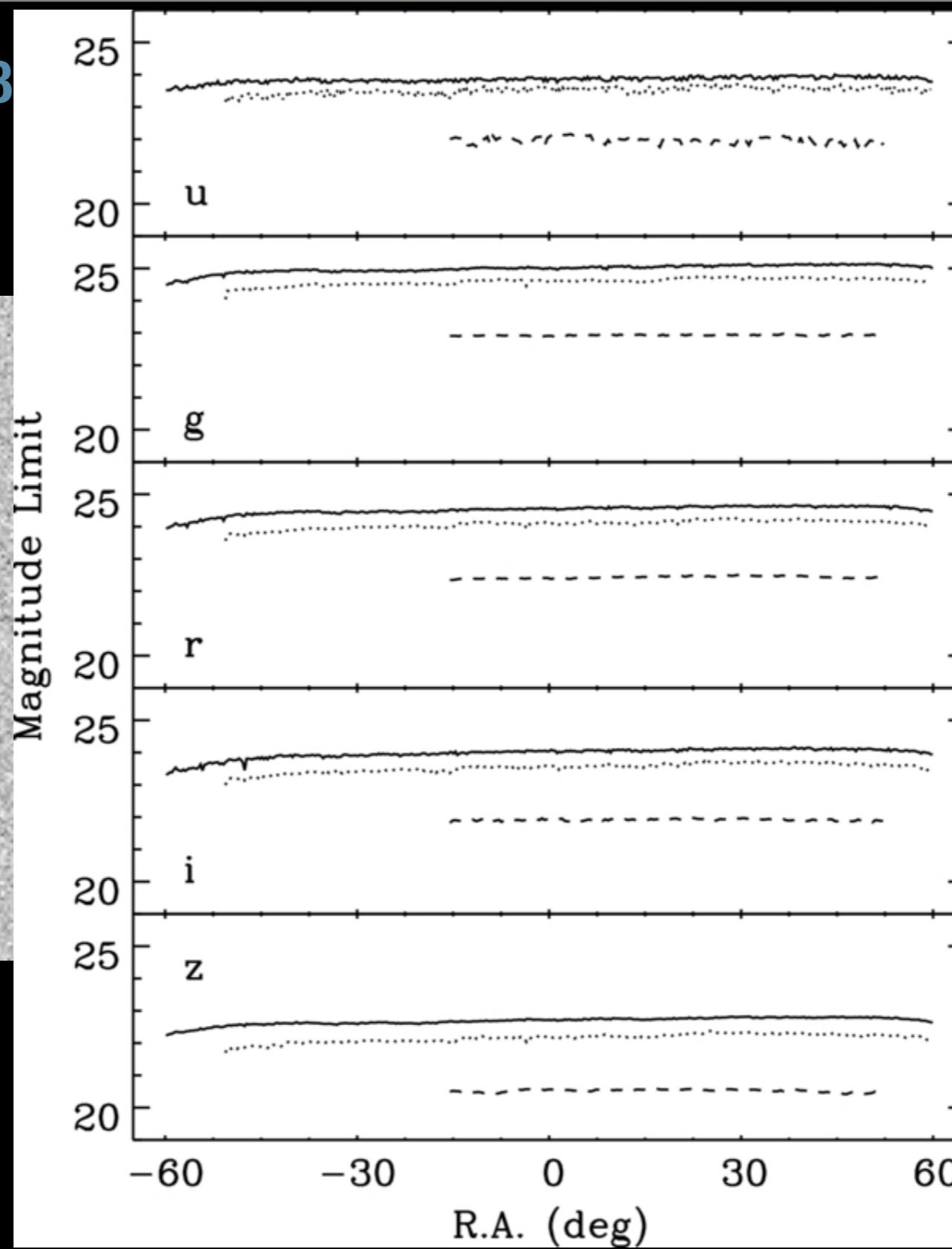
From Jian et al., 2014



**WEIGHTING CHOICE CAN HAVE STRIKING EFFECTS ON FINAL STACK
SIMILAR PSF SIZE, VISIBLY DIFFERENT DEPTHS AND BACKGROUND NOISE PROPERTIES**

SDSS Stripe 8

and Jian et al.,



WEIGHTING CHOICE CAN HAVE STRIKING EFFECTS ON FINAL STACK
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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)

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

- * **Swarz, 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>
- * **The HyperSuprime Cam pipeline:**
<http://hsc.mtk.nao.ac.jp/ssp/pipeline/>

PEANUTS

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SEE ALL
THOSE STARS,
LINUS?

THERE'S MILLIONS AND MILLIONS
AND MILLIONS OF THEM!

WHAT DO WE NEED
SO MANY FOR?

SCHULZ 9-3

“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