



Data Reduction Workshop ***Imaging & Photometry***

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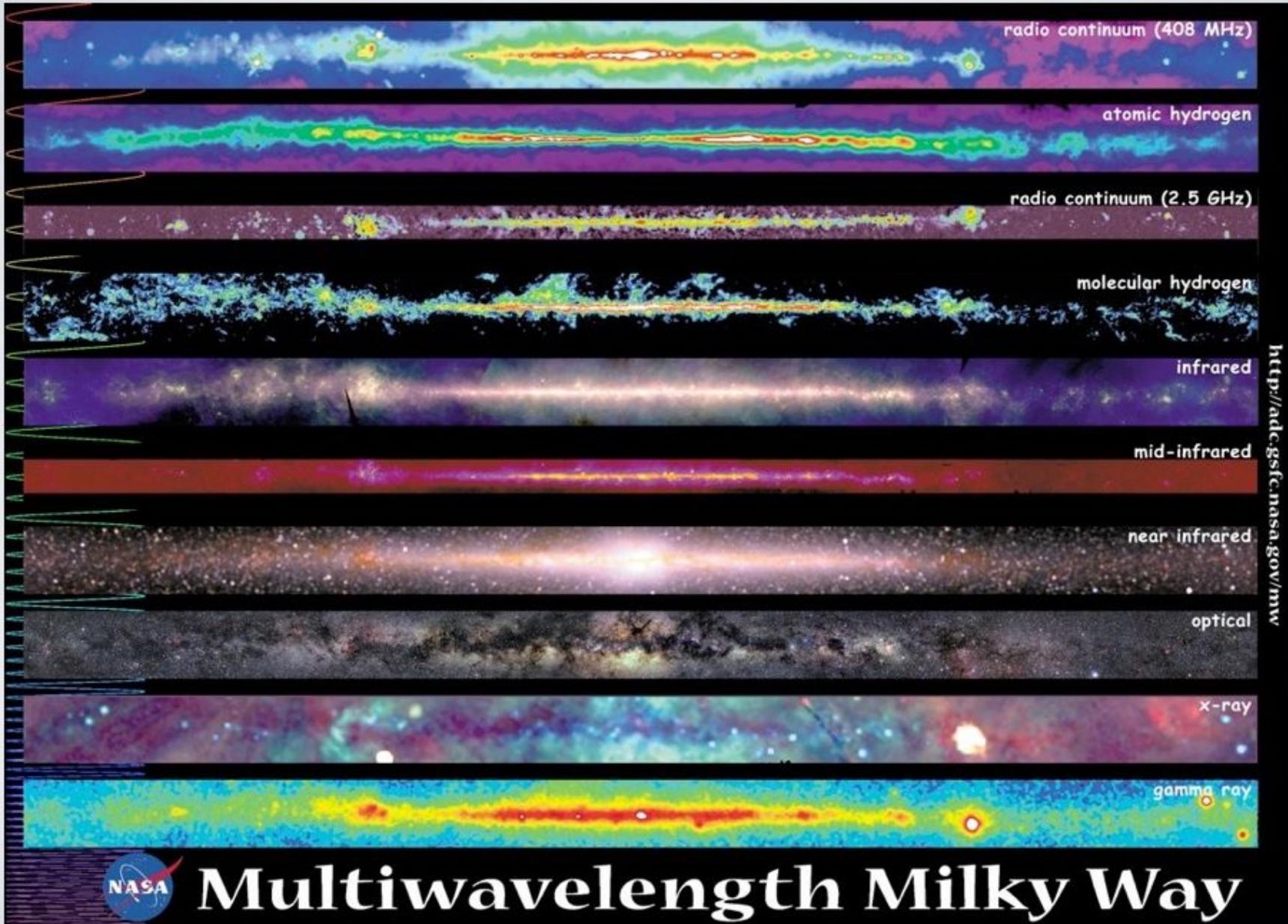
simone.scaringi@durham.ac.uk

Krystian Ilkiewicz

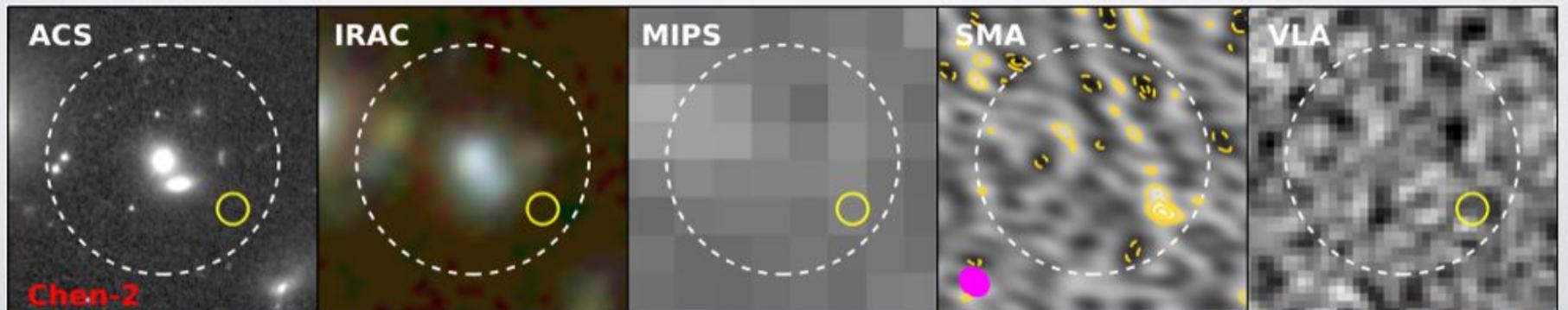
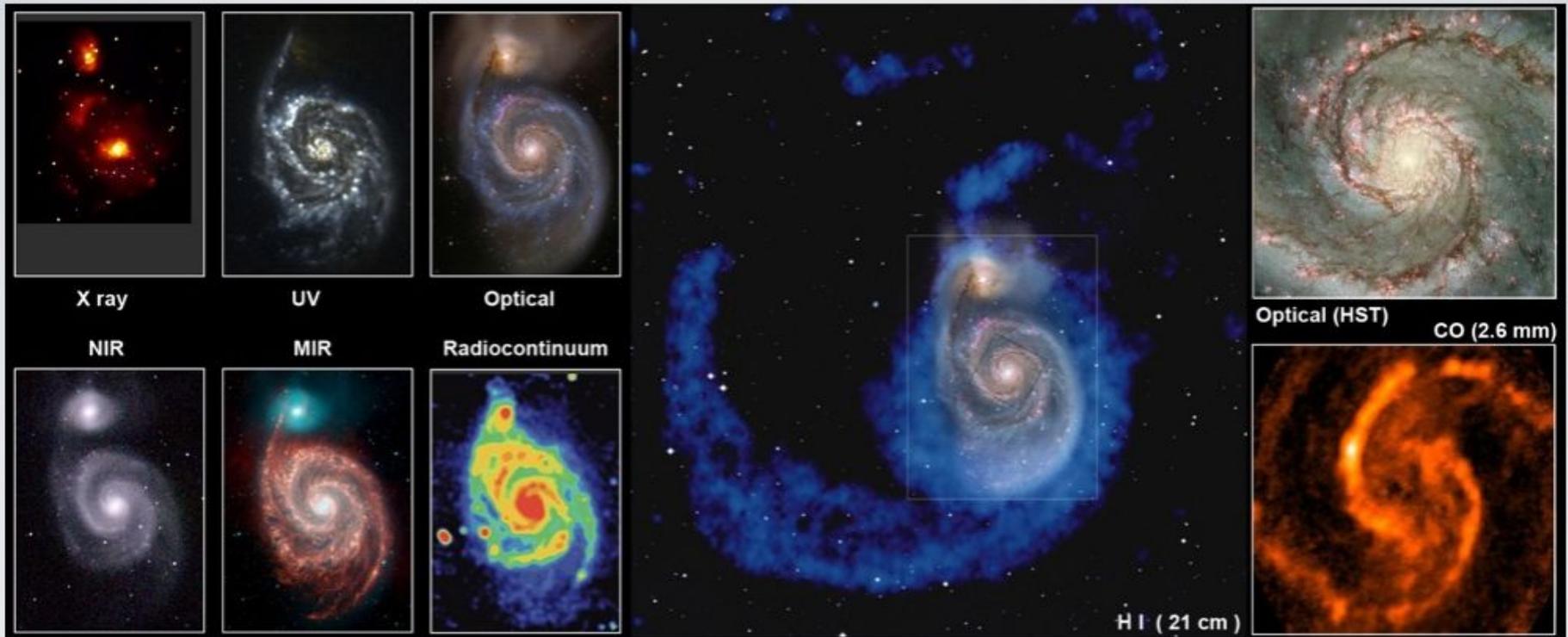
krystian.ilkiewicz@gmail.com



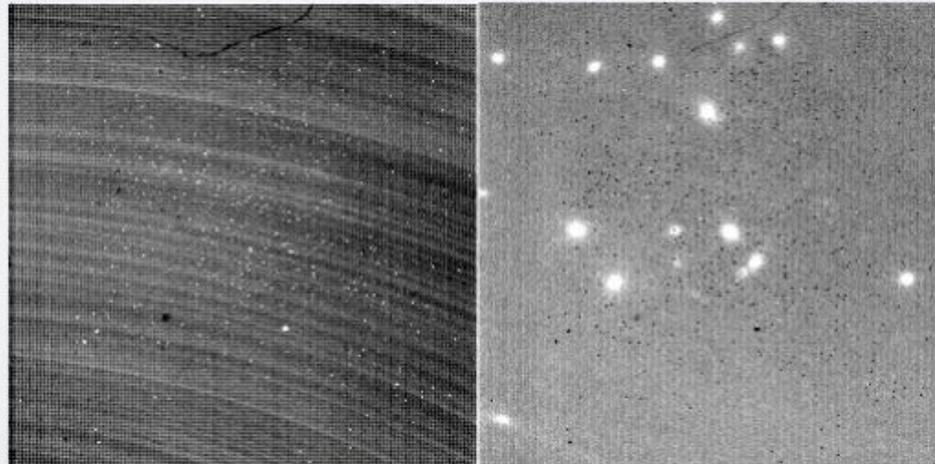
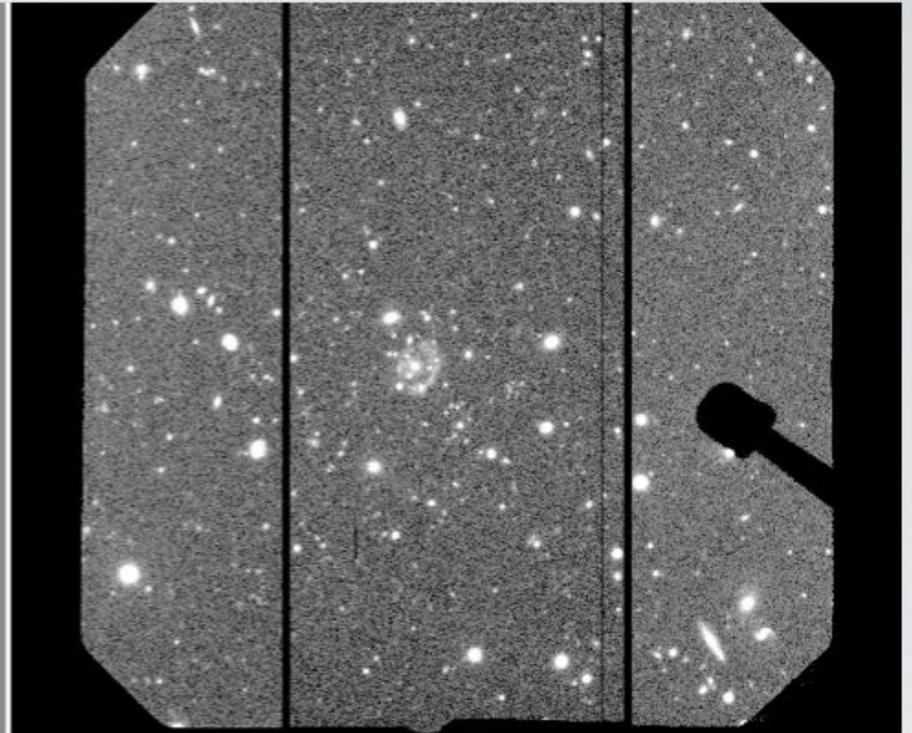
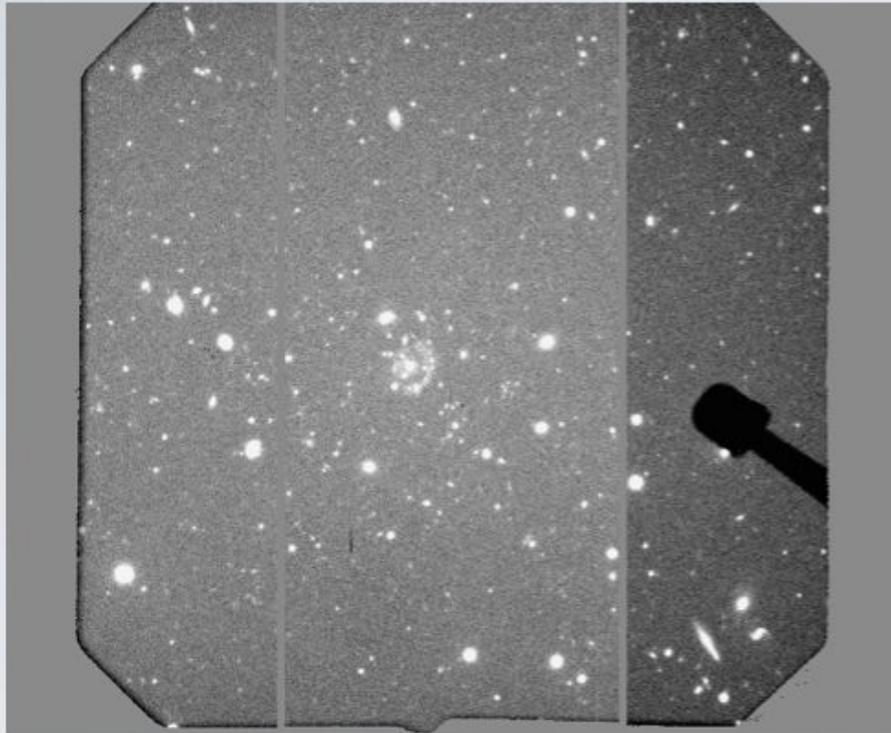
Images at different wavelengths...



Images at different wavelengths...



However, the raw data are always not as pretty



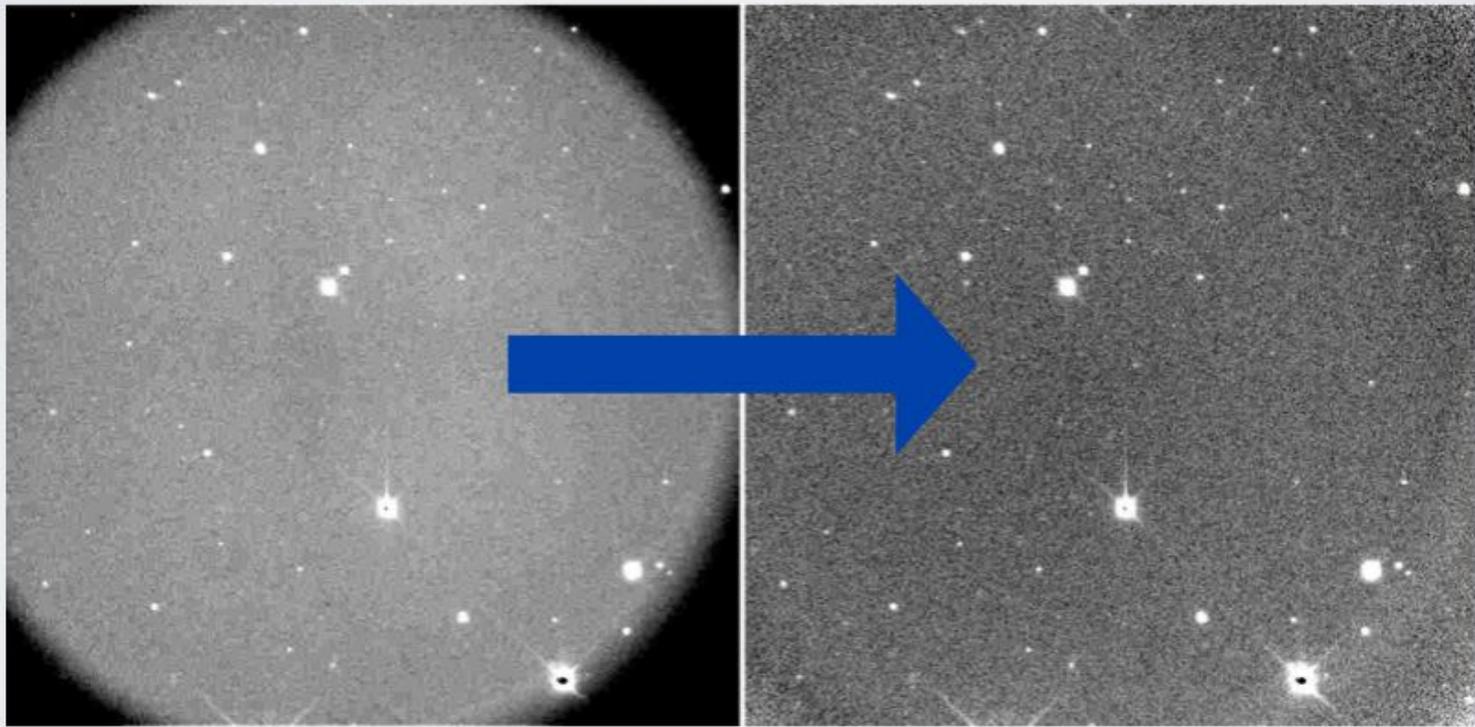
Why?

“The total amount of energy from outside the solar system ever received by all the radio telescopes on the planet Earth is less than the energy of a single snowflake striking the ground”

-Carl Sagan



- Raw images are dominated by sky background and instrumental noises/ effects
- Objects of interest are usually faint and require many exposures to detect
- Need to reduce and combine raw data into one final science image



Goal: Learn how to *in principle* do



Why do we learn how to reduce data when there are usually pipelines available?

Pipelines may not work properly.....

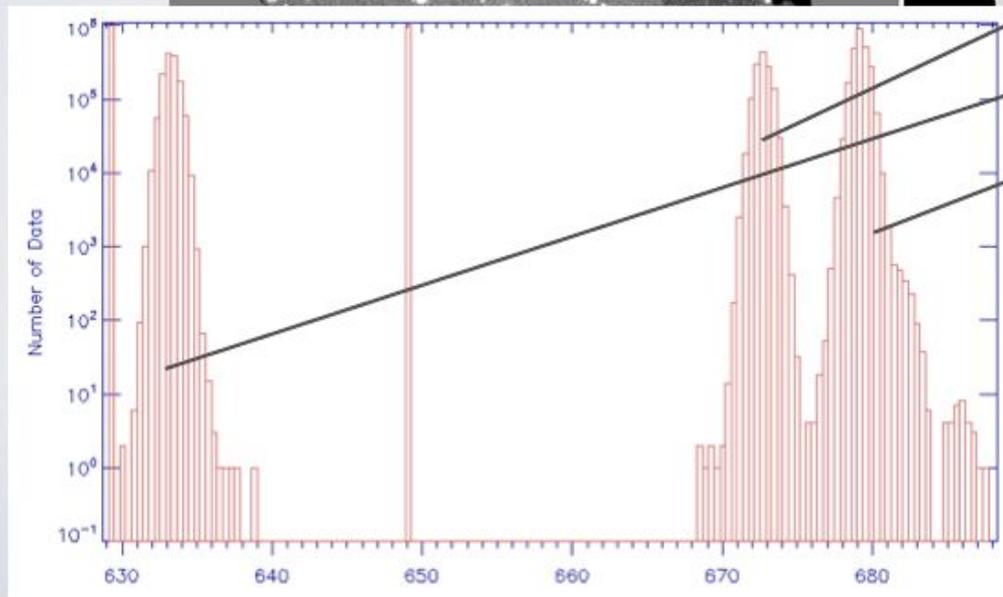
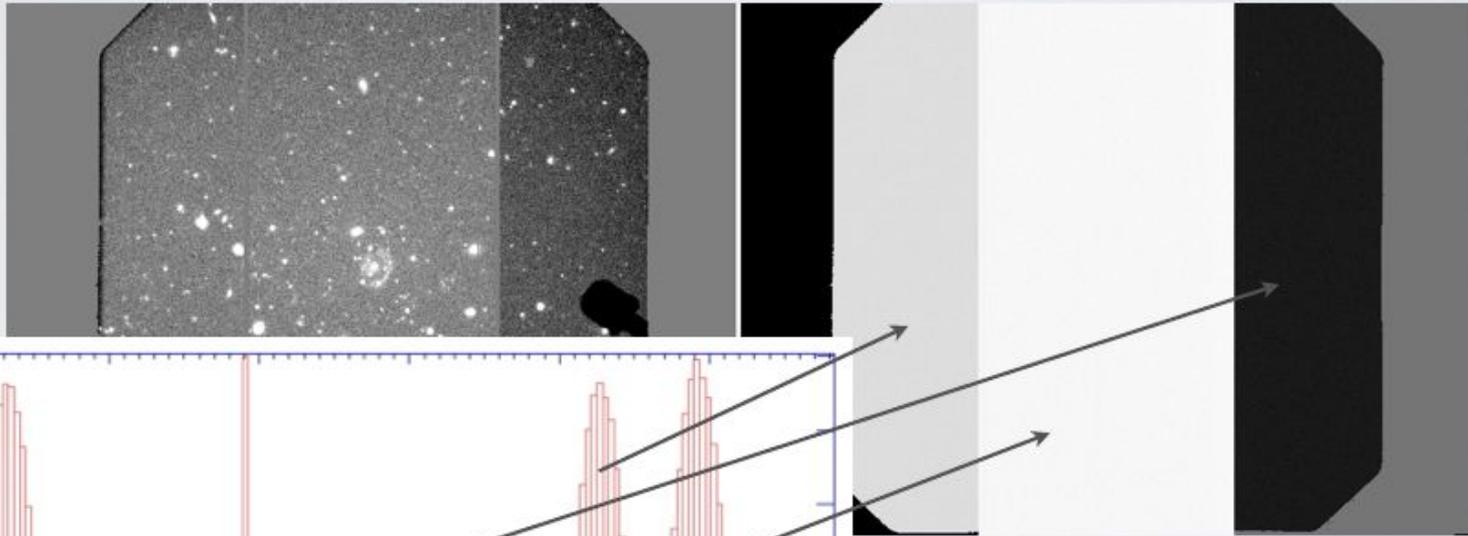
Are data in different wavelengths all reduced in the same way?

No, but the concepts are similar.....

Instrumental noises / effects :

Bias:

An offset to keep the signals positive.



Extra noises:

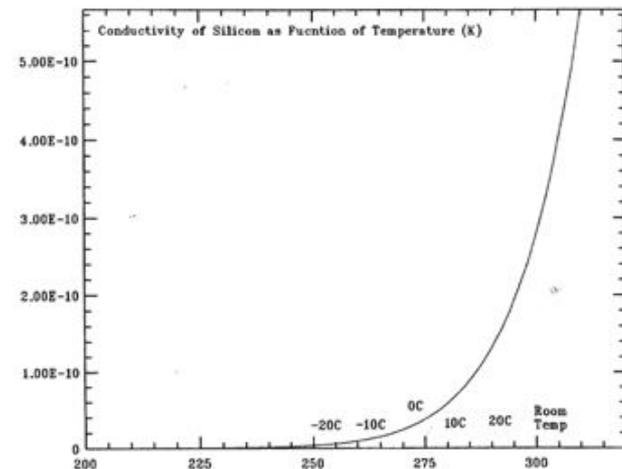
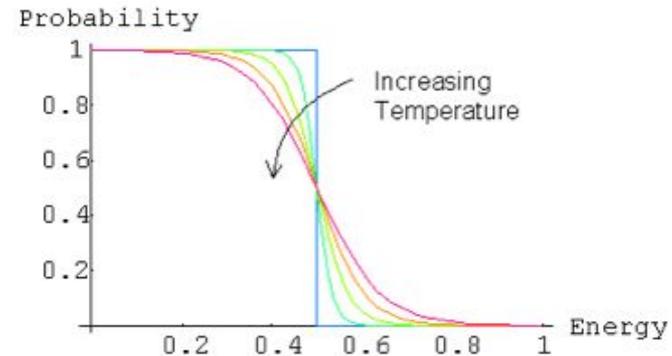
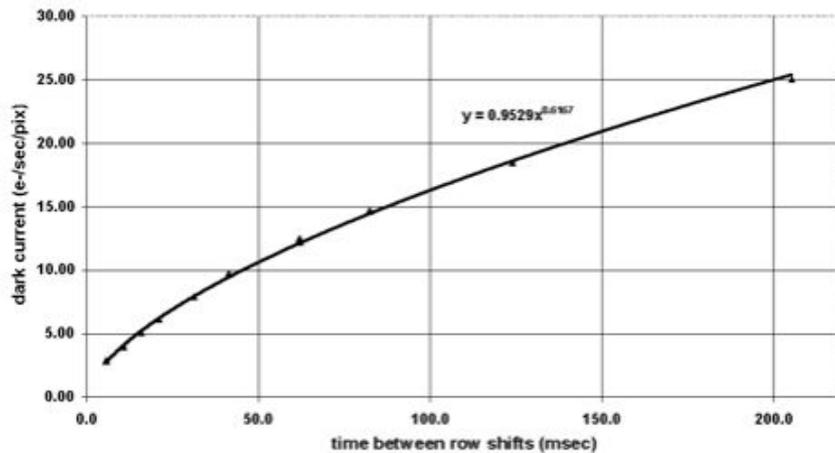
1. analog to digital conversion
2. spurious electrons (in certain type of CCD)

Instrumental noises / effects :

Dark:

Thermal signals from the detector, highly temperature dependent, non-negligible in NIR.

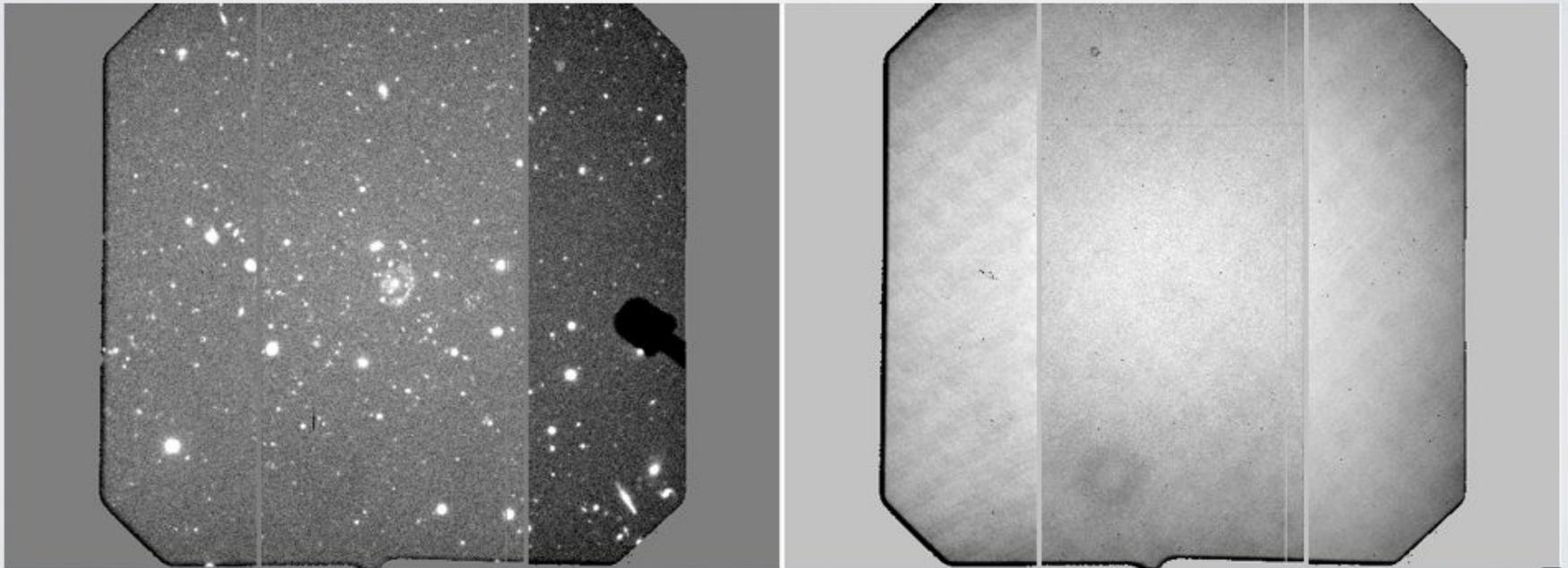
CCD42-20 NIMO
TDI dark current @-30C



Instrumental noises / effects :

Flat-field:

Non-uniformity of the quantum efficiency across the whole detector.



Ways to measure them :

Bias:

Obtain by reading-out the CCD with a zero-second exposure.

Dark:

Exposures taken with the shutter closed (dark!), with the same exposure time and temperature as the science images.

Flat-field:

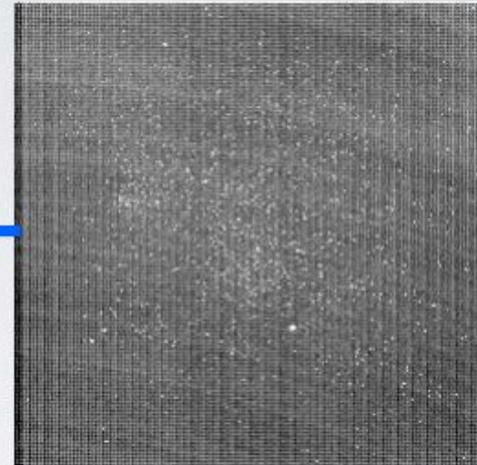
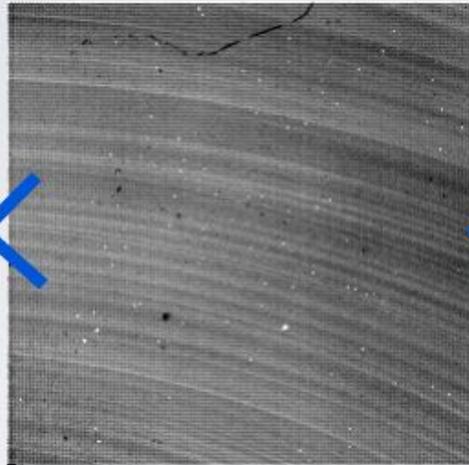
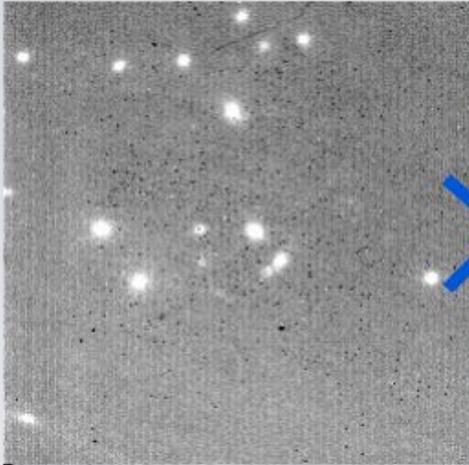
Exposures of a uniformly illuminated source. Type of flatfields: Dome, Twilight, Sky

NOTE: Often will have several exposures for each effect, and they can be averaged together to make a more robust master

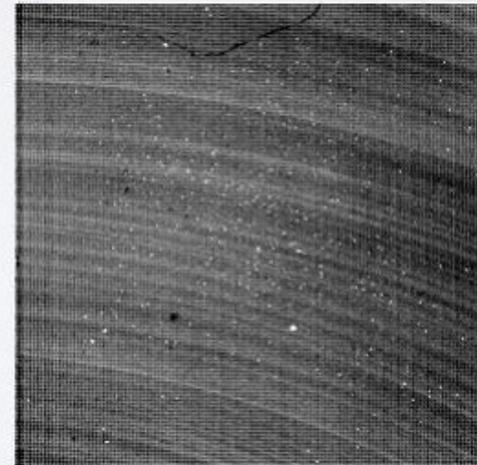
Object

Flat

Bias/Dark



Raw



Fundamental Steps :

1. Subtract bias / dark
2. Flat-fielding
3. Co-add all “reduced” frames into one final image
4. Calibrate astrometry and flux using references such as standard stars, and update FITS header.

Calibrations

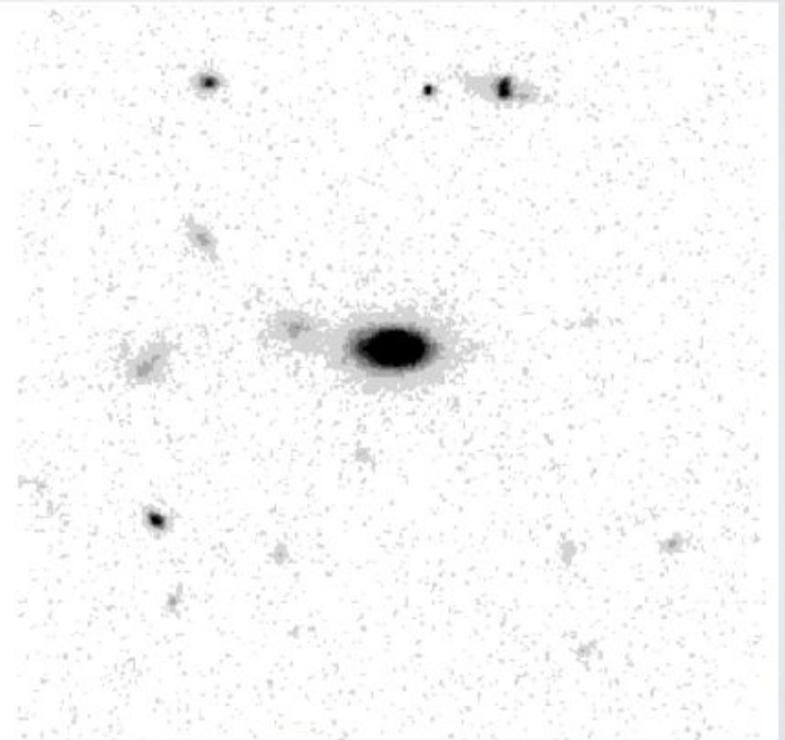
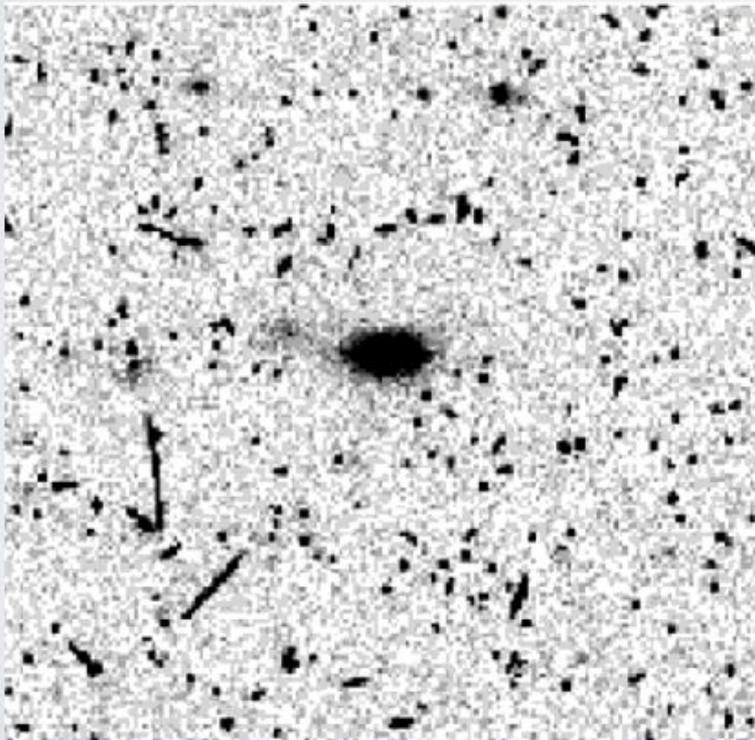
Flux:

The digital values of the reduced images are usually arbitrary. Need to convert those values to physically meaningful values, again using bright referencing objects with known fluxes and that are observed by the same instrument.

Other issues

Cosmic rays:

Cosmic rays often appear on images taken by the space telescopes. Need to be removed.

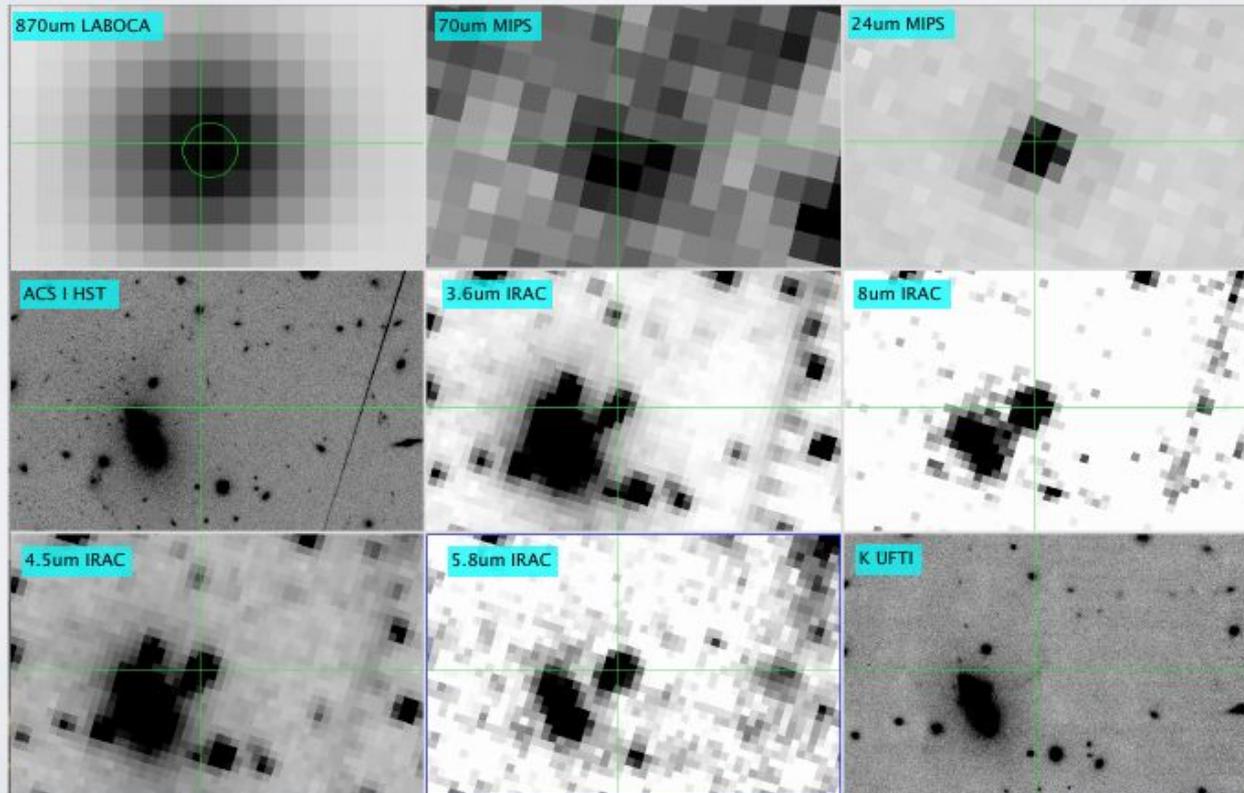


Your toolkit

1. Fundamentally, we're dealing with arithmetic operations on 2D arrays. Use your favorite computer language (IDL, Python, C, IRAF, etc) to manipulate them. Choice is yours.
2. Some invaluable tools: SExtractor (object extraction and photometry), SWarp (image co-add and re-sampling), WCSTools (manipulate/fit astrometry)

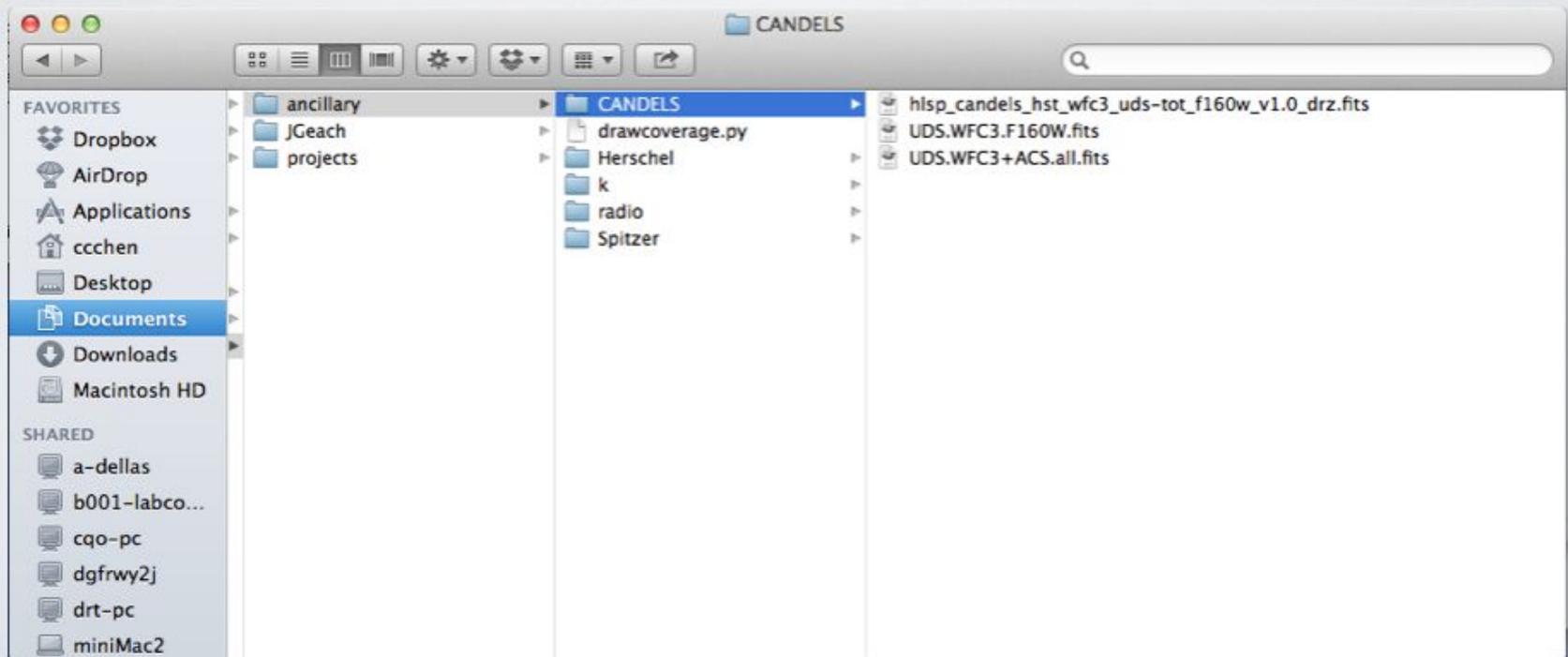
Your toolkit

3. Viewing Tools: ds9, Gaia (for example, ds9 can load many images on different pixel scale and align them).



Things that will help you

1. Naming convention : often a good idea to re-name the cryptically named raw files to something useful describing what the frame is (e.g., r102914.fits becomes object_K_10s.fits).



Things that will help you

2. Flexible Image Transfer System (FITS) file format :
Consists of 'header' containing meta-data (most important being world-coordinate system: WCS) and a binary array containing image data. FITS can also support multiple extensions (beware the hidden extension) and some catalogues come in FITS table format.

Hint: Information for sensible re-naming can be found in
the header

FITS Header

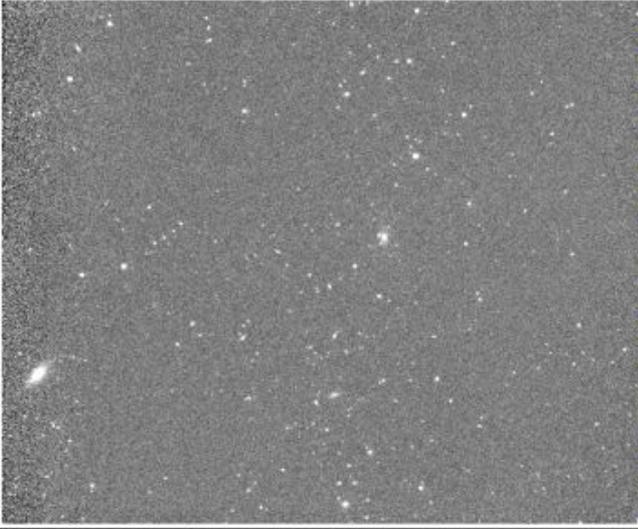
SAOImage ds9

File Edit View Frame Bin Zoom Scale Color Region WCS Analysis Help

File: rxcj0220.3_K.fits
Object: Register mosaic sum: RXCJ0220

Value: []
WCS: [] []
Physical X Y
Image X Y
Frame 1 x 0.250 0.000 *

file edit view frame bin zoom scale color region
open save header page setup print



-1.4 -1 -0.69 -0.35 0.0044 0.35 0.7 1.1

rxcj0220.3_K.fits

File Edit Font

```
CSEC12 = '[1025:2048,1:1024]' / ccd section
DSEC12 = '[1025:2048,1:1024]' / data section
TSEC12 = '[1025:2048,1:1024]' / trim section
ASEC21 = '[1:1024,1025:2048]' / amplifier section
BSEC21 = ' ' / bias section
CSEC21 = '[1:1024,1025:2048]' / ccd section
DSEC21 = '[1:1024,1025:2048]' / data section
TSEC21 = '[1:1024,1025:2048]' / trim section
ASEC22 = '[1025:2048,1025:2048]' / amplifier section
BSEC22 = ' ' / bias section
CSEC22 = '[1025:2048,1025:2048]' / ccd section
DSEC22 = '[1025:2048,1025:2048]' / data section
TSEC22 = '[1025:2048,1025:2048]' / trim section
IDETTEMP= 75.82 / Initial detector temperature
FDETTEMP= 75.82 / Final detector temperature
DATE-OBS= '2007-02-10T00:00:00.000' / Date of observation
UT = '00:48:45.0' / UT of TCS coordinates
RA = '02:20:54.92' / right ascension (telescope)
DEC = '-38:28:07.3' / declination (telescope)
EQUINOX = 2000.0 / epoch of RA & DEC
HA = '03:03:13.6' / hour angle (H:M:S)
CRPIX1 = 1292.28125 / Reference pixel on axis 1
CRPIX2 = 1333.415093 / Reference pixel on axis 2
CRVAL1 = 35.2366666666667 / Value at ref. pixel on axis 1
CRVAL2 = -38.4838888888889 / Value at ref. pixel on axis 2
CTYPE1 = 'RA--TAN' / Type of co-ordinate on axis 1
CTYPE2 = 'DEC--TAN' / Type of co-ordinate on axis 2
CDEL1 = -8.46849148788206E-5 / Pixel size on axis 1
CDEL2 = -8.47328196270999E-5 / Pixel size on axis 2
PC1_1 = 1.0 / Transformation matrix element
PC1_2 = -3.34986750110235E-4 / Transformation matrix element
PC2_1 = 0.000449691780622417 / Transformation matrix element
PC2_2 = 1.0 / Transformation matrix element
MJD-OBS = 54141.0 / Modified Julian Date of observation
RADESYS = 'FK5' / Reference frame for RA/DEC values
ST = '05:24:26.4' / sidereal time
DOMEAZ = '120.2' / dome azimuth
AIRMASS = '1.274' / airmass
ZD = '38.3' / zenith distance (degrees)
TELFOCUS= '183753' / Telescope focus
FILTNUM = '4' / Filter number
FILTNAME= 'KA' / Filter name
CRMASK = 'crmask_RXCJ0220_067_flat.pl'
COMMENT = 'dimsum.registar: Tue 17:52:49 06-Nov-2007'
COMMENT = 'dimsum.registar: Header data copied from file RXCJ0220_067_flat.fits'
```

Workshop

Two main datasets:

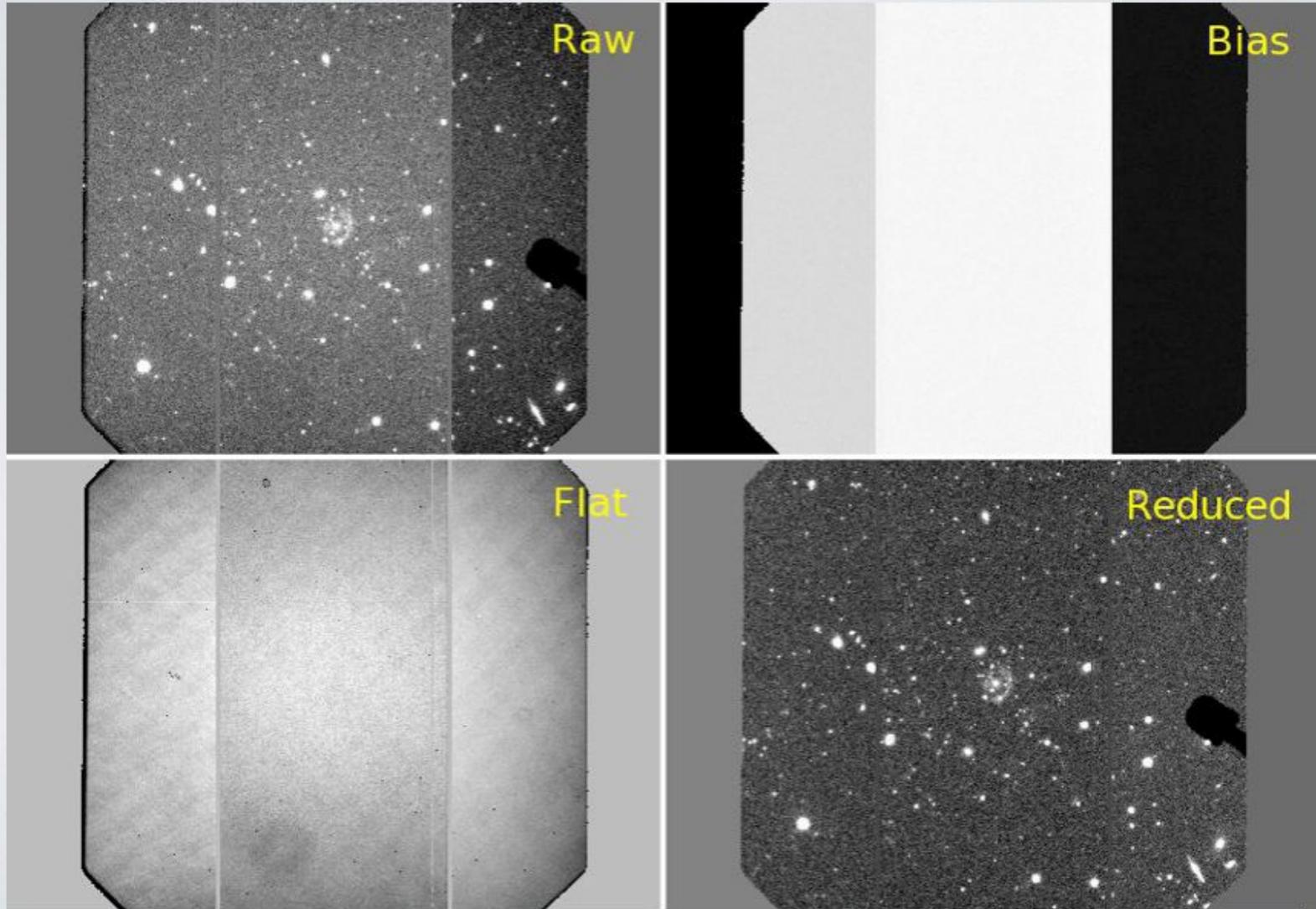
1. Optical Imaging Data: GMOS B-band imaging of cluster RXJC0220.9-3839 (@0220/optical/)
2. Near-IR imaging Data: a gravitationally lensed galaxy in Cl2243 with NIRC on Keck (@NIR/)

Ancillary datasets:

3. Pre-reduced NIR Imaging Data: J/K-band imaging of cluster RXJC0220.9-3839 (@0220/NIR)

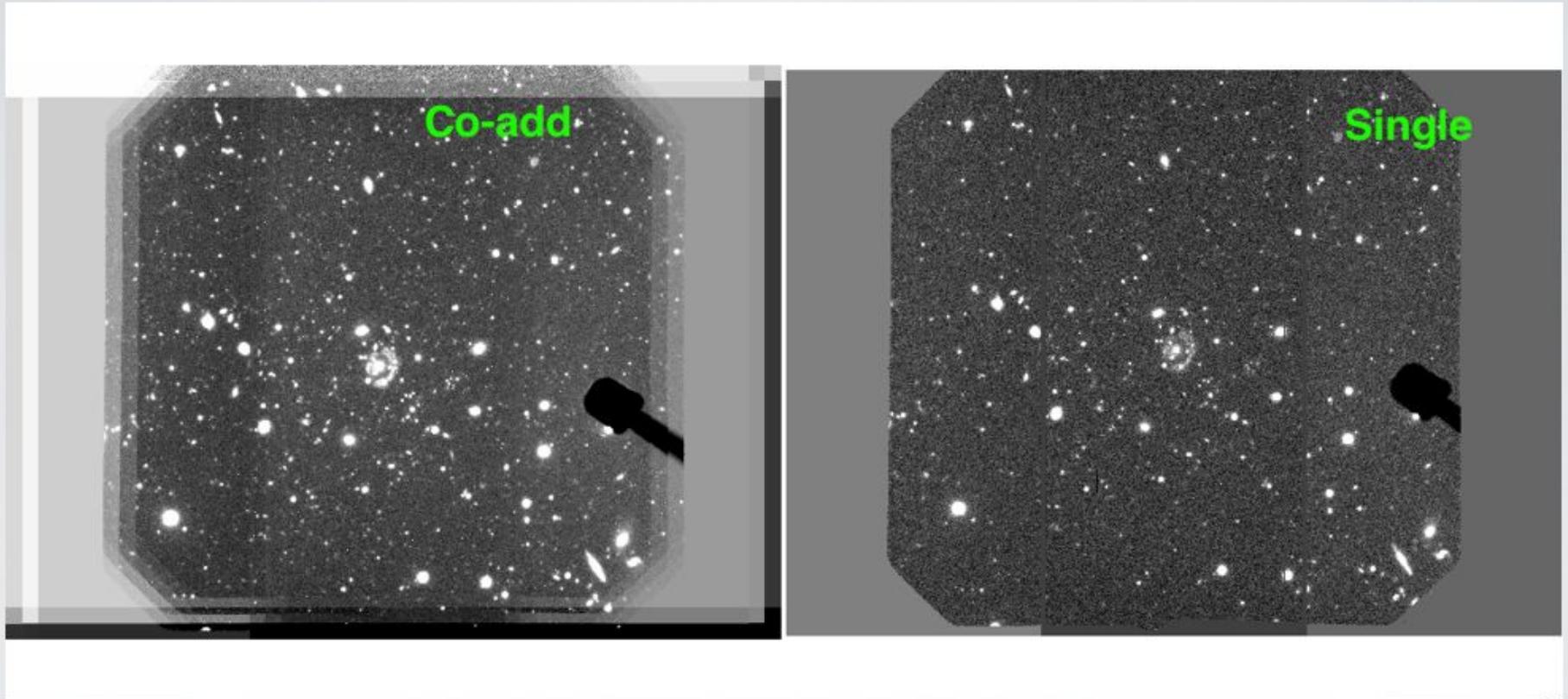
Workshop

Task I: Reduce raw data



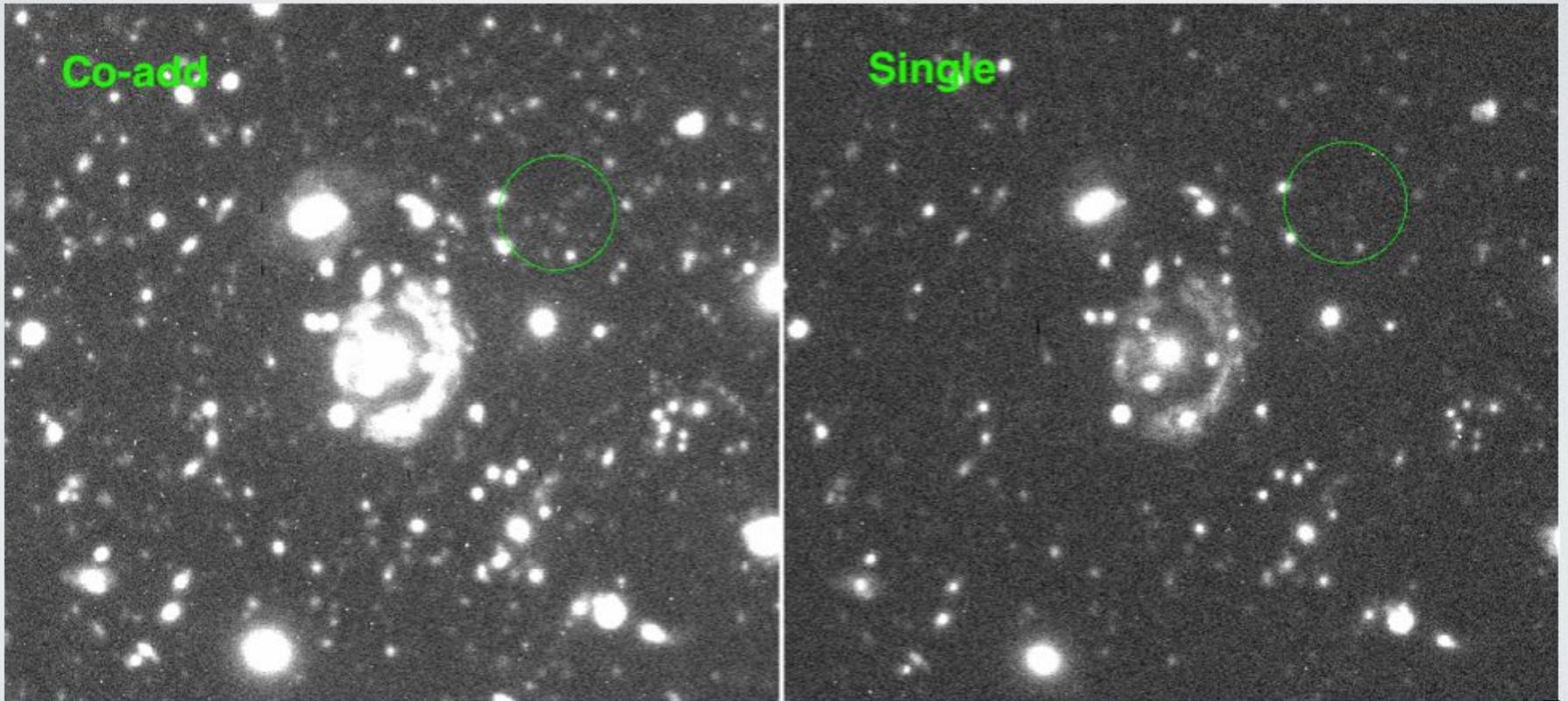
Workshop

Task 2: Co-add reduced frames



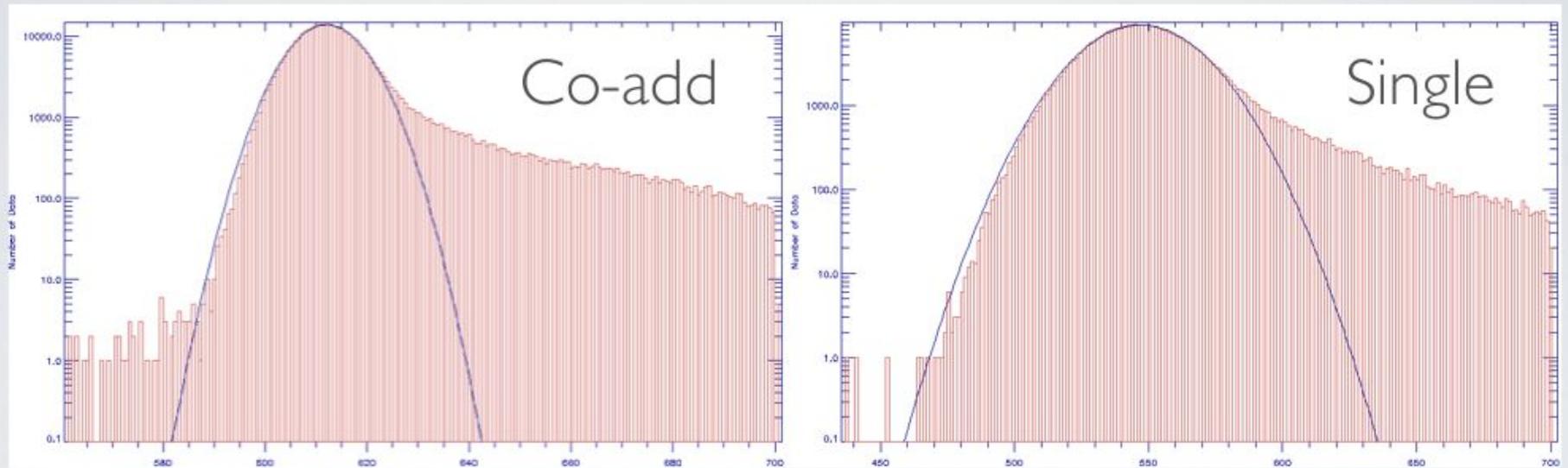
Workshop

Co-adding makes deeper images



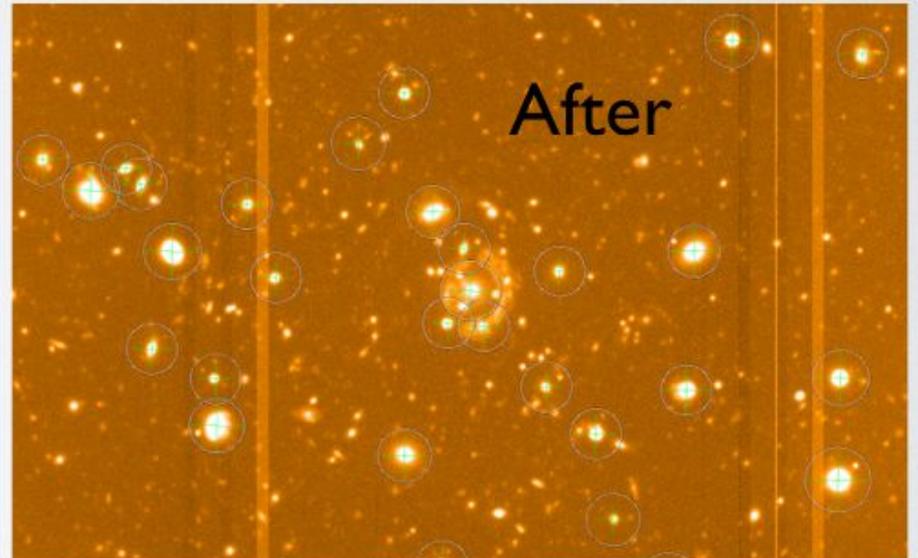
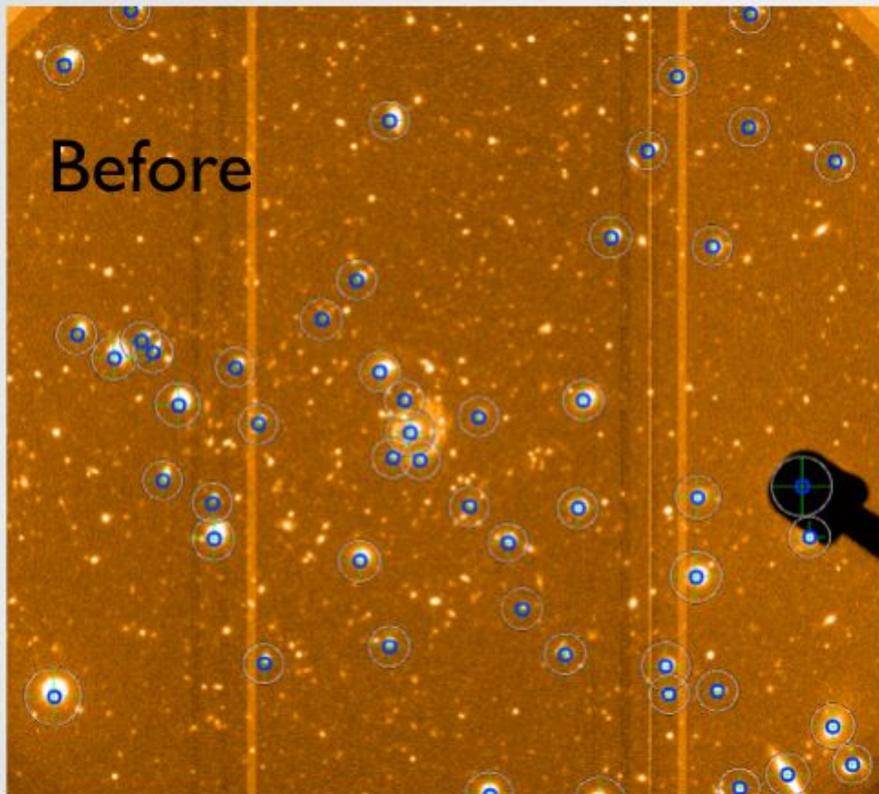
Workshop

Co-adding makes deeper images



Workshop

Task 3: Calibrate Astrometry



Workshop

Task 3: Calibrate Astrometry

Step 1: Open Co-add image in Gaia, adjust to your favorite colors and scales

The screenshot displays the Starlink GAIA-Skycat software interface. The main window shows a co-add image of a star field with a central cluster. The interface includes a control panel on the left and a detailed parameter panel on the right.

Control Panel (Left):

- Object: `82030220_9-3829 (file mosaic.fits)`
- X: `1812.0` Y: `1574.0` Value: `607.588`
- α : `2:21:00.903` δ : `-38:33:41.95` Equinox: `2000`
- Min: `553.644714355469` Max: `5274.67626953125`
- Low: `553.645` High: `5274.68`
- Scale: `1x` `Z` `z` `G` `z` `H`
- Buttons: `Auto Cut`, `Color Map`, `Color Scale` (highlighted with a green box)

Parameter Panel (Right):

- Object: `82030220_9-3829 (file mosaic.fits)`
- X: `1533.0` Y: `1328.0` Value: `620.869`
- α : `2:20:59.841` δ : `-38:33:00.28` Equinox: `2000`
- Min: `553.644714355469` Max: `5274.67626953125`
- Low: `596.145` High: `736.331`
- Scale: `In` `Z` `z` `G` `z` `H`
- Buttons: `Auto Cut`, `Color Map`, `Color Scale`

Main Window: A large field of stars with a bright cluster in the center. The interface includes a status bar at the bottom with the text: `Select a quick colour map (more in View...Colors)`.

Workshop

Task 3: Calibrate Astrometry

Step 2: Go to Data-Servers, Catalogs, bright object catalog USNO at ESO, search

The screenshot shows the Starlink GAIA-Skycat interface. The main window displays a mosaic of stars. A menu is open over the 'Data-Servers' tab, listing various catalogs. The 'USNO at ESO' catalog is highlighted. The interface includes a menu bar (File, View, Graphics, Go, Image-Analysis, Data-Servers, Interrog, Help), a toolbar, and a status bar at the bottom with the text 'Find VO cone search servers and query for catalogs'.

Object: 80030220_9-3829
X: 1619.0
Y: 231.02.294
Min: 553.644714355469
Low: 596.145
Scale: 1x

USNO at ESO

- ZMSSS Catalog at CDS
- ZMSSS at CADC
- ABELL at CADC
- ACS at CADC
- GSC-2 at ESO
- Guide Star Catalog at CADC
- Guide Star Catalog at ESO
- Hipparcos/Tycho at CADC
- IRAS Point Source Catalogue at CADC
- IRAS Point Source Catalogue at ESO
- NED at CADC
- NED at ESO
- NOMAD-1 Catalog
- PPM at ESO
- GSO at CADC
- GSO96 at CADC
- GSO98 at CADC
- RC3 at CADC
- ROGAT All-Sky Bright Source Catalogue
- SAO at CADC
- SIMBAD through CADC
- SIMBAD via ESO
- Tycho-2 at CADC
- UCAC2 Catalog at CDS
- UCAC3 Catalog at CDS
- UCAC4 Catalog at CDS
- USNO B1 B Catalog at CDS
- USNO at CADC
- USNO at ESO

The screenshot shows the 'USNO at ESO (1)' search options dialog. It contains fields for Object Name, Equinox (J2000), Right Ascension (a: 02:20:58.502), Declination (d: -38:33:13.36), Min Radius (0.0), Max Radius (4.9431), Brightest (min), Faintest (max), and Max Objects (20000). There are buttons for 'Select Area...' and 'Set From Image'. The text 'Provided by courtesy of the US Naval Observatory' is visible at the bottom.

USNO at ESO (1)

Search Options

Object Name: Equinox: J2000

a: 02:20:58.502 d: -38:33:13.36

Min Radius: 0.0 Max Radius: 4.9431

Brightest (min): Faintest (max):

Max Objects: 20000

Provided by courtesy of the US Naval Observatory

The screenshot shows the search results table for the USNO at ESO catalog. The table has columns for ID, ra, dec, r_mag, b_mag, field, and d'. The results are sorted by magnitude.

Search Results (123)

ID	ra	dec	r_mag	b_mag	field	d'
U0450.00813199	02:21:20.820	-38:32:30.65	14.1	14.8	298	4.421
U0450.00810590	02:20:56.026	-38:35:22.22	14.3	14.5	298	2.202
U0450.00812650	02:21:15.375	-38:36:48.68	14.8	16.4	298	4.874
U0450.00809883	02:20:49.578	-38:30:56.83	14.9	15.3	298	2.868
U0450.00810351	02:20:53.807	-38:30:13.10	15.4	16.8	298	3.142
U0450.00809546	02:20:46.309	-38:34:10.41	15.8	17.4	298	2.566
U0450.00810654	02:20:56.666	-38:28:48.02	15.8	16.0	298	4.437
U0450.00810295	02:20:53.250	-38:24:44.07	15.8	16.0	298	1.922
U0450.00810230	02:20:52.7	-38:24:44.07	15.8	16.0	298	1.922
U0450.00809359	02:20:44.3	-38:24:44.07	15.8	16.0	298	1.922
U0450.00809574	02:20:46.5	-38:24:44.07	15.8	16.0	298	1.922
U0450.00811261	02:21:01.9	-38:24:44.07	15.8	16.0	298	1.922

The screenshot shows the 'USNO at ESO (1)' search options dialog with the search results table visible. The search options are the same as in the previous screenshot. The search results table is empty.

USNO at ESO (1)

Search Options

Object Name: Equinox: J2000

a: 02:20:58.502 d: -38:33:13.36

Min Radius: 0.0 Max Radius: 4.9431

Brightest (min): Faintest (max):

Max Objects: 20000

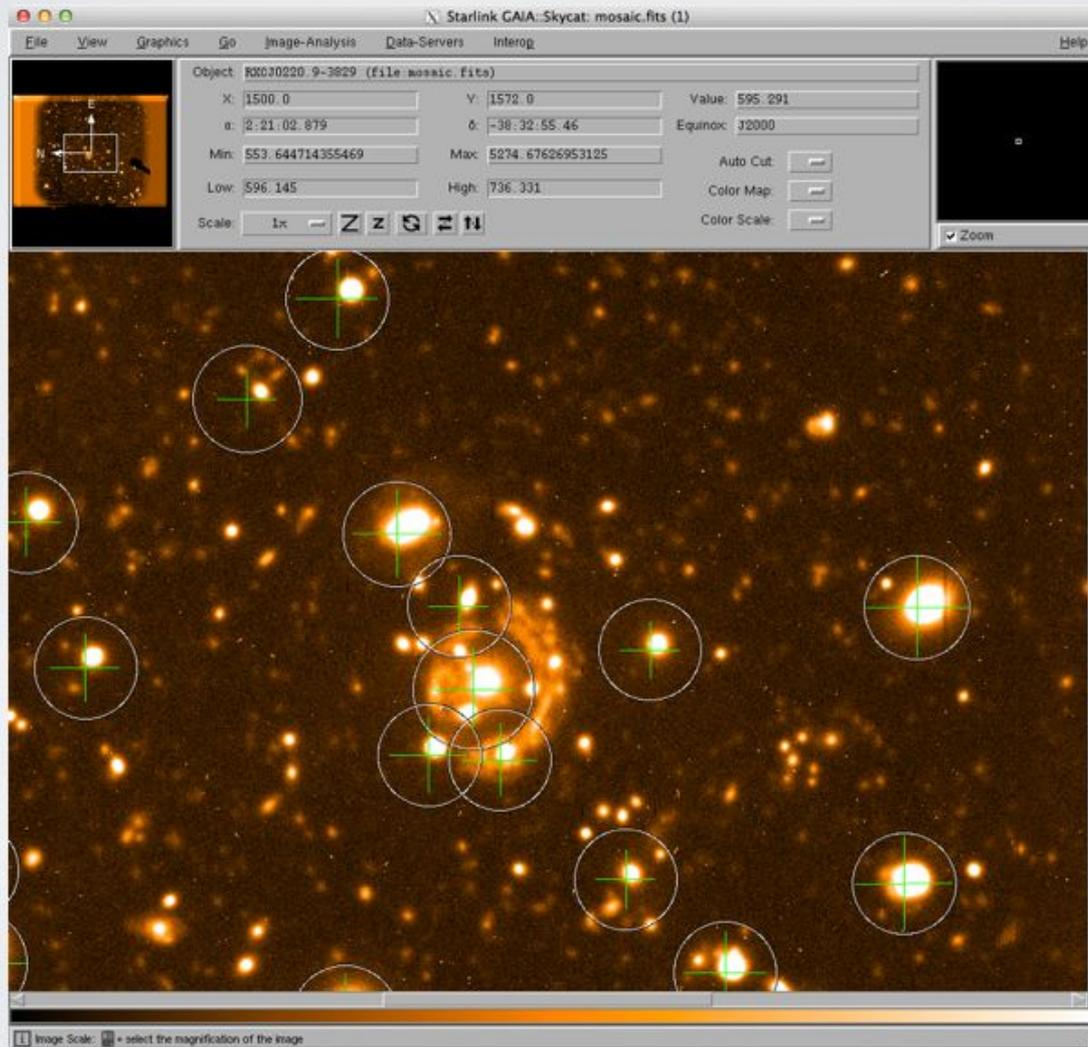
Provided by courtesy of the US Naval Observatory

Search Results

Workshop

Task 3: Calibrate Astrometry

Step 2: Once click search, sources should appear, can see mismatched positions



Workshop

Task 3: Calibrate Astrometry

Step 3: Image-Analysis -> Astrometry calibration -> Fit to star positions -> Select the USNO at ESO catalog

The screenshot displays the Starlink GAIA software interface. The main window, titled "Starlink GAIA::Skycat: mosaic.fits (1)", shows a star field with several stars circled in white and marked with green crosses. A menu is open over the "Image-Analysis" tab, with "Astrometry calibration" selected. The "Fit to star positions..." option is highlighted. A secondary dialog box, "GAIA: Fit astrometry reference positions (1)", is open, showing a table of reference positions with columns for ID, RA, DEC, X, and Y. The "USNO at ESO -- catalog (mosaic.fits)" is selected in the "Select a catalogue" dialog box. The "Fit to star positions..." option is also visible in the "Automatic position matching" sub-menu.

Starlink GAIA::Skycat: mosaic.fits (1)

Image-Analysis Data-Servers Interop

Object: R Aperture photometry
Optimal photometry
X: 2 Image regions... Control-r
α: STC-S regions...
Min: 5 Patch image... Control-u
Low: 5 Blink images... Control-b
Overlay axes grid... Control-l
Astrometry calibration
Scale: Change coordinates
Object detection... Control-j
Contouring... Control-h
Surface photometry...
Positions...
Mean X & Y profiles... Control-e
Polarimetry toolbox...
Mask image...
Demonstration mode...

Automatic position matching
Fit to star positions... Control-k
Tweak an existing calibration... Control-z
Copy from another image... Control-y
Type in known calibration... Control-w

GAIA: Fit astrometry reference positions (1)

Reference positions

id ra dec x y

USNO at ESO -- catalog (mosaic.fits)

Workshop

Task 3: Calibrate Astrometry

Step 4: Adjust the marker size and width

The screenshot displays the Starlink GAIA software interface. The main window shows a star field with several stars marked by blue circles and green crosses. The 'Fit astrometry reference positions (1)' dialog box is open, showing a table of star coordinates and various fit parameters.

id	ra	dec	Type	s	x	y
00450.00813199	02:21:20		3		7284826087748	301
00450.00810590	02:20:56		5		4445946438282	101
00450.00812650	02:21:15		7		2816428632186	251
00450.00809883	02:20:49		9		19285007985271	501
00450.00810351	02:20:53		11		3406935454464	841

The dialog box also includes sections for 'Parameters for table coordinates' (Coordinate type: Equatorial (RA/Dec), Coordinate system: FK5, Equinox: J2000) and 'Image parameters' (Projection type: Gnomonic (tangent plane) (-TAN)).

The main window shows the star field with several stars marked by blue circles and green crosses. The 'Fit astrometry reference positions' dialog box is open, showing a table of star coordinates and various fit parameters.

Workshop

Task 3: Calibrate Astrometry

Step 5: Clip objects outside the frame, extended objects, saturated stars

The screenshot displays the Starlink GAIA software interface. The main window shows a star field with several stars marked with blue and green crosses. The interface includes a menu bar (File, View, Graphics, Go, Image-Analysis, Data-Servers, Interop, Help) and a toolbar. The main panel shows a star field with several stars marked with blue and green crosses. The right panel shows a table of reference positions with columns for id, ra, dec, x, and y. The table contains the following data:

id	ra	dec	x	y
00450.00810767	02:20:57.685	-38:33:03.05	1551.9883688005002	1154
00450.00810863	02:20:58.547	-38:31:40.93	989.97969532476532	122
00450.00811260	02:21:01.927	-38:36:21.13	2907.4972004988199	1496
00450.00810553	02:20:55.689	-38:34:45.11	2250.4904198979225	995
00450.00811020	02:20:59.975	-38:31:18.38	835.63503976672098	1336

The right panel also includes a toolbar with buttons for New, Edit, Delete, Grab, Centroid, Clip, and a Transfer button. Below the toolbar, there are options for Move markers individually (checked), Parameters for table coordinates (Coordinate type: Equatorial (RA/Dec), Coordinate system: FK5, Equinox: J2000, Epoch:), and Image parameters (Projection type: Gnomonic (tangent plane) (-TAN), prop1, prop2, X coordinate type: RA/Longitude). At the bottom, there are buttons for Fit/Test, Reset, Cancel, and Accept. A status bar at the bottom indicates "Remove the selected rows from the table".

Workshop

Task 3: Calibrate Astrometry

Step 6: move markers to the right positions of the bright objects

Hint: unclick Move markers individually to move all markers

GAIA: Fit astrometry reference positions (1)

File Edit Options Markers Help

Reference positions

id	ra	dec	x	y
00450.00810590	02:20:56.026	-38:35:22.22	2512.44459464380	1030
00450.00809546	02:20:46.309	-38:34:10.41	2021.4516884572799	249
00450.00810295	02:20:53.259	-38:34:44.57	2254.8760999972601	807
00450.00809574	02:20:46.527	-38:33:31.43	1754.6769460952601	266
00450.00809983	02:20:50.495	-38:34:33.88	2181.8371517186602	586

New Edit Delete Grab Centroid Clip

Reset Set Clear Redraw

Transfer

Move markers individually:

Parameters for table coordinates:

Coordinate type: Equatorial (RA/Dec)

Coordinate system: FRS

Equinox: J2000

Epoch:

Image parameters:

Projection type: Gnomonic (tangent plane) (-TRN)

prmp1:

prmp2:

X coordinate type: RA/Longitude

Fit/Test Reset Cancel Accept

Move markers individually or all together

Workshop

Task 3: Calibrate Astrometry

Step 7: Click Centroid, and Fit/Test, re-center and re-clip till the rms good

The screenshot shows the GAIA software interface for fitting astrometry reference positions. The window title is "GAIA: Fit astrometry reference positions (1)". The menu bar includes "File", "Edit", "Options", "Markers", and "Help".

The main window displays a table of reference positions with the following data:

id	ra	dec	x	y
U0450.00810590	02:20:56.026	-38:35:22.22	2509.11	1020.62
U0450.00809546	02:20:46.309	-38:34:10.41	2015.66	245.287
U0450.00810295	02:20:53.259	-38:34:44.57	2251.18	800.964
U0450.00809574	02:20:46.527	-38:33:31.43	1749.73	265.163
U0450.00809983	02:20:50.495	-38:34:33.88	2177.25	579.81

Below the table are several control buttons: "New", "Edit", "Delete", "Grab", "Centroid", "Clip", "Reset", "Set", "Clear", "Redraw", and "Transfer". There is also a checkbox for "Move markers individually:" which is checked.

Parameters for table coordinates are set as follows:

- Coordinate type: Equatorial (RA/Dec)
- Coordinate system: FK5
- Equinox: J2000
- Epoch: (empty)

Image parameters are set as follows:

- Projection type: Gnomonic (tangent plane) (-TAN)
- proj1: (empty)
- proj2: (empty)
- X coordinate type: RA/Longitude

At the bottom, there are buttons for "Fit/Test", "Reset", "Cancel", and "Accept". The status bar at the very bottom displays the following information:

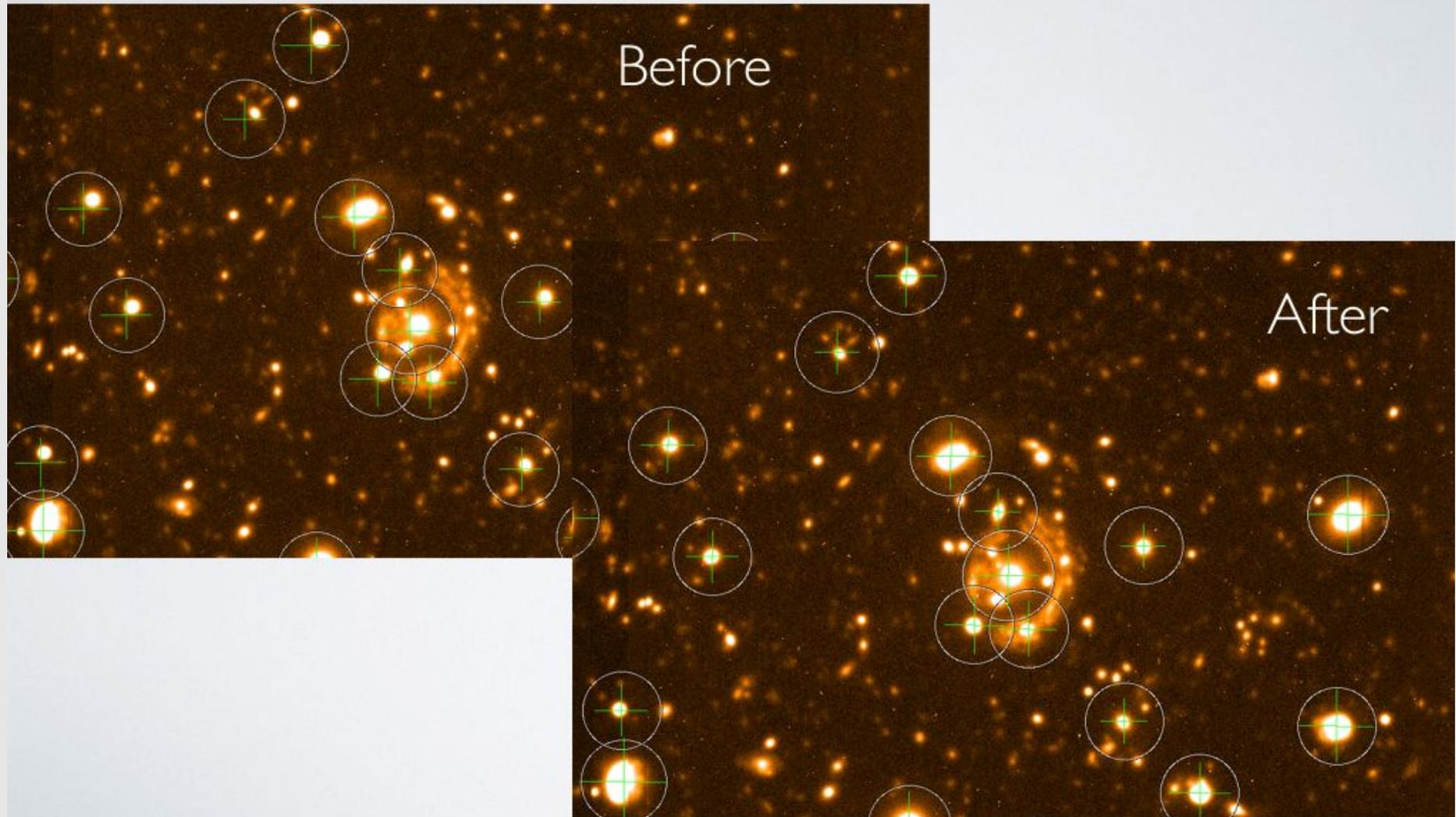
Rms of fit = 0.319886737438299 (arcsec), 2.18618225872857 (pixels)
x,y scales = 0.146524572861284, 0.14611958904344 (arcsec/pixel)
orientation = -268.796383 (degrees)

Hint: an rms of $< 0.4''$ is acceptable in this data

Workshop

Task 3: Calibrate Astrometry

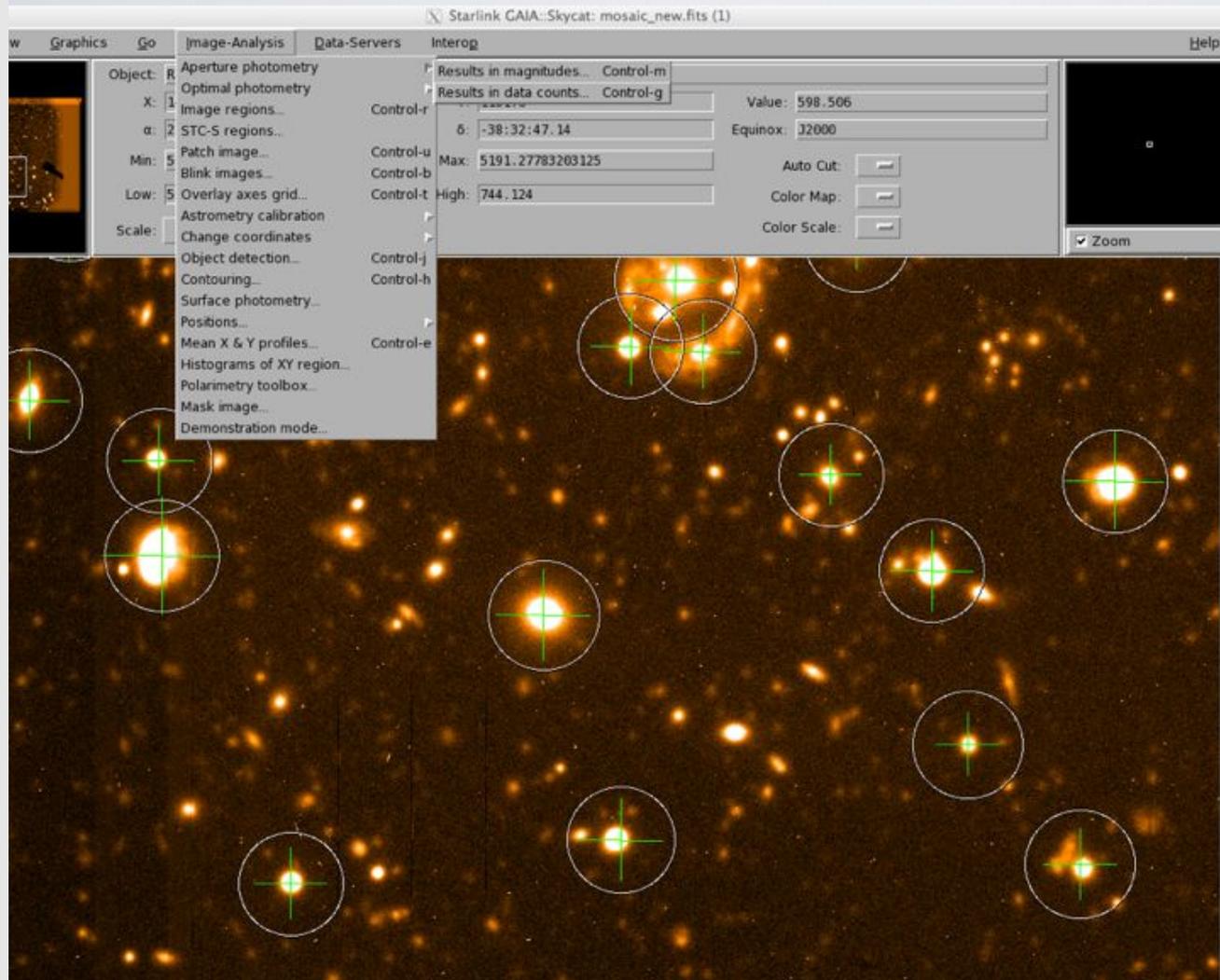
Step 8: when the fit is good, click Accept and save the image



Workshop

Task 4: Flux calibration

Step 1: Image Analysis -> Aperture Photometry -> Results in data counts



Hint:

Goal is to find the zero point (magnitude = $Z_{pt} - 2.5 \cdot \log(\text{flux})$)

Workshop

Task 4: Flux calibration

Step 2: Define an aperture by dragging the cursor -> Calculate results

Hint: Use the B-band magnitude from the catalog as the reference

USNO at ESO (1) Search Options

Object Name: Equinox: J2000

a: 02:20:59.000 d: -38:33:11.00

Min Radius: 0.0 Max Radius: 2.7

Brightest (min): Faintest (max):

Max Objects: 20000

Provided by courtesy of the US Naval Observatory

Search Results (44)

ID	ra	dec	r_mag	b_mag	field	d'
J0450.00810685	02:20:56.904	-38:32:56.97	17.9	19.6	298	0.472
J0450.00810793	02:20:57.952	-38:32:09.46	17.9	20.2	298	1.046
J0450.00810817	02:20:58.163	-38:33:27.54	17.9	20.9	298	0.321
J0450.00810871	02:20:58.689	-38:33:01.12	17.9	20.8	298	0.175
J0450.00810981	02:20:59.693	-38:32:01.30	17.9	20.1	298	1.169
J0450.00811079	02:21:00.510	-38:31:27.92	17.9	20.0	298	1.743
J0450.00811103	02:21:00.701	-38:31:05.03	17.9	19.8	298	2.126
J0450.00811310	02:21:02.368	-38:32:44.31	17.9	19.4	298	0.795
J0450.00811427	02:21:03.414	-38:34:50.39	17.9	19.2	298	1.868
J0450.00811722	02:21:06.349	-38:34:27.38	17.9	19.5	298	1.919
J0450.00811805	02:21:07.077	-38:35:03.45	17.9	20.6	298	2.450
J0450.00811826	02:21:07.273	-38:32:55.98	17.9	19.4	298	1.637

GAIA: Aperture photometry -- co...

File Options Colours Help

Results: GaiaPhotonLog.Dat

Aperture Parameters Results

Current object details

Aperture index: 1

X position: 1436.31

Y position: 1539.17

Mean count: 361.95

Error in count: 0.16335

Sky value: 613.44

Sum in aperture: 0.29528E+06

Error code: OK

Semimajor axis: 16.2

Eccentricity:

Position angle:

Annulus inner scale: 1.5

Annulus outer scale: 2.0

Workshop

Task 5: Do some science

1. What is the pixel scale, in arcsecond/pixel, on the GMOS image?
2. What is the seeing (the FWHM of a point source in arcseconds) of the GMOS image?
3. What is the zero-point of the GMOS image?
4. What is the S/N and magnitude of the galaxy at 02:20:53.754 -38:32:45.48?
5. Make a histogram of the S/N of all the detected objects in the frame, as well as a histogram of the magnitudes. What is the 5-sigma limiting magnitude?

There are also reduced J/K-band images available in 0220/NIR/ directory

6. Align these images with the optical image and make a color image (Hint: use `hastrom` in IDL to align the images)
7. Run SExtractor in dual-mode and make a color-magnitude diagram on K vs J-K of all the detected objects. (Hint: see the SExtractor manual for dual-mode extraction)