DIS MPhil : Lecture 12

Exploring the Low Surface Brightness Universe

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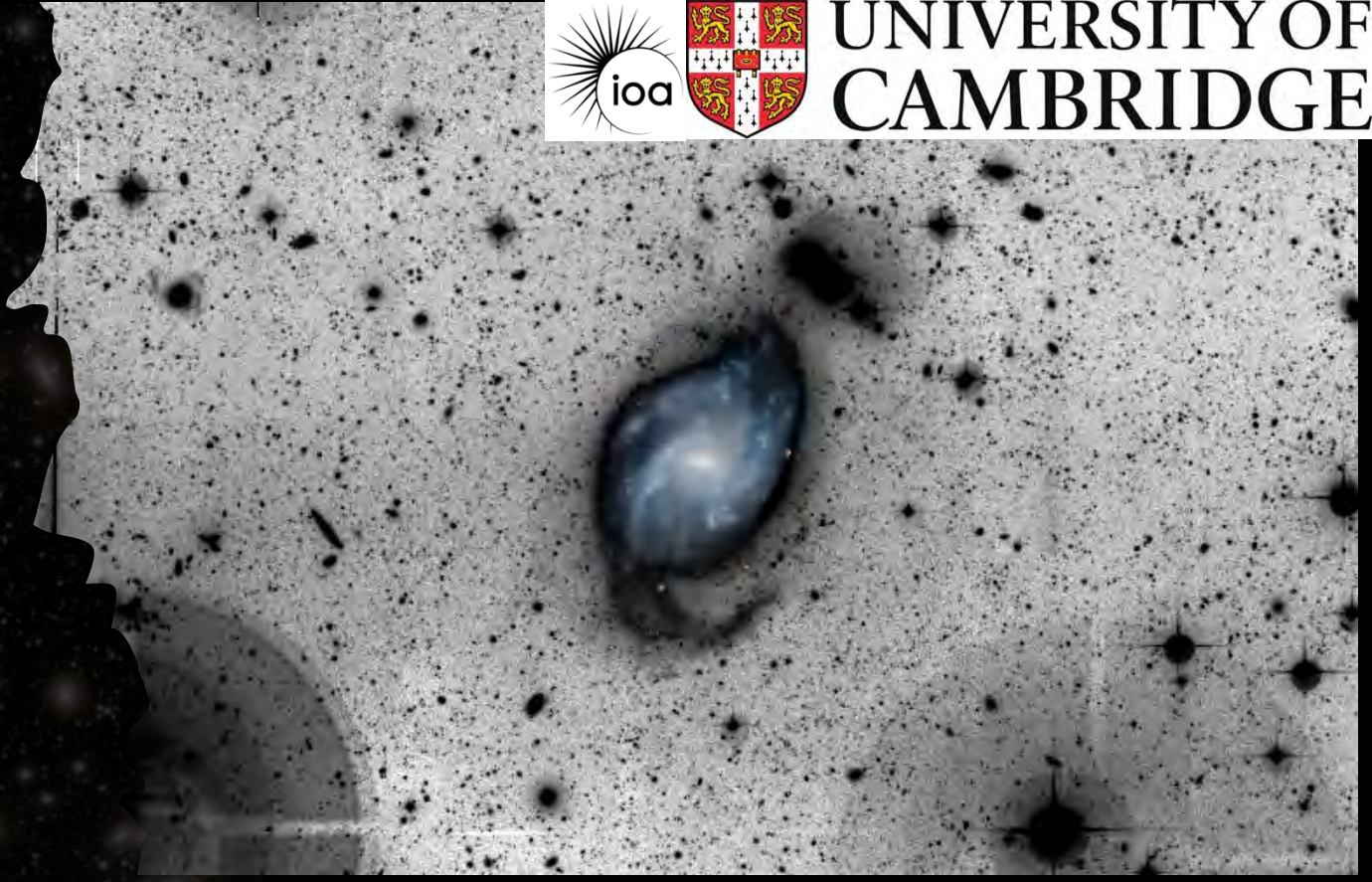
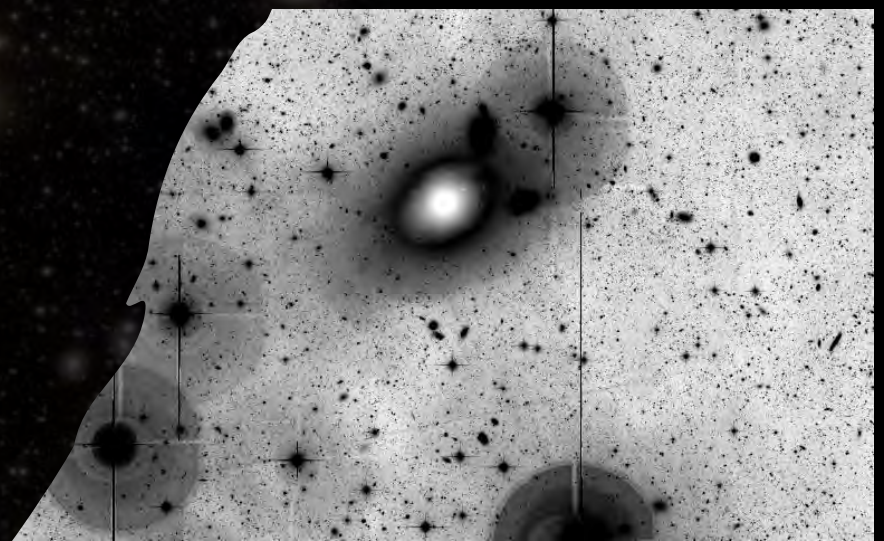
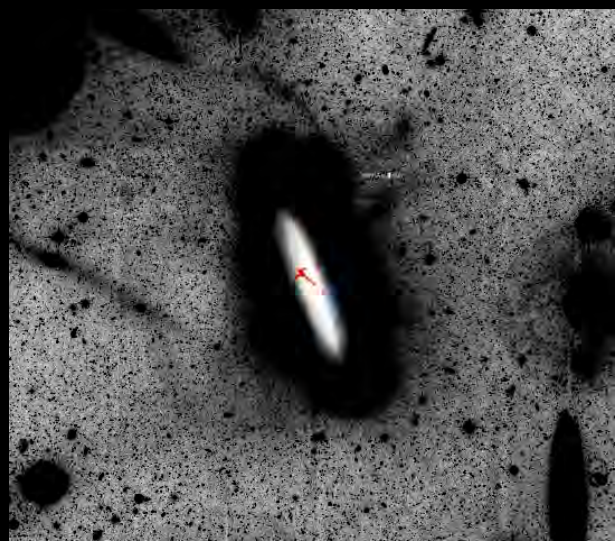
DIS MPhil – 04/03/2025







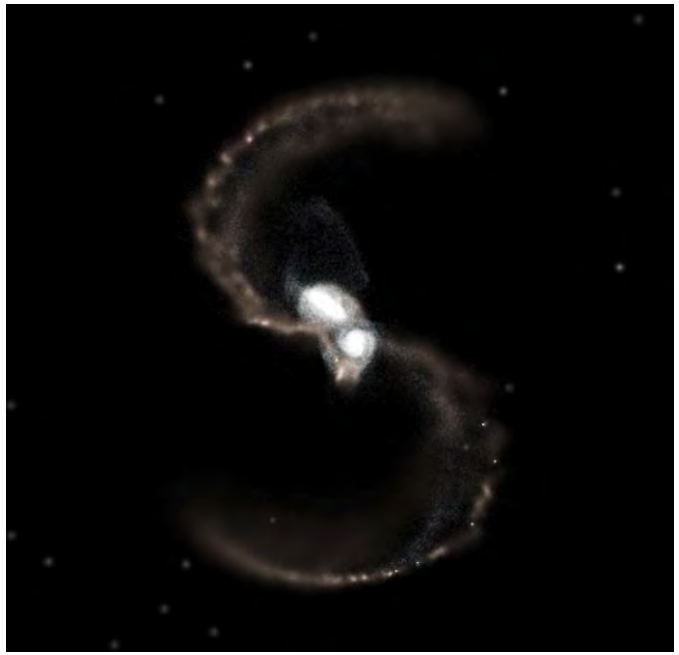
Outline of this block

Block C: Low Surface Brightness Universe & image analysis

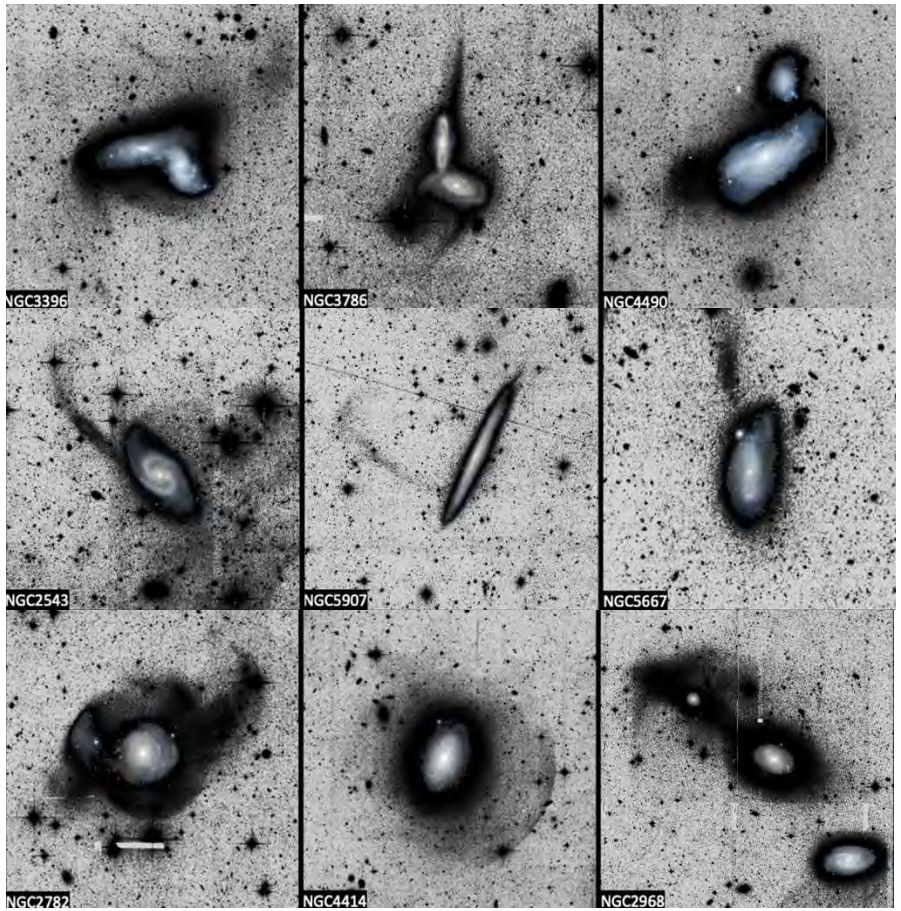
1. **28/02/2025: Galaxies in the Local Universe:** Introduction to models of galaxy formation and evolution. Galaxy mergers and tidal features. Tidal features in the Local Group and beyond.
2. **04/03/2025: Exploring the LSB Universe**: Deep astronomical imaging and data processing techniques. The LSB Universe. Hunting for tidal features in the LSB realm.
3. **07/03/2025: LSB features and galactic evolution**: LSB features as probes of galactic evolution. Ongoing and future surveys. Machine learning for LSB features.
4. **11/03/2025: Hands-on session**: explore astronomical images and catalogues with Aladin, DS9, Topcat, Python

Recap of Lecture 11

- Hierarchical build-up of galaxies through **mergers** and gas accretion
- The **environment** strongly shapes galactic evolution
- Mergers leave behind **tidal features** which hold the clues of the late galaxy assembly

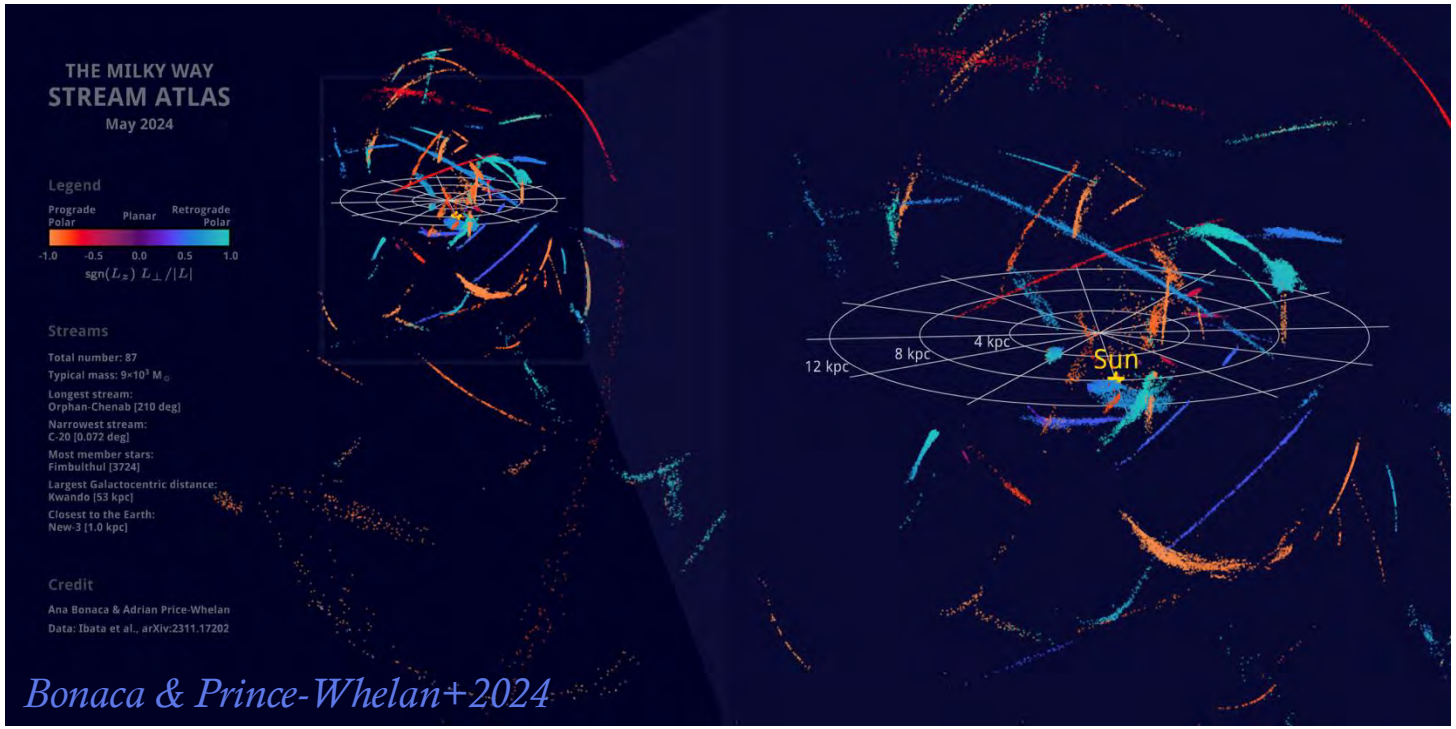


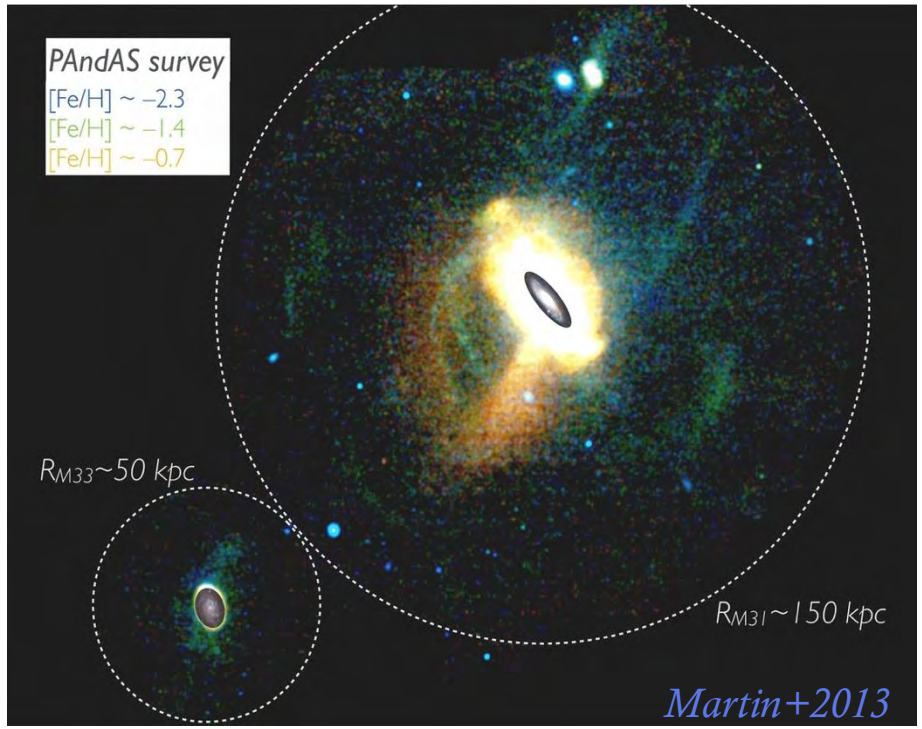
Sola+2022



Recap of Lecture 11

- Tidal features are **faint = low surface brightness**
- In the Local Group, they are disclosed by stellar count

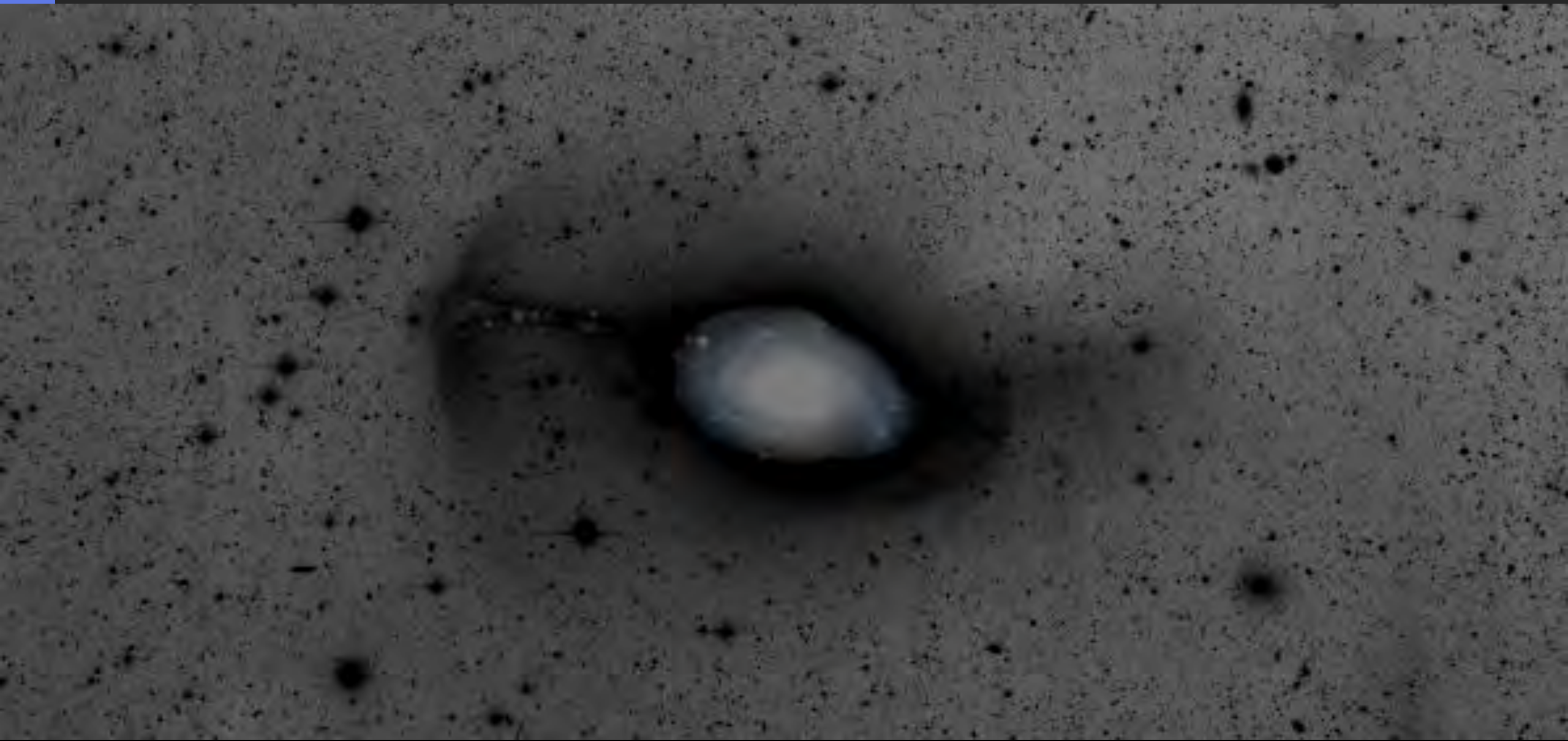




Outline: Lecture 12

- Astronomical images + catalogues
- Image processing to reveal the LSB Universe
- Finding tidal features in deep images

Astronomical images

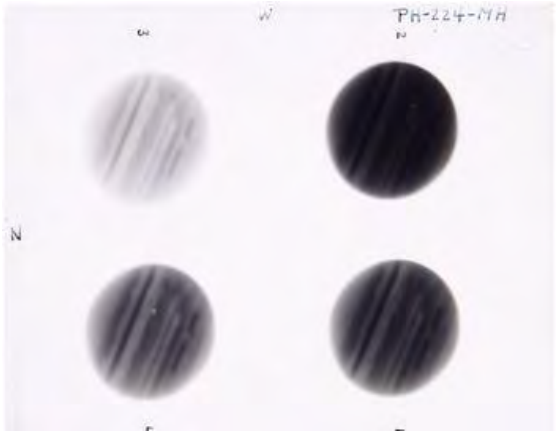


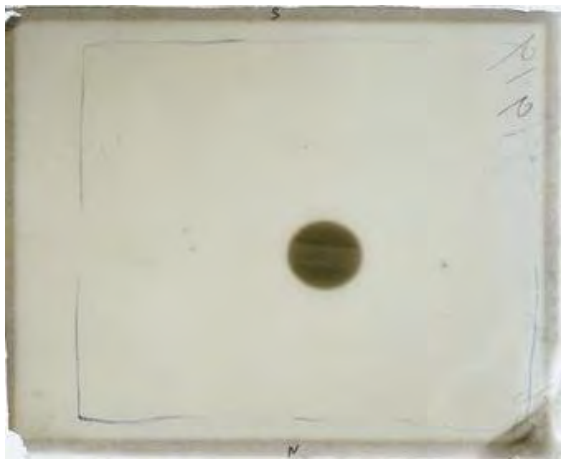
Celestial globes

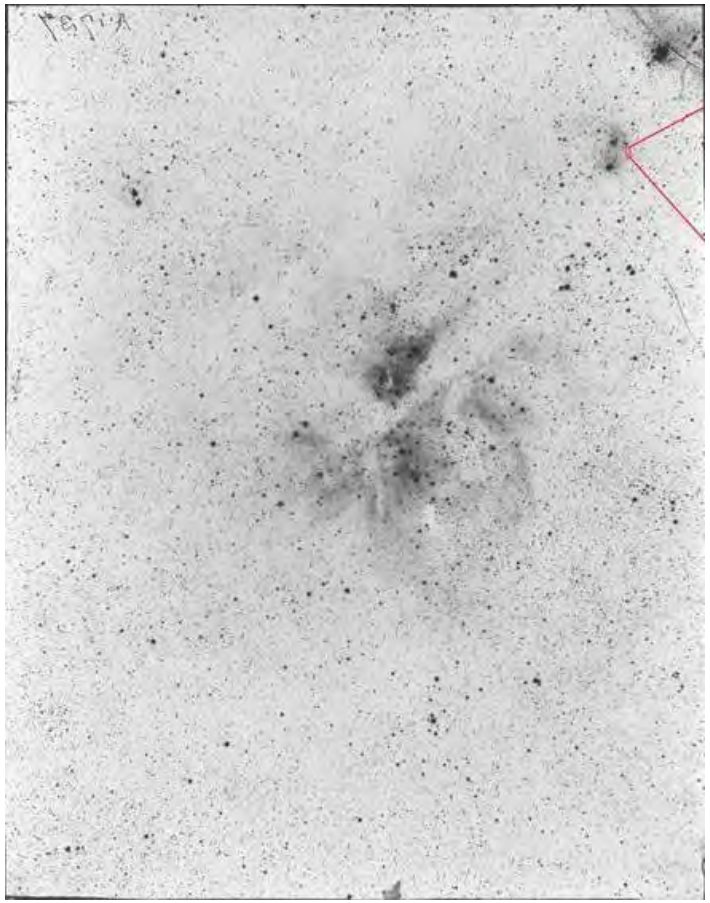
- Celestial globes: apparent position of stars on the sky

Photographic plates

- 19th century - 1980s: pictures of celestial objects on glass plates: **photographic plates**







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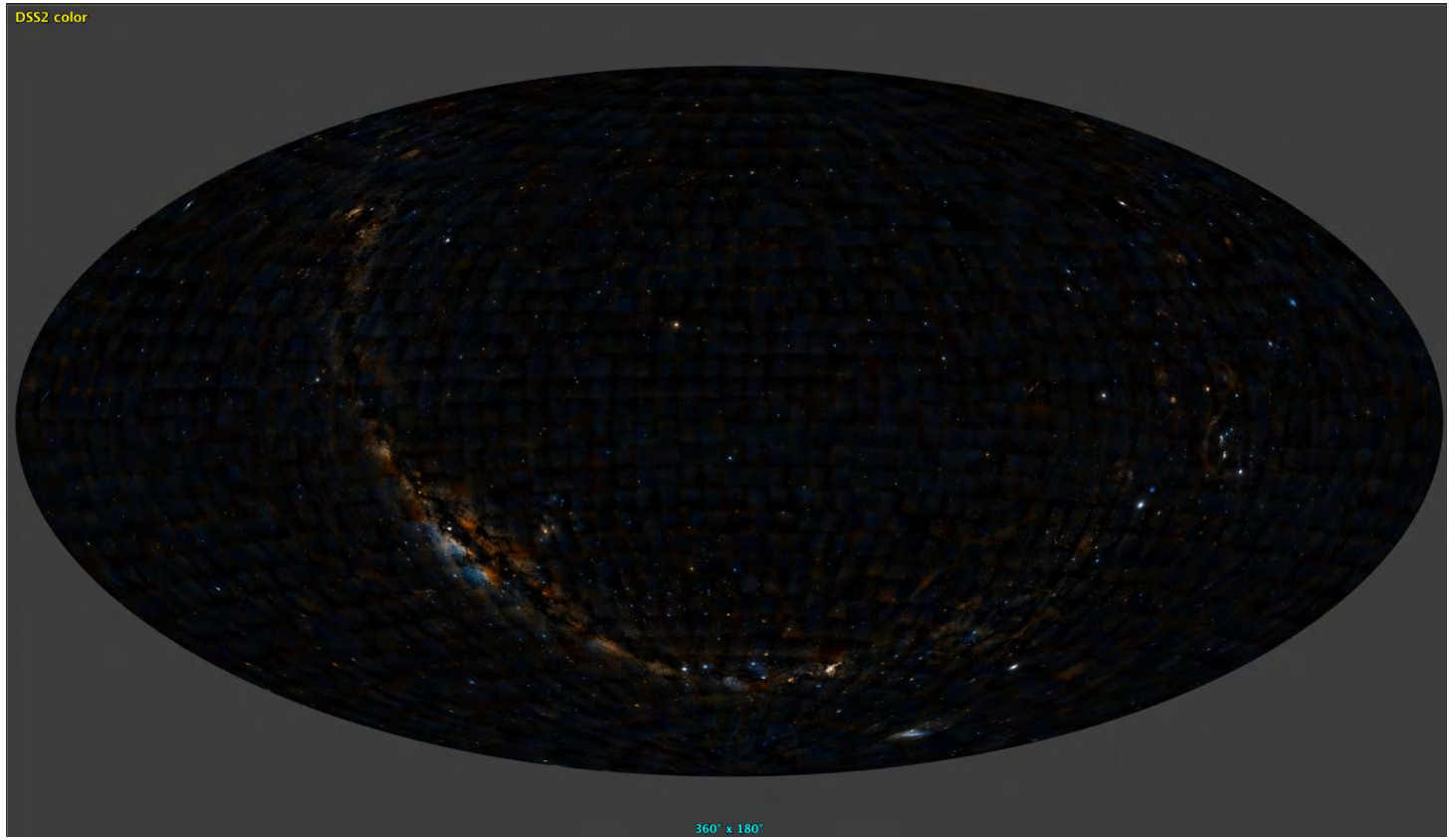
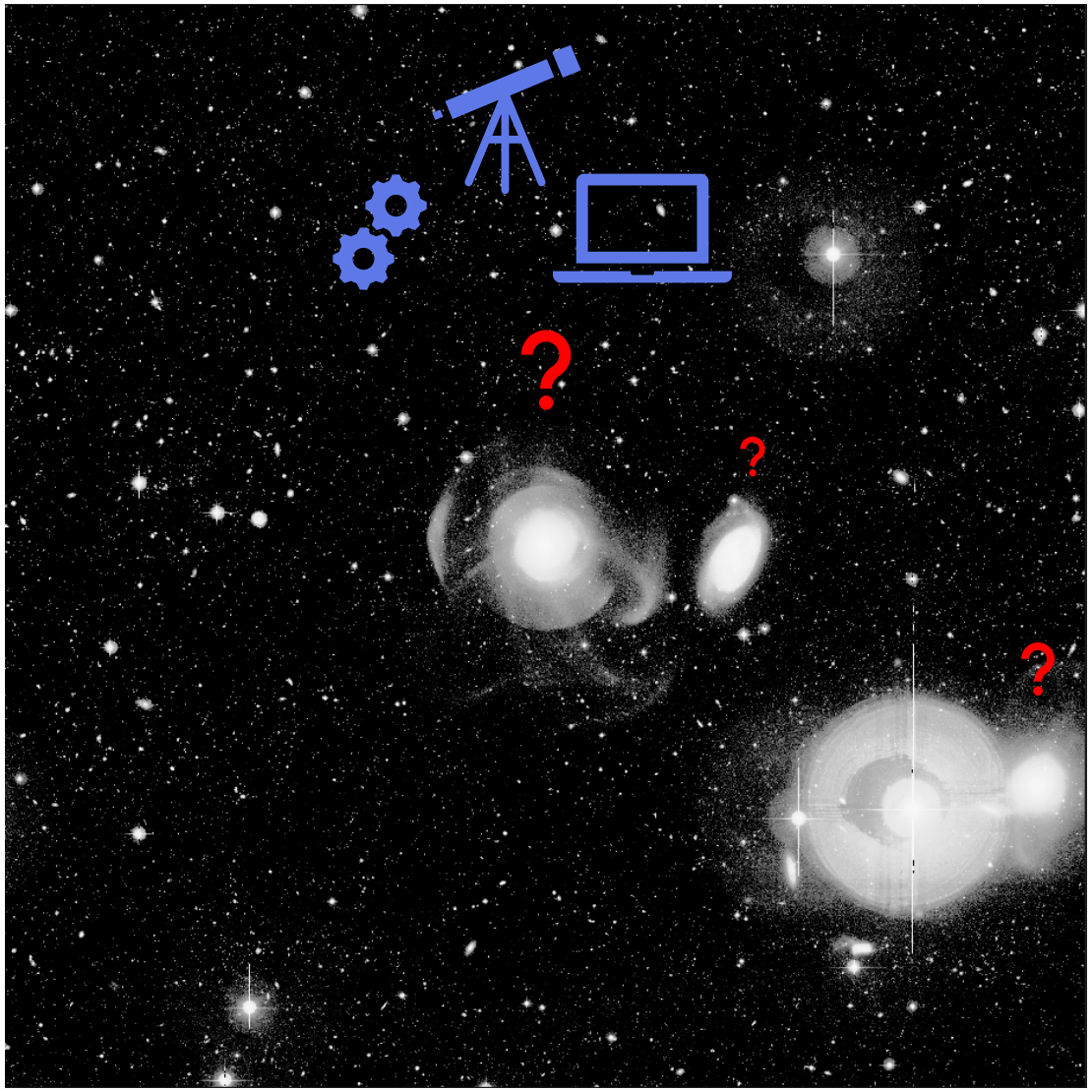
Digitalising photographic plates

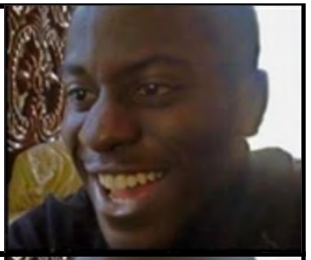
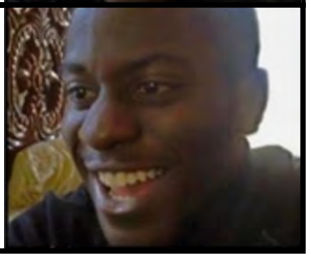
- DSS: Digitized Sky Survey: digital version of photographic plates of the entire sky obtained at Palomar and UK Schmidt telescopes



- >1980s: CDD cameras, numerical images

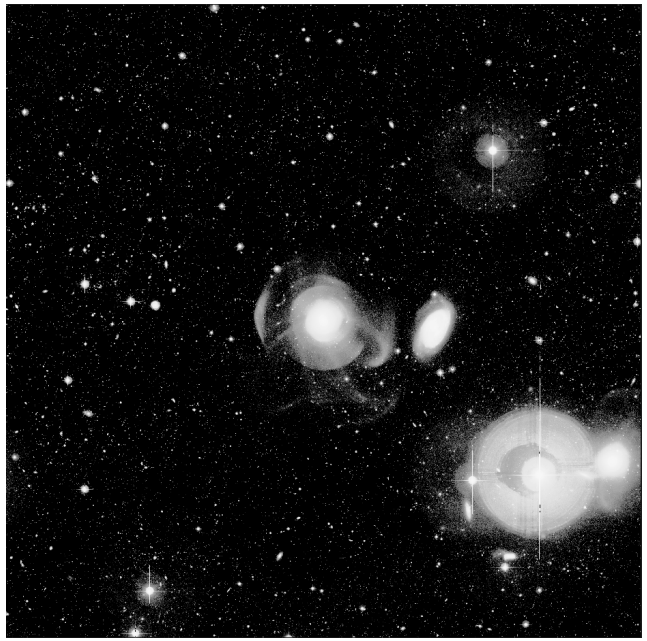
Back to basics: what is an image made of ?



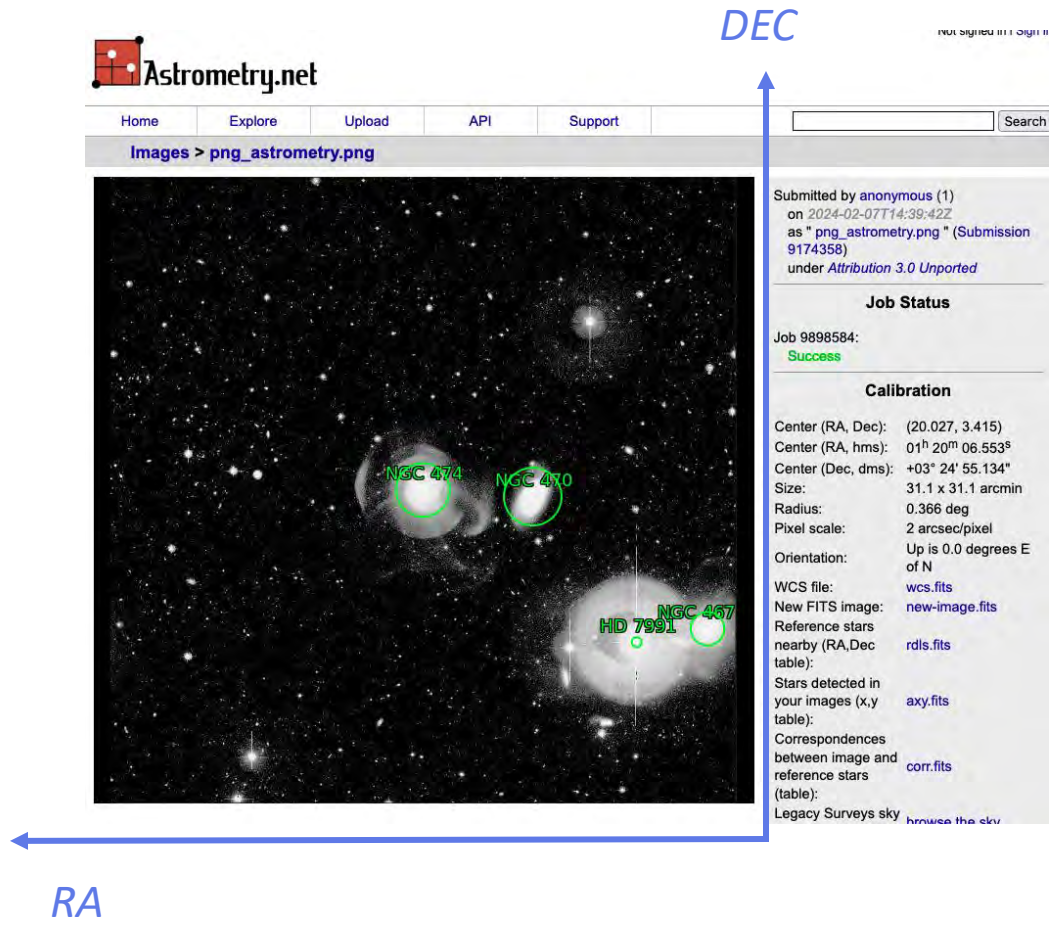
You got amazing images	
Actually, they're useless	
Unless you have astrometric calibration	

Astronomical images: pixels and what else?

Raw file
(ex: png, jpeg)



Astrometric calibration
(x,y)_image -> (RA,DEC)_sky



Astronomical images

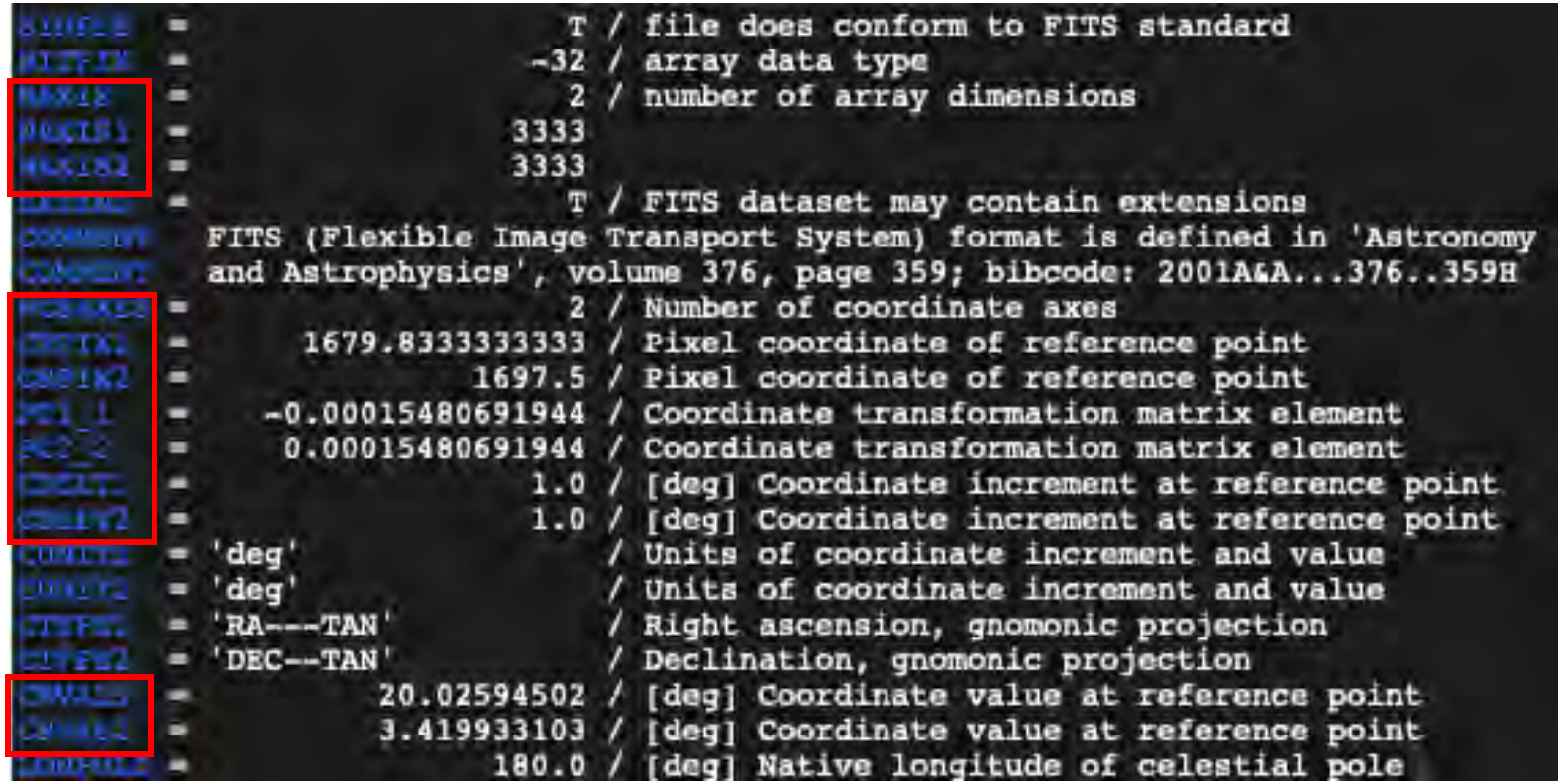
- Different formats of images: png, jpeg, tiff…
- Not appropriate for astronomical data: compression, small resolution, limited number of data channels
- ► **FITS** (Flexible Image Transport System) format widely used:
    - Can store multiple channels for multi-wavelength observations or 3D cubes
    - Metadata containing photometric and spatial calibration information
    - Unlimited metadata
    - Higher resolution
    - Huge dynamical range
- FITS = **data** + **header**

Headers

- Headers contain all the important metadata, especially the **WCS** (World Coordinate System) used to transform (x,y) pixels to (RA,Dec) in the sky
- Syntax: KEYWORD = value / Comment

Number of axes and number of pixels per axis

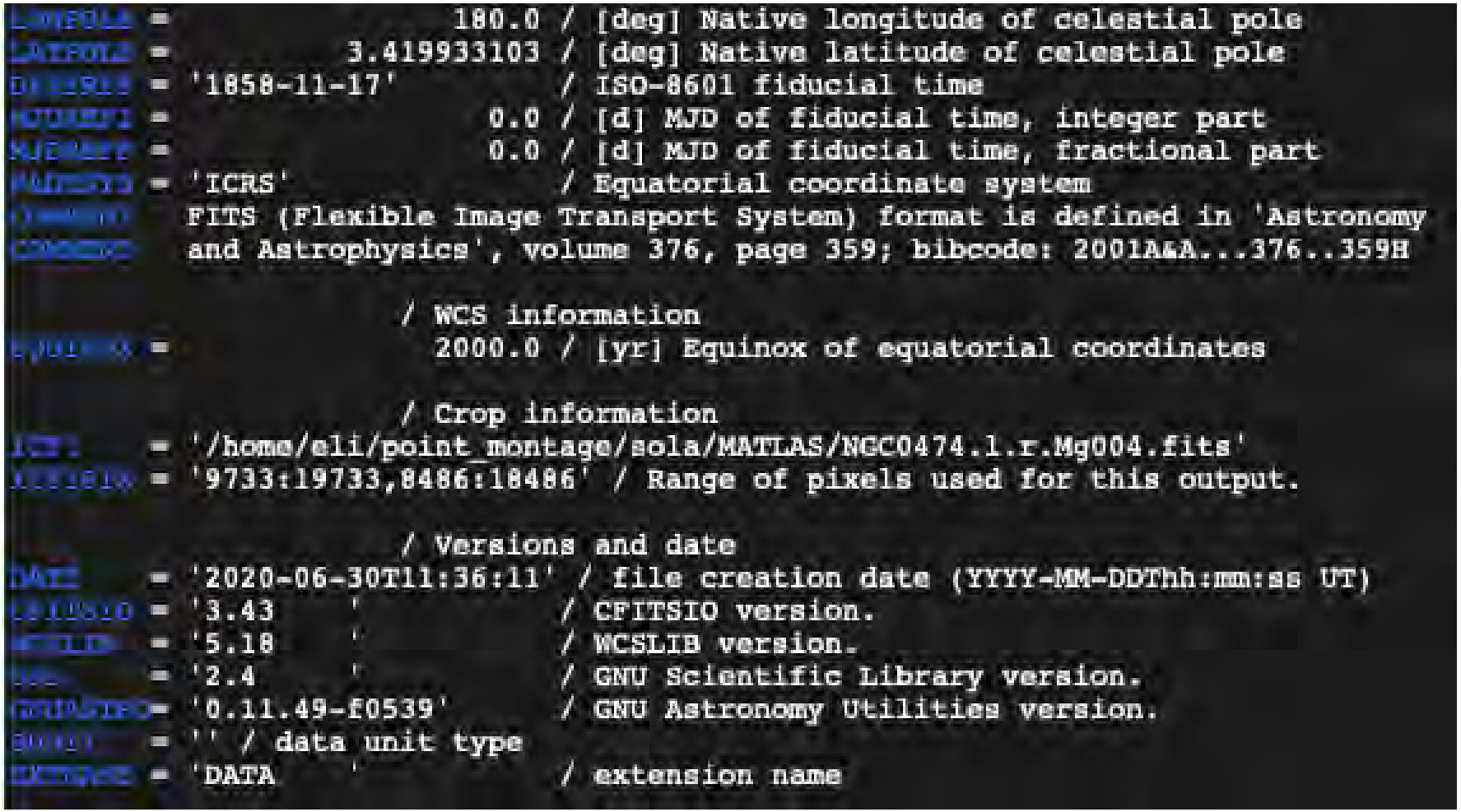
Pixel/world transformation + units and projection



```
                  T / file does conform to FITS standard
                -32 / array data type
                  2 / number of array dimensions
               3333
               3333
                  T / FITS dataset may contain extensions
FITS (Flexible Image Transport System) format is defined in 'Astronomy
and Astrophysics', volume 376, page 359; bibcode: 2001A&A...376..359H
                  2 / Number of coordinate axes
     1679.8333333333 / Pixel coordinate of reference point
              1697.5 / Pixel coordinate of reference point
   -0.00015480691944 / Coordinate transformation matrix element
    0.00015480691944 / Coordinate transformation matrix element
                1.0 / [deg] Coordinate increment at reference point
                1.0 / [deg] Coordinate increment at reference point
'deg'               / Units of coordinate increment and value
'deg'               / Units of coordinate increment and value
'RA---TAN'          / Right ascension, gnomonic projection
'DEC--TAN'          / Declination, gnomonic projection
         20.02594502 / [deg] Coordinate value at reference point
         3.419933103 / [deg] Coordinate value at reference point
               180.0 / [deg] Native longitude of celestial pole
```

Headers

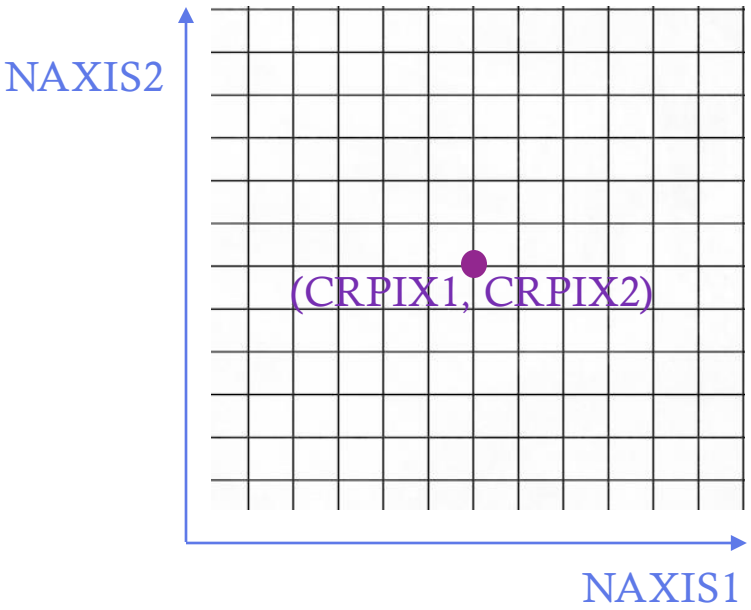
- All these are non-mandatory keywords. Read the comment to understand what they mean



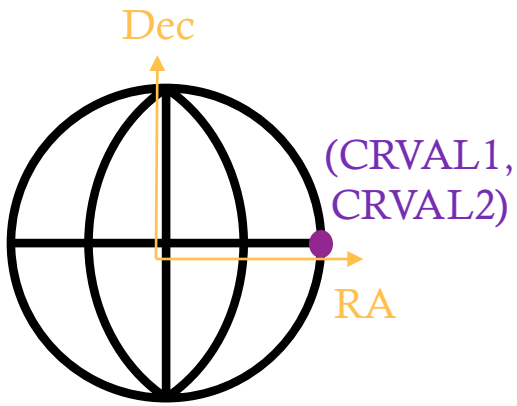
Minimal header

Other notation: PC_i_j with CDELT = 1" is equivalent to CD_i_j

```
SIMPLE  =                    T
BITPIX  =                    8
NAXIS   =                    2
NAXIS1  =                 4096
NAXIS2  =                 4096
CTYPE1  = 'TAN      '
CUNIT1  = 'degree   '
CRVAL1  =                  180
CRPIX1  =                 2048
CD1_1   = -0.00038197186341489
CTYPE2  = 'TAN      '
CUNIT2  = 'degree   '
CRVAL2  =                    0
CRPIX2  =                 2048
CD2_2   =  0.00038197186341489
END
```

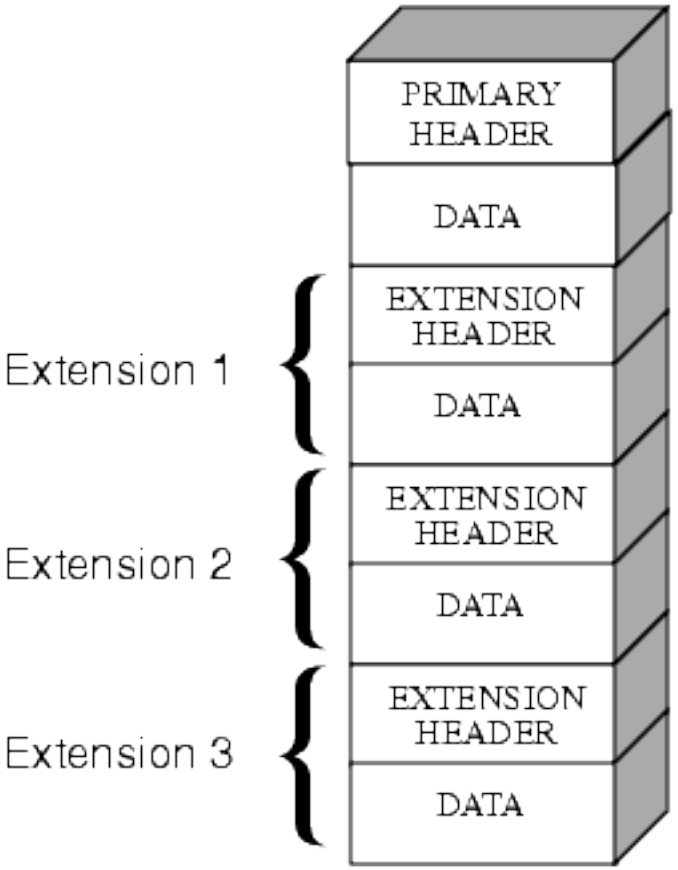


→ $\begin{pmatrix} CD1\_1 & CD1\_2 \\ CD2\_1 & CD2\_2 \end{pmatrix}$ Encodes pixel size + transformations →



Multiple extensions

- FITS can store several extensions



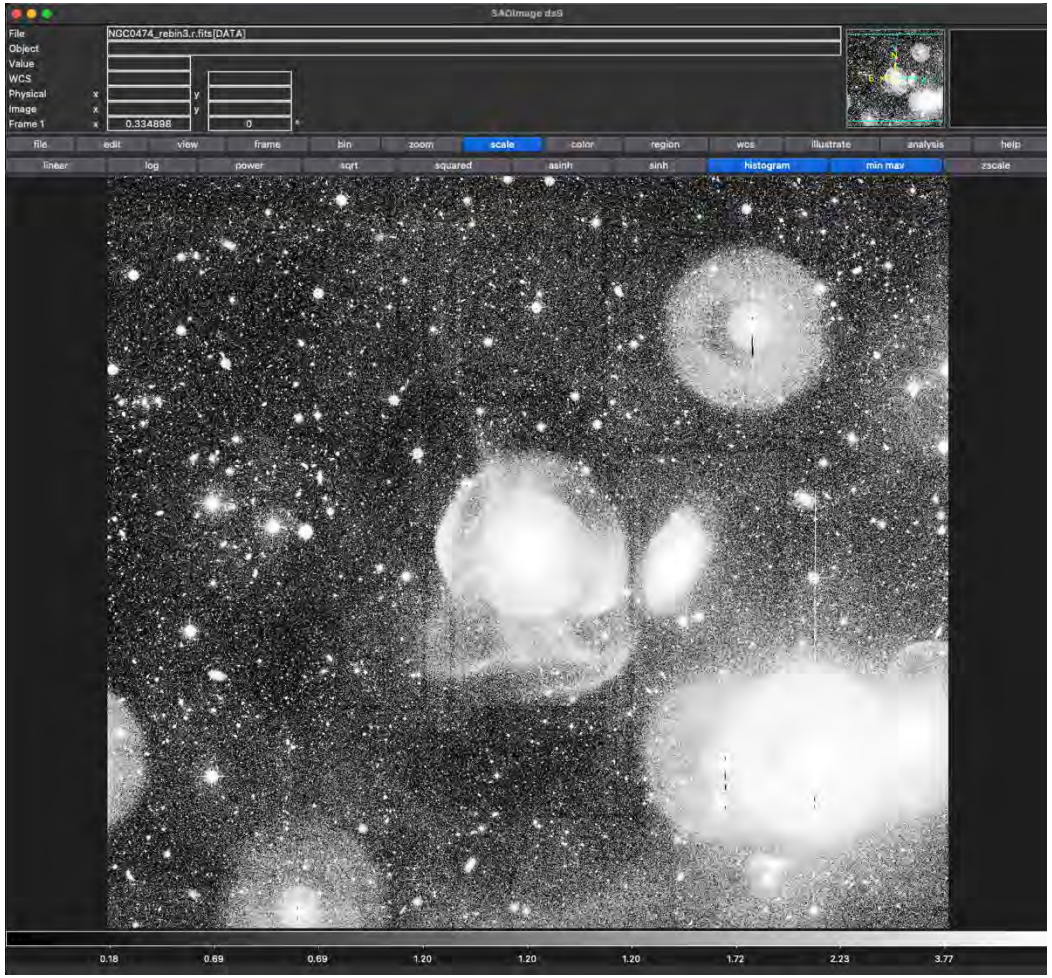
https://www.stsci.edu/hst/wfpc2/Wfpc2_dhb/intro_ch23.html

Q? Explain this header !

```
SIMPLE  =                    T / conforms to FITS standard
BITPIX  =                  -32 / array data type
NAXIS   =                    3 / number of array dimensions
NAXIS1  =                 1825
NAXIS2  =                 1825
NAXIS3  =                    3
WCSAXES =                    3 / Number of coordinate axes
CRPIX1  =                913.0 / Pixel coordinate of reference point
CRPIX2  =                913.0 / Pixel coordinate of reference point
CRPIX3  =                  0.0 / Pixel coordinate of reference point
PC1_1   = -0.00016666666666667 / Coordinate transformation matrix element
PC2_2   =  0.00016666666666667 / Coordinate transformation matrix element
CDELT1  =                  1.0 / [deg] Coordinate increment at reference point
CDELT2  =                  1.0 / [deg] Coordinate increment at reference point
CDELT3  =                  1.0 / Coordinate increment at reference point
CUNIT1  = 'deg'                / Units of coordinate increment and value
CUNIT2  = 'deg'                / Units of coordinate increment and value
CTYPE1  = 'RA---TAN'           / Right ascension, gnomonic projection
CTYPE2  = 'DEC--TAN'           / Declination, gnomonic projection
CRVAL1  =             8.008776 / [deg] Coordinate value at reference point
CRVAL2  =          -64.2533874 / [deg] Coordinate value at reference point
CRVAL3  =                  0.0 / Coordinate value at reference point
LONPOLE =                180.0 / [deg] Native longitude of celestial pole
LATPOLE =          -64.2533874 / [deg] Native latitude of celestial pole
MJDREF  =                  0.0 / [d] MJD of fiducial time
RADESYS = 'ICRS'               / Equatorial coordinate system
COMMENT grz data
COMMENT data from ls-dr9
END
```

Image visualisation tools: DS9

- **SAOImageDS9** (ds9) *https://sites.google.com/cfa.harvard.edu/saoimageds9*



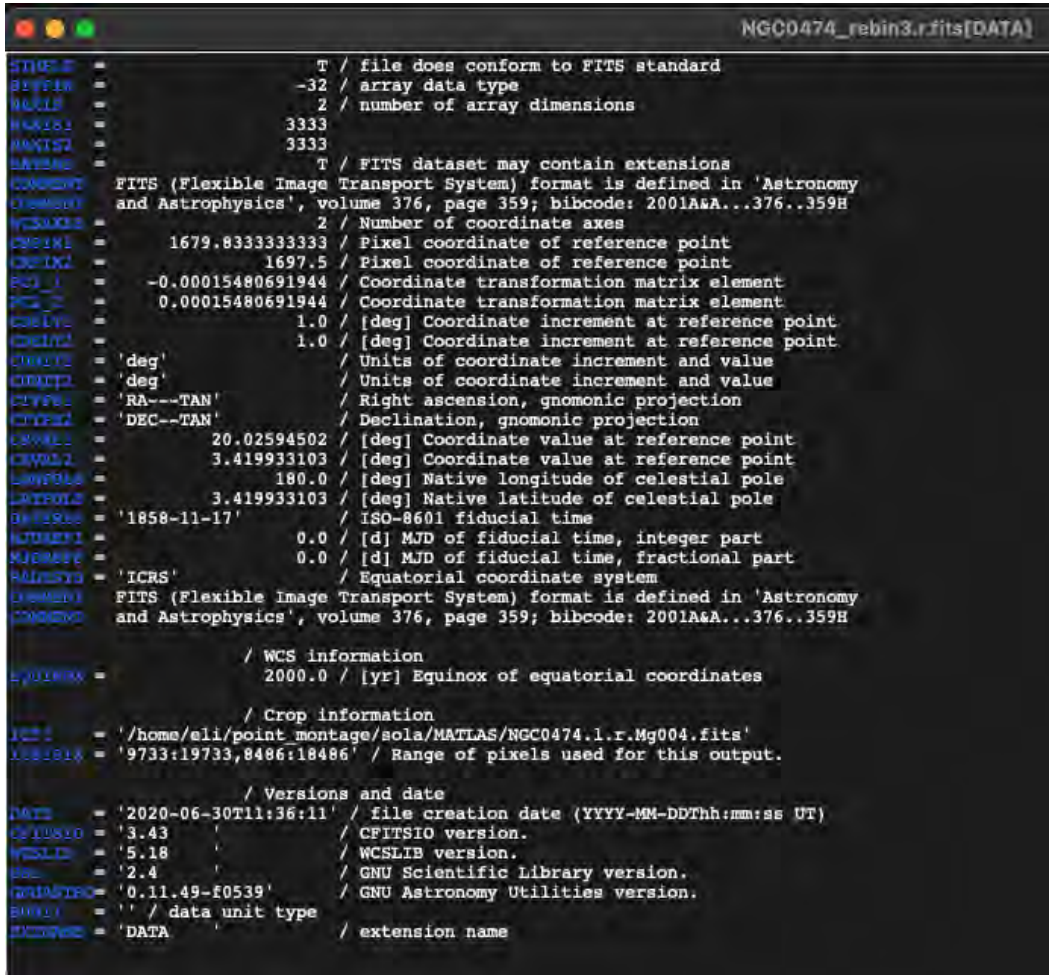


Image visualisation tools: Aladin

- **Aladin** (CDS): interactive sky atlas to visualize astronomical images or full surveys, query catalogues and entries from the Simbad database, Vizier service and other archives

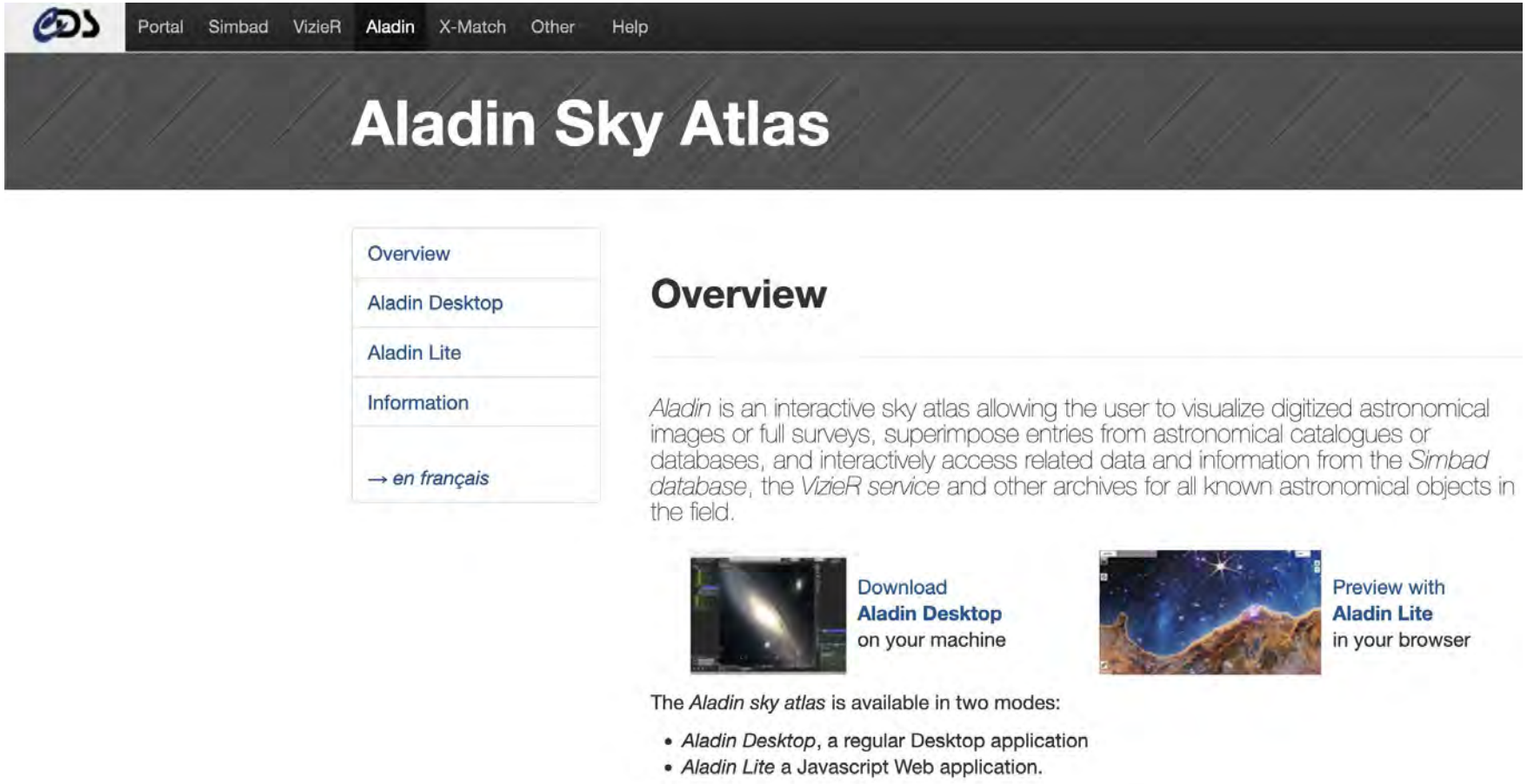


Image visualisation tools: Aladin

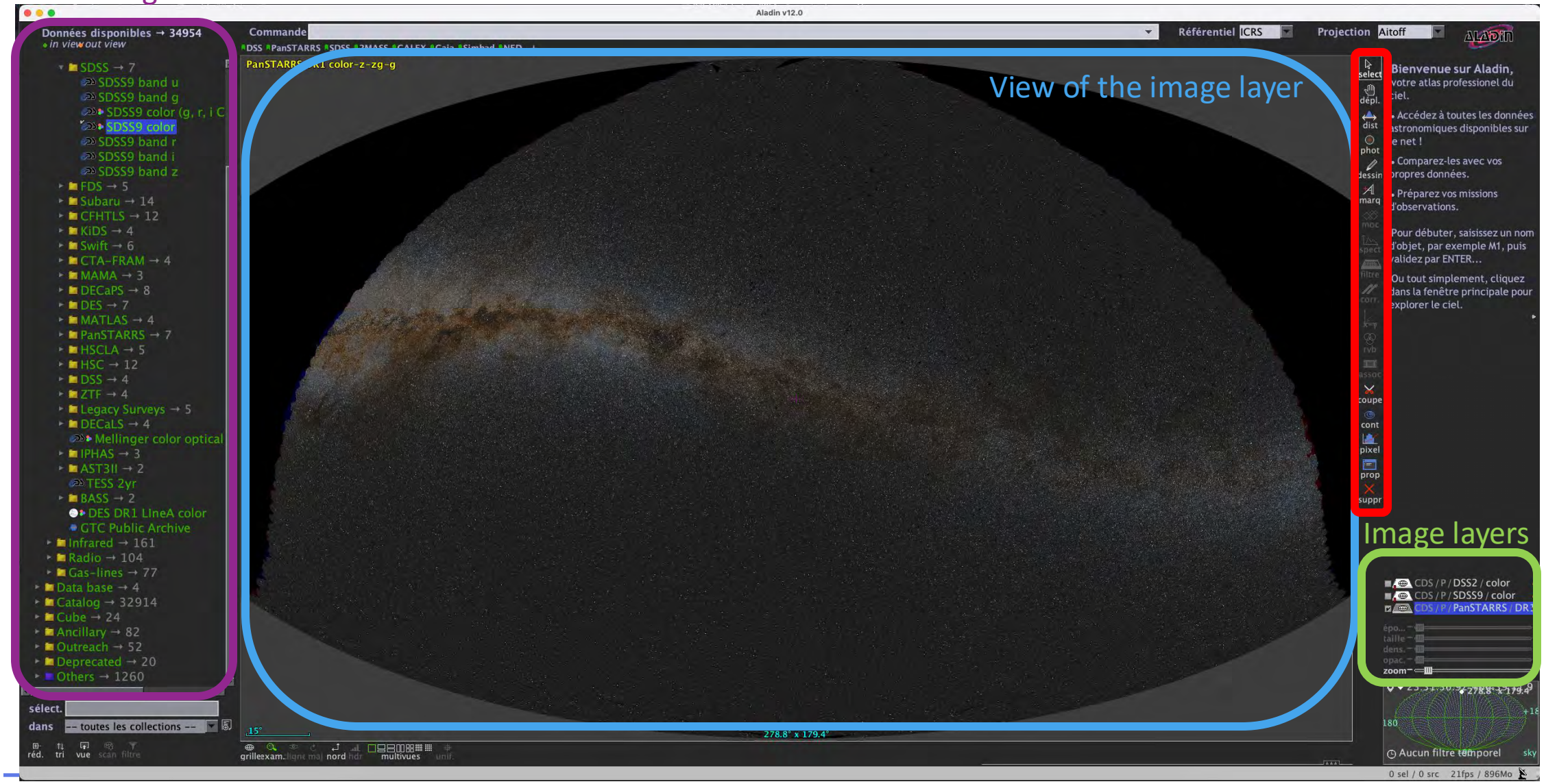


Image visualisation tools: Aladin

Image visualisation tools: others

- Plenty of other softwares

FITS Image Software Packages

for image viewing, analysis, and format conversion

The following software packages display or manipulate the relatively simple class of FITS data files that containing 2-dimensional images, often of celestial objects in the night sky. It should be noted that FITS is a very general data format that is used for many different types of astronomical data sets, so these packages are not necessarily capable of reading every type of FITS file. Developers of new image display programs should be aware of the special requirements for effectively displaying FITS images.

FITS Image Viewers

- Image viewers for PC and Macs - an extensive listing of commercial and freeware image processing software compiled by the Astronomy Education Committee.
- Aladin - Interactive Sky Atlas
- APLpy - Astronomical Plotting Library in Python is a Python module aimed at producing publication-quality plots of astronomical imaging data in FITS format.
- Aperture Photometry Tool - interactive software tool for visualizing and performing aperture photometry measurements on astronomical images.
- ASTAP: viewer, image stacker, plate solver This program, available as an executable on Windows, Macs and most varieties of Linux, supports 8, 16, and 32 bit integer images and also 32-bit floating point. including images using FITS compression. Users can determine the astrometric properties of images, stack and display them, including blind solving of the astrometry of each image using the GAIA database.
- AstroImageJ: processing, modeling and plotting astronomical image data in one package based upon the ImageJ Java library.
- Avis FITS Viewer - a FITS viewer for Windows. Only reads 8 and 16 bit FITS images. Converts to RAW, TIF, TGA, BMP, and JPEG formats
- Carta FITS Viewer - an image visualizing tool designed for professional researchers to support very large files (GB to TB size) from ALMA, VLA, and SKA pathfinders. Supports FITS, CASA, and HDF5 data formats.
- CCDLAB - a FITS image viewer and data reducer for Windows platforms based upon the JPFITS FITS file interface. Features include functionality for manipulating the image data and header keywords, batch processing, general image reduction, source detection, and automatic or manual World Coordinate solutions
- Clearsky viewer - a javascript library for viewing a FITS image. Features include multiple regions of interest, stats, contrast, magnifying glass and more.
- ds9 (SAOImage) - astronomical visualization application from SAO
- FITS Liberator - a plug-in for Adobe Photoshop for manipulating FITS format images. Also works with Photoshop Elements 2. Includes a short introduction to astronomical image processing.
- Fits4Win2 Viewer (shareware with free beta version) - a FITS viewer for Windows. Works as an extension to Windows Explorer and includes support for viewing thumbnail images of FITS files.
- FitsPlug v2.0 (shareware with free beta version) - a FITS plug-in for Adobe Photoshop for Windows
- FITSview - FITS image viewer from NRAO
- fv - FITS file viewer and editor (supports FITS images and FITS tables)
- GAIA - an image display and analysis tool from the U.K. Starlink Project. It is a derivative of the ESO SkyCat tool
- Ginga - a Python toolkit for visualizing 2D pixel data in NumPy arrays. Supports FITS format data.
- giv - A cross platform (posix and Windows) image viewer designed especially for scientific vision and computational geometry. Supports interactive brightness and contrast adjustment of 2D images and 3D cubes in various data formats, including FITS. Also supports drawing vector graphics on top of the image.
- GLnemo2 - an interactive 3D visualization program for n-body snapshots which supports 2D and 3D FITS data, as well as other data formats. GLnemo2 is open source, multi-platform (linux, MacosX, windows), and uses qt5 API and openGL hardware acceleration.
- Gluevis - a Python library designed for professional researchers to explore relationships within and between related datasets.
- ImageJ - a public domain, Java-based image processing program developed at the National Institutes of Health. ImageJ was designed with an open architecture that provides extensibility via Java plugins and recordable macros. It supports 8-bit and 16-bit integer and 32-bit floating point images and RGB color images.
- ImageTOOLSca (shareware, with a free trial period) - a FITS image viewer for Windows. Supports 16 and 32 bit integer FITS images. It can convert to or from other image formats such as TIFF, JPG, BMP, and Photoshop PSD, and can create AVI animations from a sequence of images. Also supports some image processing tasks such as bias subtraction and flatfielding.
- JS9 - next generation astronomical visualization from SAO for both desktop and web applications.
- KStars - KStars is free, open source, cross-platform (Linux, OSX, Windows) Astronomy Software. It provides an accurate graphical simulation of the night sky, from any location on Earth, at any date and time. KStars FITS Viewer tool supports grey scale and color (3D Cube) across all bit depths. It can display captured images from INDI cameras and video cameras.
- Libvips - a fully demand-driven, threaded image processing library with no image size limits and with good support for colour. Reads and writes FITS images, as well as TIFF, JPEG, PPM, PNG, and other file formats. Has interfaces to C, C++ and Python, and a command-line interface that can be called from shell scripts.
- MicroObservatory Image 2.0 - astronomical image display program works with FITS and GIF images on PCs and Macs. Can also perform mathematical image processing operations on multiple images.
- PhAst - A flexible IDL tool to display and analyze FITS images. It can calibrate raw images, provide astrometric solutions, and do circular aperture photometry. PhAst allows the user to load, process, and blink any number of images. Requires either an IDL license, or installation of the (free) IDL Virtual Machine.
- QFitsView - An image viewer for 1-D, 2-D, and 3_D FITS images. It is written in C++ and uses the Qt widget library. Binary executables for Microsoft Windows, Linux, and Mac OSX, as well as the source code, are available.
- RSpec - A Windows software package with many spectroscopic analysis features that can process 2D FITS images and 1D tables. Can remove background, rotate, extract and process profiles. 30-day free trial version available.
- Siril - an astronomical image processing tool specially tailored for noise reduction and improving the signal/noise ratio of an image by stacking multiple exposures. Siril provides a large set of dedicated algorithms which can be run manually or in automated processing scripts. This free beta-release software runs on Linux, Windows or macOS.
- SkyCat - ESO tool combines image visualization and access to catalogs
- SpacePixels - SpacePixels is an astronomical image (FITS) manipulation tool supporting object detection (asteroids, comets, spacecraft, ...). It is intended to be an easy-to-use tool for amateur astronomers. The input to SpacePixels is a set of aligned and calibrated images which can be generated by stacking software such as Deep Sky Stacker. It can stretch and blink (animate) a set of FITS images to visually detect moving objects. It can solve for the astrometric coordinates within an image, and has batch processing capabilites to process multiple images. This is an alpha-release of the software, with more features planned.
- Tna - an advanced image processing suite for Windows platforms (only), including deconvolution, image registration, and noise filtering functions. Supports FITS, TIFF, BMP, JPEG, PNG, and WMF image formats.
- xv (shareware) - interactive image manipulation program for X Window systems
- xINDI - xINDI is a suite of native astronomical software tools for MacOS X built around INDI standard. It consists of binary INDI distribution wrapped into INDI Server application, INDI Control Panel application and FITS Viewer. The viewer is based on CFITSIO library and supports all standard monochromatic and color FITS image formats. It shows both an image (zoomed and stretched automatically, but manual correction of black and white point is available) and the image metadata.

https://fits.gsfc.nasa.gov/fits_viewer.html

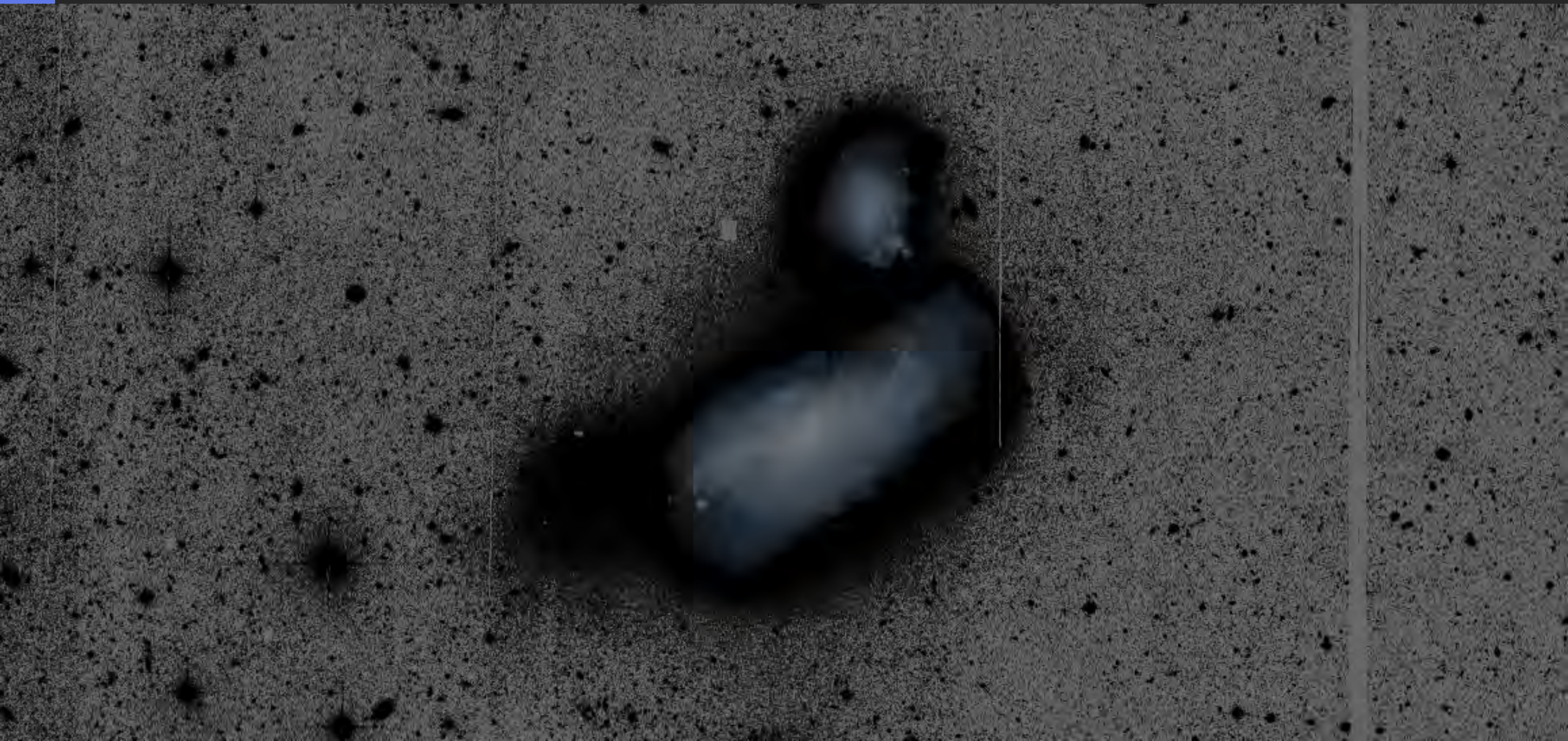
Survey specific viewers

- DESI Legacy Imaging Surveys

Survey specific viewers

- ESA sky (relies on Aladin)

Catalogues



Catalogues

- **Catalogues**: collection of astronomical objects, identified by a name/ID, position, type…
- Impossible to manually go through all of them
- **Databases** and **services** to access these catalogues: Vizier, Simbad, Gaia, NED, LEDA, SDSS…
- Accessible through APIs, SQL, TAP, …

Wikipedia

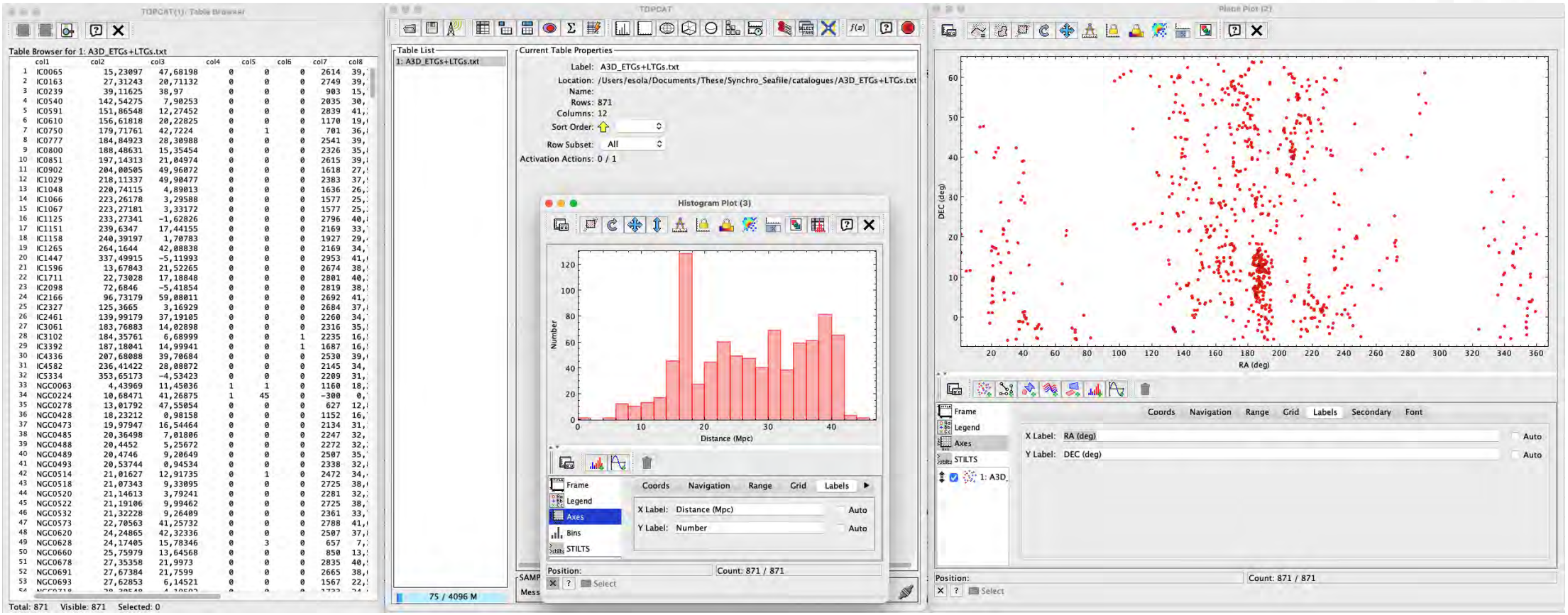
Catalogue visualisation tools

- Many softwares/services/platforms to open/read/access/catalogues
- **TOPCAT** widely used. Many tools (tables, plots, cross-match)

TOPCAT

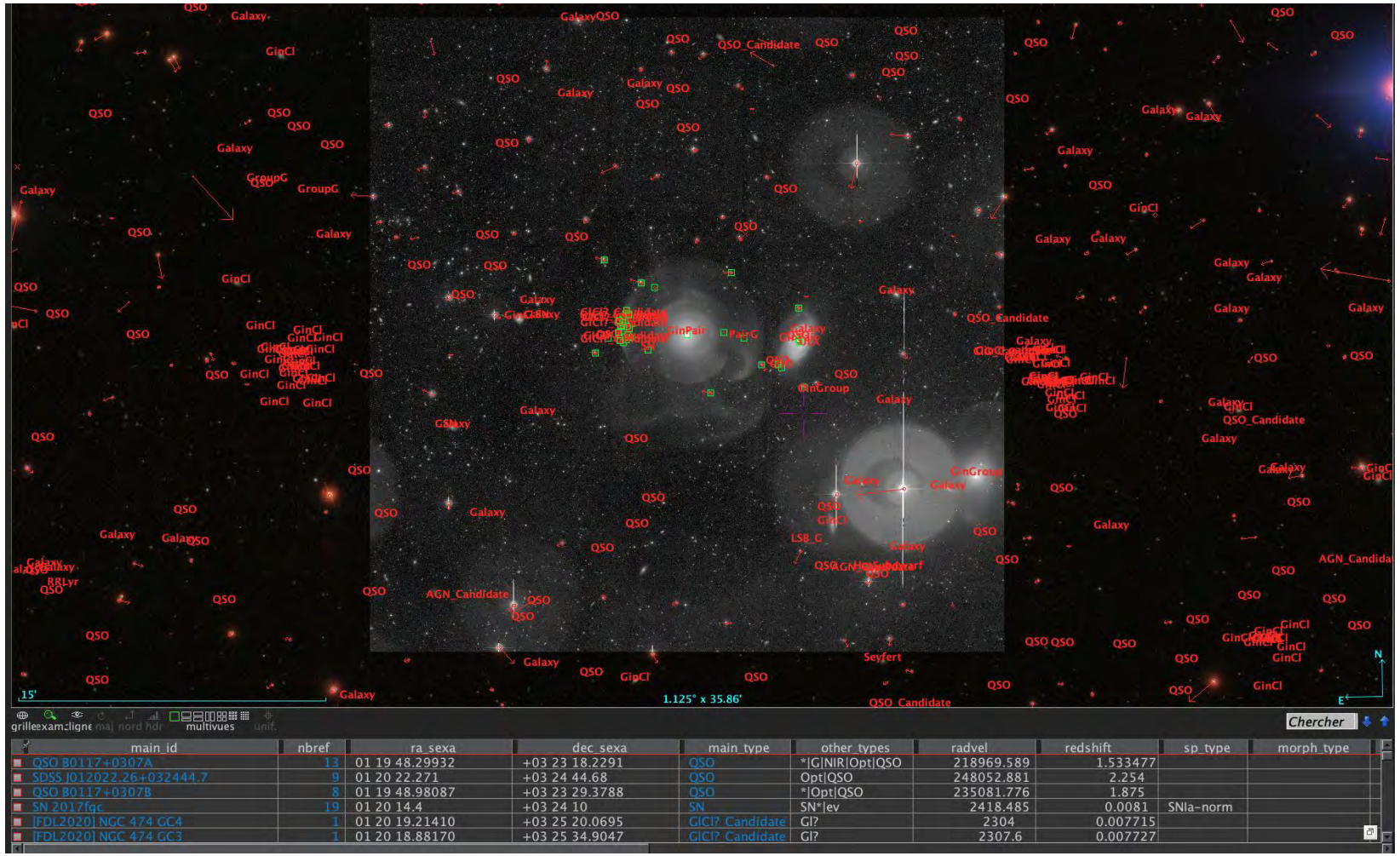
Tool for OPerations on Catalogues And Tables

Does what you want with tables



Catalogues and Aladin

- Overlay information from catalogues in Aladin from Simbad, NED, Gaia, your own tables



Cross-matching catalogues

- **Cross-match**: identify the same celestial objects from several catalogues

Q? How ?

Name	RA	Dec	Photometry
NGCXXX	0	30	18
NGCYYY	145	42	22
…	…	…	…
PGCZZZ	22	25	14

Cat A: 15 million rows

Name	RA	Dec
AbellABC	89	11
UGCXX	145	42
…	…	…
NGCYYY	145	42
PGCCDE	145	41.8

Cat B:169 rows

- **By identifier**: easiest, most obvious

… but almost never possible. Even the well-known objects have several identifiers.

- **By coordinates**: yes, but need to define a cross-match radius

Cross-matching catalogues

- **Need to specify:**
- Cross-match radius
- Cross-match type: one-to-one, one-to-many,…

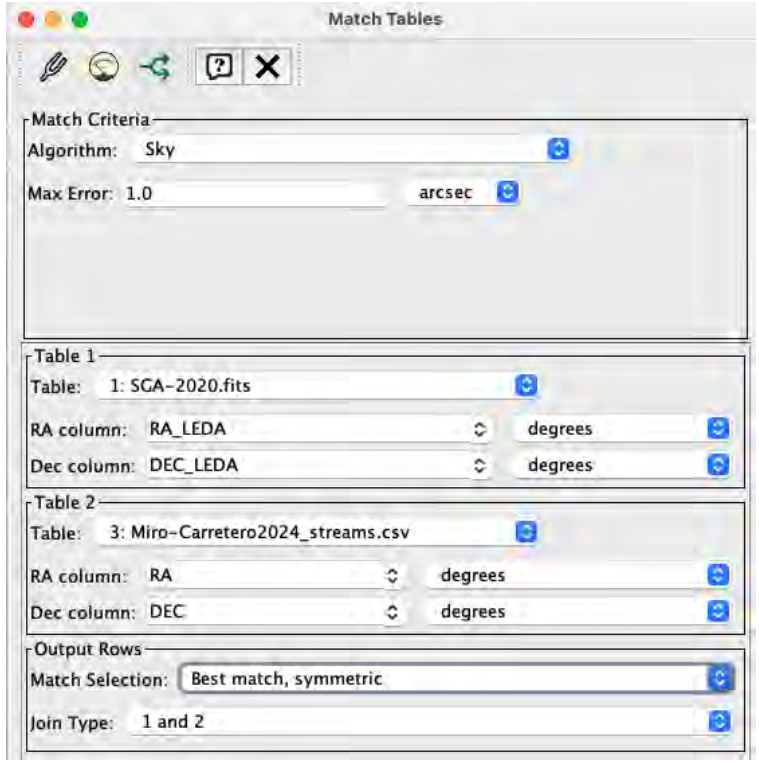
- **Need to tackle:**
- Duplicates
- Not the same precision in the coordinates
- Not the same coordinate reference frame
- Even more complicated for transients/high proper motion objects?
- All other problems you didn't think about at first

Name	RA	Dec	Photometry
NGCXXX	0	30	18
NGCYYY	145	42	22
…	…	…	…
PGCZZZ	22	25	14

Name	RA	Dec
AbellABC	89	11
UGCXX	145	42
…	…	…
NGCYYY	145	42
PGCCDE	145	41.8

Cross-matching catalogues

- You can make your own cross-matching algorithms (e.g. using astropy functions)
- Use more efficient tools: TOPCAT cross-match, CDS X-Match service, many more…



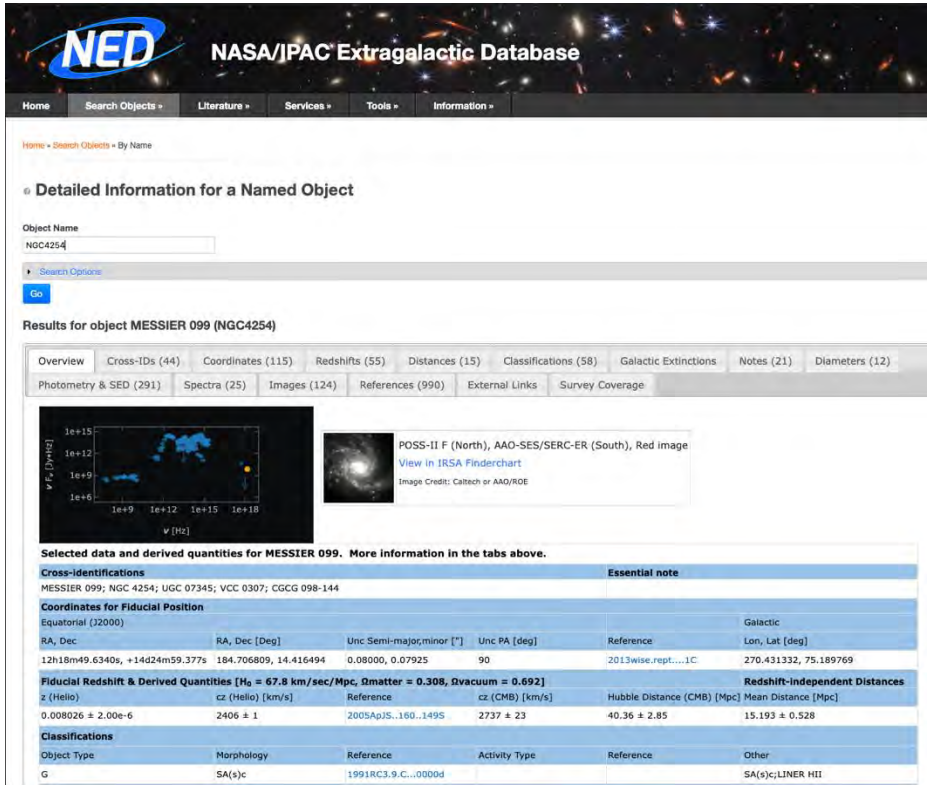
Topcat cross-match interface

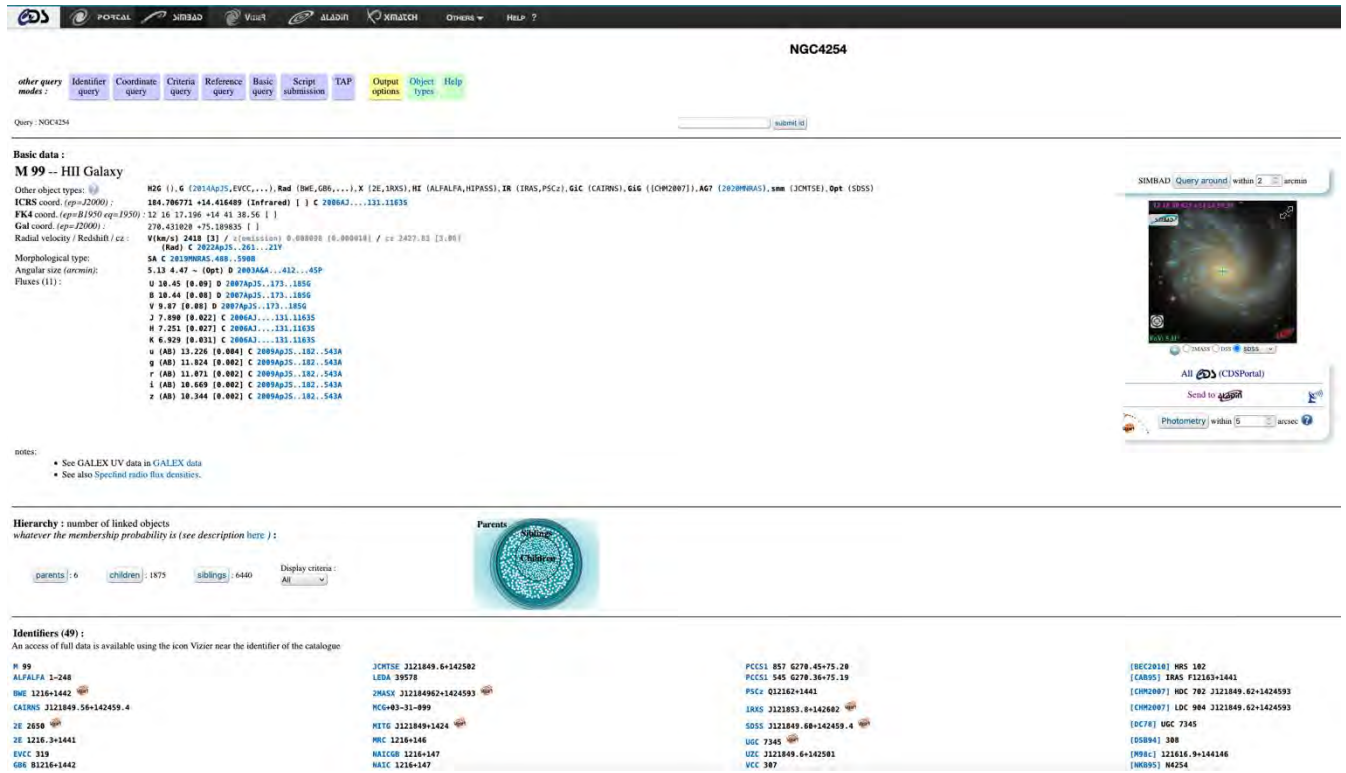
http://cdsxmatch.u-strasbg.fr/

By the way, how do you know an object's name?

- Q? How do you link an object's name to its coordinates ? Or how do you recover the many different identifiers of a same object?

►Search NED or SIMBAD databases !

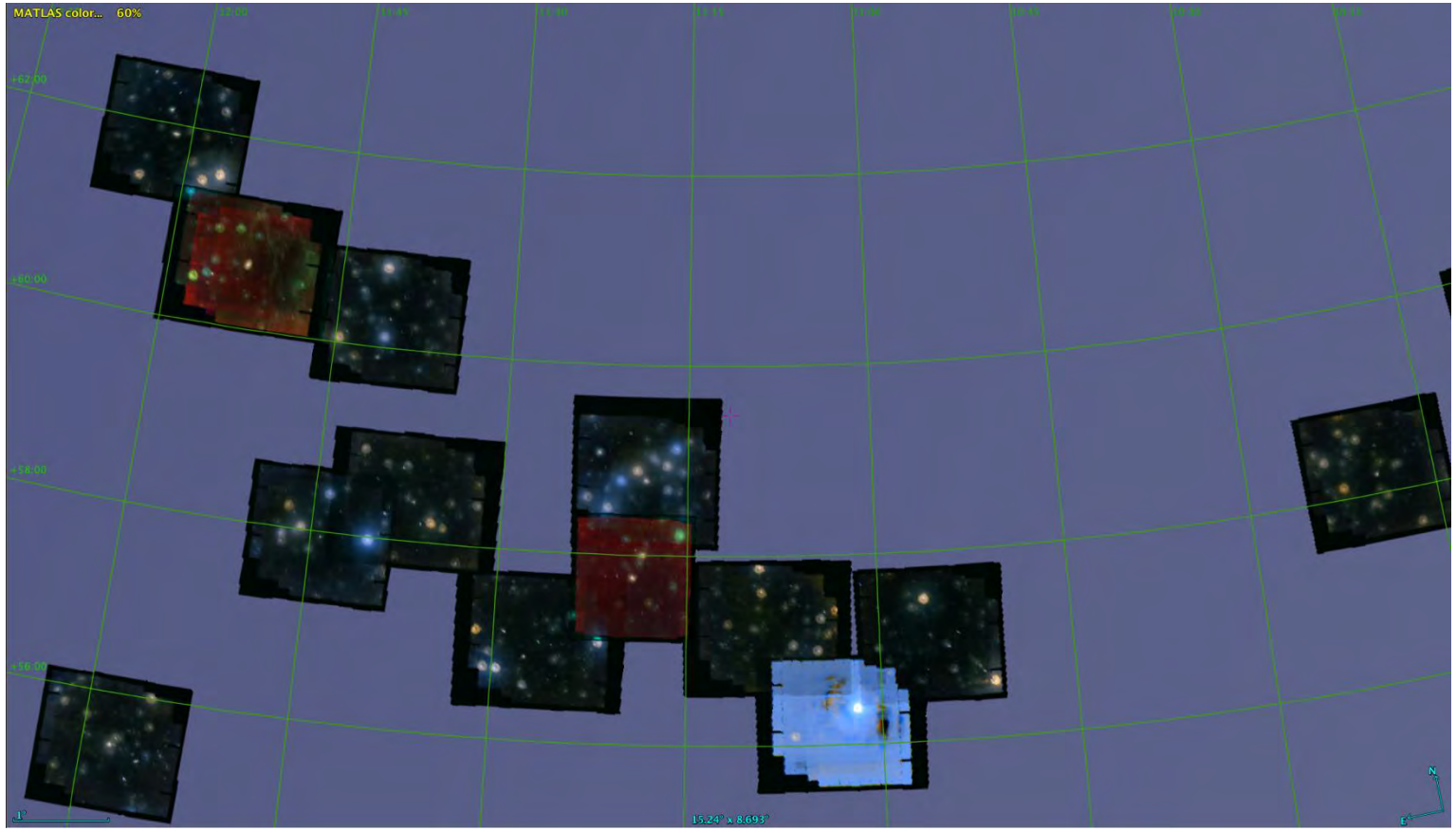




Linking catalogues and images

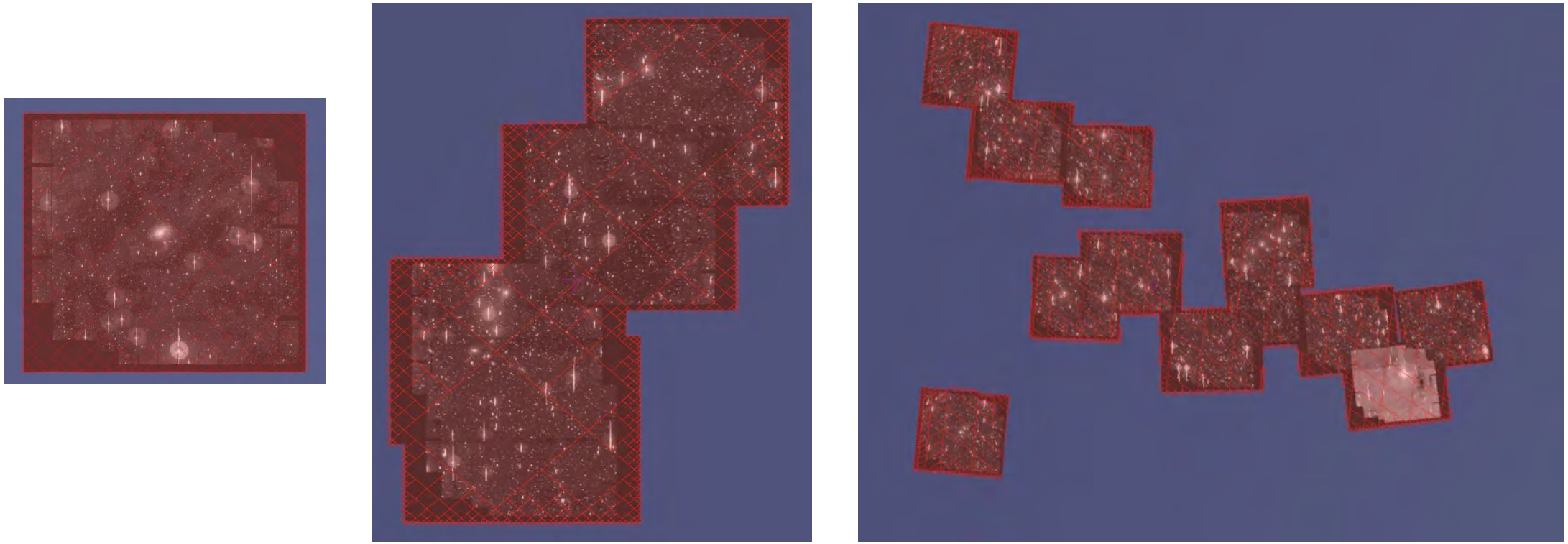
- Q? How do you know which objects of your catalogue are available in your set of images ?

Name	RA	Dec	Photo metry
NGCXXX	0	30	18
NGCYYY	145	42	22
…	…	…	…
PGCZZZ	22	25	14



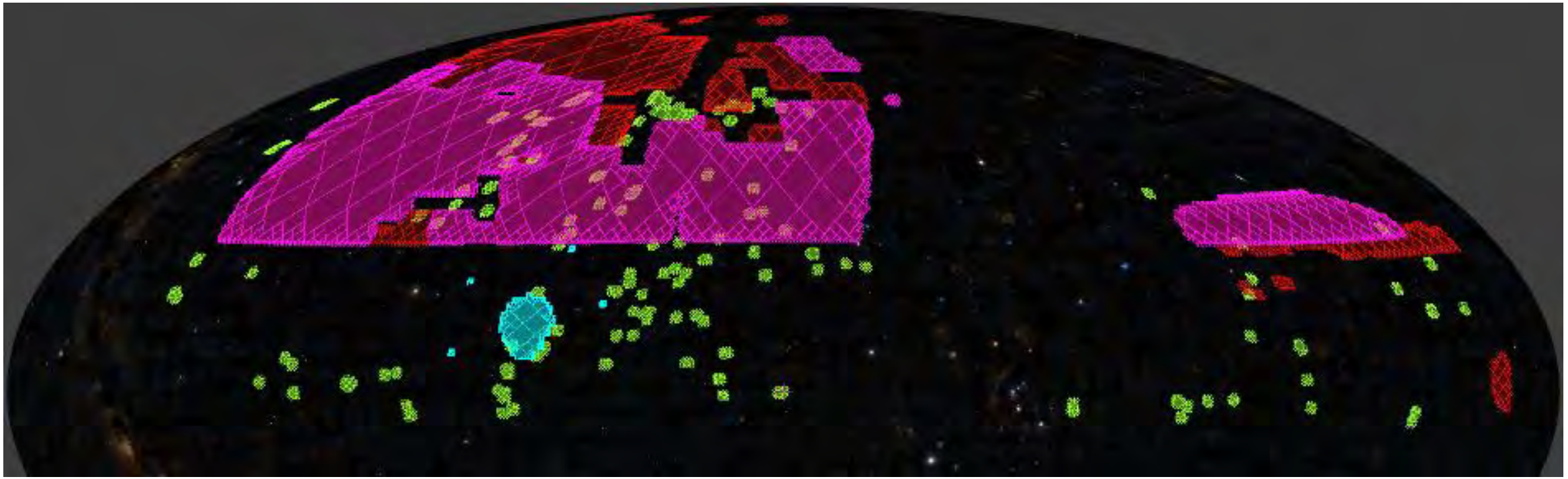
Multi-Order Coverage Maps (MOCs)

- **Multi-Order Coverage** (MOC) maps: representation of the spatial extent (= footprint) of an image on the sky. Developed by the CDS.
- Fast and easy representation of very complex footprints



MOC of some MATLAS images

Multi-Order Coverage Maps (MOCs)



Spatial footprint (MOC) of CFIS (red/pink), MATLAS (green) and NGVS/VESTIGE (blue)

- Fast and easy **intersection between MOCs and catalogues**
- Many operations on MOCs (intersection, union)

+Space-Time MOCs (STMOCs) useful for e.g. transients, objects over many observing times

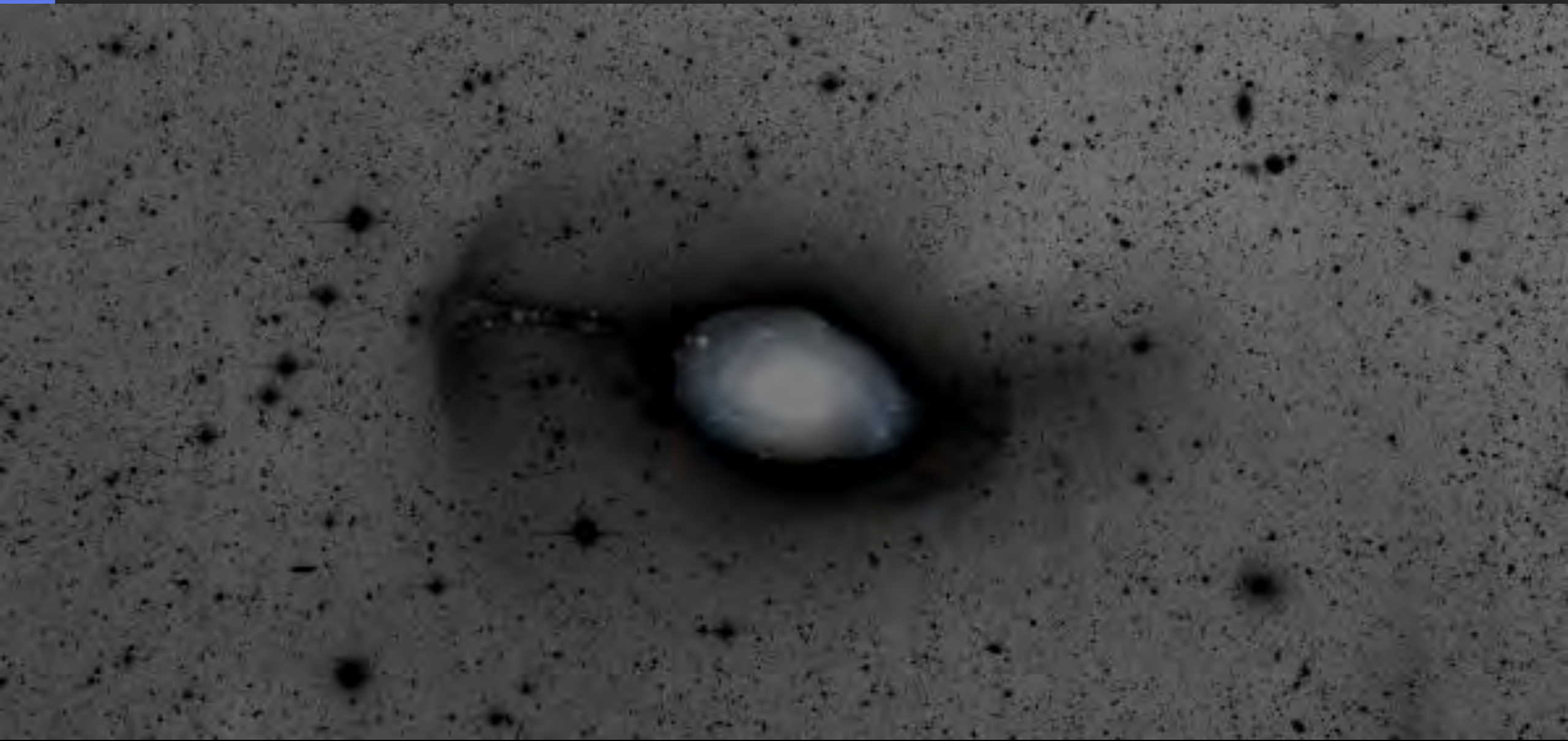
Be ready for the last lecture !

WikiCommons

Install SAOImage **DS9**, **TOPCAT** and **Aladin** desktop (at least look up at Aladin Lite online)

Look up at **NED** and **SIMBAD**

Back to the LSB Universe: image processing



Reminder: deep images

- Tidal features are faint, low surface brightness

NGC474 PMSTALARS image (SB < 28.9 mag arcsec^{-2})

Image processing

- What's wrong in the images below ?

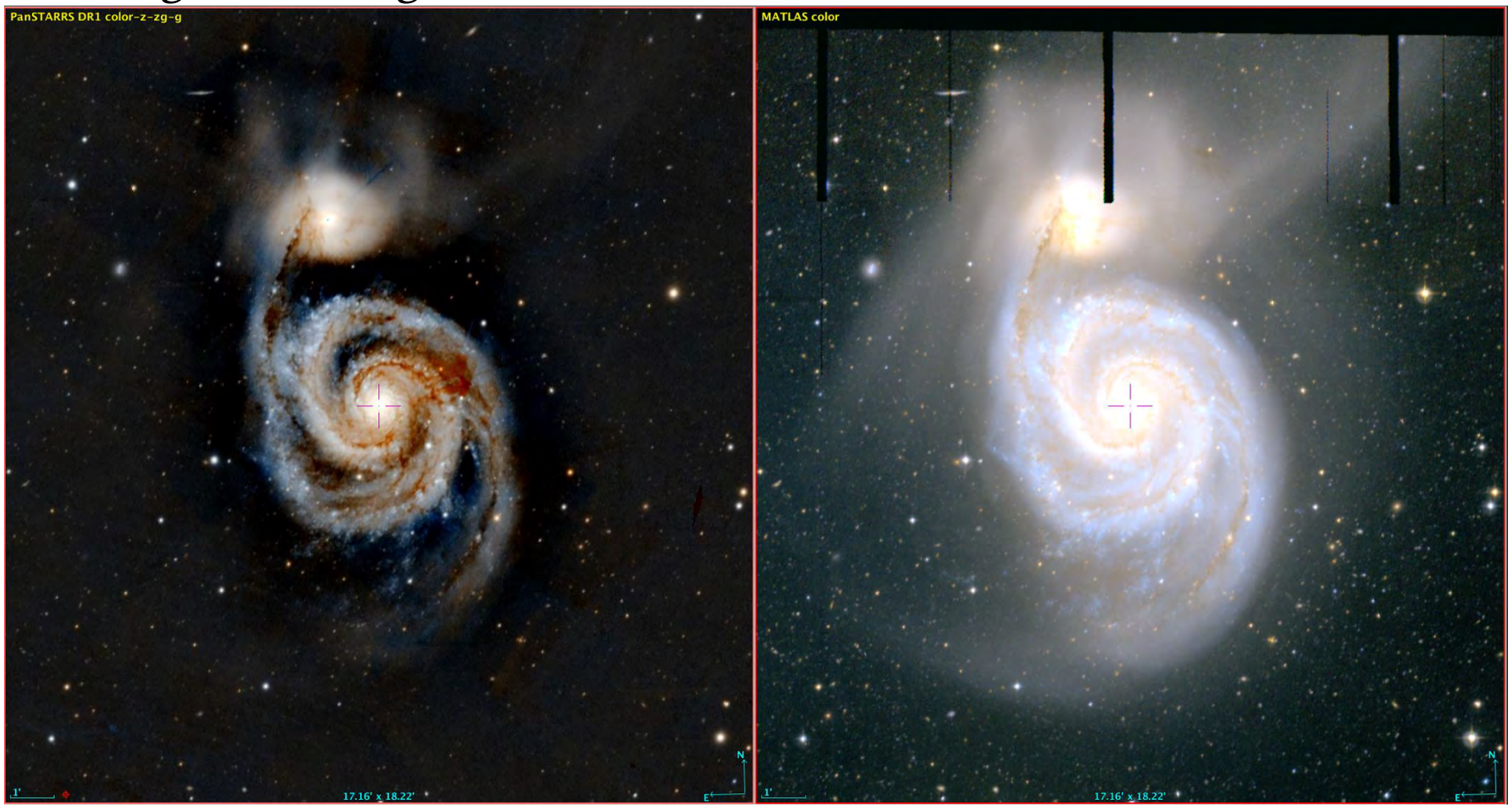


Image processing

- What's wrong in the images below ?

Image processing

- What's wrong in the images below ?

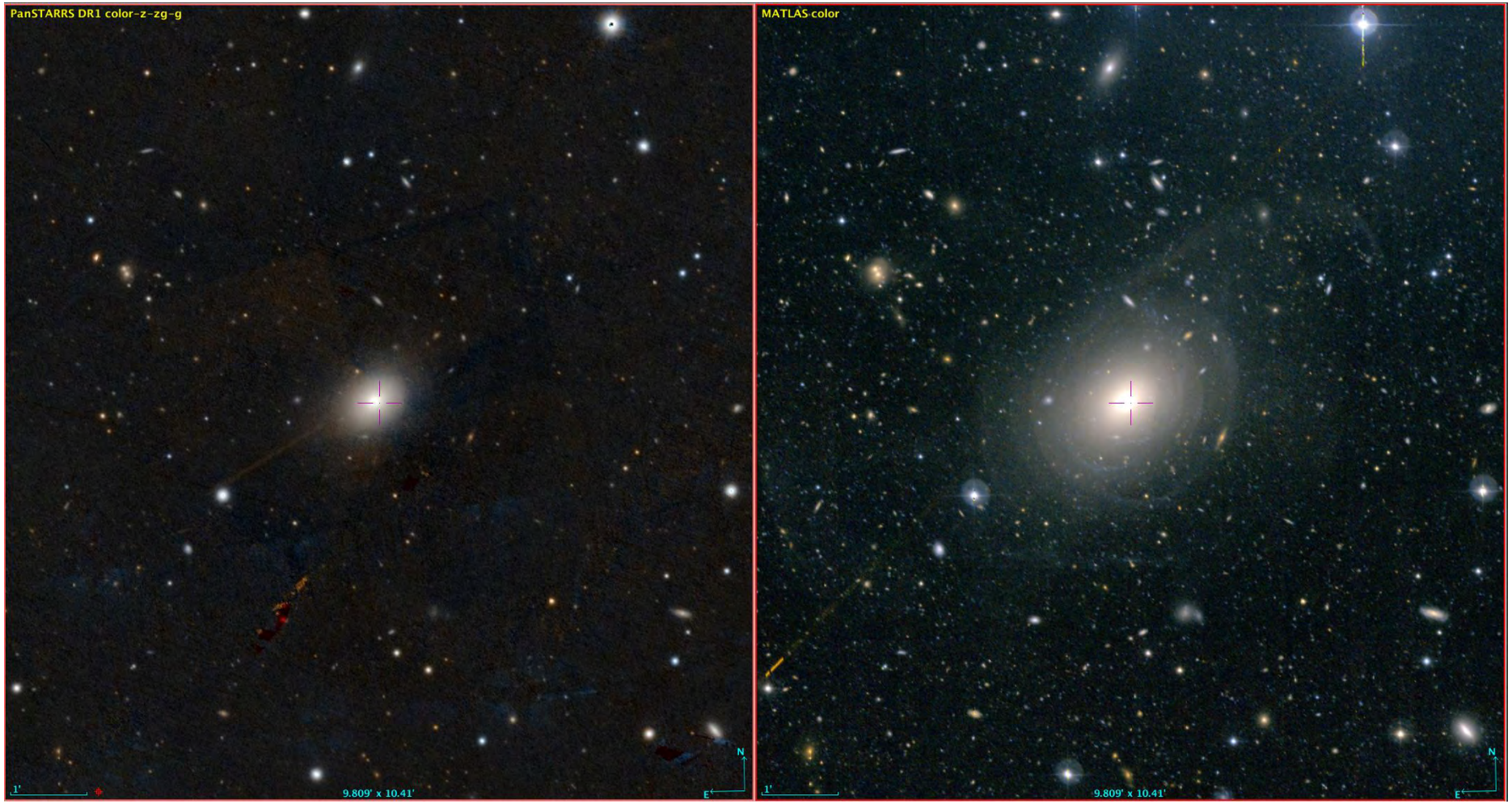
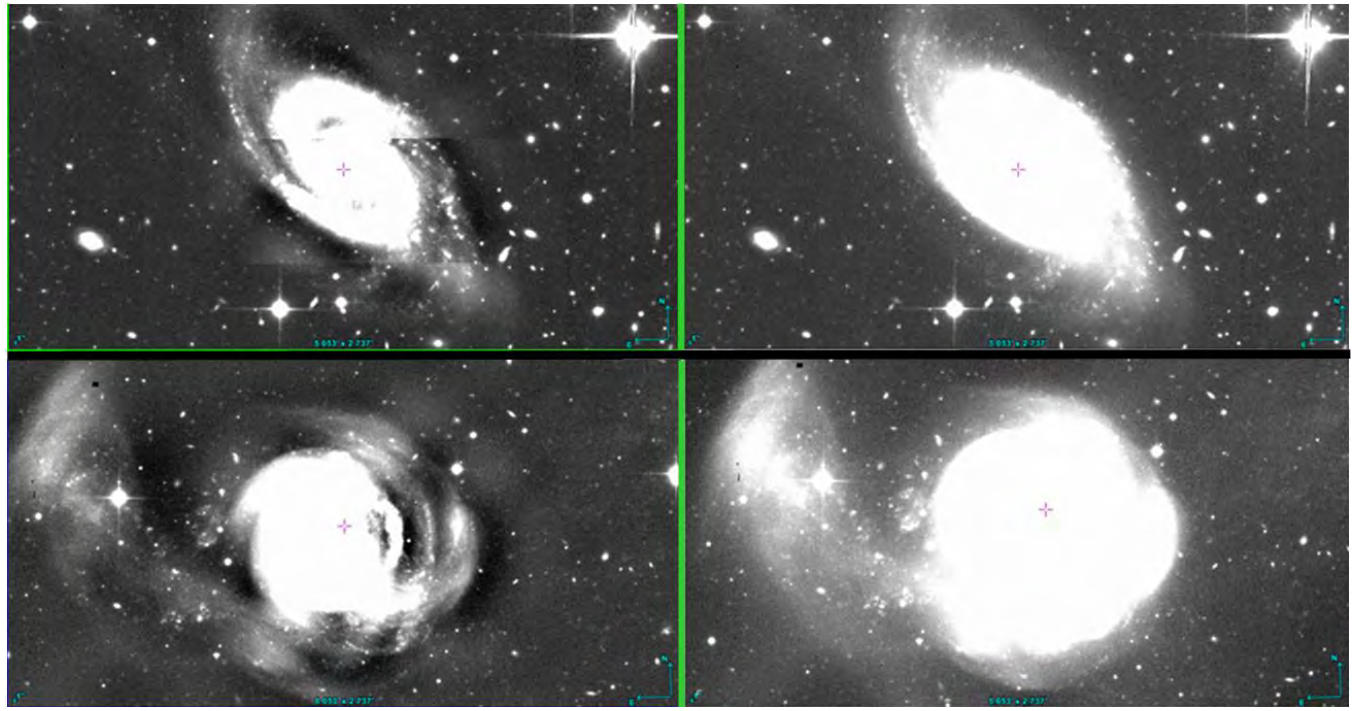


Image processing

- **Over-background subtraction**: standard pipelines are usually oriented for point-source like science (cosmology, galaxy evolution…) i.e. small objects that require a precise and local estimate and subtraction of the background.
- … but our objects are very faint and extended ! Traditional pipelines consider the galaxy outskirts as background and ends up **destroying** the LSB signal.



► **Very careful background subtraction must be performed to preserve the LSB signal !!**

Image scaling

Huge dynamical range: need non-linear transformations to reveal the faint outskirts even in LSB-compliant processed images

‘Linear’ scaling

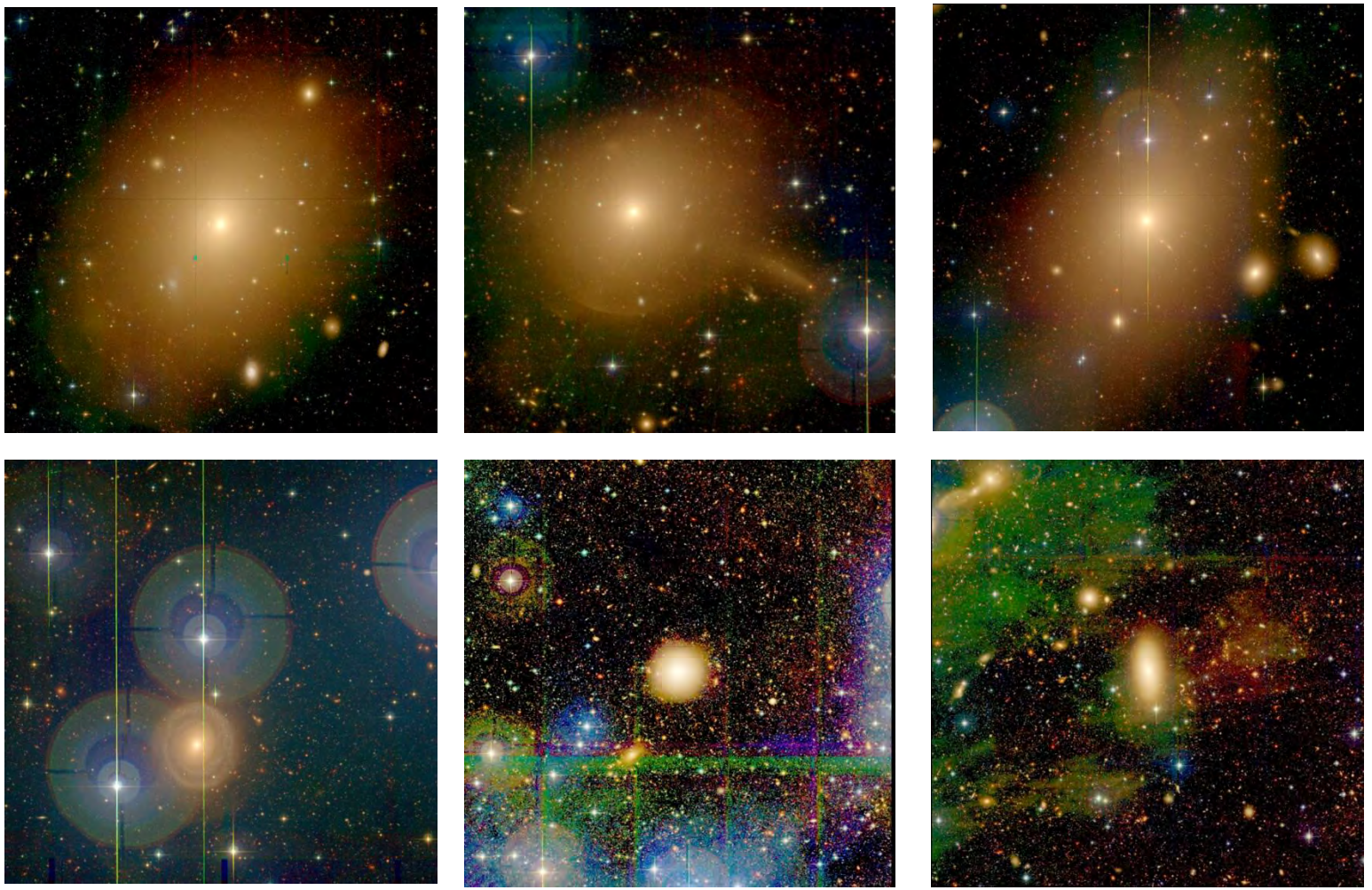
‘Asinh’ scaling

Deep images

- Deep images reveal many **stellar features:**
  - Stellar haloes
  - Tidal features
  - Intracluster light

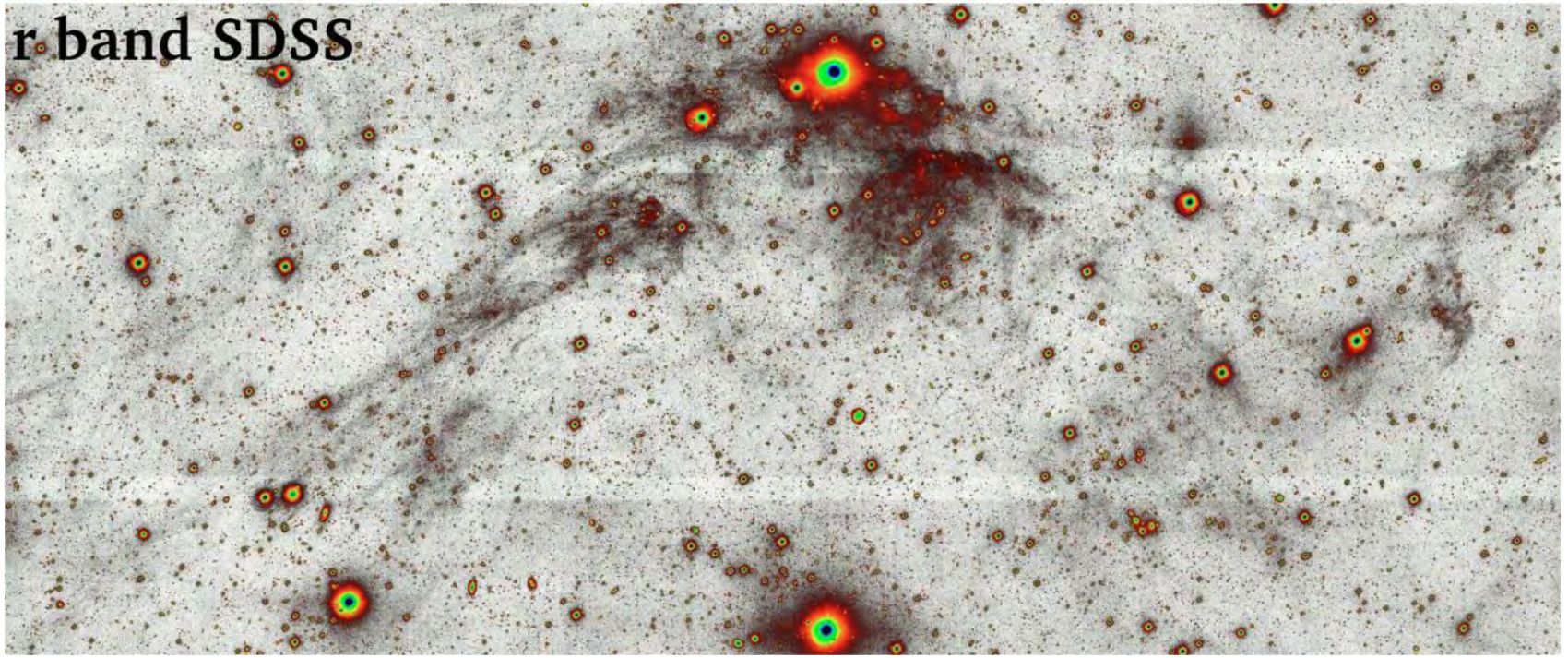
- But also **contamination sources:**
  - Artefacts
  - Internal reflections
  - Cirrus

NGVS



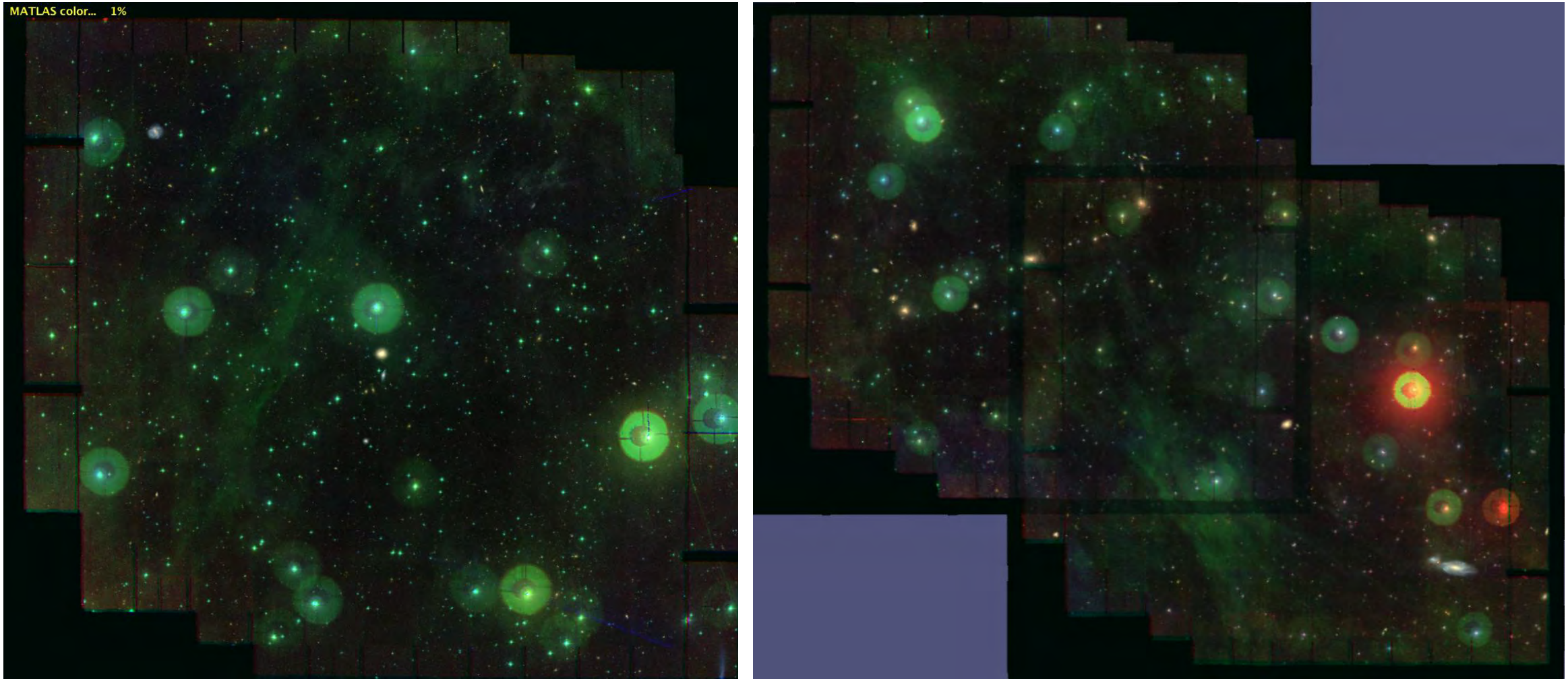
Galactic cirrus

- Cirrus: dust clouds in our Milky Way, emit in infrared, reflect in optical and UV
- Filamentary, fractal shape, LSB : hinder the observation of tidal features and/or can be confused with them !
- Big challenge to detect, characterise and remove them, no clear solution yet

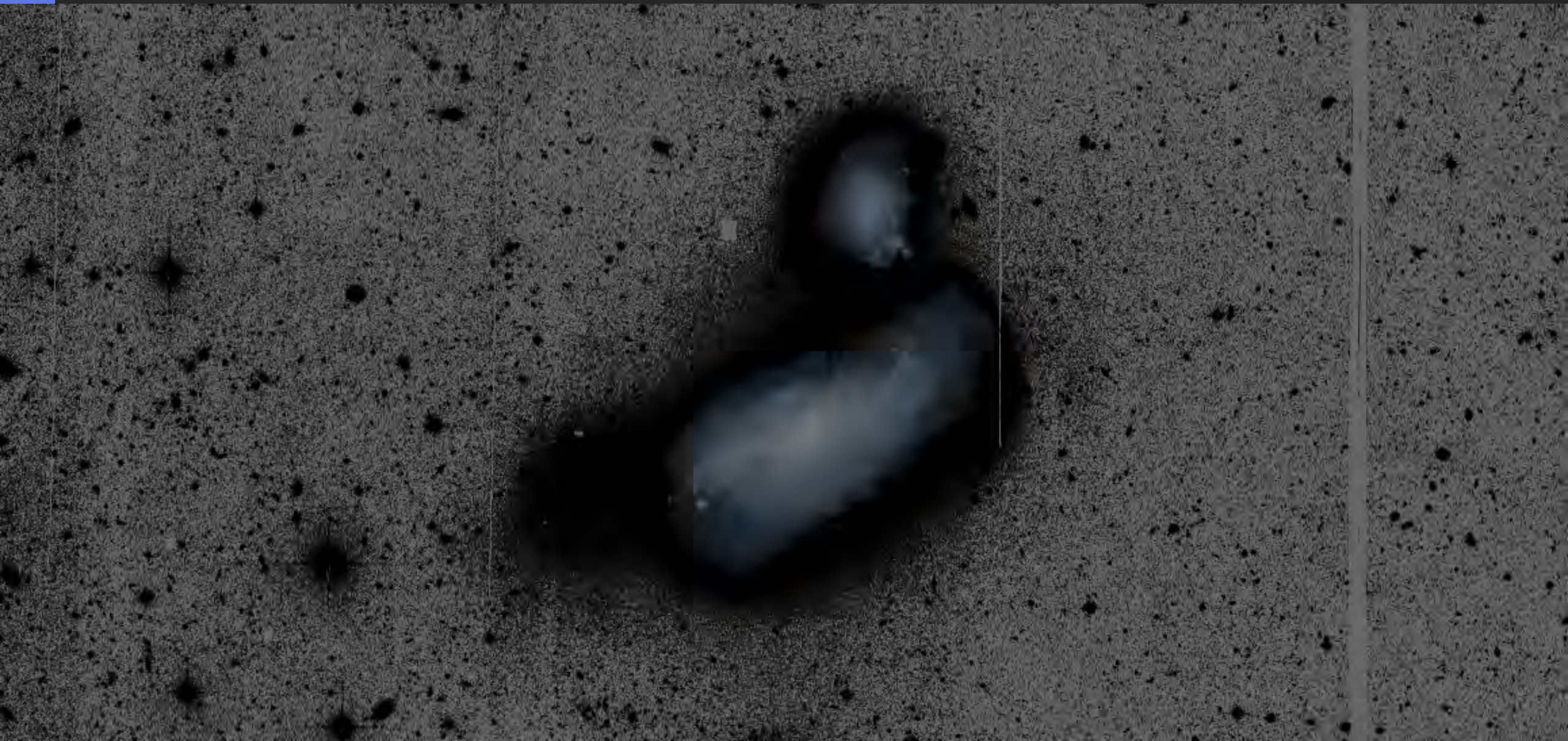


Román+2020

Galactic cirrus



Deep images and tidal features



Deep images and tidal features

- Once the deep images are available, how to characterise tidal features ?
- Several approaches: **visual** (largely used), automated methods, machine learning

- Large sample of galaxies
- Many contributors
- Decision trees

Census of simple morphological features

- Limited sample of galaxies
- One expert contributors

Detailed analyses

- **Our approach**: obtain detailed analyses of LSB features on hundreds of galaxies with few contributors

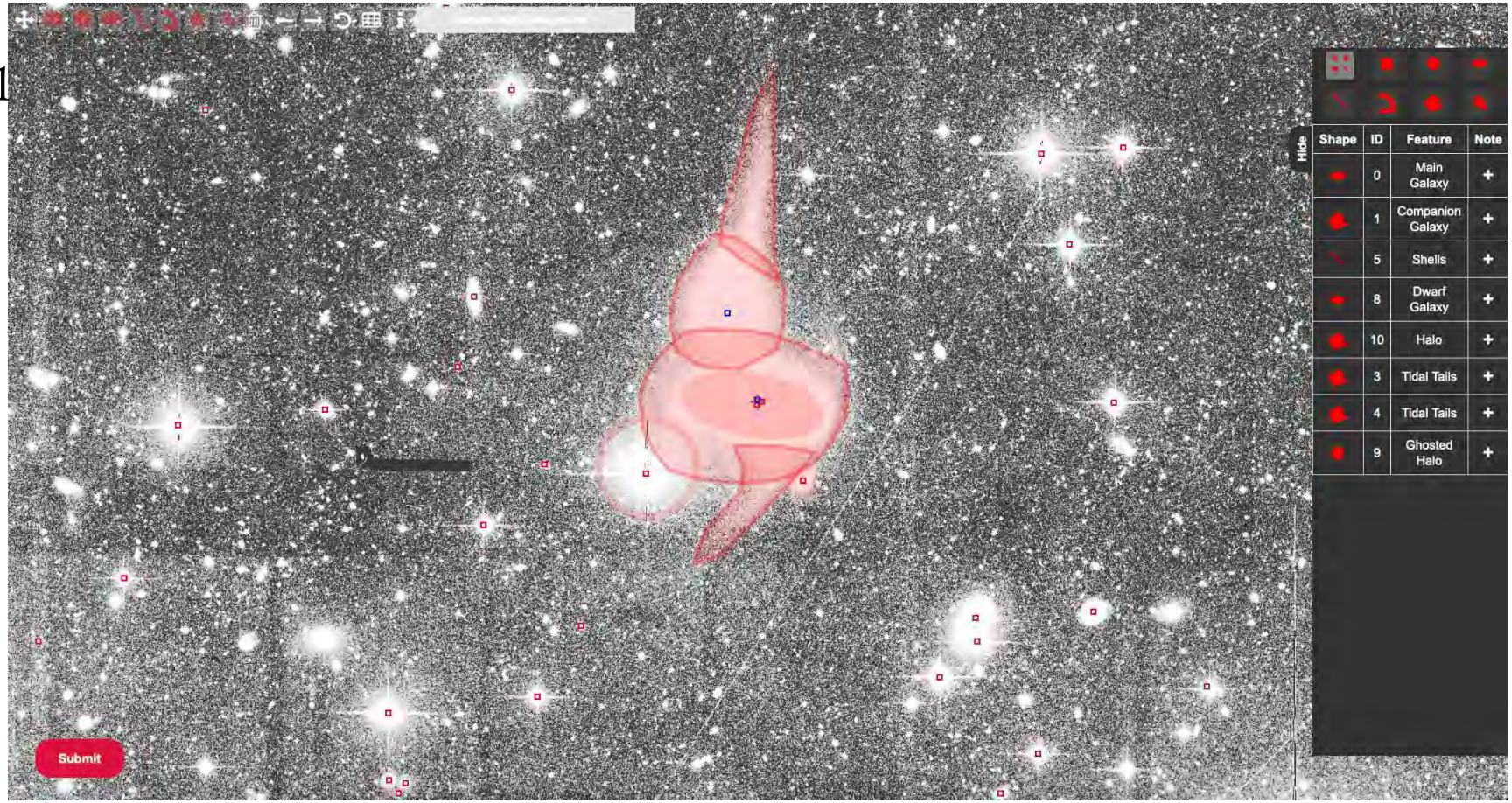
Jafar: an annotation tool for LSB structures

- Development of Jafar *(Sola+2022,2025)* an **online** tool *(with F. Richards)* to easily annotate and classify LSB structures in deep images

- Based on CDS Aladin Lite

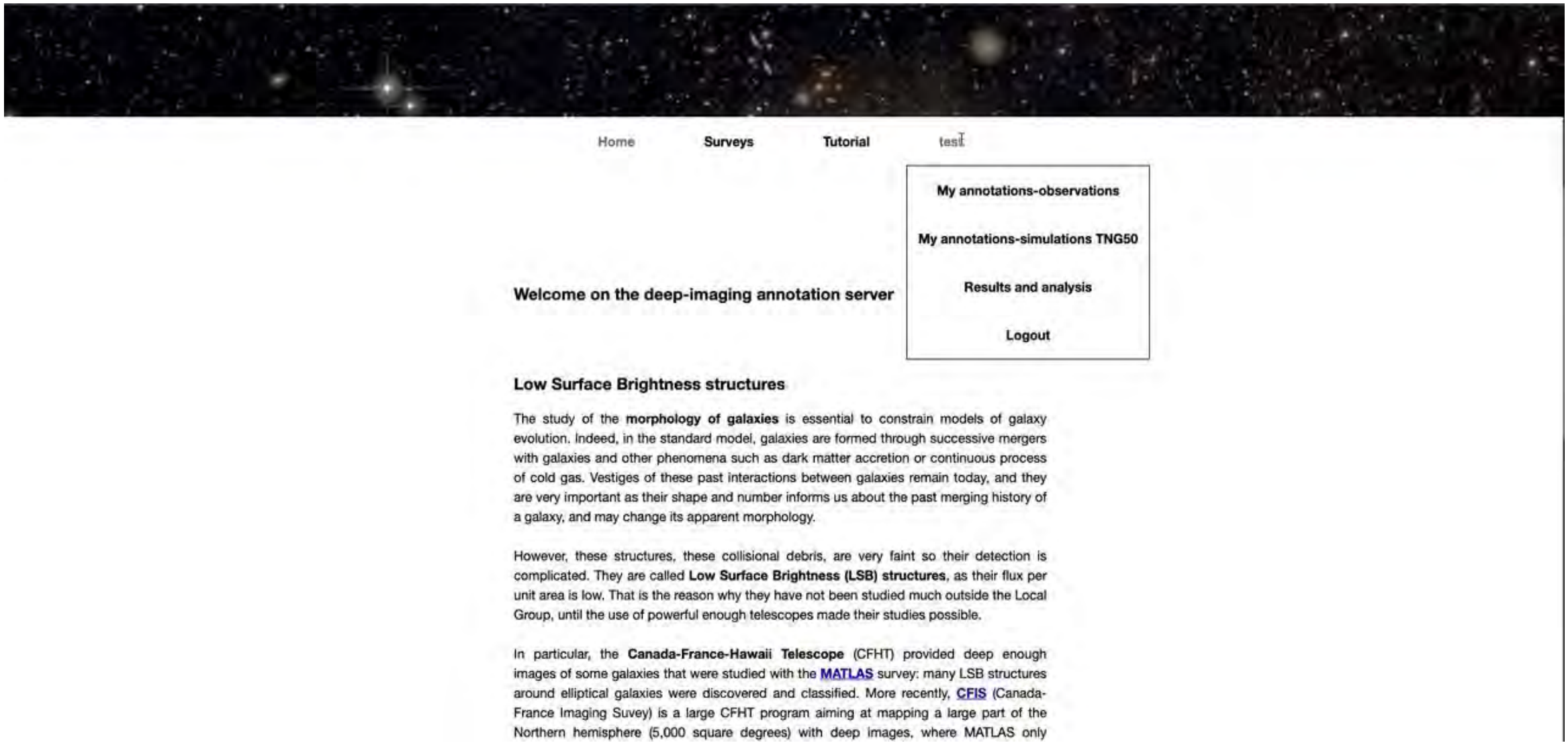
Goals:

- **Draw** with precision the **shapes** of LSB structures
- A few expert contributors
- Obtain **quantitative** results about LSB structures



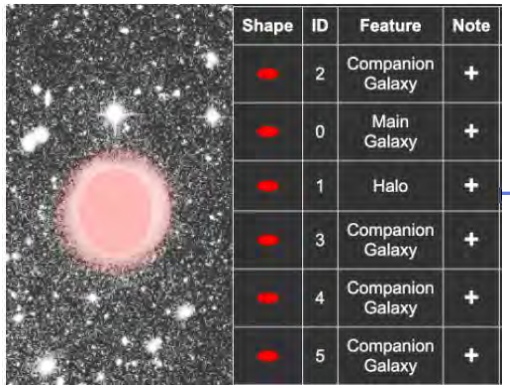
Interface of the annotation tool

Jafar: an annotation tool for LSB structures



Analyses

- Need to take into the annotations of **several users**
- **Quantitative** measurements from the annotation database + **automated aperture photometry**



Contours + labels of the annotated shapes

Area
Length
Width
Surface brightness

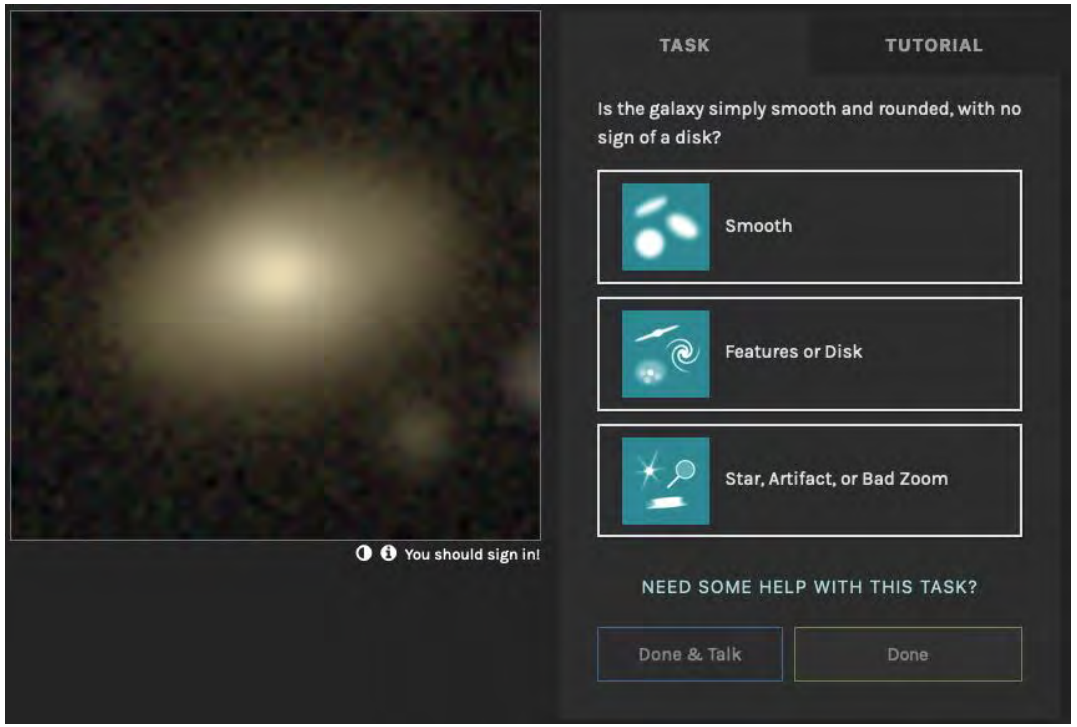
Masks of the annotations

Aperture photometry

Photometry
Colours
Mass

What about citizen science ?

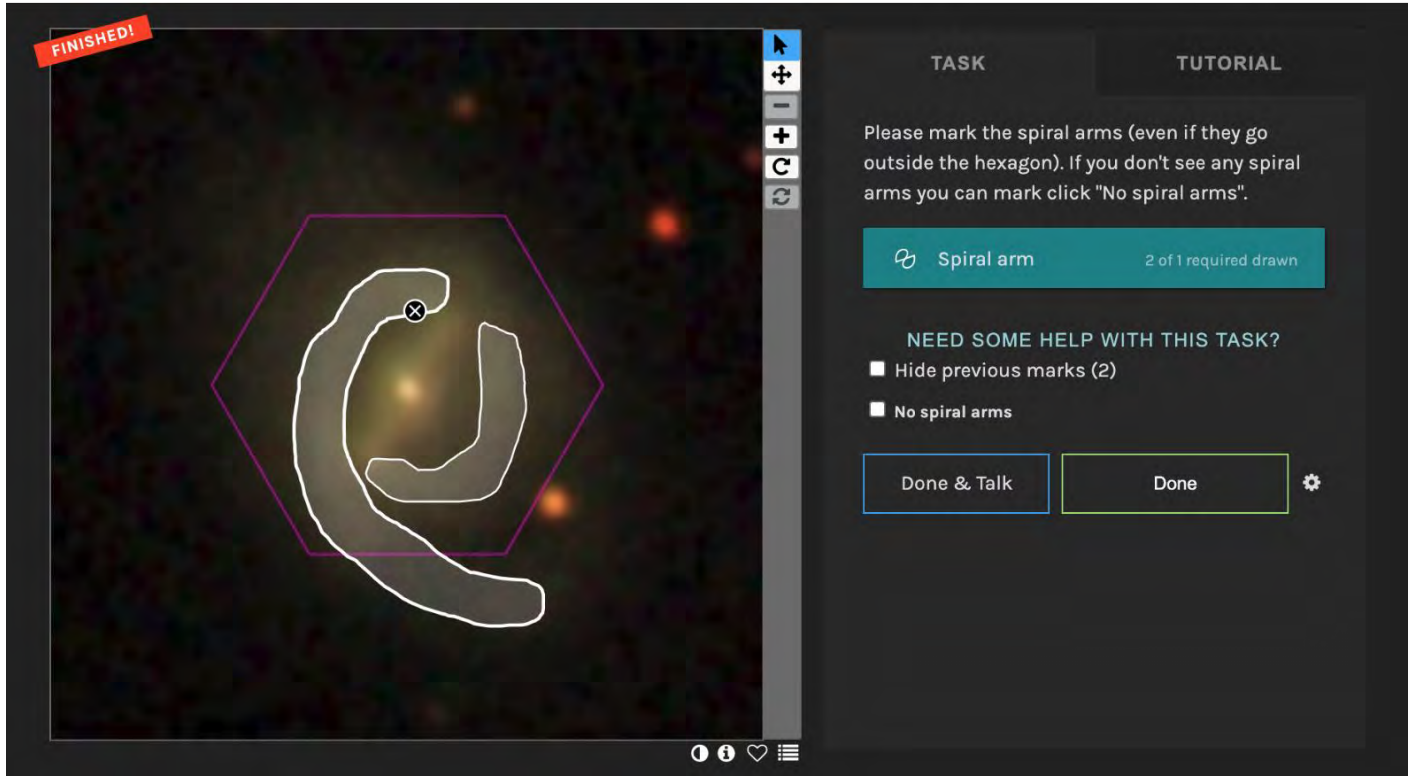
- Why not use the help of the general public for this task ? **Citizen scientists**
- A crowd of citizen scientists can classify hundreds of thousands of galaxies for simple tasks.
- Galaxy zoo is a great example: +60 million classifications about galaxy morphology

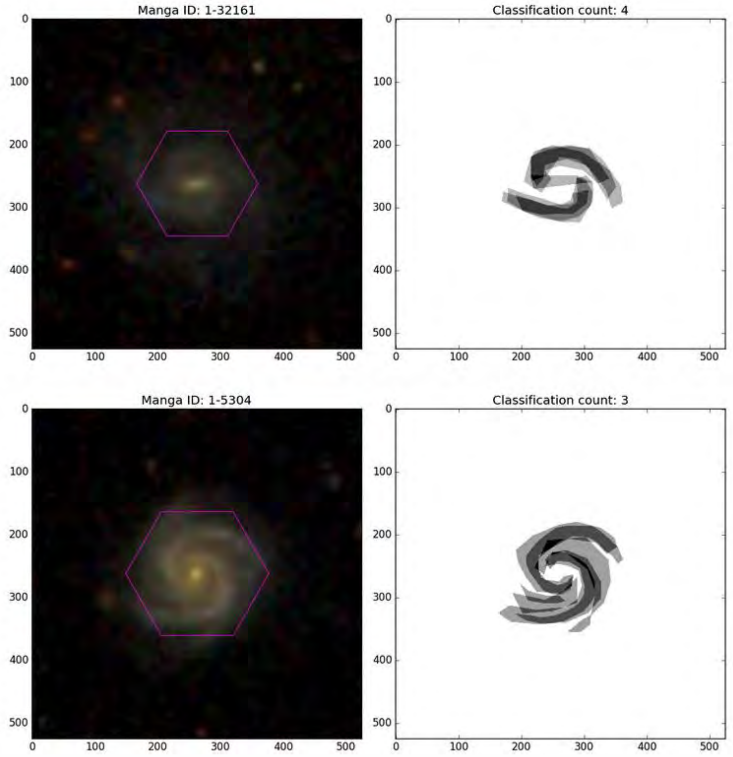


Example of the Galaxy Zoo interface

What about citizen science ?

- Galaxy Zoo 3D: recently added the possibility to draw polygons: used to count the number of spiral arms or the shape of the bar





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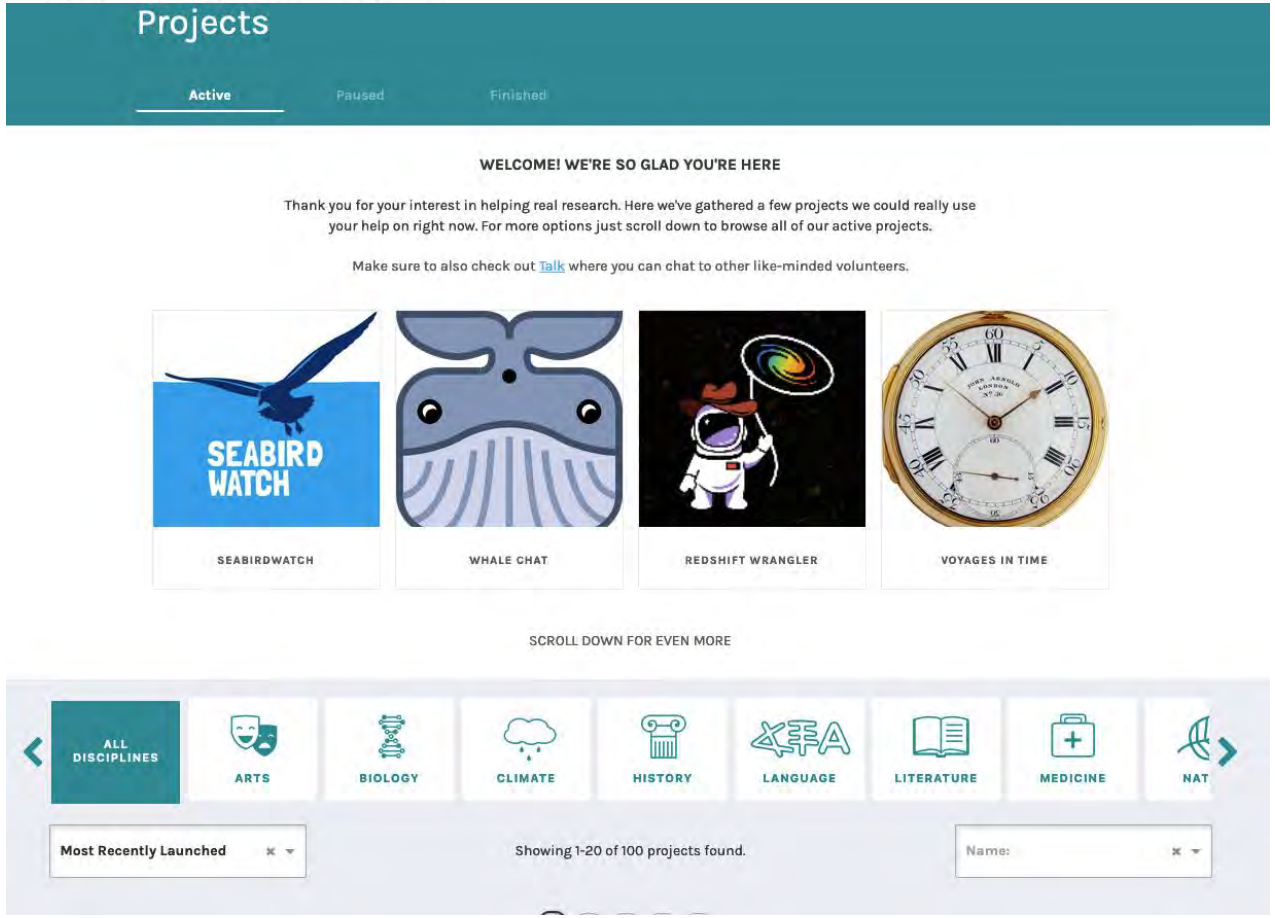
Citizen science projects

- Zooniverse: extension to many different fields of science, largest and most popular platform but many others exist (e.g., NASA..)



Citizen science projects

- Tidal feature identification: Galaxy Cruise project to classify the shapes of interacting galaxies

Fig. 1. GALAXY CRUISE's classification screen. Participants classify the target at the center, and then 'sail' to the next target. Passport stamps, souvenirs and other features are available to motivate the participants.

public. We thus choose to adopt the simplified classification scheme. Some interacting galaxies show significantly distorted shapes and their original morphology can be difficult to infer. In such a case, the participant can choose 'not sure'. When a target galaxy is too close to a nearby bright star and a fair classification

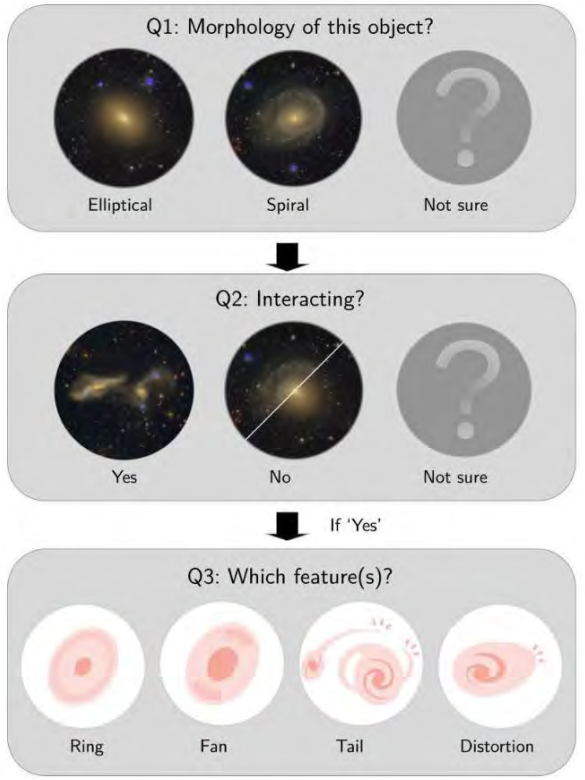


Fig. 2. GALAXY CRUISE's classification scheme. The first question is whether a galaxy is spiral or elliptical. The second question asks if the galaxy is interacting or not. If yes, the participant can choose observed feature(s).

Tanaka+2023

Then, why not use citizen scientists ?

- Highly specialized task: requires previous training and knowledge
- Subtle disentanglement between tidal tails and streams
- **Segmentation** and not just identification !
- Very time consuming

► Limited team of a few expert contributors

- But our manual approach is not possible for future surveys to come where thousands of galaxies will be studied.
- Need automated methods and **machine learning** approaches !

TO BE CONTINUED !

Summary

- Astronomical data: **images** + **metadata** (headers): FITS format very common
- Online databases, images and catalogues can be queried: e.g., Aladin, Simbad, NED, …
- Useful tools to manipulate catalogues, e.g., Topcat
- **Deep** images require careful processing to reveal the LSB Universe
- Tidal features in deep images are mostly discovered visually…. but automated methods exist and will become necessary, including Machine Learning !

- **Next lecture (07/03/2025): LSB features and galactic evolution**: Machine learning to disclose faint features. LSB features as probes of galactic evolution. Observations vs simulations. Ongoing and future surveys.

Be ready for the last lecture !

WikiCommons

Install **DS9**, **TOPCAT** and **Aladin** desktop (at least look up at Aladin Lite online)

Look up at **NED** and **SIMBAD**

+ bring your computer