Mini–Capstone Project: PSF-Aware Galaxy Modelling with SExtractor, PSFEx, and GALFIT

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Project Deliverables:

- A compressed folder containing:
  - your science and sigma cutout FITS files,
  - PSF model FITS file,
  - GALFIT input (`.feedme`) and output files (with and without PSF),
  - key figures (PNG/PDF) described below.
- A short report (1–2 pages, PDF) explaining methods, results, and interpretation.

1 Background and Physical Motivation

Fast Radio Bursts (FRBs) are extragalactic millisecond-duration radio flashes whose physical origin is still under active investigation. The host galaxies of localized FRBs provide crucial clues to their progenitors: stellar mass, star-formation rate, morphology, inclination, and the FRB's location within the host can all carry information about the underlying engine.

Future FRB host demographic studies will correlate *host-galaxy structure* with FRB observables such as:

- dispersion measure (DM): integrated free-electron column density along the line of sight,
- rotation measure (RM): line-of-sight integral of electron density times magnetic field,
- scattering time ($\tau_{\rm sc}$): temporal broadening due to multi-path propagation in turbulent plasma.

For example, more highly inclined disk galaxies may produce larger host DM and $\tau_{\rm sc}$ than face-on disks, and FRBs in dense central regions may show higher RM than those in galaxy outskirts.

To make such correlations meaningful, we need **accurate, PSF-corrected structural parameters** for FRB host galaxies: Sérsic index, effective radius, axis ratio, and position angle. This project introduces the standard extragalactic workflow:

- `SExtractor`: detect stars/galaxies and build a source catalog,
- `PSFEx`: construct an empirical point spread function (PSF) from bright stars,
- `GALFIT`: perform two-dimensional surface-brightness modelling of a galaxy, with and without PSF convolution.

Your target is the nearby elliptical galaxy NGC 3379 (M105) in the DESI Legacy Surveys DR9 r-band imaging. The key goal is to **quantify how ignoring the PSF biases the inferred galaxy structure**.

2 Data and Software

2.1 Data Provided

You will be given the following DESI Legacy Surveys DR9 brick-level coadds:

- `legacysurvey-1619p125-image-r.fits.fz` (r-band science image),
- `legacysurvey-1619p125-invvar-r.fits.fz` (r-band inverse-variance map).

These files contain a compressed image in HDU 1 with dimensions 3600×3600 pixels. NGC 3379 (M105) lies near the center of this brick at:

$$\mathrm{RA} = 161.9567^\circ, \qquad \mathrm{Dec} = 12.5817^\circ \quad \text{(ICRS)}.$$

A starter Python script (provided separately) uses `astropy` to:

- read the brick images,
- generate a $300'' \times 300''$ cutout centered on NGC 3379,
- convert the inverse-variance map into a sigma (noise) image,
- write out the cutout science and sigma images as standard FITS files.

2.2 Required Software

You are expected to install and use:

- `SExtractor`,
- `PSFEx`,
- `GALFIT`,
- Python with `astropy` (for handling FITS files and running the cutout script),
- `DS9` (or equivalent) for visualization.

No additional Python wrappers (e.g., GALFITools, `photutils`) are required.

3 Project Tasks and Requirements

Your goal is to build a complete workflow from raw brick images to PSF-aware galaxy models. Structure your work logically; you may keep a separate notebook or scripts for data preparation, but the main analysis output is a short written report plus results files.

3.1 Section 1: Preparing Science and Sigma Cutouts

- Use the provided Python script (or your own adaptation) to:
  - extract a $200'' \times 200''$ cutout centered on NGC 3379 from the brick image,
  - extract the corresponding region from the inverse-variance map,
  - convert inverse variance to sigma via $\sigma = 1/\sqrt{\mathrm{invvar}}$ for positive pixels,
  - save both cutouts as FITS images with consistent WCS headers.
- Inspect the cutouts in DS9 to confirm that:
  - NGC 3379 is centered and fully enclosed,
  - there is some sky area around the galaxy,
  - the sigma image looks reasonable (no obvious artifacts).

3.2 Section 2: Source Detection with `SExtractor`

- Run `SExtractor` on the *full brick image* to detect point sources and galaxies.
- Identify a clean sample of PSF stars using the catalog output. Guidelines:
  - CLASS_STAR > 0.8 (point-like),
  - high signal-to-noise ratio (e.g., SNR > 30),

    - FLAG = 0 (no major issues),
    - isolated, non-saturated stars (check in DS9).

- Save the catalog for use with `PSFEx`.

Comprehension Questions:

(Q1) What criteria did you use to distinguish stars from galaxies in the `SExtractor` catalog?
(Q2) Why is it important that PSF stars are isolated and not saturated?

3.3 Section 3: PSF Construction with `PSFEx`

- Run `PSFEx` on your `SExtractor` catalog to build an empirical PSF model for the r-band image.
- Inspect the PSF model FITS file (for example, by displaying the central postage stamp in DS9).
- Measure or estimate the PSF FWHM from the model.

Comprehension Questions:

(Q3) In your own words, what is the PSF and why is it critical for galaxy structural modelling?
(Q4) How does `PSFEx` use multiple stars to construct a PSF model that is more robust than any single star image?

3.4 Section 4: GALFIT Modelling Without PSF

- Using your science and sigma cutouts of NGC 3379, set up a `GALFIT` input (`.feedme`) file to fit a single Sérsic component to the galaxy *without* specifying a PSF image.
- Choose initial guesses for position, total magnitude (can be rough), effective radius, Sérsic index n, axis ratio b/a, and position angle.
- Run `GALFIT` and inspect the output model and residual images.

Comprehension Questions:

(Q5) What is the Sérsic index n, and how does changing n affect the concentration of light in the model?
(Q6) Based on the residual image, does the no-PSF model adequately describe the central region of NGC 3379? Why or why not?

3.5 Section 5: GALFIT Modelling With PSF

- Modify your `GALFIT` input file to include the PSFEx PSF image.
- Re-run the fit and record the new best-fit parameters: n, effective radius R_e, axis ratio b/a, position angle, and χ^2.
- Compare the residual image with the previous (no-PSF) run.

Comprehension Questions:

(Q7) Which parameter(s) changed the most when you included the PSF (e.g., n, R_e, b/a)? Provide numerical values.
(Q8) Why does ignoring the PSF tend to bias the structural parameters of an elliptical galaxy like NGC 3379?
(Q9) How do the residuals differ between the two runs, and what does this tell you about the model quality?

4 Final Deliverables

Your submission should include:

4.1 Files and Figures

- Science and sigma cutout FITS files for NGC 3379.
- PSF model FITS file produced by `PSFEx`.
- `GALFIT` input (`.feedme`) and output files for both:
  - the model without PSF,
  - the model with PSF.
- Key figures (PNG or PDF):
  - original science cutout,
  - sigma image,
  - PSF model stamp,
  - GALFIT model and residual (no PSF),
  - GALFIT model and residual (with PSF).

4.2 Short Report (1–2 Pages)

Write a concise report (1–2 pages, PDF) that includes:

- **Methods:** brief description of PSF star selection, PSFEx run, and GALFIT setup.
- **Results:** table summarizing best-fit parameters (with and without PSF).
- **Comparison:** quantitative discussion of how including the PSF changed the fit.
- **Interpretation:** what you learned about the importance of PSF modelling for galaxy structure, and how this connects to FRB host studies.

End of Assignment

Additional Resources: Installation Guides and Tutorials

This section provides a curated list of installation instructions, documentation, and high–quality tutorials for all software packages used in this project. These resources are recommended for students encountering SExtractor, PSFEx, GALFIT, and DS9 for the first time.

1. SExtractor (Source Extractor)

Official Website and Manual:

- Homepage: `https://www.astromatic.net/software/sextractor`
- User Manual (PDF): `https://www.astromatic.net/pubsvn/software/sextractor/trunk/doc/sextractor.pdf`

Installation:

- Linux/Mac via conda:

```
conda install -c conda-forge sextractor
```

- Source install: `https://www.astromatic.net/software/sextractor/#install`

Beginner-Friendly Tutorials:

- "SExtractor for Dummies" (highly recommended): `https://astro.dur.ac.uk/~pdraper/extractor/Guide2source_extractor.pdf`
- Using SExtractor to find stars in FITS images: `http://tdc-www.harvard.edu/wcstools/sextractor/`
- SExtractor video tutorial (YouTube): `https://www.youtube.com/watch?v=ZM-tvha6Qog`

2. PSFEx (PSF Extractor)

Official Resources:

- Homepage: `https://www.astromatic.net/software/psfex`
- User Manual (PDF): `https://www.astromatic.net/pubsvn/software/psfex/trunk/doc/psfex.pdf`

Installation:

- Linux/Mac via conda:

```
conda install -c conda-forge psfex
```

- Source install: `https://www.astromatic.net/software/psfex/#install`

Recommended Tutorials:

- Official PSFEx tutorial: `https://psfex.readthedocs.io/en/latest/Examples.html`

4. DS9 (SAOImage DS9)

Official Resources:

- Homepage: `https://ds9.si.edu`
- Downloads (Mac, Linux, Windows): `https://ds9.si.edu/site/Download.html`
- DS9 User Guide: `https://ds9.si.edu/doc/user/`

Useful Tutorials:

- SAO DS9 quick-start guide: `https://sites.psi.edu/cvs/DS9Intro`
- YouTube tutorial for beginners: `https://www.youtube.com/watch?v=5mKOvxihrd8`

5. Additional Good References

General FITS+Astropy Tutorials:

- Astropy FITS tutorial: `https://docs.astropy.org/en/stable/io/fits/`
- Astropy WCS tutorial: `https://docs.astropy.org/en/stable/wcs/index.html`

These resources should give you all the background needed to install the required tools, understand how they work, and successfully complete this capstone project.