INSTITUTO DE ASTROFÍSICA DE CANARIAS

PRESENTACIÓN FINAL BECA DE VERANO 2024

Observing the formation of the Milky Way with the James Webb Space Telescope

Fernando Valenciano Ruano

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September 11st 2024

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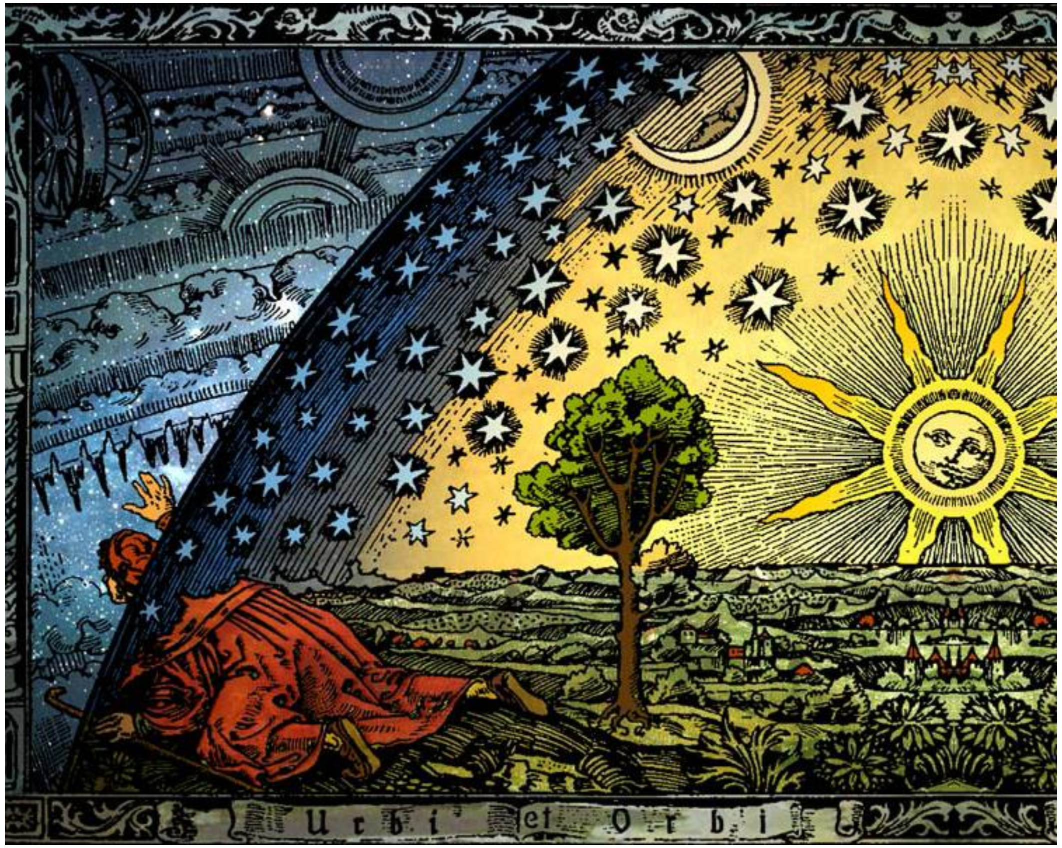


"The human being is properly that level of the nature
in which nature asks itself: "Why do I exist?"
Man in precisely that minuscule particle
which demands a meaning, a reason – the reason"

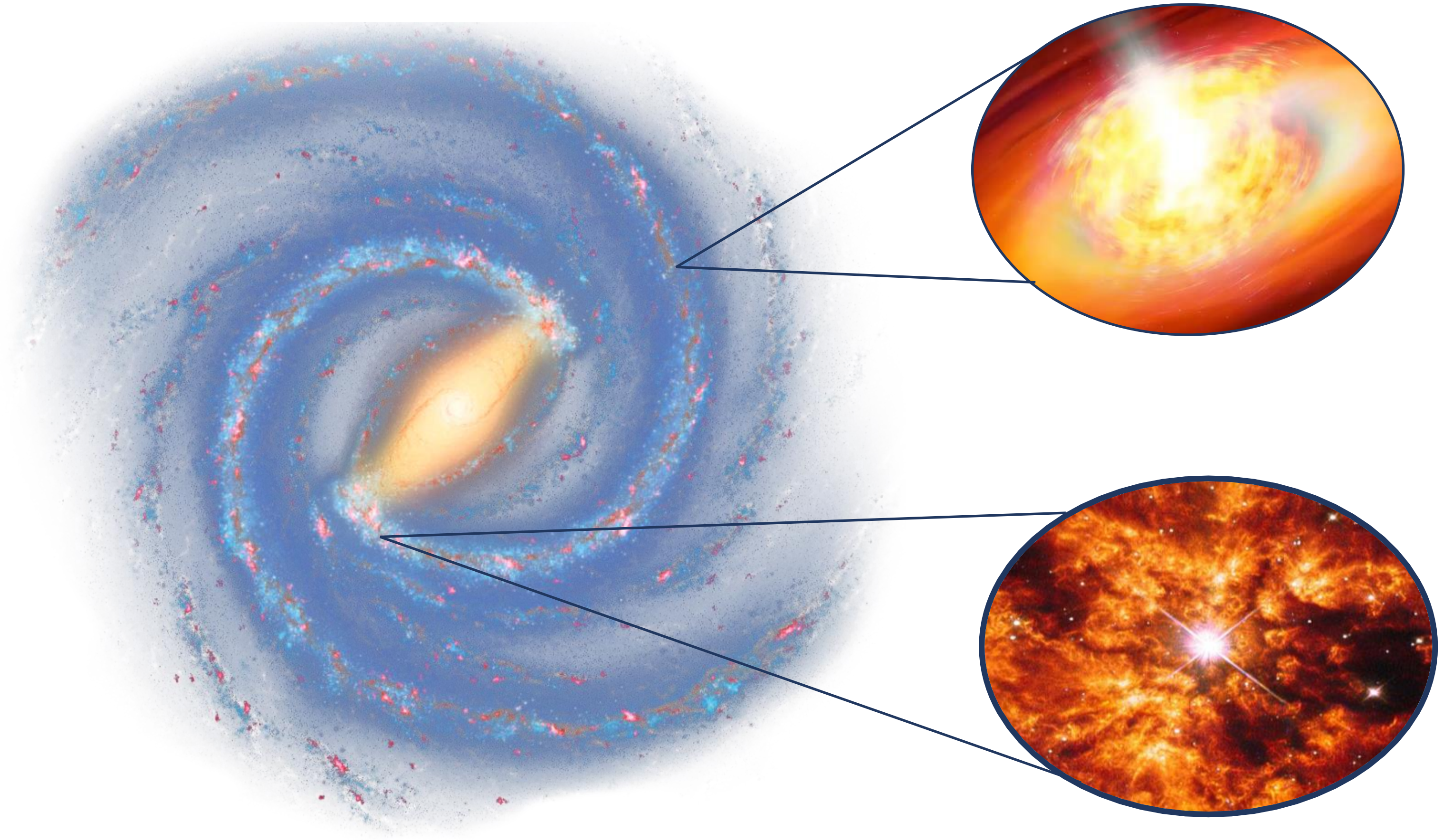
L. Giussani

1. INTRODUCTION

GOODS South Field – WFC3 Early Release Science Data
© NASA, ESA.

1.1. GALAXY FORMATION AND EVOLUTION

Galaxy evolution governed by **BALANCE** between **STAR FORMATION** processes and others that prevent it, **FEEDBACK**.



STAR FORMATION processes:

Gravitational potential of Dark Matter (DM) halos initiate collapse of dense molecular clouds.

FEEBACK processes:

Prevents the collapse of molecular clouds by SN or AGN feedback. Gas expulsion or heating.

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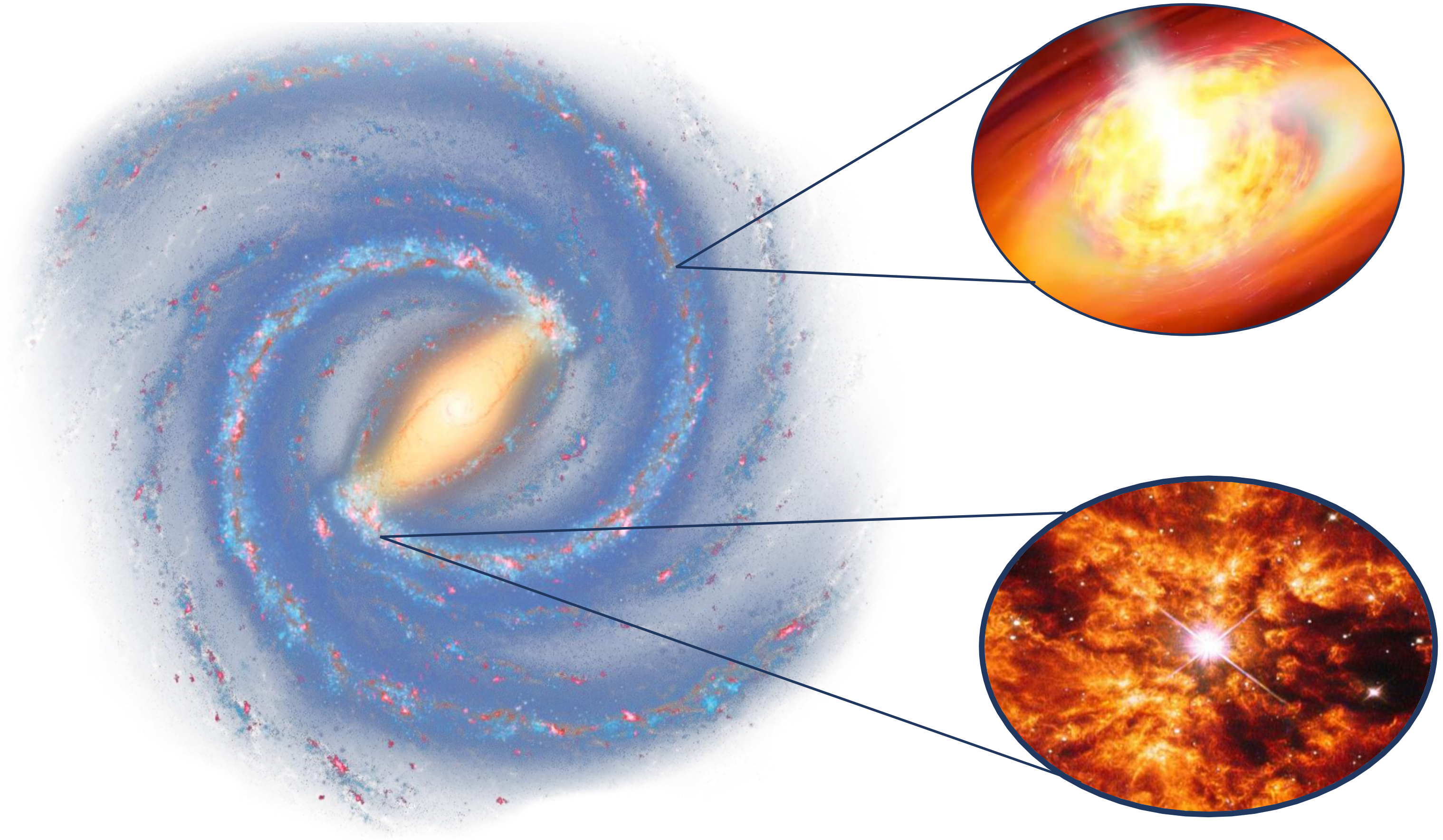
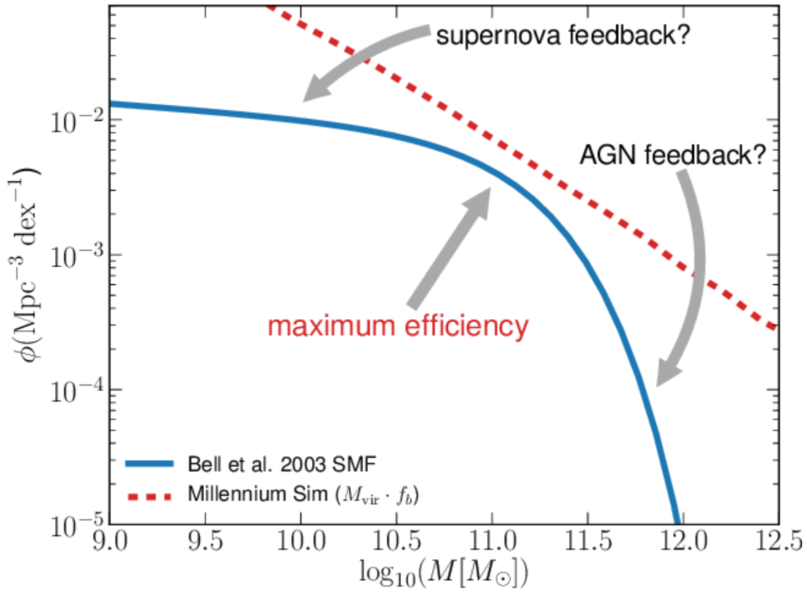


[Mutch+13]

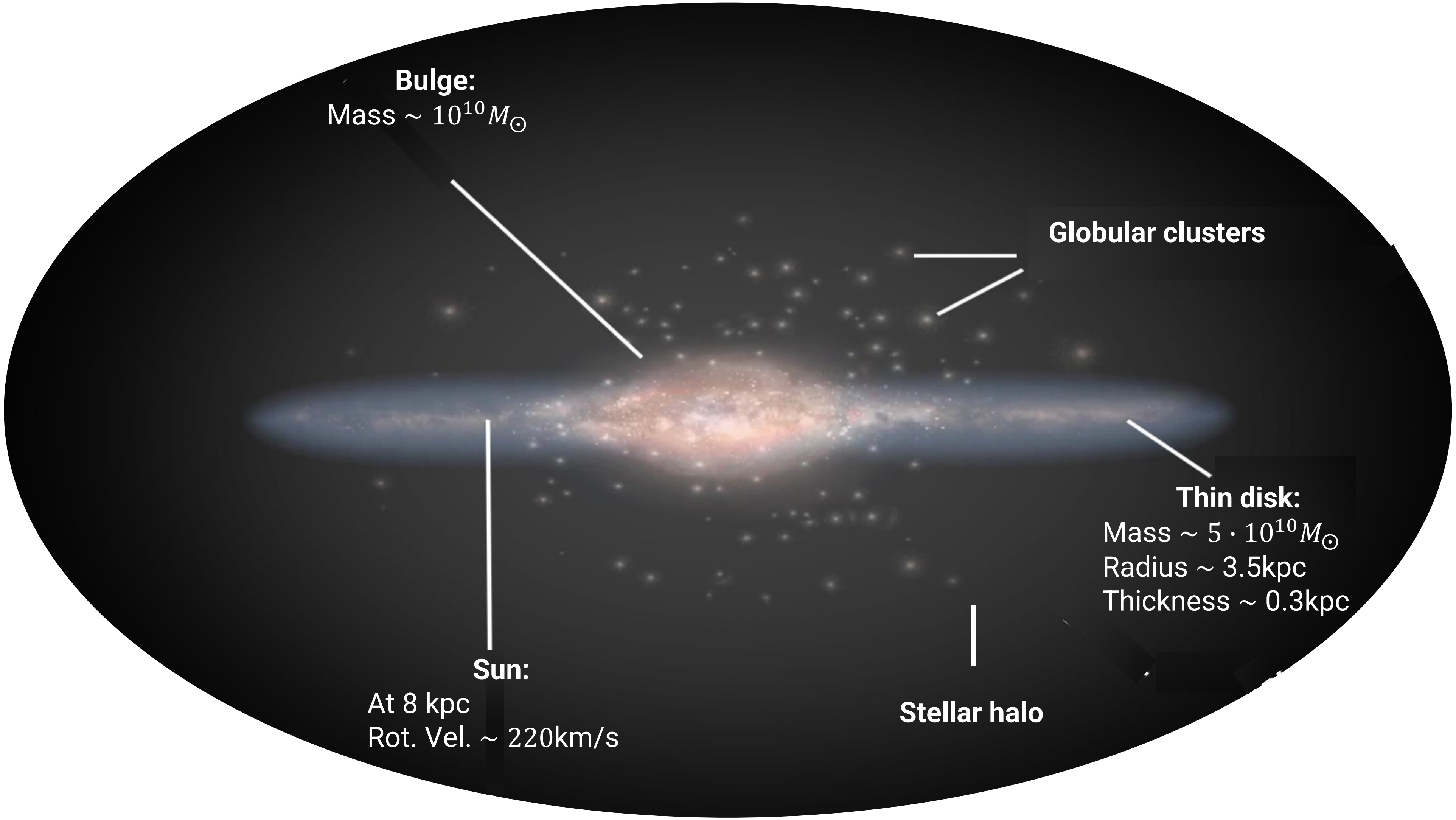


FEEBACK processes:

Prevents the collapse of molecular clouds by SN or AGN feedback. Gas expulsion or heating.

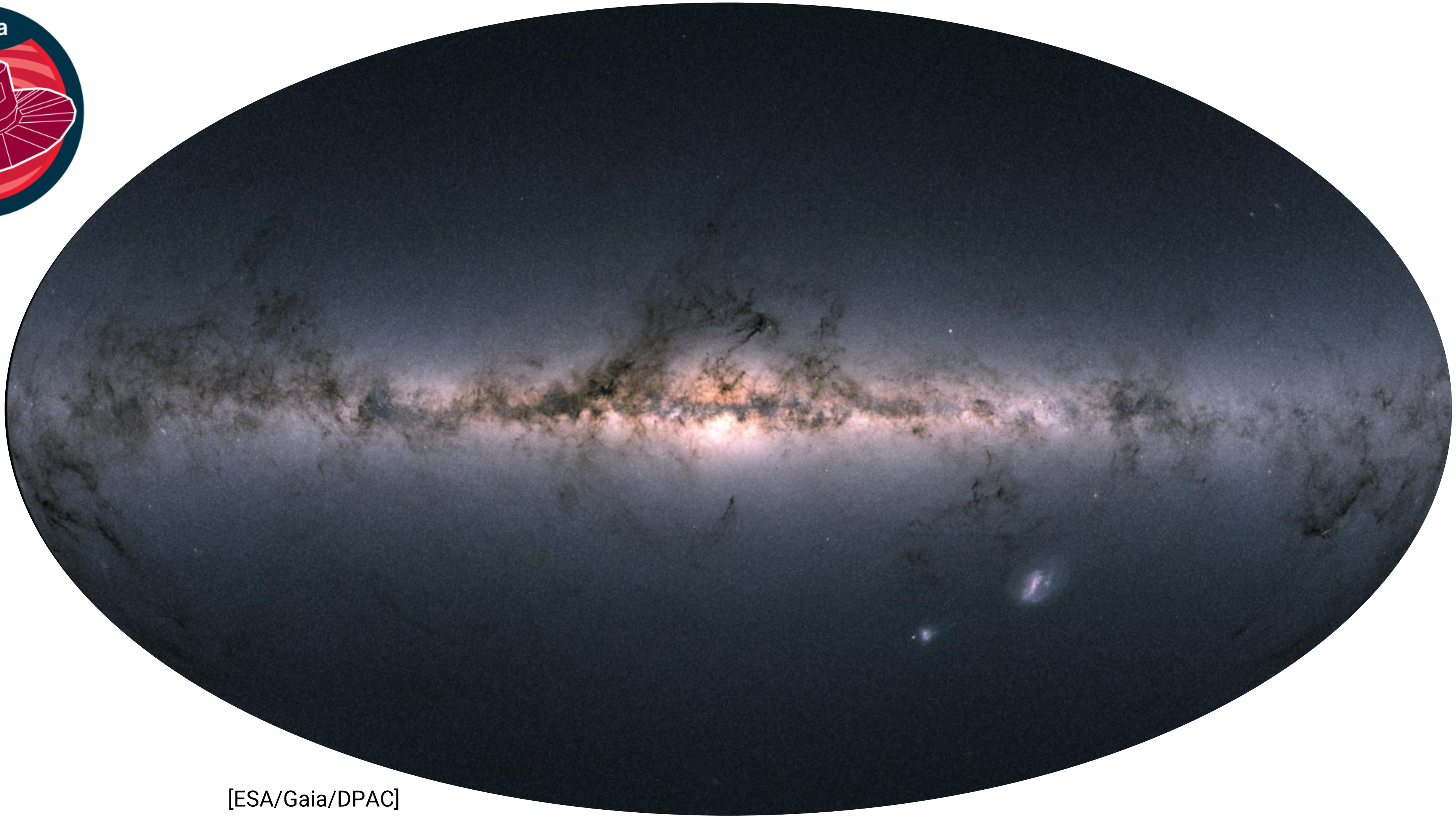
1.2. MILKY WAY-LIKE GALAXIES

MILKY WAY: Spiral barred galaxy



1.2. MILKY WAY-LIKE GALAXIES

GAIA mission has revolutionized our understanding of the formation of the MW. And divide it in three distinct phases.



[ESA/Gaia/DPAC]

1.2. MILKY WAY-LIKE GALAXIES

OPEN QUESTIONS:

1. Precise **AGE** measurements required to probe early stages are unfeasible.

2. **GAS** accretion and cooling processes remains limited due to lack of knowledge of circumgalactic medium (CGM).

Did MW-like disks develop a central **METAL-POOR** component?

How have star formation and chemical composition evolved over time?

Is **DISK FORMATION** driven by cold or hot accretion into DM halos?

How do MW-like **DISKS** form?

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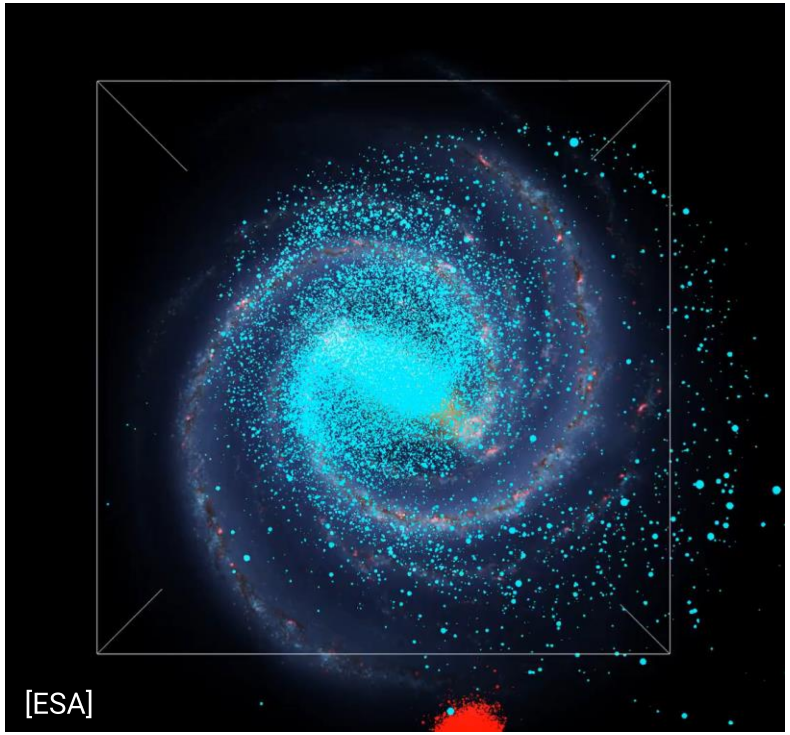
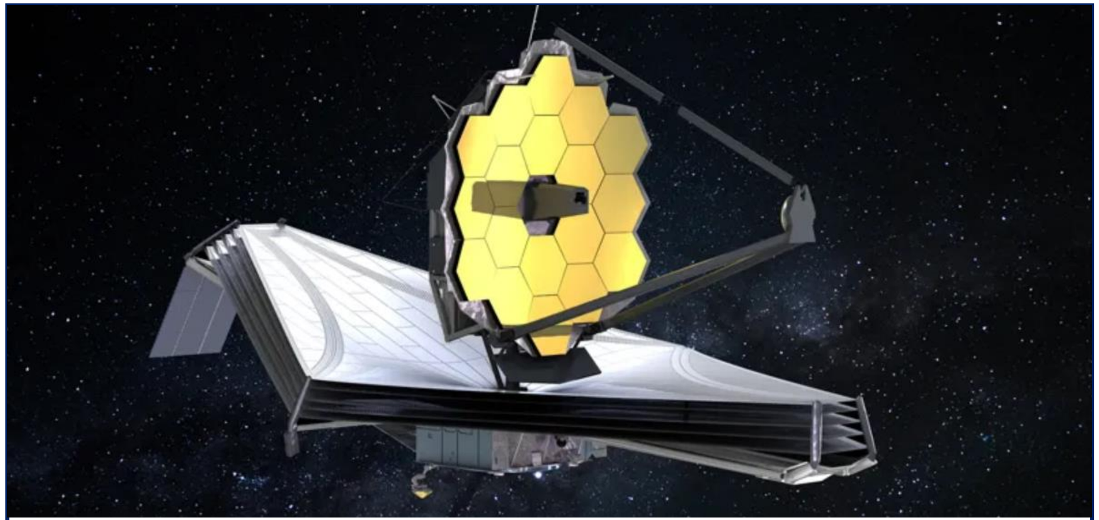


Spectroscopic observations of MW-like galaxies at certain redshifts can offer valuable insights, such as at the time of the **GAIA-SAUSAGE ENCELADUS MERGER** ($z \sim 1.5$).

JWST most suitable instrument for these observations.

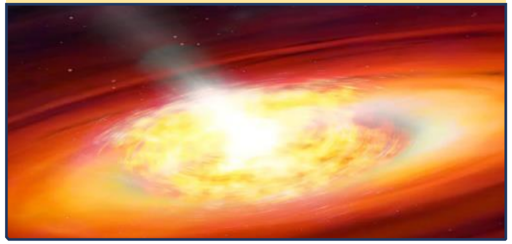
1.3. JAMES WEBB SPACE TELESCOPE



DARK AGES - REIONIZATION

GALAXY FORMATION

STAR FORMATION



EXOPLANETS

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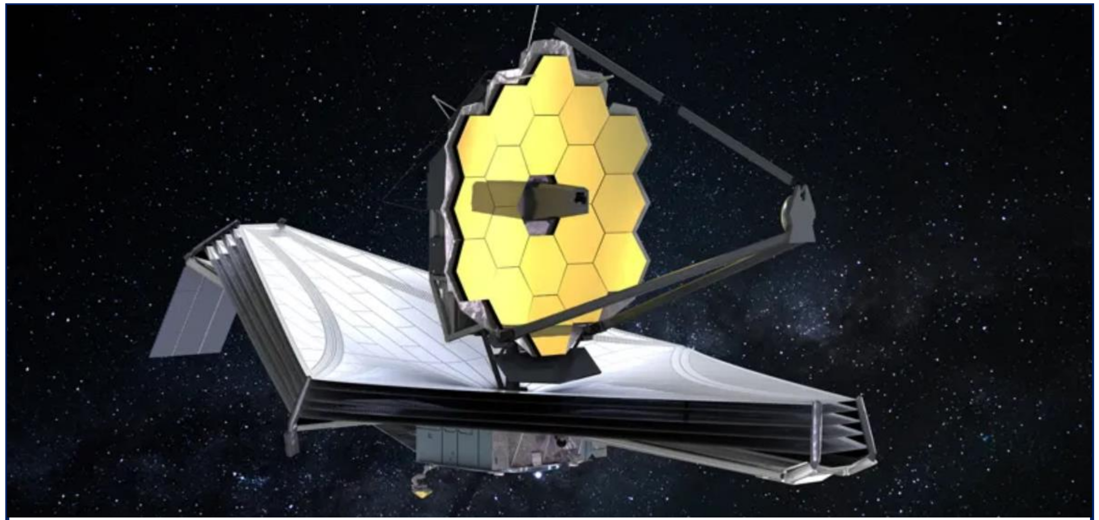

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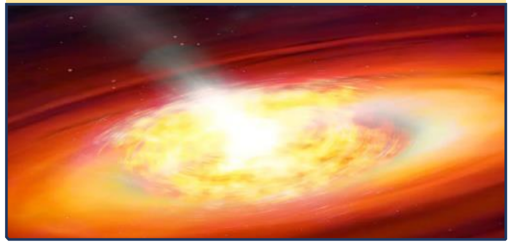


EXOPLANETS

MIRI

Mid-Infrared Instrument

NIRCam

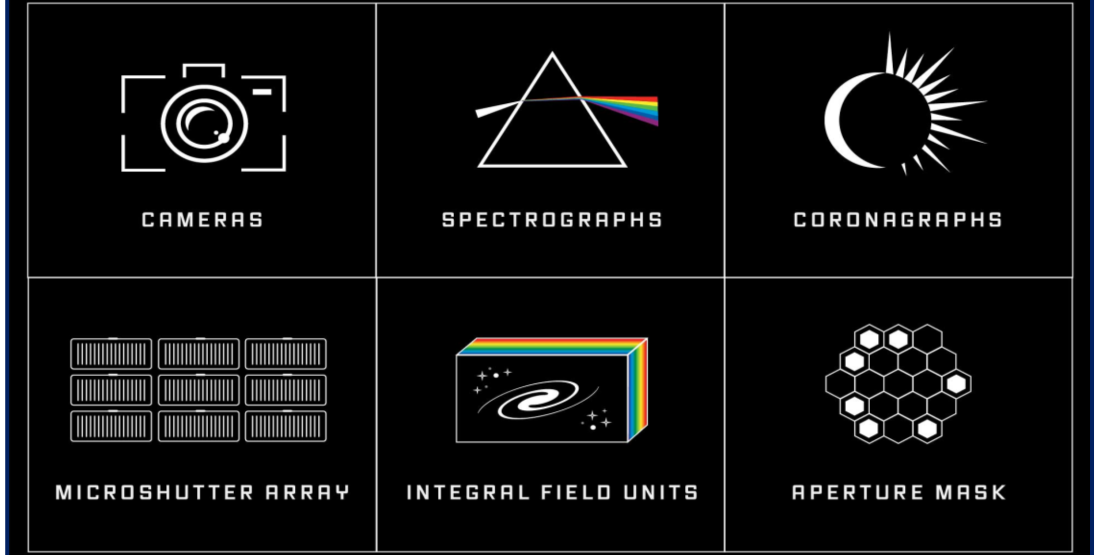
Near-Infrared Camera

NIRSpec

Near-Infrared Spectrograph

NIRISS

Near-Infrared Imager and Slitless Spectrograph



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CAMERAS

SPECTROGRAPHS

CORONAGRAPHS

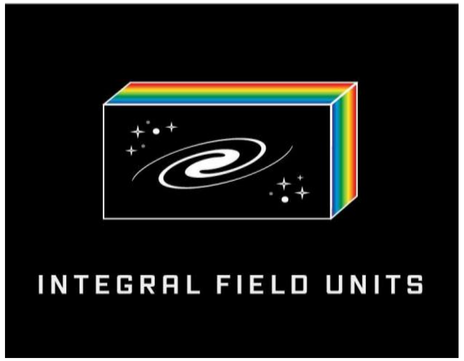
MICROSHUTTER ARRAY

INTEGRAL FIELD UNITS

APERTURE MASK

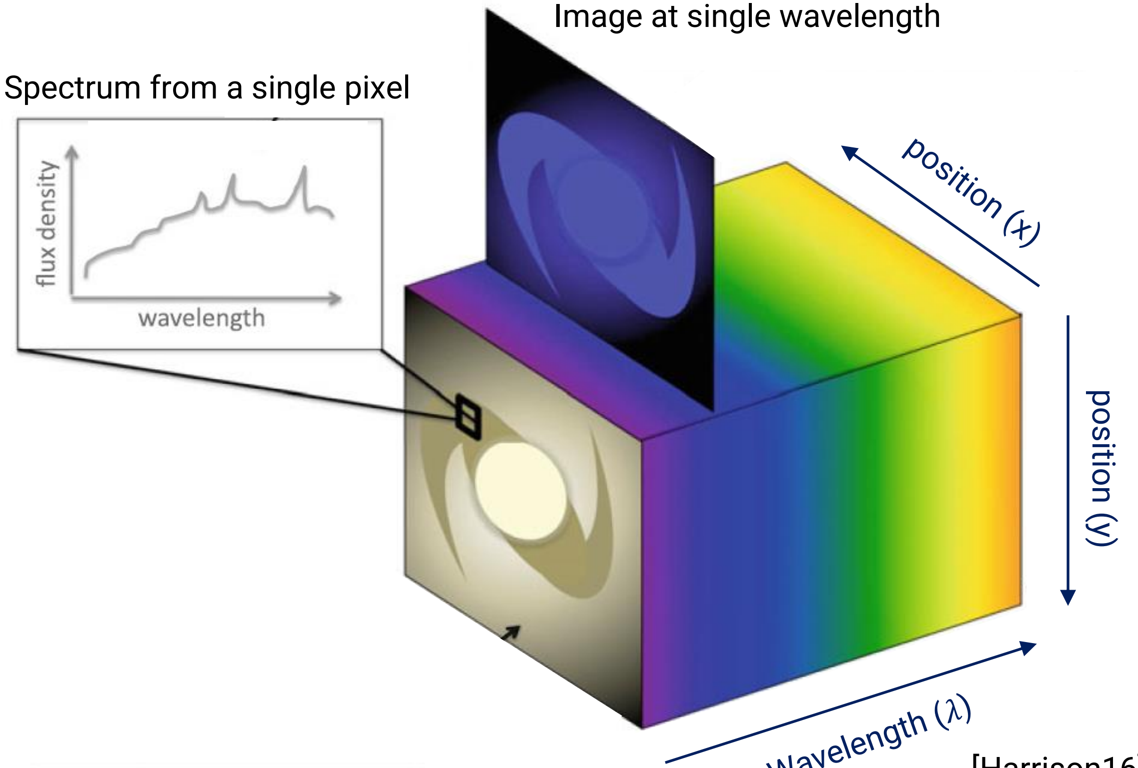
1.3. JAMES WEBB SPACE TELESCOPE

INTEGRAL FIELD SPECTROSCOPY (IFS)



IFS integrate **IMAGING** and **SPECTROSCOPIC** capabilities in optical and IR to obtain spatially resolved spectra across a 2D region.

The FOV is segmented in sub-regions (*spaxels*), and optically recombined generating **3D DATACUBES** (spatial + spectral).



[Harrison16]

2. HYPOTHESIS AND OBJECTIVES

GOODS South Field – WFC3 Early Release Science Data

2. HYPOTHESIS AND OBJECTIVES

MAIN OBJECTIVE: Develop IFU datacubes for simulated **MW-LIKE GALAXIES** at $z \sim 1.5$, and simulate how would appear through the JWST **NIRSpec** spectrograph.

Will support ongoing observational efforts by **IAC** host group to study a sample of MW-like galaxies with JWST.

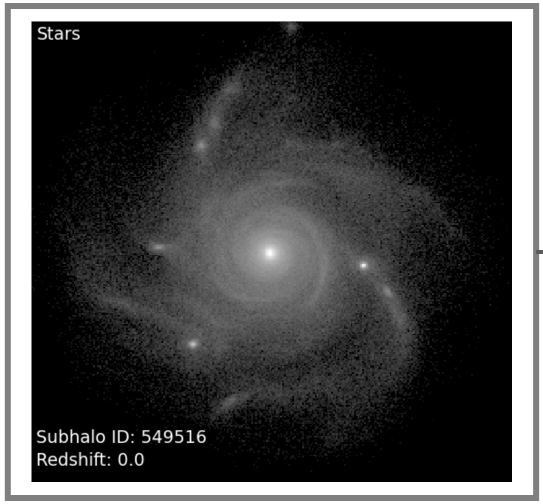
Direct **TEST** of JWST's capabilities to constrain MW-like galaxies formation history.

1. Use **TNG50** simulation to generate 2D maps of stellar population properties.
2. Develop computational framework for generating 3D IFU datacubes for TNG50 galaxies.
3. Simulate those datacubes through the JWST NIRSpec IFU instrument.
4. Simulate those datacubes through HARMONI instrument.

2. HYPOTHESIS AND OBJECTIVES

MAIN OBJECTIVE: Develop IFU datacubes for simulated **MW-LIKE GALAXIES** at $z \sim 1.5$, and simulate how would appear through the JWST **NIRSpec** spectrograph.

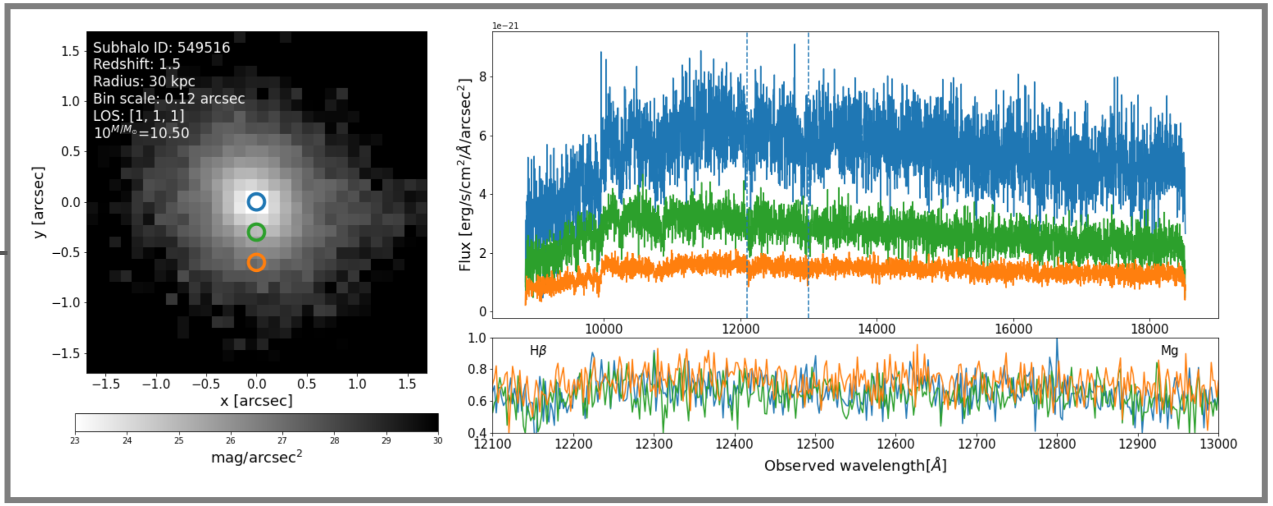
Cosmological hydrodynamical **SIMULATION**



`TNG_mockIFU`

(available on GitHub)

Simulated observation of **JWST**

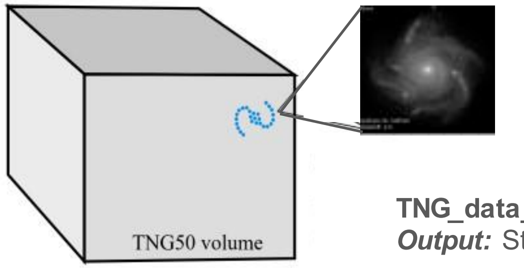


3. METHODOLOGY AND MATERIALS

GOODS South Field – WFC3 Early Release Science Data

3. METHODOLOGY AND MATERIALS

1. TNG50 MW-like galaxies:



TNG_data_loader
Output: Stellar particles file.

2. MILES stellar library:

synthetic_spectrum

Output: Each stellar particle is interpolated and associated to a synthetic spectrum from MILES template and linearly combined to form the fiber spectrum.

3. IFU datacubes:

data_cube

Output: IFU datacubes (FITS file)

Input:
TNG50 galaxy ID
TNG50 snapshot
Radius (in kpc)
Vector l.o.s.
*, spaxel size, number of bins

4. JWST NIRSpec simulation:

pass_to_jwst

Output: IFU datacubes (FITS file)

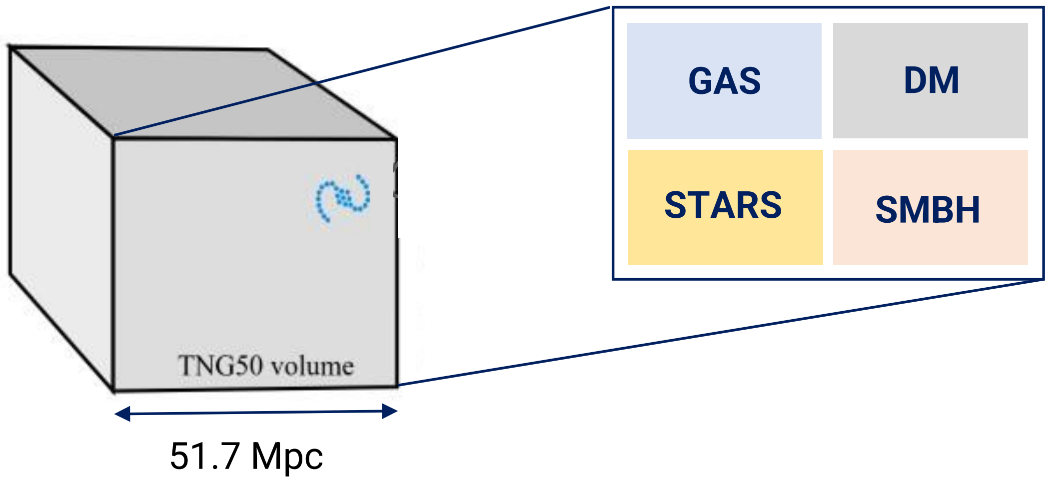
A. Spectral resolution:
Convolution to filter bandpass and Gaussian noise added.

B. Fit to NIRSpec FOV:
Fit into 30x30 spaxels.

C. Spatial resolution:
2D Gaussian Convolution to NIRCam PSF.

3.1. ILLUSTRIS TNG50 SIMULATION

Cosmological **MAGNETO-HYDRODYNAMICAL** simulation that models the formation and evolution of galaxies in a ΛCDM universe.



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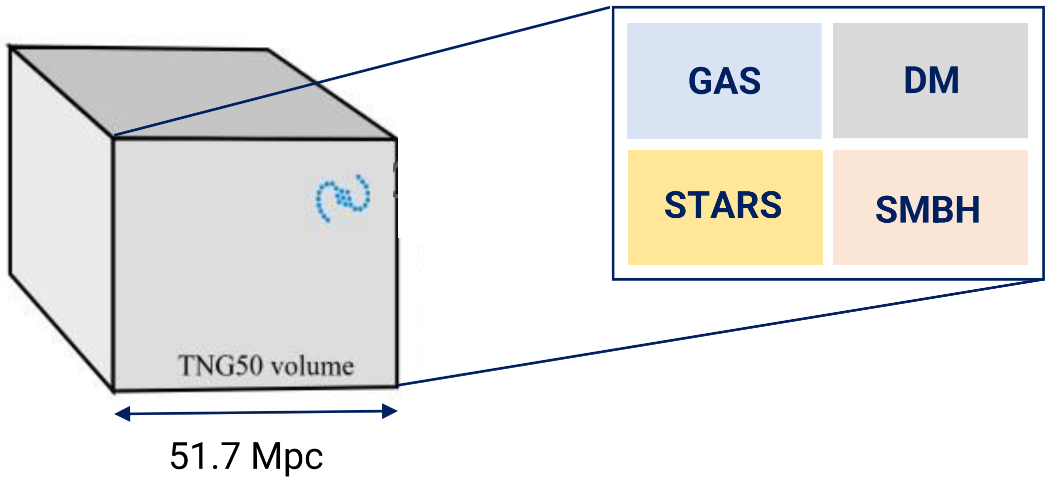

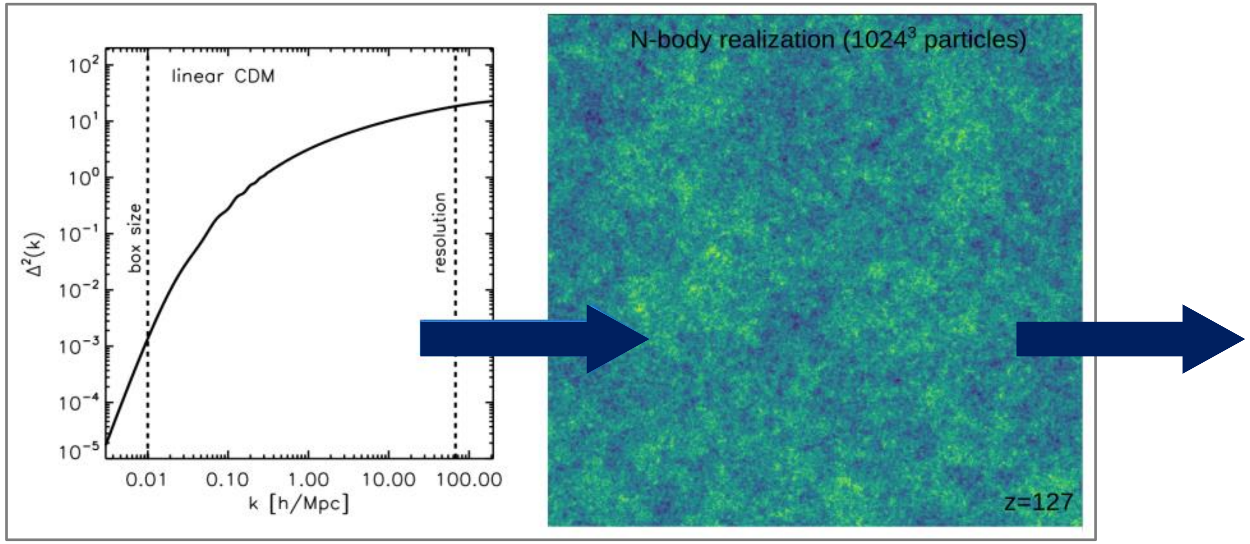

[Zavala&Frenk16]

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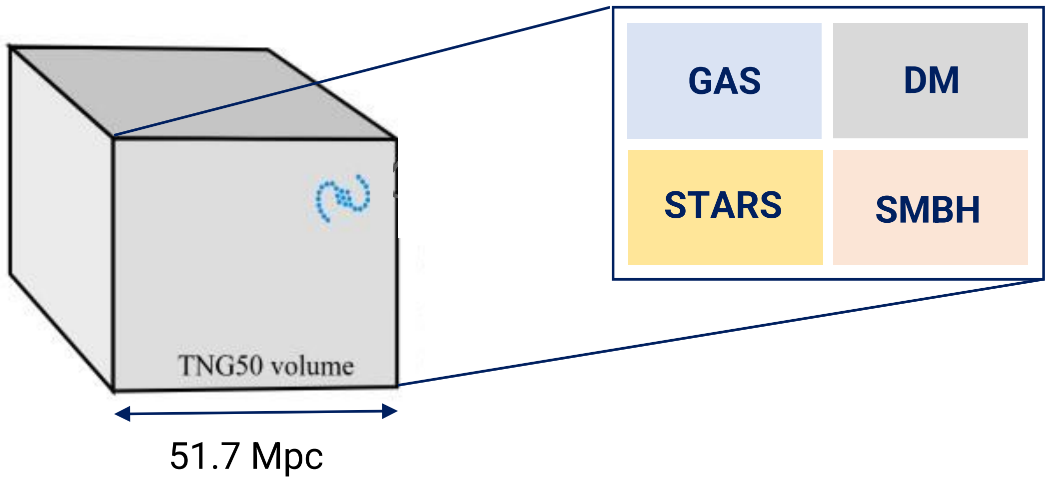
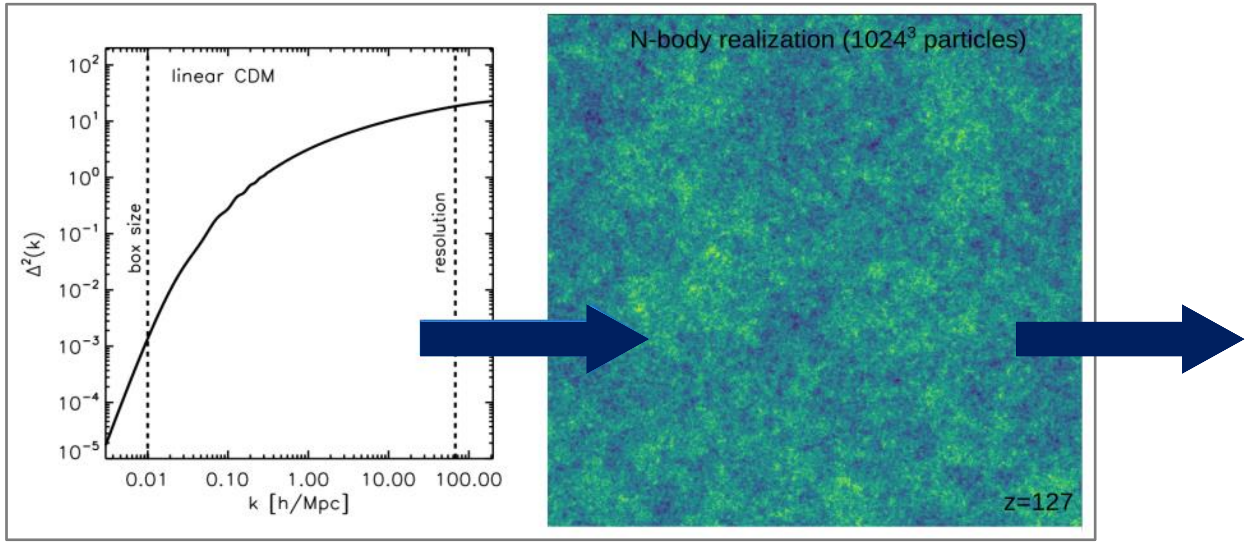
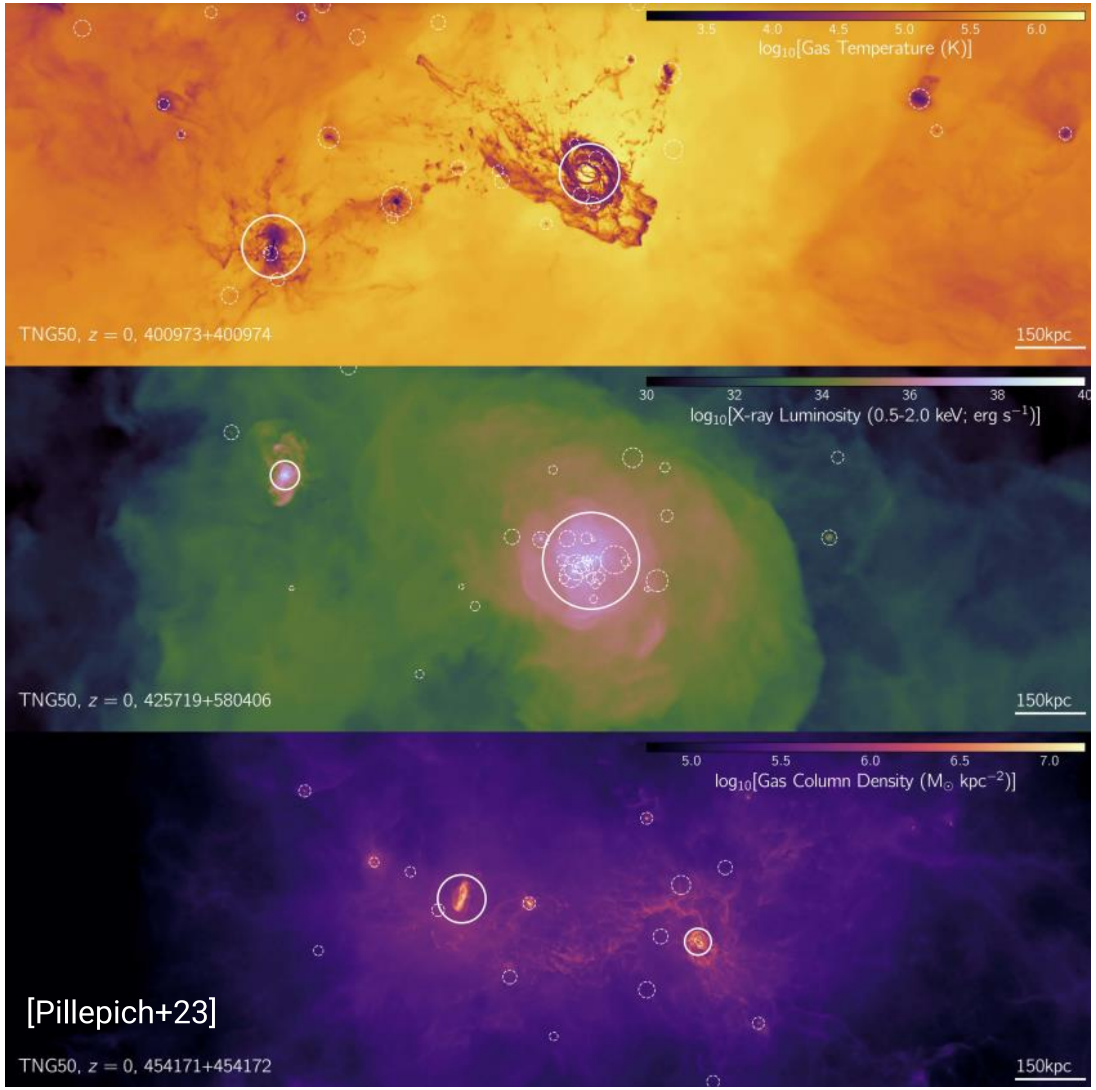




[Zavala&Frenk16]



[Pillepich+23]

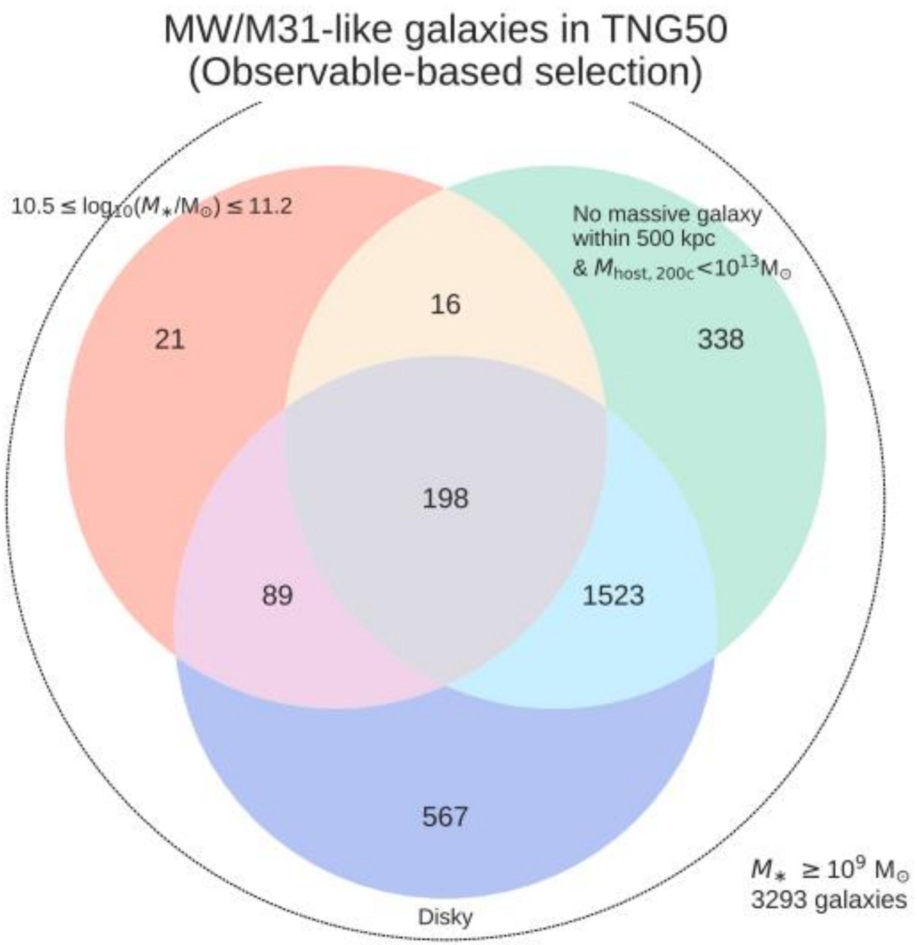
3.1. ILLUSTRIS TNG50 SIMULATION

A: TNG50 MW/M31 ANALOGS:

1. **MASS**: $M_{\odot}(< 30\text{kpc}) = 10^{10.5-11.2} M_{\odot}$
2. **MORPHOLOGY**: stellar disk-like and spiral arms.
3. **ENVIRONMENT**: no other galaxy of $\leq 10^{10.5} M_{\odot}$ within 500kpc.

198 MW/M31-like galaxies

Data available on TNG50 MW/M31 Data Release

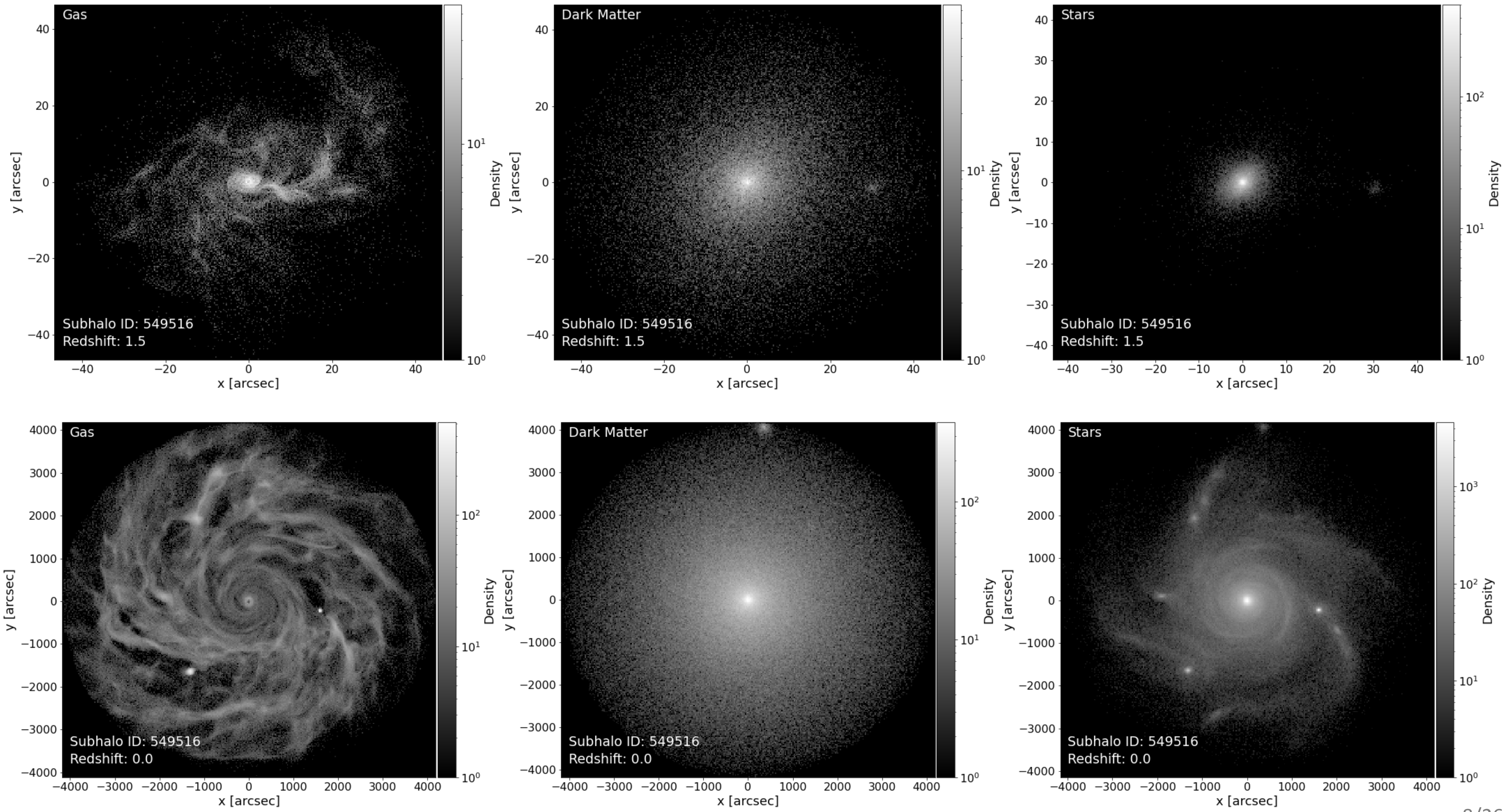


[Pillepich+23]

3.1. ILLUSTRIS TNG50 SIMULATION

$z = 1.5$

$z = 0$



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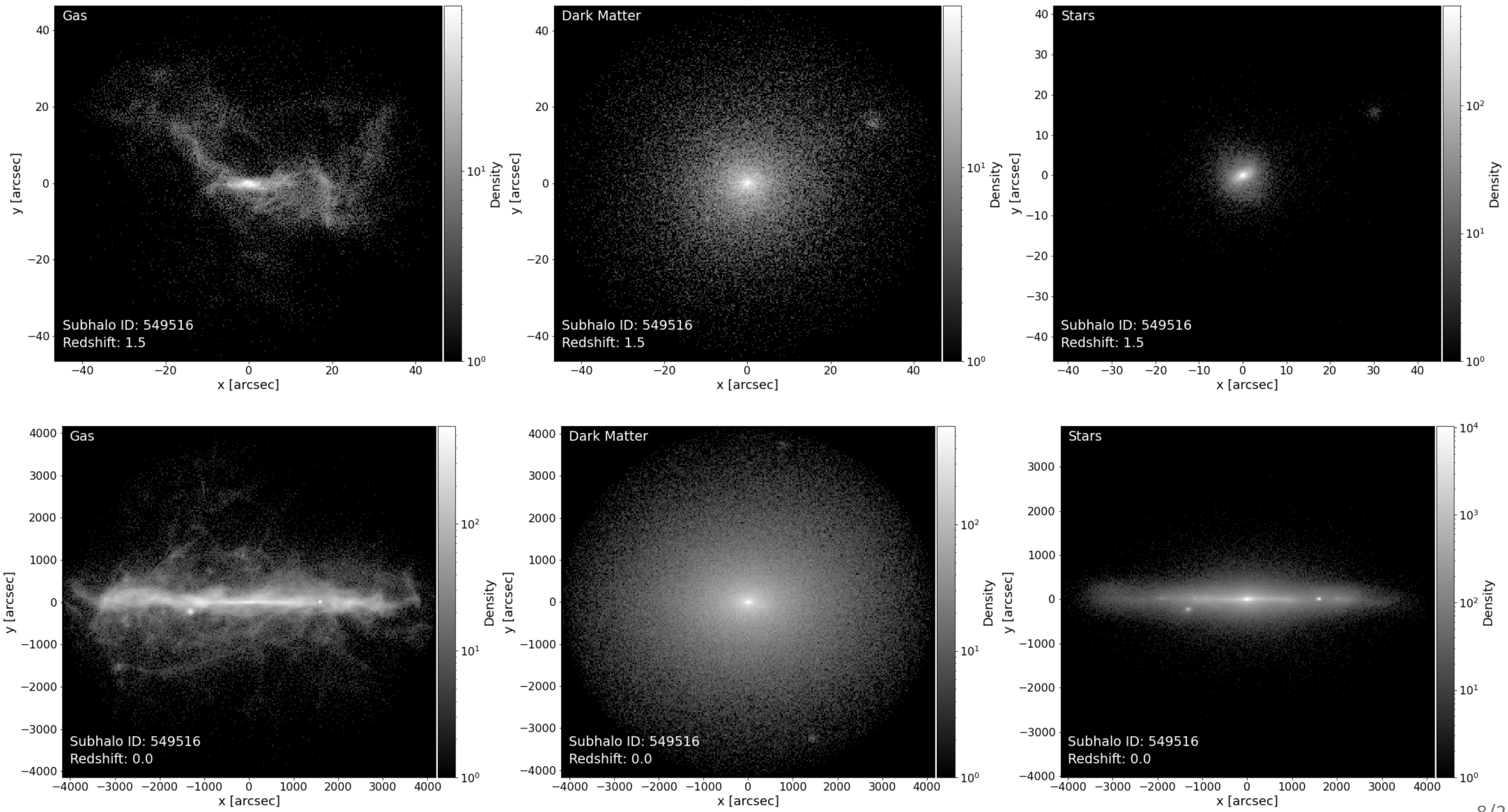

3.1. ILLUSTRIS TNG50 SIMULATION

B: STELLAR POPULATION PROPERTIES:

Save in an HDF5 the necessary stellar particles information:

`ifu.TNG_data_loader`

- **METALLICITY** [Fe / H]
- **AGE** [Gyr]
- **MASS** [$M_\odot$]
- **COORDINATES** [kpc/h]
- **VELOCITIES** [km/s]

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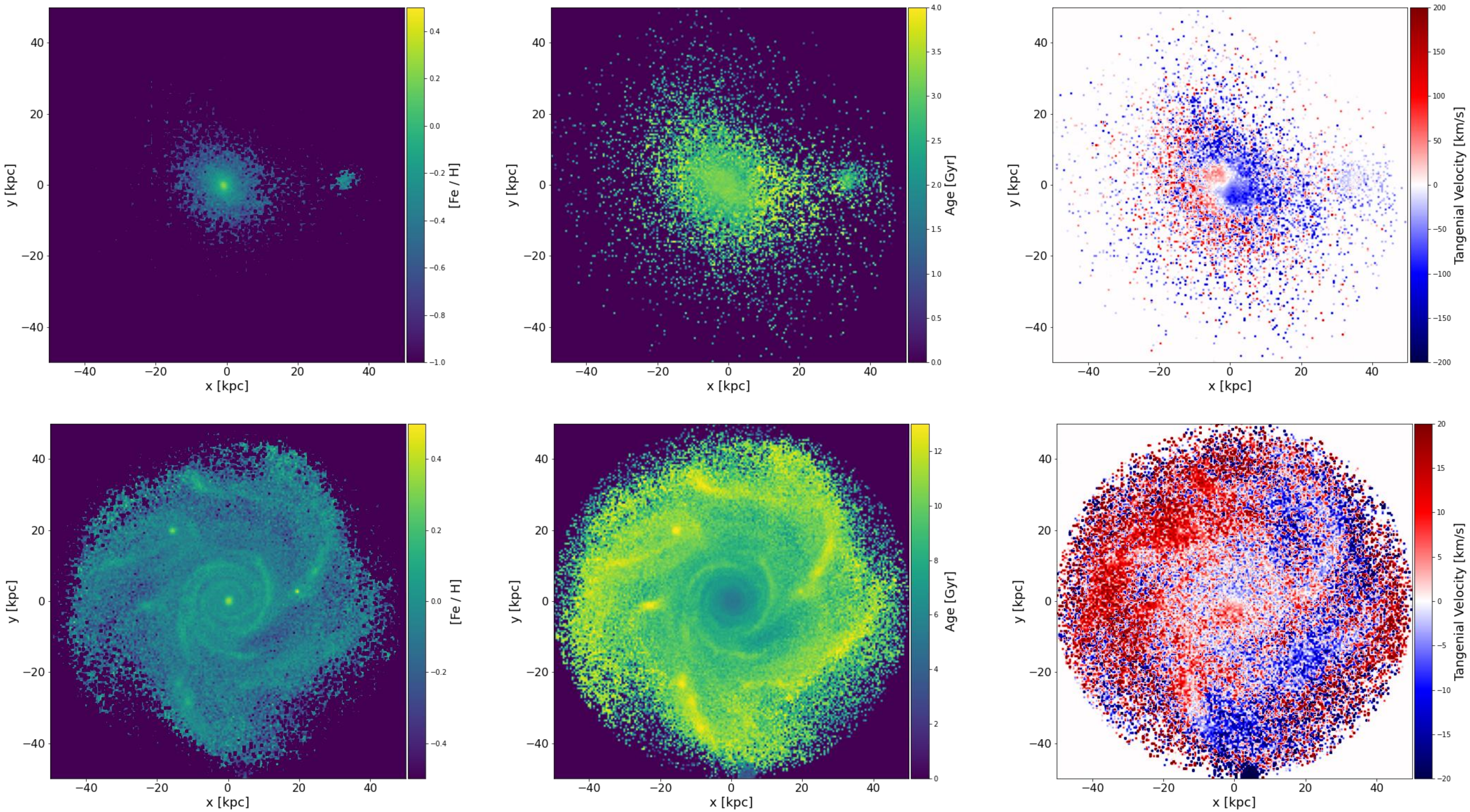

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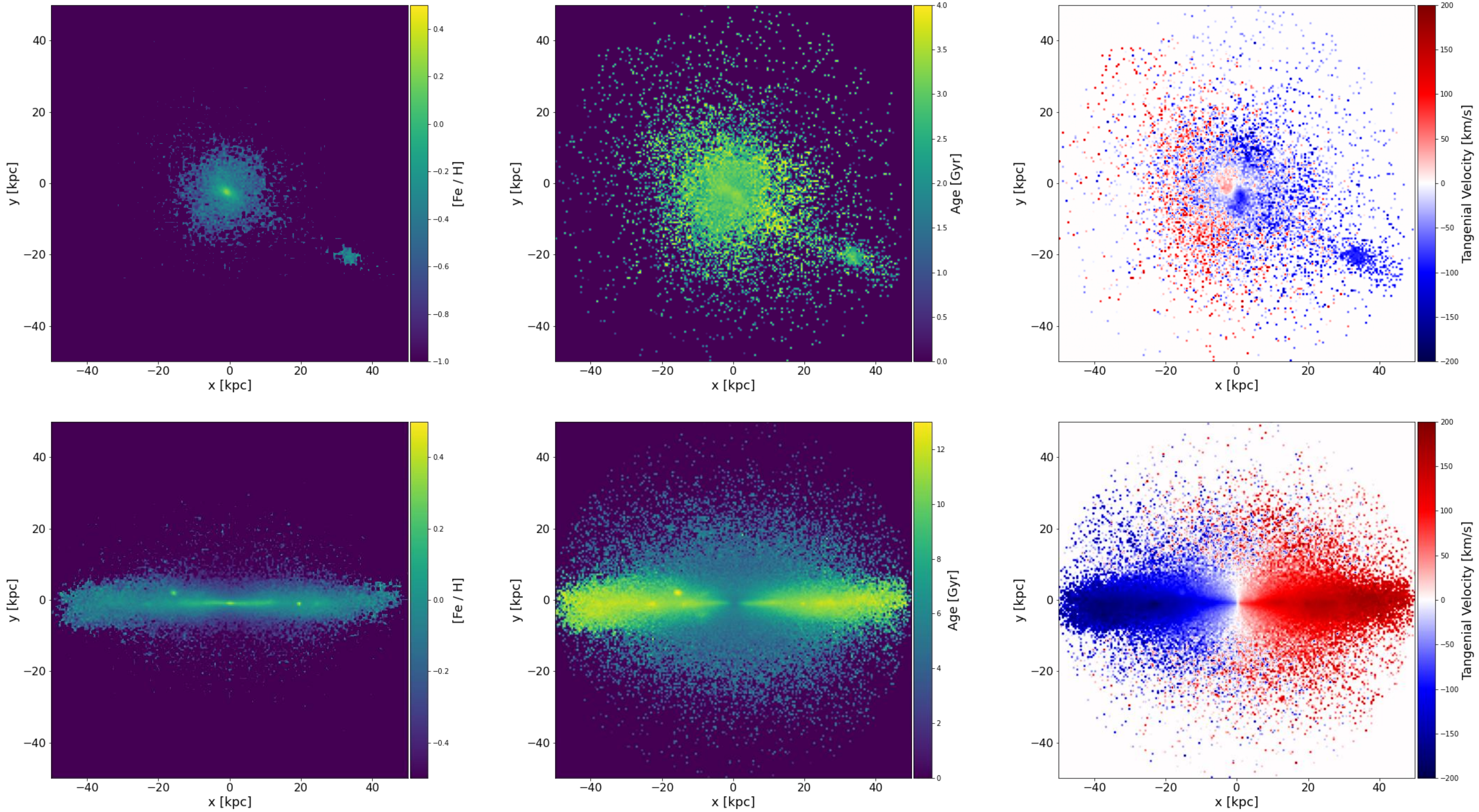
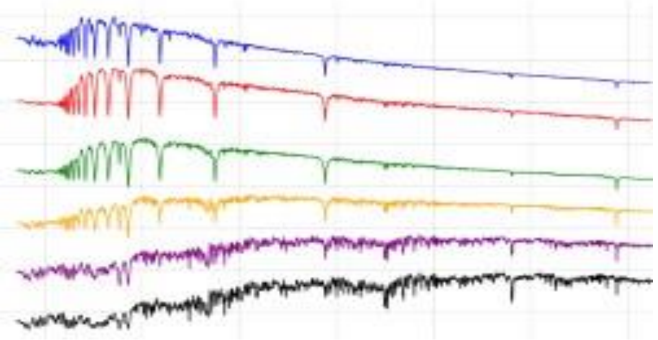


3.2. MILES STELLAR POPULATION LIBRARY

1. TNG50 MW-like galaxies:

TNG_data_loader
Output: Stellar particles file.

2. MILES stellar library:



synthetic_spectrum

Output: Each stellar particle is interpolated and associated to a synthetic spectrum from MILES template and linearly combined to form the fiber spectrum.

3. IFU datacubes:

data_cube

Output: IFU datacubes (FITS file)

Input:
TNG50 galaxy ID
TNG50 snapshot
Radius (in kpc)
Vector l.o.s.
*, spaxel size, number of bins

4. JWST NIRSpec simulation:

pass_to_jwst

Output: IFU datacubes (FITS file)

A. Spectral resolution:
Convolution to filter bandpass and Gaussian noise added.

B. Fit to NIRSpec FOV:
Fit into 30x30 spaxels.

C. Spatial resolution:
2D Gaussian Convolution to NIRCam PSF.

3.2. MILES STELLAR POPULATION LIBRARY

We need a model to asign **SYNTHETIC SPECTRUM** to a given TNG stellar particle.

Single Stellar Population (SSP) spectra characterized by **AGE** and **METALLICITY** values (3535 to 7500 Å)

A. Empirical stellar library:

985 stars from Solar neighborhood using 2.5m Isaac Newton Telescope with FWHM$\sim$2.3Å.
[Sánchez-Blázquez+06]

+

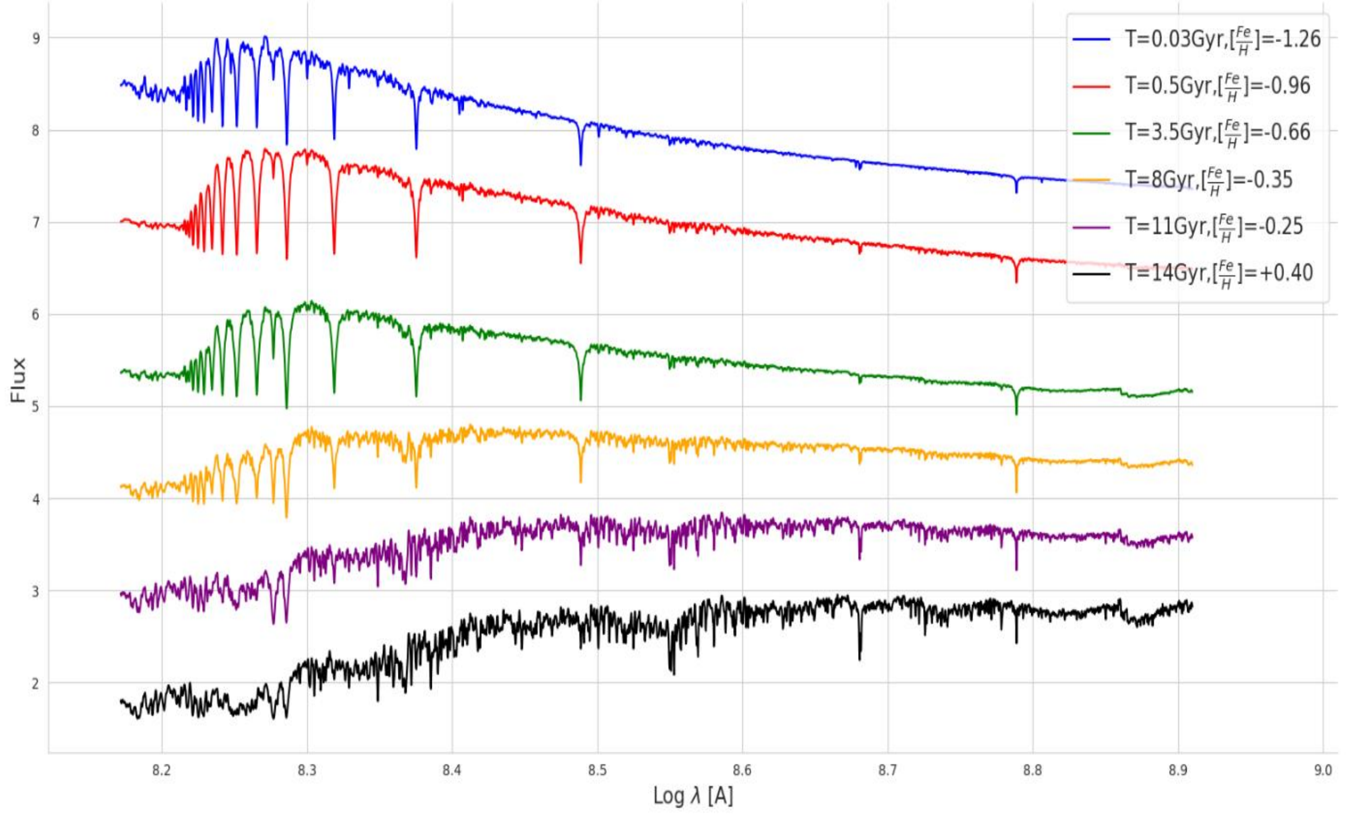
B. Isochrones:

Derived by Basti, incorporating stellar evolution in terms of age and metallicity.
[Pietrinferni+04]

+

C. IMF:

Adopted from Kroupa, power-law distribution.
[Kroupa+01]

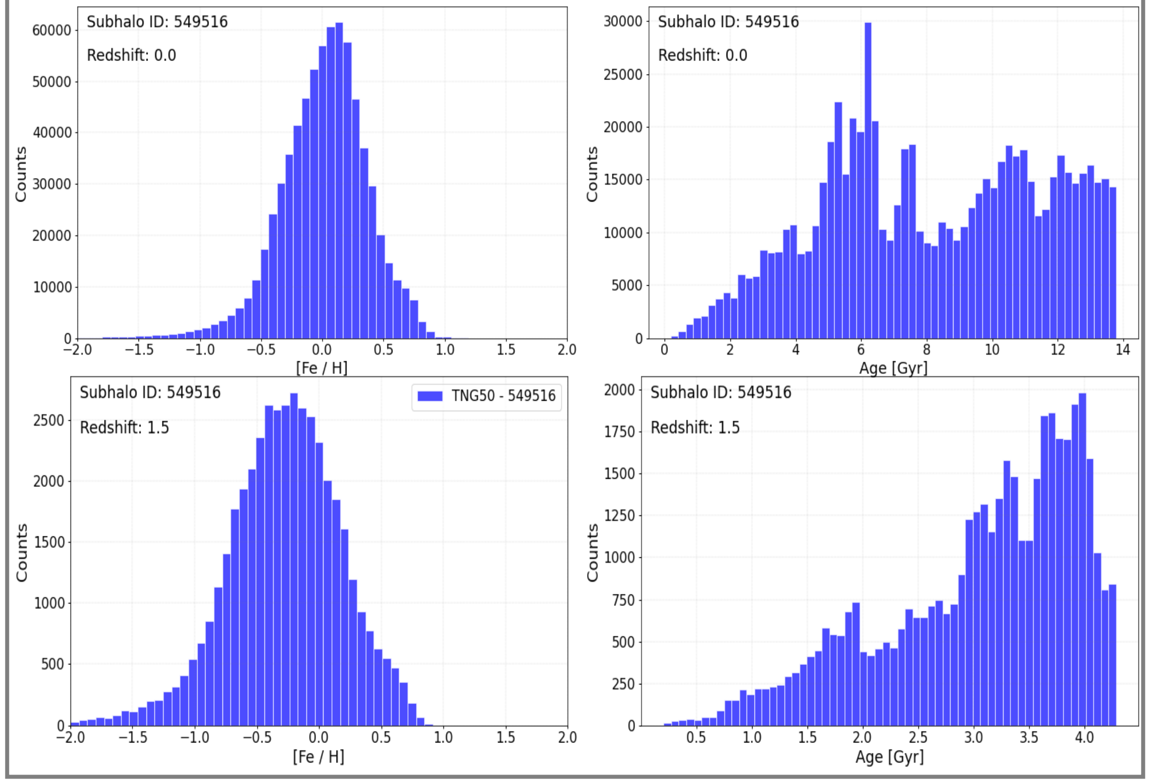


3.2. MILES STELLAR POPULATION LIBRARY

A. ASSOCIATION BETWEEN TNG50 AND MILES:

TNG50:

Continuous distribution of **AGE** and **METALLICITY** values.



MILES:

Discrete distribution with 12 **METALLICITY** values from [-2.27, 0.4] and 53 **AGE** values ranging [0.03, 14]Gyr.

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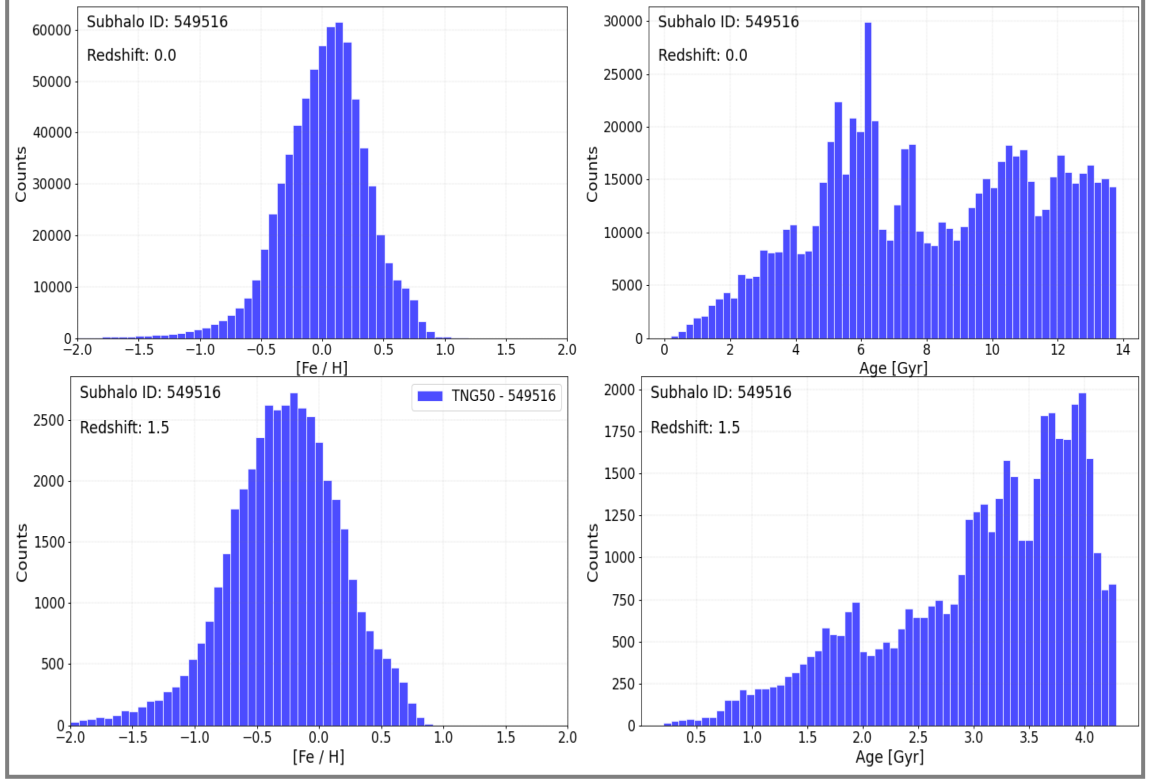
Continuous distribution of **AGE** and **METALLICITY** values.

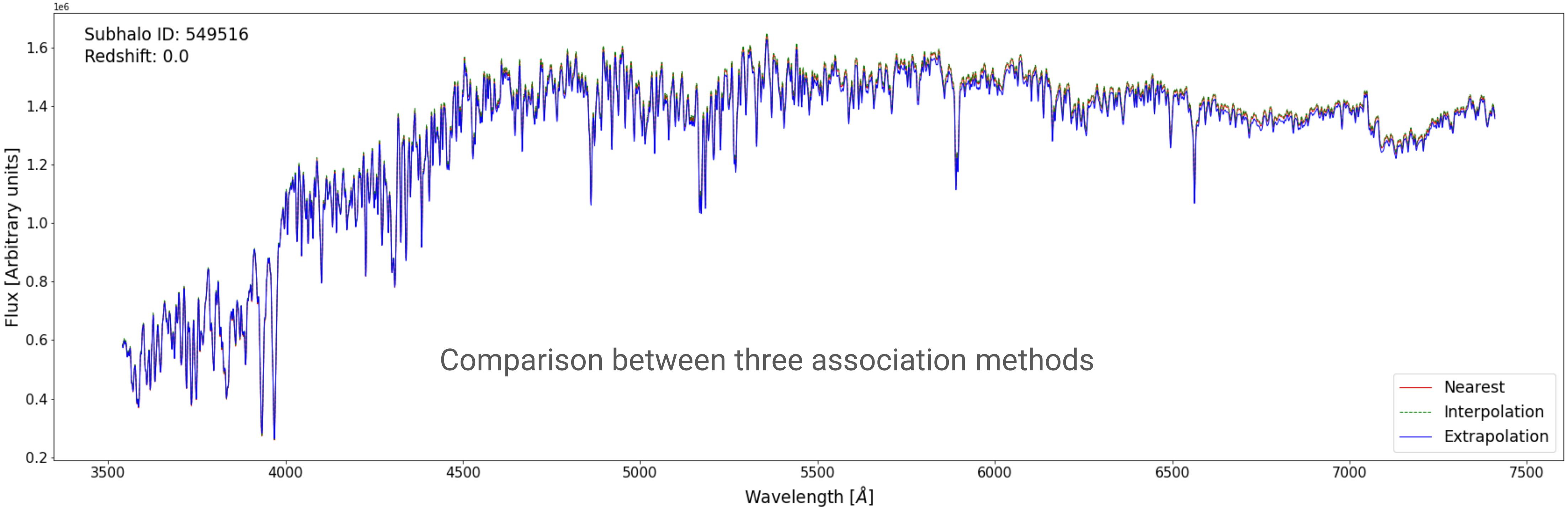


MILES:

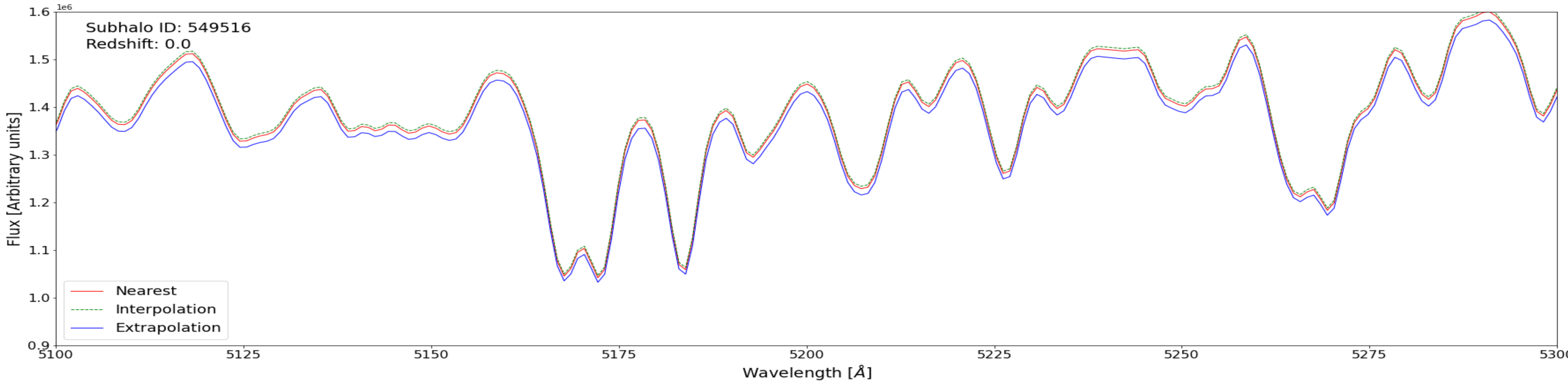
Discrete distribution with 12 **METALLICITY** values from [-2.27, 0.4] and 53 **AGE** values ranging [0.03, 14]Gyr.

1. **NEAREST**: assign to each TNG stellar particle the closest age and metallicity value from MILES.
2. **INTERPOLATION:** For metallicity values exceeding the MILES maximum the highest is assigned.
3. **EXTRAPOLATION:** Extends the interpolation linearly beyond the MILES values.

3.2. MILES STELLAR POPULATION LIBRARY



Comparison between three association methods



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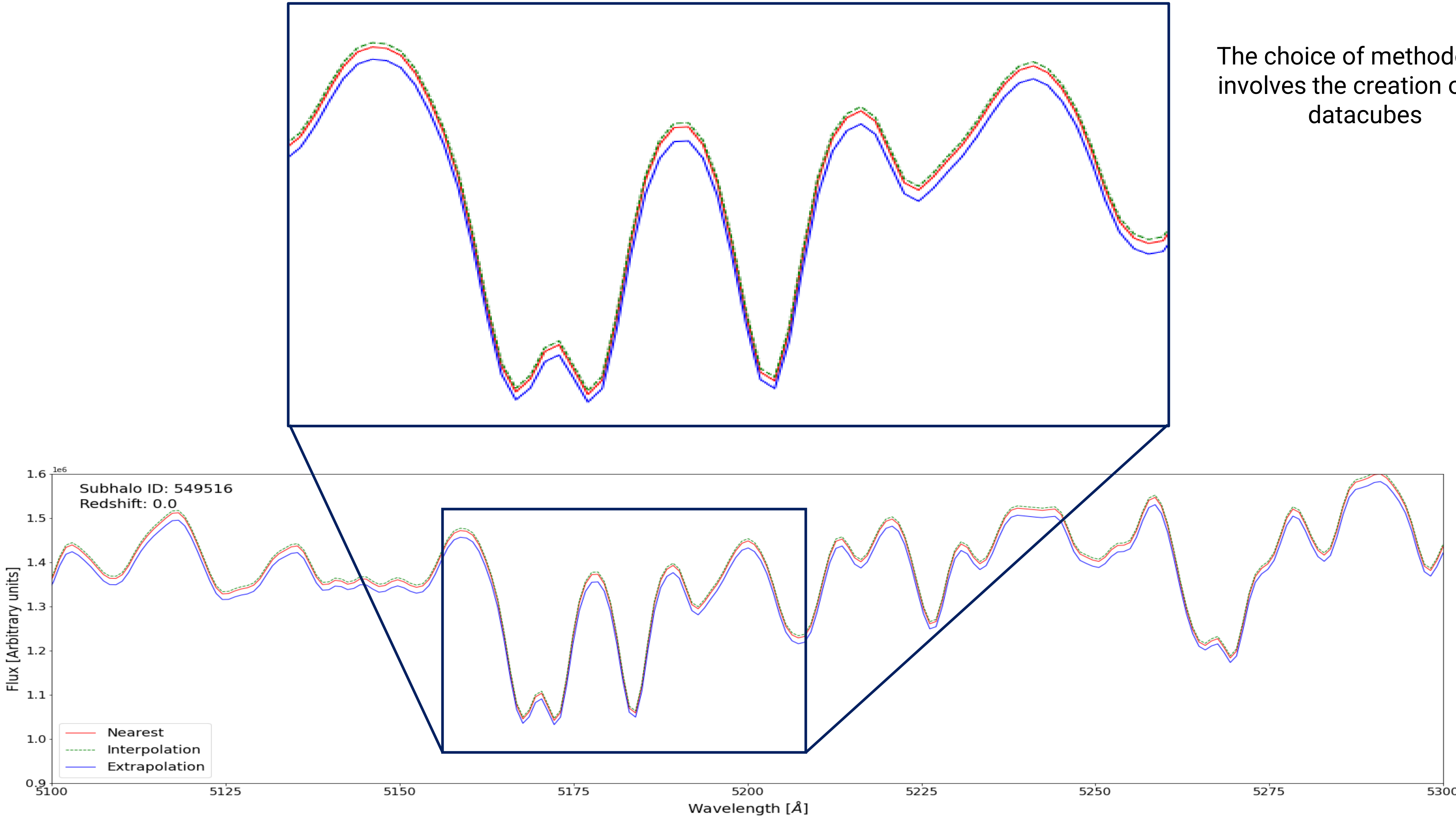
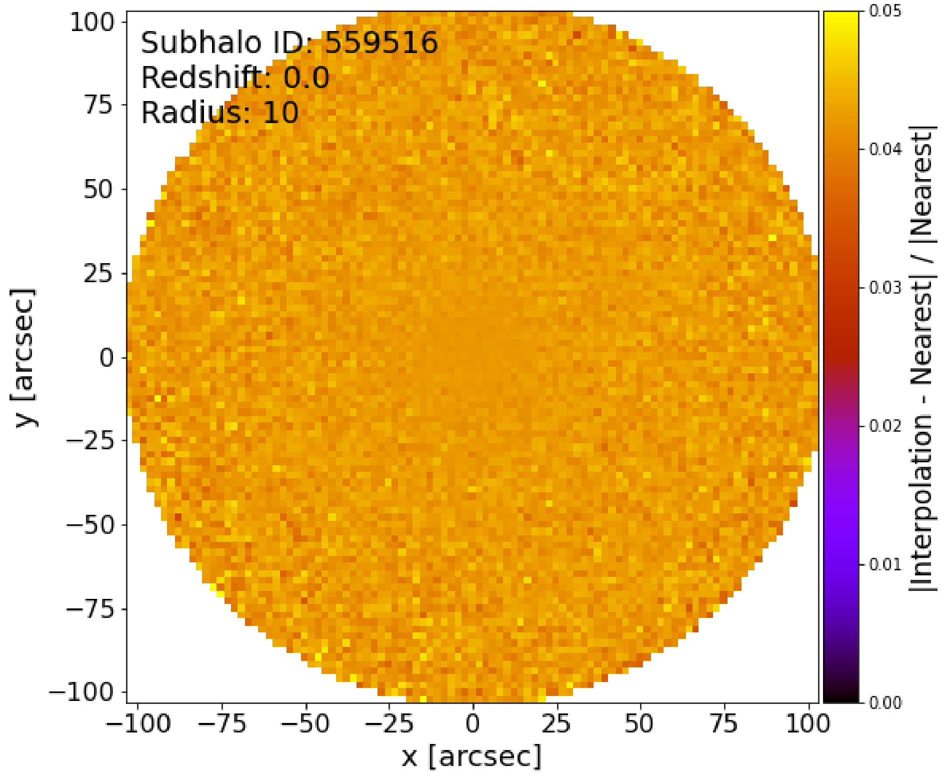


The choice of methodology involves the creation of IFU datacubes

3.2. MILES STELLAR POPULATION LIBRARY

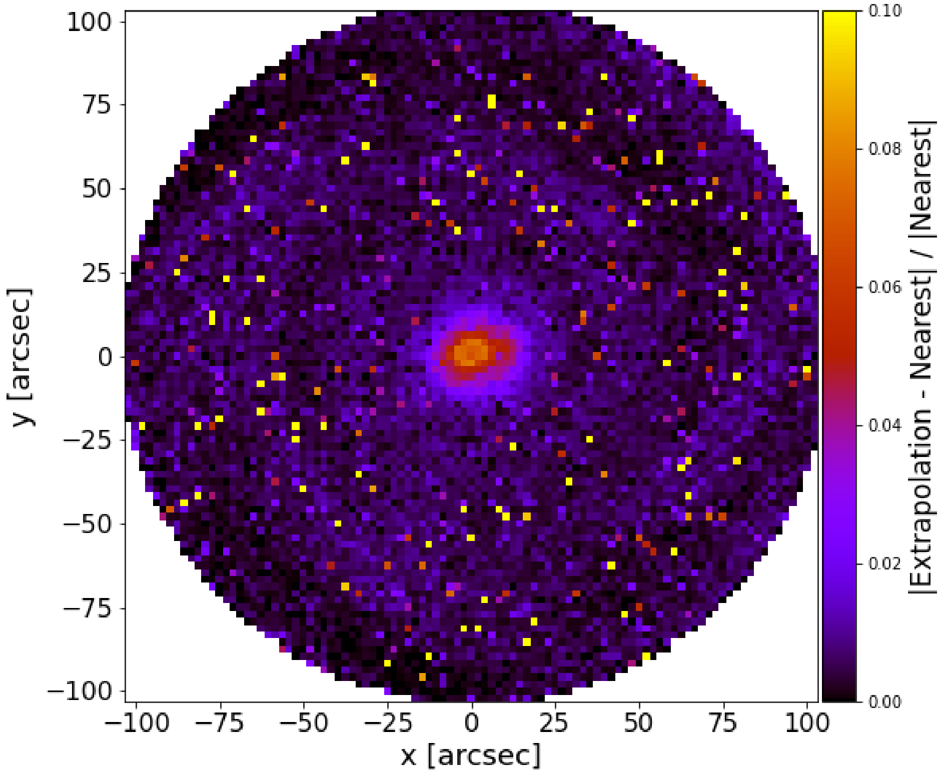
Interpolation vs. Nearest

Almost constant relative difference across the spaxels.



Extrapolation vs. Nearest

High dependency with position (spiral arms, center → high metallicity).
And with the extrapolation method adopted.



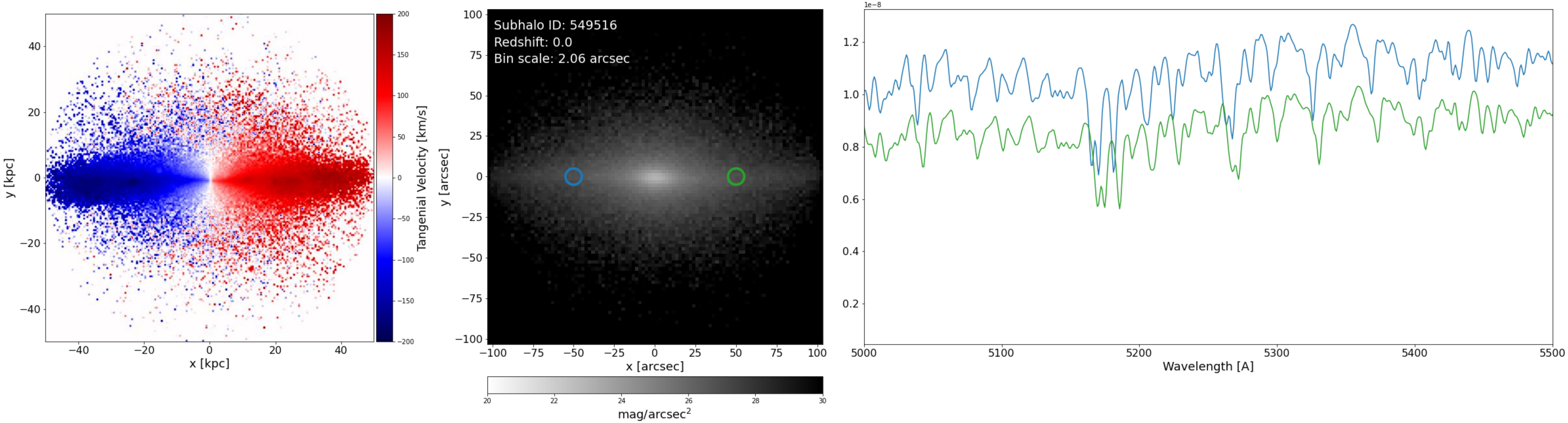
3.2. MILES STELLAR POPULATION LIBRARY

B. INCLUDING STELLAR CYNEMATICS:

Doppler shift due to rotation velocities of stellar particles.

$$\boxed{\frac{\Delta\lambda}{\lambda} = \frac{v}{c}}$$

Tangential velocity (Edge-on):



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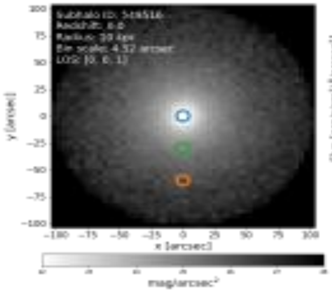

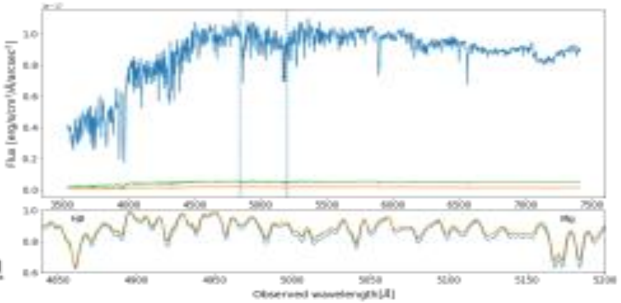

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2D Gaussian Convolution to NIRCam PSF.

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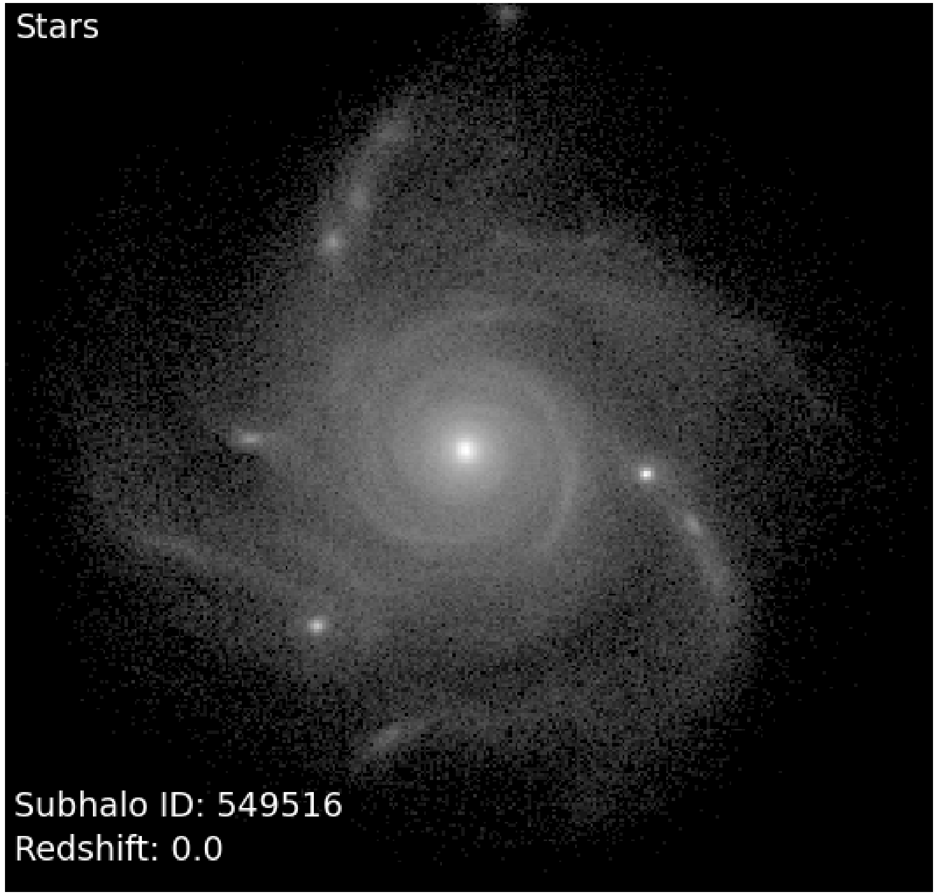

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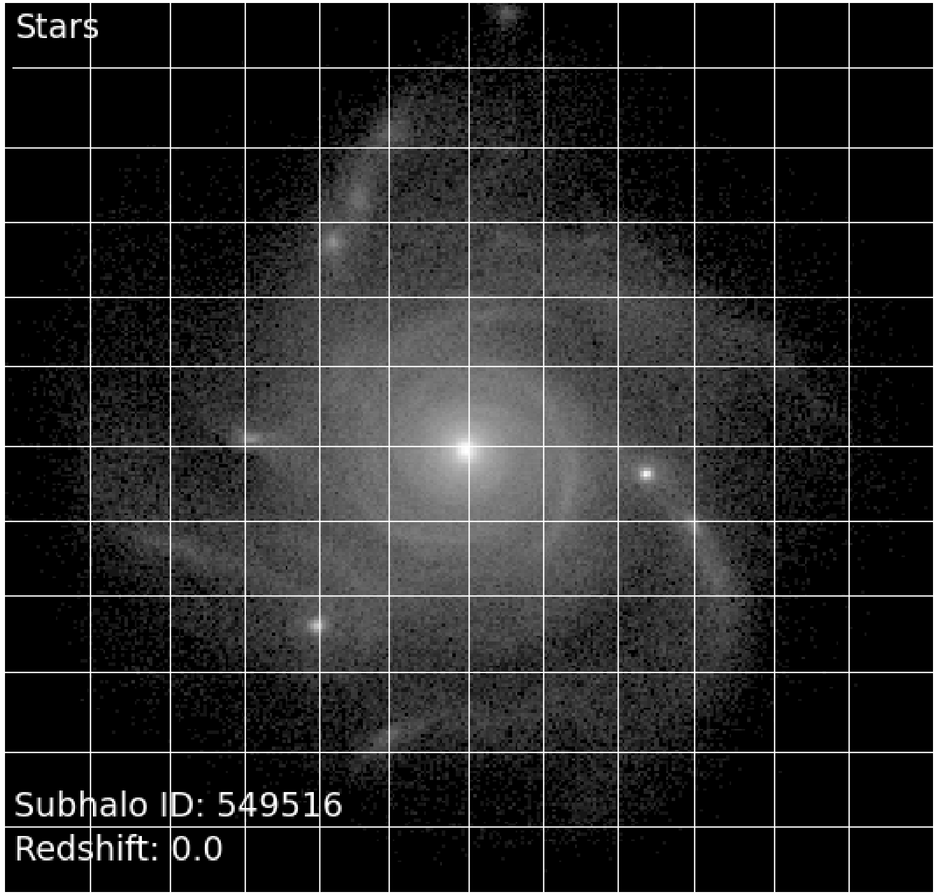
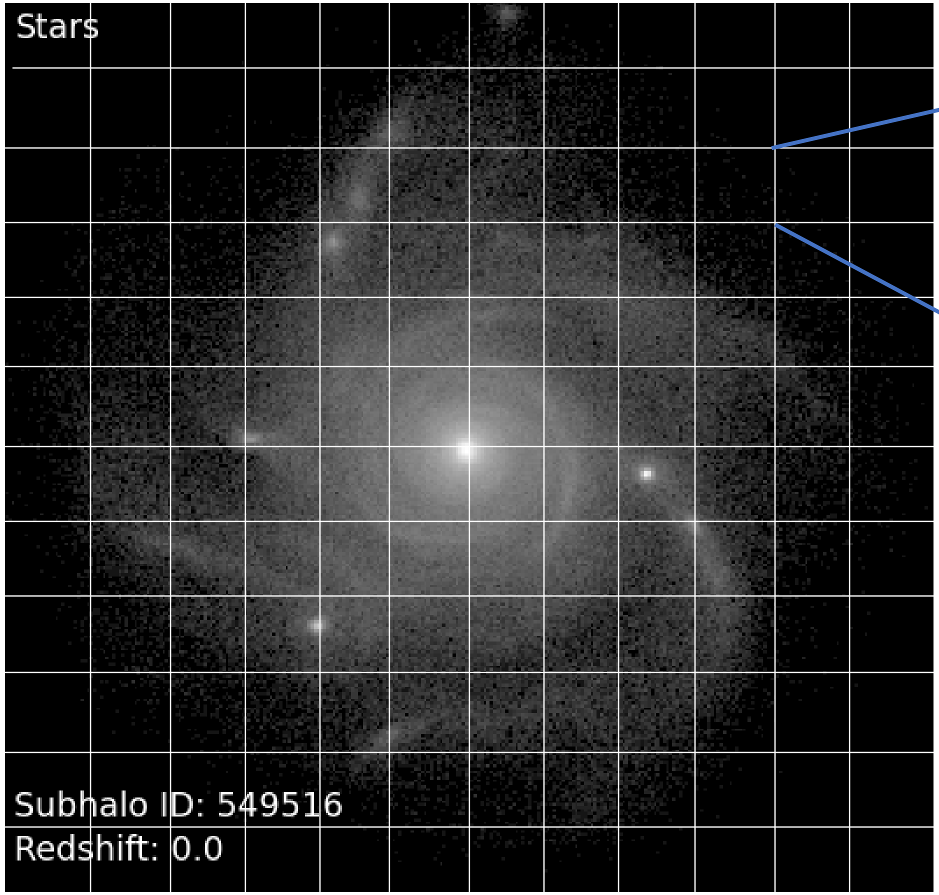
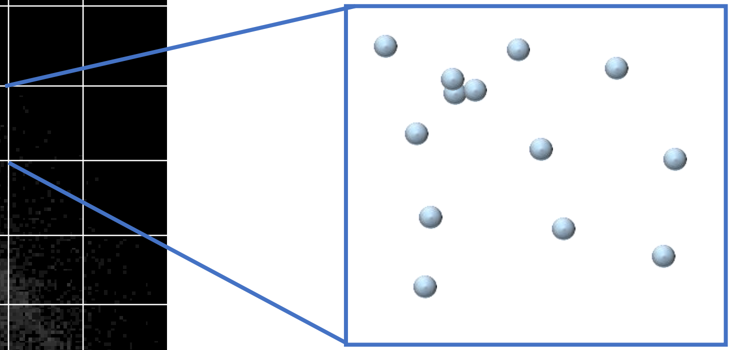


3.3. INTEGRAL FIELD SPECTROSCOPIC DATACUBES

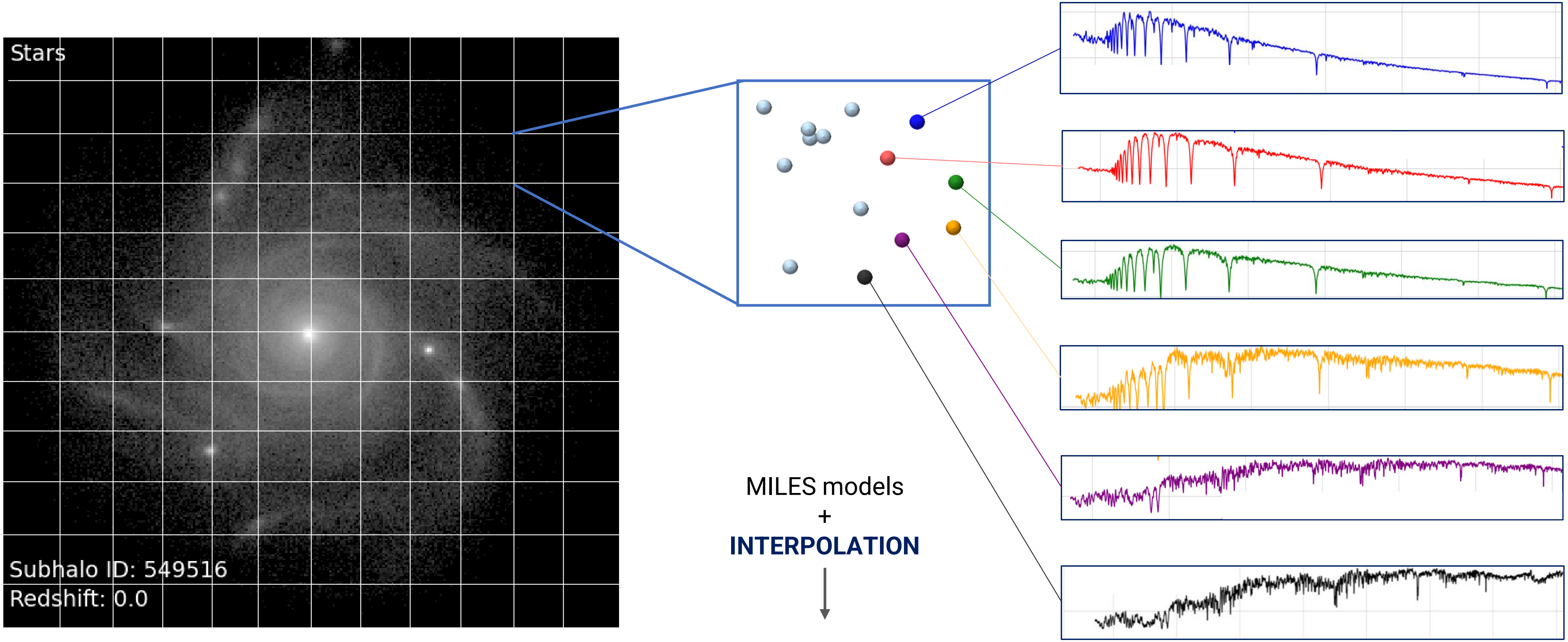
~ 700.000 stellar particles





$\sim 5 \cdot 10^4 M_\odot$

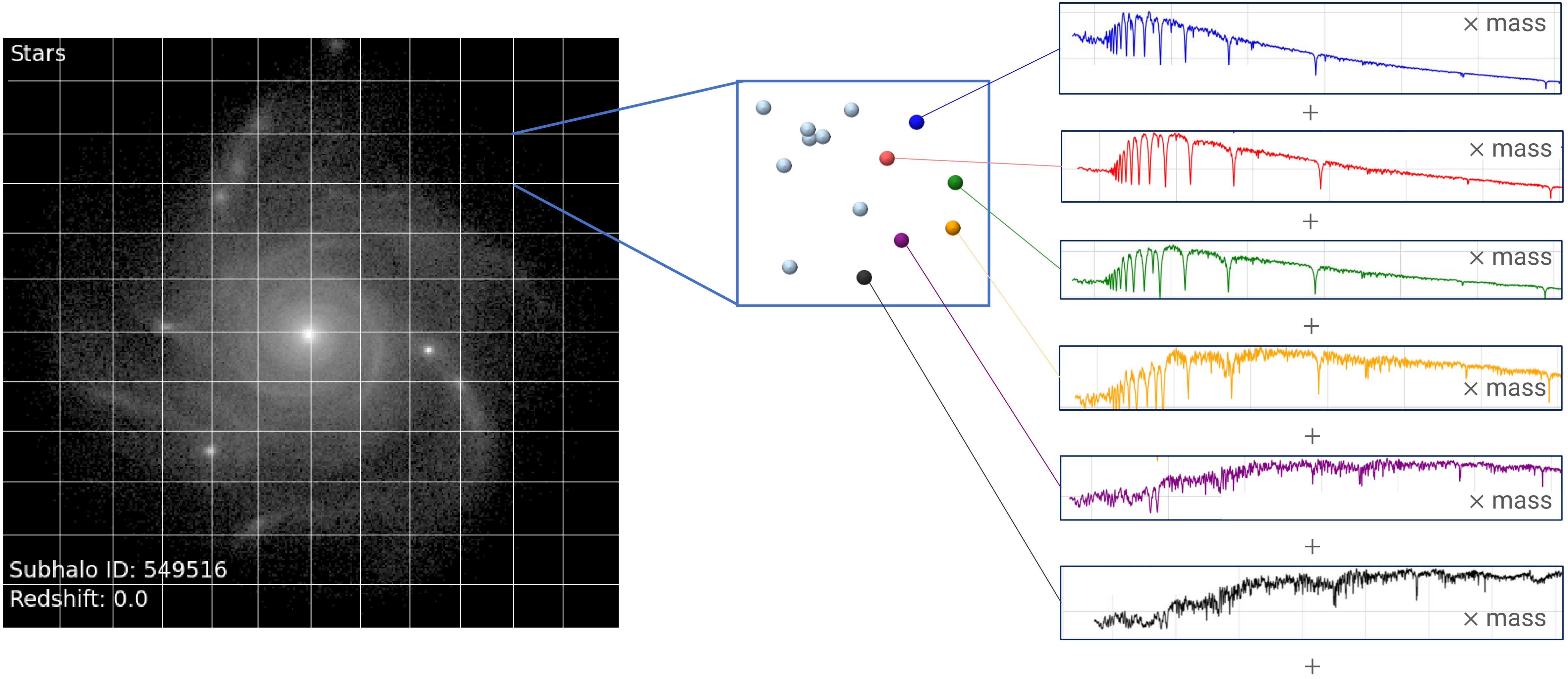
3.3. INTEGRAL FIELD SPECTROSCOPIC DATACUBES



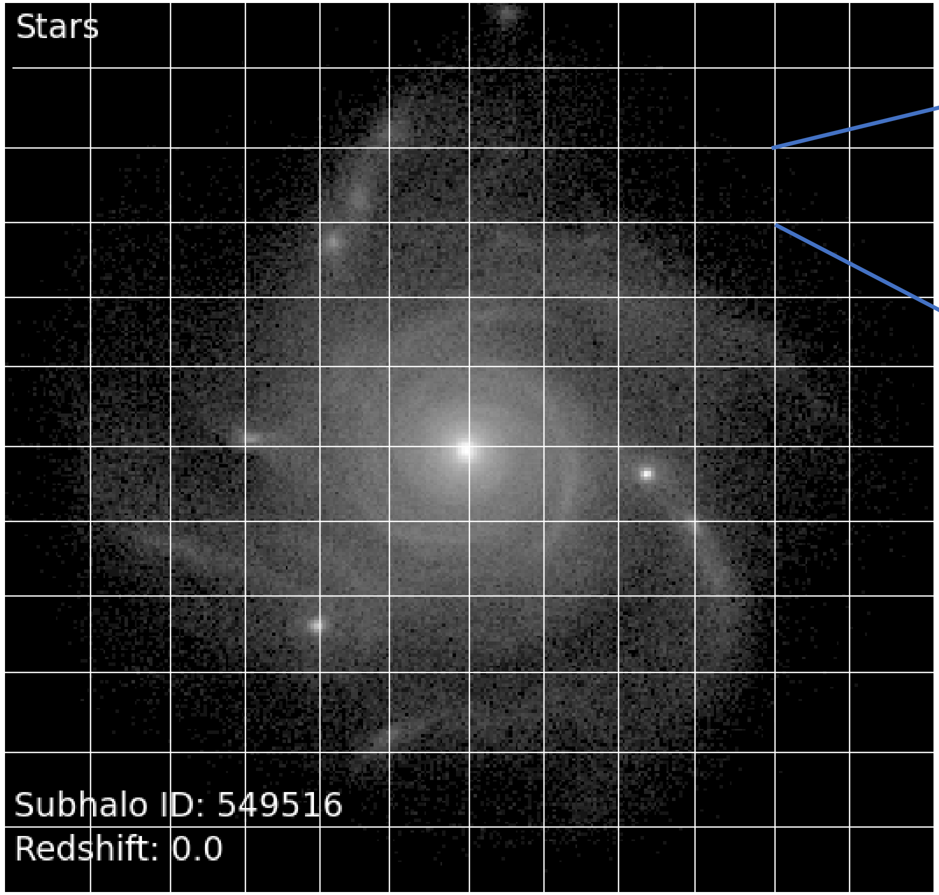
MILES models
+
INTERPOLATION

```
ifu.synthetic_spectrum
```

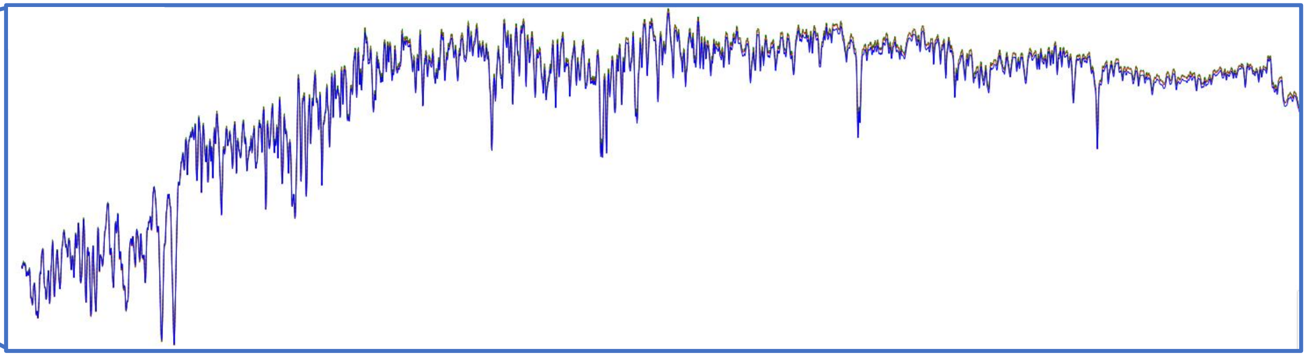
3.3. INTEGRAL FIELD SPECTROSCOPIC DATACUBES



3.3. INTEGRAL FIELD SPECTROSCOPIC DATACUBES

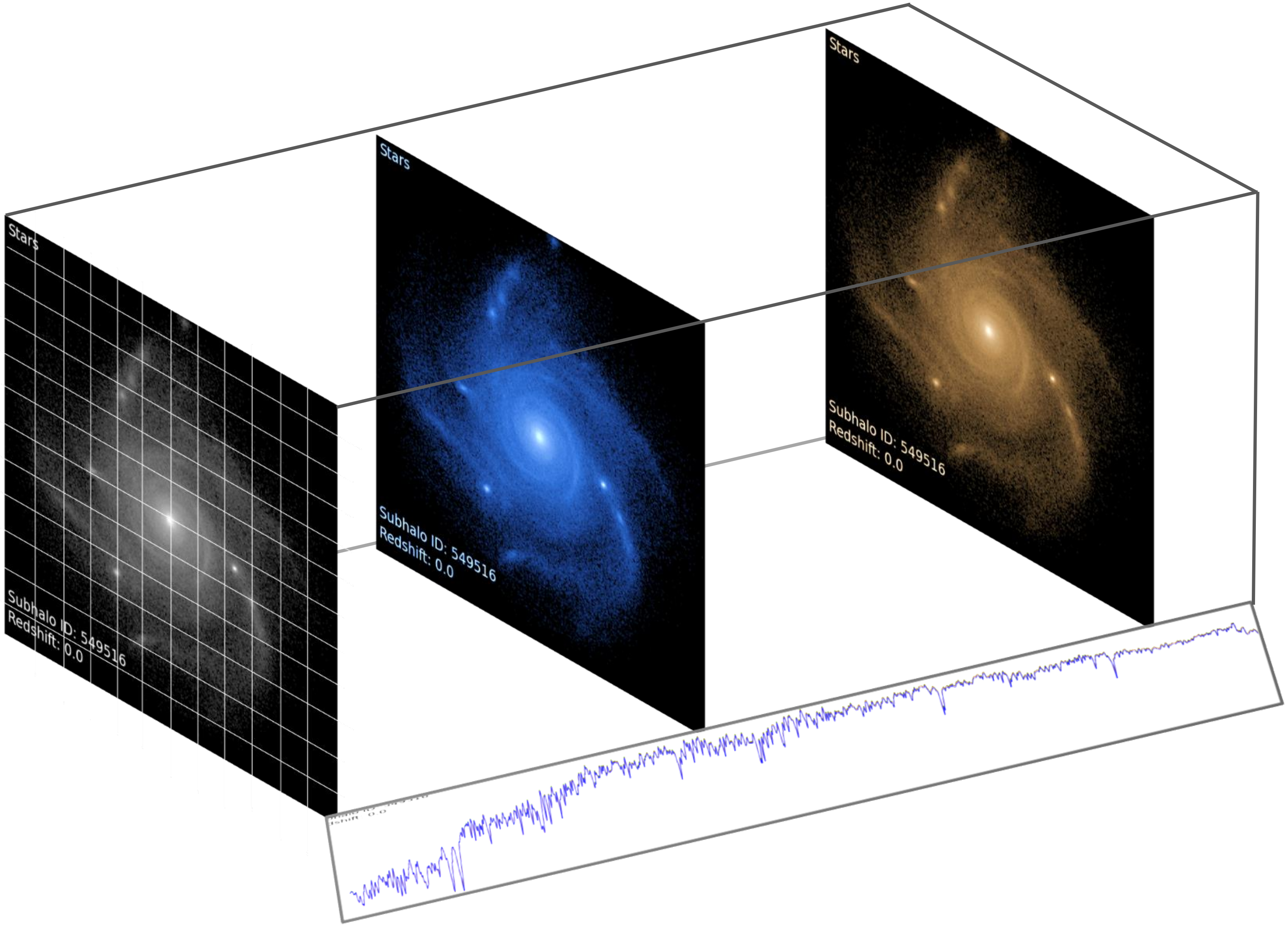


SYNTHETIC SPECTRUM



Same procedure for each pixel.

3.3. INTEGRAL FIELD SPECTROSCOPIC DATACUBES



`ifu.data_cube`

`Input:`

subhalo_ID

snapshot

radius [kpc]

v_f [vector l.o.s]

binsize or num_bins

`Output:`

FITS IFU datacube

3.3. INTEGRAL FIELD SPECTROSCOPIC DATACUBES

A. TRANSLATE TO PHOTOMETRIC UNITS:

1. Correct by **REDSHIFT**: $$\boxed{\lambda_{\text{obs}} = \lambda_0 \cdot (1 + z)}$$

3.3. INTEGRAL FIELD SPECTROSCOPIC DATACUBES

A. TRANSLATE TO PHOTOMETRIC UNITS:

1. Correct by **REDSHIFT**: $\boxed{\lambda_{\rm obs} = \lambda_0 \cdot (1+z)}$

2. **CALIBRATION**: We define a typical integrated magnitude $m_{\rm cal}$ in the 1kpc central region

For MW-like galaxies:

	$z \sim 0$	$z \sim 1.5$
$m_{\rm cal}$	20	23

3.3. INTEGRAL FIELD SPECTROSCOPIC DATACUBES

A. TRANSLATE TO PHOTOMETRIC UNITS:

1. Correct by **REDSHIFT**: $$\boxed{\lambda_{\rm obs} = \lambda_0 \cdot (1+z)}$$

2. **CALIBRATION**: We define a typical integrated magnitude $m_{\rm cal}$ in the 1kpc central region

Translate 1kpc TNG stellar particles spectra into magnitude units using a specific filter.

$$\boxed{m_{\rm AB} = -2.5 \log_{10} f_\nu - 48.6}$$

where

$$\boxed{f_\nu = \frac{1}{c} \frac{\int S T \lambda d\lambda}{\int T/\lambda d\lambda}}$$

S: spectrum [erg/s/cm^2/Å]

T: filter curve

For MW-like galaxies:

	$z \sim 0$	$z \sim 1.5$
$m_{\rm cal}$	20	23
Filter	SDSS g’	JWST F162W

3.3. INTEGRAL FIELD SPECTROSCOPIC DATACUBES

A. TRANSLATE TO PHOTOMETRIC UNITS:

1. Correct by **REDSHIFT**: $\lambda_{\text{obs}} = \lambda_0 \cdot (1+z)$

2. **CALIBRATION**: We define a typical integrated magnitude m_{cal} in the 1kpc central region

Translate 1kpc TNG stellar particles spectra into magnitude units using a specific filter.

$$m_{\text{AB}} = -2.5 \log_{10} f_\nu - 48.6$$

where

$$f_\nu = \frac{1}{c} \frac{\int ST\lambda d\lambda}{\int T/\lambda d\lambda}$$

S: spectrum [erg/s/cm^2/Å]

T: filter curve

$$m_{\text{TNG}} \longrightarrow \alpha = 10^{-|m_{\text{TNG}} - m_{\text{cal}}|/2.5}$$

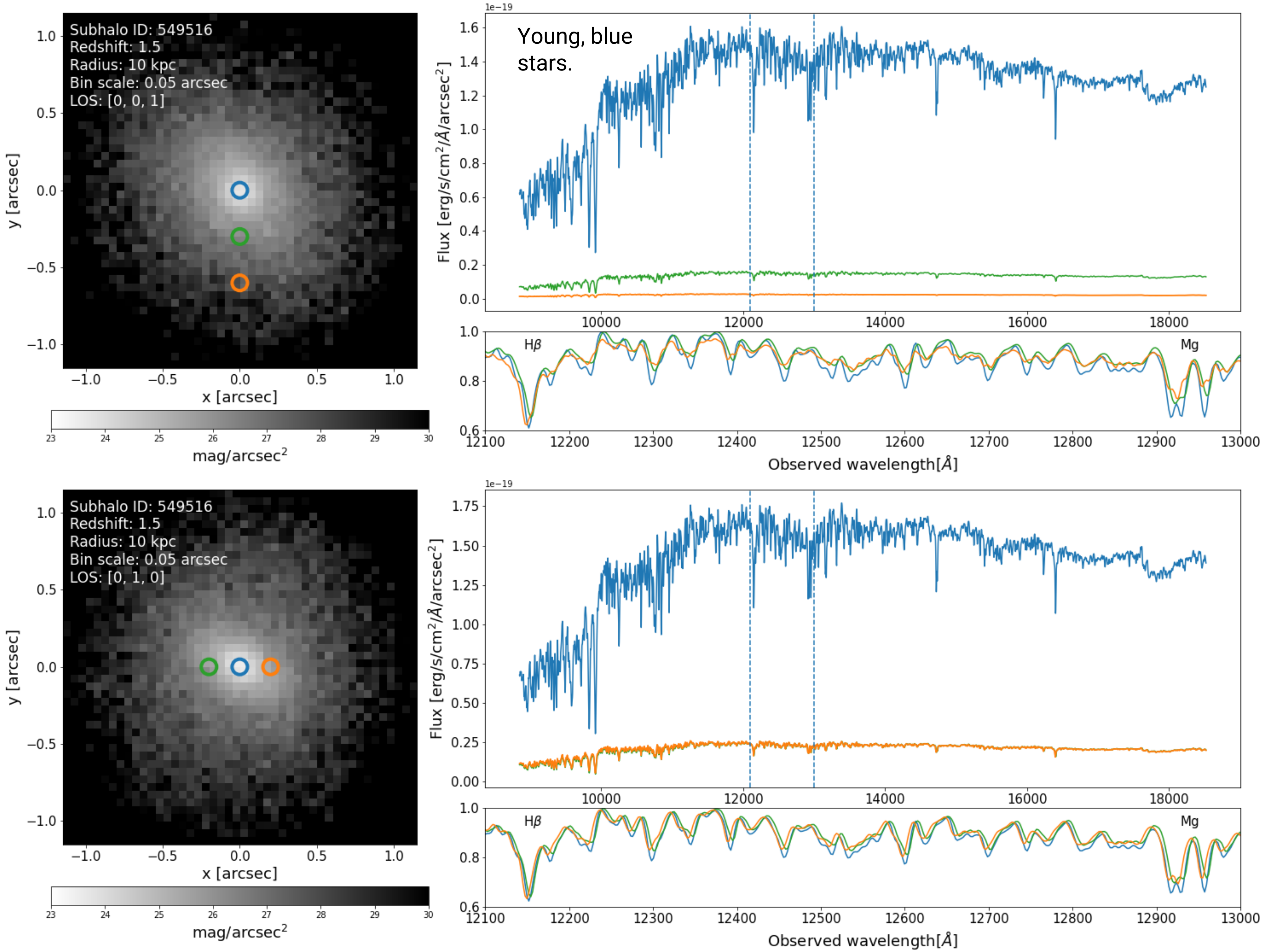
```
ifu.flux_scale_factor
```

For MW-like galaxies:

	$z \sim 0$	$z \sim 1.5$
m_{cal}	20	23
Filter	SDSS g’	JWST F162W

3.3. INTEGRAL FIELD SPECTROSCOPIC DATACUBES

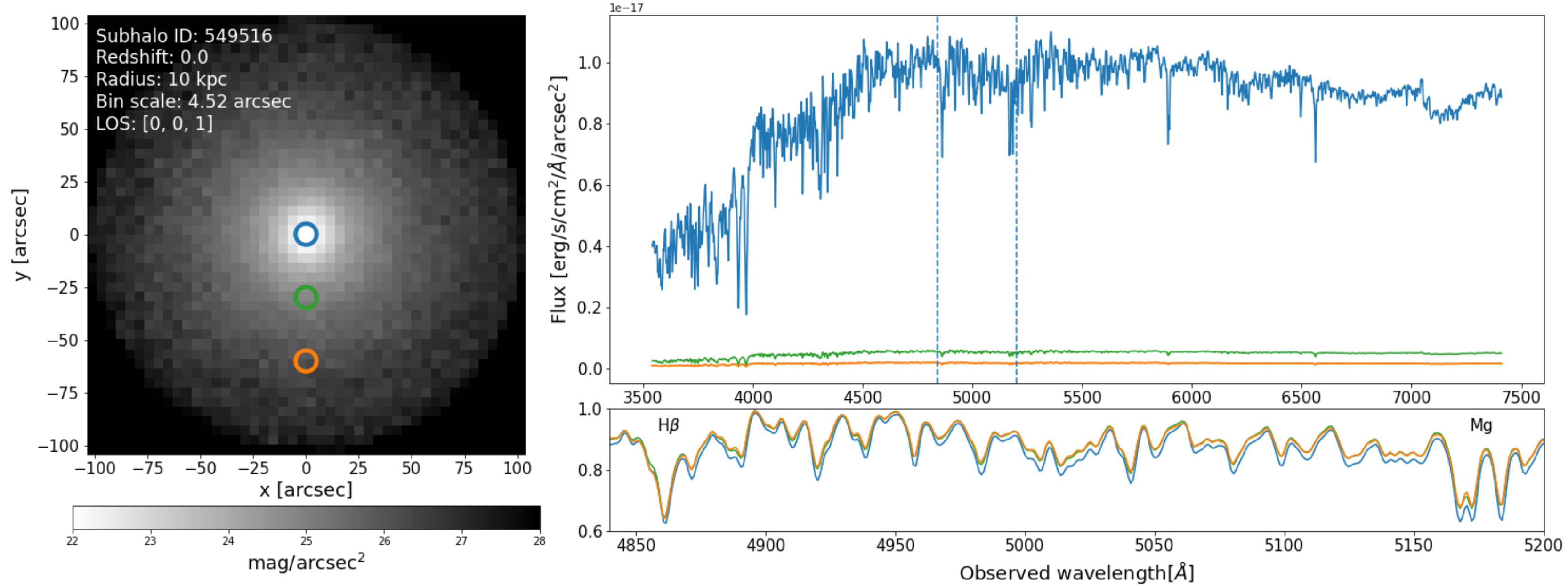
$z = 1.5$

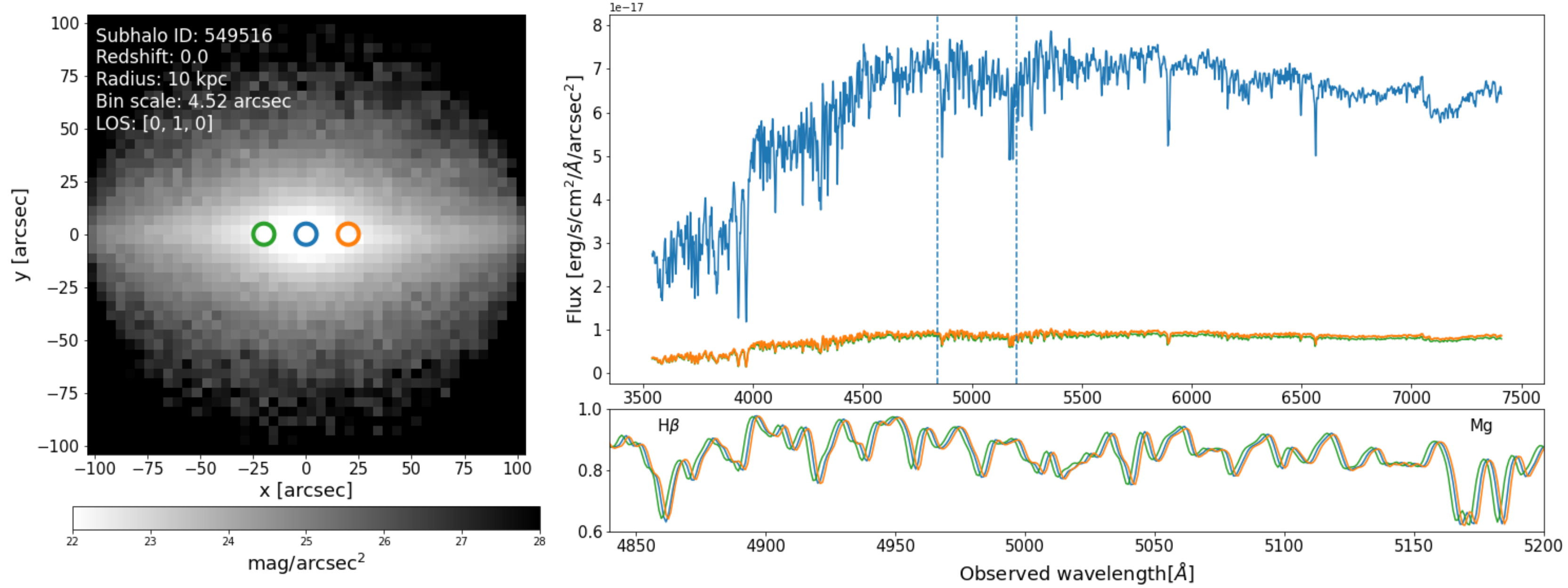


`ifu.plot_IFU`

3.3. INTEGRAL FIELD SPECTROSCOPIC DATACUBES

$z = 0$





`ifu.plot_IFU`

3.4. SIMULATE JWST OBSERVATIONS

1. TNG50 MW-like galaxies:

TNG_data_loader
Output: Stellar particles file.

2. MILES stellar library:

synthetic_spectrum

Output: Each stellar particle is interpolated and associated to a synthetic spectrum from MILES template and linearly combined to form the fiber spectrum.

3. IFU datacubes:

data_cube

Output: IFU datacubes (FITS file)

Input:
TNG50 galaxy ID
TNG50 snapshot
Radius (in kpc)
Vector l.o.s.
*, spaxel size, number of bins

4. JWST NIRSpec simulation:

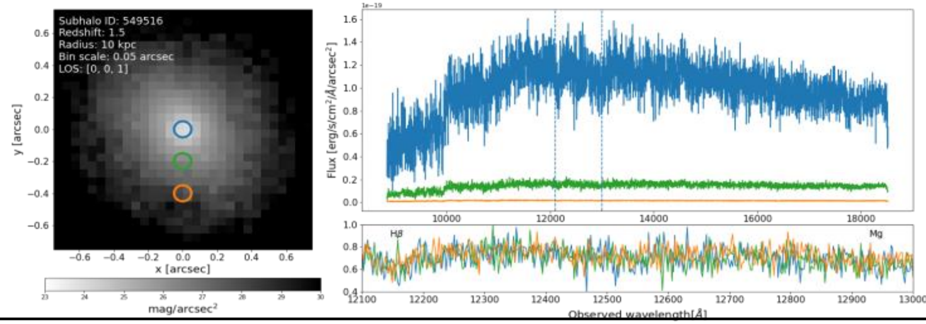
pass_to_jwst

Output: IFU datacubes (FITS file)

A. Spectral resolution:
Convolution to filter bandpass and Gaussian noise added.

B. Fit to NIRSpec FOV:
Fit into 30x30 spaxels.

C. Spatial resolution:
2D Gaussian Convolution to NIRCam PSF.



3.4. SIMULATE JWST OBSERVATIONS

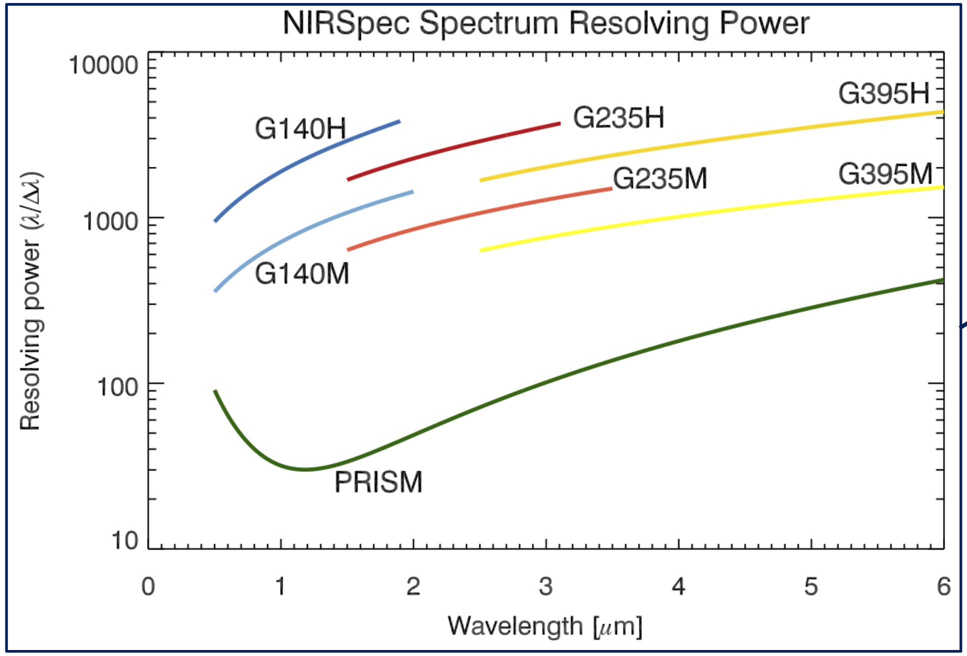
A. SPECTRAL RESOLUTION:

Implemented through a Gaussian convolution applied to the spectrum of each spaxel, using FWHM:

$$\boxed{\mathrm{FWHM}_i^2 = \mathrm{FWHM}, i_{\mathrm{JWST}}^2 - \mathrm{FWHM}_{\mathrm{MILES}}^2}$$

$$\mathrm{FWHM}^2{}_{\mathrm{MILES}} = 2.51\text{Å}$$

We will use the **PRISM** grism of NIRSpec:



$$\boxed{\mathrm{FWHM}_{\mathrm{JWST}} = \frac{\lambda}{R \cdot (1+z)}}$$

$$\boxed{\sigma = \frac{\mathrm{FWHM}_i}{2\sqrt{2\log(2)}}}$$

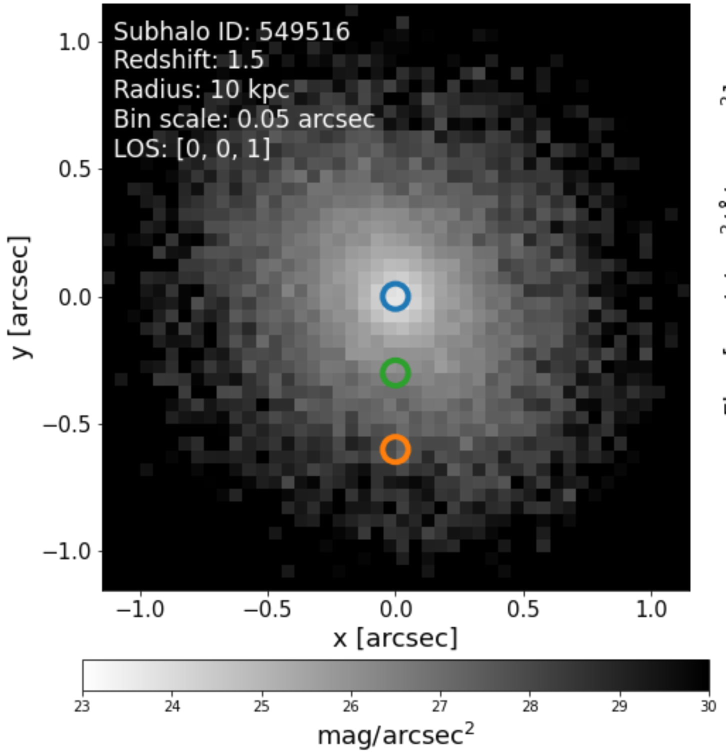
3.4. SIMULATE JWST OBSERVATIONS

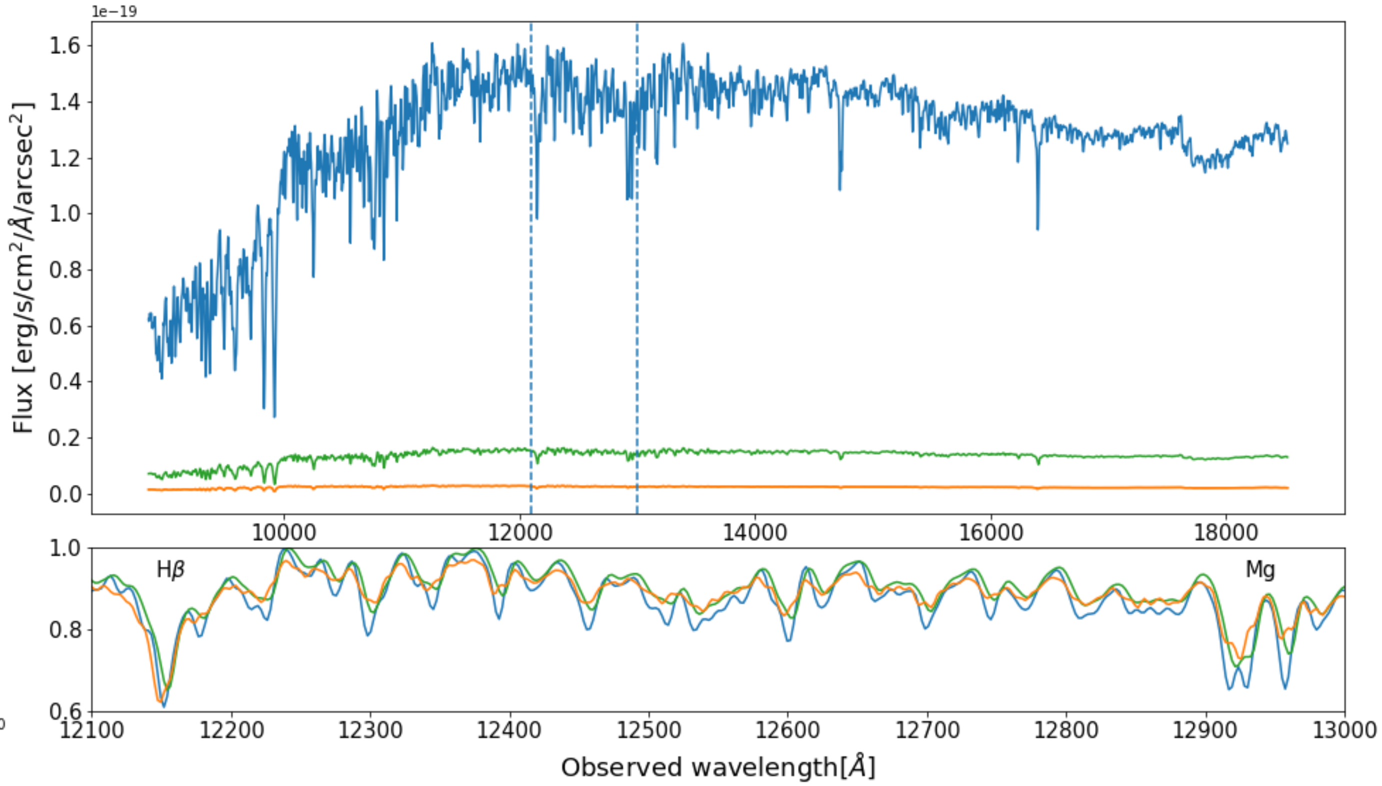
A. SPECTRAL RESOLUTION:

Implemented through a Gaussian convolution applied to the spectrum of each spaxel, using FWHM:

$$\boxed{\mathrm{FWHM}_i^2 = \mathrm{FWHM}, i_{\mathrm{JWST}}^2 -| \mathrm{FWHM}_{\mathrm{MILES}}^2}$$

$\mathrm{FWHM}^2{}_{\mathrm{MILES}} = 2.51\mathrm{Å}$





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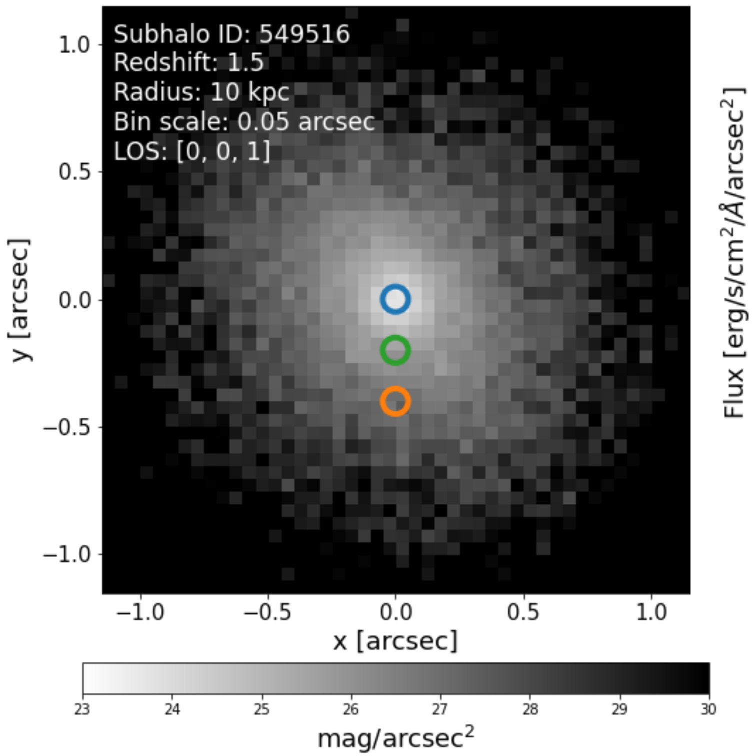
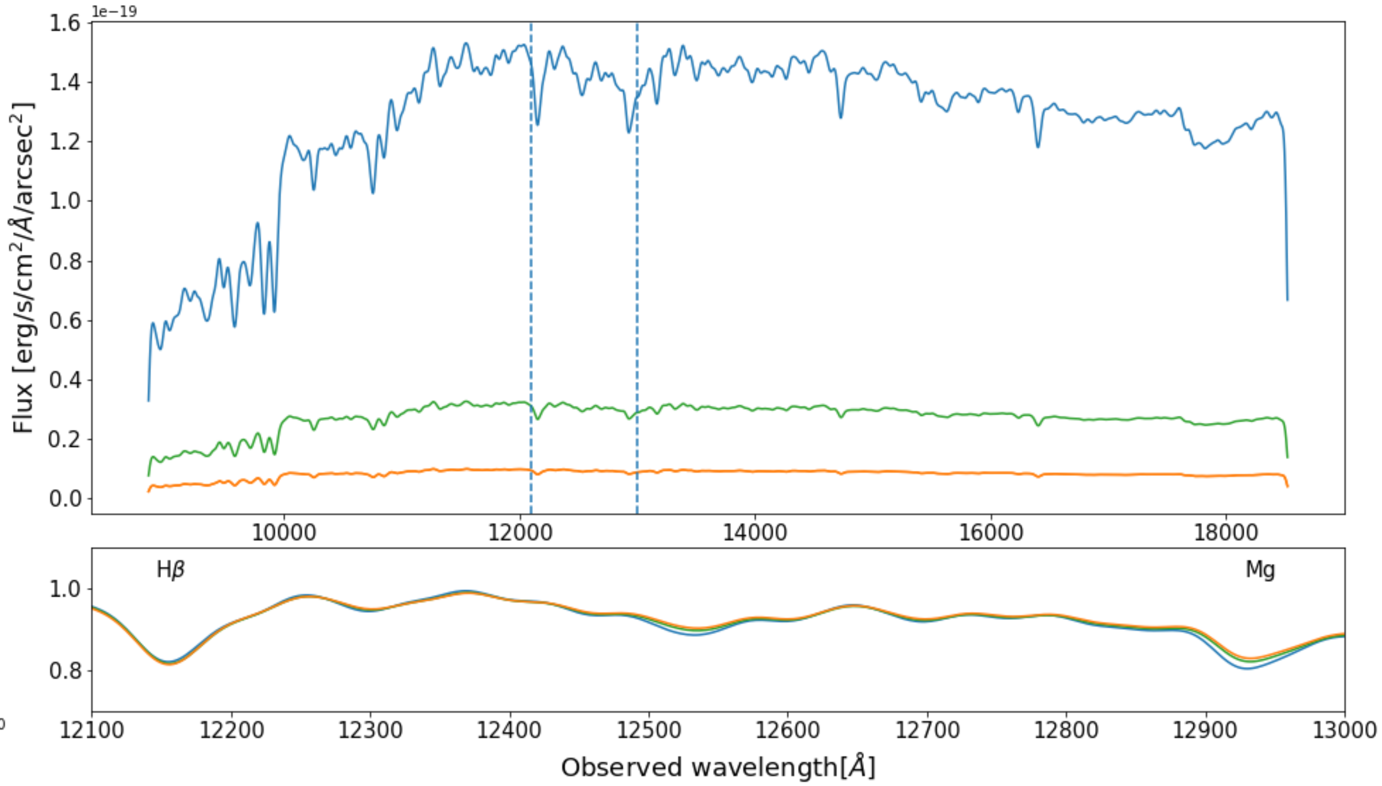
$\mathrm{FWHM}^2{}_{\mathrm{MILES}} = 2.51\text{Å}$

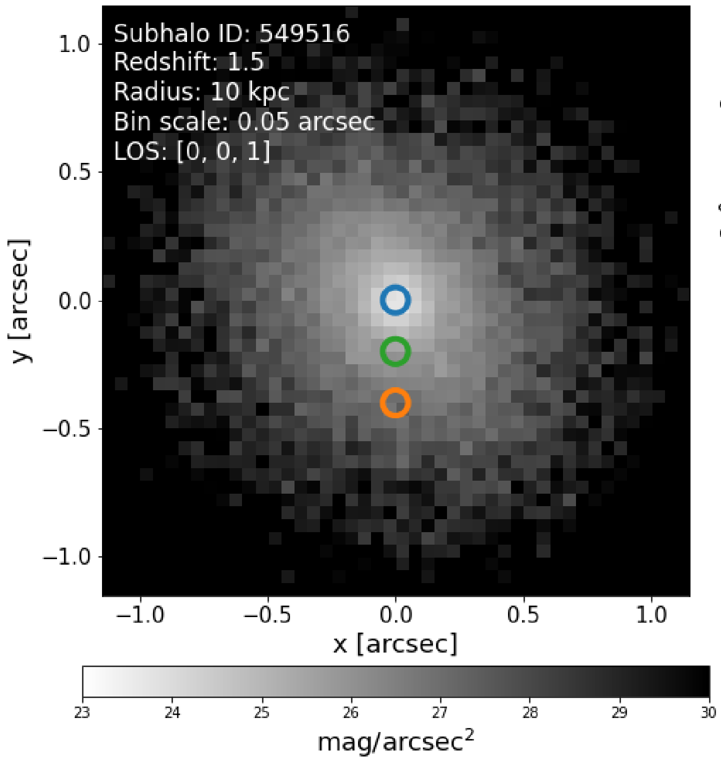


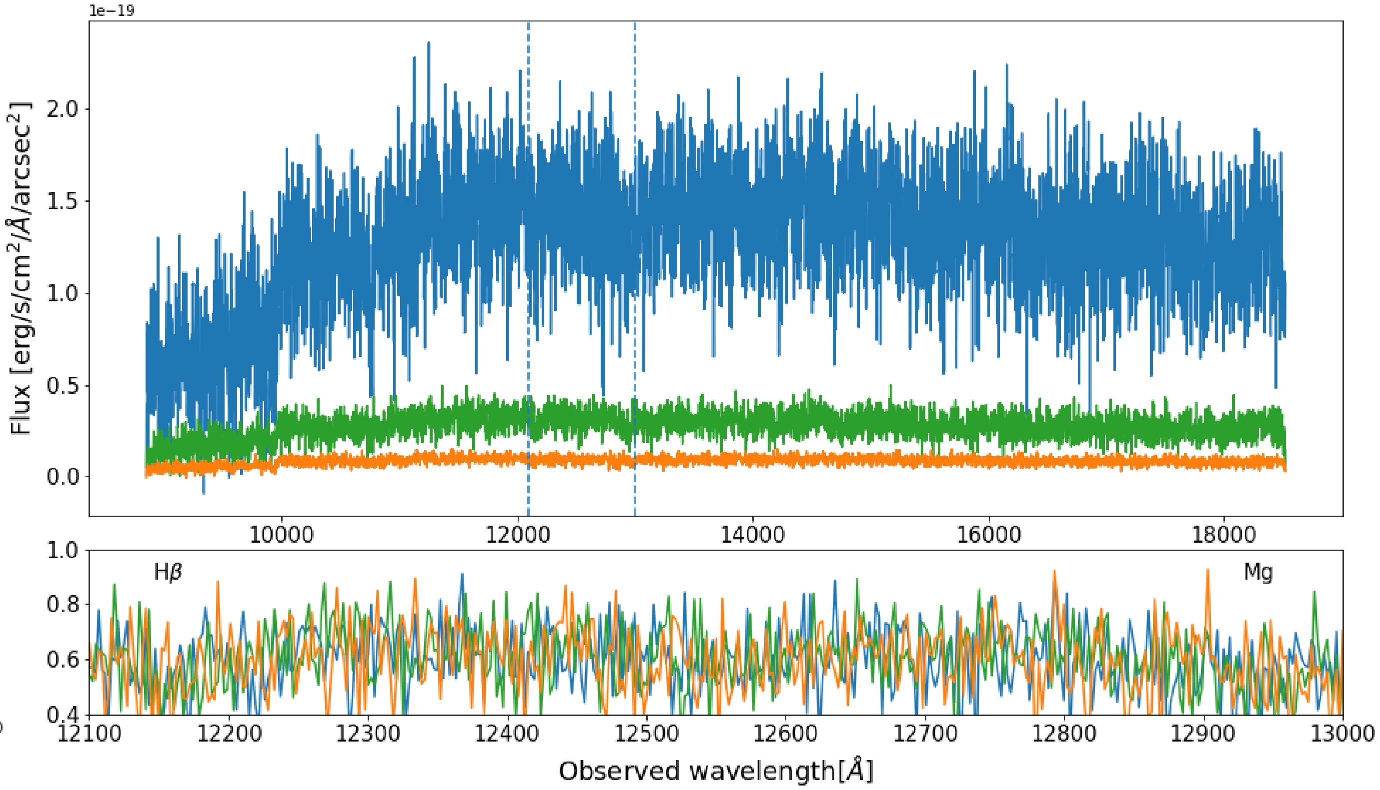


3.4. SIMULATE JWST OBSERVATIONS

A. SPECTRAL RESOLUTION – GAUSSIAN NOISE:

Add random Gaussian noise to have a **SNR = 5** ⟶ Derived for a 6h exposure for resolution 24 mag/arcsec^2.



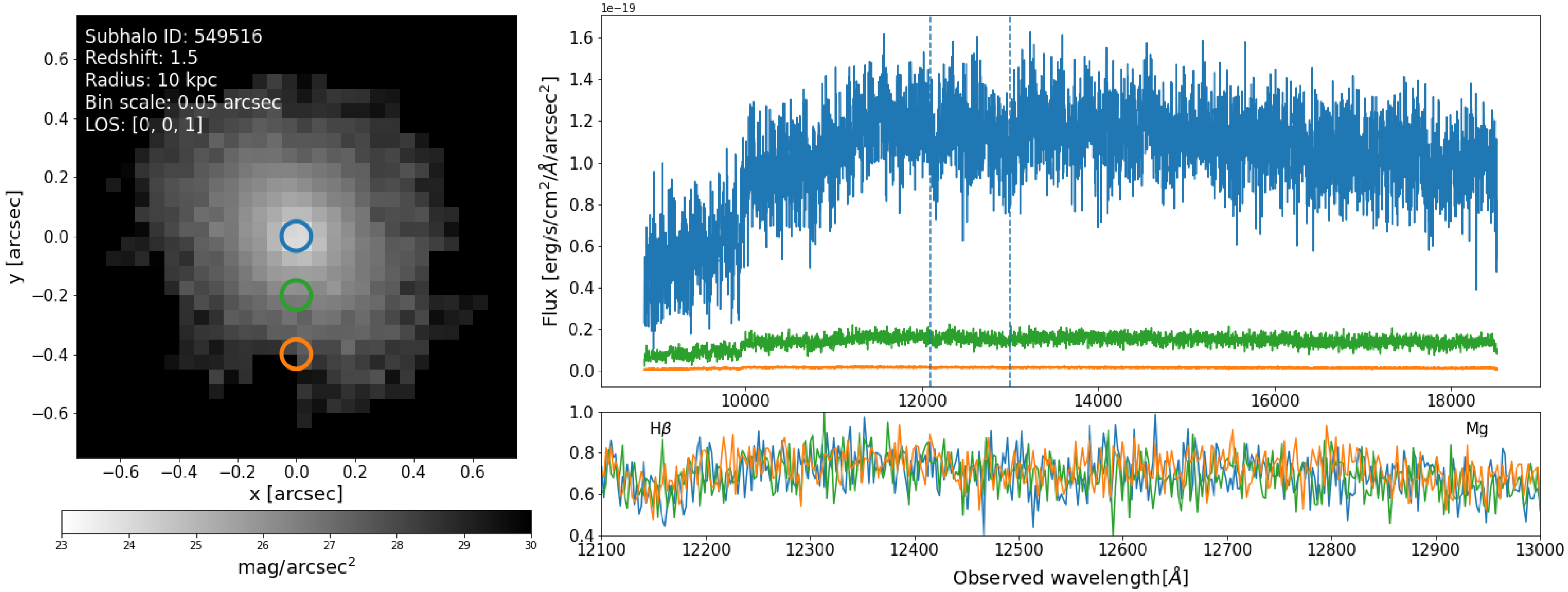


3.4. SIMULATE JWST OBSERVATIONS

B. NUMBER OF SPAXELS:

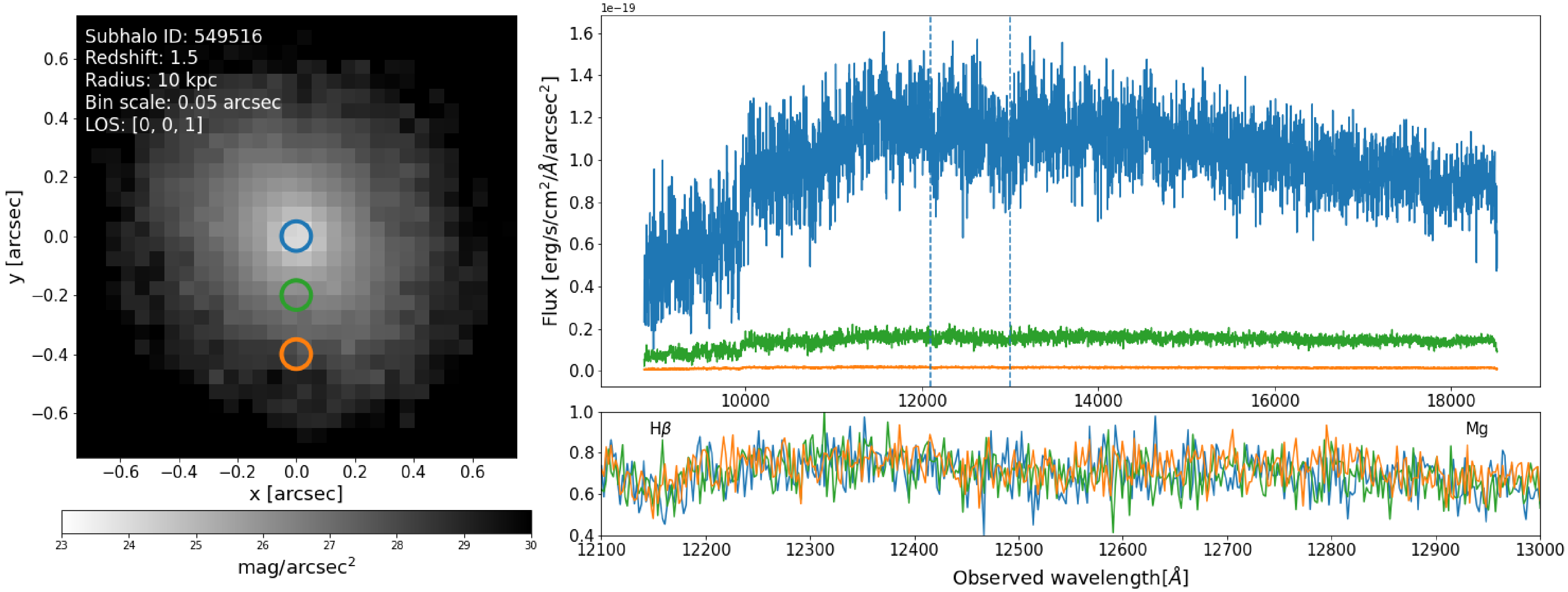
JWST IFU has a $3'' \times 3''$ FOV divided in **30 SLICES**.

We have to crop of FOV to 30×30 spaxels.



C. SPATIAL RESOLUTION:

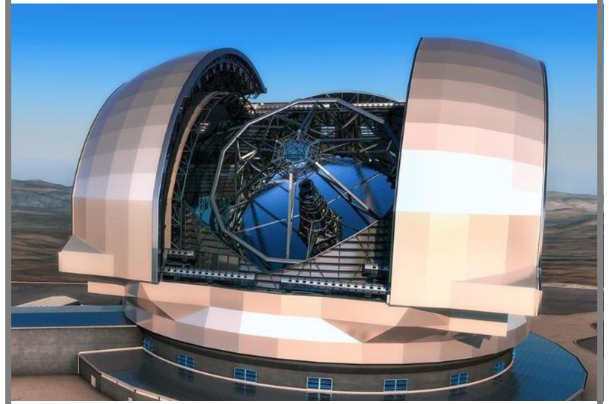
Implemented through a Gaussian convolution in 2D of the **NIRCam PSF**, with a FWHM that increases with the wavelength.



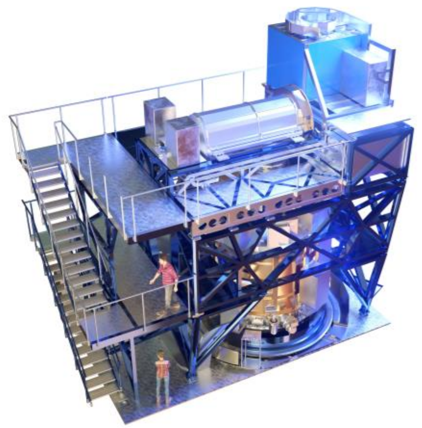
3.5. SIMULATE HARMONI OBSERVATIONS

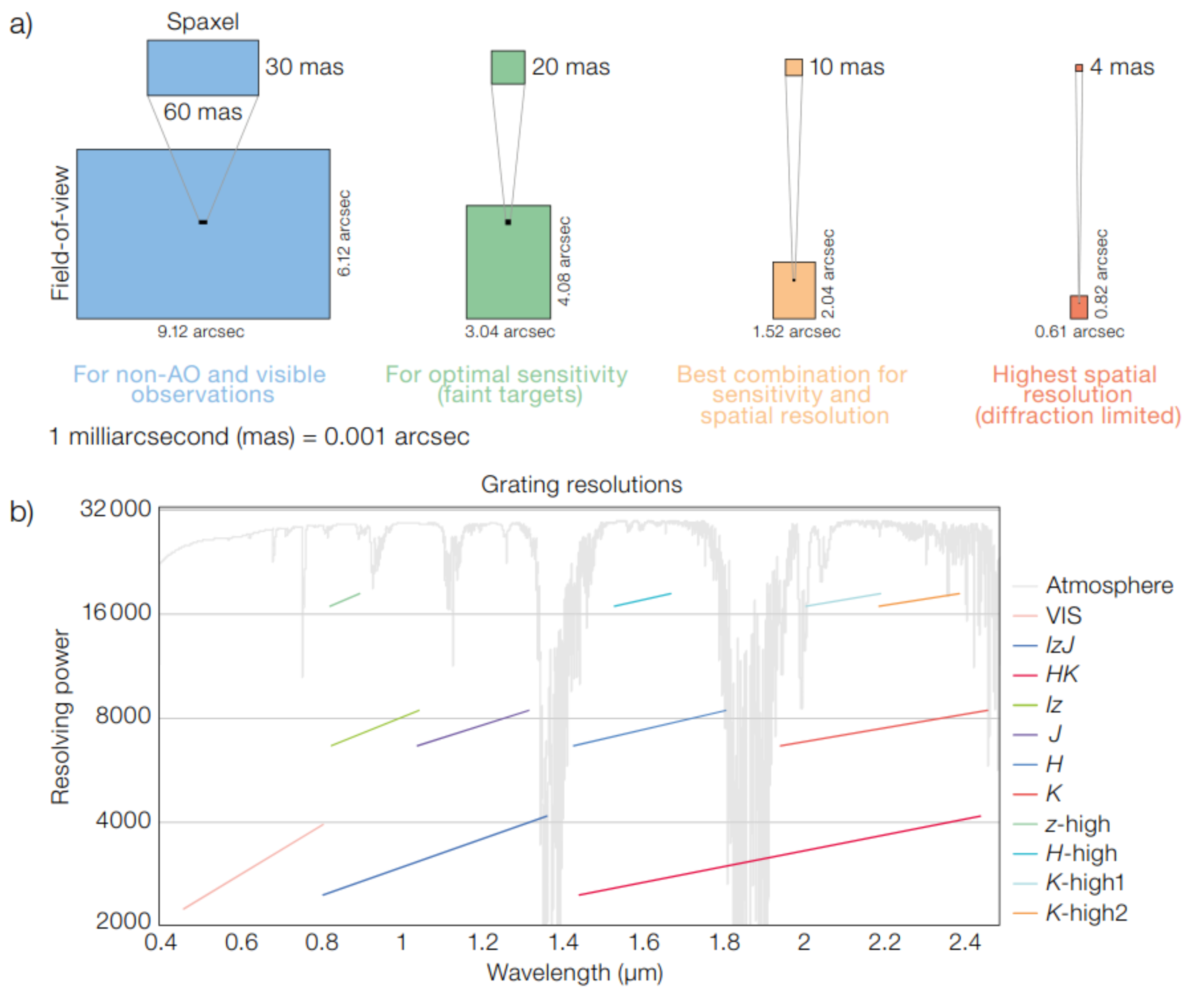
HARMONI is the IFS for ESO's Extremeley Large Telescope (ELT).

ELT



HARMONI

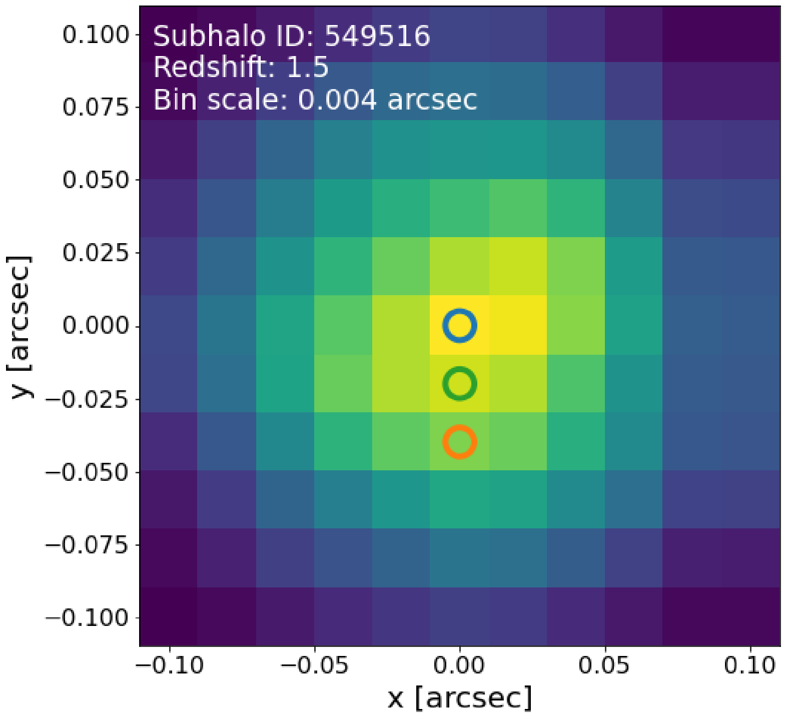


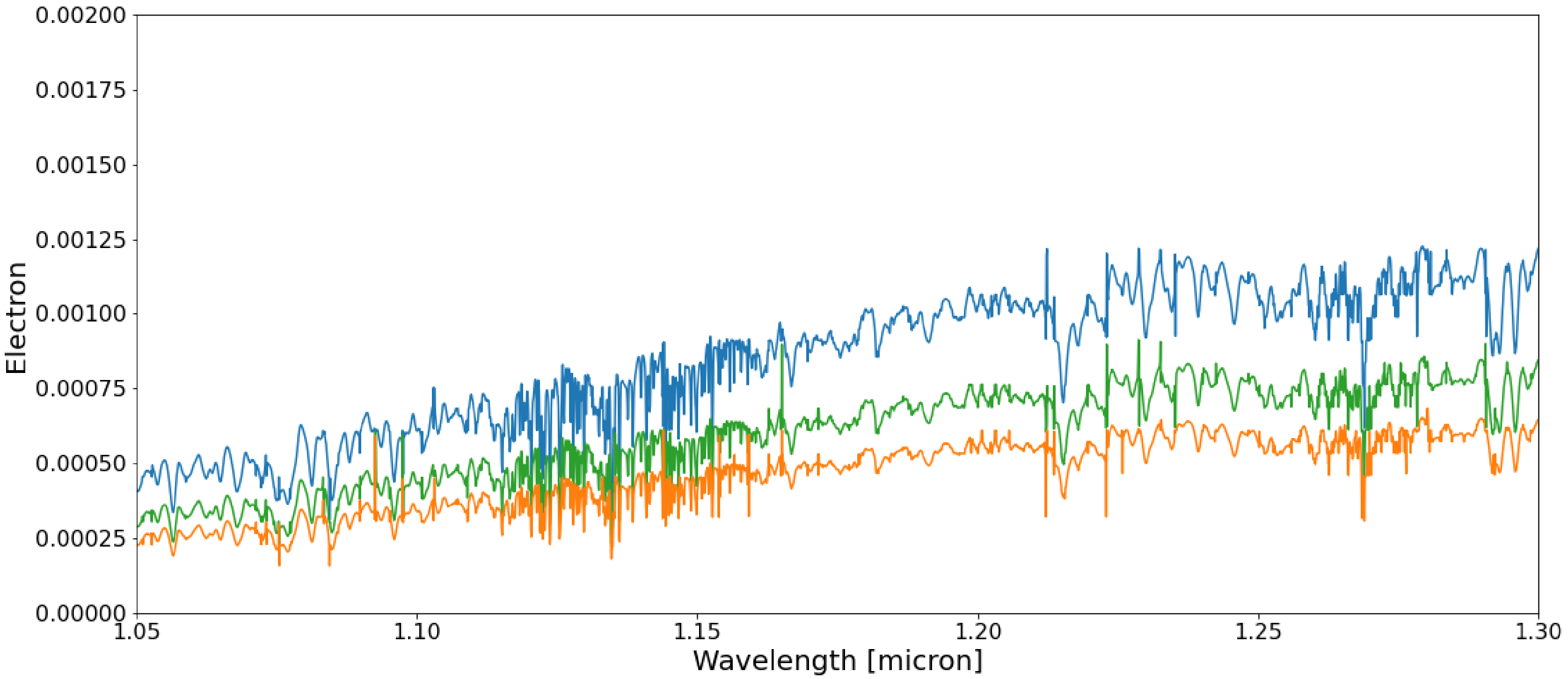


3.5. SIMULATE HARMONI OBSERVATIONS

HARMONI is the IFS for ESO’s Extremeley Large Telescope (ELT).

We use the 20 x 20 mas spaxel scale and the Iz grating. We simulat it through the HSIM3 simulator.





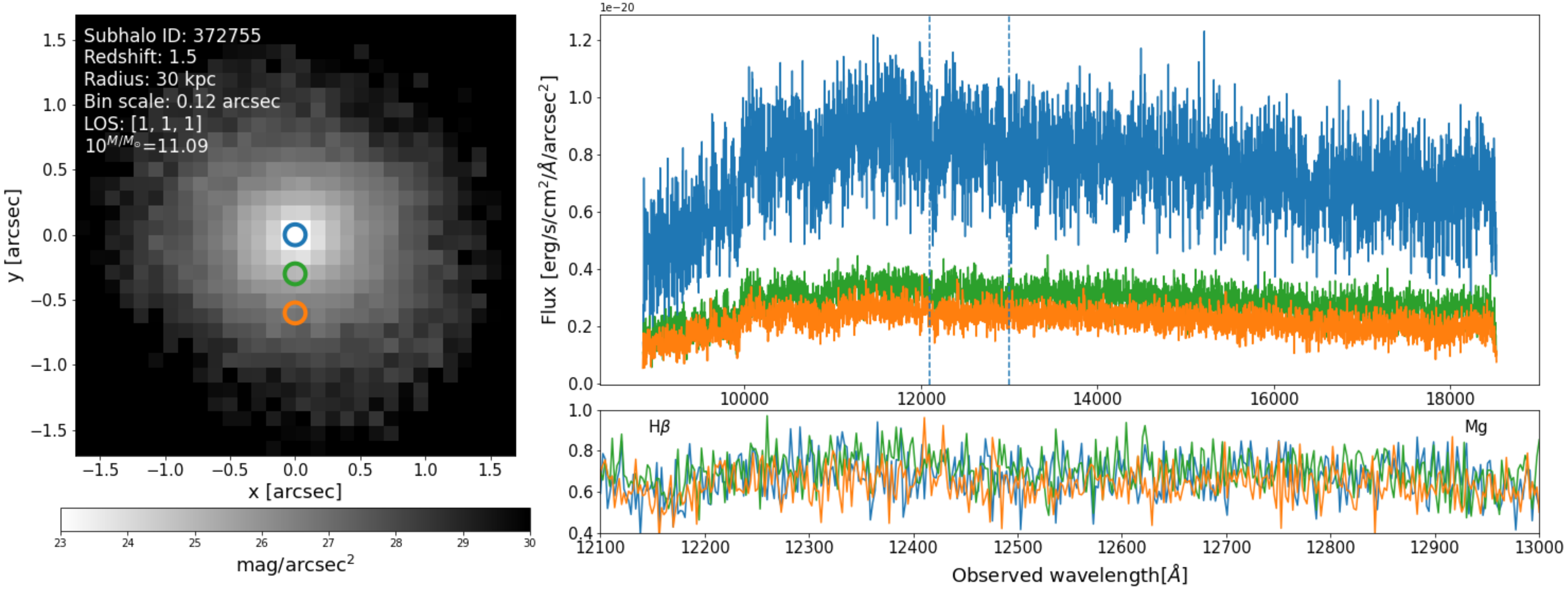
4. RESULTS AND DISCUSSION

GOODS South Field – WFC3 Early Release Science Data

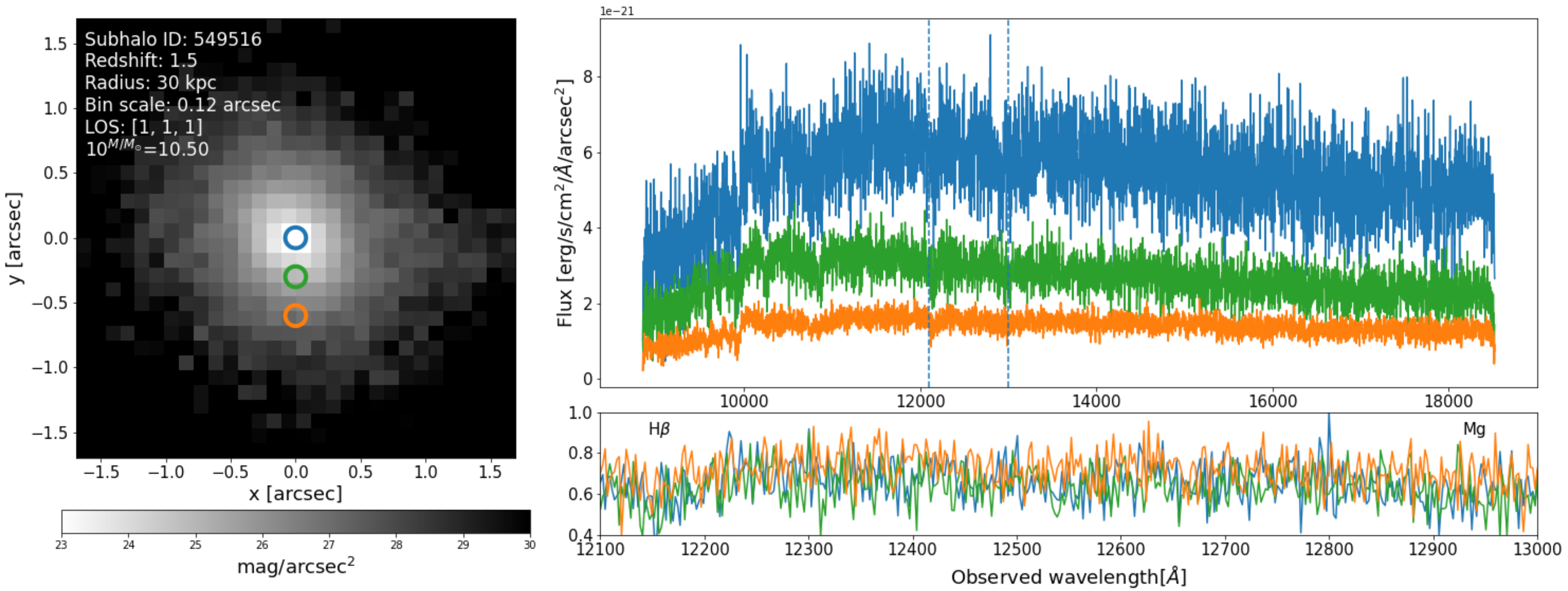
4. RESULTS AND DISCUSSION

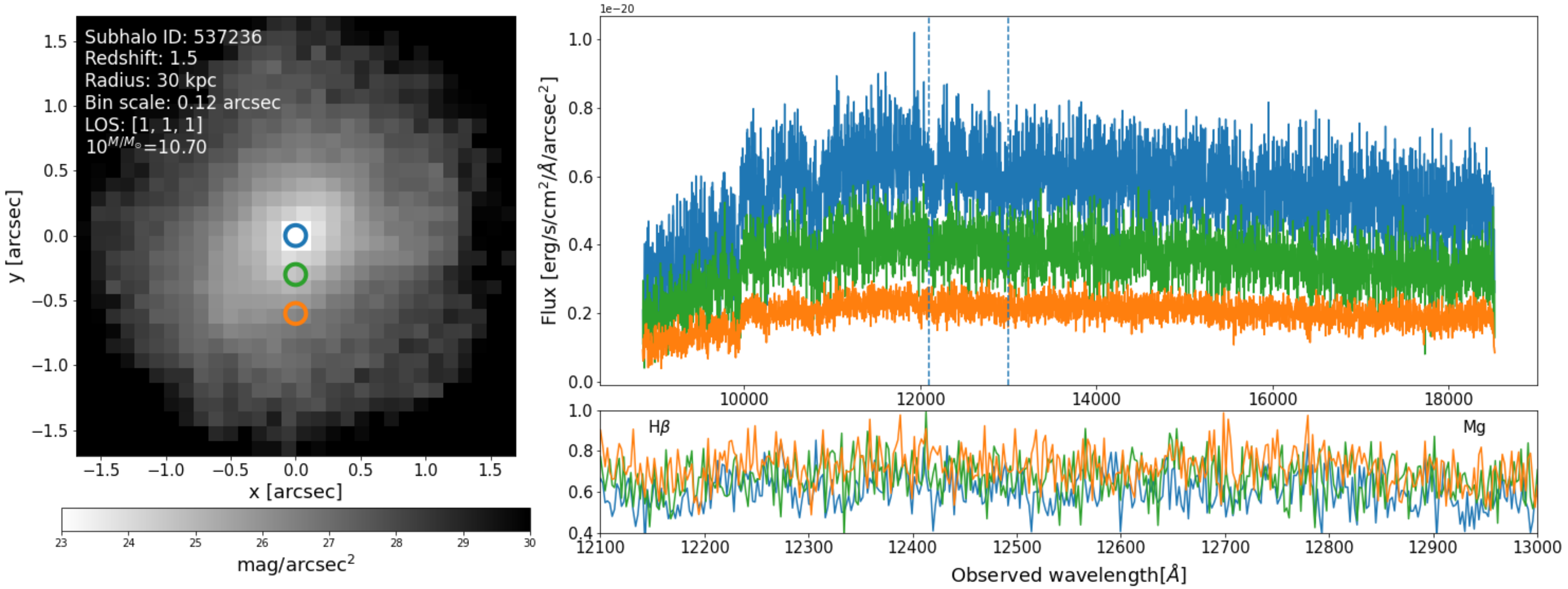
We develop a Python pipeline for generating **JWST-like IFU datacubes** of MW-like galaxies at any redshift.

We present the results for various galaxies at $z \sim 1.5$ adopting $3'' \times 3''$ FOV of NISpec IFU instrument.



4. RESULTS AND DISCUSSION





5. CONCLUSIONS

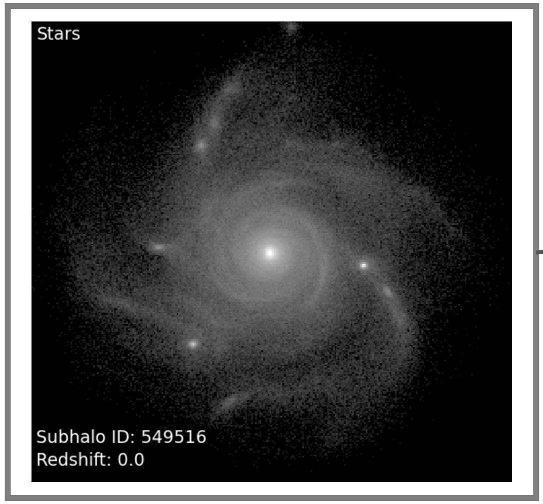
GOODS South Field – WFC3 Early Release Science Data

5. CONCLUSIONS

1. Investigated challenge of observing high-redshift galaxies with current instruments.

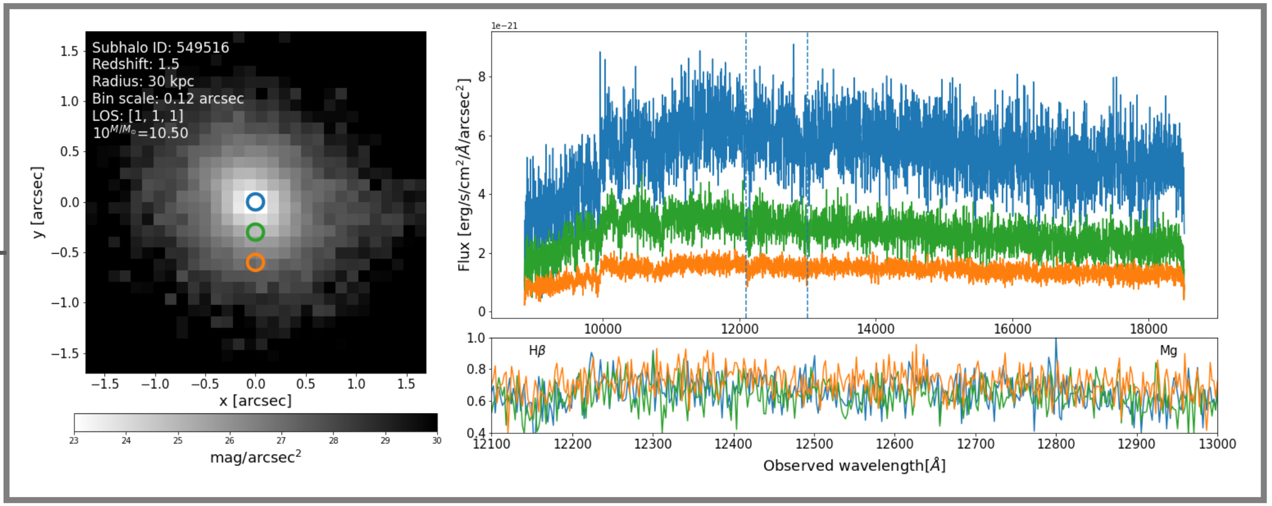
   Use state-of-the-art hydrodynamical Illustris TNG50 simulation and stellar population models.

2. **CREATION** of Python pipeline to generate JWST-like **IFU DATACUBES** of MW-like galaxies.



TNG_mockIFU

(available on GitHub)



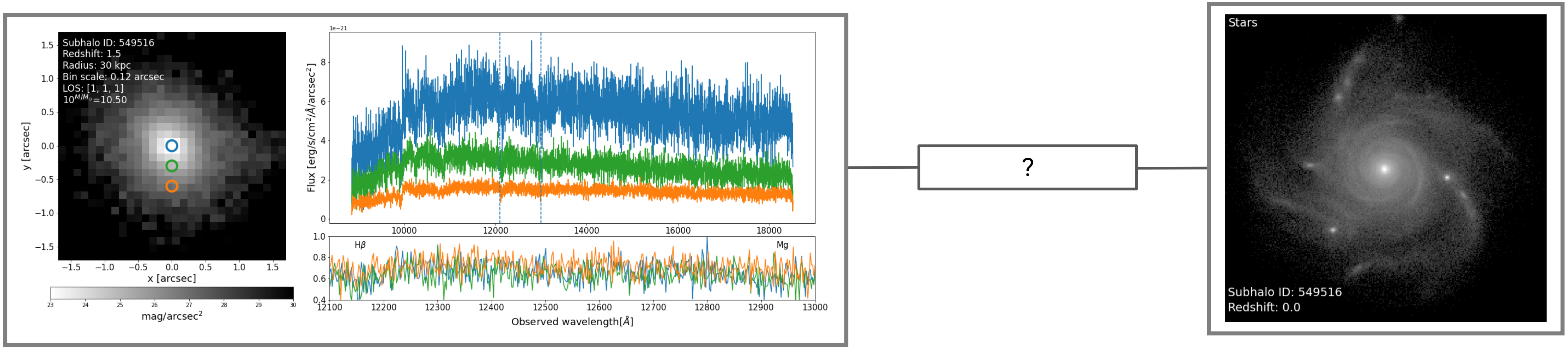
3. Revisit several expected features of **MW EVOLUTION.**

6. CONCLUSIONS

FUTURE PERSPECTIVE

1. Include simulation of required **EXPOSURE TIME** with JWST.

2. Pipeline to **REVERSE** the process: derive stellar population properties from observed JWST IFU datacubes.



GOODS South Field – WFC3 Early Release Science Data