Modelling the early universe using the James Webb Space Telescope

Giorgio Manzoni
28/06/2023
IASF Milano

Where I come from

Bachelor degree physics at Osservatorio Brera-Merate / University Milano Bicocca:

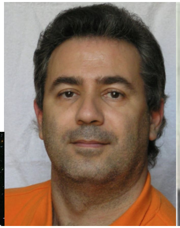
A photometric analysis of a Gamma Ray Burst using the REM telescope

(Supervisors: Stefano Covino, Monica Colpi)

Master degree astrophysics at INAF-IASF / University Milano-Bicocca:

The quenching of star formation activity and the evolution of the colour-magnitude relation in galaxies

(Supervisors: Marco Scodeggio, Giuseppe Gavazzi, Luigi Guzzo)



PhD in Physics at Durham University:

Cosmological redshift surveys, big data and semi-analytical galaxy formation models

(Supervisors: Peder Norberg, Carlton Baugh & PAUS et al.)

Where I am now (Hong Kong University of Science and Technology, **HKUST**)

HKUST JOCKEY CLUB
INSTITUTE FOR ADVANCED STUDY

The Jockey Club of Hong Kong

Where I am now (HKUST)

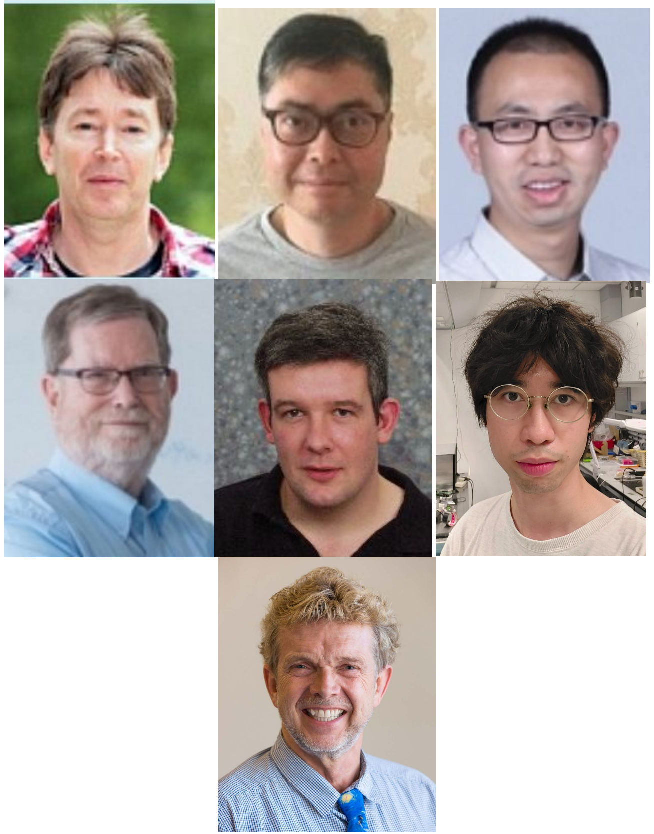
I am doing my first postdoc under the supervision of:

- Tao Liu (IAS),
- George Smoot (IAS)

And collaborating mainly with

- Tom Broadhurst (Ikerbasque),
- Jeremy Lim (HKU),
- Carlton Baugh (Durham),
- Leo Fung (IAS),
- Josh Zhang (HKU)

And the **PEARLS team** led by Rogier Windhorst (Arizona)

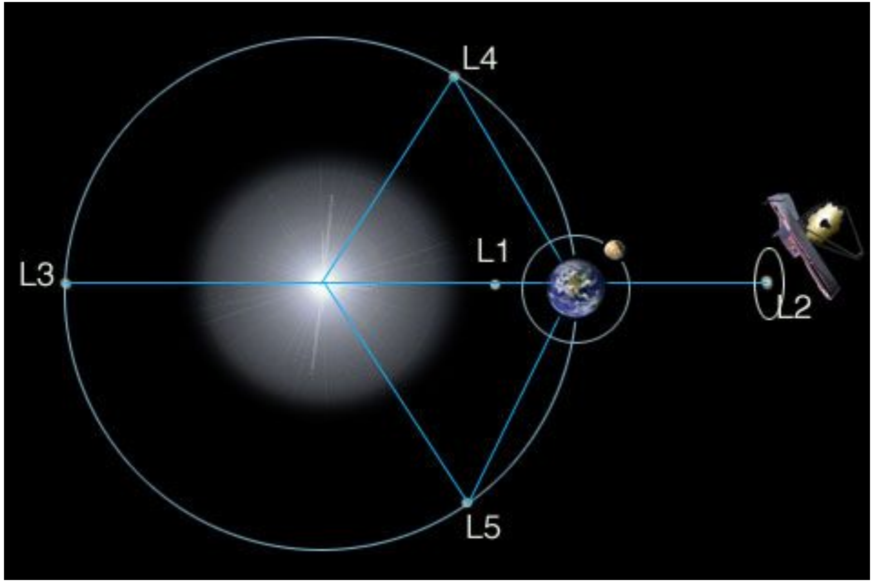


And I am making use of the **semi-analytical models** of galaxy formation to make predictions on **JWST** observation and getting some constraints on **DARK MATTER model**

The James Webb Space Telescope

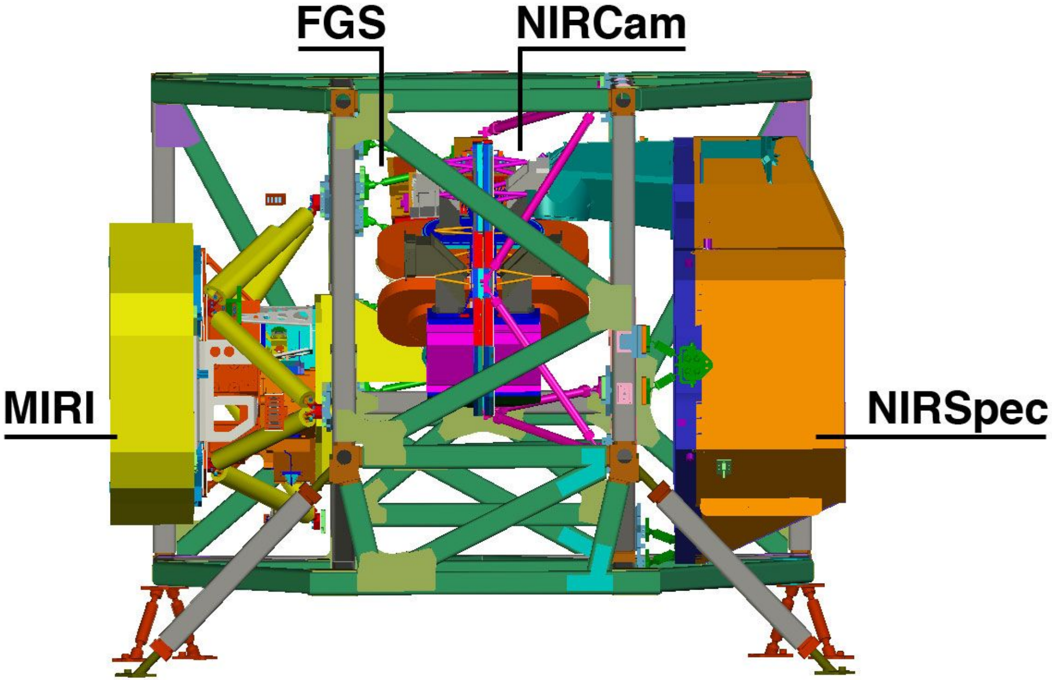
Launched on Christmas 2021 started to release scientific images on last July

Sent in L2 (darkest lagrangian point)



18 hexagonal segments, each ~1.4 m in diameter, the act as if it was a 6.5m single mirror diameter

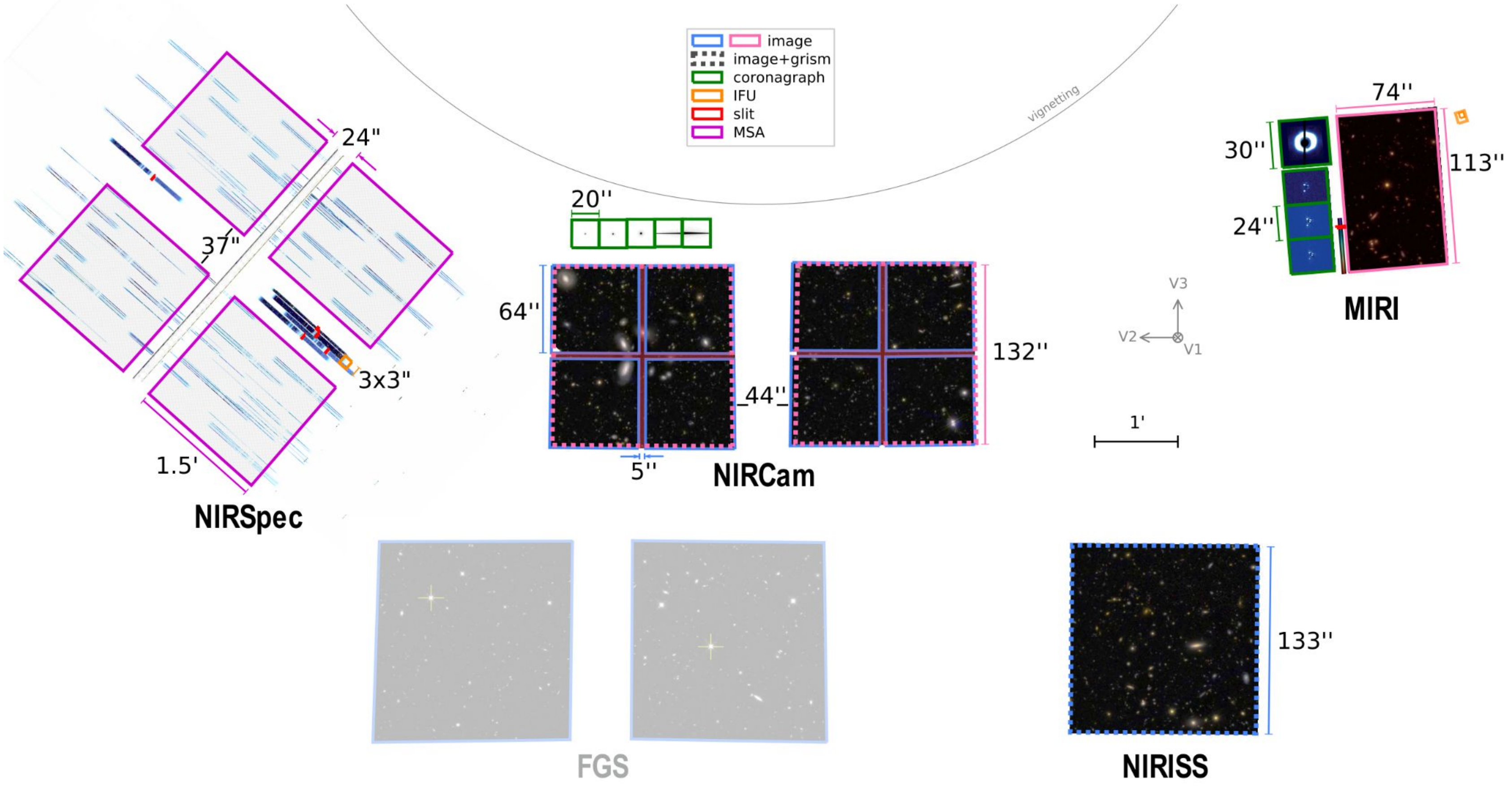
The JWST instruments



1. **NIRCam** (Near InfraRed Camera)
2. **NIRSpec** (Near InfraRed Spectrograph)
3. **MIRI** (Mid InfraRed Instrument)
4. FGS/**NIRISS** or simply NIRISS (Fine Guidance Sensor/Near Infrared Imager and Slitless Spectrograph)

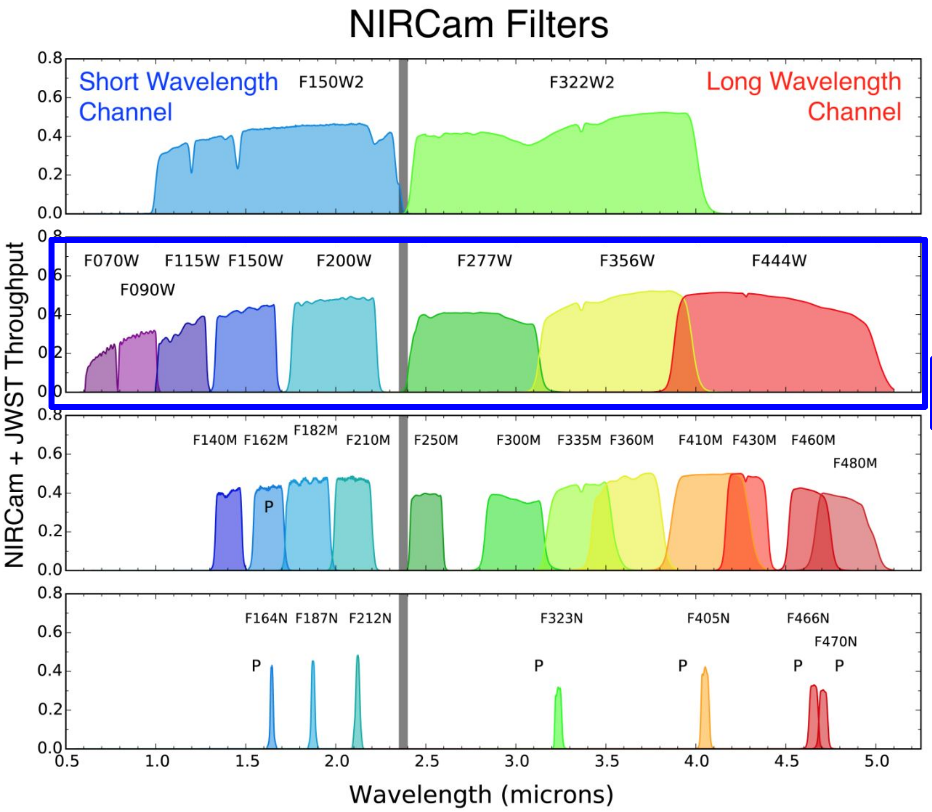
https://www.stsci.edu/jwst/instrumentation/instruments

Field of view of JWST



https://jwst-docs.stsci.edu/jwst-observatory-characteristics/jwst-field-of-view

I will be simulating NIRCam observation in the wide filters

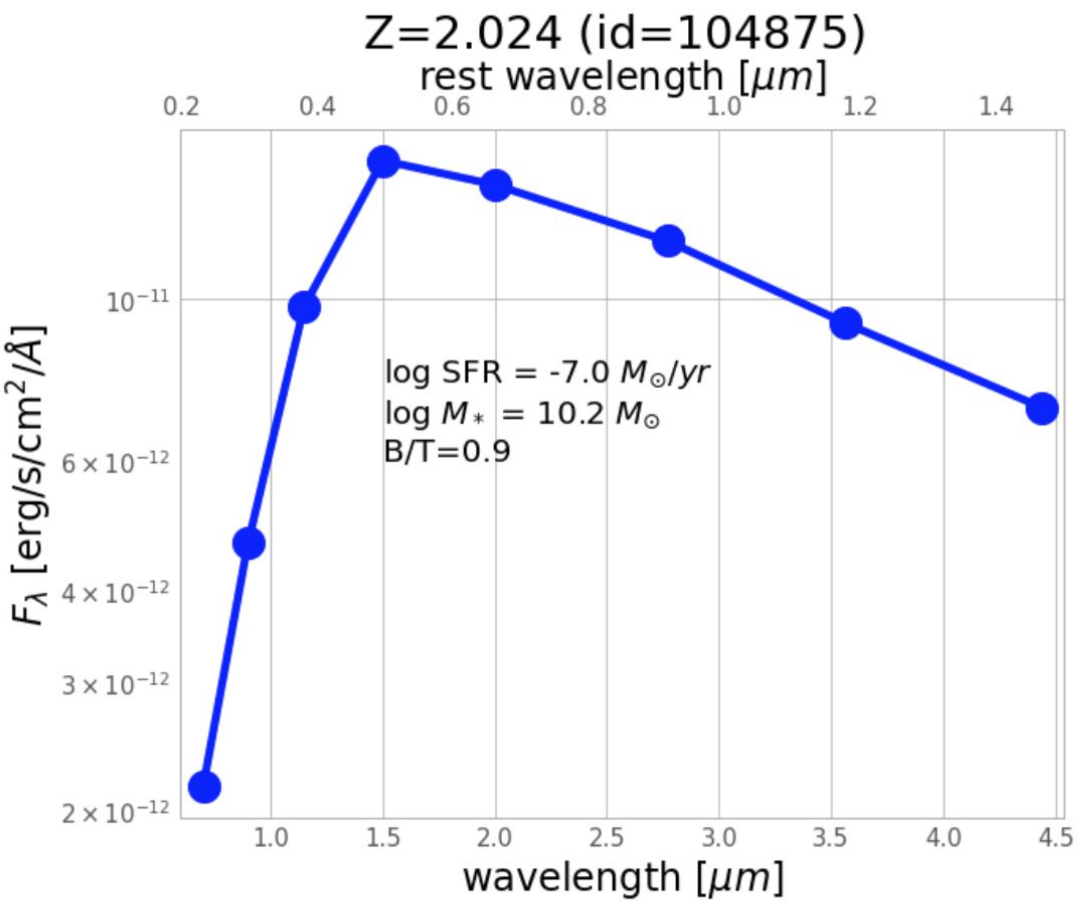


Filters	R = λ/Δλ	Short wavelength channel (0.6–2.3 μm) Number of filters	Long wavelength channel (2.4–5.0 μm) Number of filters
All	**~1–92**	**13**	**16**
Extra-wide	~1–2	1	1
Wide	~4–5	5	3
Medium	~8–20	4	8
Narrow	~78–92	3	4

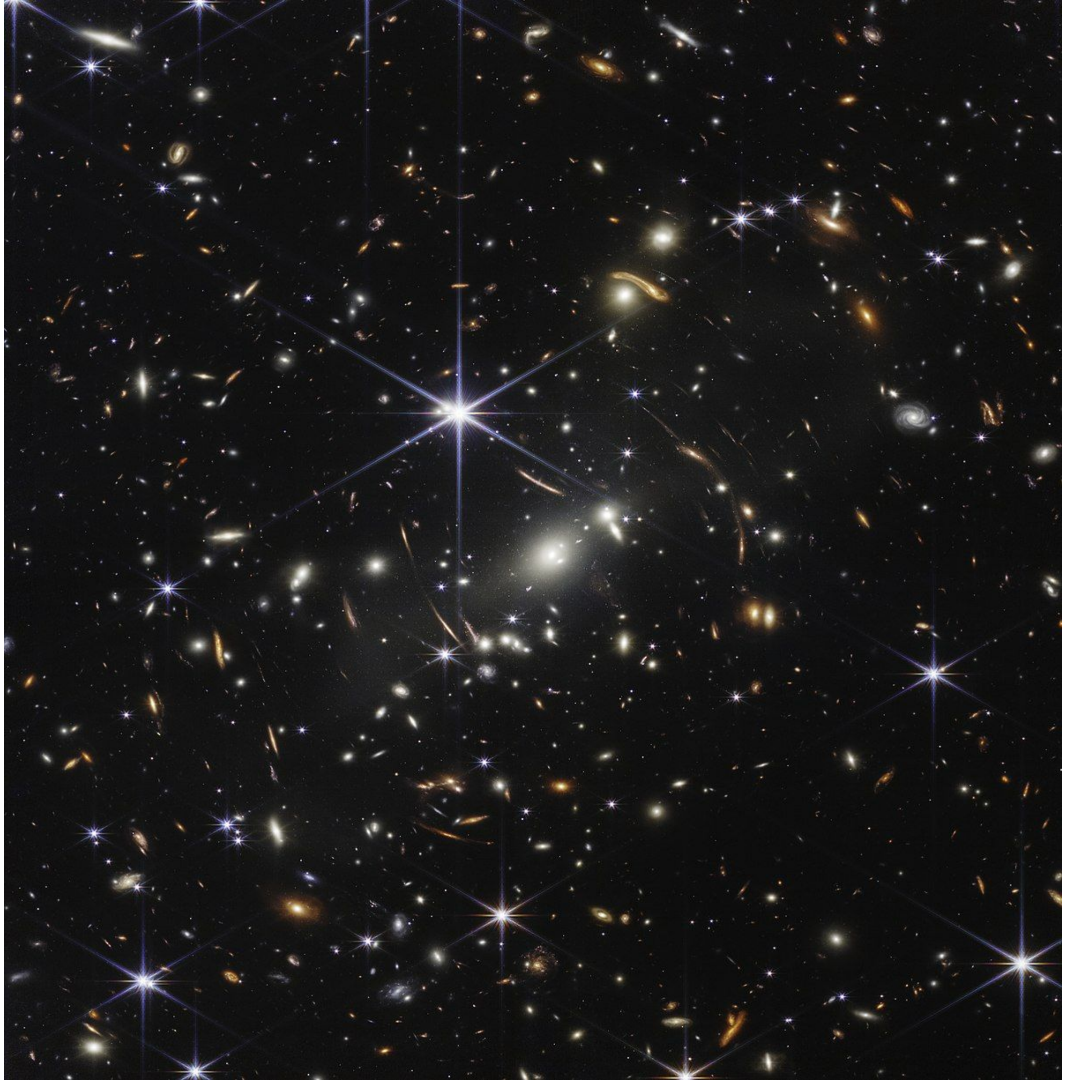
https://jwst-docs.stsci.edu/jwst-near-infrared-camera/nircam-instrumentation/nircam-filters

It observes Infrared to get the optical rest frame

$$\lambda_{\rm rest} = \frac{\lambda_{\rm obs}}{1+z}$$



SMACS 0723
z~0.39



Not representative of the entire universe as we are looking at a cluster (which is an over density)

The **homogeneity** and **isotropy** works at larger scales

We need a **parallel field**

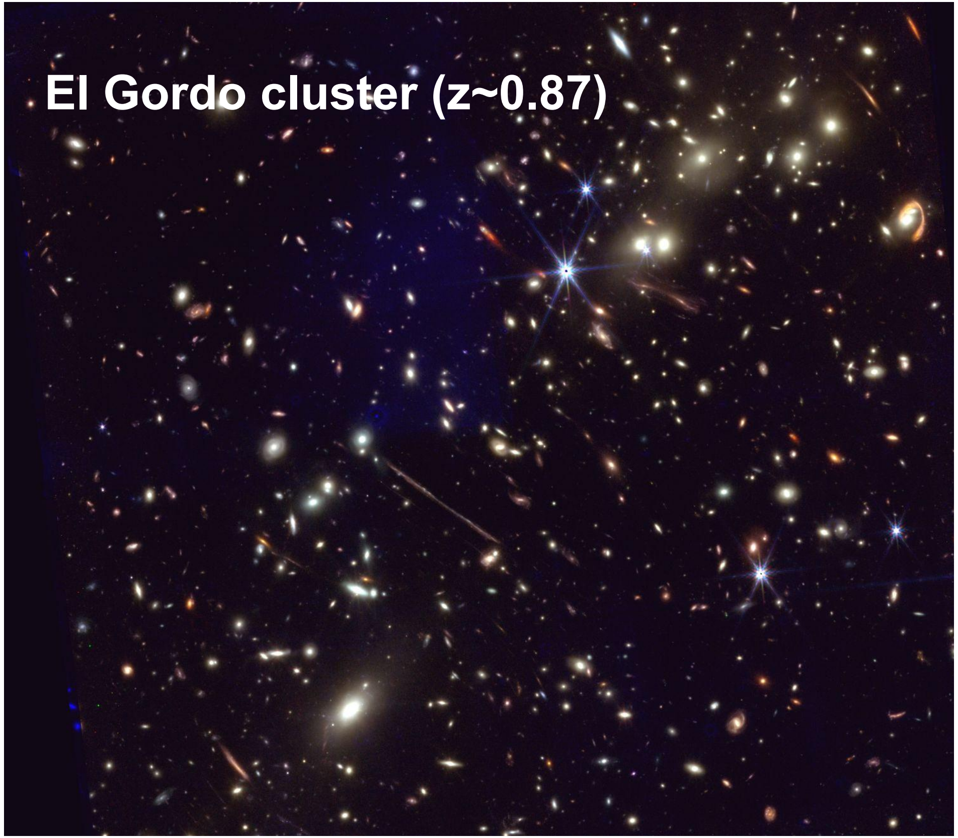
First image released on 11 July 2022

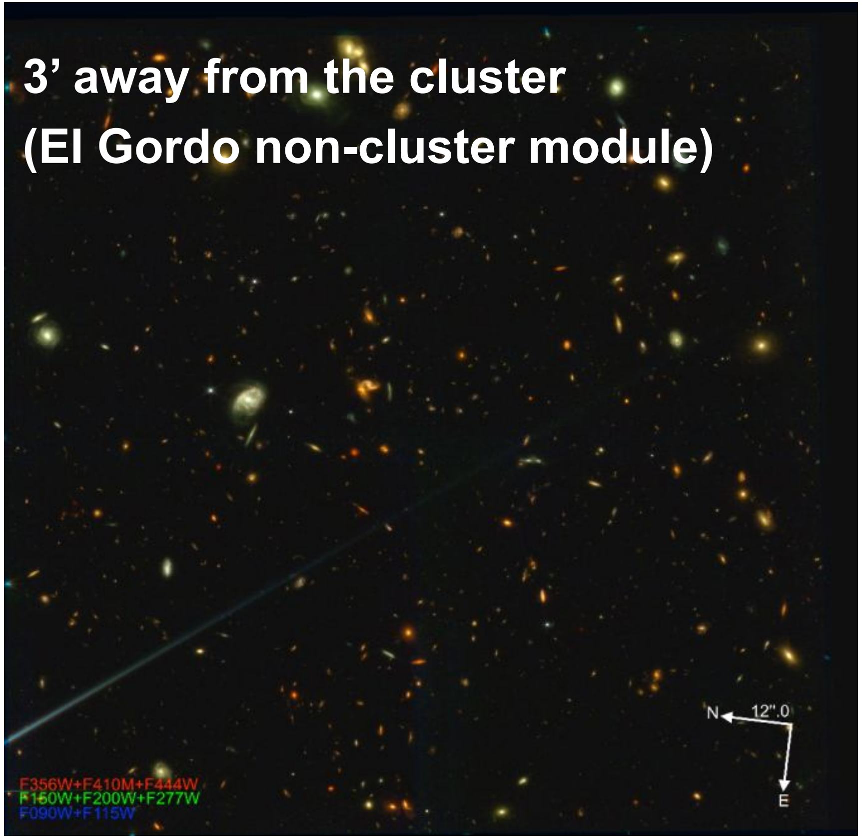
The first PEARLS overview paper

Webb's PEARLS: Prime Extragalactic Areas for Reionization and Lensing Science: Project Overview and First Results

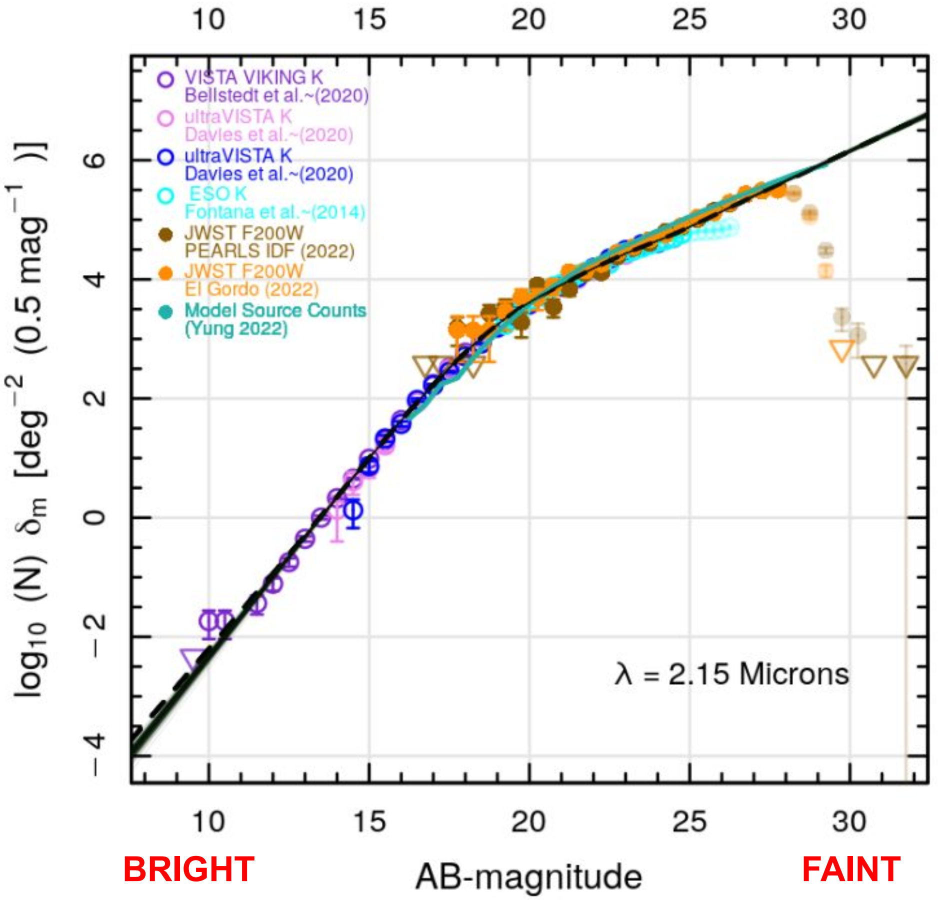
Rogier A. Windhorst,[1] Seth H. Cohen,[1] Rolf A. Jansen,[1] Jake Summers,[1] Scott Tompkins,[1] Christopher J. Conselice,[2] Simon P. Driver,[3] Haojing Yan,[4] Dan Coe,[5] Brenda Frye,[6] Norman Grogin,[7] Anton Koekemoer,[7] Madeline A. Marshall,[8,9] Rosalia O'Brien,[1] Nor Pirzkal,[7] Aaron Robotham,[3] Russell E. Ryan, Jr.,[7] Christopher N. A. Willmer,[6] Timothy Carleton,[1] Jose M. Diego,[10] William C. Keel,[11] Paolo Porto,[1] Caleb Redshaw,[1] Sydney Scheller,[12] Andi Swirbul,[1] Stephen M. Wilkins,[13] S. P. Willner,[14] Adi Zitrin,[15] Nathan J. Adams,[2] Duncan Austin,[2] Richard G. Arendt,[16] John F. Beacom,[17] Rachana A. Bhatawdekar,[18] Larry D. Bradley,[7] Tom Broadhurst,[19,20,21] Cheng Cheng,[22] Francesca Civano,[14] Liang Dai,[23] Hervé Dole,[24] Jordan C. J. D'Silva,[3] Kenneth J. Duncan,[25] Giovanni G. Fazio,[14] Giovanni Ferrami,[26,9] Leonardo Ferreira,[27] Steven L. Finkelstein,[28] Lukas J. Furtak,[29] Alex Griffiths,[27] Heidi B. Hammel,[30] Kevin C. Harrington,[31] Nimish P. Hathi,[7] Benne W. Holwerda,[32] Jia-Sheng Huang,[33] Minhee Hyun,[34,35] Myungshin Im,[34] Bhavin A. Joshi,[36] Patrick S. Kamieneski,[37] Patrick Kelly,[38] Rebecca L. Larson,[28] Juno Li,[3] Jeremy Lim,[39] Zhiyuan Ma,[37] Peter Maksym,[14] Giorgio Manzoni,[40] Ashish Kumar Meena,[15] Stefanie N. Milam,[41] Mario Nonino,[42] Massimo Pascale,[43] Justin D. R. Pierel,[7] Andreea Petric,[7] Maria del Carmen Polletta,[44] Huub J. A. Röttgering,[45] Michael J. Rutkowski,[46] Ian Smail,[47] Amber N. Straughn,[48] Louis-Gregory Strolger,[7] James A. A. Trussler,[2] Lifan Wang,[49] Brian Welch,[36] J. Stuart B. Wyithe,[26,9] Min Yun,[37] Erik Zackrisson,[50] Jiashuo Zhang,[40] and Xiurui Zhao[14]

PEARLS images

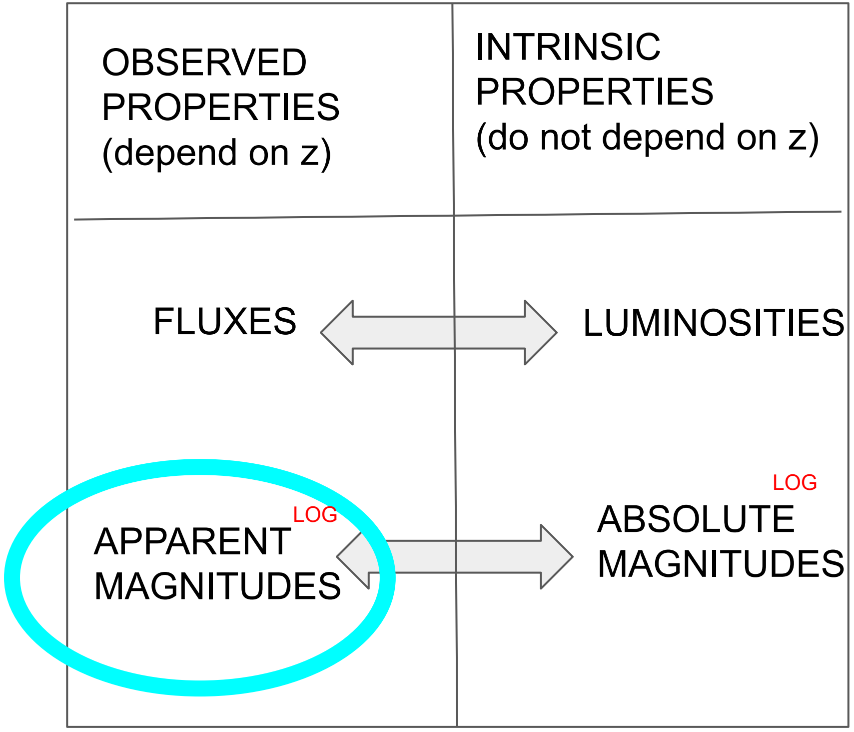




Rogier Windhorst's **number counts** (PEARLS TEAM)

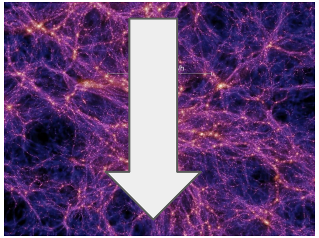


- **ALL REDSHIFTS** ARE INCLUDED!



GALAXY FORMATION IS A **2 STEP** PROCESS

Structures form in
DARK MATTER
BY
HIERARCHICAL CLUSTERING

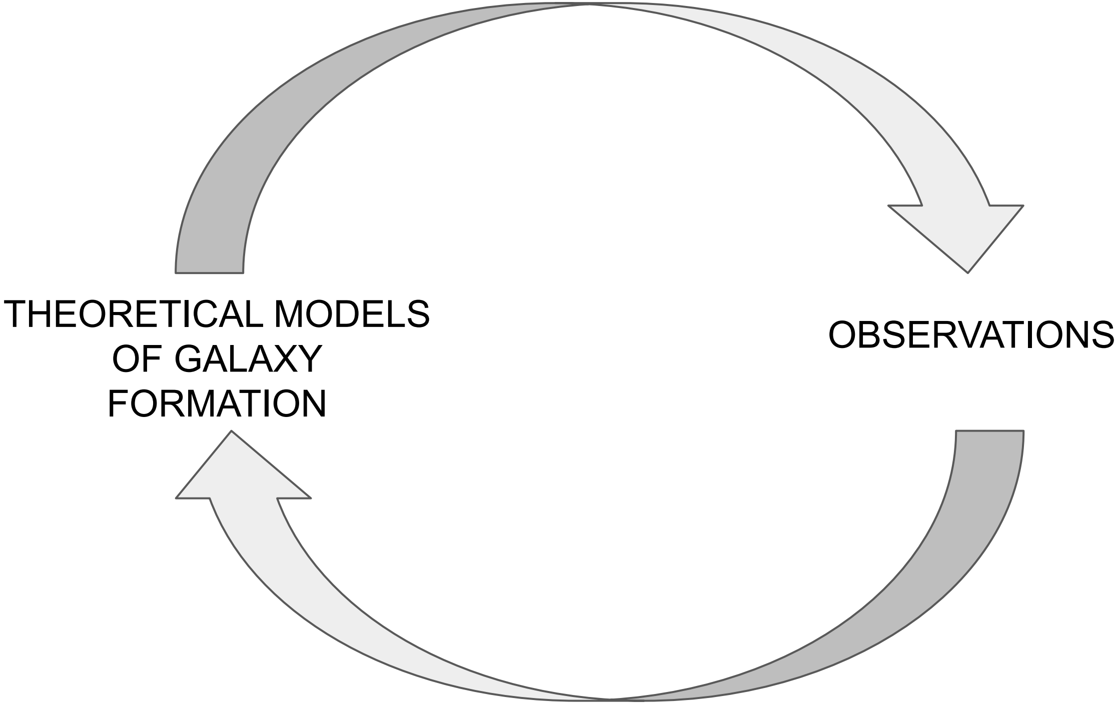


DM ONLY - N-Body
simulations
quite well understood

Galaxies form
by cooling and collapse of
baryons
inside the DM halos

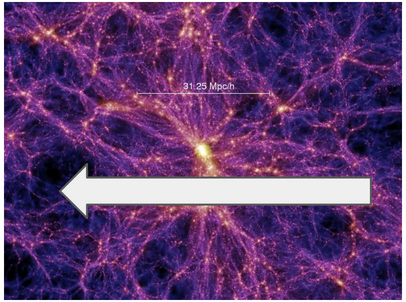
The evolution of baryons involve many physical processes not well understood

Improving the understanding of the baryonic physics



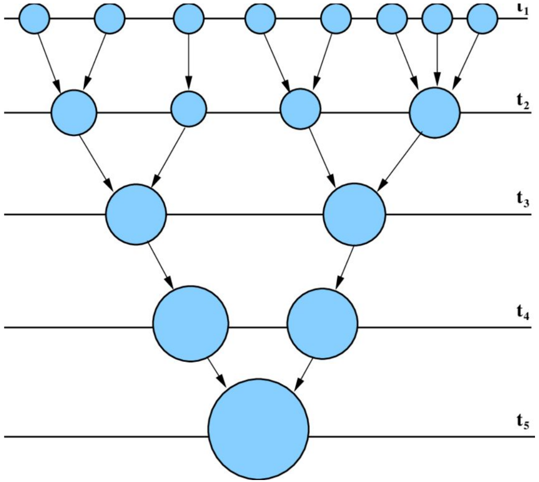
DARK MATTER COMPONENT

DM-only **N-body** Simulation



- Very **computationally expensive**, it's done once for all
- Hence it's **limited** to the **resolution used**
- And it's **limited** to the DM **model** that has been **used**

THE EVOLUTION
OF
DARK MATTER HALOS
can be tracked by a set of
DM MERGER TREES
generated by:



Monte Carlo based on Press - Schechter formalism

- Very fast
- The **resolution** can be **chosen**
- It slow down exponentially with the resolution
- **Different DM model** can be explored

Parkinson et al 2008, Benson et al. 2013

MODELLING THE BARYONIC PHYSICS

SEMI-ANALYTICAL MODELS

GLOBAL PROPERTIES

Advantages:
- Fast
- Flexible
- Give prediction for large scales

Disadvantages:
- Approximated
- Involves some calibration with observations at z=0

HYDRODYNAMICAL SIMULATION

PROPERTIES WITHIN GALAXIES

Advantages:
- More accurate physics modelling at higher resolution

Disadvantages:
- Only small scales predictions
- No luminosities
- Less processes

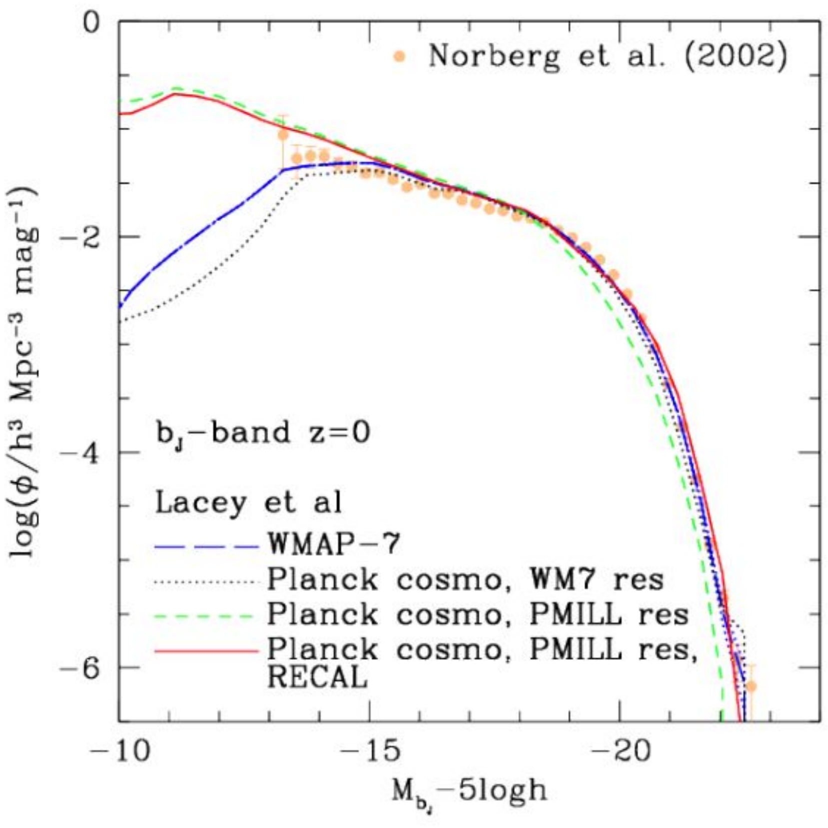
GALFORM is a semi-analytic model

The main processes modelled in GALFORM are:

- **Shock-heating** and **radiative cooling** of gas inside DM halos (leading to the **formation of galaxies**)
- **Star formation** in galaxies in galaxy **disks** (“quiescent”) and **bursts**
- **Feedback**:
  - from supernovae (**SN**)
  - from active galactic nuclei (**AGN**)
  - from **photo-ionization** of IGM
- **Galaxy mergers** driven by **dynamical friction** and **bar instabilities** in galaxy disks (both can trigger starbursts and lead to the **formation of spheroids**)
- **Chemical enrichment** of stars and gas
- **Reprocessing of starlight** by dust (calculated from gas and metal content of each galaxy):
  - **Dust extinction** from UV to near-IR
  - **Dust emission** from far IR to sub-mm wavelength

Cole et al. 2000, Lacey et al. 2016, Baugh et al. 2019

Calibration of the Luminosity Function at **redshift zero**

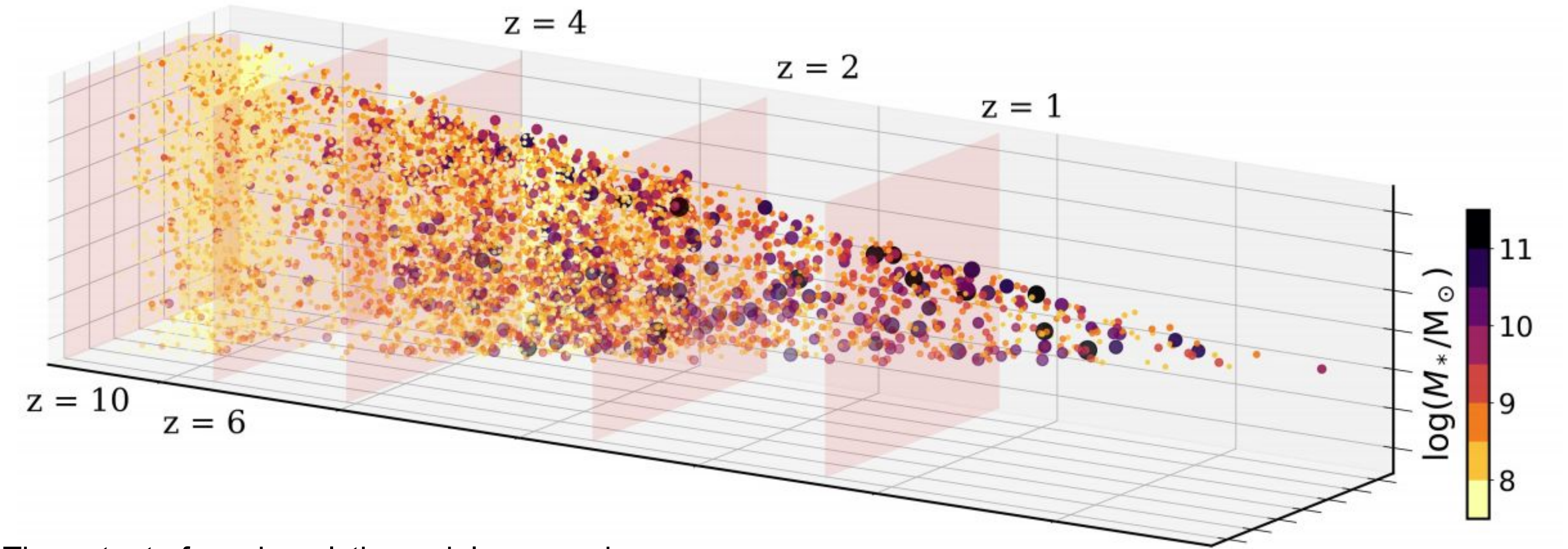


Baugh et al. 2019

$$\dot{M}_{\rm eject} = \beta(V_{\rm c})\psi = \left(\frac{V_{\rm c}}{V_{\rm SN}}\right)^{-\gamma_{\rm SN}} \psi$$

```
alpha_Cooled_Remove =    1.00000E+00
 transfer_halo_cold =              0
              vdisk =              T
          Vcirc_Fac =    1.00000E+10
              tdisk =              T
       NoDiskUseHalo =             T
           alphahot =    3.40000E+00
          vhotdisk =    3.20000E+02
          vhotburst =    3.20000E+02
   Saturate_Feedback =             F
      thresholdVcirc =   1.00000E+06
           fsw0disk =    0.00000E+00
          fsw0burst =    0.00000E+00
            vswdisk =    1.00000E+02
           vswburst =    1.00000E+02
   Sat_Evol_Feedback =             F
      alphahot_prime =   1.00000E+00
      vhotdisk_prime =   1.80000E+02
     vhotburst_prime =   1.80000E+02
         vcirc_prime =   5.00000E+01
```

Creation of a lightcone



The output of semi-analytic models comes in **snapshots** but it can be interpolated into a lightcone.

You need galaxy positions from N-body simulation.

Yung et al. 2022

COSMA FACILITIES

Hosted by the Institute of Computational Cosmology (ICC) at Durham University and used by cosmologists, astronomers and particle physicists from across the world, **COSMA** has the processing power and memory of about **28,000 home PCs.**

Using COSMA, **single run** of my current JWST simulations take an average of **5 to 6 days to end**.

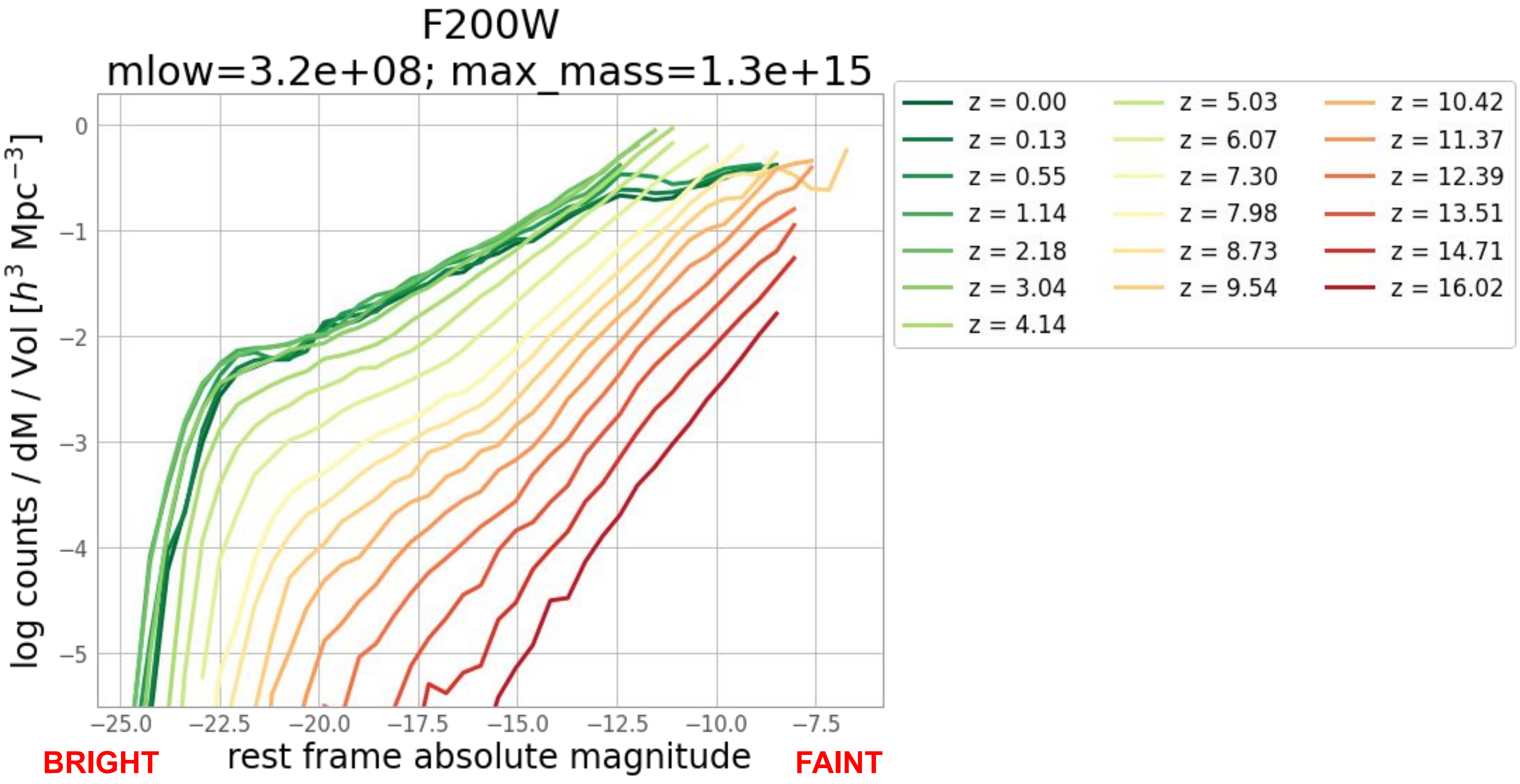
https://dirac.ac.uk/ DIRAC - DIstributed Research utilising Advanced Computing

https://www.durham.ac.uk/departments/academic/physics/cosma7/

COSMA specifics

- **360 compute nodes with 1 TB RAM** and dual 64-core AMD EPYC 7H12 water-cooled processors at 2.6GHz
- 2 login nodes with 2 TB RAM and dual 32-core AMD EPYC 7542 processors at 2.9 GHz
- 2 fat nodes with 4 TB RAM and dual 64-core AMD EPYC 7702 processors at 2.2GHz
- 1 AMD **GPU** nodes with 6 MI50 GPUs (32GB), 1TB RAM, dual 16-core AMD EPYC 7282 processors at 2.8GHz
- 1 AMD Milan node with a MI100 **GPU**, 1TB RAM, dual 64-core AMD EPYC Milan 7713 processors at 2GHz
- 1 NVIDIA **GPU** node with 10 V100 GPUs (32GB), 768GB RAM, dual Intel Xeon Gold 5218 processors at 2.3GHz
- 2 console nodes with a single 16-core AMD EPYC 7302 processor at 3GHz and 256GB RAM

Luminosity functions



The luminosity function can be converted into number counts

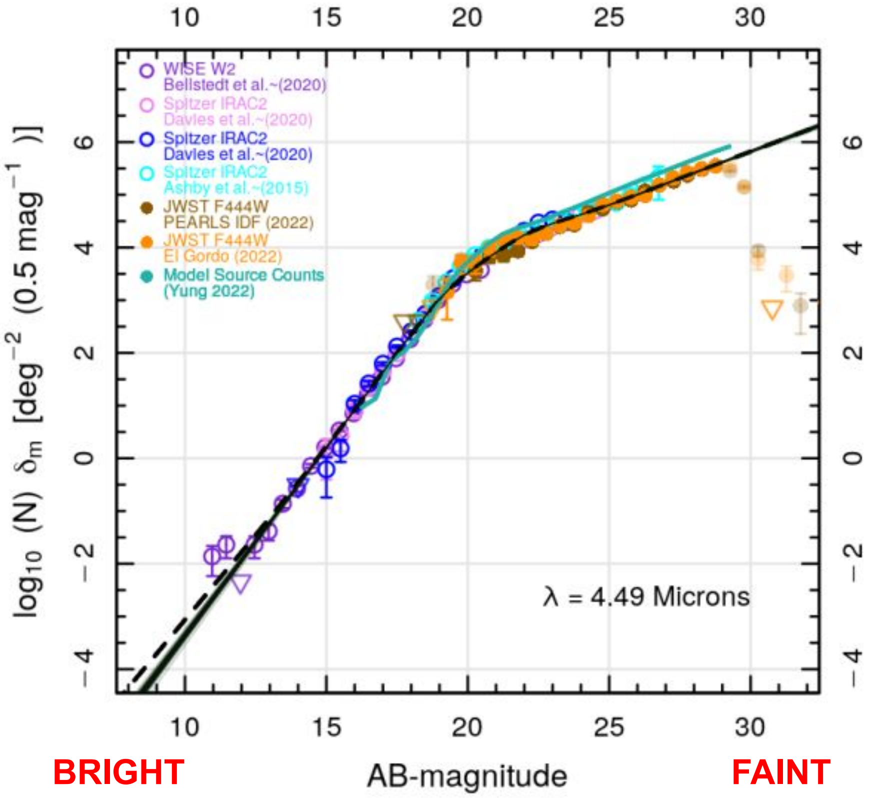
1. CONVERT INTO **APPARENT MAGNITUDE**:
2. Consider the **change in volume element with redshift**
3. **Integrate** over the **redshift range** of interest

$$d^2N/dln(S_\nu)/dz = dn/dln(L_\nu) \times dV/dz$$

NUMBER COUNTS
(all redshifts integrated together)

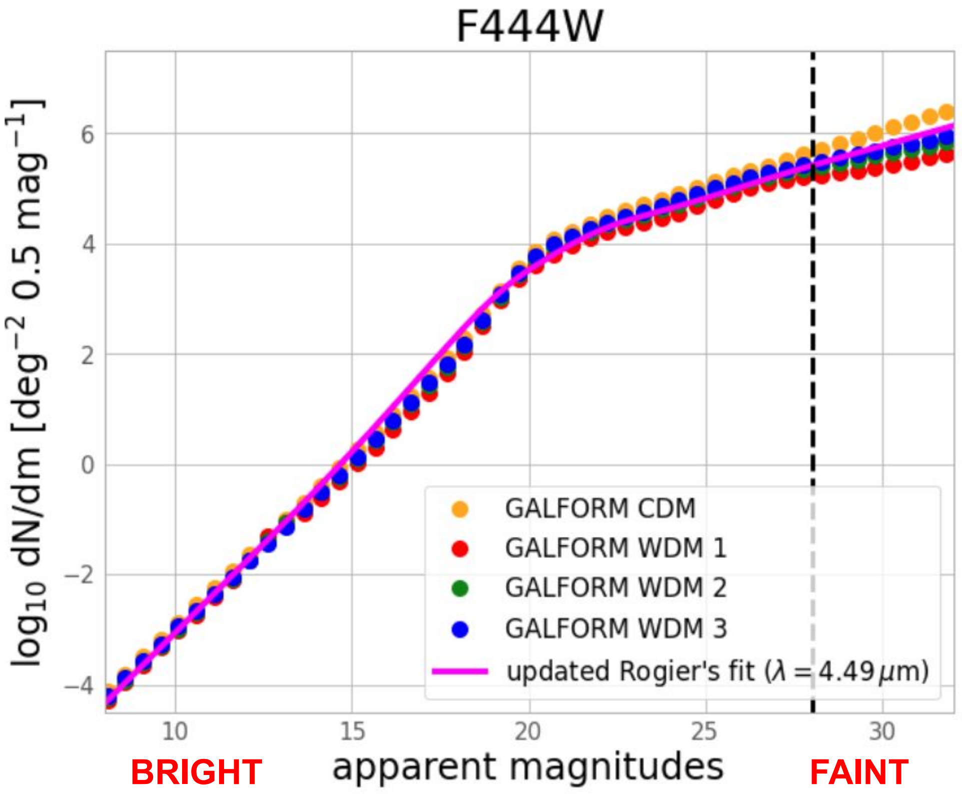
LUMINOSITY FUNCTION
(at a specific redshift snapshot)

JWST OBSERVATIONS



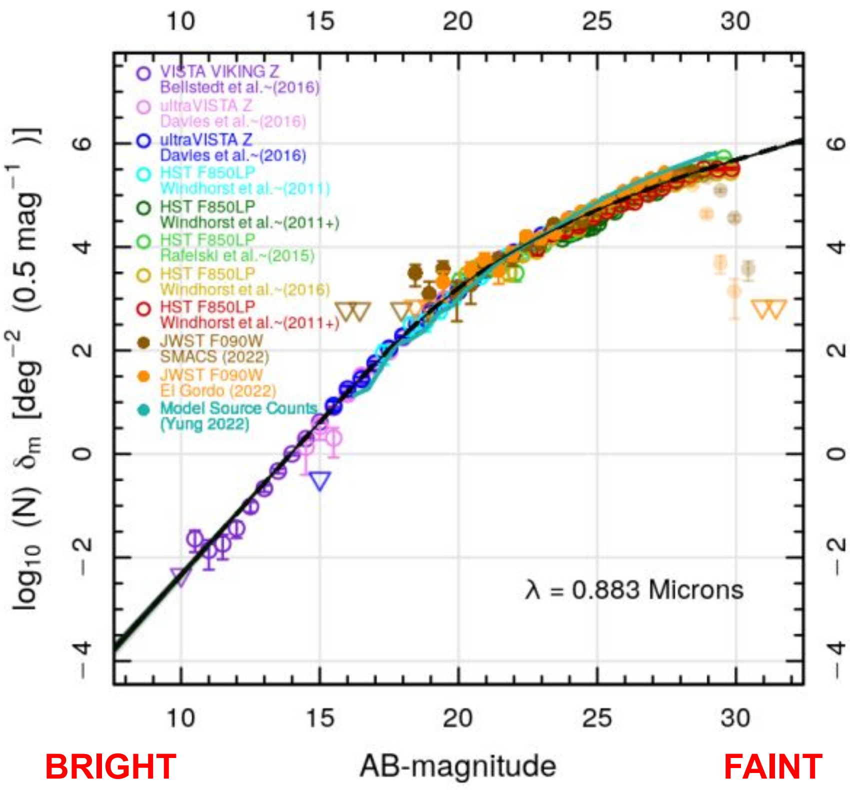
Windhorst et al. 2023

GALFORM PREDICTIONS



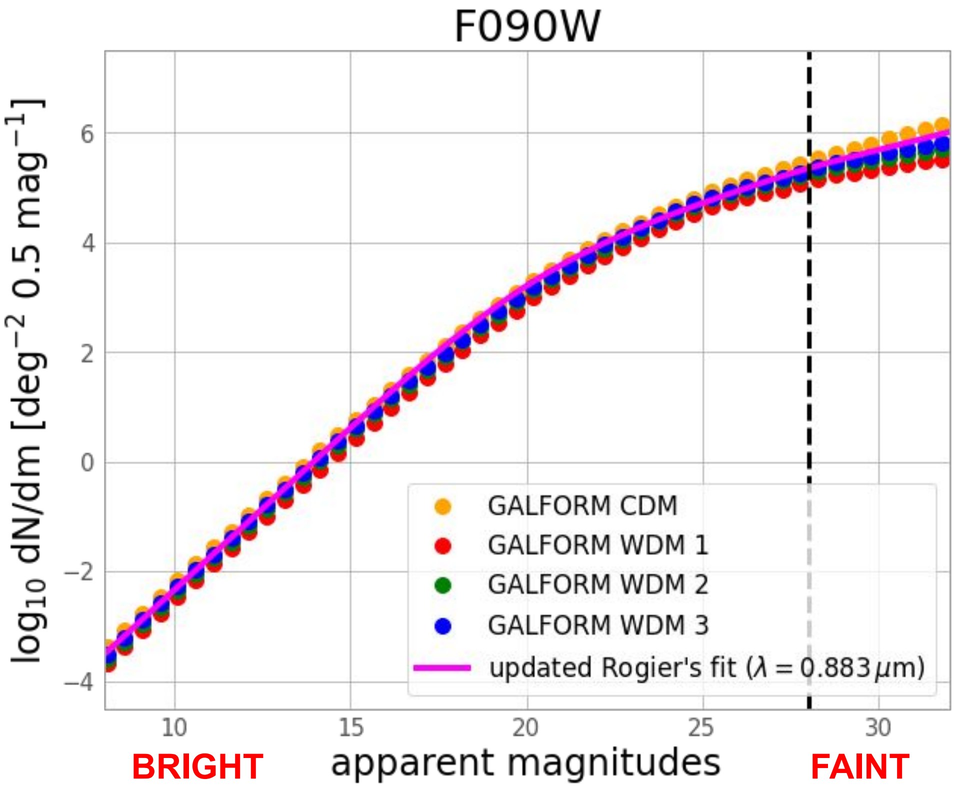
Manzoni et al. in prep.

JWST OBSERVATIONS



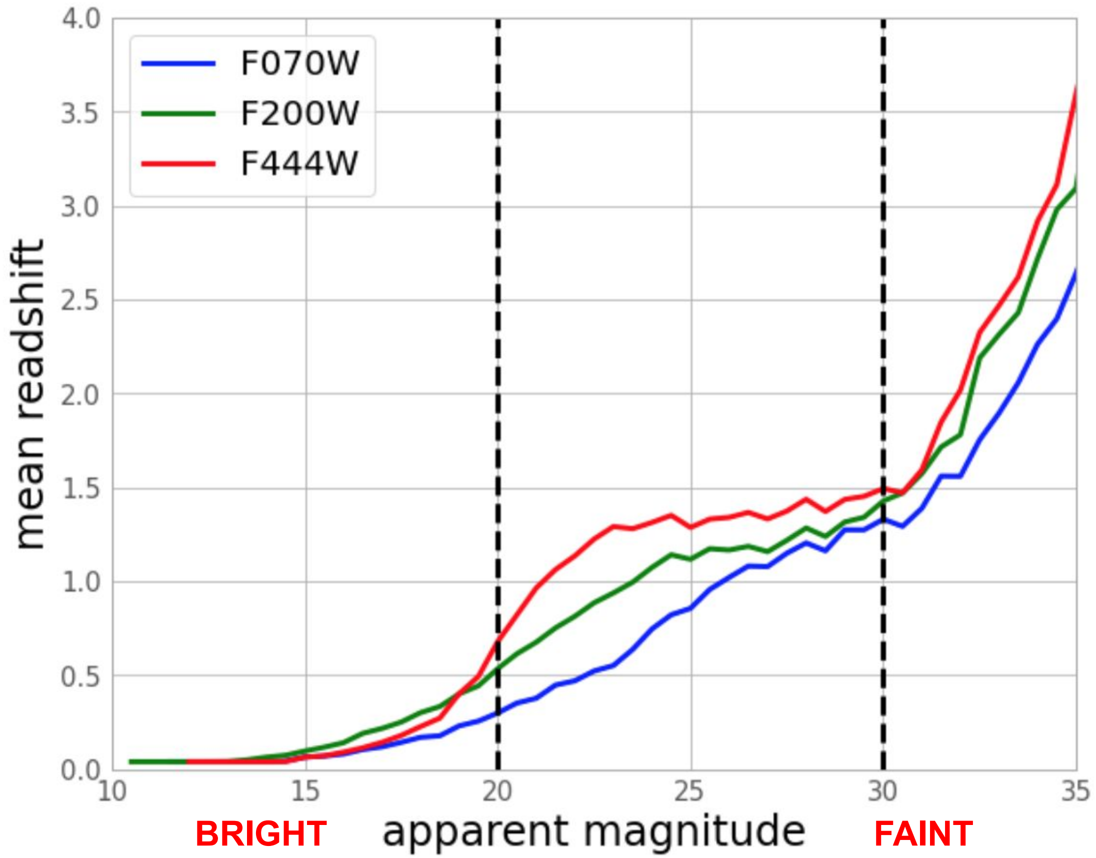
Windhorst et al. 2023

GALFORM PREDICTIONS



Manzoni et al. in prep.

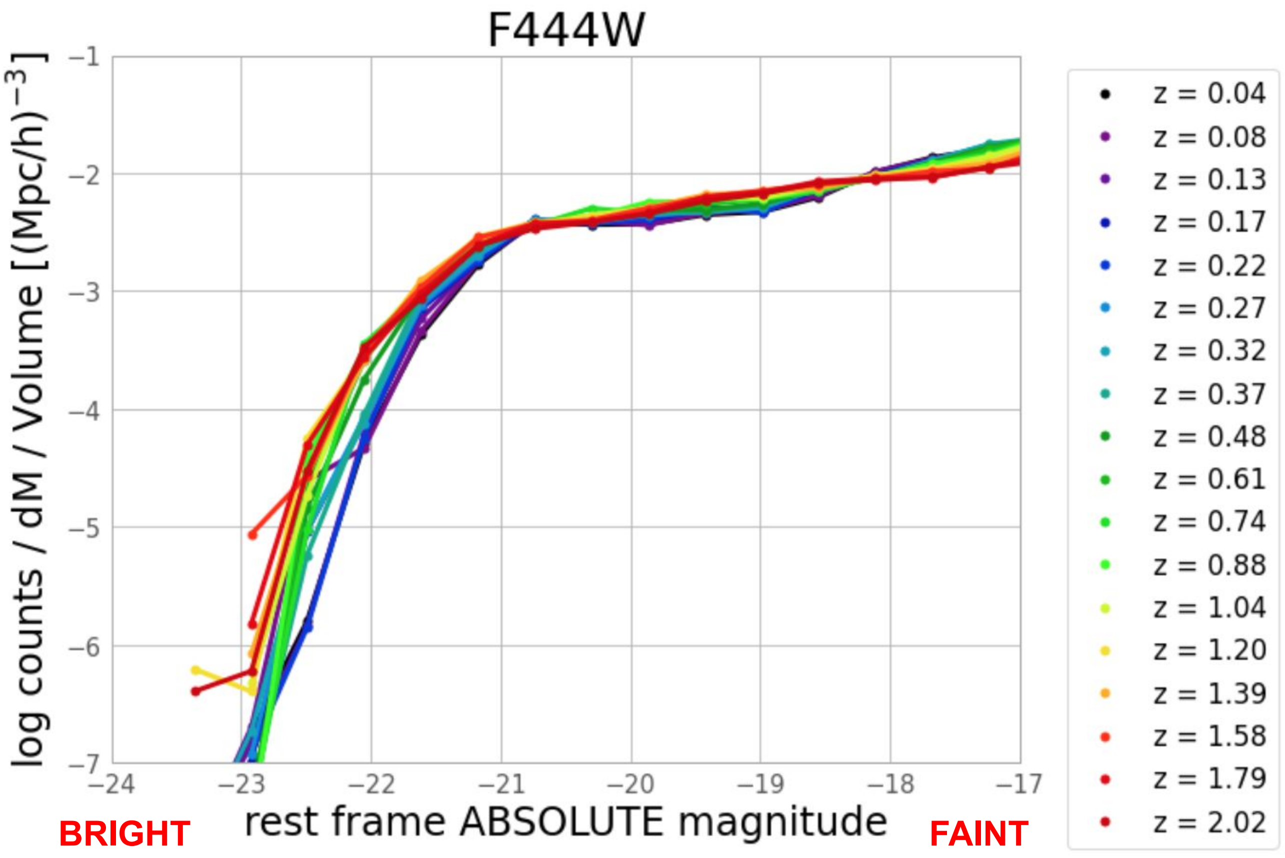
Which redshifts are really dominating?



BRIGHT

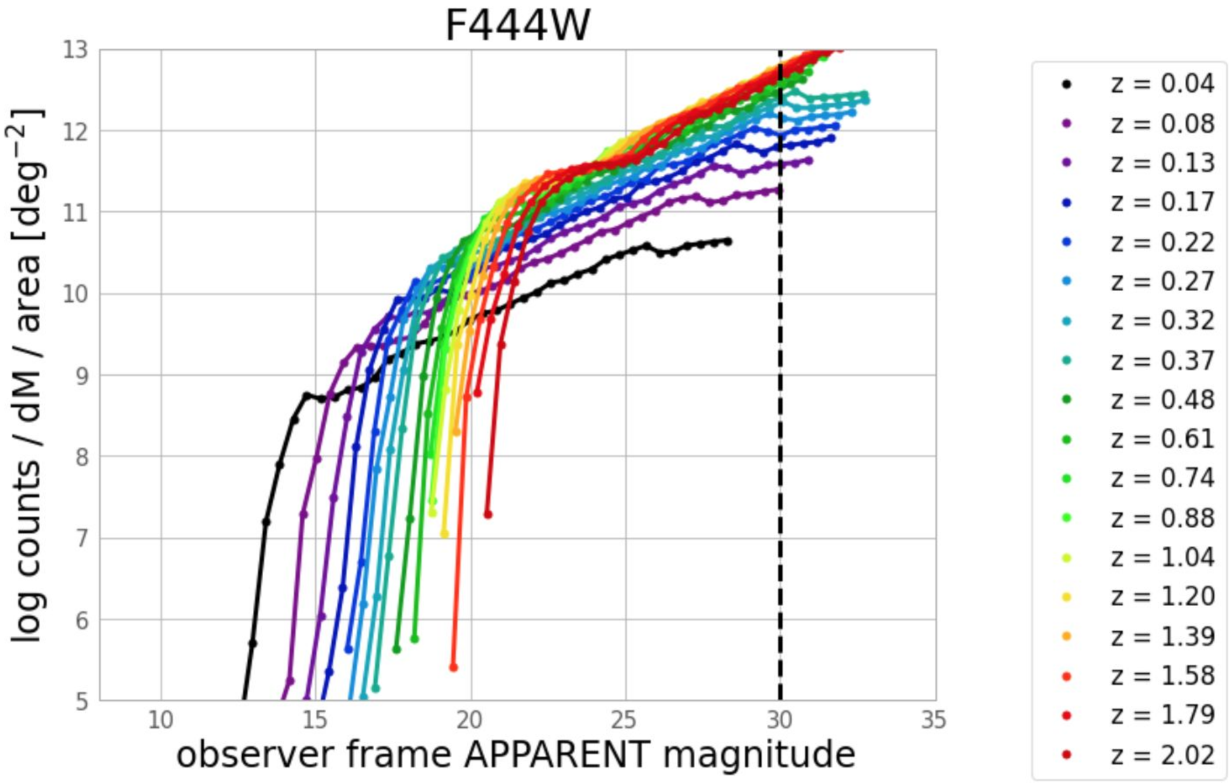
FAINT

STANDARD LUMINOSITY FUNCTION



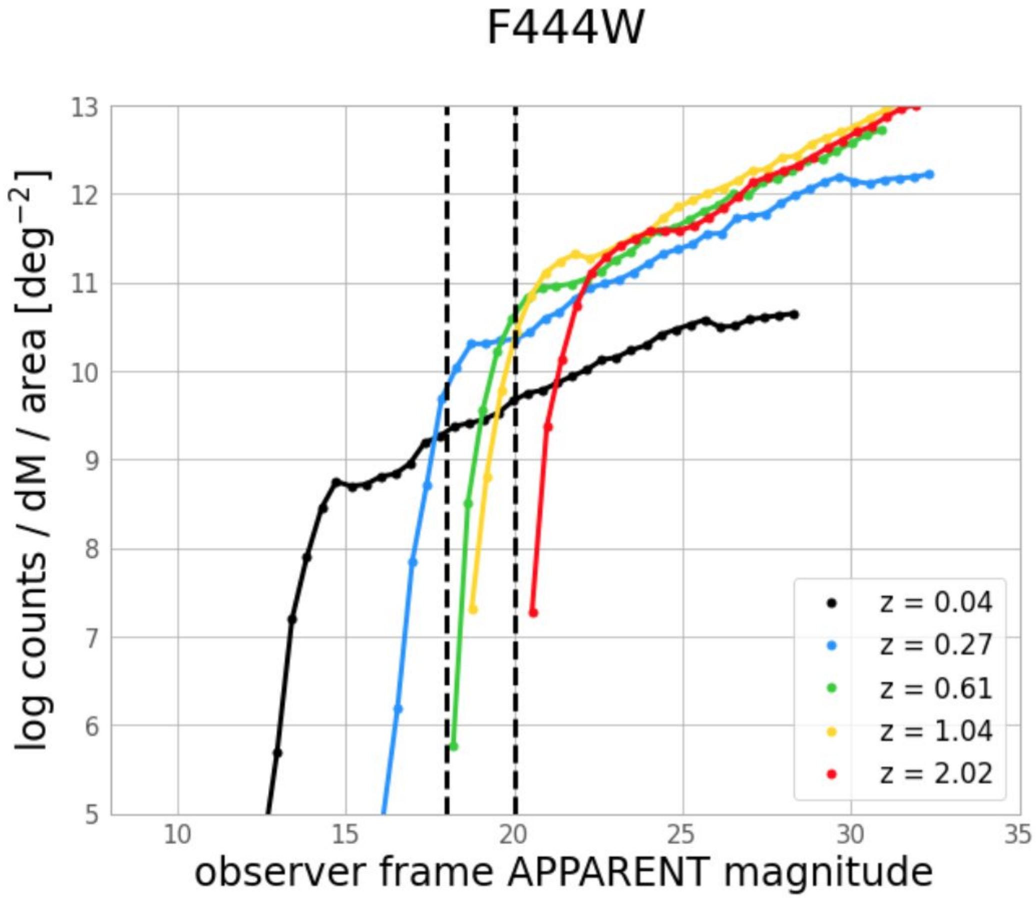
- **Rest frame** absolute magnitudes
- Counts per **unit volume**

MODIFIED LUMINOSITY FUNCTION

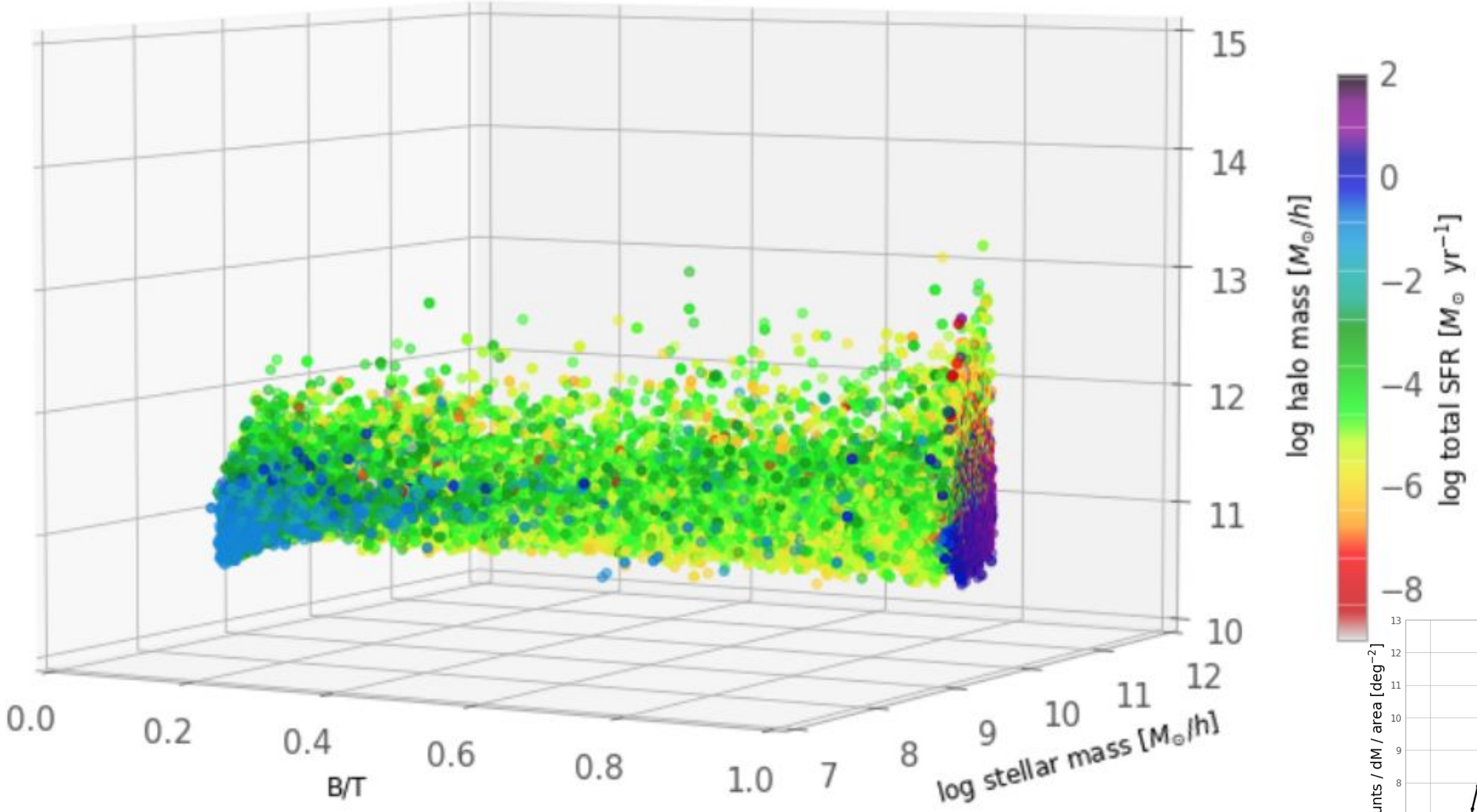


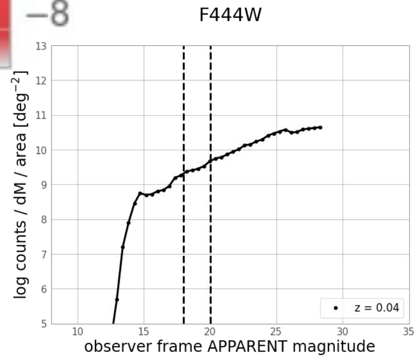
- **Observer frame** apparent magnitudes
- Counts per **unit area**

We are looking at different part of the luminosity function

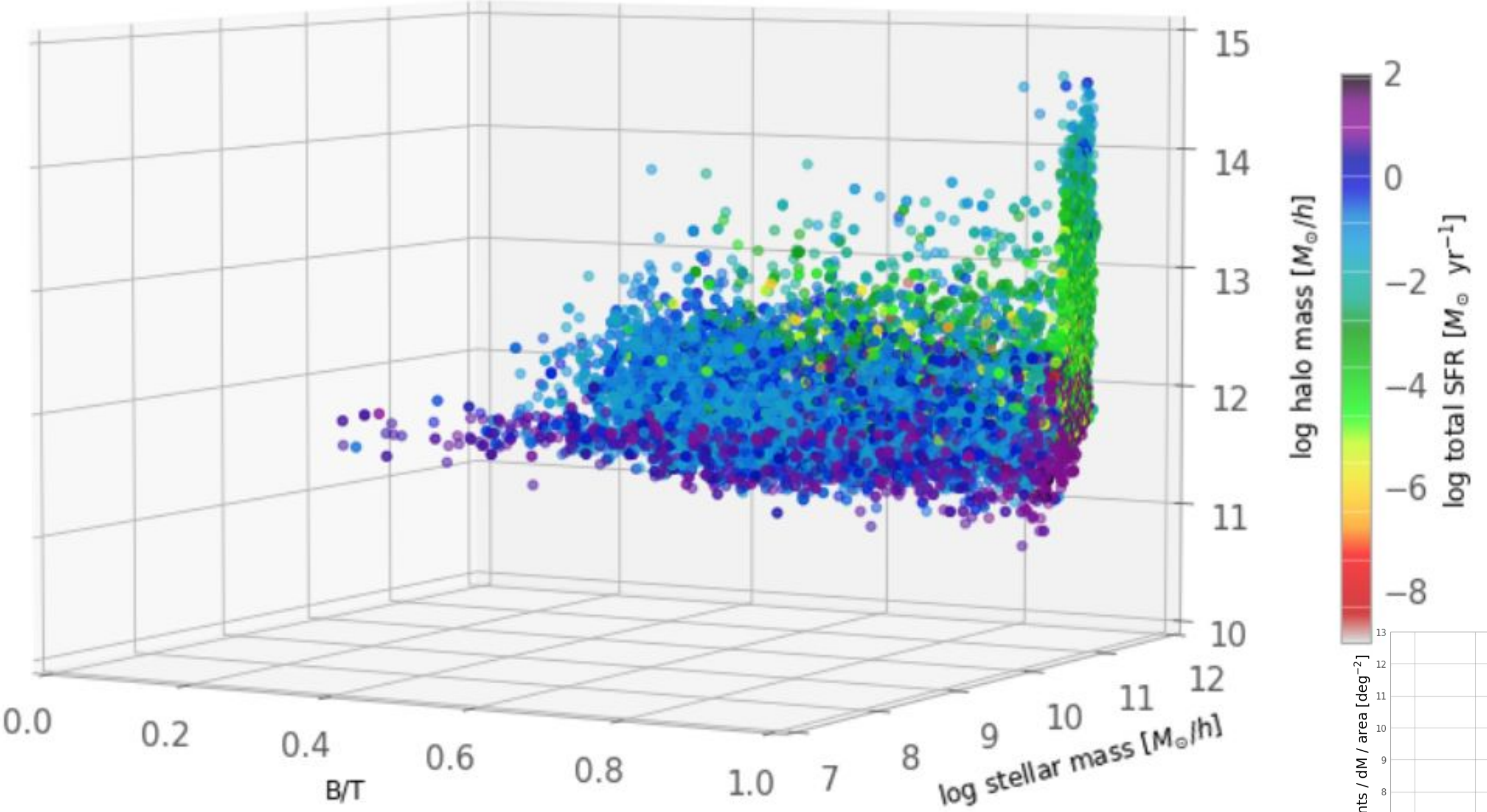


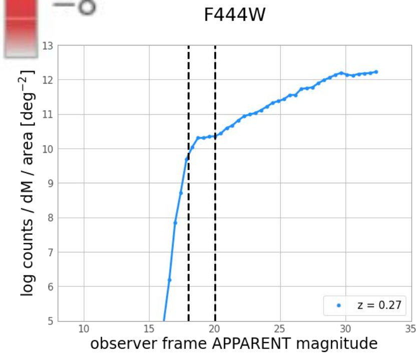
z=0.04

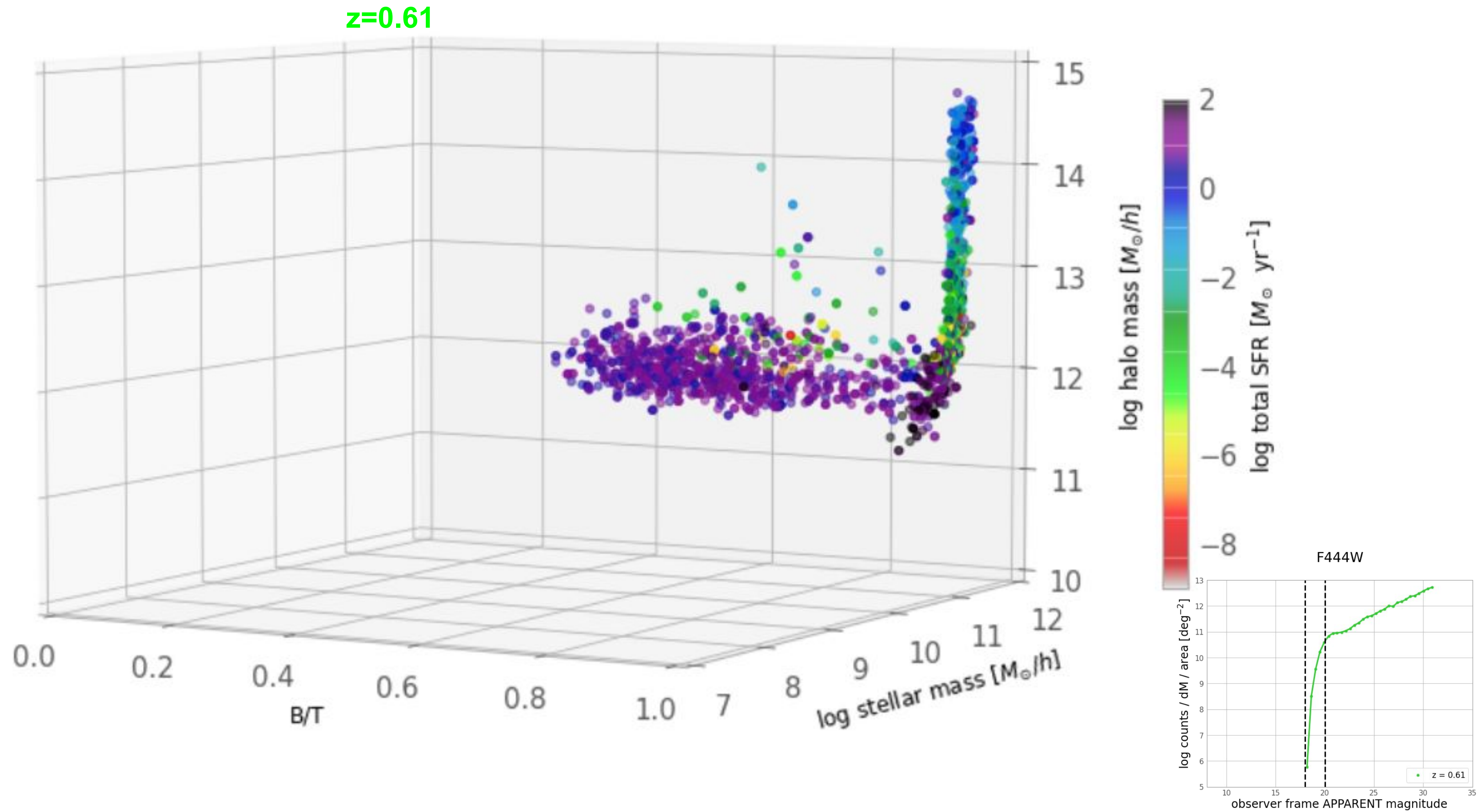

15
14
13
12
11
10
log halo mass [$M_\odot/h$]
0.0
0.2
0.4
0.6
0.8
1.0
B/T
7
8
9
10
11
12
log stellar mass [$M_\odot/h$]
2
0
−2
−4
−6
−8
log total SFR [$M_\odot$ yr^{-1}]


F444W
log counts / dM / area [deg^{-2}]
observer frame APPARENT magnitude
z = 0.04

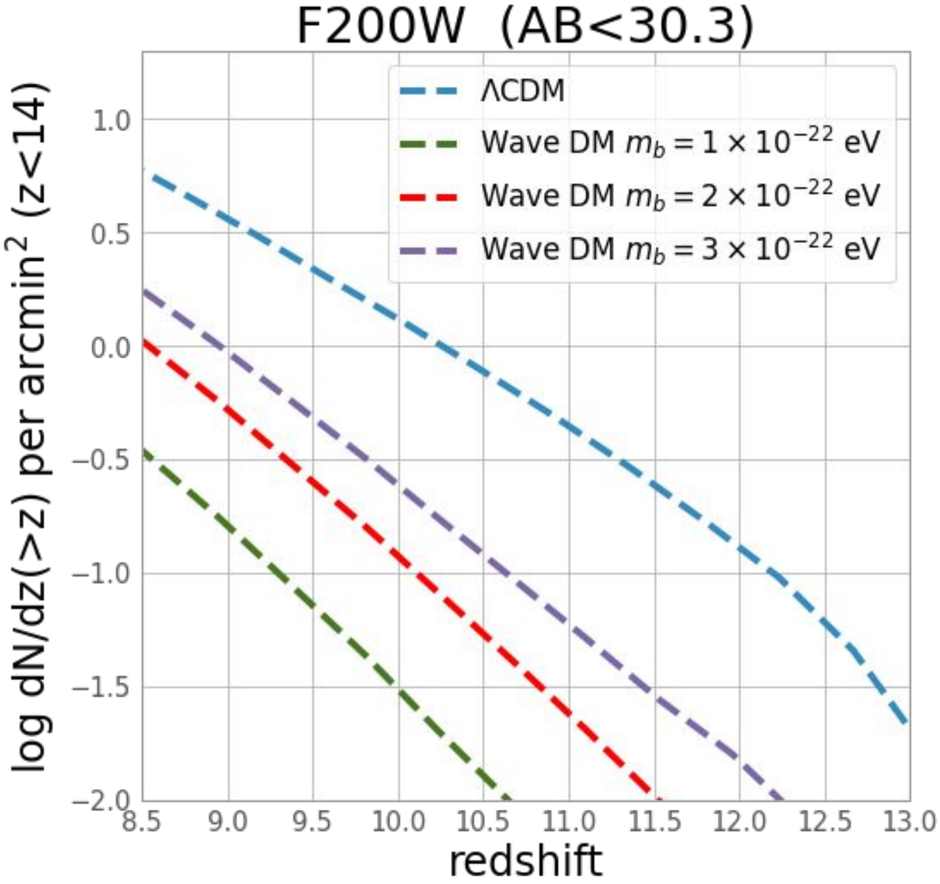
z=0.27


15
14
13
12
11
10
log halo mass [$M_\odot/h$]
2
0
−2
−4
−6
−8
log total SFR [$M_\odot$ yr^{-1}]
0.0
0.2
0.4
0.6
0.8
1.0
B/T
7
8
9
10
11
12
log stellar mass [$M_\odot/h$]

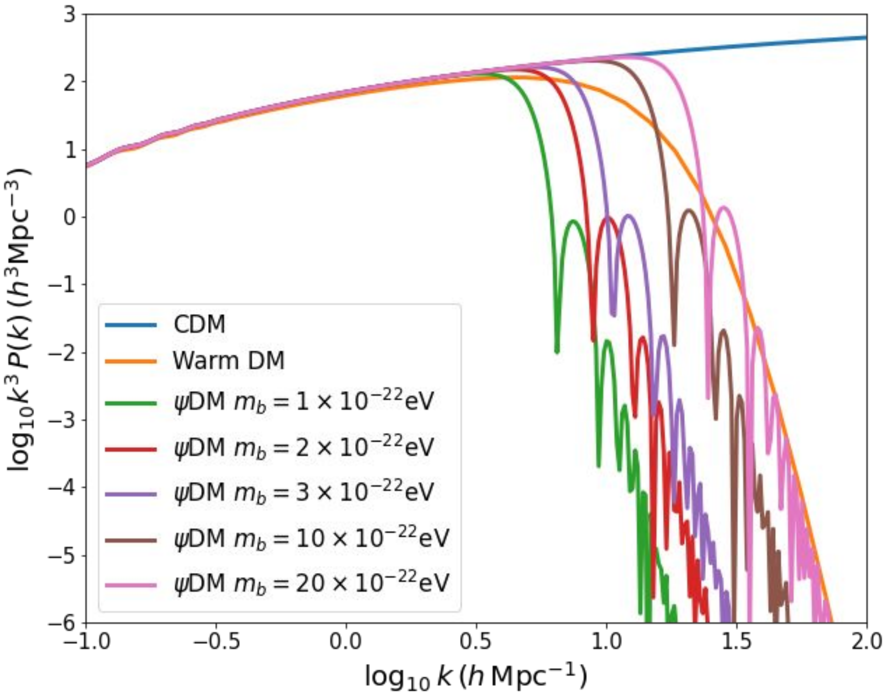

F444W
log counts / dM / area [deg^{-2}]
observer frame APPARENT magnitude
z = 0.27



z=0.61
log halo mass $[M_\odot/h]$
log total SFR $[M_\odot\ yr^{-1}]$
B/T
log stellar mass $[M_\odot/h]$
F444W
log counts / dM / area $[deg^{-2}]$
observer frame APPARENT magnitude
z = 0.61



F200W (AB<30.3)
ΛCDM
Wave DM $m_b = 1 \times 10^{-22}$ eV
Wave DM $m_b = 2 \times 10^{-22}$ eV
Wave DM $m_b = 3 \times 10^{-22}$ eV
log dN/dz(>z) per arcmin^2 (z<14)
redshift



CDM
Warm DM
ψDM $m_b = 1 \times 10^{-22}$eV
ψDM $m_b = 2 \times 10^{-22}$eV
ψDM $m_b = 3 \times 10^{-22}$eV
ψDM $m_b = 10 \times 10^{-22}$eV
ψDM $m_b = 20 \times 10^{-22}$eV
$\log_{10} k^3 P(k)\ (h^3 \mathrm{Mpc}^{-3})$
$\log_{10} k\ (h\,\mathrm{Mpc}^{-1})$

Conclusions

- I have created a **mock catalogue** for JWST using semi-analytic models of galaxy formations
- I have investigated different **variation of the model** for:
  - Standard particle CDM
  - Wave DM (for different particle masses)
- I have studied the **redshift distributions**:
  - Trying to make prediction for the high redshift tail
- I have **tested my models** to make sure they make sense (this is still work in progress and the biggest task)