Using Galaxy Formation Models to Unveil the Nature of Dark Matter in the JWST era

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16/01/2024
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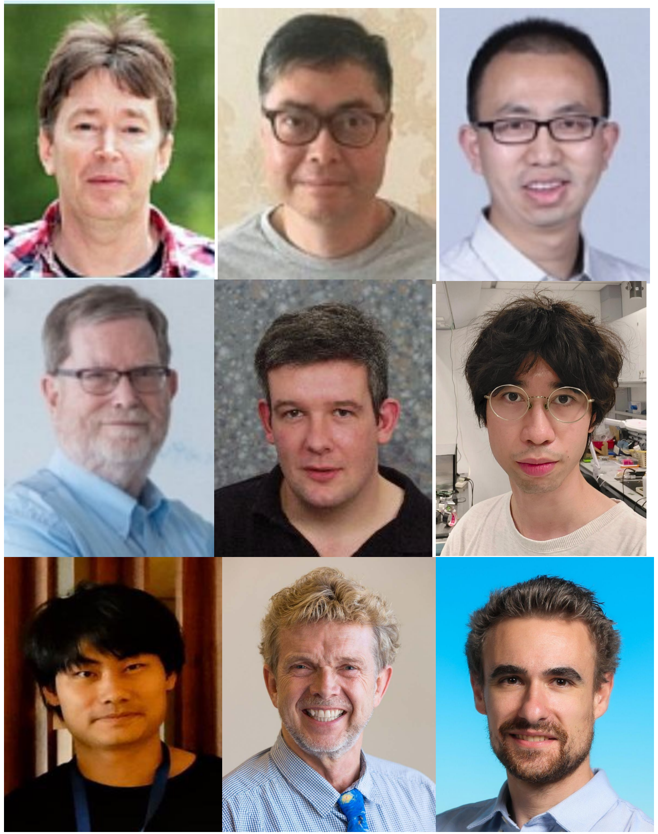
A miscellaneous TEAM

- Giorgio Manzoni (IAS)
- Tao Liu (IAS),
- George Smoot (IAS)
- Tom Broadhurst (Ikerbasque),
- Jeremy Lim (HKU),
- Carlton Baugh (Durham),
- Leo Fung (IAS),
- Josh Zhang (HKU)

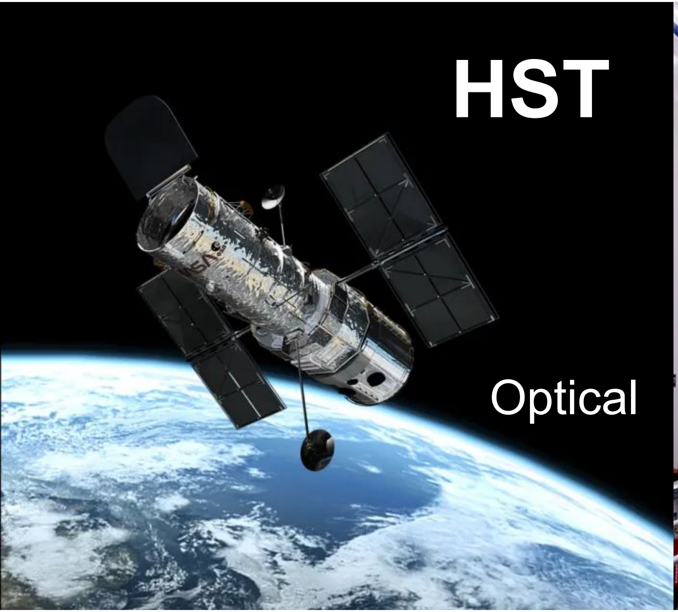


And the **PEARLS team**

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**

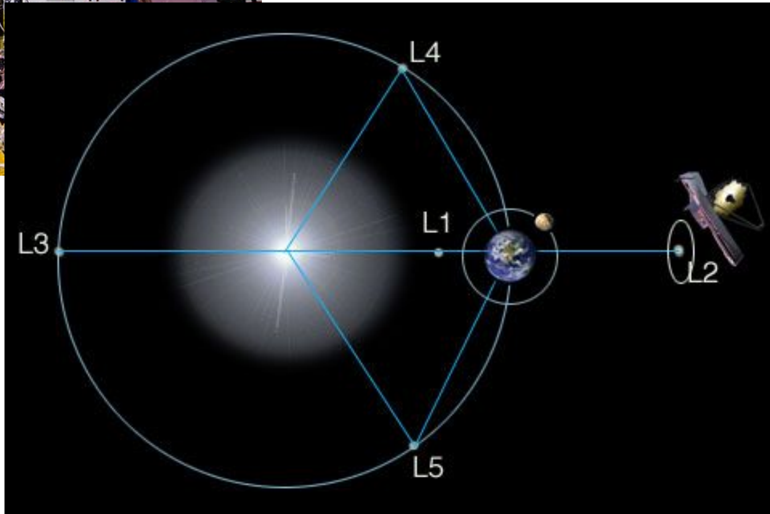
The James Webb Space Telescope vs the Hubble Space Telescope



- Launched on Christmas 2021 started to release scientific images on July 2022

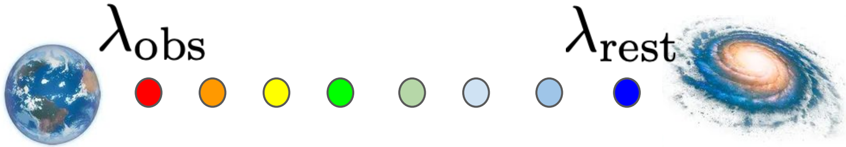
- Sent in L2 (darkest lagrangian point)

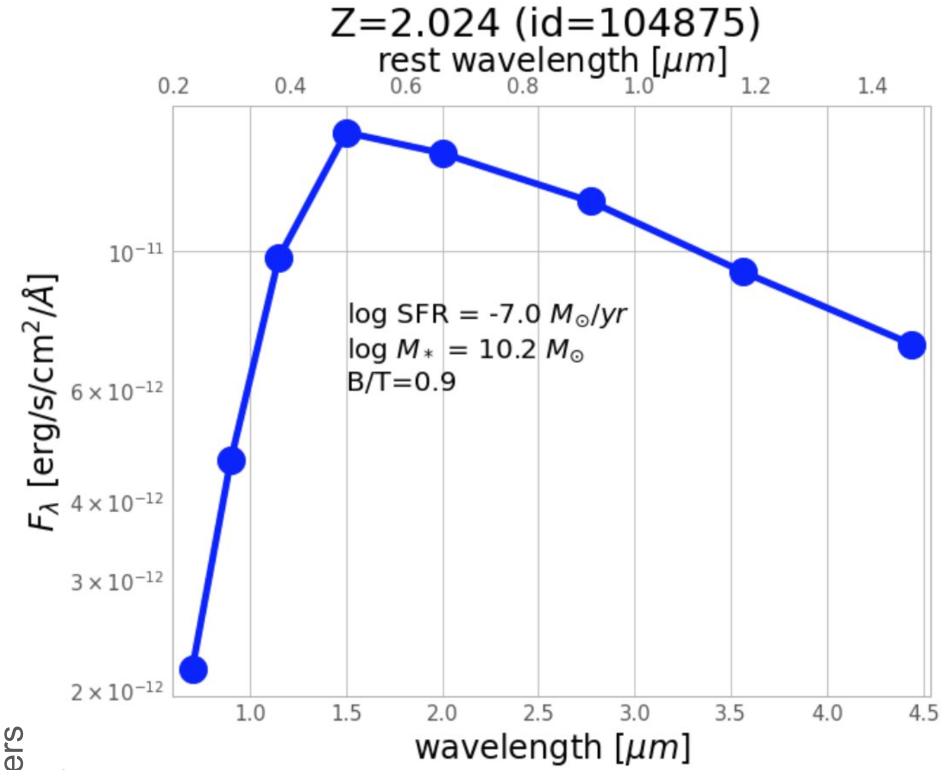
- 18 hexagonal segments, each ~1.4 m in diameter, they act as if it was a 6.5m single mirror diameter (HST is 2.4m single mirror)

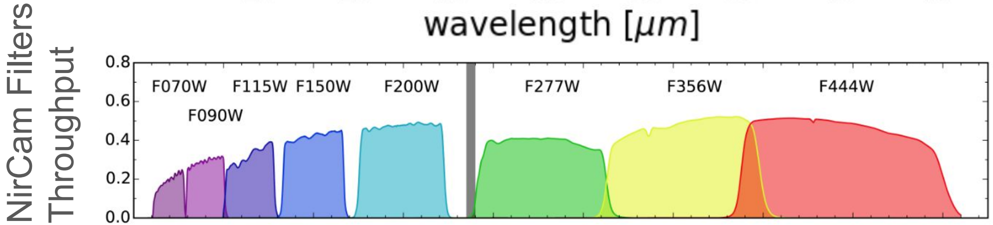


It observes Infrared to get the optical rest frame

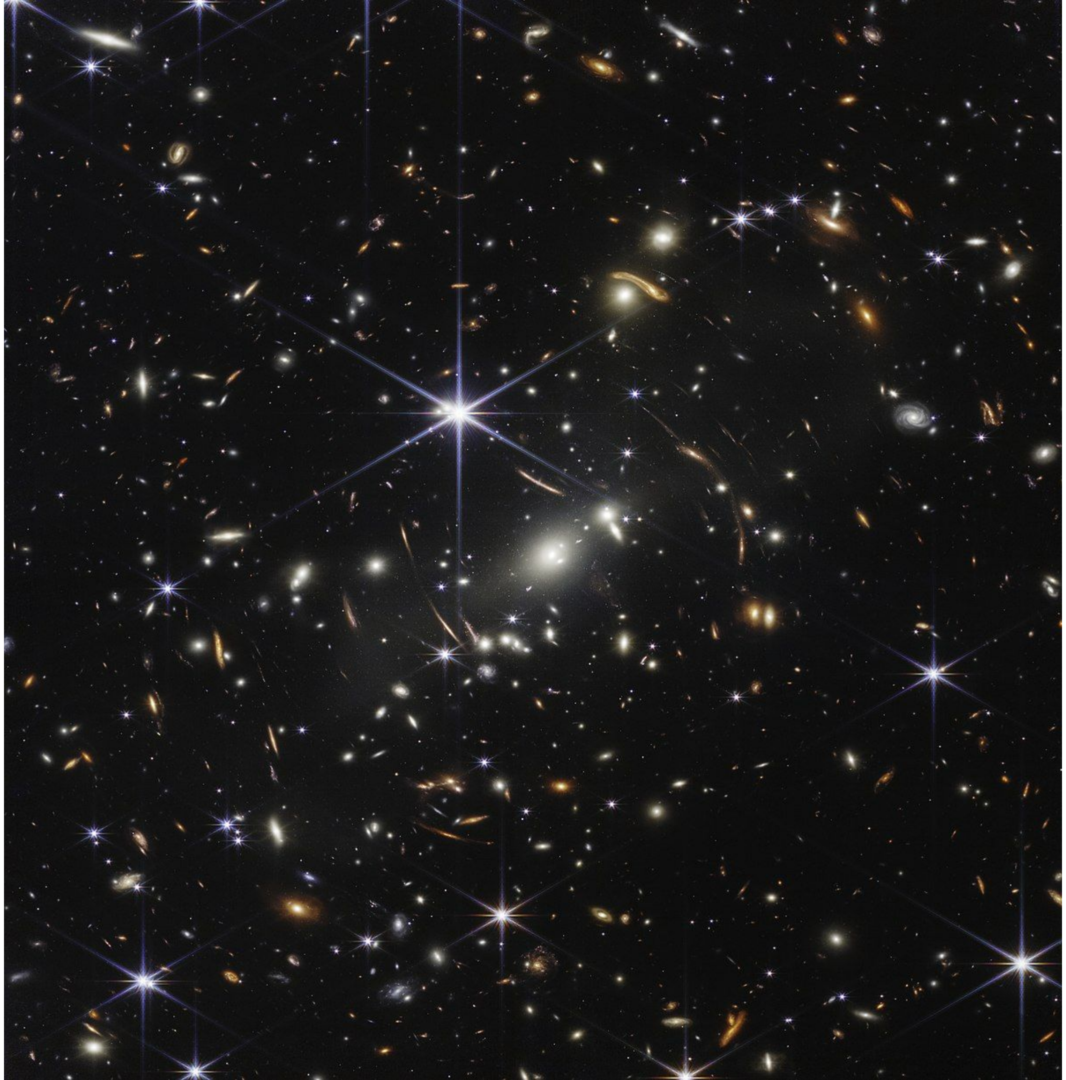
$$\lambda_{\text{rest}} = \frac{\lambda_{\text{obs}}}{1+z}$$







SMACS 0723
z~0.39



First image released on 11th July 2022

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

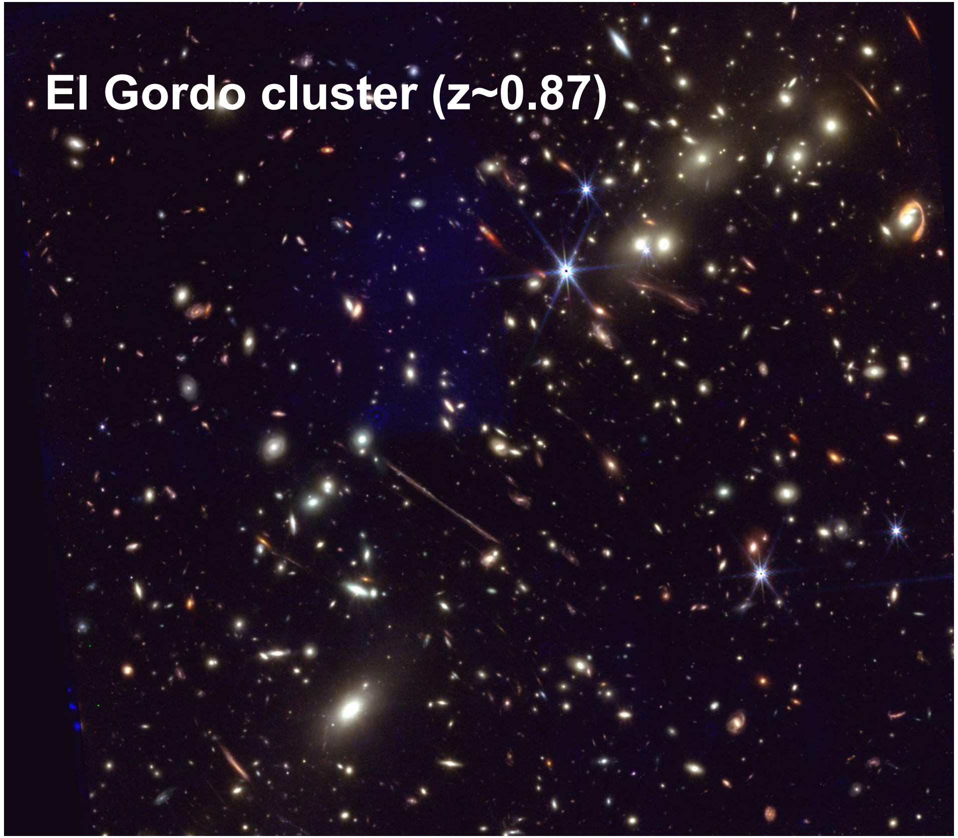
We need a **parallel field**

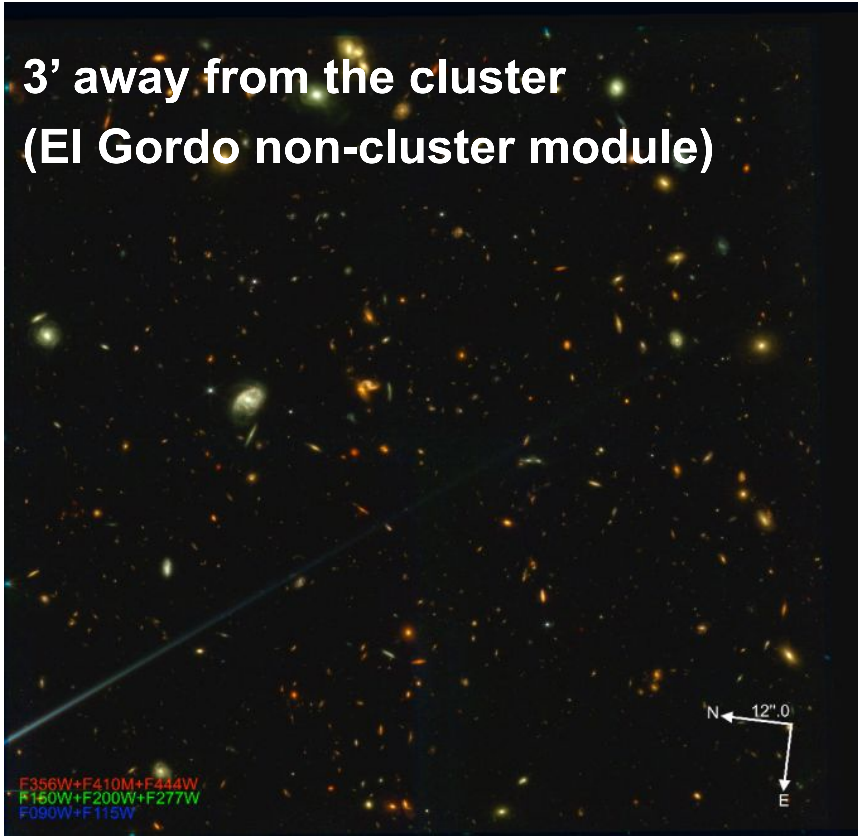
The first PEARLS overview paper

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

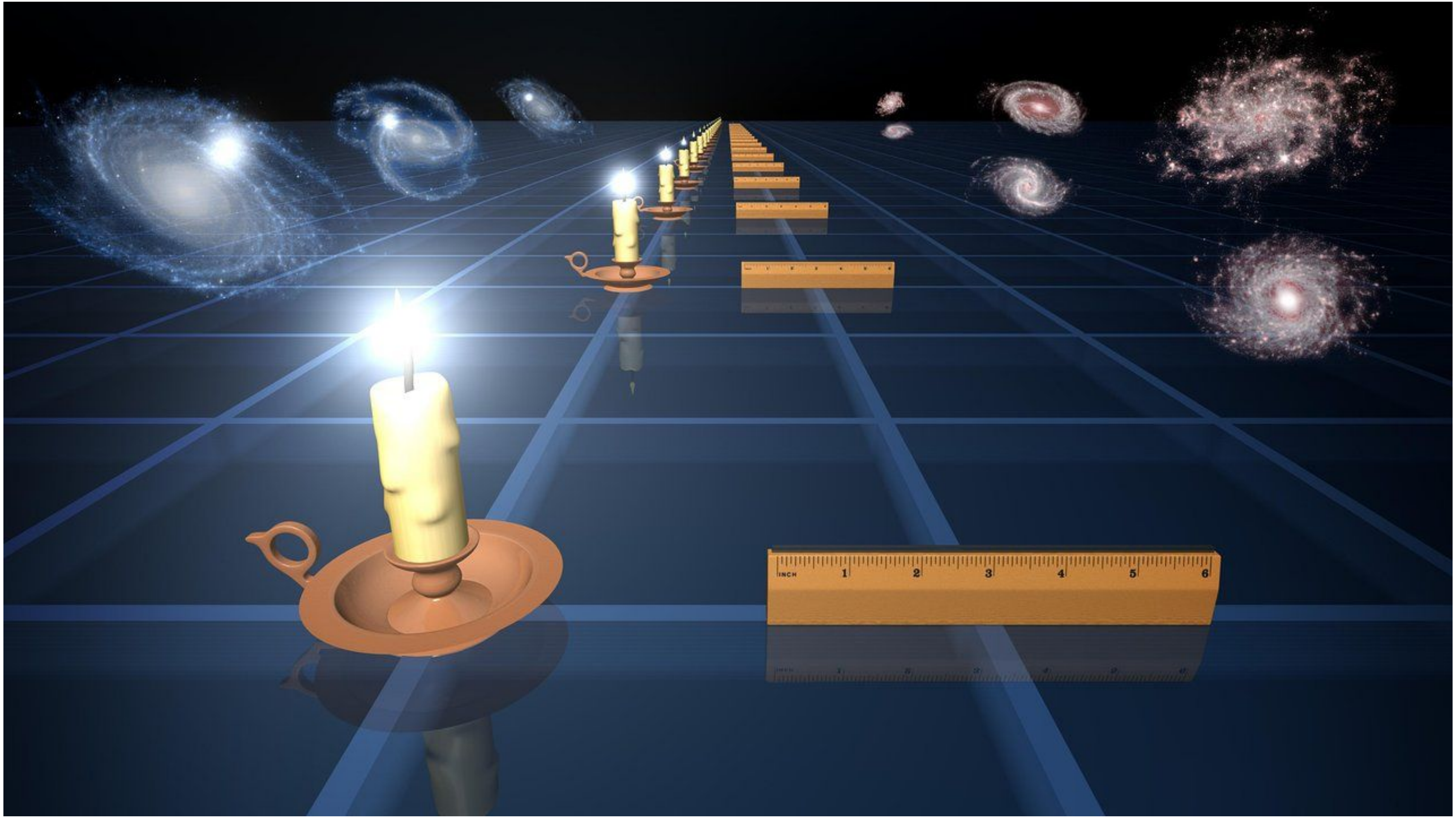
Rogier A. Windhorst,[1] Seth H. Cohen,[1] Rolf A. Jansen,[1] Jake Summers,[1] Scott Tompkins,[1] Christopher J. Conselice,[2] Simon P. Driver,[3] Haojing Yan,[4] Dan Coe,[5] Brenda Frye,[6] Norman Grogin,[7] Anton Koekemoer,[7] Madeline A. Marshall,[8,9] Rosalia O'Brien,[1] Nor Pirzkal,[7] Aaron Robotham,[3] 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

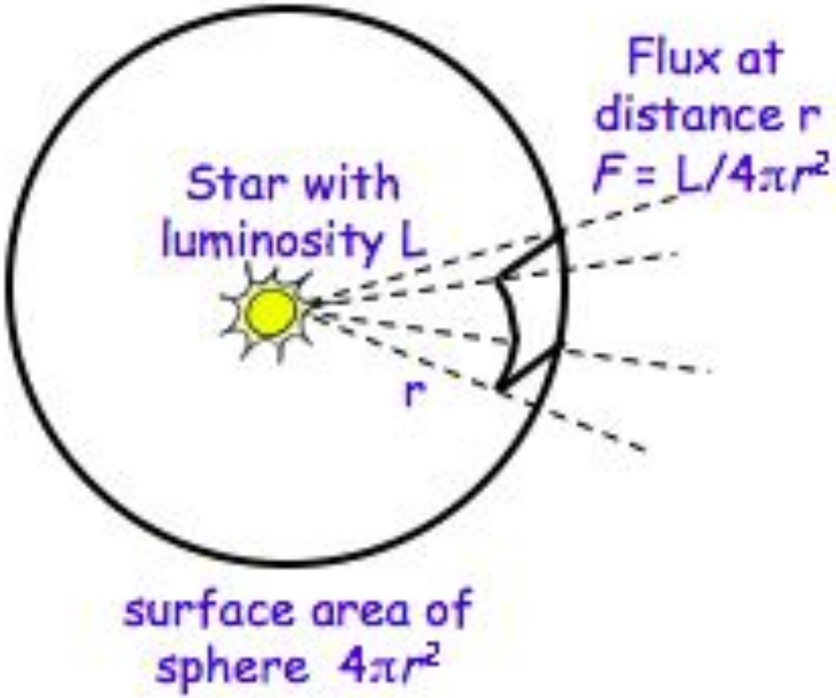




GALAXIES ARE NOT STANDARD CANDLES



Intrinsic vs observed properties



FLUX = OBSERVED

$$m - m_{\mathrm{ref}} = -2.5\log_{10}\left(\frac{F}{F_{\mathrm{ref}}}\right)$$

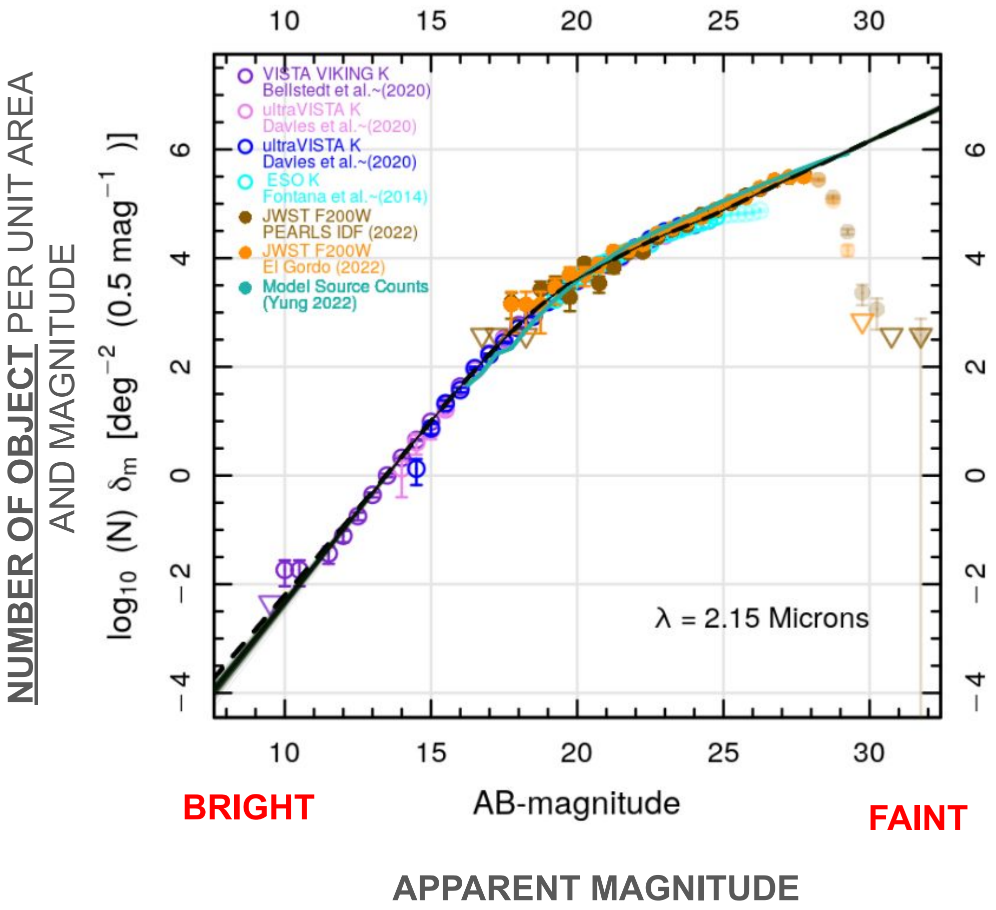
(apparent magnitude)

LUMINOSITY = INTRINSIC

$$M - M_{\mathrm{ref}} = -2.5\log_{10}\left(\frac{L}{L_{\mathrm{ref}}}\right)$$

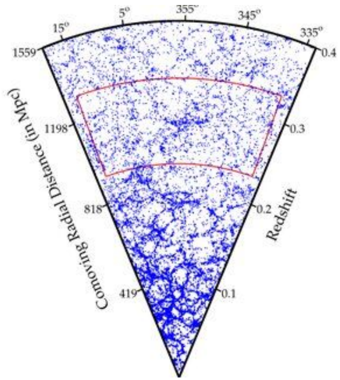
(ABSOLUTE magnitude)

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



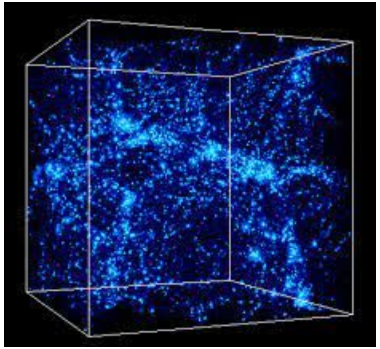
NUMBER COUNTS AND LUMINOSITY FUNCTION

NUMBER / AREA



APPARENT MAGNITUDE

NUMBER / VOLUME



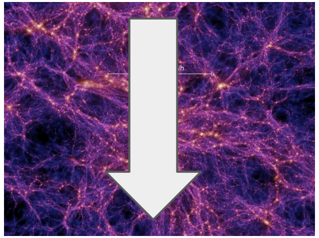
ABSOLUTE MAGNITUDE

OBSERVATION

SIMULATION

GALAXY FORMATION IS A **2 STEP** PROCESS

Structures form in
DARK MATTER
BY
HIERARCHICAL CLUSTERING



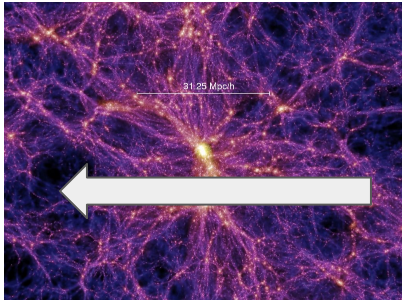
DM ONLY - N-Body
simulations
quite well understood

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

The evolution of baryons involve many physical processes not well understood

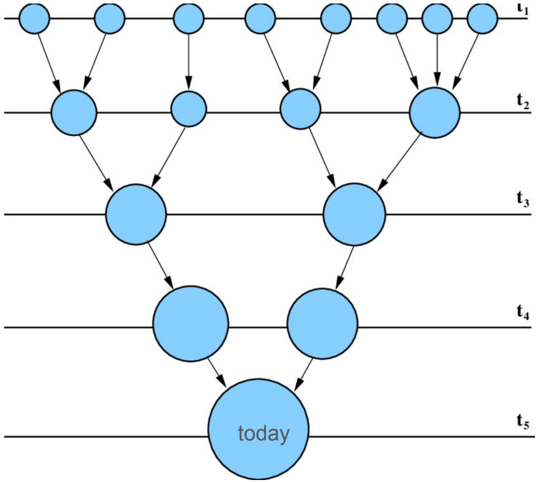
DARK MATTER COMPONENT

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

My a semi-analytic model: GALFORM

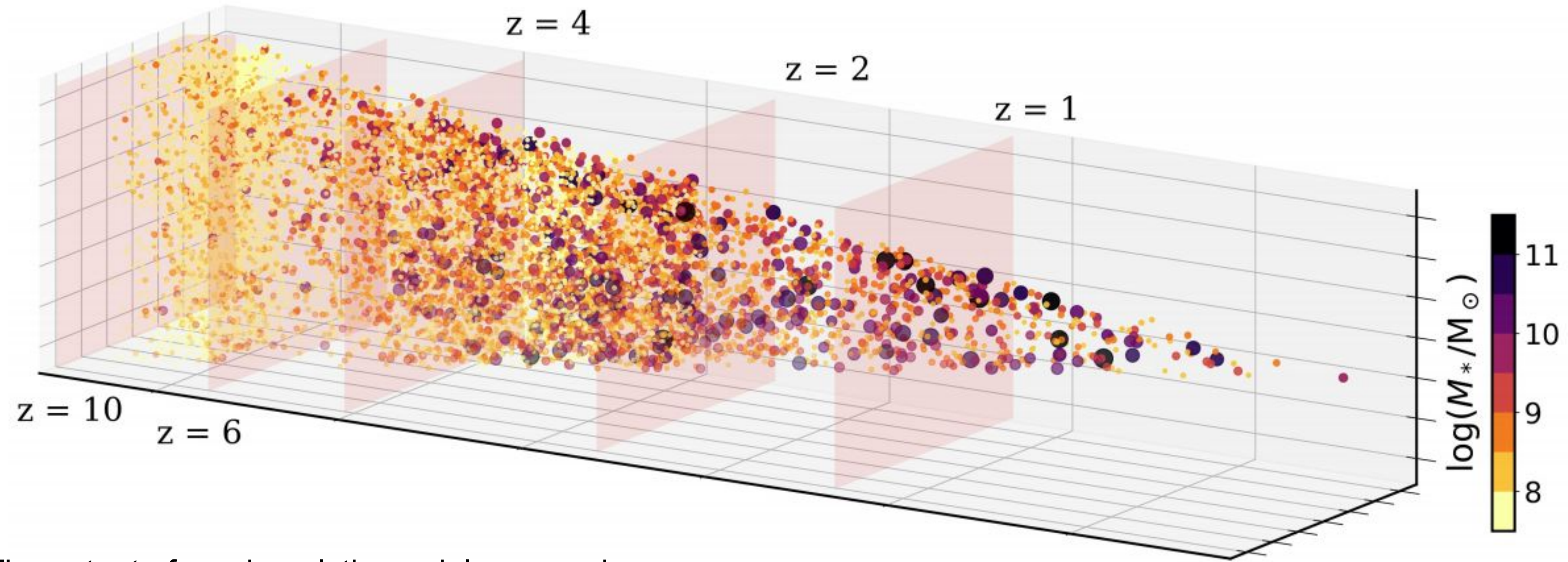
The main processes modelled in GALFORM are:

- **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

Creation of a lightcone

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

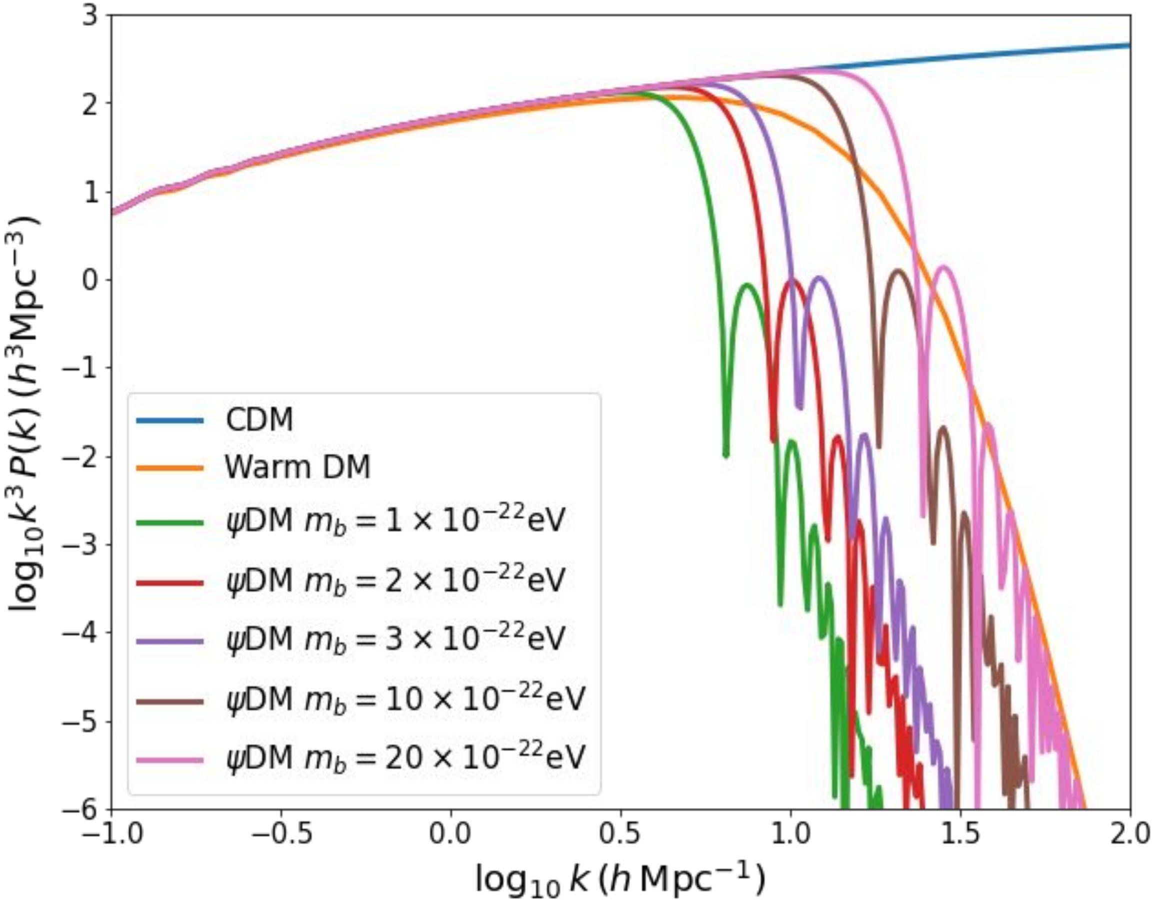


The output of semi-analytic models comes in **snapshots** but it can be interpolated into a lightcone.

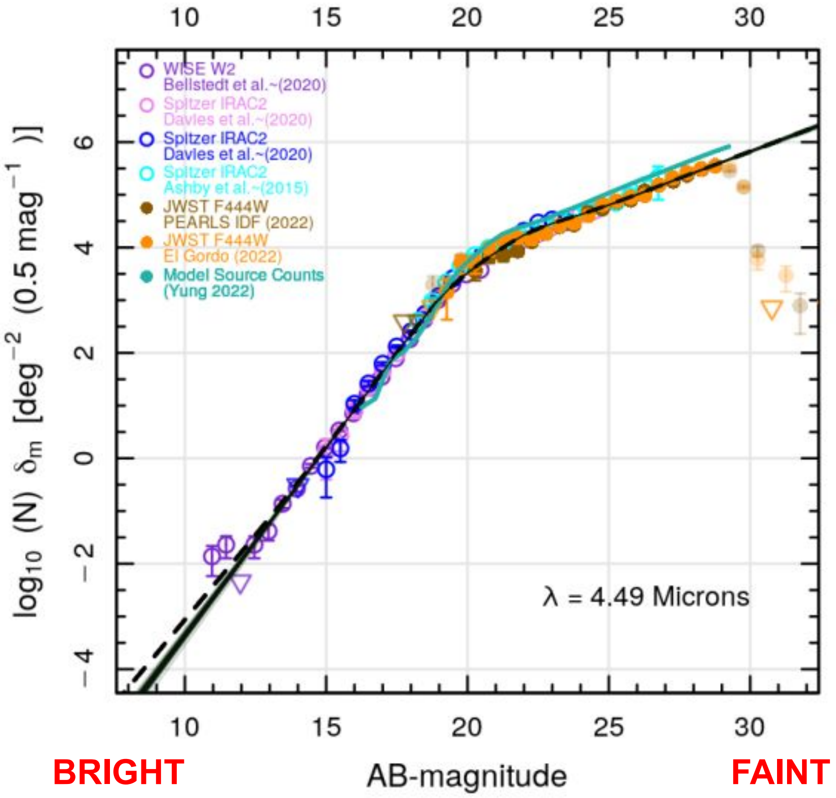
You need galaxy positions from N-body simulation.

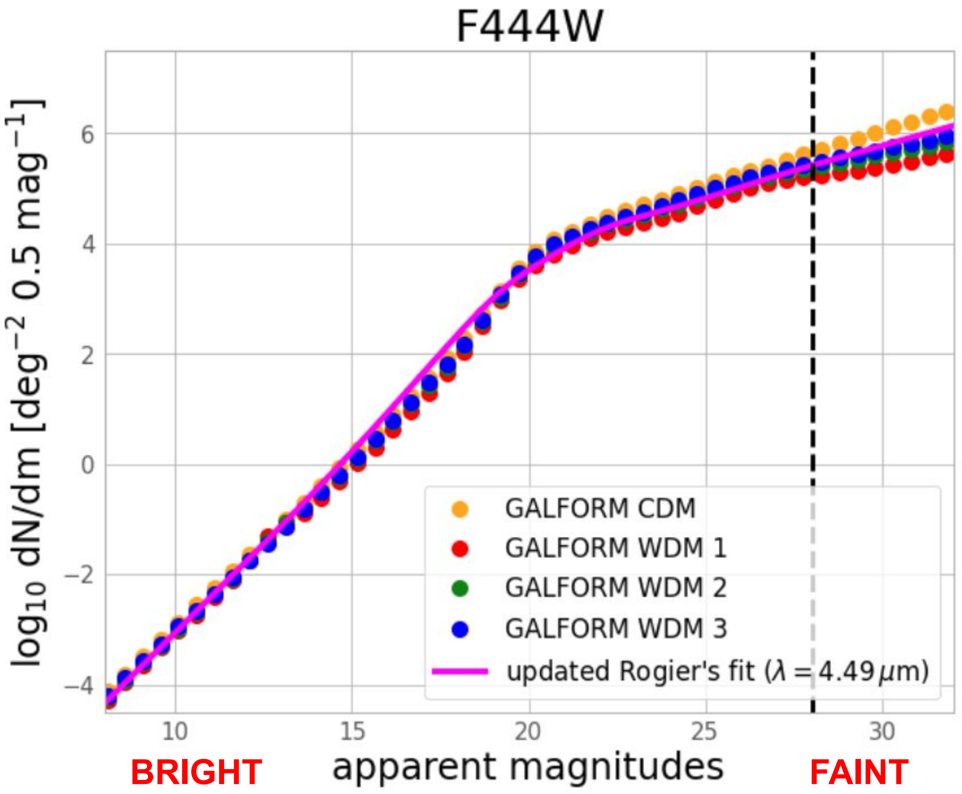
Yung et al. 2022

Power spectrum for different Dark Matter models



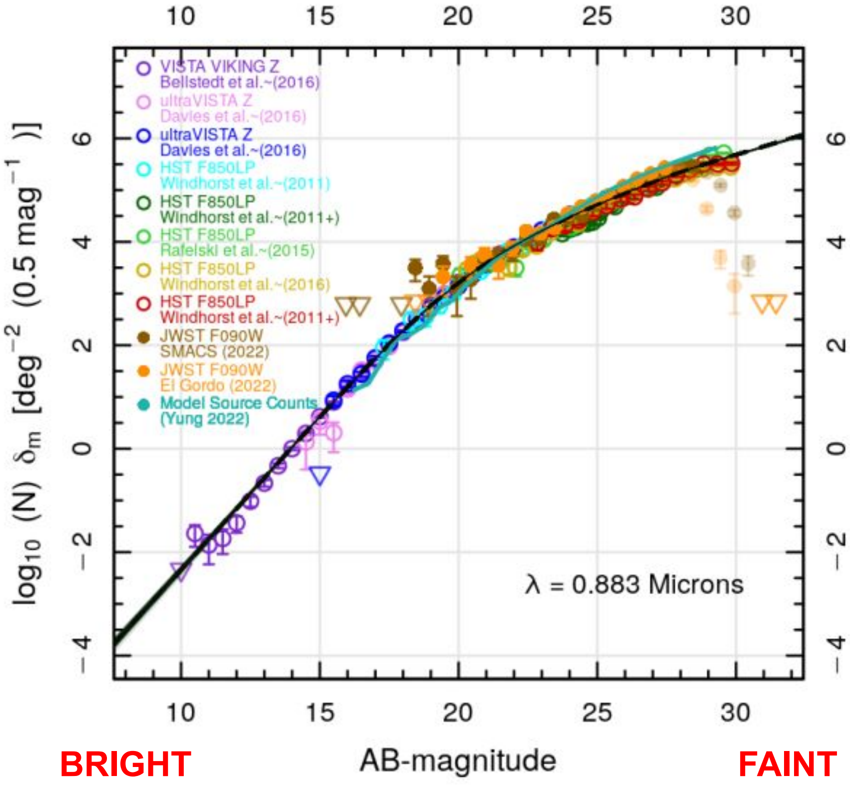
JWST OBSERVATIONS **GALFORM PREDICTIONS**





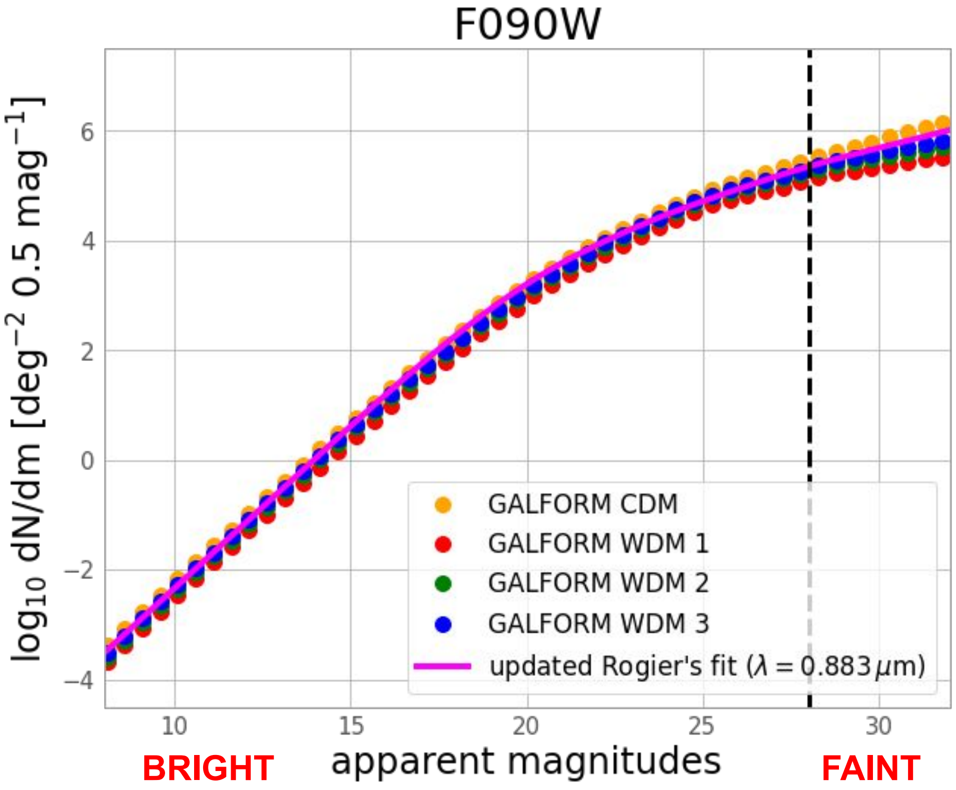
Windhorst et al. 2023 **Manzoni et al. in prep.**

JWST OBSERVATIONS



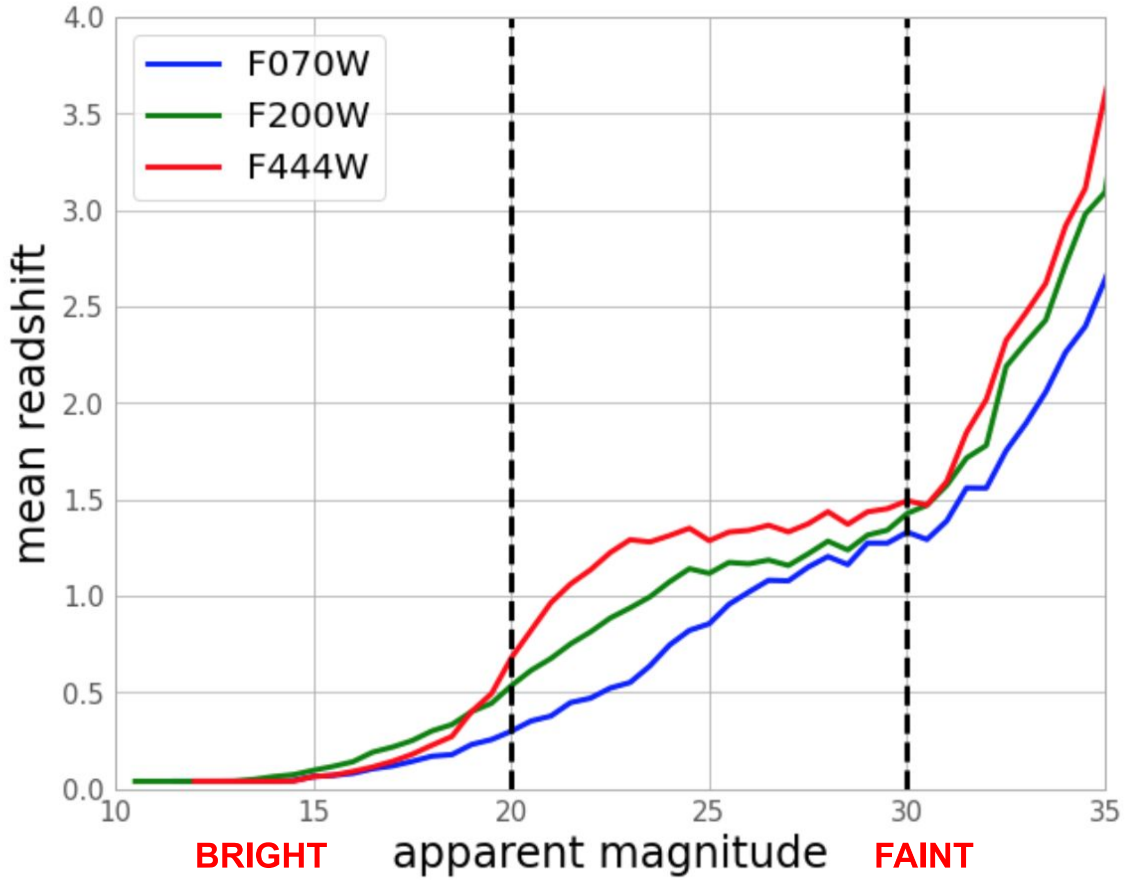
Windhorst et al. 2023

GALFORM PREDICTIONS

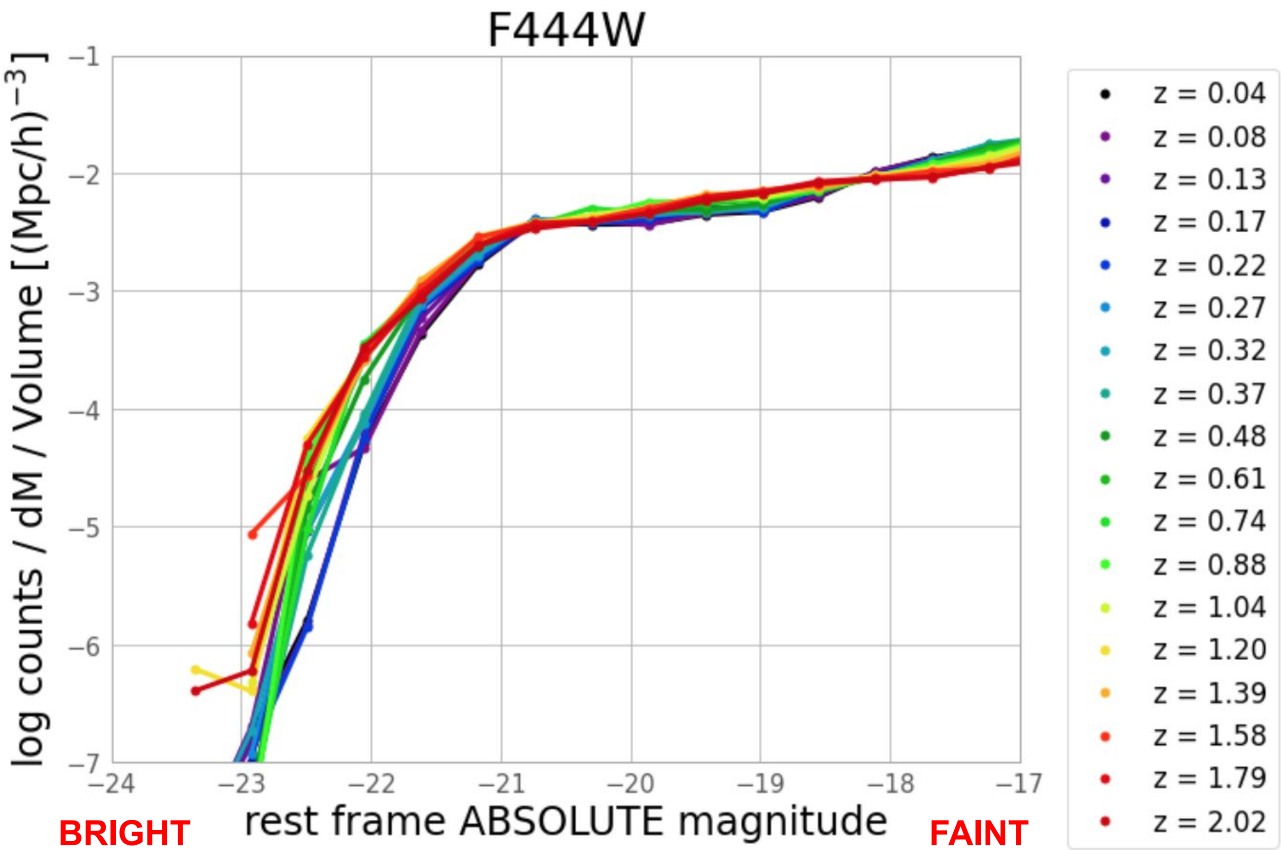


Manzoni et al. in prep.

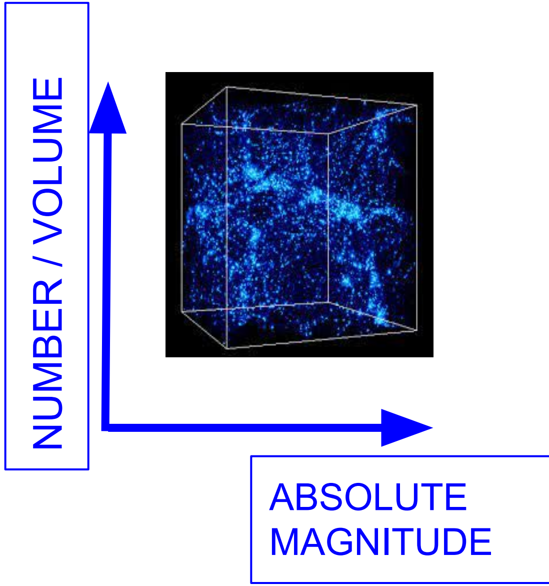
Which redshifts are really dominating?



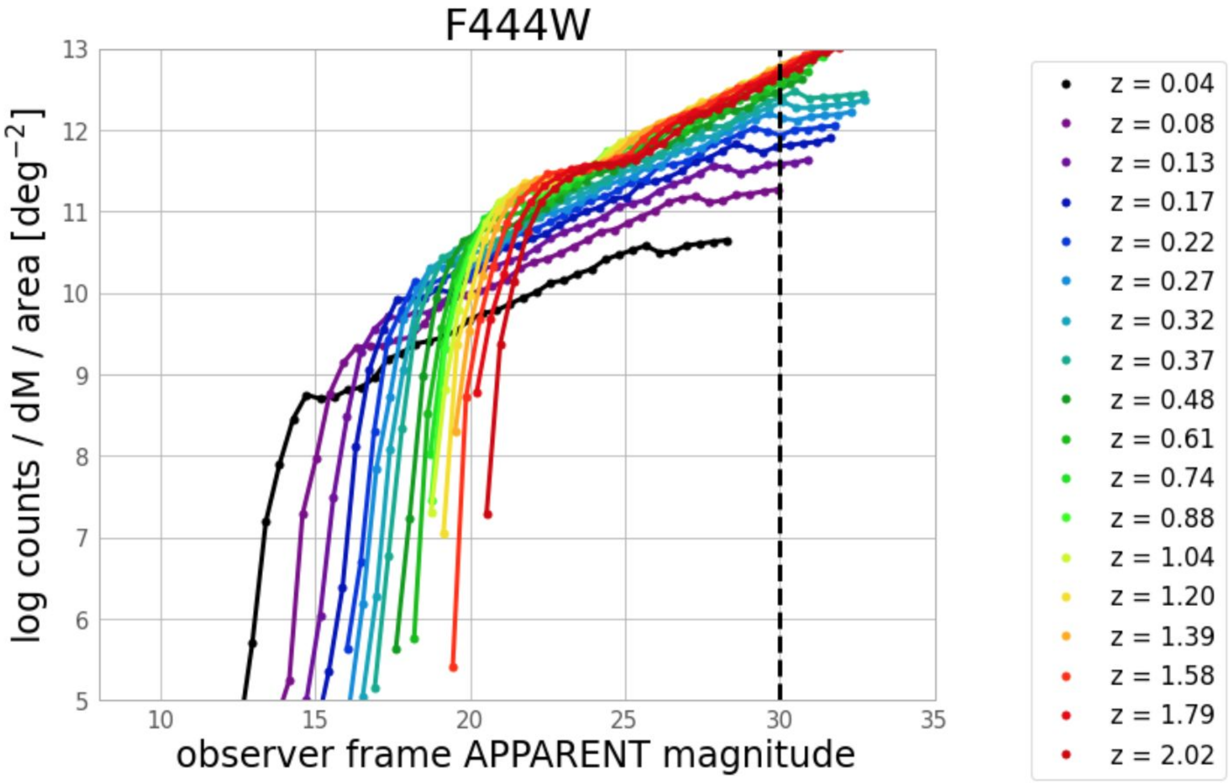
STANDARD LUMINOSITY FUNCTION

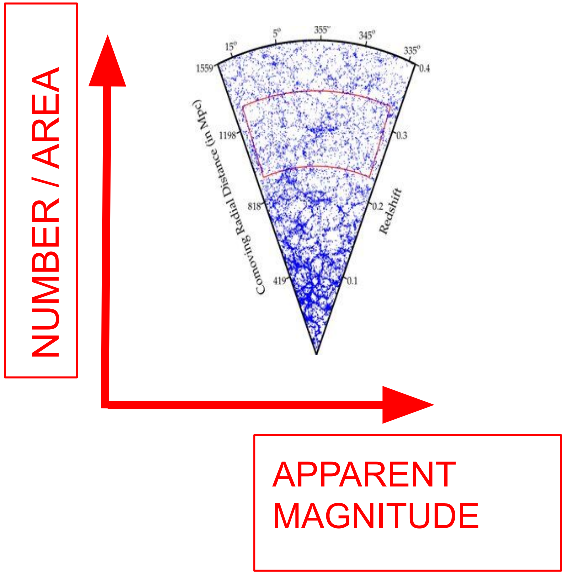


BRIGHT FAINT

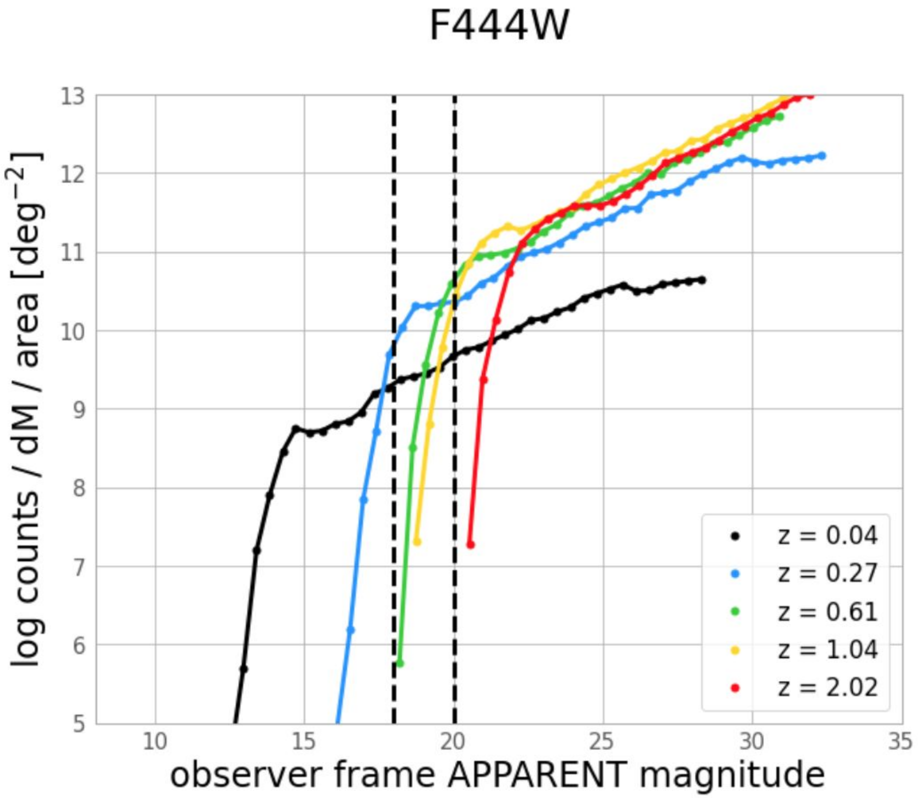


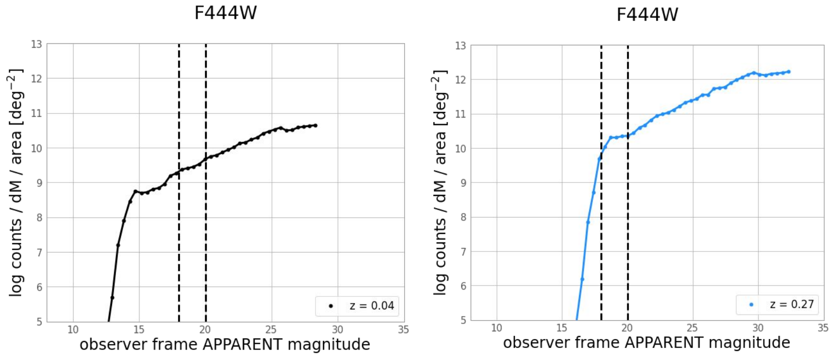
MODIFIED LUMINOSITY FUNCTION

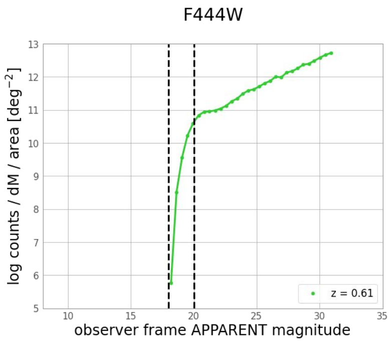


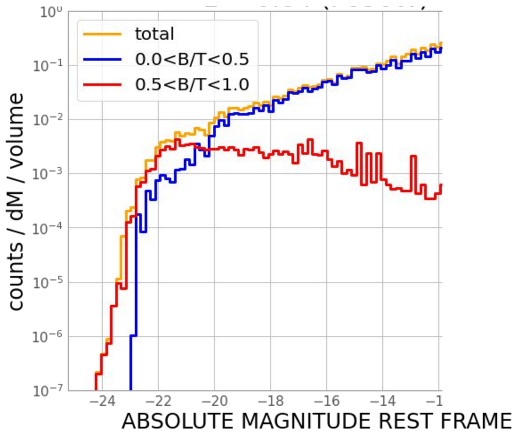


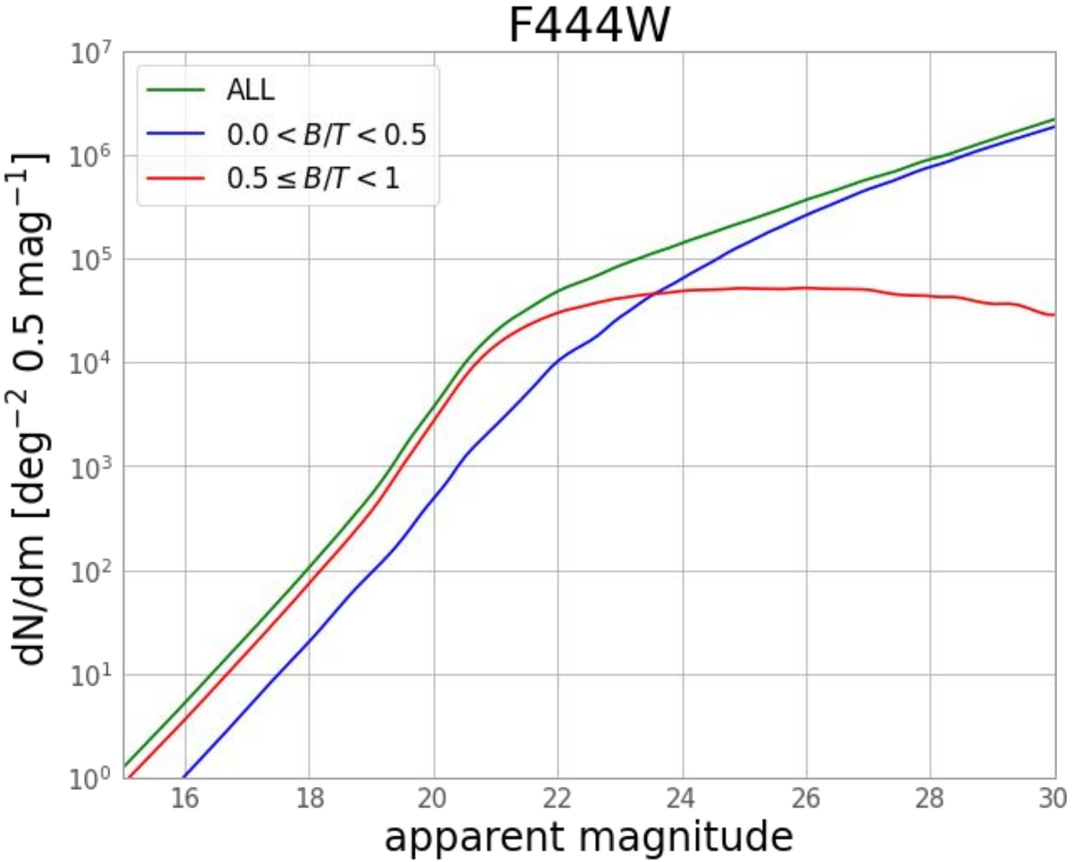
We are looking at different part of the luminosity function



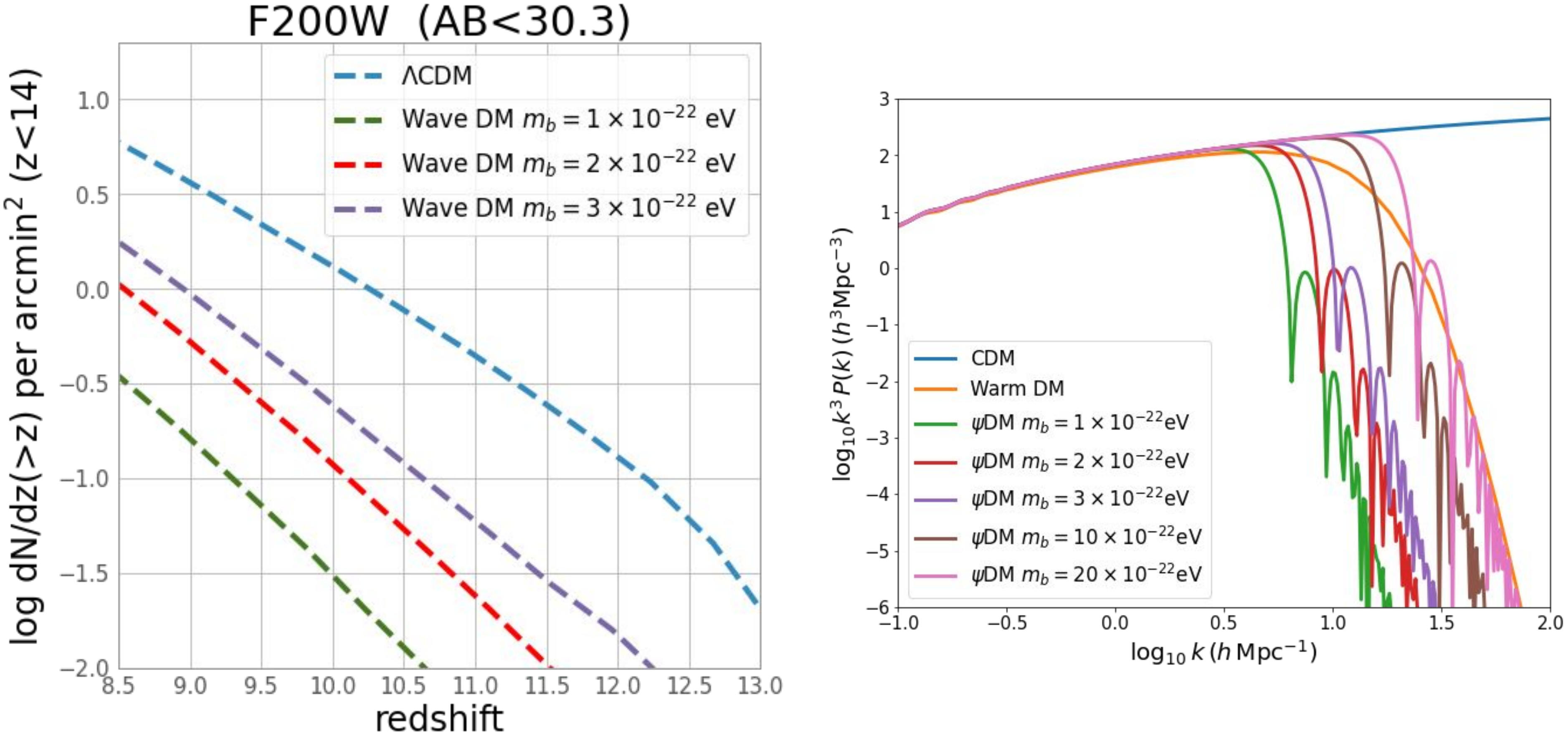








$$d^2N/dln(S_\nu)/dz = dn/dln(L_\nu) \times dV/dz$$



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)

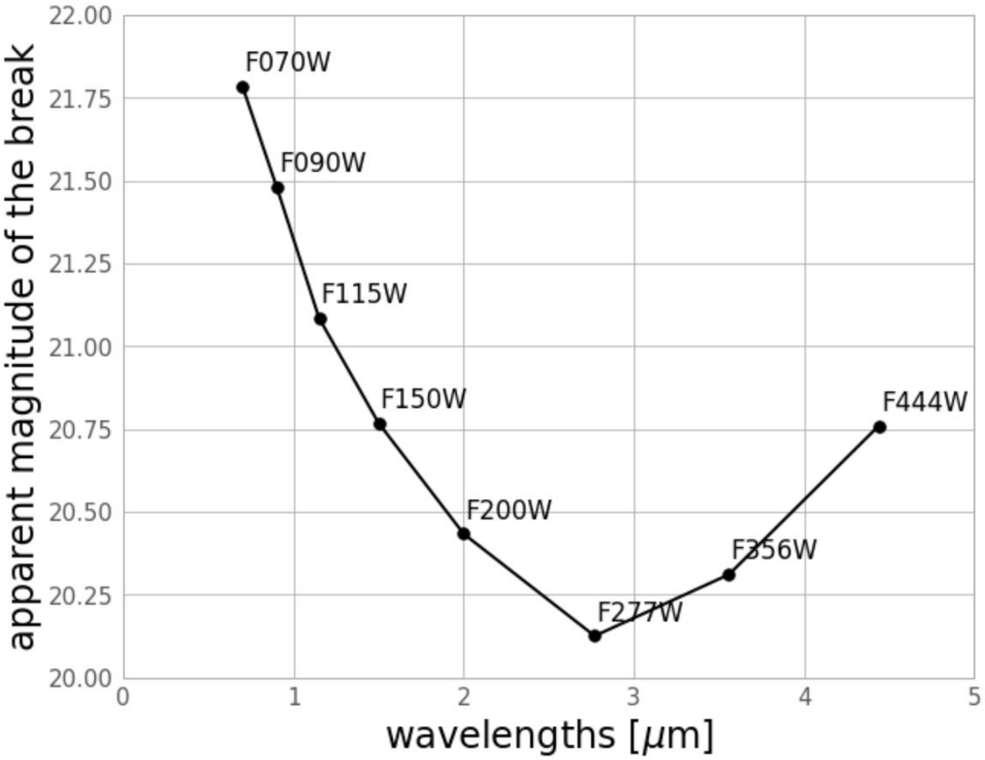
- I **split the analysis** of the number counts into simulated **luminosity functions**

- I have **explained the change in slope** of the number counts
  - Due to a change in population rather than a different DM scenario

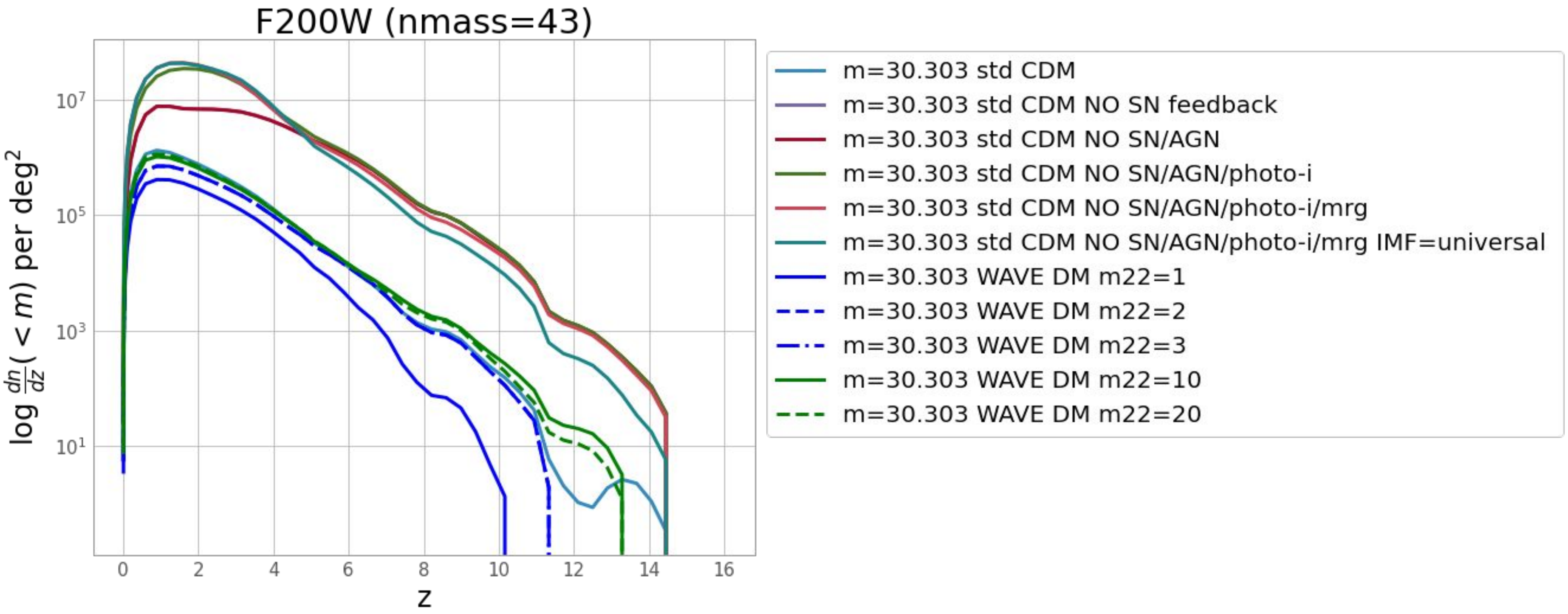
- I have studied the **redshift distributions**:
  - Trying to make prediction for the high redshift tail

Additional slides for discussion

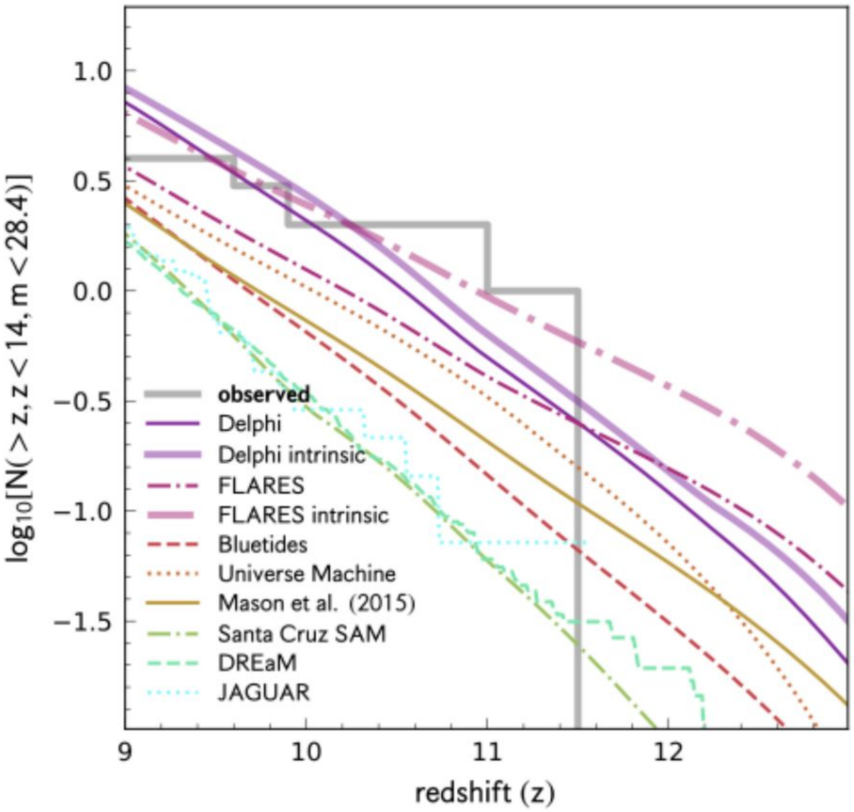
Location of the break

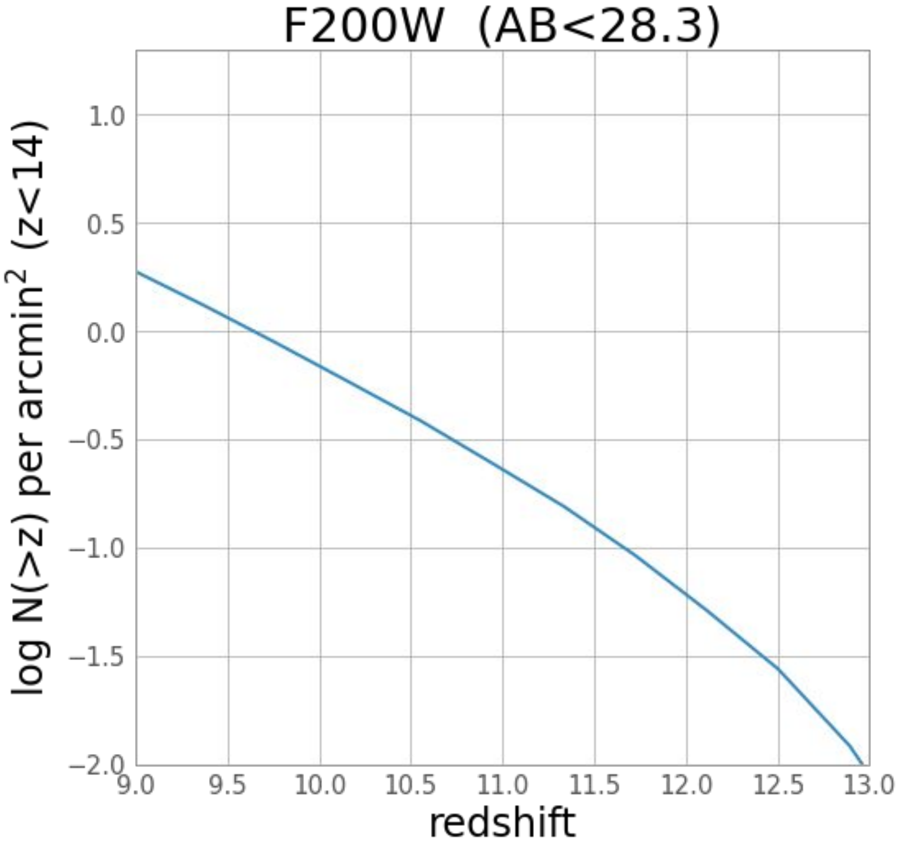


REDSHIFT DISTRIBUTION (CDM / NO FEEDBACK / Wave DM)



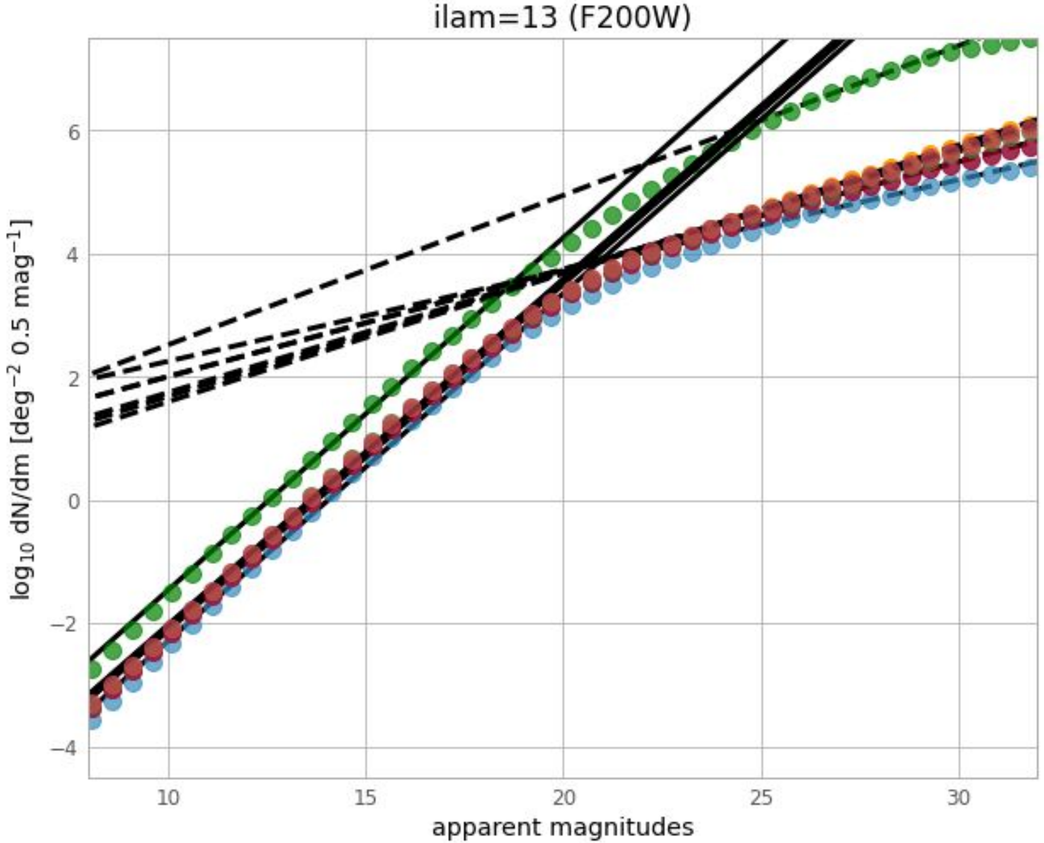
Nathan Adams et al. 2022

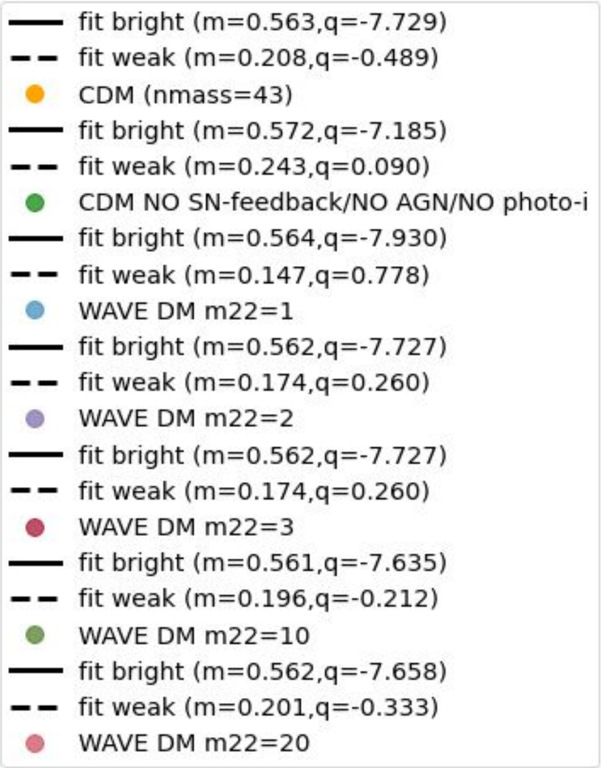




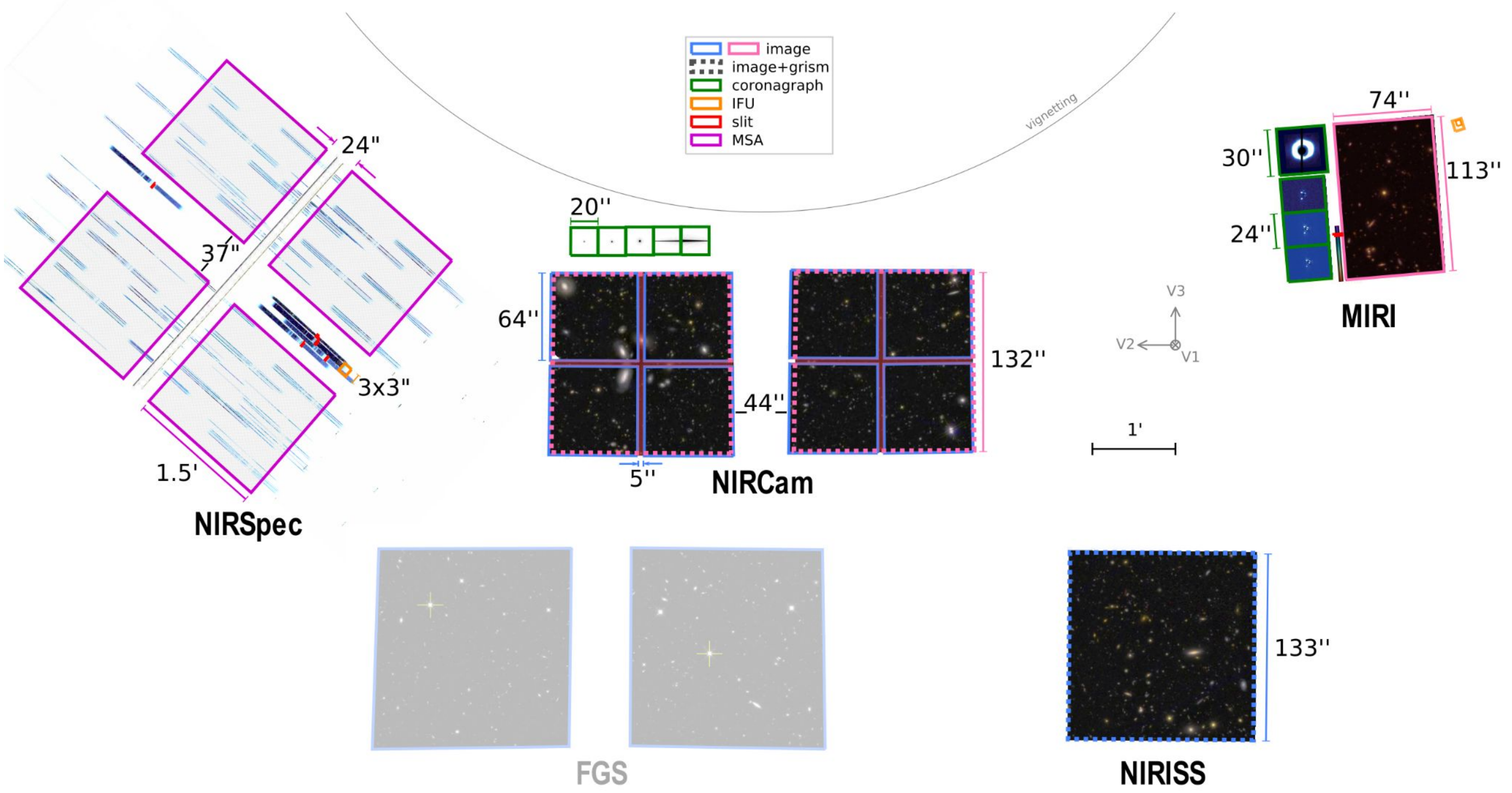
https://arxiv.org/pdf/2207.11217.pdf

Variations of the model (different DM model and feedback)

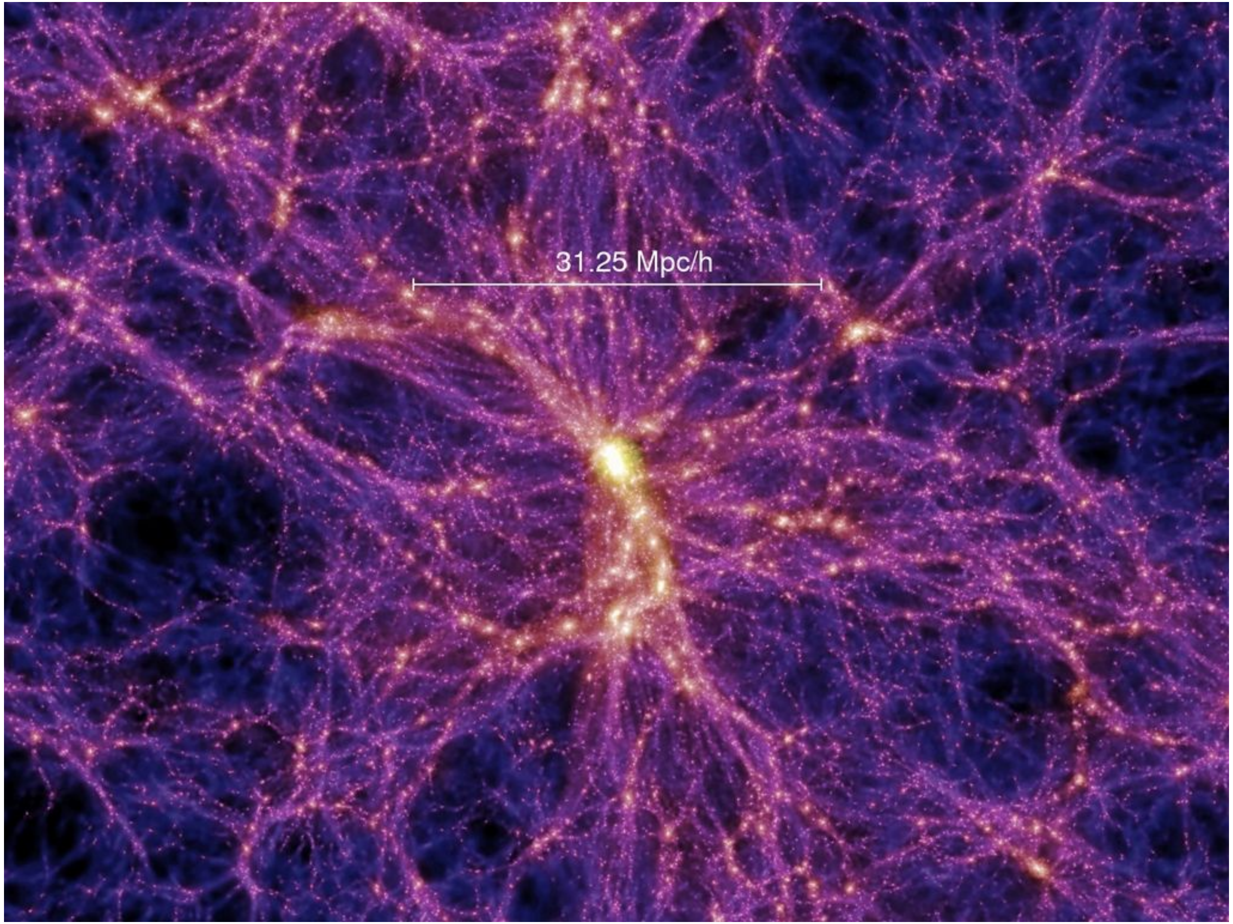




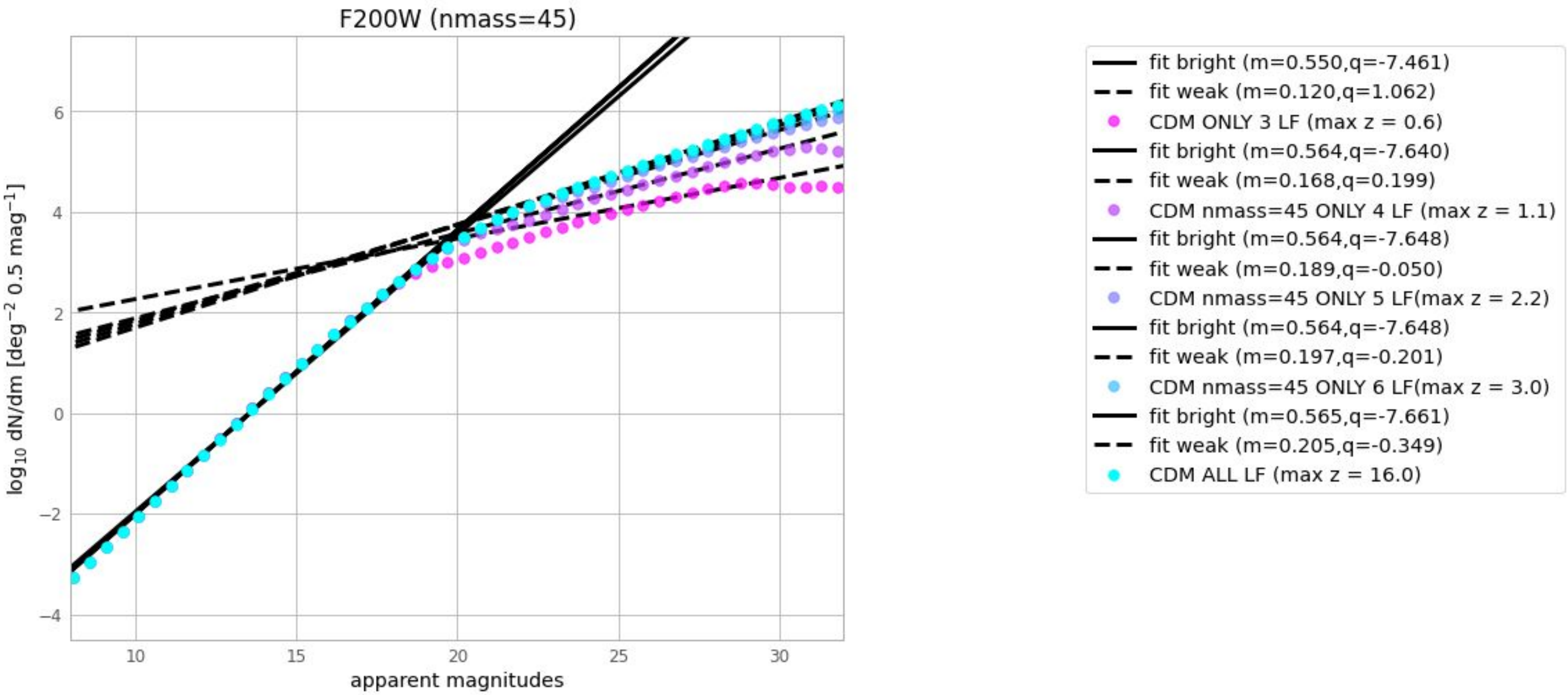
The JWST field of view

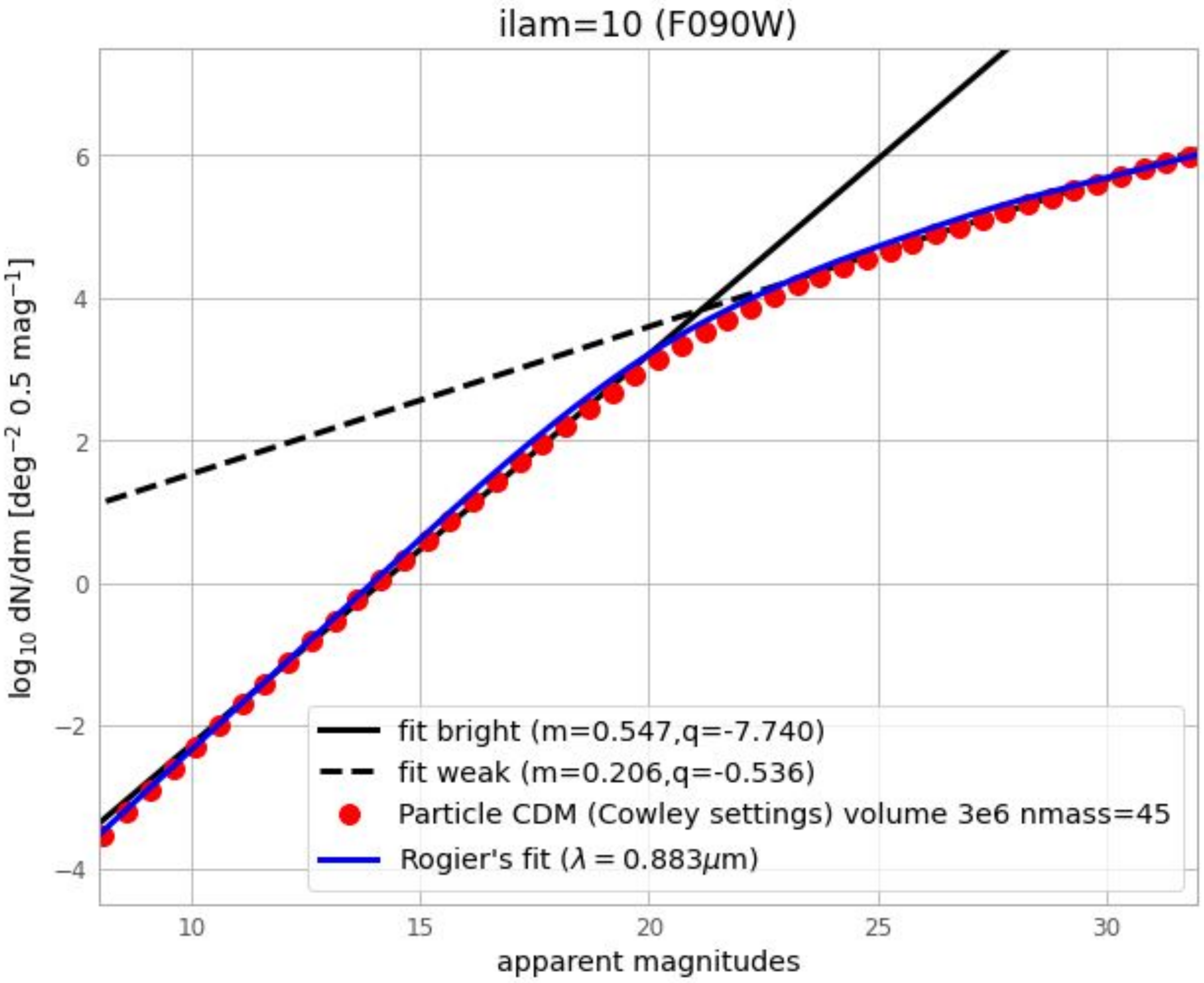


N-Body simulation (Millennium)

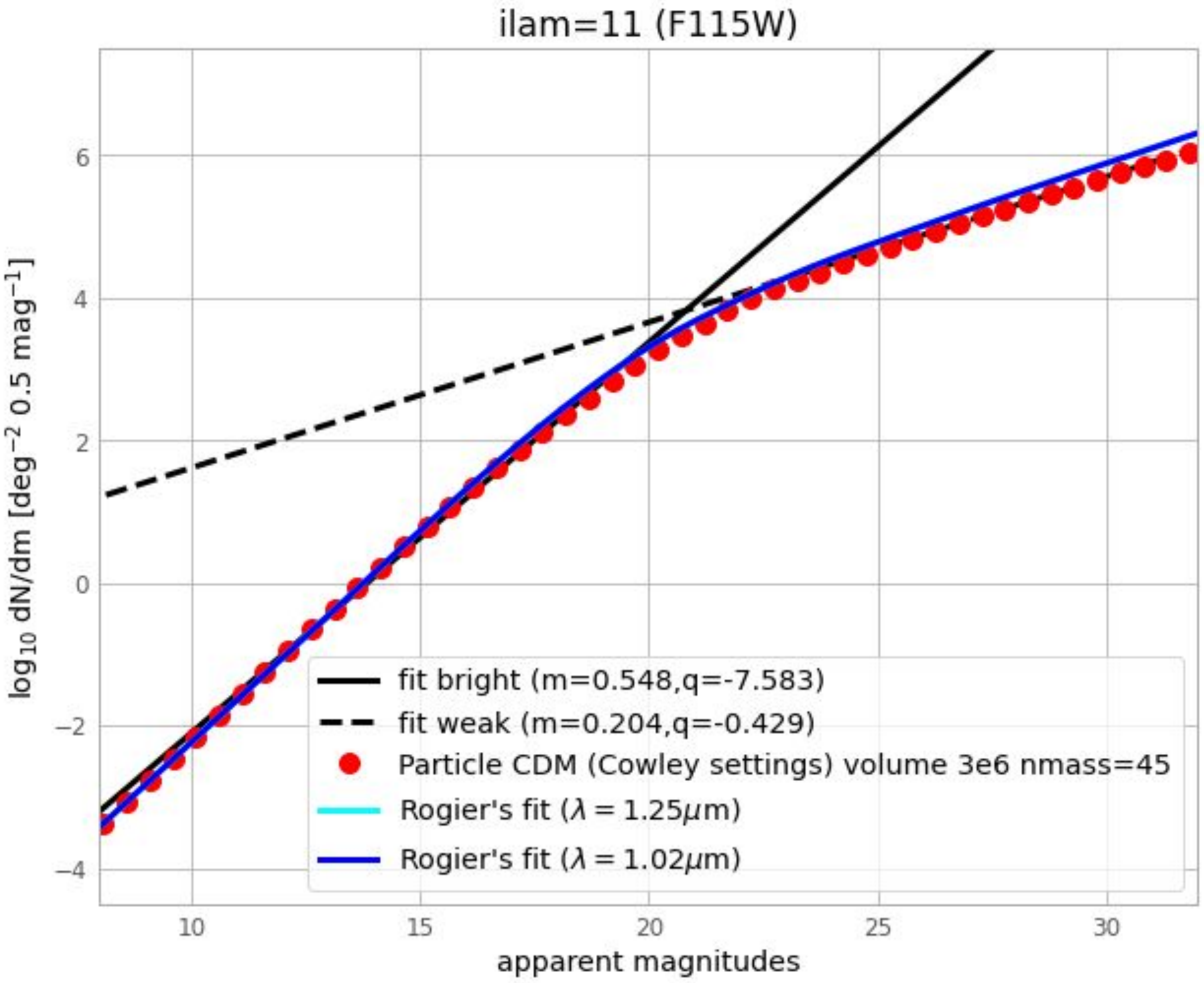


Using only low redshift luminosity functions

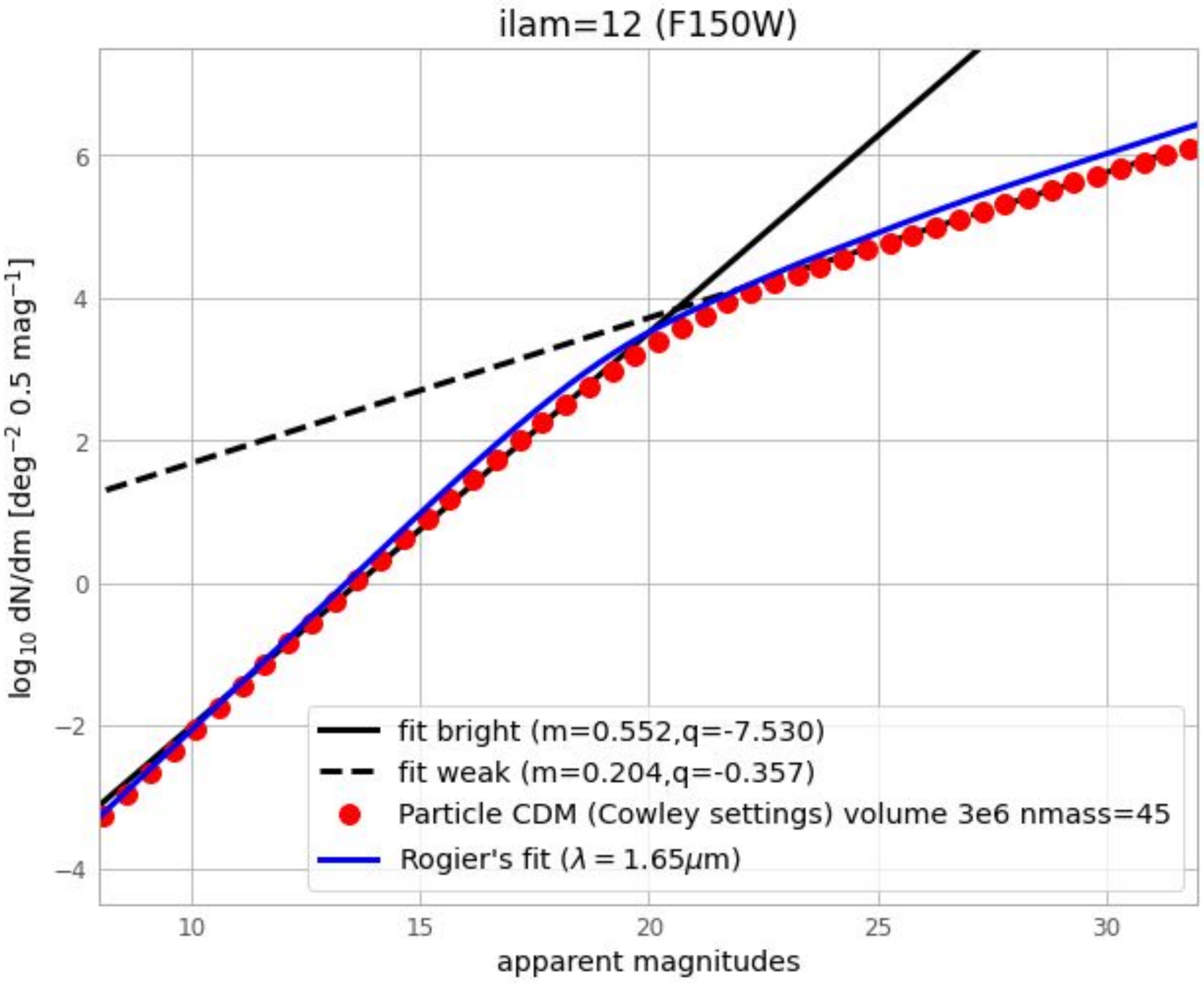




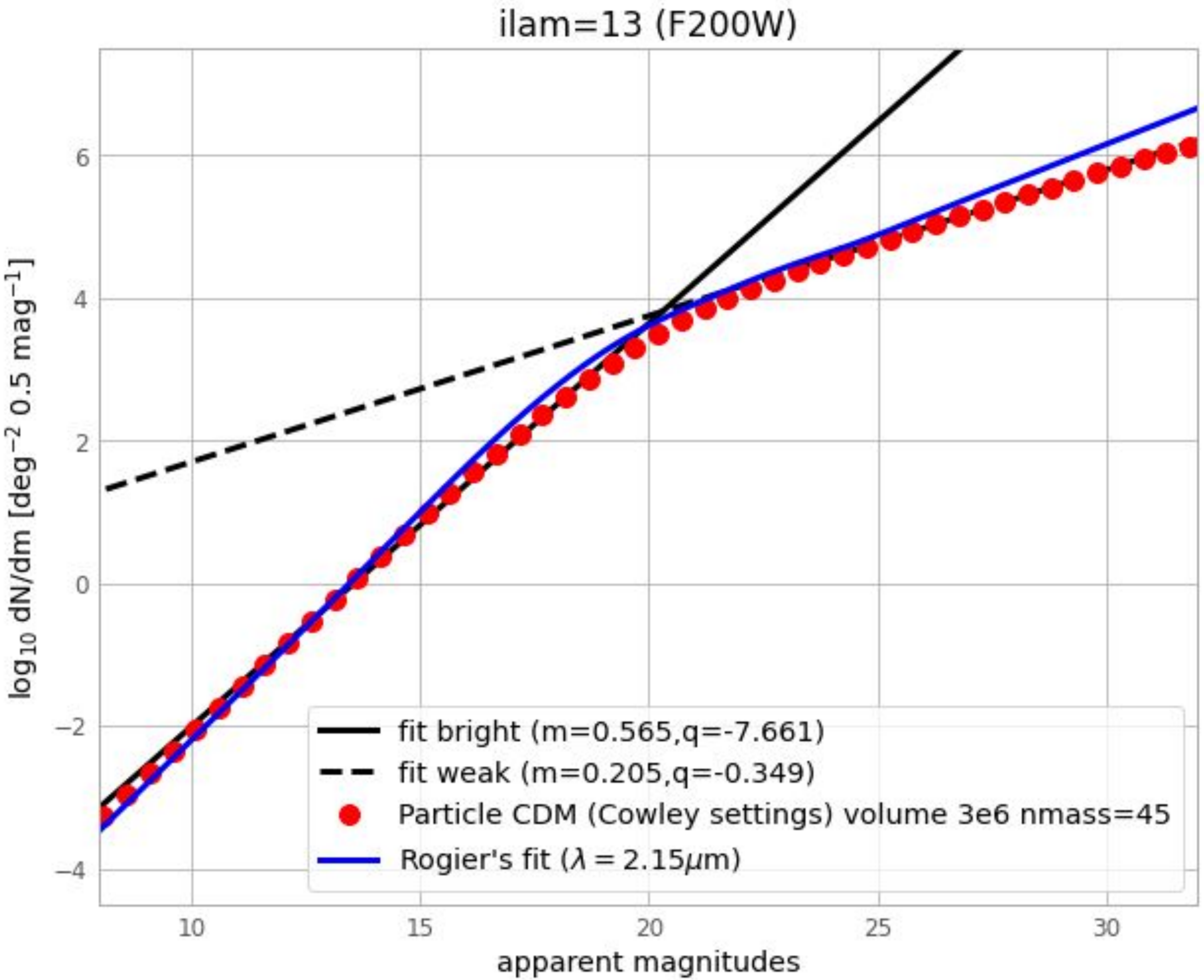
ilam=10 (F090W)
log$_{10}$ dN/dm [deg^{-2} 0.5 mag^{-1}]
apparent magnitudes
fit bright (m=0.547,q=-7.740)
fit weak (m=0.206,q=-0.536)
Particle CDM (Cowley settings) volume 3e6 nmass=45
Rogier's fit ($\lambda = 0.883\mu$m)



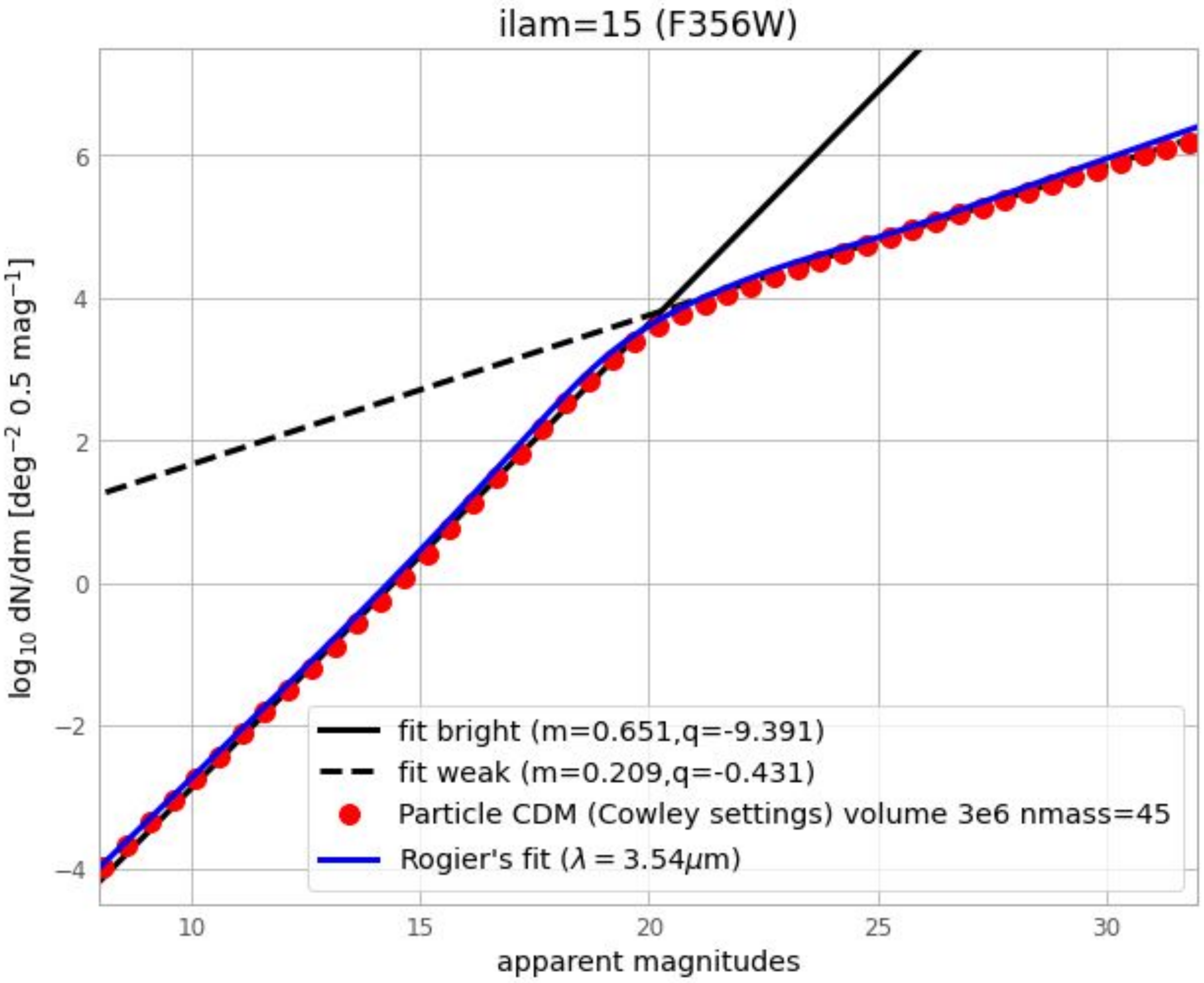
ilam=11 (F115W)
log10 dN/dm [deg−2 0.5 mag−1]
apparent magnitudes
fit bright (m=0.548,q=-7.583)
fit weak (m=0.204,q=-0.429)
Particle CDM (Cowley settings) volume 3e6 nmass=45
Rogier's fit (λ = 1.25μm)
Rogier's fit (λ = 1.02μm)



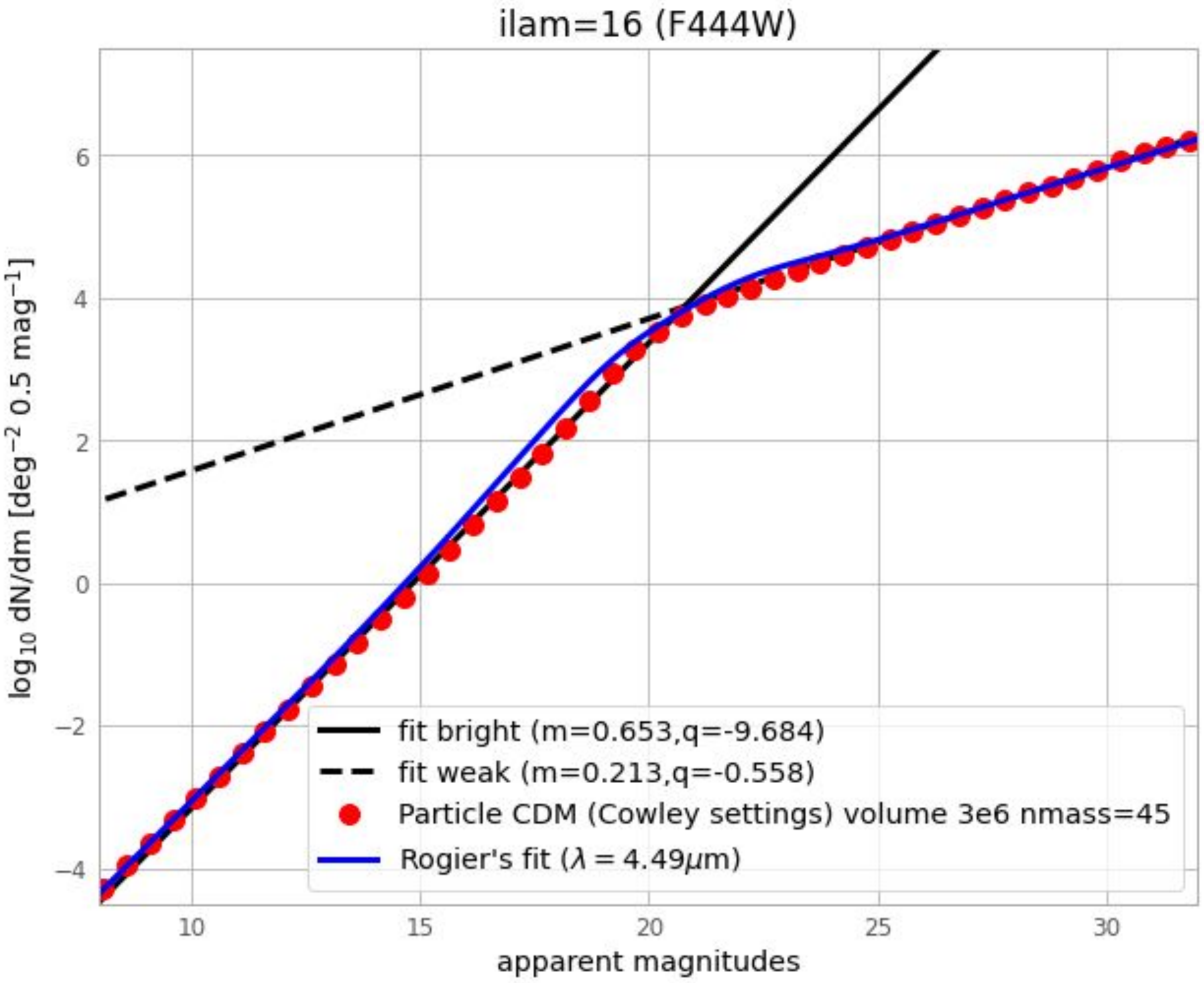
ilam=12 (F150W)
log$_{10}$ dN/dm [deg^{-2} 0.5 mag^{-1}]
apparent magnitudes
fit bright (m=0.552,q=-7.530)
fit weak (m=0.204,q=-0.357)
Particle CDM (Cowley settings) volume 3e6 nmass=45
Rogier's fit ($\lambda = 1.65\mu$m)



ilam=13 (F200W)
log$_{10}$ dN/dm [deg^{-2} 0.5 mag^{-1}]
apparent magnitudes
fit bright (m=0.565,q=-7.661)
fit weak (m=0.205,q=-0.349)
Particle CDM (Cowley settings) volume 3e6 nmass=45
Rogier's fit ($\lambda = 2.15\mu$m)
6
4
2
0
−2
−4
10
15
20
25
30



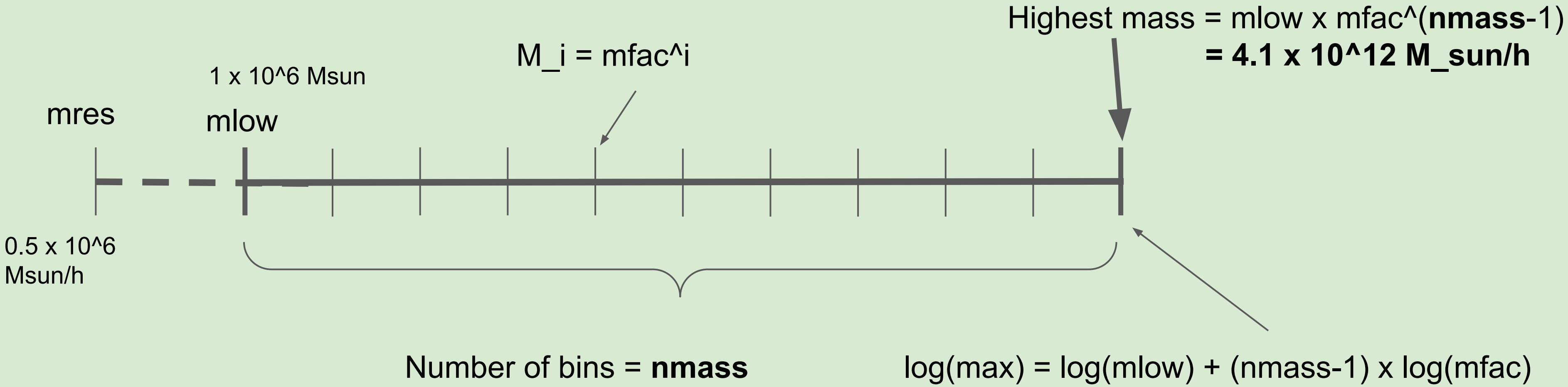
ilam=15 (F356W)
fit bright (m=0.651,q=-9.391)
fit weak (m=0.209,q=-0.431)
Particle CDM (Cowley settings) volume 3e6 nmass=45
Rogier's fit ($\lambda = 3.54\mu$m)
$\log_{10}$ dN/dm [deg^{-2} 0.5 mag^{-1}]
apparent magnitudes
6
4
2
0
−2
−4
10
15
20
25
30

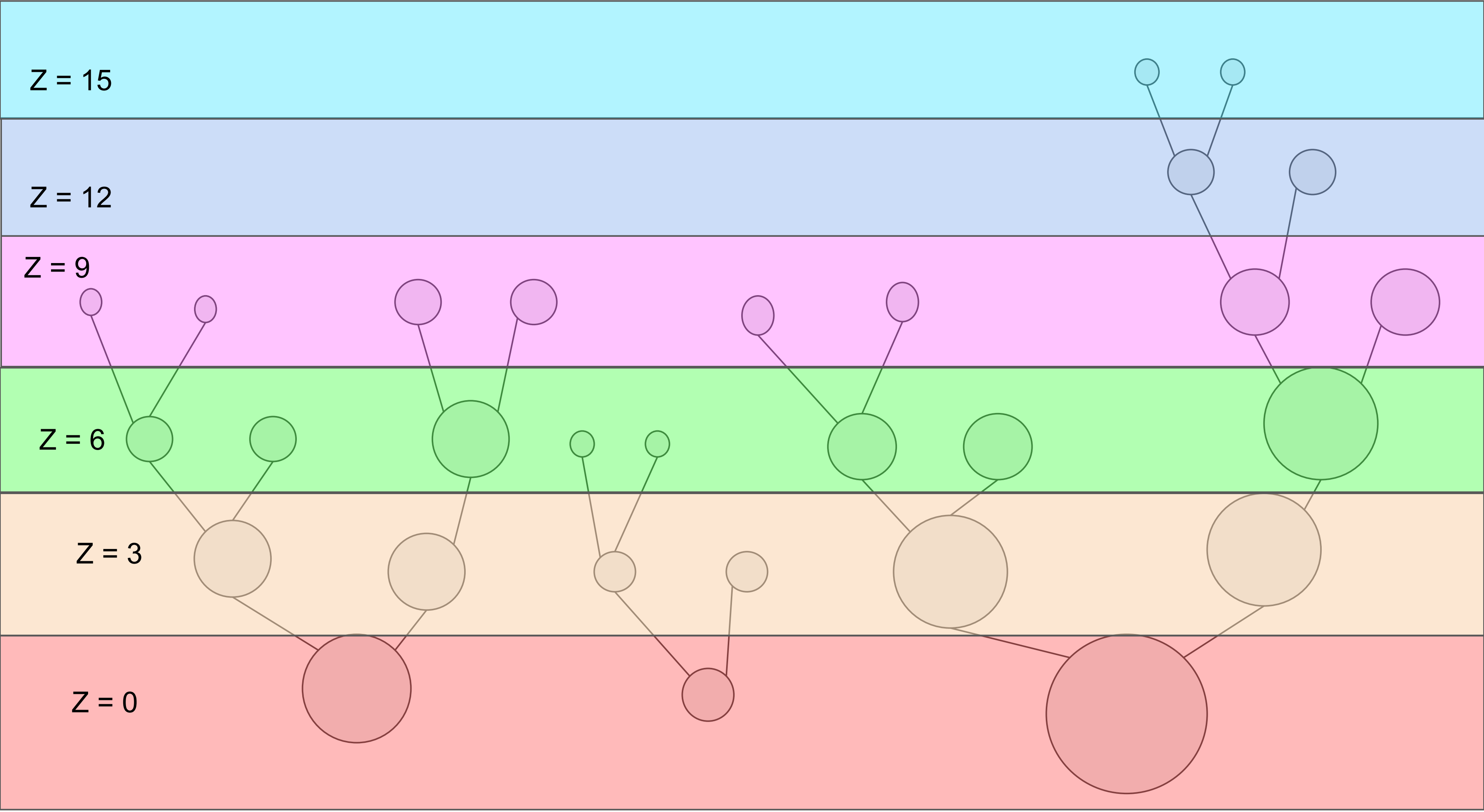

ilam=16 (F444W)
log$_{10}$ dN/dm [deg^{-2} 0.5 mag^{-1}]
apparent magnitudes
fit bright (m=0.653,q=-9.684)
fit weak (m=0.213,q=-0.558)
Particle CDM (Cowley settings) volume 3e6 nmass=45
Rogier's fit ($\lambda = 4.49\mu$m)

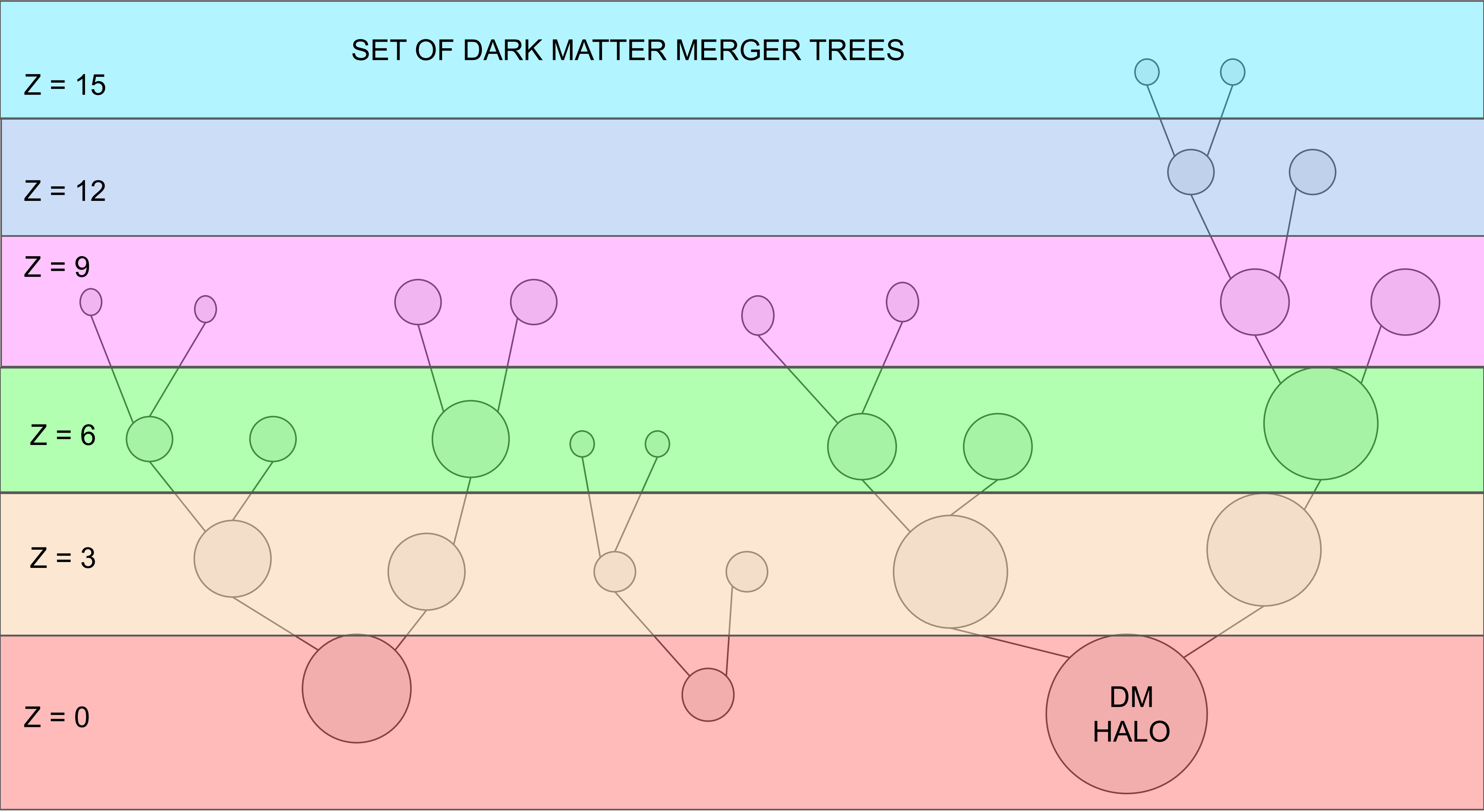
A fundamental parameter of the simulation: **nmass**

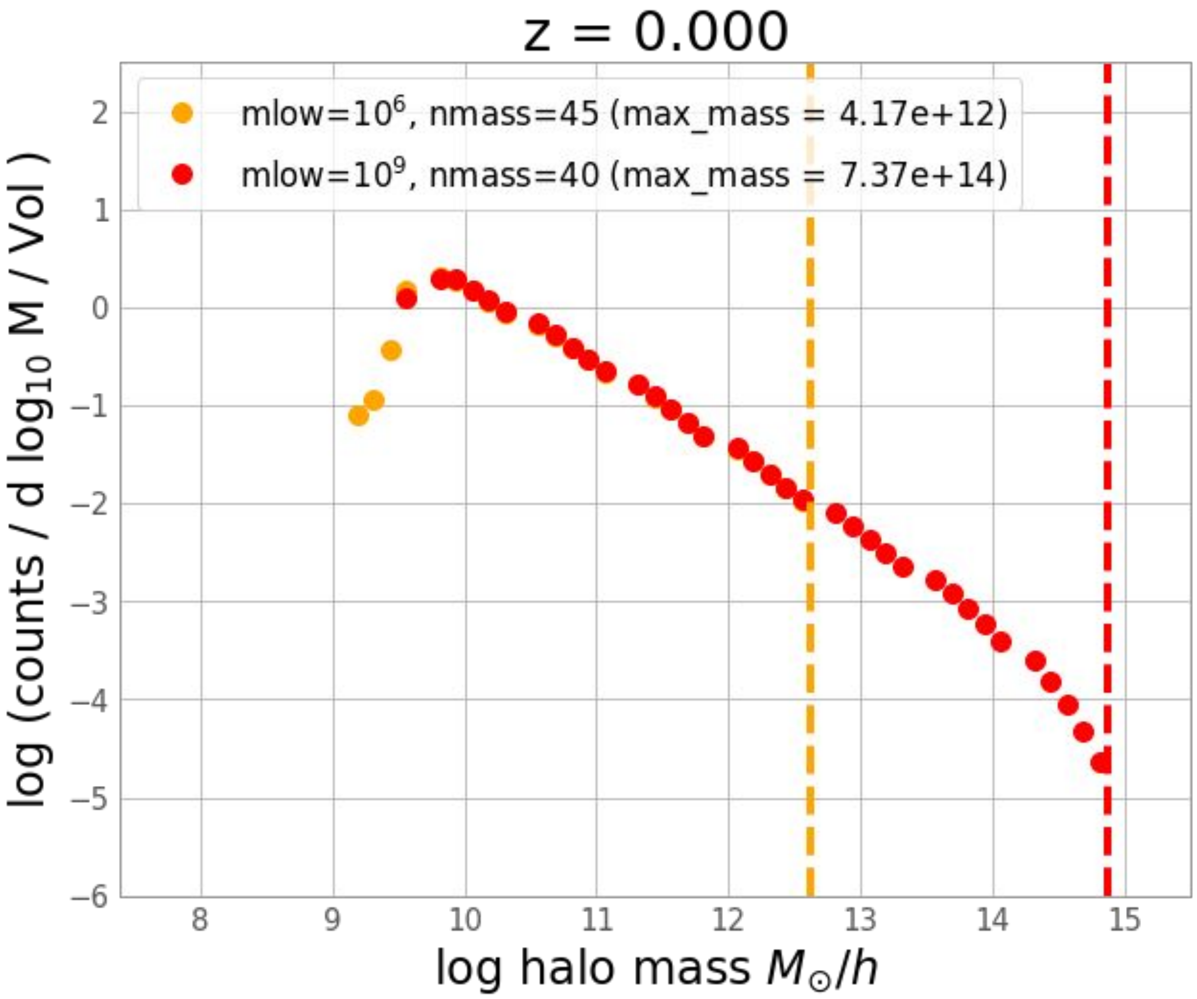
```
      nmass =                45
   nhalomin =                50
   nhalomax =               300
       mlow =    1.00000E+06
       mres =    5.00000E+05
       mfac =    1.41400E+00
```

The grid of halo masses values used by the simulation is defined as this

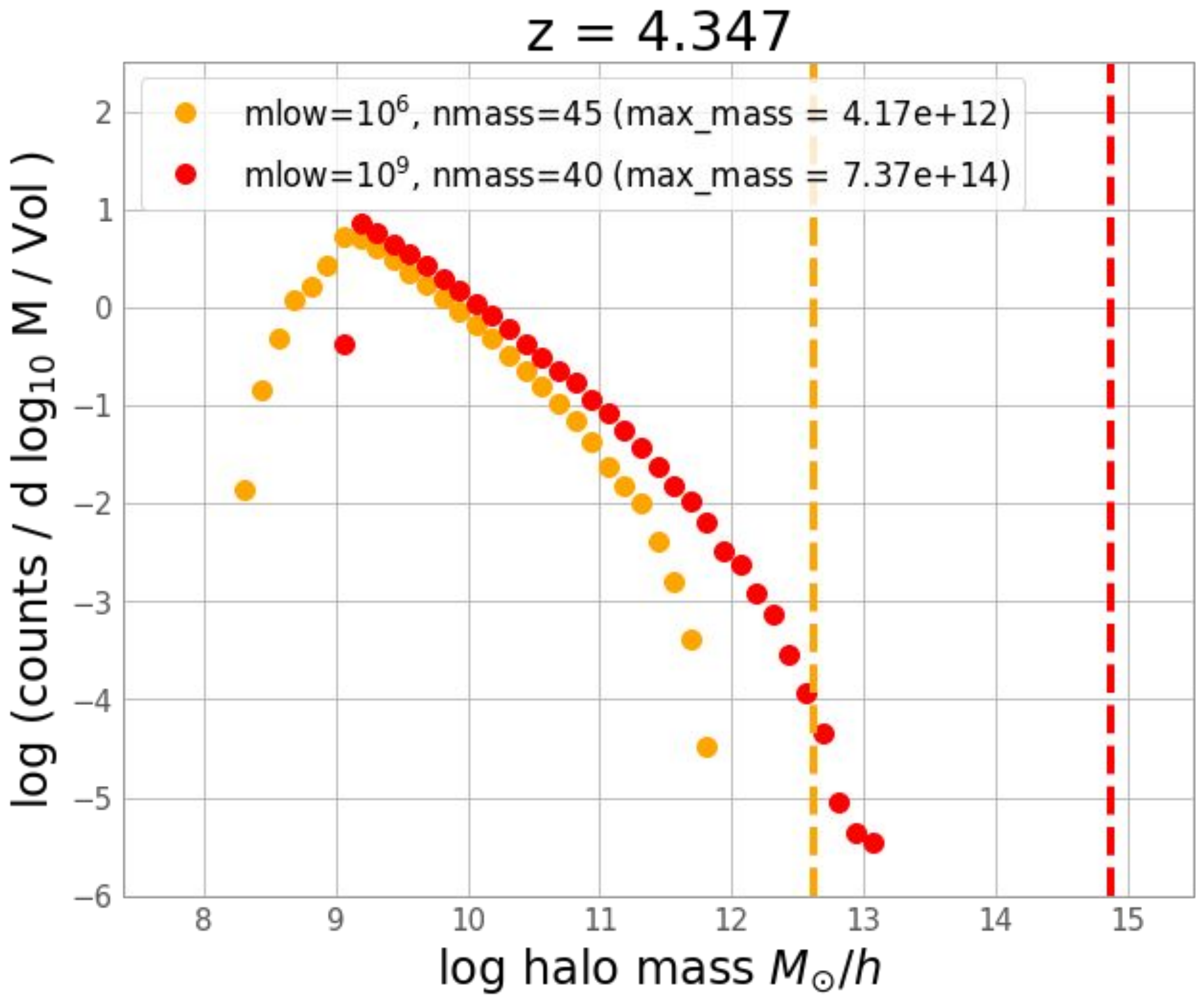



Z = 15
Z = 12
Z = 9
Z = 6
Z = 3
Z = 0

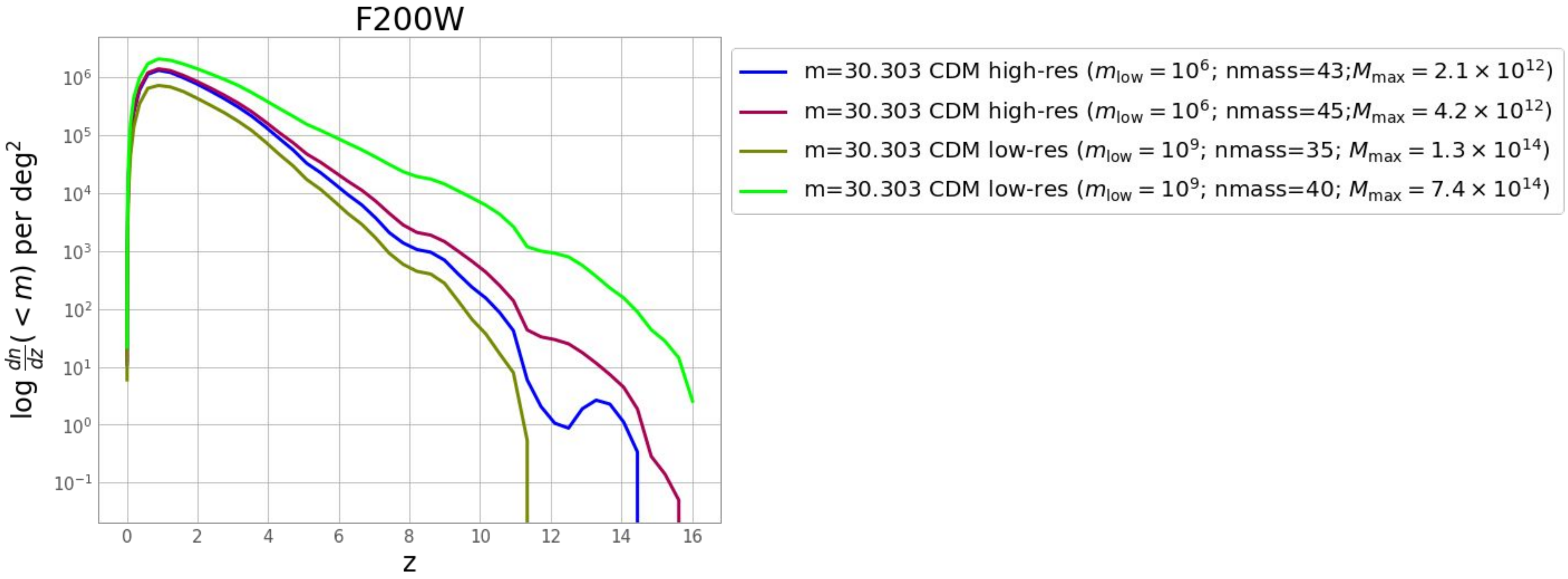

SET OF DARK MATTER MERGER TREES
Z = 15
Z = 12
Z = 9
Z = 6
Z = 3
Z = 0
DM
HALO



z = 0.000
mlow=10^6, nmass=45 (max_mass = 4.17e+12)
mlow=10^9, nmass=40 (max_mass = 7.37e+14)
log (counts / d log10 M / Vol)
log halo mass M⊙/h
2
1
0
−1
−2
−3
−4
−5
−6
8
9
10
11
12
13
14
15

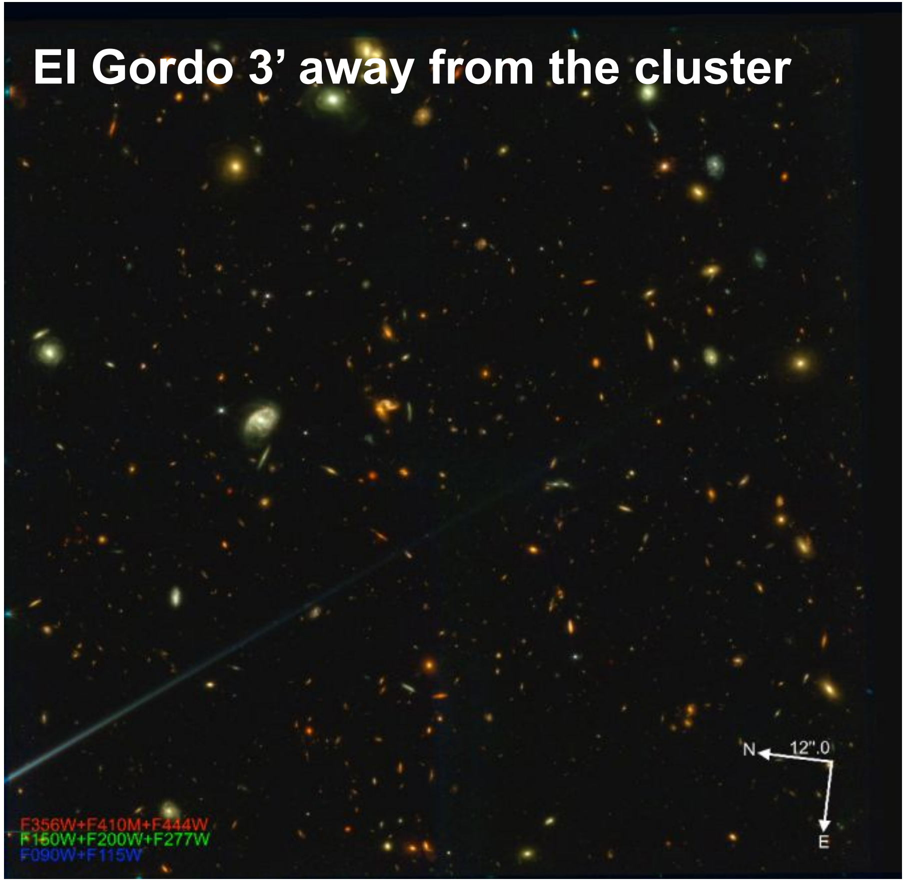

z = 4.347
mlow=10^6, nmass=45 (max_mass = 4.17e+12)
mlow=10^9, nmass=40 (max_mass = 7.37e+14)
log (counts / d log10 M / Vol)
log halo mass M⊙/h
2
1
0
−1
−2
−3
−4
−5
−6
8
9
10
11
12
13
14
15

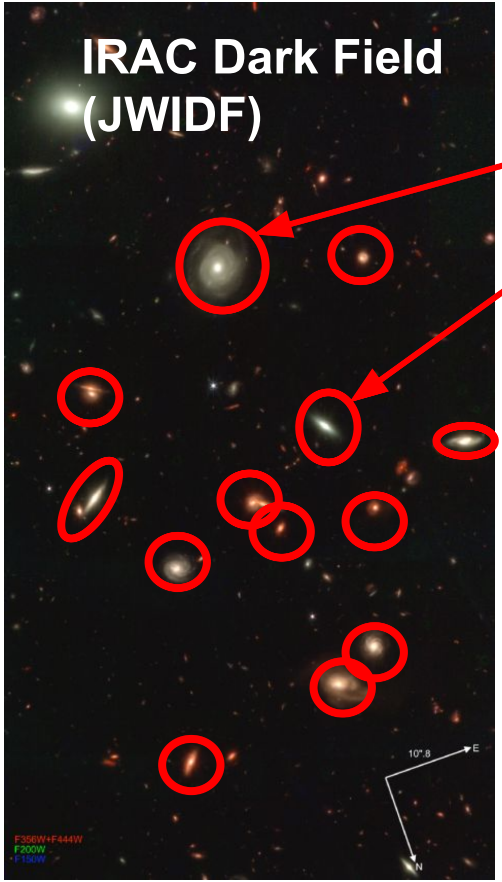
Redshift distributions for different MAX mass



The number counts can be used to estimate the:
INTEGRATED GALAXY LIGHT (IGL)

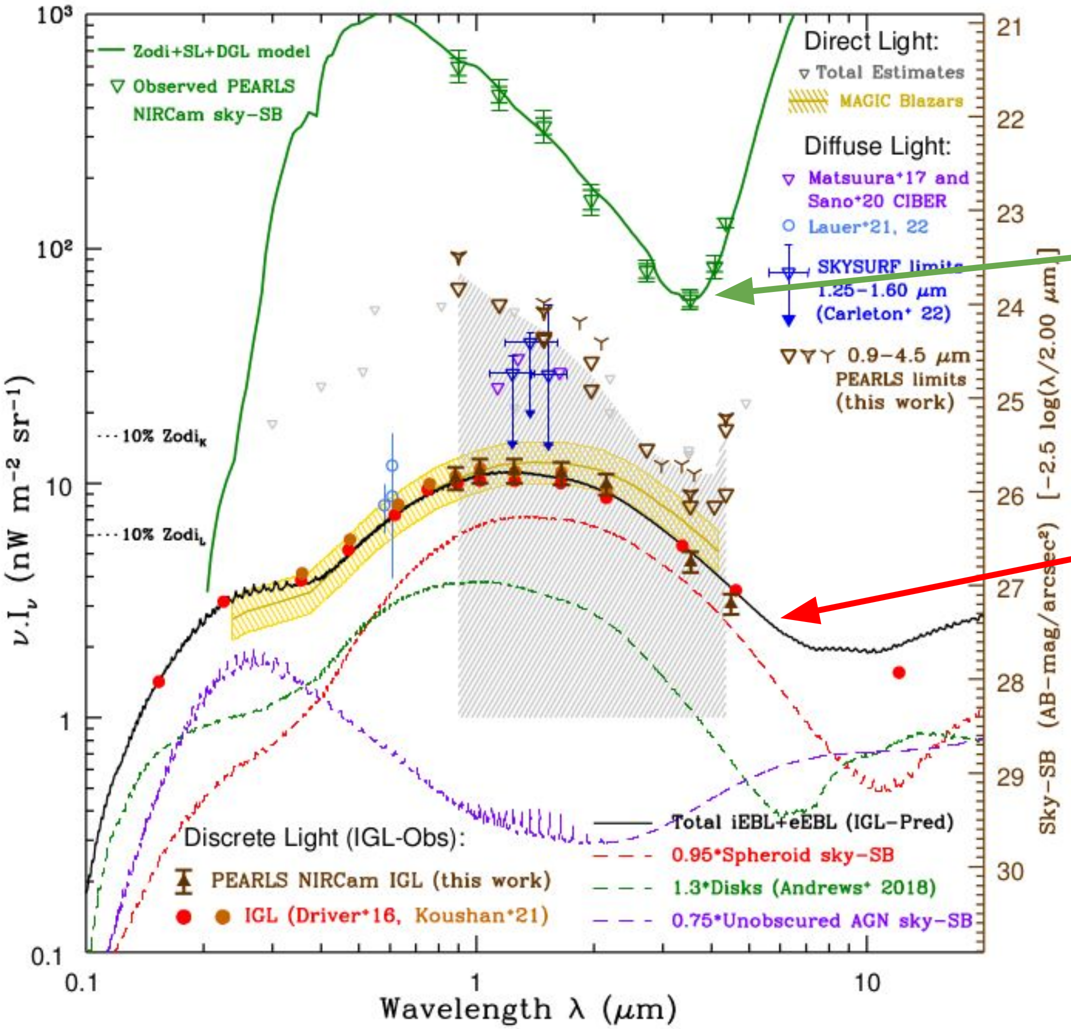
PEARLS fields used for counts and background light





Galaxies contribute to the Integrated Galaxy Light (IGL)

The rest of the light is called **Sky-SB** = Sky-Surface Brightness and it comes from many things



SKY SURFACE BRIGHTNESS = Sum of:

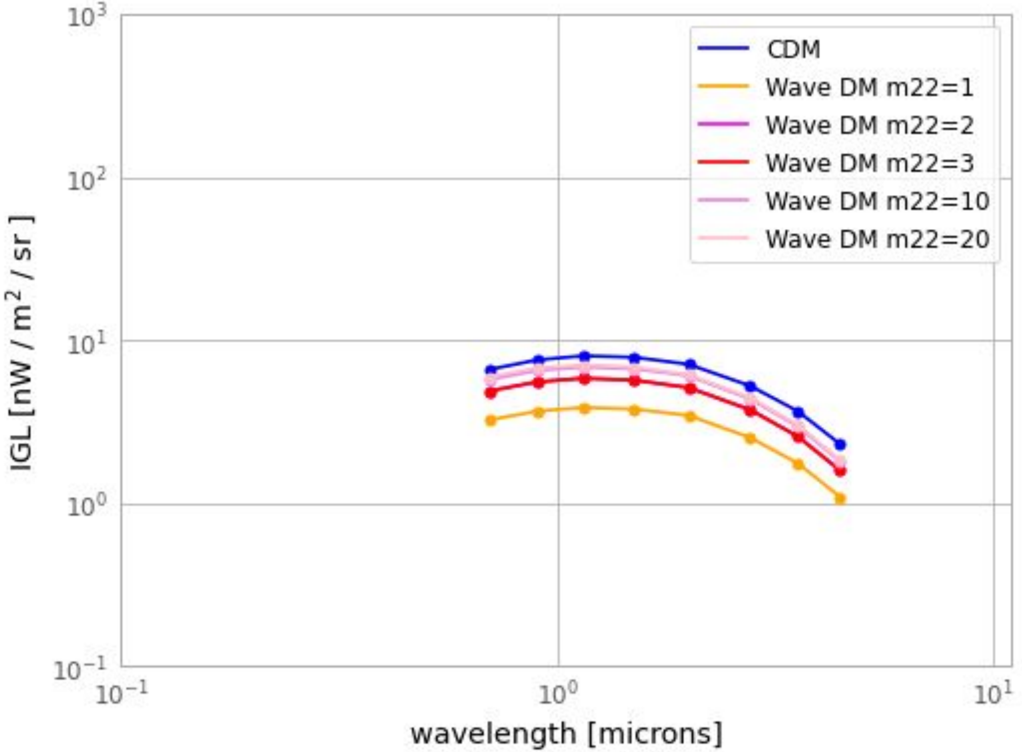
1. **Thermal**
2. **Straylights**
3. **Zodiacal light**
4. **Diffuse galaxy light (our galaxy)**
5. **Discrete objects not resolved (above the magnitude limit)**

INTEGRATED GALAXY LIGHT (IGL)

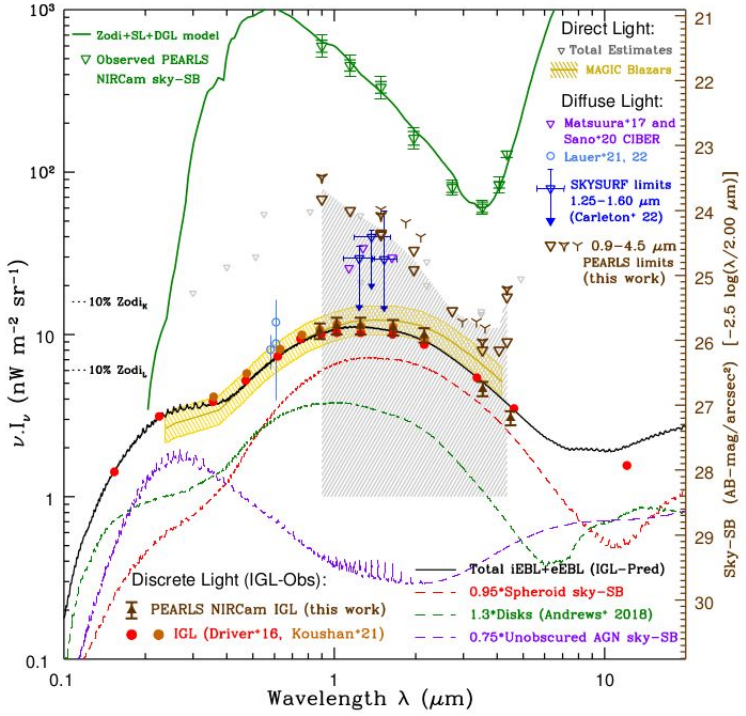
- **black line = theoretical model**
- **Brown triangles = PEARLS obs**

Diffuse light = Sky-SB (obs) - Sky-SB (predict)

(it includes all the source of lights with not known source)



CDM
Wave DM m22=1
Wave DM m22=2
Wave DM m22=3
Wave DM m22=10
Wave DM m22=20
IGL [nW / m^2 / sr]
wavelength [microns]
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}



Zodi+SL+DGL model
Observed PEARLS NIRCam sky-SB
Direct Light:
Total Estimates
MAGIC Blazars
Diffuse Light:
Matsuura+17 and Sano+20 CIBER
Lauer+21, 22
SKYSURF limits 1.25–1.60 μm (Carleton+ 22)
0.9–4.5 μm PEARLS limits (this work)
10% Zodi$_K$
10% Zodi$_L$
Discrete Light (IGL-Obs):
PEARLS NIRCam IGL (this work)
IGL (Driver+16, Koushan+21)
Total iEBL+eEBL (IGL-Pred)
0.95*Spheroid sky-SB
1.3*Disks (Andrews+ 2018)
0.75*Unobscured AGN sky-SB
$\nu . I_\nu$ (nW m^{-2} sr^{-1})
Wavelength λ (μm)
Sky-SB (AB-mag/arcsec^2) [−2.5 log(λ/2.00 μm)]

The first step is the study of the **halo mass function**

- The halo mass function is:
  - the **number of MAIN DARK MATTER HALO**
    - per unit of logarithmic **mass bin**
    - and per unit of **volume**
- It is expected to have a different behaviours between CDM and Wave DM.

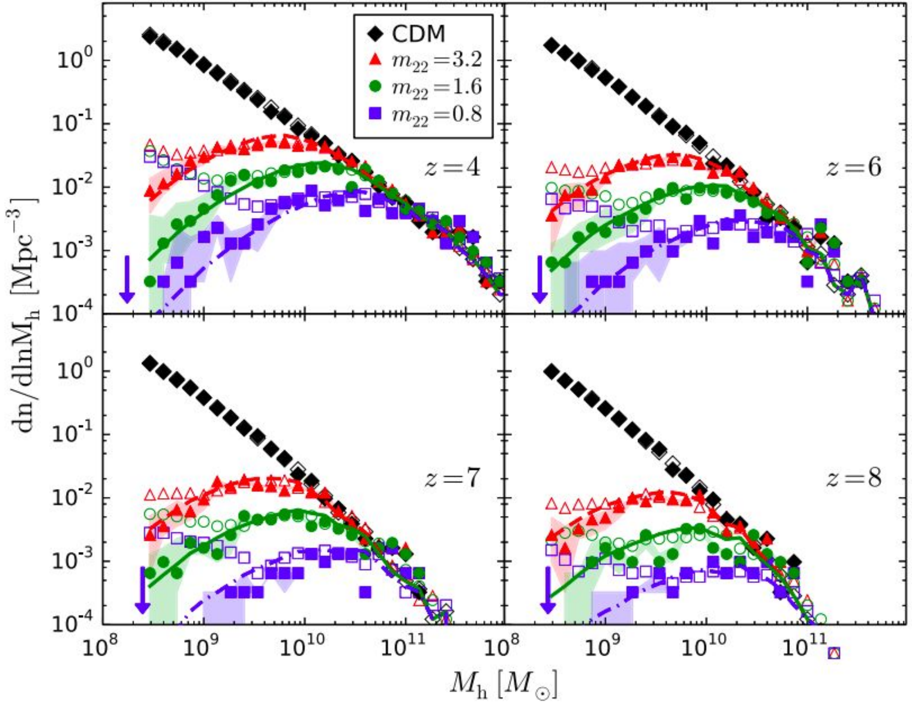
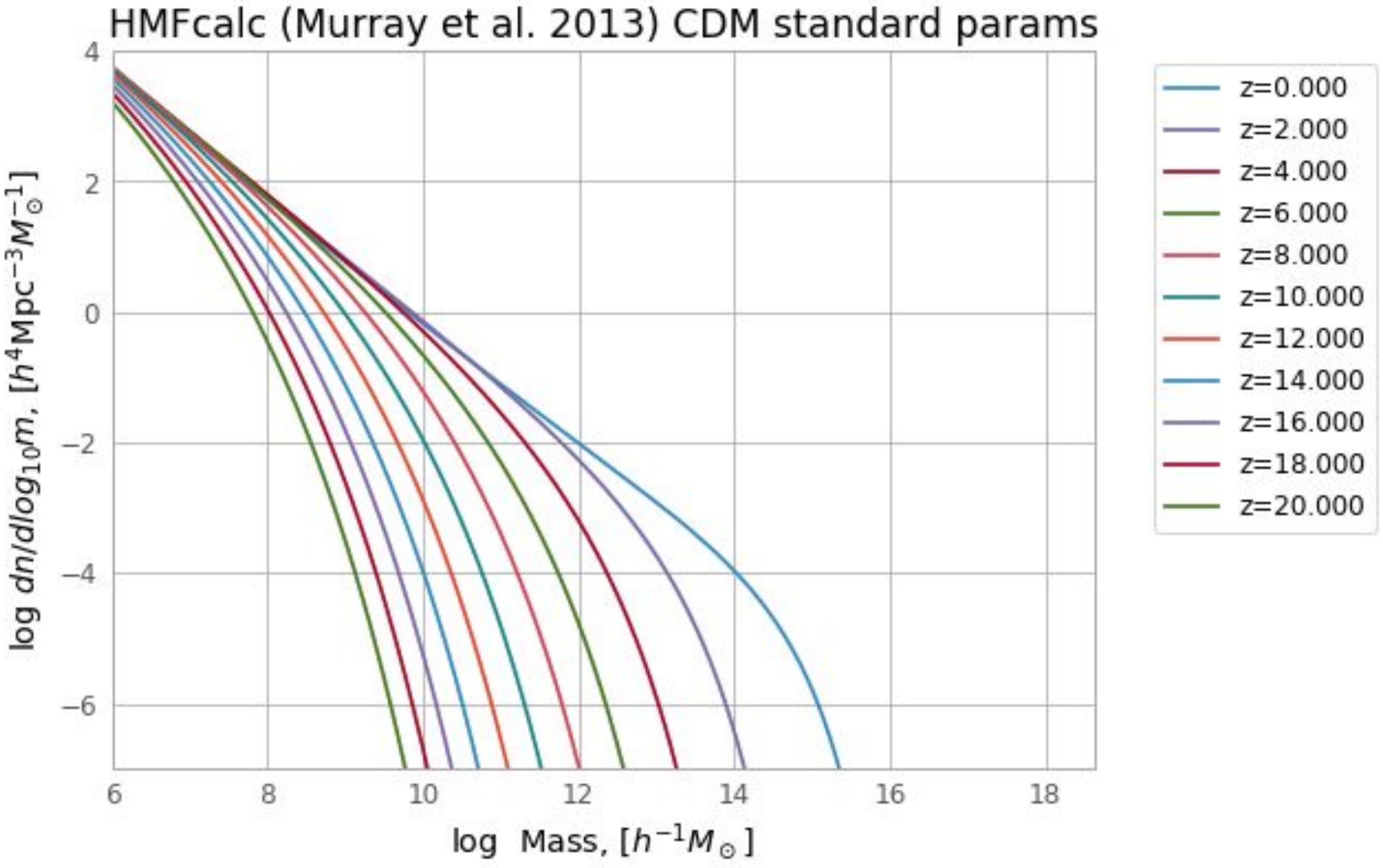
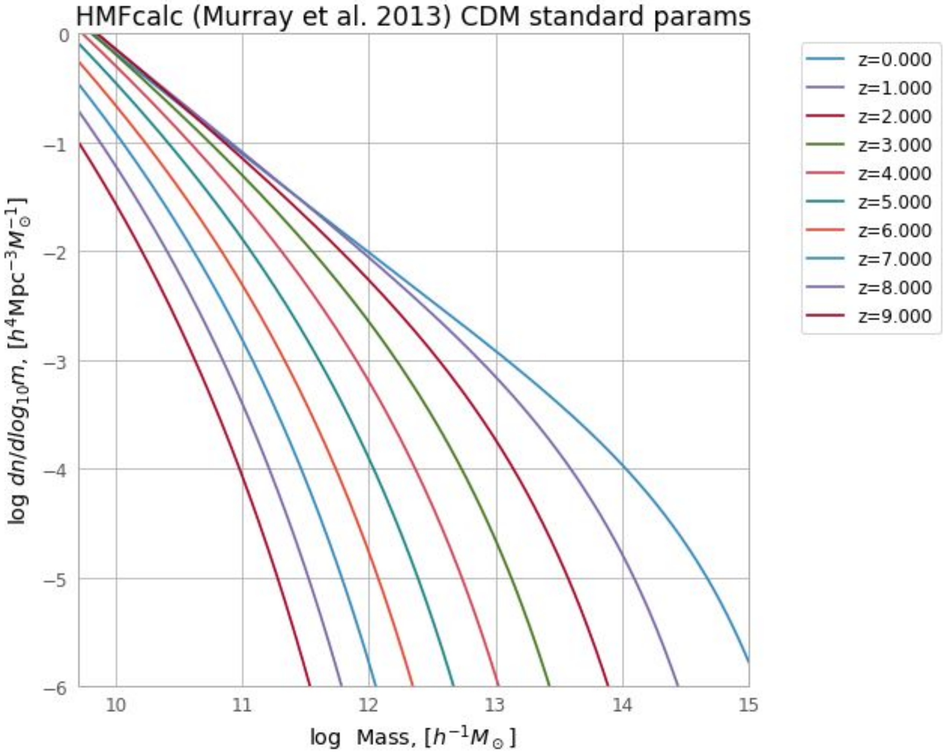


Fig. 4, Schive et al. 2016

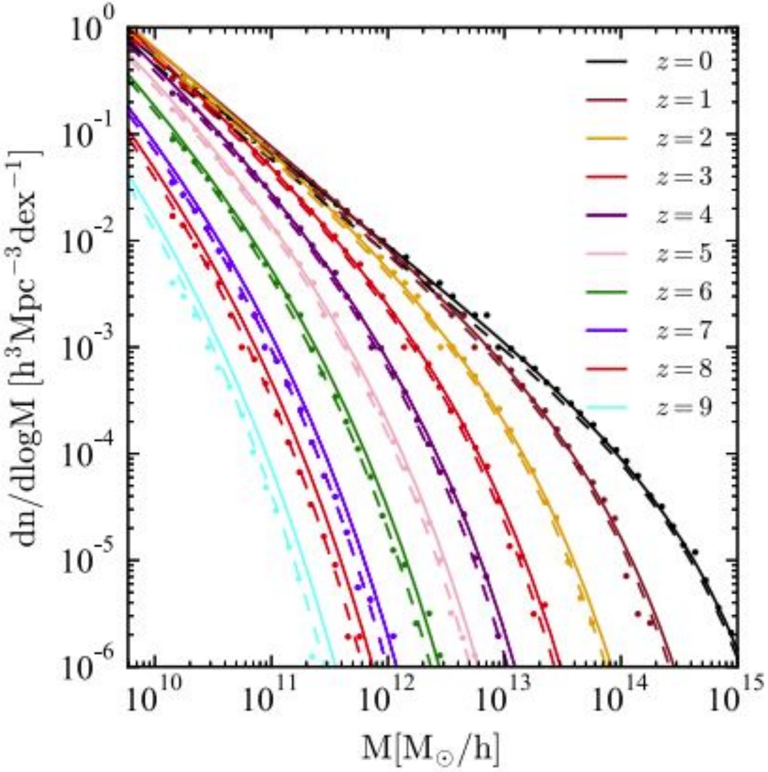
Getting a theoretical model as a reference: HMFCalc



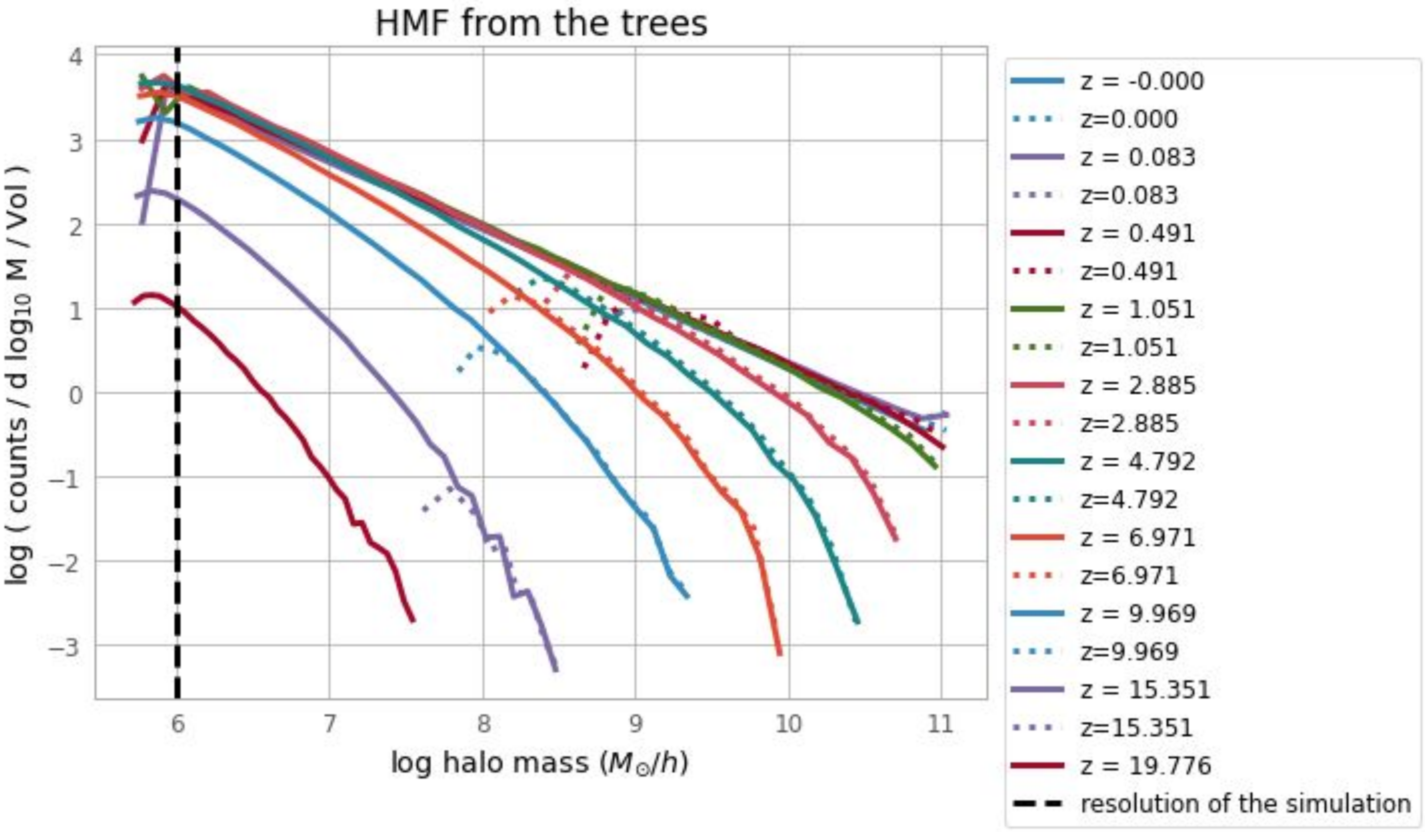
This theoretical model agrees with the literature



Safarzadeh et al. 2018 (Figure 2)



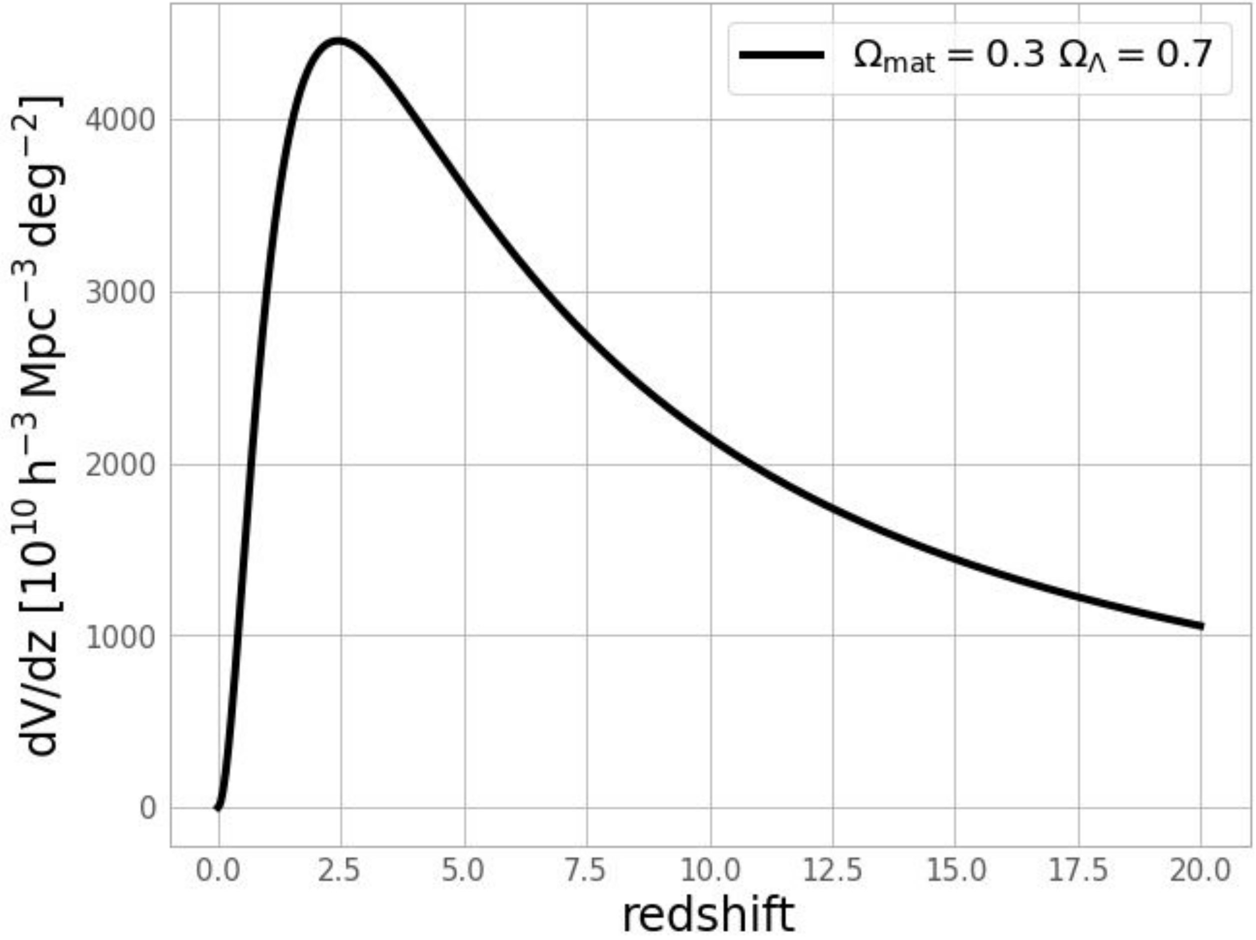
HMF for DM HALOS with and without galaxies (MCTREE)



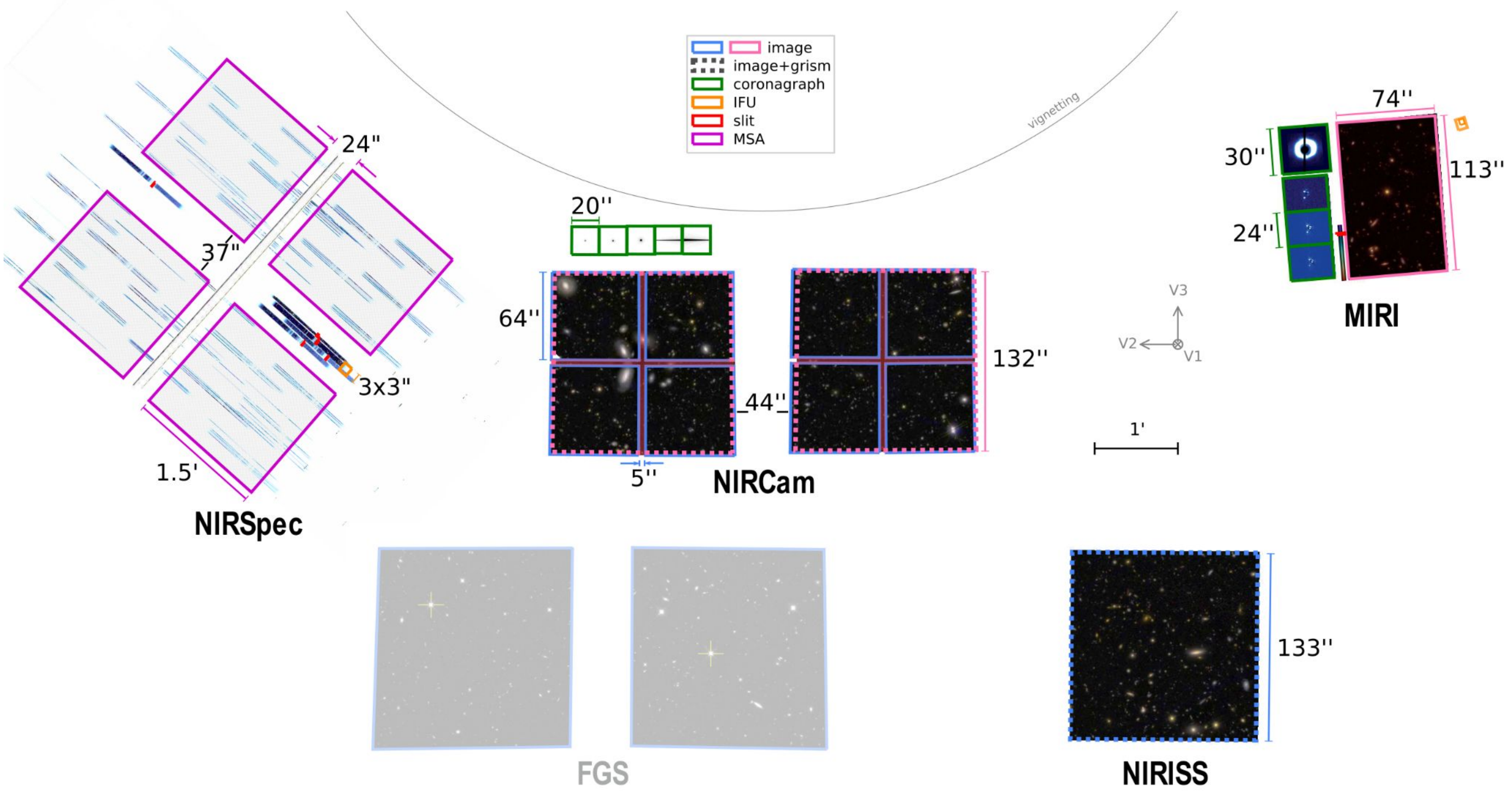
DASHED = DARK MATTER HALOS **WITH GALAXIES**

SOLID = **ALL** DARK MATTER HALOS (also when galaxies have not formed yet)

Change in volume per unit area

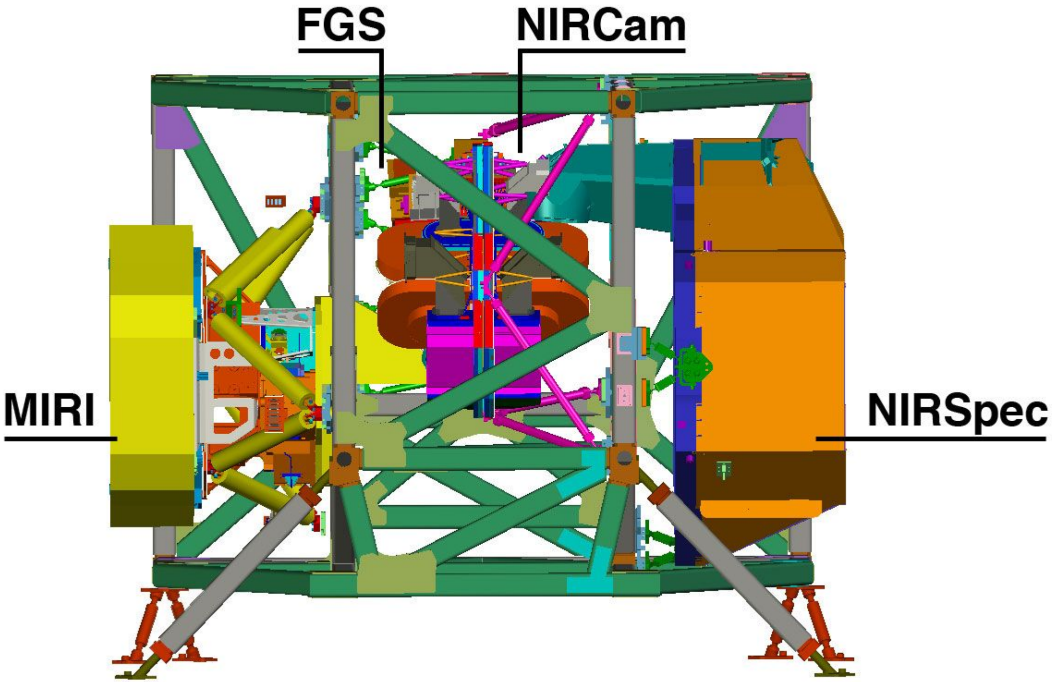


Field of view of JWST



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

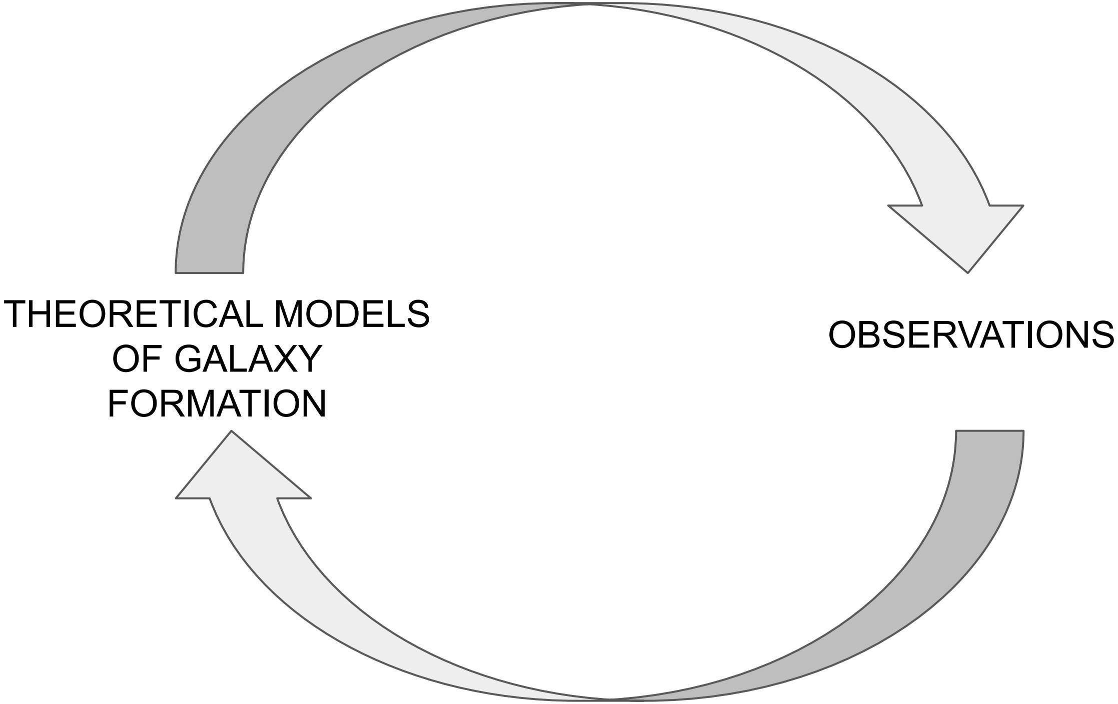
The JWST instruments



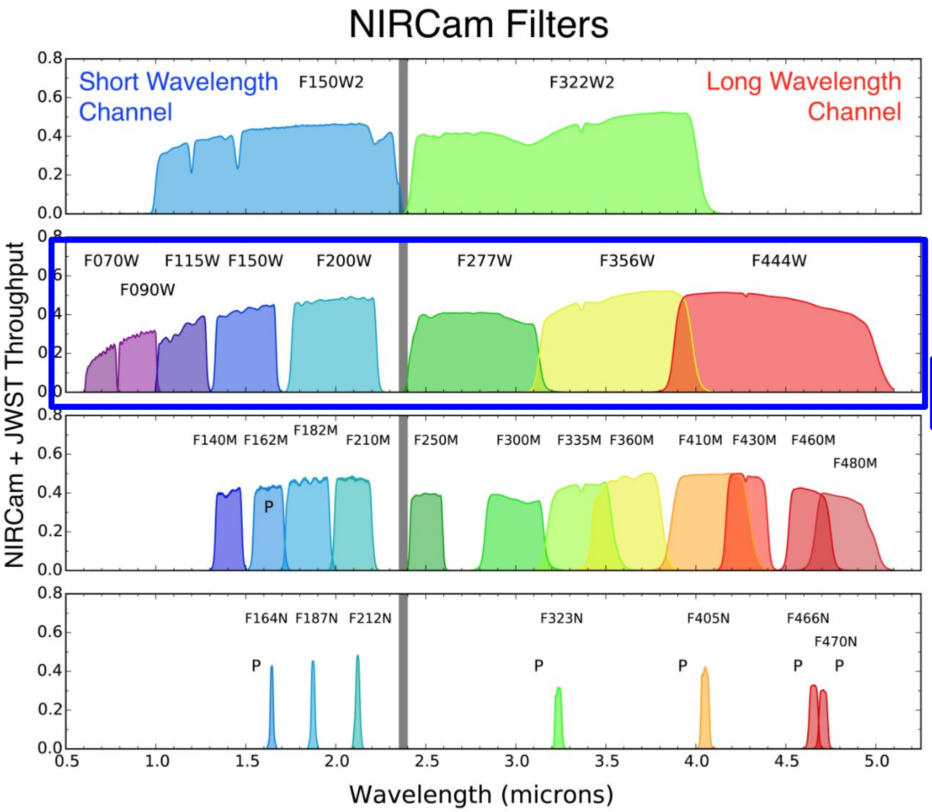
1. **NIRCam** (Near InfraRed Camera)
2. **NIRSpec** (Near InfraRed Spectrograph)
3. **MIRI** (Mid InfraRed Instrument)
4. FGS/**NIRISS** or simply NIRISS (Fine Guidance Sensor/Near Infrared Imager and Slitless Spectrograph)

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

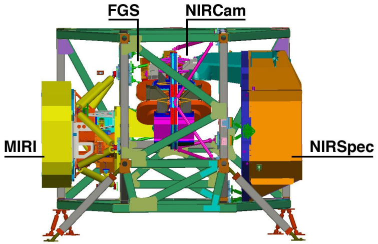
Improving the understanding of the baryonic physics



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

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**.

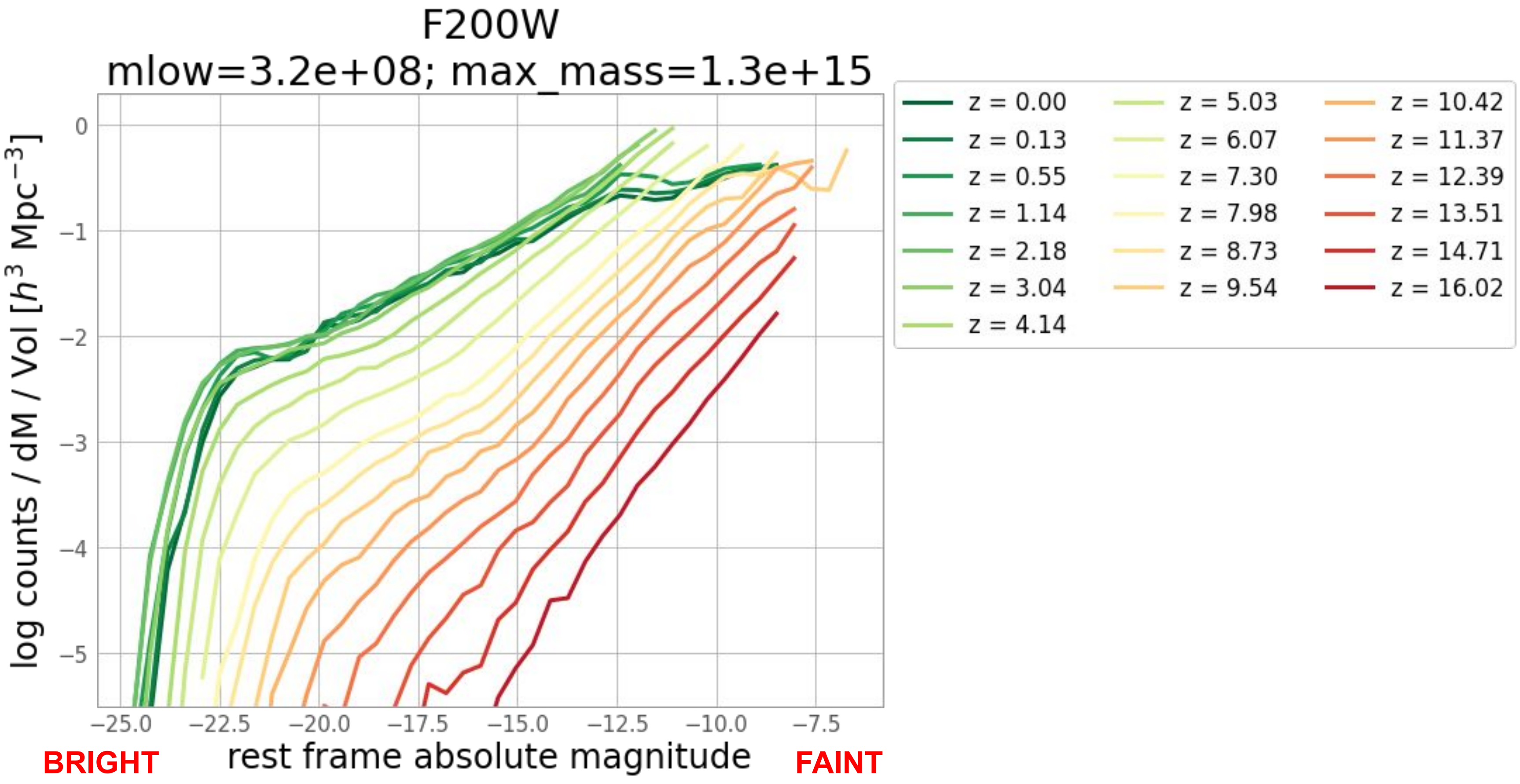
https://dirac.ac.uk/ DIRAC - DIstributed Research utilising Advanced Computing

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

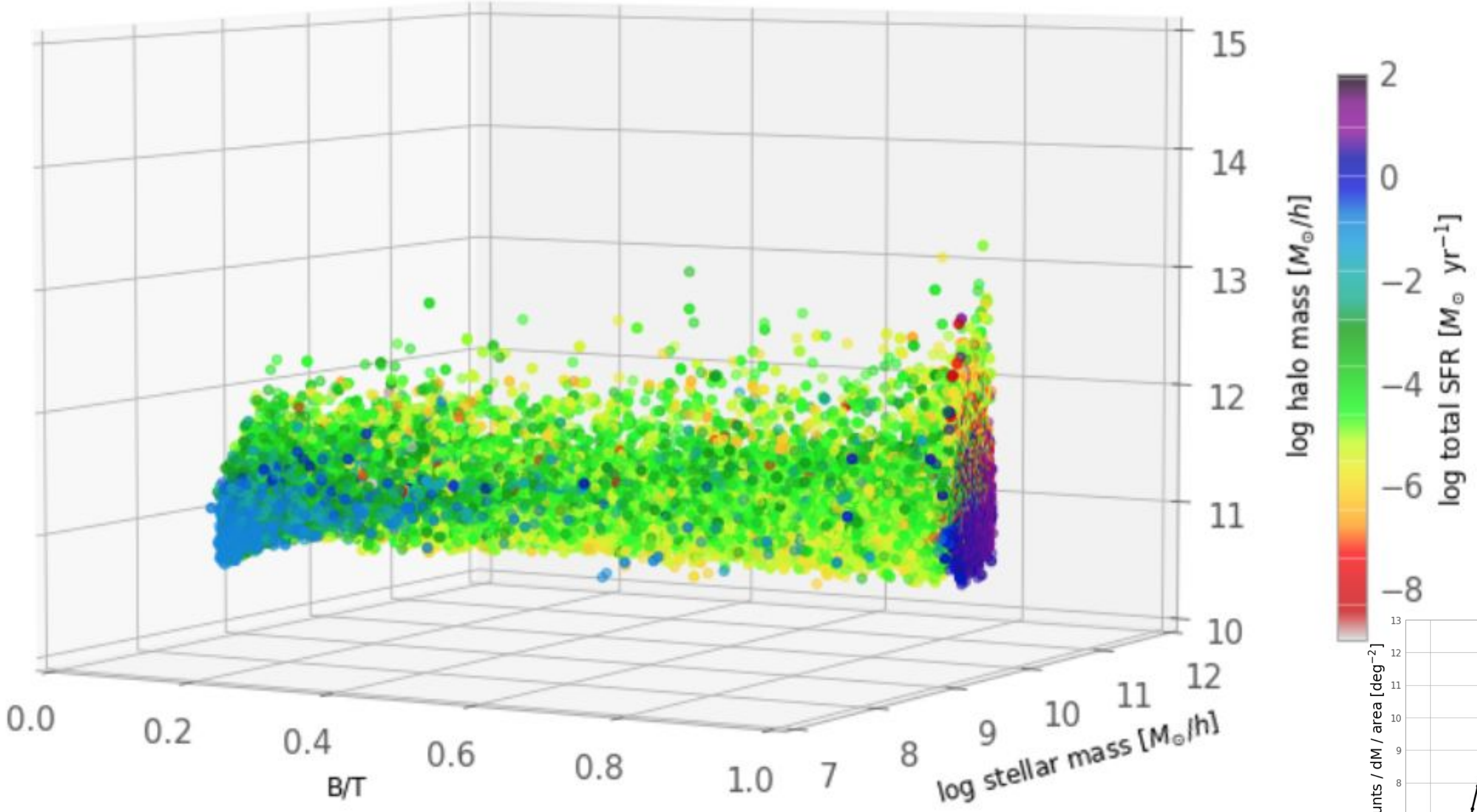
1. CONVERT INTO **APPARENT MAGNITUDE**:
2. Consider the **change in volume element with redshift**
3. **Integrate** over the **redshift range** of interest

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

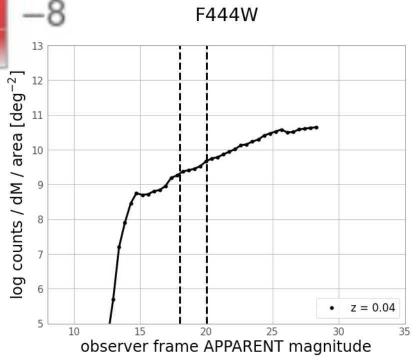
NUMBER COUNTS (all redshifts integrated together)

LUMINOSITY FUNCTION (at a specific redshift snapshot)

z=0.04

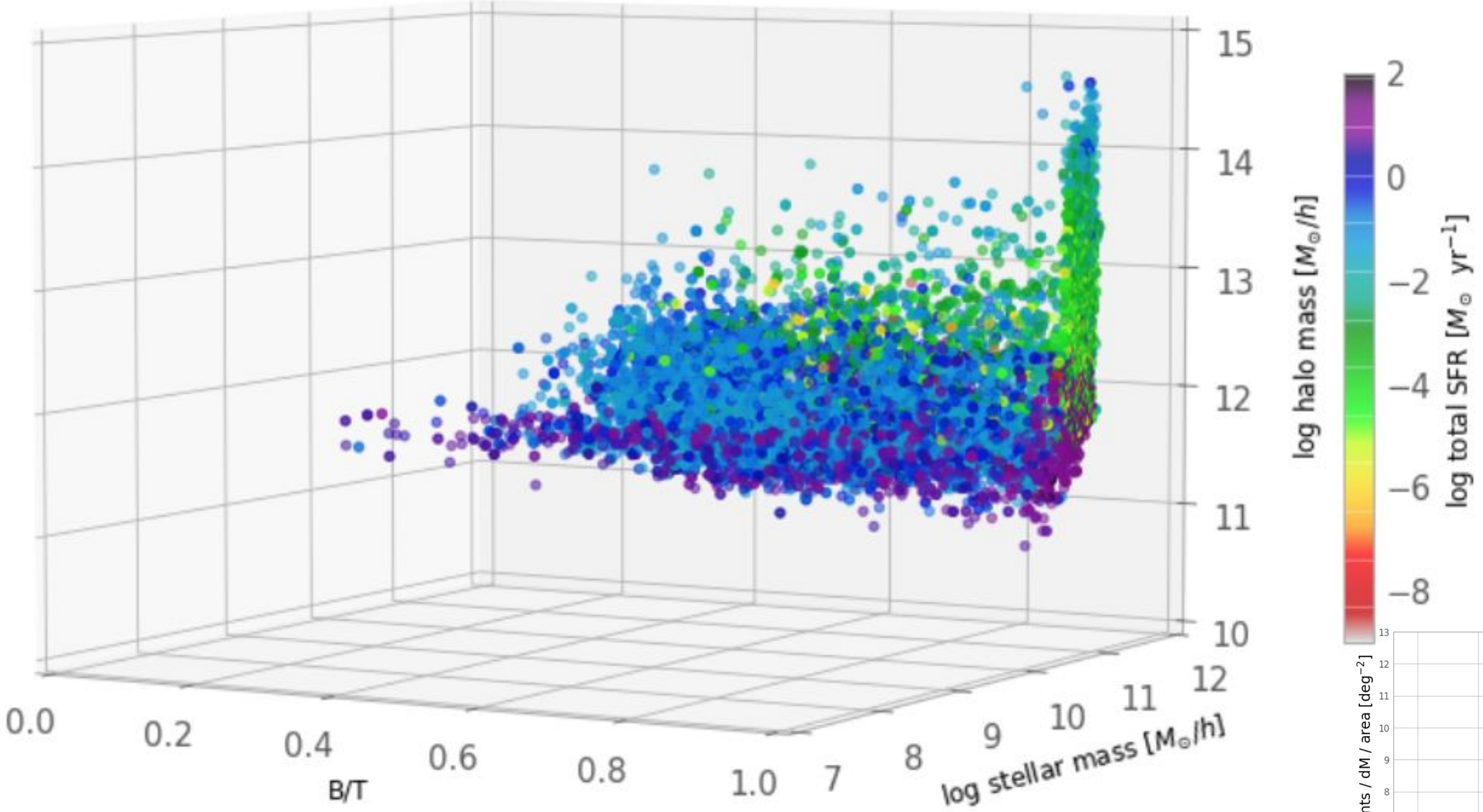


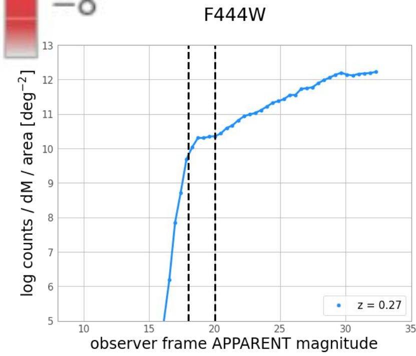
0.0
0.2
0.4
0.6
0.8
1.0
B/T
7
8
9
10
11
12
log stellar mass [M⊙/h]
10
11
12
13
14
15
log halo mass [M⊙/h]
2
0
−2
−4
−6
−8
log total SFR [M⊙ yr−1]

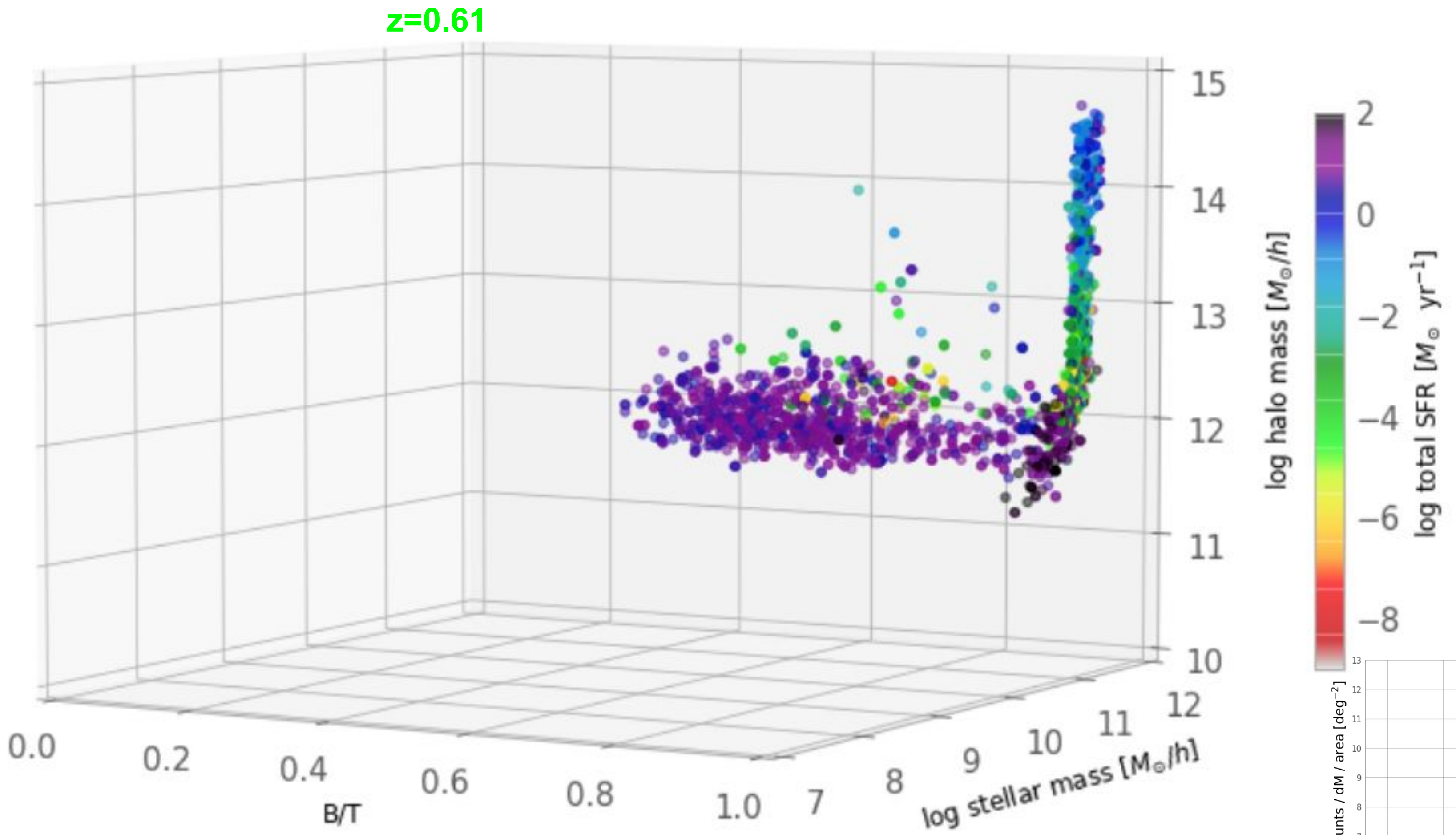


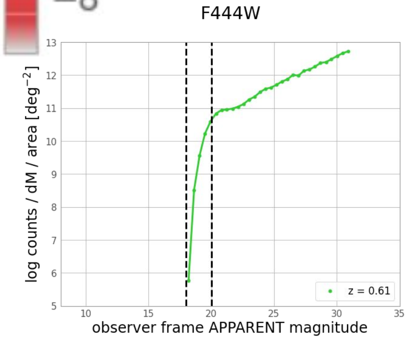
F444W
log counts / dM / area [deg−2]
observer frame APPARENT magnitude
z = 0.04
10
15
20
25
30
35
5
6
7
8
9
10
11
12
13

z=0.27

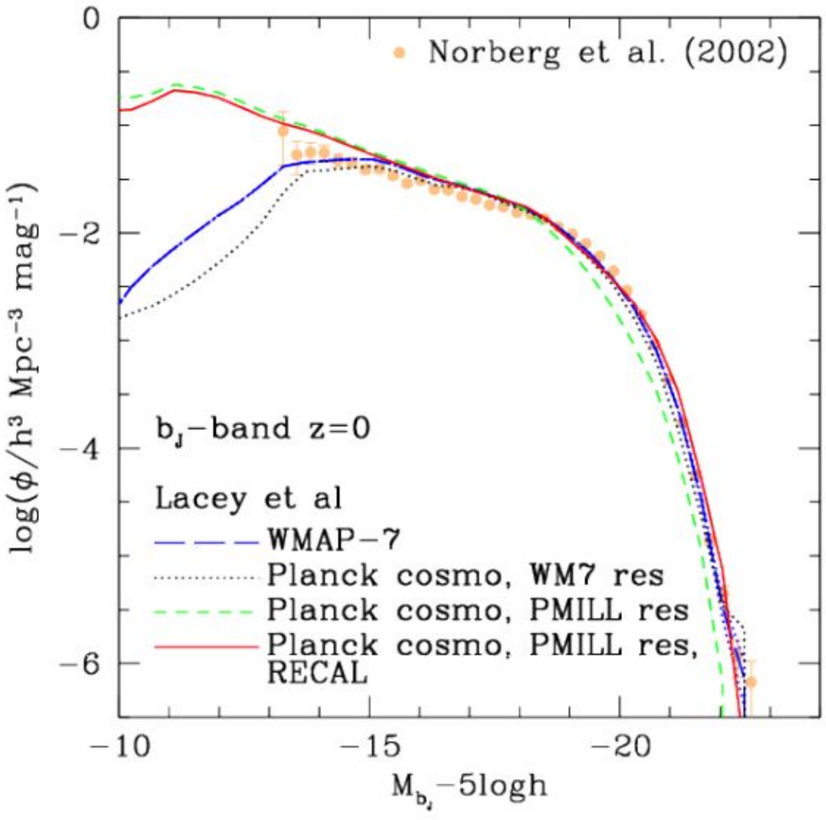

log halo mass [$M_\odot/h$]
log total SFR [$M_\odot$ yr^{-1}]
B/T
log stellar mass [$M_\odot/h$]


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


z=0.61
log halo mass [$M_\odot/h$]
15
14
13
12
11
10
log total SFR [$M_\odot$ yr^{-1}]
2
0
−2
−4
−6
−8
B/T
0.0
0.2
0.4
0.6
0.8
1.0
log stellar mass [$M_\odot/h$]
7
8
9
10
11
12


F444W
log counts / dM / area [deg^{-2}]
observer frame APPARENT magnitude
z = 0.61
5
6
7
8
9
10
11
12
13
10
15
20
25
30
35

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
```