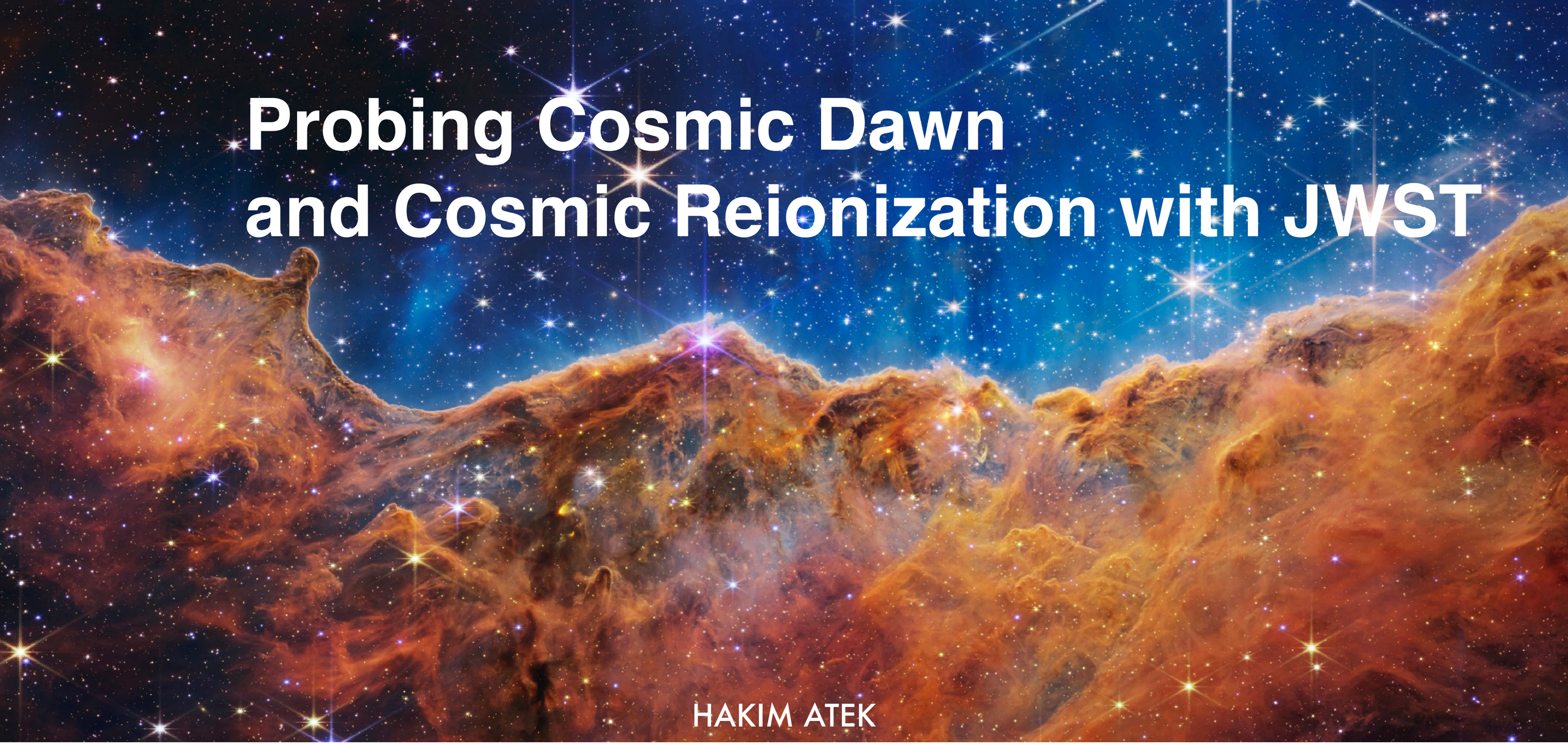
Probing Cosmic Dawn and Cosmic Reionization with JWST



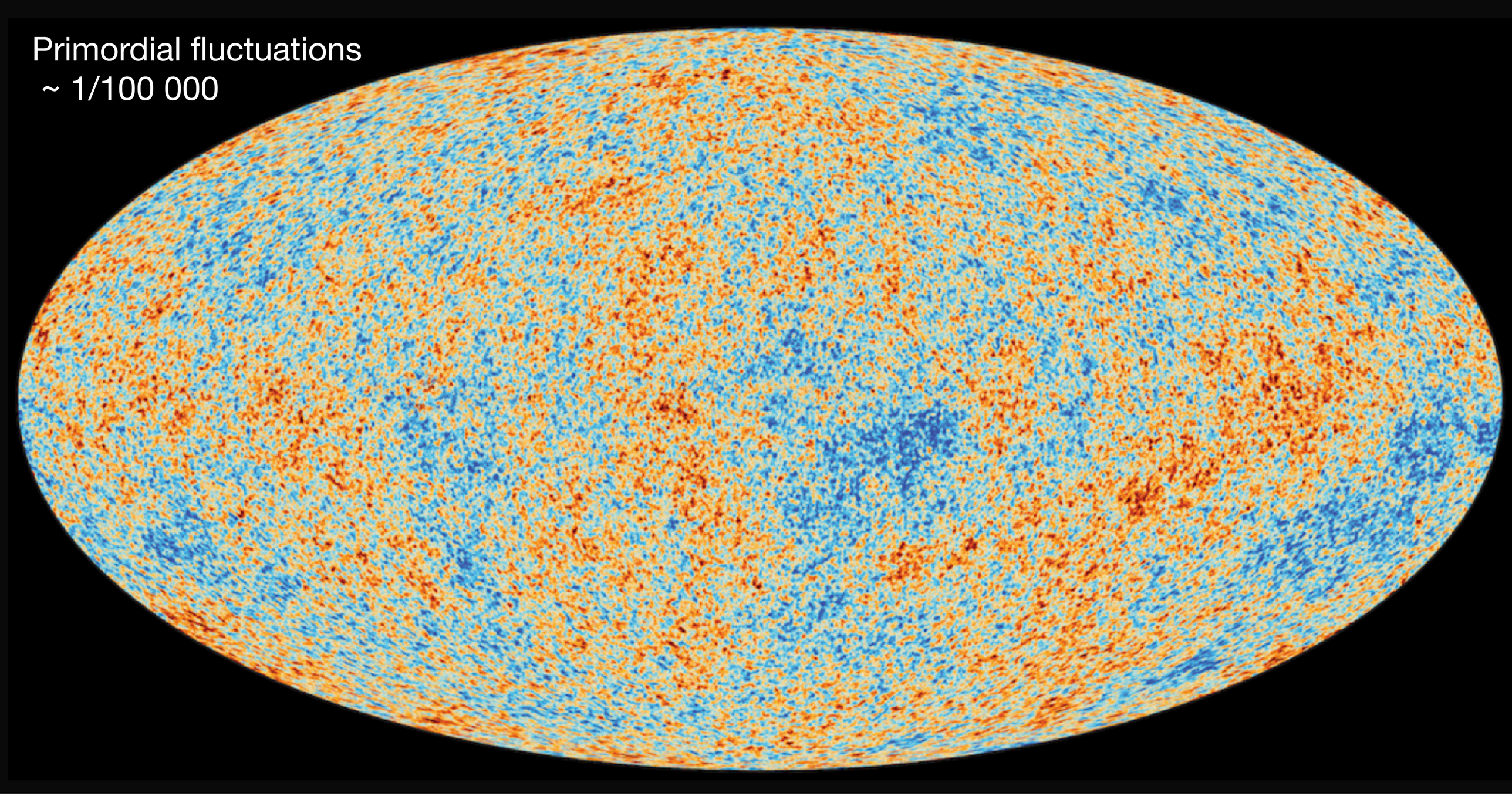
HAKIM ATEK

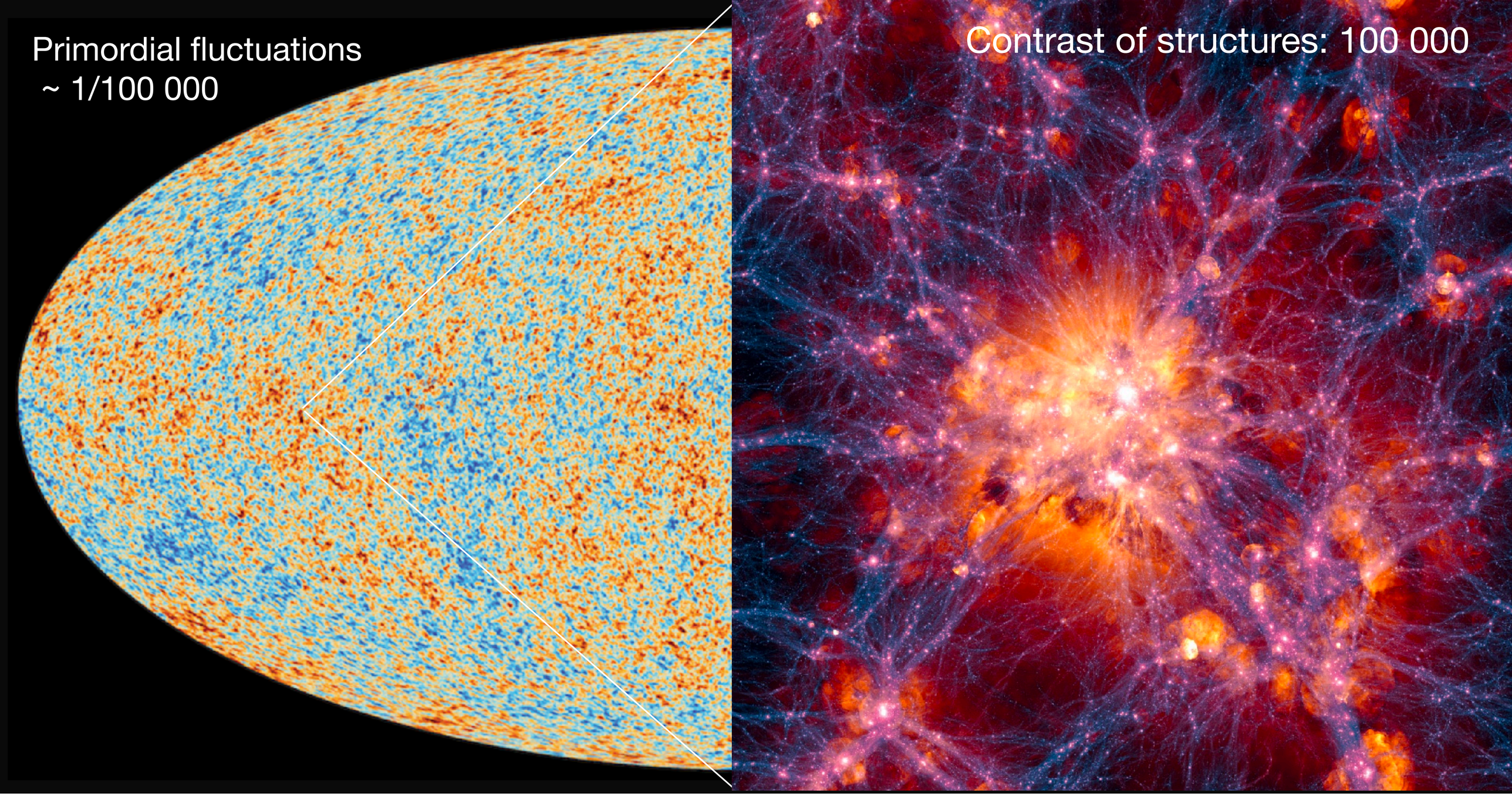
cnrs

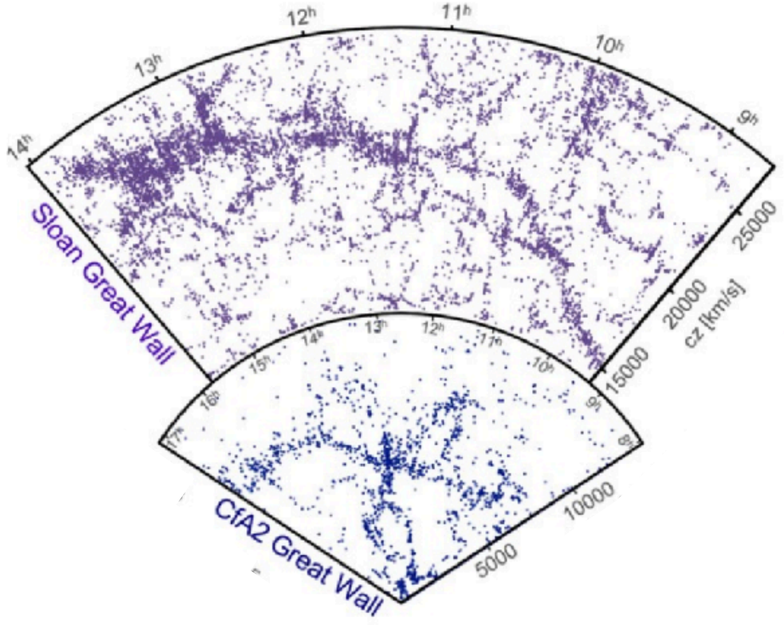
INSTITUT D'ASTROPHYSIQUE DE PARIS

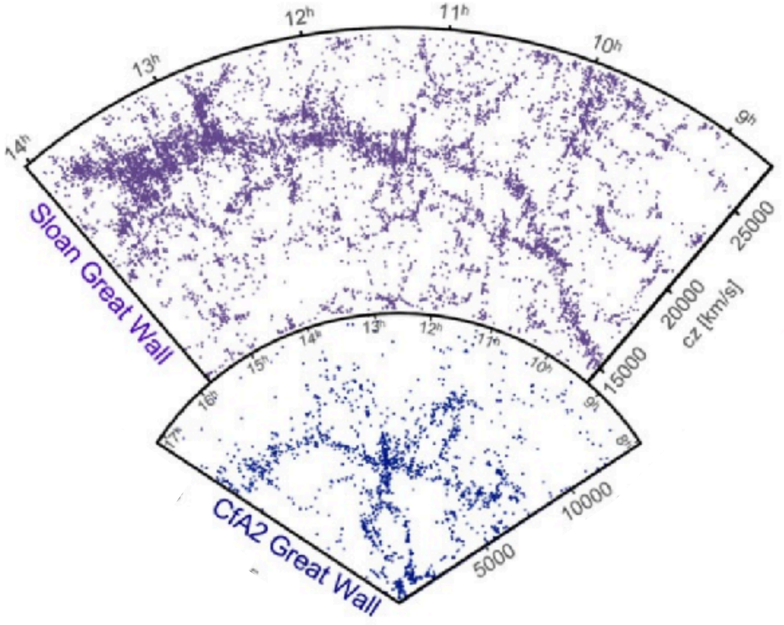
Unité mixte de recherche 7095 iAP Observatoire des sciences de l'Univers

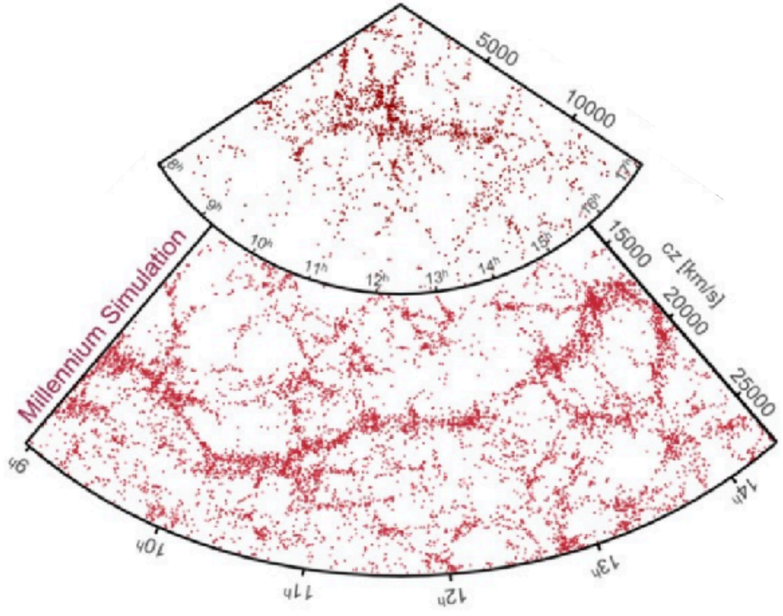
SORBONNE UNIVERSITÉ

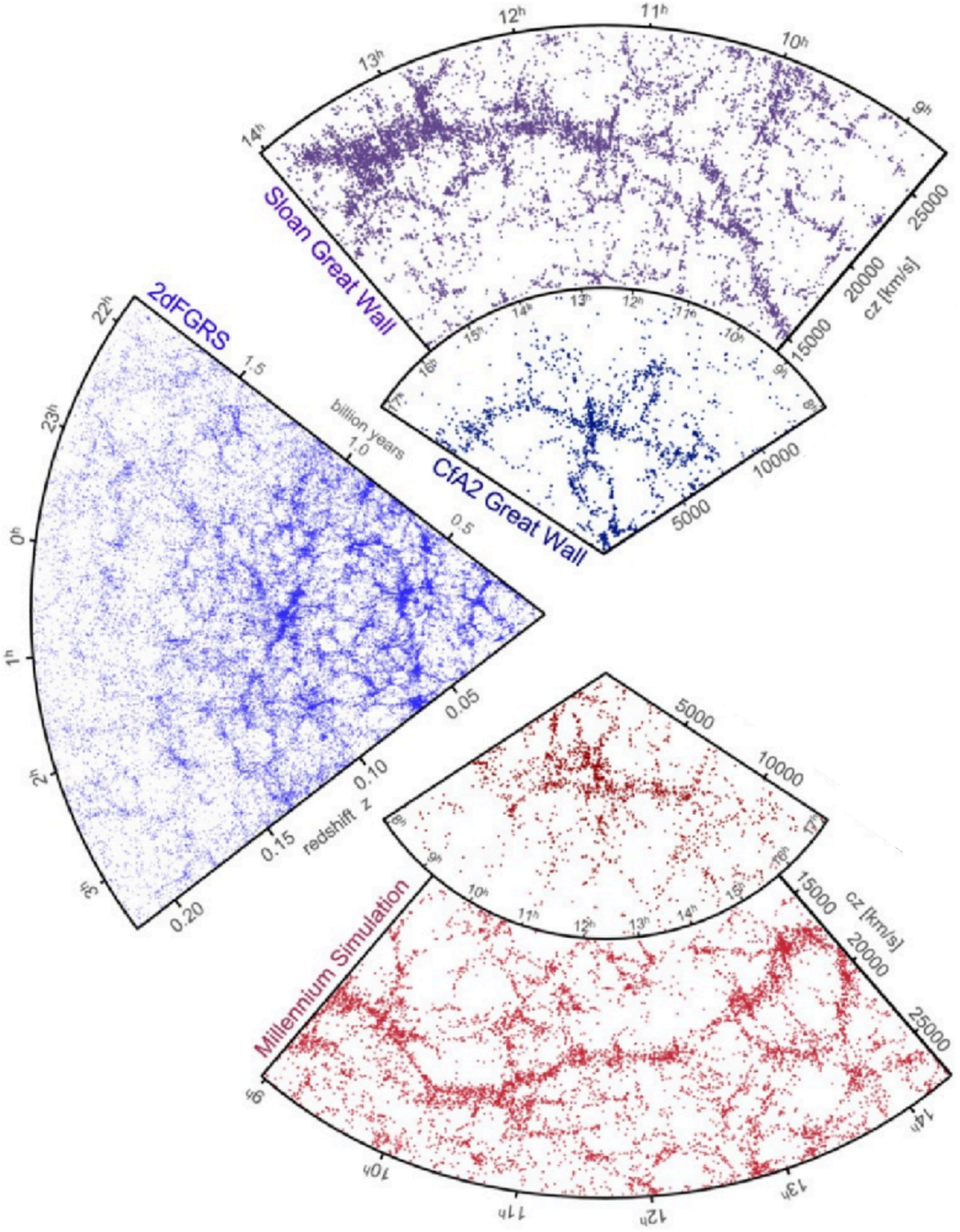

Primordial fluctuations
~ 1/100 000

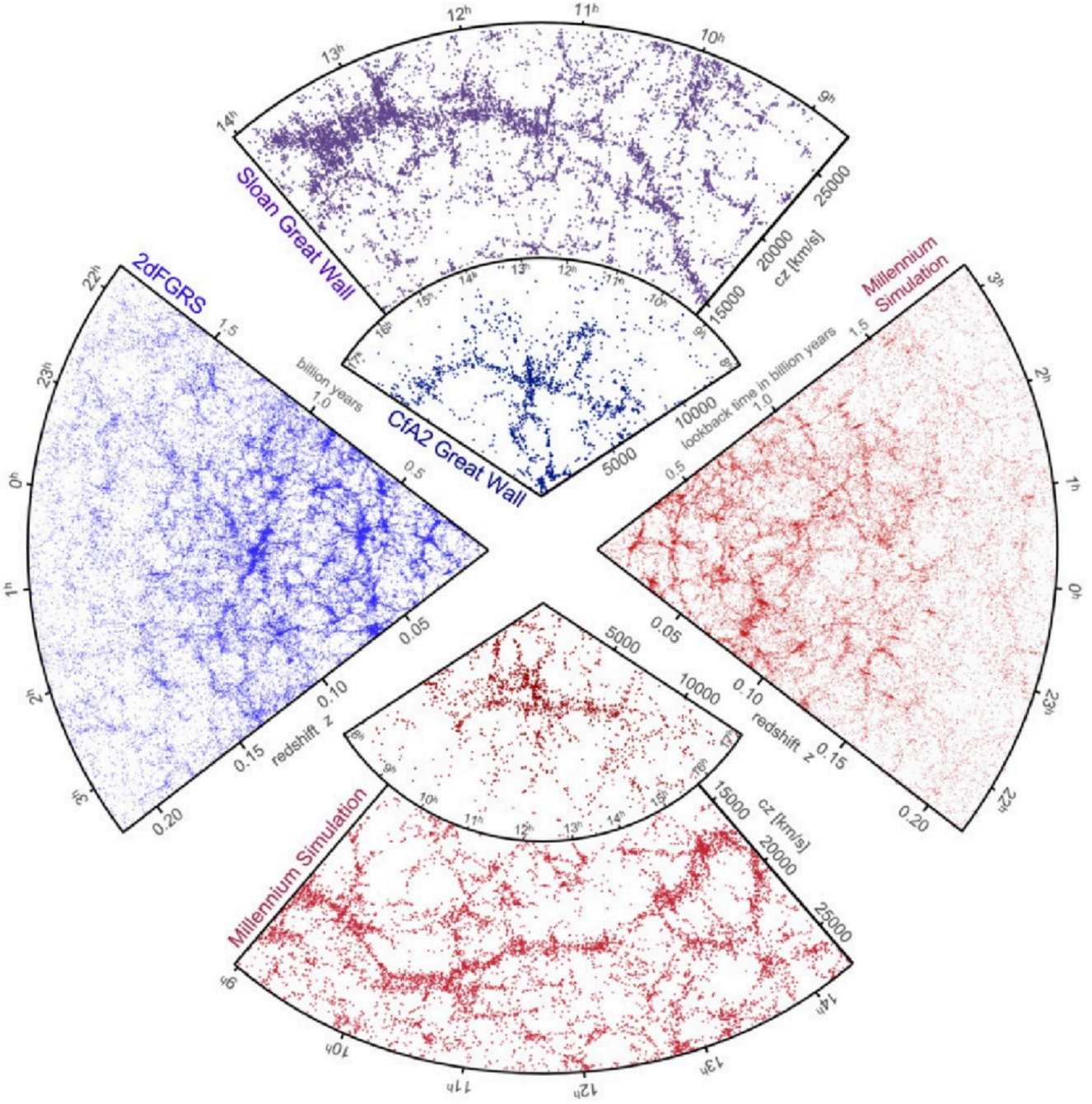

Primordial fluctuations
~ 1/100 000
Contrast of structures: 100 000


12h
11h
13h
10h
14h
9h
Sloan Great Wall
25000
20000
cz [km/s]
15000
13h
12h
14h
11h
15h
10h
16h
9h
17h
8h
CfA2 Great Wall
10000
5000


12h
11h
10h
13h
9h
14h
Sloan Great Wall
25000
20000
cz [km/s]
15000
15h
14h
13h
12h
11h
10h
16h
9h
17h
8h
CfA2 Great Wall
10000
5000


5000
10000
8h
7h
9h
16h
10h
15h
11h
14h
12h
13h
15000
cz [km/s]
20000
25000
Millennium Simulation
9h
14h
10h
13h
11h
12h


Sloan Great Wall
2dFGRS
CfA2 Great Wall
Millennium Simulation
billion years
redshift z
cz [km/s]


Sloan Great Wall
2dFGRS
CfA2 Great Wall
Millennium Simulation
Millennium Simulation
billion years
lookback time in billion years
redshift z
cz [km/s]

Star formation is regulated on multiple spatial and temporal scales!

cosmological accretion

black hole feedback

stellar feedback

bar and spiral physics

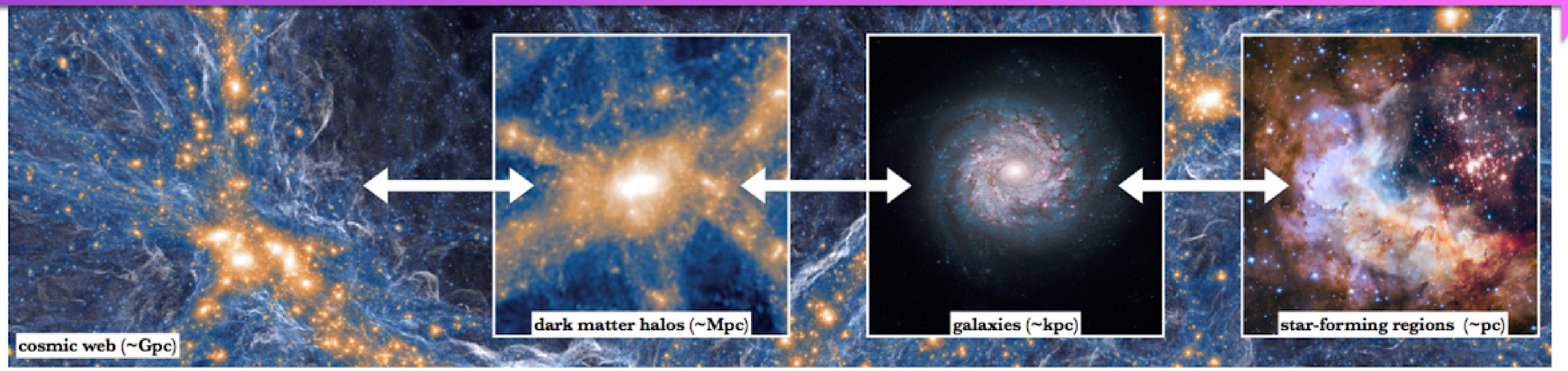
mergers

cloud physics

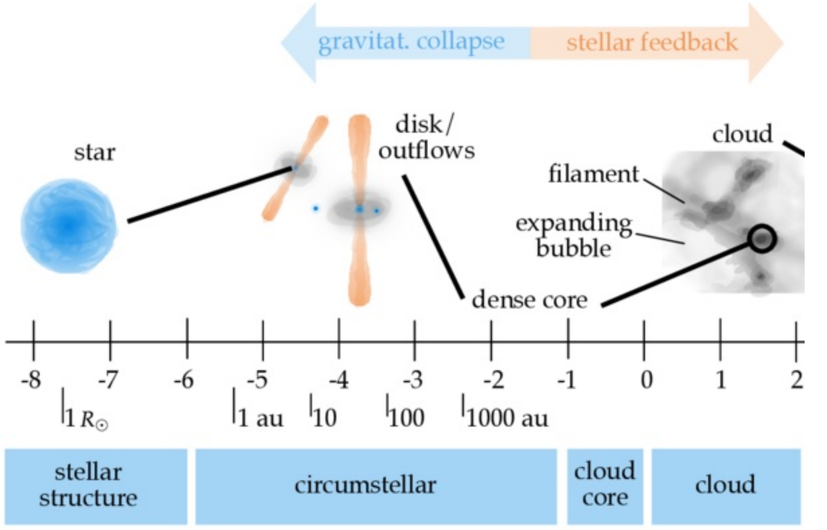
re-accretion of outflows

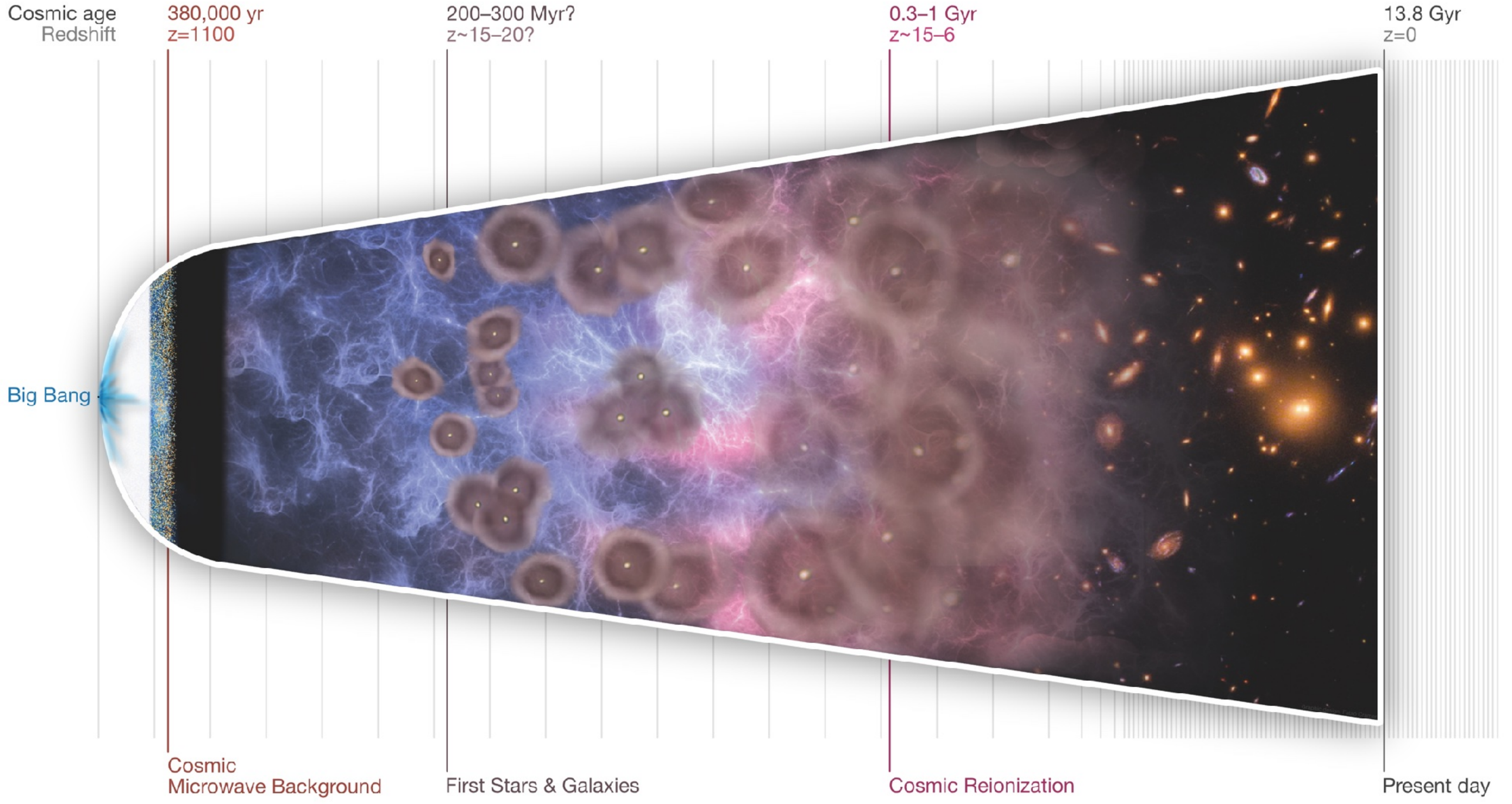
long timescales (>10^9 yr)

short timescales (<10^7 yr)



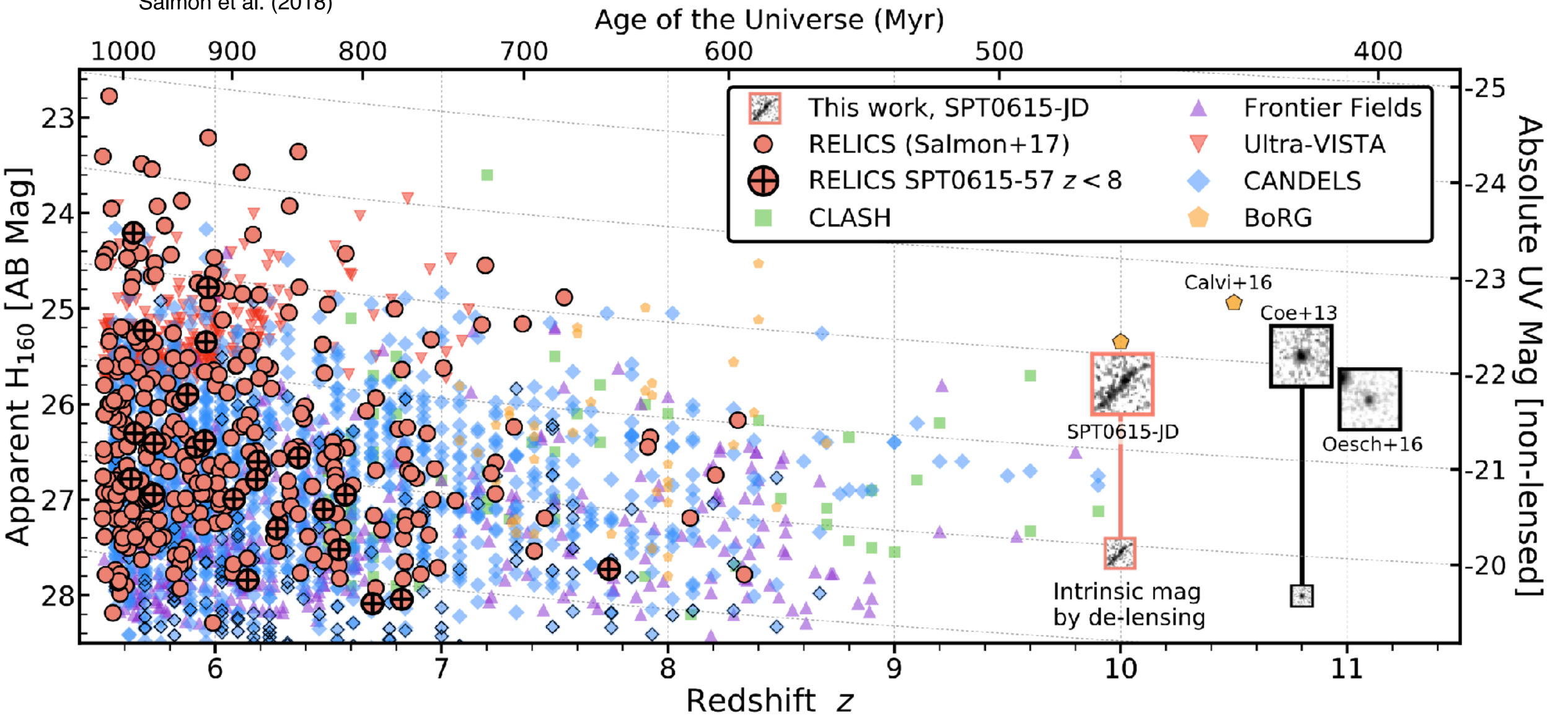
Tacchella et al. 2020
Green et al. 2022



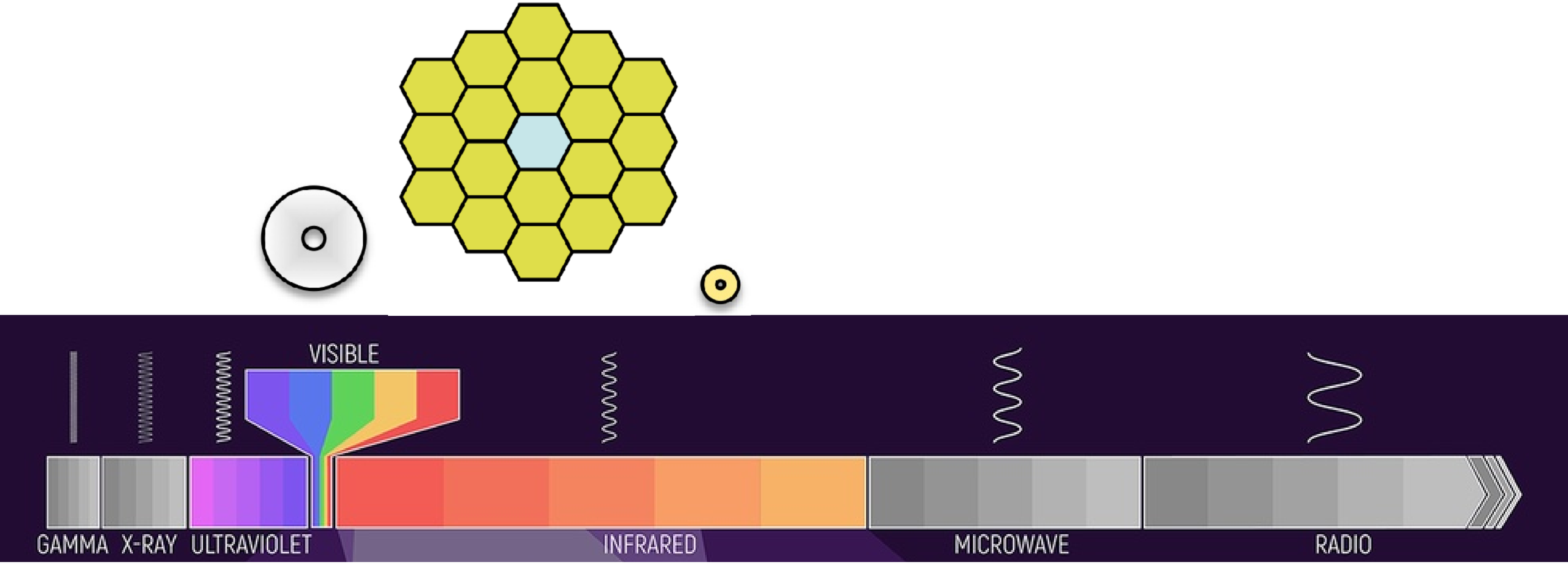

Cosmic age
Redshift
380,000 yr
z=1100
200–300 Myr?
z~15–20?
0.3–1 Gyr
z~15–6
13.8 Gyr
z=0
Big Bang
Cosmic
Microwave Background
First Stars & Galaxies
Cosmic Reionization
Present day


Moon
to scale
XDF

Salmon et al. (2018)




S
W


VISIBLE
GAMMA
X-RAY
ULTRAVIOLET
INFRARED
MICROWAVE
RADIO

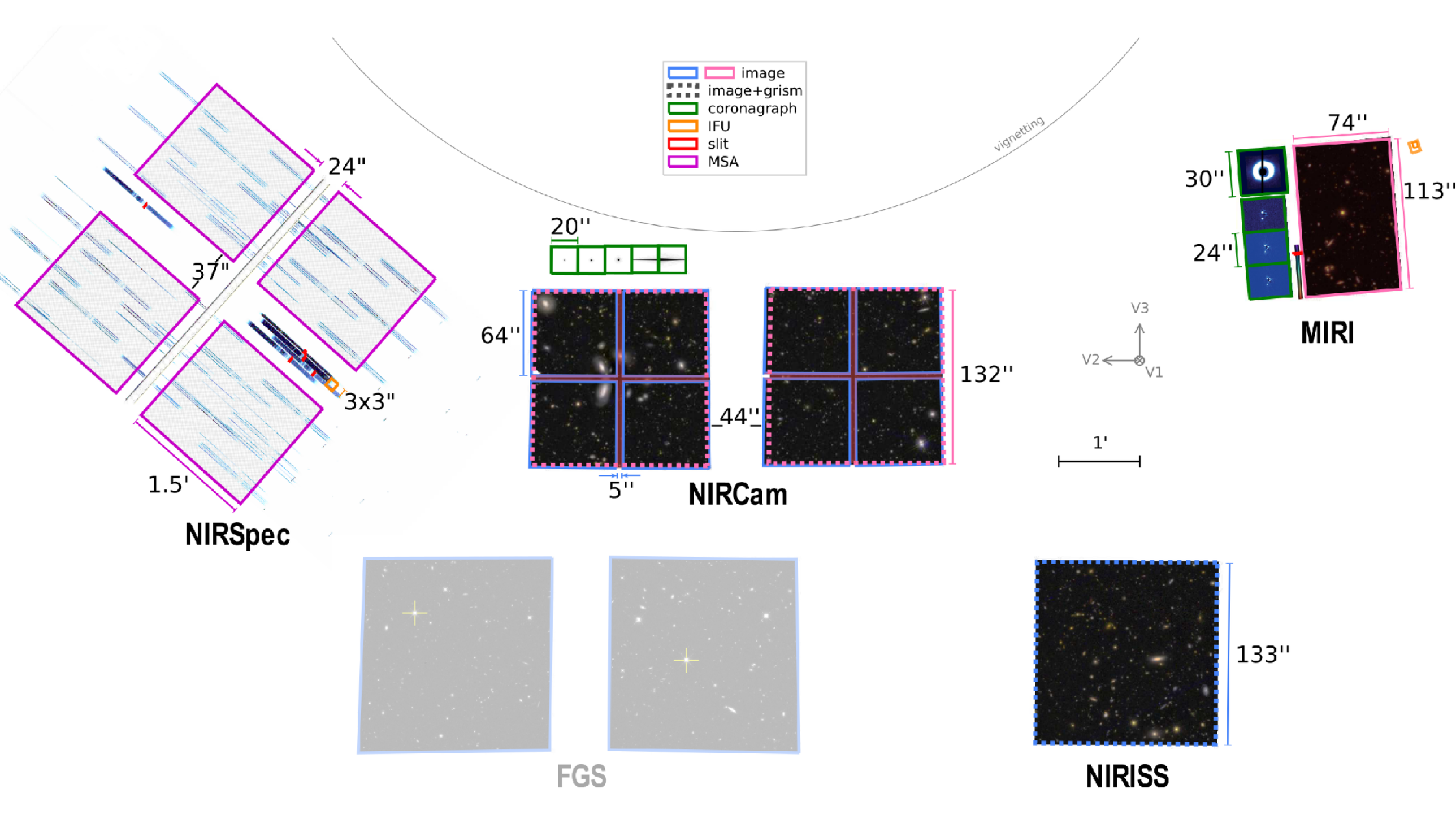
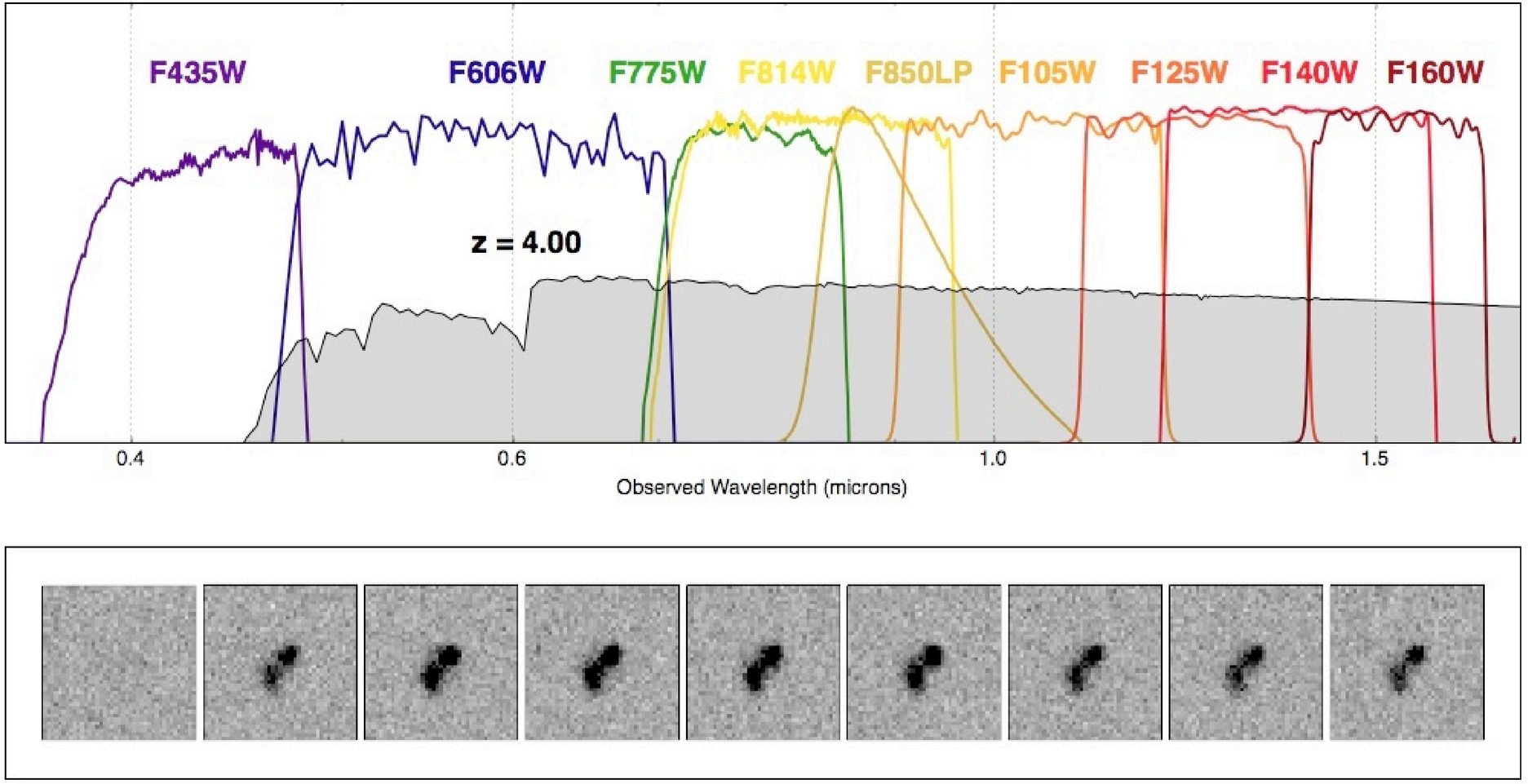


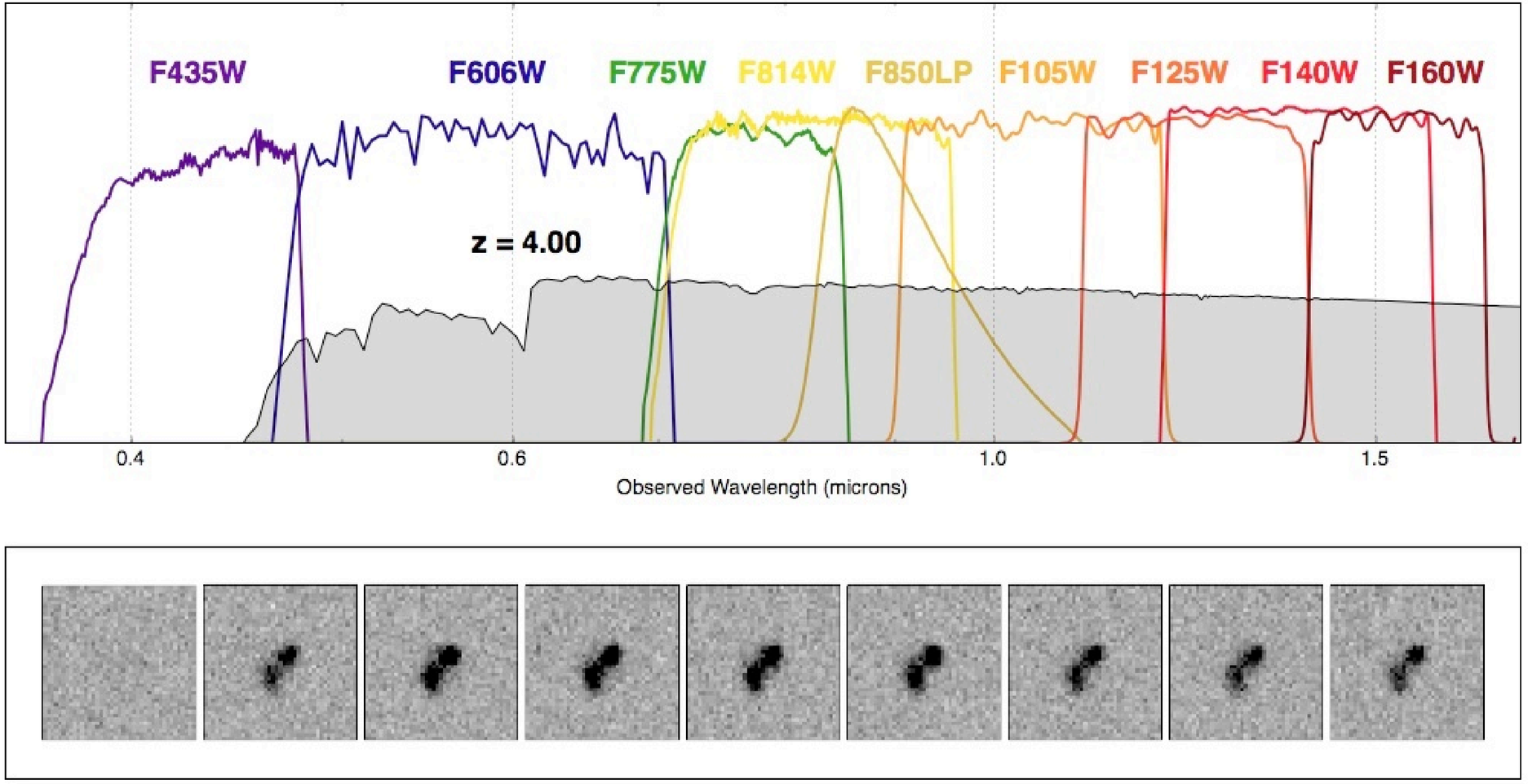
image
image+grism
coronagraph
IFU
slit
MSA
vignetting
24"
37"
3x3"
1.5'
NIRSpec
20"
64"
44"
132"
5"
NIRCam
V3
V2
V1
1'
74"
30"
24"
113"
MIRI
FGS
133"
NIRISS

Identification of distant galaxies

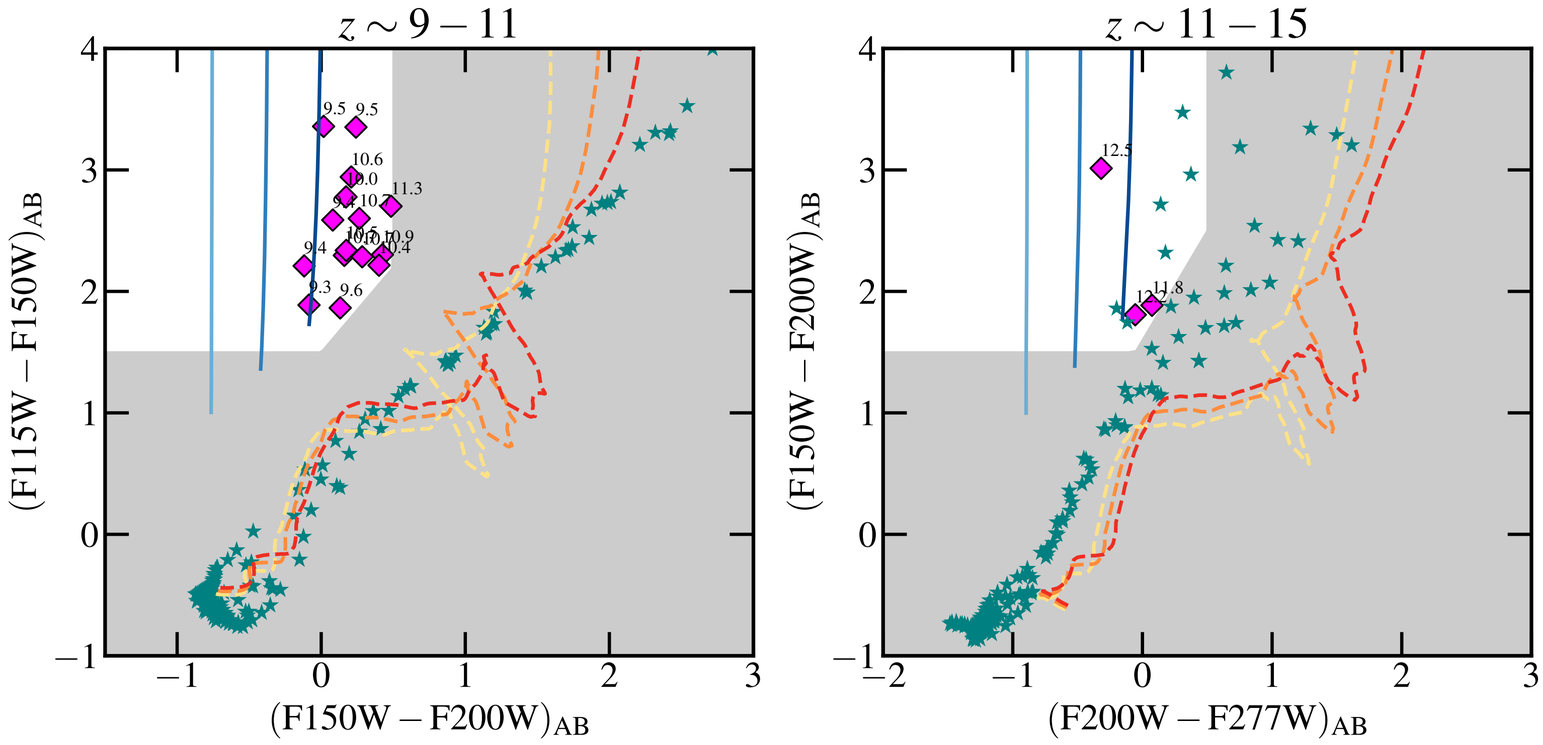


The XDF team

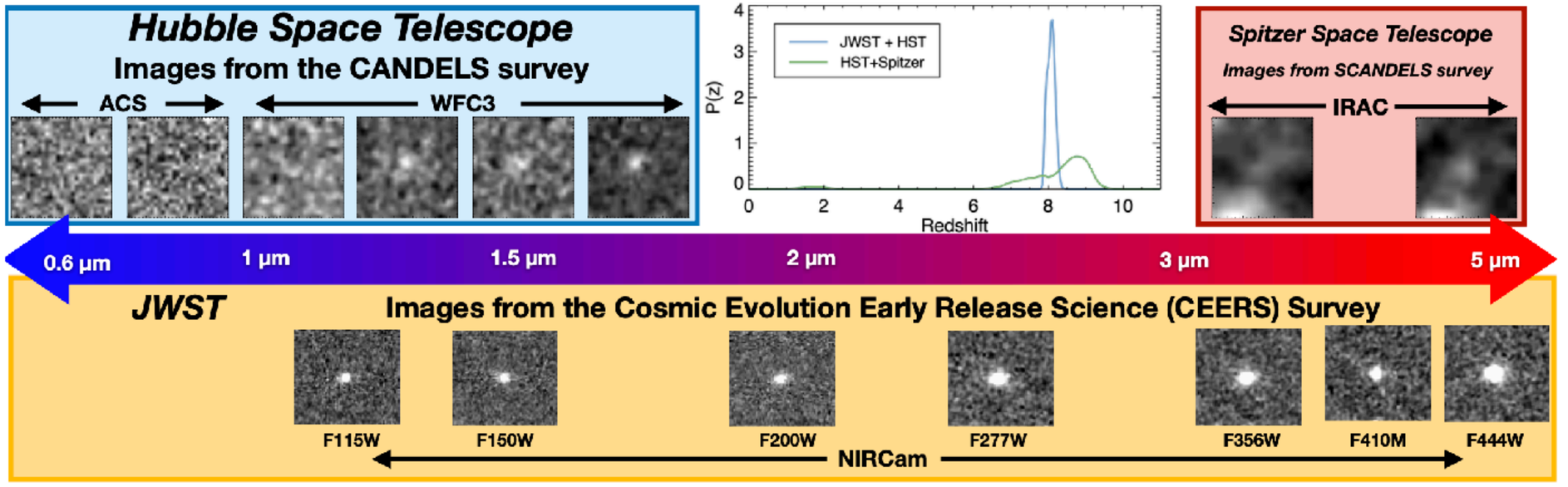
Identification of distant galaxies



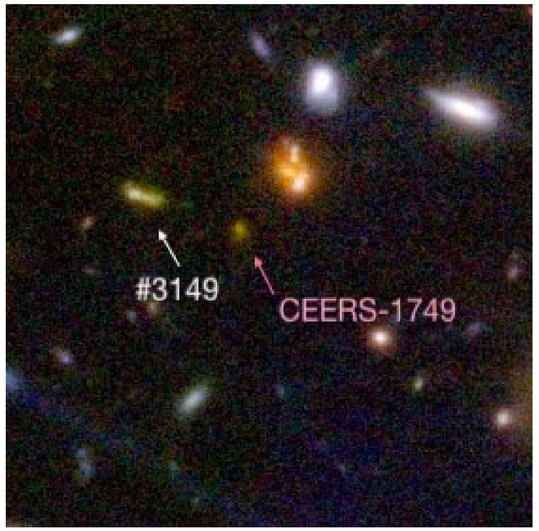
The XDF team

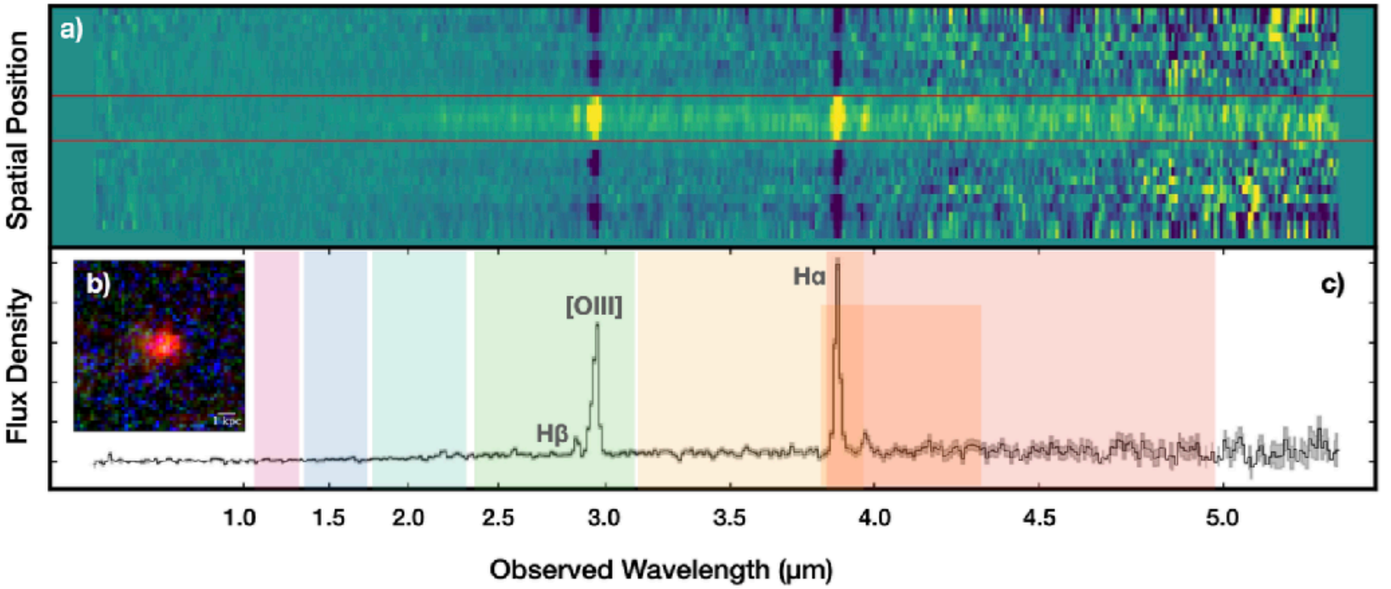


Atek et al. 2023

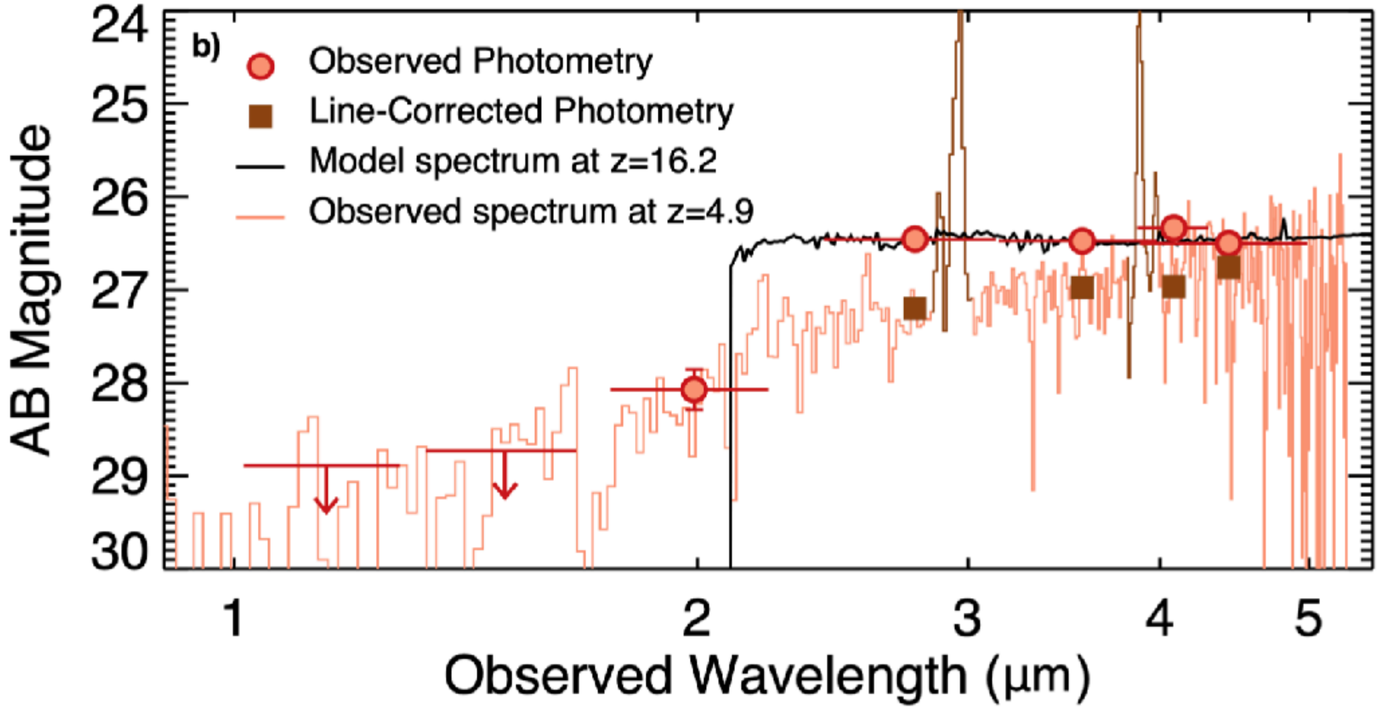


Finkelstein et al. 2023

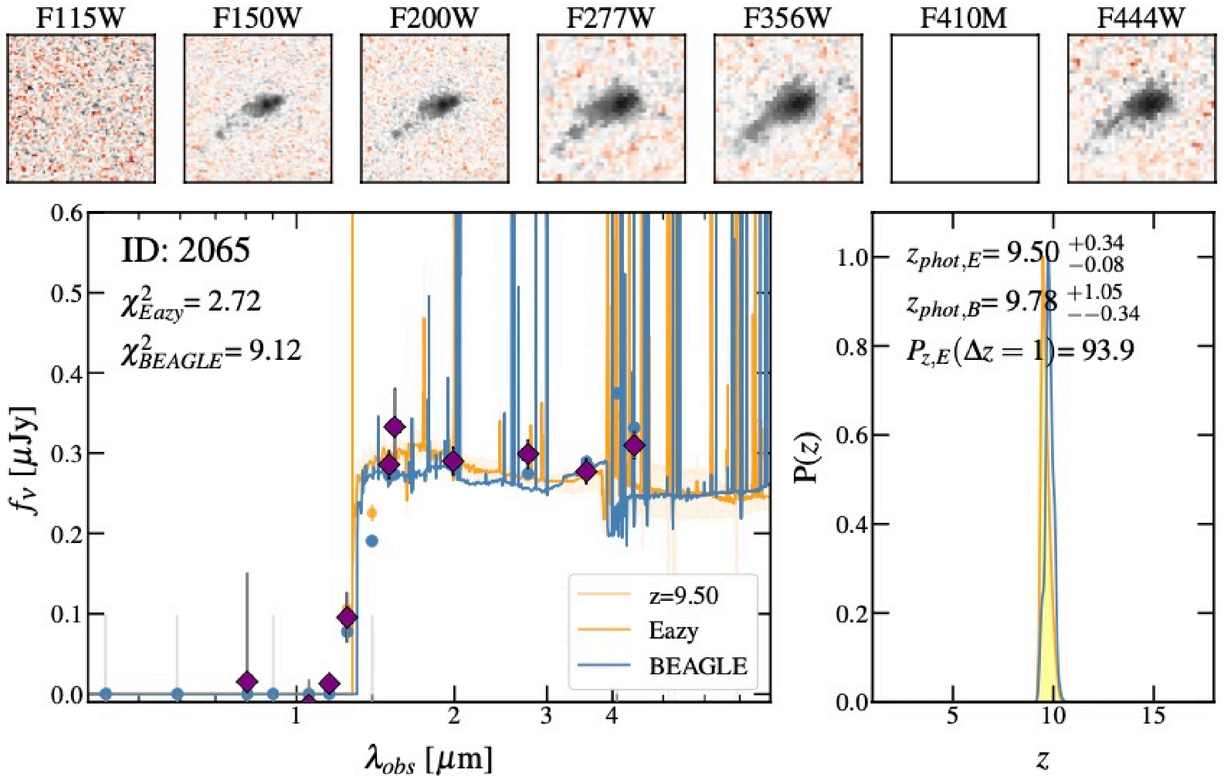


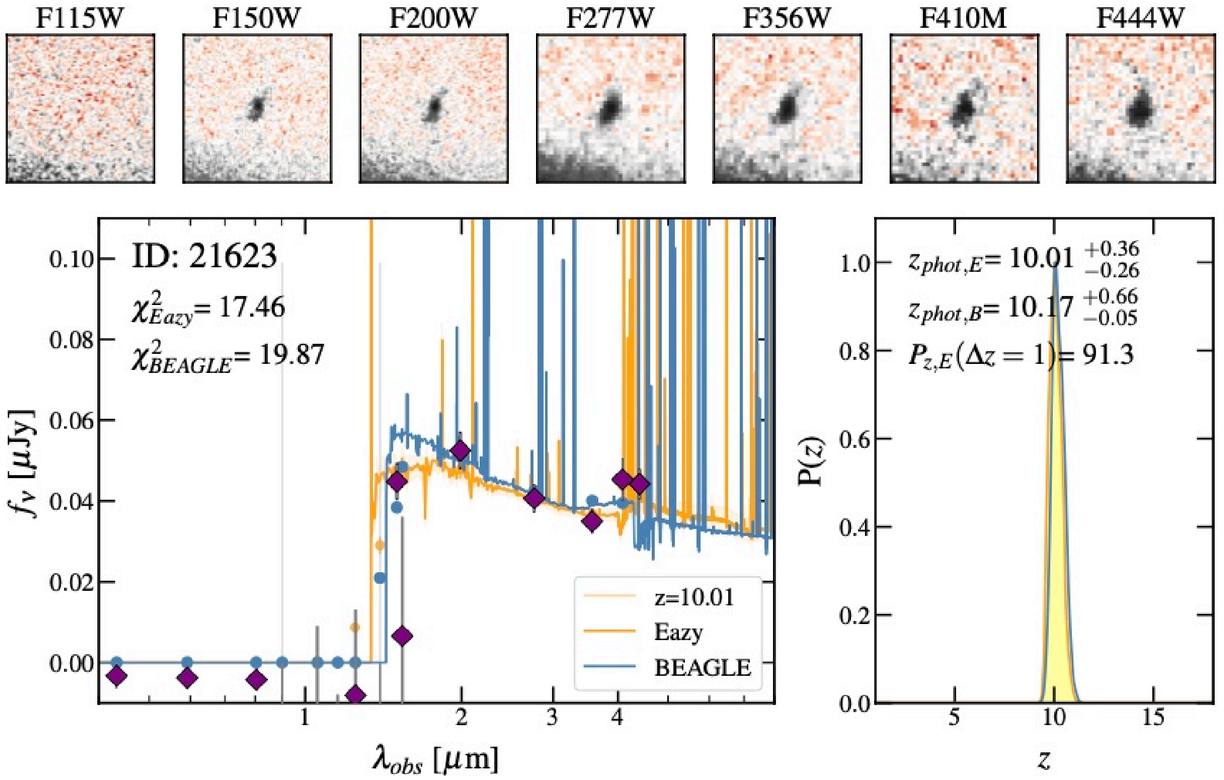


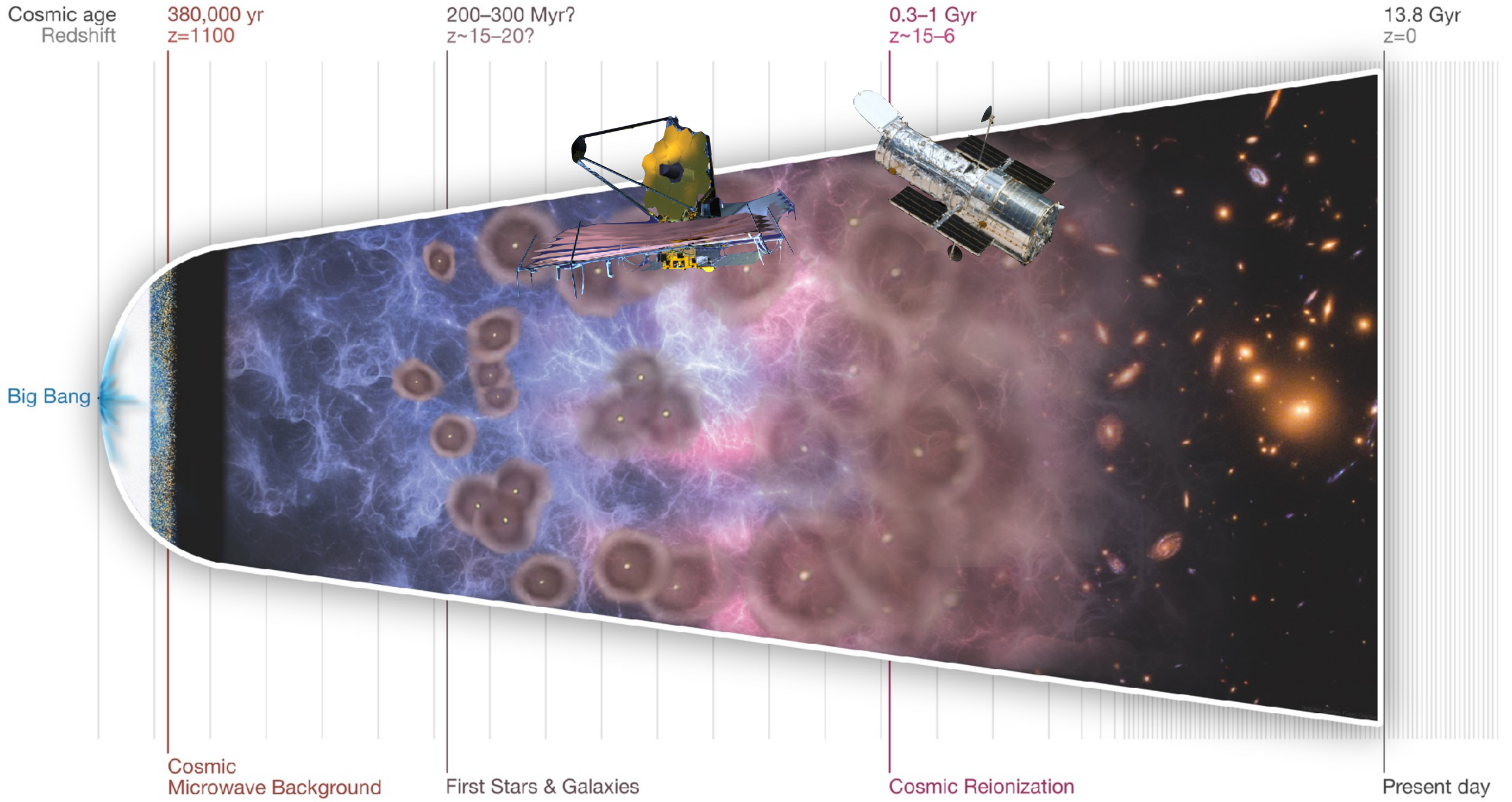
Arrabal Haro et al. 2023



Photometric redshifts with SED fitting methods






Cosmic age
Redshift
380,000 yr
z=1100
200–300 Myr?
z~15–20?
0.3–1 Gyr
z~15–6
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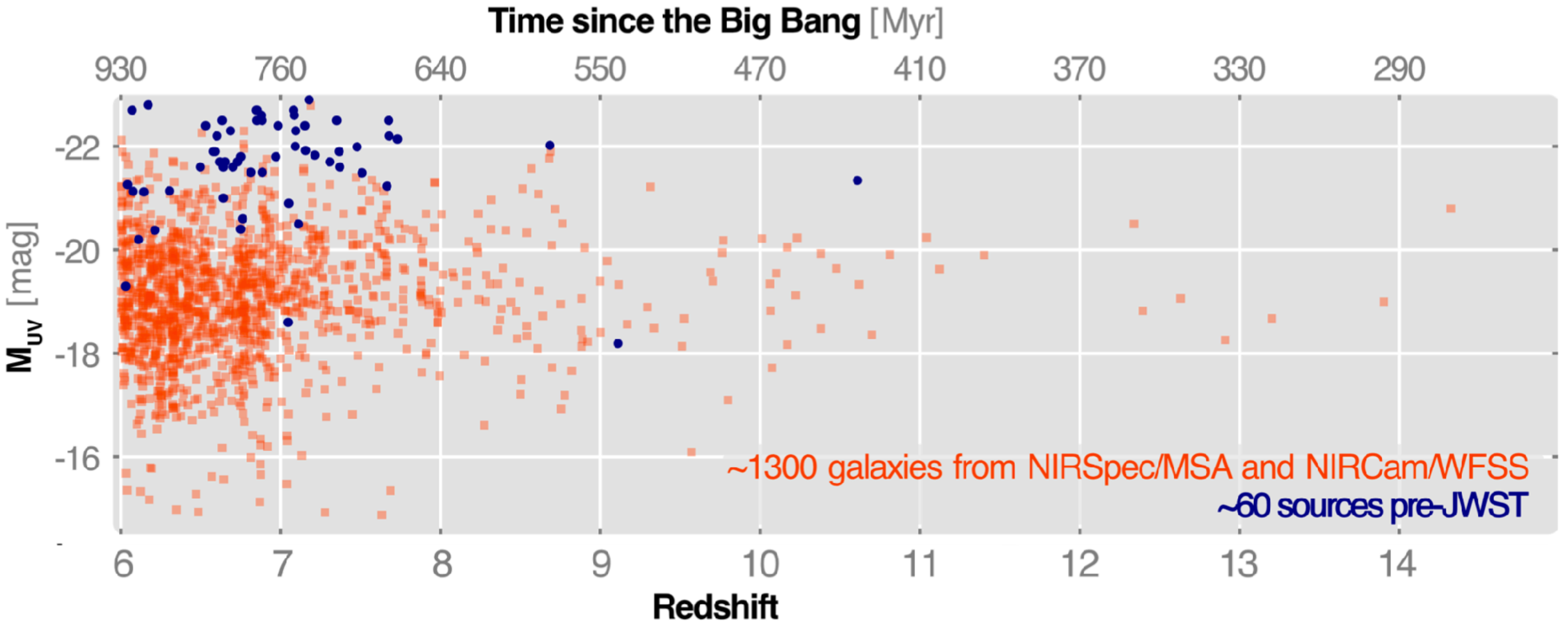
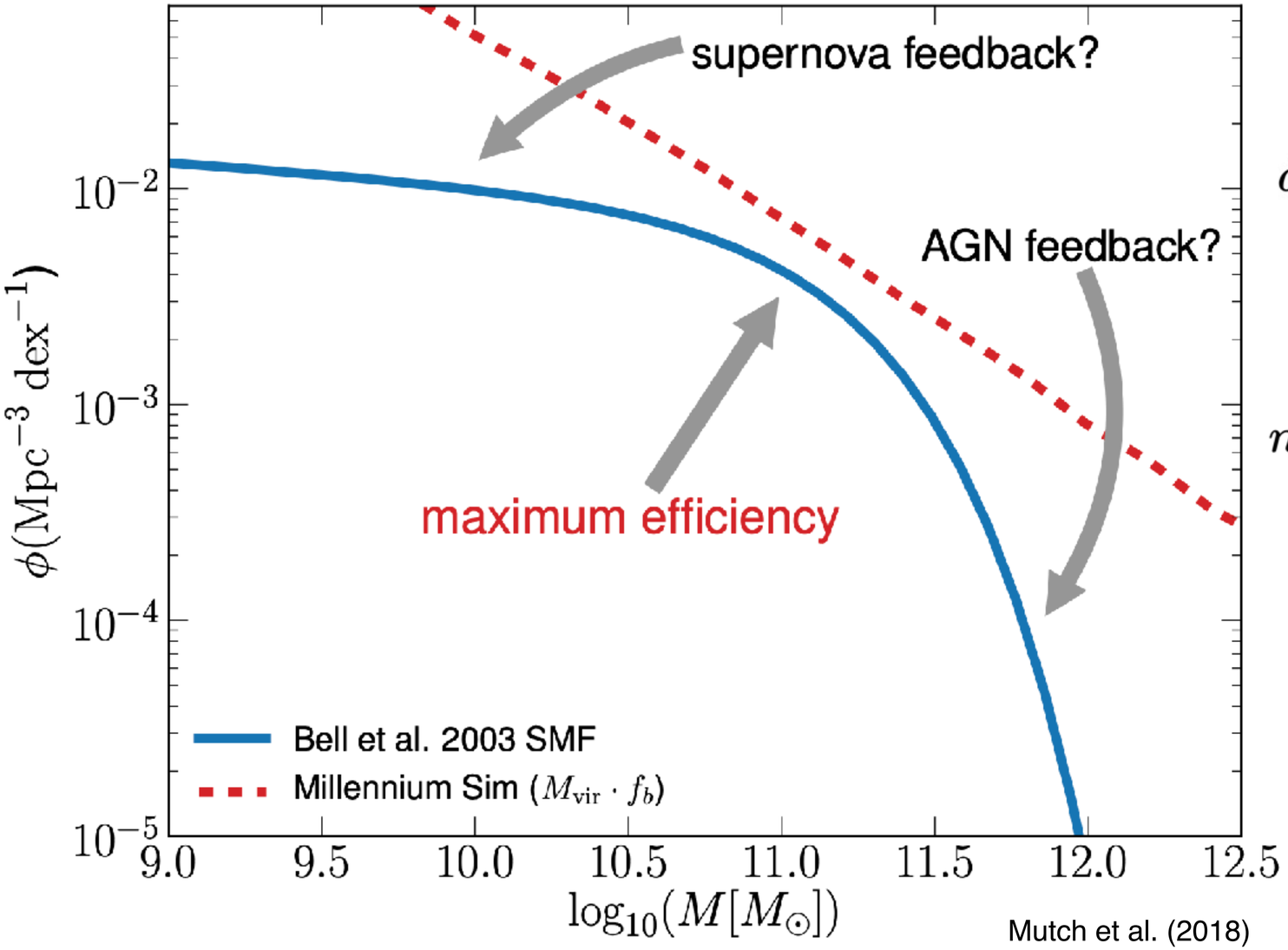
Big Bang
Cosmic
Microwave Background
First Stars & Galaxies
Cosmic Reionization
Present day


Time since the Big Bang [Myr]
930
760
640
550
470
410
370
330
290
-22
-20
-18
-16
M_{UV} [mag]
~1300 galaxies from NIRSpec/MSA and NIRCam/WFSS
~60 sources pre-JWST
6
7
8
9
10
11
12
13
14
Redshift

What Does Luminosity Functions Tell Us About Galaxy Formation ?

Halo and Galaxy Mass Functions



Mutch et al. (2018)

$$dn(L) = \phi\, dL = \phi^* \left(\frac{L}{L^*}\right)^{\alpha} \mathrm{e}^{-L/L^*}\, d\left(\frac{L}{L^*}\right)$$

$$n(M)\, dM = (0.4\, \ln 10)\, \phi^*\, [10^{0.4(M^*-M)}]^{\alpha+1}$$

$$\exp[-10^{0.4(M^*-M)}]\, dM$$

Star Formation Efficiency

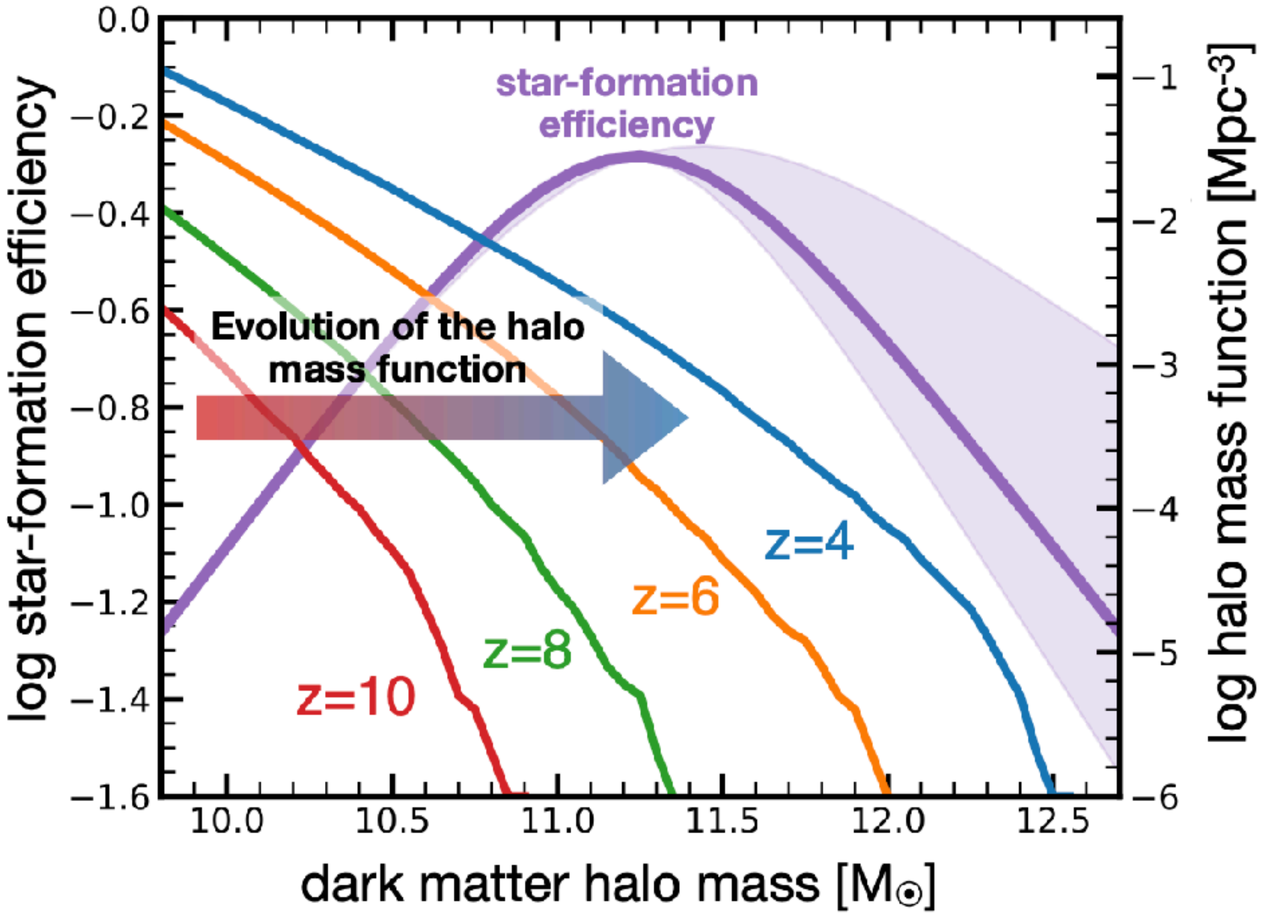
Efficiency

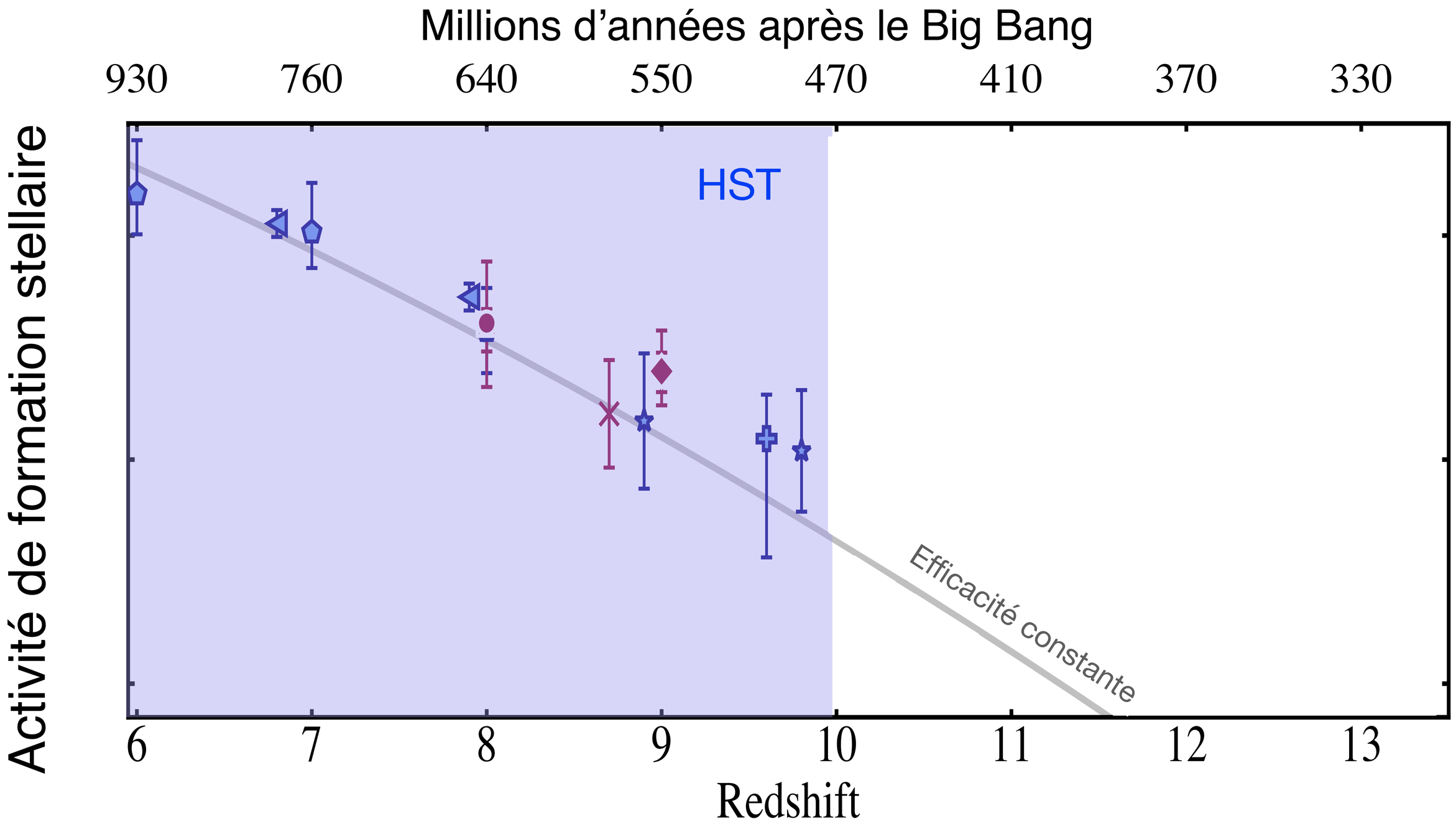
DM accretion rate

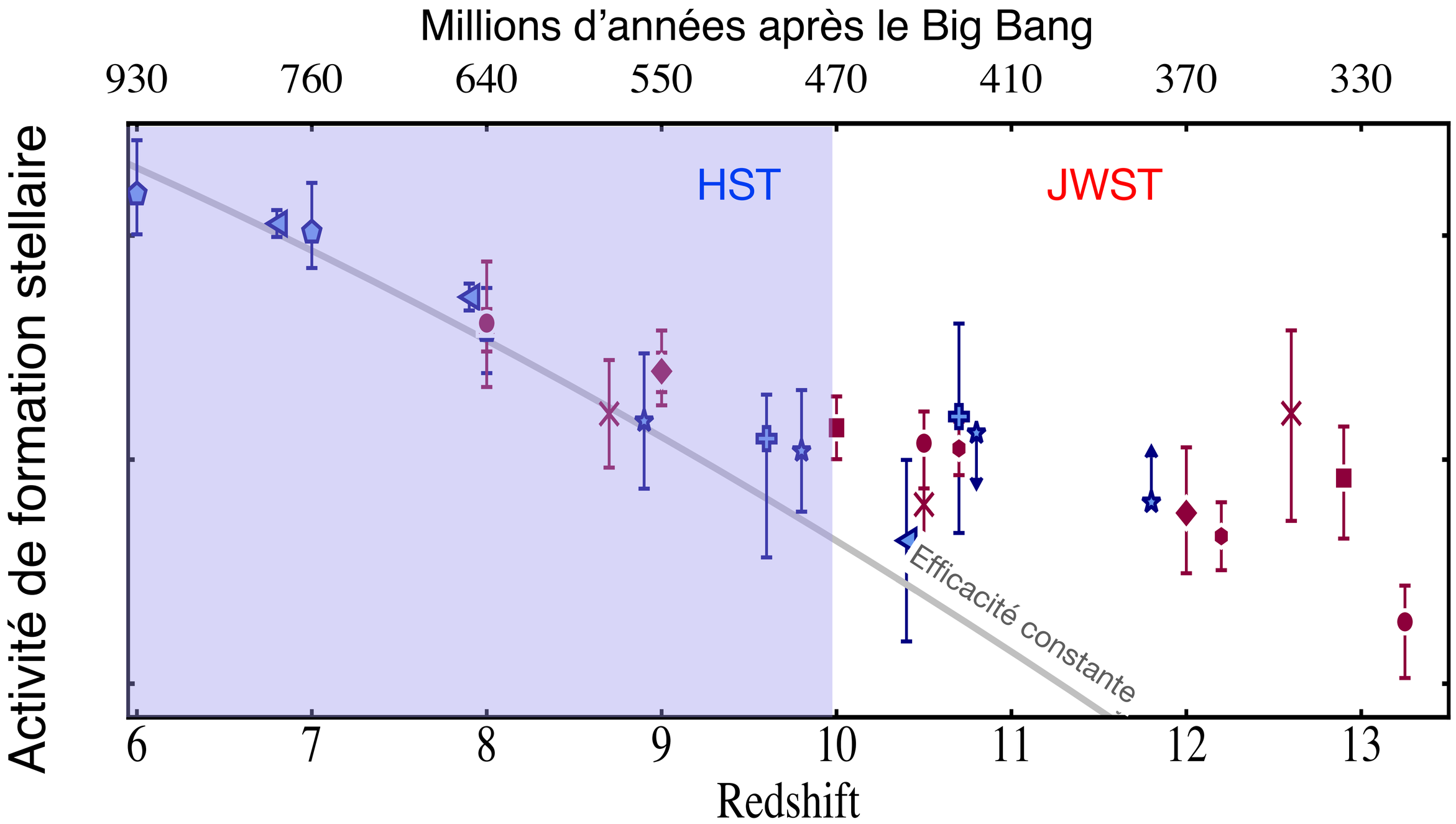
$$\mathrm{SFR}(M_h, z) = \varepsilon(M_h) f_b \frac{dM_h}{dt}$$

Baryon fraction

Tacchella et al. 2024




Millions d'années après le Big Bang
930
760
640
550
470
410
370
330
Activité de formation stellaire
HST
Efficacité constante
6
7
8
9
10
11
12
13
Redshift


Millions d'années après le Big Bang
930
760
640
550
470
410
370
330
HST
JWST
Efficacité constante
Activité de formation stellaire
6
7
8
9
10
11
12
13
Redshift

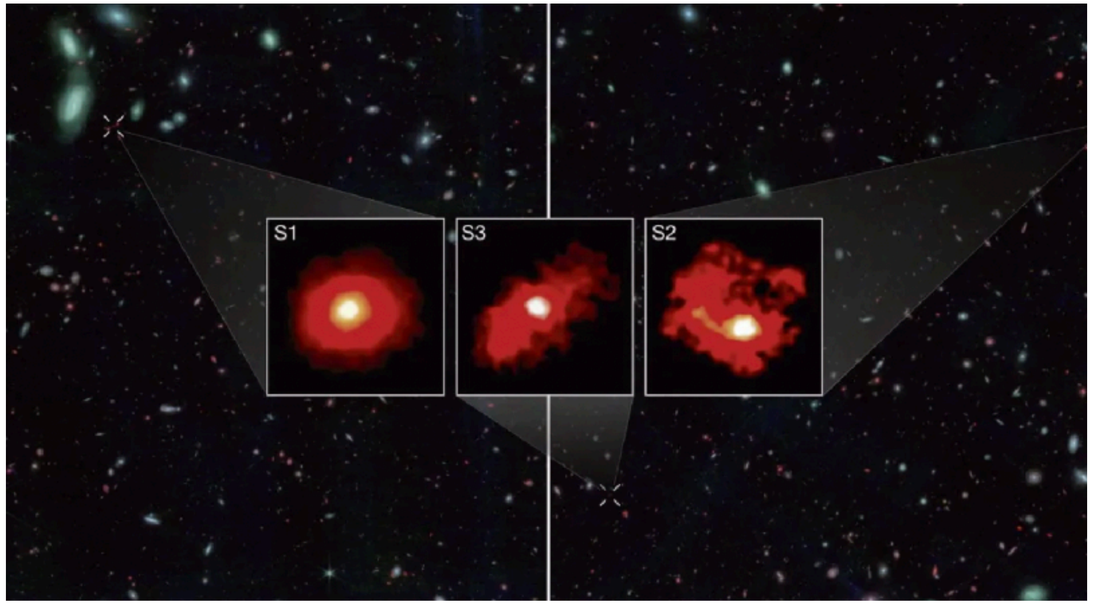
Expected properties of early galaxies

- Small, compact
- Faint, low-mass
- Irregular, no clear structure
- Metal-poor
- Young stellar population
- Number density determined by galaxy evolution (DM + baryons)

JWST, le téléscope qui a “cassé” l’Univers

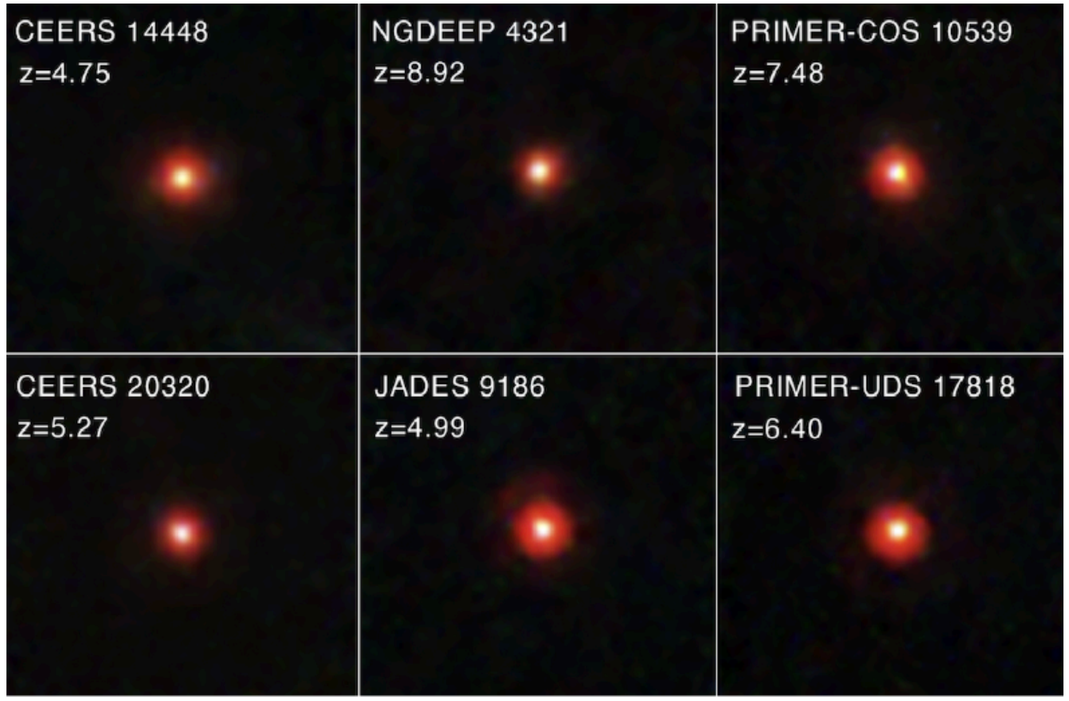
JWST’s First Glimpses of Early Galaxies Could Break Cosmology

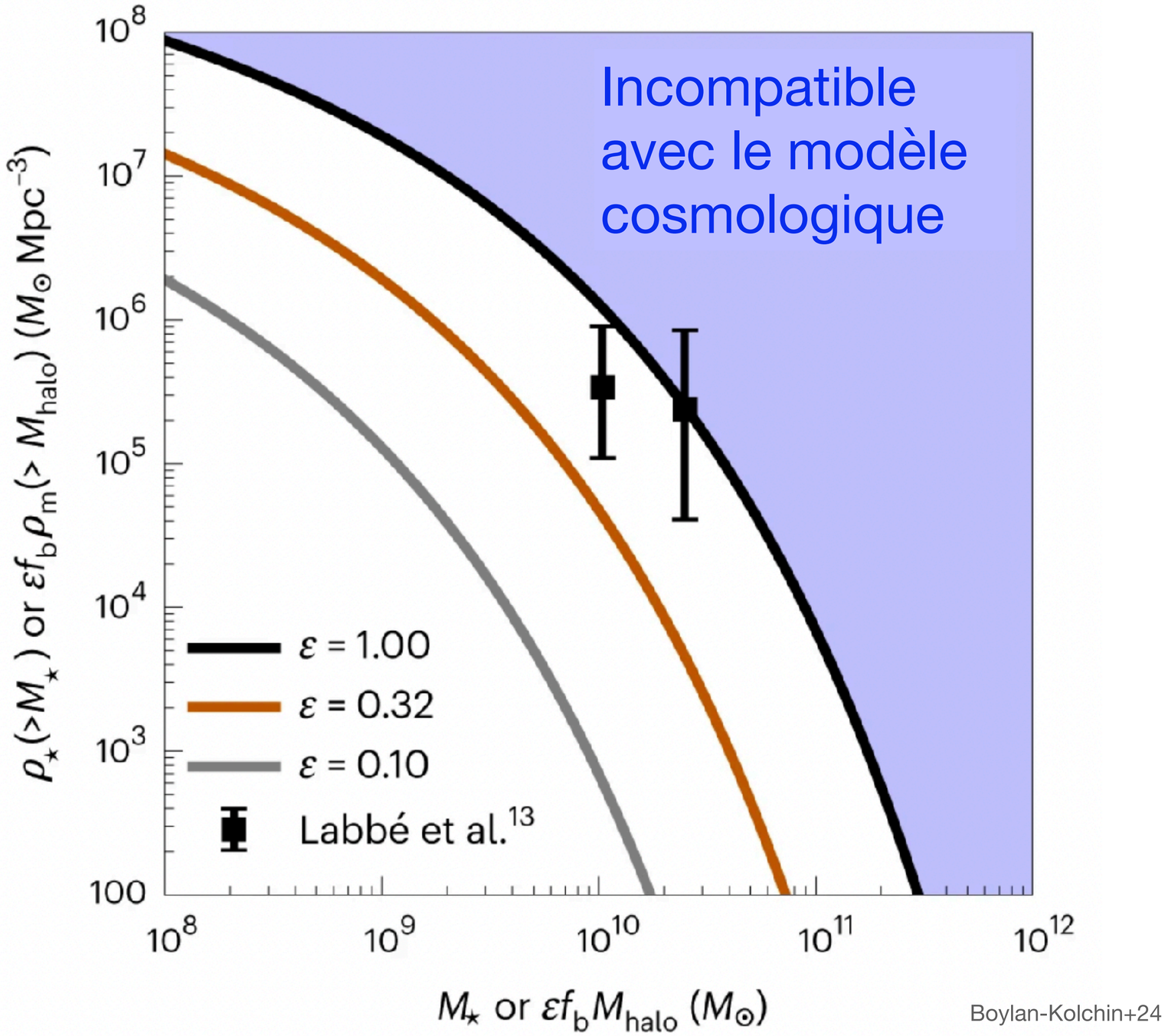
Webb Telescope Finds Evidence of Massive Galaxies That Defy Theories of the Early Universe



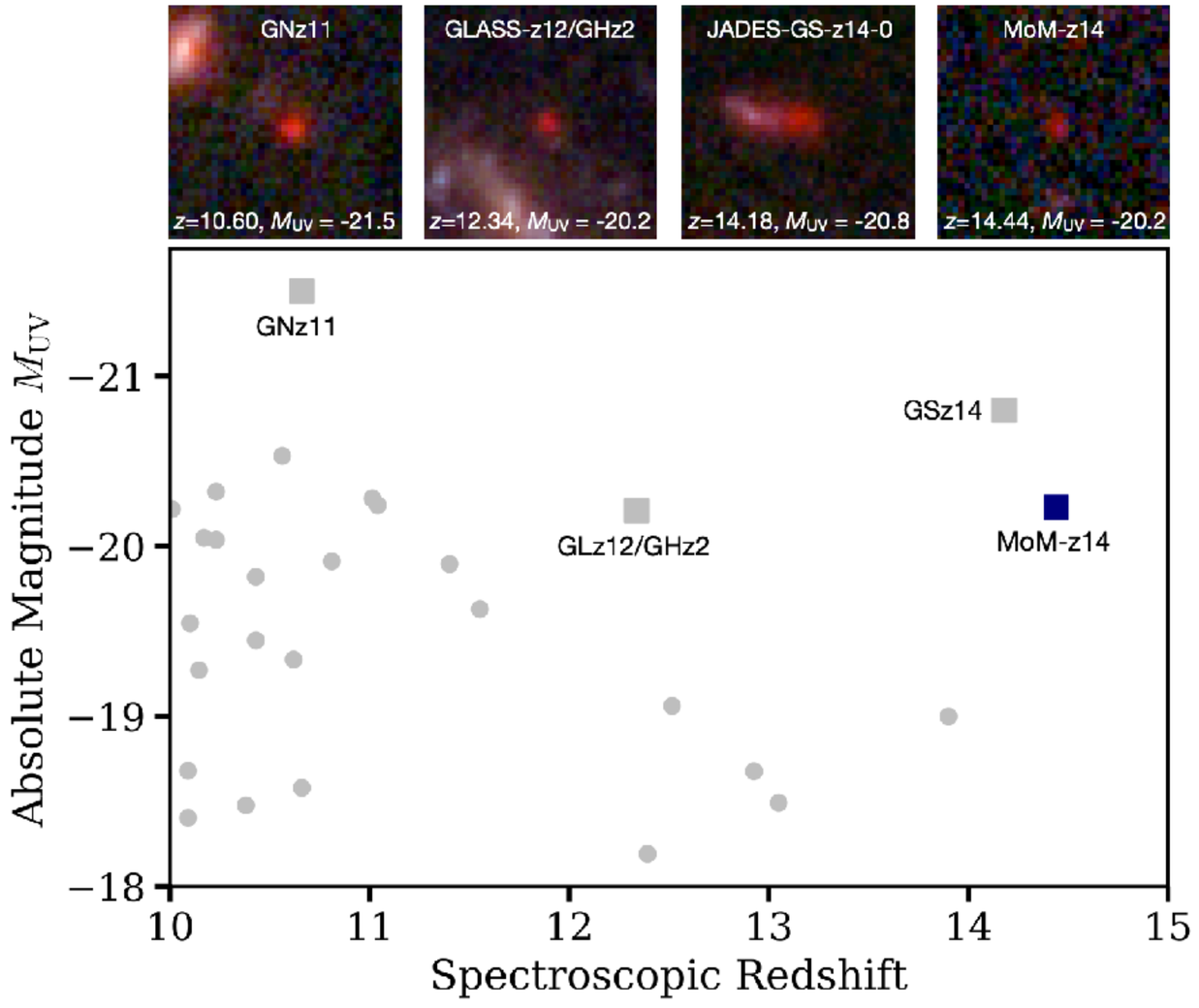
"The Universe Breakers": Six Galaxies That are Too Big, Too Early

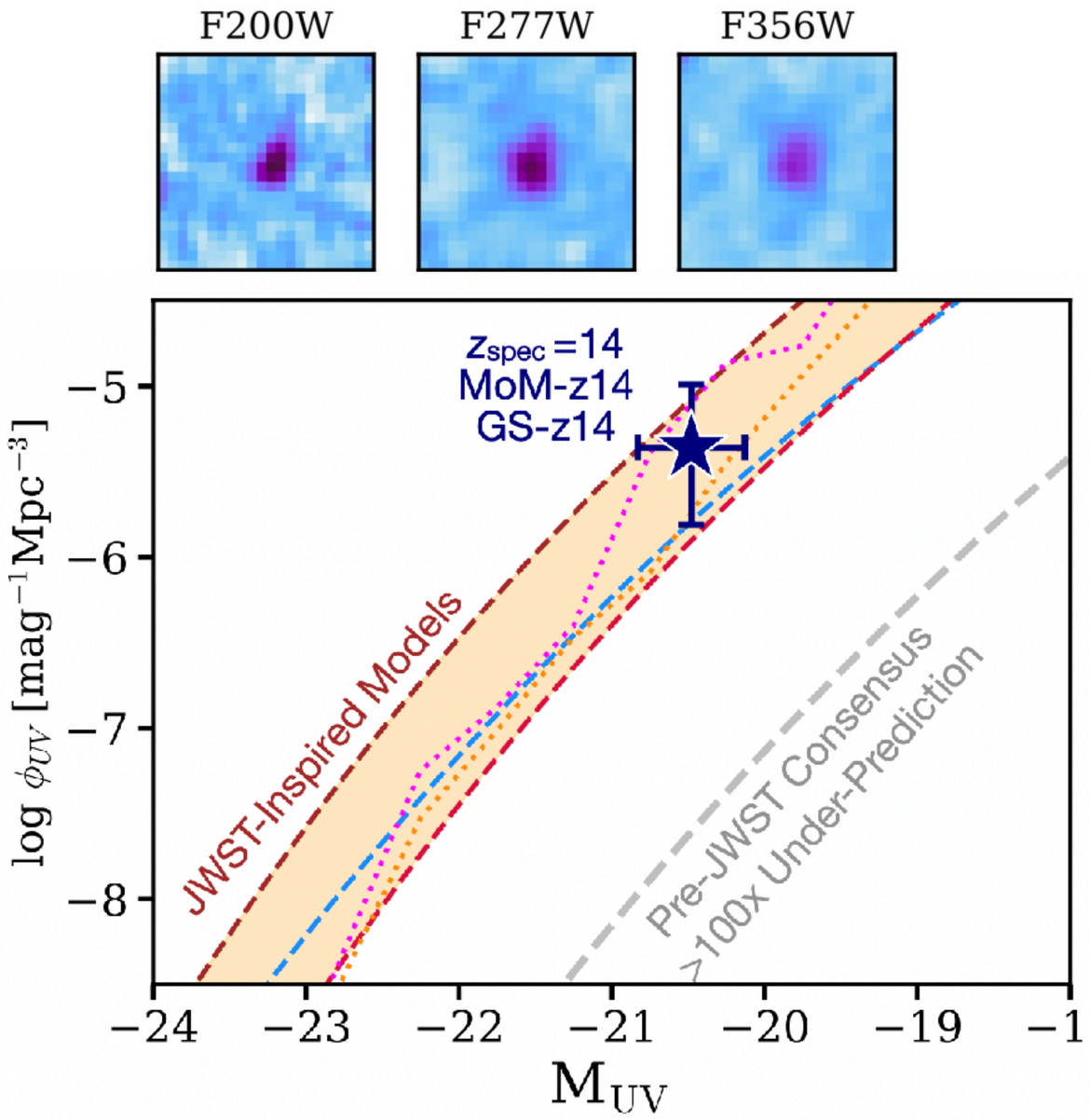
James Webb telescope detects evidence of ancient ‘universe breaker’ galaxies

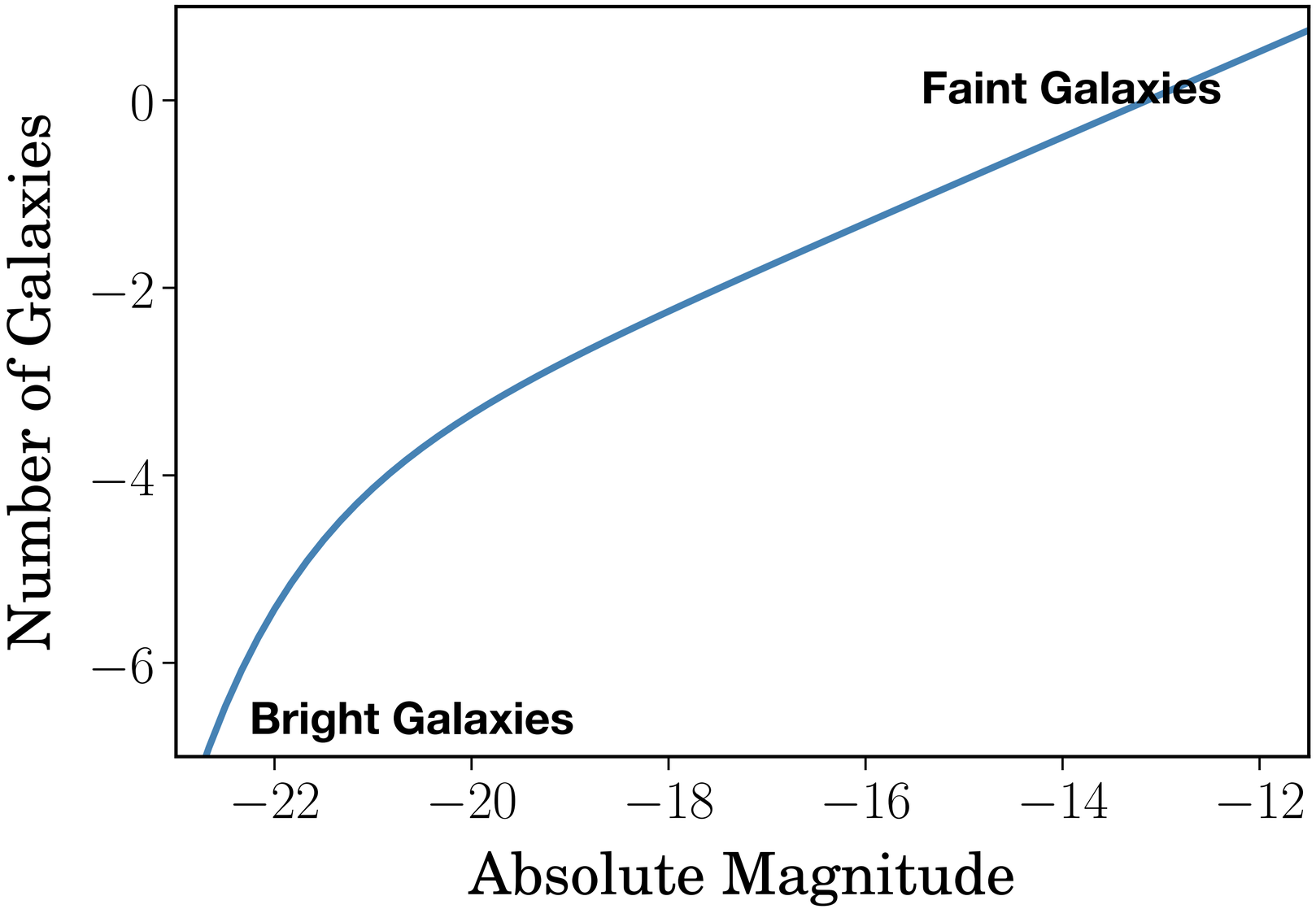


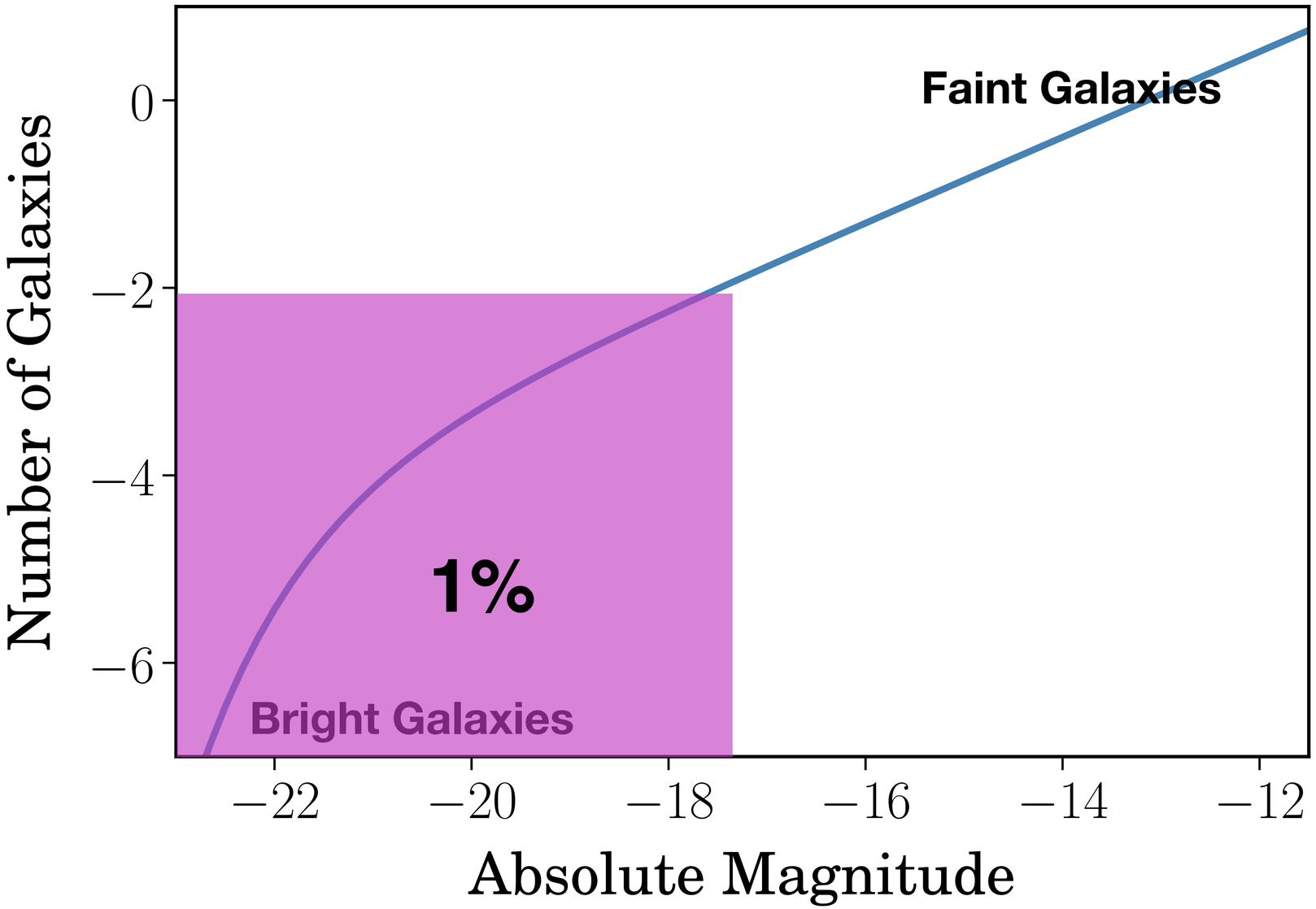


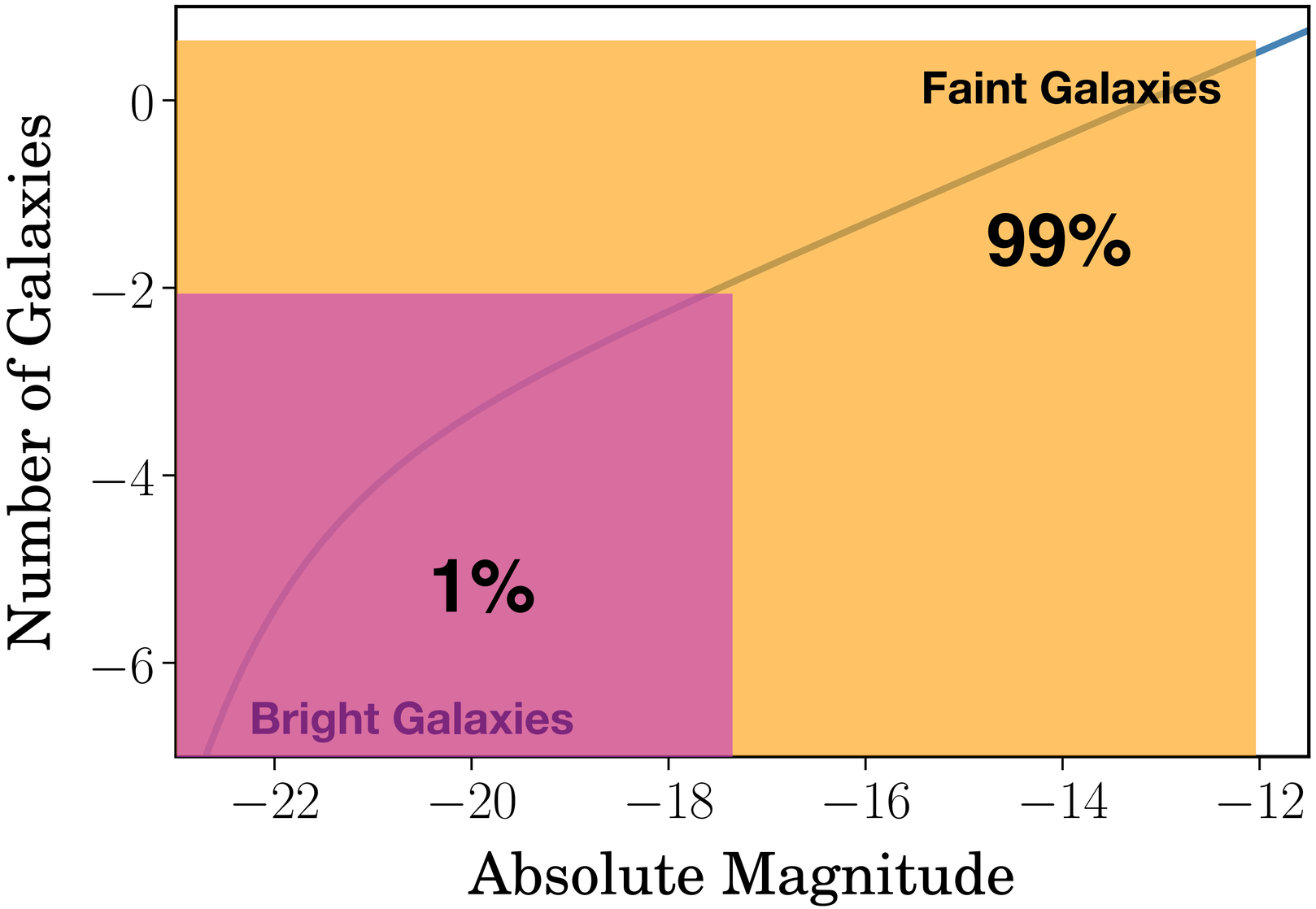
Boylan-Kolchin+24

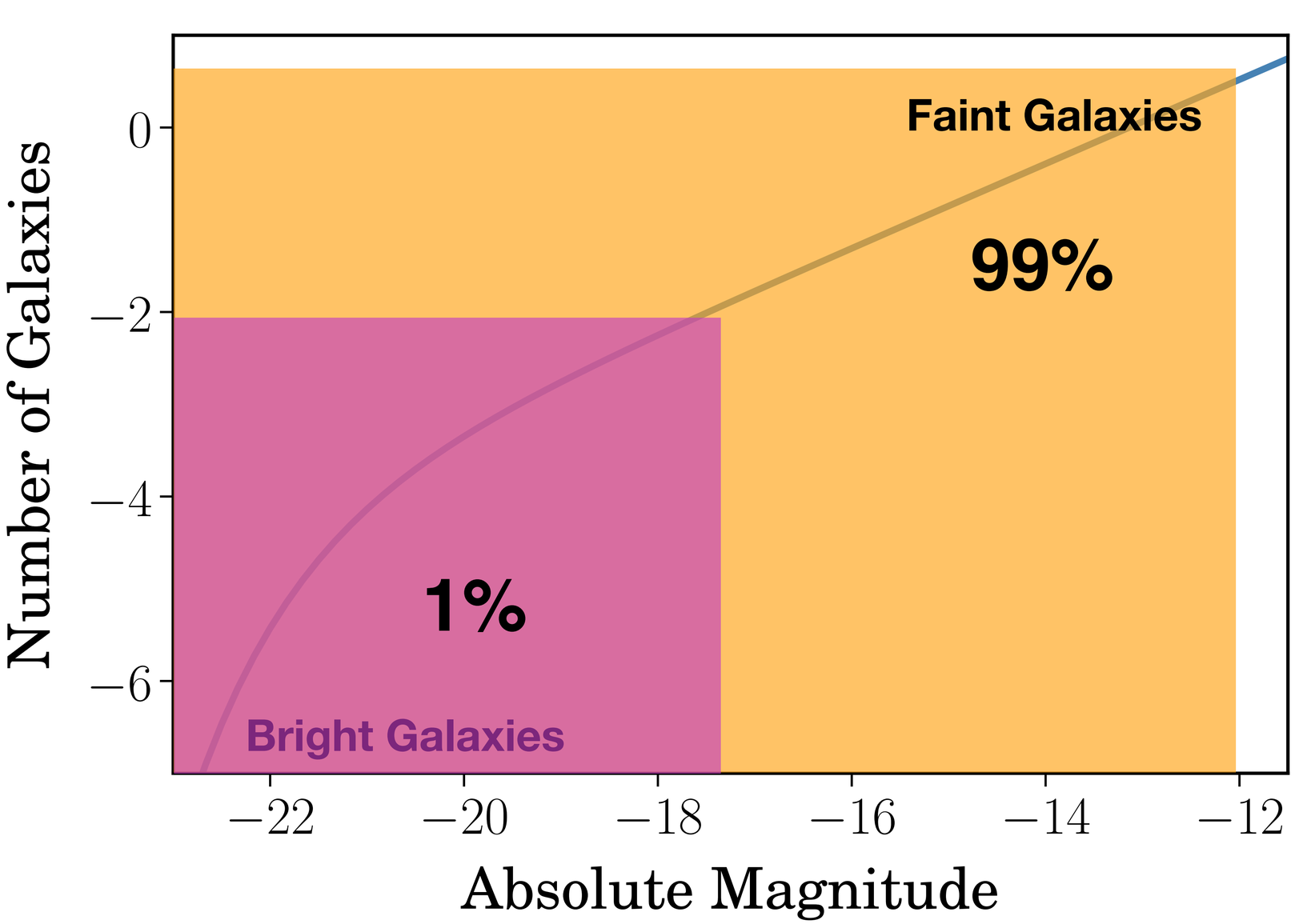

GNz11
GLASS-z12/GHz2
JADES-GS-z14-0
MoM-z14
z=10.60, MUV = -21.5
z=12.34, MUV = -20.2
z=14.18, MUV = -20.8
z=14.44, MUV = -20.2
GNz11
GSz14
GLz12/GHz2
MoM-z14
Absolute Magnitude MUV
Spectroscopic Redshift
−21
−20
−19
−18
10
11
12
13
14
15


F200W
F277W
F356W
zspec =14
MoM-z14
GS-z14
JWST-Inspired Models
Pre-JWST Consensus
>100x Under-Prediction
log ϕUV [mag−1Mpc−3]
MUV
−5
−6
−7
−8
−24
−23
−22
−21
−20
−19
−1


Faint Galaxies
Bright Galaxies
0
−2
−4
−6
−22
−20
−18
−16
−14
−12
Number of Galaxies
Absolute Magnitude


Faint Galaxies
1%
Bright Galaxies
0
−2
−4
−6
−22
−20
−18
−16
−14
−12
Number of Galaxies
Absolute Magnitude


Faint Galaxies
99%
1%
Bright Galaxies
0
−2
−4
−6
−22
−20
−18
−16
−14
−12
Number of Galaxies
Absolute Magnitude

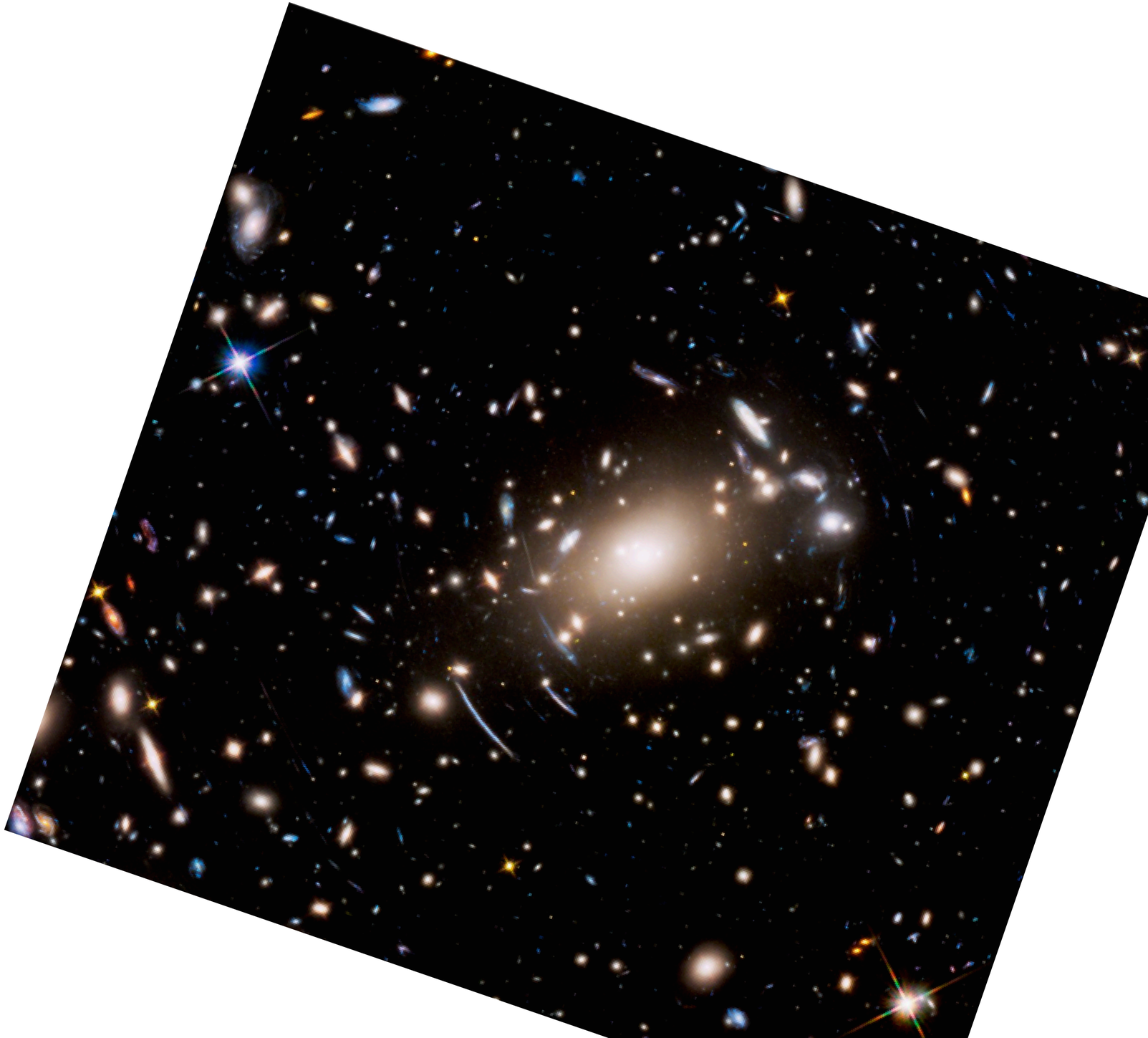

Faint Galaxies
99%
1%
Bright Galaxies
0
−2
−4
−6
−22
−20
−18
−16
−14
−12
Number of Galaxies
Absolute Magnitude

Gravitational Telescopes

GLIMPSE

NASA | ESA | CSA
jwst

esa
ESASky

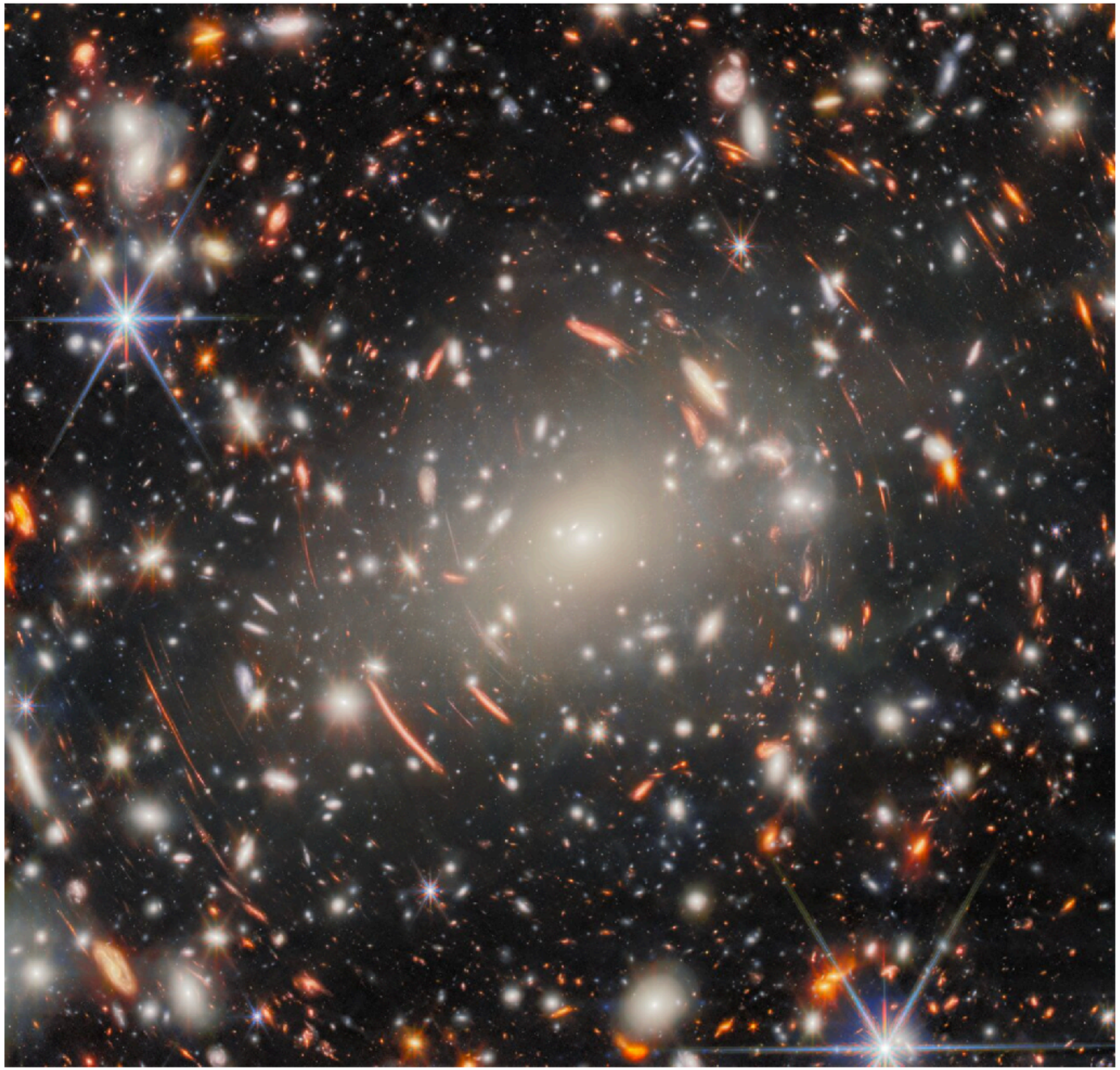


GLIMPSE

NASA | ESA | CSA
jwst

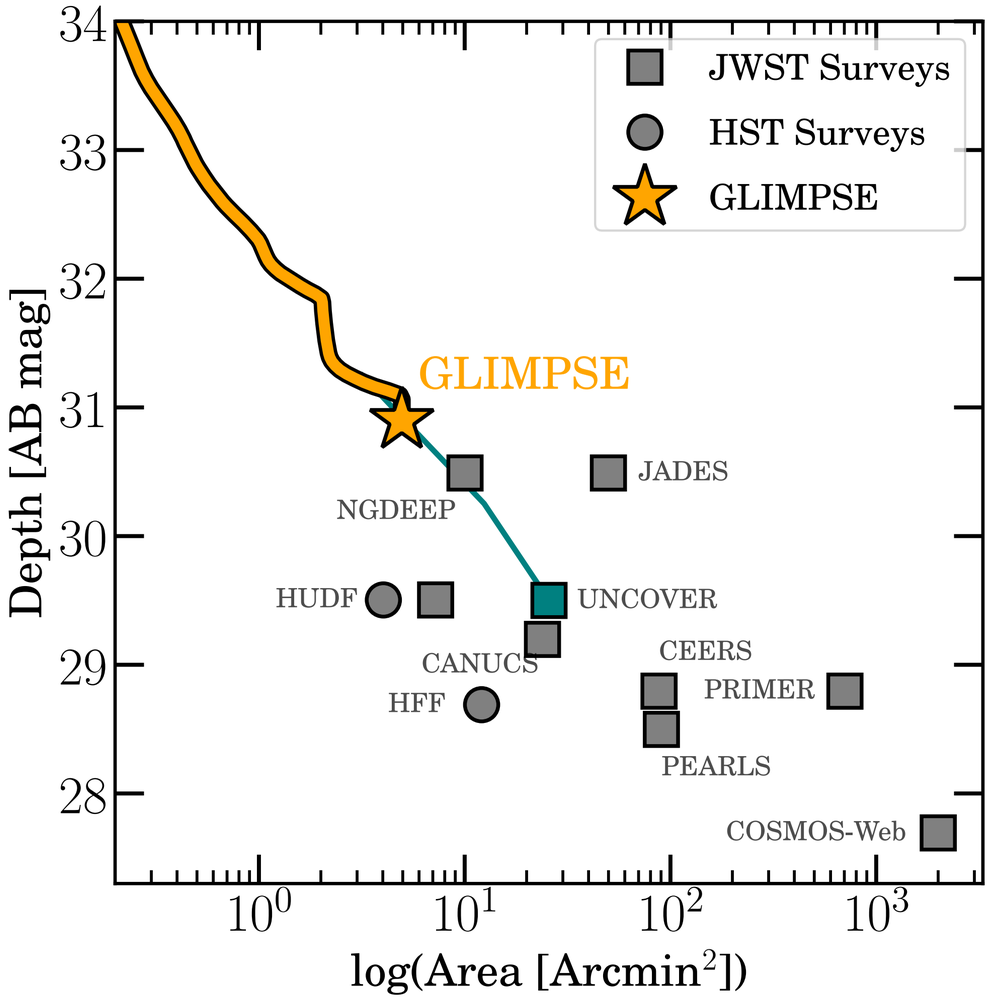
esa
ESASky

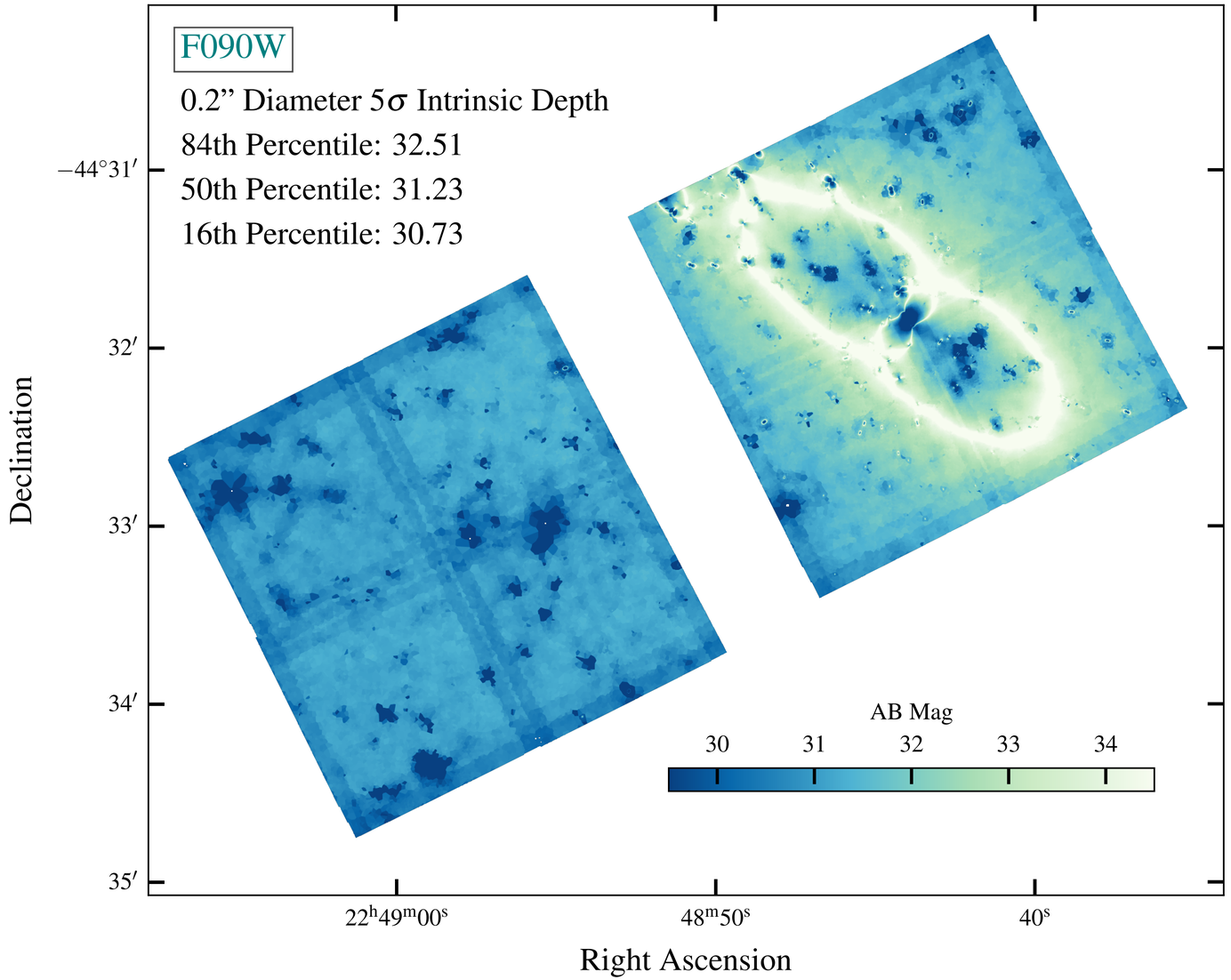
A GLIMPSE of the distant past



GLIMPSE

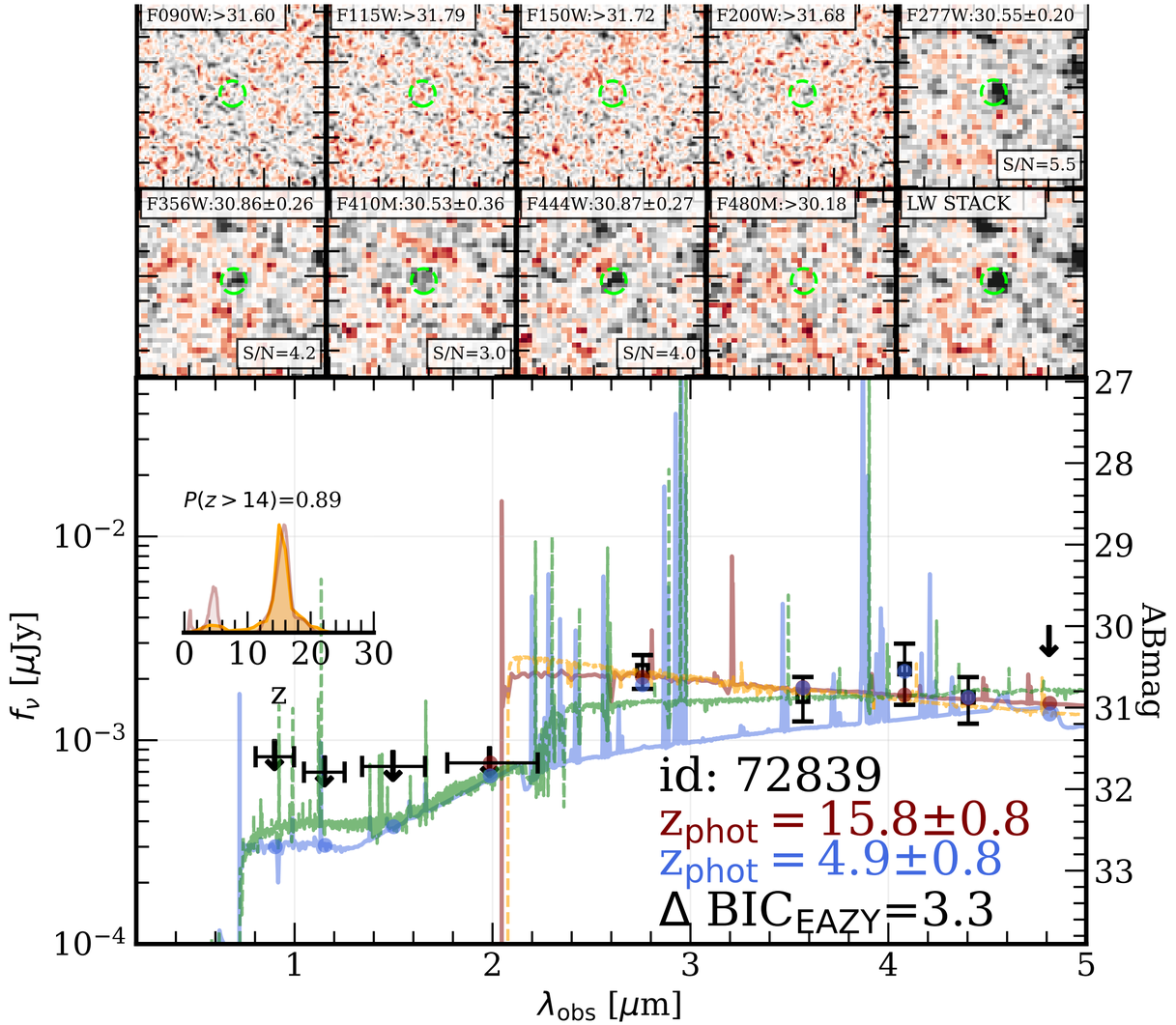
PI H. Atek





A Glimpse of the redshift frontier

Kokorev et al. 2025



GLIMPSE
This Work

Feldmann+24

Li+24

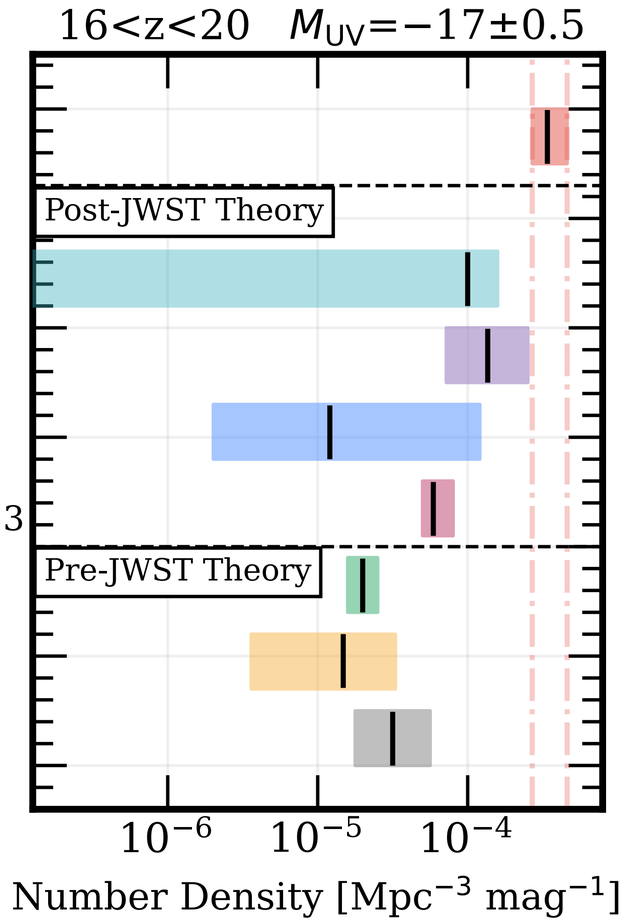
Muñoz+23

Mauerhofer+23

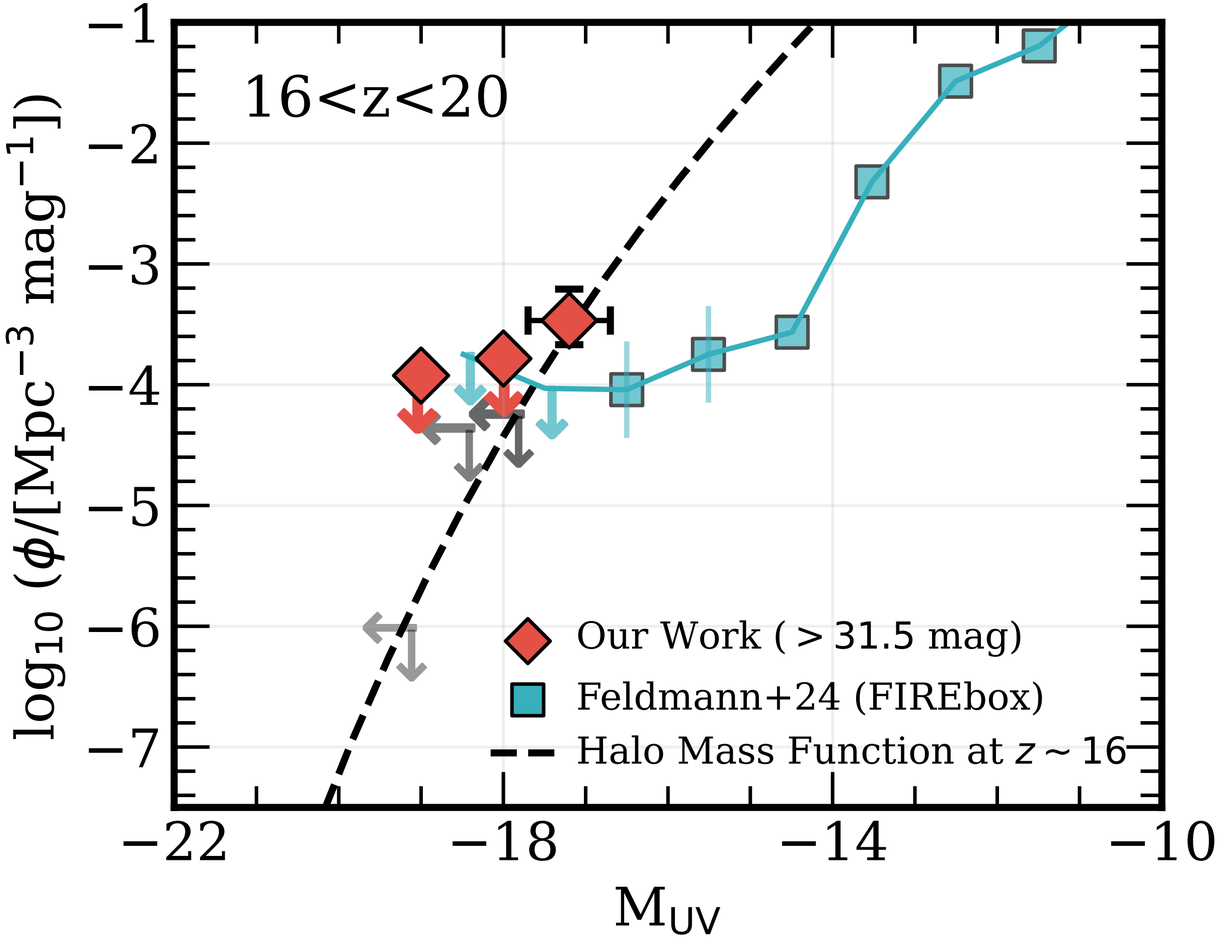
Behroozi+19

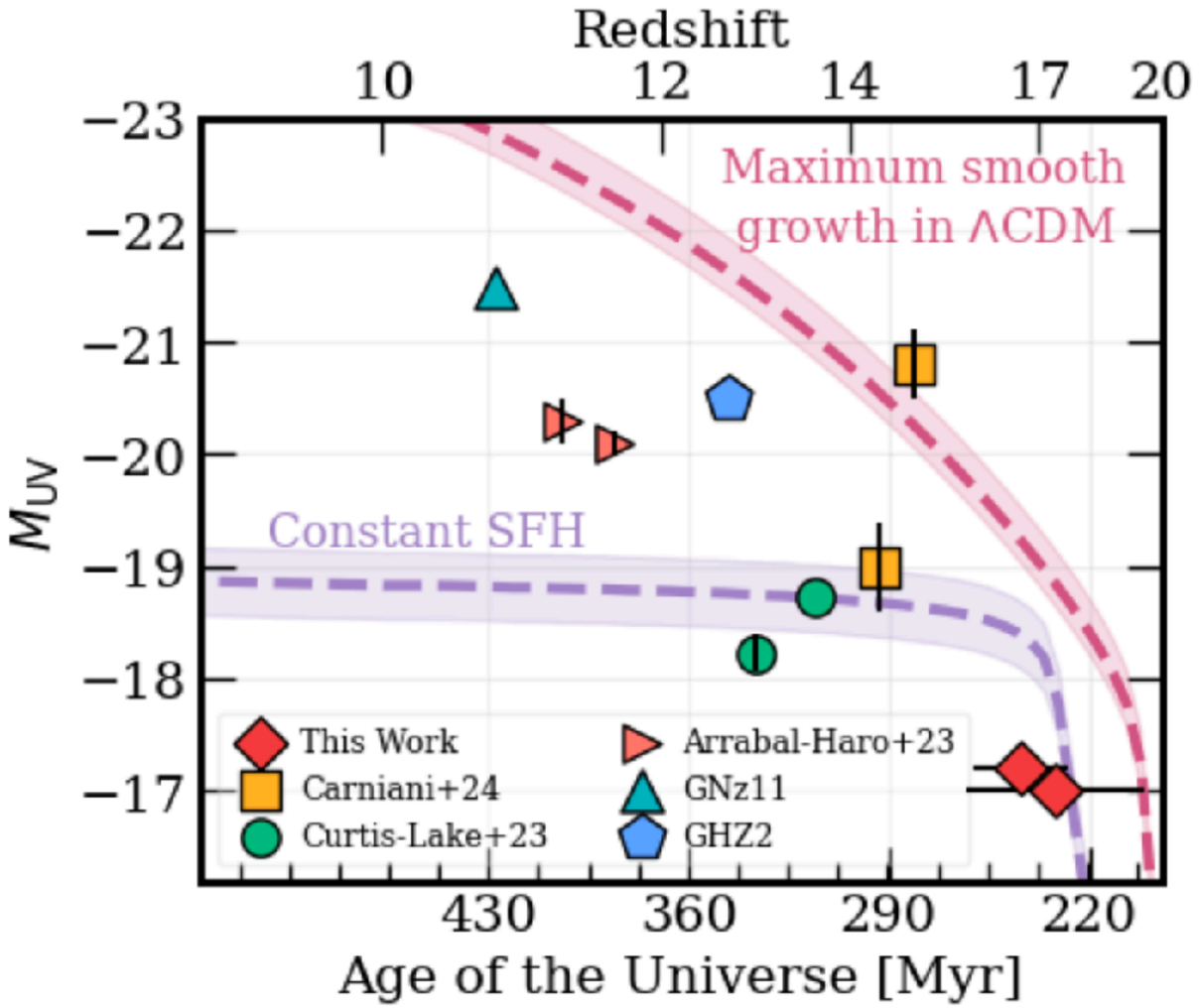
Mason+15

Dayal+14,19



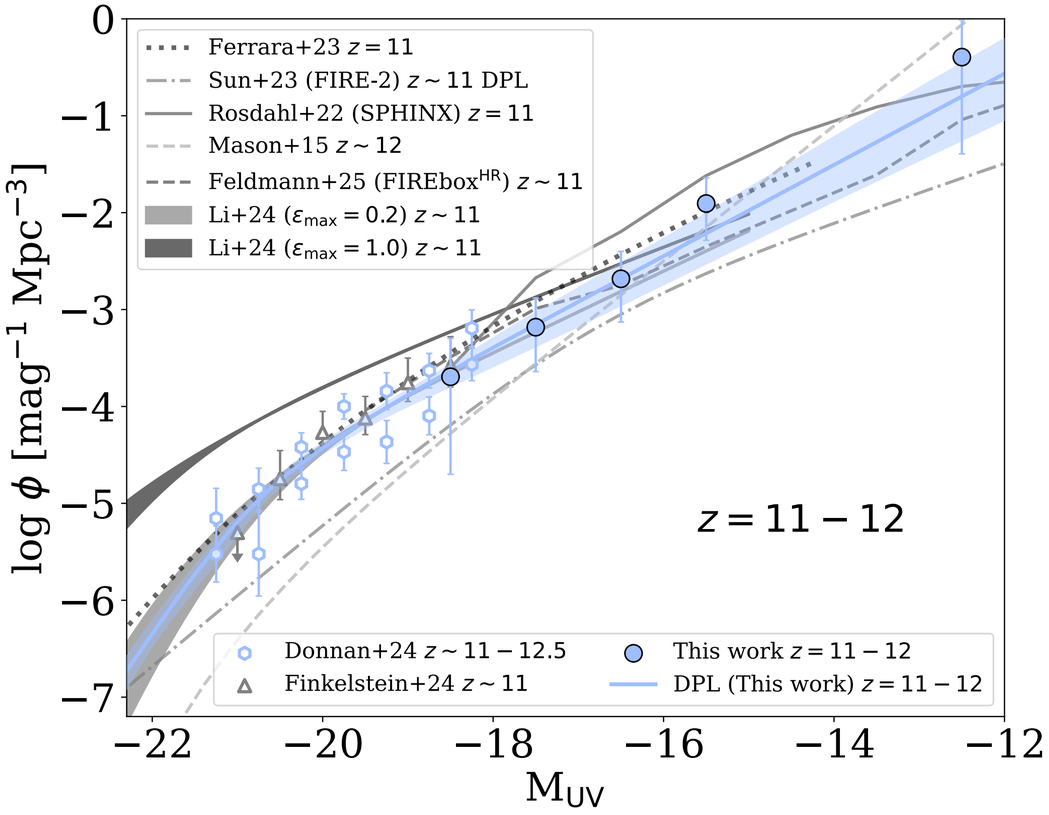
A Glimpse of the redshift frontier

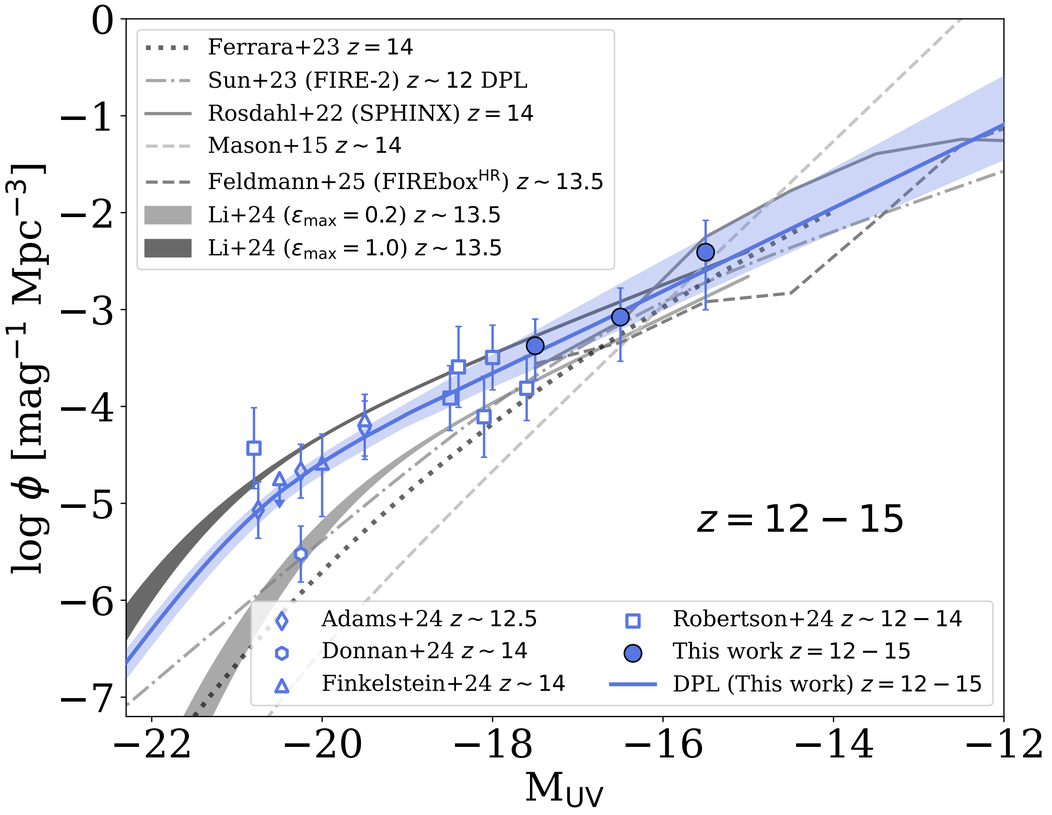




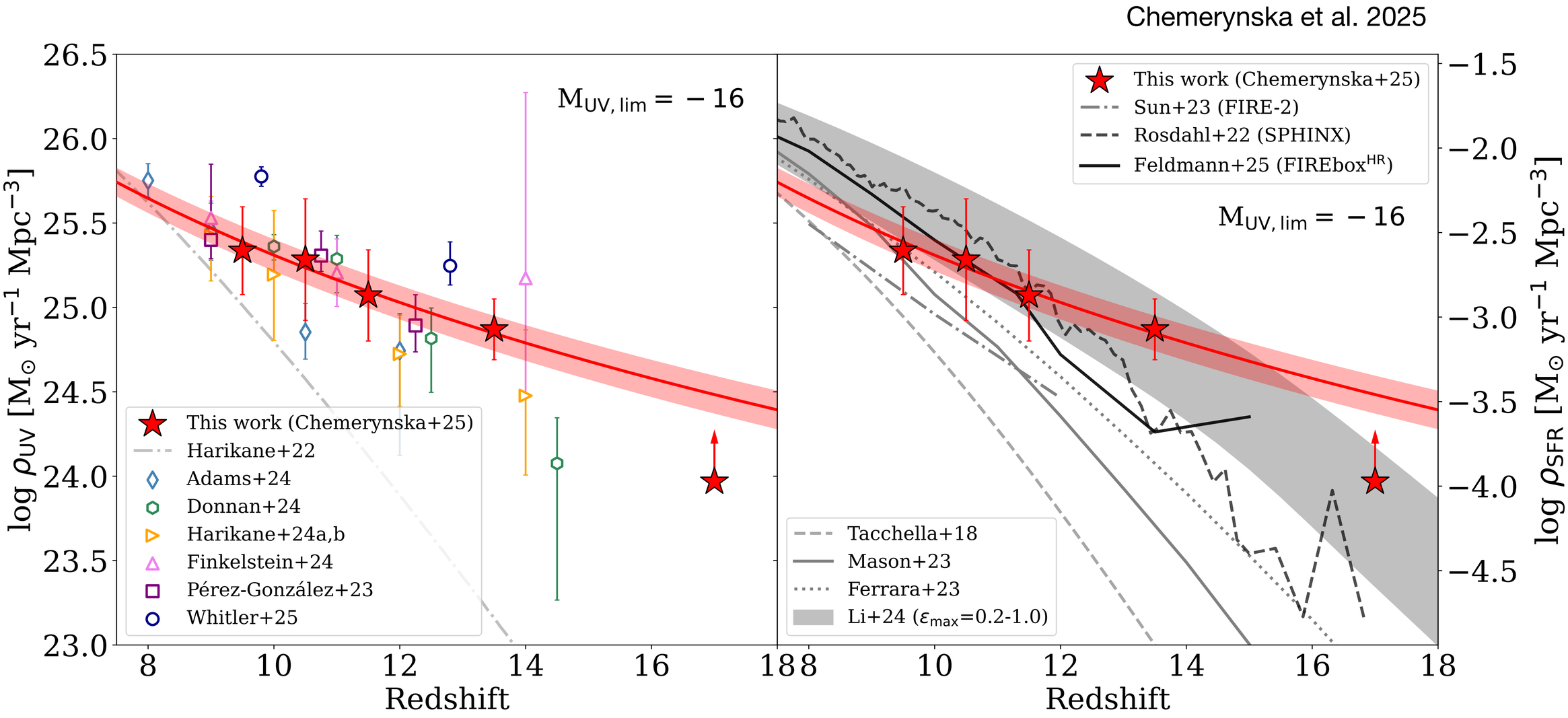
The UV Luminosity Function at z>9

Chemerynska et al. 2025





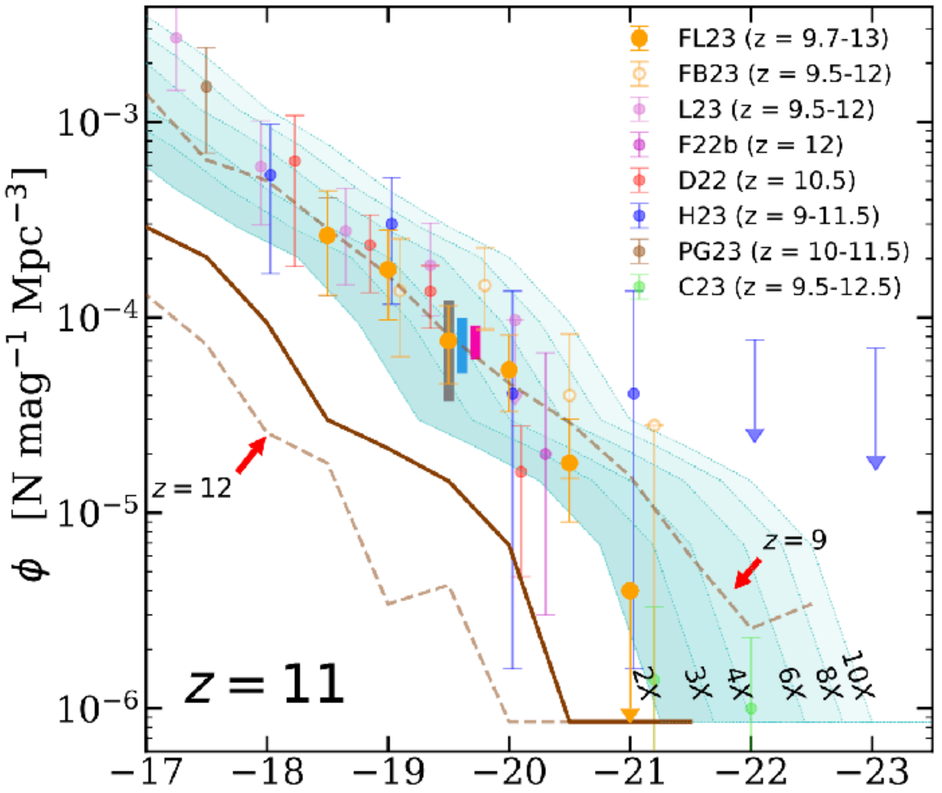
The Build-up of Stellar Mass Density at Early Epochs



Theoretical studies and scenarios to explain the overabundance of UV-bright galaxies

- Weak feedback or feedback-free SF at early times
- Top-heavy IMF, can reduce the mass, SFR by a factor of 3-5
- PopIII stellar population
- AGN activity, especially for such bright galaxies cf. GNz-11, UHZ1
- No star- formation suppression before the EoR
- Low-redshift contaminants
- Lack of dust
- Stochastic star formation

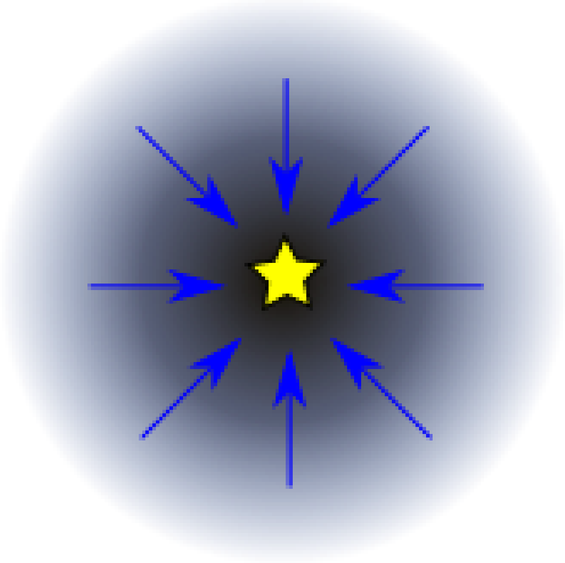
Yung et al. 2023



See Boylan-Kolchin23, Shen+23, Yung+23, Sun+23, Munoz+23, Ciesla+23, Dekel+23, Pallottini+23, Narayanan+23, Asada+23, Mason+23, Lovell+23, Ferrara+23, Fujimoto+23, Meyer+24, Naidu+23 and others

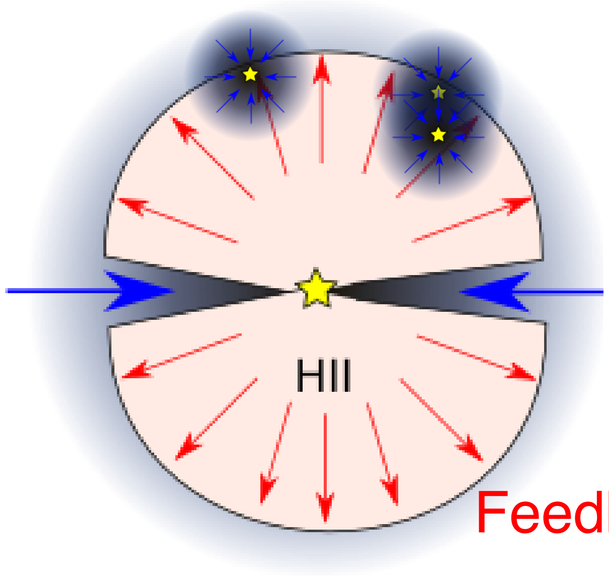
Feedback-Free Starbursts

Star Formation



$$n > n_{\rm fbk} = 2.23 \times 10^3\,{\rm cm}^{-3}$$

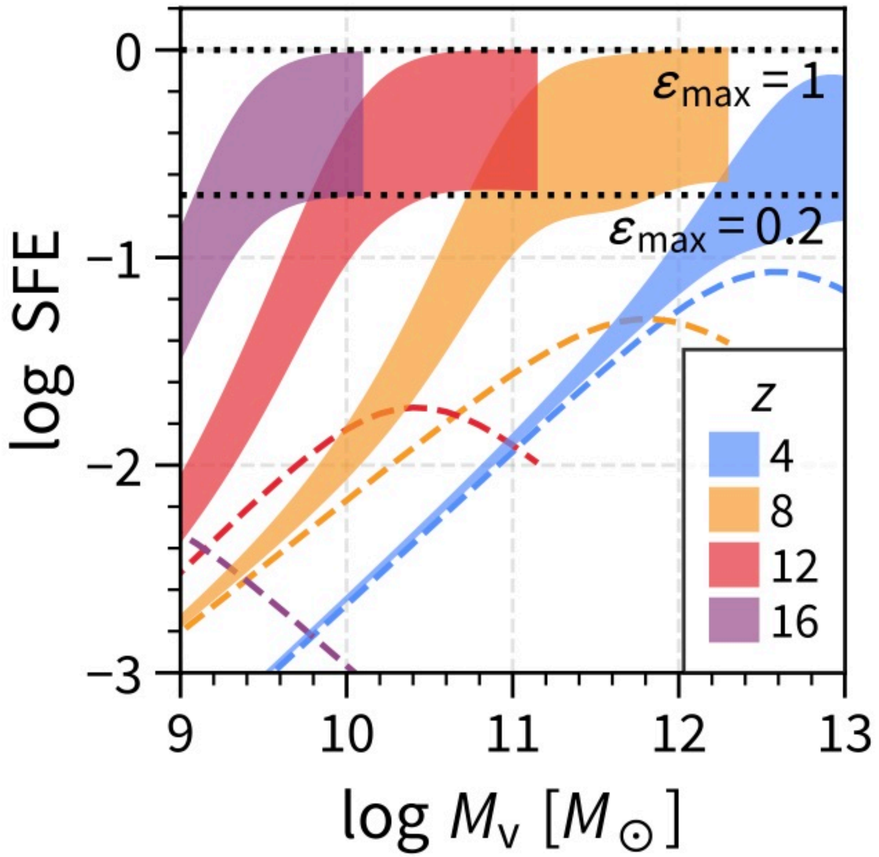
$$t_{\rm ff} \sim t_{\rm cool} < t_{\rm fbk} \approx 1{\rm Myr}$$



Gas accretion

Feedback

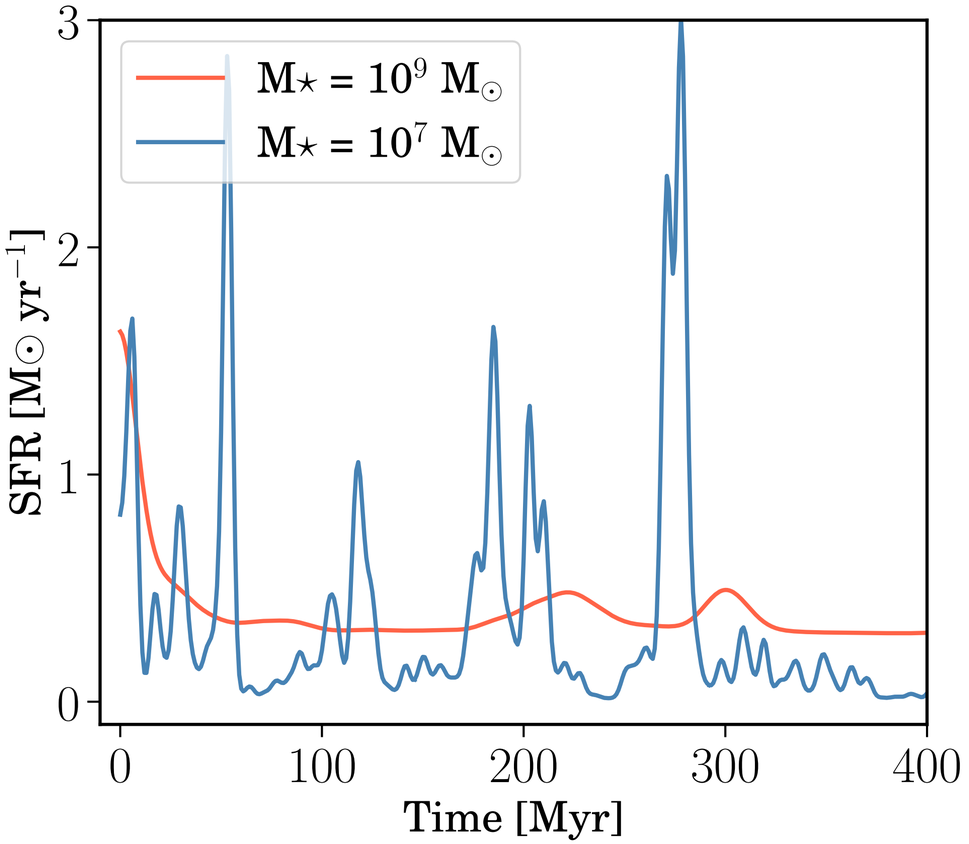
Dekel+23, Li+24



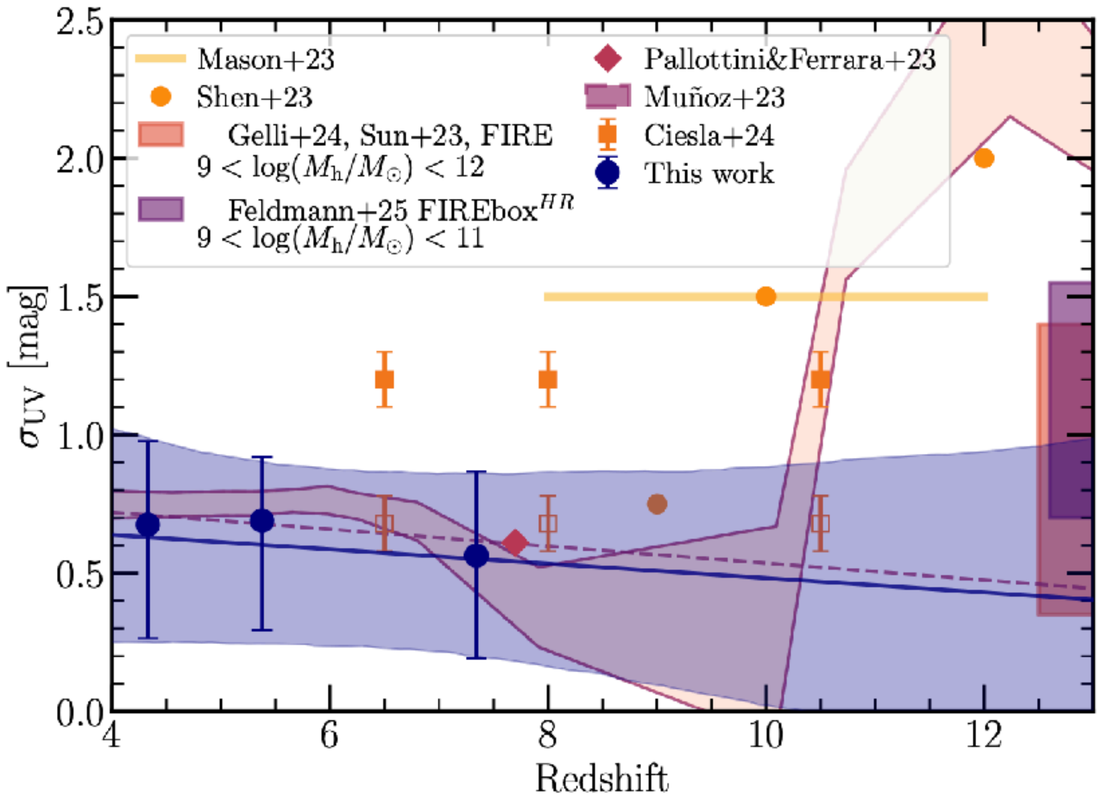
Stochastic Star Formation History

$$\mathrm{SFR}(M_h, z) = \varepsilon(M_h) f_b \frac{dM_h}{dt}$$

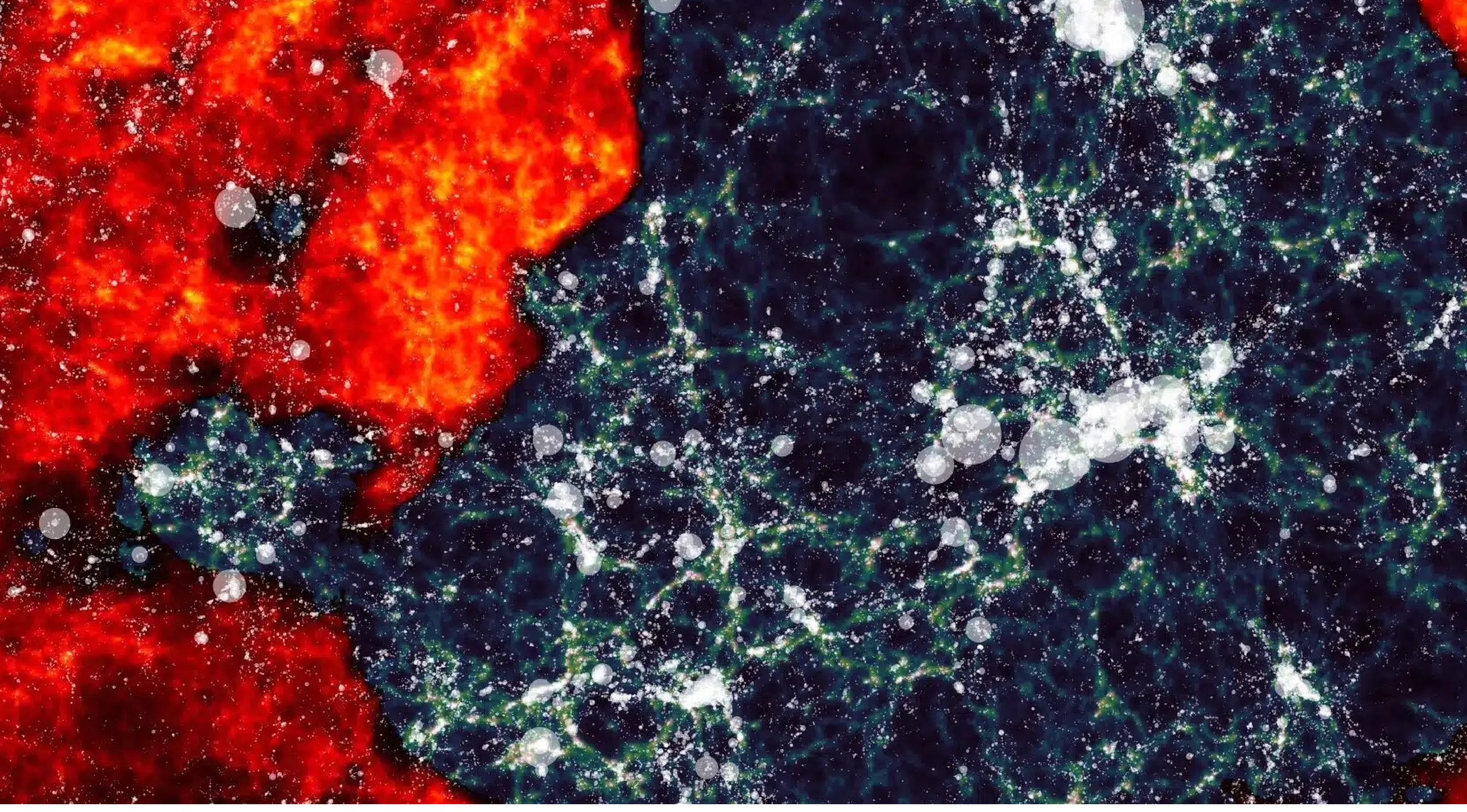
$$\frac{\mathrm{d}n}{\mathrm{d}M_{\mathrm{UV}}} = \frac{\mathrm{d}n}{\mathrm{d}\log_{10} M_{\mathrm{halo}}} \left| \frac{\mathrm{d}\log_{10} M_{\mathrm{halo}}}{\mathrm{d}M_{\mathrm{UV}}} \right|.$$

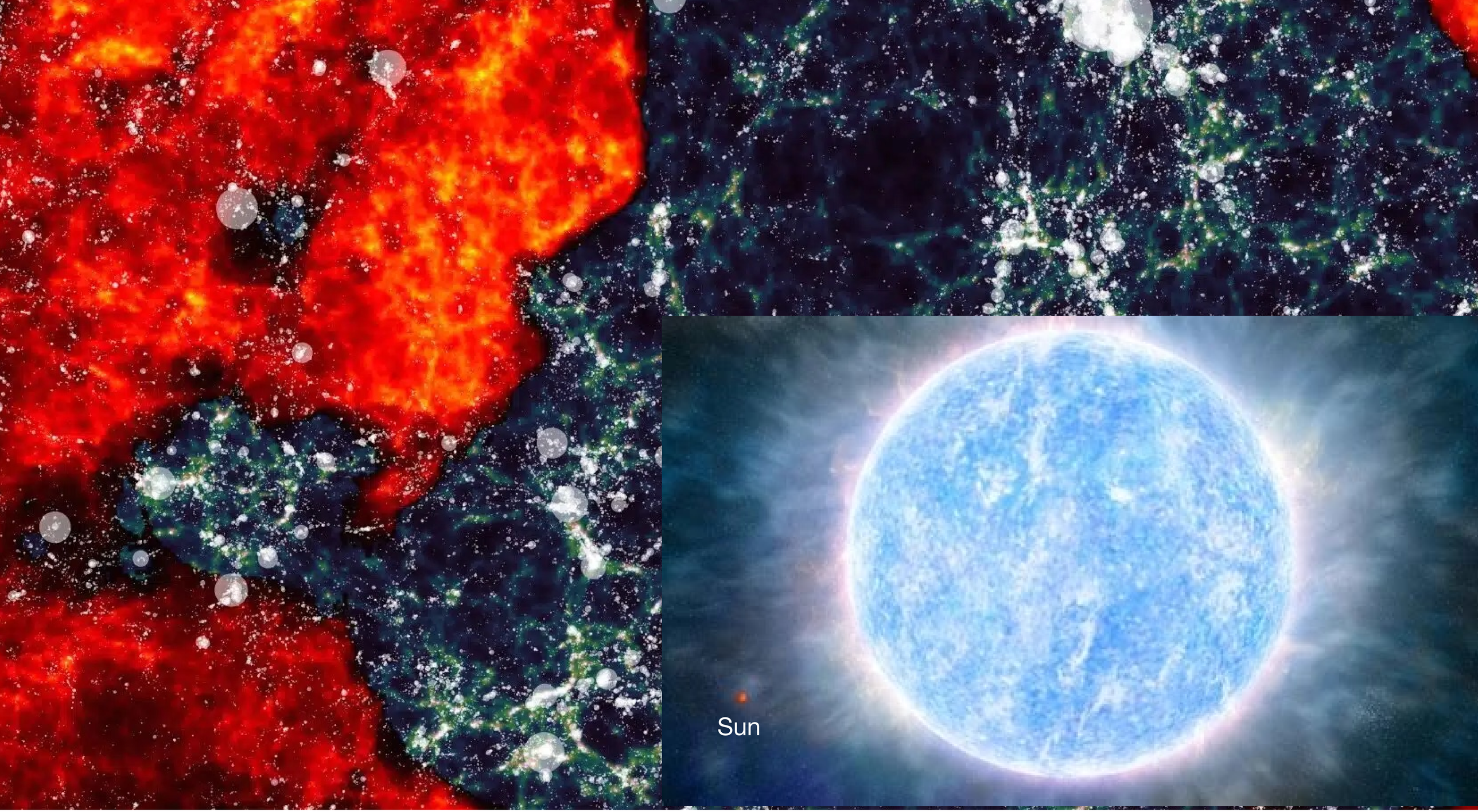


Shuntov et al. 2025

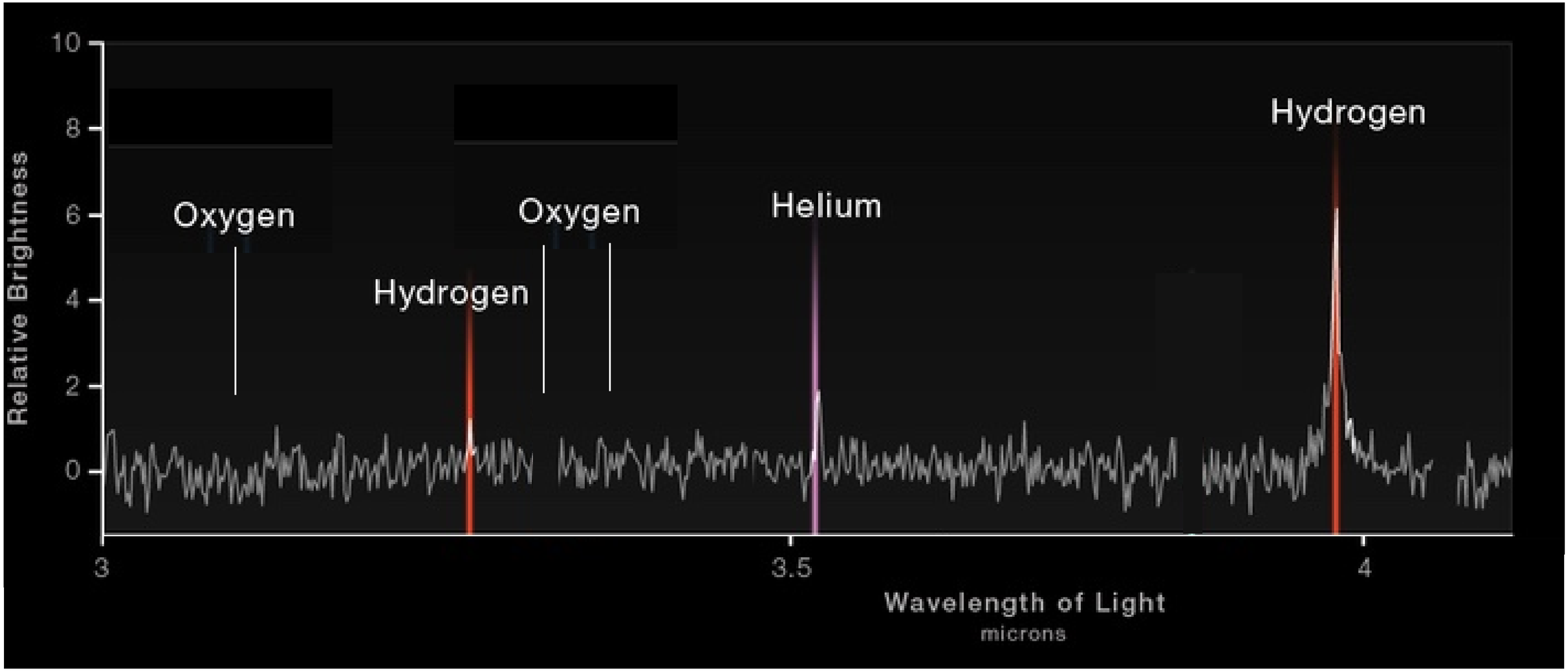


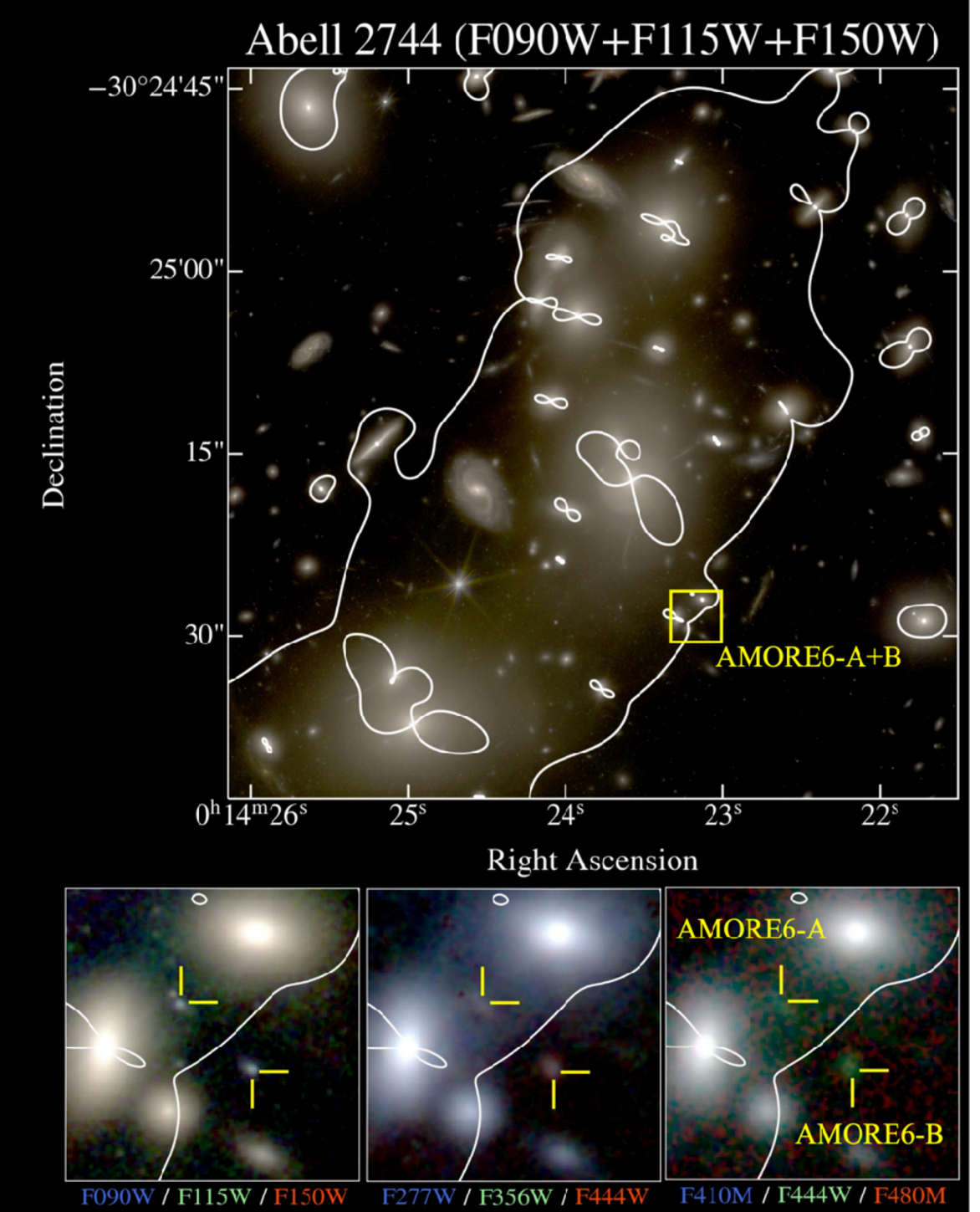
See Boylan-Kolchin23, Shen+23, Yung+23, Sun+23, Munoz+23, Ciesla+23, Asada+23, Mason+23, Lovell+23, Ferrara+23, Fujimoto+23, Meyer+24, Naidu+23 and others



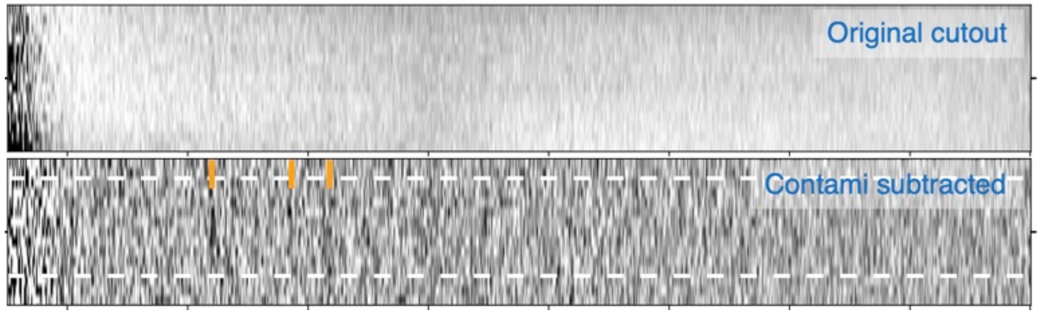

Sun

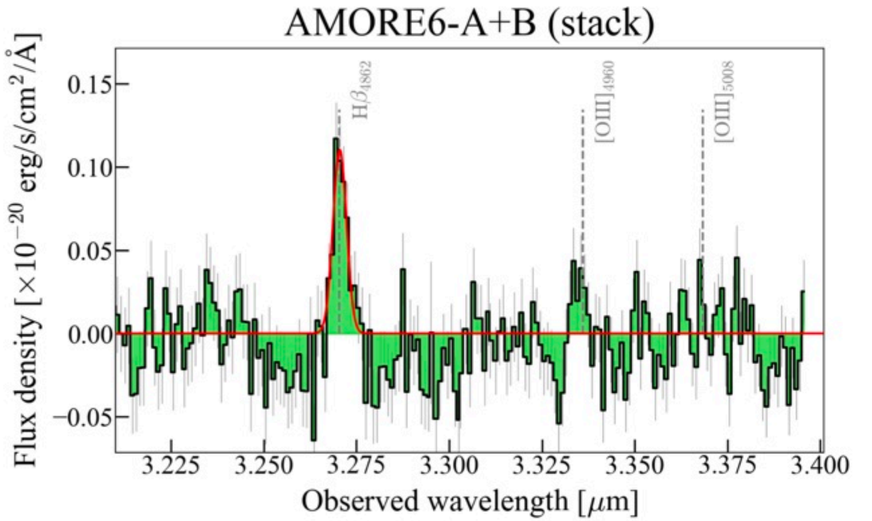
Population III features

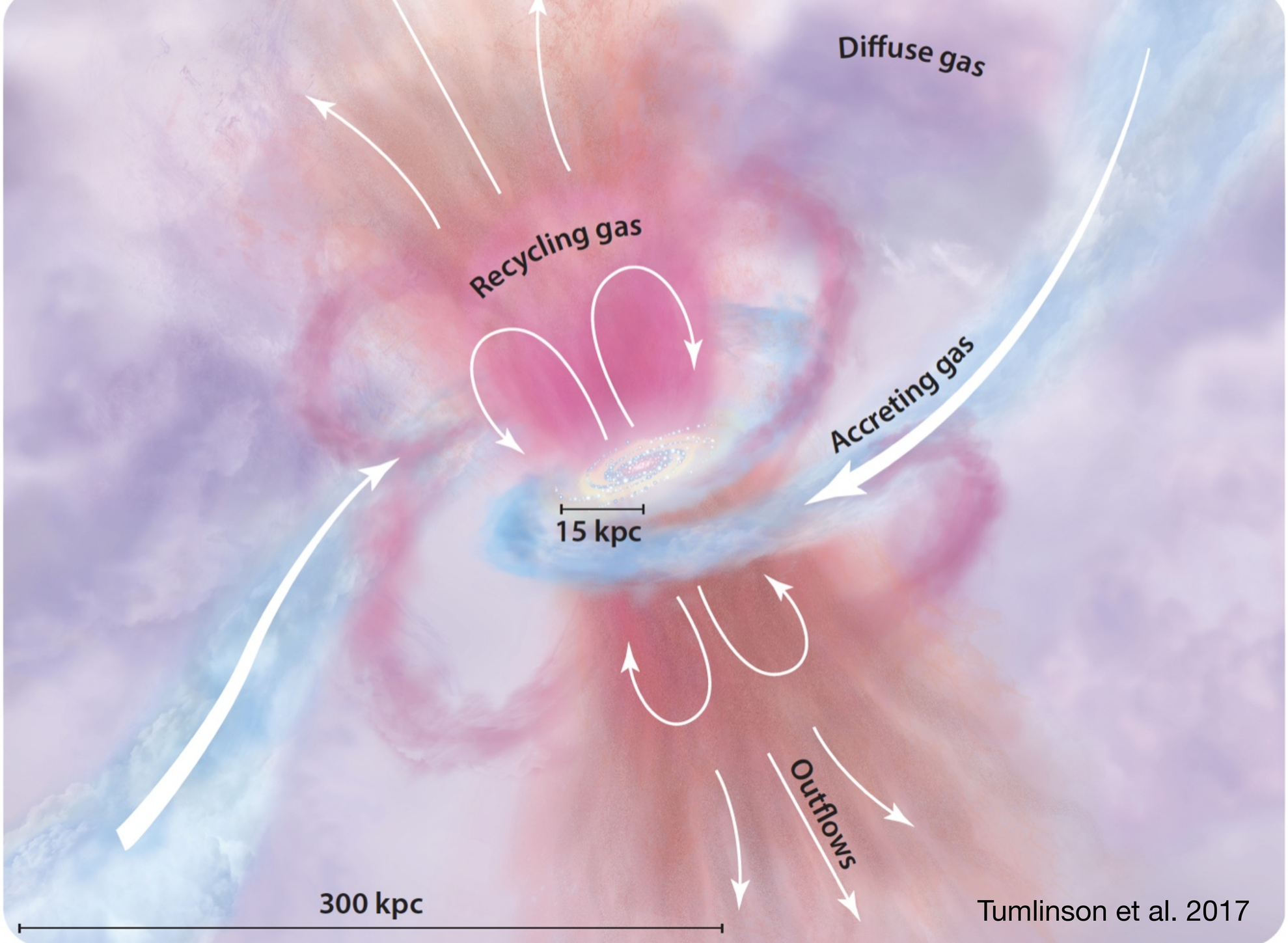




Morishita et al. 2025

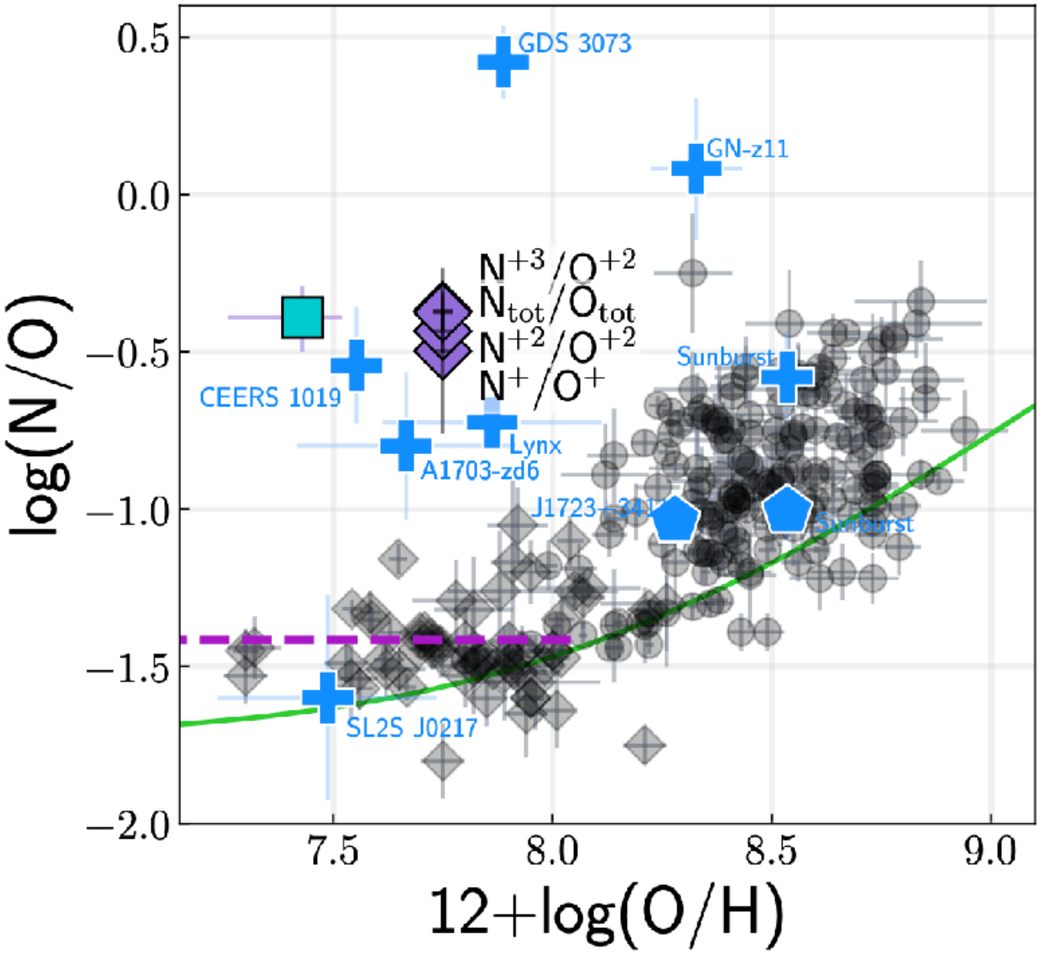


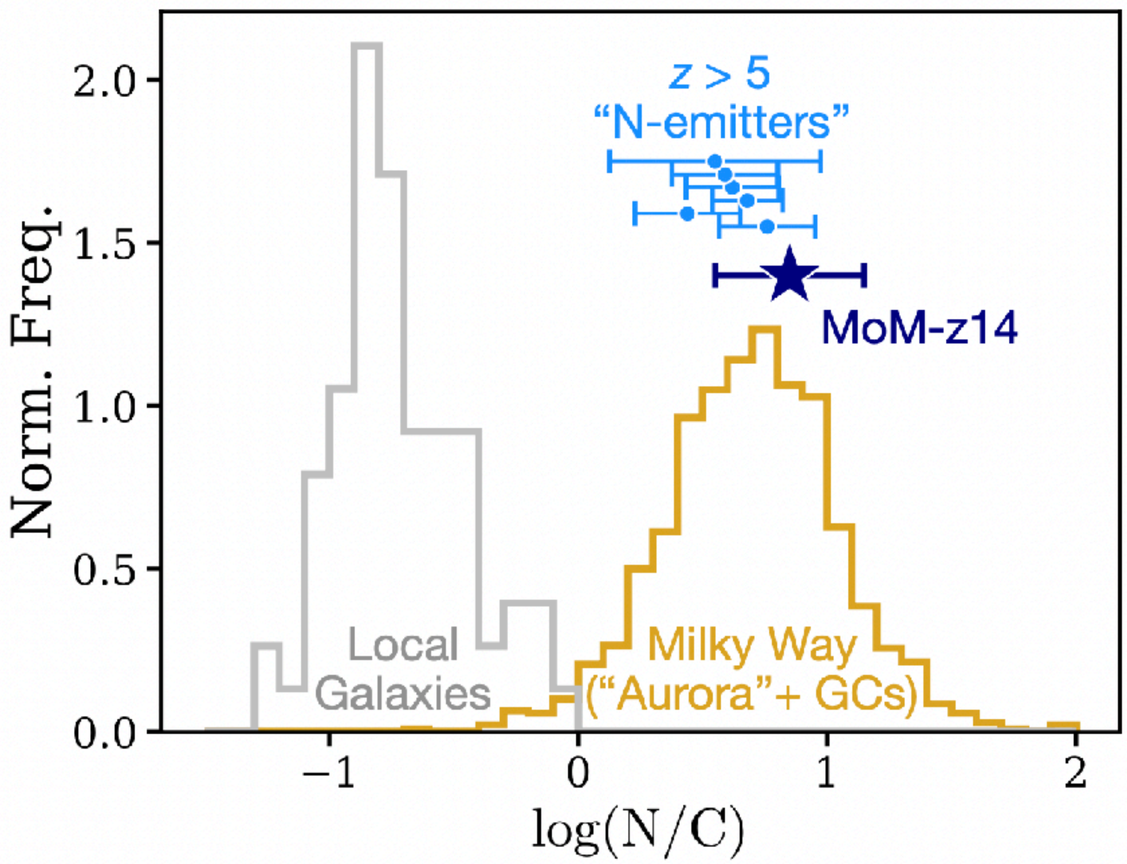




Tumlinson et al. 2017

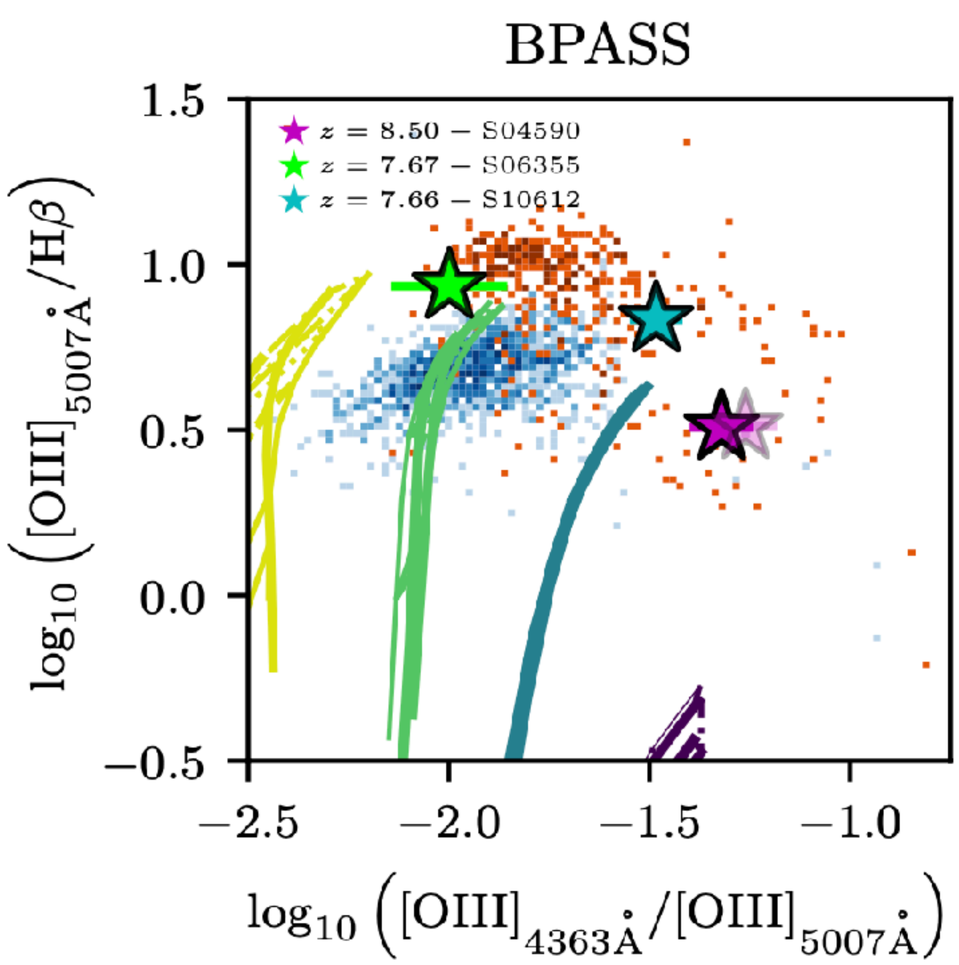
Chemical enrichment of early galaxies



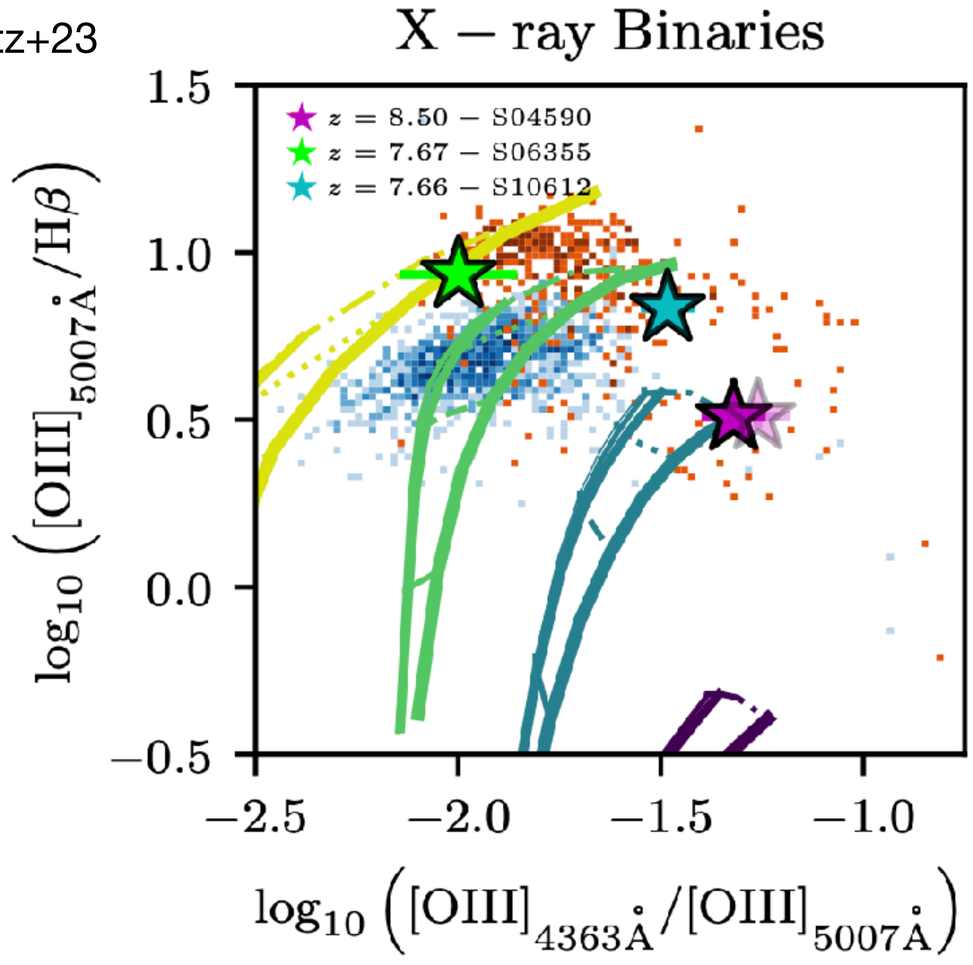


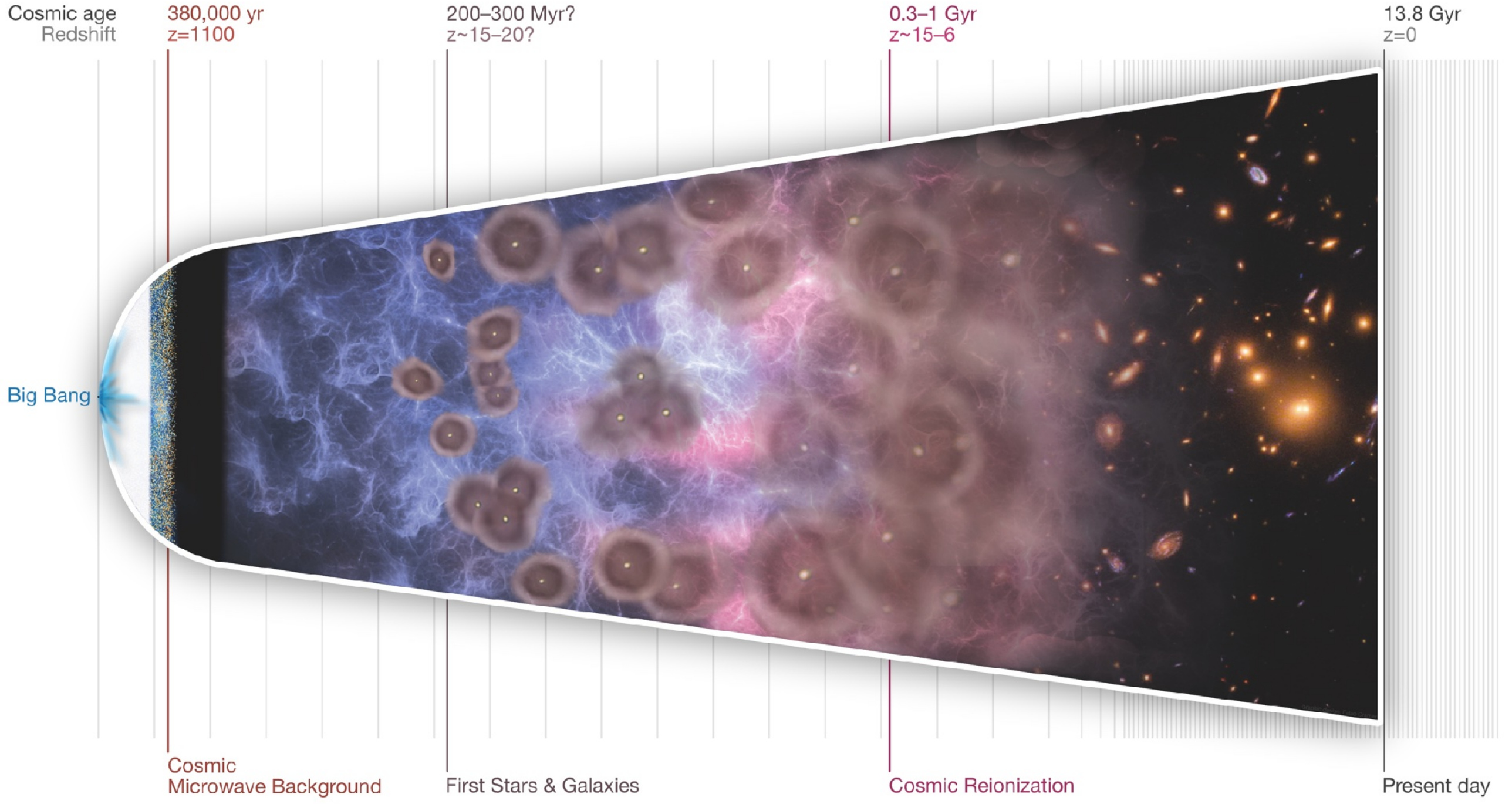
Physical properties of early galaxies

Some early galaxies seem to have different ISM properties:
e.g unusually high temperatures



Katz+23



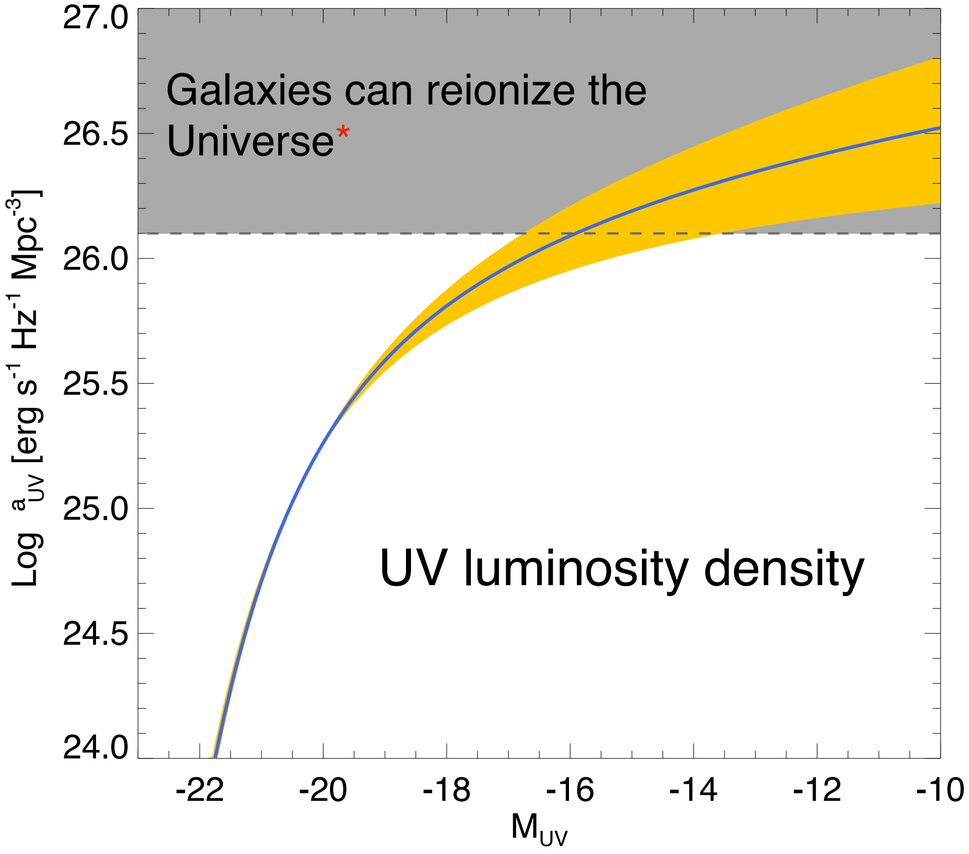

Cosmic age
Redshift
380,000 yr
z=1100
200–300 Myr?
z~15–20?
0.3–1 Gyr
z~15–6
13.8 Gyr
z=0
Big Bang
Cosmic
Microwave Background
First Stars & Galaxies
Cosmic Reionization
Present day

$$\frac{dQ_{\mathrm{H\,II}}}{dt} = \frac{\dot{n}_{\mathrm{ion,H}}}{\langle n_{\mathrm{H}} \rangle} - \frac{Q_{\mathrm{H\,II}}}{t_{\mathrm{rec,H}}}$$

$$\dot{n}_{\mathrm{ion}} = \rho_{\mathrm{UV}}\, \xi_{\mathrm{ion}}\, f_{\mathrm{esc}}$$

Contribution of star-forming galaxies to the ionizing background
Universe mostly (90%) ionized at z~6

f_{esc} =0.2, ξ_{ion} = 25.2, C_{HII} = 3

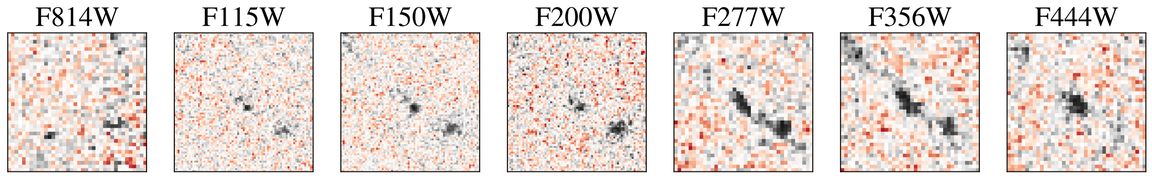


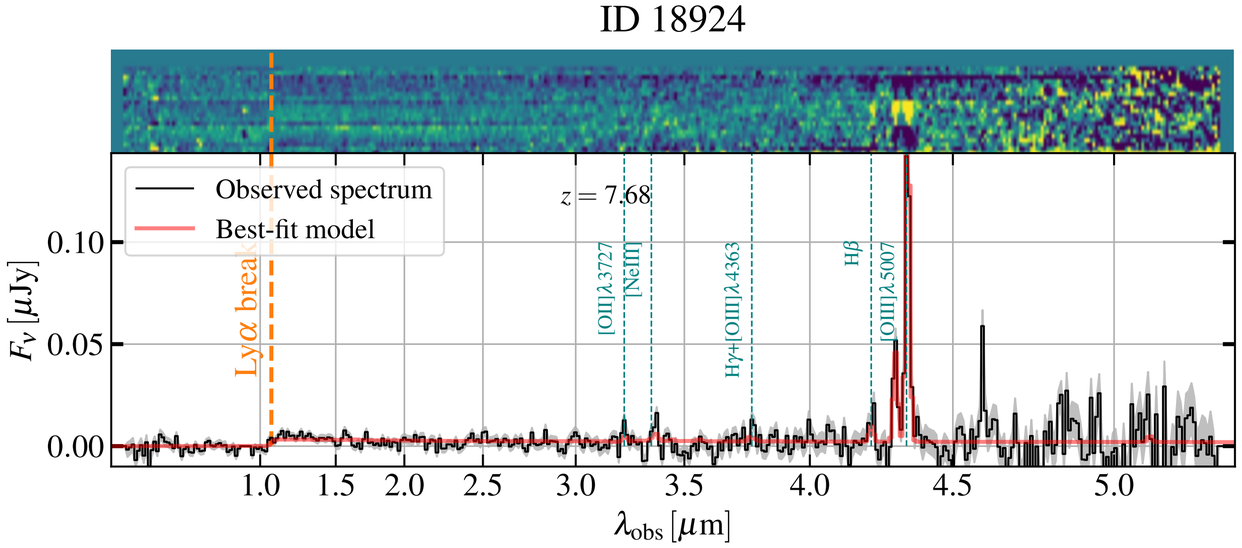
The ionizing efficiency of EoR galaxies

$$\dot{n}_{\rm ion} = \rho_{\rm UV}\, \xi_{\rm ion}\, f_{\rm esc}$$

$$\xi_{\rm ion} = \frac{N(H^0)}{L_{UV}}\ [erg^{-1}\ Hz],$$

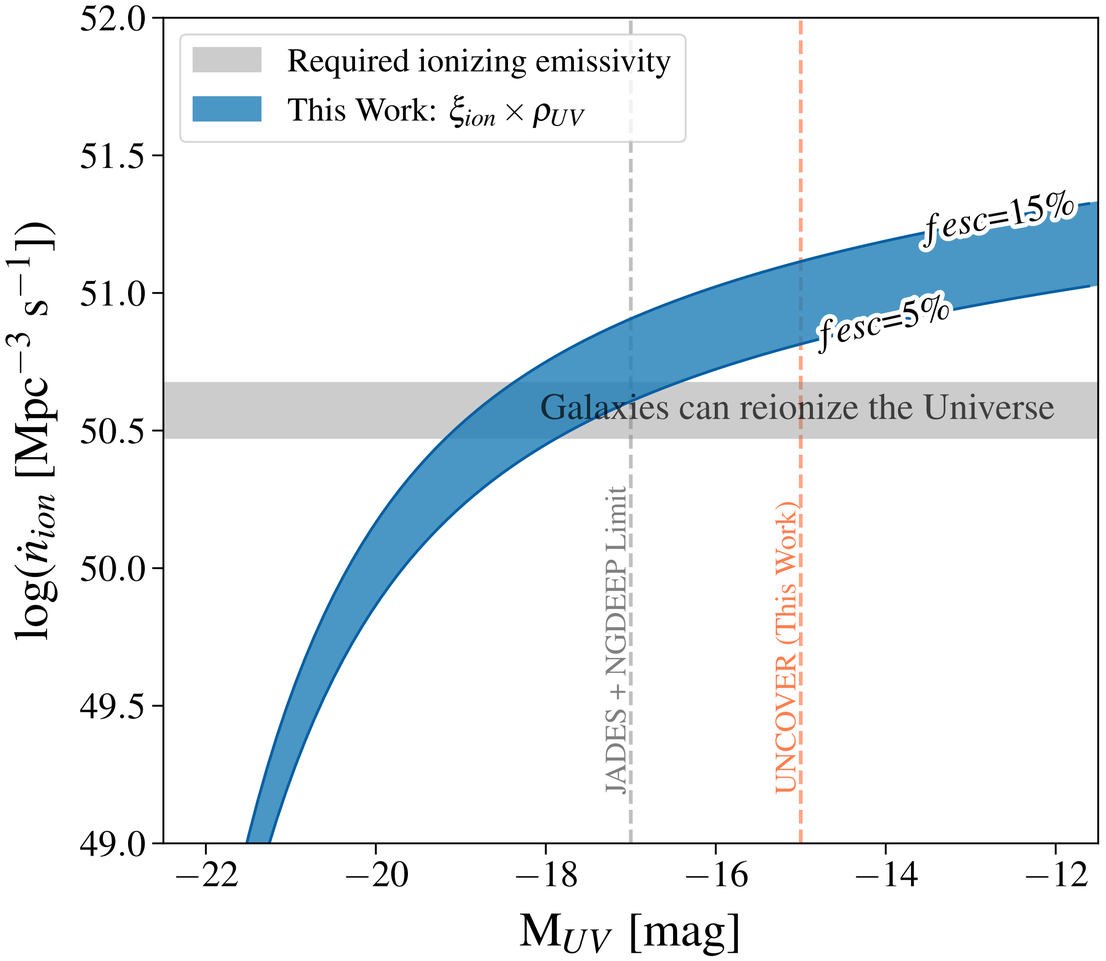
$$L(H\alpha)\ [erg\ s^{-1}] = 1.36 \times (1 - f_{esc})\ 10^{-12}\ N(H^0)\ [s^{-1}]$$





The ionizing photon production efficiency is much higher in fainter galaxies

Atek et al., Nature, 2024



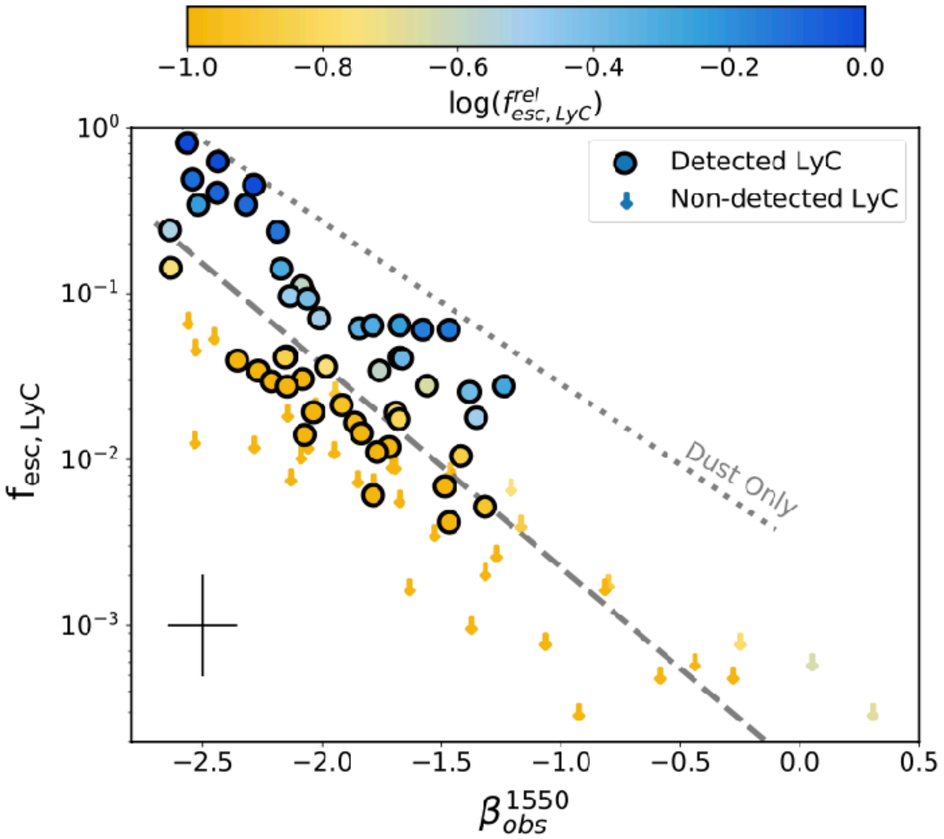
The LyC escape fraction in EoR galaxies

$$\dot{n}_{\rm ion} = \rho_{\rm UV}\, \xi_{\rm ion}\, f_{\rm esc}$$

Hubble Low-redshift LyC Survey

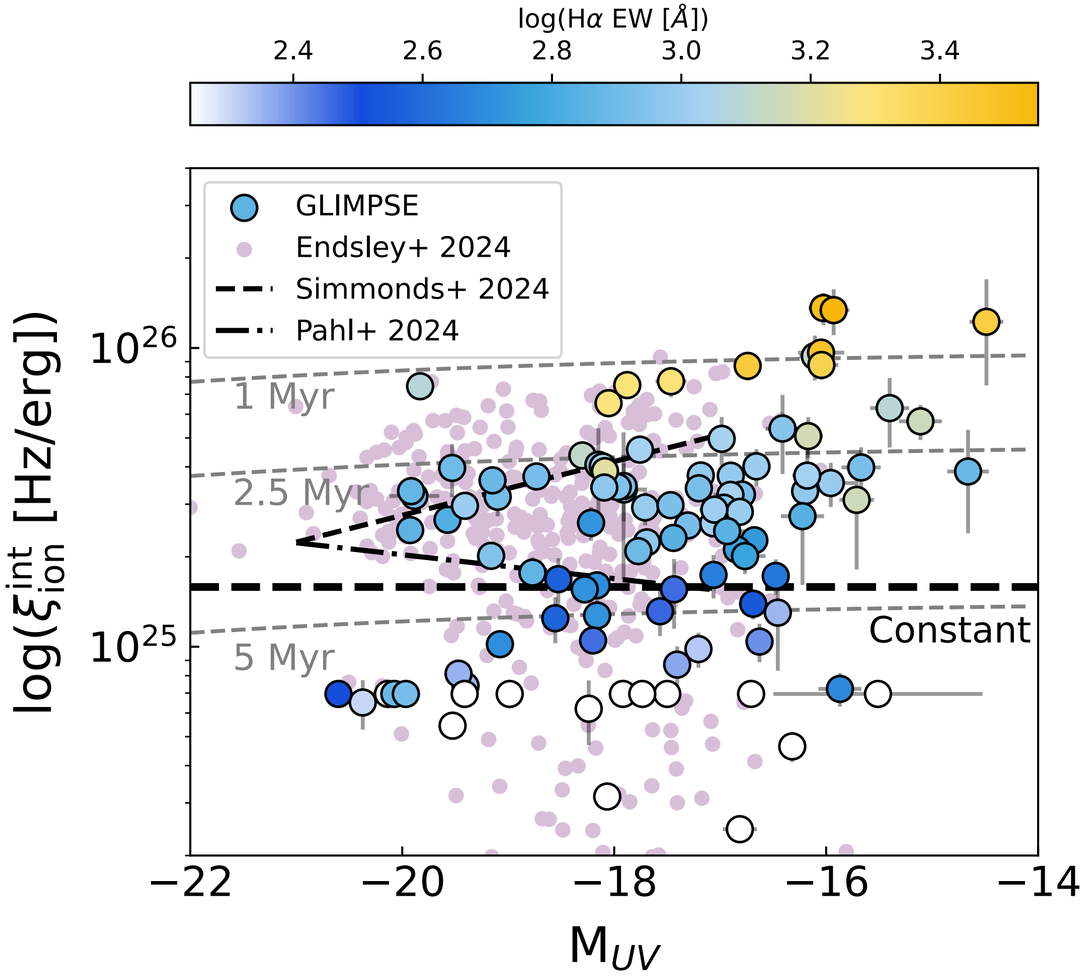
Low-redshift calibration of indirect indicators

Chisholm et al. (2023)



GLIMPSE

Chisholm et al. in prep



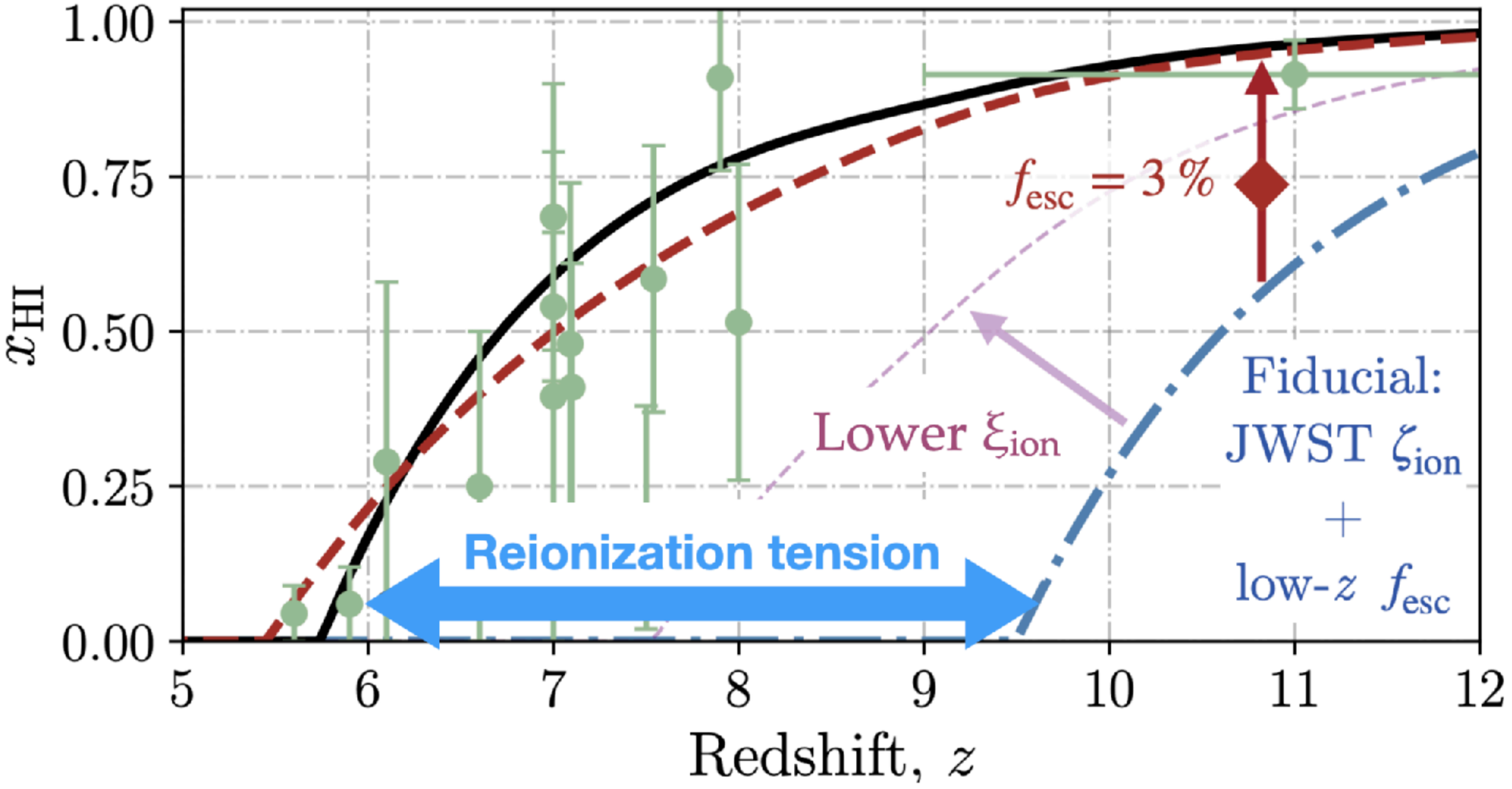
An ionizing photon budget crisis ?

JWST constraints on the ionizing efficiency leads to early reionization.

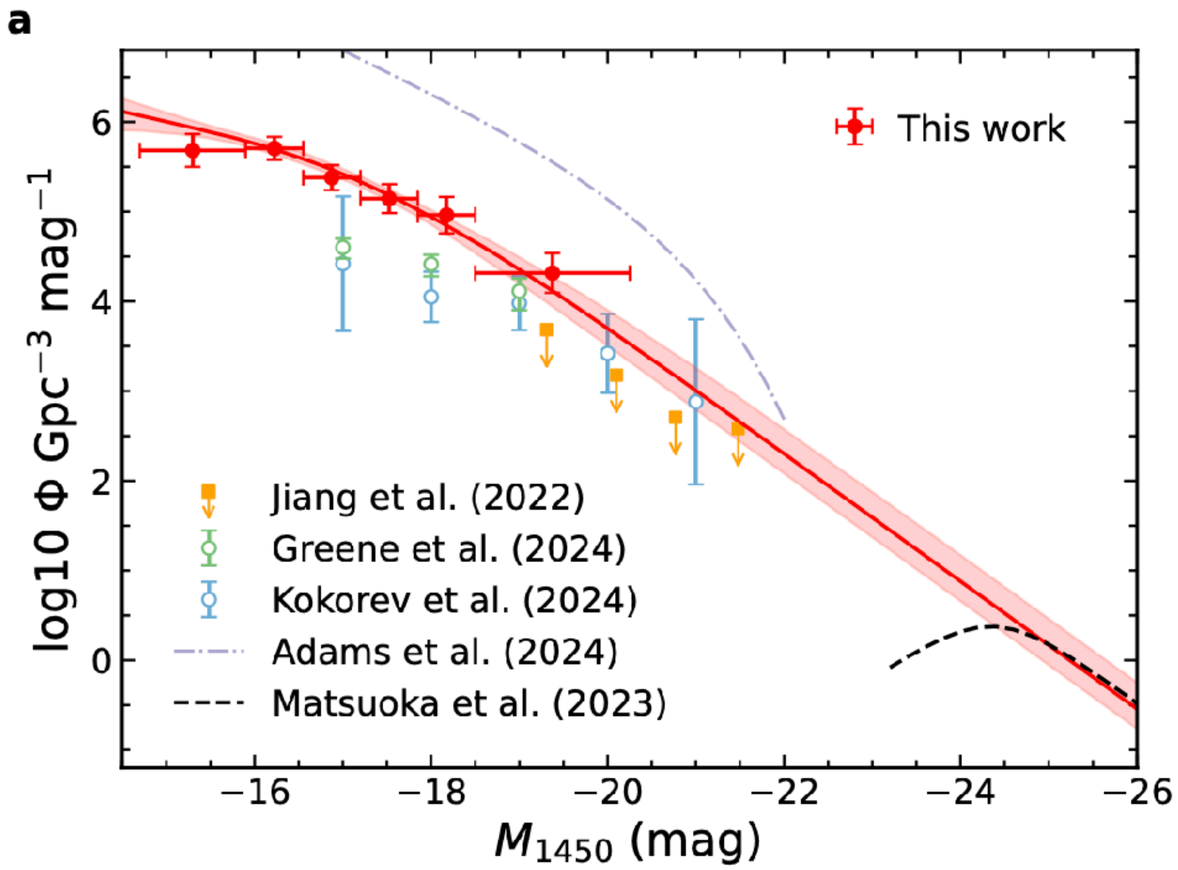
Possible ways out

- Variable Xi_ion in galaxies ?
- Lower fesc than inferred from low redshift ?
- Ingredients of reionization models ?

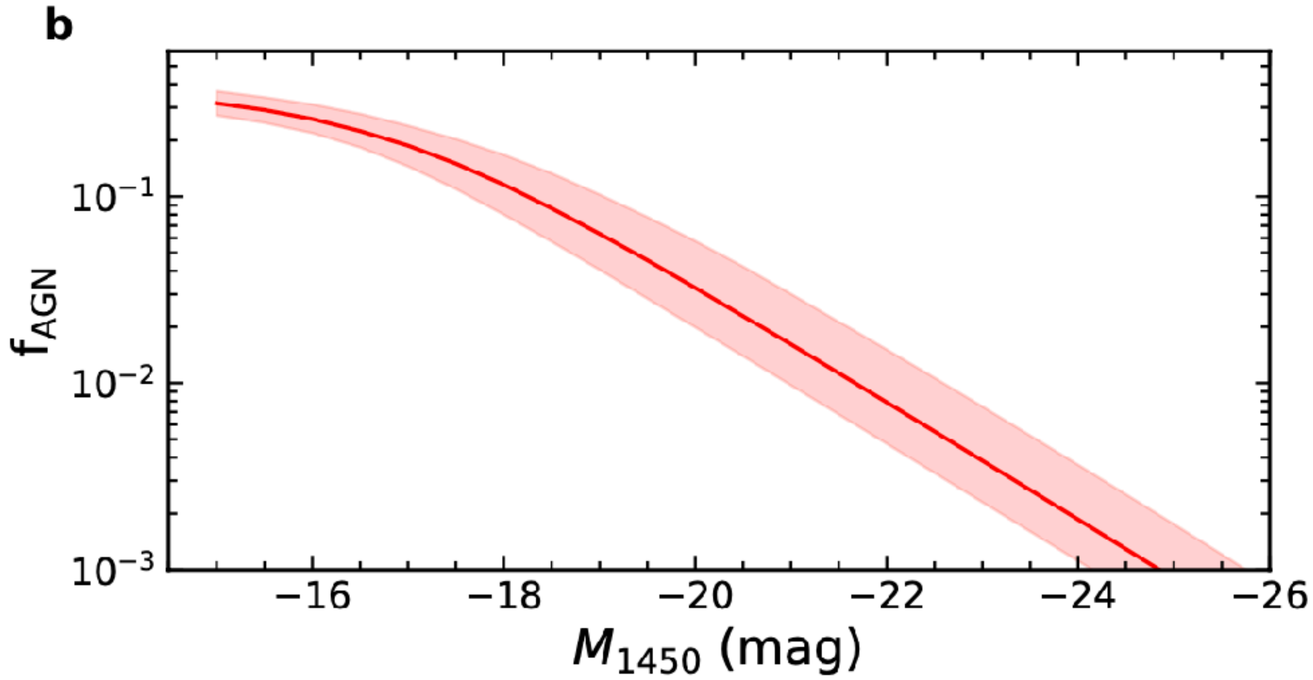
Munoz et al. (2024)



What about the contribution of AGNs ?

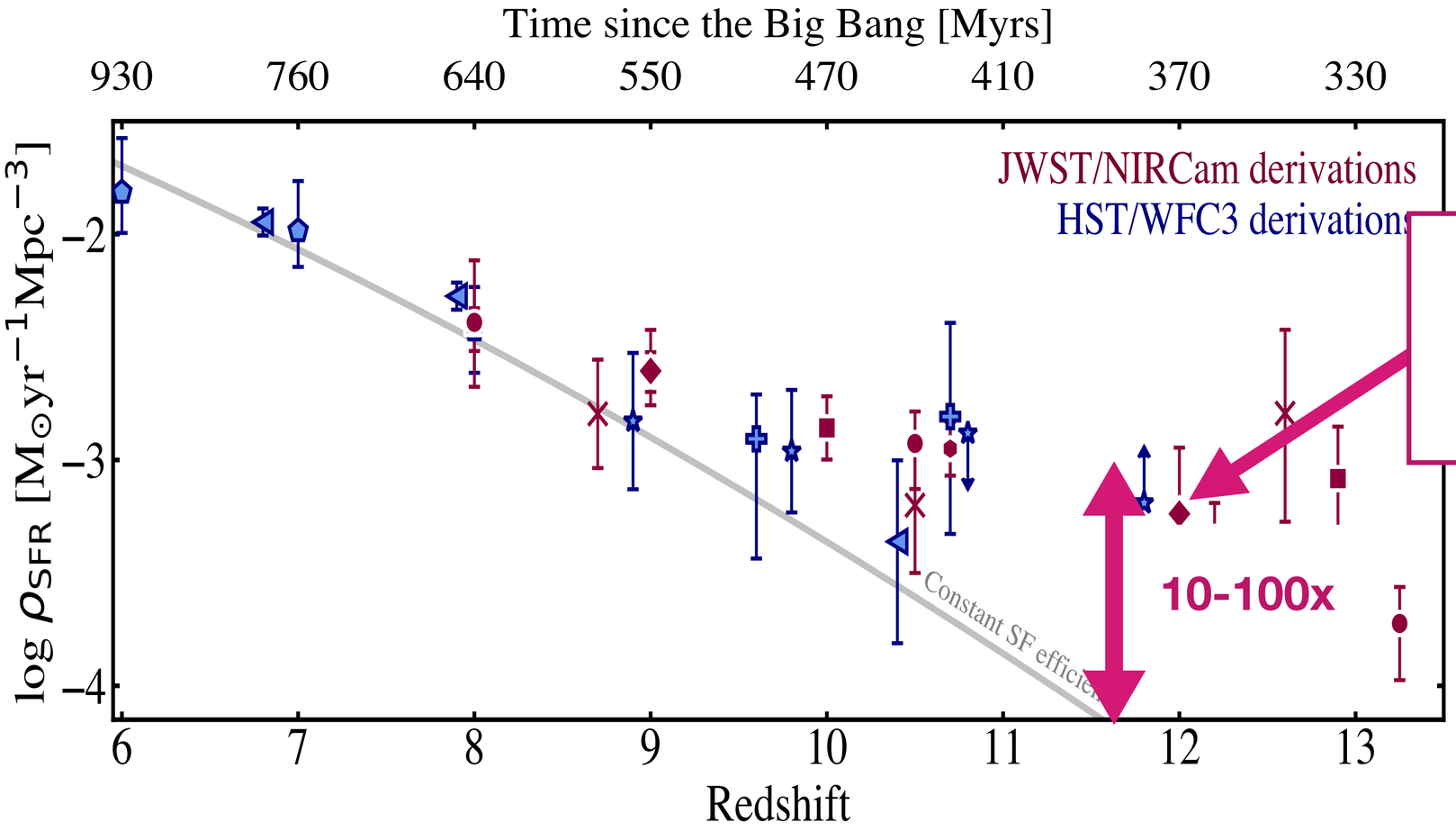


Jiang et al. 2025



A slow evolution of the star formation rate density ?

ISSI Bern, Adamo et al. 2024



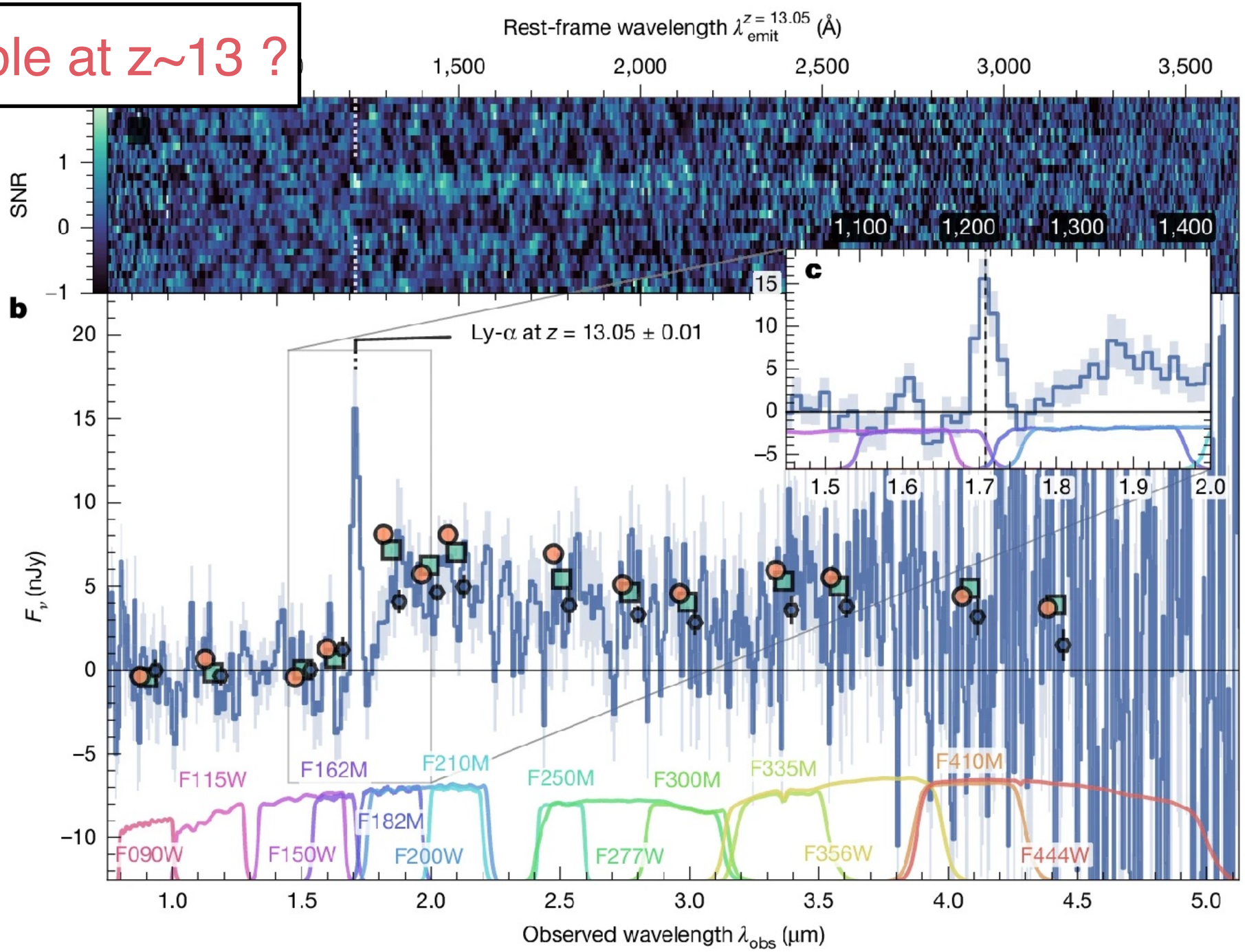
JWST

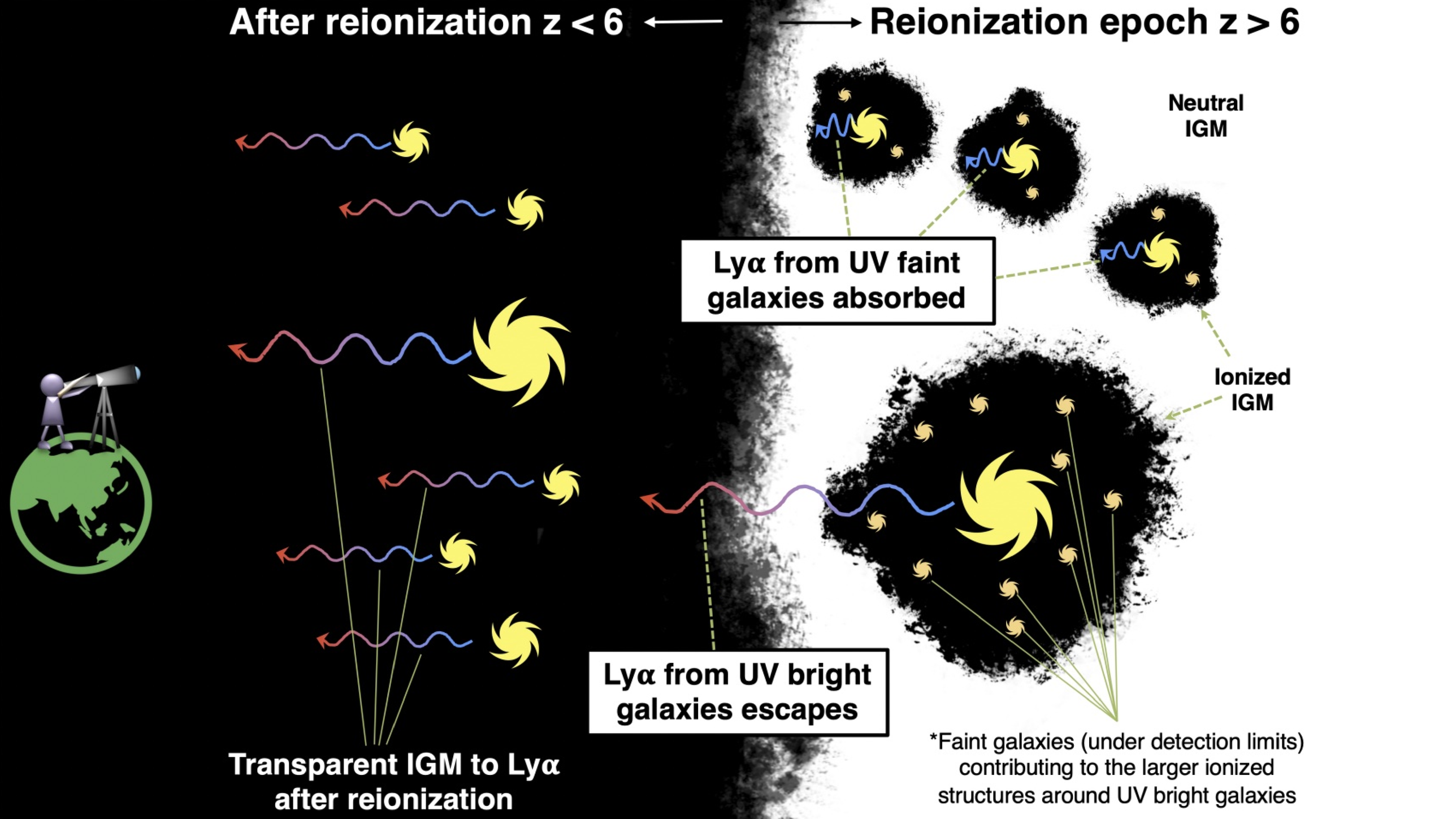
Increasing SF efficiency:

First galaxies formed earlier ?

An ionized bubble at z~13 ?

Witstok et al. (2024)




After reionization z < 6
Reionization epoch z > 6
Neutral IGM
Lyα from UV faint galaxies absorbed
Ionized IGM
Lyα from UV bright galaxies escapes
Transparent IGM to Lyα after reionization
*Faint galaxies (under detection limits) contributing to the larger ionized structures around UV bright galaxies