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The First-generation Luminous Objects (Stars, Galaxies, Black Holes) in the Universe

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Outline:

➤ The history of the Universe

- From Dark Ages, Cosmic Dawn to the Epoch of Reionization

➤ The first-generation luminous objects

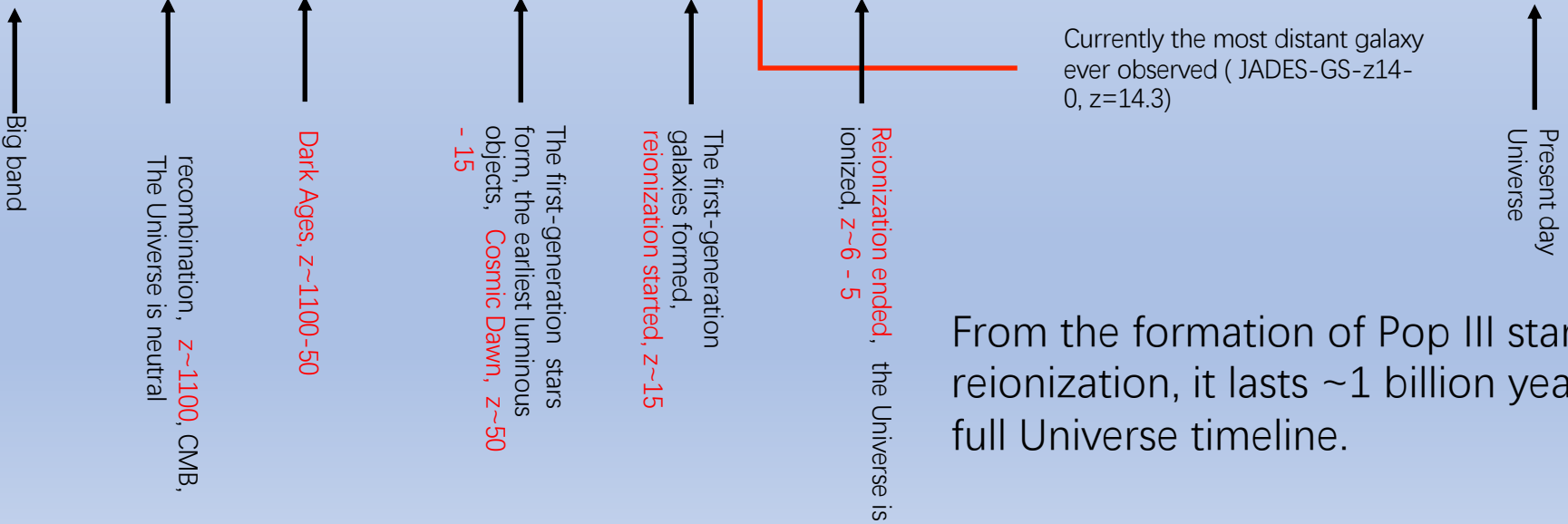
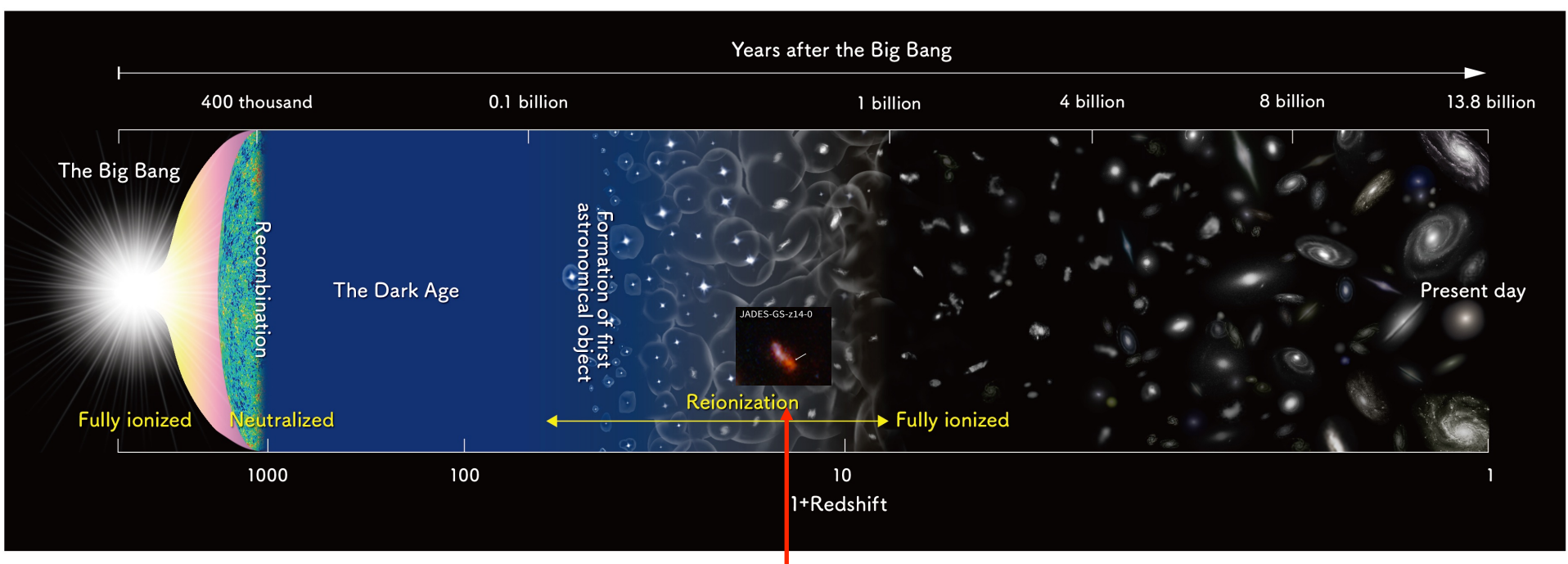
1. First stars
2. First galaxies (UV LF models, JWST observations)
3. First black holes --- direct collapse black holes (DCBH)

➤ Summary

References:

- Barkana & Loeb 2001, In the Beginning: The First Sources of Light and the Reionization of the Universe; Physics Reports, Volume 349, Issue 2, p. 125-238., July 2001.
- Yoshida & Bromm, The First Galaxies, Annual Review of Astronomy and Astrophysics, vol. 49, issue 1, pp. 373-407, September 2011.
- Ciardi & Ferrara, The First Cosmic Structures and Their Effects, Space Science Reviews, Volume 116, Issue 3-4, pp. 625-705, February 2005.
- Loeb & Furlanetto, The First Galaxies in the Universe, Princeton Series in Astrophysics, 2013.
- Bouwens et al., UV Luminosity Functions at Redshifts $z \sim 4$ to $z \sim 10$: 10,000 Galaxies from HST Legacy Fields, The Astrophysical Journal, Volume 803, Issue 1, article id. 34, 49 pp. (2015).
- Finkelstein et al. The Evolution of the Galaxy Rest-frame Ultraviolet Luminosity Function over the First Two Billion Years, The Astrophysical Journal, Volume 810, Issue 1, article id. 71, 35 pp. (2015).
- Harikane et al., Pure Spectroscopic Constraints on UV Luminosity Functions and Cosmic Star Formation History from 25 Galaxies at $z_{\text{spec}} = 8.61\text{--}13.20$ Confirmed with JWST/NIRSpec, The Astrophysical Journal, Volume 960, Issue 1, id.56, 22 pp., January 2024.
- Donnan et al. 2024, JWST PRIMER: a new multfield determination of the evolving galaxy UV luminosity function at redshifts $z \approx 9 - 15$, Monthly Notices of the Royal Astronomical Society, Volume 533, Issue 3, 2024.
- Latif & Ferrara, Formation of Supermassive Black Hole Seeds, Publications of the Astronomical Society of Australia, Volume 33, id.e051 16 pp., 2016.
- Volonteri, Formation of supermassive black holes, The Astronomy and Astrophysics Review, Volume 18, Issue 3, pp.279-315, 2010.

The history of the Universe:



Currently the most distant galaxy ever observed (JADES-GS-z14-0, $z=14.3$)

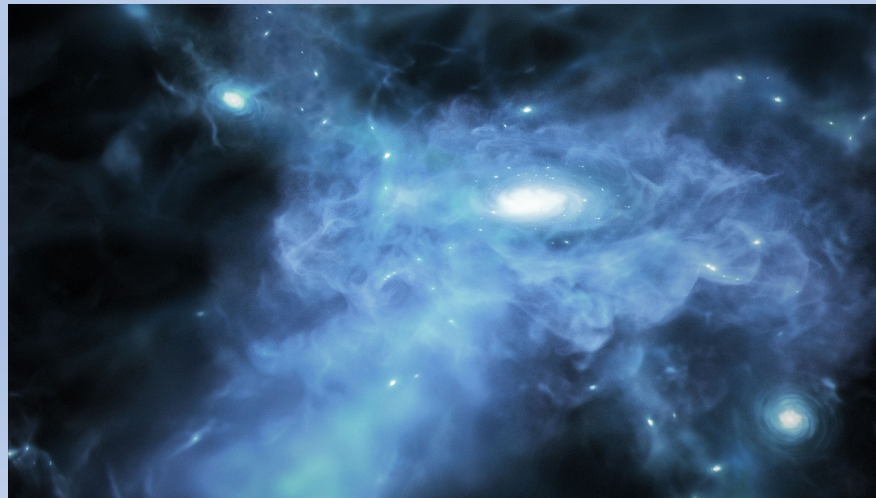
From the formation of Pop III stars to the end of reionization, it lasts ~1 billion years, ~1/14 of the full Universe timeline.

The first-generation luminous objects play crucial role in Universe evolution:

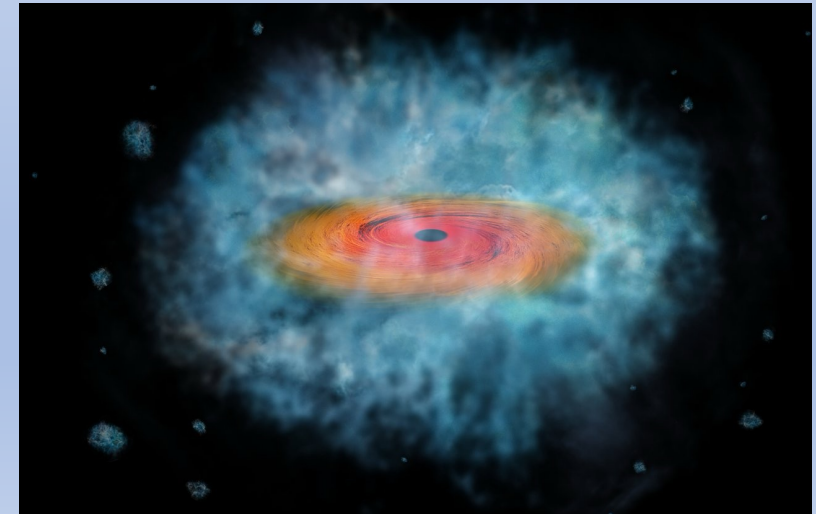
1. First stars ended the Dark Ages and started the Cosmic Dawn;
2. First galaxies completed the reionization; first stars and black holes secondarily contributed to reionization;
3. First black holes are seeds of supermassive black holes (SMBHs)



Credit: N.R. Fuller, National Science Foundation



Credit: NASA, ESA, CSA, Joseph Olmsted (STScI)

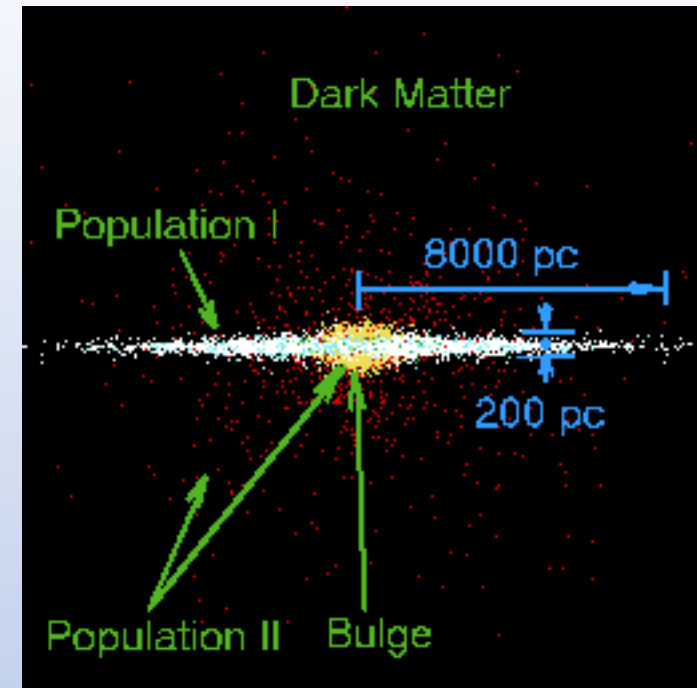


Credit: ESA/Hubble

Stellar Population:

- Pop I: higher metallicity & young, mainly found in Galactic plane (like our Sun),;
- Pop II: lower metallicity & old, mainly found in Galactic halo and globular clusters;
- Pop III: metal-free, not yet found

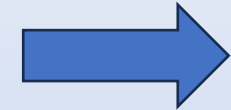
In principle, the first-generation stars must be metal-free, because metal (except a little Li) can only form via nuclear fusion within stars than spread into the environment by stellar winds/supernova explosions .



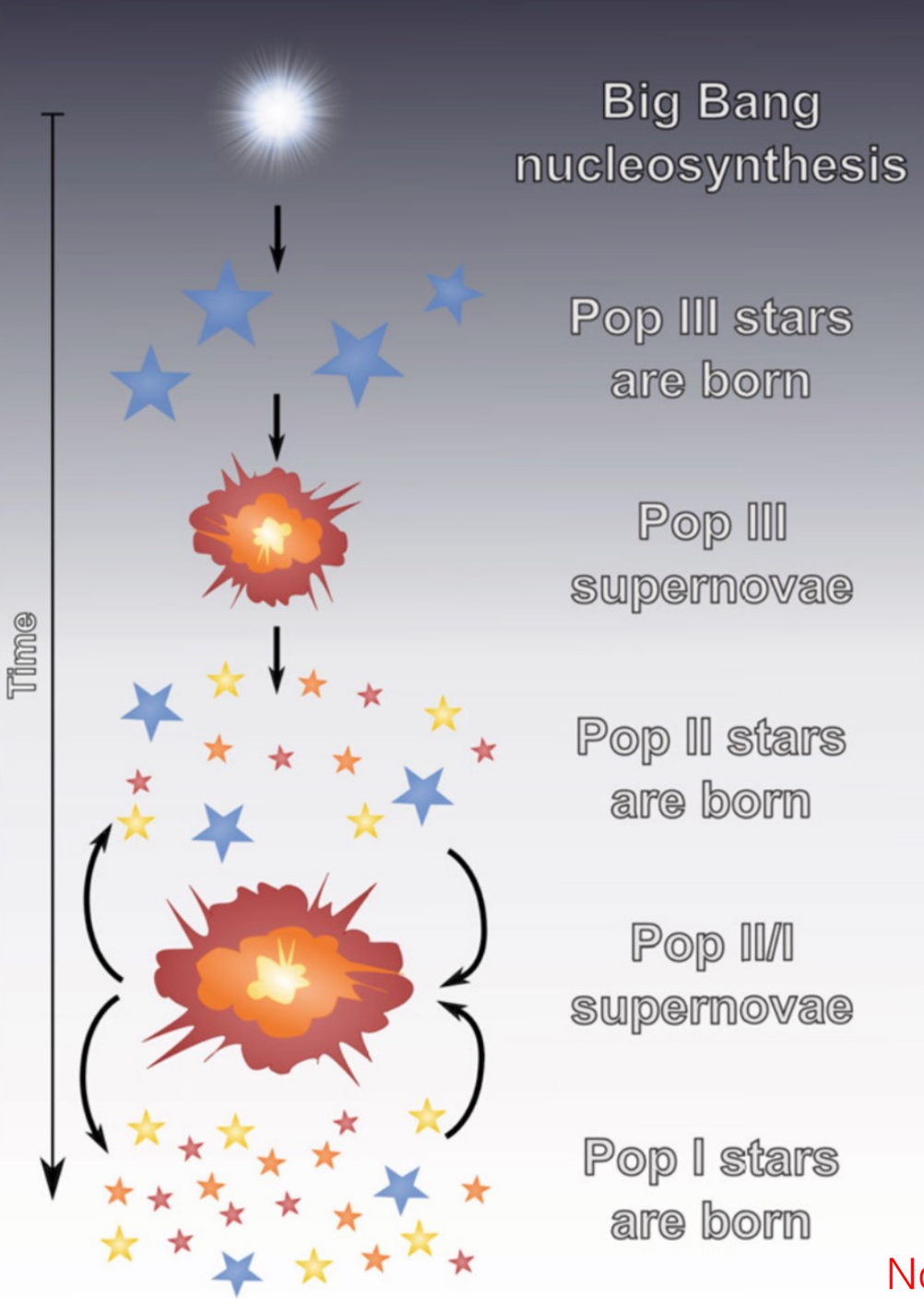
Credit:
https://jila.colorado.edu/~ajsh/courses/as-tr1120_03/text/chapter8/l8S7.htm

The first stars must be Pop III stars!

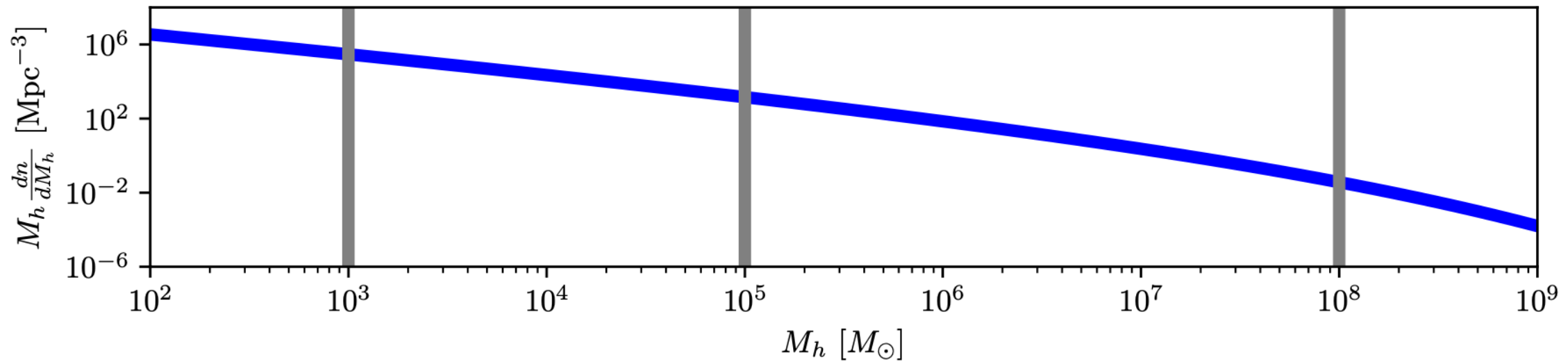
Cosmic Dawn



EoR



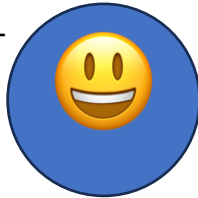
DM halo mass function at Cosmic Dawn:



No gas/DM
annihilation



No cooling/21
cm emission
signal



H₂ cooling/first
stars



H cooling/first
galaxies

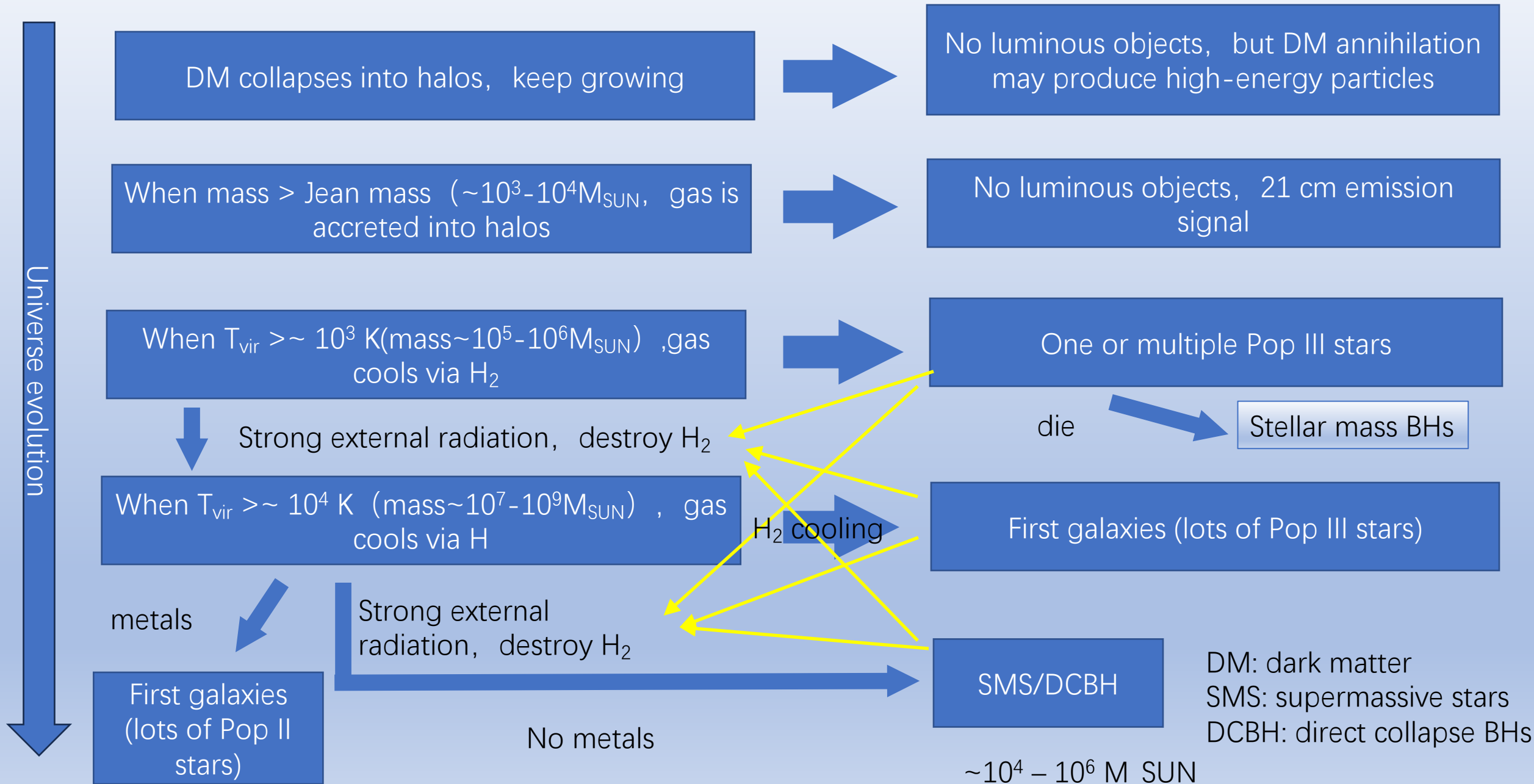
Increasing halo mass

Jeans mass
 $\sim 10^3 M_{\text{SUN}}$

$T_{\text{vir}} \sim 1000\text{K}$
 $\sim 10^5 M_{\text{SUN}}$

$T_{\text{vir}} \sim 10000\text{K}$
 $\sim 10^8 M_{\text{SUN}}$

The formation of first luminous objects and Universe evolution:



First Stars:

minihalo



A single Pop III star



A Pop III binary



A multiple Pop III stars system

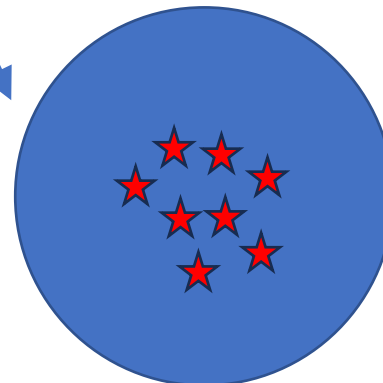
- First stars must be in minihaloes, must be Pop III stars;
- First galaxies must be in atomic-cooling halos, either Pop III or Pop II stars, or mixed.

First Galaxies:

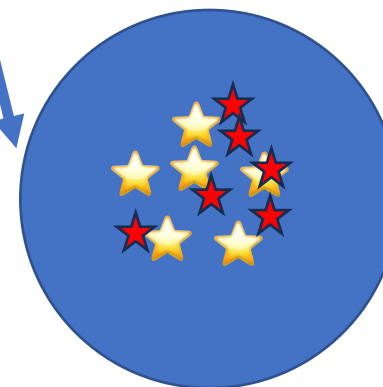
atomic-cooling halo



Many Pop III stars

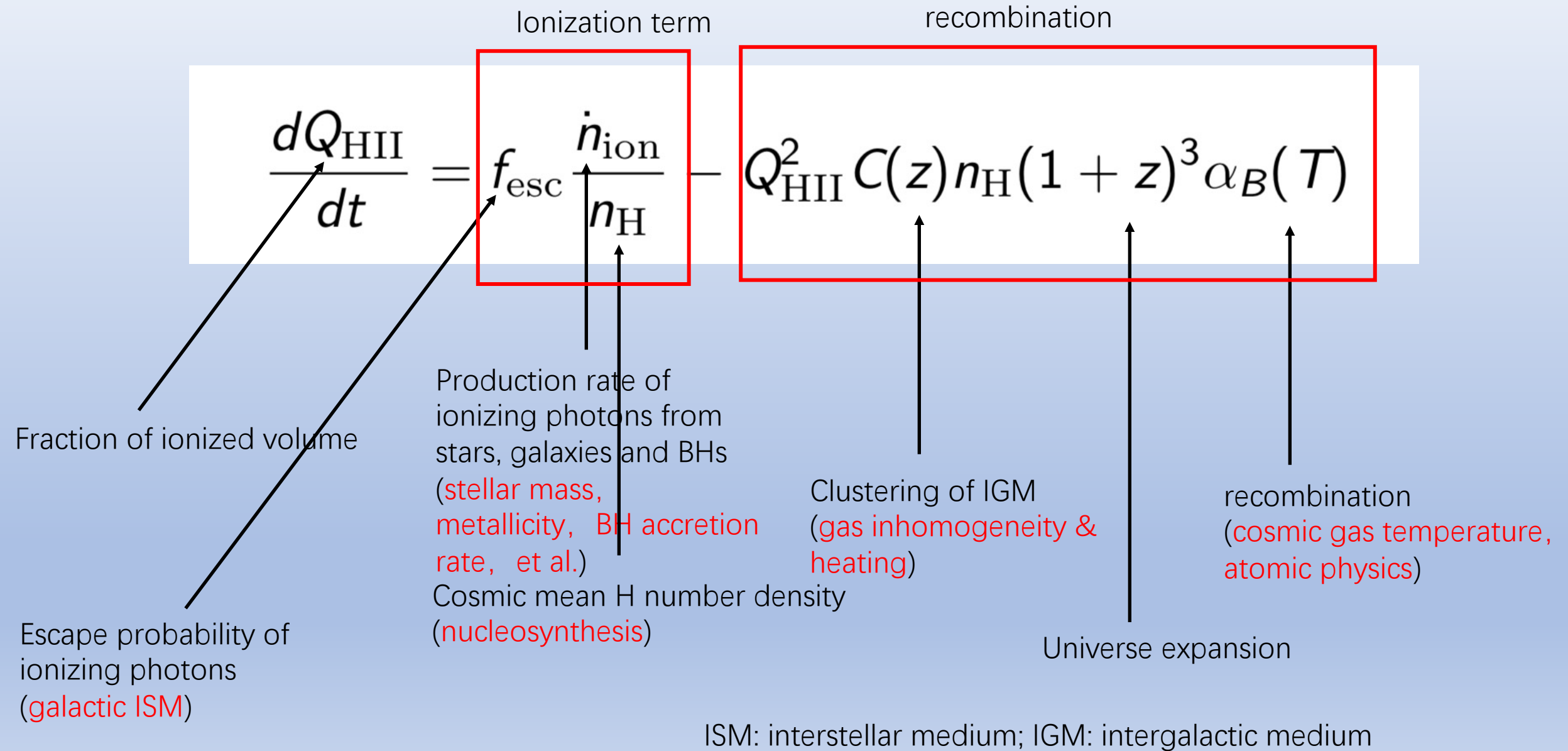


Many Pop II stars

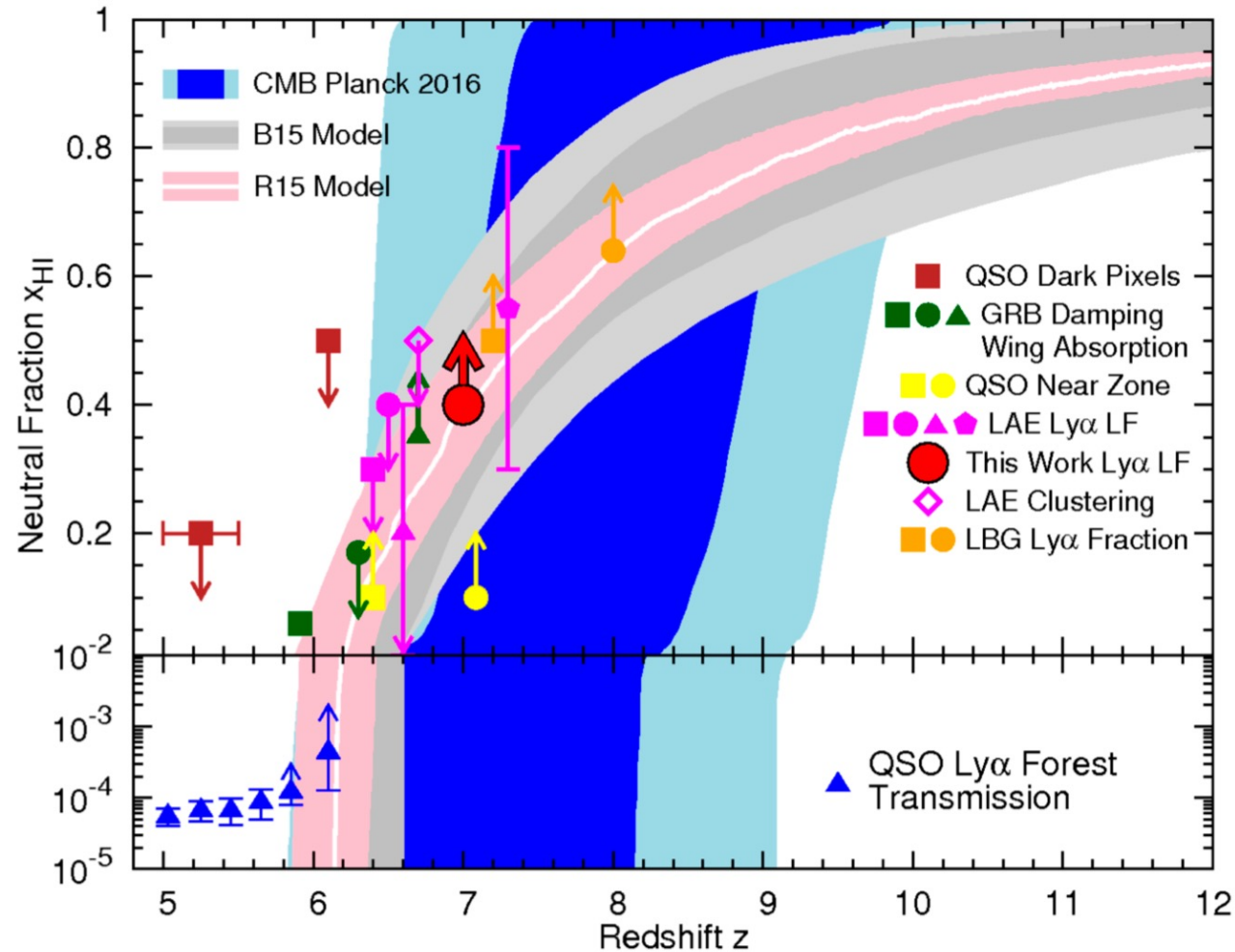


Pop III -> Pop II

The evolution of ionized regions:



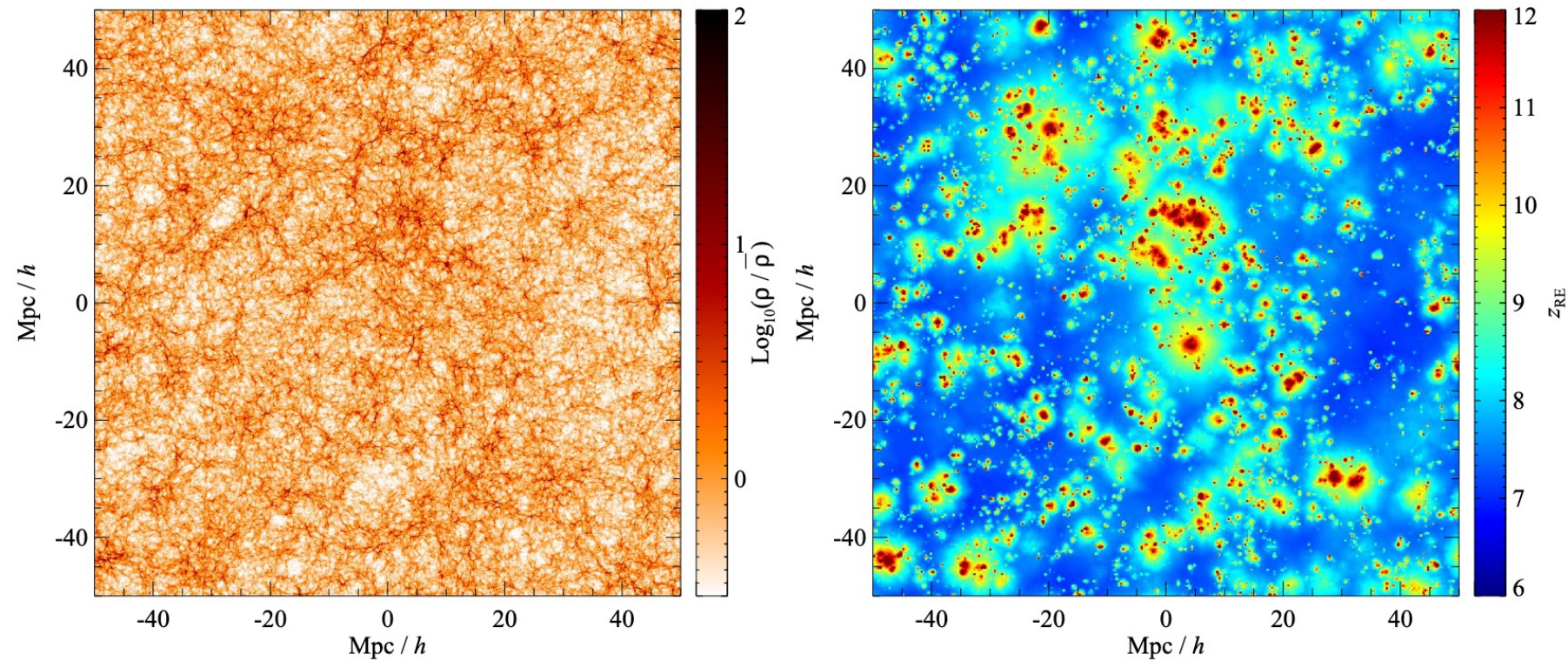
Observational constraints in cosmic neutral fraction:



- Reionization starts at $z \sim 15-10$
- Ends at $z \sim 5-6$
- Mid-point is $z \sim 7.7$

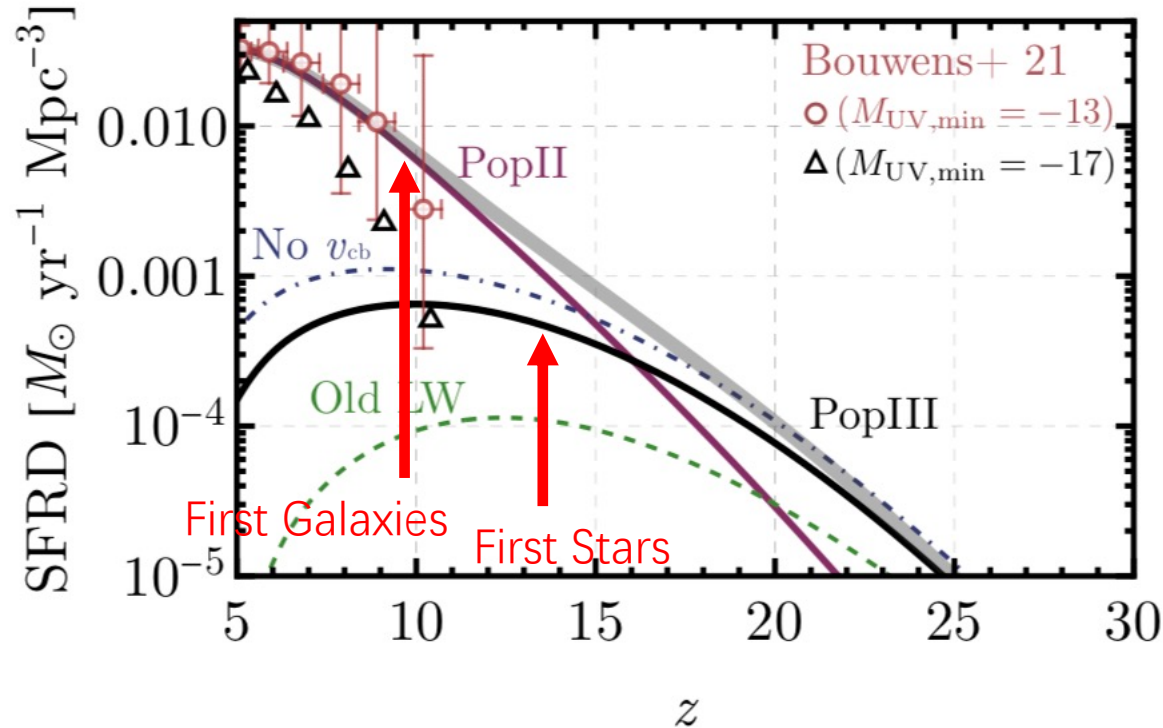
The first luminous objects formed in over-dense regions, such regions are ionized earlier.

Tight correlation: first luminous objects formation --- ionization redshift



First Stars vs. First Galaxies

$$\dot{n}_{\text{ion}} = N_{\text{ion}} \times \text{SFRD}$$



Munoz et al. 2021

Pop II stars ~4000

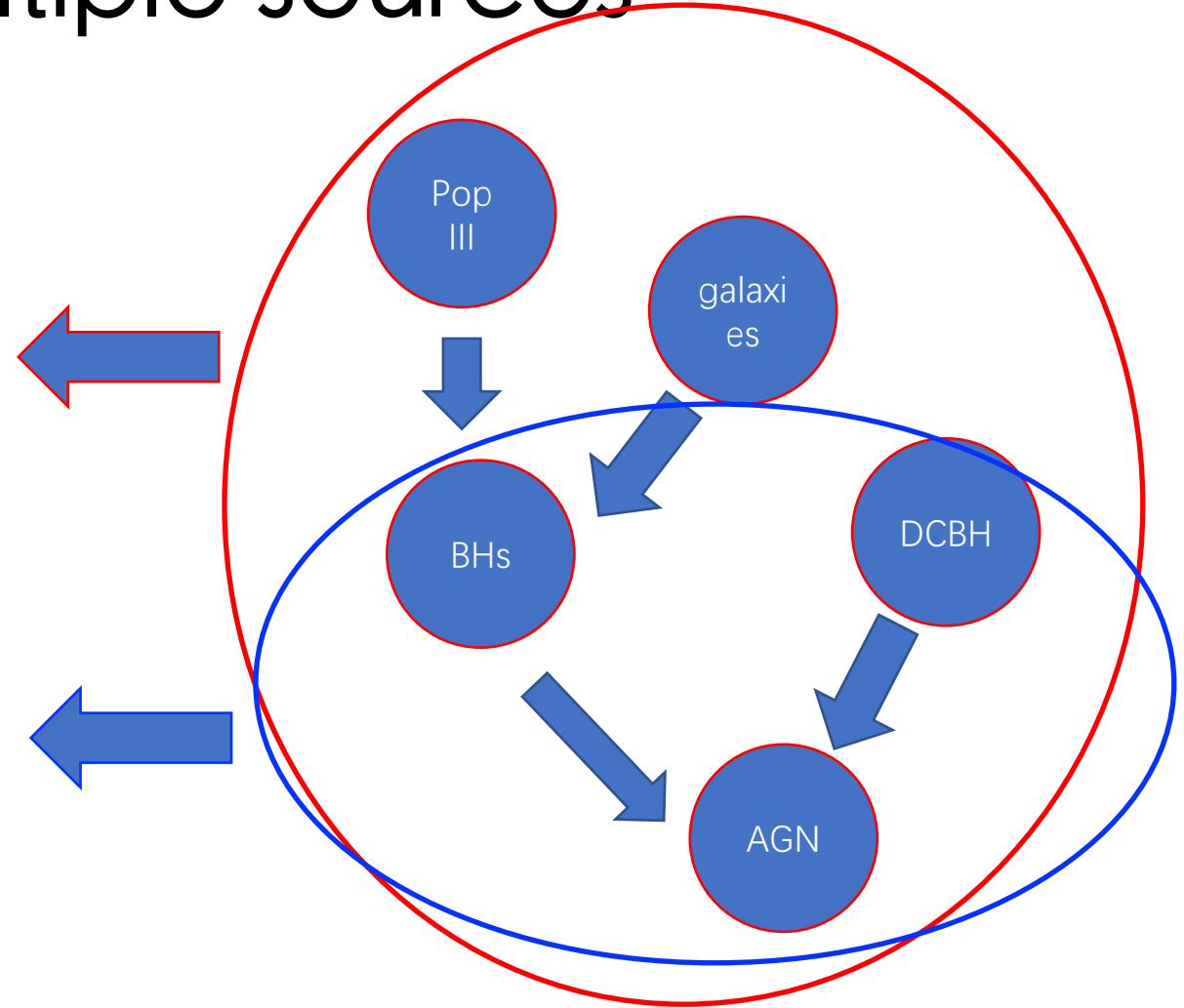
Pop III stars ~13000

- the production rate of ionizing photons for a single star, Pop III $\gg$ Pop II
- However the SFR of Pop $\ll$ Pop II star
- Pop III stars' contribution to reionization is $\sim < 10\%$

Yes! First stars ended the Dark Ages, started the Cosmic Dawn. However, their formation rely on H_2 cooling, which is rather fragile in the presence of LW radiation (from other Pop III stars, galaxies and AGNs). The global SFR of first stars is much smaller than first galaxies, so that the contribution to reionization.

Two kinds of photons, two kinds of ionization, multiple sources

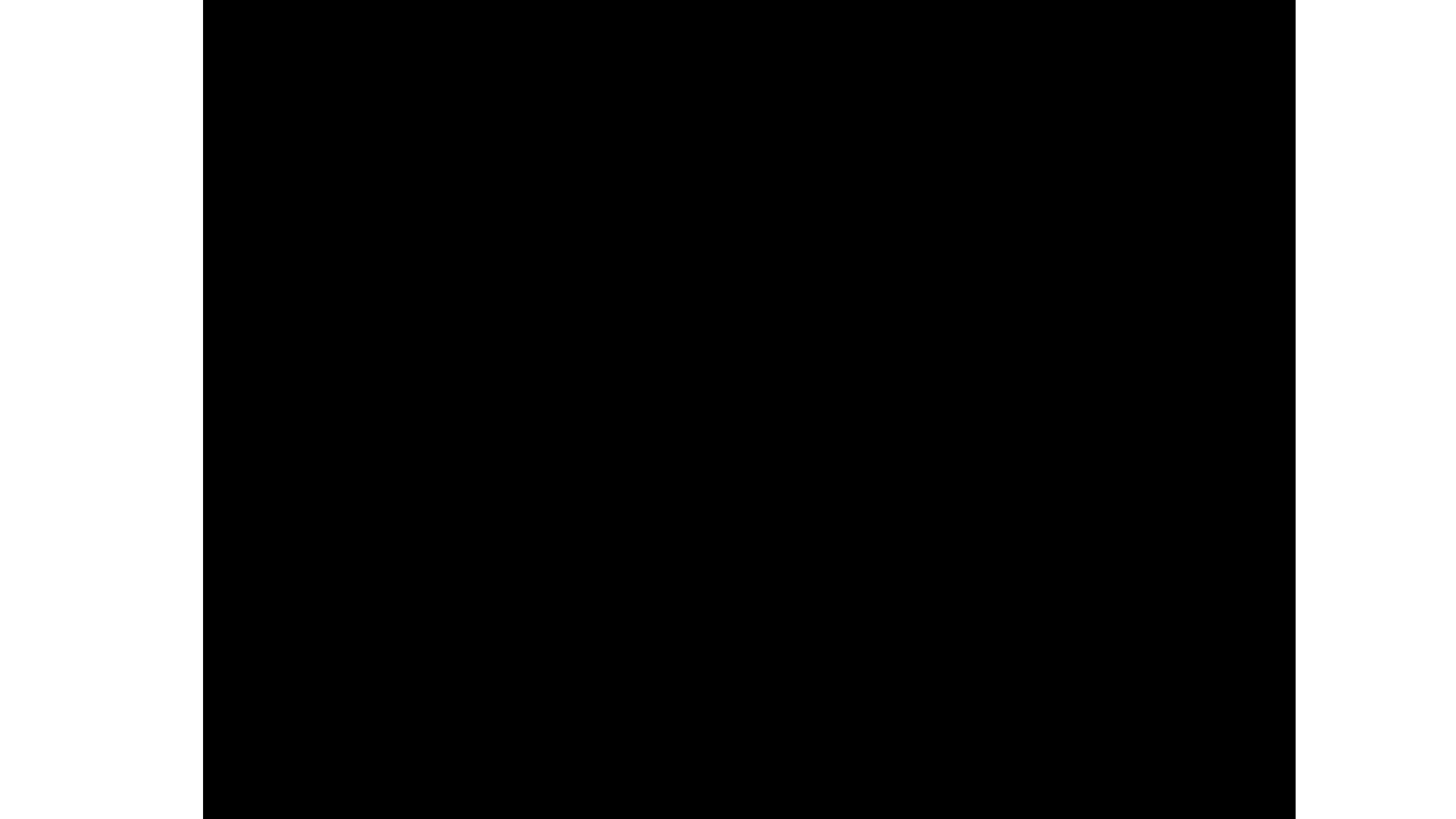
1. >13.6 eV UV photons, short mean free path, only propagate in ionized gas, mainly from nearby sources, “patched” ionization scenario;
2. X-ray photons, long mean free path, propagate in both ionized & neutral gas, homogeneous ionization scenario.



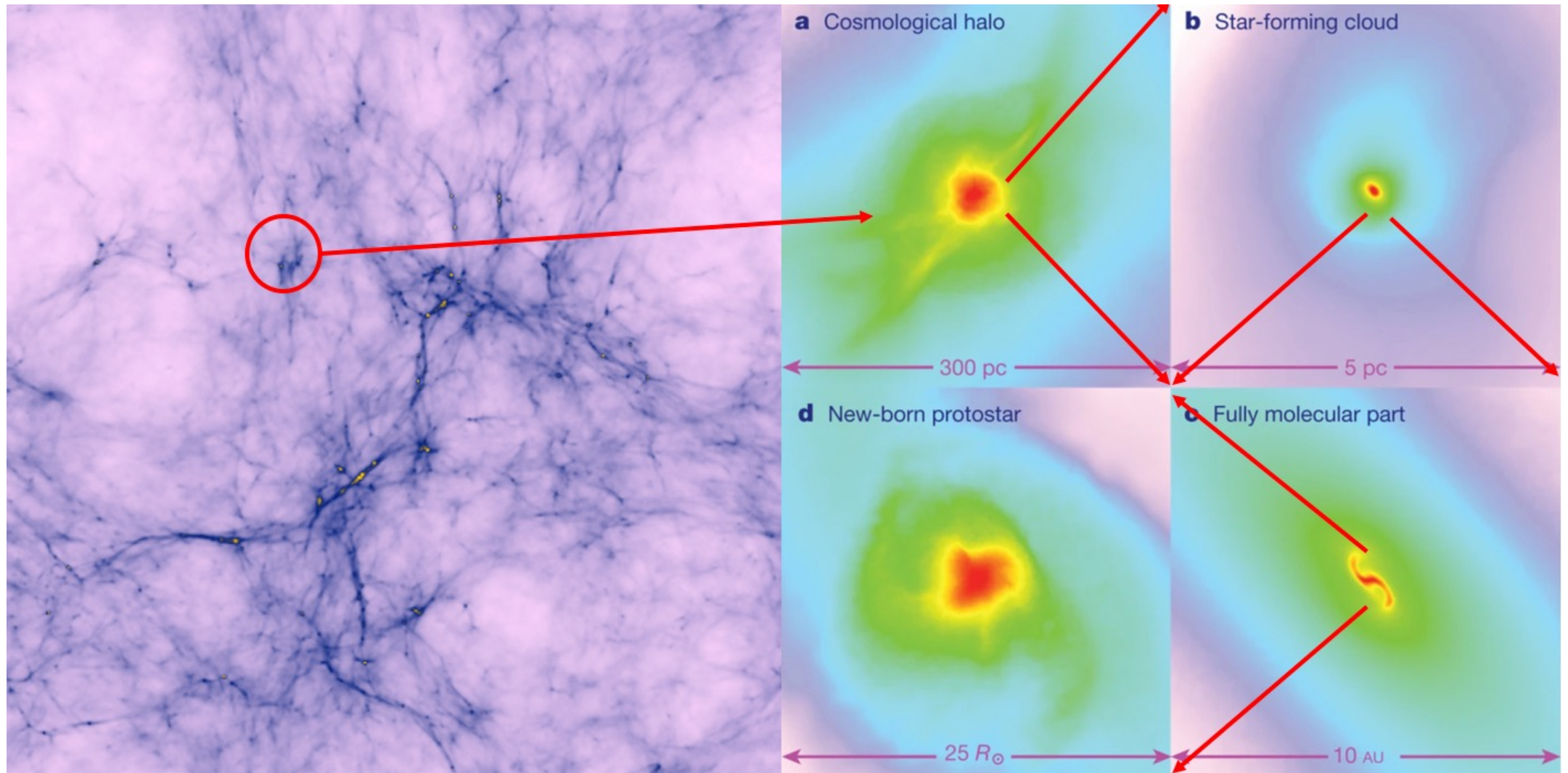
Reionization is mainly driven by UV photons from first galaxies!

I. First Stars

The terminology “first stars” refers to the earliest stellar population (Pop III), rather than the earliest single star, in the Universe.



A first star forming site:

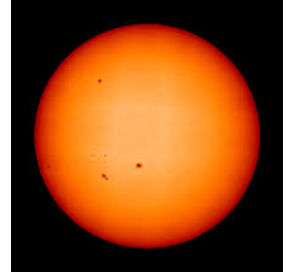


Credit: Yoshida

Characteristics of Pop III stars:

- Massive, $\sim 10 - 1000 M_{\text{SUN}}$
- Short-lived, $\sim \text{Myr}$
- High surface effective temperature, 10^5 K , hard spectrum, UV dominated
- Low formation efficiency
- Rare, isolated/binary/several

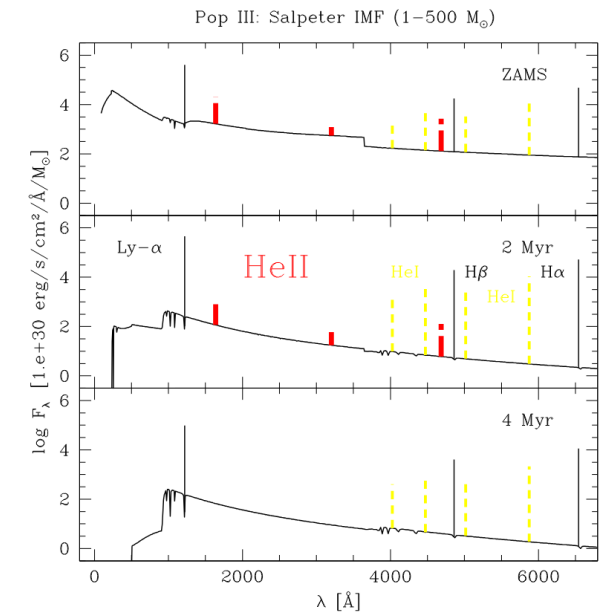
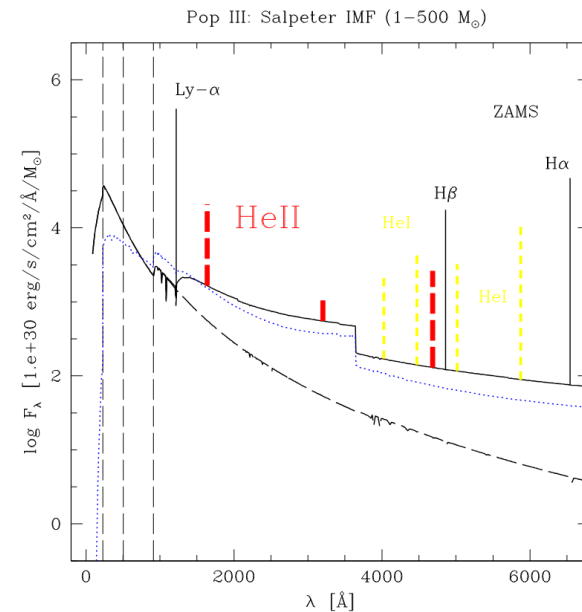
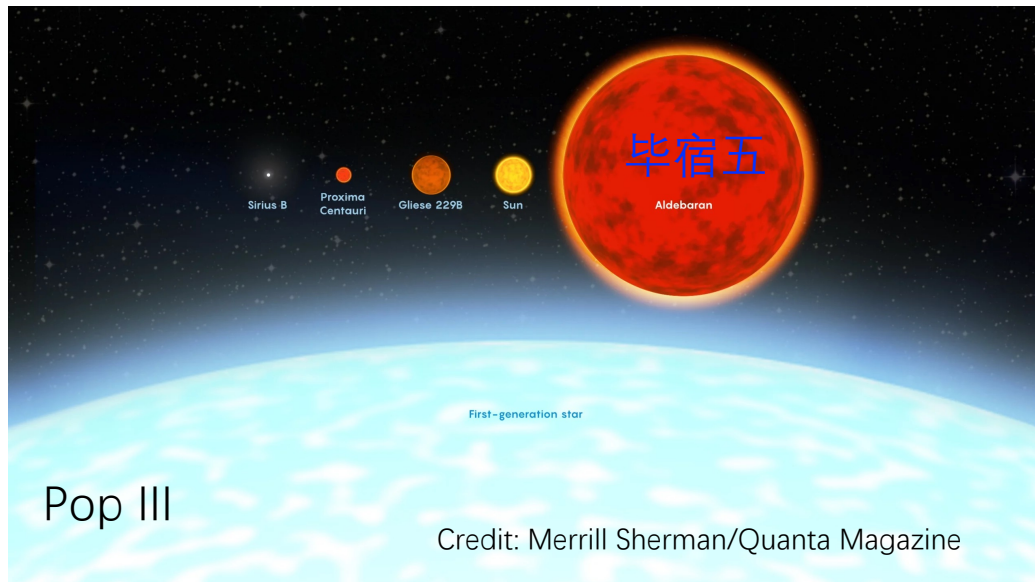
Our Sun:



- $1 M_{\text{SUN}}$
- 10^5 Myr
- 6000 K, visible dominated



Can ionize the HeII, HeII 1640 Å line (HeII recombination line) is almost the smoking gun evidence for Pop III stars (may disappear soon)



Schaerer 2002

Pop III mass= $10^6 M_{\text{SUN}}$

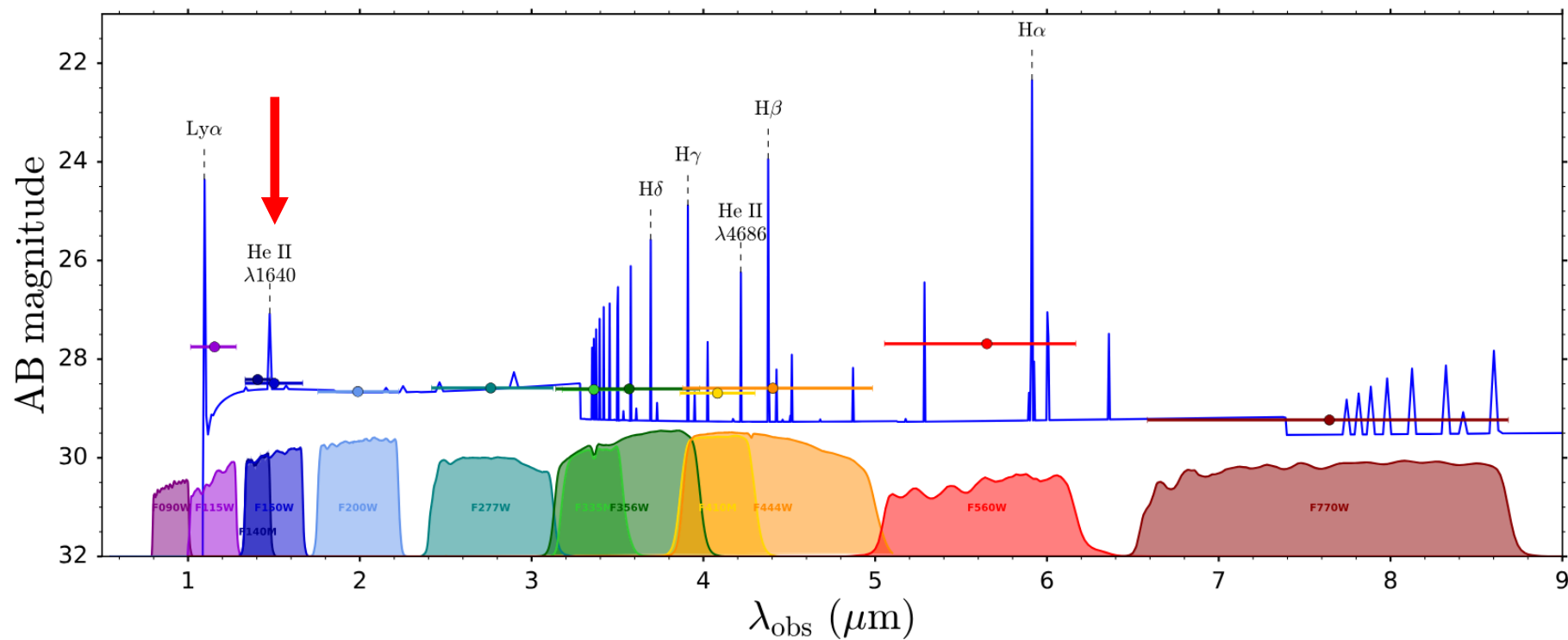
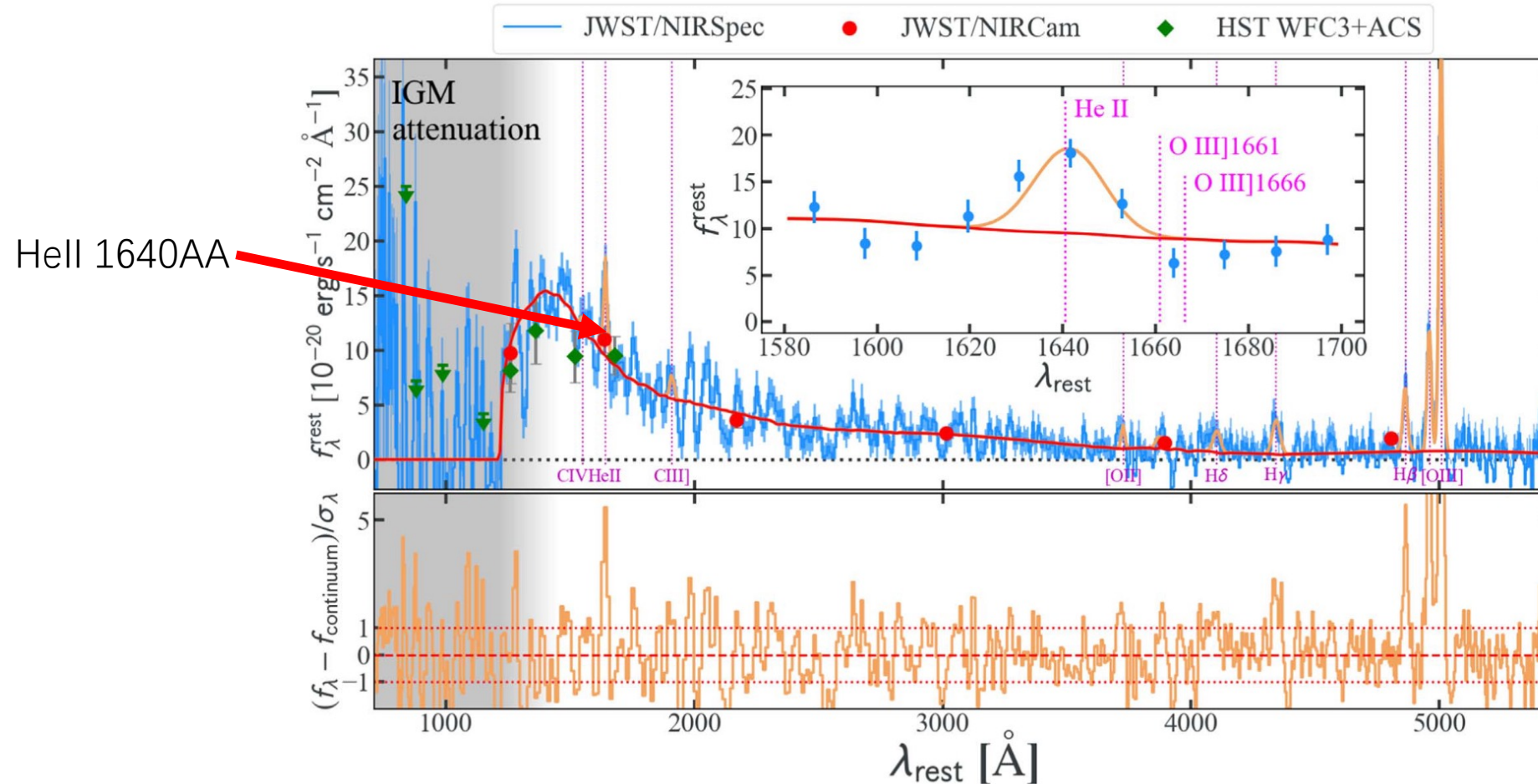


Figure 1. The spectrum of a $z = 8$ Pop III.1 galaxy (i.e. with the characteristic mass of the individual Pop III stars M_* , IMF being $\sim 100 M_{\odot}$) at the nominal stellar mass $\log(M_*/M_{\odot}) = 6$, observed immediately after (0.01 Myr) an instantaneous starburst. The filter throughputs and bandpass-averaged flux densities within the *JWST* NIRCam + MIRI bands that are used throughout our $z \sim 8$ analysis are also shown.

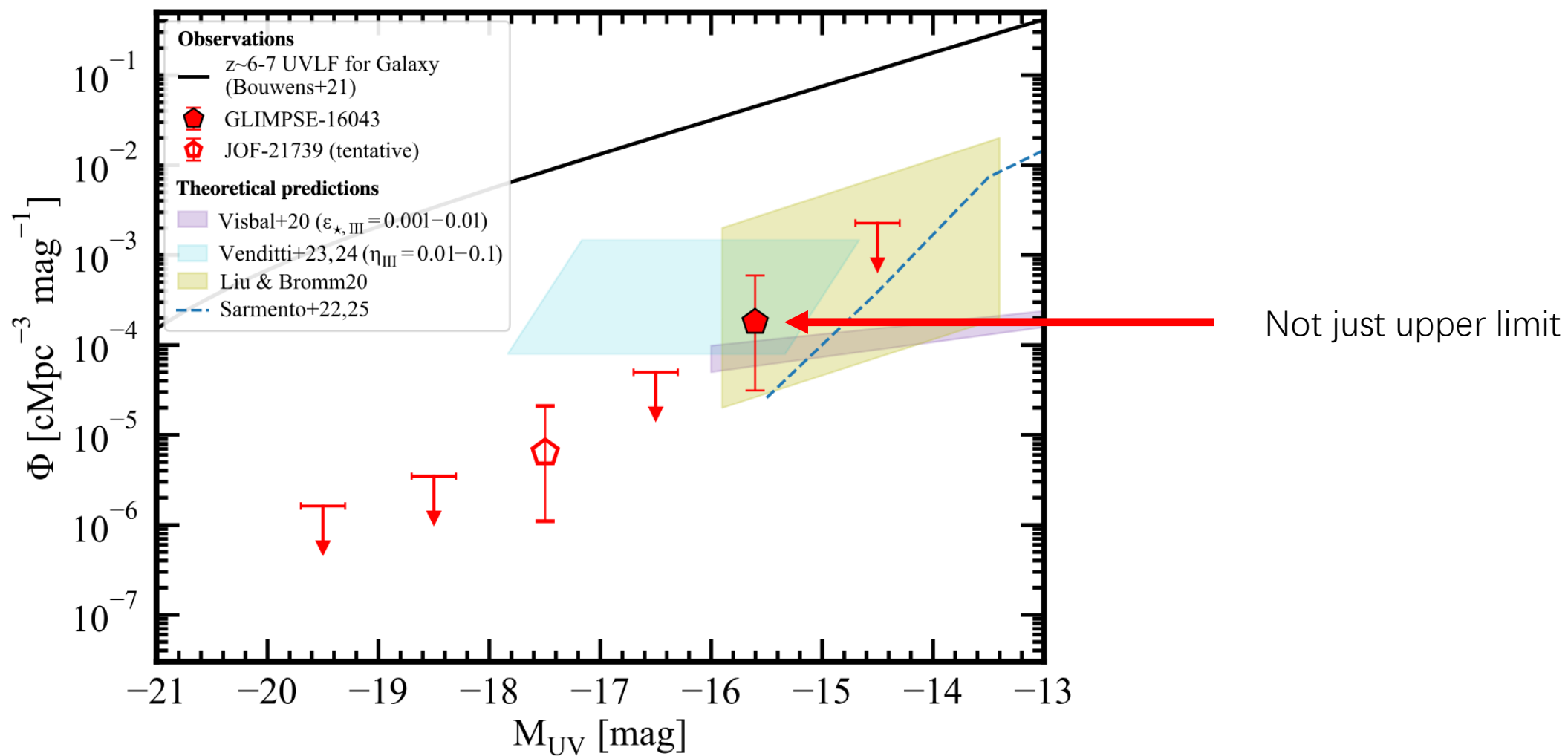
A Strong He II $\lambda 1640$ Emitter with an Extremely Blue UV Spectral Slope at $z = 8.16$: Presence of Population III Stars?

Xin Wang^{1,2,3} , Cheng Cheng⁴ , Junqiang Ge³ , Xiao-Lei Meng³ , Emanuele Daddi⁵ , Haojing Yan⁶ , Zhiyuan Ji⁷ , Yifei Jin⁸ , Tucker Jones⁹ , Matthew A. Malkan¹⁰ , Pablo Arrabal Haro¹¹ , Gabriel Brammer^{12,13} , Masamune Oguri^{14,15} , Meicun Hou¹⁶ , and Shiwu Zhang¹⁷ 



successfully reproduce the emission line flux ratios observed in RX J2129–z8He II. Assuming the Eddington limit, the total mass of the Pop III stars within this system is estimated to be $7.8 \pm 1.4 \times 10^5 M_{\odot}$. To date, this galaxy presents the most compelling case in the early Universe where trace Pop III stars might coexist with metal-enriched populations.

Observed constraints on the UV LF of Pop III stars at $z \sim 6 - 7$



Why a Pop III star is (very likely) massive?

For a gas cloud:

“When the sound-crossing time is less than the free-fall time, pressure forces temporarily overcome gravity, and the system returns to a stable equilibrium. However, when the free-fall time is less than the sound-crossing time, gravity overcomes pressure forces, and the region undergoes gravitational collapse.”

- $t_{\text{ff}} \gtrsim t_{\text{sc}}$: stable equilibrium
- $t_{\text{ff}} \lesssim t_{\text{sc}}$: gravitational collapse

Since $t_{\text{ff}} = 1/\sqrt{G\rho}$, hence the **Jean length**:

$$\lambda_J \sim c_s t_{\text{ff}} = \frac{c_s}{\sqrt{G\rho}}$$

If a gas cloud is larger than its Jeans mass, it will fragment into multiple clumps with mass $\sim$ Jeans mass!

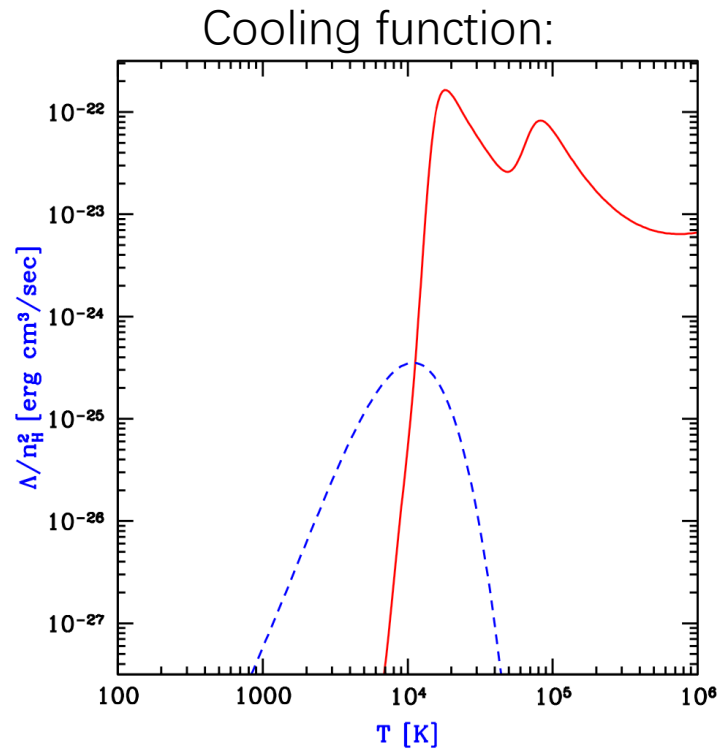
and the **Jeans mass**:

$$M_J = \frac{4\pi}{3}\rho \left(\frac{\lambda_J}{2}\right)^3 \propto T^{3/2}\rho^{-1/2}$$

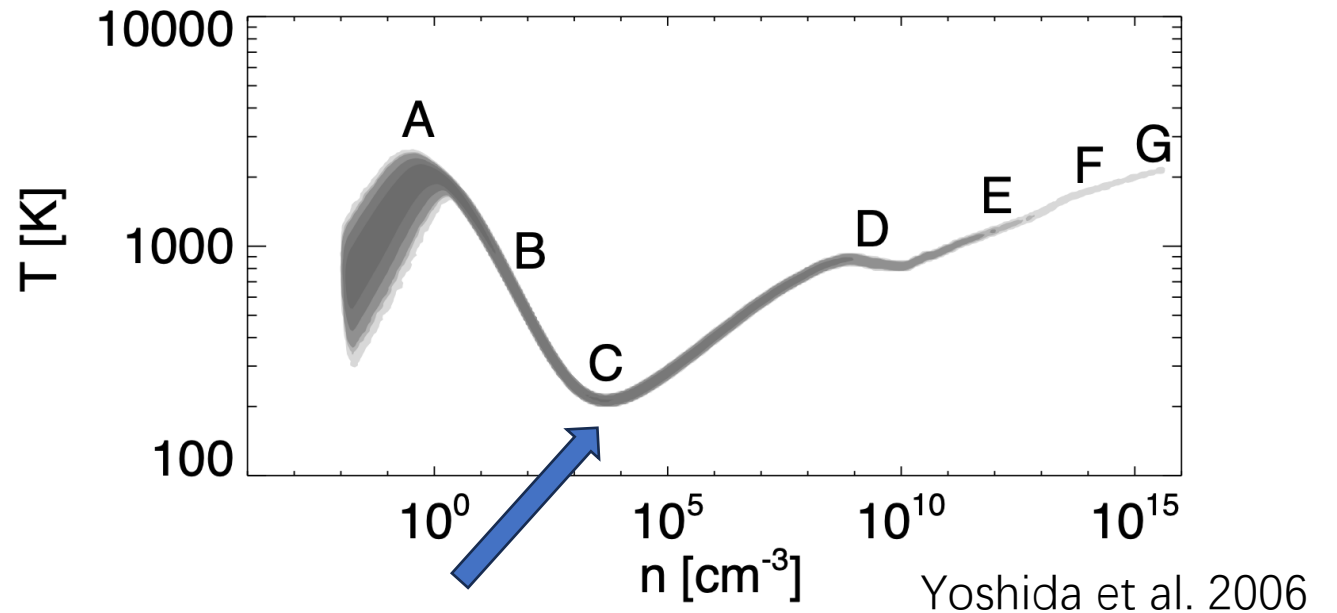
- The higher the temperature, the larger the Jeans mass
- H₂ cooling becomes less efficient below 1000 K
- The Jeans mass of star-forming gas cloud is large

$$M_J \approx 1000 \left(\frac{T}{200\text{K}} \right)^{3/2} \left(\frac{n}{10^4 \text{cm}^{-3}} \right)^{-1/2} M_{\odot}$$

Hirano et al. 2015



Barkana & Loeb 2001

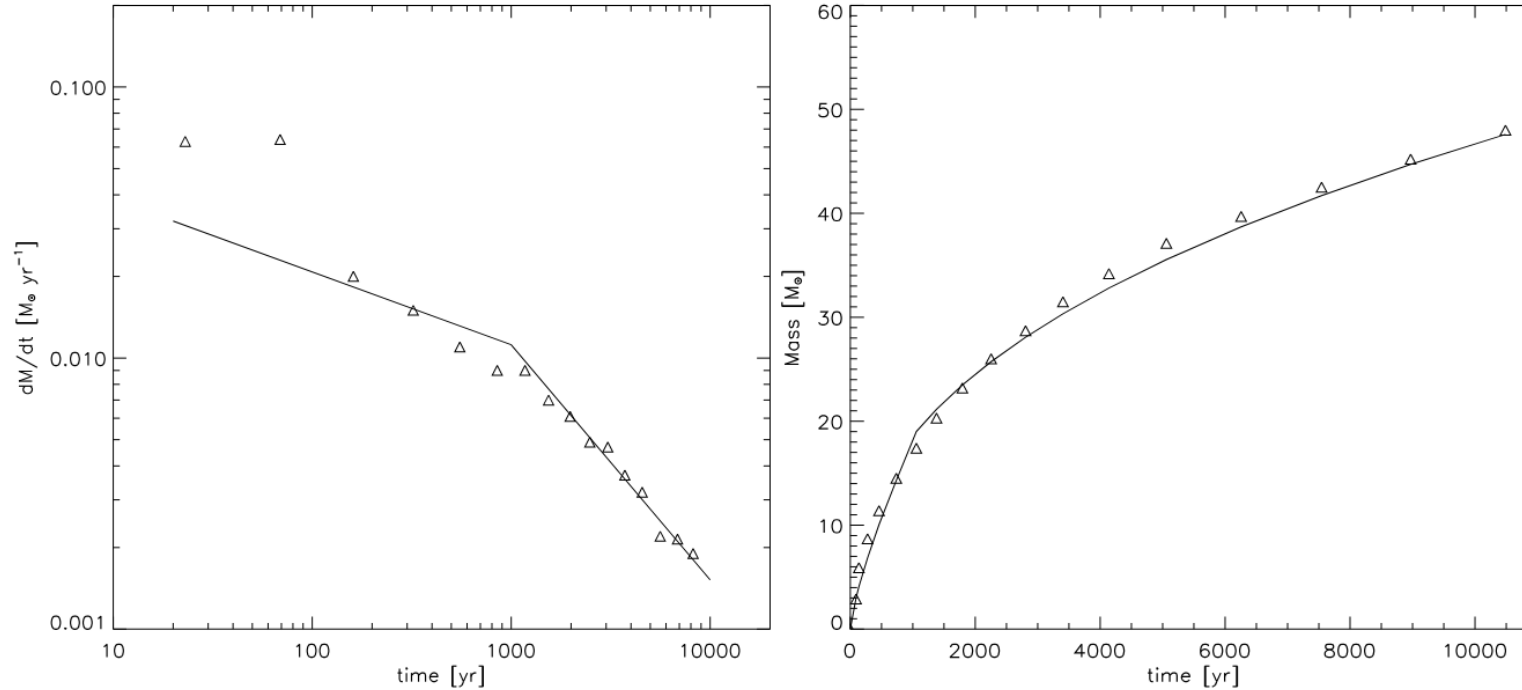


Yoshida et al. 2006

Minimum Jeans mass, ~ 300 M_{SUN}

The final mass depends on mass and accretion rate of the proto-star, and how long the accretion lasts

Initial proto-star: 1 M_{SUN}

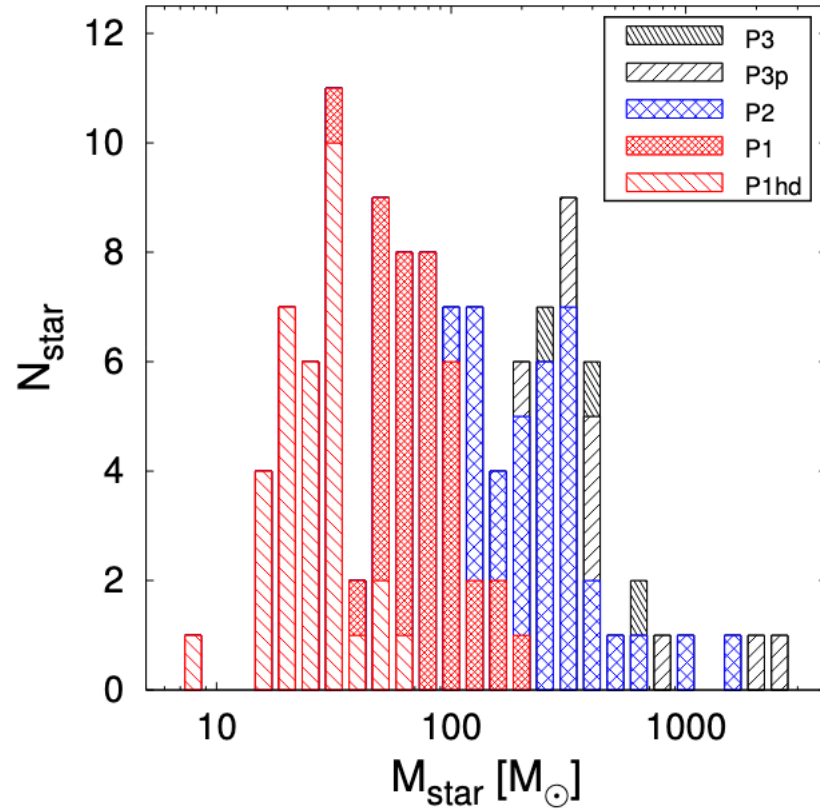


$$\dot{M} = \begin{cases} 5.6 \times 10^{-2} \left(\frac{t}{1 \text{ yr}} \right)^{-0.25} M_{\odot} \text{ yr}^{-1} & t \leq 10^3 \text{ yr} \\ 6.3 \times 10^{-1} \left(\frac{t}{1 \text{ yr}} \right)^{-0.6} M_{\odot} \text{ yr}^{-1} & t > 10^3 \text{ yr} \end{cases}$$

$$\dot{M}_* \simeq 20 M_{\odot} (t/10^3 \text{ yr})^{0.4}.$$

So if the accretion lasts for $\sim 10^5$ yr, the final mass is $\sim 120 M_{\text{SUN}}$

IMF of Pop III stars

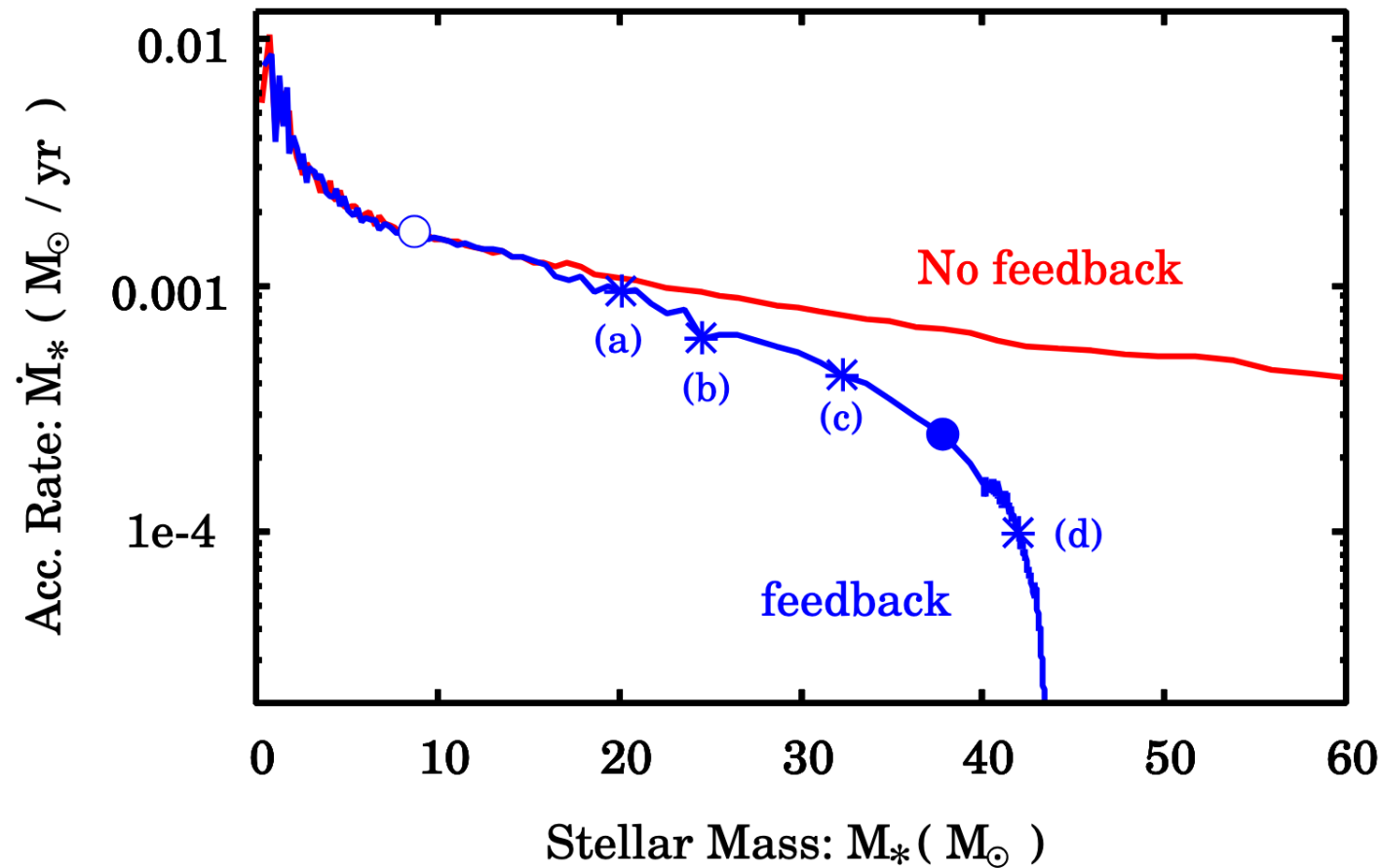


Hirano et al. 2014

$$M_{\text{popIII}} = 100 M_{\odot} \left(\frac{\dot{M}_{\text{cloud}}}{2.8 \times 10^{-3} M_{\odot} \text{ yr}^{-1}} \right)^{0.8}$$

$$M_{\text{popIII}} = 100 M_{\odot} \left(\frac{1+z}{20} \right)^3 \left(\frac{M_{\text{virial}}}{3 \times 10^5 M_{\odot}} \right)^2$$

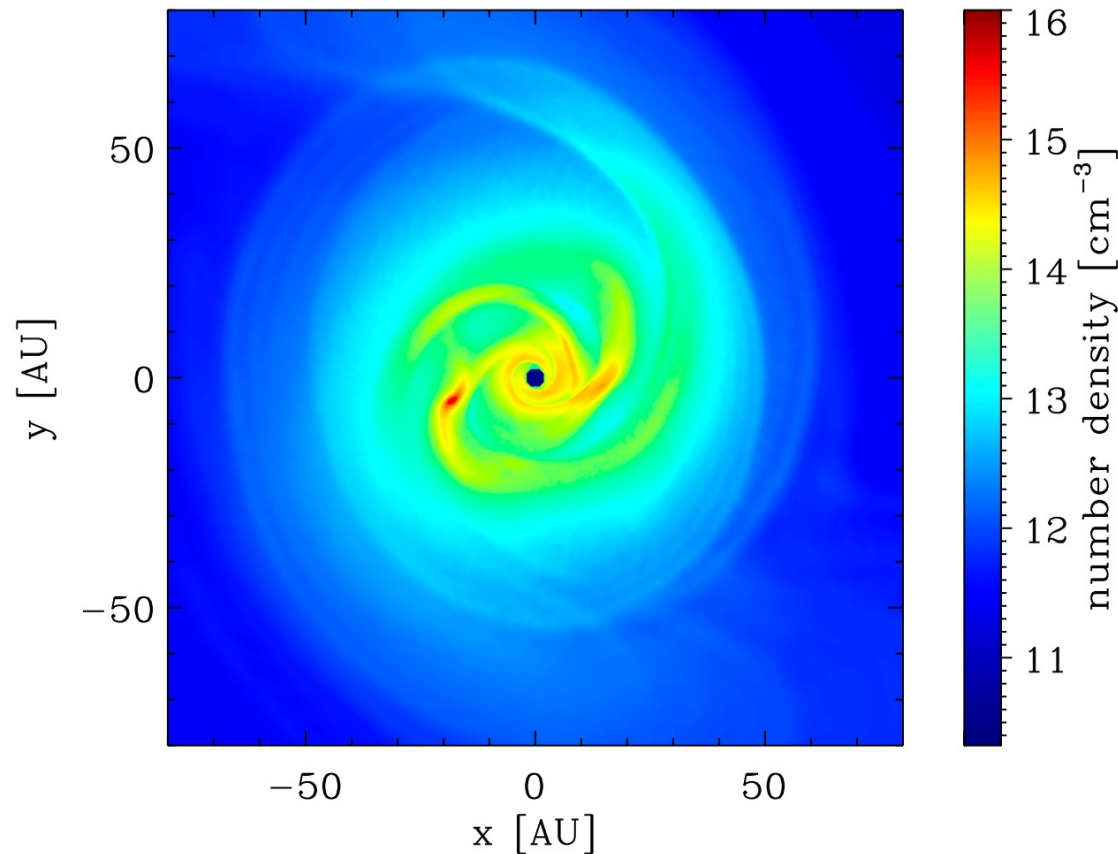
However, feedback may halt the accretion, limit the growth of a proto star via accretion:



A proto-star deposit energy into the surrounding via various radiation, this halts the accretion and limits the stellar mass to $\sim 43 M_\text{SUN}$

Pop III stars are still massive, however not that massive

Fragmentation, Pop III star binary/multiple stars system

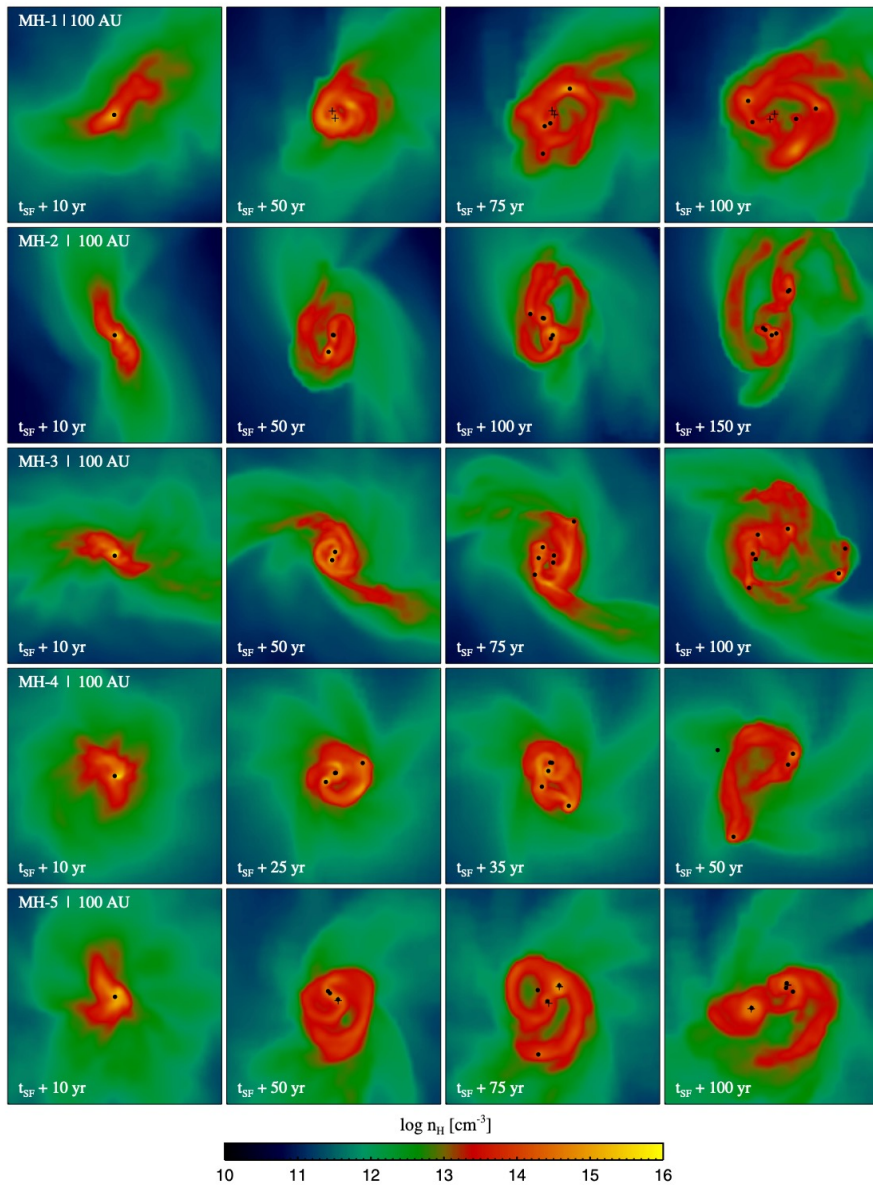


Clark et al. 2011, see Stacy et al. 2010 as well

- Around the central protostar, an accretion disk forms and keeps growing
- The disk is gravitationally unstable, and forms several spiral arms
- The disk fragments into several low-mass protostars

Gas falling onto the disk faster than accreted into protostar, therefore the disk has high surface density

Not an isolated, but a multiple stars system form!

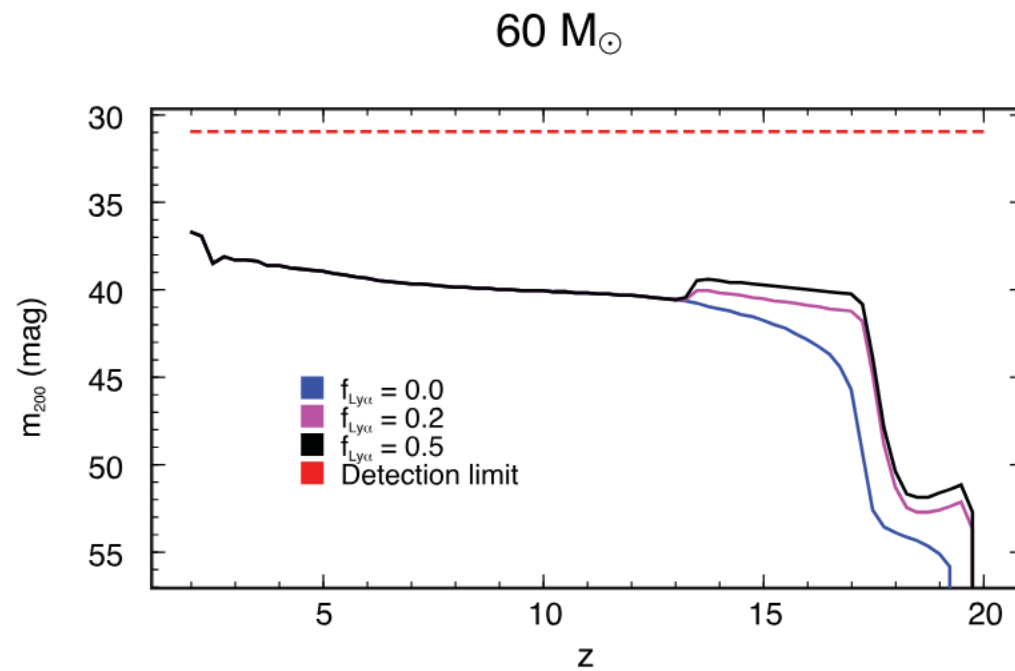


- In all the cases, the disk around the first protostar (the center) fragment into several clumps
- Multiple stars system (cluster) form

Even in minihalos, the formation of Pop III protostars is clustered

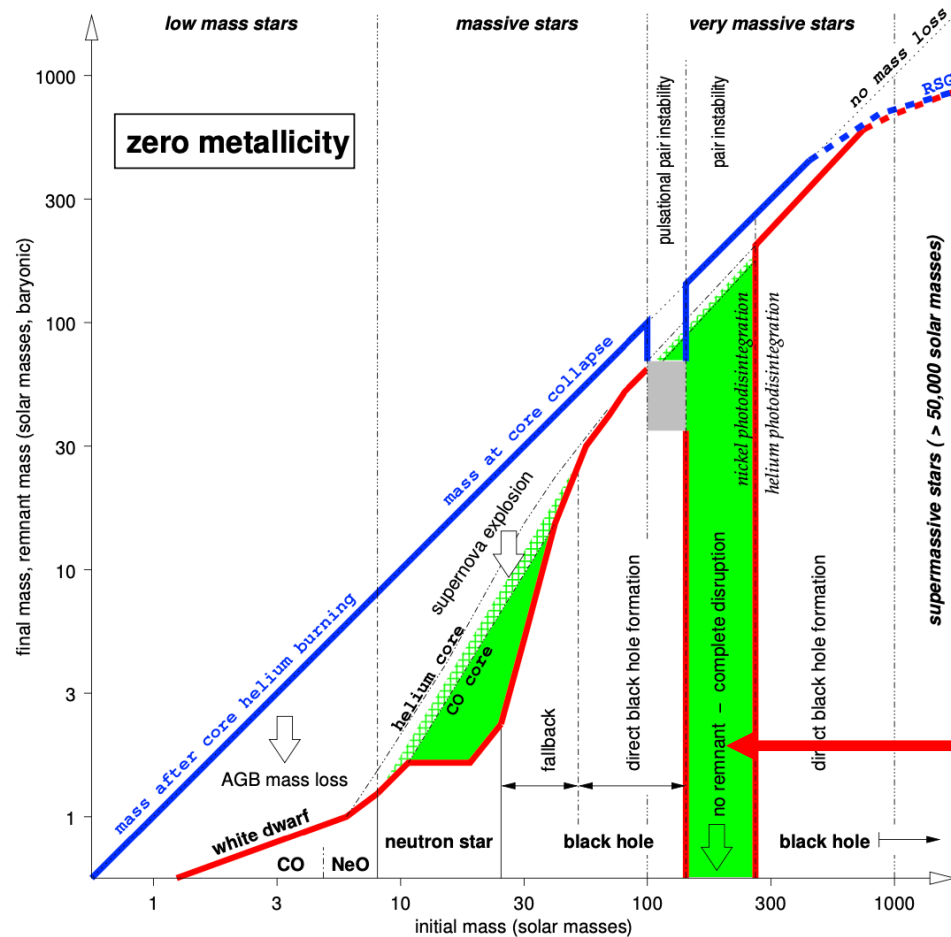
However, still it is possible that these protostars may merger into a single main sequence star in a short timescale (Greif et al. 2012)

An isolated Pop III star is far below the sensitivity of the JWST



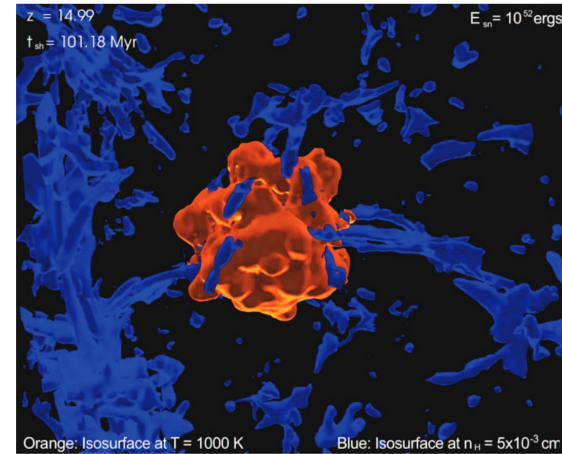
Rydberg et al. 2013

Final fate & first SN explosion



Heger et al. 2003

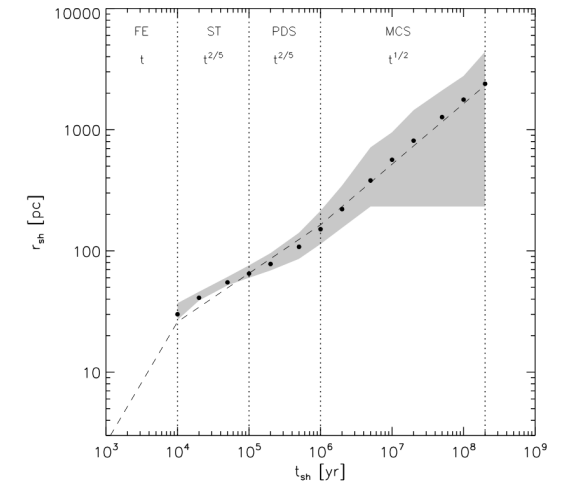
Remnant of a PISN



Greif et al. 2007

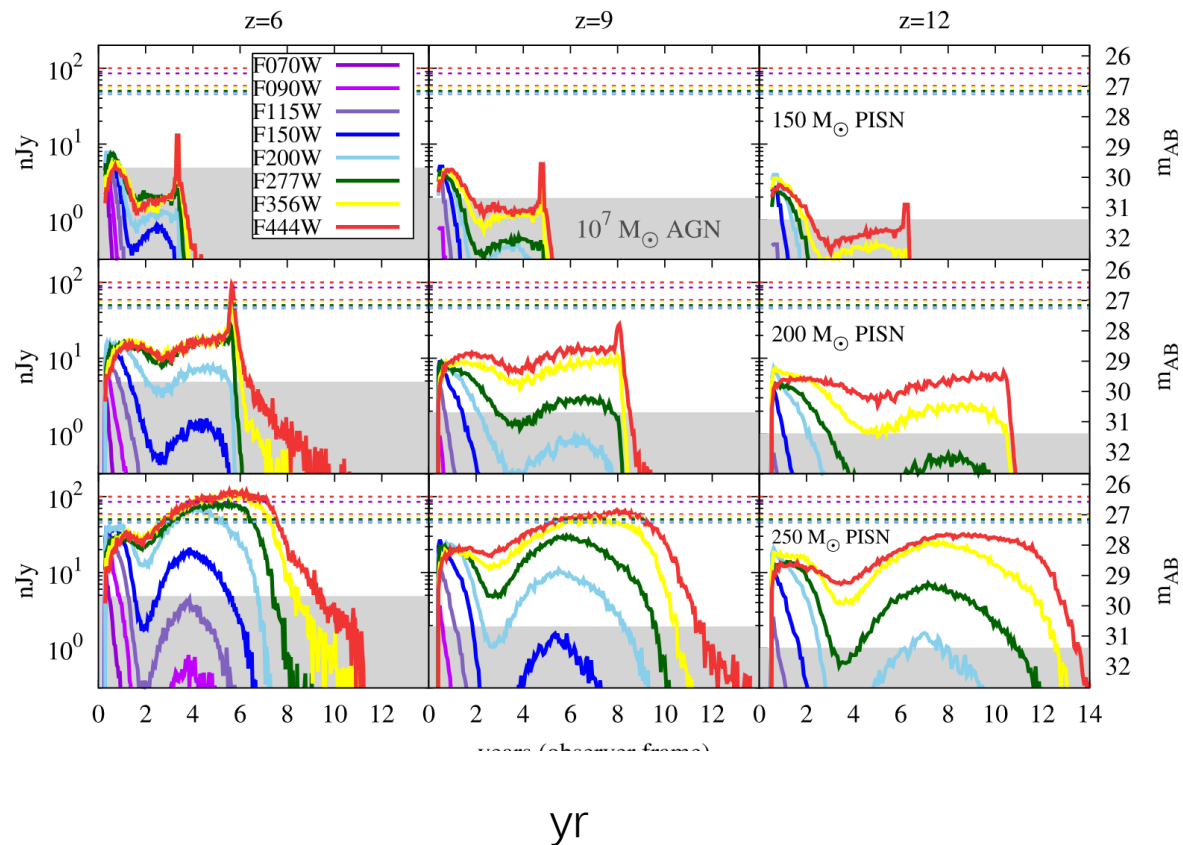
For stellar mass in 140 – 260 M_{SUN}
Pair instability supernova (PISN),
Released energy 10^{52} erg!

Explosion of a PISN



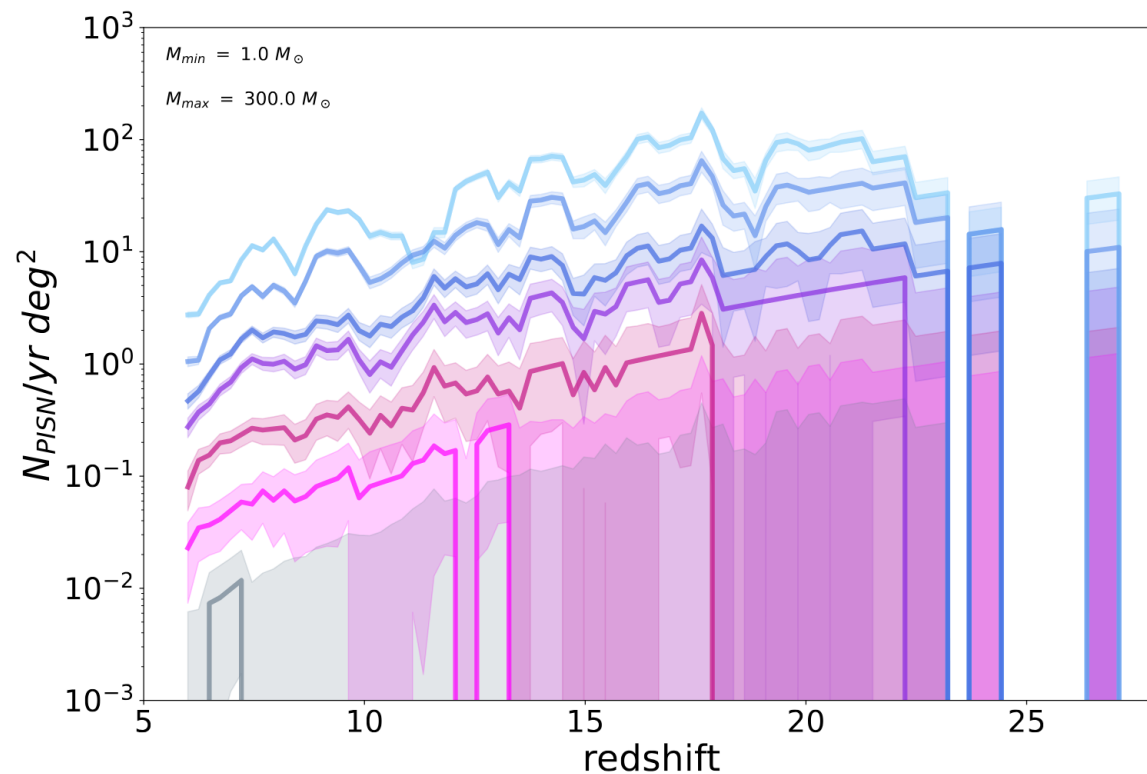
PISN is another tool for detecting the Pop III stars indirectly!

Predicted light curve



Hartwig et al. 2018

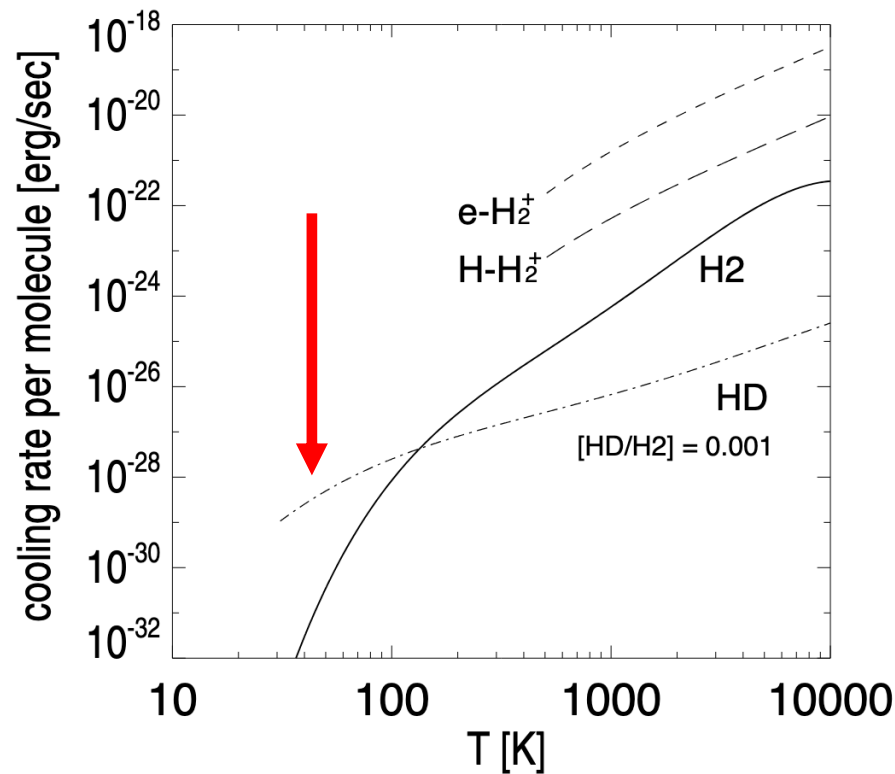
Predicted PISN rate for different IMFs



Wiggins et al. 2024

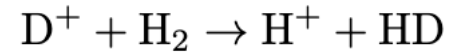
Pop III.1 & Pop III.2

- Below ~ 100 K, hydrogen deuteride (HD) cooling is more efficient, gas is cooled **down to CMB floor**
- The Jeans mass is several tens, instead of several hundred M_{SUN}
- Stars formed via HD cooling (Pop III.2) is much smaller than via H_2 cooling (Pop III.1)



Yoshida et al. 2007

Pop III.2 stars formed in ionized bubbles, where the formation of HD is promoted and HD finally reaches 1% of H_2

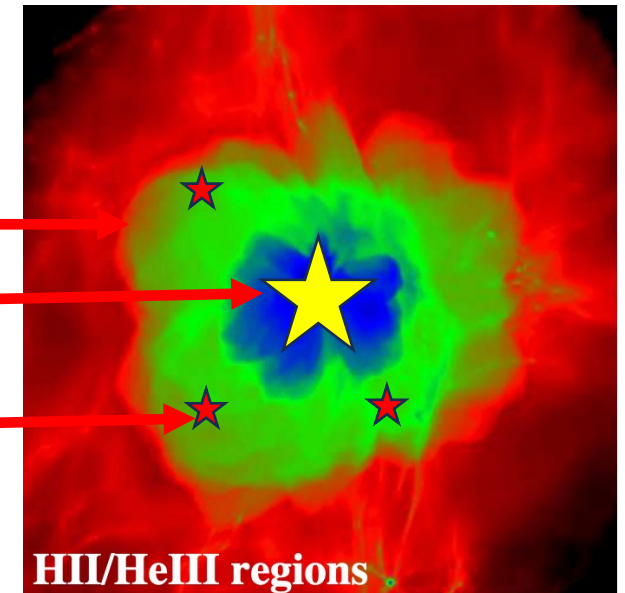


$$\frac{n(\text{HD})}{n(\text{H}_2)} = 2 \frac{n(\text{D})}{n(\text{H})} \exp\left(-\frac{465\text{K}}{T}\right),$$

Ionized bubble

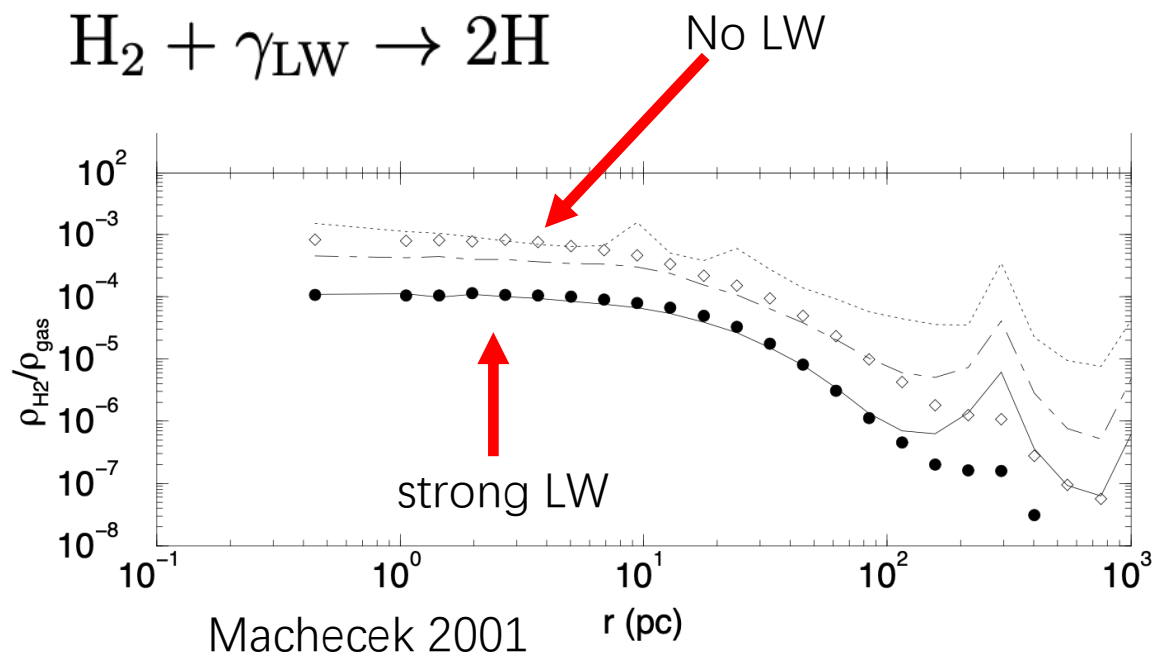
Pop III.1

Pop III.2

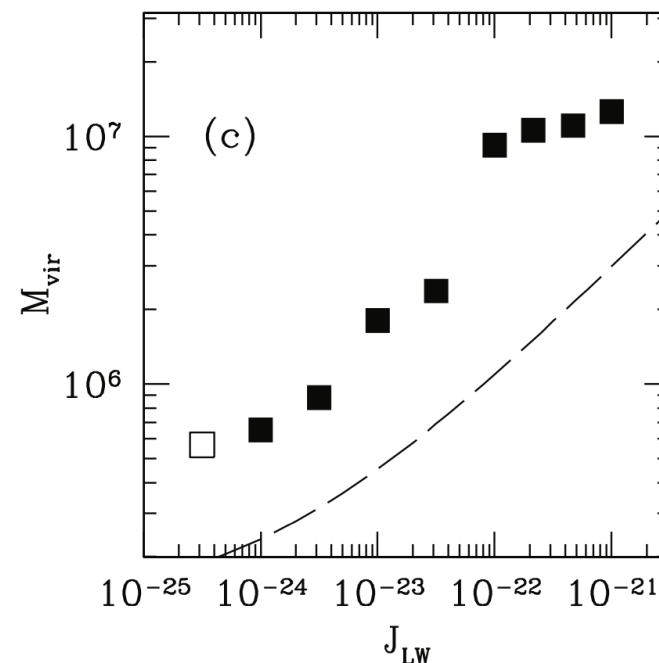


Minimum halo mass for Pop III star formation, LW feedback, self-shielding

- First stars formed in minihalos with $T_{\text{vir}} \gtrsim 1000$ K;
- However, LW radiation (from other Pop III stars/galaxies/BHs) dissociates the H_2 , only massive halos can protect their H_2 from being destroyed;
- Pop III formation is delayed, the minimum mass of star-forming halo is boosted.



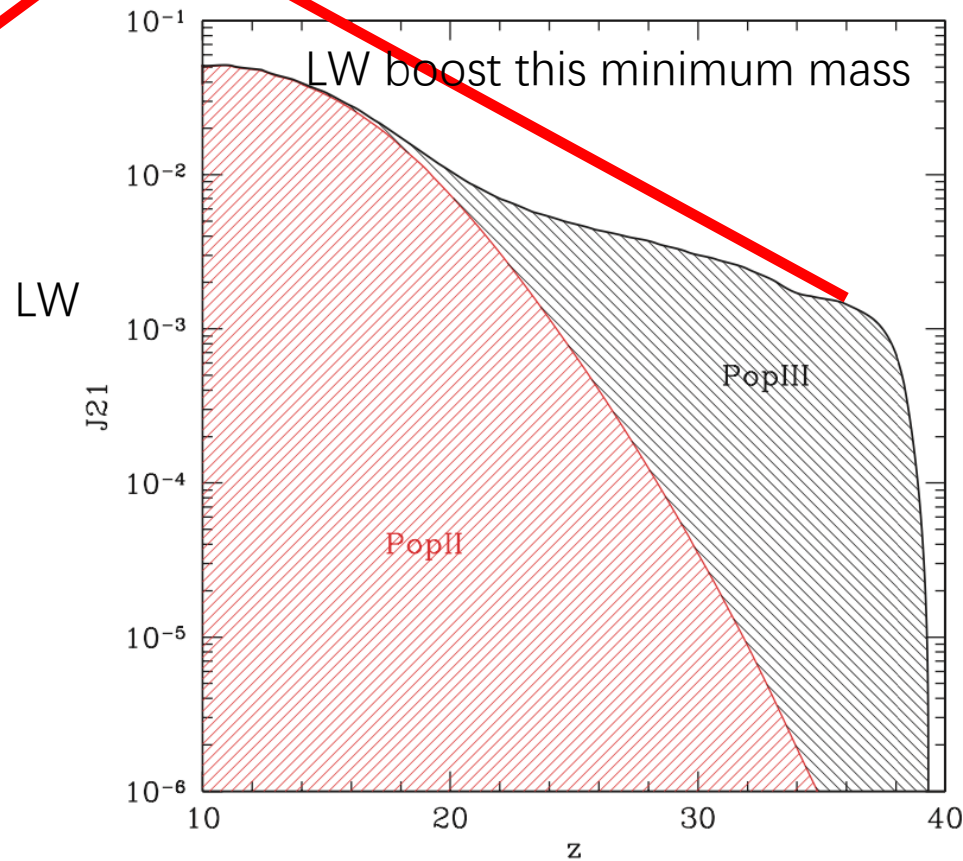
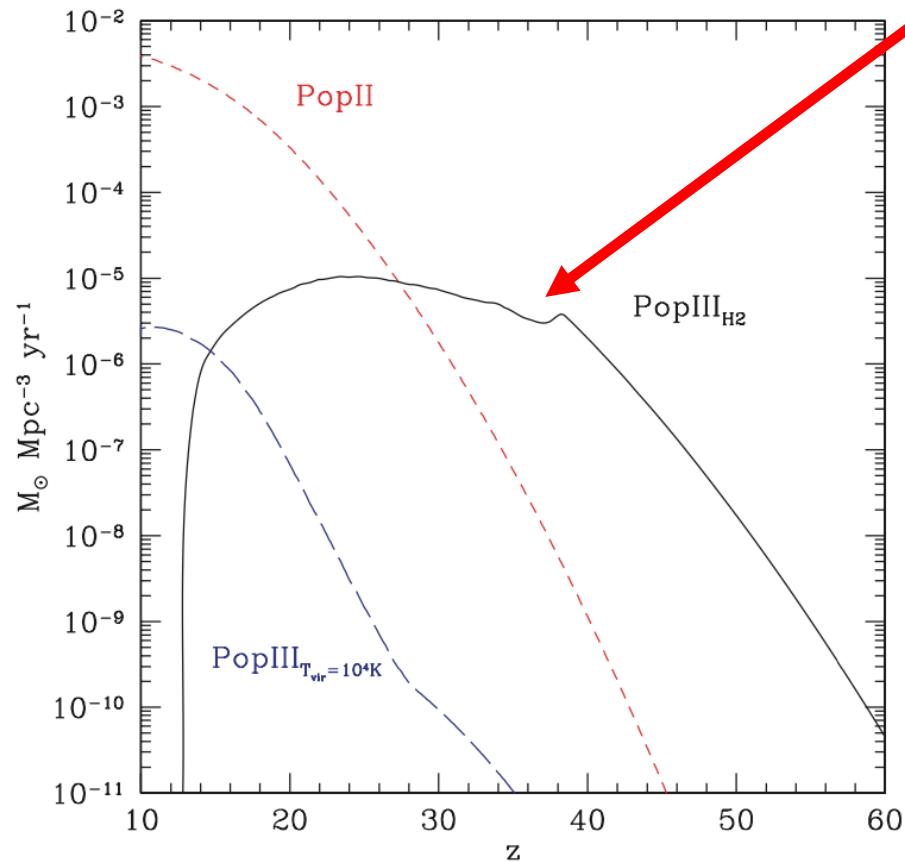
$$M_{\text{min}} = 1.25 \times 10^5 + 8.7 \times 10^5 \left(\frac{4\pi J_{\text{LW}}}{10^{-21} \text{erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1} \text{sr}^{-1}} \right)^{0.47} [M_{\odot}]$$



O'Shea & Norman 2008

The formation of Pop III stars is self-regulated:

$$M_{\text{H}_2\text{-cool}} \simeq 6.44 \times 10^6 M_{\odot} J_{21}^{0.457} \left(\frac{1+z}{31} \right)^{-3.557}.$$

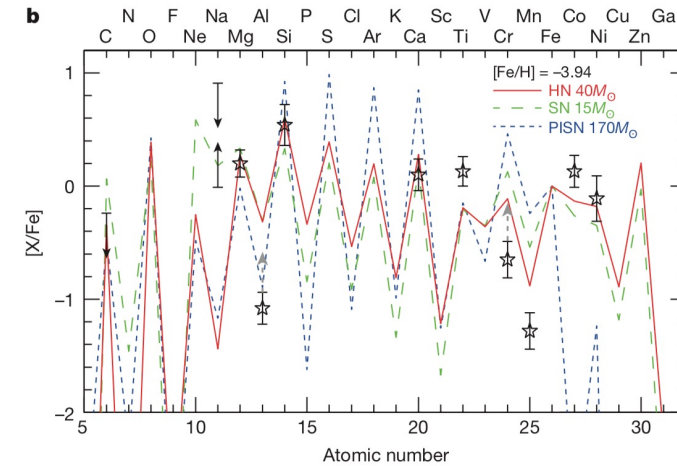


- LW from previously-formed Pop III suppresses the formation of following Pop III stars
- Pop III stars formation rate density is limited

Trenti et al. 2009

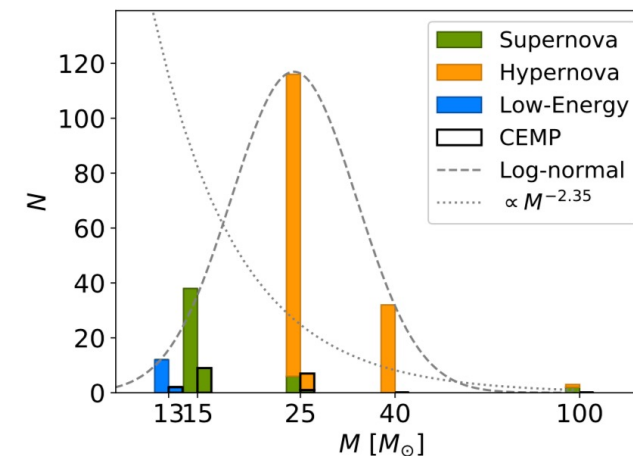
Stellar archaeology (恒星考古学), not Archaeoastronomy (考古天文学)

- No survival first stars in present-day Universe, however, in our Milky Way there are extremely metal poor star (EPMs, 极端贫金属星);
- They have small mass, low metallicity, lifetime comparable to age of the Universe, must formed just after Pop III died, **they are alive “fossils” of the early Universe**;
- **Their metals are produced by first stars!**



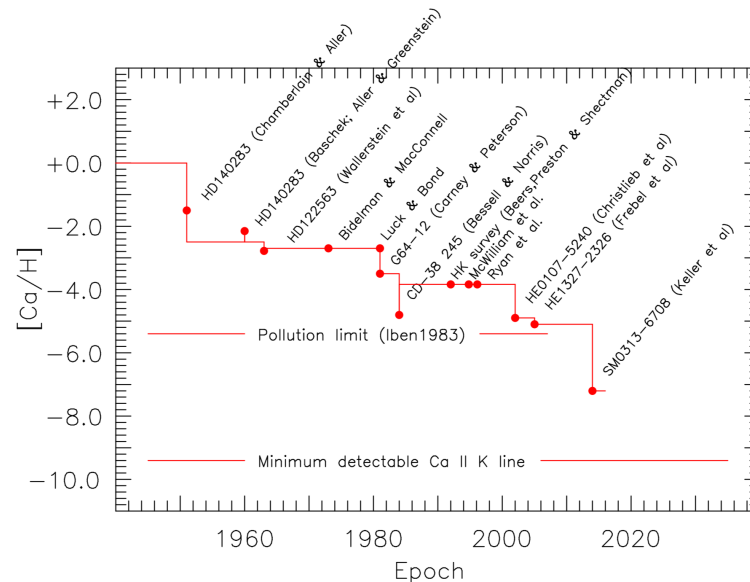
Howes et al. 2015

Pop III stars with different masses yield different metals, The mass function of Pop III stars are derived from metallicities of EMPs

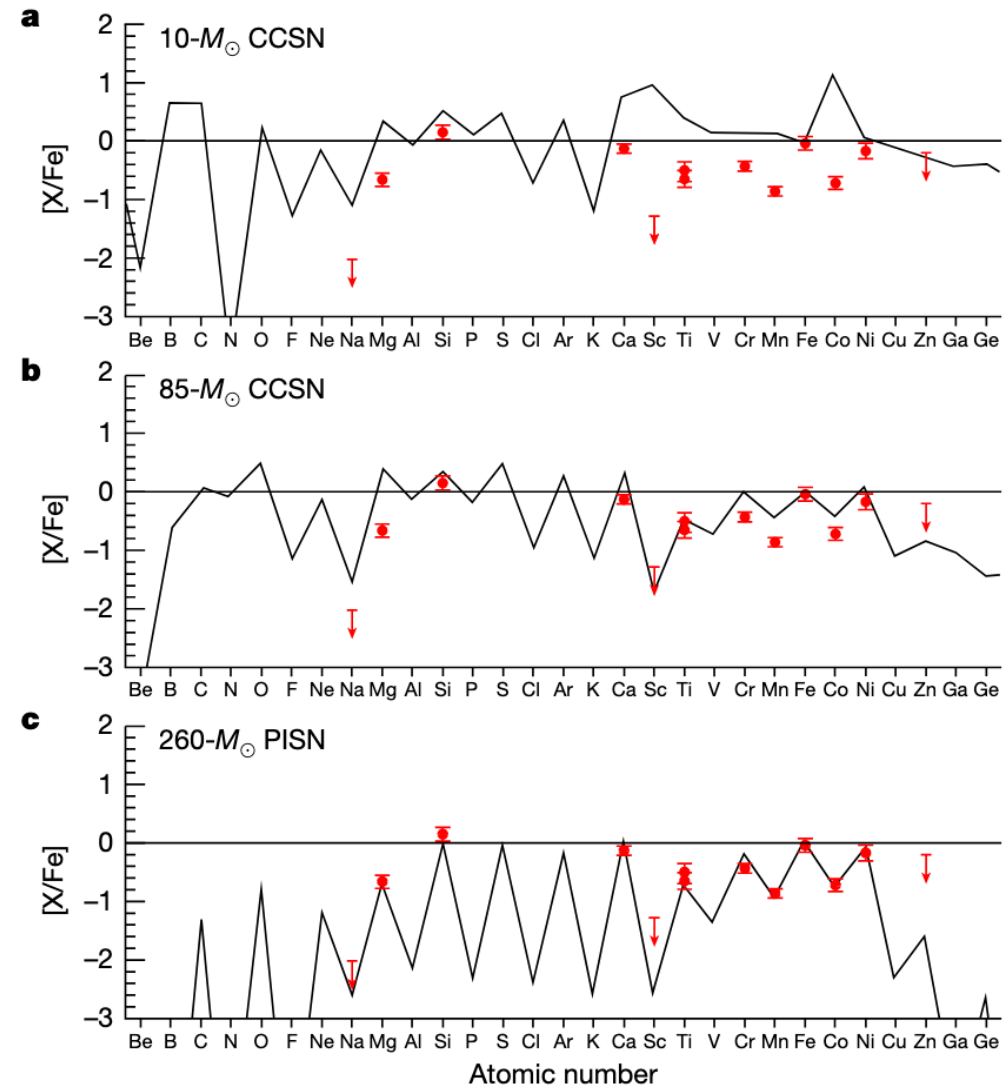


Ishigaki et al. 2018

Frebel & Norril 2015



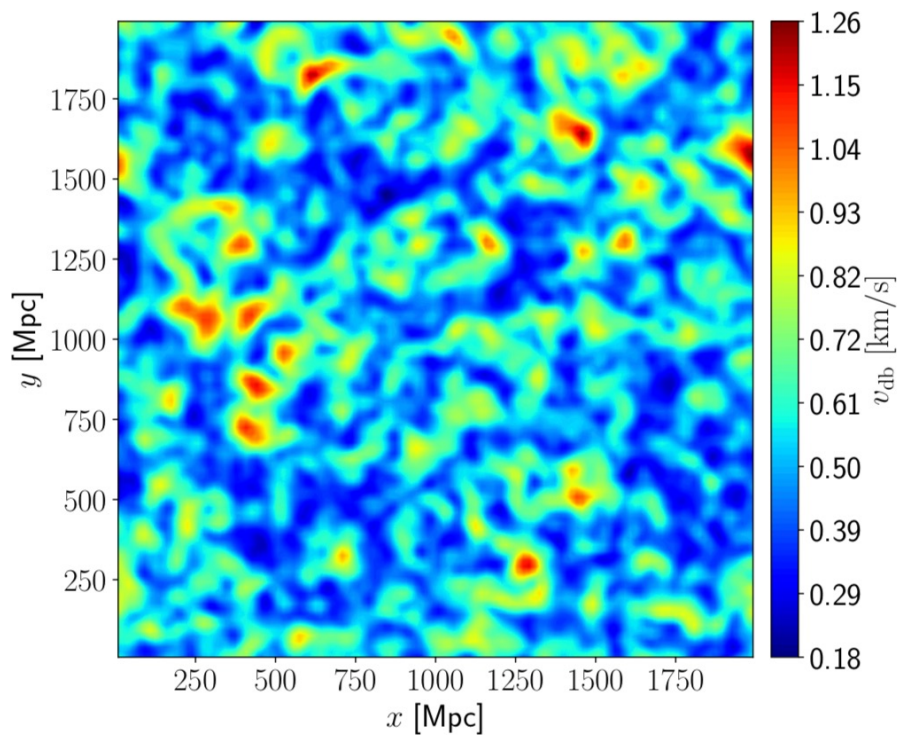
PISN abundances signature in very-metal poor star observed by LAMOST



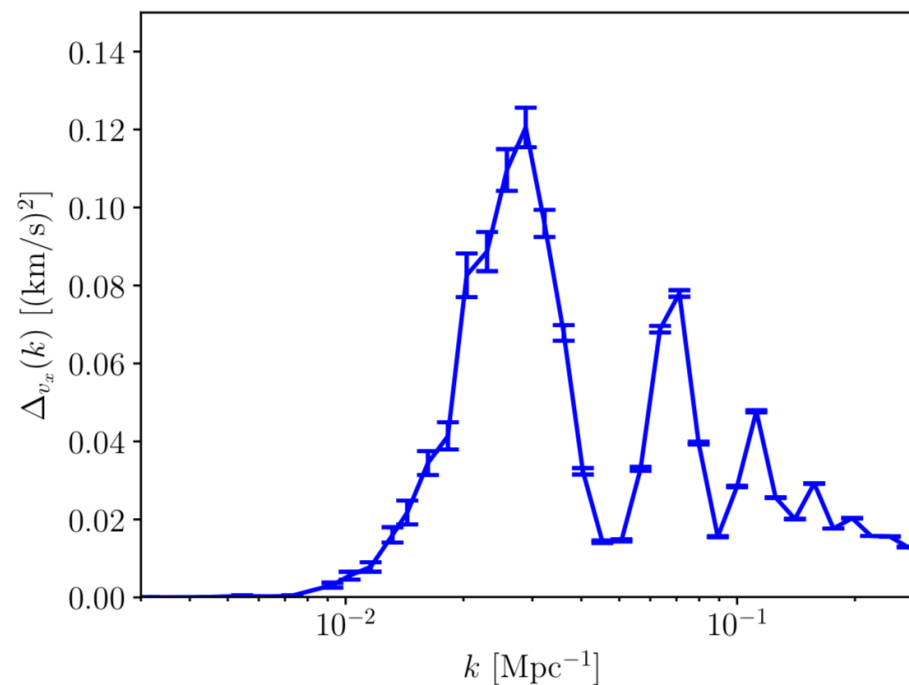
The Velocity Acoustic Oscillations (VAO)

- Before recombination, gas has pressure but DM no, resulting in velocity difference between them;
- In Fourier, v_{bc} has oscillations feature;

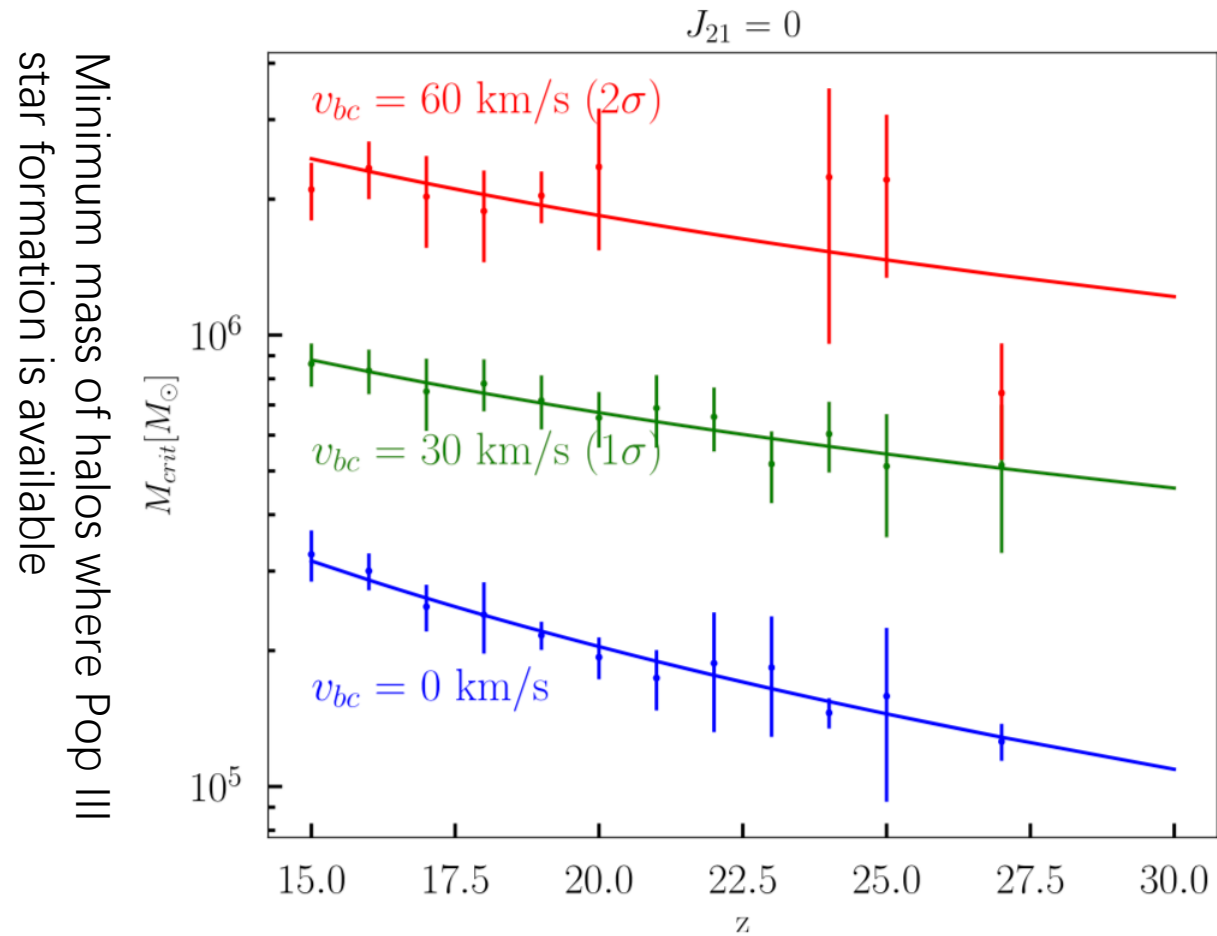
V_{bc} field



Wiggles on the power spectrum of v_{bc}

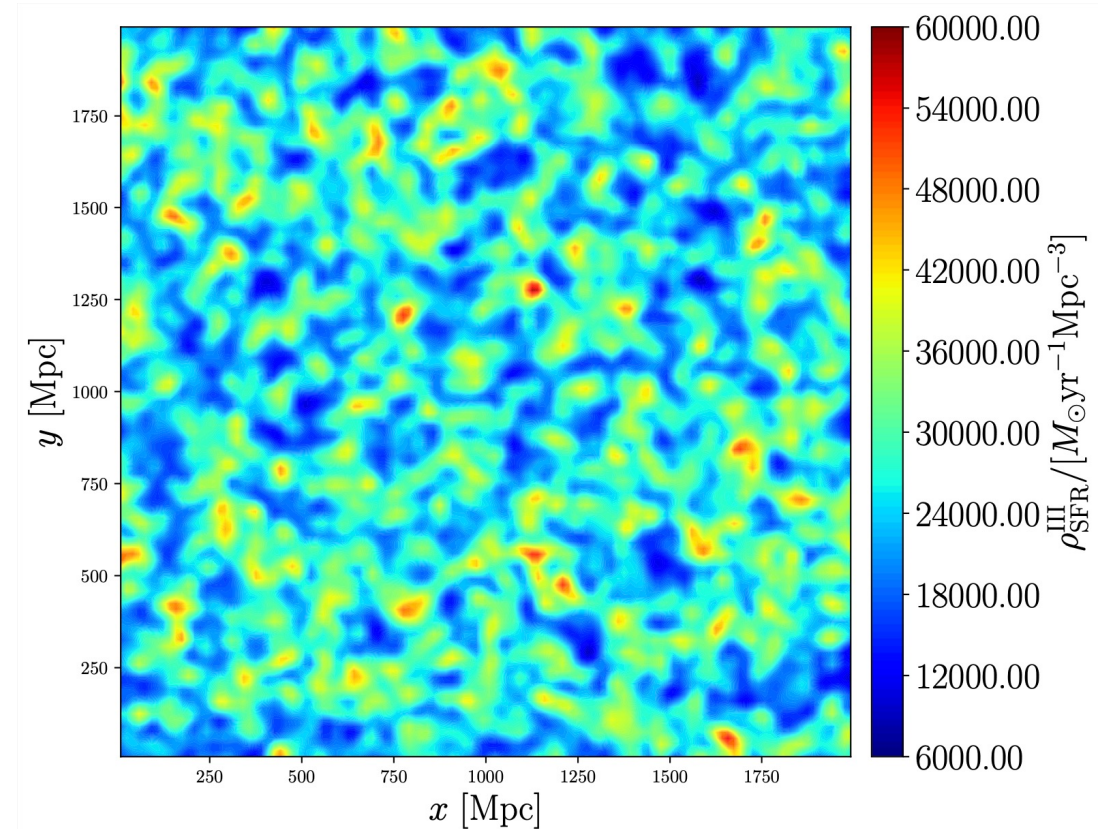


- At Cosmic Dawn, the relic v_{bc} is still supersonic, suppressing Pop III star formation in smaller minihalos;
- SFRD field of Pop III stars is modulated by v_{bc} field.



Kulkarni et al. 2021

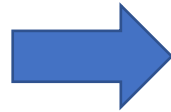
SFRD field of Pop III stars at Cosmic Dawn



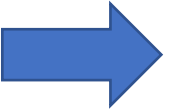
Zhang et al. 2024

Finally, the 21 cm signal from Cosmic Dawn is also modulated by v_{bc} field

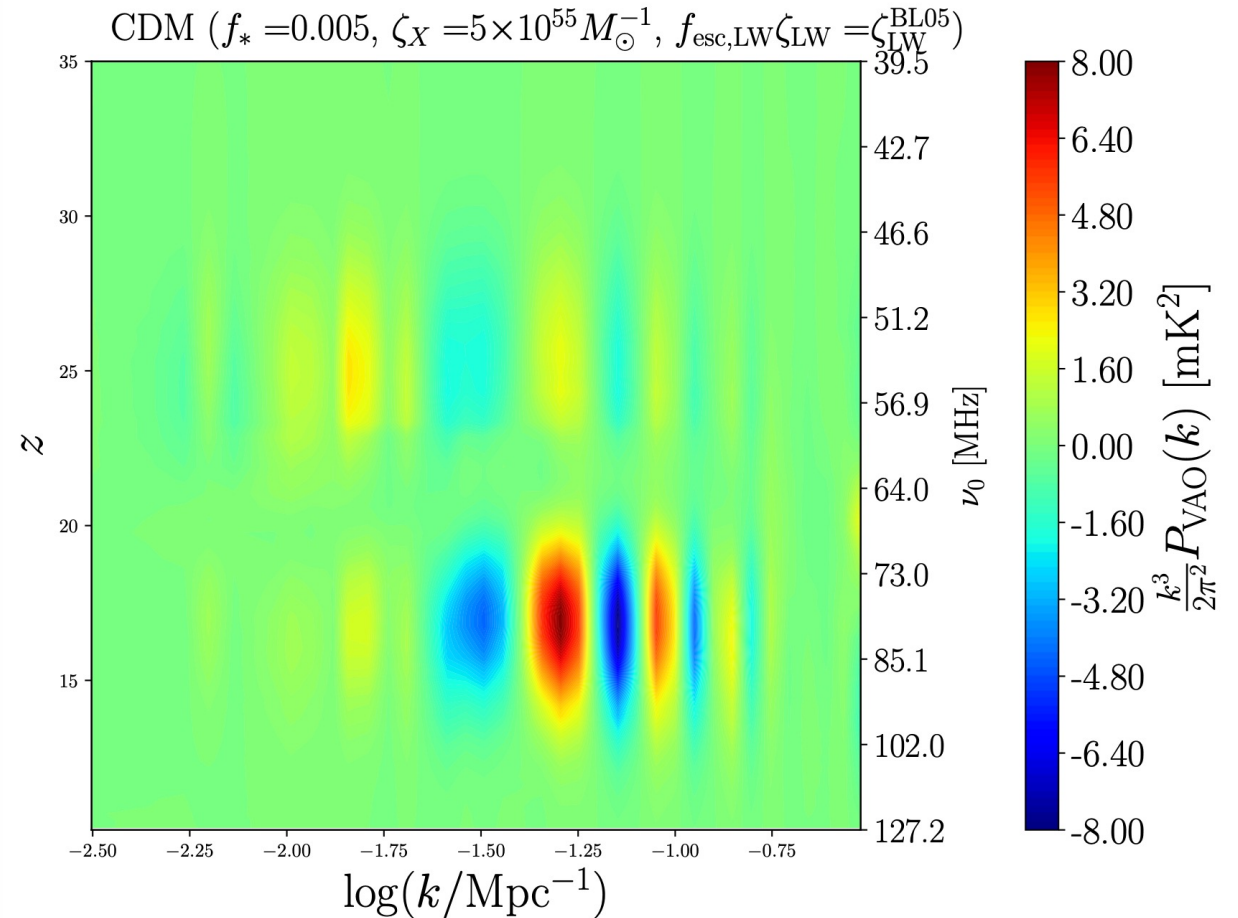
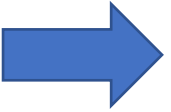
Before Cosmic Dawn, no Pop III stars,
no/weak wiggles



At Cosmic Dawn, strongest wiggles



After Cosmic Dawn, Ly α coupling/X-ray
heating saturated, wiggles disappear



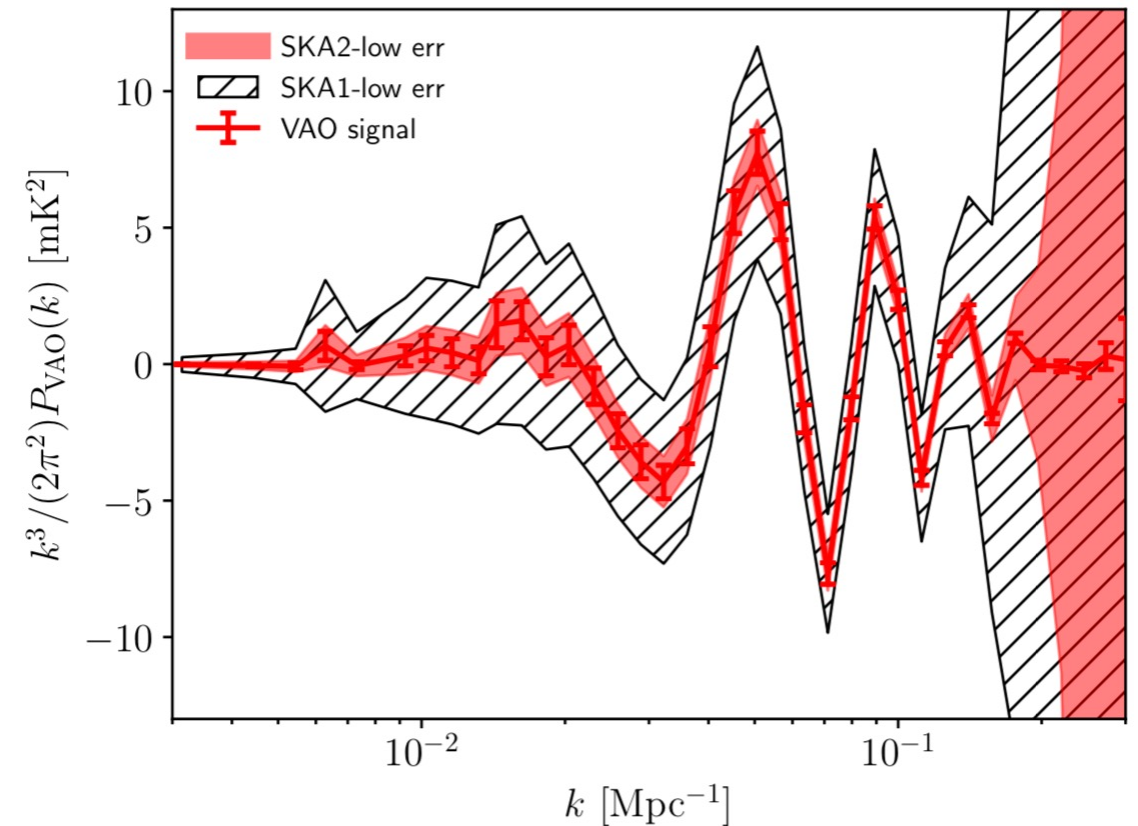
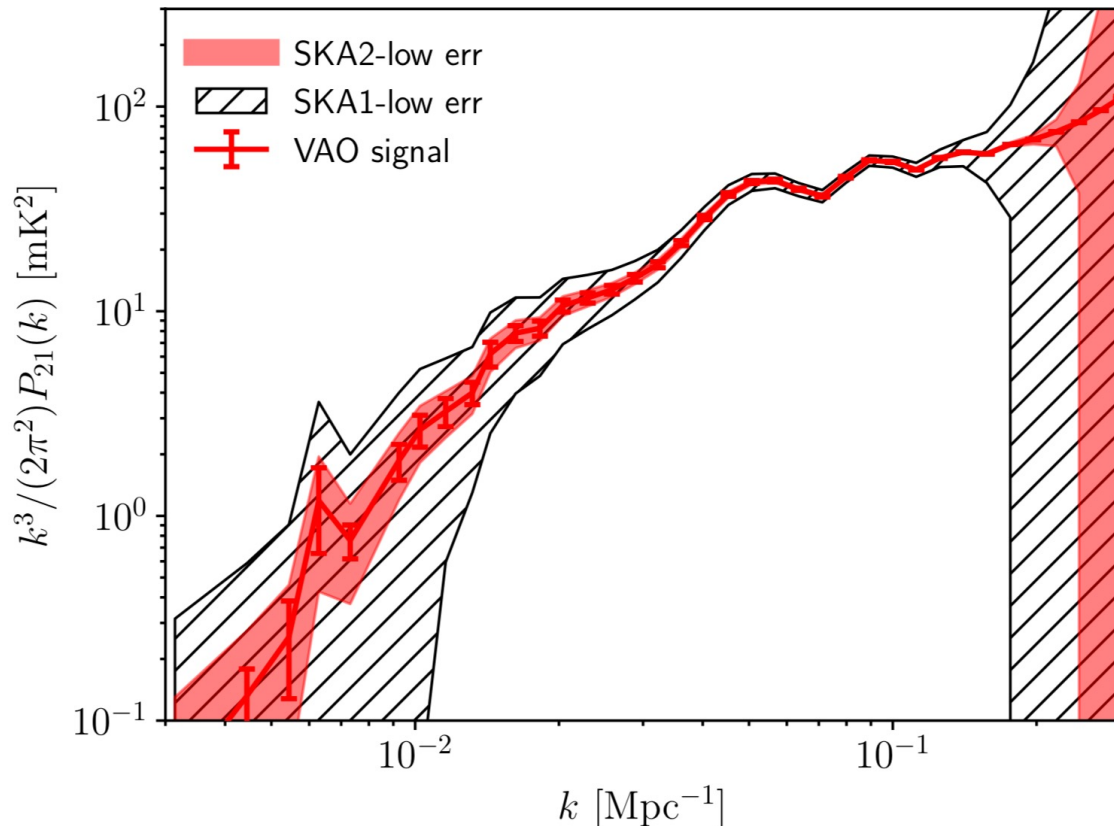
Zhang et al. 2024

VAO wiggles on the 21 cm signal from Cosmic Dawn is almost the smoking gun evidence of Pop III stars at Cosmic Dawn!

The wiggles feature are detectable for SKA1-low and SKA2-low:

- $\mathcal{O}(1000)$ hour integration time; • $\mathcal{O}(10)$ deg² survey area for SKA1-low;
- $\mathcal{O}(100)$ deg² survey area for SKA2-low.

Forecasts on SKA-low observations of VAO wiggles:

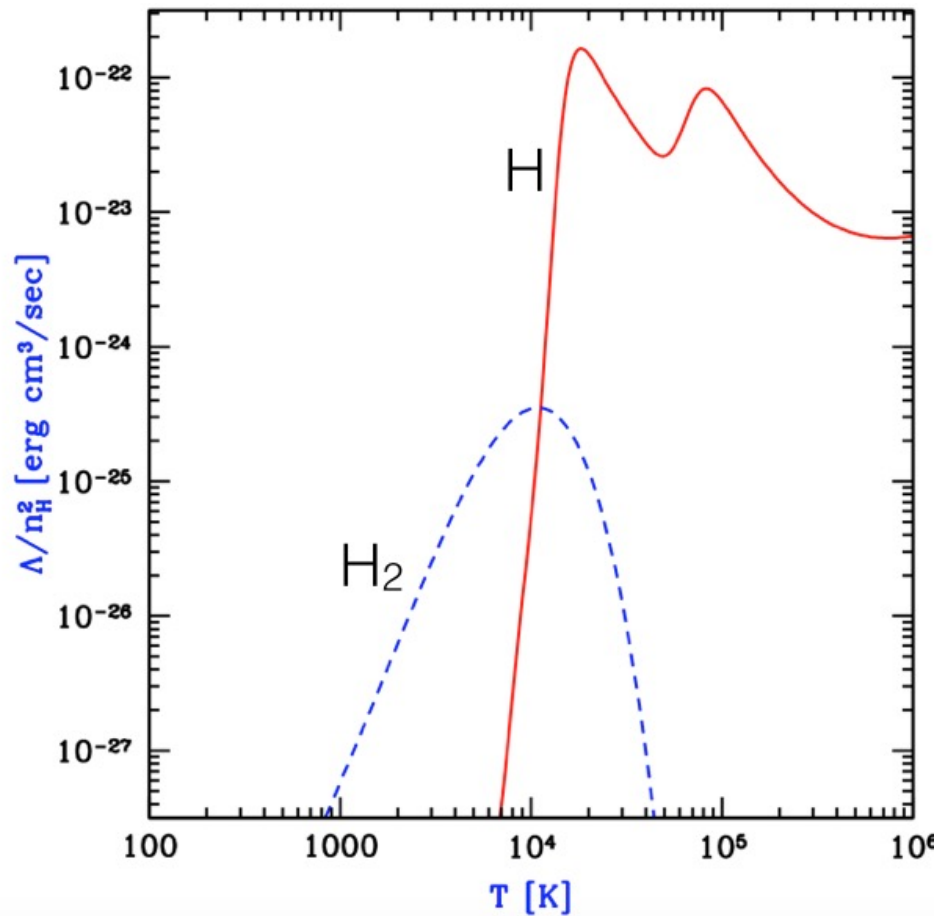


A break of ~15 minutes

A visualization of the cosmic web, showing a complex network of blue, filamentary structures against a black background. Several bright, glowing yellowish-white points are scattered throughout, representing galaxy clusters or individual galaxies. The central region features a particularly dense and bright cluster of these structures.

II. First Galaxies

- In pristine gas, the only coolants are H₂ and H;
- H₂ cooling works at >~1000K;
- H cooling works at >~10000K →
- In halos, gas is heated to virial temperature by shock;
- In halos with T_{vir} >~10000K, gas cools by H.



Barkana & Loeb 2001

$$T_{\text{vir}} = \frac{\mu m_p V_c^2}{2k_B} = 1.98 \times 10^4 \left(\frac{\mu}{0.6} \right) \left(\frac{M}{10^8 h^{-1} M_\odot} \right)^{2/3} \left[\frac{\Omega_m}{\Omega_m^z} \frac{\Delta_c}{18\pi^2} \right]^{1/3} \left(\frac{1+z}{10} \right) \text{ K} ,$$

Binding energy:

$$E_b = \frac{1}{2} \frac{GM^2}{r_{\text{vir}}} = 5.45 \times 10^{53} \left(\frac{M}{10^8 h^{-1} M_\odot} \right)^{5/3} \left[\frac{\Omega_m}{\Omega_m^z} \frac{\Delta_c}{18\pi^2} \right]^{1/3} \left(\frac{1+z}{10} \right) h^{-1} \text{ erg} .$$

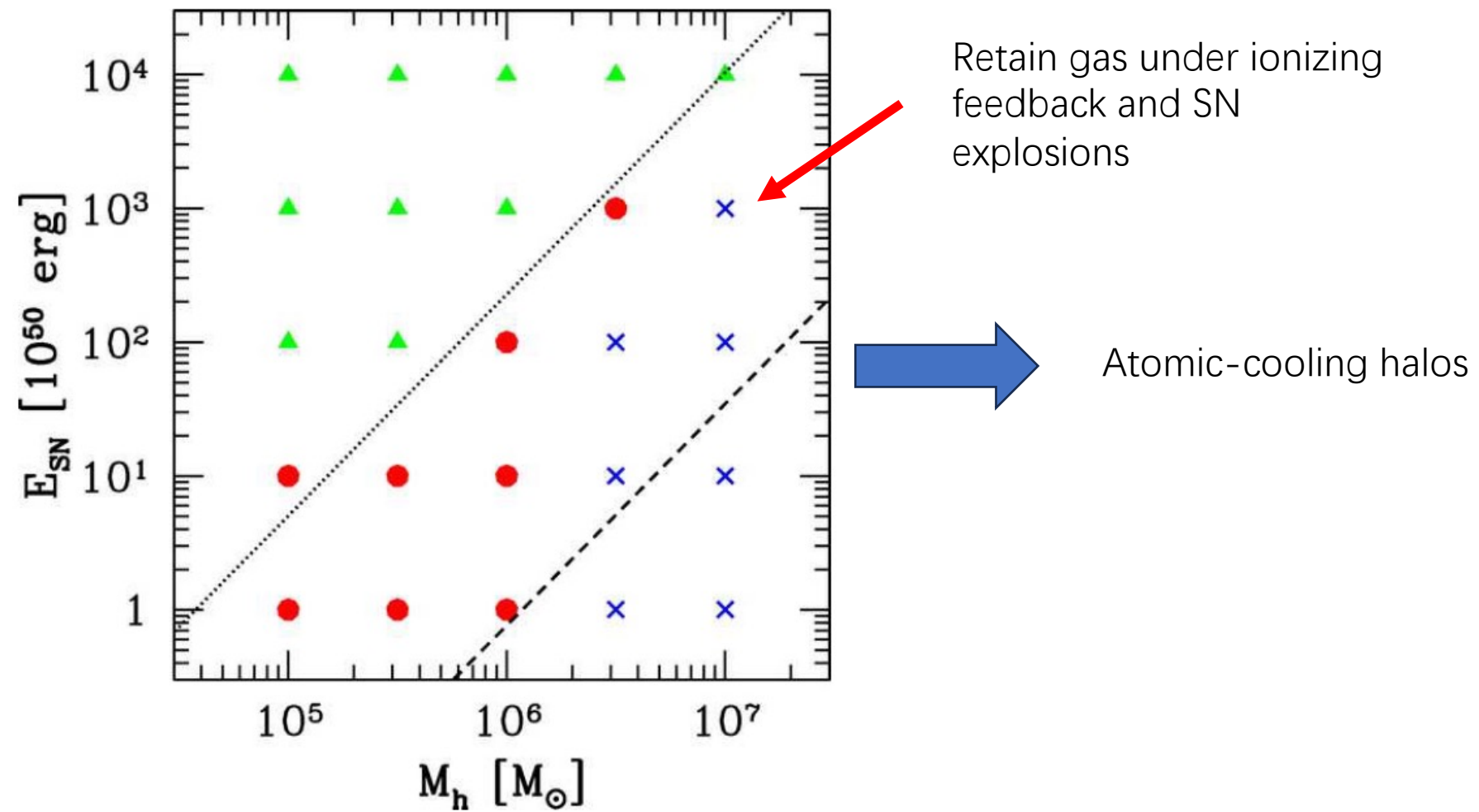
A typical Pop III supernova explosion releases $E_{\text{SN}} \sim 10^{51-53}$ erg energy.

Kitayama et al. 2005

A halo with mass $T_{\text{vir}} \gtrsim 10000$ K can:

1. cool the gas by H;
2. retain ionized gas;
3. retain gas even after a series of SN explosions.

→ **A galaxy!**



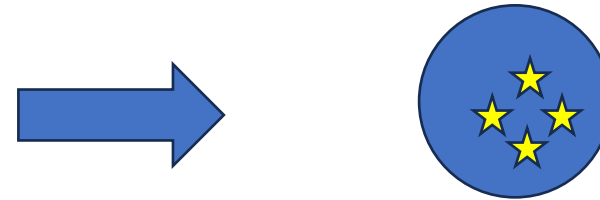
Kitayama & Yoshida (2005)

poor (HMP) $10^{-6} < Z/Z_{\odot} < 10^{-5}$. Because we know so little about the first galaxies, it is difficult to establish a precise terminology for them. A galaxy is a system of many stars and gas that is gravitationally bound in a dark matter halo. We define a *first galaxy* as one comprised of the very first system of stars to be gravitationally bound in a dark matter halo. Such stars could be Pop III or Pop II stars with very low metallicities—EMP or below

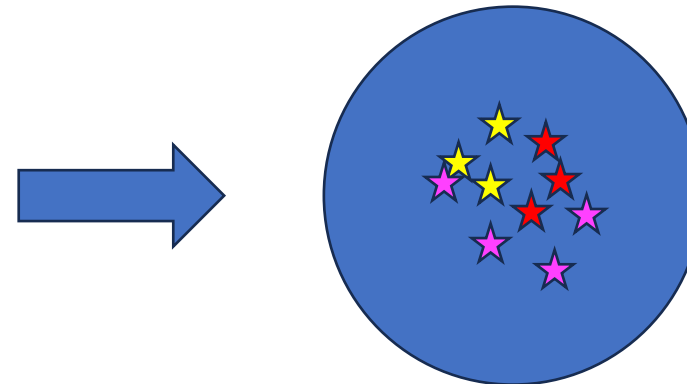
What is the difference between:

1) a minihalos hosting multiple first stars (Greif et al. 2007)
and 2) a first galaxy reside in atomic-cooling halos?

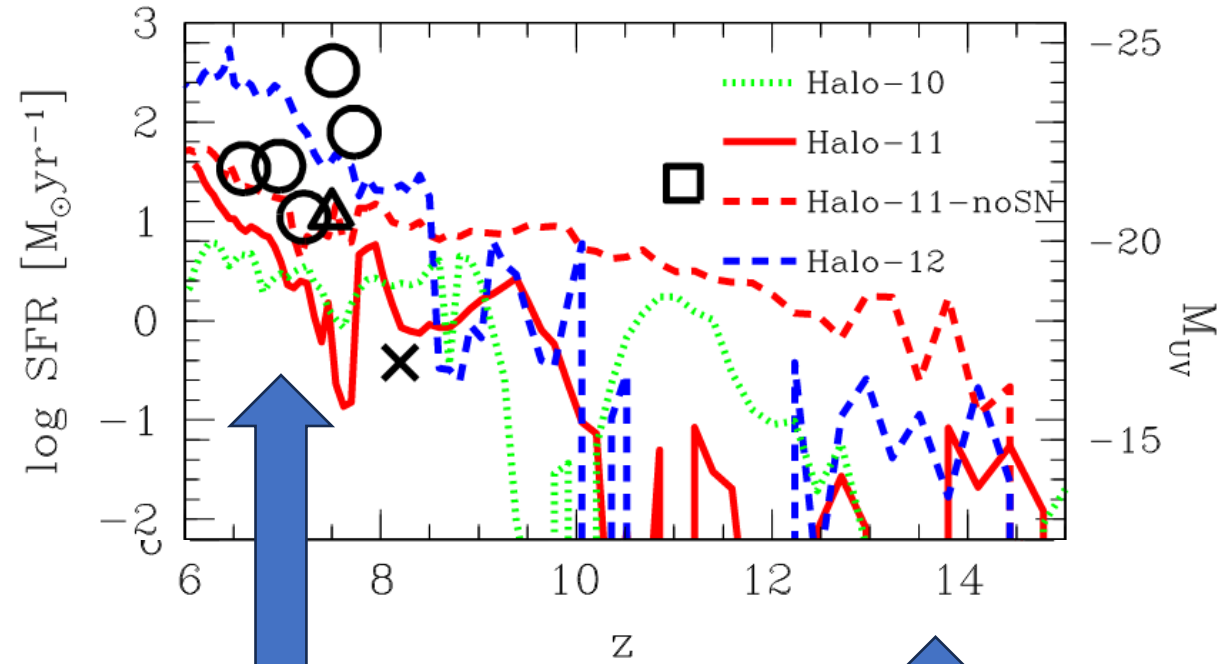
- In minihalos, the star formation process is feedback regulated, all stars formed simultaneously, no following star formation until the host halo becomes an atomic-cooling halo



- First galaxy in atomic-cooling halos, it can sustain continuous star formation mode (even though at the beginning the star formation is bursty)



The simulated star formation history in first galaxies

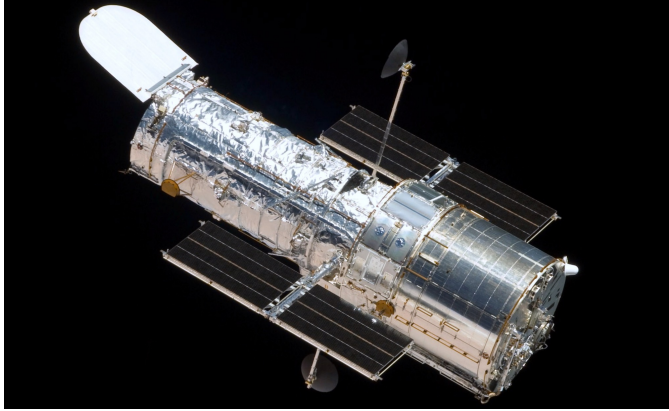


Later on, it become smoothly

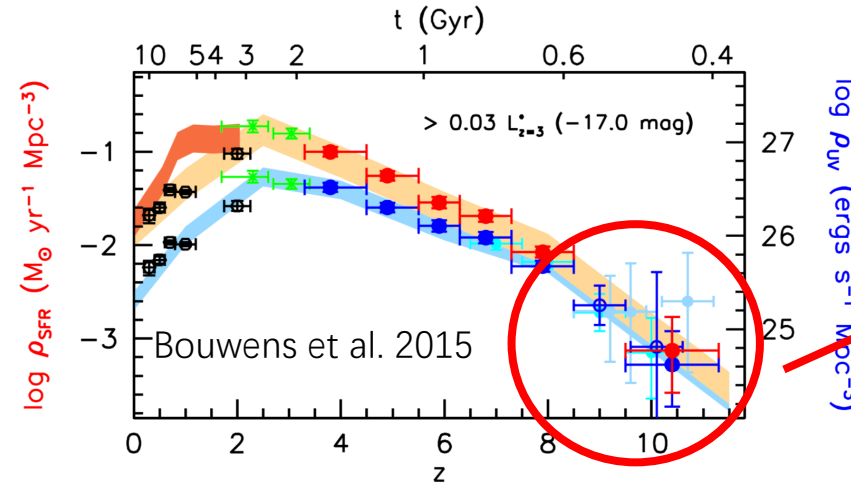
At the beginning, the star formation is bursty

Observations of high- z galaxies:

HST has discovered more than one thousand galaxies with $z > \sim 6$; the highest redshift is ~ 11 (GNz-11).

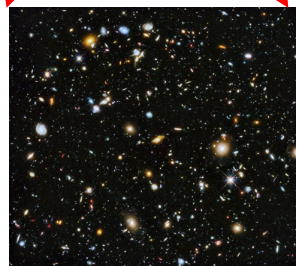
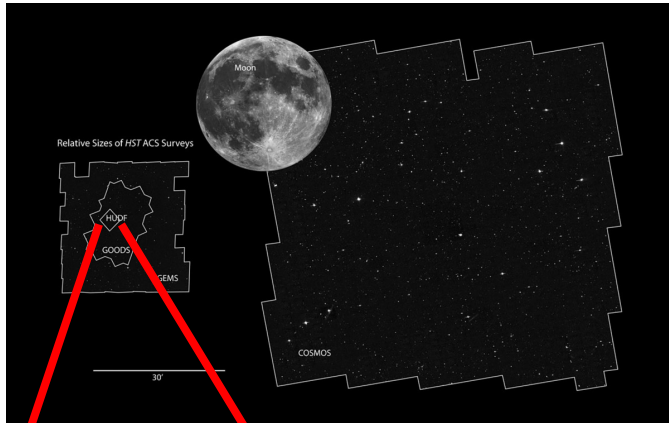


The constructed SFH from HST observations

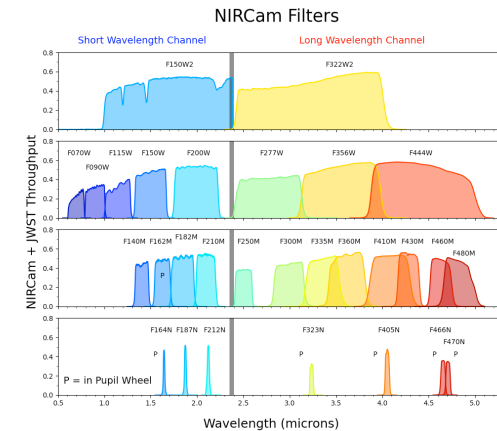
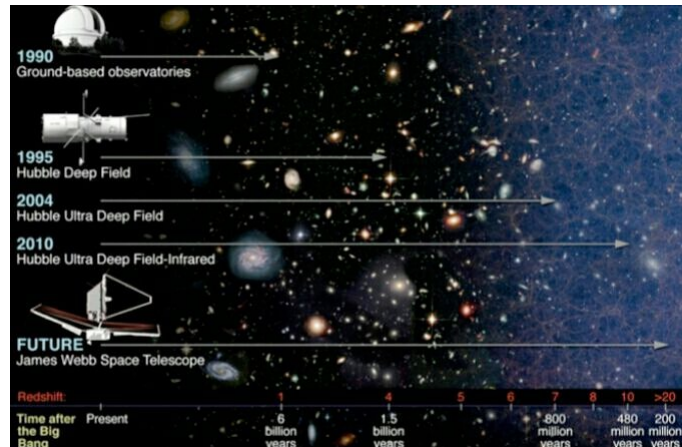


SFRD at EoR is still highly uncertain!

JWST can directly observe the Cosmic Dawn!



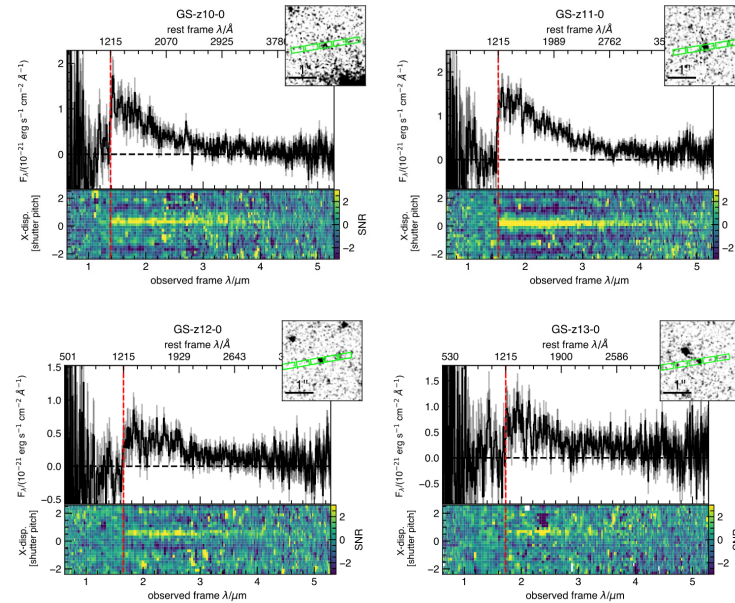
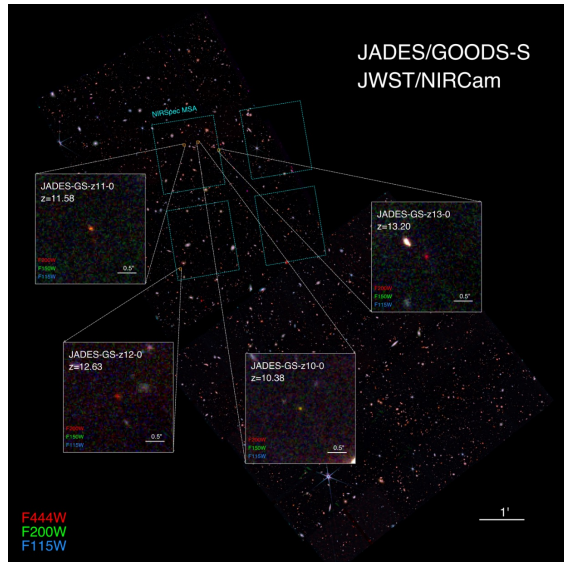
XDF/HUDF as deep as $\sim 30 m_{\text{AB}}$!



Credit: NASA

JWST discovered some highest redshifts galaxies (spectroscopically confirmed):

JADES-GS-z10-0, JADES-GS-z11-0, JADES-GS-z12-0, JADES-GS-z13-0



JADES-GS-z14-0, JADES-GS-z14-1

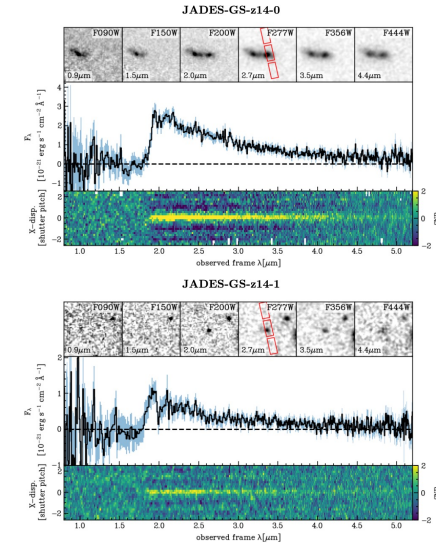
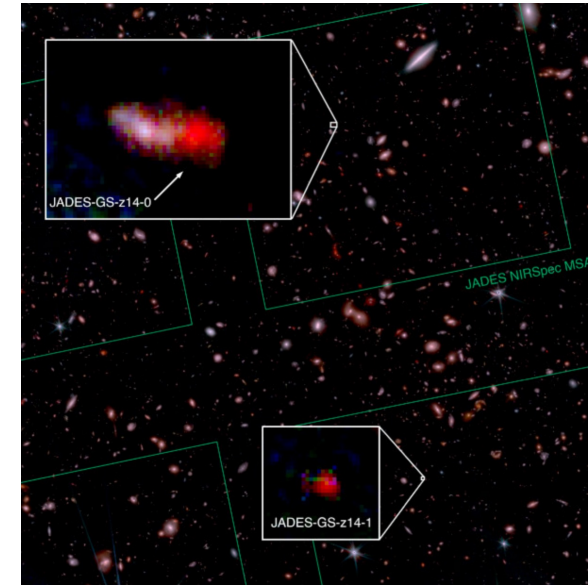
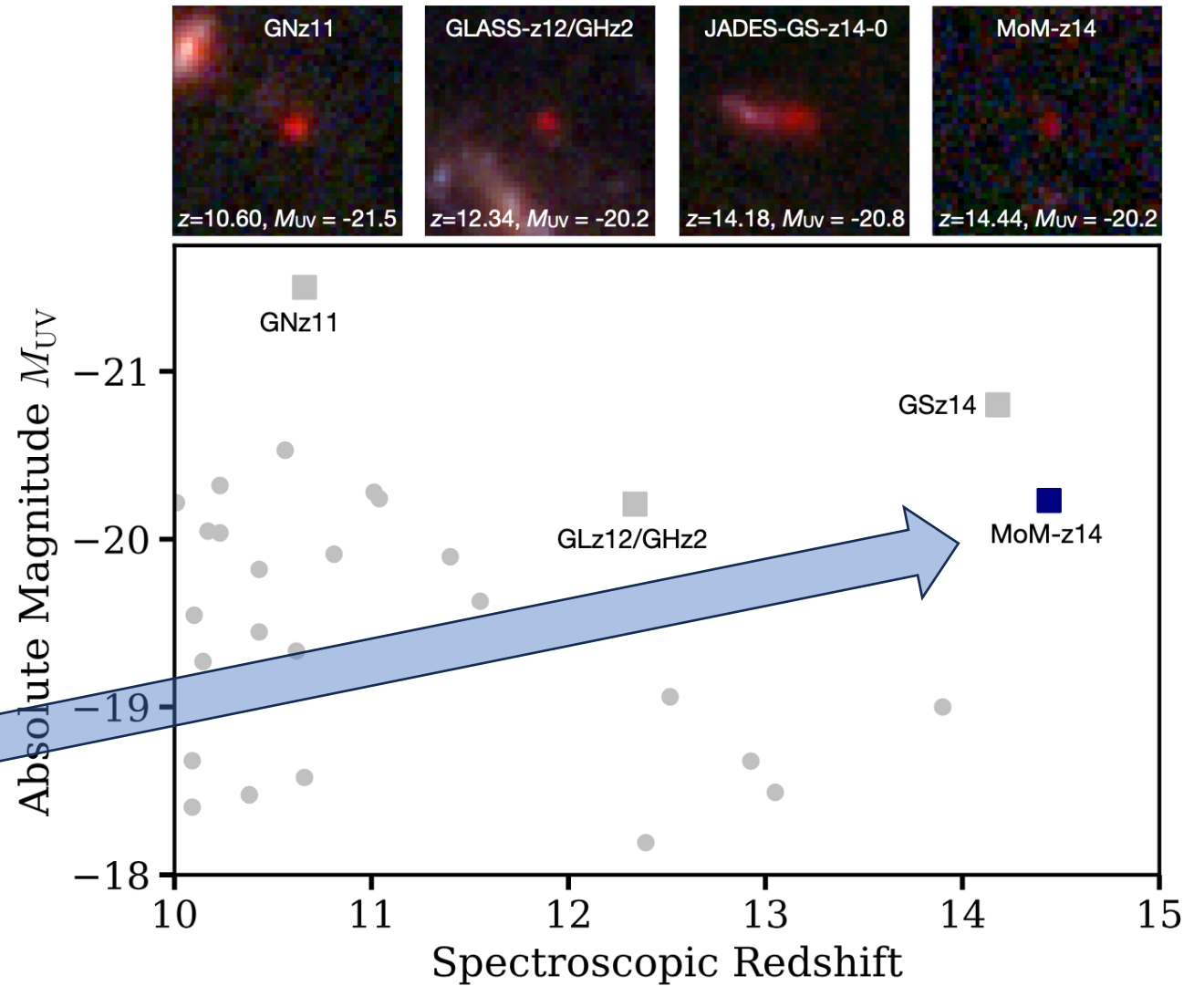
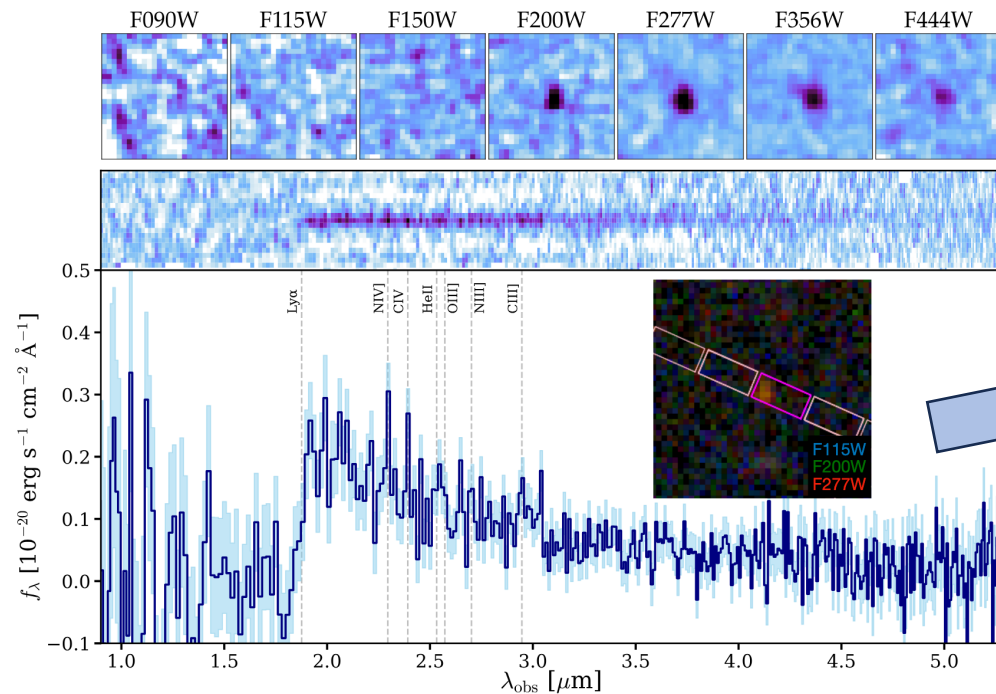


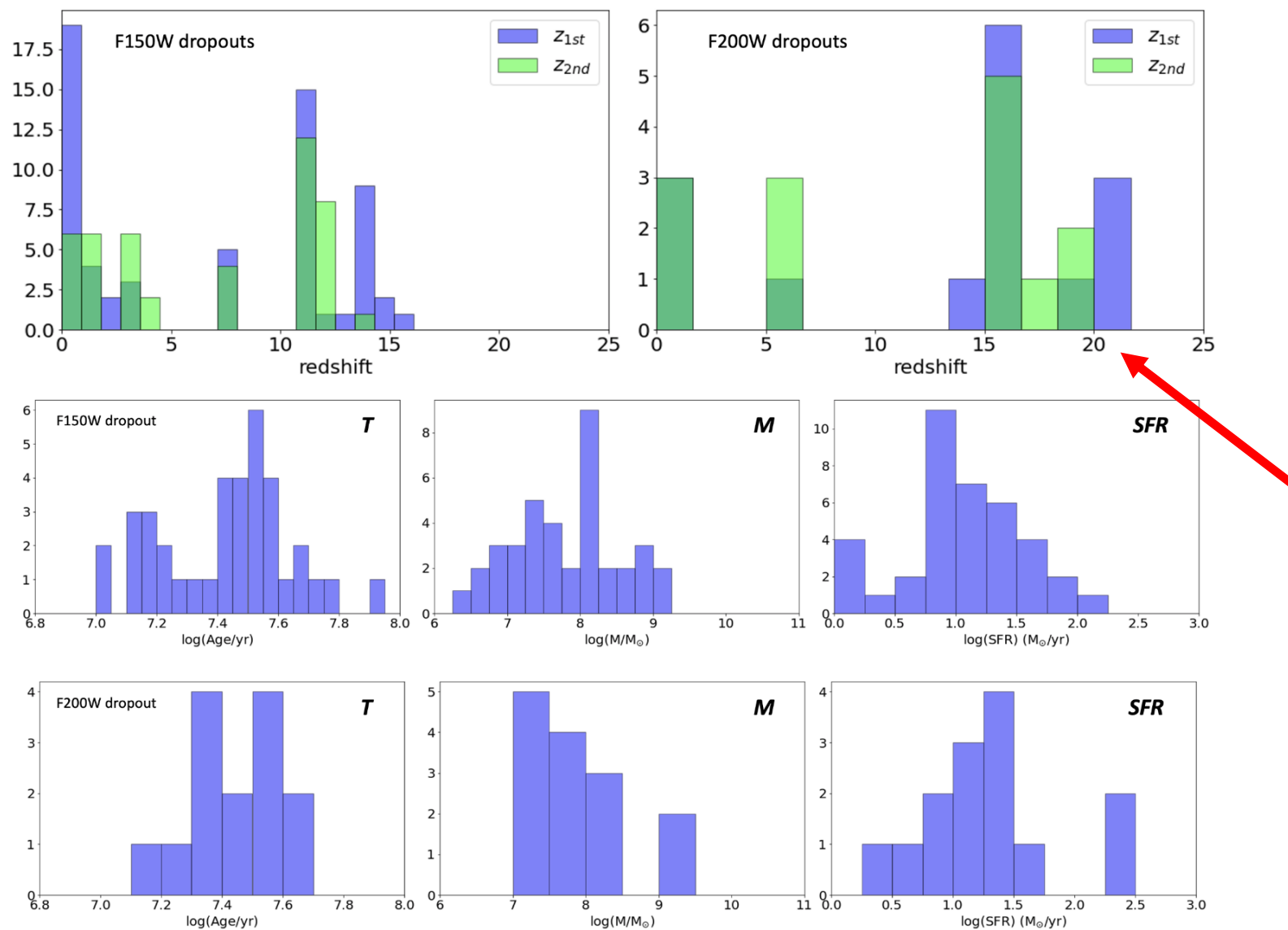
Table 1 Galaxy properties inferred from NIRSpect data corrected for slit-losses based on NIRCam fluxes.

ID	JADES-GS-z14-0	JADES-GS-z14-1
extended ID	JADES-GS-53.08294-27.85563	JADES-GS-53.07427-27.88592
NIRCam ID	183348	18044
RA[ICRS]	3:32:19.9049	3:32:17.8251
DEC[ICRS]	-27:51:20.265	-27:53:09.338
redshift	$14.32^{+0.08}_{-0.20}$	13.90 ± 0.17
UV slope β	-2.20 ± 0.07	-2.71 ± 0.19
M_{UV}	-20.81 ± 0.16	-19.0 ± 0.4
UV radius (r_{UV}) [pc]	260 ± 20	< 160
$\log_{10}(M_{star}/M_{\odot})$	$8.7^{+0.7}_{-0.2}$	$8.0^{+0.4}_{-0.3}$
SFR ₁₀₀ [$M_{\odot} \text{ yr}^{-1}$]	5^{+9}_{-3}	$1.2^{+0.7}_{-0.9}$
SFR ₁₀ [$M_{\odot} \text{ yr}^{-1}$]	22^{+6}_{-3}	$2^{+0.7}_{-0.4}$
sSFR ₁₀ [Gyr^{-1}]	45^{+56}_{-35}	18^{+75}_{-38}
A_V [mag]	$0.31^{+0.14}_{-0.07}$	$0.20^{+0.11}_{-0.07}$
$\log_{10}(Z/Z_{\odot})$	$-1.5^{+0.7}_{-0.4}$	$-1.1^{+0.6}_{-0.5}$
τ_{LyC}	$0.84^{+0.09}_{-0.16}$	$0.63^{+0.23}_{-0.29}$

A new galaxy MoM-z14, with redshift 14.44 (spectroscopically confirmed), even higher than GSz14 which is 14.32.

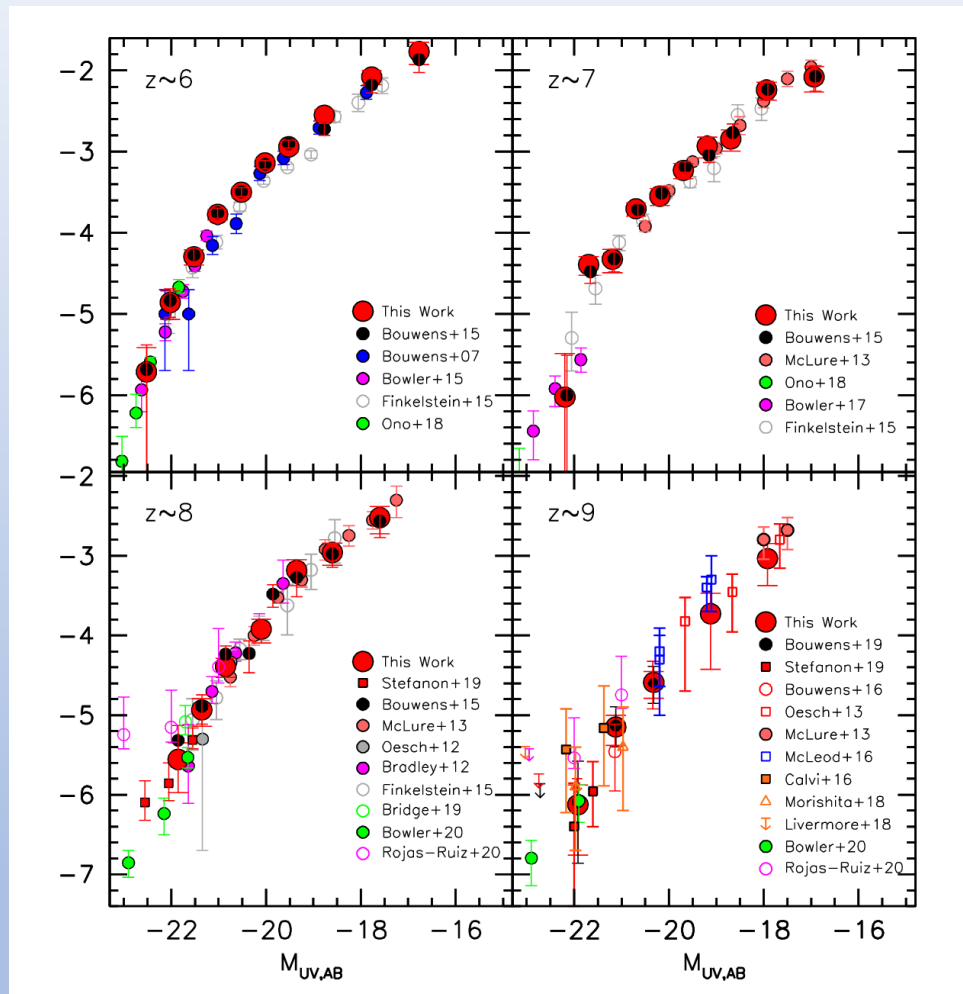


JWST photometric candidates have redshifts extend to ~20!

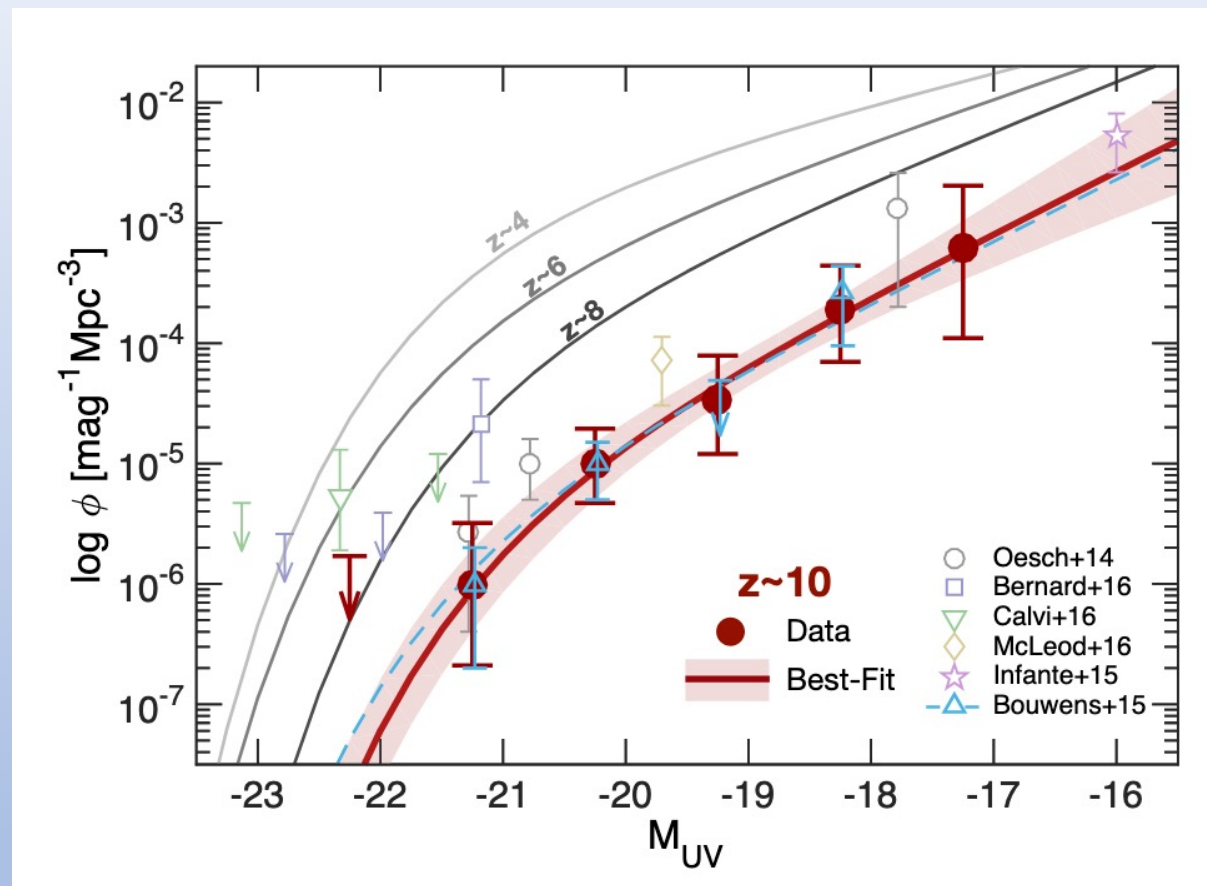


High- z galaxies statistics

UV luminosity functions (LFs) constructed from HST observations :

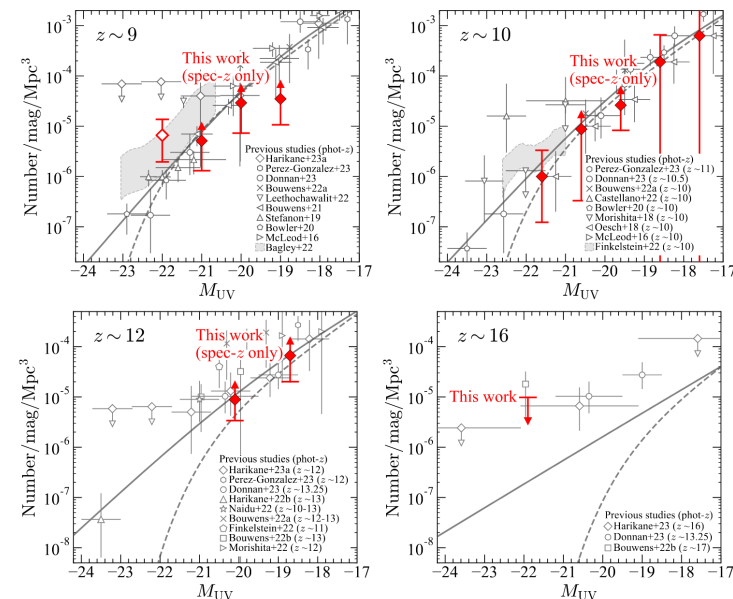
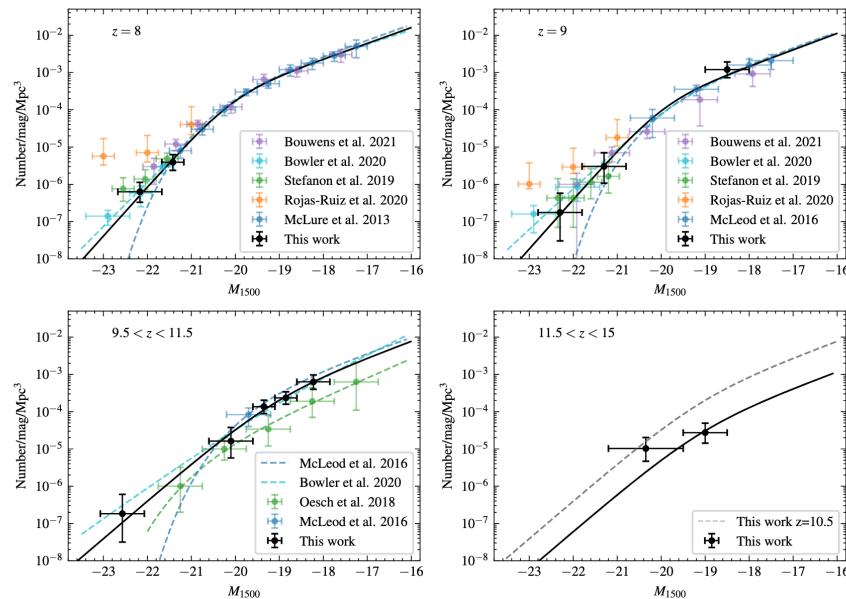
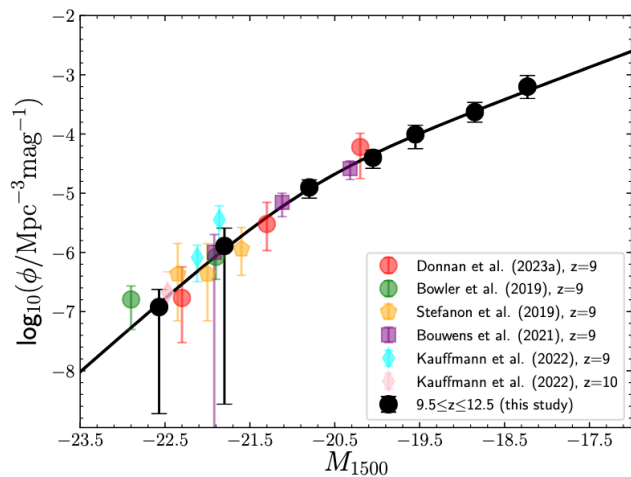


Bouwens et al. 2021



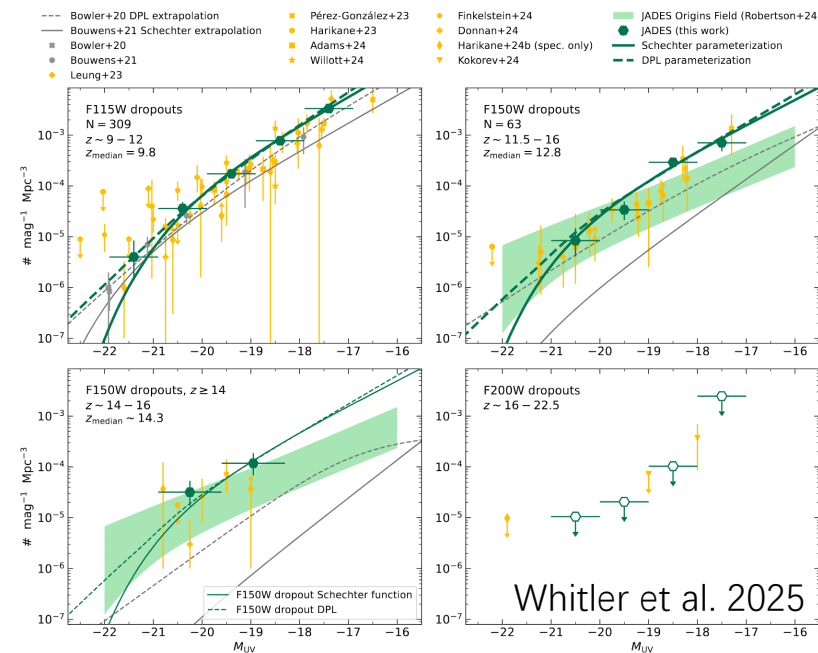
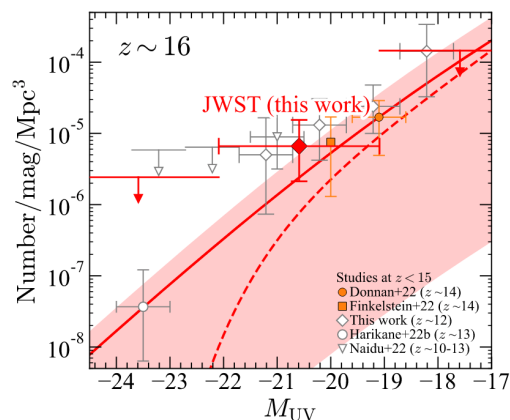
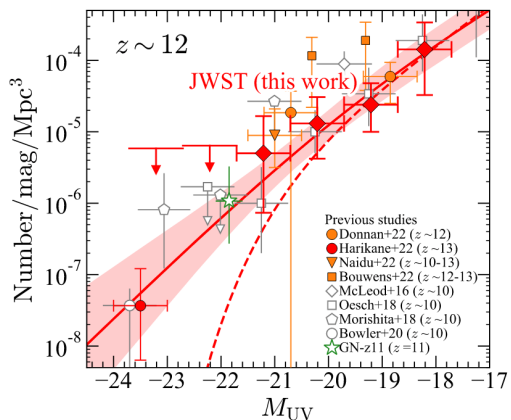
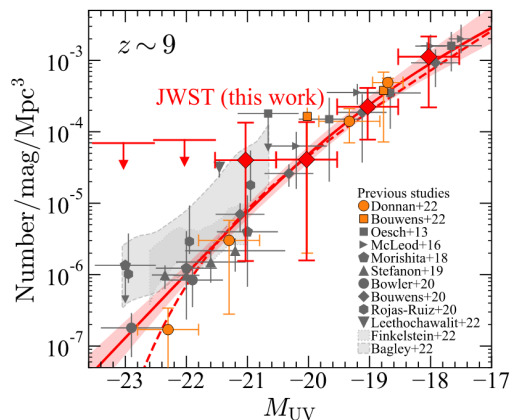
Oesch et al. 2018

UV LFJs from JWST:



Donnan et al. 2023

McLeod et al. 2024

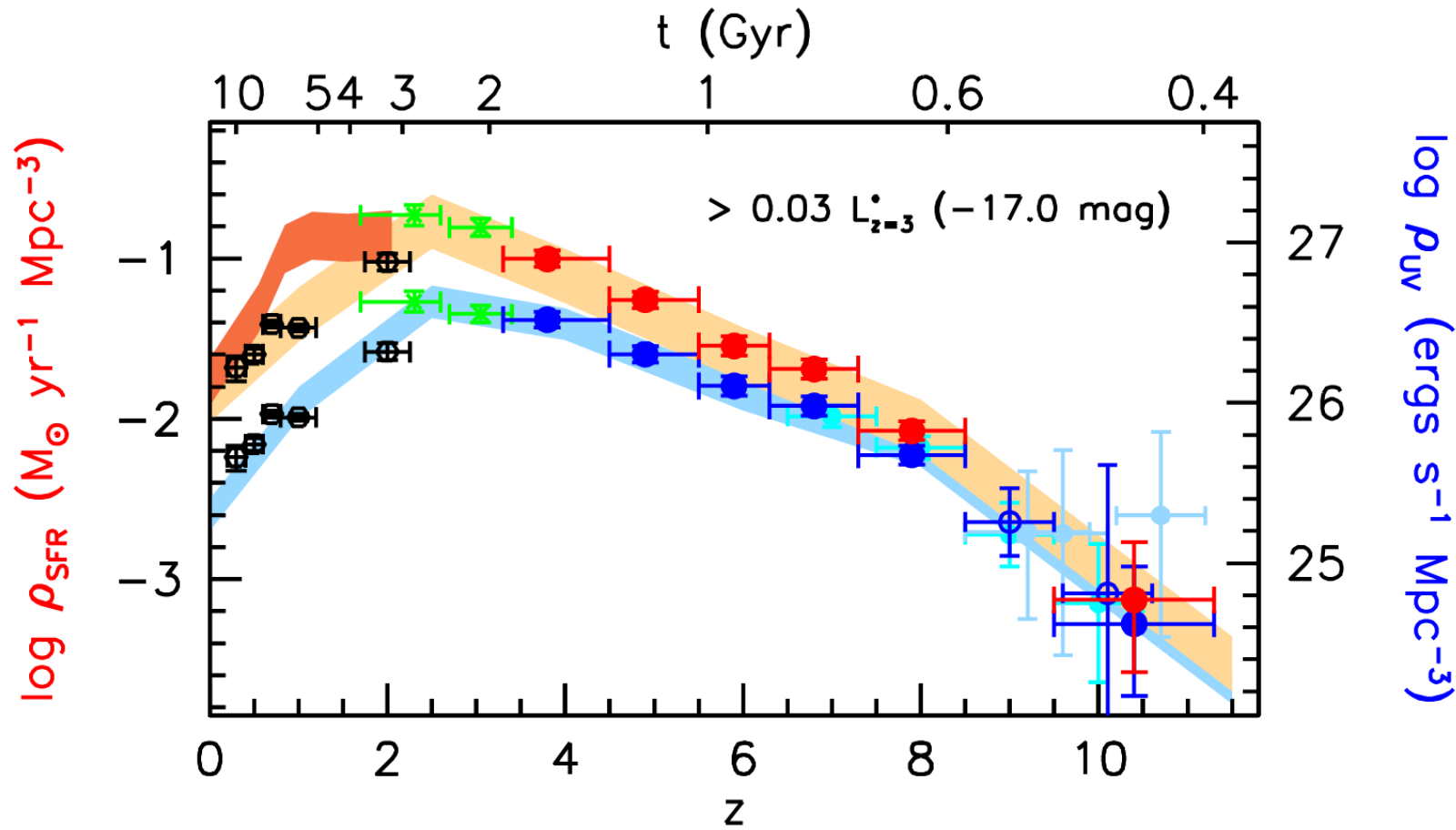


Harikane et al. 2023, photometric

Harikane et al. 2024, spectroscopical

Whitler et al. 2025

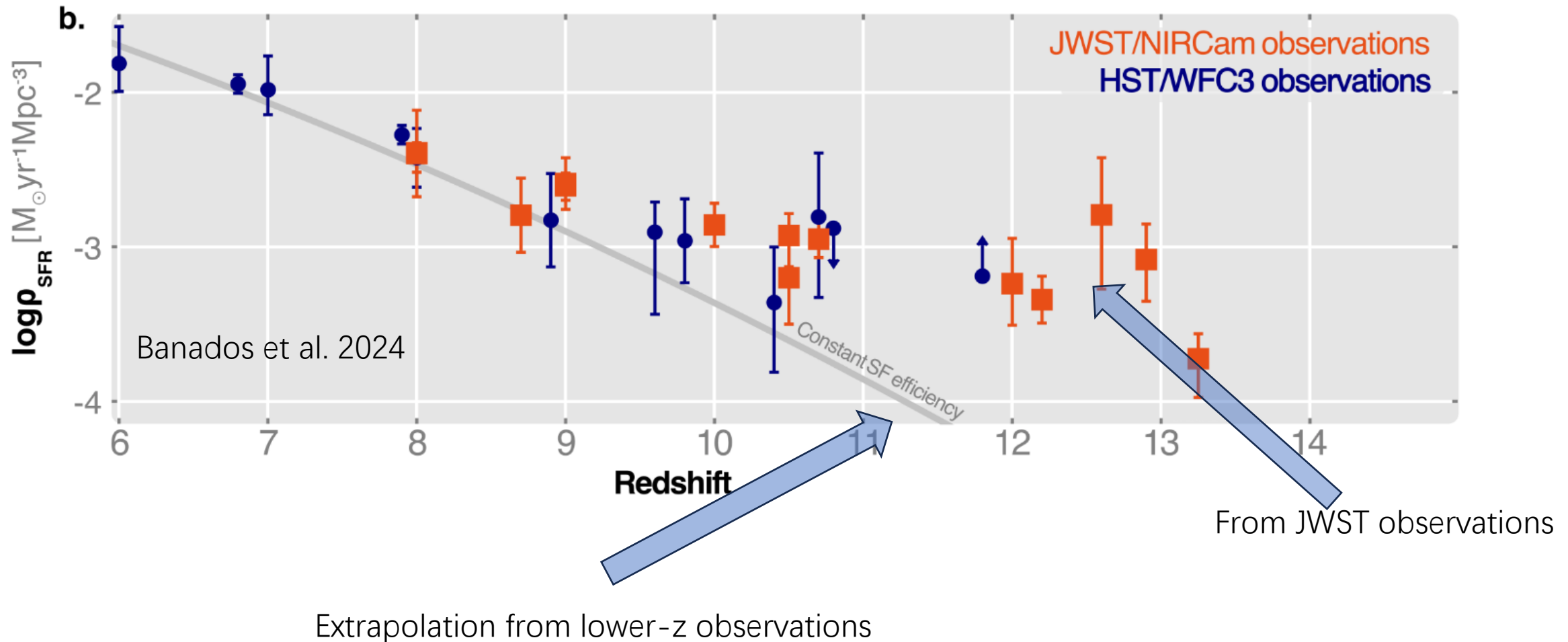
SFRD constructed from HST observations (UV LFs):



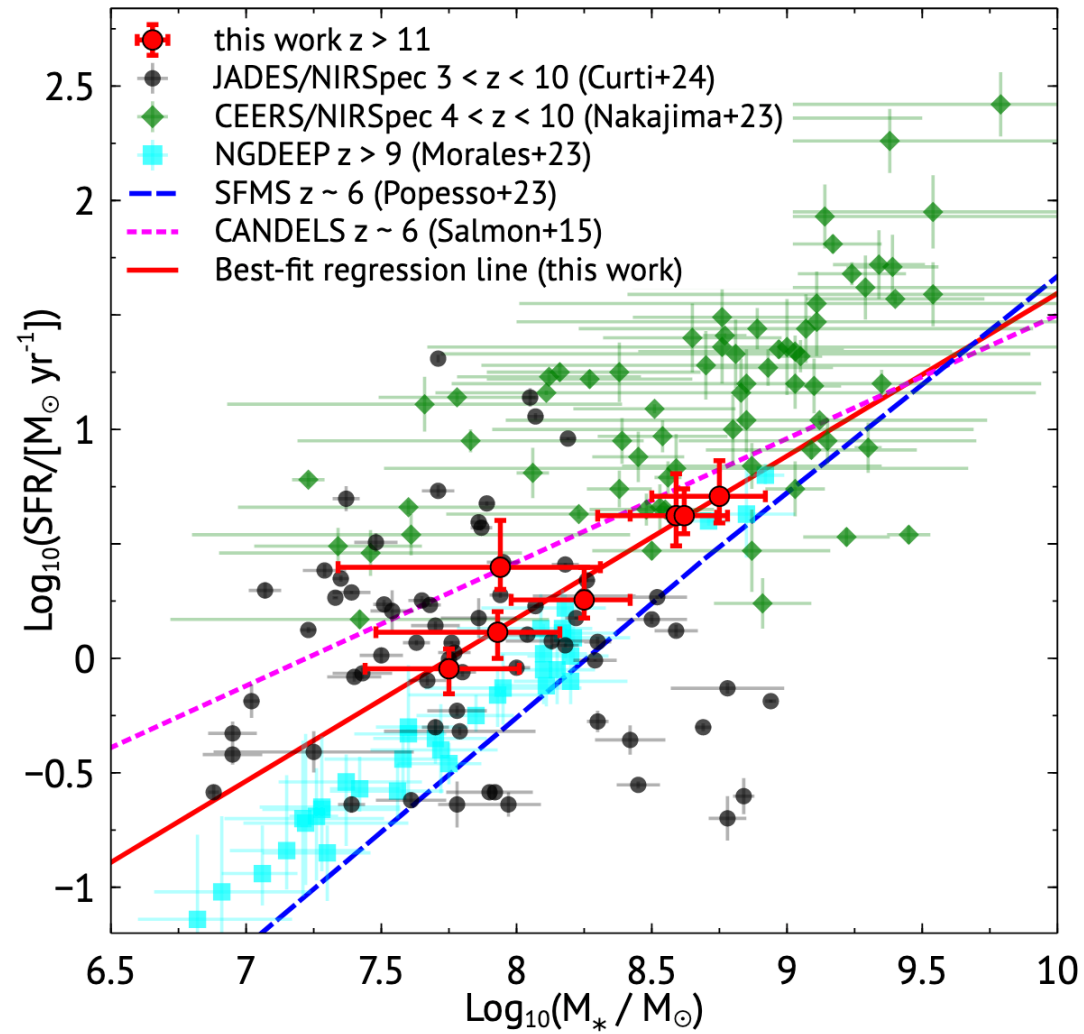
$$\rho_{\text{SFR}}(z) \propto \rho_{\text{UV}}(z)$$

$$= \int L_{\text{UV}}(M_{\text{UV}}) \Phi(M_{\text{UV}}, z) dM_{\text{UV}}$$

SFRD constructed from JWST observations, at $z > \sim 10$, it is much higher than the extrapolation of models based on HST observations

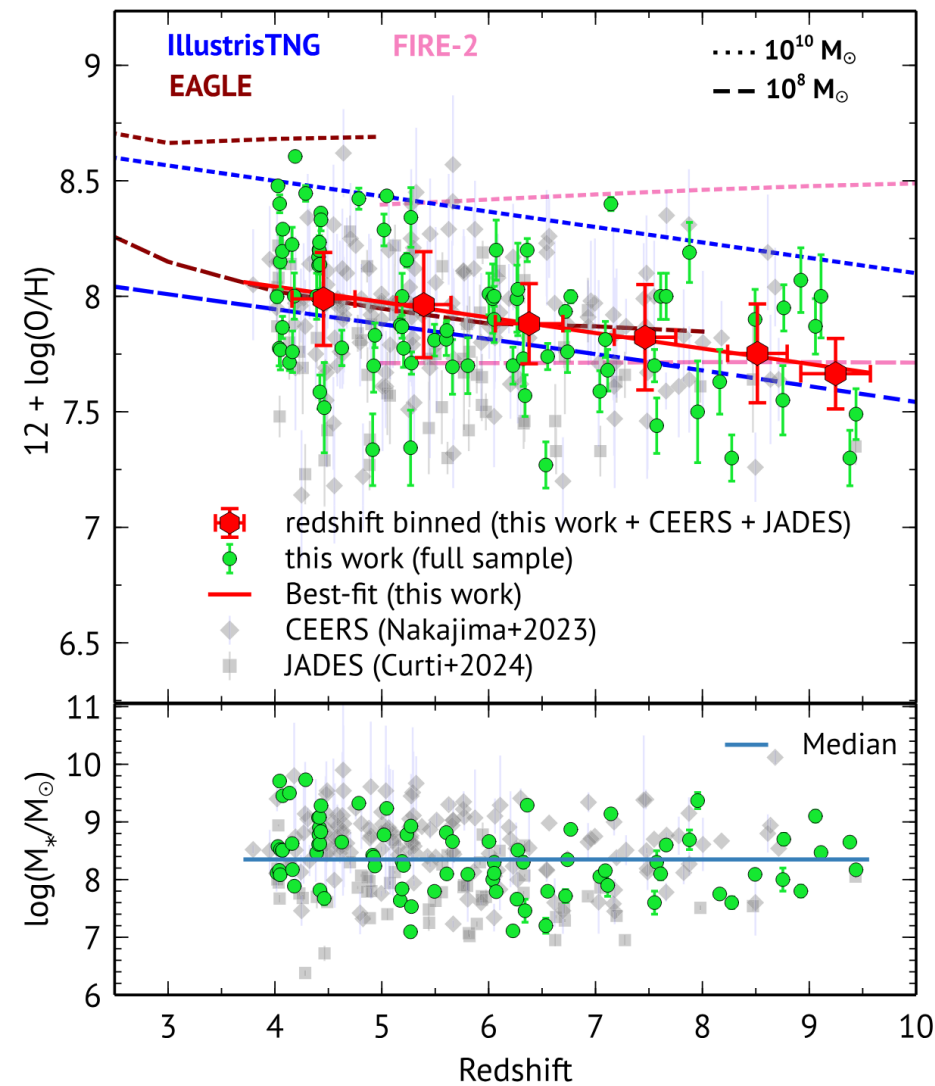
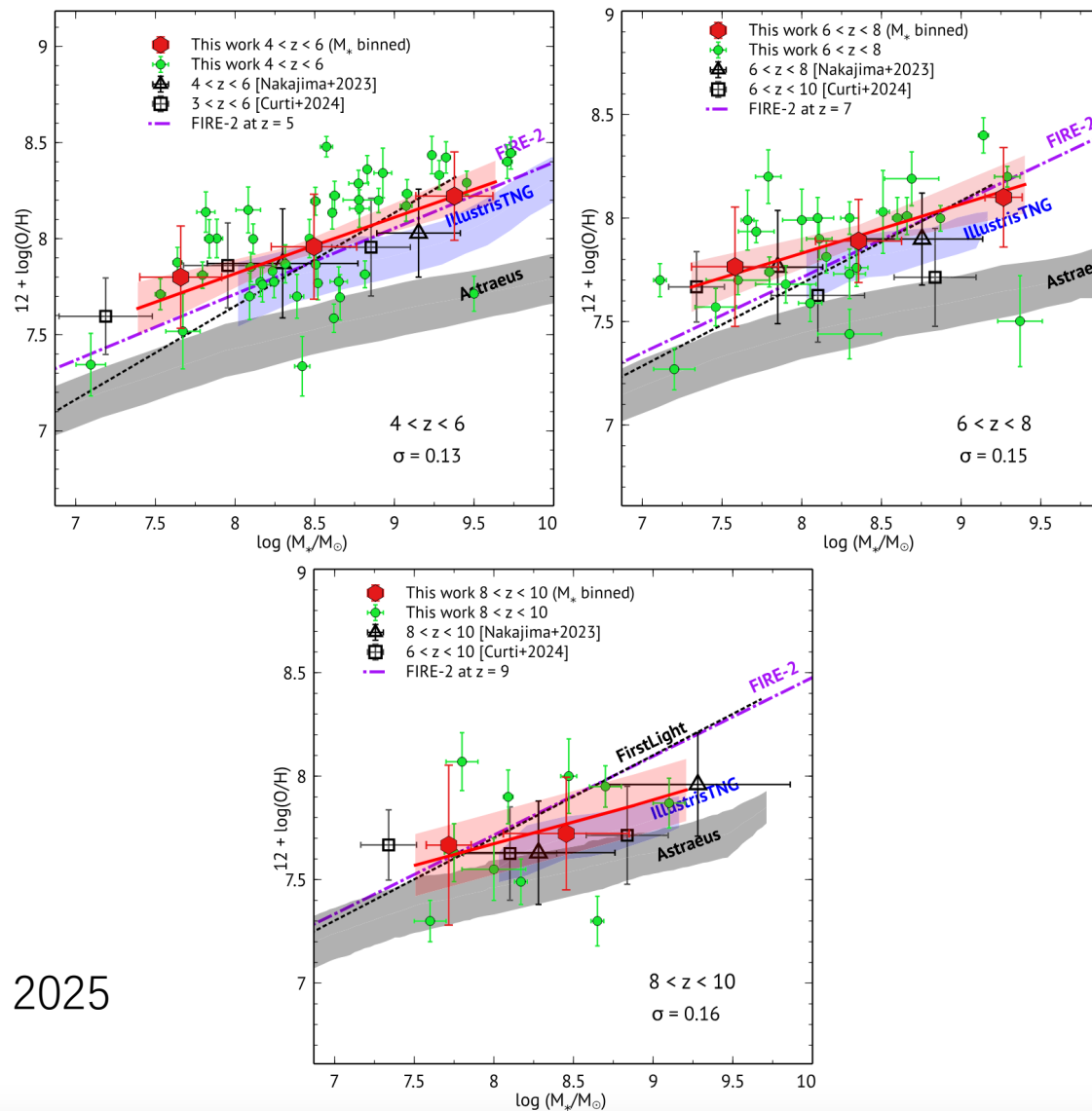


The SFR- M_* relations:



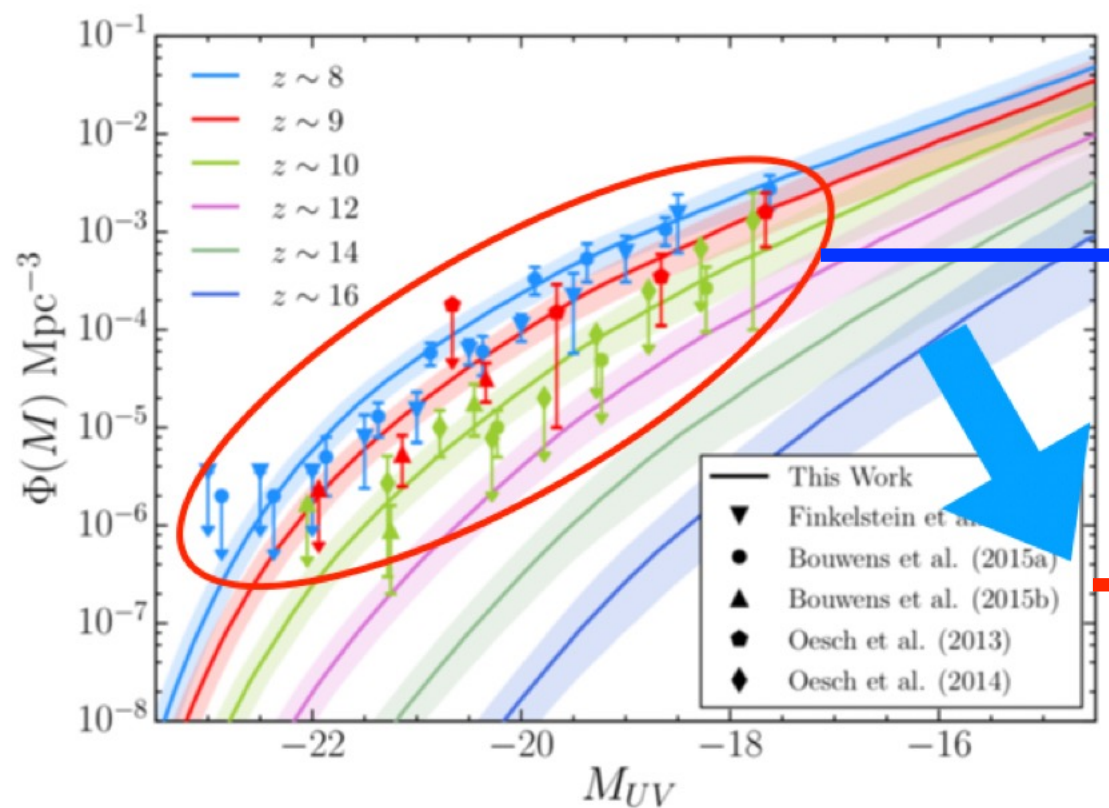
The MZR do evolve!

The MZR evolves:

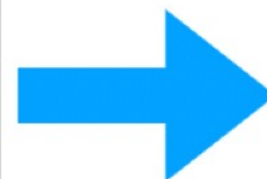


Sarkar et al. 2025

- Pre-JWST stage: for $z > 6$ galaxies only “a tip of the iceberg” was observed.
- JWST stage: it is still true!



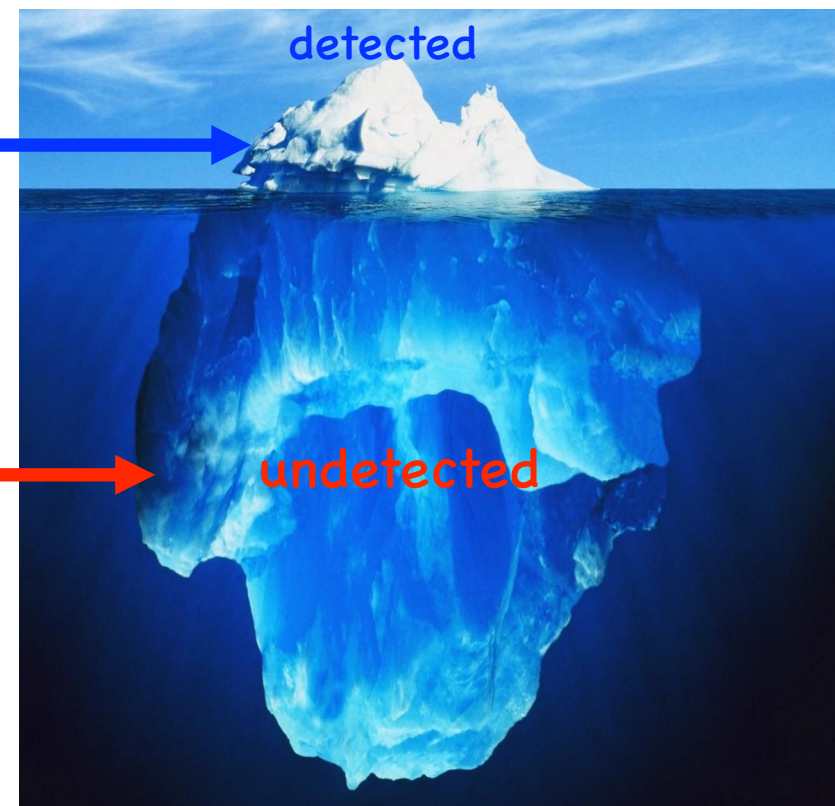
Mason et al. 2015



To fainter luminosity

To higher redshift

冰山一角！



- What is the minimum luminosity of the first galaxies?
- The UV LF is steeper at higher redshift ?

However, most ionized photons are from those undetected galaxies.

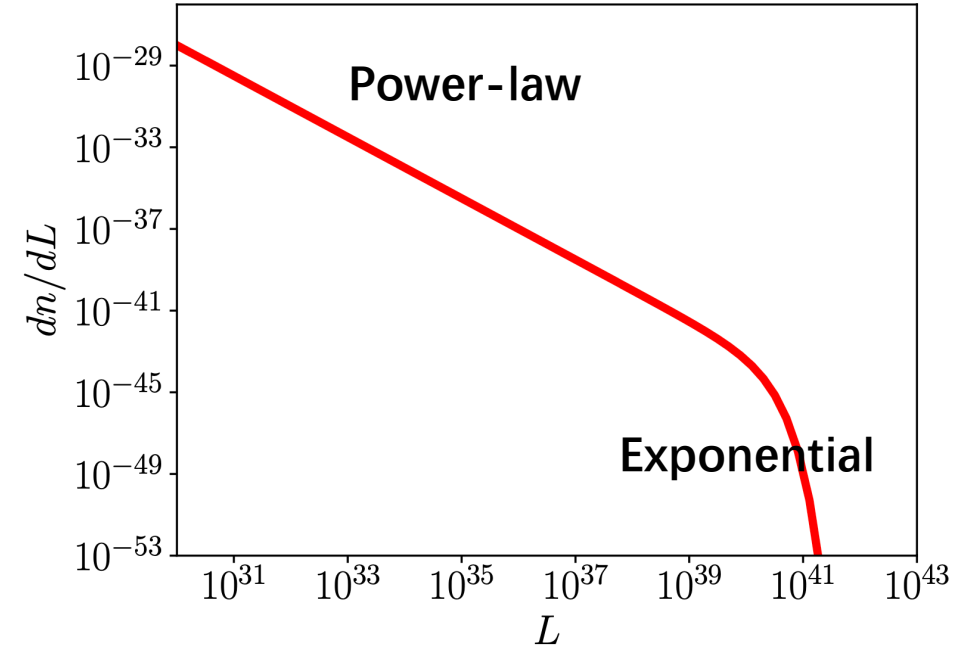
Parameterizing the UV LFs of high- z galaxies:
The Schechter function

Generally, the luminosity function is well-described by a formula named “Schechter function”:

$$\frac{dn}{dL} = \frac{\phi_*}{L_*} \left(\frac{L}{L_*} \right)^\alpha e^{-L/L_*}$$

Power-law term,
dominates the faint-
end

Exponential term,
dominates the bright-end



Three free parameters: ϕ_* , L_* and α .

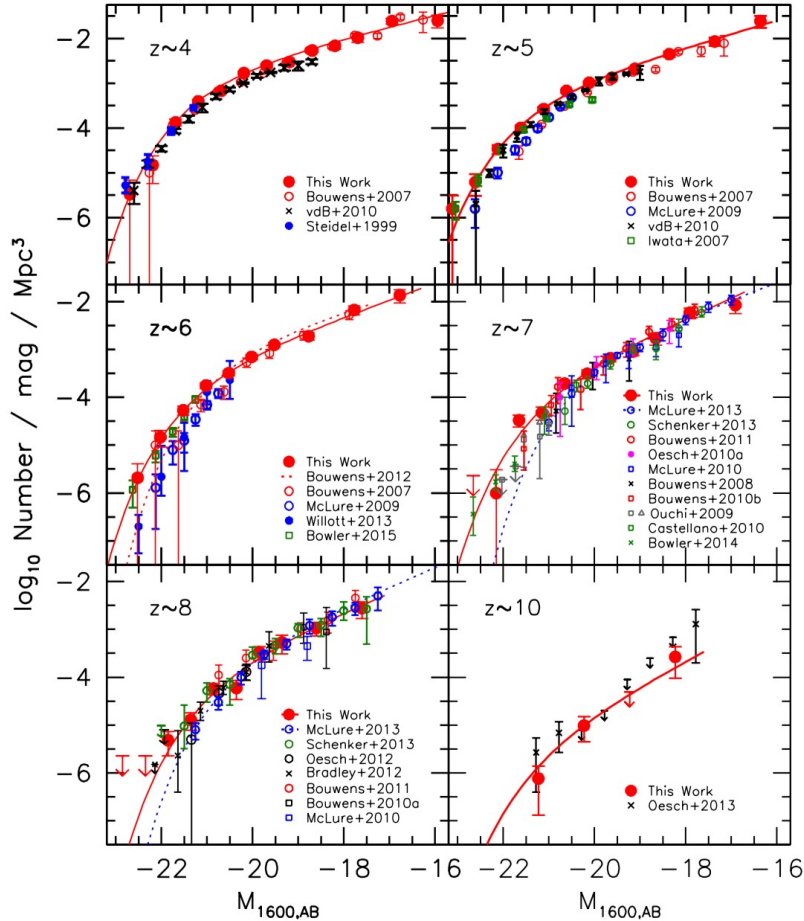
In observations, generally use the absolute magnitude rather than the luminosity

$$\text{Mag} = -2.5 \log(L/\text{erg s}^{-1}\text{Hz}^{-1}) + 51.6$$

The Schechter function writes in absolute magnitude as variable:

$$\frac{dn}{d\text{Mag}} = 0.4 \ln 10 \phi_* 10^{0.4(M_* - \text{Mag})(1+\alpha)} \exp[-10^{0.4(M_* - \text{Mag})}]$$

Observed luminosity functions (HST):



Bouwens et al. 2015

$M_{1600,AB}^a$	ϕ_k (Mpc $^{-3}$ mag $^{-1}$)	$M_{1600,AB}^a$	ϕ_k (Mpc $^{-3}$ mag $^{-1}$)	$M_{1600,AB}^a$	ϕ_k (Mpc $^{-3}$ mag $^{-1}$)
$z \sim 4$ galaxies		$z \sim 6$ galaxies		$z \sim 8$ galaxies	
-22.69	0.000003 ± 0.000004	-22.52	0.000002 ± 0.000002	-22.87	$< 0.000002^b$
-22.19	0.000015 ± 0.000009	-22.02	0.000015 ± 0.000006	-22.37	$< 0.000002^b$
-21.69	0.000134 ± 0.000023	-21.52	0.000053 ± 0.000012	-21.87	0.000005 ± 0.000003
-21.19	0.000393 ± 0.000040	-21.02	0.000176 ± 0.000025	-21.37	0.000013 ± 0.000005
-20.69	0.000678 ± 0.000063	-20.52	0.000320 ± 0.000041	-20.87	0.000058 ± 0.000015
-20.19	0.001696 ± 0.000113	-20.02	0.000698 ± 0.000083	-20.37	0.000060 ± 0.000026
-19.69	0.002475 ± 0.000185	-19.52	0.001246 ± 0.000137	-19.87	0.000331 ± 0.000104
-19.19	0.002984 ± 0.000255	-18.77	0.001900 ± 0.000320	-19.37	0.000533 ± 0.000226
-18.69	0.005352 ± 0.000446	-17.77	0.006680 ± 0.001380	-18.62	0.001060 ± 0.000340
-18.19	0.006865 ± 0.001043	-16.77	0.013640 ± 0.004200	-17.62	0.002740 ± 0.001040
-17.69	0.010473 ± 0.002229	$z \sim 7$ galaxies ^c		$z \sim 10$ galaxies	
-16.94	0.024580 ± 0.003500	-22.66	$< 0.000002^b$	-22.23	$< 0.000001^b$
-15.94	0.025080 ± 0.007860	-22.16	0.000001 ± 0.000002	-21.23	0.000001 ± 0.000001
$z \sim 5$ galaxies		-21.66	0.000033 ± 0.000009	-20.23	0.000010 ± 0.000005
-23.11	0.000002 ± 0.000002	-21.16	0.000048 ± 0.000015	-19.23	$< 0.000049^b$
-22.61	0.000006 ± 0.000003	-20.66	0.000193 ± 0.000034	-18.23	0.000266 ± 0.000171
-22.11	0.000034 ± 0.000008	-20.16	0.000309 ± 0.000061		
-21.61	0.000101 ± 0.000014	-19.66	0.000654 ± 0.000100		
-21.11	0.000265 ± 0.000025	-19.16	0.000907 ± 0.000177		
-20.61	0.000676 ± 0.000046	-18.66	0.001717 ± 0.000478		
-20.11	0.001029 ± 0.000067	-17.91	0.005840 ± 0.001460		
-19.61	0.001329 ± 0.000094	-16.91	0.008500 ± 0.00294		
-19.11	0.002085 ± 0.000171				
-18.36	0.004460 ± 0.000540				
-17.36	0.008600 ± 0.001760				
-16.36	0.024400 ± 0.007160				

Observed galaxies number:

$z \sim 4$: 5859;

$z \sim 5$: 3001;

$z \sim 6$: 857;

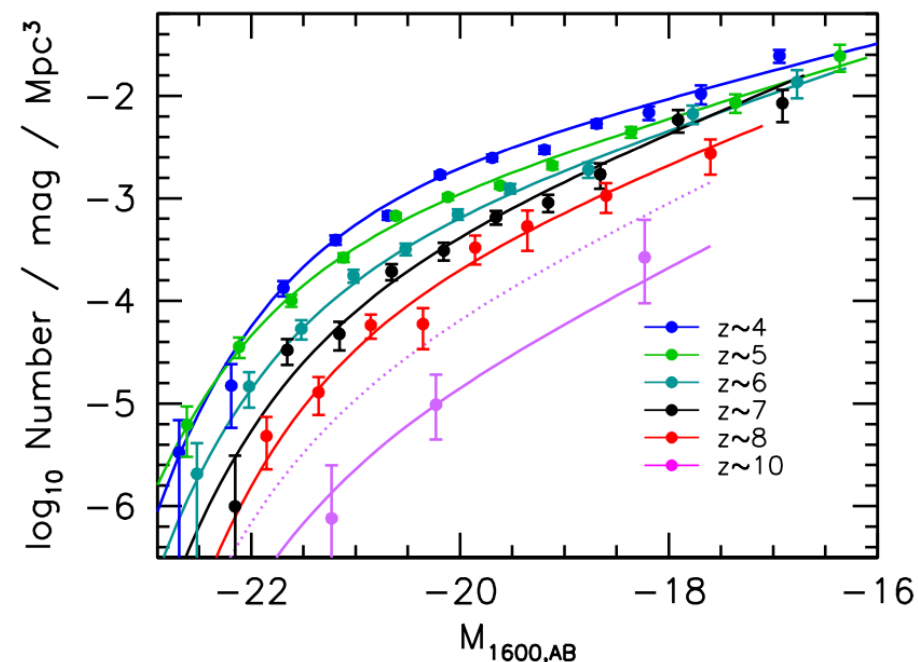
$z \sim 7$: 481;

$z \sim 8$: 217;

$z \sim 10$: 6

Parameters derived from observations:

Dropout Sample	$\langle z \rangle$	M_{UV}^* ^a	ϕ^* (10^{-3} Mpc $^{-3}$)	α
Reddy & Steidel 2009				
<i>U</i>	3.0	-20.97 ± 0.14	1.71 ± 0.53	-1.73 ± 0.13
XDF+HUDF09-Ps+CANDELS-GN+GS+ERS				
<i>B</i>	3.8	-20.88 ± 0.08	$1.97^{+0.34}_{-0.29}$	-1.64 ± 0.04
<i>V</i>	4.9	-21.10 ± 0.15	$0.79^{+0.23}_{-0.18}$	-1.76 ± 0.06
<i>i</i>	5.9	-21.10 ± 0.24	$0.39^{+0.21}_{-0.14}$	-1.90 ± 0.10
<i>z</i>	6.8	-20.61 ± 0.31	$0.46^{+0.38}_{-0.21}$	-1.98 ± 0.15
<i>Y</i>	7.9	-20.19 ± 0.42	$0.44^{+0.52}_{-0.24}$	-1.81 ± 0.27
<i>J</i>	10.4	-20.92 (fixed)	$0.013^{+0.007}_{-0.005}$	-2.27 (fixed)
All Fields (excluding CANDELS-EGS) ^b				
<i>z</i>	6.8	-20.77 ± 0.28	$0.34^{+0.24}_{-0.14}$	-2.03 ± 0.13
<i>Y</i>	7.9	-20.21 ± 0.33	$0.45^{+0.42}_{-0.21}$	-1.83 ± 0.25
All Fields				
<i>B</i>	3.8	-20.88 ± 0.08	$1.97^{+0.34}_{-0.29}$	-1.64 ± 0.04
<i>V</i>	4.9	-21.17 ± 0.12	$0.74^{+0.18}_{-0.14}$	-1.76 ± 0.05
<i>i</i>	5.9	-20.94 ± 0.20	$0.50^{+0.22}_{-0.16}$	-1.87 ± 0.10
<i>z</i>	6.8	-20.87 ± 0.26	$0.29^{+0.21}_{-0.12}$	-2.06 ± 0.13
<i>Y</i>	7.9	-20.63 ± 0.36	$0.21^{+0.23}_{-0.11}$	-2.02 ± 0.23
<i>J</i>	10.4	-20.92 (fixed)	$0.008^{+0.004}_{-0.003}$	-2.27 (fixed)



Redshift-evolution fitting of the three parameters

$$M_{UV}^* = (-20.95 \pm 0.10) + (0.01 \pm 0.06)(z - 6)$$

$$\phi^* = (0.47^{+0.11}_{-0.10}) 10^{(-0.27 \pm 0.05)(z-6)} 10^{-3} \text{Mpc}^{-3}$$

$$\alpha = (-1.87 \pm 0.05) + (-0.10 \pm 0.03)(z - 6)$$

So now you have an analytical formula to calculate the UV LF at any redshifts!

Exercises 1:

- Derive the best-fit Schechter parameters of the measured UV LFs data (from HST) at $z \sim 5, 6, 7, 8, 9$ in Bouwens et al. 2021; and the data (from JWST) at $z \sim 9, 12, 16$ in Harikane et al. 2023

$M_{1600,AB}$	ϕ_k (Mpc $^{-3}$ mag $^{-1}$)
$z \sim 5$ galaxies	
-23.11	0.000001 $\pm$ 0.000001
-22.61	0.000004 $\pm$ 0.000002
-22.11	0.000028 $\pm$ 0.000007
-21.61	0.000092 $\pm$ 0.000013
-21.11	0.000262 $\pm$ 0.000024
-20.61	0.000584 $\pm$ 0.000044
-20.11	0.000879 $\pm$ 0.000067
-19.61	0.001594 $\pm$ 0.000156
-19.11	0.002159 $\pm$ 0.000346
-18.36	0.004620 $\pm$ 0.000520
-17.36	0.008780 $\pm$ 0.001540
-16.36	0.025120 $\pm$ 0.007340
$z \sim 6$ galaxies	
-22.52	0.000002 $\pm$ 0.000002
-22.02	0.000014 $\pm$ 0.000005
-21.52	0.000051 $\pm$ 0.000011
-21.02	0.000169 $\pm$ 0.000024
-20.52	0.000317 $\pm$ 0.000041
-20.02	0.000724 $\pm$ 0.000087
-19.52	0.001147 $\pm$ 0.000157
-18.77	0.002820 $\pm$ 0.000440
-17.77	0.008360 $\pm$ 0.001660
-16.77	0.017100 $\pm$ 0.005260
$z \sim 7$ galaxies	
-22.19	0.000001 $\pm$ 0.000002
-21.69	0.000041 $\pm$ 0.000011
-21.19	0.000047 $\pm$ 0.000015
-20.69	0.000198 $\pm$ 0.000036
-20.19	0.000283 $\pm$ 0.000066
-19.69	0.000589 $\pm$ 0.000126
-19.19	0.001172 $\pm$ 0.000336
-18.69	0.001433 $\pm$ 0.000419
-17.94	0.005760 $\pm$ 0.001440
-16.94	0.008320 $\pm$ 0.002900

$M_{1600,AB}$	ϕ_k (Mpc $^{-3}$ mag $^{-1}$)
$z \sim 8$ galaxies	
-21.85	0.000003 $\pm$ 0.000002
-21.35	0.000012 $\pm$ 0.000004
-20.85	0.000041 $\pm$ 0.000011
-20.10	0.000120 $\pm$ 0.000040
-19.35	0.000657 $\pm$ 0.000233
-18.60	0.001100 $\pm$ 0.000340
-17.60	0.003020 $\pm$ 0.001140
$z \sim 9$ galaxies	
-21.92	0.000001 $\pm$ 0.000001
-21.12	0.000007 $\pm$ 0.000003
-20.32	0.000026 $\pm$ 0.000009
-19.12	0.000187 $\pm$ 0.000150
-17.92	0.000923 $\pm$ 0.000501

Bouwens et al. 2021

Table 7 Obtained Luminosity Function at each Redshift	
M_{UV} (ABmag)	Φ (Mpc $^{-3}$ mag $^{-1}$)
F115W Dropouts ($z \sim 9$)	
-23.03	$< 6.95 \times 10^{-5}$
-22.03	$< 7.67 \times 10^{-5}$
-21.03	$(4.00^{+9.42}_{-3.85}) \times 10^{-5}$
-20.03	$(4.08^{+9.60}_{-3.92}) \times 10^{-5}$
-19.03	$(2.24^{+1.87}_{-1.46}) \times 10^{-4}$
-18.03	$(1.12^{+1.03}_{-0.90}) \times 10^{-3}$
F150W Dropouts ($z \sim 12$)	
-23.21	$< 5.85 \times 10^{-6}$
-22.21	$< 6.40 \times 10^{-6}$
-21.21	$(5.00^{+11.56}_{-4.27}) \times 10^{-6}$
-20.21	$(1.31^{+1.75}_{-0.89}) \times 10^{-5}$
-19.21	$(2.40^{+2.38}_{-1.40}) \times 10^{-5}$
-18.21	$(1.42^{+1.97}_{-1.10}) \times 10^{-4}$
F200W Dropouts ($z \sim 16$)	
-23.59	$< 2.42 \times 10^{-6}$
-20.59	$(6.62^{+8.84}_{-4.49}) \times 10^{-6}$

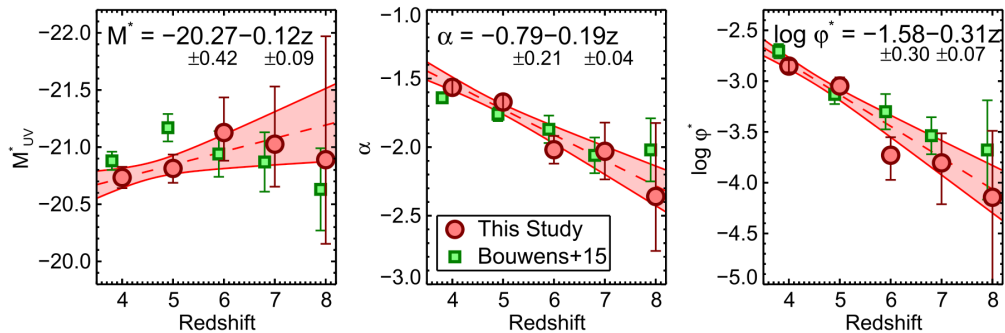
Note. Errors and upper limits are 1σ .

Harikane et al. 2023

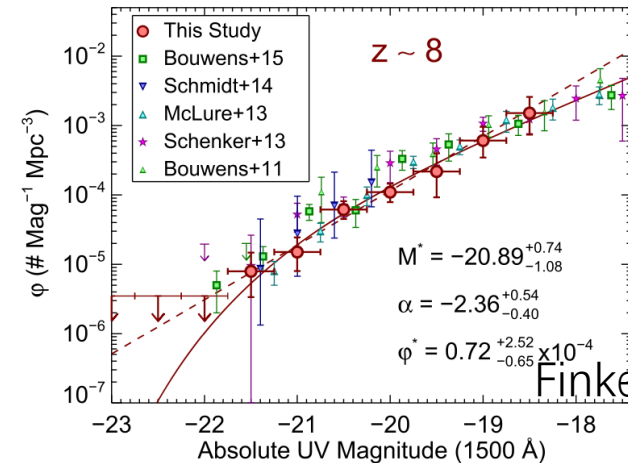
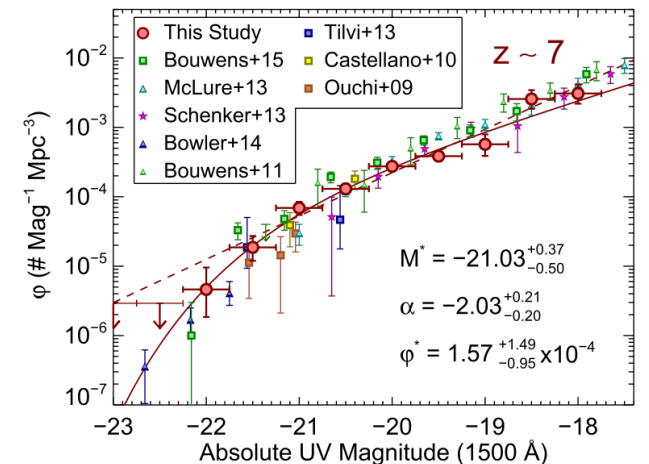
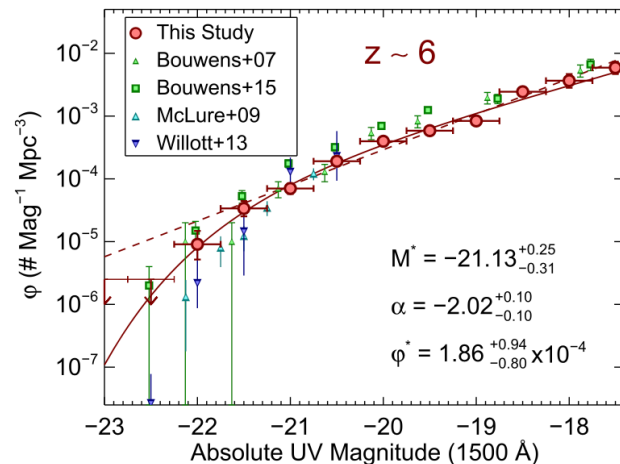
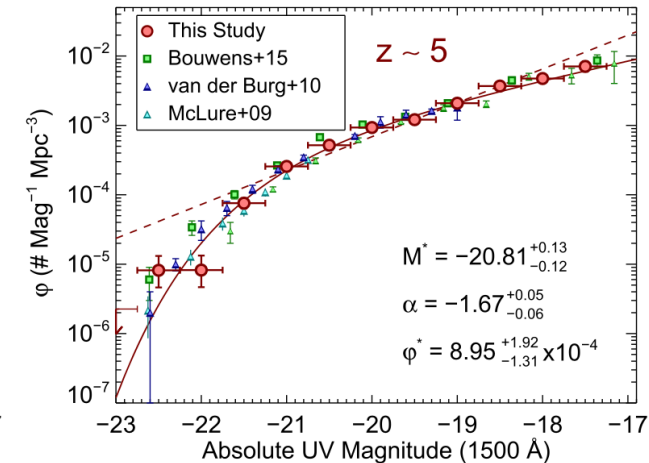
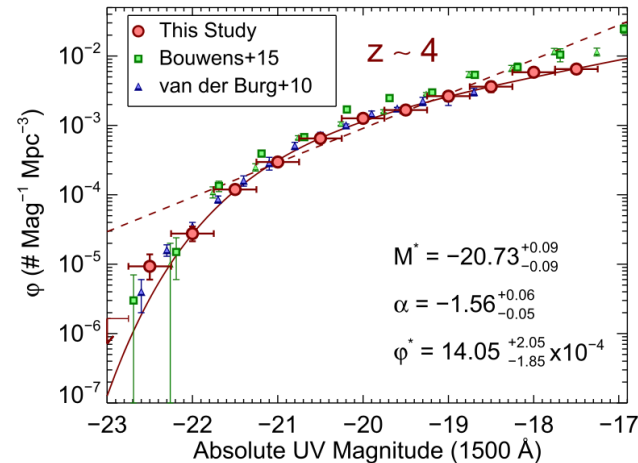
Schechter Function Fits to the Luminosity Function

Redshift	M_{UV}^*	α	φ^* (Mpc^{-3})
4	$-20.73^{+0.09}_{-0.09}$	$-1.56^{+0.06}_{-0.05}$	$(14.1^{+2.05}_{-1.85}) \times 10^{-4}$
5	$-20.81^{+0.13}_{-0.12}$	$-1.67^{+0.05}_{-0.06}$	$(8.95^{+1.92}_{-1.31}) \times 10^{-4}$
6	$-21.13^{+0.25}_{-0.31}$	$-2.02^{+0.10}_{-0.10}$	$(1.86^{+0.94}_{-0.80}) \times 10^{-4}$
7	$-21.03^{+0.37}_{-0.50}$	$-2.03^{+0.21}_{-0.20}$	$(1.57^{+1.49}_{-0.95}) \times 10^{-4}$
8	$-20.89^{+0.74}_{-1.08}$	$-2.36^{+0.54}_{-0.40}$	$(0.72^{+2.52}_{-0.65}) \times 10^{-4}$

Redshift-evolutions:

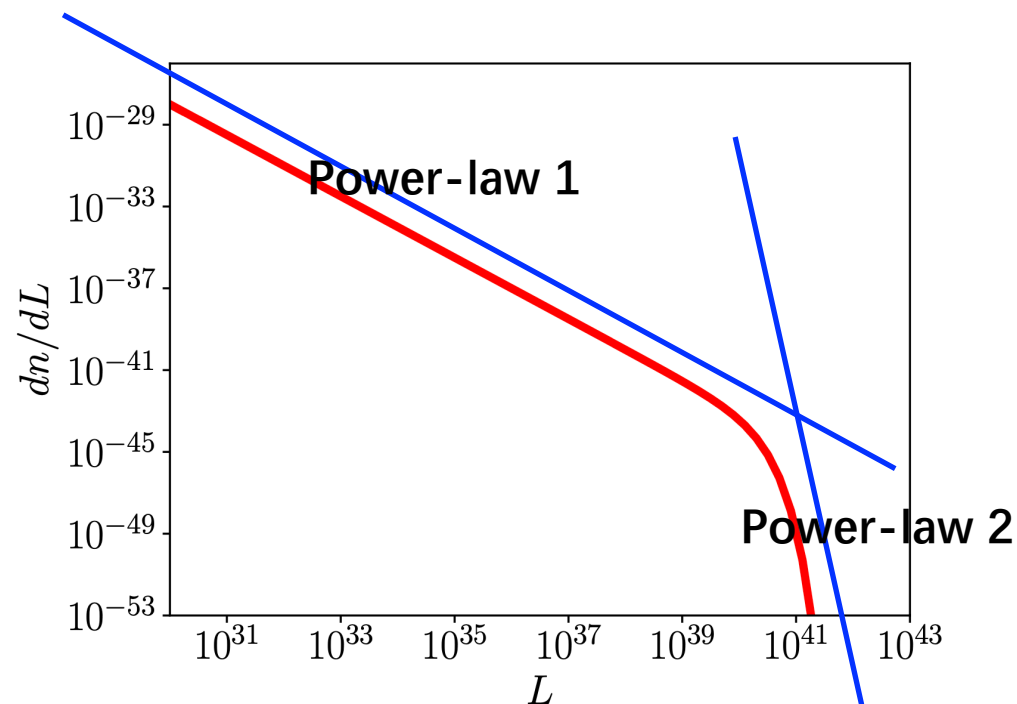


M_{1500}	$\varphi(z \approx 4)$ ($10^{-3} \text{ Mpc}^{-3} \text{ mag}^{-1}$)	$\varphi(z \approx 5)$ ($10^{-3} \text{ Mpc}^{-3} \text{ mag}^{-1}$)	$\varphi(z \approx 6)$ ($10^{-3} \text{ Mpc}^{-3} \text{ mag}^{-1}$)	$\varphi(z \approx 7)$ ($10^{-3} \text{ Mpc}^{-3} \text{ mag}^{-1}$)	$\varphi(z \approx 8)$ ($10^{-3} \text{ Mpc}^{-3} \text{ mag}^{-1}$)
-23.0	<0.0016	<0.0023	<0.0025	<0.0029	<0.0035
-22.5	$0.0093^{+0.0045}_{-0.0033}$	$0.0082^{+0.0050}_{-0.0035}$	<0.0025	<0.0029	<0.0035
-22.0	$0.0276^{+0.0074}_{-0.0062}$	$0.0082^{+0.0051}_{-0.0036}$	$0.0091^{+0.0057}_{-0.0039}$	$0.0046^{+0.0049}_{-0.0028}$	<0.0035
-21.5	$0.1192^{+0.0145}_{-0.0132}$	$0.0758^{+0.0137}_{-0.0125}$	$0.0338^{+0.0105}_{-0.0085}$	$0.0187^{+0.0085}_{-0.0067}$	$0.0079^{+0.0068}_{-0.0046}$
-21.0	$0.2968^{+0.0230}_{-0.0219}$	$0.2564^{+0.0255}_{-0.0240}$	$0.0703^{+0.0148}_{-0.0128}$	$0.0690^{+0.0156}_{-0.0144}$	$0.0150^{+0.0094}_{-0.0070}$
-20.5	$0.6491^{+0.0361}_{-0.0347}$	$0.5181^{+0.0365}_{-0.0338}$	$0.1910^{+0.0249}_{-0.0229}$	$0.1301^{+0.0239}_{-0.0200}$	$0.0615^{+0.0197}_{-0.0165}$
-20.0	$1.2637^{+0.0494}_{-0.0474}$	$0.9315^{+0.0477}_{-0.0482}$	$0.3970^{+0.0394}_{-0.0357}$	$0.2742^{+0.0379}_{-0.0329}$	$0.1097^{+0.0356}_{-0.0309}$
-19.5	$1.6645^{+0.0630}_{-0.0618}$	$1.2086^{+0.0488}_{-0.0666}$	$0.5858^{+0.0527}_{-0.0437}$	$0.3848^{+0.0633}_{-0.0586}$	$0.2174^{+0.1805}_{-0.1250}$
-19.0	$2.6392^{+0.1192}_{-0.1165}$	$2.0874^{+0.1212}_{-0.1147}$	$0.8375^{+0.0916}_{-0.0824}$	$0.5699^{+0.2229}_{-0.1817}$	$0.6073^{+0.3501}_{-0.2616}$
-18.5	$3.6169^{+0.6799}_{-0.6091}$	$3.6886^{+0.3864}_{-0.3725}$	$2.4450^{+0.3887}_{-0.3515}$	$2.5650^{+0.8735}_{-0.7161}$	$1.5110^{+1.0726}_{-0.7718}$
-18.0	$5.8343^{+0.8836}_{-0.8204}$	$4.7361^{+0.4823}_{-0.4413}$	$3.6662^{+1.0076}_{-0.8401}$	$3.0780^{+1.0837}_{-0.8845}$	...
-17.5	$6.4858^{+1.0166}_{-0.9467}$	$7.0842^{+1.2829}_{-1.1364}$	$5.9126^{+1.4481}_{-1.2338}$	...	...



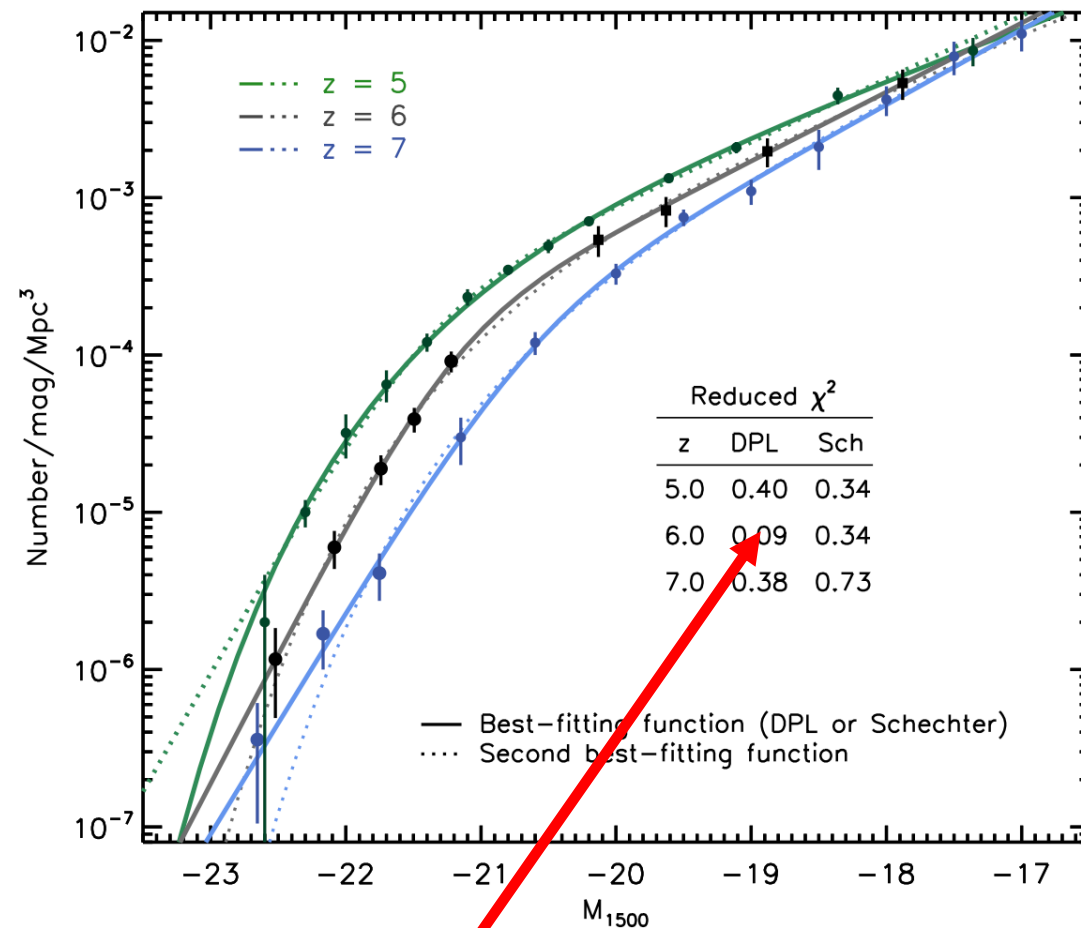
Finkelstein et al. 2015

Double power-law form:



$$\frac{dn}{d\text{Mag}} = \frac{1}{10^{0.4(1+\alpha)(\text{Mag}-M_*)} + 10^{0.4(1+\beta)(\text{Mag}-M_*)}}$$

Essential for estimating the bright-end of the LF.



At $z \sim 6-7$, DPL fits the observations better than Schechter Function

How we know the star formation rate (SFR) of a galaxy from observed UV luminosity?

Based the Single Stellar Population (SSP) and the star formation history, then the luminosity at frequency ν is

$$L_\nu(t|\text{IMF}, Z) = \int_t^\infty \text{SFR}(t') s_\nu(t - t'|\text{IMF}, Z) dt',$$

where s_ν is the UV luminosity per stellar mass for stars formed at t' and still alive at t . It depends on Initial Mass Function (IMF) and metallicity Z , normally provided by the SSP model (e.g. Starburst99, bc03).

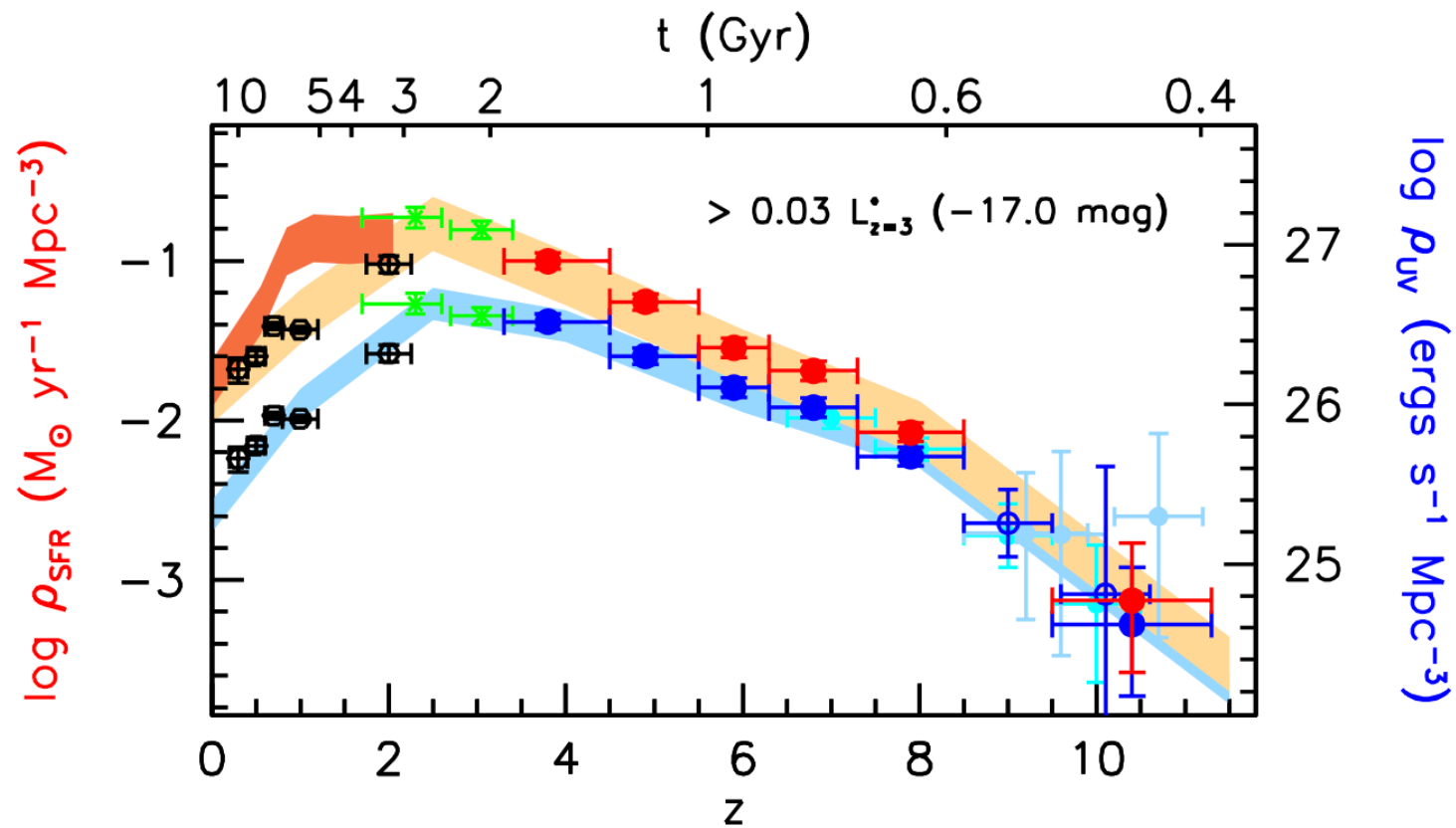
However, for UV luminosity, since the frequency is high, it is mainly from short-lived massive stars, therefore s_ν is approximated as a δ function, then

$$L_{\text{UV}}(t) \approx 1/\mathcal{K}_{\text{UV}} \text{SFR}(t),$$

where $\mathcal{K}_{\text{UV}} = 1.4 \times 10^{-28} M_\odot \text{yr}^{-1} \text{erg s}^{-1} \text{Hz}^{-1}$ (Kennicutt 1998).

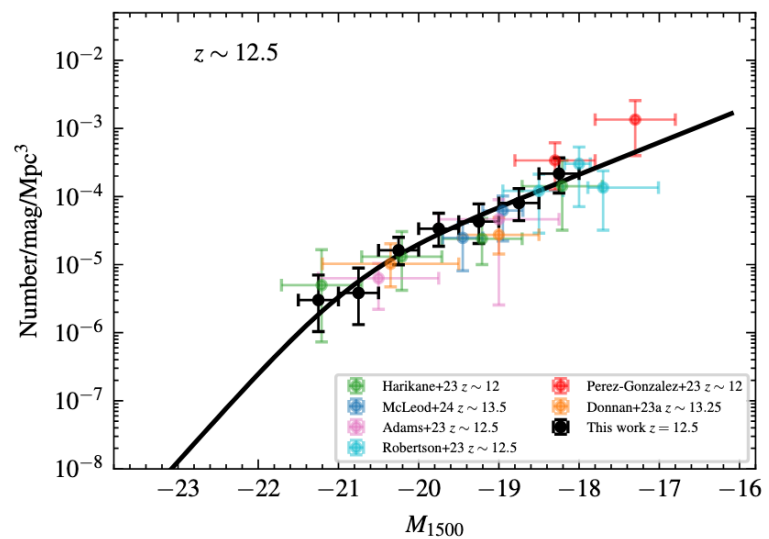
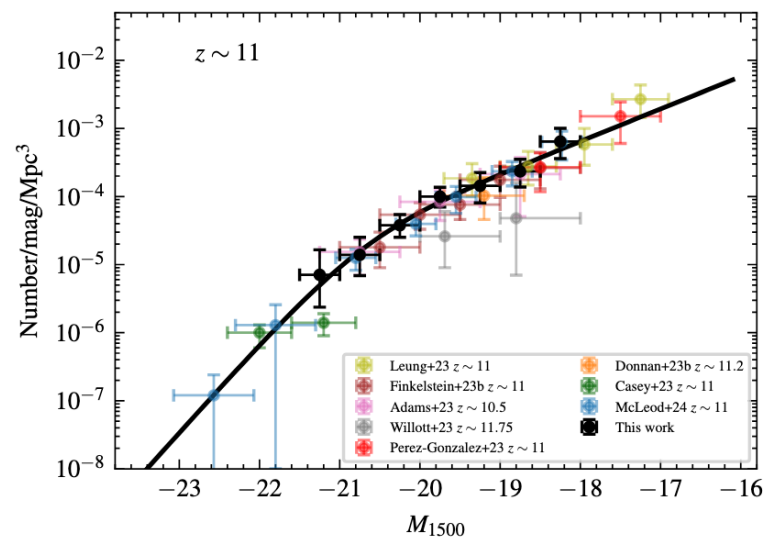
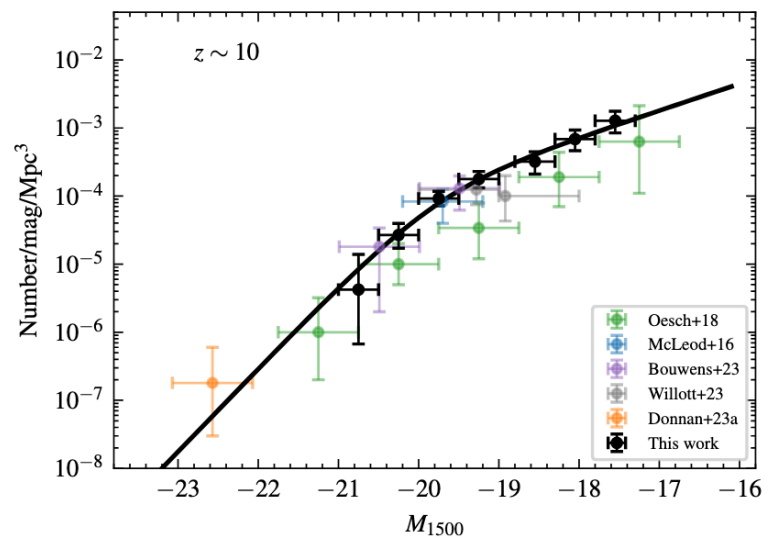
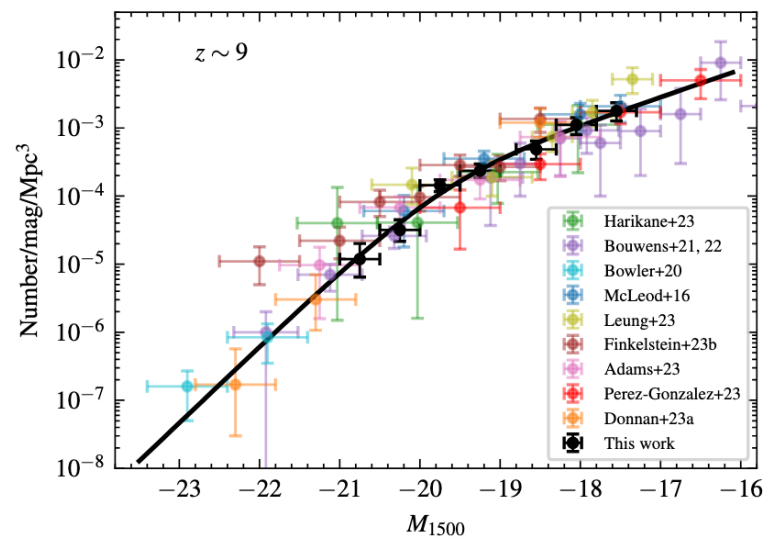
The star formation rate density (SFRD) ρ_{SFR} is

$$\begin{aligned} \rho_{\text{SFR}}(z) &= \mathcal{K}_{\text{UV}} \rho_{\text{UV}}(z) \\ &= \mathcal{K}_{\text{UV}} \int L_{\text{UV}} \frac{dn}{dL_{\text{UV}}}(z) dL_{\text{UV}} \end{aligned}$$

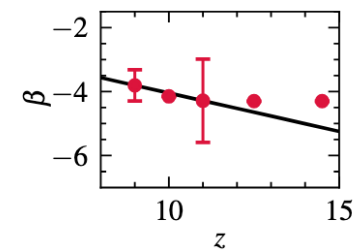
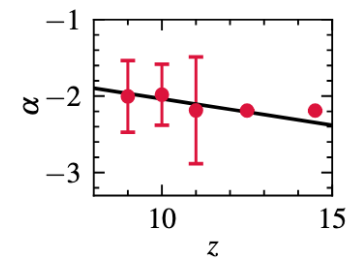
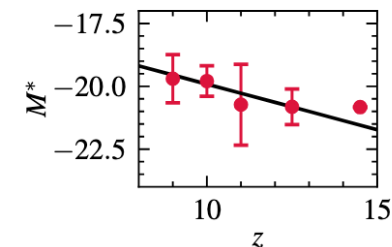
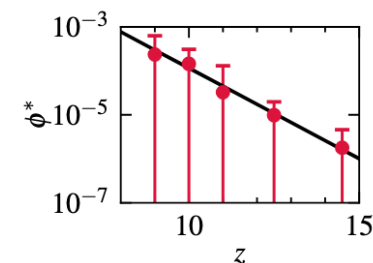


Bouwens et al. 2015

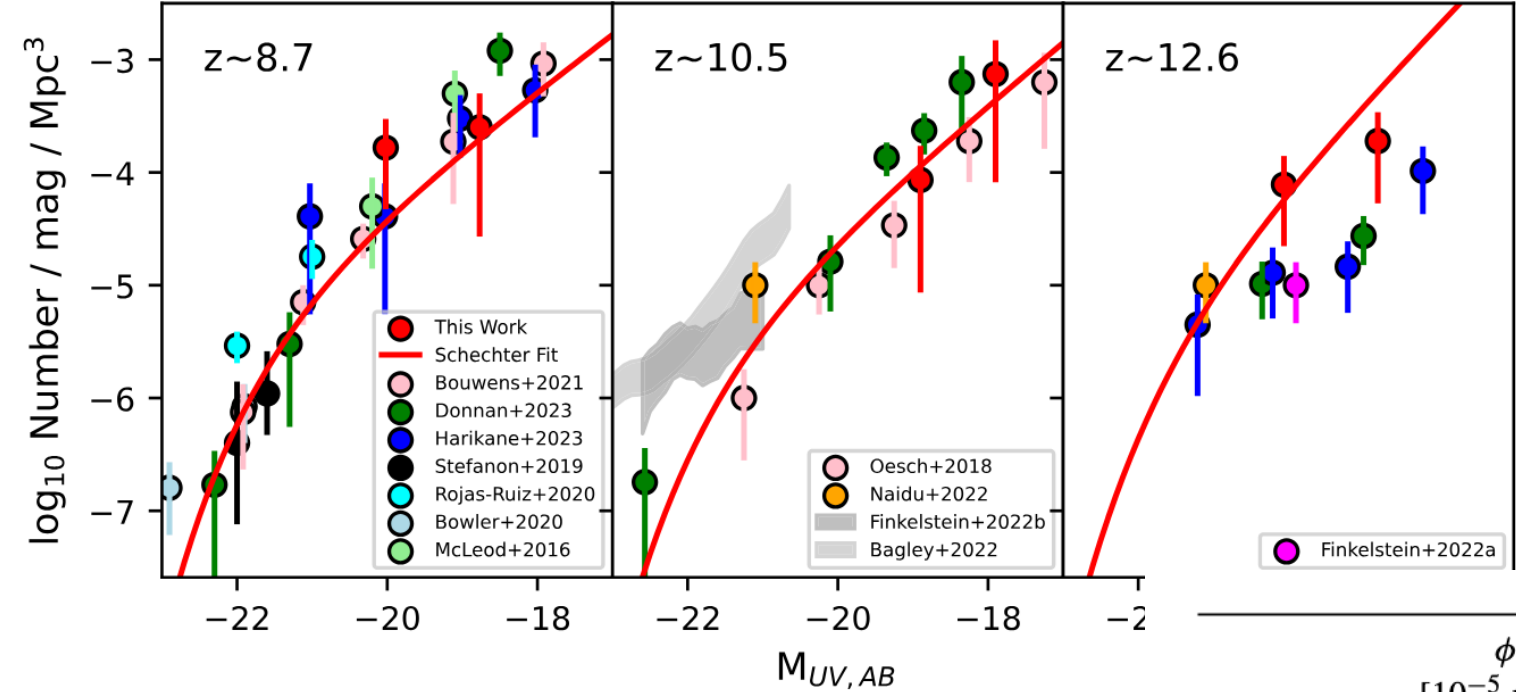
JWST observations



DPL parameters



JWST observations



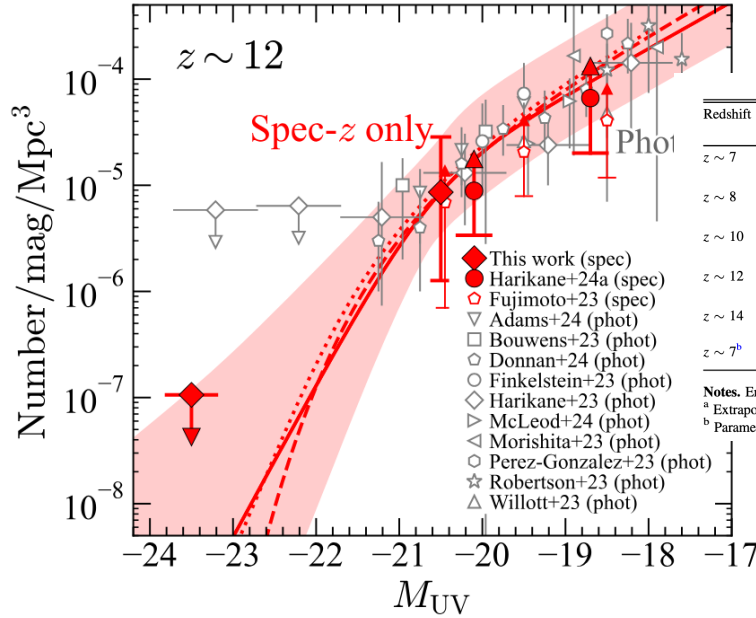
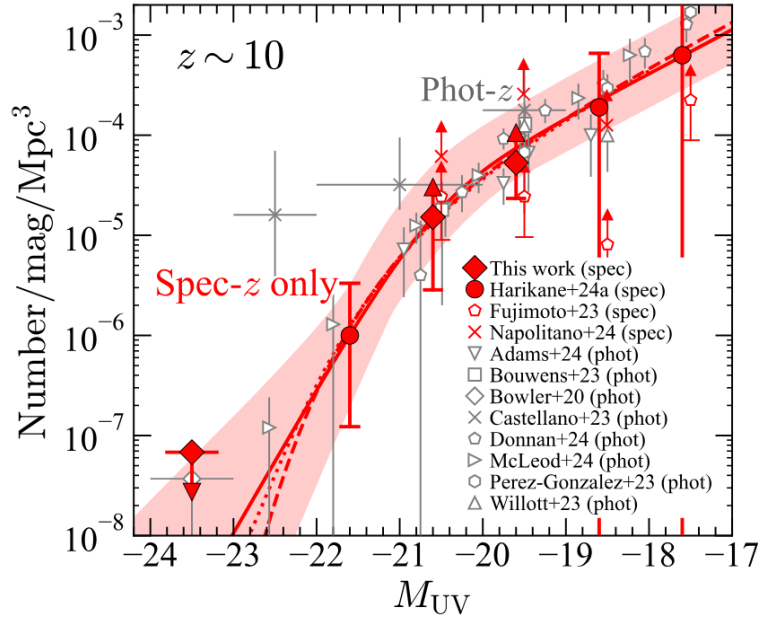
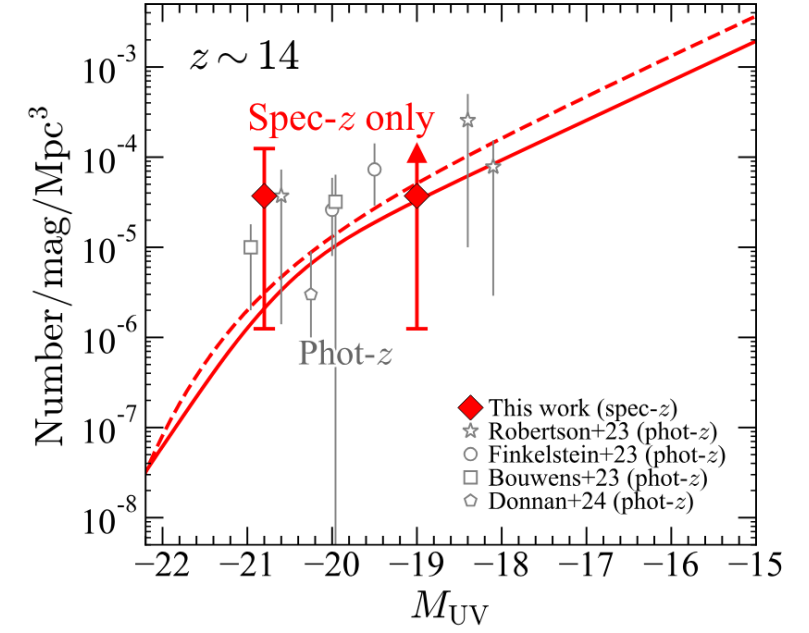
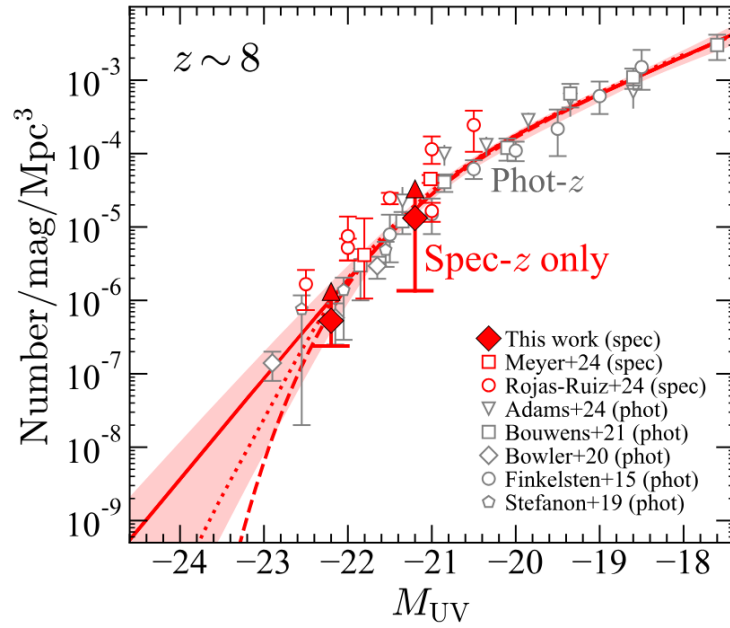
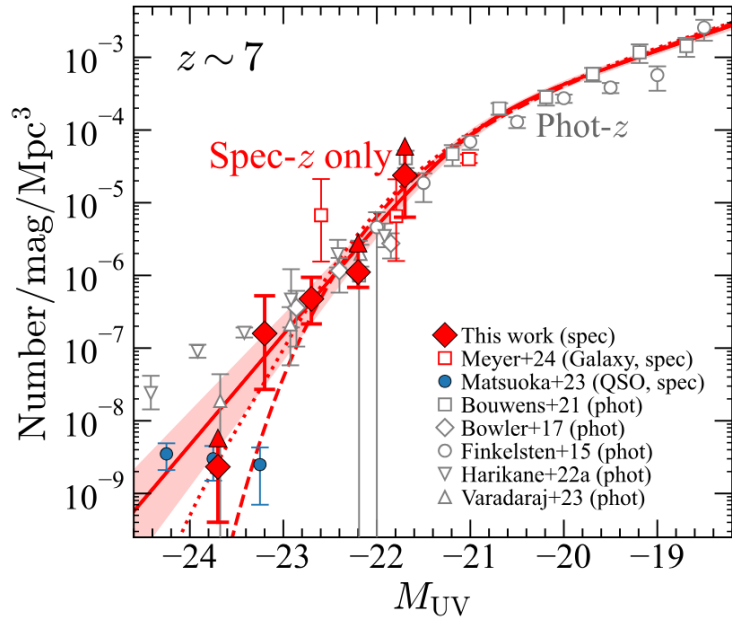
Schechter parameters

Bouwens et al. 2023

Redshift	ϕ^* [$10^{-5} \text{ mag}^{-1} \text{ Mpc}^{-3}$]	M^* [mag]	α
Schechter			
8.7	$1.5^{+1.0}_{-0.6}$	-21.15 (fixed)	-2.26 (fixed)
10.5	$0.8^{+0.8}_{-0.4}$	-21.15 (fixed)	-2.38 (fixed)
12.6	$1.6^{+2.0}_{-1.0}$	-21.15 (fixed)	-2.71 (fixed)
14.7	$<2.7^a$	-21.15 (fixed)	-2.93 (fixed)

^a Upper limit is 1σ .

JWST observations:



Redshift	Fitted Function	M_{UV}^* (ABmag)	$\log \phi^*$ (Mpc^{-3})	α	β
$z \sim 7$	DPL	$-21.01^{+0.30}_{-0.26}$	$-3.74^{+0.23}_{-0.22}$	$-2.08^{+0.12}_{-0.11}$	$-4.81^{+0.50}_{-0.56}$
	Schechter	$-20.89^{+0.27}_{-0.23}$	$-3.51^{+0.22}_{-0.20}$	$-1.97^{+0.14}_{-0.12}$	
$z \sim 8$	DPL	$-20.88^{+0.25}_{-0.23}$	$-4.10^{+0.22}_{-0.20}$	$-2.27^{+0.16}_{-0.12}$	$-4.45^{+0.31}_{-0.24}$
	Schechter	$-20.82^{+0.36}_{-0.55}$	$-3.92^{+0.34}_{-0.31}$	$-2.16^{+0.24}_{-0.21}$	
$z \sim 10$	DPL	$-20.61^{+0.71}_{-0.90}$	$-4.50^{+0.66}_{-0.68}$	$-2.10(\text{fixed})$	$-4.60(\text{fixed})$
	Schechter	$-20.65^{+0.65}_{-1.10}$	$-4.43^{+0.56}_{-0.59}$	$-2.10(\text{fixed})$	
$z \sim 12$	DPL	$-20.60(\text{fixed})$	$-4.82^{+0.52}_{-0.40}$	$-2.10(\text{fixed})$	$-4.60(\text{fixed})$
	Schechter	$-20.60(\text{fixed})$	$-4.67^{+0.51}_{-0.43}$	$-2.10(\text{fixed})$	
$z \sim 14$	DPL	$-20.60(\text{fixed})$	-5.14^*	$-2.10(\text{fixed})$	$-4.60(\text{fixed})$
	Schechter	$-20.60(\text{fixed})$	-4.86^*	$-2.10(\text{fixed})$	
$z \sim 7^b$	DPL	$-21.08^{+0.21}_{-0.22}$	$-3.80^{+0.17}_{-0.20}$	$-2.10^{+0.10}_{-0.11}$	$-5.56^{+0.70}_{-0.92}$

Notes. Errors are 1σ .

* Extrapolated from the results at $z \sim 10$ and 12 .

^b Parameters when multiple subcomponents are split into separate "galaxies" (see Section 4.2).

Modeling the UV LFs of first galaxies

Suppose the mass function of dark matter halos is known,

$$\frac{dn}{dM_h}$$

and the connection between dark matter halo and galaxy luminosity is also known,

$$L_{\text{UV}}(M_h, z),$$

then the UV LF is simply

$$\frac{dn}{dL_{\text{UV}}} = \frac{dn}{dM_h} \frac{dM_h}{dL_{\text{UV}}}.$$

Normally L_{UV} is defined at wavelength 1500Å or 1600Å.

If the galaxy luminosity scatters around a mean luminosity $\bar{L}_{\text{UV}}$, for example the luminosity follows log normal distribution,

$$P(\log L_{\text{UV}}|M_h) = \frac{1}{\sqrt{2\pi}\sigma_{\log L}} \exp \left[-\frac{(\log L_{\text{UV}} - \log \bar{L}_{\text{UV}})^2}{2\sigma_{\log L}^2} \right],$$

then

$$\frac{dn}{d\log L_{\text{UV}}} = \int P(\log L_{\text{UV}}|M_h) \frac{dn}{dM_h} dM_h.$$

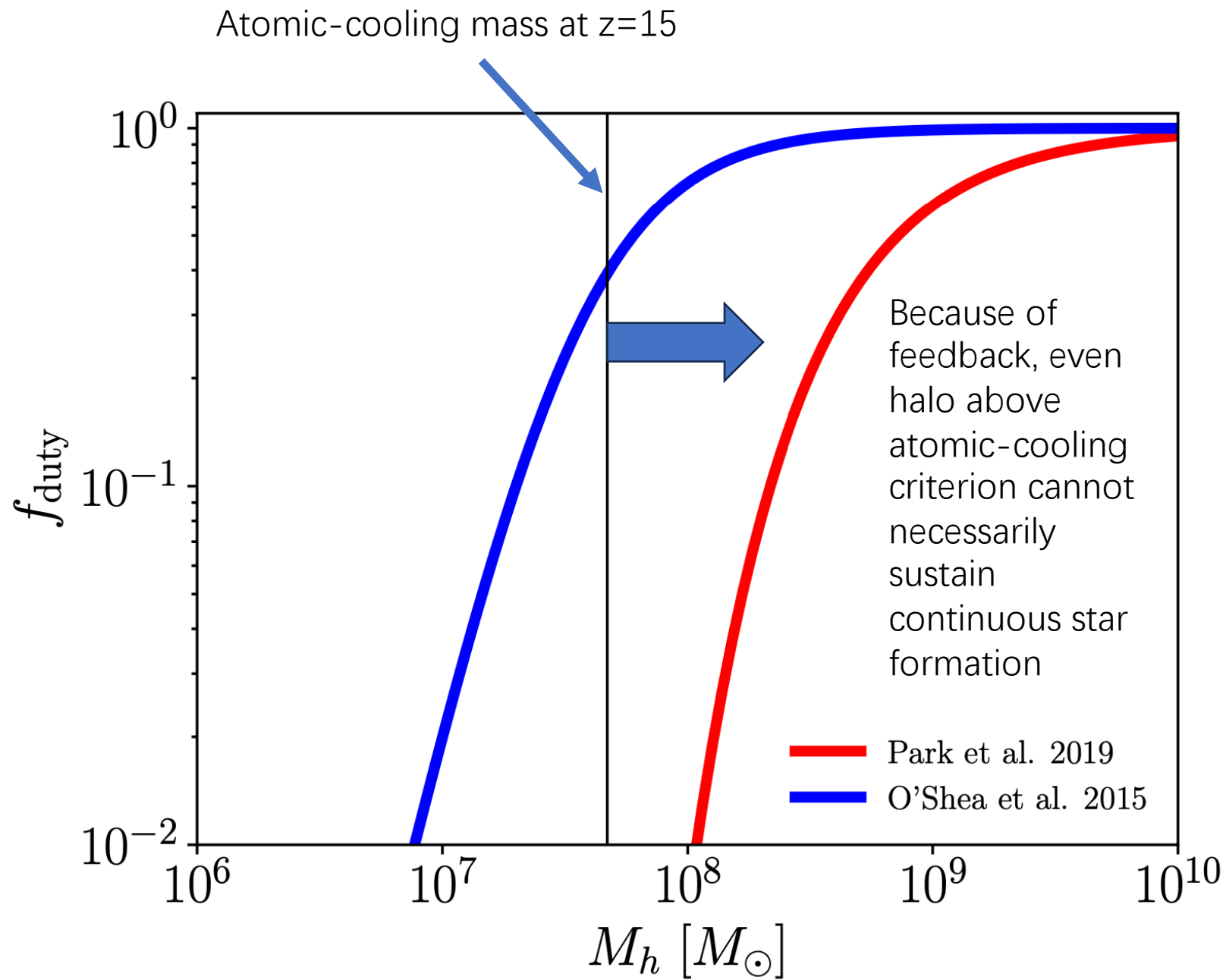
Duty-cycle: for small dark matter halos, only a small fraction of them can sustain continuous star formation

Park et al. 2019

$$f_{\text{duty}}(M_h) = \exp\left(-\frac{M_{\text{turn}}}{M_h}\right) \quad M_{\text{turn}} = 5 \times 10^8 M_{\odot}.$$

O'Shea et al. 2015

$$f_{\text{duty}} = \left[1 + (2^{\alpha/3} - 1) \left(\frac{M_h}{M_c}\right)^{-\alpha}\right]^{-3/\alpha} \quad M_c = 6 \times 10^7 M_{\odot}, \alpha = 1.5$$



The UV luminosity

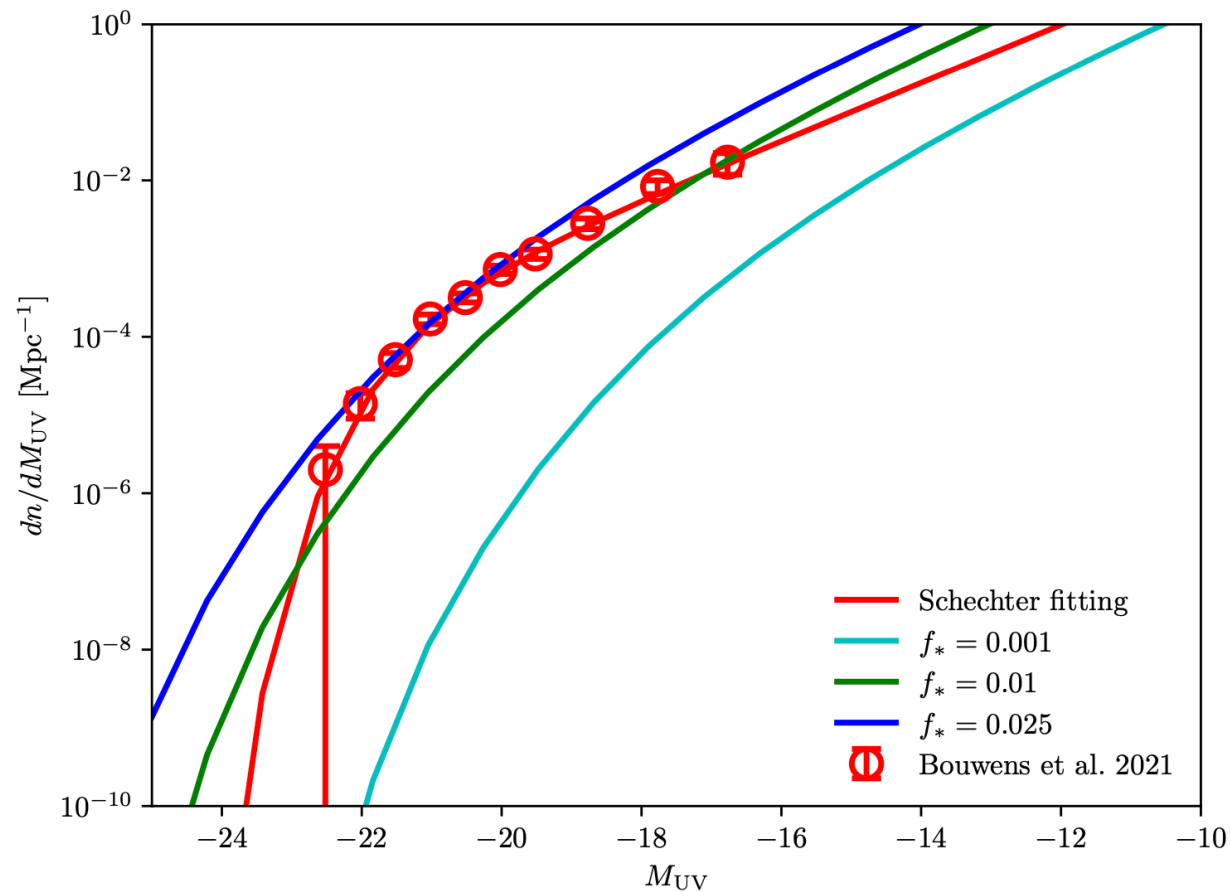
$$\begin{aligned} L_{\text{UV}}(M_h, z) &\approx \frac{1}{\mathcal{K}_{\text{UV}}} f_*(M_h, z) \frac{\Omega_b}{\Omega_m} \frac{dM_h(M_h, z)}{dt} \\ &\approx \frac{1}{\mathcal{K}_{\text{UV}}} f_*(M_h, z) \frac{\Omega_b}{\Omega_m} \frac{M_h}{t_{\text{SF}}} \end{aligned}$$

The typical time scale for star formation, t_{SF} , is generally about 10% of the Hubble time-scale.

One can also use the accretion rate for halo growth fitted from numerical simulations (McBride et al. (2009)),

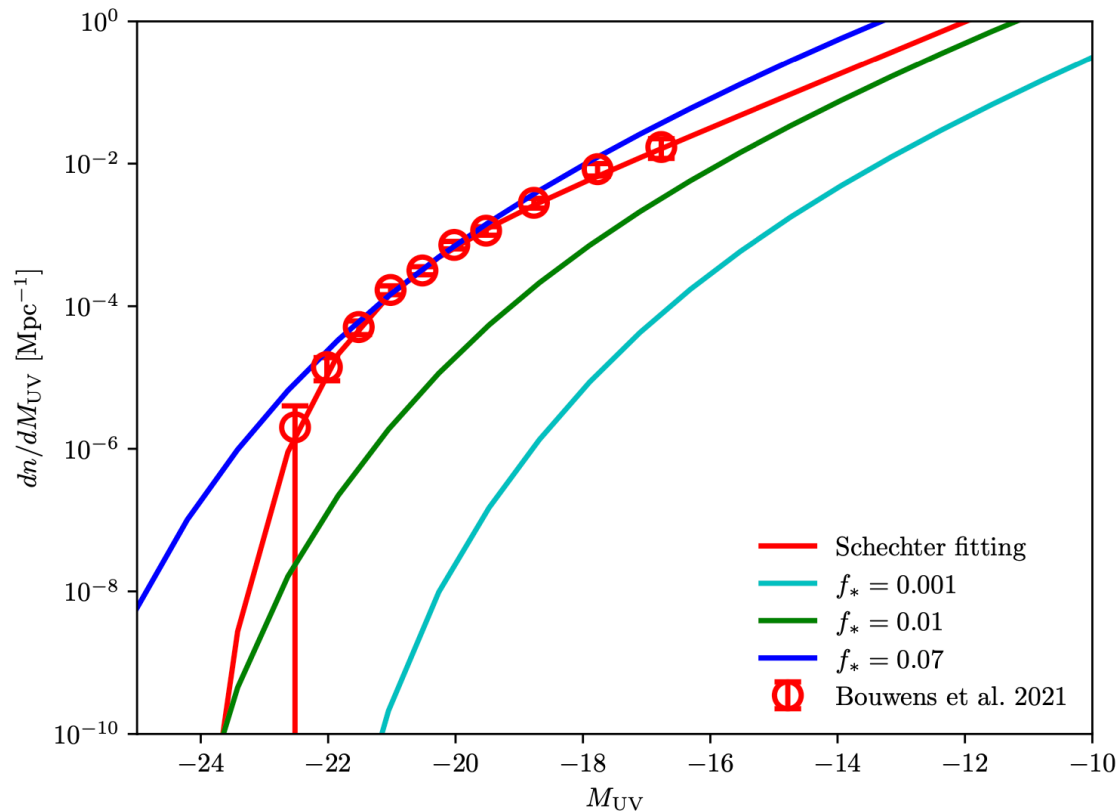
$$\frac{dM_h(M_h, z)}{dt} = 24.1 \left(\frac{M_h}{10^{12} M_\odot} \right)^{1.094} \times (1 + 1.75z) \sqrt{\Omega_m (1 + z)^3 + \Omega_\Lambda} \quad [M_\odot \text{yr}^{-1}].$$

If we set $f_*(M_h, z) = \text{const}$,
we cannot reproduce the slope of the observed UV LF.



$$\begin{aligned} \text{SFR} &= f_* \frac{\Omega_b}{\Omega_m} \frac{dM_h}{dt} \\ &= f_* \frac{\Omega_b}{\Omega_m} \frac{M_h}{0.1 t_H(z)} \end{aligned}$$

If we set $f_*(M_h, z) = \text{const}$,
we cannot reproduce the slope of the observed UV LF.



$$\begin{aligned} \text{SFR} &= f_* \frac{\Omega_b}{\Omega_m} \frac{dM_h}{dt} \\ &= f_* \frac{\Omega_b}{\Omega_m} 24.1 \left(\frac{M_h}{10^{12} M_\odot} \right)^{1.094} \times (1 + 1.75z) \sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda} \quad [M_\odot \text{yr}^{-1}]. \end{aligned}$$

A popular scenario:

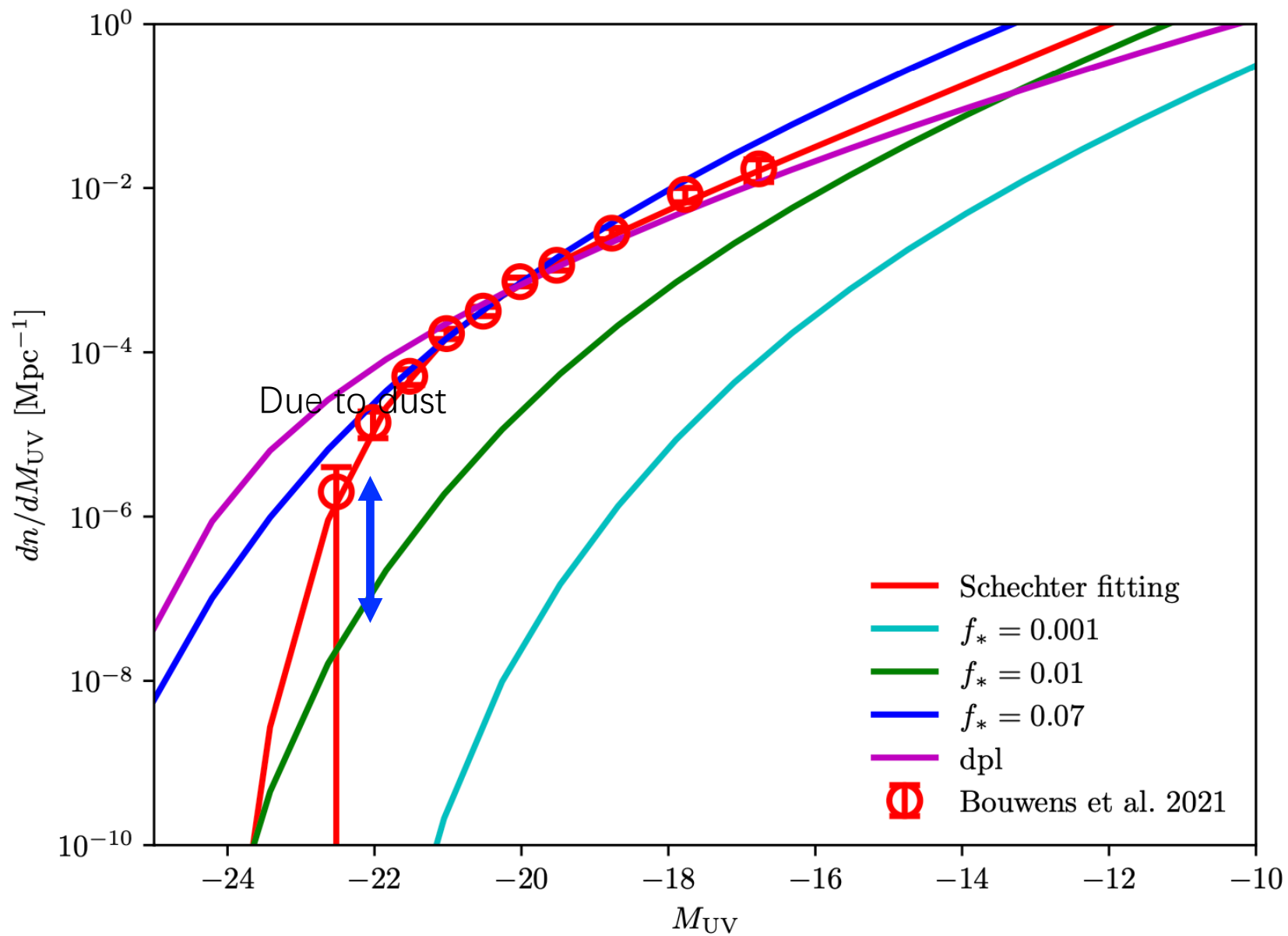
At high- z , the star formation efficiency depends on halo mass, however independent of redshift, the evolution of star formation rate is purely ascribed to the halo growth, therefore:

$$L_{\text{UV}}(M_h, z) \approx \frac{1}{\mathcal{K}_{\text{UV}}} f_*(M_h) \frac{\Omega_b}{\Omega_m} \frac{dM_h(M_h, z)}{dt}$$

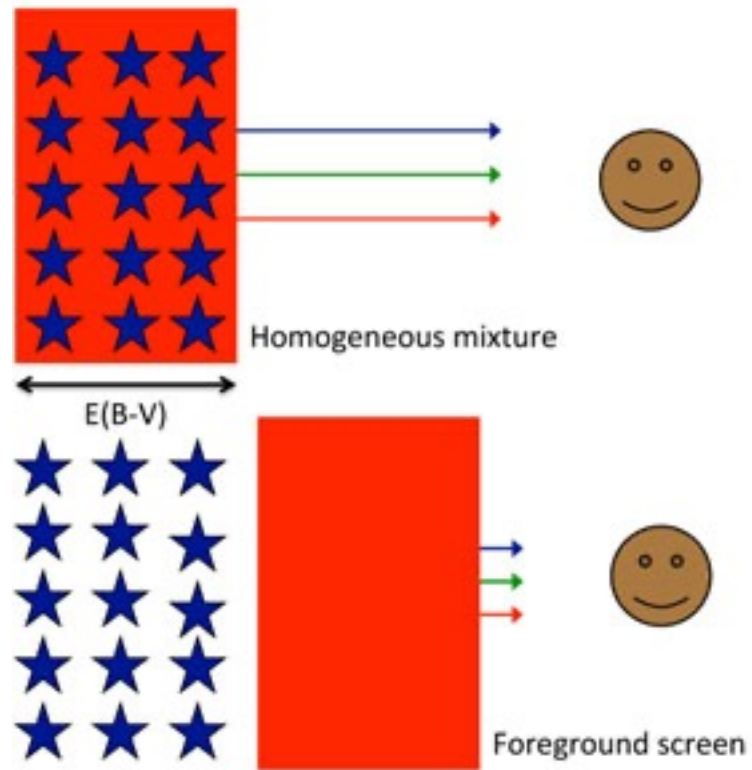
A widely used analytical form for $f_*(M_h)$ is the double power law form, that is

$$f_*(M_h) = \frac{2f_0}{\left(\frac{M_h}{M_p}\right)^{-\gamma_{\text{lo}}} + \left(\frac{M_h}{M_p}\right)^{\gamma_{\text{hi}}}},$$

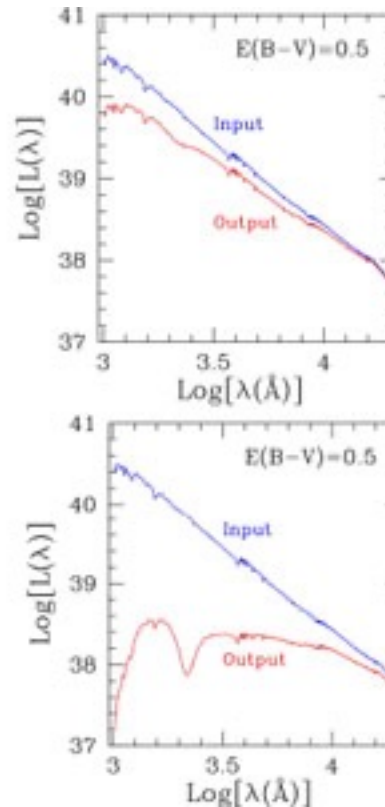
There are four parameters, f_0 , M_p , γ_{lo} and γ_{hi} , that can be derived from observed UV LFs. For example, using the observations at $z \sim 5$, one derive $f_0 = 0.14$, $M_p = 10^{12.3} M_{\odot}$, $\gamma_{\text{lo}} = 0.46$ and $\gamma_{\text{hi}} = 0.82$.



Dust attenuation, mainly in UV band:



Calzetti (2012)

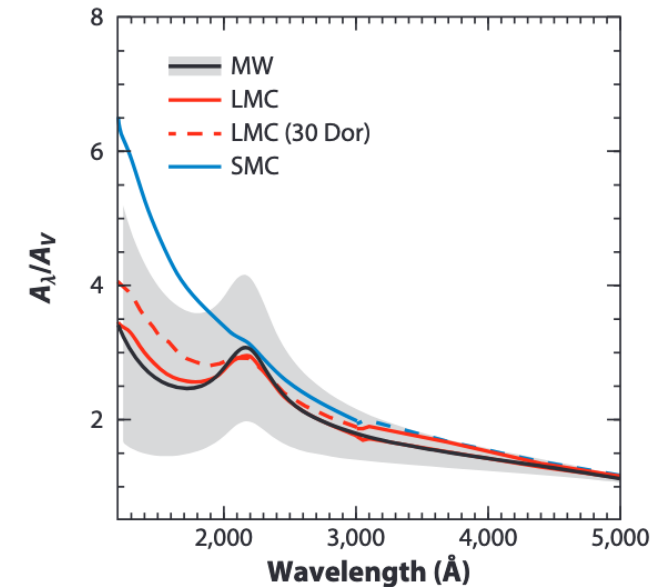


Dust attenuation: the difference between the observed and intrinsic magnitude

$$A_{\lambda} = m_{\lambda}^{\text{obs}} - m_{\lambda}^{\text{intrinsic}}.$$

Dust attenuation curve:

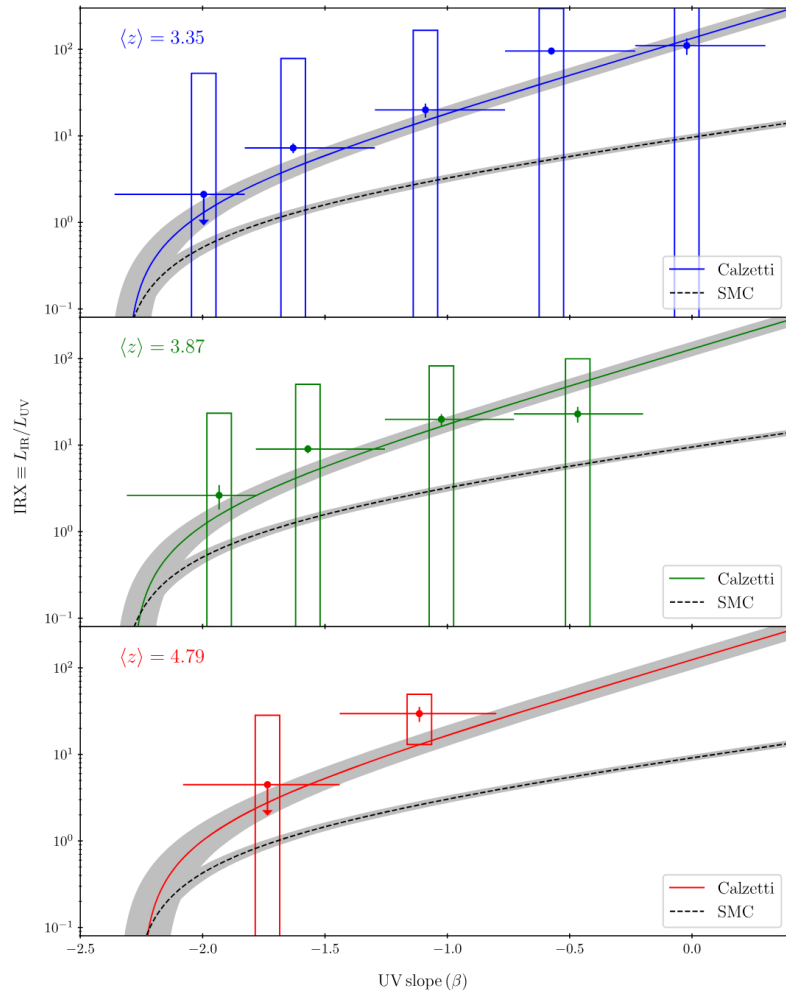
A_{λ} vs. λ , normalized at 5500 Å (A_V).



The intrinsic UV absolute magnitude is derived by minus the dust attenuation from the observed UV absolute magnitude,

$$M_{\text{UV}} = M_{\text{UV}}^{\text{obs}} - A_{\text{UV}},$$

where the dust attenuation A_{UV} is derived from the infrared excess-UV spectral slope relation (IRX – β),



Koprowski et al. (2018)

IRX_{UV} is tightly related to A_{UV}

The relation is fitted linearly (Meurer, Heckman & Calzetti 1999),

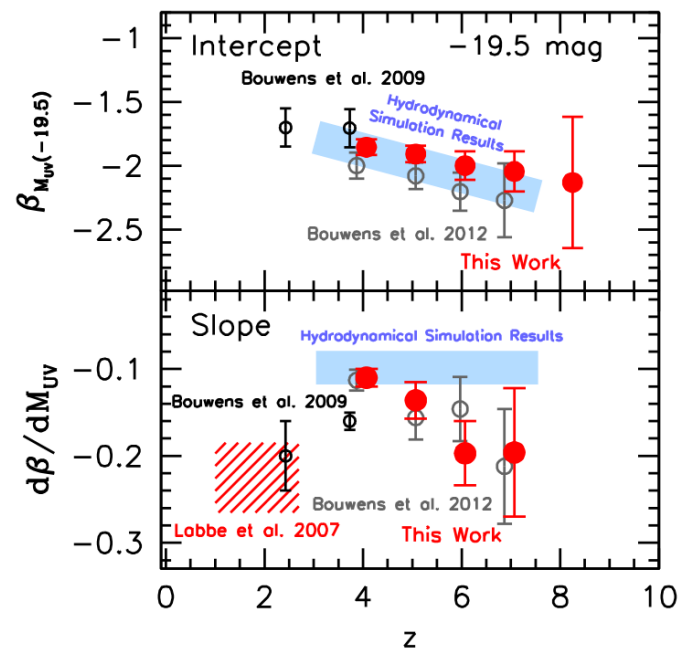
$$A_{UV} = C_0\beta + C_1 \quad (A_{UV} \geq 0).$$

Meurer et al. (1999) gave $C_0 = 1.99$, $C_1 = 4.43$. Koprowski et al. (2018) gave $C_0 = 2.10$ and $C_1 = 4.85$.

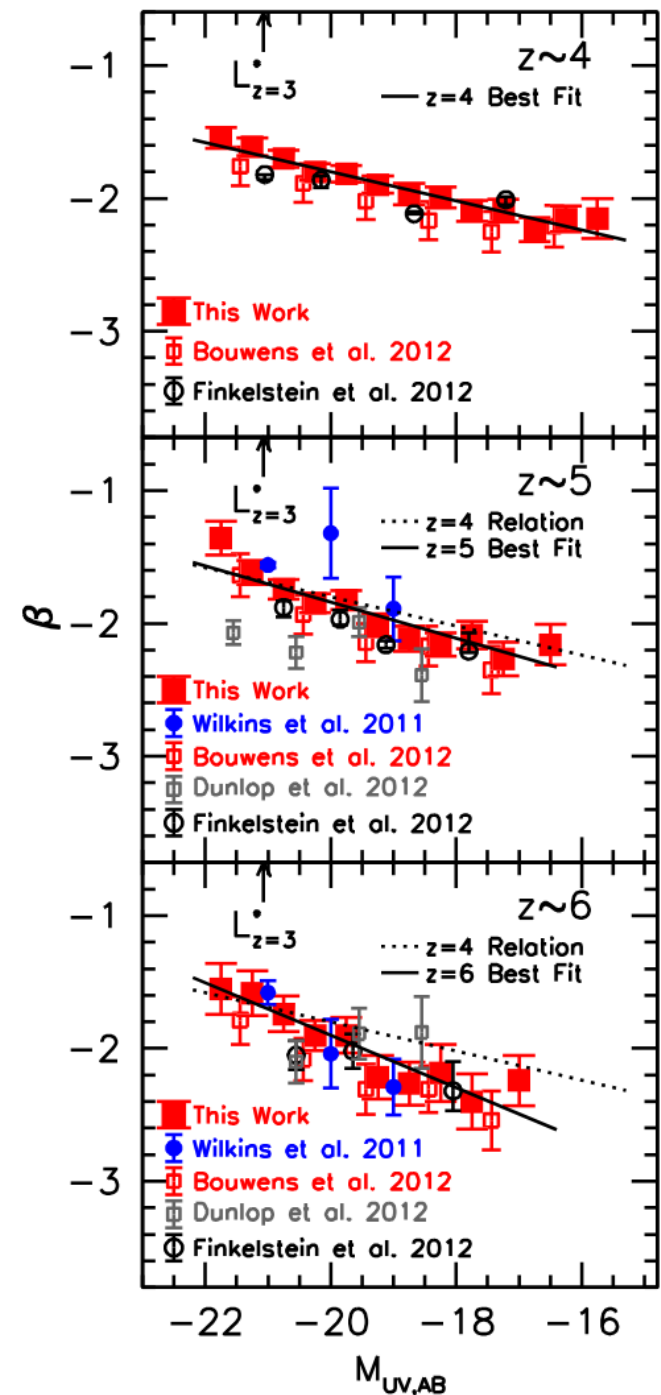
While the UV spectral slope also follow a linear relation

$$\beta = \beta_0 + \frac{d\beta}{dM_0}(M_{UV}^{obs} - M_0).$$

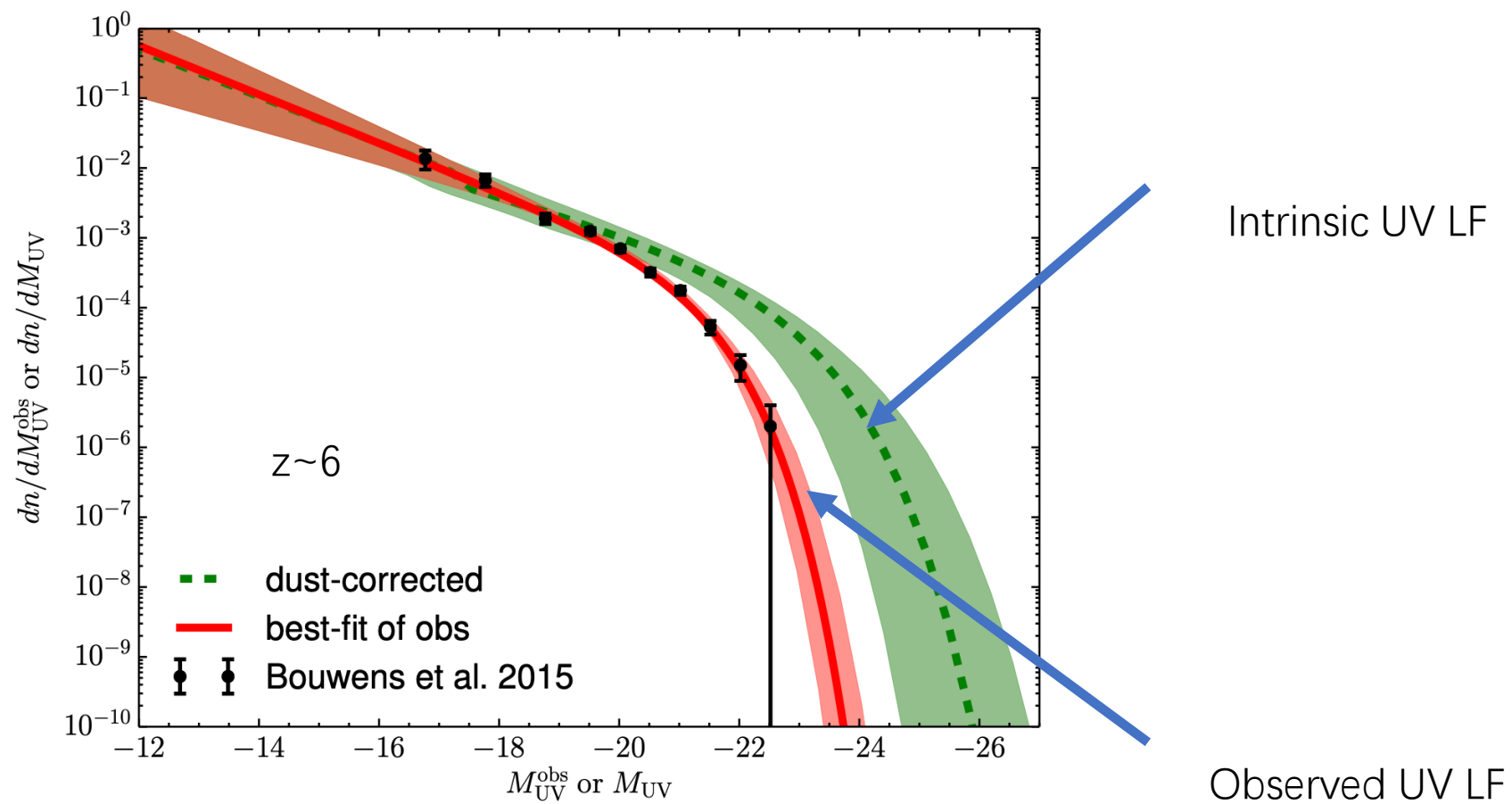
Bouwens et al. (2014) derived $\beta_0 = -2.00$ and $d\beta/dM_0 = -0.20$, $M_0 = -19.5$ at $z \sim 6$.

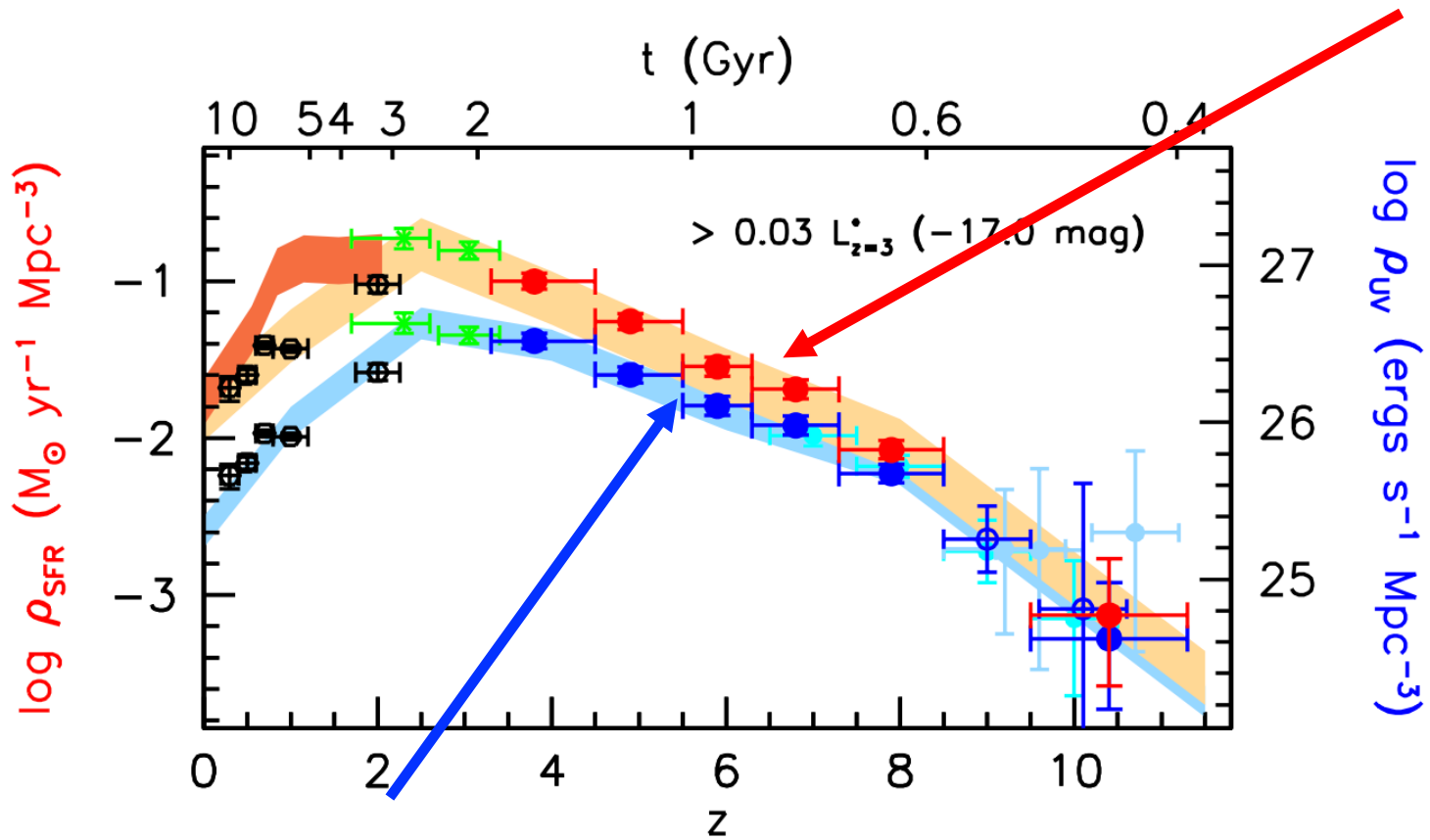


Bouwens et al. 2014



Even for high- z galaxies, the bright ones are heavily dust obscured.





Correcting the dust attenuation

At $z > \sim 8$, dust attenuation has negligible influence on the global star formation history

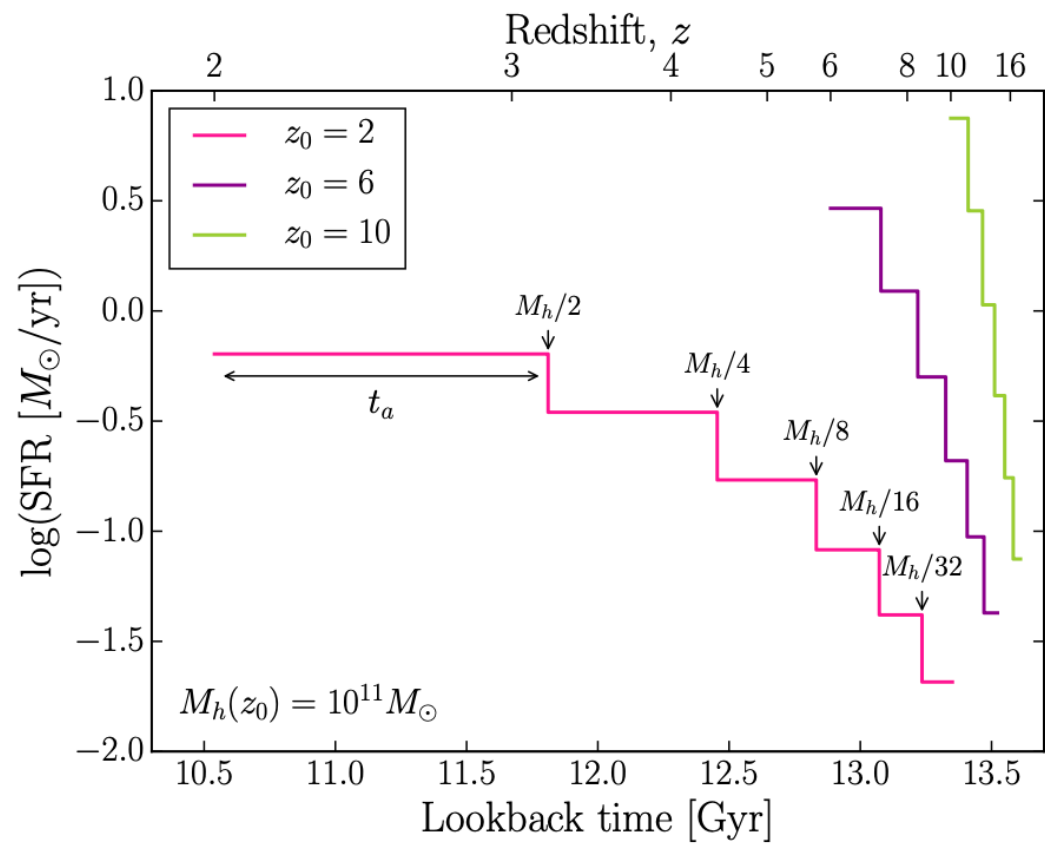
Bouwens et al. 2015

Alternatively, one can directly derive f_* as a function of M_h by matching the observed UV LF with the derived form based on the following relation:

$$L_{\text{UV}}(M_h, t) = \int_t^\infty s_{\text{UV}}(t - t') f_*(M_h(t')) \frac{\Omega_b}{\Omega_m} \frac{dM_h(t')}{dt'} \\ \approx \sum_{i=1}^N s_{\text{UV}} \left(\sum_{i=1}^N \Delta t_i \right) f_*(M_h/2^i) \frac{\Omega_b}{\Omega_m} \frac{M_h}{2^i \Delta t_i}$$

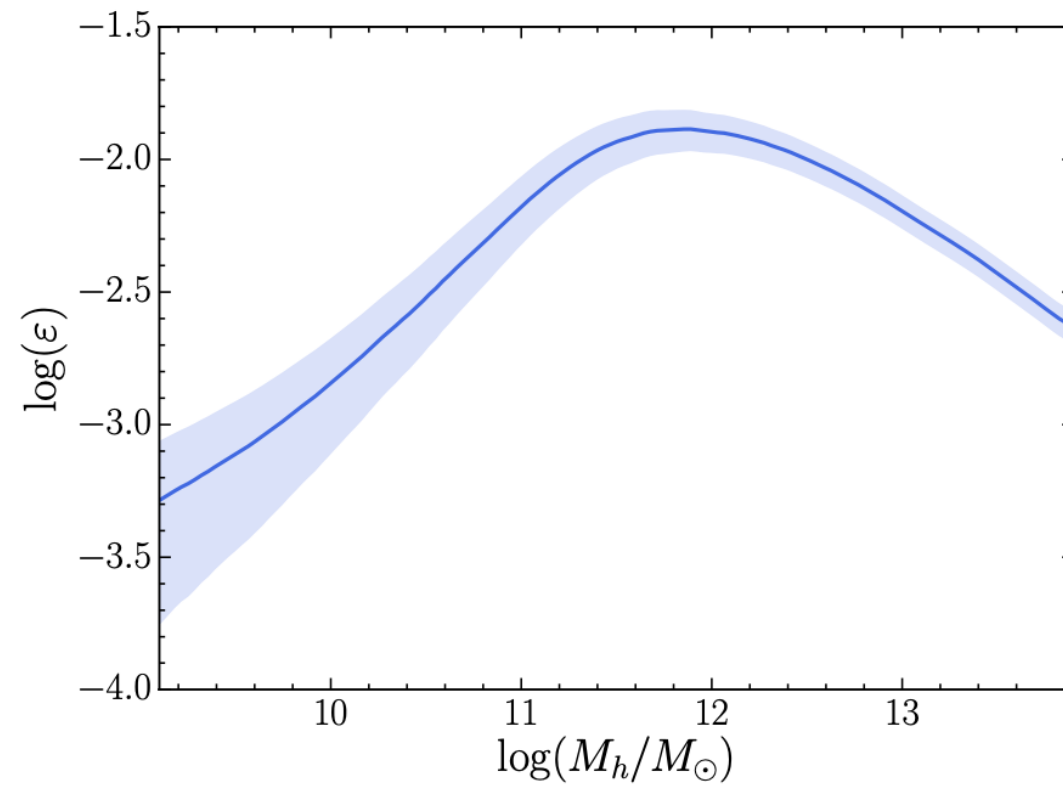
where Δt_i is the timescale for the halo growth $M_h/2^i \rightarrow M_h/2^{i-1}$, derived from halo growth model.

The SFR history based on halo growth:



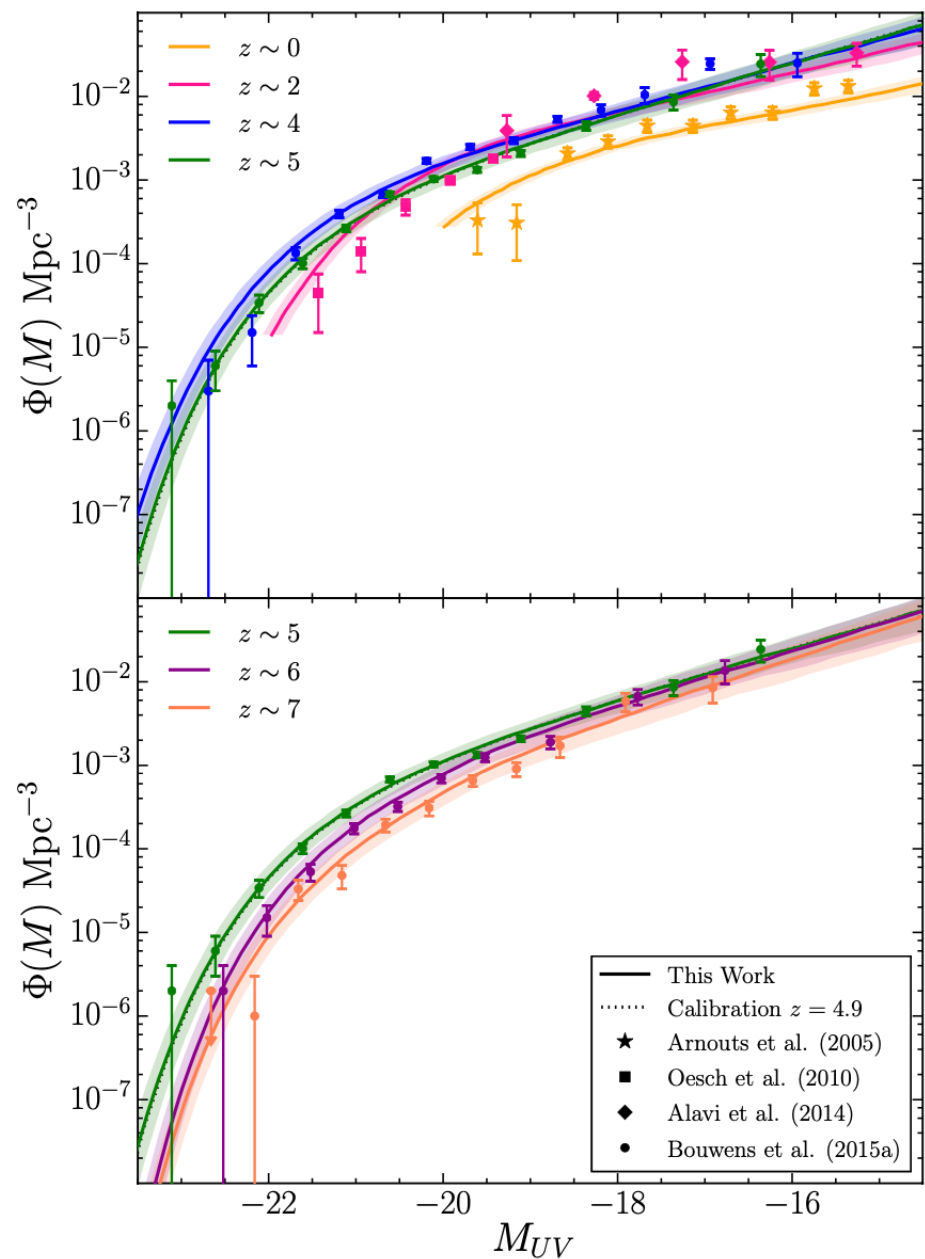
Mason et al. 2015

The derived star formation efficiency:

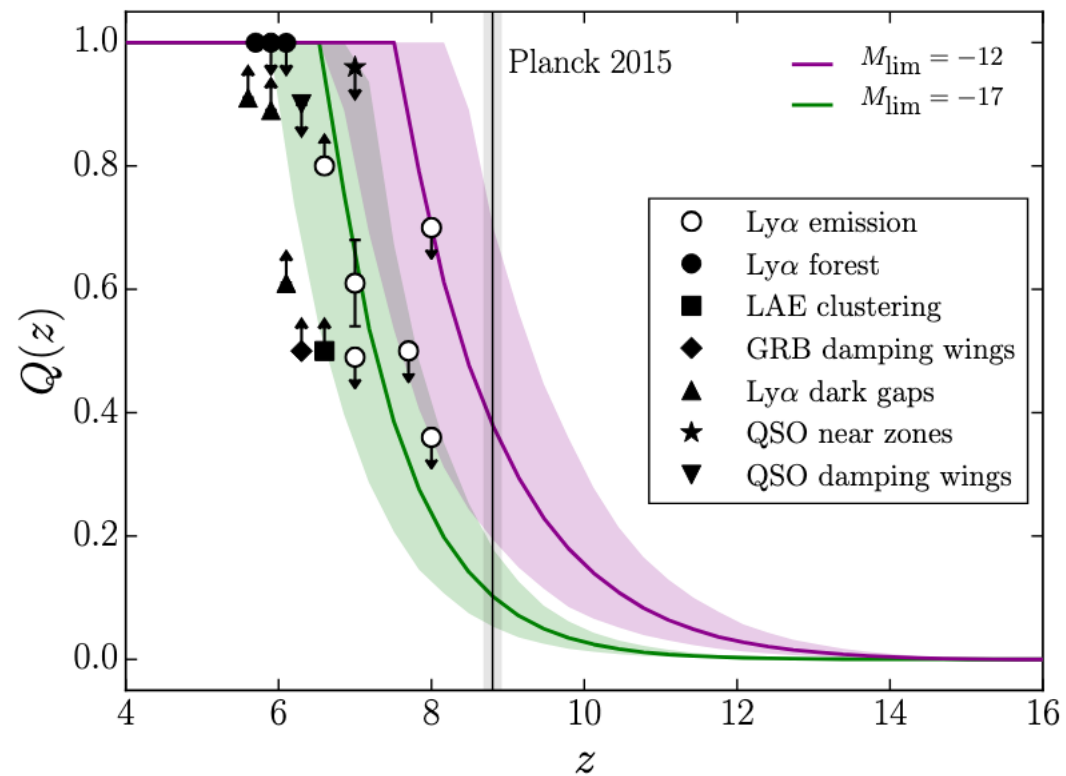


Similar to double power law form

Predicted UV LFs:



Predicted reionization history **under the constraints of the observed UV LFs:**

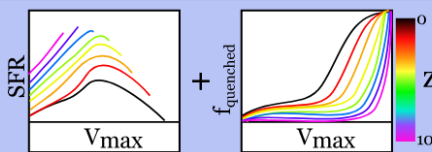


Empirical model for galaxy formation : UniverseMachine

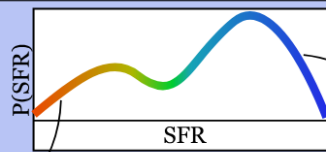
<https://bitbucket.org/pbehroozi/universemachine>

Markov Chain Monte Carlo

1. Choose SFR - $v_{\max}$ and $f_{\text{quenched}}(v_{\max})$ relations from parameter space.



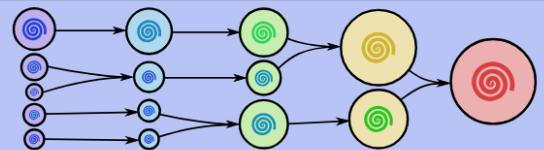
2. This gives the probability distribution of SFRs for any chosen halo $v_{\max}$ and redshift.



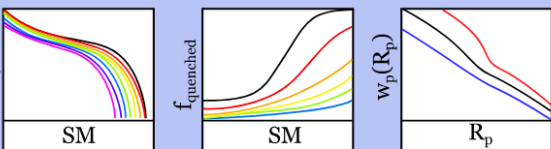
3. Map these SFR distributions to halos such that earlier-forming halos get lower SFRs.



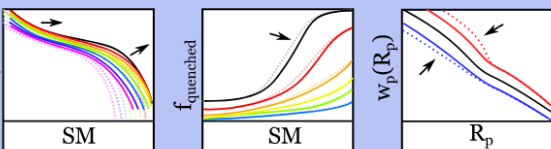
4. Integrate SFRs along halo merger trees to infer galaxy growth.



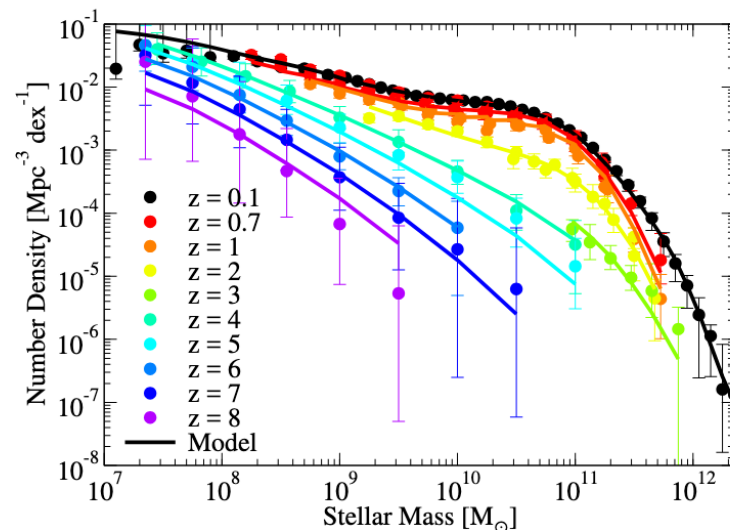
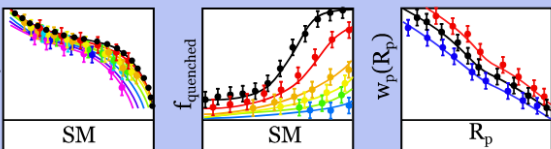
5. Predict observables: SMFs, quenched fracs., correl. funcs. ϕ for SF, quenched galaxies, etc.



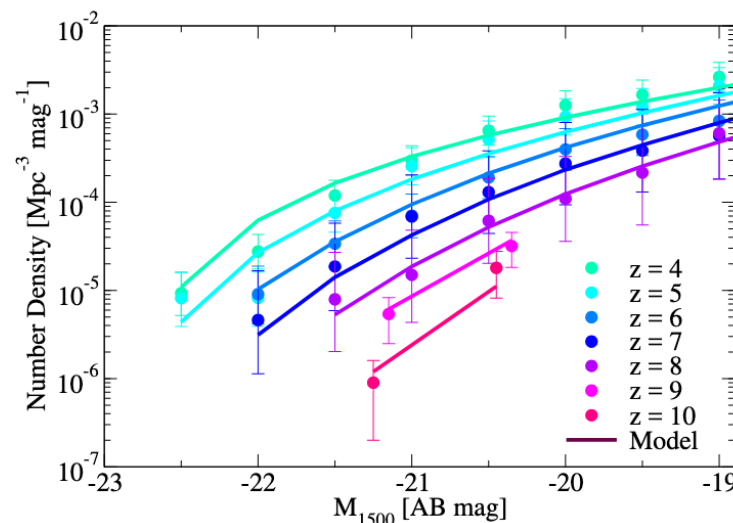
6. Apply effects to simulate observational errors and biases.



7. Compare to data and calculate likelihood of the chosen parameters.



Stellar mass function



Luminosity function

Behroozi et al. 2019

Interpreting the star formation excess observed by JWST:

1) Enhanced SFE at $z > \sim 10$

$$f_*(M_h) = \frac{2f_0}{\left(\frac{M_h}{M_p}\right)^{-\gamma_{\text{lo}}} + \left(\frac{M_h}{M_p}\right)^{\gamma_{\text{hi}}}},$$

Model B:

$$f_0 = 0.14$$

$$M_p = 10^{12.3} M_{\odot}$$

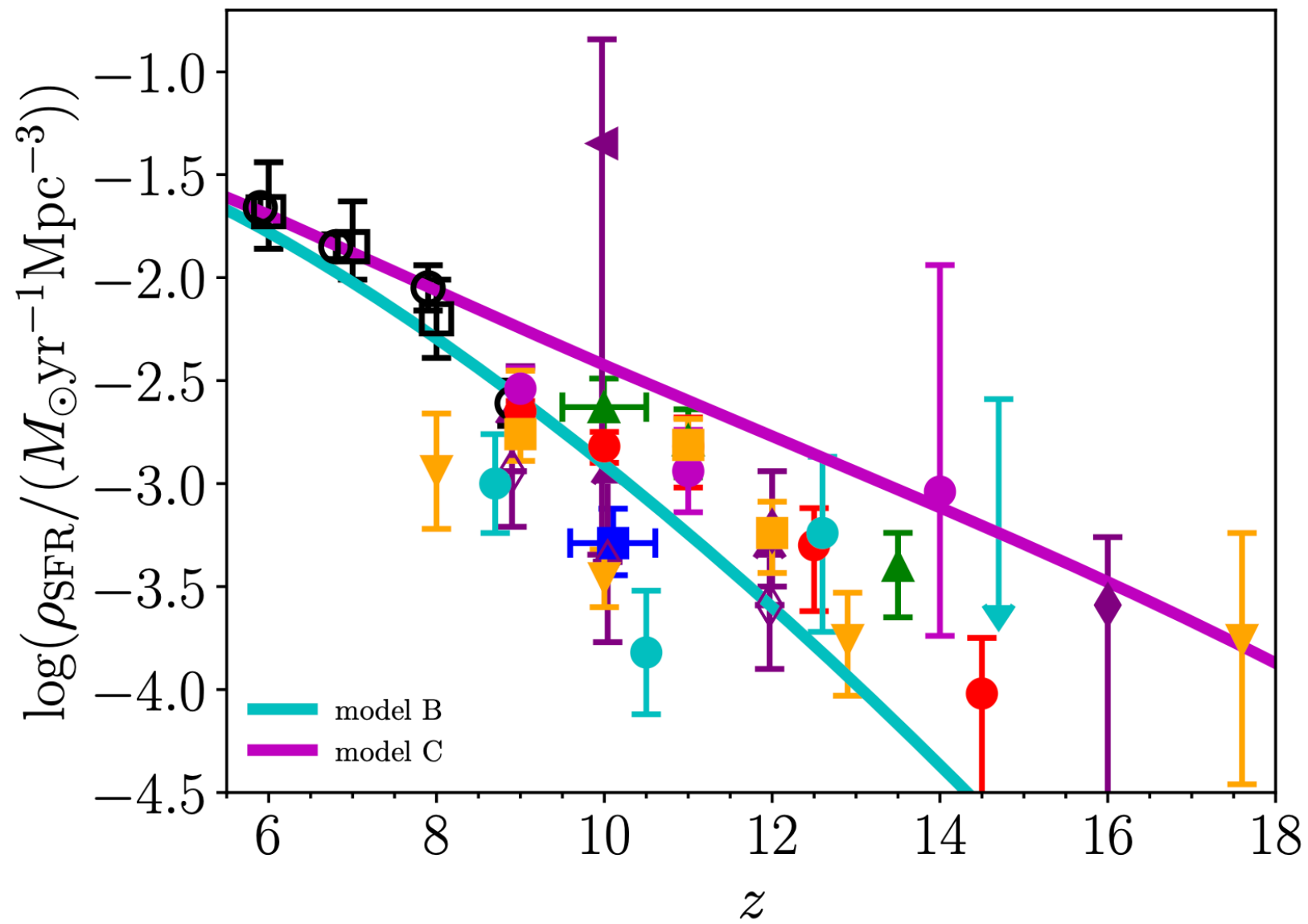
$$\gamma_{\text{lo}} = 0.46$$

$$\gamma_{\text{hi}} = 0.82$$



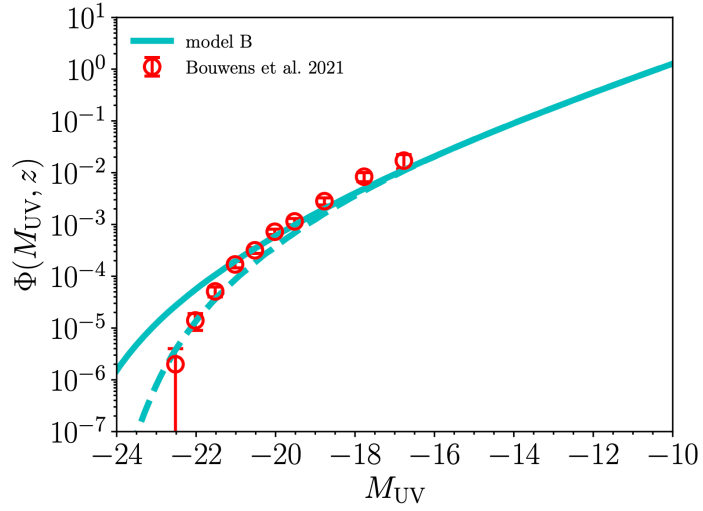
Model C:

$$\gamma_{\text{lo}} = \frac{0.46}{0.5[(1+z)/11]^3 + 1}$$

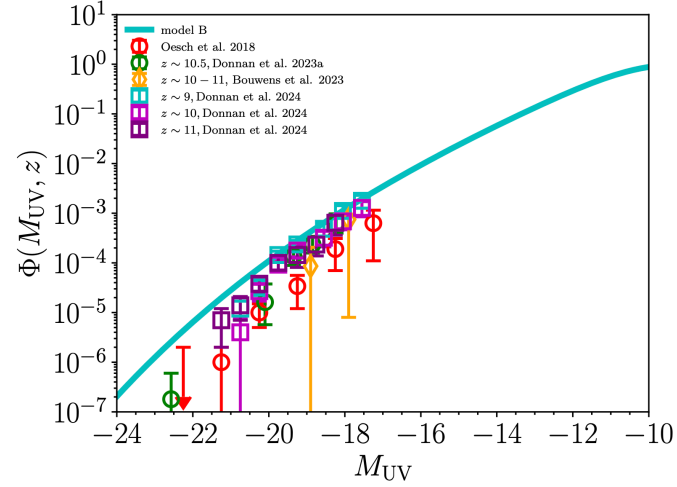


The UV LFs:

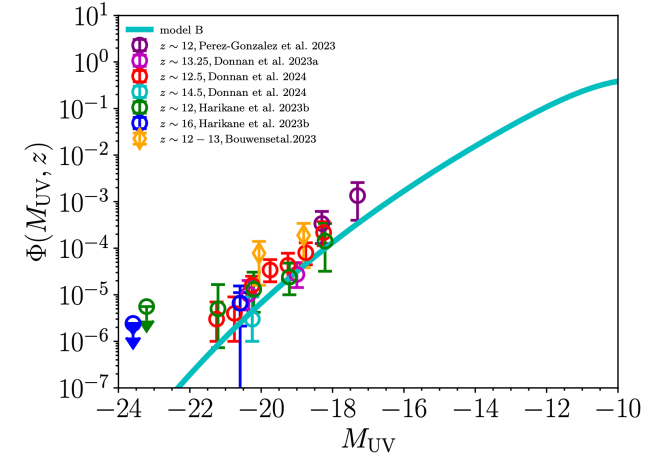
$z \sim 6$



$z \sim 10$

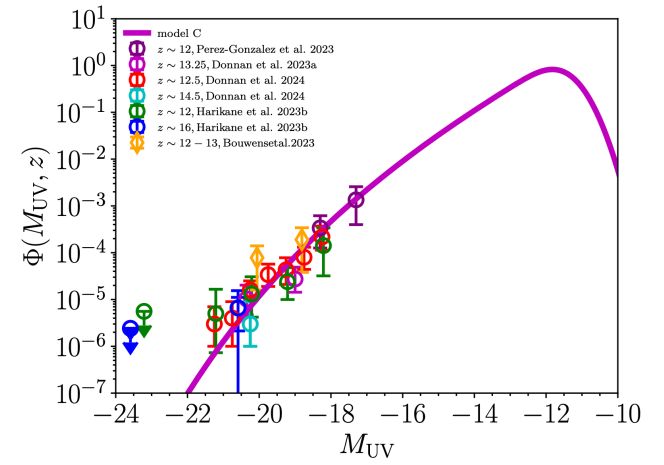
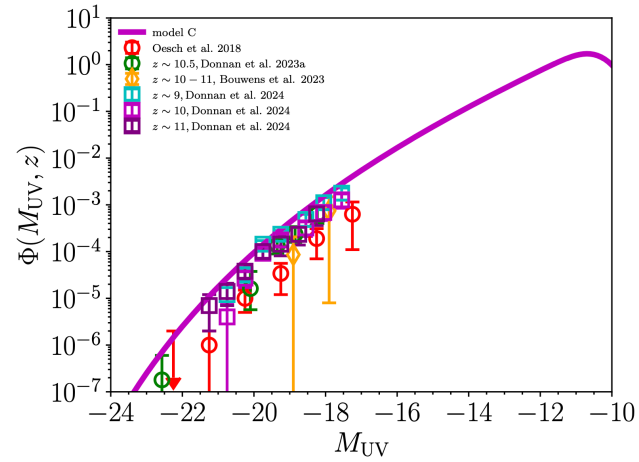
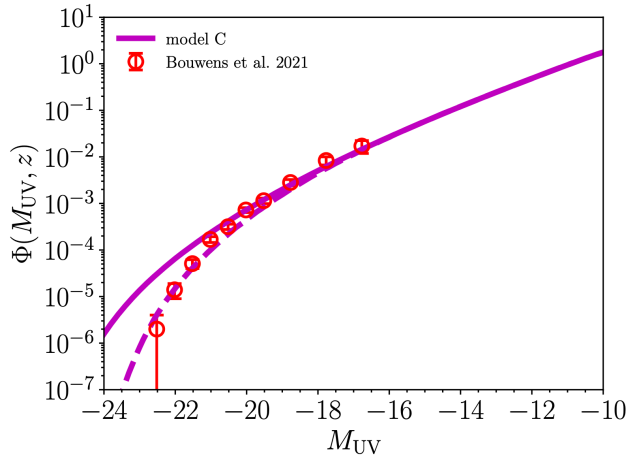


$z \sim 13.5$



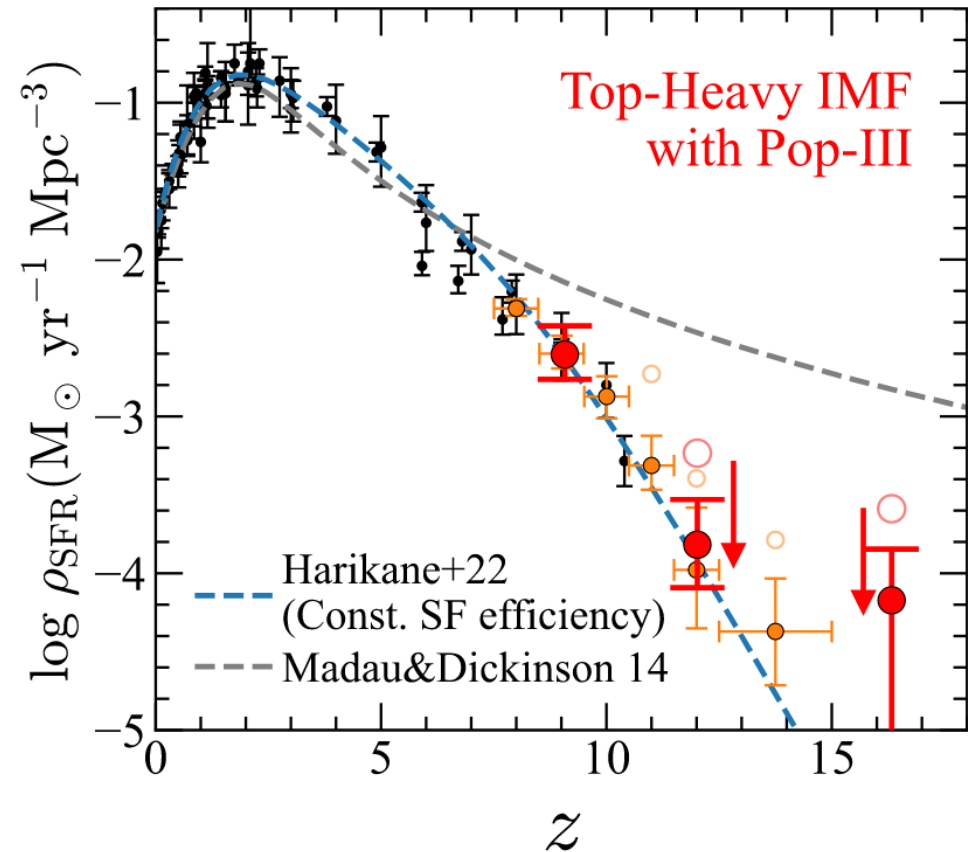
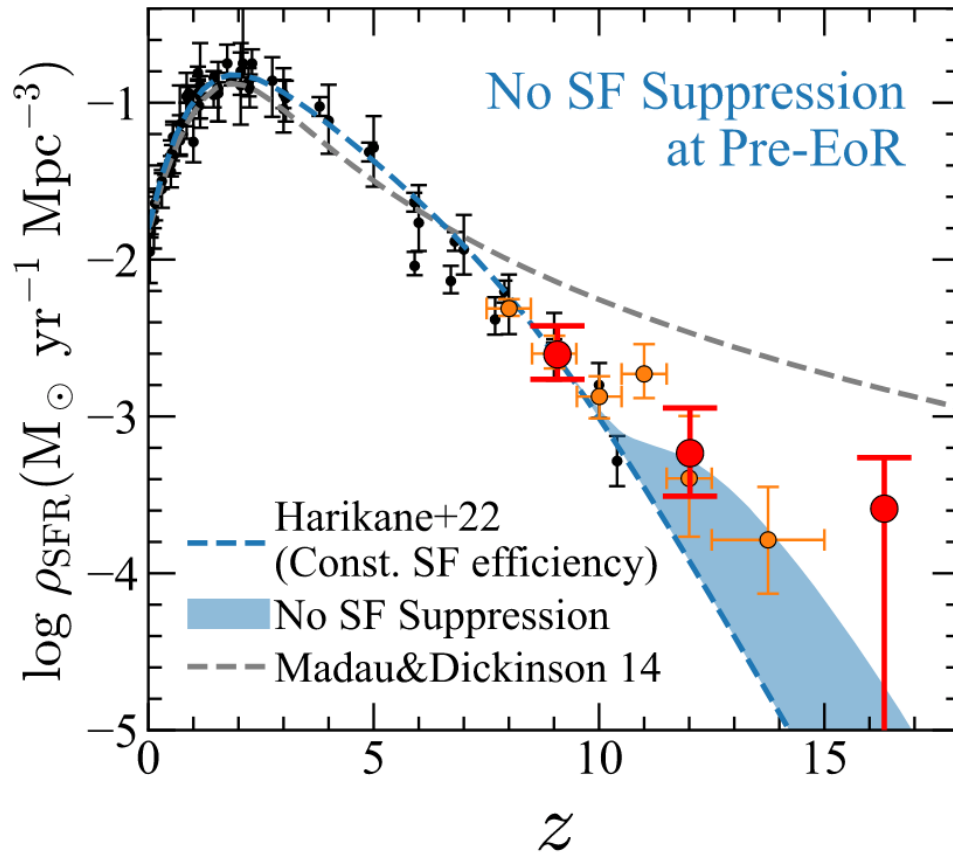
Constant SFE

Enhanced SFE at $z > \sim 10$



2) JWST discovered more than expected high- z galaxies: top-heavy IMF?

The SFE does not change, however stars are brighter per unit mass



3) No need to enhance the SFE at higher redshifts

No evidence (yet) for increased star-formation efficiency at early times

C. T. Donnan^{ib},[★] J. S. Dunlop, R. J. McLure, D. J. McLeod^{ib} and F. Cullen^{ib}

Institute for Astronomy, University of Edinburgh, Royal Observatory, Edinburgh EH9 3HJ, UK

Predicted UV LFs

$$\frac{M_*}{M_h} = \epsilon(M_h) f_b,$$

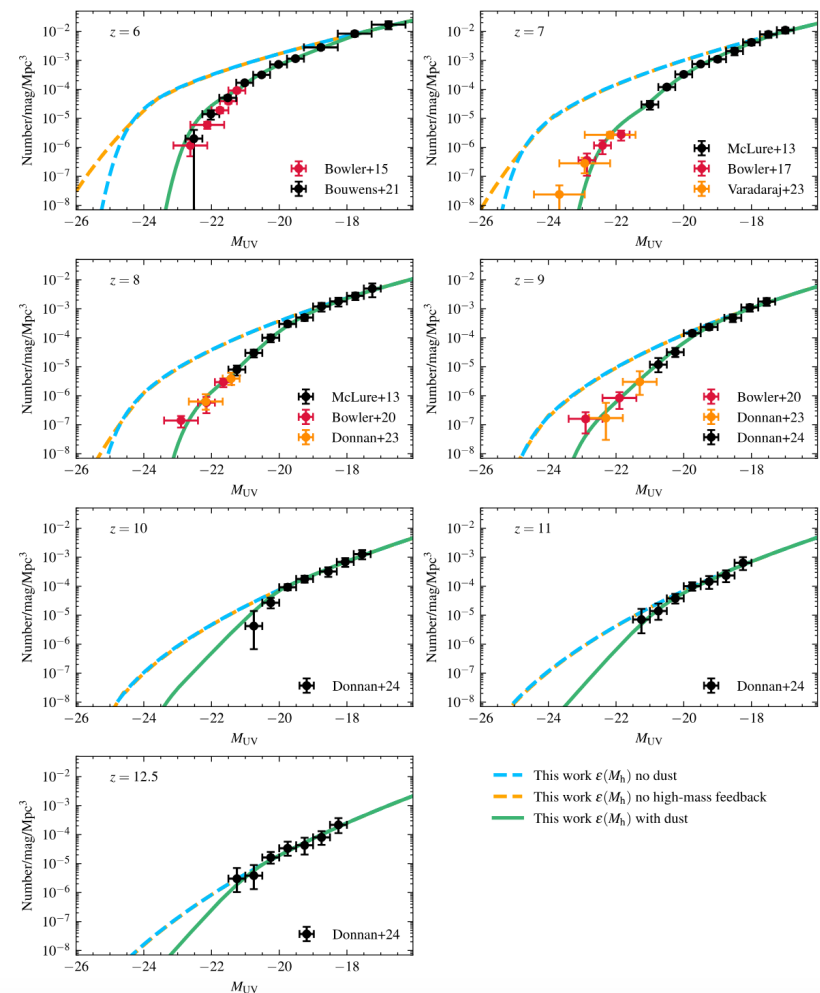
$$\epsilon(M_h) = 2\epsilon_0 \left[\left(\frac{M_h}{M_c} \right)^{-\beta} + \left(\frac{M_h}{M_c} \right)^{\gamma} \right]^{-1},$$

use $(\epsilon_0, M_c/M_\odot, \beta, \gamma) = (0.16, 10^{11.7}, 0.9, 0.65)$,

$$M_{UV} = M_{UV,*} - 2.5 [\log_{10}(M_*/M_\odot) - 9],$$



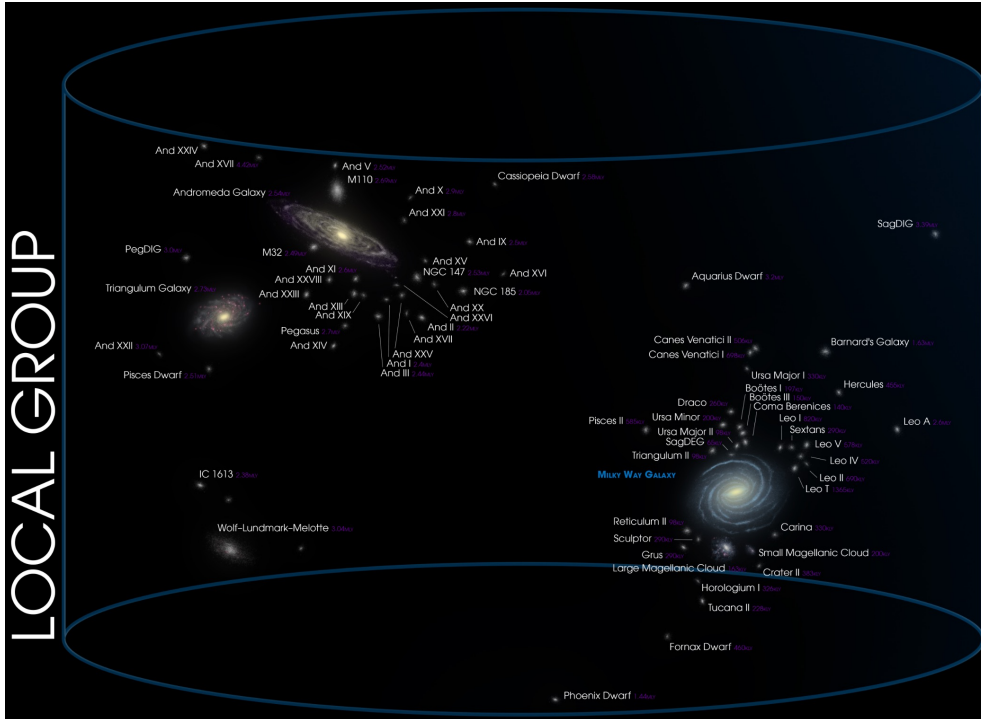
Predict the UV LFs from constrained SMF model



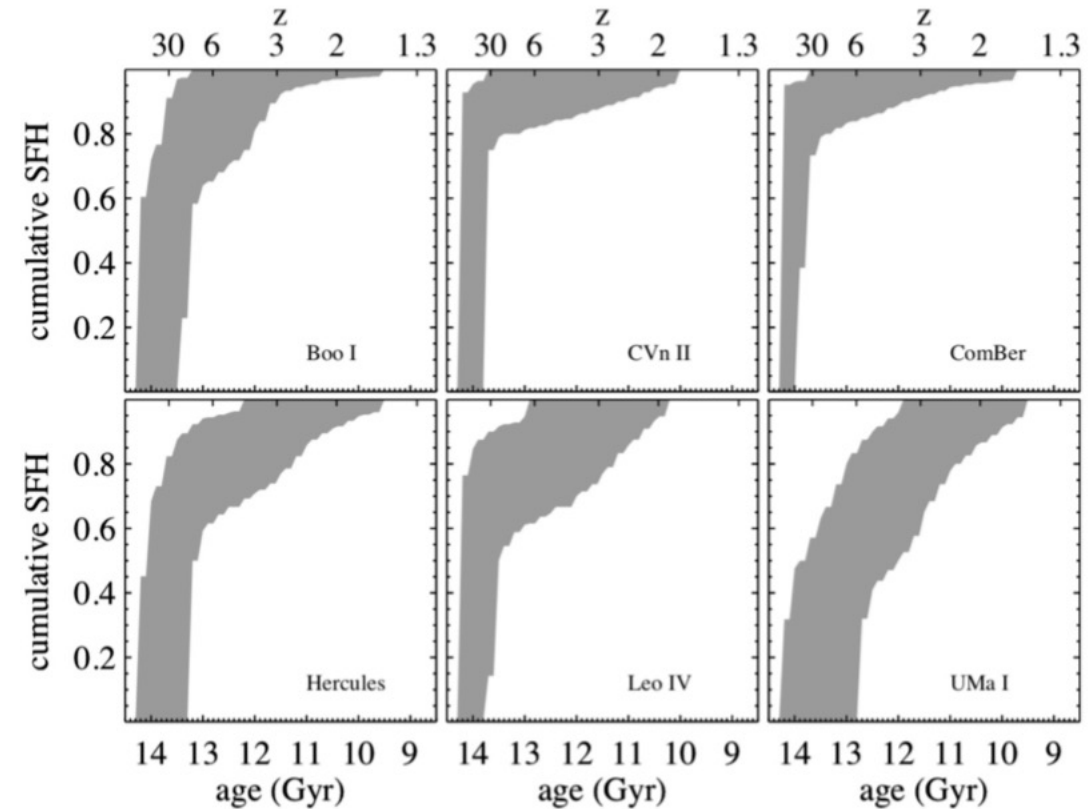
Predictions are consistent with observations, without boosting the SFE at higher redshifts

Dwarf galaxies are frozen first galaxies?

- There are low-luminosity dwarf galaxies in our Milky Way;
- After EoR, the IGM is ionized/heated, hard to form small galaxies;
- Dwarf galaxies formed (very likely) before EoR, fossils of pre-EoR Universe



Star formation history (SFH) if 6 dwarf galaxies:



More than 80% of stars formed before $z > 6$ (Brown et al. 2014)

Exercise 2:

Using the double power law form for star formation efficiency,

$$f_*(M_h) = \frac{2f_0}{\left(\frac{M_h}{M_p}\right)^{-\gamma_{\text{lo}}} + \left(\frac{M_h}{M_p}\right)^{\gamma_{\text{hi}}}},$$

the luminosity scatter

$$P(\log L_{\text{UV}}|M_h)d\log L_{\text{UV}} = \frac{1}{\sqrt{2\pi}\sigma_{\log L}} \exp\left[-\frac{(\log L_{\text{UV}} - \log \bar{L}_{\text{UV}})^2}{2\sigma_{\log L}^2}\right] d\log L_{\text{UV}},$$

where $\sigma_{\log L} = 0.2$, and the duty-cycle

$$f_{\text{duty}} = \left[1 + (2^{\alpha/3} - 1) \left(\frac{M_h}{M_c}\right)^{-\alpha}\right]^{-3/\alpha},$$

where $M_c = 6 \times 10^7 M_{\odot}$, $\alpha = 1.5$, further assume that the ratio between ionizing photons rate and UV luminosity is

$$\frac{\dot{N}_{\text{ion}}}{L_{\text{UV}}} = 10^{25.5} \text{s}^{-1} / (\text{ergs}^{-1} \text{Hz}^{-1}),$$

calculate the emission rate of ionizing photons per unit volume as a function of redshift, from halo mass function.

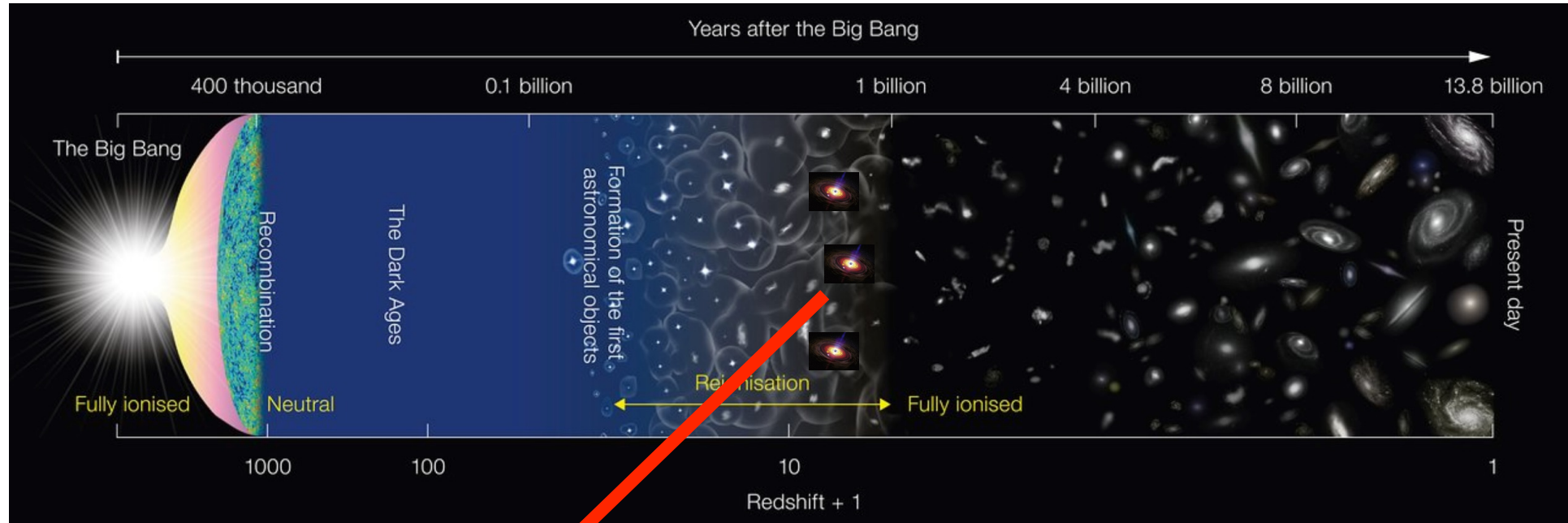
A break of ~15 minutes

A black hole is depicted at the center, surrounded by a glowing accretion disk with orange and red hues. The disk is set against a background of turbulent, glowing blue gas clouds. Several small, distant star-like objects are visible in the black background.

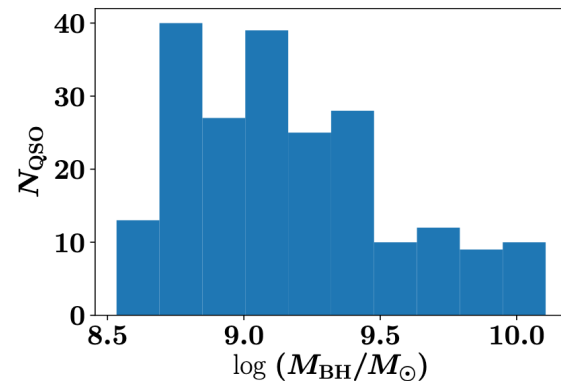
III. First Black Holes

Supermassive black holes (SMBHs) at the high- z Universe:

More than 200 SMBHs with $z > \sim 6$ have been detected



Mass distribution of $z > 6$ SMBHs:



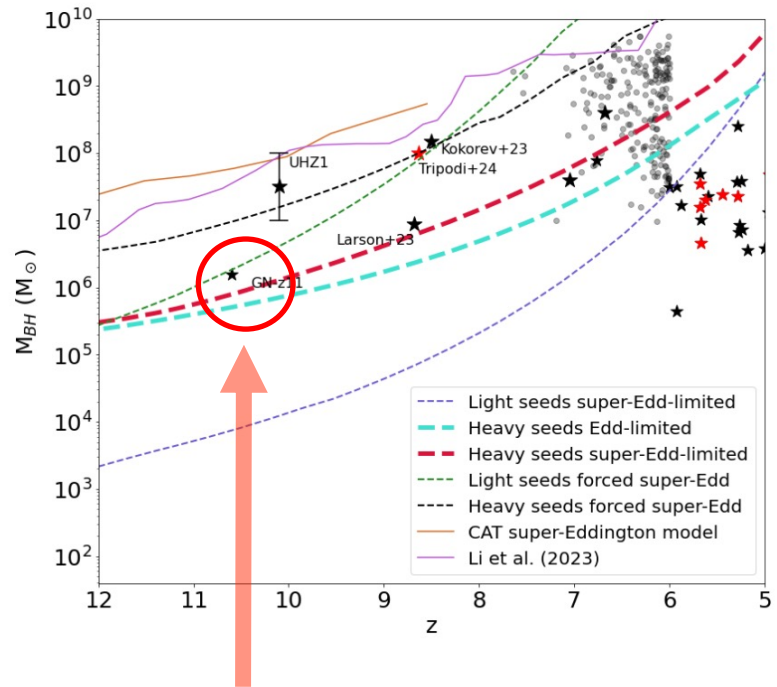
Padmanabhan & Loeb 2023

When the Universe is younger than 1 billion years ($z \gtrsim 6$), BHs are already as massive as $\sim 10^9 - 10^{10} M_{\text{sun}}$

Question: how did they form?

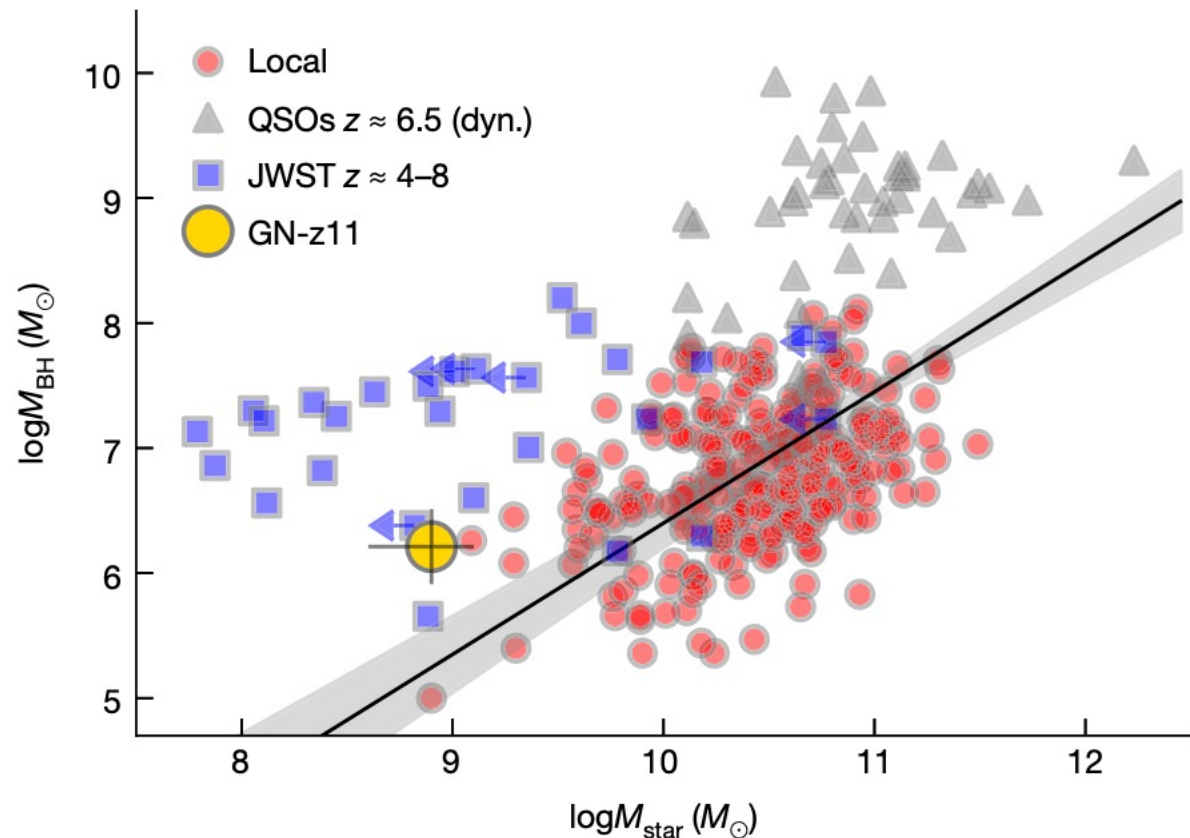
The observed high- z SMBHs

- They generally have BH mass/stellar mass ratio larger than local SMBHs.
- The extreme case: UHZ1, $M_{\text{BH}}/M_{\text{*}} \sim 1$.



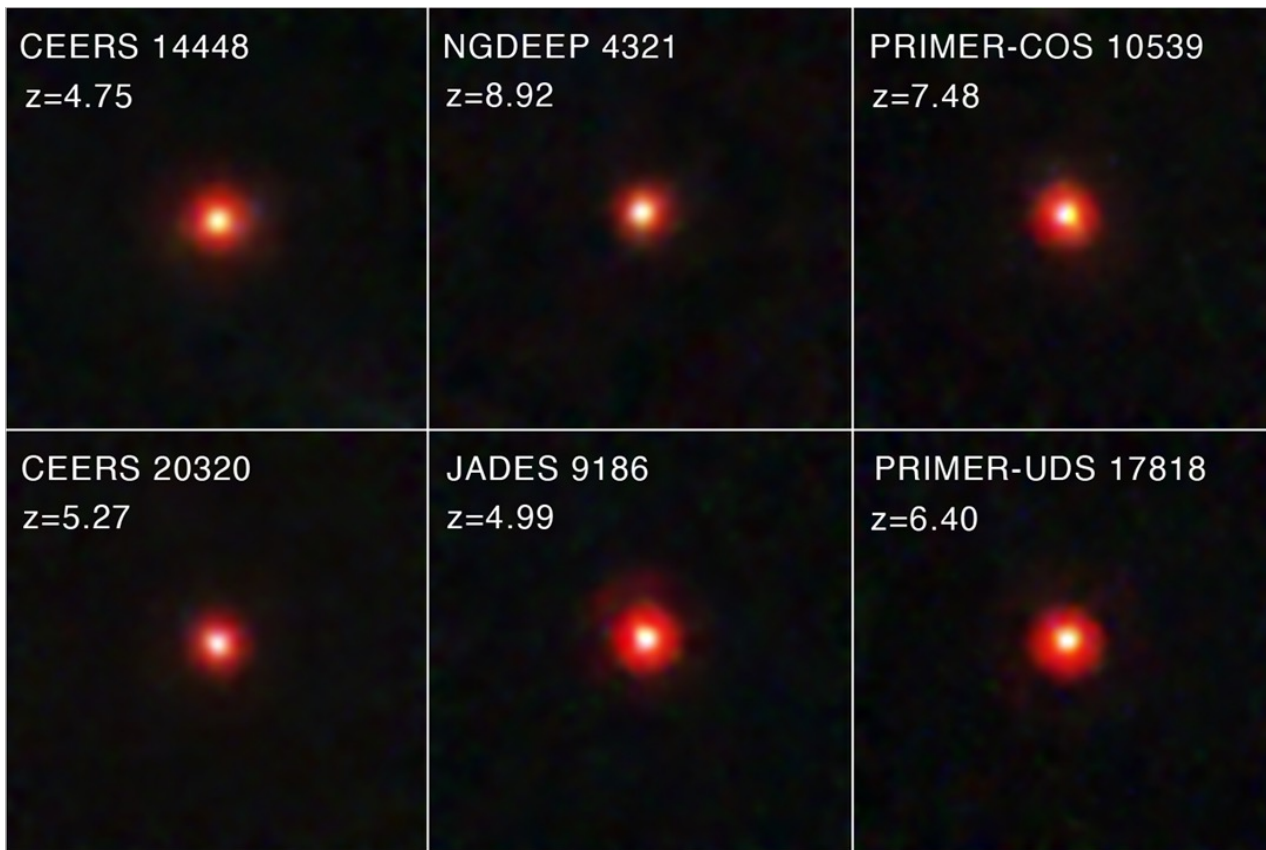
The most distant, $z \sim 11$

Jeon et al. 2025

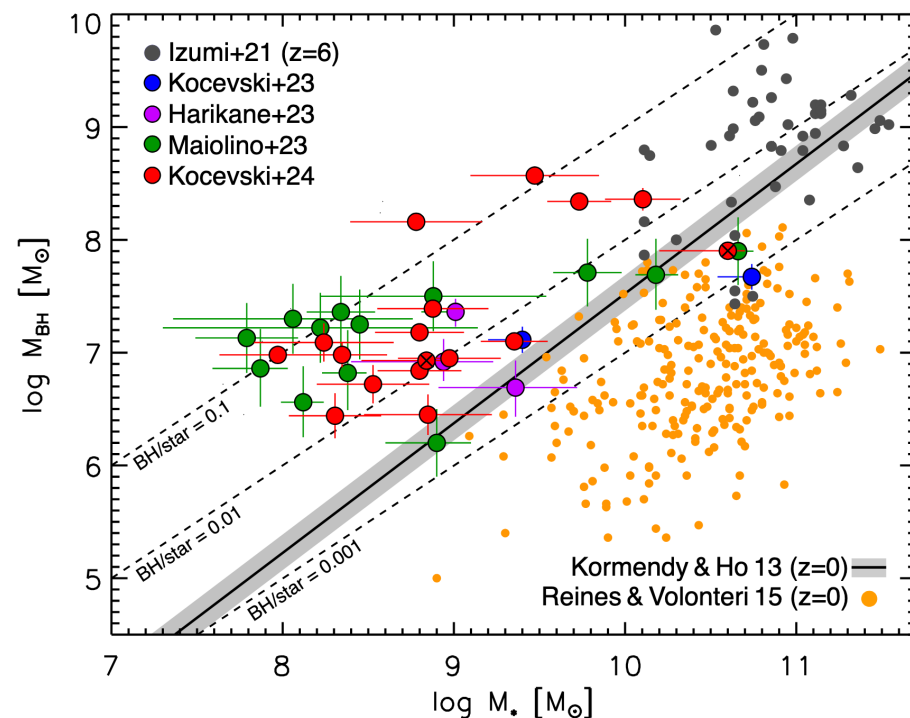


Maiolino et al. 2023

The little red dots (LRDs):



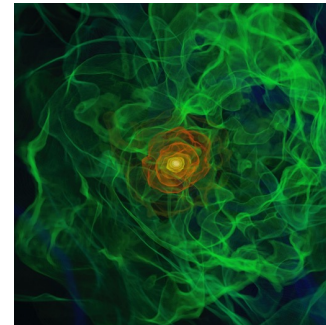
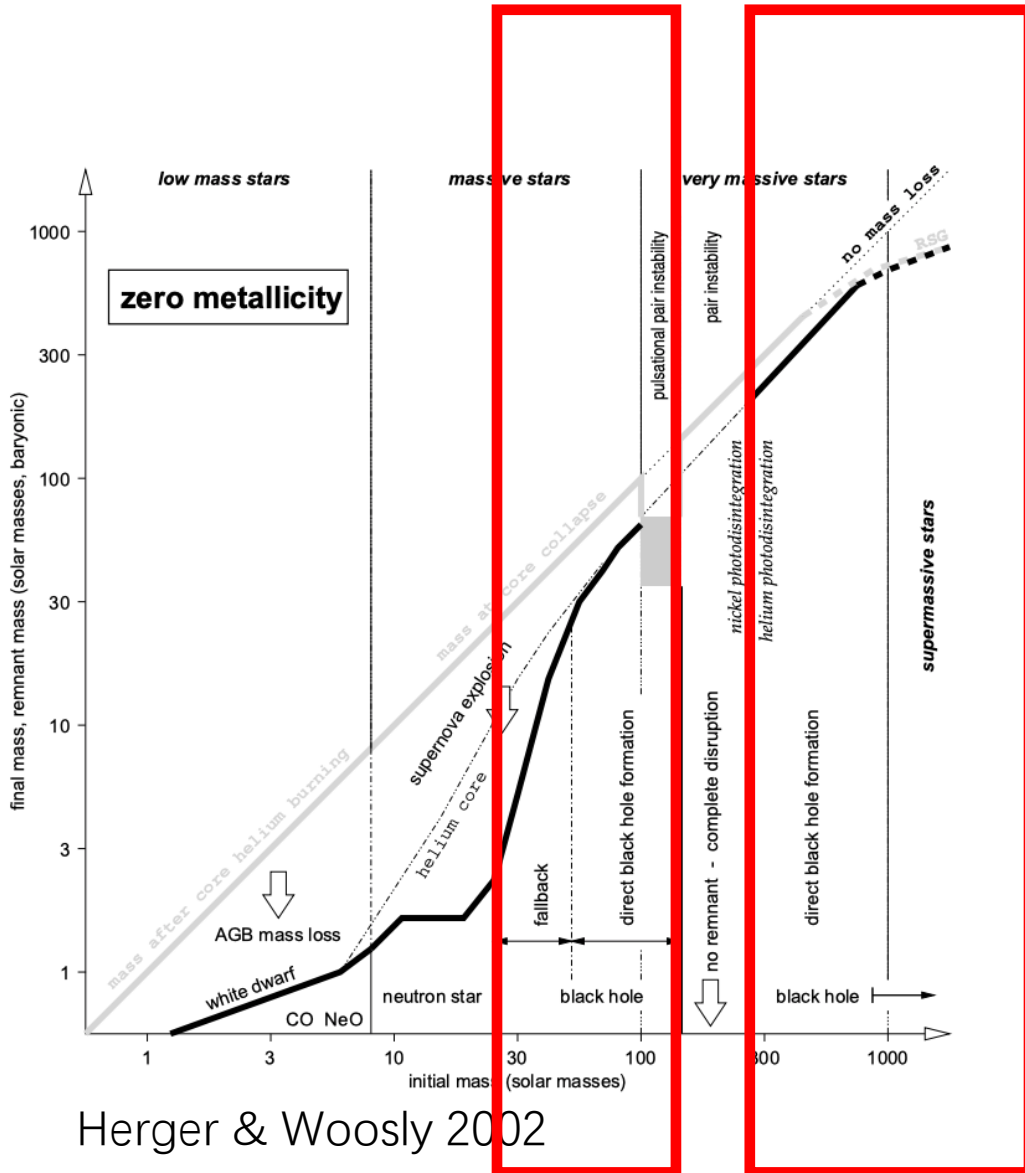
- Above $z \sim 4$
- Blue in UV and red in optical spectrum
- Extremely compact, $\sim 2\%$ of Milky Way's radius
- Number density 10^{-5} - 10^{-4} Mpc^3
- BH mass 10^6 - 10^8 M_{SUN}
- Larger M_{BH}/M_* ratio than local samples



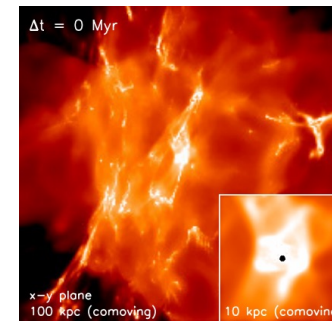
Credit: NASA, ESA, CSA, STScI, Dale Kocevski (Colby College)

- Pop III stars $\sim 100 M_{\text{SUN}}$ $\rightarrow$ relic BHs with comparable mass, this the first generation BHs in the Universe.
- These stellar mass BHs are seeds, they keep growing since birth, finally become IMBHs or SMBHs. Is this true?

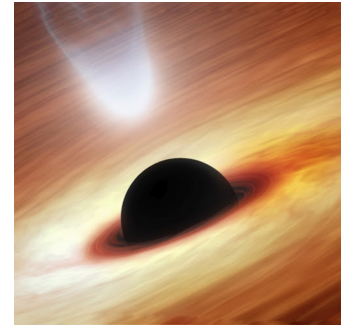
If this is true, then the BH grow by a factor $\sim 10^8$ in ~ 800 million years!!!



die

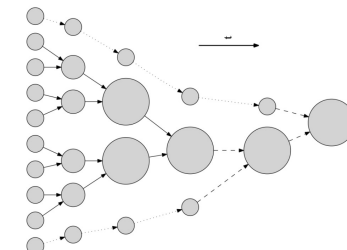


accrete merger



Credit: Visualization: Ralf Kaehler. Simulation: Tom Abel.

Credit: Joen et al. 2012



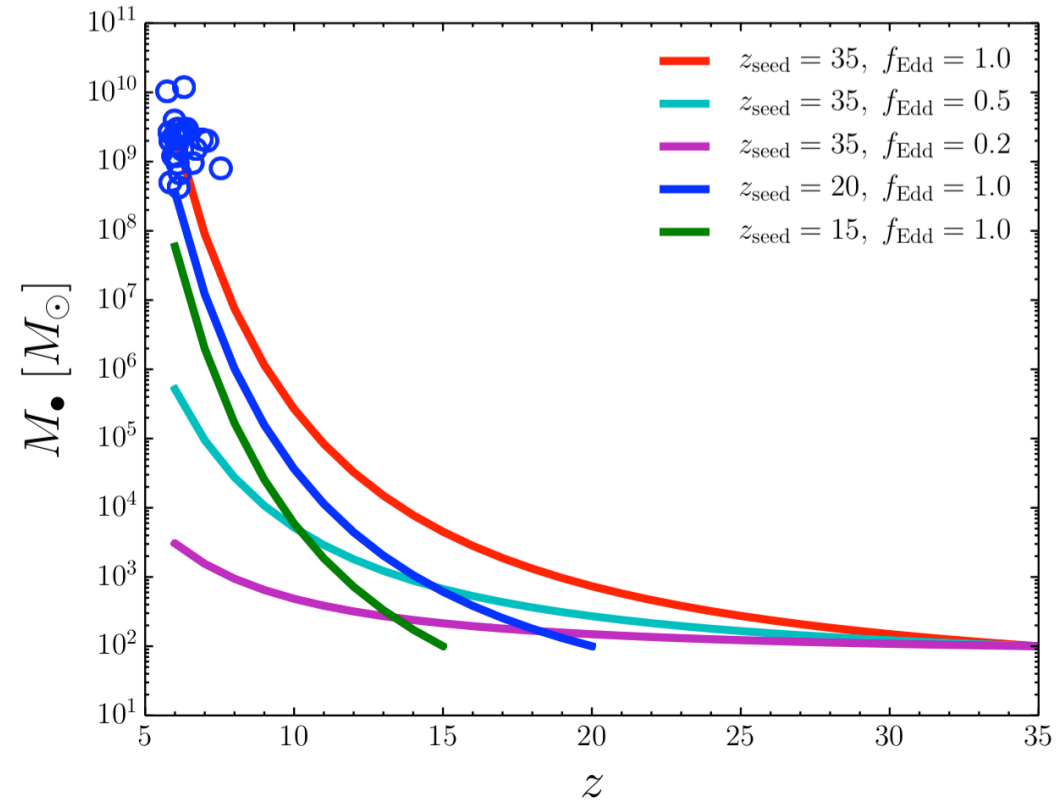
The Eddington limit on BH growth:

Balance the gravity and the radiation pressure

$$F_{\text{rad}} = F_{\text{grav}}$$

$$\frac{L_{\text{Edd}}\sigma_T}{4\pi r^2 c} = \frac{GM_{\bullet}m_p}{r^2}$$

$$\begin{aligned}\dot{M}_{\bullet} &= \frac{1-\epsilon}{\epsilon} f_{\text{Edd}} L_{\text{Edd}} / c^2 \\ &= \frac{1-\epsilon}{\epsilon} f_{\text{Edd}} \frac{4\pi G M_{\bullet} m_p}{c\sigma_T} \\ &\approx 2.22 \times 10^{-6} \left(\frac{M_{\bullet}}{100 M_{\odot}} \right) \left(\frac{\epsilon}{0.1} \right)^{-1} M_{\odot} \text{yr}^{-1}\end{aligned}$$

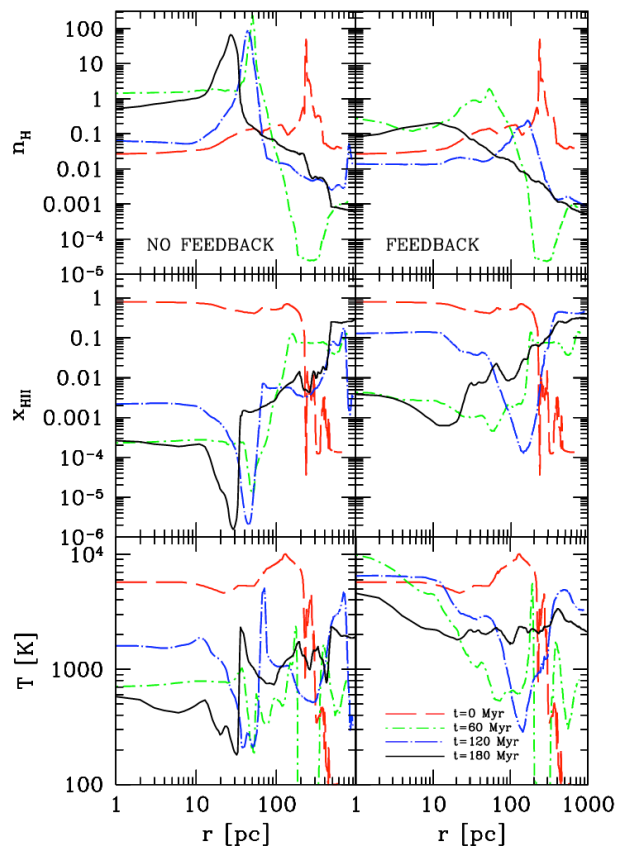


To make SMBHs as $\sim 10^9 - 10^{10} M_{\text{sun}}$ at $z \sim 6$, Pop III seeds should form at $z \gtrsim 35$ and since then always have highest growth rate ($f_{\text{Edd}} \sim 1$).

Seems not physically impossible, however...

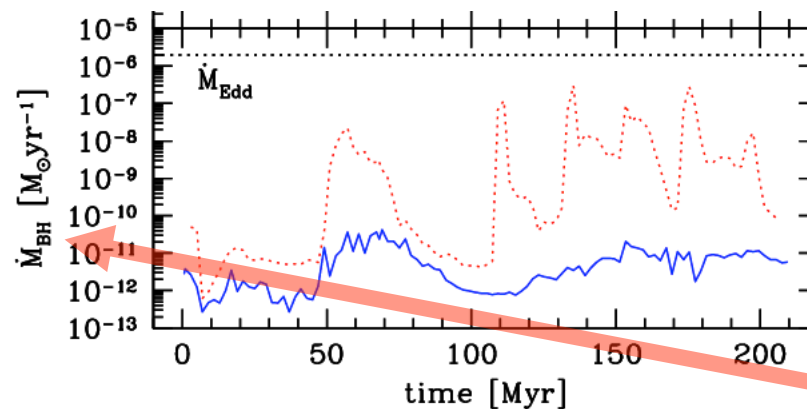
The environment of the Pop III seed:

- Minihalos hard to keep hot gas;
- Main sequence Pop III stars generate HII regions far beyond the halo boundary;
- The seed BH find itself in a low density ($\sim 0.5 \text{ cm}^{-3}$) and hot ($\sim 10^4 \text{ K}$).



Bondi accretion rate:

$$\dot{M}_{\bullet} = \frac{4\pi G^2 M_{\bullet}^2 \rho}{(c_s^2 + v_{rel}^2)^{3/2}}$$

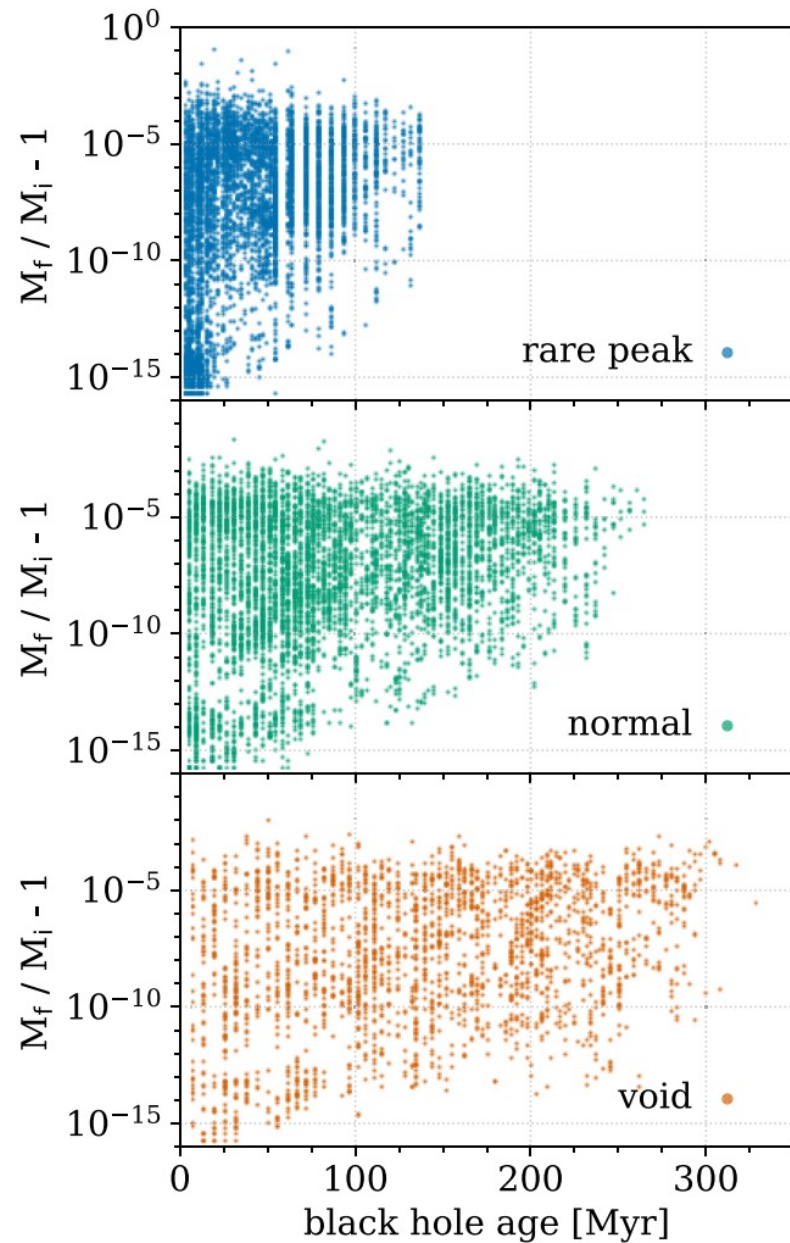


$f_{\text{Edd}} \sim 10^{-5}$ (Alvarez et al. 2009)

Dense gas clumps rise accretion burst,
however it will be destroyed if radiative feedbacks are
considered.

Always much
lower than
Eddington limit!

The ratio of the net growth mass compared to the initial mass



For a stellar-mass BH, no matter it formed in dense, normal or low-density region, the **growth ratio is much much smaller than 1** throughout hundreds Myrs since its birth!

However, we need 10^8 !

The origin of SMBH seeds has puzzled us for long time:

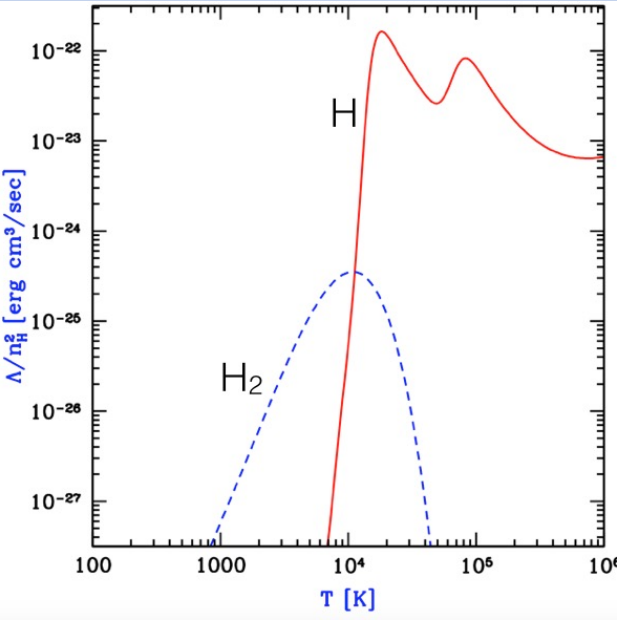
Since $\dot{M}_\bullet \propto M_\bullet$, the BH growth must be exponential, the larger the initial seed, the faster the growth.

The natural solution: to directly form intermediate mass black holes (IMBHs, $\sim 10^4 - 10^6 M_{\text{SUN}}$) as seeds.

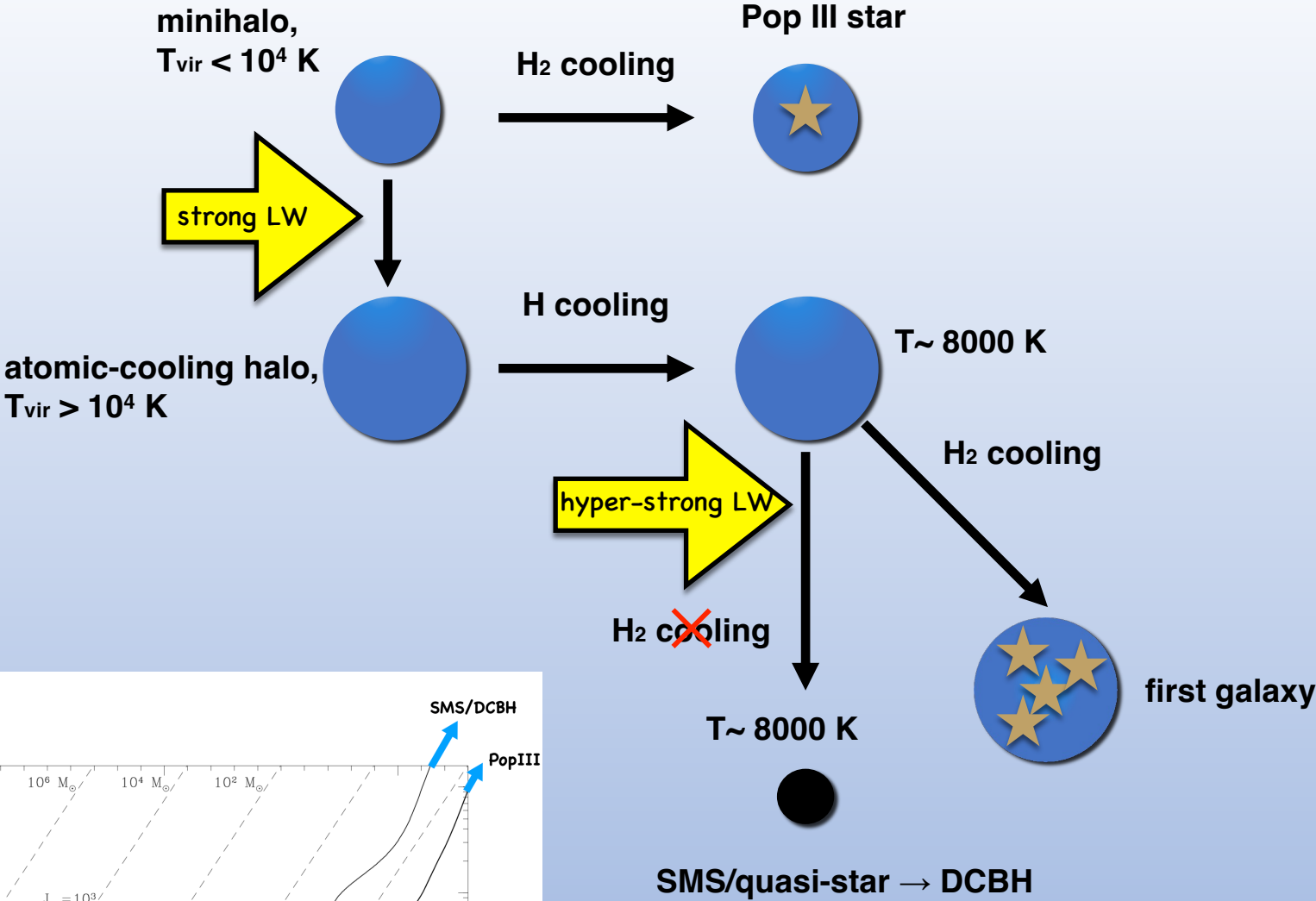
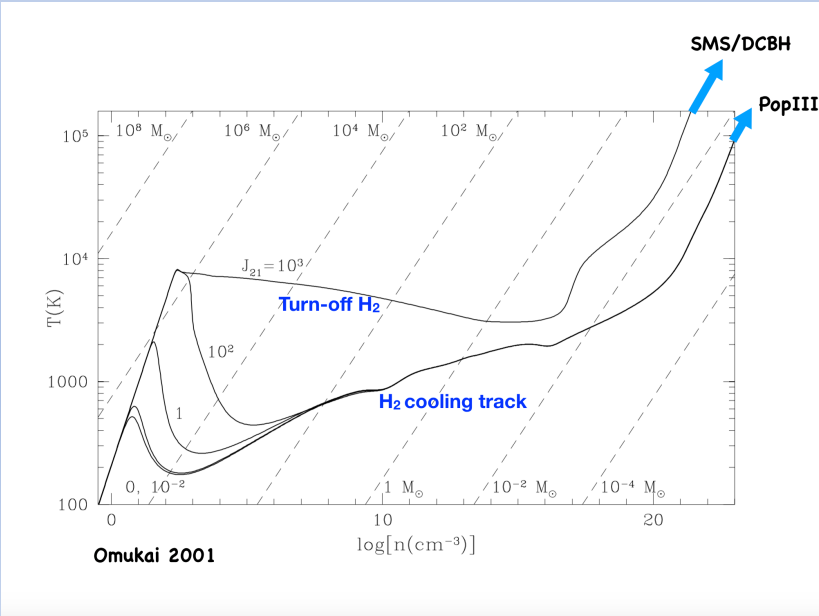
The direct collapse black holes (DCBHs)

The formation of Pop III stars requires H₂ cooling, if such molecular formation is suppressed, then gas can only cool by atomic H, finally, the full gas could collapse into a single supermassive stars/BH!

- H-cooling, works at $T \gtrsim 10^4$ K
- H₂-cooling, works at $T \gtrsim 10^3$ K



Barkana & Loeb 2001

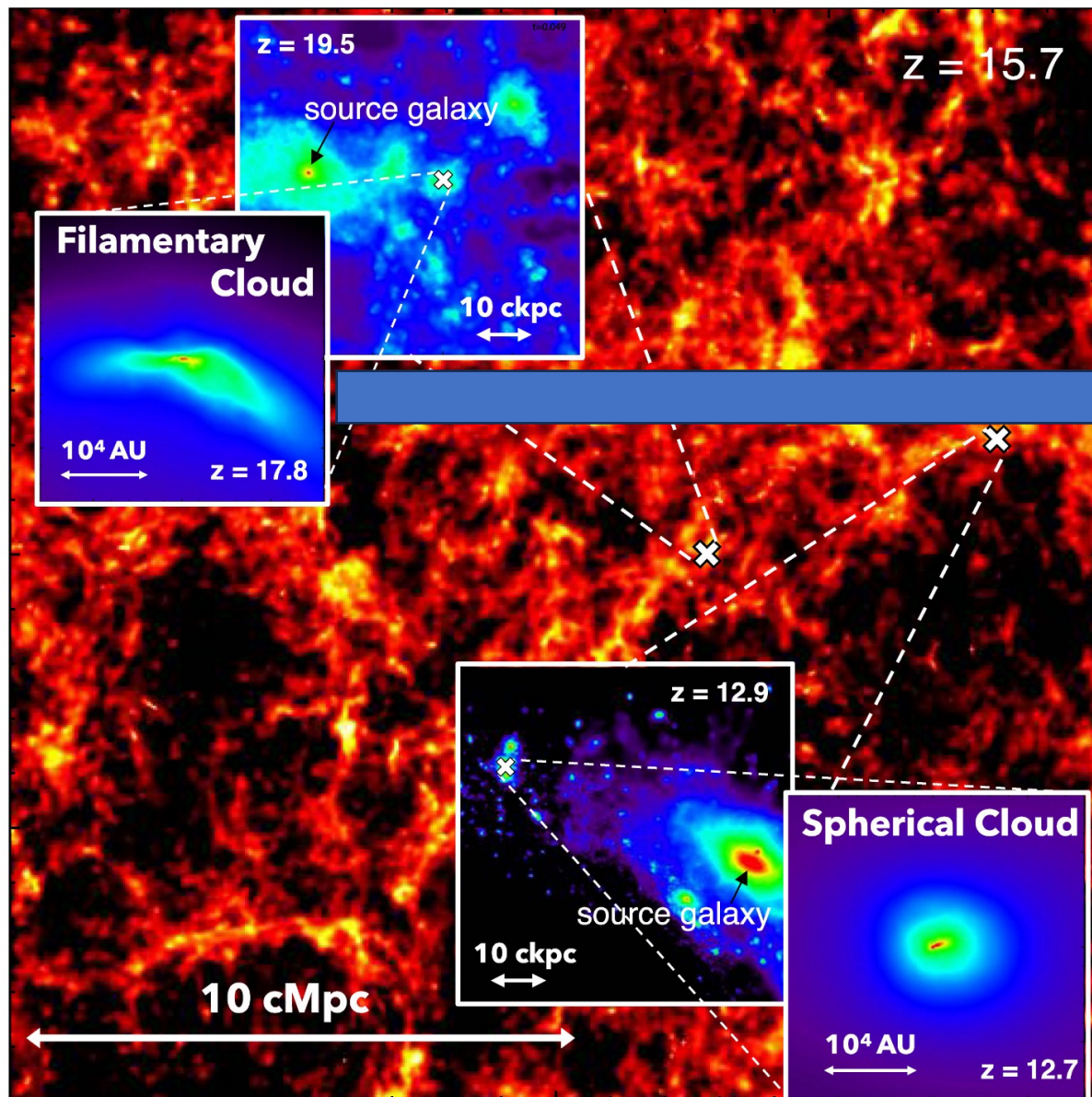


1. The accretion rate (because the gas is warm) to the center sink:
 $\sim 0.1 - 10 M_{\text{SUN}}/\text{yr}$;
2. The angular momentum transfer mechanisms do works;
3. The SMS/quasi-star has size $\sim 5000 R_{\text{SUN}}$, effective temperature $\sim 5000\text{K}$ and inefficient in producing ionizing photons;
4. After the formation of a DCBH, the accretion could be intermittent and $\sim$ Eddington rate on average.

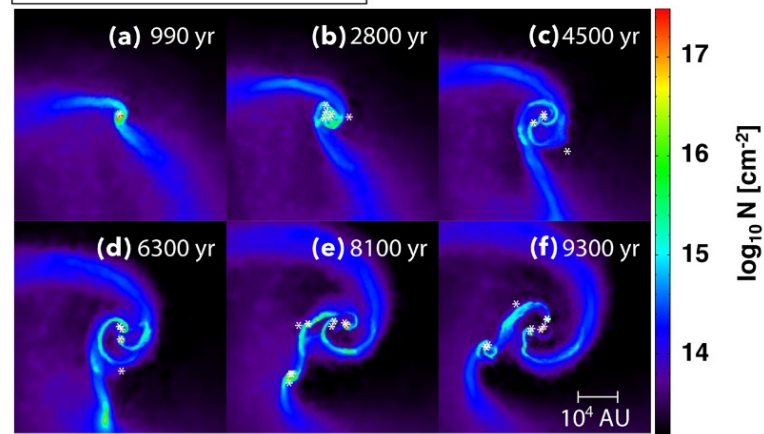
e.g. Latif et al. 2013, Regan et al. 2008, Hosokawa et al. 2013, Schleicher et al. 2013, Pacucci et al. 2015, Inayoshi et al. 2016,...

In summary:

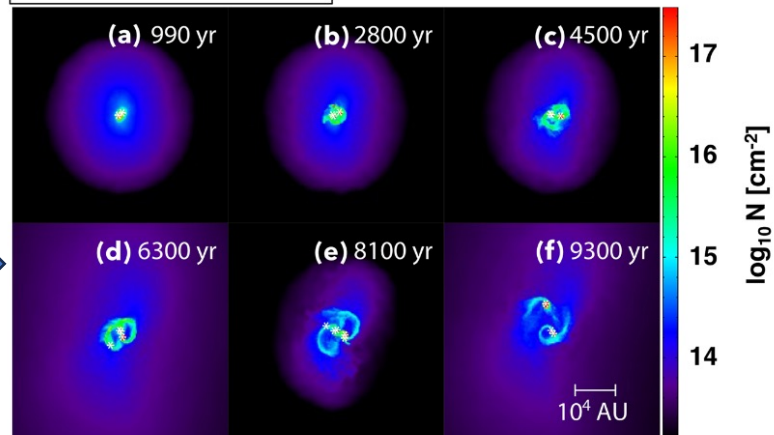
1. High accretion rate;
2. No fragmentation, an IMBH($10^4 - 10^6 M_{\text{SUN}}$) form directly as a seed.



I. Filamentary Cloud

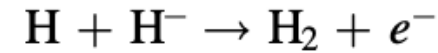
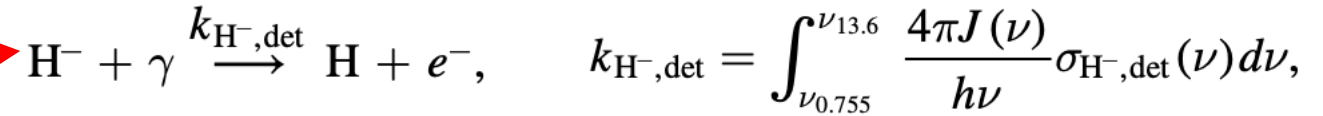
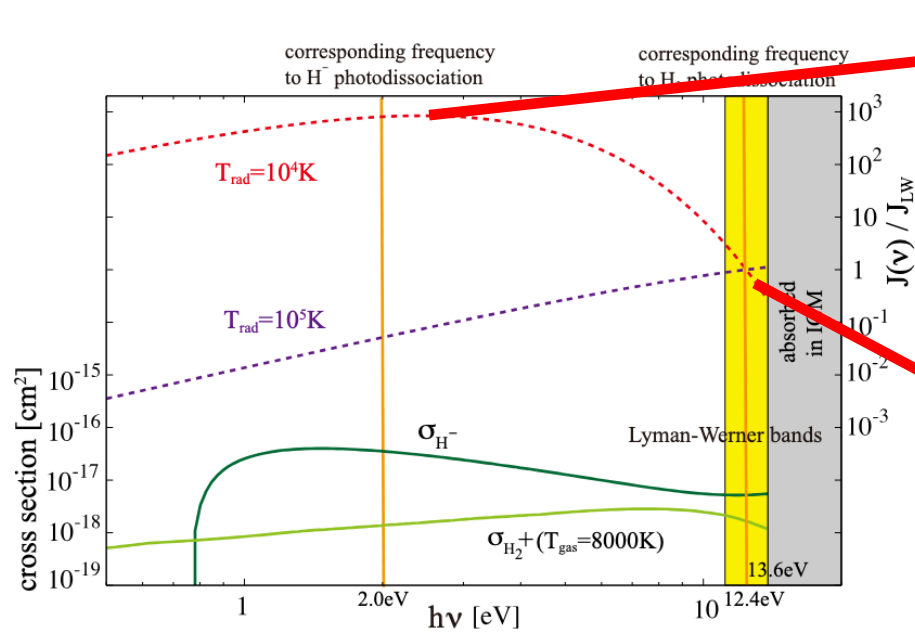


II. Spherical Cloud

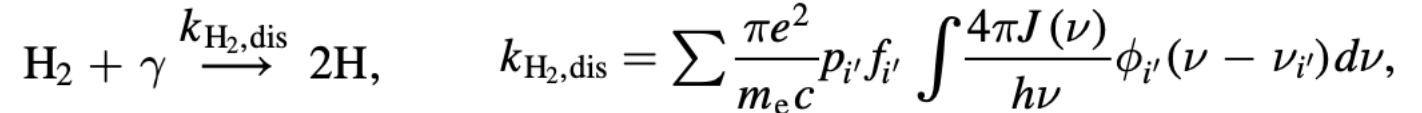


To suppress the H₂ formation, it requires a strong LW radiation, how strong?

A soft SED ($T_{\text{rad}} = 10^4$ K) mainly directly detaches the H⁻.



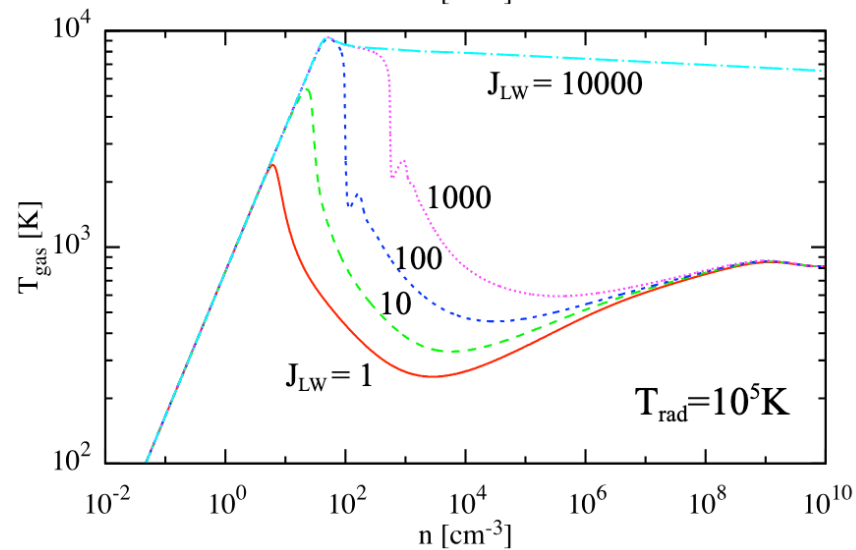
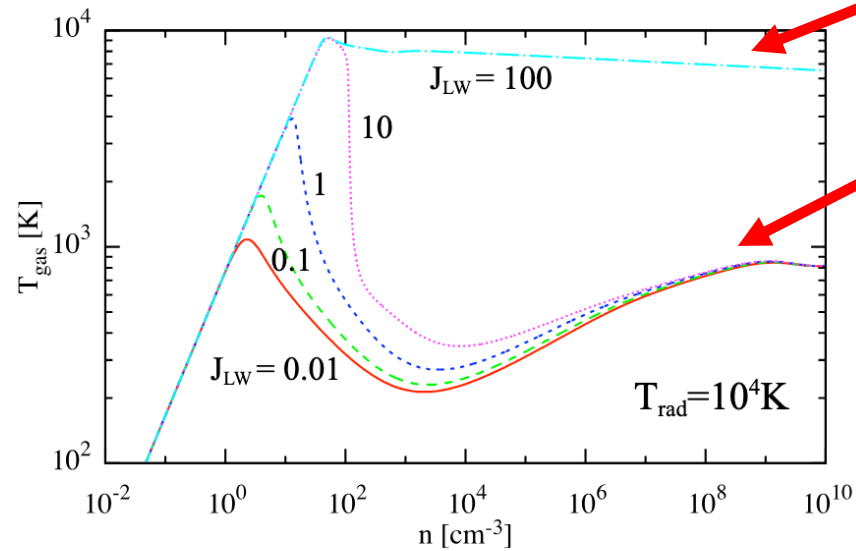
A hard SED ($T_{\text{rad}} = 10^5$ K) mainly directly dissociates the H₂.



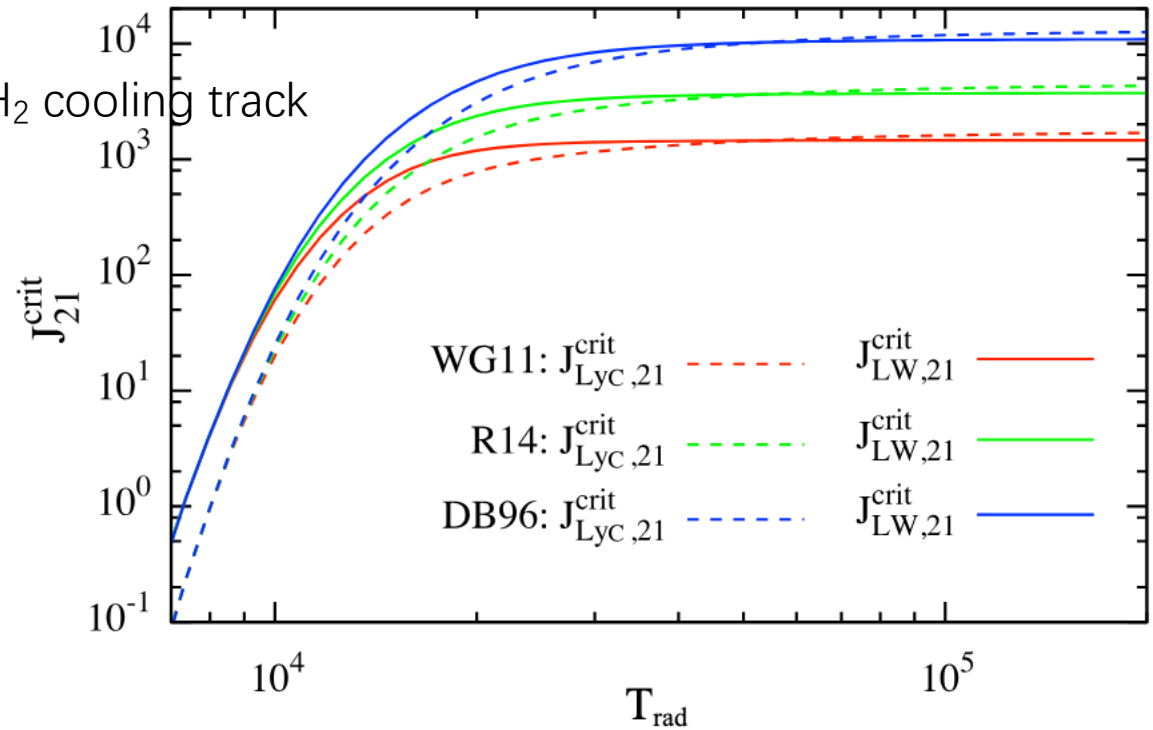
So J_{crit} depends on SED.

To suppress the H_2 formation, it requires a strong LW radiation, how strong?

Atomic-cooling track



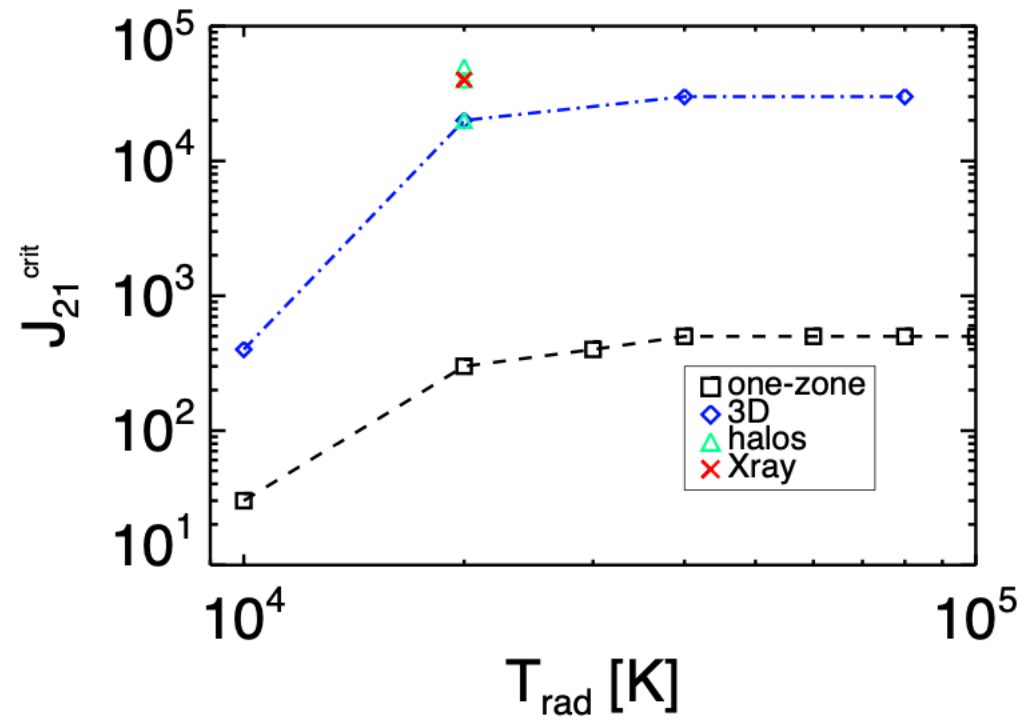
H_2 cooling track



In one-zone simulation:

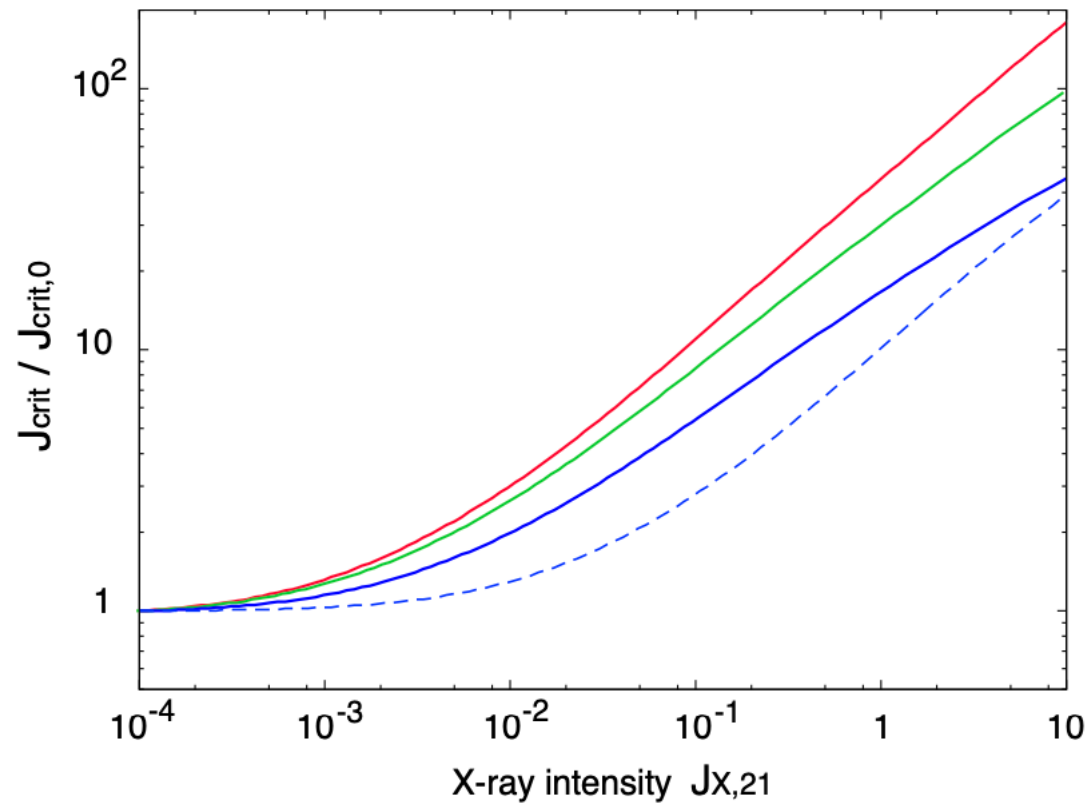
- For $T_{\text{rad}} = 10^5 \text{ K}$, $J_{\text{crit}} \sim 10^4 \text{ } 10^{-21} \text{ erg/s/cm}^2/\text{Hz/sr}$;
- For $T_{\text{rad}} = 10^4 \text{ K}$, $J_{\text{crit}} \sim 10^2 \text{ } 10^{-21} \text{ erg/s/cm}^2/\text{Hz/sr}$;

However, J_{crit} found by 3D simulations are generally one orders of magnitude higher!



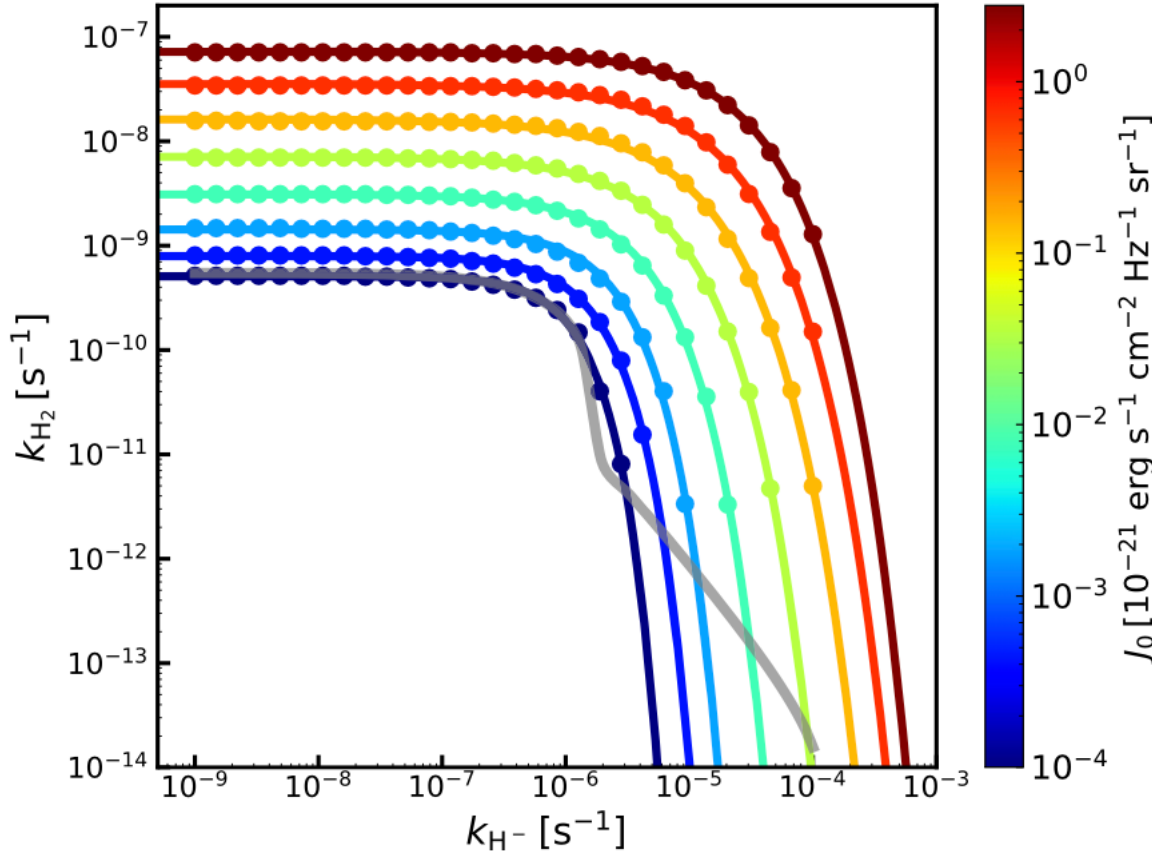
Latif et al. 2015

X-ray boosts the required LW radiation



Inayoshi et al. 2015

X-ray can boost the required LW radiation



Zhang et al. 2015

$$\log(k_{\text{H}_2}) = \frac{A}{1 + e^{-B \log(k_{\text{H}^-})}} + C \quad (2)$$

both A, B, and C, are functions of J_0

$$Y = f_1(x) \exp(-kJ_0) + [1 - \exp(-kJ_0)] f_2(x), \quad (3)$$

where $Y \in [\log(-A), B]$, $x = \log(J_0)$, $f_1(x) = a_0x + a_1$ and $f_2(x) = a_2x + a_3$. For C, the relationship is given by

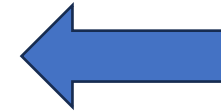
$$C = a_0 + a_1 \log(J_0) + a_2 \log^2(J_0). \quad (4)$$

Fitting Parameters in Equations (3), (4)

	a_0	a_1	a_2	a_3	k
A	-1.11	3.60	-0.11	3.37	20.75
B	-0.37	1.75	0.12	1.73	15.25
C	-7.40	0.73	0.06	...	...

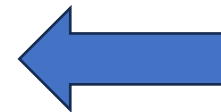
A source galaxy can provide LW strong enough to suppress the H_2 cooling only if it is **very very close to the gas cloud**, however then negative feedbacks come:

- Metal pollution;
- Mechanic feedback from supernova explosion;
- Tidal disruption;
- Ionizing radiation
- X-ray radiation
- ...



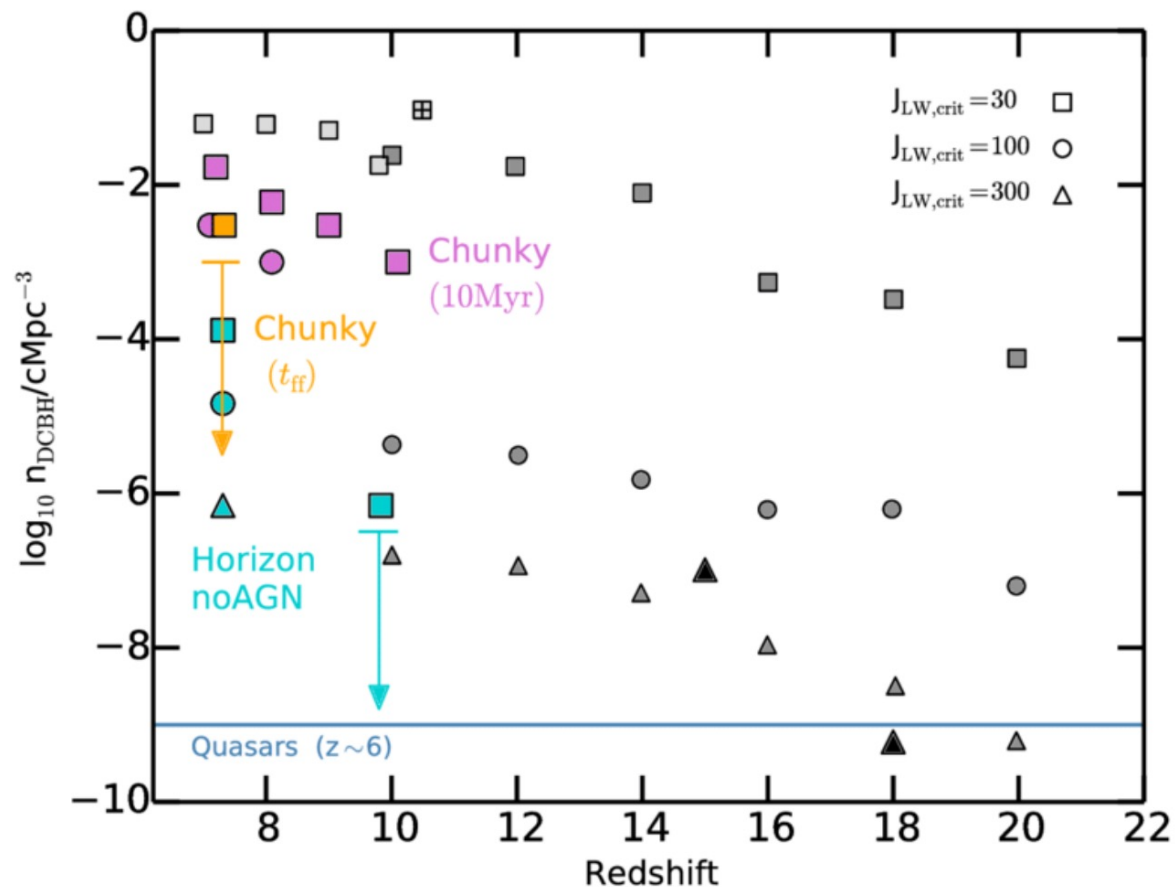
Negative

- LW



positive

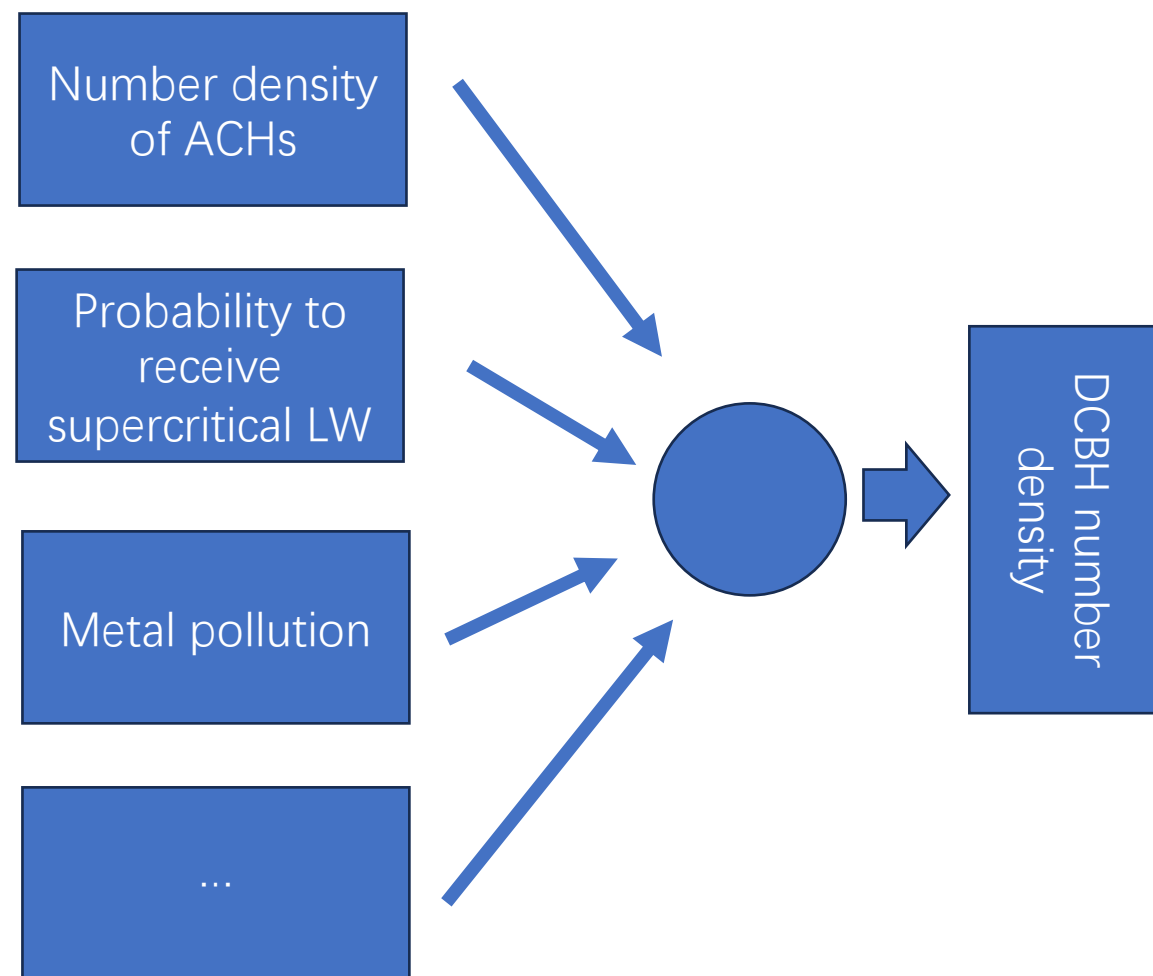
What is the number density of DCBHs?



Habouzit et al. 2016

If DCBHs are seeds of SMBHs:

- The **upper limit** is set by the number density of atomic-cooling halos;
- The **lower limit** is set by the observed SMBHs/AGNs



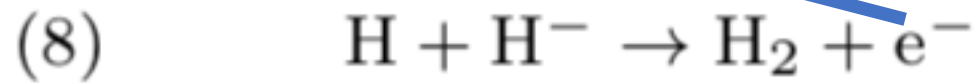
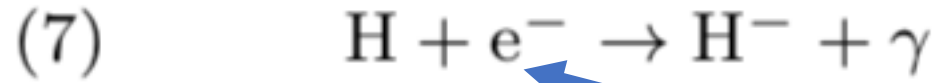
In a word:

- Stellar mass black holes are **easy to form**, but **hard to grow**;
- DCBHs are **hard to form**, however seems **easy to grow**.

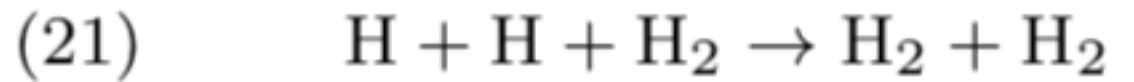
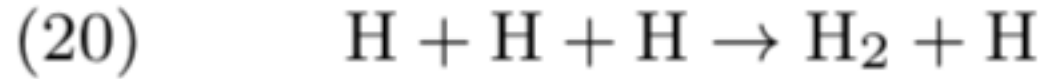
Is it possible to make DCBH form easier?

DCBH is the dominant population at Cosmic Dawn?

Chemistry for H_2 formation:



Crucial for H_2 formation

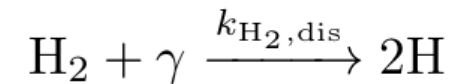


Suppressing the H_2

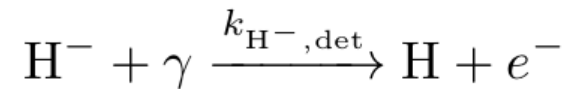
External radiation from:

- Pop III stars,
- first galaxies,
- and, **even other DCBHs**

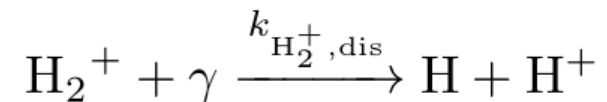
H_2 photo-dissociation: $11.2\text{eV} \leq E_\gamma \leq 13.6\text{eV}$



H^- photo-detachment: $0.76\text{eV} \leq E_\gamma$



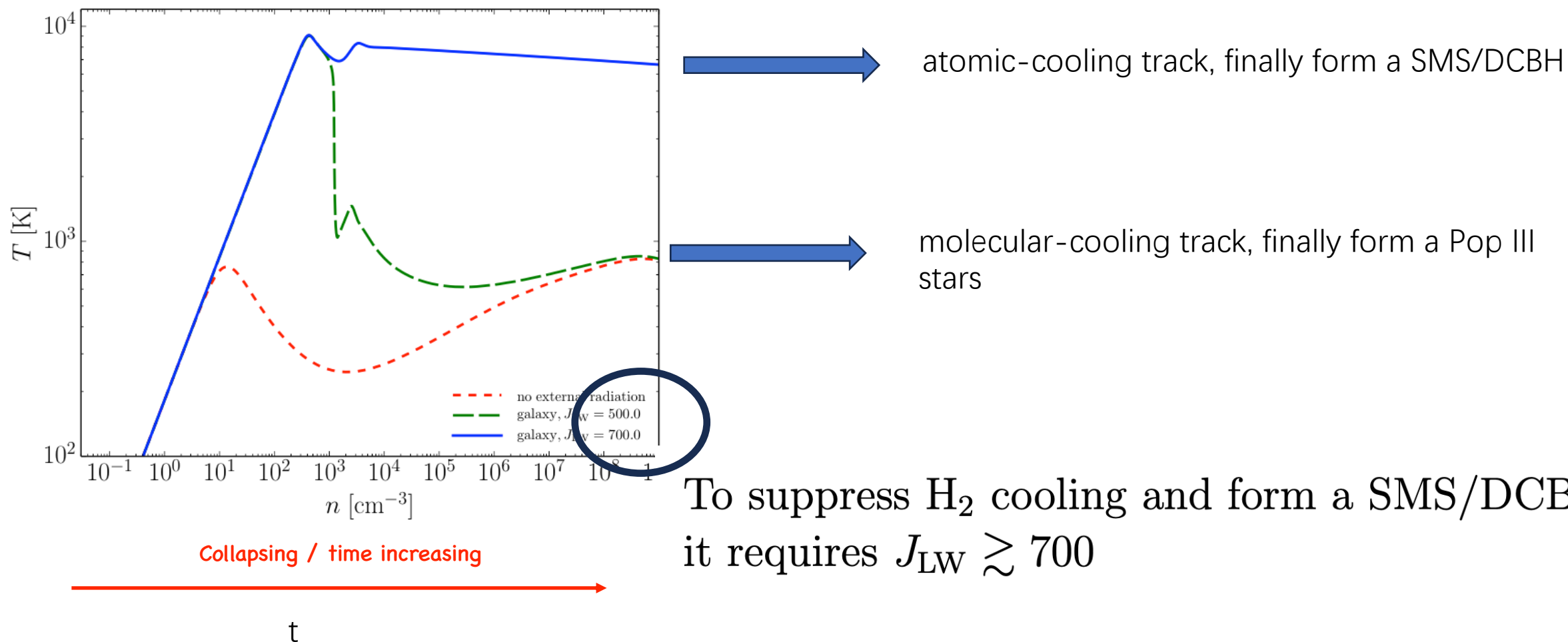
H_2^+ photo-dissociation:



If the external radiation is from a star-forming galaxy (SB99):

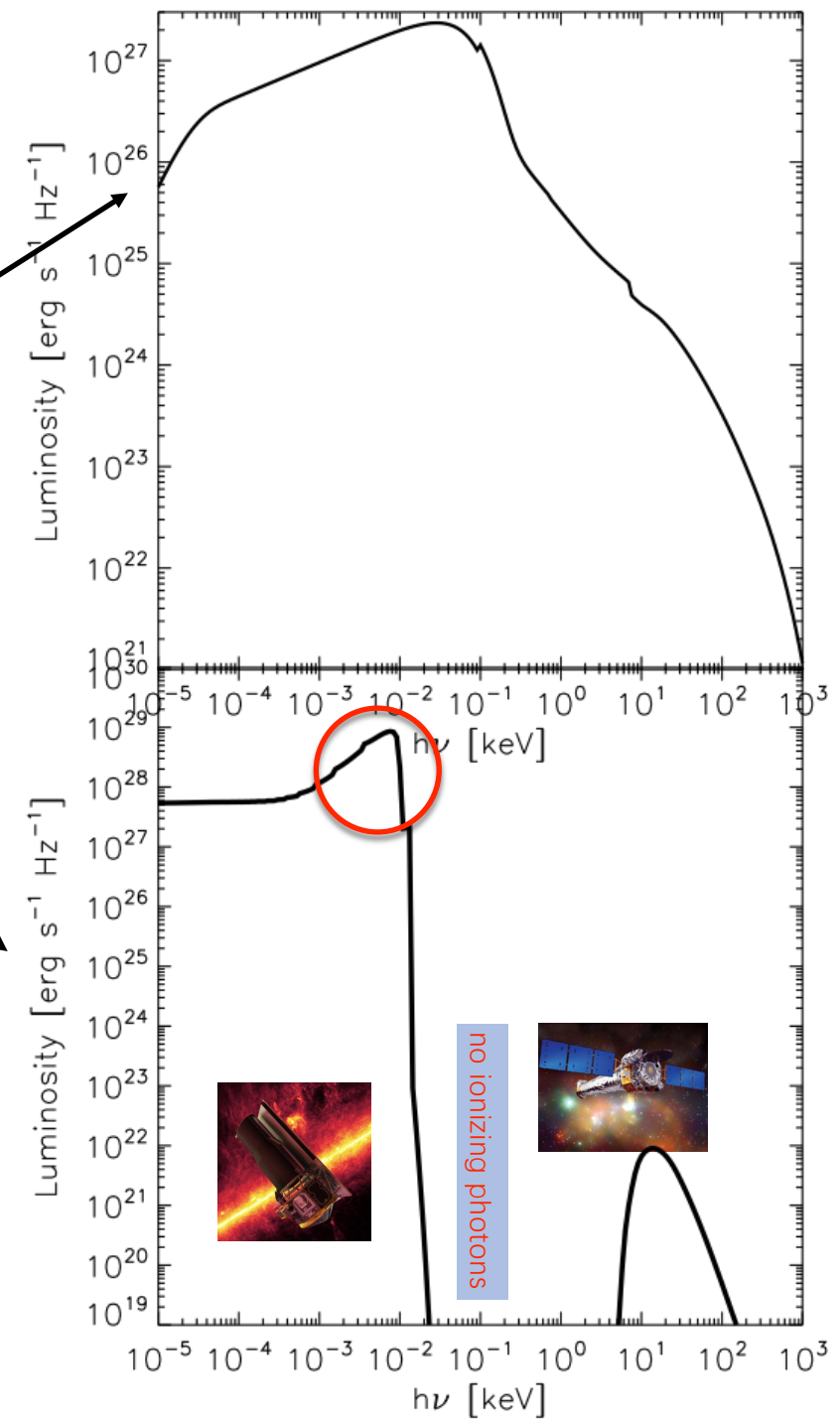
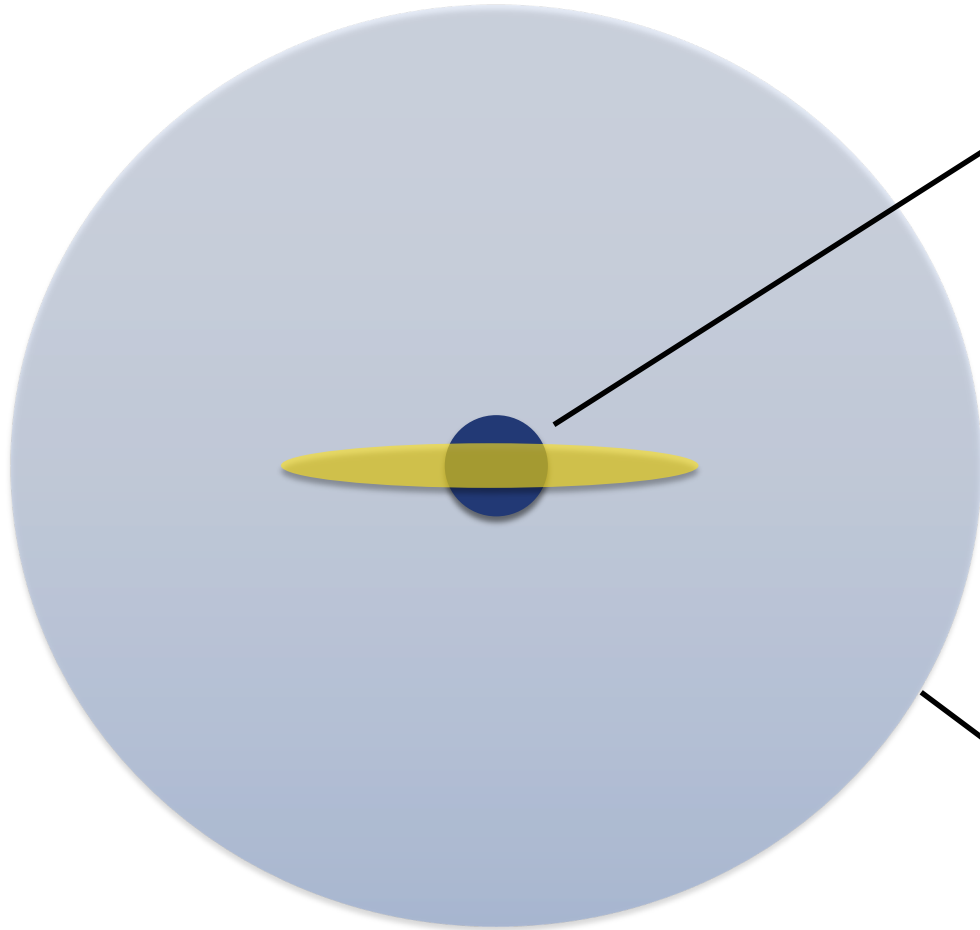
J_{LW} units : $10^{-21} \text{erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1} \text{sr}^{-1}$

Evolution of a pristine gas cloud irradiated by external radiation field



To suppress H_2 cooling and form a SMS/DCBH, it requires $J_{\text{LW}} \gtrsim 700$

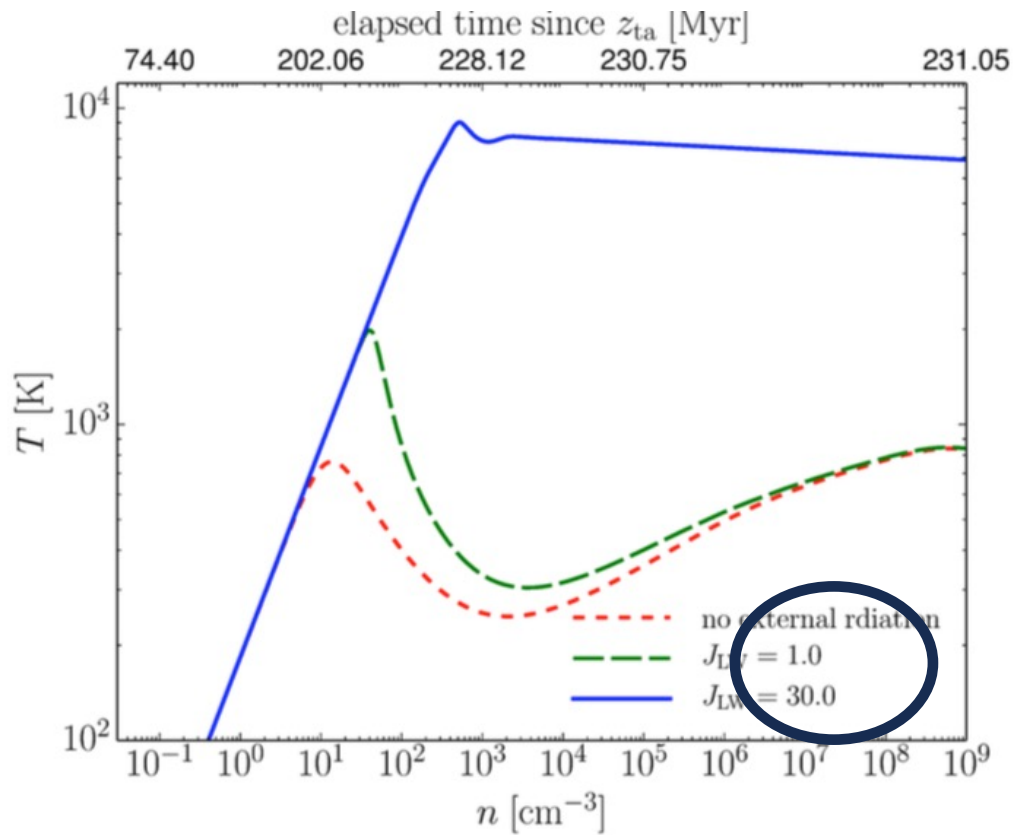
SED of Compton-thick BHs



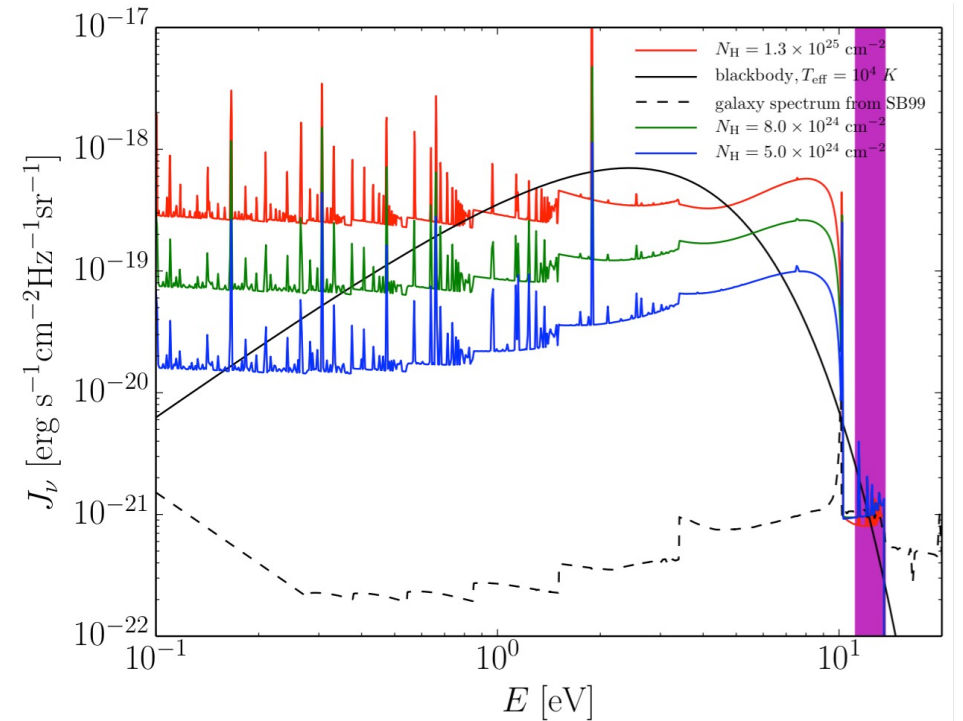
If the external radiation is from a another DCBH:

J_{LW} units : $10^{-21} \text{erg s}^{-1} \text{cm}^{-2} \text{Hz}^{-1} \text{sr}^{-1}$

Evolution of a pristine gas cloud irradiated by external radiation field



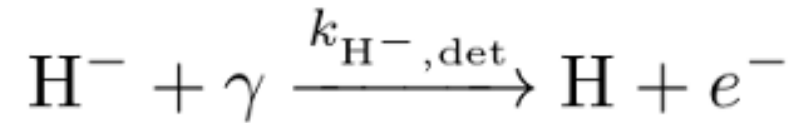
DCBHs ($N_{\text{H}}=1.5 \times 10^{25} \text{cm}^{-2}$, $N_{\text{H}}=8.0 \times 10^{24} \text{cm}^{-2}$, $N_{\text{H}}=5.0 \times 10^{24} \text{cm}^{-2}$) are from Pacucci's simulation



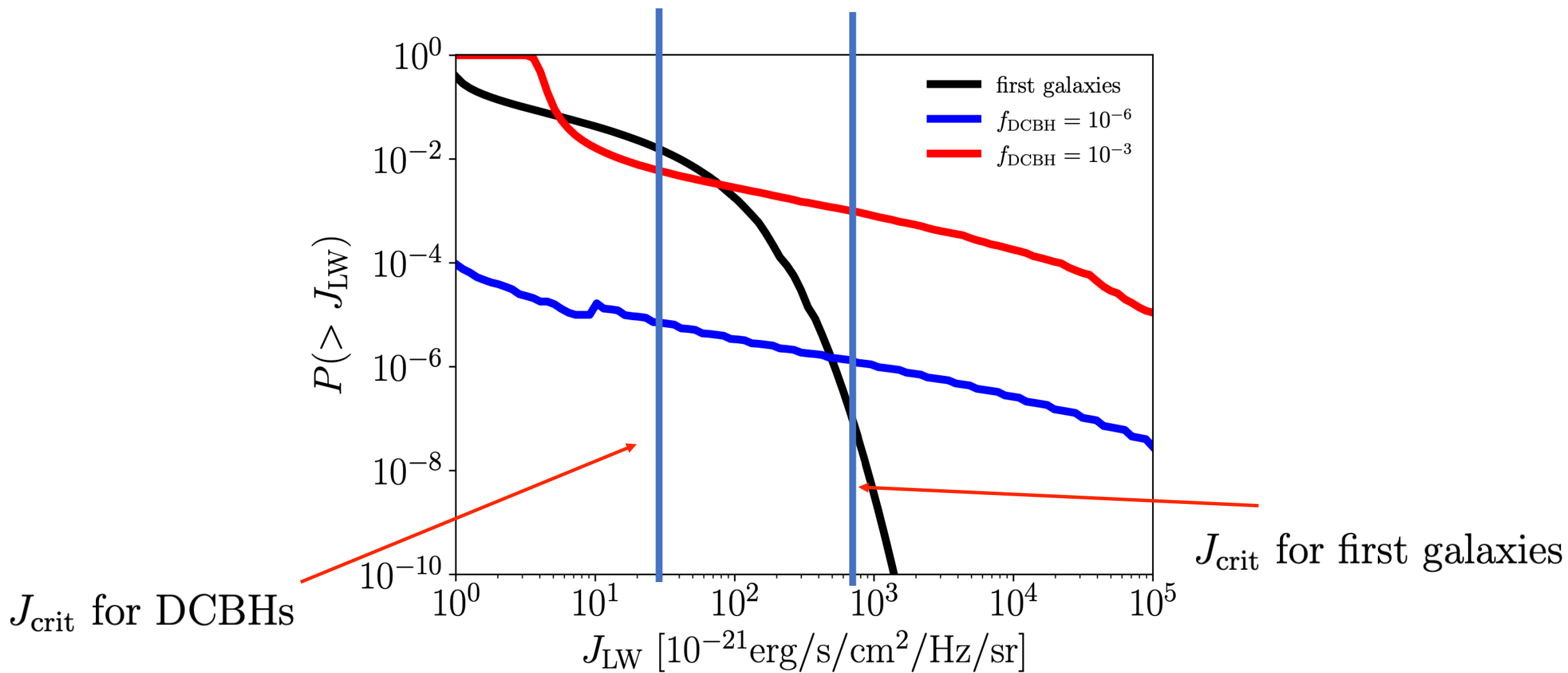
To suppress H_2 cooling and form a SMS/DCBH, it requires $J_{\text{LW}} \gtrsim 30$

The radiation from DCBH can suppress the H_2 formation efficiently, because its SED is more efficient for detaching the H^-

H^- photo-detachment:



we provide some reference numbers in the following. At $z = 20$, the mean LW luminosity of a star-forming normal galaxy in a host with mass M_{T4} is $4.0 \times 10^{25} \text{ erg s}^{-1} \text{ Hz}^{-1}$. For comparison, the LW luminosity of a $10^6 M_{\odot}$ DCBH is $2.3 \times 10^{27} \text{ erg s}^{-1} \text{ Hz}^{-1}$. Hence, at this epoch, a typical Compton-thick DCBH is more than 50 times brighter than the smallest normal galaxies (these small galaxies, however, provide most of the integrated light as they are much more numerous).



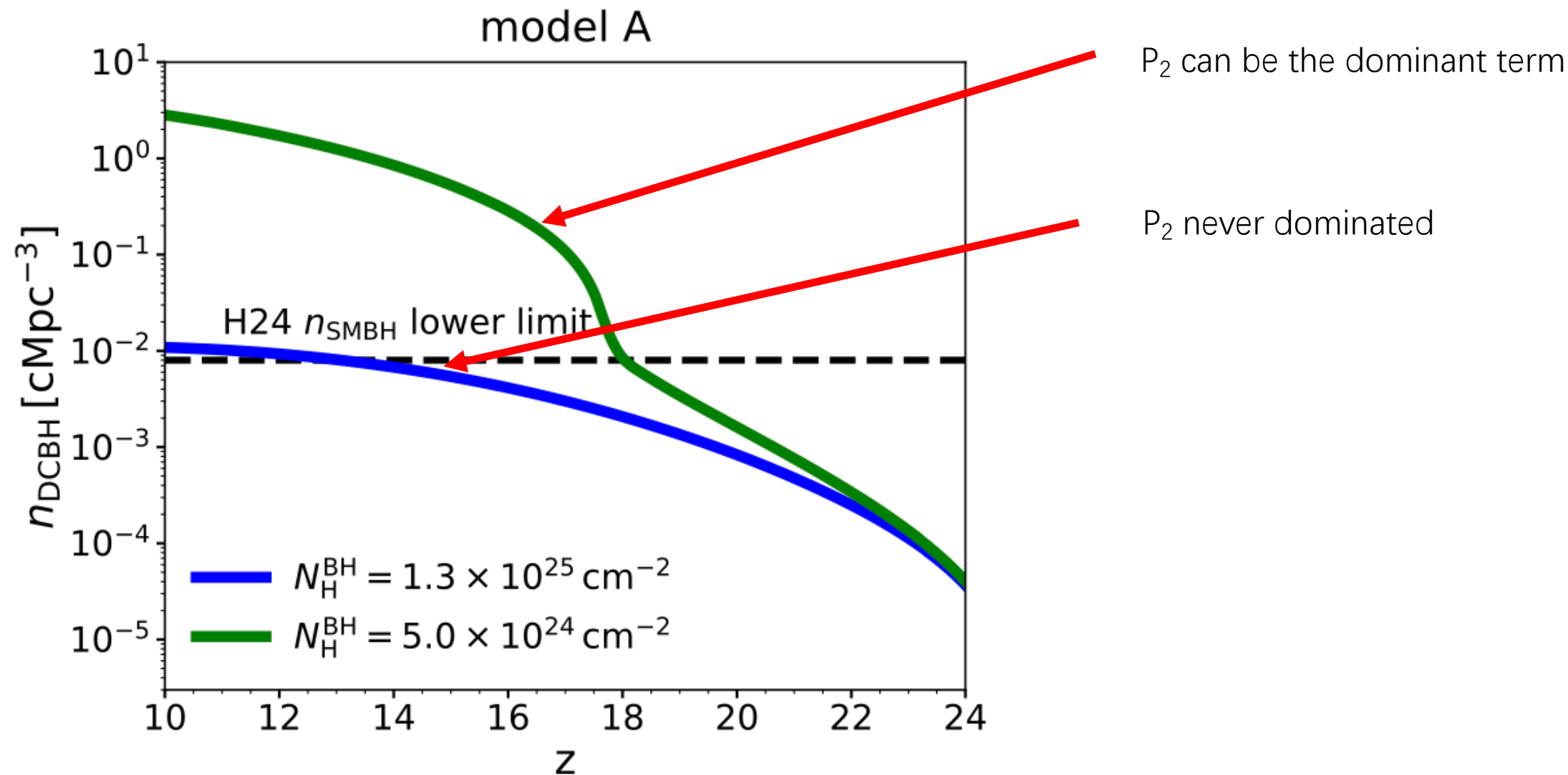
n_{DCBH} 越大 $\Rightarrow P_{\text{DCBH}}(> J_{\text{crit}})$ 越大 $\Rightarrow n_{\text{DCBH}}$ 更多……正反馈!

$$\frac{dn_{\text{DCBH}}}{dz} \sim \left[P_1(> J_{\text{crit}}^{\text{gal}}) + P_2(> J_{\text{crit}}^{\text{DCBH}}) \right] \frac{dn_{\text{ACHs}}}{dz}$$

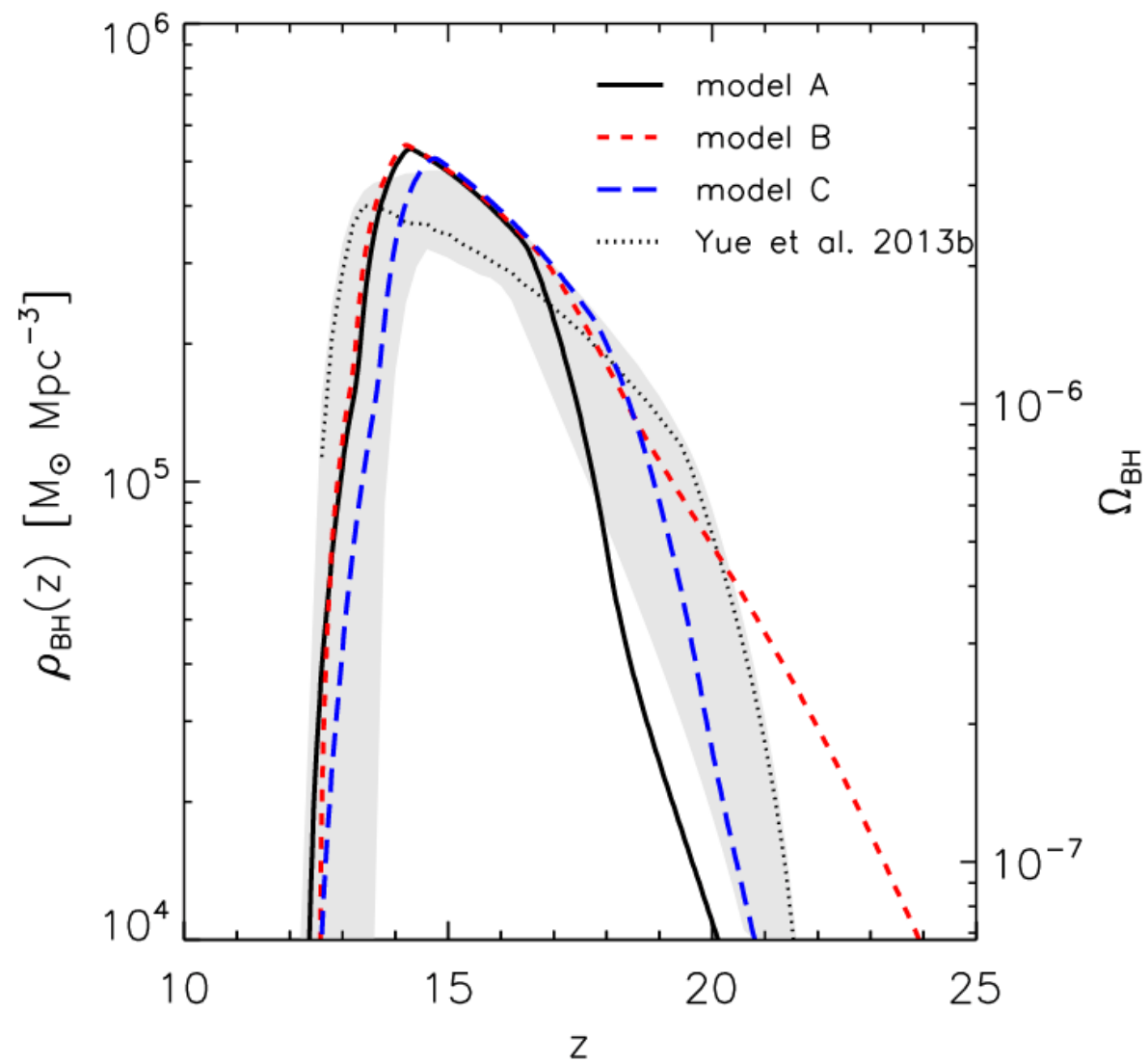
By first galaxies

By other DCBHs

- P_1 and P_2 depend on source's brightness and clustering
- P_1 and P_2 are derived from numerical simulations/semi-analytical simulations, or Monte Carlo simulations
- A typical DCBH is much brighter than a typical first galaxy, therefore P_2 can be $\gg P_1$
- P_2 is roughly proportional to n_{DCBH} , if P_2 is the dominant term, then n_{DCBH} grows exponentially
- However, the clustering decreases with decreasing redshift/feedback works efficiently, so n_{DCBH} growth becomes slower at the end of Cosmic DAwn

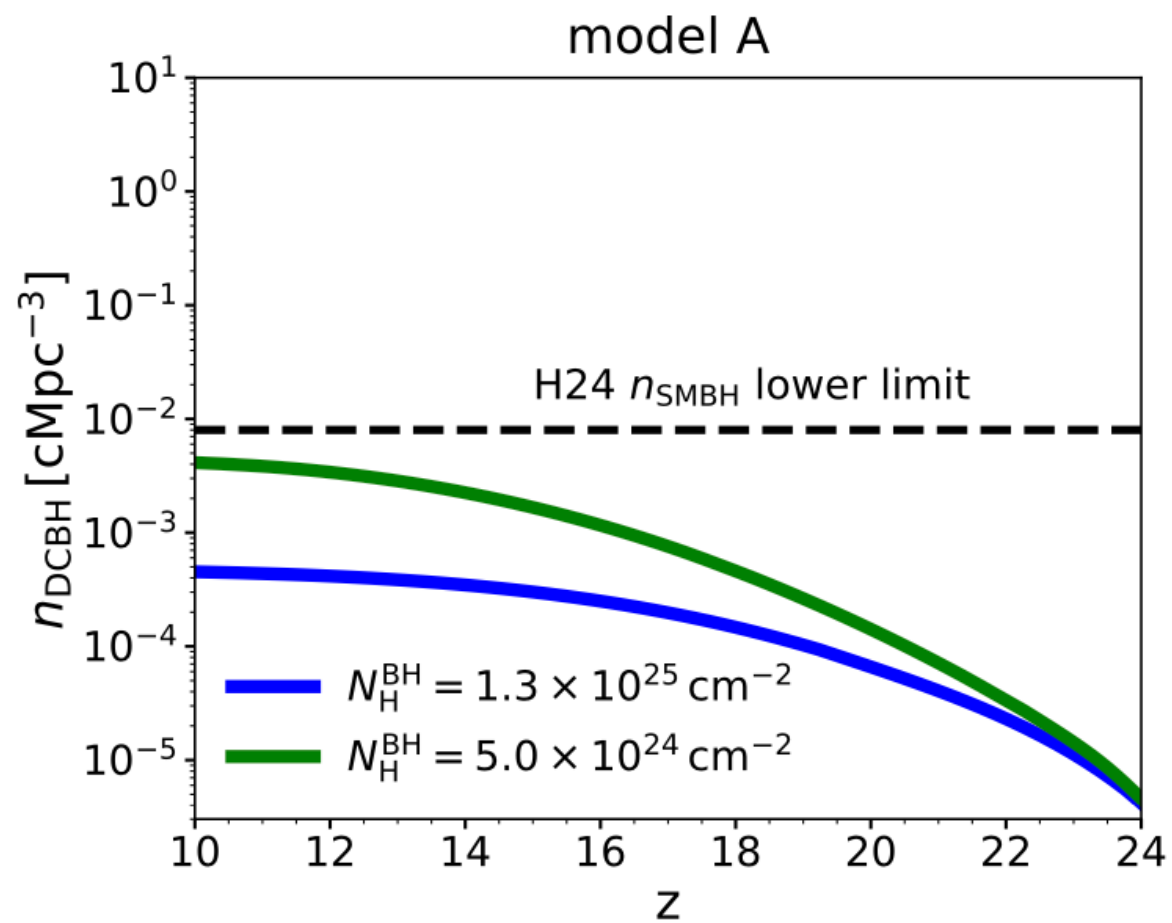


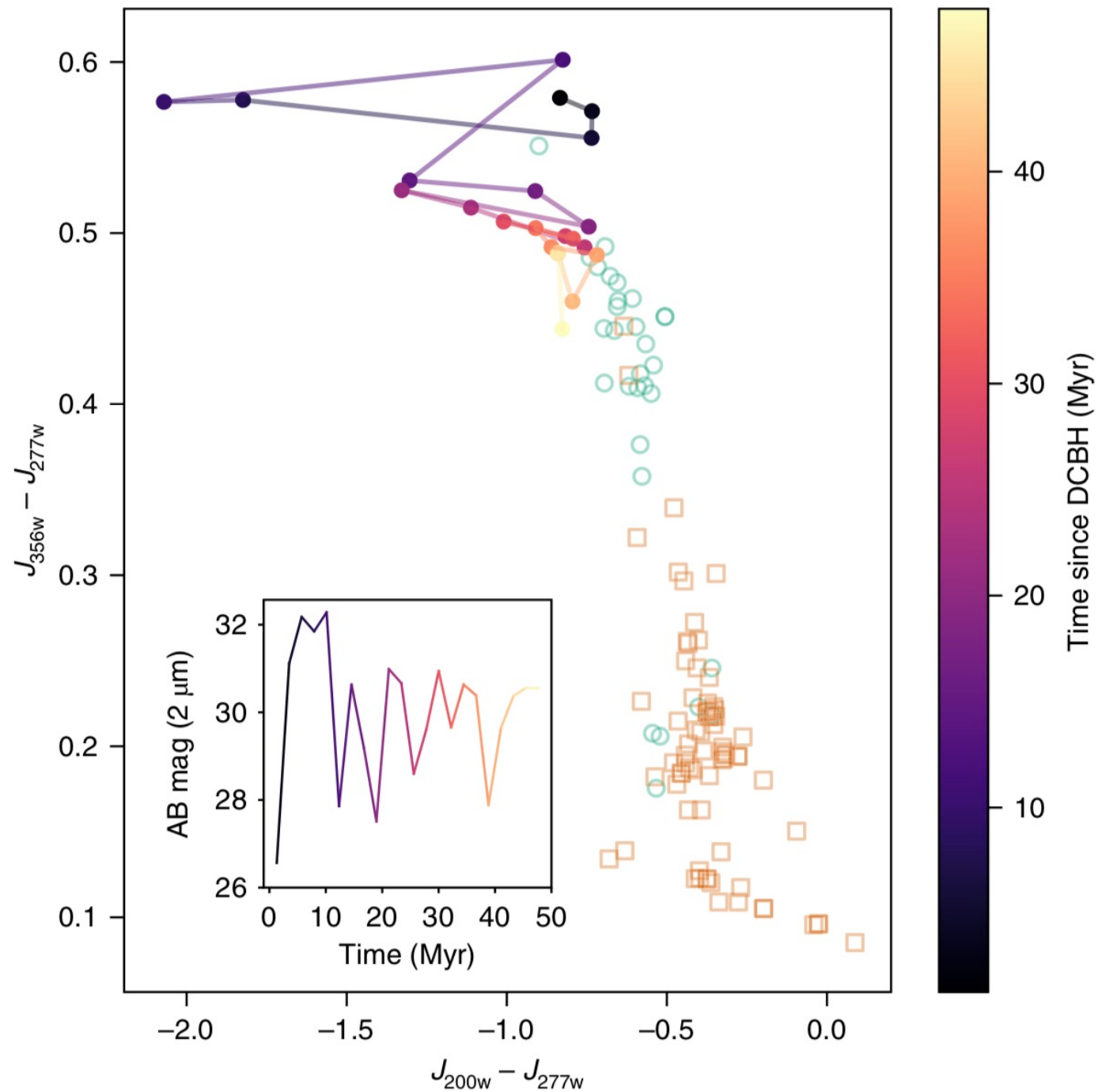
The “rise and fall” of DCBH population at Cosmic Dawn:



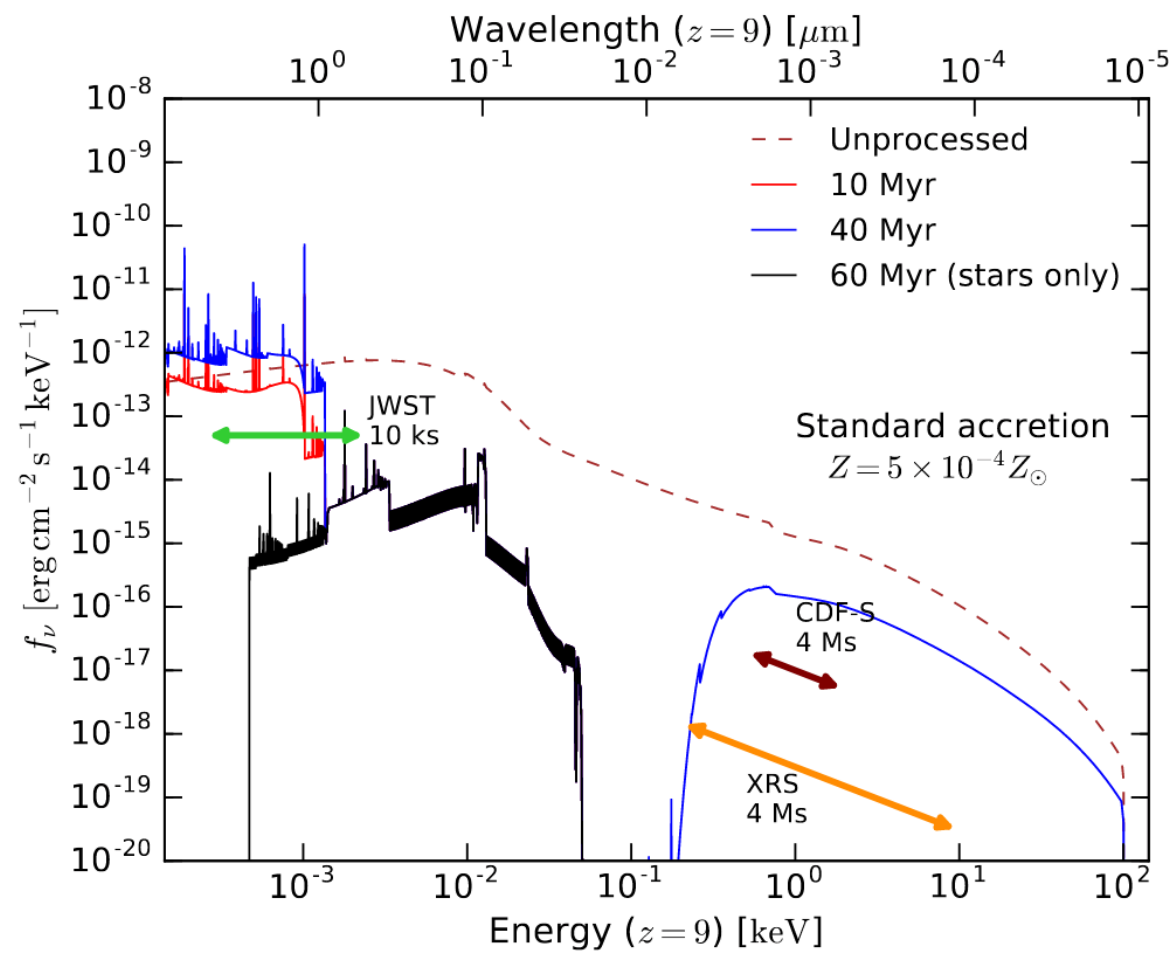
Yue et al. 2014

X-ray may reduce the formation rate of DCBH:





It is possible to identify DCBH candidates via photometric Observations.



Predicted X-ray of DCBH, Natarajan et al. 2017

We wrote a science outreach piece on WeChat Official Account of NAOC to introduce the first luminous objects

我们在国家天文台微信公众号上的一篇科普文章

宇宙中的那些第一代发光天体

原创 岳斌、张萌 中国科学院国家天文台

2020年10月20日 12:00 北京 2人

↑ 点击上方蓝字关注我们

现在，大家已经基本接受了这样的观念：

宇宙并不是从来都是这个样子的，而是一直在演化，其中的天体也不是与生俱来的，而是经历了从无到有，从少到多的过程。

那么，现在宇宙中那些我们熟知的发光天体：恒星、星系、黑洞等等，它们最早是怎么来的呢？我们的银河系非常古老，其中最老的恒星有一百多亿岁。宇宙中最早的发光天体必然形成于更早的时期，那时的宇宙还是一个小孩儿。

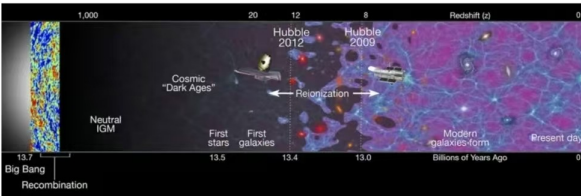


图1：宇宙的演化历史。宇宙的年龄约137亿年，第一代发光天体大概形成于宇宙年龄在几千万年到几亿年之

Summary:

- First stars must be Pop III stars, they formed in minihalos. First galaxies formed in atomic-cooling halos, either Pop III stars, or Pop II stars, or Pop III $\rightarrow$ Pop II. First black holes are either the relic stellar mass black holes after the death of Pop III stars, or the IMBHs formed through direct collapse of atomic-cooling gas.
- JWST has discovered some high- z galaxies at EoR and Cosmic Dawn, however the real first galaxies have not yet observed.
- DCBH scenario is the most promising model for origin of SMBH seeds, however the formation mechanisms are still poorly understood. Until now no DCBHs have been identified.

In a word: until now none of any first-generation luminous objects have been detected.

We are looking forward to seeing the first discovery of first luminous objects in (near) future!

Thanks!