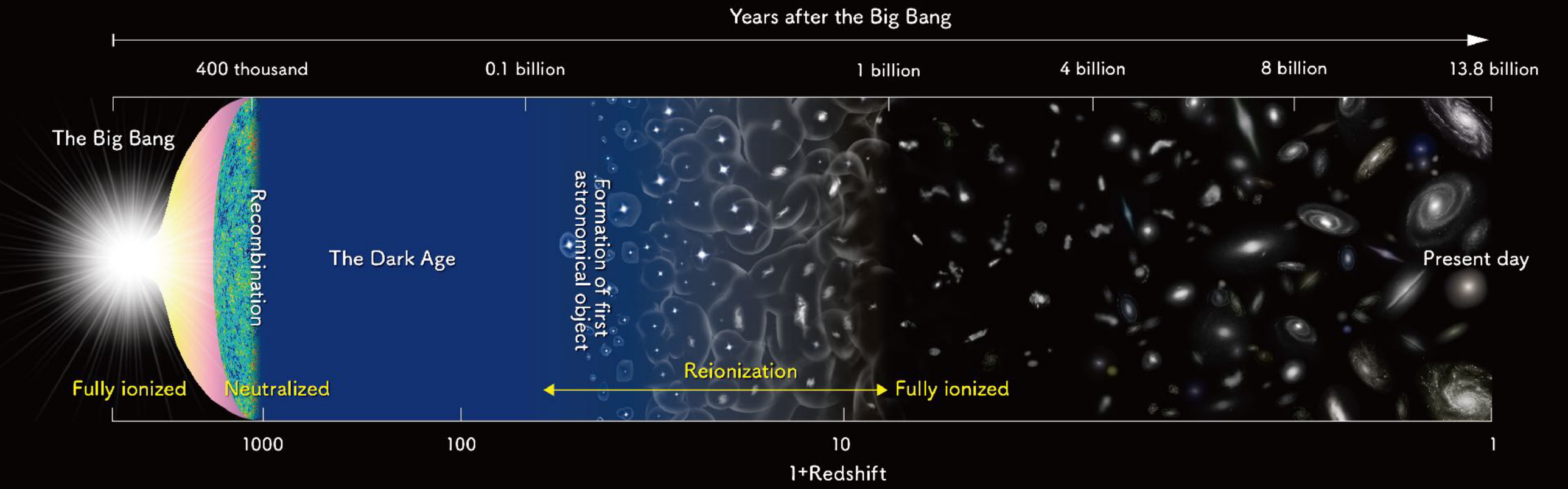
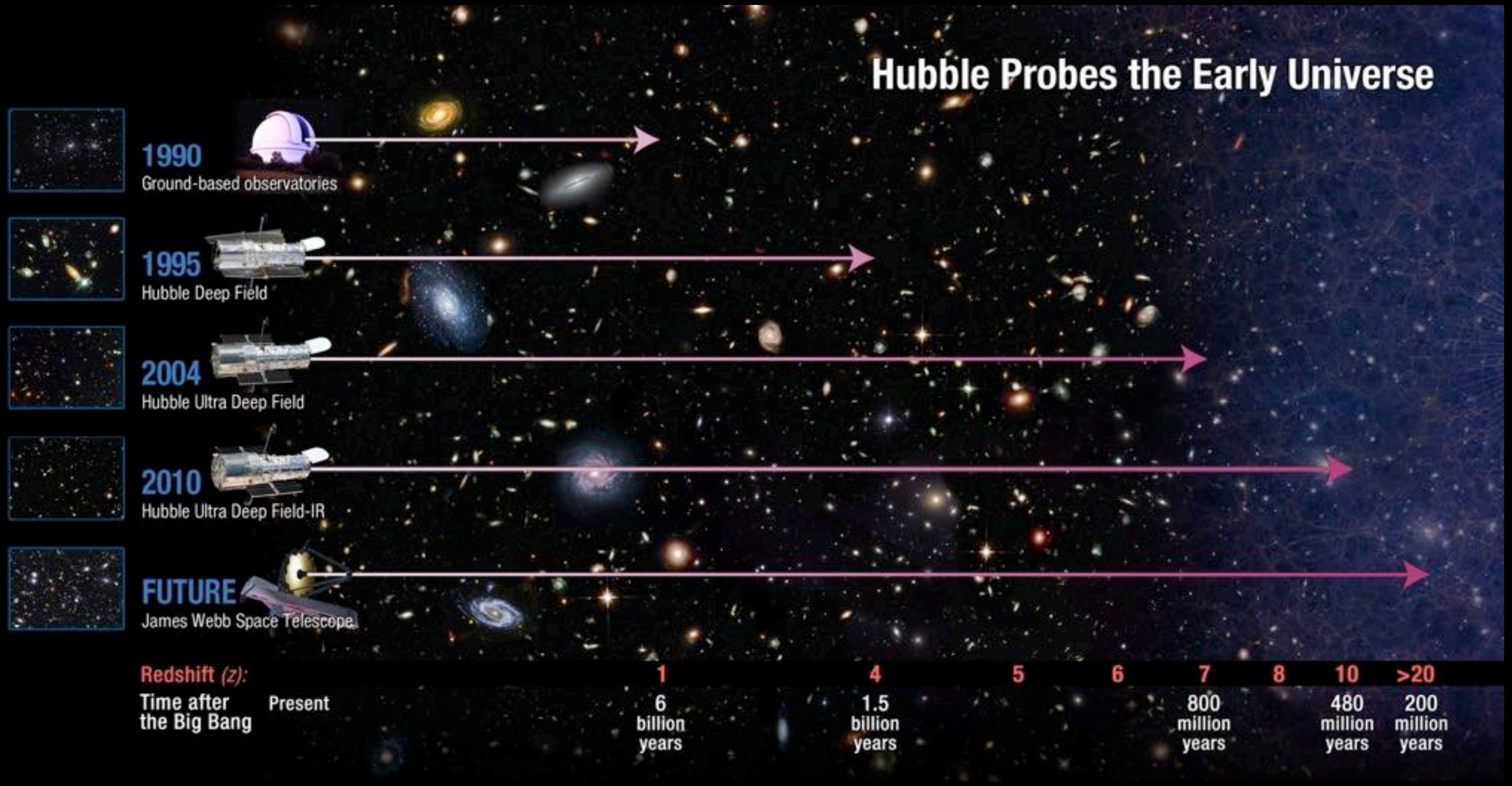
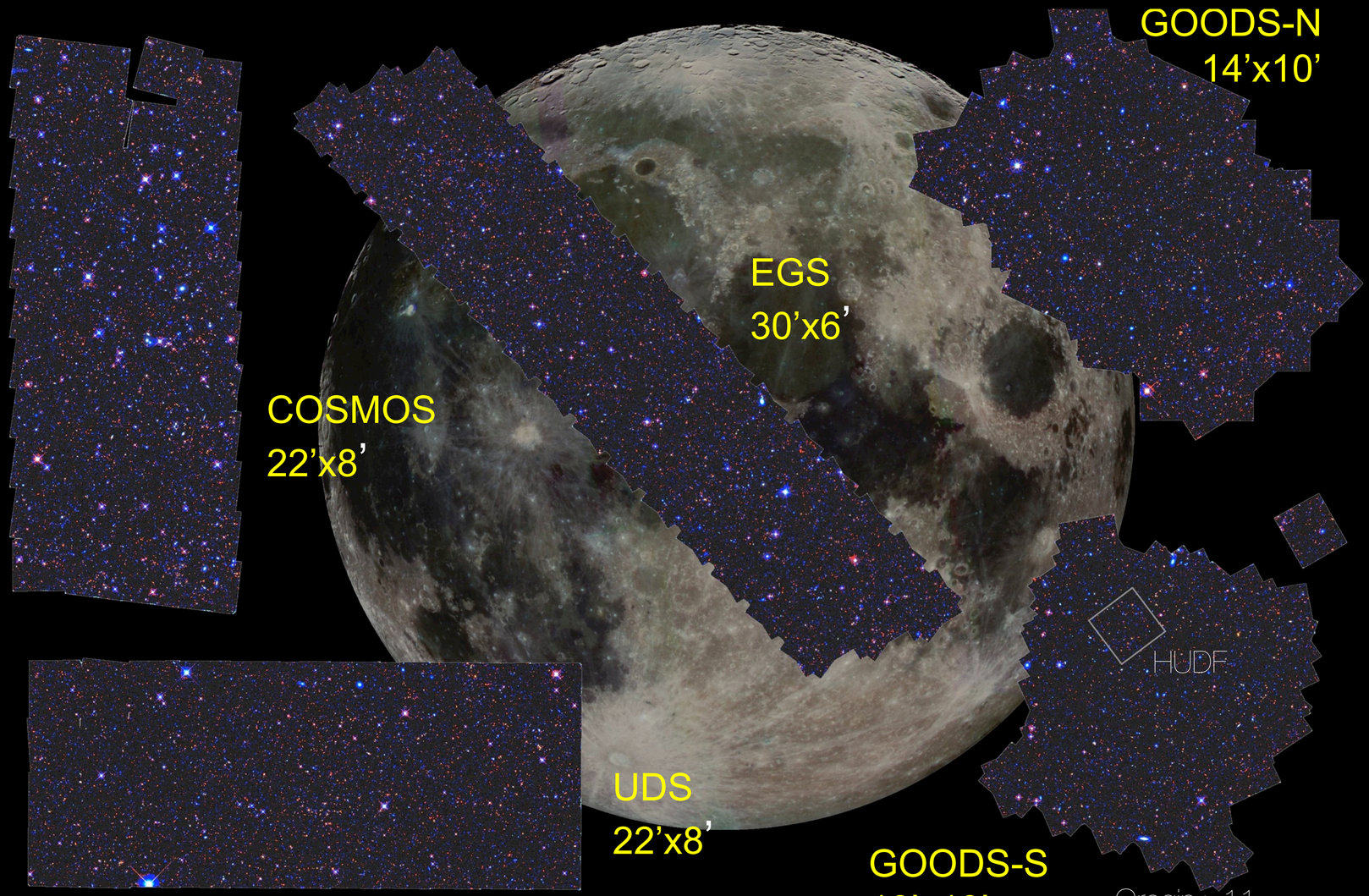
LBG and LAE Surveys: Constraints on (Late) Reionization

Andrea Weibel, 16.06.2022

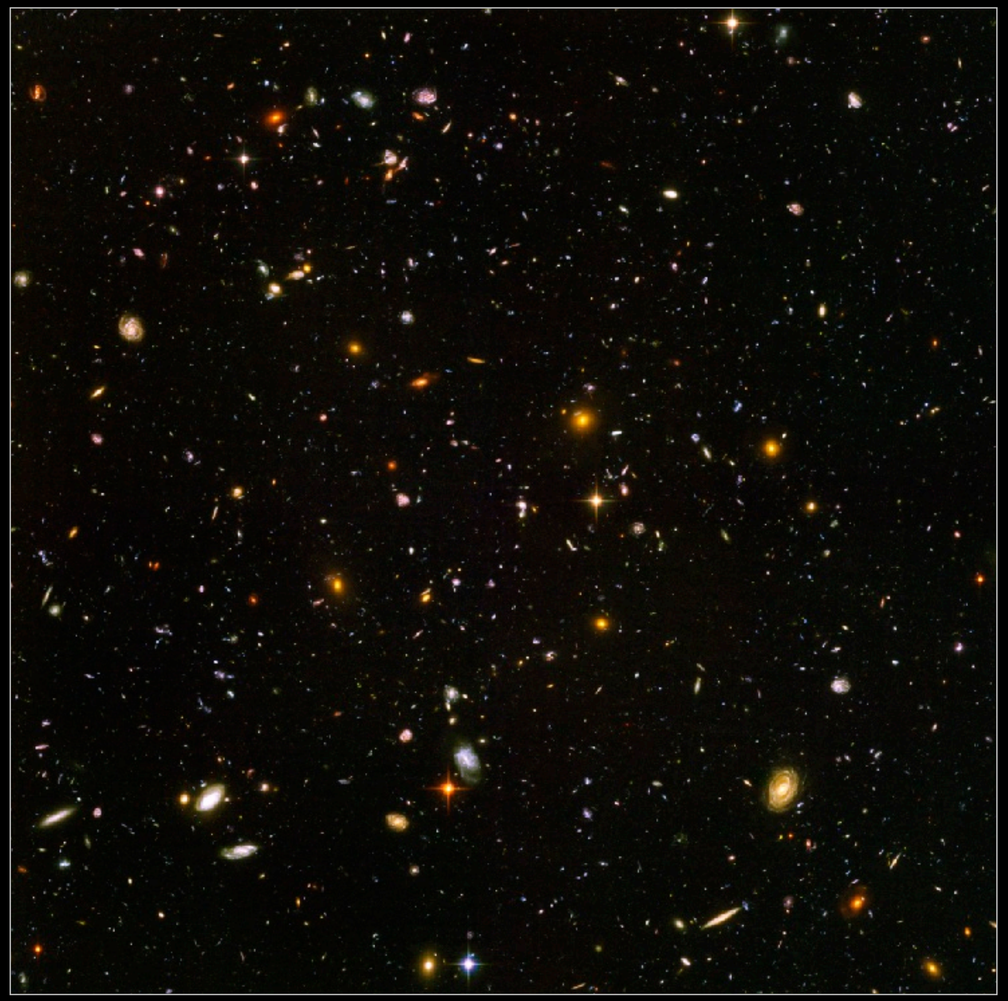

Years after the Big Bang
400 thousand
0.1 billion
1 billion
4 billion
8 billion
13.8 billion
The Big Bang
Recombination
The Dark Age
Formation of first astronomical object
Reionization
Present day
Fully ionized
Neutralized
Fully ionized
1000
100
10
1
1+Redshift

History of the redshift frontier with HST





Same fields covered with WFC3 Grism in AGHAST & 3D-HST



HUDF

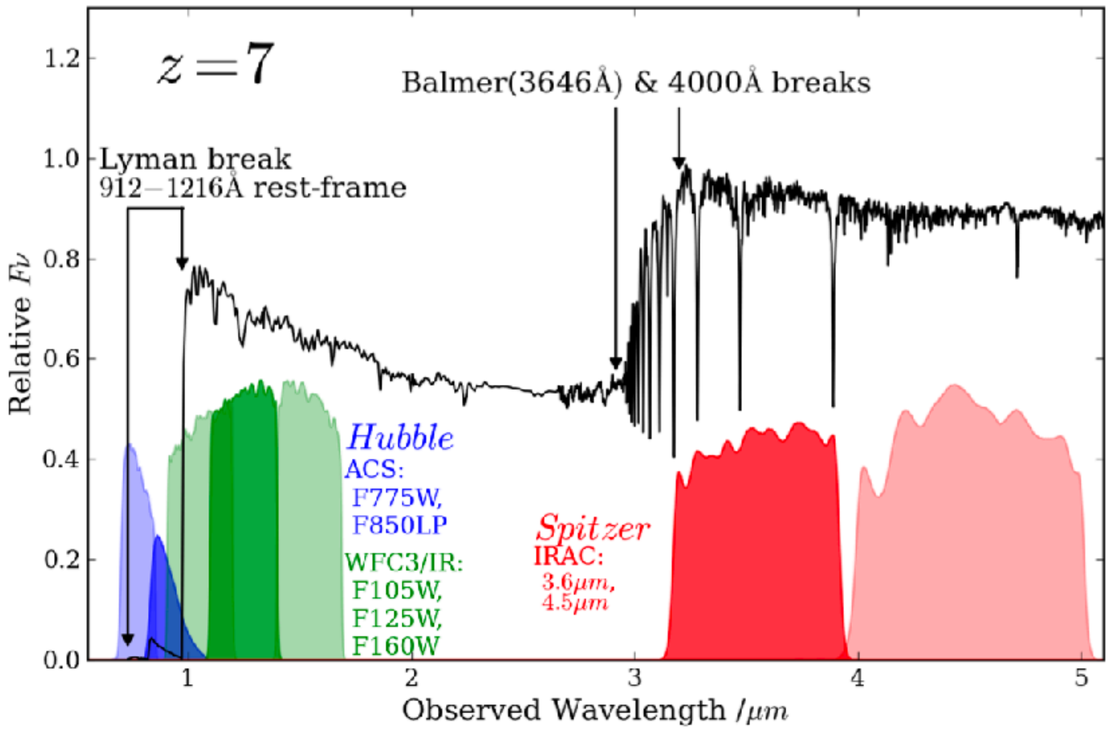
XDF

The Concept of LBGs

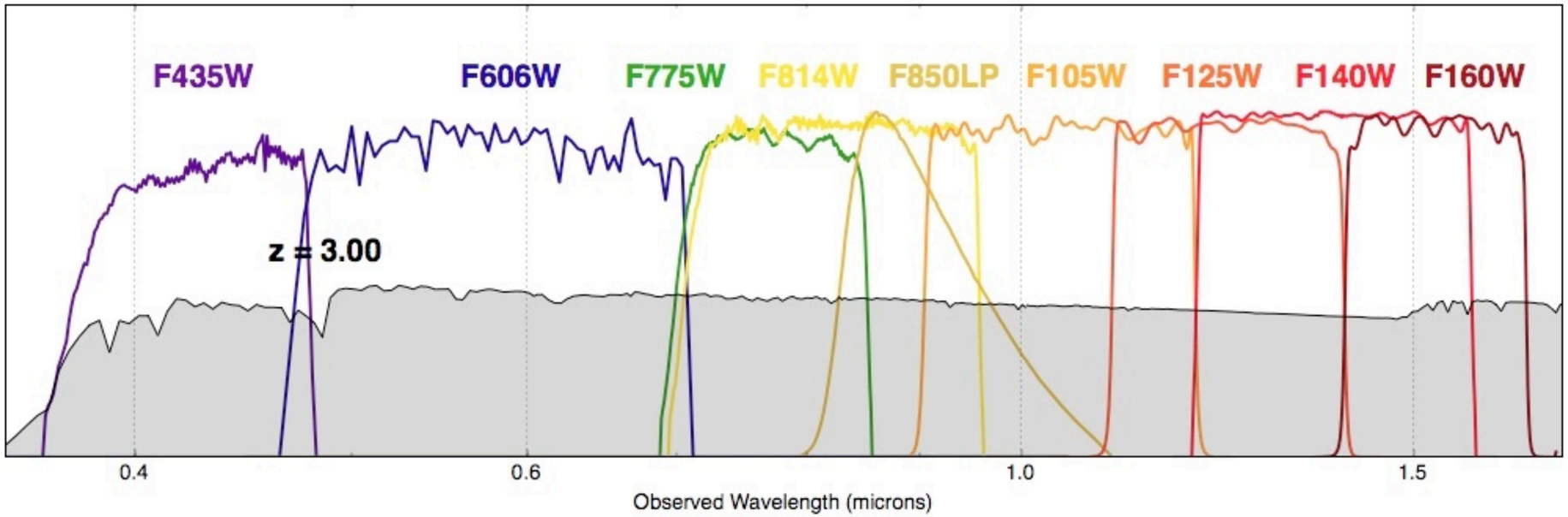
- Only a neutral fraction of $\sim 10^{-5}$ in the IGM is required to absorb (and re-emit) all photons around the Lyα - line.

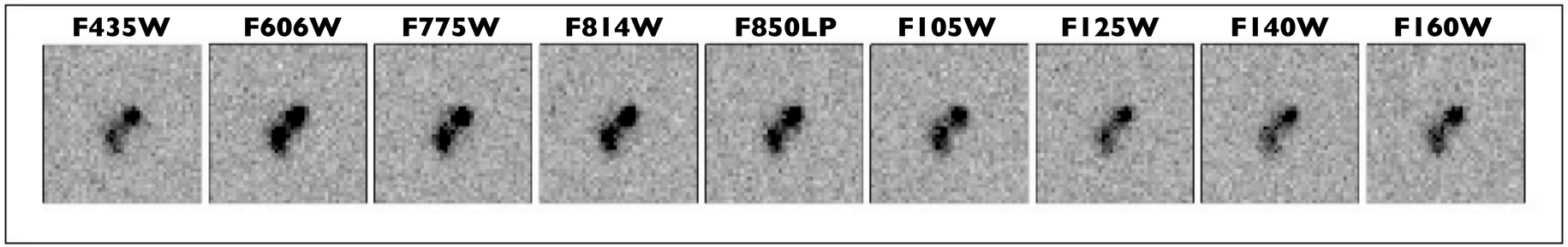
- Everything emitted at $\lambda < \lambda_\alpha = 1216\text{Å}$ gets redshifted into resonance with the Lyα - line and absorbed —> Lyman break.

Dunlop 2012



LBGs with HST

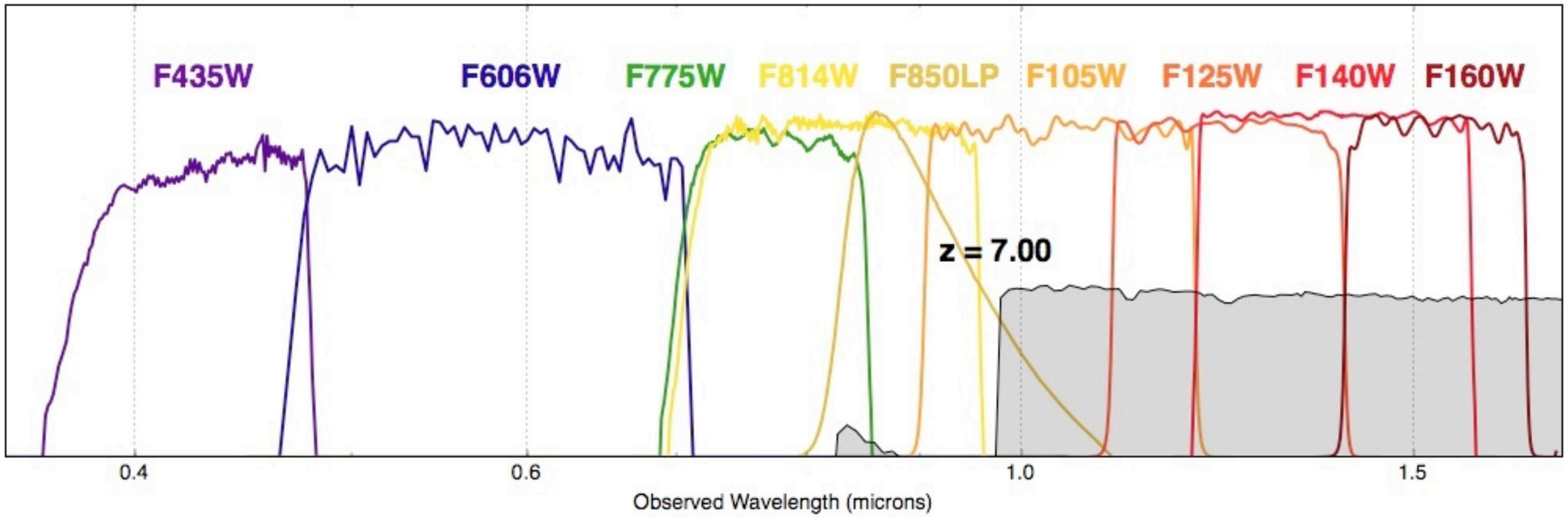


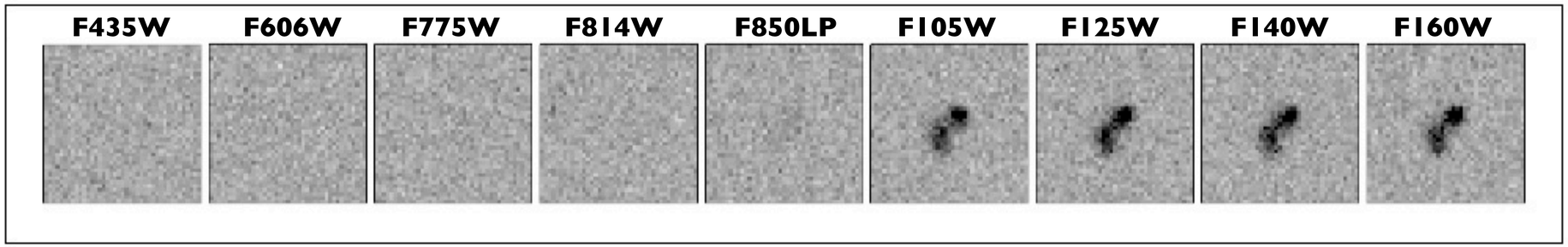


optical ACS

near-IR WFC3/IR

LBGs with HST

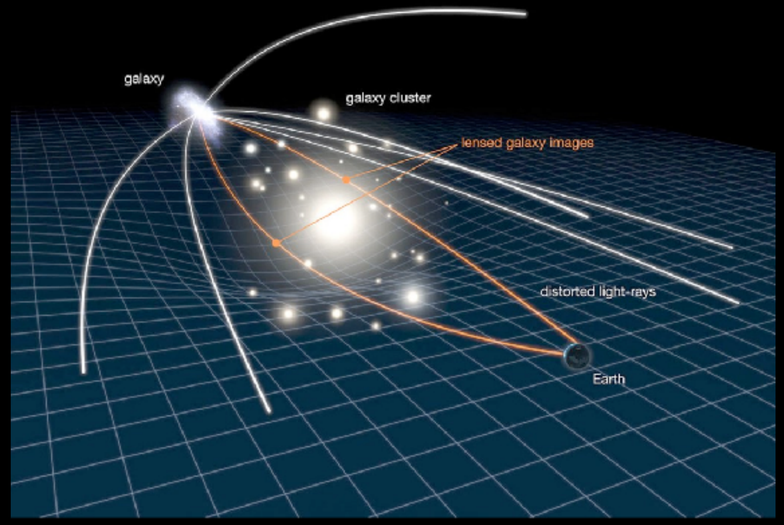


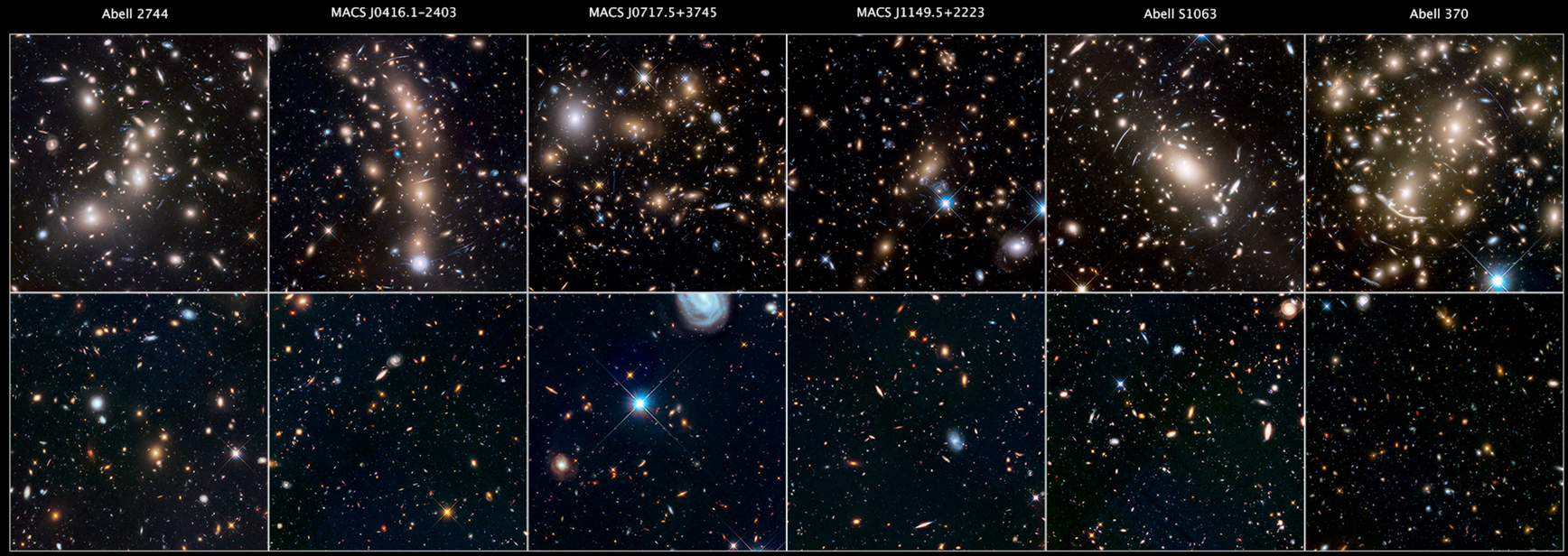


optical ACS

near-IR WFC3/IR

Natural telescopes: Gravitational Lensing





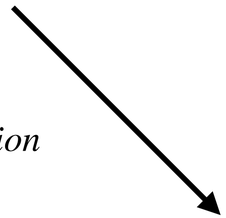
Path to Constraining Reionization from LBG surveys

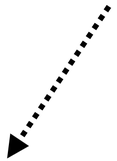
Nr. of LBGs found in a given survey at a given z

UV Luminosity function, ρ_{UV}

Cosmic Star Formation Rate Density

ξ_{ion}

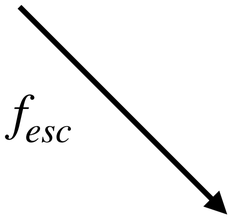




Intrinsic Production Rate of Ionizing Photons

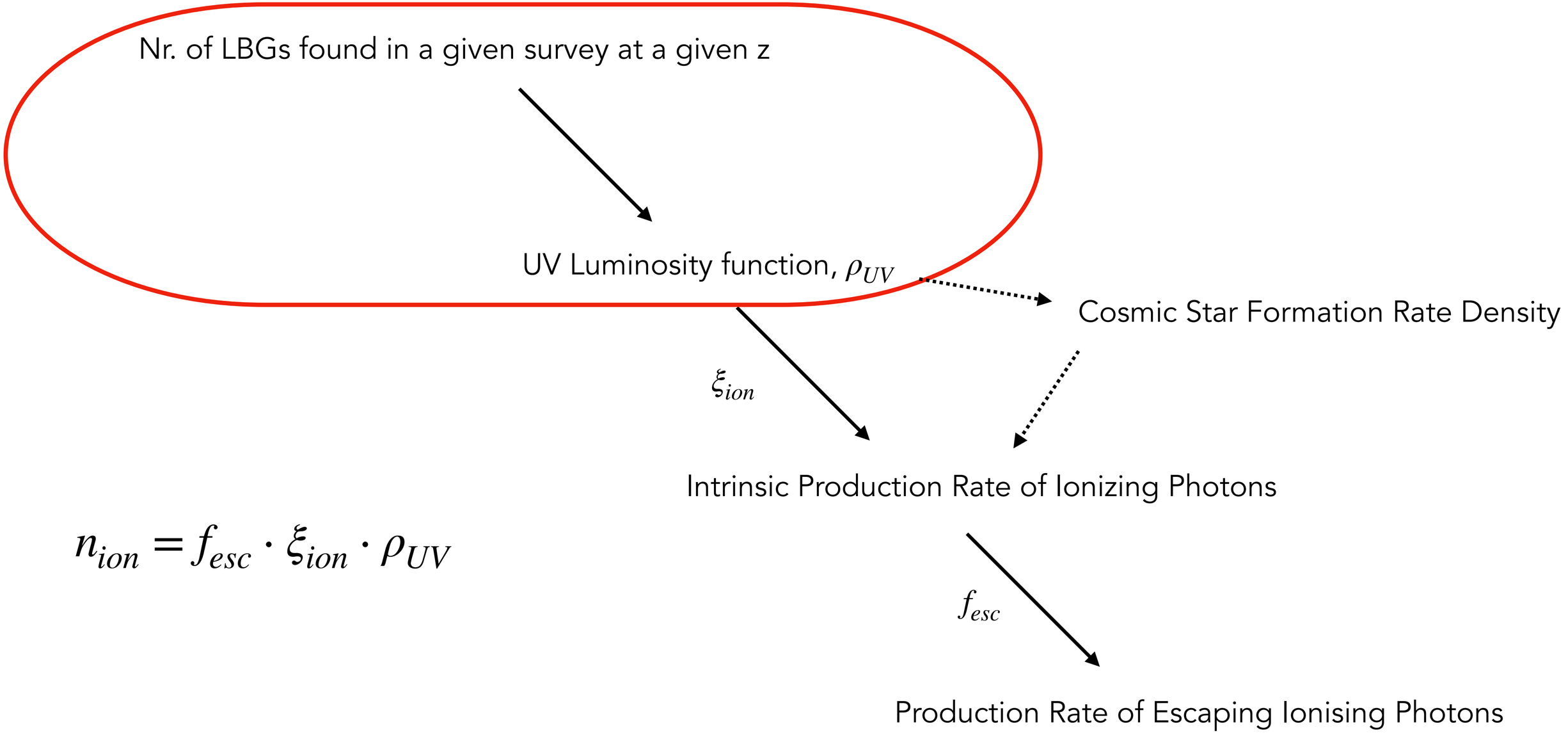
$$n_{ion} = f_{esc} \cdot \xi_{ion} \cdot \rho_{UV}$$

f_{esc}



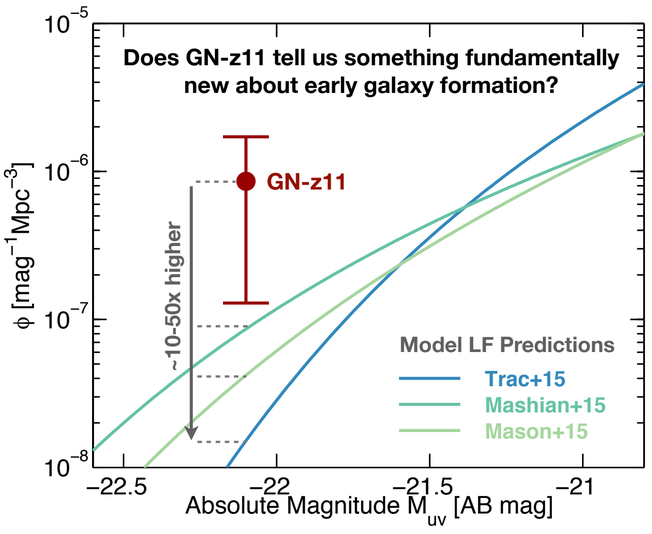
Production Rate of Escaping Ionising Photons

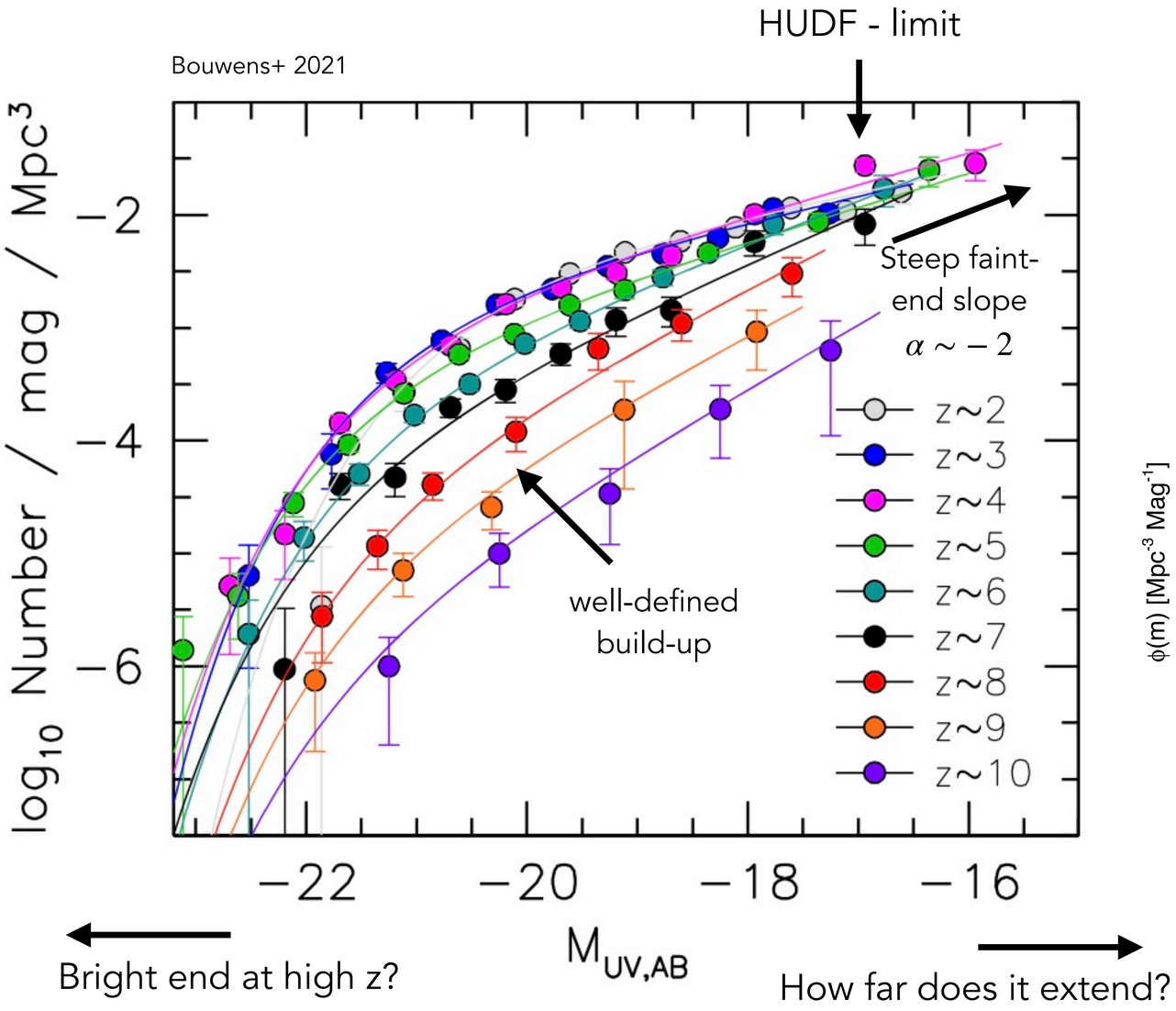
Path to Constraining Reionization from LBG surveys

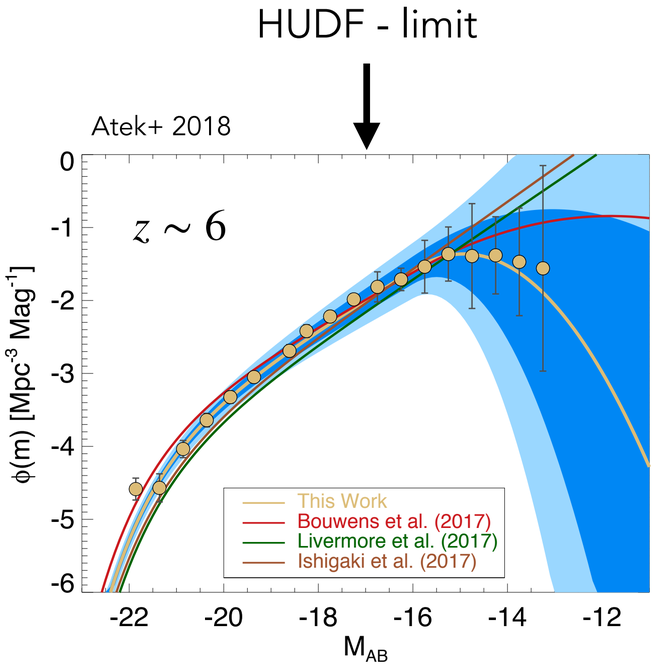


$$n_{ion} = f_{esc} \cdot \xi_{ion} \cdot \rho_{UV}$$

UV Luminosity Function



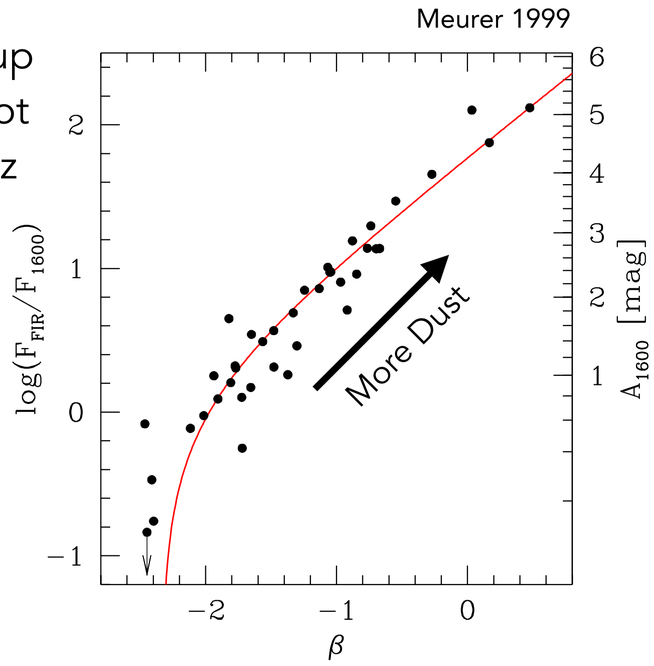


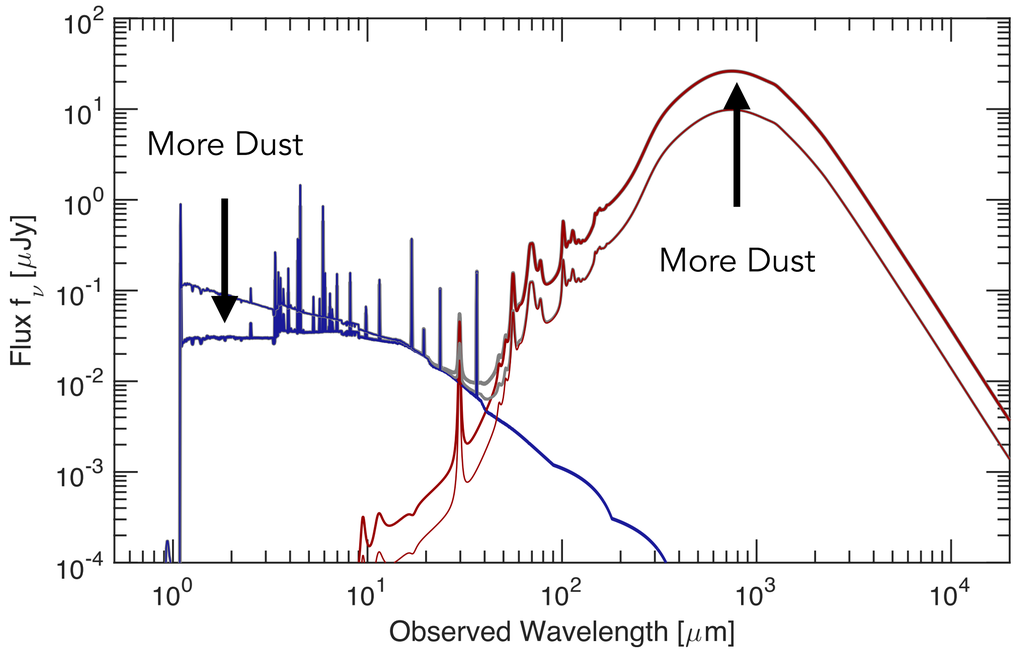


Dust Correction: The IRX-β relation

- UV-slope β: $f_\lambda \propto \lambda^\beta$, measured as color at wavelengths of $1500 - 2500\text{Å}$
- IRX = L_{IR}/L_{UV}, fraction of energy that is re-emitted in the IR

Shown to hold up To z~2-3, but not clear at higher z

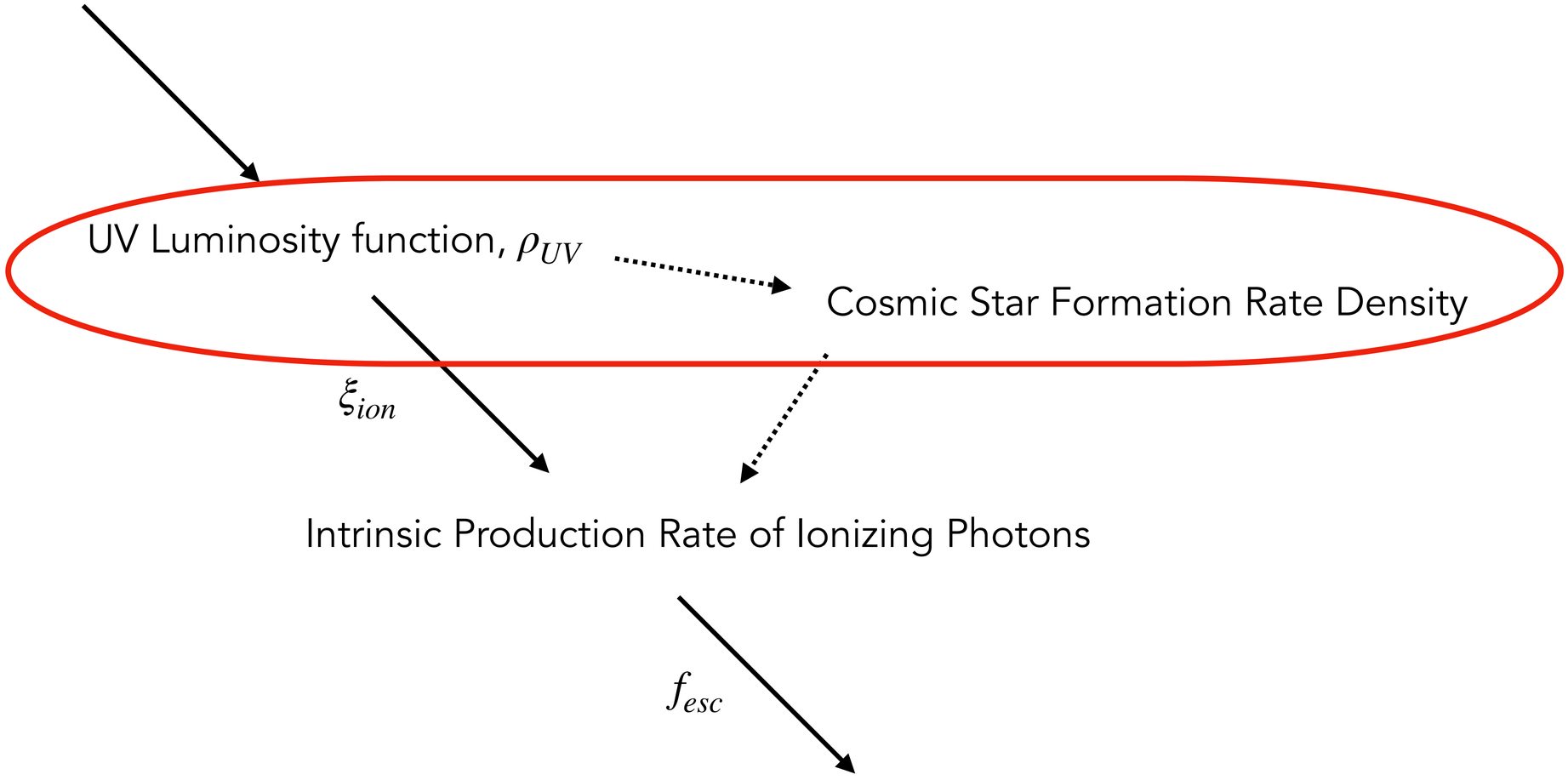




- (+IMF, usually assumed to be universal, based on MW measurements…)

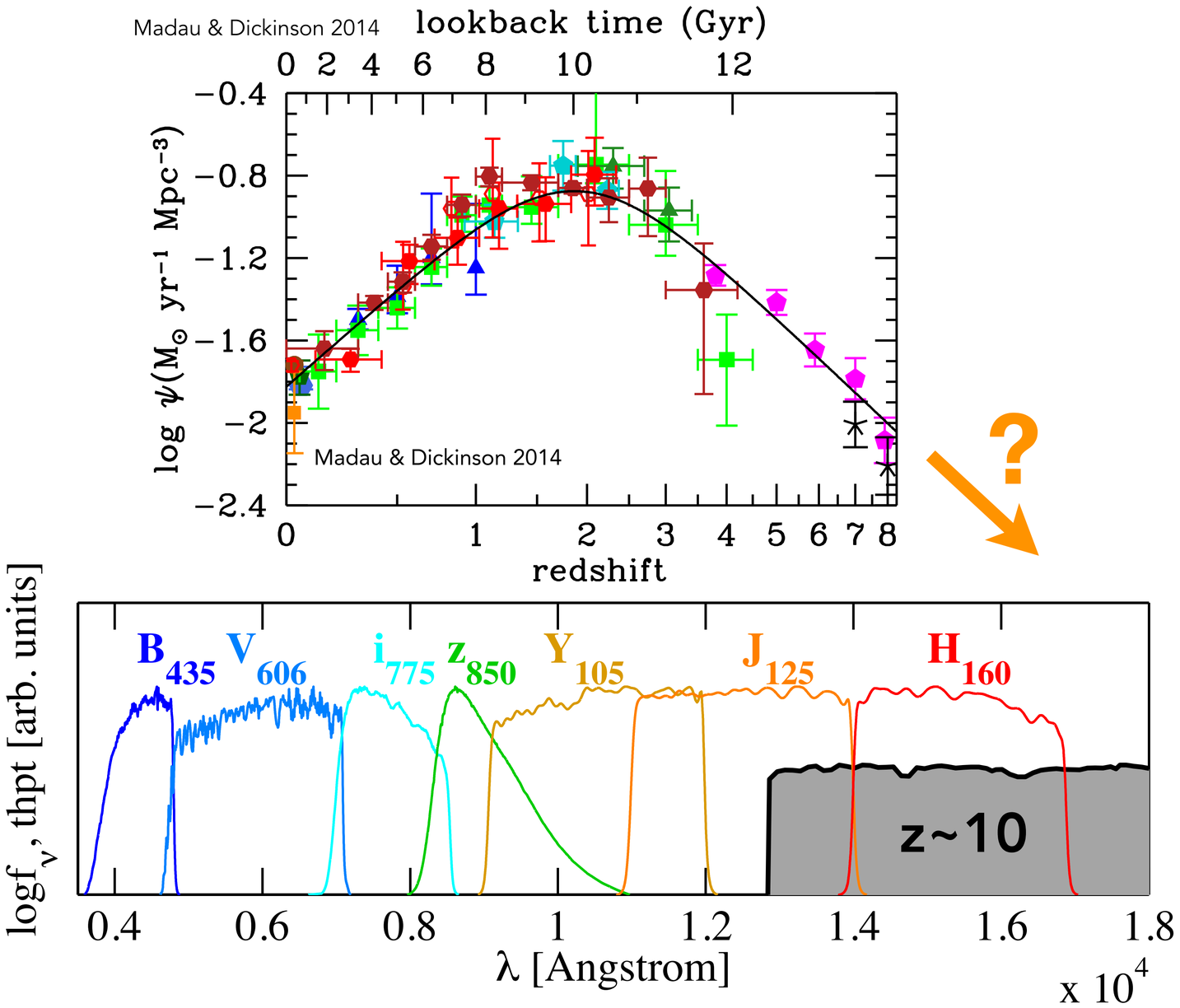
Path to Constraining Reionization from LBG surveys

Nr. of LBGs found in a given survey at a given z

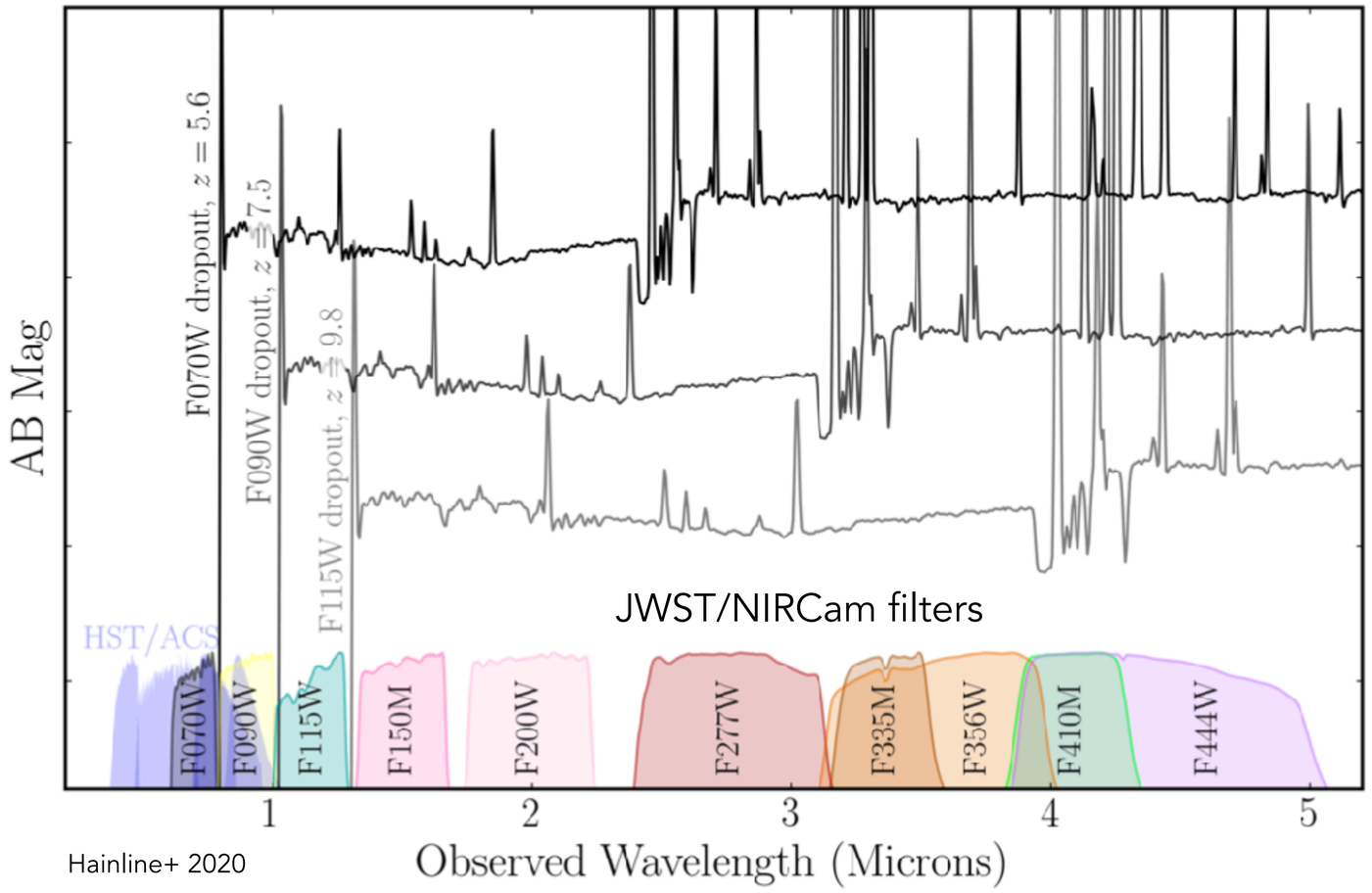


$$n_{ion} = f_{esc} \cdot \xi_{ion} \cdot \rho_{UV}$$

Cosmic Star Formation Rate Density (1)

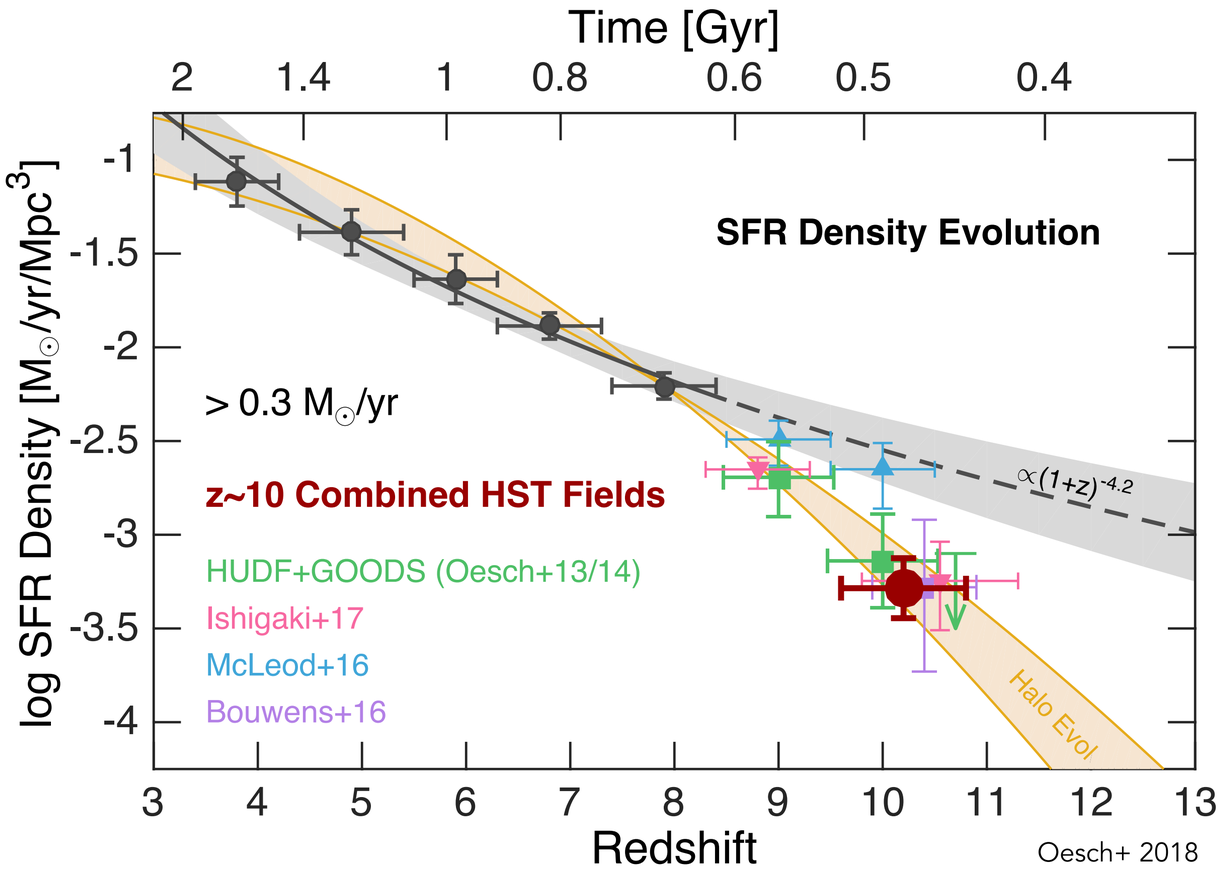


New Possibilities with JWST



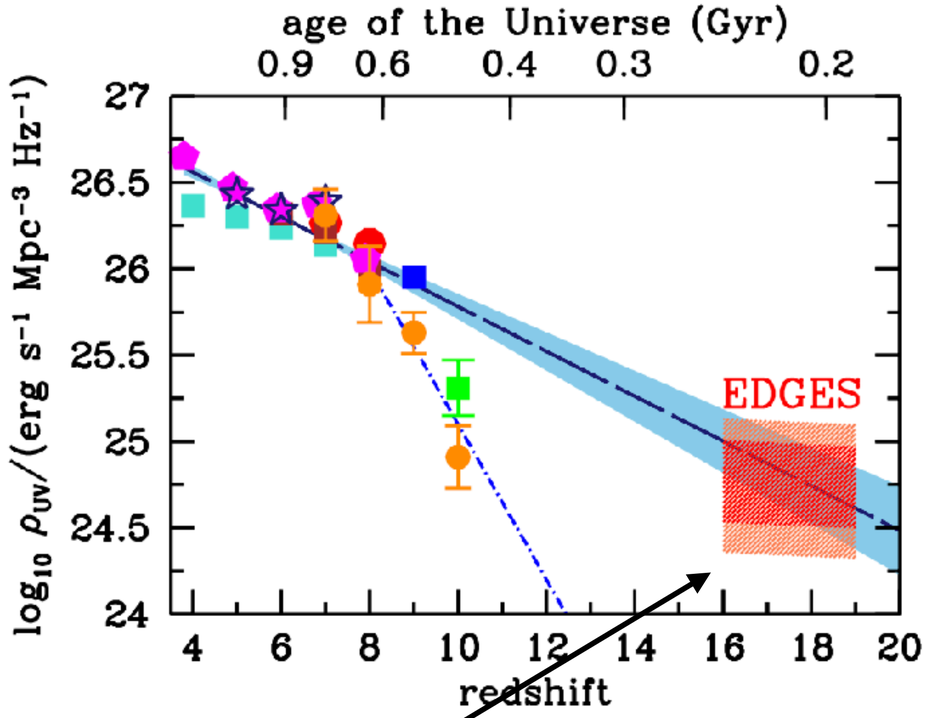
Hainline+ 2020

Cosmic Star Formation Rate Density (2)



Oesch+ 2018

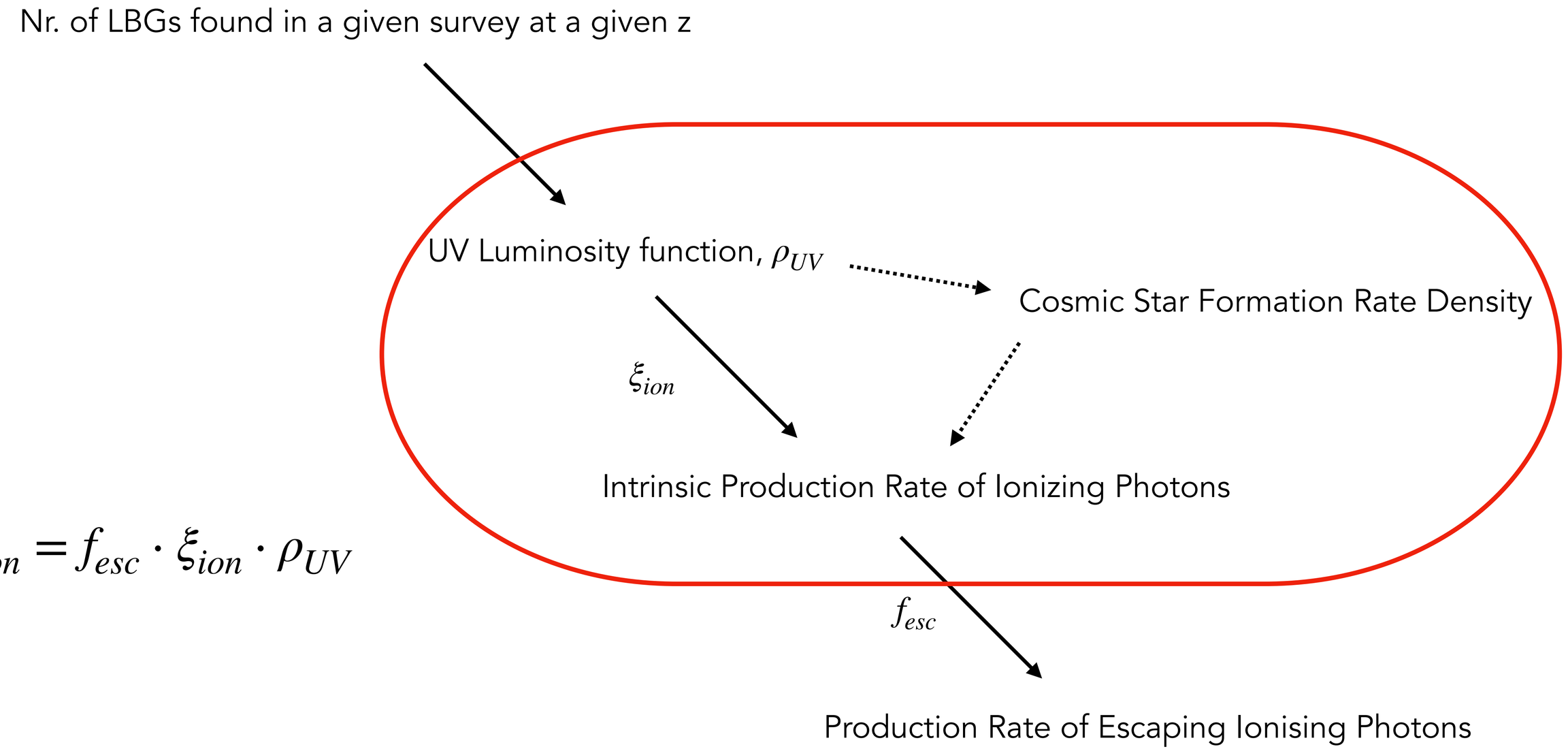
Madau 2018



Gray: extrapolation from low-z results —> accelerated evolution at high z.
Orange: Halo MF, normalised to the z=8 SFRD value.

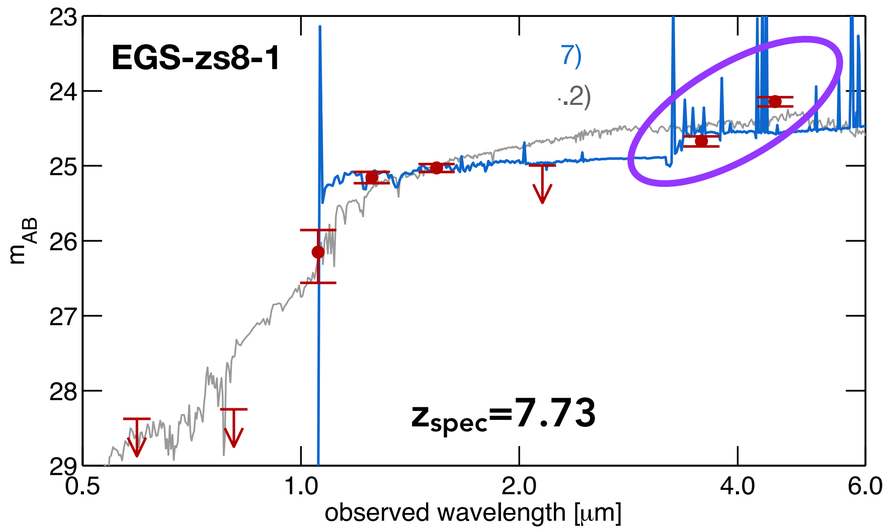
BUT:

Path to Constraining Reionization from LBG surveys

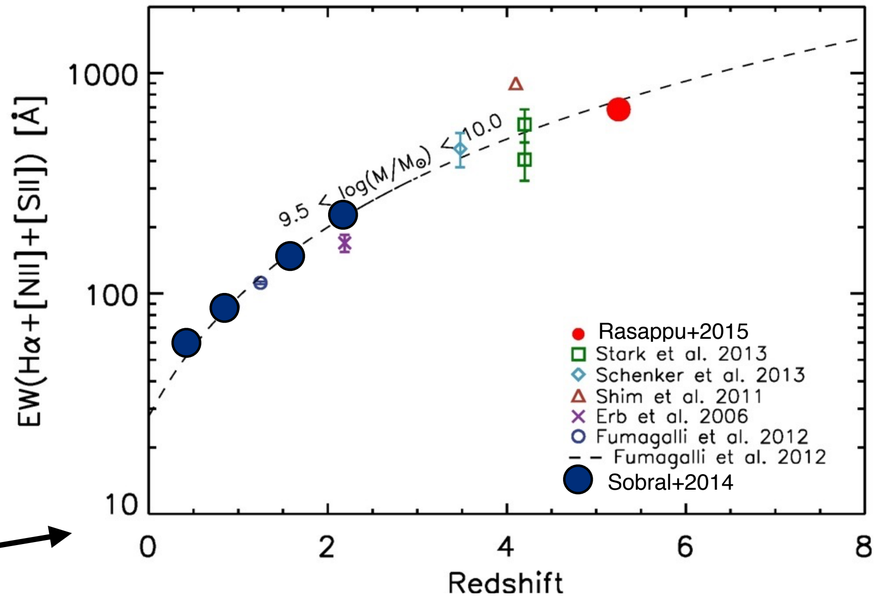


$$n_{ion} = f_{esc} \cdot \xi_{ion} \cdot \rho_{UV}$$

Intrinsic Production Rate of Ionizing Photons: Higher at high z?

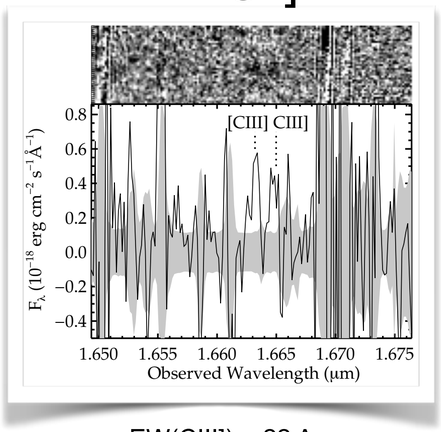


Oesch+15



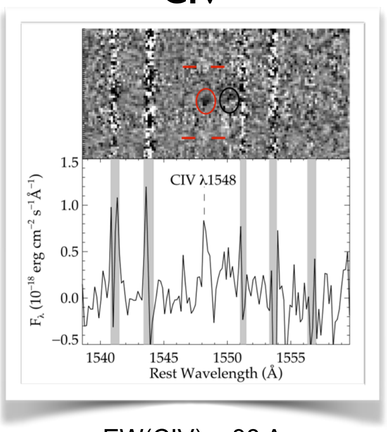
Strong rest-frame optical emission lines indicated by the IRAC/Spitzer photometry in z>7 galaxies

CIII]



EW(CIII]) ~ 22 A
z = 7.73

CIV



EW(CIV) ~ 38 A
z = 7.045

Stark+15, Stark+17, Schmidt+17

High-ionization lines found in high-z galaxy spectra

Path to Constraining Reionization from LBG surveys

Nr. of LBGs found in a given survey at a given z

UV Luminosity function, ρ_{UV}

Cosmic Star Formation Rate Density

ξ_{ion}

Intrinsic Production Rate of Ionizing Photons

f_{esc}

Production Rate of Escaping Ionising Photons

$$n_{ion} = f_{esc} \cdot \xi_{ion} \cdot \rho_{UV}$$

The Escape Fraction of Ionizing Photons

- Direct detections of so-called Lyman continuum leakers are rare and only possible up to $z \sim 4$, above that the IGM is opaque to LyC-emission.
- High escape fractions are observed in the few leakers that we know. But we would need an *average* f_{esc} of $\sim 10\%$ if galaxies are driving reionization alone.
- Various indirect tracers of the escape fraction have been proposed, e.g.:
  - The [OIII]/[OII] ratio (tracing density-bounded HII-regions)
  - The Lyα line-properties (profile, peak separation, see later)
  - UV absorption lines (tracing cold ISM gas covering fractions, via e.g. CII, SiII)
  - Nebular emission lines (e.g. CIV, recently proposed)

The Lyα forest at $z \lesssim 5$

- Optical depth of the Lyα - line :

$$\tau_\alpha = 1.6 \cdot 10^5 x_{HI}(1+\delta)\left(\frac{1+z}{4}\right)^{3/2}$$

$$n_{HI}(z) = \overline{n_{HI}}(z)(1+\delta)$$

- Net transmission

$$T_\alpha = \int d\delta\, p(\delta)\, exp(-\tau_\alpha(\delta)) =: exp(-\tau_{eff,\alpha}),\ \tau_{eff,\alpha} \leq \tau_\alpha$$

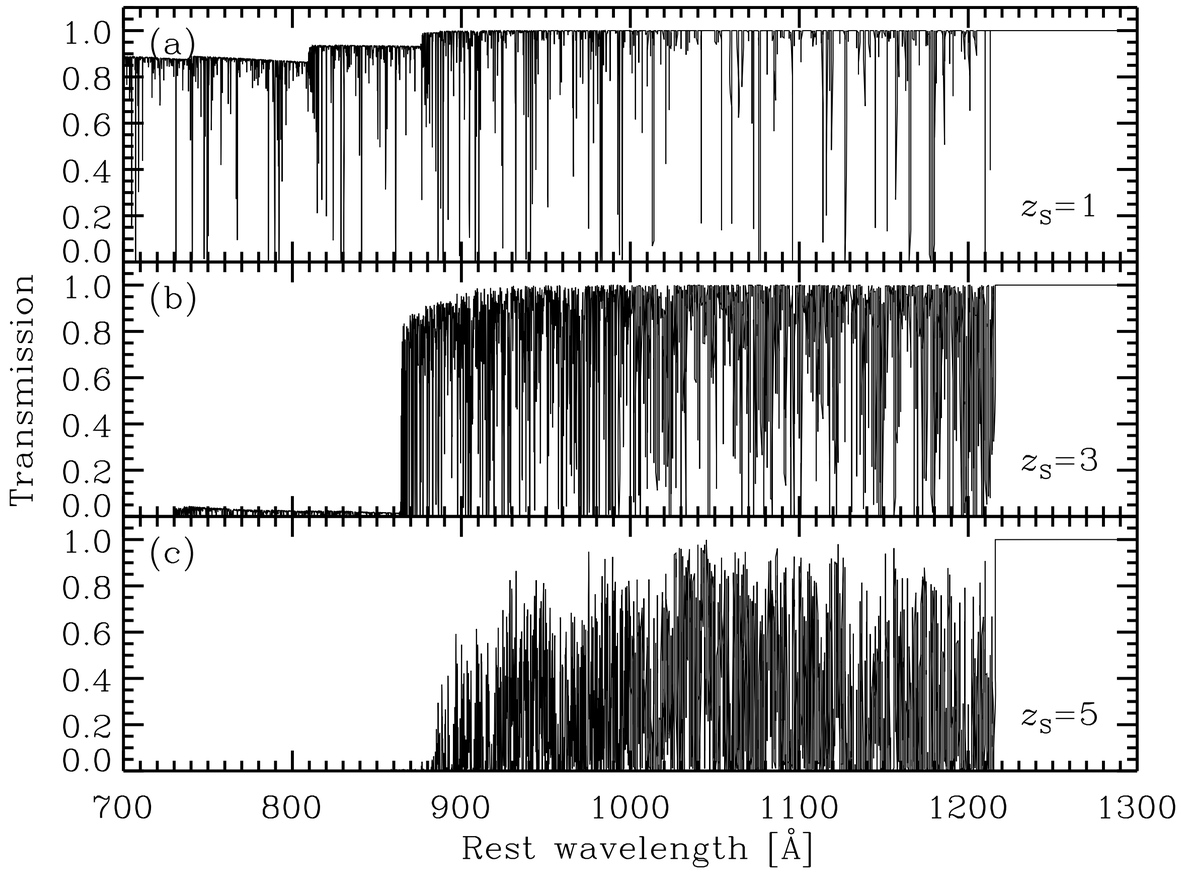
- Observationally,

$$\tau_{eff,\alpha} = (0.85 \pm 0.06)\left(\frac{1+z}{5}\right)^{4.3\pm0.3} \sim 2.6 \text{ at } z \sim 5.5$$

$\Longrightarrow$ 7% transmission

- Lyα - forest statistics works up to $z \sim 5.5$, based on the most underdense pockets of the Universe.

Inoue & Iwata 2008

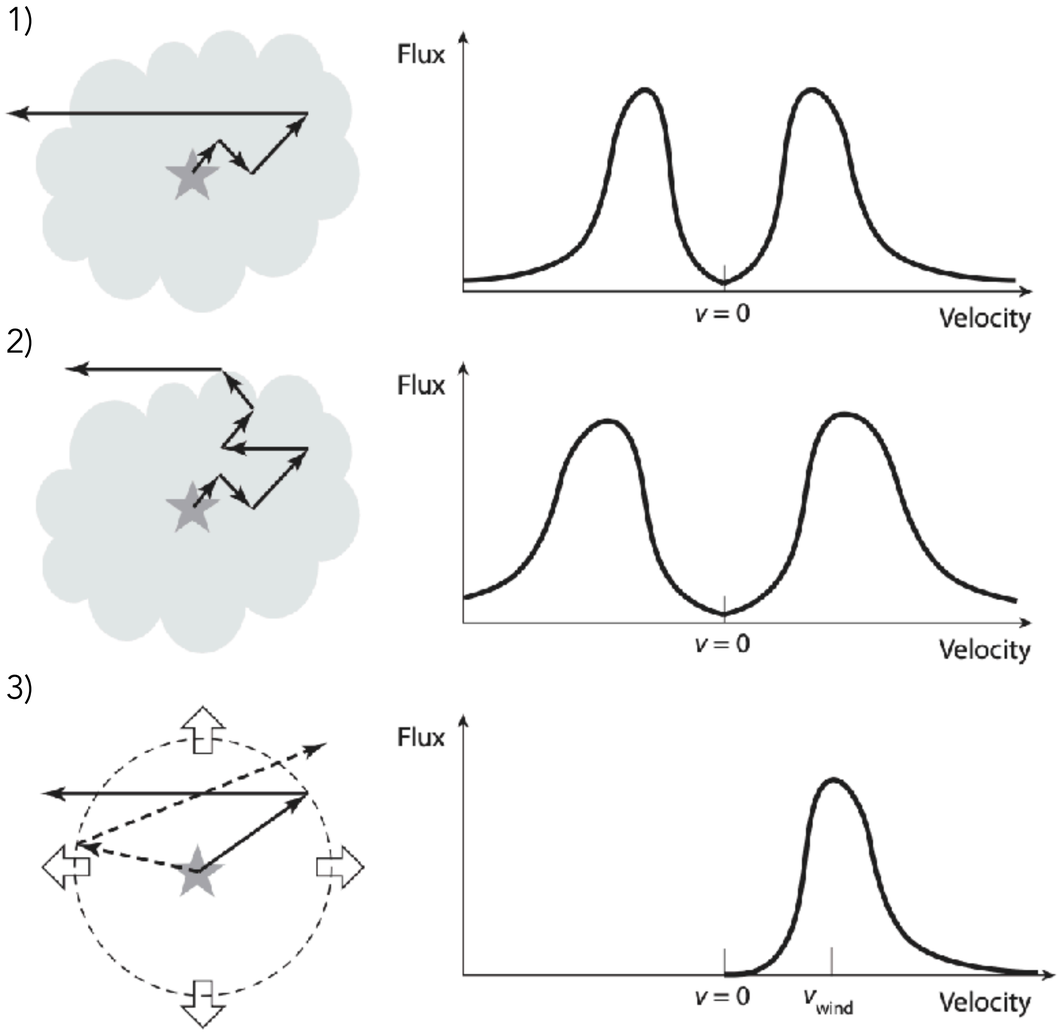


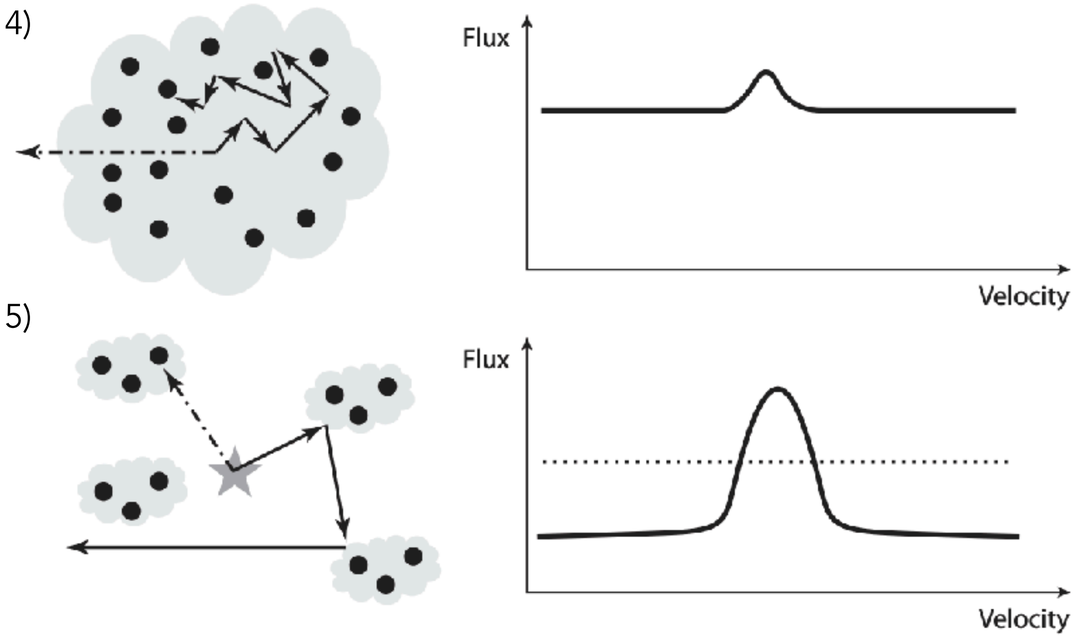
At $z \gtrsim 5$, we can still observe the Lyα line

- First detection at $z > 5$ in 1998 (Dey et al.)
- Narrow-band photometry: Detected flux in a narrow band around the Lyα line center ($\lambda_{obs} = (1 + z_s)\lambda_\alpha$, $\lambda_\alpha = 1216\text{Å}$), little/no flux in adjacent bands.
- Ground-based searches are constrained to windows between the OH emission lines of the atmosphere and correspond to $z = 5.7$, 6.5, 7.0 and 7.3
- Most line emitters in these bands are low-z interlopers ([OII], [OIII] or [Hα] at $z \sim 0.5 - 1.5$) —> use additional color selections to get robust LAEs

Mechanisms of Lyα Escape

Loeb & Furlanetto 2013



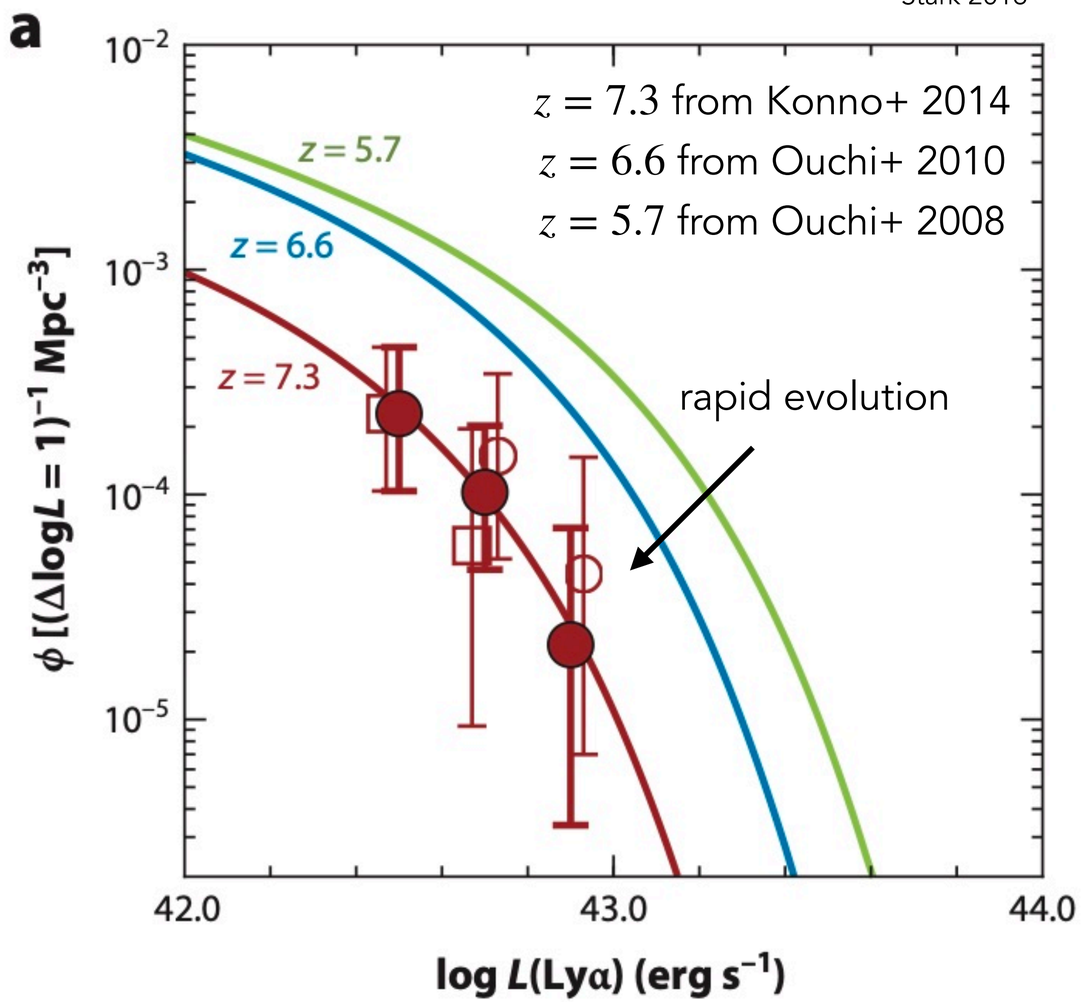


The complexity and variety of observed line profiles makes the interpretation complicated but also contains a lot of information…

Approaches to Constraining Reionization through LAE surveys

1. The LAE Luminosity Function

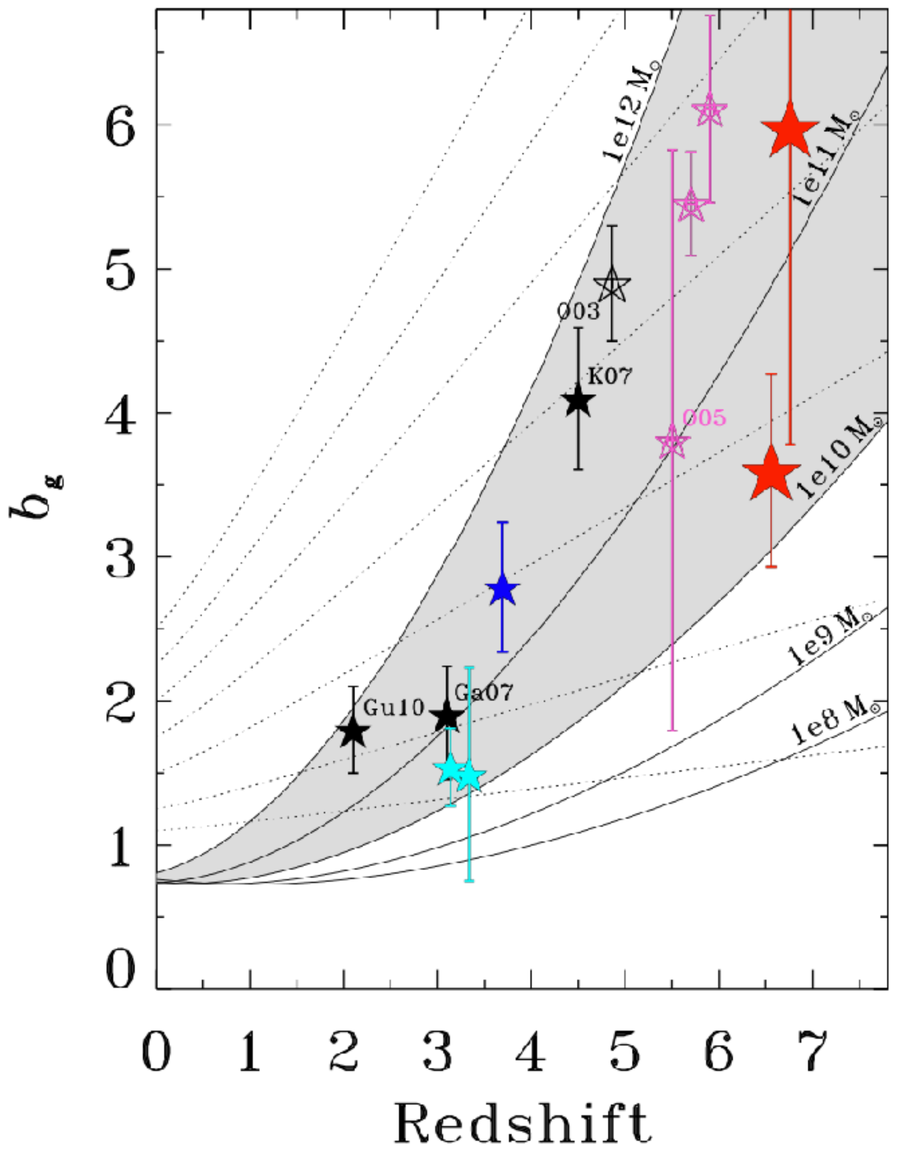
Stark 2016



Approaches to Constraining Reionization through LAE surveys

2. Clustering of LAEs

Ouchi+ 2010

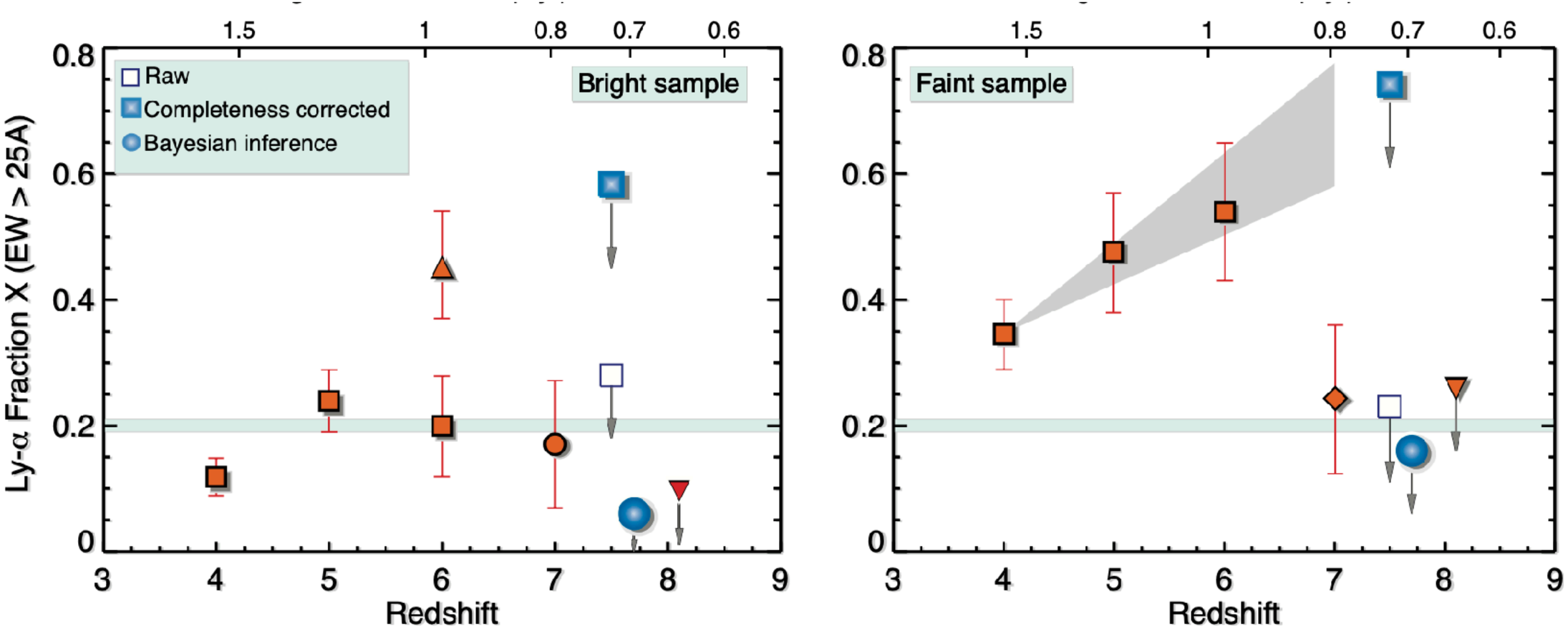


A neutral fraction $x_{HI} < 0.5$ is required at $z = 6.5$ to account for the fact that we do NOT see a clustering effect.
This result has been confirmed by otherauthors after 2010 but there do not seem to be more recent results…

Approaches to Constraining Reionization through LAE surveys

3. LAE fraction in LBGs

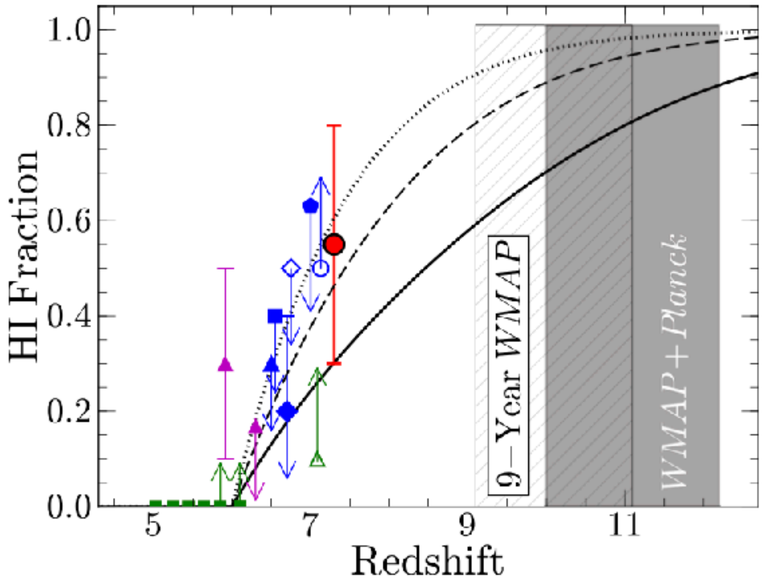
Tilvi+ 2014



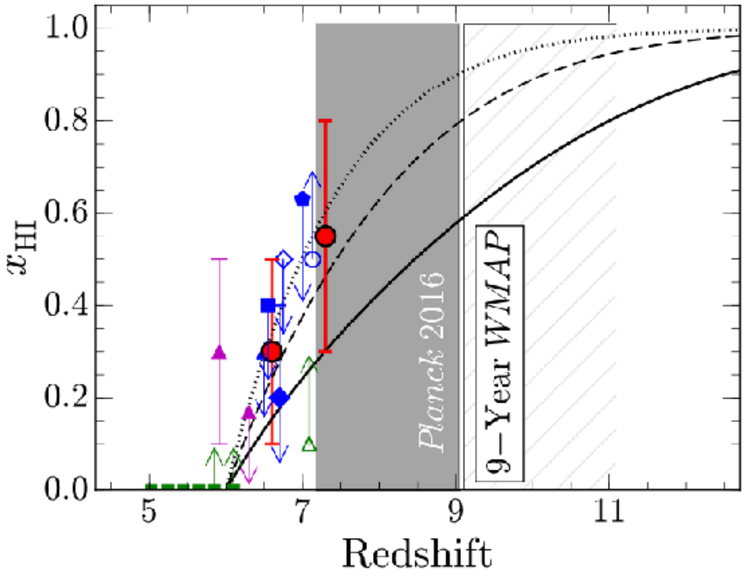
Red markers compiled from Stark+ 2011, Curtis-Lake+ 2012 and Ono+ 2012

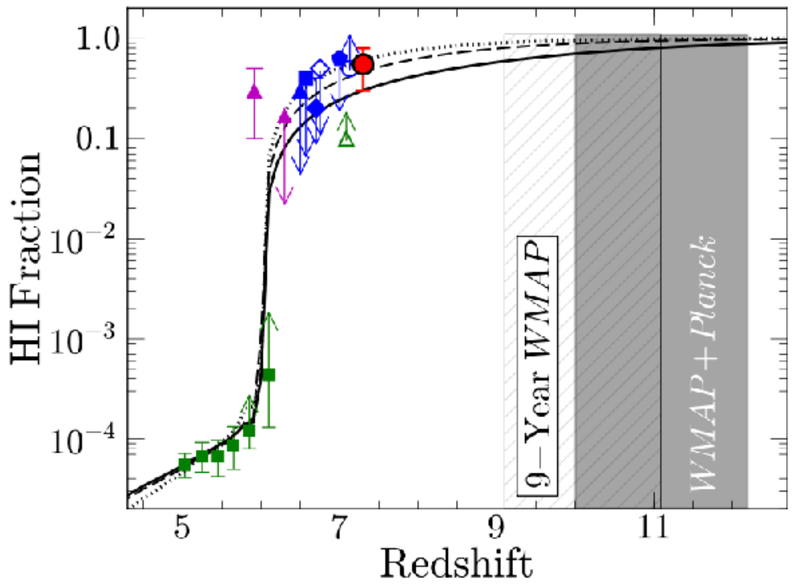
Neutral Fraction as a function of z from different methods

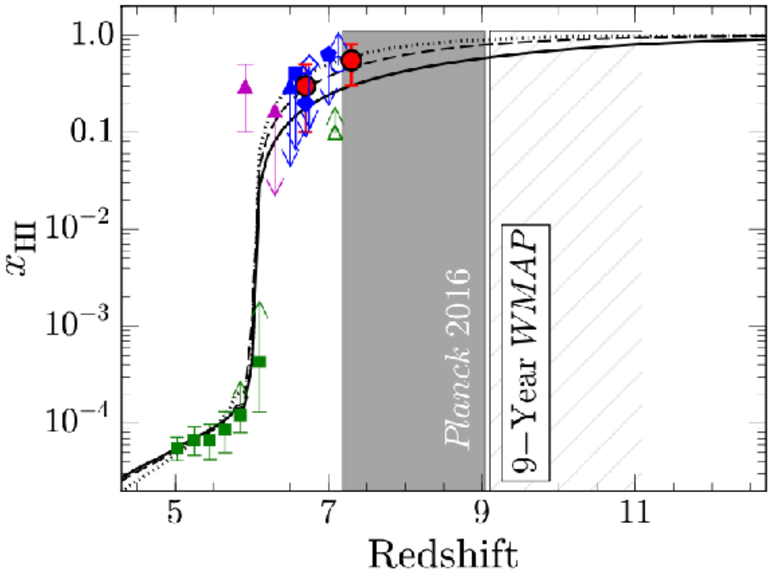
Konno+ 2014



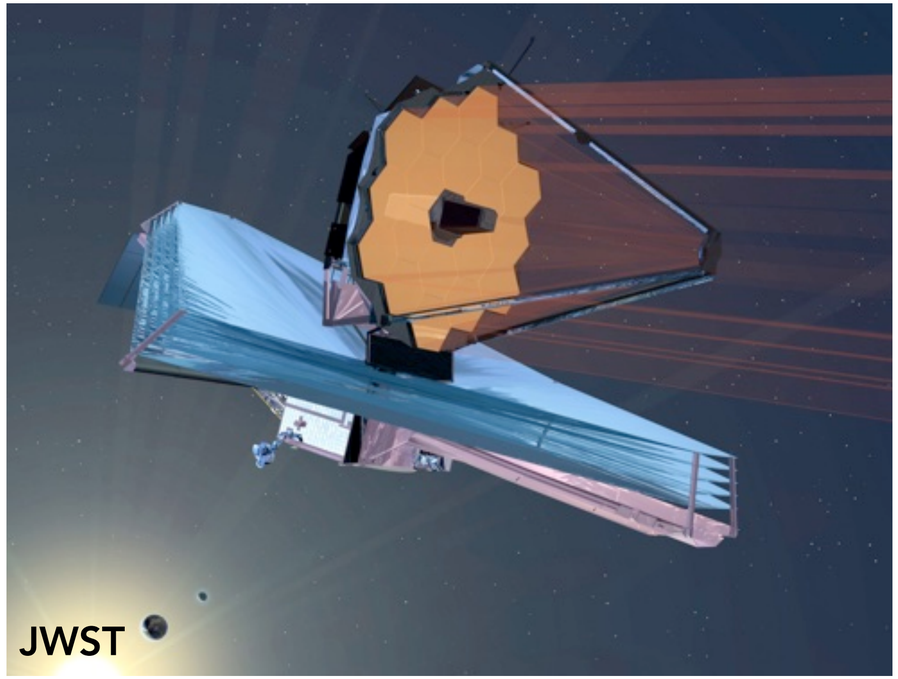
Konno+ 2018

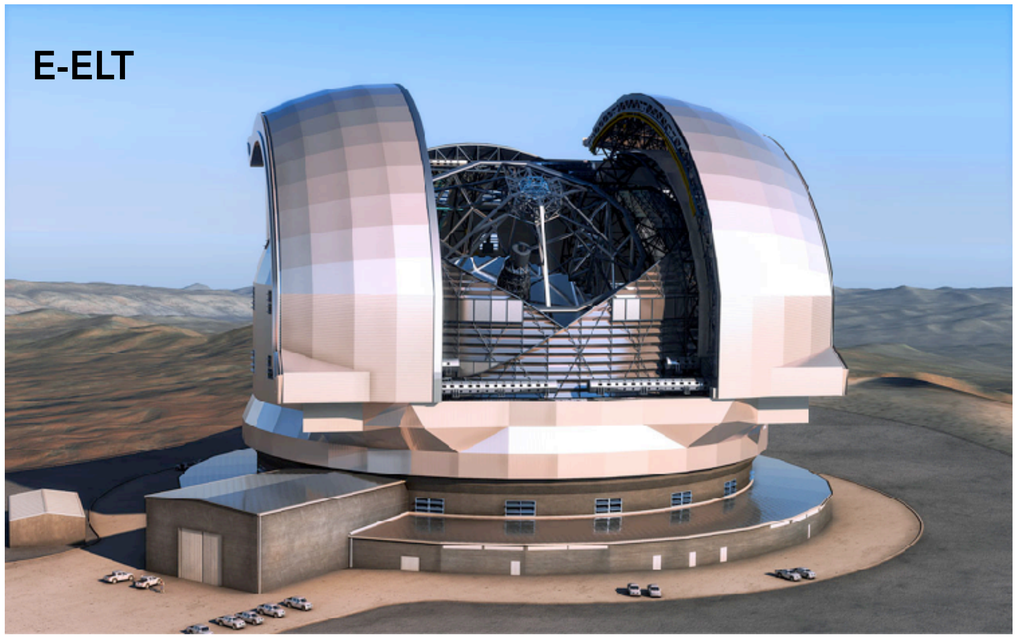




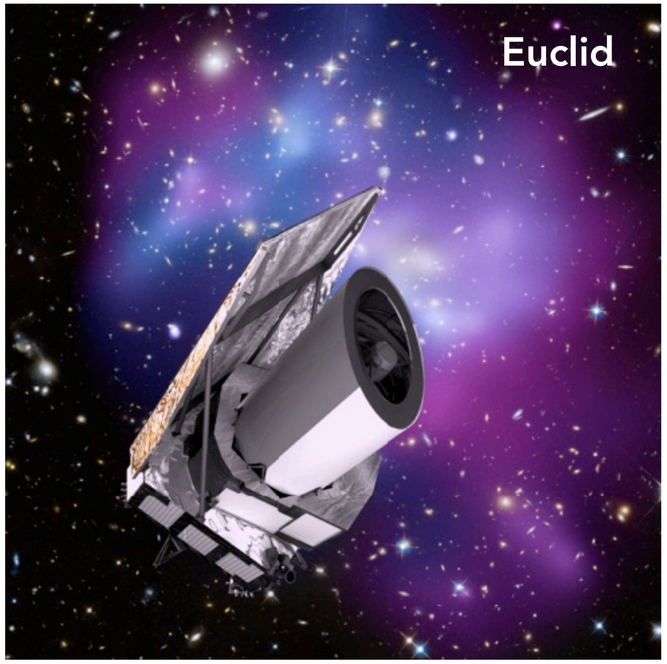


- Red filled circles: LAE LF at $z = 6.6,\ 7.3$
- Blue filled markers: LAE LF evolution
- Blue open markers: Clustering of LAEs and LAE fraction
- Magenta filled triangles: Optical afterglows of GRBs
- Green filled squares and open triangle: quasar observations.


JWST


E-ELT

Outlook


Euclid


MOONS
Multi Object Optical and
Near-infrared Spectrograph