EXPLORING THE FIRST GALAXIES

Stephen M. Wilkins

University of Sussex

MSSL Seminar Jan. 2014

EXPLORING THE FIRST GALAXIES

20,000 times further away
(luminosity distance)

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WITH HELP FROM:

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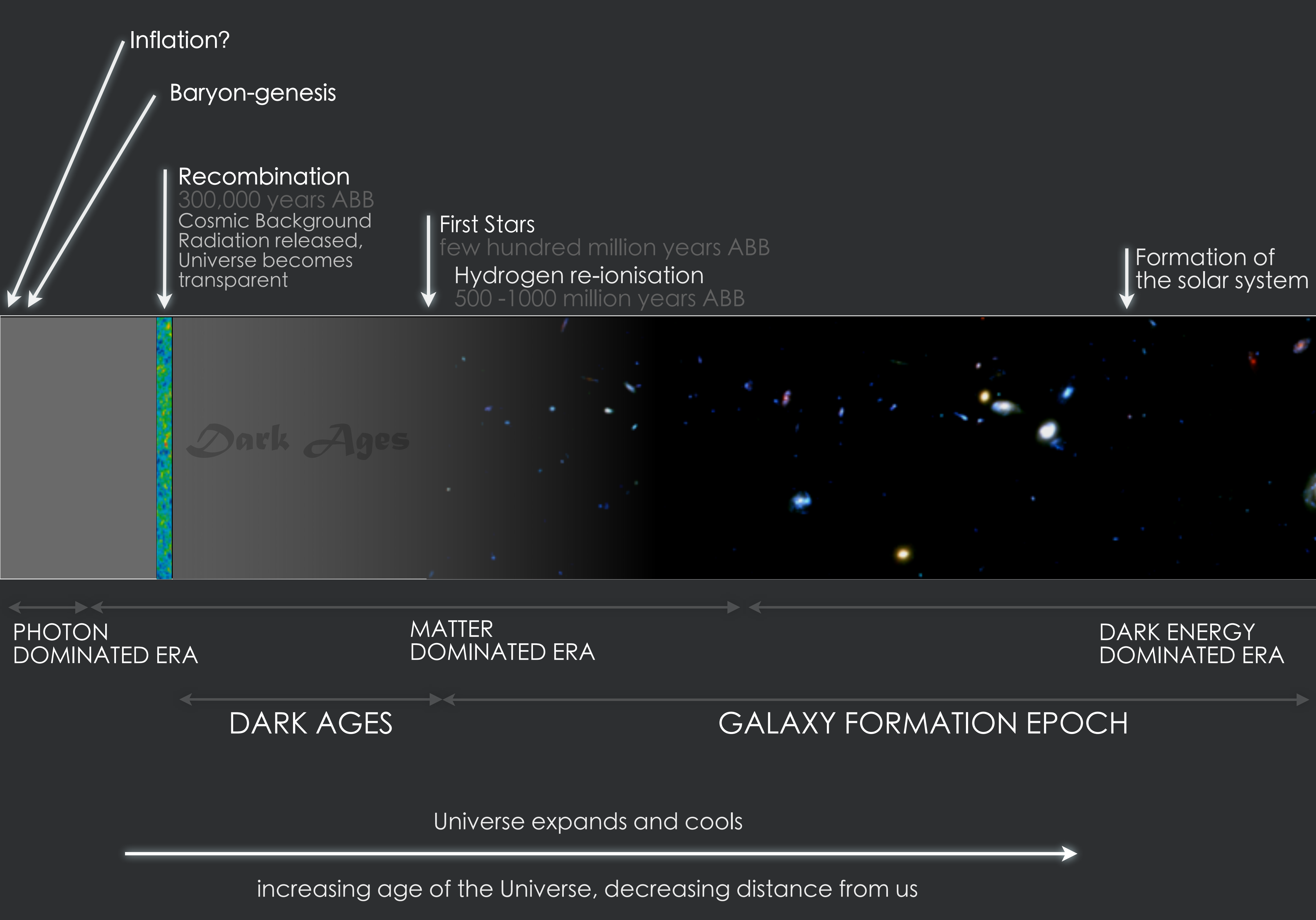
Nishikanta Khandai (Brookhaven National Lab)



Inflation?
Baryon-genesis
Recombination
300,000 years ABB
Cosmic Background Radiation released, Universe becomes transparent
First Stars
few hundred million years ABB
Hydrogen re-ionisation
500 -1000 million years ABB
Formation of the solar system
Dark Ages
PHOTON DOMINATED ERA
MATTER DOMINATED ERA
DARK ENERGY DOMINATED ERA
DARK AGES
GALAXY FORMATION EPOCH
Universe expands and cools
increasing age of the Universe, decreasing distance from us

THE FIRST GALAXIES

First Stars
few hundred million years ABB

Hydrogen re-ionisation
500 -1000 million years ABB

THE FIRST
BILLION YEARS

THE FIRST GALAXIES

First Stars
few hundred million years ABB

Hydrogen re-ionisation
500 -1000 million years ABB

THE FIRST
BILLION YEARS

How did the first galaxies form and evolve?

Pop III star formation

How much?
What does the Pop III IMF look like?

Reionisation

What is the source of the photons responsible for re-ionisation?

nascent SMBH formation:

What was the formation mechanism - merging stellar mass black holes? collapse of metal free gas?

CONTEXT

SIMULATIONS

The early Universe is an excellent place to test models of galaxy formation and evolution

A visualisation of the re-ionisation of the Universe.

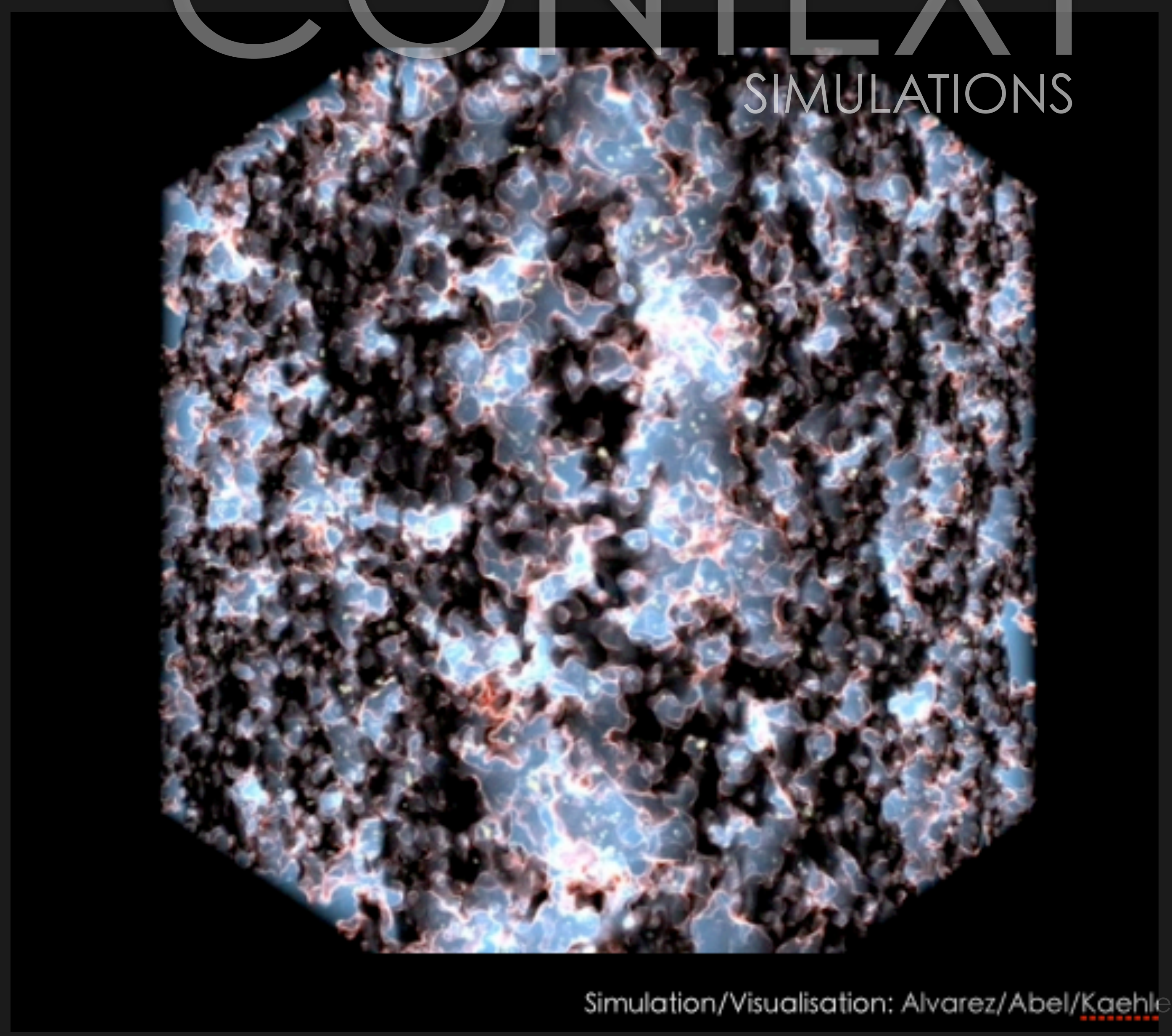
CONTEXT

SIMULATIONS

The early Universe is an excellent place to test models of galaxy formation and evolution.

Exploiting large simulations is a key aspect of my ongoing and future work and I will mention some results later.

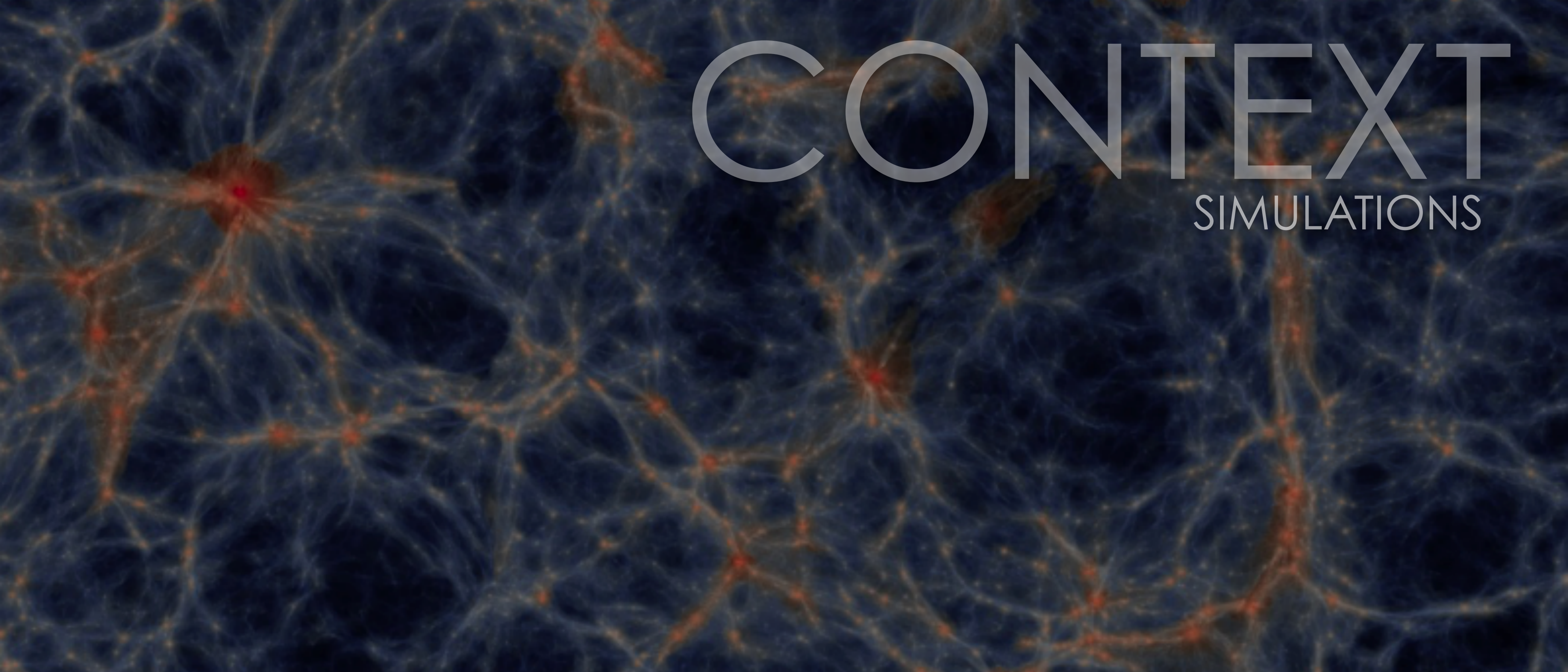
Specifically, I am part of a team currently analysing two large cosmological hydro-dynamic simulations: MassiveBlack and MassiveBlack-II.



A visualisation of the re-ionisation of the Universe.

CONTEXT

SIMULATIONS



A visualization of the MassiveBlack-II simulation used in this work, Credit: Yu Feng.

- Includes AGN and SN feedback
- default Pegase.2 SPS model (with ad hoc implementation of others)
- Metallicity dependent nebular emission
- Matches observations at high-redshift though breaks by z=0

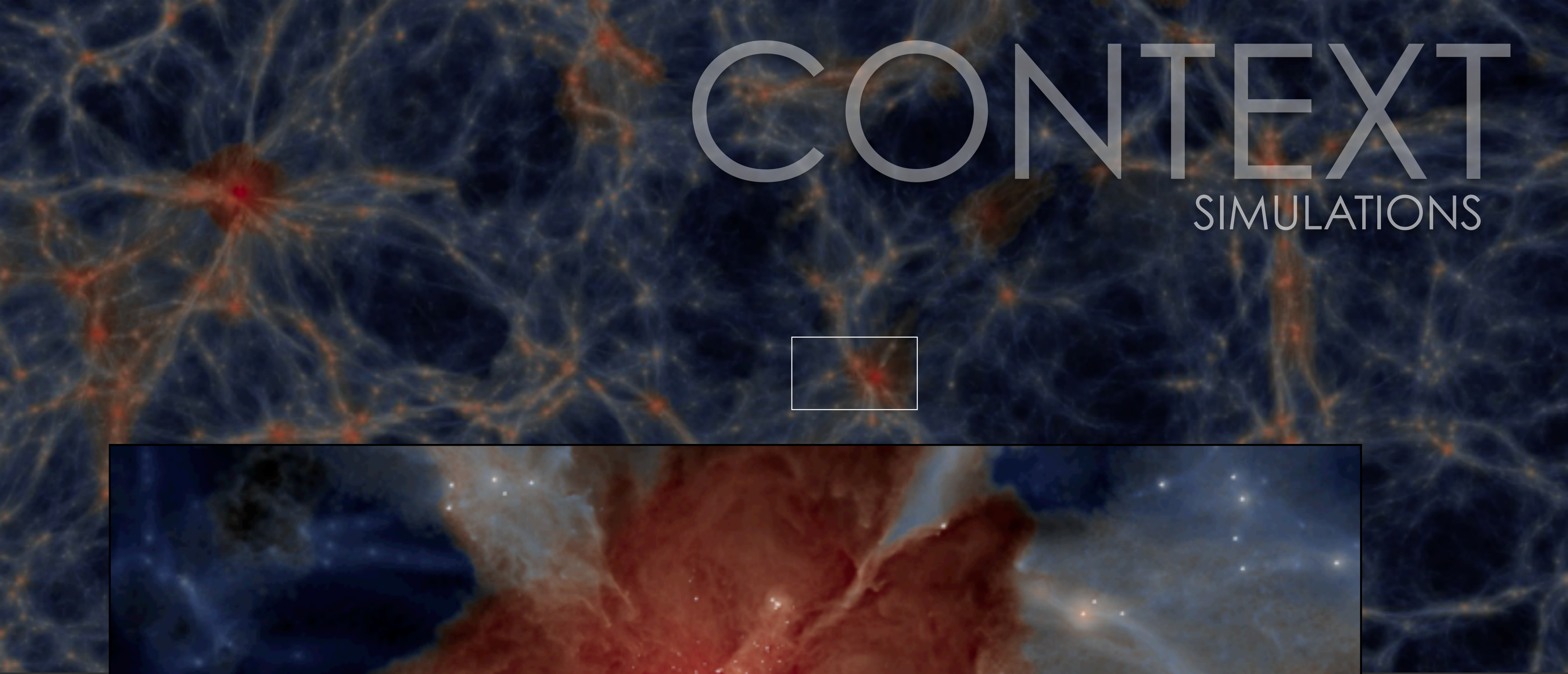
Run	N_{part}	L_{box} (Mpc/h)	ϵ (kpc/h)	z_f
MassiveBlack	2×3200^3	533	5.0	4.75
MassiveBlack-II	2×1792^3	100	1.85	0

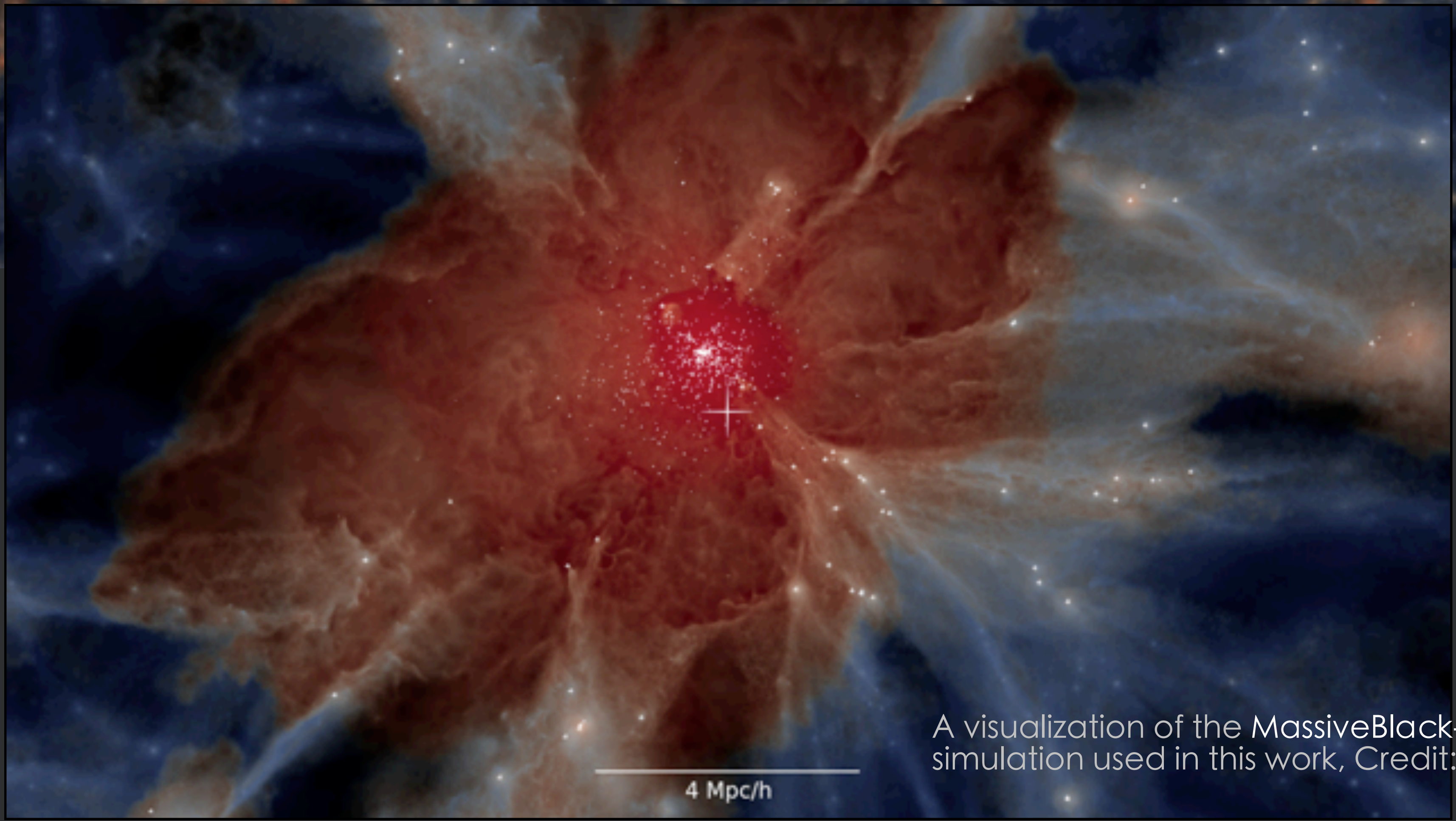
The gas and dark matter particle masses are mg = $5.7 \times 10^7 M_\odot$ and mDM = $2.8 \times 10^8 M_\odot$ respectively.

See Di Matteo et al. (2011), Khandai et al., in-prep for more details.

CONTEXT

SIMULATIONS

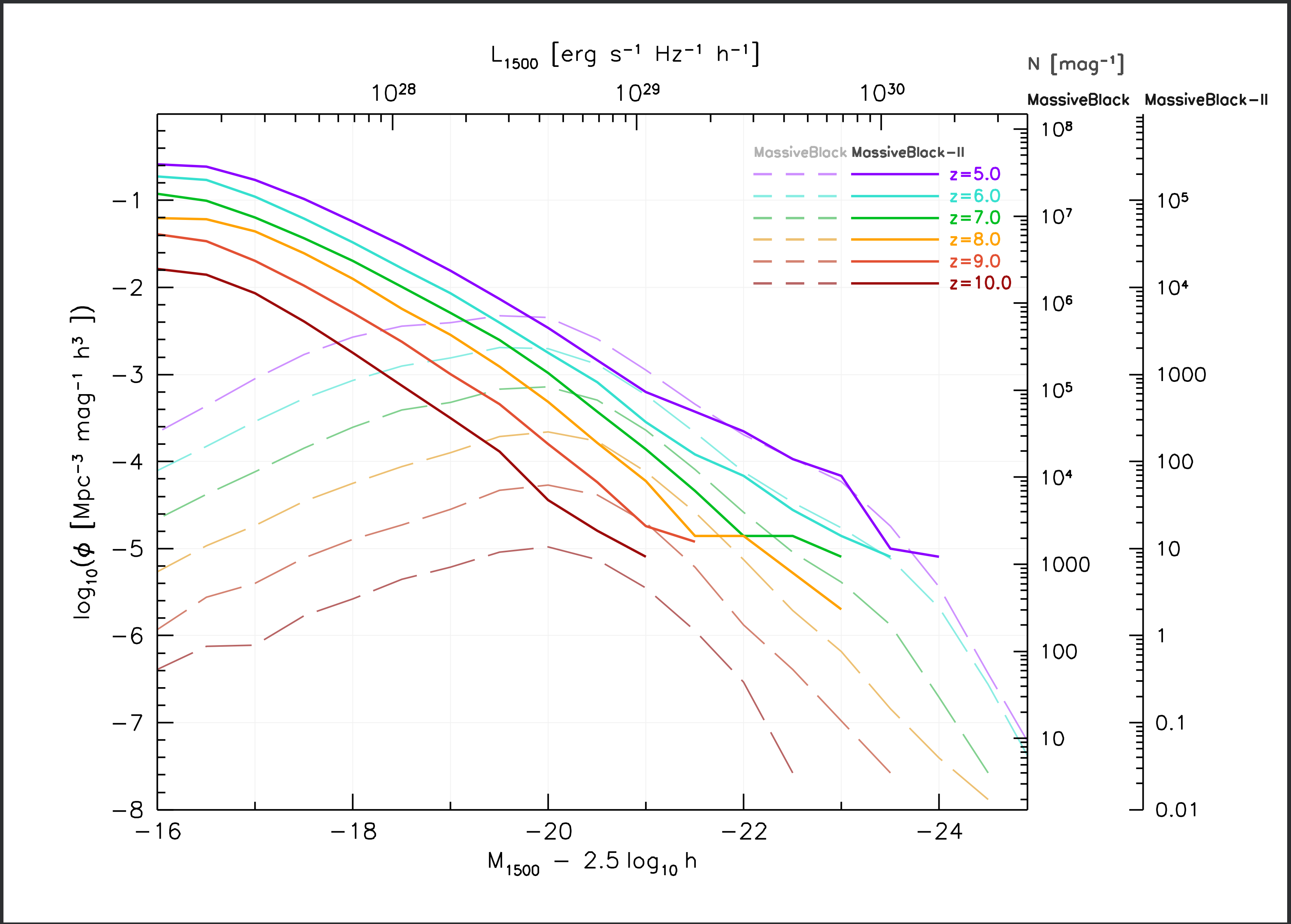




A visualization of the MassiveBlack-II simulation used in this work, Credit: Yu Feng.

CONTEXT
SIMULATIONS

The evolution of the intrinsic UV LF in Massive Black and Massive Black II



Khandai et al., in-prep

Wilkins et al., 2013a, MNRAS

CONTEXT

OBSERVATIONS

FINDING GALAXIES IN THE EARLY UNIVERSE IS HARD

Galaxies we observe in the early Universe are at extremely large distances* and can only be seen in the IR**.

* At z=7 the luminosity distance is >70 Gpc.

** Due to cosmological redshift.

CONTEXT

OBSERVATIONS

Until relatively recently neither ground nor space based instrumentation were good enough to discover more than a few relatively bright candidates. This changed with the installation of WFC3 on Hubble in 2009.

CONTEXT

OBSERVATIONS

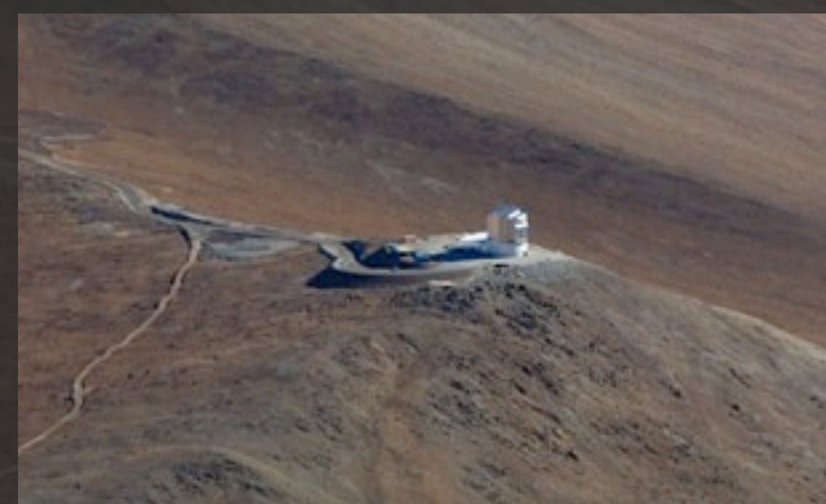
Wide Field Camera 3: WFC3

WFC3 provides imaging and slitless spectroscopy from the near-UV to the near-IR.

The Carina Nebula imaged in both the optical (top) and near-IR (bottom) by WFC3

CONTEXT

OBSERVATIONS



VIDEO

UltraVISTA

CANDELS ERS

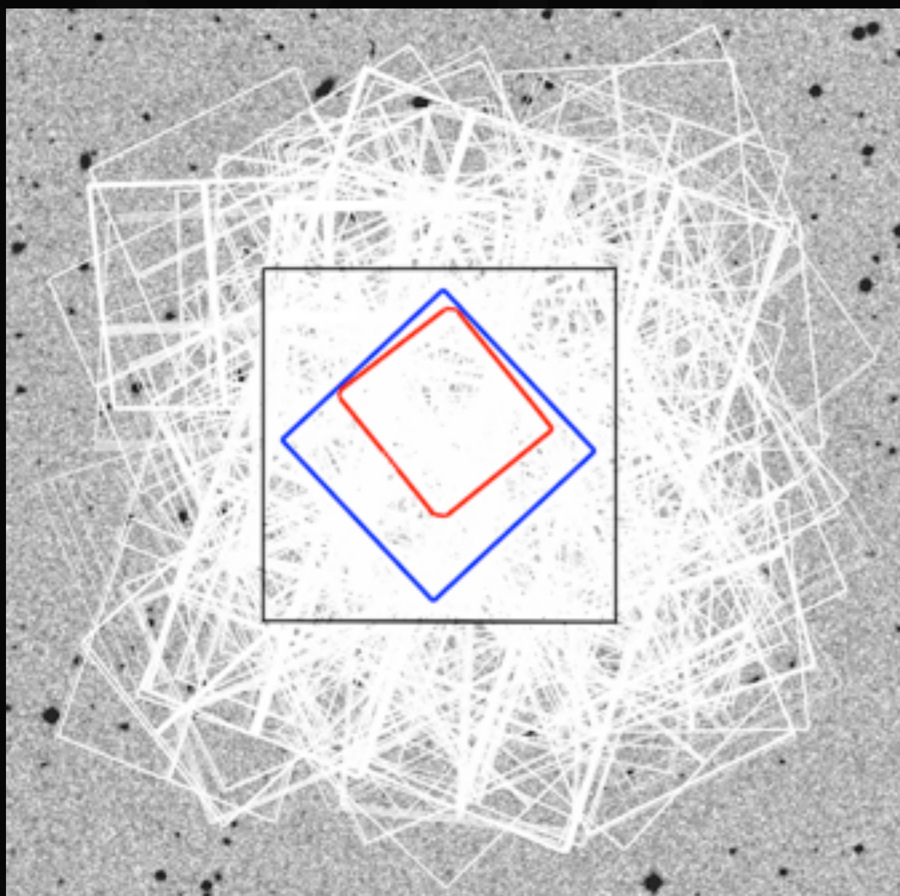
Frontier Fields BORG

HUDF09-P12 HUDF09-P34 XDF

eXtreme Deep Field

(Illingworth et al. 2013)

2 million seconds / 23 days over 10 years of exposures with HST alone.



SN Searches

HUDF

HUDF09

CANDELS

HUDF12

ERS

Frontier Fields

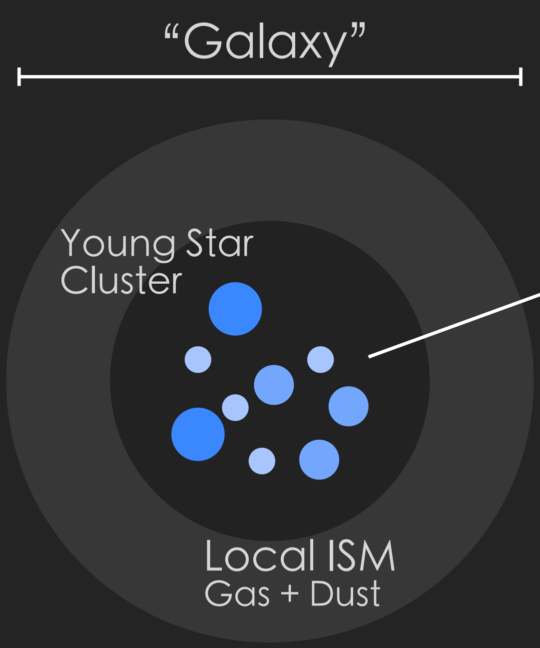
HUDF09-P12 HUDF09-P34

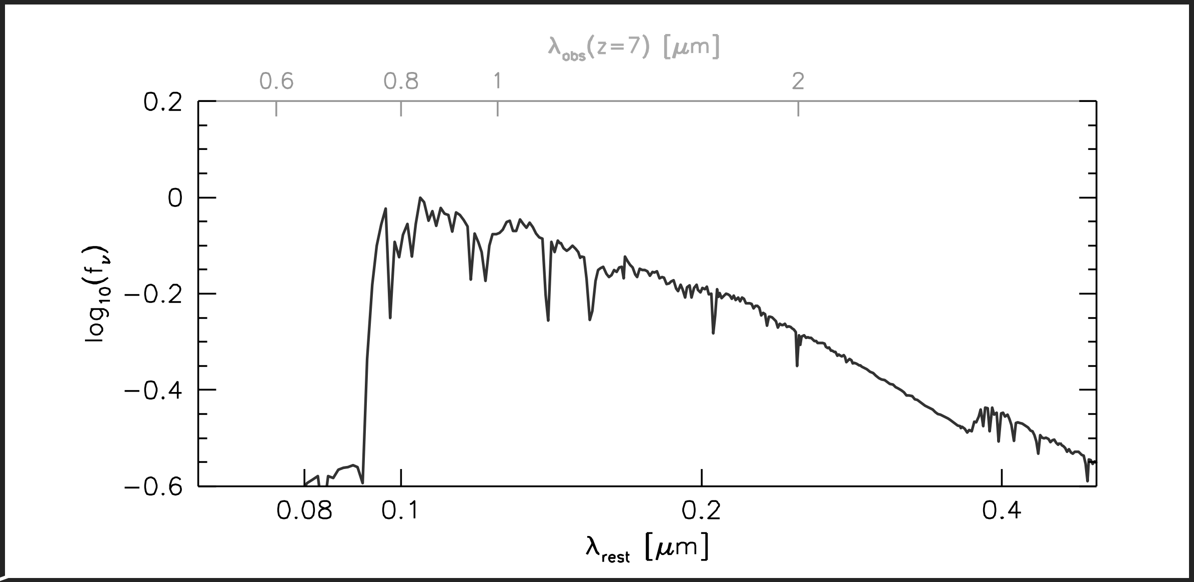
XDF

CONTEXT

OBSERVATIONS

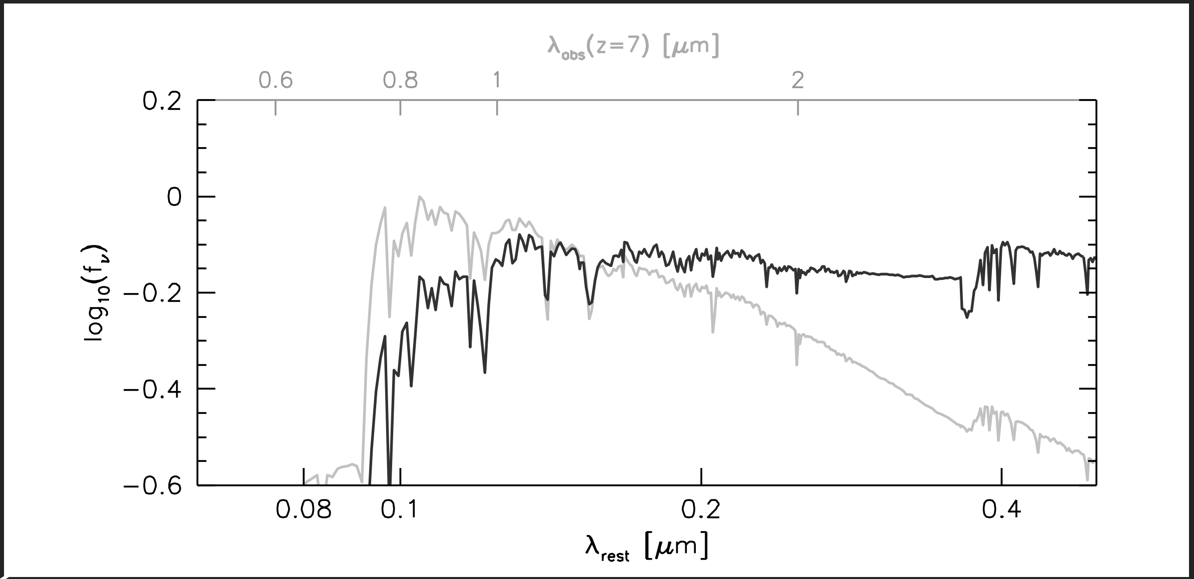
IDENTIFYING HIGH-REDSHIFT STAR FORMING GALAXIES



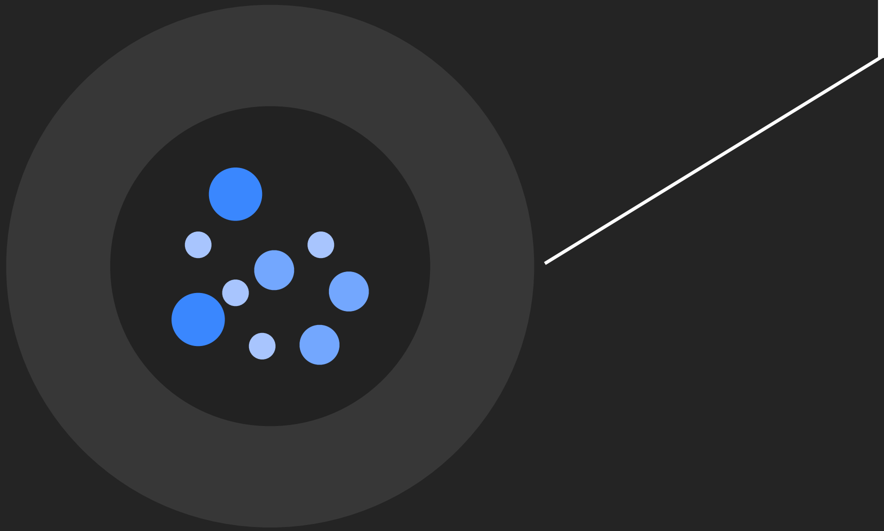


Intrinsic UV Spectrum Emitted By (young, massive) Stars:

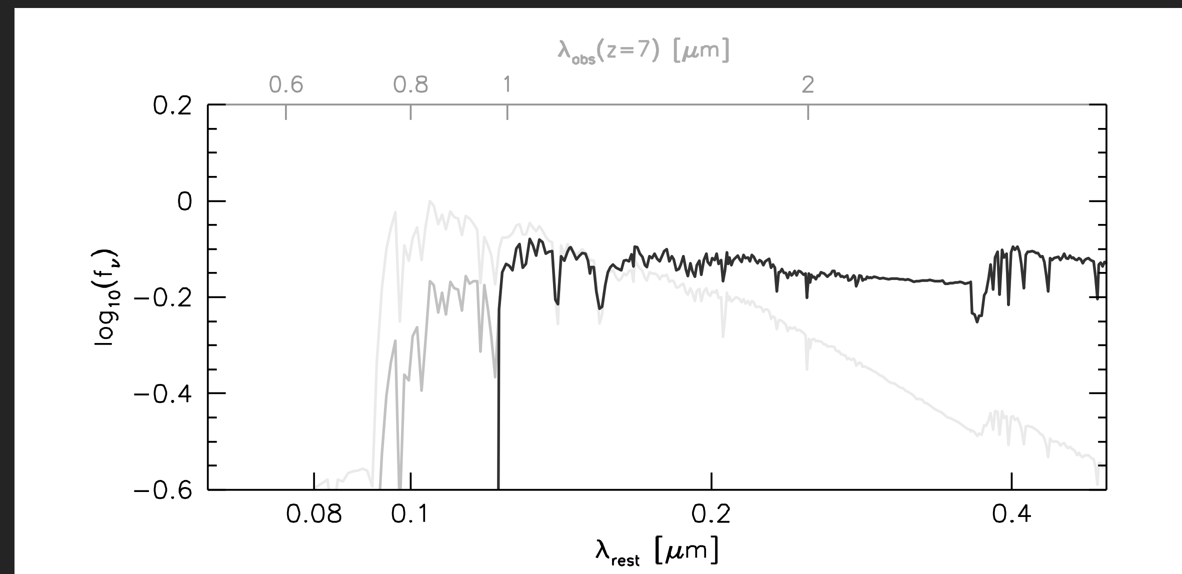
IDENTIFYING HIGH-REDSHIFT STAR FORMING GALAXIES



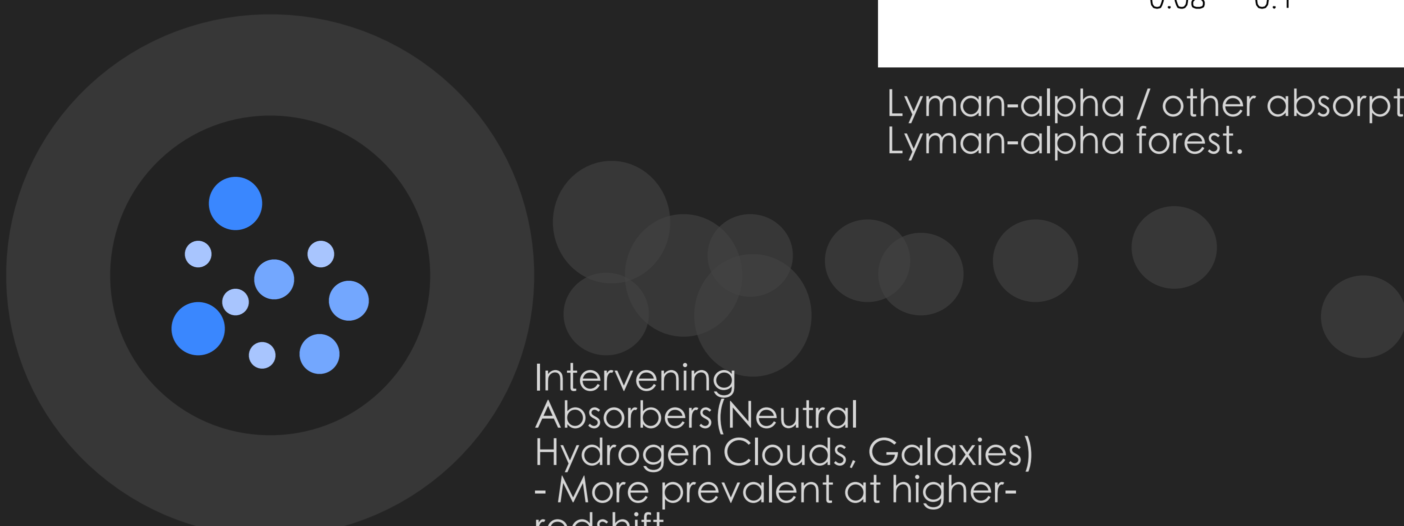
rest-frame less than 912Å (Lyman-limit) absorbed by local Hydrogen **and spectrum modified by dust.**

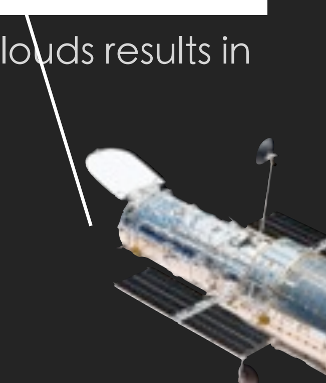


IDENTIFYING HIGH-REDSHIFT STAR FORMING GALAXIES



Lyman-alpha / other absorption from intervening clouds results in Lyman-alpha forest.

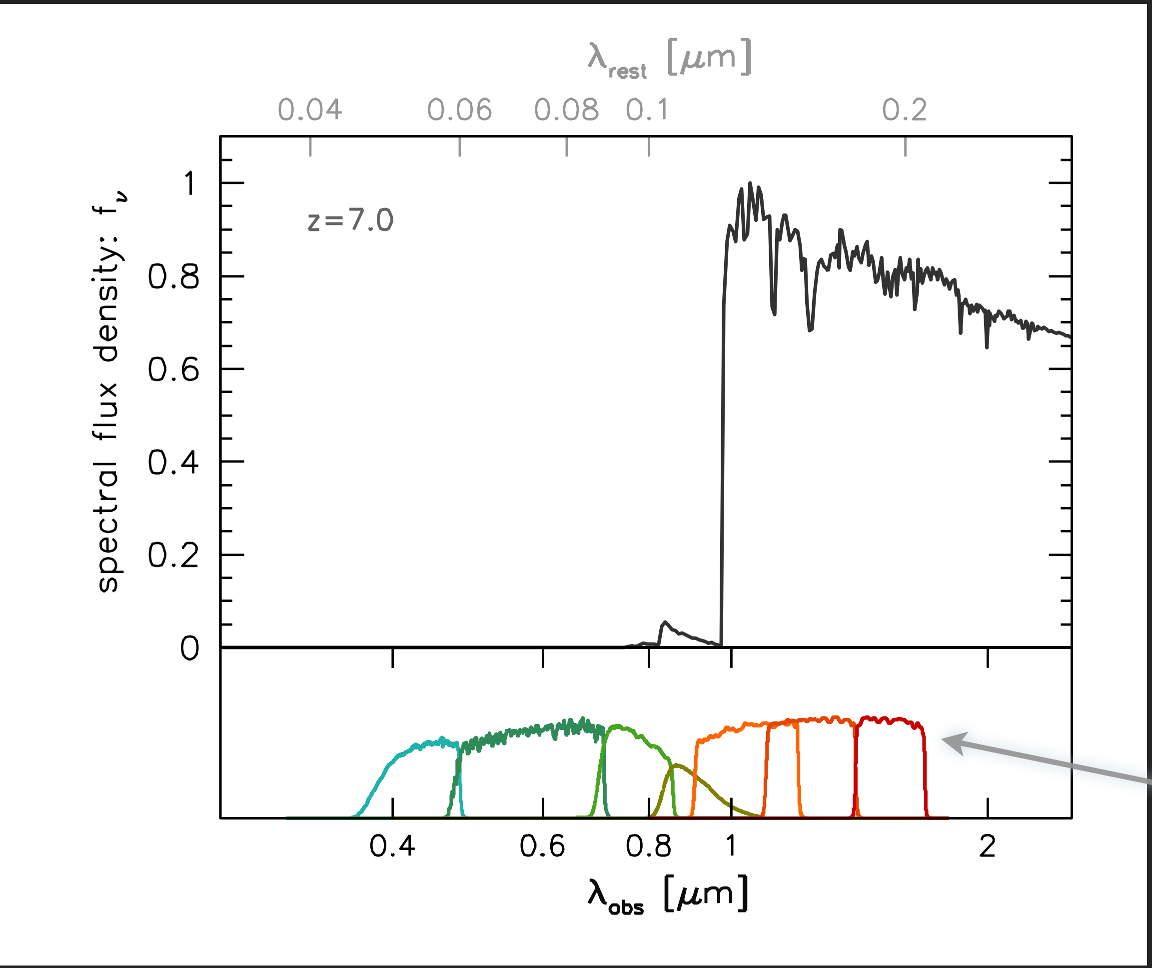




Intervening Absorbers(Neutral Hydrogen Clouds, Galaxies) - More prevalent at higher-redshift

Increasing distance / lookback time

IDENTIFYING HIGH-REDSHIFT STAR FORMING GALAXIES



Zero flux is transmitted in the ACS optical bands and very-little flux is transmitted in the ACS z-band compared to the WFC3 YJH bands.

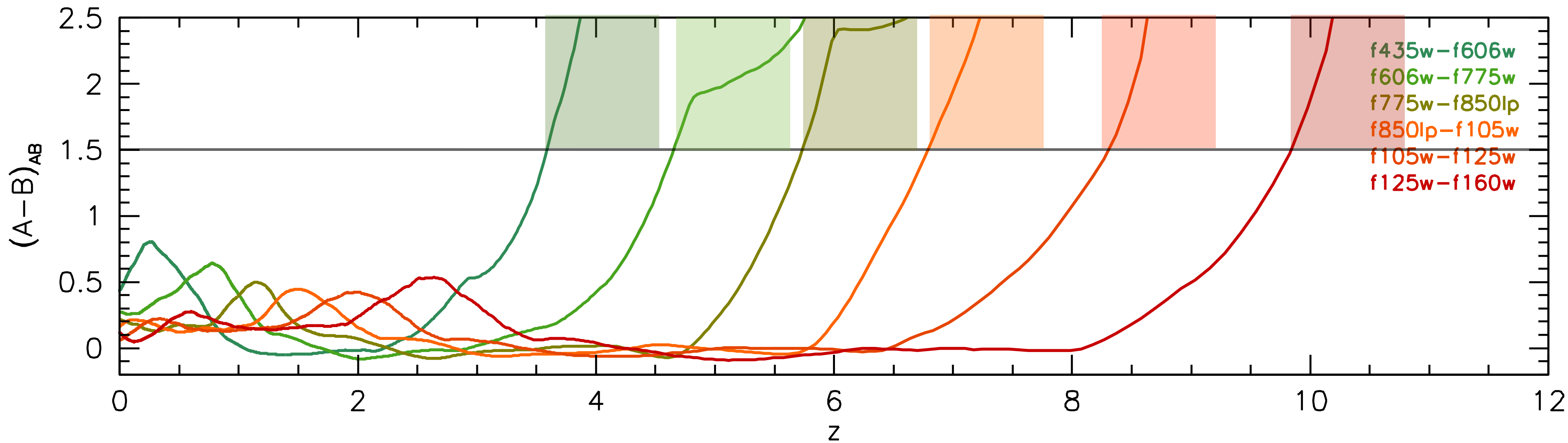
This object would "drop out" in the ACS z-band and could be selected on the basis of a very red z-Y colour.

ACS optical and WFC3 NIR bands

Observed frame SED of a star forming galaxy at z=7.0

The theoretical (PEGASE.2+Madau96) SED of a z=7 galaxy with the ACS/WFC3 filter transmission curves.

IDENTIFYING HIGH-REDSHIFT STAR FORMING GALAXIES



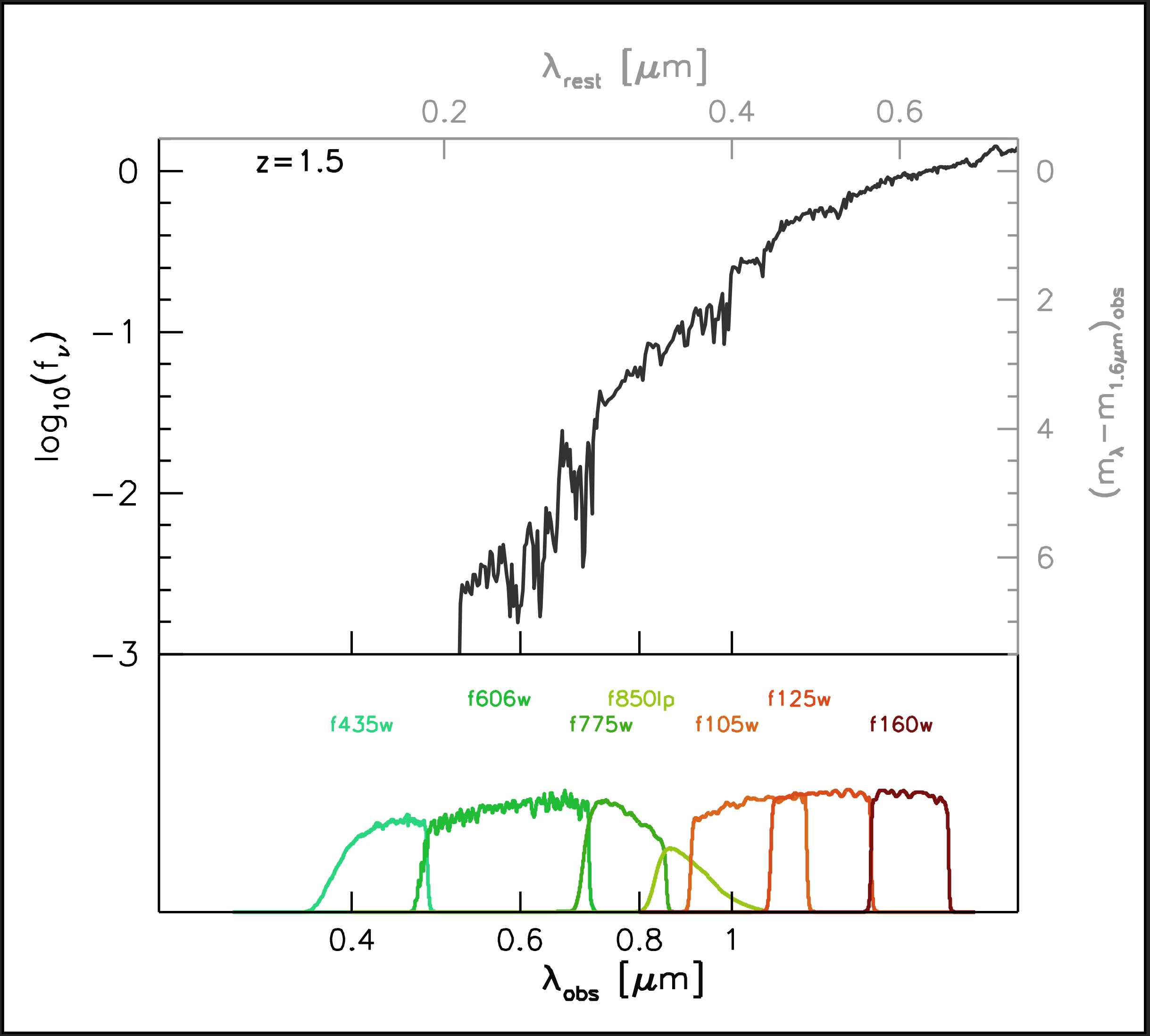
The observed colour of a galaxy continuously forming stars at a constant rate (from PEGASE.2, corrected for ISM/intervening absorption using M96)

Introducing a simple colour selection would initially appear to allow you to select galaxies at your choice of redshift.

CONTAMINATION

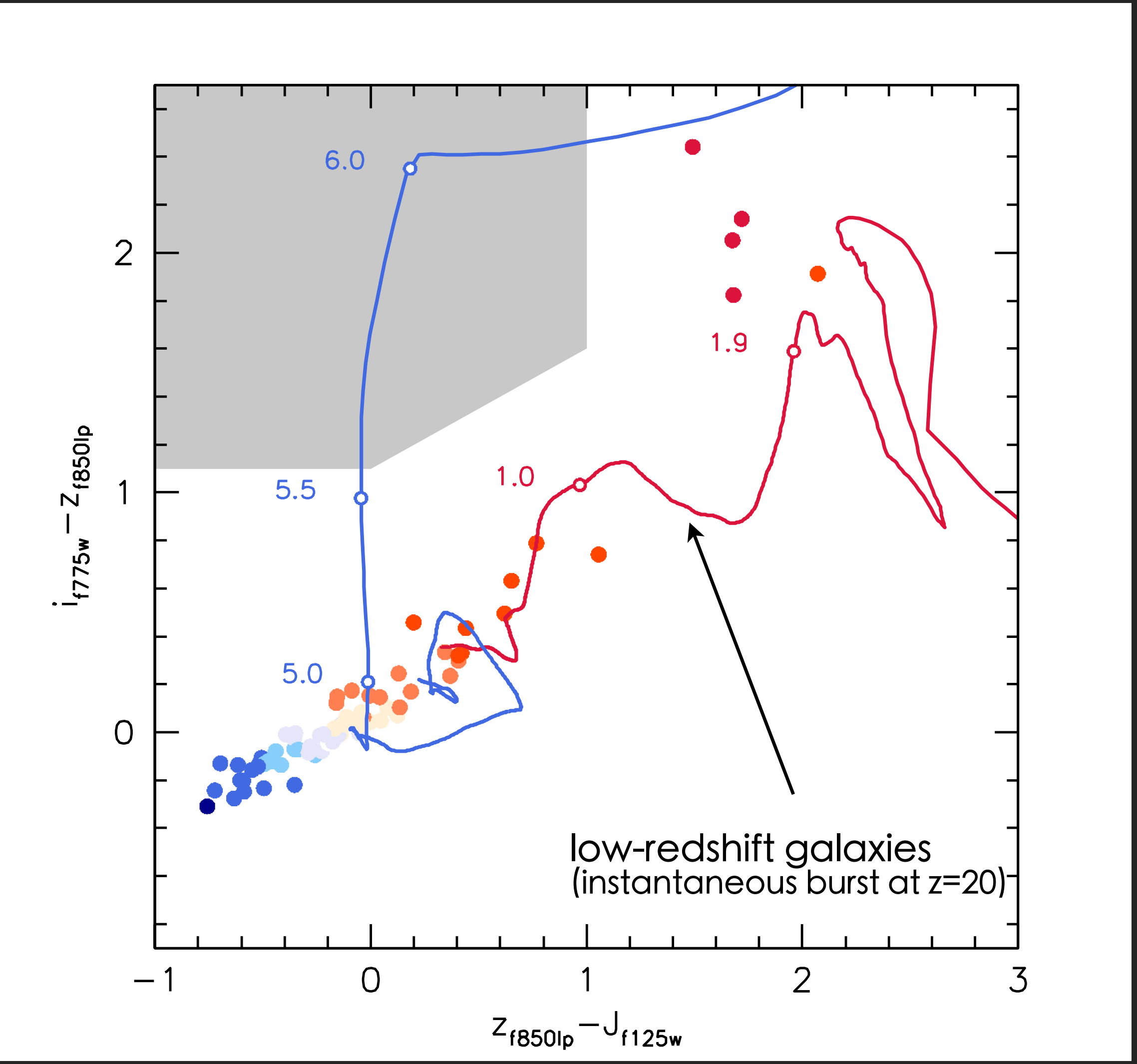
Several other types of object can also have very-red NIR colours.

One of the largest potential contaminants are passive galaxies at intermediate redshift where we probe the Balmer/ 4000A break.



The SED of a galaxy which formed all its stars at z=20 and has been subsequently passively evolving.

CONTAMINATION



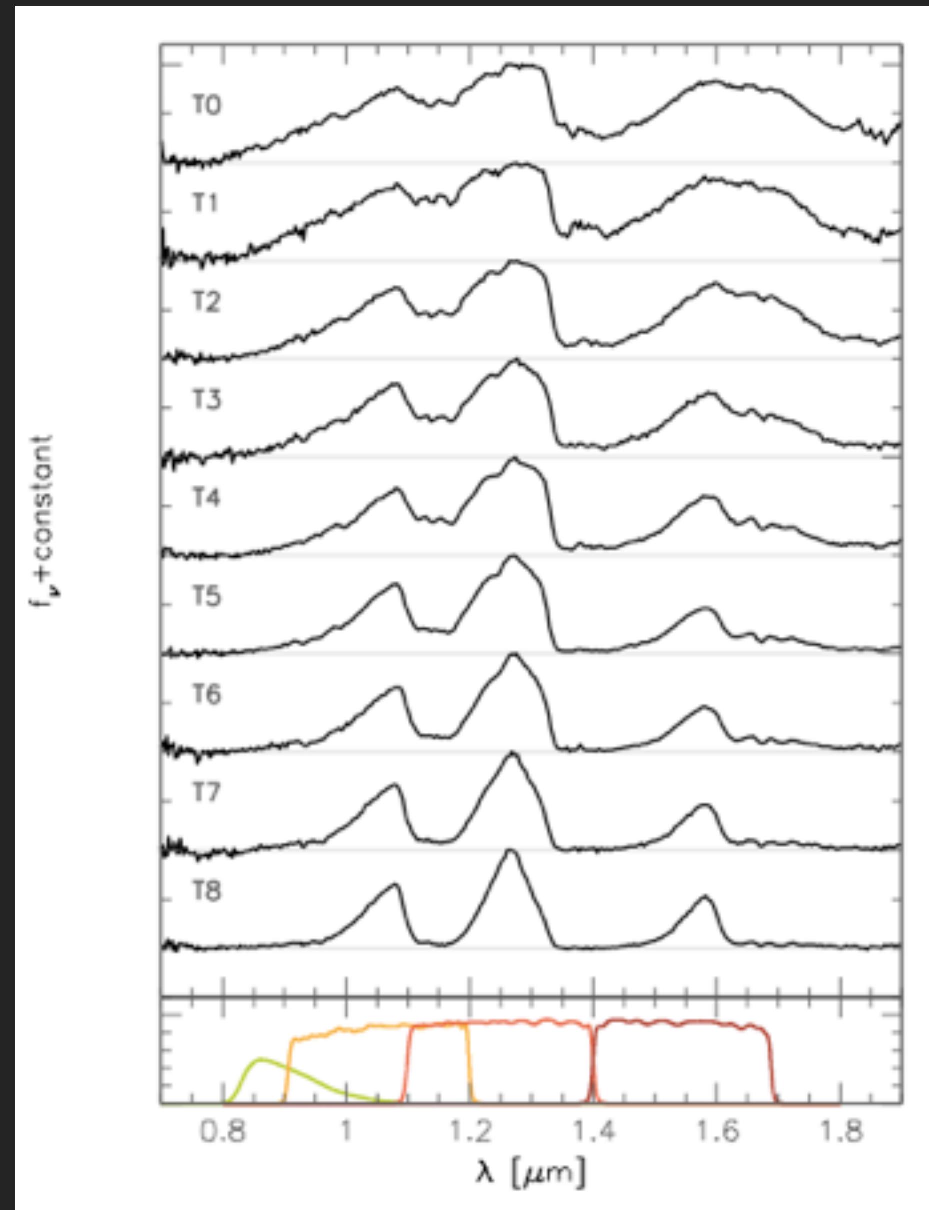
By including additional information it is often possible to design a selection window which excludes most contaminants.

SHAMELESS ADVERTISING

CONTAMINATION

However, in some cases this becomes increasingly difficult to fully exclude contaminant population. A good example is contamination of the Y-drop selection (z~8) by cool stars.

This contamination continues to the predicted Y-dwarf class.



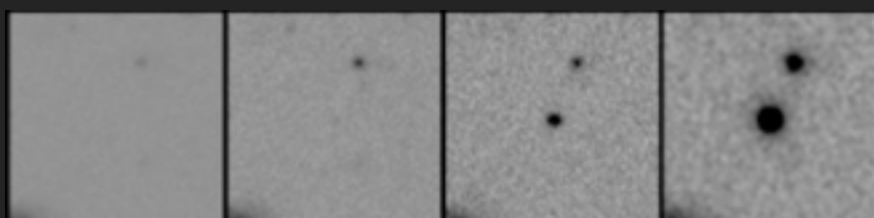
The observed spectra of T-dwarfs.

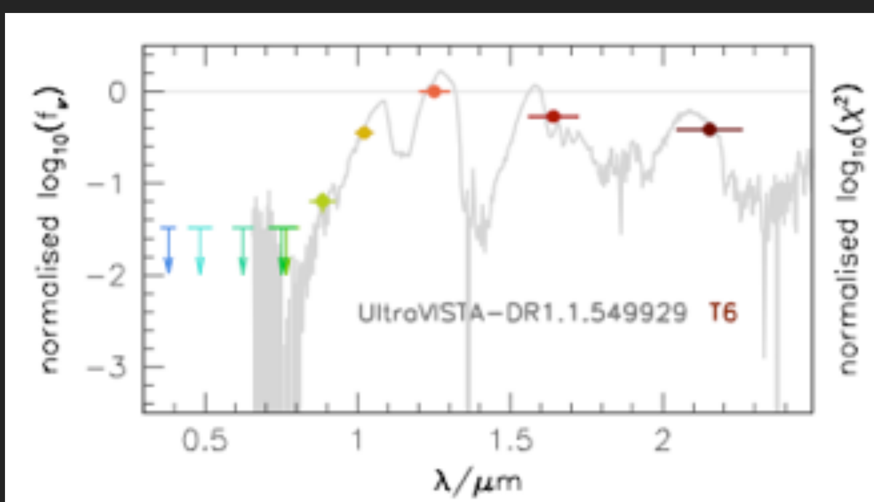
Wilkins, Stanway & Bremer, 2014

SHAMELESS ADVERTISING
FINDING BROWN DWARFS

You can use similar techniques to select brown dwarfs (though then you suffer contamination from high-redshift galaxies).

Wilkins et al., in prep





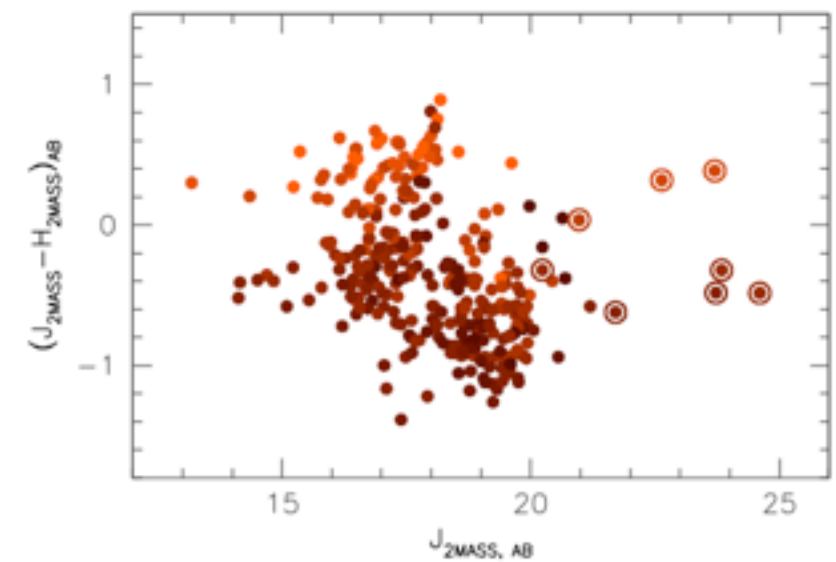
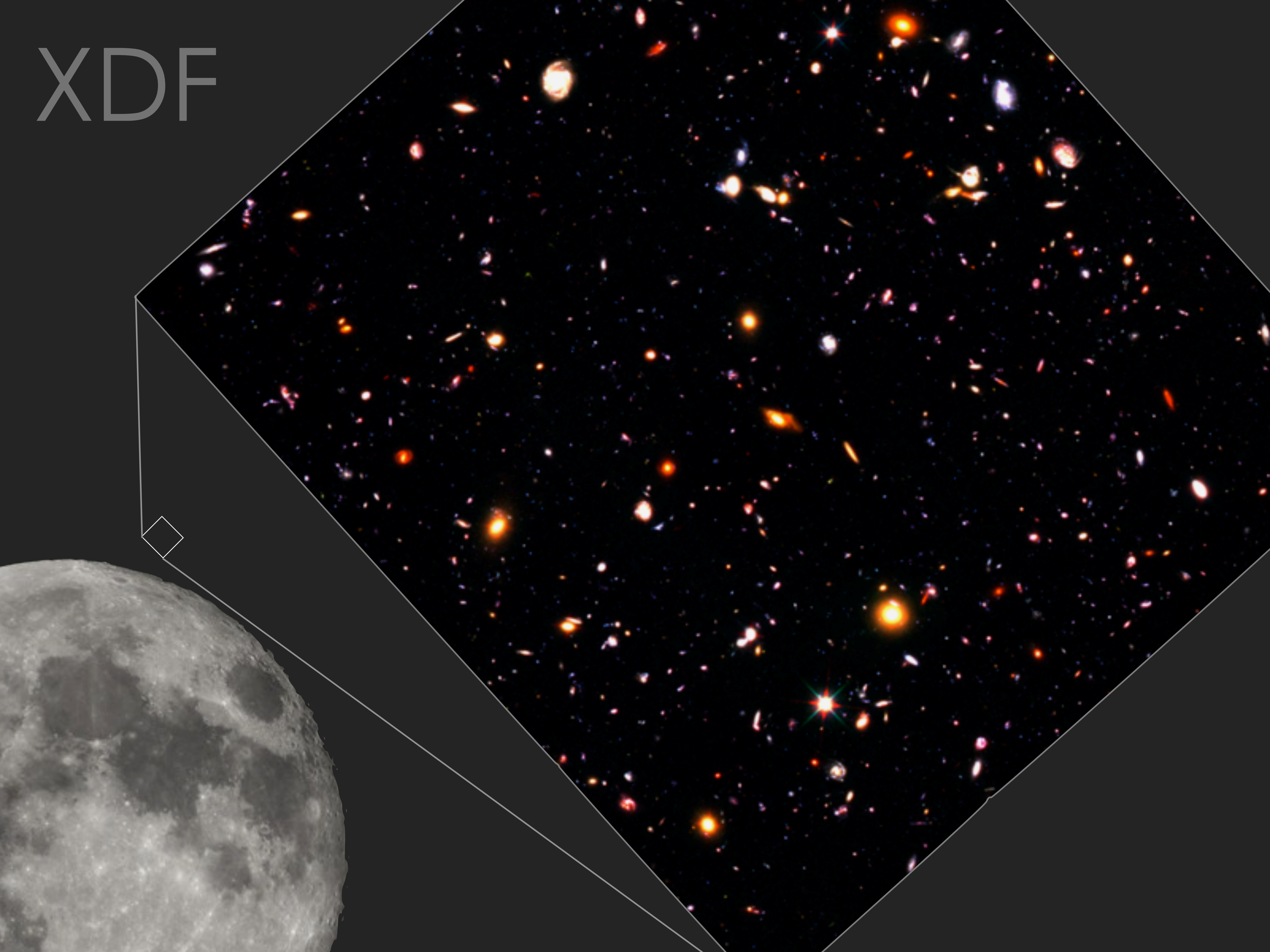
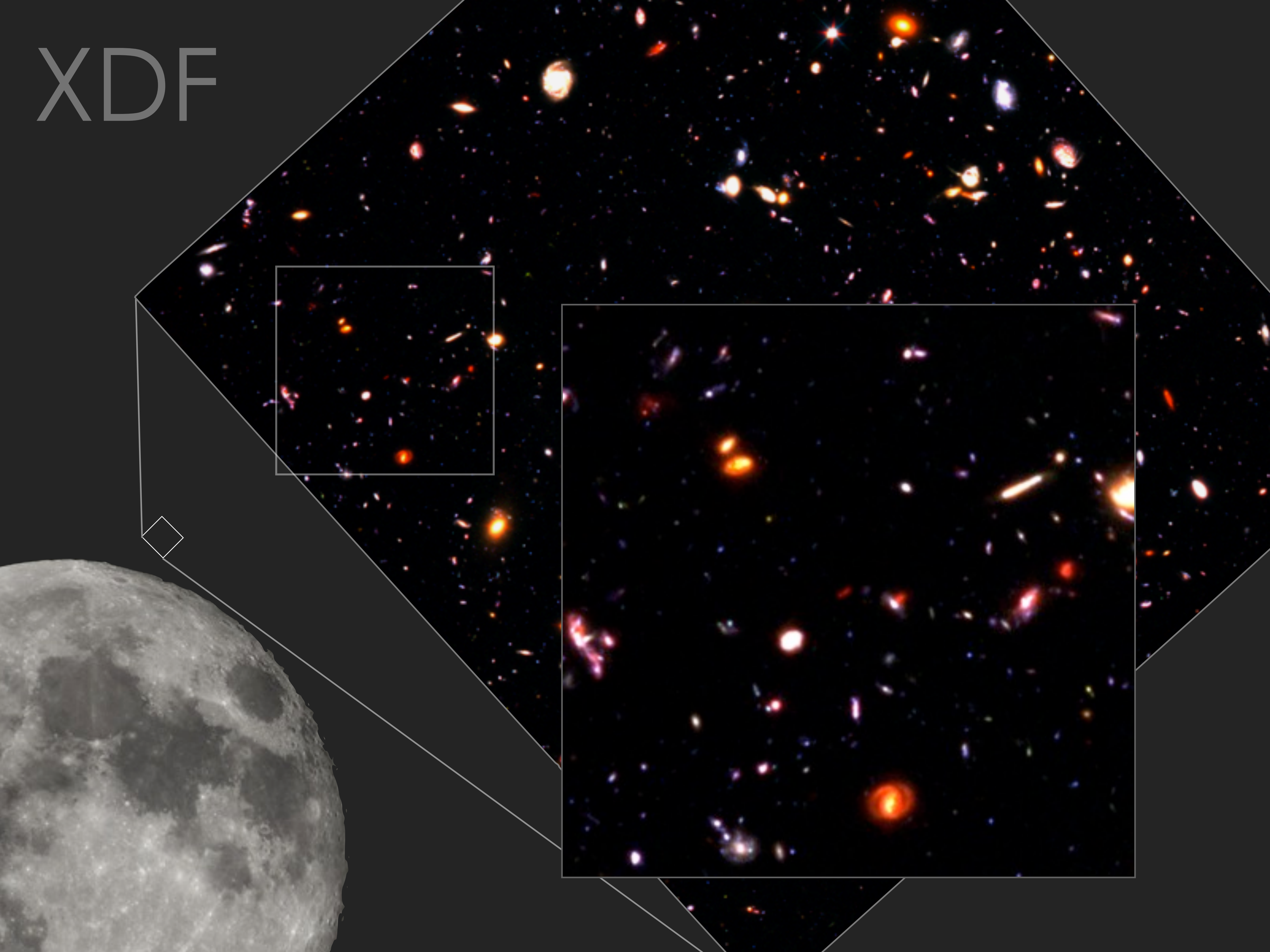


Figure 6. Colour-magnitude diagram of our T-dwarf candidates (circled) compared with spectroscopically classified sources from the literature.

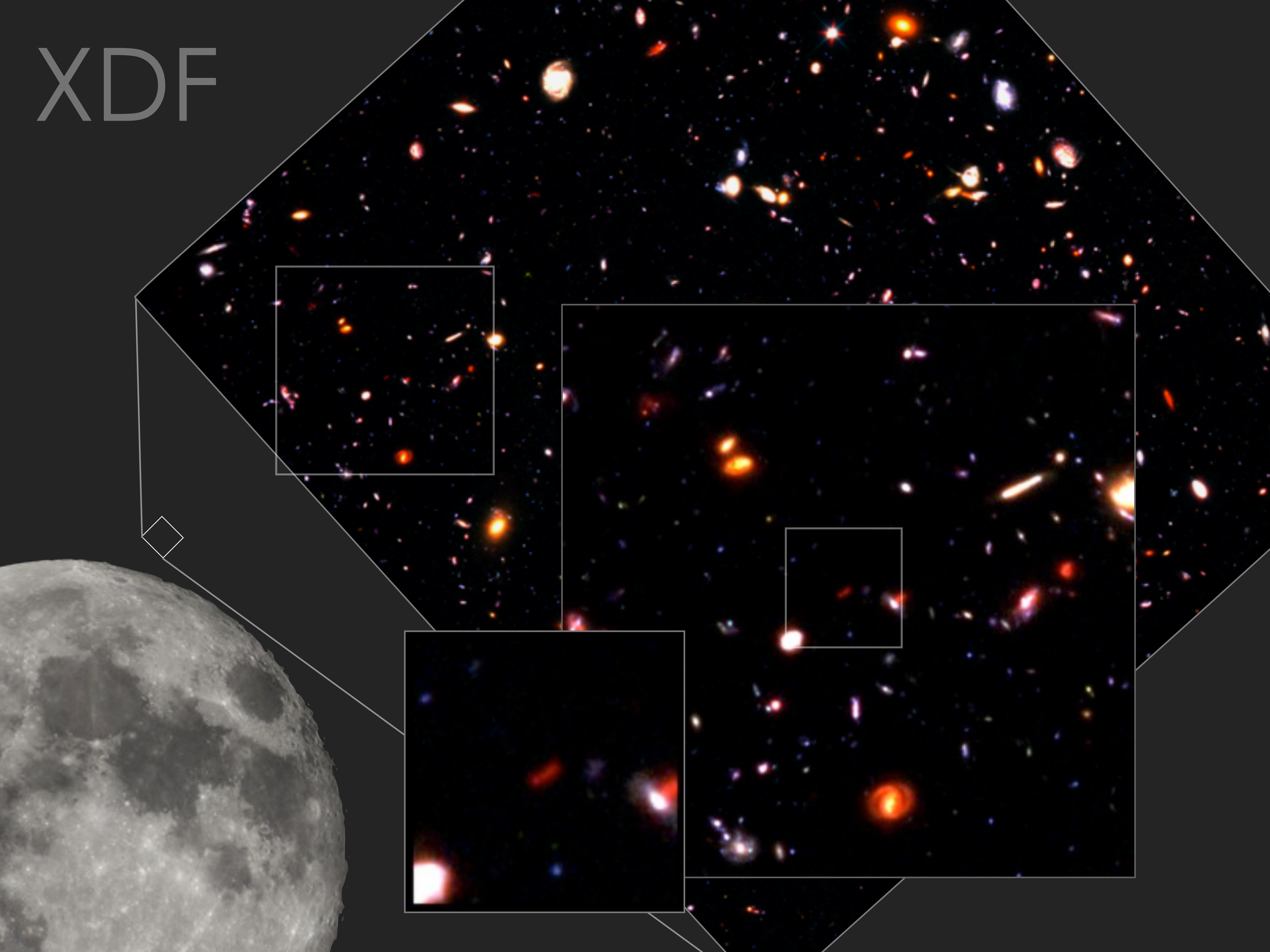
XDF



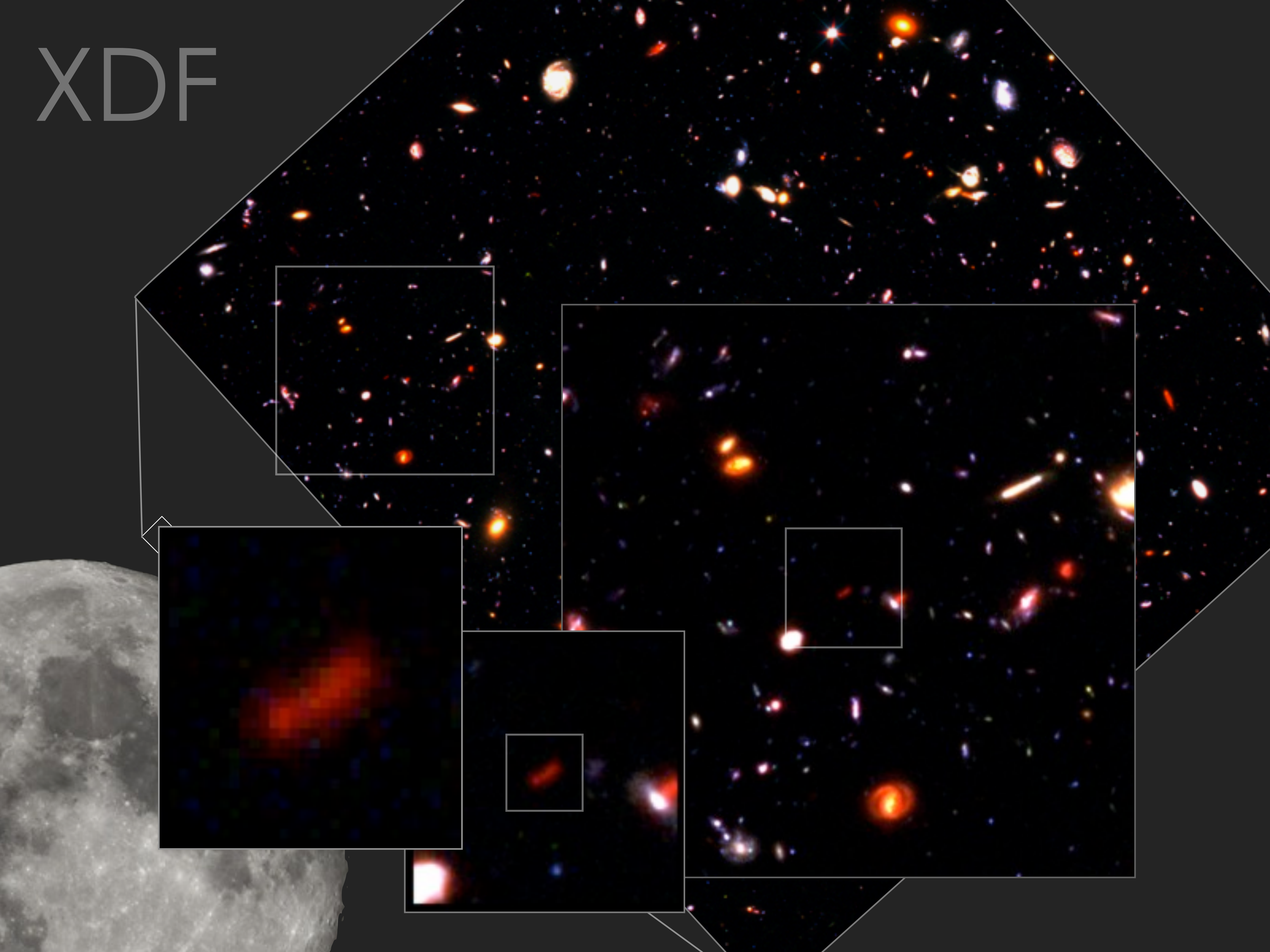
XDF



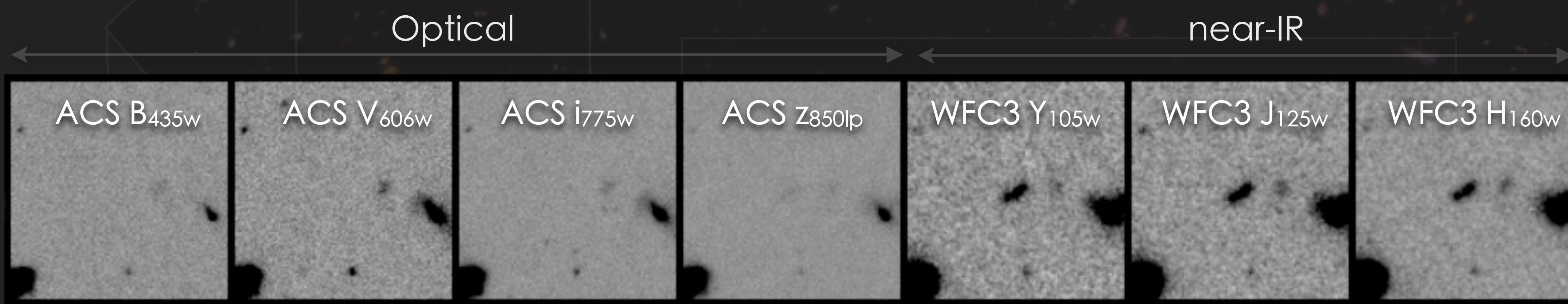
XDF

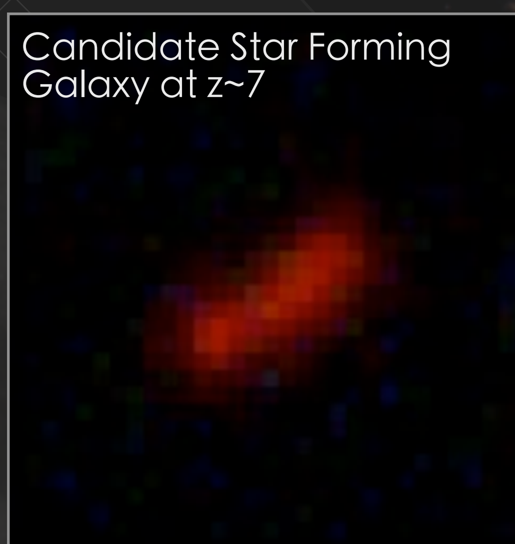


XDF



A CANDIDATE


Optical
near-IR
ACS B435w
ACS V606w
ACS i775w
ACS z850lp
WFC3 Y105w
WFC3 J125w
WFC3 H160w

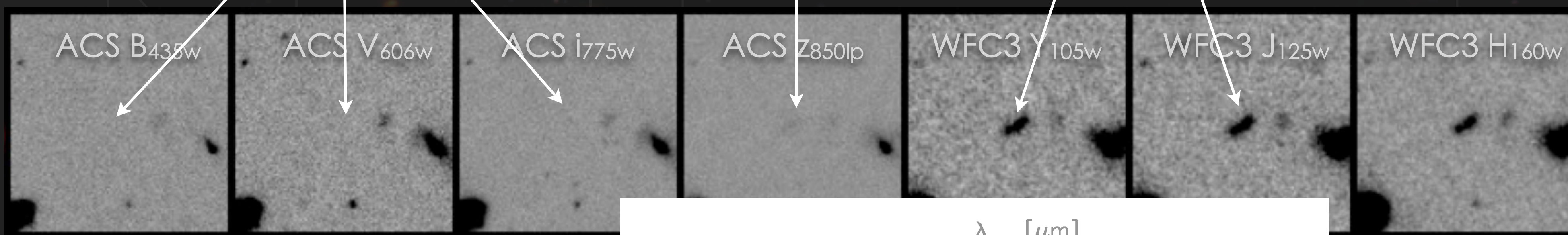

Candidate Star Forming Galaxy at z~7

A CANDIDATE

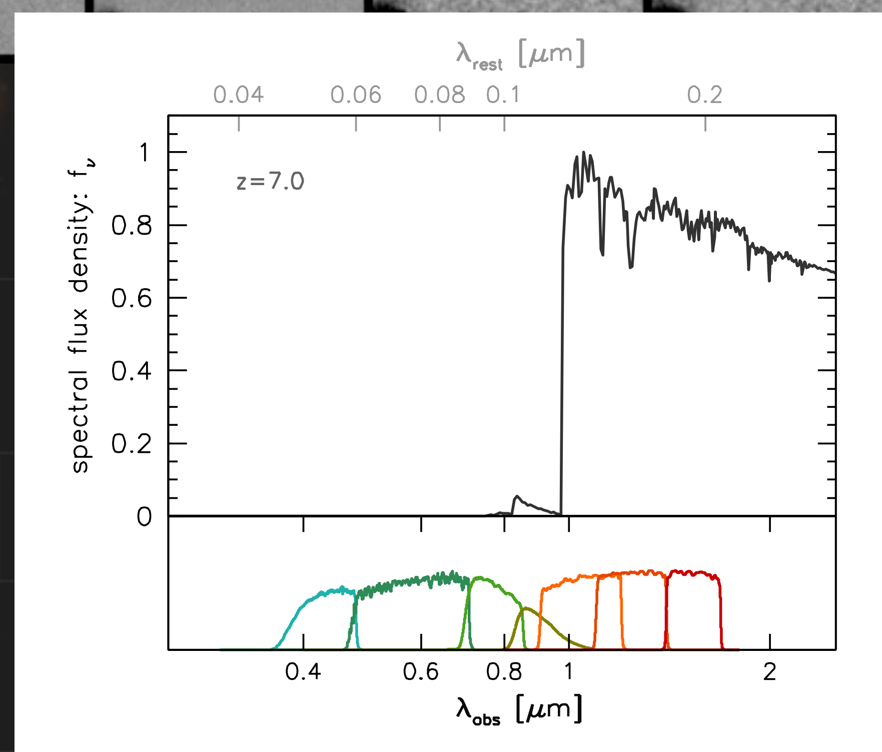
no detection at 1.5σ

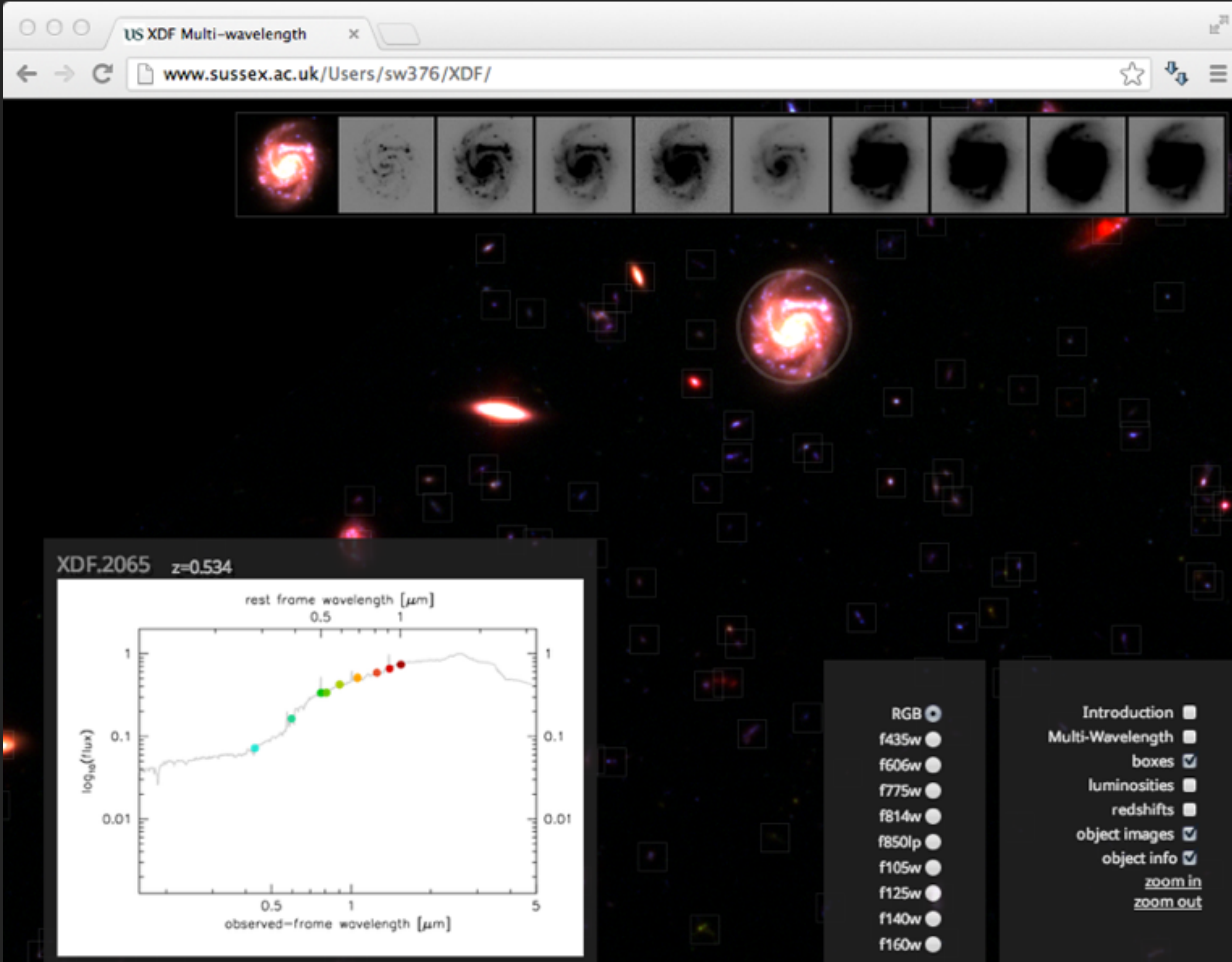
detected at low significance (to be expected)

detected at high significance, blue colour



Candidate Star Forming Galaxy at z~7





XDF Multi-wavelength
www.sussex.ac.uk/Users/sw376/XDF/
XDF.2065
z=0.534
rest frame wavelength [μm]
0.5
1
1
0.1
0.01
log10(flux)
0.5
1
5
observed-frame wavelength [μm]
RGB
f435w
f606w
f775w
f814w
f850lp
f105w
f125w
f140w
f160w
Introduction
Multi-Wavelength
boxes
luminosities
redshifts
object images
object info
zoom in
zoom out

2013: SEVERAL HUNDRED CANDIDATES

WHAT CAN WE MEASURE?

Hubble optical and near-IR photometry alone*:

=

imprecise redshifts

Morphologies

Clustering

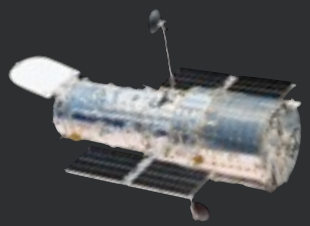
observed UV continuum slope → *rough* dust attenuation

observed UV luminosities → intrinsic UV luminosities → Star Formation Rates

ionising photon density

SFR density

WHAT ELSE CAN WE MEASURE?



+

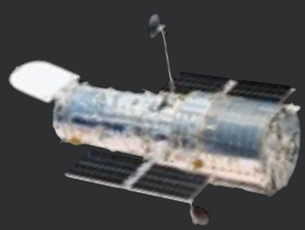
near-IR spectroscopy with current instrumentation

=

Lyman-alpha emission
for bright candidates and if you are lucky → precise redshifts

HeII
for bright candidates and if you are VERY VERY lucky → Pop-III tracer?

WHAT ELSE CAN WE MEASURE?

 +  = rest-frame UV-optical colours

Spitzer IRAC
near-IR

rest-frame UV-optical colours → Stellar Masses → Galaxy Stellar Mass Function

rest-frame UV-optical colours → Nebula emission
(Kind of)

SPECTROSCOPY

Because of the possibility of contamination from low-redshift sources it would be ideal to obtain **spectroscopic confirmation** of the high-redshift candidates. At present, the only realistically accessible diagnostic is Lyman-alpha.

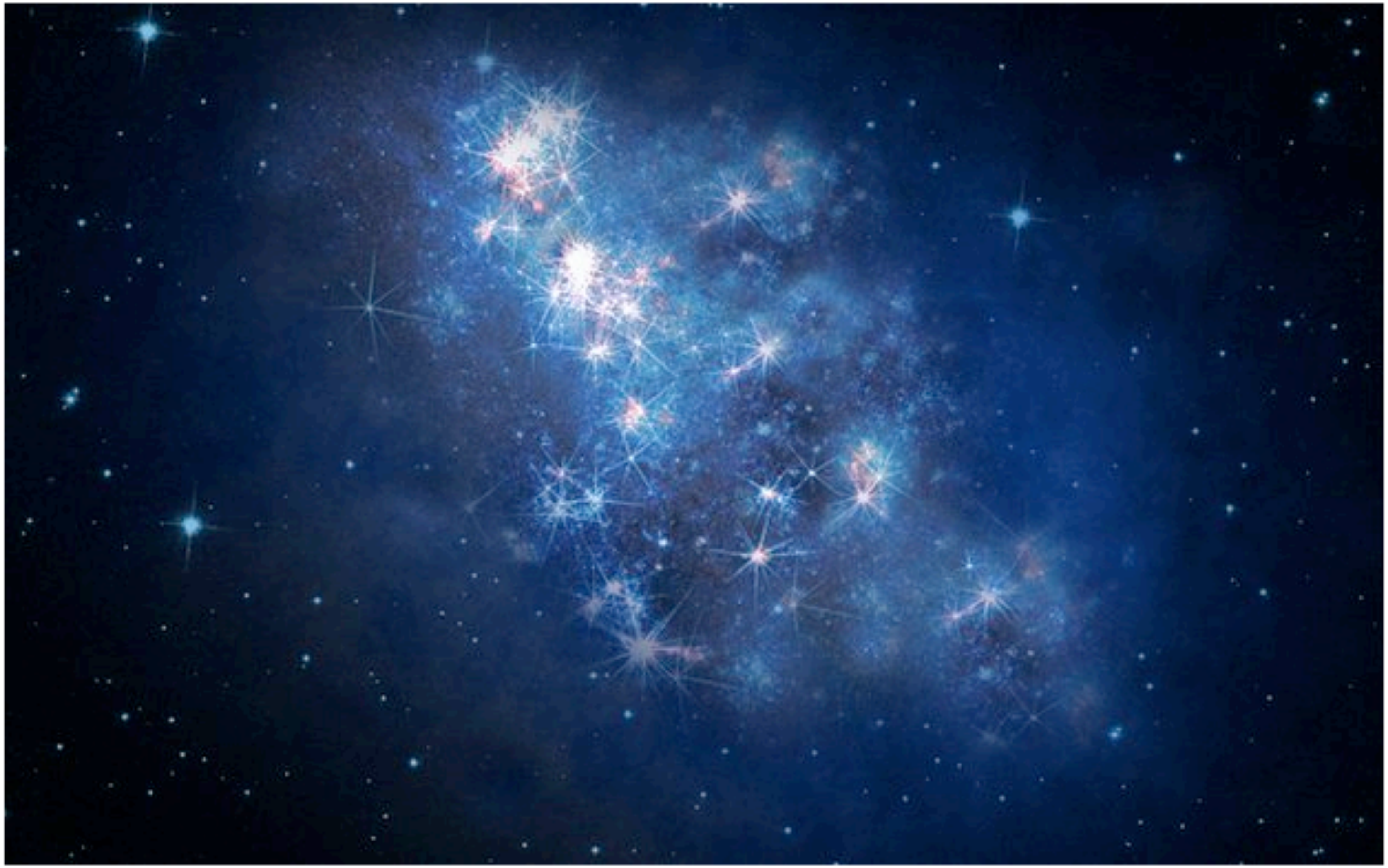
After the current cycle we will have had ~50 hours on various candidates (at z=7-9) using **XSHOOTER, FORS2 (VLT) and MOIRCS (Subaru)**.

Caruana, Bunker, Wilkins et al. 2012
No evidence for Lyman-alpha emission in spectroscopy of z>7 candidate galaxies

Bunker, Caruana, Wilkins et al., accepted
VLT/XSHOOTER & Subaru/MOIRCS Spectroscopy of HUDF-YD3: No Evidence for Lyman-a Emission at z=8.55

New galaxy 'most distant' yet discovered

By Rebecca Morelle
Science reporter, BBC World Service



The galaxy, shown in this artist's impression, is 1-2% the Milky Way's mass

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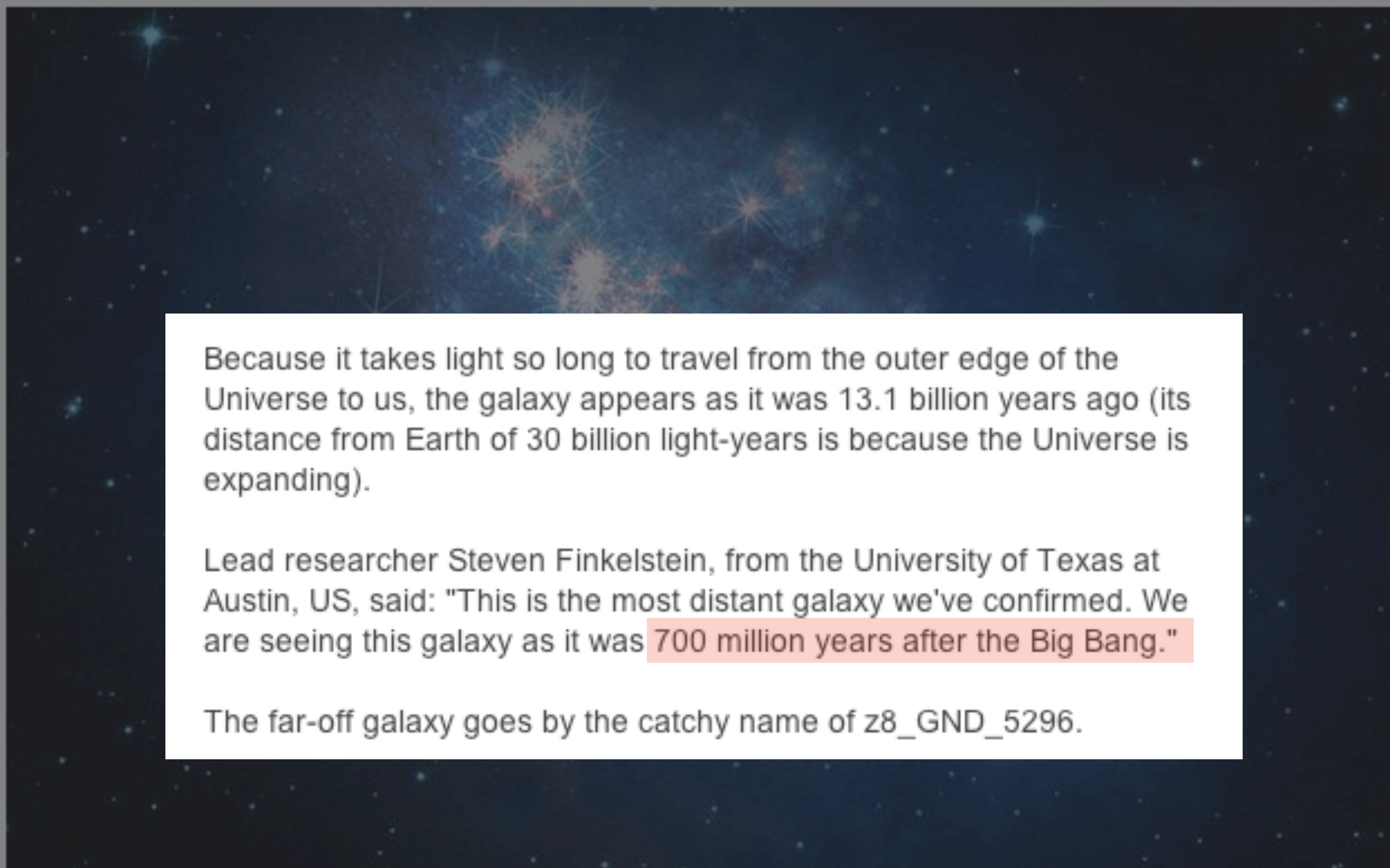


Because it takes light so long to travel from the outer edge of the Universe to us, the galaxy appears as it was 13.1 billion years ago (its distance from Earth of 30 billion light-years is because the Universe is expanding).

Lead researcher Steven Finkelstein, from the University of Texas at Austin, US, said: "This is the most distant galaxy we've confirmed. We are seeing this galaxy as it was 700 million years after the Big Bang."

The far-off galaxy goes by the catchy name of z8_GND_5296.

The galaxy, shown in this artist's impression, is 1-2% the Milky Way's mass

20 October 2010 Last updated at 18:44

2.6K Share

Galaxy is most distant object yet

By Jonathan Amos
Science correspondent, BBC News

They tell the journal Nature that we are seeing the galaxy as it was just 600 million years after the Big Bang.

A tiny faint dot in a Hubble picture has been confirmed as the most distant galaxy ever detected in the Universe.

700>600

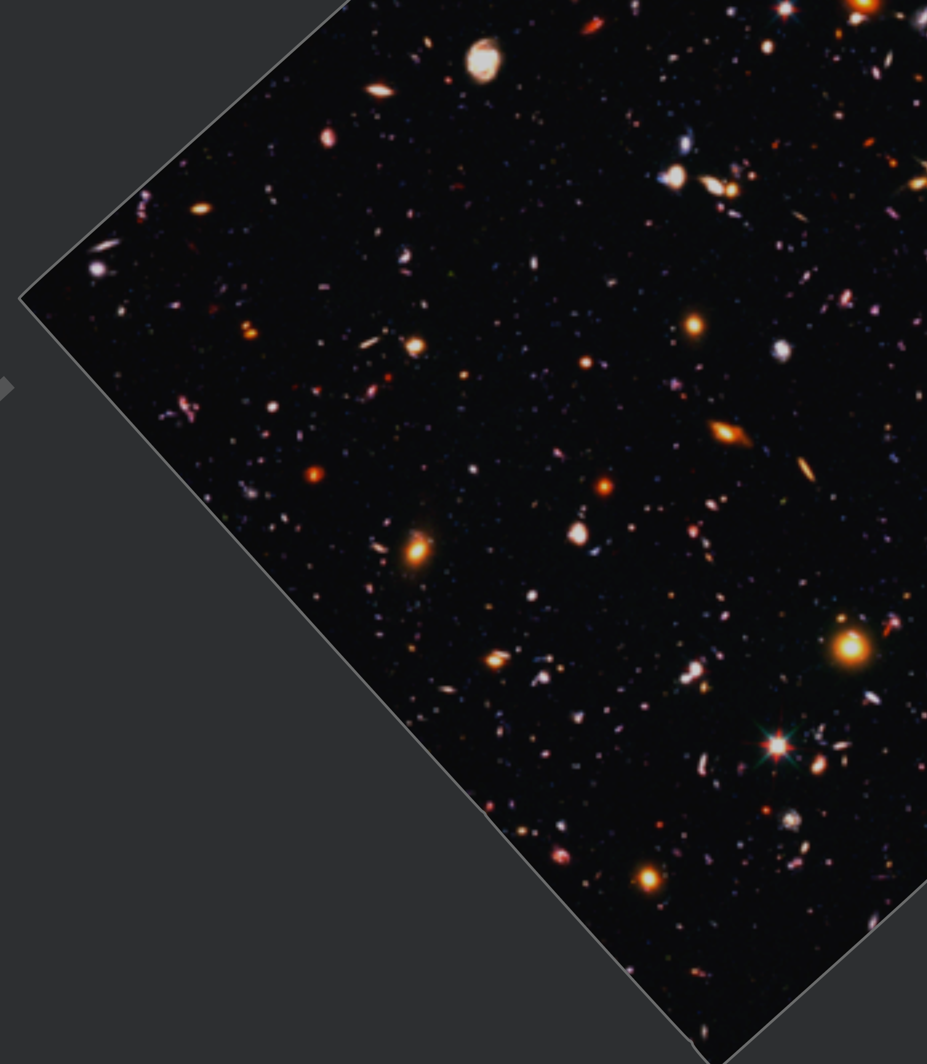
SPECTROSCOPY

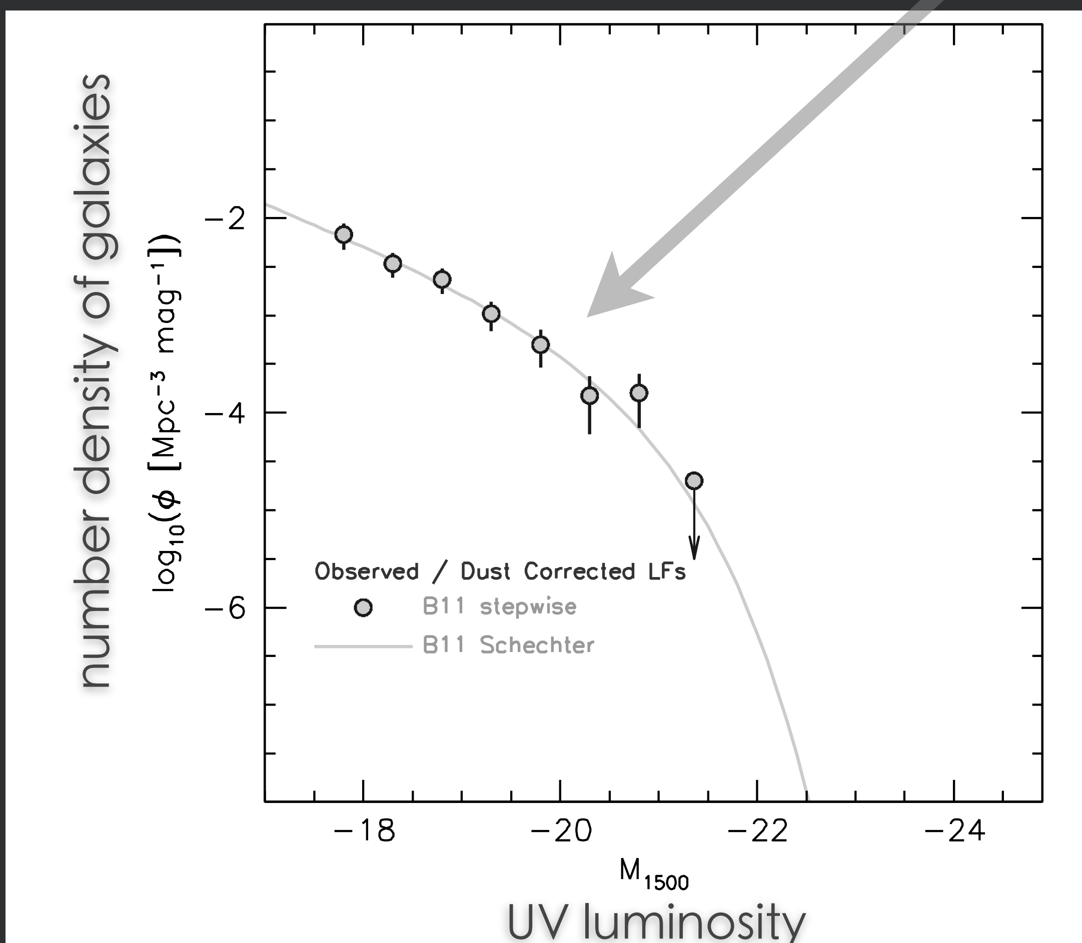
VLT/XSHOOTER & Subaru/MOIRCS Spectroscopy of HUDF-YD3: No Evidence for Lyman-α Emission at $z = 8.55^{\star}$

Andrew J. Bunker[1]†, Joseph Caruana[1,2], Stephen M. Wilkins[1], Elizabeth R. Stanway[3,4], Silvio Lorenzoni[1], Mark Lacy[5], Matt J. Jarvis[1,6,7] & Samantha Hickey[6]

[1] *University of Oxford, Department of Physics, Denys Wilkinson Building, Keble Road, OX1 3RH, U.K.*
[2] *Leibniz-Institut für Astrophysik Potsdam, An der Sternwarte 16, 14482 Potsdam, Germany*
[3] *H. H. Wills Physics Laboratory, Tyndall Avenue, Bristol, BS8 1TL, U.K.*
[4] *Department of Physics, University of Warwick, Gibbet Hill Road, Coventry, CV4 7AL, U.K.*
[5] *NRAO, 520 Edgemont Road, Charlottesville, VA 22903, USA*
[6] *Centre for Astrophysics, Science & Technology Research Institute, University of Hertfordshire, Hatfield, Herts AL10 9AB, U.K .*
[7] *Physics Department, University of the Western Cape, Cape Town, 7535, South Africa*

OBSERVED LUMINOSITY FUNCTION





The observed z~7 UV LF.

With the hundreds of candidates at z=6-9 we can begin to place meaningful constraints on the observed UV luminosity function.

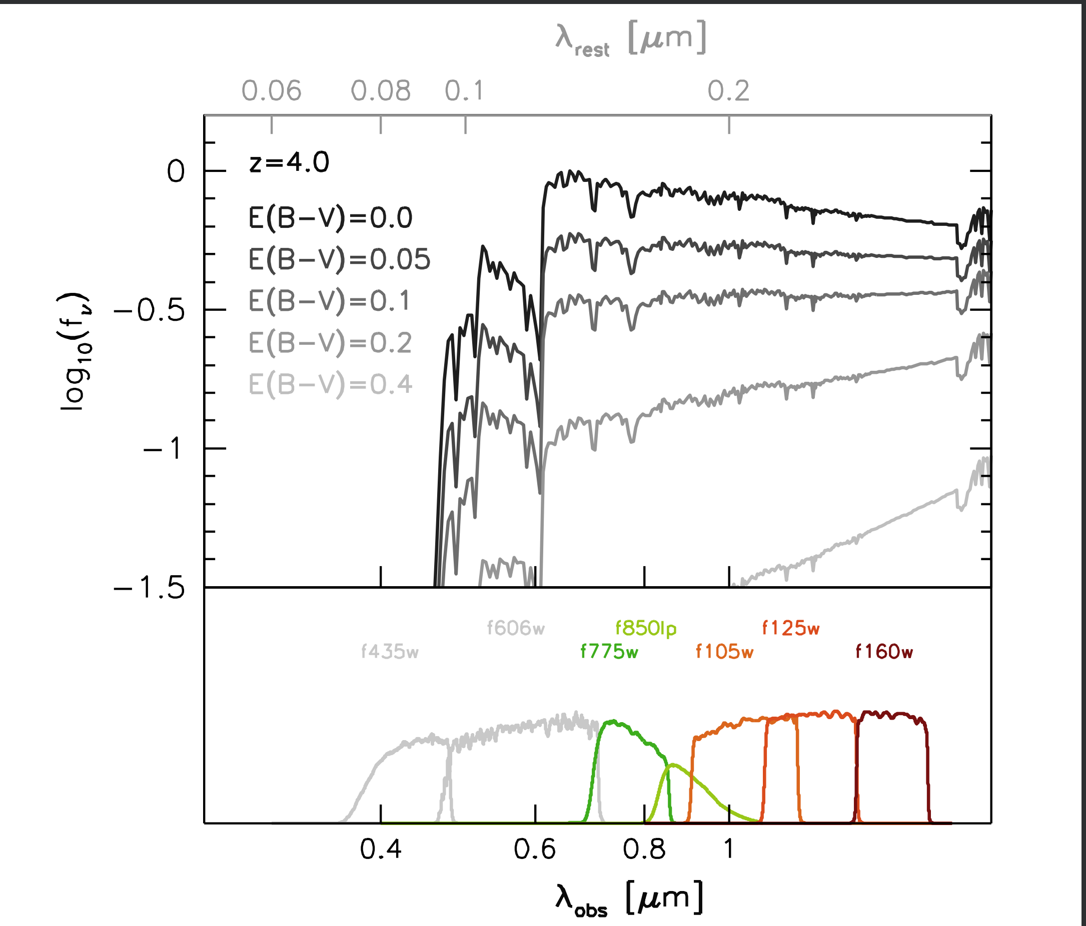
DUST ATTENUATION

UV emission is easily* attenuated by dust thus observed UV luminosities and star formation rates **are only lower limits.**

While the presence of obscured star formation can be probed at lower-redshift using the FIR (e.g. **Herschel, SCUBA-2**) this is not accessible for the bulk of galaxies observed in the very early Universe.

Clearly noticeable dust in CenA (ESO).

DUST ATTENUATION



The UV Continuum of a star forming subjected to various levels of attenuation assuming the Calzetti et al. 2001 reddening curve.

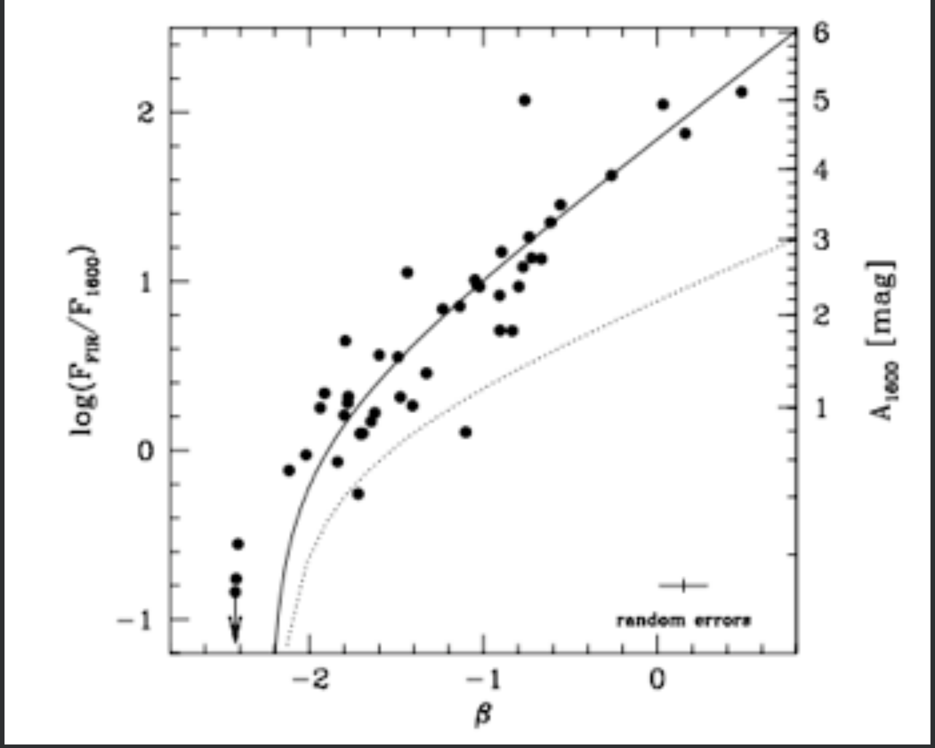
The only currently accessible diagnostic of dust attenuation (for the bulk of galaxies) at very-high redshift is the UV continuum slope.

The UV Continuum of a star forming subjected to various levels of attenuation assuming the Calzetti et al. (2001) reddening curve.

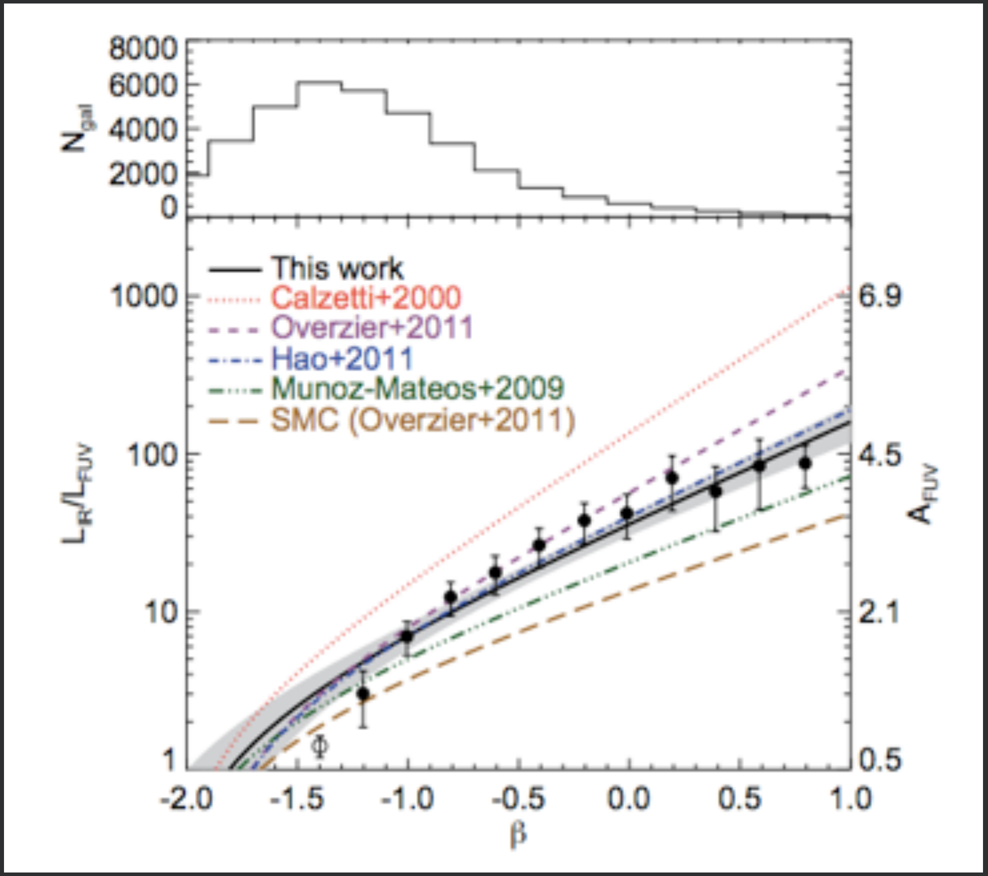
DUST ATTENUATION

A popular empirical calibration of this the **Meurer relation**. This relates the observed UV continuum slope to the attenuation in the UV.

$$A_{1600} = 4.43 + 1.99 \times \beta_{\rm obs}.$$



Meurer et al. (1999)



Heinis et al. (2013)

DUST ATTENUATION

A popular empirical calibration of this the **Meurer relation**. This relates the observed UV continuum slope to the attenuation in the UV.

$$A_{1600} = 4.43 + 1.99 \times \beta_{\rm obs}.$$

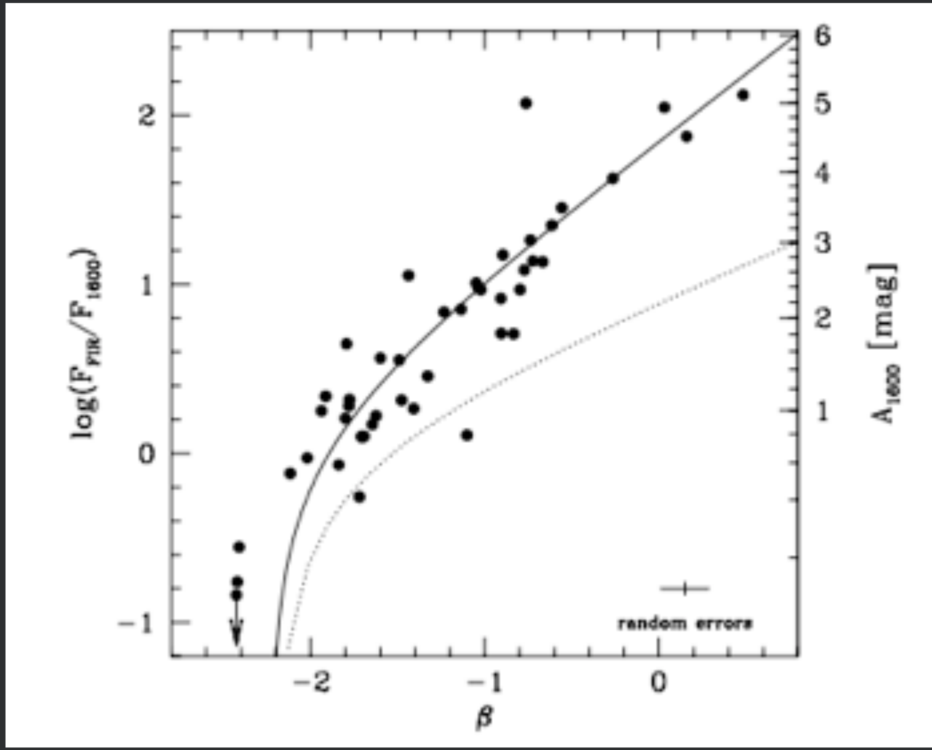
$\equiv$

Sensitive to the dust law
(SMC: 1.12, Calzetti: 2.10, SN: 2.49)

$$D_\lambda = {\rm d}A_\lambda/{\rm d}\beta,$$

$$A_\lambda = D_\lambda \times [\beta_{\rm obs} - \beta_{\rm int}],$$

Intrinsic UV continuum slope
Sensitive to the SFH, metal enrichment history, and IMF.



Meurer et al. (1999)

DUST ATTENUATION

There is scatter in the intrinsic slope

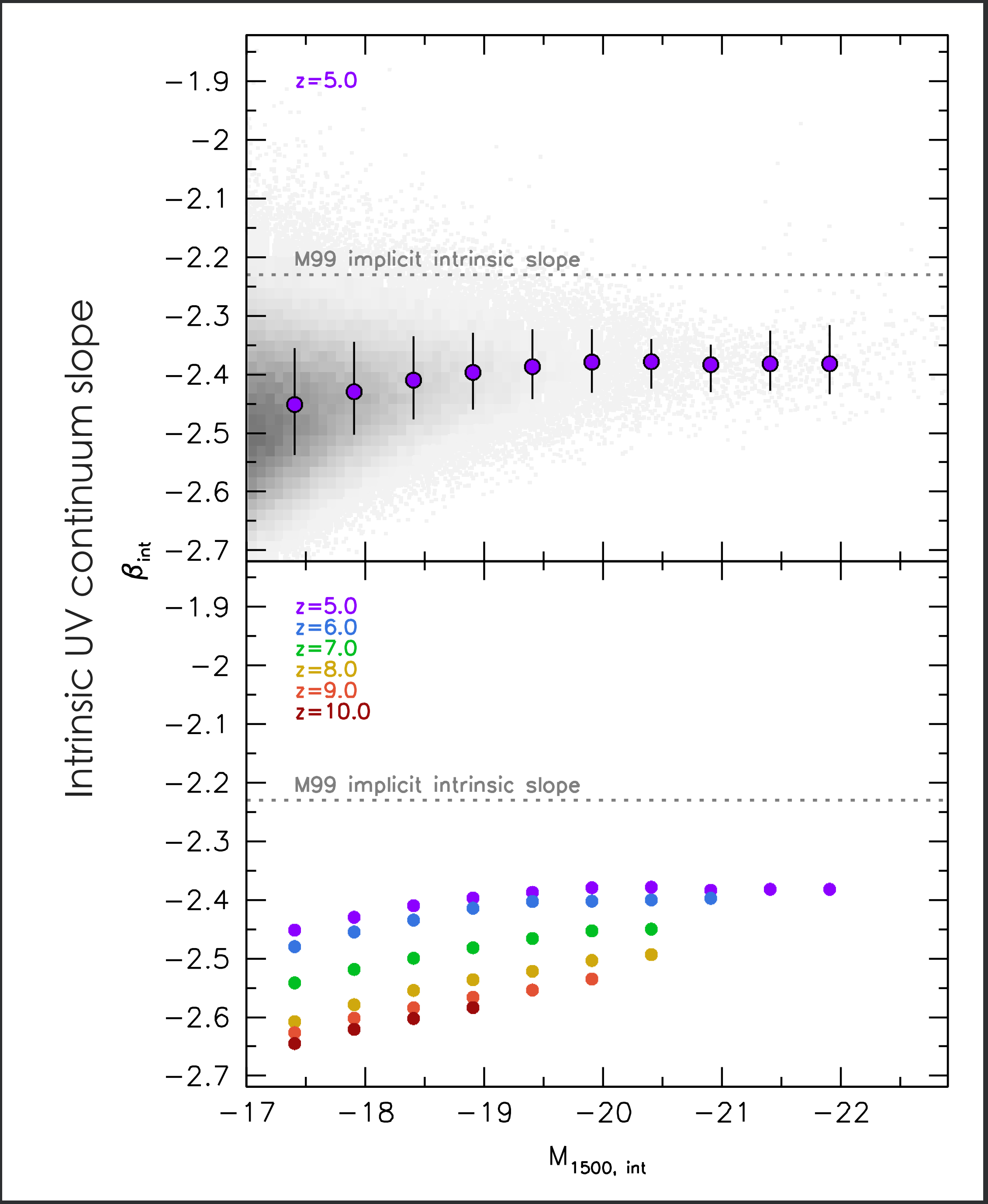
The median intrinsic slope varies with luminosity

The median intrinsic slope varies with redshift

The median intrinsic slope is bluer than implicit in the Meurer relation

See: Wilkins et al. (2012a), Wilkins et al. (2013b)

The simulated predicted intrinsic UV slope at high-redshift.

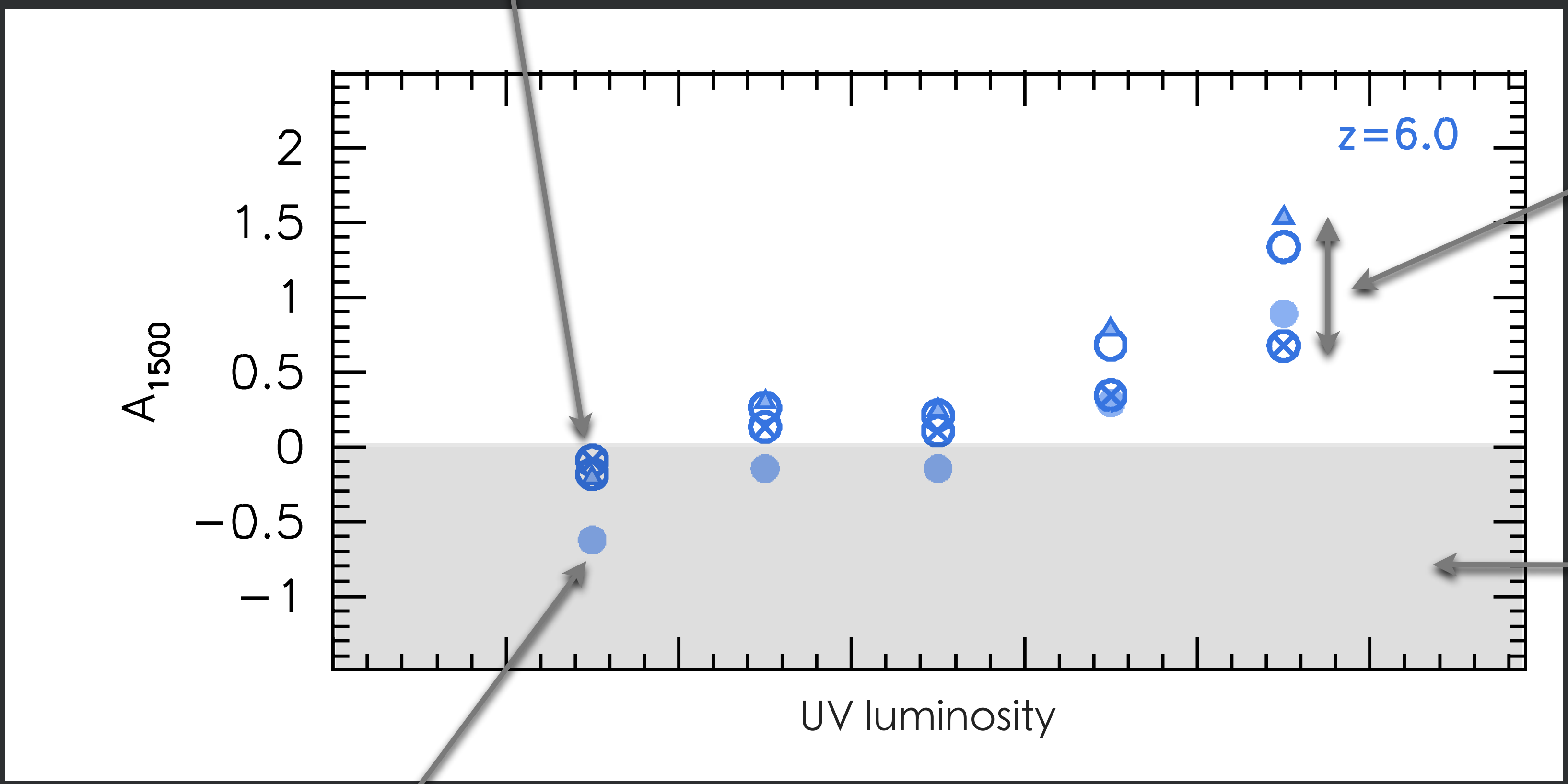


DUST ATTENUATION

Using different assumptions for the intrinsic slope and dust curve you get different answers.

Assuming MassiveBlack predictions for intrinsic slope and different dust curves.

difference of 0.8 mag!

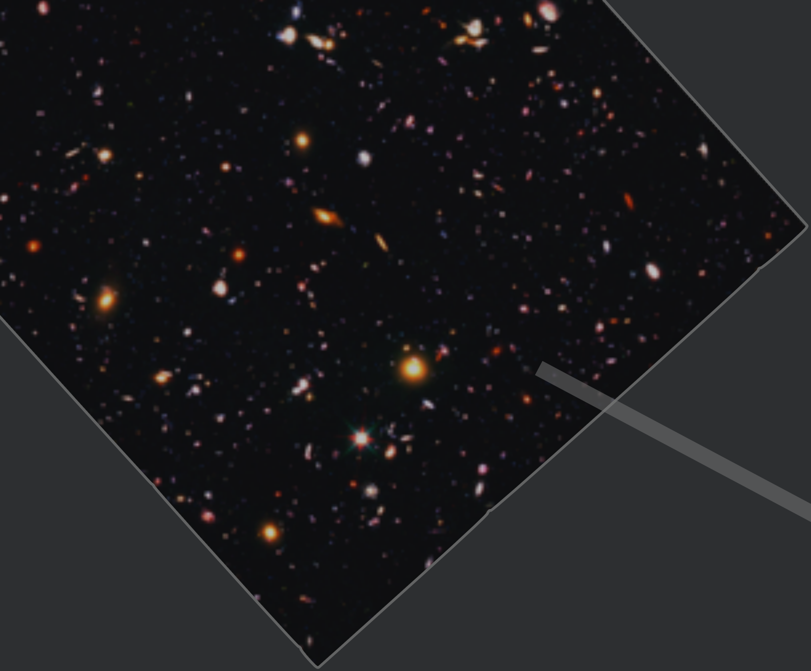


unphysical!

Simply assuming Meurer et al. (1999)

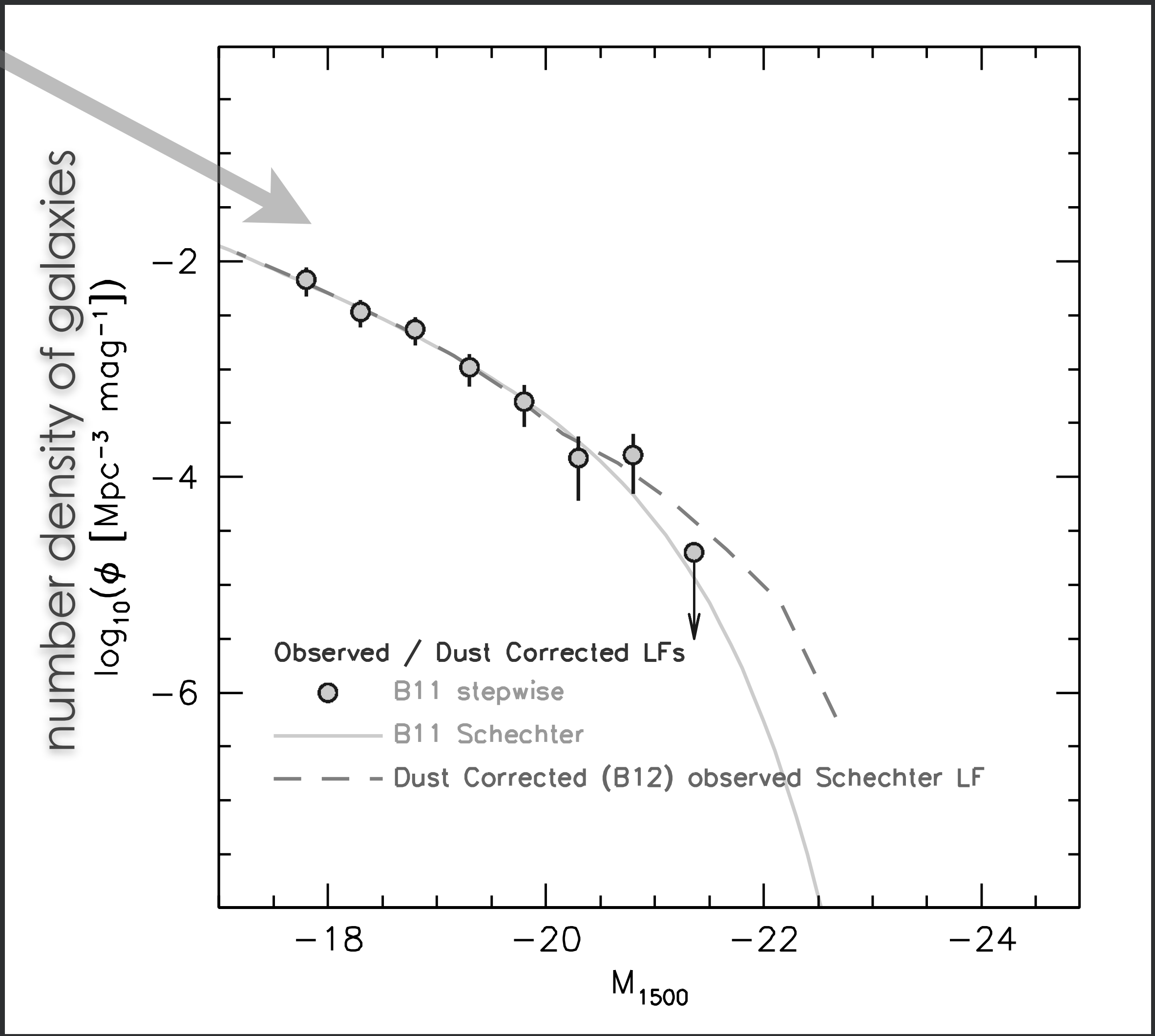
Based on Bouwens et al. (2012) measurements of the UV continuum slope, see also Wilkins et al. (2011b), Wilkins et al. (2012a), Wilkins et al. (2013b)

INTRINSIC LUMINOSITY FUNCTION



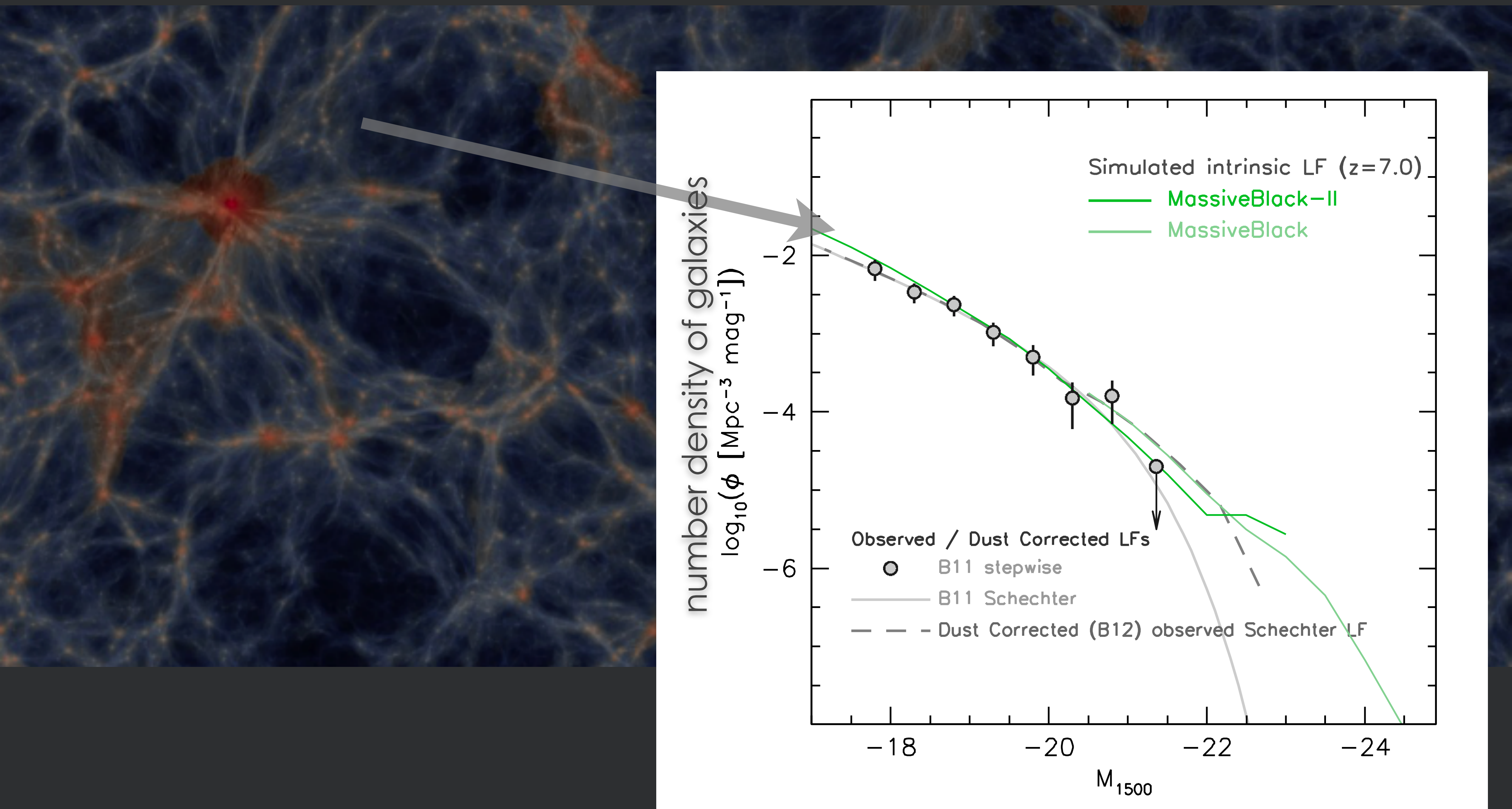
Using observations of the UV continuum slope we can correct the luminosities of the observed galaxies to estimate the intrinsic UV luminosity function.

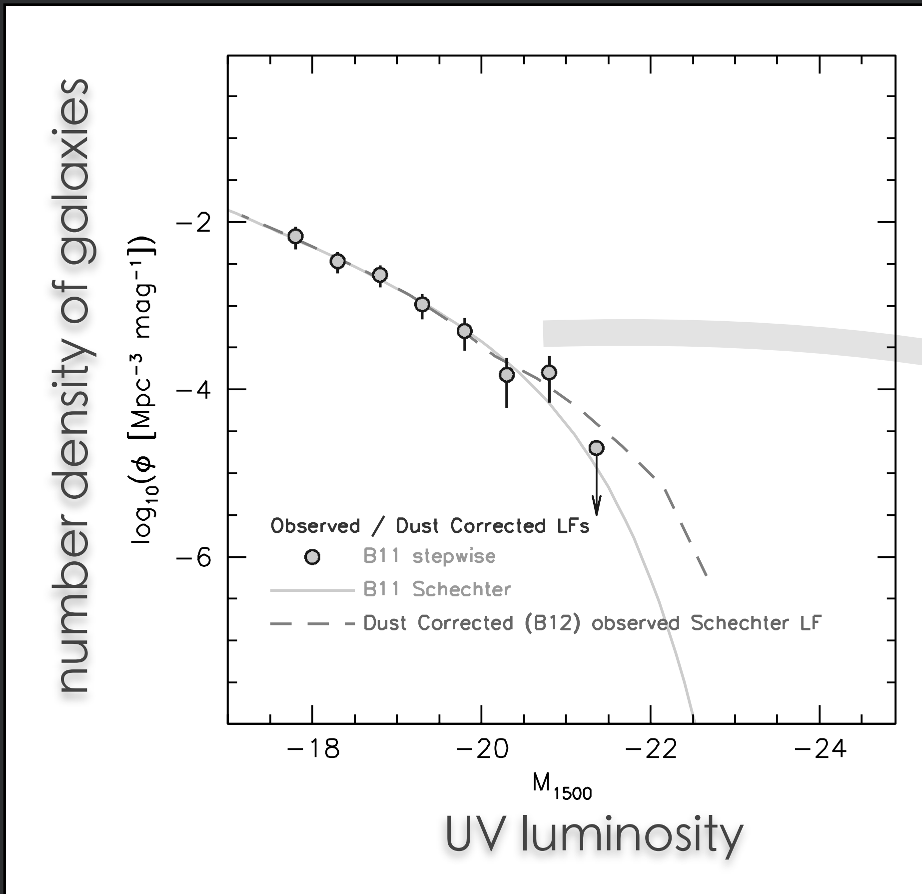
This is a key property of the Universe which can be easily predicted by simulations...



COMPARISON WITH SIMULATIONS

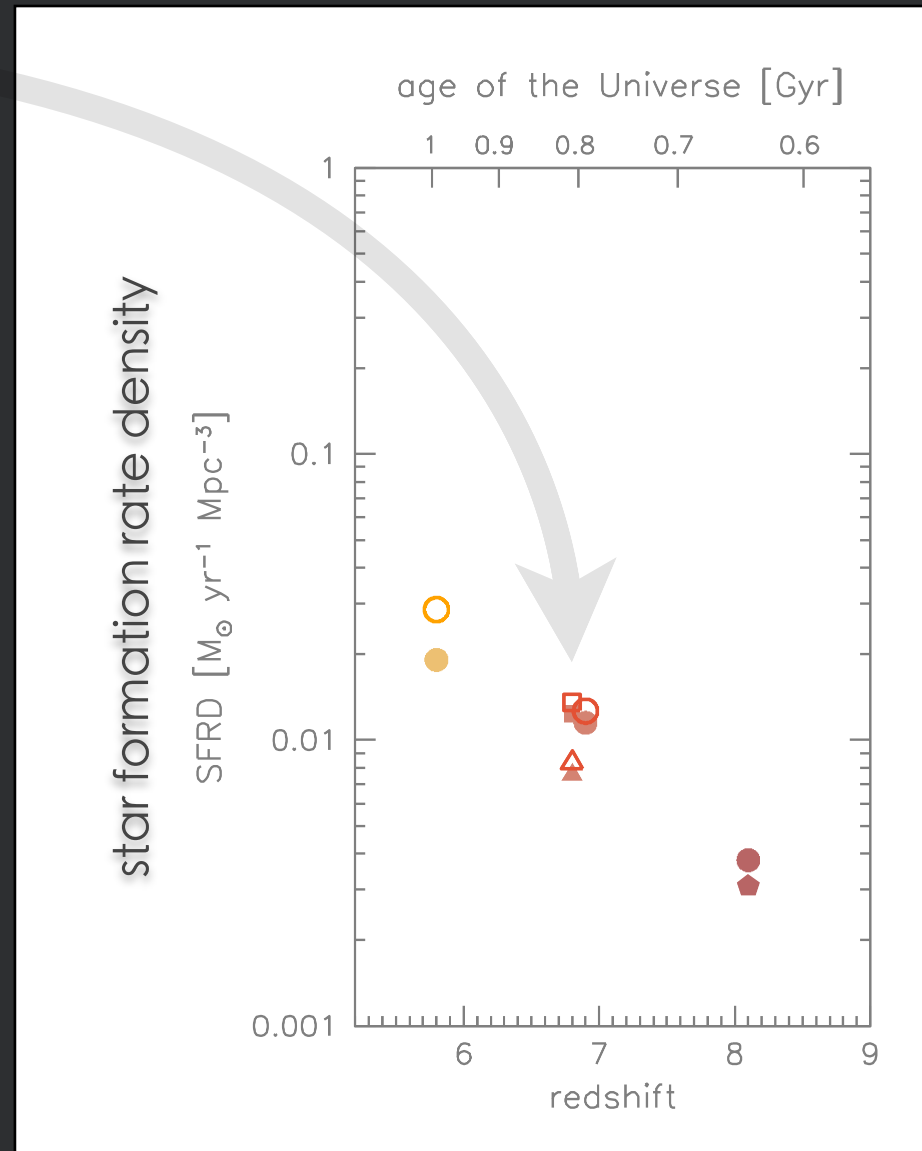
Predictions from MassiveBlack and MassiveBlack-II closely match the dust corrected observations, at least at z~7.





The observed and dust-corrected (intrinsic, dashed line) UV luminosity function at z=7.

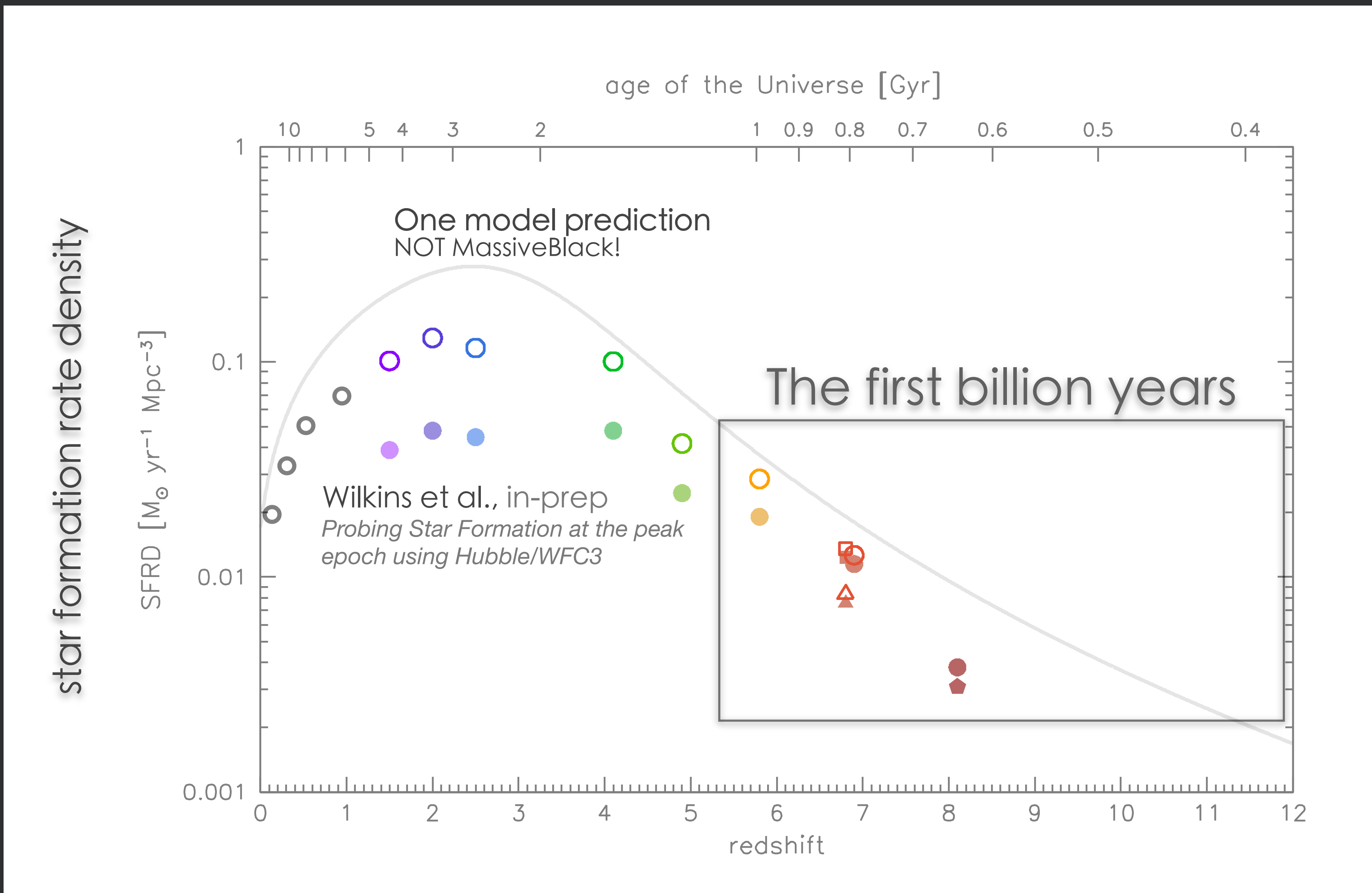
Observational constraints on the star formation rate density of the Universe during the first billion years.



The first moment of the UV LF is the UV luminosity density. This can be converted to a star formation rate density.

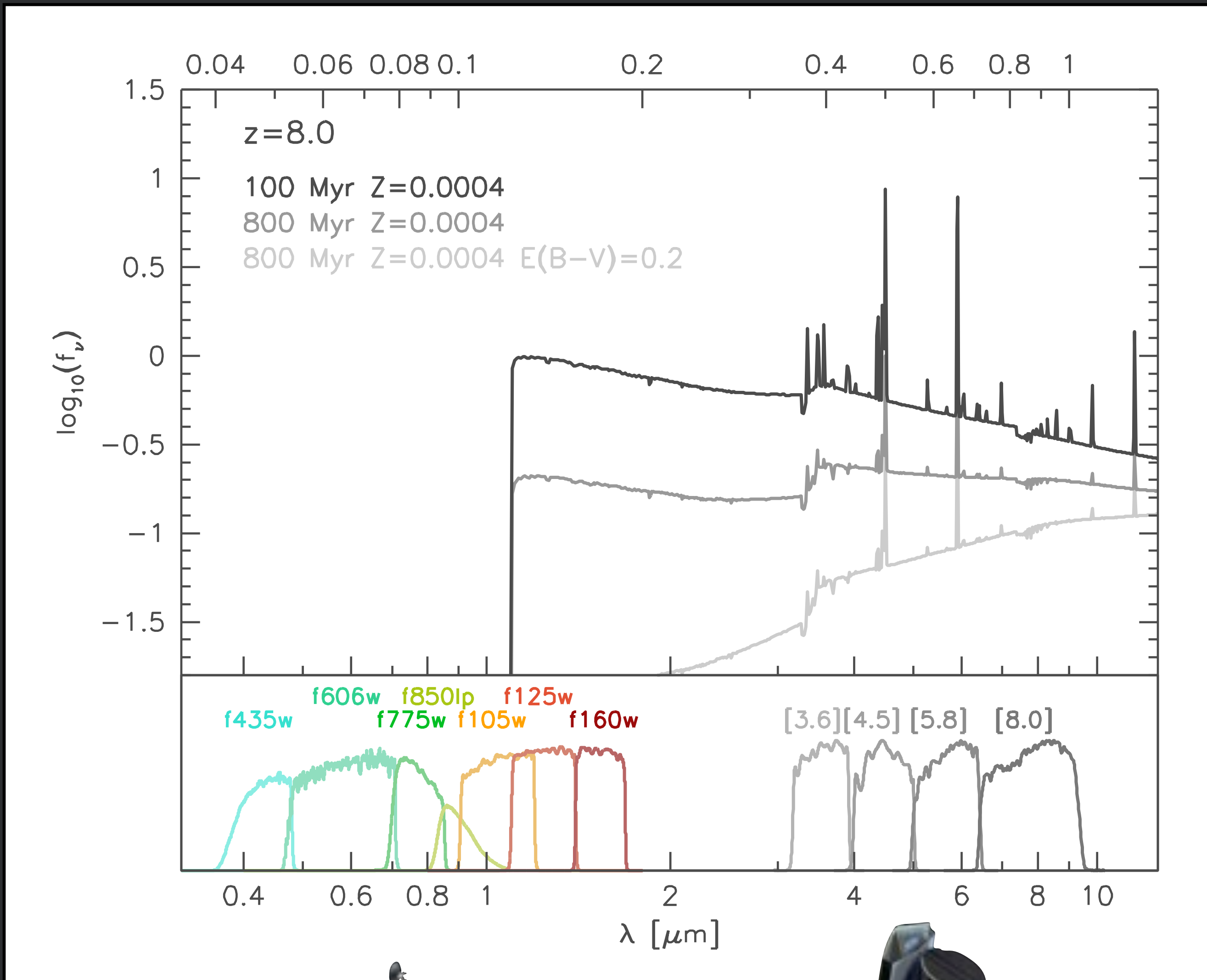
COSMIC STAR FORMATION HISTORY

Combined with constraints at lower redshift we now have a picture of the CSFH over >90% the history of the Universe.



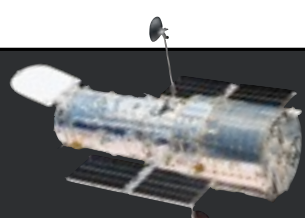
The Cosmic Star Formation History (CSFH), NOTE: there are many other studies that have probed the CSFH, especially at low-redshift.

STELLAR MASSES



Model SEDs with f_esc=0.0 at z=8

Combining with Spitzer IRAC we can probe the rest-frame UV-optical

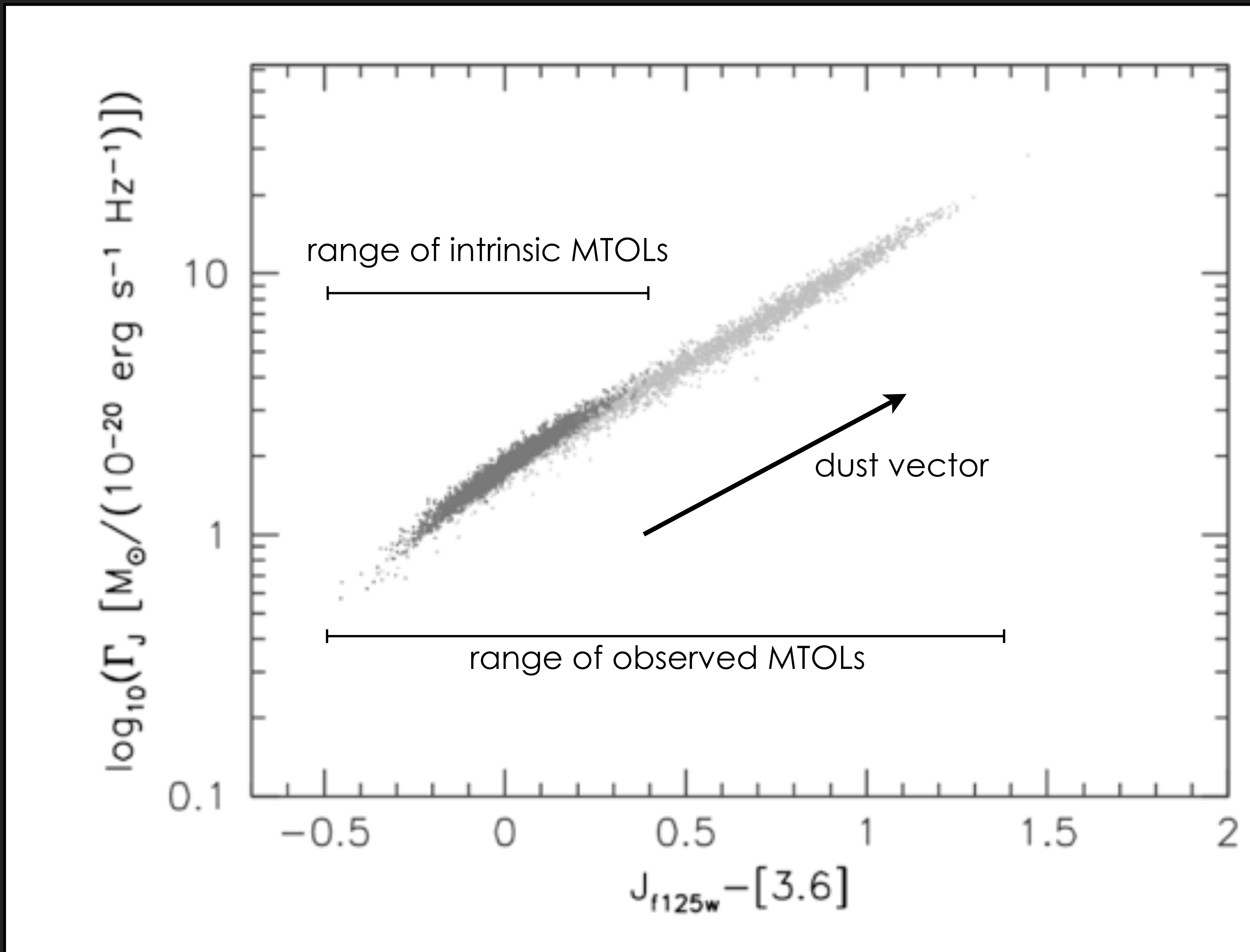


+

= rest-frame UV-optical luminosities → Stellar MTOLS?

STELLAR MASSES

Wilkins et al., in prep

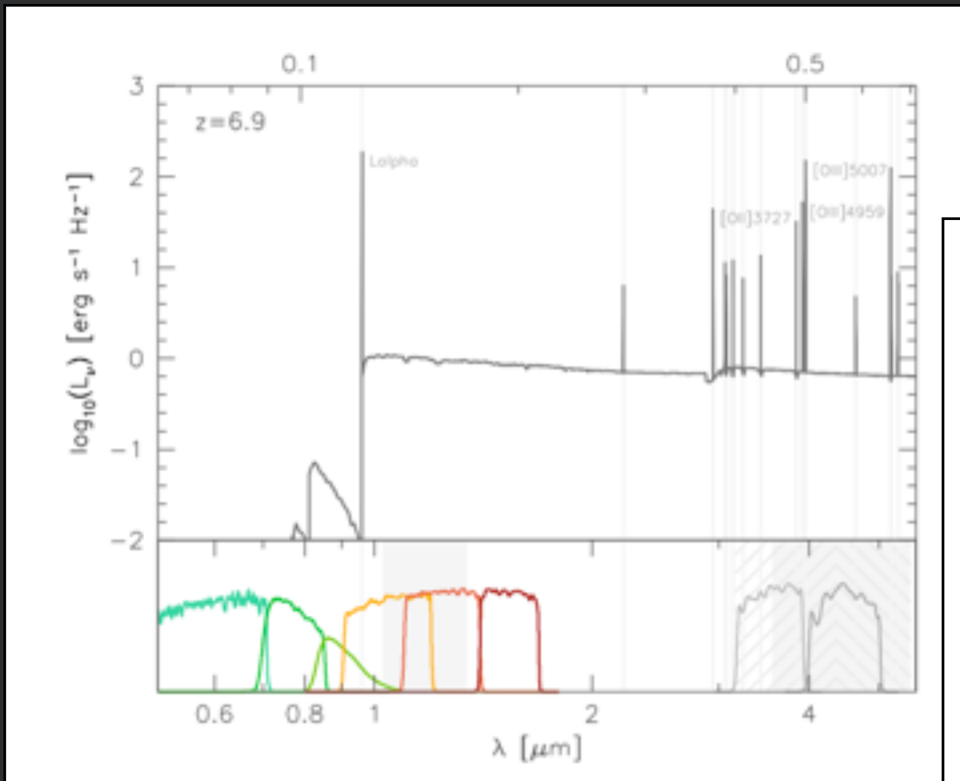


The Mass-to-light ratio as a function of J-[3.6] colour for galaxies at z=7.

In principal the observed J-[3.6] colour is a robust diagnostic of the MTOL, at z=7, even when dust is included.

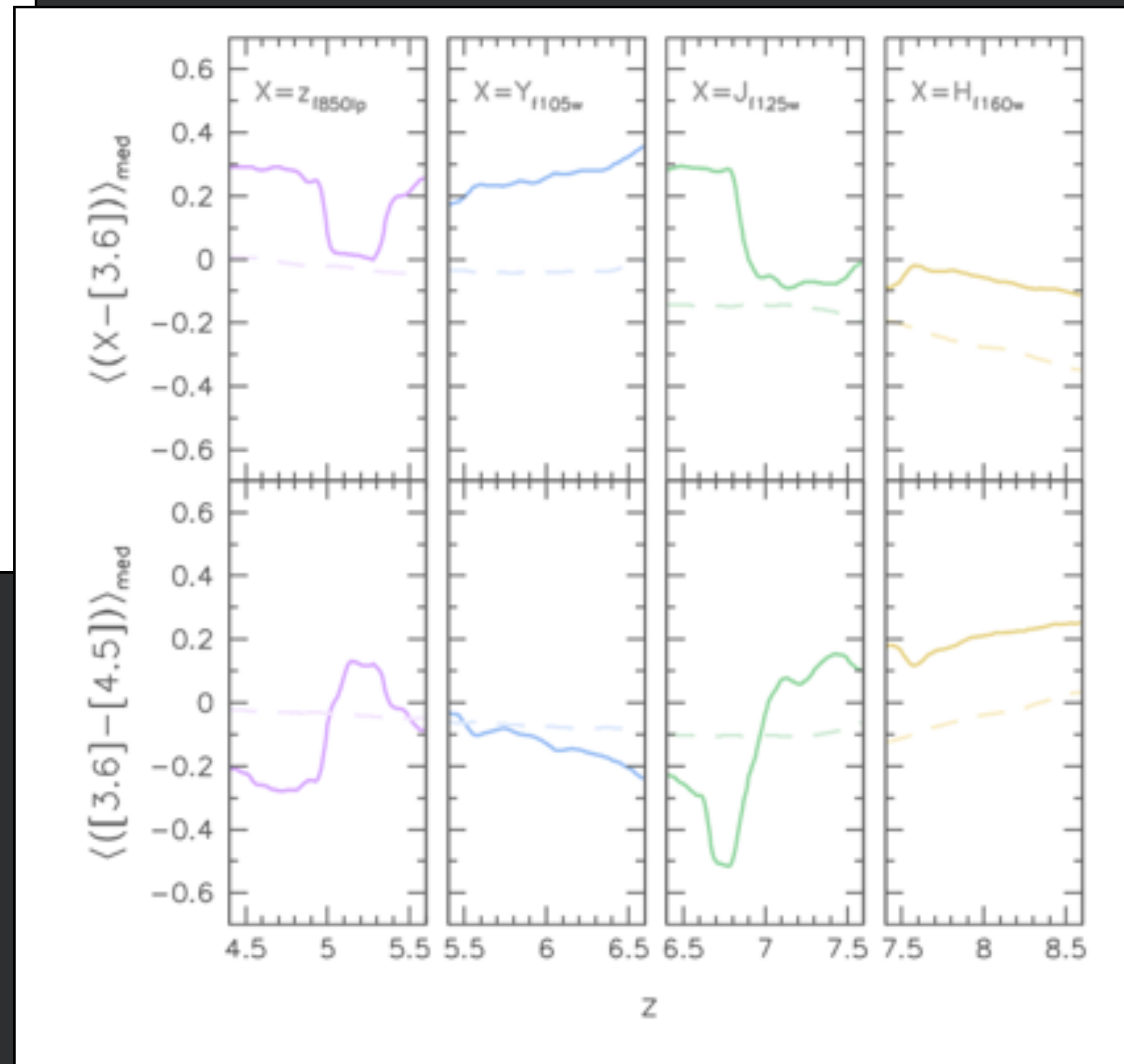
See also Wilkins et al. (2013c) for a demonstration of this technique at low-redshift using simulations or Taylor et al. (2012) from observations.

NEBULAR EMISSION



Model SED of a star forming galaxy at z=6.9

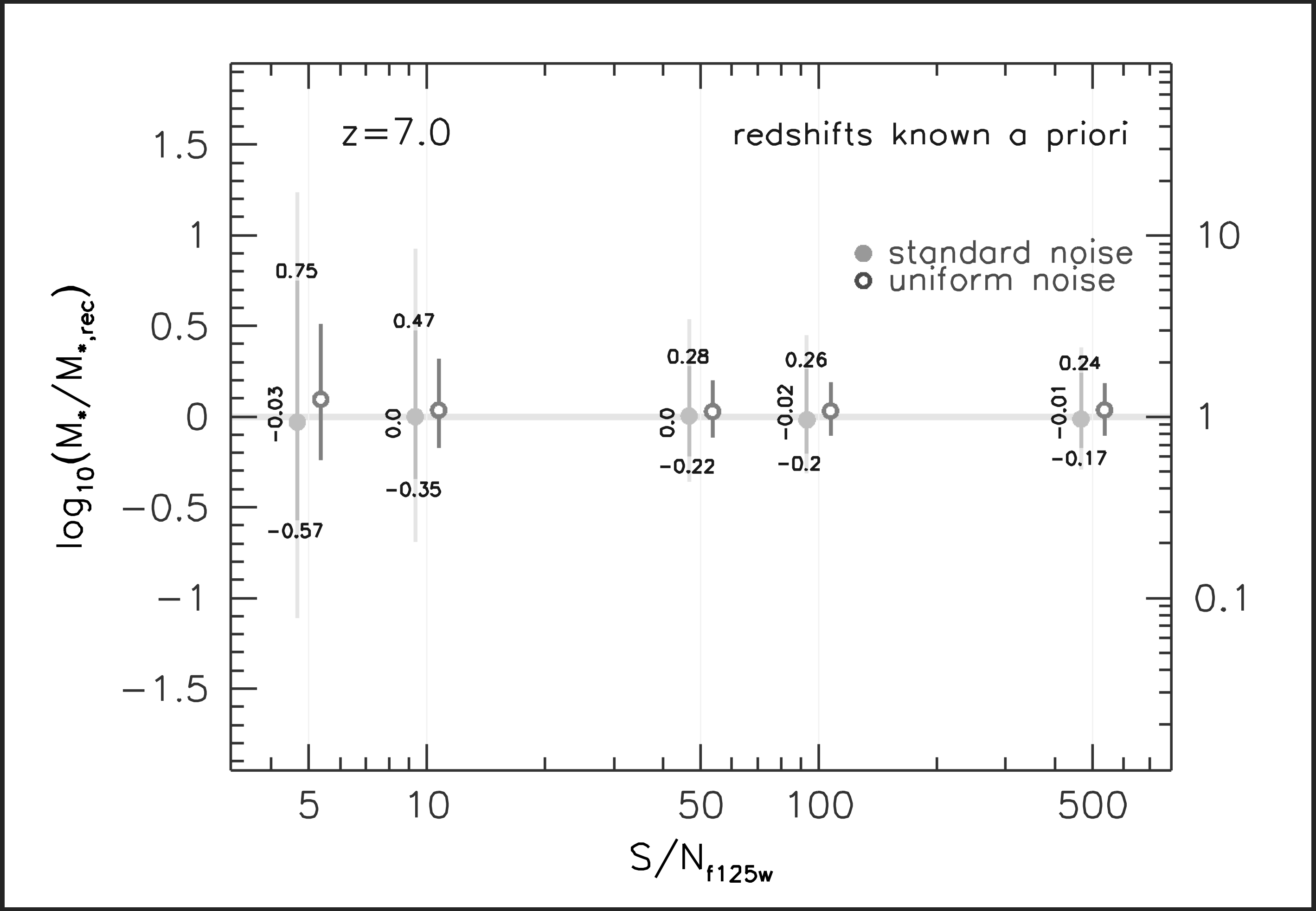
Wilkins et al., submitted
Predicted observed frame colours of high-redshift galaxies.



Nebular emission can have a large effect on the observed colours.

STELLAR MASSES

Full SED fitting to all the ACS, WFC3, and IRAC bands.

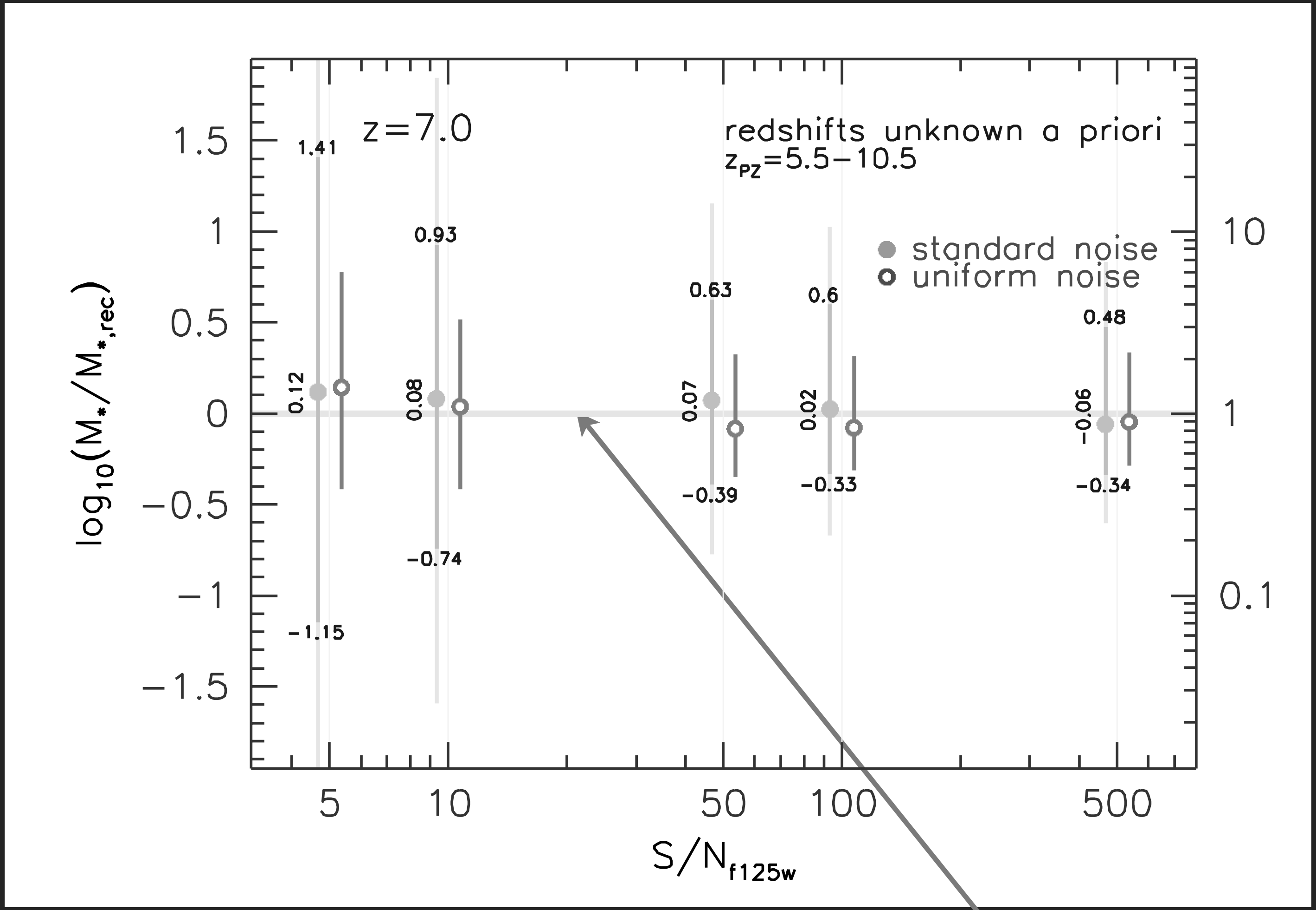


The difference between the measured and true stellar mass-to-light ratios.

This assumes the relative noise throughout the ACS and WFC3 bands is uniform, the relative noise in the IRAC channels is chosen to reflect the sensitivities in the GOODS-South field.

STELLAR MASSES

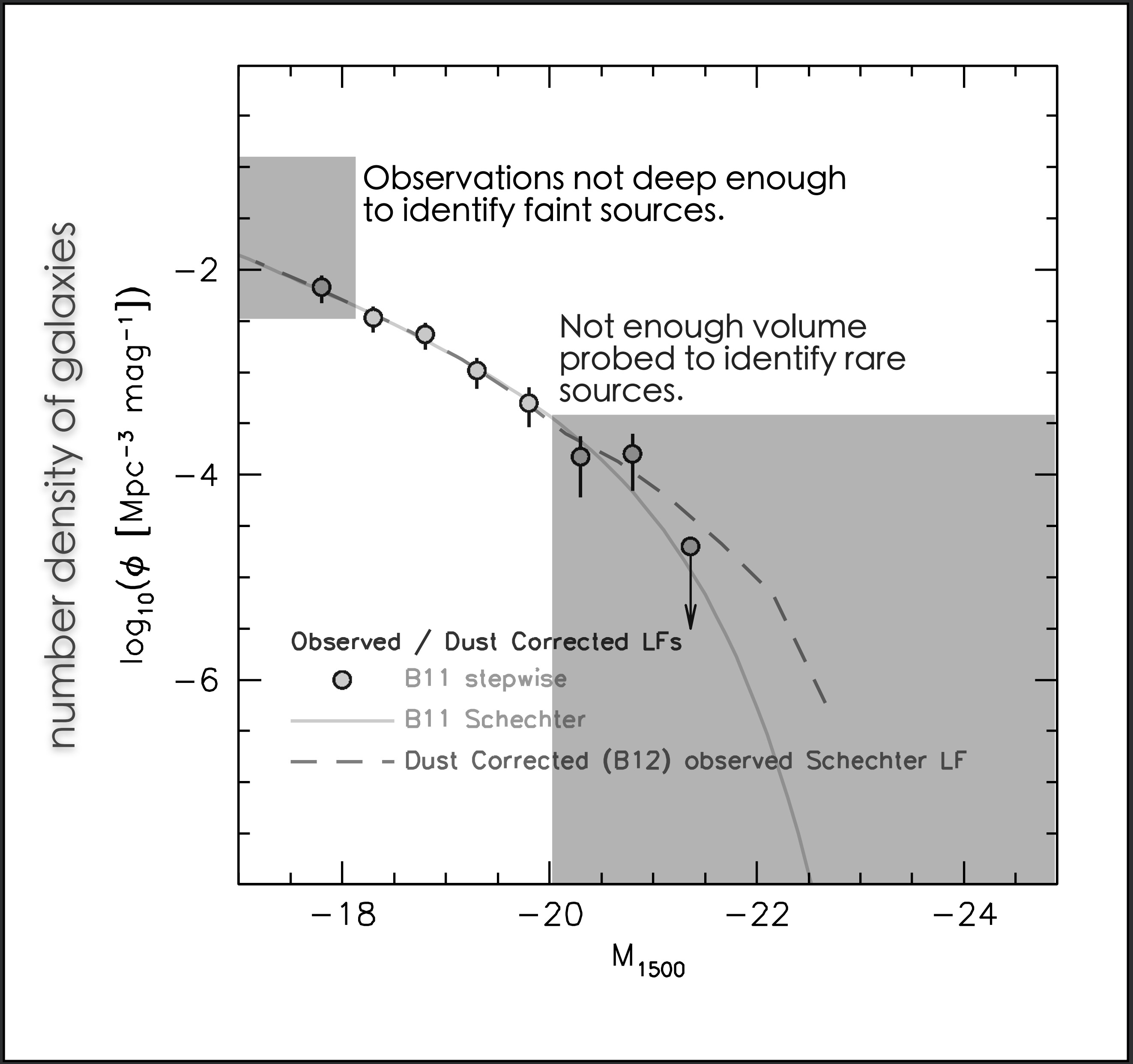
Full SED fitting to all the ACS, WFC3, and IRAC bands.



The difference between the measured and true stellar mass-to-light ratios.

These now assume the noise is uniform across all the bands. This is unrealistic with current instrumentation.

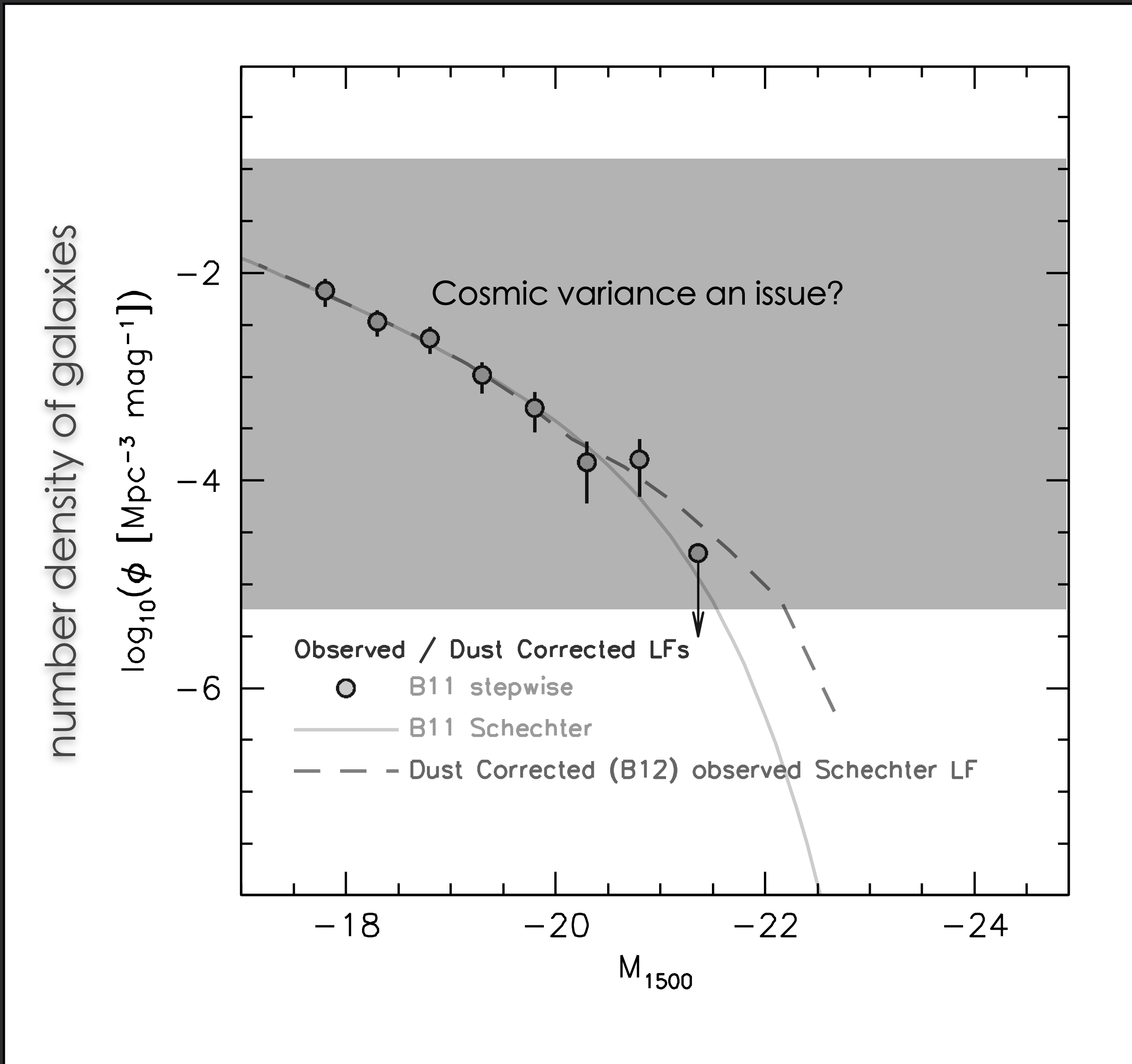
FUTURE



The observed and dust-corrected (intrinsic, dashed line) UV luminosity function at z=7.

FUTURE

FUTURE



The observed and dust-corrected (intrinsic, dashed line) UV luminosity function at z=7.

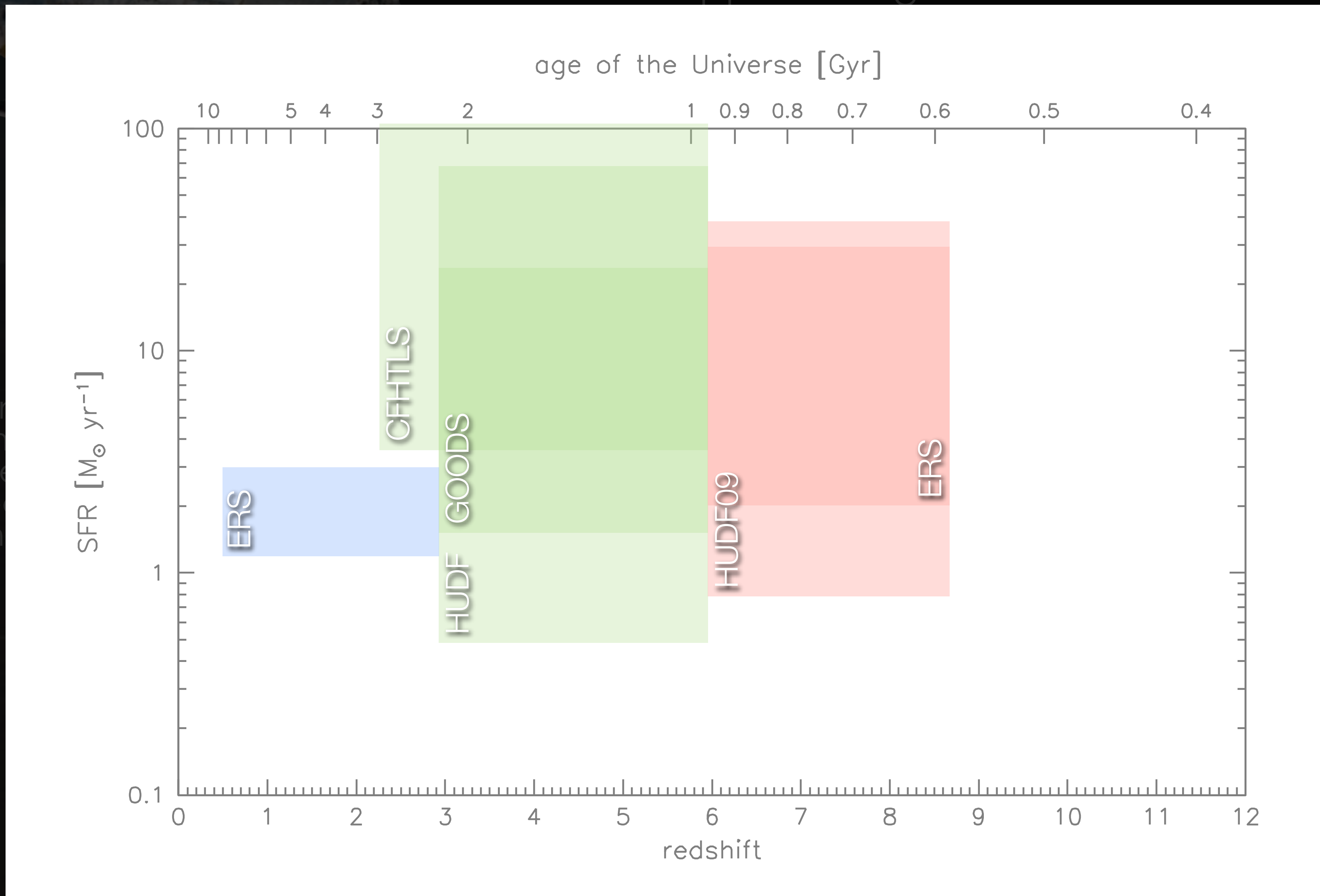
The CANDELS and HUDF12 programmes are currently acquiring WFC3 near-IR observations. There is the possibility of further programmes but Hubble is approaching its End Of Life.

The VISTA telescope is also acquiring deep near-IR imaging over several fields.

Paranal Observatory (ESO)

PROBING THE UV CONTINUUM

The CANDELS and HUDF12 programmes are currently acquiring WFC3 near-IR observations. There is the possibility of further programmes but Hubble is approaching its End Of Life.



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optical
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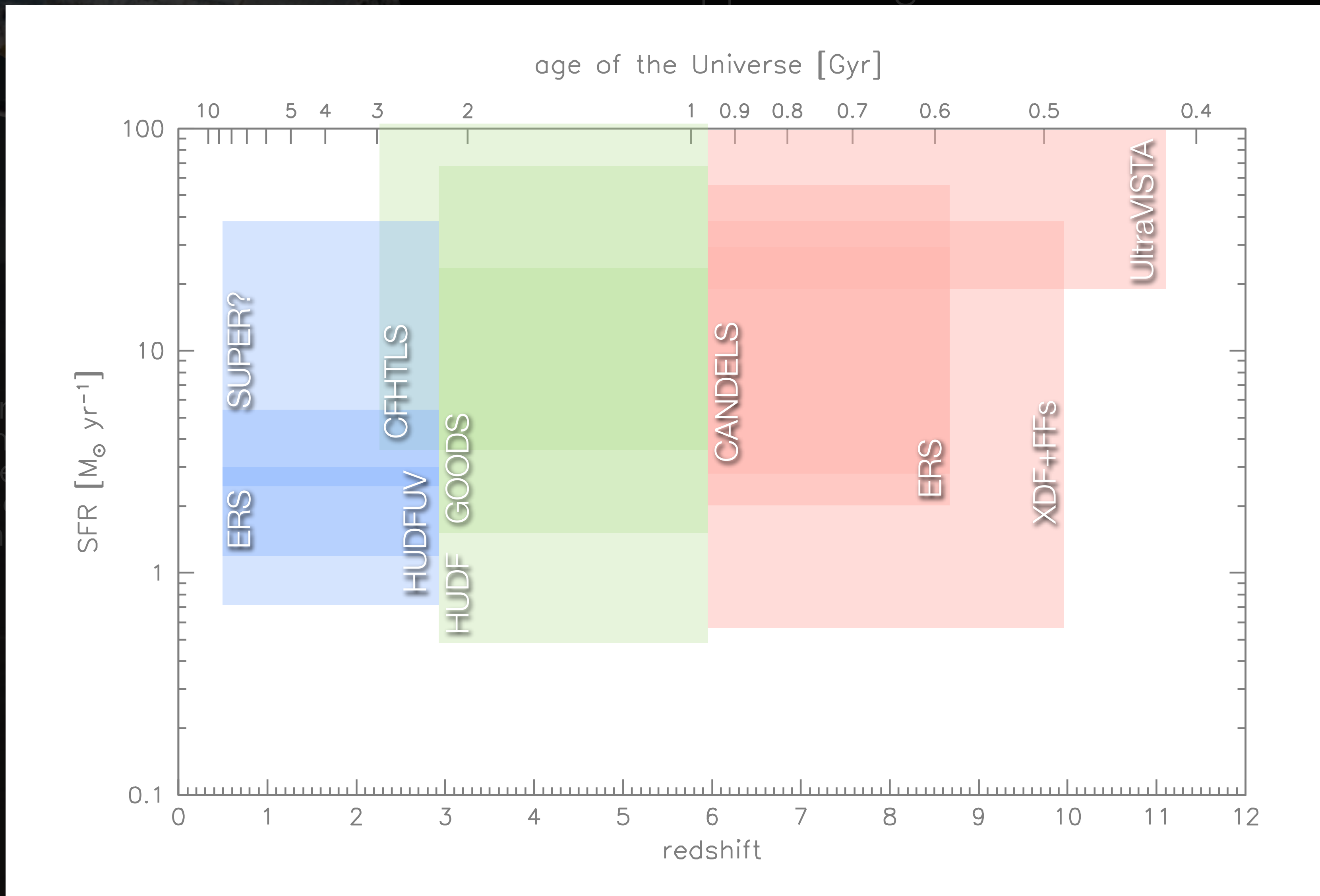
at z=6-10.

2012

Paranal Observatory (ESO)

PROBING THE UV CONTINUUM

The CANDELS and HUDF12 programmes are currently acquiring WFC3 near-IR observations. There is the possibility of further programmes but Hubble is approaching its End Of Life.



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2016

Paranal Observatory (ESO)

MULTI-WAVELENGTH OBSERVATIONS

Many of the brighter candidates will also be amenable to spectroscopic followup using the VLT.

Paranal Observatory (ESO)

MULTI-WAVELENGTH OBSERVATIONS

In the intermediate term facilities such as ALMA will also become useful, especially to probe the most luminous systems.

ALMA test facility (ESO)

MULTI-WAVELENGTH OBSERVATIONS

In the longer term the generation of **Extremely Large Telescopes** will permit detailed rest-frame UV and optical spectroscopy of galaxies in the first billion years.

Cerro Amazones, future home of the E-ELT (ESO)

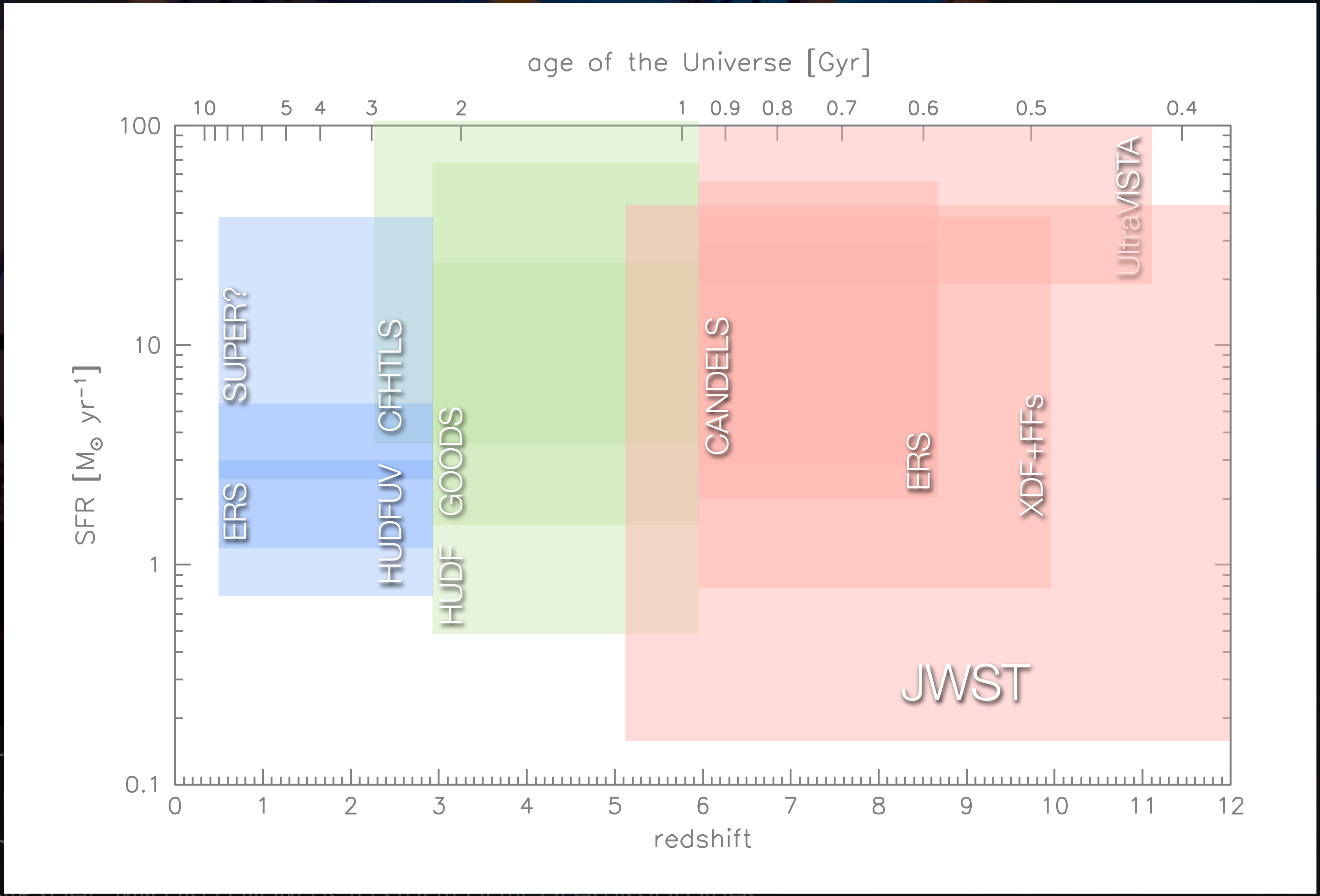
JWST primary mirror segment (NASA/ESA/CSA)

The James Webb Space Telescope will revolutionise the study of the early Universe allowing us to push to much higher redshift and fainter luminosities.

NIRSpec will also allow us to study optical emission lines in galaxies to z~7 (making confirmation possible for many candidates) as well as identifying the presence of Pop-III stars (through HeII emission).

JWST primary mirror segment (NASA/ESA/CSA)

PROBING THE UV CONTINUUM



NIRSpec will also allow us to study optical emission lines in galaxies to z~7 (making confirmation possible for many candidates) as well as identifying the presence of Pop-III stars (through HeII emission).

2023

CONCLUSIONS

Hubble/WFC3 observations now allow us to explore galaxies present in the first billion years of the Universe's history.

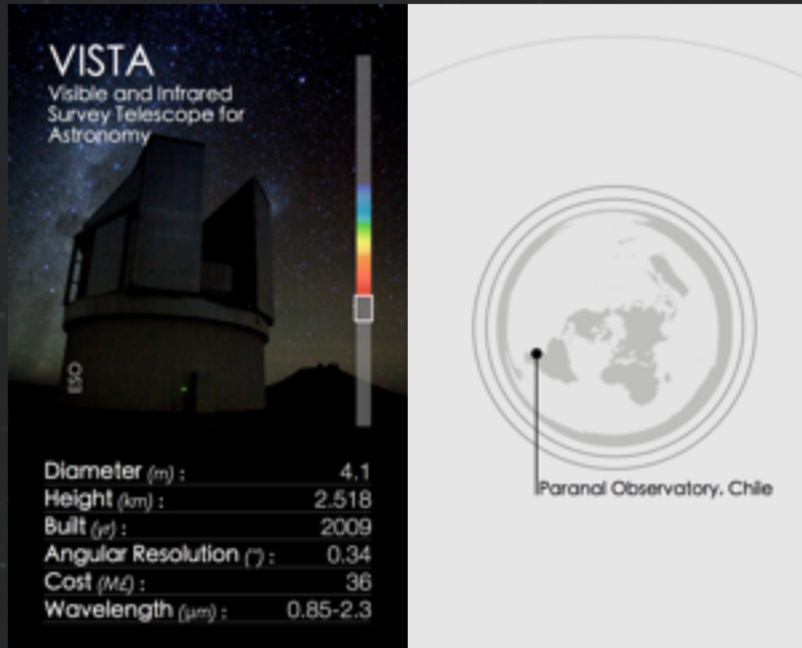
Predictions from large hydro-dynamical are in fairly good agreement with the observed intrinsic UV LF.

These simulations can also be used to test and refine observational techniques. This testing suggests that while certain properties can be measured accurately they can often not be measured precisely.

In the near future programmes such as the Frontier Fields and UltraVISTA will provide stronger constraints. In the further future JWST will allow us to probe much lower luminosities and to much higher redshift.

Stephen M. Wilkins

www.stephenwilkins.co.uk

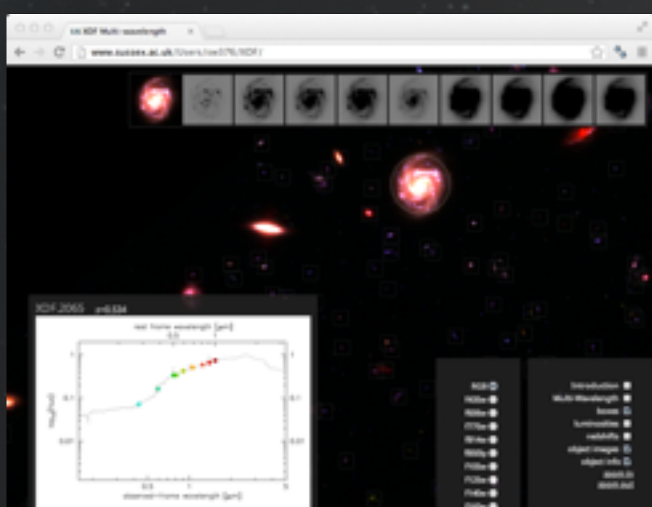


Shameless promotion for an STFC funded outreach programme I have been running:

Astronomy Top Trumps

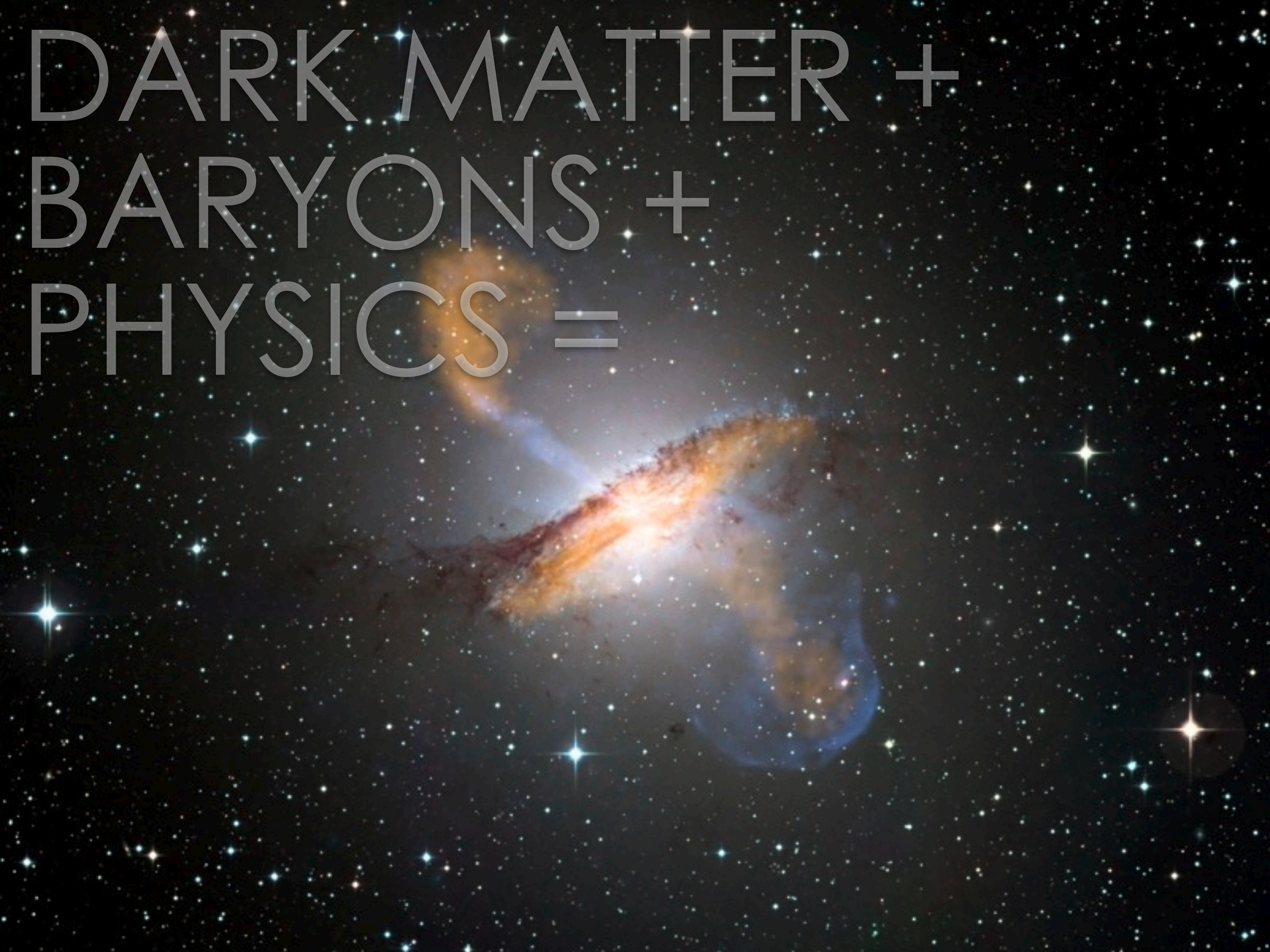
(Five decks of astronomy goodness Observatories, the Solar System, Milky Way: Stars, Milky Way: Nebulae, Clusters, and Exotica, the Universe)

OUTREACH

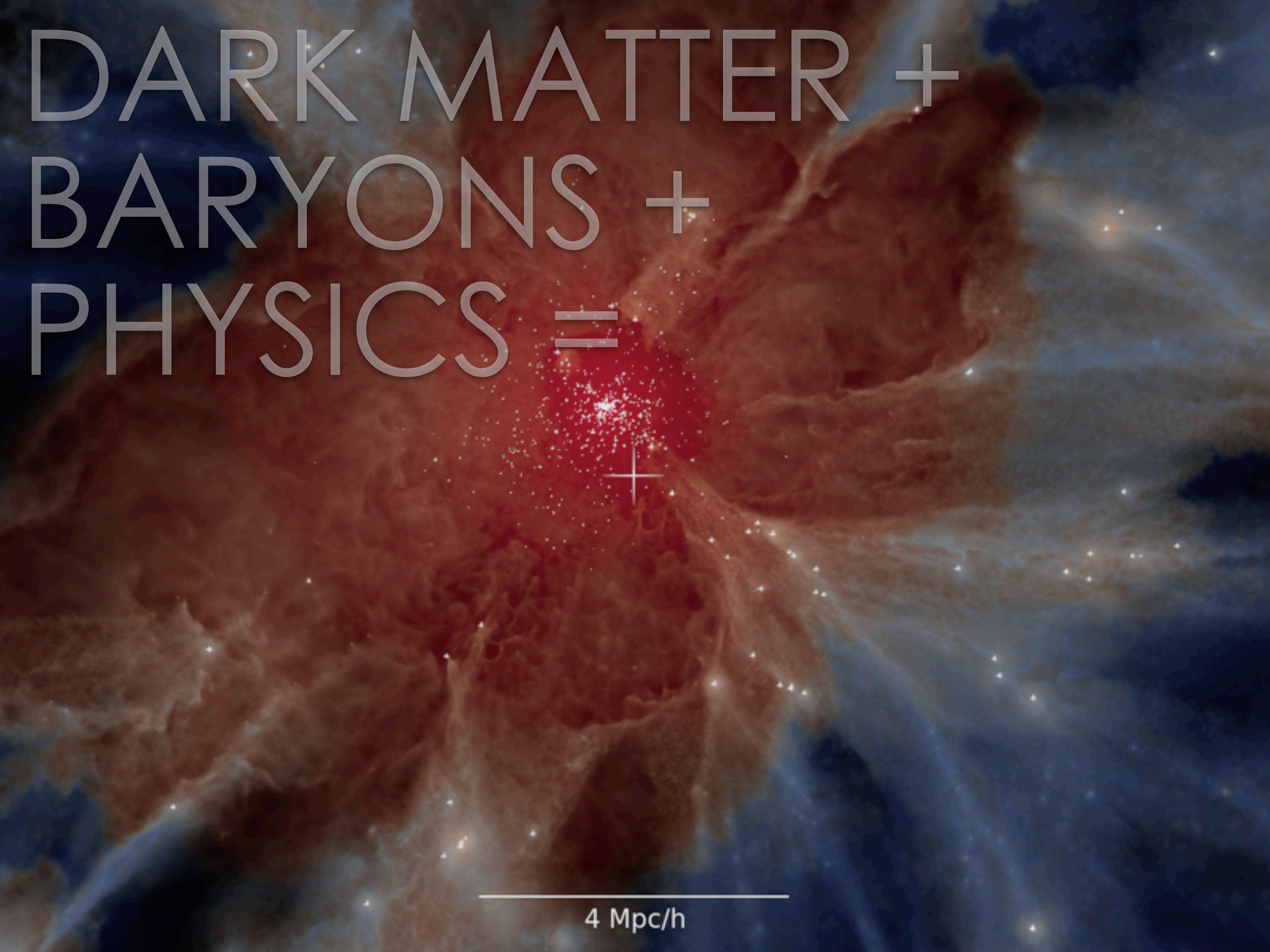


XDF Explorer

DARK MATTER + BARYONS + PHYSICS =

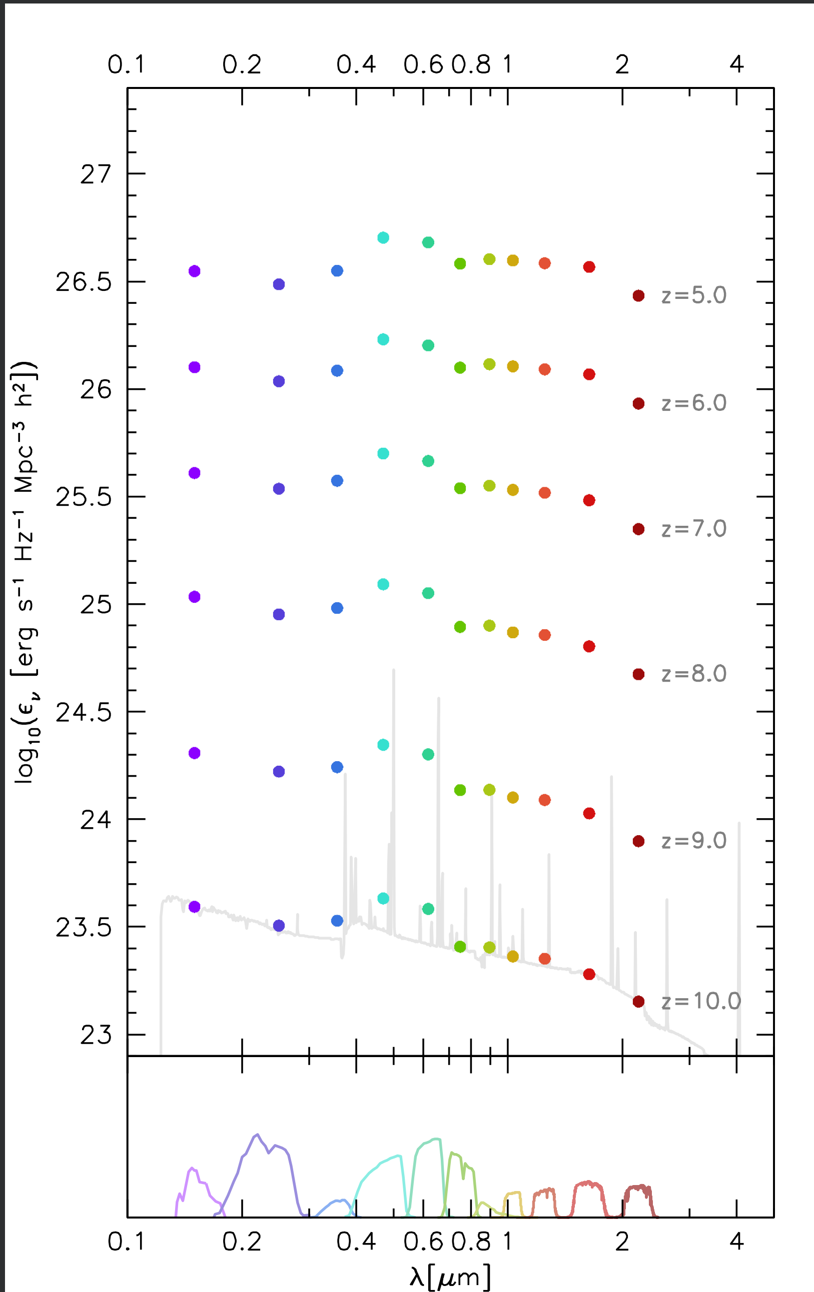


DARK MATTER + BARYONS + PHYSICS =



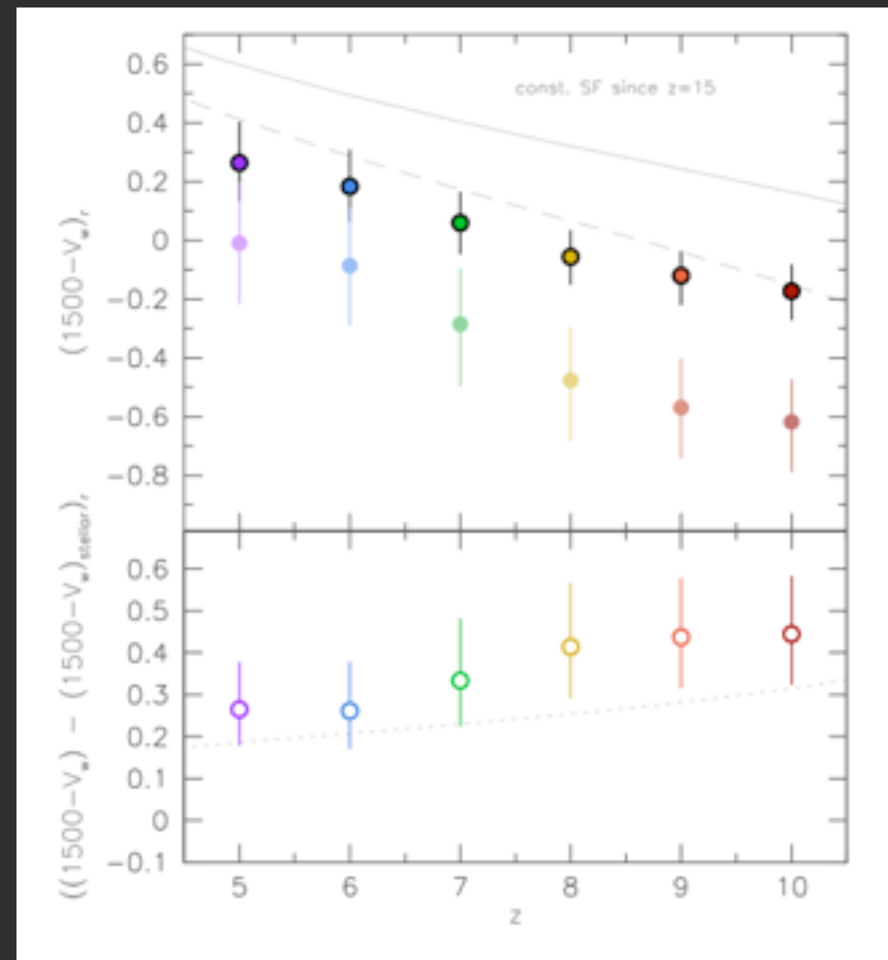
CONTEXT

SIMULATIONS



Khandai et al., in-prep

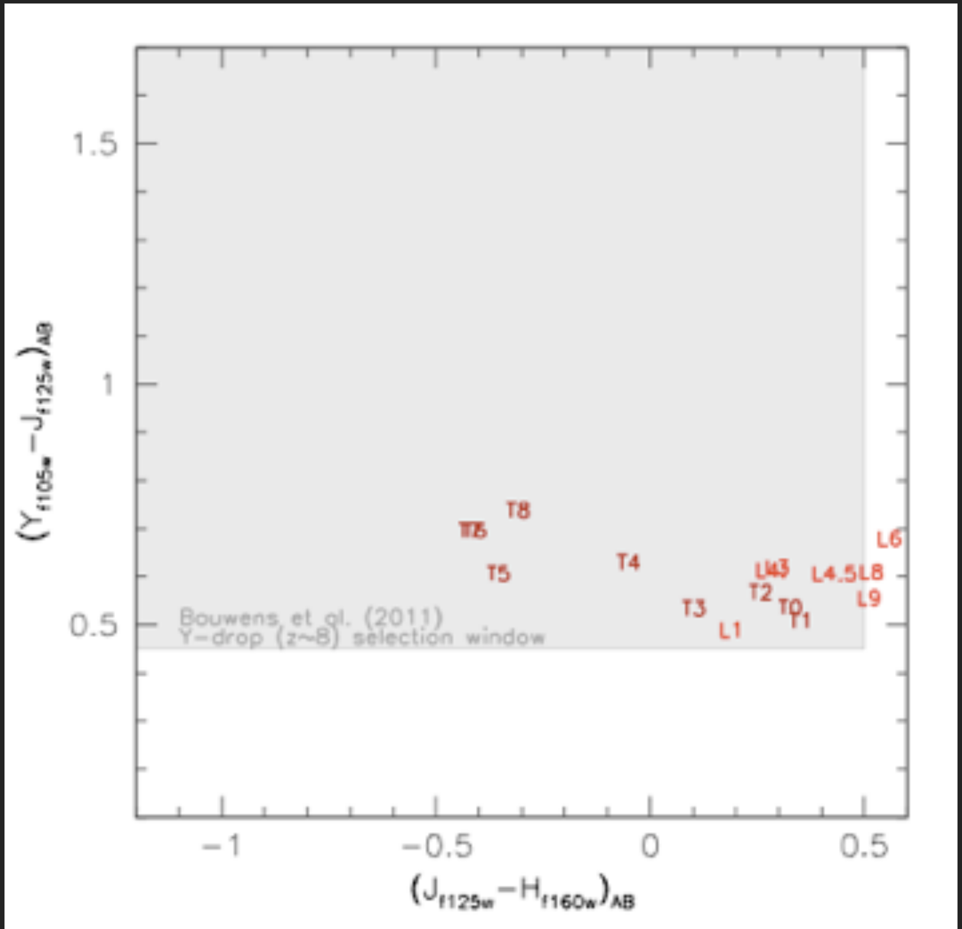
The evolution of the rest-frame intrinsic UV-NIR luminosity density of galaxies with log10(M*)>9; assumes escape fraction is zero.



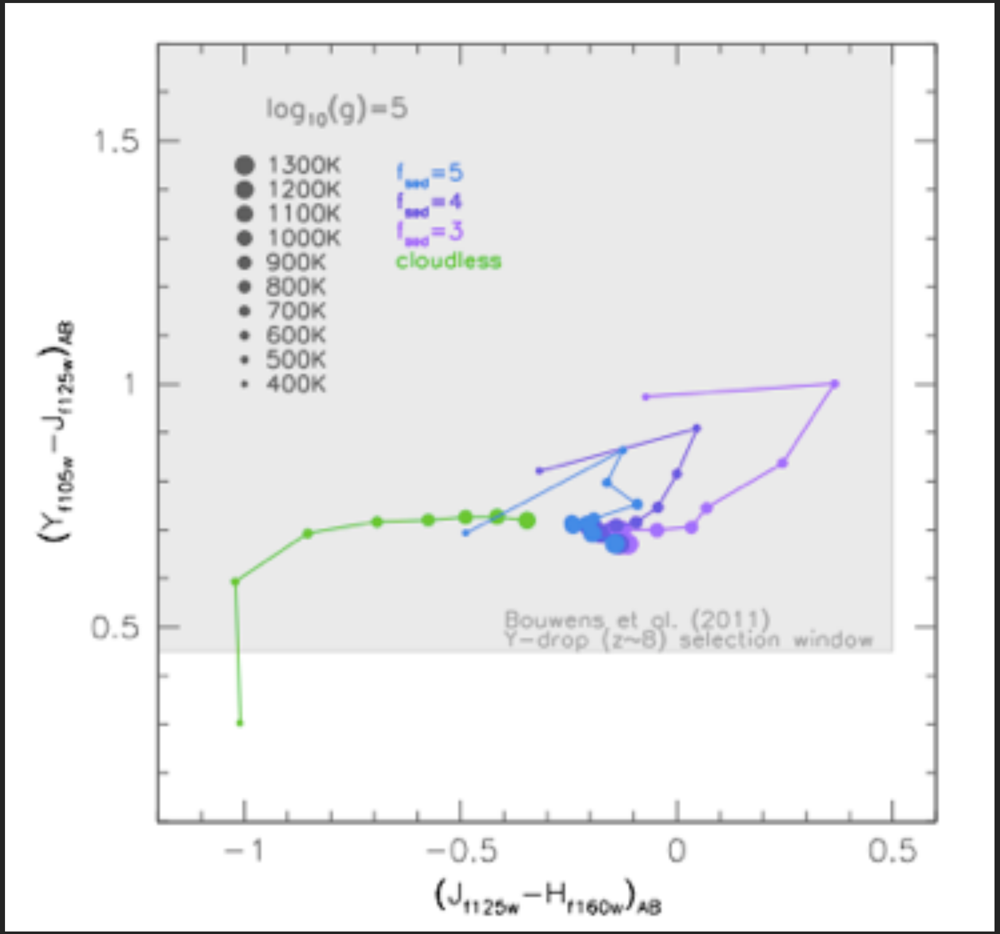
Wilkins et al., 2013d

The average rest-frame UV-optical colours of galaxies at high-redshift. Both f_esc=1.0 (pure stellar) and f_esc=0.0 are shown.

CONTAMINATION



The location of L and T dwarf stars in the Y-drop selection window.

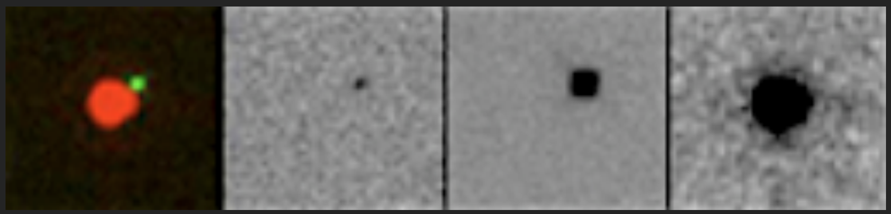


Theoretical tracks of cool stars in the Y-drop selection.

Wilkins, Stanway & Bremer, 2014

CONTAMINATION

Transient objects (SN/high-apparent motion objects) can be a problem when combining datasets obtained at different epochs. These transient objects will manifest as z-drop (z=7) candidates due to the difference in observation epoch between the ACS and WFC3 observations.



A low-mass star that has moved (the audacity) between ACS and WFC3 observations. In this case the object was initially selected as (albeit flagged) z-drop candidate.