Probing the earliest galaxies and reionization

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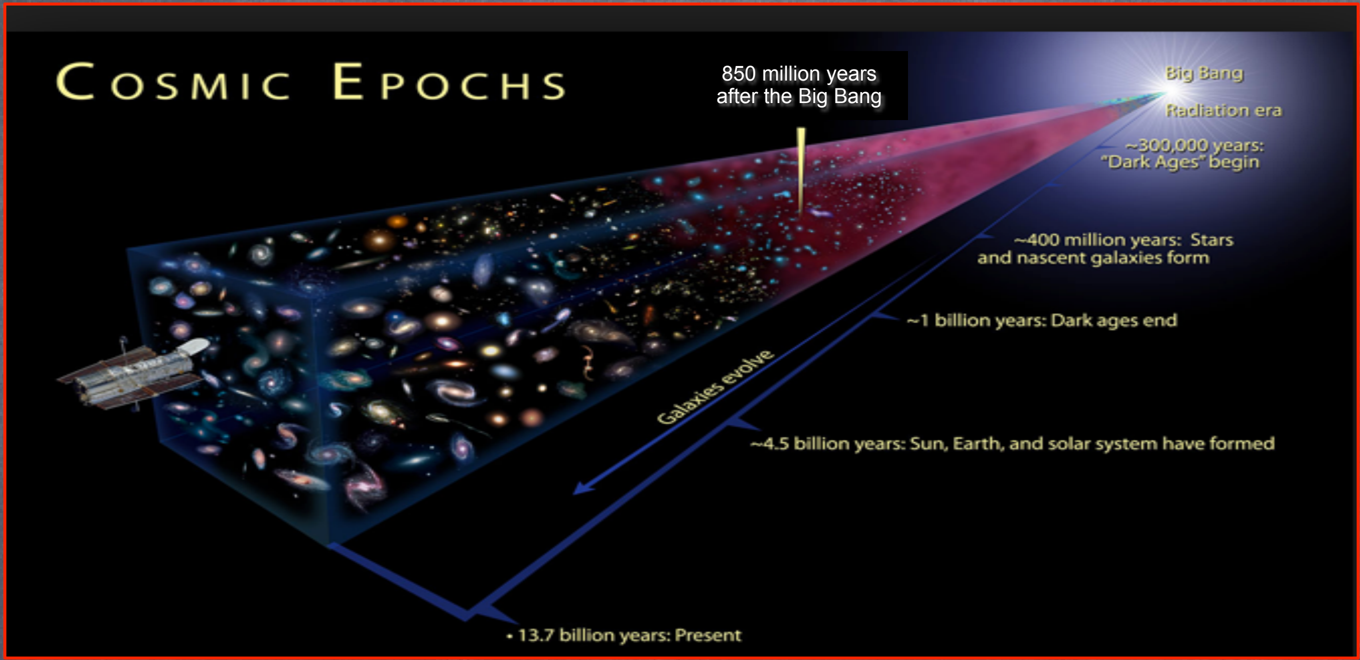
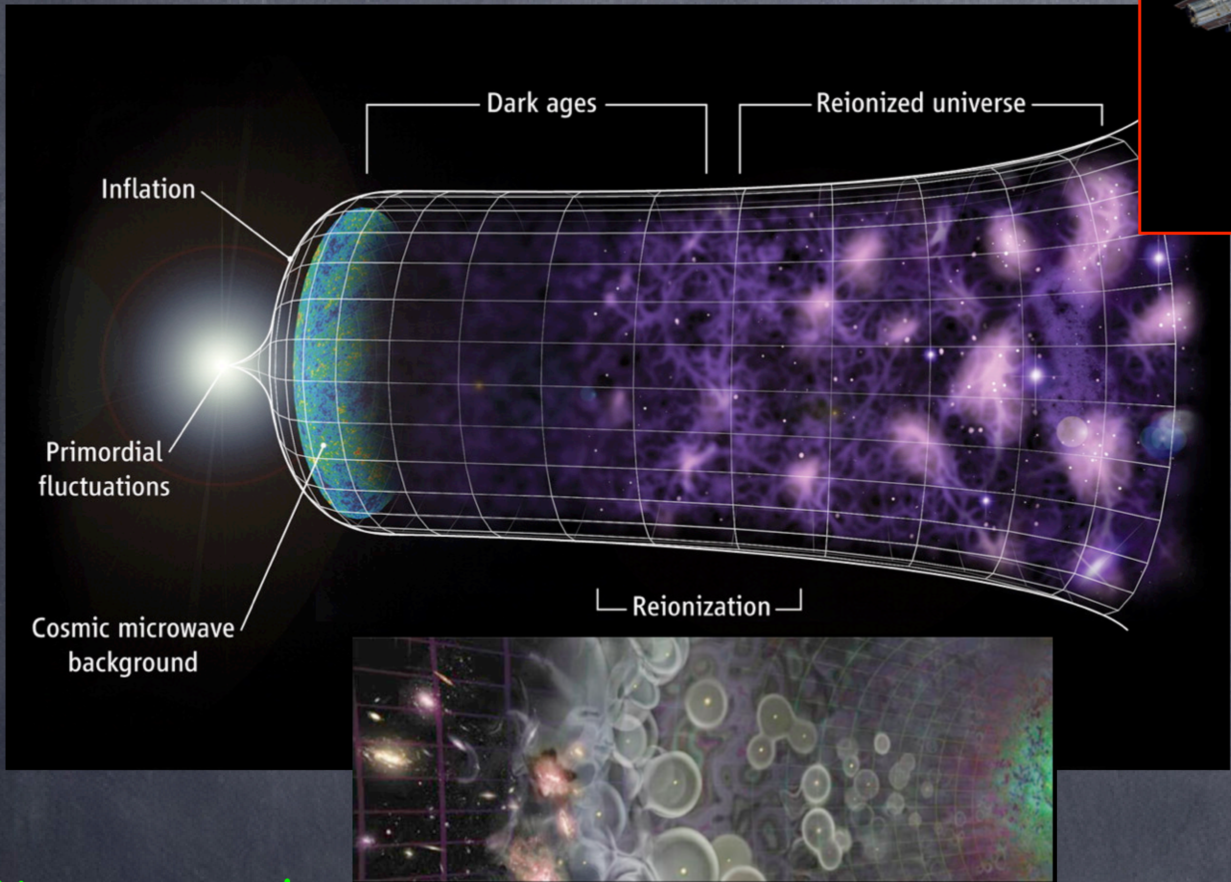


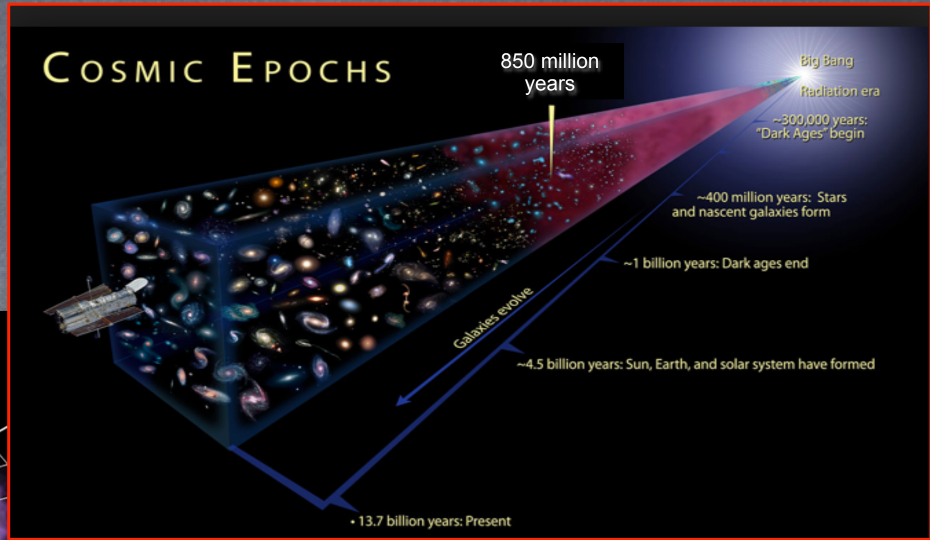
Lectures #1 and #2

Lectures

Lecture 1 Monday 2hr	Ionized IGM Deep surveys UV LFs	Cosmic reionization: how was the IGM reionized? Probes of cosmic reionization (and ionization) Selection techniques of high-redshift galaxies Redshift evolution of the UV luminosity function
Lecture 2 Tuesday 1hr	Escaping ion. radiation	Is all cosmic reionization made by galaxies ? Issues on the escape fraction
Lecture 3 Thursday 1hr	Spectr. observations	Exploring the farthest and faintest galaxies with deep spectroscopy: the first two Gyrs after the Big-Bang
Lecture 4 Friday 1hr	Current limitations: the future	Next generation optical/near-IR facilities: JWST and ELT

Cosmic history of the Universe





When it happened ?
Who reionized the Universe ?
How reionization proceeded ?

Key aspects:

- A major event in the cosmic history of the Universe that impacted on almost every baryon in the Universe
- Detailed measurements of the IGM properties inform models of high-z structure formation
- Early generation of ionizing sources influenced the formation of subsequent galaxy populations

Investigate hydrogen reionization: **a way to proceed**

who, when, how ...

Design Panchromatic Surveys to search for faint (L<<L*) and distant sources (z<20)

Strong observational effort in the last 20 years

count galaxies/ AGNs; compute UV LFs

Search for the farthest sources ?
... ongoing ...

Compute ionizing UV luminosity density

Compare with UVB 0<z<6
post-reionization

Approaching EoR z>6
reionization

Problem Solved ?

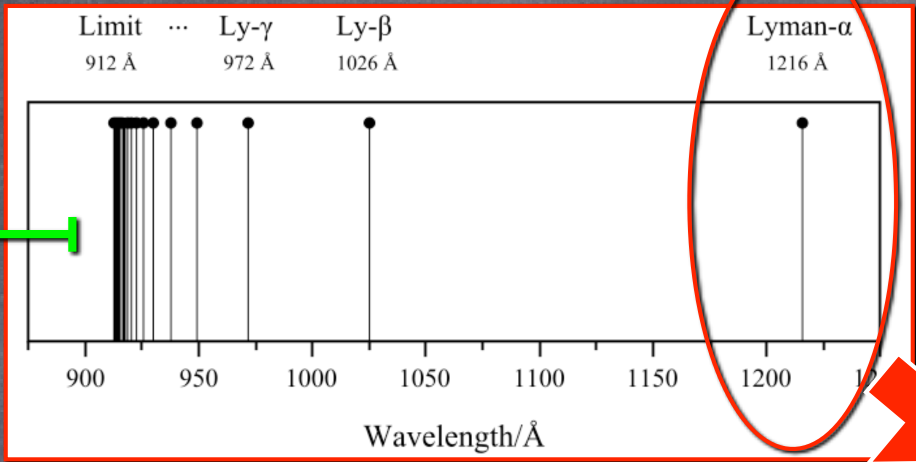
? No

Investigate ionizing emission: physics, feedback
... ongoing ... ?

Connection with IGM physics ?
... ongoing ...

The Ly-alpha transition:

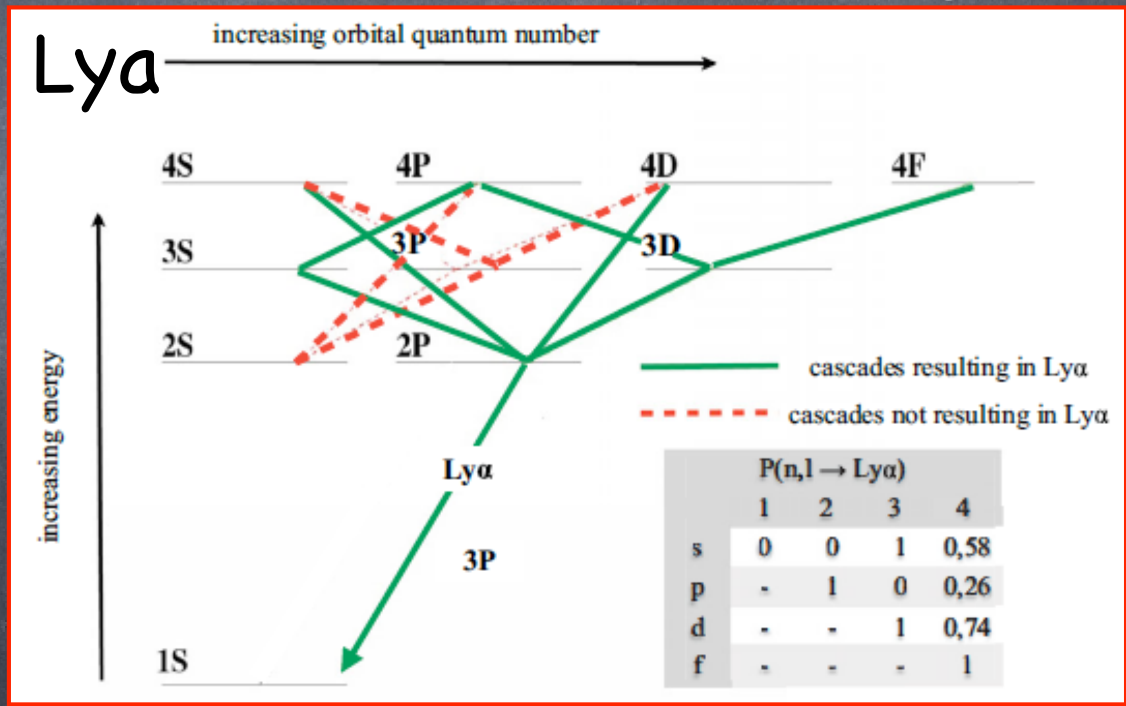
Lyman-alpha
1215.7A



Lyman continuum

(photons with λ<912A, E>13.6eV photoionize hydrogen atoms)

Grotrian Diagram

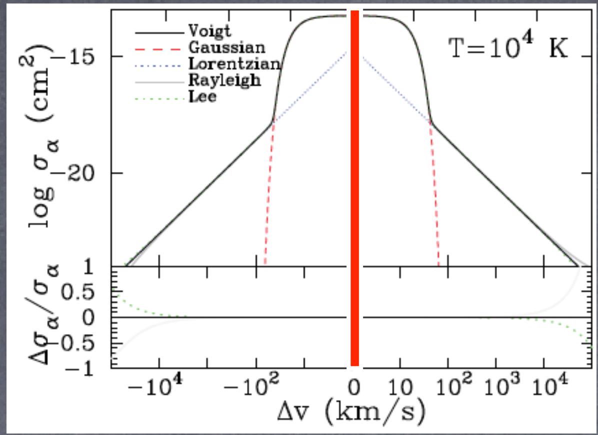


$A_{2p1s} \approx 10^{-9}s$

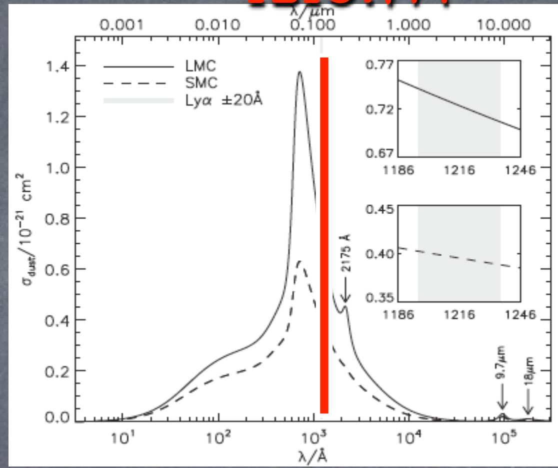
Lya Radiative Transfer Equation [λ=1215.7A; $\nu=2.46\times10^{15}$Hz]

1215.7A

Lya absorption cross section



1215.7A



dust absorption cross section per hydrogen atom and SMC, LMC grain type

attenuation coefficient $\alpha(\nu) \equiv n_{\rm HI}(\sigma_\alpha(\nu) + \sigma_{\rm dust})$

recombination radiation

$j(\nu) = j_{\rm rec}(\nu) + j_{\rm coll}(\nu)$ **Volume emissivity of Lya, $s^{-1}cm^{-3}$**

collisional-excited radiation (cooling)

Ly=alpha

Change in intensity of radiation I(ν) at frequency ν and propagating into direction **n** (|**n**|=1)

$$\mathbf{n}\cdot\nabla I(\nu,\mathbf{n}) = -\alpha(\nu)I(\nu,\mathbf{n}) + j(\nu,\mathbf{n}) + \int d\Omega' \int d\mathbf{n}' I(\nu',\mathbf{n}')R(\nu',\nu,\mathbf{n}',\mathbf{n})$$

Integro-differential equation, studied for decades (e.g. Chandrasekhar 1945; Unno 1950; Harrington 1973; Neufeld 1990; Yang+11; Higgins & Meiksin 2012; Dijkstra+14).

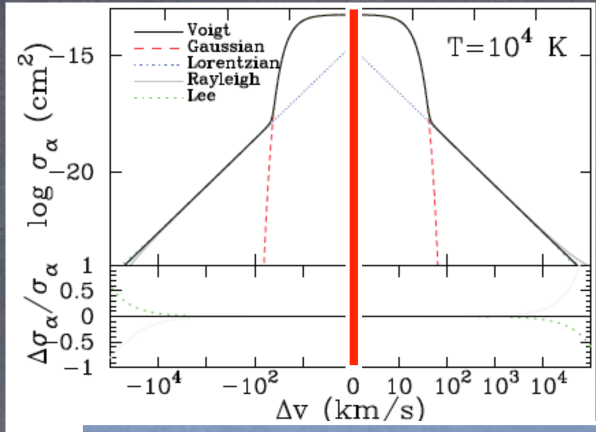
$R(\nu',\nu,\mathbf{n}',\mathbf{n})$

"Redistribution function" (diffusion in space and frequency)

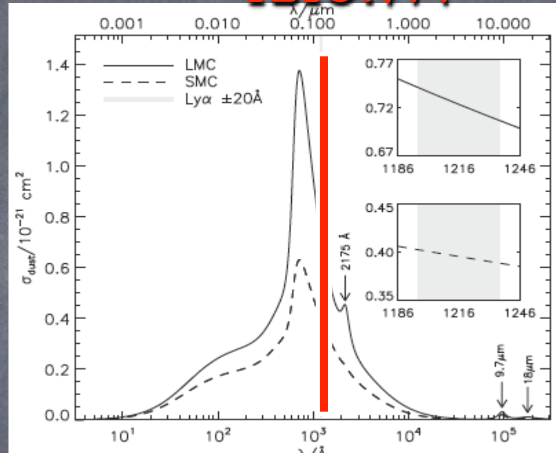
Lya Radiative Transfer Equation [λ=1215.7A; ν=2.46x10^{15}Hz]

1215.7A

Lya absorption cross section



1215.7A



dust absorption cross section per hydrogen atom and SMC, LMC grain type

Messages:
- Lya is a resonant transition
- Lya can be destroyed by dust
- Neutral HI diffuse Lya photons in space and frequency (resonantly)

attenuation coefficient $\alpha(\nu)$ =

...on radiation

...missivity of Lya, s^{-1}cm^{-3}

...ional-excited ...tion (cooling)

Change in intensity of radiation I(ν) at frequency ν and propagating into direction **n** (|**n**|=1)

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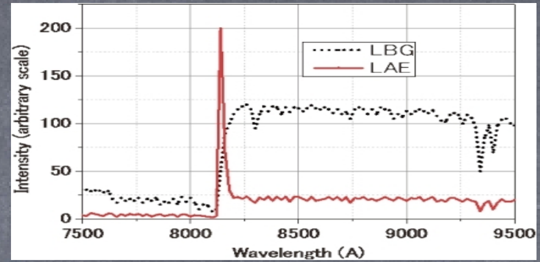
$R(\nu',\nu,\mathbf{n}',\mathbf{n})$

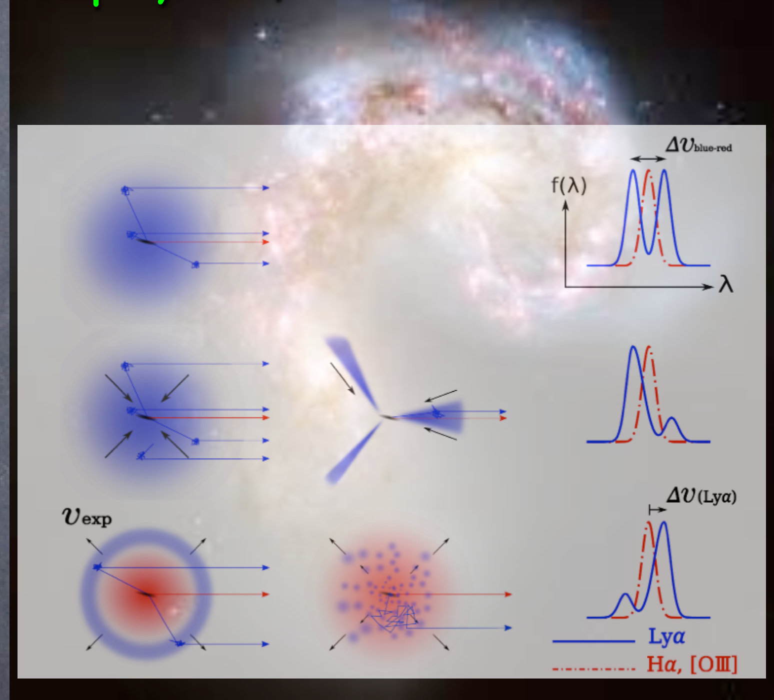
"Redistribution function" (diffusion in space and frequency)

Lya transition is an astrophysical and cosmological tool

Combination of the two:
Lya demography in galaxies vs. redshift probes cosmic reionization
Lecture #4

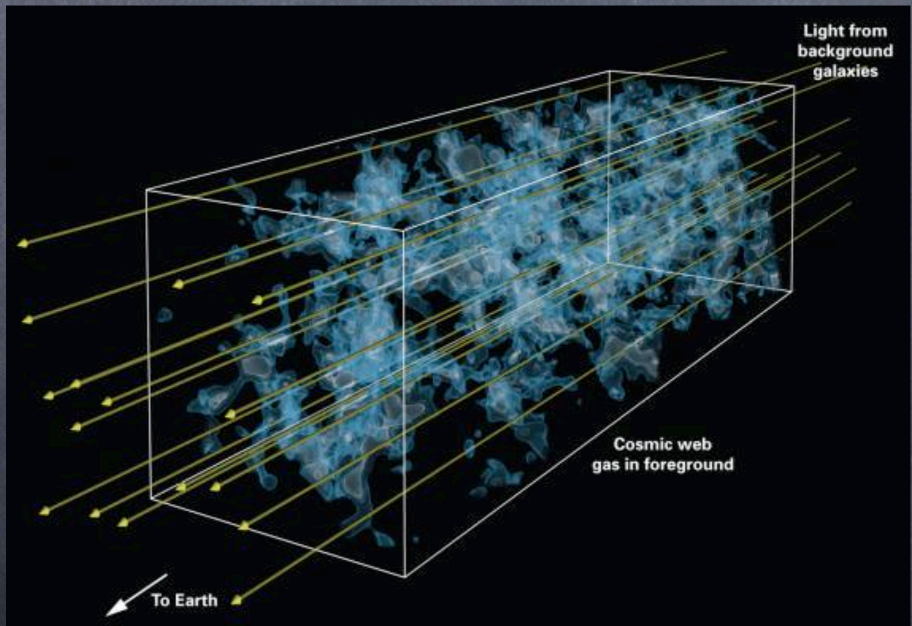


... the emergent Lya in galaxies: ISM physics, nature of ion. source



"Partially coherent" scattering: the transition is resonant, and the bulk motion of the optically thick gas and dust in the ISM and CGM, shapes the emerging Lya profile

... Lya absorption in the intergalactic medium (IGM) - Cosmic web



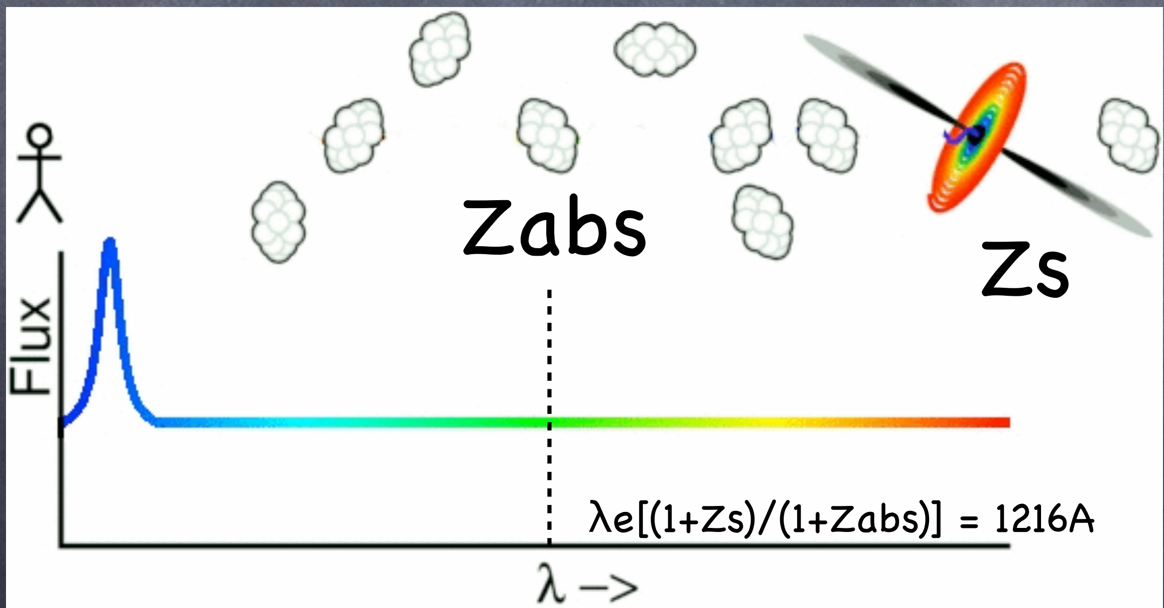
ionization is imprinted in the IGM...

Ly-alpha Forest

- Consider a photon emitted by a source (placed at Zs) with wavelength $\lambda e < \lambda a$, where λa is 1215.7A (Lya)
- Suppose there is a hydrogen atom at some redshift Zabs < Zs, where the photon is redshifted to the resonant Lya line according to $1215.7 = \lambda e[(1+Zs)/(1+Zabs)]$ (from our point of view)
- This atom will scatter the photon out of the line of sight.
- Therefore Lya scattering with neutral hydrogen will remove light from QSO spectrum at wavelengths $(1+\text{redshift})\lambda a$ and $0<\text{redshift}<Zs$.

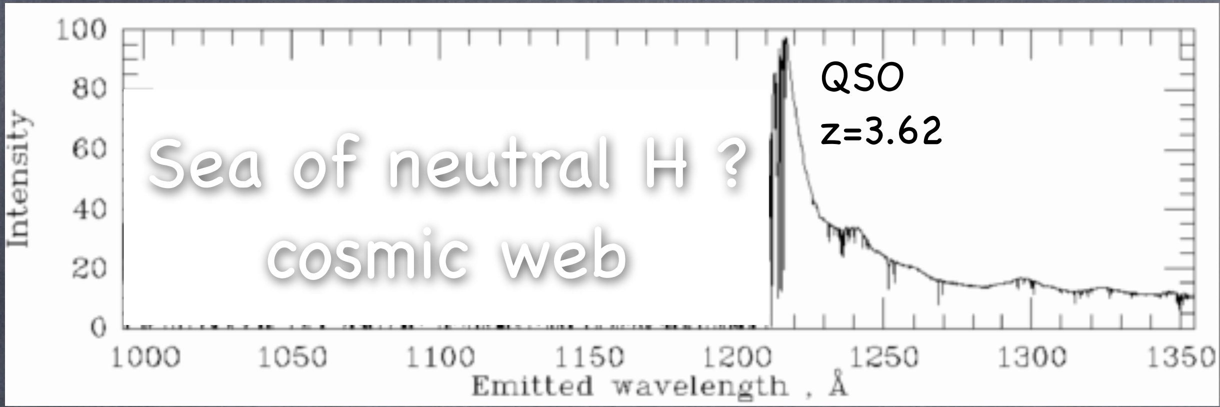
For example:

photon emitted at 1000A @ Zs=3.5 is redshifted to 1215.7A @ Zabs=2.701



The Gunn Peterson optical depth

in a smoothly distributed "sea" of neutral hydrogen in the expanding universe **(Gunn and Peterson 1965)**



However we measure significant signal at wavelengths < 1215.7A

What does it mean ??

$$\tau_{GP}(\nu_{em}) = \int_0^{\infty} ds\, n_{HI}(s)\sigma_{\alpha}(\nu[s, \nu_{em}])$$

Along the proper differential distance ds a photons is redshifted by an amount **dν = −ds H(z) ν/c** . Photons that were initially emitted at $\nu_{em} > \nu\alpha$ will thus redshift into the line resonance (1215.7A)

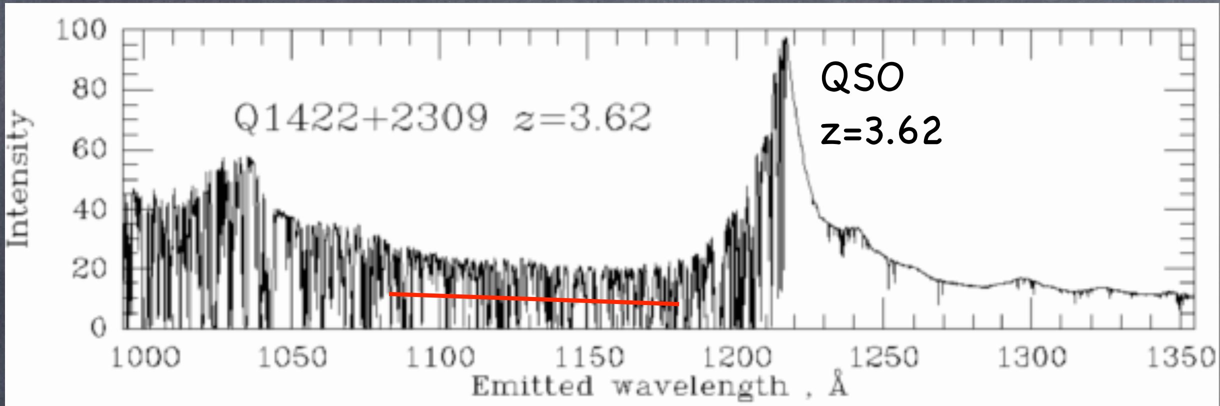
$$= \frac{\bar{n}_{HI}(z)\lambda_{\alpha}}{H(z)} f_{\alpha} \frac{\pi e^2}{m_e c} \approx 7.0 \times 10^5 \left(\frac{1+z}{10}\right)^{3/2} = \tau_{GP}$$

see Becker+15; Dijkstra+14

where $\bar{n}_{HI}(z)$ is the mean number density of neutral hydrogen atoms at redshift z

$\tau_{GP} > 1e5$ Transmission $T_{GP} = e^{-\tau GP} = 0$!

The Gunn Peterson optical depth



Average IGM transmission (T) at z=2(4) is 85%(50%)

$\tau_{eff(IGM)} \equiv -\ln|T| =$ z=2 → **0.15**, z=4 → **0.90**

e.g., Faucher-Gihurere 2008

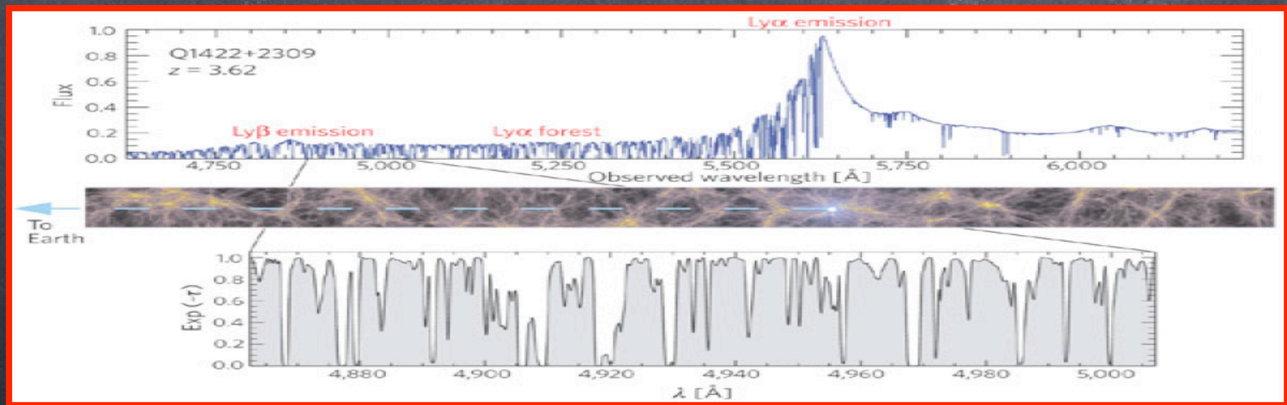
Observations: $\tau_{eff(IGM)} \ll \tau_{GP}$ (>1e5)

Note: Even a modest neutral fraction produces a complete absorption

$\langle X_{HI} \rangle = N_{HI} / N_{HII} = 10^{-4.5}$

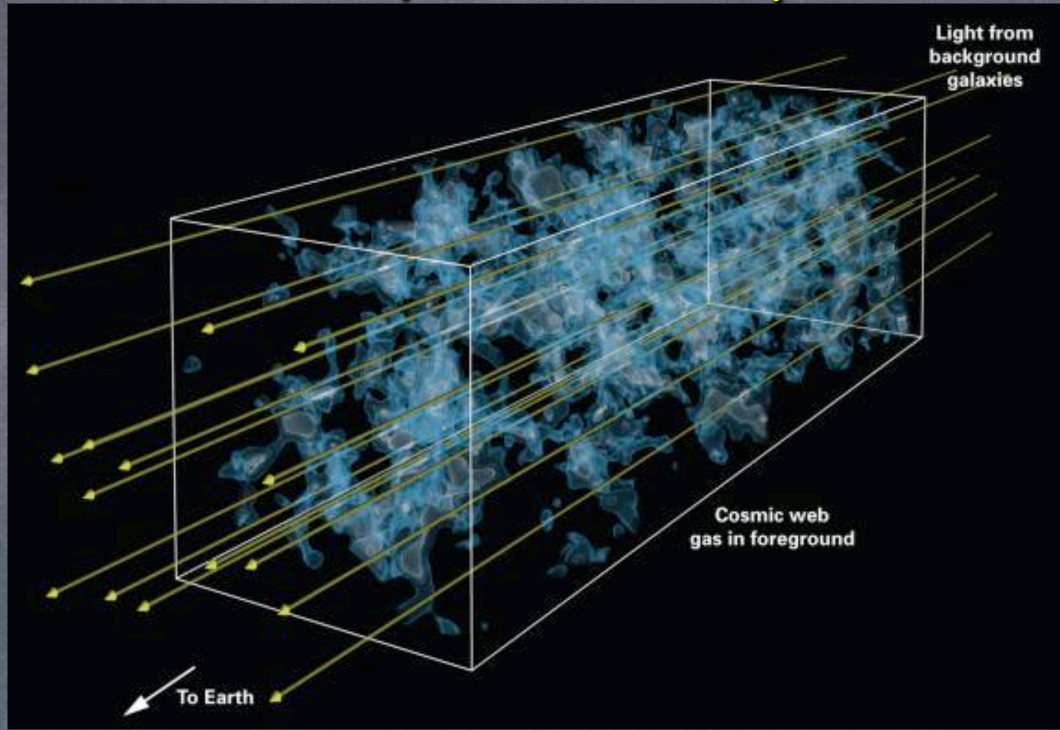
$e^{-\tau GP} \approx 0$

The IGM at z<6 is highly ionized



Ly-alpha Forest: Observations many L.O.S. up to z=7

… numerous Lya absorption lines in the spectra of distant quasars are called "Lya Forest" (LAF)



"LAF is the observable manifestation of the intergalactic neutral hydrogen that traces the cosmic web of large-scale structure" (Rauch 1998)

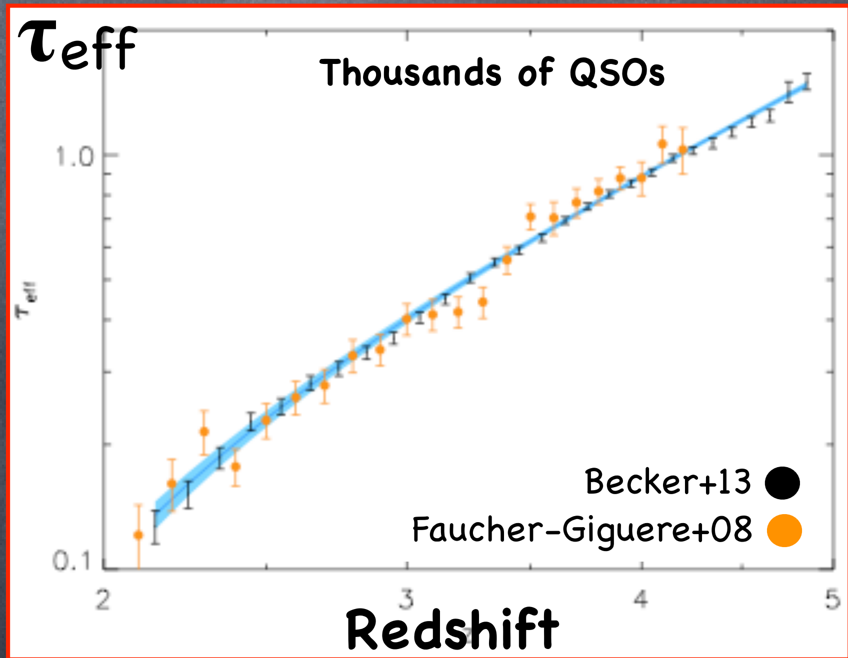
$$\langle f_{\rm H\,I}\rangle(z) = (1.3\times10^{-5})\left(\frac{1+z}{5.6}\right)^{\eta}$$

η=2.9(z≤4.6)

η=5.0(z>4.6)

Volume-average neutral fraction

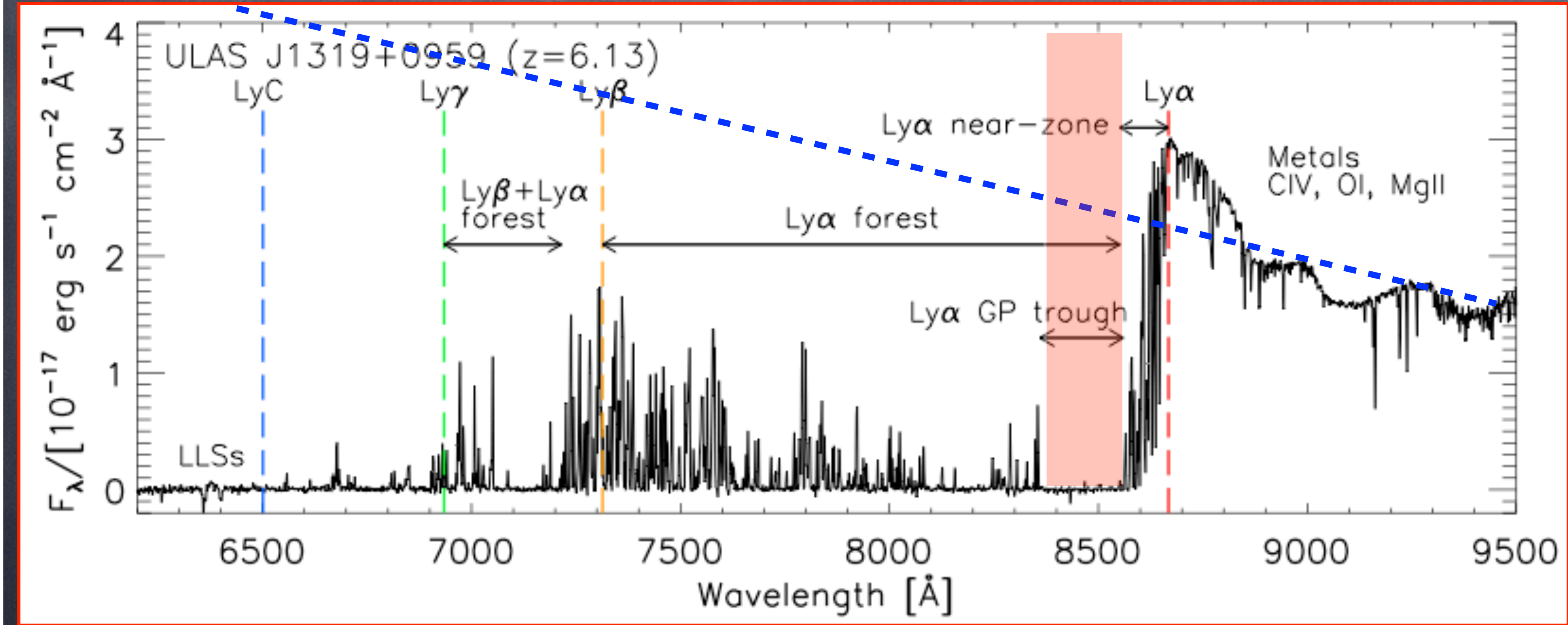
Becker+15



Adapted from Becker+13

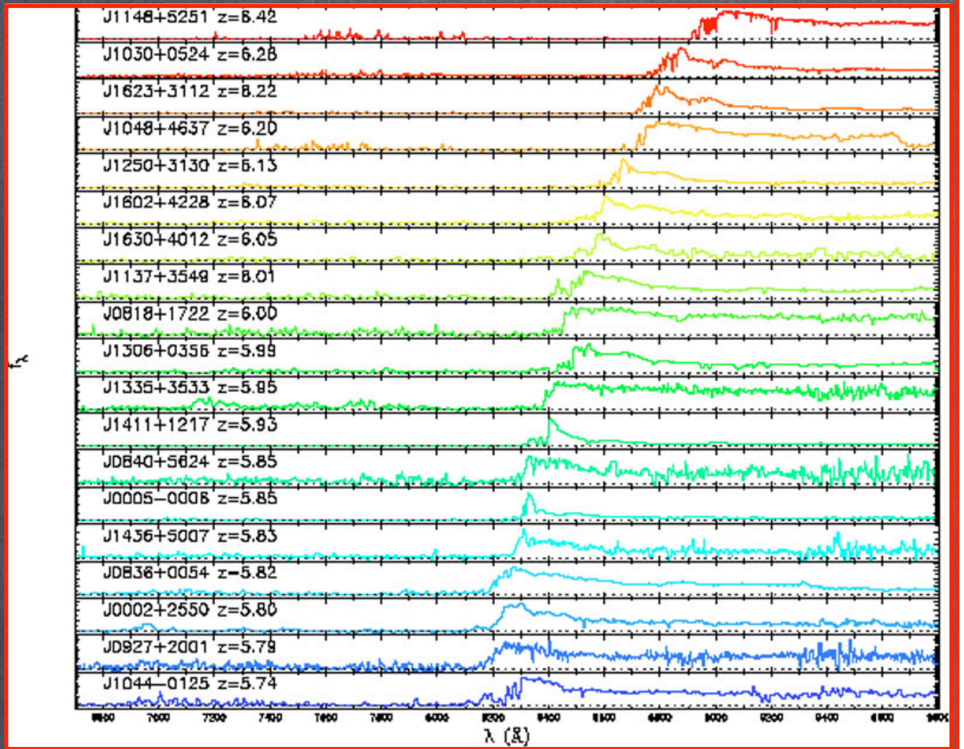
what about z>5.5 …

At z>5.5 the Lya GP trough is observed, suggesting an increase of the neutral fraction in the IGM

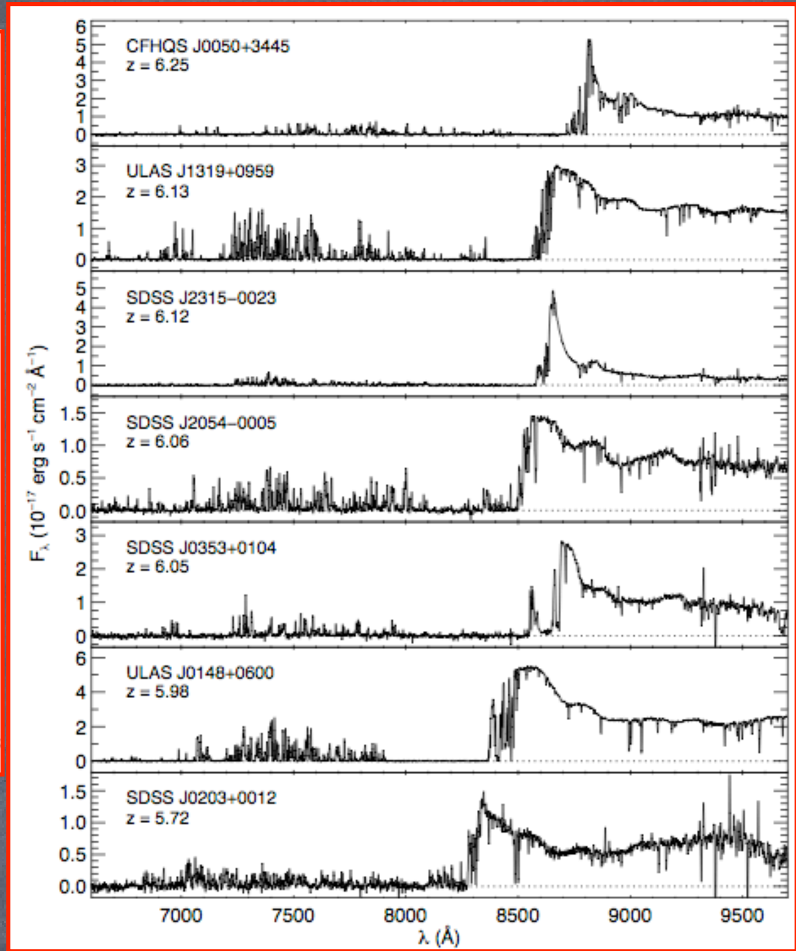


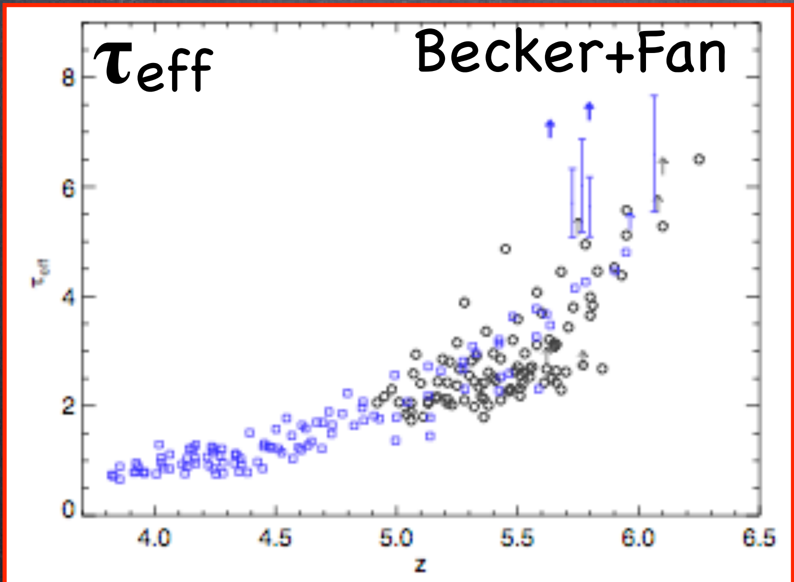
adapted from Becker+15

Lya GP trough, approaching reionization z>5.5



Fan et al. (2006)



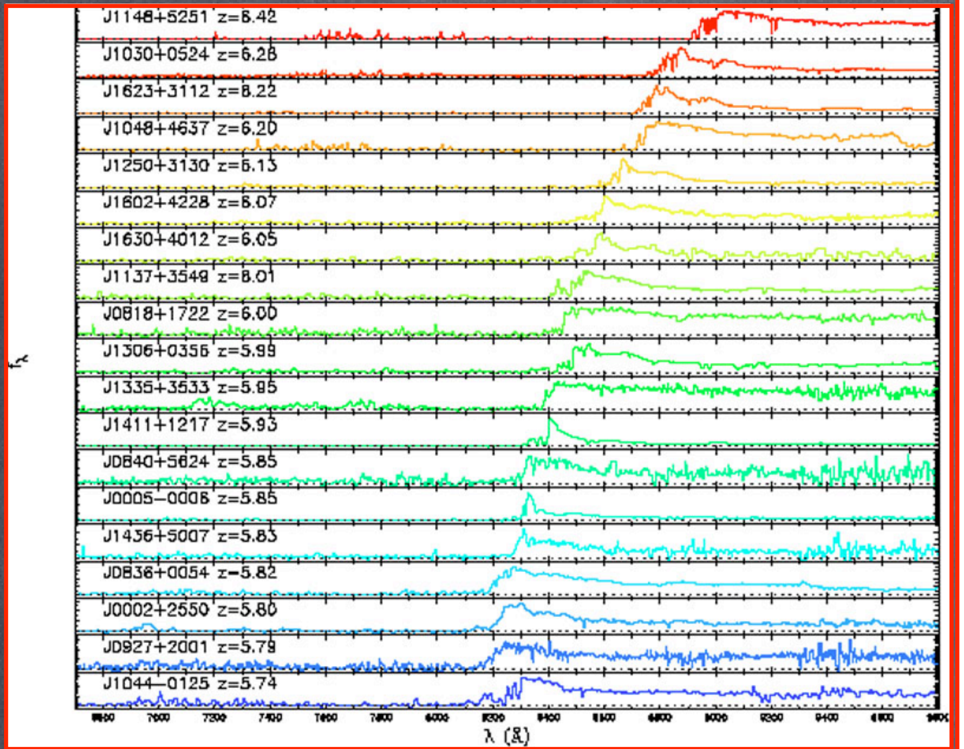


Becker+15

The IGM neutral fraction is increasing toward z=6 (Becker+15) (see also Mortlock+11 in QSO at z=7.08)

Reionization happened at z>~6, within the first Gyr

Lya GP trough, approaching reionization z>5.5



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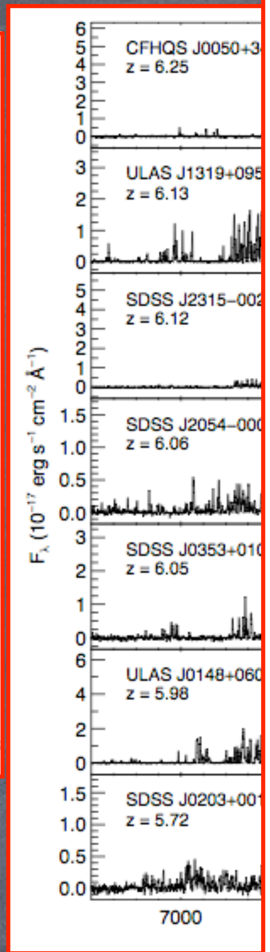
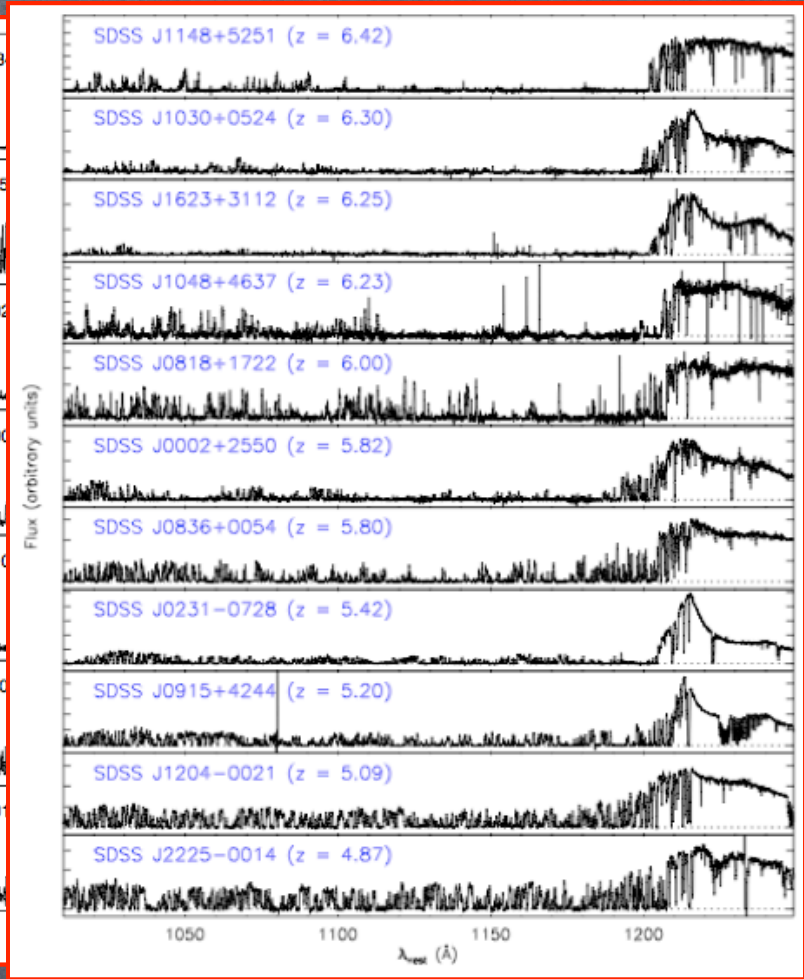
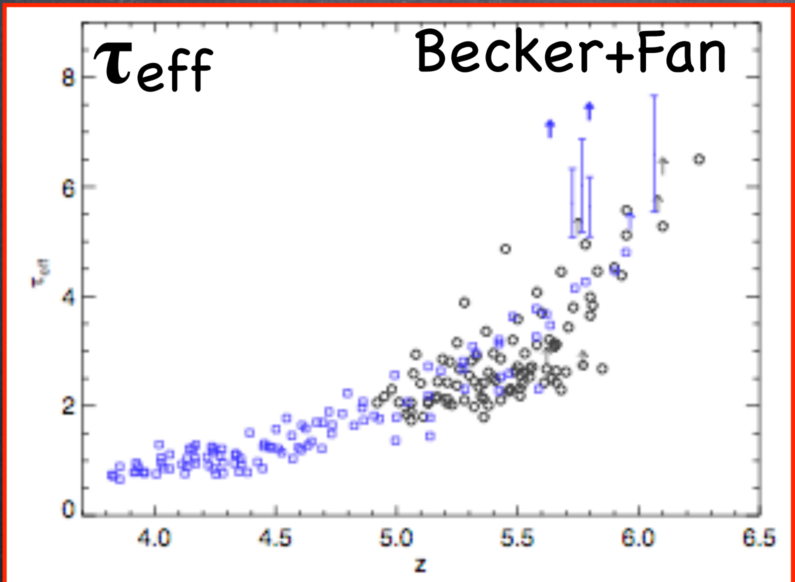




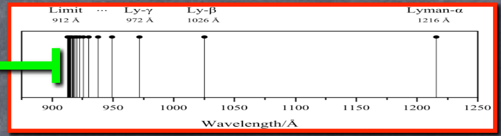
Becker+15



The IGM neutral fraction is increasing toward z=6 (Becker+15) (see also Mortlock+11 in QSO at z=7.08)

Reionization happened at z>~6, within the first Gyr

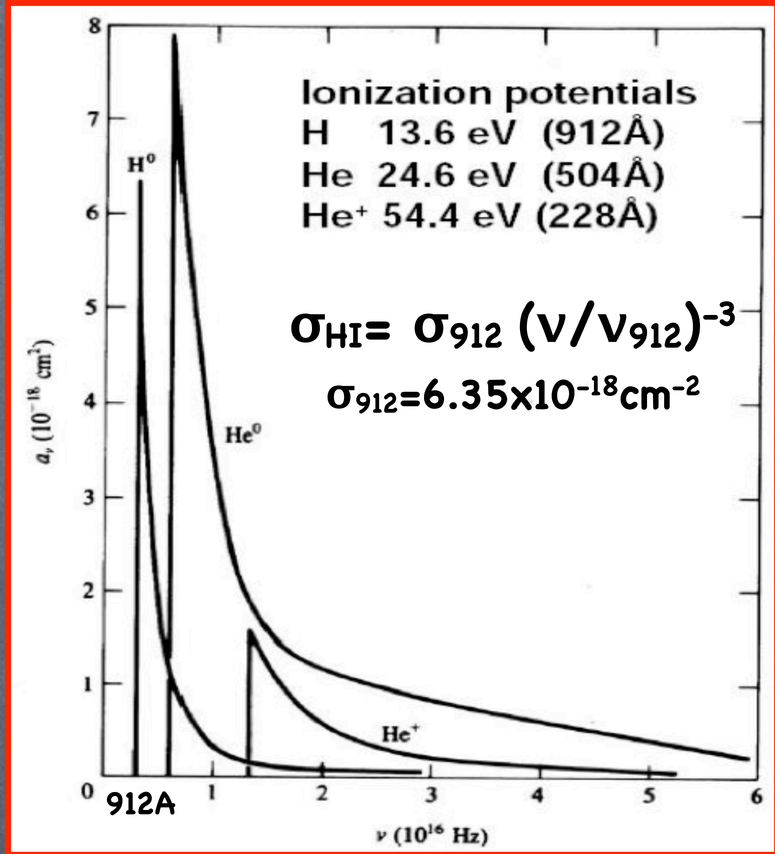
Measuring the ionizing background from the LAF (I)



Total photo-ionization rate Γ

$$\Gamma_{\rm HI}(z) = 4\pi \int_{\nu_{912}}^{\infty} \frac{d\nu}{h\nu} J_\nu(z)\sigma_{\rm HI}(\nu)$$

Number of ionized phot. per unit time, s^{-1}



Measuring Γ_{HI} :

Measuring Γ_{HI}

QSO proximity effect

Deficit of IGM abs. depends on the relative contributions of ionizing photons from the local source and the UVB. Knowing the QSO luminosity, the UV background photoionization rate can be estimated (Carswell et al. 1987; Calverley+11)

Modeling the mean transmitted flux in the LAF

The mean level of transmission of the Lyα forest is set by the equilibrium between the ionizing background and recombinations in the IGM. Thus, given a model of the density fluctuations in the IGM and its gas temperature-density relation, the mean transmission of the Lyα forest can be inverted to give Γ_{HI} (e.g. Rauch et al. 1997; Rollinde+13 and many others)

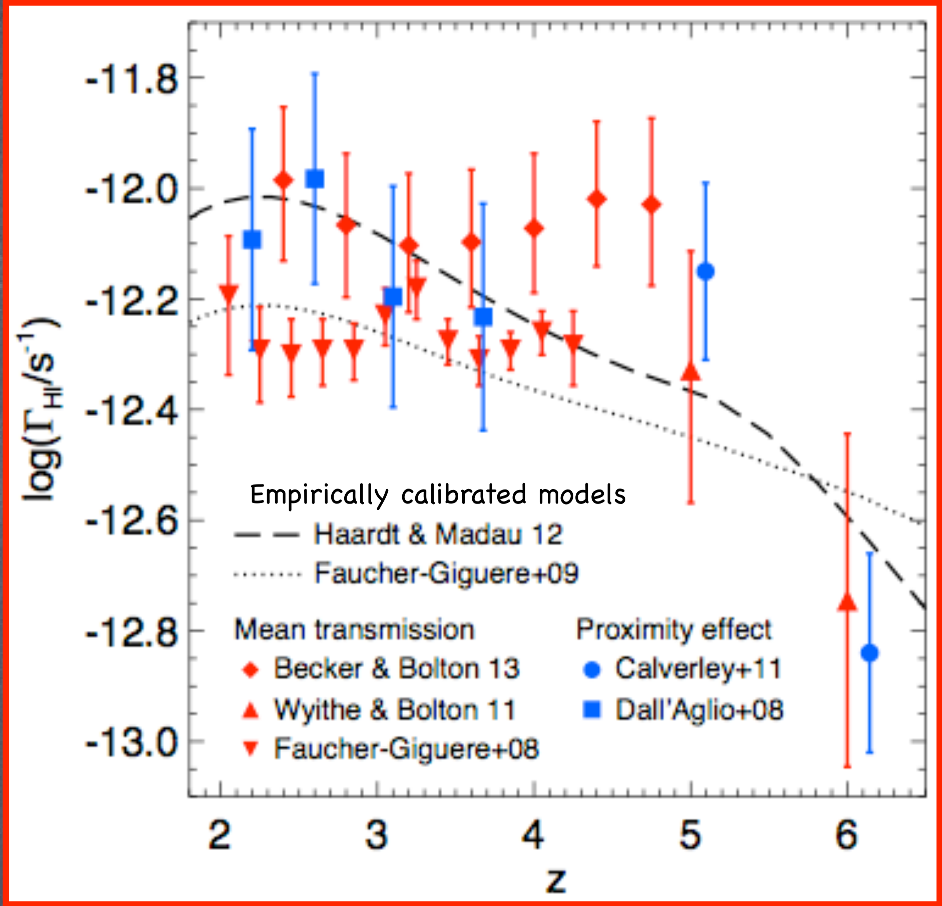
Ionizing background UVB

Average Specific intensity at ν and z (erg/s/cm2/sr/Hz)

$$J_{\nu_{912}} = \frac{\Gamma_{\rm HI} h(\gamma_{\rm bg}+3)}{4\pi\sigma_{\rm HI}(\nu_{912})}\left[1-\frac{1}{4^{\gamma_{\rm bg}+3}}\right]^{-1}$$

$J(\nu) = J_{912}(\nu/\nu_{912})^{-\gamma_{bg}}$

Measuring the ionizing emissivity from the LAF (II)



Flat behavior at 2<z<4.5, useful to anchor reionization models

"photon-starved" process at z=6 ? Just enough photons present to reionize the IGM

at z=6 the measured num. of ion. phot. emitted per hydrogen atom over the Hubble time (2-5) $\gtrapprox$ the required photons (2-3)

Total comoving emissivity of ionizing photons (LAF)

$$\dot{n}_{\rm ion}^{\rm com}(z) = \frac{1}{(1+z)^3}\int_{\nu 912}^{\infty} \frac{d\nu}{h\nu}\epsilon_\nu(z)$$

emissivity (ϵ_ν [erg/s/Hz/Mpc3] ➔ Jν ➔ $\Gamma_{\rm HI}$)

IGM

(phot/s/Mpc3) $\approx 10^{51}\ s^{-1}Mpc^{-3}$ (2<z<6)

Total comoving emissivity of ionizing photons (LFs)

$$\dot{n}_{\rm ion}^{\rm com} = \int_{M_{\rm lim}}^{\infty} dM_{\rm UV}\, \phi(M_{\rm UV})\gamma_{\rm ion}(M_{\rm UV})\, f_{\rm esc}$$

Ionizing Sources

LFs: Galaxies, AGN

Observational facts:

1) From Lya-forest effective optical depth of distant QSOs:
The Universe was highly ionized up to 90% of its age (0<z<6).

2) A ionizing background has been measured and evolve with redshift (z<6)

3) At z>6 we are entering into the epoch of reionization, GP trough at z>5.5 (+ LAE demography, see also Lecture#4)

3a) reionization may be a "photon-starved" process:

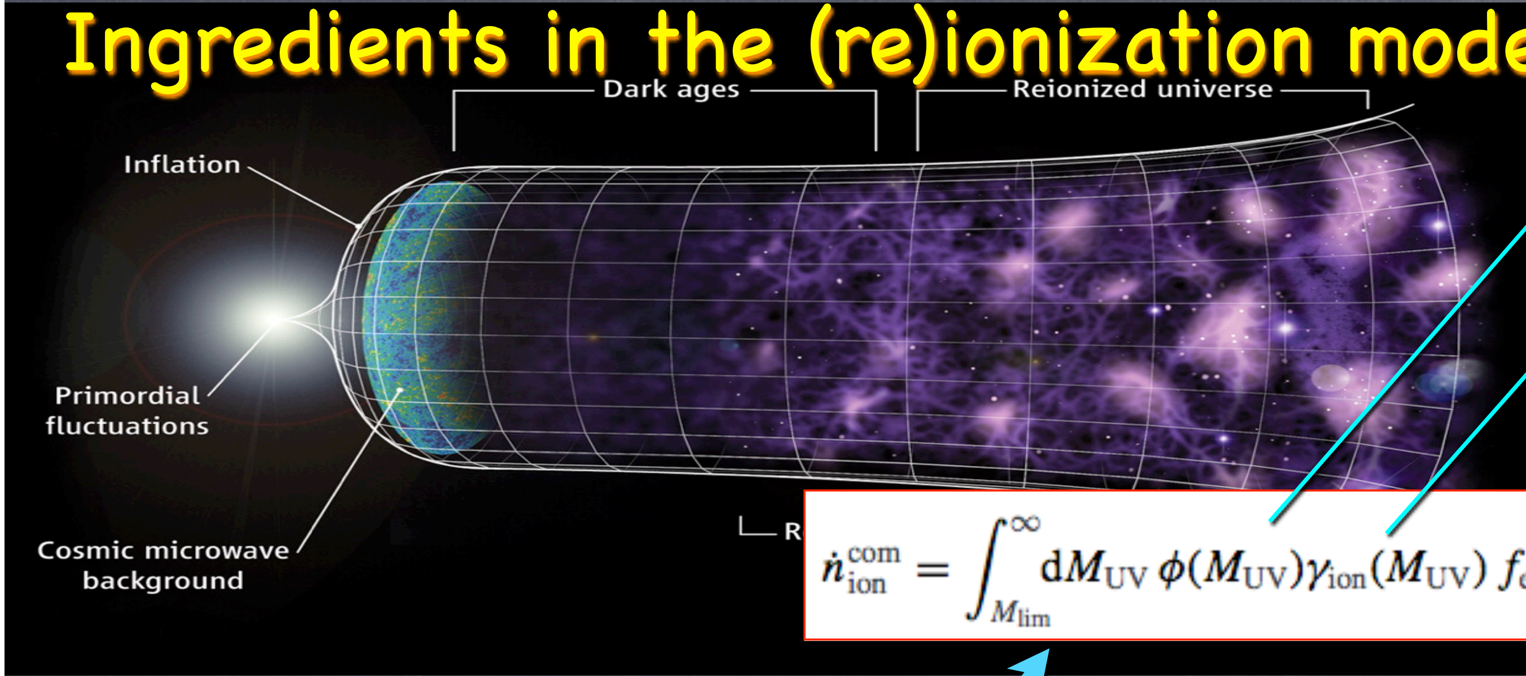
There are only just enough photons present to reionize the IGM at z~6 (Becker et al. 2015)

Question:

- What were the sources responsible to the (re)ionization of the Universe ?
- What was the nature of the first ionizing sources?

Natural candidates are star-forming galaxies and AGNs

Ingredients in the (re)ionization modeling



$$\dot{n}_{\rm ion}^{\rm com} = \int_{M_{\rm lim}}^{\infty} {\rm d}M_{\rm UV}\,\phi(M_{\rm UV})\gamma_{\rm ion}(M_{\rm UV})\,f_{\rm esc}$$

UV lum. funct. (N/mag/Mpc3)

ioniz. luminosity (phot/s)

(spectrum of sources)

escape fraction ion. photons: transmission

Ionizing sources:

Volume filling factor:

Volume(HII) / Volume Universe

$$\frac{dQ_{\rm H\,II}}{dt} = \frac{\dot{n}_{\rm ion}}{\bar{n}_{\rm H}} - \frac{Q_{\rm H\,II}}{\bar{t}_{\rm rec}}$$

$Q_{HII}=1$ $z<6$

$Q_{HII}(z)<1$ $z>6$

mean comoving hydrogen number density

$$\bar{t}_{\rm rec} = \frac{1}{C_{\rm H\,II}\alpha_{\rm B}(T_0)\,\bar{n}_{\rm H}(1+Y/4X)(1+z)^3}$$

$$\approx 0.93\ {\rm Gyr}\left(\frac{C_{\rm H\,II}}{3}\right)^{-1}\left(\frac{T_0}{2\times10^4\ {\rm K}}\right)^{0.7}\left(\frac{1+z}{7}\right)^{-3}$$

IGM Physics

Hui (2012)

$$C_{\rm HII} \equiv \langle n_{\rm HII}^2\rangle / \langle n_{\rm HII}\rangle^2$$

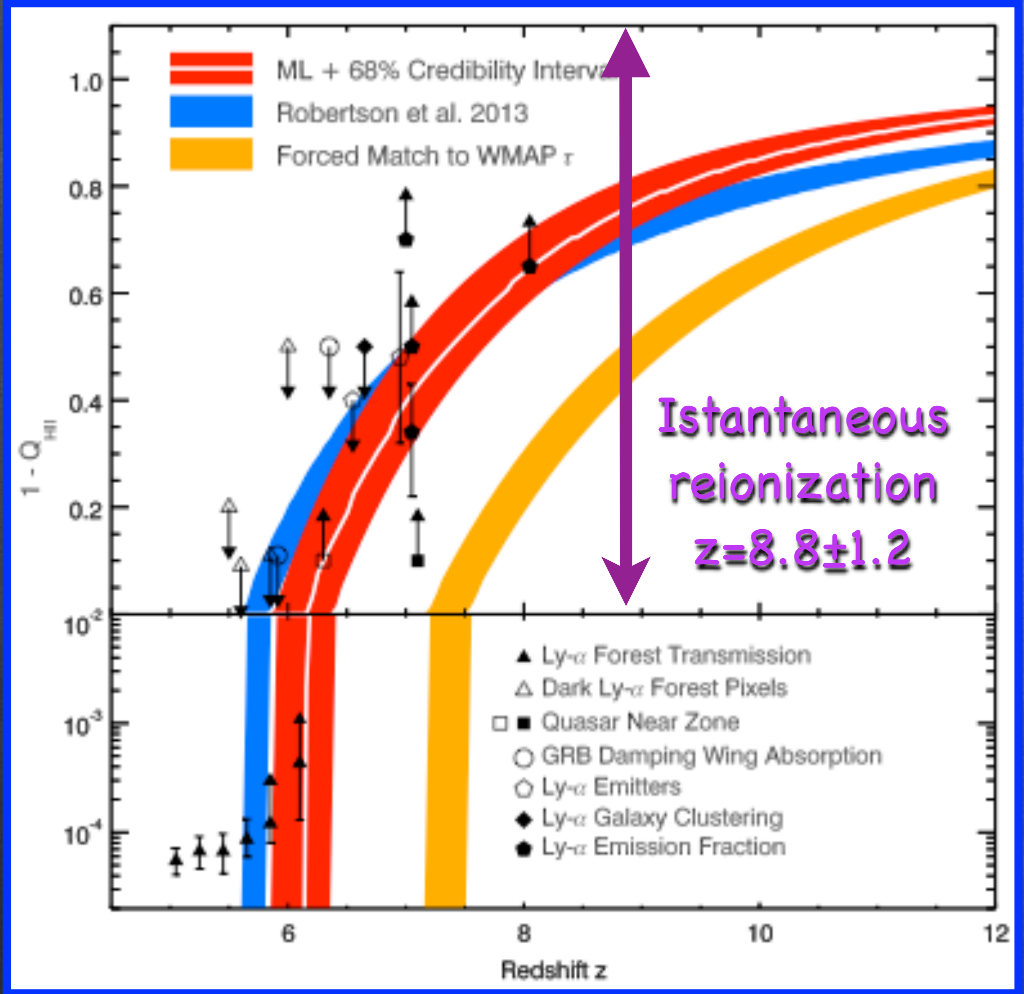
$$C_{\rm H}(z) = (2.9)\left[\frac{(1+z)}{6}\right]^{-1.1}$$

Shull et al. (2012)

Time evolution of QHII

Volume(HII) / Volume Universe

$$\frac{dQ_{\rm H\,II}}{dt} = \frac{\dot{n}_{\rm ion}}{\bar{n}_{\rm H}} - \frac{Q_{\rm H\,II}}{\bar{t}_{\rm rec}}$$



Robertson+15

Once $Q_{\rm HII}$ is determined it is linked to Thomson optical depth

$$\tau_e = \int_0^\infty dz \frac{c(1+z)^2}{H(z)} Q_{\rm H\,II}(z)\, \sigma_T\, \bar{n}_{\rm H}\, (1 + \eta Y/4X) = 0.066 \pm 0.013$$

Constraints from CMB

Thomson electron cross section

Helium
=1 single ionized (z>4)
=2 doubly ionized (z<4)

CMB photons undergo Thomson scatering with free electrons along the los, this introduce signatures in the CMB: small suppression of signal and linear polarization

Probes:

- QSO near zones
- CMB
- UV luminosity functions
- Ly-alpha emitter surveys (Lecture #3)
- Gamma ray bursts optical afterglows
- Redshifted 21-cm line
- Cosmic infrared and X-ray background
- …

see Becker (2015)

Time evolution of QHII

Volume(HII) / Volume Universe

$$\frac{dQ_{\rm H\,II}}{dt} = \frac{\dot{n}_{\rm ion}}{\bar{n}_{\rm H}} - \frac{Q_{\rm H\,II}}{\bar{t}_{\rm rec}}$$

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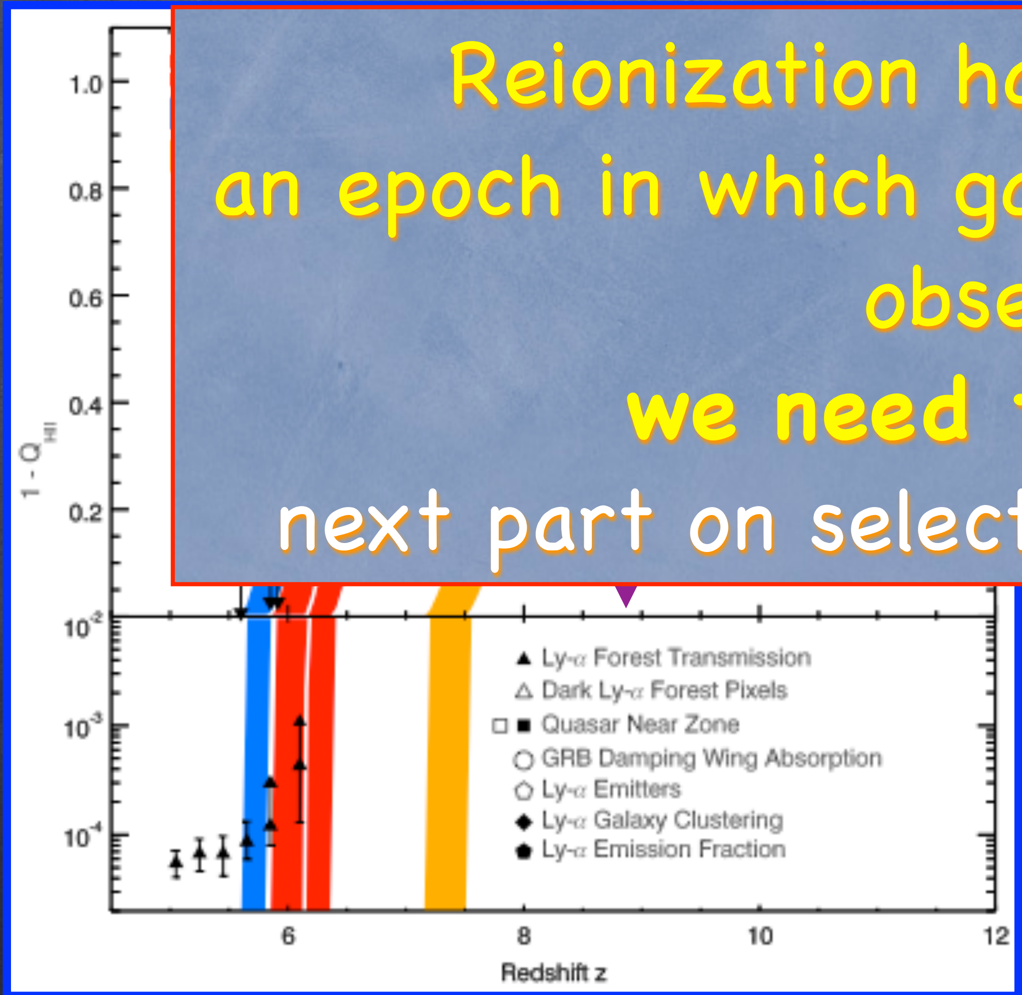


Robertson+15

Reionization happened at 6<z<11, an epoch in which galaxies and AGNs can be observed …

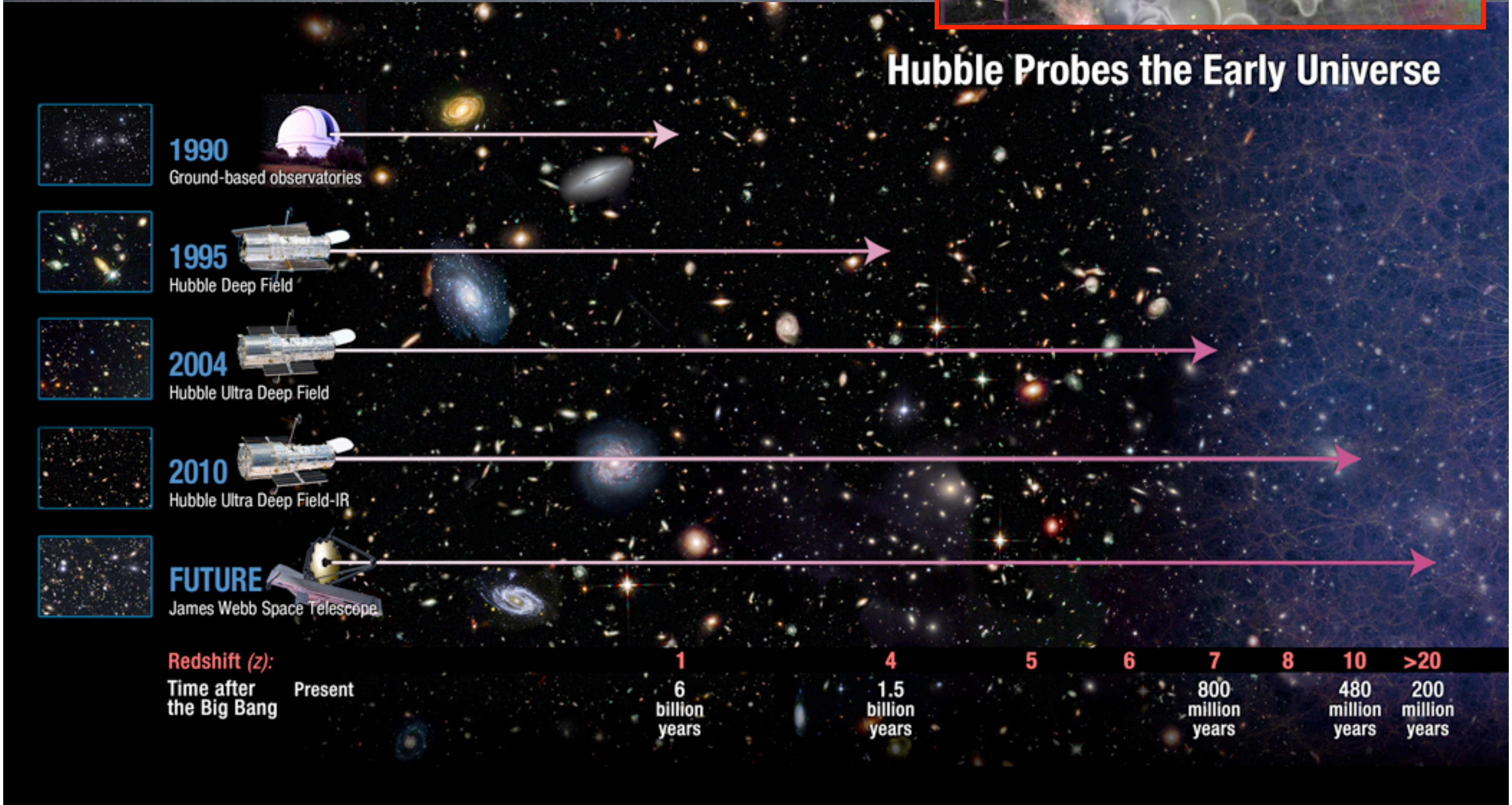
we need to find them:

next part on selection methods (galaxies)

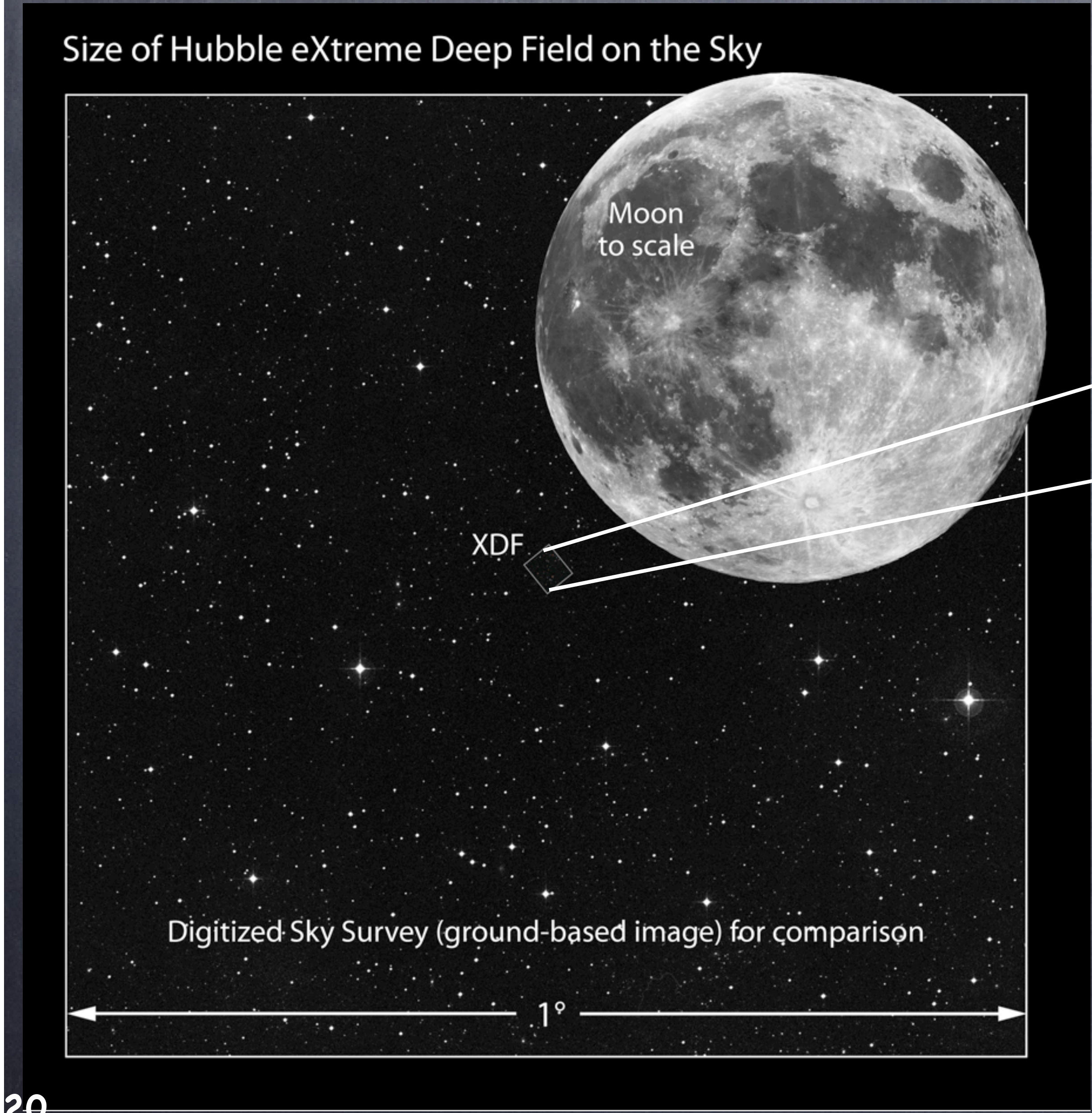
- UV luminosity functions
- Ly-alpha emitter surveys (Lecture #3)
- Gamma ray bursts optical afterglows
- Redshifted 21-cm line
- Cosmic infrared and X-ray background
- …

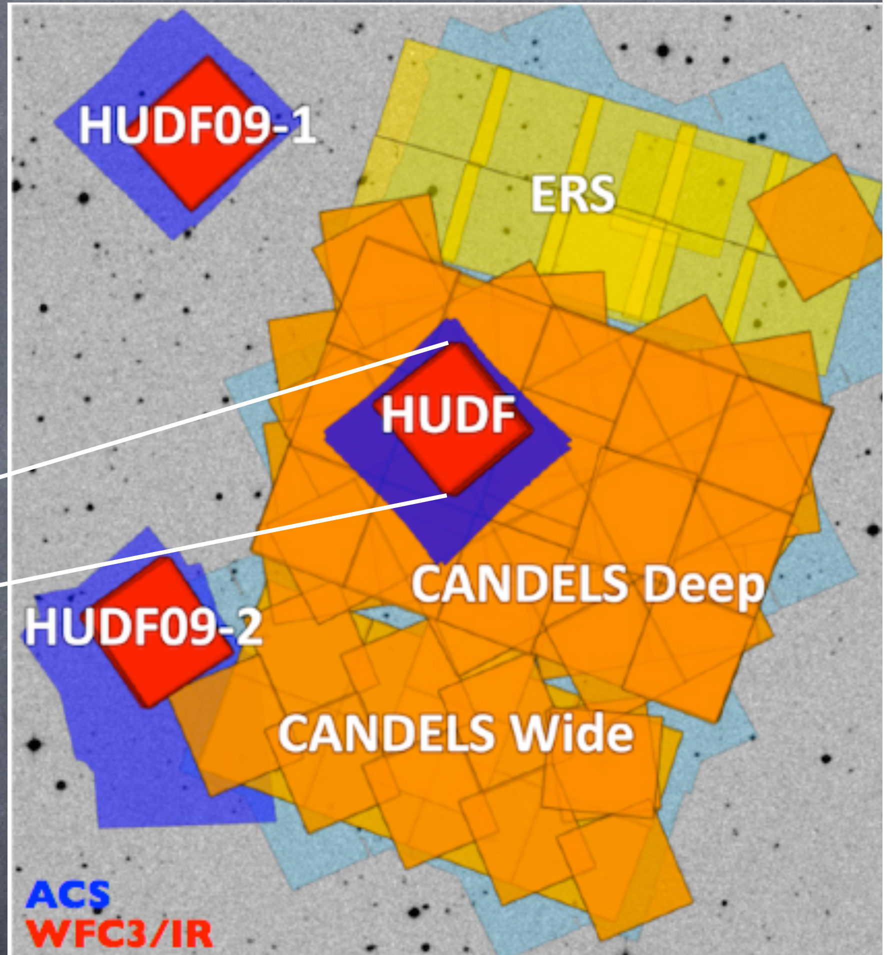
see Becker (2015)

Searching for distant star-forming galaxies



Panchromatic deep surveys
The deepest optical & near-infrared field ever

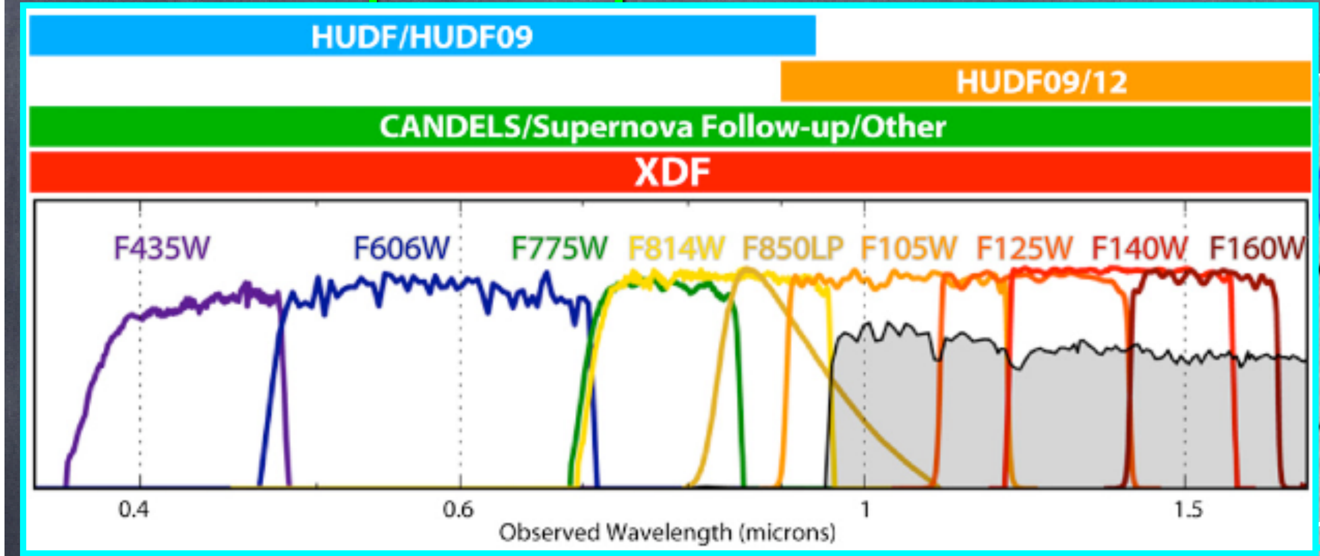


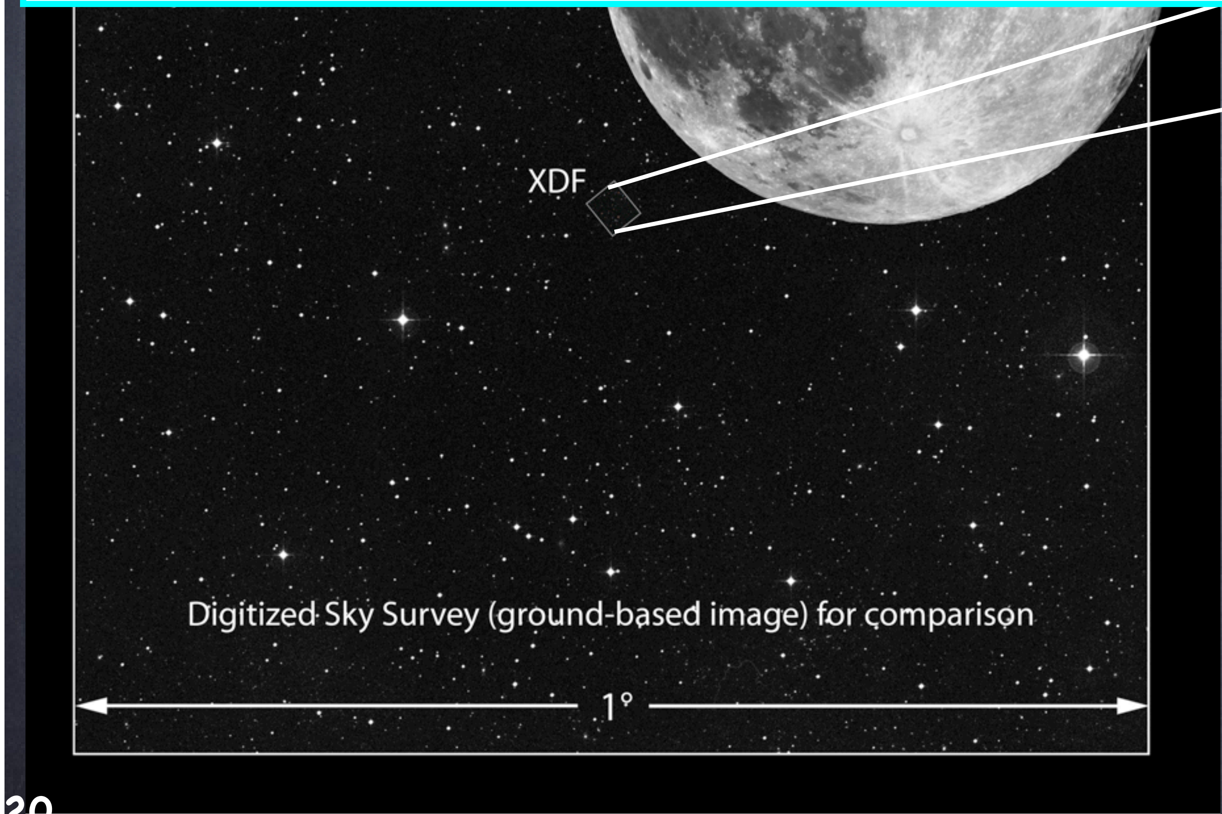


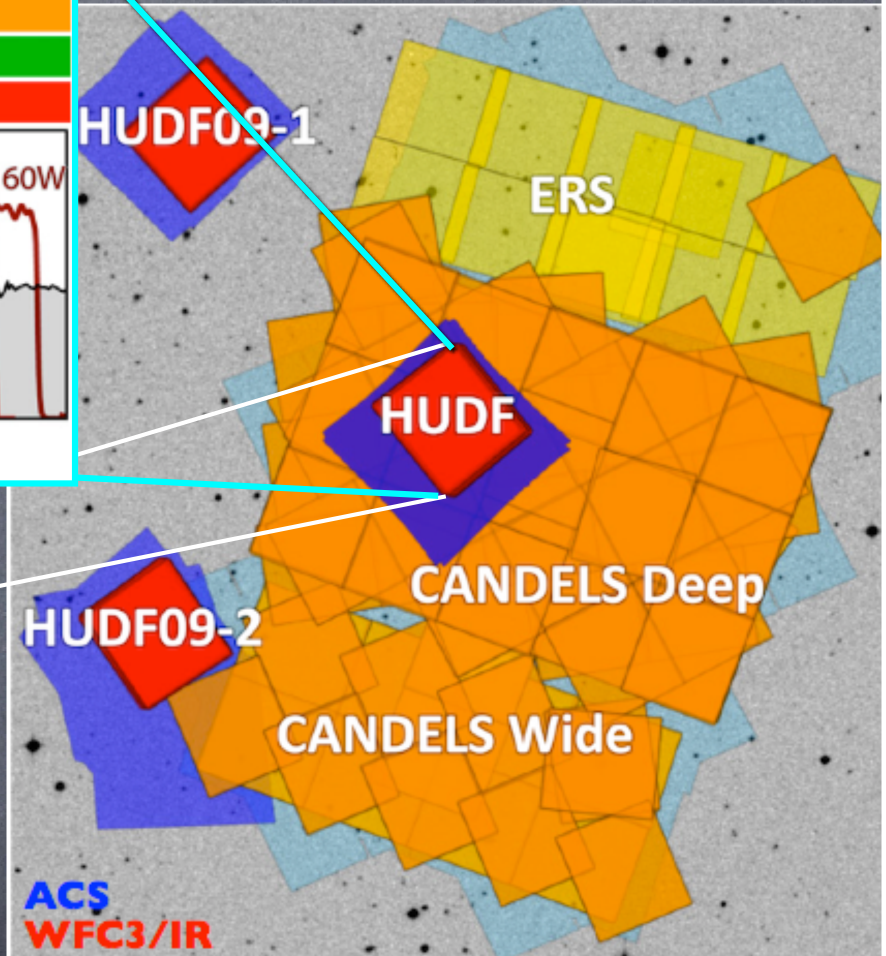
GOODS-S/CANDELS

ACS/optical Giavalisco et al. (2004)
WFC3/NIR Grogin et al. (2011)

Panchromatic deep surveys
The deepest optical & near-infrared field ever







GOODS-S/CANDELS

ACS/optical Giavalisco et al. (2004)
WFC3/NIR Grogin et al. (2011)

Hubble Ultra Deep Field:

(Credit: NASA; ESA; and G. Bacon and Z. Levay, STScI)

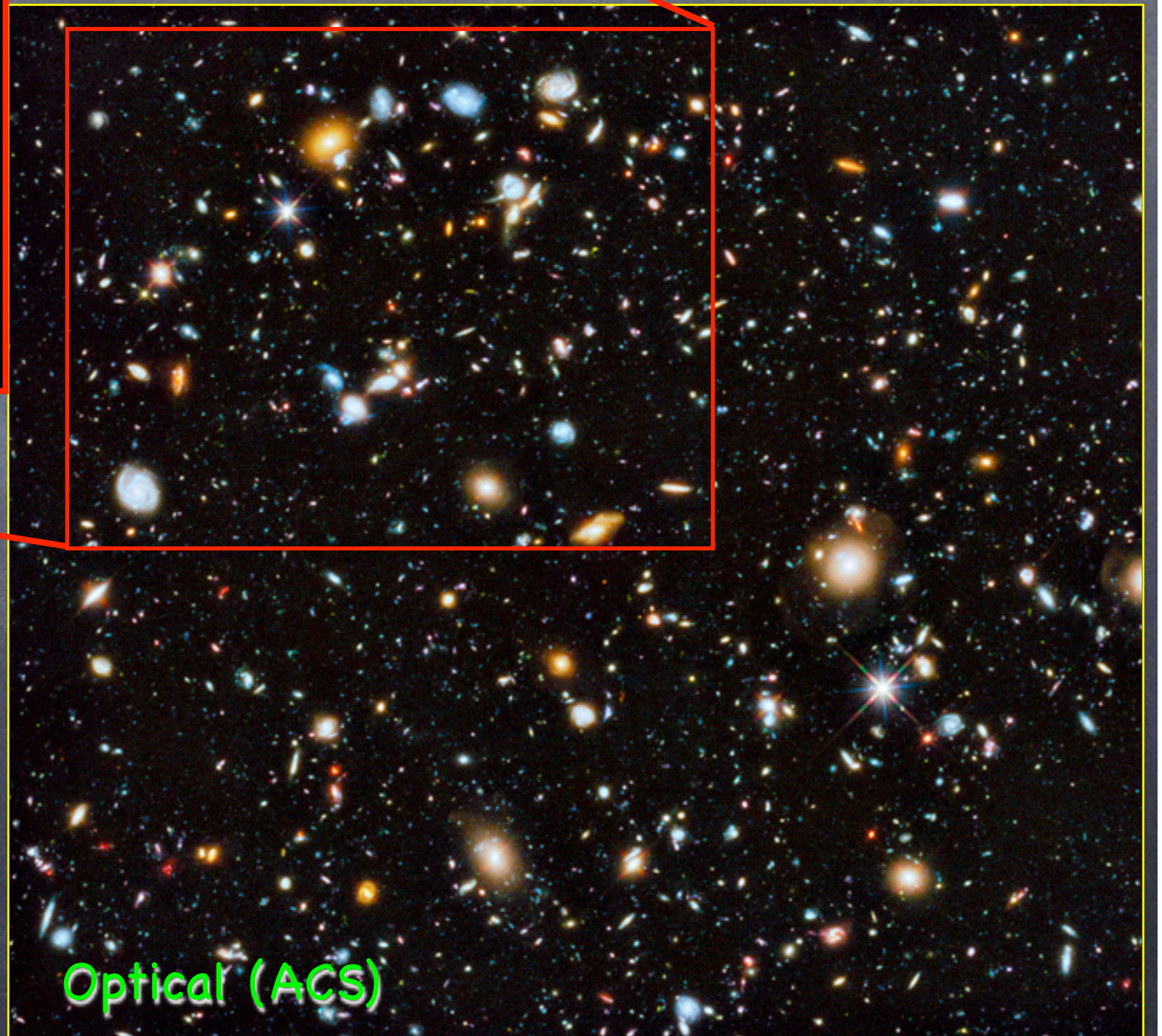
An example: Extreme deep field observations

http://xdf.ucolick.org/

Hubble Extreme Deep Field XDF
two millions seconds exposure
time (24 days) with HST!

num.galaxies 7200
area 4.7 sq.arcmin
ACS+WFC3

Near Infrared (WFC)



Optical (ACS)

An example: Extreme deep field observations

http://xdf.ucolick.org/

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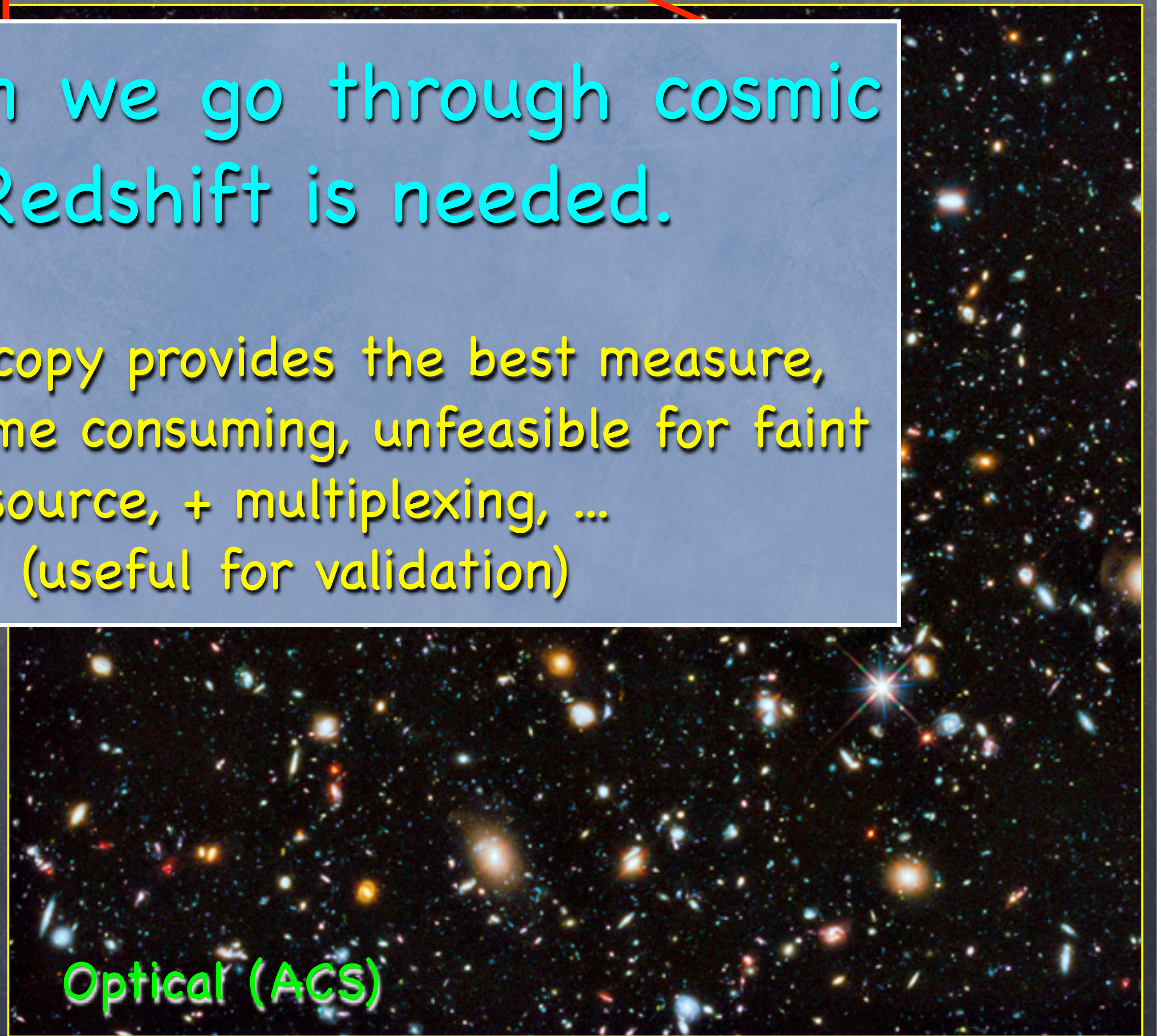


How can we go through cosmic time ? Redshift is needed.

Spectroscopy provides the best measure, but it is time consuming, unfeasible for faint source, + multiplexing, ...
(useful for validation)

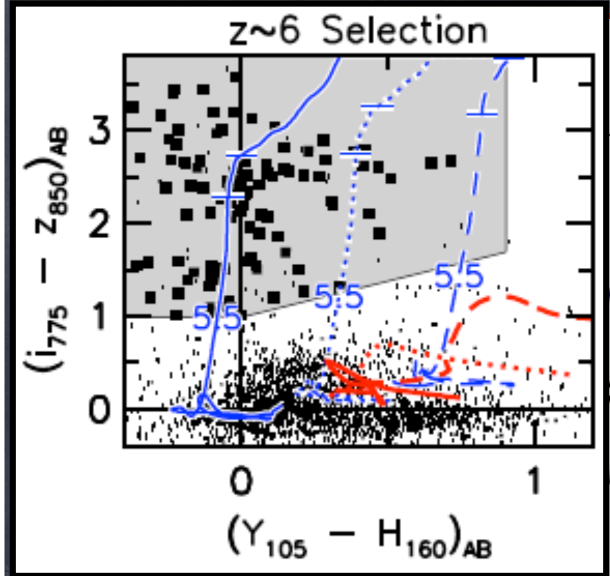
Dropout selection technique - high redshift

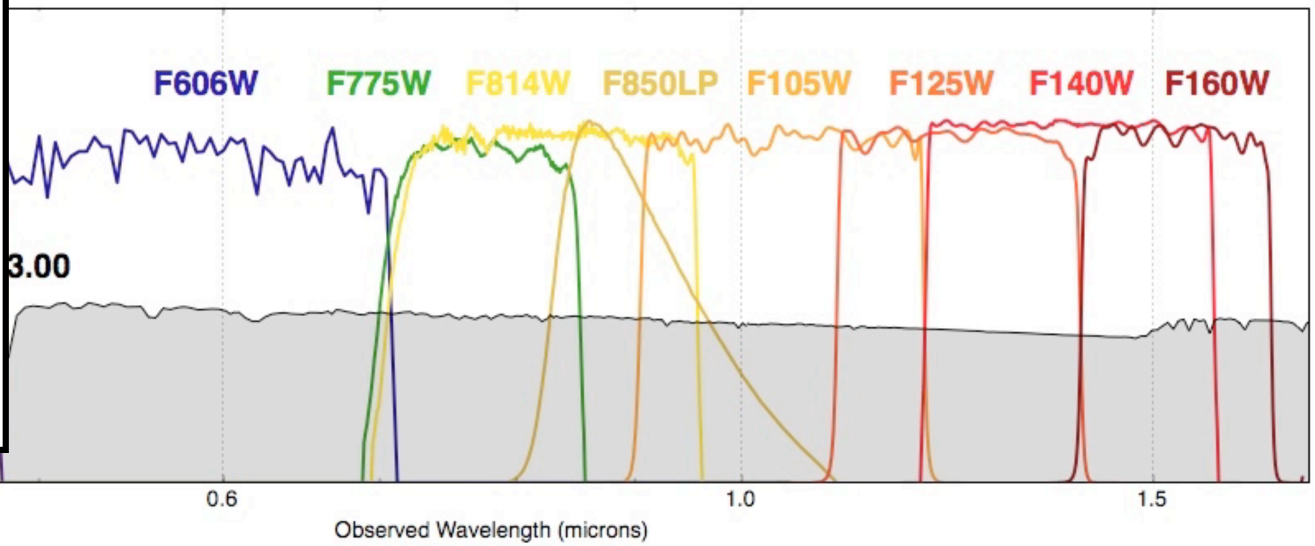
Steidel et al. (1999)

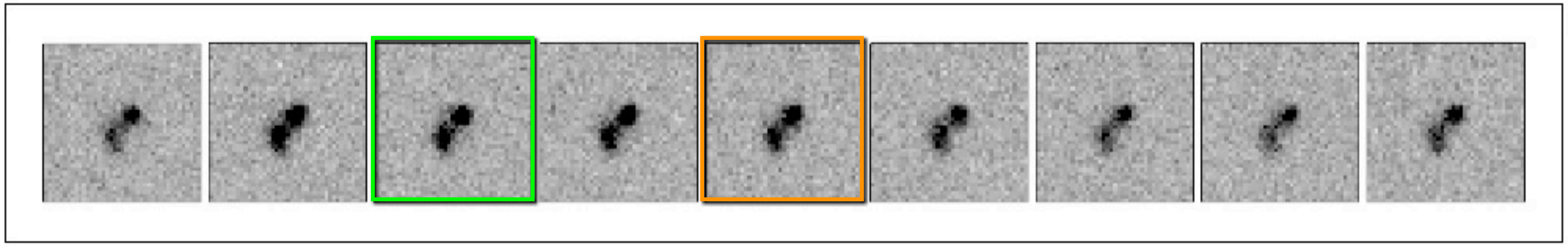
- Lyman Break Galaxy Selection: based on IGM absorption

  Remember τ_{eff}(IGM)

  - z>7 (<0.8 Gyr) can only be seen at Near Infrared wavelengths , lambda > 1um



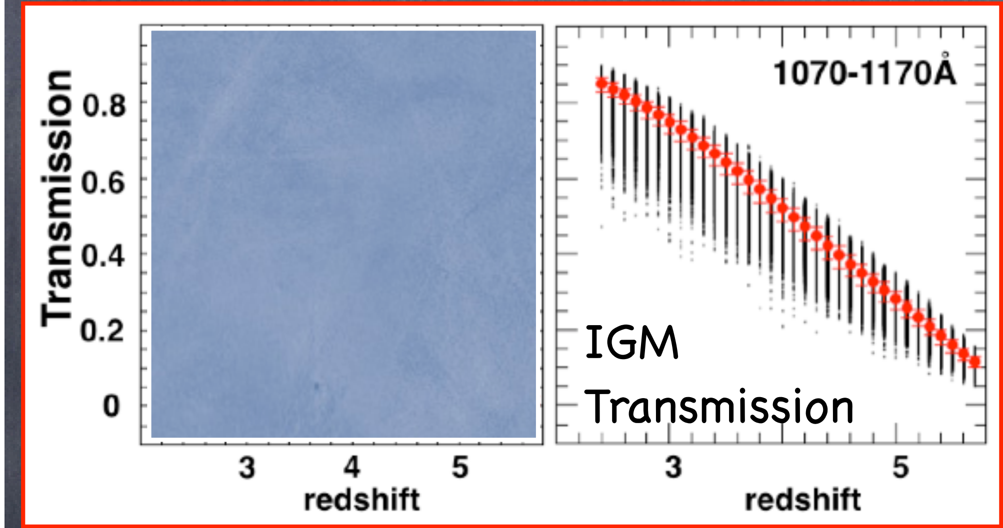




$i_{775} - z_{850} \approx 2$

Animation available at http://xdf.ucolick.org/

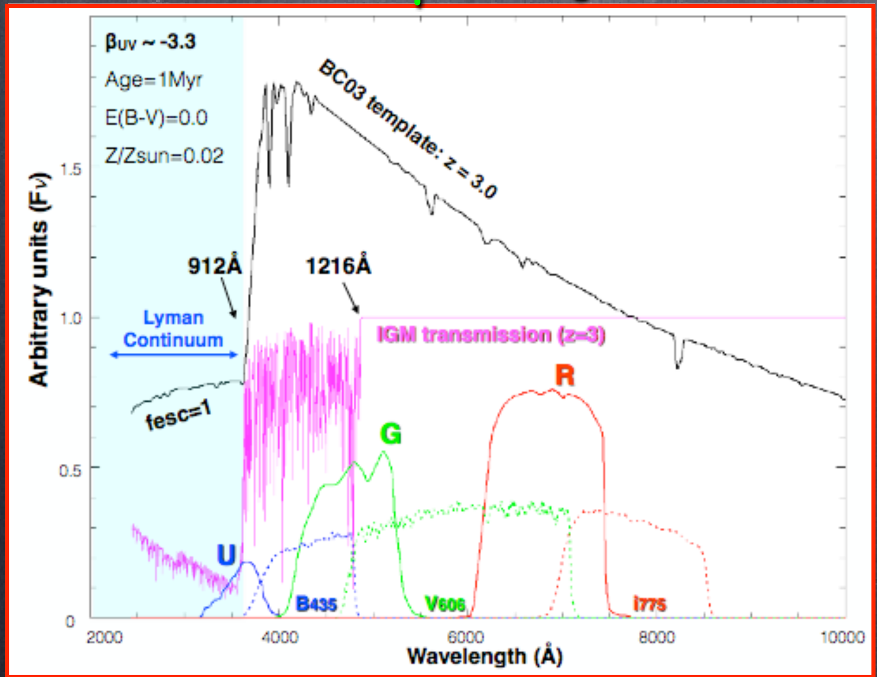
Selecting high-z galaxies: Color-color diagrams



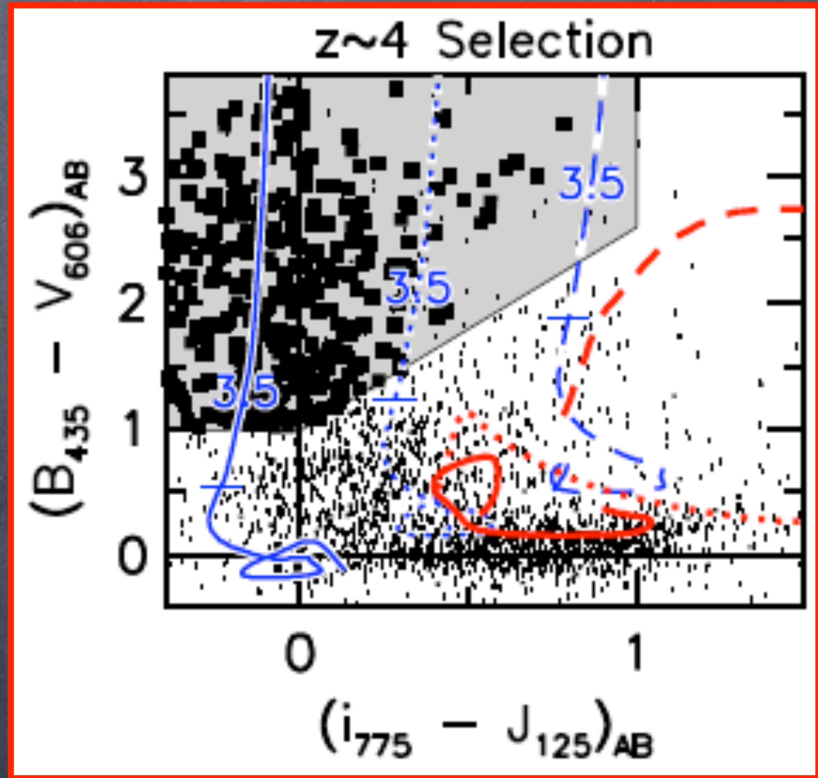
1) One color captures the IGM attenuation (z) [LAF + Lyman C.]

Tight relation with z, small scatter

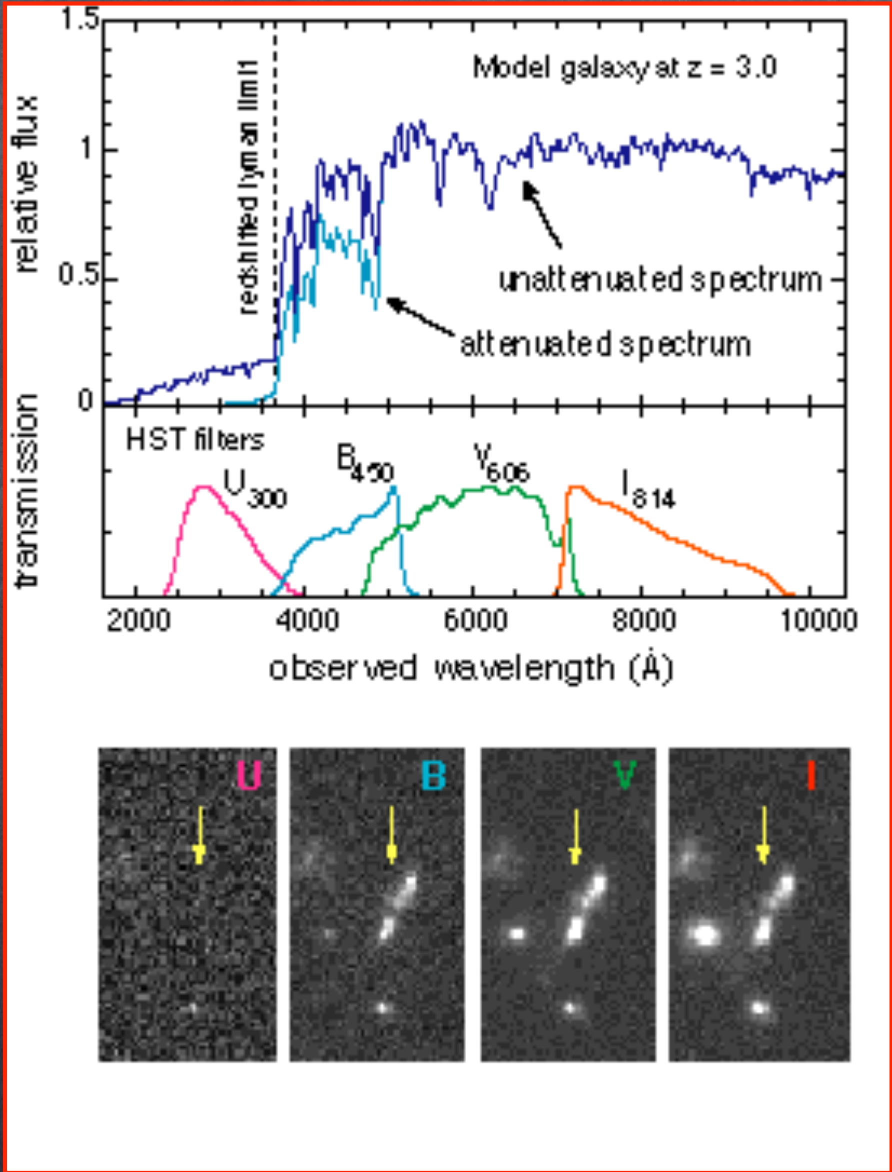
2) The other color sets constraints on the UV slopes (age+metallicity+dust extinction)



e.g., Giavalisco et al. (2004); Bouwens+15



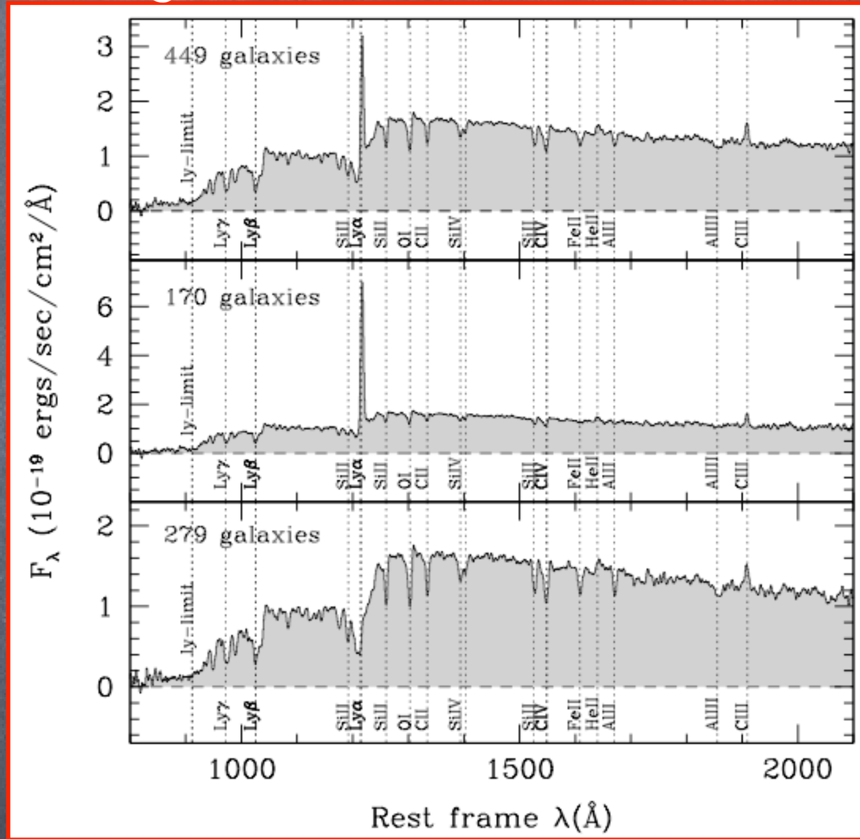
Example: U-band dropout selection (z=3)



Color selection:

Guess on redshift with typical error 0.3-0.5 + systematic (could be catastrophic)

Validation (spectroscopy)
e.g., Le Fevre 2015

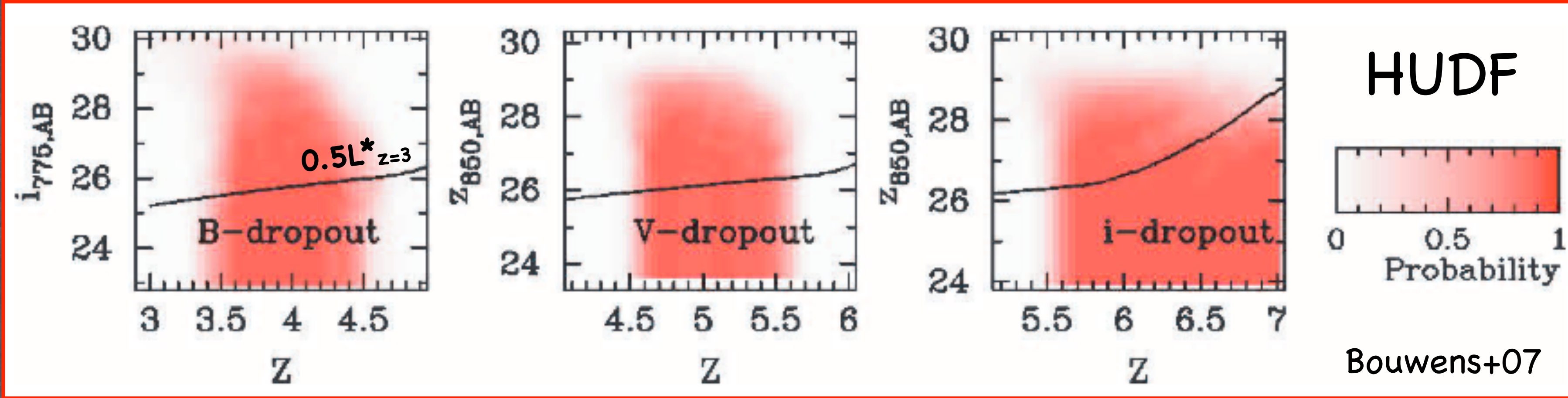


Typical error on redshift < 0.003

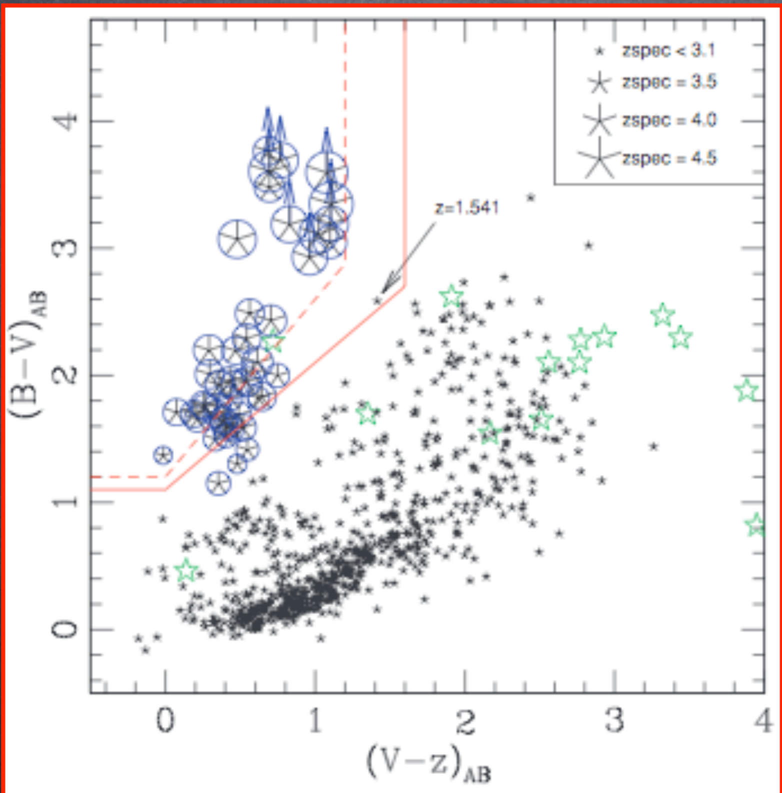
1+zspec = λobs / λo

=> limited to bright galaxies mag<25-26

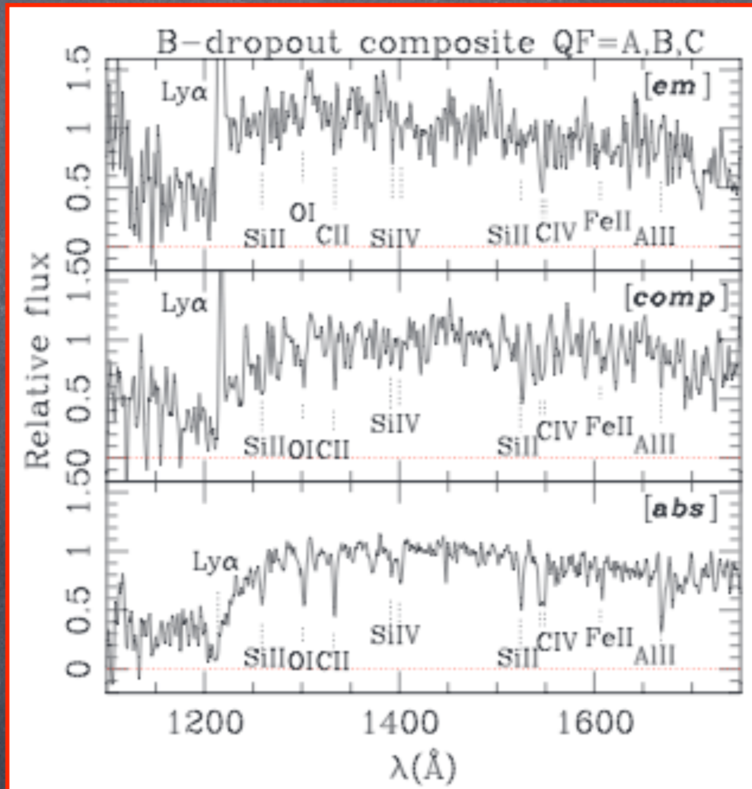
Color-color diagrams



Simulating the selection functions



Spectroscopy

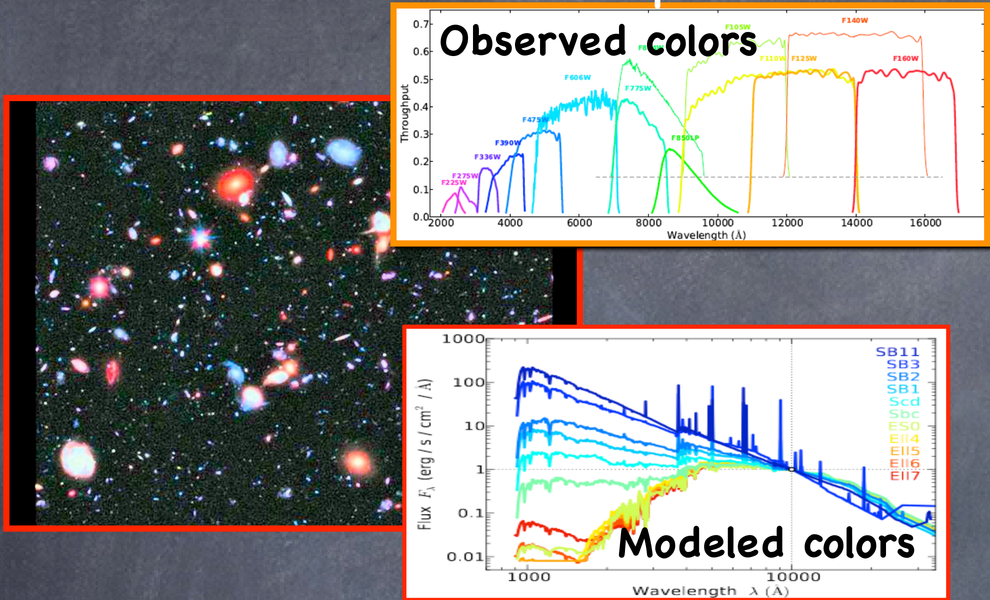


efficient, >90%

Vanzella et al. 2009

Photometric redshifts (I): Template fitting technique

Multi-band Deep fields



Starbust99;Bruzual&Charlot2003

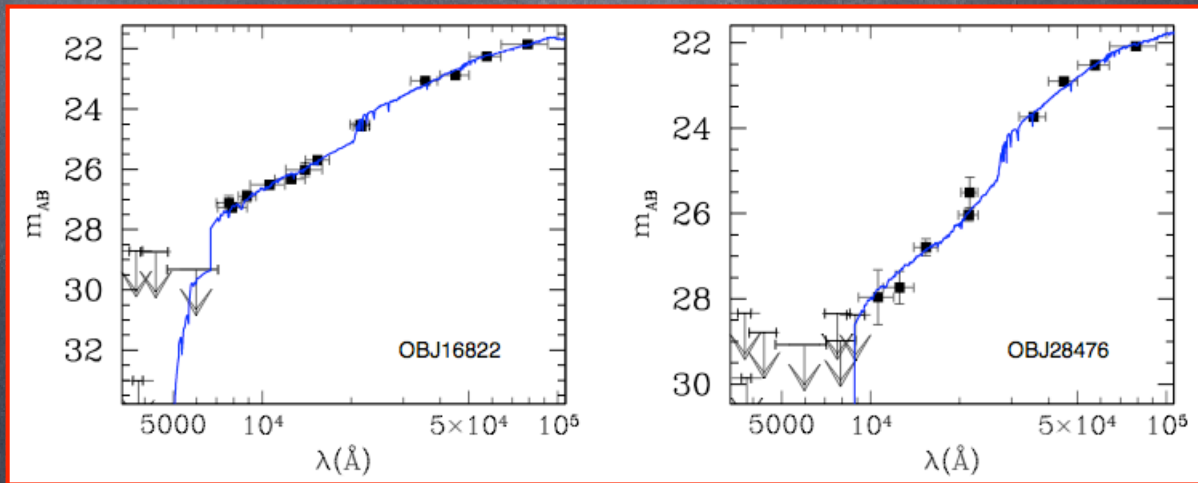
Stellar populations synthesis models: stellar evolutionary tracks vs. ages vs. metallicites + dust extinction (e.g., Calzetti law)

Exploit the full set of filters Nm

$$\chi^2 = \sum_{k=1}^{N_m} \left[\frac{F_{\rm obs}^k - a \cdot F_{\rm temp}^k(z)}{\sigma_F^k} \right]^2$$

Find the best fitting template; redshift as a free parameter

see, e.g., Bolzonella et al. (2000)



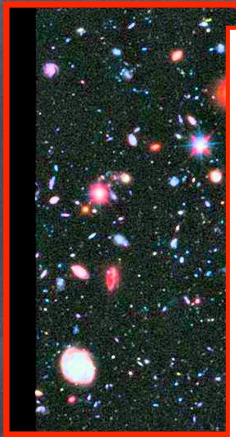
Can be used for galaxies or AGN from z=0 to 10

Giallongo et al. (2015), Salvato et al. 2011

Arnouts 2003

Photometric redshifts (I): Template fitting technique

Multi-band Deep fields



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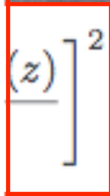
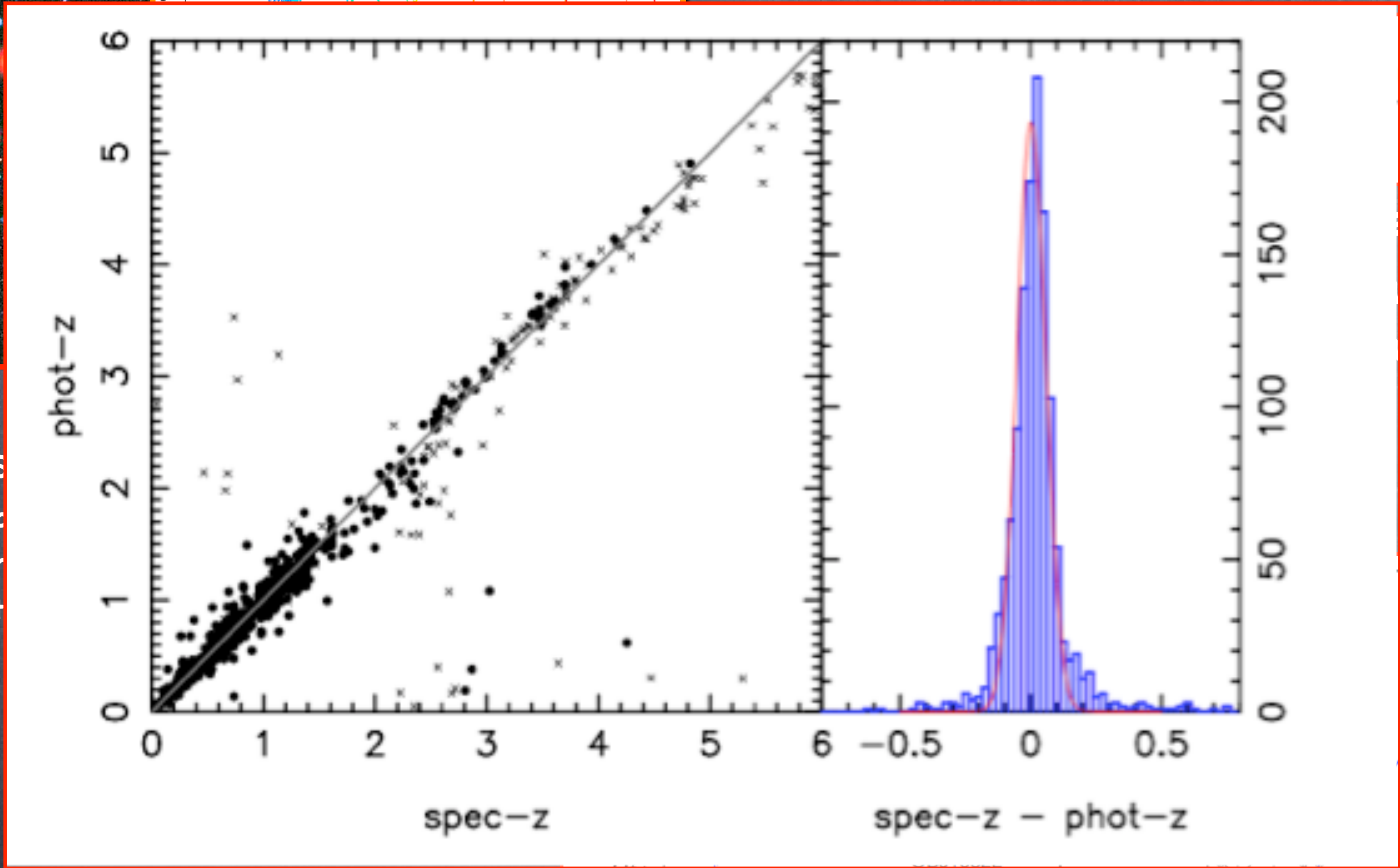




...mplate;

...meter

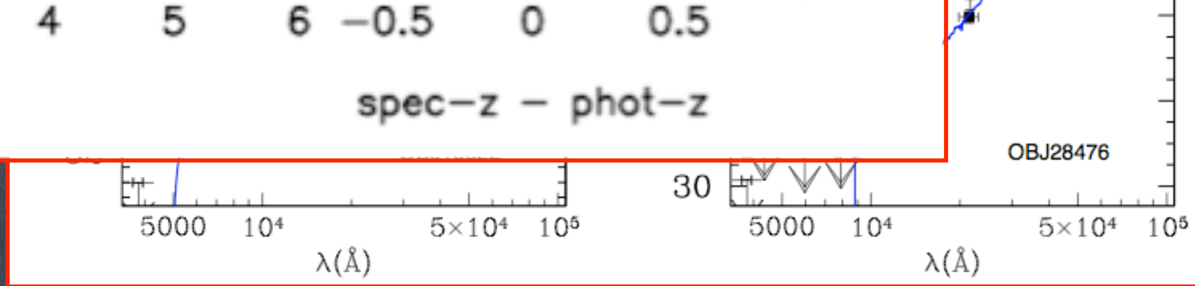
...l. (2000)

Starbus...

Stellar pop...

evolutionar...

+ dust ext...



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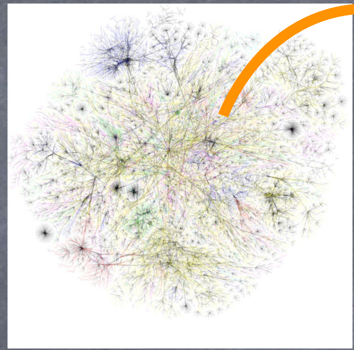
Photometric redshifts (II): Empirical techniques

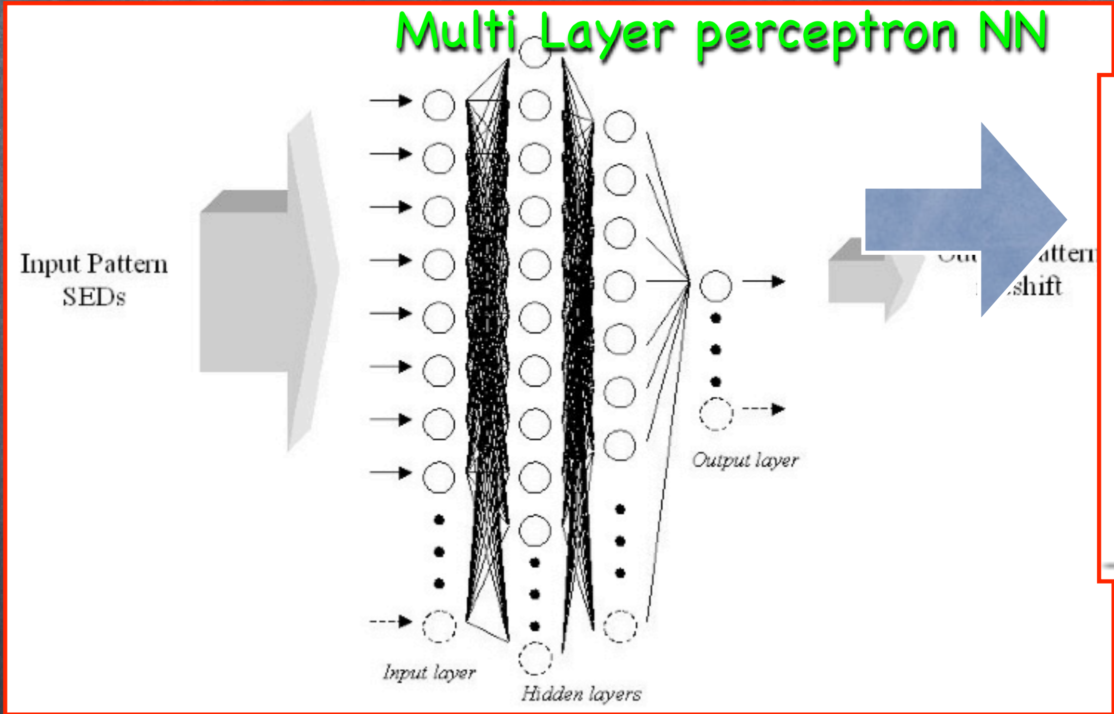
Example: machine learning

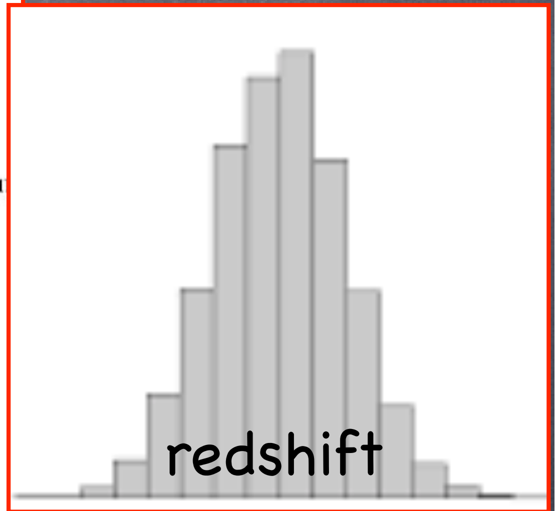
find a map between multi-dim colors
and redshift, minimization of a merit function
based on a training sample
(e.g., Vanzella et al. 2004; Simm et al. 2015)



z=f(colors, priors)

Multi Layer perceptron NN





Vanzella et al. (2004)

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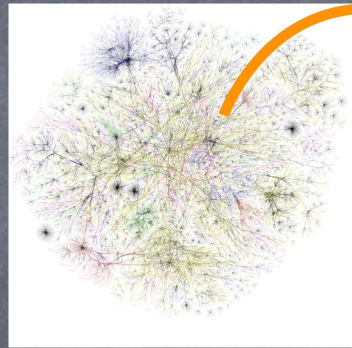
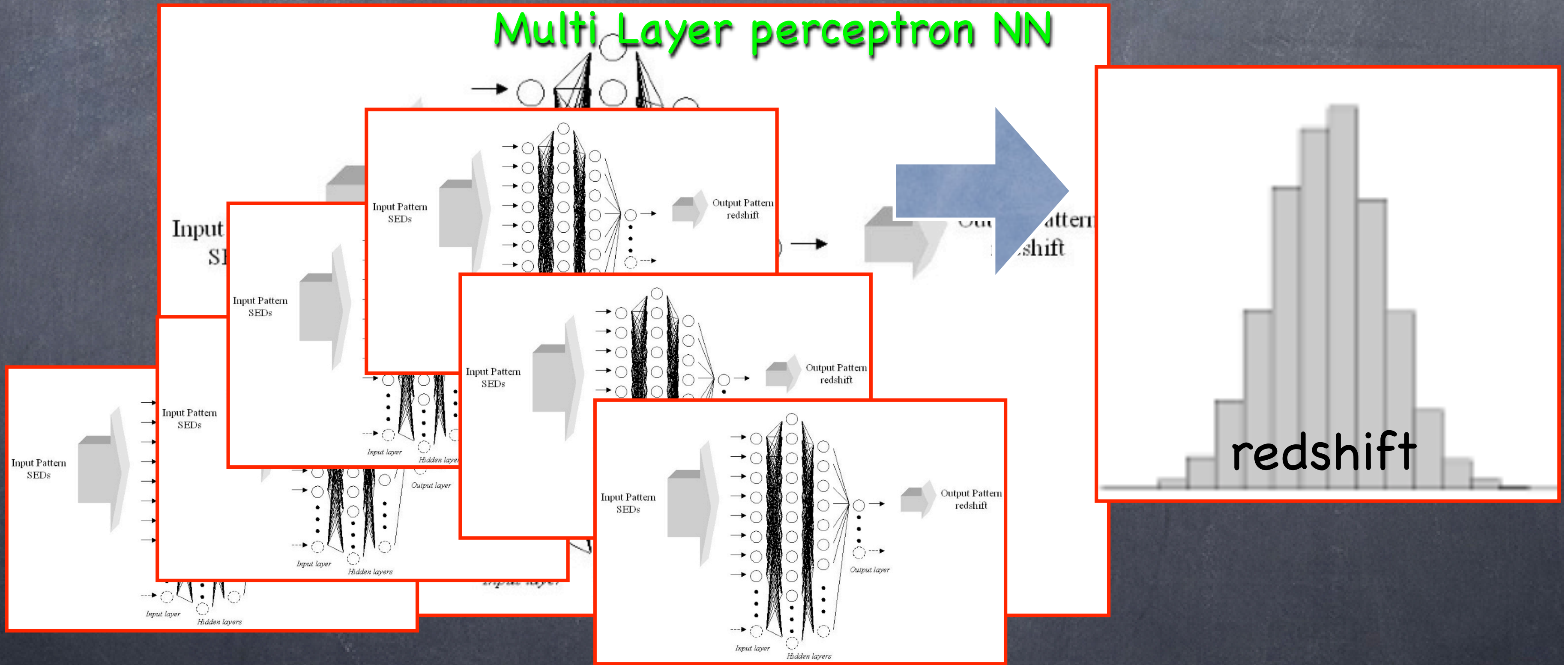


z=f(colors, priors)

Committee of Neural Networs



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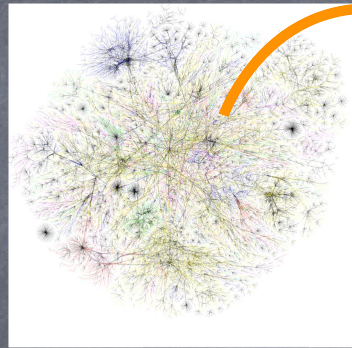

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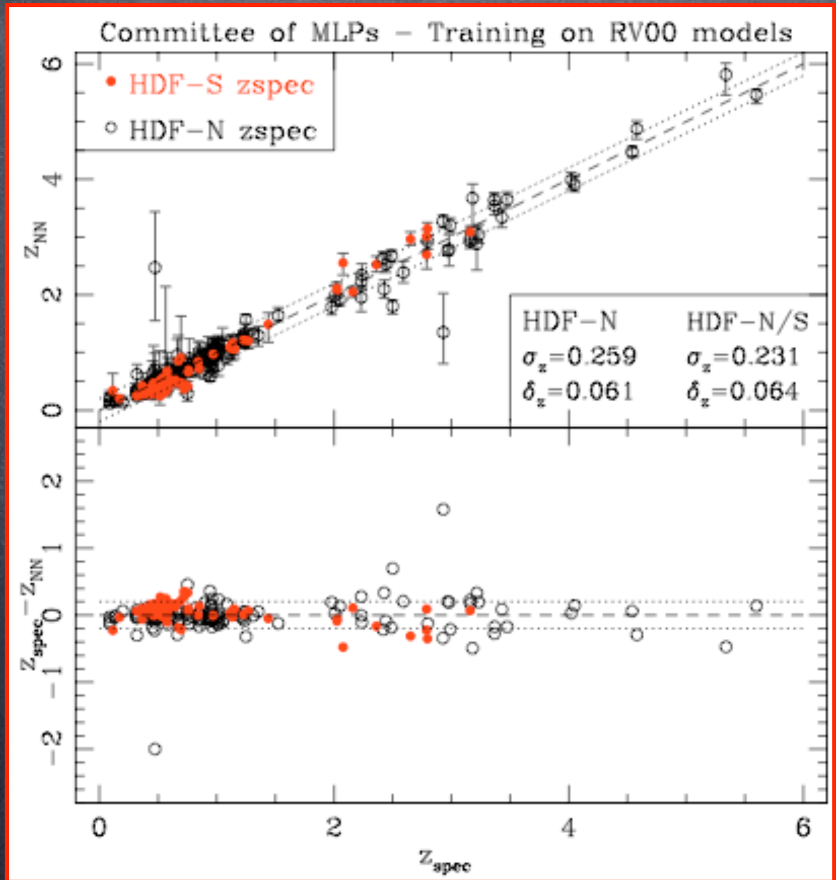
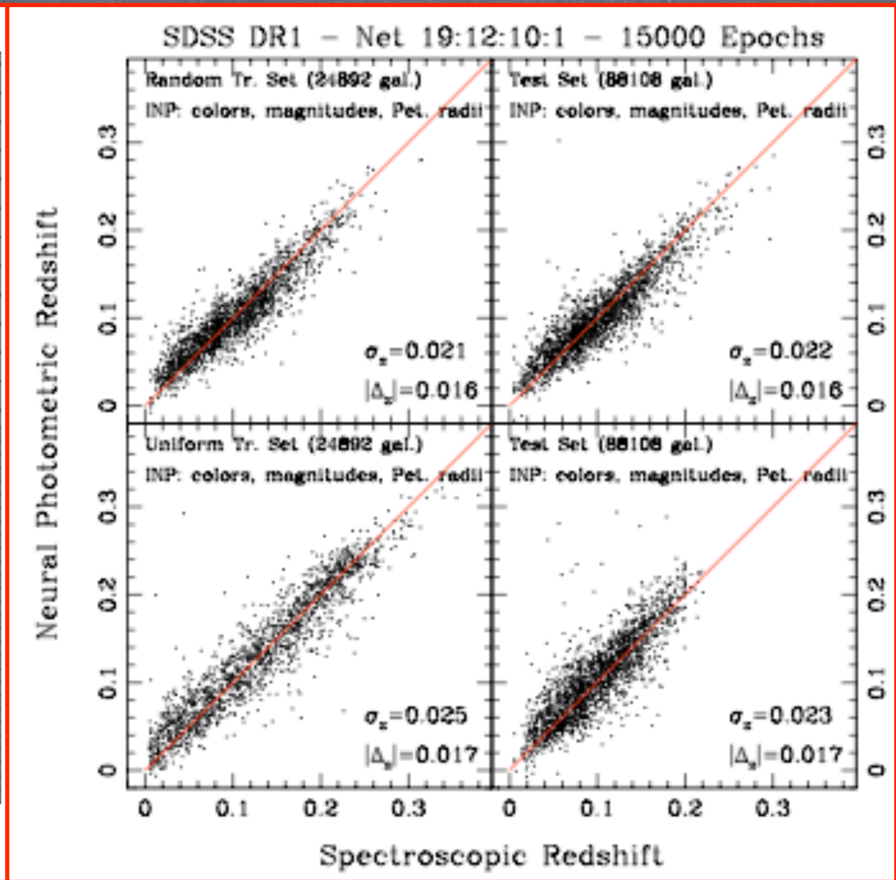
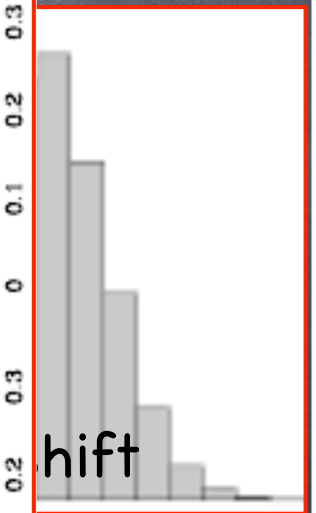
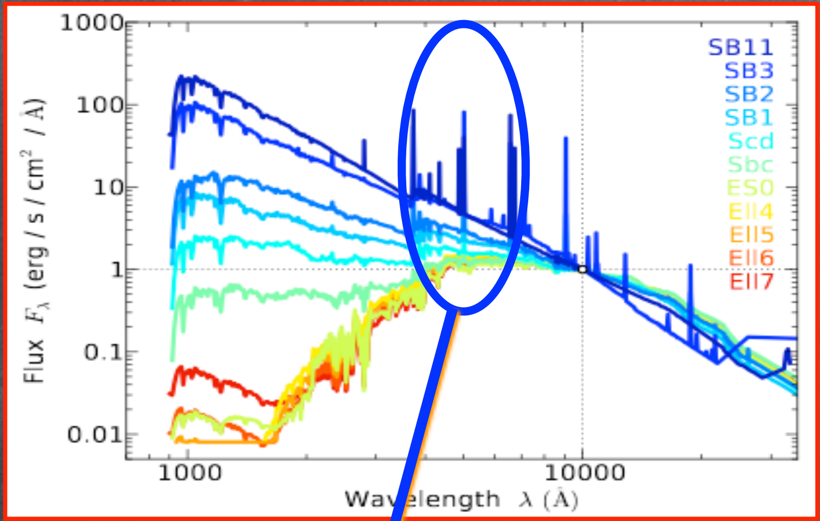






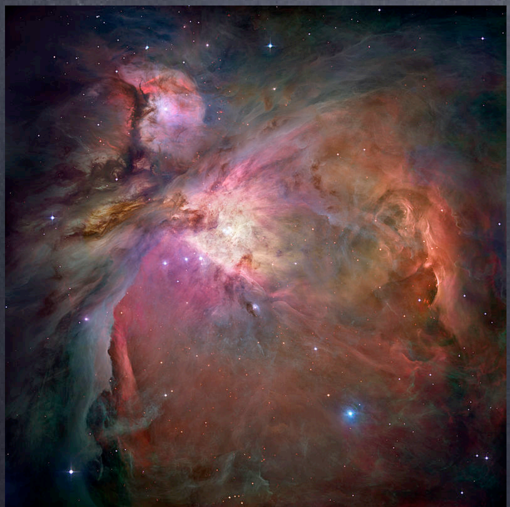
Vanzella et al. (2004)

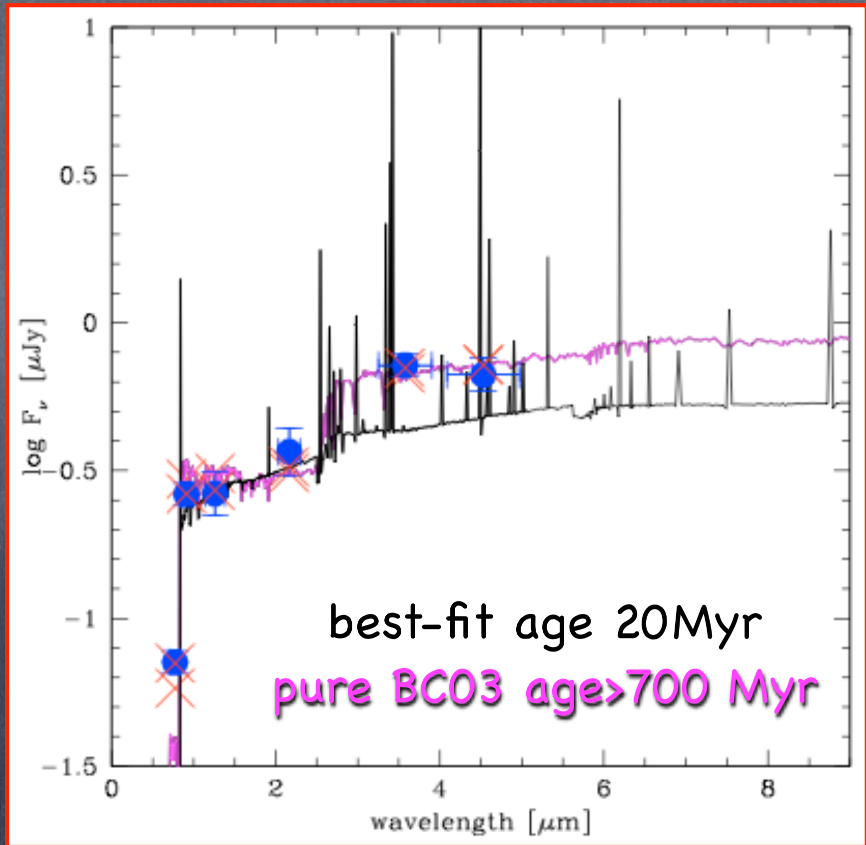
Photometric redshifts: captures broad features (breaks: Lyman limit; Lya-break; Balmer break) + global shape



... the nebular contribution to photometry is important, in some cases dominant, as redshift increases (proportional to (1+z)):

Star-forming regions (HII): Nebular recombination lines like Oxigen, Balmer, Lyman lines



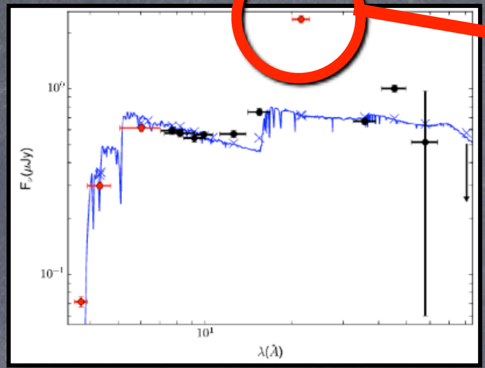


Schaerer & de Barros (2009)

Examples of emission lines signature a high redfshift

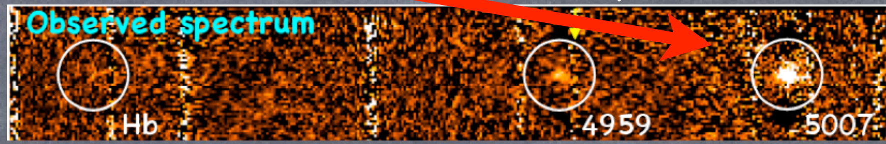
zphot = 3.0

zspec = 3.212

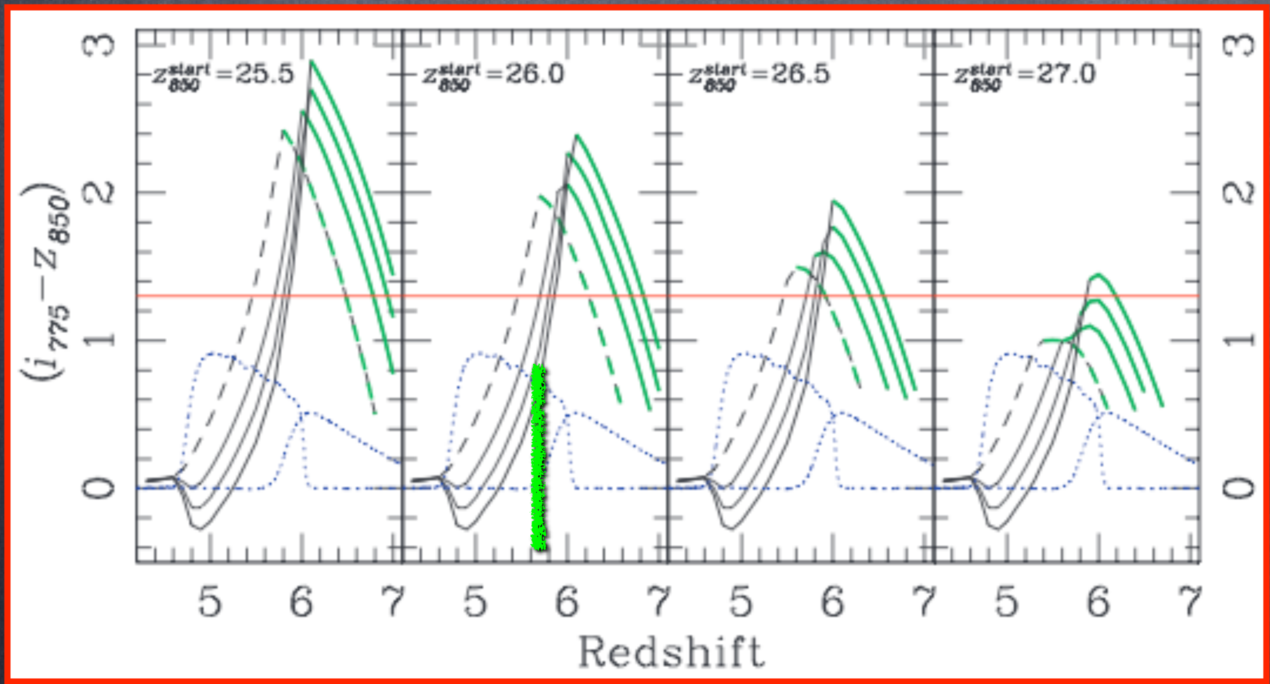


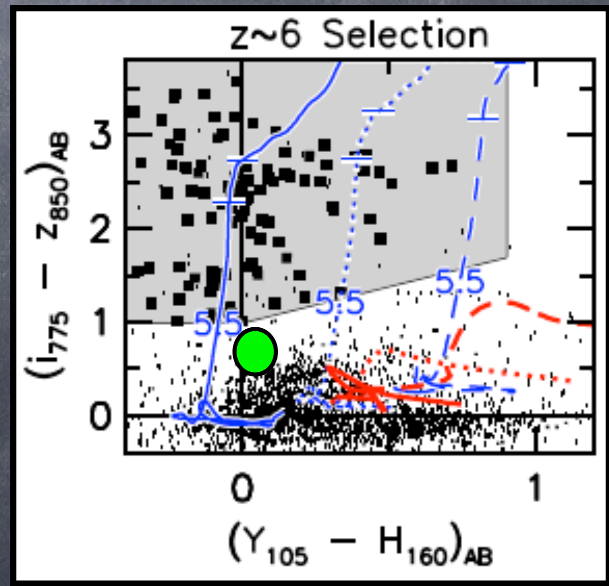
Strong [OIII]5007 line

MOSFIRE spectrum (Keck)



From De Barros et al. (2015)





Effect of Lya emission on photometry at z>5.5, Vanz+09

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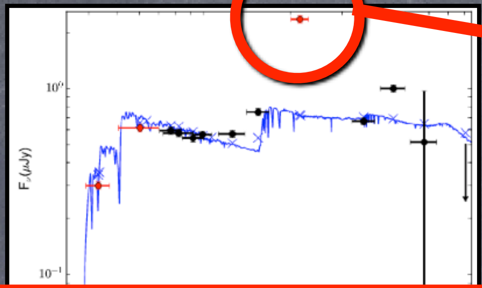

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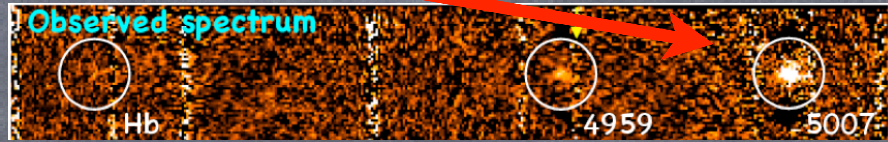
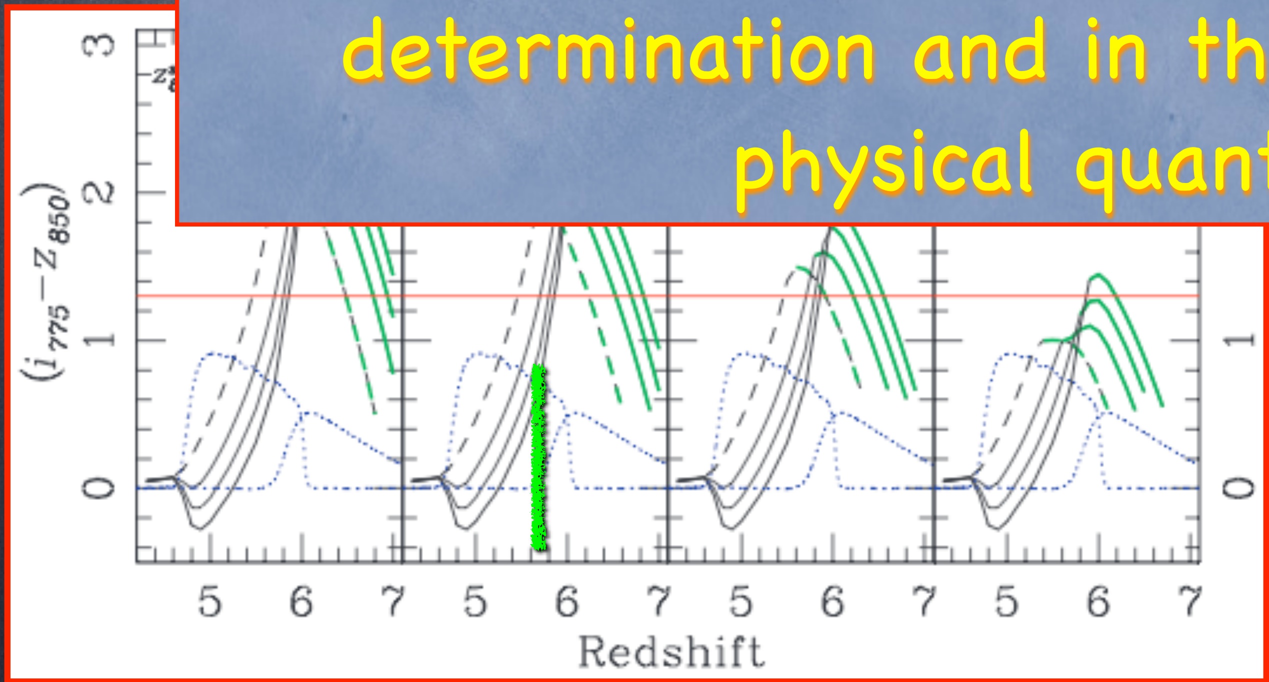
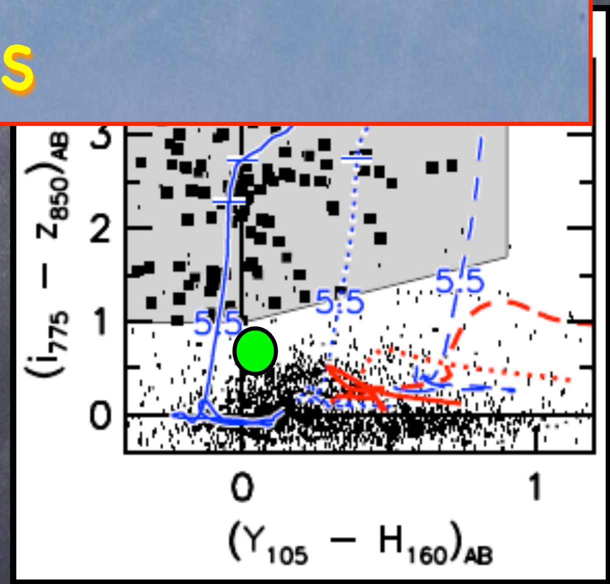


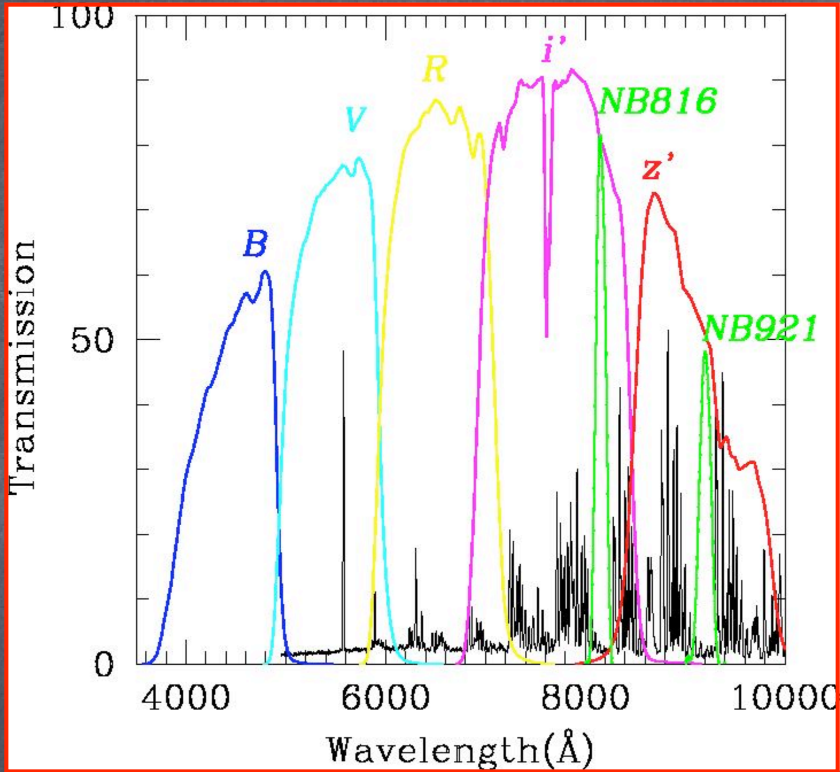
Line contribution must be taken into account, both in the zphot determination and in the derivation of physical quantities





Effect of Lya emission on photometry at z>5.5, Vanz+09

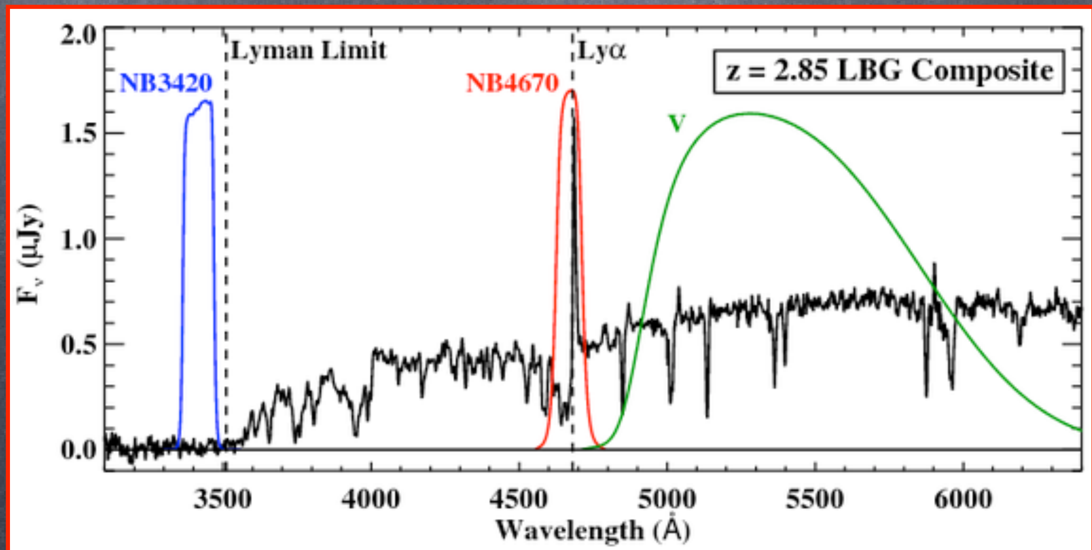
Narrow band selection technique



Green: Narrow bands centered at 8160A and 9210A, corresponding to z=5.7 and 6.5 **IF** Lya is captured, similarly at z=7 with the NB9700 filter

Ouchi (2010)

NB filters have also been customized: designed to investigate a specific redshift value (Hayes et al.)



Mostardi et al. (2013)

Summarizing: high-z selection

Photometric redshifts: captures broad features (breaks: Lyman limit; Lya-break; Balmer break) + neb. emission + global shape

Template fitting	Empirical (machine learning)
Advantages: - flexible (filter set) - derive physical properties (nebular+physics)	Advantages: - fast computation (once training is done) e.g., one billion galaxies in 5 hours - model-independent (- photometric zeropoints)
Disadvantages: - "model-dependent" e.g., nebular emission introduce recently - need accurate phot. zeropoints	Disadvantages: - training on the same filter set - uncertain extrapolation toward faint limits

Color-color diagrams

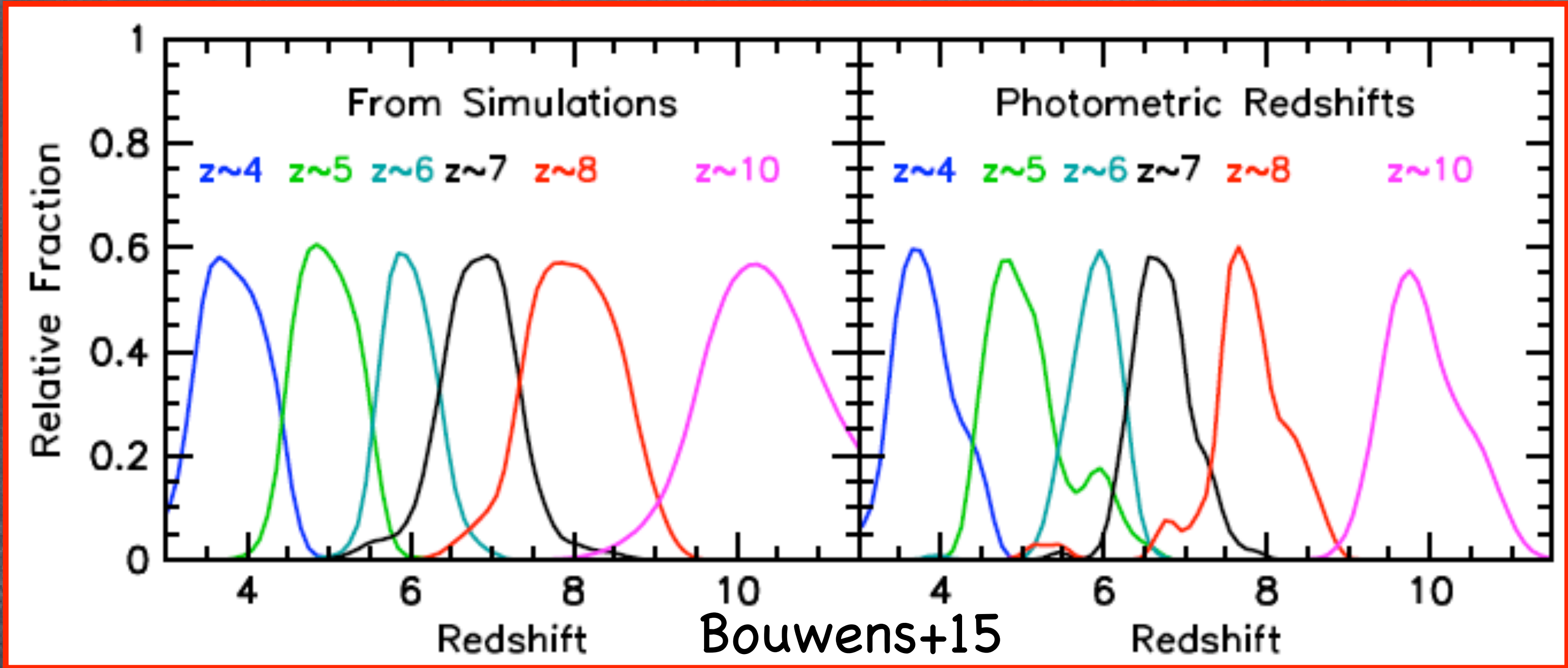
Efficient to select high-z sources: IGM break+UV slope

Narrow-band selection

Efficient to select line emission: small volume, line contamination

High redshift Selection functions: Color-color vs. Photometric redshifts

Color-color selection Photometric redshifts



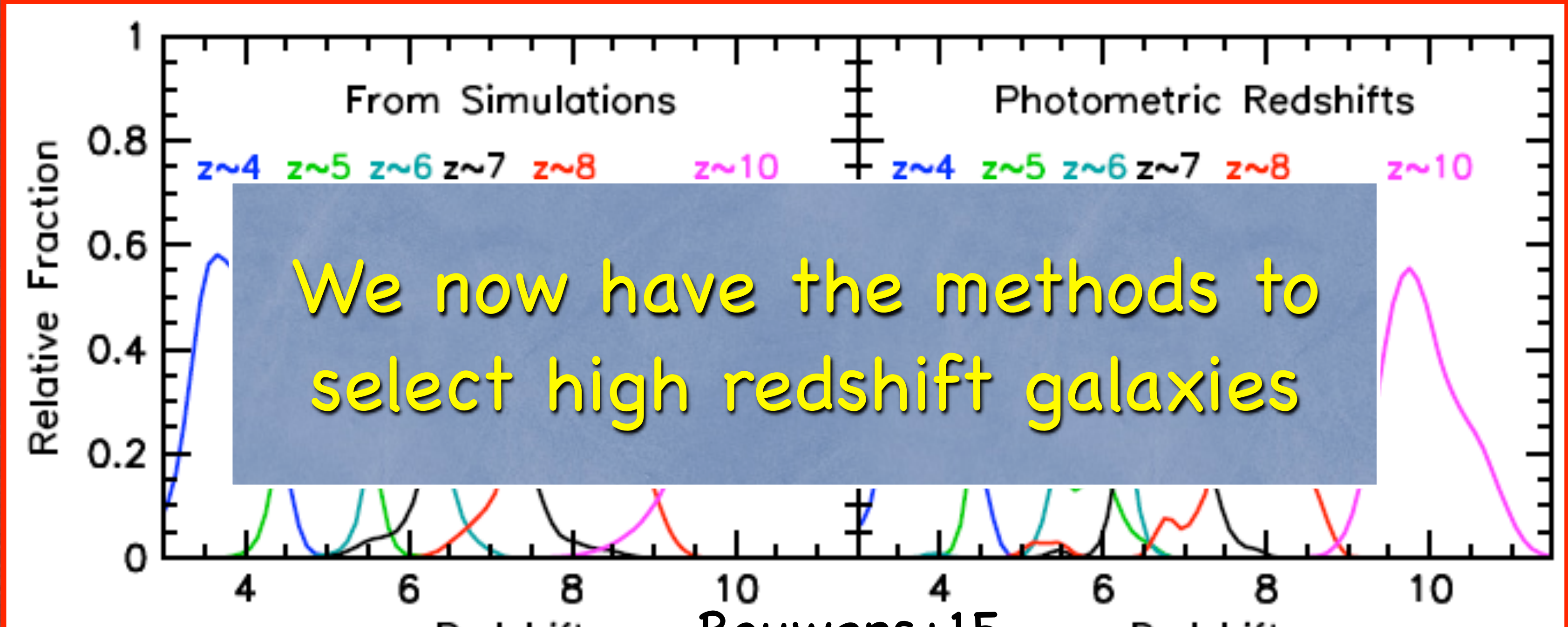
Simulating high-z selection, adding noise to real data, dim galaxies re-select them -> monitor selection criteria.

Expected small fraction of contamination: (2,3,6,7,10%, for z=4,5,6,7,8, redshift dependent)

- Cold galactic stars
- Supernovae
- **Photometric scatter (dominant)**
- EELG
- Spurious sources

High redshift Selection functions: Color-color vs. Photometric redshifts

Color-color selection Photometric redshifts



Bouwens+15

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Galaxy luminosity function

Consider a sample of galaxies S with an estimated redshift. We can define the following quantities:

$n_S(L)$ → number of galaxies in S per unit luminosity

$n_S(L)dL$ → number of galaxies in S with luminosity between L & L+dL

$\phi_S(L)$ → Luminosity function such that

$$\phi_S(L) = n_S(L) \,/\, V_S(L)$$

Number of galaxies in S per unit Volume and L

$$\phi_S(L) \rightarrow \phi(L) \quad \text{as } V_S \rightarrow \infty$$

Universal luminosity function

The Schechter function (Schechter 1976)

$\phi(L) = (\phi^*/L^*)\,(L/L^*)^{a}\,e^{-(L/L^*)}$ Luminosity domain

$\phi(M)dM = \phi(L)d(-L)$ $\quad M-M^* = -2.5\log(L/L^*)$

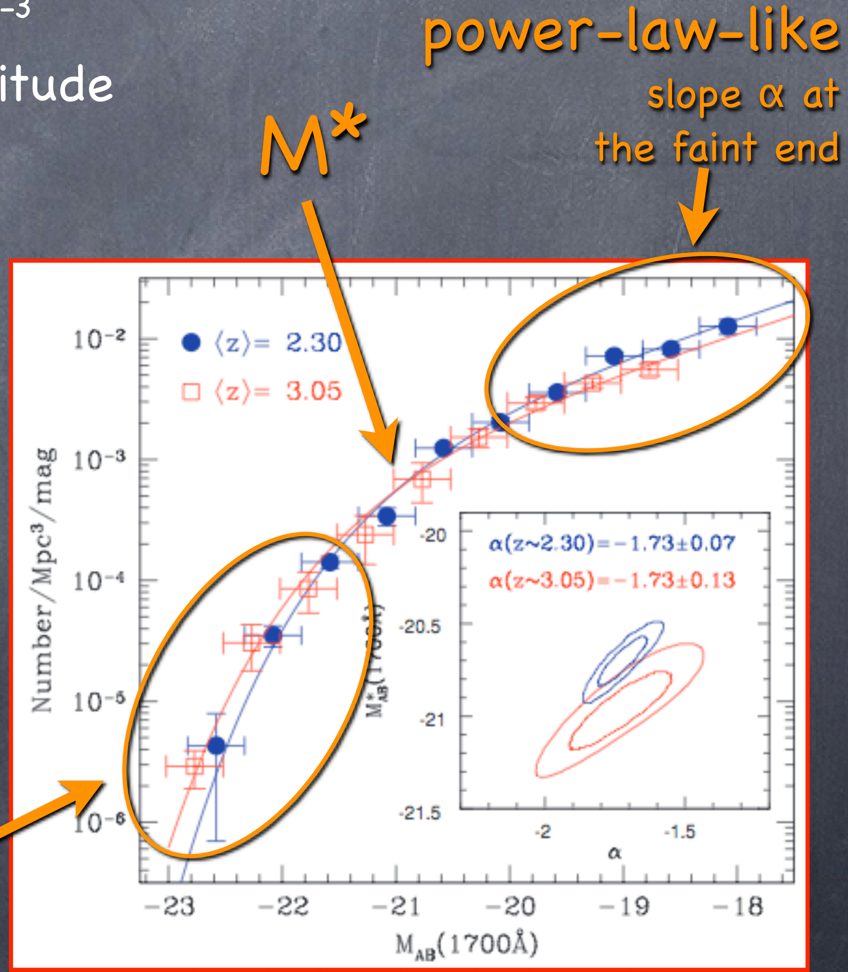
$\phi(M) = \phi^*(\ln(10)/2.5)\,10^{-0.4(M-M^*)(a+1)}\,e^{-10^{-0.4(M-M^*)}}$ Magnitude domain

- ϕ^* = normalization density h^{-3} Mpc^{-3}
- M^* = characteristic absolute magnitude
- a = faint-end slope

Example: UV LF at z≈3

Best-fit Schechter parameters (Reddy & Steidel 2009)

Redshift Range	α	M^*_{AB}(1700 Å)	ϕ^* ($\times 10^{-3}$ Mpc^{-3})
$1.9 \leqslant z < 2.7$	-1.73 ± 0.07	-20.70 ± 0.11	2.75 ± 0.54
$2.7 \leqslant z < 3.4$	-1.73 ± 0.13	-20.97 ± 0.14	1.71 ± 0.53



Reddy & Steidel (2009)

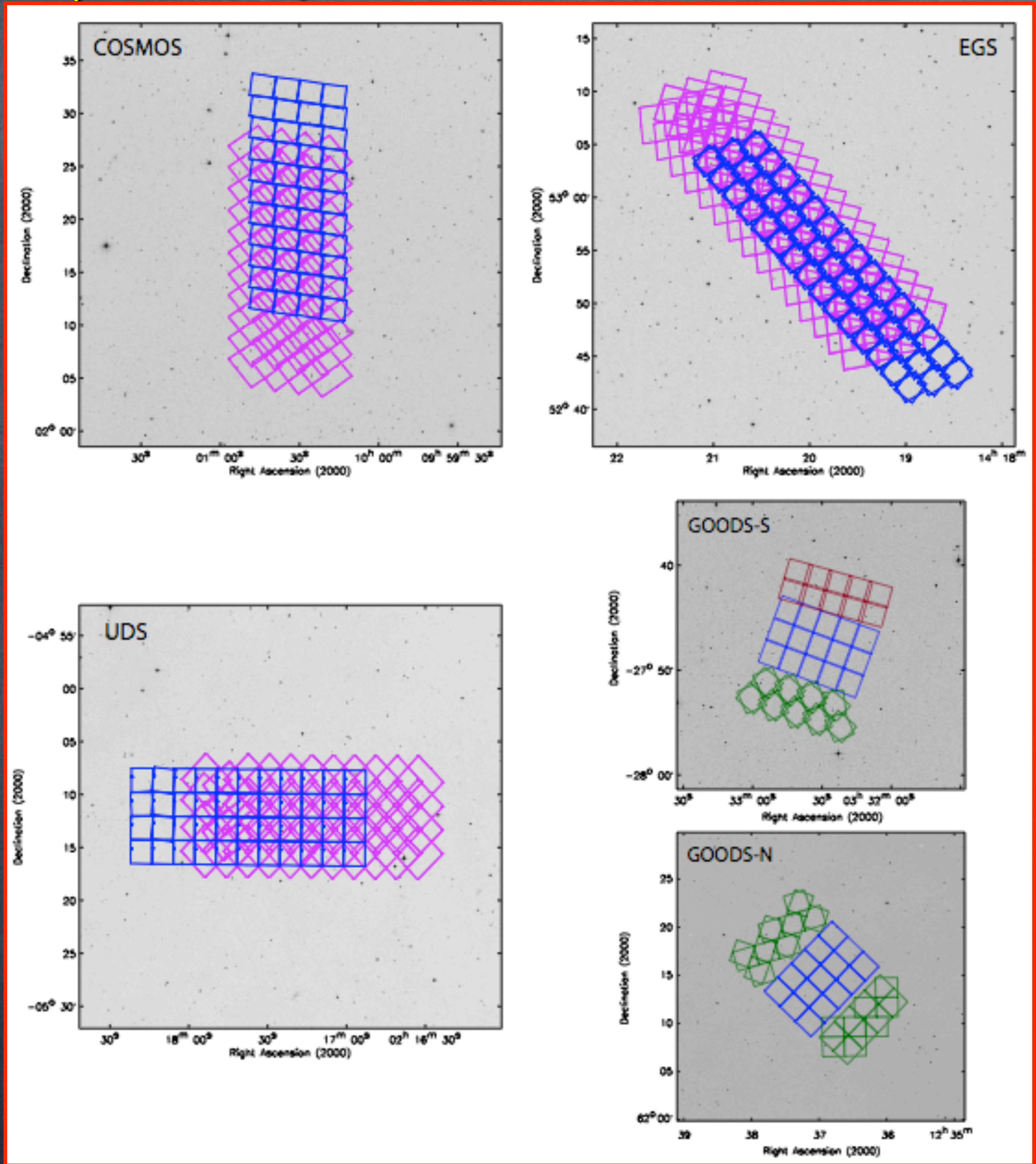
Probing LFs along cosmic time: need multi-frequency deep surveys

We want to probe faint and distant galaxies to z=10
- i.e., redshifted radiation + faint emission
  - this implies to access deeply near infrared bands

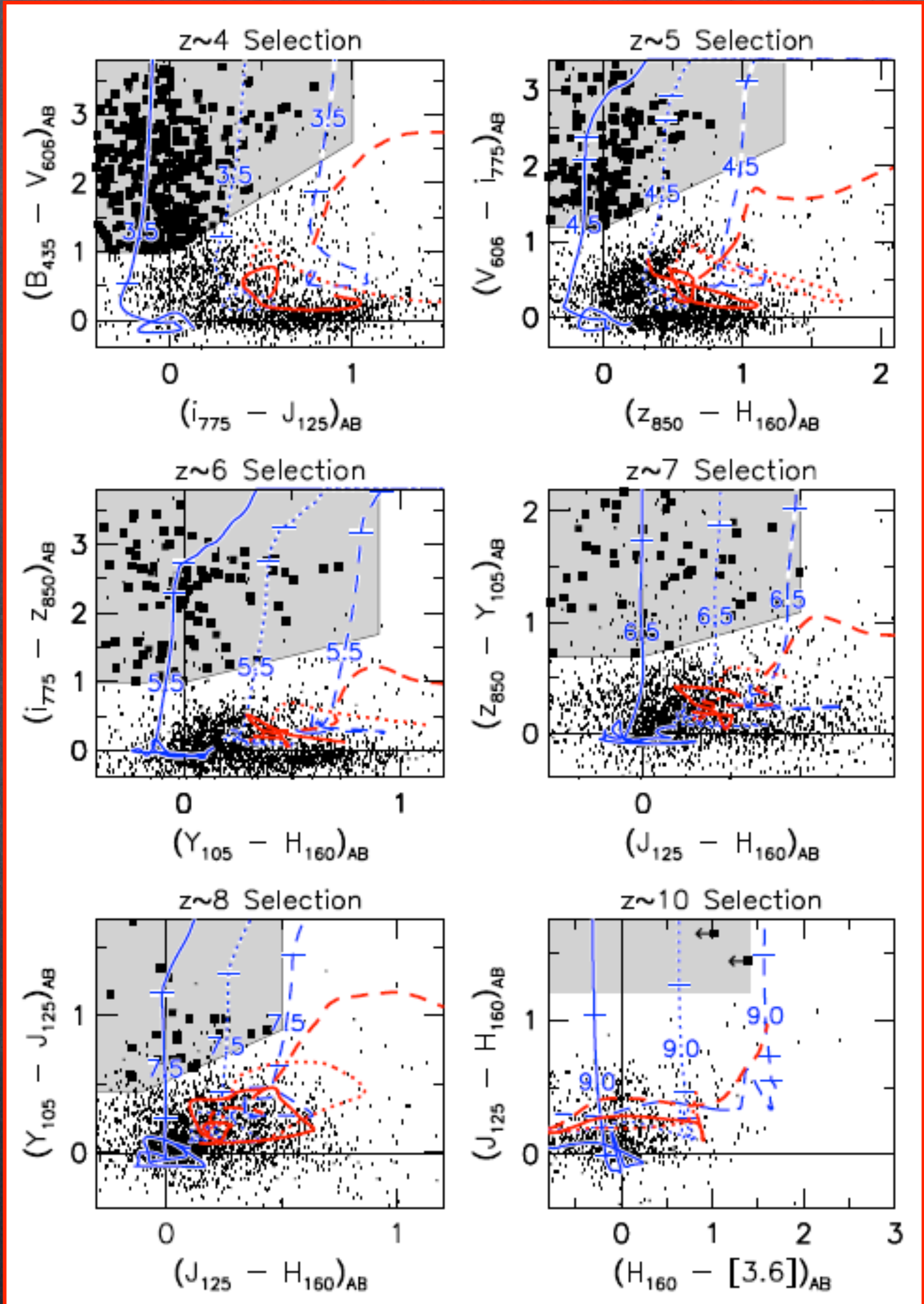
Wavelength coverage: access NIR (but also UV is important for re-ionization)

Access faint sources:
- Long integration time
- "Cosmic Telescopes" (lensing)
- Future facilities: increase collecting area and wavelength coverage (e.g., JWST, ELT) - see lecture #5

Deep surveys: GOODS+CANDELS (HST, Spitzer, Chandra, Herschel, Ground-based ...)



Giavalisco et al. (2004); Grogin et al. (2011)



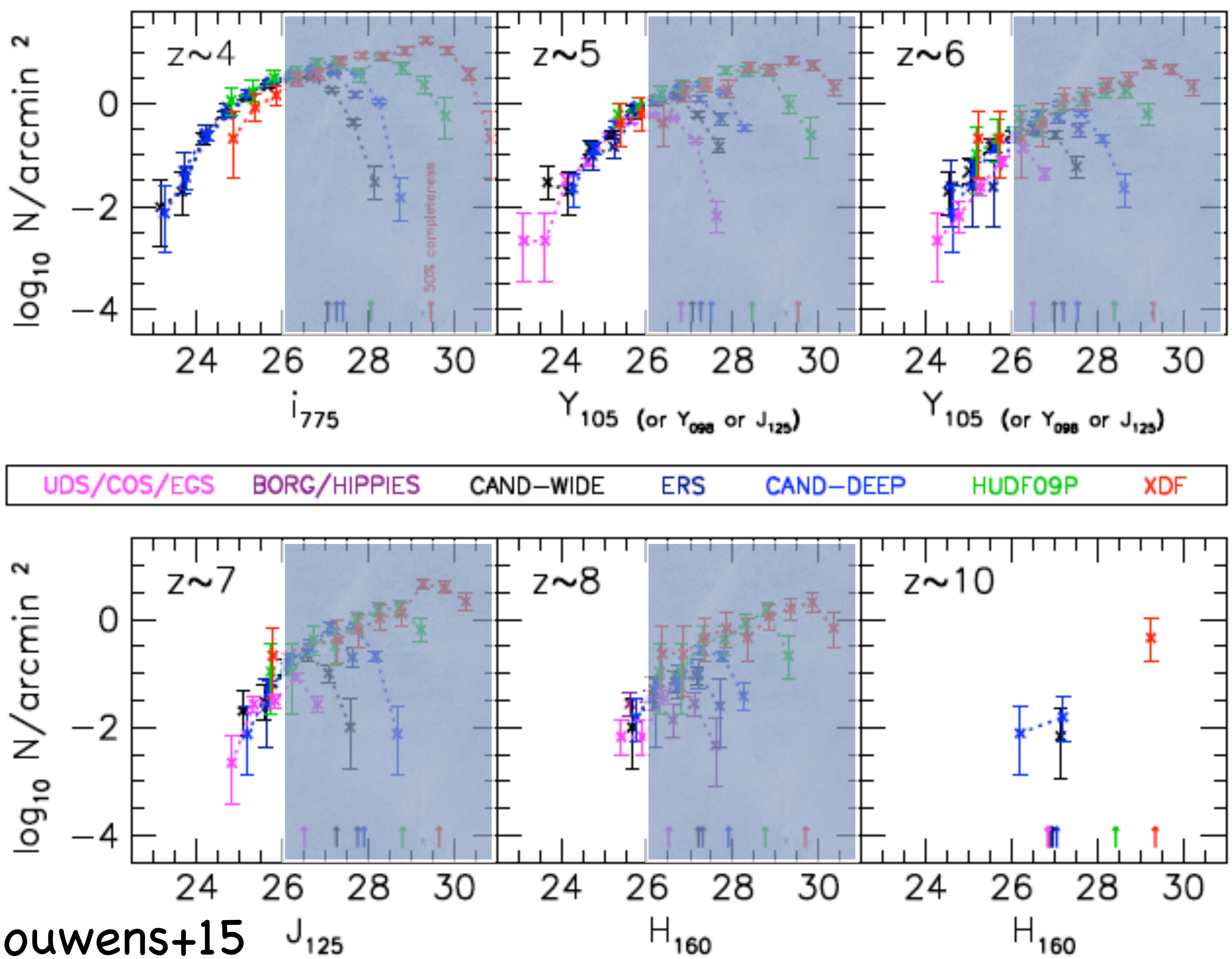
"Dropout technique" Color-color diagrams

Selectiong galaxies at redshift 4 to 10

1000 sq.armin

#n. gal.	
5859	z≈4
3001	z≈5
857	z≈6
481	z≈7
216	z≈8
6	z≈10

Surface densities of candidates z>3.5 galaxies



Bouwens+15

XDF 5mags (x100 times fainter) than M*(z=3) ≈ -20.8

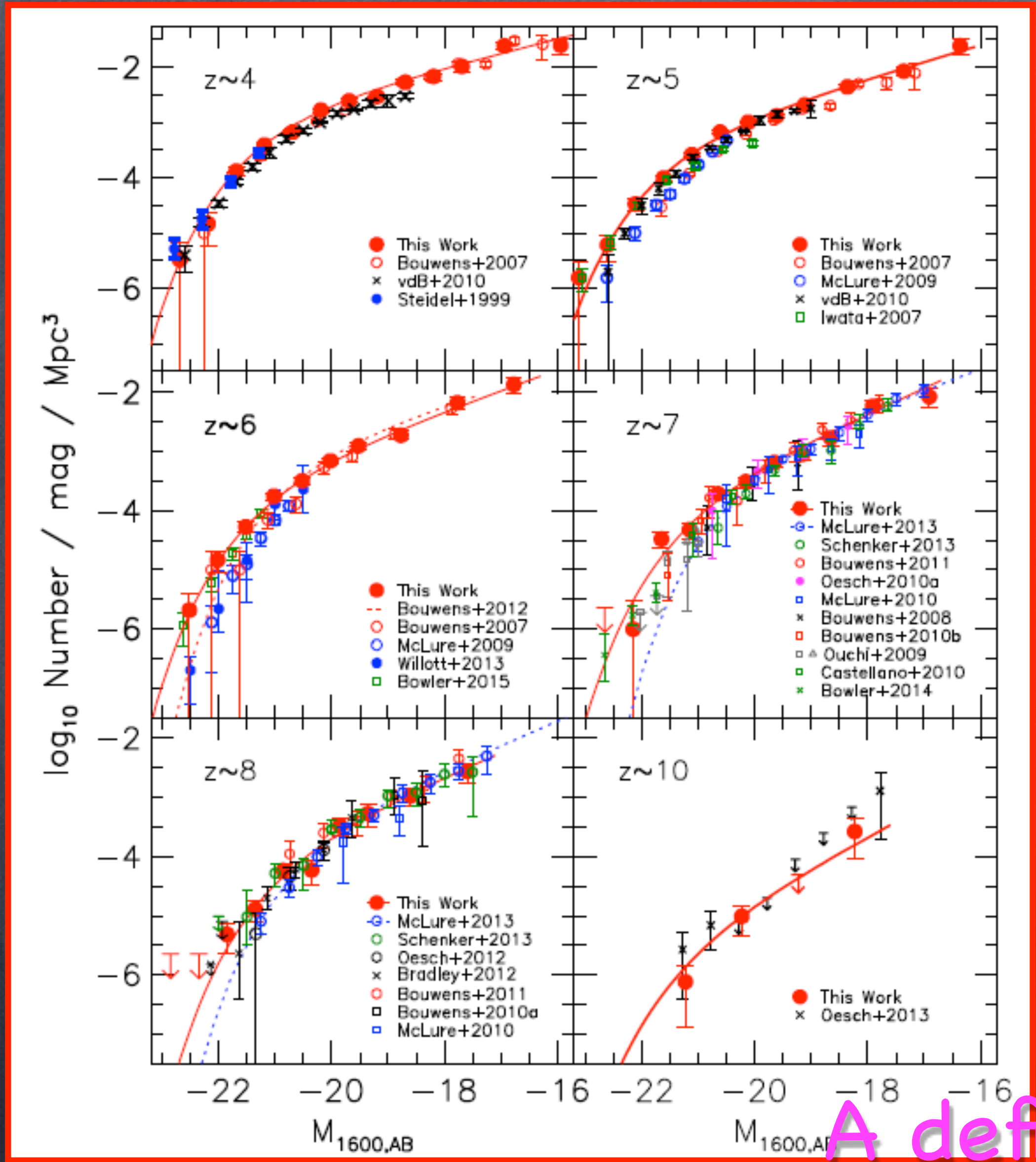
= 1000 sq.armin

cand.		zspec
5859	z≈4	300
3001	z≈5	200
857	z≈6	90
481	z≈7	7
216	z≈8	2
6	z≈10	0

Validating selection criteria at faint limits with spectroscopy: challenging (Finkelstein+14; Oesh+15; Zitrin+15)

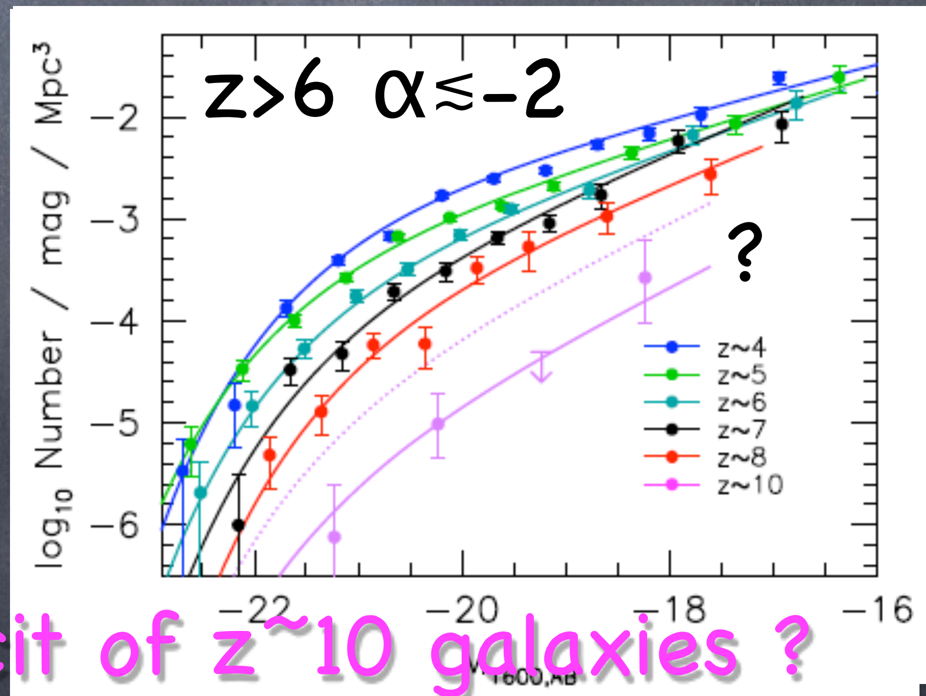
Luminosity functions at redshift 4<z<11   (0.5-1.8 Gyrs)

$$\phi(M) = \phi^*(\ln(10)/2.5)\, 10^{-0.4(M-M^*)(\alpha+1)}\, e^{-10^{-0.4(M-M^*)}}$$



Dropout Sample	<z>	M^*_{UV} [a]	ϕ^* (10^{-3} Mpc^{-3})	α
U	3.0	-20.97 ± 0.14	1.71 ± 0.53	-1.73 ± 0.13
B	3.8	-20.88 ± 0.08	$1.97^{+0.34}_{-0.29}$	-1.64 ± 0.04
V	4.9	-21.17 ± 0.12	$0.74^{+0.18}_{-0.14}$	-1.76 ± 0.05
i	5.9	-20.94 ± 0.20	$0.50^{+0.22}_{-0.16}$	-1.87 ± 0.10
z	6.8	-20.87 ± 0.26	$0.29^{+0.21}_{-0.12}$	-2.06 ± 0.13
Y	7.9	-20.63 ± 0.36	$0.21^{+0.23}_{-0.11}$	-2.02 ± 0.23
J	10.4	-20.92 (fixed)	$0.008^{+0.004}_{-0.003}$	-2.27 (fixed)

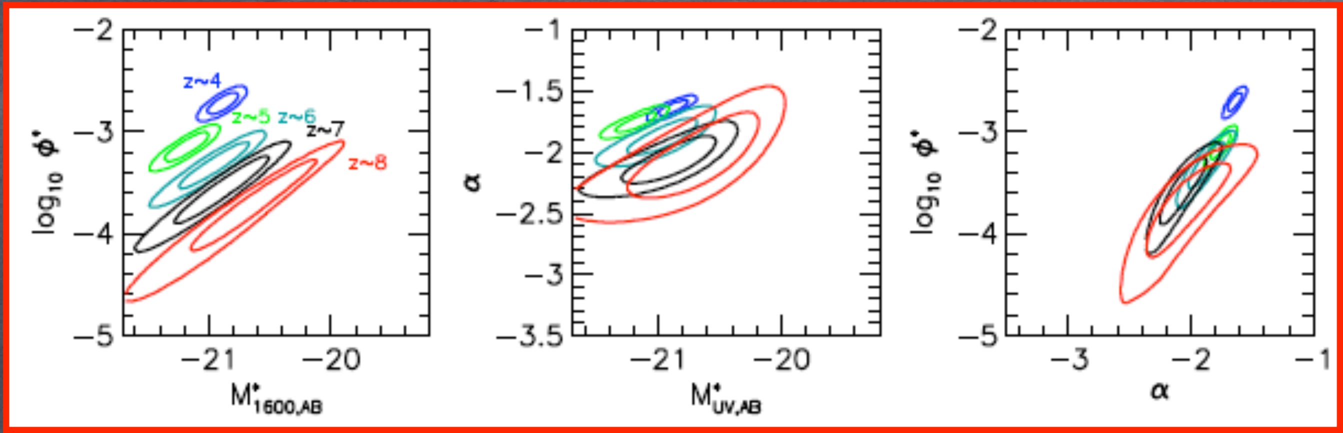
adapted from Bouwens+15



A deficit of z~10 galaxies ?

Bouwens+15 (see also Finkelstein+15)

Luminosity functions at redshift 4<z<11 (0.5-1.8 Gyrs)



		M^*_{UV} [a]	ϕ^* (10^{-3} Mpc^{-3})	α
		-20.97 ± 0.14	1.71 ± 0.53	-1.73 ± 0.13
		-20.88 ± 0.08	$1.97^{+0.34}_{-0.29}$	-1.64 ± 0.04
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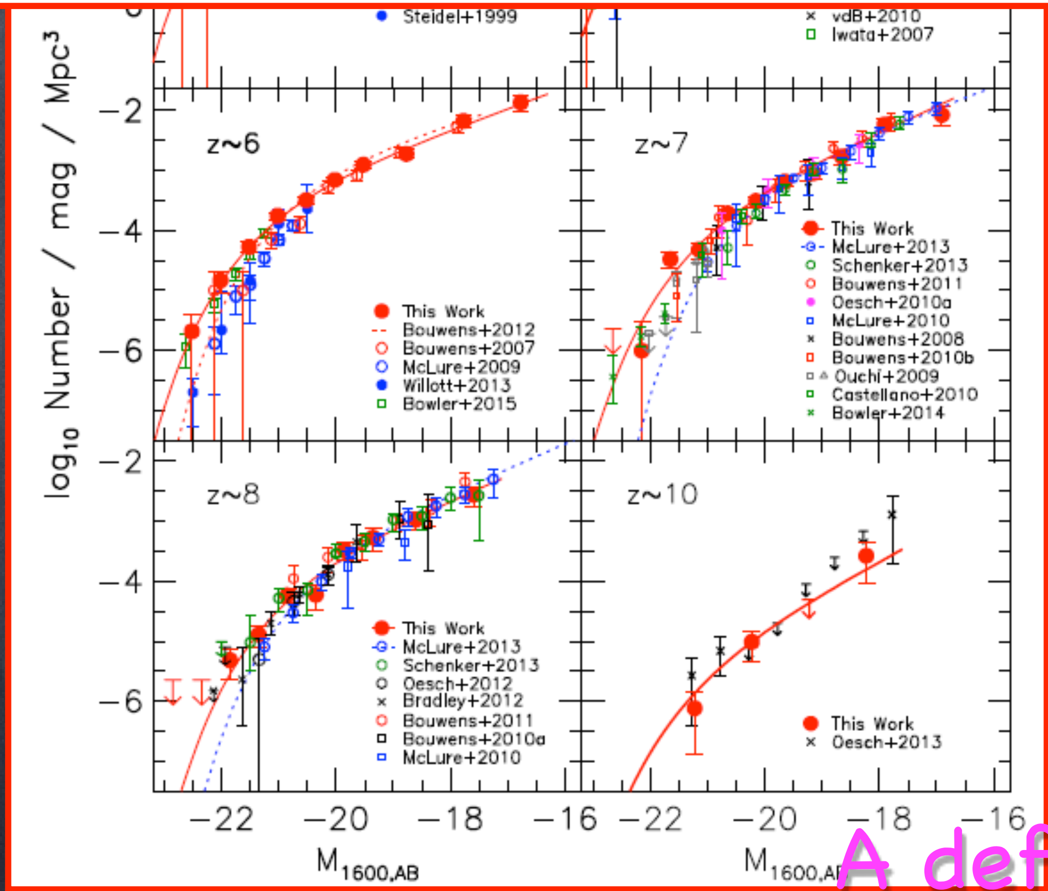
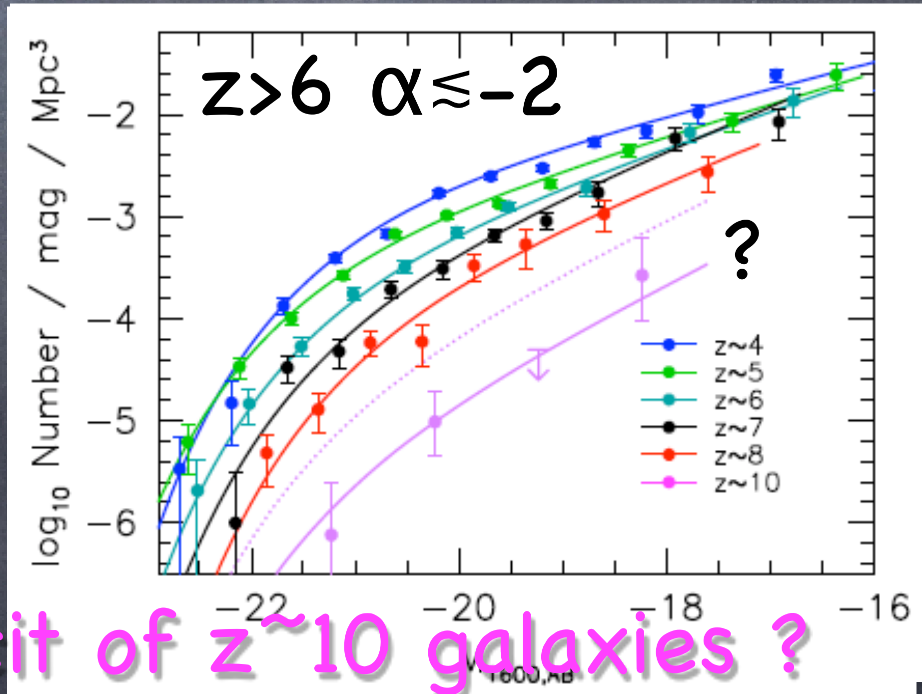
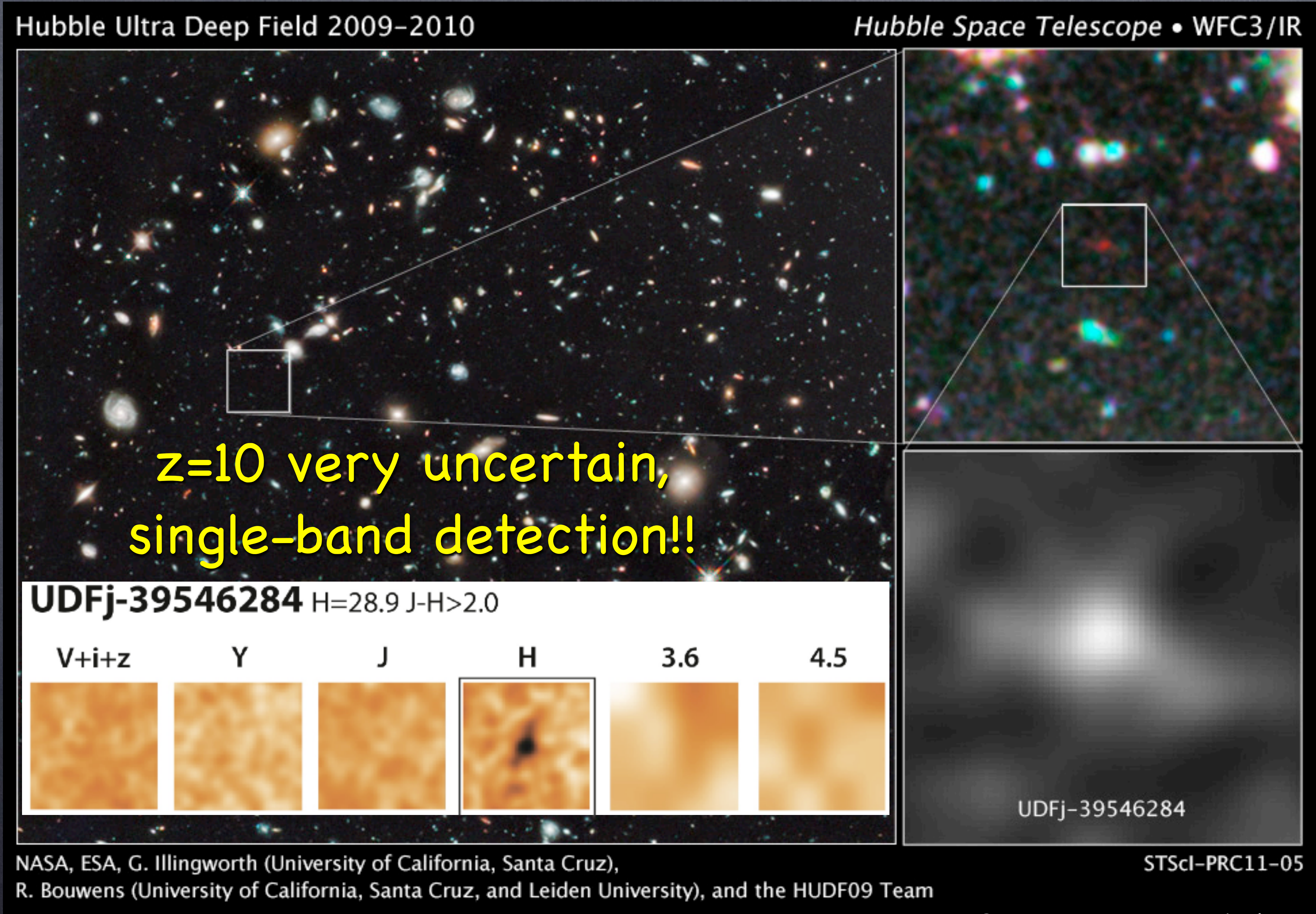




A deficit of z~10 galaxies ?

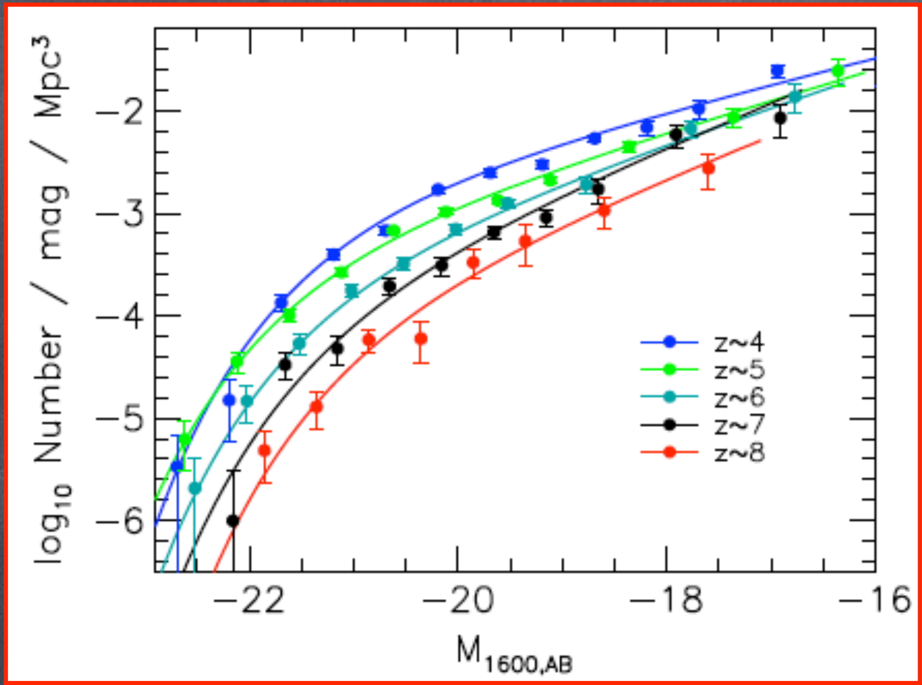
Bouwens+15 (see also Finkelstein+15)

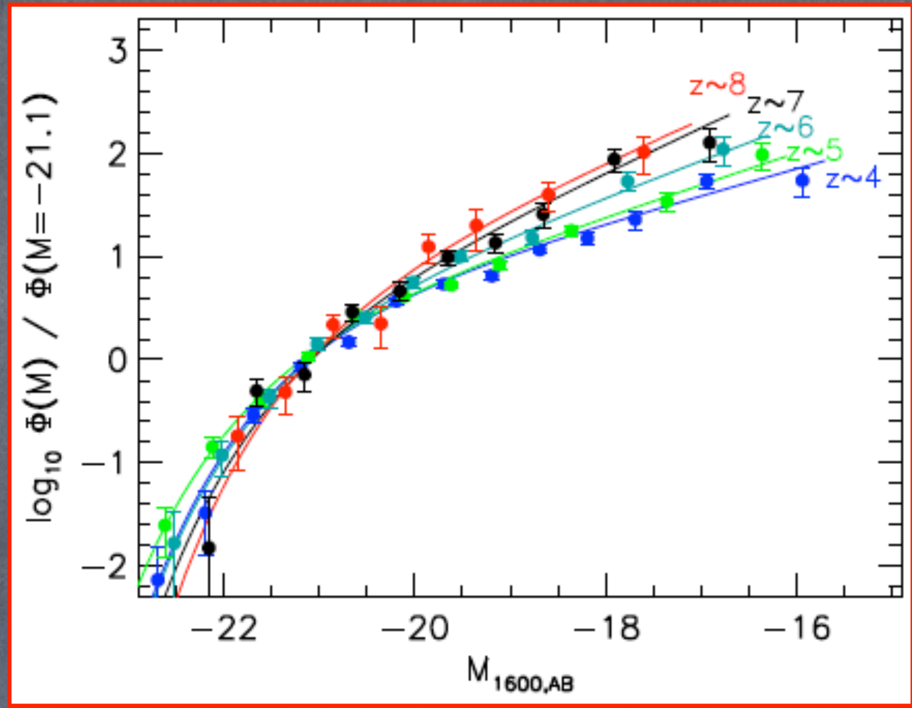
A z=10 galaxy (candidate) - challenging

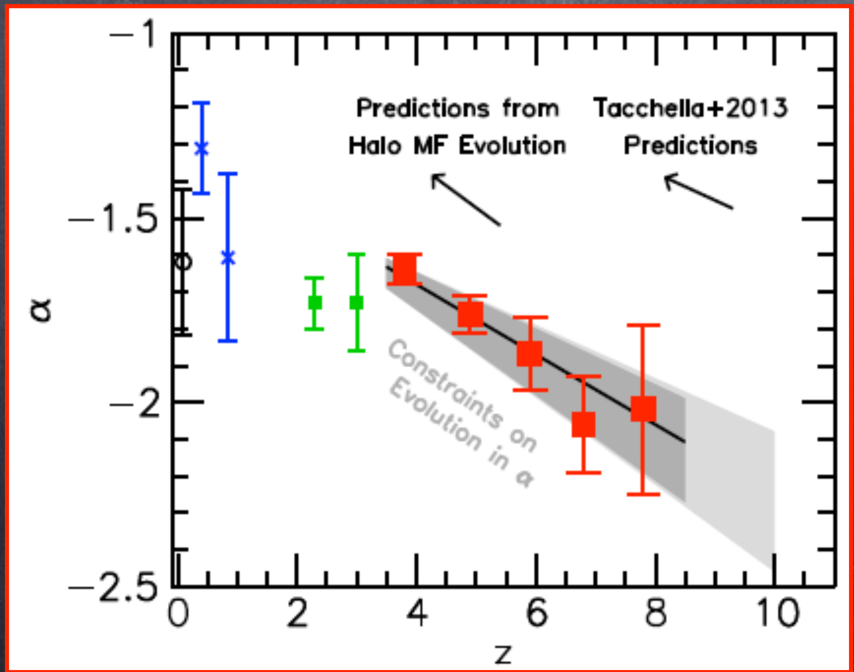


Bouwens+11, Nature

Evolution of the faint-end slope α







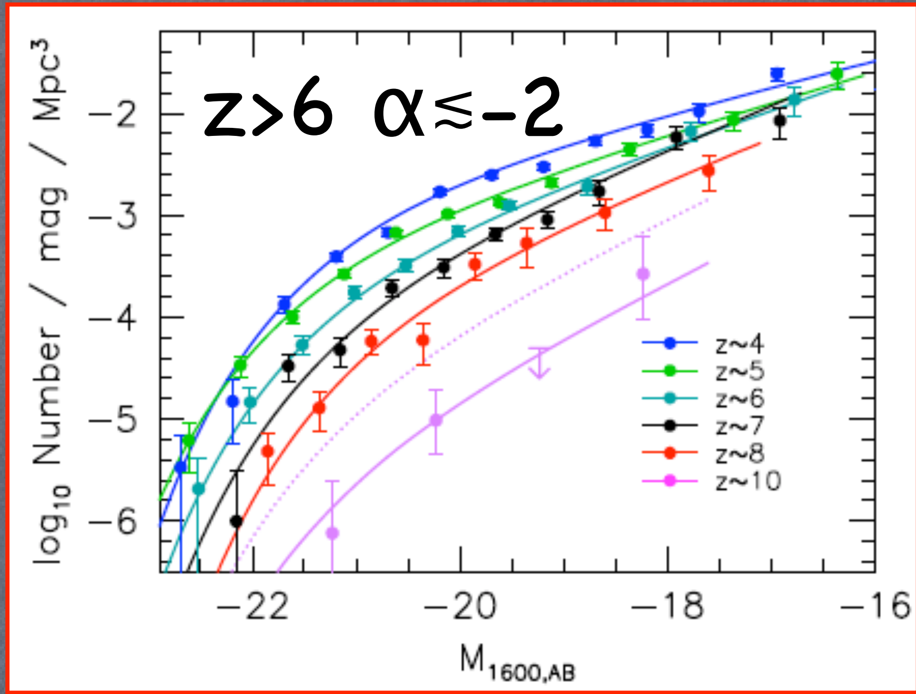
$d\alpha/dz = -0.10 \pm 0.02$

Steepening of faint-end slope of the LFs with redshift: this means the number of faint galaxies is very large

=> relevant for reionization

The cosmic ultraviolet luminosity density

Bouwens+15



$$\rho_{1500} = \int_{L_{min}}^{\infty} L\,\phi(L)\,dL$$

$$= L^* \phi^* \Gamma(2+a, L_{min}/L^*)$$

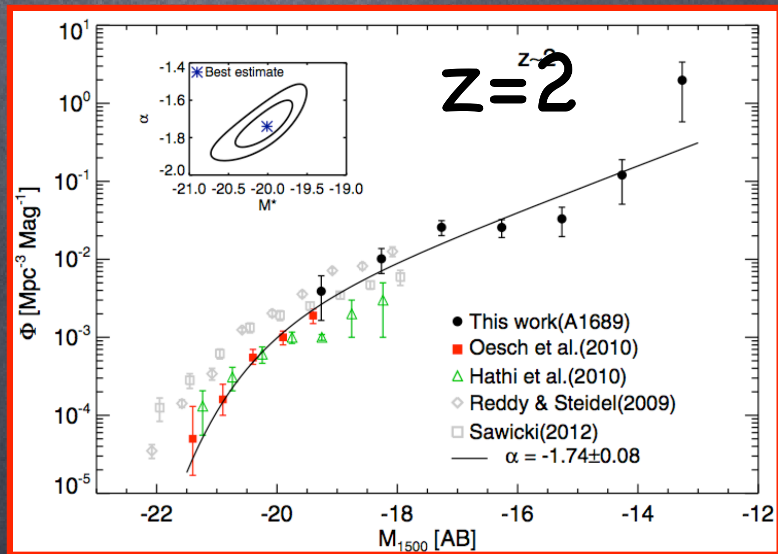
Γ Incomplete gamma function

integral diverge if alpha ≦ -2 and Lmin=0

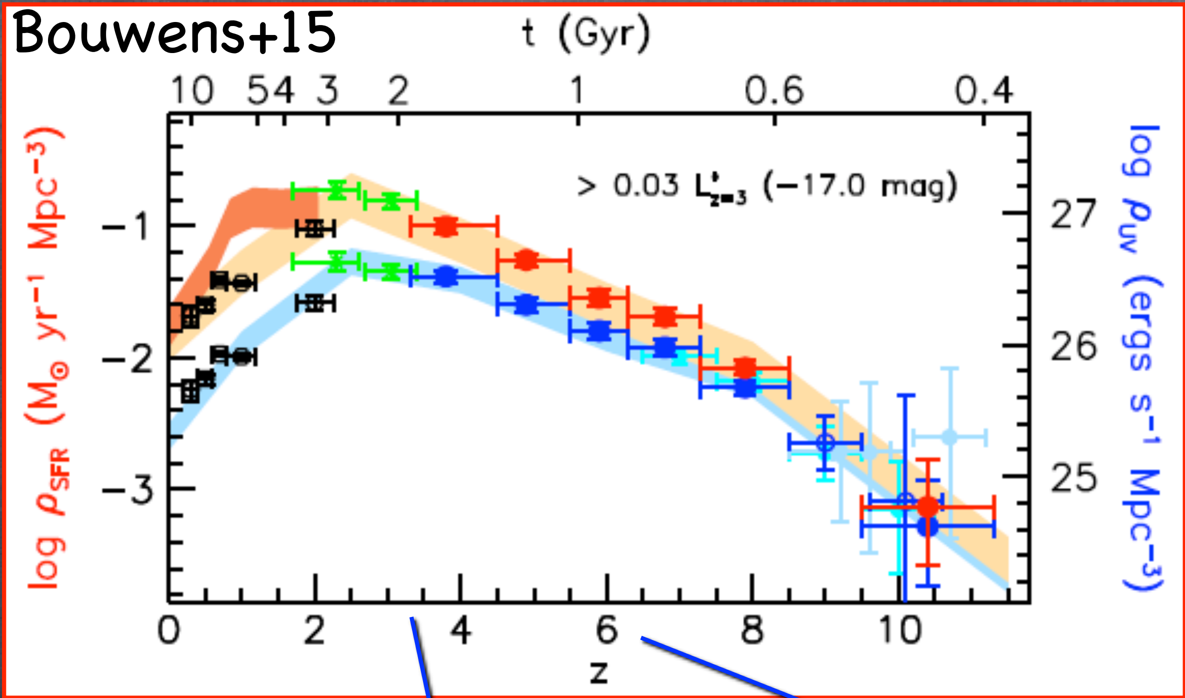
Lmin

Trenti et al. (2010): a DM halo with mass > 0.6-1.8 x $10^8 M_\odot$ is required to cool and form stars (when irradiated by a UV field as during the EoR), this corresponds to a minimum Muv=-10

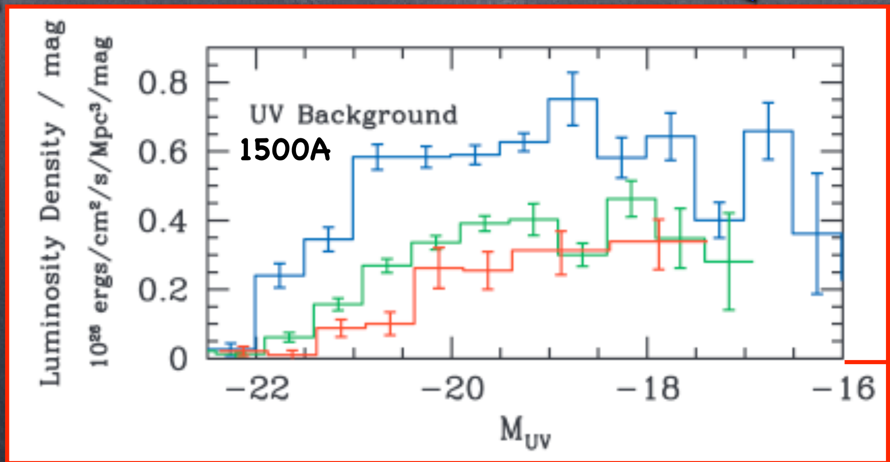
Alavi+14 (observations)



Luminosity density at 1500A, ρ_{1500}



The following step is to relate to $\rho_{1500} \rightarrow \rho_{<912A}$

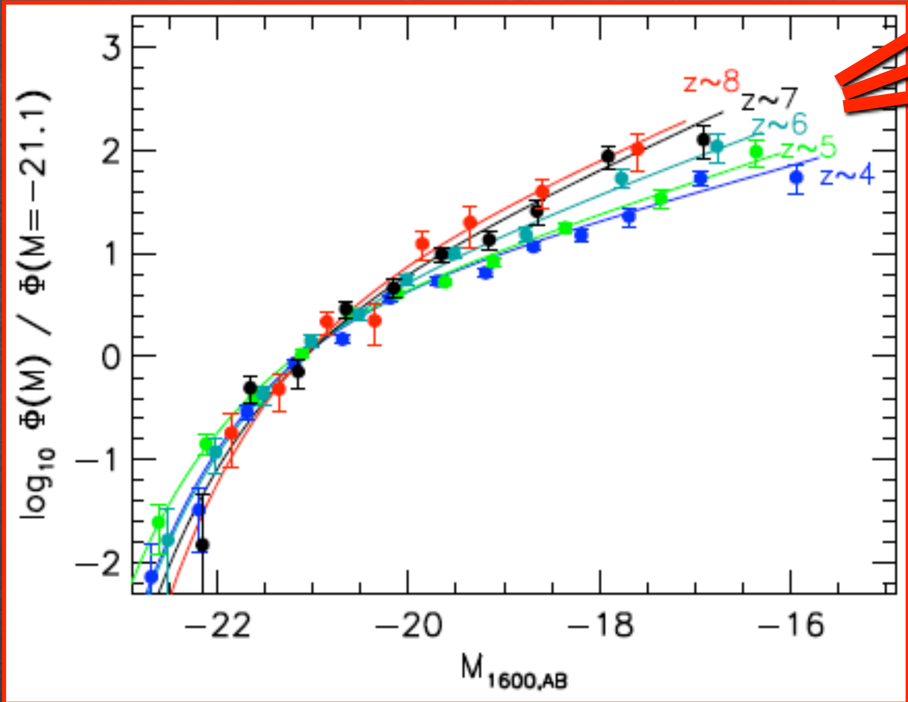


Faint, high-redshift dwarf galaxies are therefore widely postulated as likely candidates for making up the ionizing photon budjet

-14 -12 -10
Muv

We need reliable constraints at the deepest lum. limits

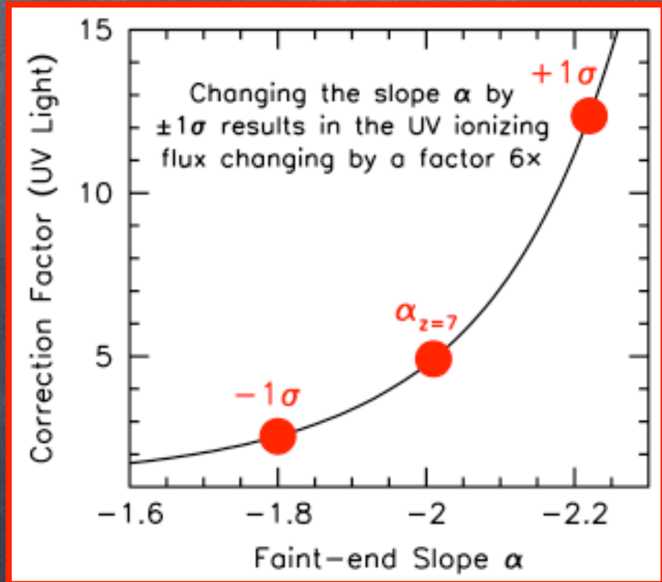
$$\phi(M_{1400}) \xrightarrow[\text{assume } M_{\rm lim}]{\text{integrate;}} \rho_{L_{1400}} \xrightarrow[\langle N_{\gamma<912}/N_{\gamma 1400}\rangle]{} \dot{N}^{int}_{ion} \xrightarrow[f_{esc,rel}]{} \dot{N}_{ion}$$



?

Faint contribution have to extrapolate to below detection limits

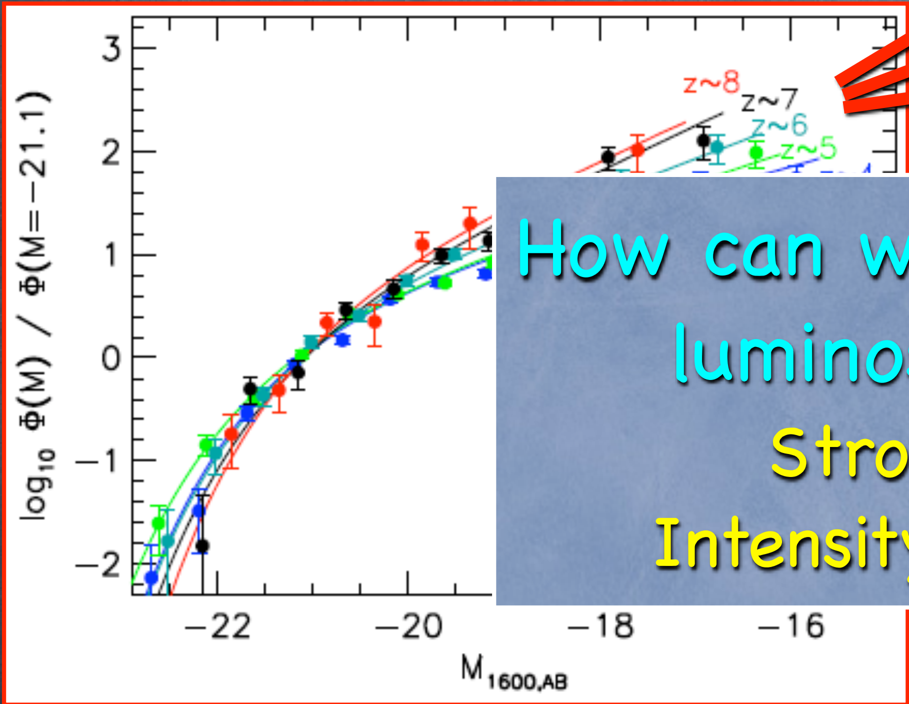
With the faint-end slopes as observed (field): luminosity density completely dominated by faint galaxies



Bouwens+12

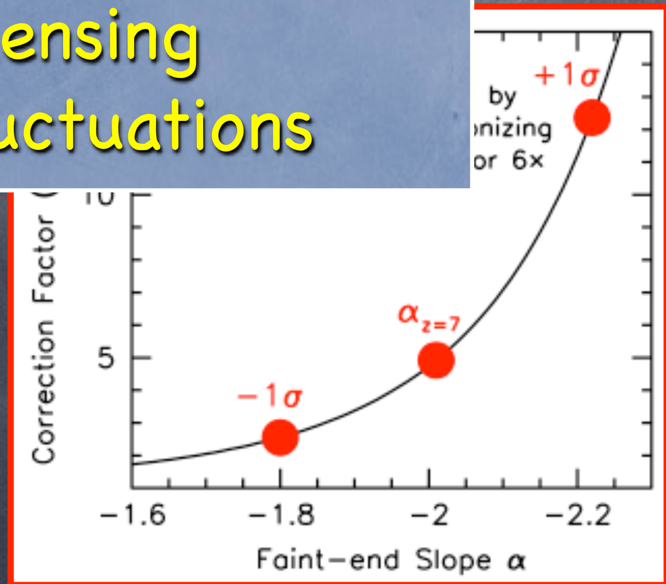
We need reliable constraints at the deepest lum. limits

$$\phi(M_{1400}) \xrightarrow[\text{integrate; assume } M_{\rm lim}]{} \rho_{L_{1400}} \xrightarrow[\langle N_{\gamma<912}/N_{\gamma 1400}\rangle]{} \dot{N}_{ion}^{int} \xrightarrow[f_{esc,rel}]{} \dot{N}_{ion}$$



? Faint contribution have to extrapolate to below detection limits

...lopes as observed
...ensity completely
...alaxies



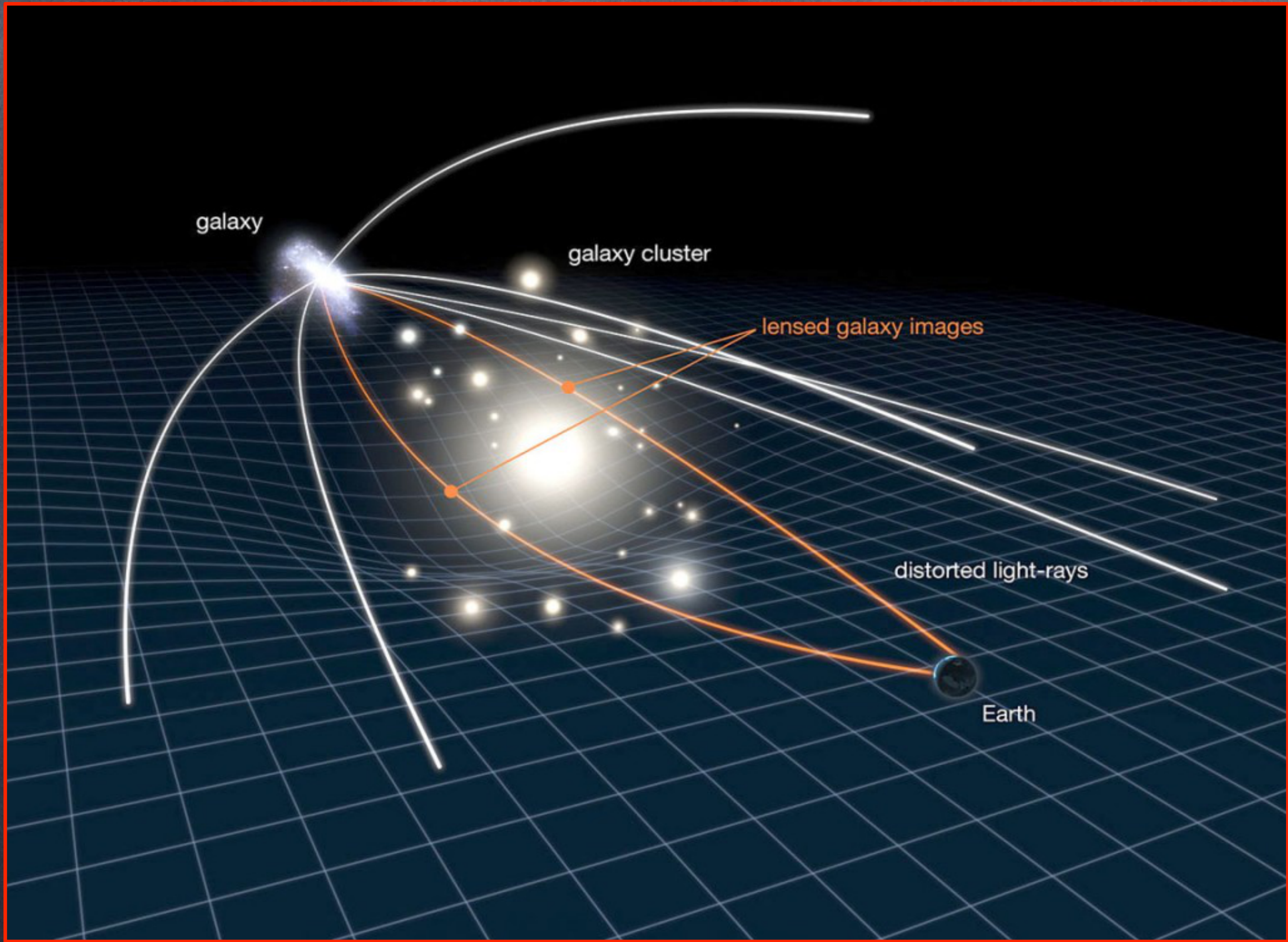
How can we probe fainter luminosity limits ?

Strong lensing

Intensity fluctuations

Bouwens+12

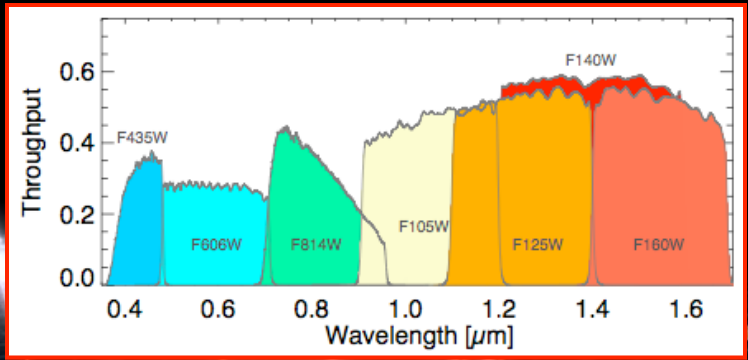
Exploiting "Cosmic Telescopes" : strong lensing magnification



Hubble Frontier Fields
(P.I. Mountain, Loz)
initiative, 140 orbits
cluster/blank fields
m≈28.7-29 5-sigma
+ magnification

CLASH: 500 HST orbits
(P.I Postman, M.)
25 galaxy clusters
m~27.5 5-sigma
(16-band filters)
+ magnification

Exploiting "Cosmic Telescopes" : strong lensing magnification

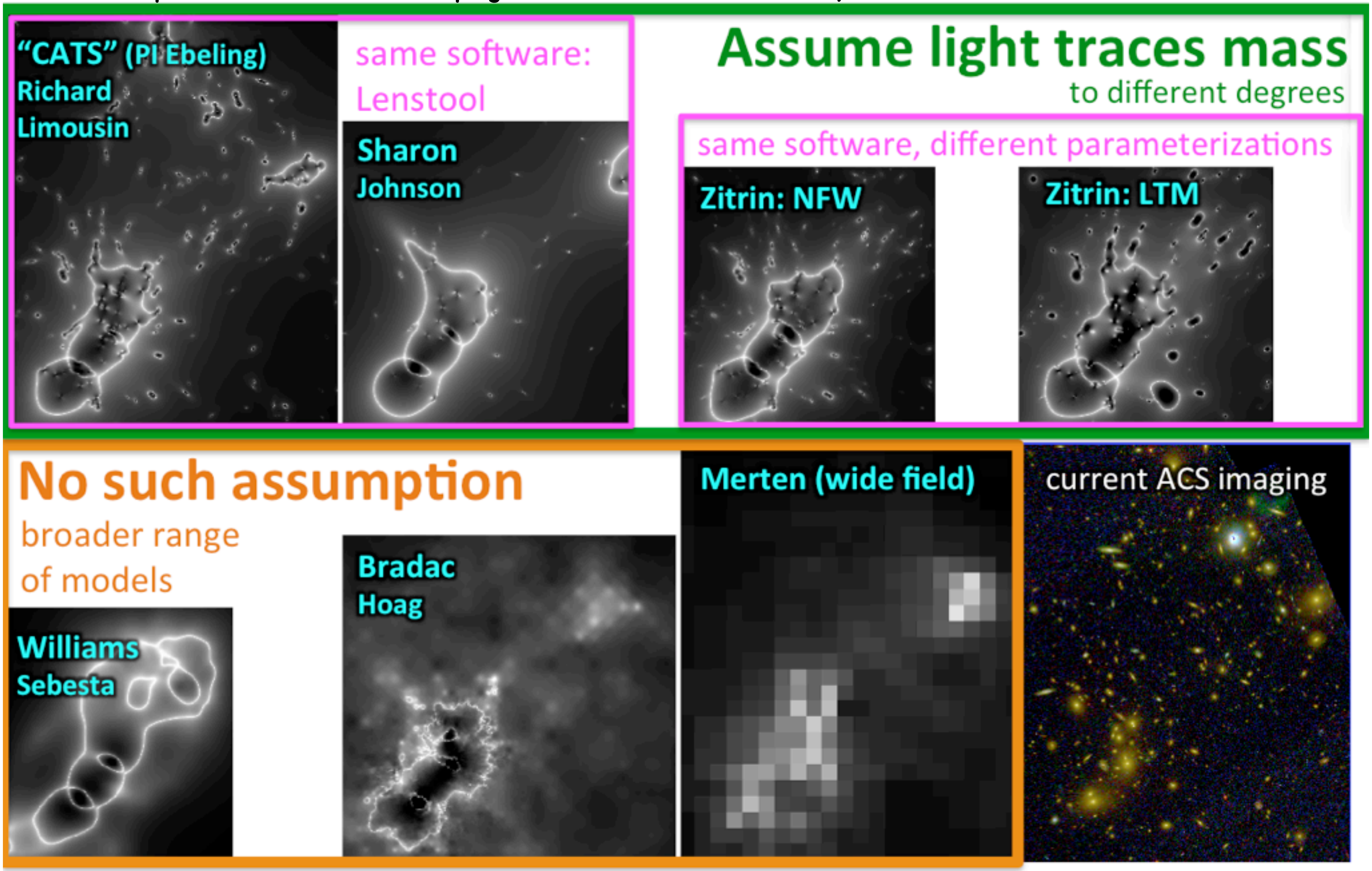


ACS: (70 orbits per position)			WFC3/IR: (70 orbits per position)		
Filter	Orbits	AB_mag	Filter	Orbits	AB_mag
F435W	18	28.8	F105W	24	28.9
F606W	10	28.8	F125W	12	28.6
F814W	42	29.1	F140W	10	28.6
			F160W	24	28.7

Magnification maps

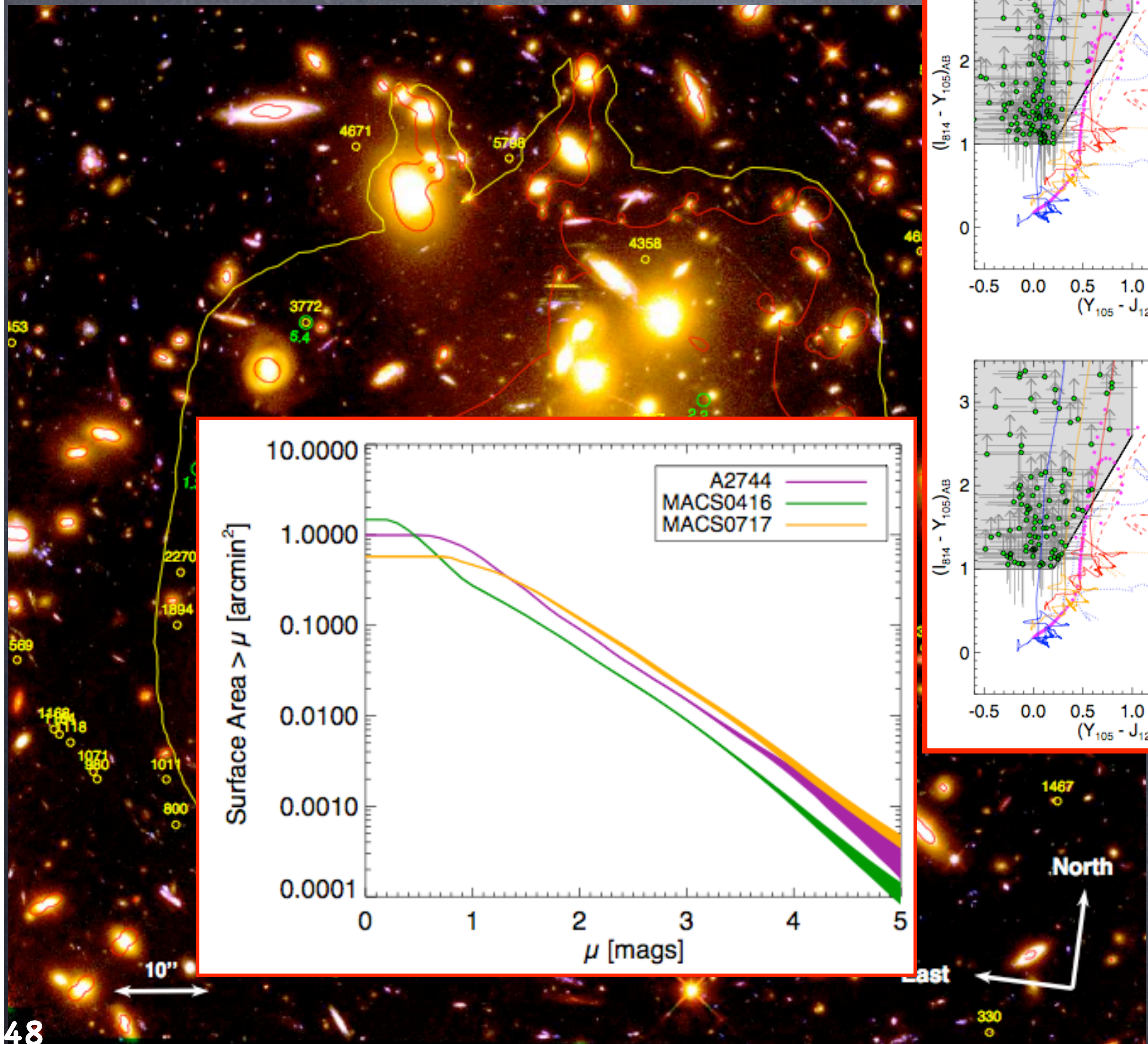
http://www.stsci.edu/hst/campaigns/frontier-fields/HST-Survey

for a lensed source at z = 9

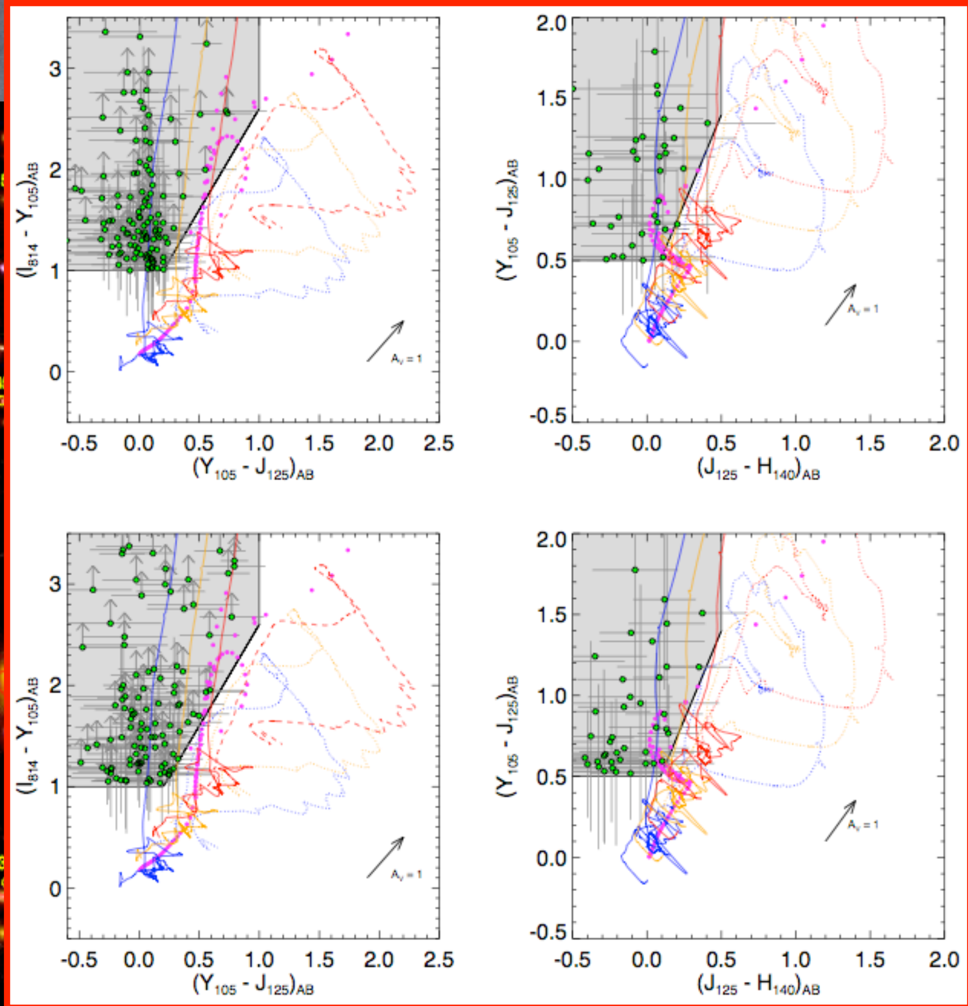


Using Strong lensing to probe the faintest ultraviolet luminosity limits

(based on Frontier Fields project)

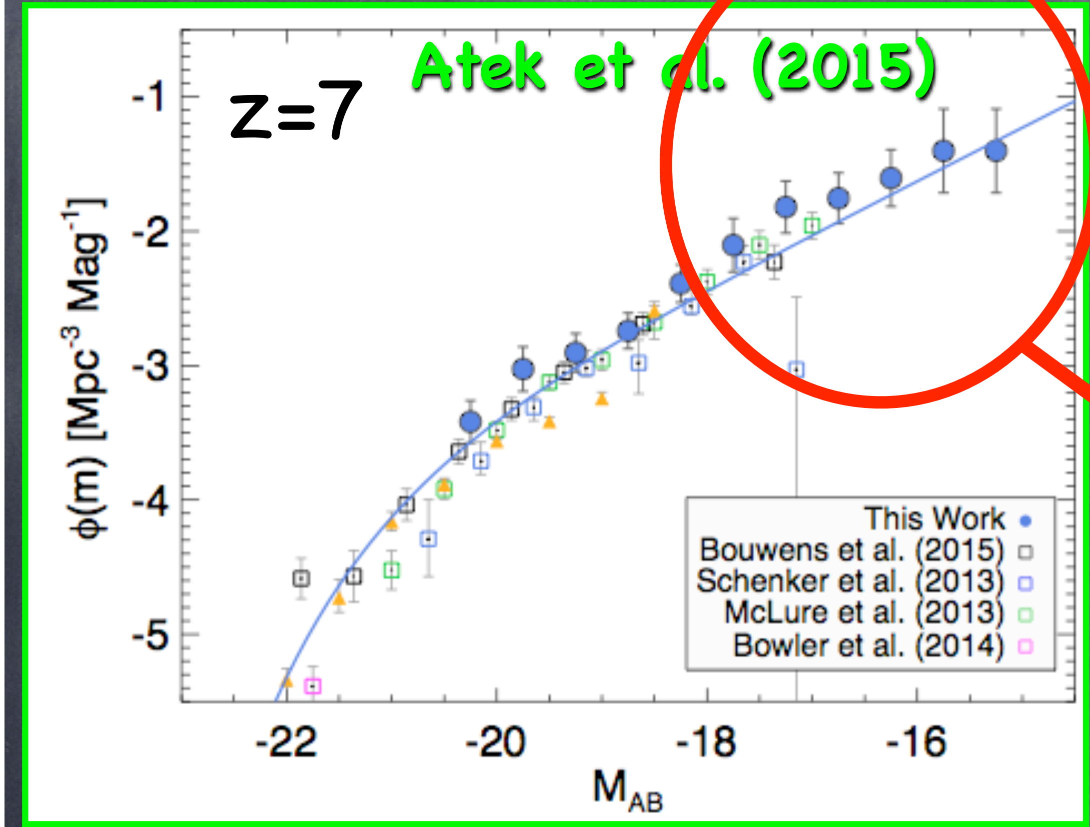


Color-selections



Very similar to field studies, but we gain in magnitude (Atek+15)

Ultraviolet luminosity functions at z 7 and 8 from Frontier Fields project ("Cosmic Telescopes") probes fainter limits

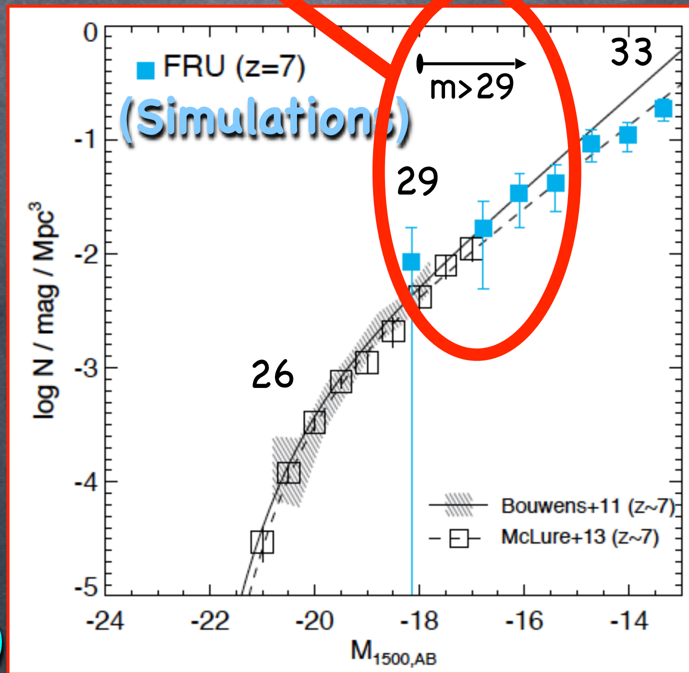


Comparison of the best fit $z \sim 7$ Schechter parameters

Reference	$M^\star_{UV}$ [AB mag]	α	$\log_{10} \phi^\star$ [Mpc^{-3}]
This work	$-20.89^{+0.60}_{-0.72}$	$-2.04^{+0.17}_{-0.13}$	$-3.54^{+0.4[illegible]}_{-0.45}$
Atek et al. (2015) [a]	$-20.90^{+[illegible]}_{-0.73}$	$-2.01^{+[illegible]}_{-0.28}$	$-3.55^{+0.57}_{-0.57}$
Ishigaki et al. (2015a) [a]	$-20.45^{+0.1}_{-0.2}$	$-1.94^{+0.09}_{-0.10}$	$-3.30^{+0.10}_{-0.20}$
Bouwens et al. (2015b)	-21.04 ± 0.26	-2.06 ± 0.12	$-3.65^{+[illegible]}_{-[illegible]}$
Finkelstein et al. (2014)	$-21.03^{+0.37}_{-0.50}$	$-2.03^{+0.21}_{-0.20}$	$-3.80^{+0.41}_{-0.26}$

are we detecting reionizing sources ?

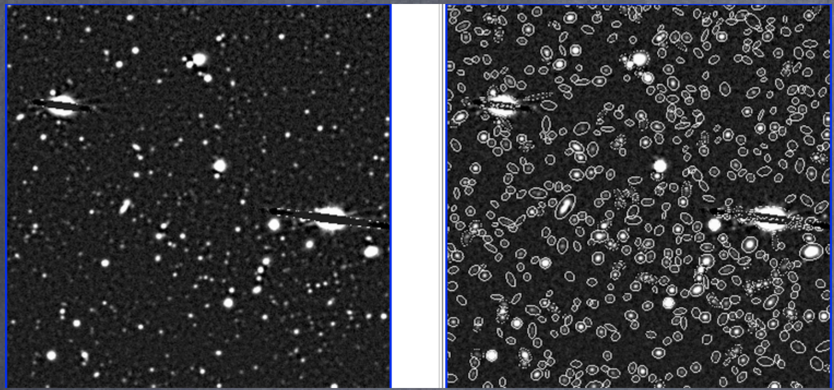
Possibly just starting...



Kimm & Cen (2014)

Intensity of the UV fluctuation of the background

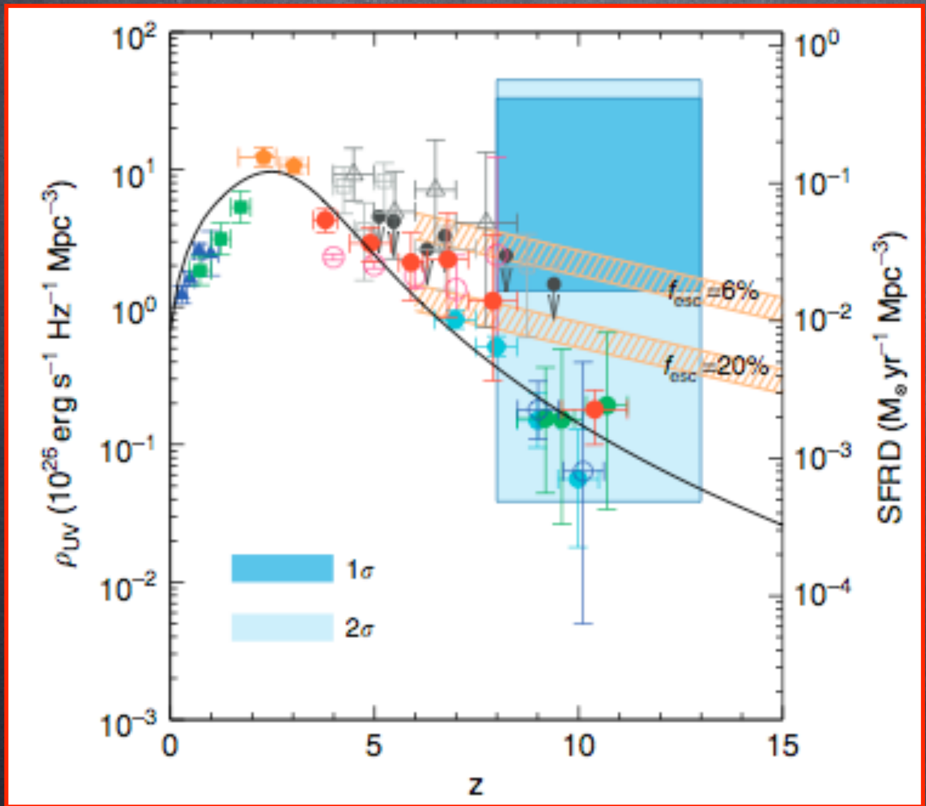
Based on the strength of the drop-out signature
in the fluctuations measured in different bands



Redshift ~ 6

From HUDF: i775 and z850 -> Fourier space -> P(K)

e.g., Calvi et al. (2013) derive α=-1.9 at z=6, 2.5 mags fainter than HUDF depth (m~29)



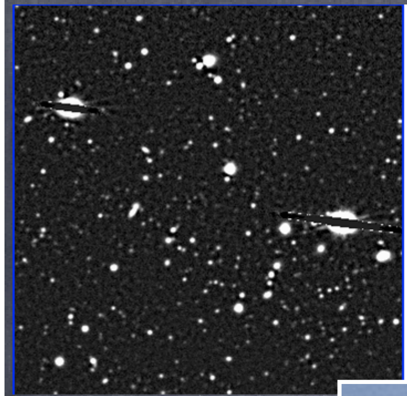
8 < redshift < 15

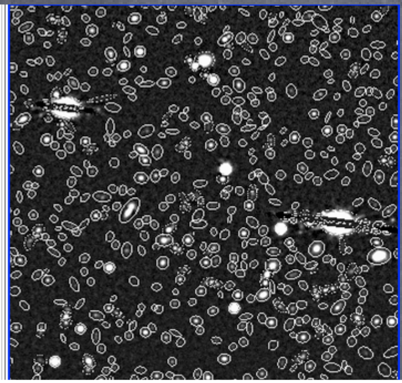
Mitchell-Wynne et al. (2015), Nature
GOODS+CANDELS

Cross and Auto-corr in the Fourier space,
V, i, z, J and H bands.
At 8<z<15, the signal is present in
J and H, it disappears in the optical:
Ly-break is probed down to faint limits,
possibly contribution of sources fainter
than Muv = -16

Intensity of the UV fluctuation of the background

Based on the strength of the drop-out signature
in the fluctuations measured in different bands





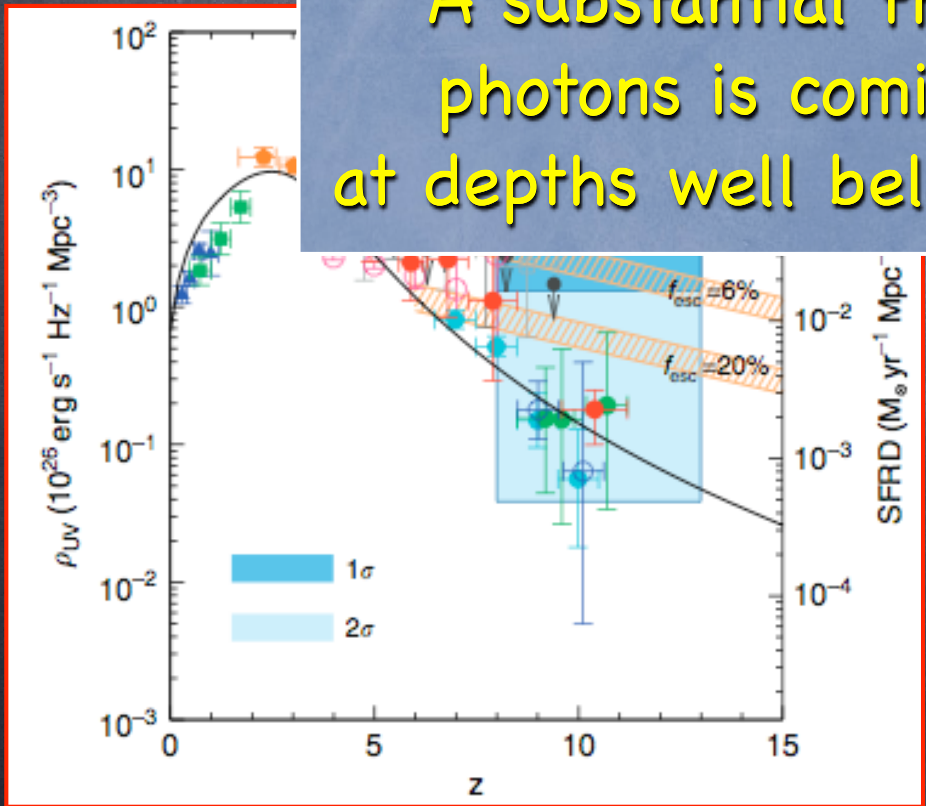
Redshift ~ 6

From HUDF: i775 and z850 -> Fourier space -> P(K)

e.g., Calvi et al. (2013) derive $\alpha=-1.9$ at $z=6$, 2.5 mags fainter than HUDF depth (m~29)

A substantial fraction of the ultraviolet photons is coming from fainter sources at depths well below the detection threshold

Nature



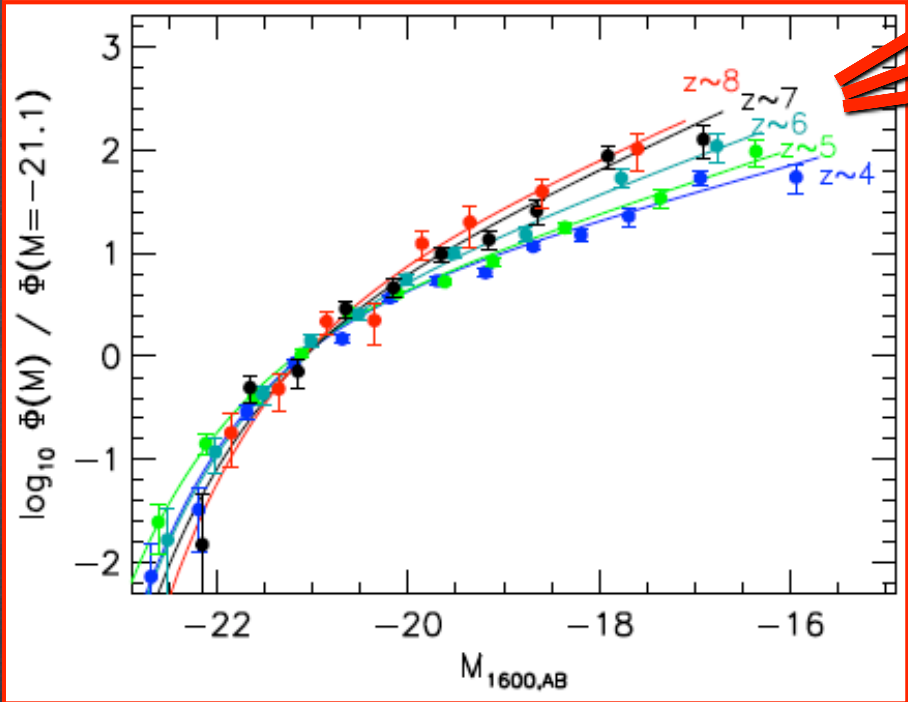
Cross and Auto-corr in the Fourier space, V, i, z, J and H bands.
At 8<z<15, the signal is present in J and H, it disappears in the optical: Ly-break is probed down to faint limits, possibly contribution of sources fainter than Muv = -16

... there are "a lot" of SF galaxies, are they sufficient ??

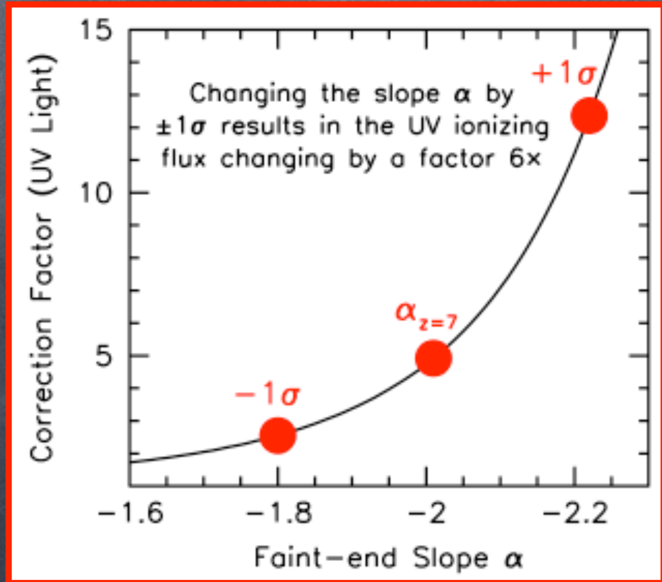
$$\phi(M_{1400}) \xrightarrow[\text{integrate; assume } M_{\mathrm{lim}}]{} \rho_{L_{1400}} \xrightarrow[\langle N_{\gamma<912}/N_{\gamma 1400}\rangle]{} \dot{N}^{int}_{ion} \xrightarrow[f_{esc,rel}]{} \dot{N}_{ion}$$

Lesson #3

?



With the faint-end slopes as observed (field): luminosity density completely dominated by faint galaxies



Bouwens+12

Summary

- The Universe is highly ionized at z<6, $\tau_{eff(IGM)}$ (LAF)
- At z>6 we are approaching the reionization epoch, GP trough
- The search for distant galaxies, "dropout" efficient method
- Ultraviolet luminosity functions of galaxies have been calculated, 0<z<10 and down to Muv ~ -16

➡ Steep faint-end slope, α<-2 at z>6:
faint galaxies dominate UV lum. density, 1500A

➡ Are they dominating also the ionizing emission <912A ?? (re)ionization