GRAVITATIONAL LENSING AND HIGH REDSHIFT GALAXIES

LECTURE II - HIGH-REDSHIFT GALAXIES AND REIONIZATION (THROUGH GRAVITATIONAL LENSES)

Adi Zitrin

FIRST LIGHT: STARS, GALAXIES AND BLACK HOLES IN THE EPOCH OF REIONIZATION
Advanced School, São Paulo

Aug 01

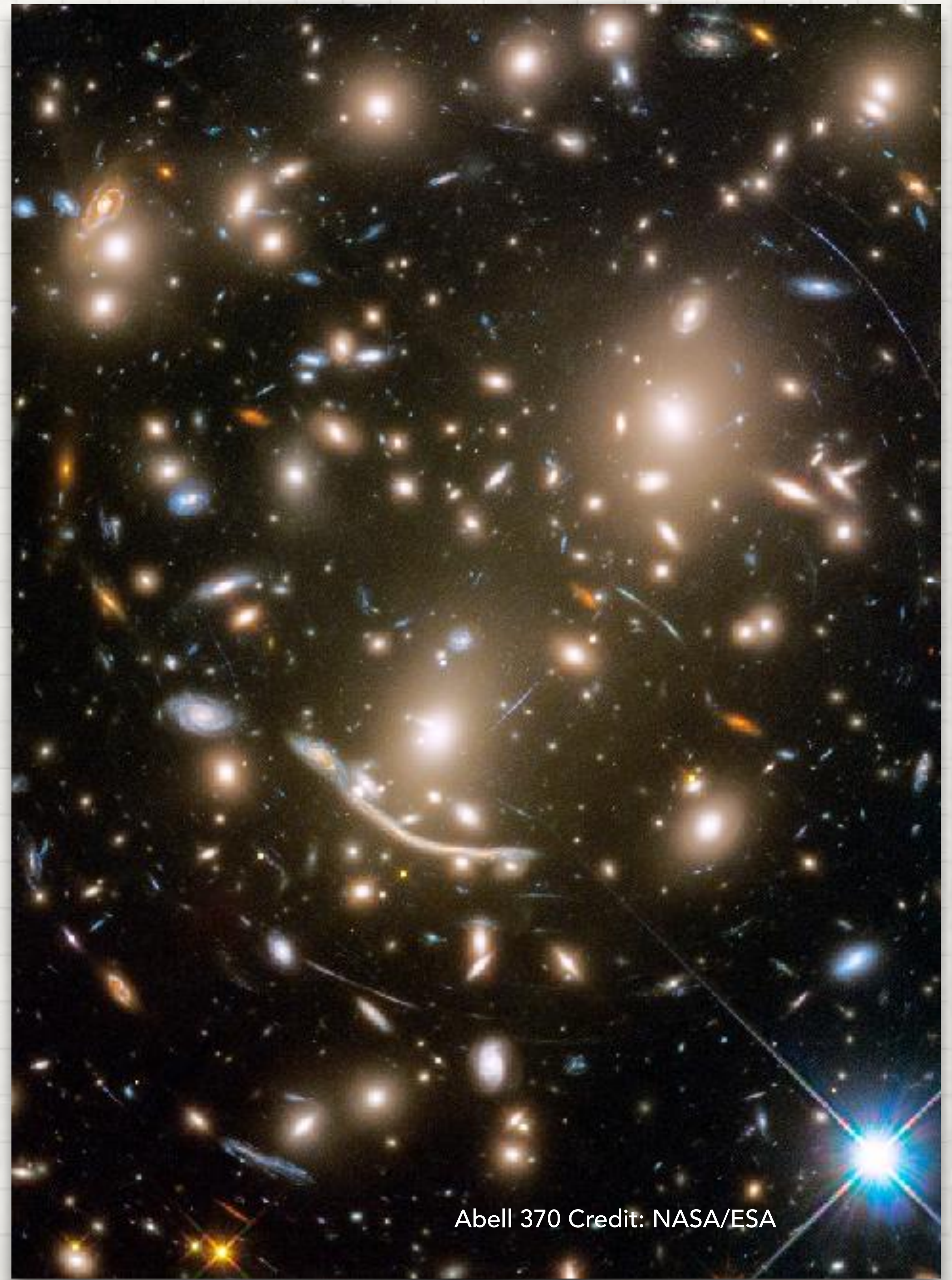
Rule number 8:
PLEASE DON'T BE POLITE –
ASK QUESTIONS THROUGHOUT
(It will be alright)

SERIES OF THREE ~90 MIN TALKS:

I. **Gravitational lensing**

II. **Gravitational lensing of high-redshift galaxies**

III. **“~Hands on” - build your own lens model, luminosity function, and other fun stuff.**



LECTURE II. **GRAVITATIONAL LENSING OF HIGH-REDSHIFT GALAXIES**

Outline:

- **Part 1. High-redshift galaxies and reionization**
  Brief review - won't get into too much details - you will hear this from leading experts throughout the school.
  Will talk about: History of Universe, galaxy formation and reionization, some physical properties of high-redshift galaxies, evidence and observational constraints, goals for high-redshift galaxy science, detecting high redshift galaxies photometrically (dropout technique) and spectroscopically, Lyman limit, Schechter Luminosity Function (LF).

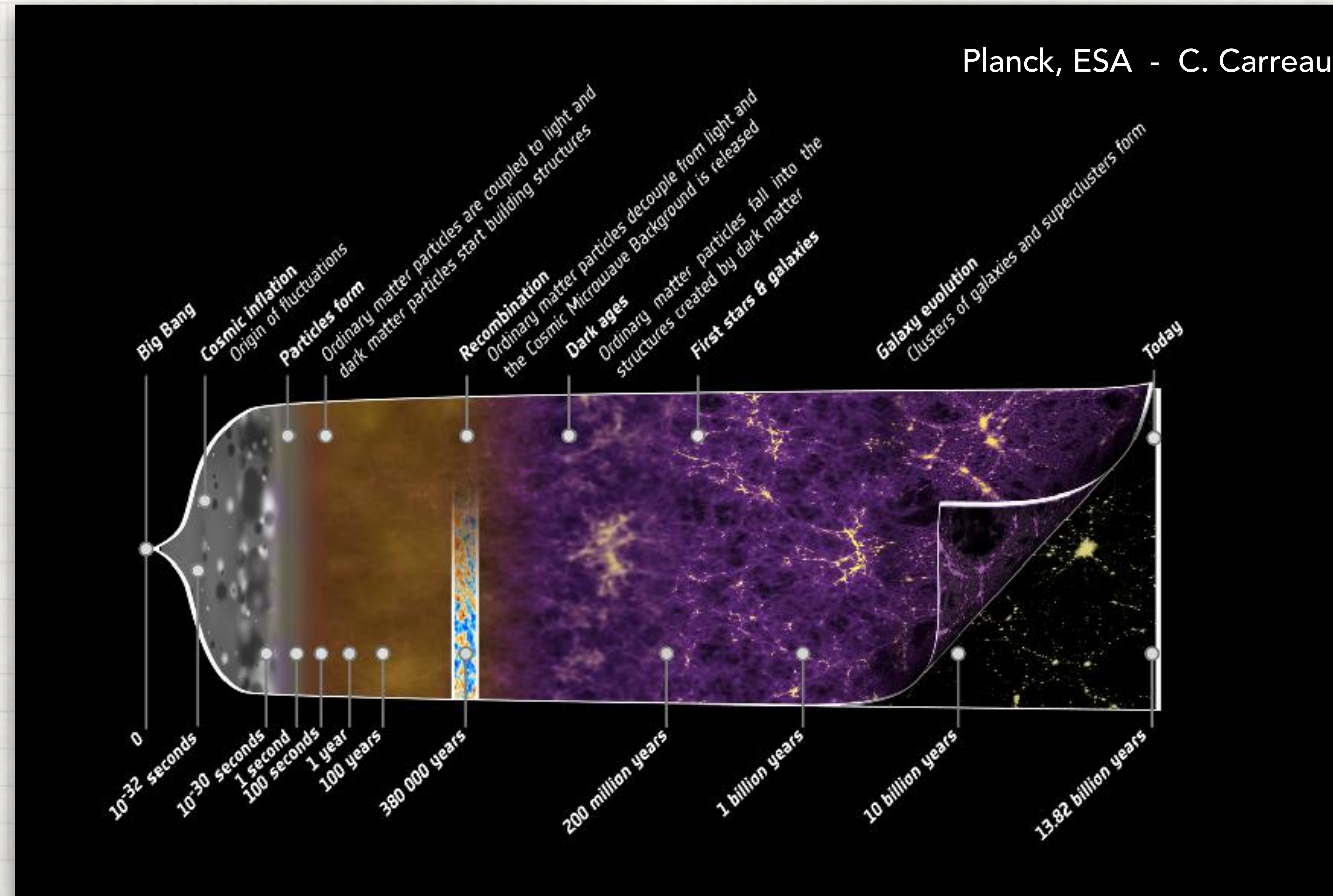
- **Part 2. (main part) Lensing of high redshift galaxies**
  Refresh of memory Re. lensing, how does lensing help detect high-z objects, how does it affect the LF, faint and bright end sources, magnification bias, systematics and completeness simulations, internal details, stretched arcs and clumps, lensed emission lines (mention Equivalent Width), multiple images of high-redshift objects and geometric confirmation.

HIGH REDSHIFT GALAXIES AND REIONIZATION

KEY POINTS

HIGH REDSHIFT GALAXIES

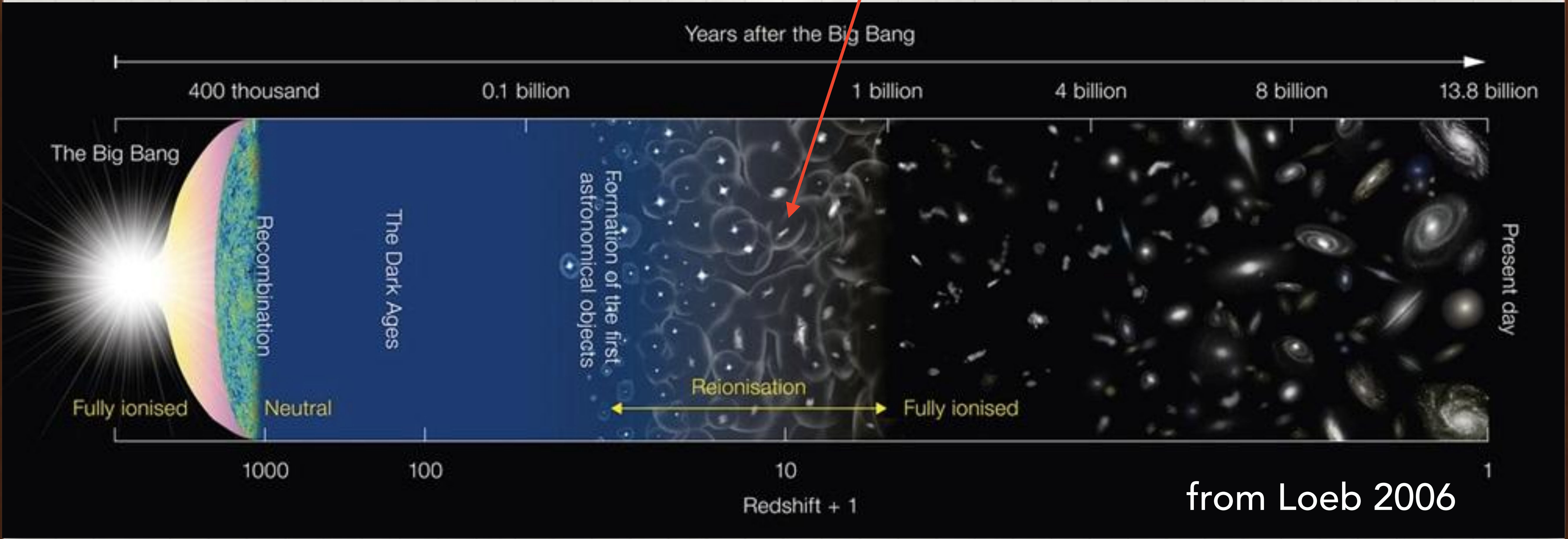
FRAMEWORK - BRIEF HISTORY OF THE UNIVERSE



HIGH REDSHIFT GALAXIES

FRAMEWORK - BRIEF HISTORY OF THE UNIVERSE

ionized bubbles



from Loeb 2006

HIGH REDSHIFT GALAXIES

MAIN GOALS

- Want to **learn about the first galaxies**, their individual (physical) properties such as SF, gas content, metallicity, escape fraction, sizes, etc, and as a population (LF)
- How did the first galaxies form? made stars? evolved? on what timescale?
- Understand the reionization process, an important evolutionary phase of the Universe. Could regular galaxies have even reionized the Universe via stars, or does one need AGN or more exotic forms of reionization? when did this happen? how smooth/patchy?
- These are some of the main questions high-z science tries to address, and as we shall see, is aided by lensing.

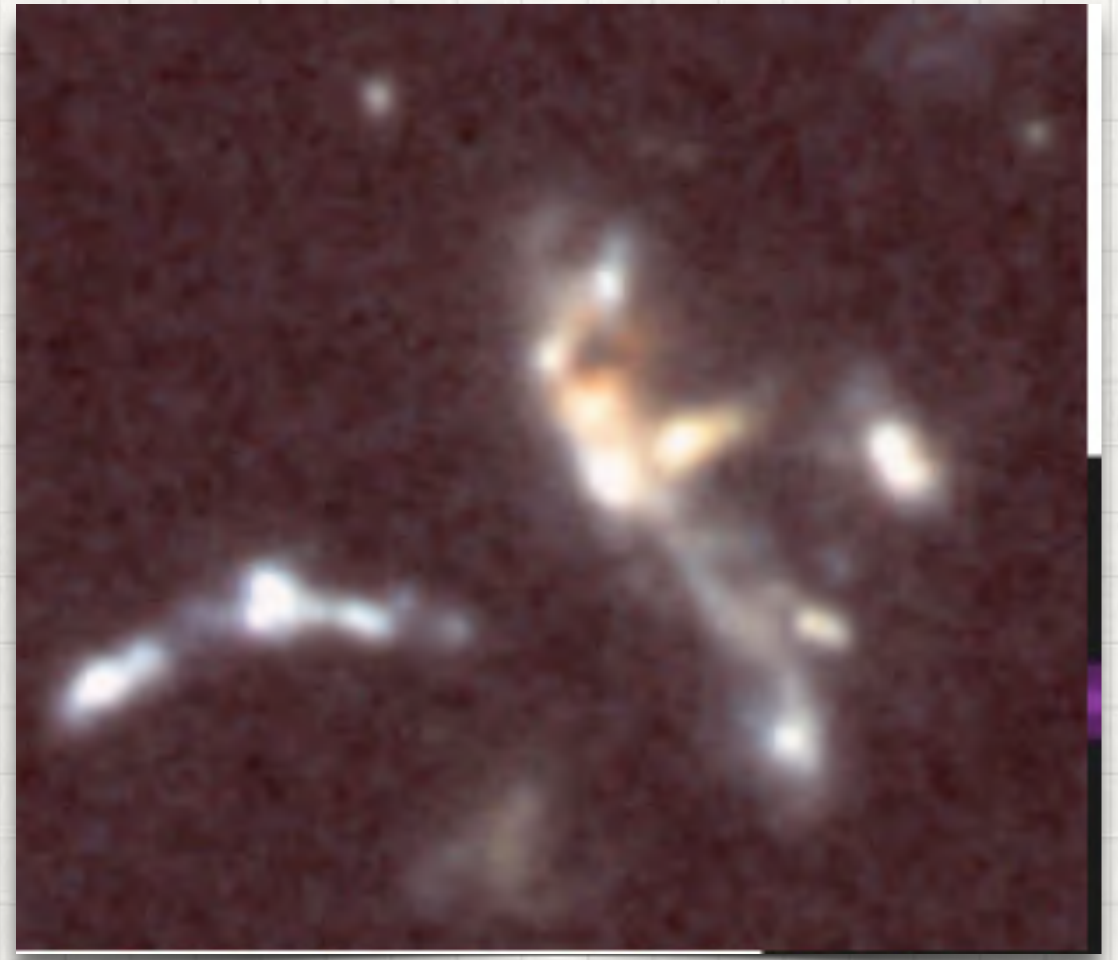
HIGH REDSHIFT GALAXIES

GALAXY FORMATION, PHYSICAL PROPERTIES

- **Masses:** stellar mass of about 10^8-10^9 solar masses
- **Shape:** not a well defined shape, probably more like clumps merging, train like structures perhaps
- **Rotation:** however, quite quickly, at least “only” a few Myr after formation, rotation is already detected
- **Gas composition, metallicity:** pristine gas, or very low metallicity
- **Star Formation:** Pop III stars, rates of about a few solarM per yr, typically, sSFRs usually on the high side, log(sSFR) of about -8
- **Dust:** already in place at least in some galaxies already at z~8, indicating galaxies formed at least around 200 Myr Universe age (but other work find little dust in z~5-6 galaxies, see Capak et al. 2005).
- **Size:** effective radius of order 0.1-1 kpc

HIGH REDSHIFT GALAXIES

SHAPE



From web; credit: Frédéric Bournaud

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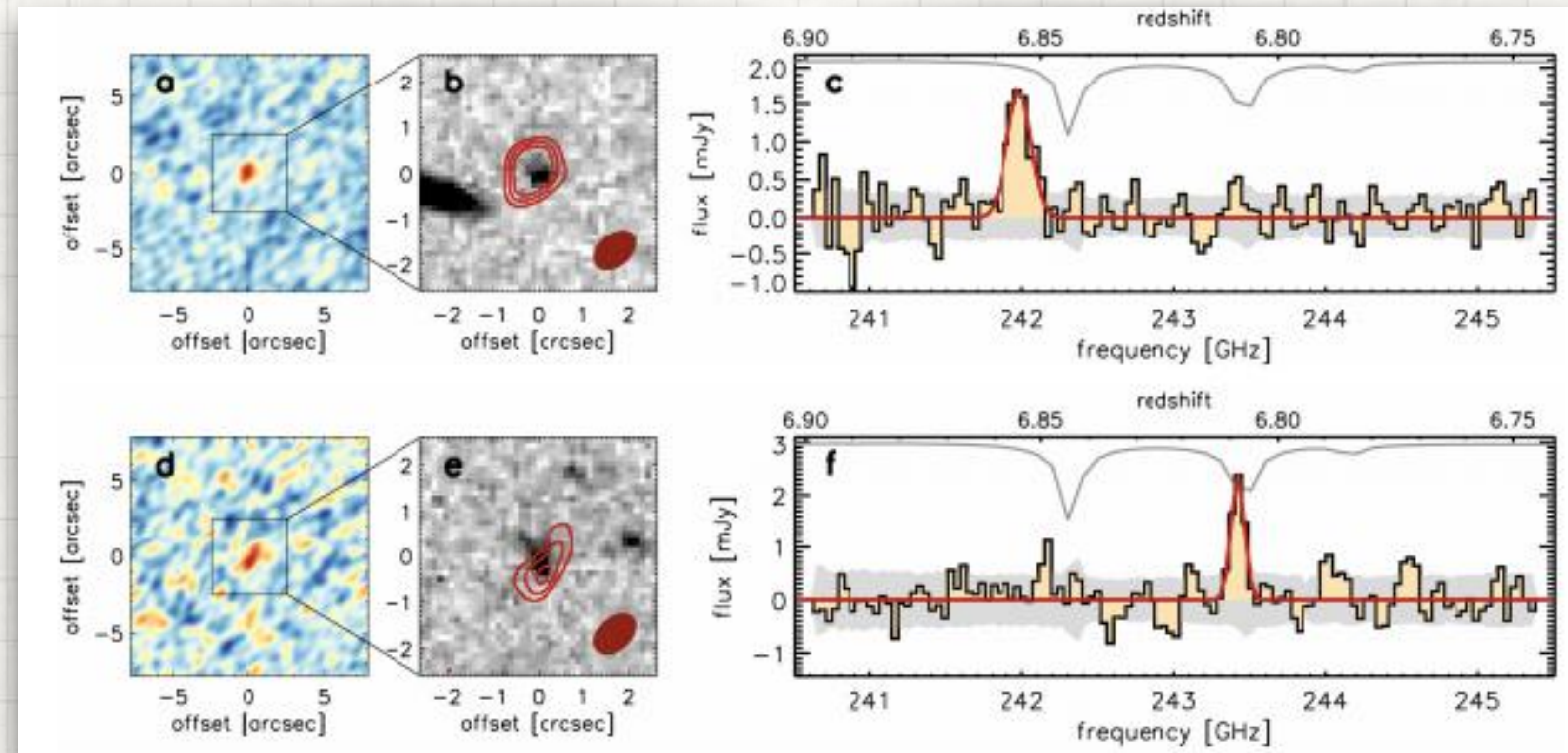
LENSING OF HIGH REDSHIFT GALAXIES

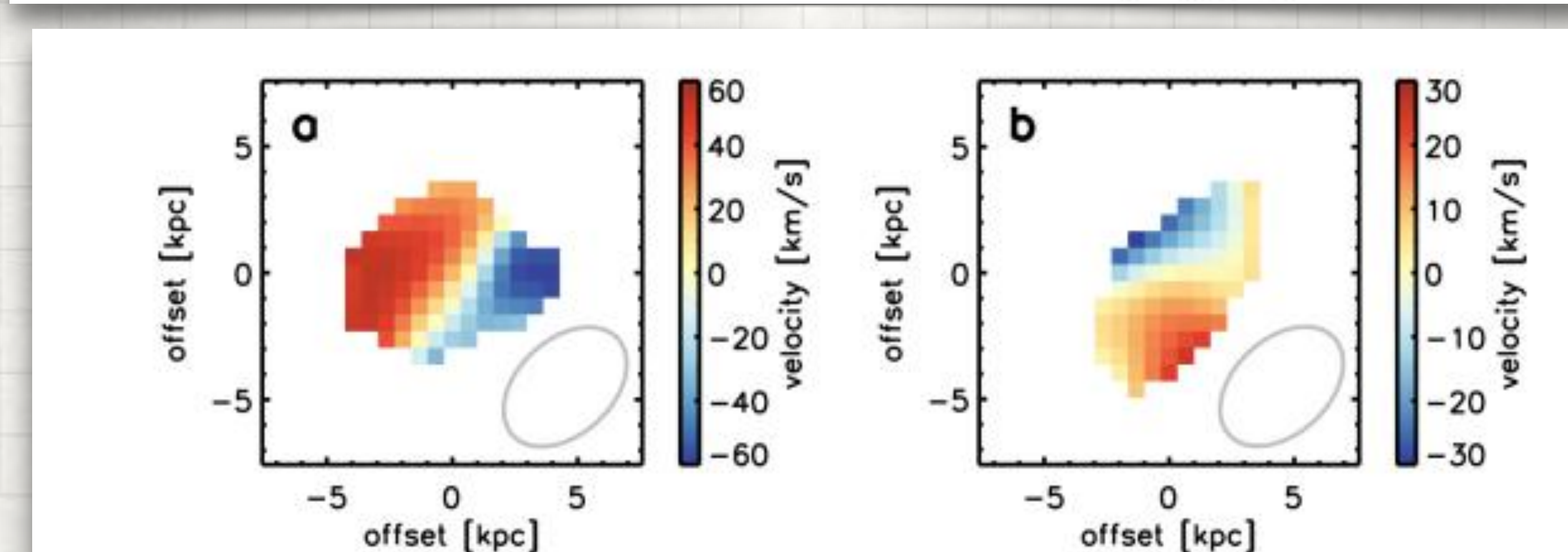
ROTATION

Some examples:

Smit+2018 (z~6.8)



C[II]



Rotation

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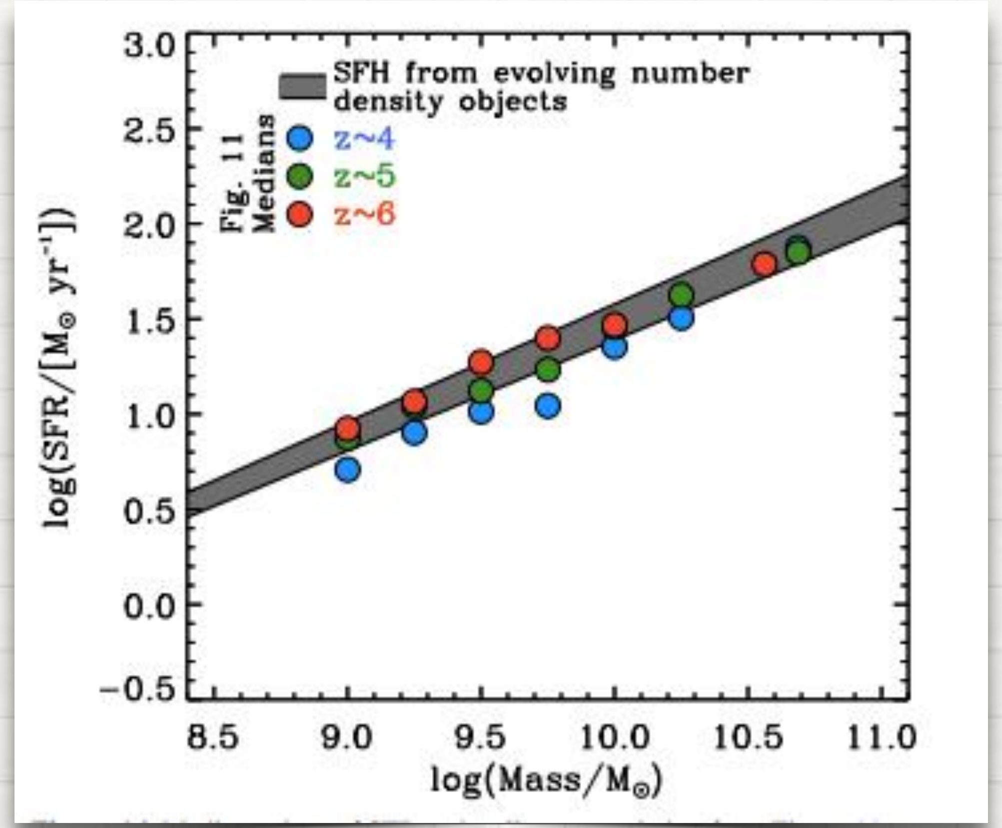
HIGH REDSHIFT GALAXIES

SFRS



Salmon+2015

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HIGH REDSHIFT GALAXIES

DUST

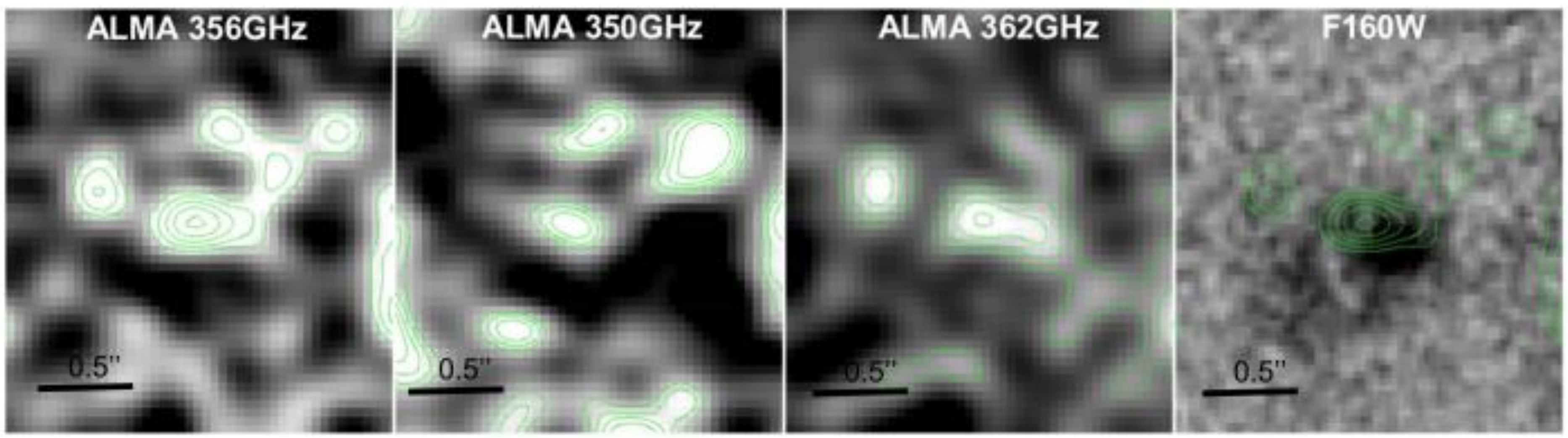
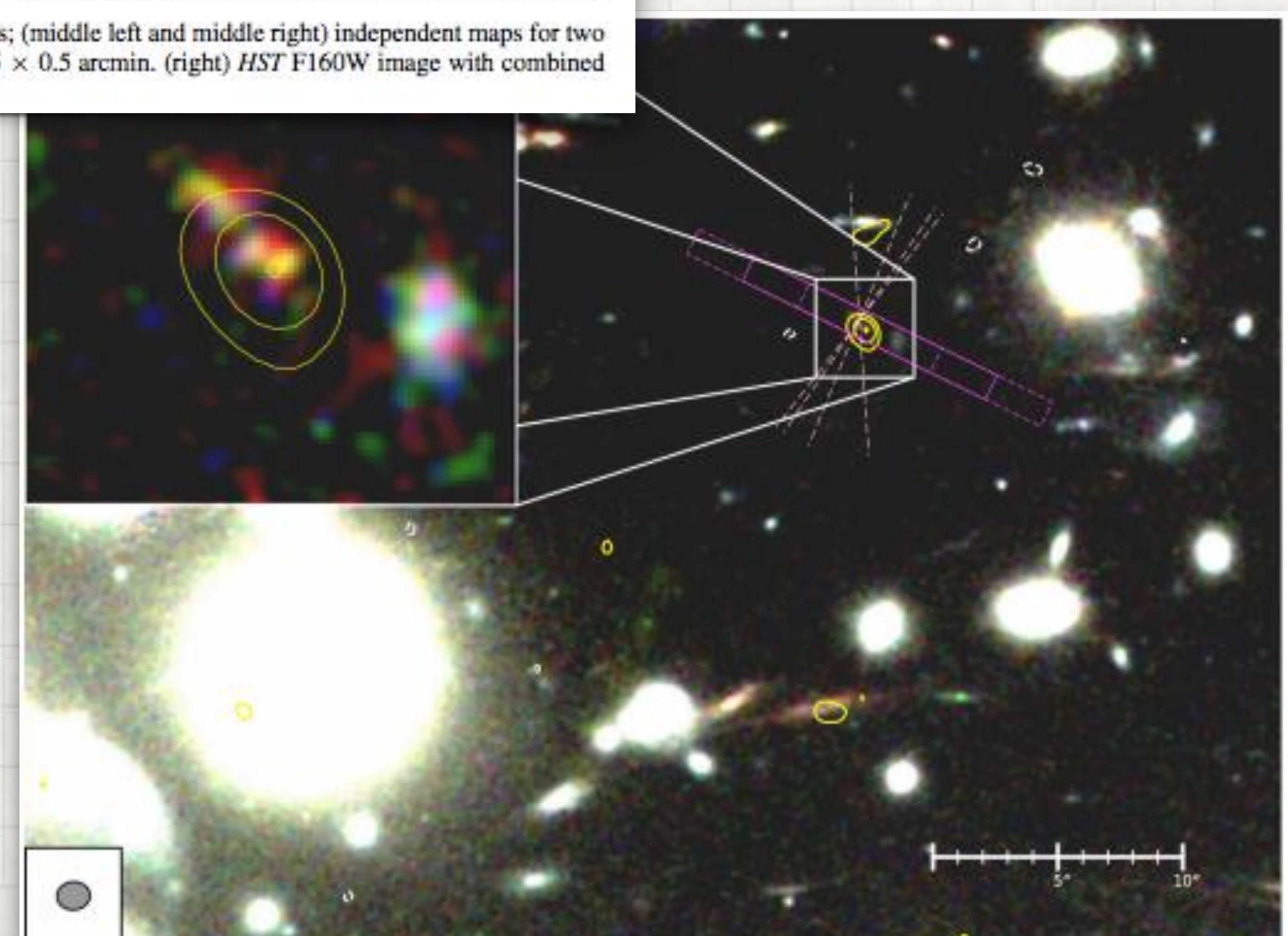


Figure 1. ALMA Band 7 continuum detection for A2744_YD4. (left) Map combining all frequency channels; (middle left and middle right) independent maps for two equal frequency ranges. Contours are shown at 1, 2, 3, 4, and 5σ adopting a noise level from an area of 0.5 × 0.5 arcmin. (right) *HST* F160W image with combined ALMA image contours overplotted.

Laporte+ 2017



Dust masses around 10^7 solar masses

Watson+2015

HIGH REDSHIFT GALAXIES

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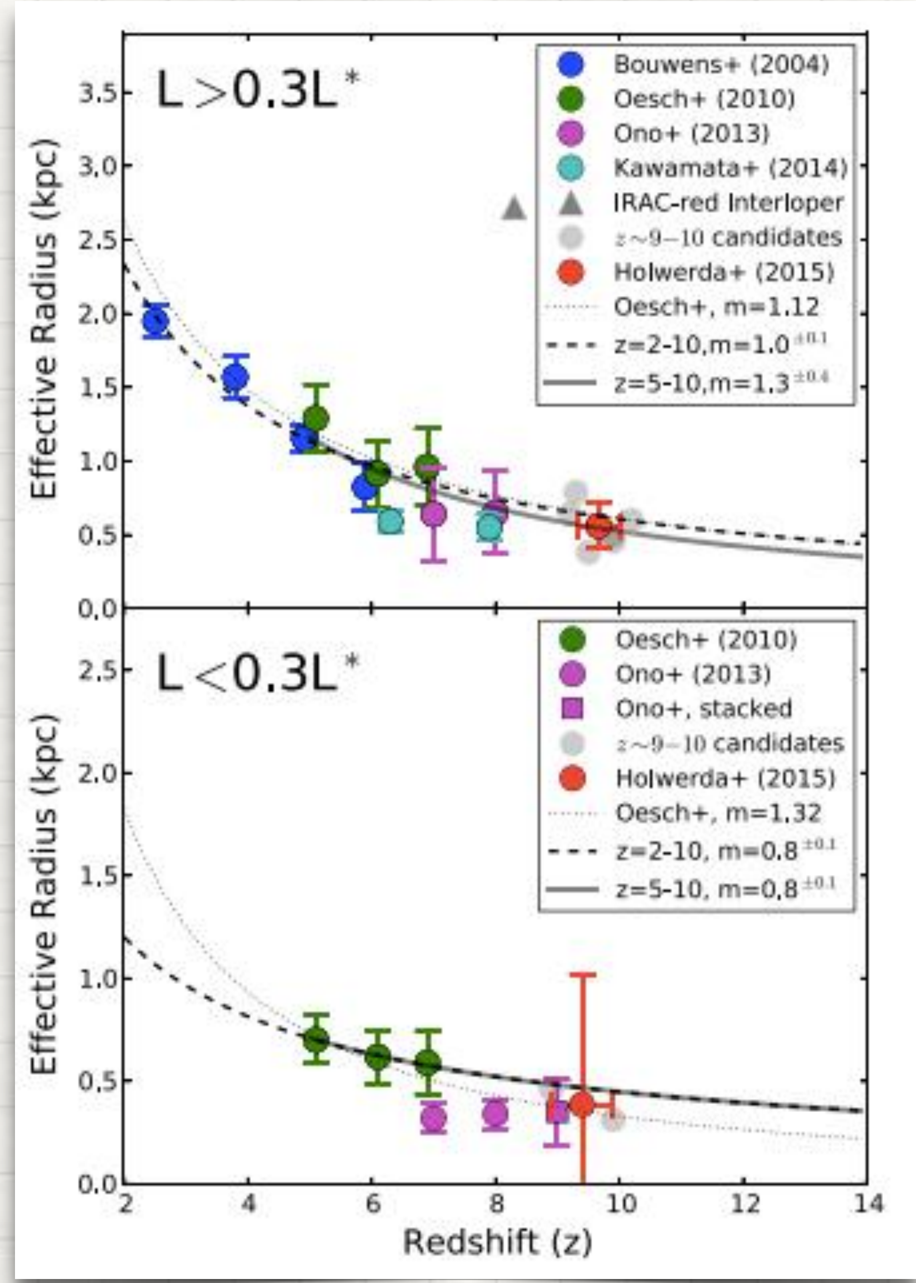
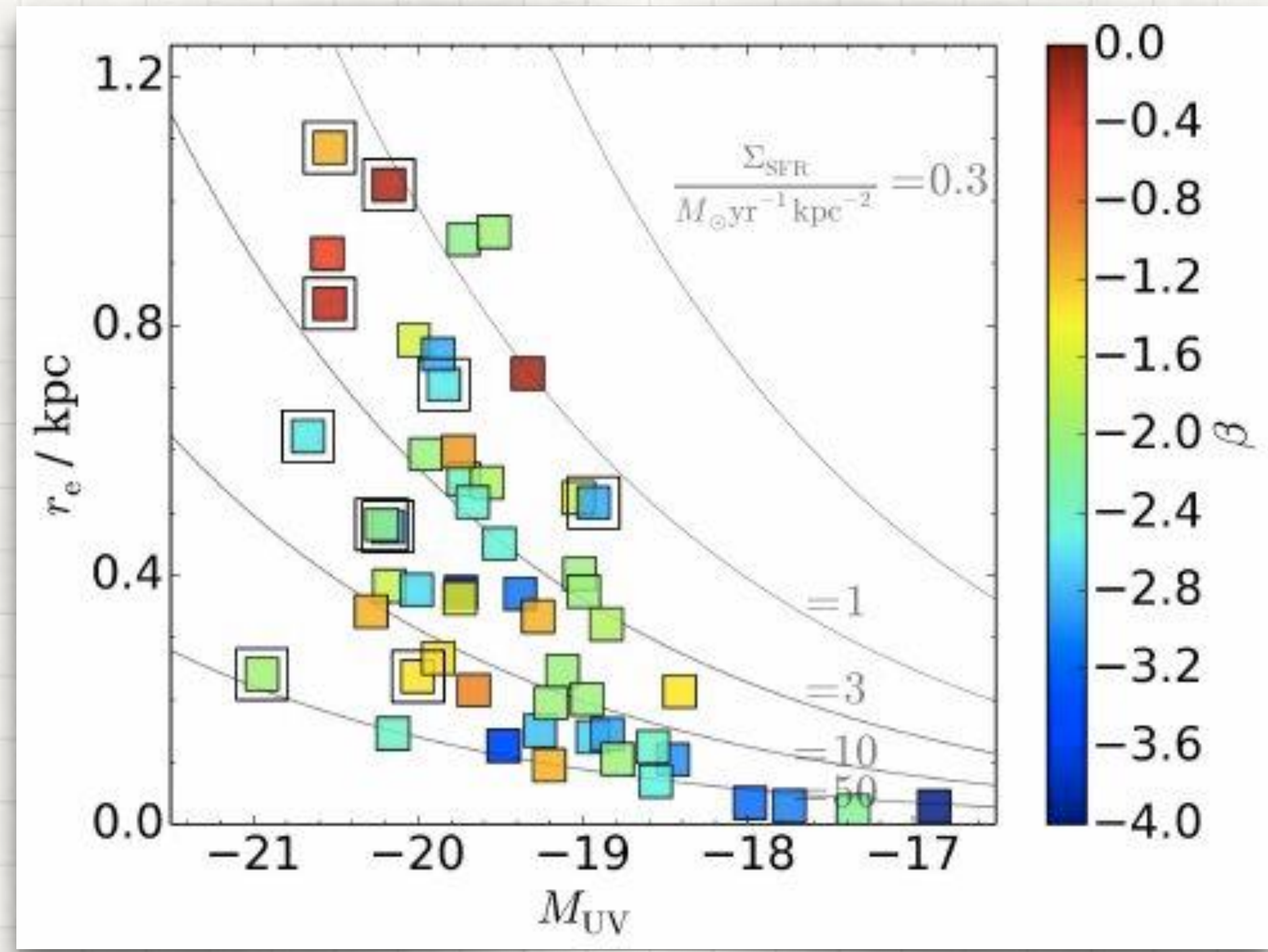
HIGH REDSHIFT GALAXIES

SIZES



Holwerda+ 2015



Kawamata+ 2014

HIGH REDSHIFT GALAXIES

REIONIZATION: HOW DO WE KNOW REIONIZATION OCCURRED AND WHEN?

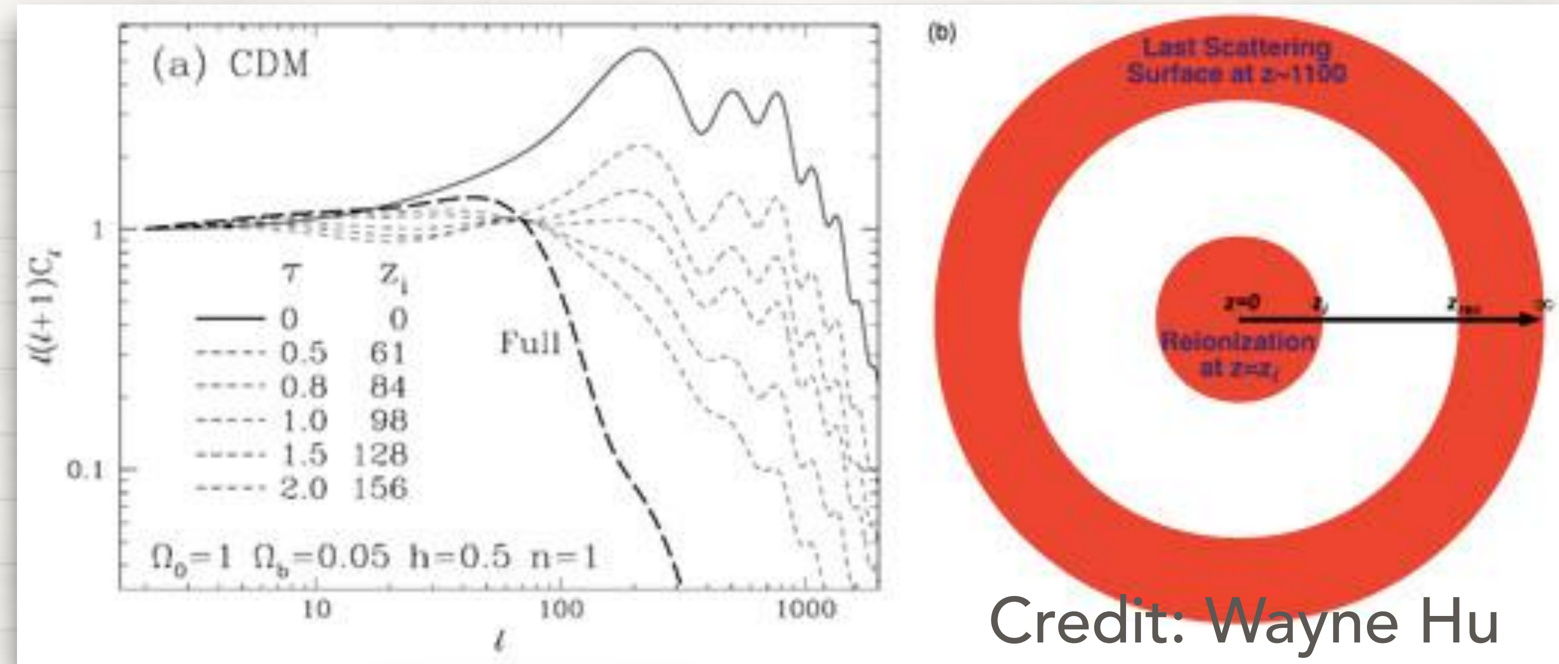
- Various probes, perhaps three main ones are:
- Cosmic Microwave Background (CMB)
- The Gunn-Peterson troughs in Quasars
- Decline rate of Lyman-alpha emitting galaxies

HIGH REDSHIFT GALAXIES

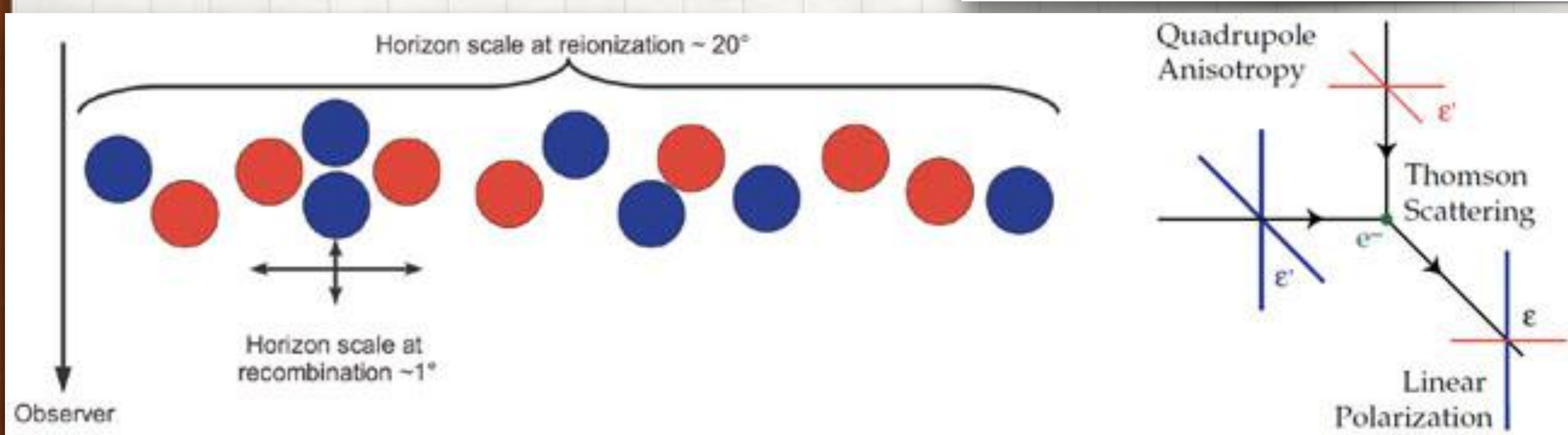
Reionization: The CMB and the optical depth for reionization

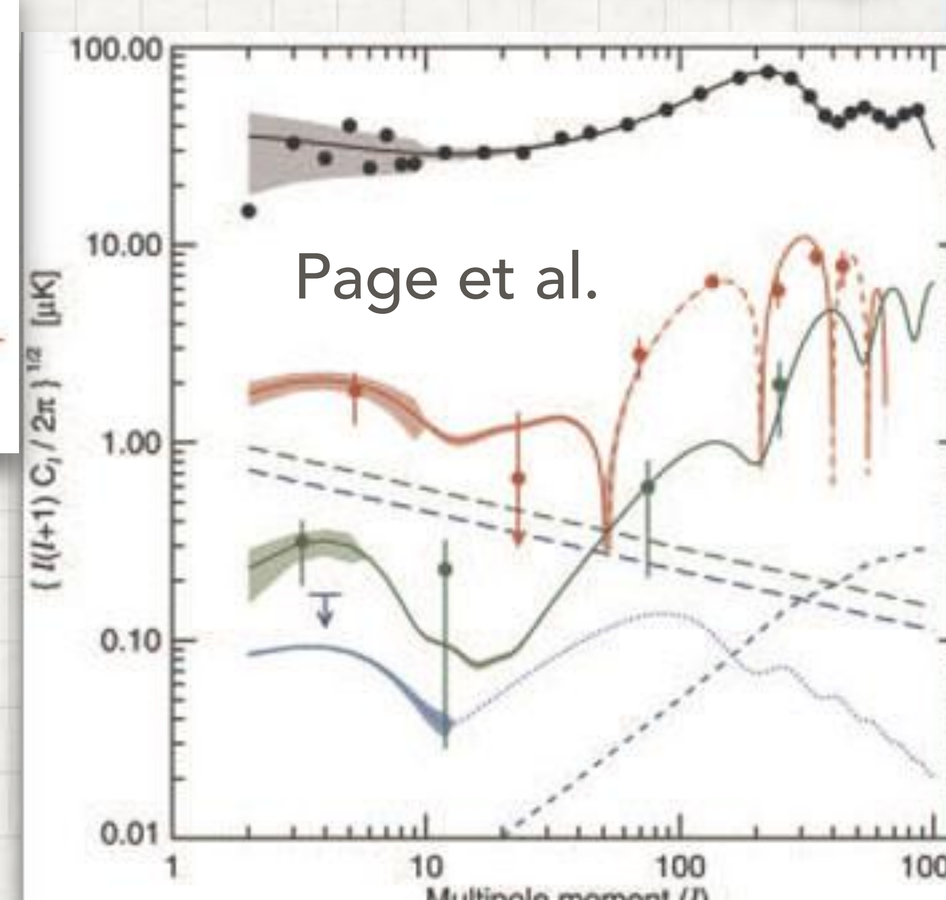
From S. Zaroubi's review 2012

$$\tau = \int_0^{z_{dec}} \sigma_T n_e \frac{cH_0^{-1} dz}{(1+z)\sqrt{\Omega_m(1+z)^3+\Omega_\Lambda}}.$$



Credit: Wayne Hu



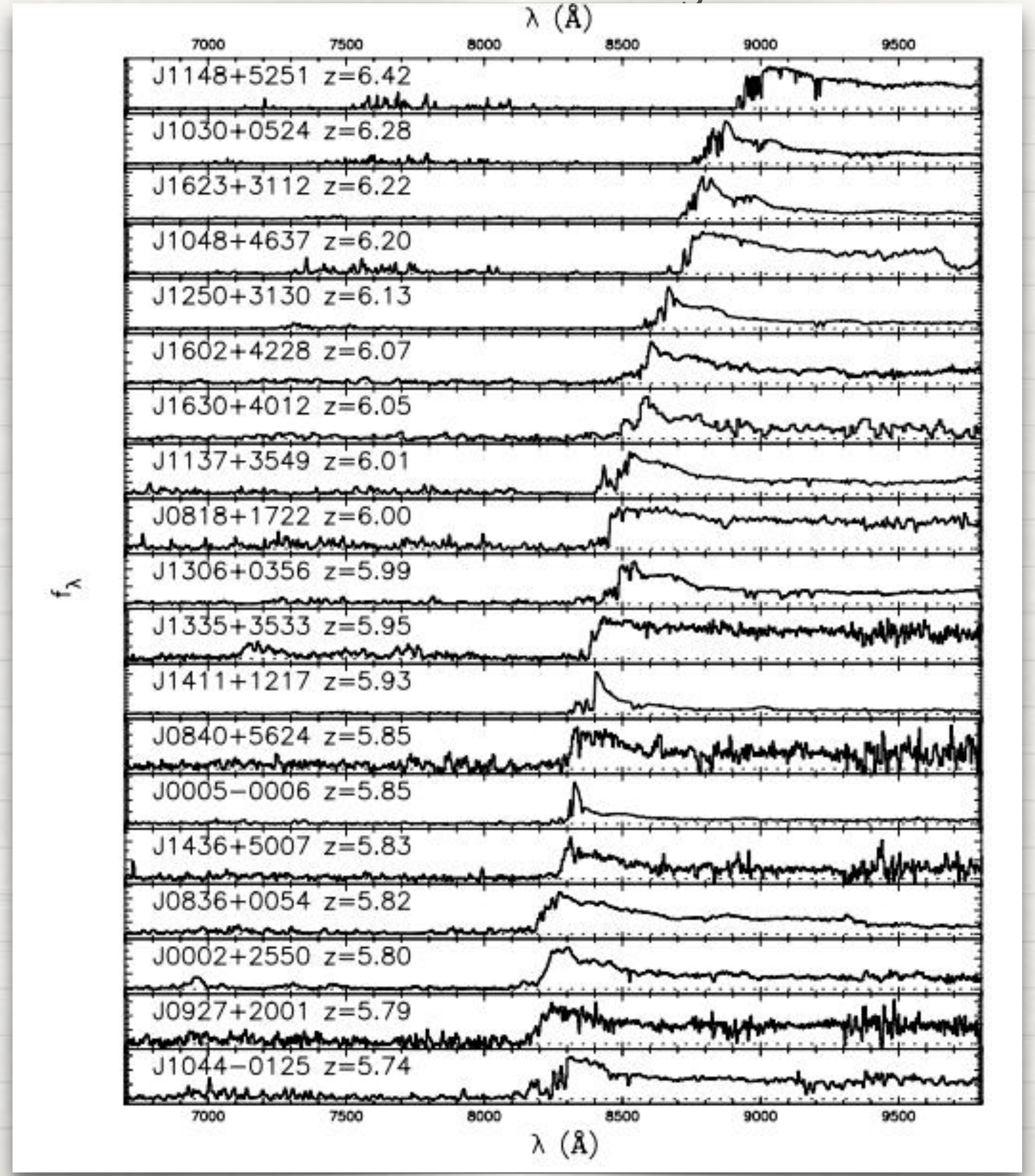


A sketch that shows why the CMB polarization is sensitive to the quadrupole momentum of temperature fluctuations. Right hand panel: Thomson scattering of radiation with quadrupole anisotropy generates linear polarization. The blue and red lines represent cold and hot radiation.

HIGH REDSHIFT GALAXIES

Reionization: The Gunn-Peterson troughs in Quasars

X. Fan et al. 2006



HIGH REDSHIFT GALAXIES

Reionization: The decline rate of Lyman alpha emitting galaxies

Schenker+ 2014

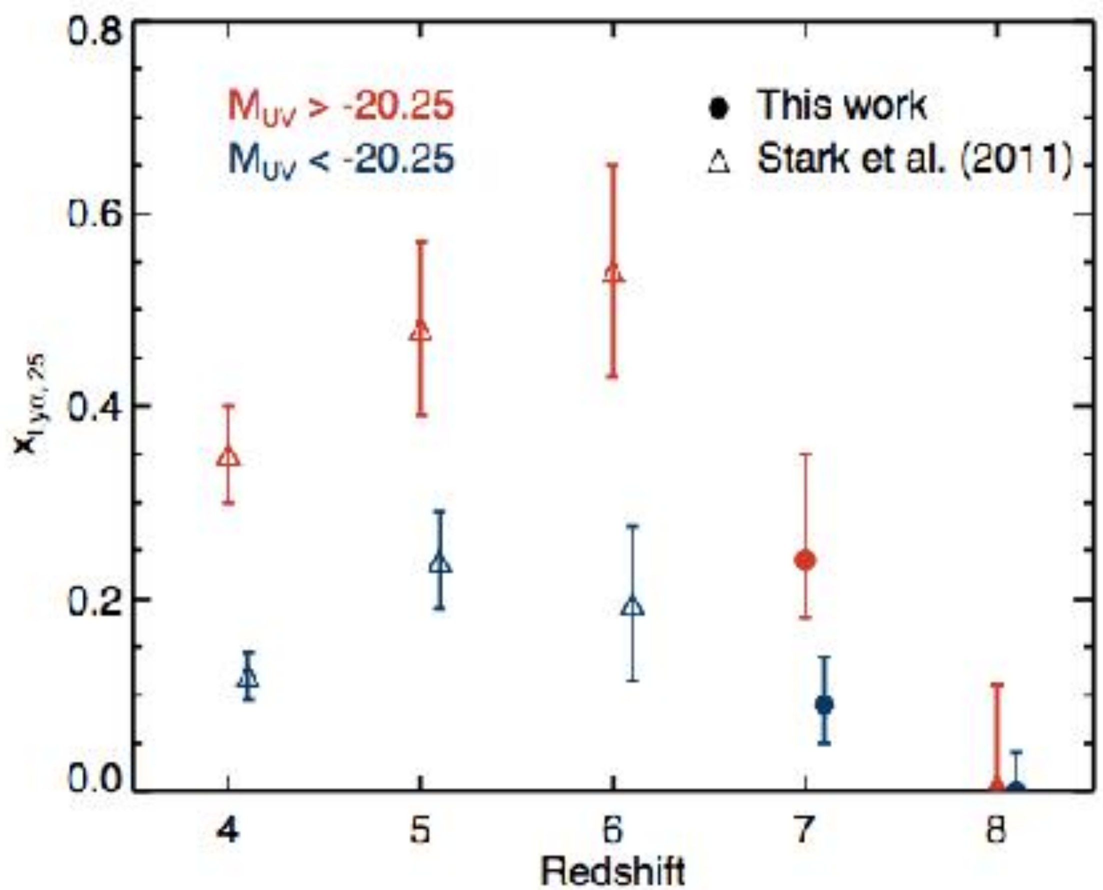


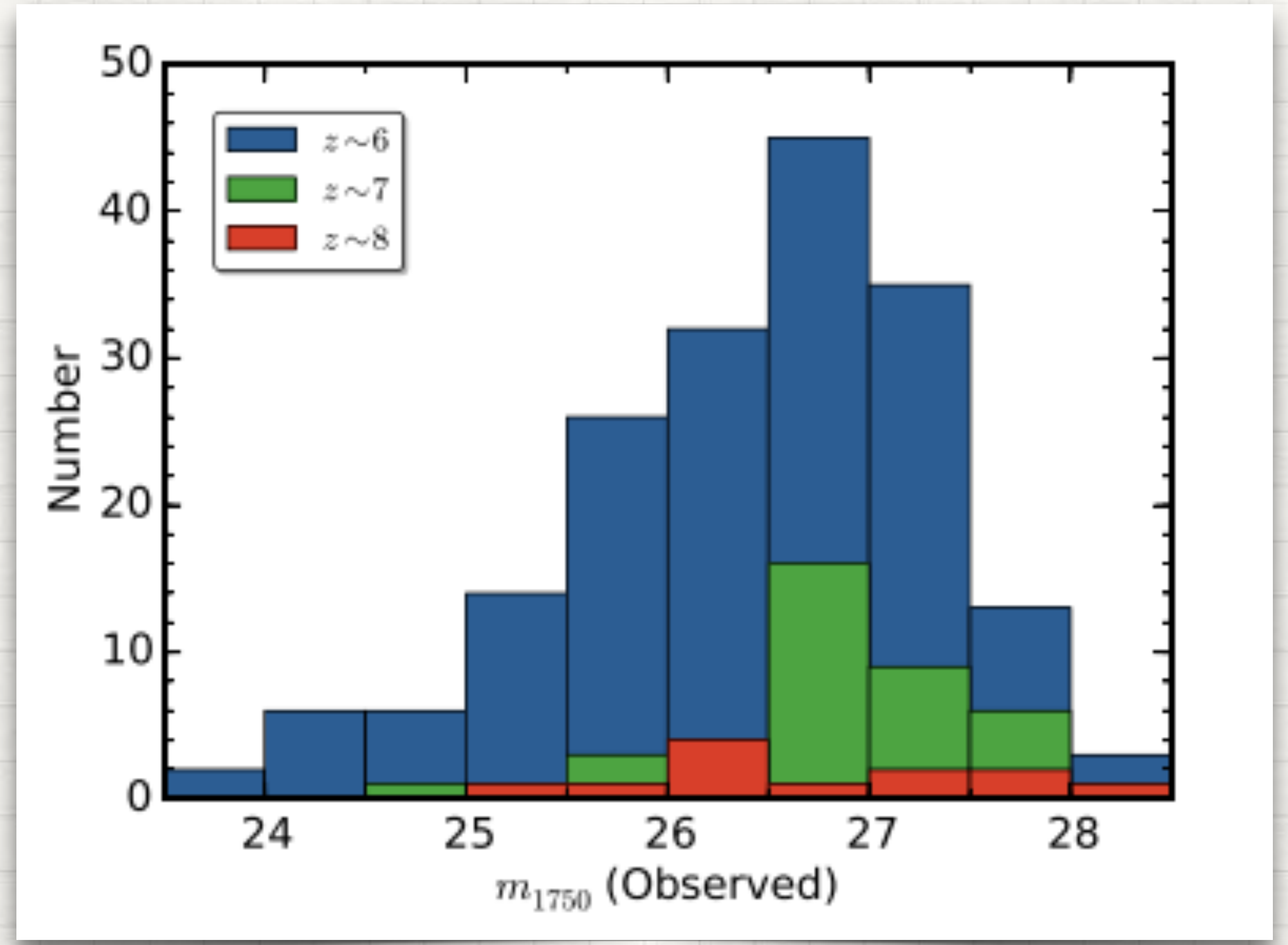
Figure 9. Fraction of LBGs that display Lyα in emission at an EW ⩾ 25 Å, plotted as a function of redshift. The values at $z = 7$ and 8 reflect differential measurements with the data at $z = 6$, as described in the text. Thus, these data points and errors are simply the convolution of the $x_{Ly\alpha}$ pdf at $z = 6$ and the transmission fraction pdf at $z = 7$ and 8.

See also Stark et al. 2011, Pentericci et al. 2011, and others.

HIGH REDSHIFT GALAXIES

THE LUMINOSITY FUNCTION

Number counts:



Bradley et al. 2014

HIGH REDSHIFT GALAXIES

THE LUMINOSITY FUNCTION

- A mathematical form describing the number of galaxies per luminosity bin per volume
- The Schechter function (1976) is typically used, which is not only empirical but also motivated by a physics self-similar halo formation model (Press & Schechter 1974)

We propose here a new analytic approximation for the luminosity function for galaxies. Letting $\varphi(L)dL$ be number of galaxies per unit volume in the luminosity interval from L to $L + dL$, we investigate the expression

$$\varphi(L)dL = \varphi^*(L/L^*)^\alpha \exp(-L/L^*)d(L/L^*)$$

where φ^*, L^*, and α are parameters to be determined from the data. The parameter φ^* is a number per unit volume, and L^* is a "characteristic luminosity" (with an equivalent "characteristic absolute magnitude," M^*) at which the luminosity function exhibits a rapid change in the slope in the ($\log \varphi$, $\log L$)-plane. The existence of such a characteristic magnitude has long been stressed by Abell (1962, 1965), and his notation M^* has been pirated for the present discussion. The dimensionless parameter α gives the slope of the luminosity function in the ($\log \varphi$, $\log L$)-plane when $L \ll L^*$.

The proposed representation derives from a self-similar stochastic model for the origin of galaxies (Press and Schechter 1974) but differs in that we allow ourselves the latitude of adjusting the "faint-end slope parameter" α to fit the available data. The

Schechter 1976

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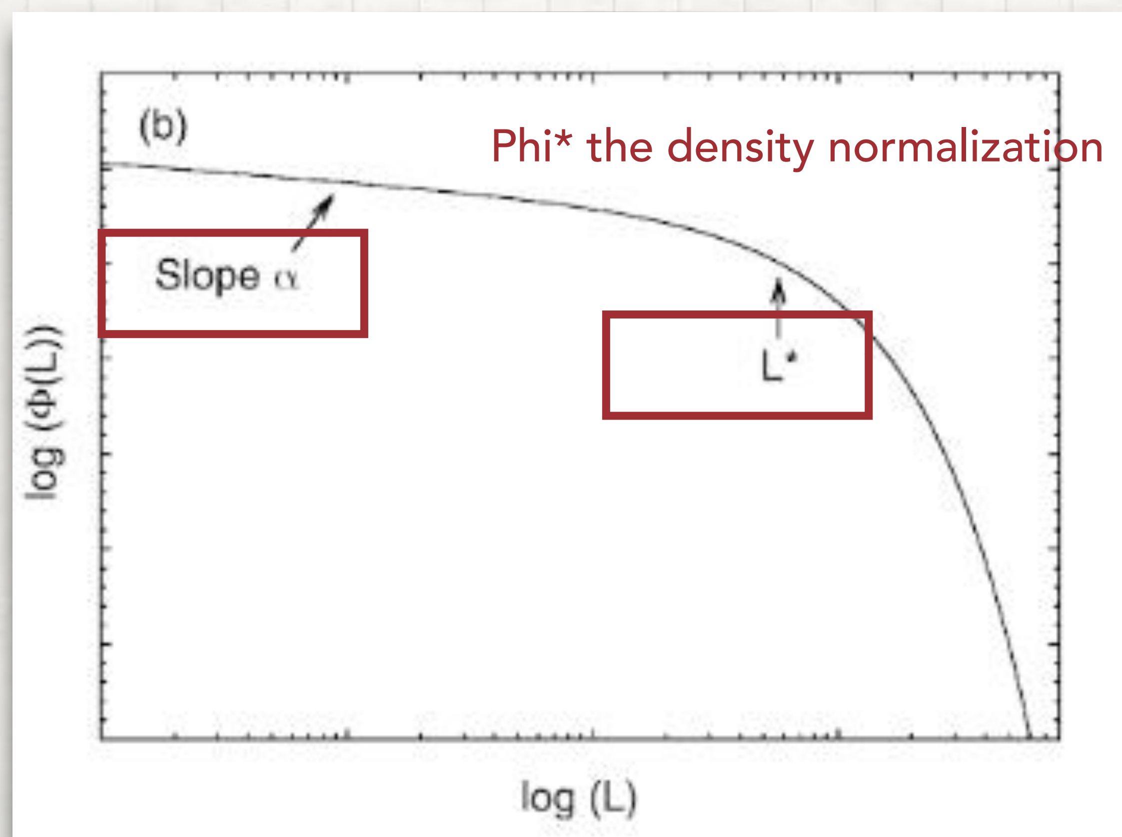
$$\Phi(L) = \left(\frac{\Phi^*}{L^*}\right)\left(\frac{L}{L^*}\right)^{\alpha} \exp\left(-L/L^*\right)$$

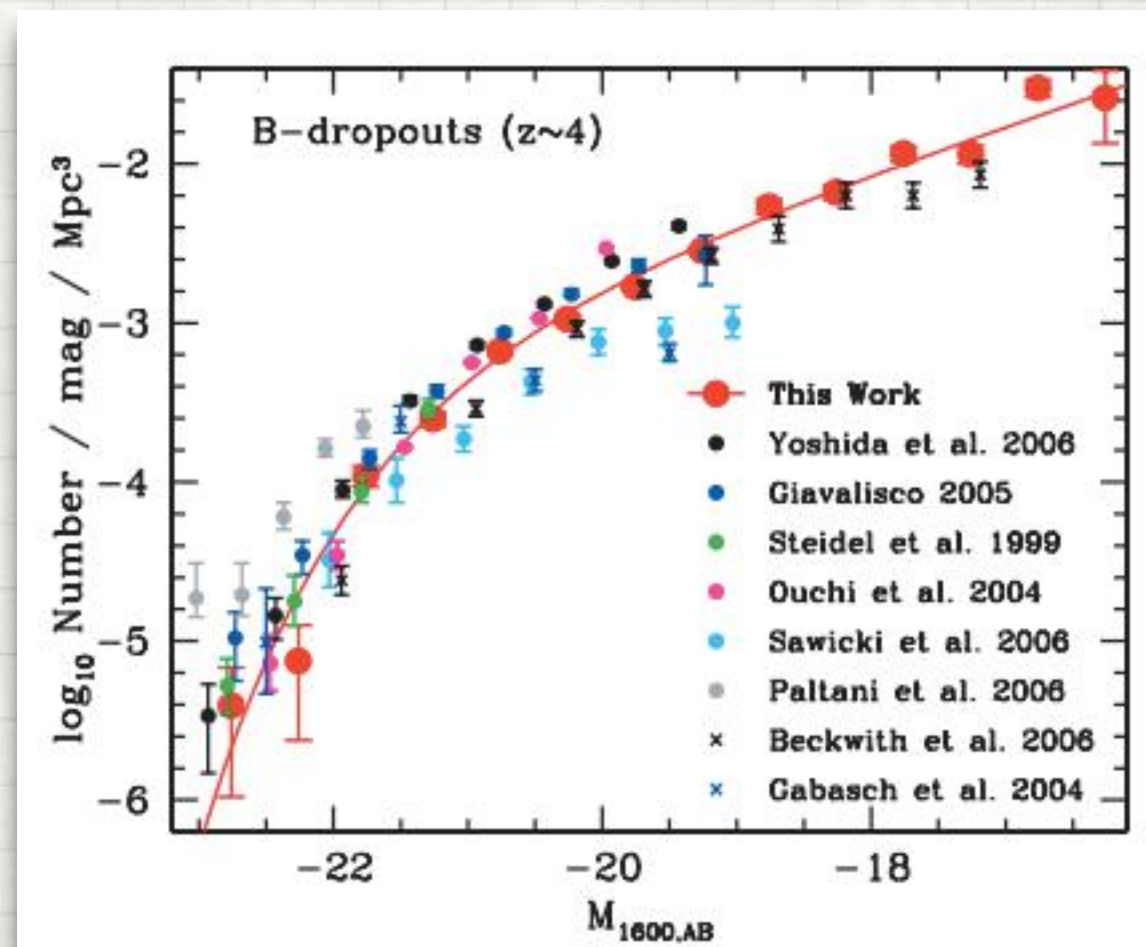
or

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

P. Schneider's book



Bouwens+ 2007



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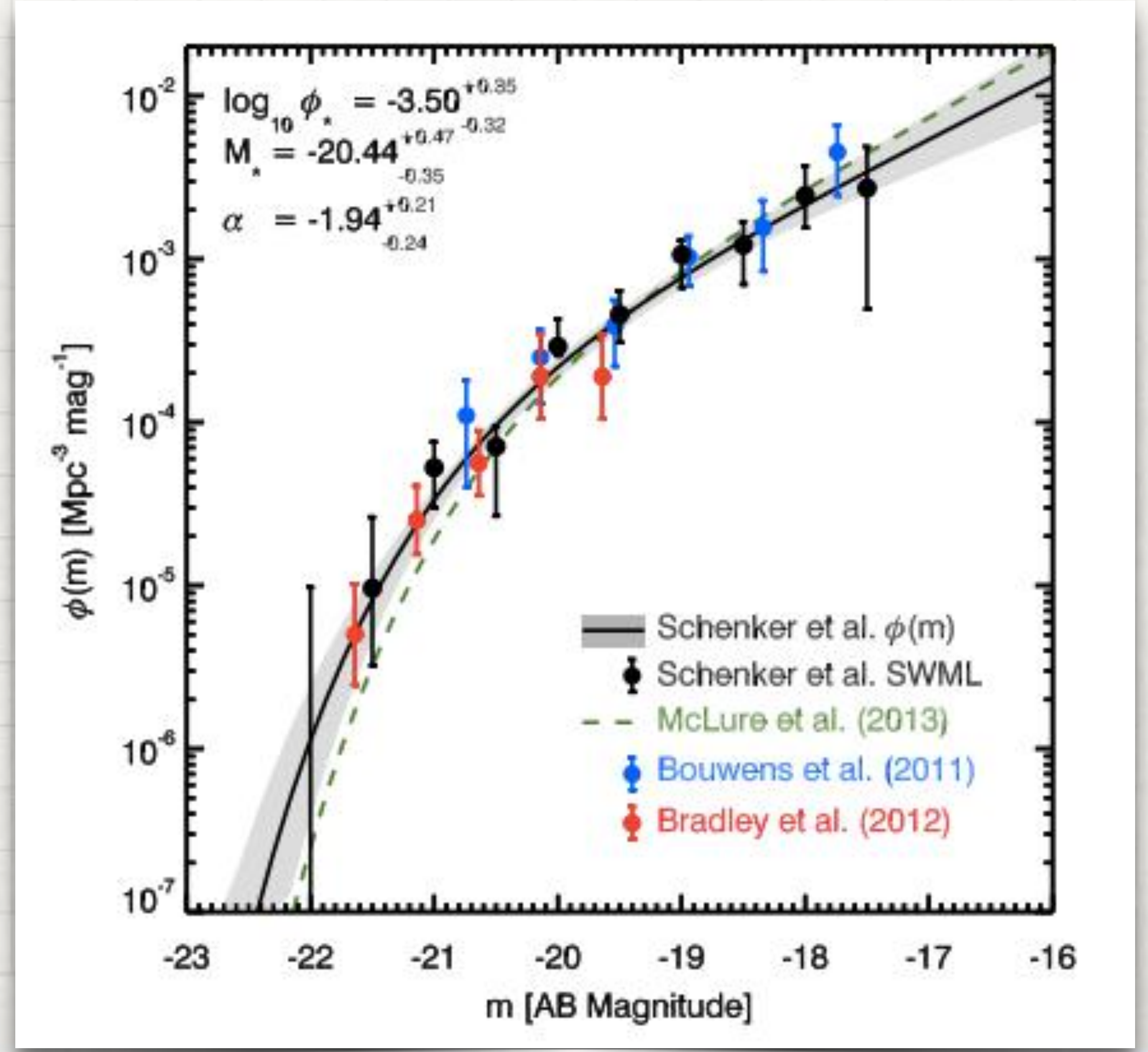
  - Let's note a few things:
  - break in slope
  - many more faint galaxies than bright ones
  - uncertainties on bright end larger (fewer objs, rare*)
  - uncertainties on faint end also (fainter, noise, photometric errors etc.)

*but wide field surveys like the HyperSupreme cam could be changing this

Schenker+ 2012



LENSING OF HIGH REDSHIFT GALAXIES

HOW ARE HIGH-REDSHIFT GALAXIES DETECTED?

- **Photometrically:** attenuation of Lambda<912 A photons due to resonant scattering by neutral hydrogen around galaxy
- Flux drops out galaxy would look "red" in a color composite image
- Verified **Spectroscopically**
- Via Lyman alpha, typically, individual objects or narrow band imaging
- But this line is rear. Alternative UV lines (CIII] ~1908A, CIV ~1550A, HeII~1640 etc.), redshifted to near infrared, or C+ (158 mum), [OIII] 88 mum in radio/ sub-mm/mm
- As we shall see, can also be further supported geometrically from lensing

LENSING OF HIGH REDSHIFT GALAXIES

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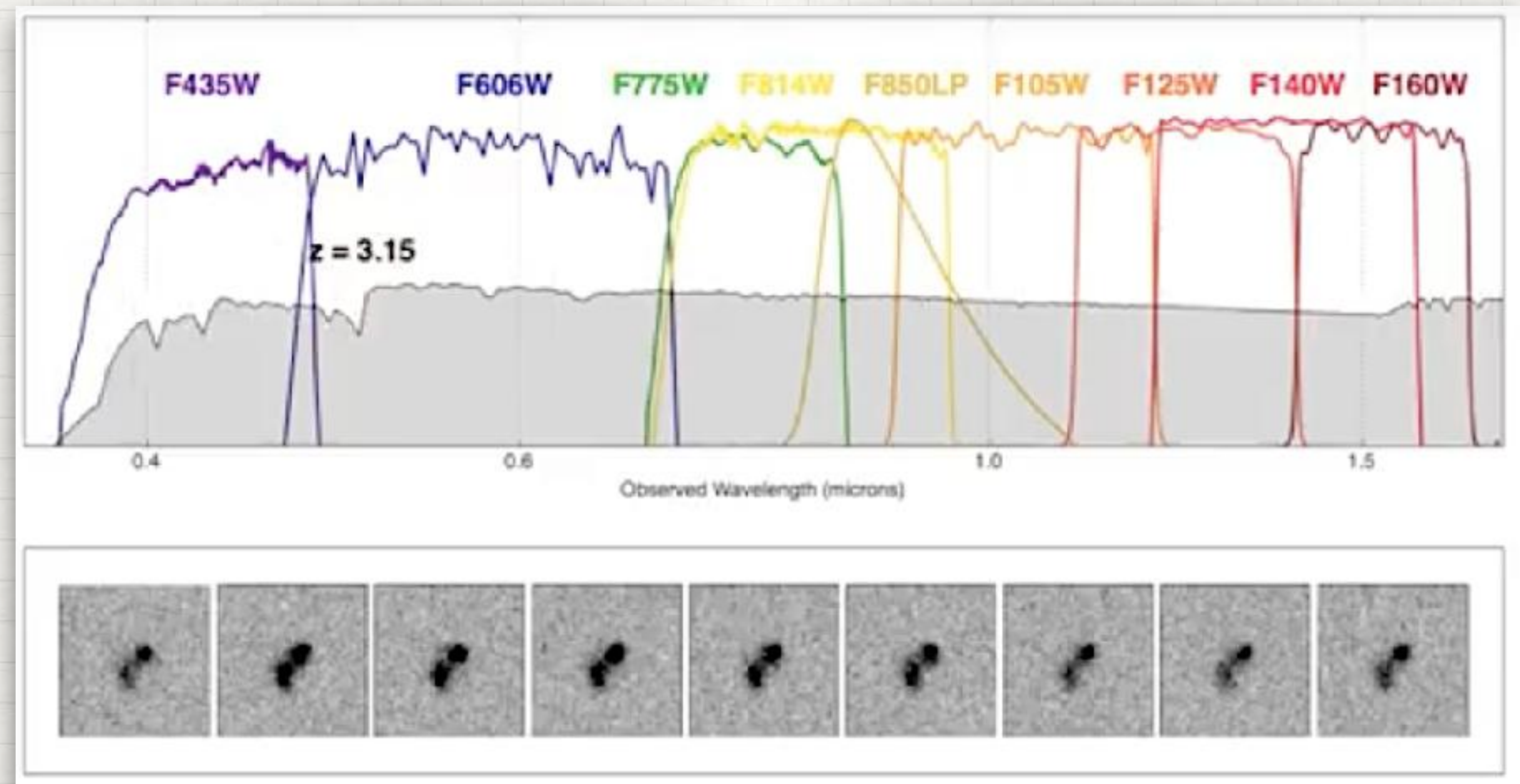
- Dropout or Lyman-break technique :



From web; Credit: D. Magee, R. Bouwens, P. Oesch, G. Illingworth

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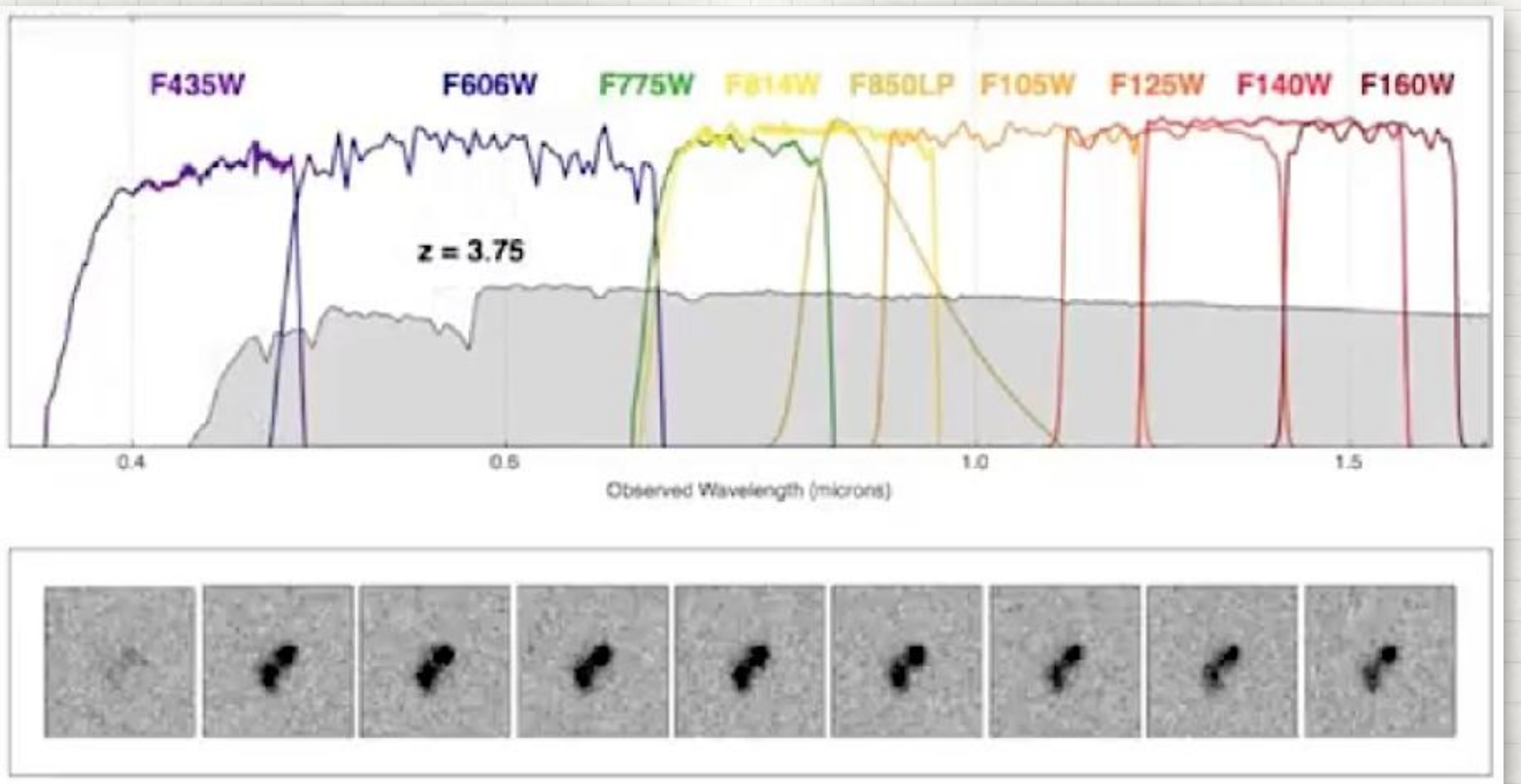

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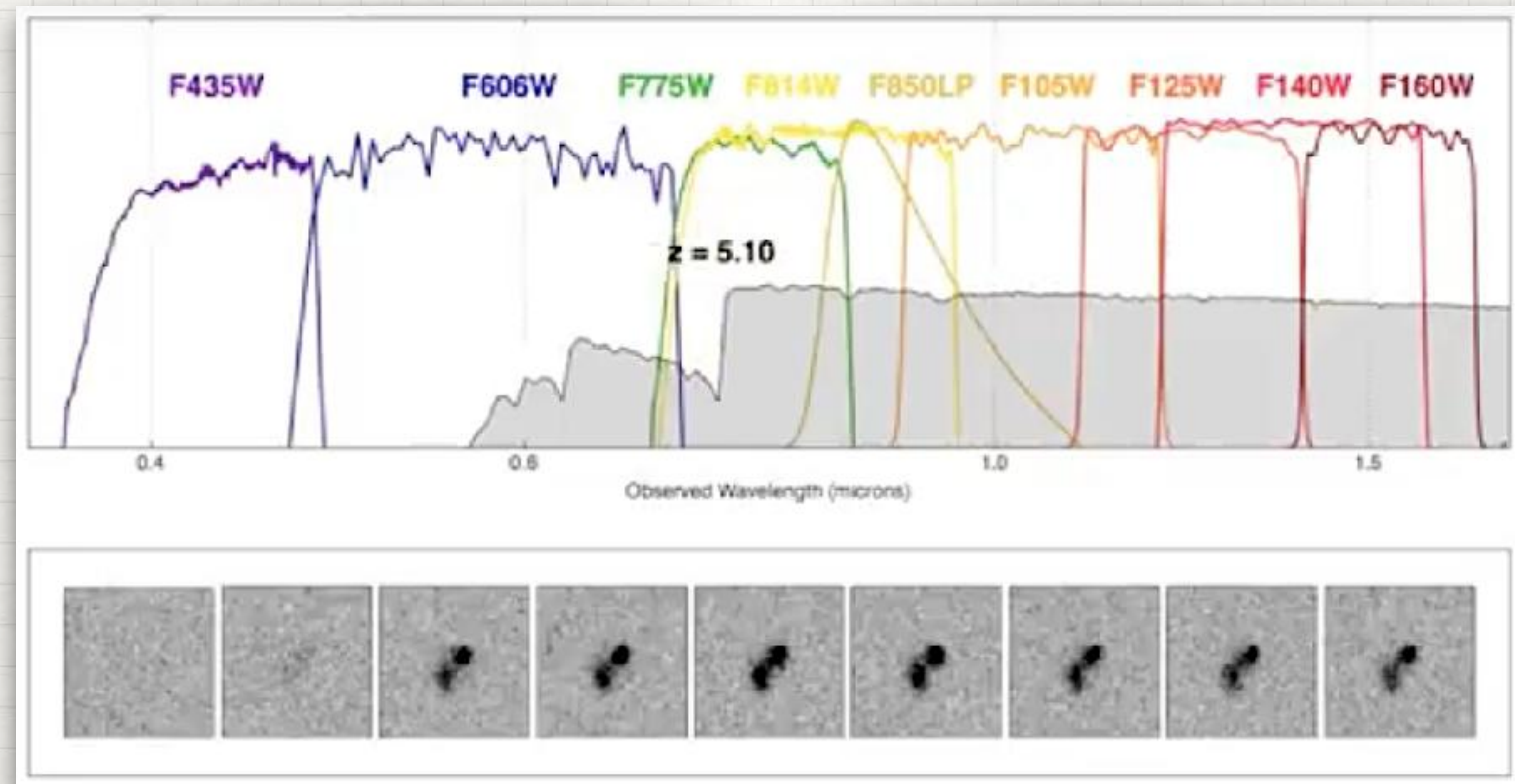

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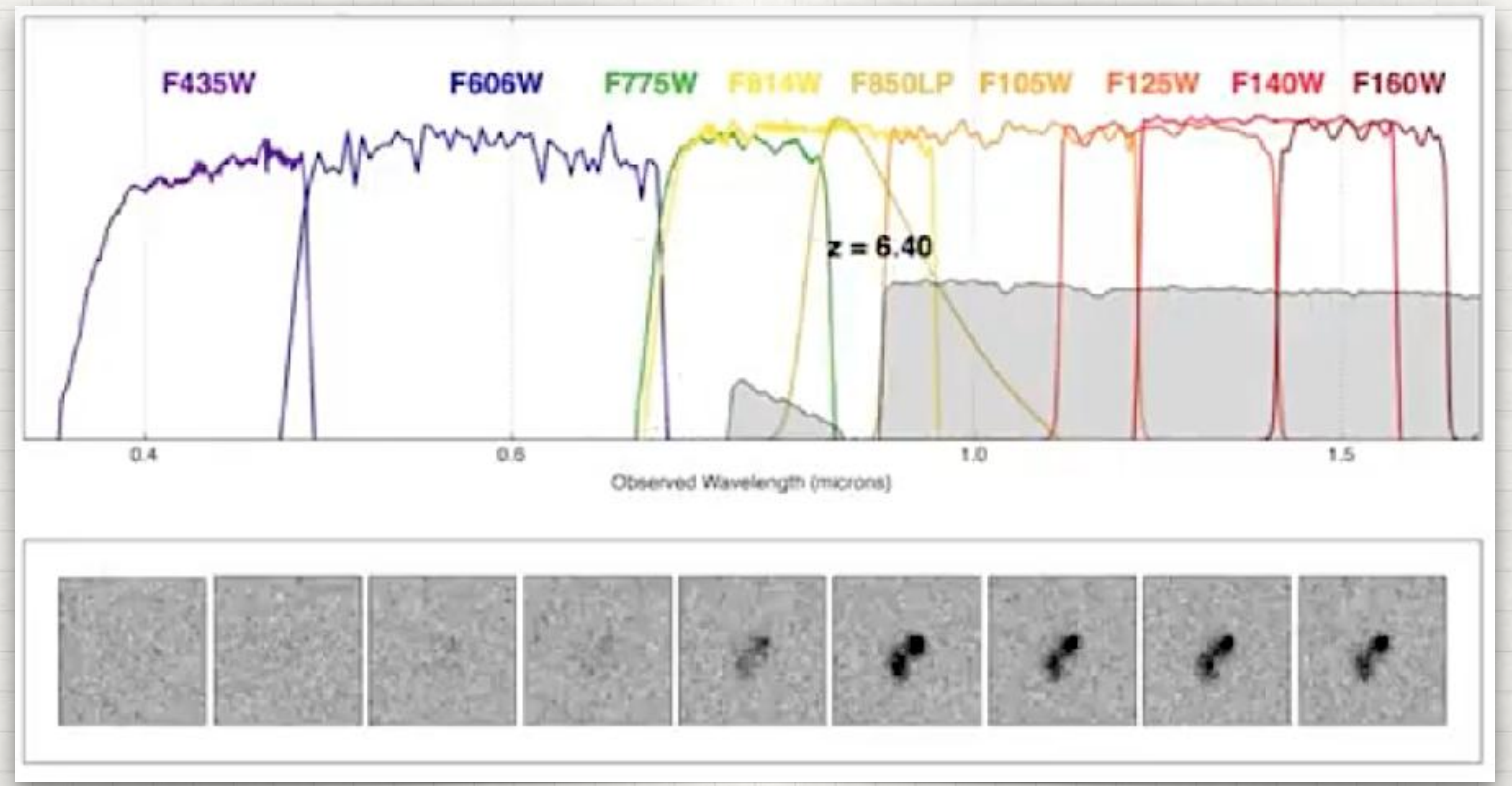

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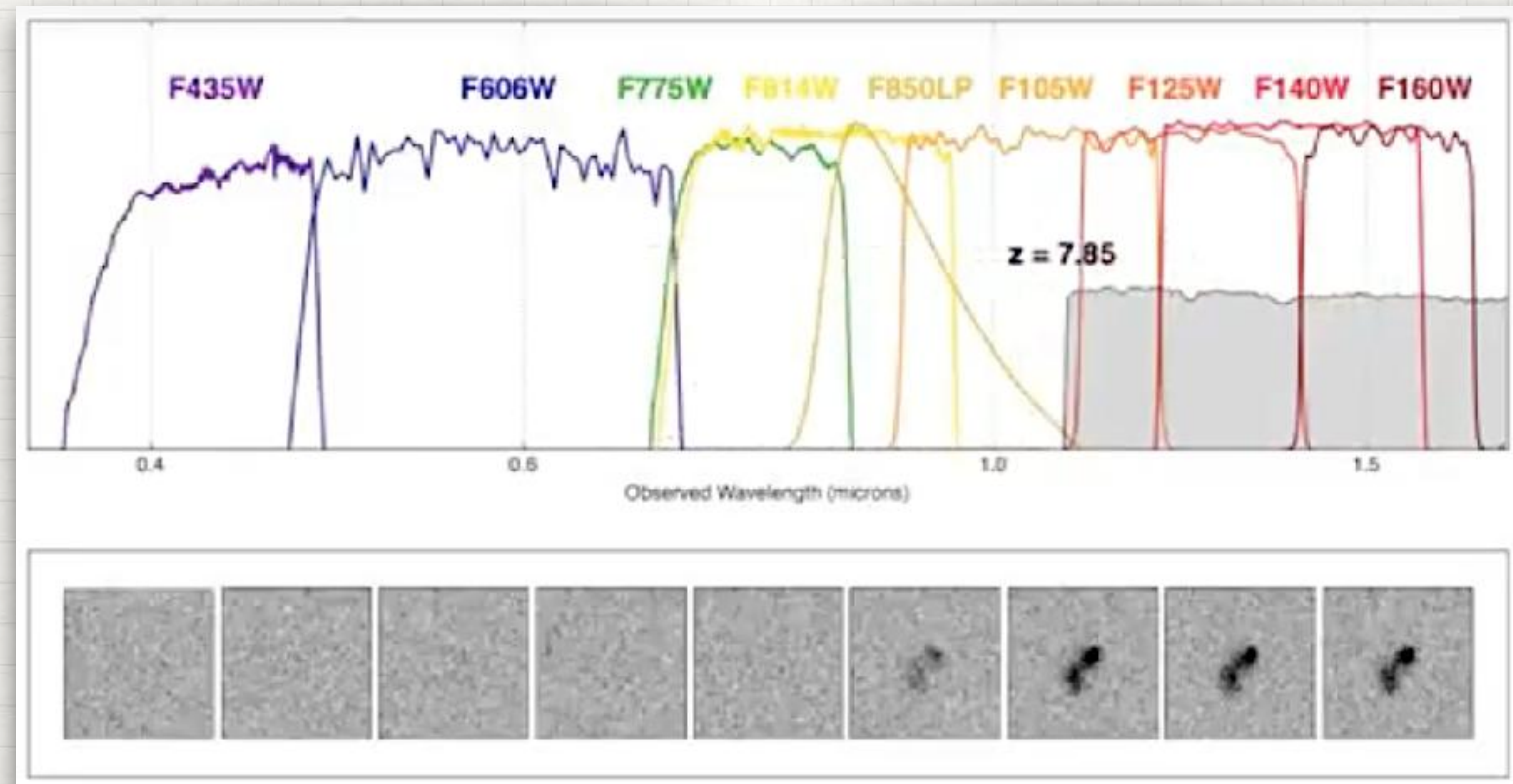

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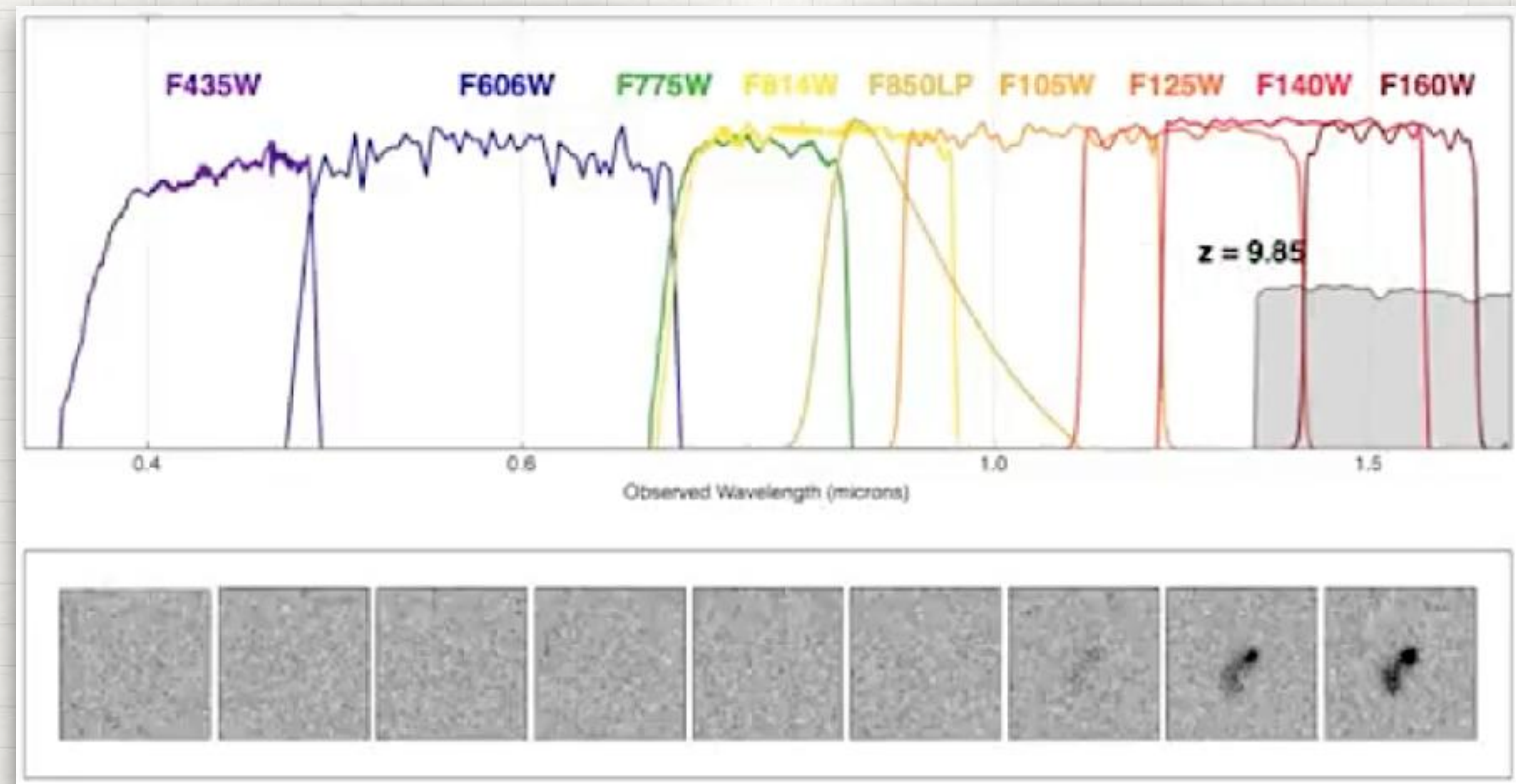

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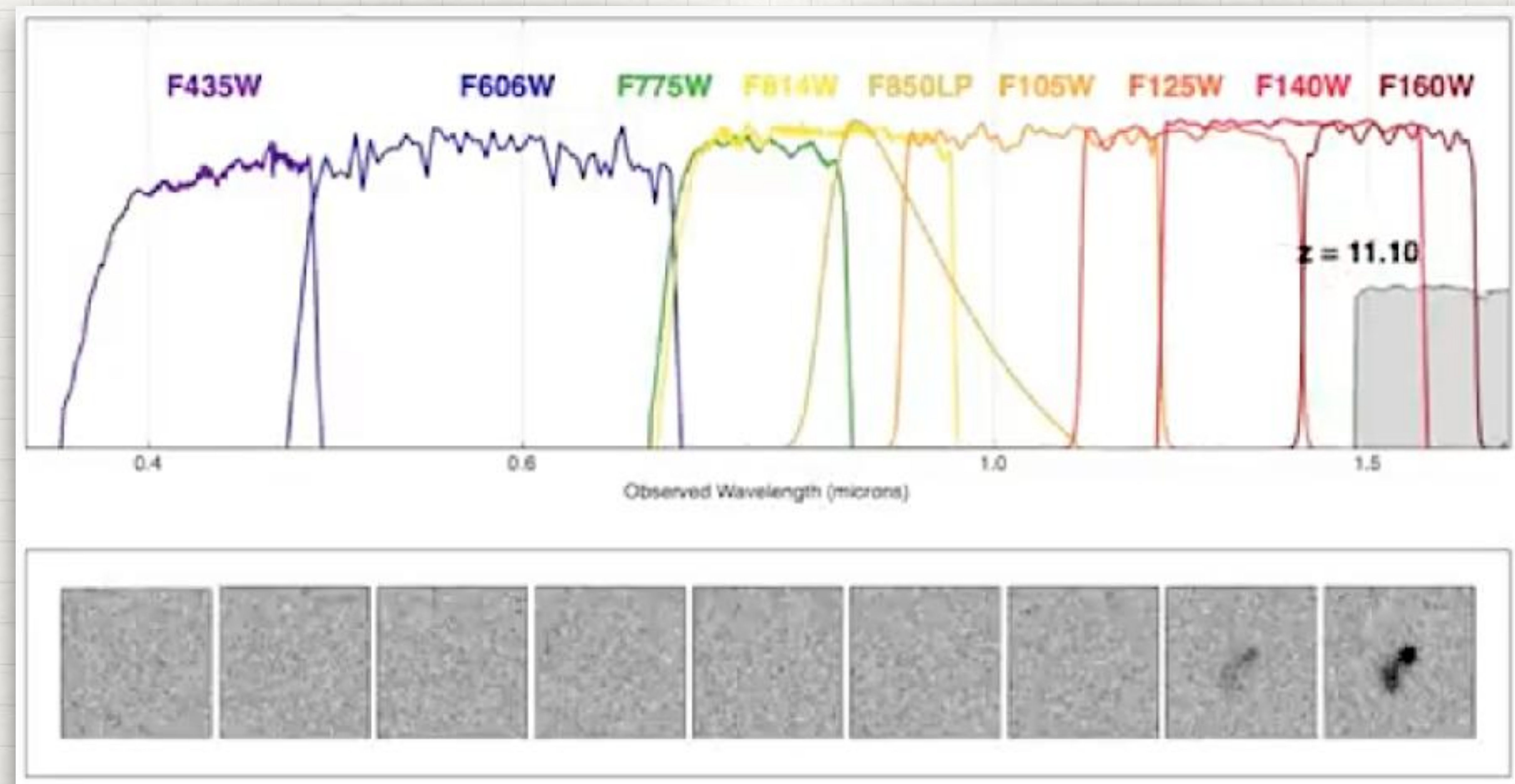

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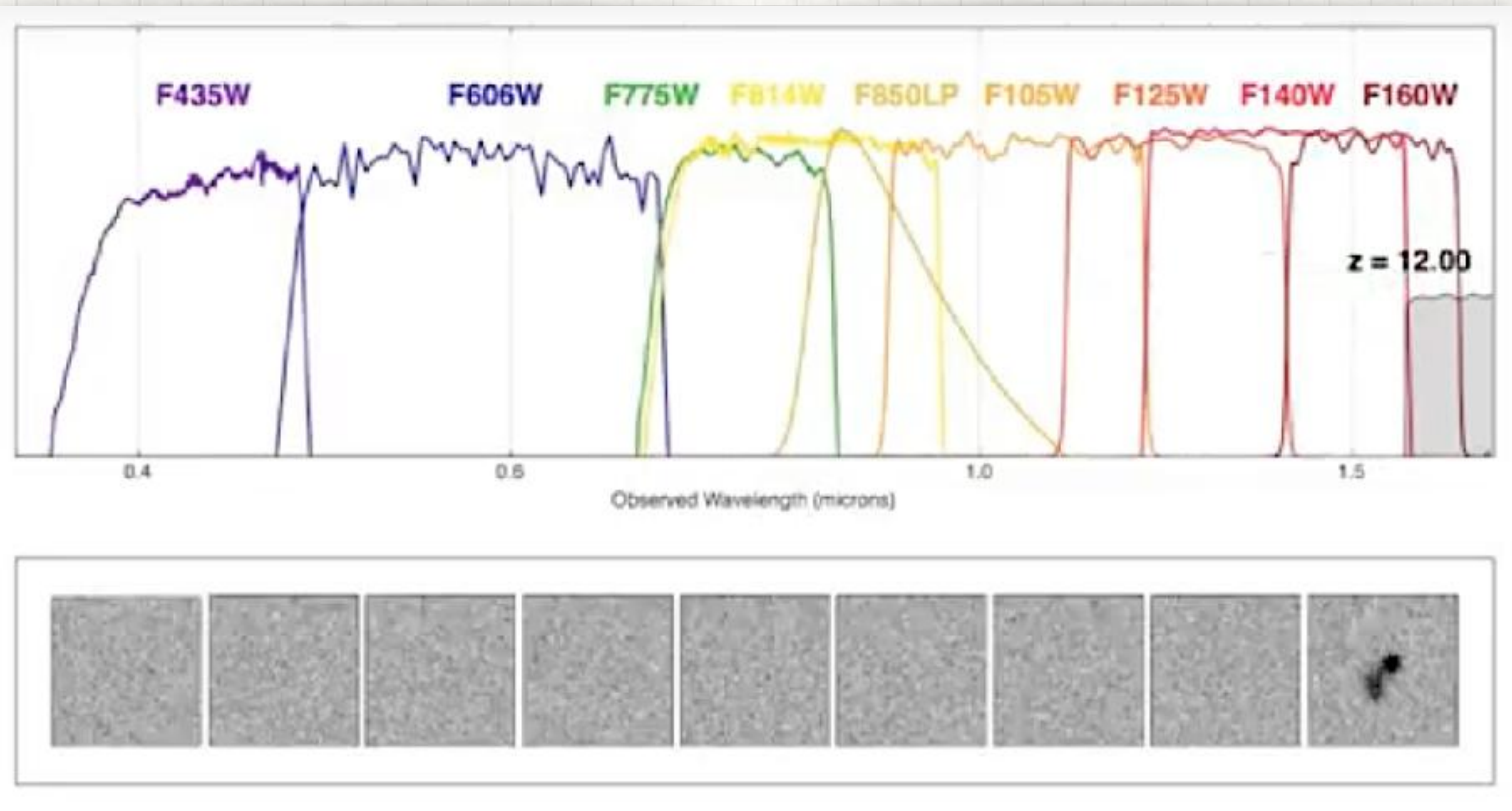

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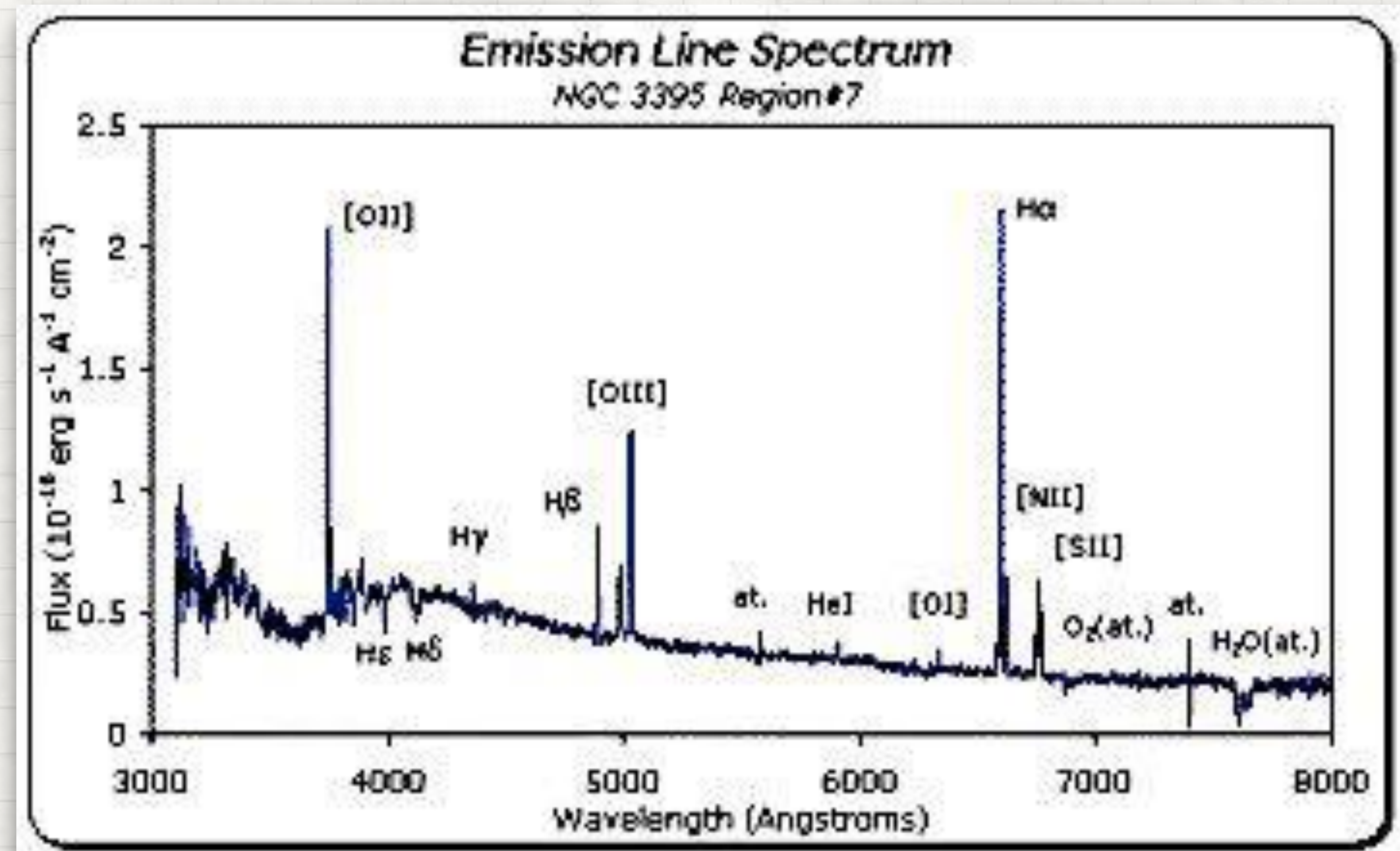


Optical spectra of a star forming region/galaxy

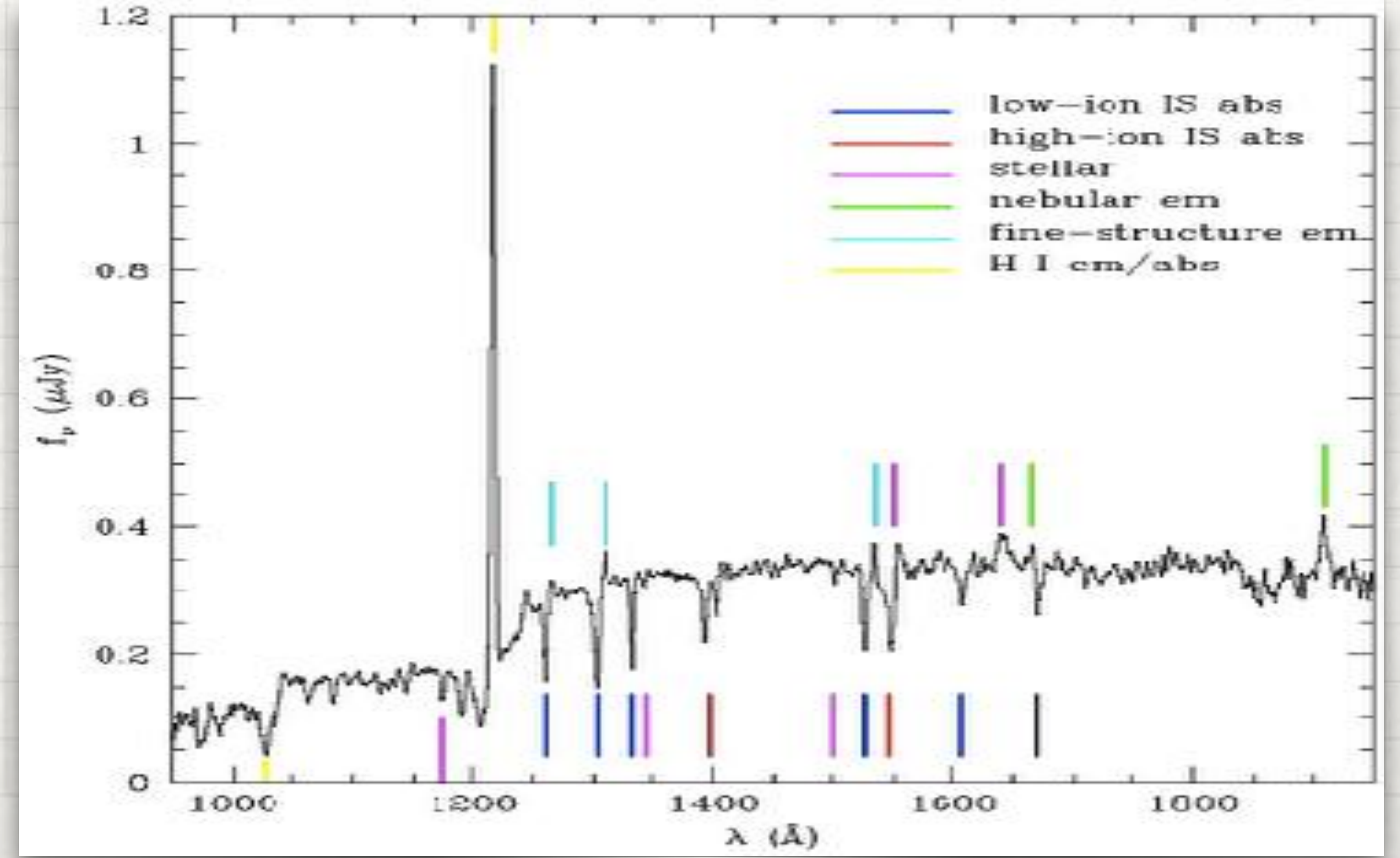
From web - credit: Robert Bachilla, Donna E. Weistrop

LENSING OF HIGH REDSHIFT GALAXIES

HOW ARE HIGH-REDSHIFT GALAXIES DETECTED?

- Spectroscopically:
  - But optical rest-frame spectra is redshifted way beyond optical spectrographs: say Hbeta or [OIII] at ~5000 A, redshifted by (1+z) close to ~10 for z~8 sources, so in mid infrared. Can't be reached from ground with the leading instruments form large observatories (covering the *near* inferred).
  - Instead, we need to look at rest frame the UV spectrum, which is redshifted into the *near* infrared:

Shapley+ 2003



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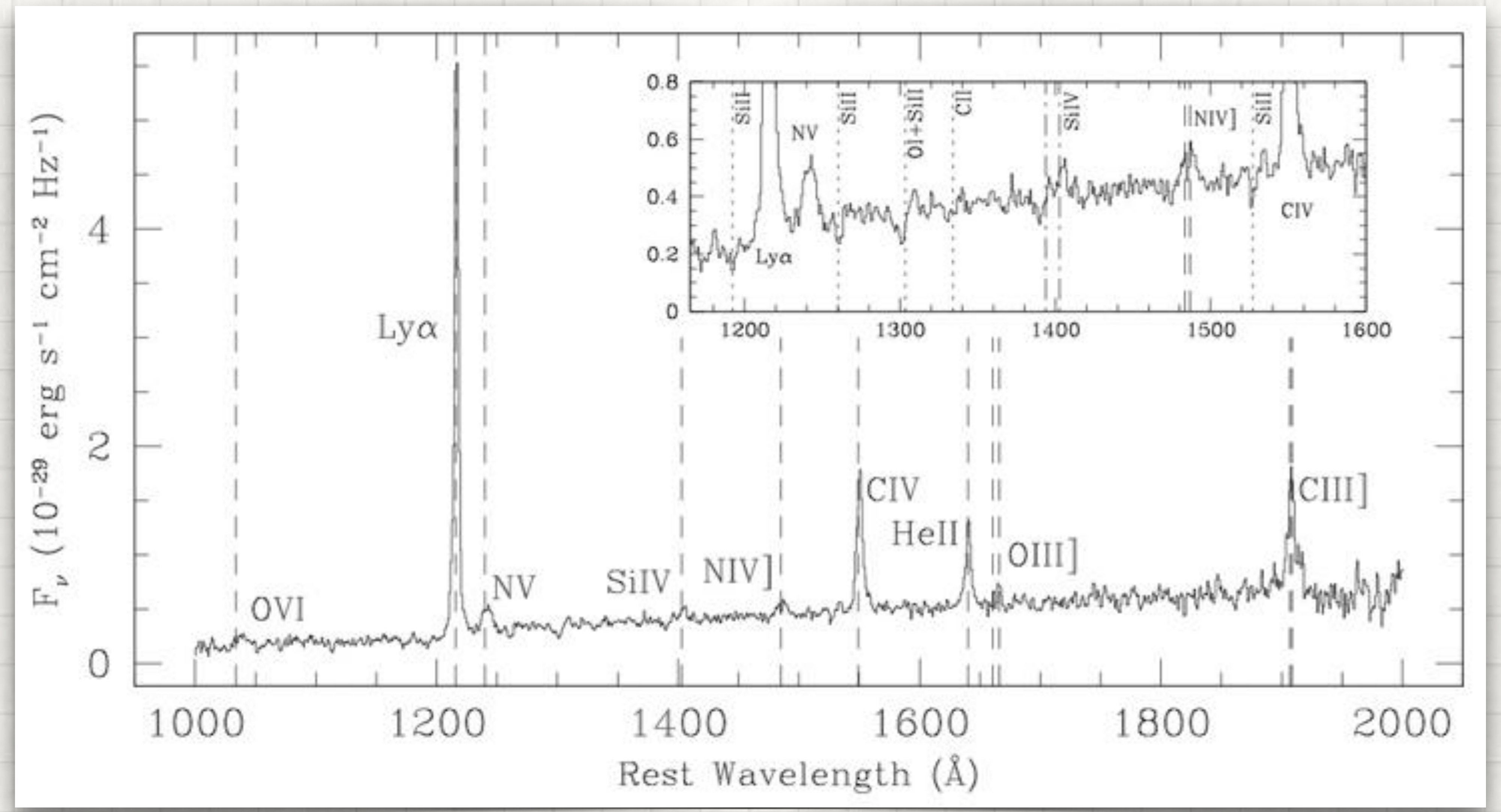


UV spectrum for a likely AGN

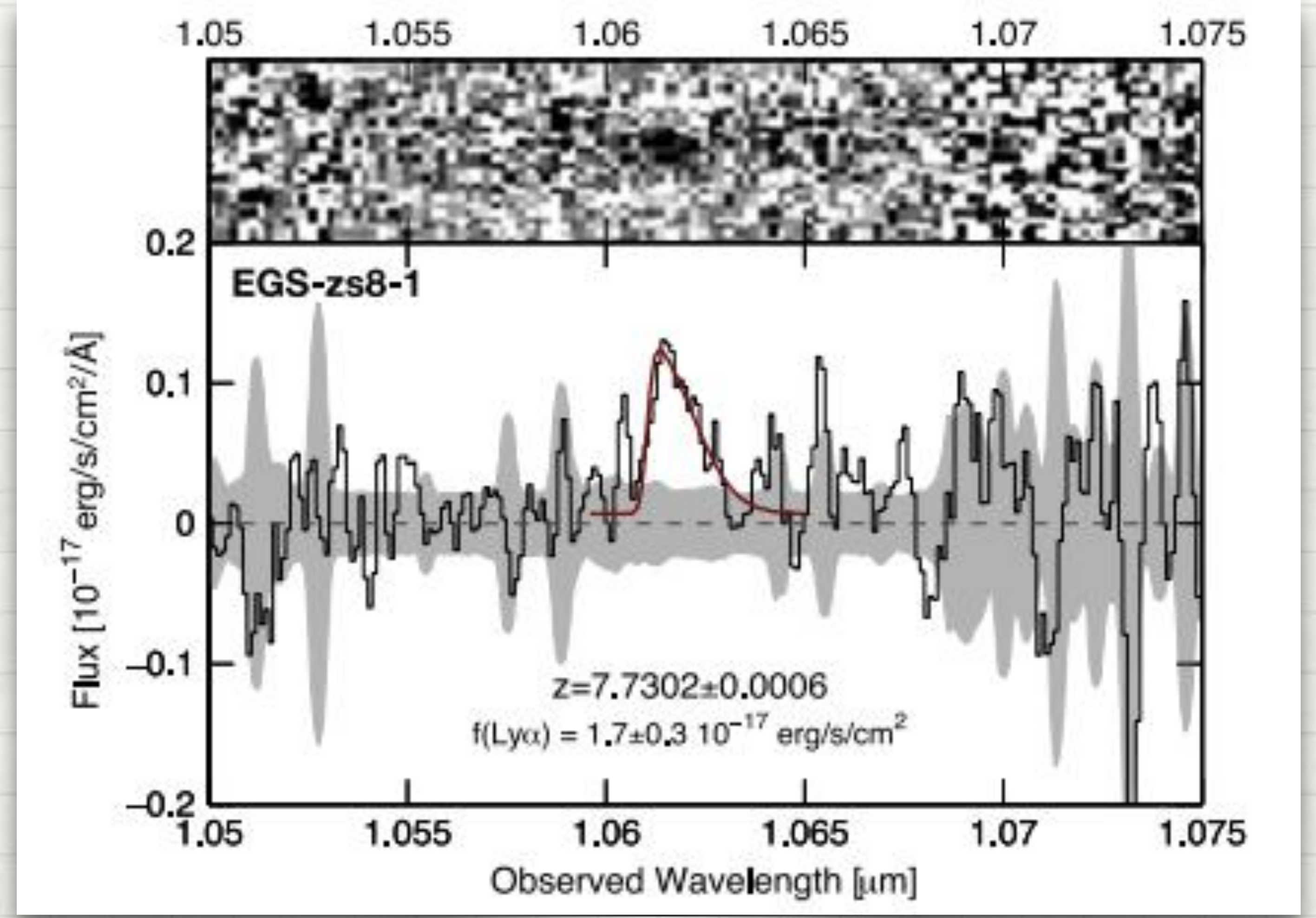
(Hainline et al. 2011)

LENSING OF HIGH REDSHIFT GALAXIES

HOW ARE HIGH-REDSHIFT GALAXIES DETECTED?

- Spectroscopically: Example, detection of Lyman alpha at z=7.73

Oesch+2015



Lyman alpha is redshifted to near infrared

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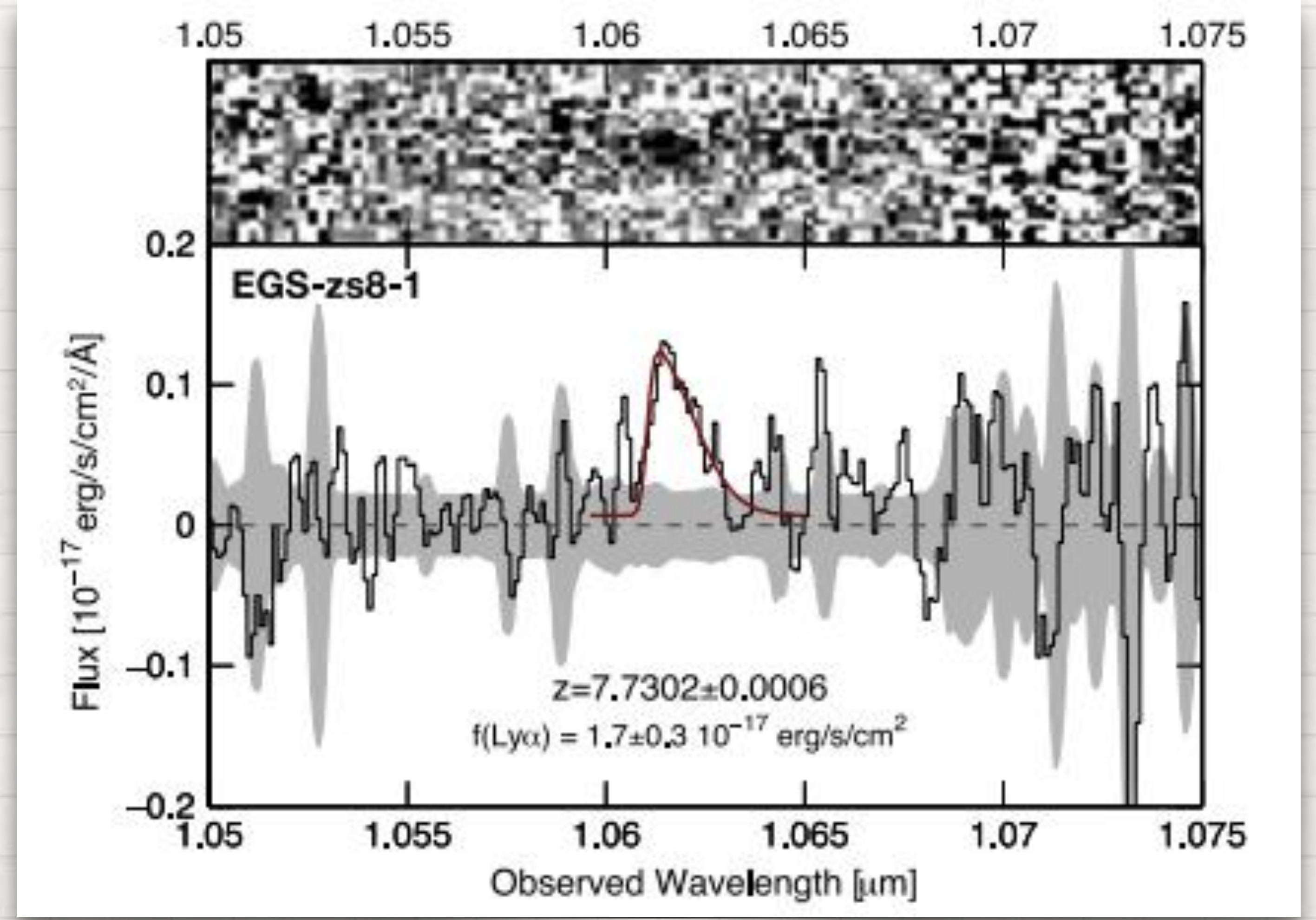


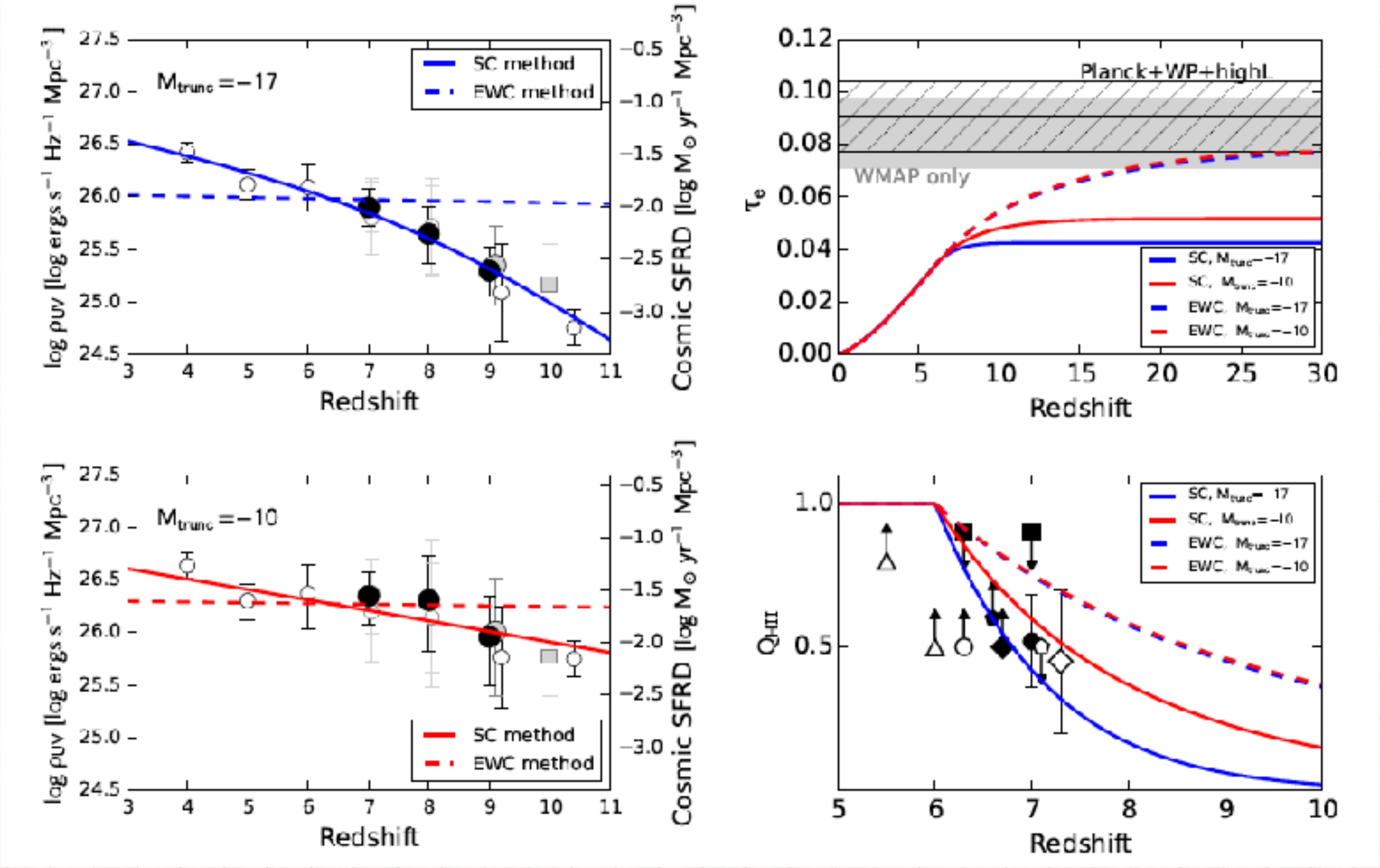
Lyman alpha is redshifted to near infrared

PS - everybody knows how Lya is formed right?

LENSING OF HIGH REDSHIFT GALAXIES

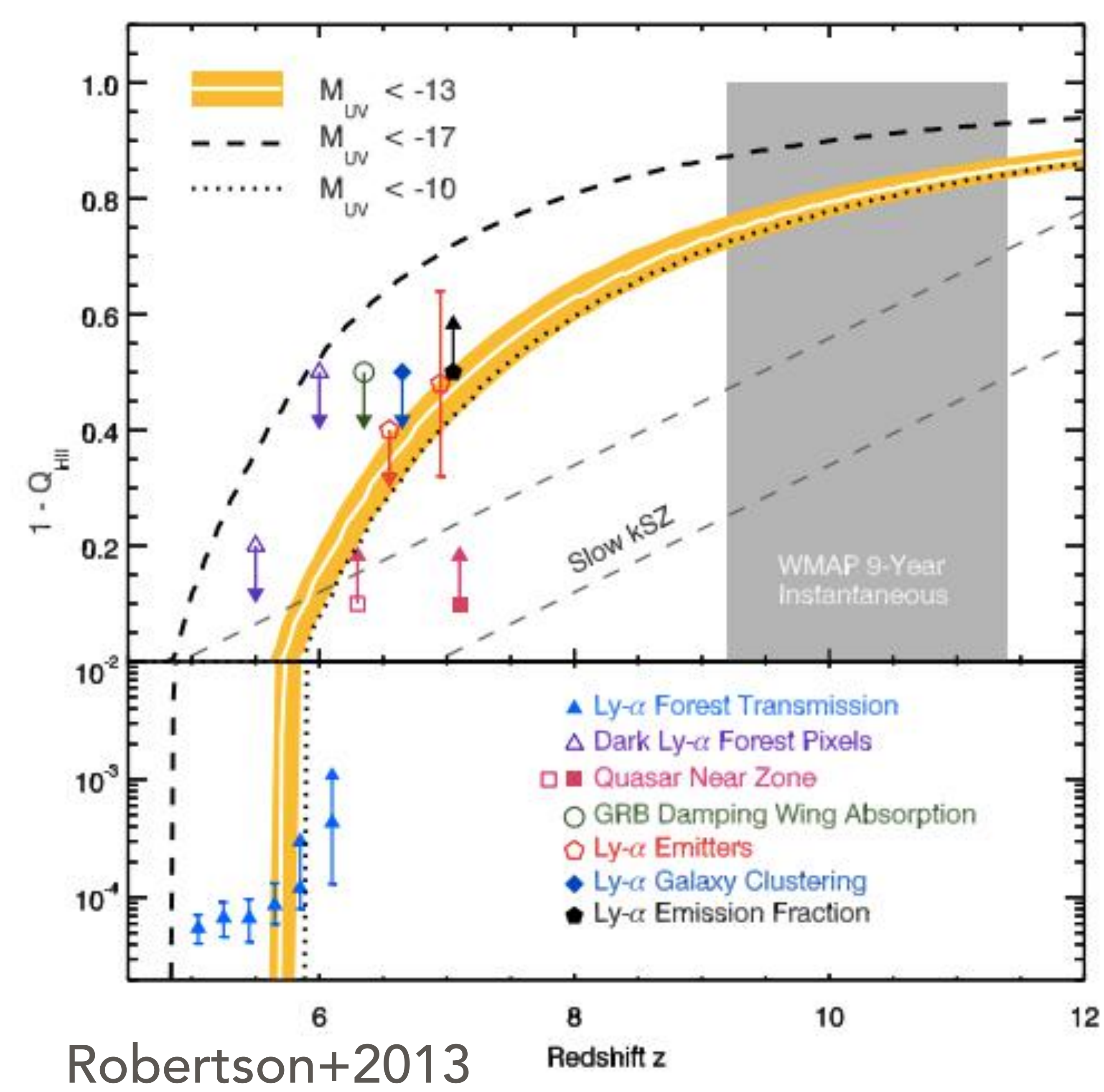
INSIGHT ON REIONIZATION HISTORY

Ishigaki+ 2015



LENSING OF HIGH REDSHIFT GALAXIES

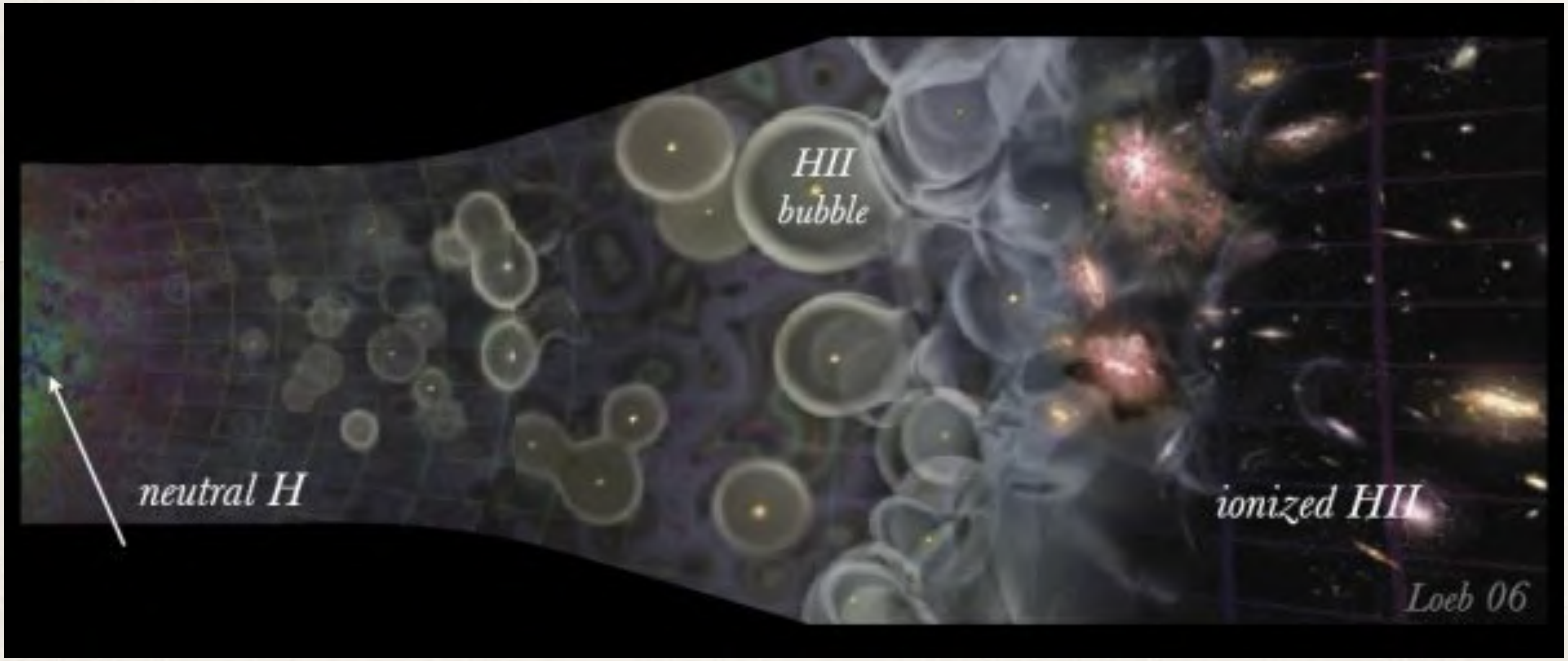
INSIGHT ON REIONIZATION HISTORY



Robertson+2013

High Objects - spectroscopy

- What does it tell us about the origin of the observed decline rate? on the neutrality of the IGM? patchiness? the ionizing sources?



Escape of Lya emission form High galaxies

- Size of Ionizing bubbles around such a bright galaxy at high-z is order Mpc:

Haiman (2002) gives the radius of an HII region R_s in a uniform IGM with neutral fraction $f_{\rm HI}$ around a star forming galaxy with star formation rate of $\dot{M}_*$,

$$R_s = 0.65 \left(\frac{\dot{M}_*}{40\ M_\odot {\rm yr}^{-1}}\right)^{1/3} \left(\frac{t_*}{10^7{\rm yr}}\right)^{1/3} f_e^{1/3} f_{\rm HI}^{-1/3} \left(\frac{1+z}{7}\right)^{-1} \text{proper Mpc}, \quad (15)$$

where t_* is the duration of the starburst, and f_e is the escape rate of Lyman Limit photons.

- —> just about enough to indeed make Lya escape beyond damp wing:

$$\tau(\Delta\lambda) = \frac{\tau_0 R_\alpha}{\pi} \int_{\Delta\lambda/\lambda}^{\infty} \frac{d(V/c)}{(V/c)^2 + R_\alpha^2} \cdot$$

or for reasonable $\left(\frac{\Delta\lambda}{\lambda}\right)$

(MiraldaEscude)

$$\tau(\Delta\lambda) = \frac{\tau_0 R_\alpha}{\pi} \left(\frac{\Delta\lambda}{\lambda}\right)^{-1} = 1.3 \times 10^{-3} \times \frac{\Omega_b h(1-Y)}{0.03} \frac{H_0(1+z)^{3/2}}{H(z)} \left(\frac{1+z}{6}\right)^{3/2} \left(\frac{\Delta\lambda}{\lambda}\right)^{-1}$$

for reaching as low as say tau ~0.5, requires $\left(\frac{\Delta\lambda}{\lambda}\right)$ ~10^-2; **which is ~1 Mpc (about 10 comoving Mpc)**

LENSING OF HIGH REDSHIFT GALAXIES

LENSING

SUMMARY

- All background is lensed to some extent
- Lensing effects and size of lens depend on mass and on distances, and position of source
- By how much something is lensed? Deflection angle formula for point mass:

$$\hat{\alpha} = \frac{4GM}{c^2 b}$$

- Alpha is constrained with multiple images through lens equation (SL): $\boldsymbol{\beta} = \boldsymbol{\theta} - \frac{D_{LS}}{D_{OS}} \hat{\boldsymbol{\alpha}}$.
- Alpha is then related to the mass distribution through: $\vec{\nabla}_\theta \vec{\alpha}(\vec{\theta}) = 2\kappa(\vec{\theta})$
- Shear is constrained in WL regime through ellipticity measurements, also invertible to kappa
- Magnification is given by

$$\mu = \frac{1}{\det A} = \frac{1}{[(1-\kappa)^2 - \gamma^2]}$$

LENSING

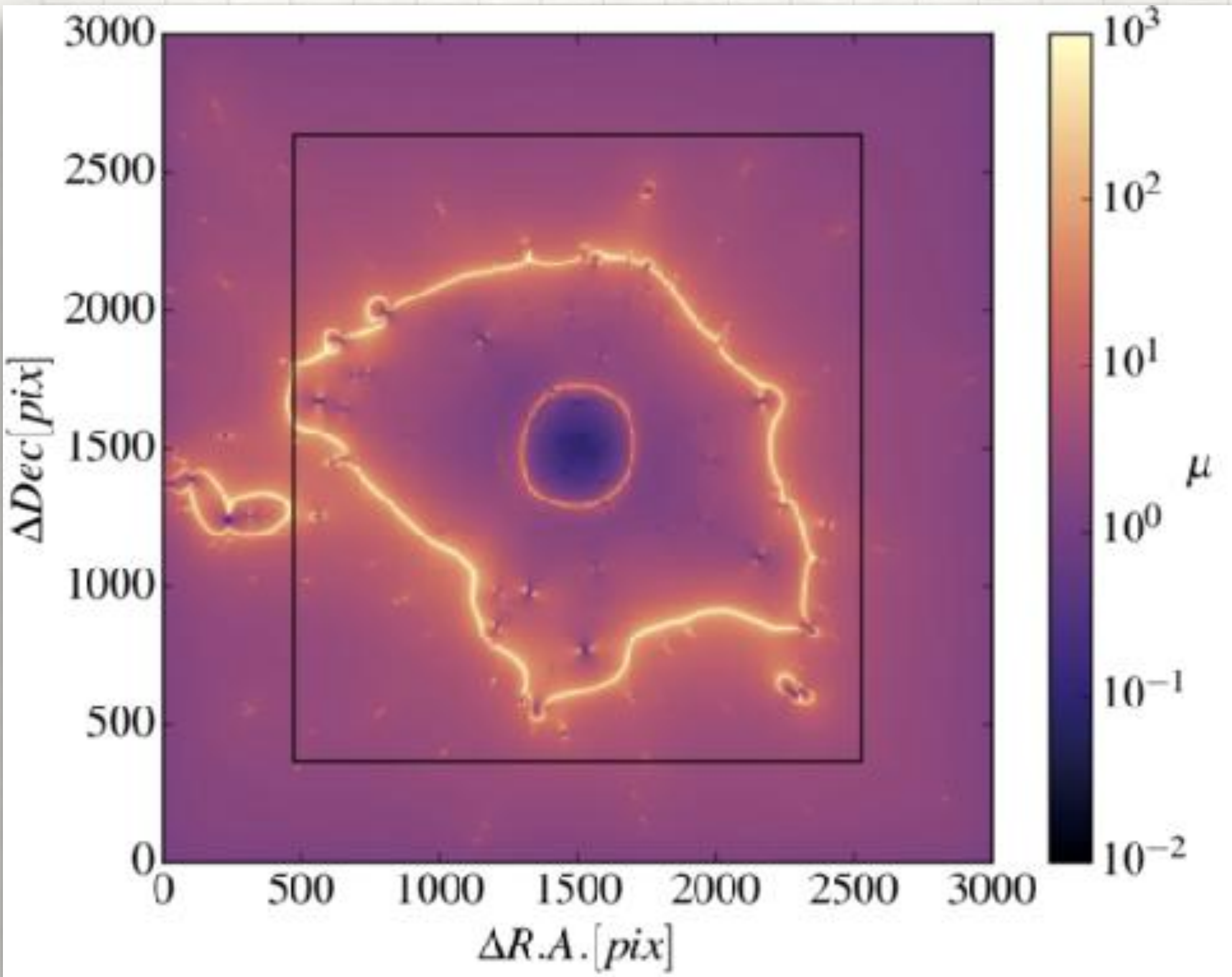
SUMMARY

- With lensing we can:
- **Map the mass distribution of lens, including dark matter** (via multiple images, shear), probe cosmological parameters (via distances), H_0 (via time delays), constraints on DM particles (microlensing and caustic crossing events), other transient phenomena (lensed SNe, gravitational waves)
- Study **high-redshift galaxies** and reionization (magnification, spectroscopy of high redshift galaxies) —> our next theme.

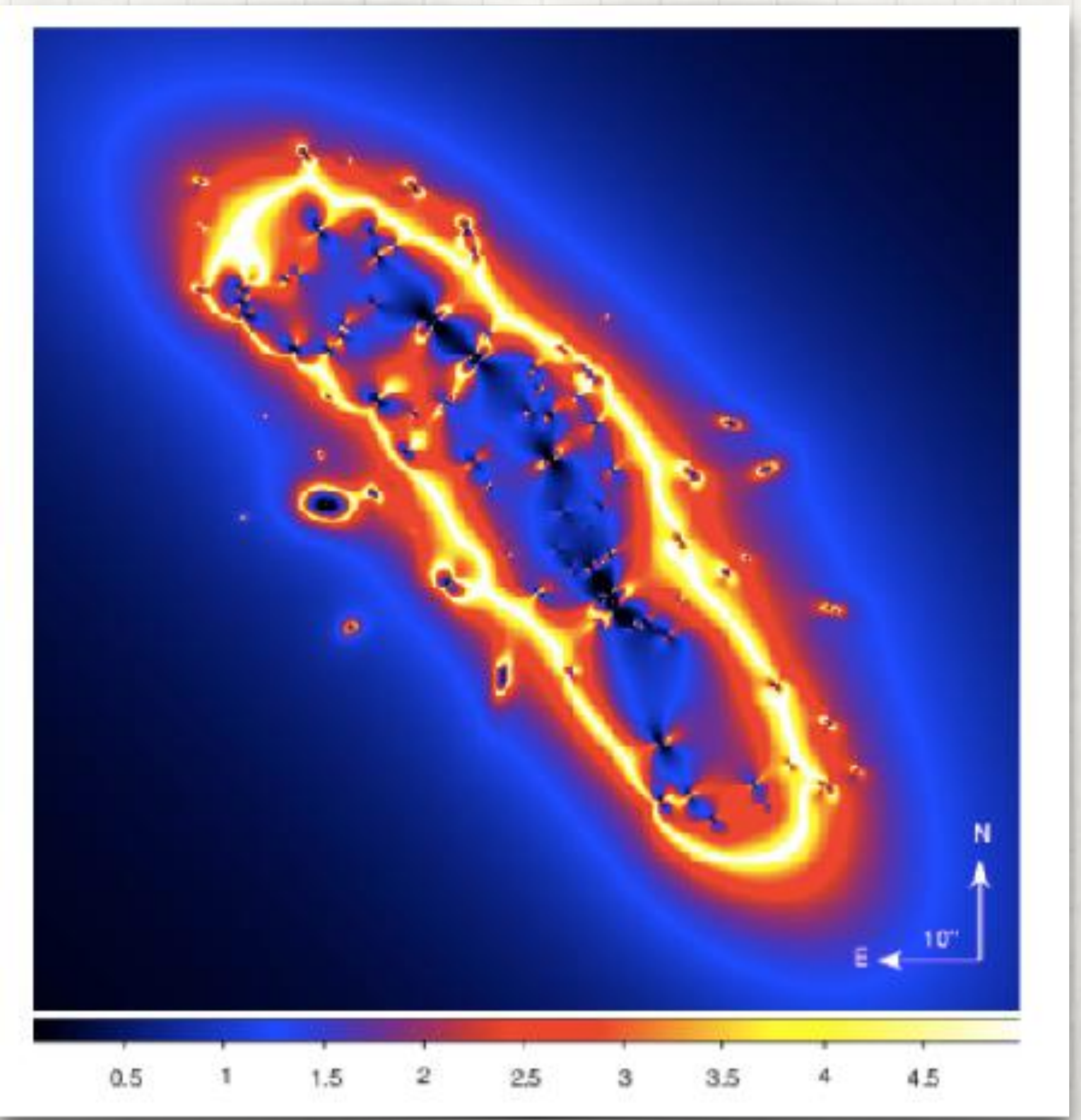
LENSING OF HIGH REDSHIFT GALAXIES

KEY POINT: BACKGROUND HIGHZ GALAXIES ARE MAGNIFIED!

Magnification map for MACS0308
Acebron+ 2018



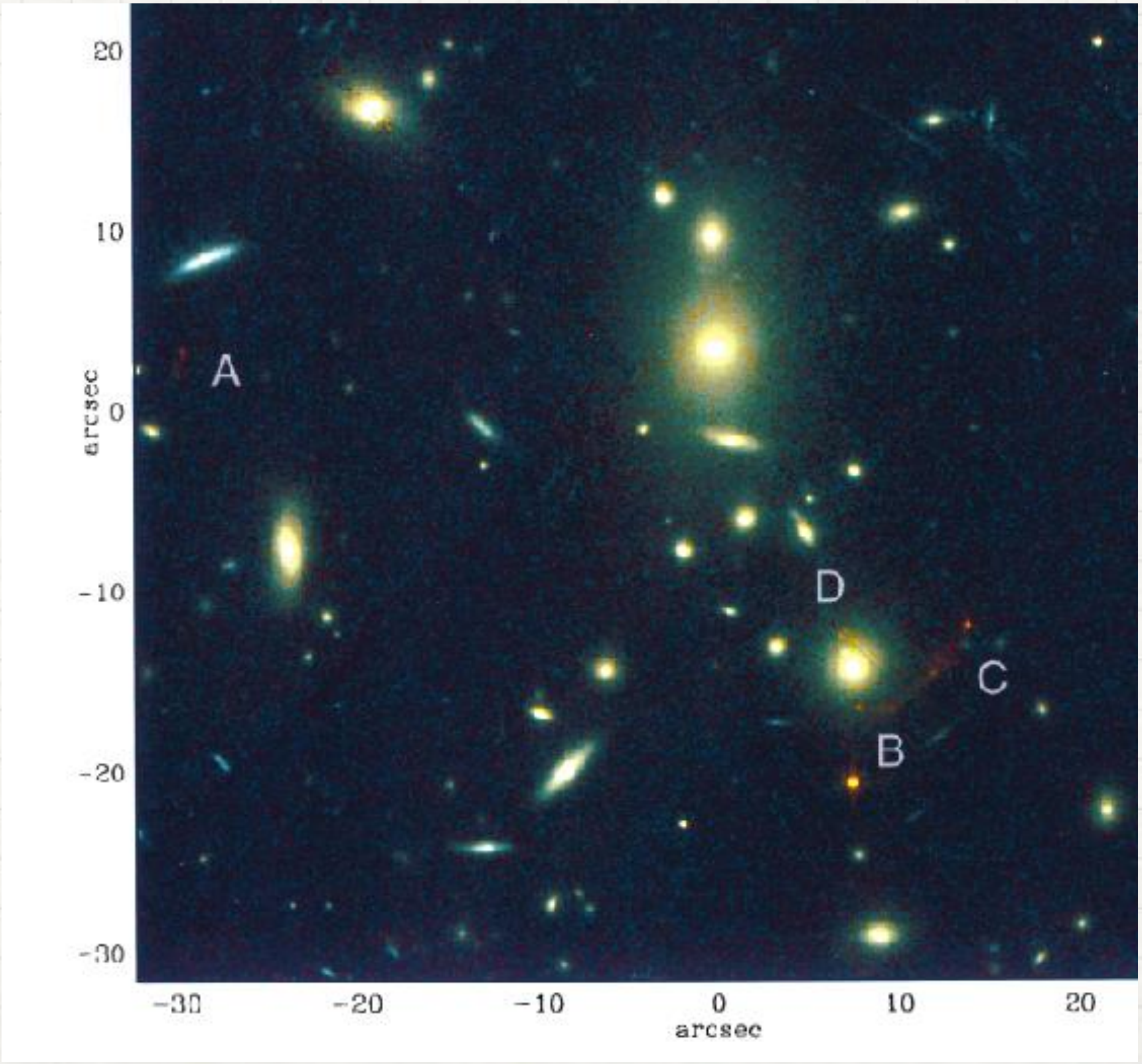
Magnification map for MACS0416
Jauzac+ 2014



LENSING OF HIGH REDSHIFT GALAXIES

KEY POINT: BACKGROUND HIGHZ GALAXIES ARE MAGNIFIED!

Some examples:
Franx+1997 (z=4.92)

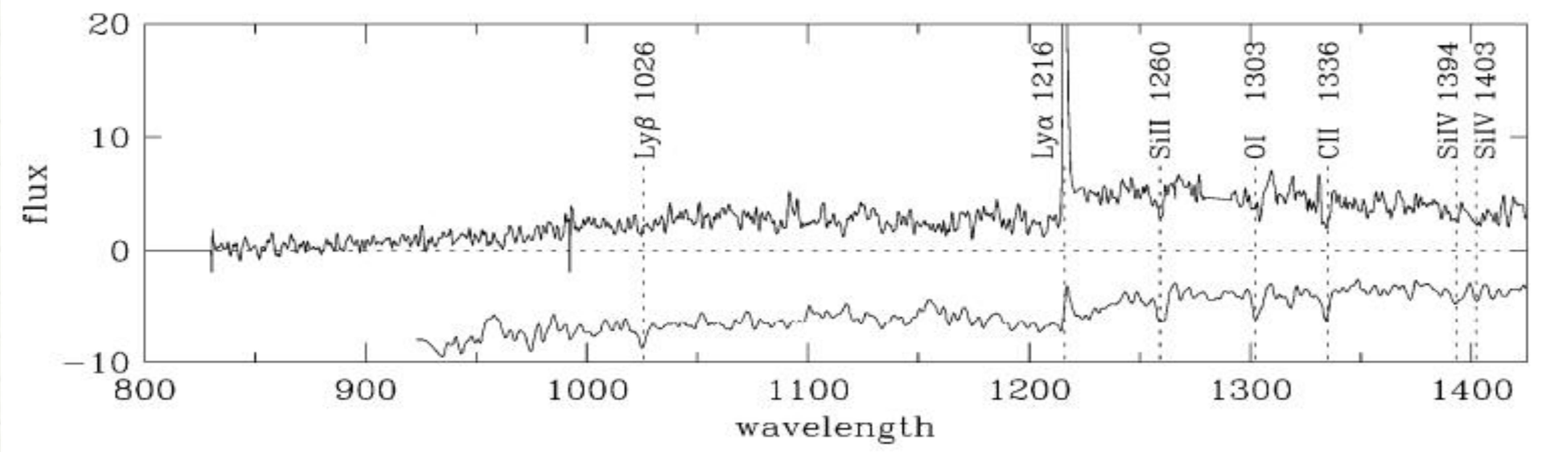


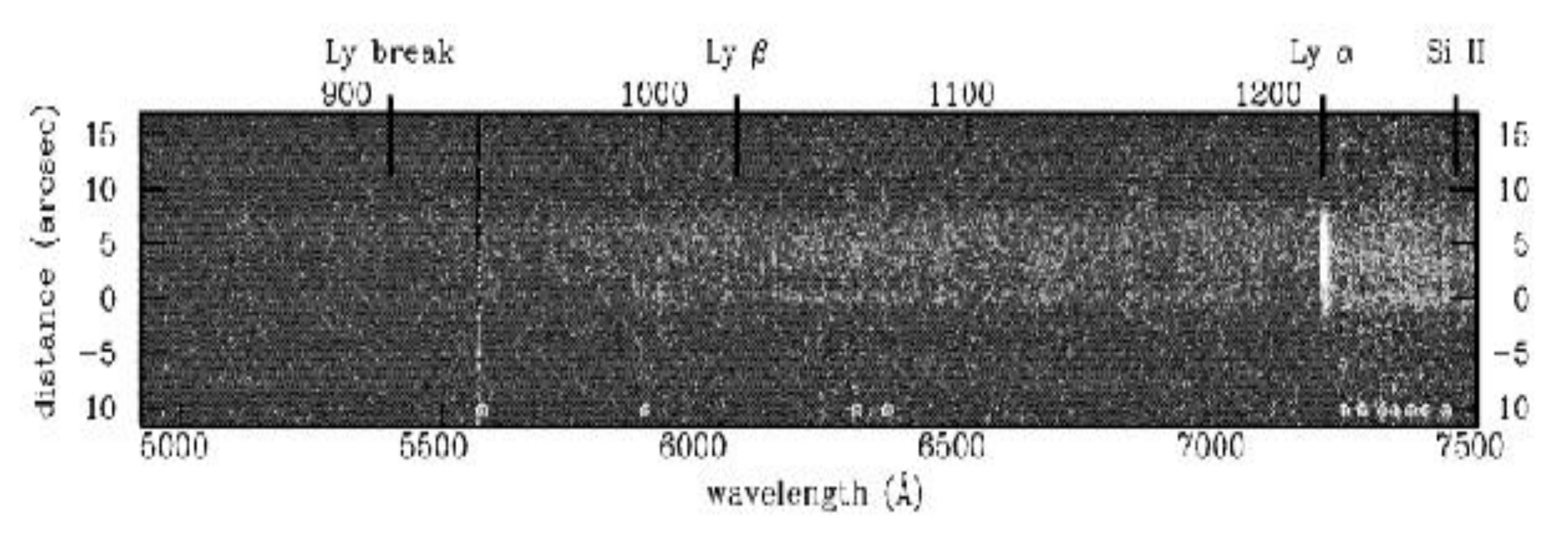
Why red?
(dropout)

LENSING OF HIGH REDSHIFT GALAXIES

KEY POINT: BACKGROUND HIGHZ GALAXIES ARE MAGNIFIED!

Some examples:
Franx+1997 (z=4.92)





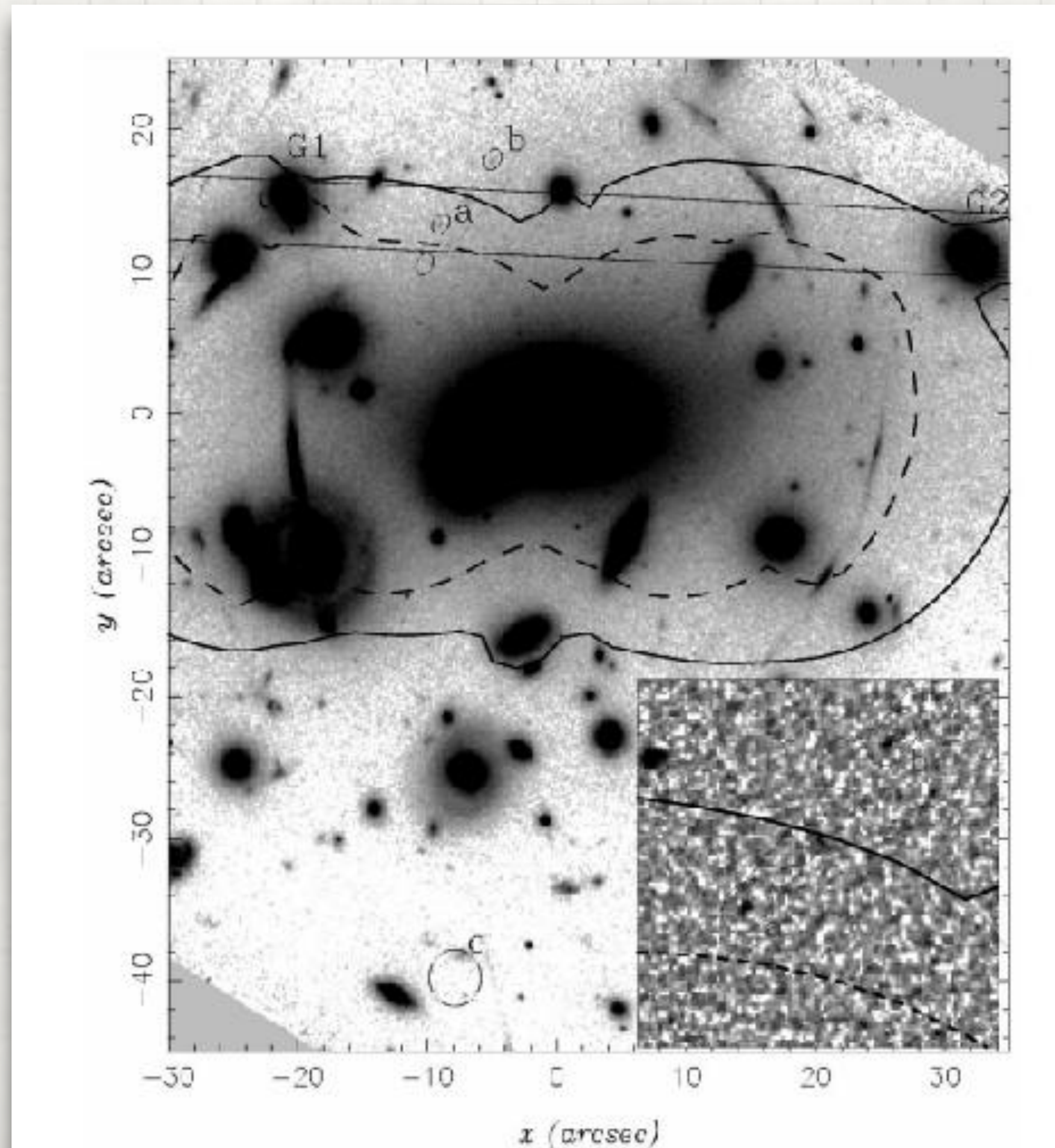
Spectrum of one of the images

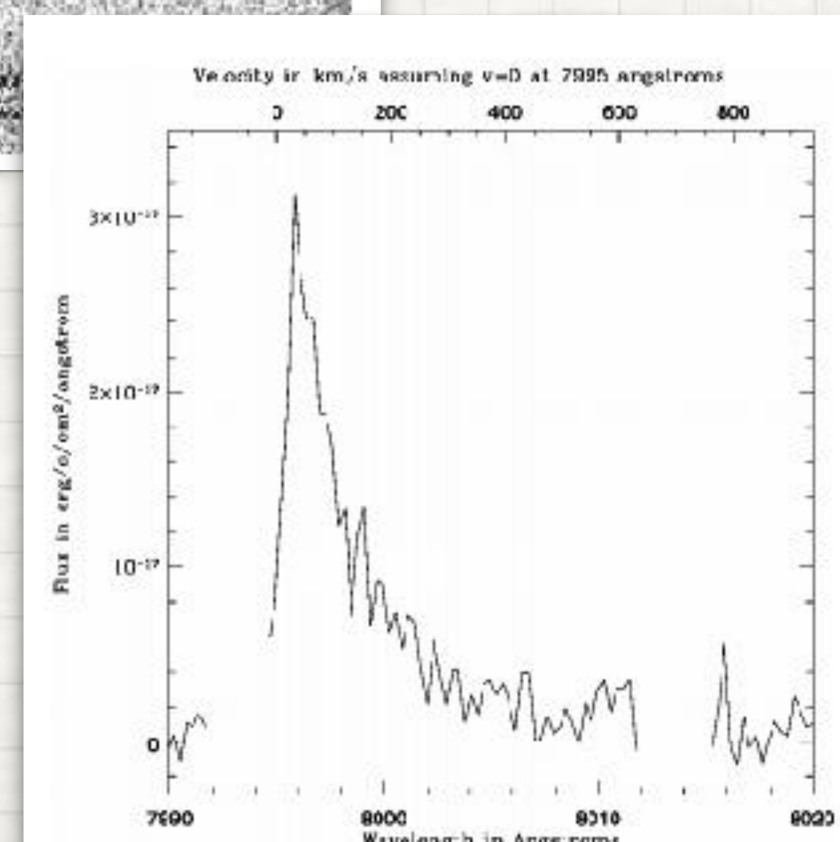
LENSING OF HIGH REDSHIFT GALAXIES

KEY POINT: BACKGROUND HIGHZ GALAXIES ARE MAGNIFIED!

Some examples:

Ellis+2001 (z=5.576)

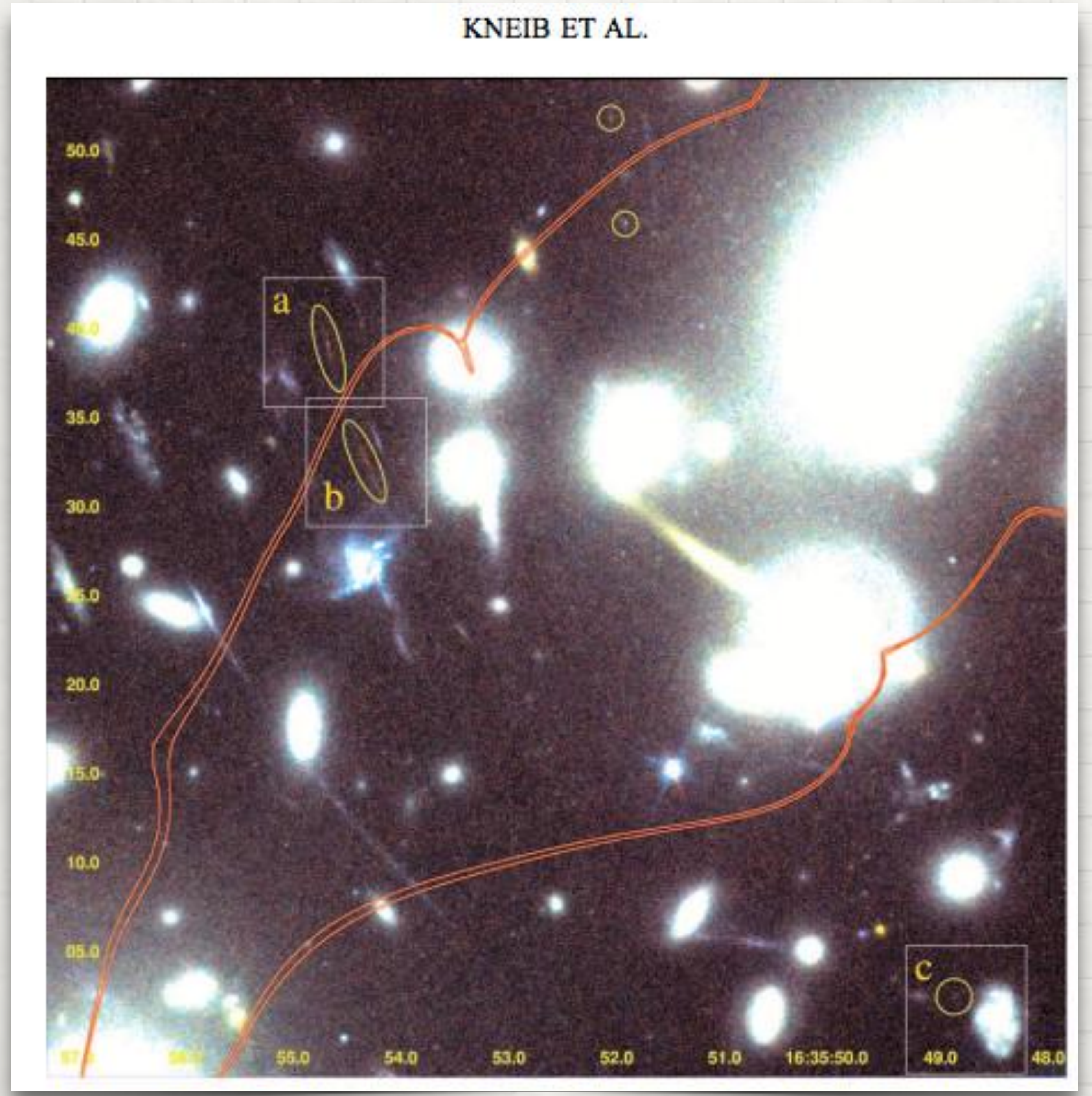




LENSING OF HIGH REDSHIFT GALAXIES

KEY POINT: BACKGROUND HIGHZ GALAXIES ARE MAGNIFIED!

Some examples:
Kneib+2004 (z~7)

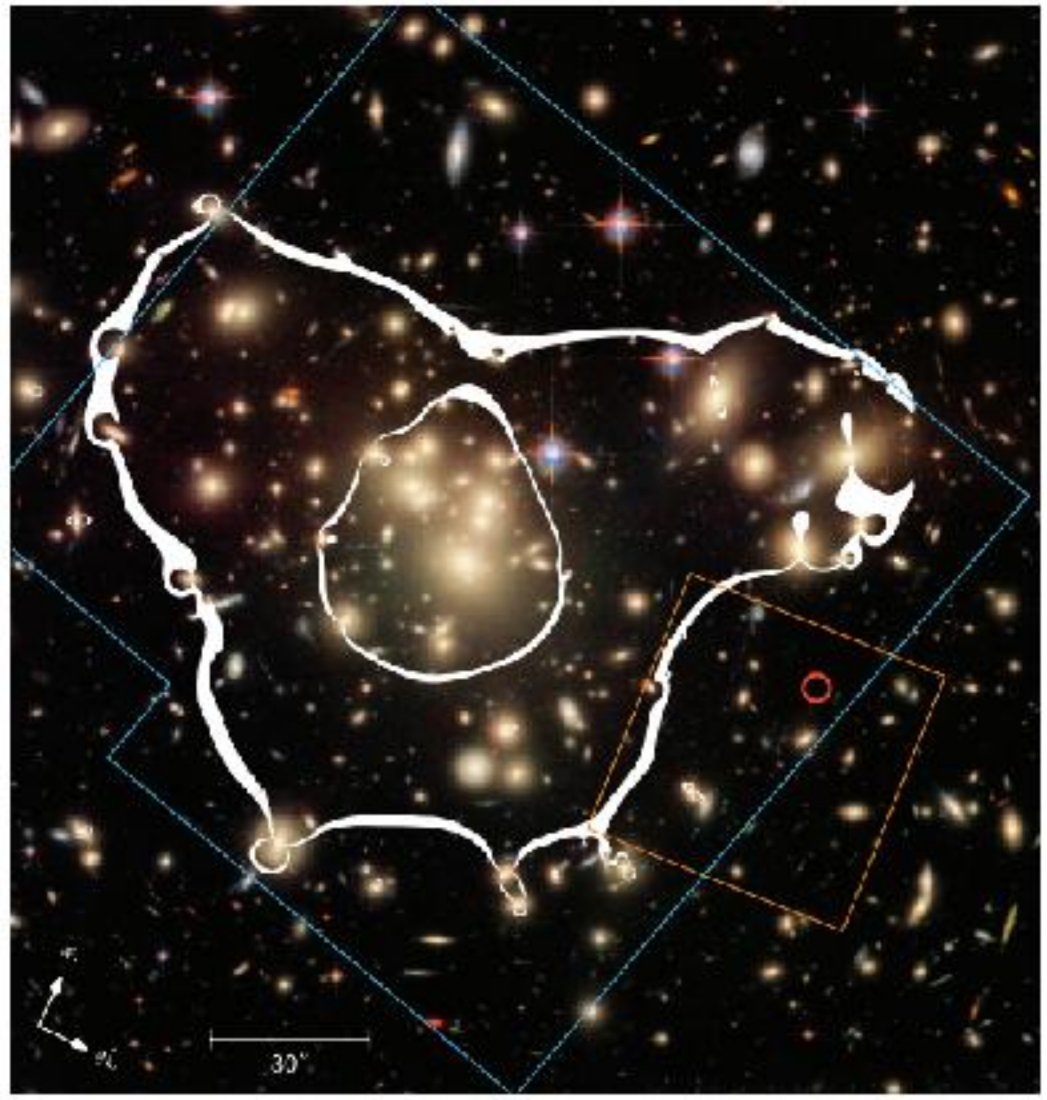


Spectrum taken but
no Lya seen, as is often the case

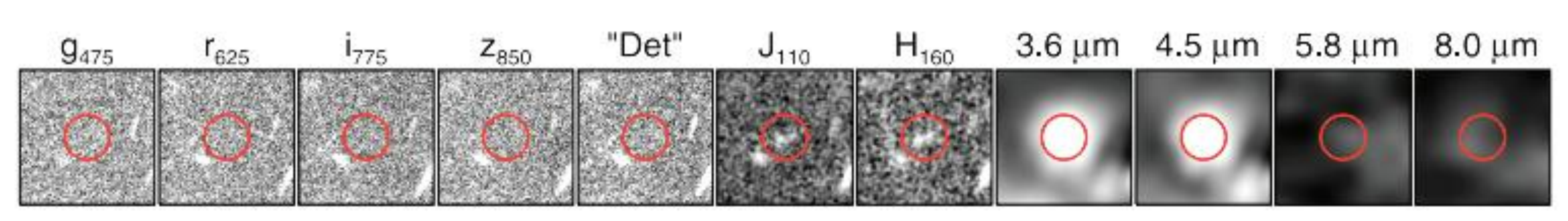
LENSING OF HIGH REDSHIFT GALAXIES

KEY POINT: BACKGROUND HIGHZ GALAXIES ARE MAGNIFIED!

Some examples:
Bradley+2008 (z~7.6)



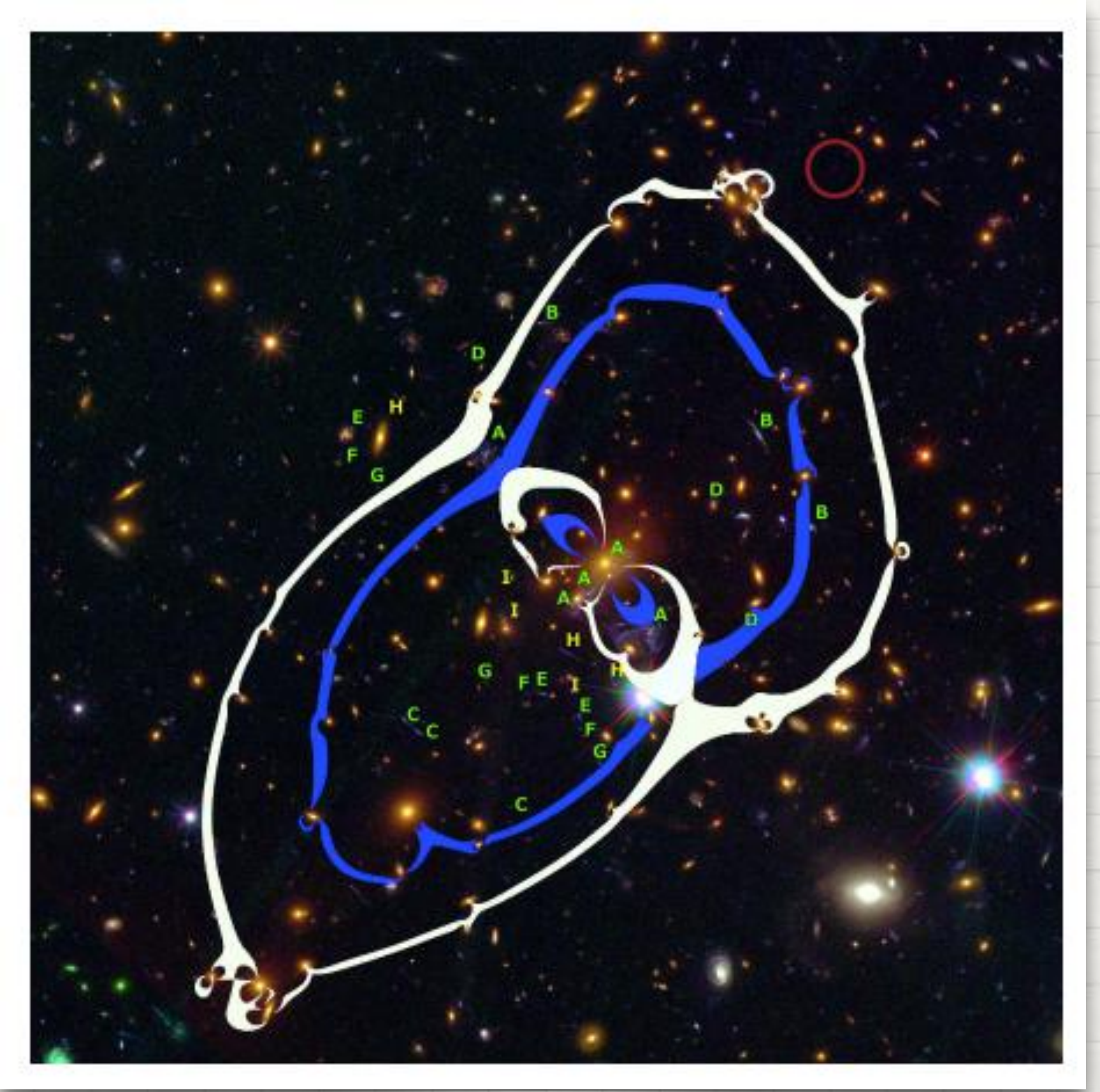
z_850 Dropout:



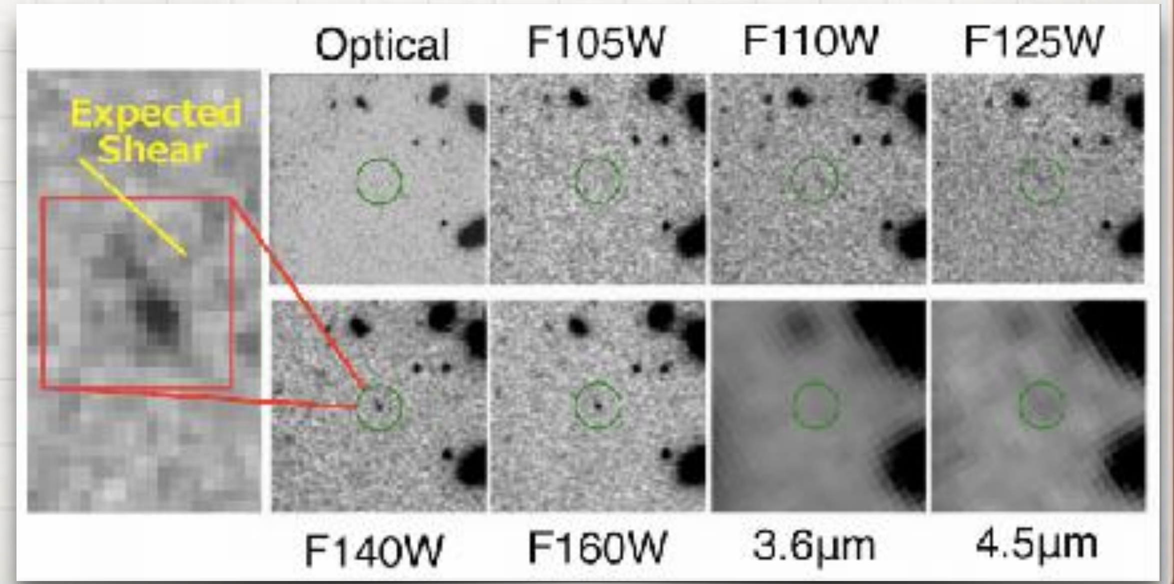
LENSING OF HIGH REDSHIFT GALAXIES

KEY POINT: BACKGROUND HIGHZ GALAXIES ARE MAGNIFIED!

Some examples:
Zheng+2009 (z~9.6)



J_110 Dropout:



LENSING OF HIGH REDSHIFT GALAXIES

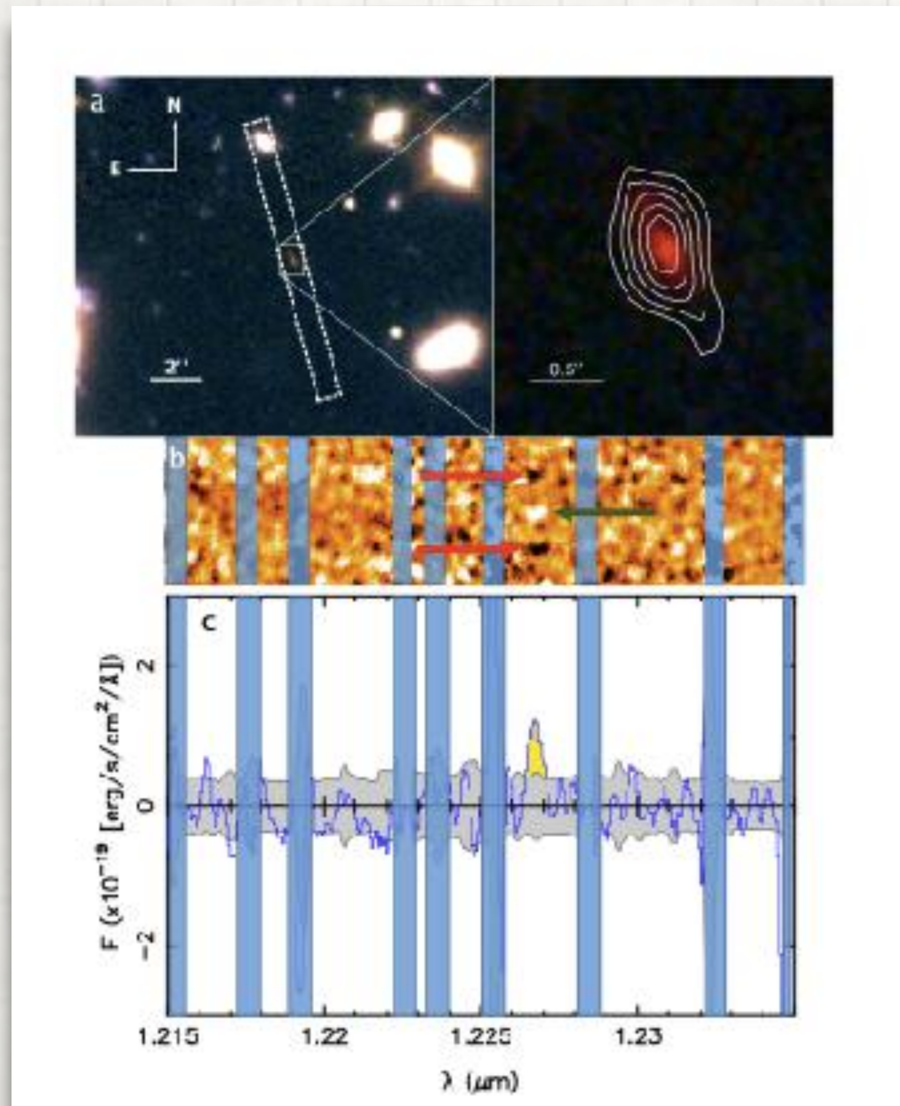
KEY POINT: BACKGROUND HIGHZ GALAXIES ARE MAGNIFIED!

Some examples:
Zheng+2009 (z~9.5)

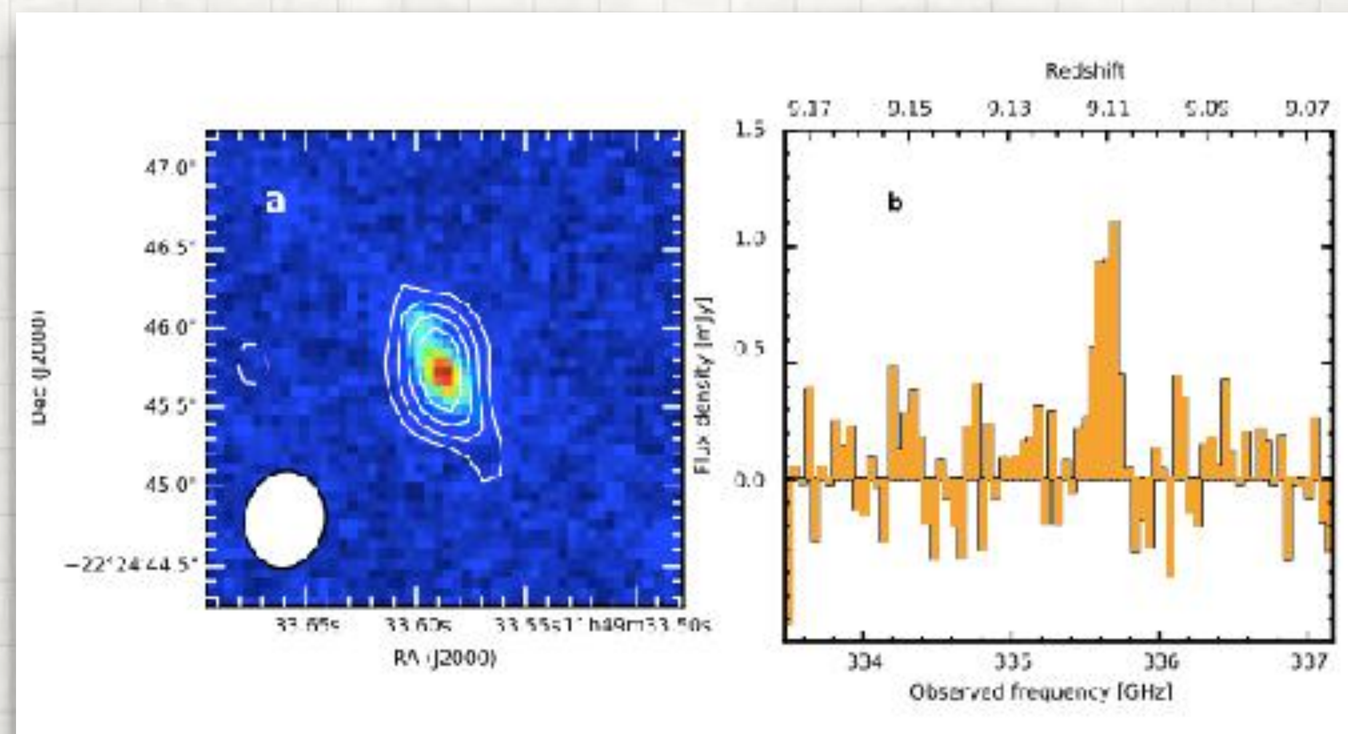
Later verified spectroscopically at z=9.11
(farthest galaxy known verified spectroscopically via Lya)

Hashimoto+ 2018

Lya



[OIII]

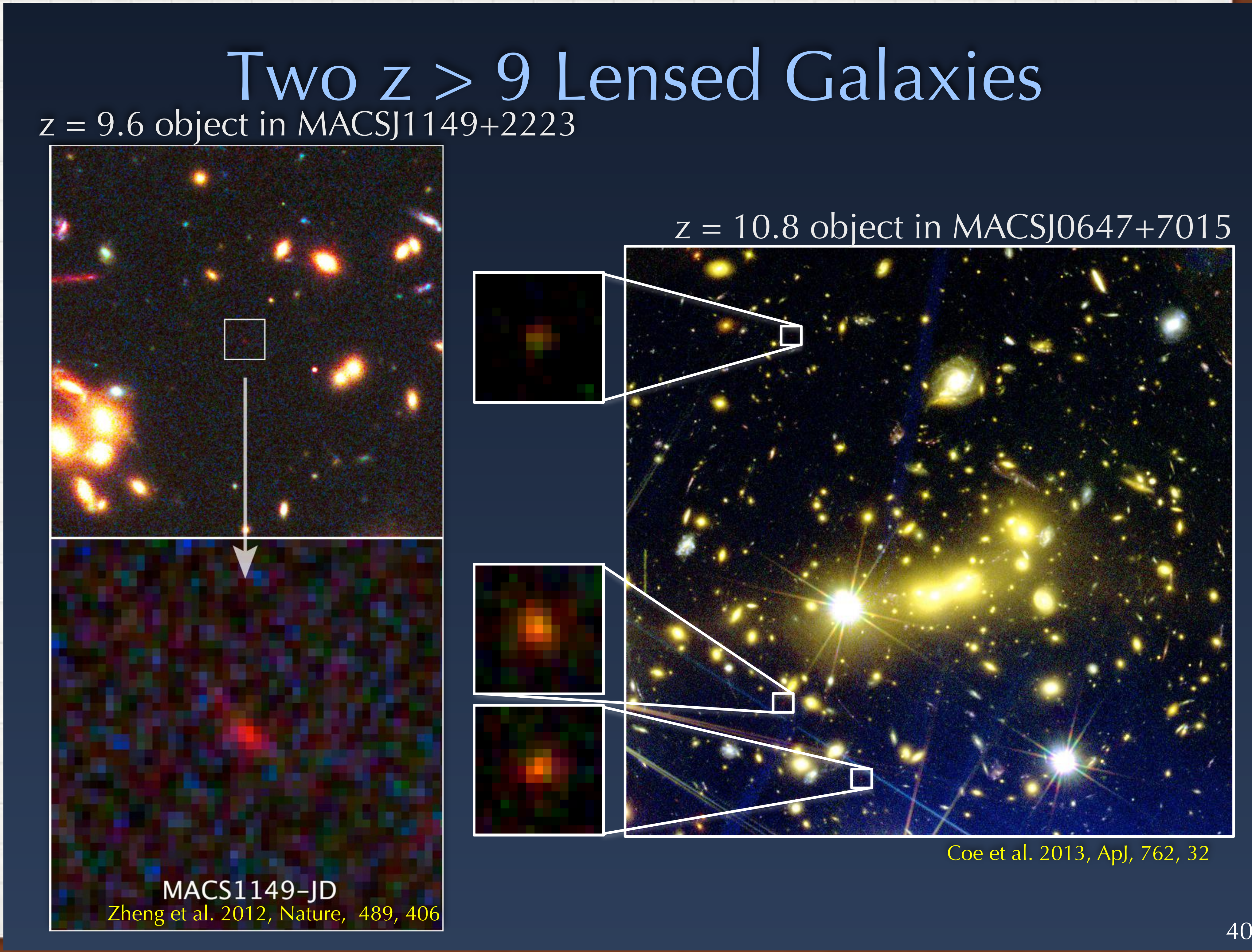


LENSING OF HIGH REDSHIFT GALAXIES

KEY POINT: BACKGROUND HIGHZ GALAXIES ARE MAGNIFIED!

Some examples:

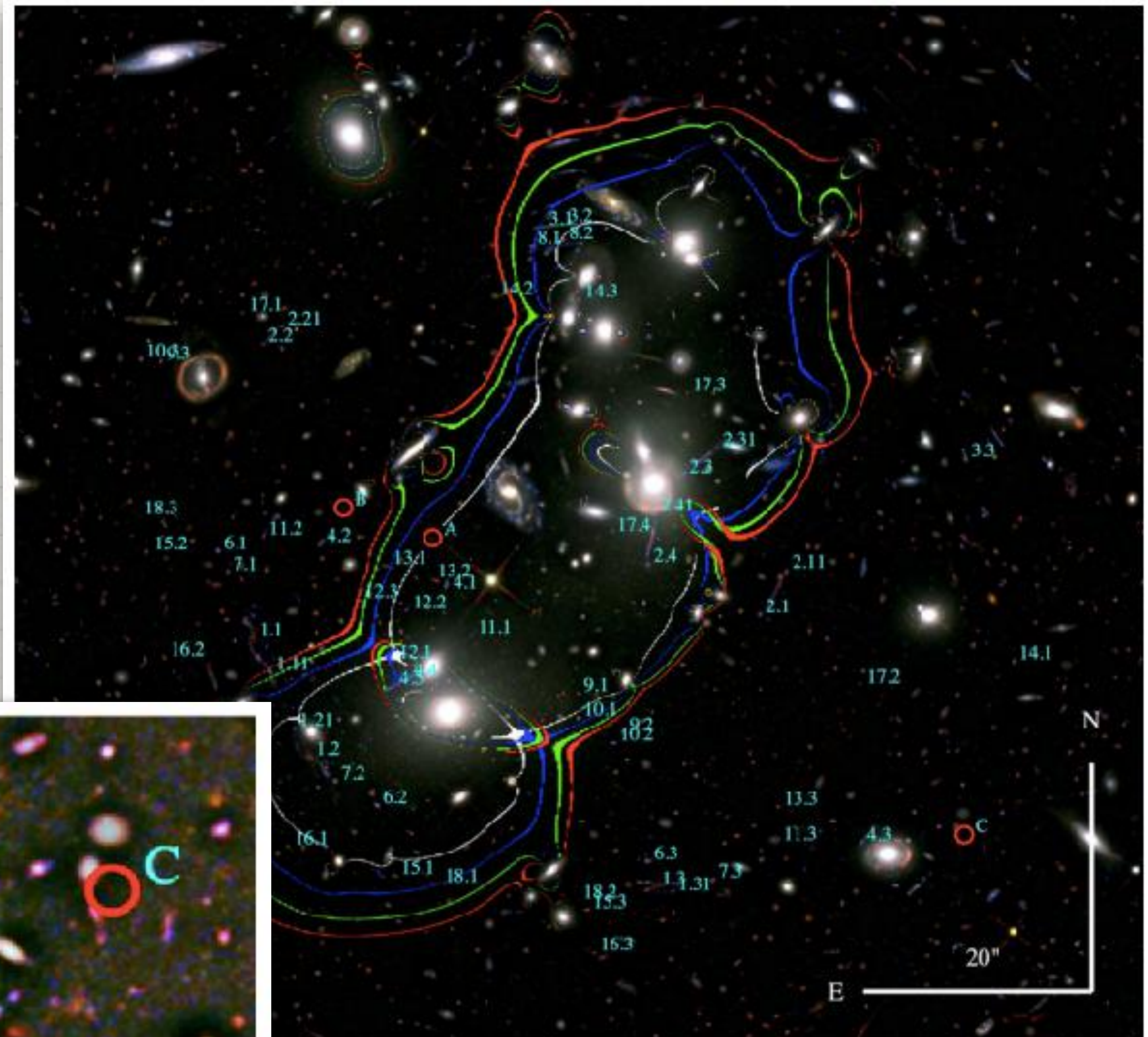
Coe+2013 (z~10.8)

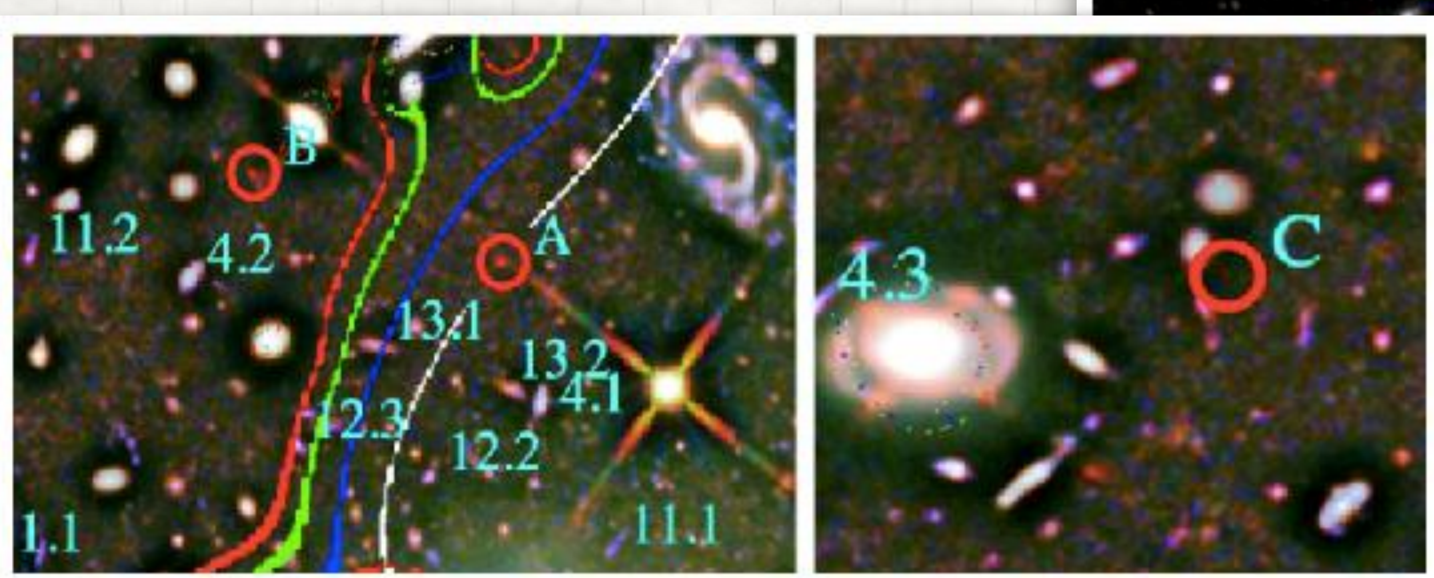


LENSING OF HIGH REDSHIFT GALAXIES

KEY POINT: BACKGROUND HIGHZ GALAXIES ARE MAGNIFIED!

Some examples:
Zitrin+2014 (z~9.8)

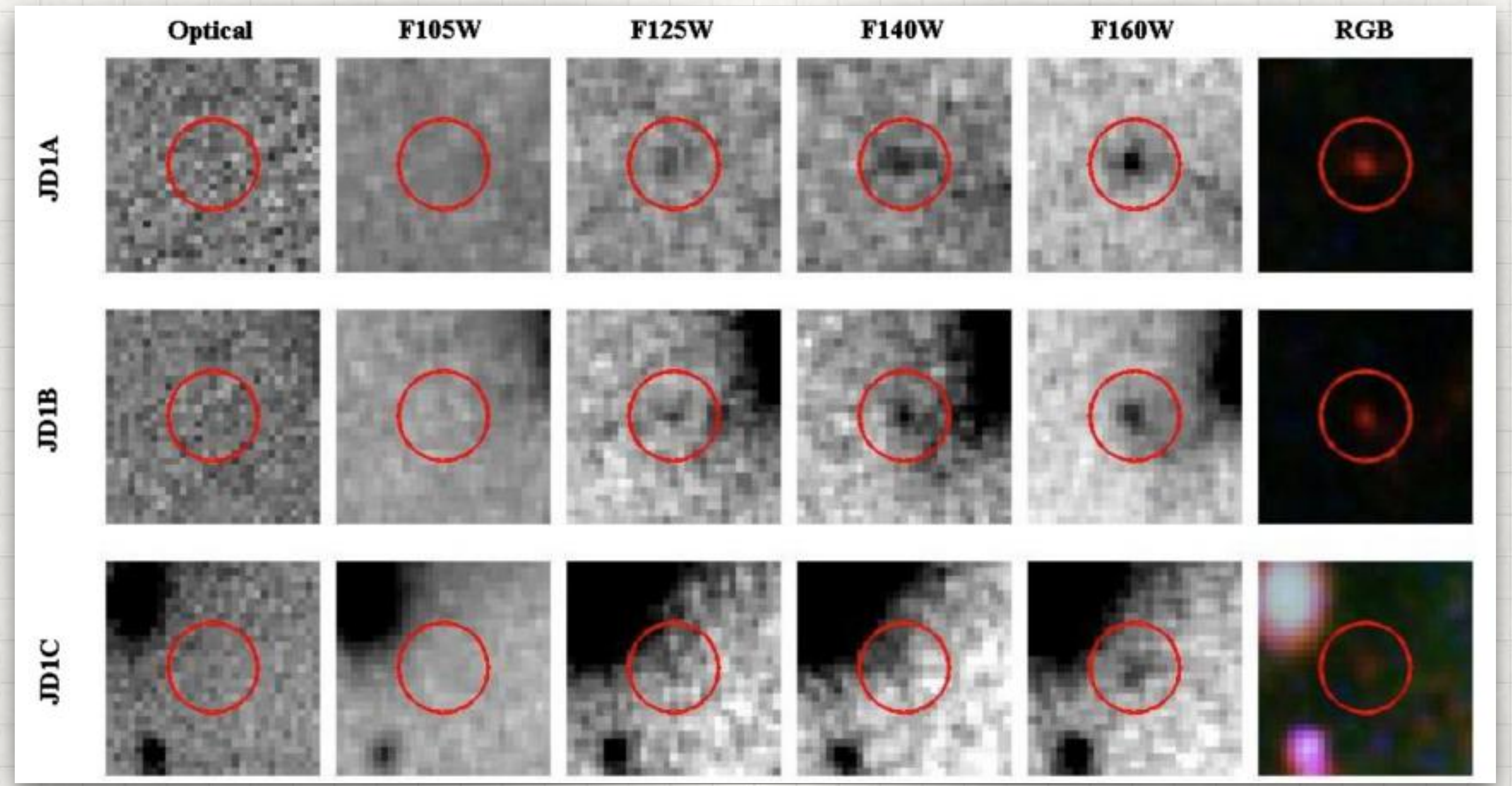




LENSING OF HIGH REDSHIFT GALAXIES

KEY POINT: BACKGROUND HIGHZ GALAXIES ARE MAGNIFIED!

Some examples:
Zitrin+2010 (z~9.8)

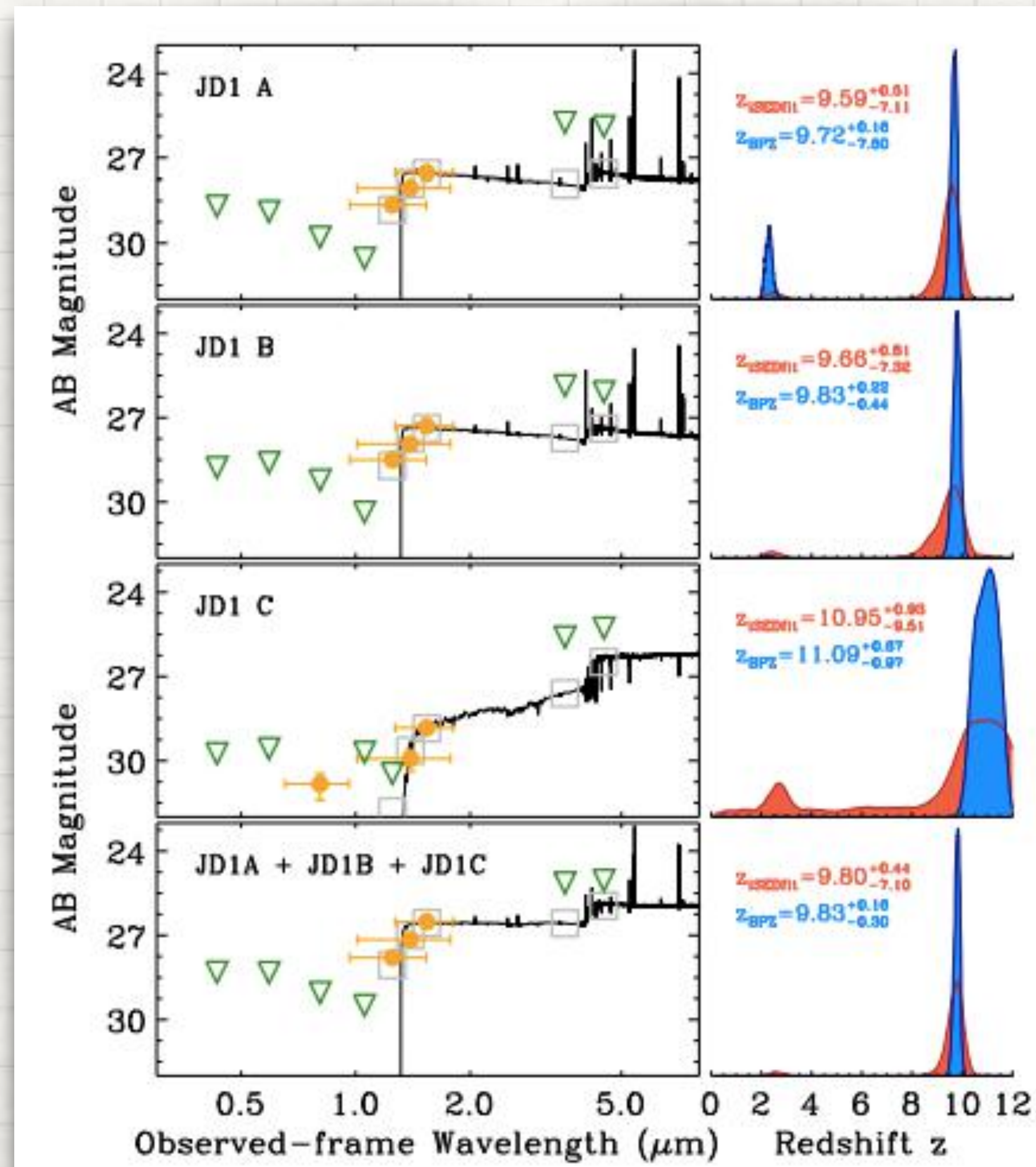


LENSING OF HIGH REDSHIFT GALAXIES

KEY POINT: BACKGROUND HIGHZ GALAXIES ARE MAGNIFIED!

Some examples:
Zitrin+2010 (z~9.8)

Photometric Redshift Distribution

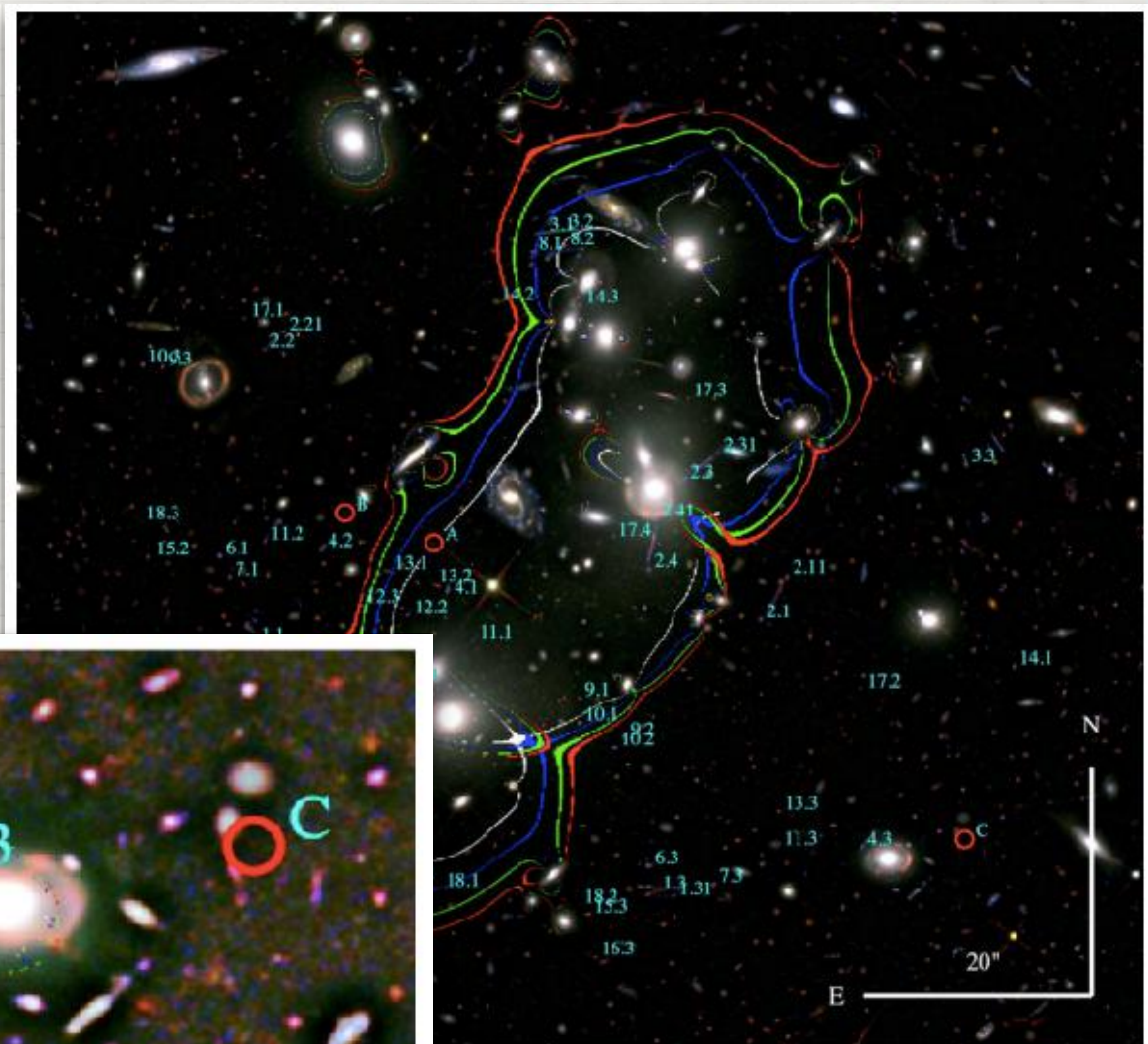


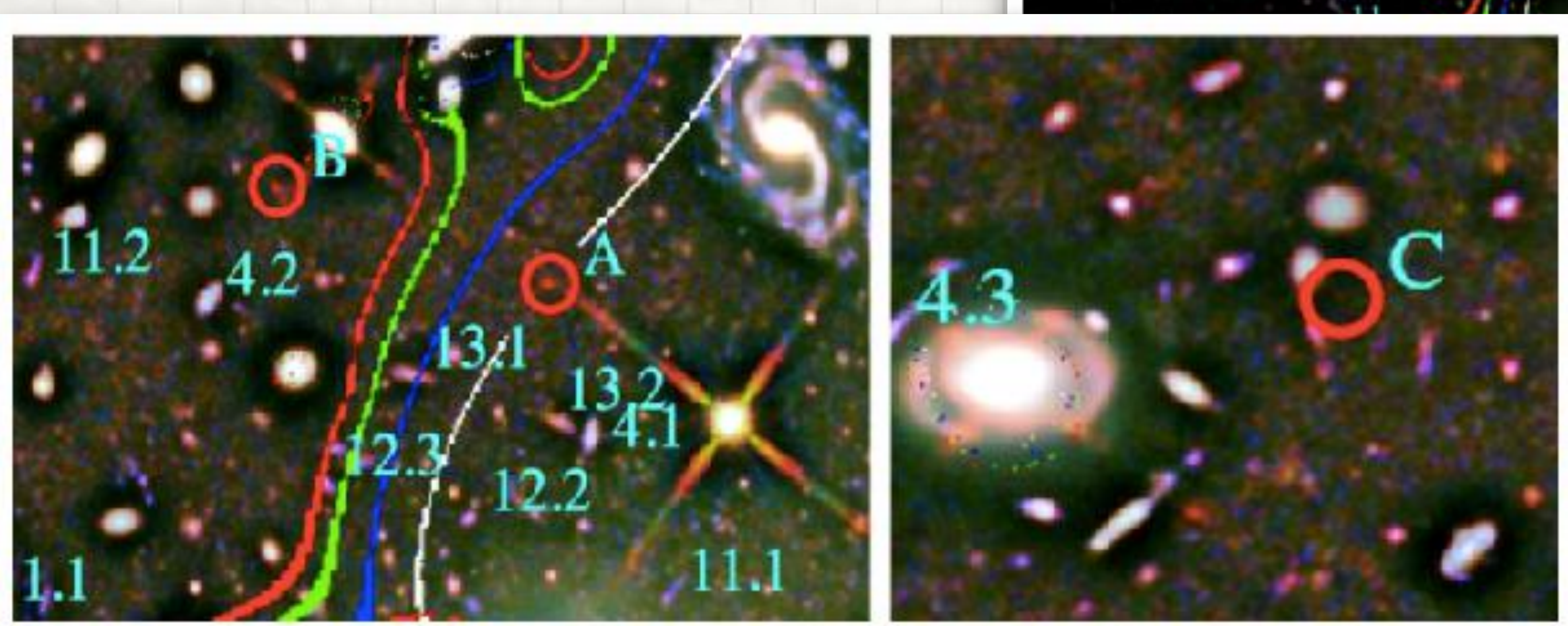
LENSING OF HIGH REDSHIFT GALAXIES

KEY POINT: BACKGROUND HIGHZ GALAXIES ARE MAGNIFIED!

Some examples:
Zitrin+2014 (z~9.8)

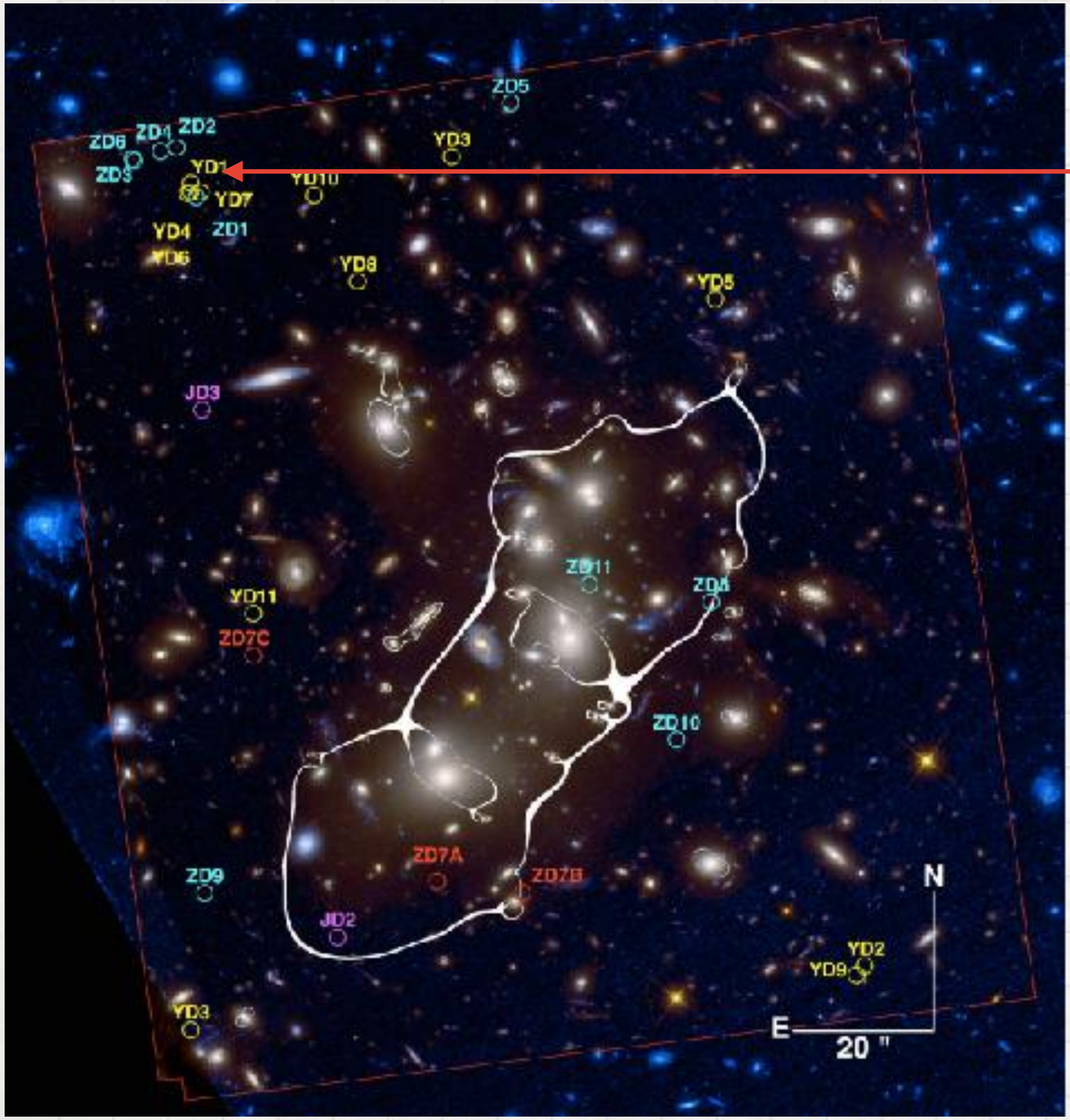
And geometrically supported





LENSING OF HIGH REDSHIFT GALAXIES

KEY POINT: BACKGROUND HIGHZ GALAXIES ARE MAGNIFIED!



z~8

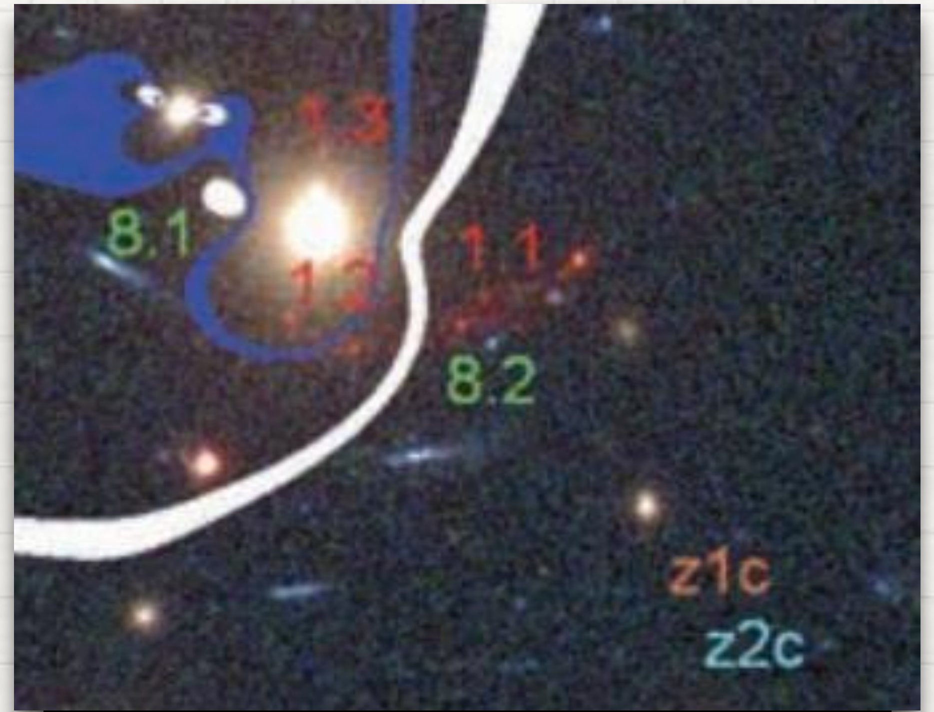
helps us see overdensities!

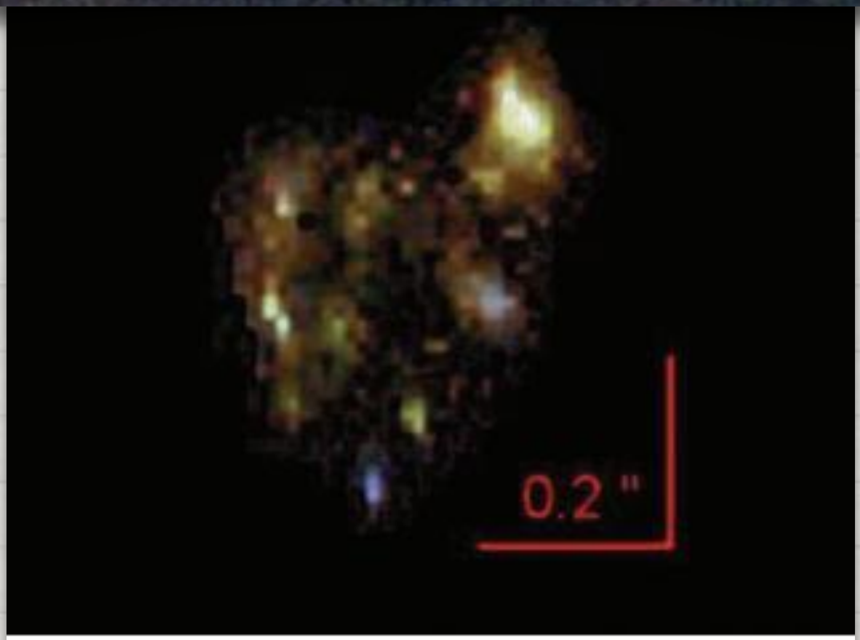
Zheng et al. 2014

LENSING OF HIGH REDSHIFT GALAXIES

MAG. MEANS: INTERNAL DETAILS OF LENSED HIGH REDSHIFT GALAXIES

z~5 lensed arc (found by Franx+ 1997)





model+source reproduction by Zitrin+2011
note source plane resolution ~50 pc!!

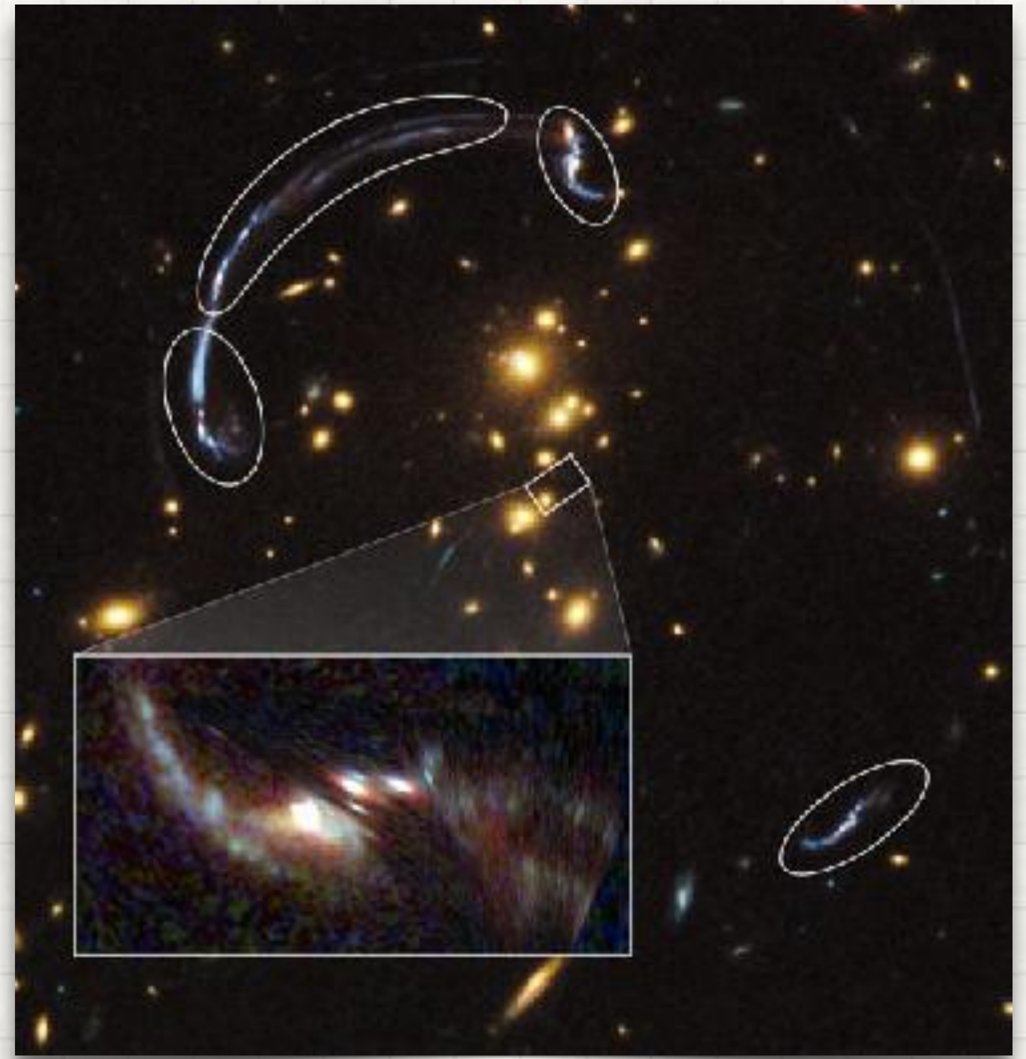


Illustration Credit: NASA, ESA, and Z. Levay (STScI) Science Credit: NASA, ESA, J. Rigby (NASA Goddard Space Flight Center), K. Sharon (Kavli Institute for Cosmological Physics, University of Chicago), and M. Gladders and E. Wuyts (University of Chicago)

LENSING OF HIGH REDSHIFT GALAXIES

SOME RECENT CLUSTER LENSING SURVEYS WITH HUBBLE

- Cluster Lensing And Supernova survey with Hubble (**CLASH**, PI: M. Postman) - 25 clusters, 20 X-ray selected and relatively relaxed, 5 high-magnification clusters

- Grism Lens-Amplified Survey from Space (**GLASS**, PI: T. Treu) - 10 clusters observed with ACS and WFC3 Grisms

- **Hubble Frontier Fields** (DDT program, PIs: M. Mountain \& J. Lotz) - 6 clusters, very deep (~30-32 AB in lensed source plane).

- REionization LensIng Cluster Surveys (**RELICS**, PI: D. Coe) ~40 clusters that are mostly SZ bright (but also, X-ray bright or potentially strong lenses)

- Beyond Ultra-deep Frontier Fields And Legacy Observations (**BUFFALO,** PIs: M. Jauzac \& C. Steinhardt) - extending the area around HFF clusters

- Follow-up and extensive complementing datasets from Spitzer Space Telescope (e.g. PIs, Egami, Bradac, Bauer, as few examples), ALMA (**ALCS** program, PI: Kohno).

LENSING OF HIGH REDSHIFT GALAXIES

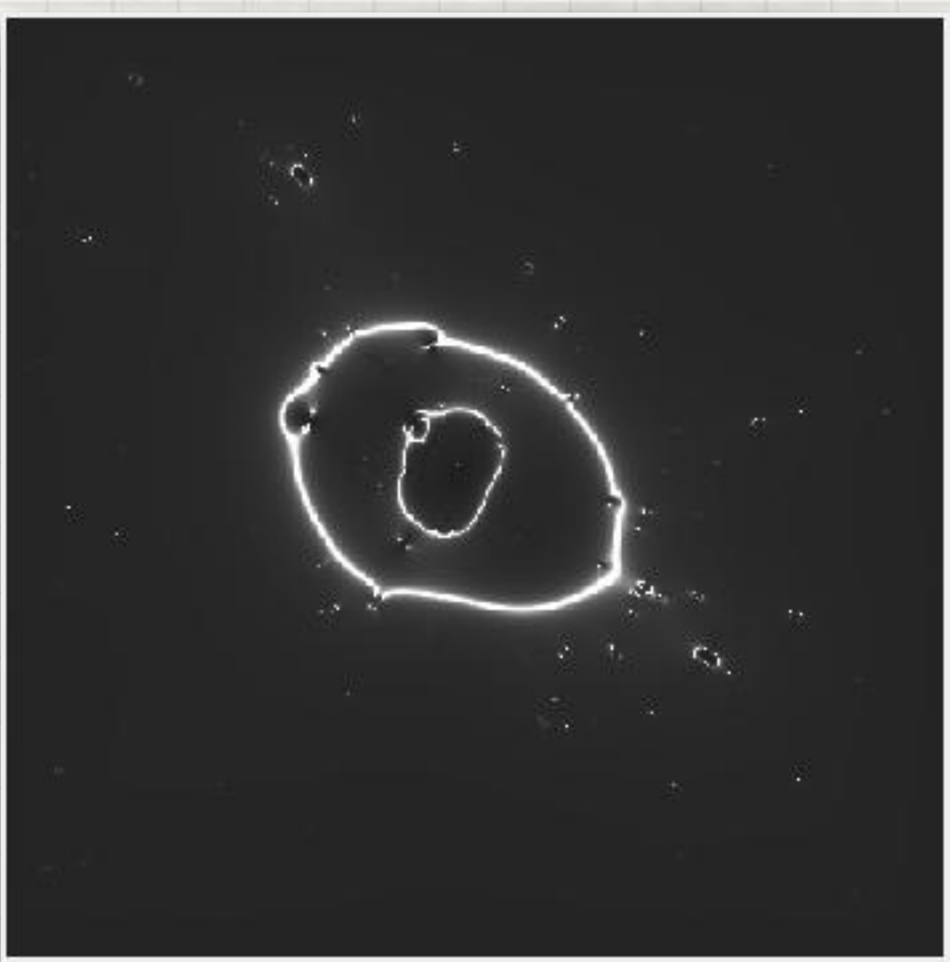
MAGNIFICATION BIAS

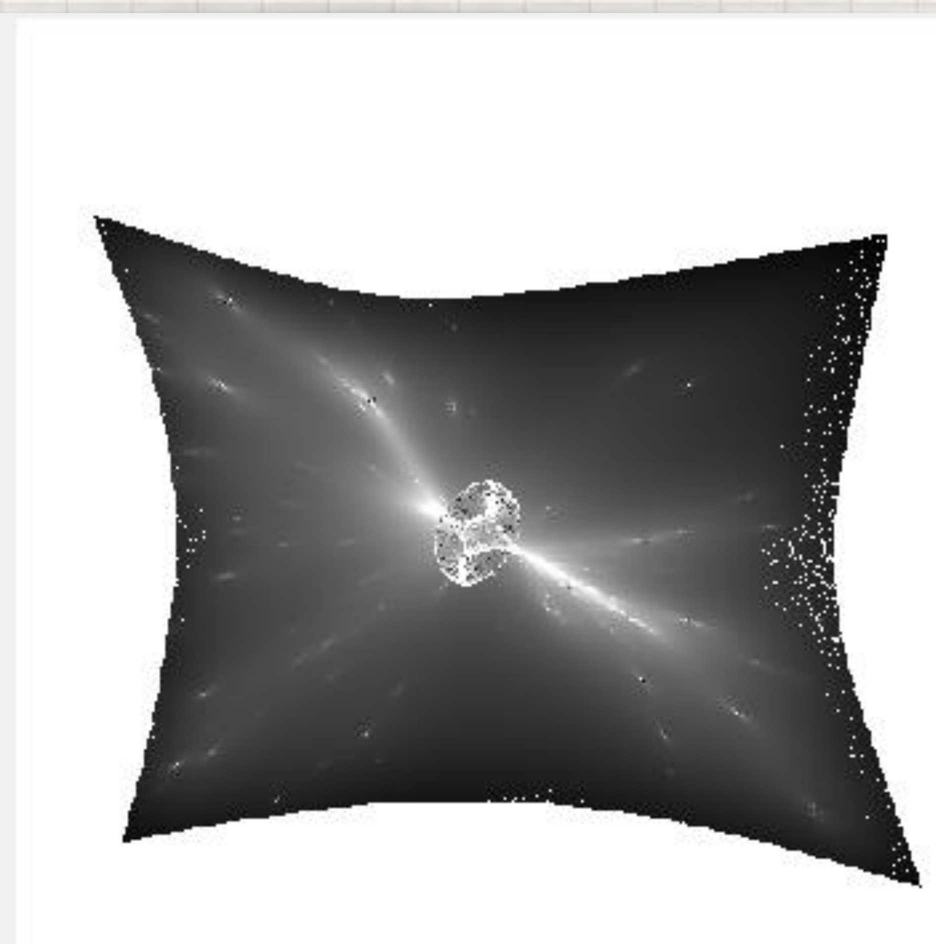
- Now, we said that the magnification aids us for high-redshift studies because it magnifies background objects that would otherwise not be detected.
- But is the picture really that simple? is that the end of the story?
- When we observe we have a finite field-of-view. Now, if the FOV contains a lens, then the effective background being lensed into the FOV is smaller than would otherwise be seen without a foreground gravitational lens:

LENSING OF HIGH REDSHIFT GALAXIES

MAGNIFICATION BIAS

- To see this let's relens back one FOV we modeled:





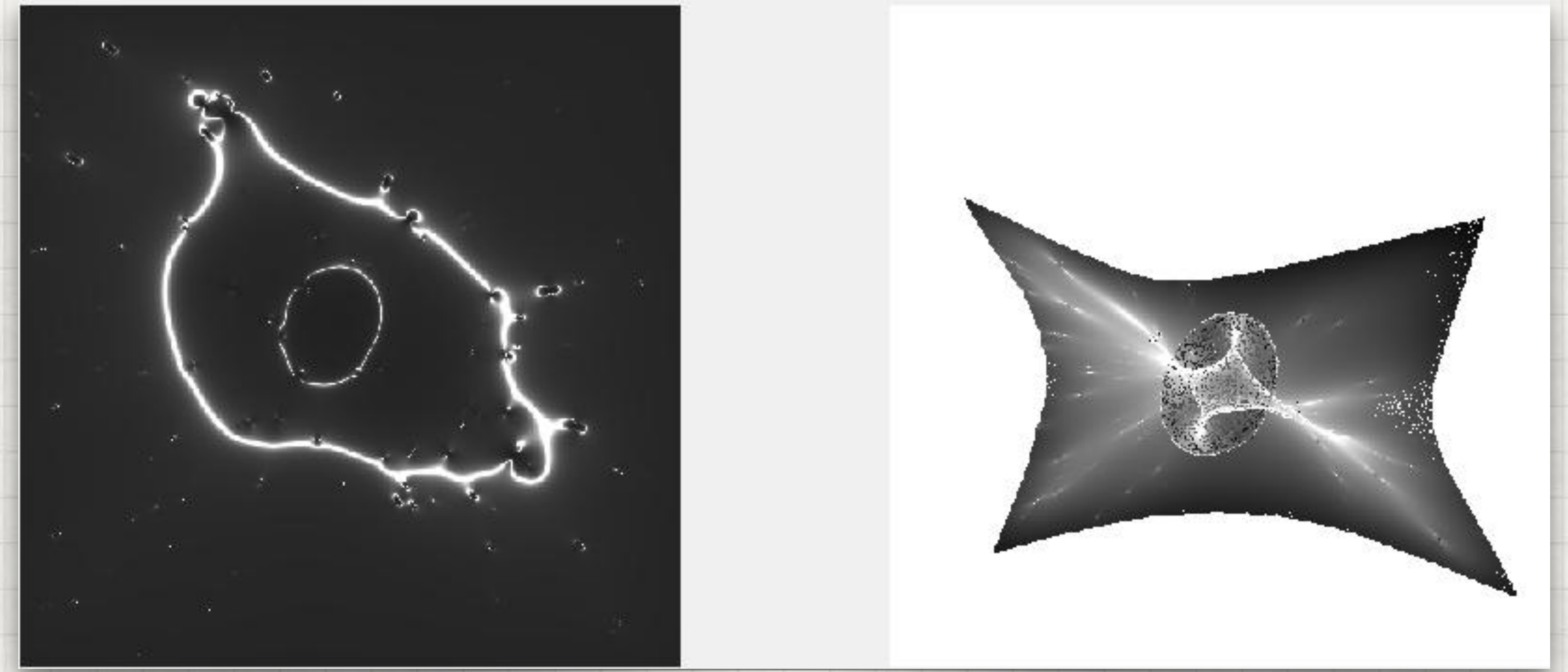
Only 44% of original FOV is effectively observed in this case!

(not full HST FOV was modeled/lensed, smaller)

LENSING OF HIGH REDSHIFT GALAXIES

MAGNIFICATION BIAS

- The situation is even worse for higher redshift sources:



Only 27% of original modeled FOV is effectively observed in this case!

(and further decreasing with redshift; the exact percentages depends on model, size of lens, and FOV that was modeled)

LENSING OF HIGH REDSHIFT GALAXIES

MAGNIFICATION BIAS

- So, there is a *trade off* between source plane area being magnified and the magnification of background objects. The net effect will depend on the shape of the luminosity function.
  Some Refs: Broadhurst+ 1995, Kochanek+2004, Mason+2015, Mansion & Loeb 2013, See also Turner 1980
- It turns out that if the LF is steep enough, one gains from lensing in terms of number of galaxies that would be identified, and if flat, one “loses”.

LENSING OF HIGH REDSHIFT GALAXIES

MAGNIFICATION BIAS

Consider a class of sources in a narrow redshift interval, and denote by $p(\mu)\,\mathrm{d}\mu$ the probability that one of these sources is magnified by a factor within $\mathrm{d}\mu$ of μ. Let $N_0(>S)$ be the number of these sources per unit solid angle that without lensing would be observed to have flux greater than S. If these sources get magnified by a factor μ, two things happen: first, a source with unlensed flux S will attain an observed flux μS. Second, since magnification enlarges the solid angle, sources that without lensing would be contained in a solid angle ω on the sky, will now be spread over the solid angle $\mu\omega$, i.e., the number density of sources decreases by a factor $1/\mu$. Together, if the magnification would be (locally) a constant μ, the observed source counts are

$$N(>S) = \frac{1}{\mu}\,N_0\left(>\frac{S}{\mu}\right) \; . \qquad (108)$$

Considering a probability distribution $p(\mu)$ in magnifications, this result generalizes to

$$N(>S) = \frac{1}{\langle\mu\rangle}\int \mathrm{d}\mu\, p(\mu)\, N_0\left(>\frac{S}{\mu}\right) \; , \qquad (109)$$

where $\langle\mu\rangle$ is the mean magnification within the regio[n]
If source counts are taken over random regions on the s[ky]
the magnification bias is considered around foregroun[d]

regions, $\langle\mu\rangle > 1$. The probability $p(\mu)$ satisfies

$$\int \mathrm{d}\mu\, p(\mu) = 1 \; ; \quad \int \mathrm{d}\mu\, \mu\, p(\mu) = \langle\mu\rangle \; ;$$

the first relation expressing normalization, the second the definition o[f] mean magnification. Of course, $p(\mu)$ depends on the source redshift an[d] density of lenses, as mentioned in the previous section.

From Schneider, Kochanek, Wambsganss' book: Gravitational Lensing: Strong, Weak and Micro: Saas-Fee Advanced Course 33

LENSING OF HIGH REDSHIFT GALAXIES

MAGNIFICATION BIAS

This functional behavior implies that the integral in (111) formally diverges as the slope β approaches 2. Hence, for a population of sources with steep number counts, the magnification bias can become very large. In fact, the formal divergence is due only to the assumption of a pure power law for $N_0(> S)$; whereas such a functional form is a good description, e.g., for the QSO counts over a limited range of fluxes (or luminosities), it cannot continue with a steep slope for arbitrarily faint sources, in order for the source population not to produce infinite total flux. Nevertheless, if the counts are steep, and one considers a value of S much larger than a break flux (where the steep counts turn into flatter ones towards lower fluxes), the ratio $N(> S)/N_0(> S)$ can be very high indeed. This is the reason why we see extreme QSOs like the one mentioned above, APM 08279+5255. Furthermore, if the source population is better described by a Schechter luminosity function, which implies an exponential decrease in the counts for high luminosities, the bias can be even larger: the probability with a Schechter function to find a single source far out in the exponential tail is very small, and if such an apparently luminous source is observed, it is most likely a lensed one, as is the case for F10214+4724 and cB58.

LENSING OF HIGH REDSHIFT GALAXIES

MAGNIFICATION BIAS

That's not alpha, beta_here +1 =alpha

alpha=2,
for N(S)~S^-alpha

We shall now consider the simple example of source counts which behave like a power law, $N_0(>S) = A\,S^{-\beta}$. Inserting this into (109) yields

$$N(>S) = \frac{1}{\langle\mu\rangle}\int \mathrm{d}\mu\; p(\mu)\, A\left(\frac{\mu}{S}\right)^{\beta} = N_0(>S)\,\frac{1}{\langle\mu\rangle}\int \mathrm{d}\mu\; p(\mu)\,\mu^{\beta}\;. \qquad (111)$$

Thus, if the unlensed source counts behave like a power law, so do the lensed ones, with the same slope. The ratio between lensed and unlensed counts depends on the magnification probability distribution $p(\mu)$, as well as on the slope β of the counts. The first remarkable result is that, if $\beta = 1$, then (111) together with the second of (110) imply that $N(>S) = N_0(>S)$, i.e., the counts are unchanged in this case, independent of $p(\mu)$. Hence, in this case the enlargement of the solid angle over which sources are distributed just compensates the brightening of the sources. For $\beta < 1$, the number counts are depleted, whereas they are increased for $\beta > 1$. The larger the slope β, the larger is the ratio $N(>S)/N_0(>S)$, i.e., the stronger is the magnification bias.

If one considers point sources, or more generally, sources whose angular sizes are much smaller than the characteristic angular scale of the lenses, then one can show (Blandford and Narayan 1986) that for very high magnification, $p(\mu) \propto \mu^{-3}$, up to an upper limit for μ at which the finite size of the source

LENSING OF HIGH REDSHIFT GALAXIES

MAGNIFICATION BIAS

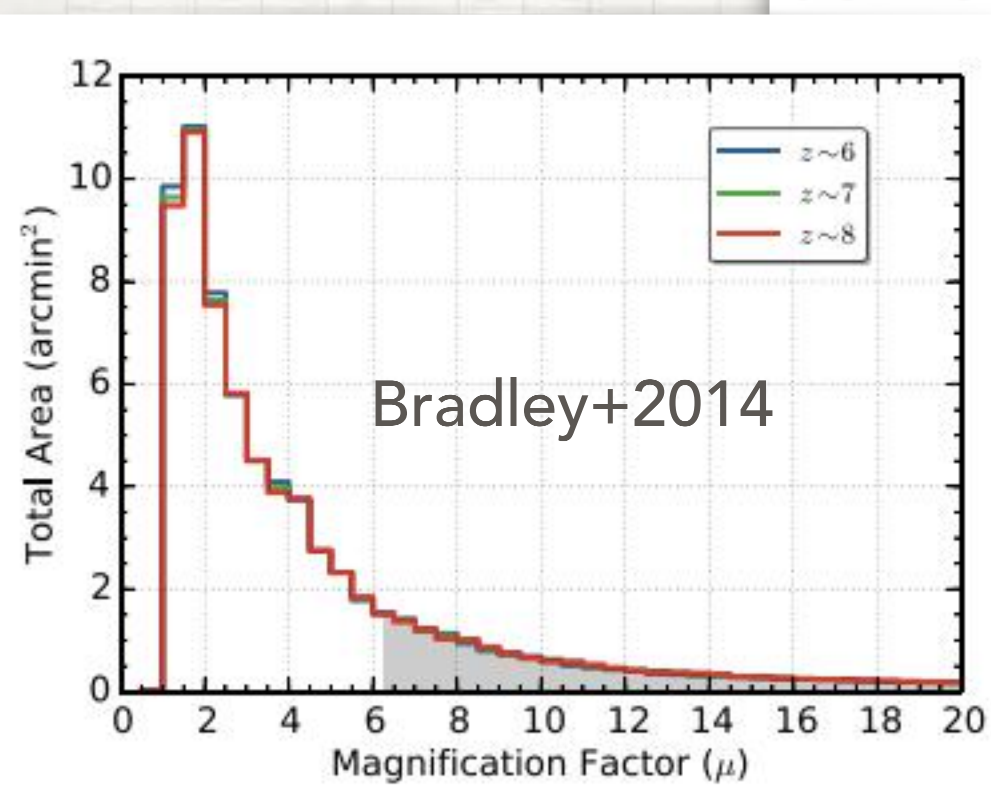
The bias itself is defined as (screenshot from Mason+2015)

The magnification bias for sources with observed luminosities above $L_{\rm lim}$ in a flux-limited sample is given by:

$$B = \frac{\int_{\mu_{\rm min}}^{\mu_{\rm max}} d\mu\, p(\mu) N\left(> \frac{L_{\rm lim}}{\mu}\right)}{N(> L_{\rm lim})} \quad (8)$$

assuming that each source could be magnified between $\mu_{\rm min}$ and $\mu_{\rm max}$. Where $p(\mu)$ is the probability distribution for magnification of a source and $N(> L_{\rm lim})$ is the ted galaxy LF (Wyithe et al. 2011).

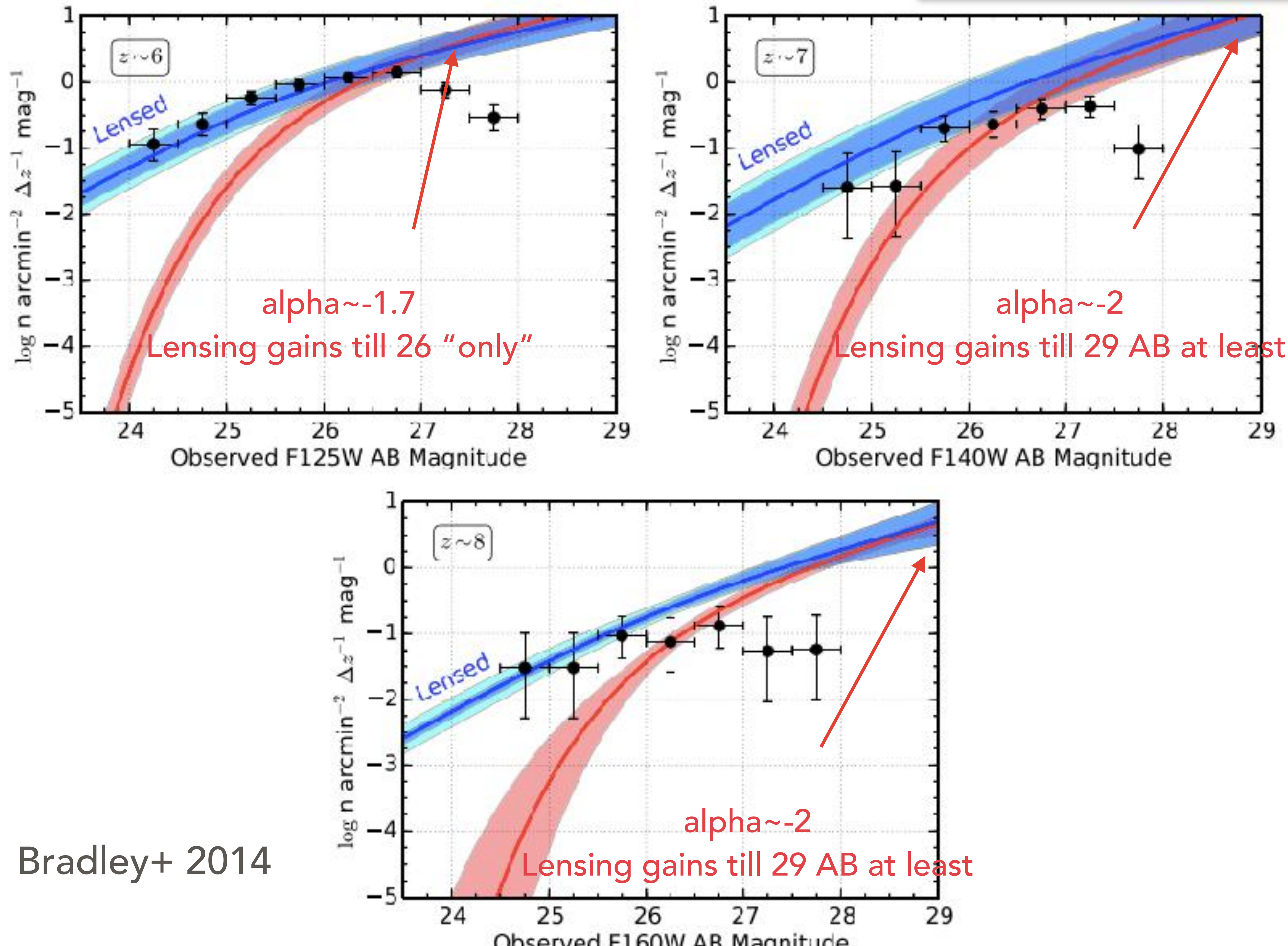
Known from lens models



Bradley+2014

LENSING OF HIGH REDSHIFT GALAXIES

MAGNIFICATION BIAS



Bradley+ 2014

LENSING OF HIGH REDSHIFT GALAXIES

MAGNIFICATION BIAS

- So, we said there is a *trade off* between source plane area being magnified and the magnification of objects bringing them above flux limit. The net effect will depend on the shape of the luminosity function.
- If steep —> gain in number of high sources; if flat, "lose" (see a figure in next slide).
- Lensing not only affects the LF, but also the size and redshift distributions, naturally.
- Extinction in the lens also plays a role compared to unlensed sources
- When constructing the LF, also multiplicity of images must be taken into account (not to count the same source galaxy several times)!

LENSING OF HIGH REDSHIFT GALAXIES

MAGNIFICATION BIAS / GAIN FROM LENSING

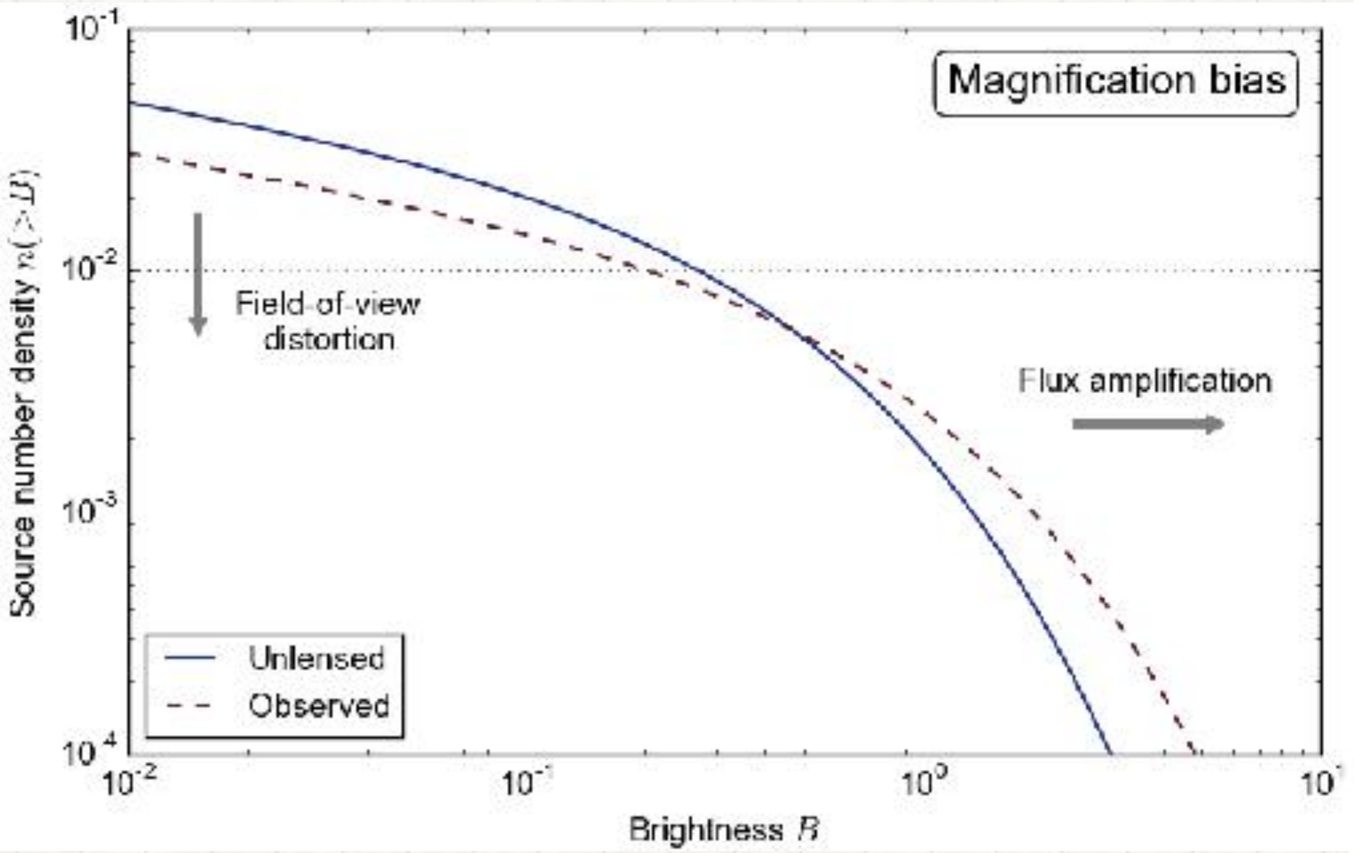
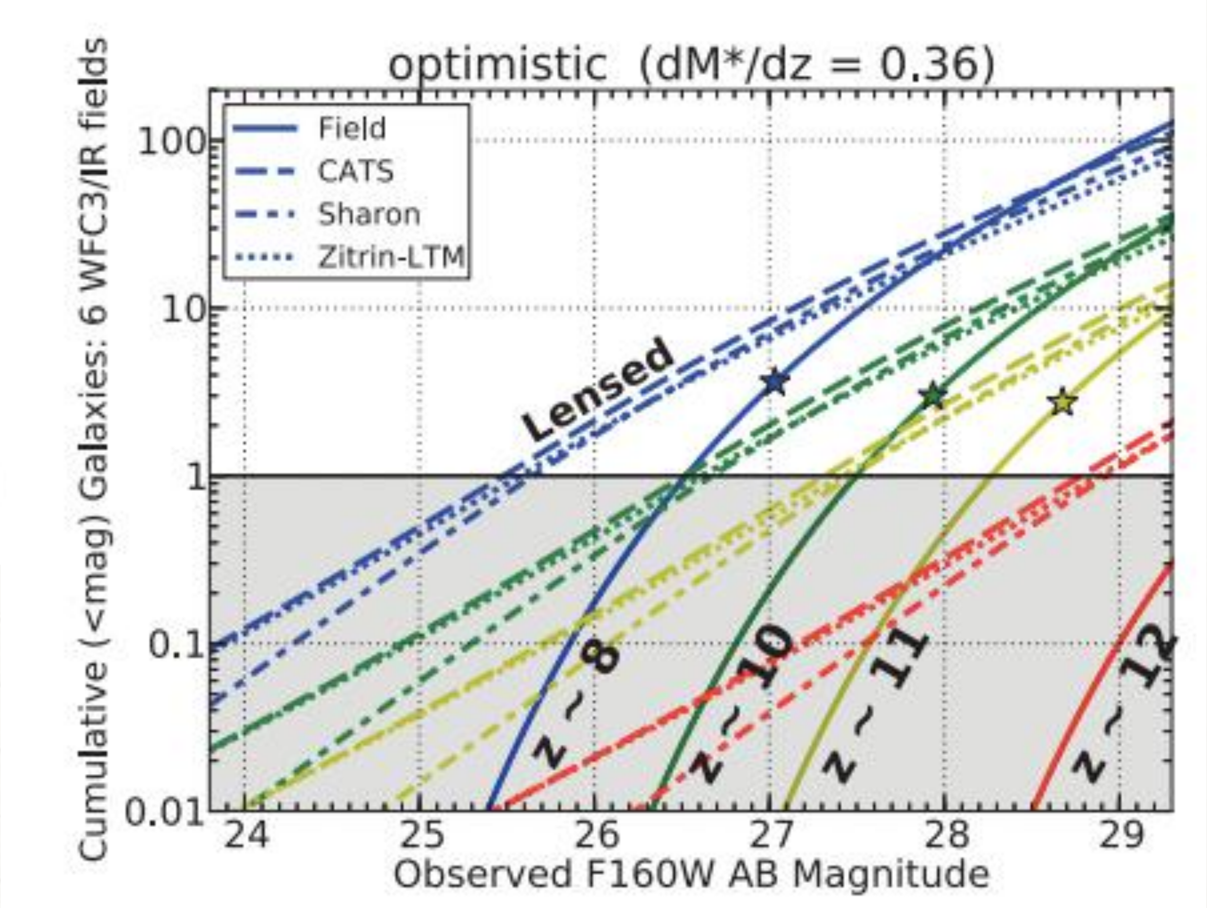


Fig by Chieh-An Lin found at:

https://linc.tw/magbias.html

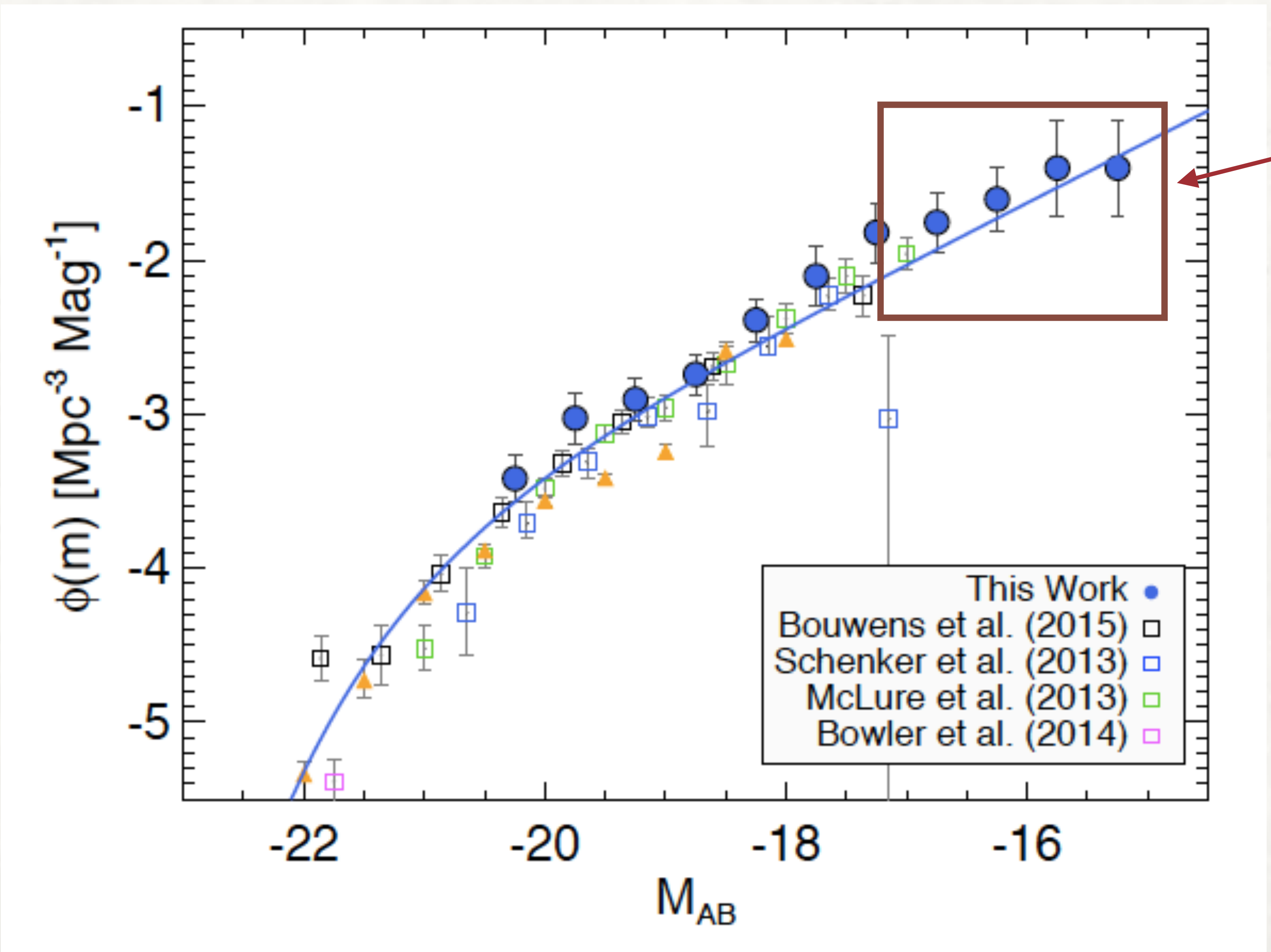


Coe+ 2015

LENSING OF HIGH REDSHIFT GALAXIES

GAIN FROM LENSING: EXAMPLE

- Reaching fainter and fainter on the luminosity function (results from some HFF clusters combined):



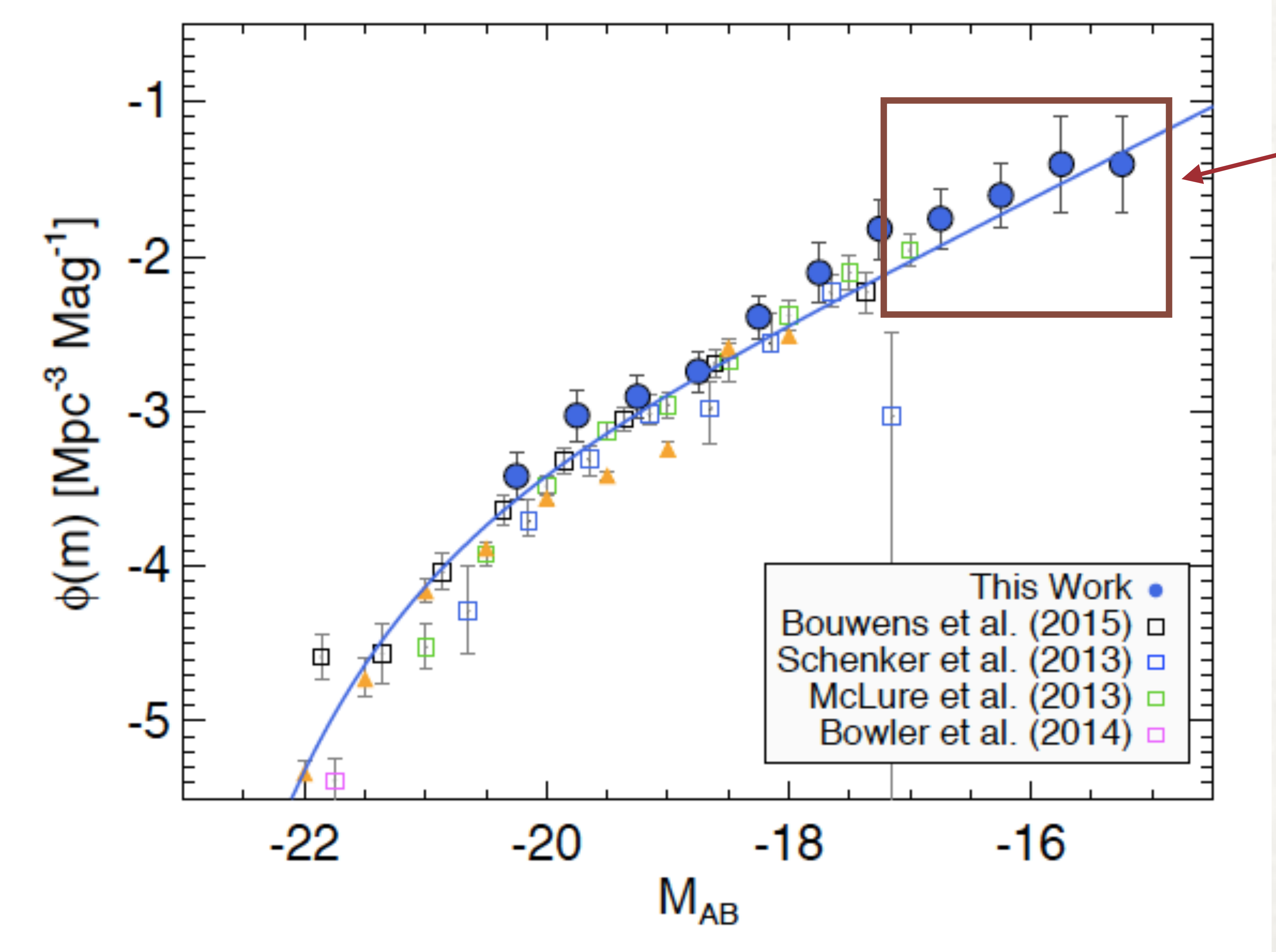
Atek+ 2015

Maybe sufficient for reionization with fesc~10-15%

LENSING OF HIGH REDSHIFT GALAXIES

GAIN FROM LENSING: IMPORTANCE FOR REIONIZATION

- Reaching fainter and fainter on the luminosity function is important for reionization because fainter galaxies are more abundant and thus are those believed to be **responsible for reionization**.



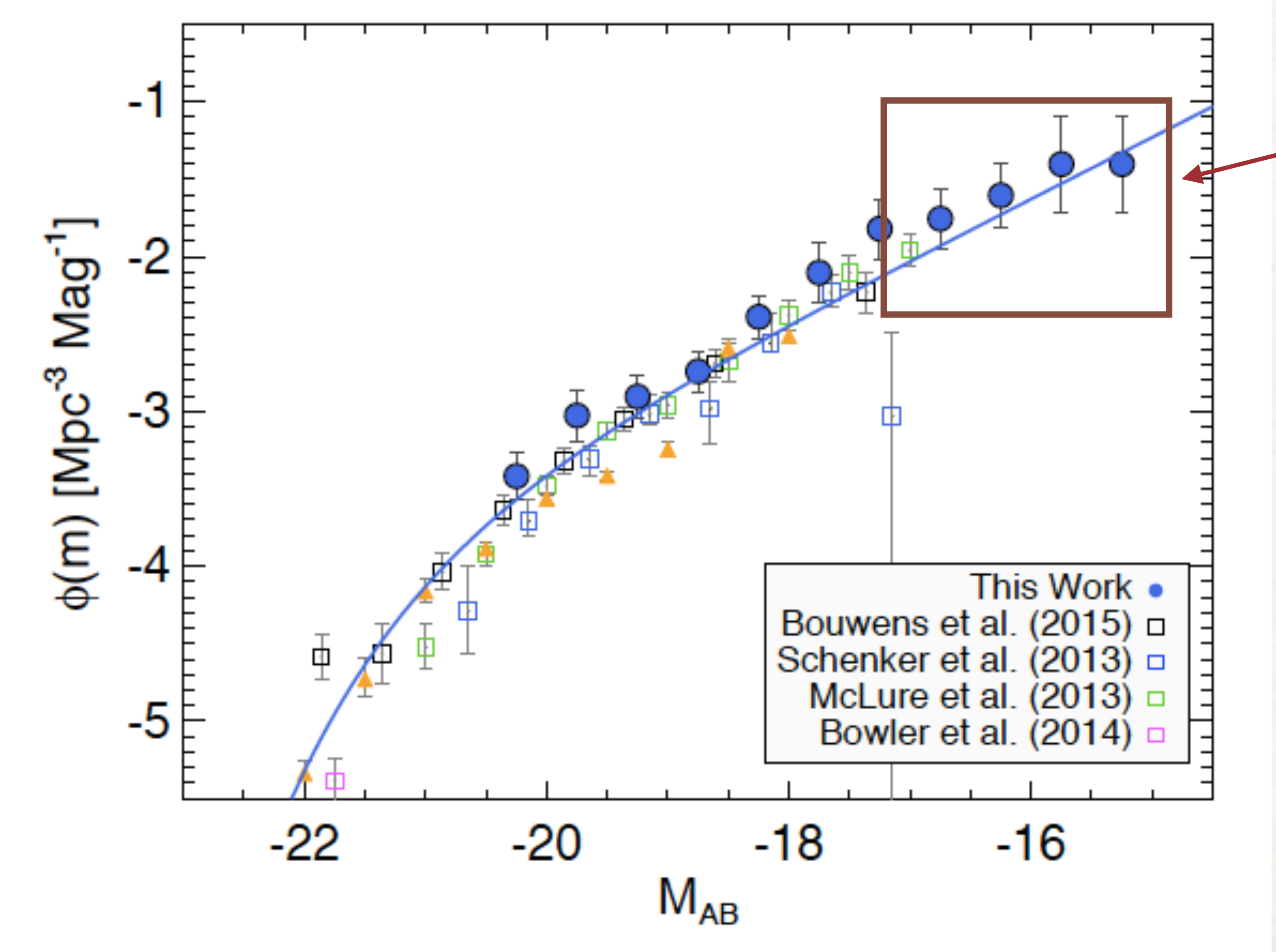
Atek+ 2015

Maybe sufficient for reionization with fesc~10-15%

LENSING OF HIGH REDSHIFT GALAXIES

GAIN FROM LENSING: IMPORTANCE FOR REIONIZATION

- Studying these galaxies also by other means (e.g., spectroscopically) is important because we need to understand if sufficient ionizing radiation escapes from them to reionize the universe.

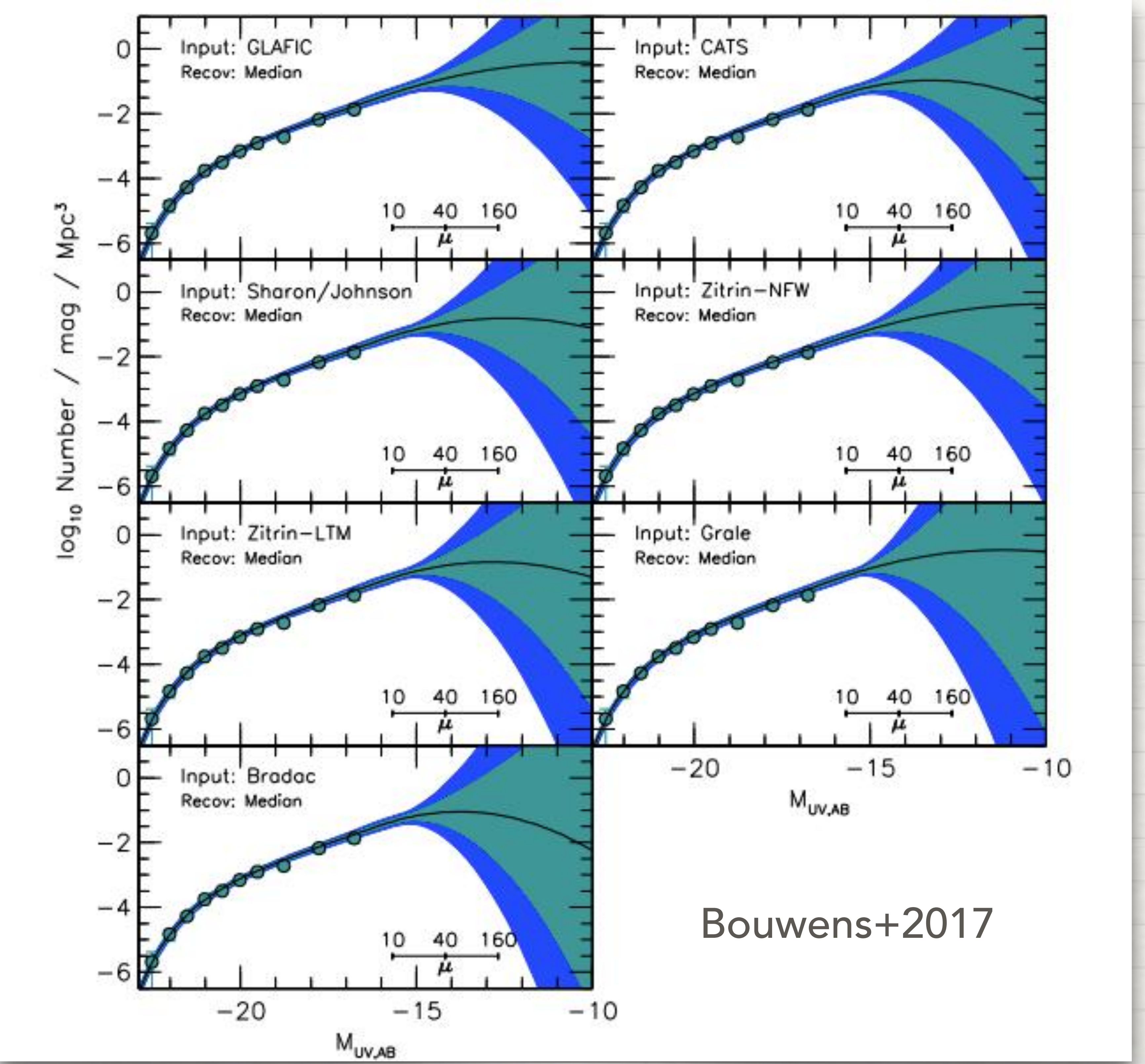


Atek+ 2015

Maybe sufficient for reionization with fesc~10-15%

LENSING OF HIGH REDSHIFT GALAXIES

TURNOVER AT FAINTER MAGNITUDES (E.G. AT Z~6)?



Bouwens+2017

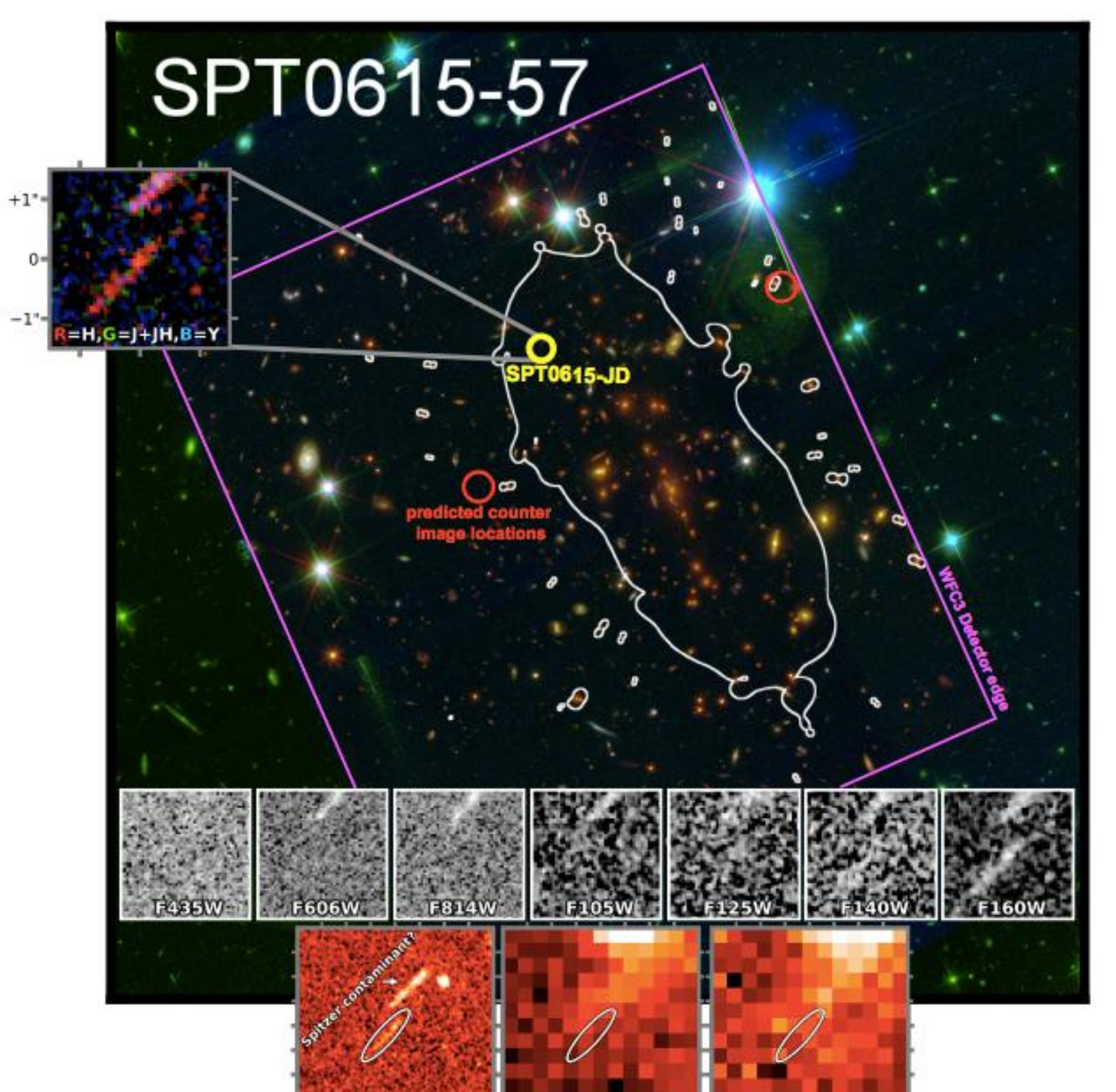
LENSING OF HIGH REDSHIFT GALAXIES

SURFACE BRIGHTNESS VERSUS FLUX LIMIT

- Another point to think about: lensing preserves surface brightness. Why, then, does it help to discover faint high-z sources anyhow?
- Thick Hint - high-redshift objects are typically small enough and clumpy, as we've seen. Observations are mostly flux limited.

LENSING OF HIGH REDSHIFT GALAXIES

SOME BIASES AND SYSTEMATICS



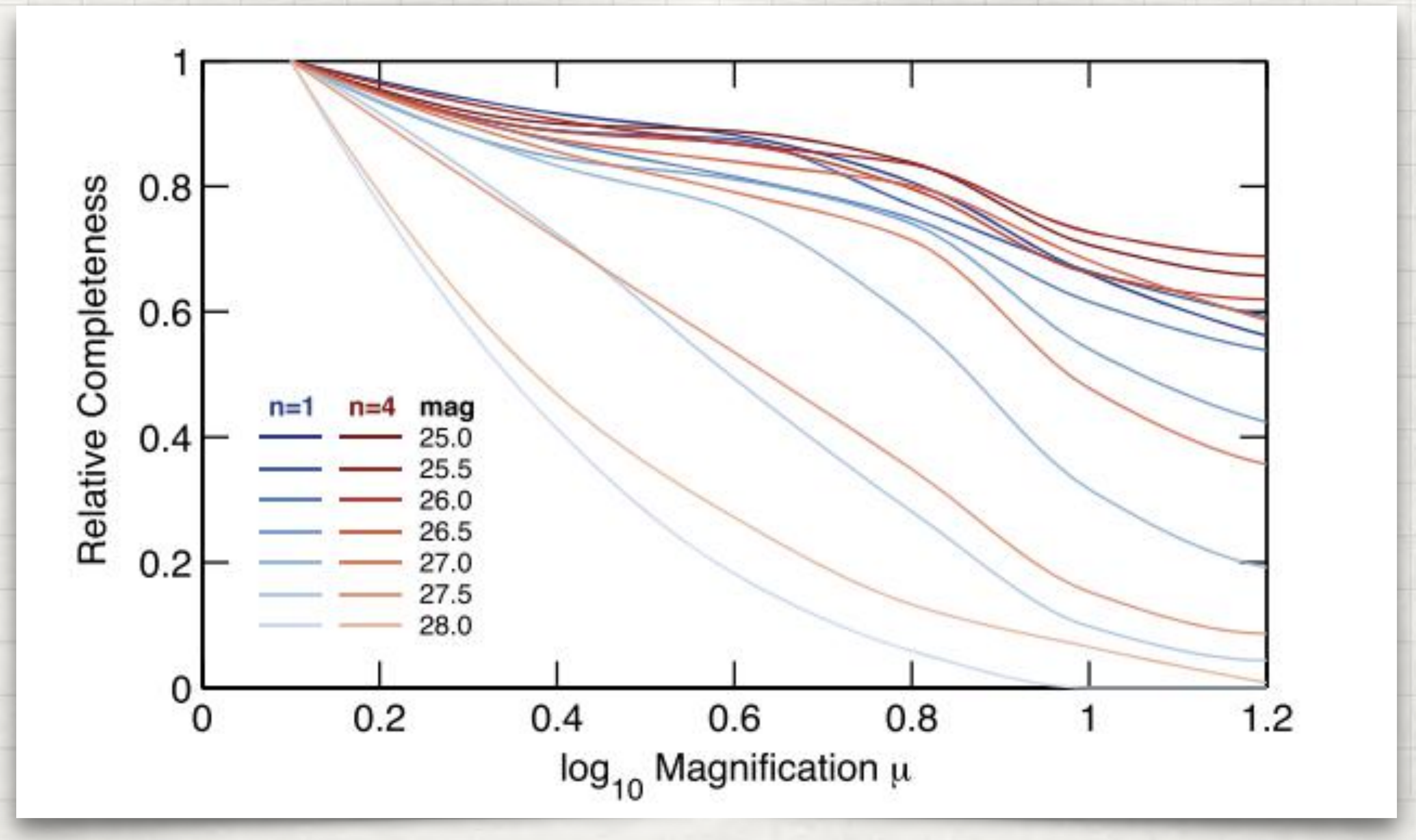
Salmon+2018

2.5″ arc at z~10 candidate

LENSING OF HIGH REDSHIFT GALAXIES

SOME BIASES AND SYSTEMATICS

- For example, Oesch et al. 2015 showed that strong *shear* significantly affects the detection rate (and thus completeness) of lensed high-redshift galaxies, especially at the faint end



SYSTEMATICS AND COMPLETENESS

*CRUCIAL

- Because higher magnification correspond to smaller areas in source plane, when constructing LF from lensed sources, one must have a proper control of the systematic uncertainties, biases, and *completeness.*

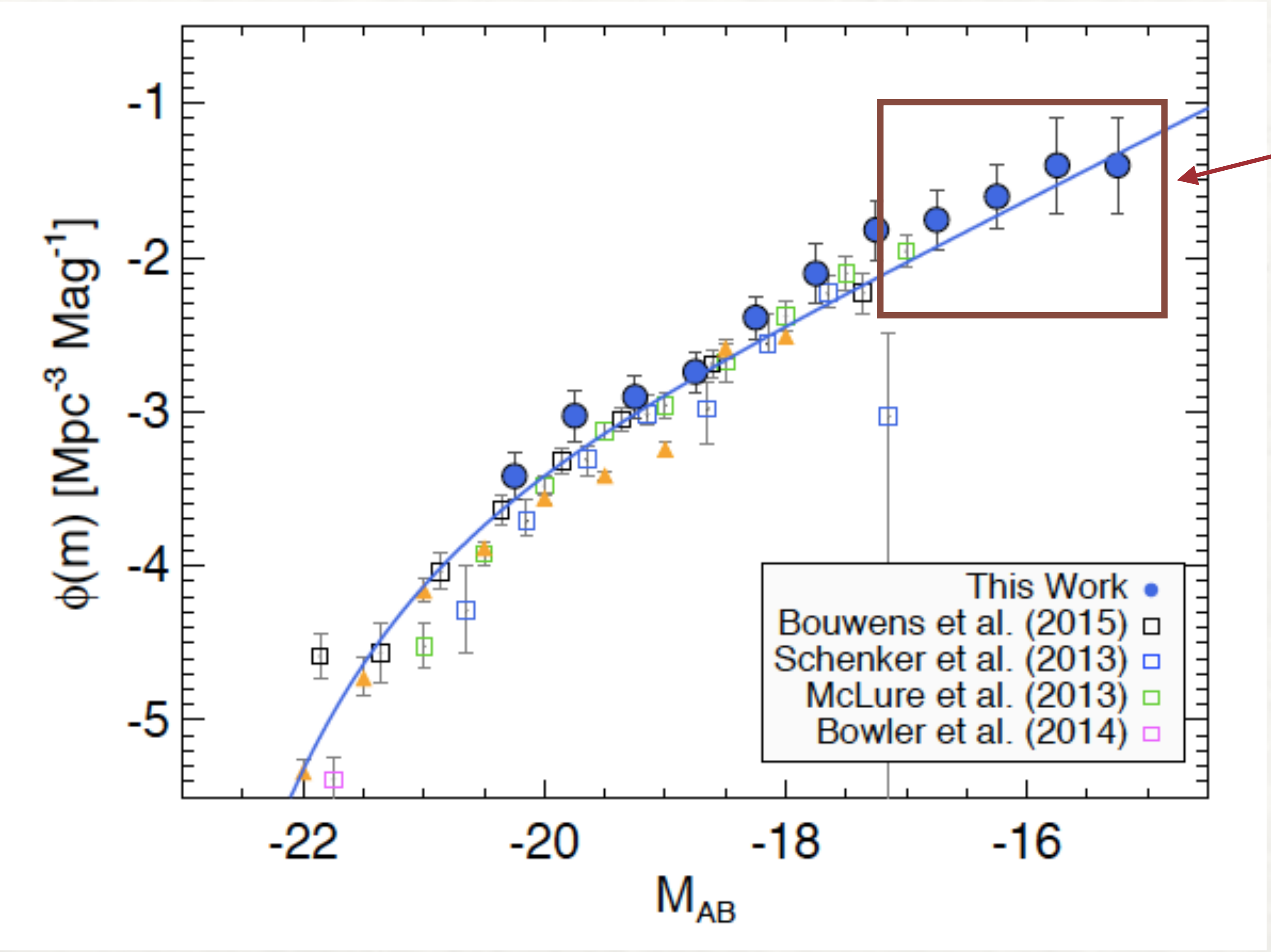
- In order to understand the completeness, for example, simulations are undertaken in which sources are planted in the source/image plane, lensed through the lens, and then the same procedure for LF construction (identifying objects, photometric redshift measurement, etc.) is performed on the mock images. This allows one to estimate how may sources are “missed” by the procedure, and correct for these.

- Since very high magnifications (corresponding to the fainter end of the LF, intrinsically) the faint end form lensing can often be *dominated* by the completeness corrections.

LENSING OF HIGH REDSHIFT GALAXIES

(IN)COMPLETENESS

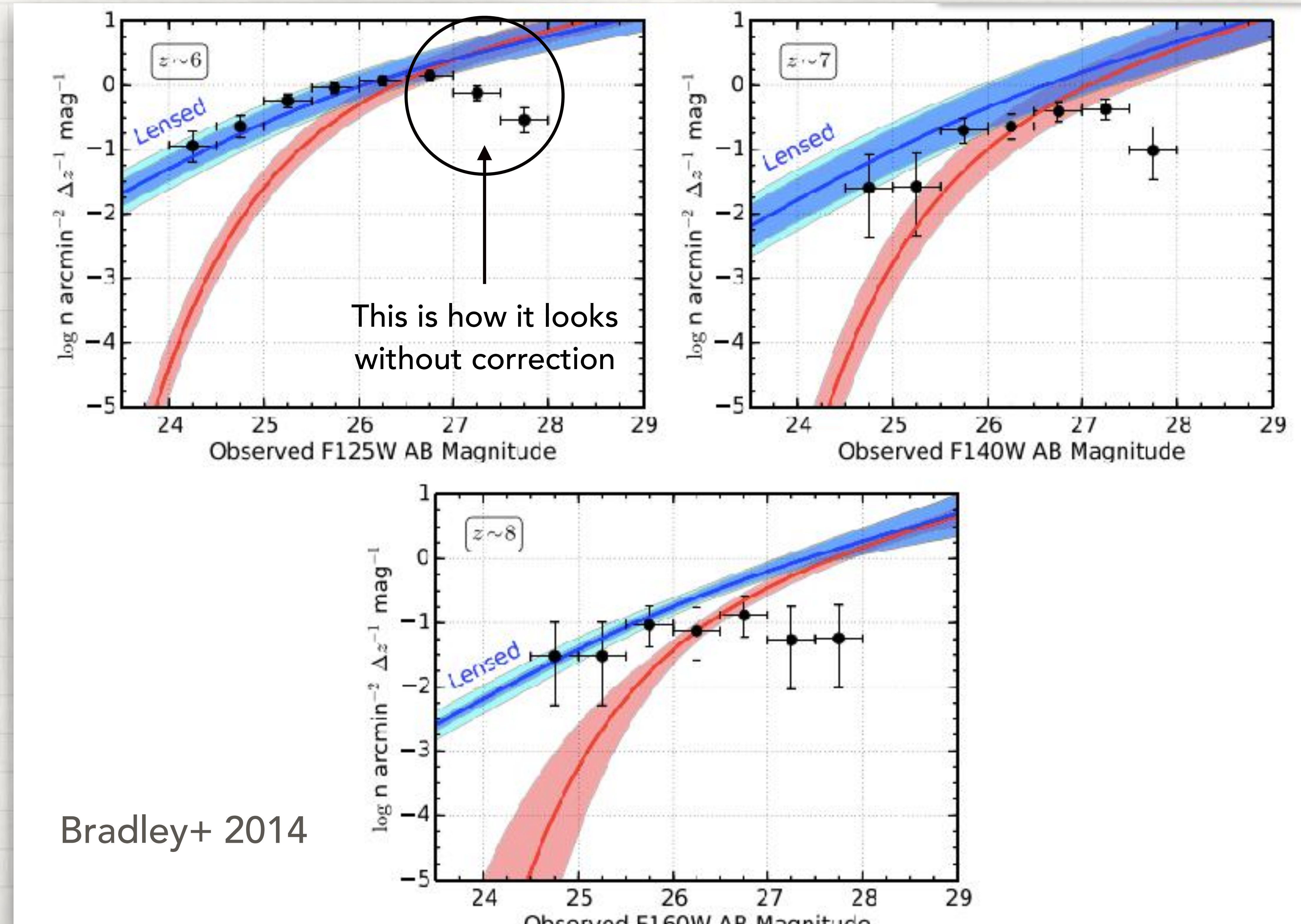
- The faint end might be governed by completeness



From Atek+ 2015. Pushing LF faint end fainter

LENSING OF HIGH REDSHIFT GALAXIES

(IN)COMPLETENESS



Bradley+ 2014

LENSING OF HIGH REDSHIFT GALAXIES

EFFECT OF LENSING ON STRENGTH OF EMISSION LINES

EQUIVALENT WIDTH AND FLUX UNDER LENSING

EW is simply a measure of the line's strength: an integral of the line flux above the continuum, relative to the continuum (i.e., in units of wavelength)

$$W_\lambda = \int \frac{F_1(\lambda) - F_c(\lambda)}{F_c(\lambda)} d\lambda,$$

https://ned.ipac.caltech.edu/level5/Cambridge/Cambridge1_3_4.html

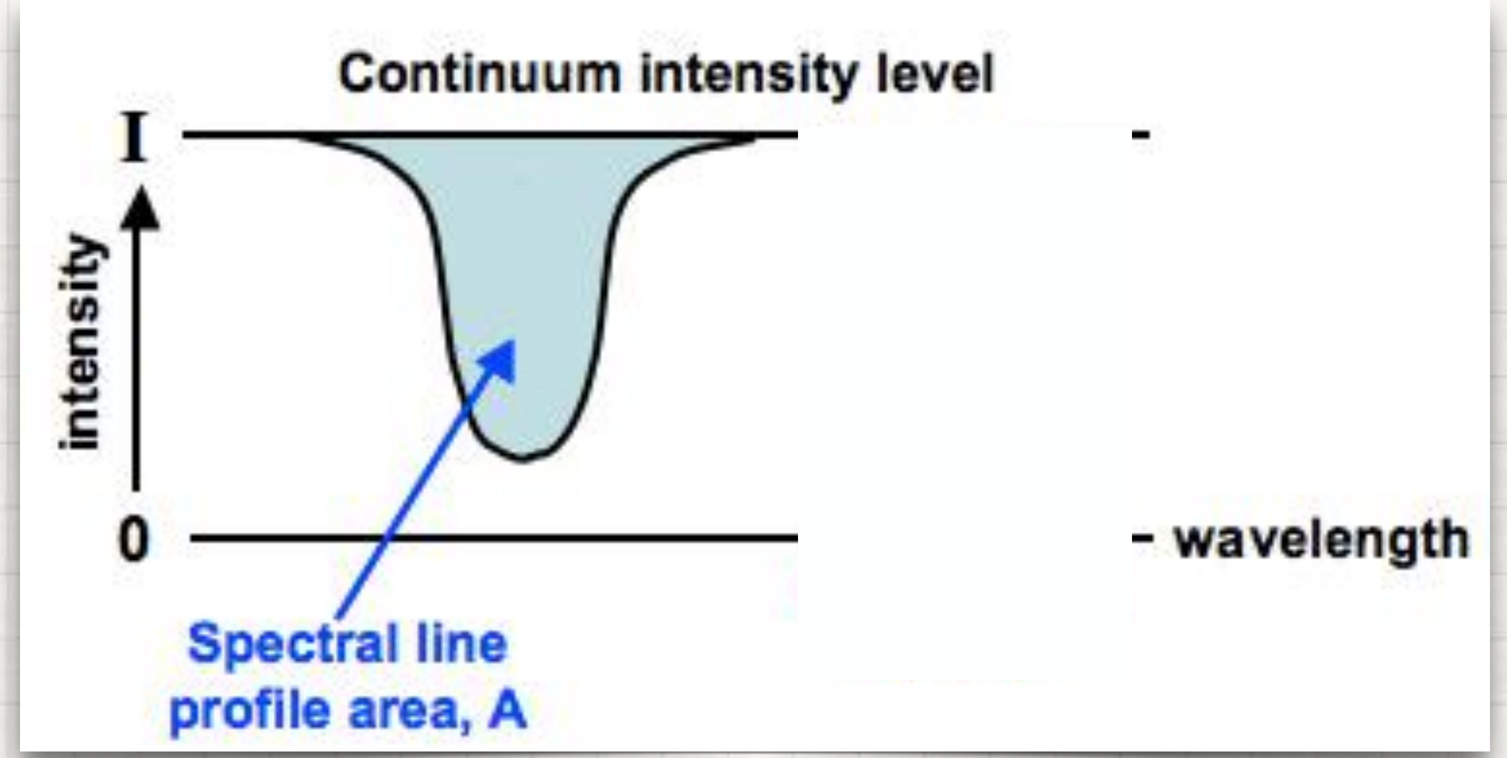


Figure from web:
http://astronomy.swin.edu.au/cosmos/E/Equivalent+Width

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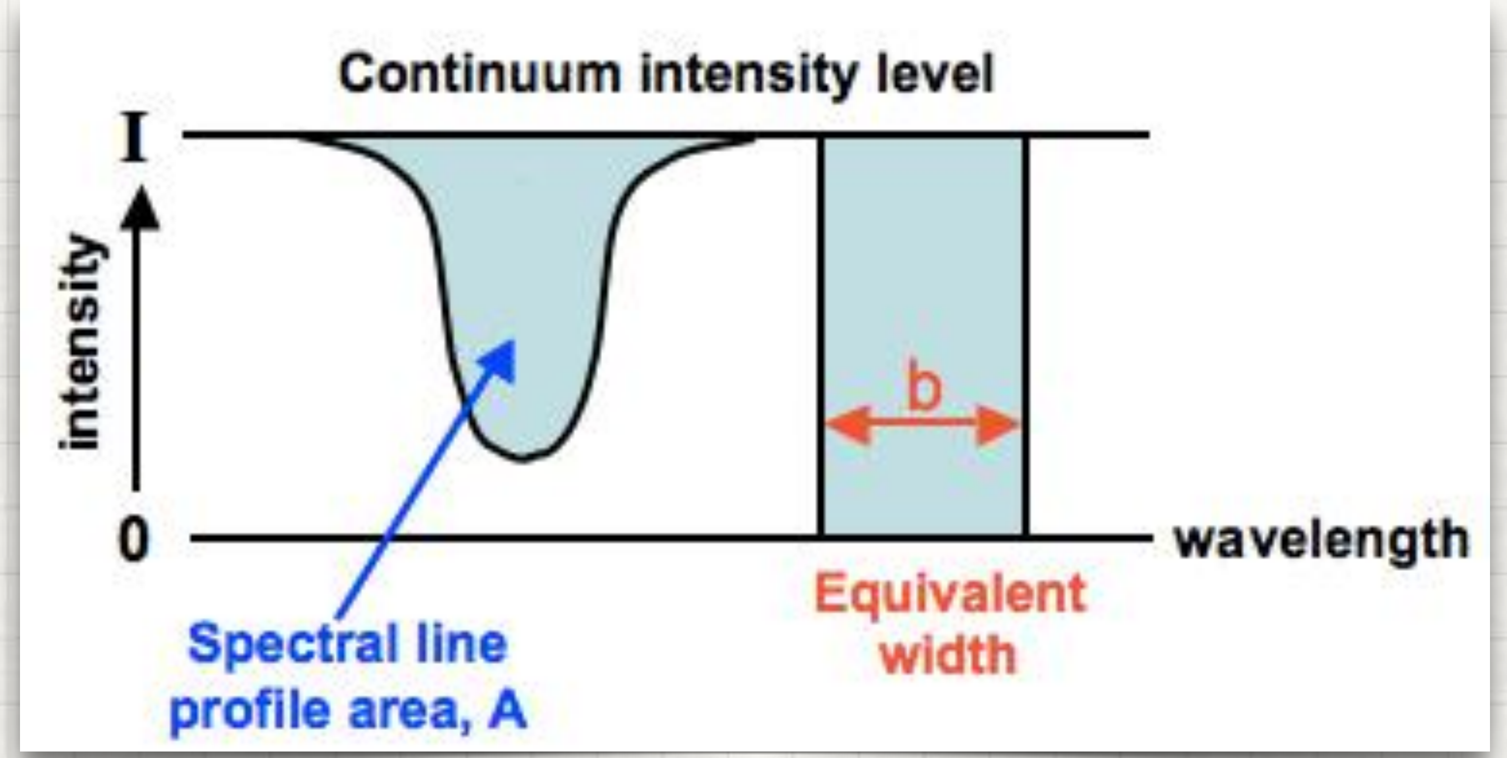

Name shows that the width in wavelength is equivalent to this

Figure from web:
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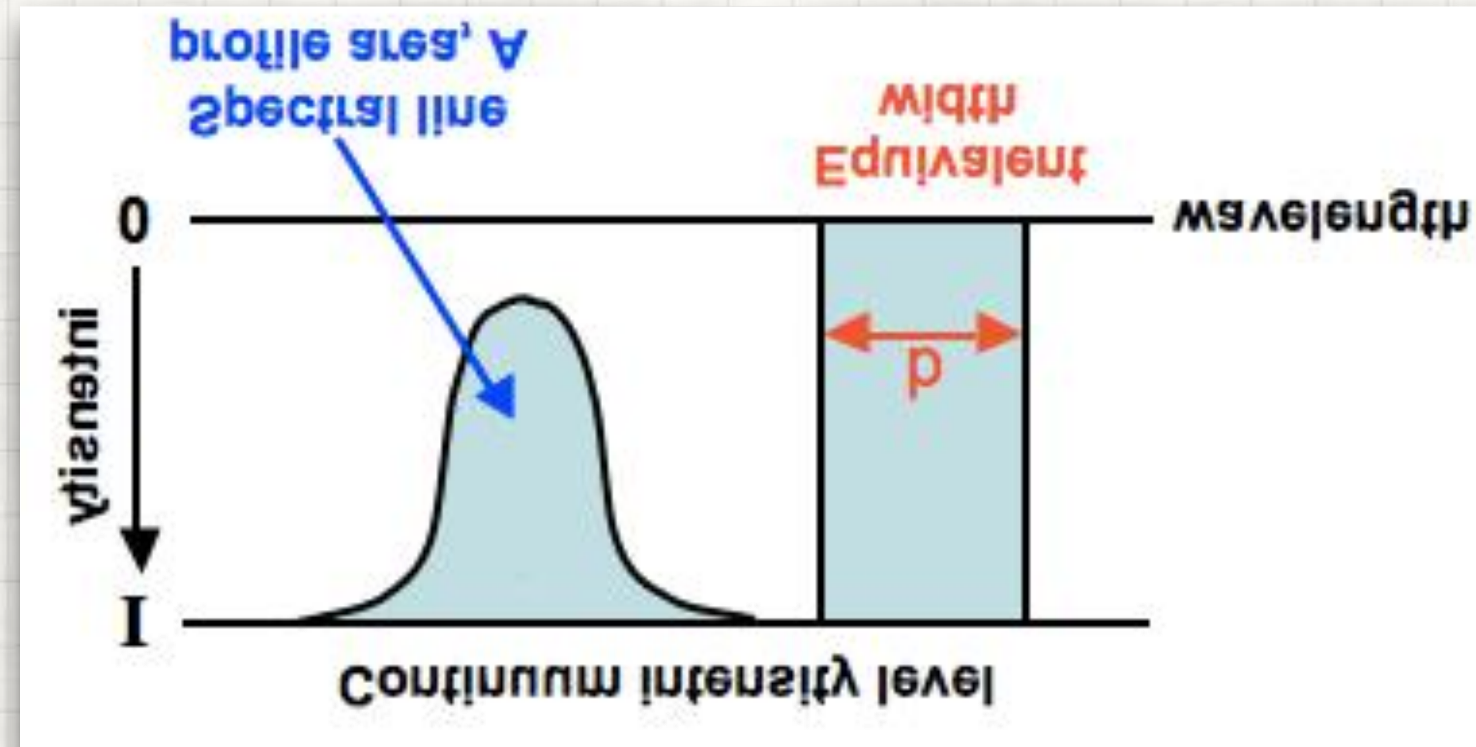

And of course applies both for absorption and emission

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LENSING OF HIGH REDSHIFT GALAXIES

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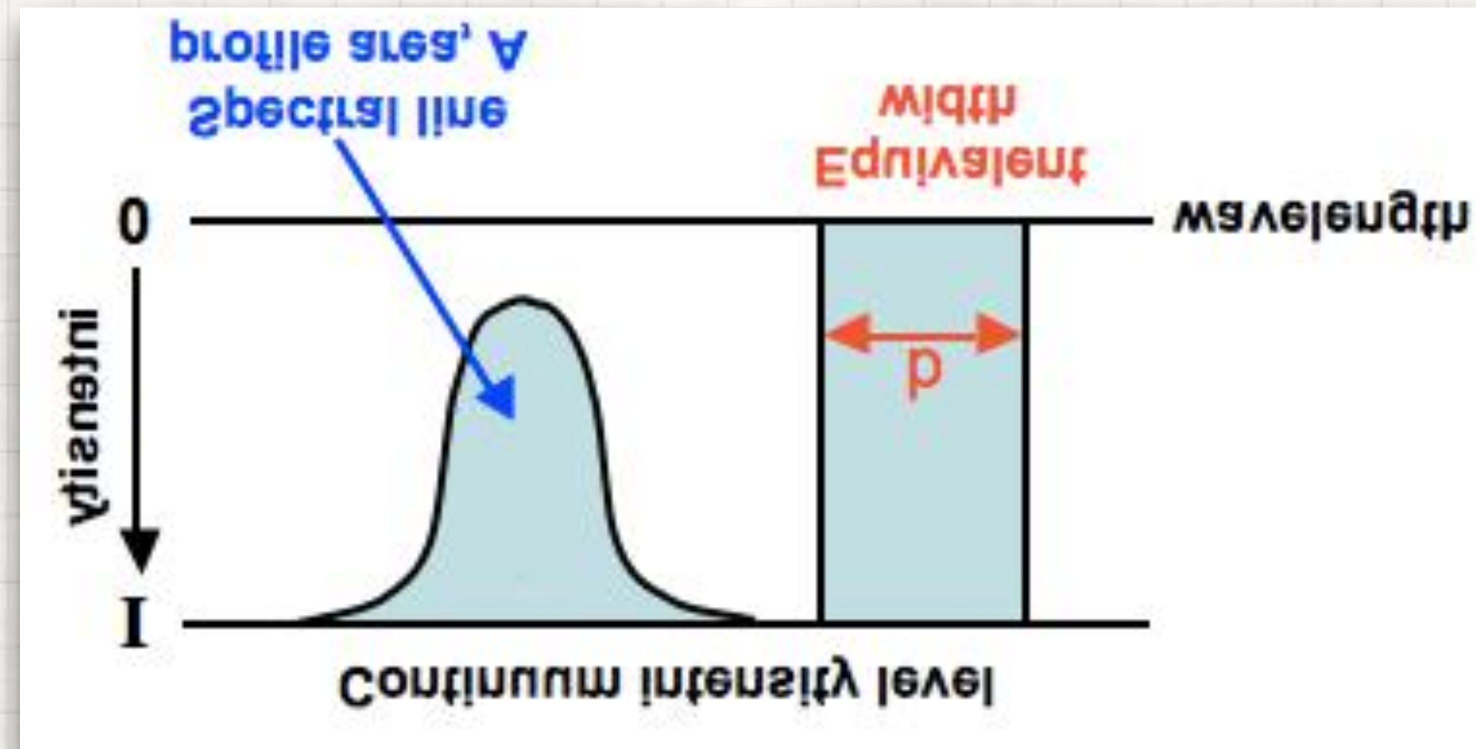

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LENSING OF HIGH REDSHIFT GALAXIES

SOME PROSPECTS AND SPECULATIONS FOR THE NEAR FUTURE

- JWST: one of its main goals, if not "the goal", is to detect first light sources. Roderik reviewed the capabilities of JWST, you have seen that it is unique in IR wavelengths - compared to ELTs, and with great power and resolution. It will be able to detect galaxies down to z~15 or more (where currently we are at z~10).

- ELTs: at slightly lower wavlengths (near-infrared) we would get excellent sensitivity and resolution, so what we know now of redshift.

- LSST, Euclid, other ground base surveys - more high-z quasars and black holes?

- Main persisting questions: turnover? did galaxies reionize the universe and how did the process look? first / pop III stars powering it? AGN? various more…

  —> most likely be answered in the next decade with these instruments.

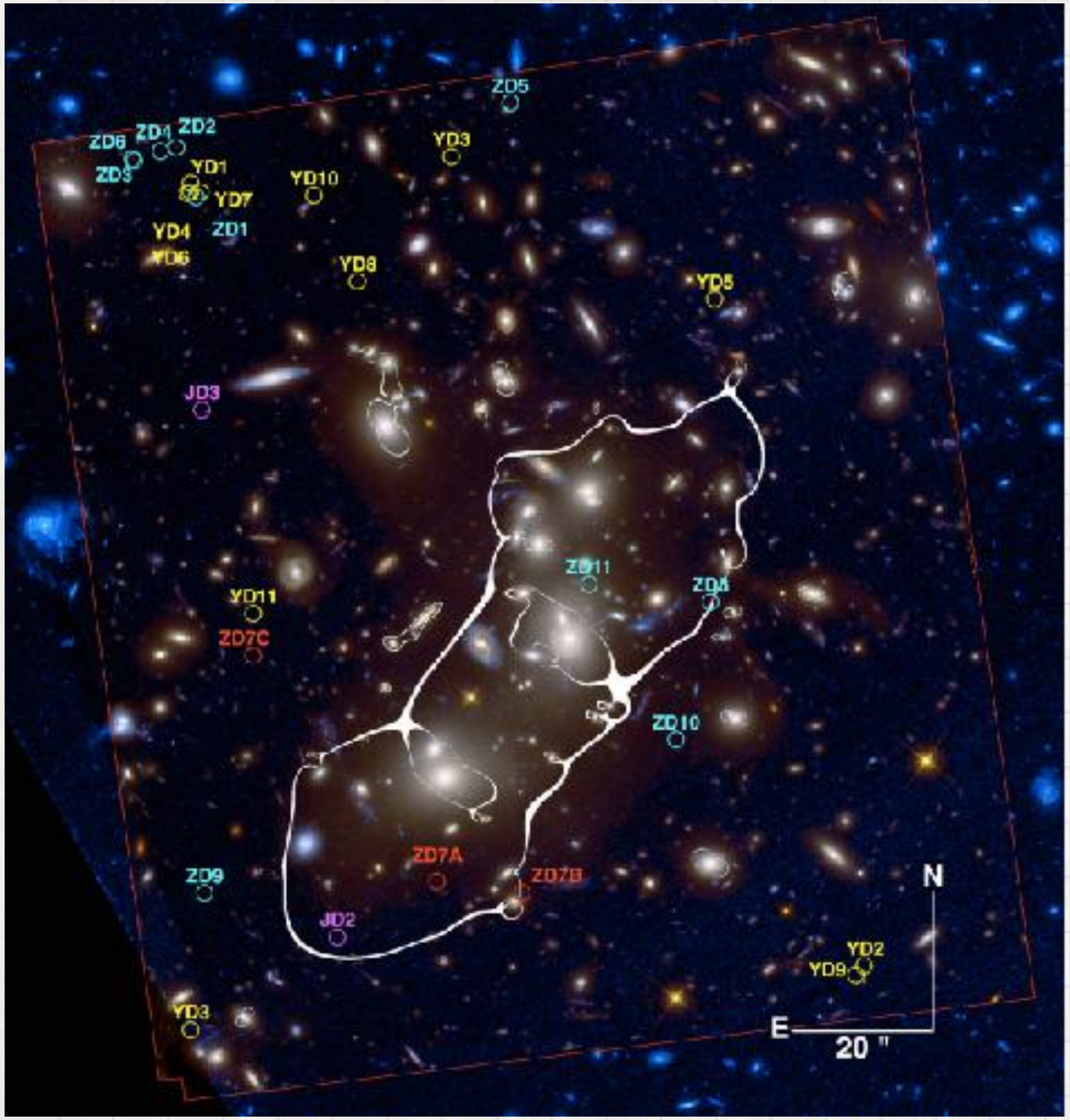
LENSING OF HIGH REDSHIFT GALAXIES

SUMMARY

- Physical properties of high redshift galaxies (mass, shape, size, SFR, gas and metallicity, dust).
- History of universe and how do we know Universe was reionized (CMB, Gunn-Peterson effect in Quasars, Ly alpha fraction decline)
- How do we detect high-redshift objects observationally (photometrically via the dropout technique, narrow band surveys, spectroscopically with UV lines, mostly)
- Luminosity function, Schechter function, faint end slope important for reionization, uncertain, turnover, bright end fewer sources,
- Lensing of high sources - gain from lensing. We can see fainter objects otherwise below flux limit, much improved internal details
- But there is a trade off with smaller source plane area: magnification bias
- Depends on LF slope: if steep—> gain, if flat —> lose. Generally because of typical LF shape we usually gain on the brighter end (but can still get faint enough!)
- Flux versus EW and spectroscopic gain from lensing.

LENSING OF HIGH REDSHIFT GALAXIES

SUMMARY



Zheng et al. 2014

Thank you!

LENSING OF HIGH REDSHIFT GALAXIES

EMISSION LINES - WE ALL KNOW THIS WIRGHT?

Lyα line emission is obtained when a hydrogen atom goes down from the second energy level to the first).
Ionizing radiation emitted by hot young O and B stars ionize their surrounding, dense interstellar gas,
which recombines on a relatively short timescale, trec = 10^5 years . A significant fraction of the
resulting recombination radiation emerges as Lyα line emission

A second mechanism: Lyα photons are emitted by collisionally excited HI (atoms that became excited thank to collisions with free electrons). As we discuss briefly in § 3.2, the collisionally excited Lyα flux emitted by galaxies appears subdominant to the Lyα recombination radiation (but may
become more important towards higher redshifts.) **[mostly from M. Dijkstra 2014 review]**

CIV 47.9 eV
CIII] 24.4 eV
[CII] 11.3 eV

Emission from ionized carbon is one important tool for FIR studies of early galaxies. Carbon is the fourth most abundant element in the Universe, and it takes 11.3 eV photons to form C+, so the low-lying (91 K above ground) 157.7 μm [CII] fine-structure line was long ago predicted to be the dominant coolant of the neutral ISM (Dalgarno & McCray 1972). The [CII] line is also usually optically thin and suffers very little extinction, so it is an excellent probe of the properties of the atomic gas heated by the far-UV (FUV) (6 - 13.6 eV) flux in galaxies. Indeed, the first [CII] detections from local galaxies revealed that the [CII] line can be the brightest single emission line from star forming galaxies, amounting to between 0.1 and 1% of the total FIR luminosity2
(Crawford et al. 1985; Stacey et al. 1991).