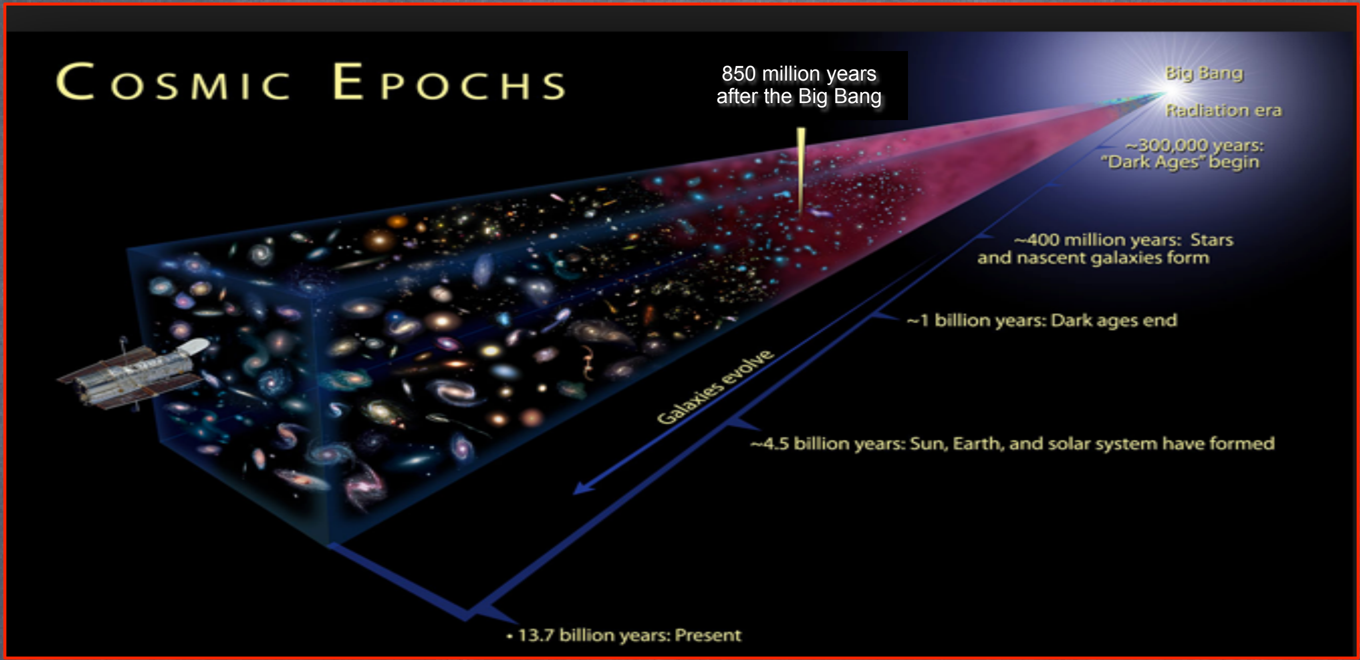
Probing the earliest galaxies and reionization

Eros Vanzella

INAF - Astronomical Observatory of Bologna

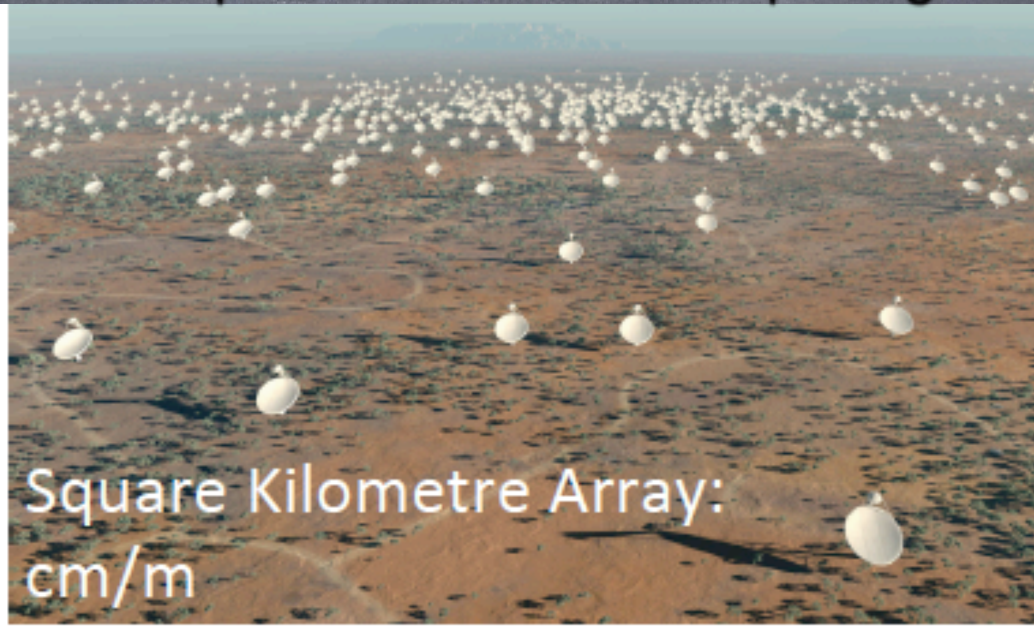


Lecture #5

Future instrumentation

https://www.eso.org/sci/facilities/eelt/

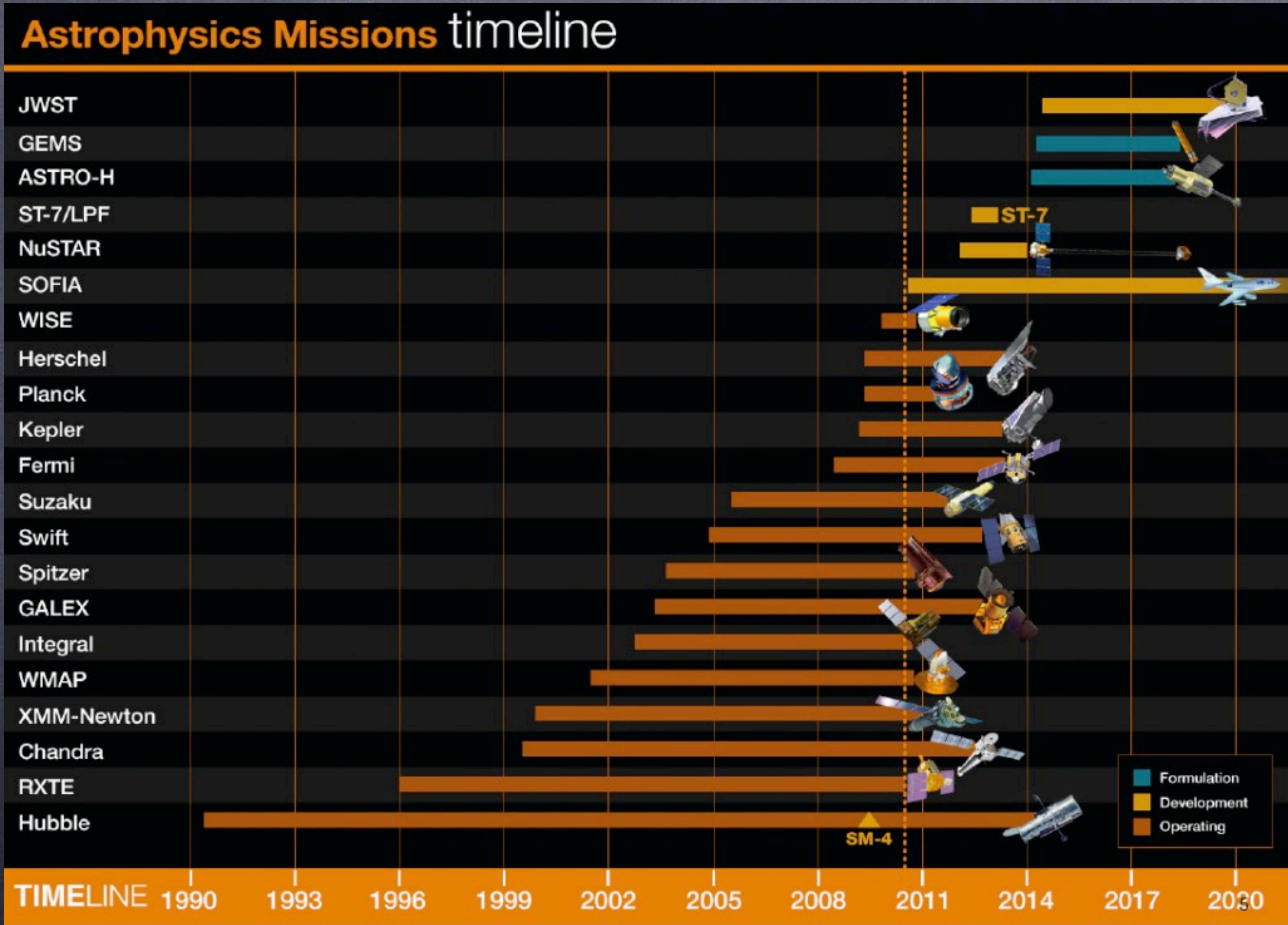
https://www.skatelescope.org/



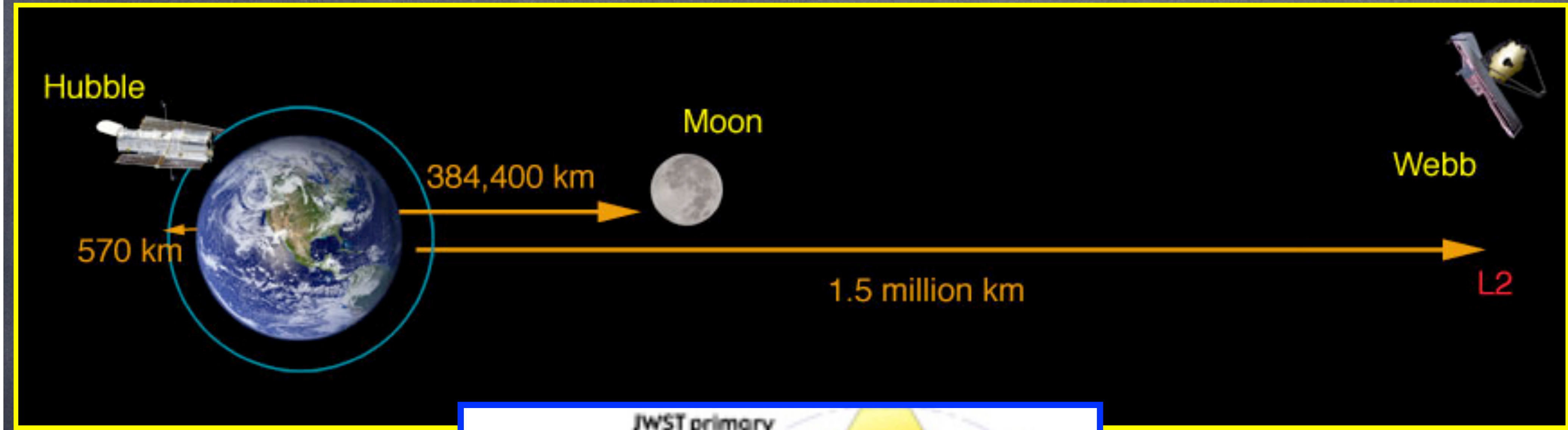
http://www.stsci.edu/jwst/instruments

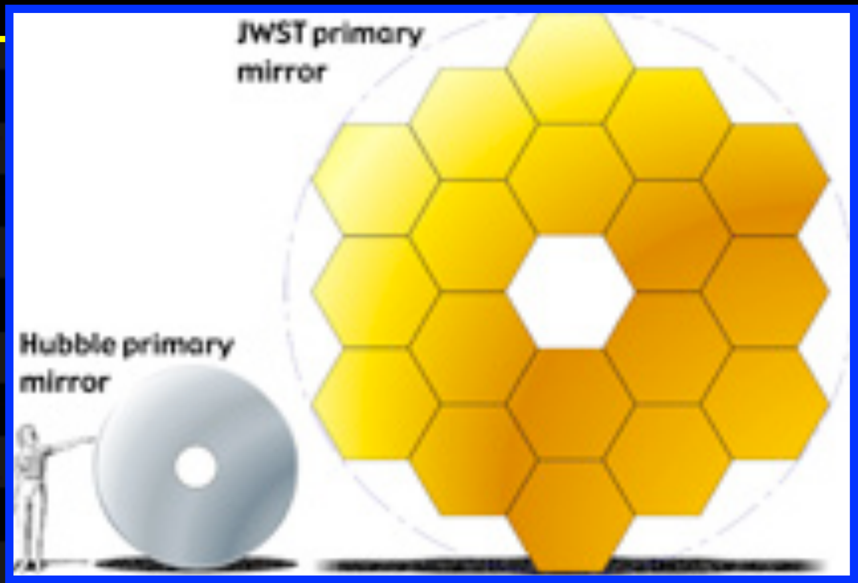
http://www.almaobservatory.org/

James Webb Space Telescope (JWST)

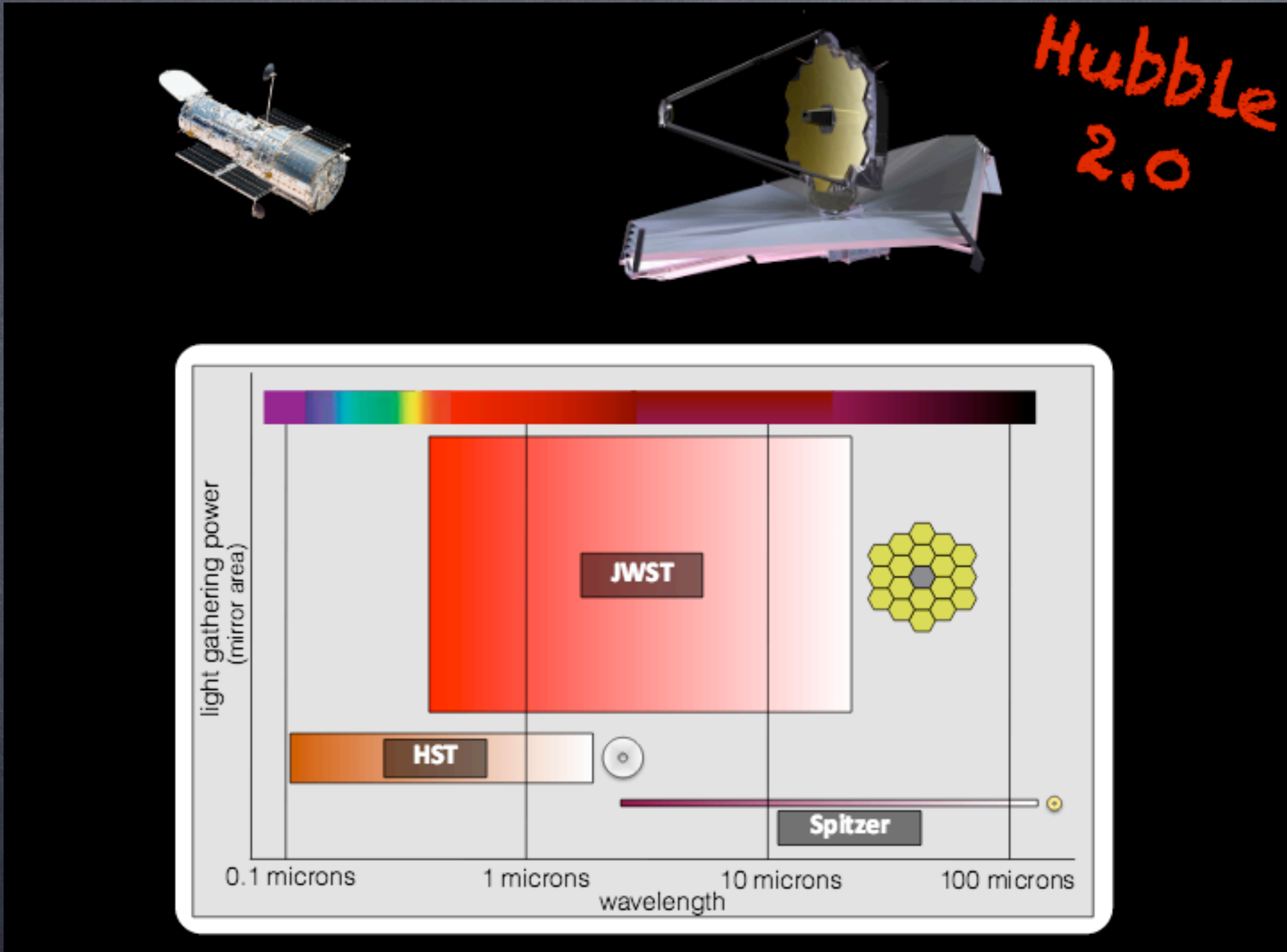


James Webb Space Telescope (JWST)

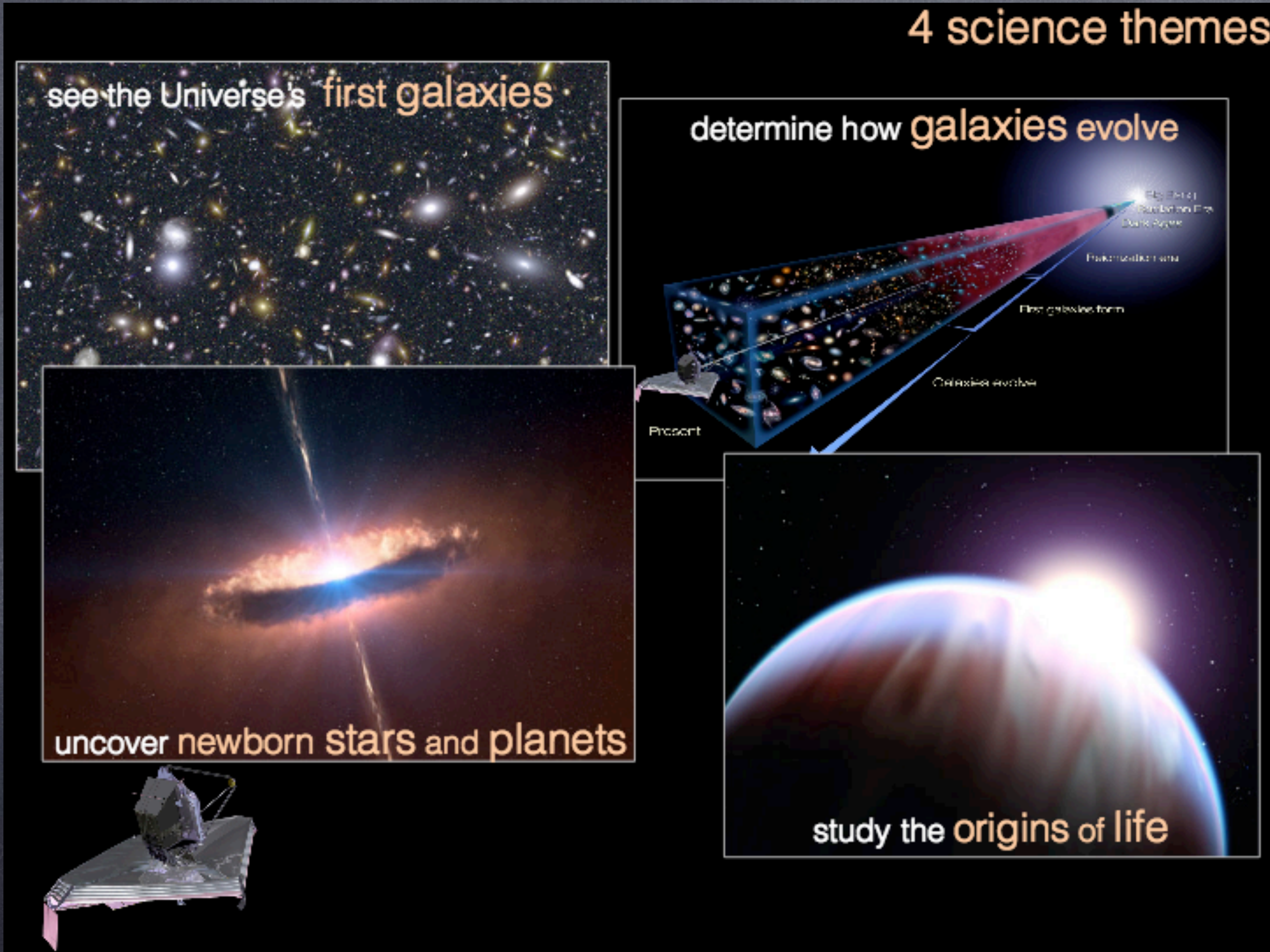




JWST


Hubble 2.0
JWST
HST
Spitzer
light gathering power
(mirror area)
0.1 microns
1 microns
10 microns
100 microns
wavelength

JWST


4 science themes
see the Universe's first galaxies
determine how galaxies evolve
First galaxies form
Galaxies evolve
Present
uncover newborn stars and planets
study the origins of life

JWST

NIRCam Imaging Properties:

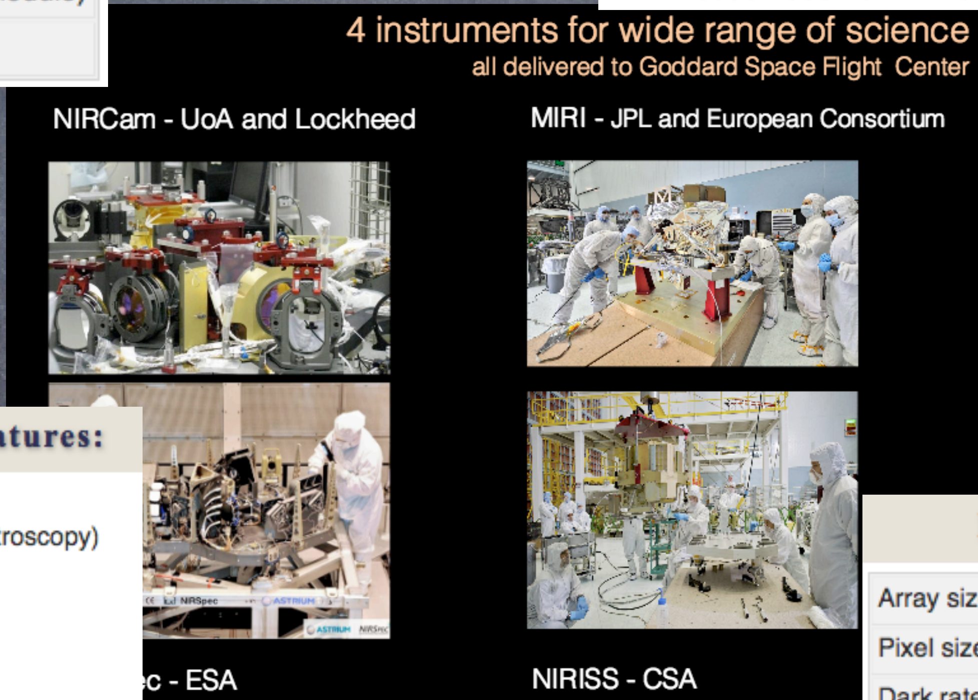
Wavelength range (μm)	0.6 to 2.3
	2.4 to 5
Nyquist λ (μm)	2/4
Pixel Format	4096^2 (short λ)
	2048^2(long λ)
Pixel Scale	0.032″ (short λ)
	0.065″ (long λ)
Field (arc min)	2.2 x 2.2 (one module)
Spectral Resolution	4,10,100

Imaging:

- λ = 5 - 28.3 μm
- 1.25' x 1.88' field of view
- Low resolution spectrograph, R~100, 5-10 μm
- Three 4-quadrant phase mask coronagraphs, one Lyot coronagraph

Medium Resolution Spectroscopy:

- λ = 5 - 27 μm (goal is 28.3 μm)
- Integral field spectroscopy, 3.5" x 3.5" FOV (or more)
- R ~ 3000-1000 from λ = 5- 27 μm



Slitless spectroscopy (R~150-700)
Aperture Masking interferometry
Imaging 1-5um

NIRSpec Features:

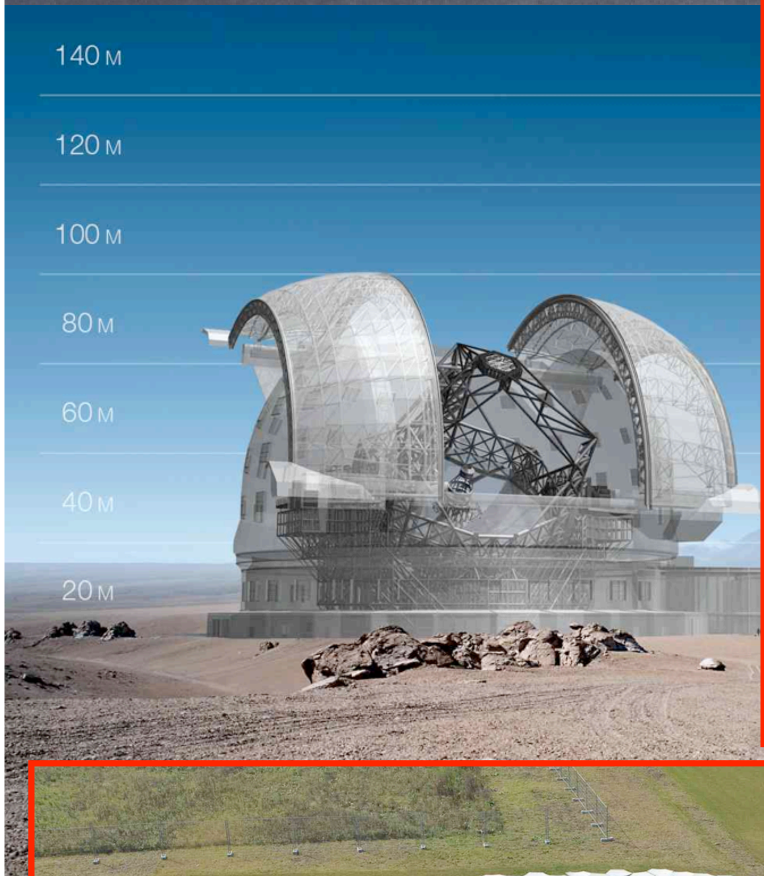
- All Reflective Optics
- 3.4' x 3.6' FOV (3' x 3' for Multi-object Spectroscopy)
- 200 mas nominal slit width
- 3 slit selection devices:
  - Micro-Shutter Array
  - Fixed slits
  - 3" x 3" Integral Field Unit
- 3 spectral resolutions:
  - R=100 (0.7 - 5.0 μm - single prism)
  - R=1000 (1.0 - 5.0 μm - 3 gratings)
  - R=2700 (1.0 - 5.0 μm - 3 gratings)
- 2 x 2k x 2k HgCdTe arrays

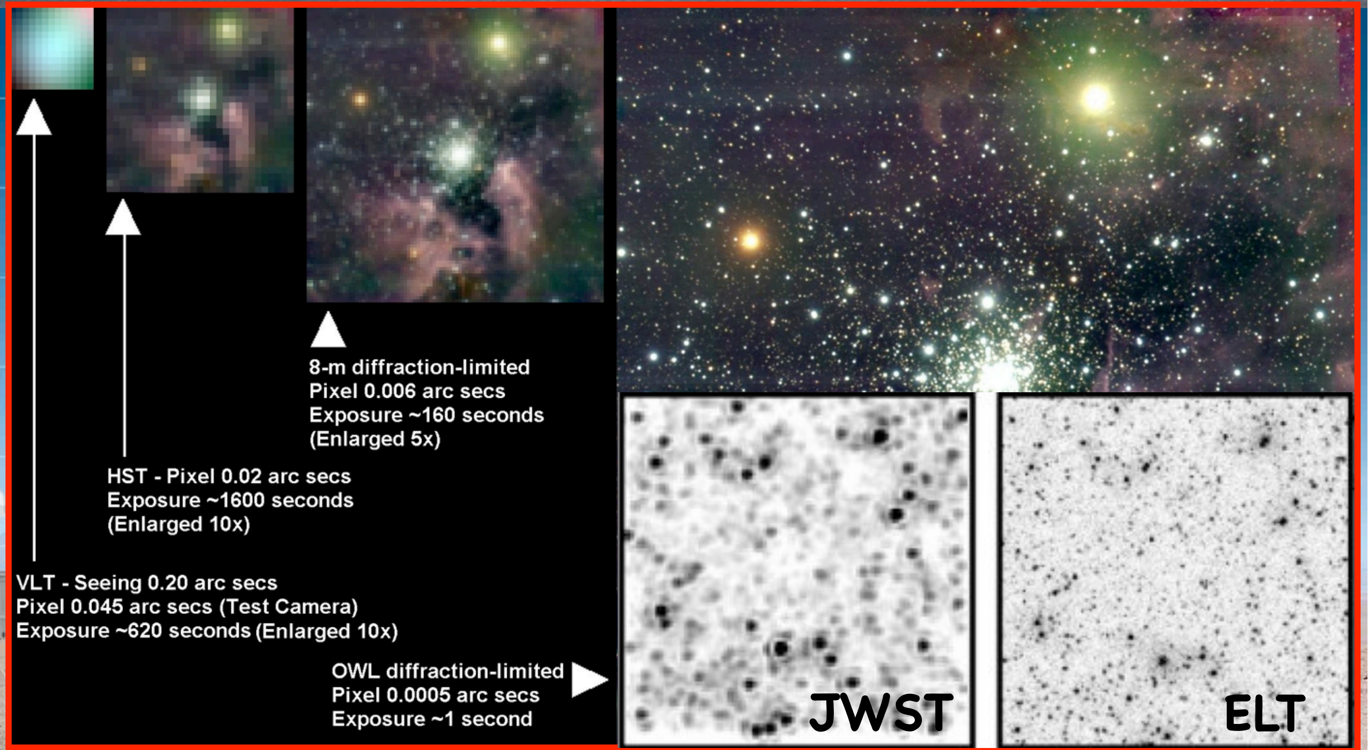
Detector Characteristics

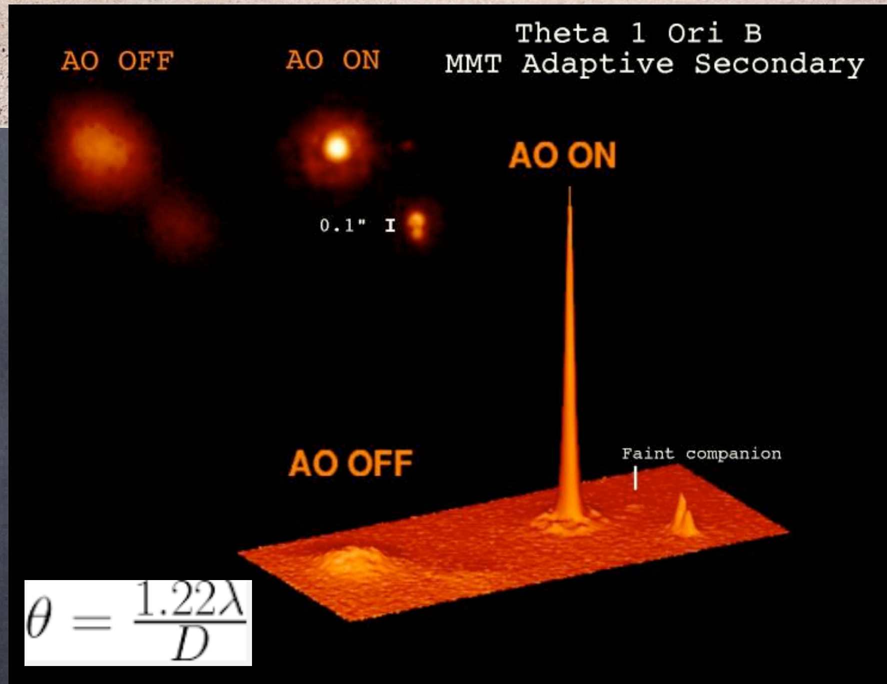
Array size	2048 x 2048 pixel HgCdTe array
Pixel size	18 μm x 18 μm
Dark rate	< 0.02 e-/s
Noise	23 e- (correlated double sample)
Gain	1.5 e-/ADU
Field of View (FOV)	2.2' x 2.2'
Plate scale in x	0.0654 arcsec/pixel
Plate scale in y	0.0658 arcsec/pixel

http://www.stsci.edu/jwst/instruments

European Extremely Large Telescope (39m diameter)





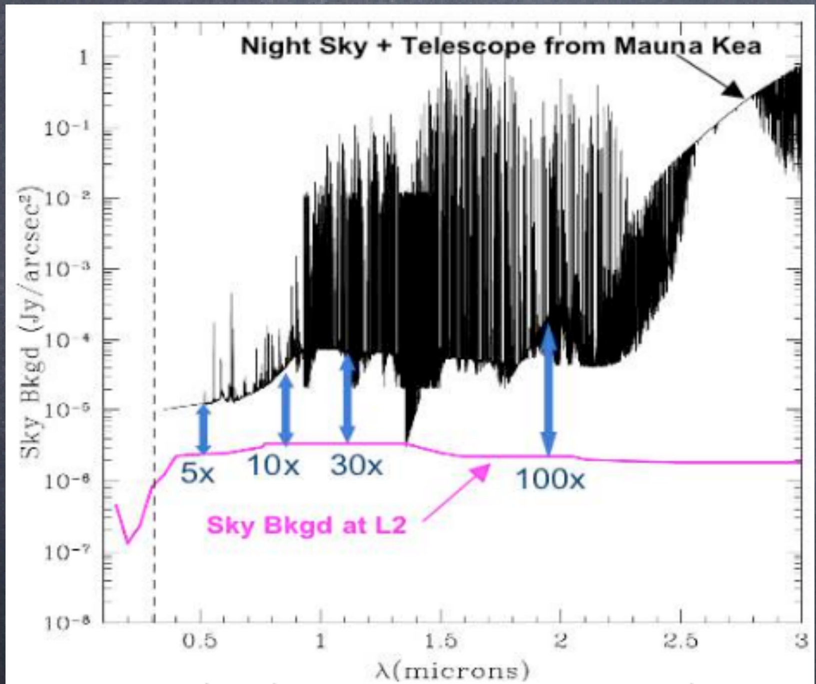


JWST E-ELT comparison (Mountain+10)

JWST

6.5m diameter

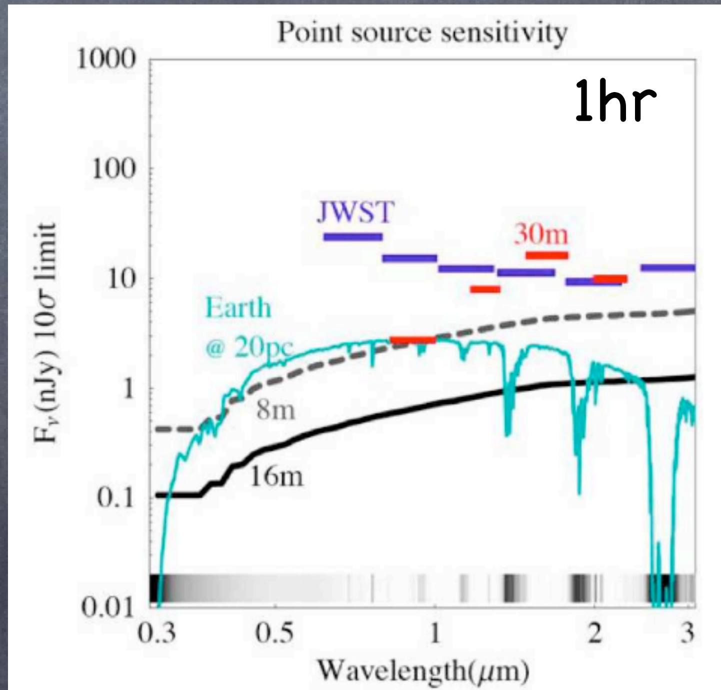
- low background - zodi at λ≲10 μm
- diffraction limited & stable
- spectroscopy R≲3000
- fixed instrument complement



E-ELT

39m diameter

- diffraction limited with AO
- spectroscopy R >> 3000
- instrumentation can be upgraded



For extremely faint sources (e.g.,V > 30), the atmospheric sky background emission, even at the best ground-based sites, is at least 10^4–10^6 times brighter than the source

JWST E-ELT comparison (Mountain+10)

JWST

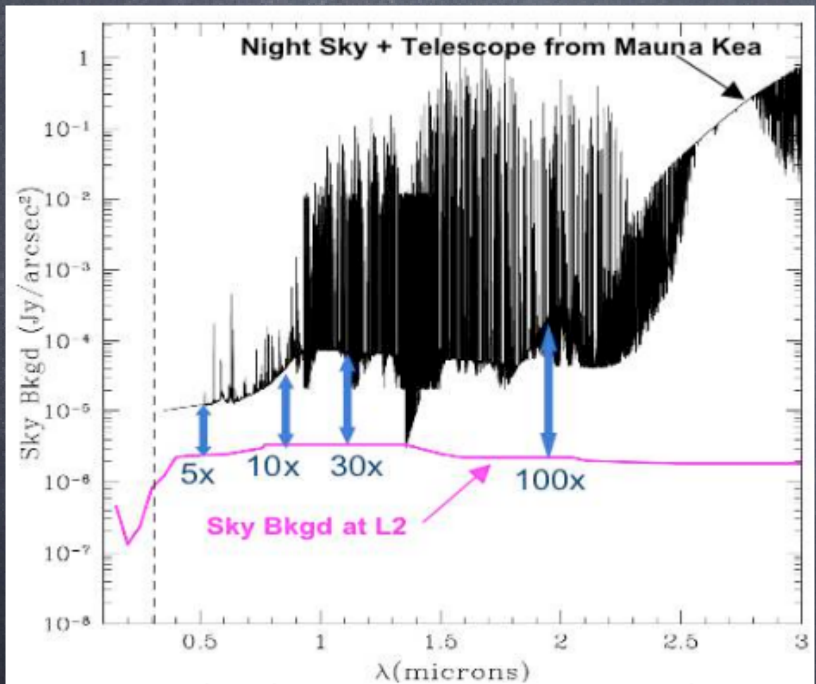
6.5m diameter

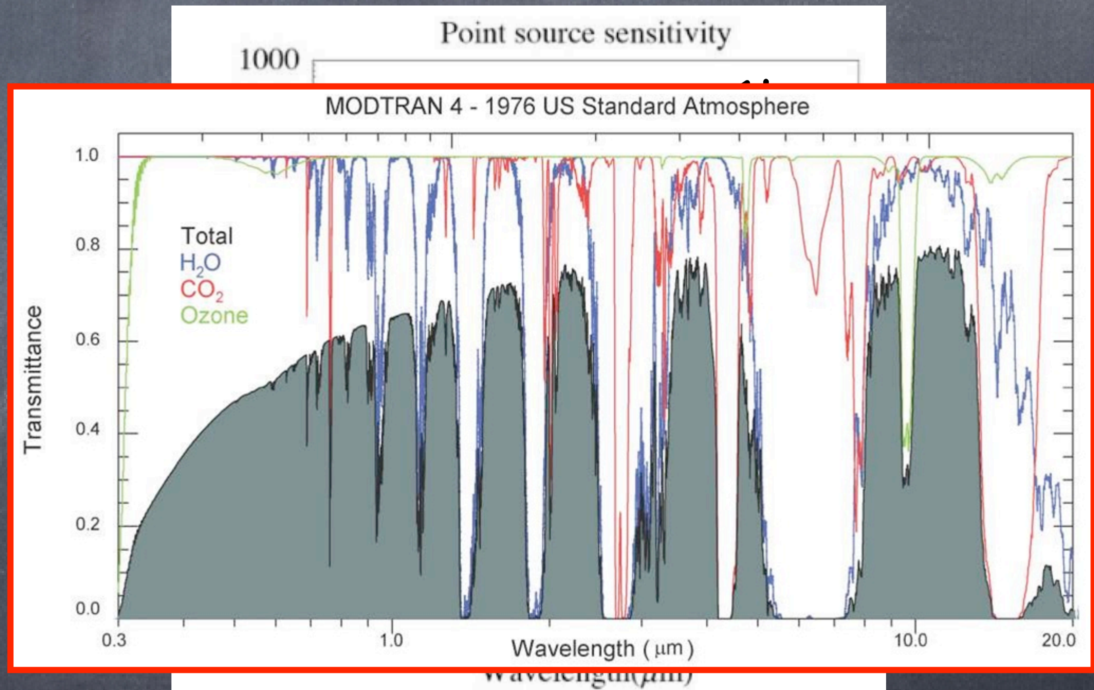
- low background - zodi at $\lambda \lesssim 10$ μm
- diffraction limited & stable
- spectroscopy $R \lesssim 3000$
- fixed instrument complement

E-ELT

39m diameter

- diffraction limited with AO
- spectroscopy R >> 3000
- instrumentation can be upgraded

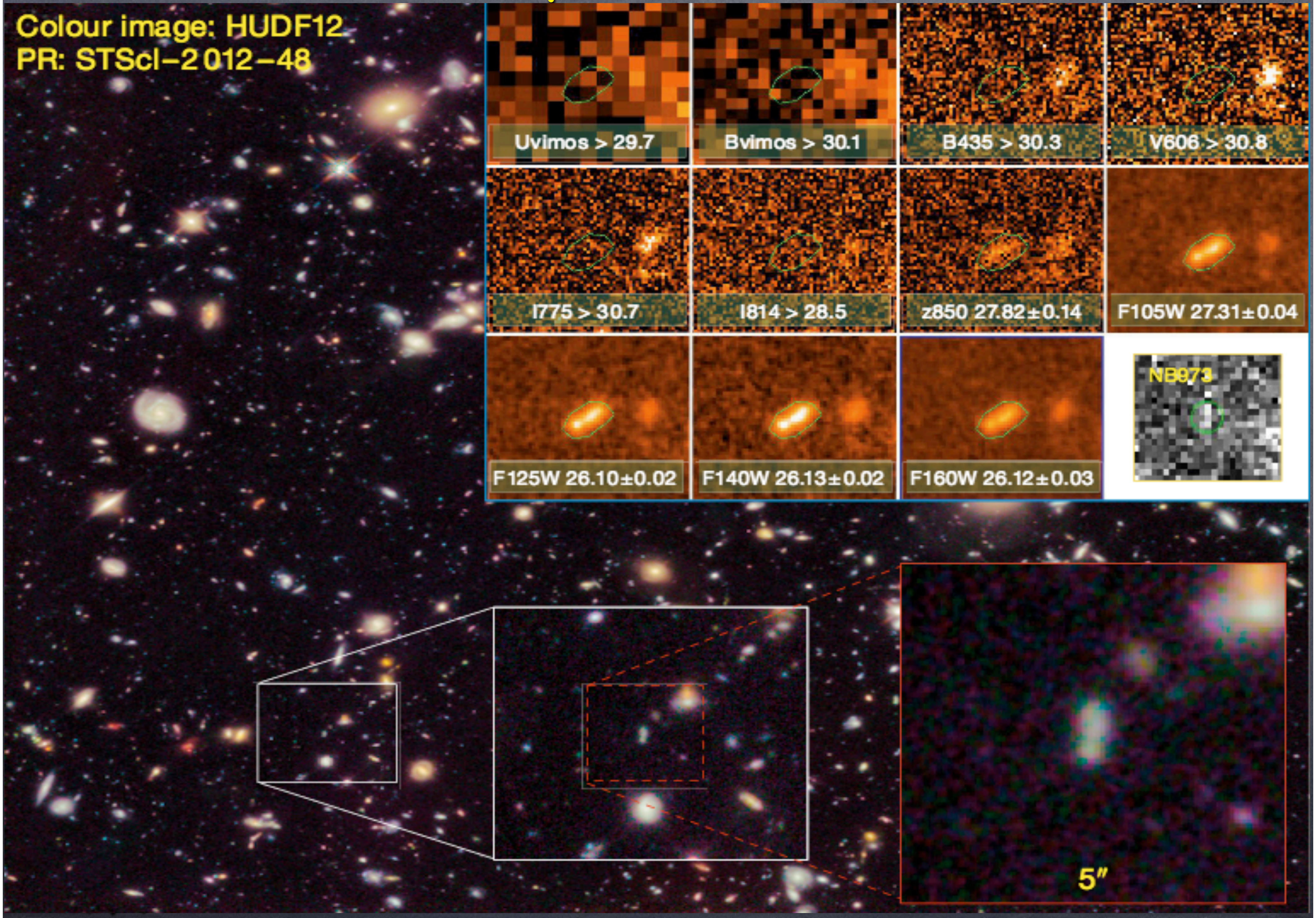




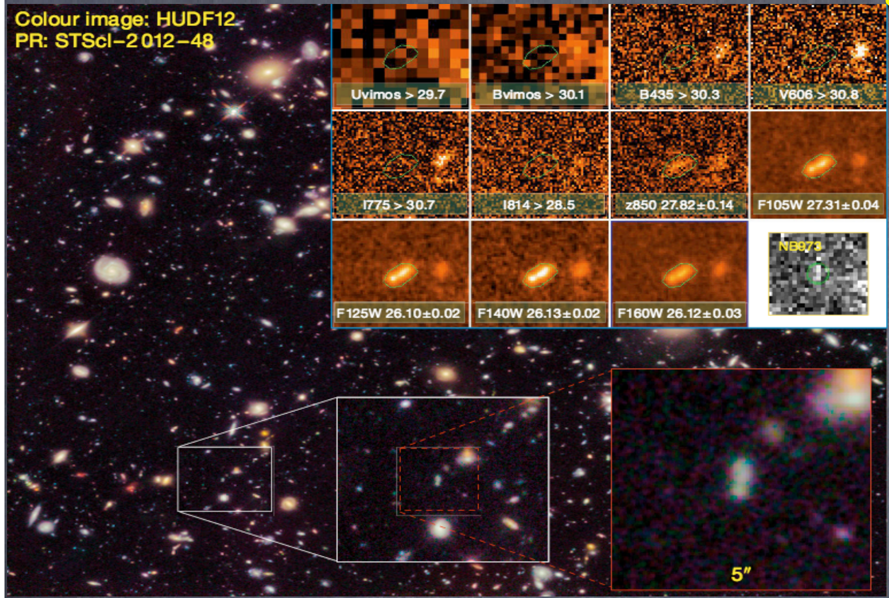
For extremely faint sources (e.g., V > 30), the atmospheric sky background emission, even at the best ground-based sites, is at least 10^4–10^6 times brighter than the source

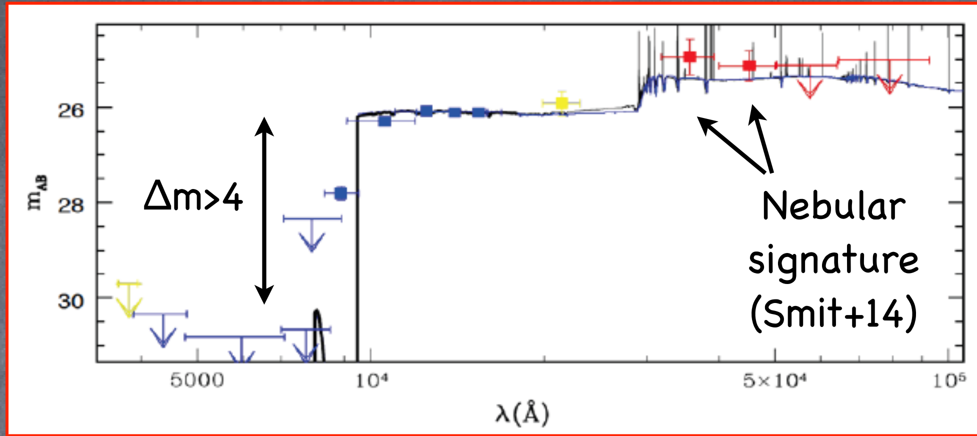
An example of
what we cannot do with
the current large telescopes...
linked to previous lectures

A 52 hours VLT/FORS2 spectrum of the best z=7 candidate

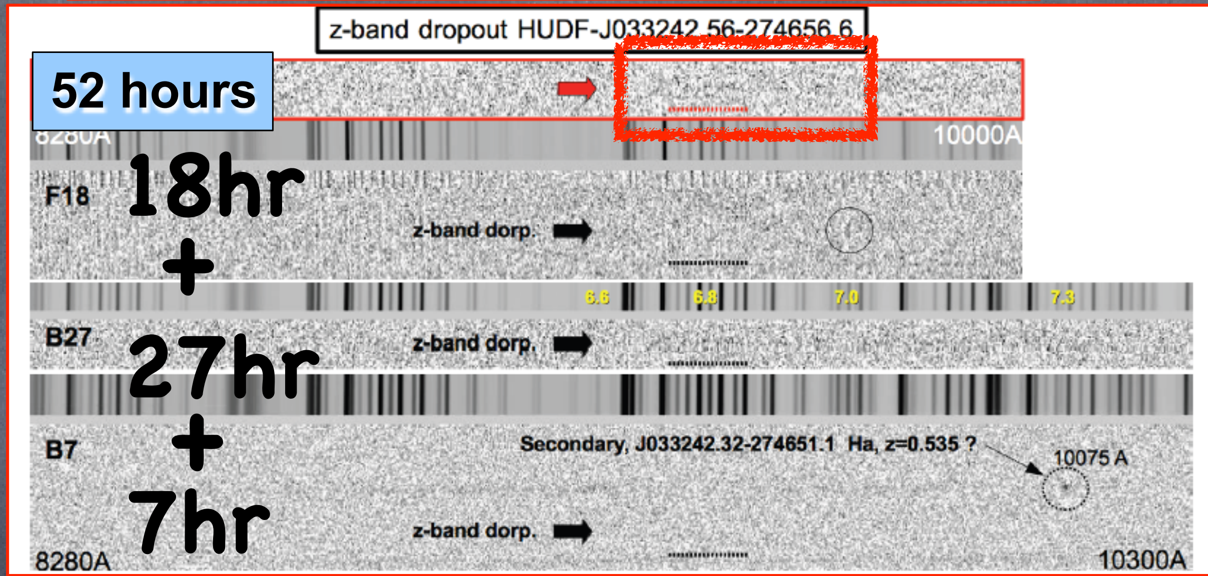


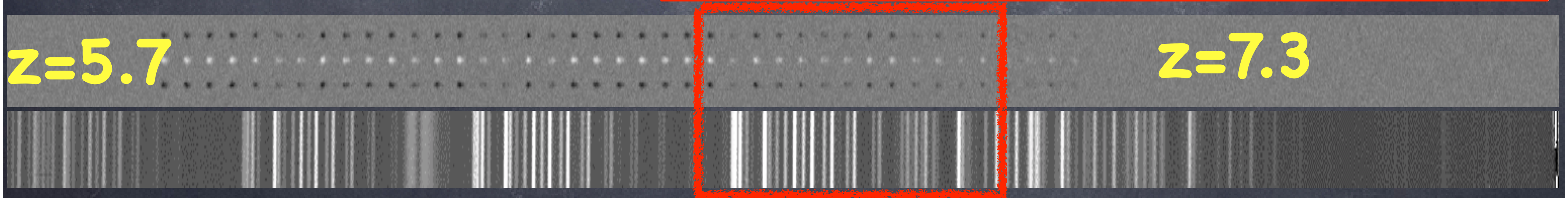
A 52 hours VLT/FORS2 spectrum of the best z=7 candidate





Yan & Windhorst 2004; Bouwens et al. 2004; Bouwens & Illingworth 2006; Labbé et al. 2006; Bouwens et al. 2008; Oesch et al. 2010; Fontana et al. 2010; McLure et al. 2010; Bunker et al. 2010; Yan et al. 2010; Finkelstein et al. 2010; Castellano et al. 2010; Wilkins et al. 2011; Bouwens et al. 2011; Grazian et al. 2011; McLure et al. 2013; Bouwens etal. 2014





f(Lya)<3e-18 erg/s/cm2 3-9 sigma, 6.5<z<7.0

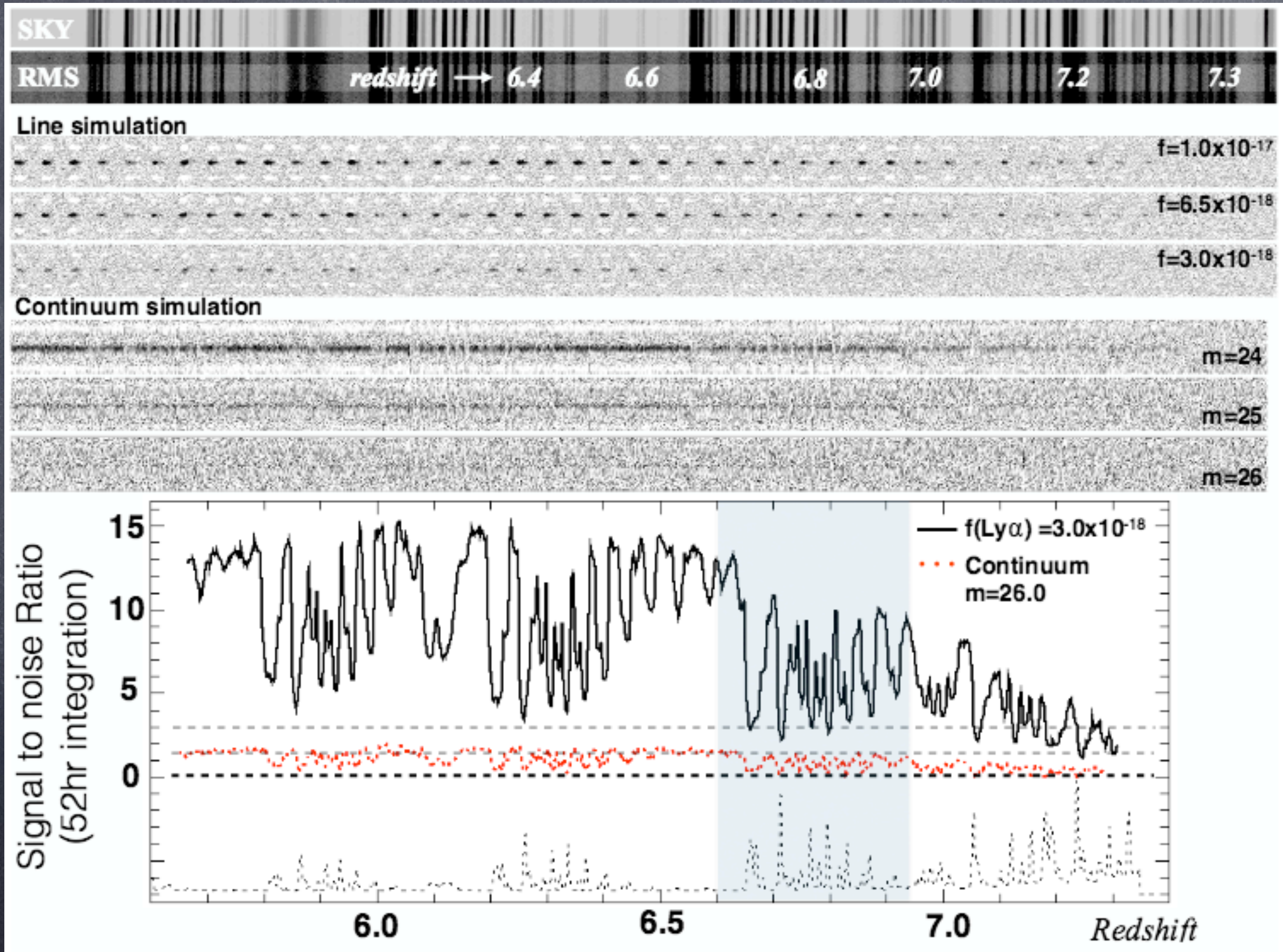
EW(Lya)<9A rest-frame

ESO-VLT

Current limitations of an 8/10m-class telescope: optical spectroscopy

(realistic simulations, EV+14) [note: in the NIR limits are even shallower]

1um



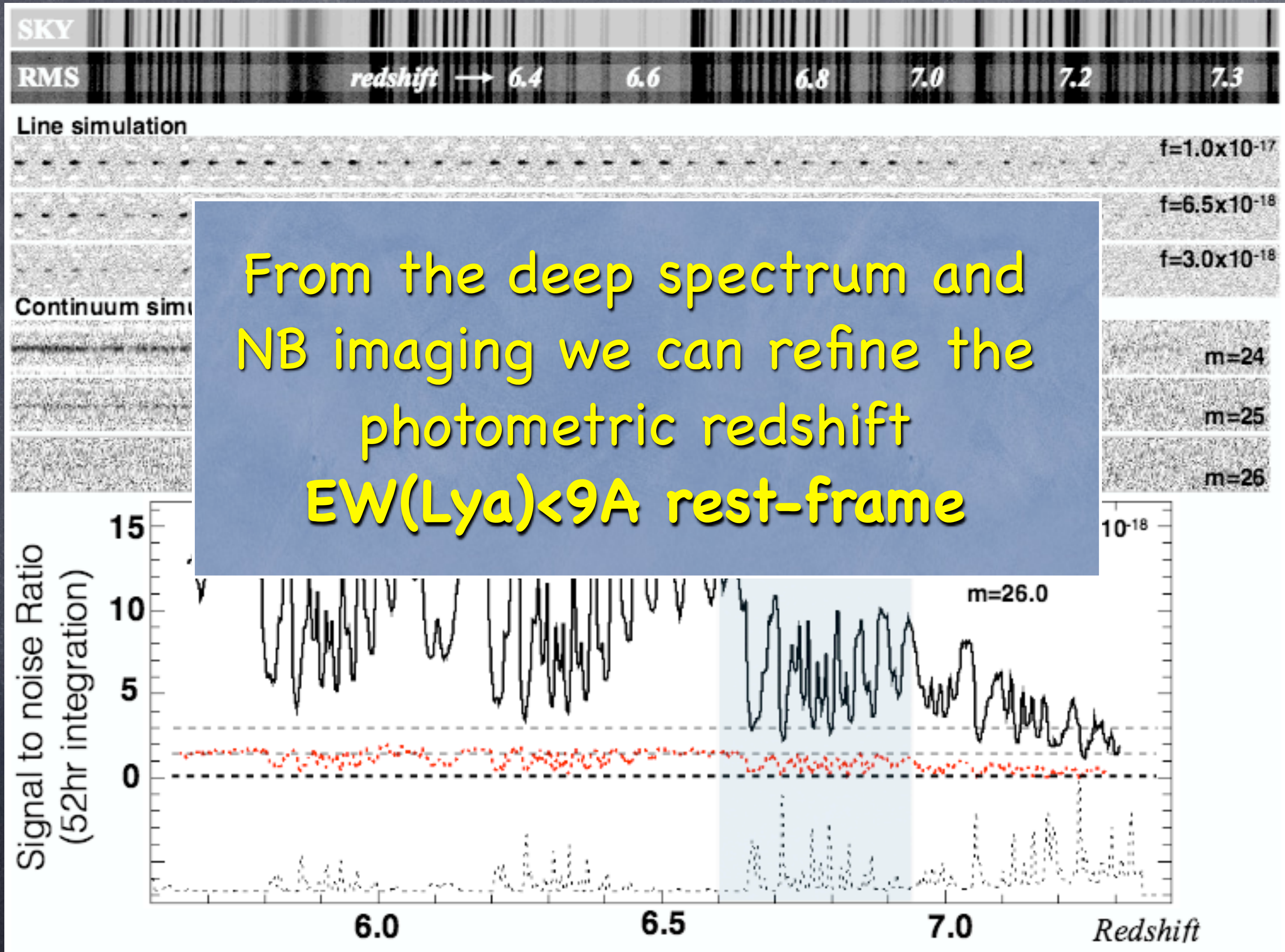
Texp

52hr

Current limitations of an 8/10m-class telescope: optical spectroscopy

(realistic simulations, EV+14) [note: in the NIR limits are even shallower]

1um

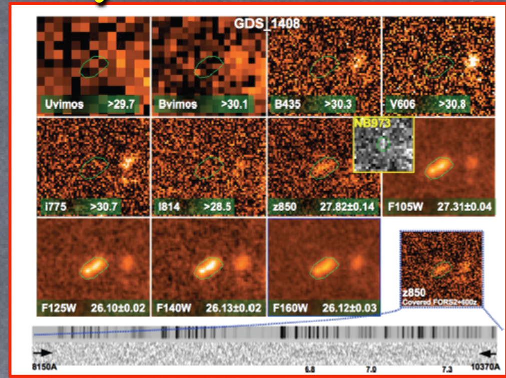


From the deep spectrum and NB imaging we can refine the photometric redshift

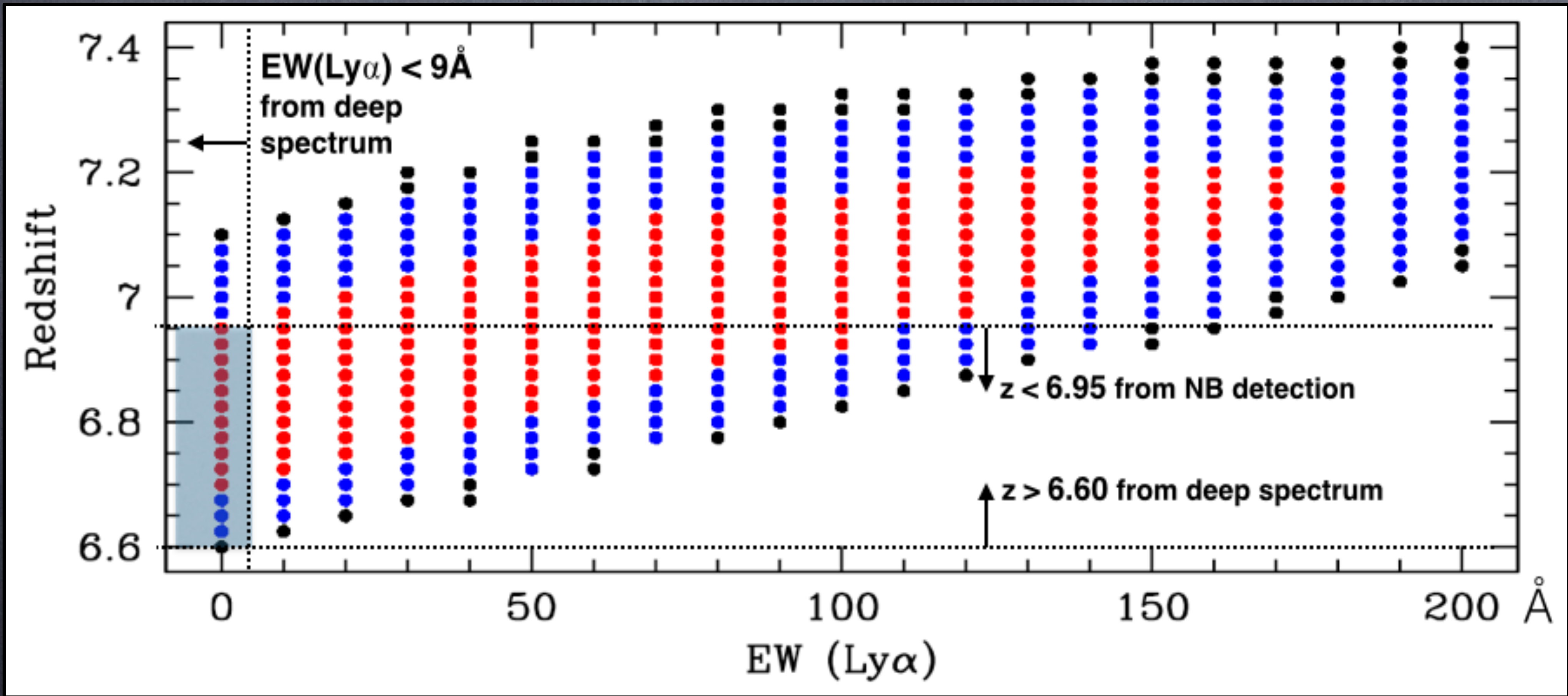
EW(Lya)<9A rest-frame

Texp 52hr

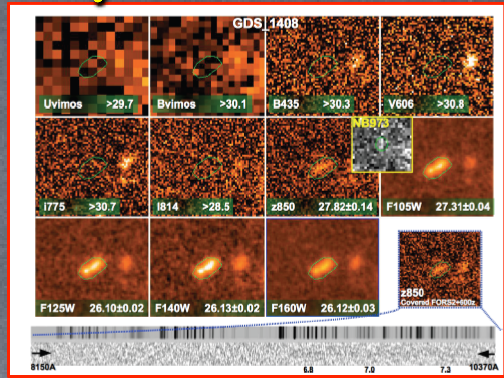
Combining deep spectrum and photometry



Refined redshift
z("photospec")=**6.82+/-0.1**



Combining deep spectrum and photometry



Refined redshift

z("photospec")=**6.82+/-0.1**

Astronomical Science

The Deepest VLT/FORS2 Spectrum of a z ~ 7 Galaxy: An Easy Target for the E-ELT

=> ~2hr integration time will be enough to measure z

Eros Vanzella[1]
Adriano Fontana[2]
Laura Pentericci[2]
Marco Castellano[2]
Andrea Grazian[2]
Mauro Giavalisco[3]
Mario Nonino[4]
Stefano Cristiani[4]
Gianni Zamorani[1]
Cristian Vignali[5]

[1] INAF-Osservatorio Astronomico di Bologna, Italy

gets have been established by photometric redshifts, relying on the cut-off at the Lyman-α break, but spectroscopic confirmation of these redshifts is very challenging. The Lyman-α line is the most prominent emission feature in the optical/near-infrared region (e.g., Vanzella et al., 2011) and is thus seen as a standard for reliable redshift confirmation. Despite immense efforts, only a few objects are spectroscopically confirmed and some of the faint line detections have been proved doubtful when subjected to deeper observations or more elaborate reduction.

(S/N ~ 20–50 with HST's Wide Field Camera 3 [HST-WFC3]). It has been repeatedly selected as a high-redshift candidate from the earliest Near Infrared Camera and Multi-Object Spectrometer (NICMOS) data to the current ultradeep HUDF data over the past ten years (Vanzella et al. [2014a] and references therein), including extensive Very Large Telescope (VLT) spectroscopy with the Focal Reducer/low dispersion Spectrograph (FORS). All these spectra have now been collected and assessed, combining them into an ultradeep spectrum and compared with

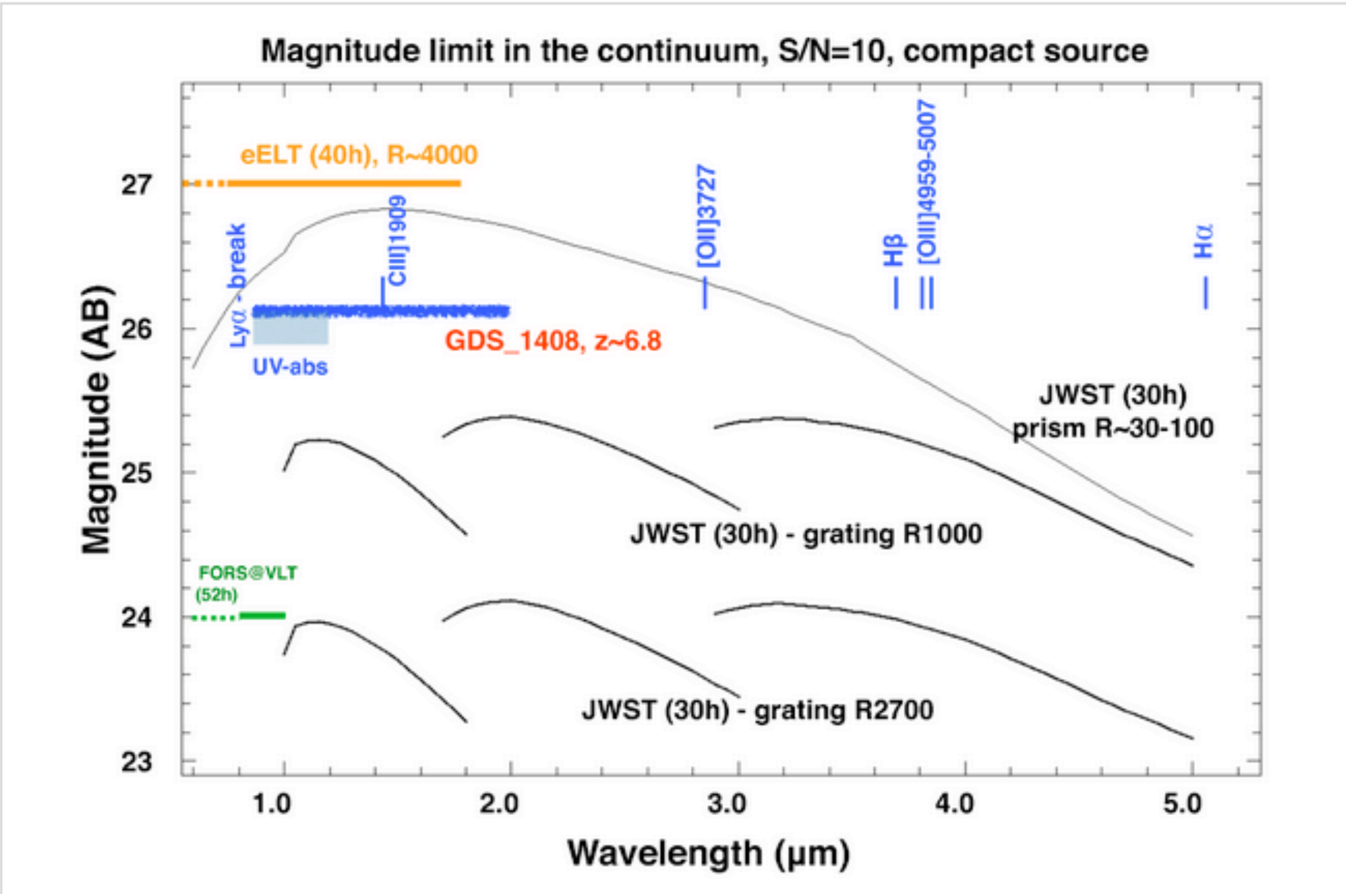
ESO Messenger no. 157

James Webb Space Telescope
JWST Science Corner

Recent JWST Science Abstracts - High Redshift Galaxies

A 52 hours VLT/FORS2 spectrum of a bright z ~ 7 HUDF galaxy: no Ly-α emission

Reference: Eros Vanzella, INAF - Bologna Observatory, Co-authors:- Fontana A., Pentericci L., Castellano M., Grazian A., Giavalisco M., Nonino M., Cristiani S., Zamorani G., Vignali C., 2014,A&A,569,78



JWST

Lya -> z=40

[OII]3727 -> z=12.4

[OIII]5007 -> z=9

Ha -> 6.6

ELT

continuum J=27-28

http://www.stsci.edu/jwst/jwst-science-corner/paper-abstracts-high-redshift-galaxies

James Webb S
JWST Scie

Recent JWST Science

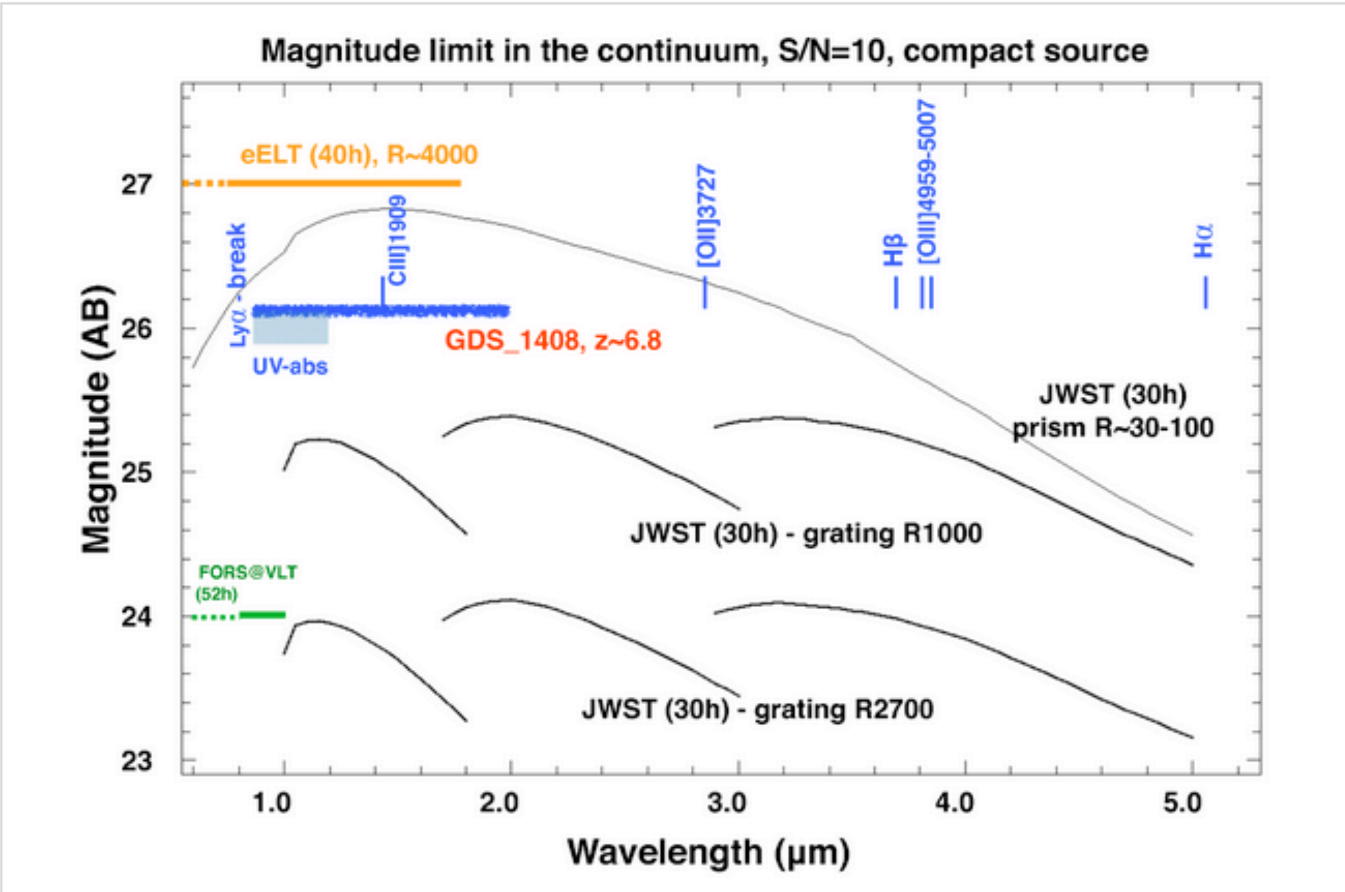
A 52 hours VLT/FORS2 spectr emission

JWST will capture rest-frame optical lines ([OII]3727, Hb, [OIII]4959-5007, Ha)

ELT will capture UV continuum (IGM break + ISM abs. lines)

NOT ONLY REDSHIFT, BUT PHYSICAL PROPERTIES

Reference: Eros Vanzella, INAF - Bologna Observatory, Co-authors:- Fontana A., Pentericci L., Castellano M., Grazian A., Giavalisco M., Nonino M., Cristiani S., Zamorani G., Vignali C., 2014,A&A,569,78



JWST

Lya -> z=40

[OII]3727 -> z=12.4

[OIII]5007 -> z=9

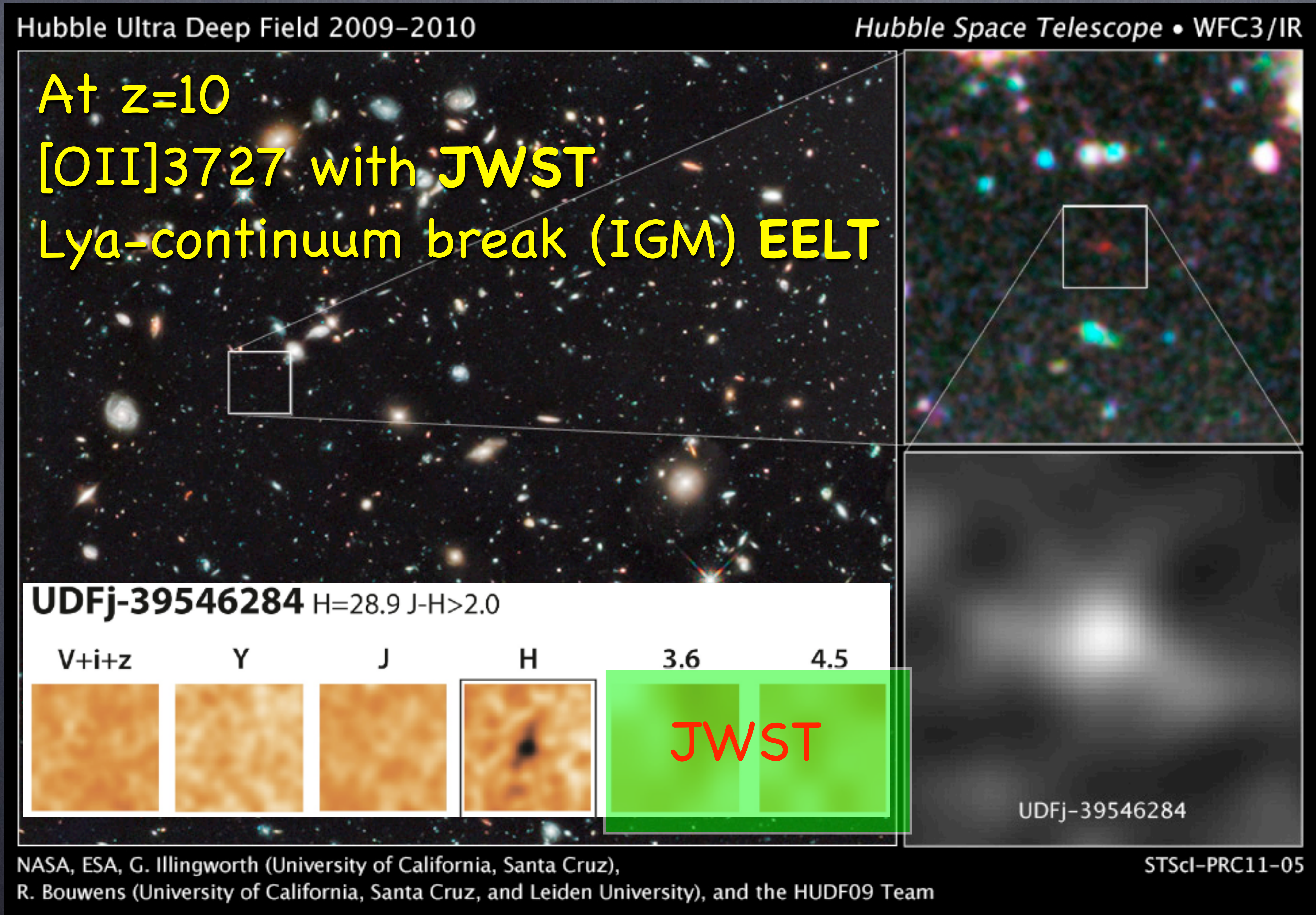
Ha -> 6.6

ELT

continuum J=27-28

http://www.stsci.edu/jwst/jwst-science-corner/paper-abstracts-high-redshift-galaxies

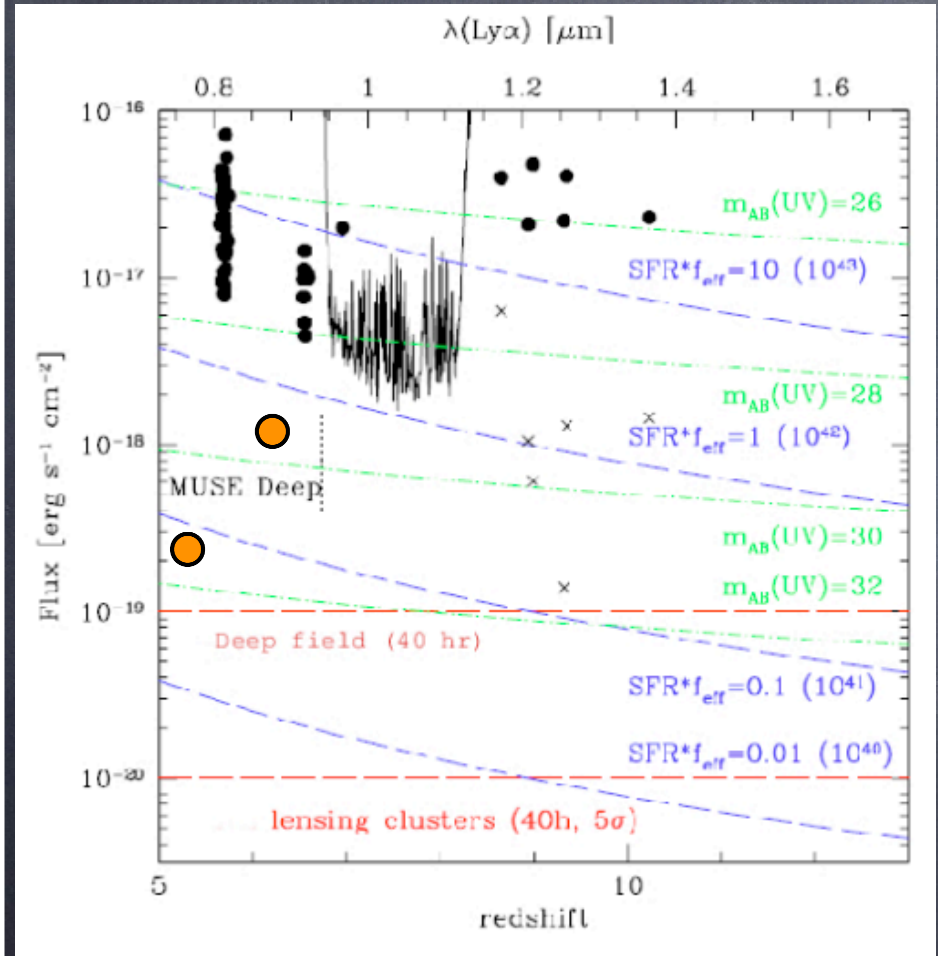
A z=10 galaxy (candidate)



Bouwen+11, Nature

Line fluxes limits ELT/MOS and JWST/NIRSpec

ELT-MOS



Evans et al. (2013)

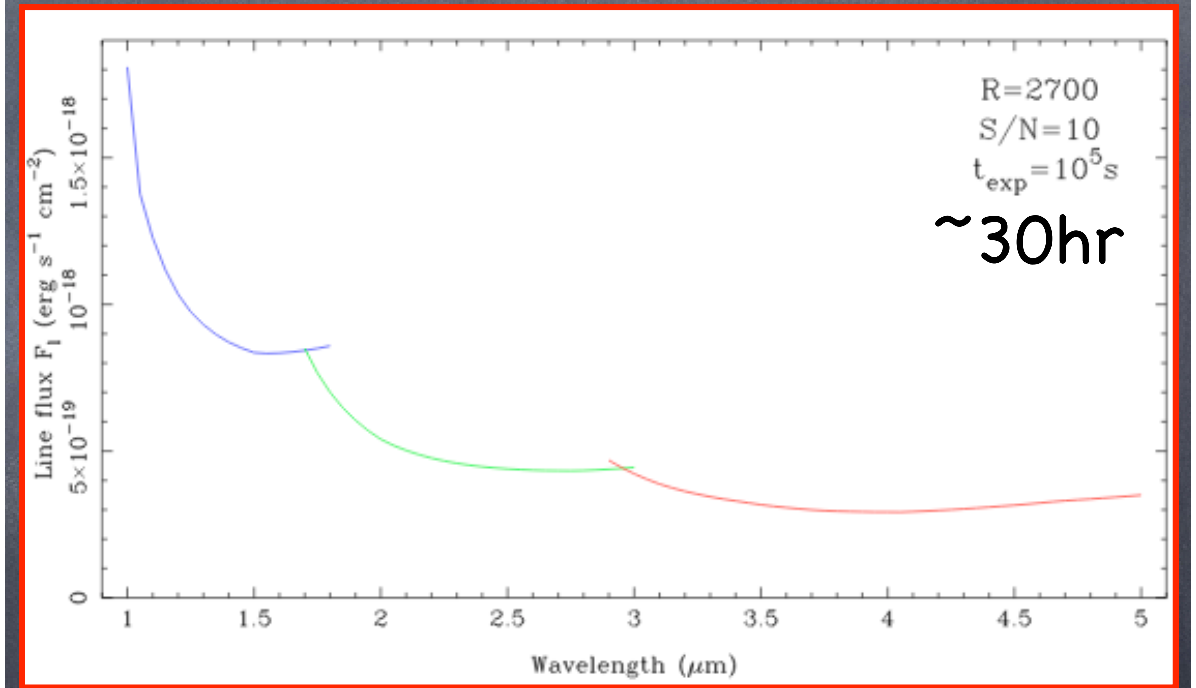
JWST

Lya -> z=40

[OII]3727 -> z=12.4

[OIII]5007 -> z=9

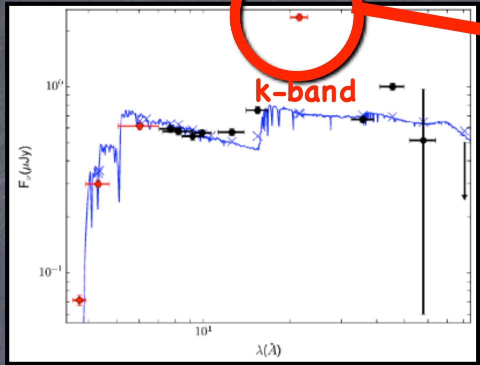
Ha -> 6.6



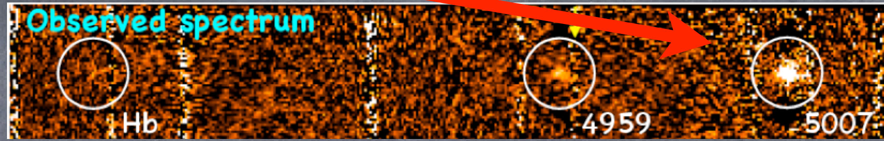
www.stsci.org

Examples of emission lines signature in the photometry at high-z

zspec = 3.212



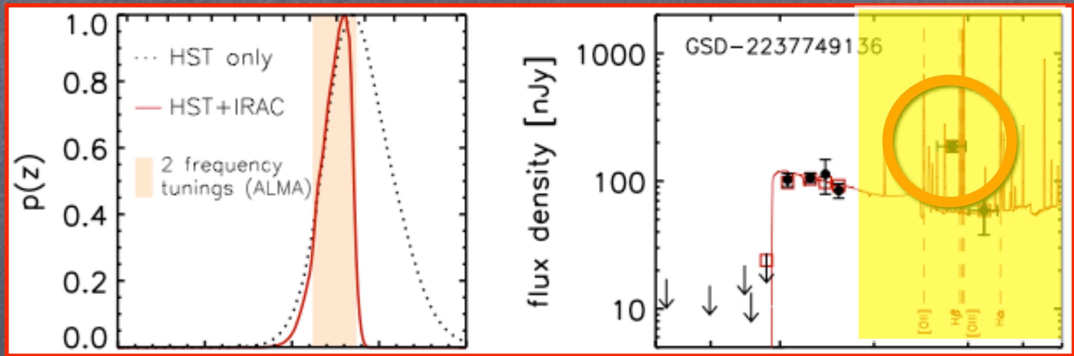
MOSFIRE spectrum (Keck)



This is what we can do now

---

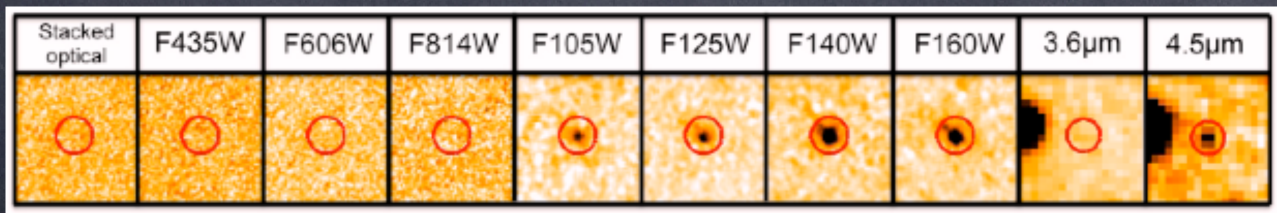
zphot = 6.8±0.15

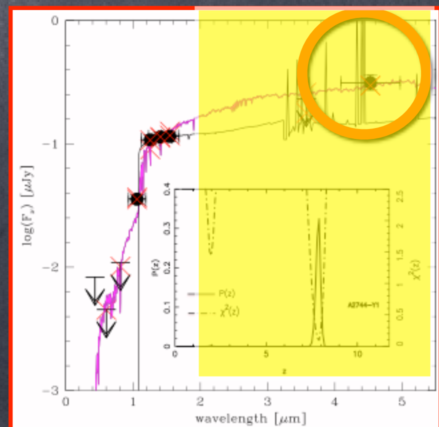


JWST will finally observe spectral optical lines - zspec

From Smit et al. (2014)

zphot 8.0



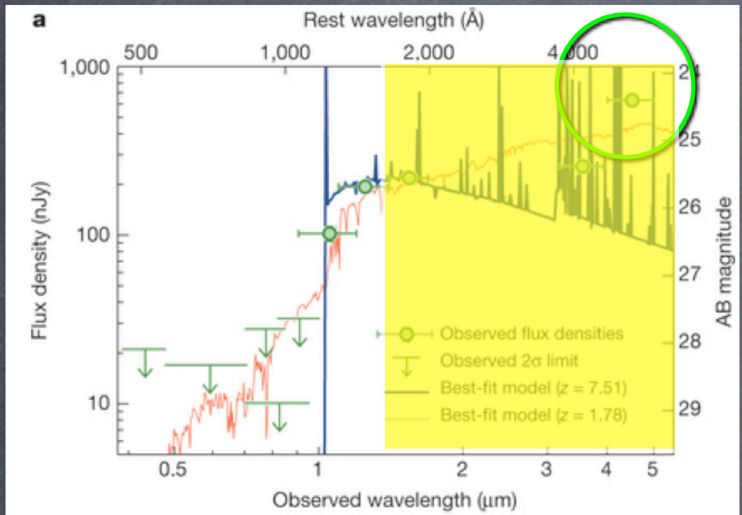


From LaPorte et al. (2014)

The most distant spectroscopically confirmed galaxies

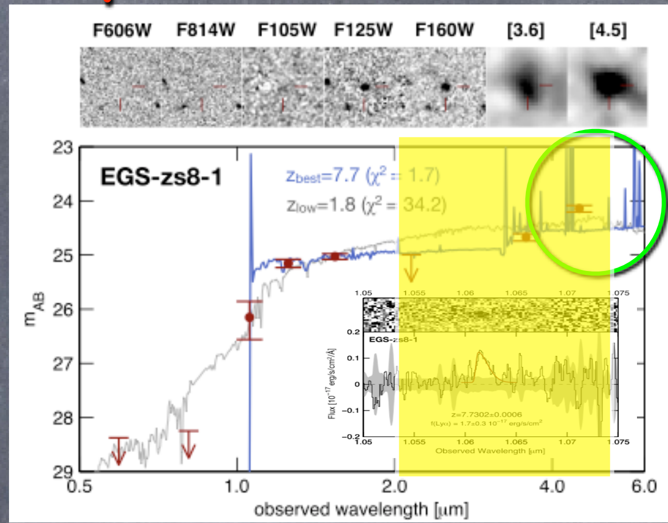
Lya+UV continuum (ELT) ; Oxigen+Balmer (JWST)

zspec=7.51 (Finkelstein+13)



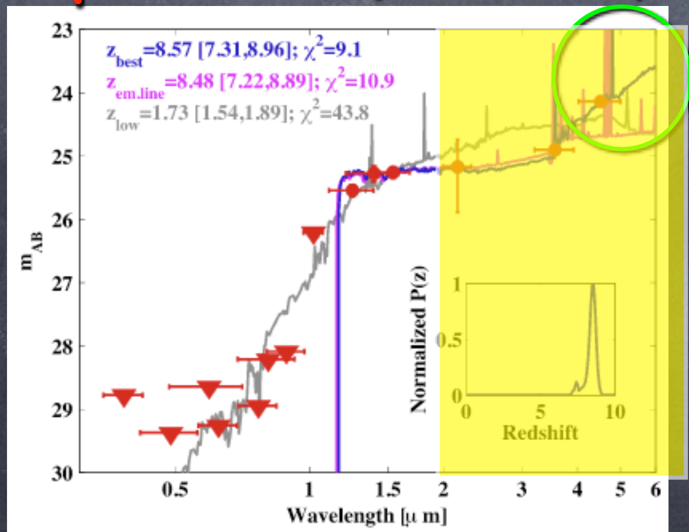
EW([OIII]+Hb) ~ 600A

zspec=7.73 (Oesch+15)



EW([OIII]+Hb) ~ 720A

zspec=8.68 (Zitrin+15)



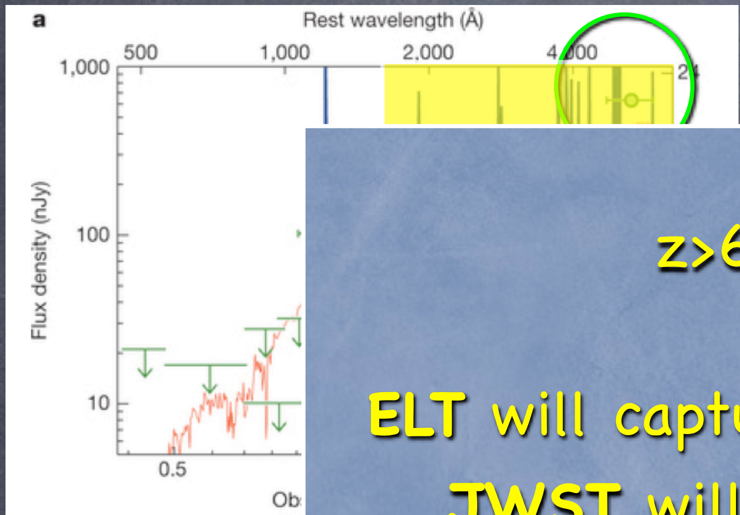
large EW([OIII]+Hb)

JWST will finally observe spectral optical lines - zspec

The most distant spectroscopically confirmed galaxies

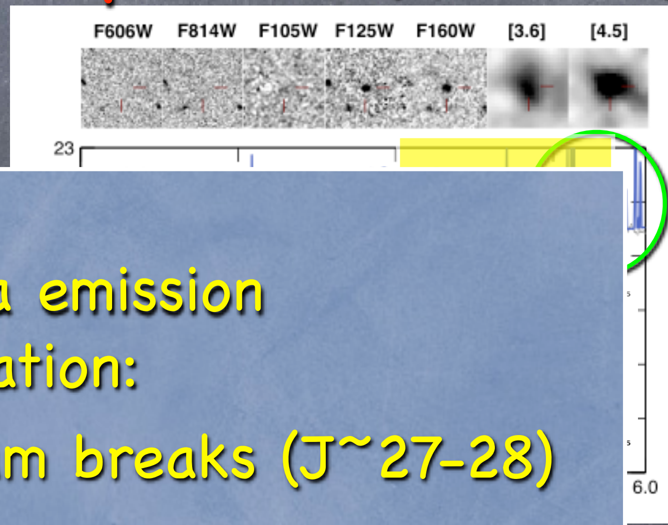
Lya+UV continuum (ELT) ; Oxigen+Balmer (JWST)

zspec=7.51 (Finkelstein+13)



EW([OIII

zspec=7.73 (Oesch+15)

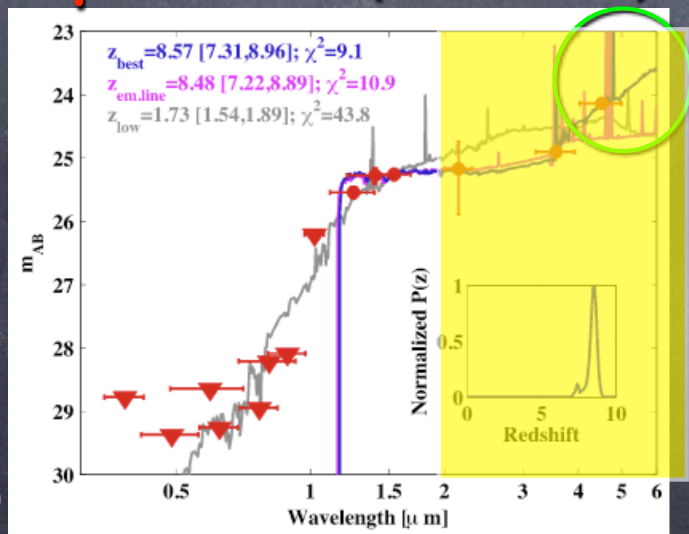


z>6.5 deficit of Lya emission
due to reionization:

ELT will capture UV continuum breaks (J~27-28)

JWST will capture rest-frame optical lines

zspec=8.68 (Zitrin+15)



JWST will finally observe spectral optical lines - zspec

large EW([OIII]+Hb)

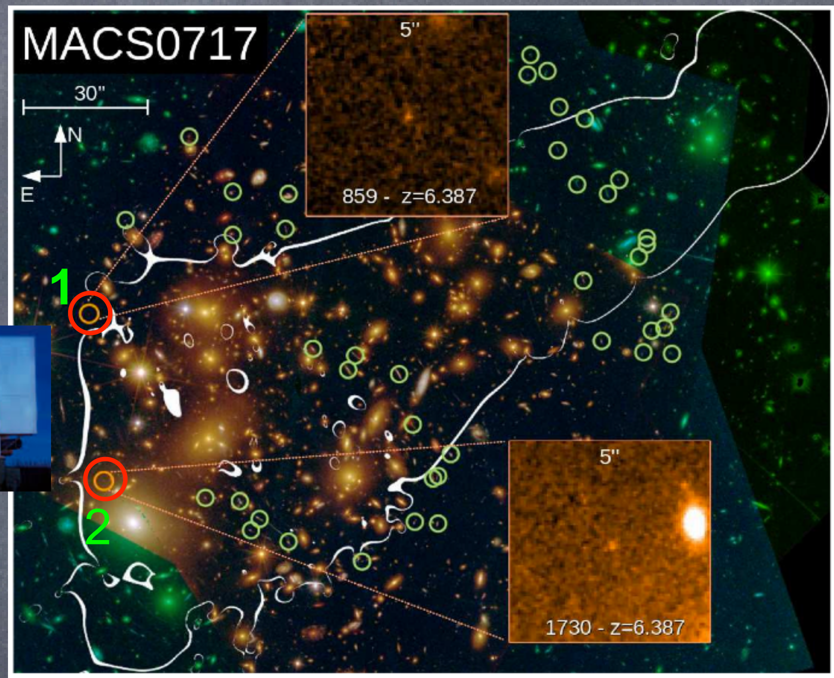
An example of a faint galaxy at z=6.4

M_{UV} = -17

The faintest spectroscopically confirmed galaxies at z>6

2014, ApJL, 783,12

Two sources have been confirmed at zspec=6.4



Magnification:

Frontier Fields LENS models:

http://archive.stsci./prepds/frontier/lensmodels/

publicly available, 7 different groups provide magnifications (D. Coe, STScI)

$$\mu = 17.4^{+25}_{-13}(^{+50}_{-12})$$

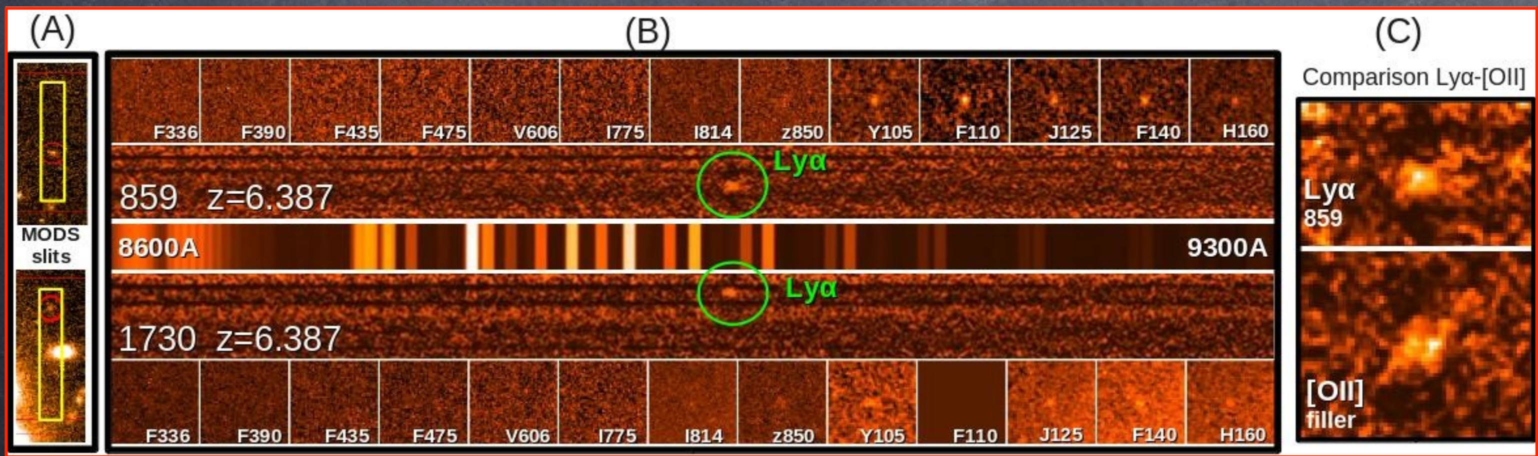
$$\mu = 6.9^{+1}_{-1}(^{+30}_{-2})$$

→

Intrinsic

m_{1500} ~ 29-30

M1500 ~ -17.2

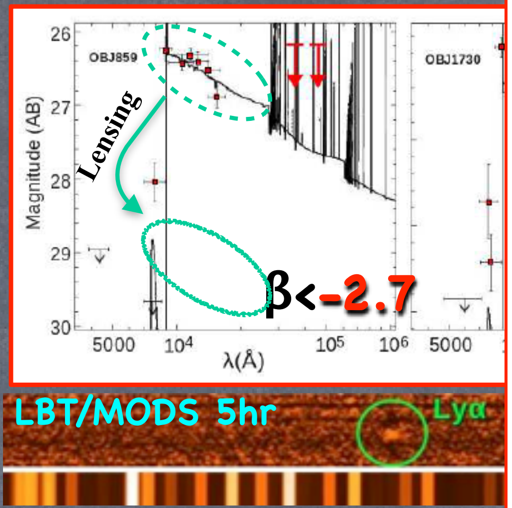


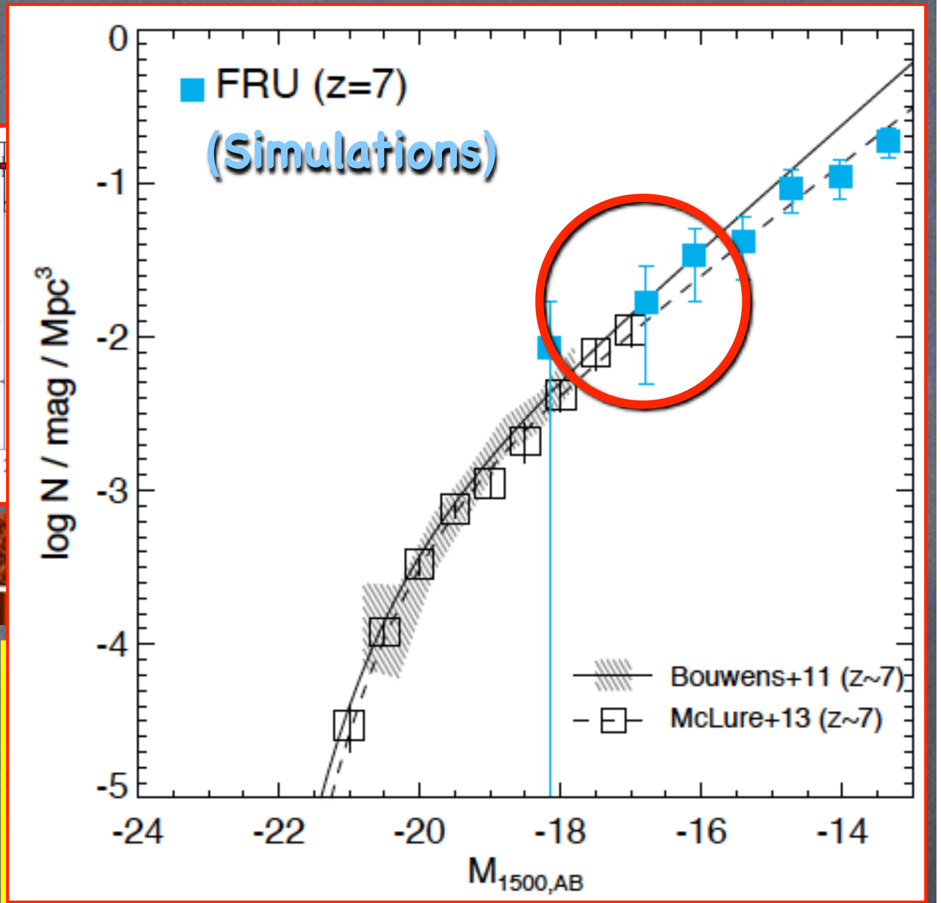
LBT/MODS

The faintest z>6 spectroscopically confirmed galaxy
extremely blue source

Newborn galaxy?
z=6.4
Vanz(2014a)

Mabs = -17,
SFR<2 $M_\odot$/yr
size< 0.5 sq.kpc
$M^* \approx 10^7 M_\odot$
$E(B-V) \approx 0$
age ≈ 20Myr
$Z < 0.02 Z_\odot$





NIR(CLASH)$_{OLD}$ S/N≈8

Have we found a "ionizer" ?

gas abs. dust. abs

λ <912A $f_{esc} = \exp[-\tau_{HI,ISM}(LyC)] \times 10^{-0.4(A_{LyC})}$ > 0 (possibly)

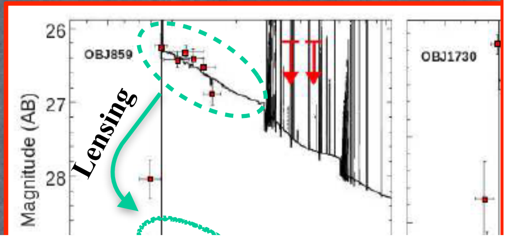
> 0 ? ≈1

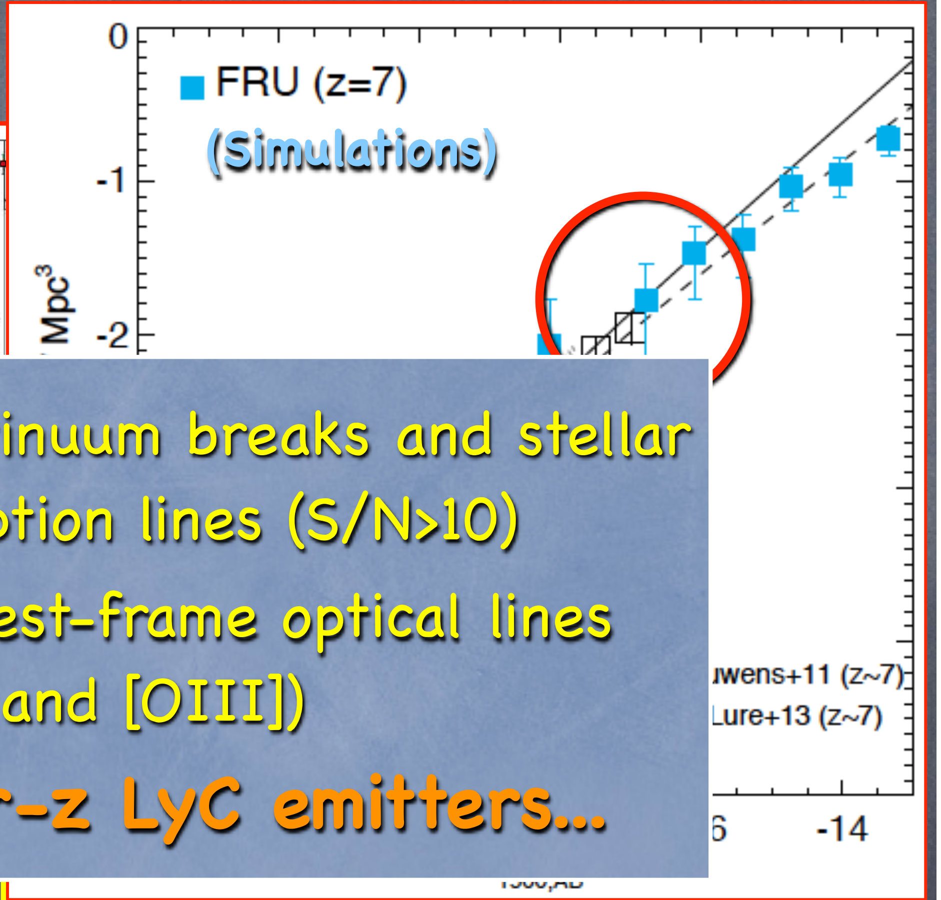
fesc <-> UV slope
Inoue +11
Zackrisson+13
Schaerer+11

The faintest z>6 spectroscopically confirmed galaxy
extremely blue source

Newborn galaxy?
z=6.4
Vanz(2014a)

Mabs = -17,
SFR<2 $M_{\odot}$/yr
size< 0.5 sq.kpc
M* ~ 10^7M
E(
ag
Z





ELT will capture UV continuum breaks and stellar + interstellar absorption lines (S/N>10)

JWST will capture rest-frame optical lines (Hb,Ha,[OII] and [OIII])

comparison with lower-z LyC emitters…

NIR(CLA

Have we found

gas abs. dust. abs

λ <912A $f_{esc} = \exp[-\tau_{\mathrm{H\,I,ISM}}(\mathrm{LyC})] \times 10^{-0.4(A_{\mathrm{LyC}})}$ > 0 (possibly)

> 0 ? ≈1

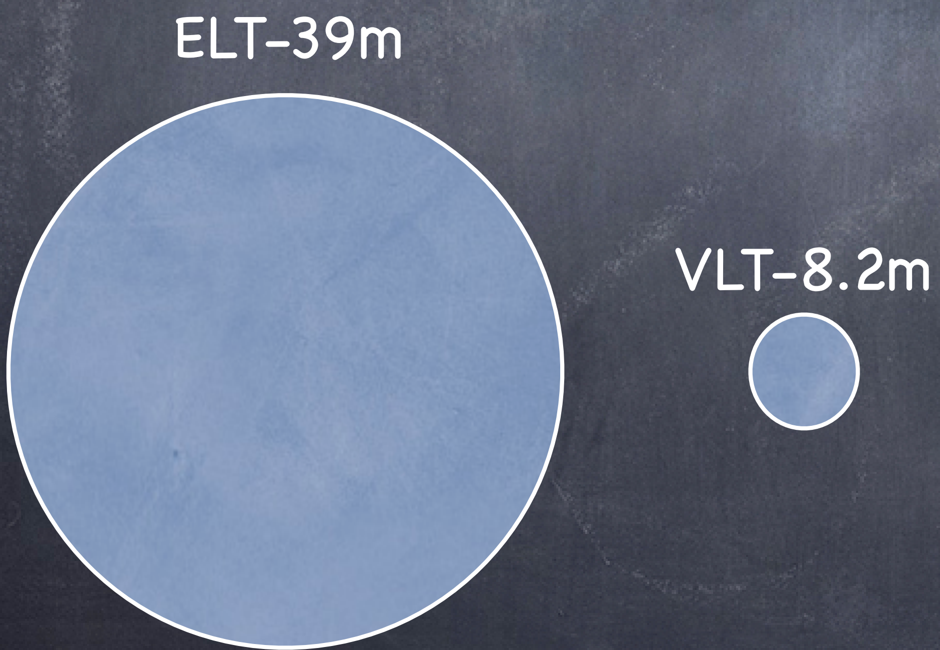
fesc <-> UV slope
Inoue +11
Zackrisson+13
Schaerer+11

How an ELT spectrum would appear ?

Suppose to target a m~29 galaxy with R~5000-7000

Thanks to strong lensing we have an anticipation...

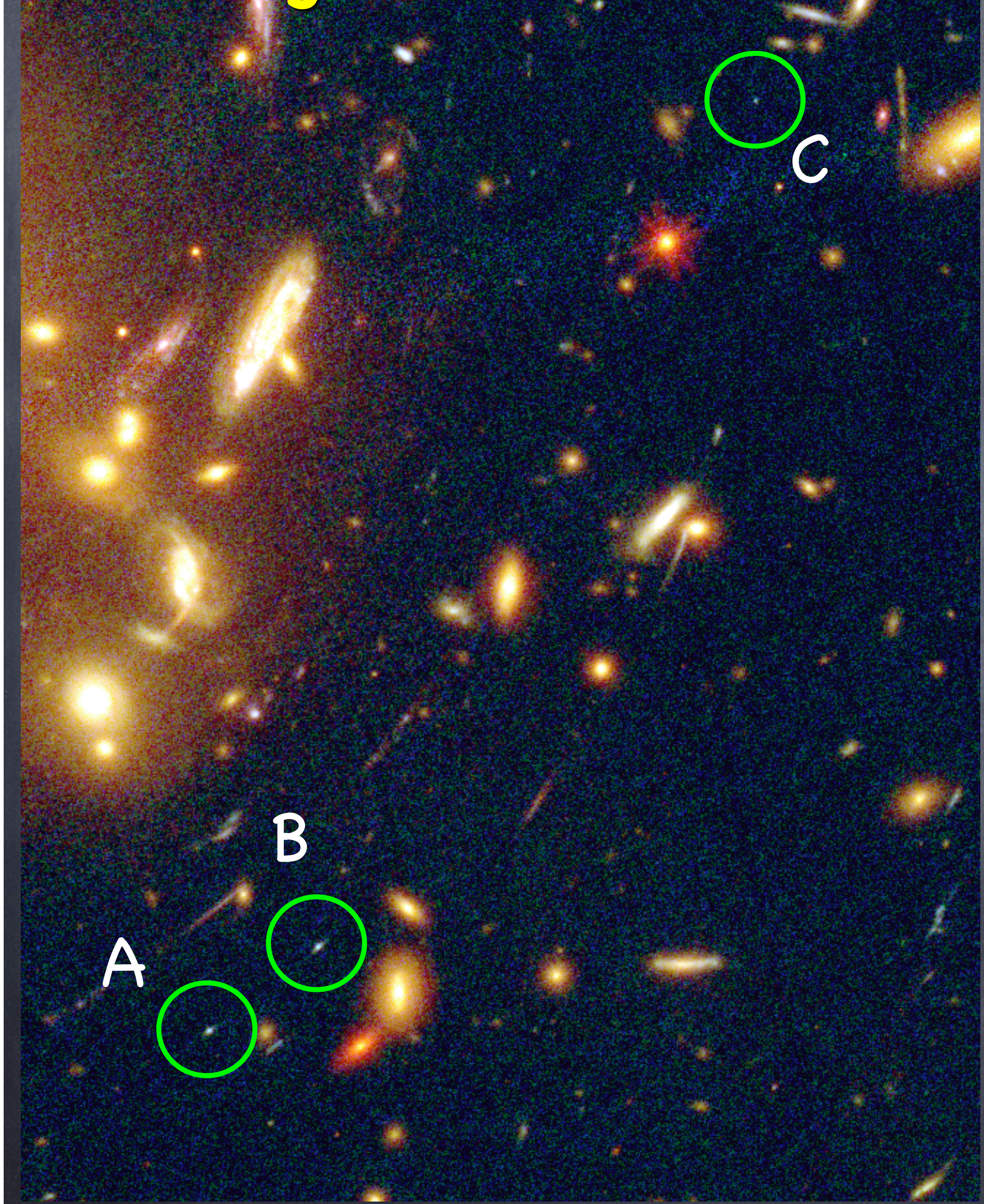
X-Shooter + strong lensing (magnification factor ~20)



note:

E-ELT 23 times larger collecting area than VLT

Assessing ultrafaint sources with spectroscopy



Hubble Frontier Fields

z=3.11

m(1500)~29.30

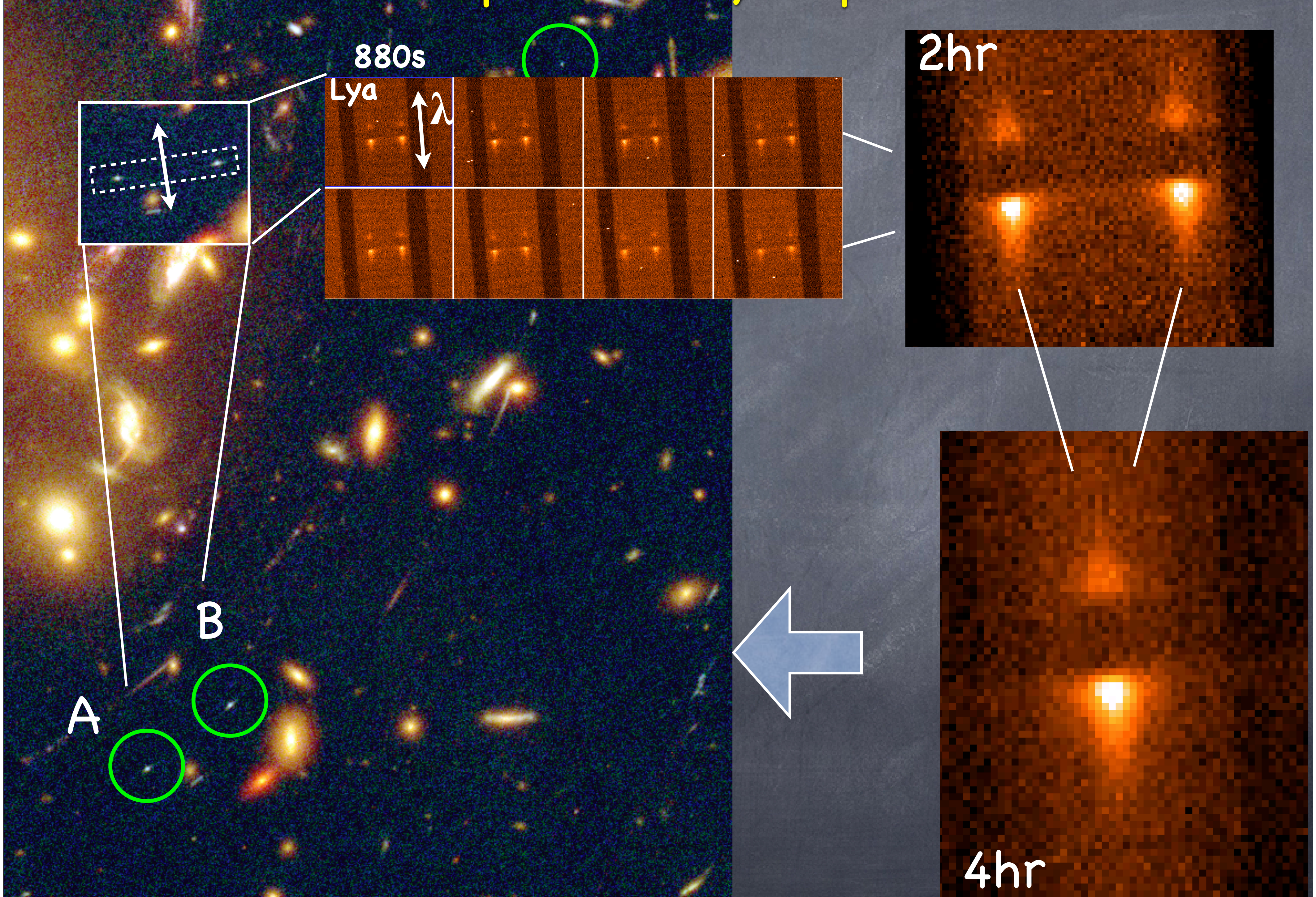
Muv = -16

L = 0.015L*

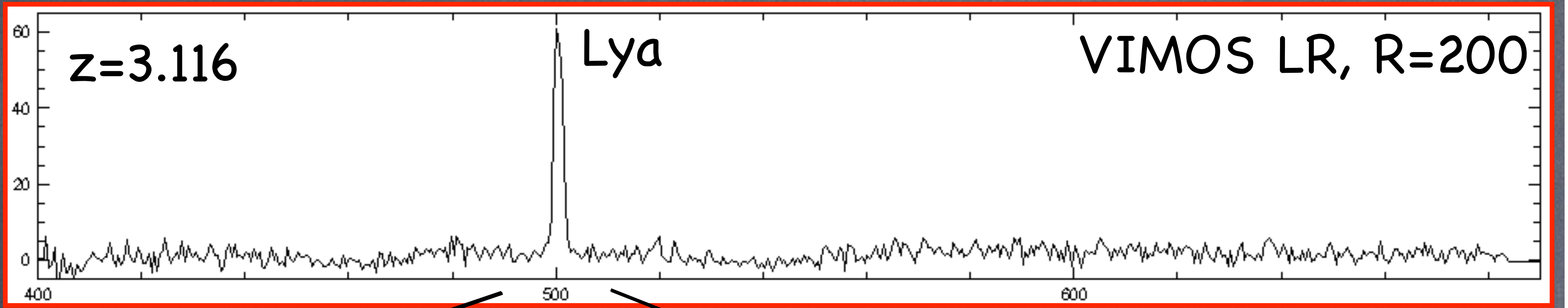
Reff ~ 200 pc

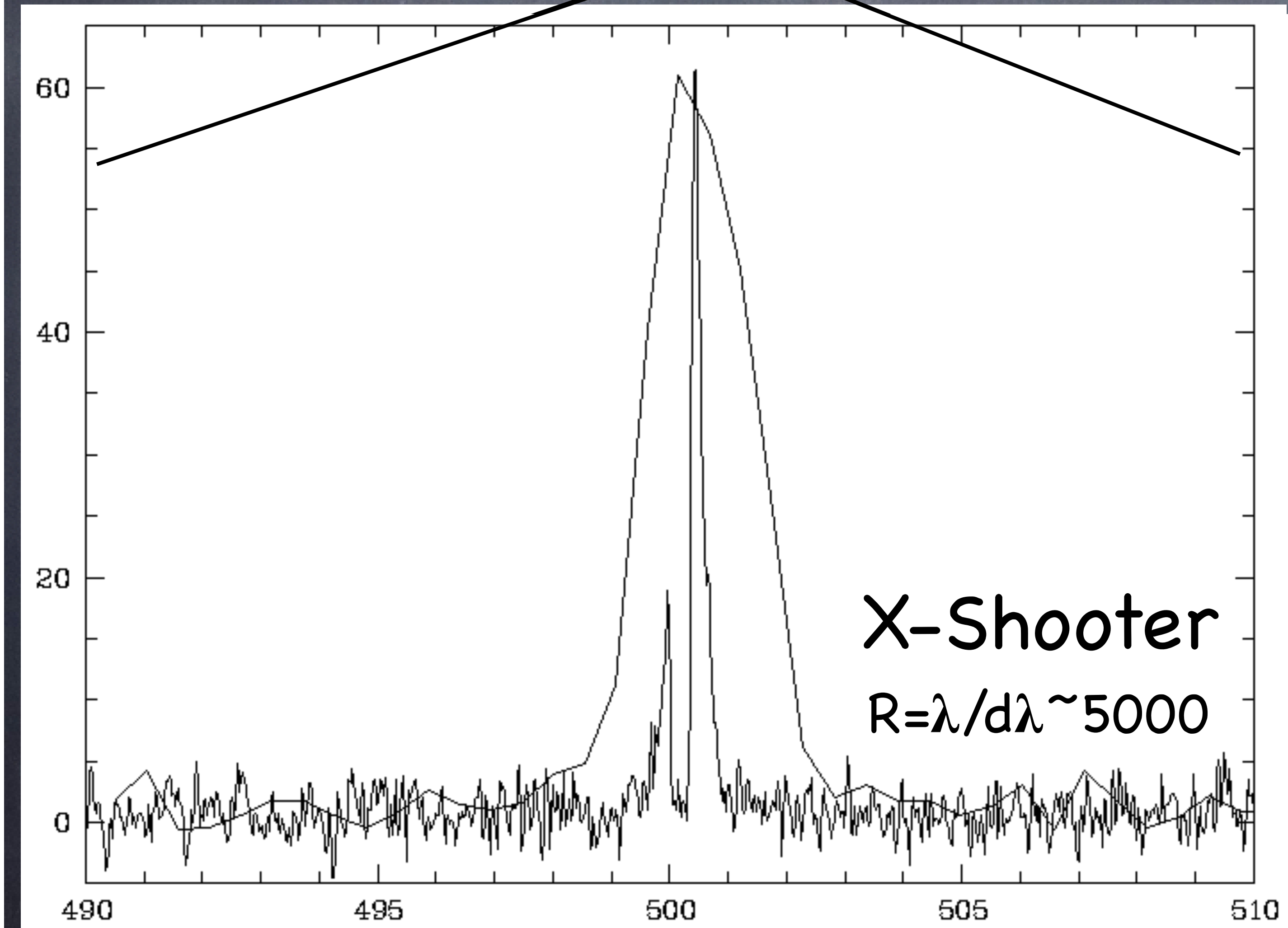
OBSERVED is V=25.7

Double peaked Ly-alpha



Initially discovered by CLASH-VLT





VLT/X-Shooter, R=4350

8.2m ⌀, in lensed fields

Lya(blue)=8.0e-19 cgs **S/N=25**

Lya(red)=3.0e-18 cgs **S/N=60**

1 OB -> 2hr

ELT/MOS MOSAIC, R=5000

39m ⌀, in blank fields

Evans, Puech et al. 2015

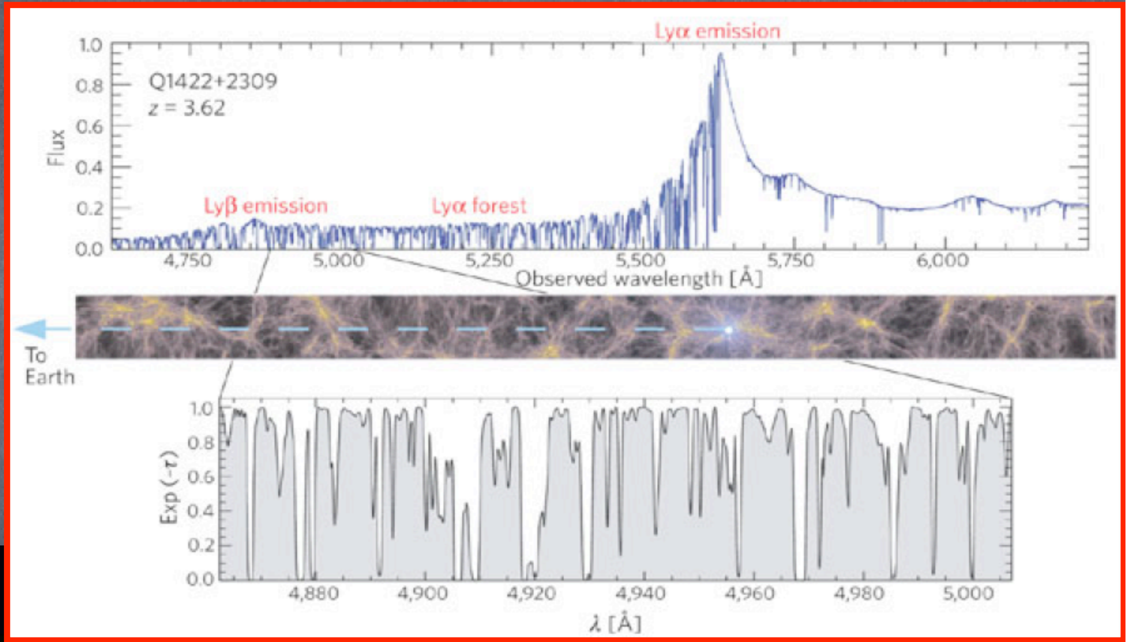
Lya(blue)=8.0e-19 cgs **S/N~15**

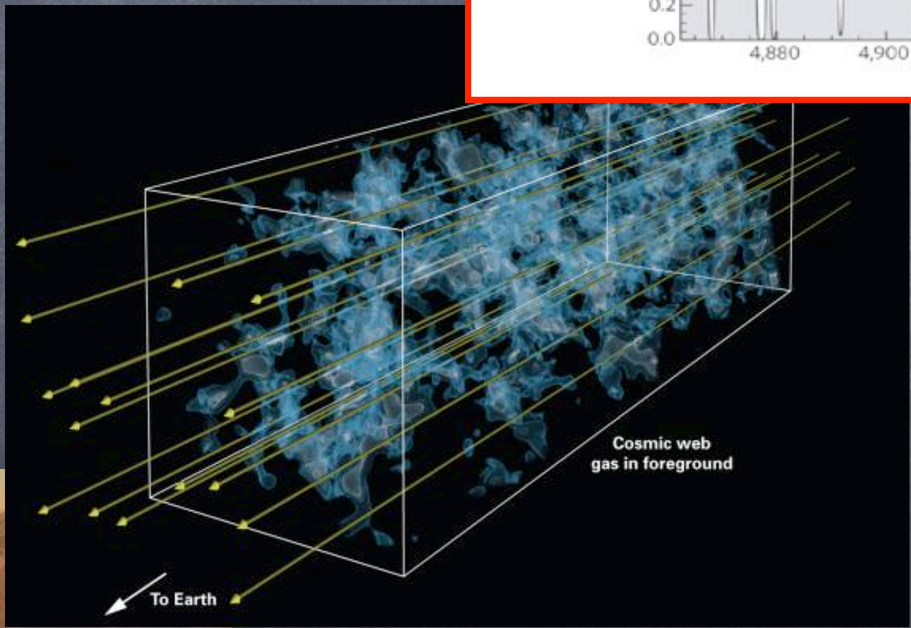
Lya(red)=3.0e-18 cgs **S/N~30**

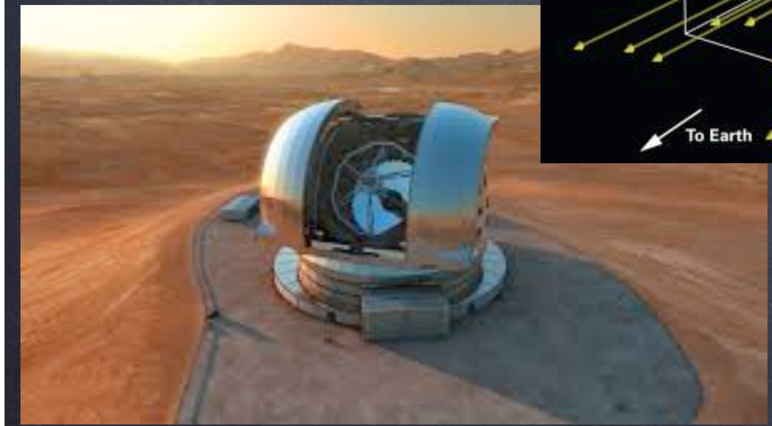
2hr exposure!!

Lyman alpha forest Using galaxies (not QSO only)

We have a lot of Galaxies
(more than QSOs)
Detailed Tomography of the cosmic web
ELT/HIRES spectrograph

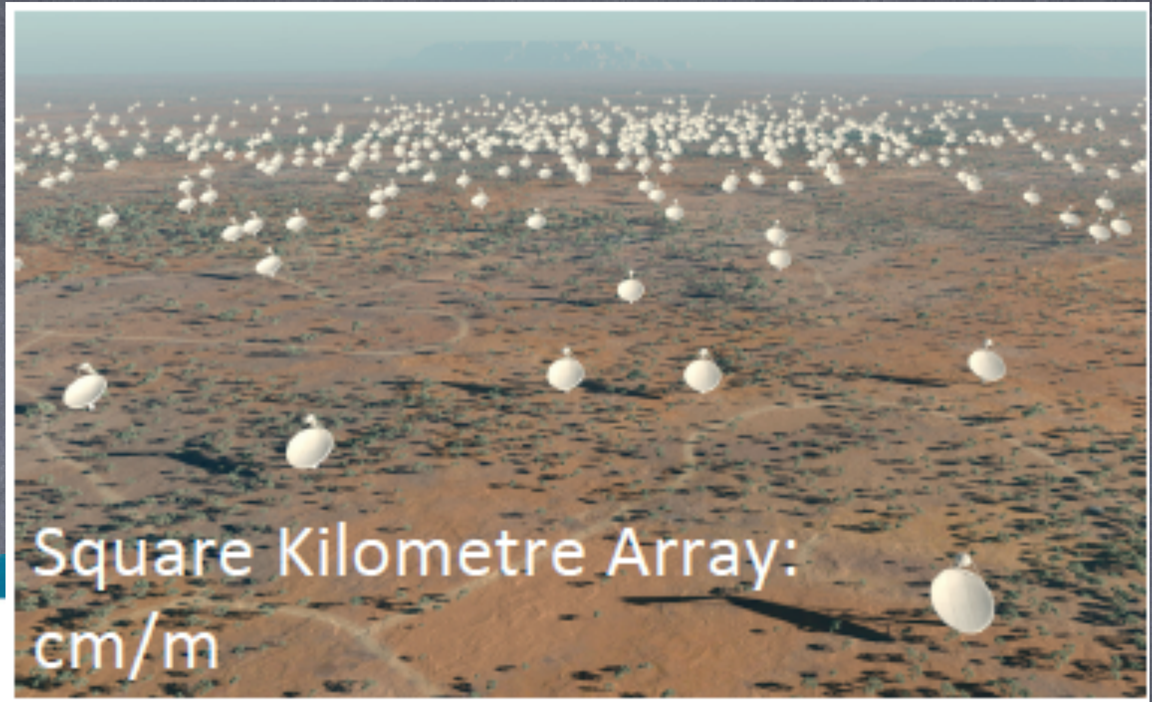






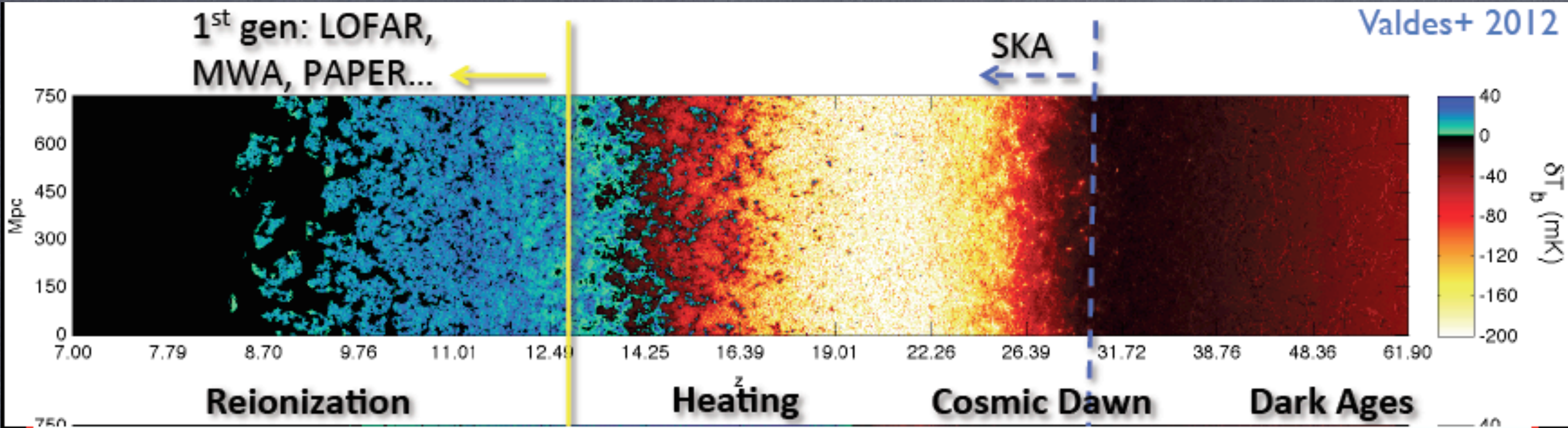
e.g., Rauch et al.
(2001,2005)

SKA



SKA Science

- SKA: will be one of the great physics machines of 21st Century and, when complete, one of the world's engineering marvels.
- Science goals:
  - Fundamental physics: Gravity, Dark Energy, Cosmic Magnetism
  - Astrophysics: Cosmic Dawn, First galaxies, galaxy assembly and evolution; proto-planetary discs, biomolecules, SETI + much more
  - The unknown: transients; +…????



Possible hints of neutral hydrogen at z~7, e.g. z=7 QSO, LAE/LBG ratio

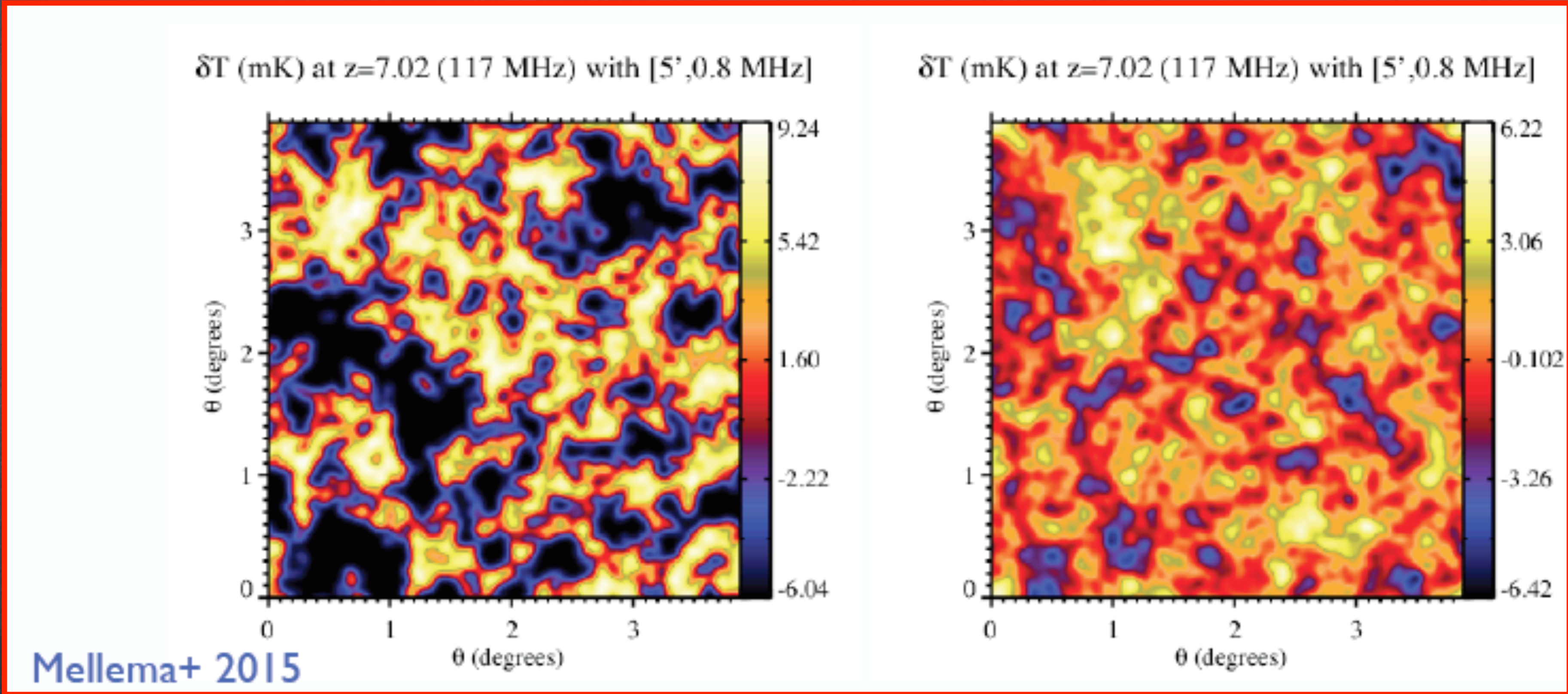
By 2020: possible advances...

1) Planck polarisation could constrain redshift and duration of reionization
2) HST+JWST will have observed bright end of luminosity function to higher redshifts (faint end will still be incomplete; connection to ionizing photons may still be unclear)
3) Little advance in QSO (more at z~7) - wait for Euclid in 2020 to push to z~8
4) LAE surveys into EoR will be more advanced (HSC) - maybe clustering => patchy reionization?

21 cm is a unique probe of reionization and cosmic dawn

Topology and processes of reionization

- Power spectrum measurements from z=28 - 6
- Imaging of 21cm signal during reionization >5 arcmin, 1 mK
- Spectral 21cm forest observations to z>6 bright radio sources



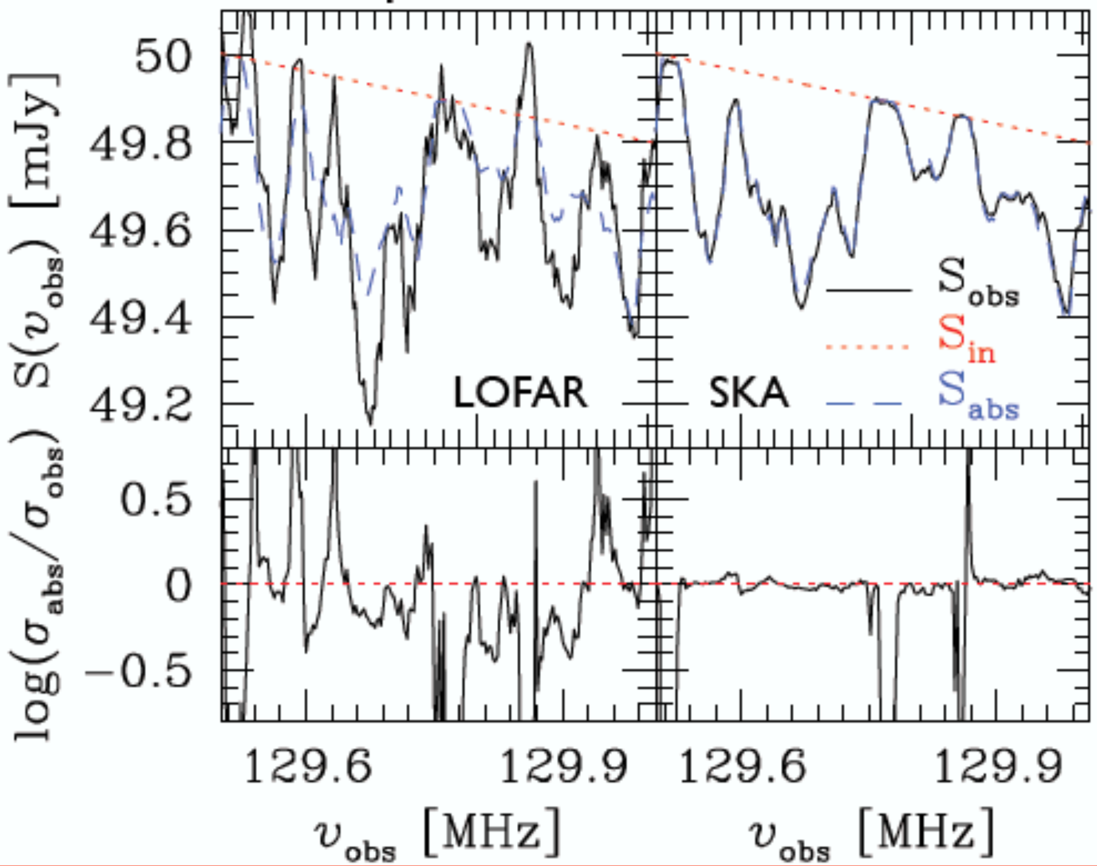
3D maps of topology of reionization
Direct imaging of HII regions

21-cm forest

~kHz resolved spectra of 21cm forest in bright radio sources at z>6

Alternative view of reionization/thermal history

Resolve dense ~kpc scale structures in IGM



50mJy source @z=10

Ciardi+ 2015

The future

“ At the time of HST’s launch, we had a very different view of the universe than now.
- The universe of the 1980s was thought to be decelerating and the expansion rate was greatly uncertain.
- Black holes at the centers of galaxies were only suspected, and extrasolar planets had not been seen (let alone had their atmospheres’ measured).
-Galaxies were not known to evolve strongly through mergers over time; the notion of hierarchical assembly and structure formation was in its observational infancy.
This was the universe HST was released into.”

Matthew D. Lallo (2012)
http://arxiv.org/ftp/arxiv/papers/1203/1203.0002.pdf

Hubble's top five scientific achievements (1990-2015)

The Hubble Constant ✗

Dark Energy

Galaxy formation and evolution

Supermassive black holes

Extrasolar planets

JWST ?? (2018-2023/2028)
ELT ?? 2020-2040...

...

Patchy reionization or what ?? ....

... see the problem from different view angles