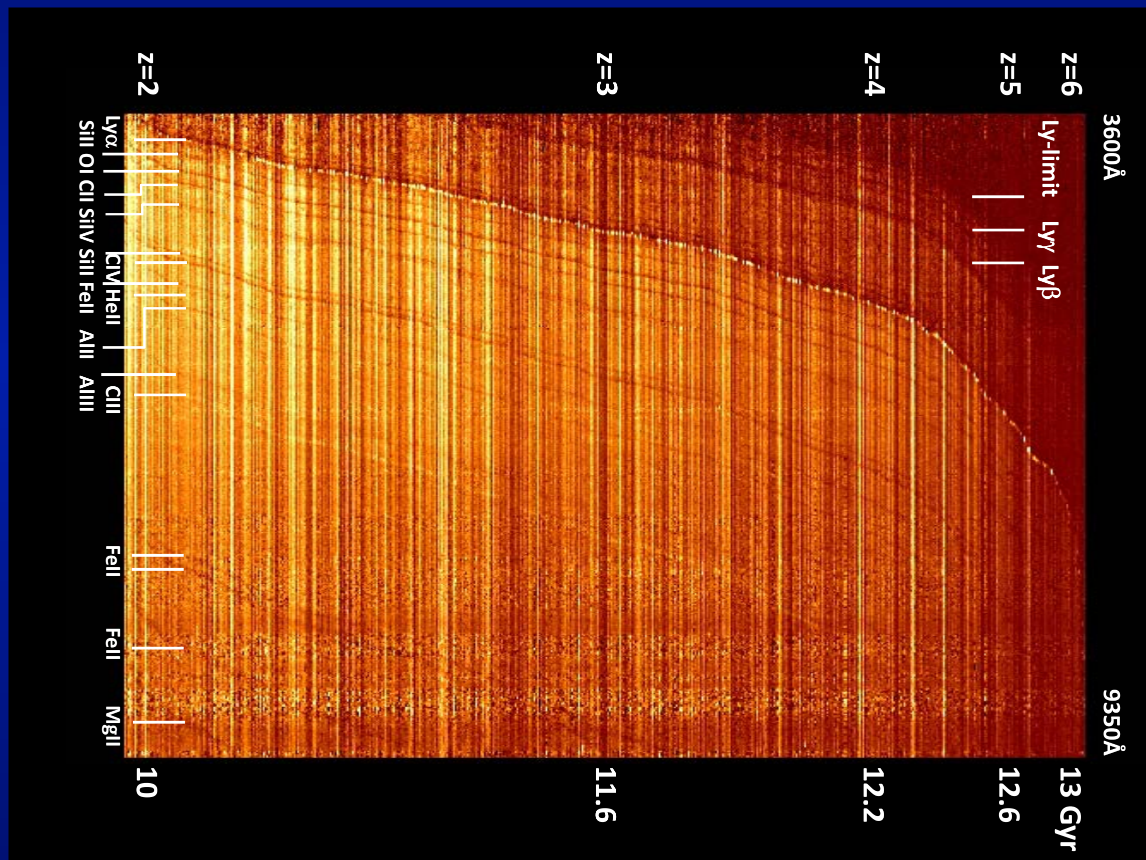
The Landscape of Current and Future Galaxy Spectroscopic Surveys at High Redshift



(VUDS; LeFevre et al. 2015)

Alice Shapley

UCLA

Key Questions

• What are the physical processes driving star formation in individual galaxies?

• What causes the bimodal distribution of galaxy properties?

• How are stellar mass and structure assembled in galaxies?

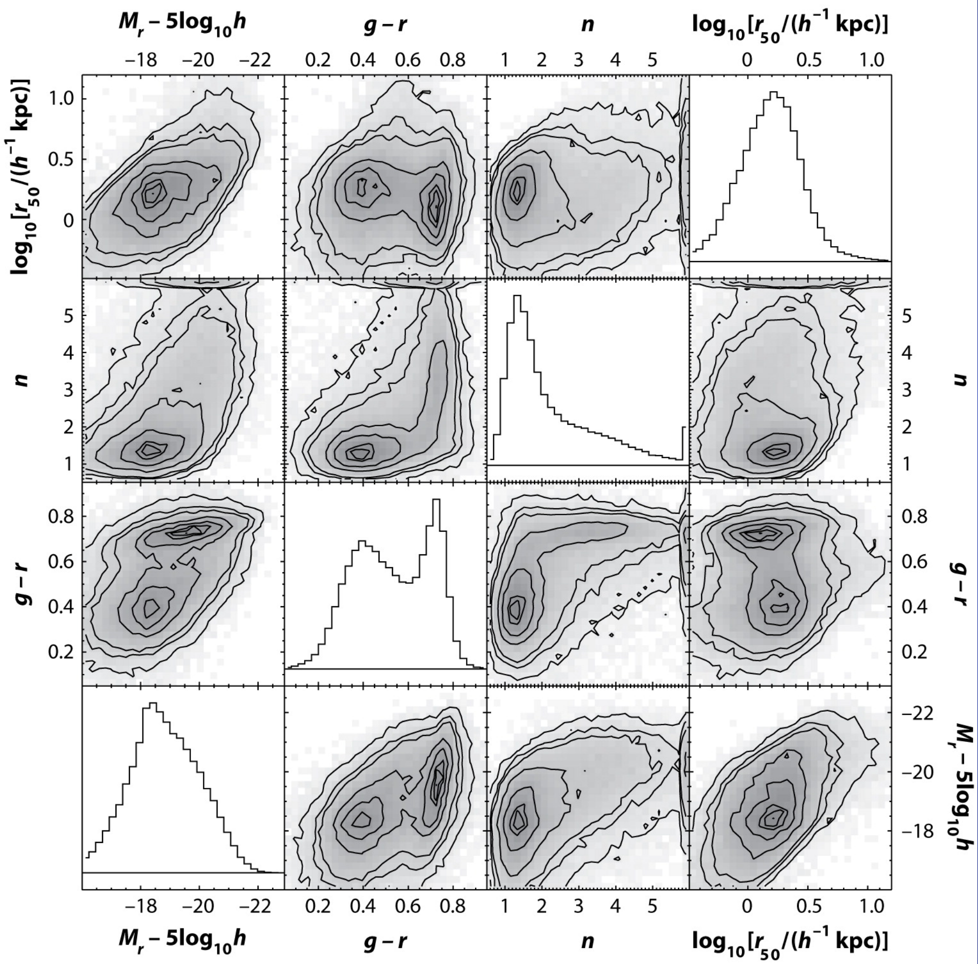
• What determines the “efficiency” of galaxy formation as a function of mass?

• How do galaxies exchange gas and heavy elements with the intergalactic medium?

• How are a galaxy’s internal properties reflective of its larger-scale environment?

• What is the nature of the co-evolution of black holes and stellar populations?

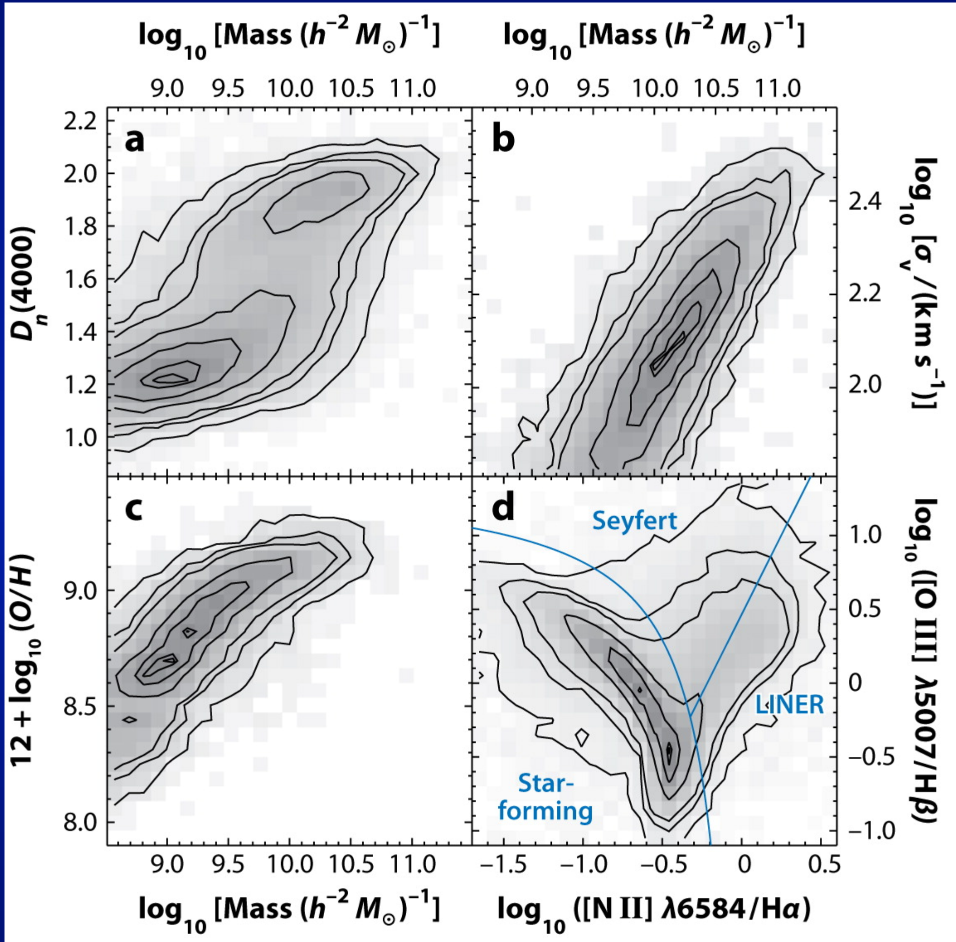
The Local Universe



Blanton MR, Moustakas J. 2009.
Annu. Rev. Astron. Astrophys. 47:159–210

- Massive surveys like the Sloan Digital Sky Survey (SDSS) and 2dF Galaxy Redshift Survey (2dFGRS) provide a detailed description of local galaxy population: the endpoint.
- Spectra of $>10^6$ galaxies.
- Distributions in luminosity, color, mass (stellar, dynamical, BH), structure, gas content, metallicity, environment.
- Correlations among these properties.

The Local Universe



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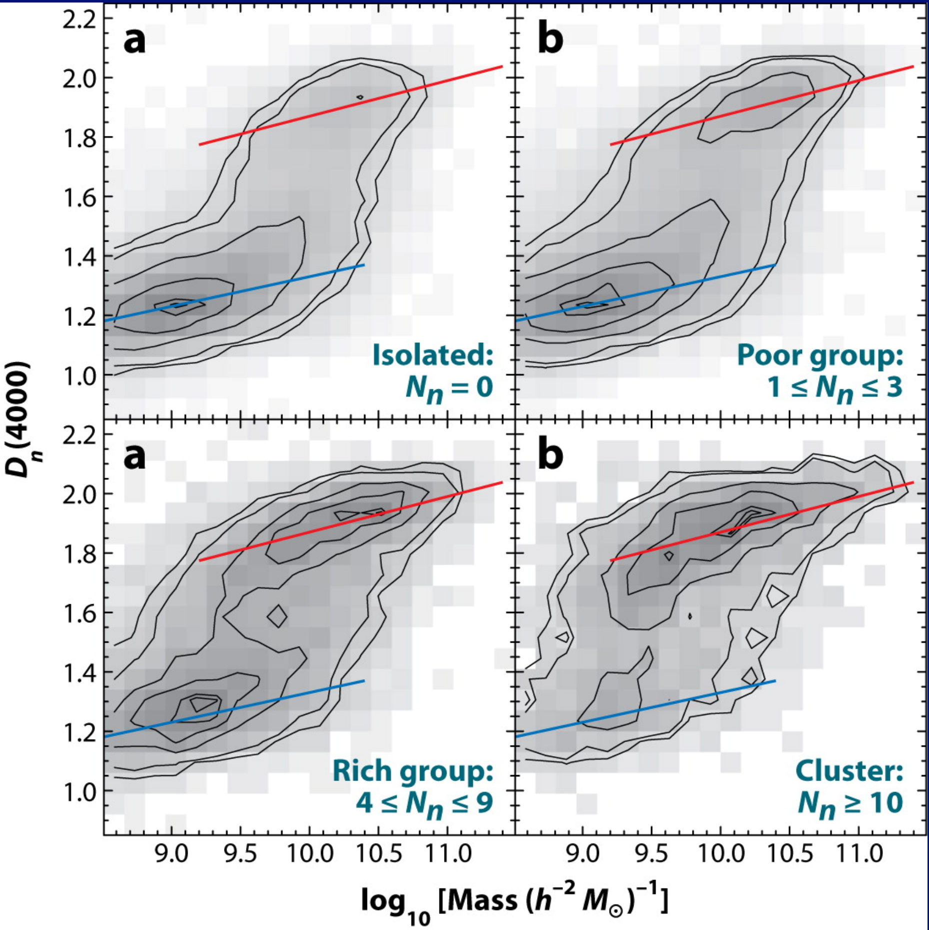

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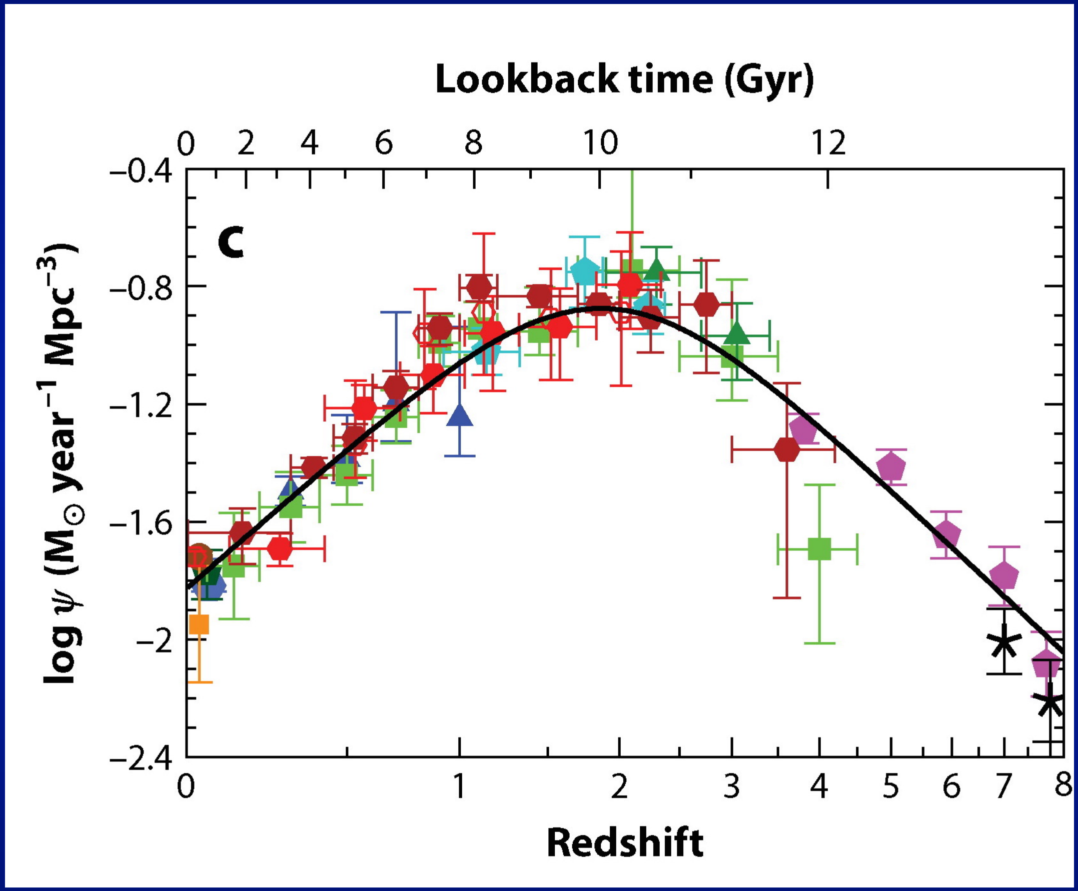
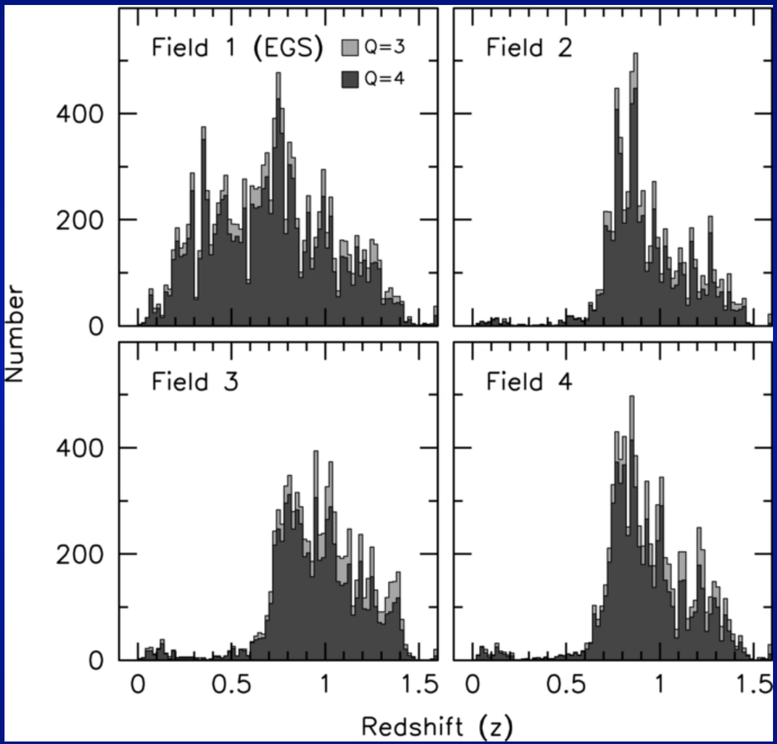
Galaxies Across Cosmic Time

(Madau & Dickinson 2014)



- Complete theory of galaxy formation must predict/describe properties of galaxy population over all cosmic time.

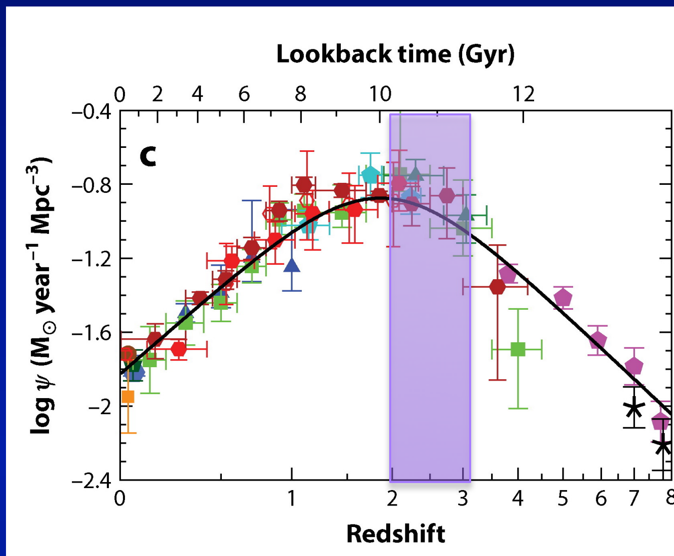
Halfway back (in time): z~1



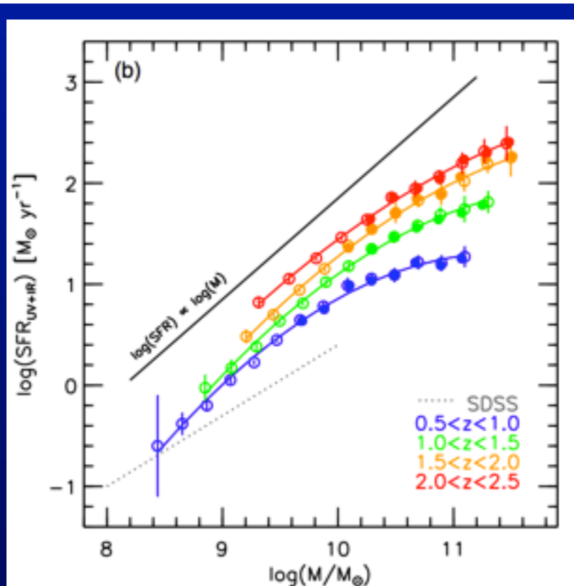
(DEEP2; Newman et al. 2013)

- Several spectroscopic surveys probe out to z~1, i.e., lookback times of ~8 Gyr, a little more than half the age of the universe.
- Surveys: DEEP2, VVDS, zCOSMOS, PRIMUS, VIPERS with sample sizes of $\sim 10^4$-10^5 galaxies.
- Demonstrate smooth evolution of galaxies: similar structures, more star formation. Similar overall patterns.

Cosmic “High Noon”: z~2-3



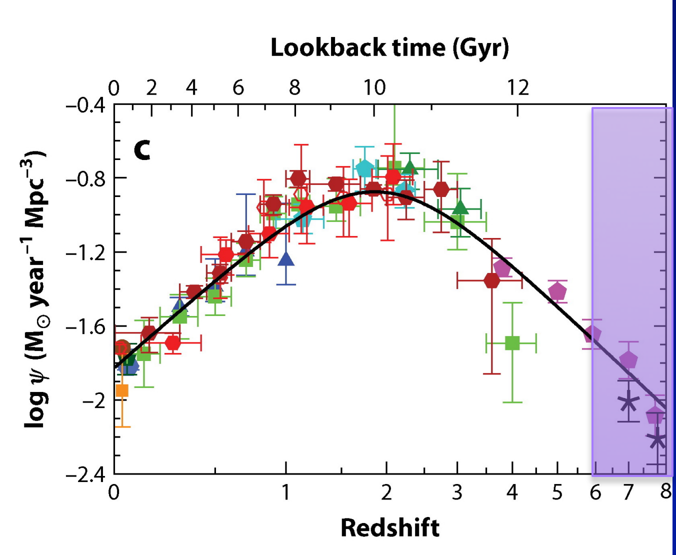
(Madau & Dickinson 2014)



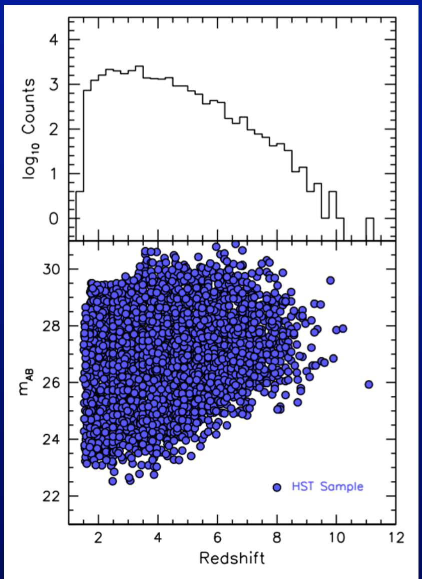
(Whitaker et al. 2014)

- This epoch hosts the peak of both star formation and BH accretion activity.
- Qualitative imprints of local galaxy population.
- Big differences as well: diversity among massive galaxies; absence of cold, quiescent disks; smaller sizes; higher sSFR, Σ_{SFR}, gas fraction, ubiquitous galaxy outflows.
- Many exciting recent developments in surveying the universe at z>1.5…..

Cosmic "Dawn": z>6



(Madau & Dickinson 2014)

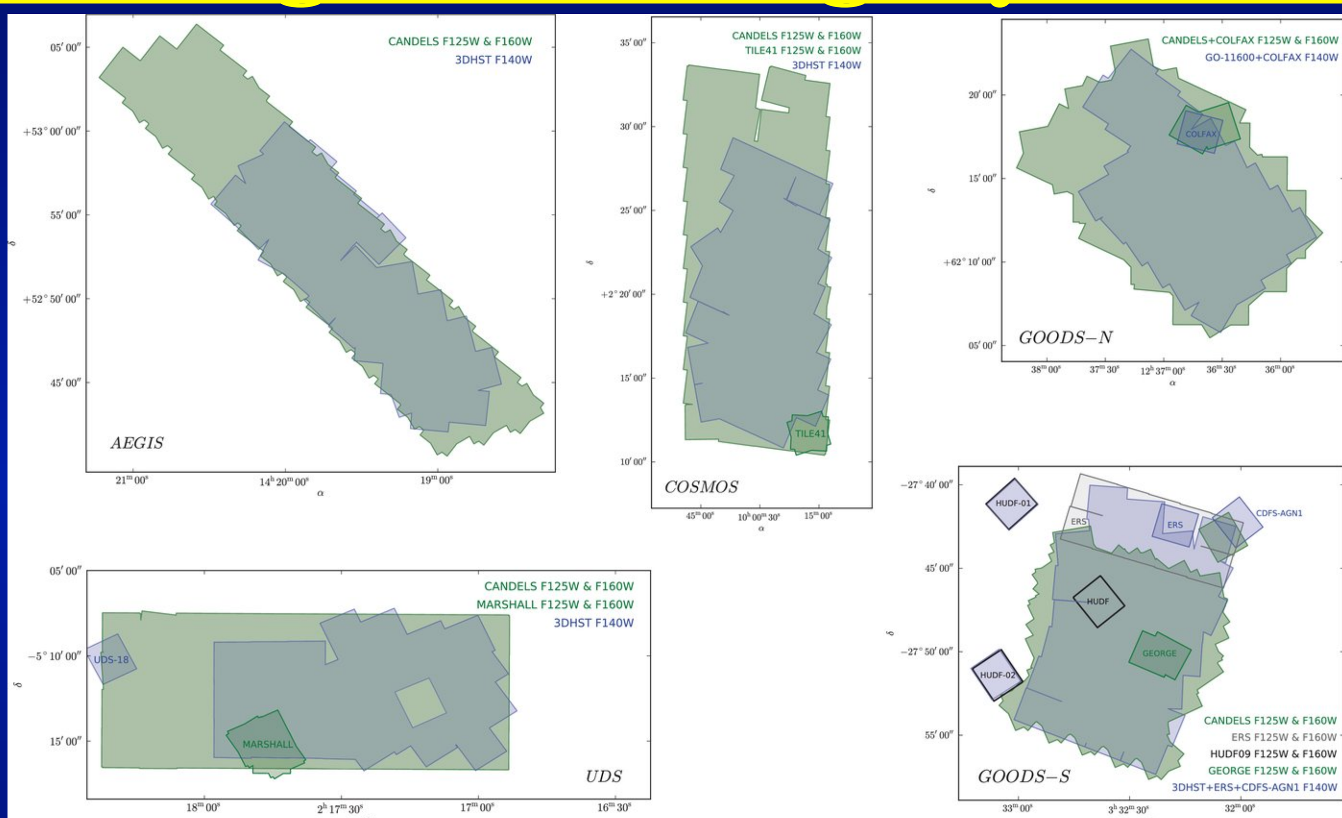


(Bouwens et al. 2019)

- This epoch hosts the epoch of reionization, the first stars, black holes, galaxies.
- Over 1000 photometric targets at z>6.
- Enables estimate of luminosity functions.
- Number with spectroscopic confirmation is very small (<30 at z>7).

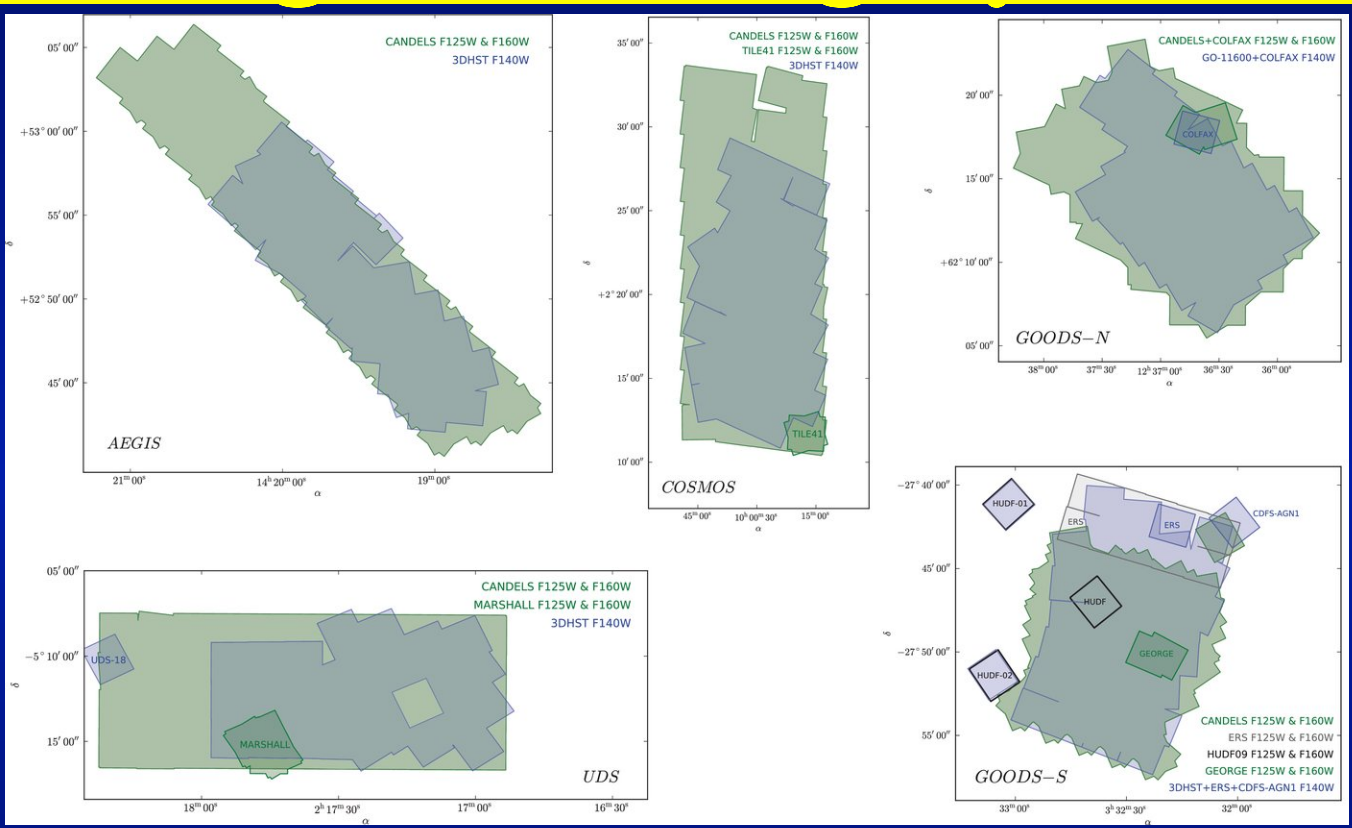
Extragalactic Legacy Fields

(Skelton et al. 2014)



- Large, multi-wavelength datasets in select areas of the sky.
- HST, Spitzer, Chandra, Herschel, VLA, ground-based imaging.
- Ground-based and HST-grism spectroscopy.

Extragalactic Legacy Fields

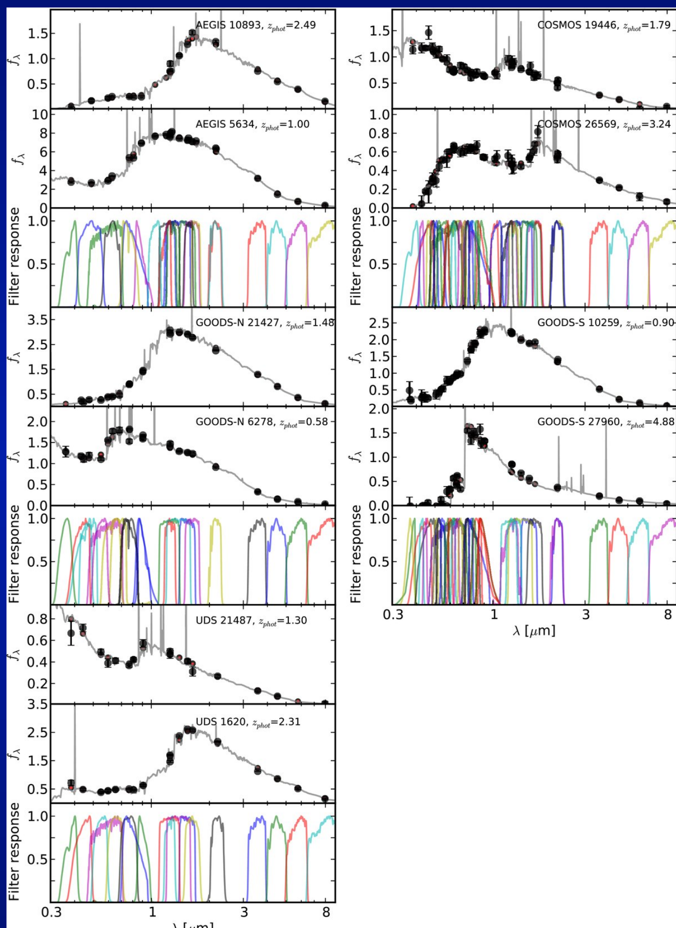


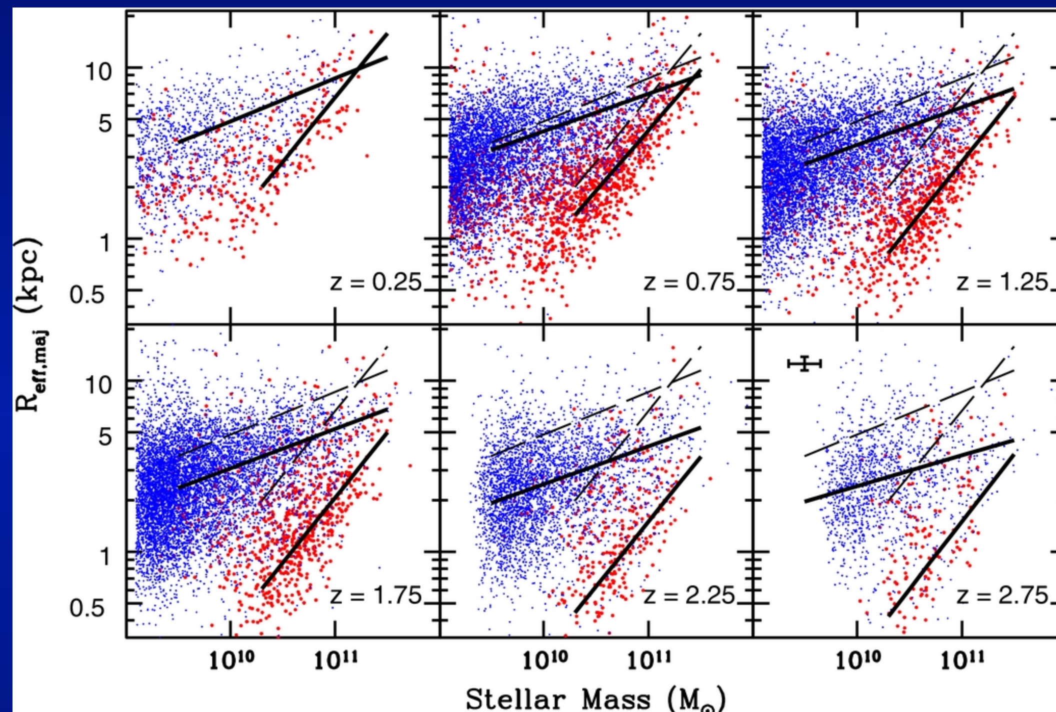
(Skelton et al. 2014)

- CANDELS: HST imaging (PIs: Faber and Ferguson)
- 3D-HST: HST imaging and grism spectroscopy (PI: van Dokkum)

Extragalactic Legacy Fields

(Skelton et al. 2014)



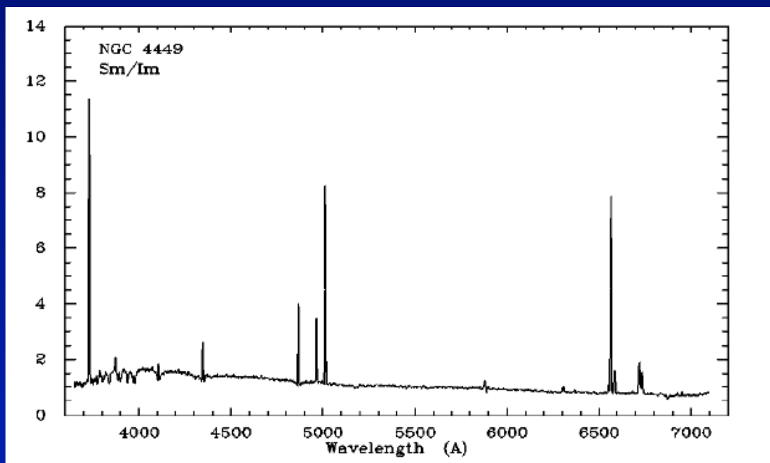


(van der Wel et al. 2014)

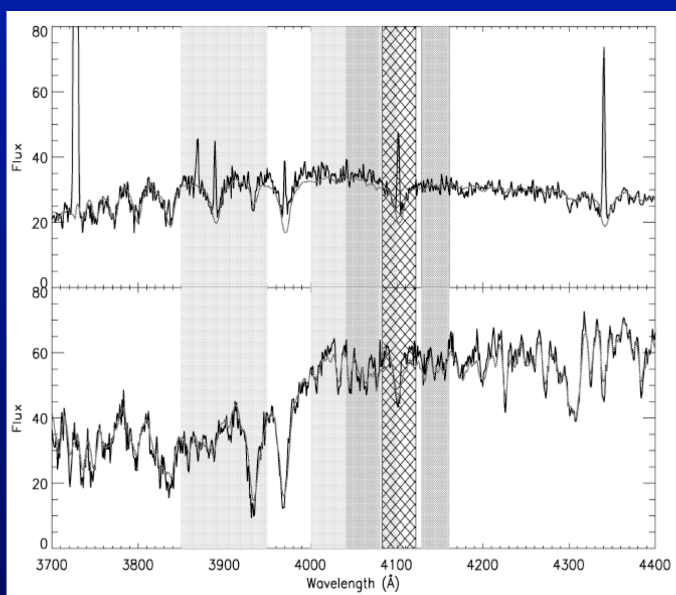
- **Stellar masses, SFRs, morphologies/sizes, AGN identification.**
- **Multi-wavelength catalogs (e.g., 3D-HST): photometric redshifts, target selection, in addition to stellar population modeling.**

Rest-frame Optical Galaxy Spectra

(Kennicutt 1998)

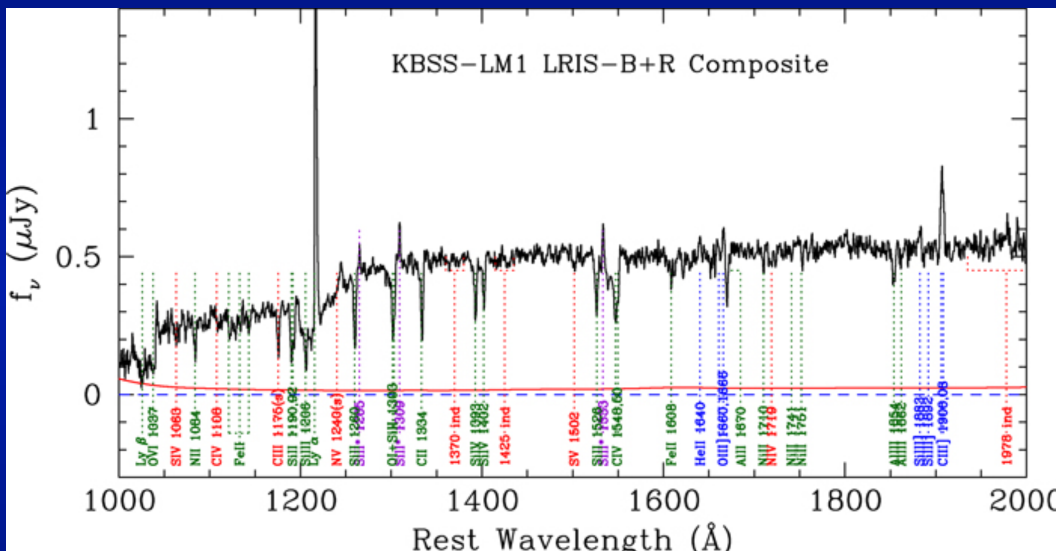


(Kauffmann et al. 2003)



- Emission-lines: [OII], Hβ, [OIII], Hα, [NII], [SII]
- Absorption-lines: Balmer lines, Ca H&K, Mgb, 4000Å break
- Provide key insights into the stellar and gaseous contents of galaxies.
- At $z > 1.4$, [OII] moves past 9000Å. Becomes a near-IR problem.
- Transformative boost in S/N and survey efficiency for near-IR spectrographs enabled statistical samples of rest-frame optical measurements at cosmic “high noon” over the past decade.

Rest-UV Galaxy Spectra

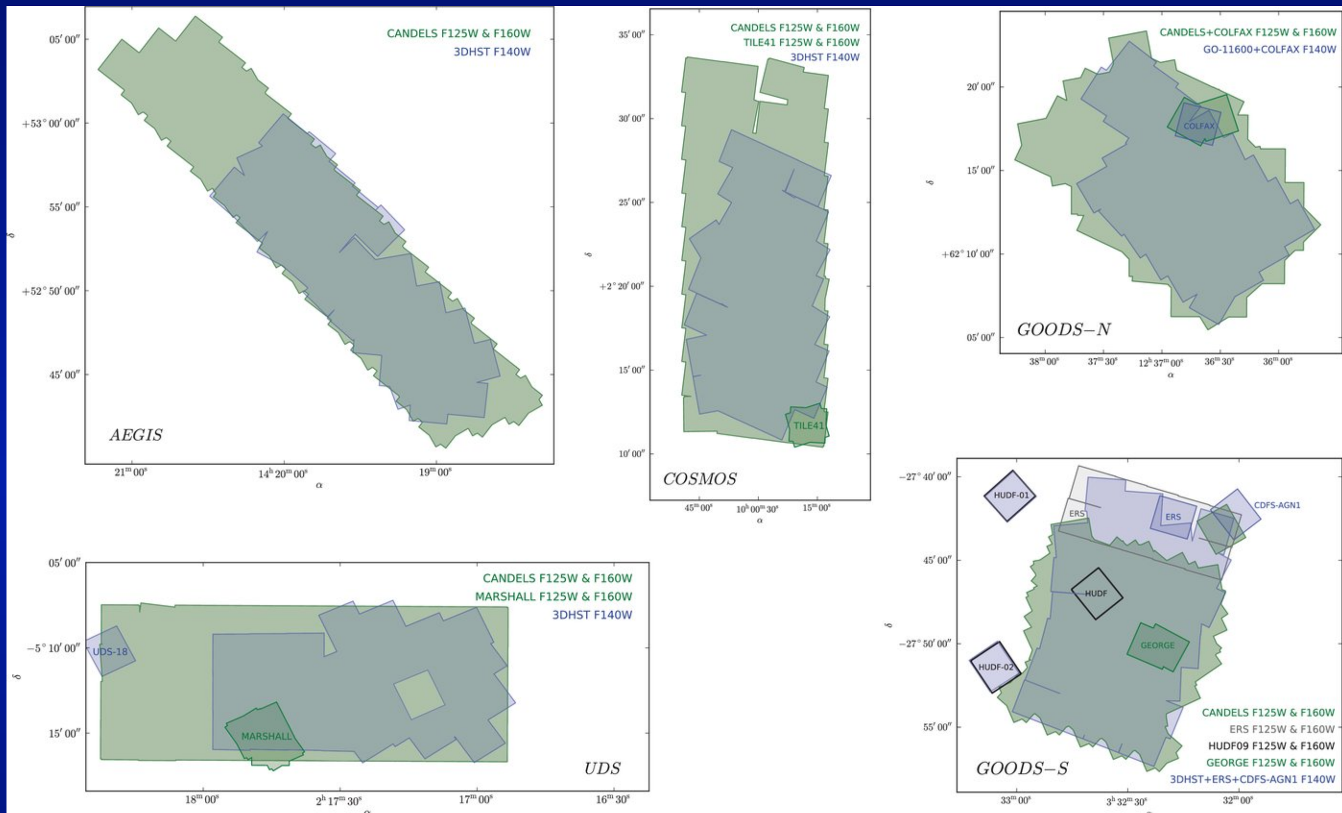


(Steidel et al. 2016)

Ironically, we've long known more about rest-UV spectra at z>1.5 than the "traditional" rest-optical – and rest-UV spectra at z~0.

- Incredibly rich window into stars, gas, and dust in SF galaxies.
- Stellar wind, photospheric features from massive stars.
- Interstellar metal absorption and HI Lyα absorption/emission lines tracing outflowing gas.
- Nebular emission lines tracing HII regions.
- Fluorescent fine structure emission lines tracing circumgalactic gas.

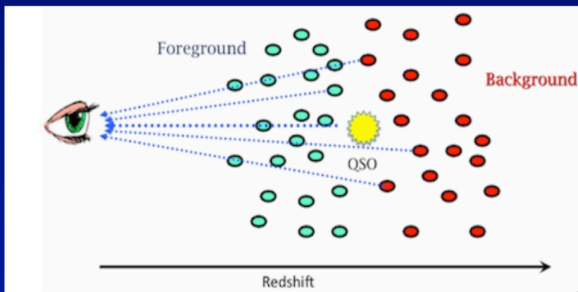
Legacy Spectroscopic Surveys at z>1.5



(Skelton et al. 2014)

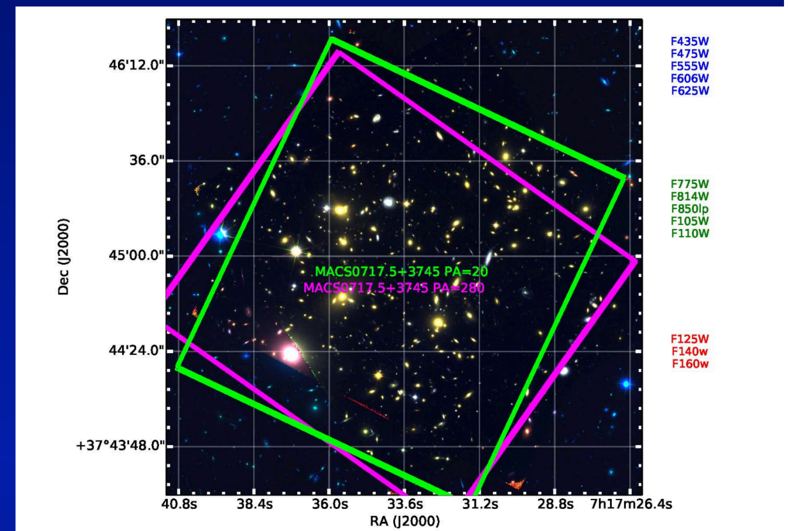
- **Optical (rest-UV): VUDS (LeFevre et al. 2015), VANDELS (McLure et al. 2018).**
- **Near-IR (rest-optical): 3D-HST (Momcheva et al. 2016), FMOS/COSMOS (Kashino et al. 2019), MOSDEF (Kriek et al. 2015), KMOS^{3D} (integral field unit; Wisnioski et al. 2015), ZFOURGE (Nanayakkara et al. 2017).**
- ***Spectra of >10^4 galaxies at z>1.5 with rich multi-wavelength datasets.***

Other High-z Spectroscopic Surveys

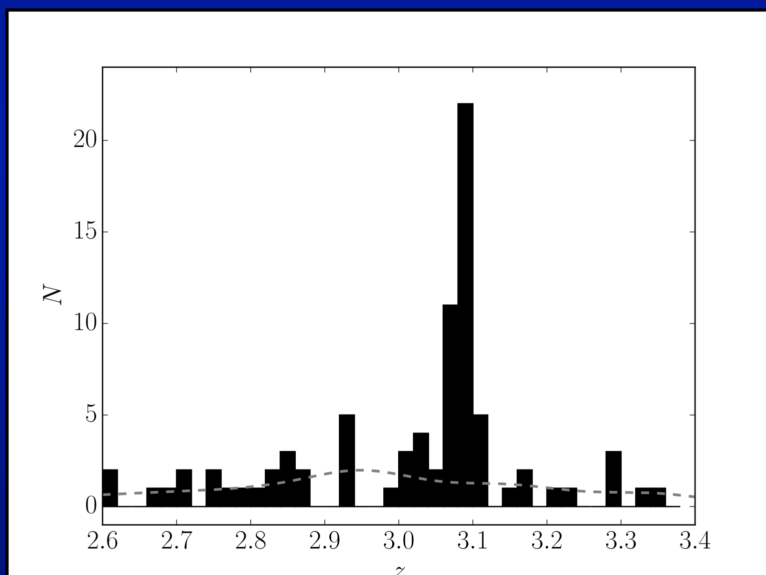


(Credit: Chuck Steidel)

1000s of galaxies in KBSS



(Treu et al. 2015)

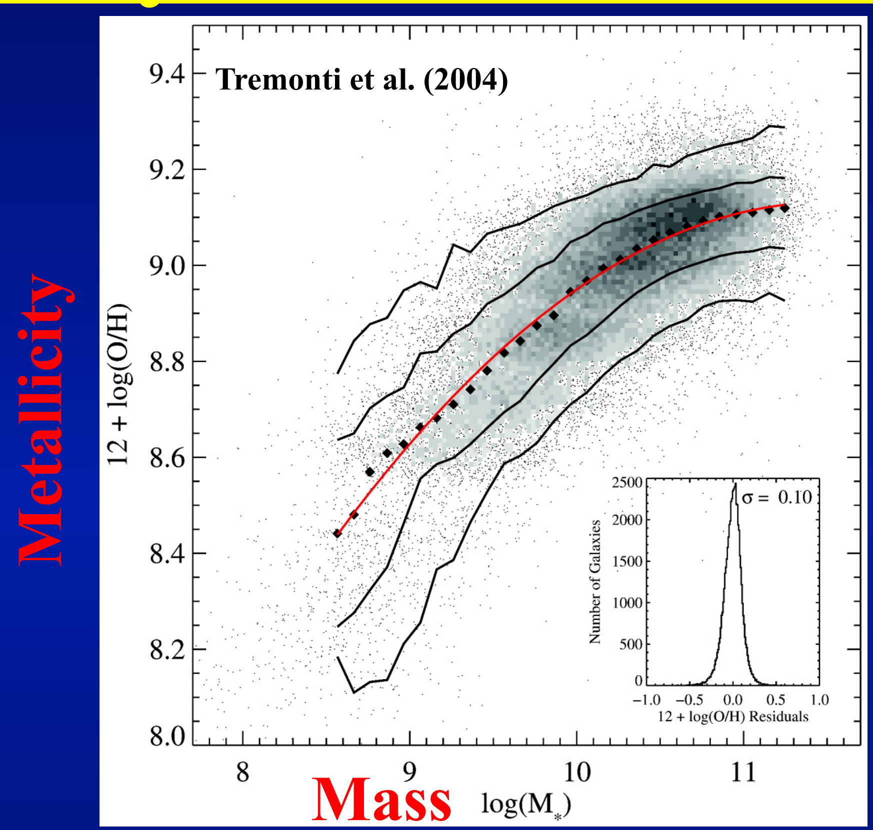


(Topping et al. 2018)

- QSO fields: e.g., Keck Baryonic Structure Survey (Steidel et al. 2014)
- Gravitationally lensed: e.g., GLASS survey (Treu et al. 2015)
- Protoclusters/High-z clusters: e.g., SSA22 (Topping et al. 2018, Wang et al. 2016)

Feedback

Metallicity and the MZR/FMR

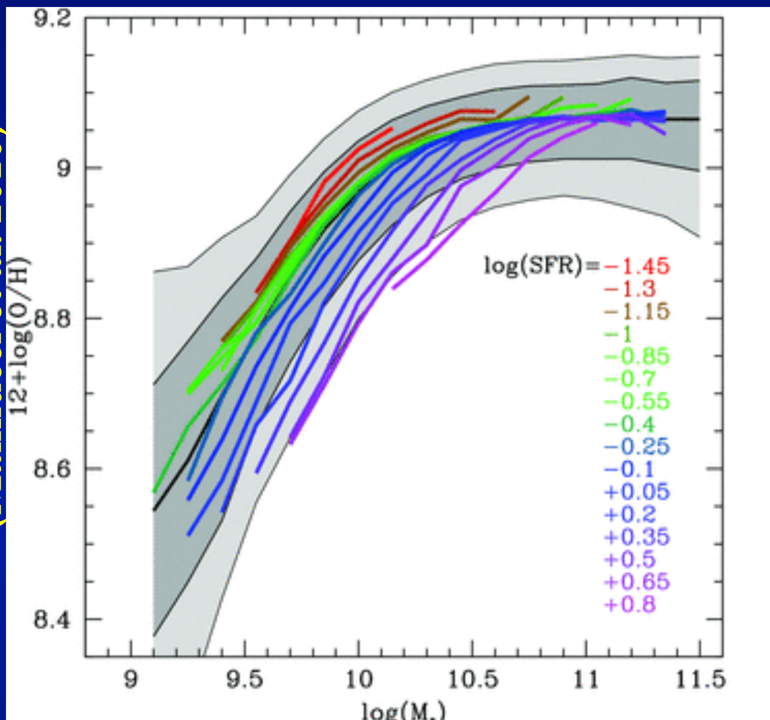


• Variation of metal content with galaxy mass reflects cycle of gas in and out of galaxies (inflows, outflows, feedback). – i.e. how does outflow mass-loading factor vary with galaxy mass and redshift?

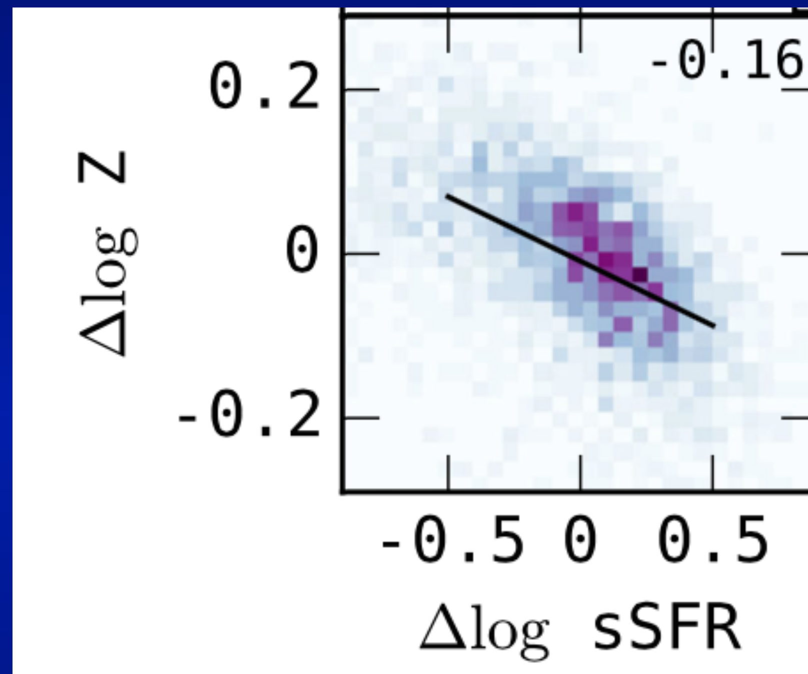
• Secondary dependence of MZR on SFR → "Fundamental Metallicity Relation" (FMR).

Metallicity and the MZR/FMR

(Mannucci et al. 2010)



FMR MODEL



(Dave et al. 2017)

- Variation of metal content with galaxy mass reflects cycle of gas in and out of galaxies (inflows, outflows, feedback). – i.e. how does outflow mass-loading factor vary with galaxy mass and redshift?
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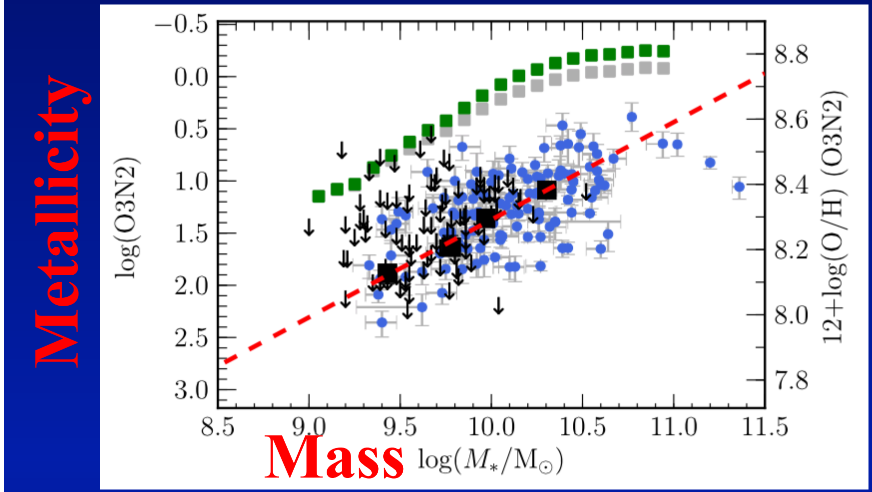
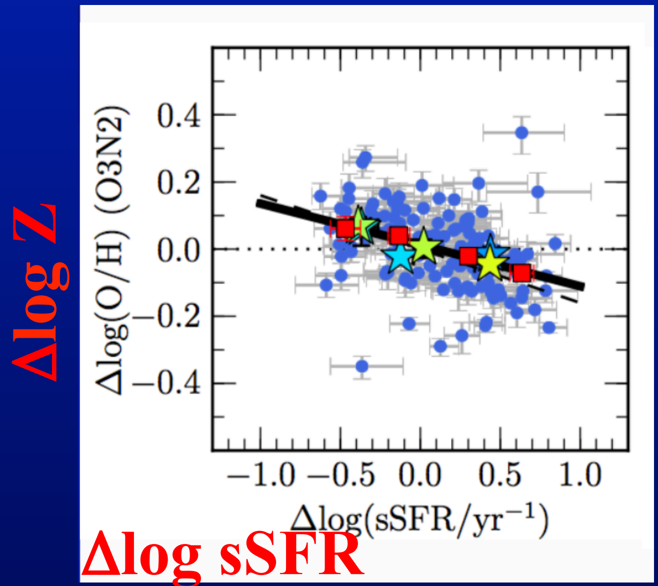
z~2 MZR/FMR

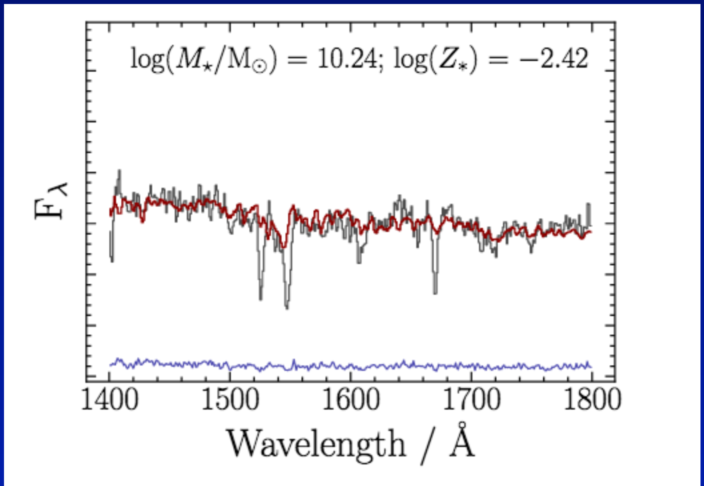


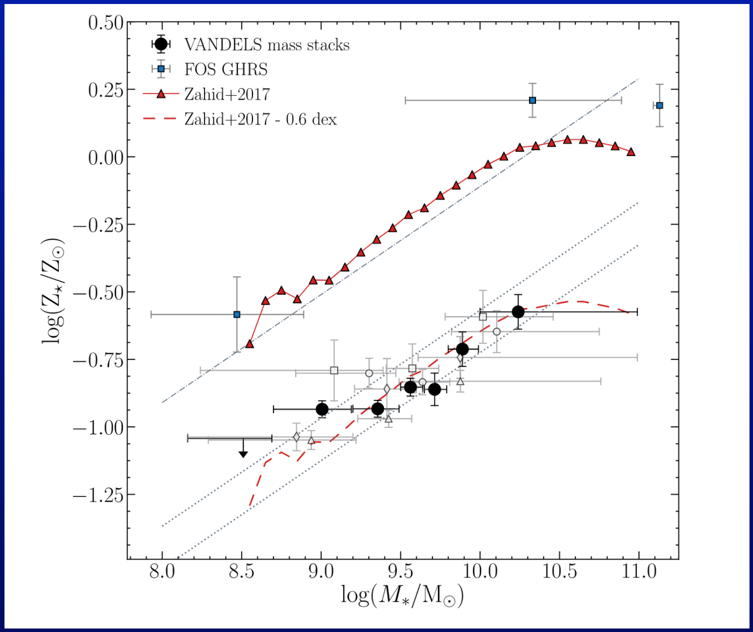


(Sanders et al. 2018)

- Based on strong emission-line ratios, z~2 MOSDEF galaxies [blue points, black stacked points] have systematically lower metallicity (~0.3 dex) at fixed mass than those at z~0 [green squares].
- M*-SFR-Z relation present at z~2.3!
- z~2.3 galaxies have ~0.1 dex lower metallicities at fixed M_* and SFR compared to z=0.
- →The M*-SFR-Z relation evolves with redshift (the FMR is not "fundamental").

Stellar MZR at <z>=3.5



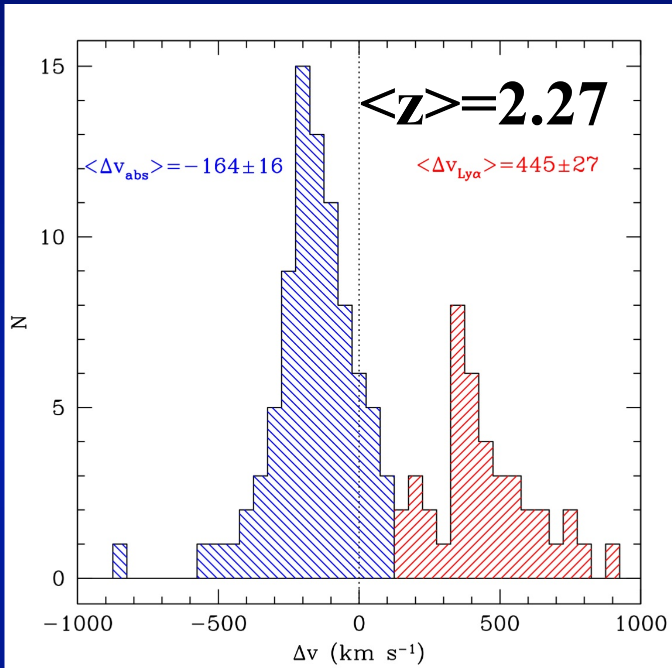


(Cullen et al. 2019)

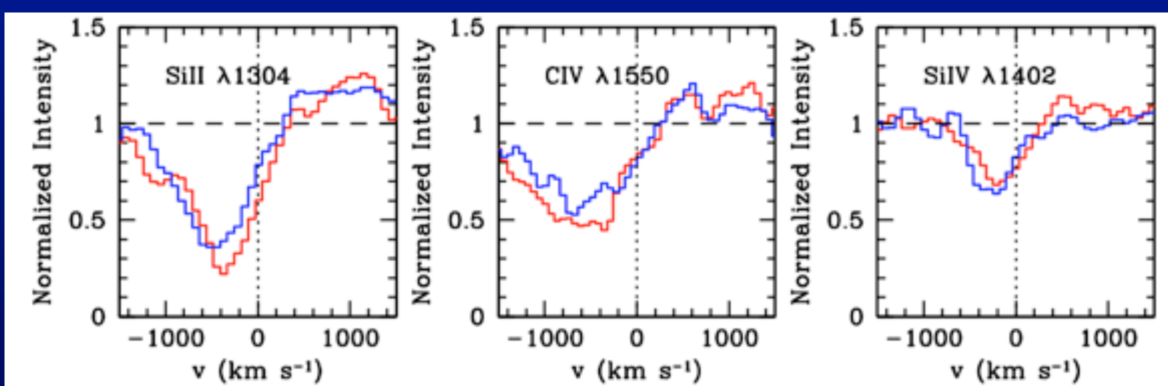
- Deep VANDELS rest-UV spectral stacks for z=2.5-5.0 star-forming galaxies.
- Stellar MZR estimated from Fe abundance in massive stars.
- Evolution of 0.6 dex relative to z=0 relation (red triangles).
- Suggestive of α-enhancement in high-redshift galaxies → Chemically young!
- Constraints on the outflow mass loading factor.

z~2 Galaxy Outflows: UV Absorption

(Steidel et al. 2010)

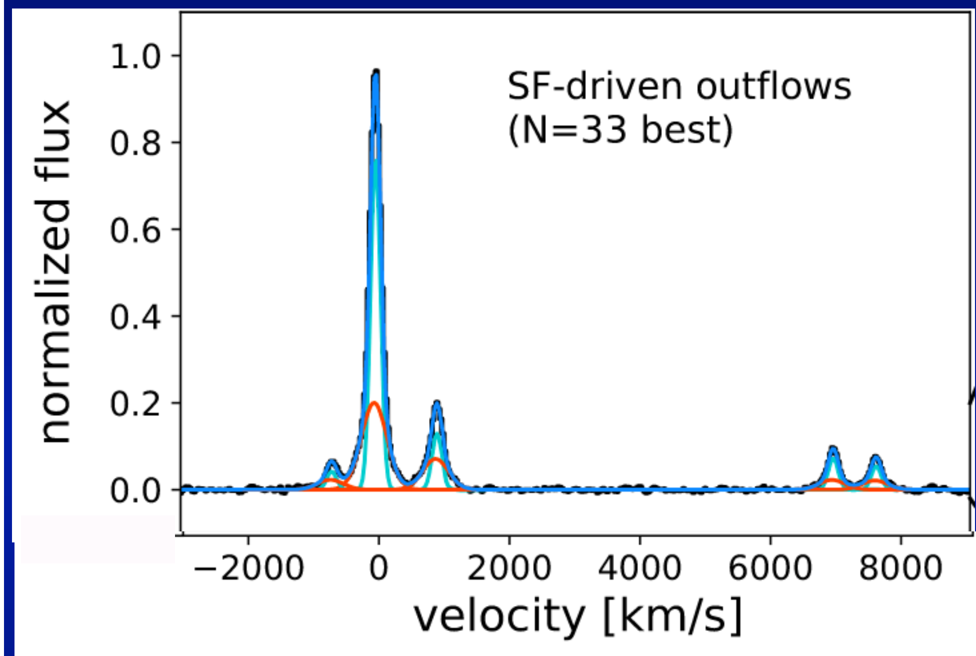


- Kinematic outflow signature: redshift offsets.
- Detected in almost all z>2 UV-selected galaxies (in contrast to lower-z results). Plus no apparent correlation between v_{out} and inclination.
- Suggests z>2 outflows are not collimated! More spherical in geometry?



(Image credit: Subaru Observatory)

z~2 Galaxy Outflows: Hα emission



(Förster Schreiber et al. 2019)

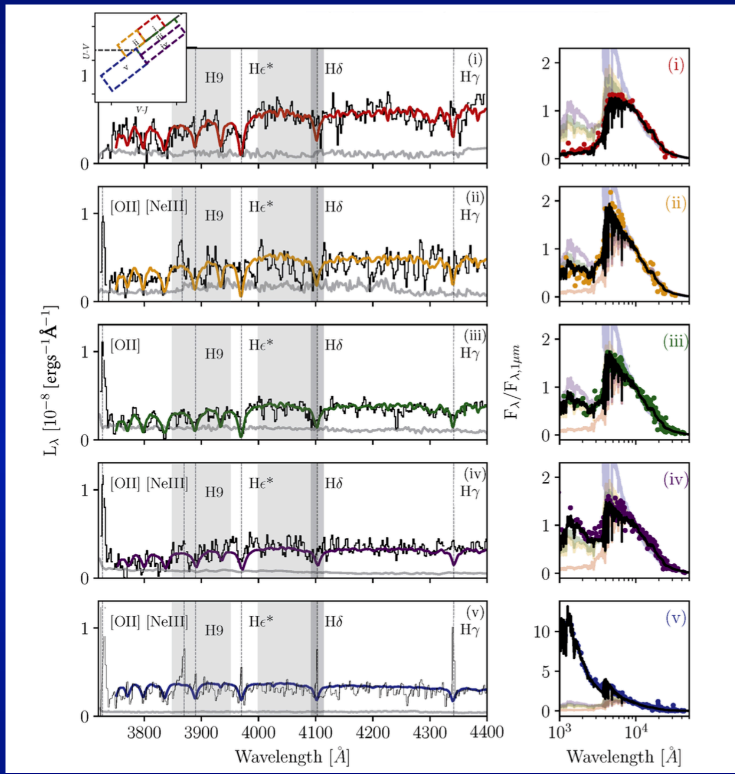
- **Kinematic outflow signature (broad Hα emission).**
- **Detected in ~20% of KMOS^{3D} SF galaxy maps (Förster-Schreiber et al. 2019).**
- **Different detection frequency of H^{a} and UV outflow signatures may indicate multi-phase structure of outflows.**

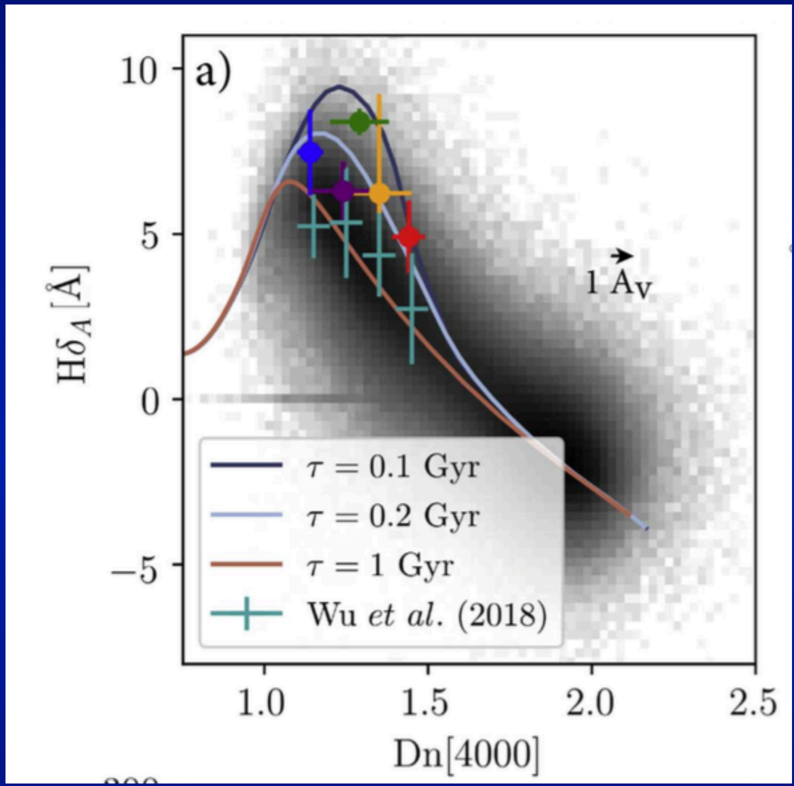
(Image credit: Subaru Observatory)

The Rise and Fall of Star Formation

Star-formation Histories at z~2

(Zick et al. 2018)

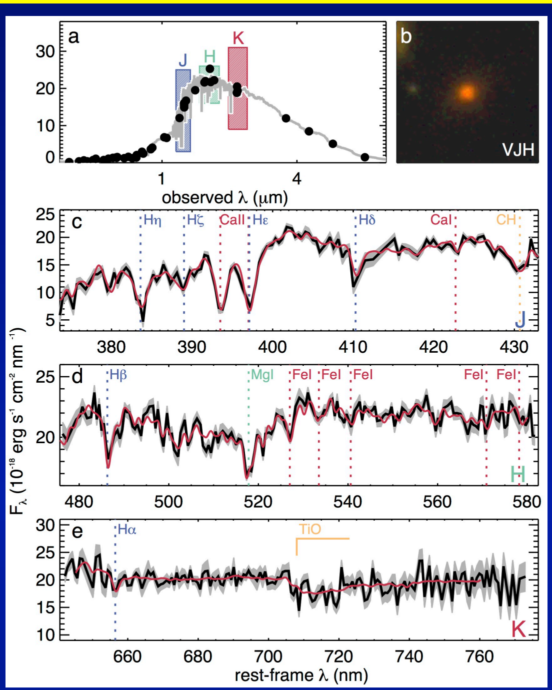




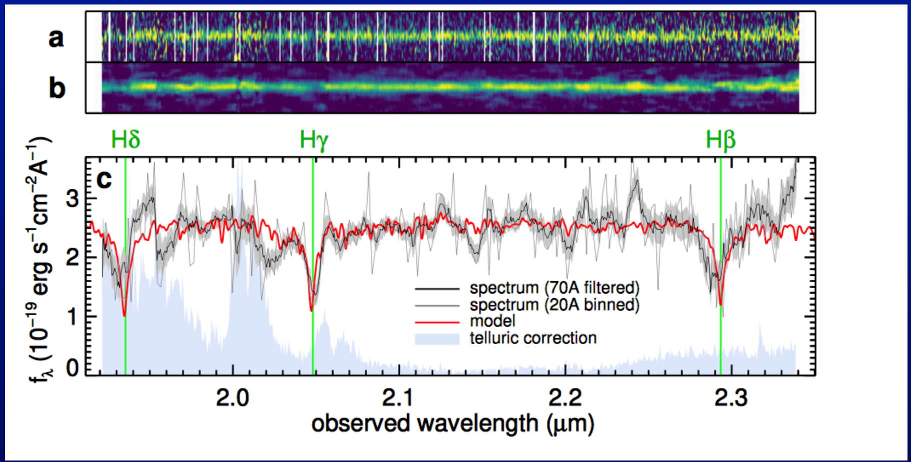
- **For the first time, star-formation histories of high-z galaxies based on spectral indices.**
- **Stacked spectra of z~2 galaxies with different spectral types (star-forming, quiescent) from the MOSDEF survey.**
- **Shut-down of star formation at z~2 is an order of magnitude faster than at z~0.**

Stellar Absorption Lines at z>2

(Kriek et al. 2016)



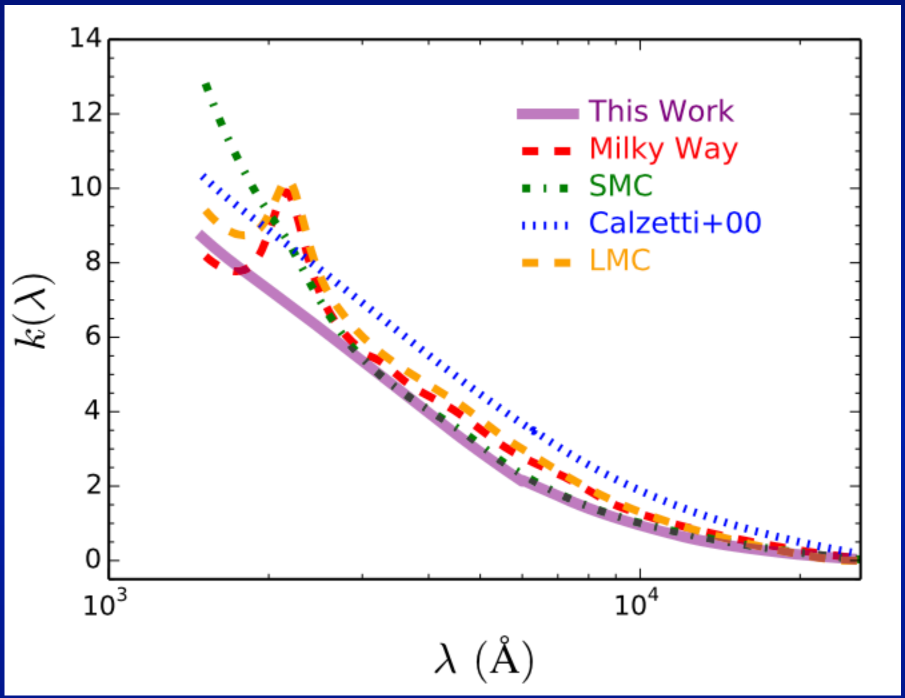
(Glazebrook et al. 2017)



- Deep Keck/MOSFIRE stellar absorption spectrum for z=2.09 and z=3.71 quiescent galaxies in COSMOS.
- Measure the Mg/Fe ratio at z=2.09. Most Mg-enhanced galaxy found to date. Elemental abundance pattern consistent with exclusive Type II SNe enrichment, 0.1-0.5 Gyr star-formation timescale, with past SFR~600-3000 M_{sun}/yr!
- Measure Balmer absorption lines at z=3.71. Source may be associated with submm galaxy, but post-starburst spectrum at z~4 is spectacular.
- Only a handful of such stellar continuum+absorption measurements to date at high redshift.

Dust Attenuation at High Redshift

(Reddy et al. 2015)

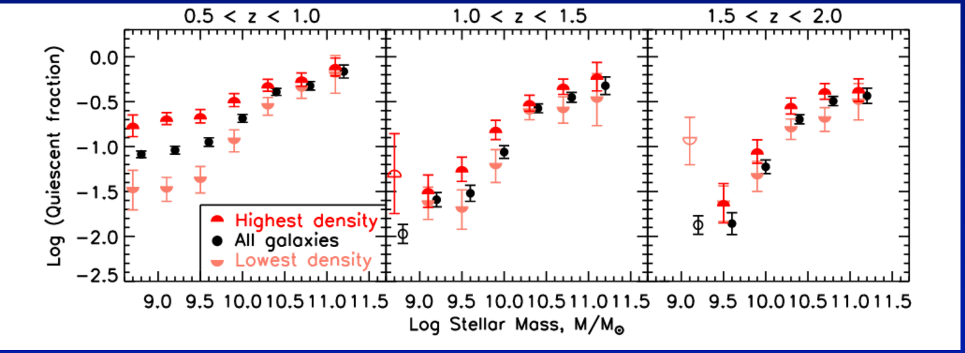


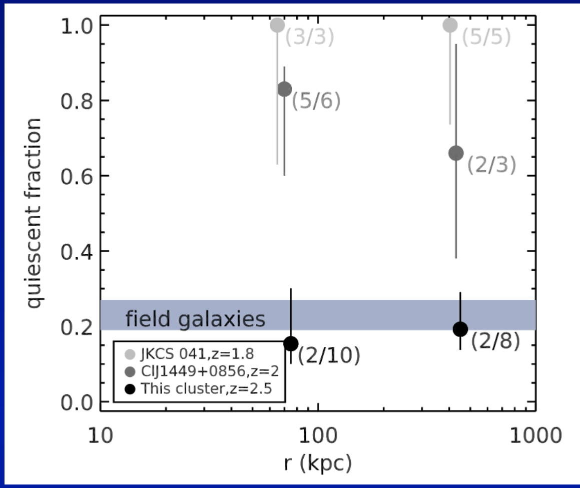
- Dust corrections are crucial for census of star formation over cosmic time.
- Standard assumptions at high redshift: Calzetti or SMC dust attenuation law.
- Dust law has been determined from high-redshift observations at z~2-4 (Reddy et al. 2015, Cullen et al. 2018).
- Shape consistent with Calzetti.

What about Environment?

Galaxy Properties vs. Environment

(Kawinwanichakij et al. 2017)



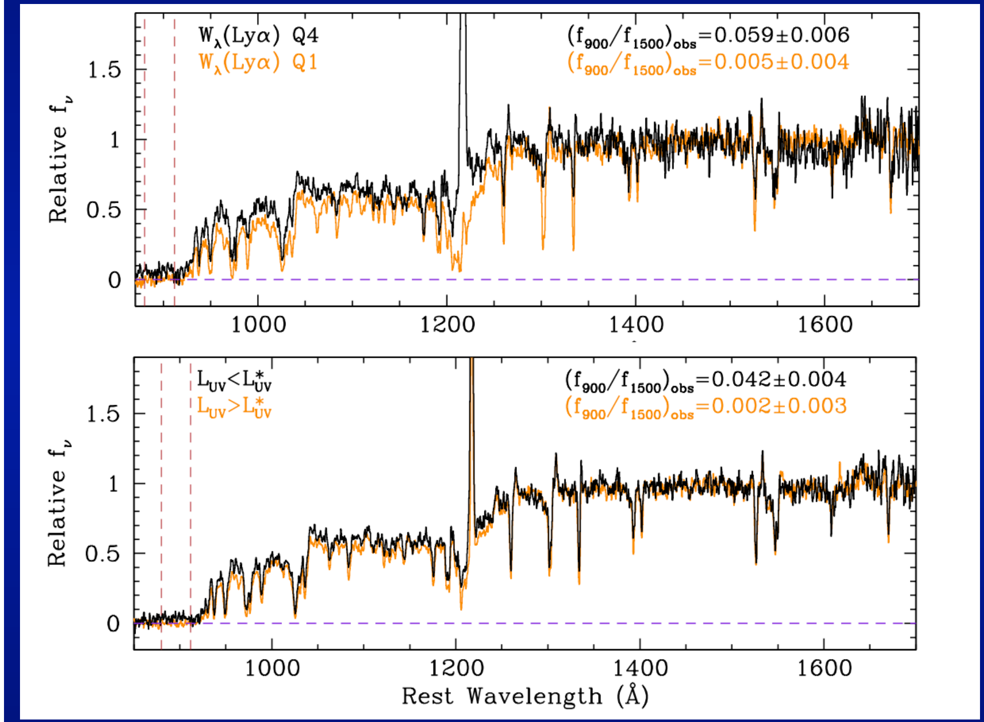


(Wang et al. 2016)

- Lack of consensus regarding z>1.5 environmental trends.
- Some results show quiescent fraction increasing vs. density. Some show quiescent fraction decreasing or remaining constant in rich high-z cluster.
- Some results show increase in SFR density in dense regions (Tran et al. 2010).
- Need for more systematic spectroscopic identification of high-z clusters, robust environmental measures, spectroscopic confirmation of all galaxy types.

Cosmic Noon as a Window into Cosmic Dawn

Galaxy Contributions to Reionization

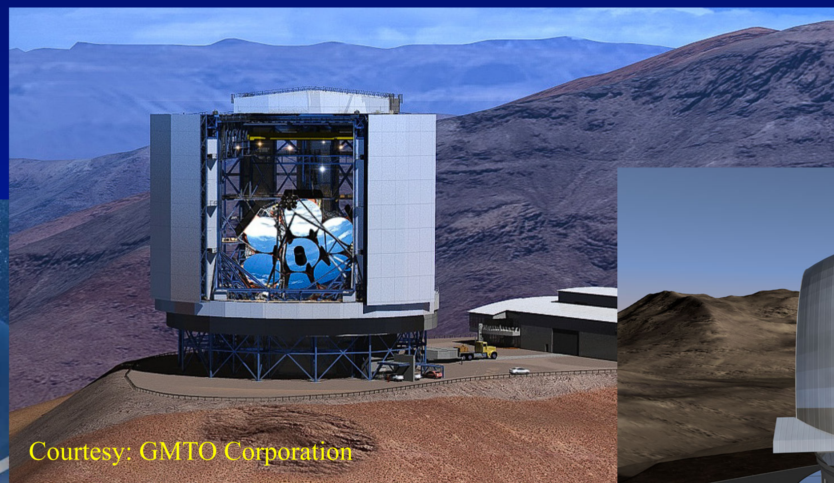


Steidel et al. (2018)

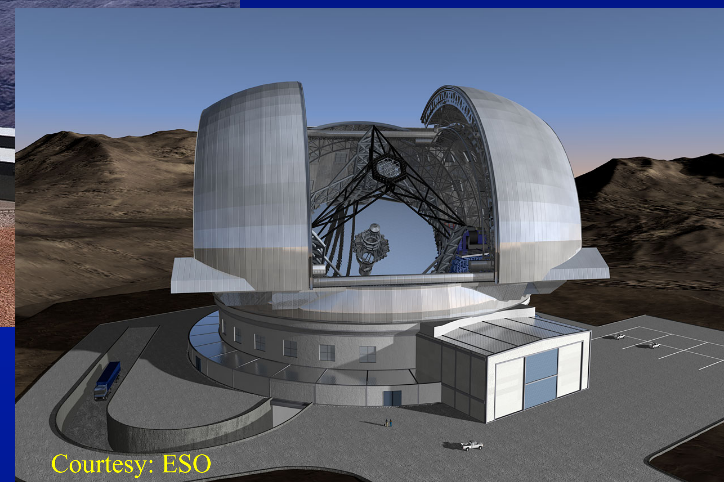
- **Steidel et al. (2018): Sample of 124 LBGs. 8-hour Keck spectra covering the LyC region.**
- **15/124 apparently detected spectroscopically in LyC.**
- **Sample average is f_{esc}=0.09±0.01. 0.25≤L_{UV}/L_{UV}*≤3 galaxies contribute ≥50% of the ionizing emissivity at z~3.**
- **LyC leakage % higher for larger Lyα EW and fainter UV luminosity.**
- ***See also Fletcher et al. (2018) Nakajima et al. (2019), Tang et al. (2019), Stark et al. (2014).***

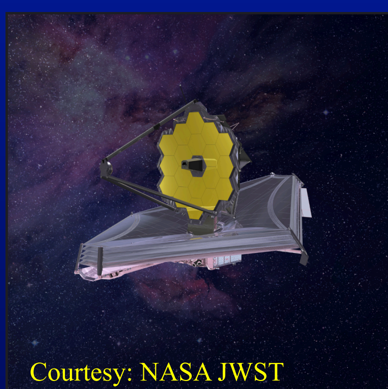
Looking ahead…

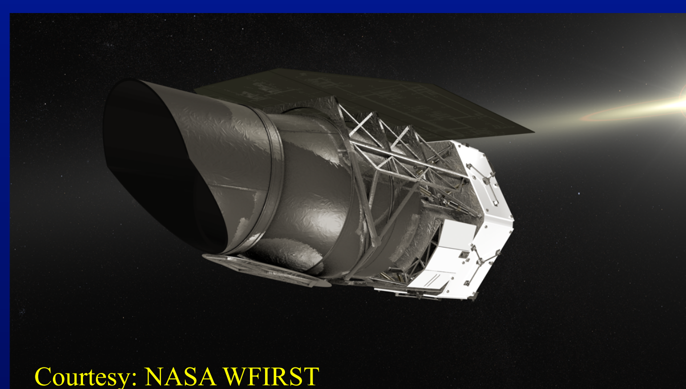
Next-Generation Facilities

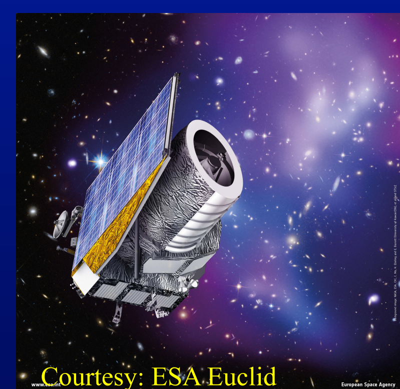

Courtesy: GMTO Corporation


Courtesy: TMT International Observatory


Courtesy: ESO

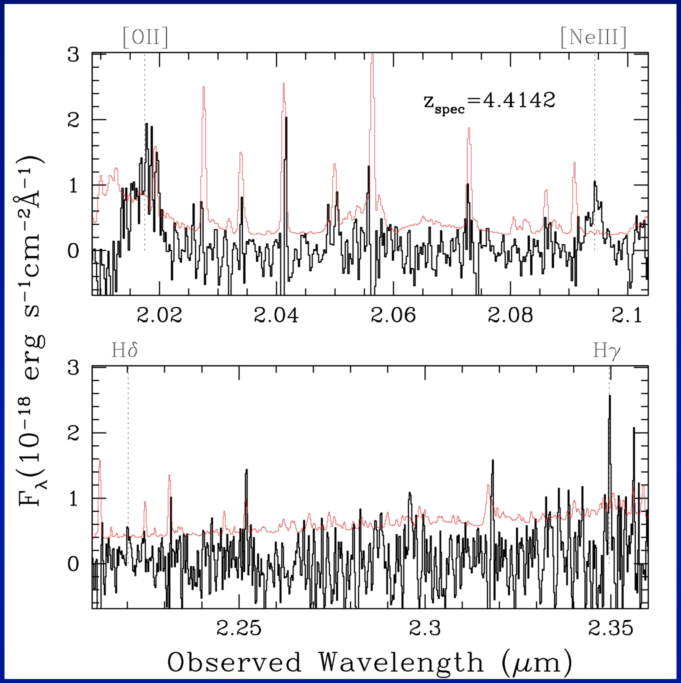

Courtesy: NASA JWST

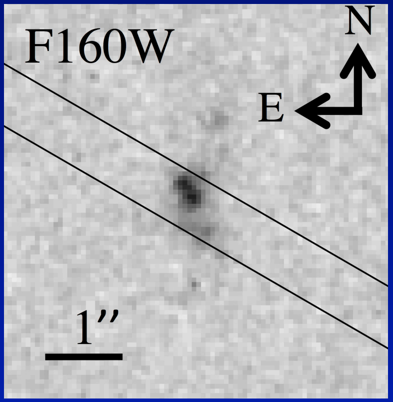

Courtesy: NASA WFIRST

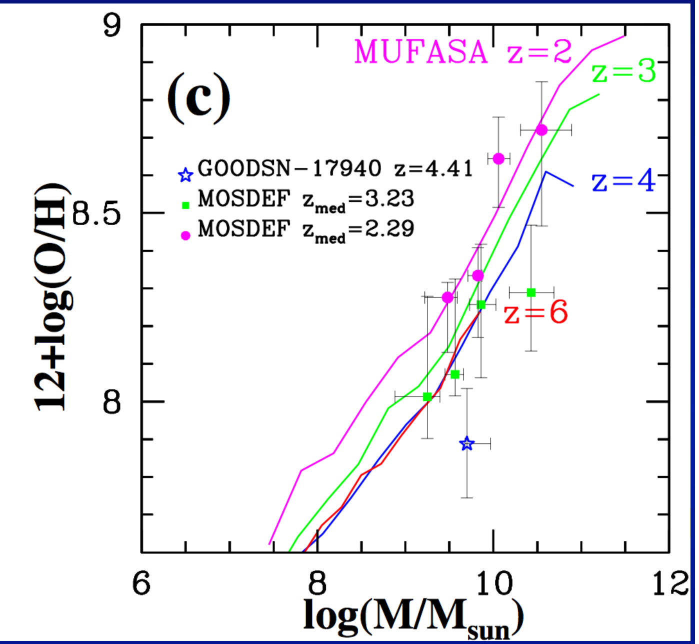

Courtesy: ESA Euclid

MZR/FMR to z~10

(Shapley et al. 2017)



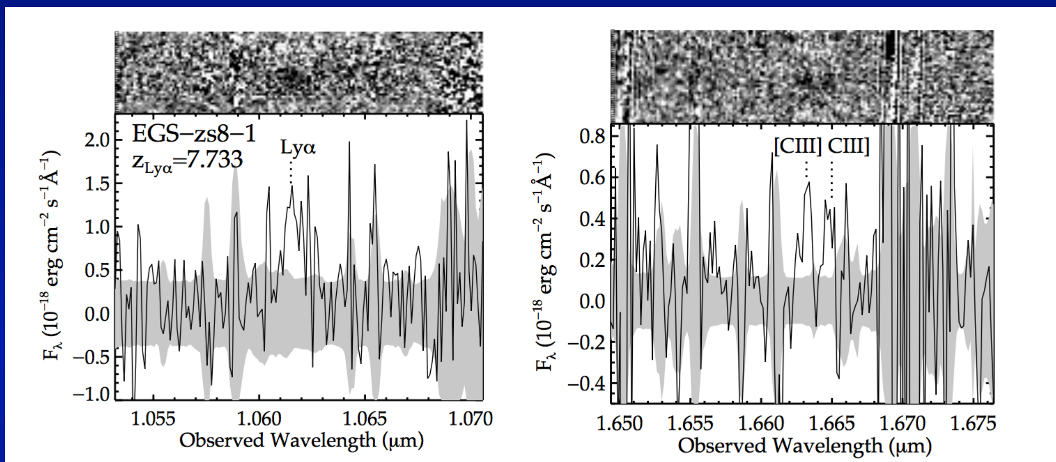


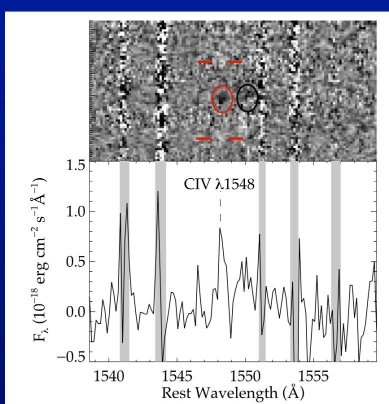


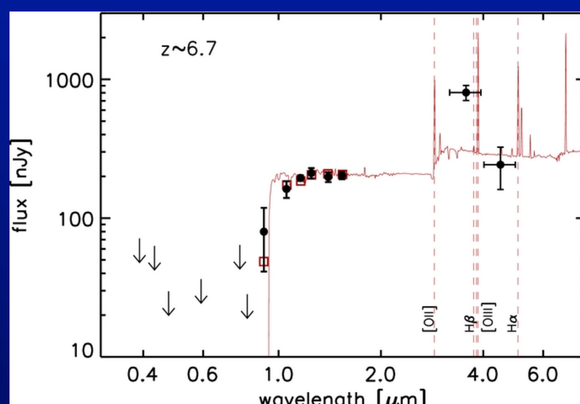
- First spectroscopic detection of multiple rest-optical emission lines at z>4 (Keck/MOSFIRE)!
- [NeIII]/[OII] suggests O/H~0.2 $(O/H)_\odot$.
- Preview of JWST-era spectroscopy, with O/H measured out to z~10!

Spectra and “Spectra” of Star-forming Galaxies at z~7

(Stark et al. 2015, 2017; Smit et al. 2014)







Very small number of rest-UV spectra at z≥7.

Large CIII]1909 and CIV1548 EWs (10-20 Å). Qualitatively different from typical LBGs at z~2-3.

IRAC photometry also suggests large rest-optical [OIII]+Hβ EWs (low metallicity, young, implications for ξ_{ion}).

An actual spectroscopic census is needed at z≥7, for “typical” galaxies. ELTs and JWST will do this.

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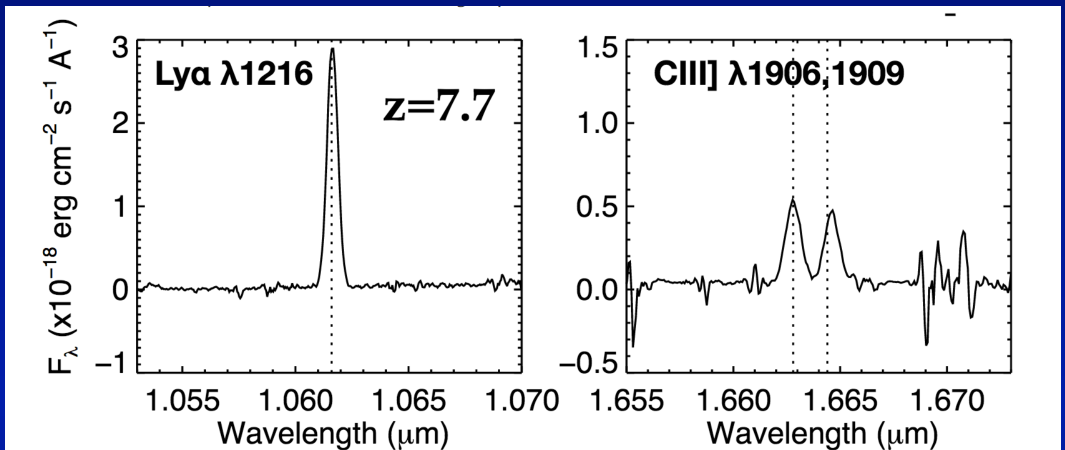
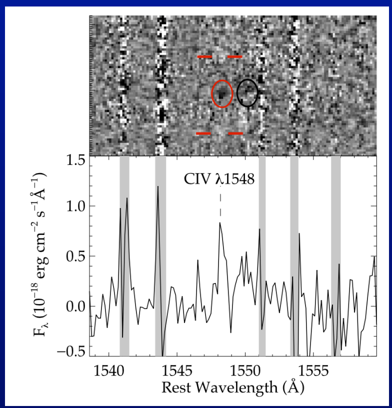
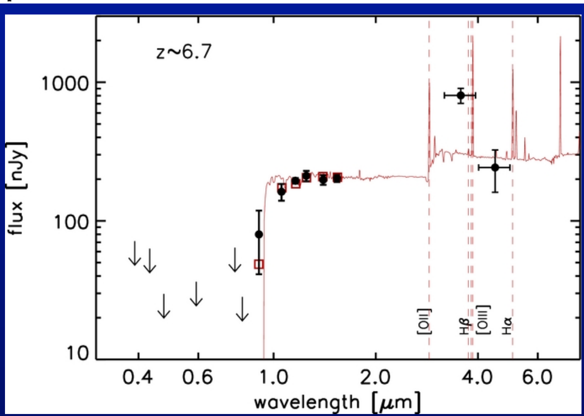


Courtesy: Stark, Finkelstein, Simcoe

~4 hrs with GMT SuperFIRE-like instrument





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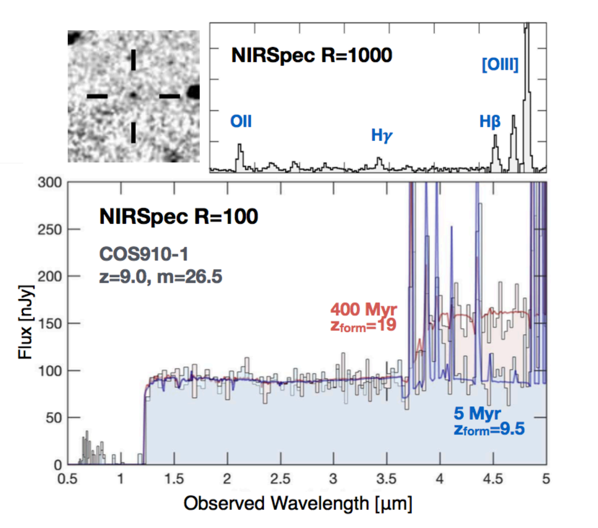
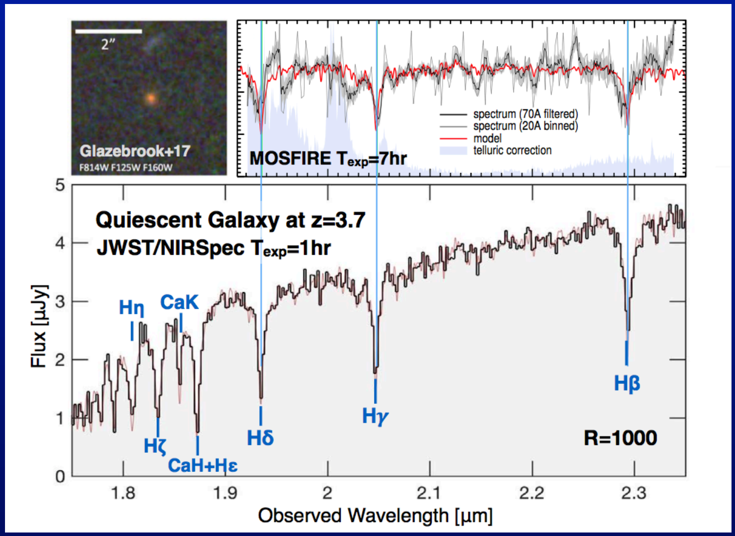
The Future with JWST/NIRSpec





- JWST/NIRSpec will:
  - Extend the study of nebular chemical enrichment into the reionization epoch! Tremendous discovery space!
  - Enable robust continuum/ absorption spectroscopy.

- Faint emission lines, continuum spectroscopy – all transformed by future instrumentation on the ground and in space.

Summary

• Tremendous progress in our census of the universe at Cosmic “Noon” over the past decade.

• Coupled with extensive multi-wavelength databases, we have used optical and near-IR spectroscopy to learn about the key processes in galaxy formation for $>10^4$ galaxies.

• The next frontier for spectroscopy is the first billion years, i.e., Cosmic “Dawn.”

• Many outstanding questions remain: What is the nature of feedback and galaxy outflows at early times? What are the detailed star-formation histories of individual galaxies? Why and how does star formation shut down in galaxies of different masses and environments? What is the relation between galaxy properties and environment over all cosmic time?

• We will continue to assemble a statistical description of the galaxy population over the first few billion years of the universe, to confront state of the art galaxy formation models.