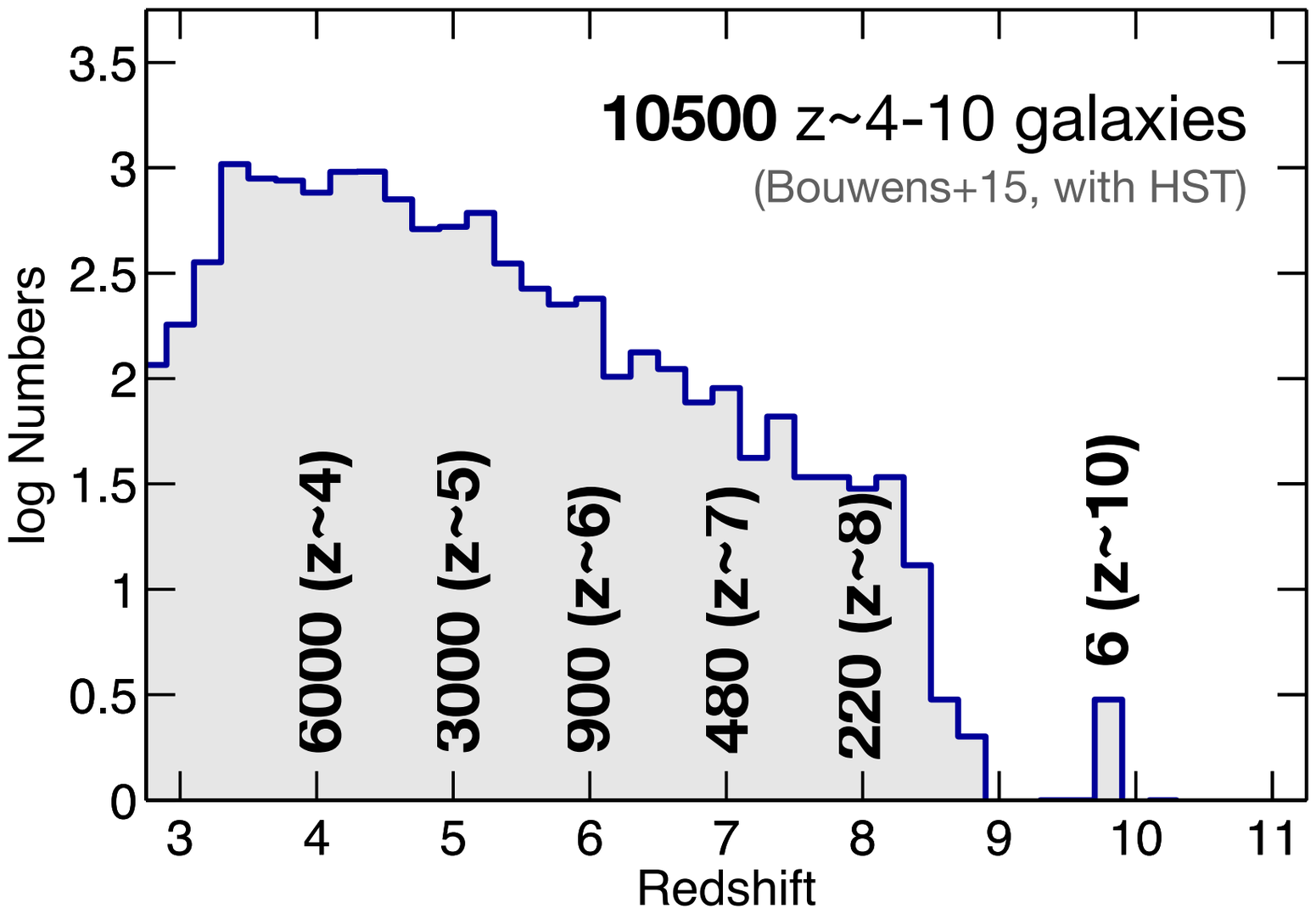
Galaxies Across Cosmic Time

Overview:

1. Epoch of Reionization (z>6)
2. Stellar Mass Functions to z~6
3. Deep Spectroscopy at z~2-3
4. Circumgalactic Medium (z<1)
5. AGN outflows

Unprecedented Galaxy Samples at z>=4

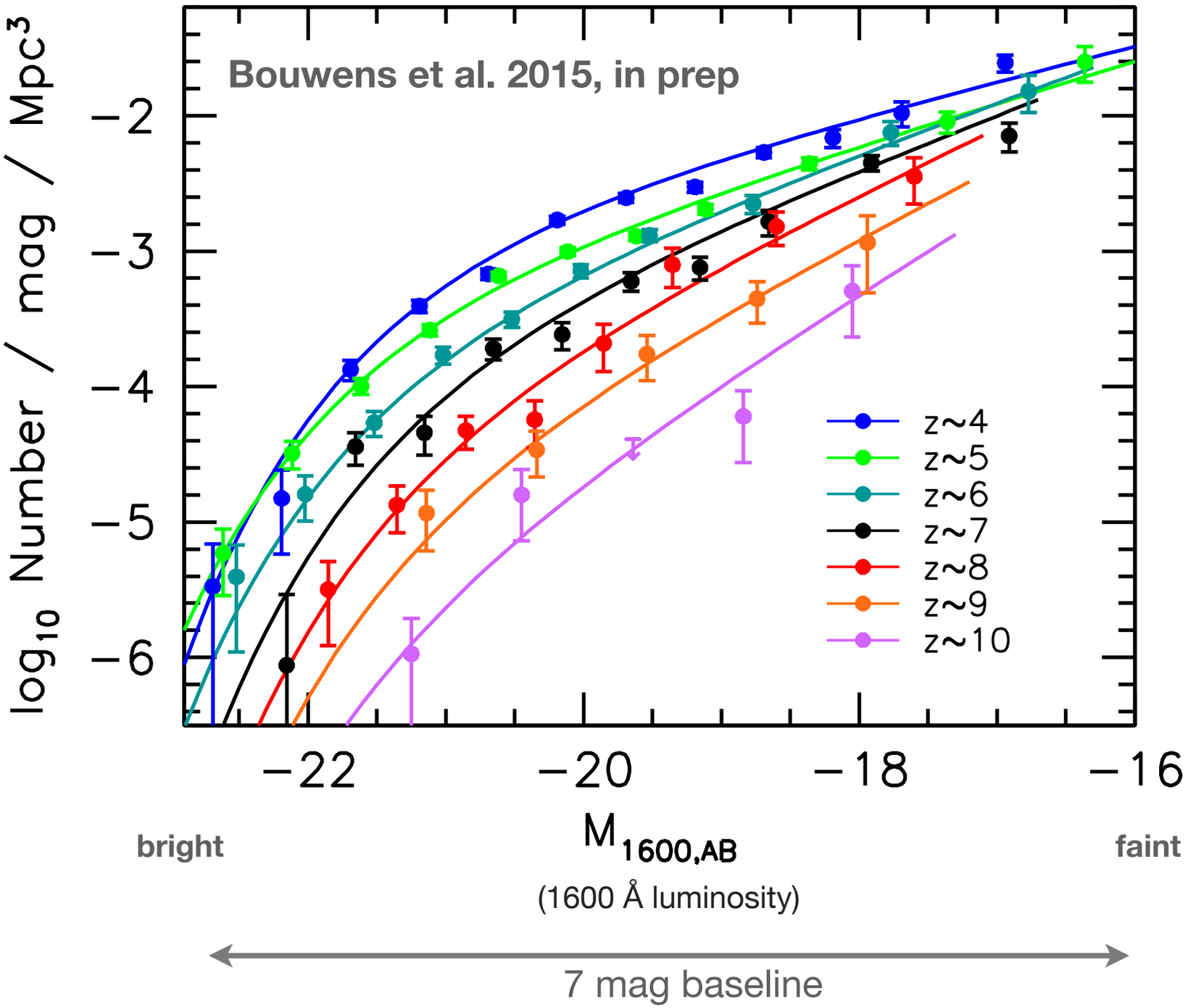
(from HST's blank fields only: CANDELS+HUDF)



Almost 1000 galaxies in the epoch of reionization at z>6

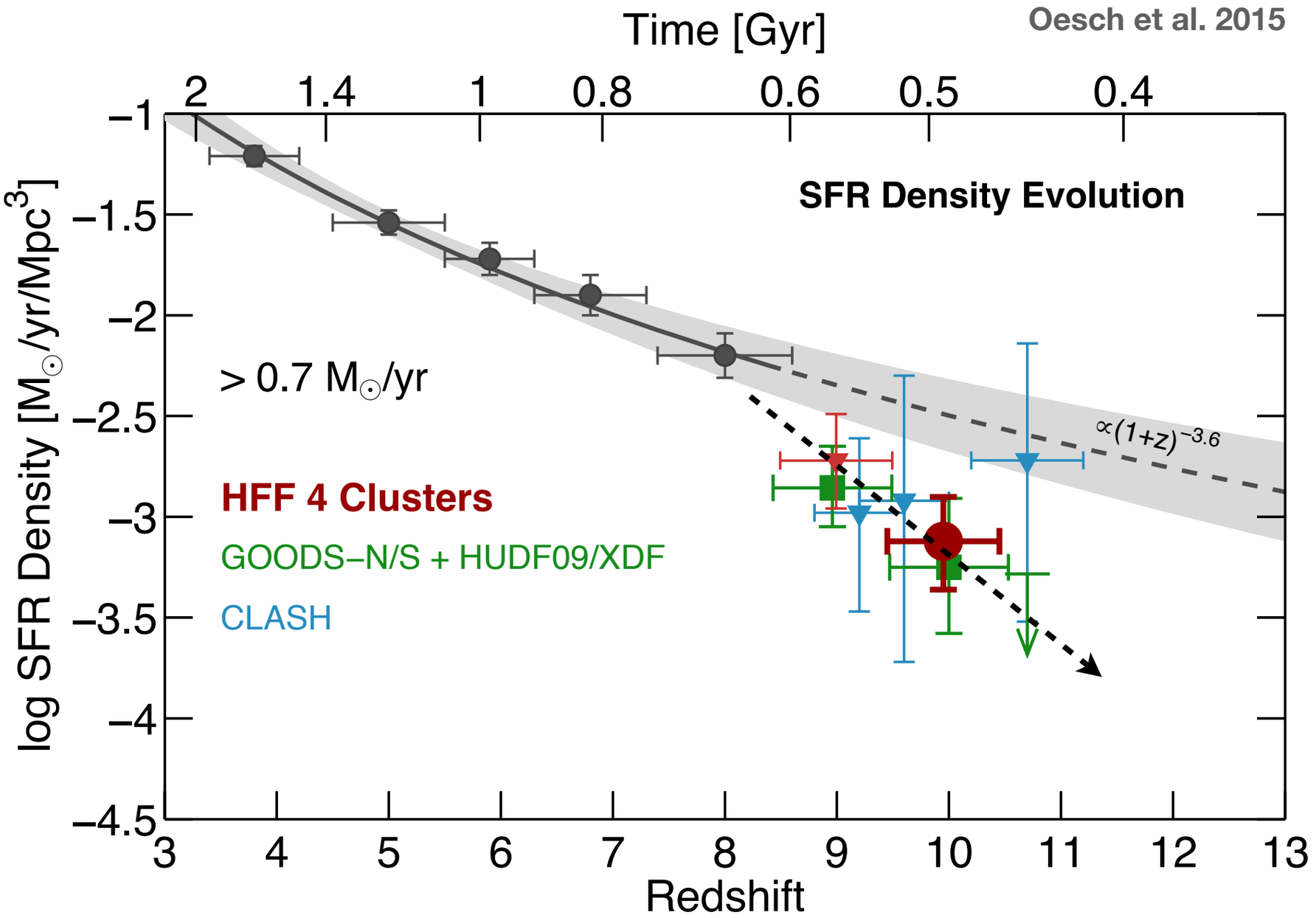
Current frontier: z~9-10

The Evolution of the UV Luminosity Function to z~10



See also: e.g. Oesch+10a/12, Bouwens+10a,11,12; Bunker+10, Finkelstein+10/14, Wilkins+10/11, McLure+10/13, Yan+12, Bradley+12, ...

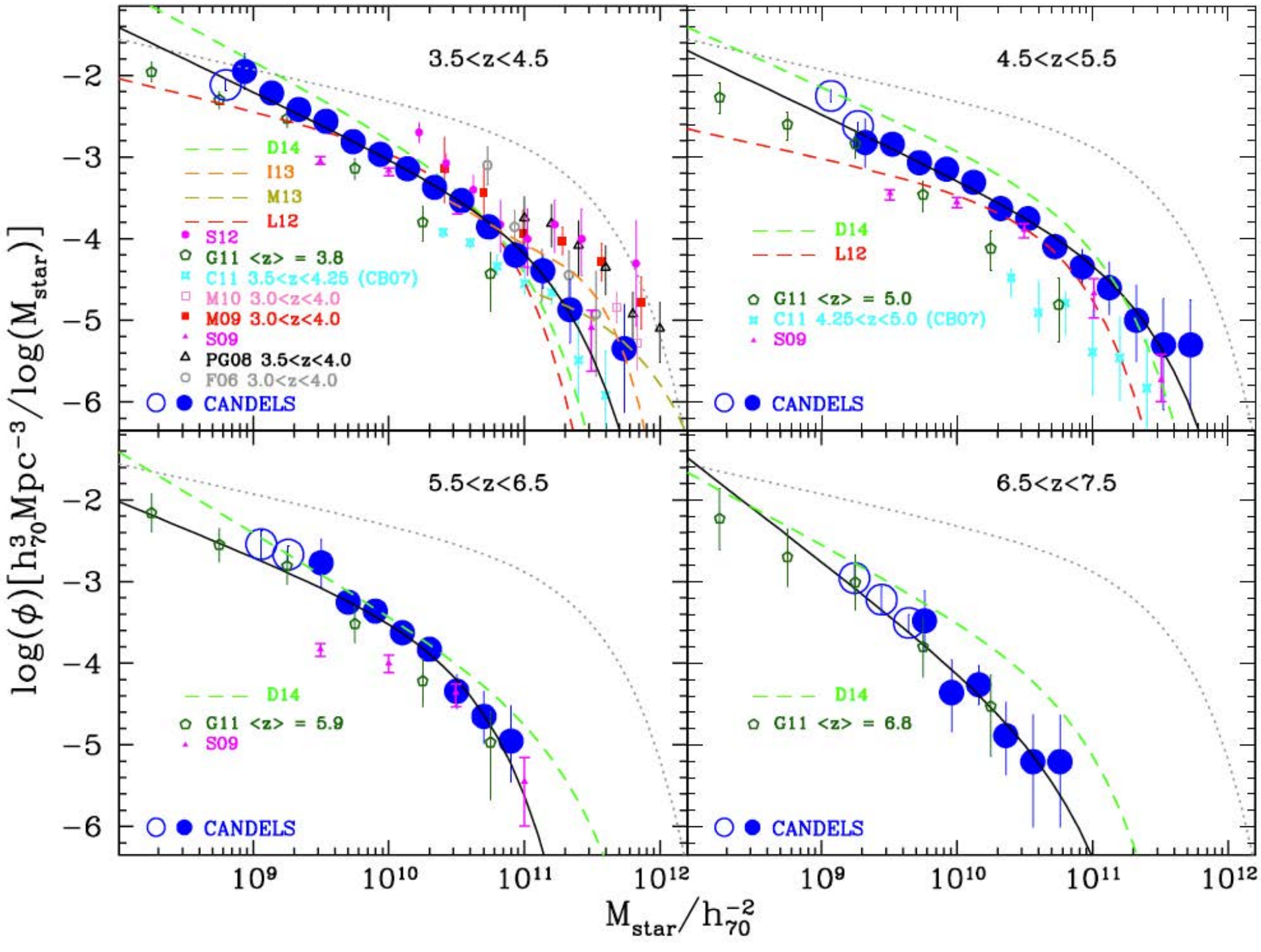
SFRD Evolution at z>8



Current estimates seem to indicate that the cosmic SFRD evolves more rapidly at z>8 than at lower redshift!

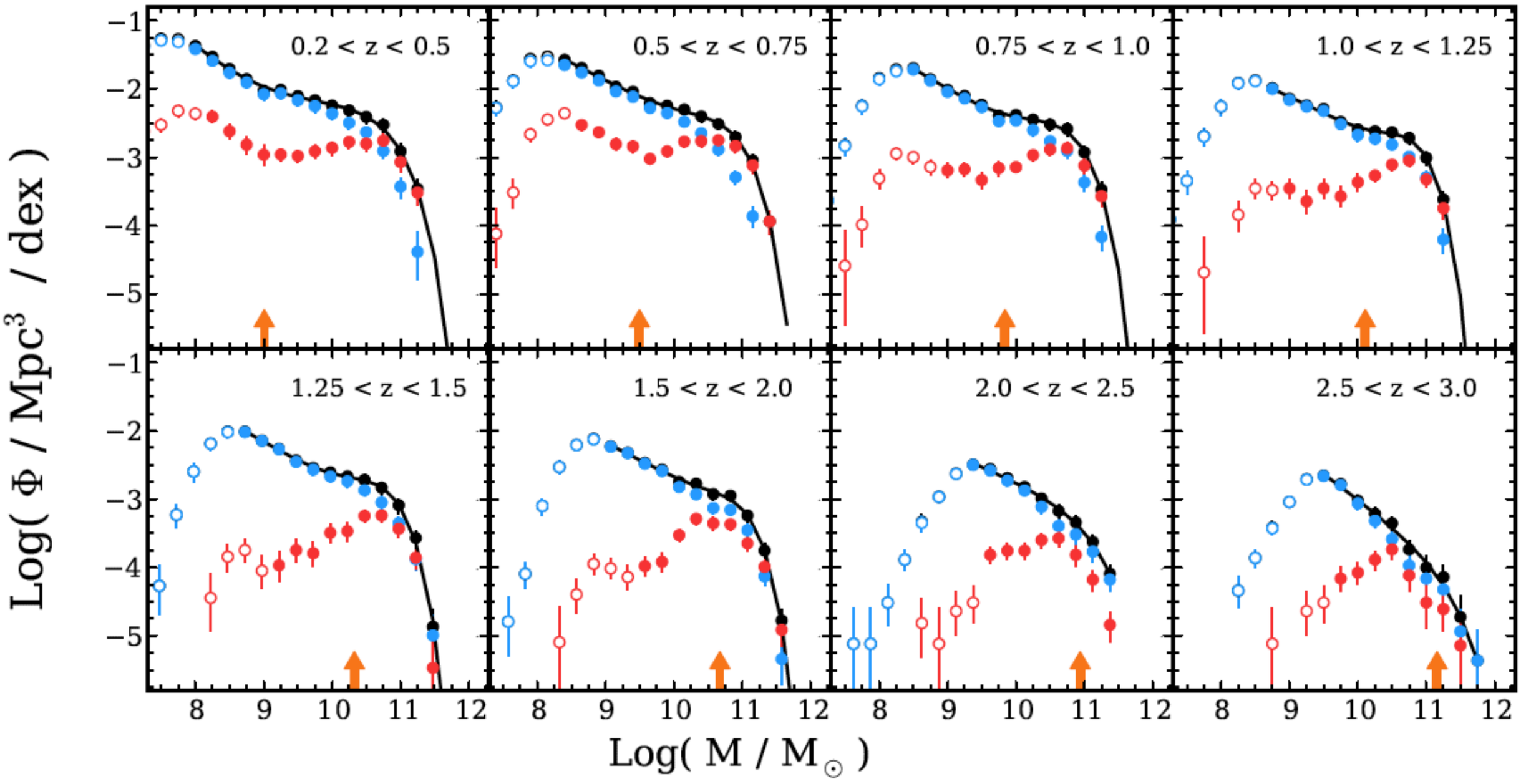
see also: Zheng+12, Coe+13, Bouwens+13/14, Ellis+13, McLure+13, Ishigaki+14

Stellar Mass Functions to z=7



Grazian et al. 2014 - CANDELS

Stellar Mass Function of Quiescent vs Star-forming Galaxies

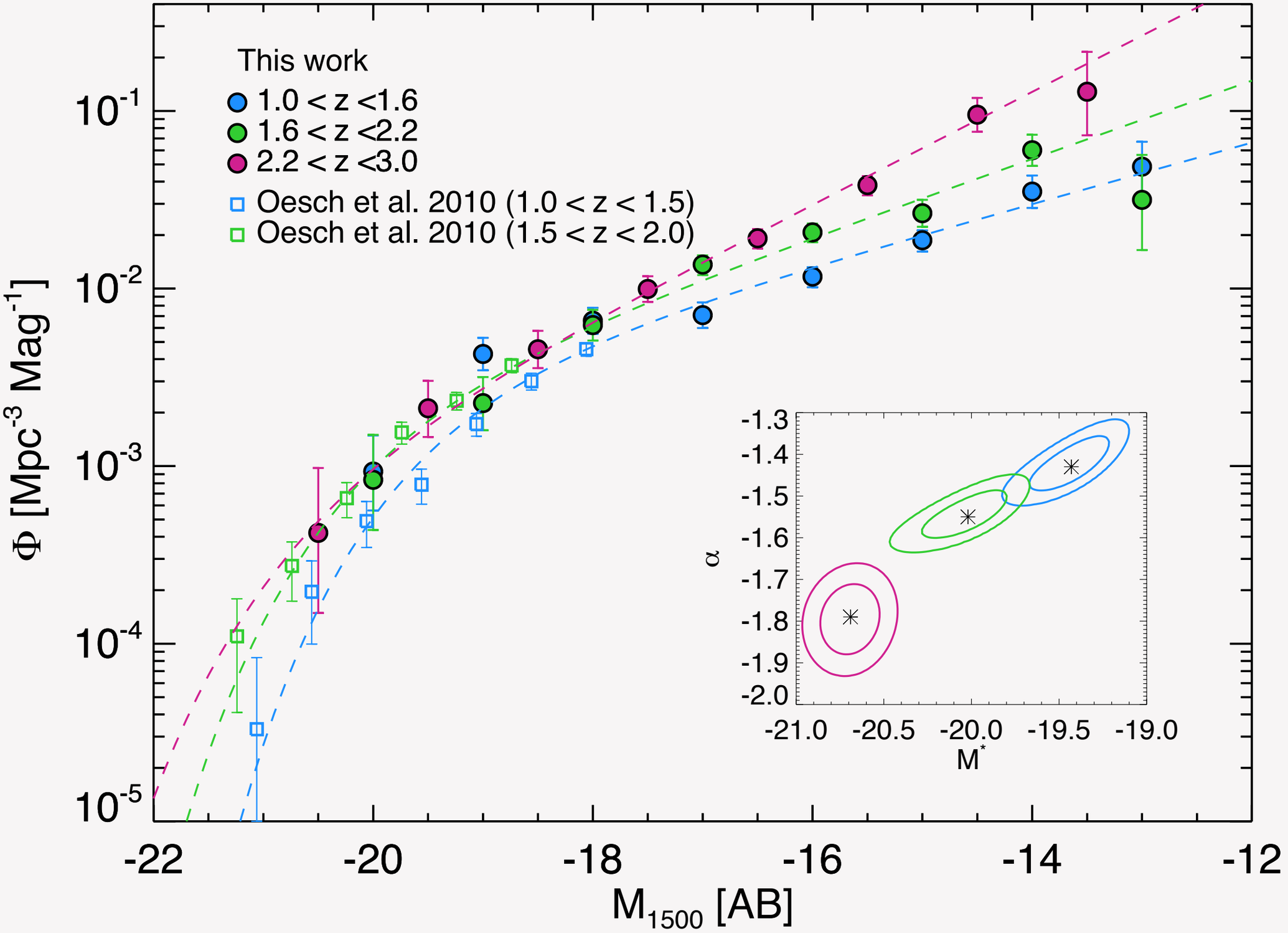


Tomczak et al. 2014 - ZFOURGE/CANDELS

Dwarf Galaxies @ 1<z<3

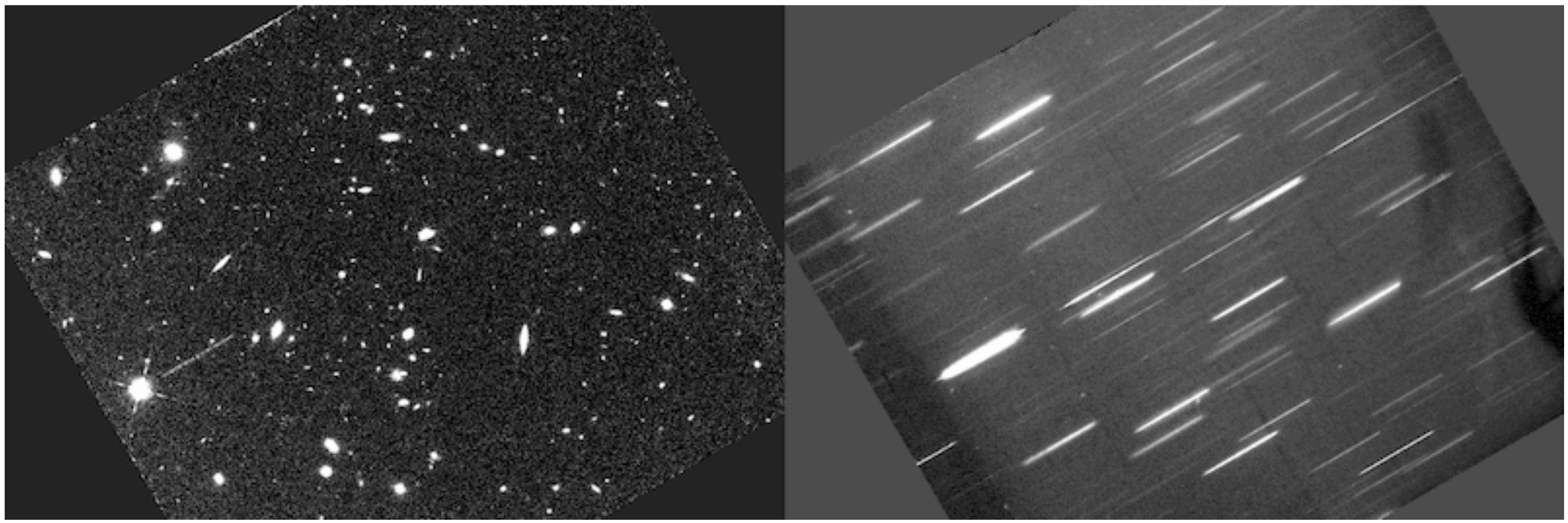
- HST Frontier fields
- 900 Galaxies now (in 3 of 7 clusters)
- 2000 total expected
- $10^6 < M^* < 10^9$ M_{SUN} !!!!
- 100x fainter than previous surveys

LF Evolution



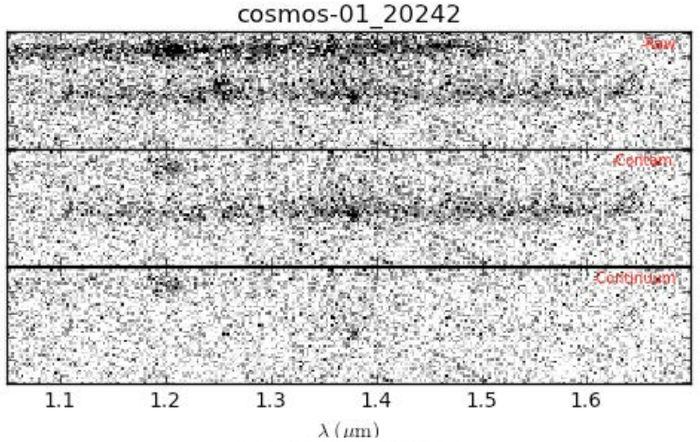
Alavi et al. (2015, in prep)

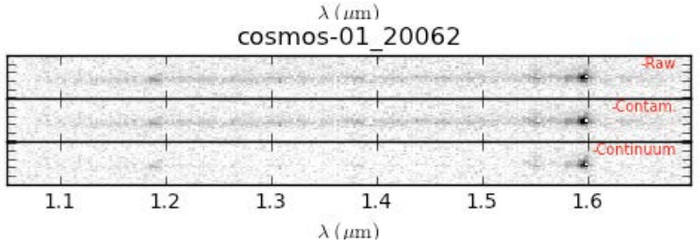
HST IR Grism Surveys

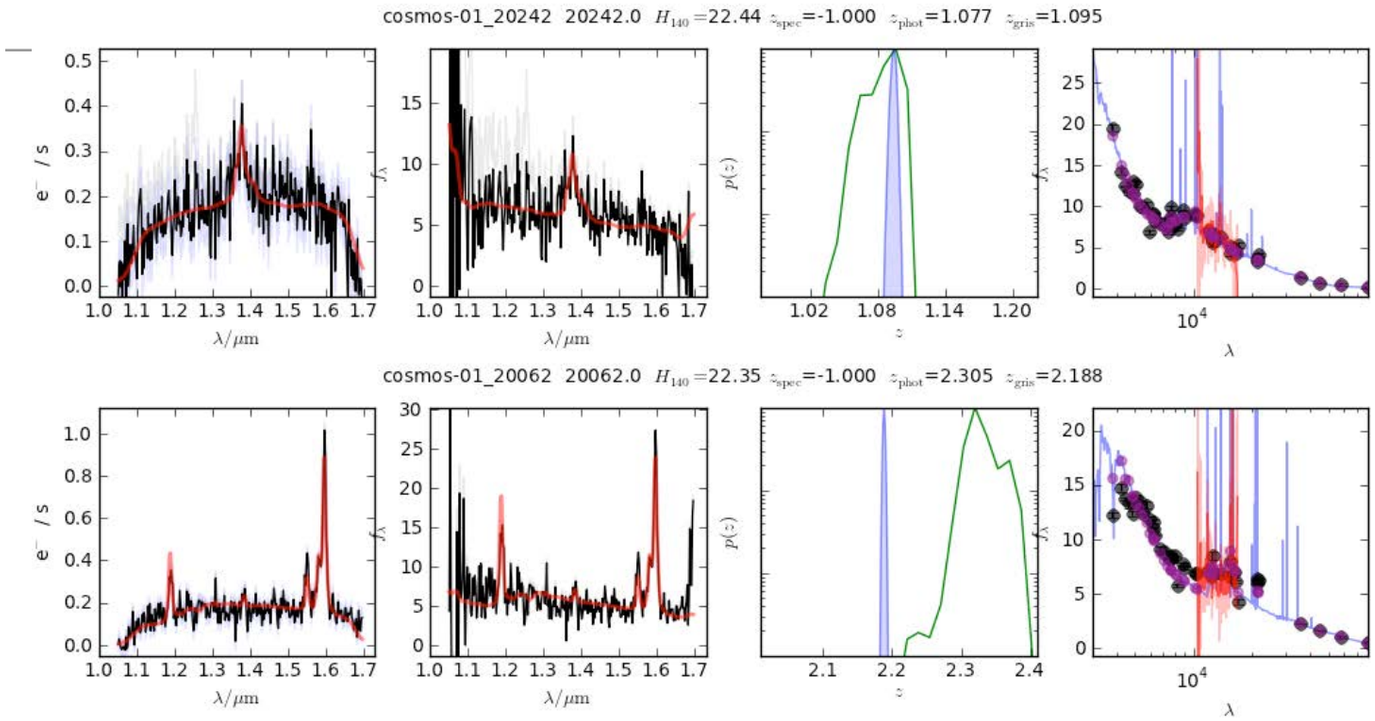


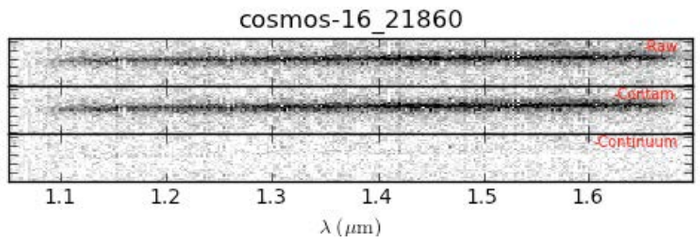
Various HST grism surveys (WISP, 3D-HST, AGHAST) using WFC3-IR camera to take slitless grism spectroscopy of deep fields. Detect continuum + strong emission lines at z~1-3, with R~50.
(Relevant for future WFIRST grism surveys.)

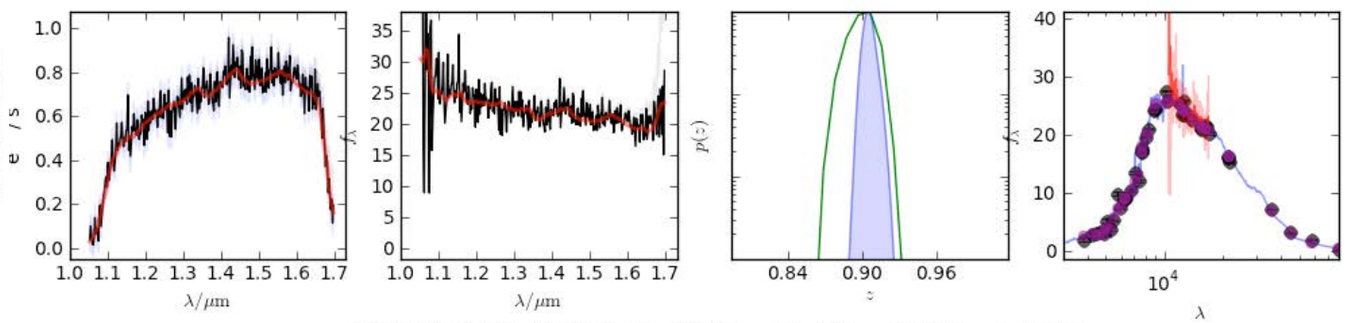
Example images and spectra from 3D-HST survey
~250,000 extracted spectra; ~24,000 down to H=24

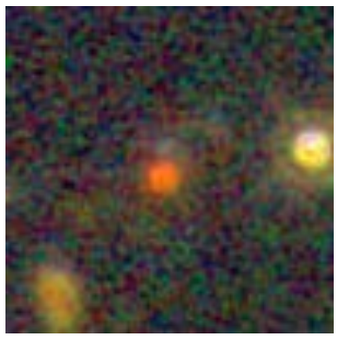


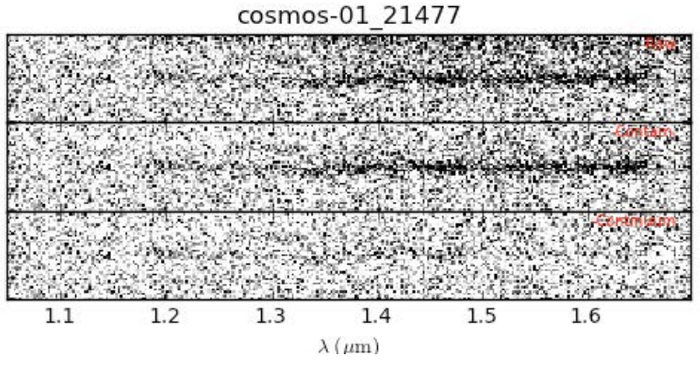


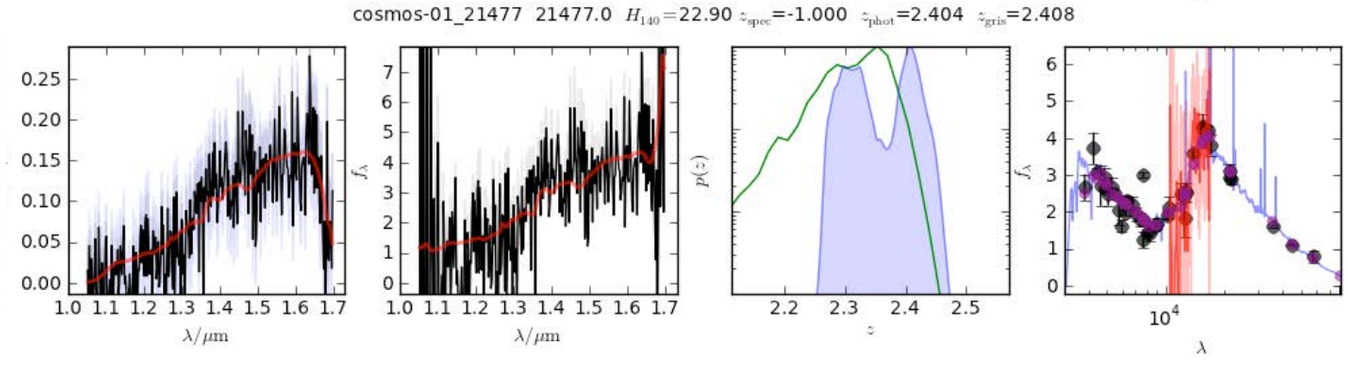












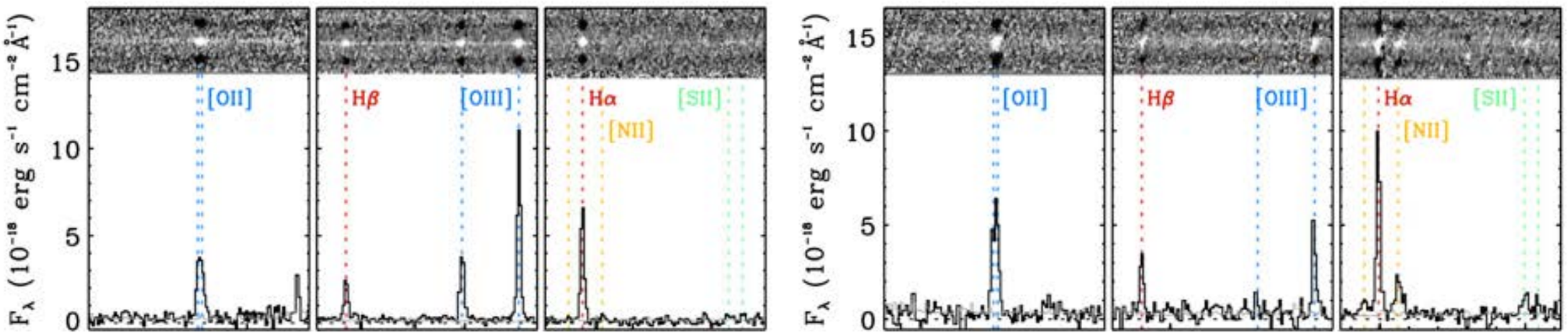
Momcheva et al 2015 (arXiv:1510:02106)

Deep Spectroscopic Surveys at z~2-3

With new multi-object NIR spectrographs on 10m telescopes (MOSFIRE, KMOS), can do deep spectroscopic surveys at moderate resolution at z~2-3.

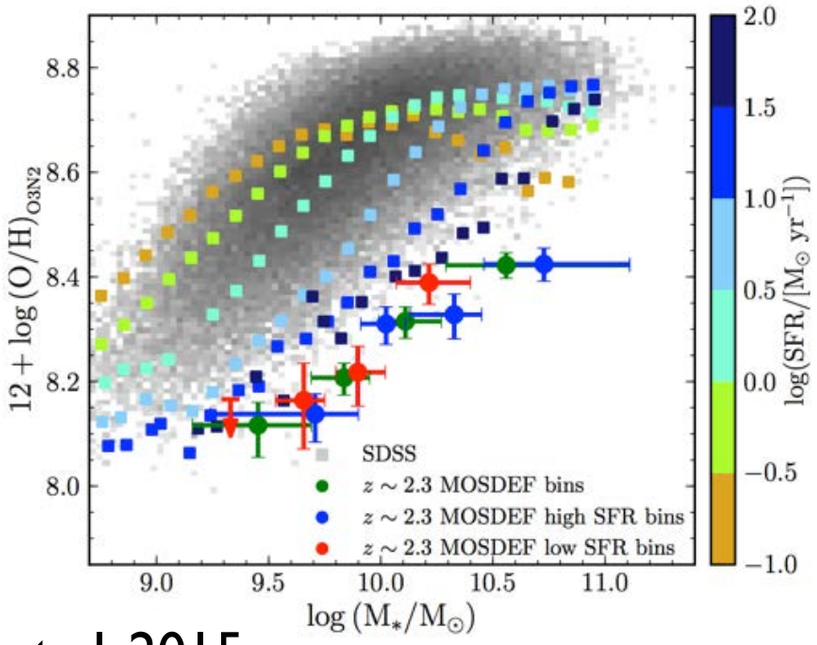
Obtain full suite of rest-frame optical lines that are studied at low-z:
probe star formation, dust attenuation, metallicity, ionization parameter, AGN activity, electron density, shocks, kinematics, outflows, etc…

The MOSDEF survey: Total sample of ~1500 galaxies and ~150 AGN at 1.4 < z < 3.8 in the CANDELS fields



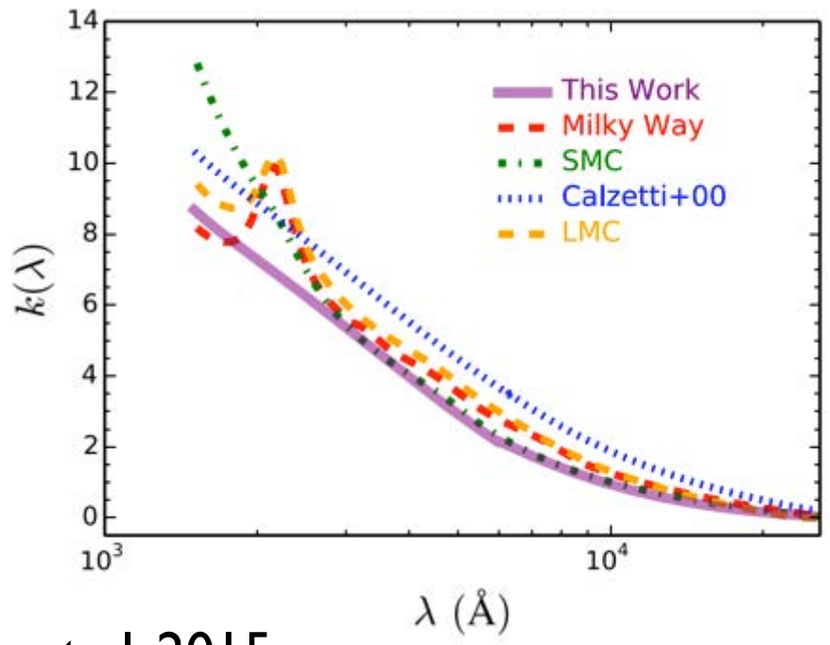
Kriek et al. 2015

Mass-Metallicity-SFR at z~2



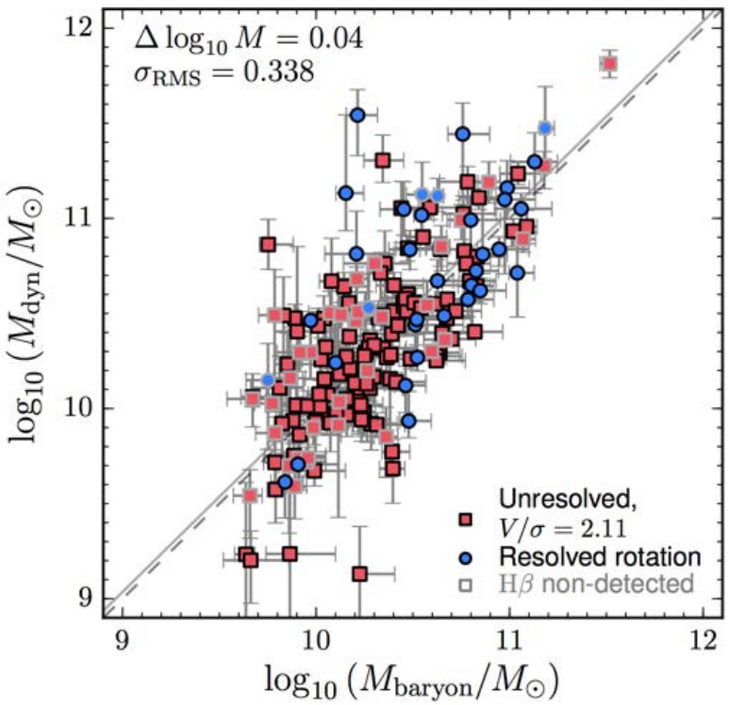
Sanders et al. 2015

Dust Attenuation at z~2



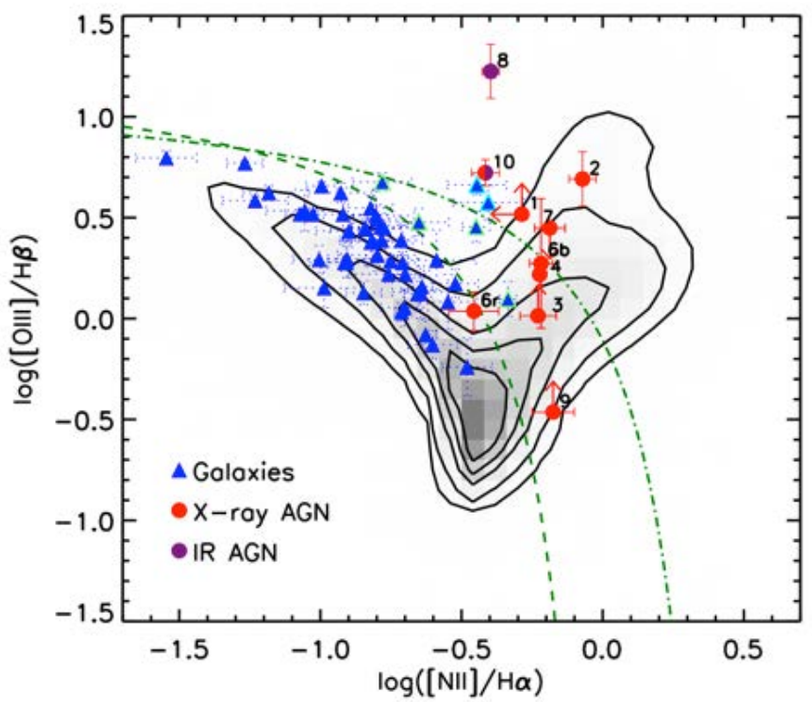
Reddy et al. 2015

Galaxy Kinematics at z~2



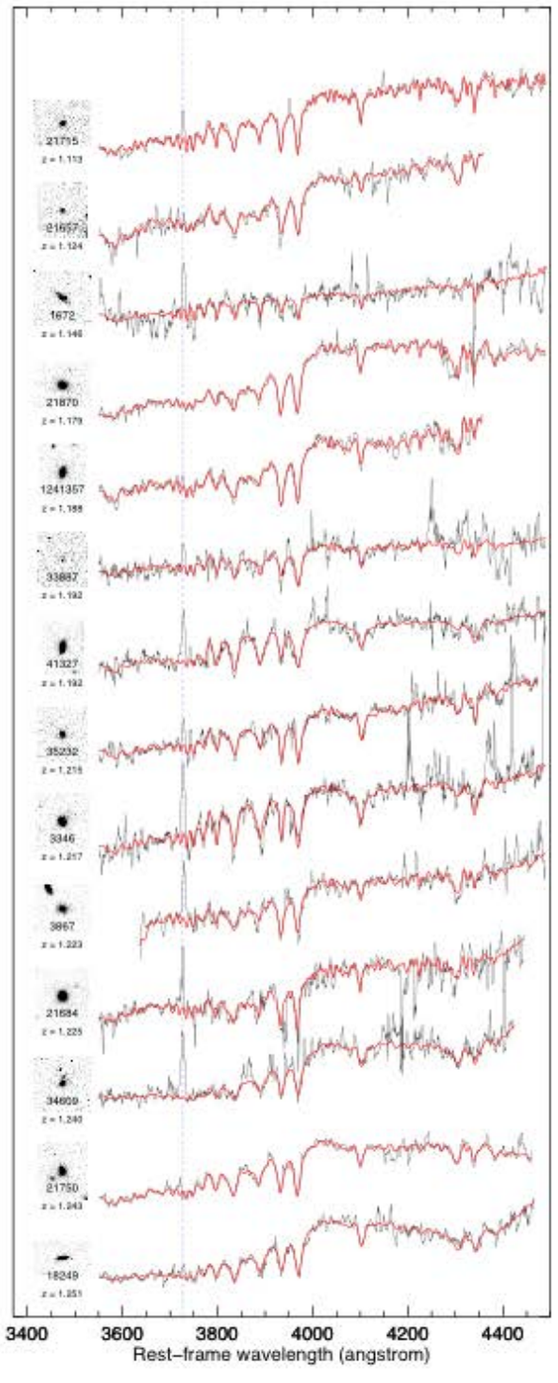
Price et al. 2015

AGN Diagnostics at z~2



Coil et al. 2015

Keck deep spectroscopy at z > 1



LRIS

1 < z < 1.6

56 galaxies

CANDELS fields

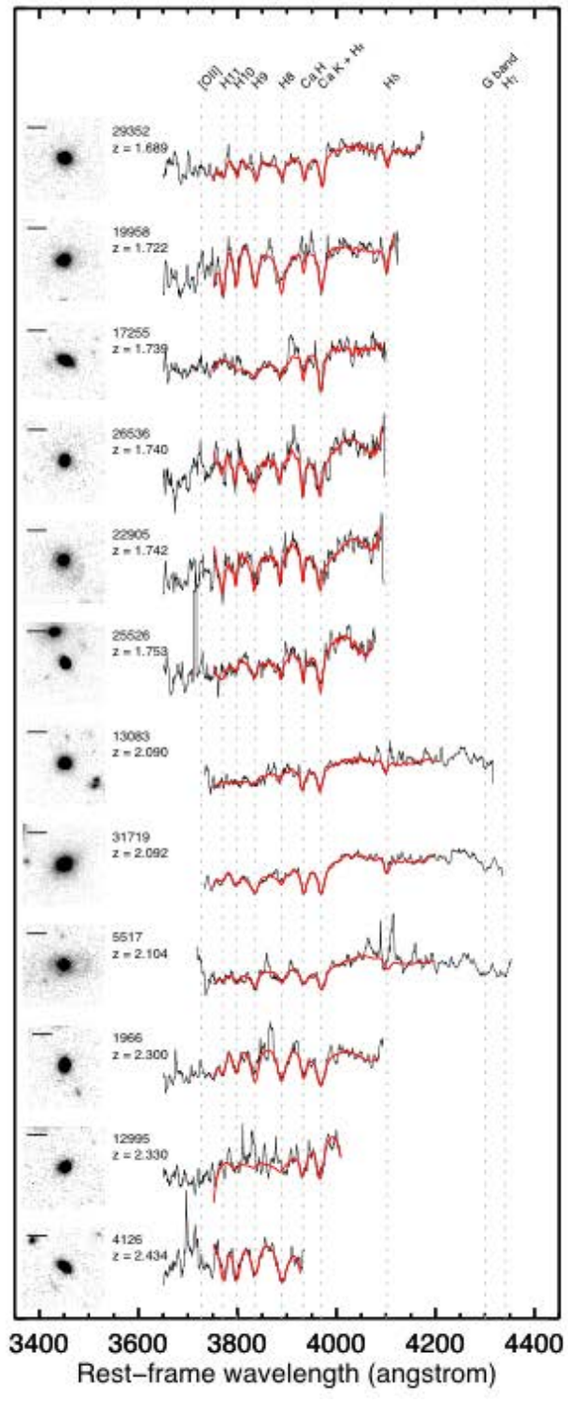
5 - 10 hours

2010 - 2015

MOSFIRE

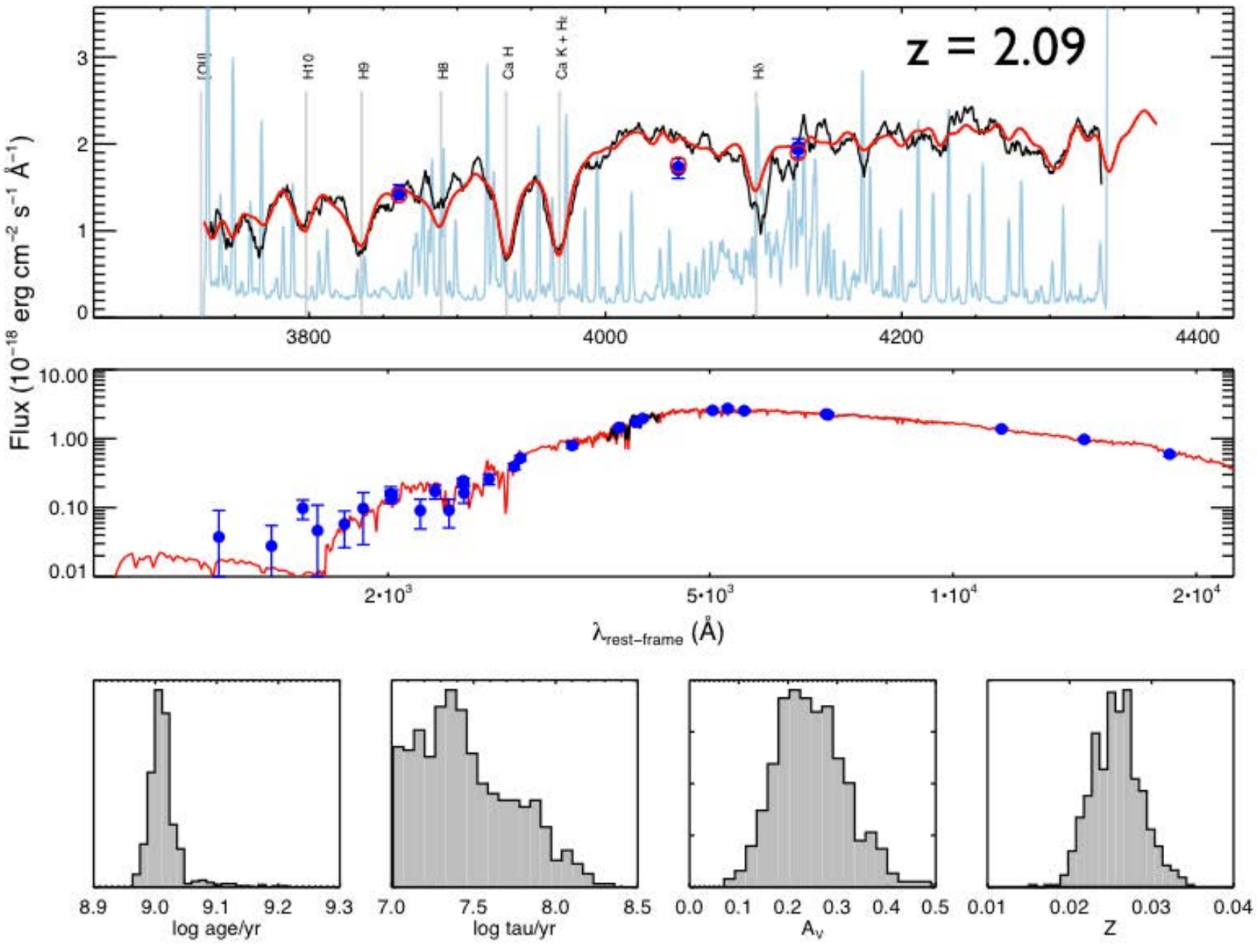
1.5 < z < 2.5

~30 galaxies



From Sirio Belli

Stellar populations at z ~ 2



Keck MOSFIRE spectrum

CANDELS / 3D-HST photometry

posterior distributions obtained with **pyspecfit** (Newman et al. 2014)

From Sirio Belli

Galaxy Growth and Quenching

Less focus on major mergers as primary driver of galaxy evolution

Minor Mergers and Secular Evolution

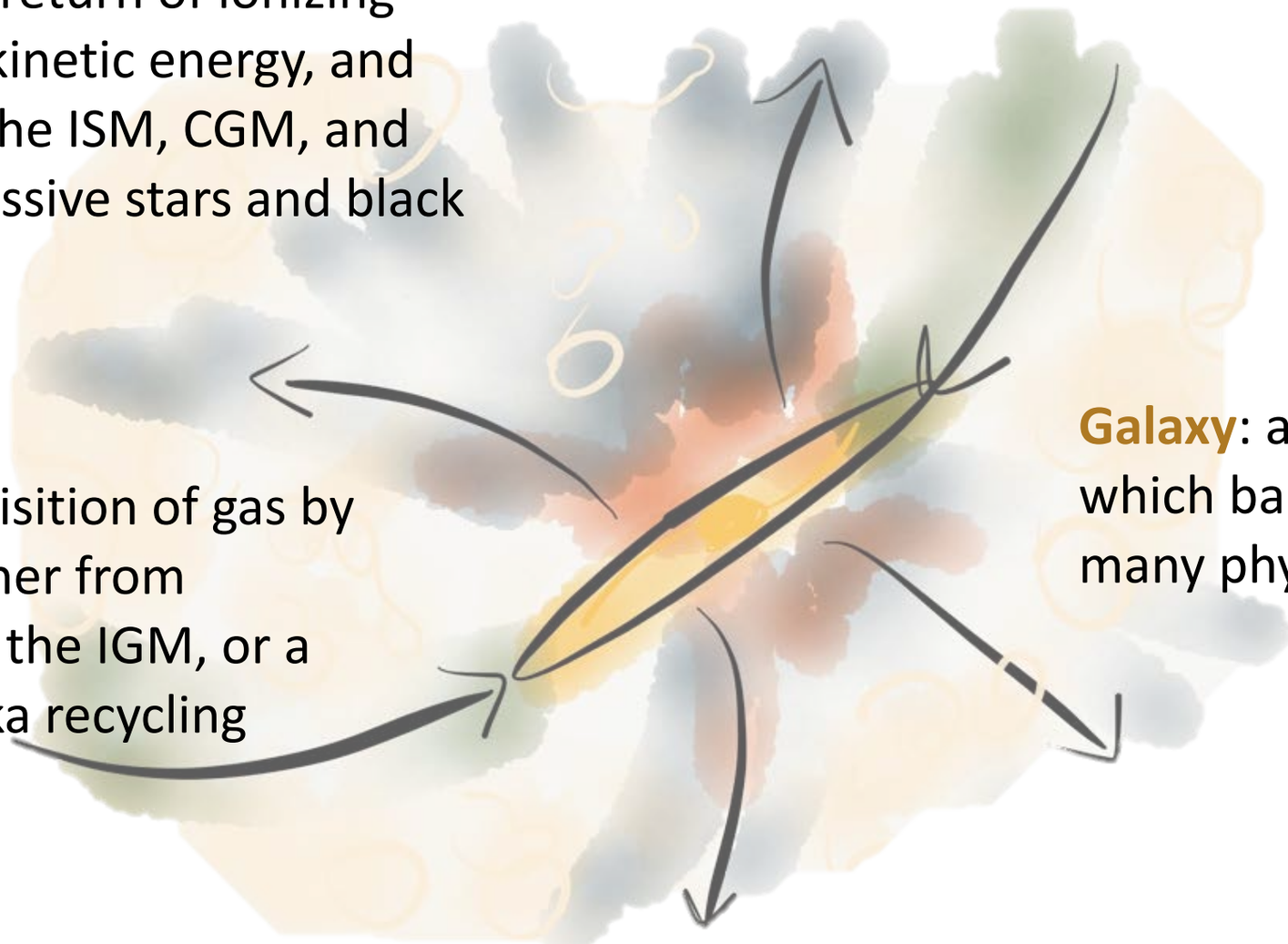
Inside-out galaxy growth

Bulge formation precedes quenching

Two modes / timescales for quenching

Born of Violence, Living in Turmoil

Feedback: return of ionizing radiation, kinetic energy, and metals to the ISM, CGM, and IGM by massive stars and black holes



Accretion: An acquisition of gas by the galaxy disk, either from satellites, mergers, the IGM, or a galactic fountain aka recycling

Galaxy: a complex system in which baryons cycle through many physical phases

CGM: Circumgalactic Medium where accreting gas meets feedback material perhaps extending to R_{vir}

Slide by Jessica Werk

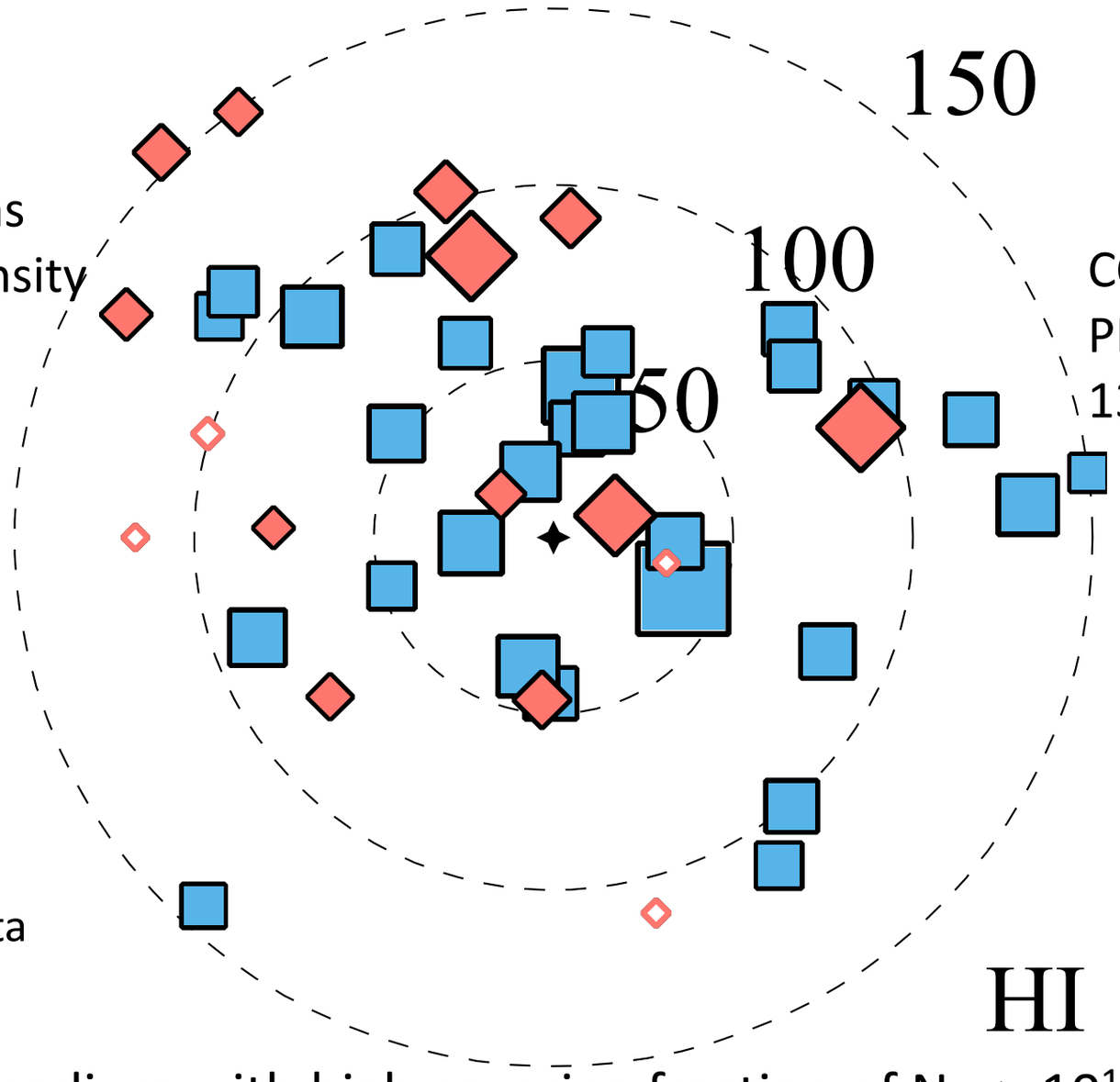
Observed Properties of the CGM: The HI Gas

= star-forming

= quiescent

= non-detections

Point size ≈ column density



COS-Halos
PI: Jason Tumlinson
134 orbits with HST/COS

Max $N_{HI} = 10^{19}$

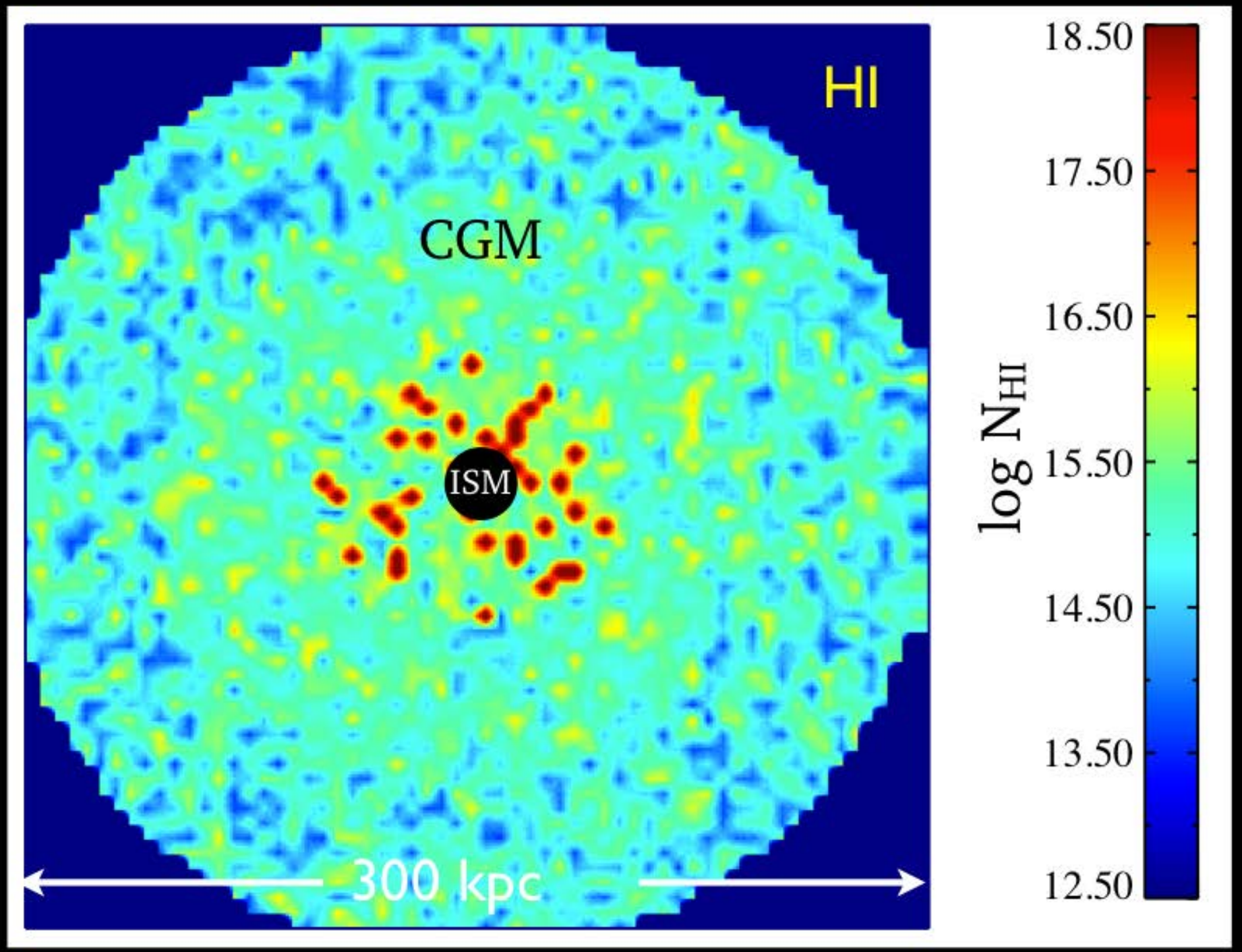
Min $N_{HI} = 10^{14.5}$

Line saturation → many of these are lower limits

NB: Blank space = no data

A cool (10^4 K) medium with high covering fraction of $N_{HI} > 10^{15}$ cm^{-2} exists around nearly every L* galaxy, **even ellipticals**, to 150 kpc.

CGM "Map"

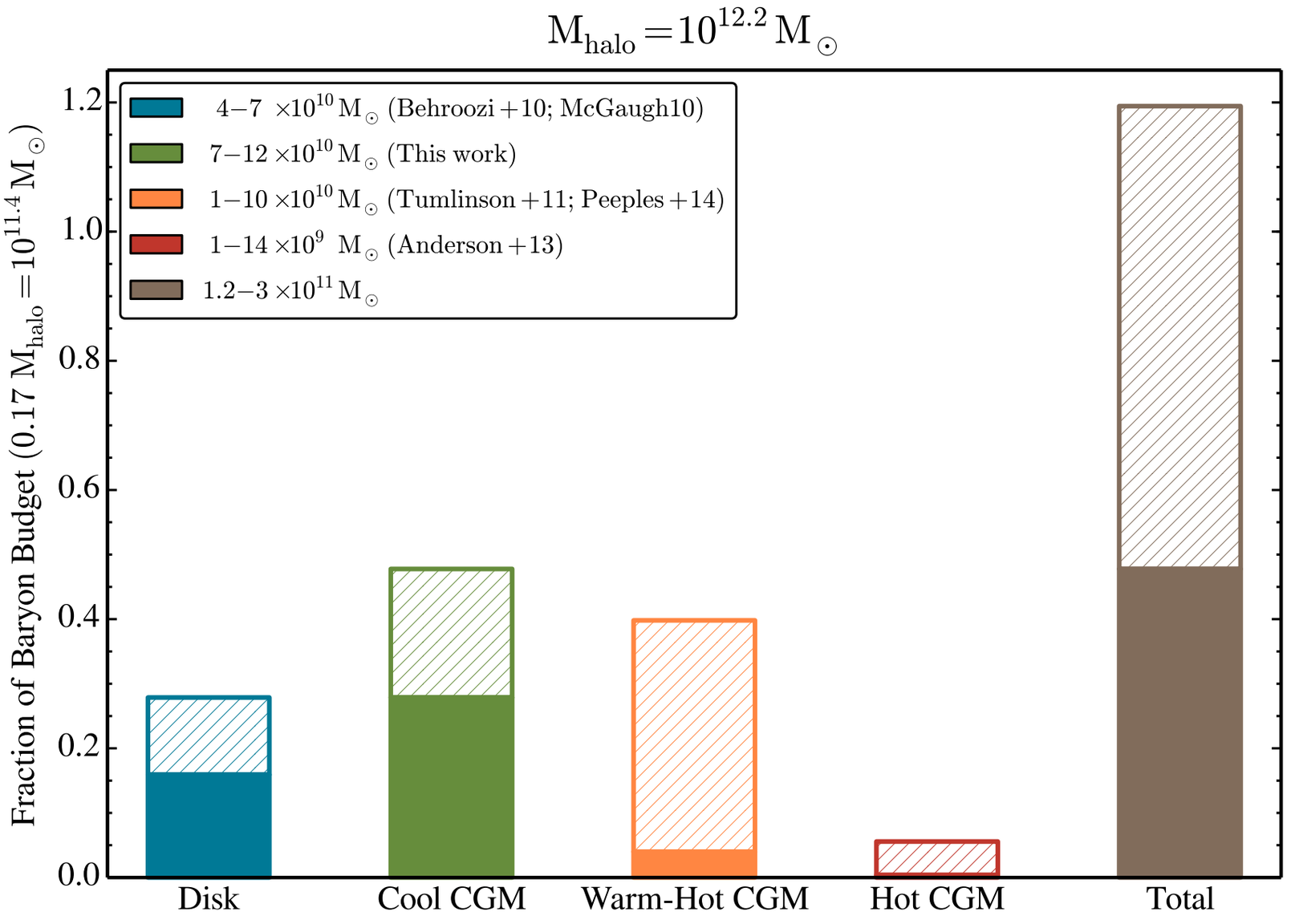


COS-Halos, COS-Dwarfs

Mass of the CGM

Werk+ 2014:
$M_{CGM} > 2 \times 10^{10} M_{\odot}$

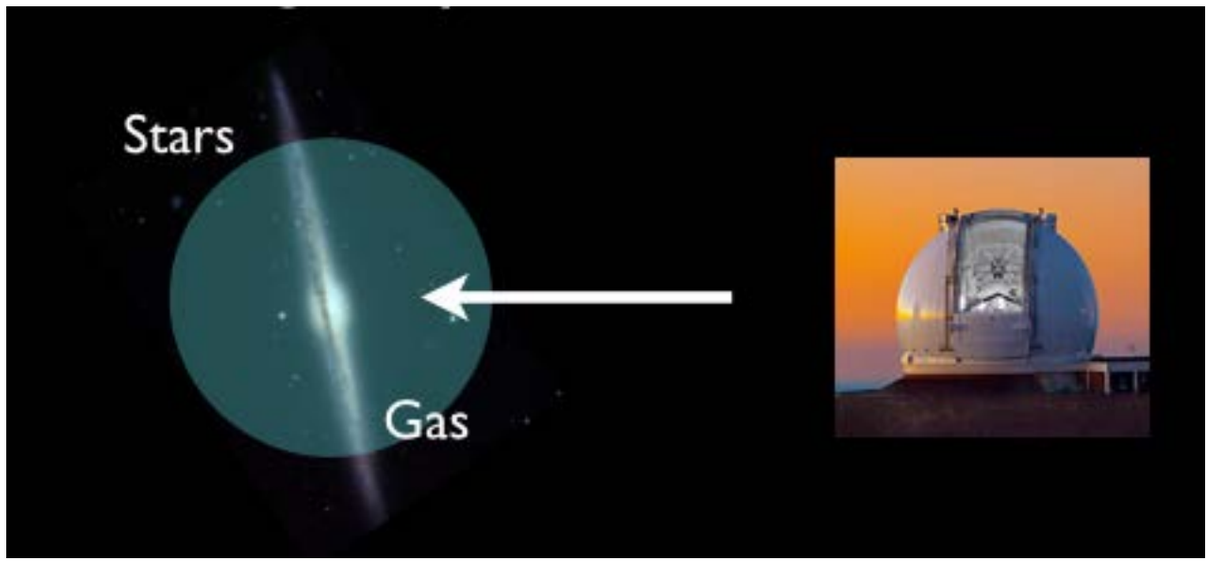
Stocke+2013:
$M_{CGM} > 10^{10} M_{\odot}$

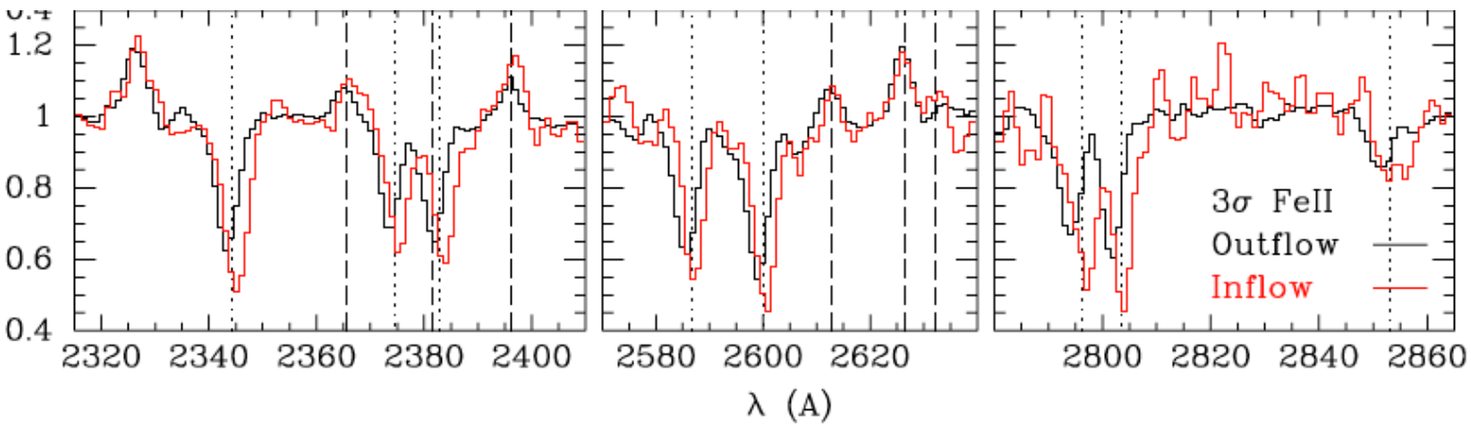


The CGM is a major reservoir of galactic baryons, containing at least as many as the disk, and within reach of closing the baryon budget around L* galaxies (Werk+14)

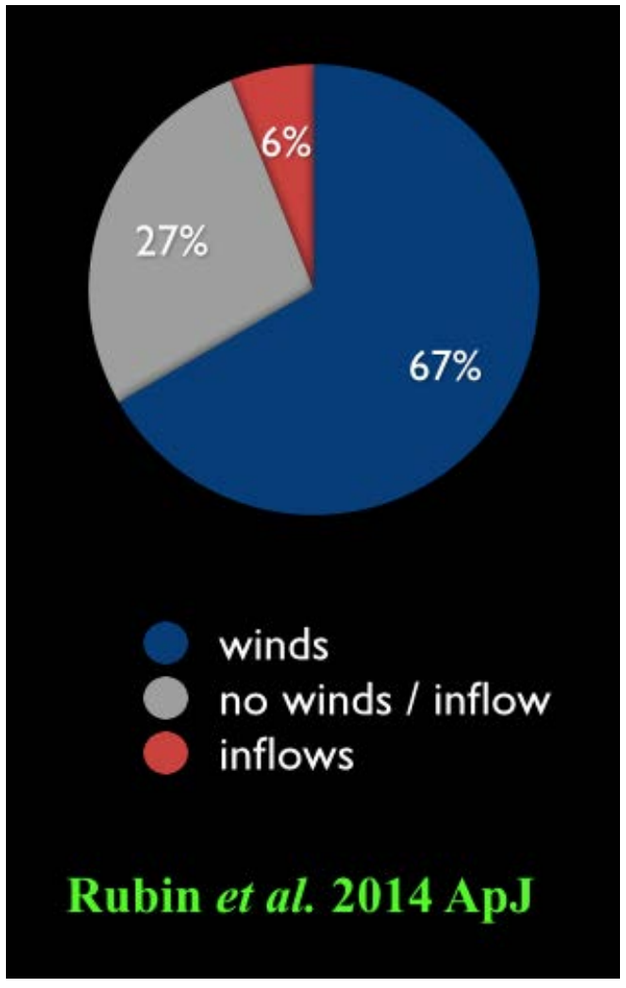
Gas Inflow Onto Galaxies

Have detected unambiguous gas inflow at z~1, using LRIS on Keck:

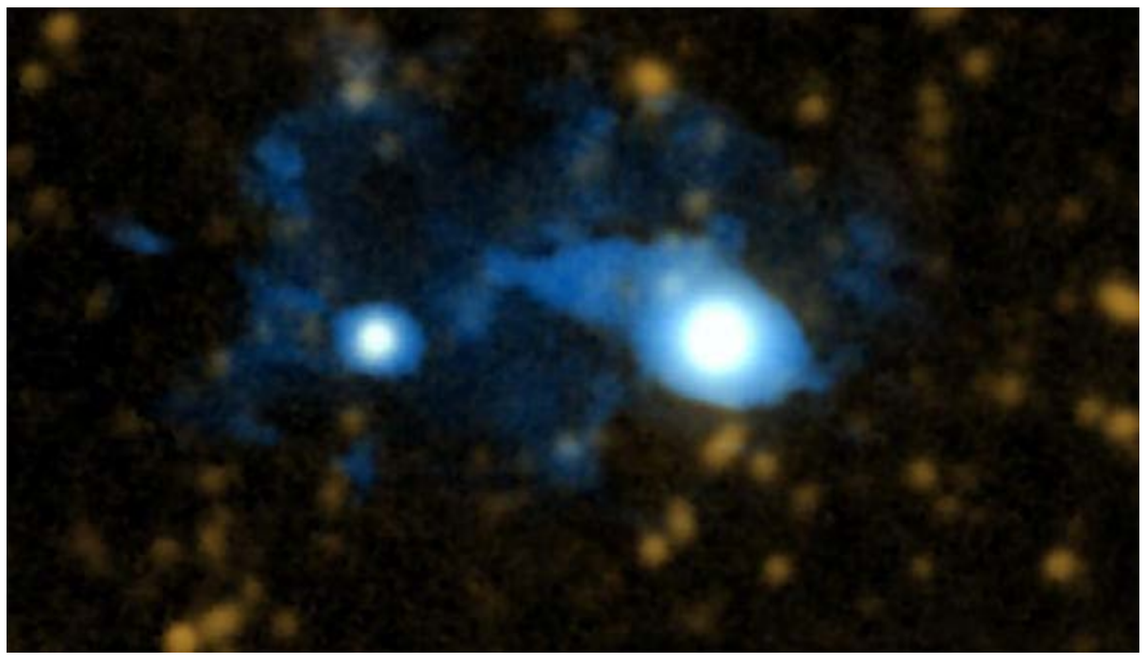




Martin et al. 2012

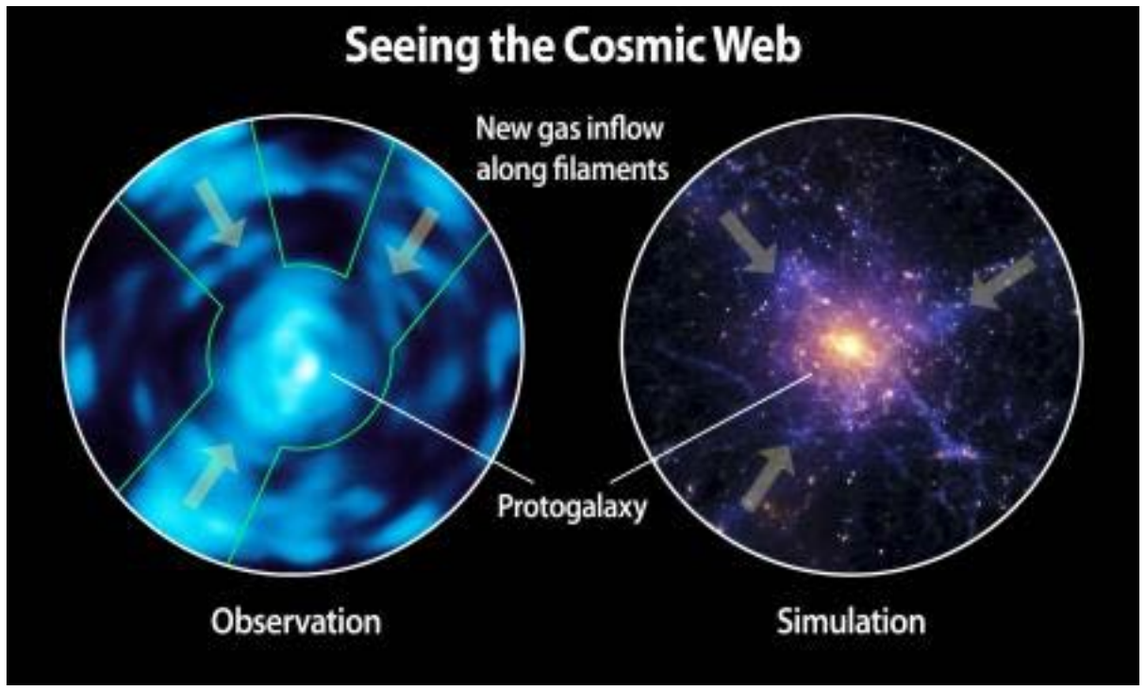


Palomar Cosmic Web Imager



Integral field spectrograph covering full optical spectrum.

Now detecting IGM in emission using Ly-alpha near quasars at $1.5 < z < 4$.



Beginning to map filaments of cold gas between galaxies, watch gas accretion in action (velocity gradients along filaments).

Upcoming Keck Cosmic Web Imager will probe low surface brightness IGM gas.

Martin et al. 2015

AGN Demographics and Fueling

Host demographics don't argue for AGN quenching star formation, in that AGN are found in all types of galaxies - little dependence on stellar mass, found in roughly similar fraction of star-forming and quiescent galaxies (even bulge-less galaxies!).

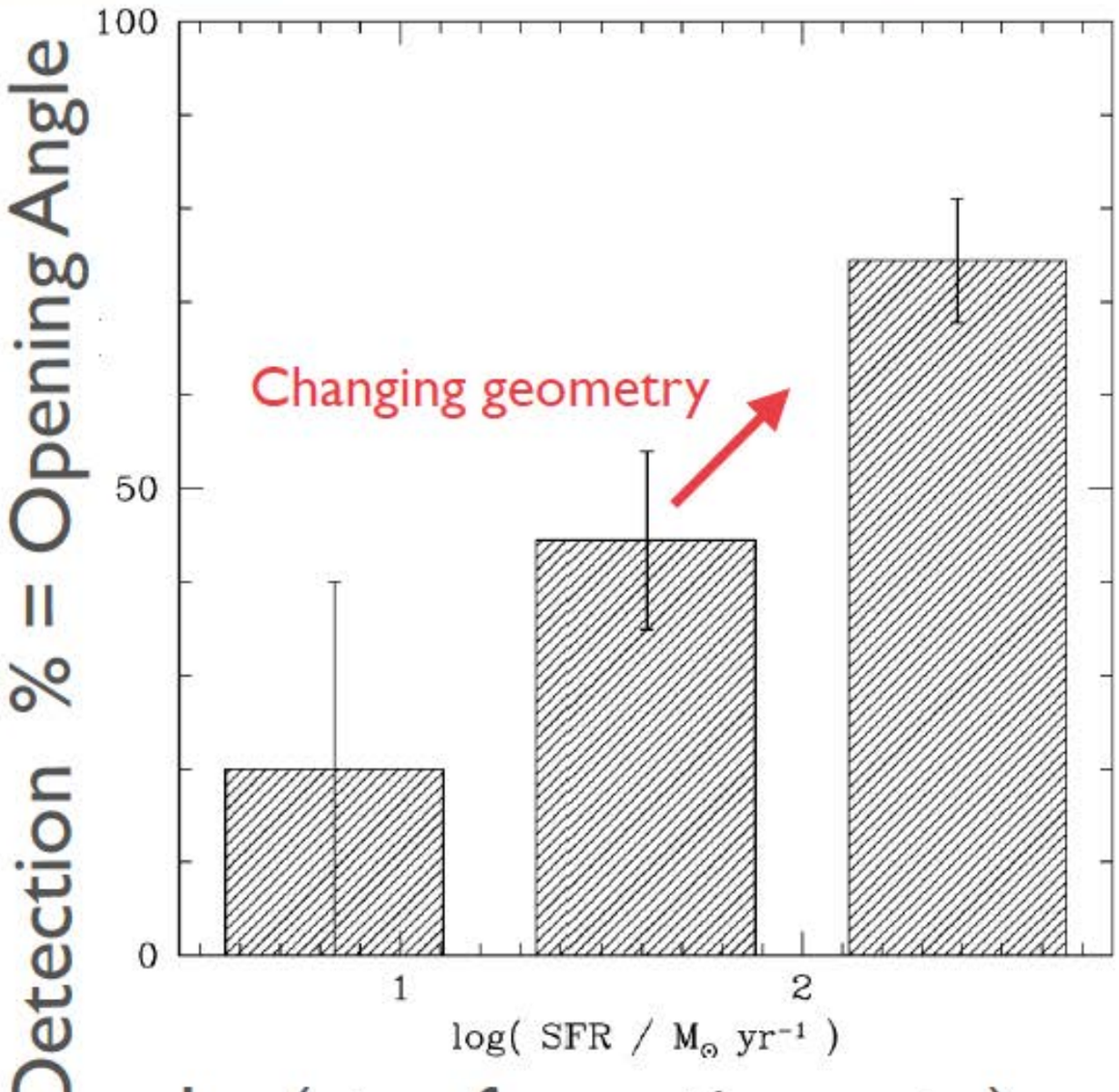
Major mergers probably most relevant for fueling quasars, not moderate-luminosity AGN.

Weak correlations are seen between SFR and AGN activity.

The big open question is whether AGN-driven feedback is important for quenching star formation…

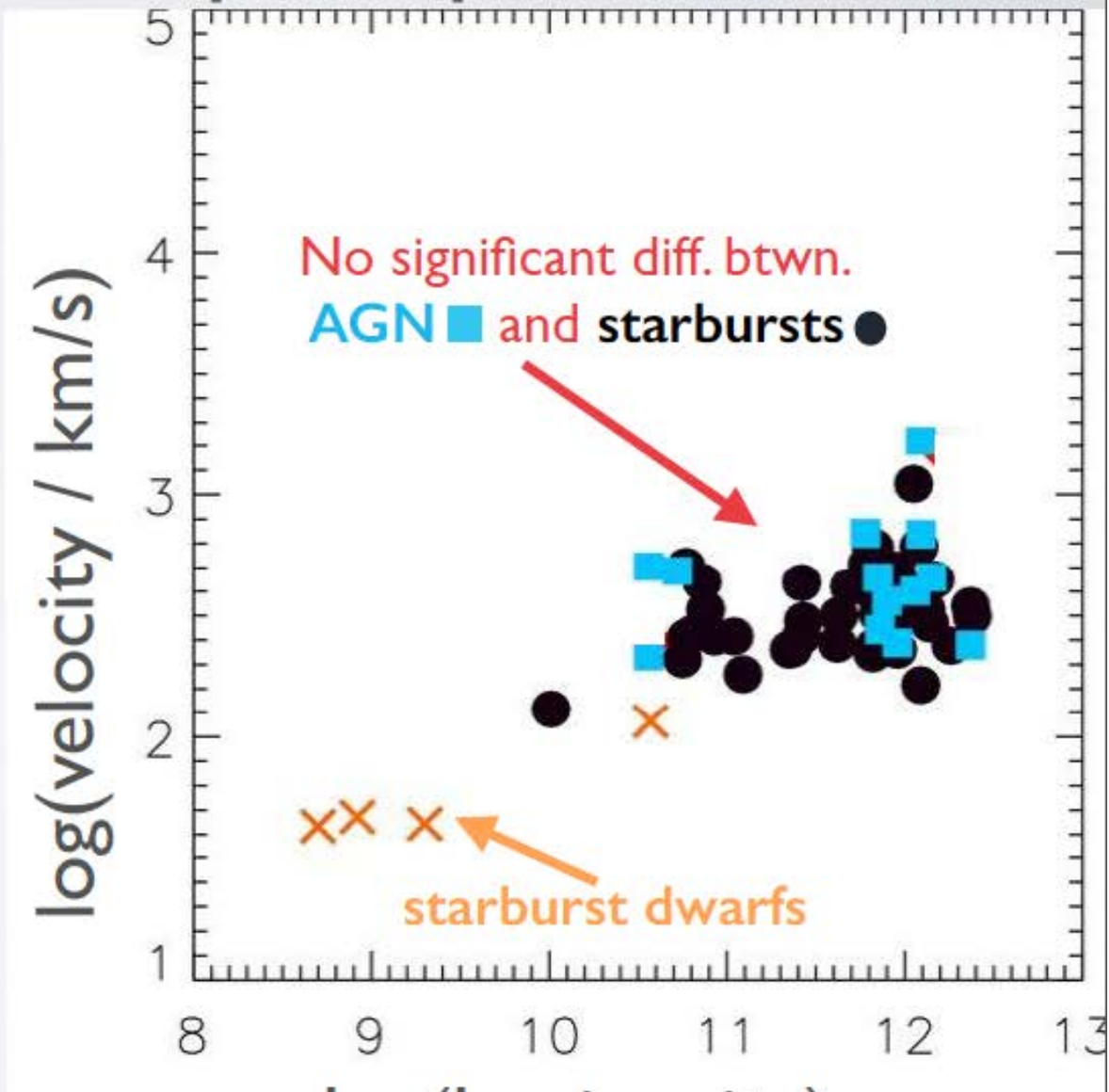
WHERE WE WERE 5 YEARS AGO

Outflows, outflows everywhere …



Heckman+00, Rupke+02, 05abc, Martin 05, 06

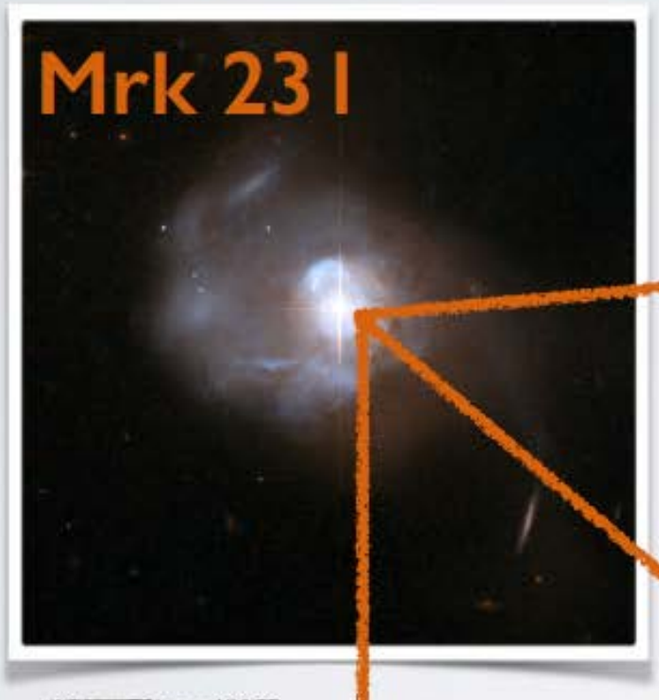
… but not a drop of quasar power to drink.

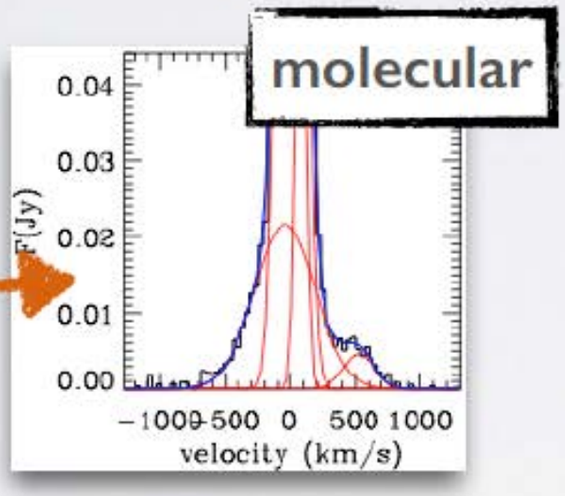


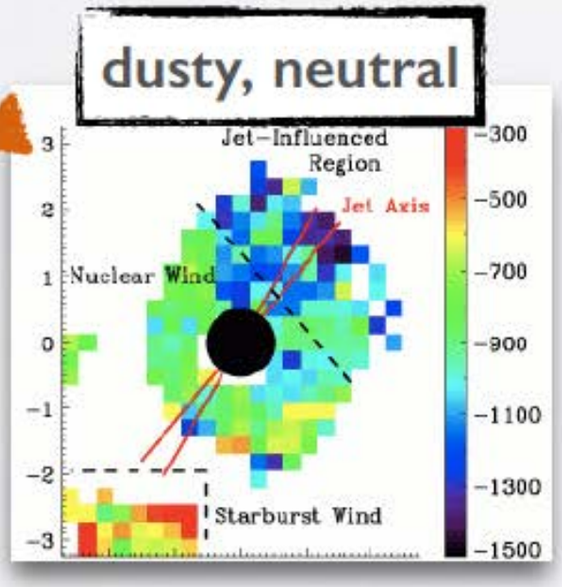
Schwartz+04, Martin 05, Rupke+05abc, Krug+10

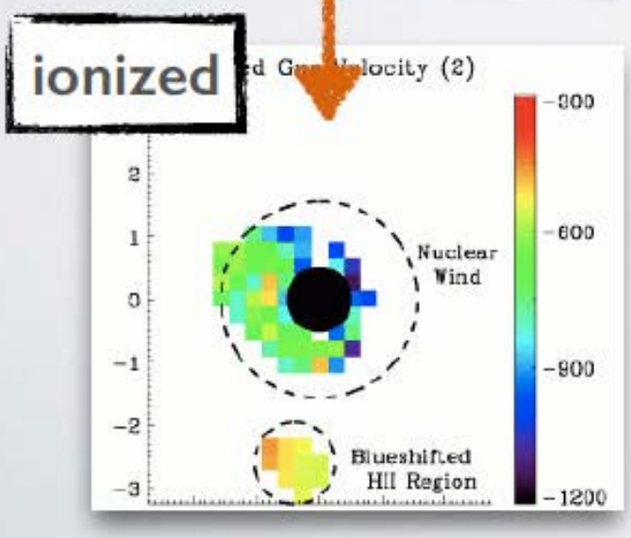
WHERE WE ARE TODAY (THANKS IN PART TO IFS)

Multiphase outflows everywhere … **… driven by quasars.**

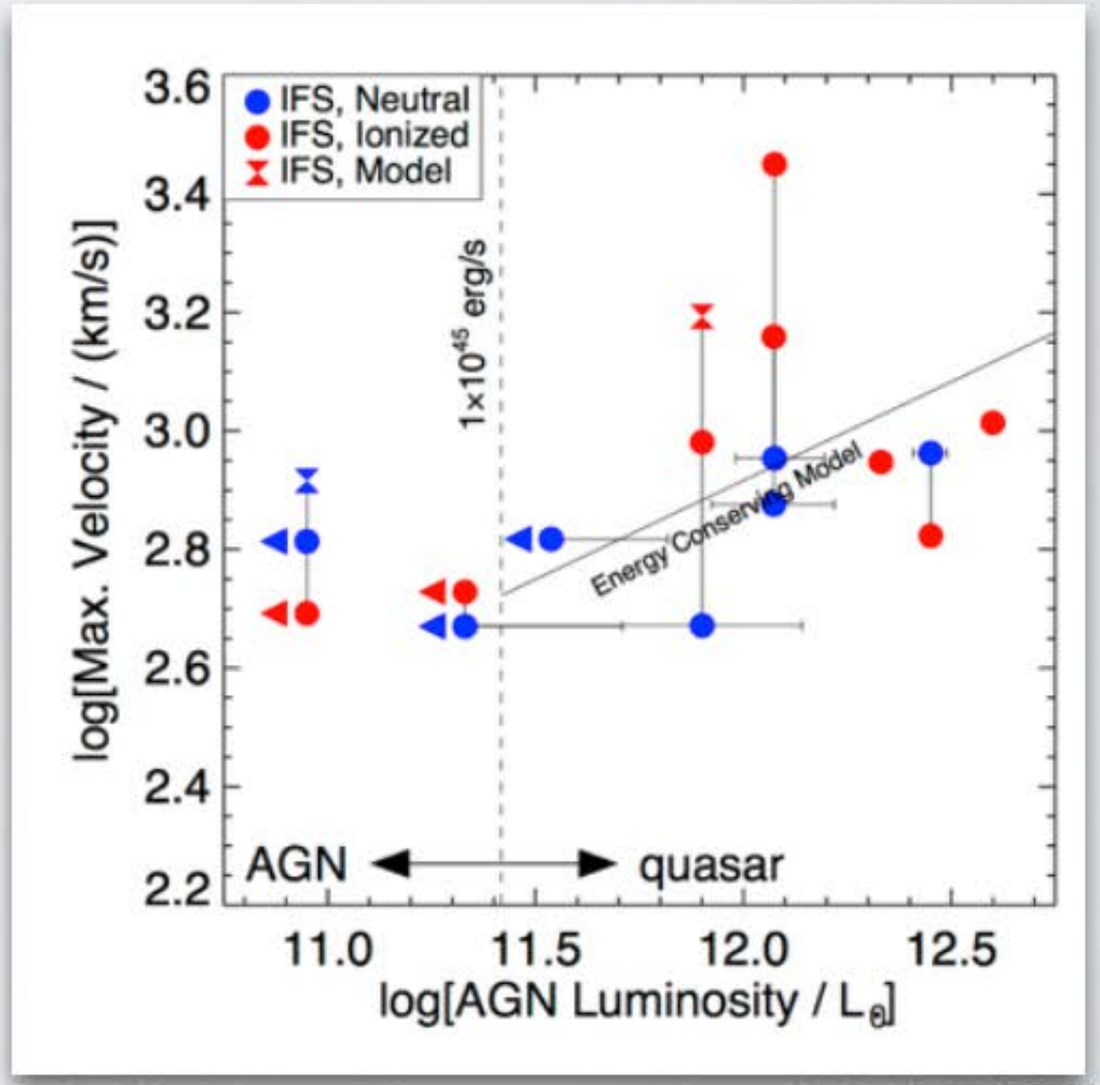








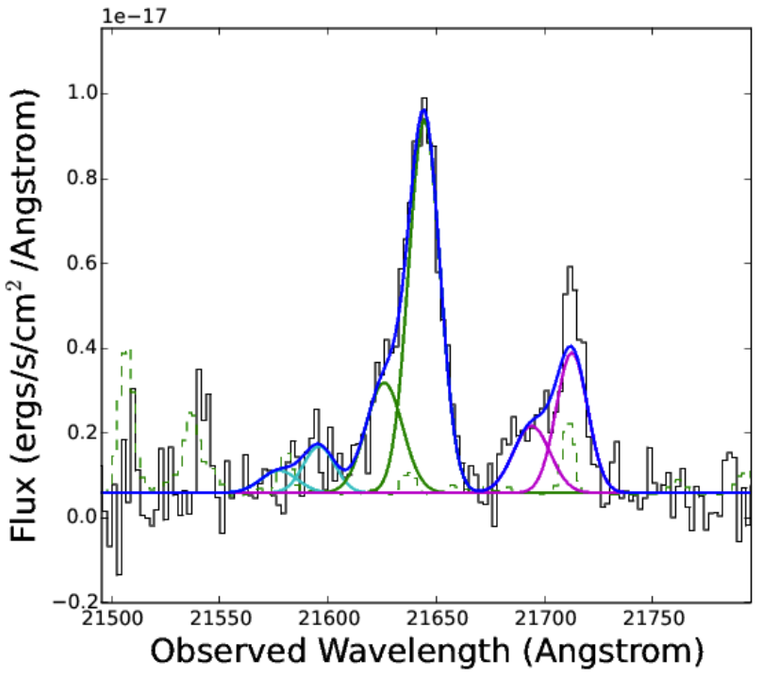
Rupke+Veilleux 11, Cicone+12, Armus+09, Kim+13 (pictured) … and lots more!

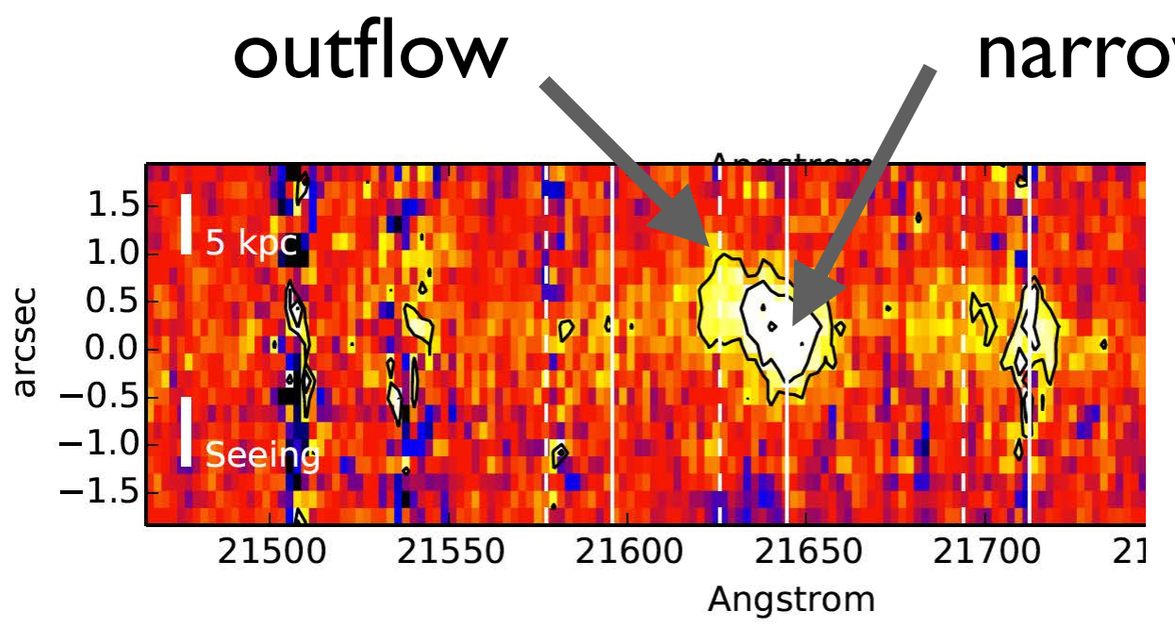


data: Rupke+Veilleux 11, 13a, Rupke+15 in prep.
models: Zubovas+King 2012

AGN Outflows

Now at z~2 can study moderate-luminosity AGN-driven outflows using NIR multi-slit spectrographs and IFUs:
incidence, kinematics, physical extent





Leung et al. in prep

Find a high incidence of AGN-driven outflows that are galaxy wide, in typical star-forming galaxies.

Summary

The multi-wavelength deep fields with HST imaging have led to big changes!

- probing epoch of reionization with UV LFs at z>6
- stellar mass functions to z~6
- dwarf galaxies at z~3

New ways of thinking about galaxy growth and quenching: inside-out galaxy growth, importance of minor mergers, secular evolution, bulge growth precedes star formation quenching, multiple quenching timescales.

We are now studying full suite of rest-frame optical emission lines at z~2-3 in large, representative galaxy and AGN samples (>1000 sources).

Studying AGN feedback in detail (incidence, kinematics, spatial extent) in both quasar and moderate-luminosity AGN samples, out to z~2-3.