Observations that Challenge to Our Understanding of Central Galaxies

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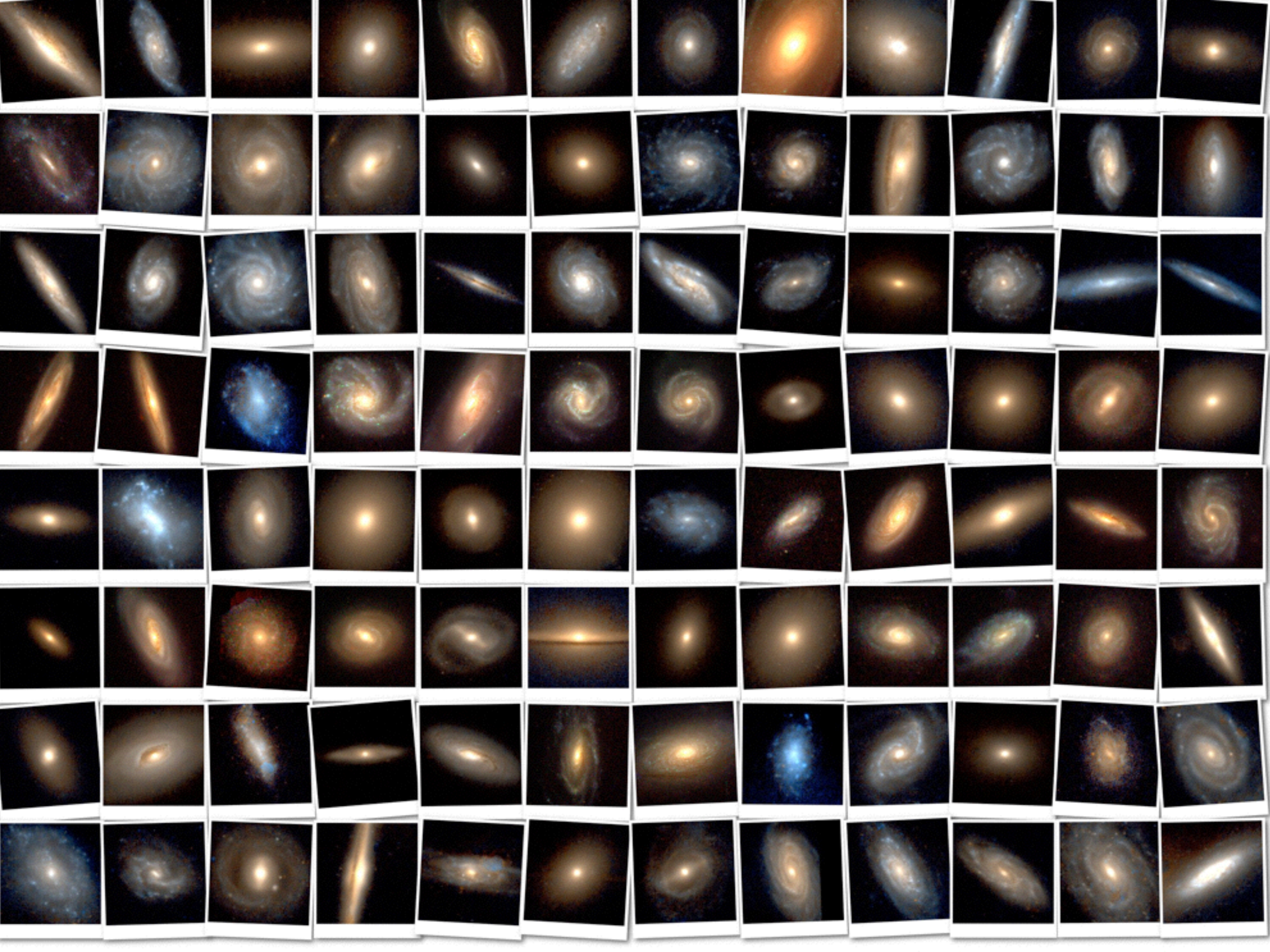
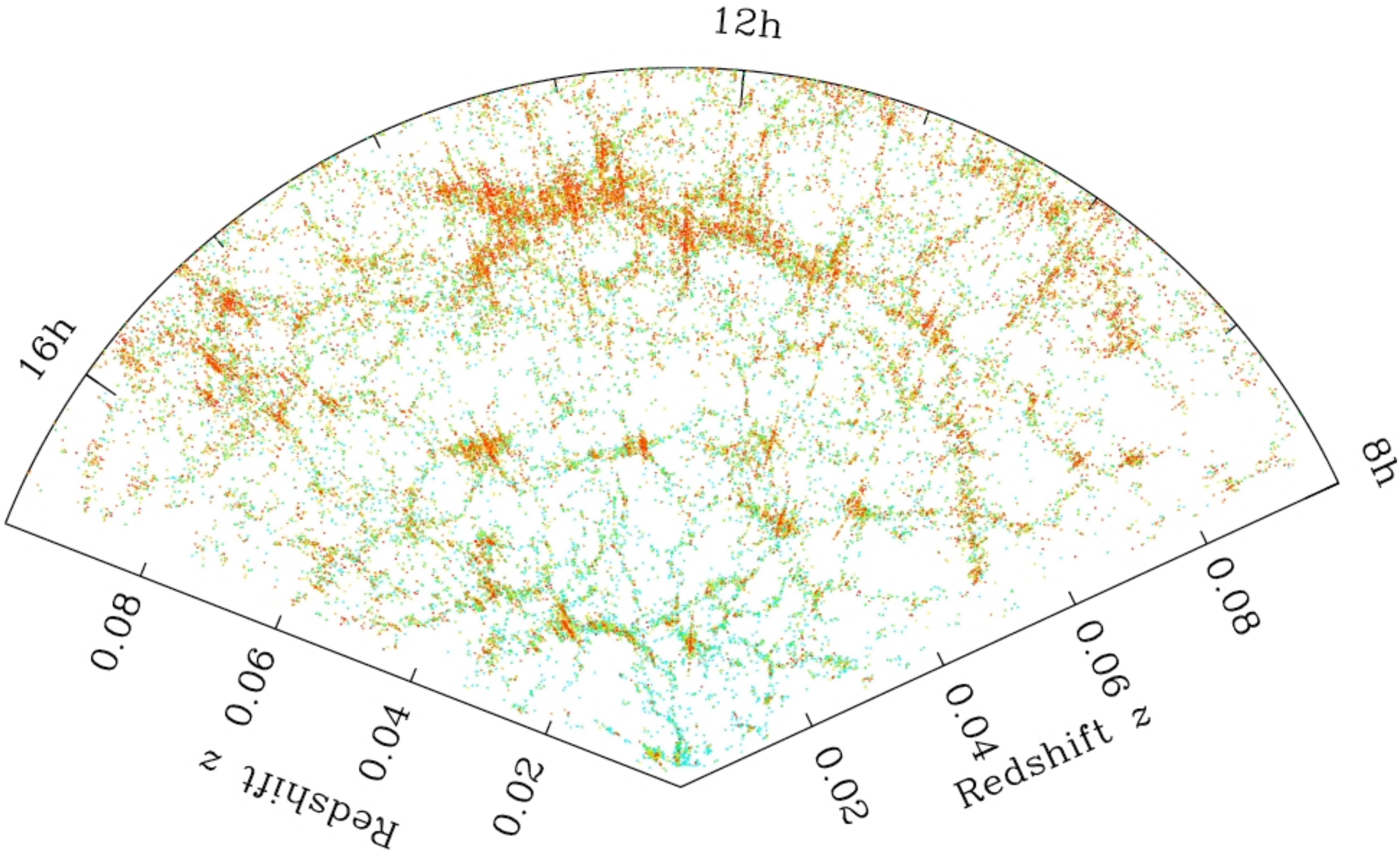
Highlights of 2014

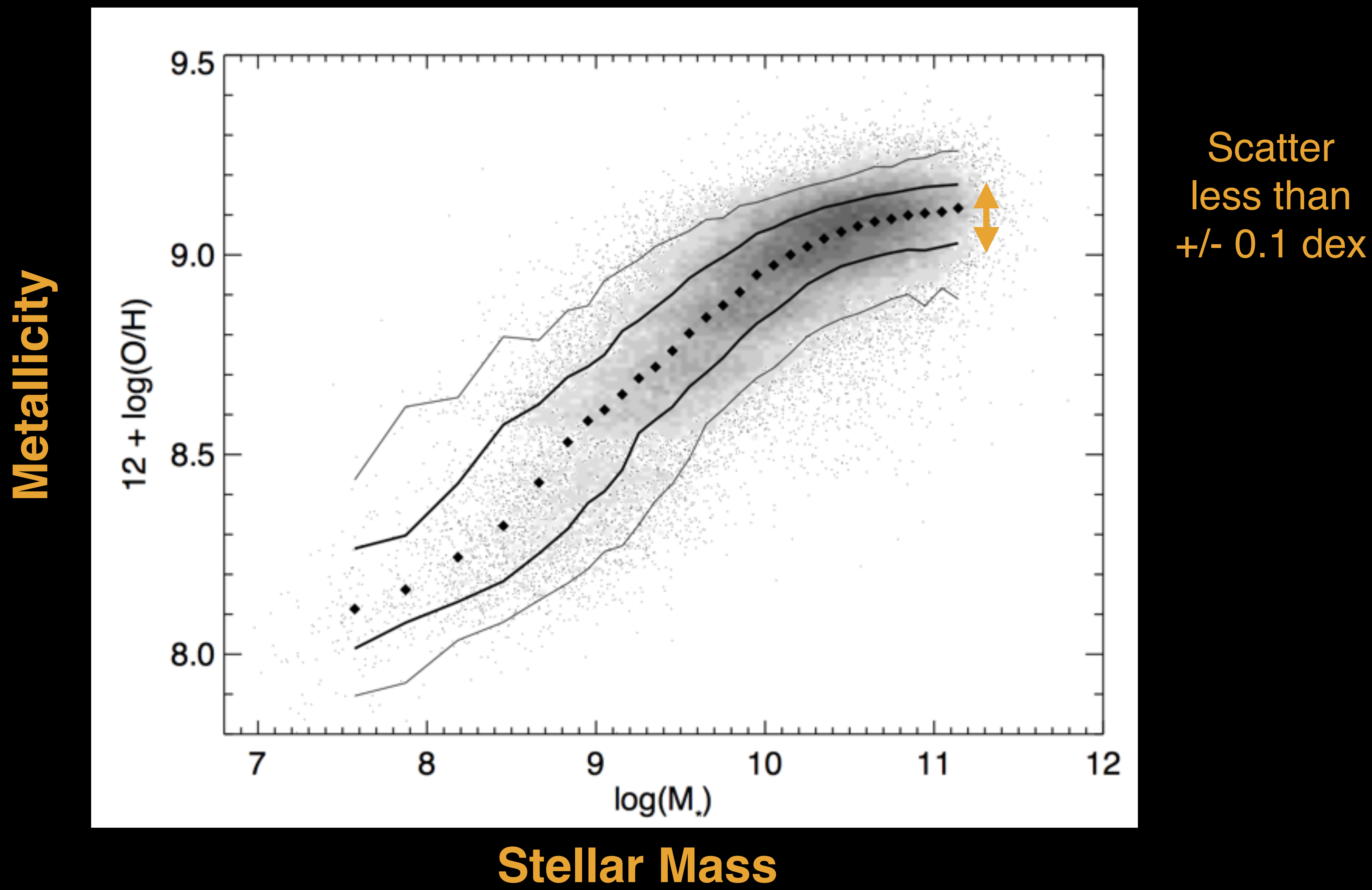
**Disclaimer: my selection has high purity
but low completeness



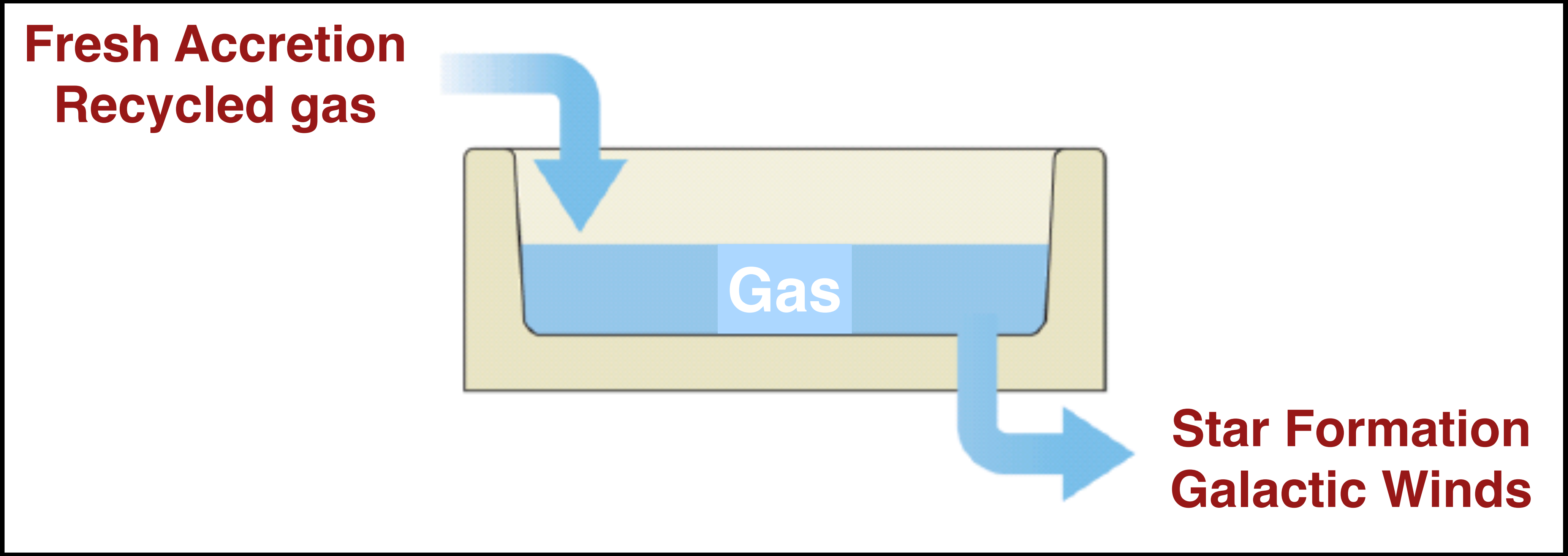


Large Scale Structure Map from the Sloan Digital Sky Survey I

Many fundamental physical parameters of galaxies are tightly correlated



The “Bathtub” Model
(equilibrium, gas regulator)



SFR ∝ Gas Mass; Outflows ∝ SFR → equilibrium

Finlator et al. 2008; Bouche et al. 2010; … Peng et al. 2014; Dekel et al. 2014

The bathtub model provide some intuition into which physical parameters are important

equilibrium timescale

$$\tau_{\mathrm{eq}} = \frac{1}{\mathrm{sSFR} \cdot (1 - R + \lambda)} \frac{f_{\mathrm{gas}}}{1 - f_{\mathrm{gas}}}$$

$\frac{\mathrm{SFR}}{M^*}$

Fraction of stellar mass that is returned promptly to the ISM

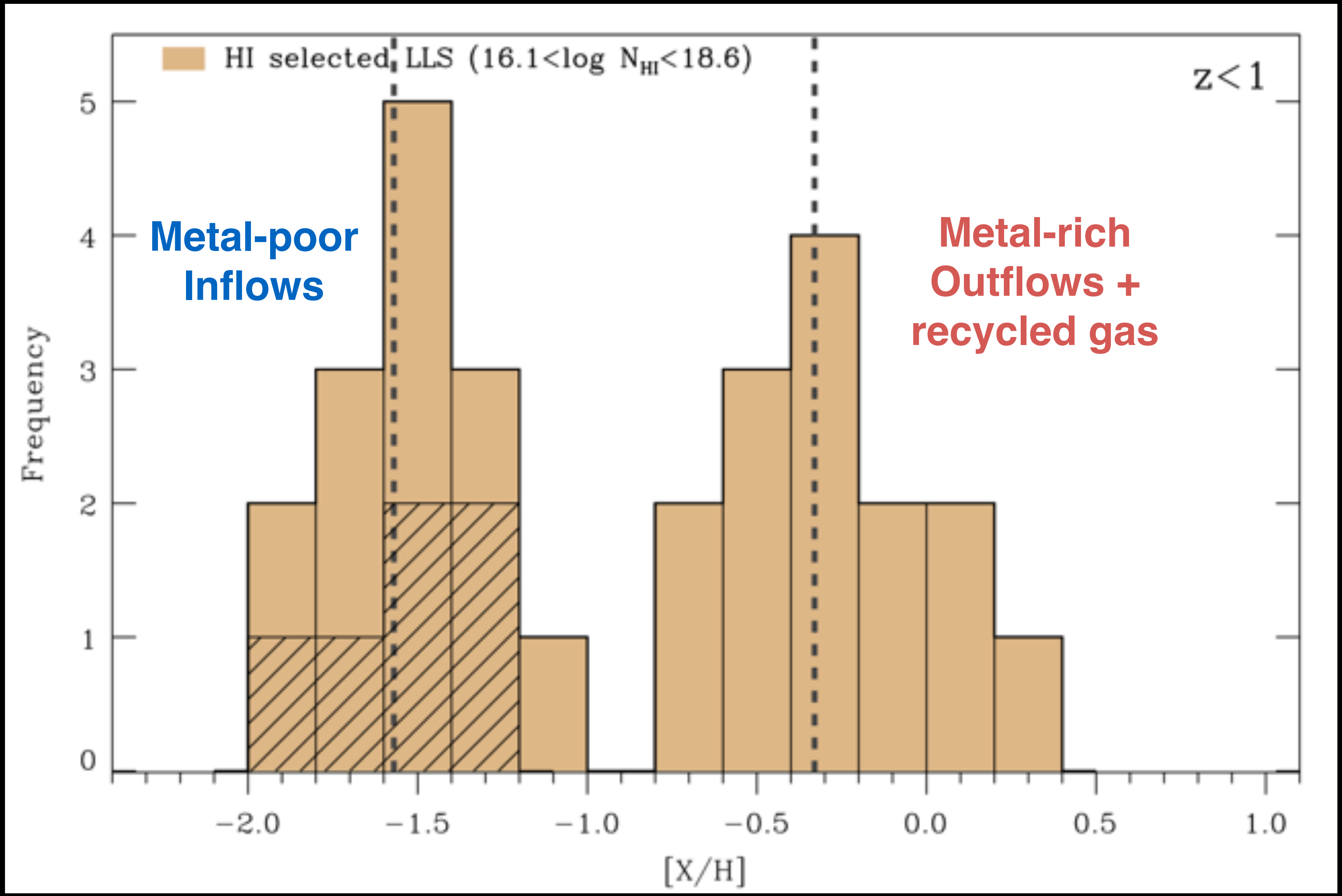
$\frac{\dot{M}_{\mathrm{out}}}{\mathrm{SFR}}$

gas fraction

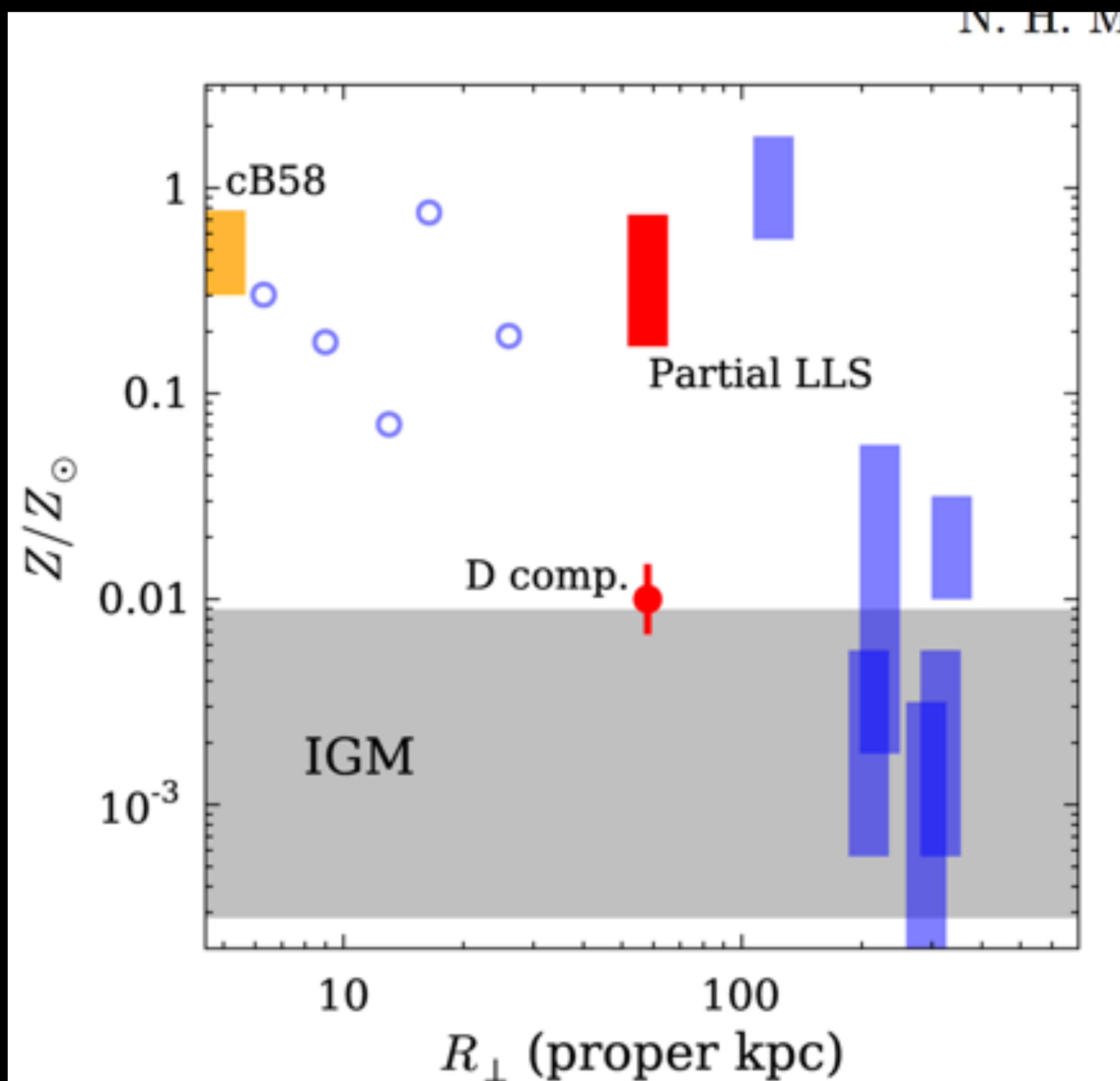
Gas accretion is difficult to directly observe - focus is on individual detections at present

(see A&A review by Sánchez Almeida+ 2014)

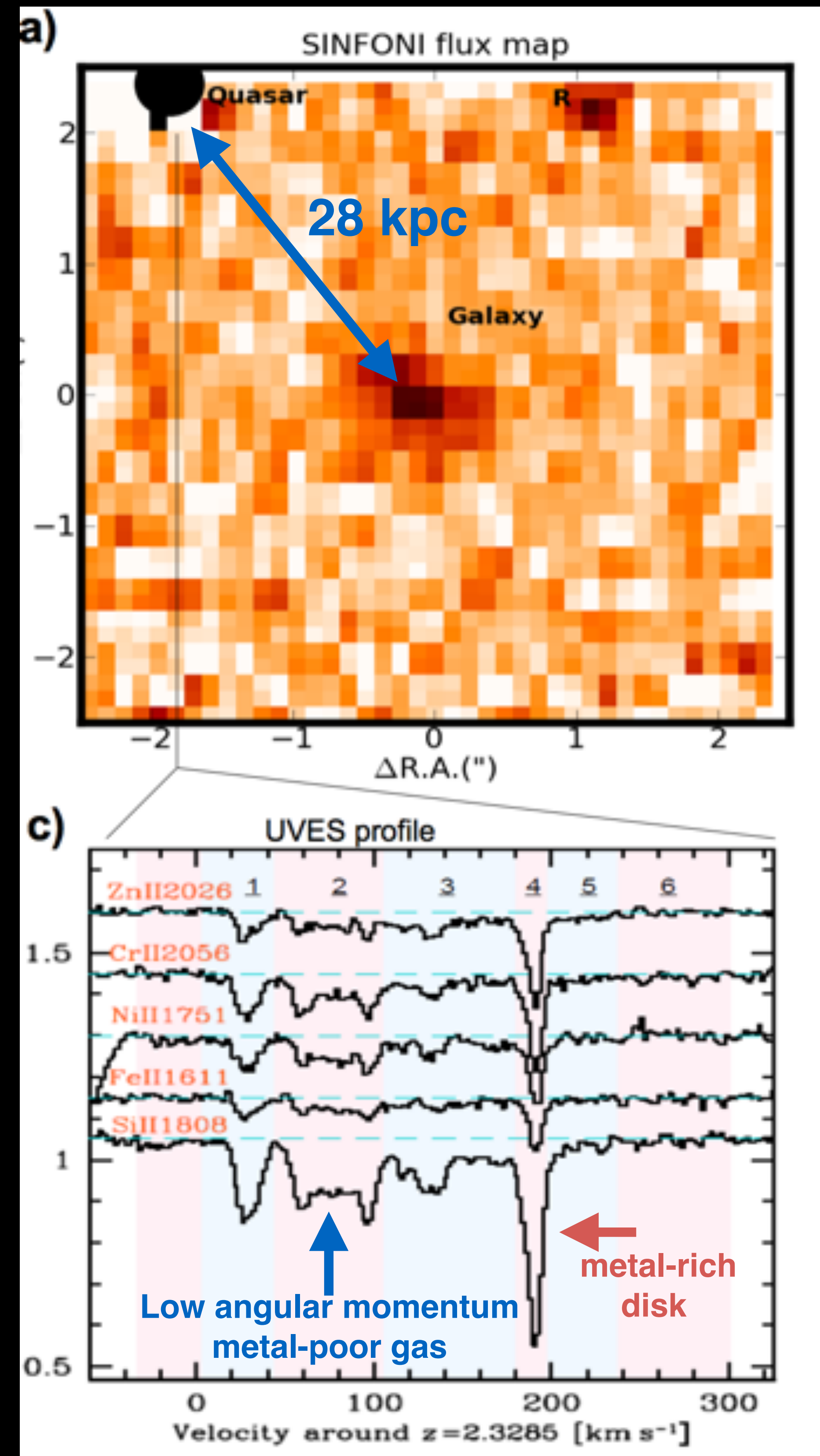
Lener+ 2013 showed that Lyman Limit Systems have a bi-modal metallicity distribution - metal poor LLS may trace accretion



The gas around z~2.5 star forming galaxies is a complex mix of metal rich and poor components

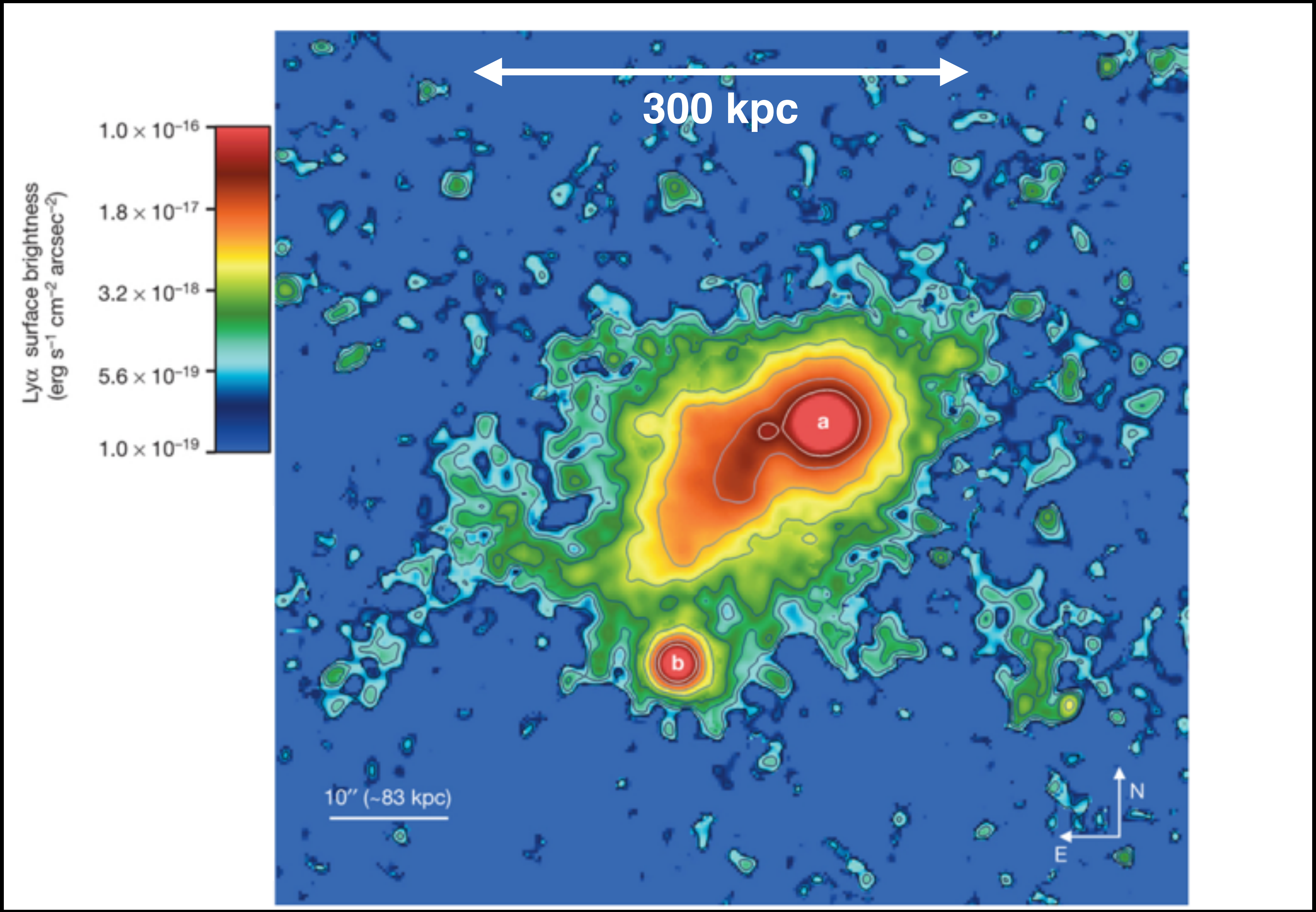


Crighton+ 2014

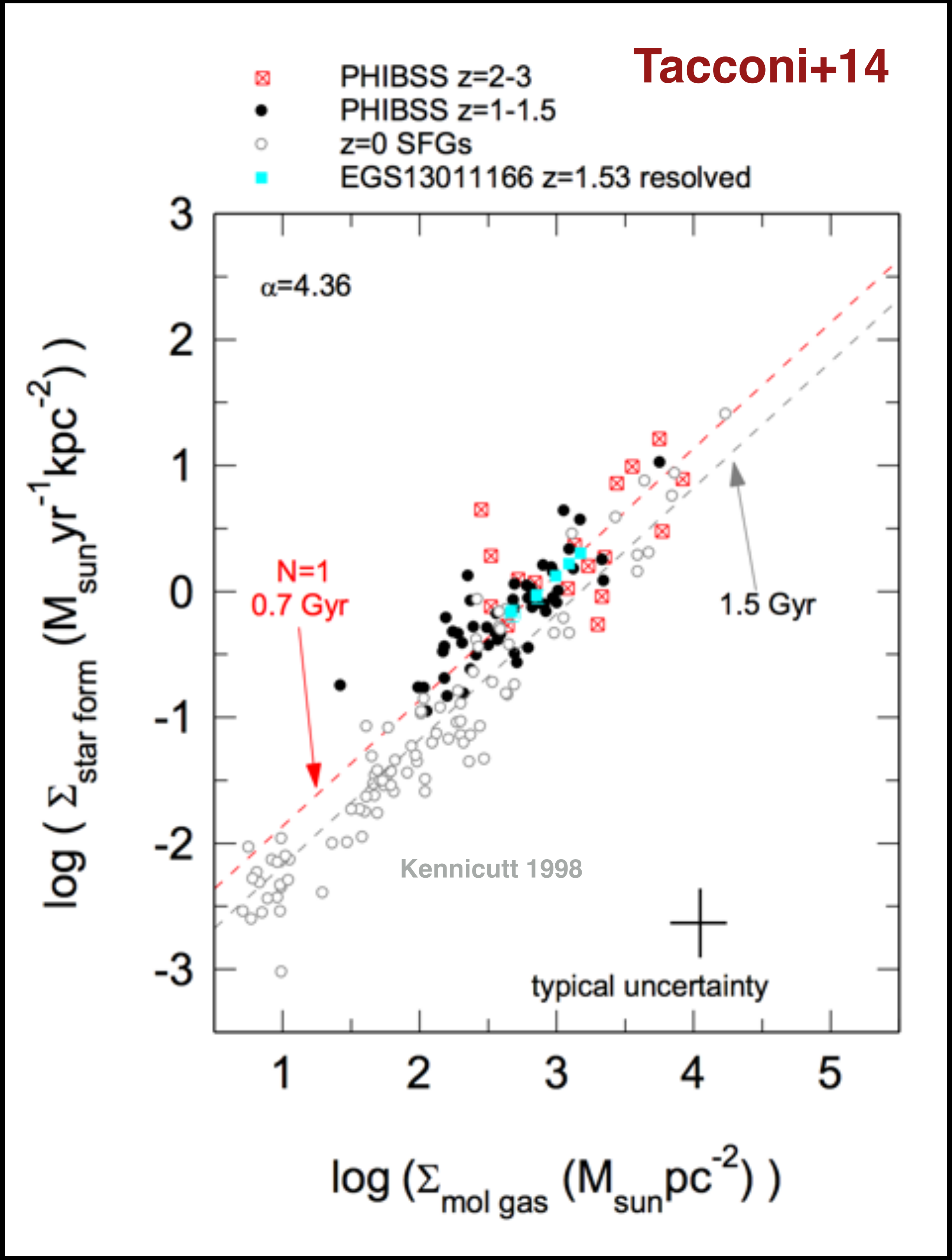


Bouche+ 2013

Intergalactic gas in Ly α emission around two quasars (Cantalupo+ 2014)



CO Measurements of normal star forming galaxies indicate redshift evolution of the Kennicutt-Schmidt relation ➔ SF efficiency higher at z>1



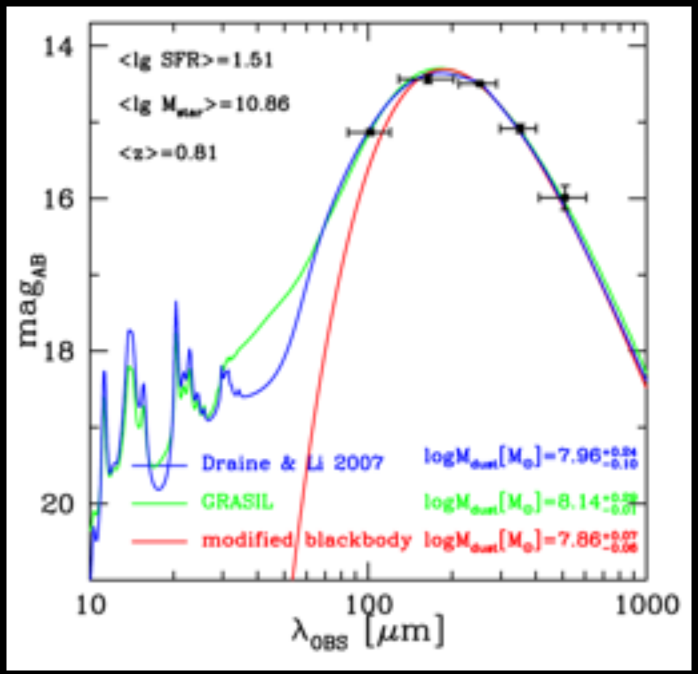
PHIBSS - IRAM PdB high-z CO 3-2 survey of 56 normal star forming galaxies:

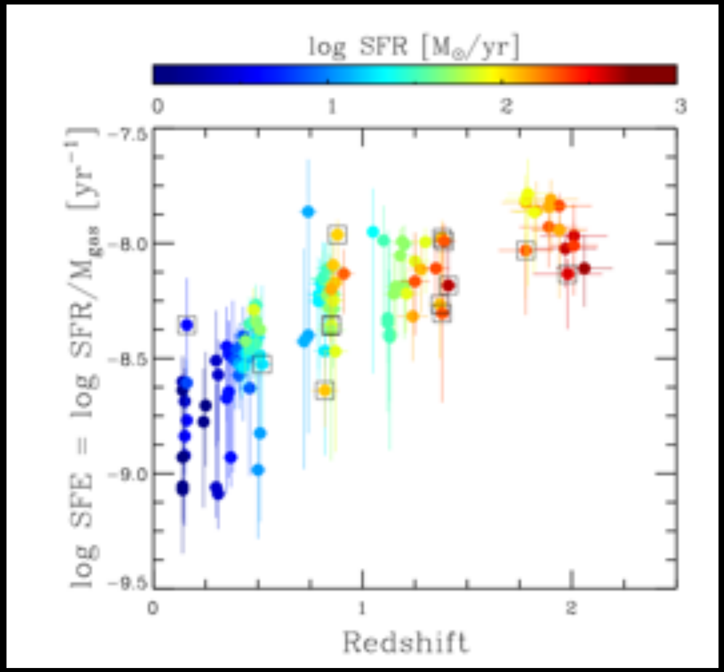
$\log(M_*) \geq 10.4$

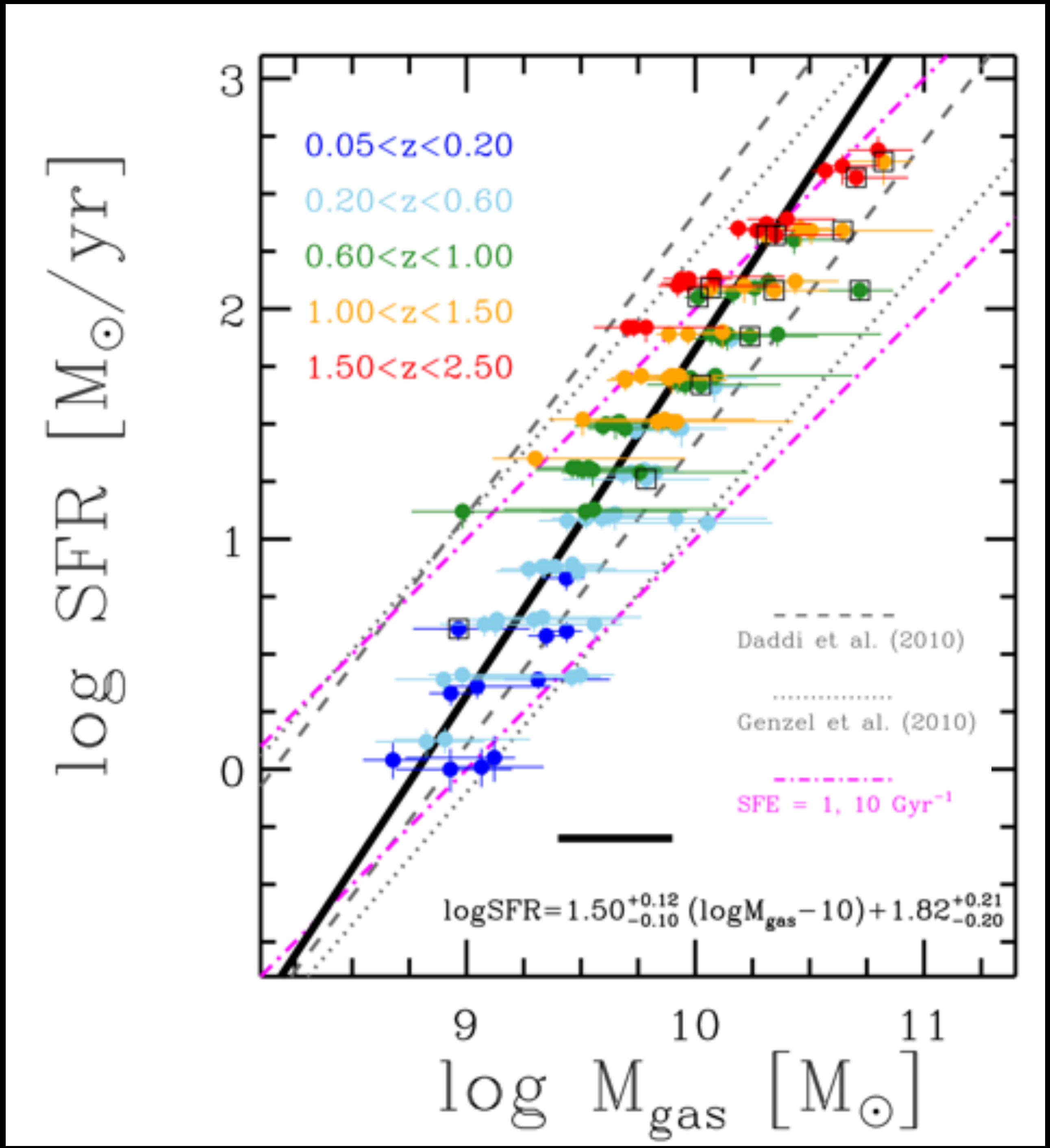
$\log(\mathrm{SFR}) \geq 1.5$.

A very similar trend is seen when dust mass is used to calculate the total gas mass (Santini+ 2014)

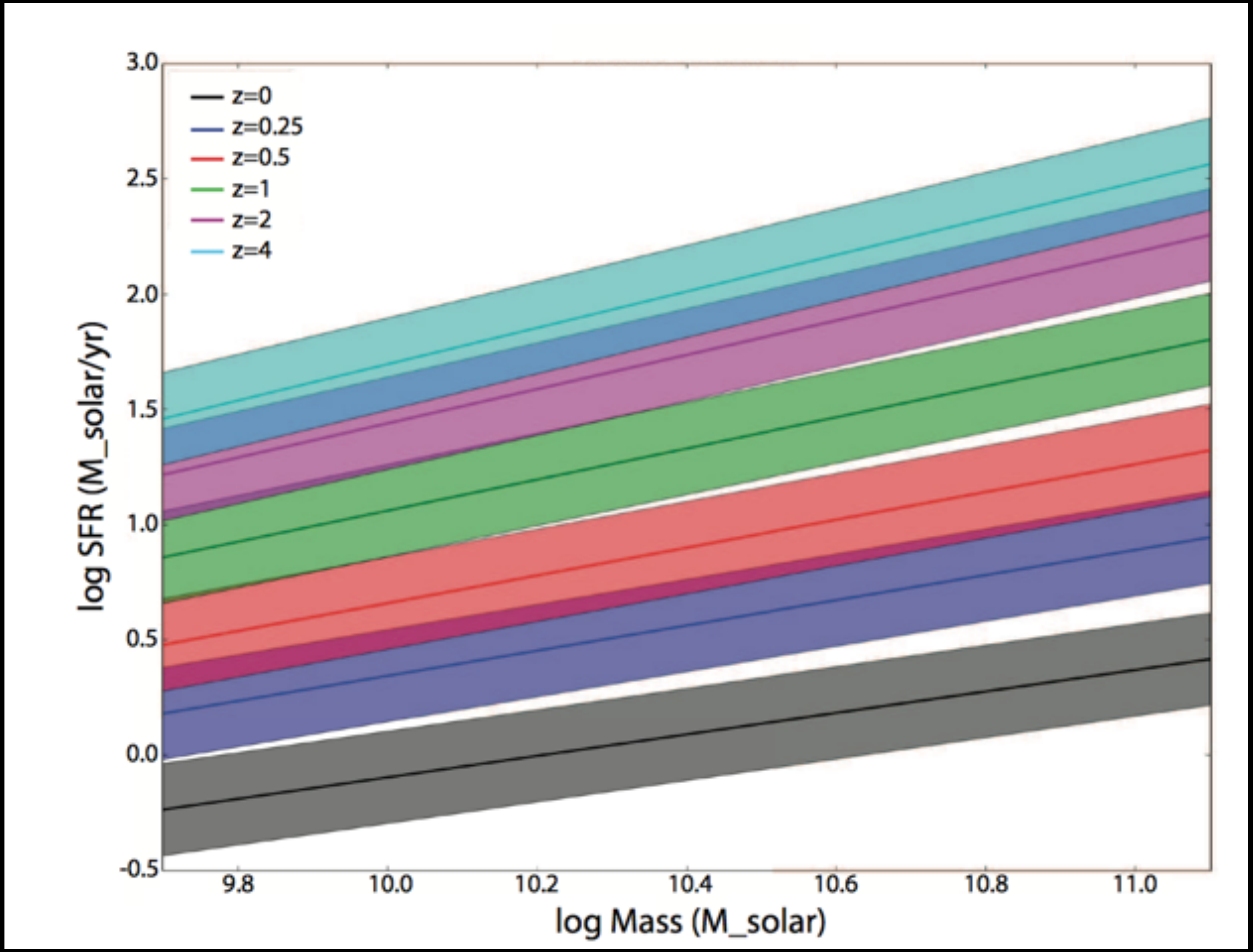
Herschel PACS+SPIRE







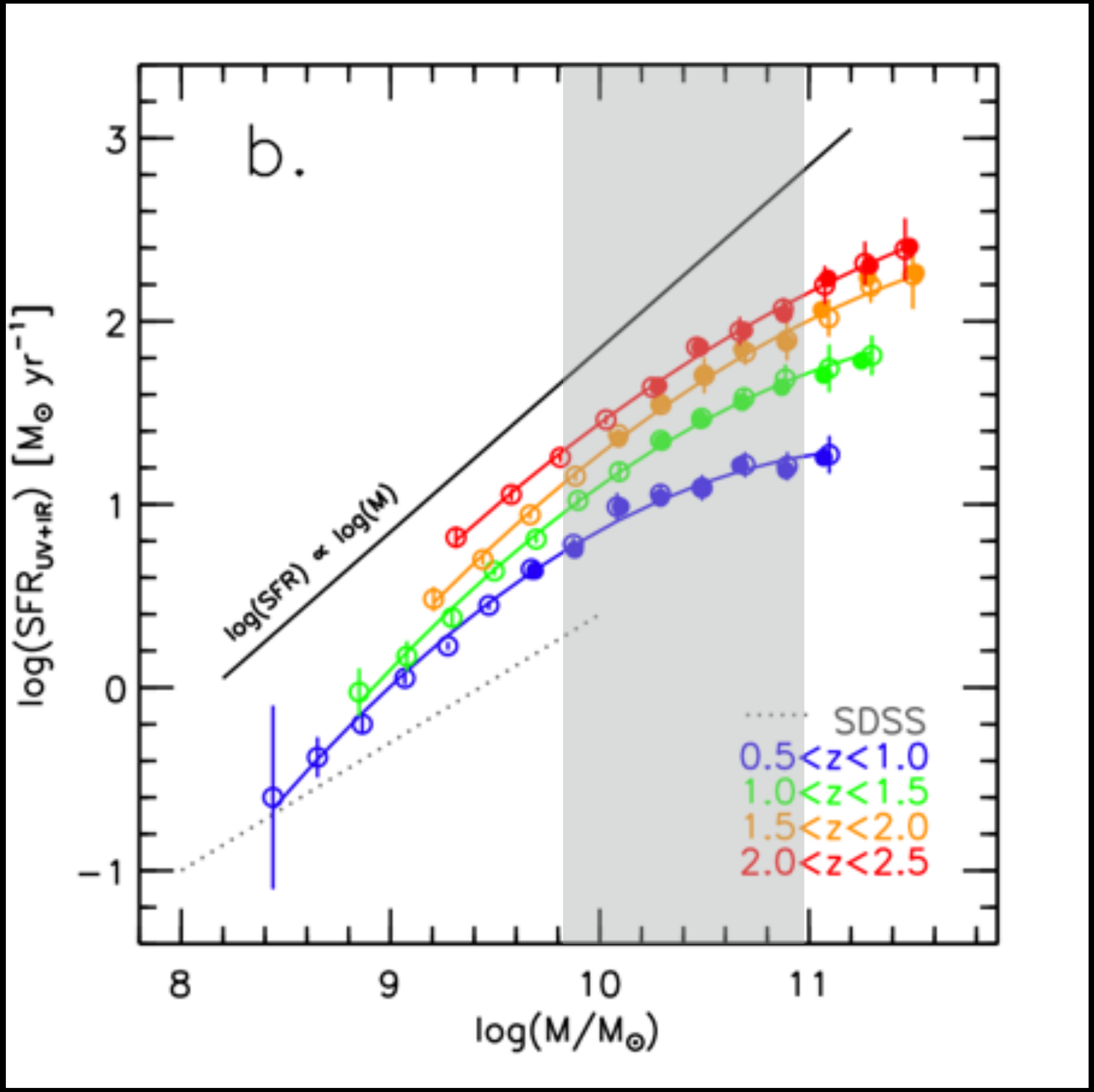
The Star Formation Main Sequence: z = 0 - 6



Speagle+2014 compiled MS observations from 25 studies and converted them to the same absolute calibrations (IMF, L-SFR, cosmology, etc)

Linear SFR-M* trend with **intrinsic** scatter of 0.2 dex

Probing the Main-Sequence at Lower Masses



Whitaker+2014 analyze a mass-complete sample of ~39,000 star-forming galaxies with deep CANDELS 0.3 - 8 um photometry, Spitzer/MIPS 24µm, grism redshifts and Hα from 3D-HST

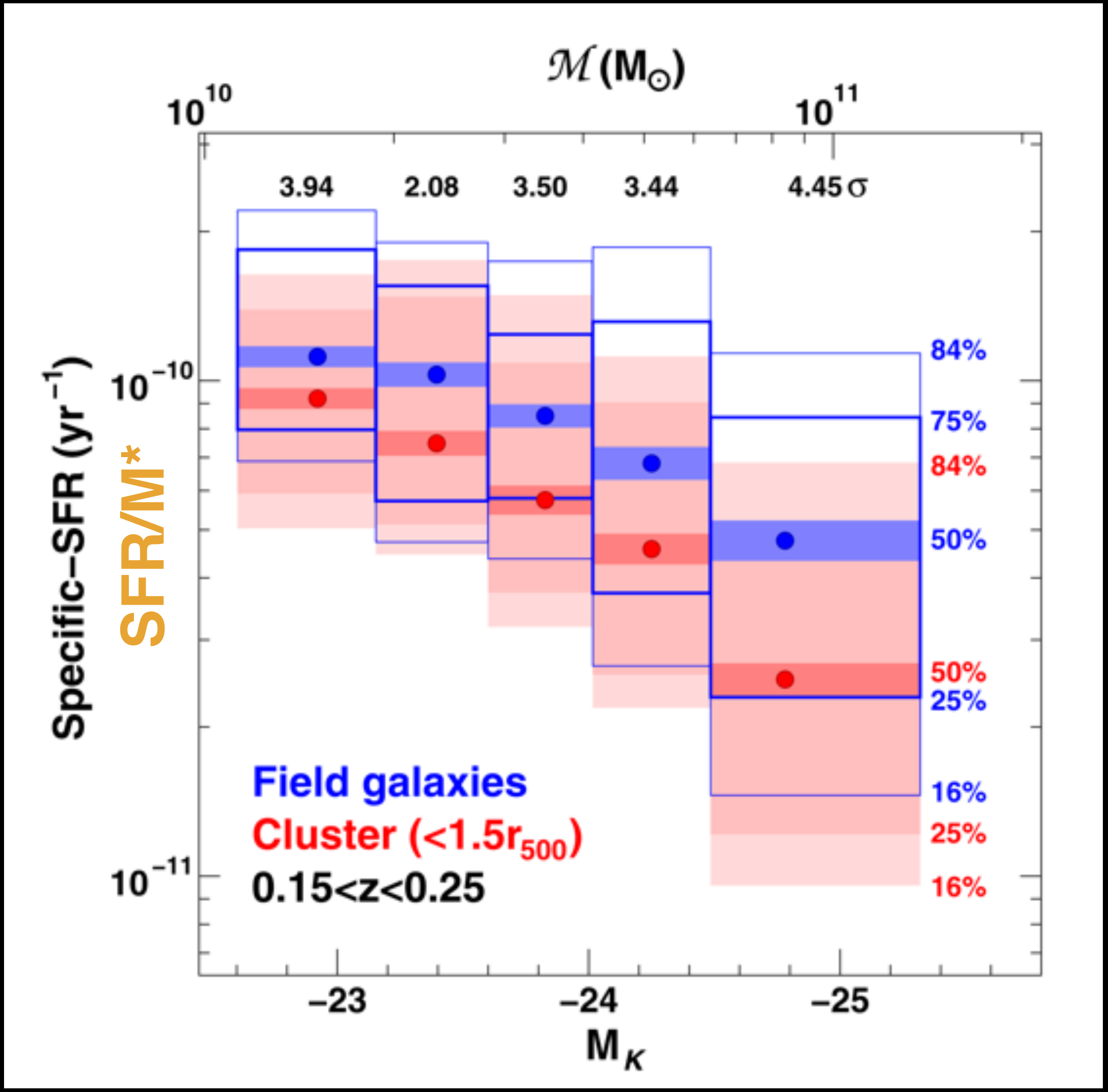
Steeper slope (SFR∝M*) at lower masses, evolution in slope at massive end (slow quenching?)

The Main Sequence is influenced by Environment at Low Redshift

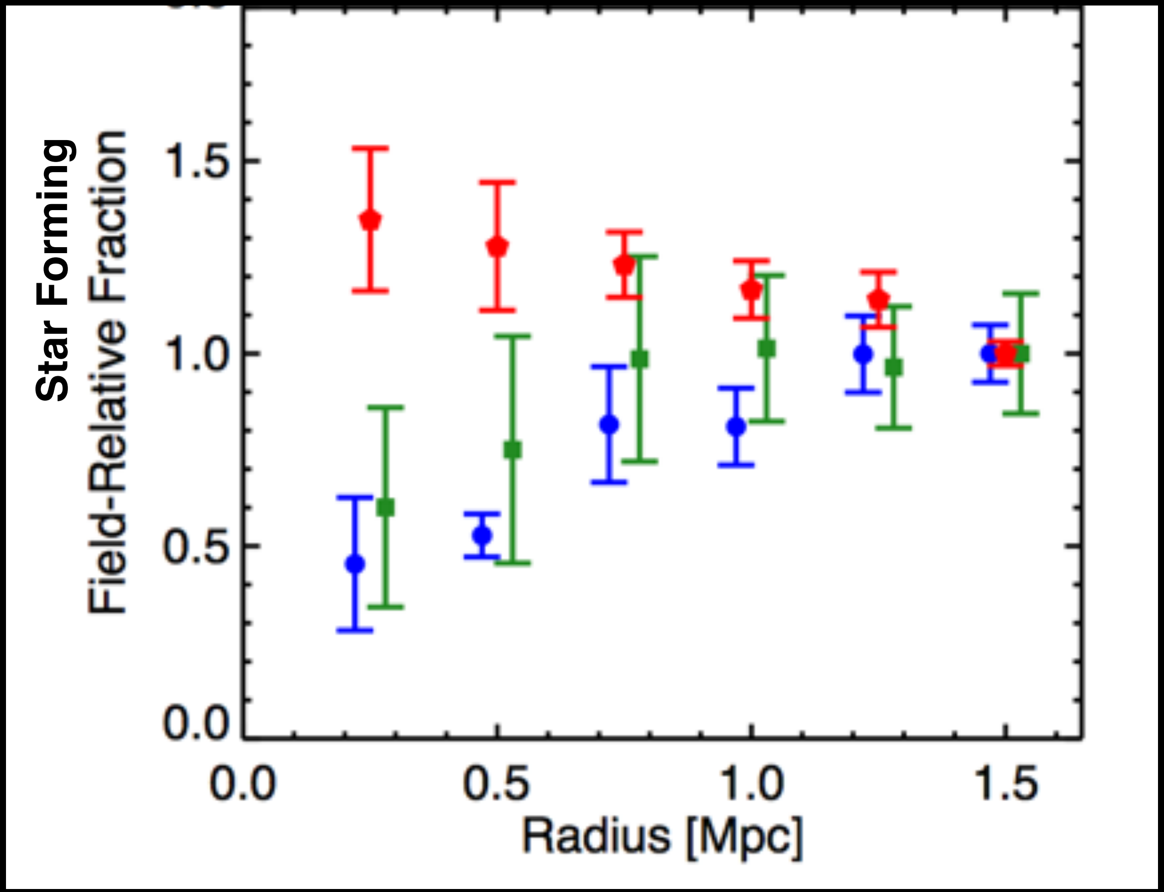
Haines+2013

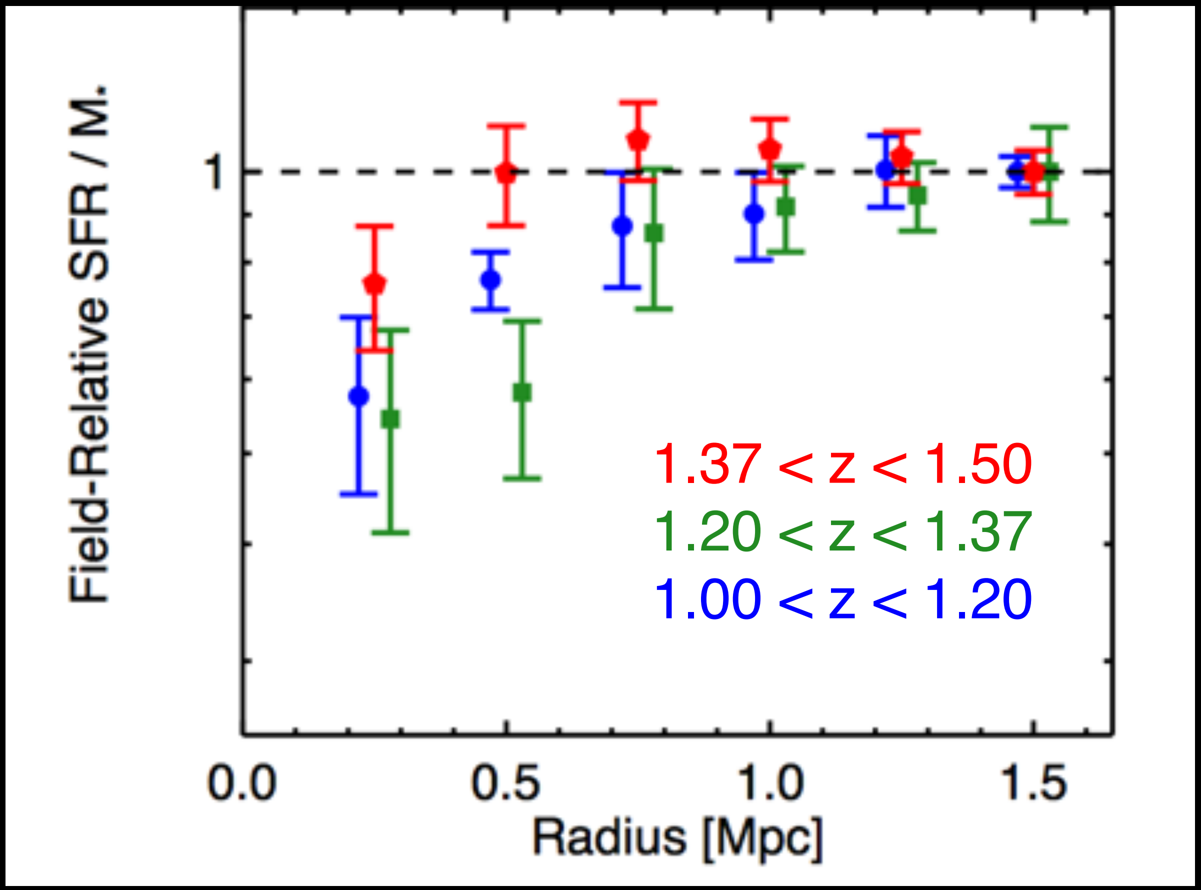
LoCuSS
MIPS 24um +
optical spectra
of clusters at
z=0.15-0.3

SFR/M* in massive
cluster galaxies is
suppressed by
~30% relative to
the field



Cluster-related quenching does not seem to be at work above z~1.4 (Brodwin+ 2013)

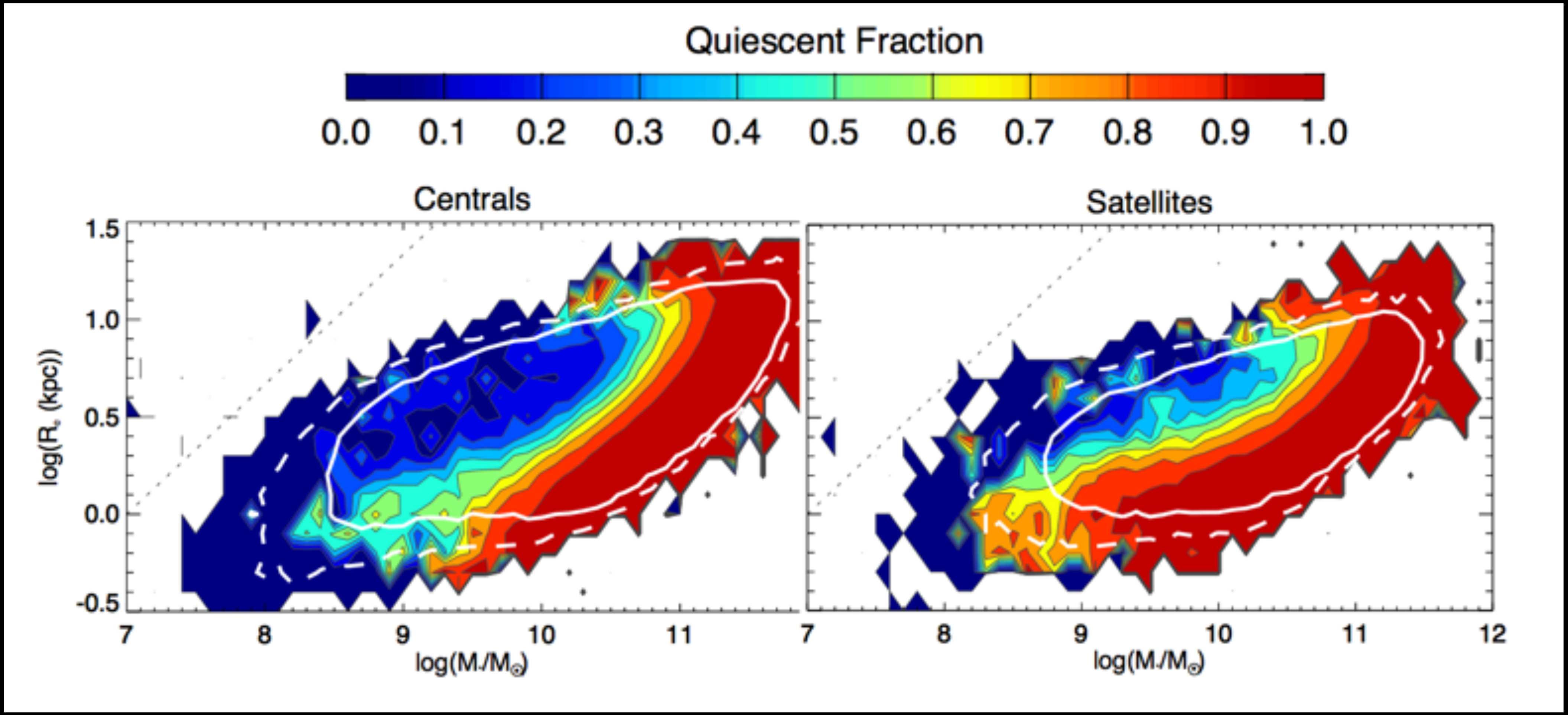




Quenching: a stronger function of central stellar mass **density** (bulge) rather than stellar mass

Omand+ 2014

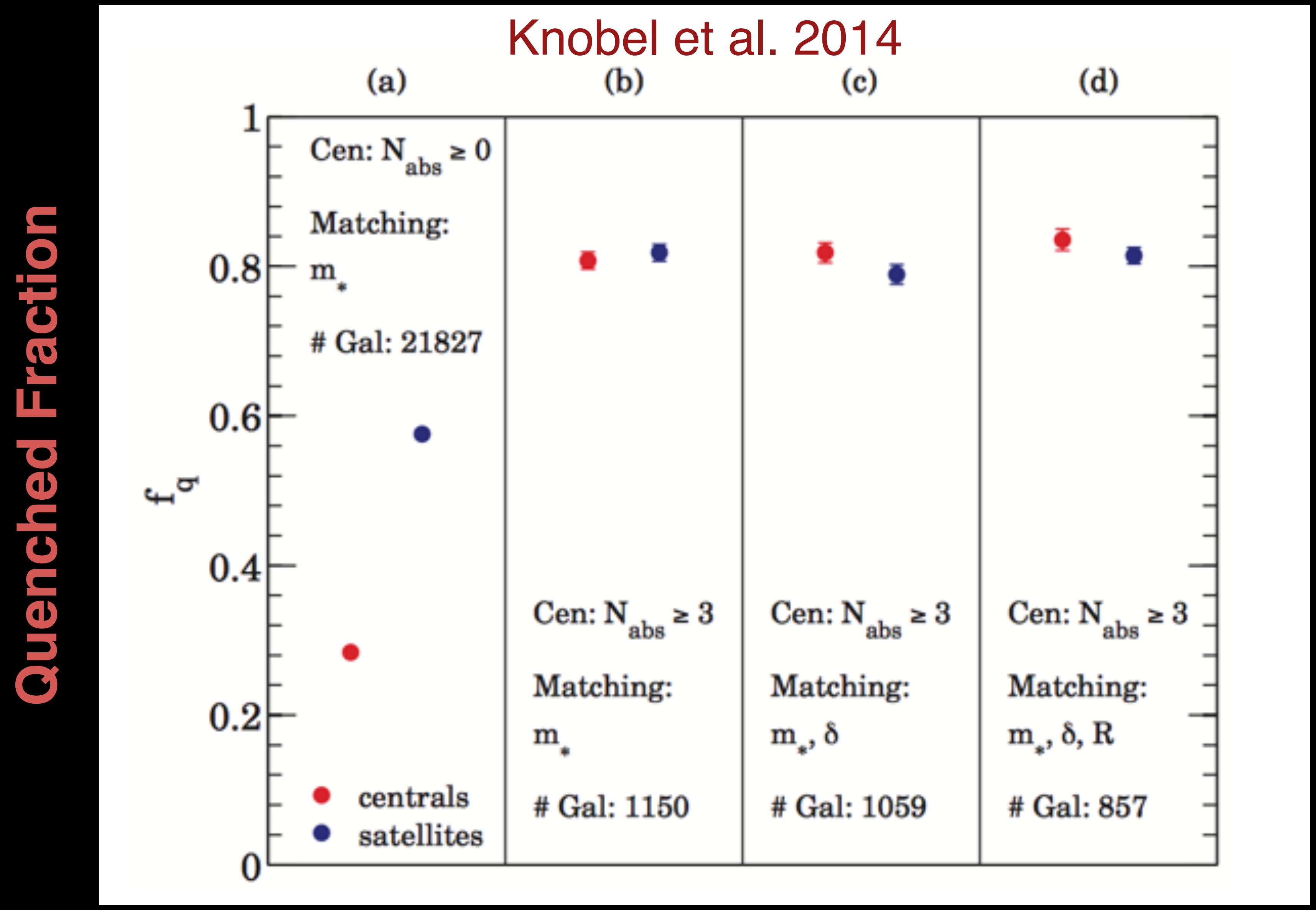
Effective Radius



Stellar Mass

Stellar Mass

Do Centrals Suffer Environmental Quenching?

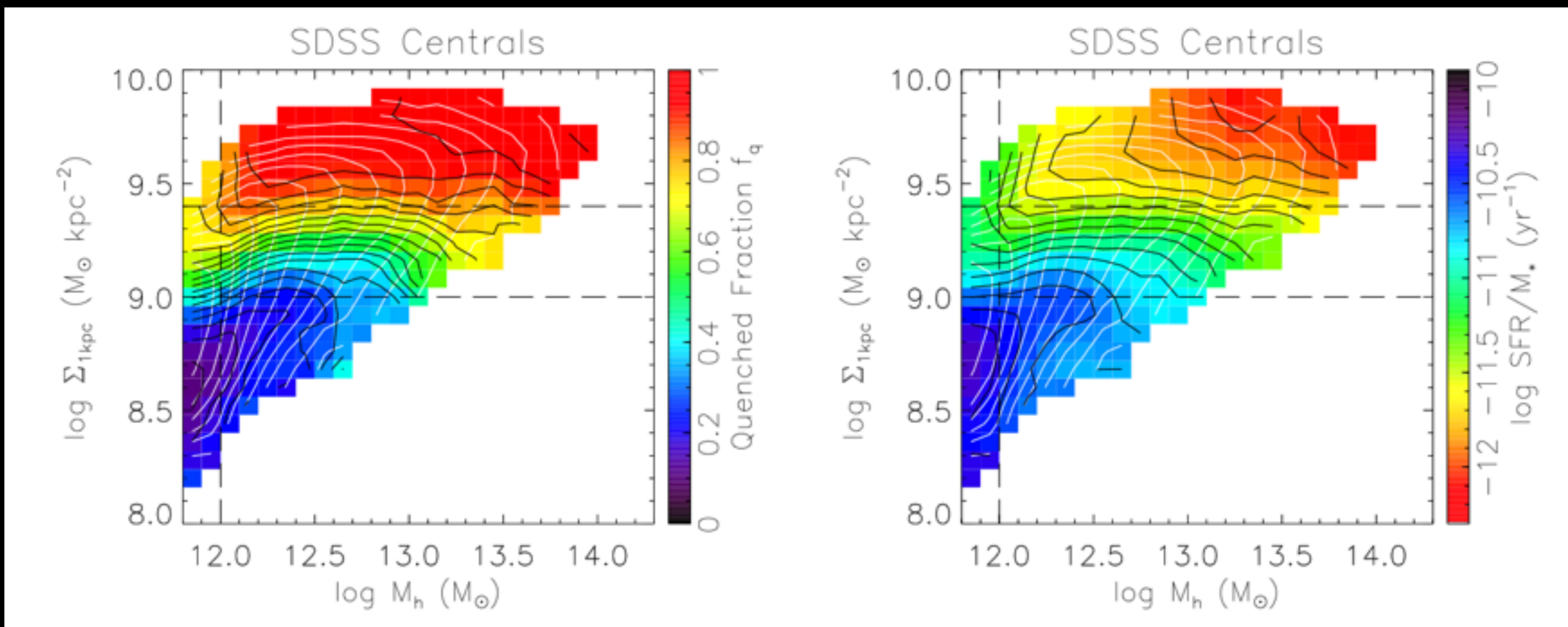


Knobel+2014 showed that when the study was limited to centrals in groups with more than 3 massive galaxies the quenched fractions of satellites and centrals were similar

Central quenching: a function of central density and halo mass

Woo+ 2014

Mass density in central kpc

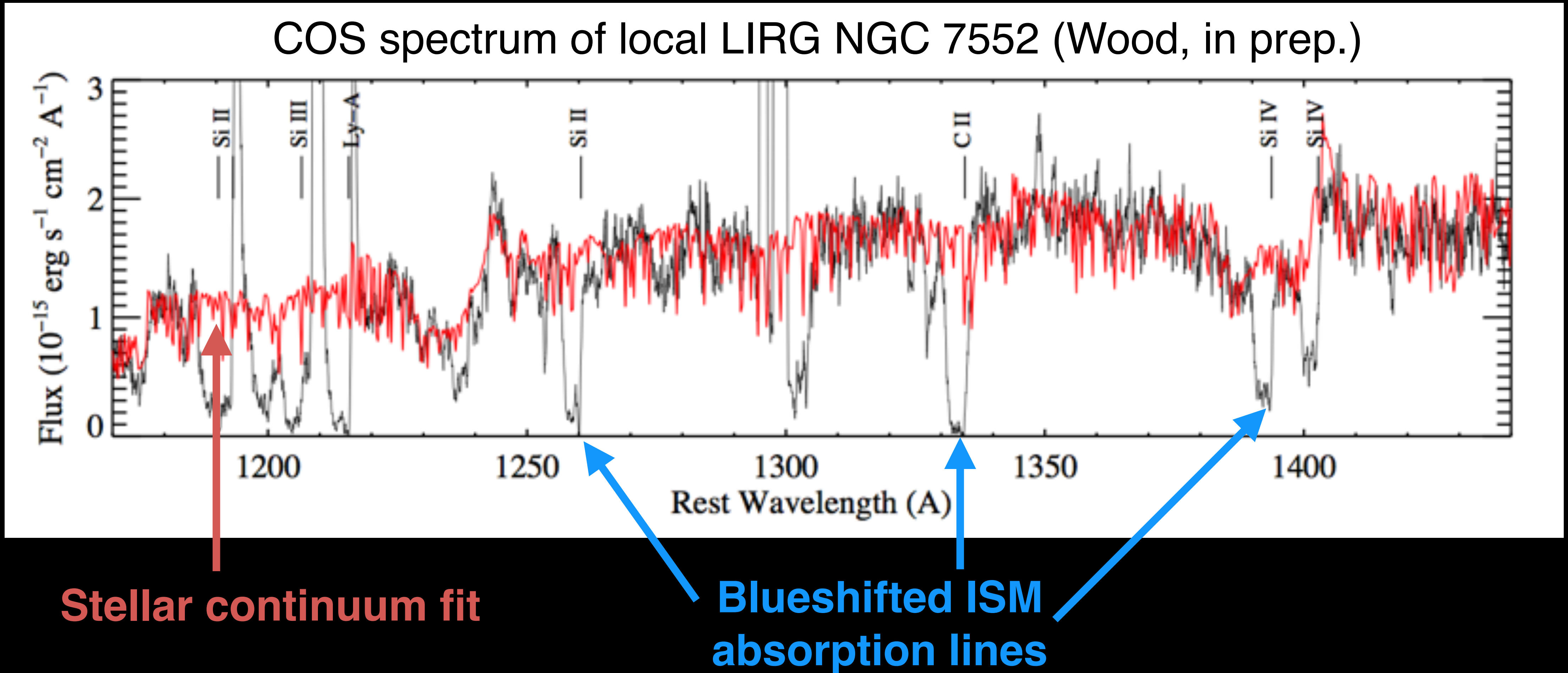


Halo Mass **Halo Mass**

Fast quenching: central density (mergers, violent disk instability)
Slow quenching: halo mass (viral shock heating)

Outflows are ubiquitous in actively star forming galaxies. So why don't we know more about them?

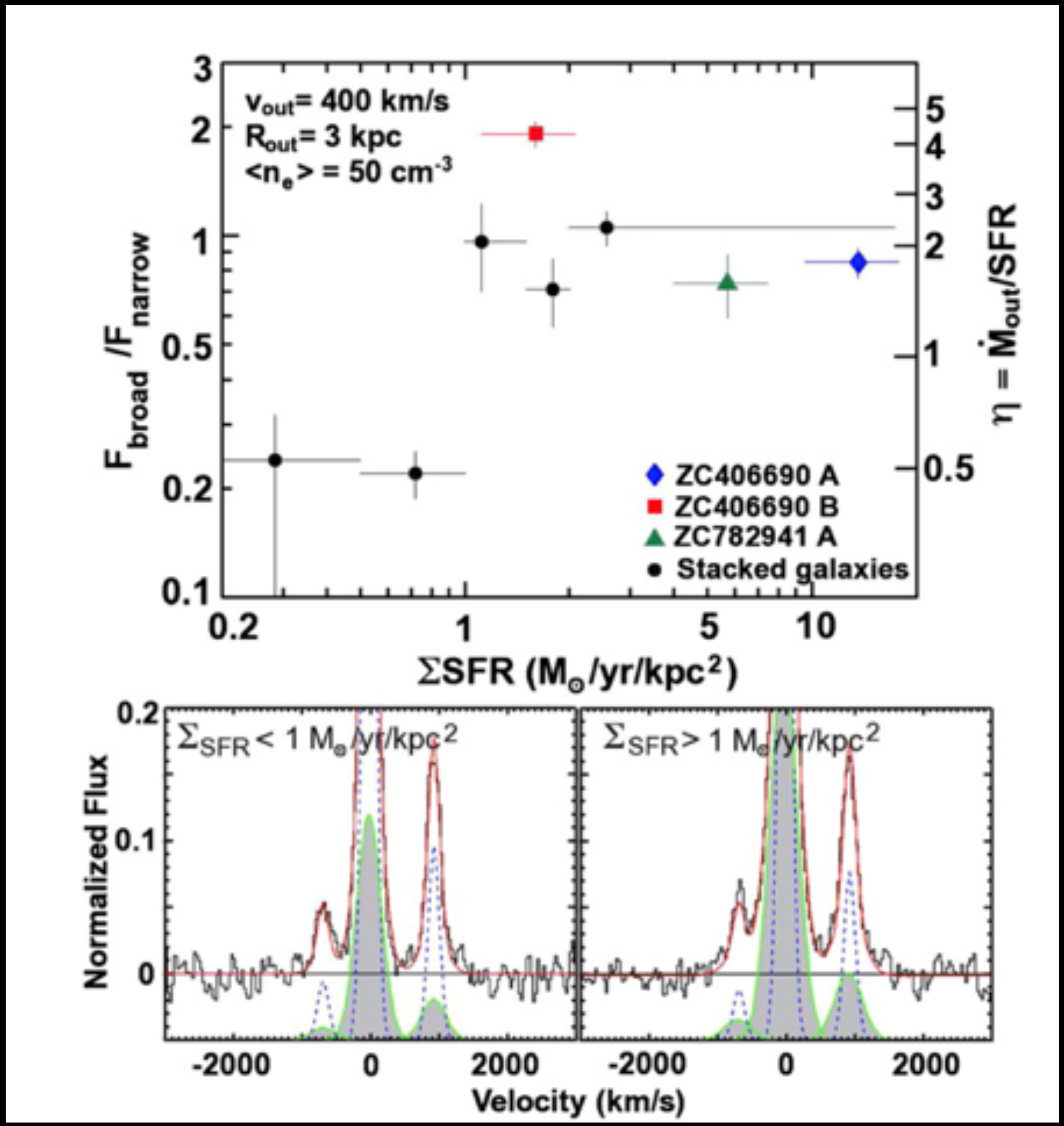
Velocities of the warm/cool phase are easy, masses are hard!



UV interstellar absorption lines are great for measuring wind velocities, but many strong lines are saturated - difficult to measure column density

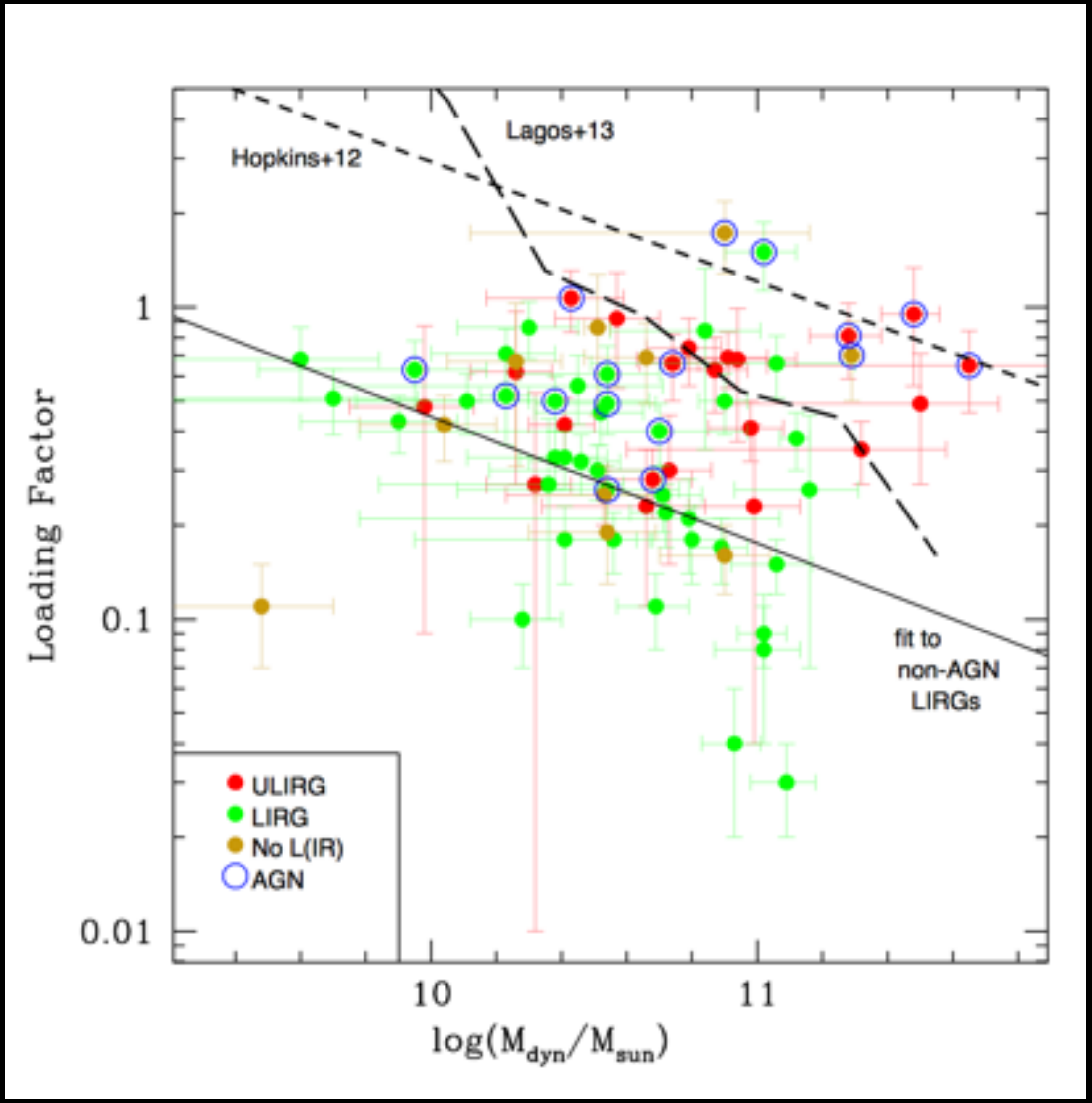
Broad Hα and [S II] emission lines have been used to estimate mass outflow rates in local (U)LIRGs and z~2 galaxies

Newman+ 2012



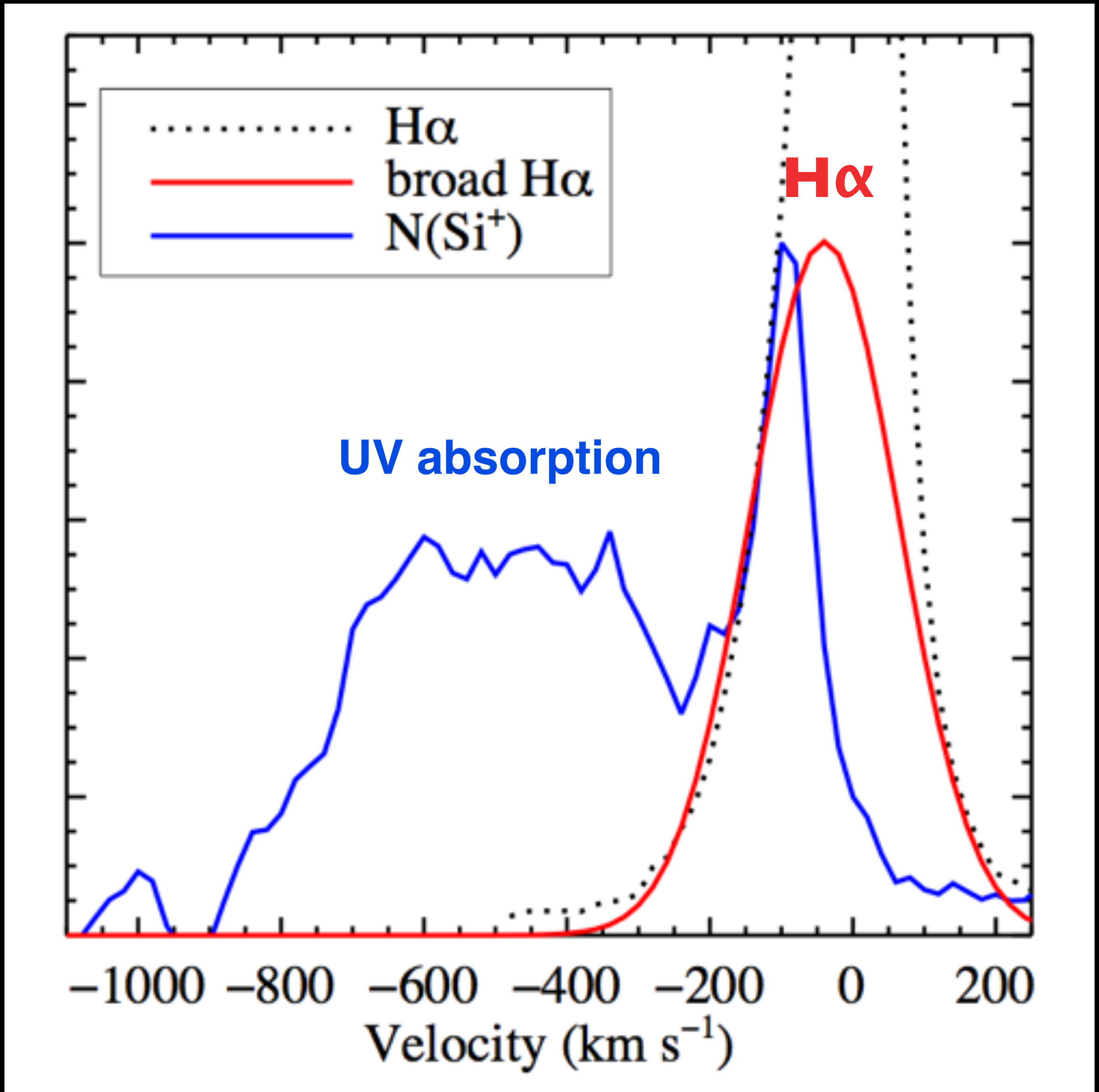
Arribas+ 2014

M_{out}/SFR

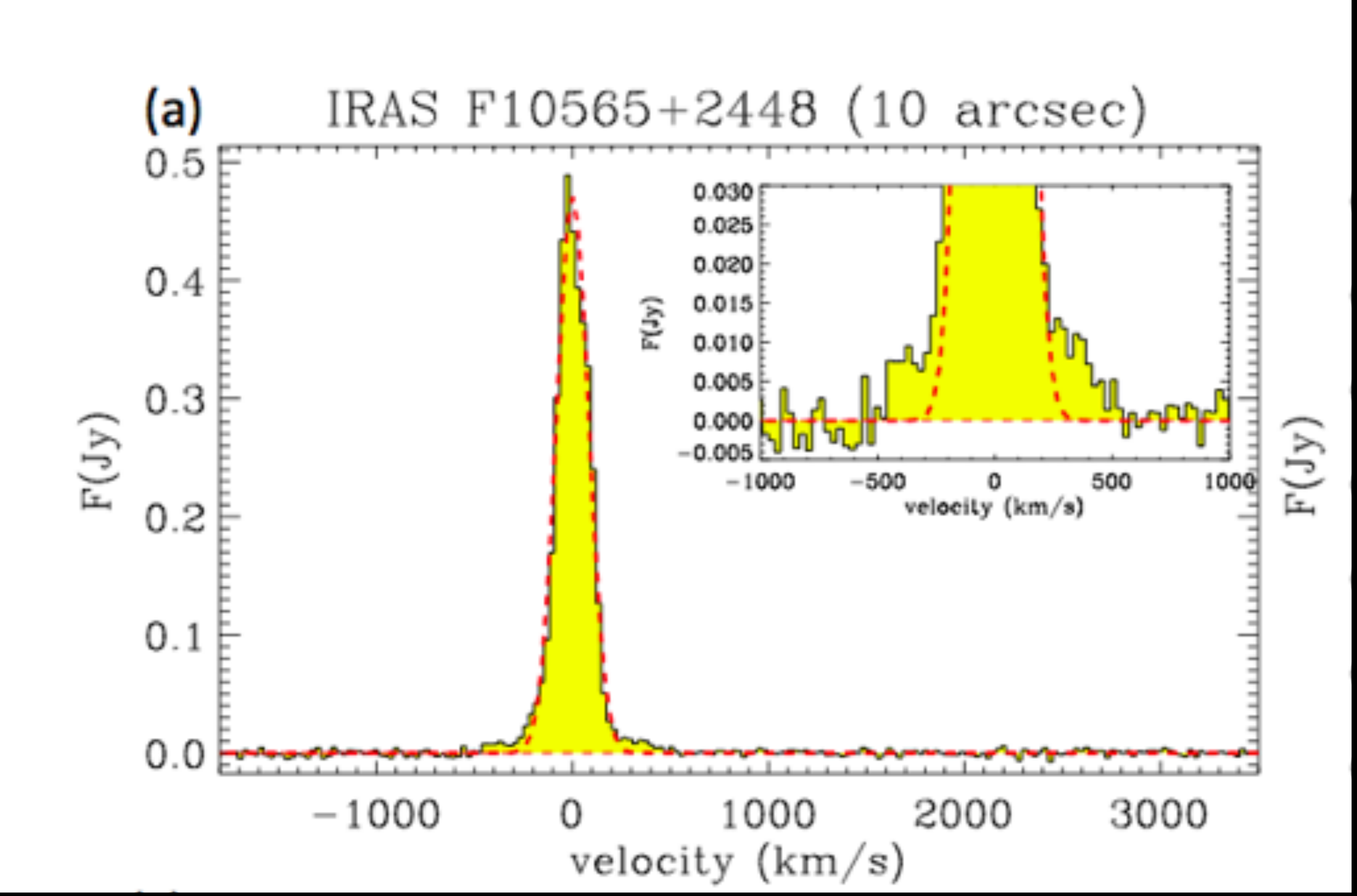


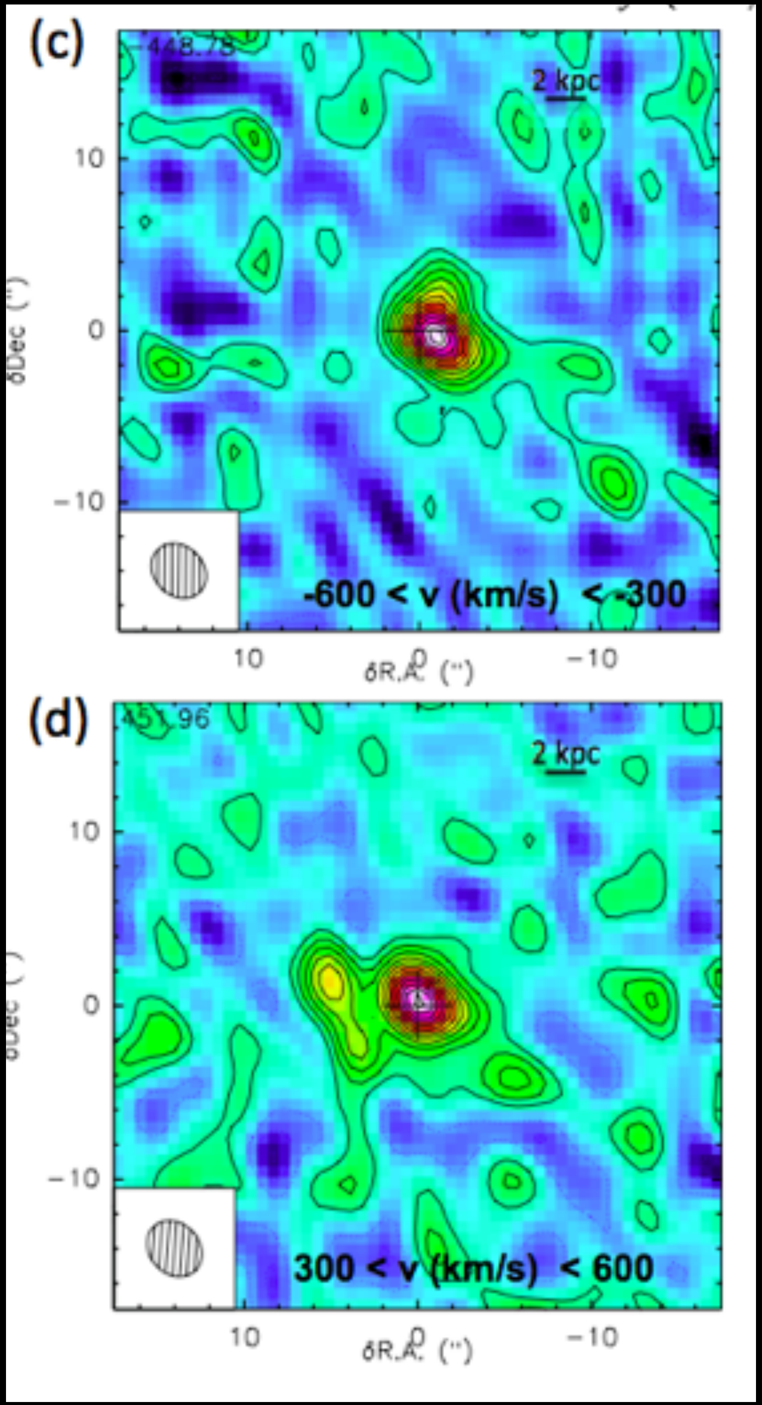
But Hα is only sensitive to the highest density gas - traces inner shocked wind not large scale outflow

NGC 7552 (Wood, in prep)



Powerful **molecular outflows** have been observed in many star forming galaxies and AGN

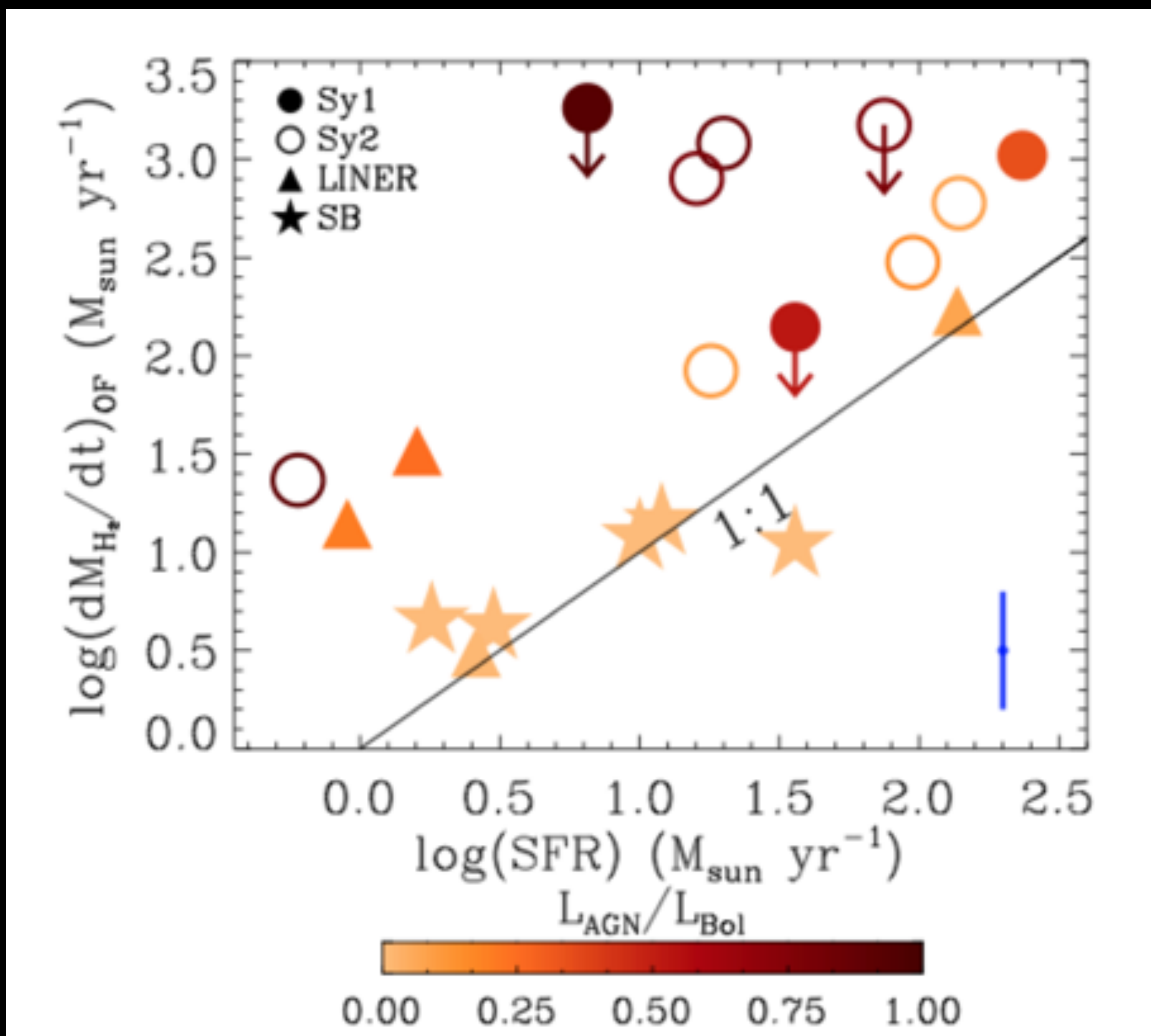


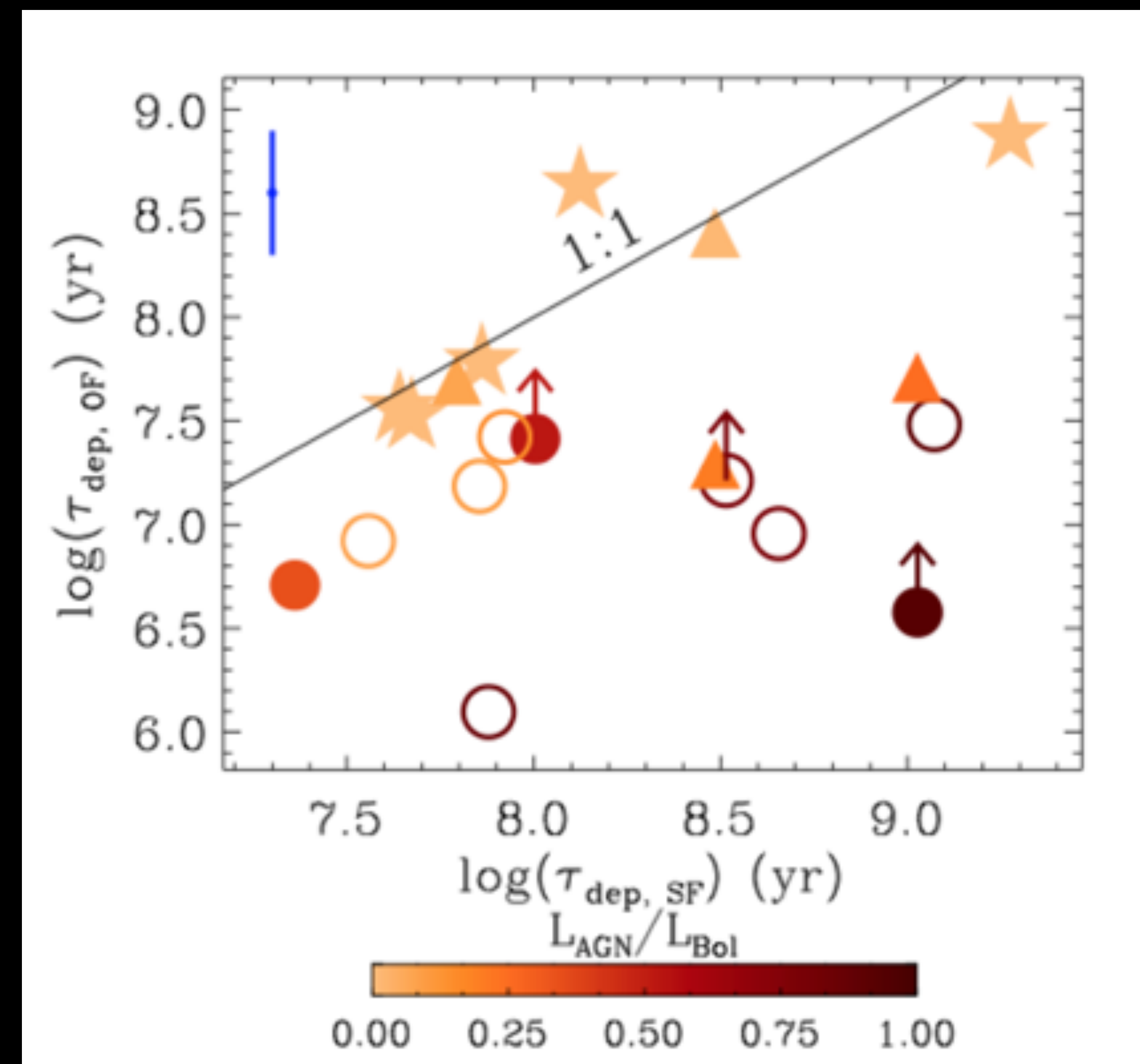


Cicone+2014

Molecular Outflows are observed in starbursts and AGN, but mass outflow rates are higher in AGN.

Cicone+2014





AGN Outflows greatly reduce gas repletion times (~10 Myr) ➔ Quenching

Molecular Gas observations of BCGs: outflows and inflows

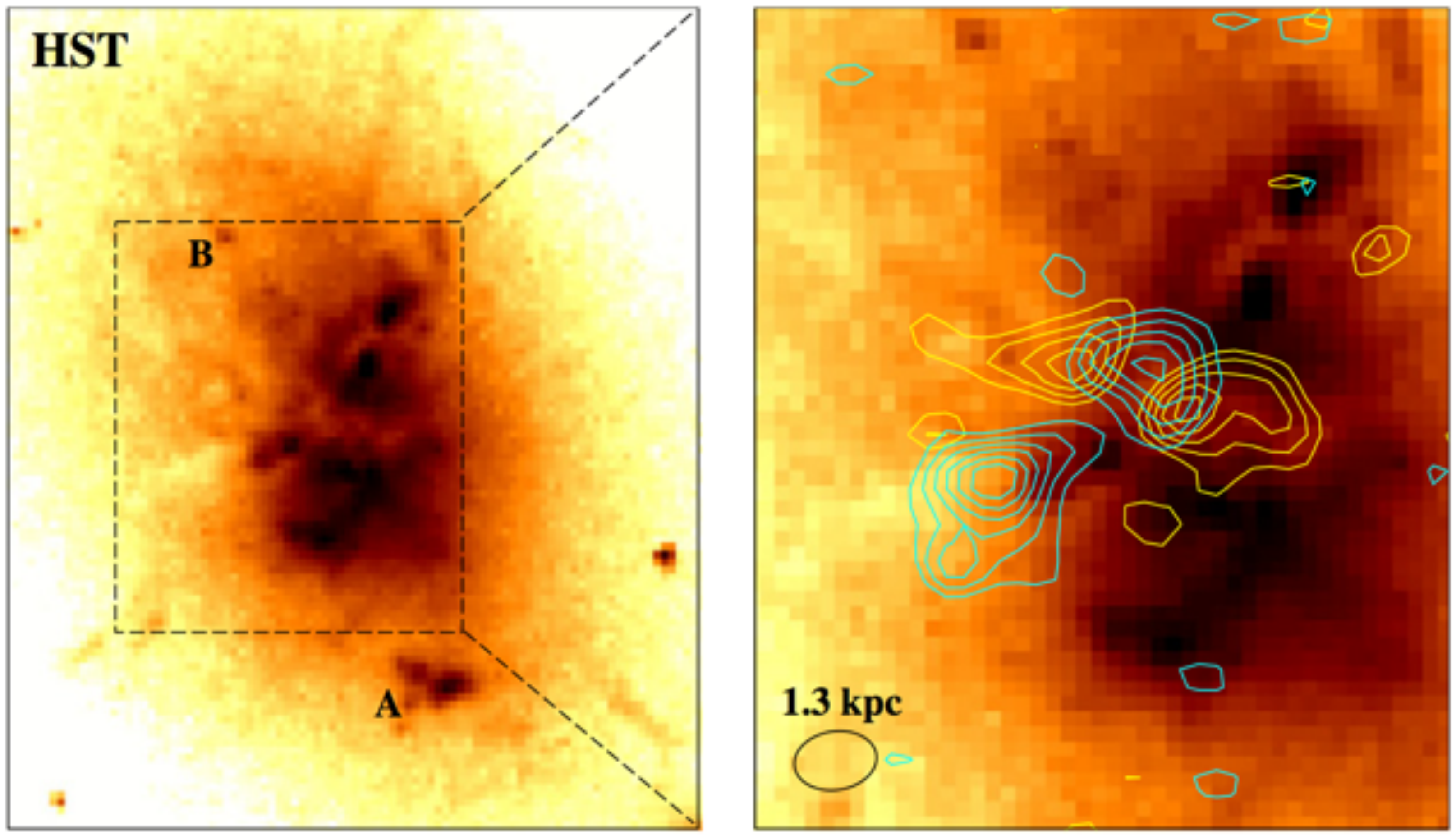
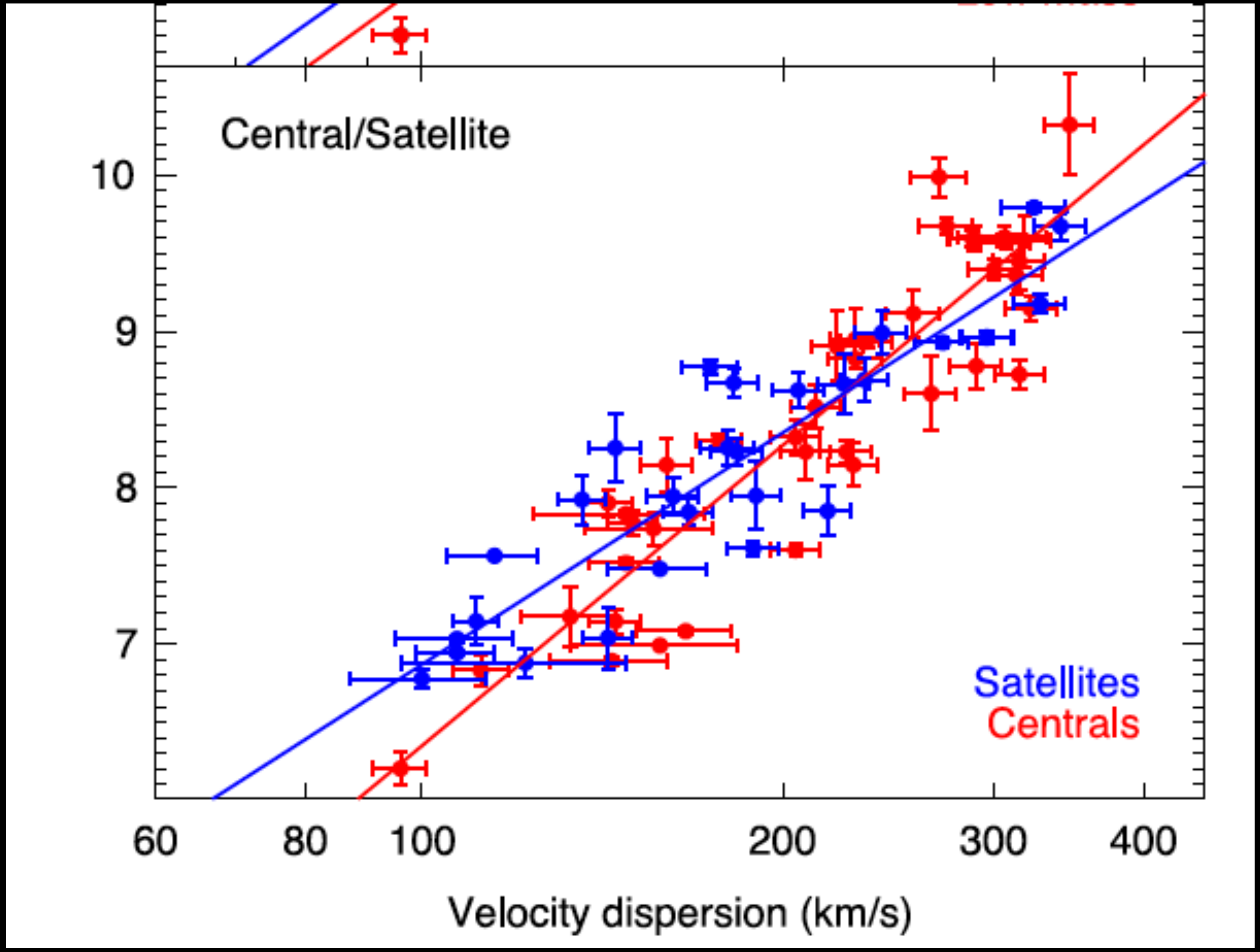


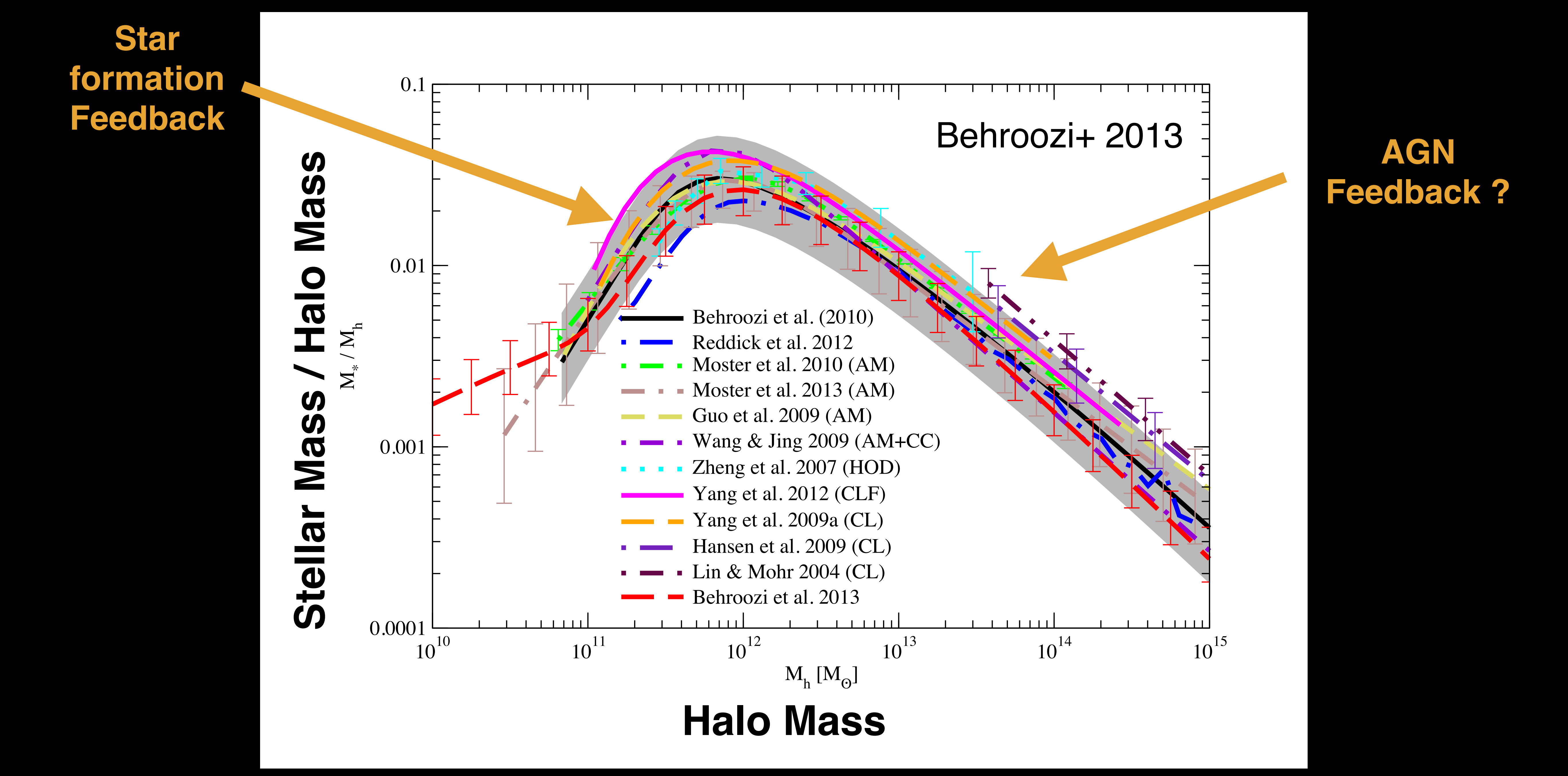
Figure 6. Left: *Hubble Space Telescope (HST)* WFPC2 F606W optical image of the BCG in A1664. Right: zoom-in of the *HST* image with ALMA CO(3–2) contours representing the BCG's systemic component (−285 to 285 km s^{-1}; yellow) and HVS (−705 to −405 km s^{-1}; cyan). The ALMA beam size for CO(3–2) is shown to the lower left.

Russell+ 2014, see also McDonald+ 2014, Labiano+ 2014, Werner+ 2014, McNamara+ 2014

McGee 2014

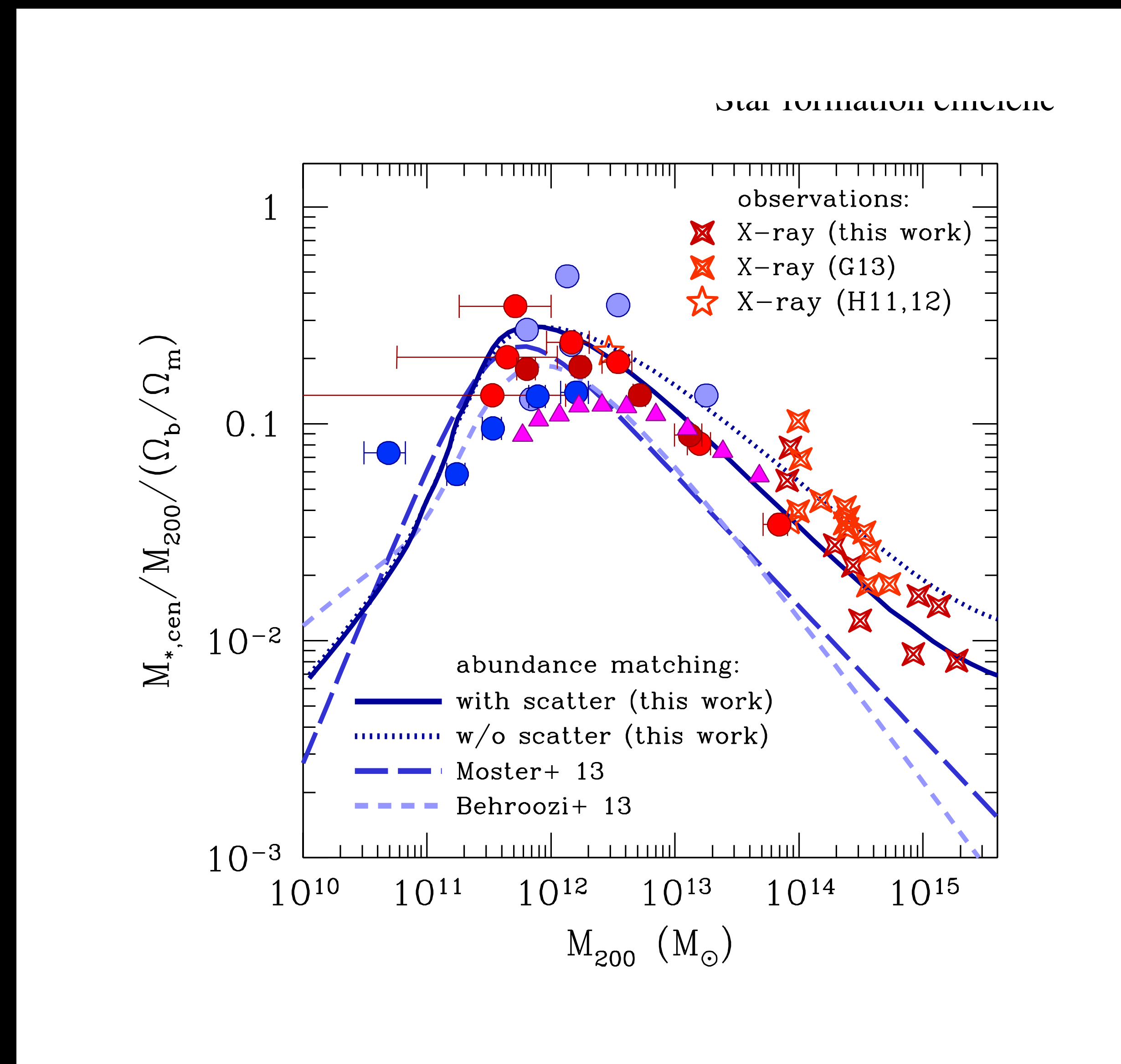

Central/Satellite
10
9
8
7
Satellites
Centrals
60
80
100
200
300
400
Velocity dispersion (km/s)

A key constraint on outflows comes from the ratio of stellar to halo mass



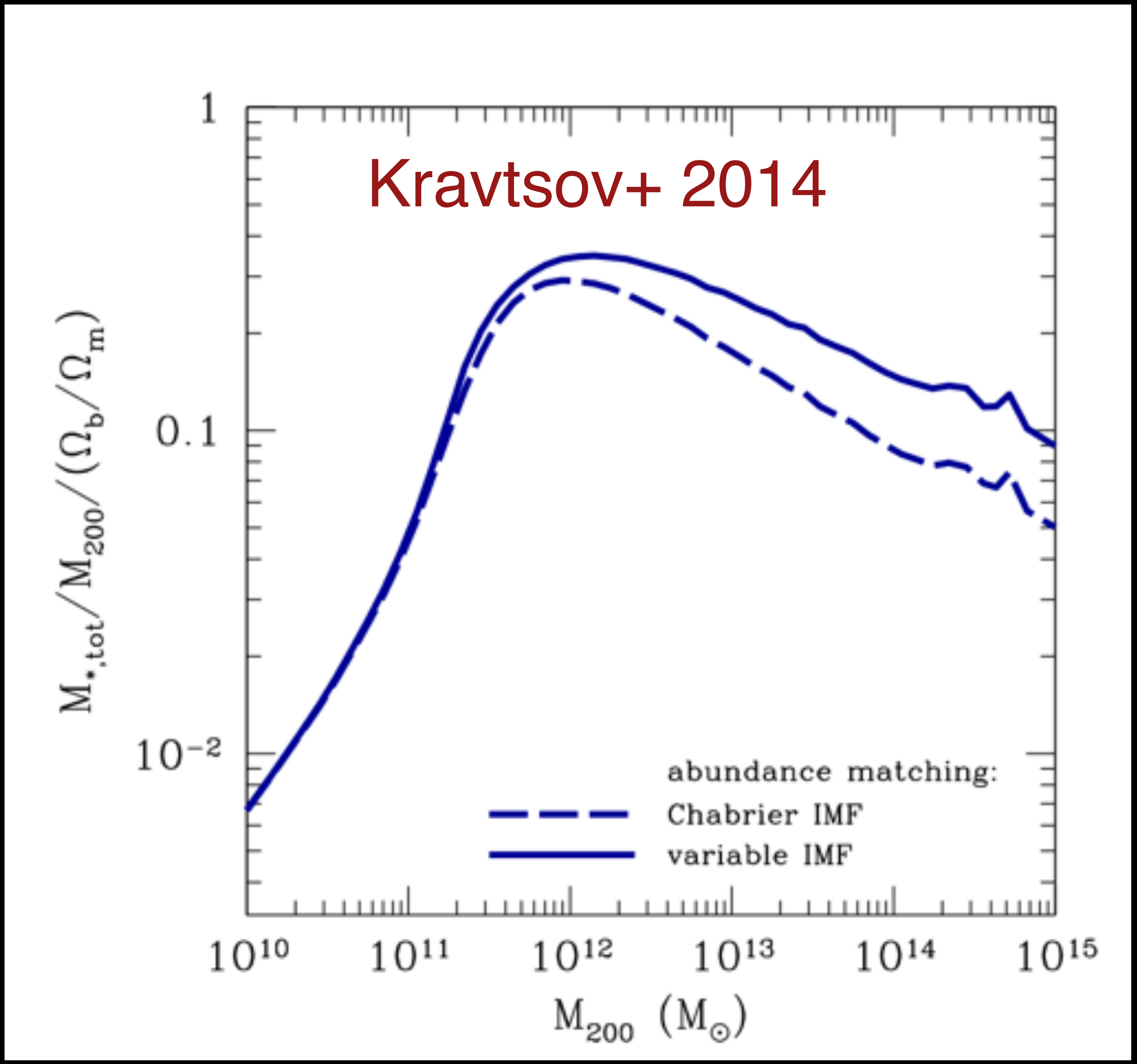
At most only 15% of the available baryon have turned into stars by the present

Improved photometry of BCG results in stellar masses that are larger by factors of 2-6



Bernardi+2013, Karvtsov+2014

If, in addition, the IMF becomes more bottom heavy with increasing M* …



The efficiency of SF in massive halos appears only moderately suppressed (2-3x) compared to L* galaxies

Less AGN feedback needed?

A galaxy's **gas phase metallicity** is sensitive to many important parameters of its evolution

Equilibrium solution from Lilly+ 2013

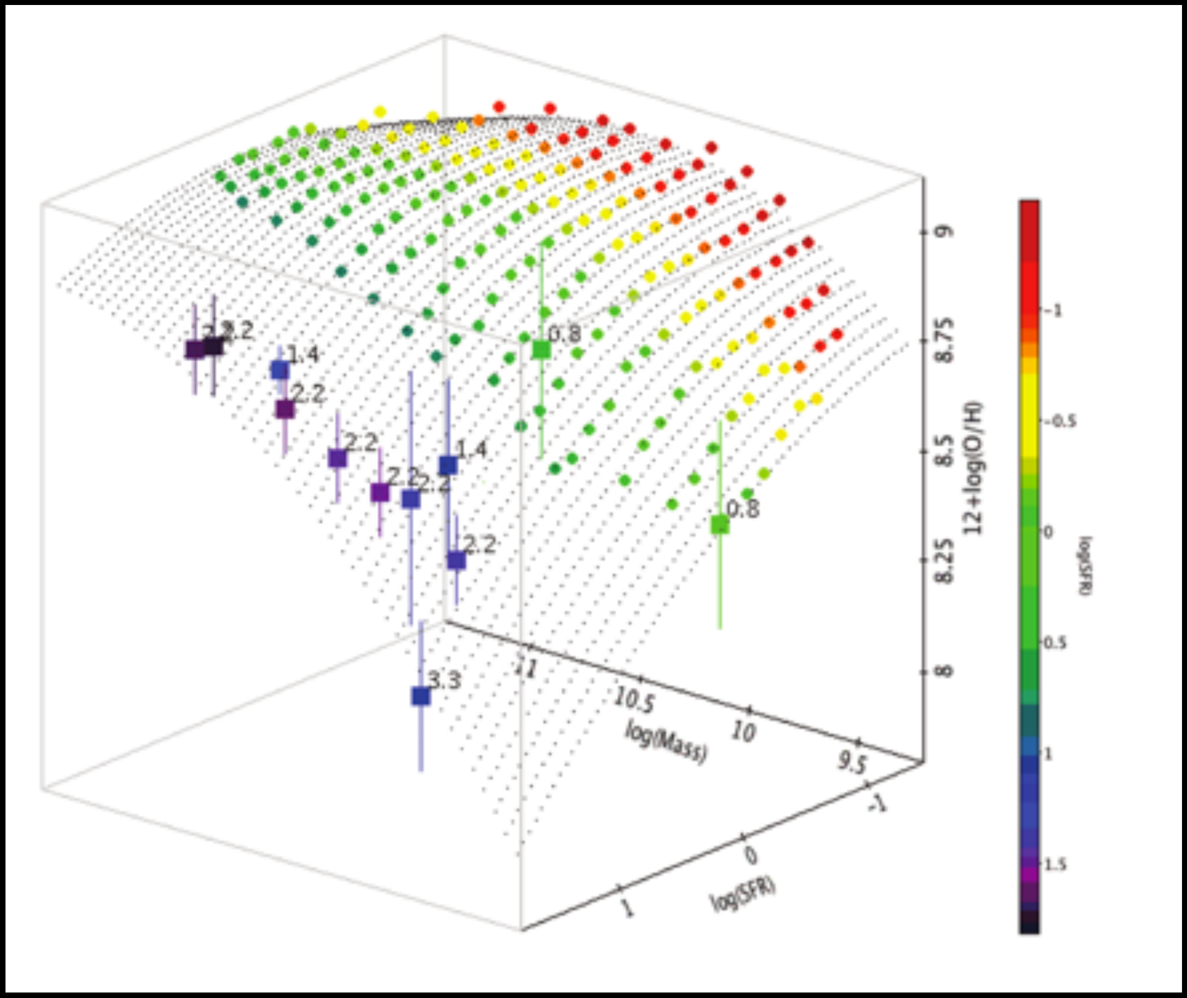
$$Z_{\mathrm{eq}} = Z_0 + \frac{y}{1 + \lambda(1-R)^{-1} + \varepsilon^{-1} m_{\mathrm{star}}^{-1} \cdot \mathrm{SFR}}.$$

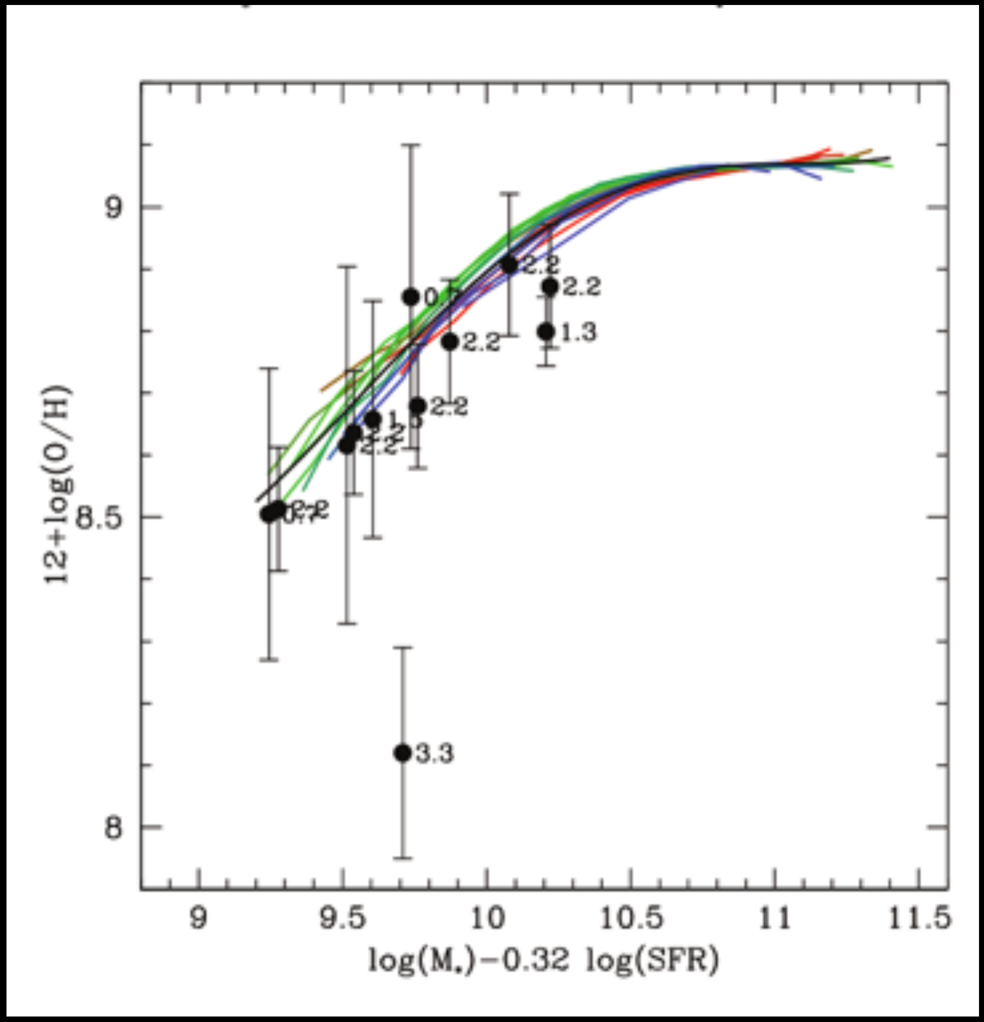
Z_0: metallicity of accreted gas

λ: $\frac{\dot{M}_{\mathrm{outflow}}}{\mathrm{SFR}}$

ε: star formation efficiency

The Fundamental metallicity relation (Mannucci+ 2010)

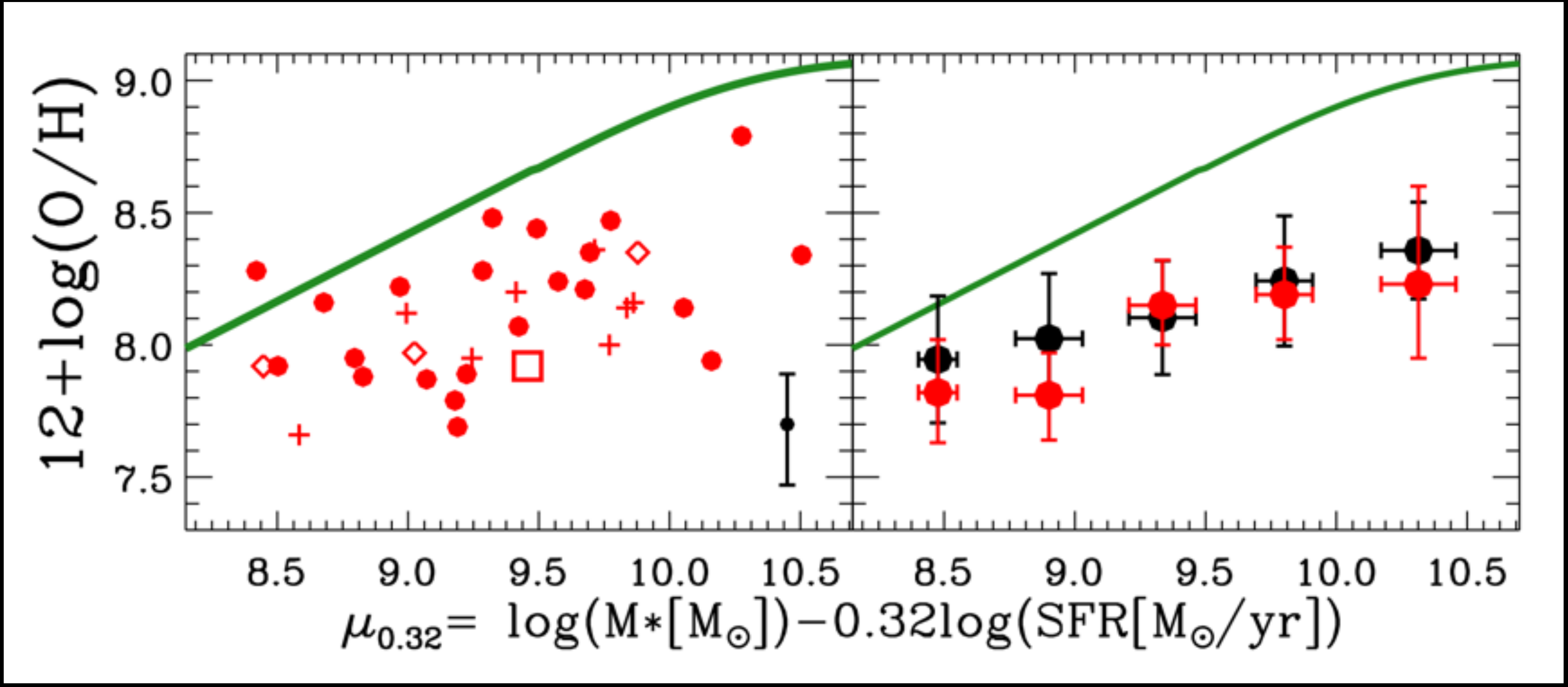




Metallicity correlates with stellar mass and SFR.
Galaxies along on this surface surface

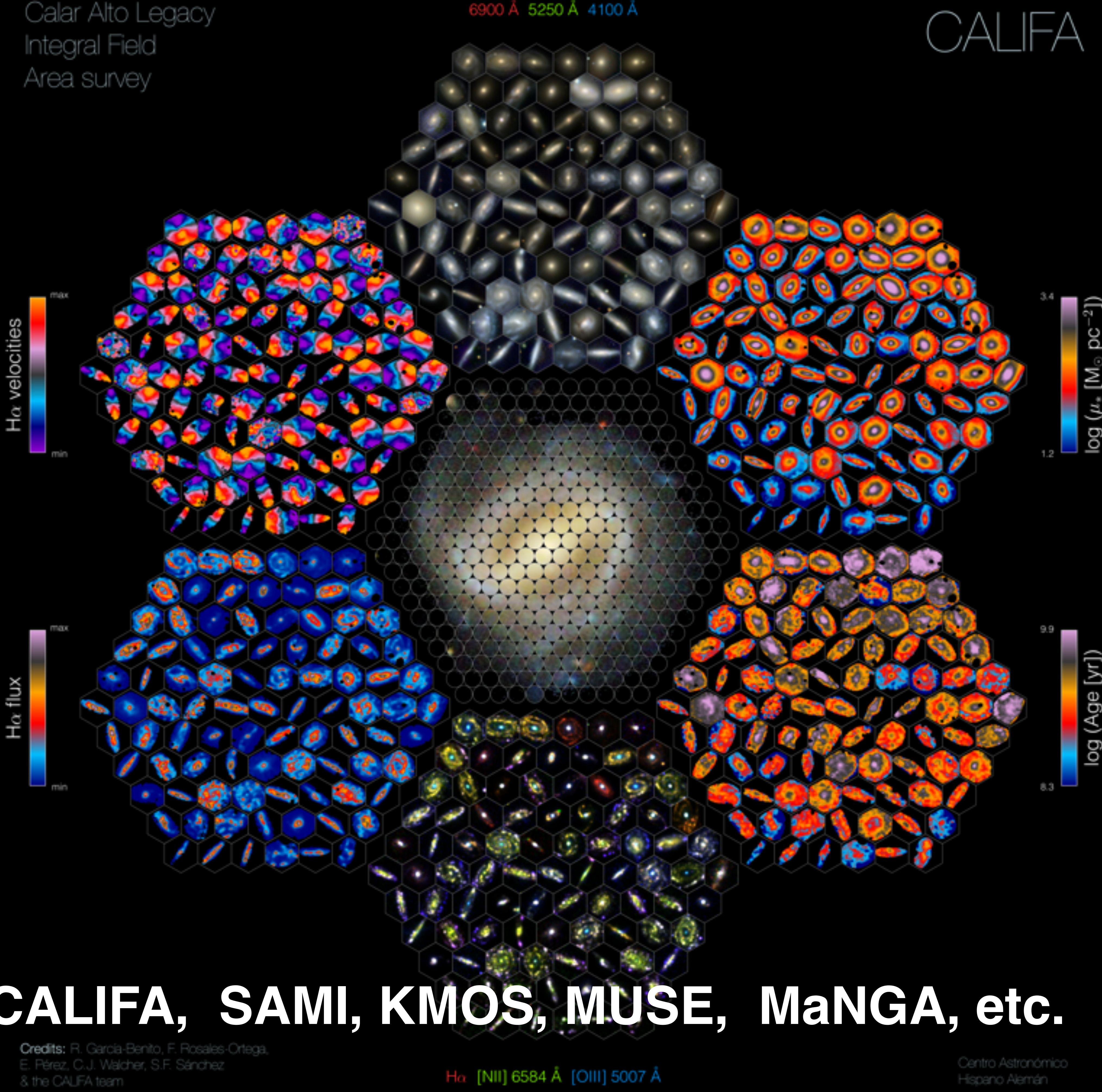
M-Z-SFR: Not So Fundamental Any More?

Troncoso+2014
AMAZE + LSO: star forming galaxies at z~3.4



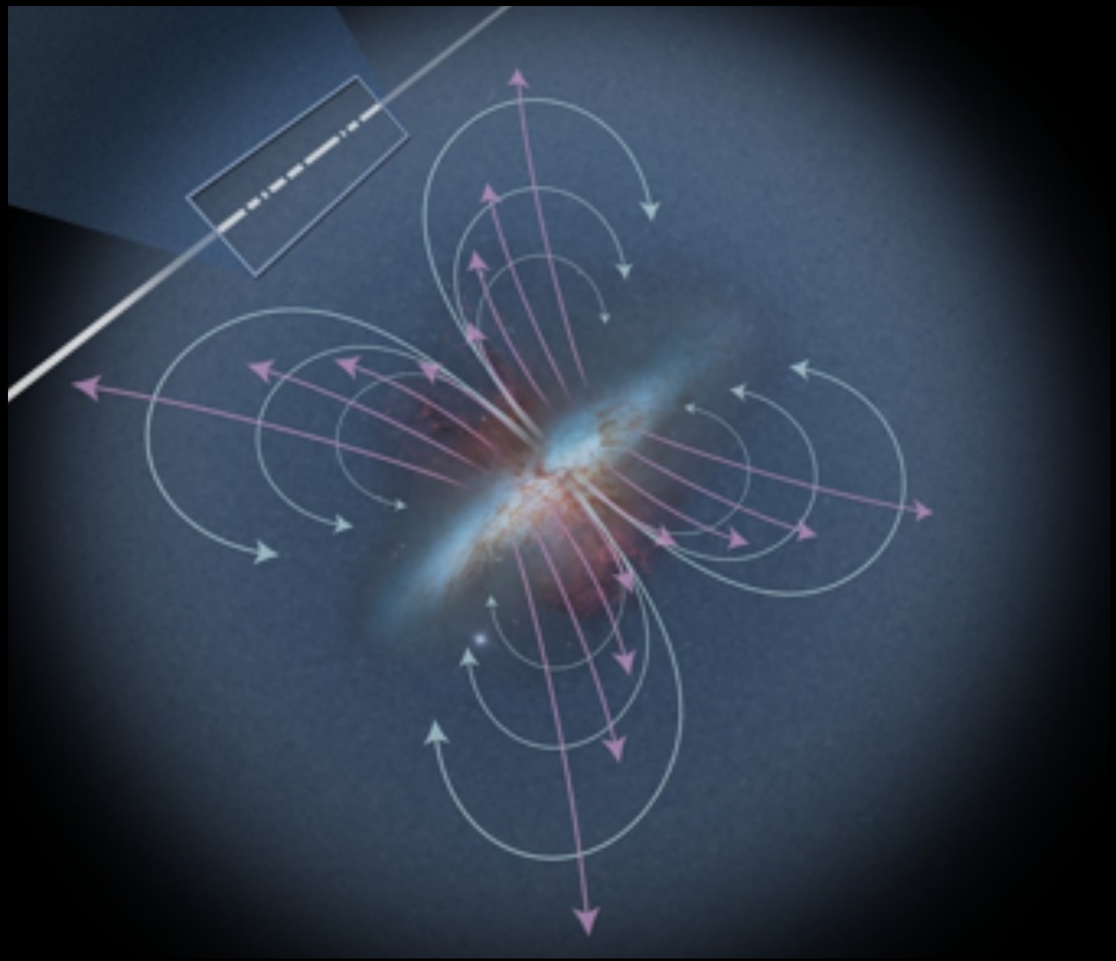
See also Zahid+ 2014, Steidel+ 2014

How do we make progress?



CALIFA, SAMI, KMOS, MUSE, MaNGA, etc.

Metallicity gradients trace a galaxy's history of star formation, inflow, outflow and interaction with the large scale environment



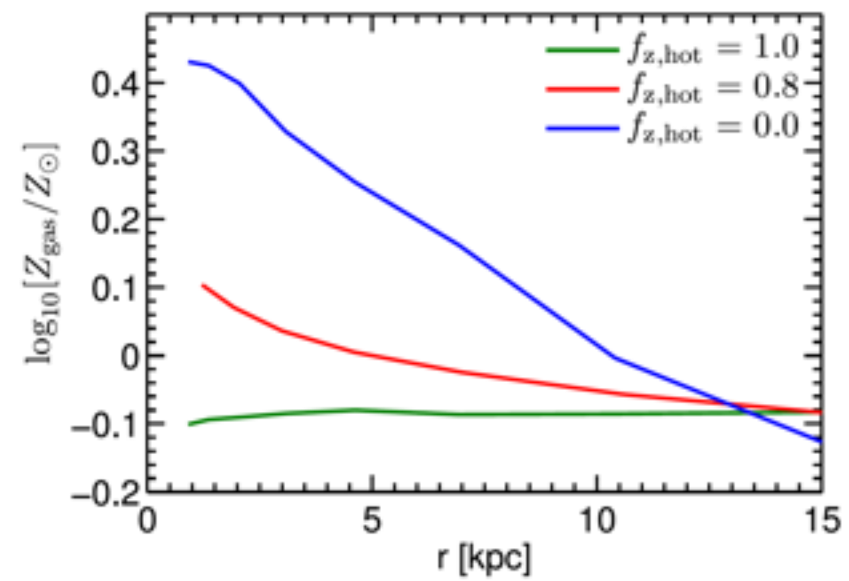


Figure 6. The radial gas-phase metallicity gradient for disc galaxies with stellar mass $10^{10.0} < M_*/\mathrm{M}_{\odot} < 10^{10.5}$ from the model results at $z = 0$. The three different colour curves represent the model results with $f_{z,\mathrm{hot}} = 0.0, 0.8, 1.0$, respectively.

Fu, Kauffmann et al. 2013

Mapping Nearby Galaxies at APO

PI: Kevin Bundy (IPMU, Japan)

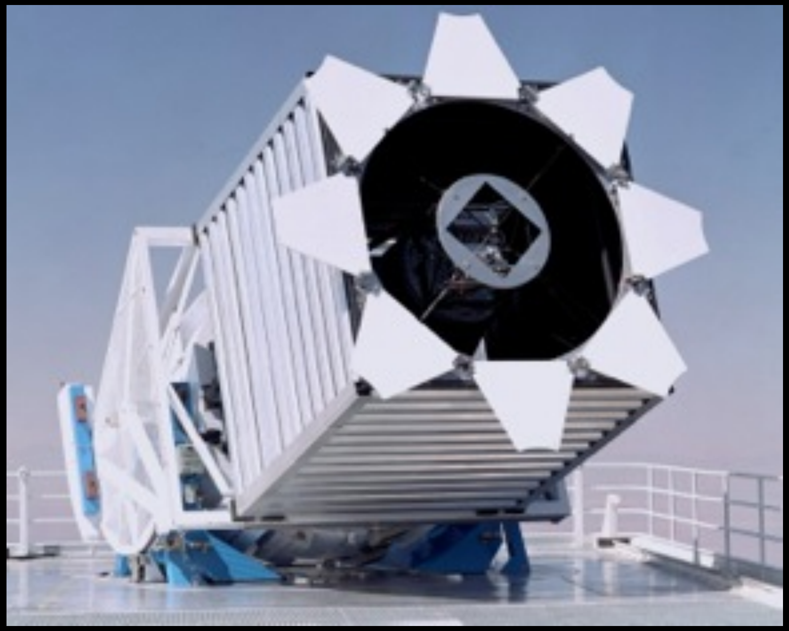
Project Scientist: Renbin Yan (U. Kentucky, USA)

One of 3 new SDSS-IV surveys

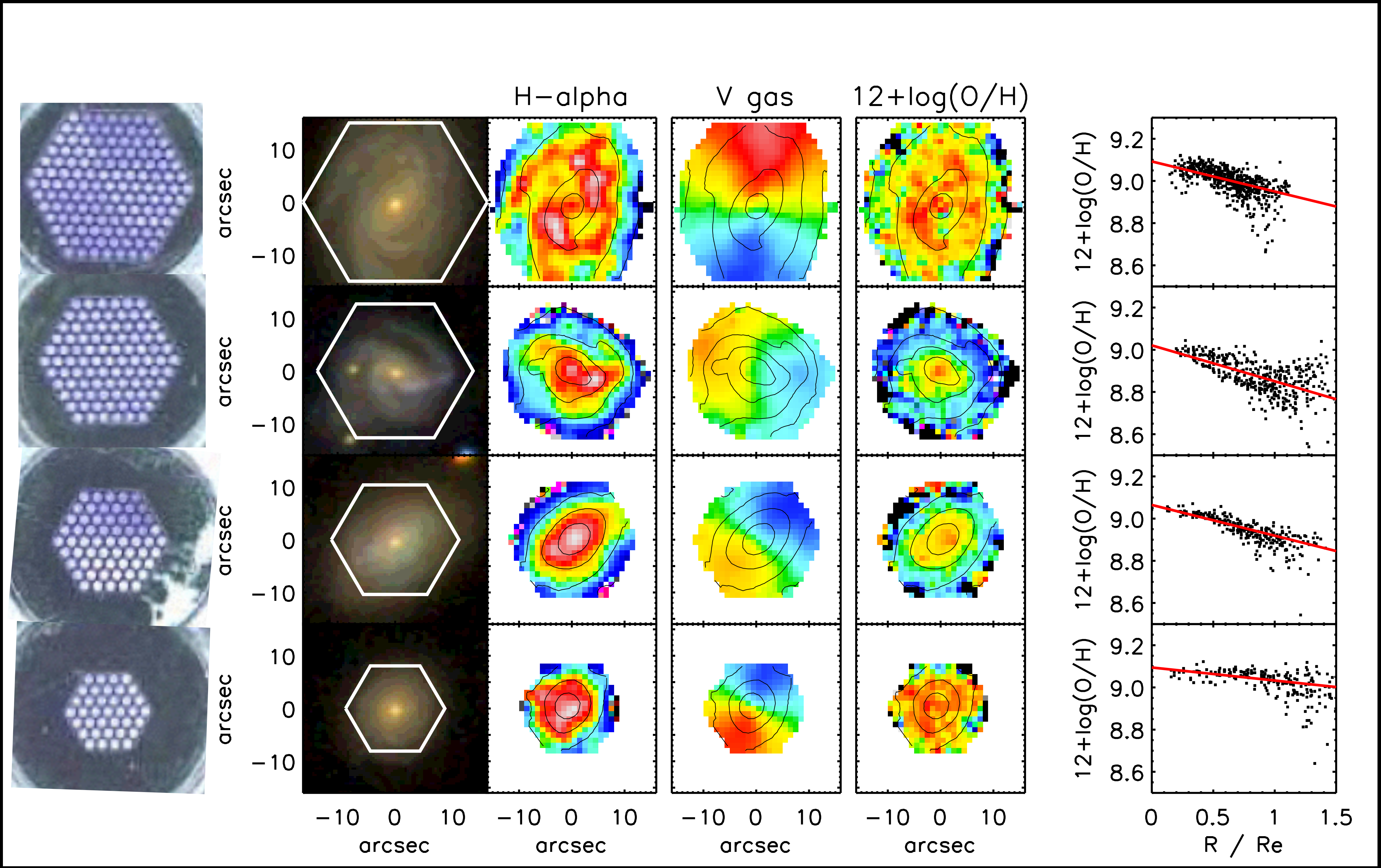
- half of dark time for 6 years
- began July 2014

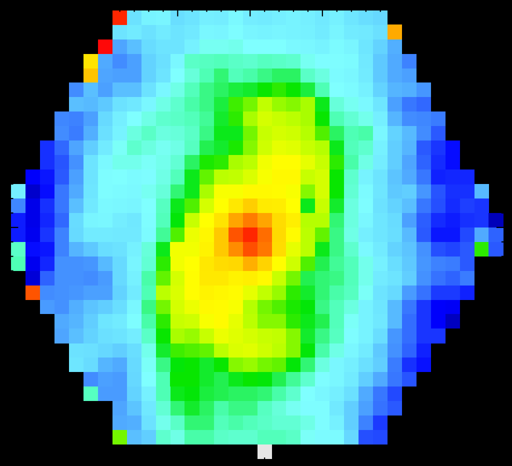
IFU spectra of 10,000 galaxies

- $z \sim 0.03$
- coverage to 1.5 and 2.5 Re
- λ=3600-10300 Å at $R \sim 2000$
- Survey overview paper to be submitted this month (Bundy et al.)

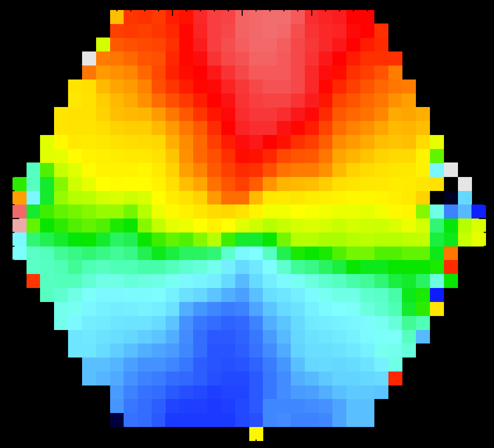


The early MaNGA data looks great!



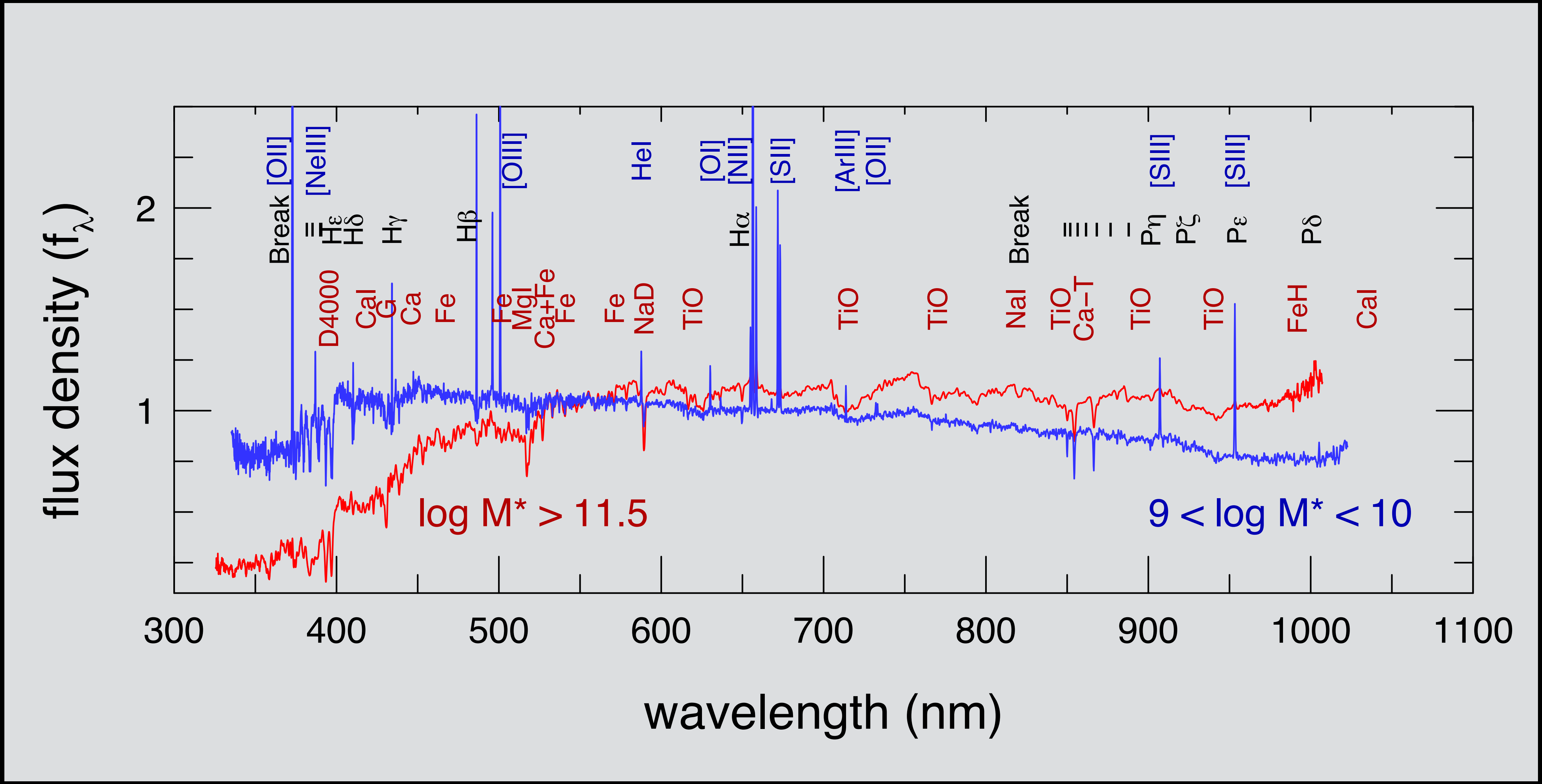


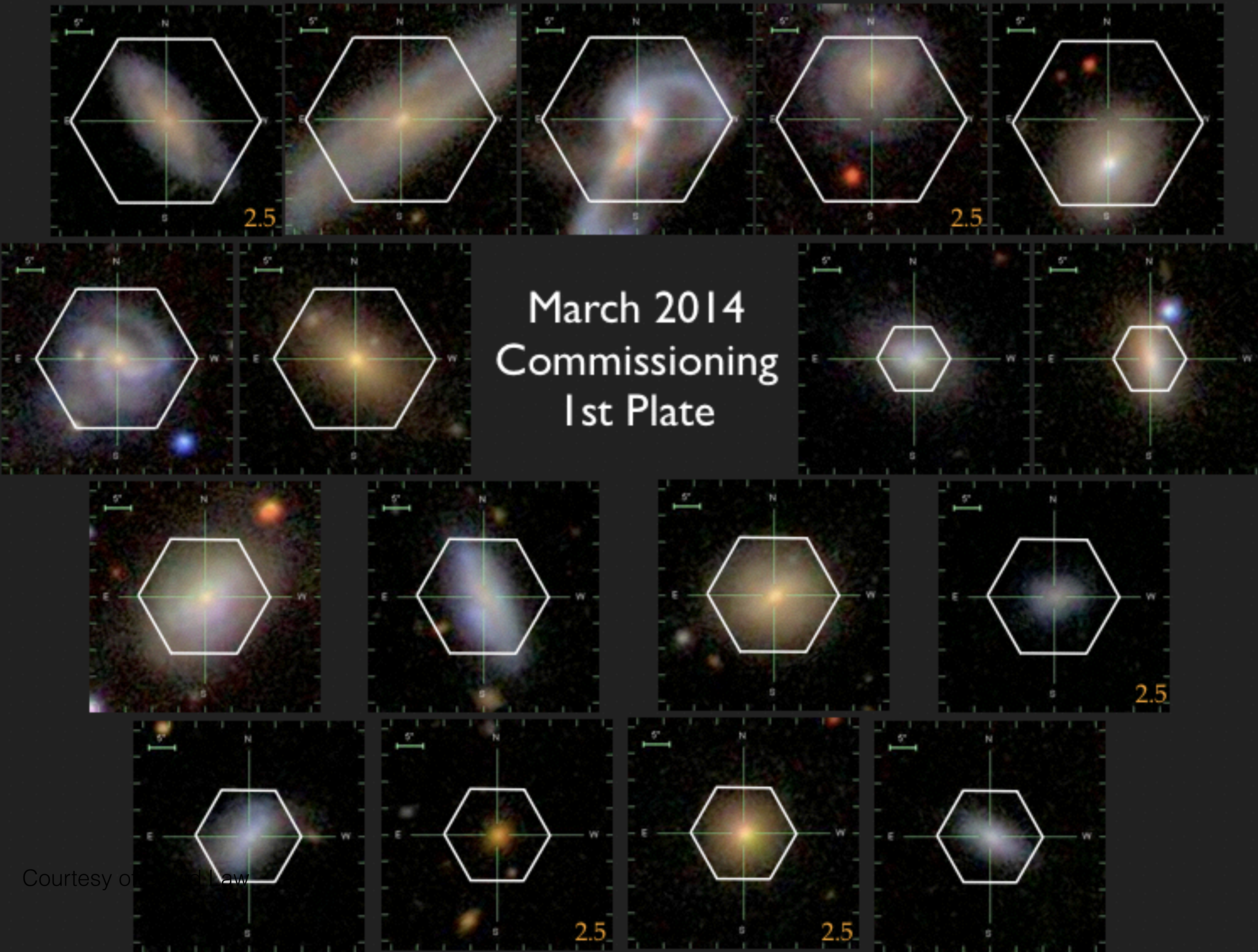
2014 Highlights:



- ⋆ Metal-poor gas accretion co-exists with outflows and recycled gas
- ⋆ The SFR "main sequence" is not flat. Its shape is modified by redshift and environment
- ⋆ Star formation efficiency (gas consumption time) changes with redshift
- ⋆ Quenching is more strongly associated with galaxy compactness than stellar mass
- ⋆ Molecular outflows are prevalent in star forming galaxies and AGN - so far only AGN appear to eject enough molecular gas to bring about quenching
- ⋆ Metallicity is a sensitive barometer of many important ingredients in galaxy evolution - high z galaxies fall off the "fundamental" Z-M*-SFR relation

The BOSS spectrographs provide wide wavelength coverage at R~2000

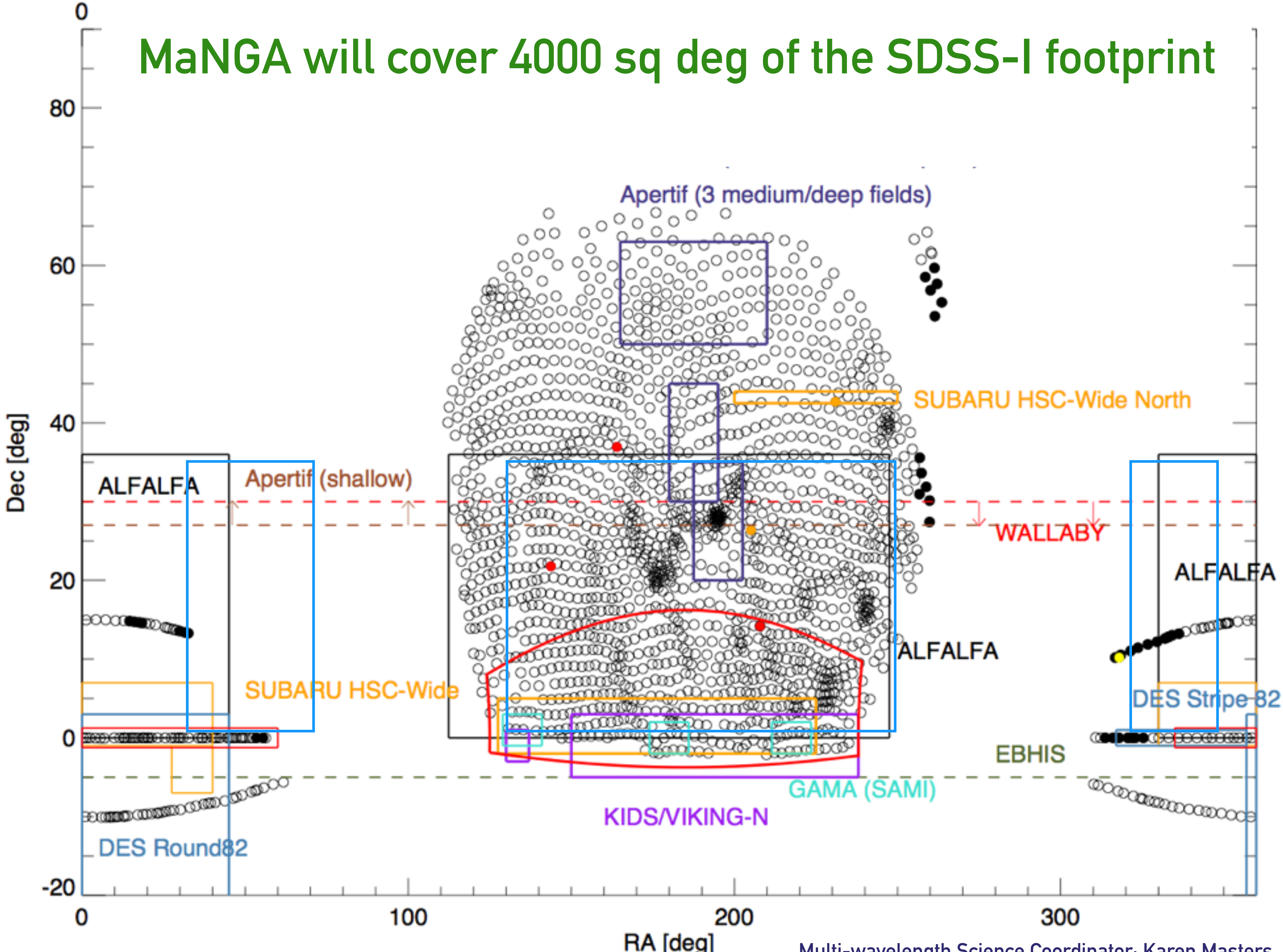




March 2014
Commissioning
1st Plate

Courtesy of [illegible]d Law

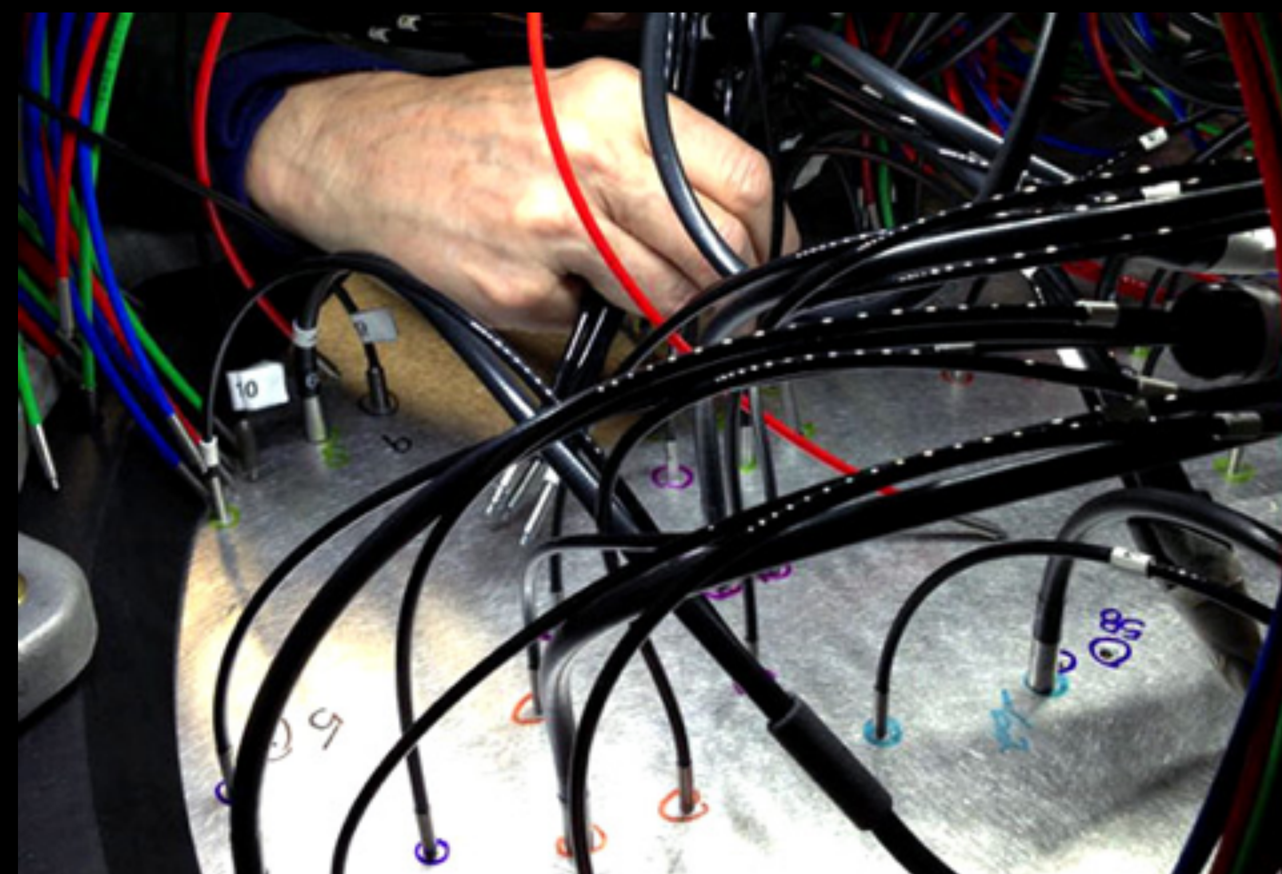
MaNGA will cover 4000 sq deg of the SDSS-I footprint



Multi-wavelength Science Coordinator: Karen Masters

MaNGA IFUs

29 deployable fiber-IFUs (17 science, 12 calibration) housed in metal ferrules that can be plugged into SDSS plates (7 sq deg)



Instrument team: Niv Drory, Matt Bershady, Nick MacDonald, Arthur Eigenbrot (here!), et al.