Star-formation Quenching:
New insights from spectroscopic surveys

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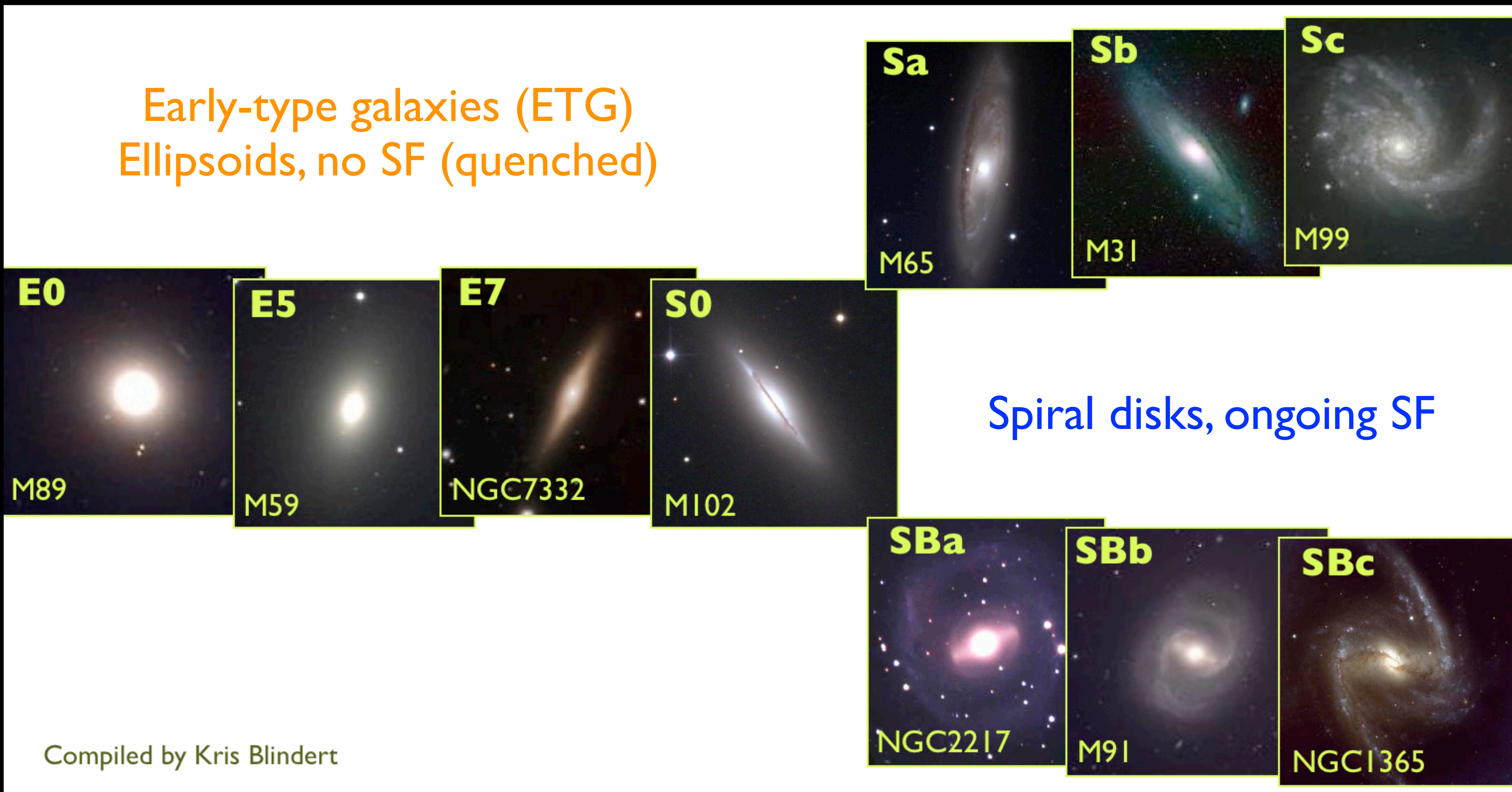
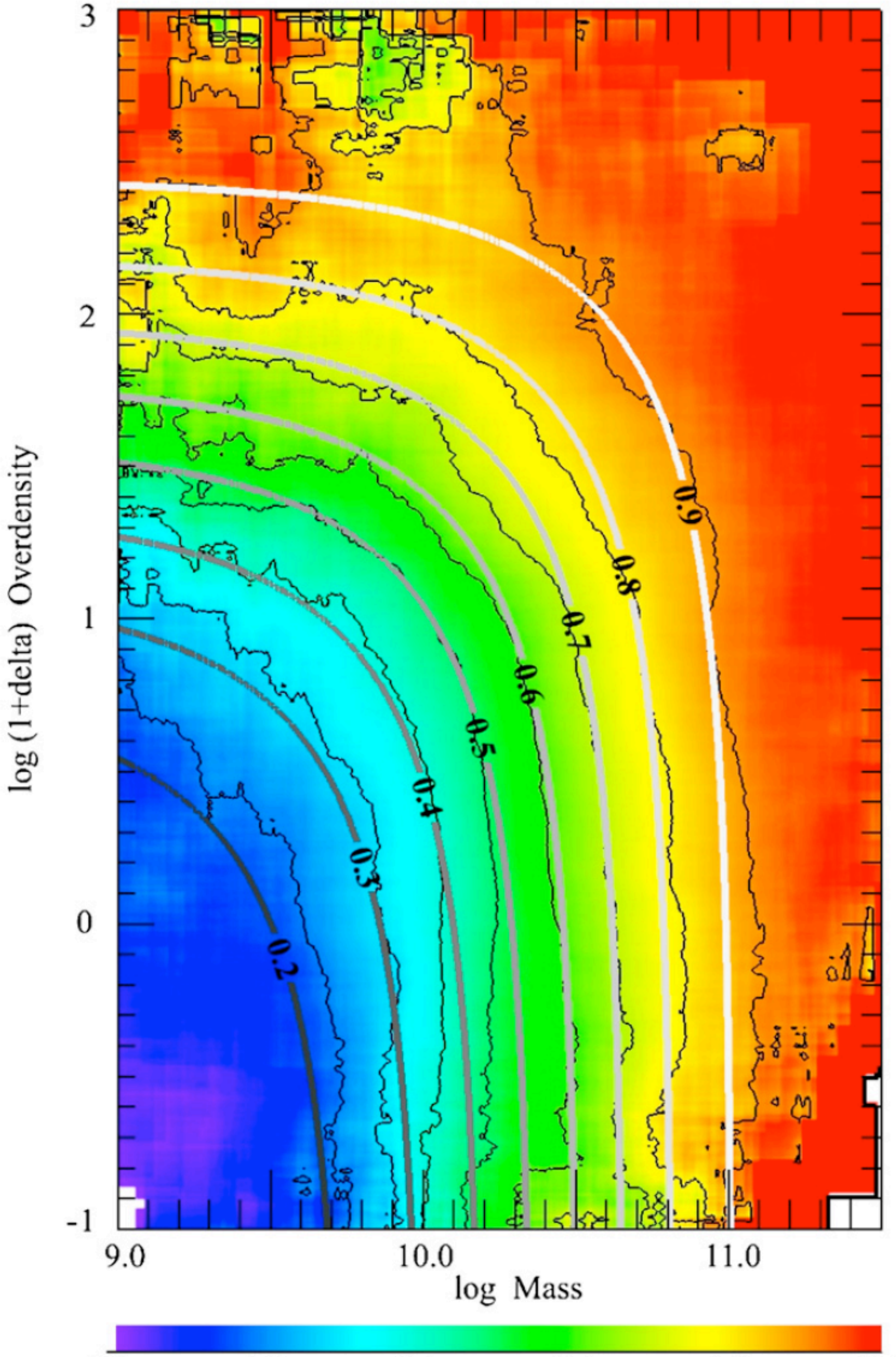
**The early growth of galaxies:
The HST, Spitzer, and Herschel joint legacy
January 11, 2016
Sesto, Italy**

Local galaxy diversity:
The end result of physical processes that affect galaxies



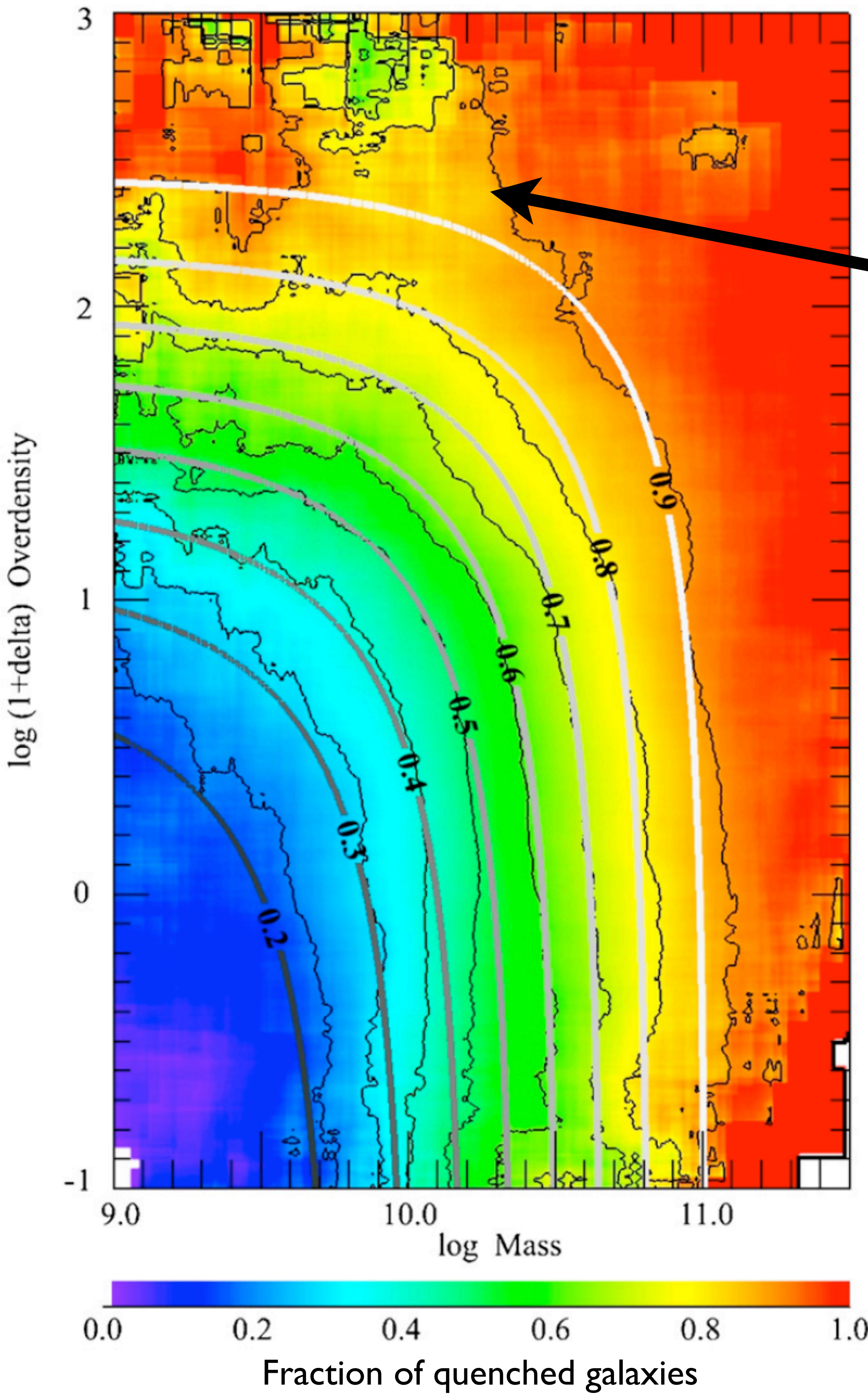
SDSS Galaxies, Peng et al. 2010, Renzini 2009

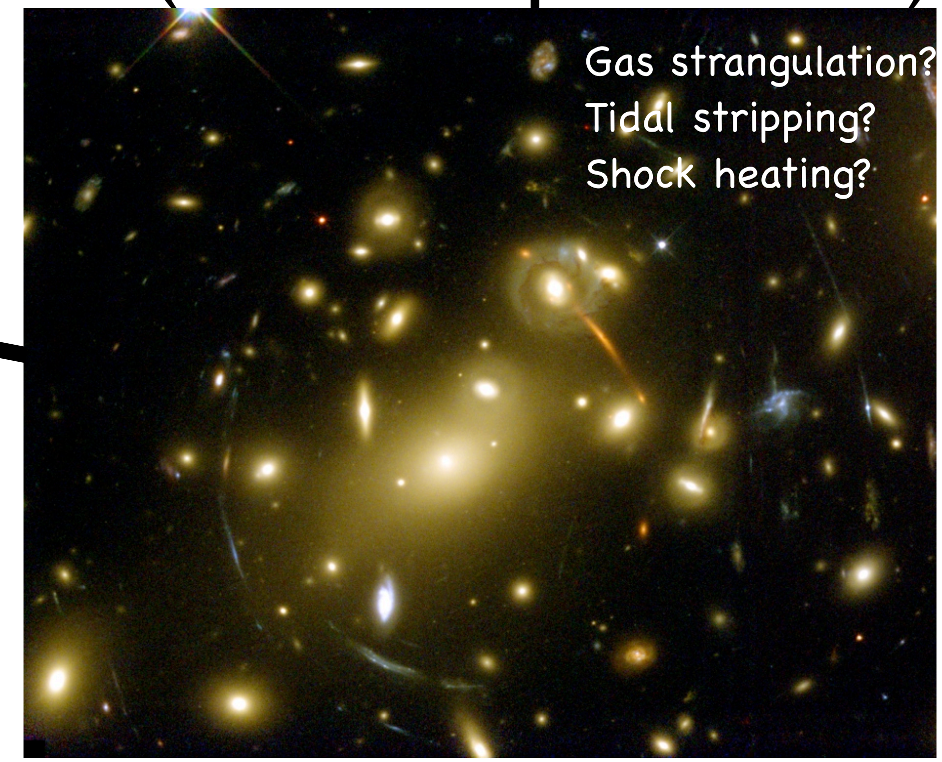


Fraction of quenched galaxies

Environment Quenching (external processes)

SDSS Galaxies, Peng et al. 2010, Renzini 2009





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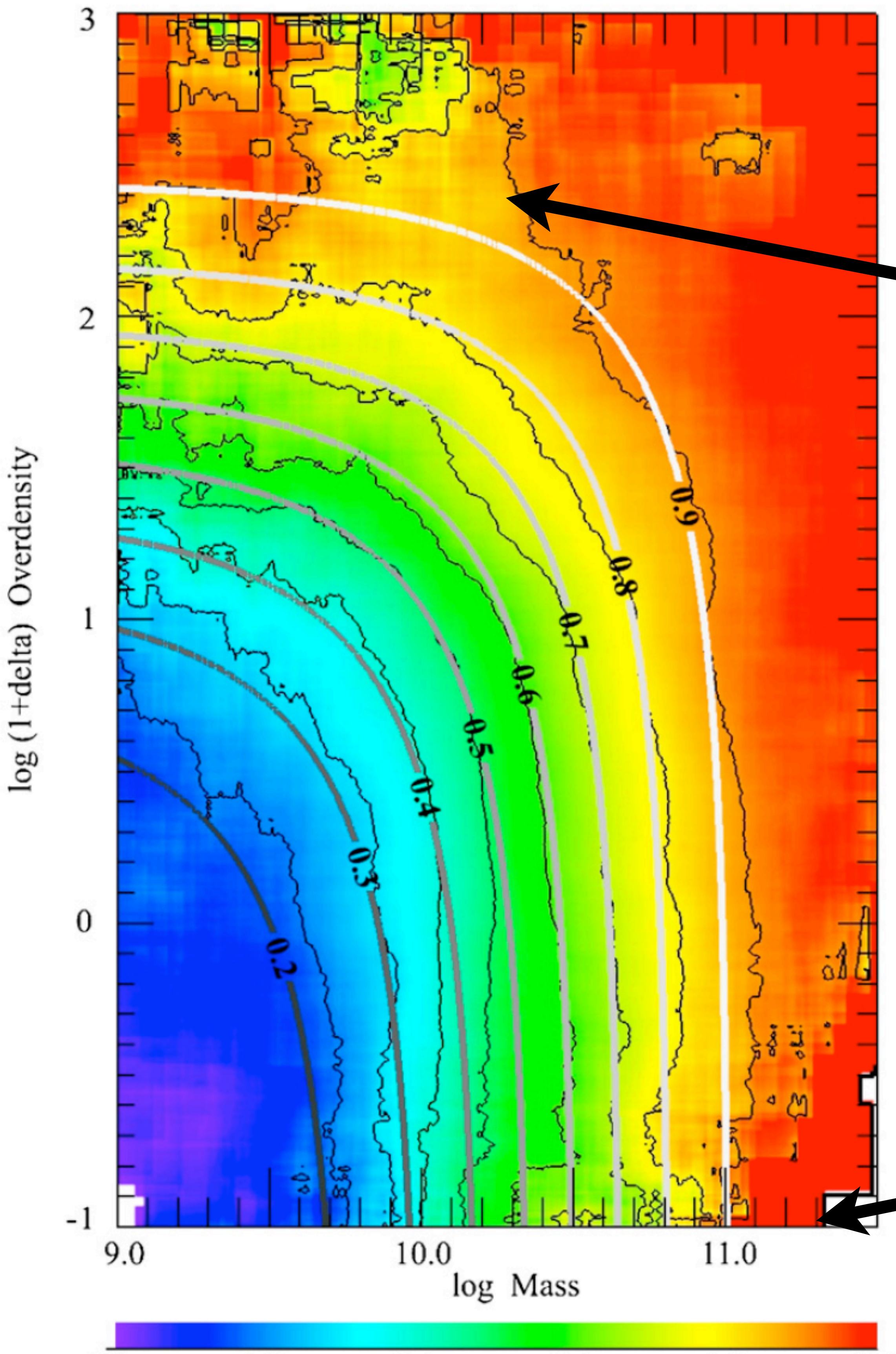

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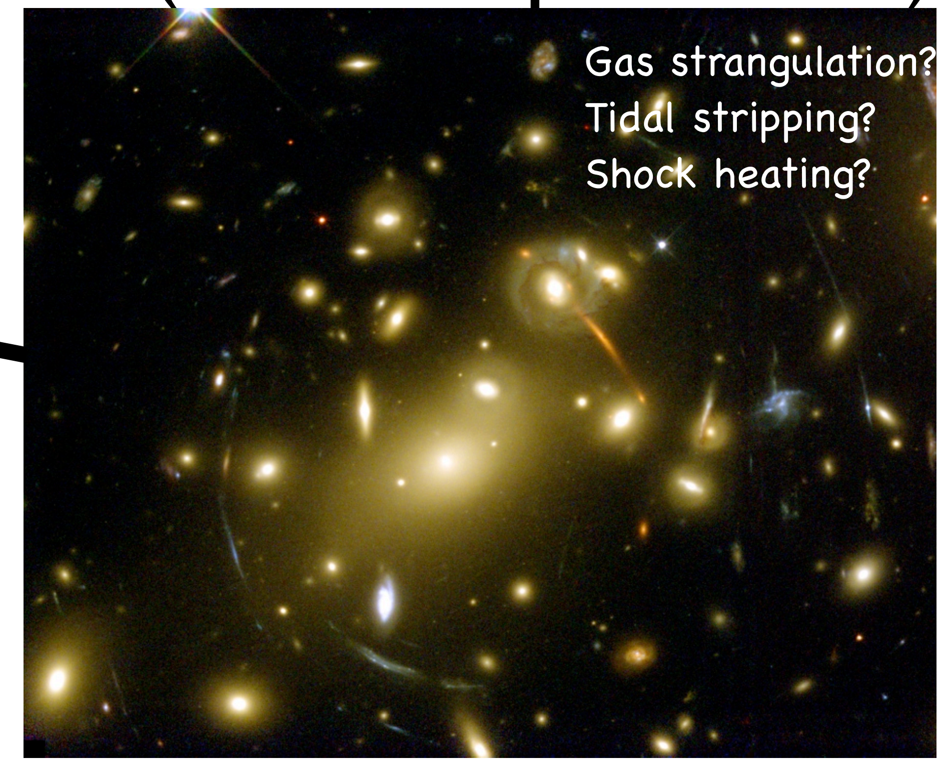
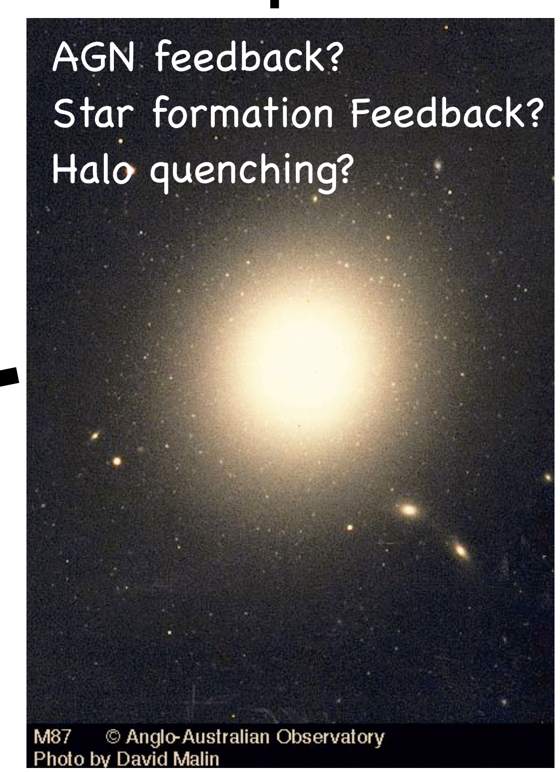
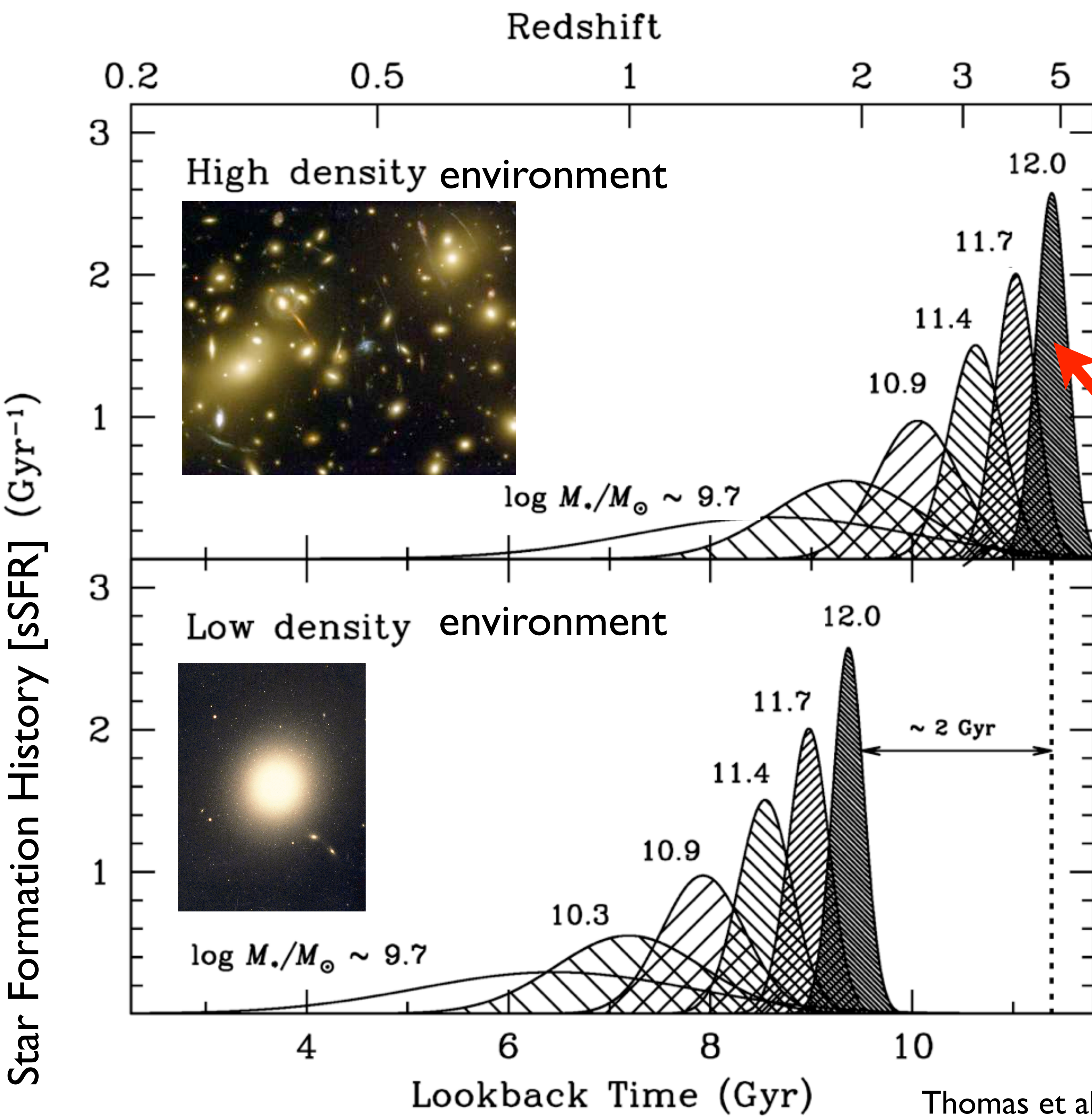


Mass Quenching (internal processes)



Local ETG star-formation histories from "archaeology"

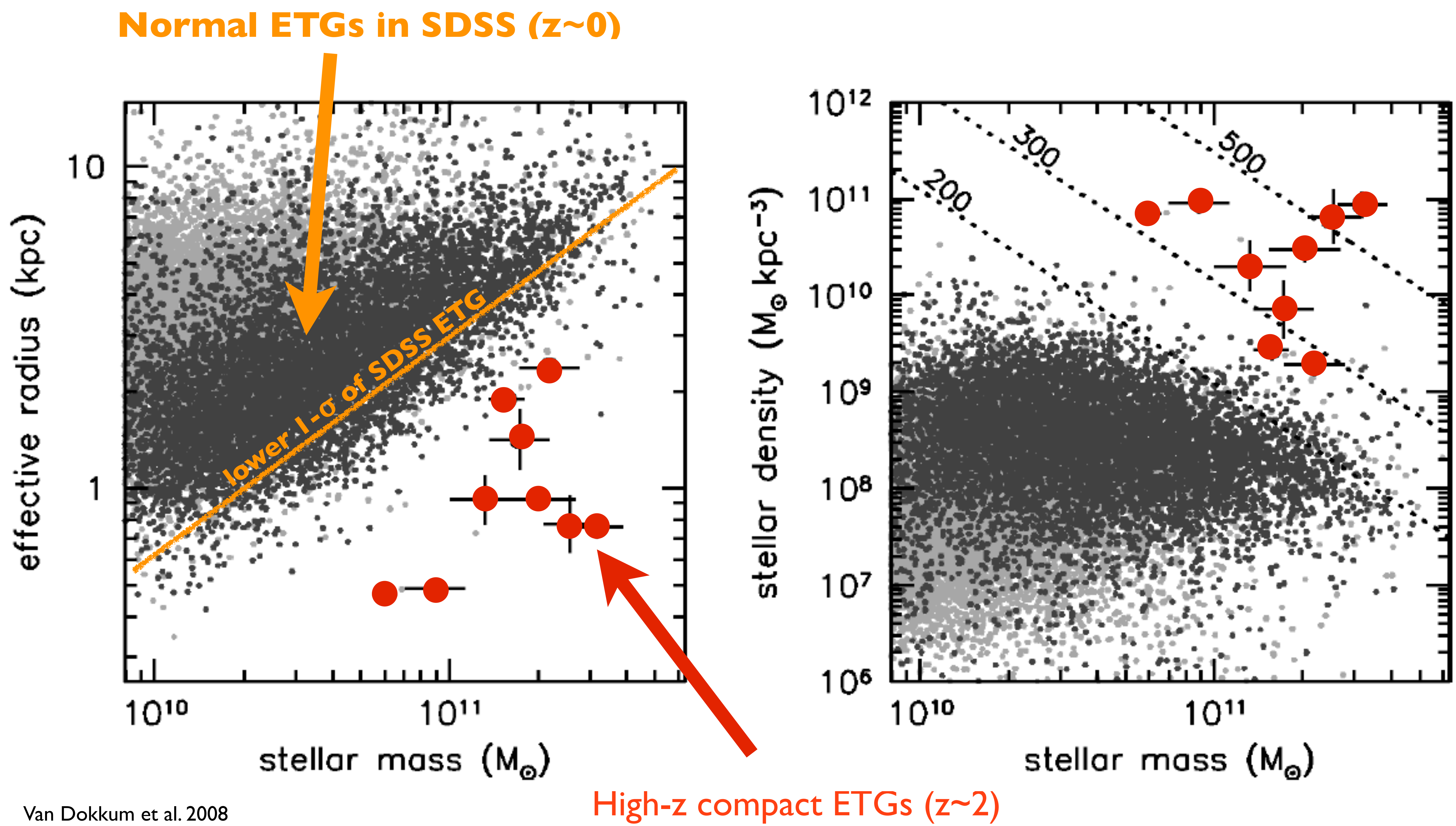


Thomas et al. 2005

Massive local ETG: rapid burst of SF

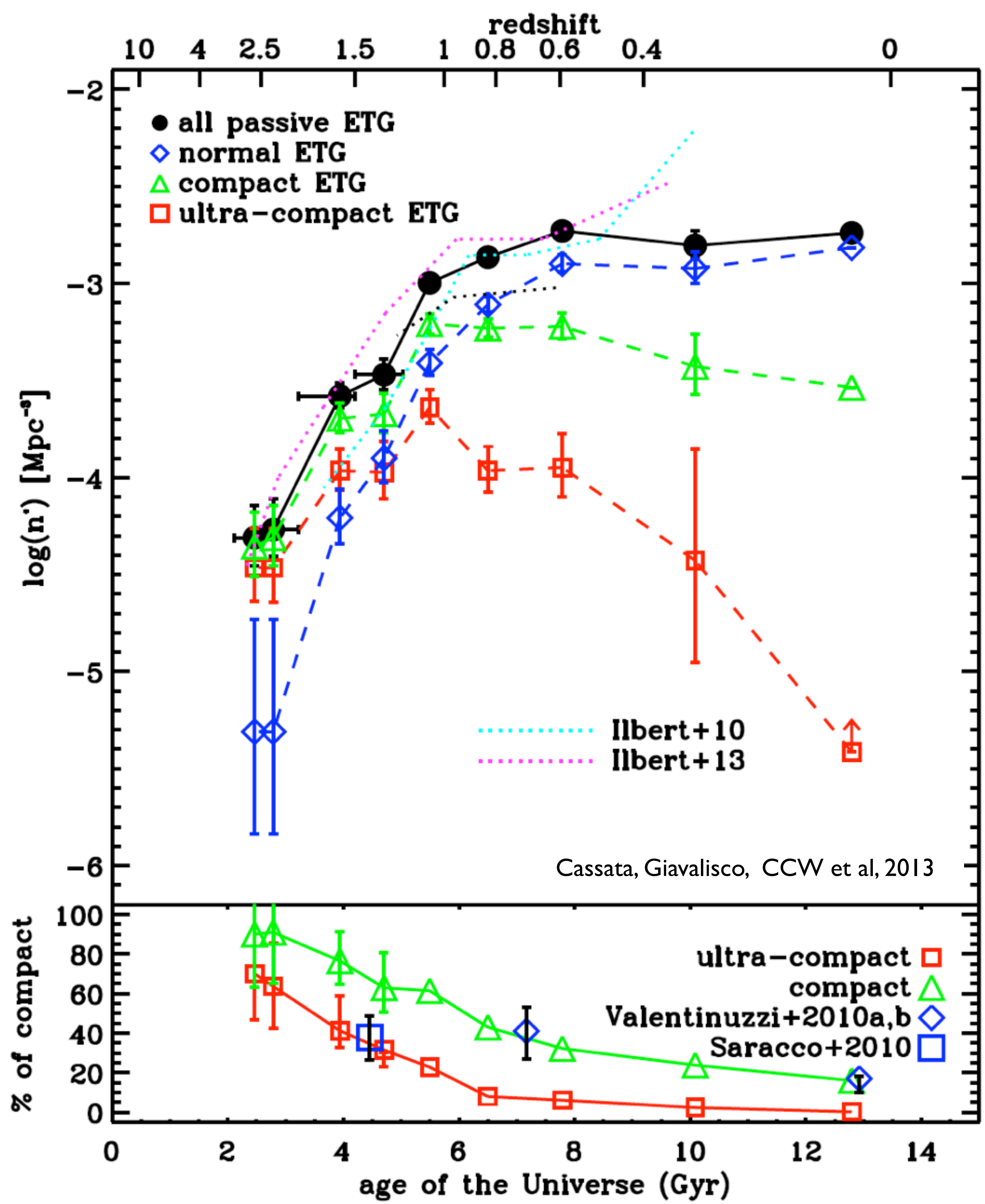
Quenching occurs at high-z

The first galaxies to quench SF: very compact (small size, high stellar density)



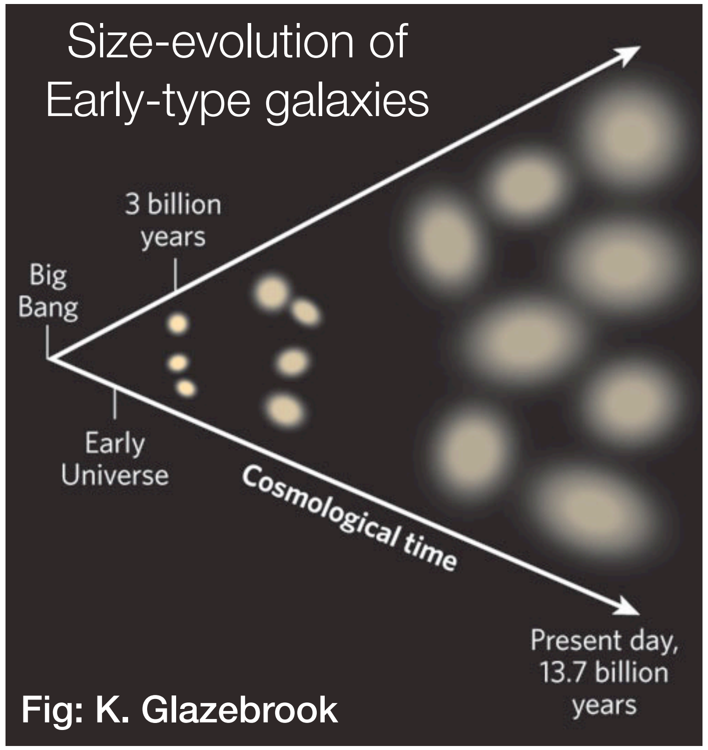
Van Dokkum et al. 2008

First galaxies to quench SF are compact



compact > 3×10^9 $M_\odot/kpc^2$
(denser than lower 1-σ of local ETG)

ultra-compact: > 1.2×10^{10} M_{sun}/kpc^2



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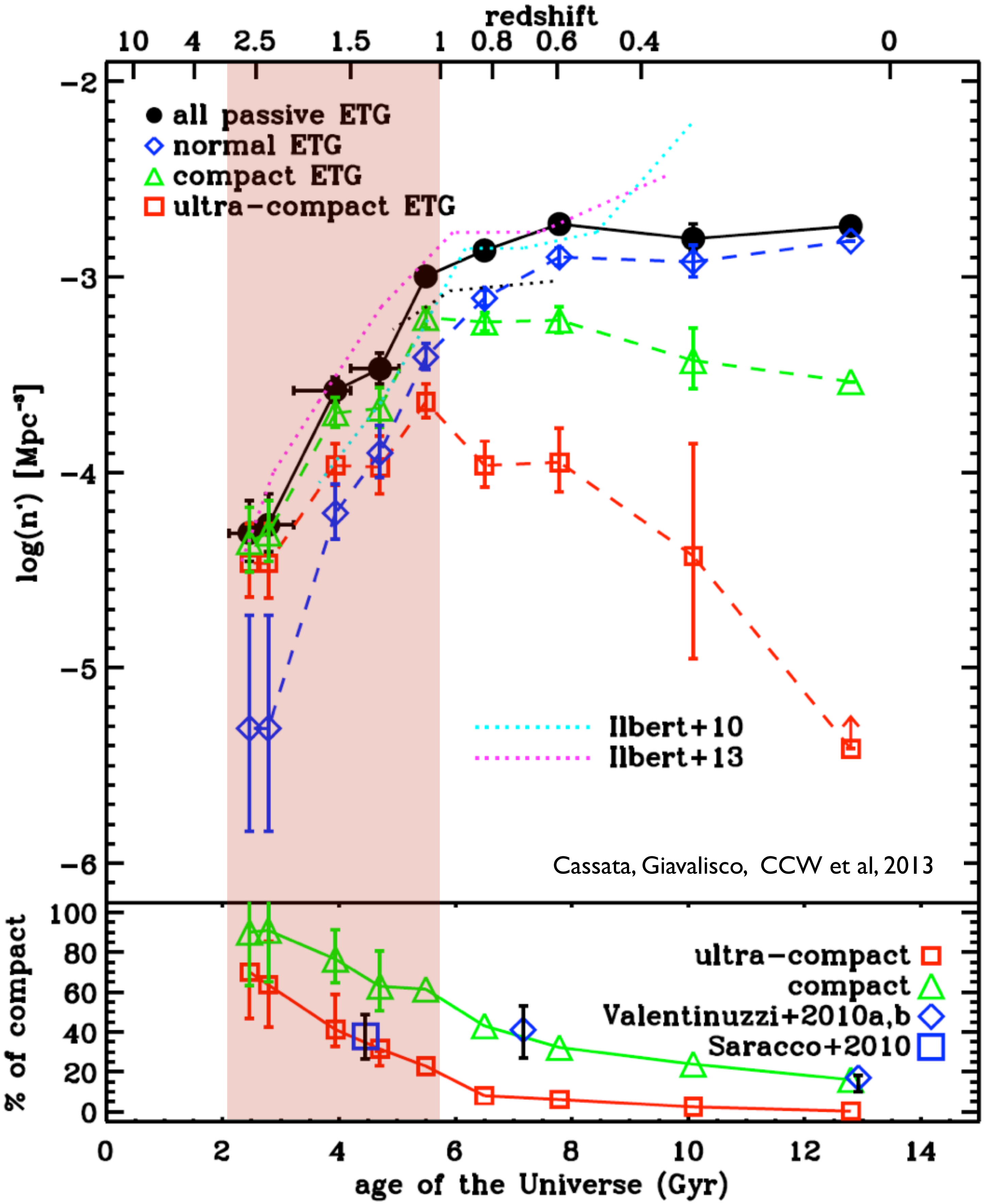
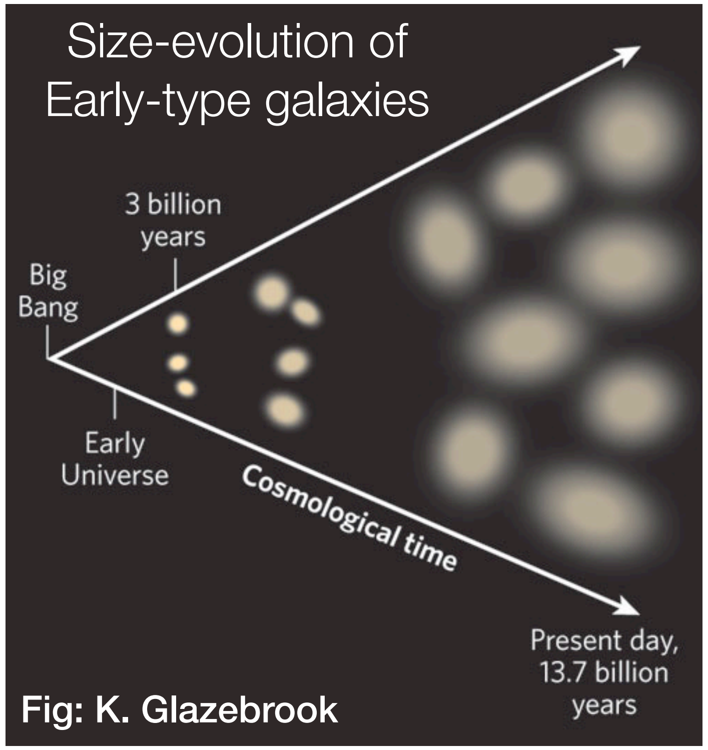


Compact/Ultra-compact dominate at z > 1



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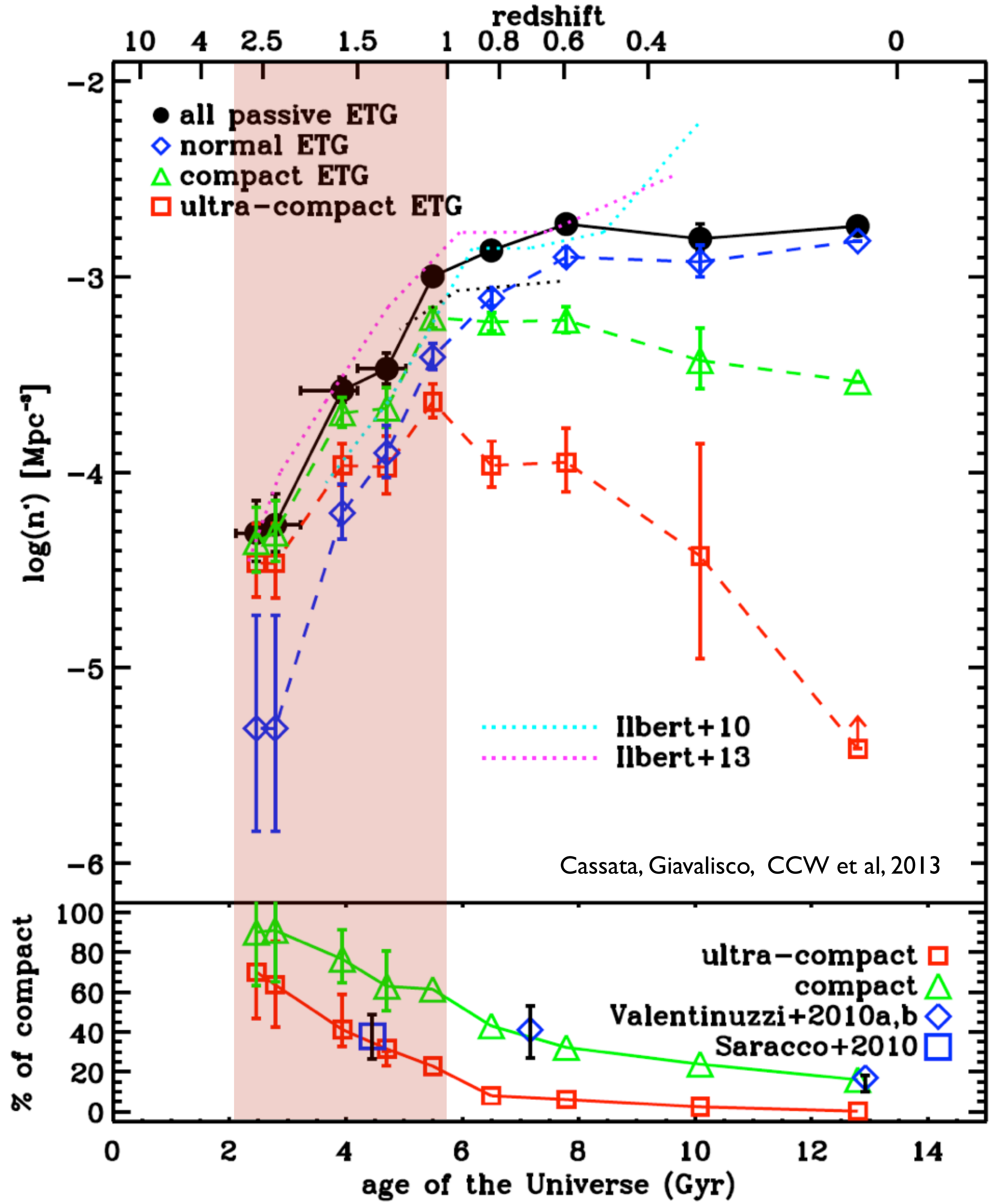
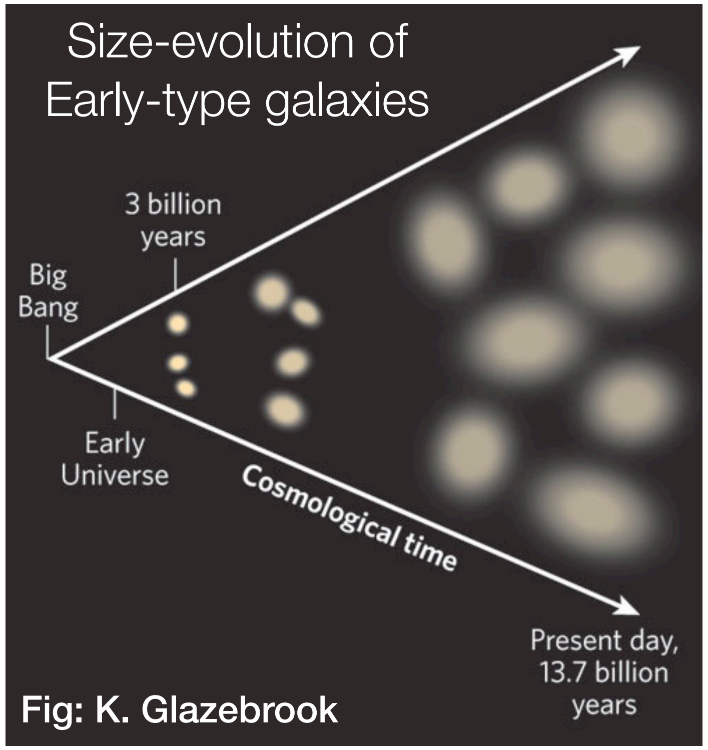


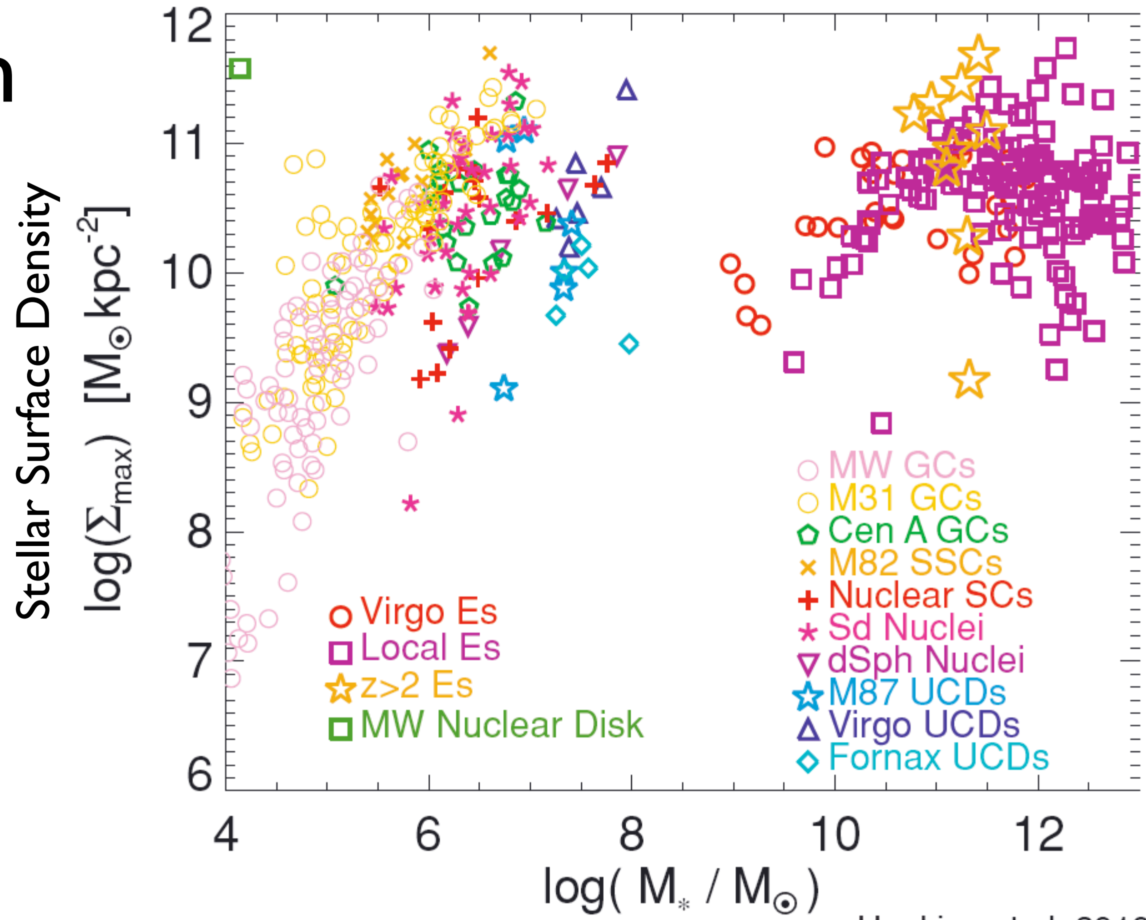
Compact/Ultra-compact dominate at z > 1

Fundamental relationship between compactness and quenching?
(e.g. Bell et al. 2012, Cheung et al. 2012)



What is relationship (if any) between compactness and quenching?

Does high stellar density cause quenching?
(e.g. Hopkins et al. 2010)



Hopkins et al. 2010

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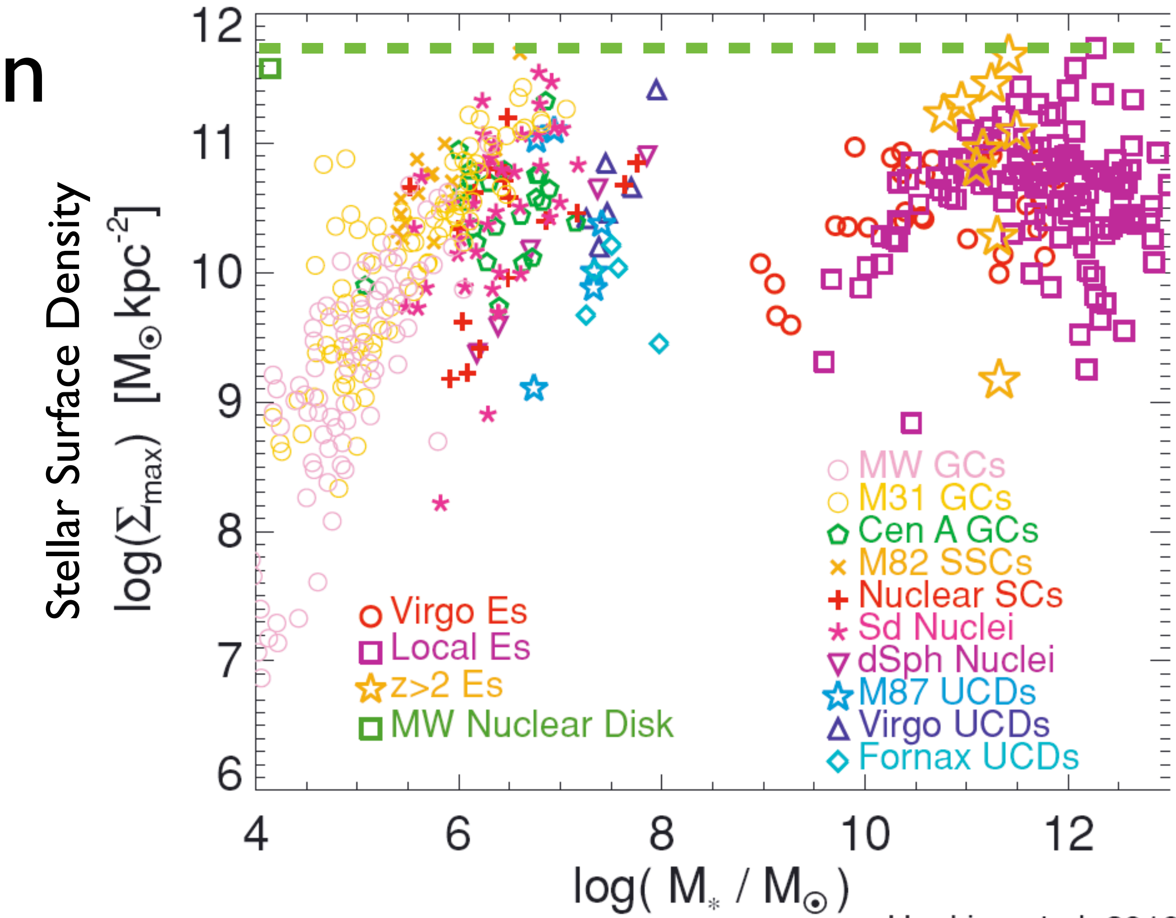

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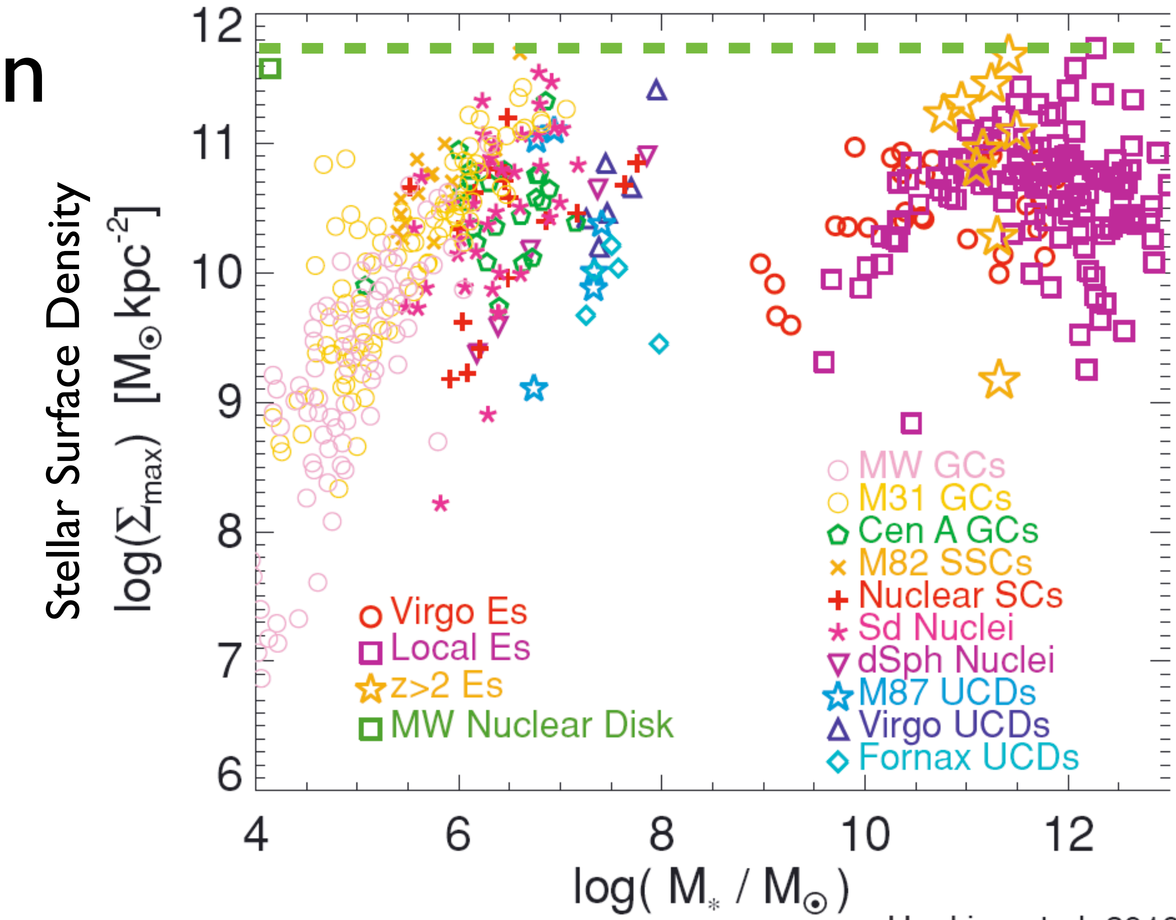
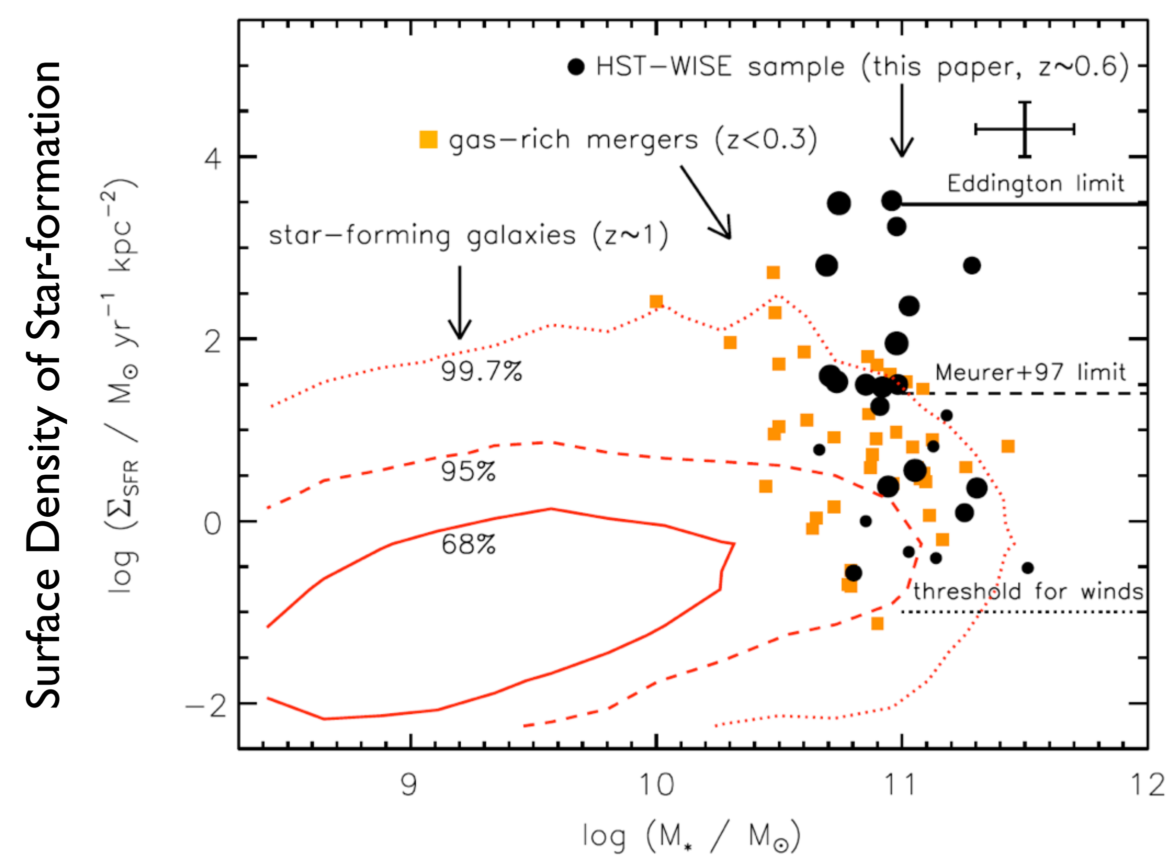


Hopkins et al. 2010

High surface density of SF regulate growth via stellar feedback?
(e.g. Diamond-Stanic et al. 2012)



Diamond-Stanic et al. 2012

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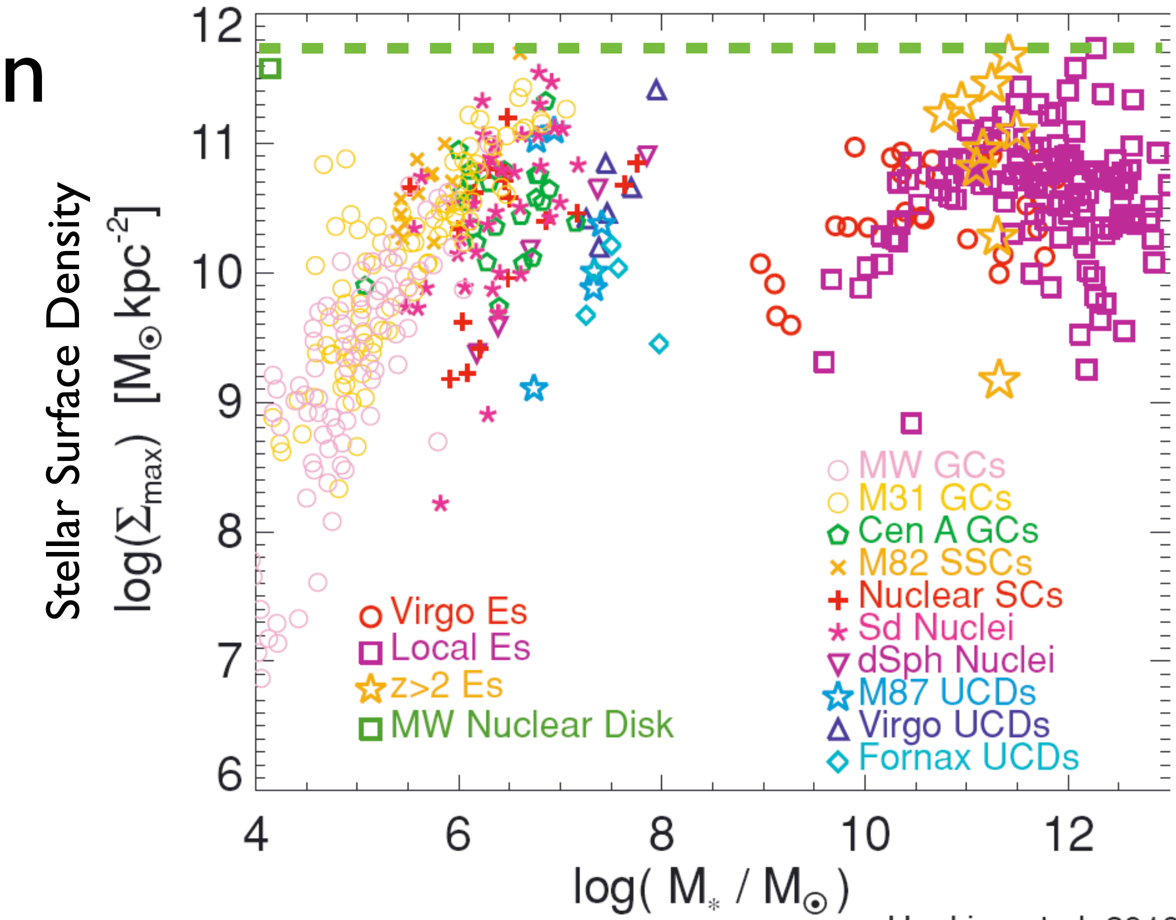

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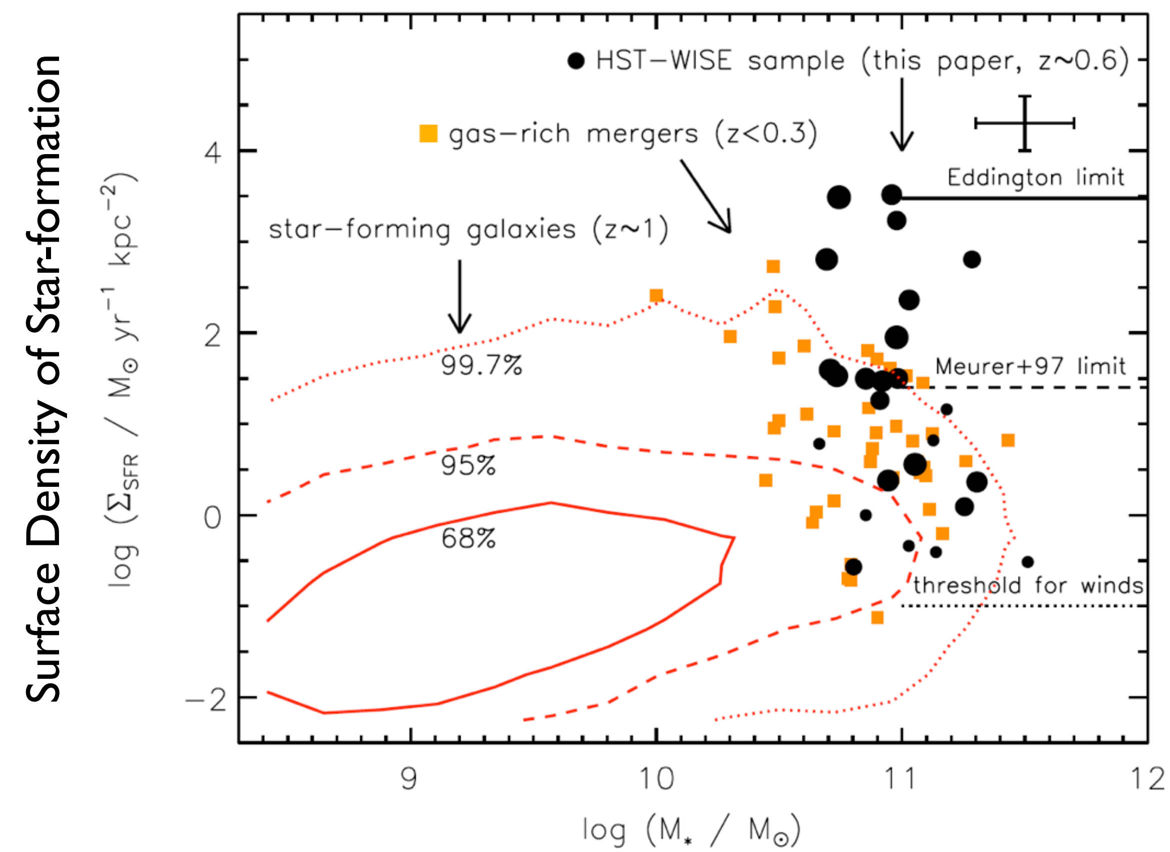


Diamond-Stanic et al. 2012

-OR-

Coincidence? Compact galaxies stop SF first because they formed earlier in cosmic time?
(e.g. Carollo et al. 2013)

Combining high-resolution HST surveys with ground-based spectroscopy: New insights into quenching at high-redshift

1. Early-Type Galaxies (ETG) at z~1.2: the connection between morphology (stellar density) and quenching (in collaboration with Mauro Giavalisco)

2. Observing the feedback mechanisms and learning their physics during the SF phase (using ETG progenitors) at z > 2

3. Upcoming programs: observing the energy input into ISM in compact galaxies

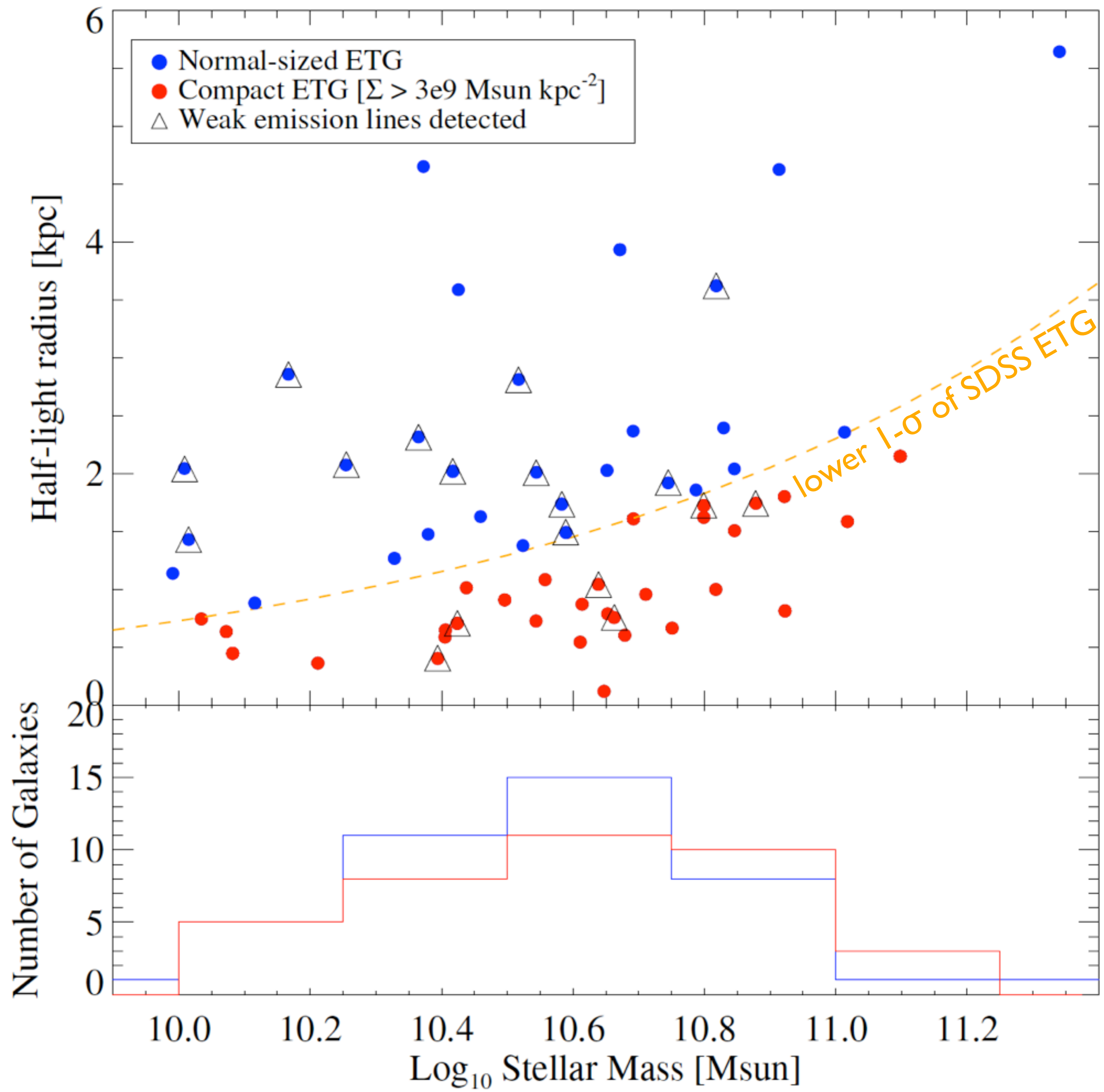
1. ETG at z~1.2: the connection between morphology (stellar density) and quenching

Selected from CANDELS H-band data in GOODS-South
(Cassata, Giavalisco, CCW et al 2013)

Deep optical spectroscopy from VLT: Fors2 and VIMOS
(Vanzella et al. 2008, Popesso et al. 2009, Kurk et al.)

log sSFR < -2 Gyr-1 (very quenched) from SED-fitting

Split into "compactness" categories:
~30 are "normal" relative to SDSS
~30 are more compact than SDSS



Williams, Giavalisco et al. (in prep)

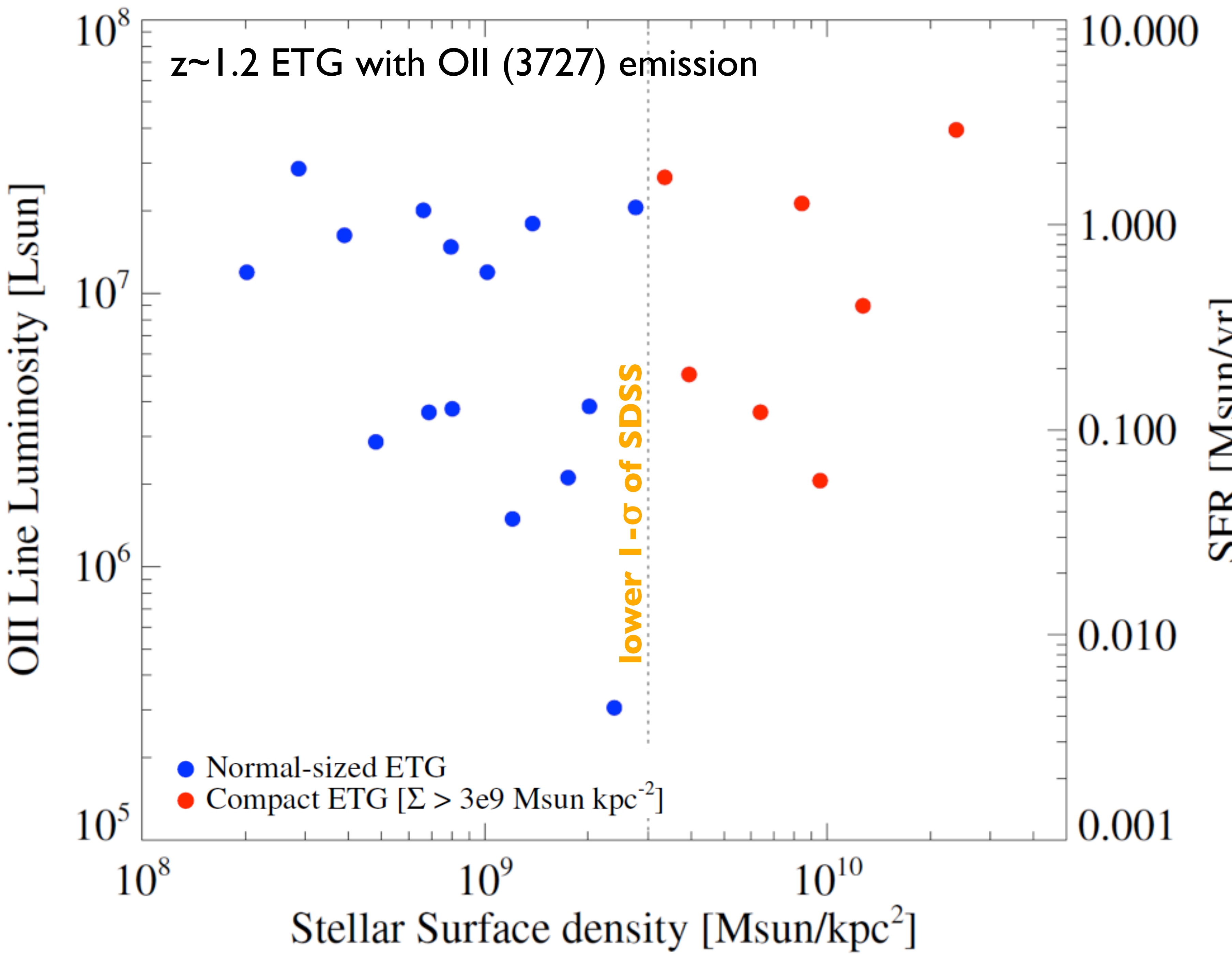
1. ETG at z~1.2: the connection between morphology (stellar density) and quenching

uniform range of OII (3727A) line luminosity:

Low Equivalent widths:
Residual or rejuvinated SF?
or low-ionization nuclear emission (LINER)?

(see also Kriek et al. 2009; Belli et al. 2015)

~30 are extended and
~30 are compact
OII detection drops with increasing stellar density!



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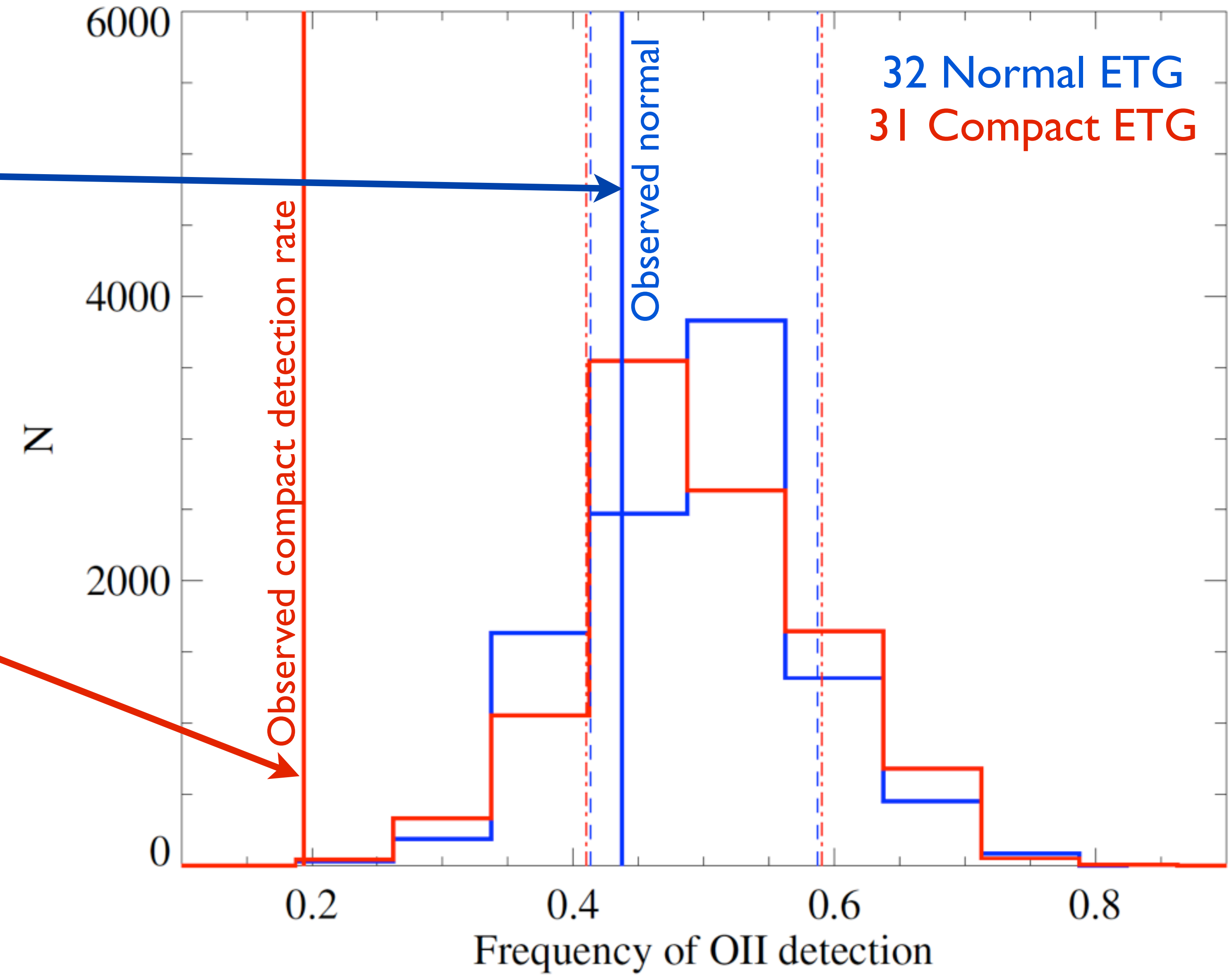
MC simulation of frequency of OII detection (assuming binomial dist)

OII emission in extended ETG are consistent with binomial distribution (i.e. 50% random chance of emission)

OII emission in compact ETG is rare: inconsistent with random chance (inconsistent with normal ETG) at 3.2-sigma



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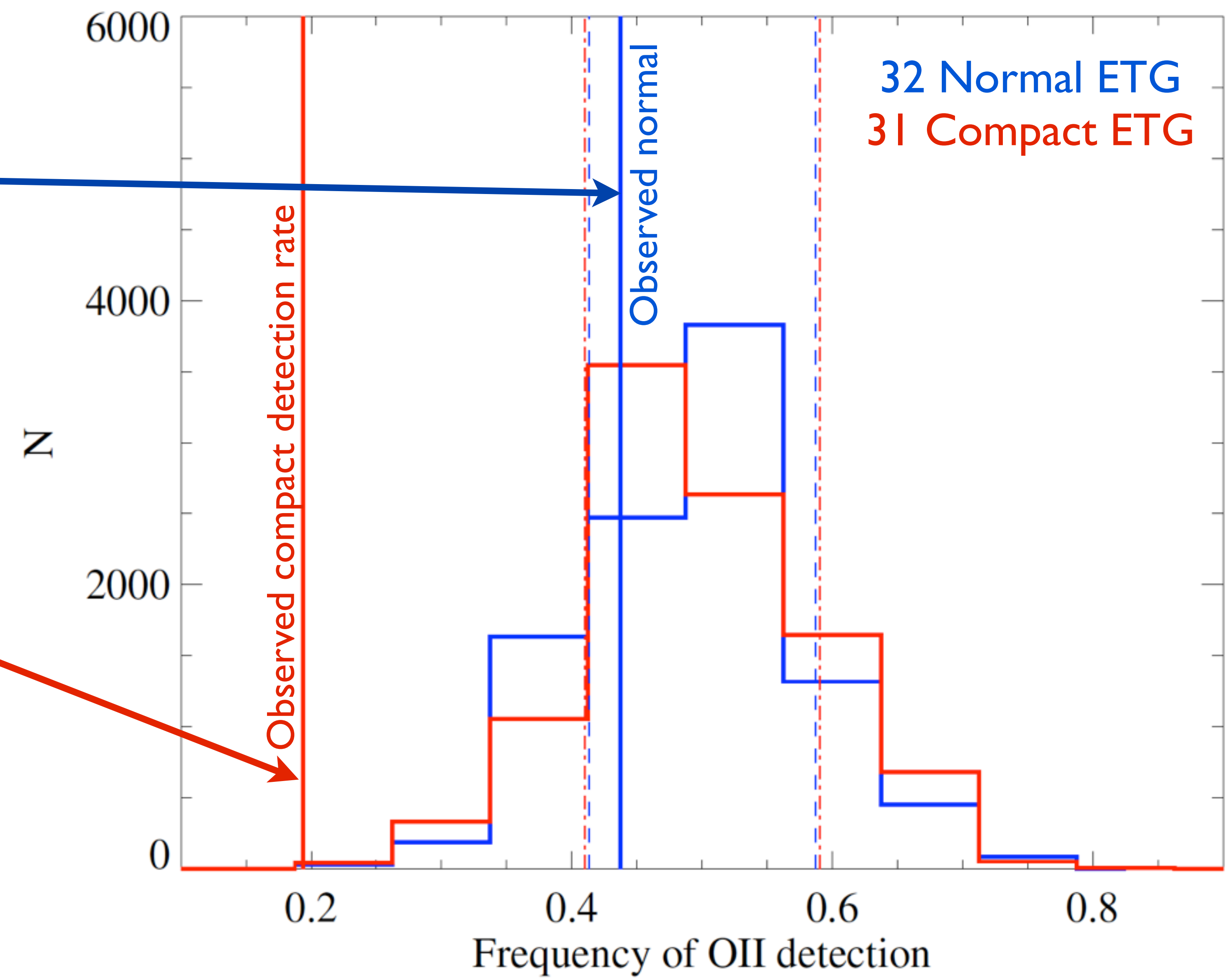
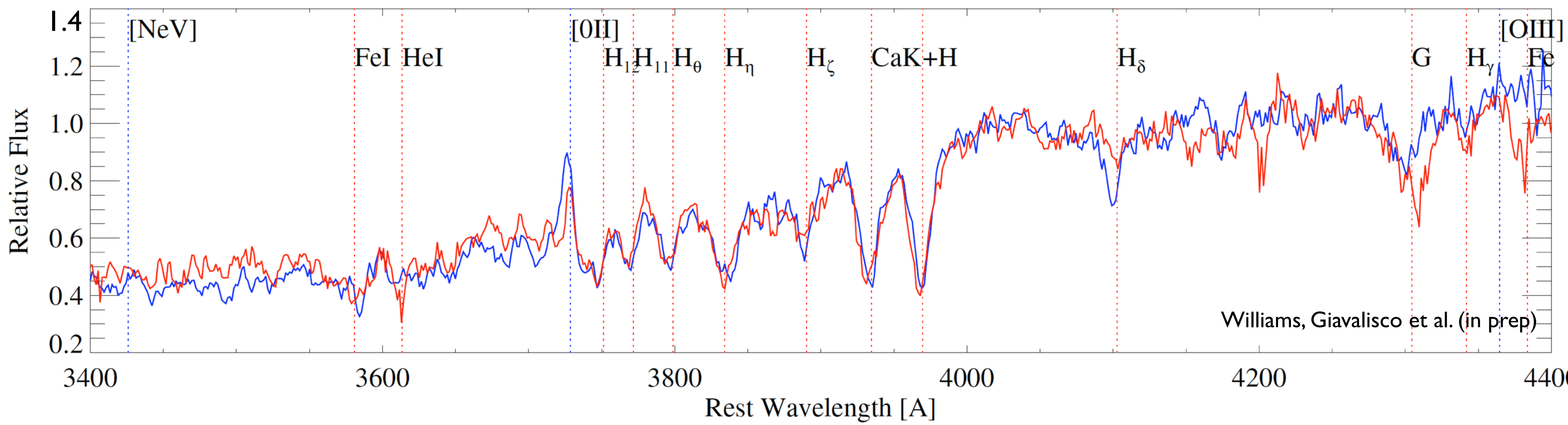


Williams, Giavalisco et al. (in prep)

Is OII residual SF? Whatever the energy source, suggests normal on avg. have quenched more recently than compact ones

1. ETG at z~1.2: the connection between morphology (stellar density) and quenching

Composite (average, sigma-clipped) VLT spectra of z~1.2 compact and normal-sized ETG



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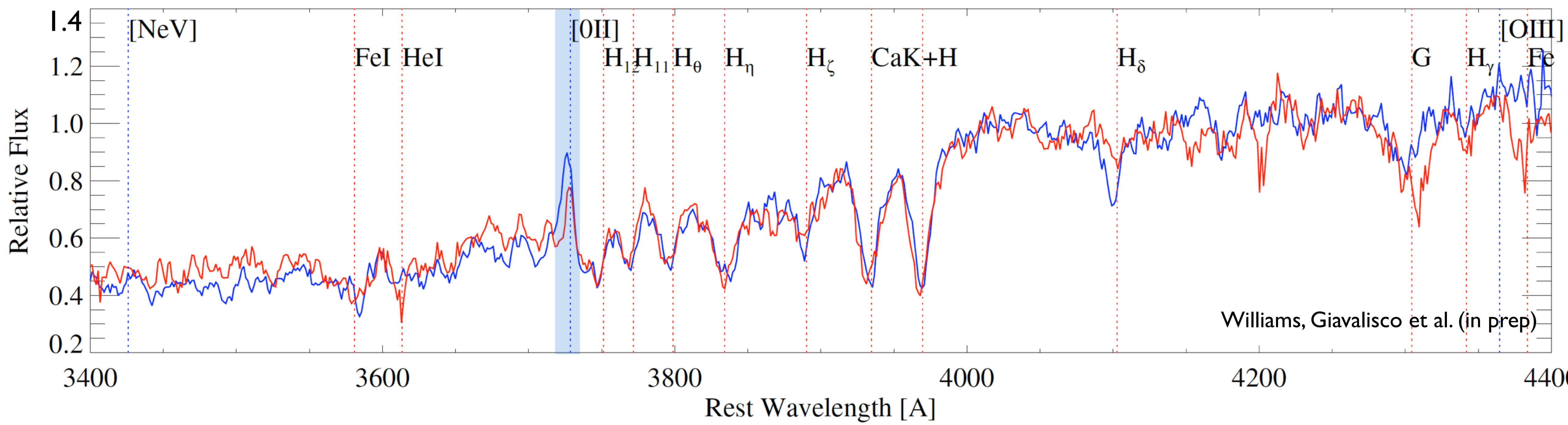

* Lower detection rate of OII emission among compact sample visible

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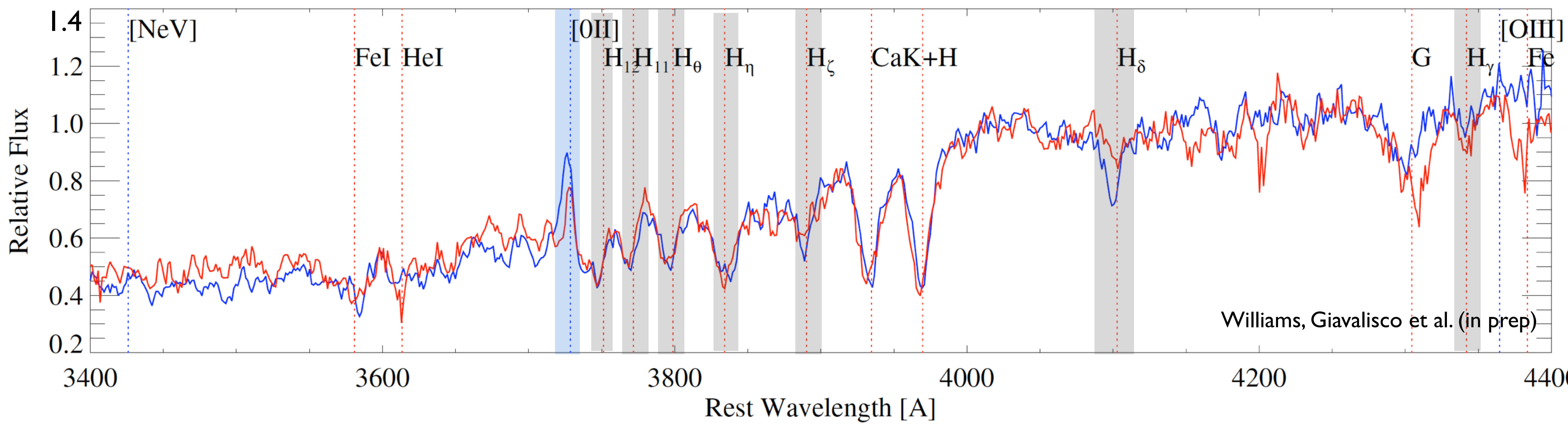

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* Both samples exhibit post-starburst features (balmer absorption, characteristic of A-stars, 1Gyr)

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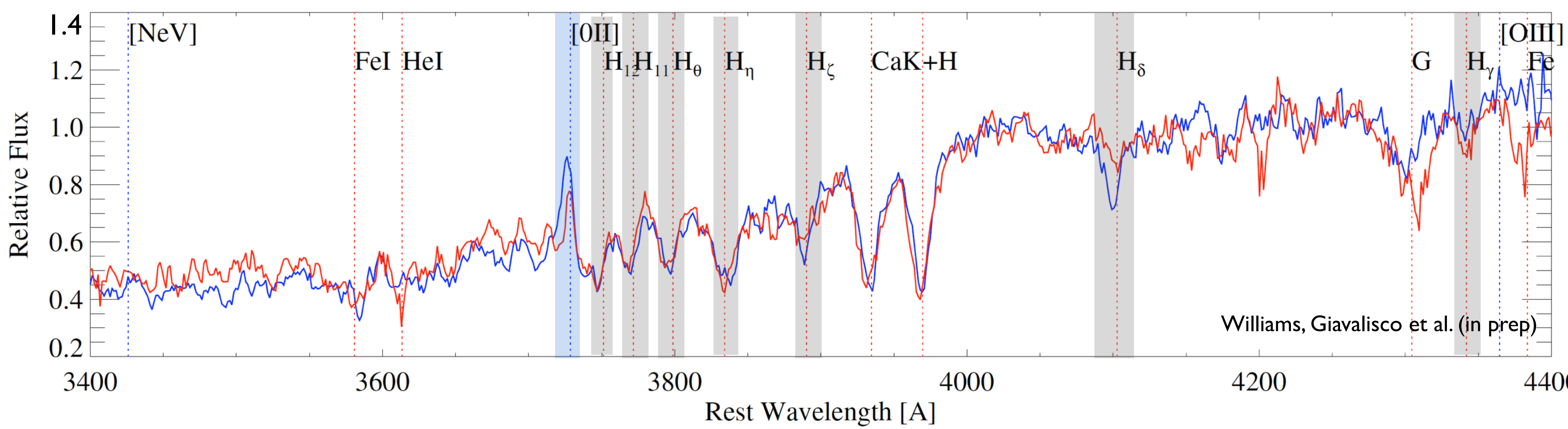

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* Stellar age diagnostics: both samples are composed of old stellar populations

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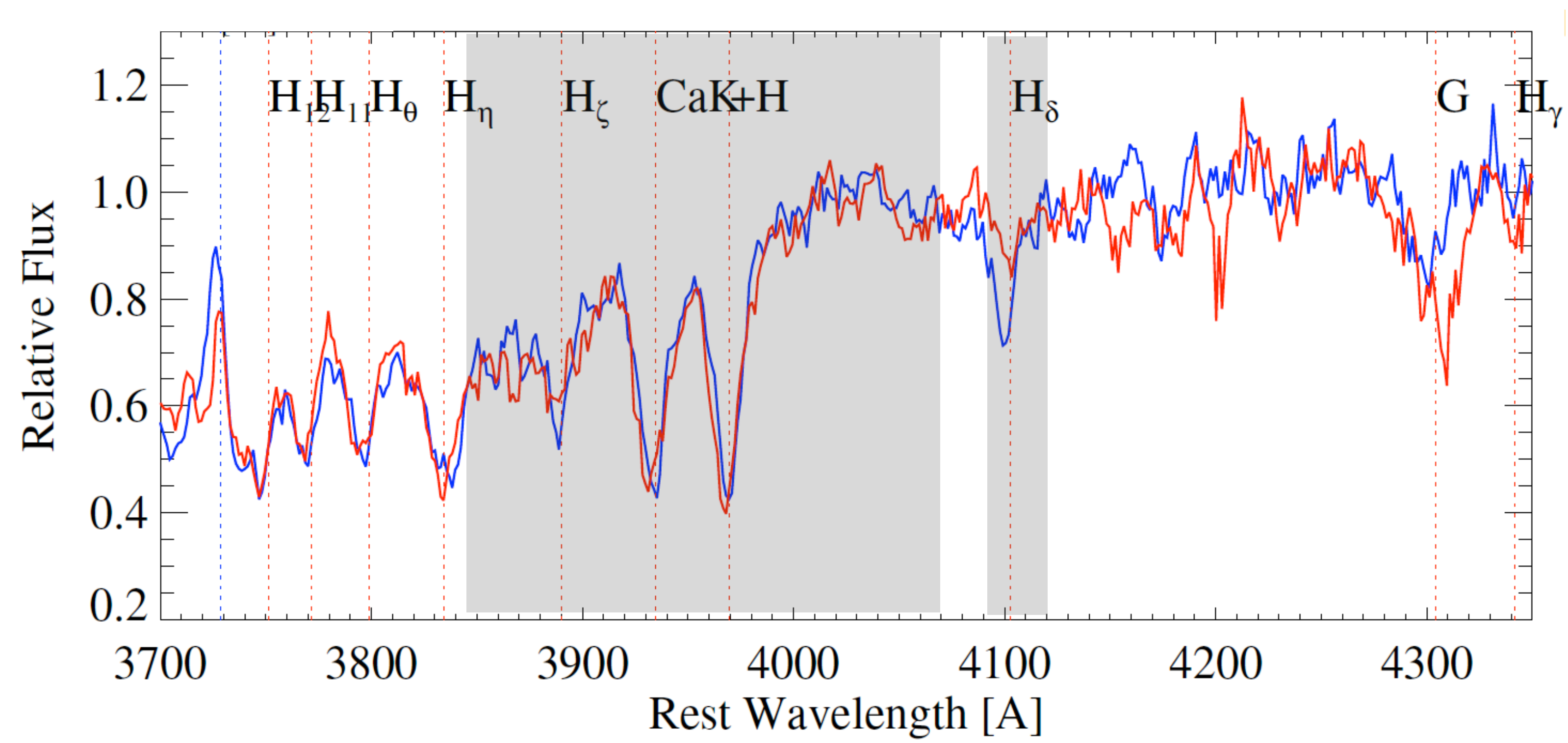


Williams, Giavalisco et al. (in prep)

Normal:
smaller 4000A break = 1.39 +/- 0.01
larger H-delta absorption = 2.73 +/- 0.06

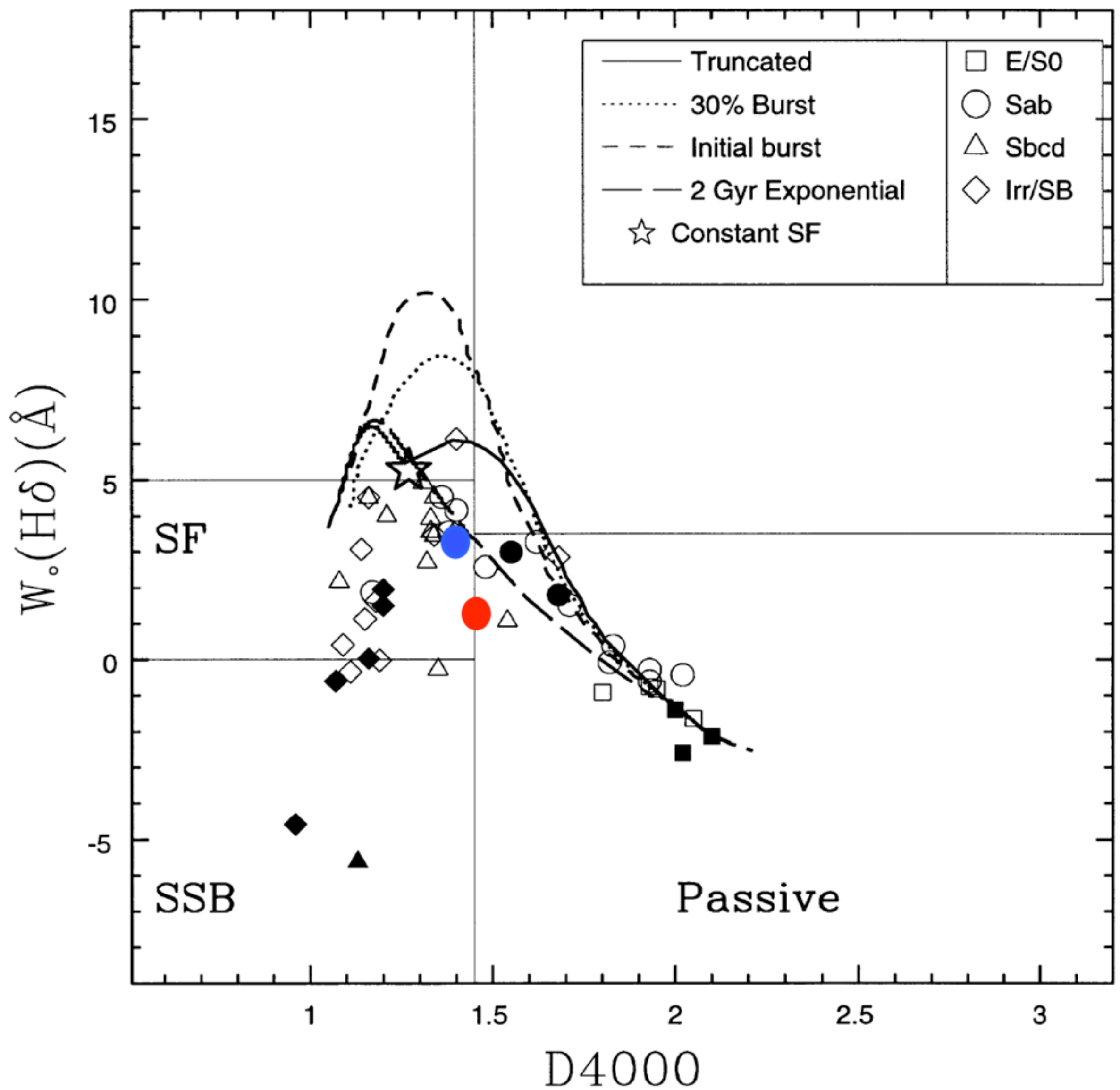
→ Younger stellar ages and/or more recent quenching

Compact:
larger 4000A break = 1.45 +/- 0.03
smaller H-delta absorption = 1.83 +/- 0.30

→ Older stellar ages and/or earlier quenching

Confirms with independent sample the trend that smaller quenched galaxies at 1<z<2 have quenched earlier (e.g. Belli, Newman & Ellis 2015)

1. ETG at z~1.2: the connection between morphology (stellar density) and quenching



Balogh et al. 1999

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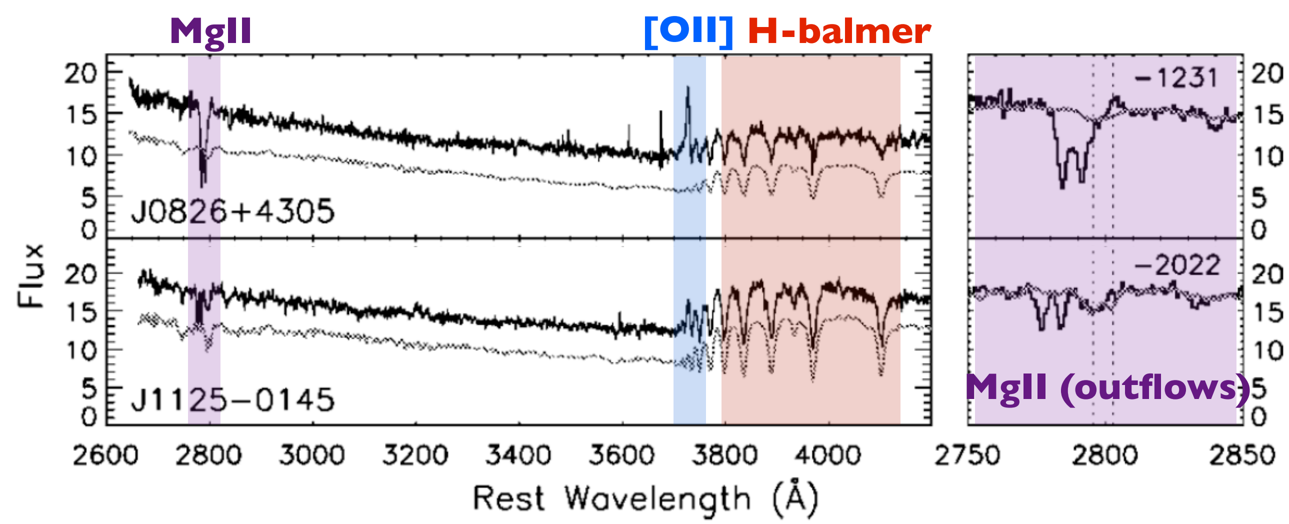
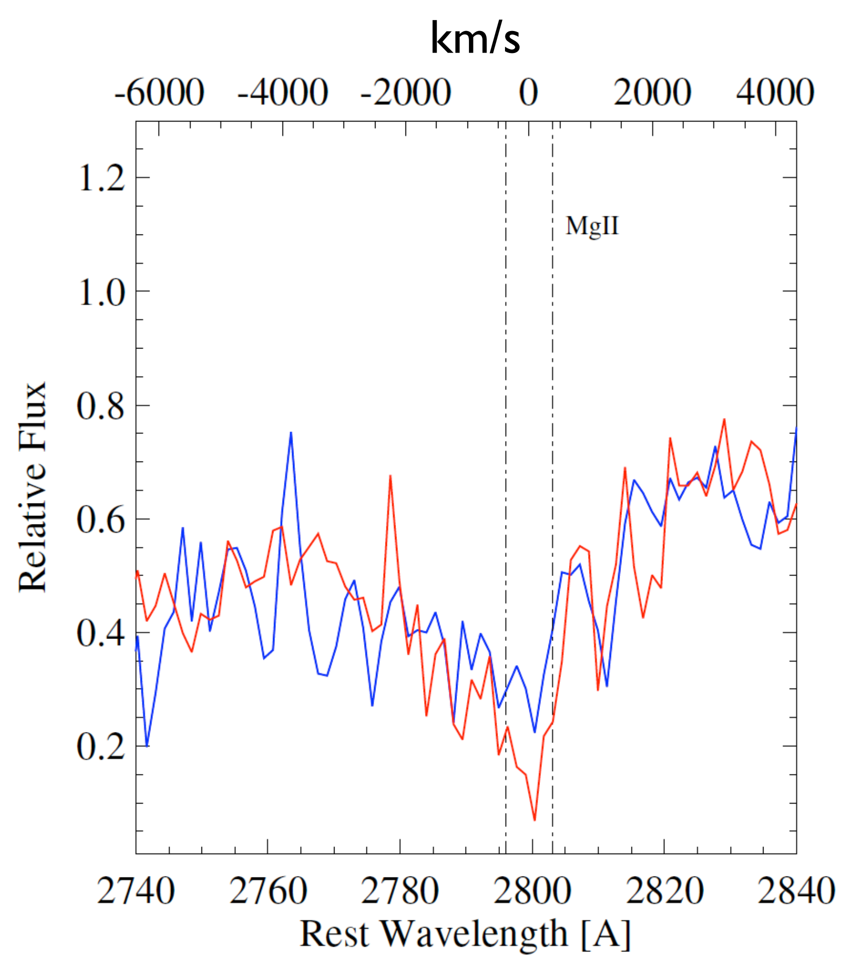
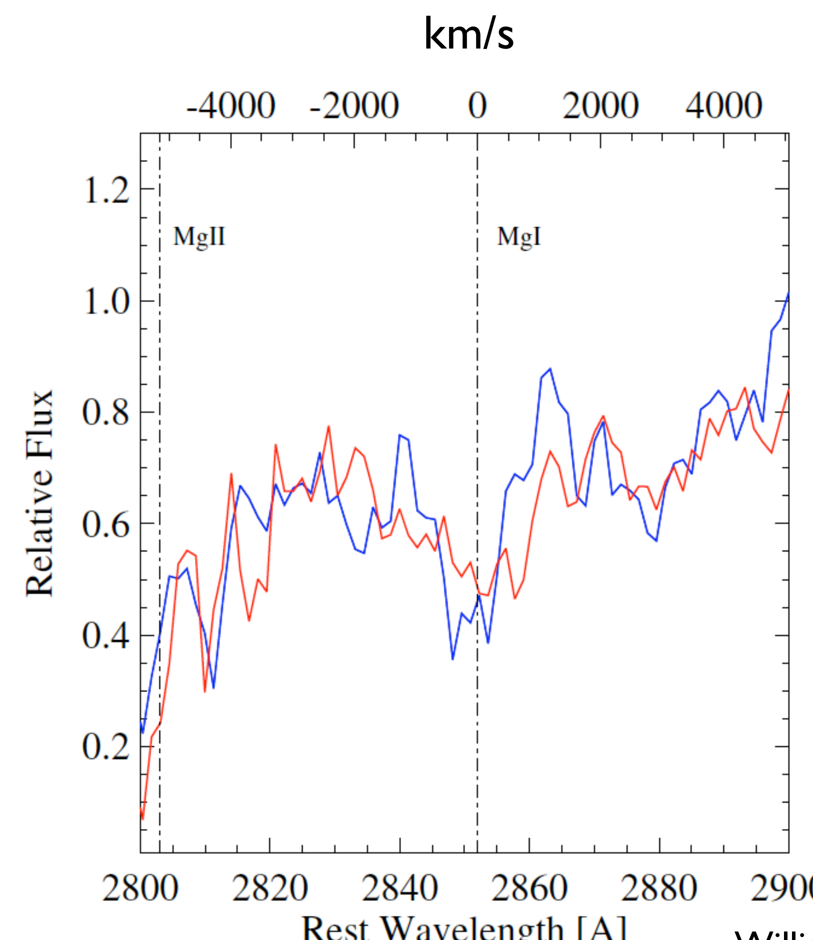
Evidence for relic feedback in ISM (e.g. outflows)?



Tremonti et al. 2007

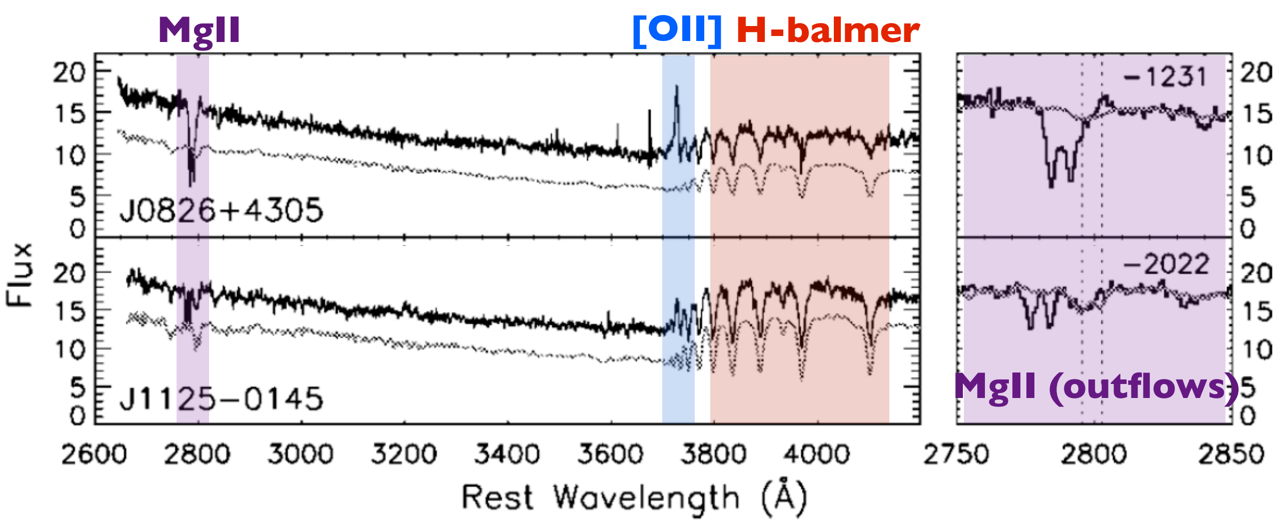




Williams, Giavalisco et al. (in prep)

1. ETG at z~1.2: the connection between morphology (stellar density) and quenching

Evidence for relic feedback in ISM (e.g. outflows)? Some unexplained spectral features.



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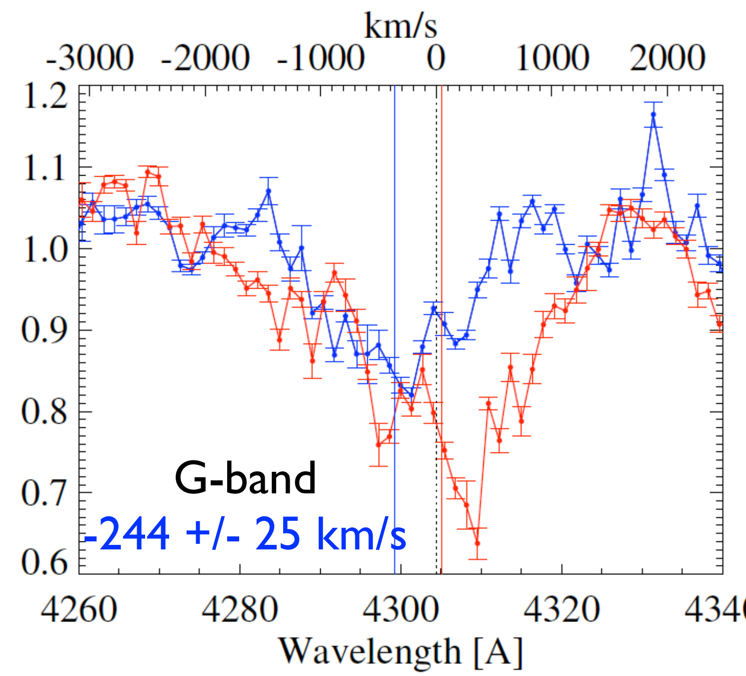
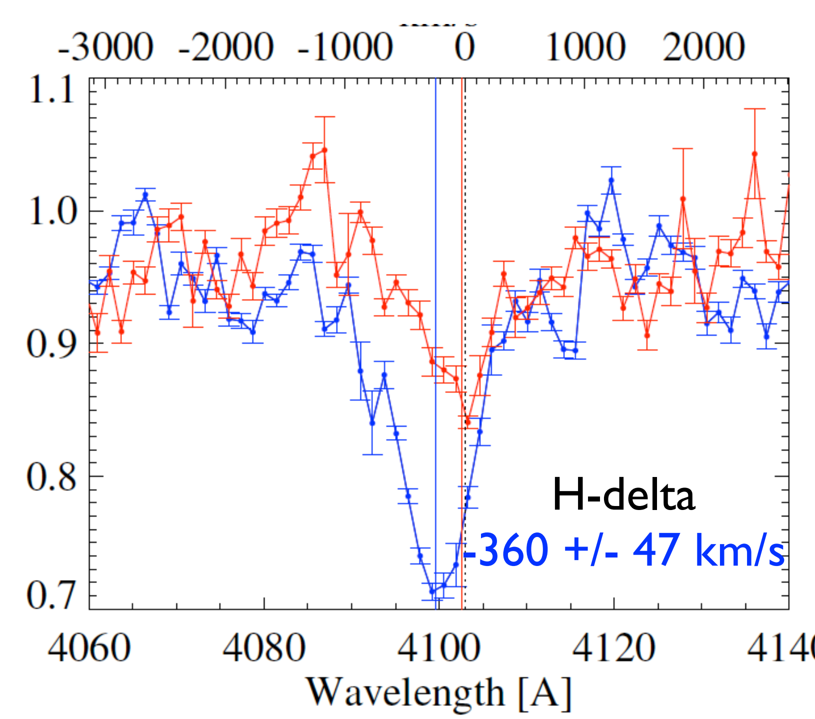


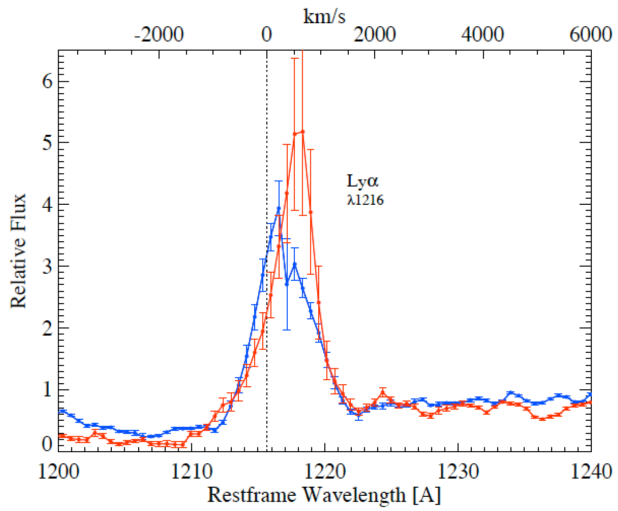


Normal ETG sample: some "stellar" line centroids blueshifted 250-350 km/s (relative to CaH+K, OII)

Compact ETG centroids consistent with systemic velocity:

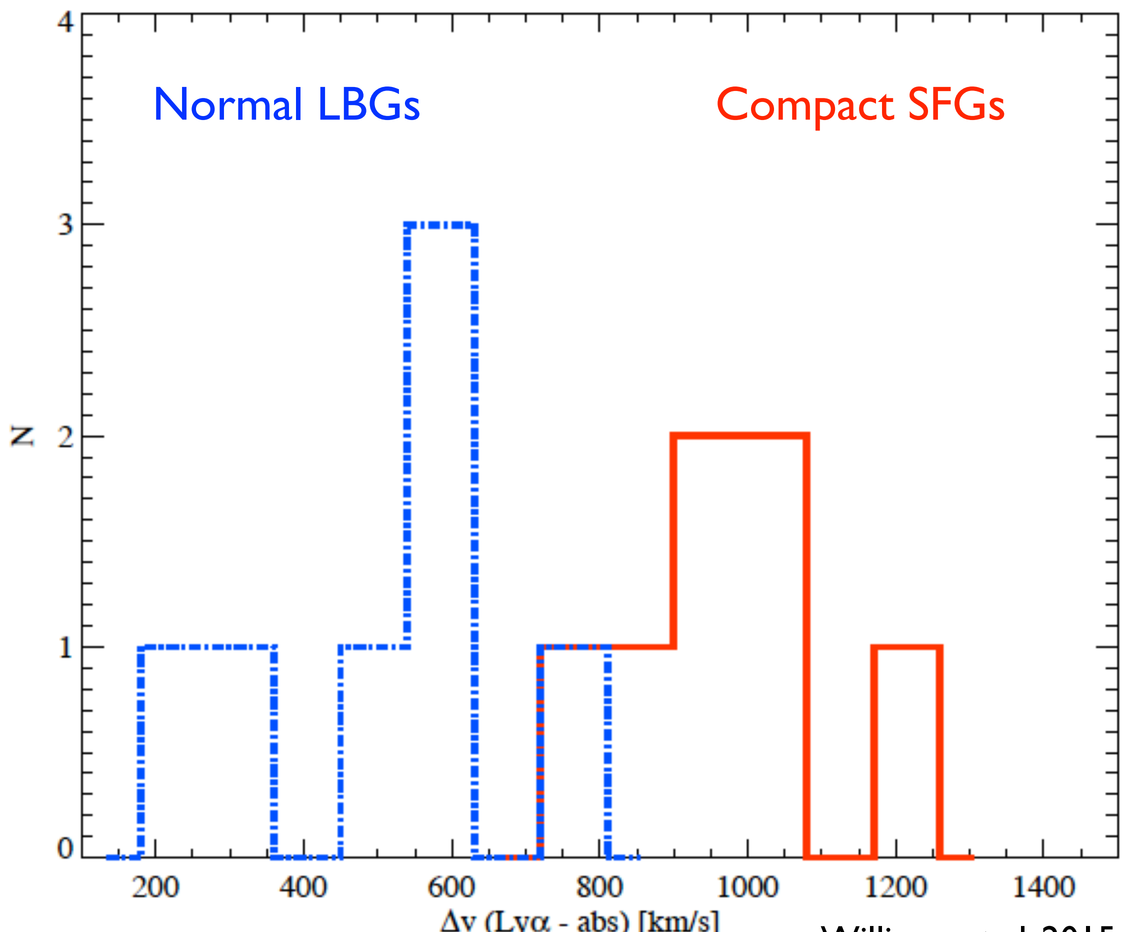
G-band: 50 +/- 47 km/s

H-delta: -24 +/- 59 km/s



2. Feedback during the SF phase (using ETG progenitors) at z > 2

Compact SFGs (compact ETG progenitors) show evidence for higher gas velocities compared to normal LBGs



Williams et al. 2015

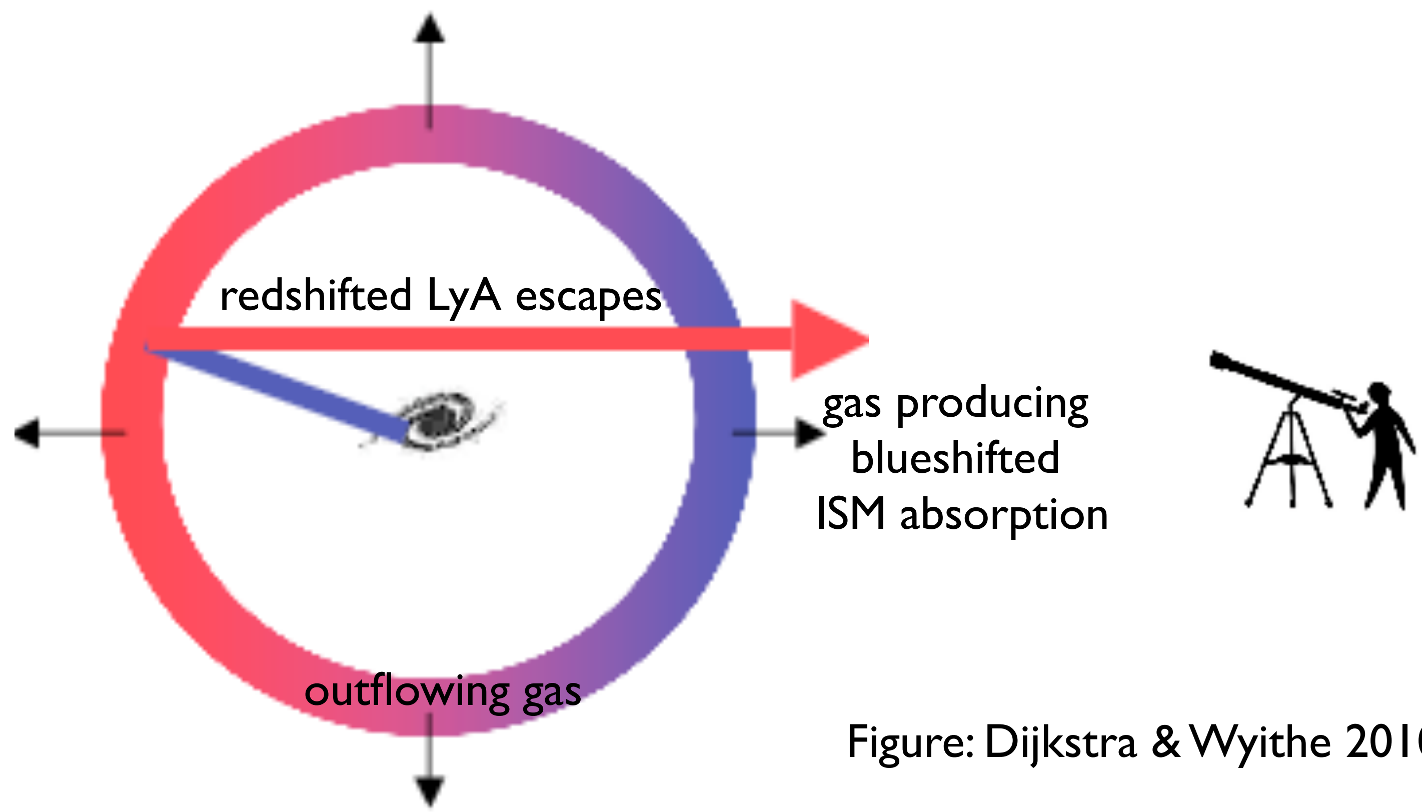
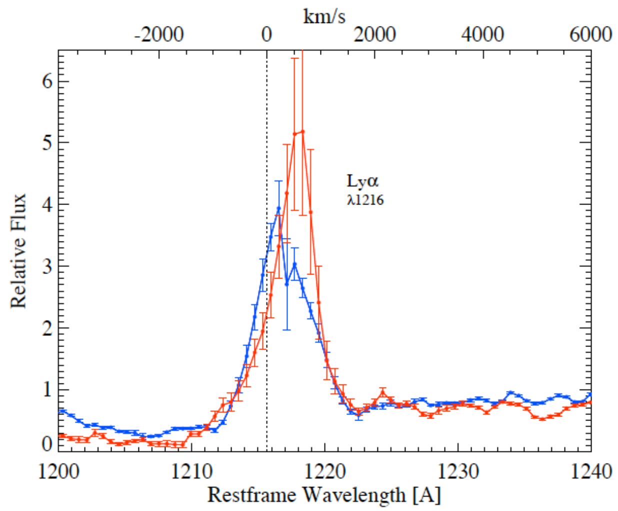


Figure: Dijkstra & Wyithe 2010

velocity difference between LyA emission and ISM absorption lines



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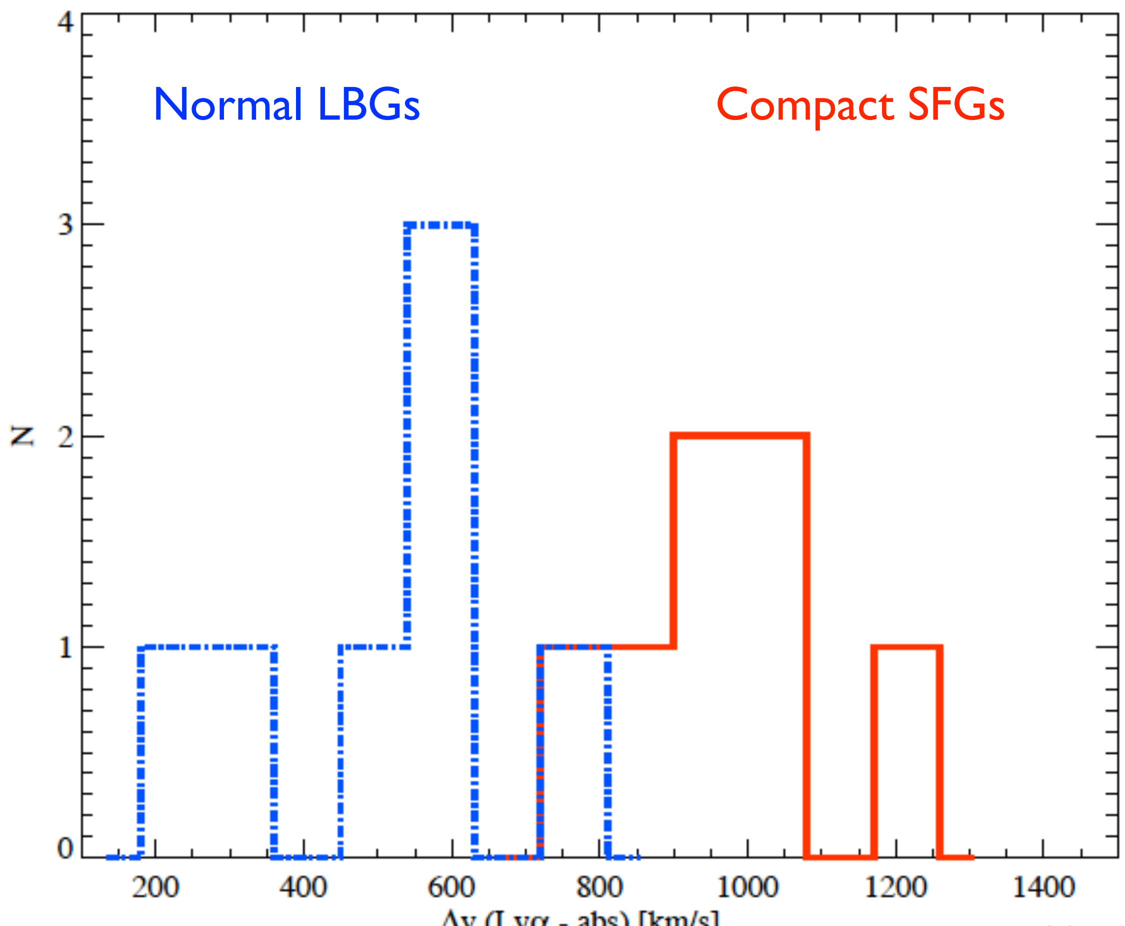
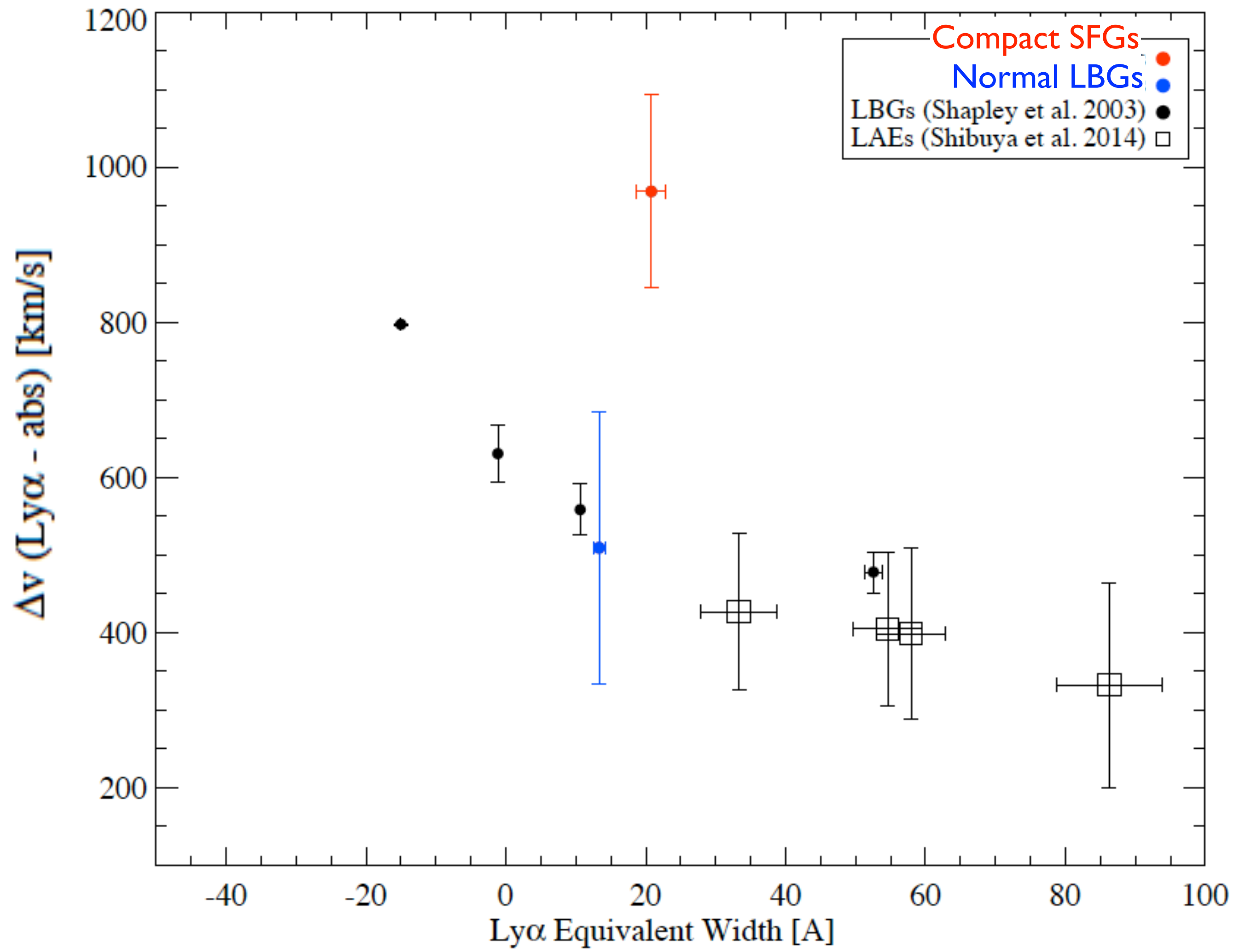


Williams et al. 2015

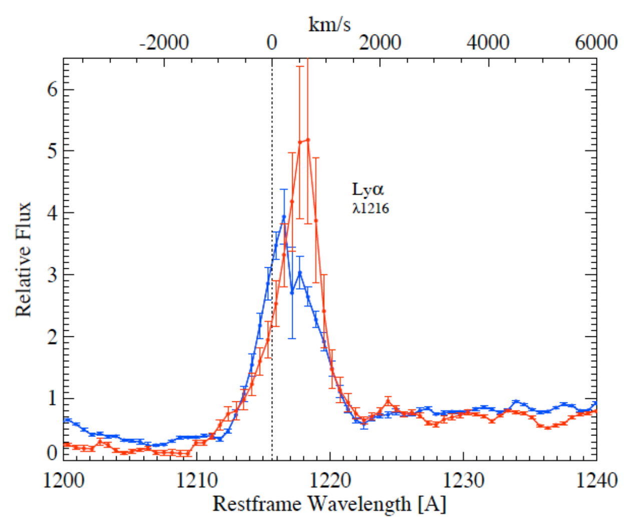


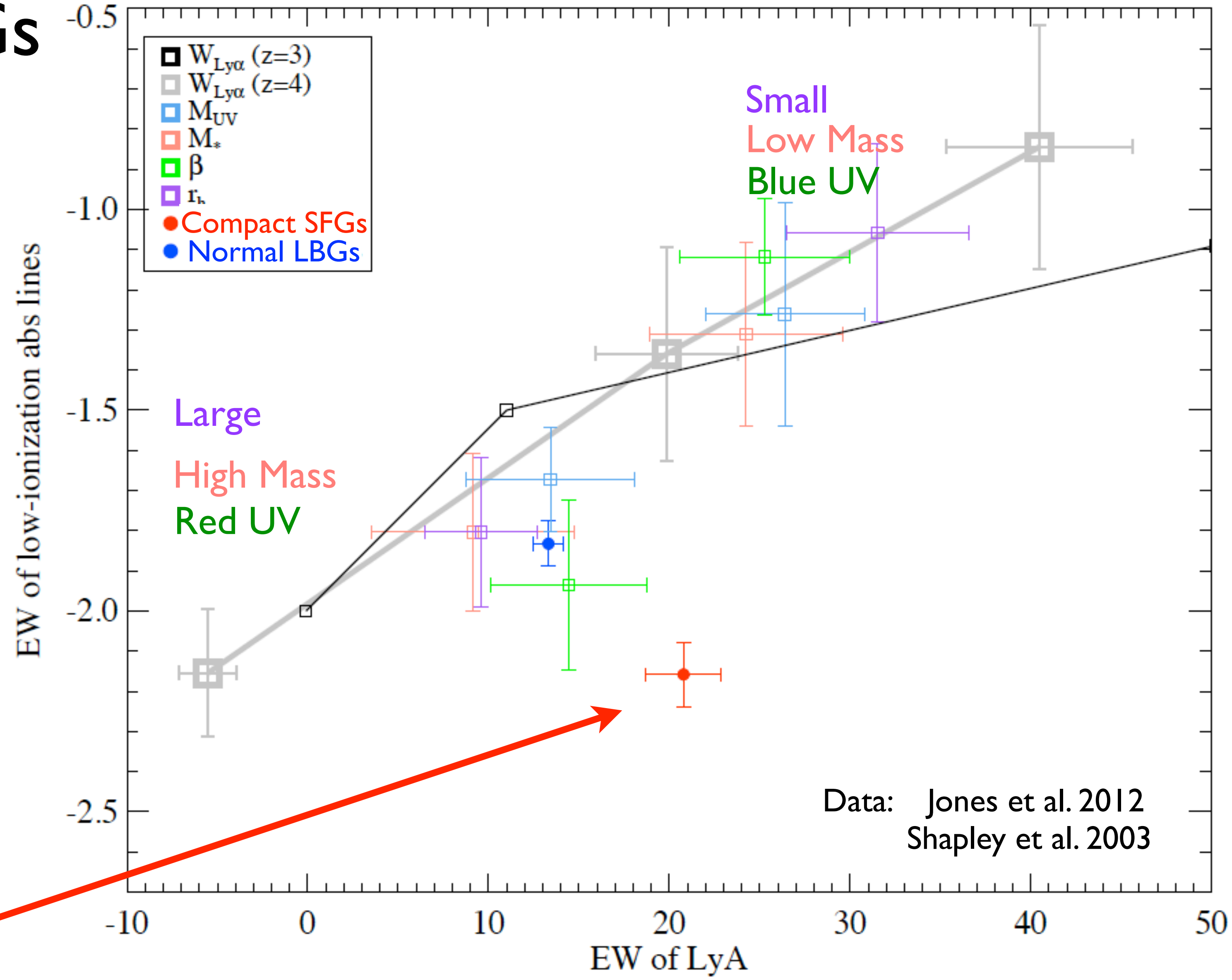
velocity difference between LyA emission and ISM absorption lines

Williams et al. 2015

2. Feedback during the SF phase (using ETG progenitors) at z > 2

Compact SFGs at z~3: Evidence for more extreme feedback than extended SFGs



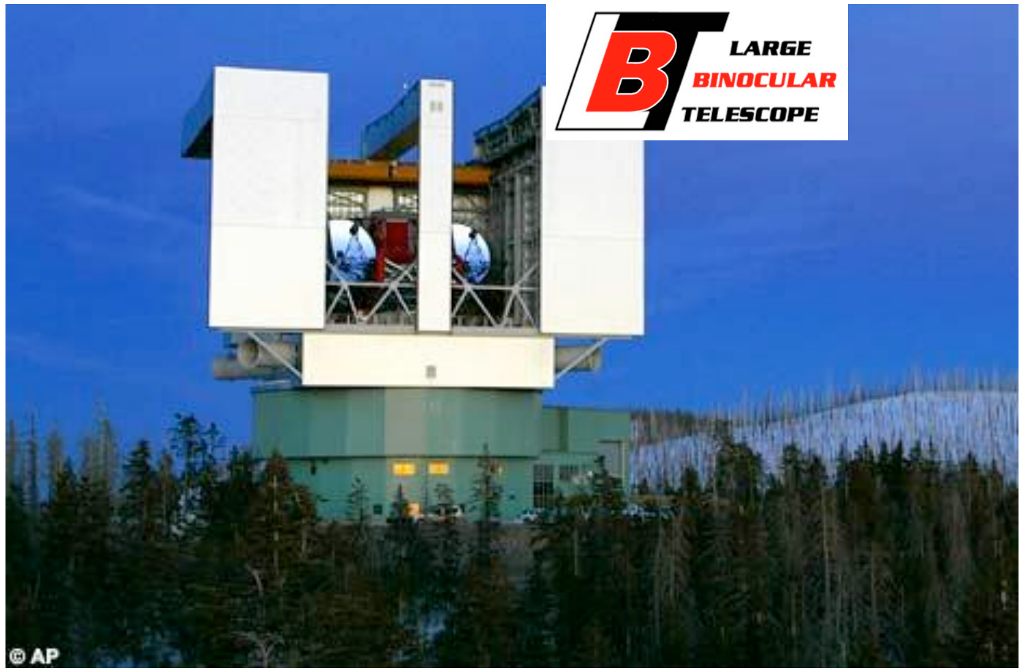


Compact SFGs are outliers among LBGs at z~3: given their high ISM absorption, LyA should have been weak

Williams et al. 2015

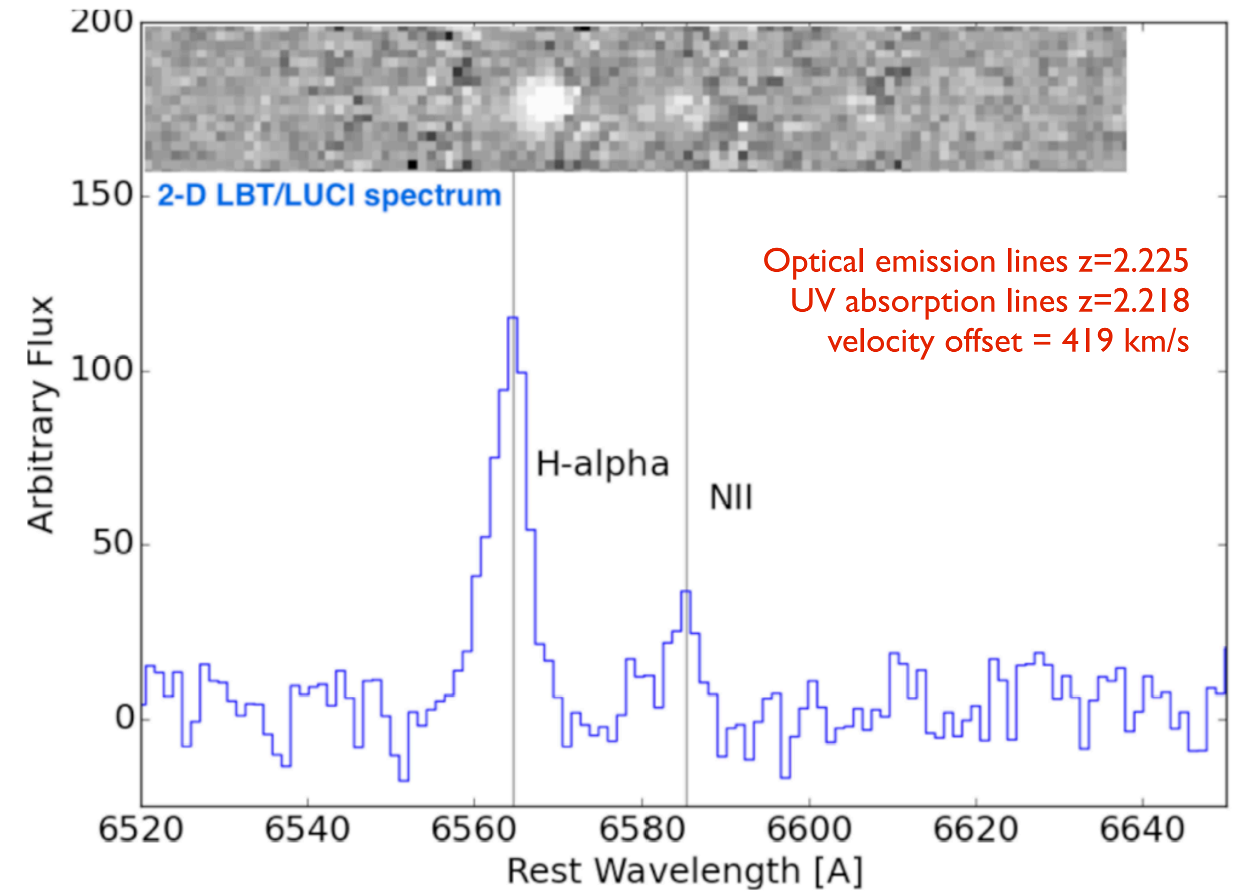
LyA is escaping more readily than in normal LBGs
ionized holes? high velocity gas?
(see also Alexandroff et al. 2015, Taniguchi et al. 2015)

3. Upcoming programs: observing the energy input into ISM in compact galaxies



Data:

Near-IR spectroscopy with LUCI/LBT of z~2 star-forming galaxies (PI: Williams), with existing deep Keck rest-UV spectroscopy



LUCI spectroscopy of one CANDELS galaxy (PI: C. C. Williams)

Purpose:

Investigate ISM gas conditions (excitation, kinematics, LyA escape, as probes of feedback) as a function of galaxy morphology (from CANDELS)

Collaborators:
Mauro Giavalisco (UMass)
Paolo Cassata (U. Valparaiso)
Naveen Reddy (UC-Riverside)

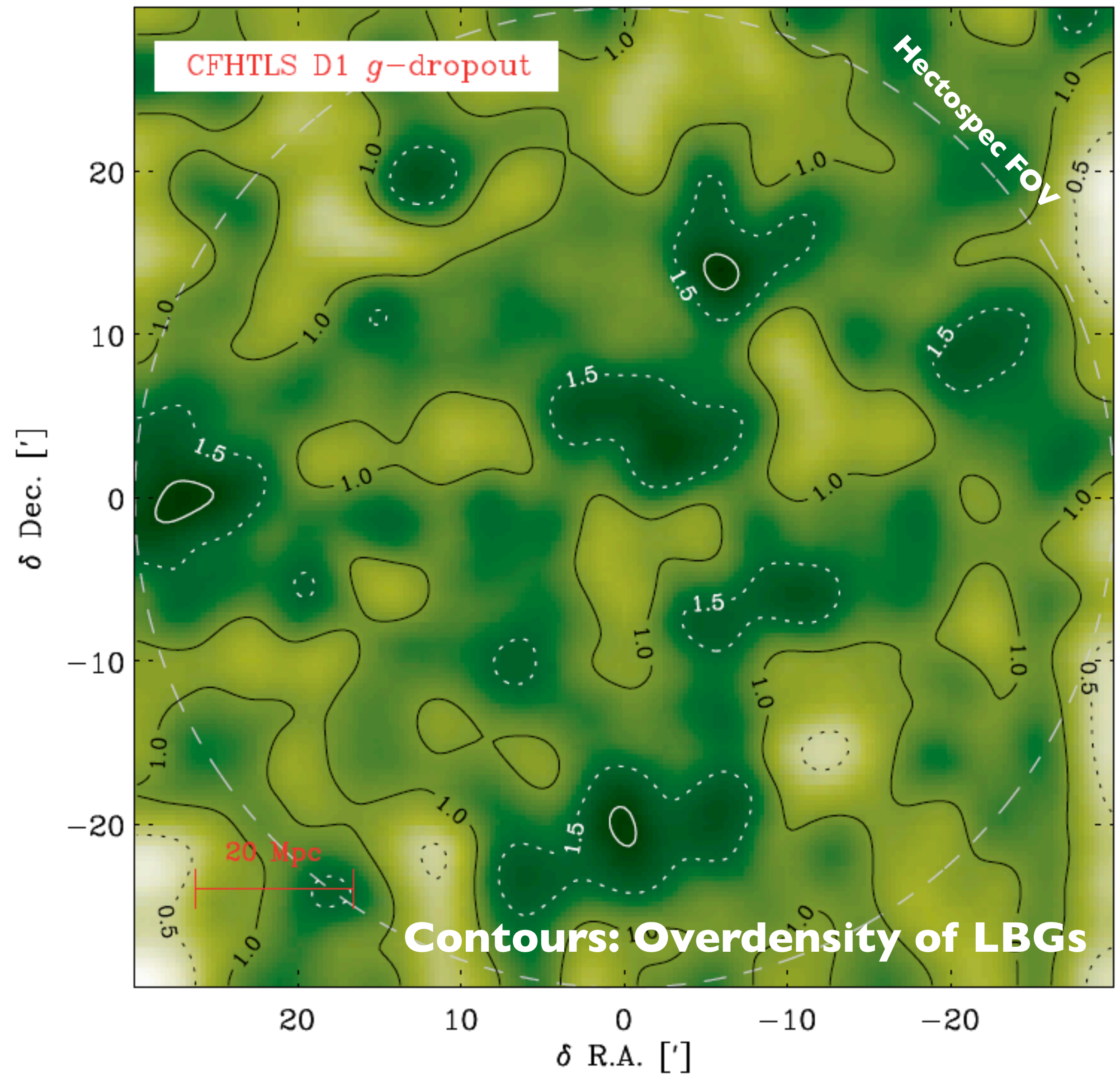
3. Upcoming programs: observing the energy input into ISM in compact galaxies

Data:

Rest-UV spectroscopy of z~3-4 star-forming galaxies over 3 sq deg with Hectospec/MMT (PI: Williams)

Purpose:

Investigate ISM gas conditions (excitation, kinematics, LyA escape, as probes of feedback) as a function of both environment (~12 overdensities) and galaxy morphology (1000s of compact galaxies!)
(see also Williams et al. 2014; Williams et al. 2015)



Collaborators:
Kyoung-Soo Lee (Purdue)
Mauro Giavalisco (UMass)
Arjun Dey (NOAO)
Ke Shi (Purdue)
Rui Xue (Purdue)

Summary

- Quenching physics at high-redshift remains poorly understood: a goal for future surveys

- Spectroscopic and CANDELS data indicate compactness correlates: more compact = older ages, earlier quenching

- Quenching probably rapid: obvious signatures absent in this data (age ~ 1 Gyr)

- Outstanding questions: is quenching causally related to compactness or just a coincidence?

- Future surveys with LBT and MMT to observe feedback in star-forming progenitors may answer these questions