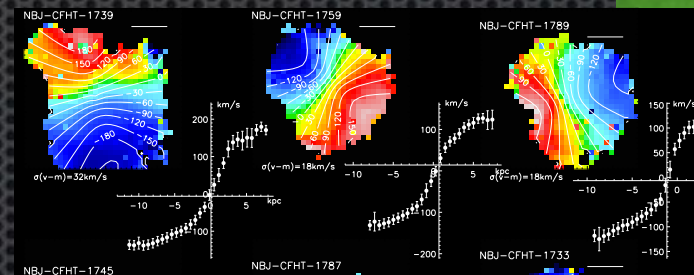
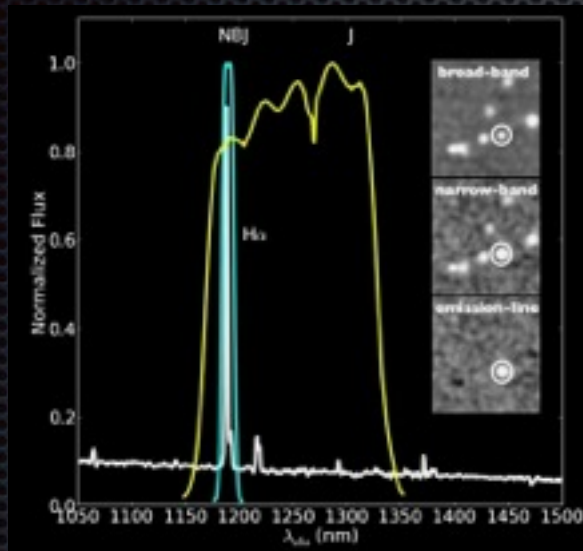
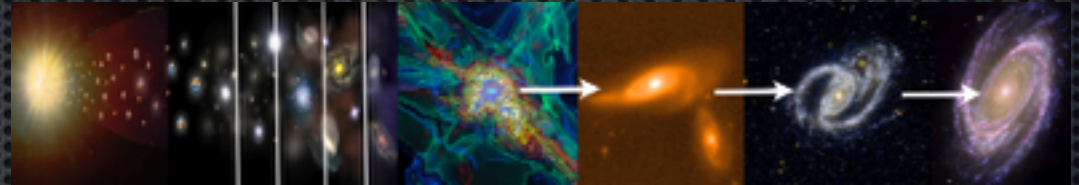


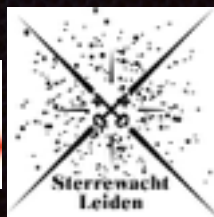
# The nature and evolution of star-forming galaxies over the last 11 Gyrs with a robust, homogeneous selection

David Sobral

IA- CAAUL Lisbon/Leiden Obs.

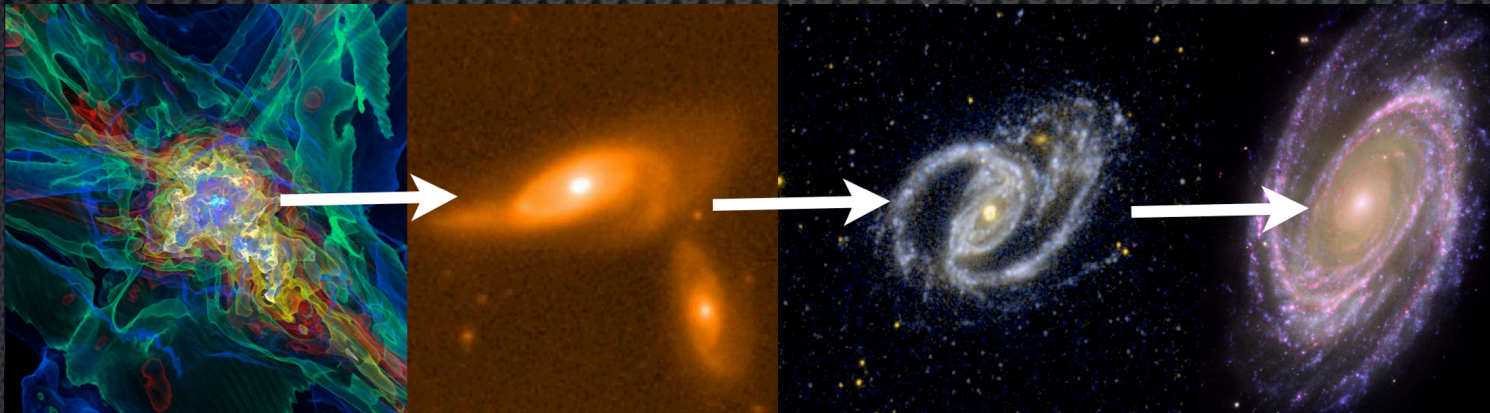


Mark Swinbank, John Stott, Jorjyt Matthee, Ian Smail, Philip Best, Ivan Oteo, R. Bower, Edo Ibar, Y. Koyama, Andra Stroe, Jim Geach, +



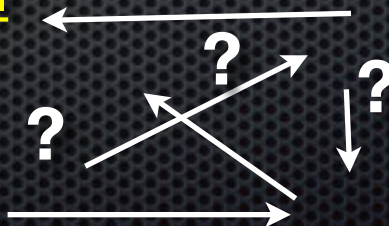
How (and driven by which mechanisms)

do galaxies form and evolve?



● Morphological change?

● Dynamics



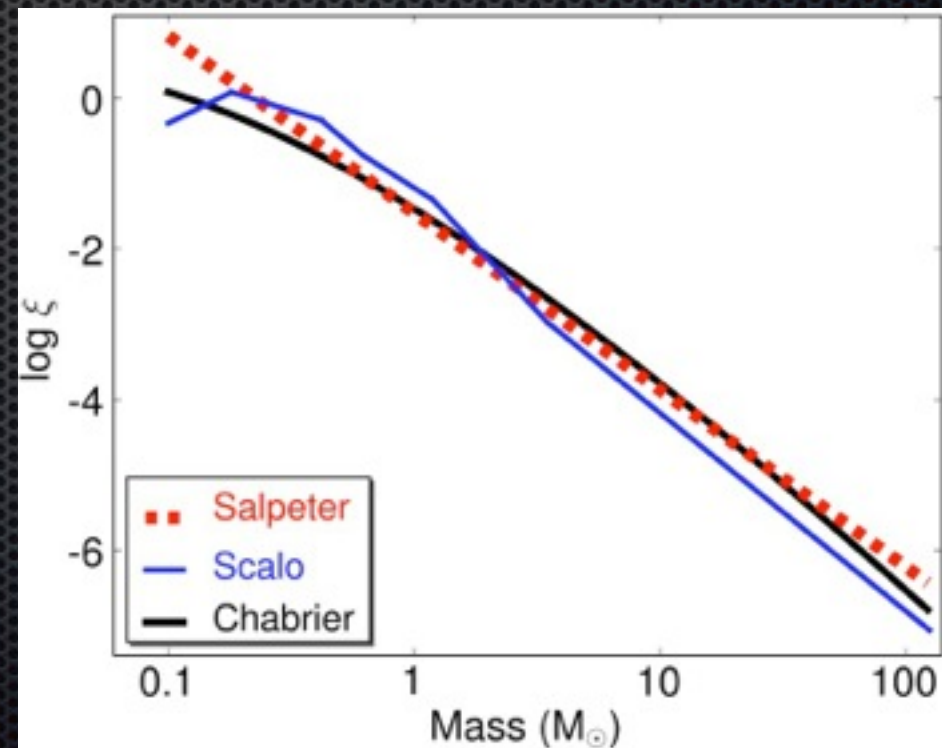
● Star formation

● “Quenching”

# Probing Star Formation

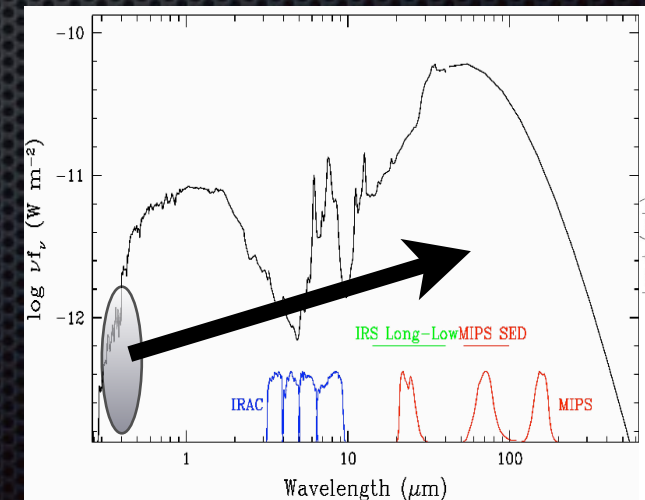
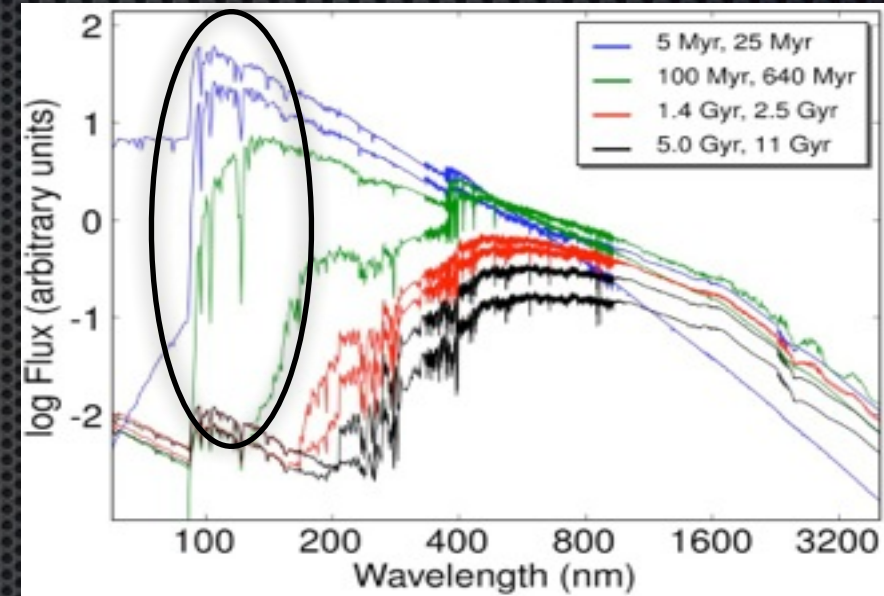
- Individual stars or star-forming regions impossible to resolve outside ~Local Universe
- SF inferred from signatures of blue, massive, bright stars (as these are short lived)
- Then use Initial Mass Function (IMF) to predict all the others (usual cut-off 0.1-100  $M_{\odot}$ )

Star	$M_{\odot}$	Lifetime
O3	60	3 Myr
O7	30	11 Myr
B4	10	30 Myr
A5	3	0.3 Gyr
F5	1.5	3 Gyr
G2	1	10 Gyr
M7	0.1	1 Tyr



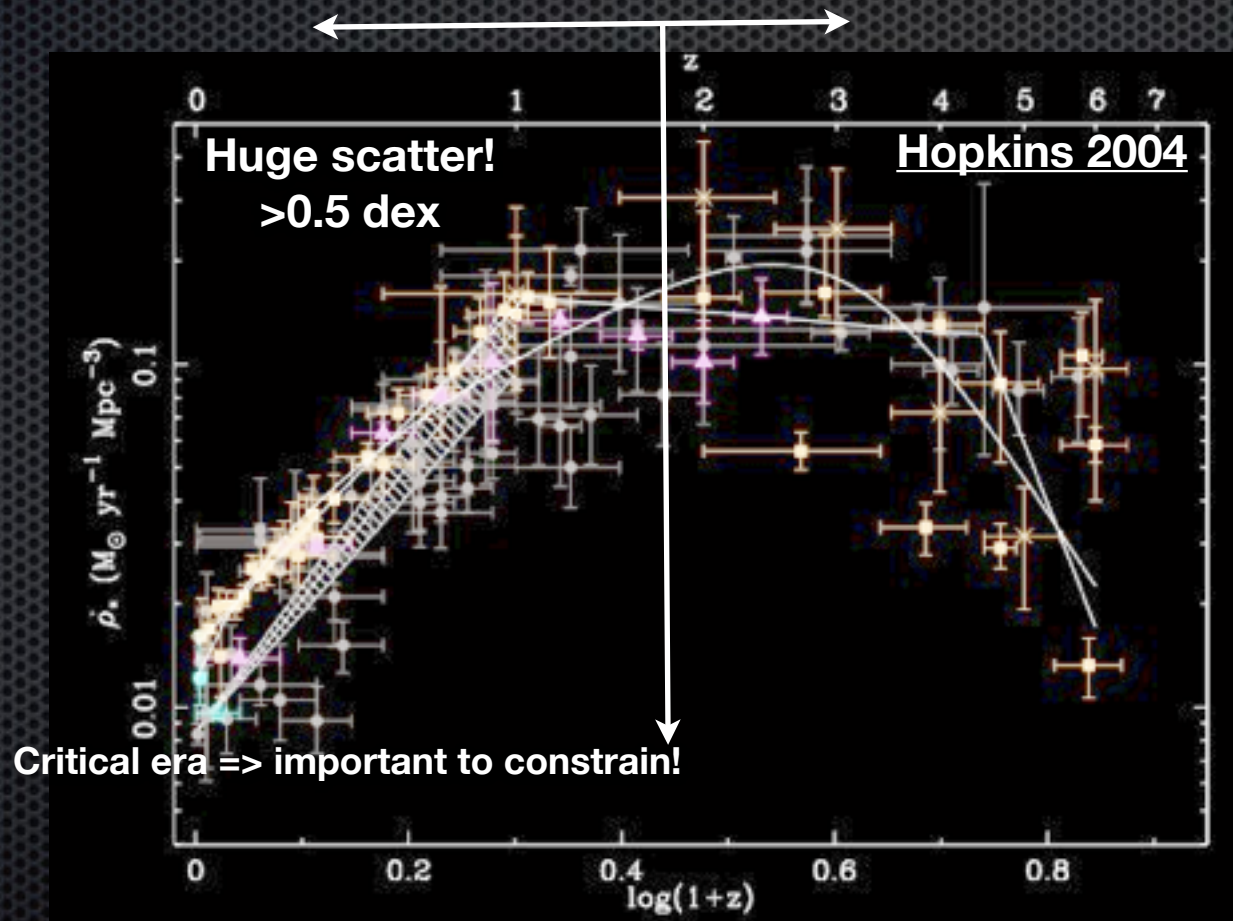
# Star formation Tracers

- Massive newly born stars => strong **UV** and only for a short time
- But... UV highly affected by extinction (up to 3 mag!). Can (and does) miss a huge part of the population
- **Absorbed UV light is re-emitted**
- 1) Ionizing photons... thus **emission-lines** can be used!
- 2) Dust re-emits in the **Far-infrared** thermally
- 3) Radio/Far-infrared correlation + Supernova events => Use **radio** as well
- but... different extinctions, biases, timescales



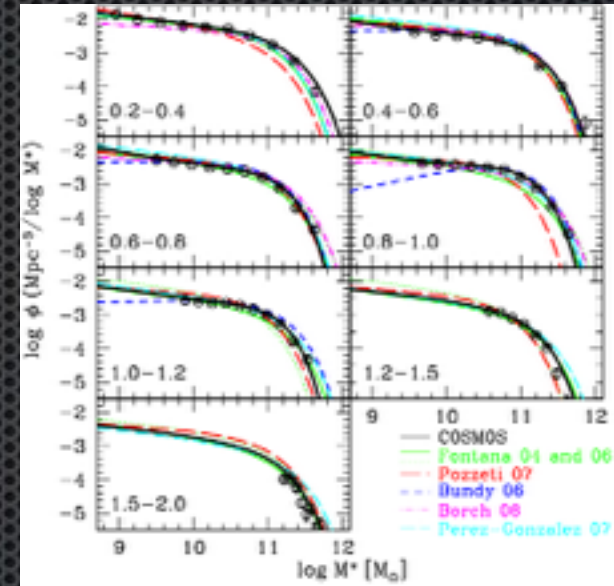
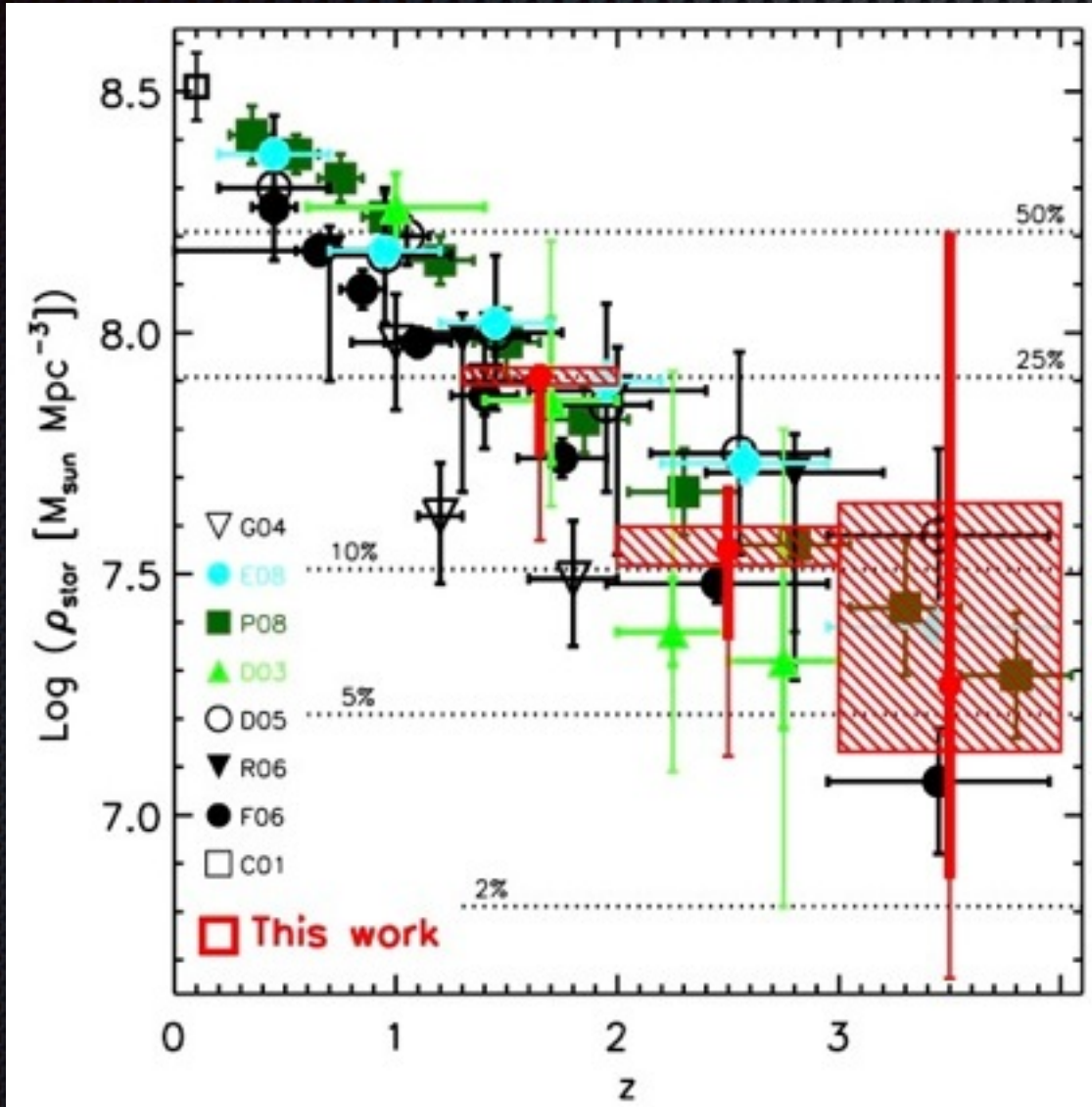
# Star formation Activity

- Combining all tracers doesn't really help...
- Dust dependence + selection biases + sensitivity + etc.



# Stellar Mass Assembly

- Stellar Mass function



- Ilbert et al. 2010

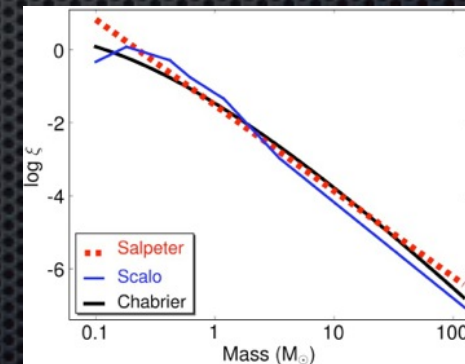
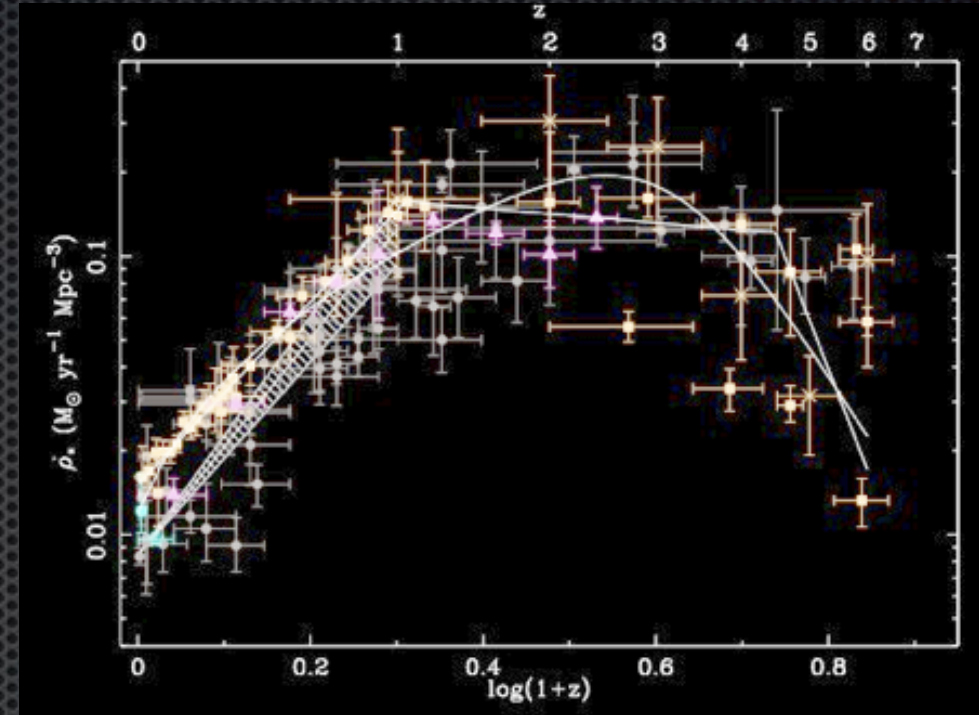
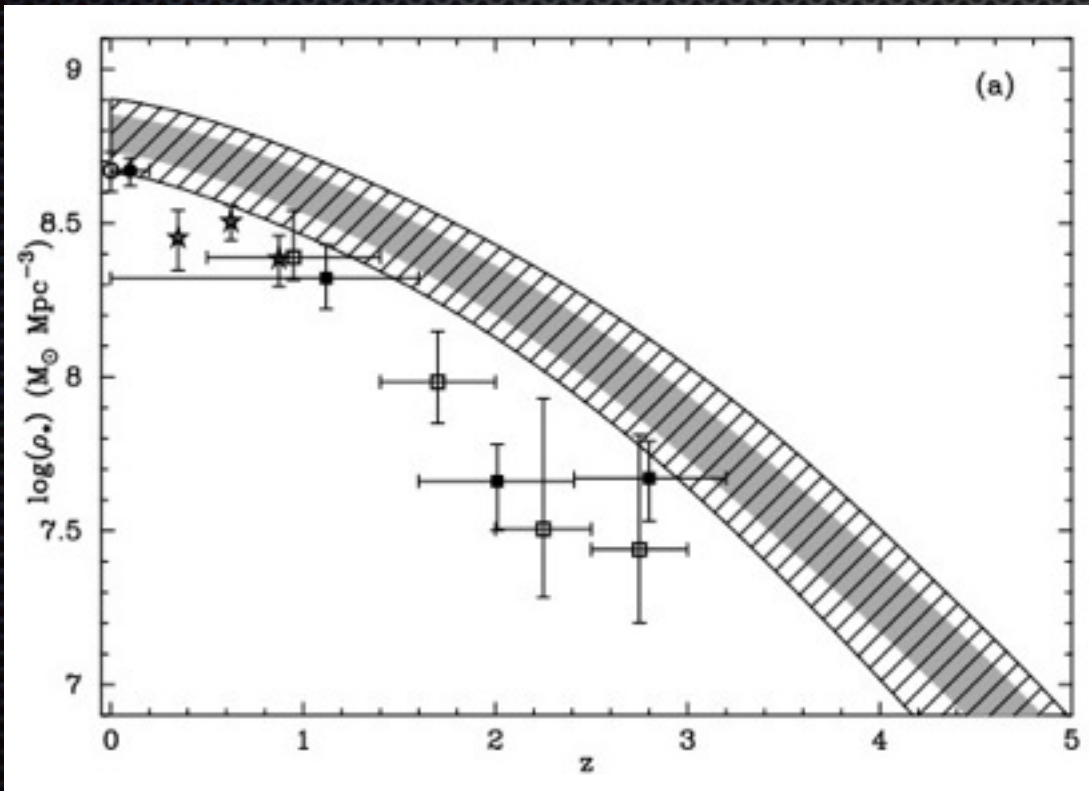
- Stellar mass density evolution

- Marchesini et al. 2009
- Muzzin et al. 2013

# Combining both...

• Hopkins 2004

- Selection effects?
- Completeness?
- IMF? • Missing Mass?



- Hopkins & Beacom 2006
- Different tracers? Biases?

# What we need:

## Improve SFH/ Part I

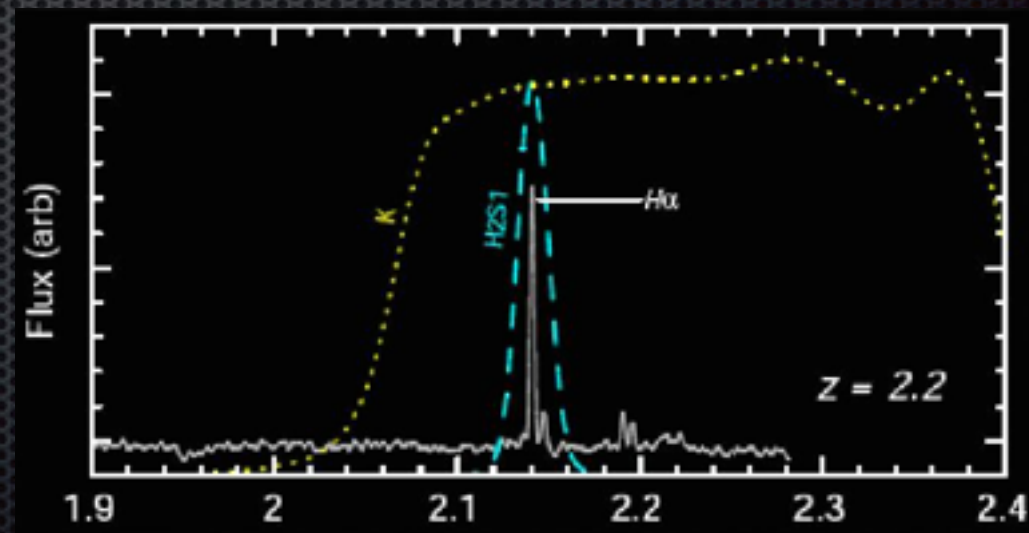
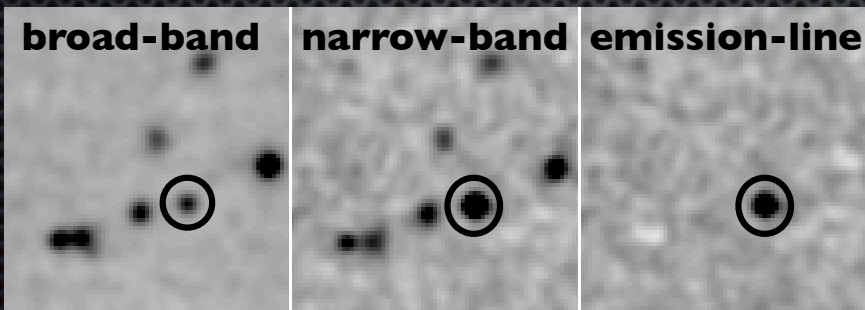
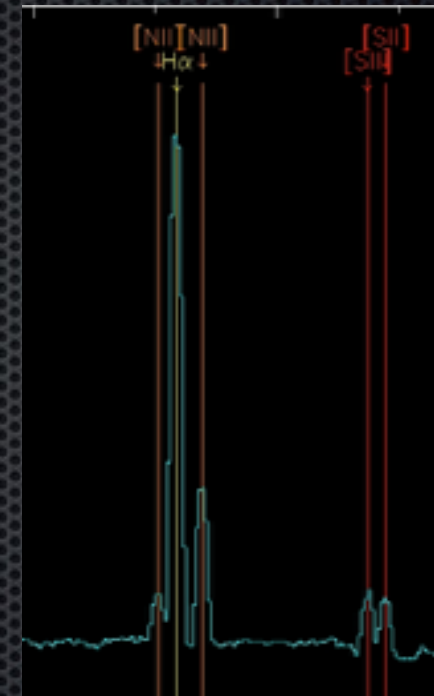
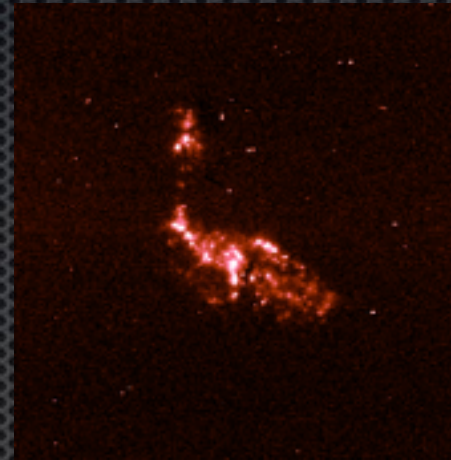
- ✦ A **good (single)** star-formation tracer that can be applied from  $z=0$  up to  $z\sim 3$  (with current instrum.)
- ✦ Well calibrated + sensitive

## Understand the SFH/ Part II

- ✦ Able to uniformly select large samples
- ✦ Different epochs + Large areas + Best-studied fields

# H $\alpha$ (+NB)

- ✧ Sensitive, good selection
- ✧ Well-calibrated
- ✧ Traditionally for Local Universe
- ✧ Narrow-band technique
- Now with Wide Field near-infrared cameras:  
can be done over large areas
  - And traced up to  $z \sim 3$



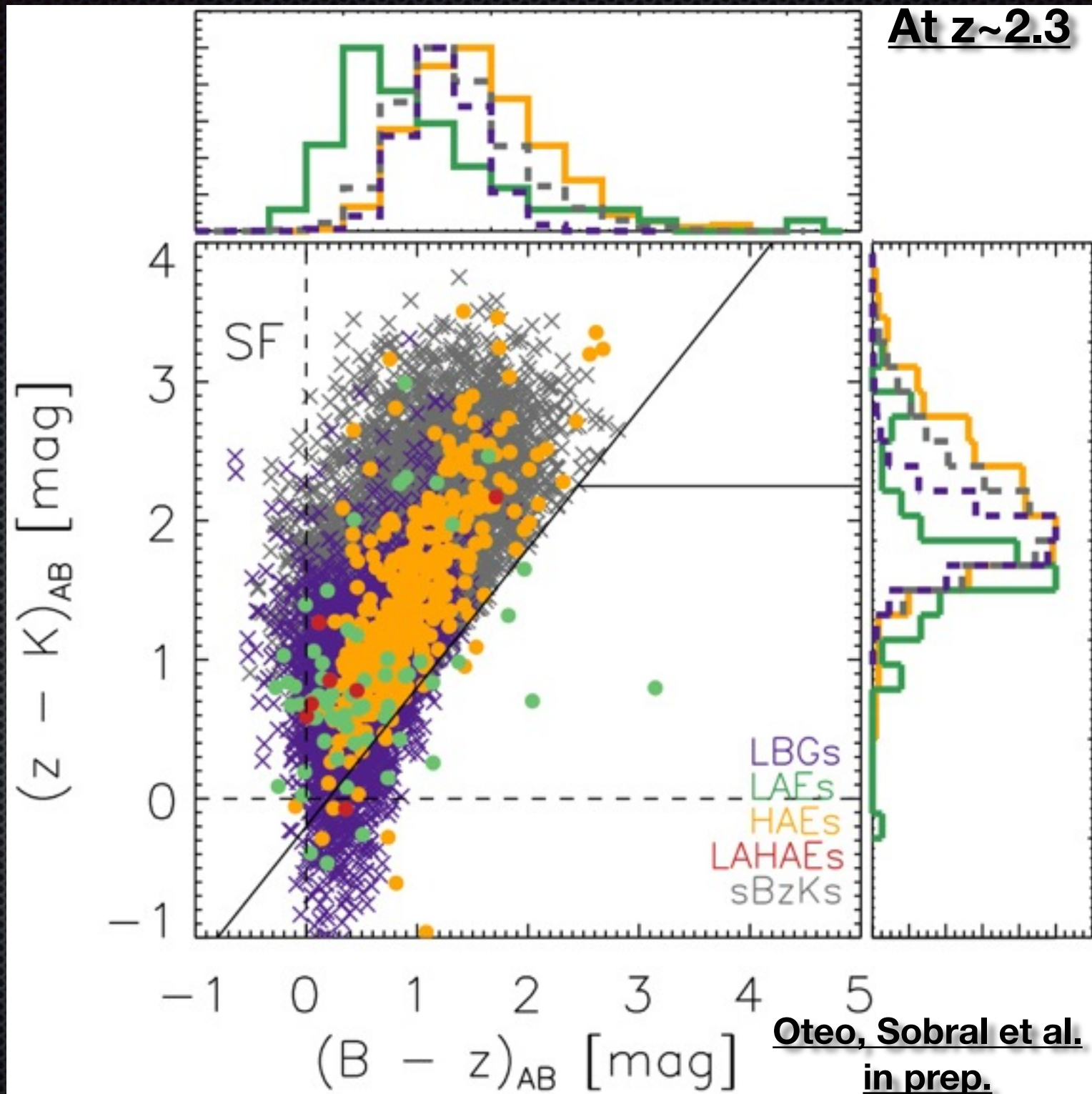
## Selection really matters

Lyman-break selection: misses ~65-70% of star-forming galaxies! (metal-rich, dusty)

LAEs: miss ~80% of star-forming galaxies

HAEs get ~100% down to the Ha flux limit they sample

See also Hayashi et al. 2013 for [OII]

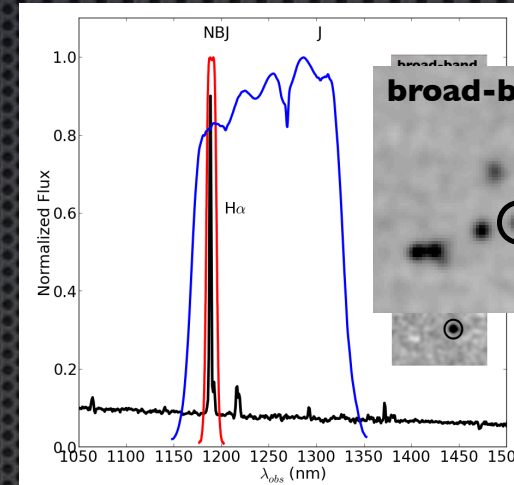


# HiZELS

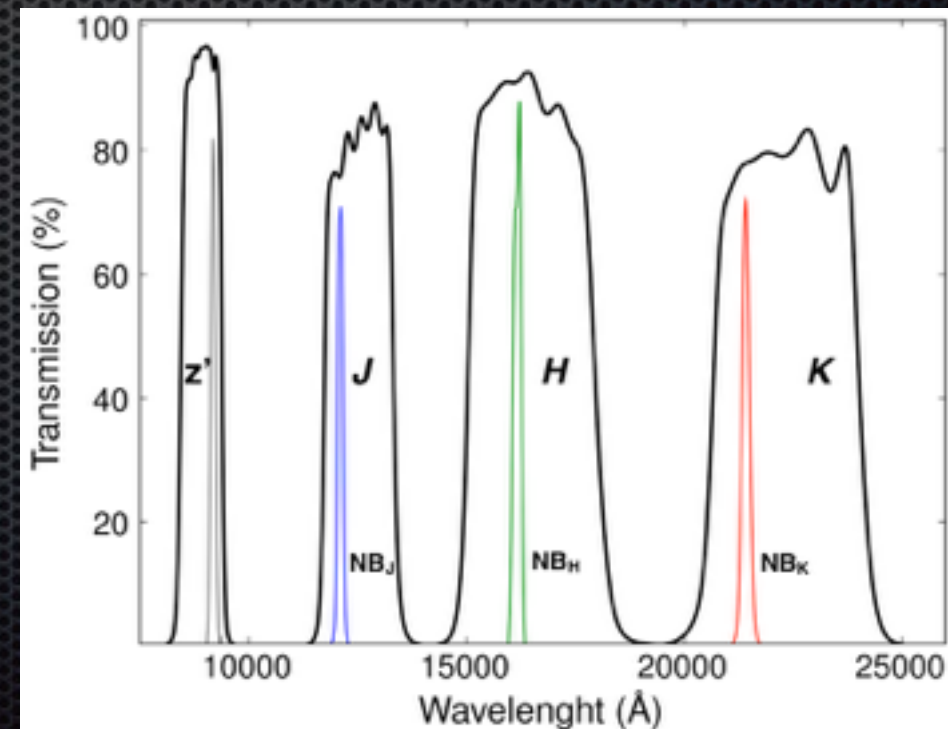
## The High Redshift Emission Line Survey

(Geach+08,Sobral+09,12,13a) (+Deep NBH + Subar-HiZELS + HAWK-I)

- **Deep & Panoramic extragalactic survey**, narrow-band imaging (NB921, NB<sub>J</sub>, NB<sub>H</sub>, NB<sub>K</sub>) **over ~ 5-10 deg<sup>2</sup>**
- ✦ **~80 Nights UKIRT+Subaru +VLT+CFHT+INT**
- ✦ **Narrow-band Filters target H $\alpha$  at  $z=(0.2), 0.4, 0.8, 0.84, 1.47, 2.23$**
- ✦ **Same reduction+analysis**
- **Other lines (simultaneously; Sobral+09a,b,Sobral+12,13a,b, Matthee+14)**



- **>1000 galaxies per NB slice**



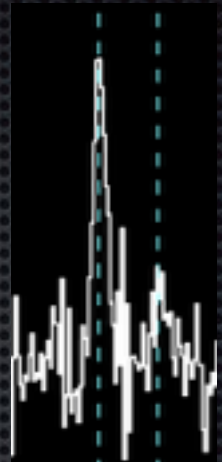
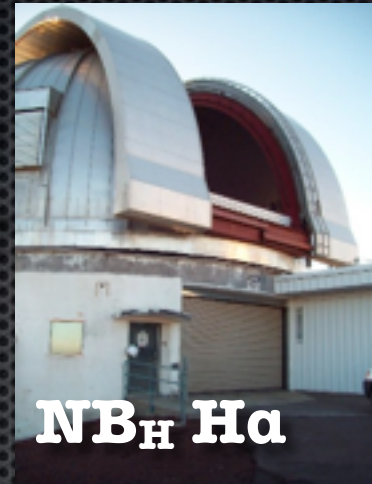
Sobral et al. 2013a

## Double-NB survey

Sobral+12

400 H $\alpha$ + [OII] / night!

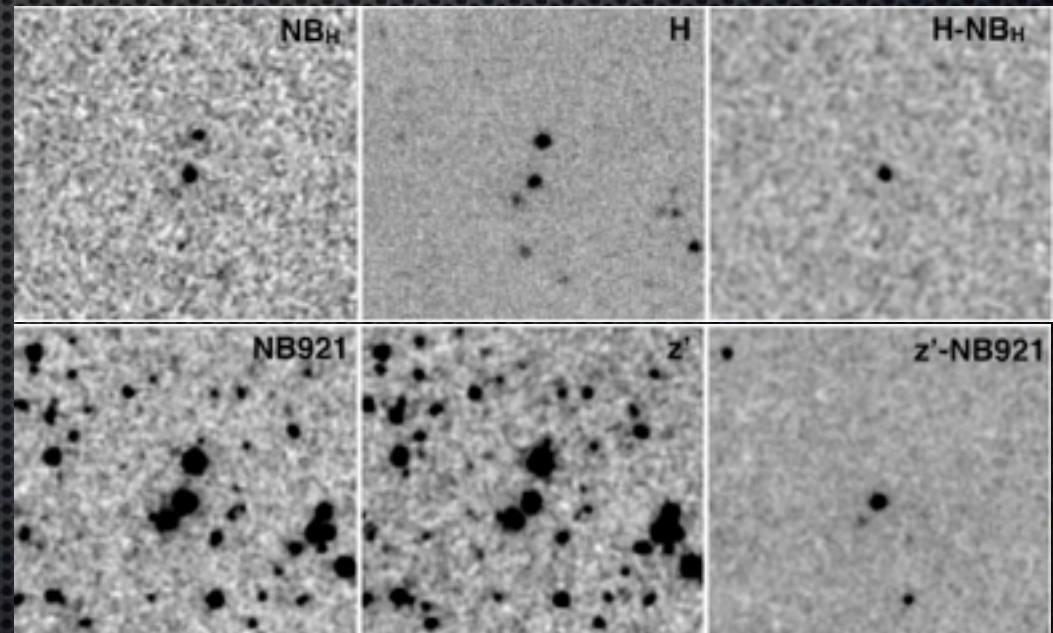
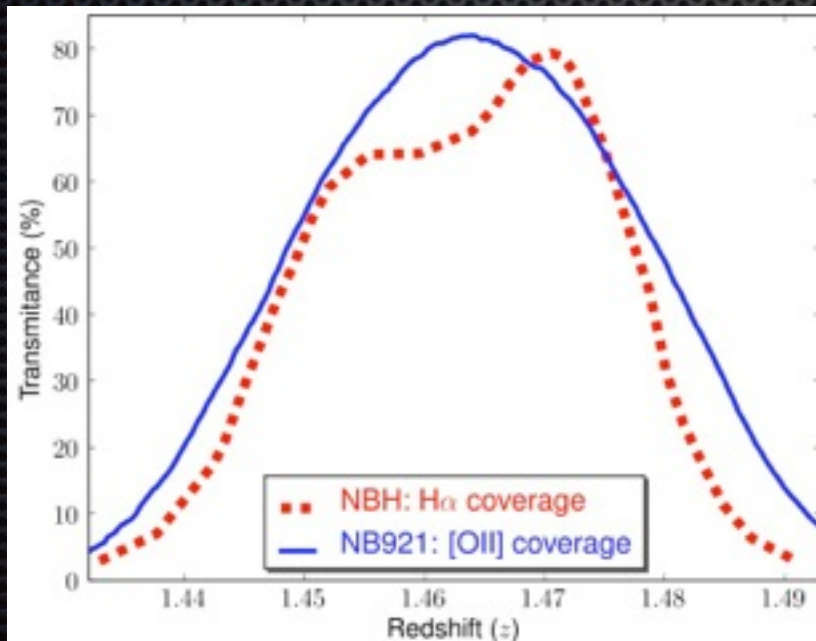
Subaru joins UKIRT  
to “walk through  
the desert”



NB921 [OII]

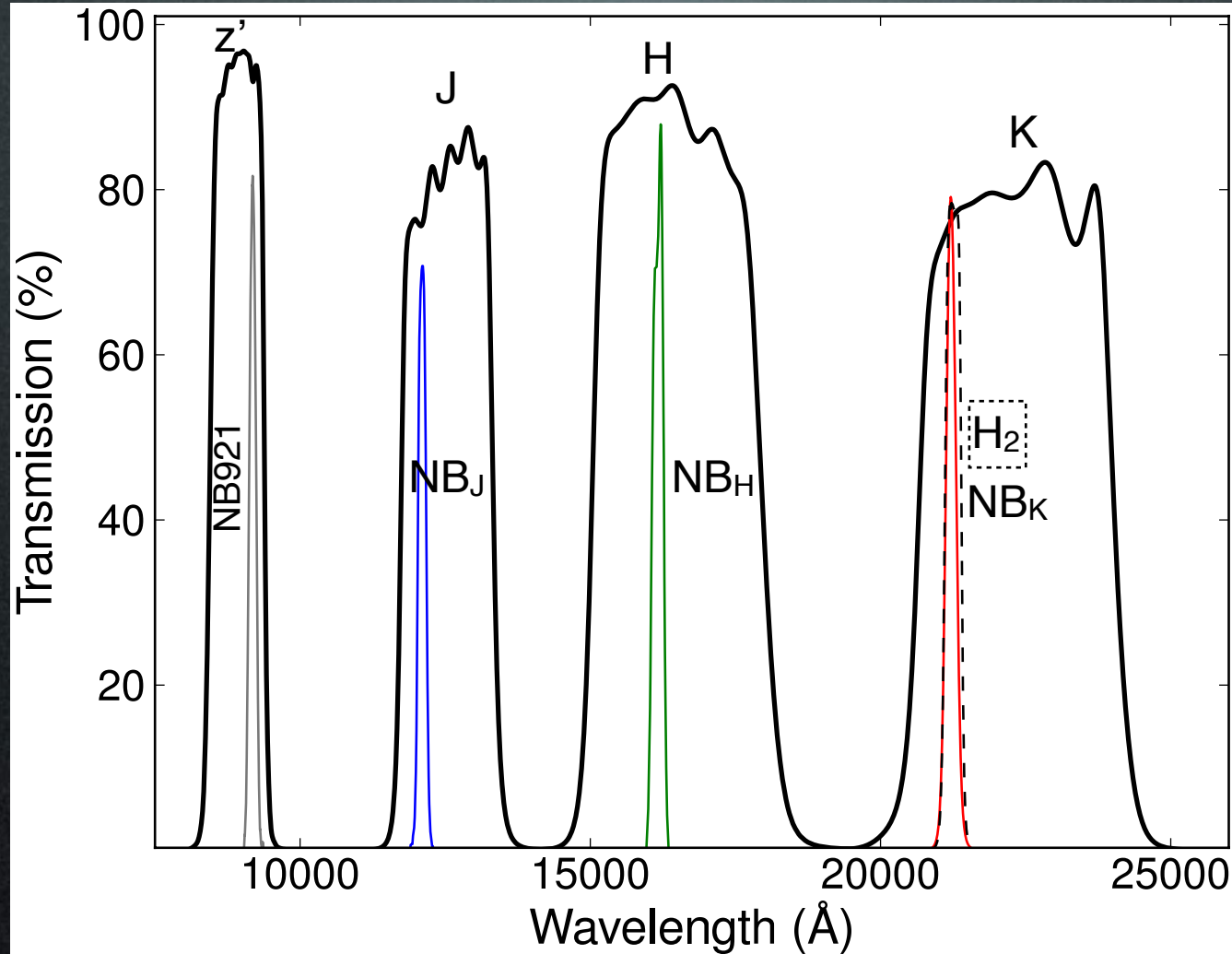
The first H $\alpha$ -[OII] large double-blind survey at high- $z$   
Sobral et al. 2012

See Hayashi, Sobral et al. 2013: [OII] SFRs at  $z=1.5$



without any need for colour or photometric redshift selections

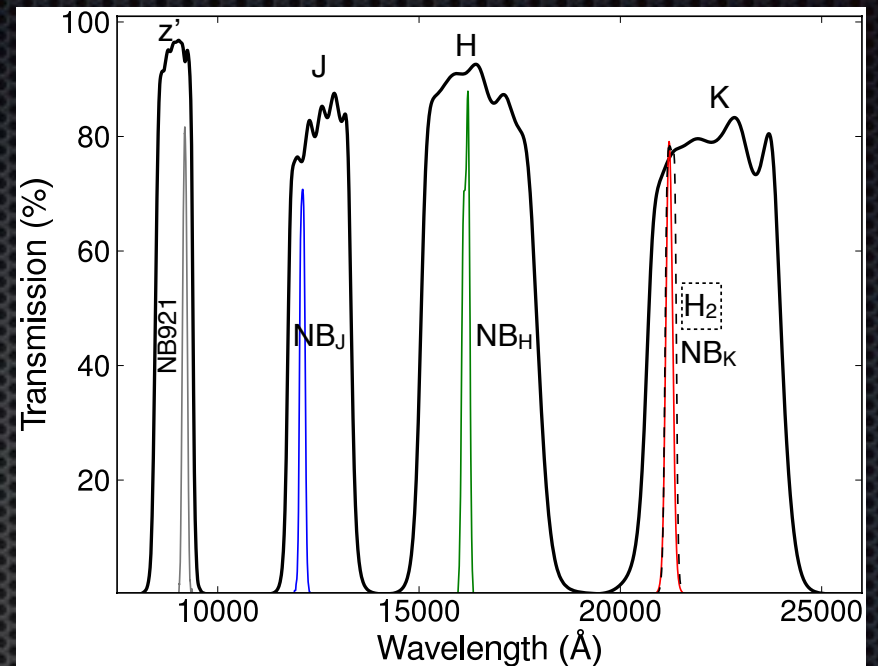
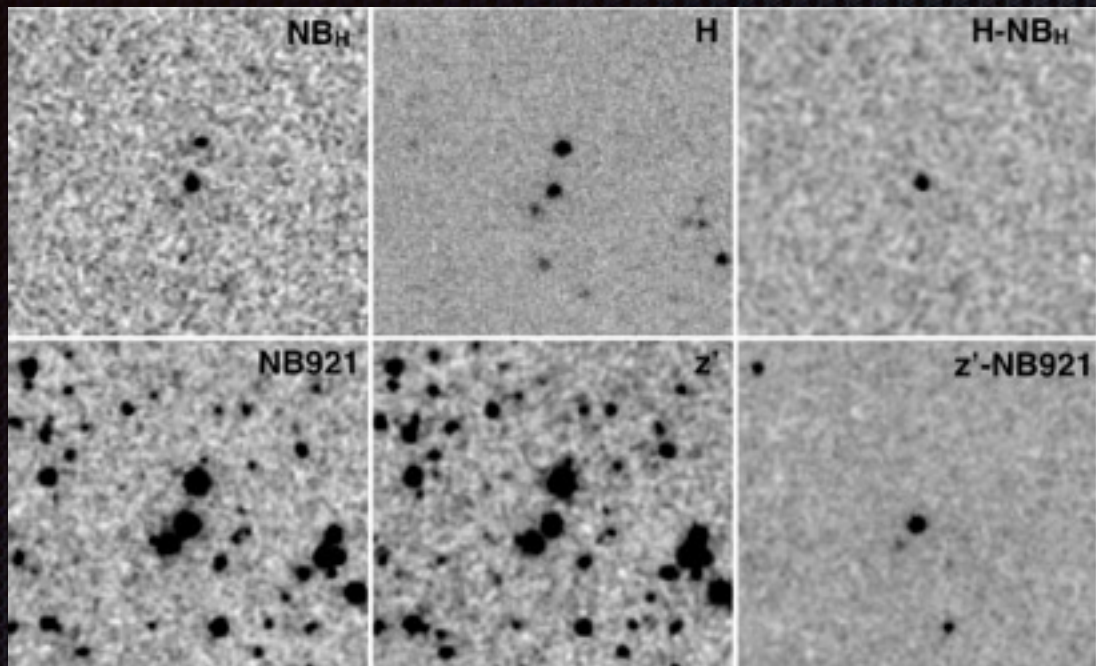
# Filters combined to improve selection: double/triple line detections



**z=2.23** : [OII] (NB<sub>J</sub>), [OIII] (NB<sub>H</sub>), H $\alpha$  (NB<sub>K</sub>)

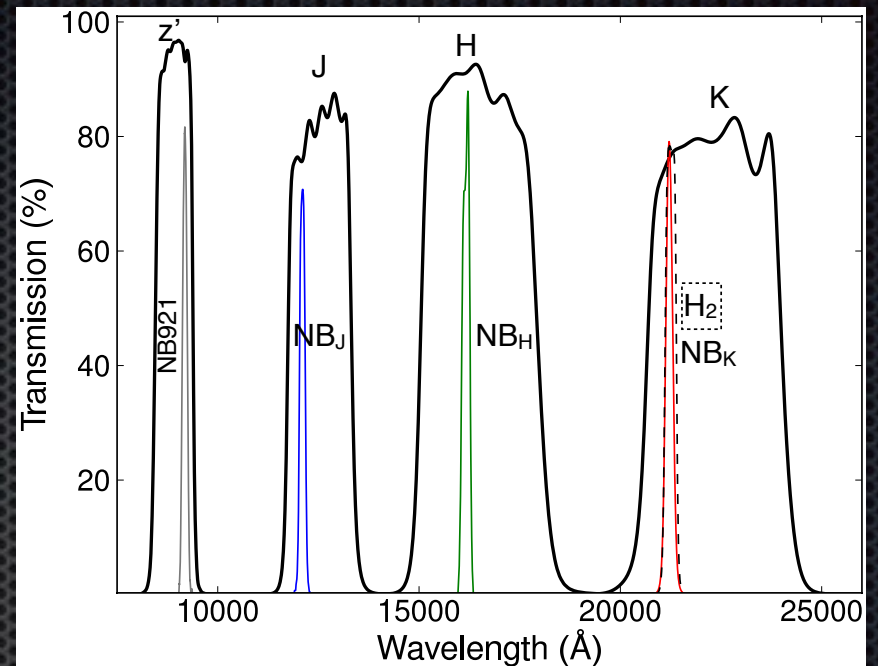
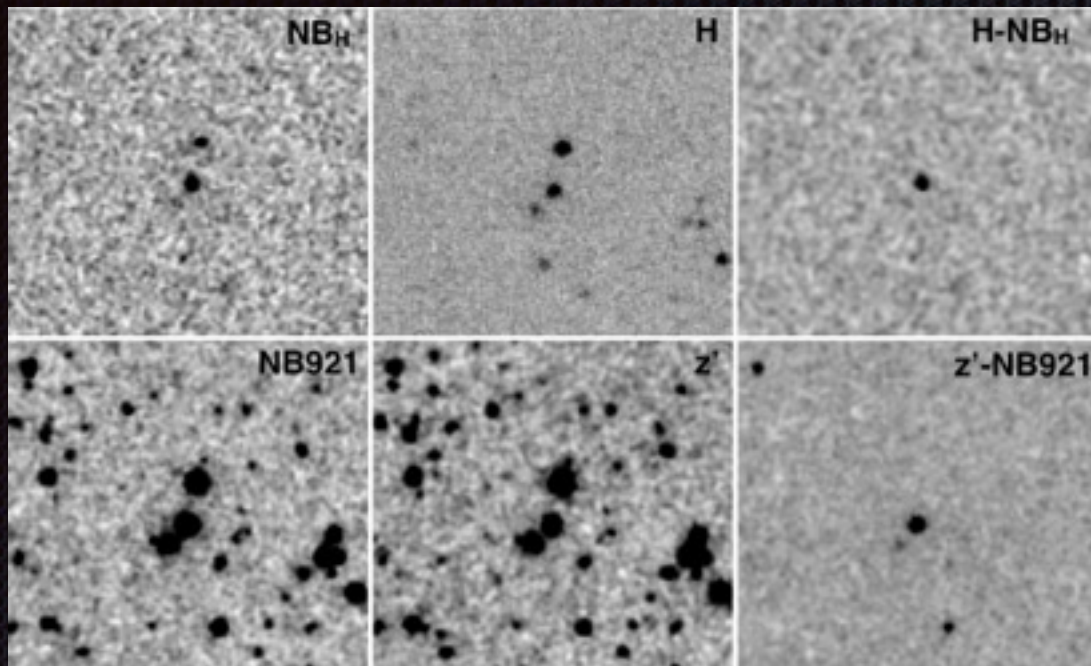
**z=1.47** : [OII] (NB921), H $\beta$  (NB<sub>J</sub>), H $\alpha$  (NB<sub>H</sub>)

**z=0.84** : [OIII] (NB921), H $\alpha$  (NB<sub>J</sub>)



**Ha emitters in HiZELS**  
**2 sq deg: COSMOS + UDS**

**Prior to HiZELS:**  
**~10 sources**



## Ha emitters in HiZELS

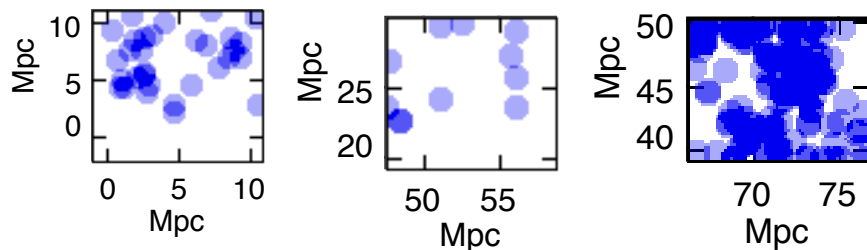
2 sq deg: COSMOS + UDS

**z=0.4: 1122    z=0.8: 637    z=1.47: 515 and z=2.23: 807**

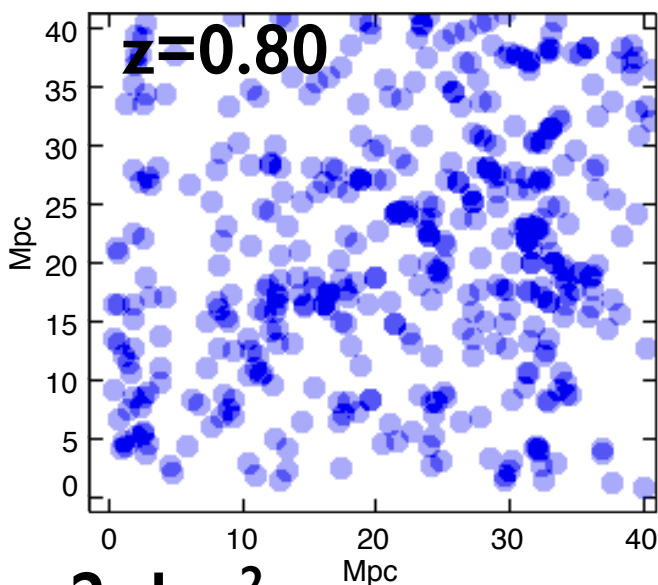
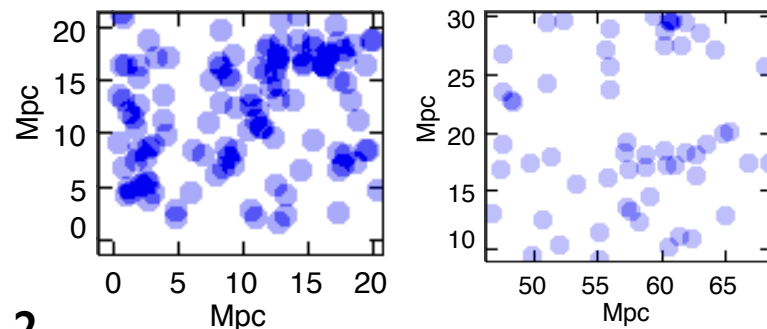
Right now: Full HiZELS (UKIDSS DXS fields) + CFHT (SA22):

**z=0.8: 6000    z=1.47: 1200 and z=2.23: 1500  
along with 1000s of other z~0.1-9 emission line  
selected galaxies**

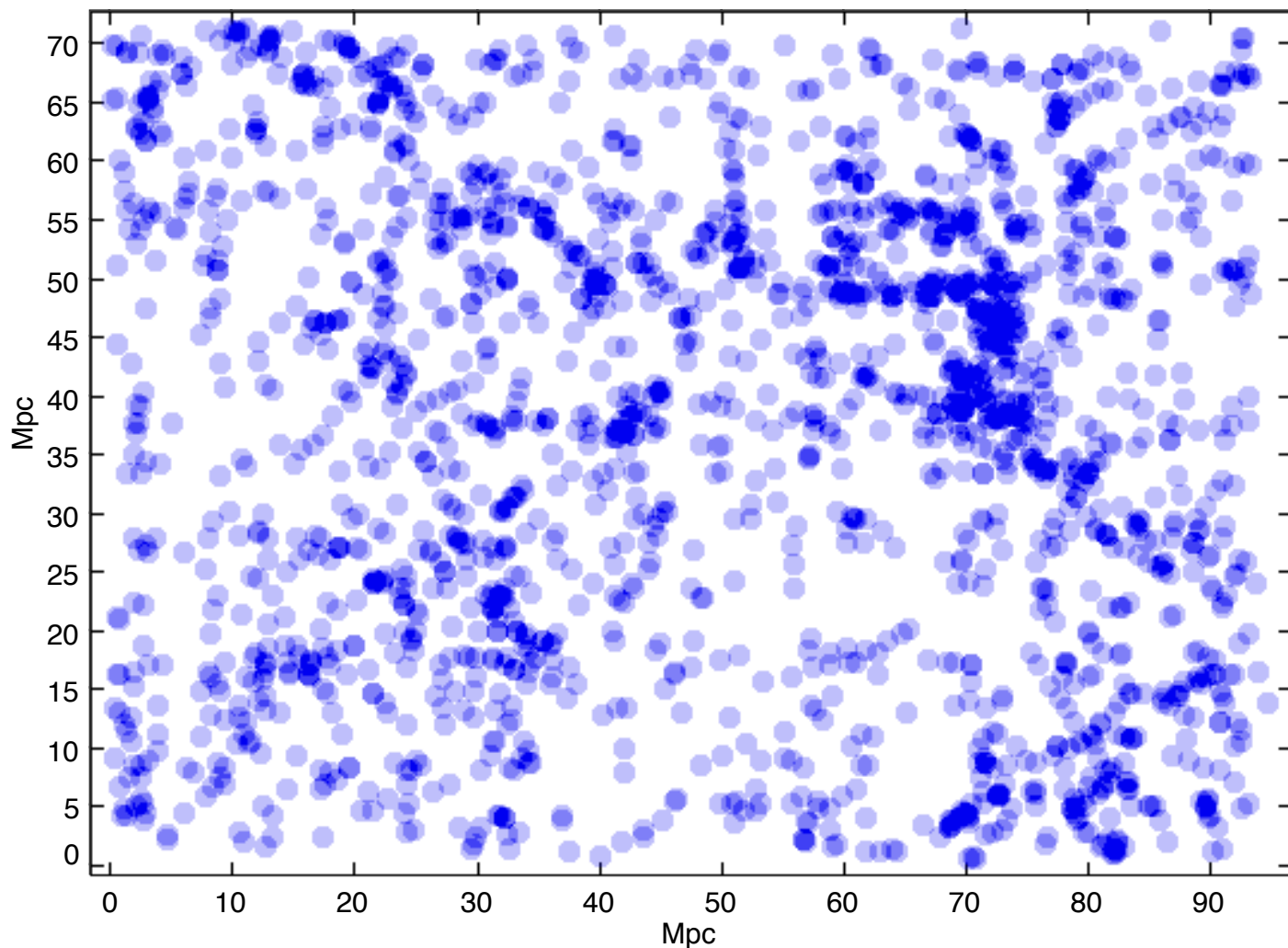
**10x10 Mpc ~ 100 arcmin<sup>2</sup>**



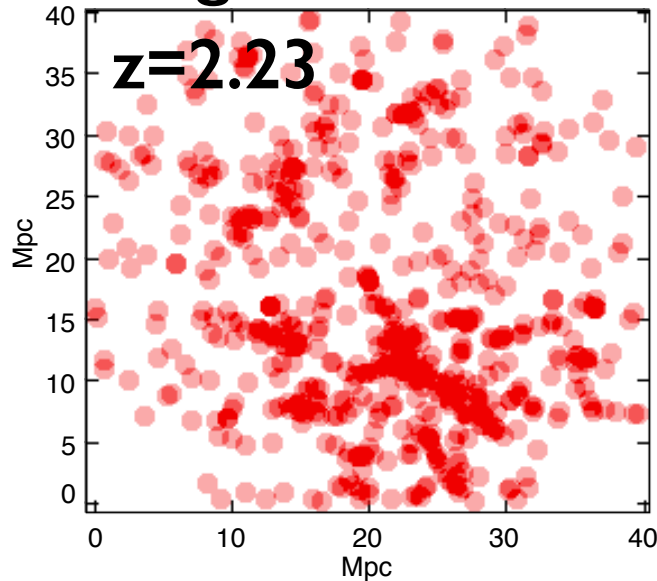
**20x20 Mpc ~ 0.7 deg<sup>2</sup>**



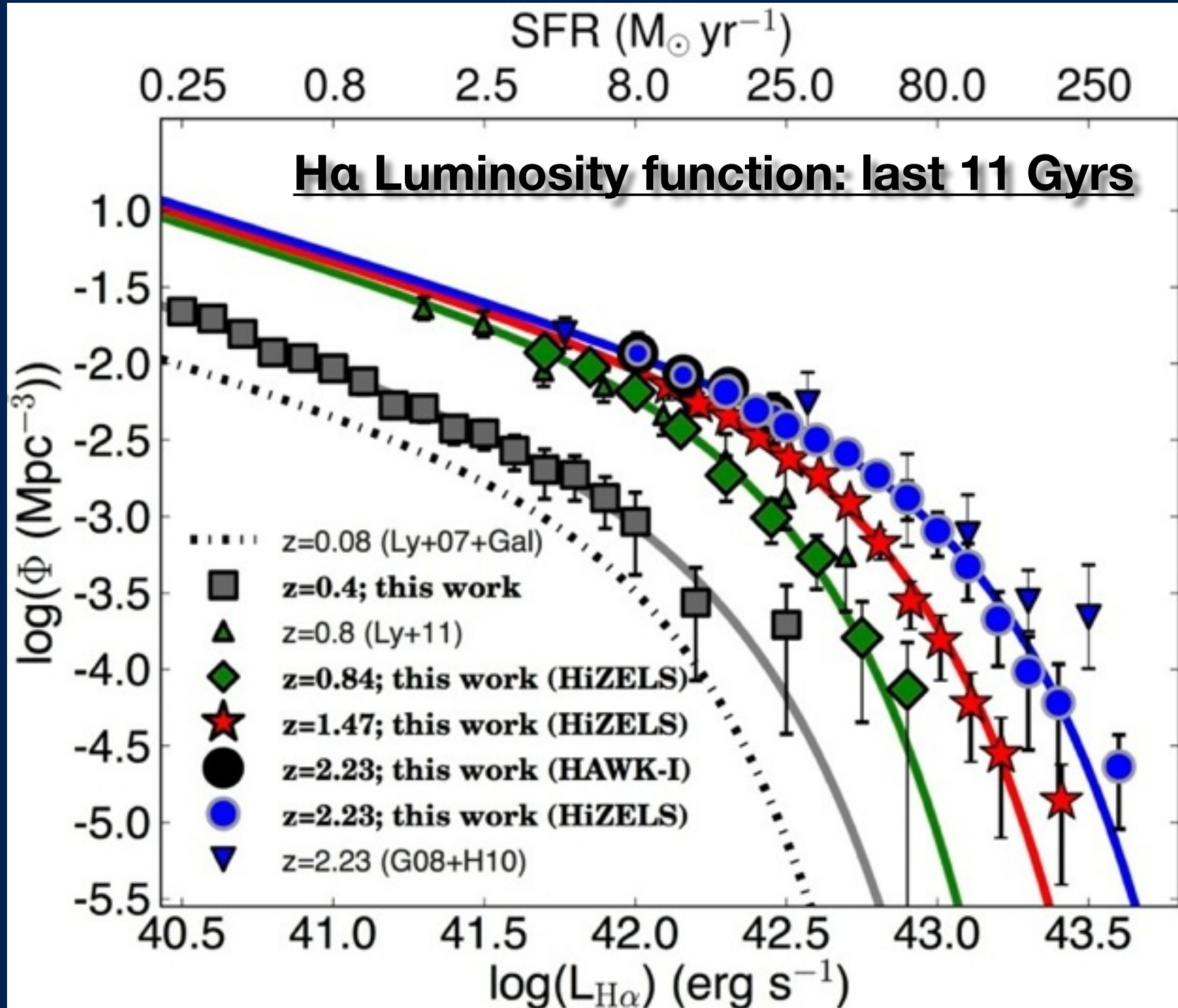
**~ 10 deg<sup>2</sup>**

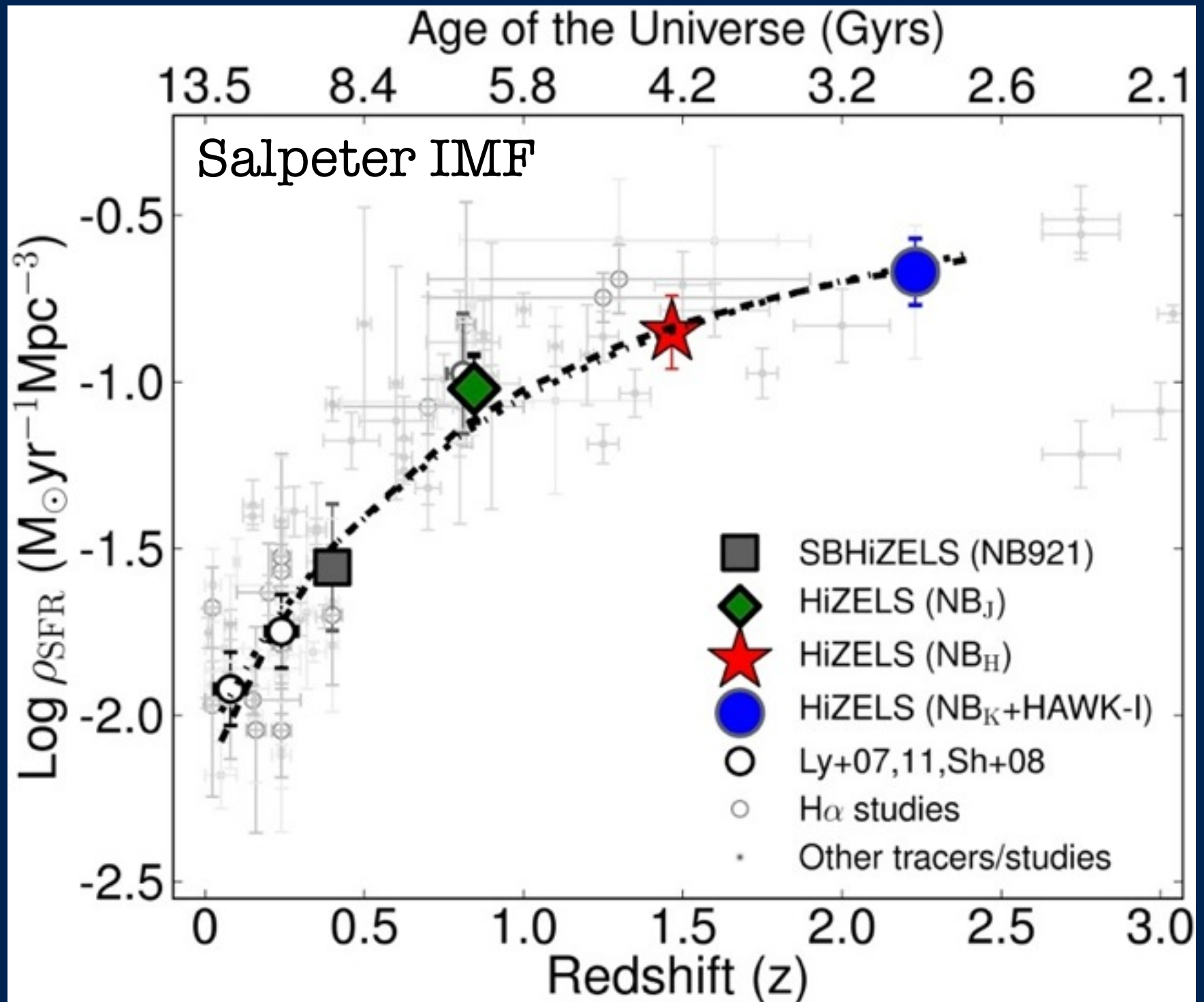


**~ 2 deg<sup>2</sup>**



**H $\alpha$  emitters  $z=0.8 \pm 0.0$**





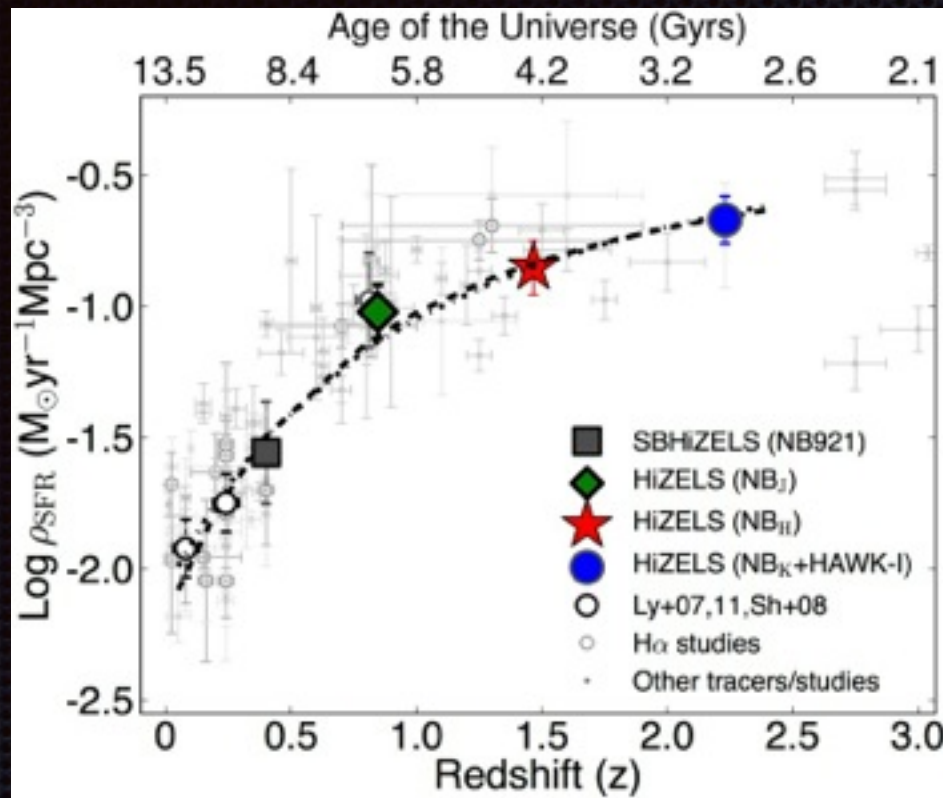
# H $\alpha$ Star formation History

Strong decline with time

$$\log \rho_{\text{SFR}} = -0.14T - 0.23$$

$$\log_{10}(\text{SFRD}) = -2.1/(1+z)$$

Sobral+13a



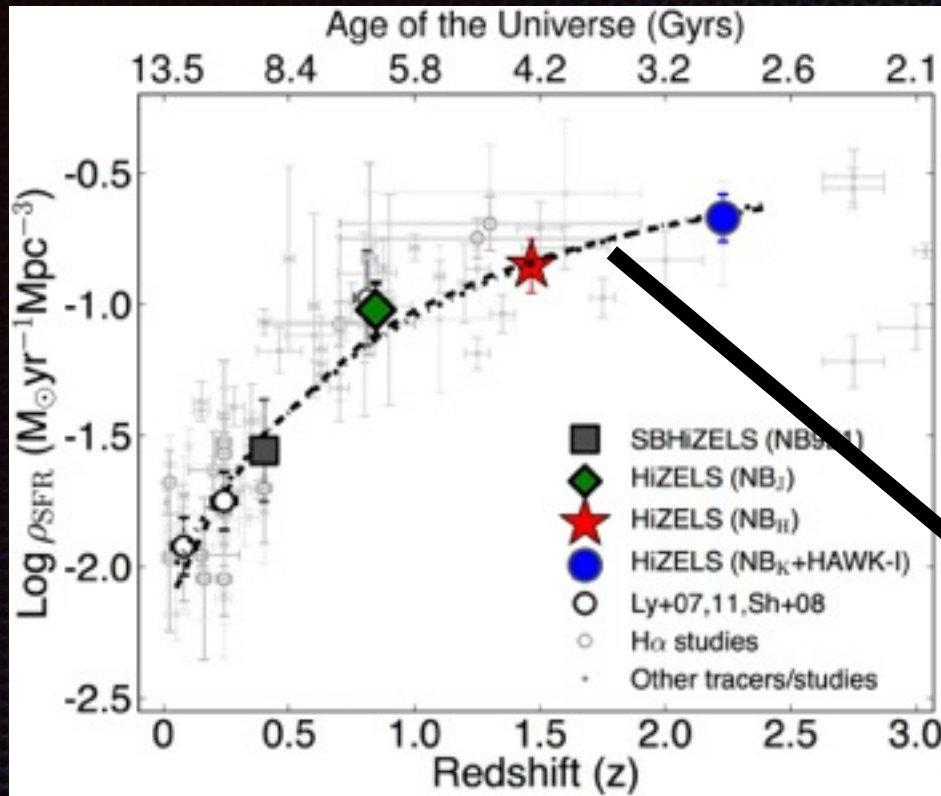
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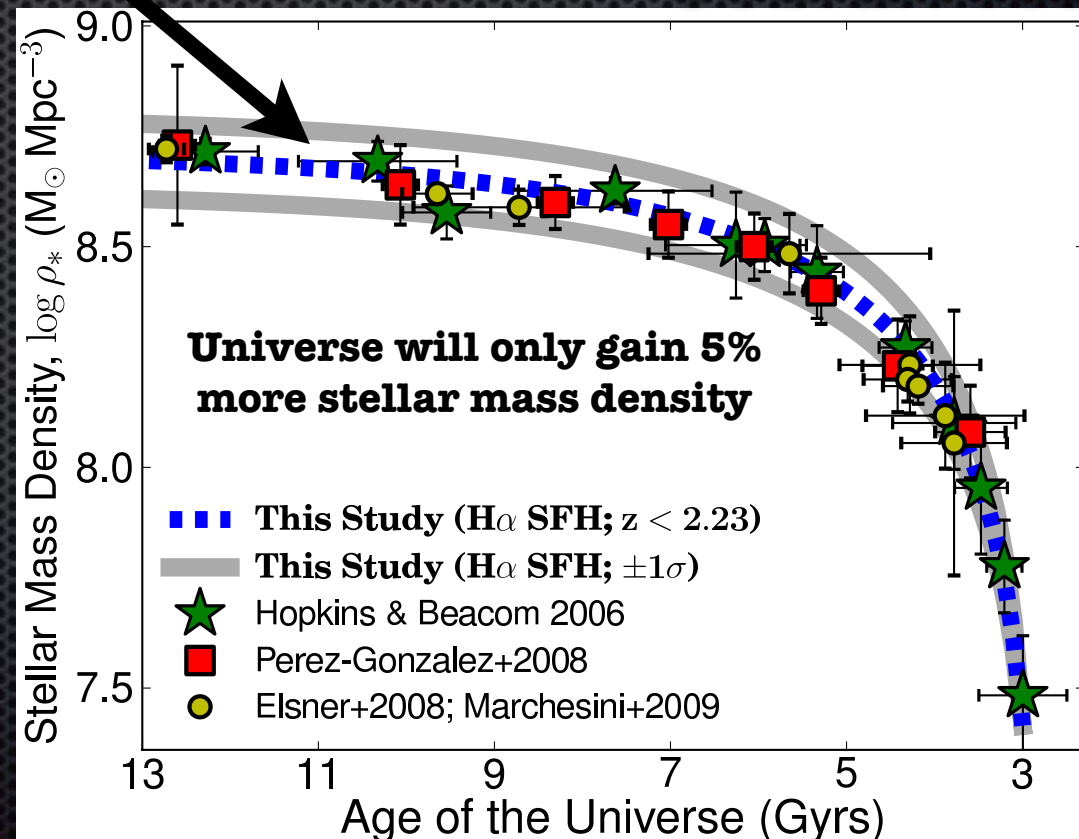
$$\log_{10}(\text{SFRD}) = -2.1/(1+z)$$

Sobral+13a



**Stellar Mass density  
evolution assembly**

Star formation history  
prediction matches  
observations



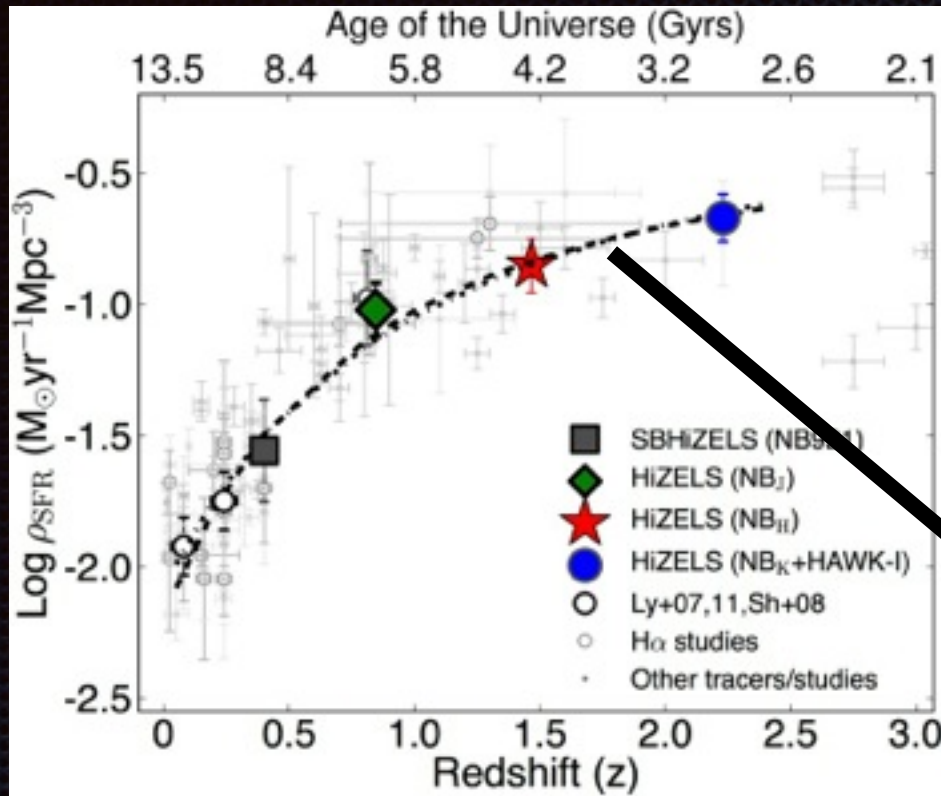
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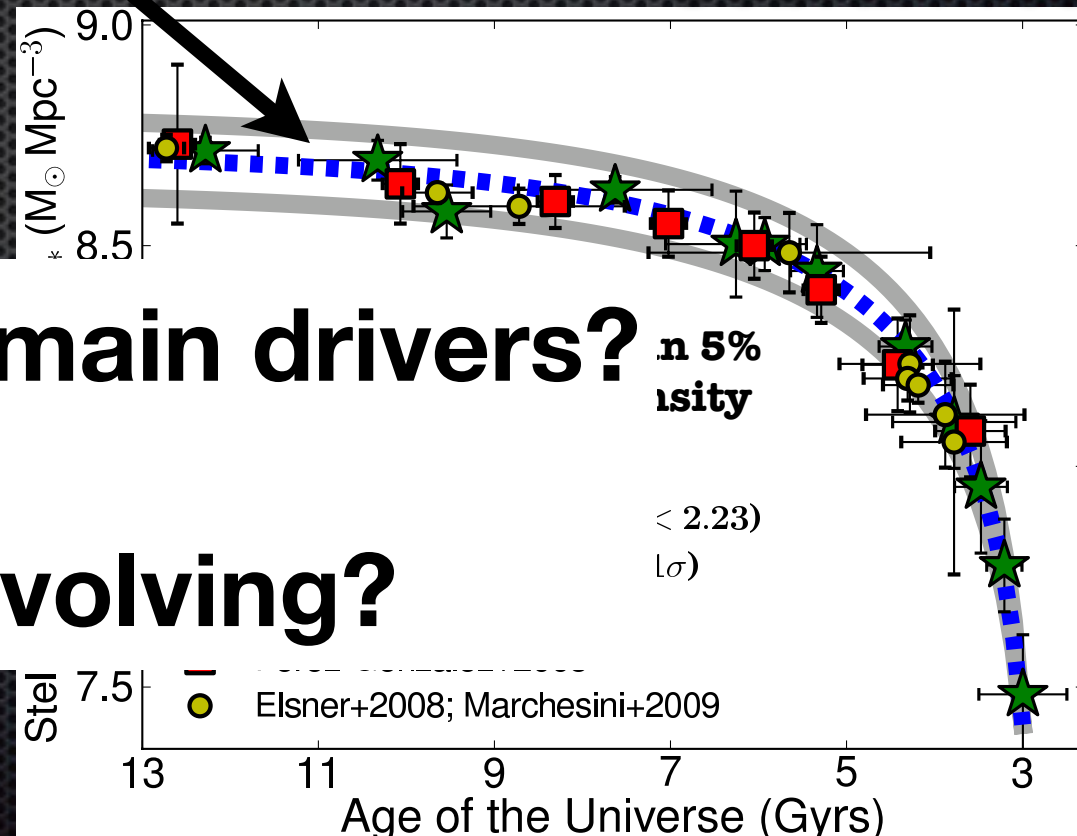
Stellar Mass density  
evolution

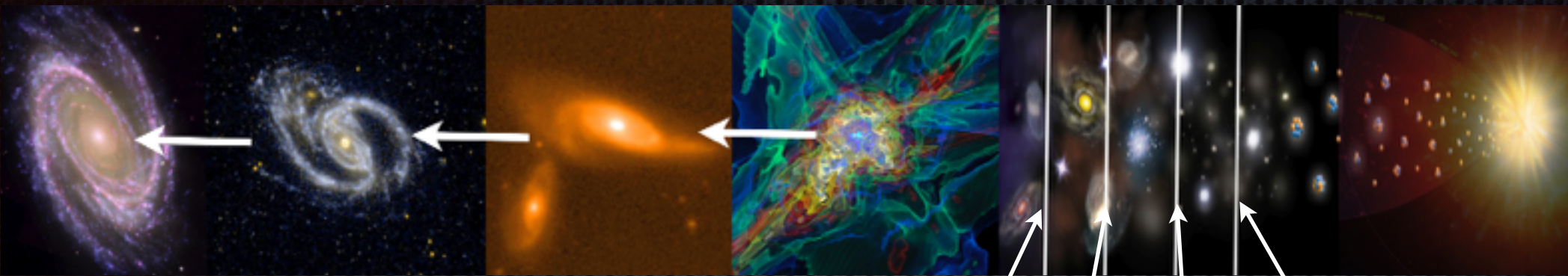
What are the main drivers?

Star  
prec

observations

What's evolving?

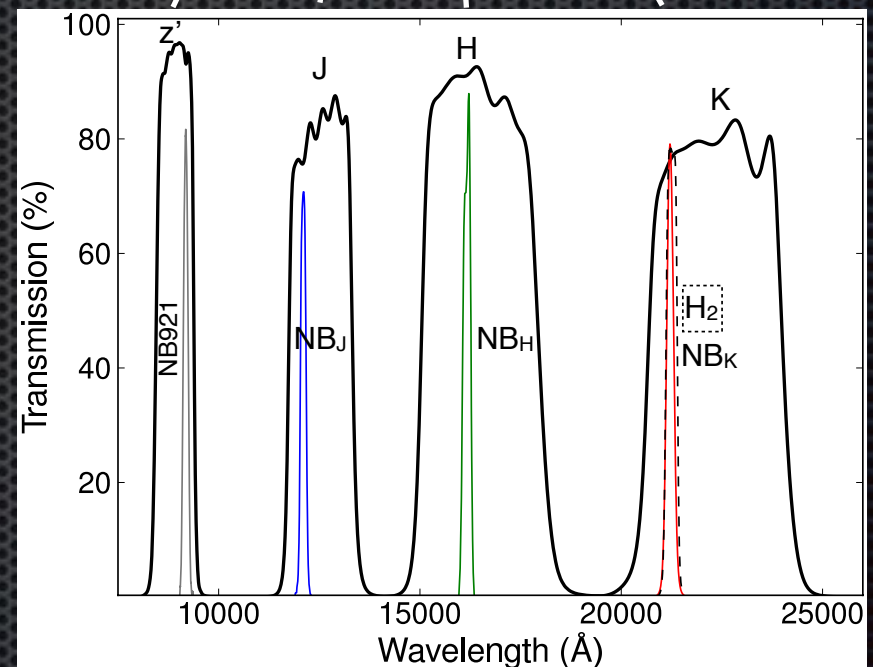




**Equally selected  
“Slices” with  $>1000$   
star-forming galaxies in  
multiple environments  
and with a range of  
properties**

**Check out the latest results:**

Size + merger evolution: **Stott+13a**  
Metallicity evolution + FMR: **Stott+13b,14**  
[OII]-Ha at high-z: **Hayashi+13, Sobral+12**  
Dust properties: **Garn+10, S+12, Ibar+13**  
Clustering: **Geach+08,13, Sobral+10**



**Catalogues are public!**

Dynamics: e.g. **Swinbank+12a,b, Sobral+13b**  
Lyman-alpha at  $z>7$ : **Sobral+09b, Matthee+14**  
Environment vs Mass: e.g. **Sobral+11, Koyama+13**  
AGN vs SF: **Garn+10, Lehmer+13, Kohn+**

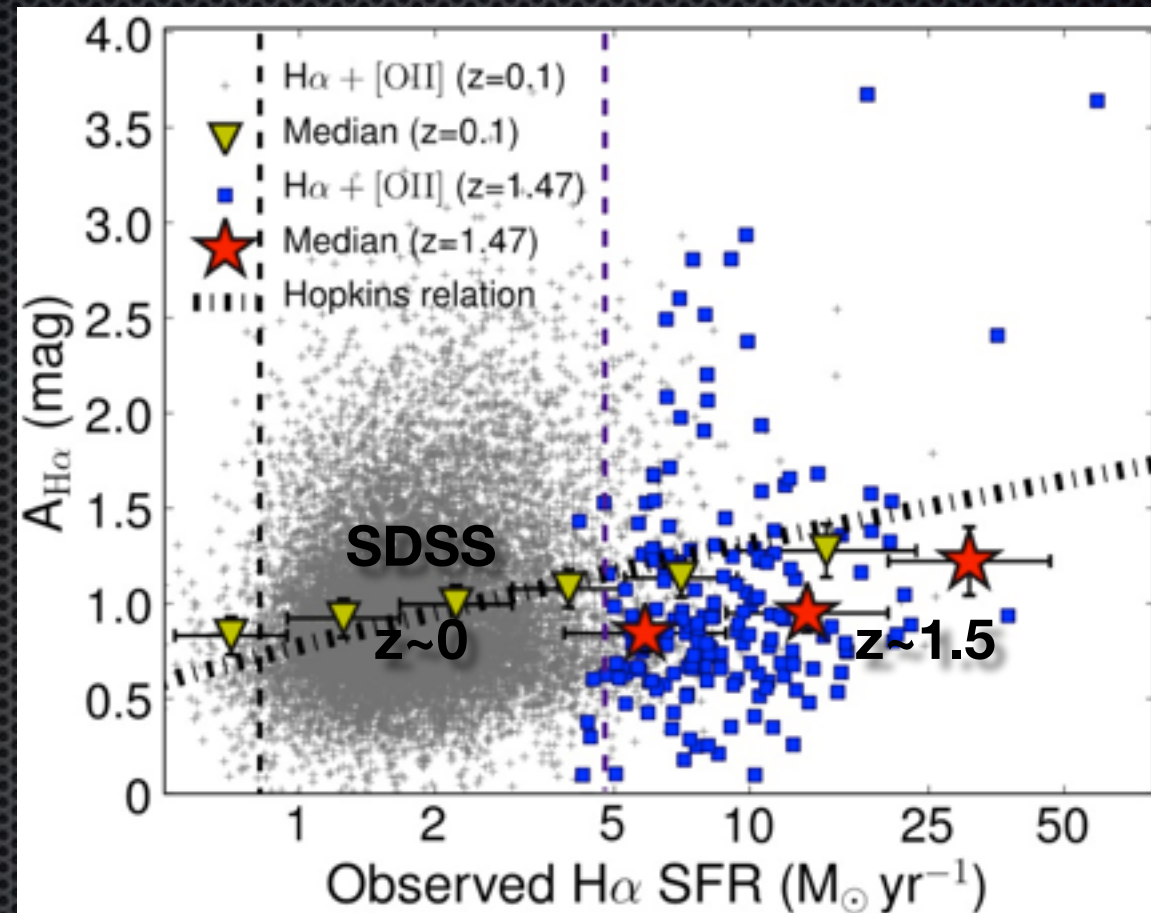
# Dust extinction-SFR in the last 9 Gyrs

Sobral et al. (2012)

Does the empirical SFR-dust extinction dependence hold at  $z \sim 1.5$ ?

**No! Offset of  $\sim 0.5$  mag**

**Star-forming galaxies at higher- $z$  are NOT dustier than local ones at the same SFR**



Local relations (extinction corrections as a function of observed luminosity) over-predict dust-corrections at high redshift

see also Domínguez et al. 2013

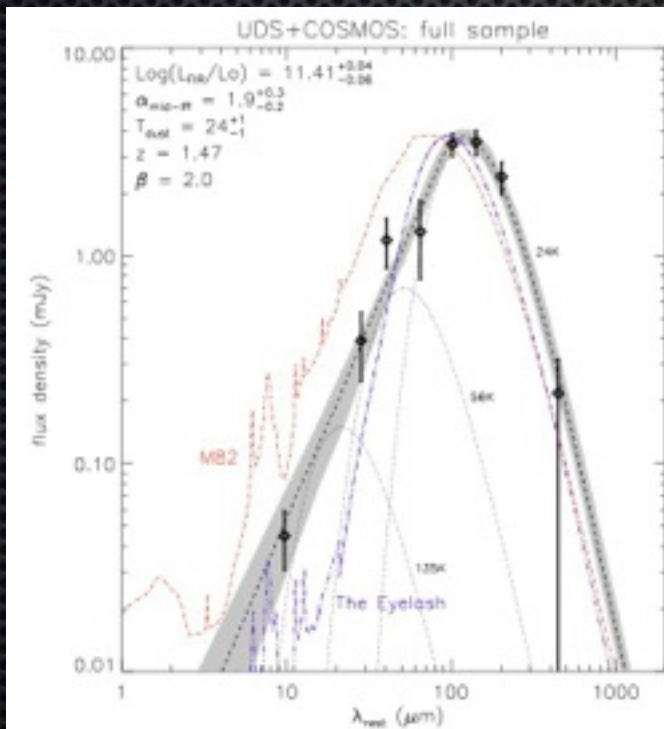
# Extinction-Mass $z\sim 0-1.5$

Garn & Best 2010: Stellar Mass correlates with dust extinction ( $z\sim 0$ )

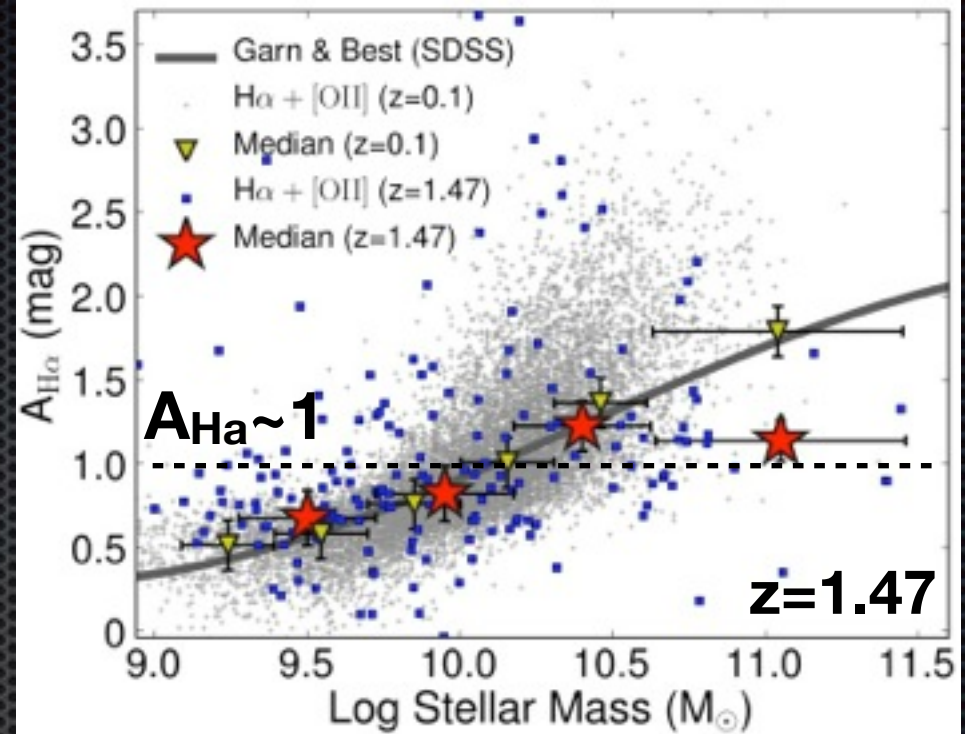
**Valid up to  $z\sim 1.5-2$ ! (Sobral+12;**

discovery further confirmed by e.g. Kashino+14, Ibar+13, Price+13 + many others in many different samples)

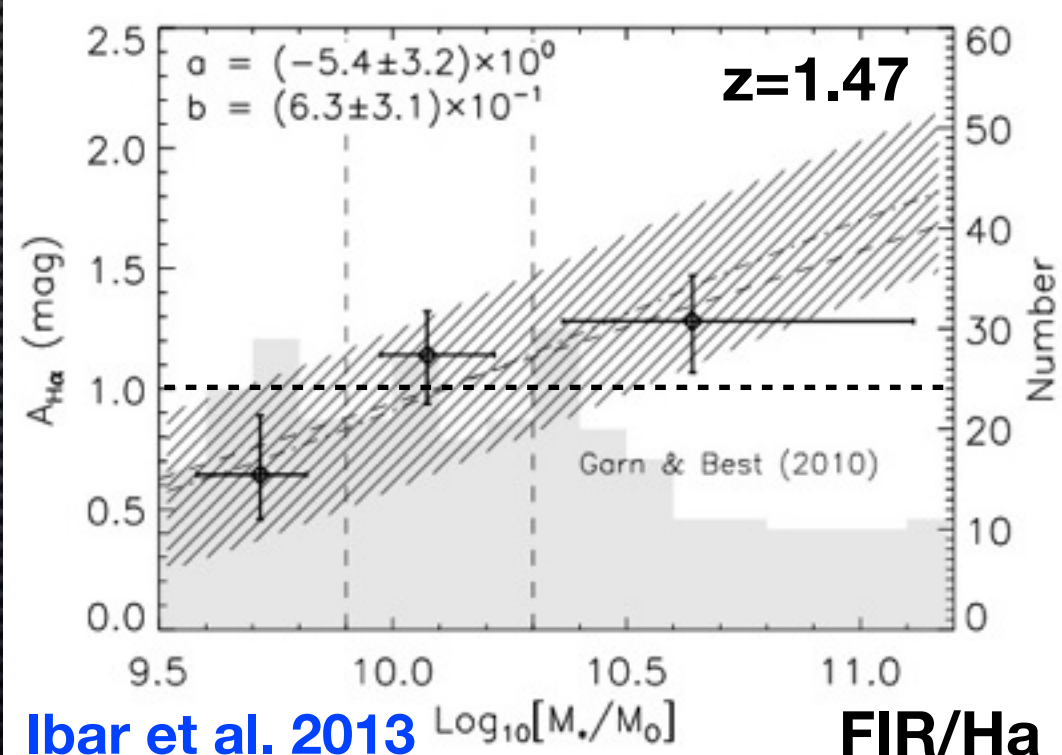
Now confirmed by Herschel



FIR derived  $A_{\text{H}\alpha} = 0.9-1.2$  mag



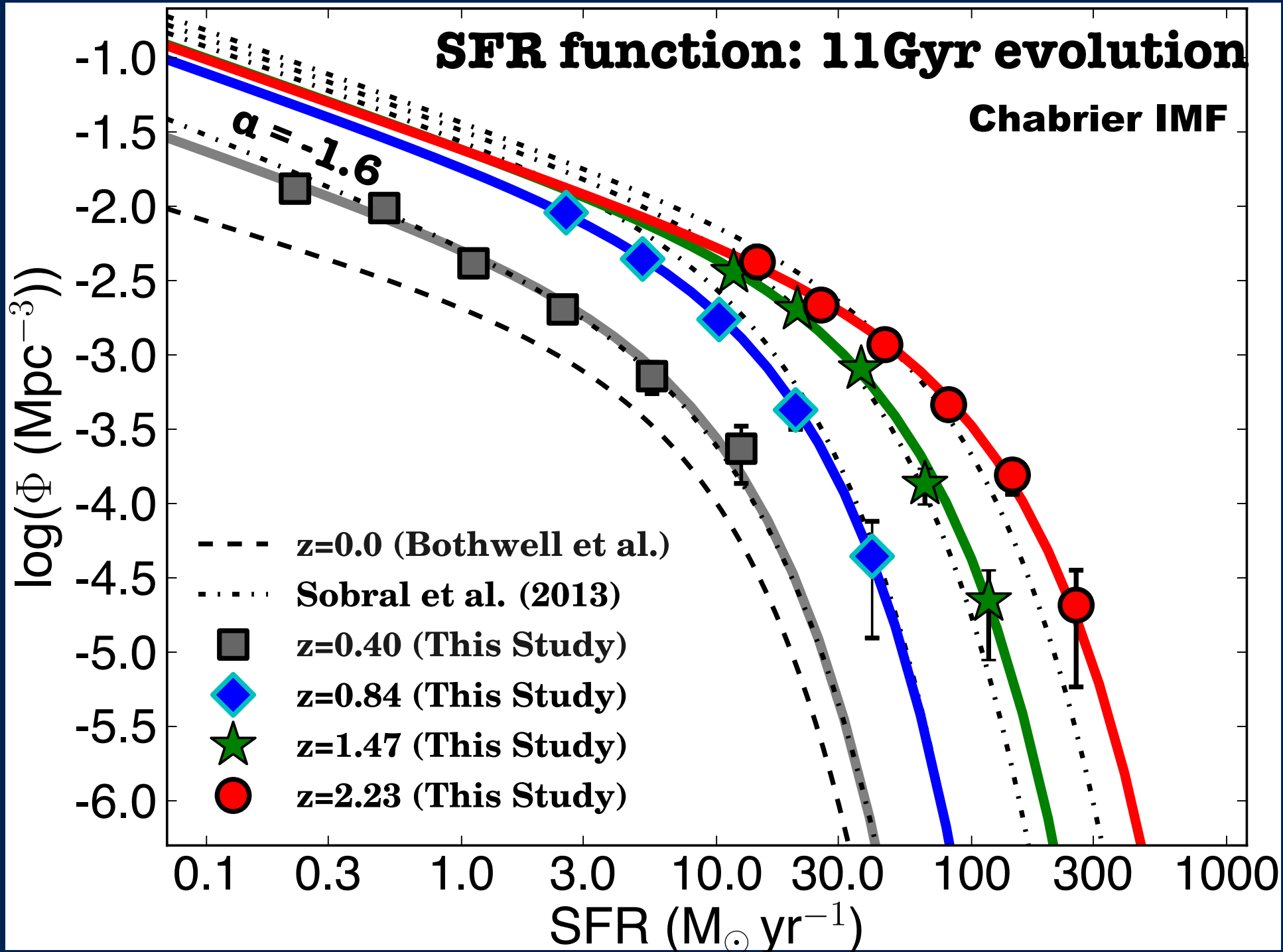
**Sobral et al. 2012**



**Ibar et al. 2013**

$\text{Log}_{10}[M_*/M_\odot]$

**FIR/Ha**



Sobral et al. (2014)

# SFR function: Strong SFR \* evolution

$$\text{SFR}^*(T) = 10^{(4.23/T + 0.37)} \text{ M}_\odot/\text{yr}$$

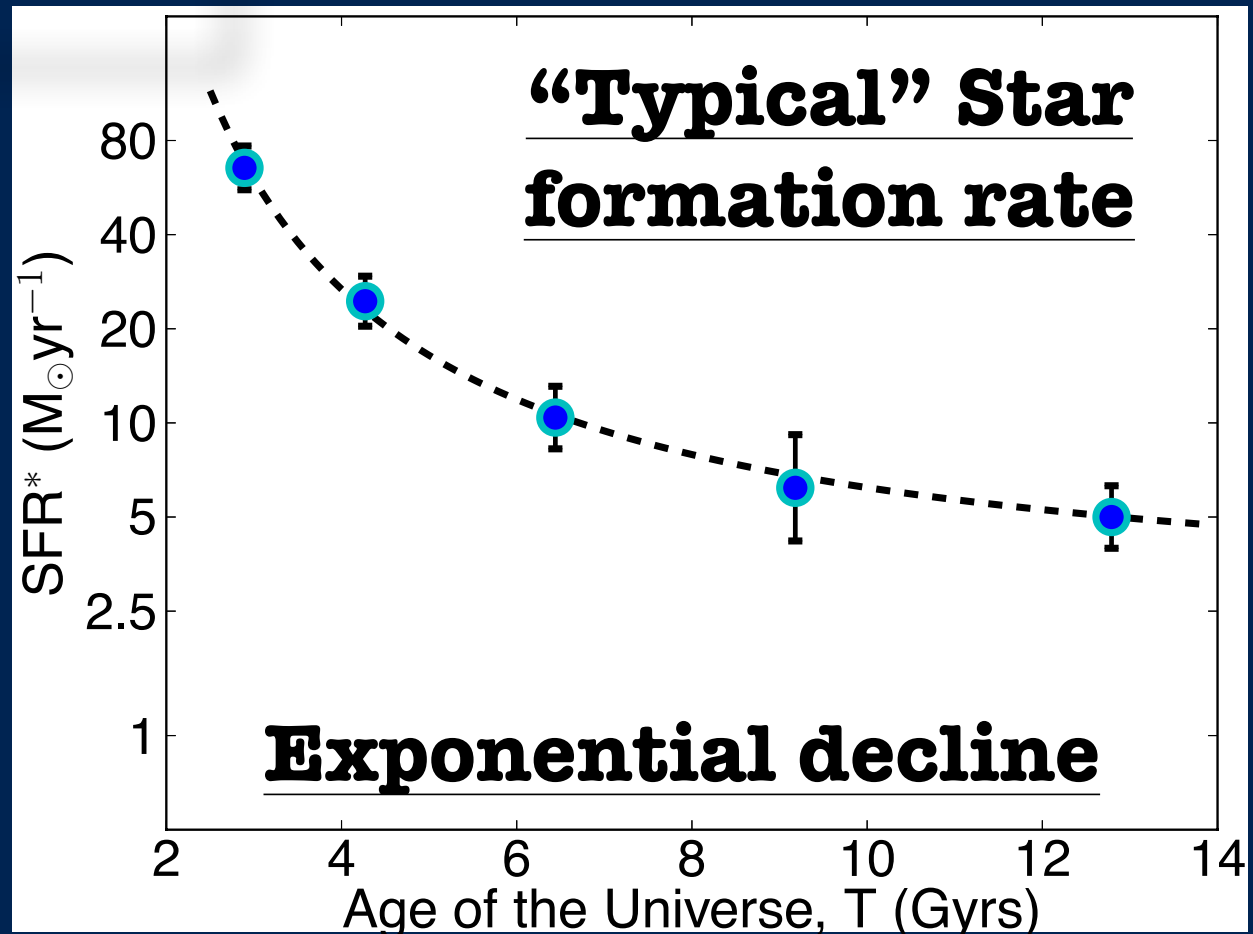
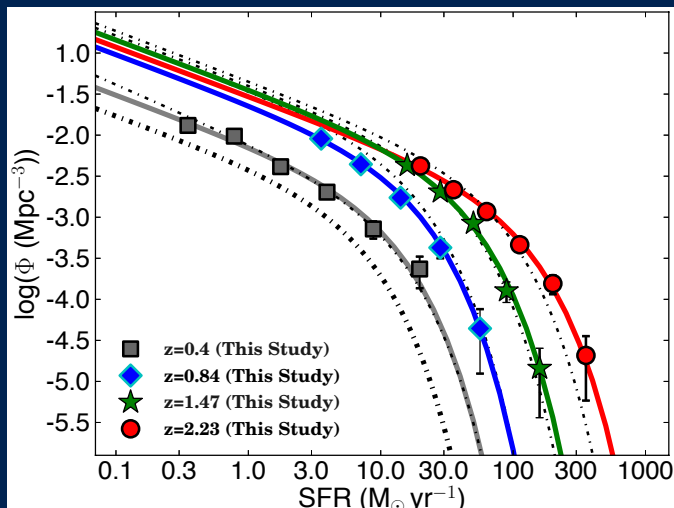
T, Gyrs

**13x decrease over last 11 Gyrs**

**Sobral+14, MNRAS**

Faint-end  
slope:  $\alpha = -1.6$

$$\alpha = -1.60 \pm 0.08$$



$$\log_{10}(\phi^*) = 0.004231T^3 - 0.1122T^2 + 0.858T - 4.659$$

**T, Gyrs**

# SFR function: Strong SFR\* evolution

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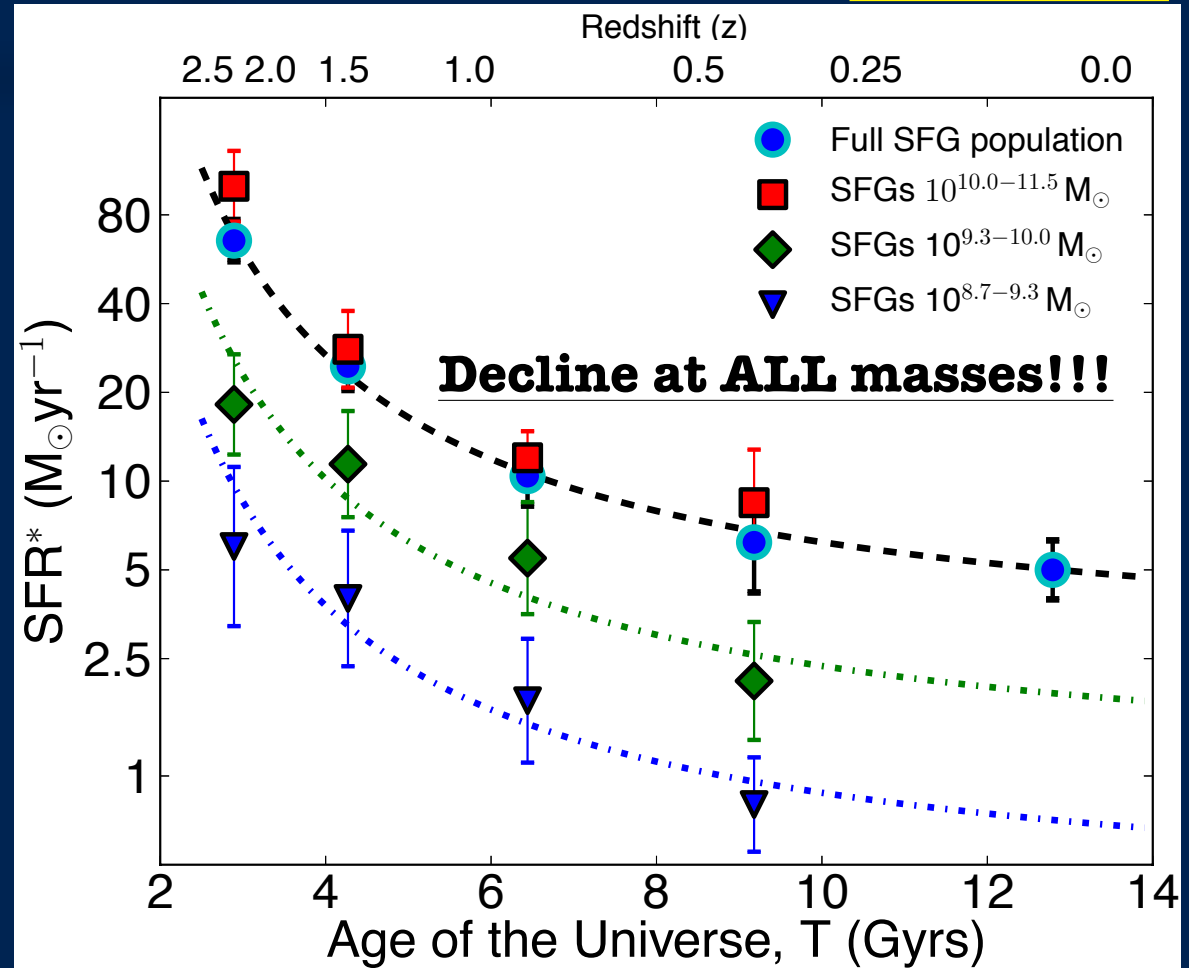
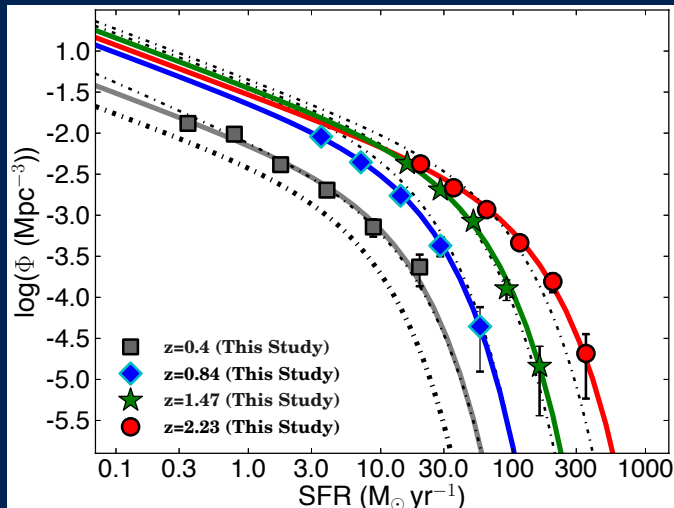
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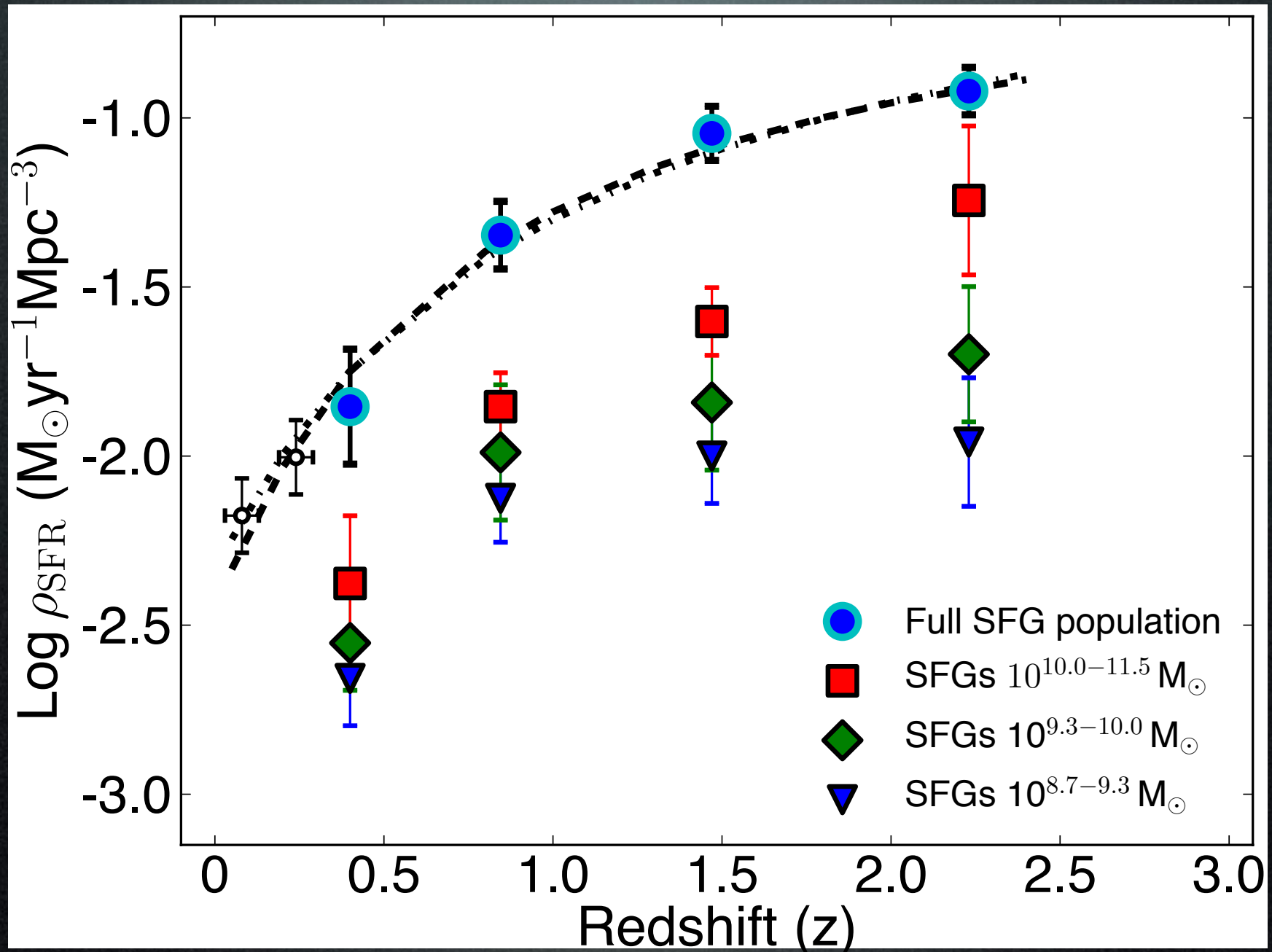


$\Phi^*$   
z=0  $\nearrow$  z=1  $\searrow$  z=2

$$\log_{10}(\phi^*) = 0.004231T^3 - 0.1122T^2 + 0.858T - 4.659$$

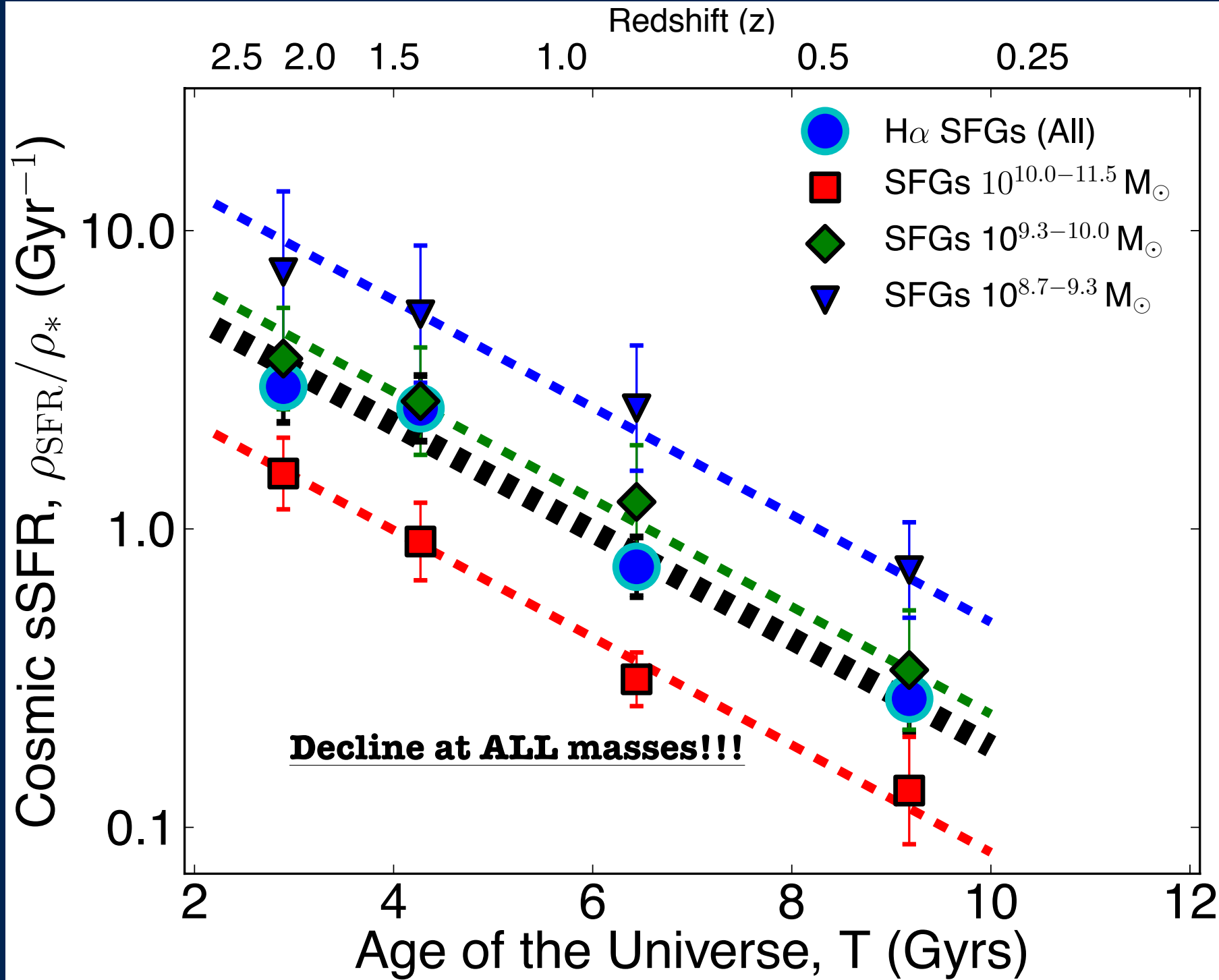
**T, Gyrs**

# SF History - No “Downsizing”!!

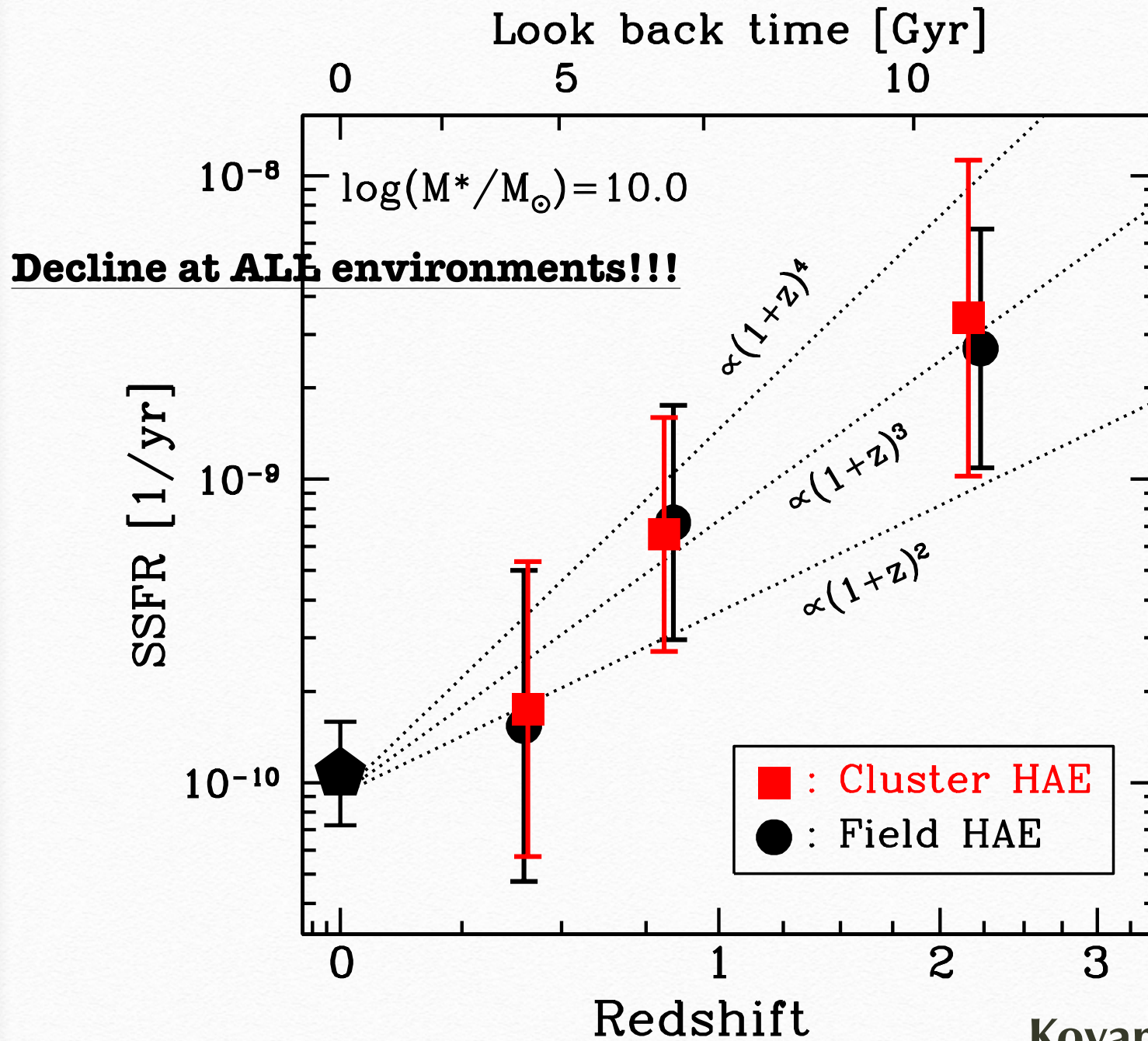


Decline at all masses

Sobral et al. (2014)



# Evolution of SFR\* (SSFR) same in fields and clusters since $z=2.23$



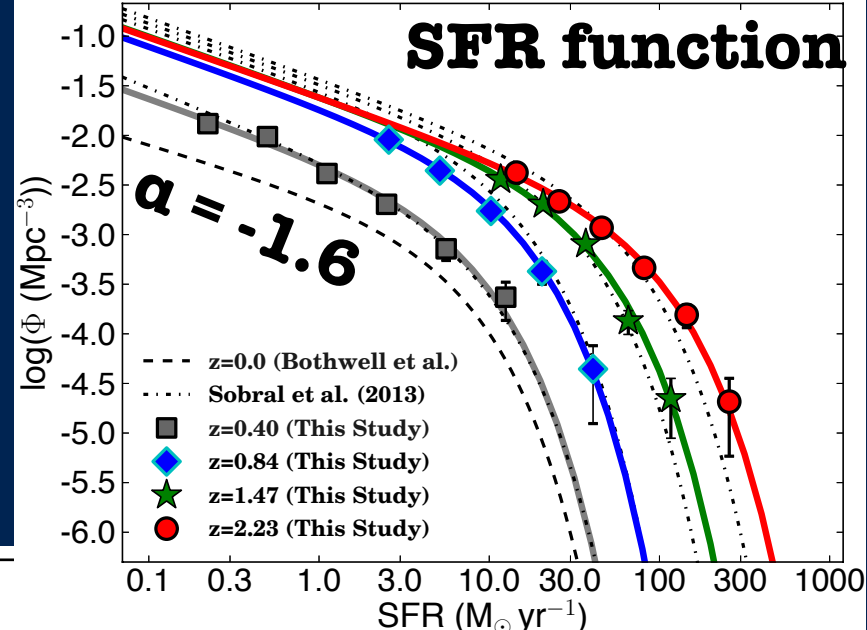
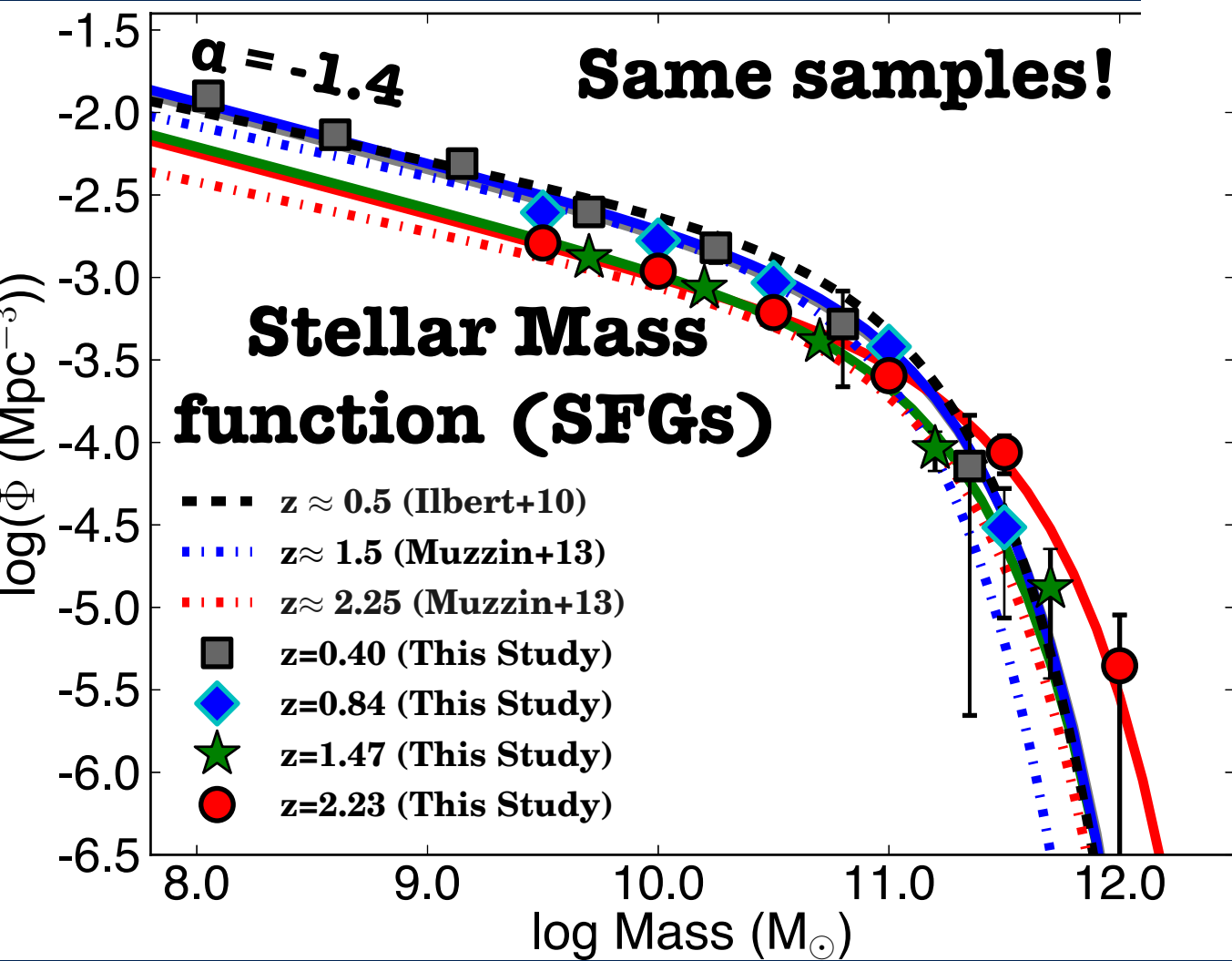
Koyama et al. 2013

# Strong SFR\* evolution

$$\text{SFR}^*(T) = 10^{(4.23/T + 0.37)} \text{ M}_\odot/\text{yr}$$

**T, Gyrs**

13x decrease over last 11 Gyrs

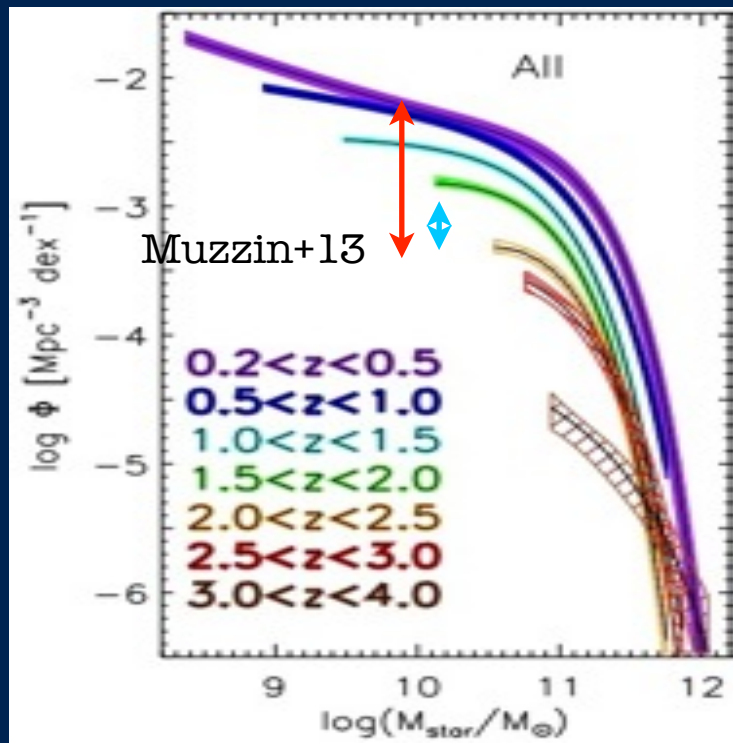


Mass function:  
Little evolution

$$M^* = 10^{11} \text{ M}_\odot$$

Faint-end  
slope:  $\alpha = -1.4$

Sobral et al. (2014)

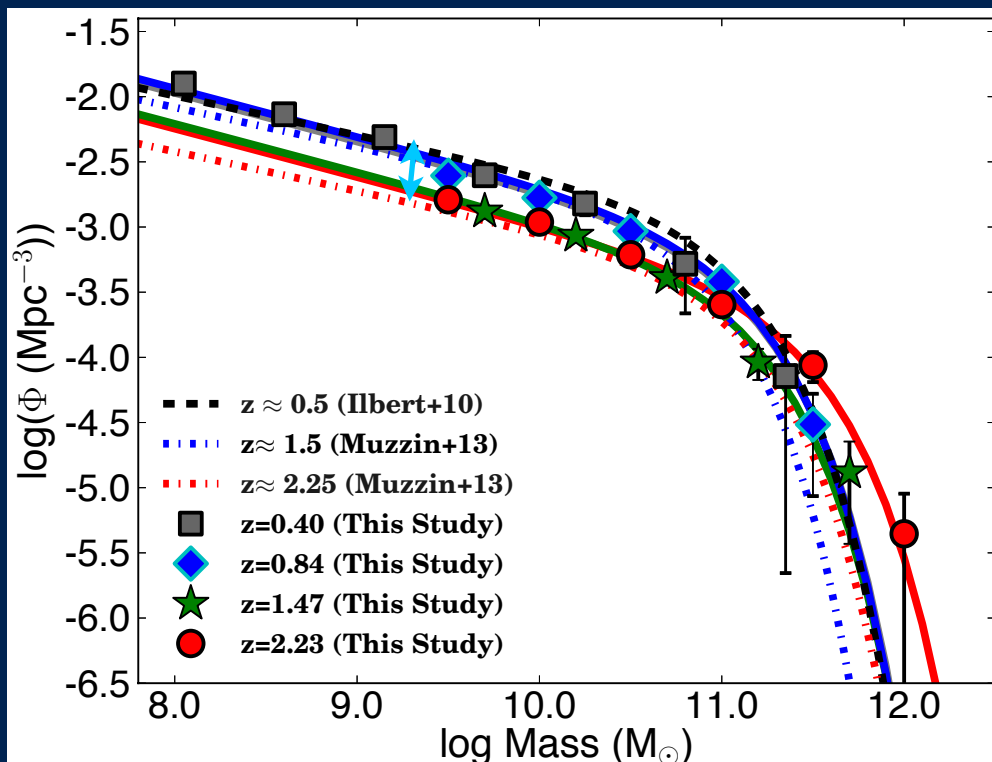


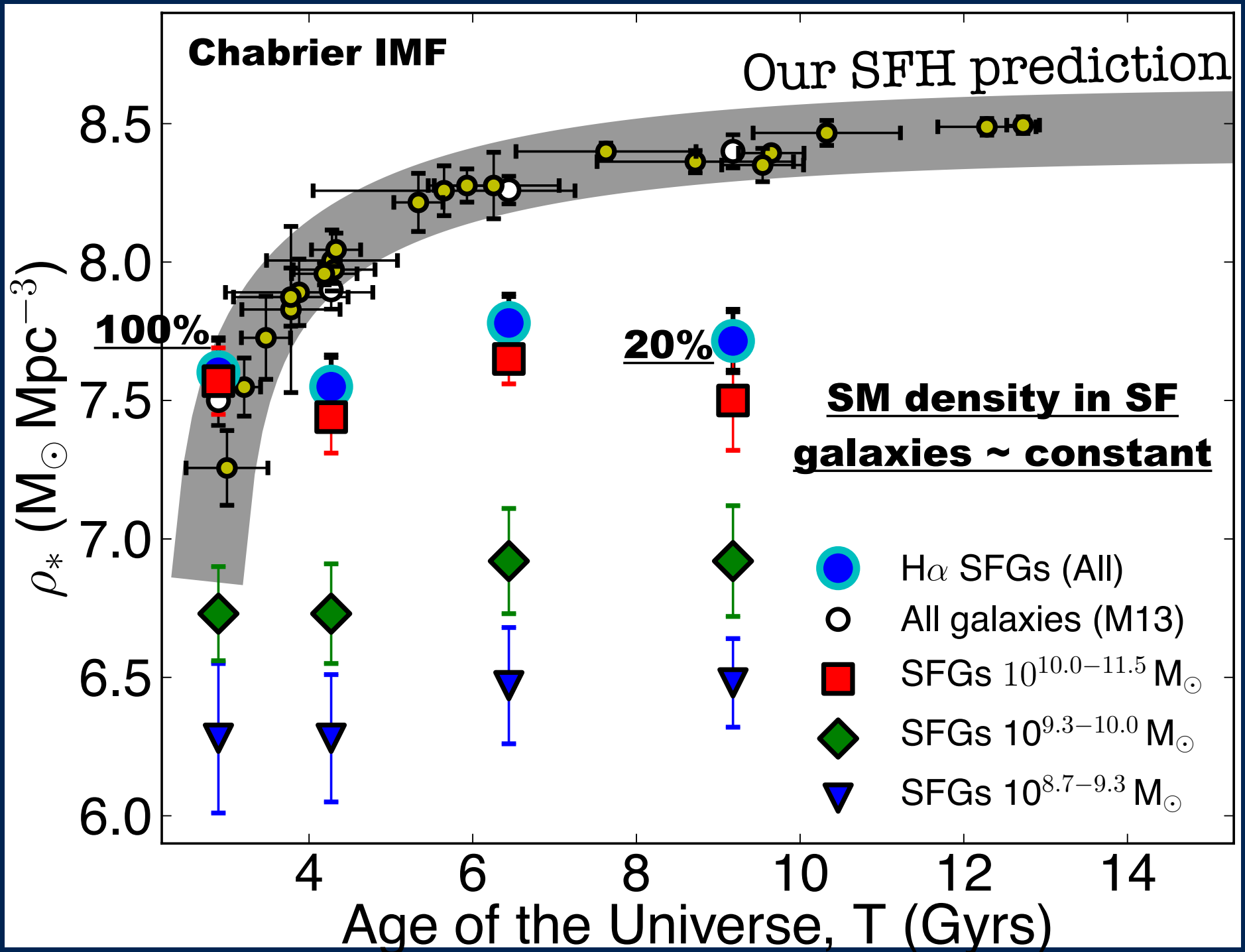
**Mass function of SFGs with much weaker evolution than that of the “entire” population**

**Driven by the \*rise\* of the “quenched” population**

**\*Fraction\* of SM density in SF galaxies:**

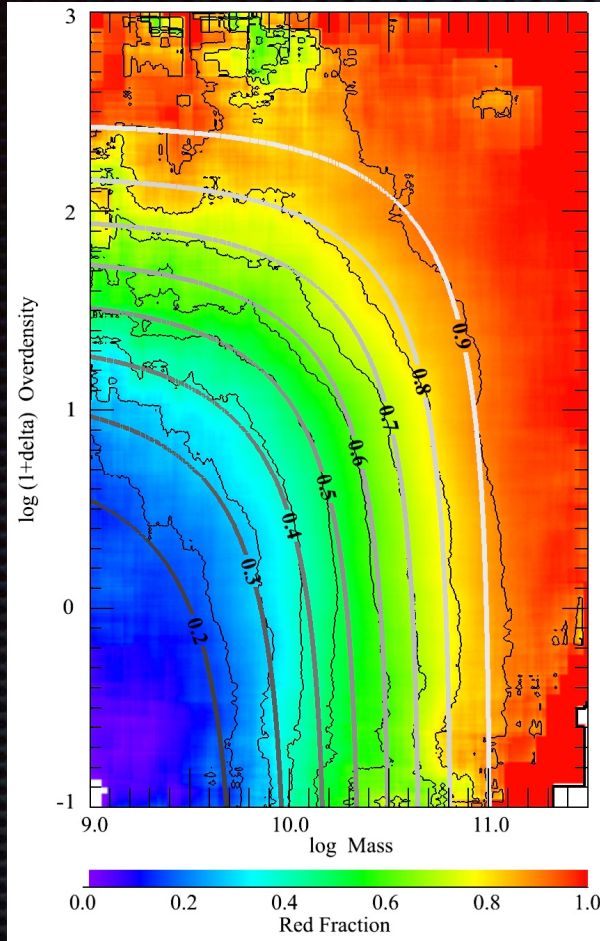
**Drops from ~100% ( $z=2.2$ ) to ~20% ( $z=0.4$ )**





# Mass and Environment?

$z \sim 0$

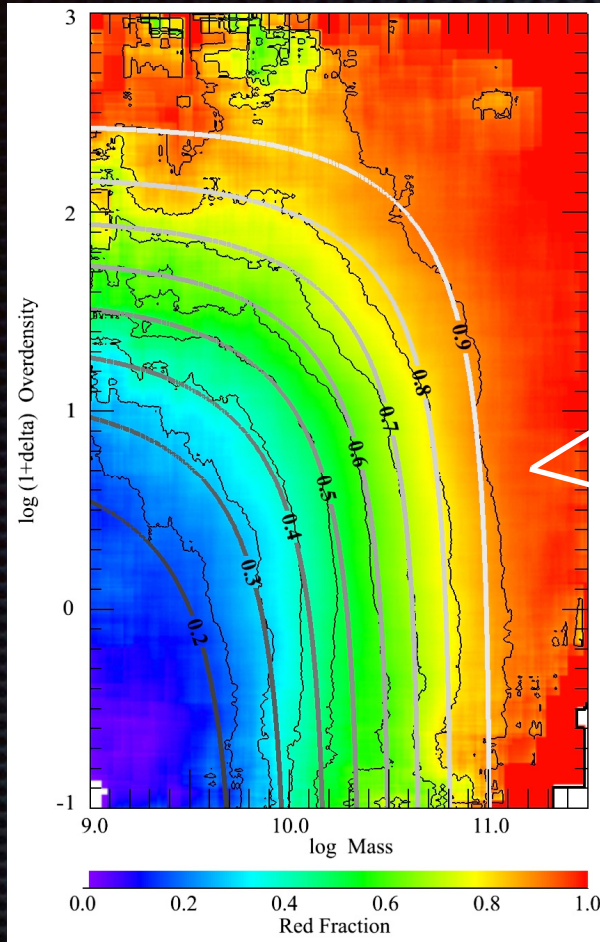


SDSS (Peng+10)

The fraction of star-forming galaxies declines with **both** mass and environment at  $z \sim 0$

# Mass and Environment?

$z \sim 0$

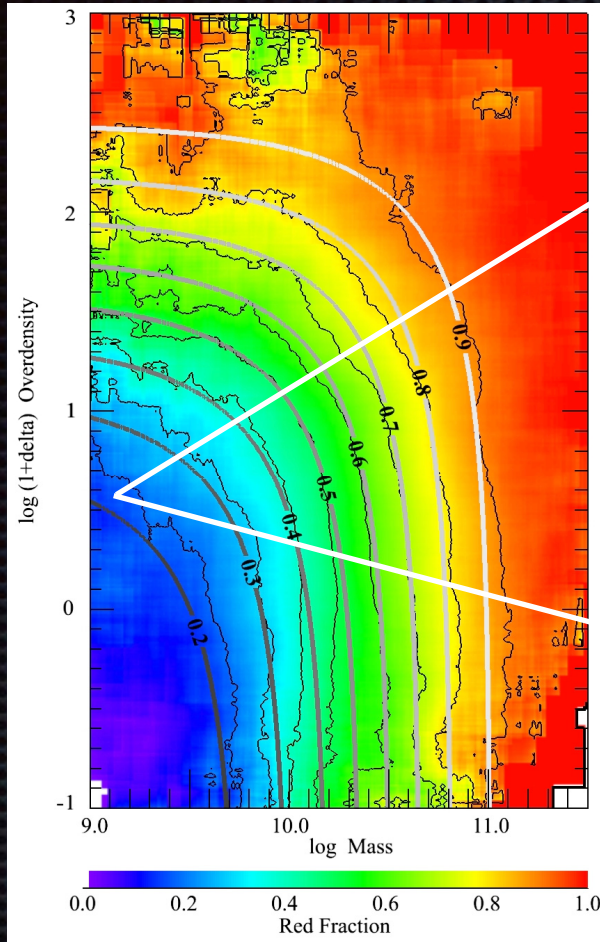


SDSS (Peng+10)

The fraction of star-forming galaxies declines with **both** mass and environment at  $z \sim 0$

# Mass and Environment?

$z \sim 0$

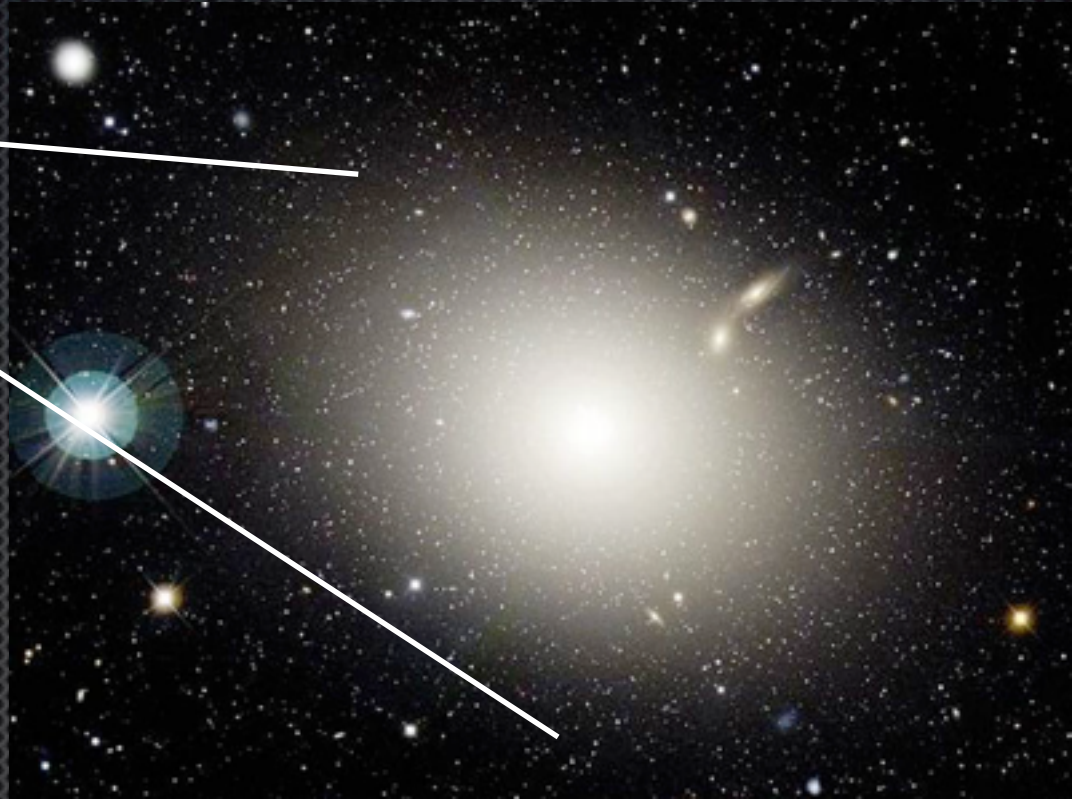
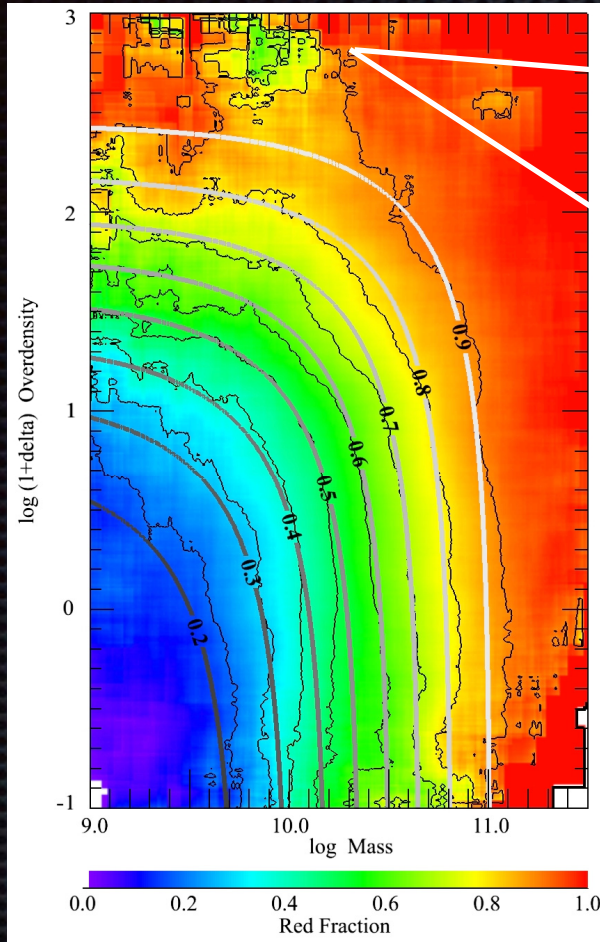


SDSS (Peng+10)

The fraction of star-forming galaxies declines with **both** mass and environment at  $z \sim 0$

# Mass and Environment?

$z \sim 0$

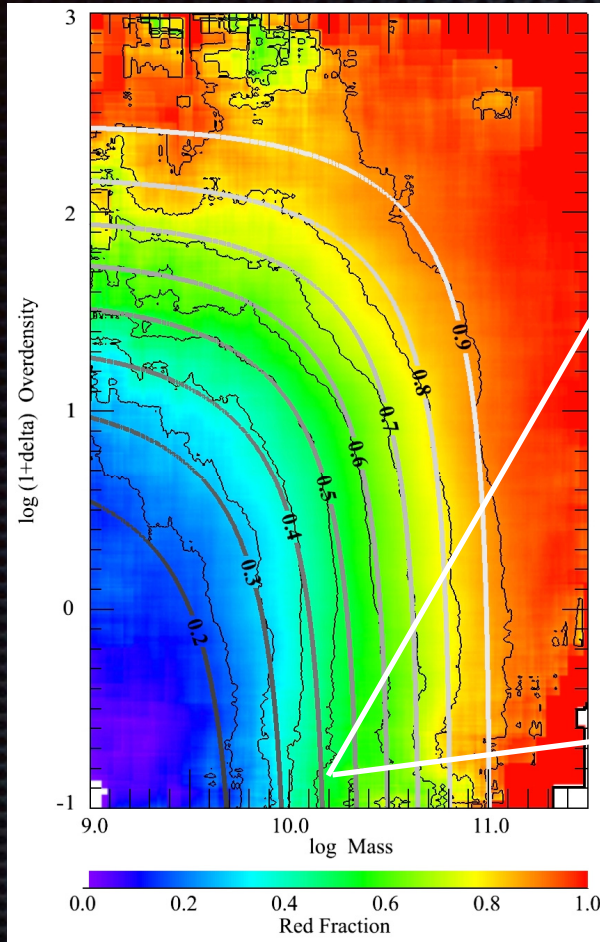


SDSS (Peng+10)

The fraction of star-forming galaxies declines with **both** mass and environment at  $z \sim 0$

# Mass and Environment?

$z \sim 0$

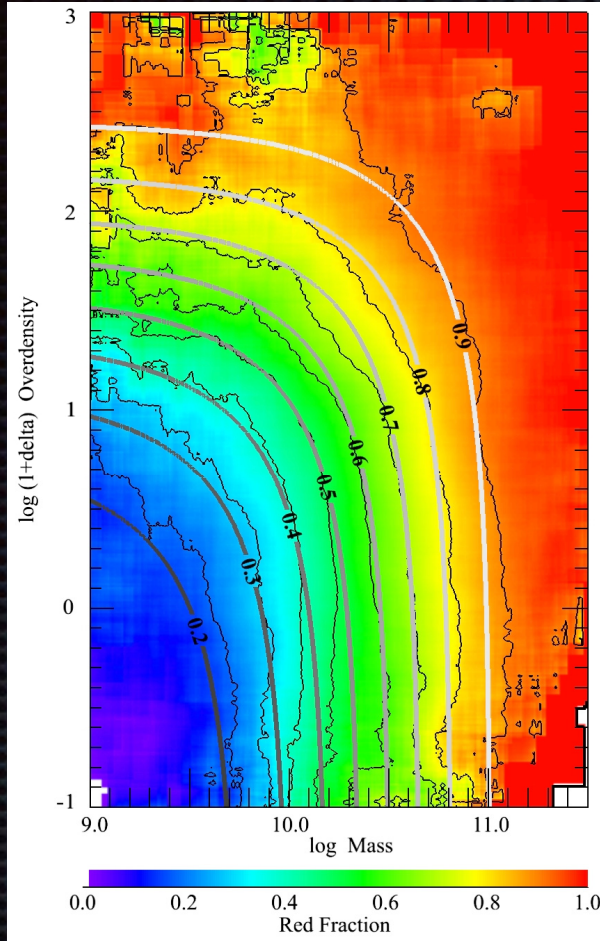


SDSS (Peng+10)

The fraction of star-forming galaxies declines with **both** mass and environment at  $z \sim 0$

# Mass and Environment?

$z \sim 0$



$z \sim 1, z > 1?$

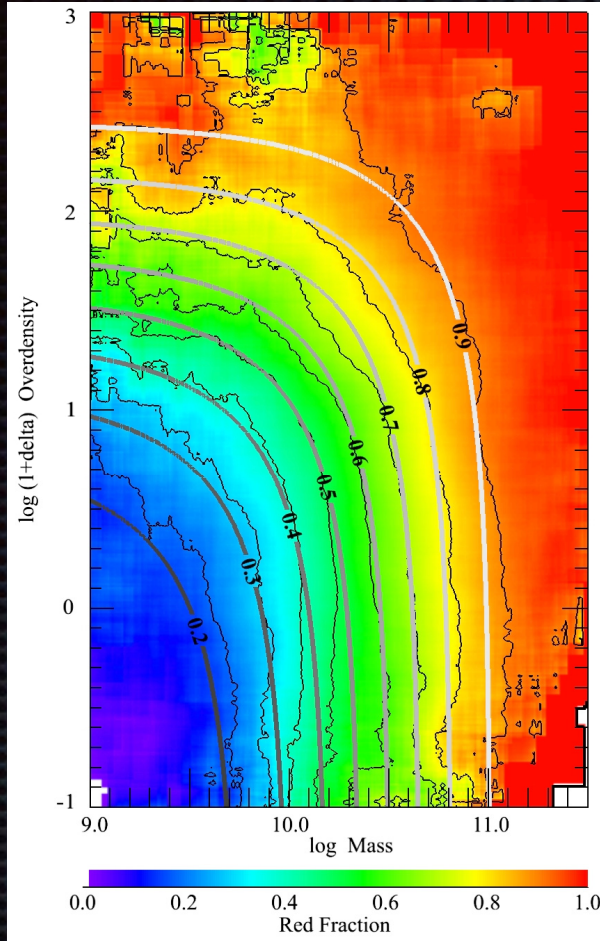
?

SDSS (Peng+10)

The fraction of star-forming galaxies declines with **both** mass and environment at  $z \sim 0$

# Mass and Environment

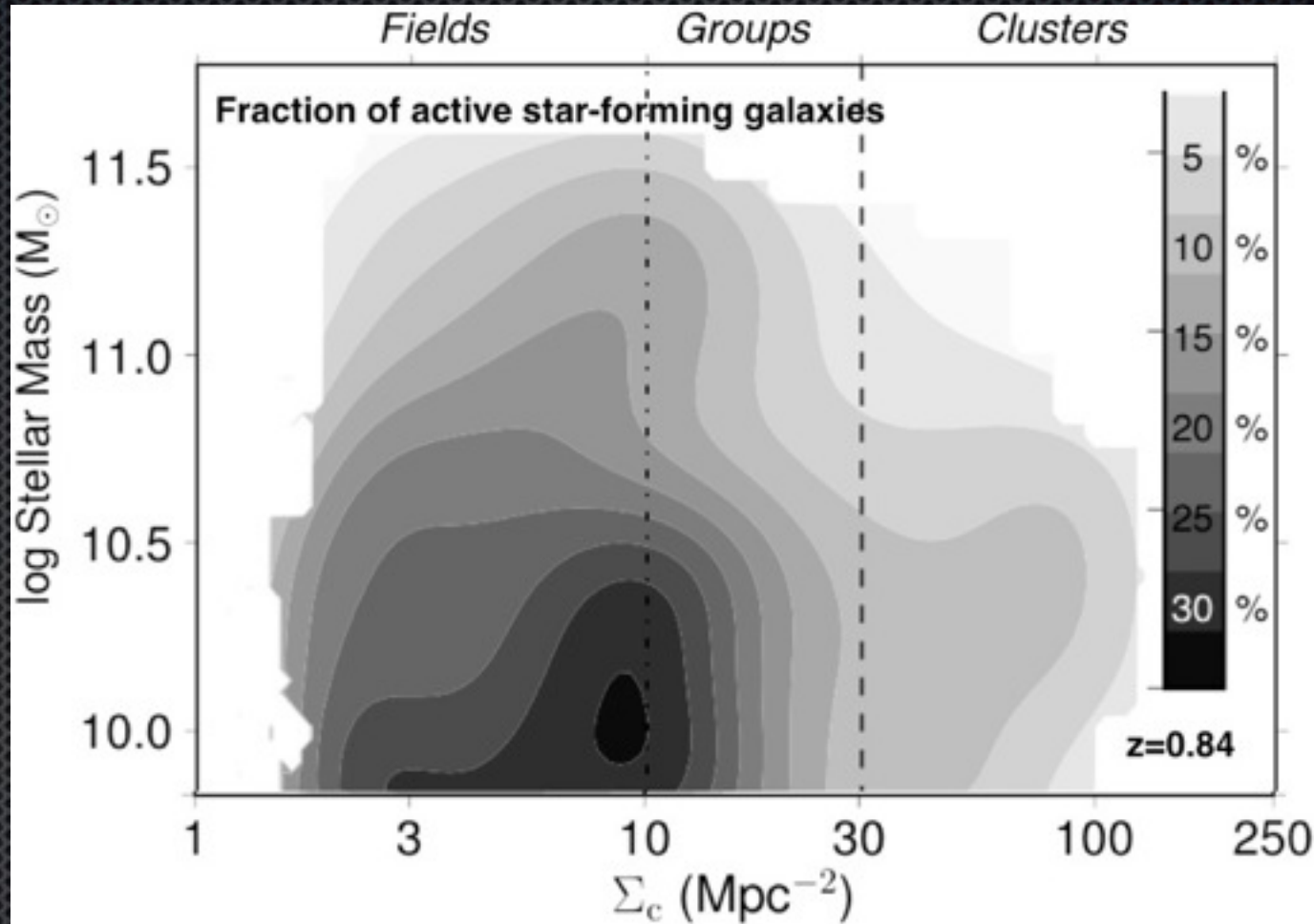
$z \sim 0$



SDSS (Peng+10)

$z \sim 1$

Sobral et al. 2011



Mass trend at least up to  $z \sim 1.5$

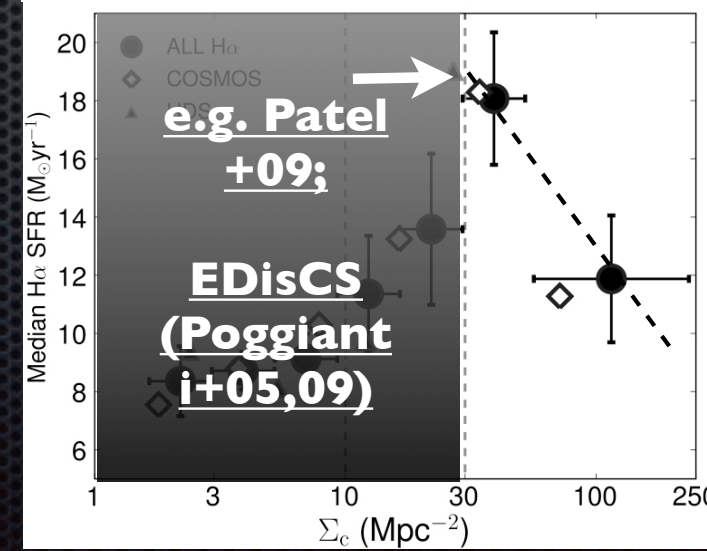
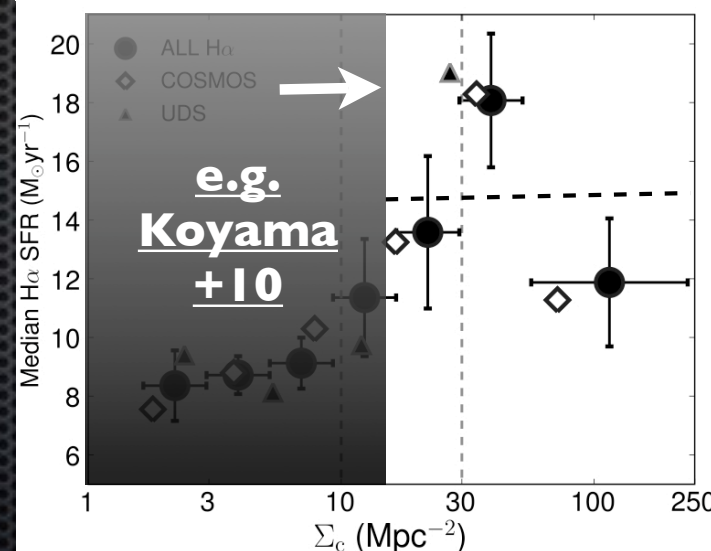
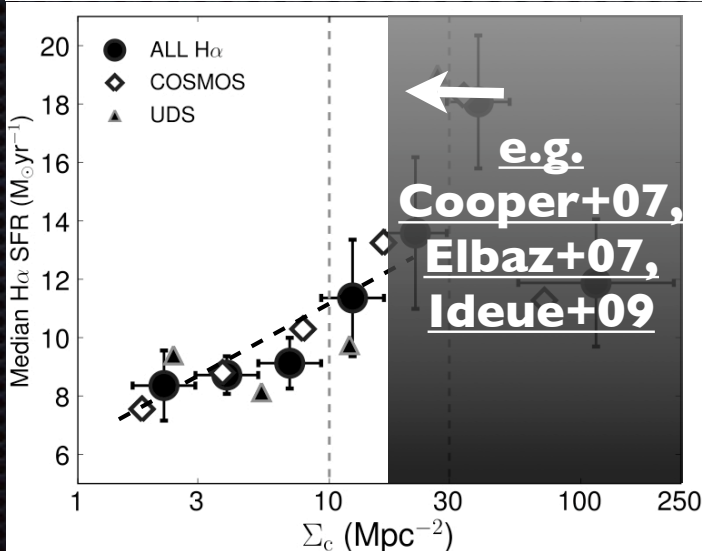
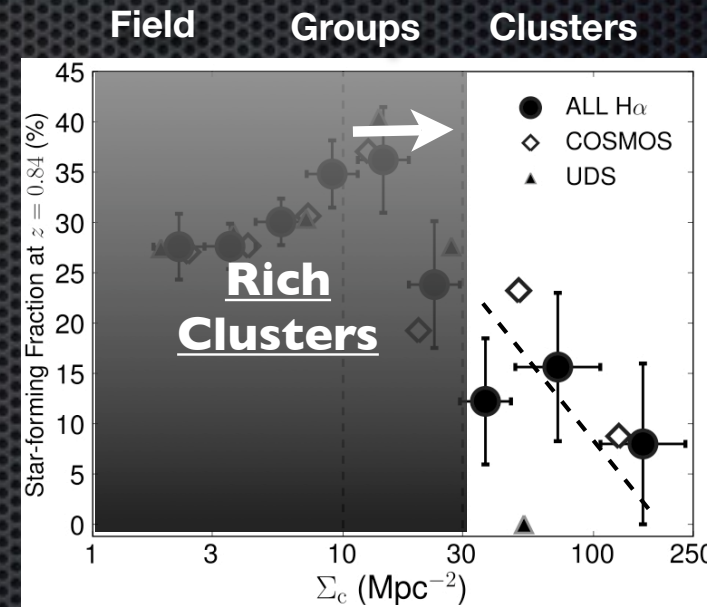
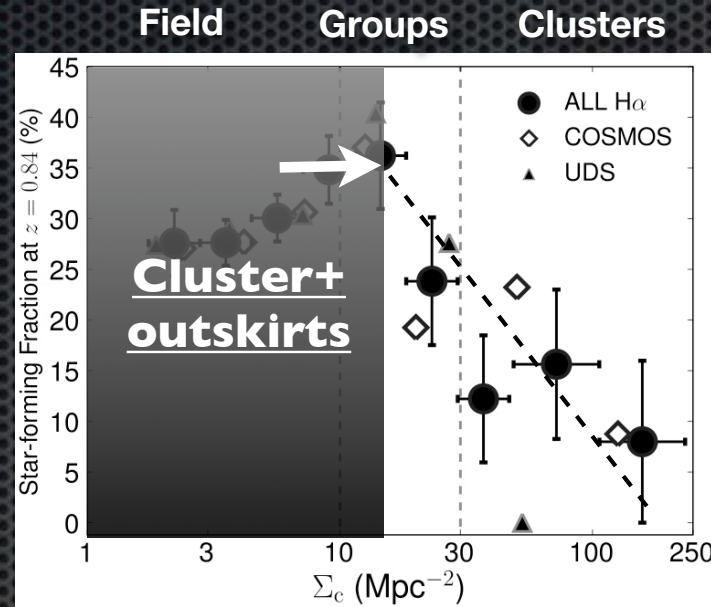
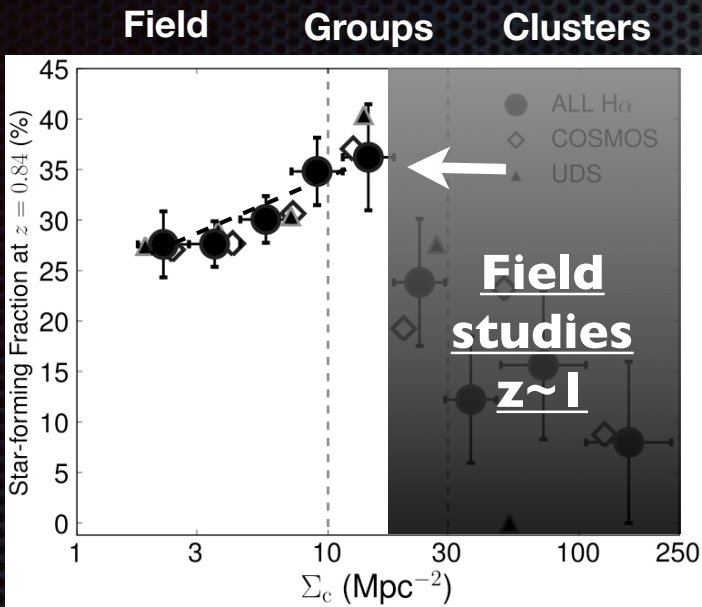
The fraction of (non-merging) star-forming galaxies declines with **both** mass and environment

# Environment at $z \sim 1$

Sobral et al. (2011)

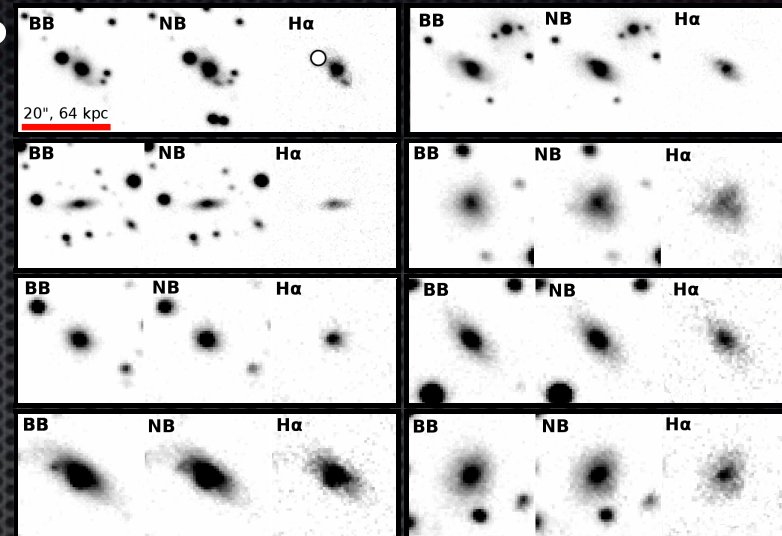
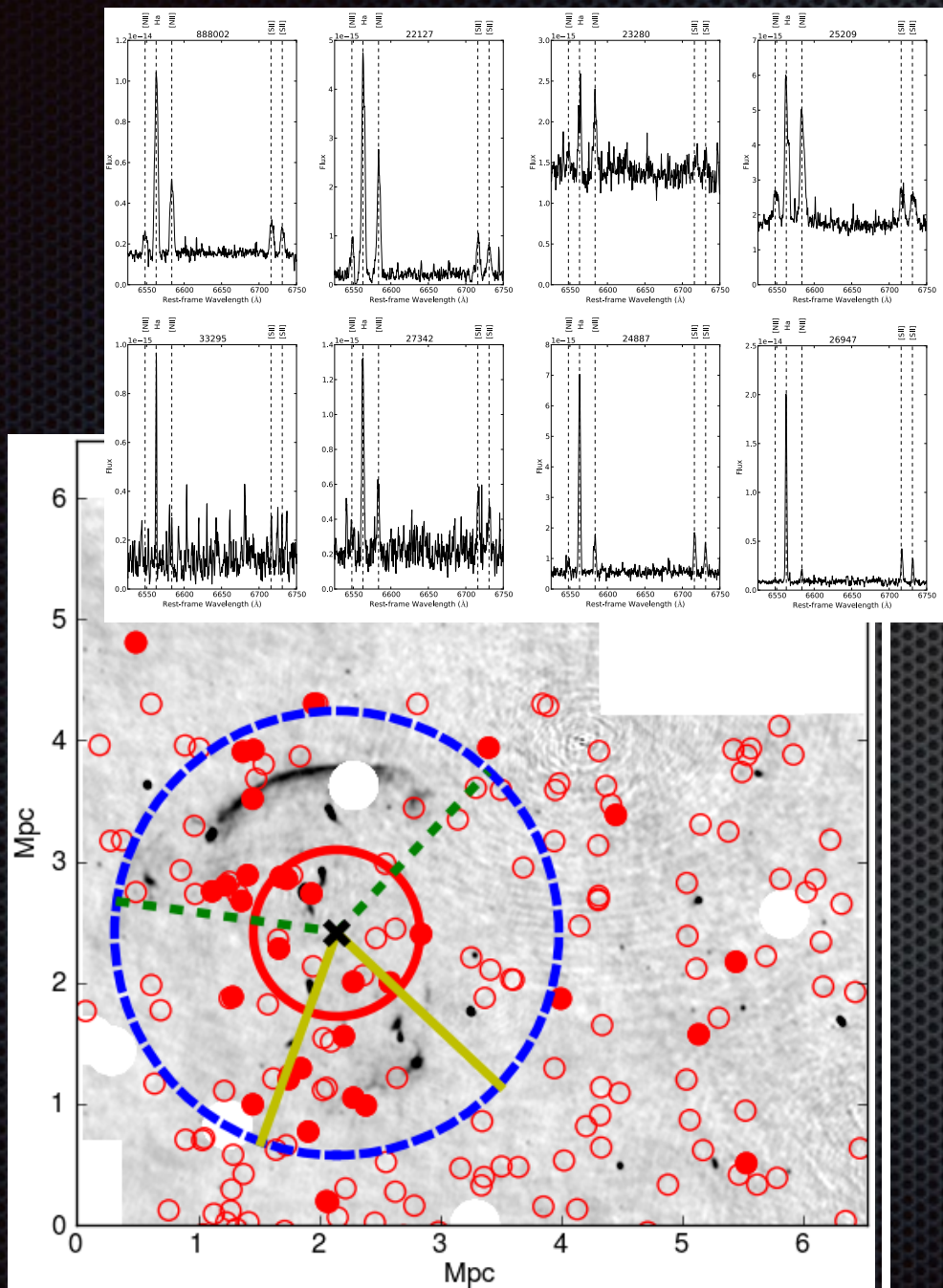
Results reconcile previous apparent contradictions

There is **\*NO reversal\*** of the relations



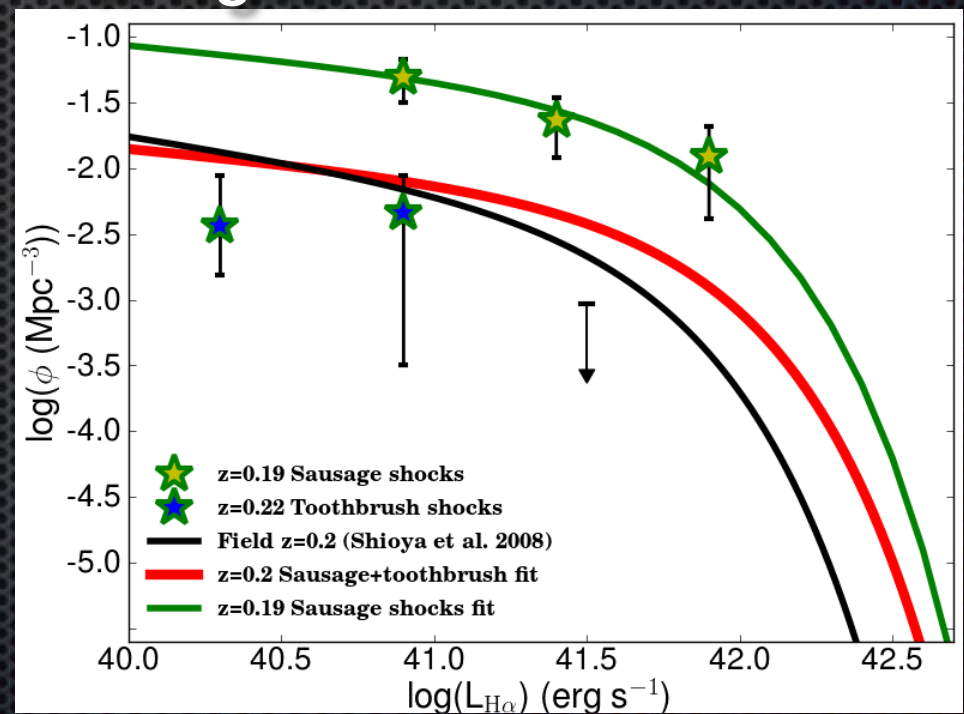
# Shock-induced Star-formation + AGN activity?

## Major cluster merger mass of $\sim 3 \times 10^{15} M_{\odot}$



## Merger of massive clusters

$\sim 10\times$  higher



Stroe, Sobral et al. 2014

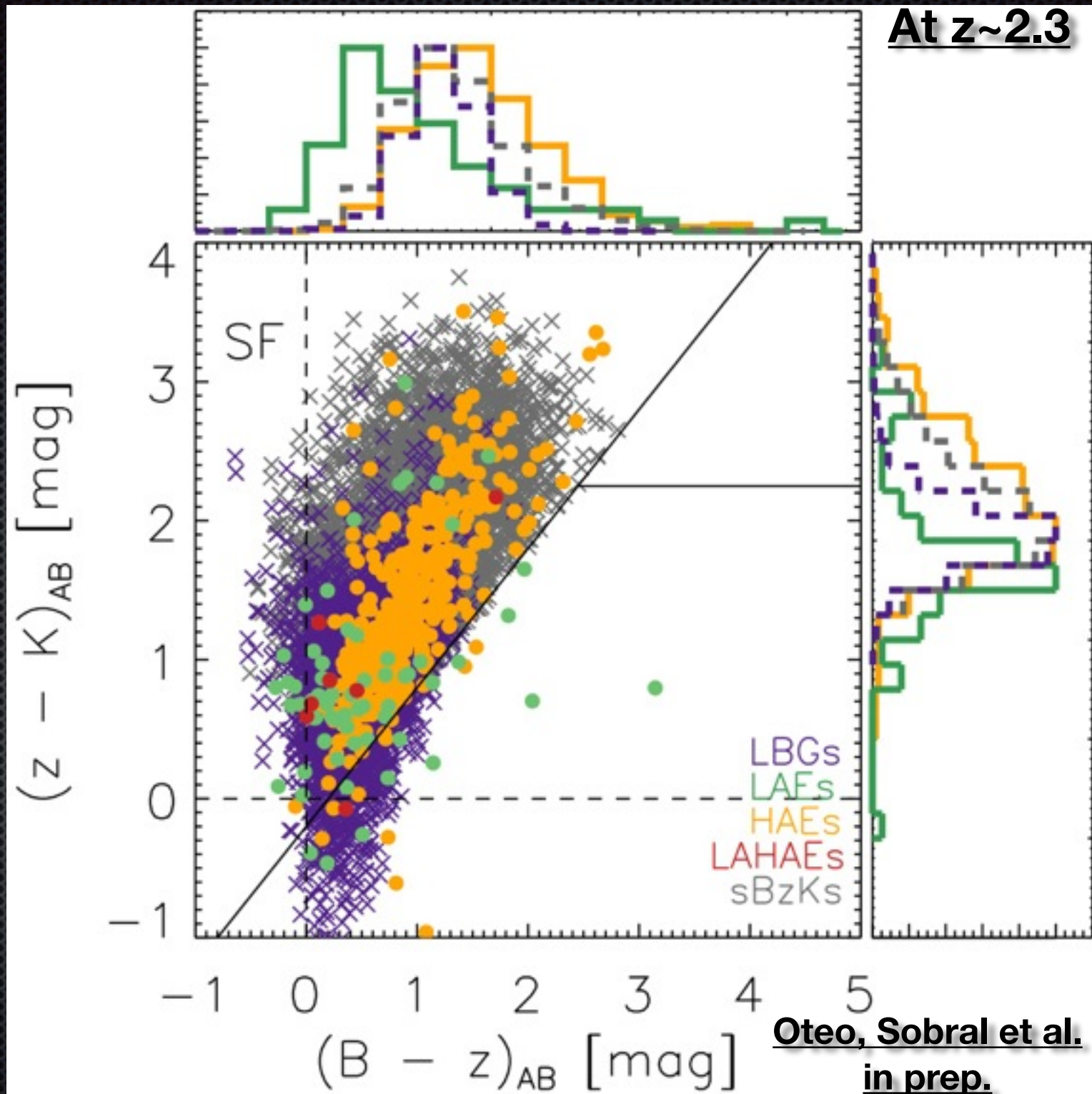
## Selection really matters

Lyman-break selection: misses ~65-70% of star-forming galaxies! (metal-rich, dusty)

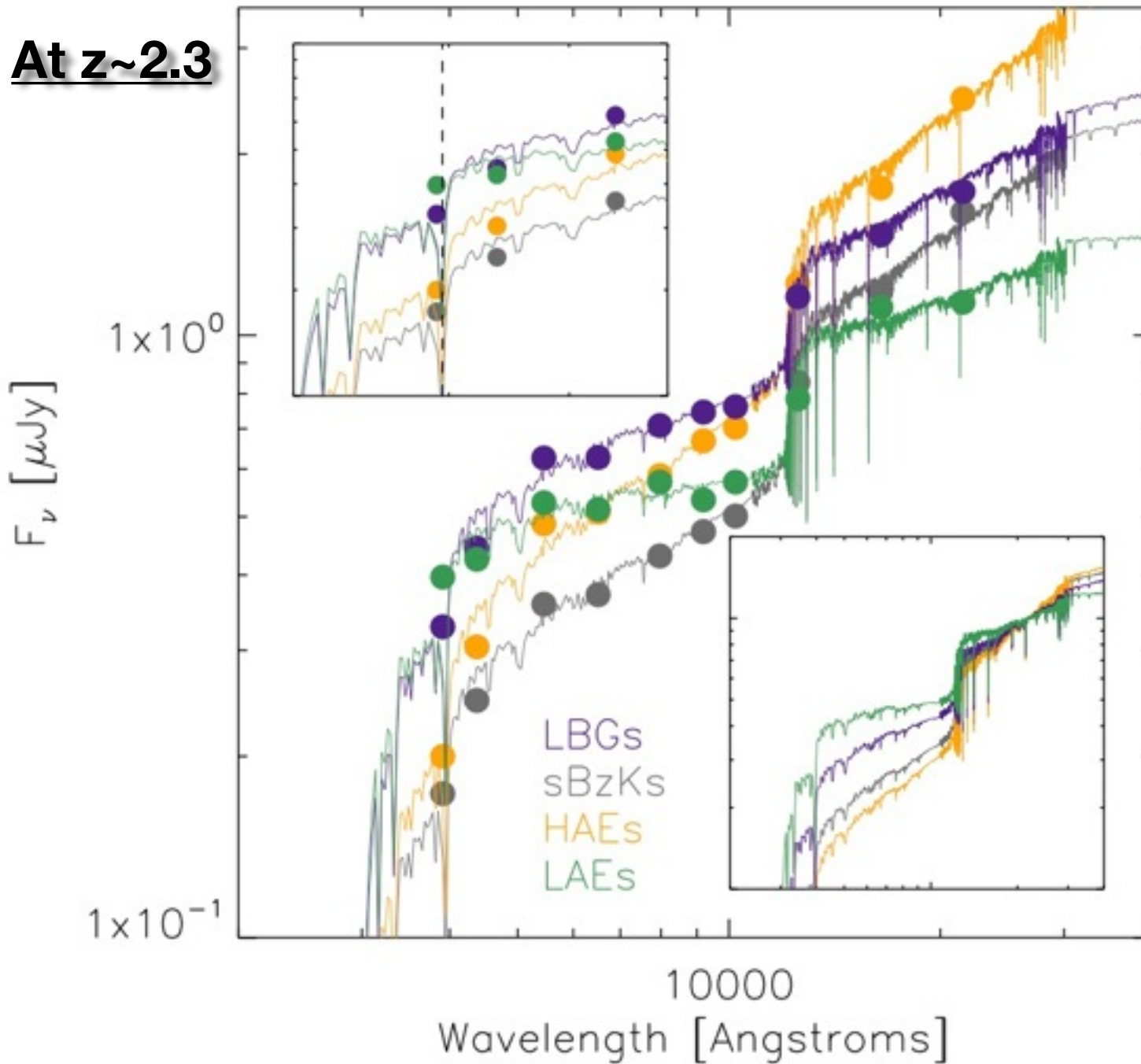
LAEs: miss ~80% of star-forming galaxies

HAEs get ~100% down to the Ha flux limit they sample

See also Hayashi et al. 2013 for [OII]



At  $z \sim 2.3$



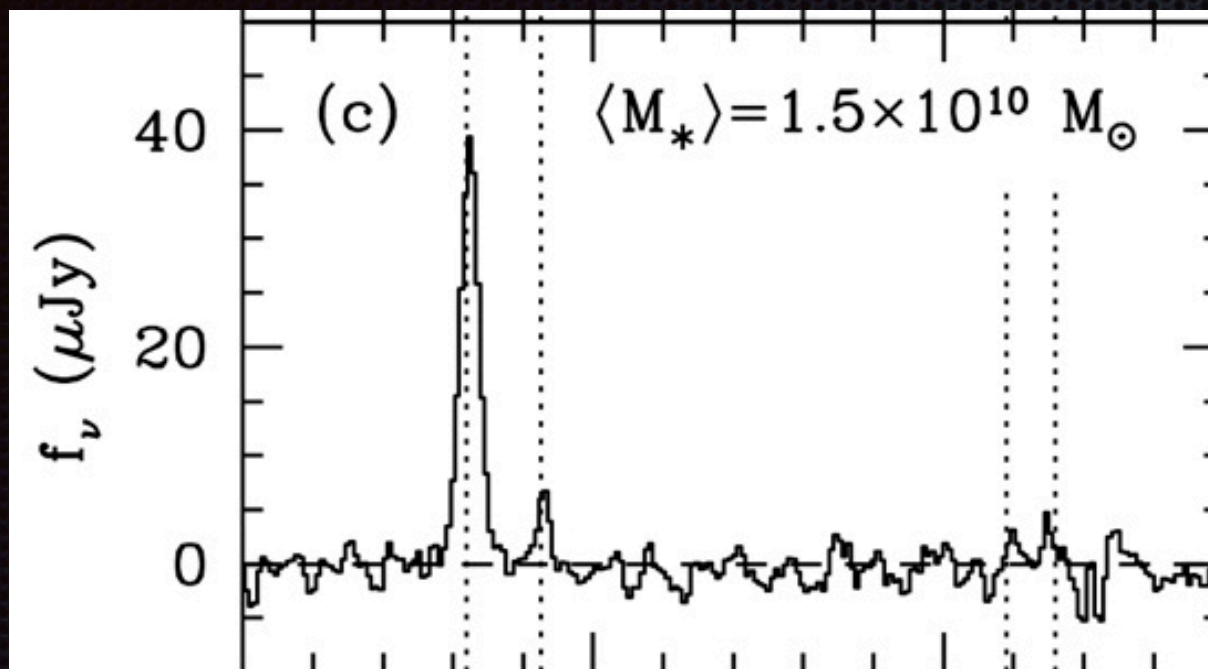
Selection  
makes all the  
difference

UV selection

BzK Selection

LAE and HAE  
selections

Oteo, Sobral et al. in prep.



## Selection Matters:

$z \sim 1.5\text{--}2.23$

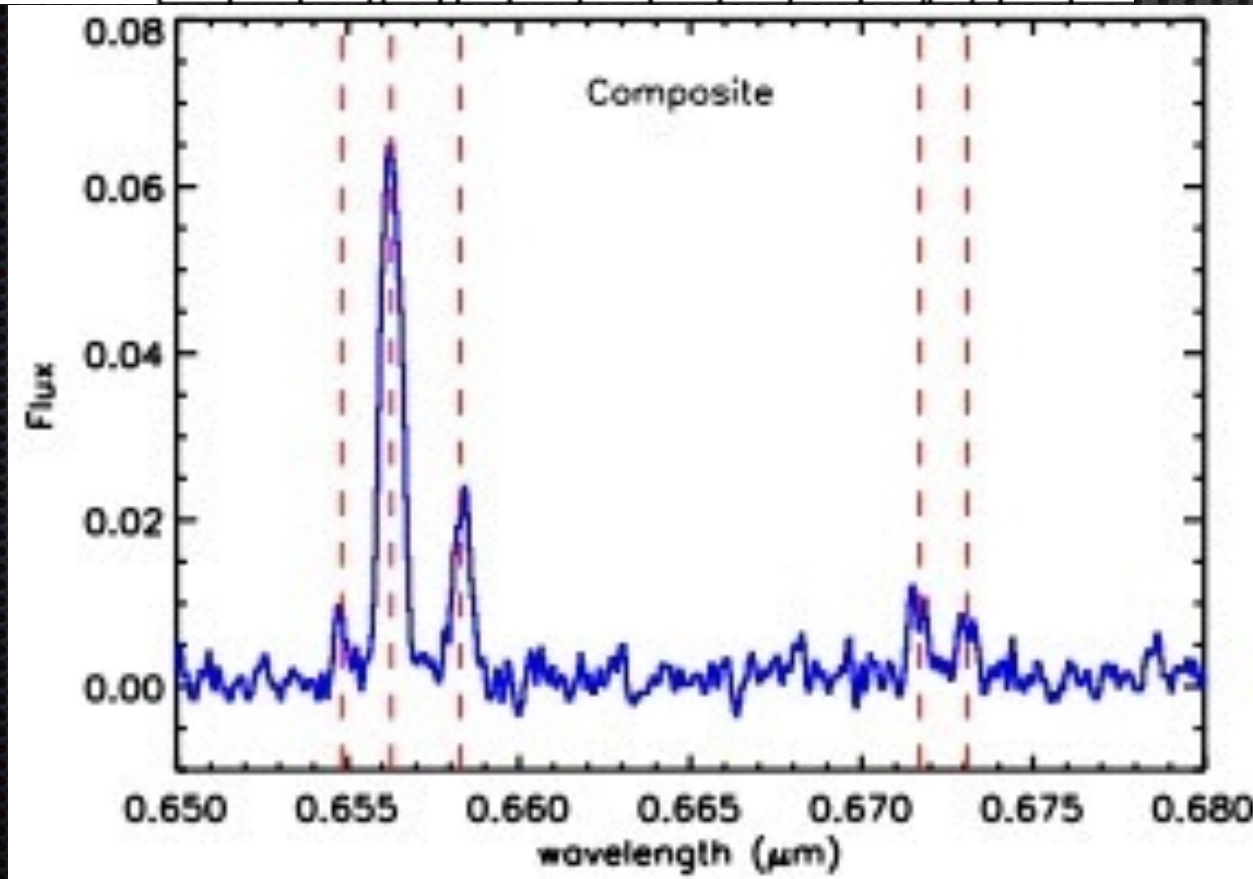
UV selection:  
metal-poor

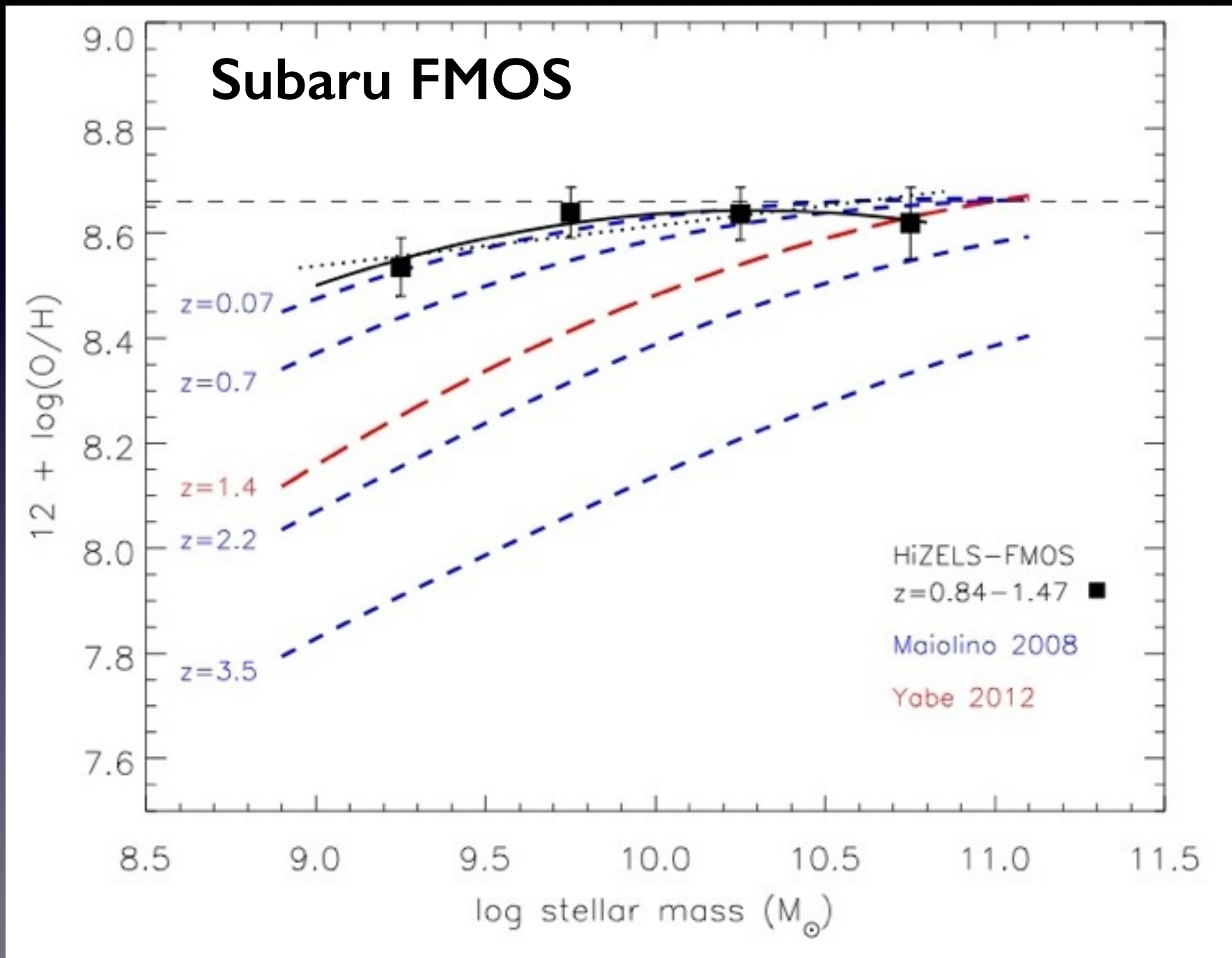
Same masses

Ha selection:  
only slightly sub-solar

Swinbank+12a

Stott+13b

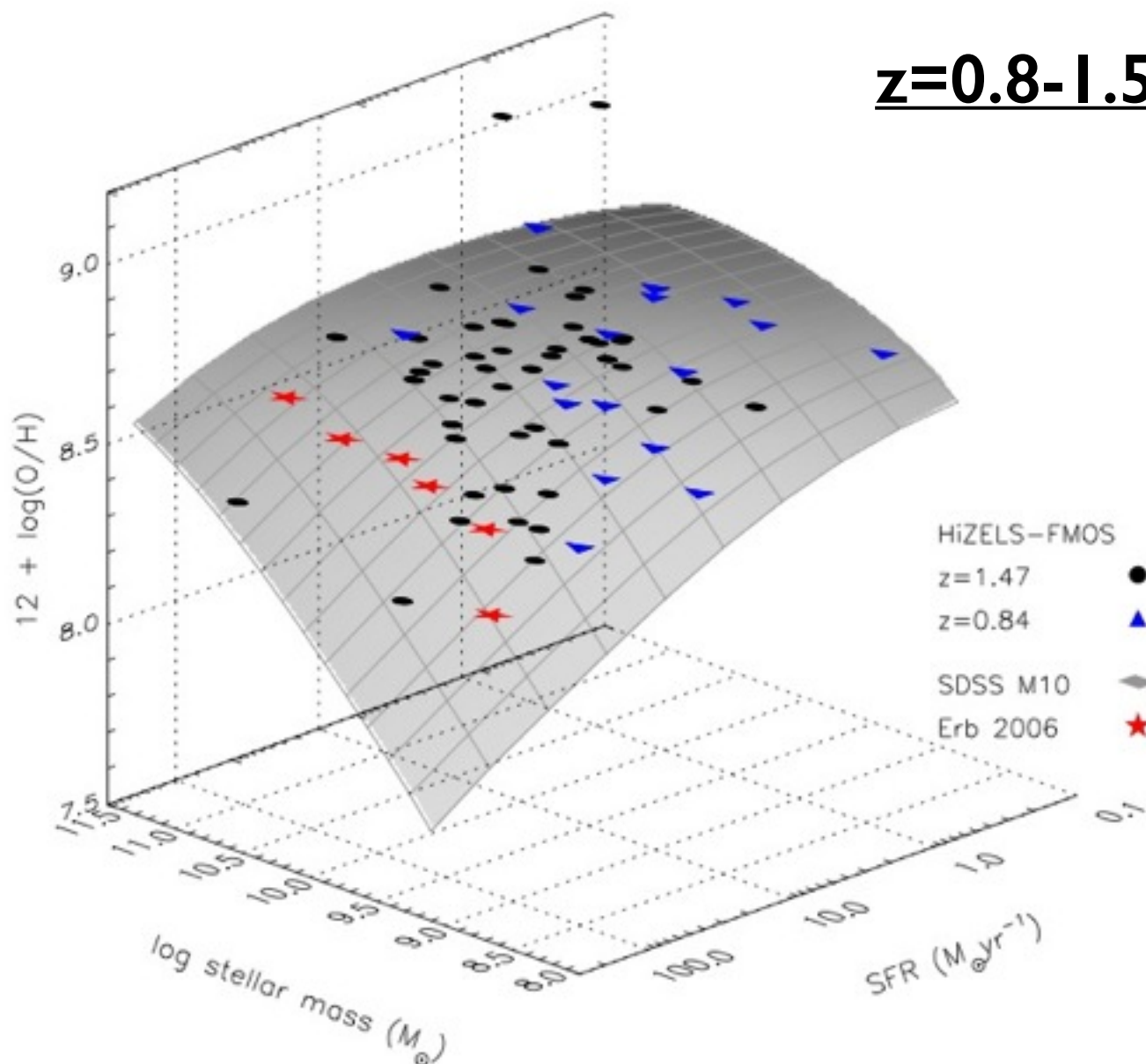




# HiZELS “Fundamental” Mass-Metallicity-SFR relation

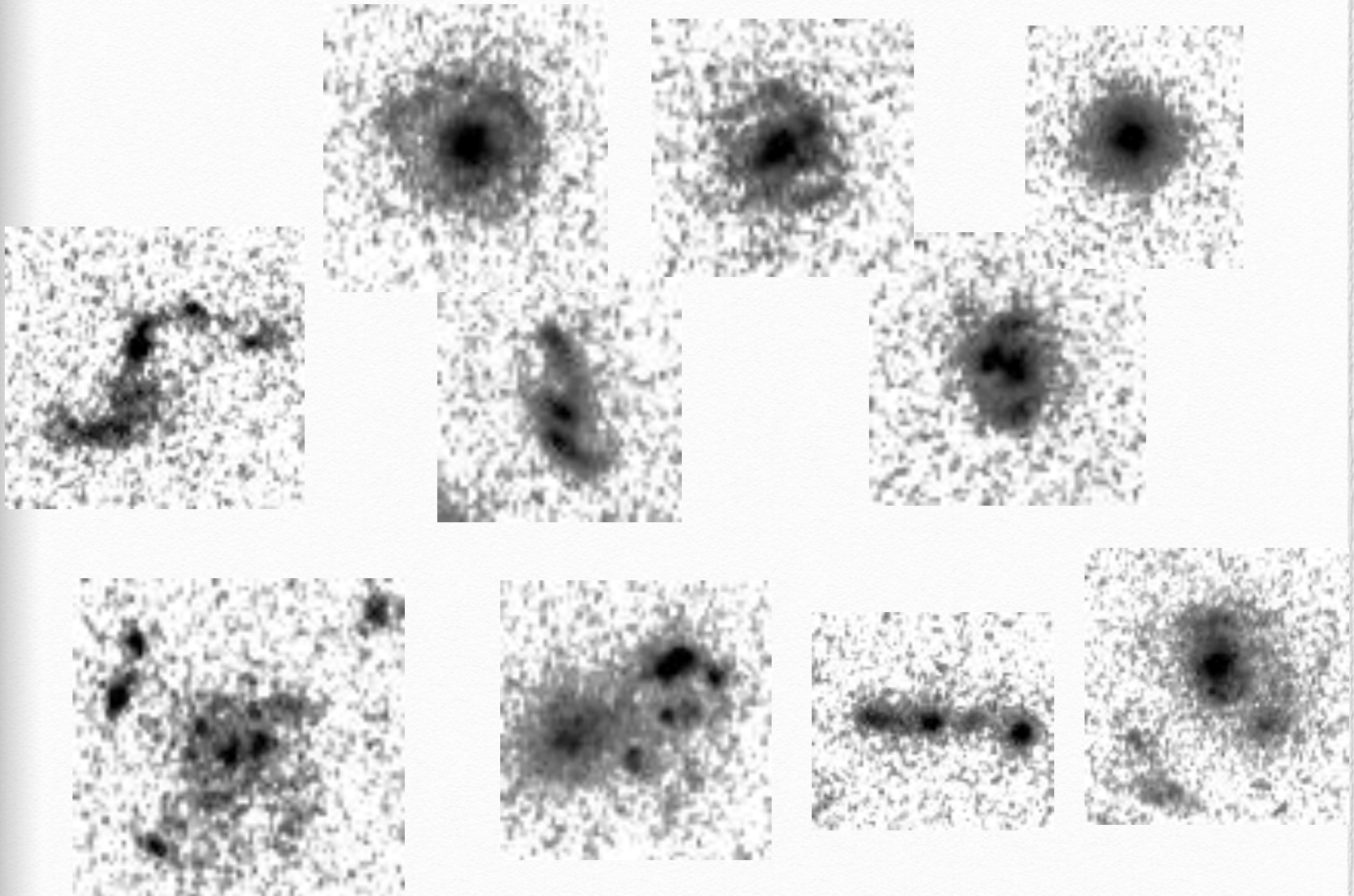
FMOS/Subaru

$z=0.8-1.5$



Stott, Sobral et al. 2013b

# With the Hubble Space Telescope: What do distant star-forming galaxies look like?



# Morphologies: ACS+CANDELS

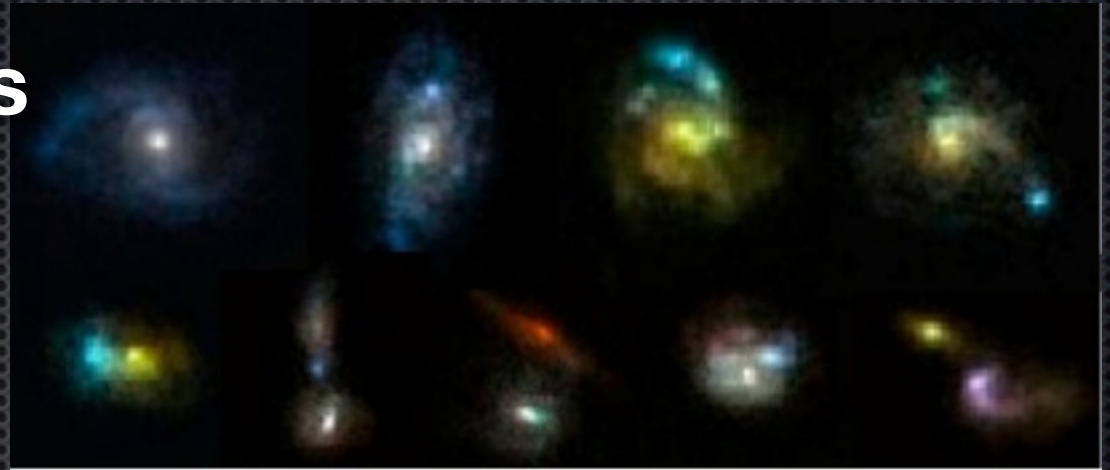
## H $\alpha$ Star-forming galaxies since $z=2.23$

Disk-like/Non-mergers

$\sim 75\%$

Mergers/Irregulars

$\sim 25\%$



Mergers  $\sim$   
20-30% up to  
 $z=2.23$

Sizes ( $M_*$ ):  
3.6 $\pm$ 0.2 kpc

**Table 1.** The size-mass relations at each redshift slice, of the form  $\log_{10} r_e = a (\log_{10} (M_*) - 10) + b$ . Where  $r_e$  and  $M_*$  are in units of kpc and  $M_\odot$  respectively.

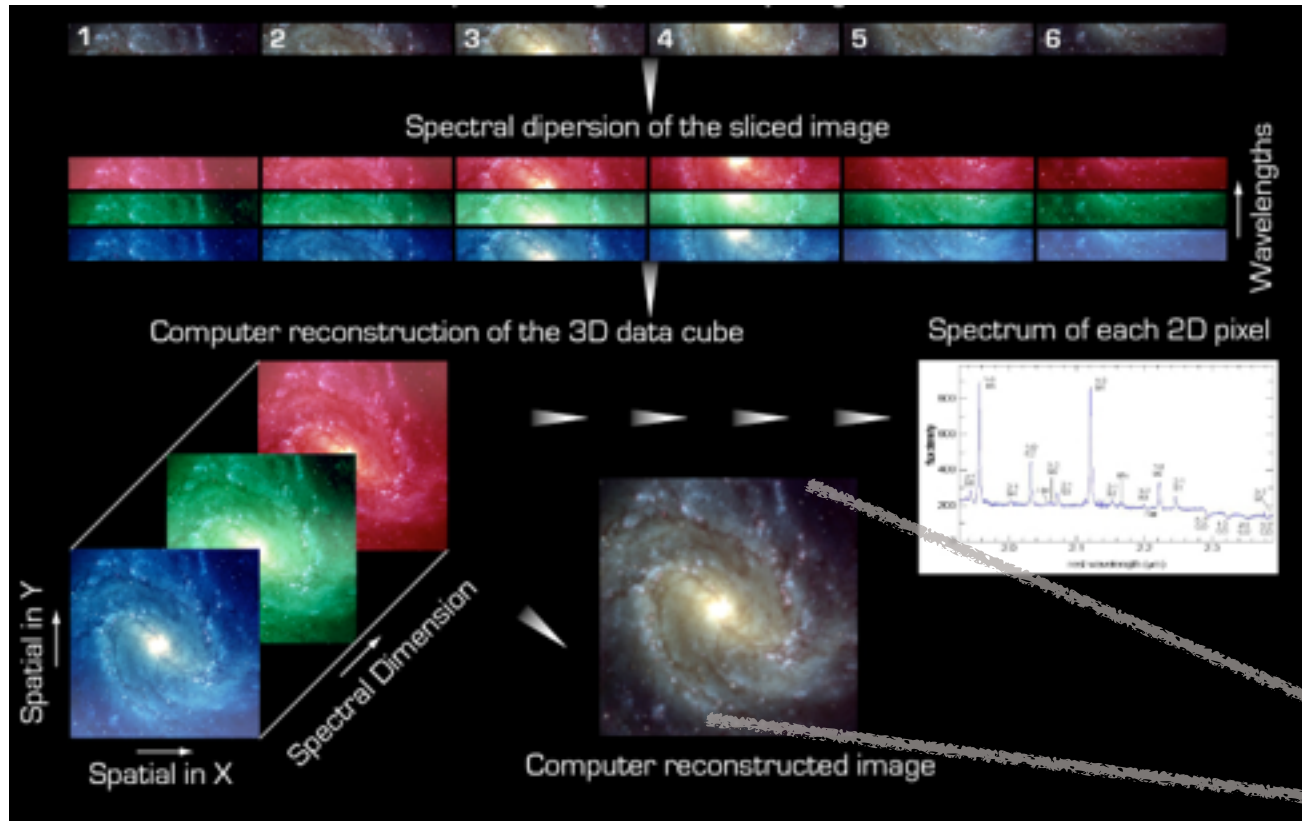
$z$	$a$	$b$	$r_e$ at $\log_{10} (M_*) = 10$ (kpc)
0.40	$0.08 \pm 0.02$	$0.55 \pm 0.03$	$3.6 \pm 0.2$
0.84	$0.03 \pm 0.02$	$0.54 \pm 0.01$	$3.5 \pm 0.1$
1.47	$0.03 \pm 0.02$	$0.59 \pm 0.01$	$3.9 \pm 0.2$
2.23	$0.08 \pm 0.03$	$0.51 \pm 0.02$	$3.3 \pm 0.2$

# Galaxy Dynamics at $z \sim 0.8-2.2$

Integral Field Units, IFUs

e.g. SINFONI / VLT

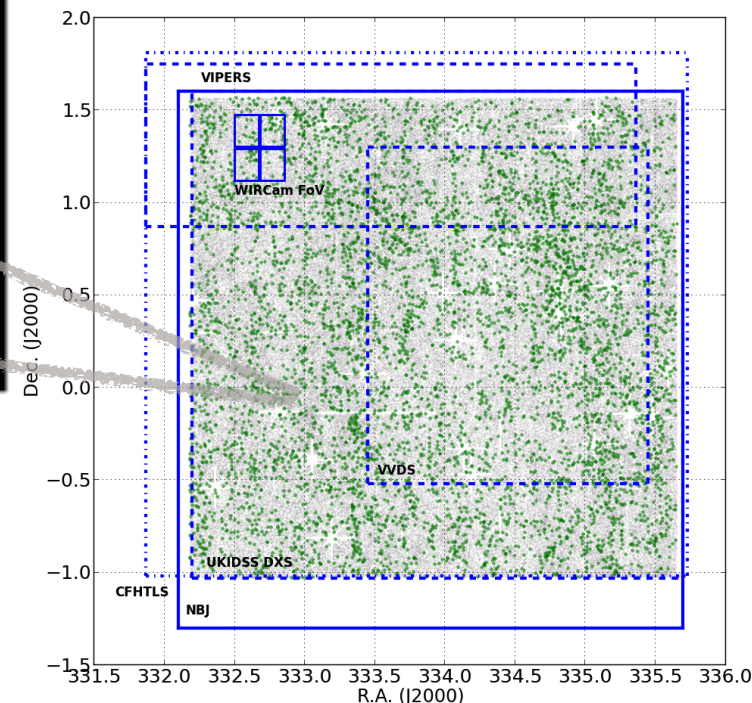
H $\alpha$ -selected targets are ideal



Large areas (+ 4-5 fields): easy to find NGS

Known H $\alpha$  fluxes

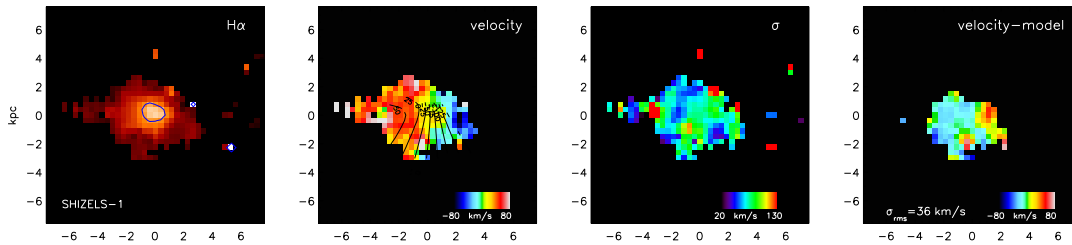
Very efficient combination to get sub-kpc resolution



# Galaxy Dynamics at $z \sim 0.8-2.2$

Swinbank et al. 2012a,b

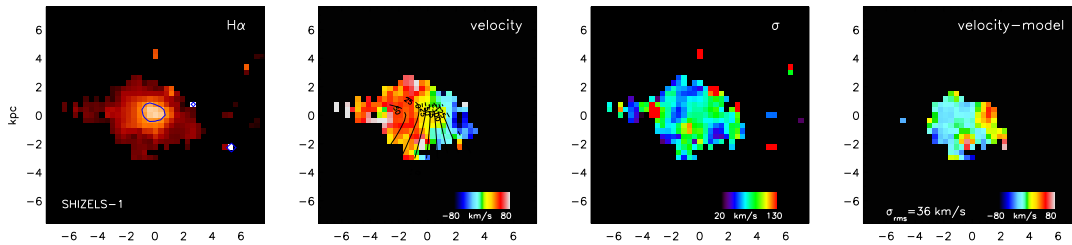
From AO IFU observations



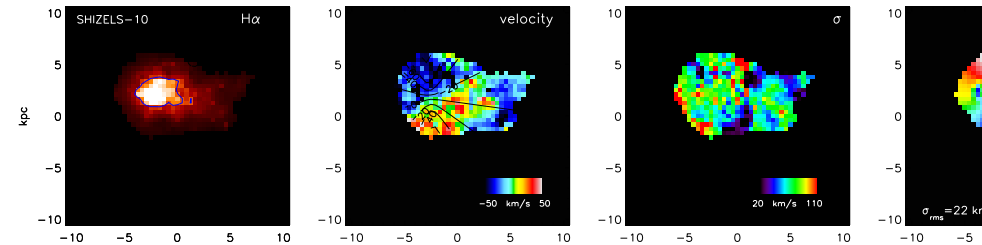
~5 hours of VLT time

# Galaxy Dynamics at $z \sim 0.8-2.2$

Swinbank et al. 2012a,b



From AO IFU observations

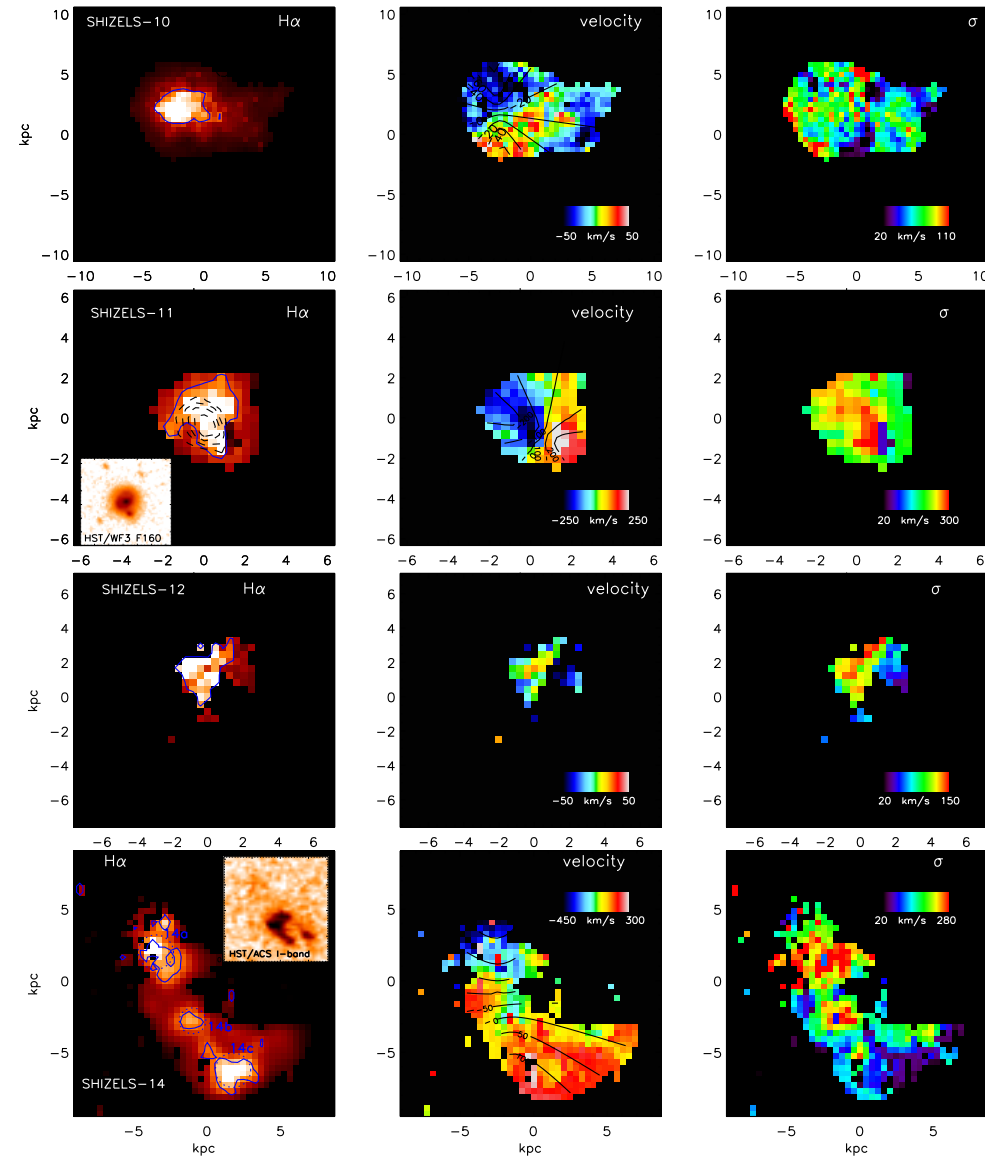
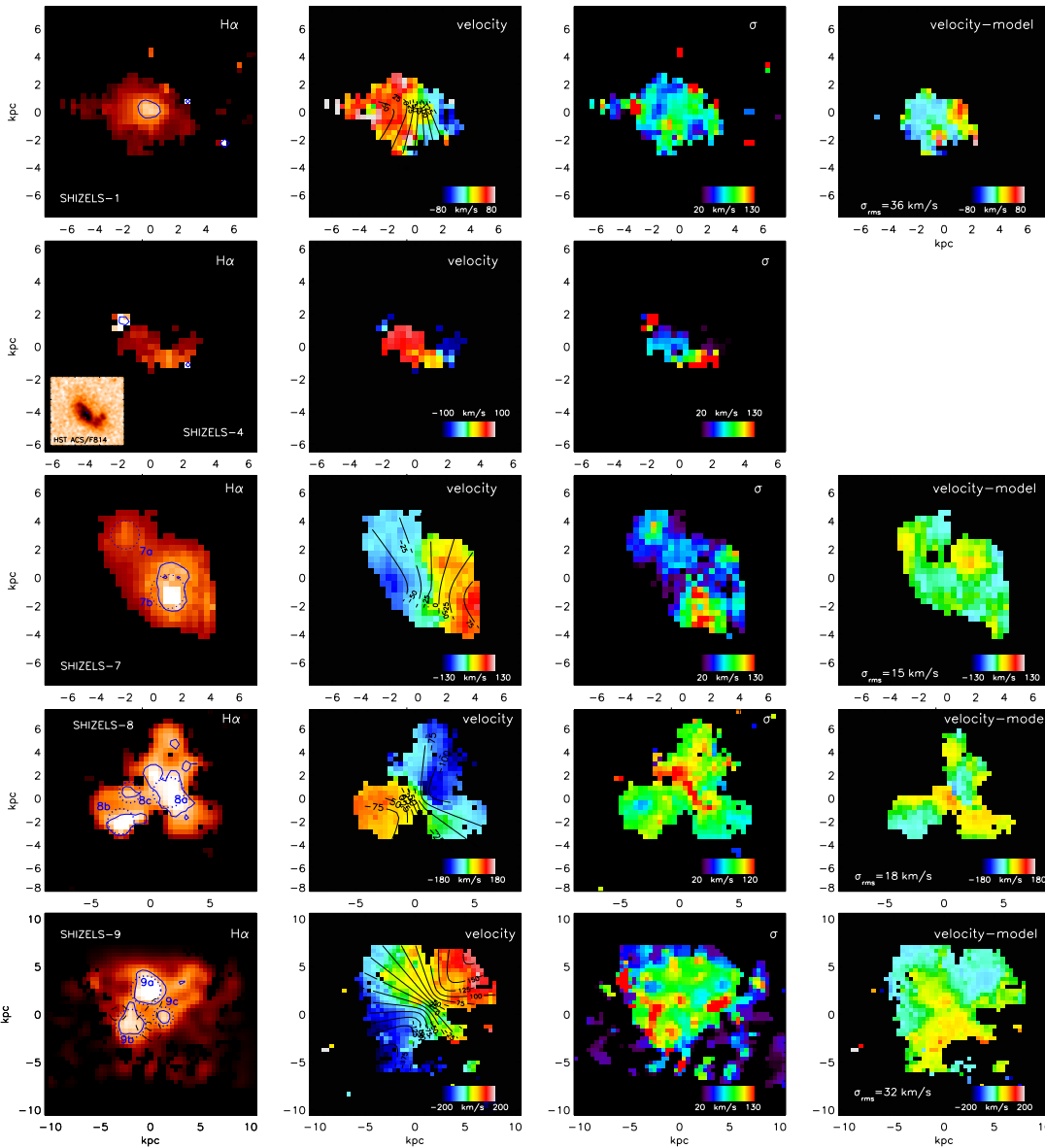


~10 hours of VLT time

# Galaxy Dynamics at $z \sim 0.8-2.2$

Swinbank et al. 2012a,b

From AO IFU observations



$\sim 45$  hours of VLT time

# Galaxy Dynamics at $z \sim 0.8-2.2$

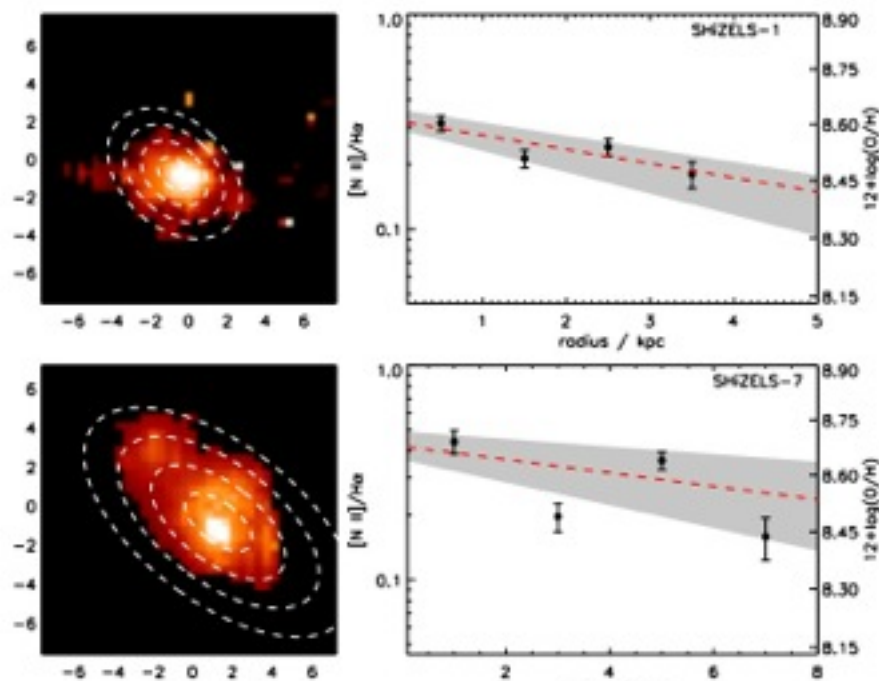
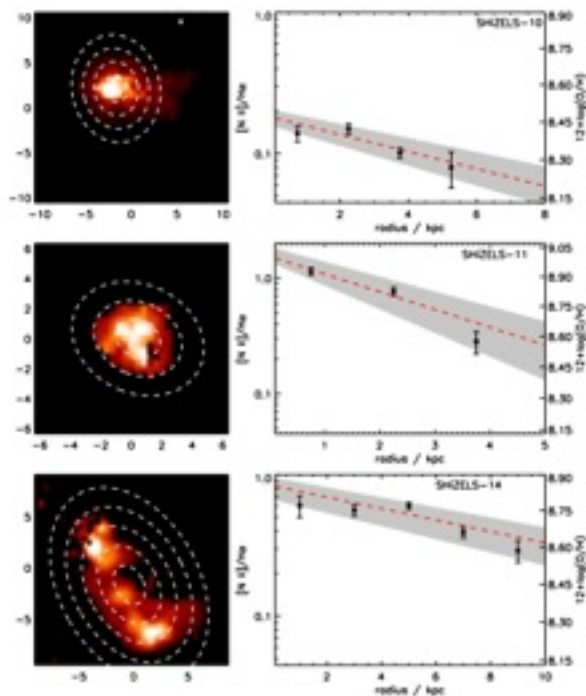
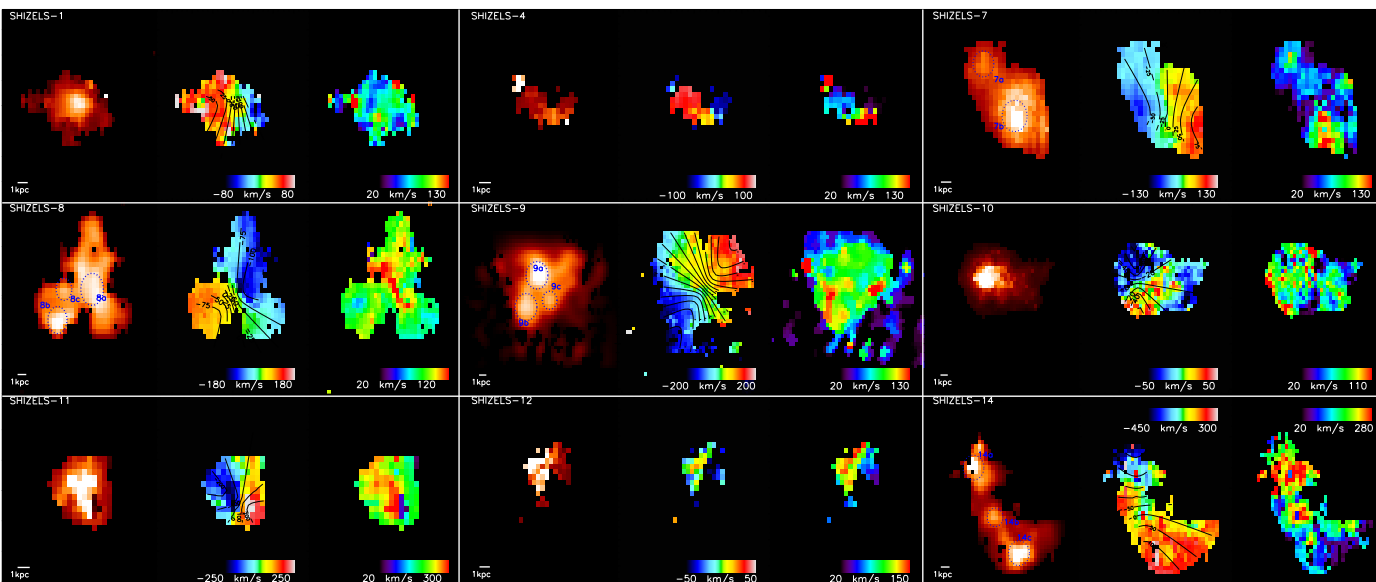
Swinbank et al. 2012a

Swinbank et al. 2012b

(MNRAS/ApJ):

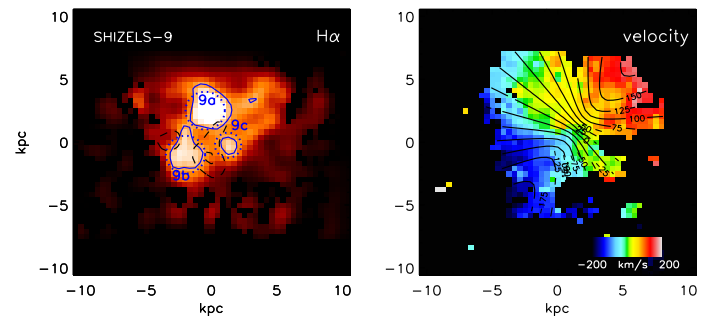
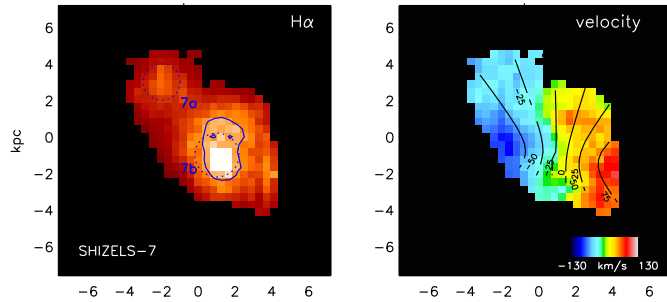
- Star-forming clumps: scaled-up version of local HII regions

- Negative metallicity gradients: “inside-out” growth



# SINFONI

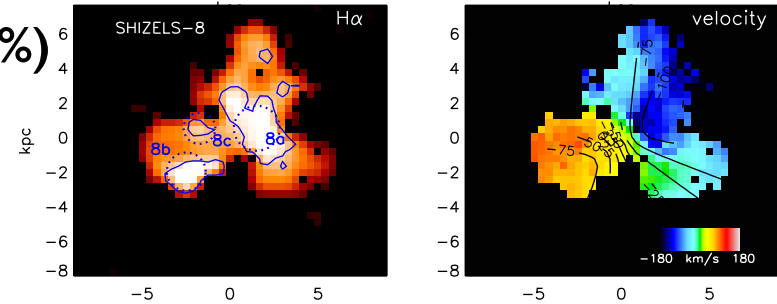
~50 hours of VLT time



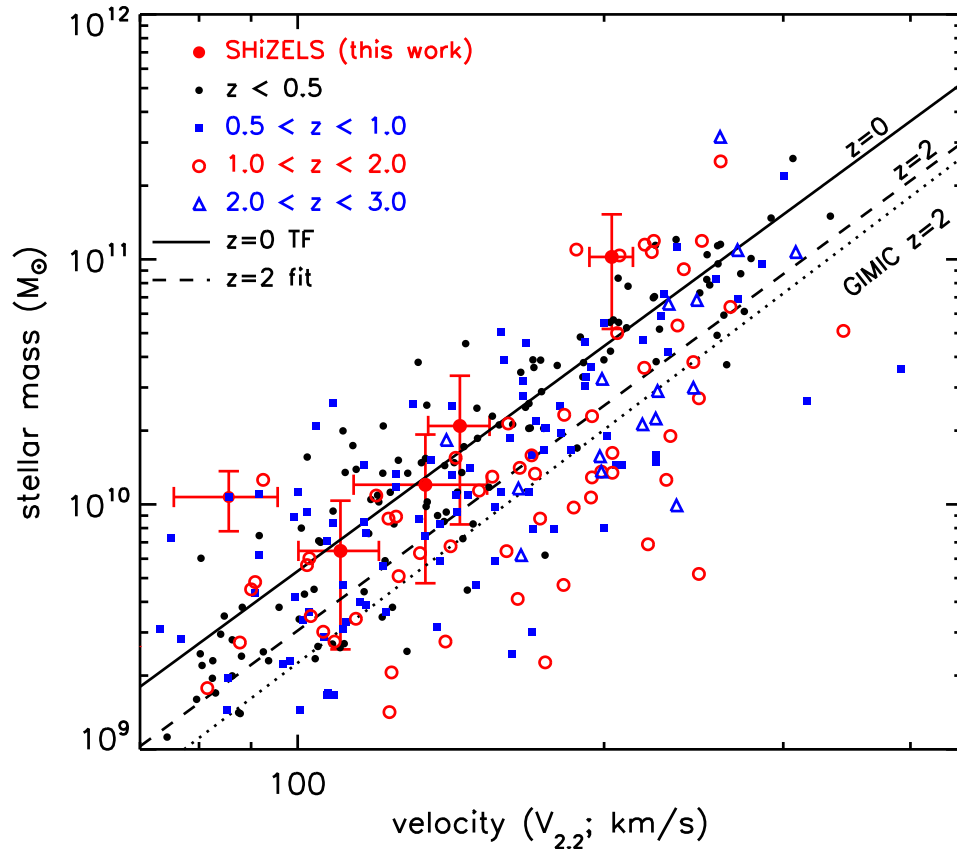
Mostly disks-like (~70-80%)

Many “clumpy” (c.f. Swinbank+12b)

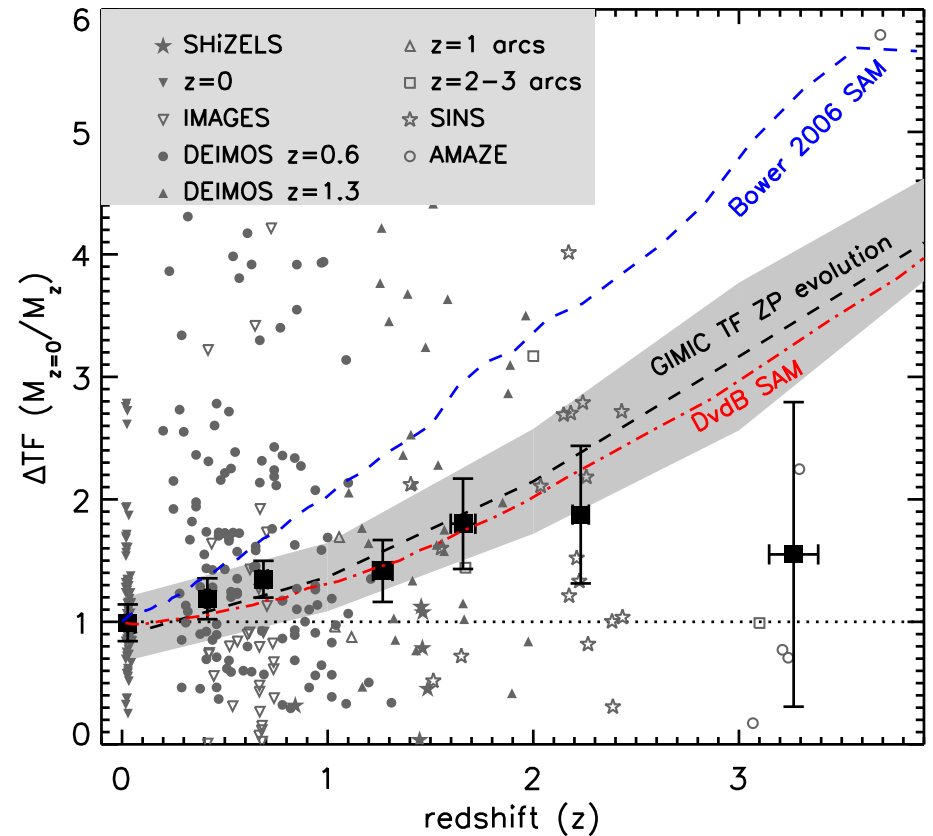
Rotation ~70-200 km/s



## Stellar mass TF relation

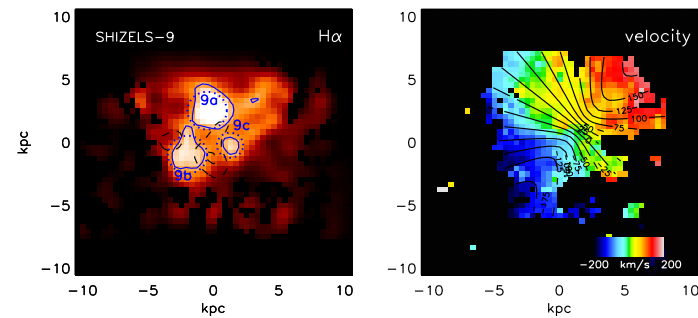
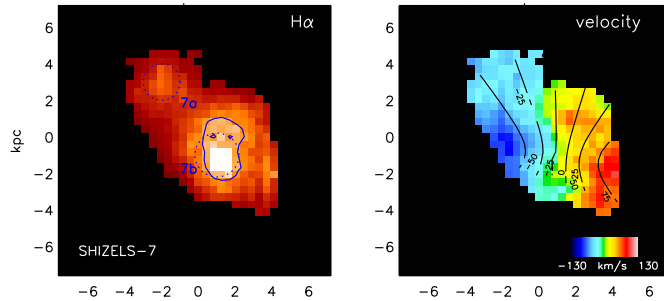


## Swinbank, Sobral et al. 2012



# SINFONI

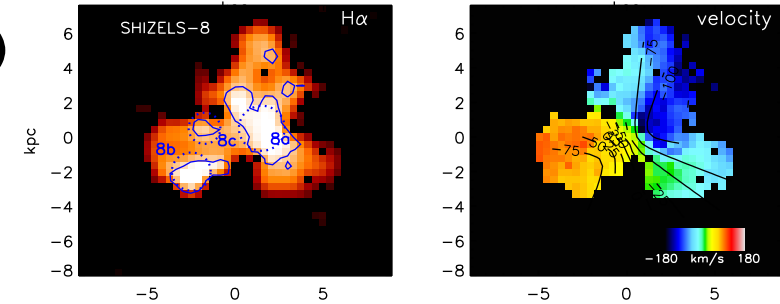
~50 hours of VLT time



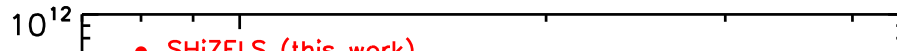
Mostly disks (~70-80%)

Many “clumpy”

Rotation ~70-200 km/s



Swinbank, Sobral et al. 2012

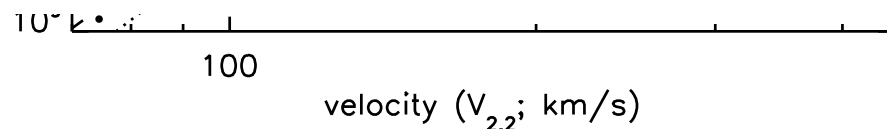


## NEED LARGER SAMPLES!

1 by 1 is simply not good enough

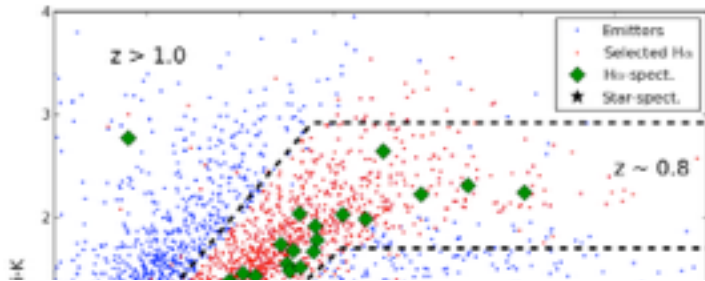
Can we do better?

stellar mass ( $M_{\odot}$ )

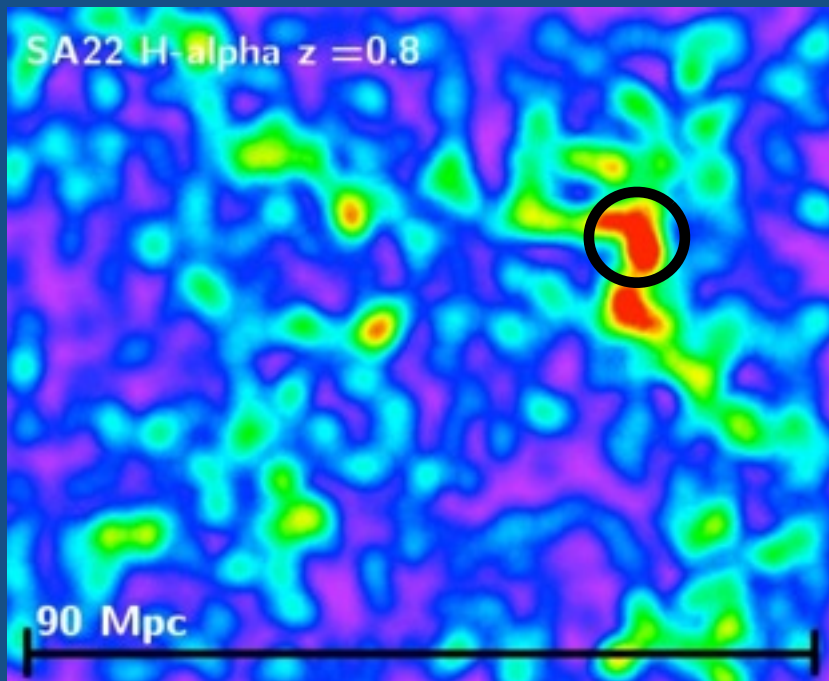
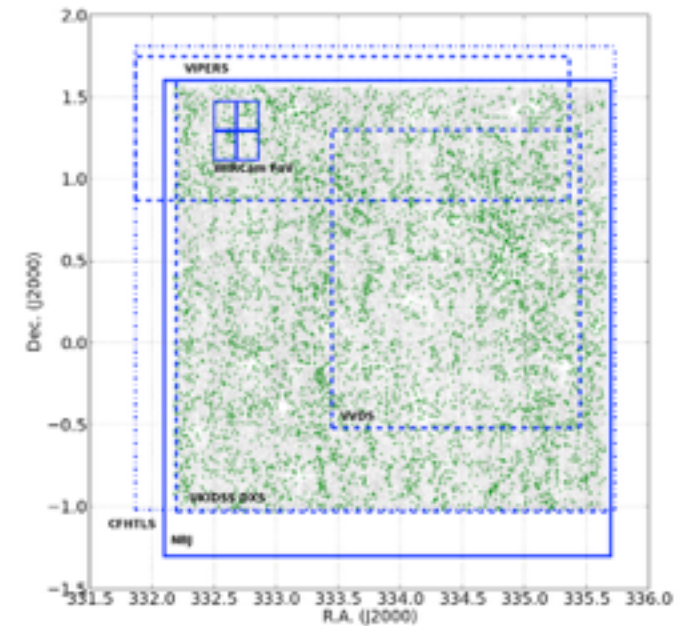


**10 sq deg**

**CFHT  
WIRCam**



**See Jorryt's talk next!**



**300 k NB detections**

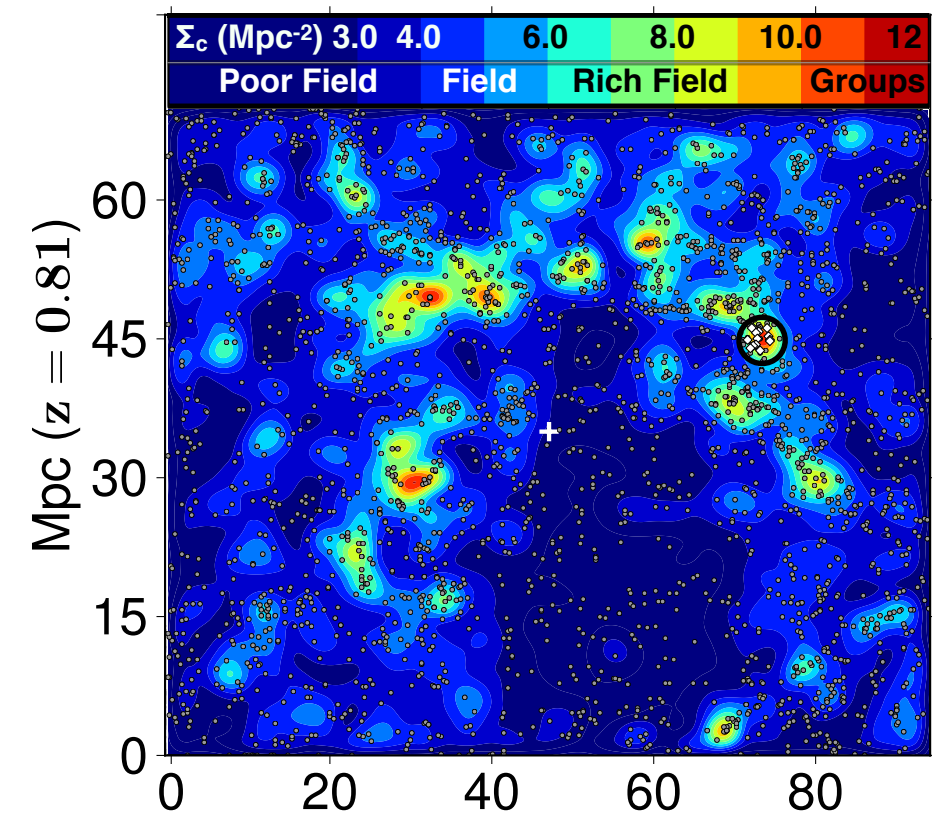
**6400 line emitters**

**3500 H $\alpha$   $z=0.8$**

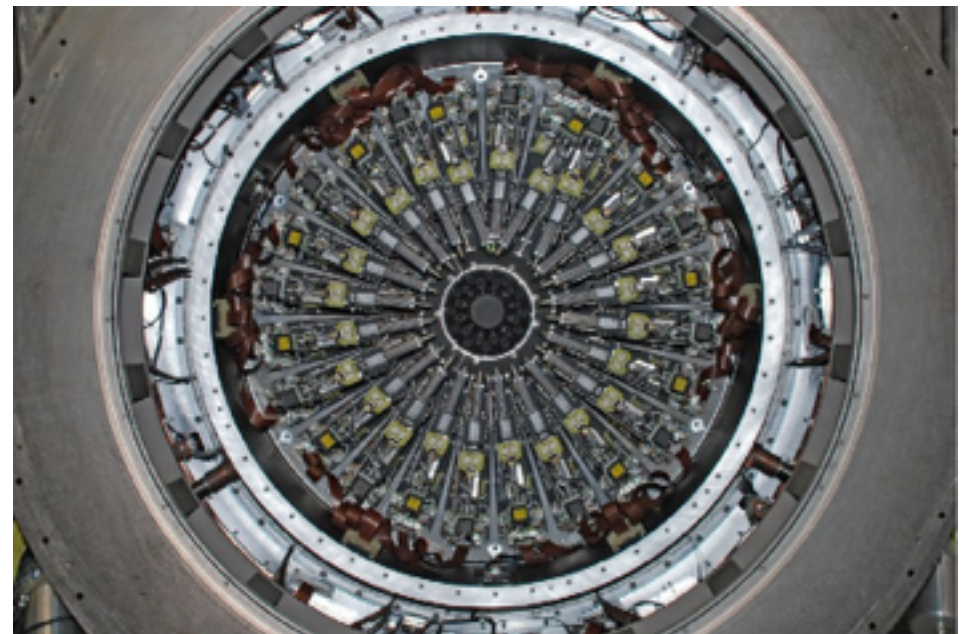
**Density of H $\alpha$  emitters  
 $z=0.81 \pm 0.01$**

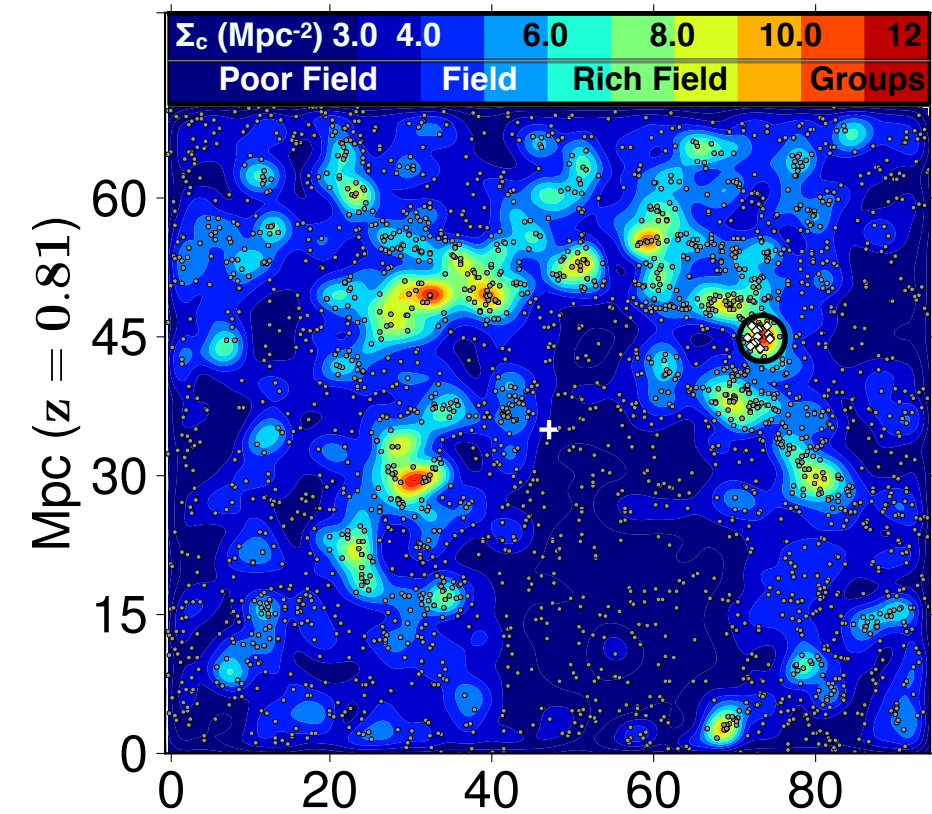
**8 sigma over-density**

**Matthee+14, S+14b**



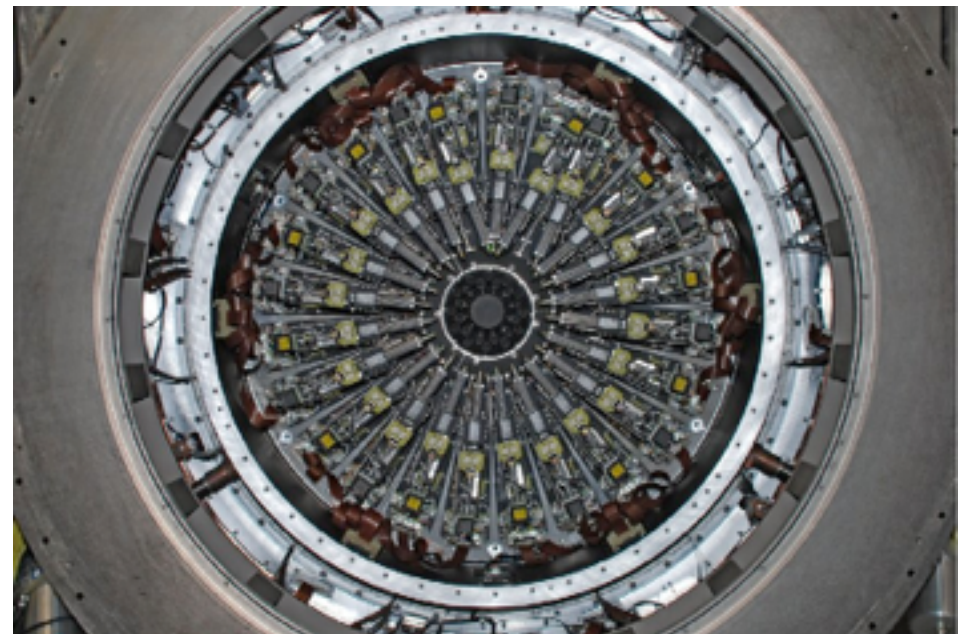
Perfect for  VLT  
24 IFUs at the same time!





4h Science Verification time  
Observations June 2013 +  
September 2013

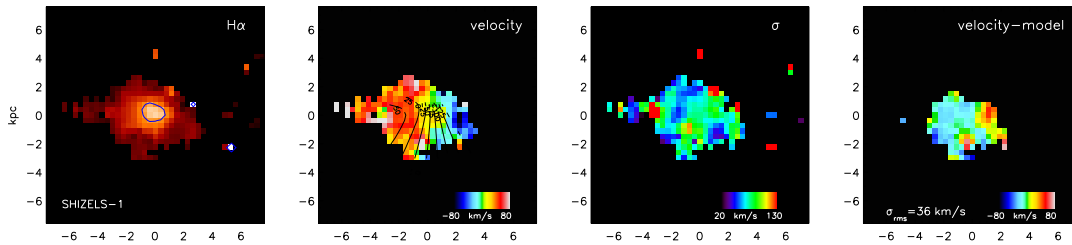
Perfect for  VLT  
 24 IFUs at the same time!



# Galaxy Dynamics at $z \sim 0.8-2.2$

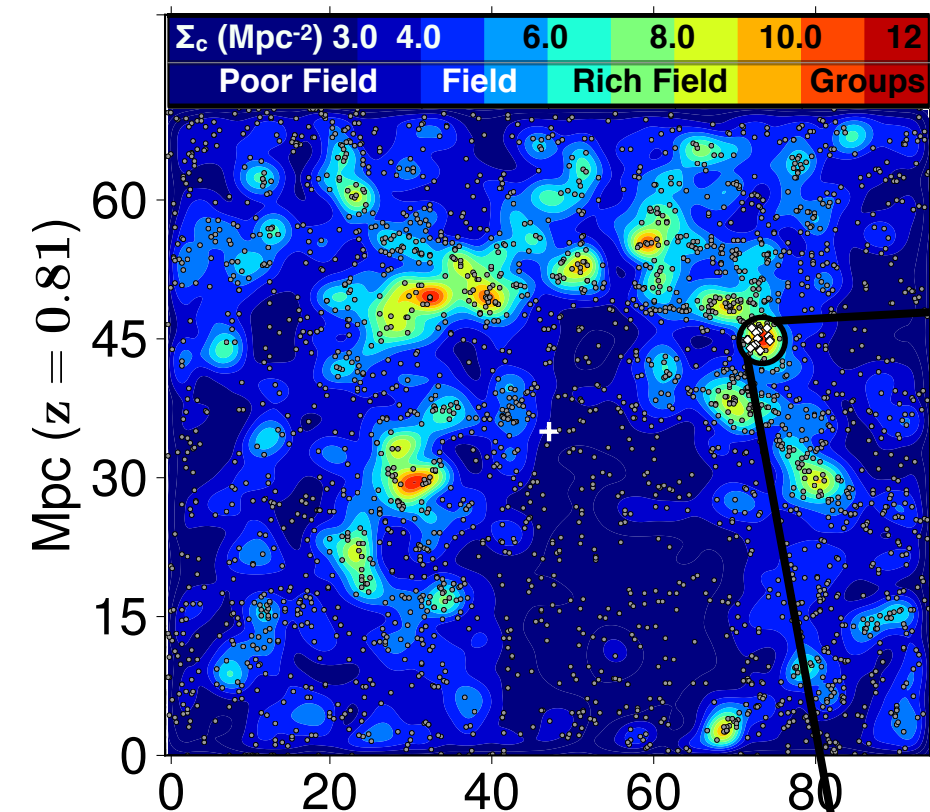
Swinbank et al. 2012a

From AO IFU observations



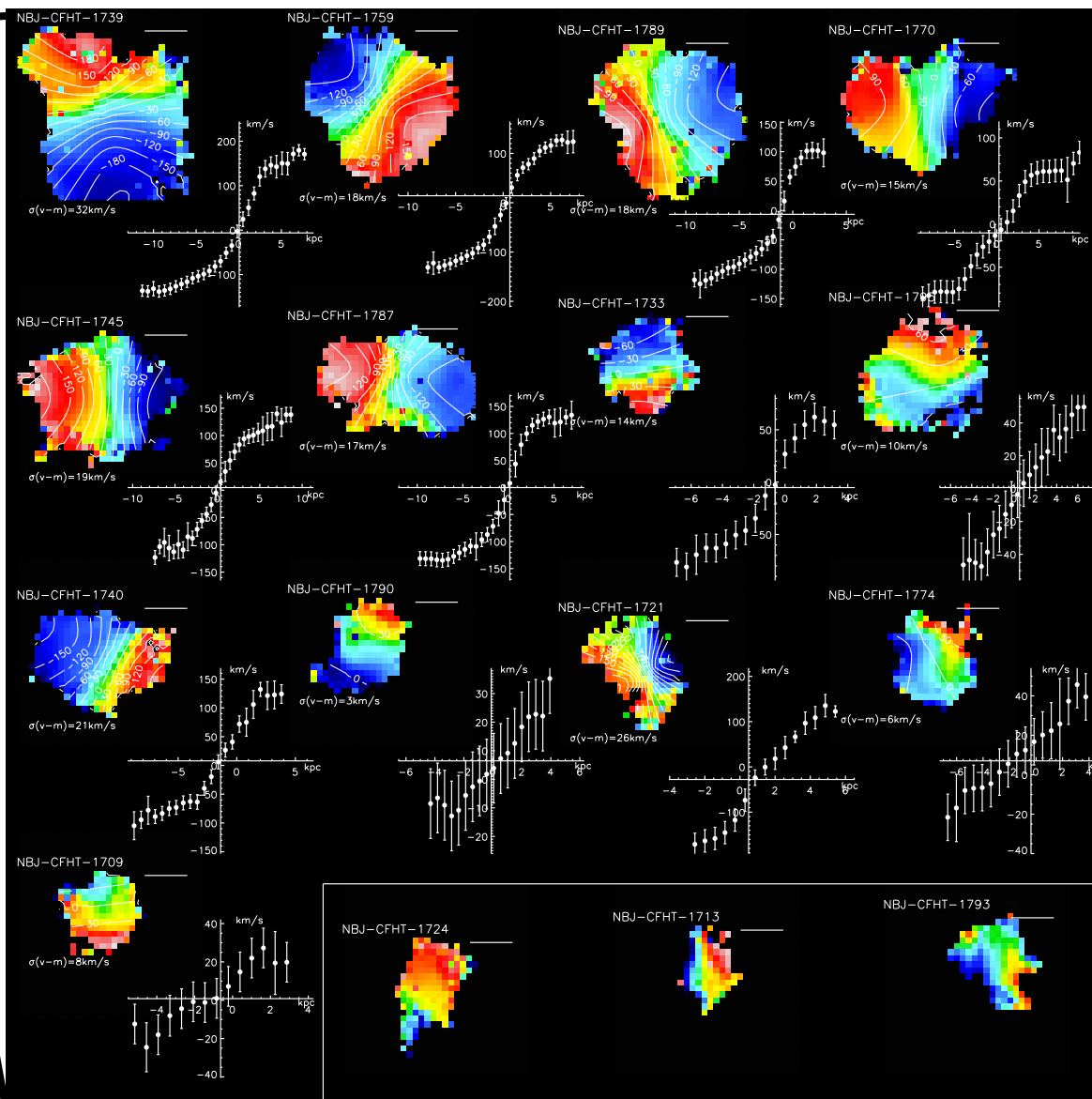
**$\sim 5$  hours of VLT time**

2 hours of VLT time



First Science  
results from  
KMOS

Sobral et al. (2013b),  
ApJ, 779, 139

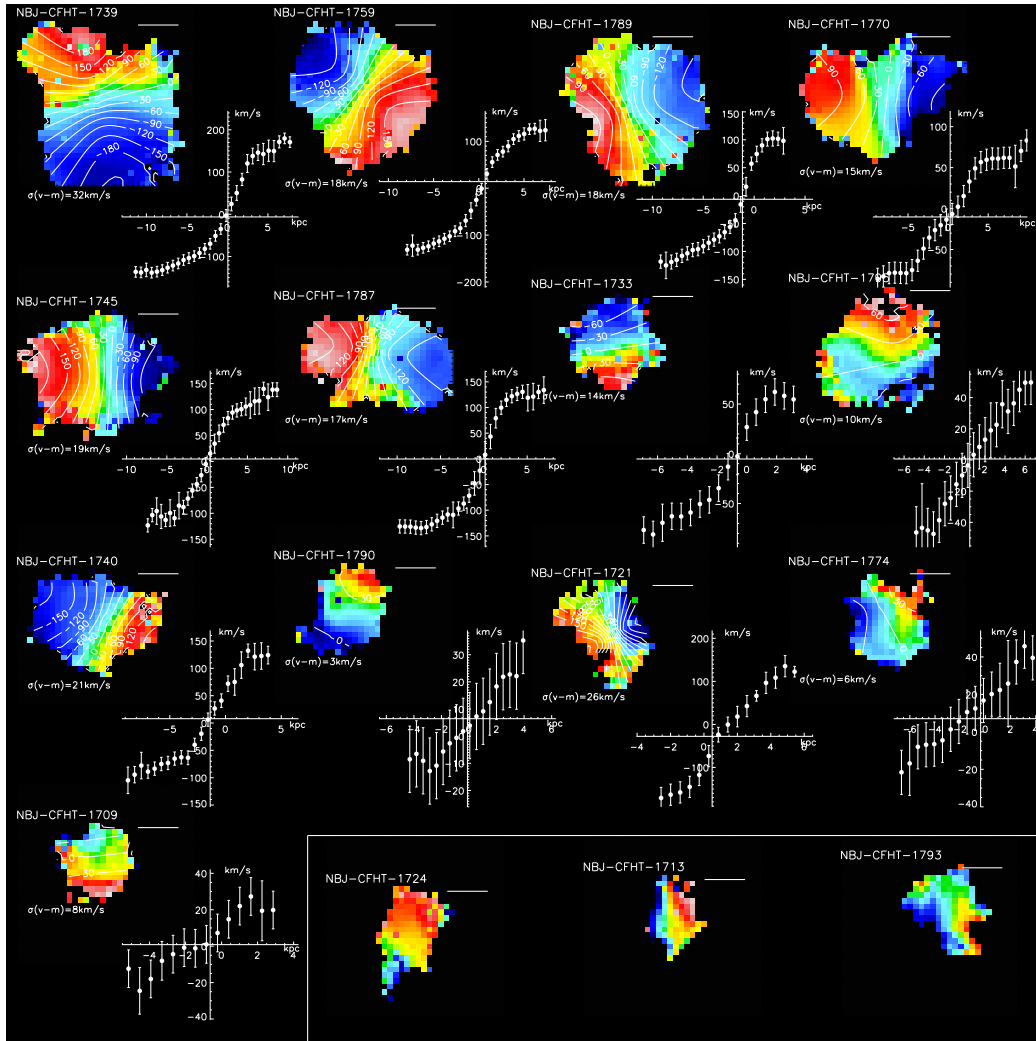


# Metallicities

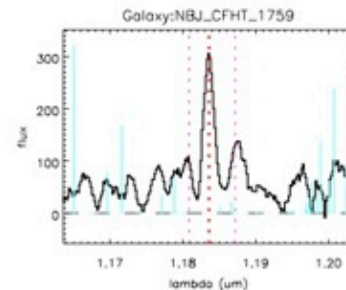
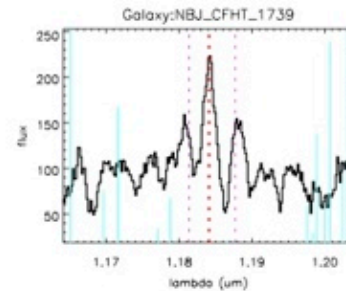
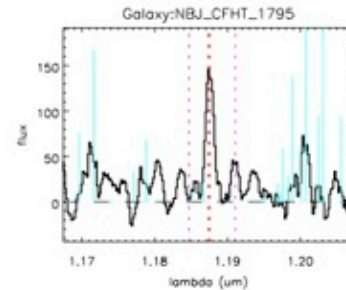
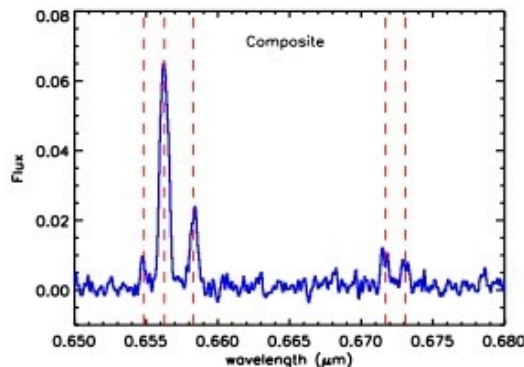
KMOS galaxies  $z=0.81$

$$12+\log(\text{O}/\text{H}) = 8.62 \pm 0.07$$

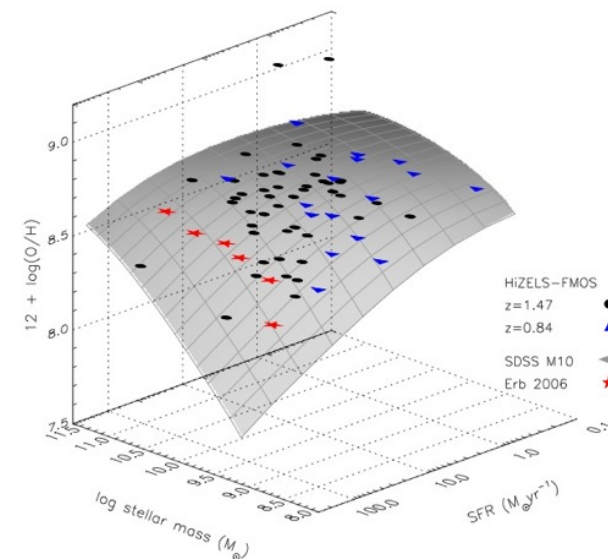
Solar value:  $8.66 \pm 0.07$



$$[\text{NII}]/\text{H}\alpha = 0.32 \pm 0.13$$



Rotation  $\sim 70\text{-}200$  km/s



# Evolution of the Tully Fisher relation?

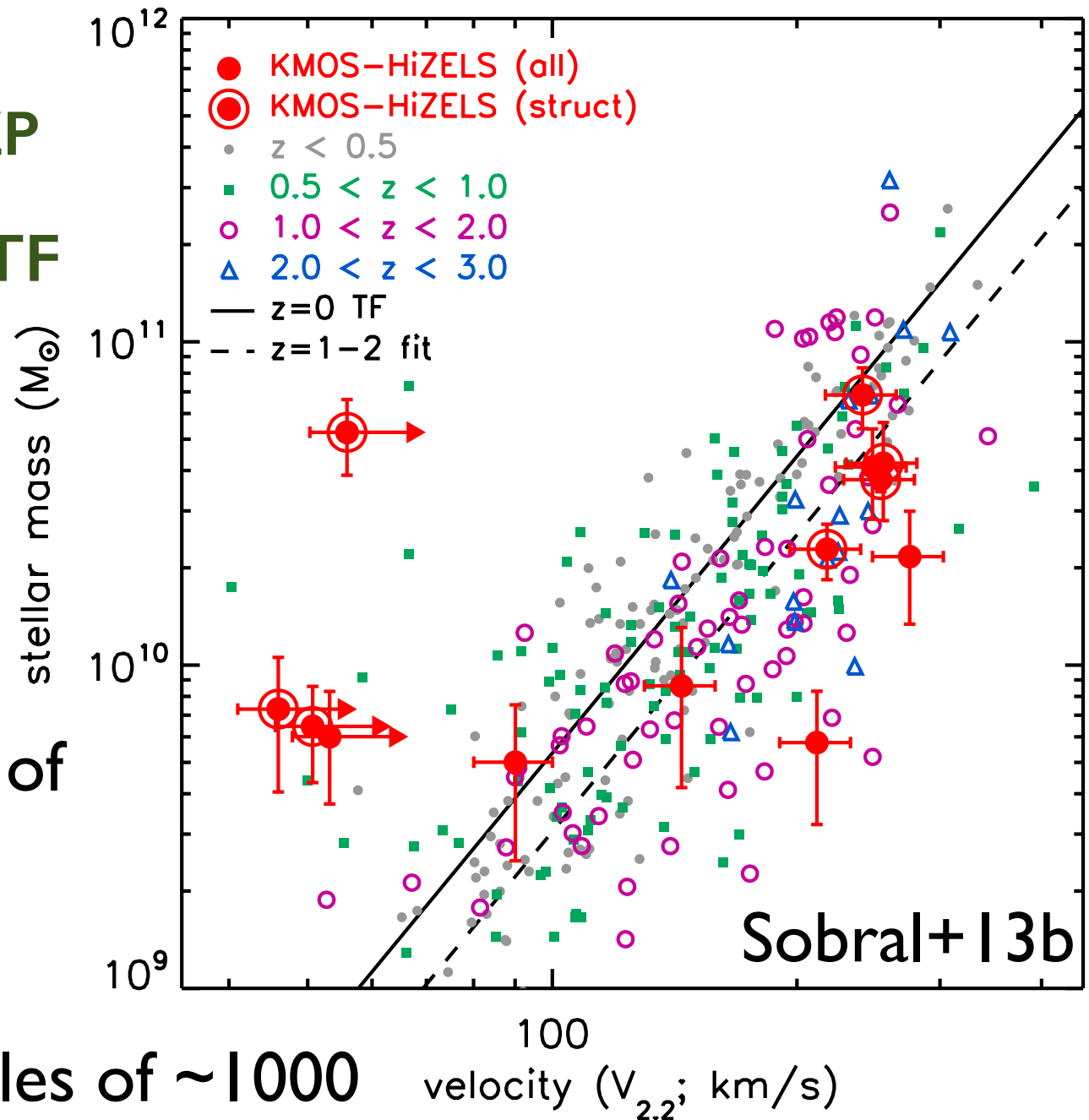
Small Evolution in ZP

Agrees with  $z \sim 1-2$  TF

No difference  
field vs group

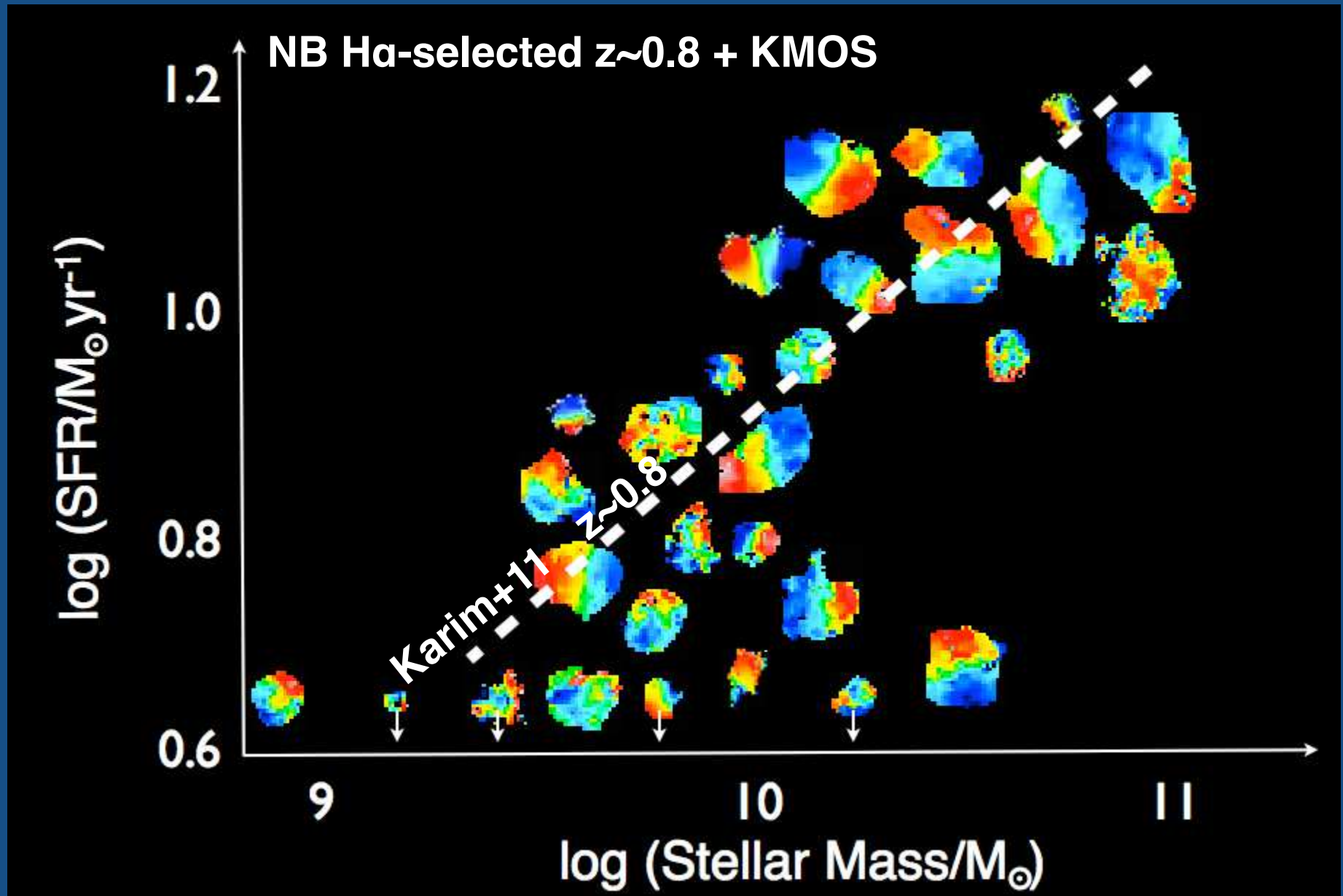
With just  $\sim 2$  hours of  
VLT time

“Easy” to build samples of  $\sim 1000$

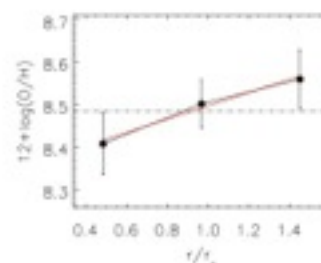
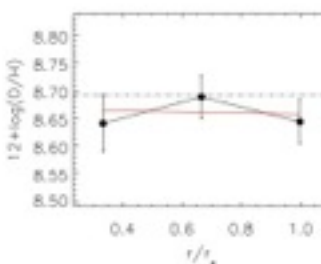
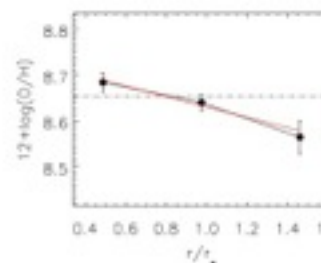
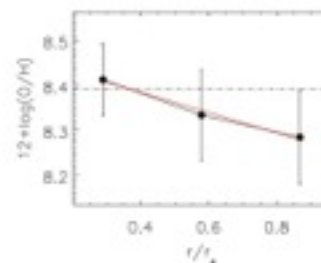
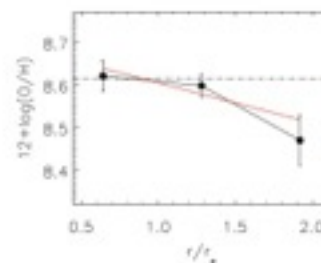
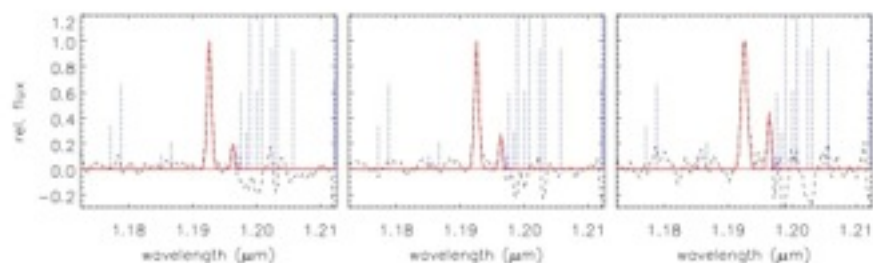
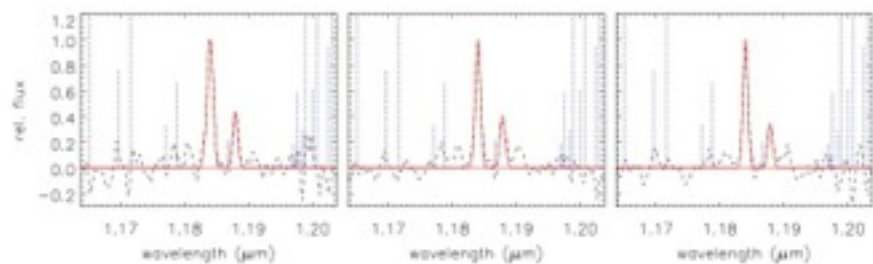
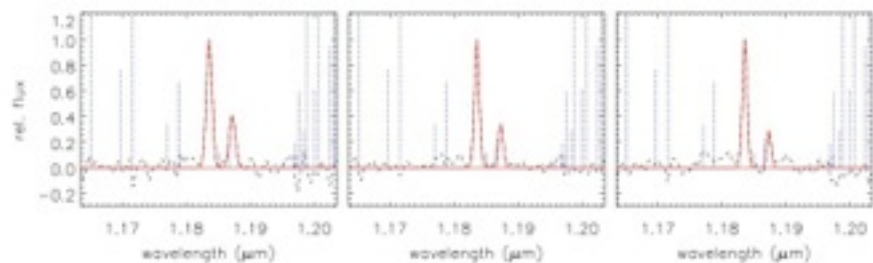
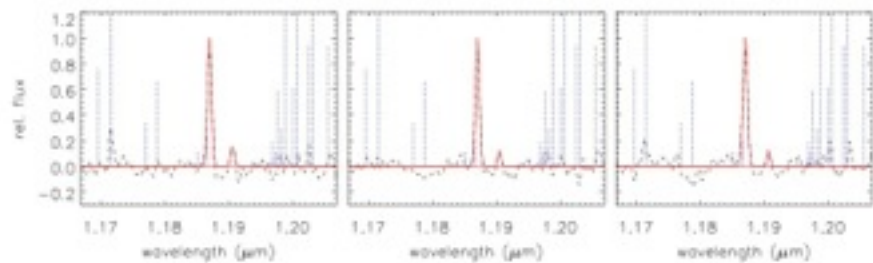
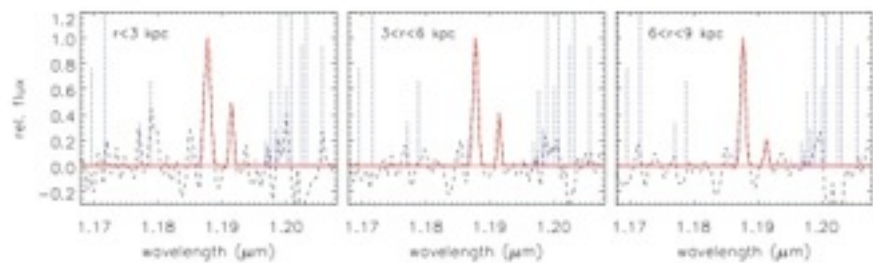


# CF-HIZELS KMOS SAMPLE

just 4 hours! (with overheads)



Sobral et al. 2013b, Stott et al. 2014



**Metallicity gradients  
for CF-HiZELS  
KMOS sample**

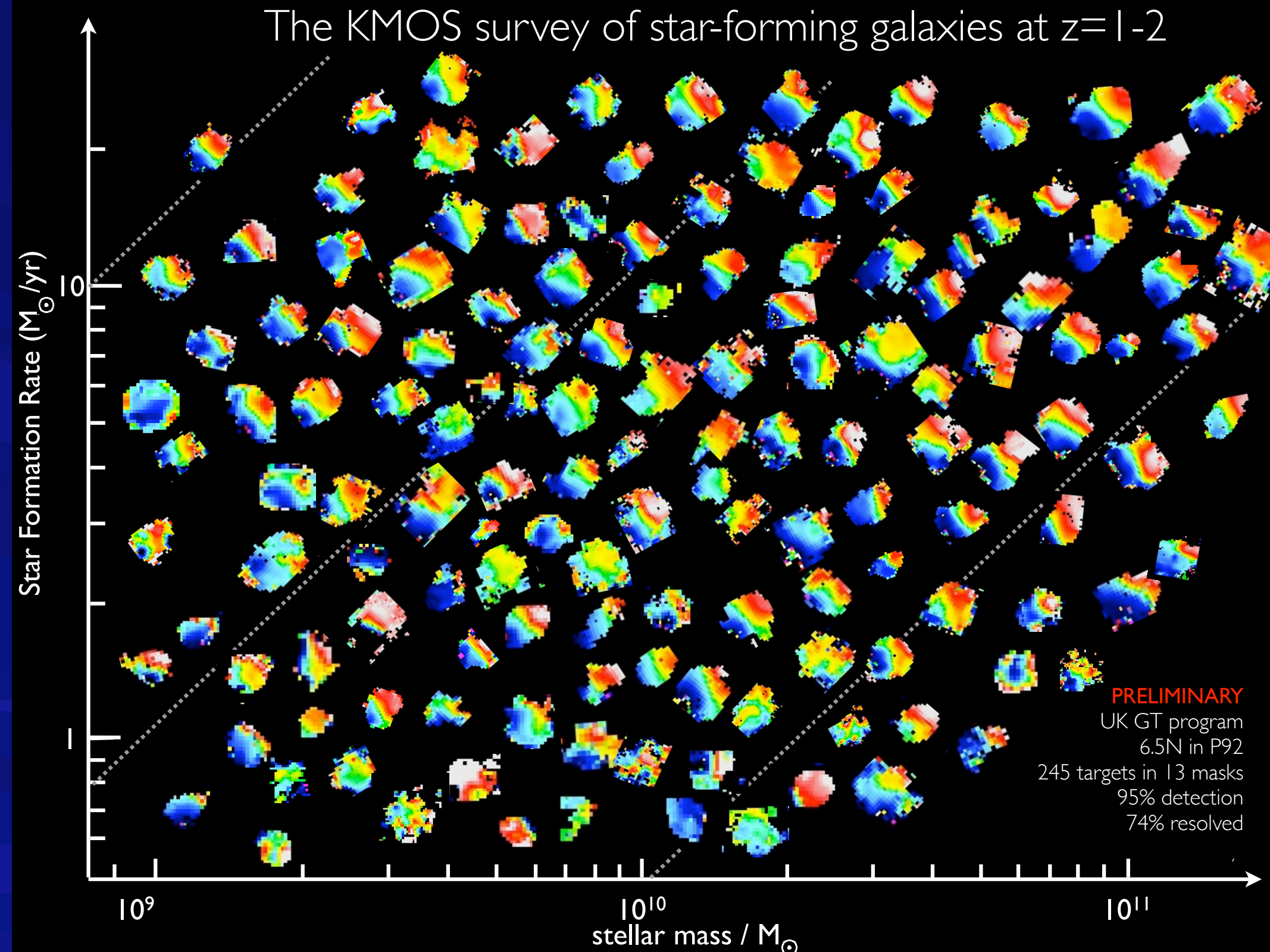
**Agreement with  
SINFONI results  
(Swinbank+12a)**

**Mostly negative or  
flat, very few positive**

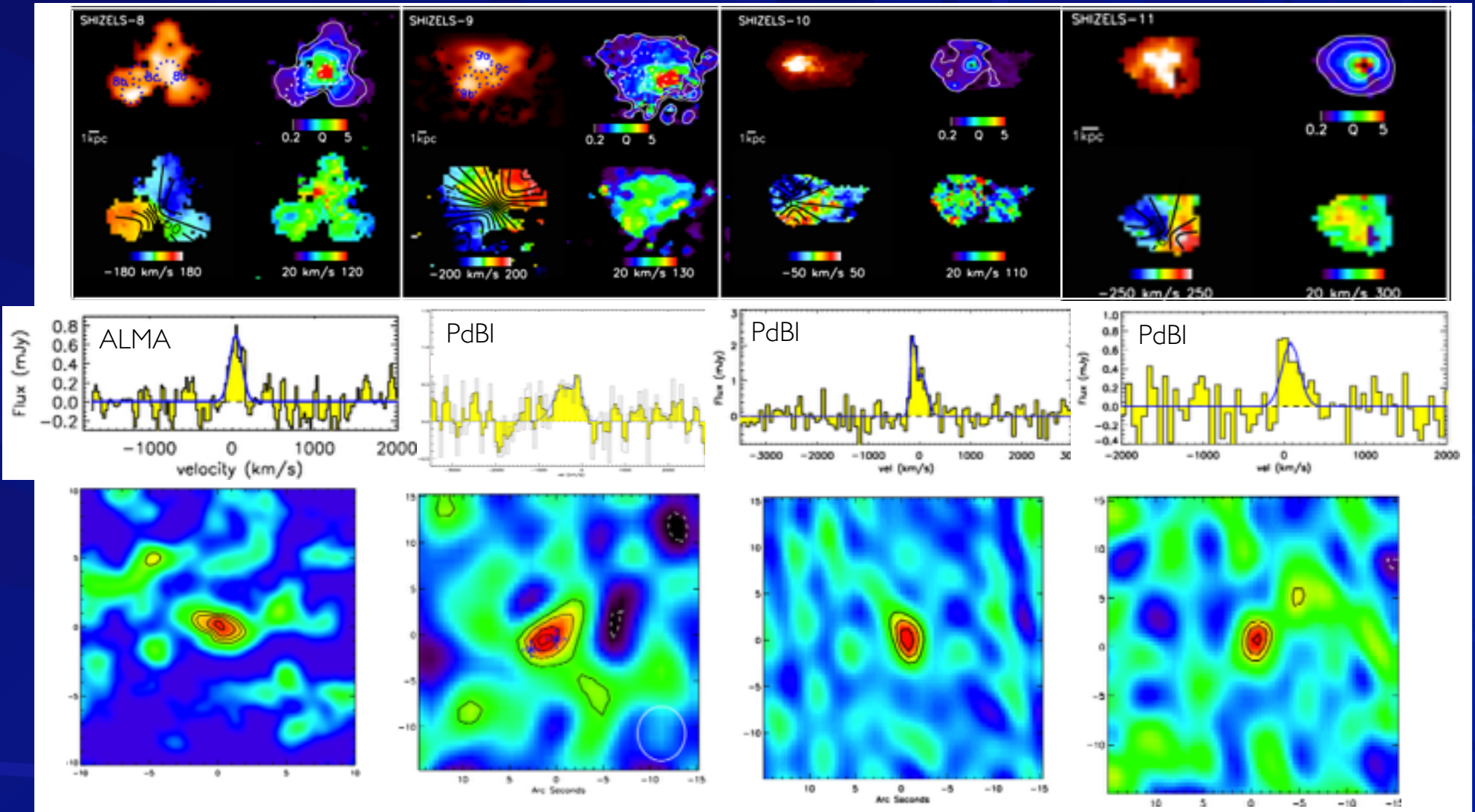
**Stay tuned...**

**Stott, Sobral et al. 2014**

# The KMOS survey of star-forming galaxies at $z=1-2$



# CO follow-up well underway with ALMA and PdBI



Towards resolved ( $\sim$ sub-kpc) Ha + CO + dust maps and evolution from  $z \sim 2$  to  $z \sim 0$  for “typical” SFGs

$$M_{\text{gas}} = 1-3 \times 10^{10} M_{\odot} \quad (a=2)$$

$$M^* = 2-4 \times 10^{10} M_{\odot}$$

$$f_{\text{gas}} \sim 30-50\%$$

$$M_{\text{gas}} / \text{SFR} \sim 1 \text{ Gyr}$$

[deep15.oal.ul.pt](http://deep15.oal.ul.pt)

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Twitter: @deepconf

# Back at the Edge of the Universe

Latest results from the deepest astronomical surveys

Sintra, Portugal, 15-19 March 2015

Home

The Conference

The People

Sintra



An international conference organised by the  
Centro de Astronomia e Astrofísica da Universidade de Lisboa

**SOC:** José Afonso (chair, CAAUL), Andrea Cimatti (U. Bologna), Carlos De Breuck (ESO), Mark Dickinson (NOAO), James Dunlop (ROE), Henry Ferguson (STScI), Mauro Giavallisco (U. Massachusetts), Ken Kellermann (NRAO), Jennifer Lotz (STScI), Bahram Mobasher (co-chair, U. California), Ray Norris (CASS), Laura Pentericci (Obs. Roma), Piero Rosati (U. Ferrara), David Sobral (CAAUL/Leiden), Linda Tacconi (MPE)

**LOC:** Joana de Medeiros, Marlise Fernandes, Sandra Fonseca, Elvira Leonardo, Silvio Lorenzoni, Katrine Marques, Hugo Martins, Hugo Messias, Joana Oliveira, Ciro Pappalardo, João Retrê (chair)

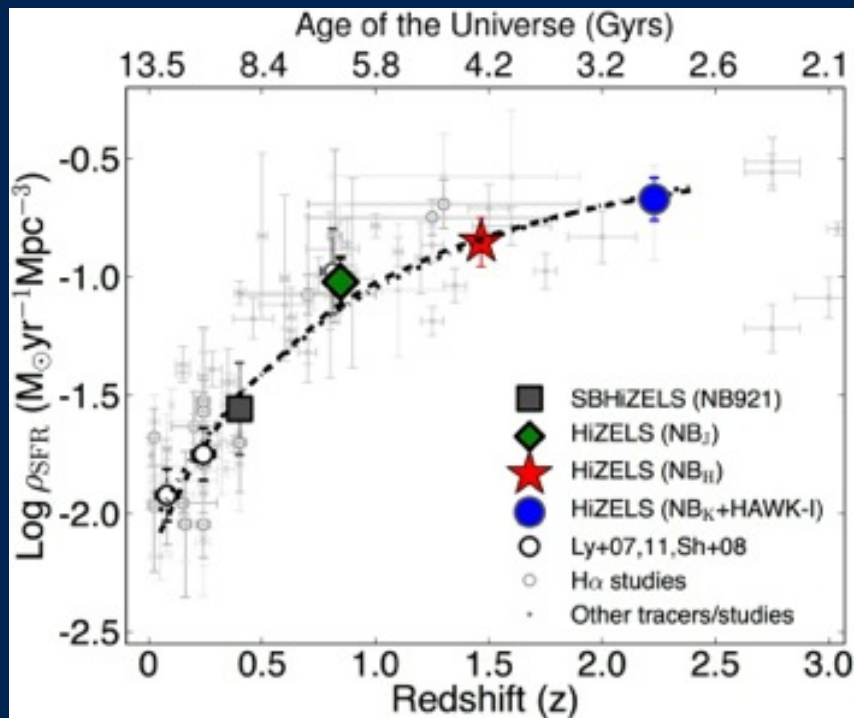
# Conclusions:

last 11 Gyrs

- **H $\alpha$  selection  $z \sim 0.2-2.2$ : Robust, self-consistent SFRH + **Agreement** with the **stellar mass density growth****
- The bulk of the evolution over the last 11 Gyrs is in the **typical SFR (SFR\*) at all masses and all environments: factor  $\sim 13x$**
- SINFONI w/ AO: Star-forming galaxies since  $z=2.23$ :  $\sim 75\%$  “disks”, negative metallicity gradients, many show clumps
- KMOS+H $\alpha$  (NB) selection works extraordinarily well: resolved dynamics of typical SFGs in  $\sim 1-2$  hours,  $75 \pm 8\%$  disks,  $50-275 \text{ km/s}$

Most of claimed “evolution” with redshift is driven by:

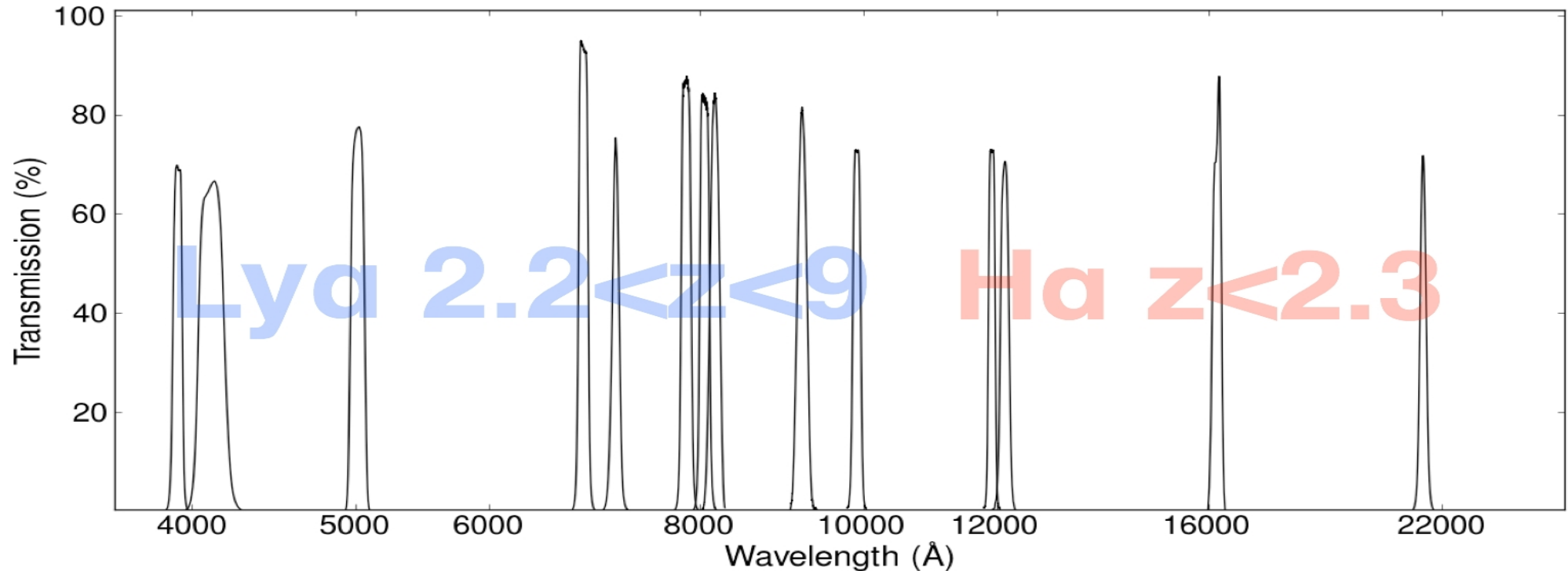
- The evolution of SFR\* (typical SFR( $z$ ))
- Selection effects: selection really matters! Need to compare like with like!

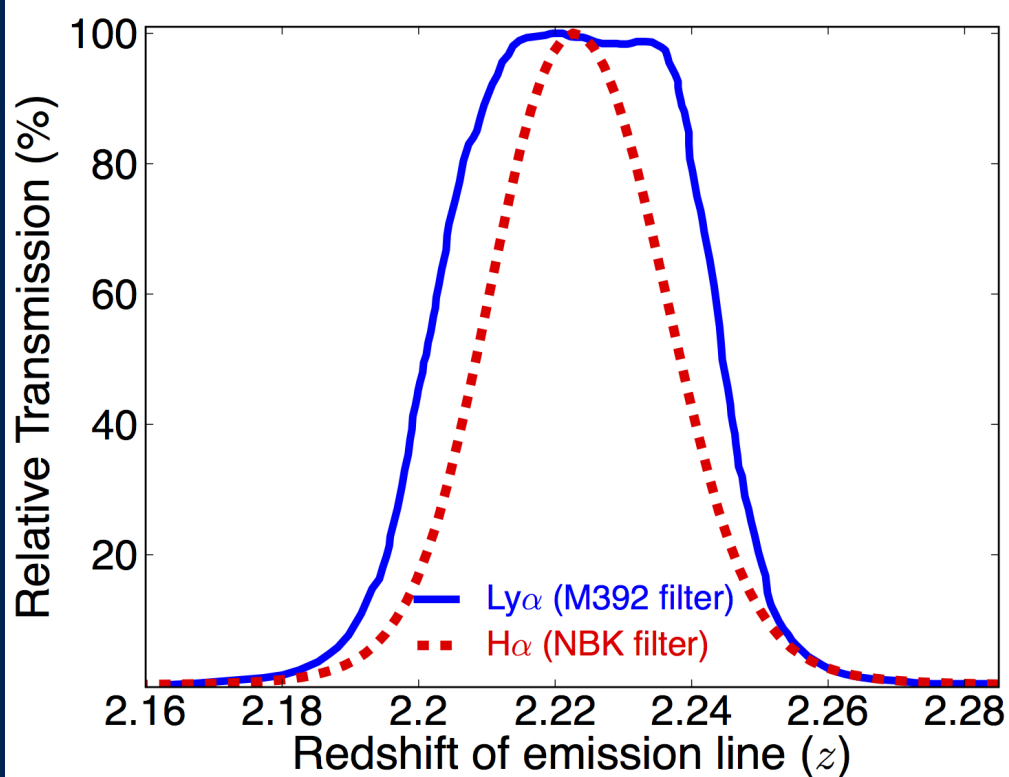


Probe to even earlier times

Calibrate Ly $\alpha$  at  $z=2.23$

Survey areas >20x larger than before

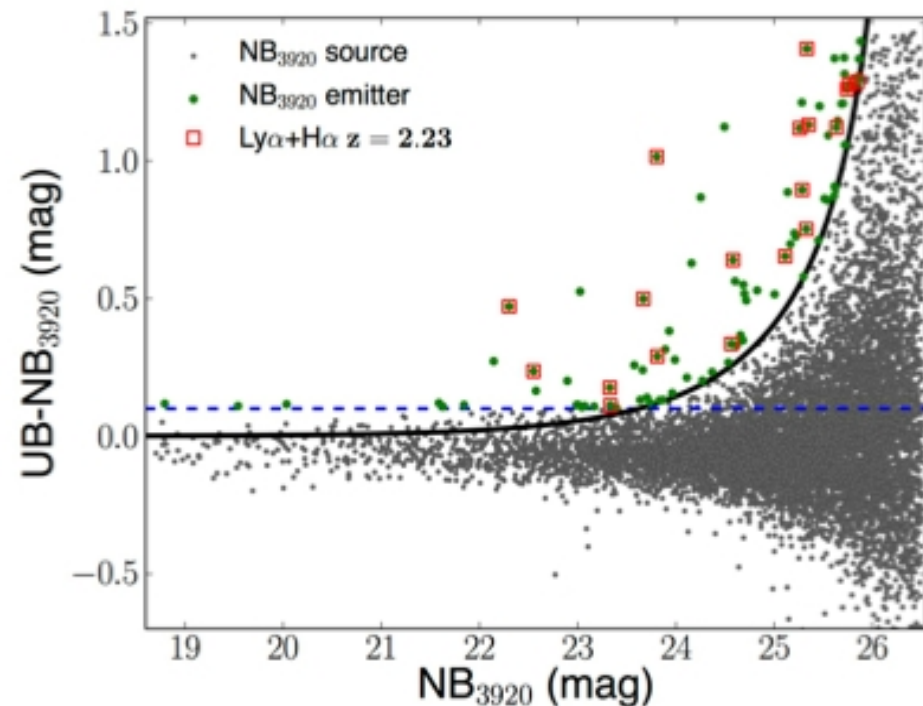
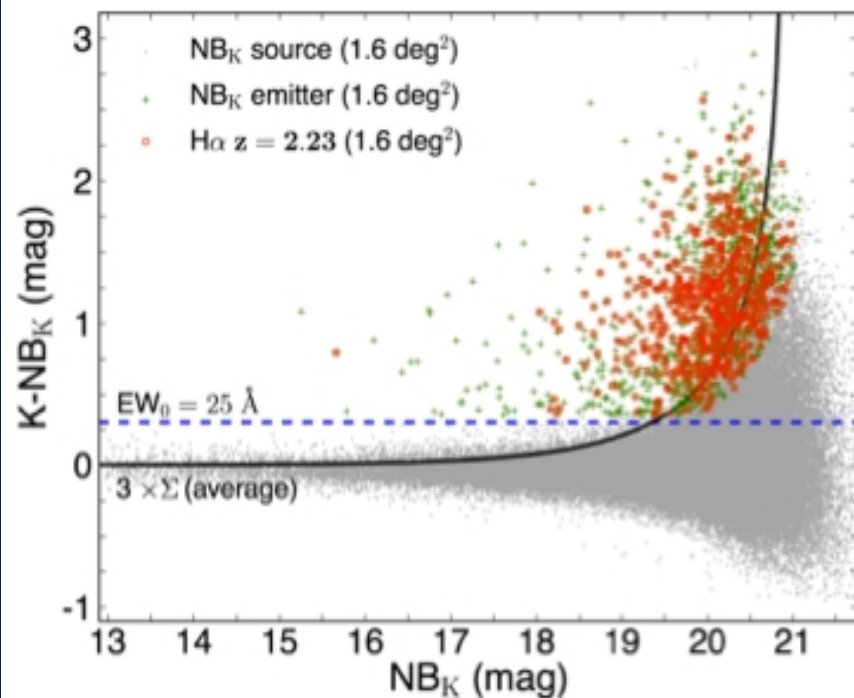




**Calibrate  $\text{Ly}\alpha$  at  $z=2.23$**

**5 deg<sup>2</sup> deep double-blind matched  $\text{Ly}\alpha$ - $\text{H}\alpha$  survey.**

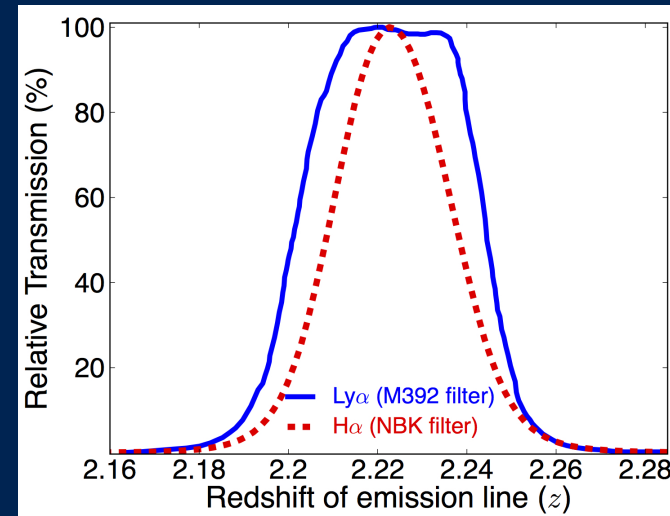
**Pilot survey: INT => CFHT**



# 5 deg<sup>2</sup> deep double-blind matched Ly $\alpha$ -H $\alpha$ survey z=2.23

~30 PI nights... but highly weathered out (~60%) in La Palma (including this week!)

but... Preliminary space fraction (Ly $\alpha$ ): ~7% (consistent with Hayes+)



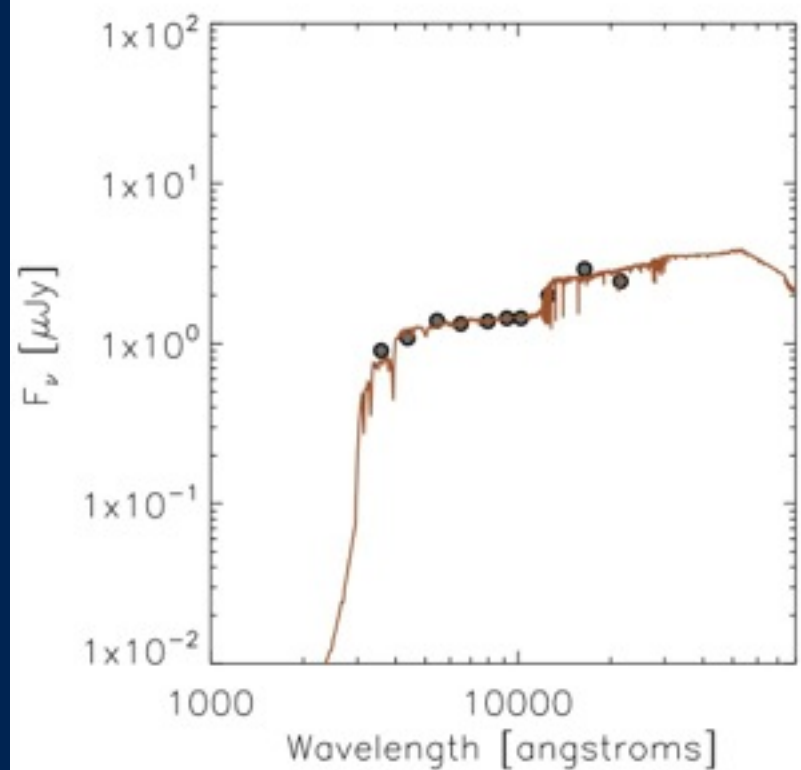
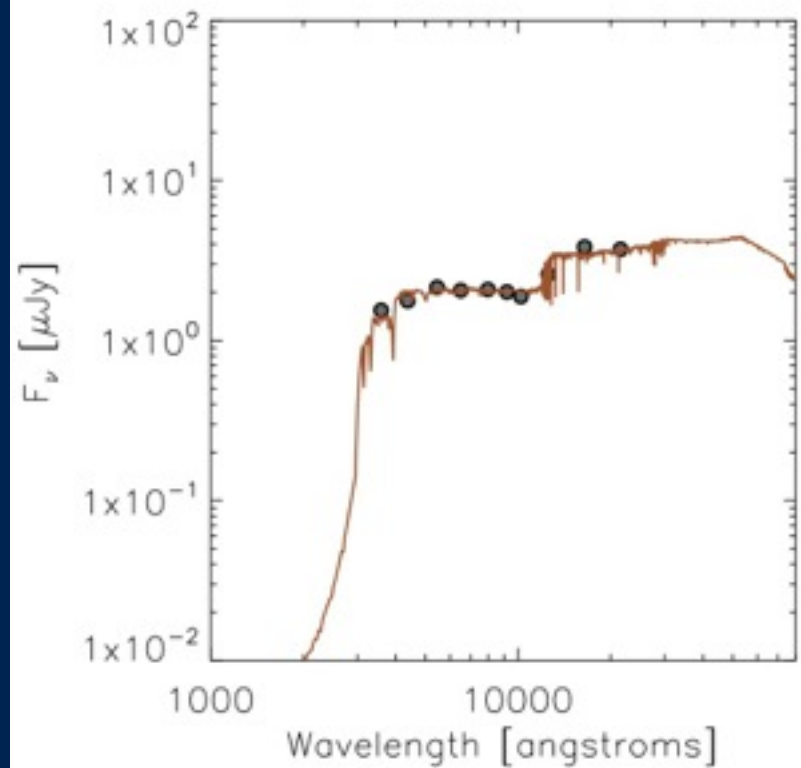
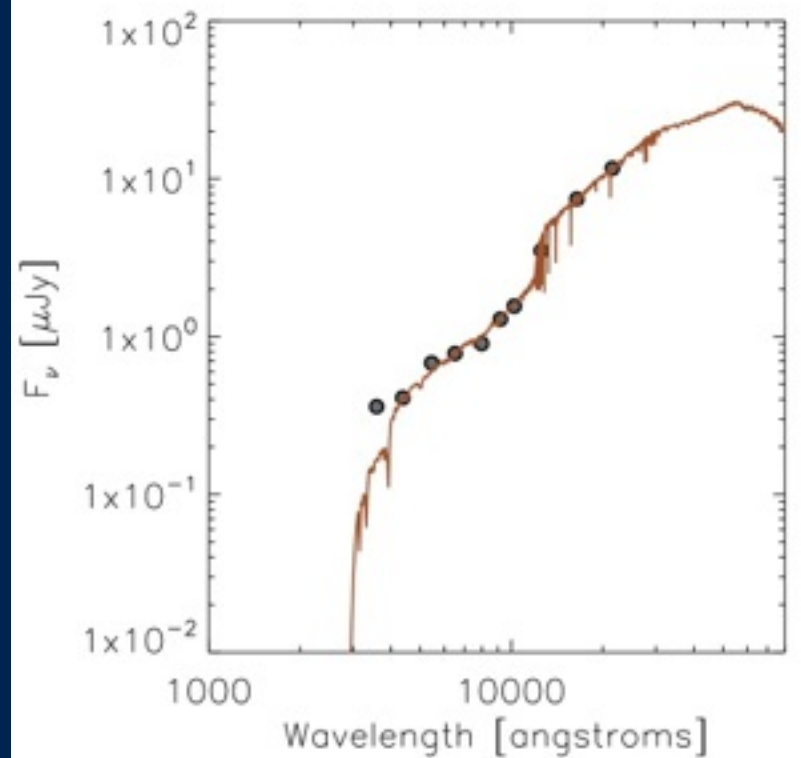
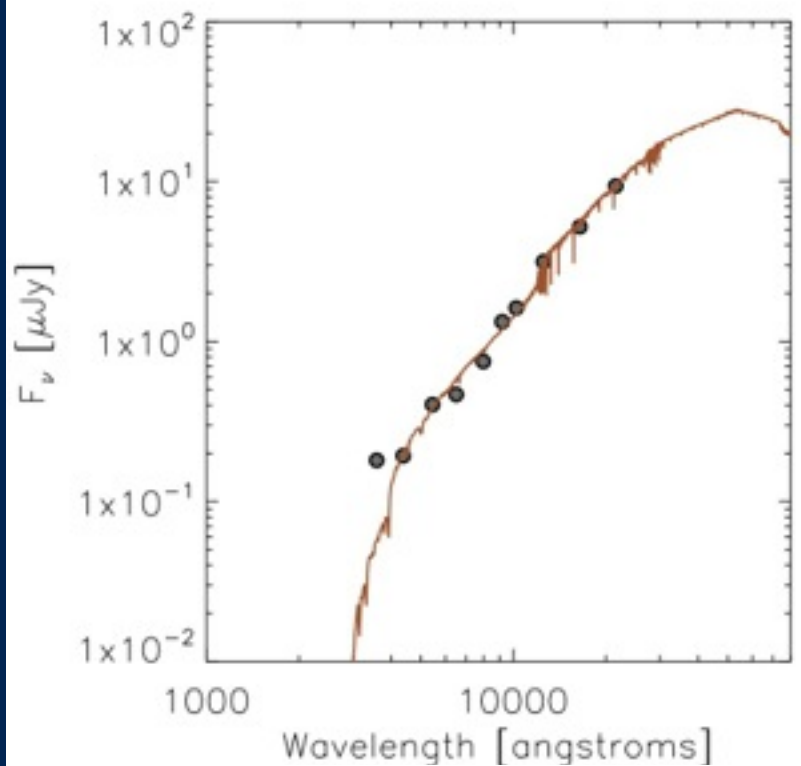
Wide range of properties of matched Ly $\alpha$ -H $\alpha$  emitters:

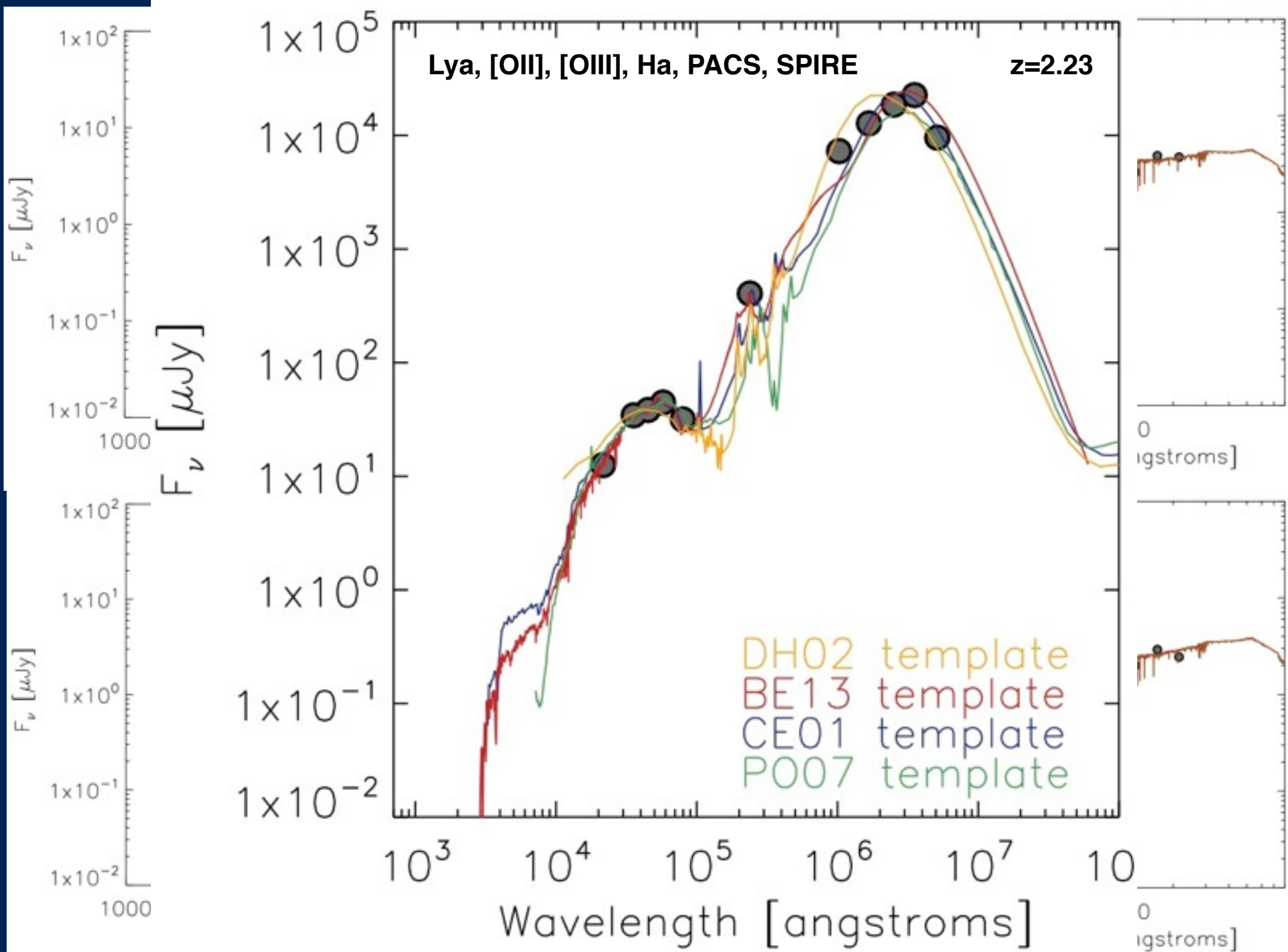
Masses:  $10^9$ - $10^{11}$  M $_{\odot}$  SFRs: ~5-200 M $_{\odot}$ /yr

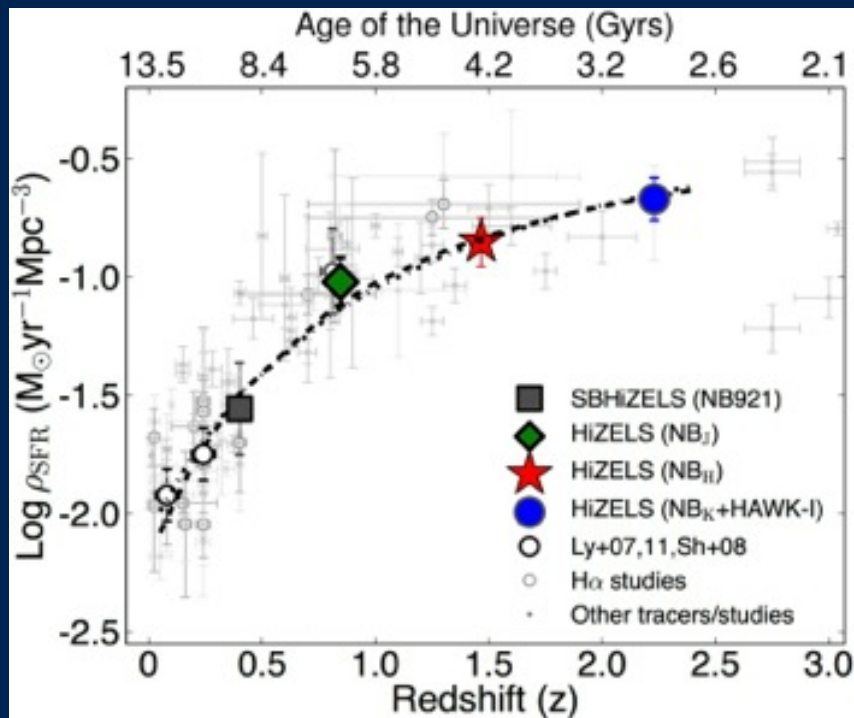
Dust: ~0 to 2 mags From Blue to red

Calibrate Ly $\alpha$  using H $\alpha$  for range of masses, SFRs, extinction, colour, etc

## Lya-Ha emitters



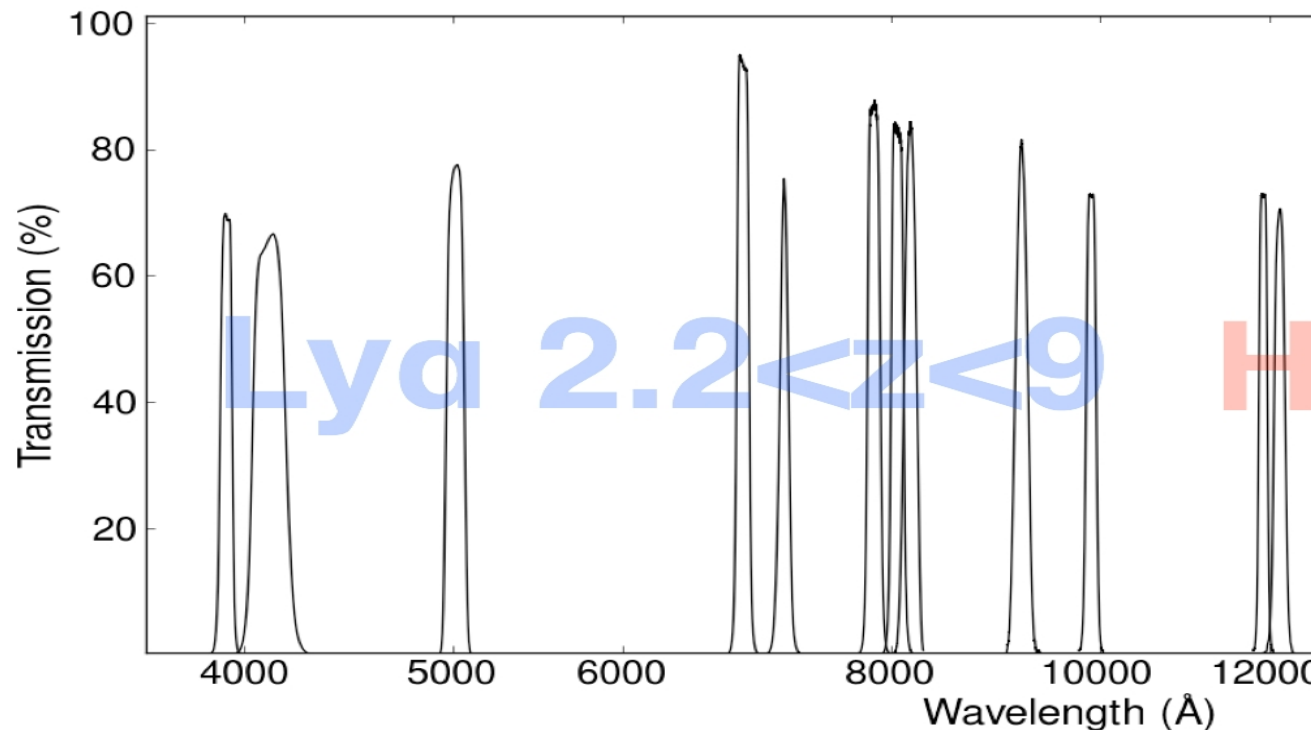


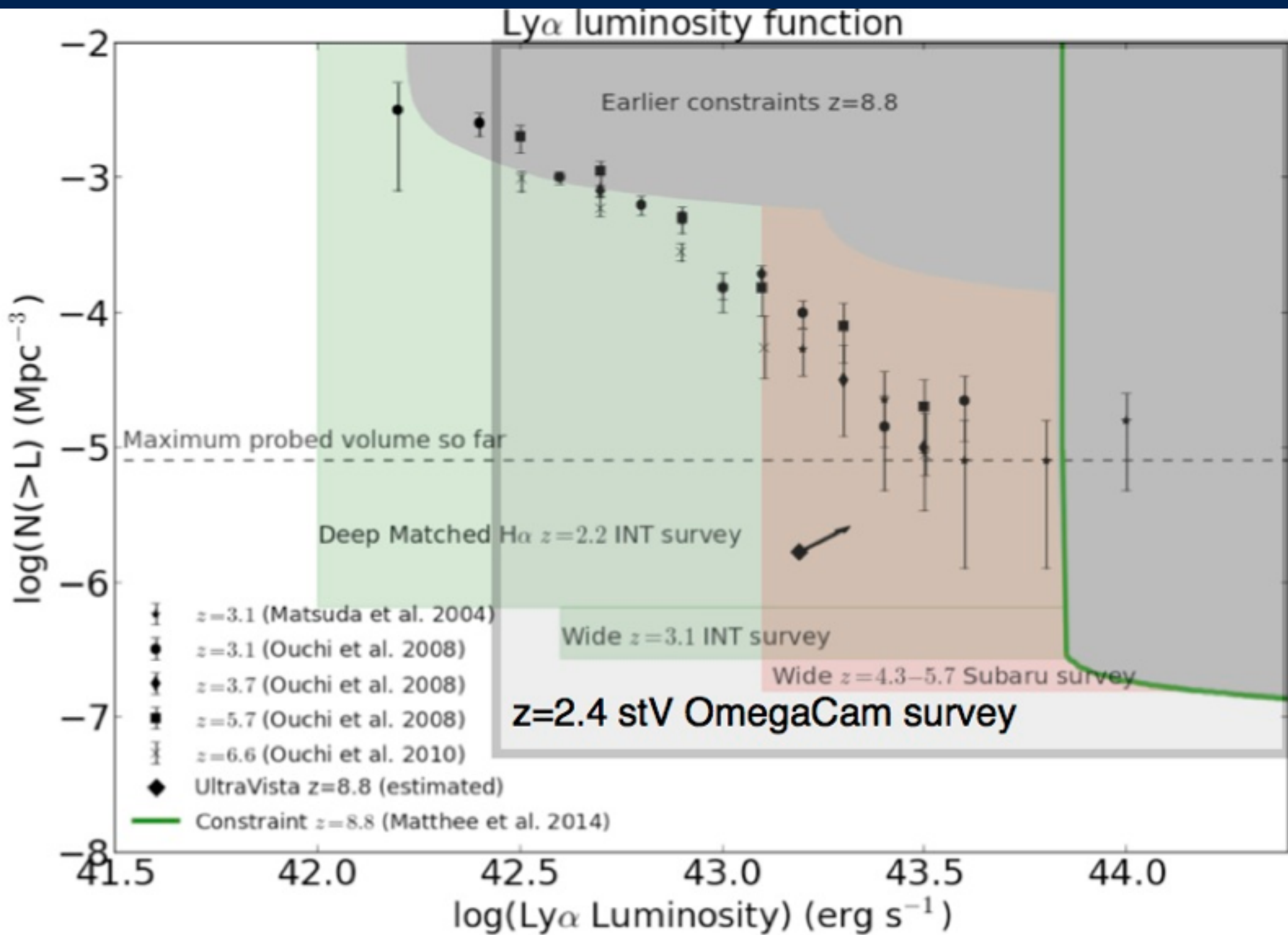


Probe to even earlier times

Calibrate Ly $\alpha$  at  $z=2.23$

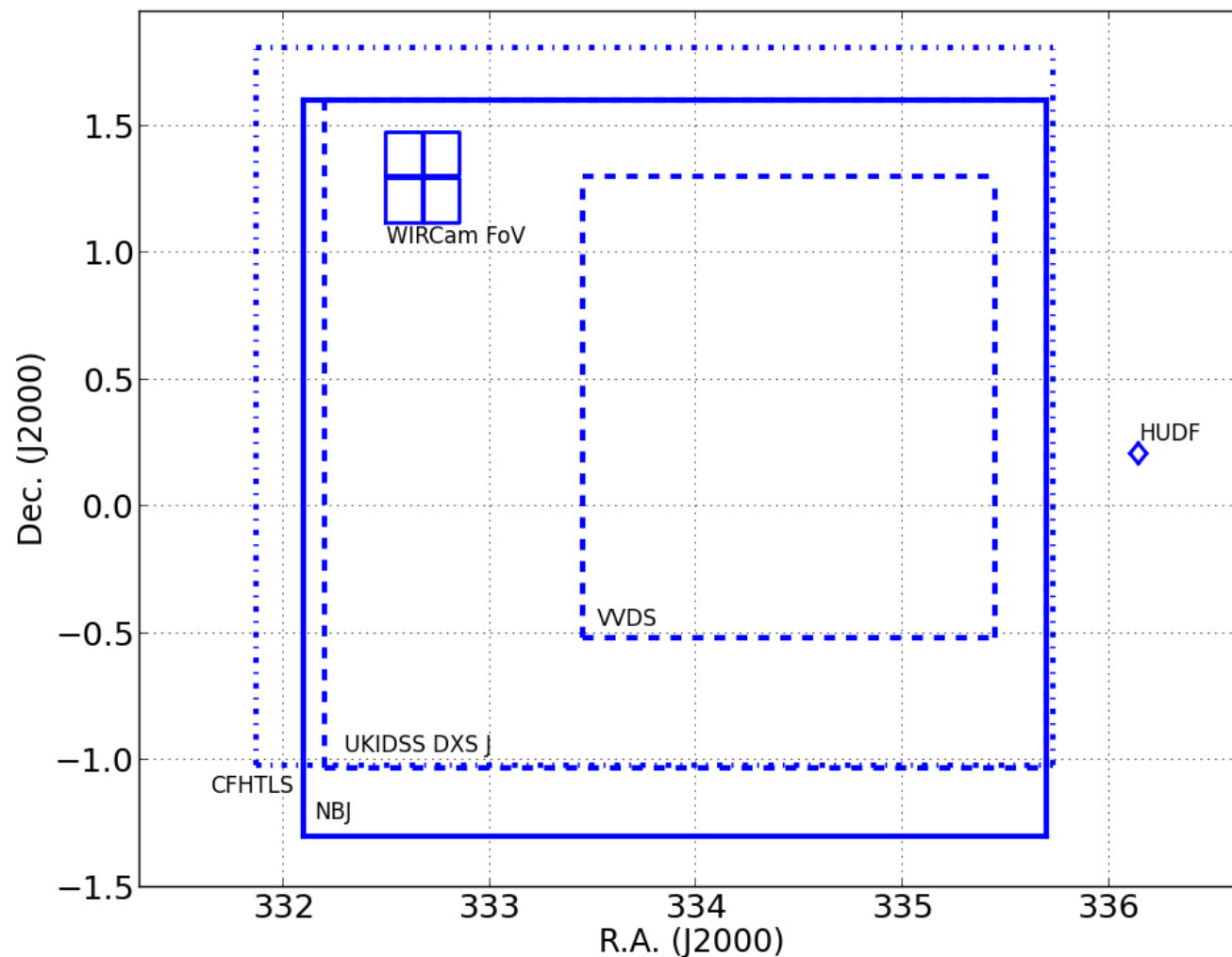
Ly $\alpha$ : Survey areas >20x larger than before





**WIRCam/  
LowOH2**

**Down to about  
1Mo/yr  $z=0.8$**



**10 sq deg. SA22**

**S+13b, Matthee+14**

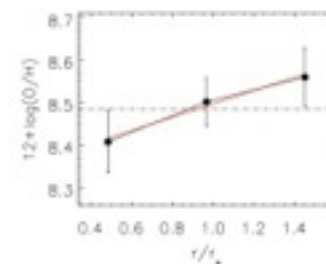
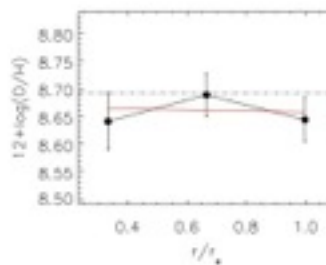
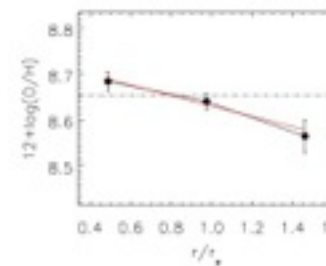
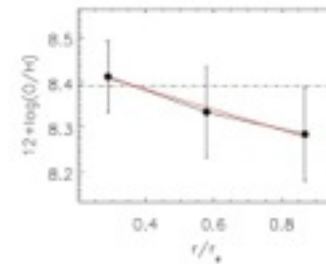
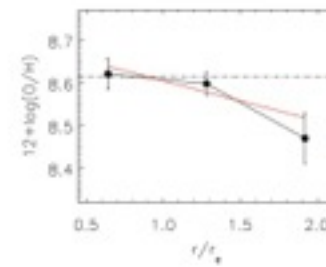
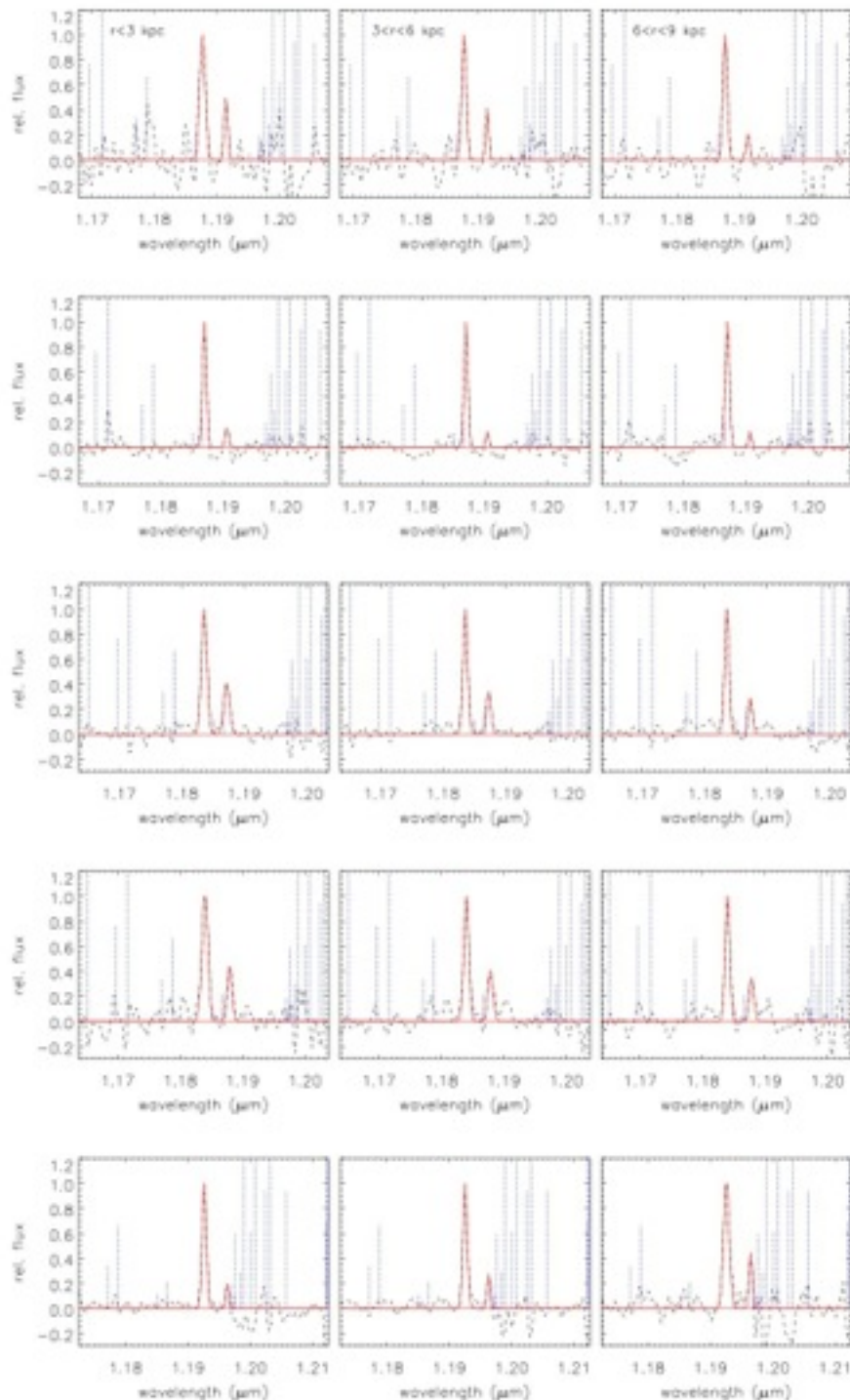
# Metallicity gradients for CF-HiZELS KMOS sample

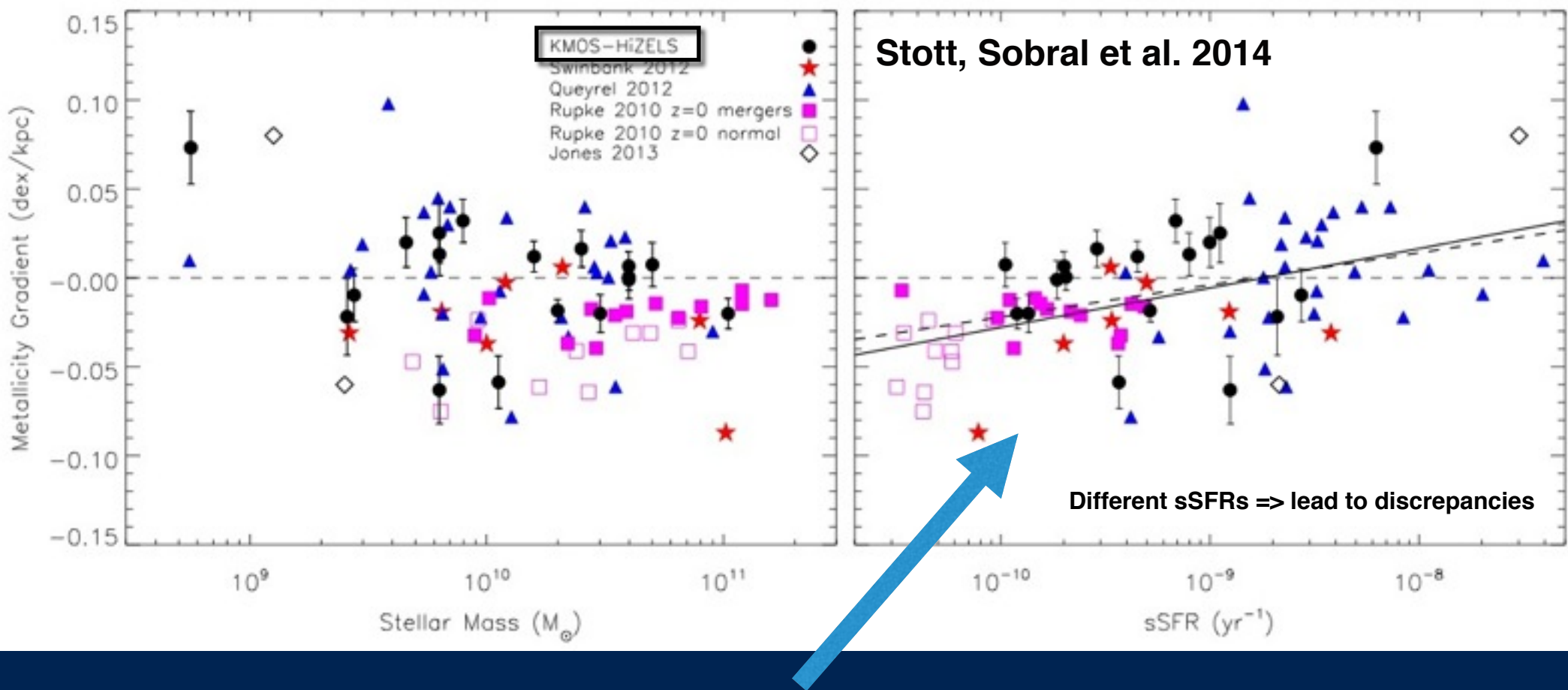
Agreement with SINFONI results (Swinbank+12a)

Mostly negative or flat, very few positive

Can we reconcile apparently discrepant results at  $z \sim 1-2$  (negative vs positive metallicity gradients)?

Stott, Sobral et al. 2014





**Metallicity Gradients increase with increasing sSFR**

**Suggests high sSFRs may be driven by funnelling of “metal poor” gas into their centres**

**Results may help to explain the FMR (negative correlation between metallicity and SFR at fixed mass)**

**300 k NB detections**

**7000 line emitters**

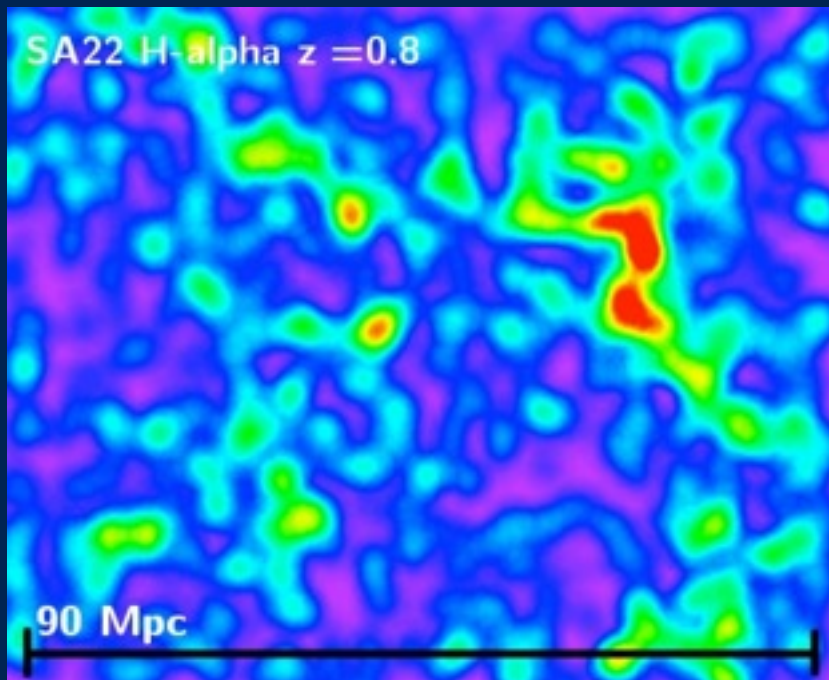
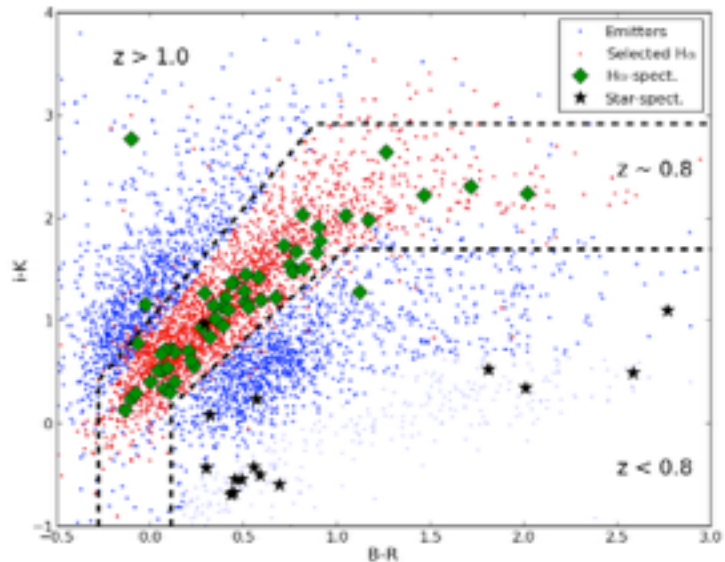
**3500 H $\alpha$   $z=0.8$**

**1100 [OIII]+H $\beta$   $z=1.4$**

**900 [OII]  $z=2.2$**

**300 at  $z>2.5$**

**Any Ly $\alpha$  at  $z=8.8$ ?**



**8 sigma over-density**

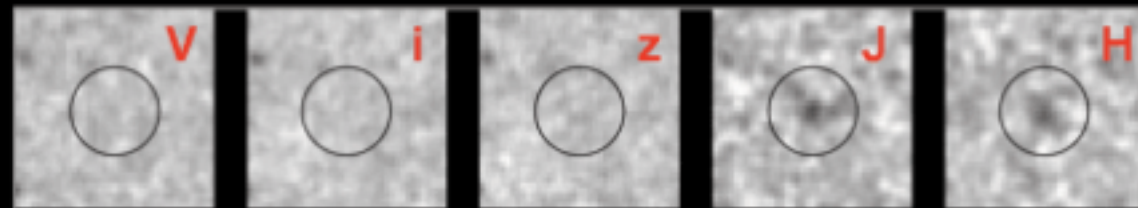
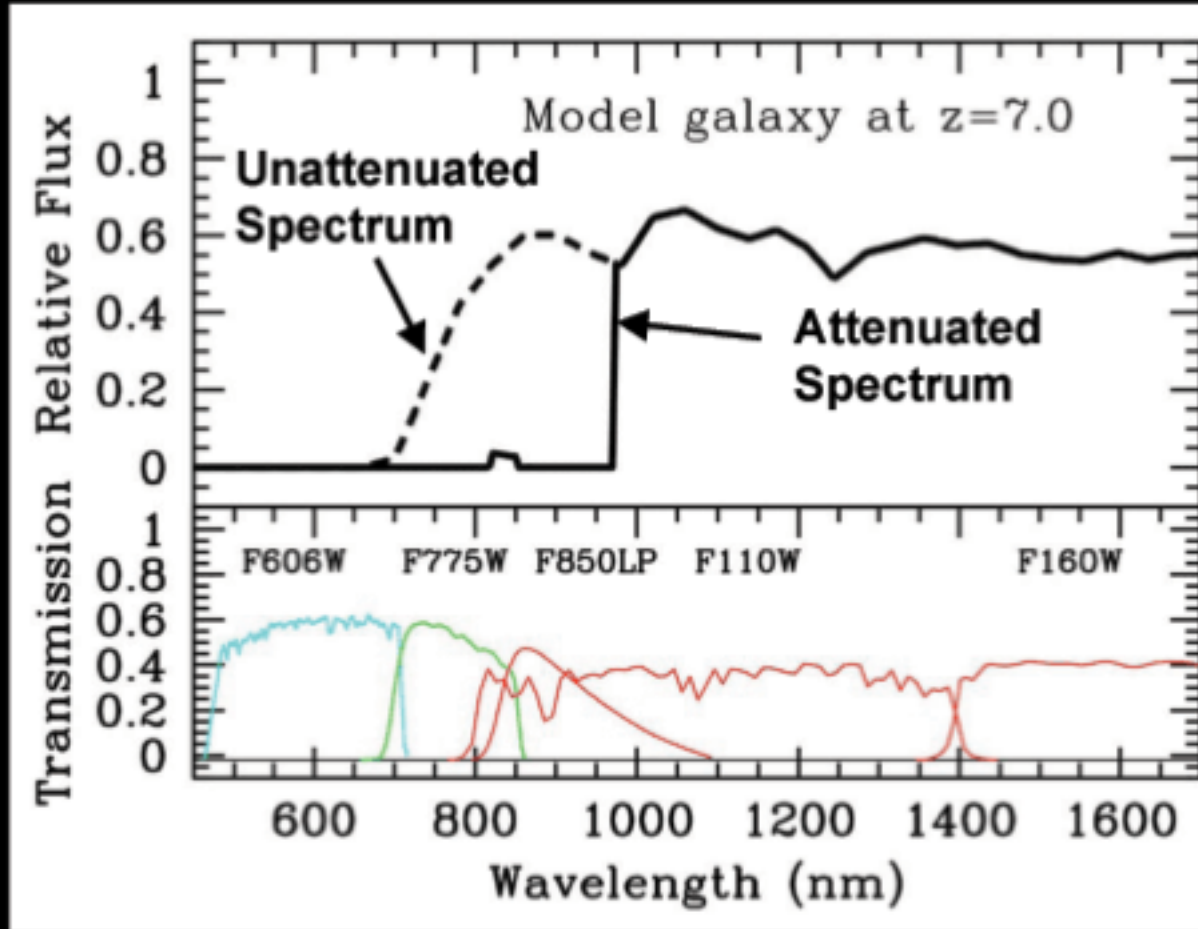
- No detection in optical individual bands

## Looking for $z=8.8$ Ly $\alpha$ emitters: CFHTLS + UKIDSS

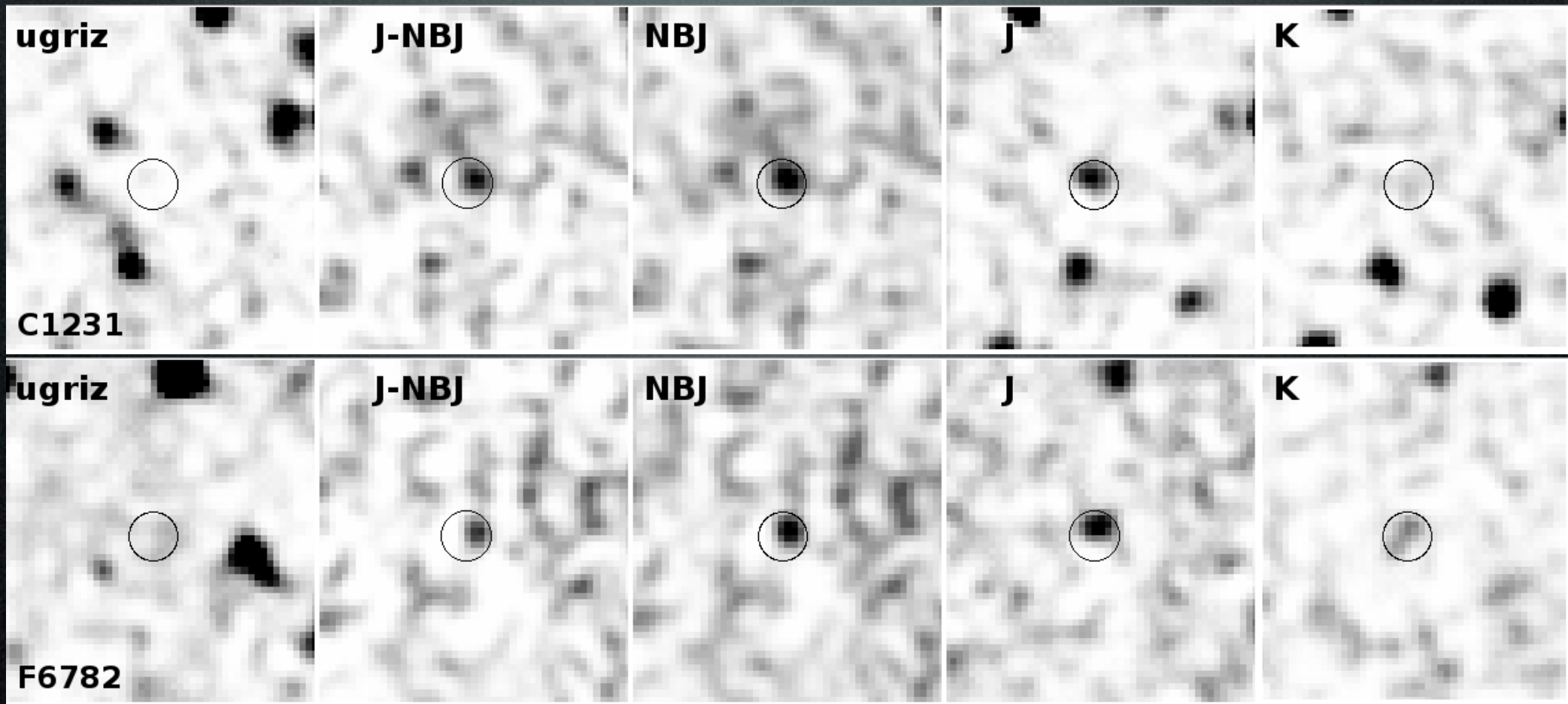
- No detection in CFHTLS optical stack

- SED fitting +  $z$ -J, J-K information (to reject  $z=2.2$  sources)

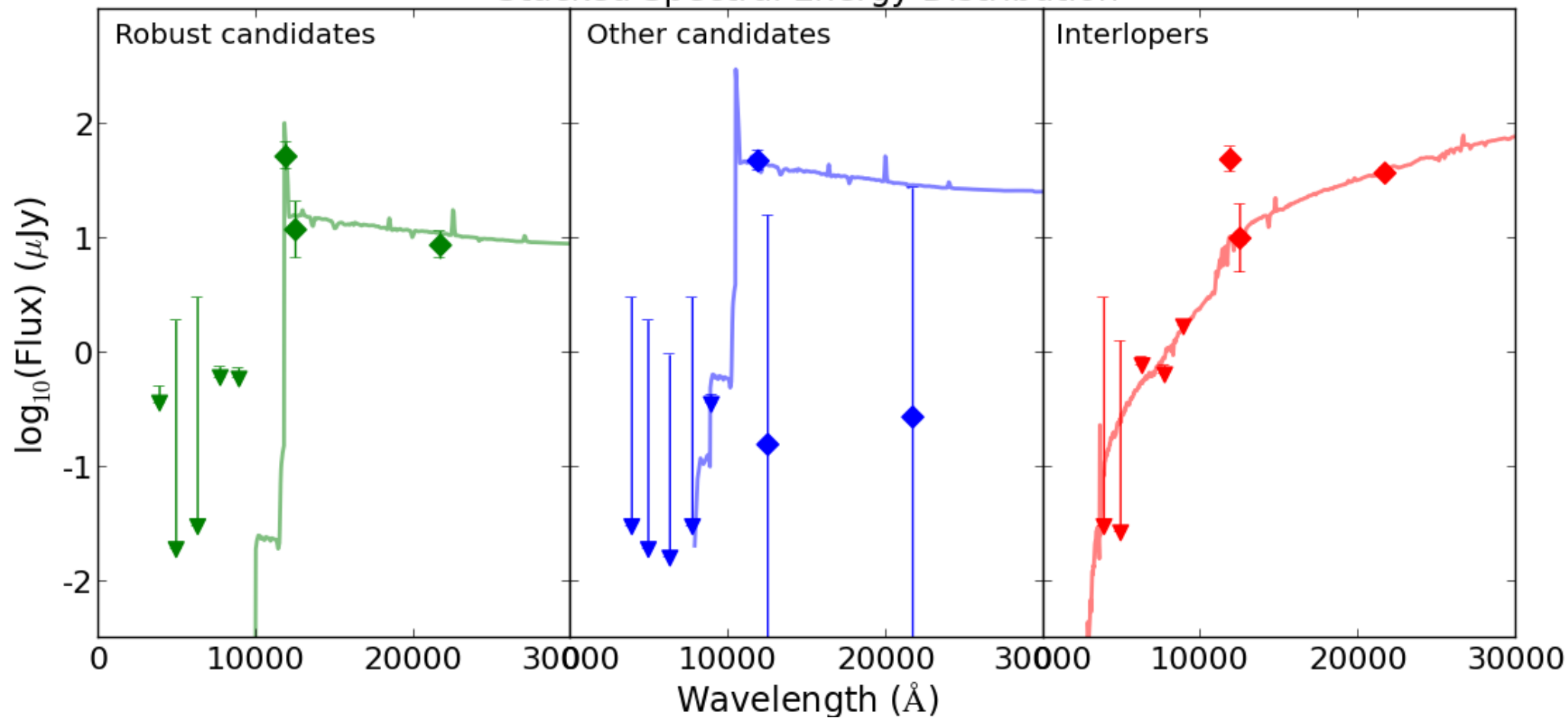
- Results in **6** good candidates



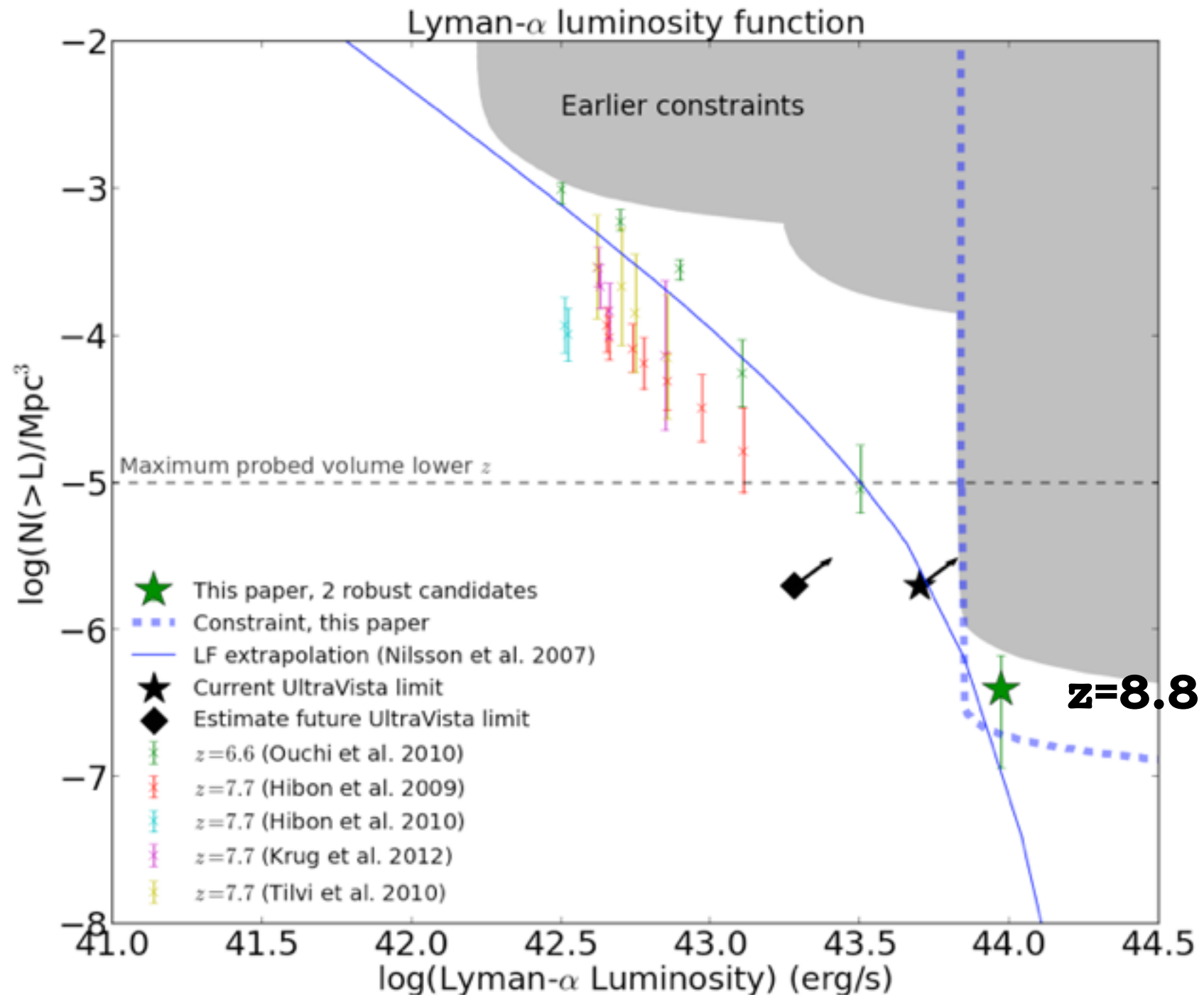
## 2 out of 6 Lyman-alpha candidates $z=8.8$



# Stacked Spectral Energy Distribution

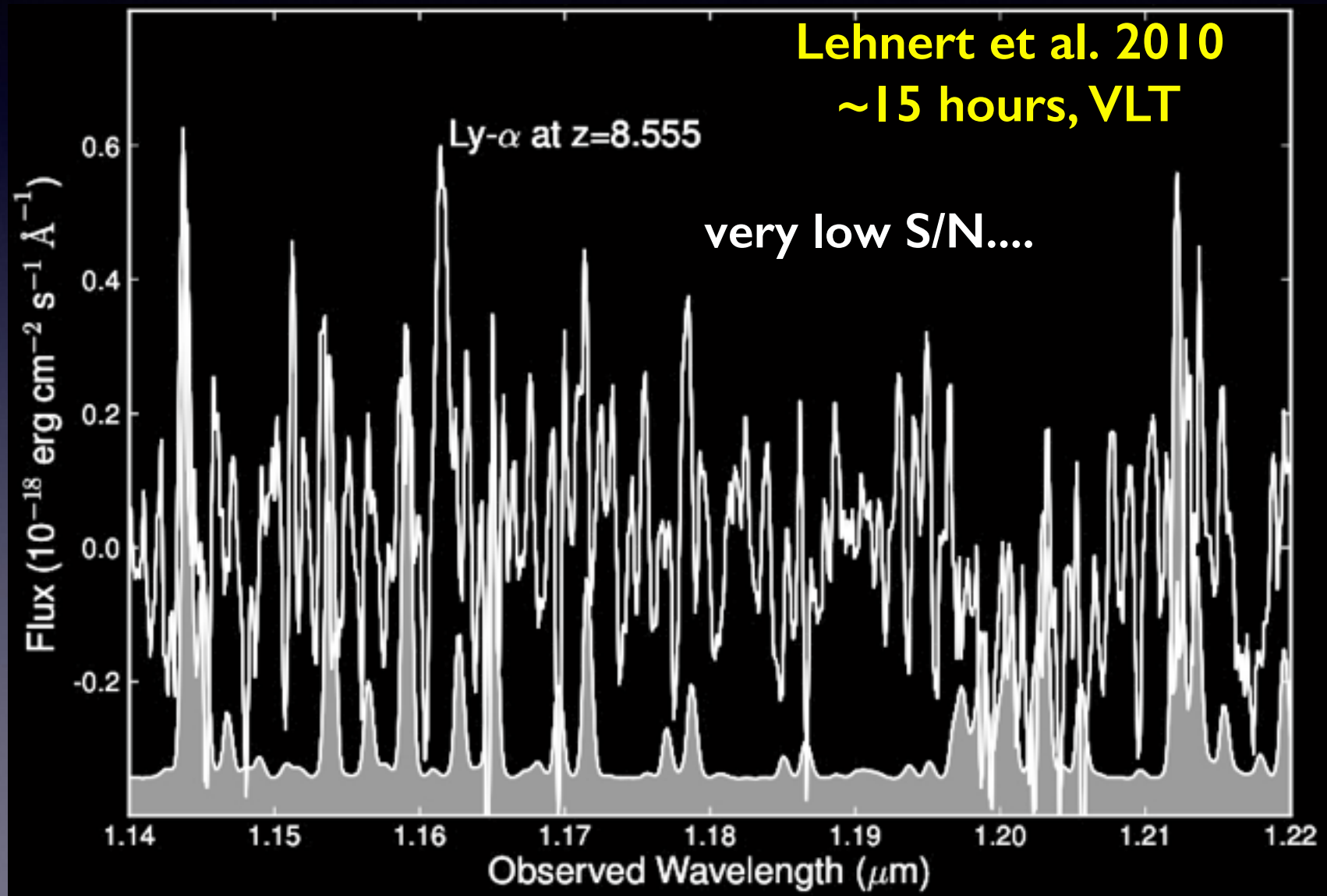


# Matthee, Sobral et al. 2014



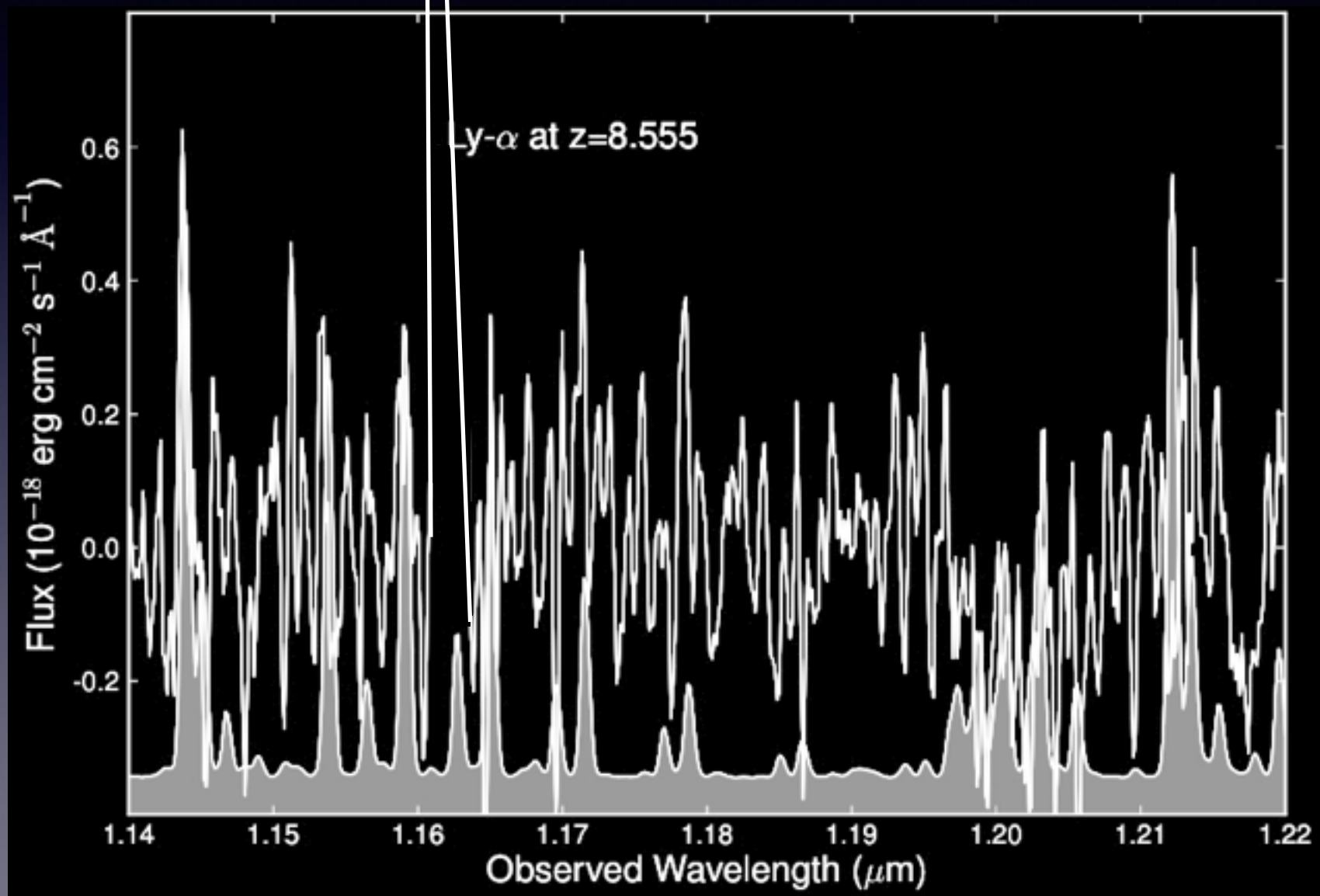
The big advantage for spectroscopic follow-up is that they will  
\*not\* look like this:

(see Bunker et al. 2013)



In  $\sim$  couple of  
hours

They will look like this!

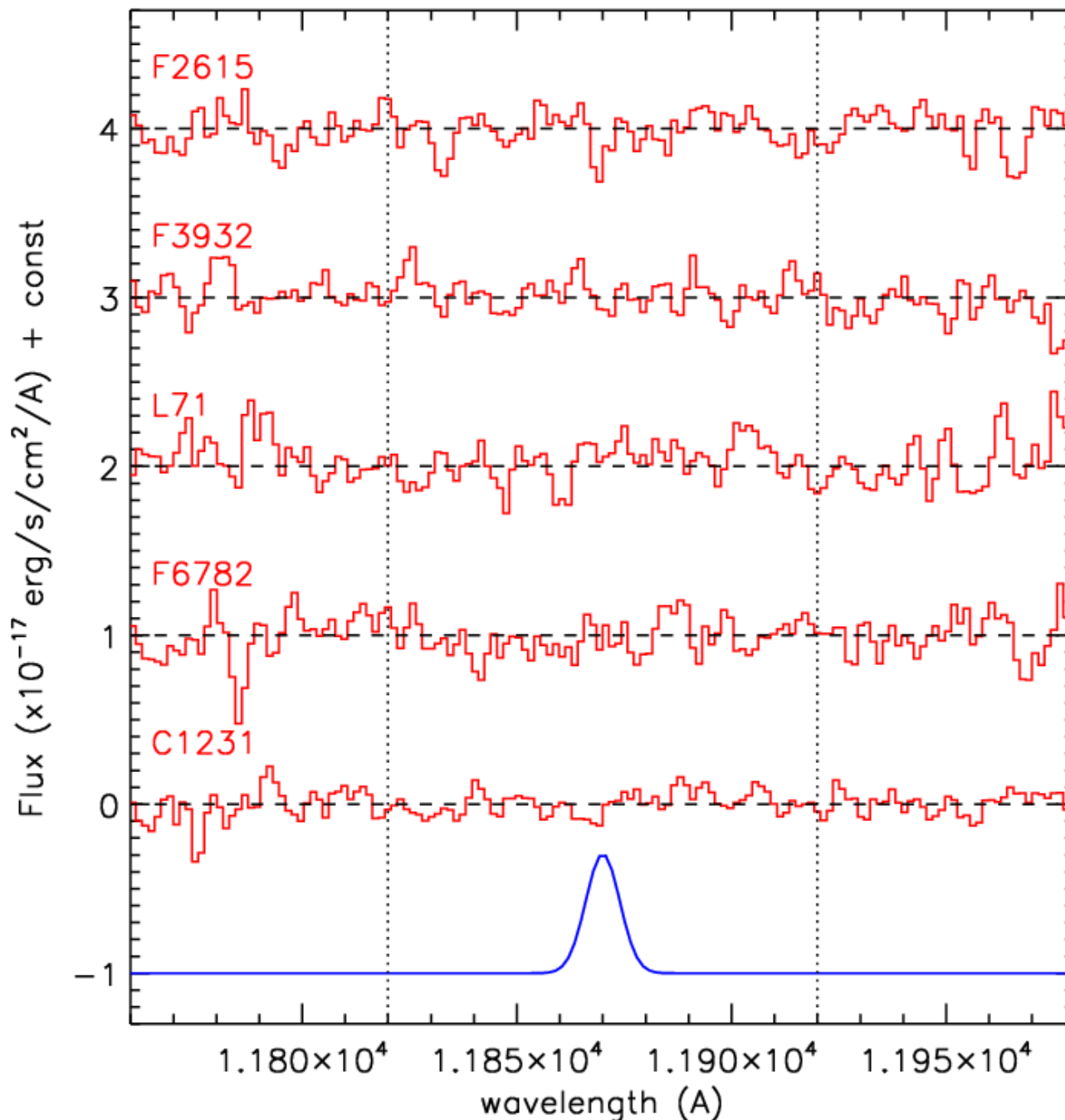


# SINFONI/VLT

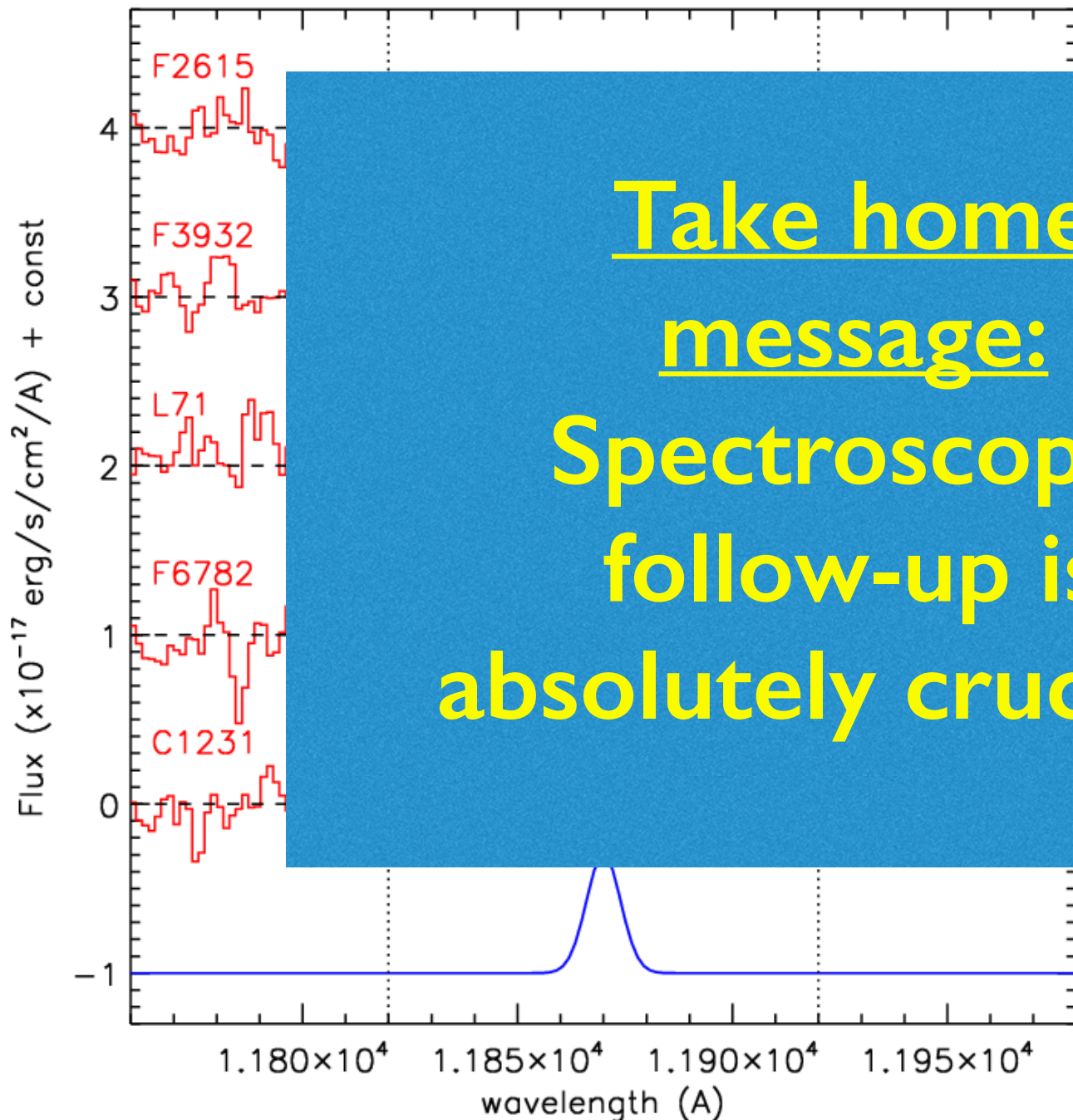
5 best candidates:  
1 hour per source

All shown not to be  
at  $z=8.8$

And now the little  
follow-up of other  
“candidates” is  
showing the same  
(e.g. Faisst et al.  
2014)



Matthee et al. 2014



Take home  
message:  
Spectroscopic  
follow-up is  
absolutely crucial!!!

candidates:  
per source

not to be  
 $z=8.8$

the little  
up of other  
candidates” is  
the same

(e.g. Faisst et al.  
2014)

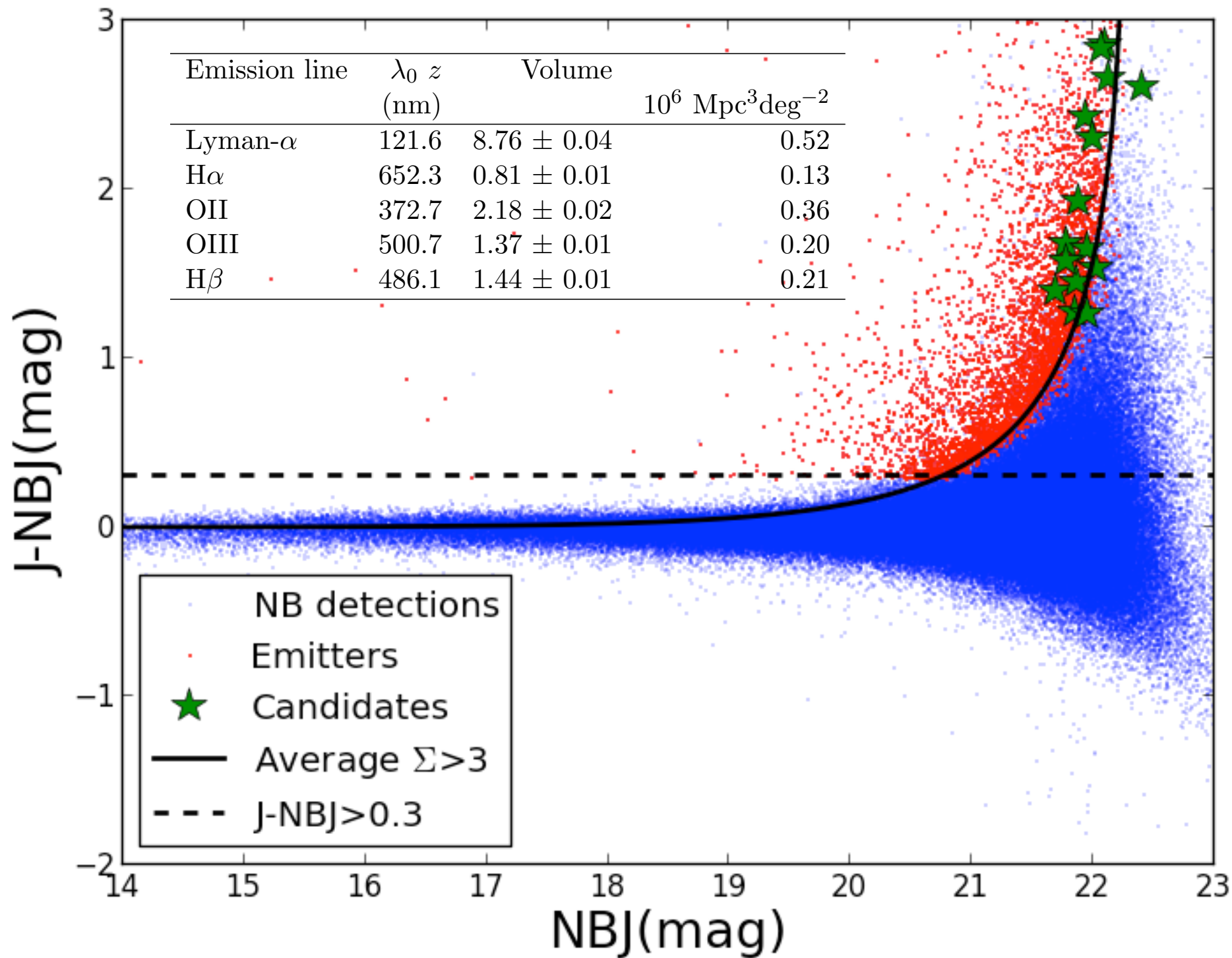
# Conclusions:

last 11 Gyrs

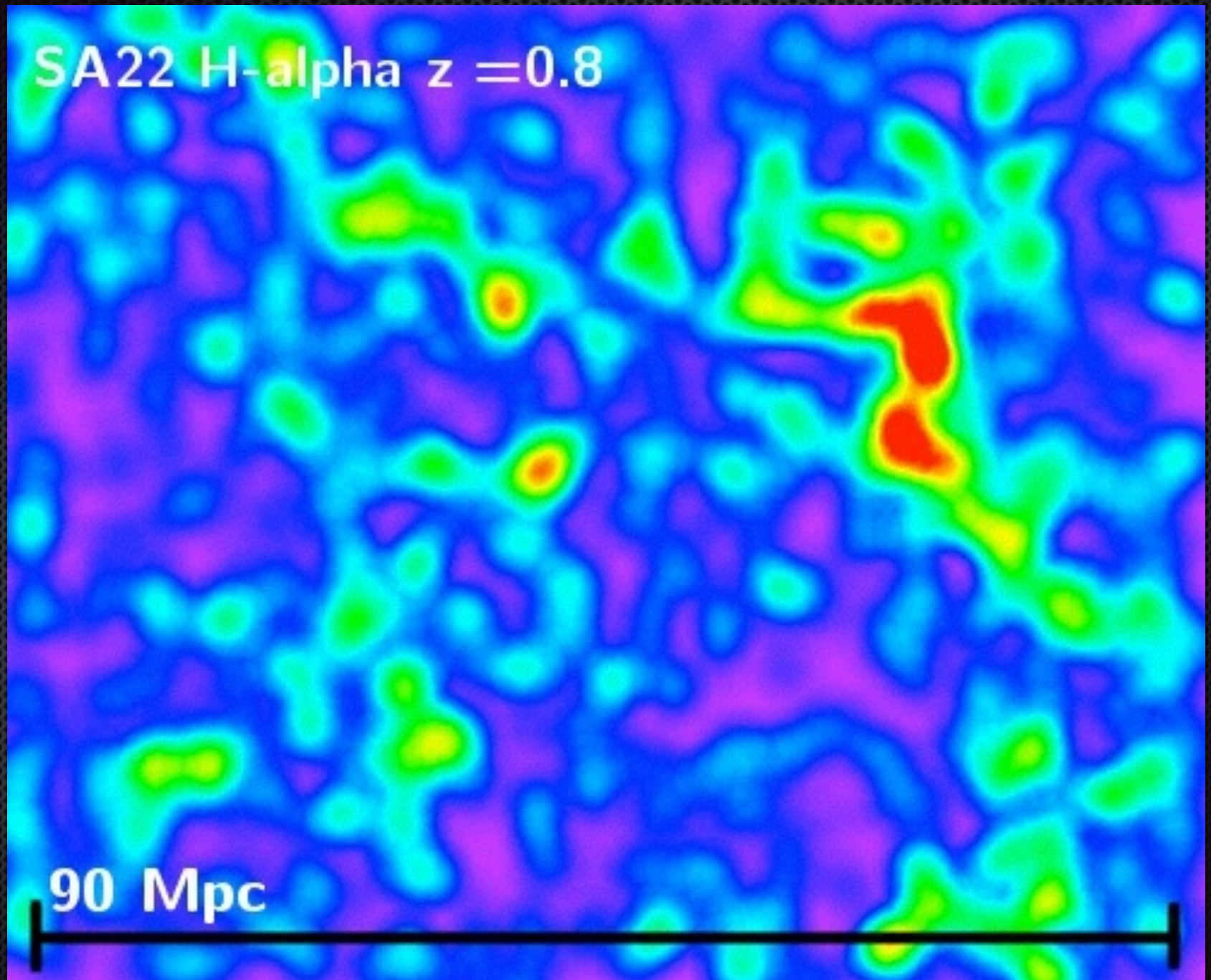
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**Most of claimed “evolution” with redshift is driven by:**

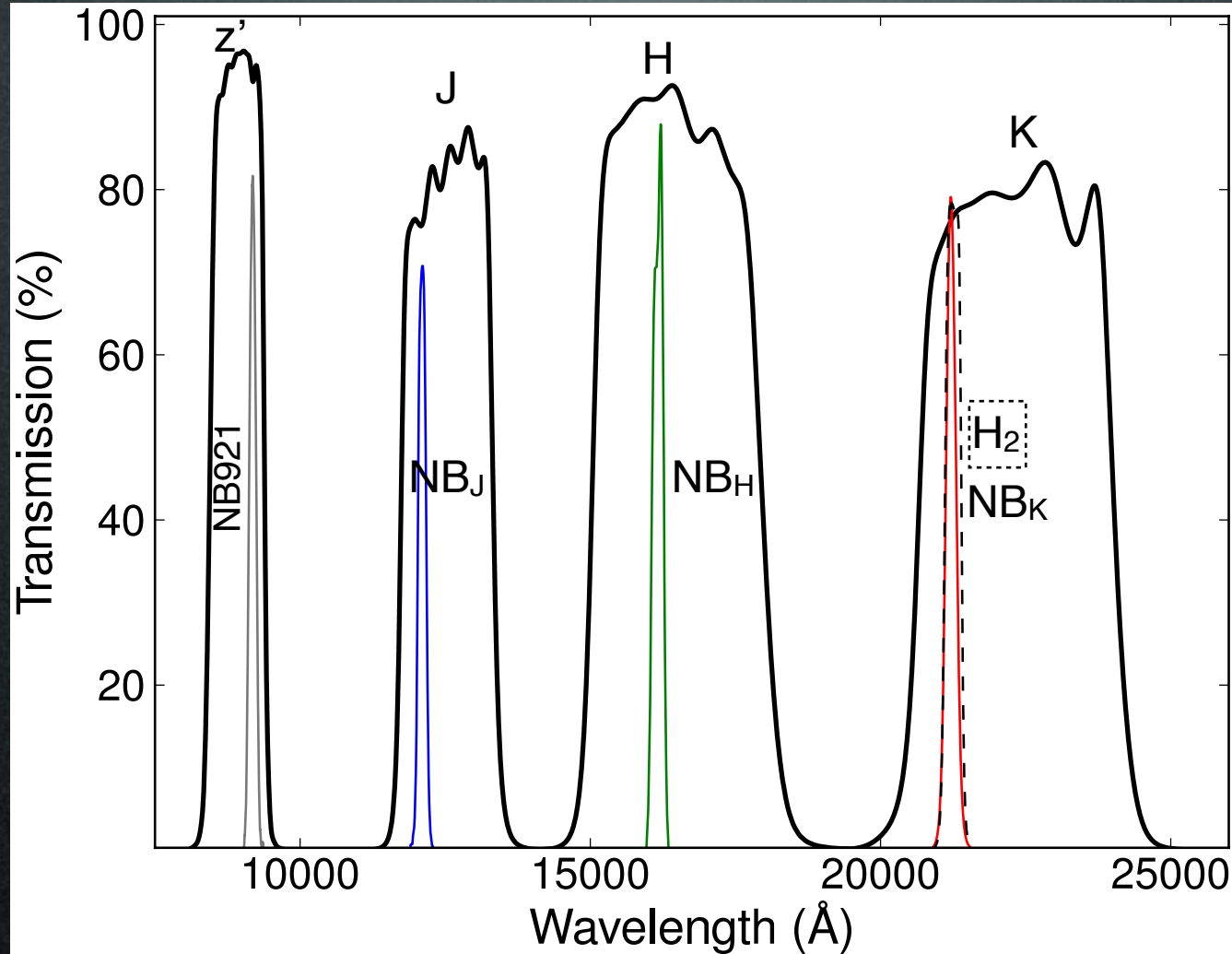
- The evolution of SFR\* (typical SFR( $z$ ))
- Selection effects + not comparing like with like



# CFHT/WIRcam survey



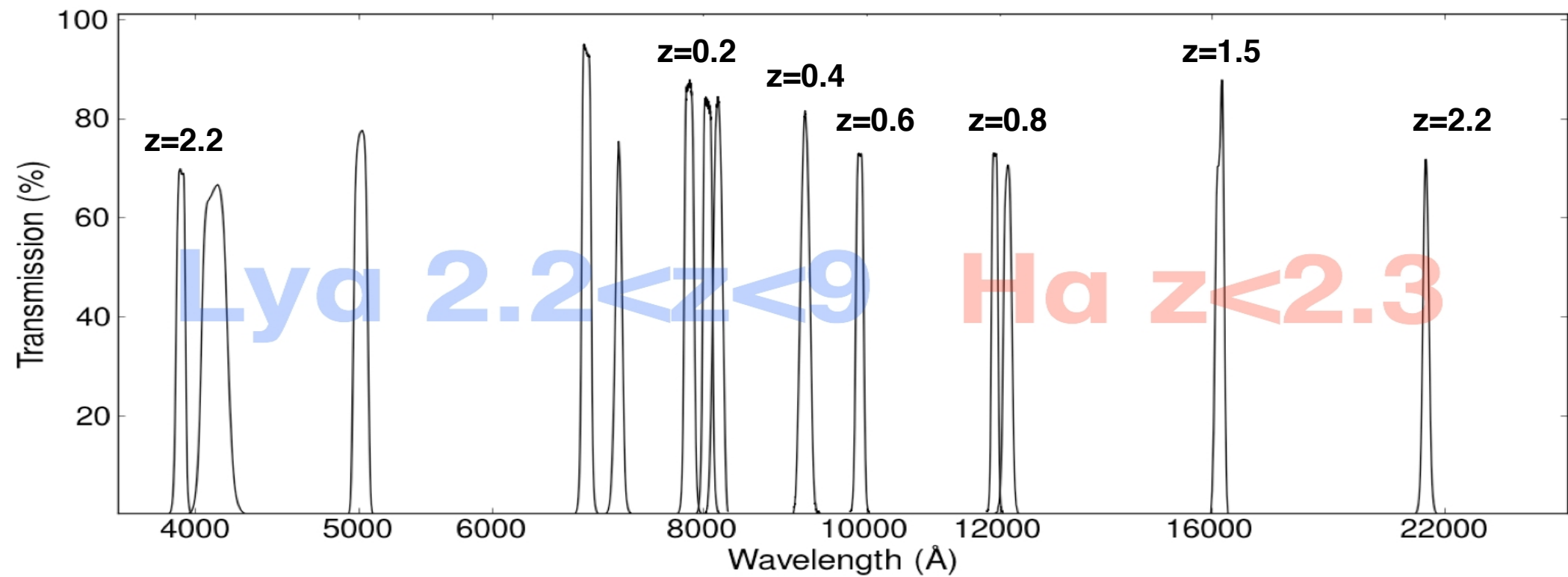
# Filters combined to improve selection: double/triple line detections

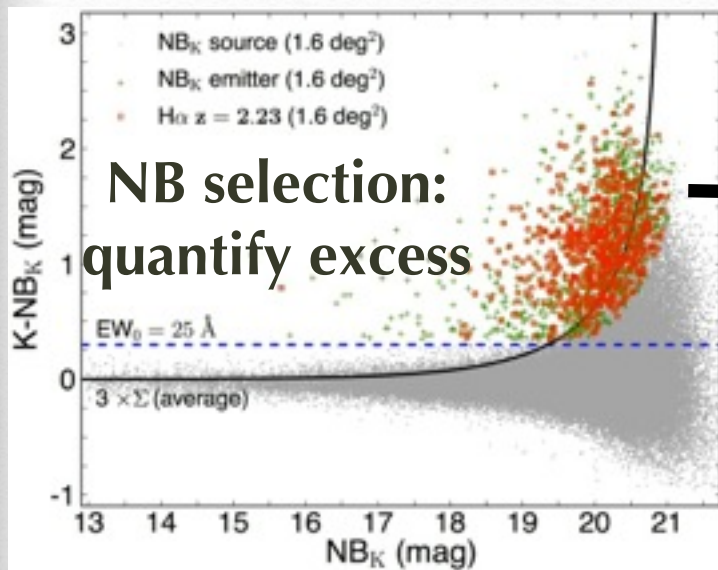


**z=2.23** : **Ly $\alpha$**  (NBm\*) [**OII**] (NB<sub>J</sub>), [**OIII**] (NB<sub>H</sub>), **H $\alpha$**  (NB<sub>K</sub>)

**z=1.47** : [**OII**] (NB921), **H $\beta$**  (NB<sub>J</sub>), **H $\alpha$**  (NB<sub>H</sub>)

**z=0.84** : [**OIII**] (NB921), **H $\alpha$**  (NB<sub>J</sub>)



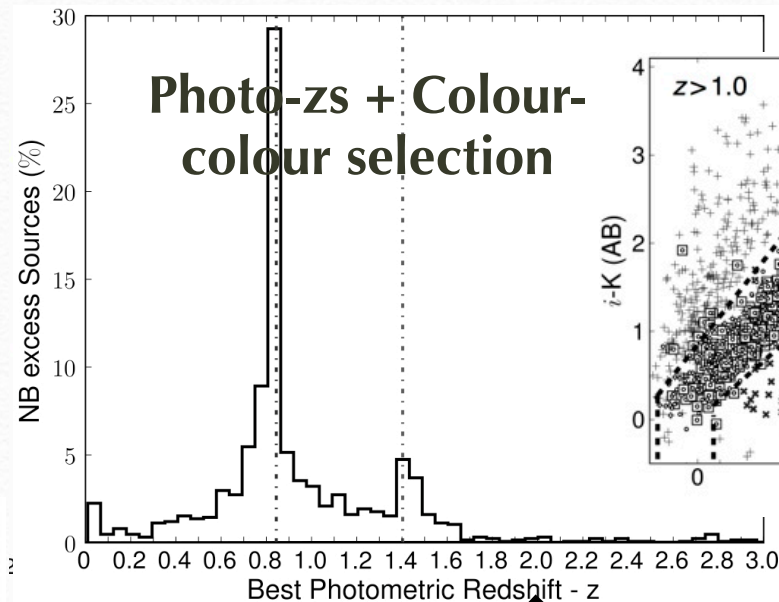


**NB selection:  
quantify excess**

**Source extraction**

**Potential line emitters**

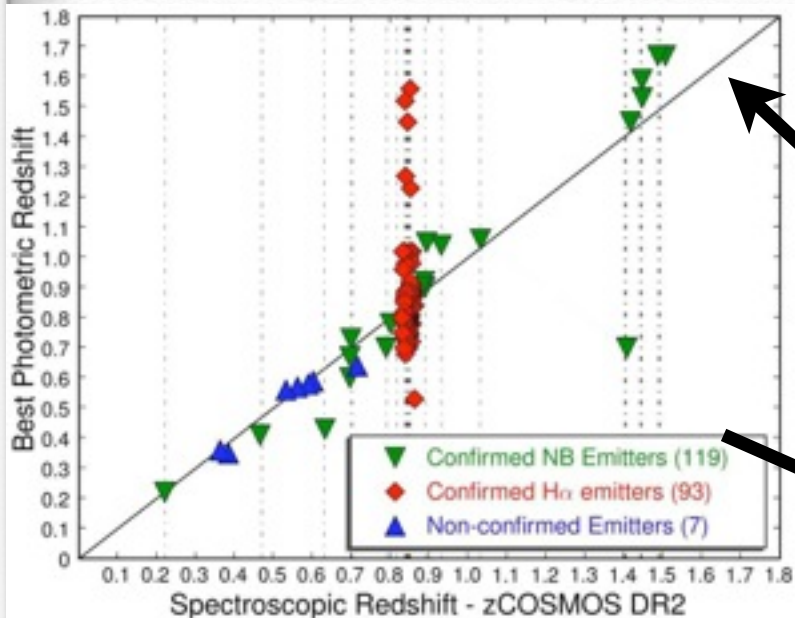
**Which emission line?**



**Photo-zs + Colour-  
colour selection**

**Spectro-z confirmation**

**Double-line confirmation**



**Select  $H\alpha$  emitters**

**Samples >90-95% complete,  
<5-10% contamination**

# Observations

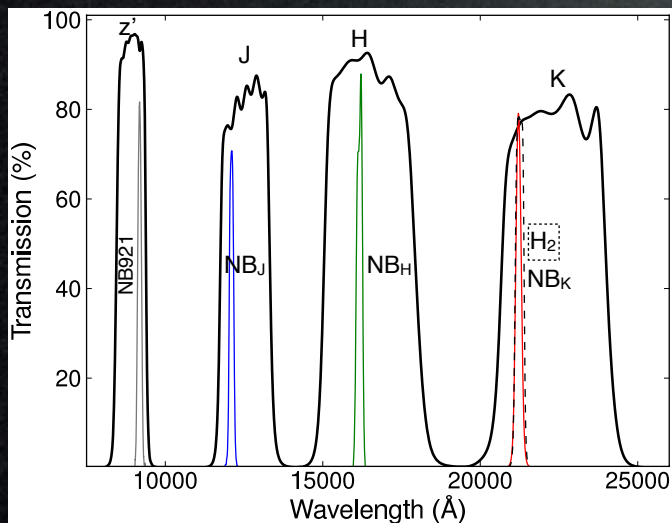
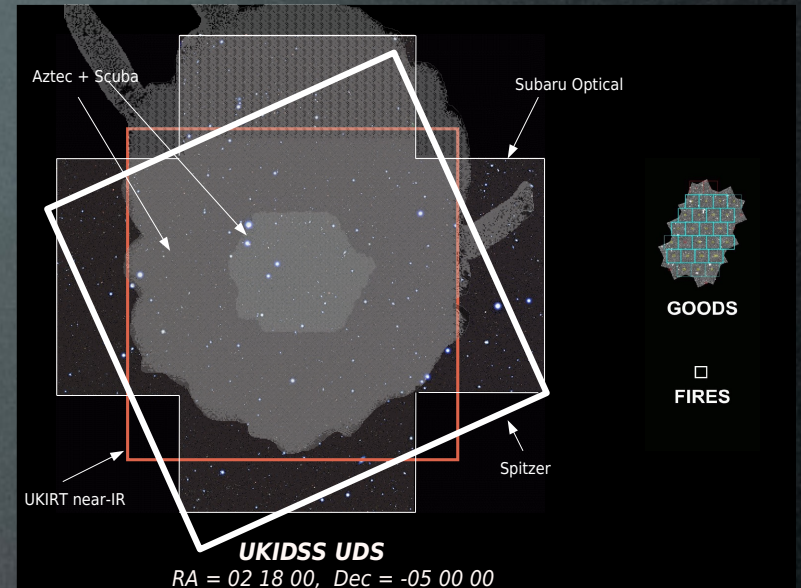
COSMOS + UDS

2 deg<sup>2</sup>

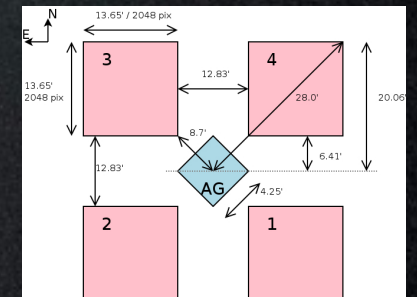
UKIRT/WFCAM: 25 nights

VLT/HAWK-I: 3 nights

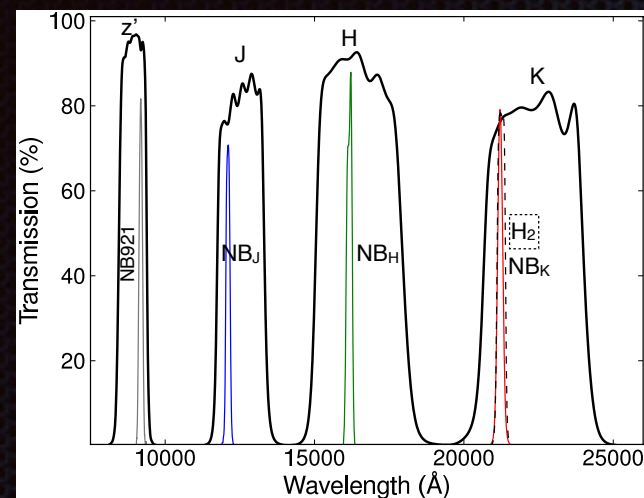
Subaru/Suprime-cam: 5 nights



	A	B	A	B	
E <sub>i</sub>	3	4+E	3+G	4	G
F <sub>i</sub>	1+A	2+B+F	1+A+H	2+B	H
E <sub>i</sub>	3+C	4+D+E	3+C+G	4+D	G
F <sub>i</sub>	1	2+F	1+H	2	H
13.5"	C	D	C	D	N
COSMOS	10:00:28.6 +02:12:21.0				E



Sobral et al. 2013



NB filter	$\lambda_c$ ( $\mu\text{m}$ )	FWHM ( $\text{\AA}$ )	$z \text{ H}\alpha$	Volume ( $\text{H}\alpha$ ) ( $10^4 \text{ Mpc}^3 \text{ deg}^{-2}$ )
NB921	0.9196	132	$0.401 \pm 0.010$	5.13
NB <sub>J</sub>	1.211	150	$0.845 \pm 0.015$	14.65
NB <sub>H</sub>	1.617	211	$1.466 \pm 0.016$	33.96
NB <sub>K</sub>	2.121	210	$2.231 \pm 0.016$	38.31
HAWK-I H <sub>2</sub>	2.125	300	$2.237 \pm 0.023$	<b>54.70</b>

**~16 kpc apertures  $z=0.4-2.23$**

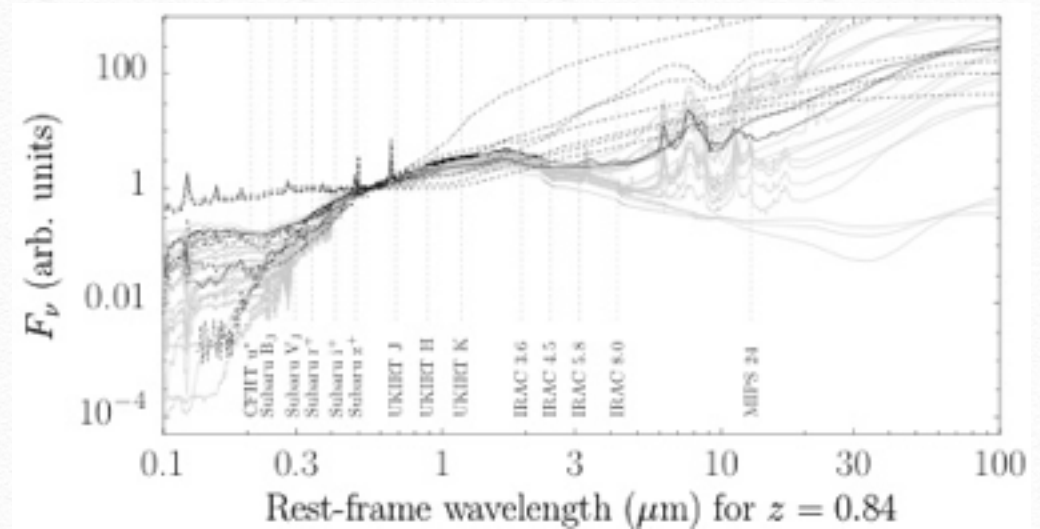
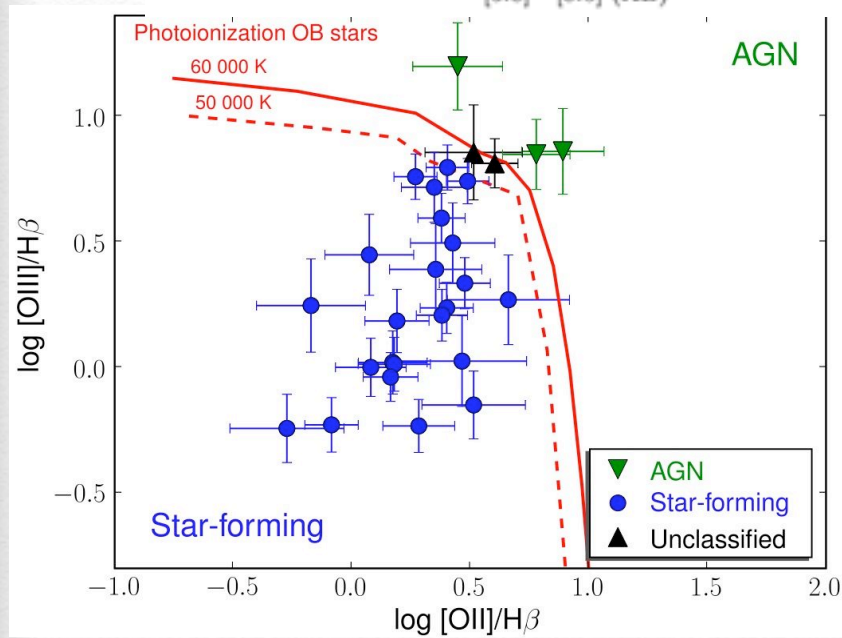
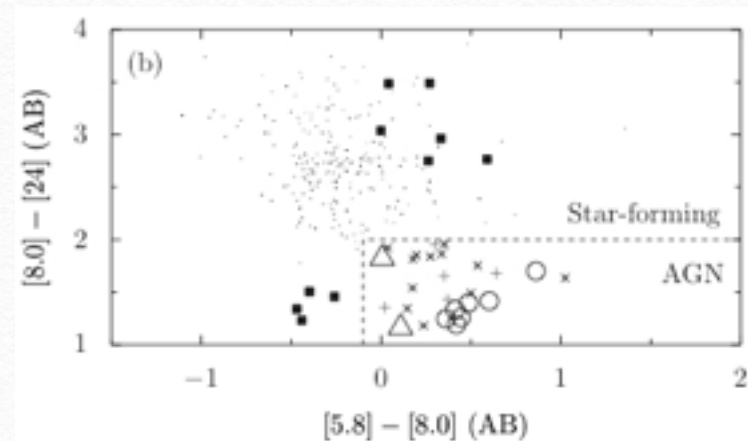
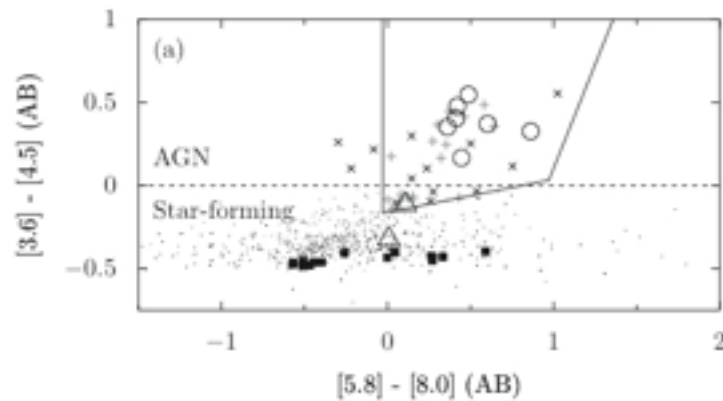
Redshift	Limit SFR	Volumes (UDS + COSMOS)
<b><math>0.401 \pm 0.010</math></b>	<b>0.01</b>	<b><math>\sim 1 \times 10^5 \text{ Mpc}^3</math></b>
<b><math>0.845 \pm 0.015</math></b>	<b>1.5</b>	<b><math>\sim 2 \times 10^5 \text{ Mpc}^3</math></b>
<b><math>1.466 \pm 0.016</math></b>	<b>3.0</b>	<b><math>\sim 8 \times 10^5 \text{ Mpc}^3</math></b>
<b><math>2.231 \pm 0.016</math></b>	<b>3.5</b>	<b><math>\sim 7 \times 10^5 \text{ Mpc}^3</math></b>

**$z=0.4-2.23$**

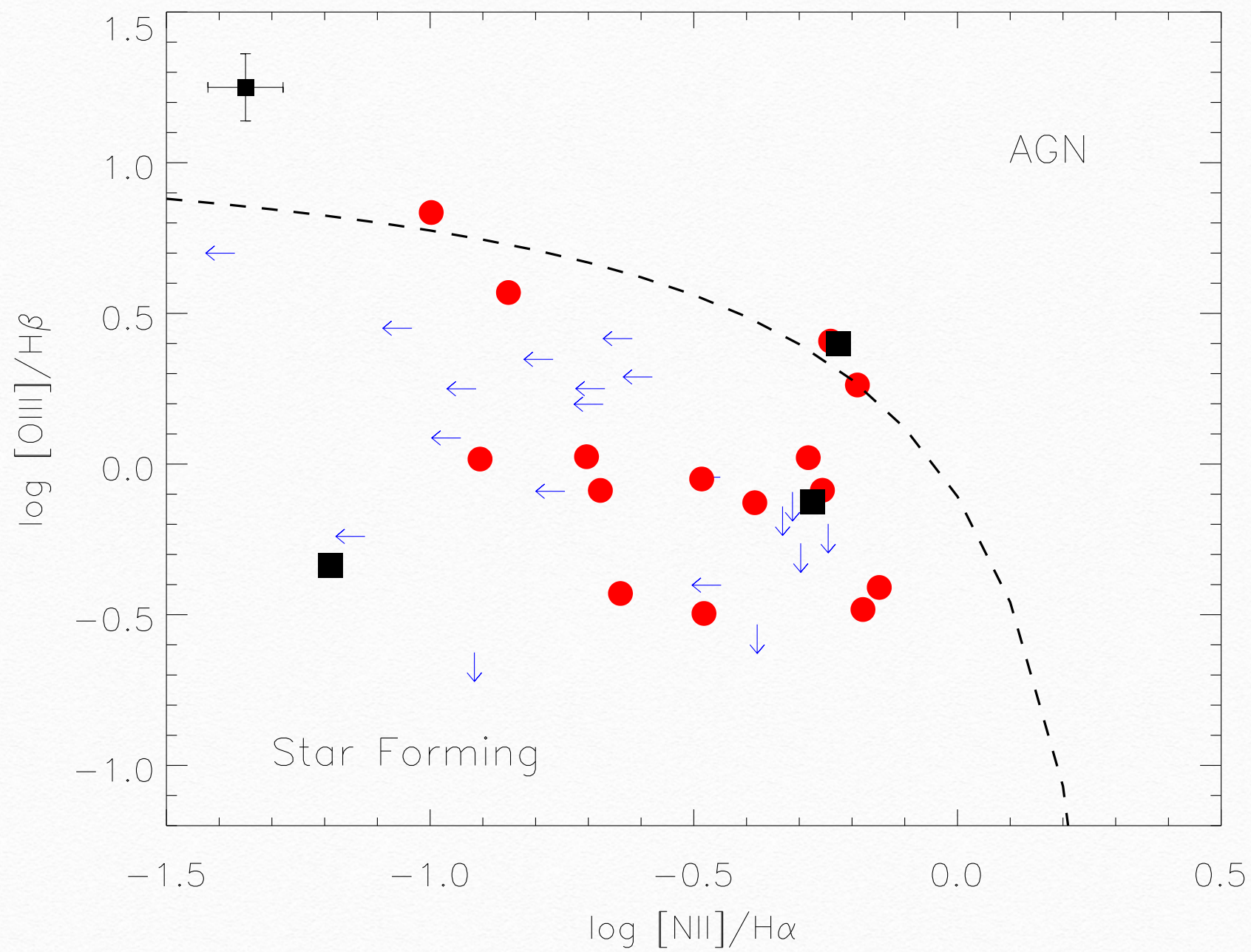
$$\Sigma > 3, EW_{(\text{Ha} + [\text{NII}])} > 25 \text{ \AA}$$

# AGN

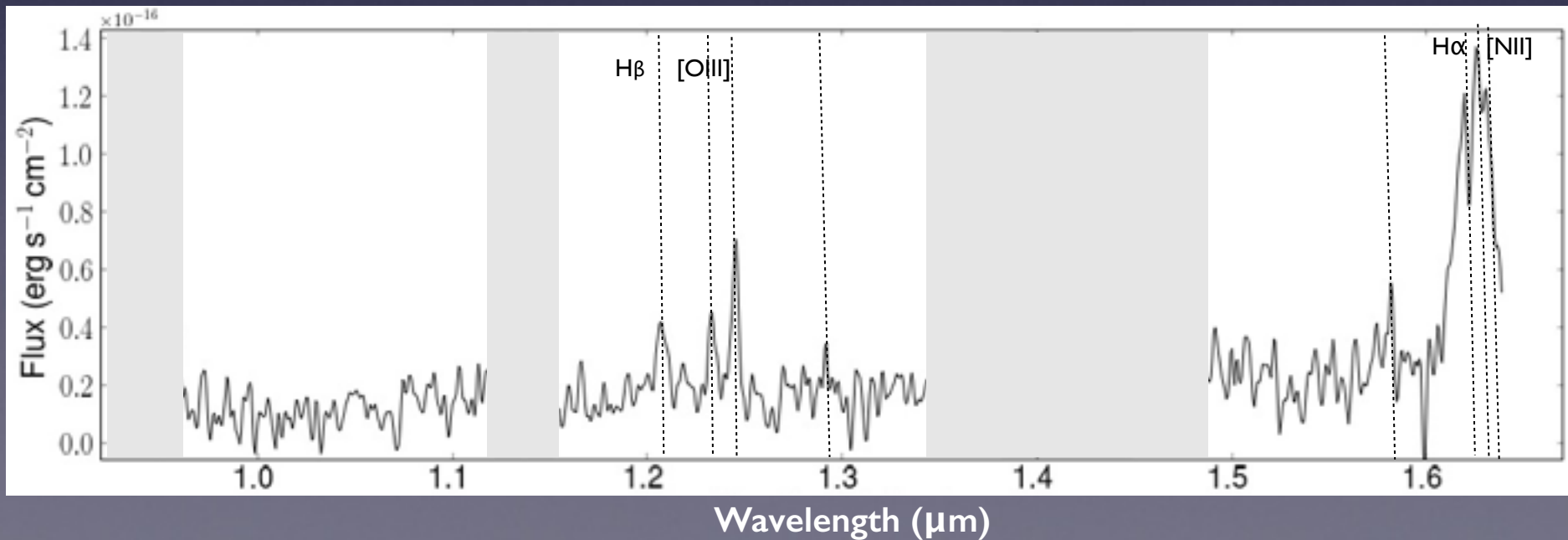
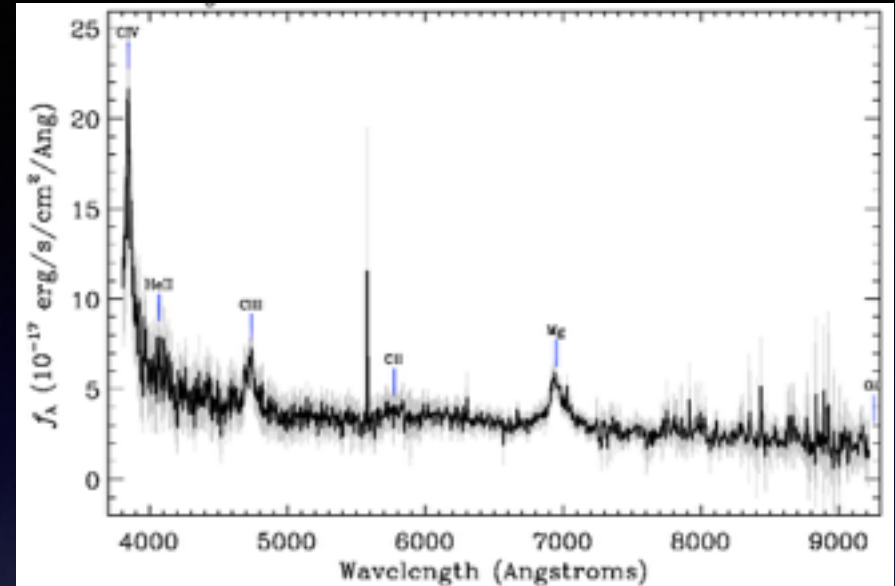
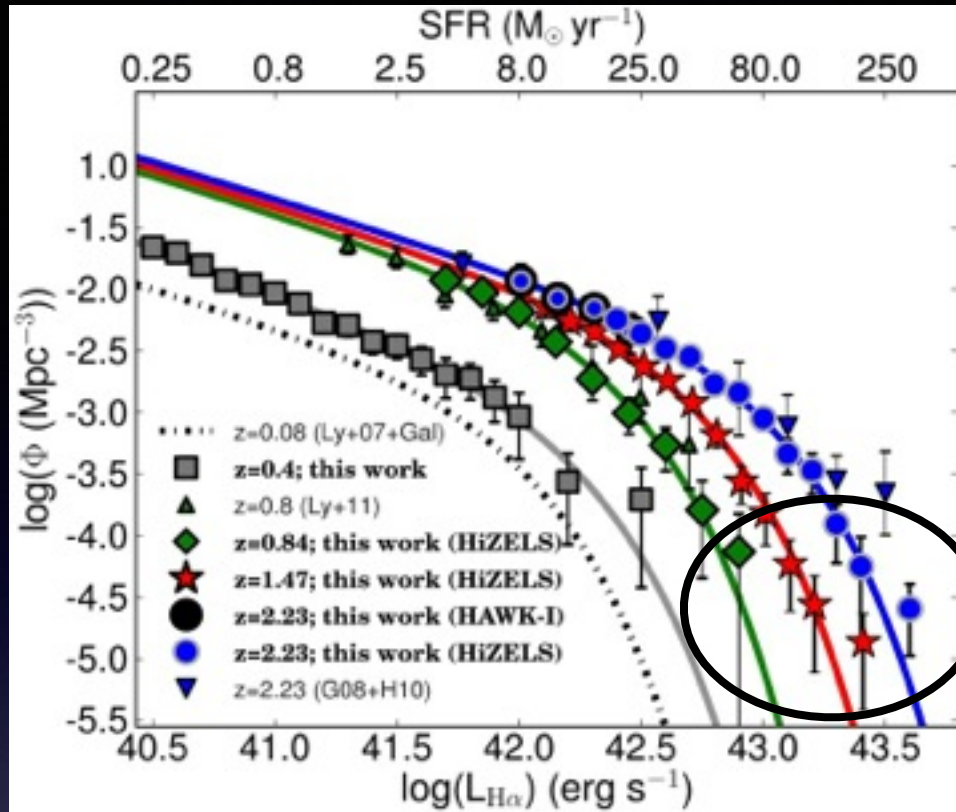
Garn et al. 2010

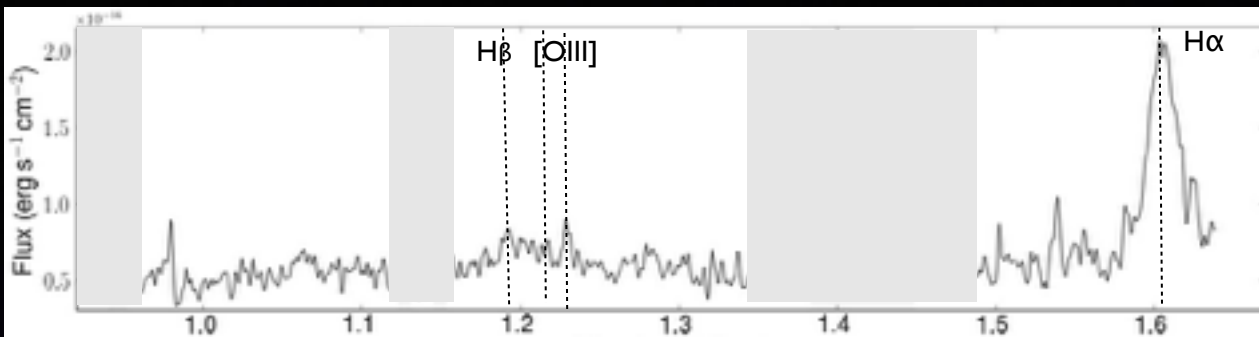


- Emission-line ratios (optical spectroscopy)+ X-rays+ radio+ mid-infrared colours+ SED fitting: ~10% of H $\alpha$  emitters at  $z=0.84$  are AGN.

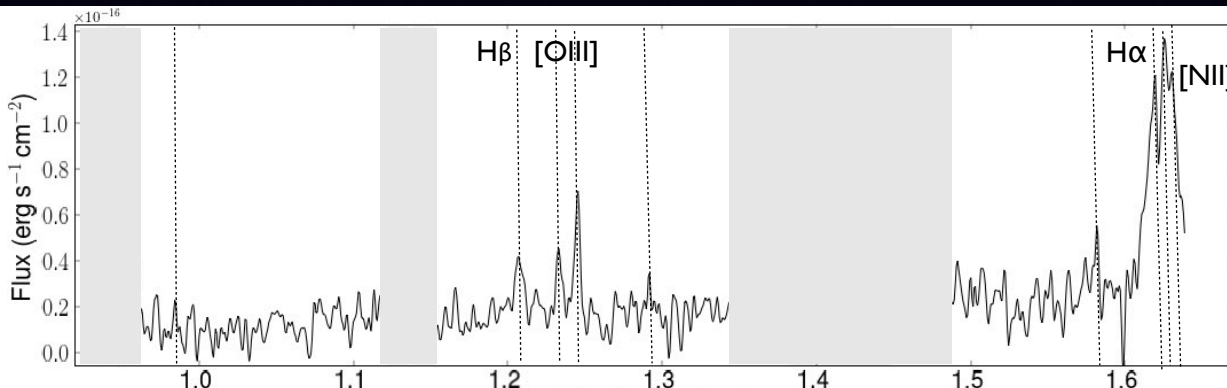


# Subaru FMOS + NTT + WHT

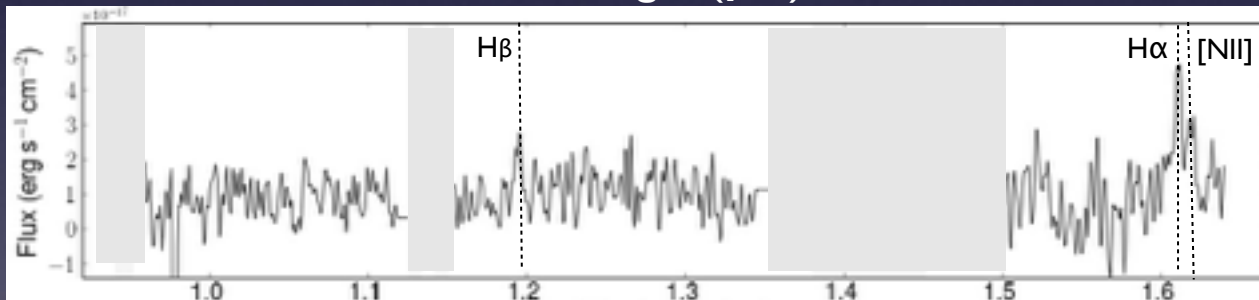




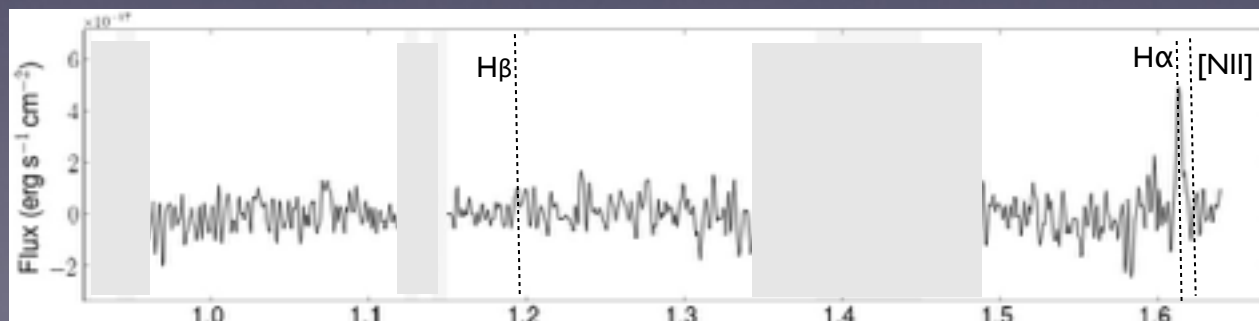
Wavelength ( $\mu\text{m}$ )



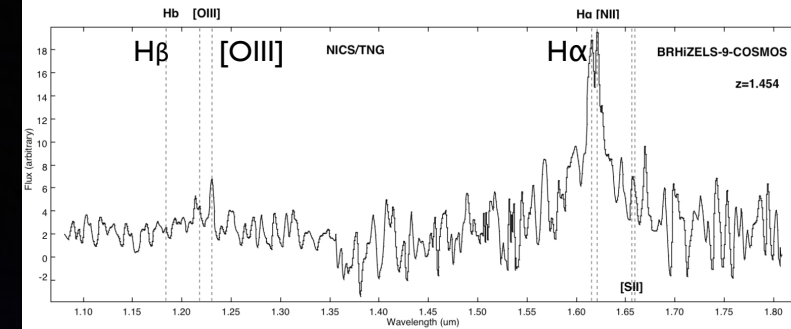
Wavelength ( $\mu\text{m}$ )



Wavelength ( $\mu\text{m}$ )



Wavelength ( $\mu\text{m}$ )



H $\alpha$  Luminosity  $z=1.47$

Broad-line AGN

AGN dominated

AGN + SF

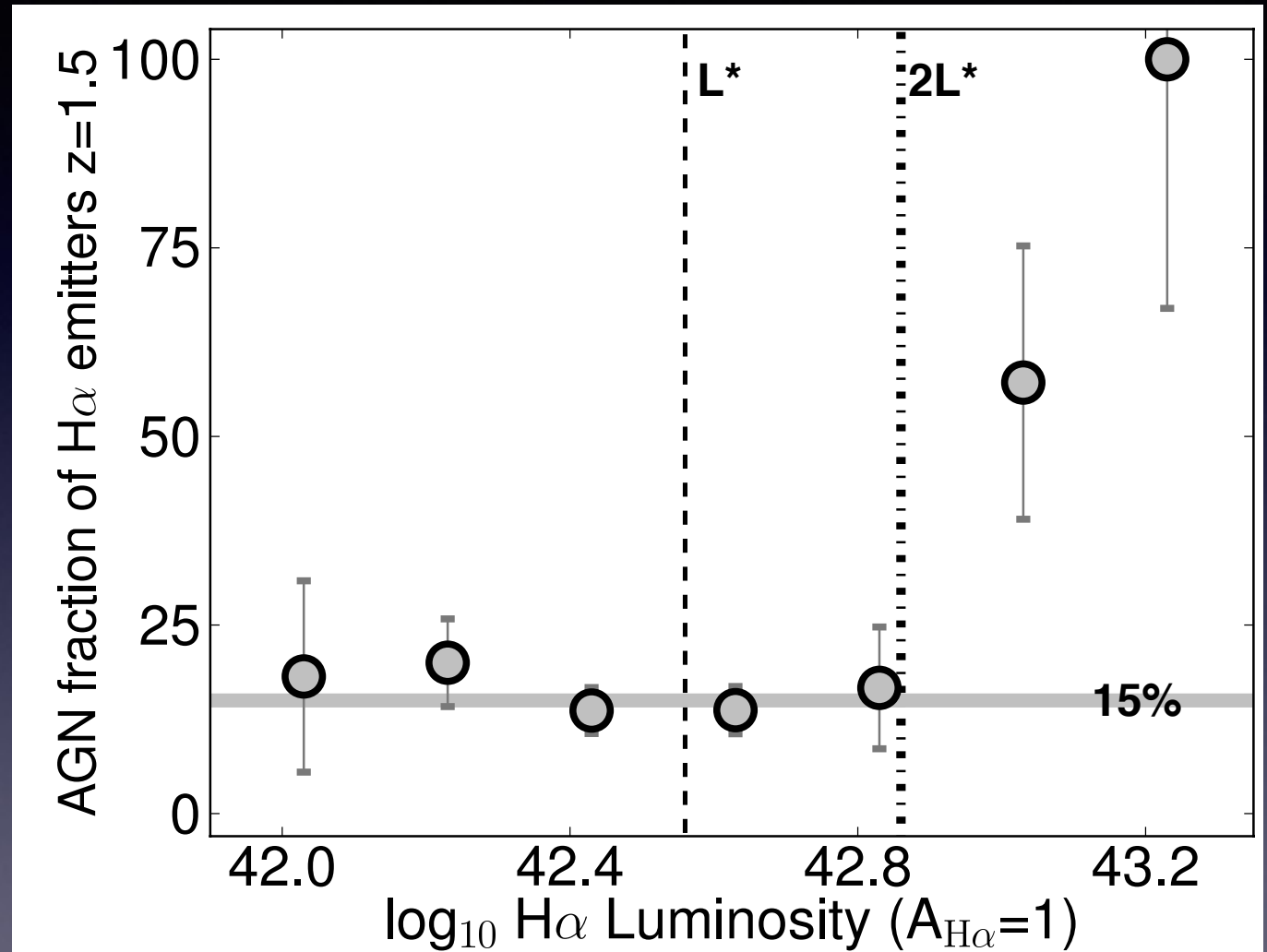
More Metal-rich

More Metal-poor

Star-forming

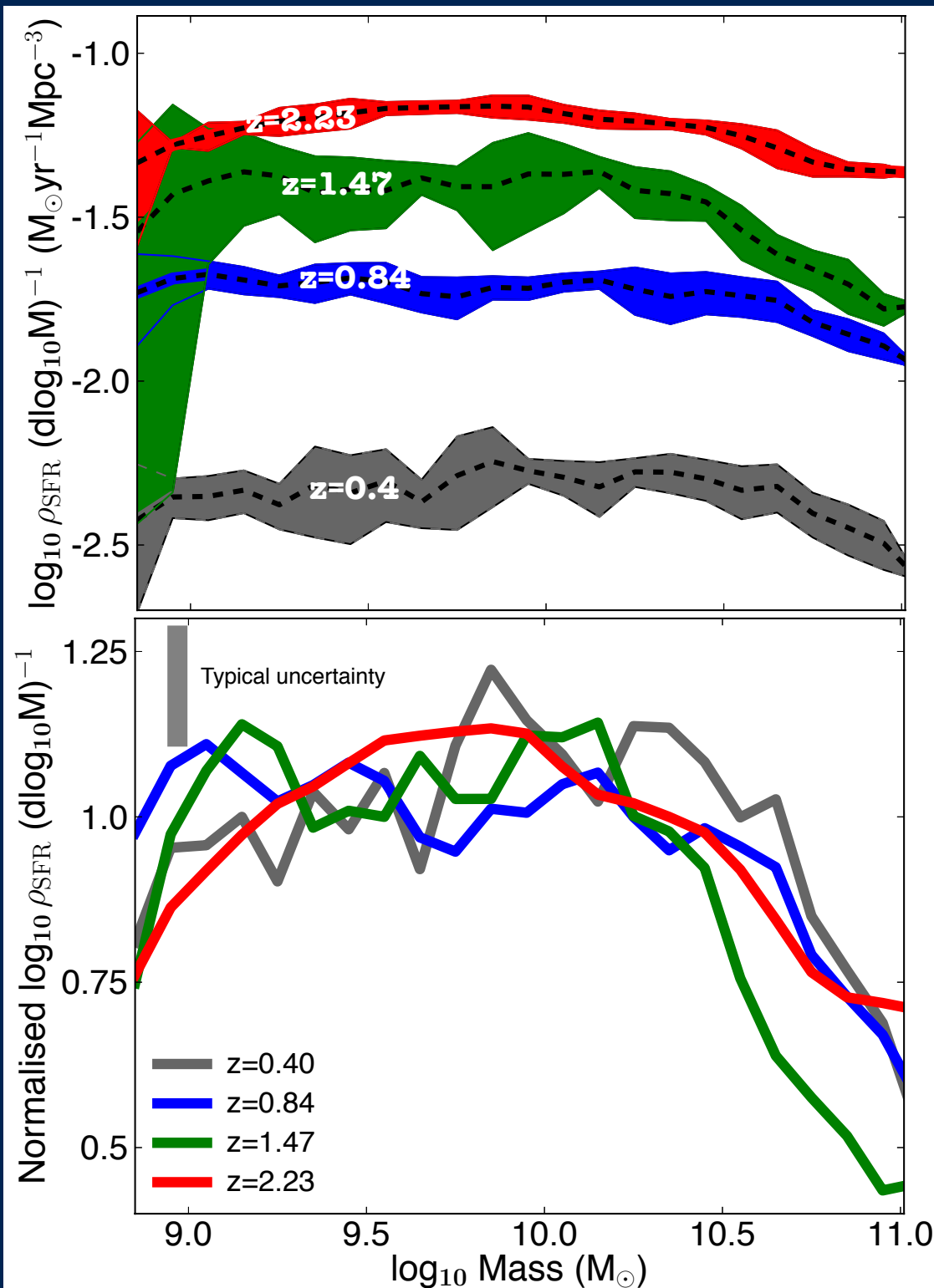
# AGN

- $\sim 10\%$   $z \sim 0.8$
- $\sim 15\%$   $z \sim 1.47$
- $\sim$  Become dominant at  $L > 2L^*$  (H-alpha)



**SFRD per dLogM**

**Normalised**



**Over the last 11 Gyrs**

**Decrease with time**  
**at all masses**

**Tentative peak per**  
**dLogM at  $\sim 10^{10} \text{ M}_{\odot}$**   
**since  $z=2.23$**

**Mostly no evolution**  
**apart from**  
**normalisation**

Sobral et al. (2014)

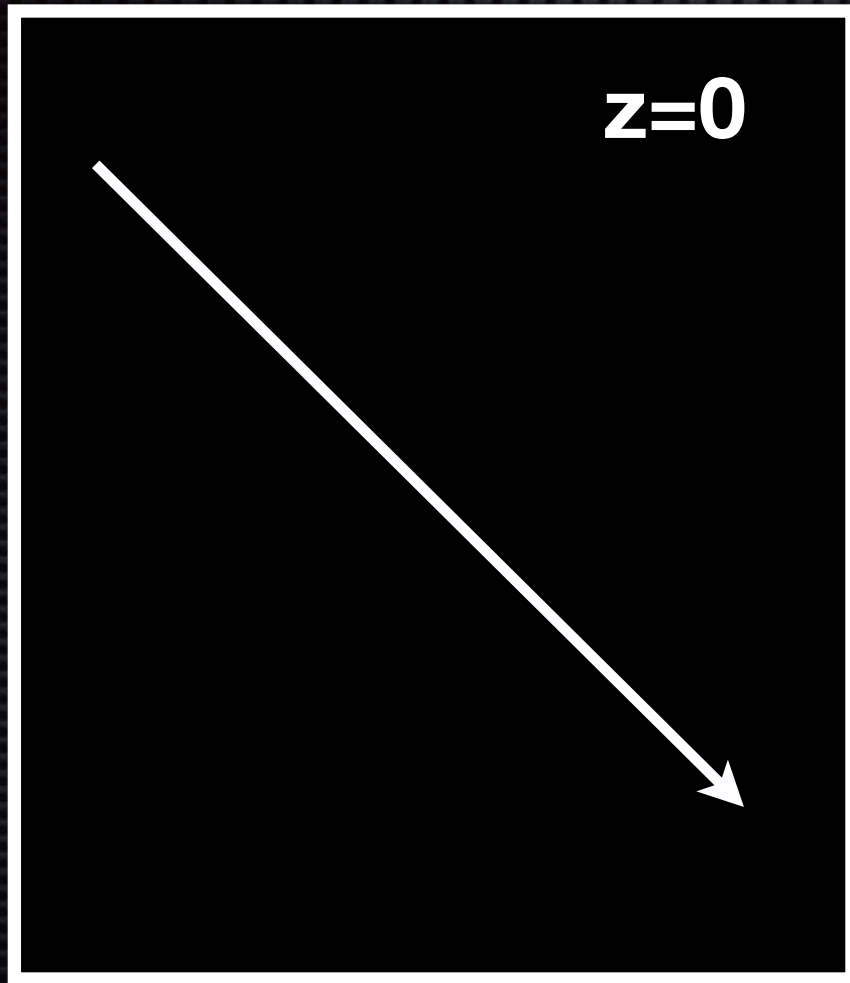
# The Environment at $z \sim 1$

~Field Studies

Cluster+outskirts

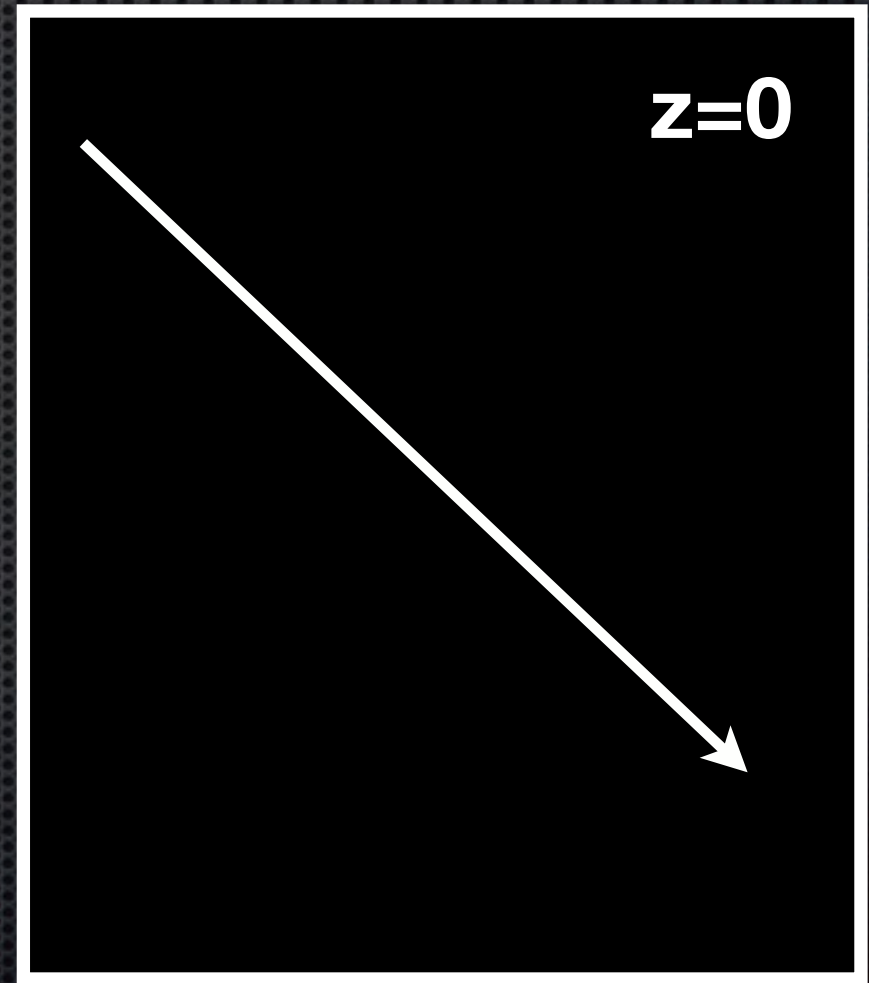
Rich Clusters

Star-forming Fraction



Local Projected Density

Star-formation rate



Local Projected Density

# The Environment at $z \sim 1$

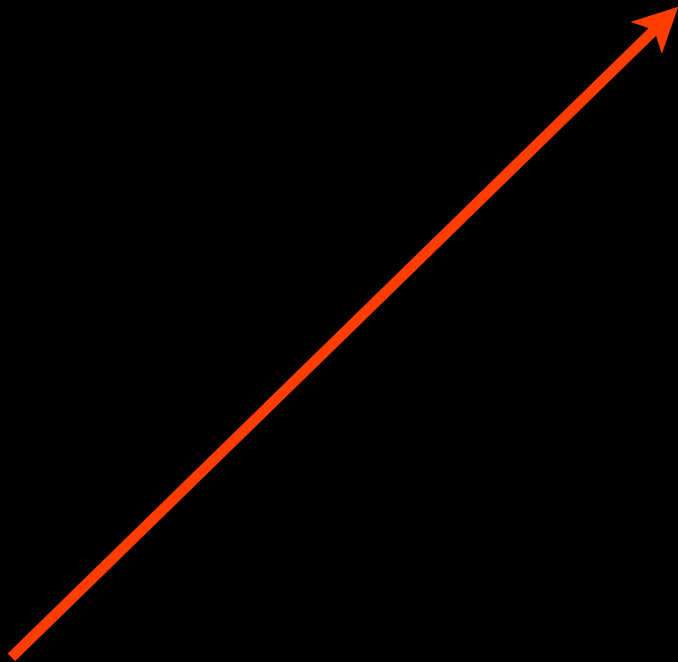
~Field Studies

Cluster+outskirts

Rich Clusters

Star-forming Fraction

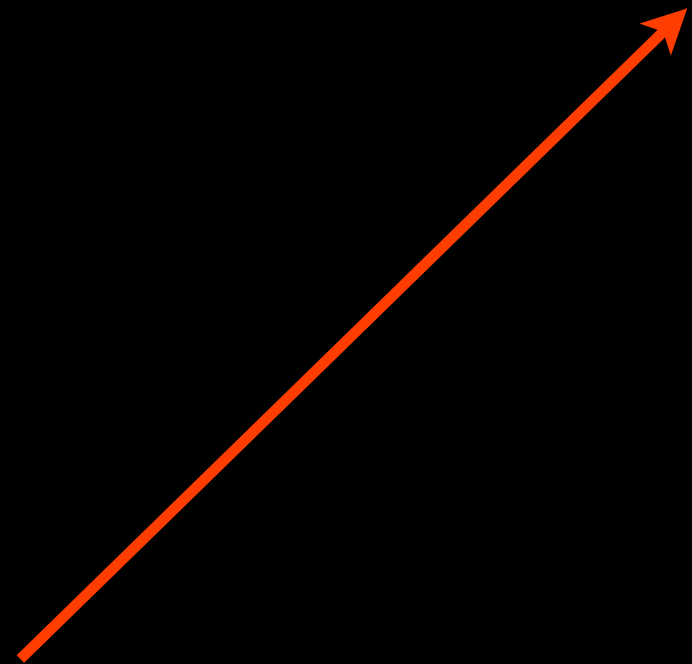
(e.g. Elbaz+07, Ideue+09)



Local Projected Density

Star-formation rate

$z \sim 1$



Local Projected Density

# The Environment at $z \sim 1$

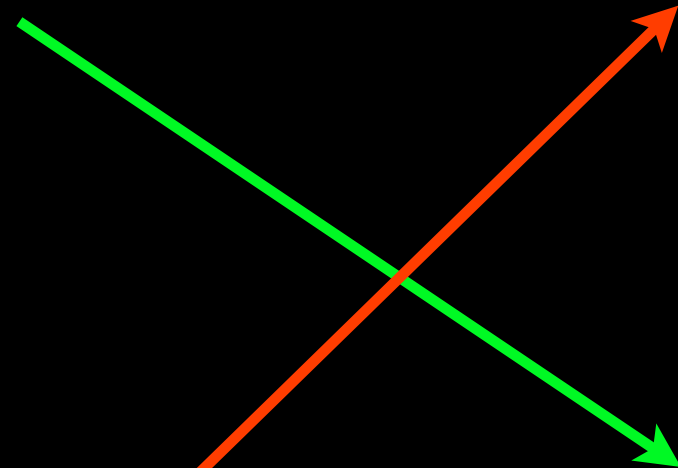
~Field Studies

Cluster+outskirts

Rich Clusters

Star-forming Fraction

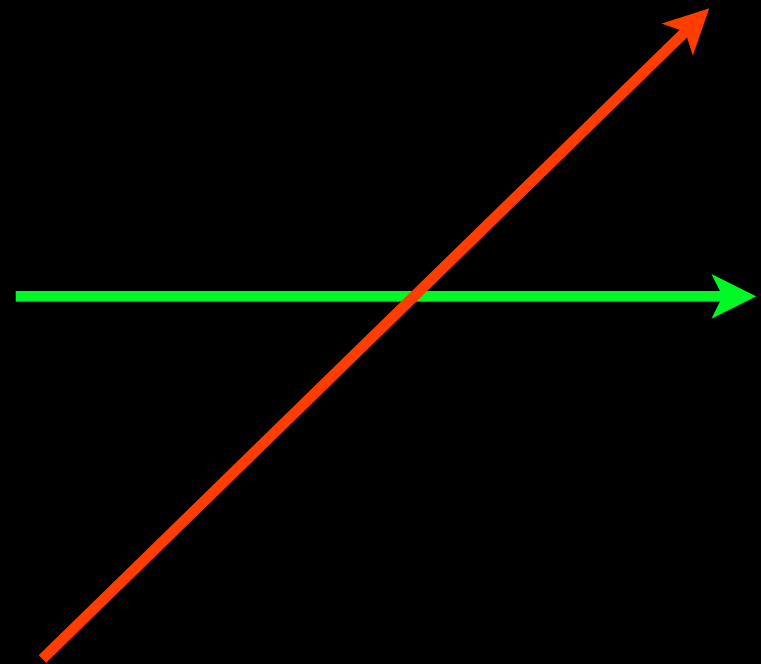
(e.g. Elbaz+07, Ideue+09)  
Koyama+10



Local Projected Density

Star-formation rate

$z \sim 1$



Local Projected Density

# The Environment at $z \sim 1$

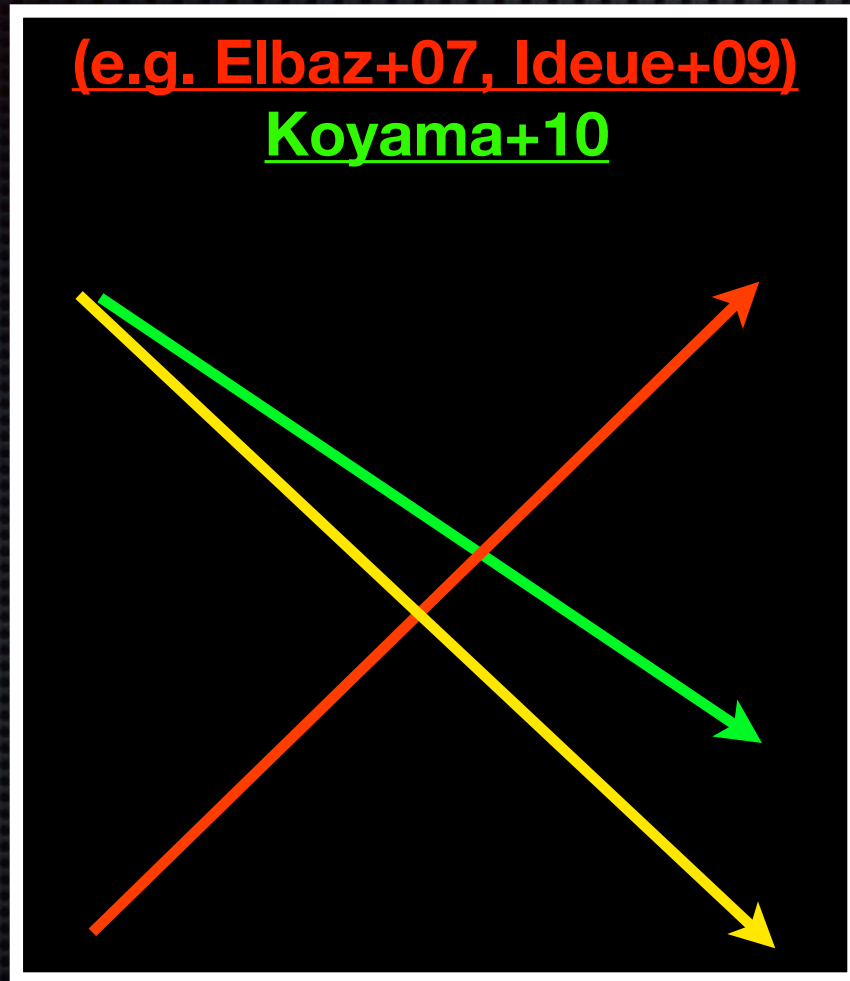
~Field Studies

Cluster+outskirts

Rich Clusters

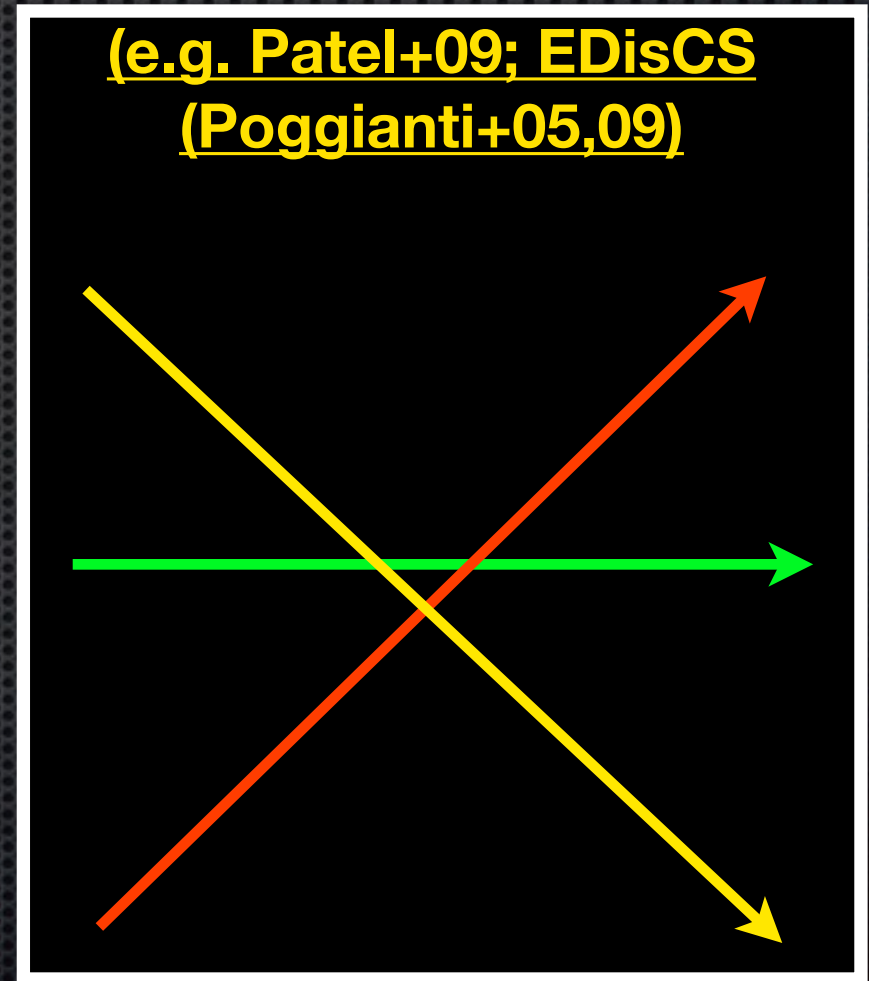
Can we reconcile the apparent contradictions?

Star-forming Fraction



Local Projected Density

Star-formation rate

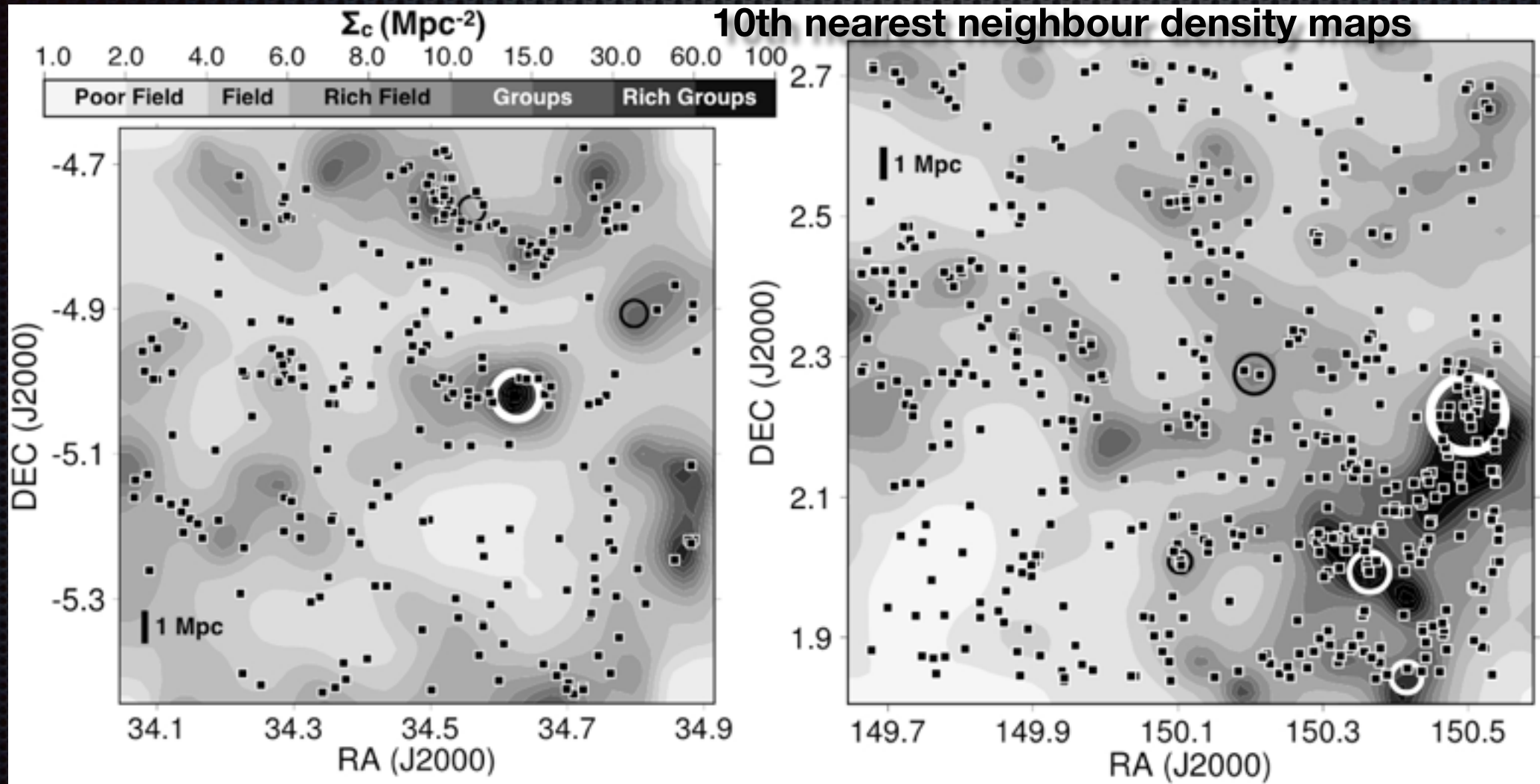


Local Projected Density

# The role of the Environment

- A very wide range of environments - from the fields to a super-cluster (Sobral et al. 2011)

○ X-rays



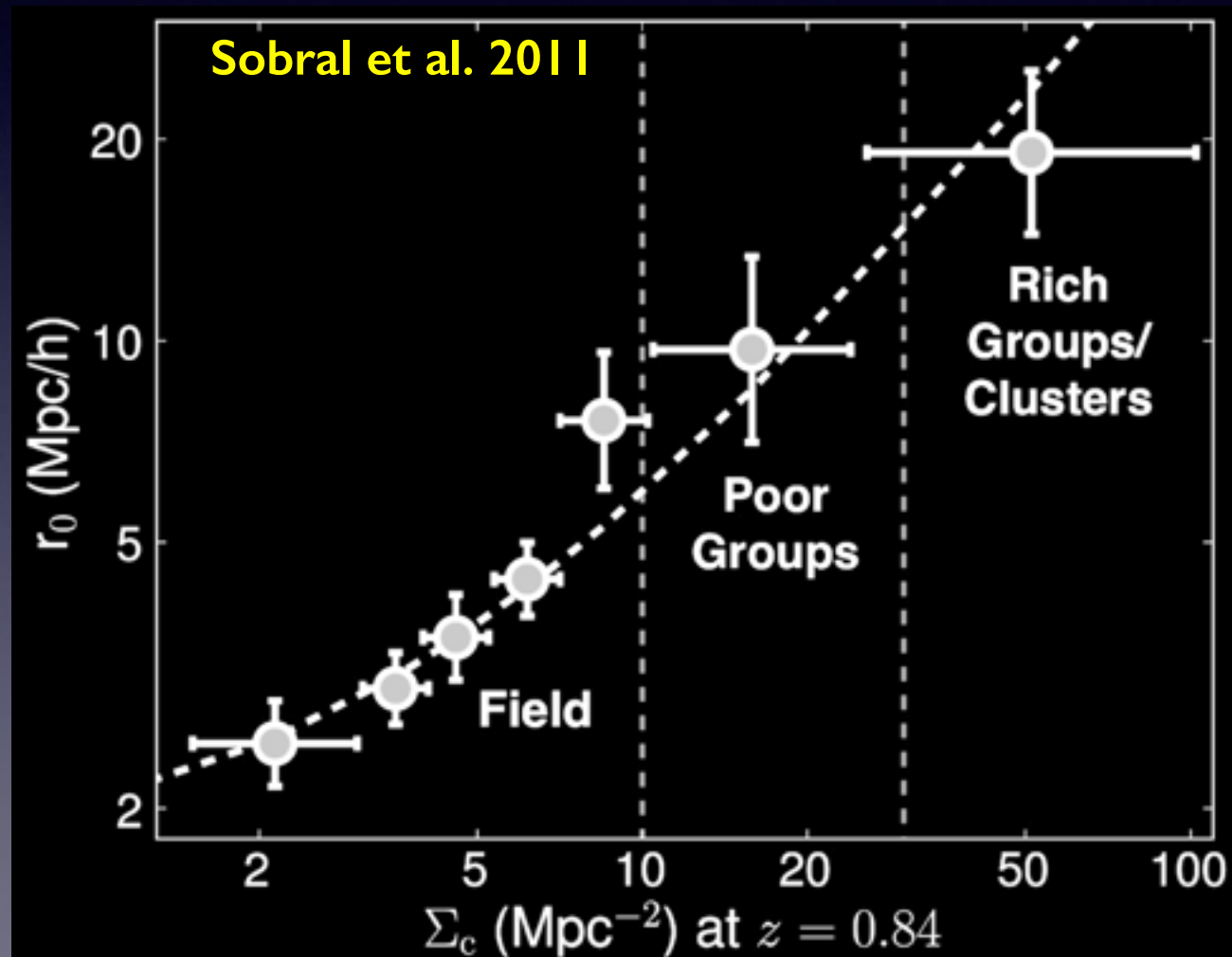
● UKIDSS UDS  $z=0.84$

● COSMOS  $z=0.84$

# The role of the Environment

- Use high quality photo-zs to estimate distance to 10th nearest neighbour  
>> use spect-z to estimate completeness and contamination >> compute corrected local densities

“Calibrate”  
environments in a  
reliable way using the  
accurate clustering  
analysis and real-space  
correlation lengths of  
field, groups and  
clusters



# The Environment at $z \sim 1$

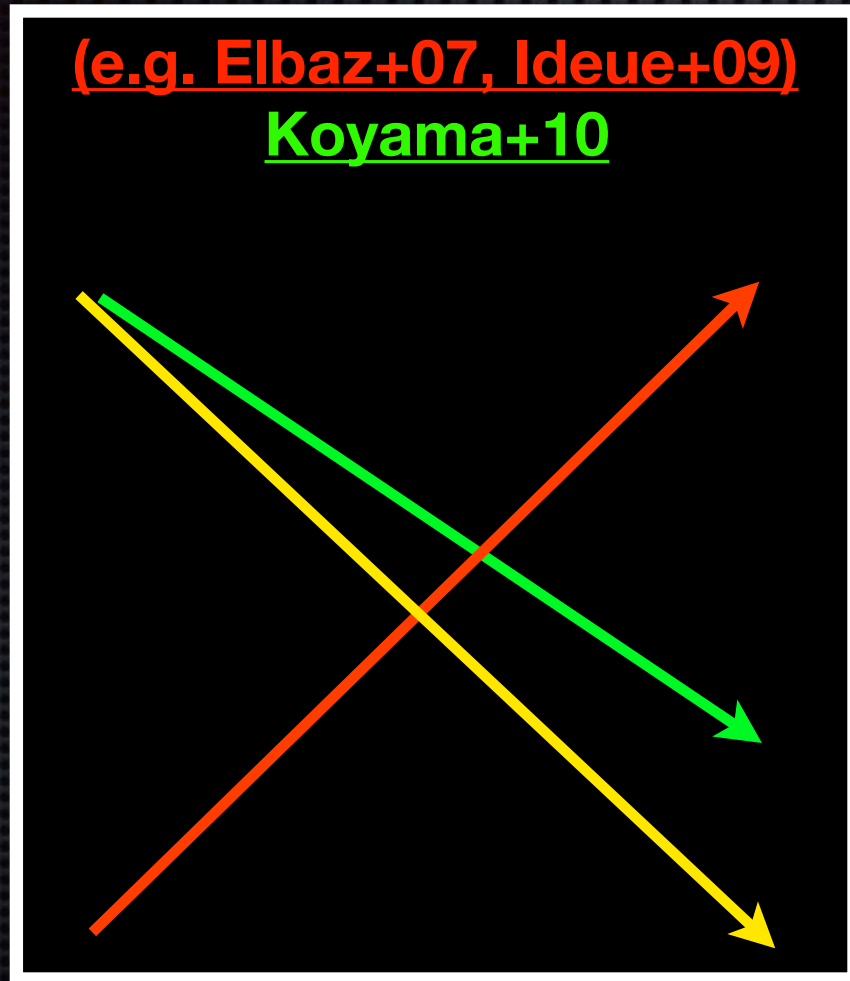
~Field Studies

Cluster+outskirts

Rich Clusters

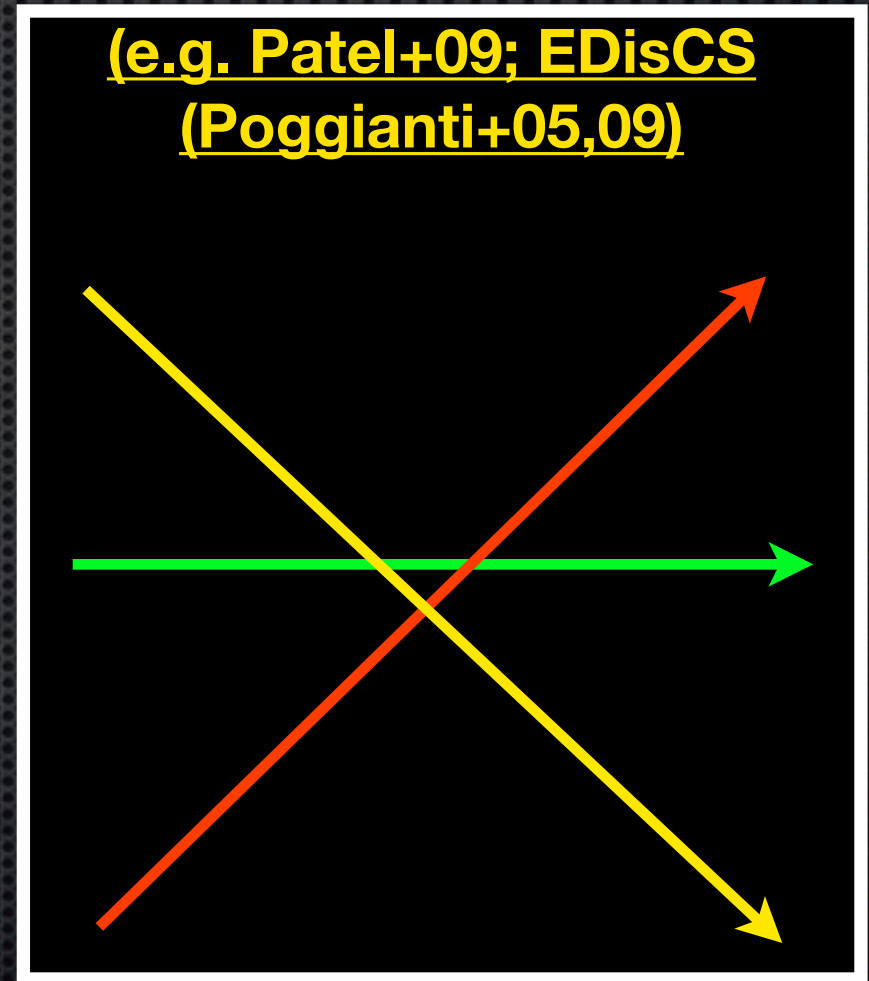
Can we reconcile the apparent contradictions?

Star-forming Fraction



Local Projected Density

Star-formation rate

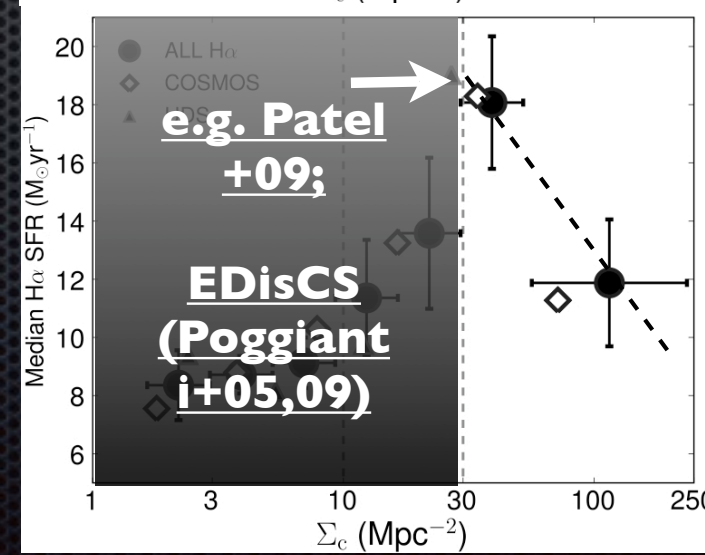
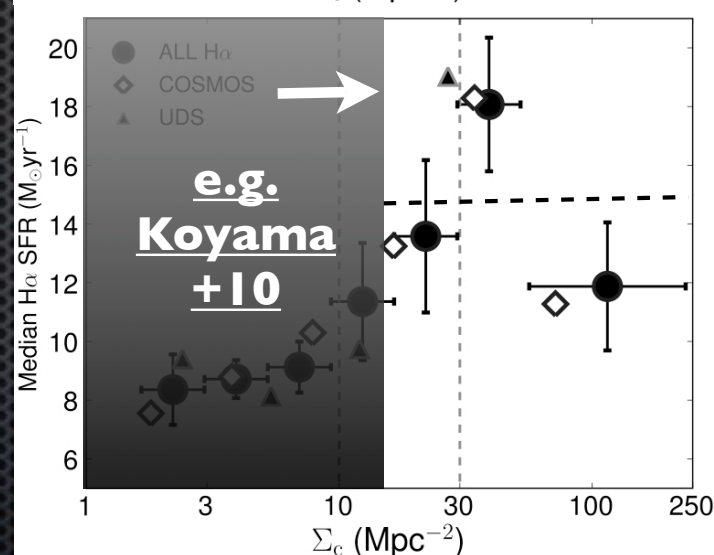
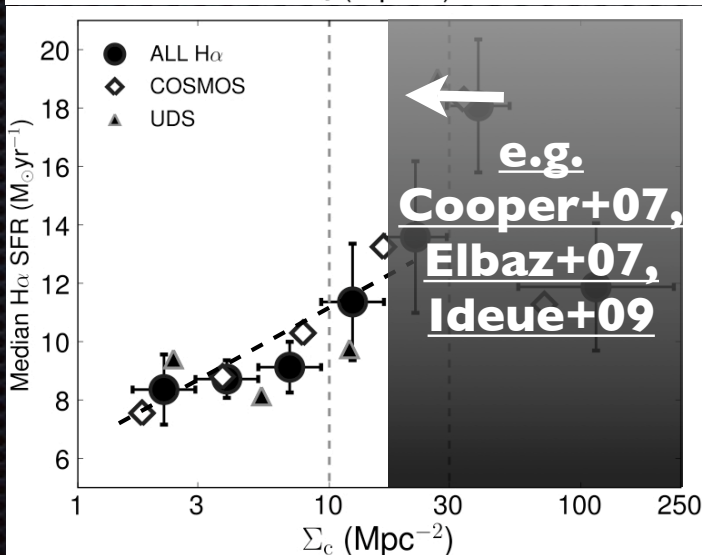
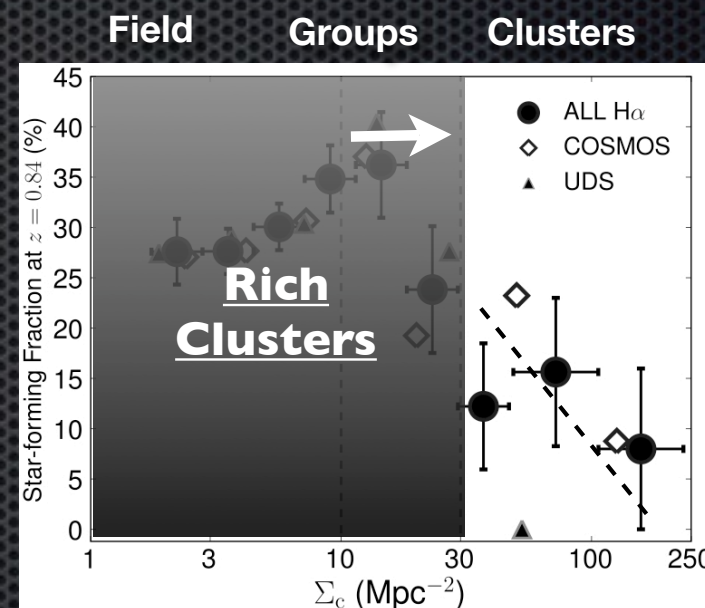
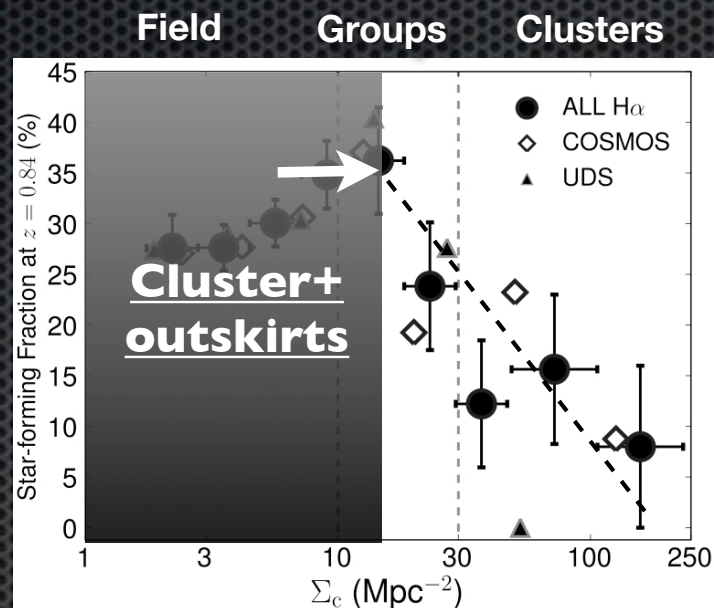
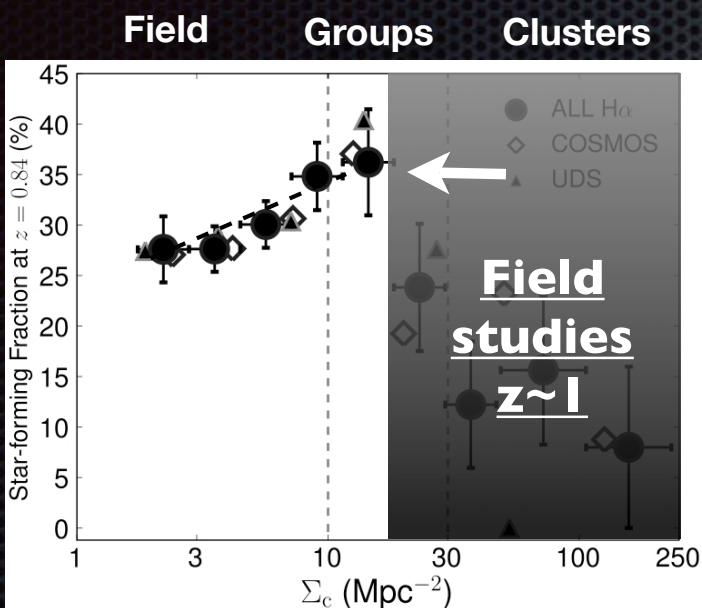


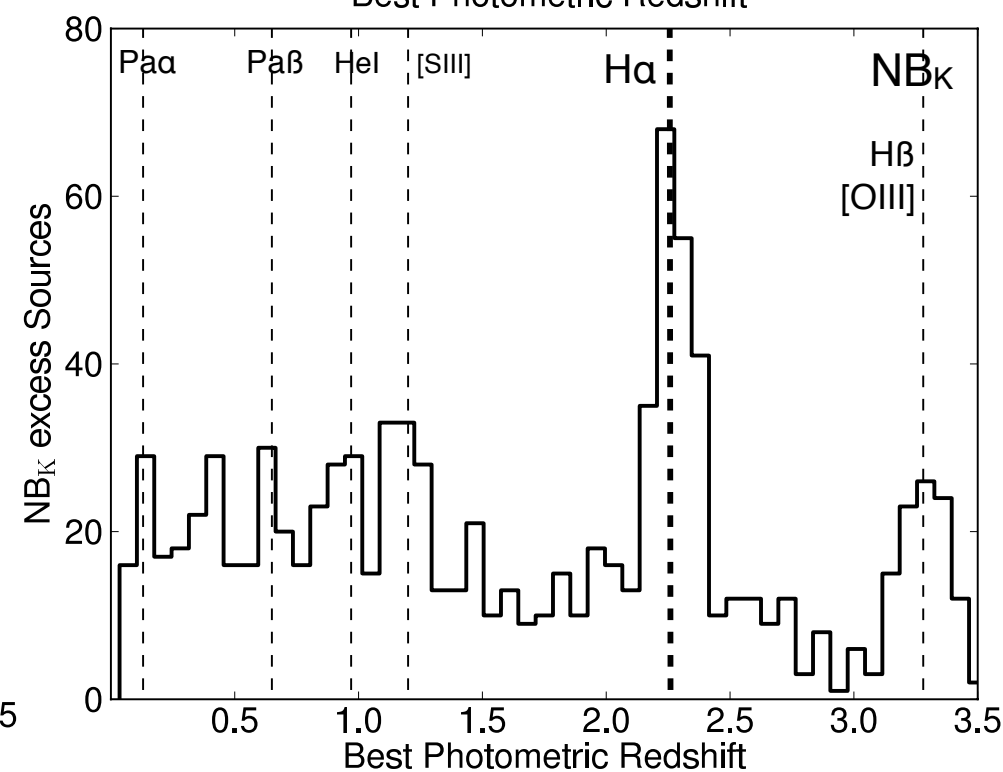
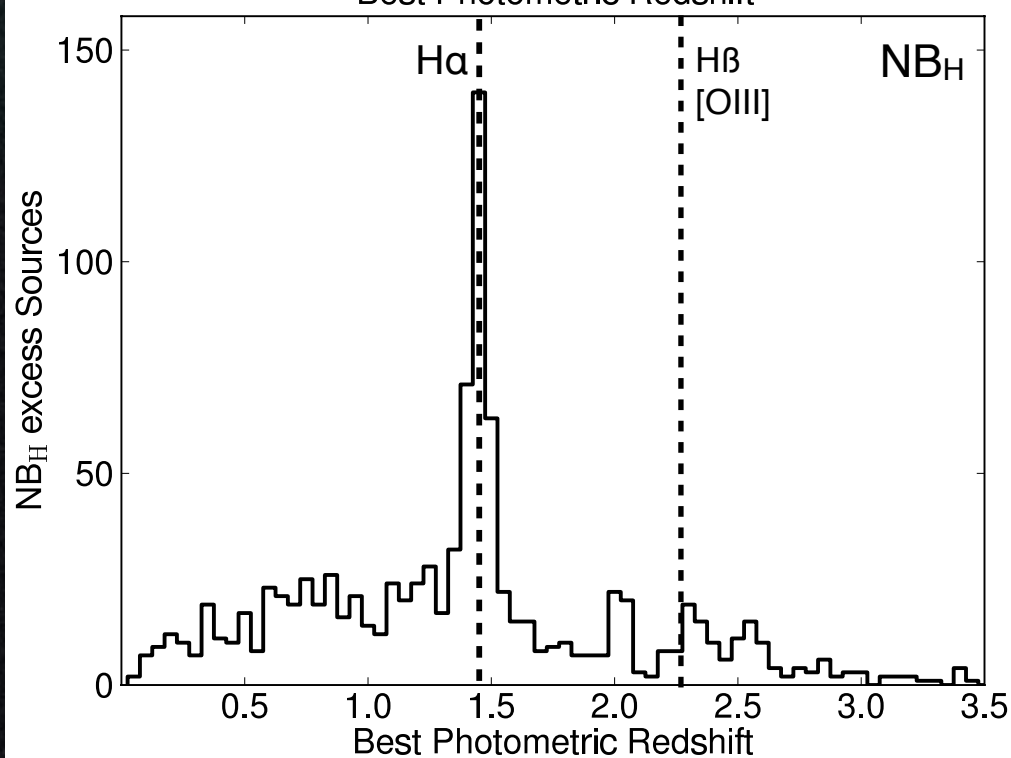
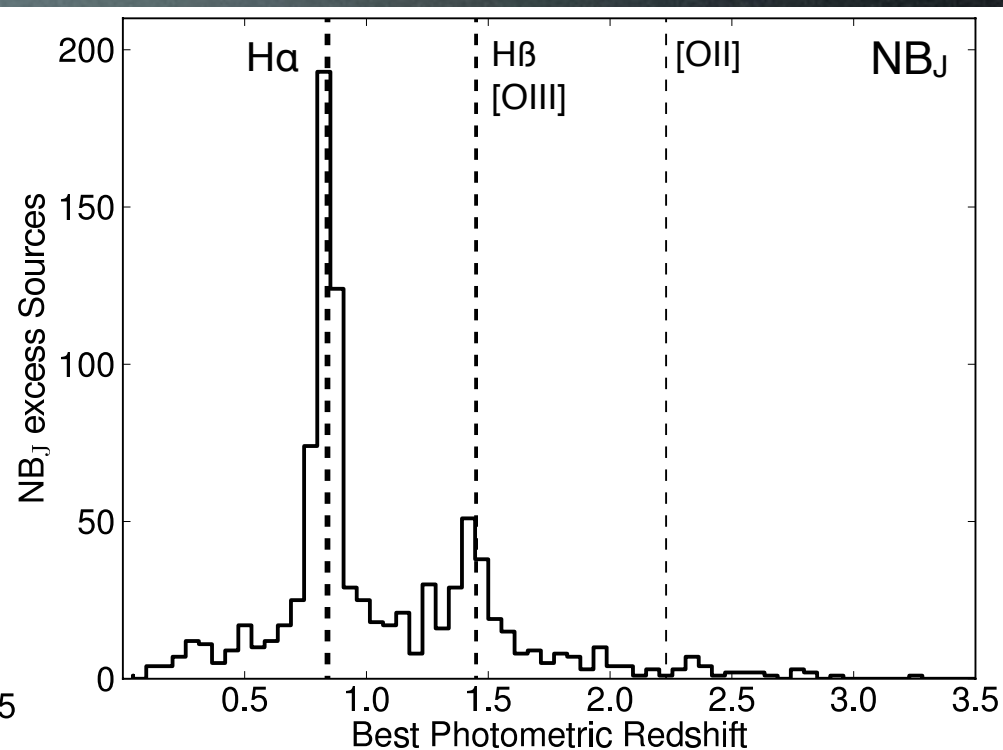
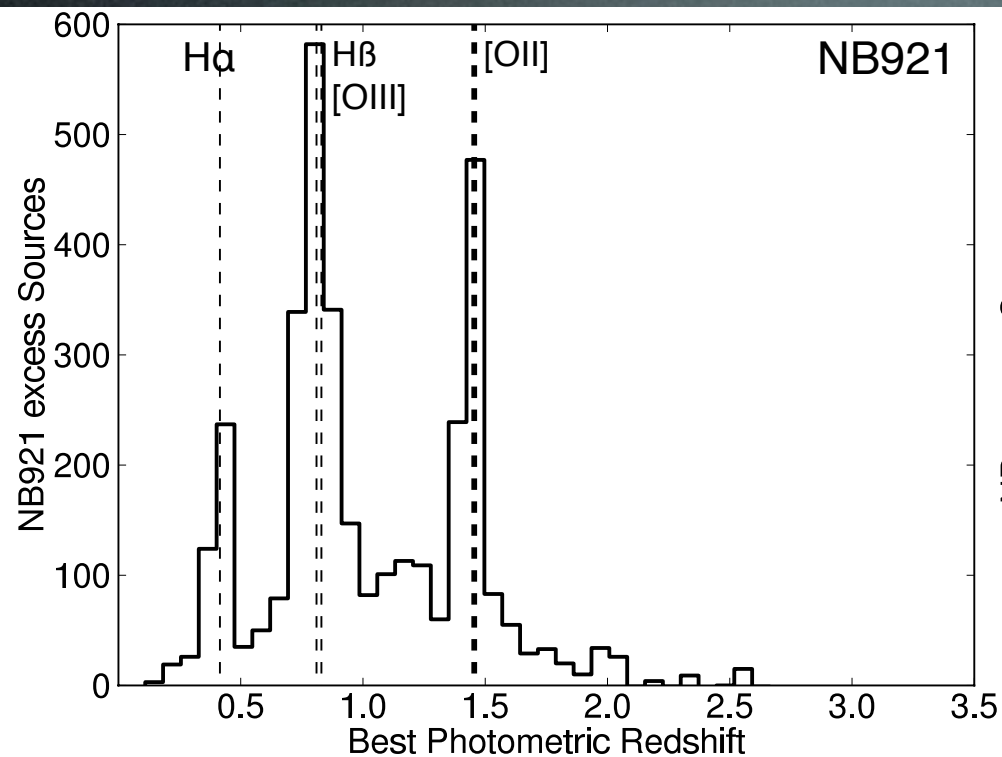
Local Projected Density

# Environment at $z \sim 1$

Sobral et al. (2011)

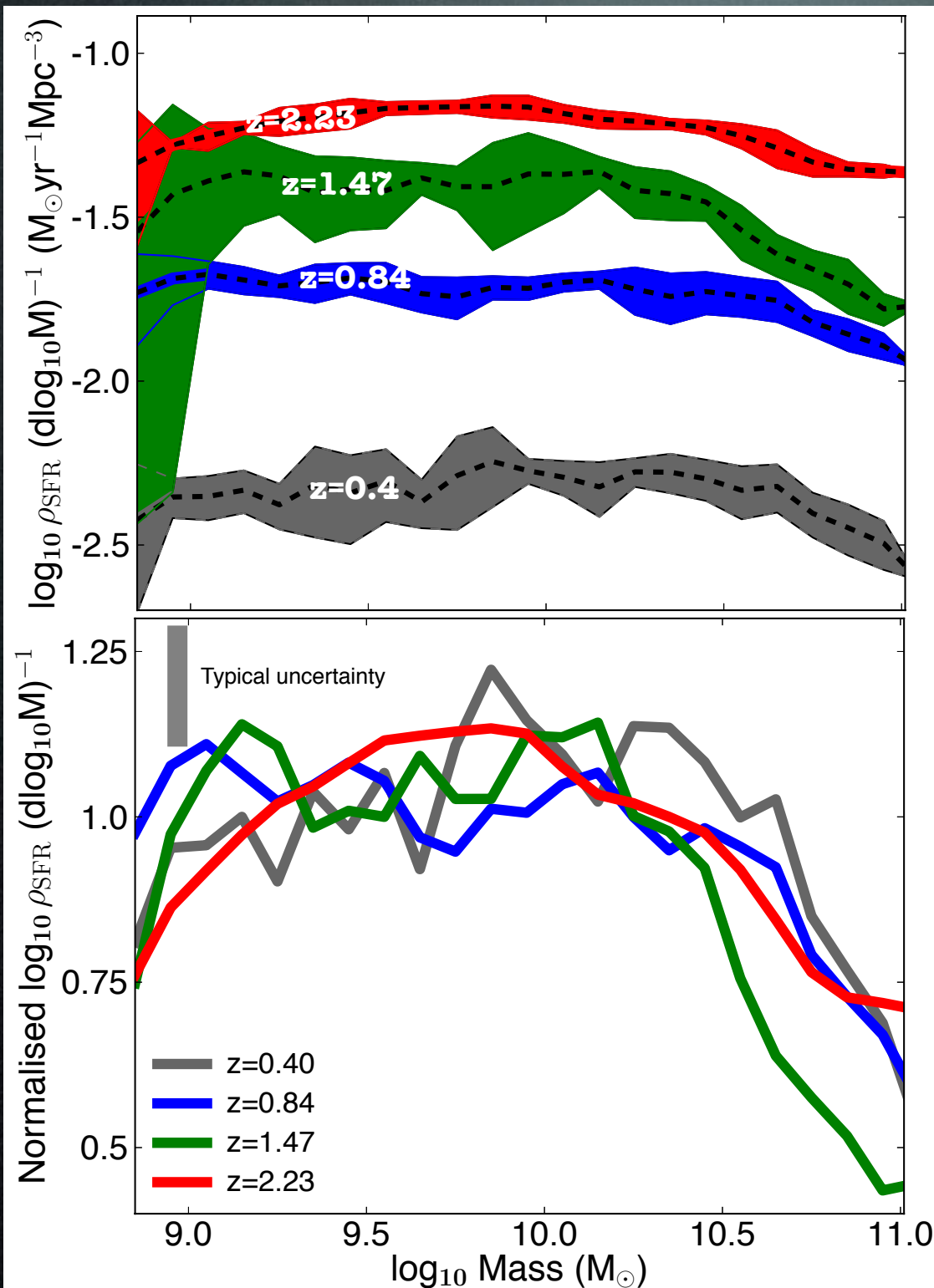
Results reconcile previous apparent contradictions





**SFRD per dLogM**

**Normalised**



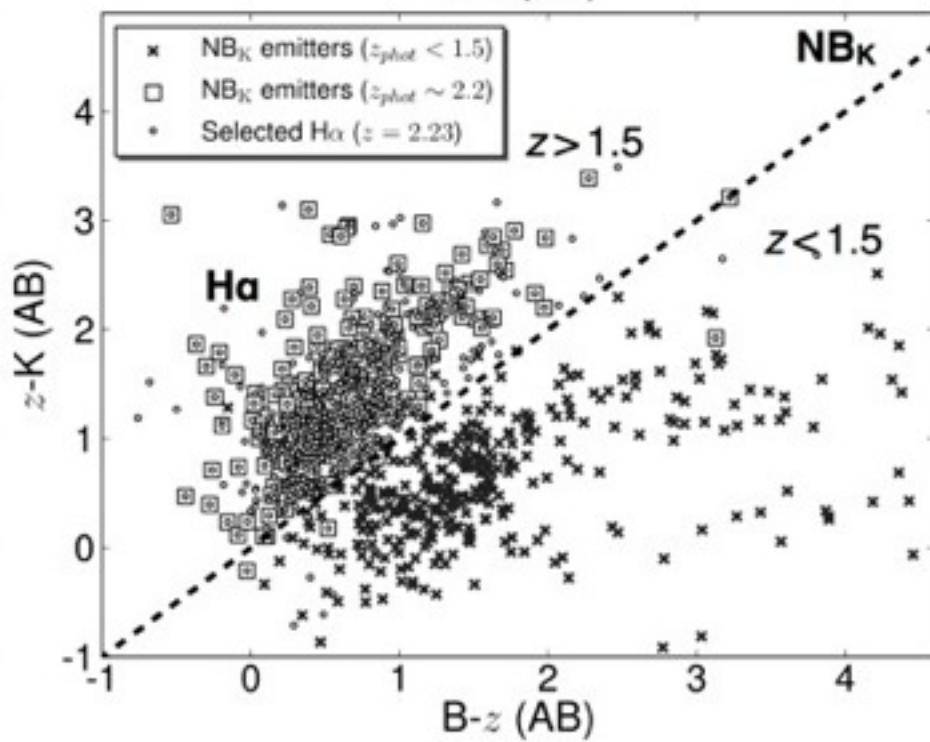
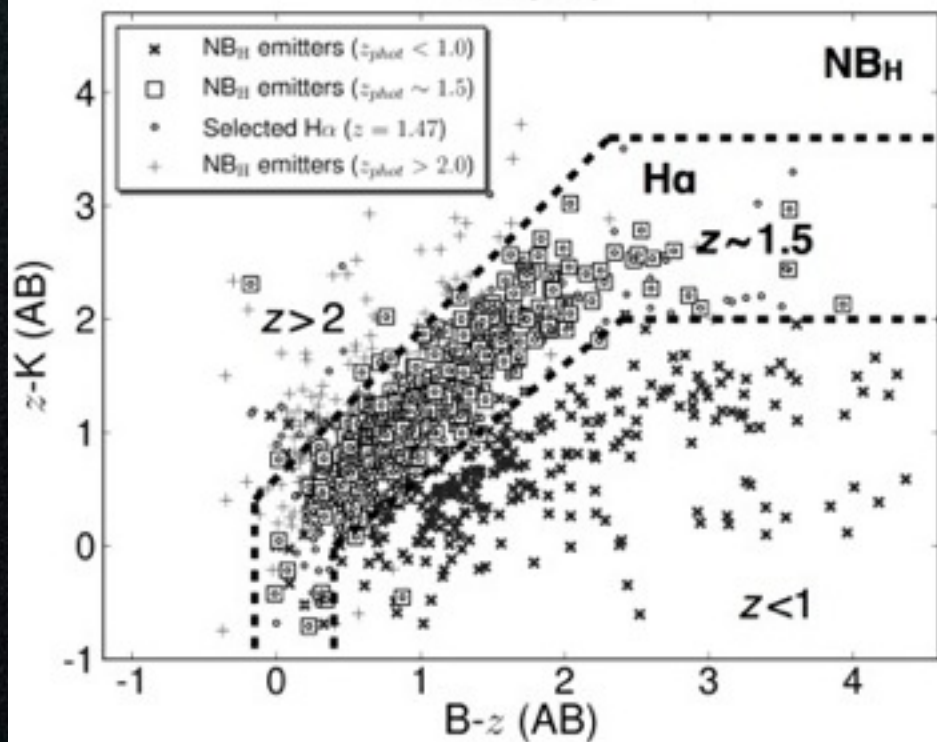
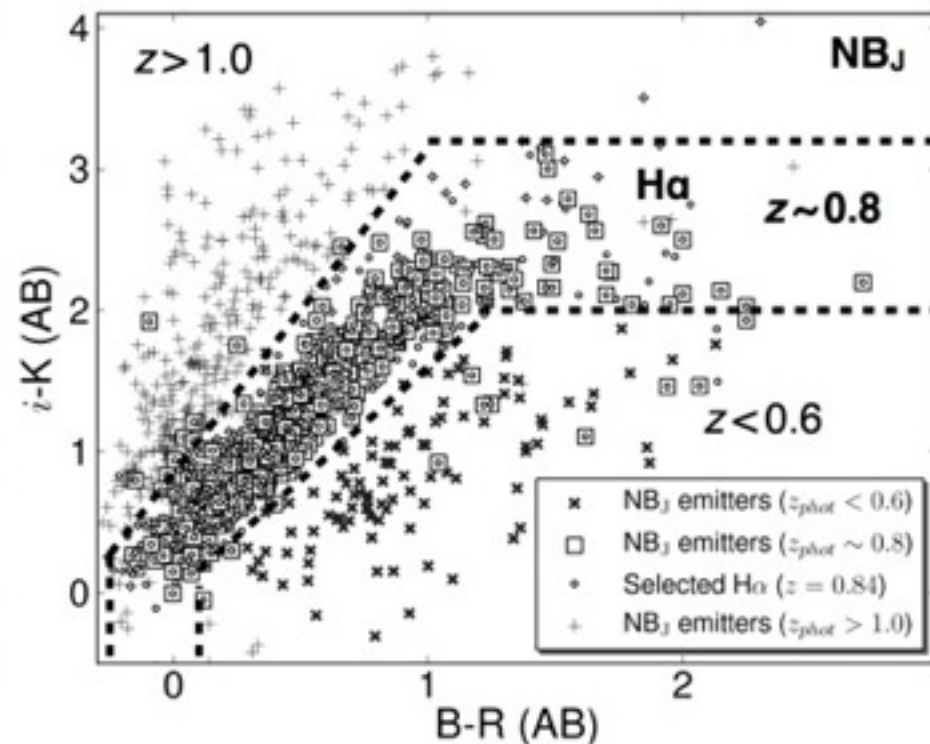
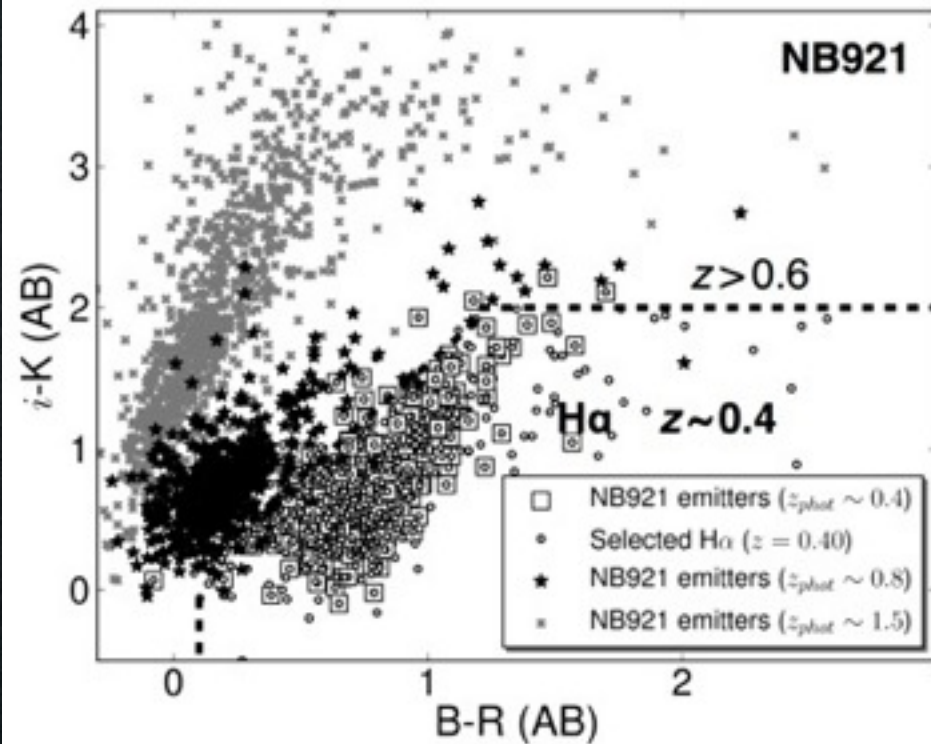
**Over the last 11 Gyrs**

**Decrease with time**  
**at all masses**

**Tentative peak per**  
**dLogM at  $\sim 10^{10} \text{ M}_{\odot}$**   
**since  $z=2.23$**

**Mostly no evolution**  
**apart from**  
**normalisation**

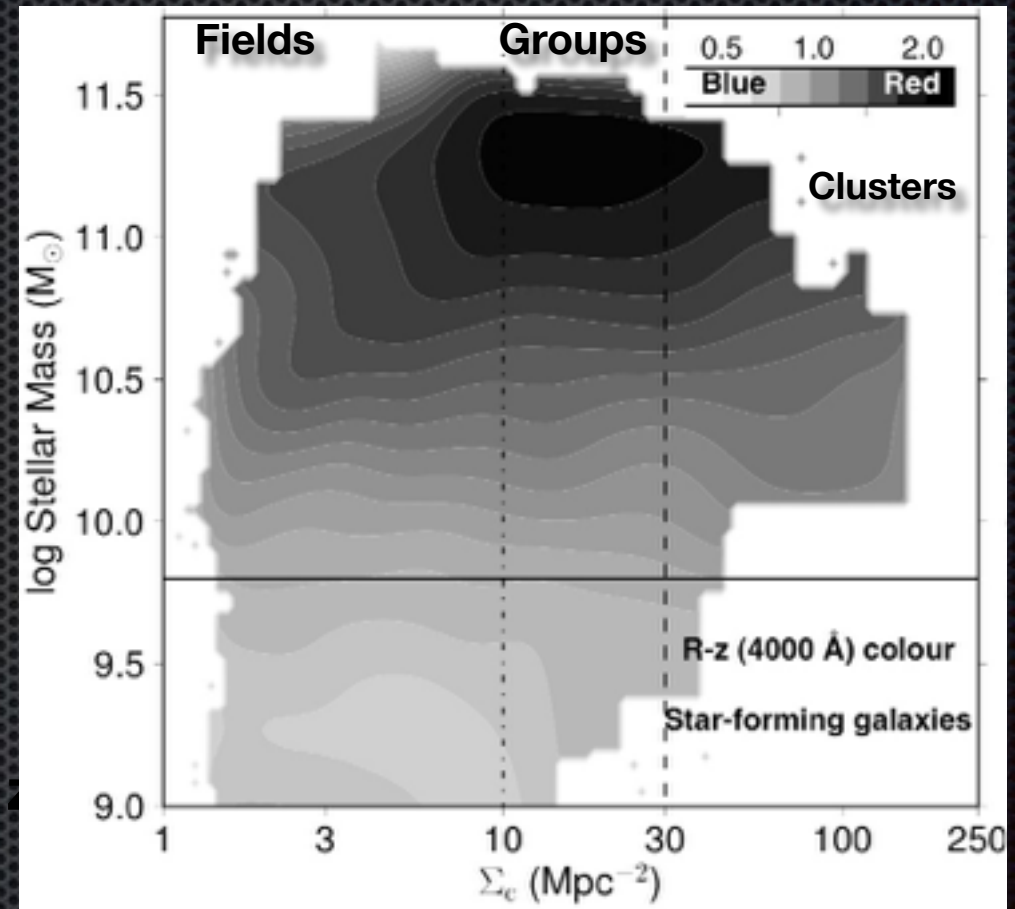
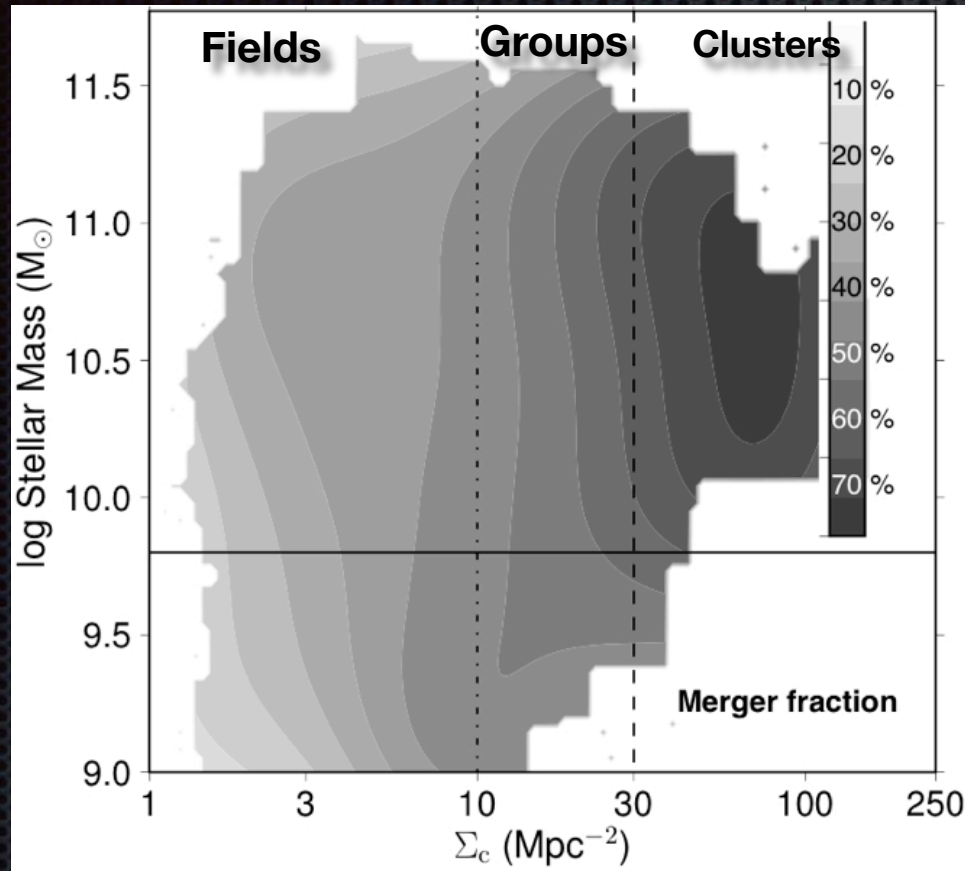
Sobral et al. (14)



# Mass and/or environment?

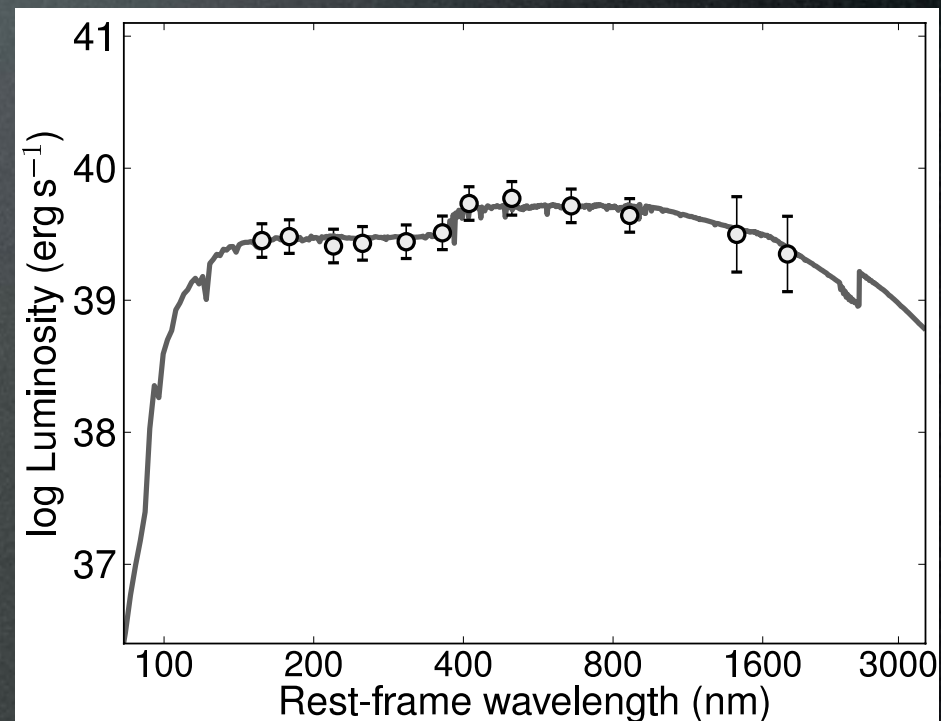
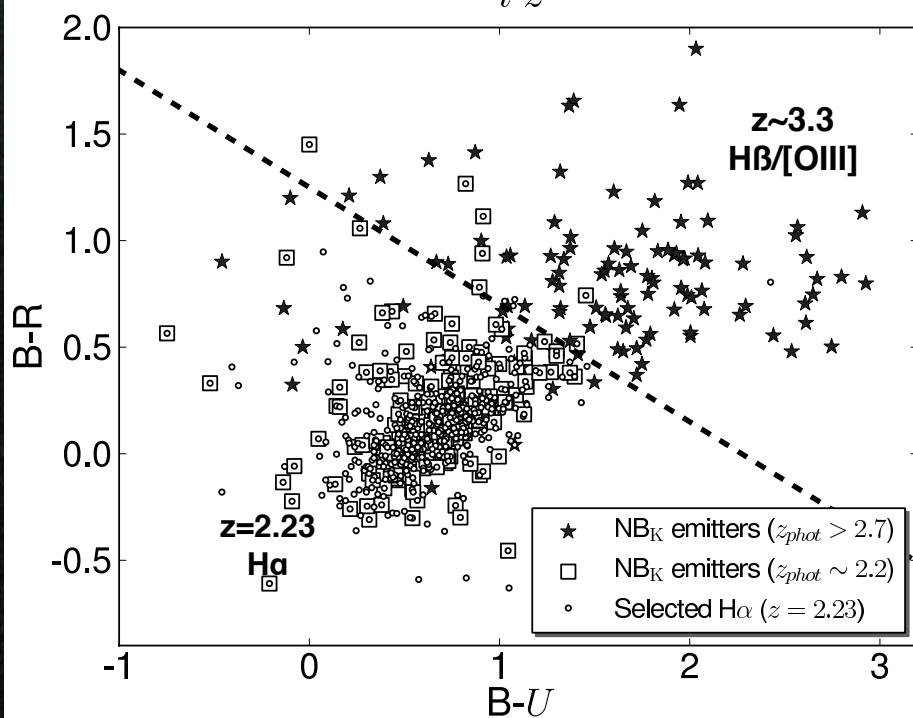
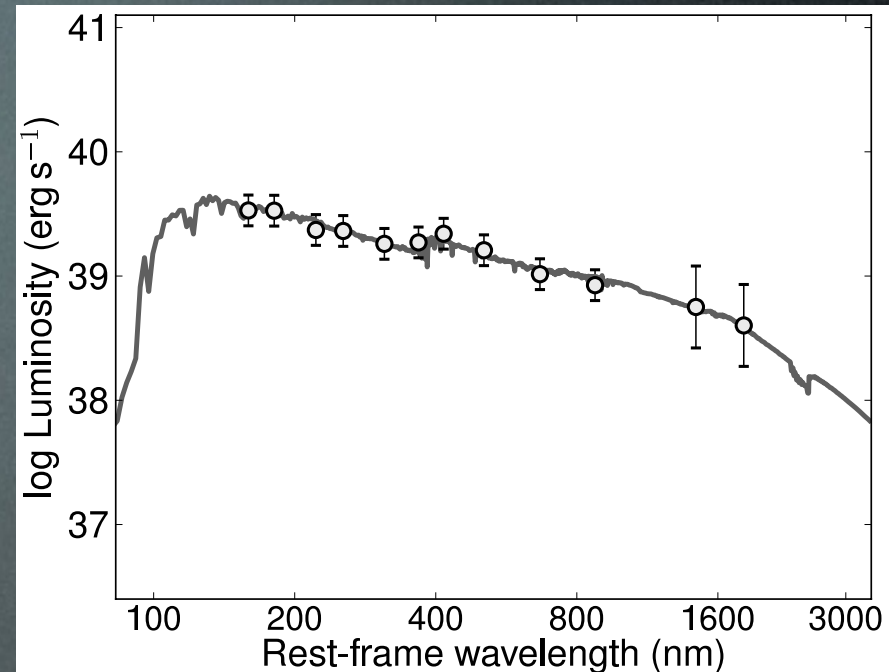
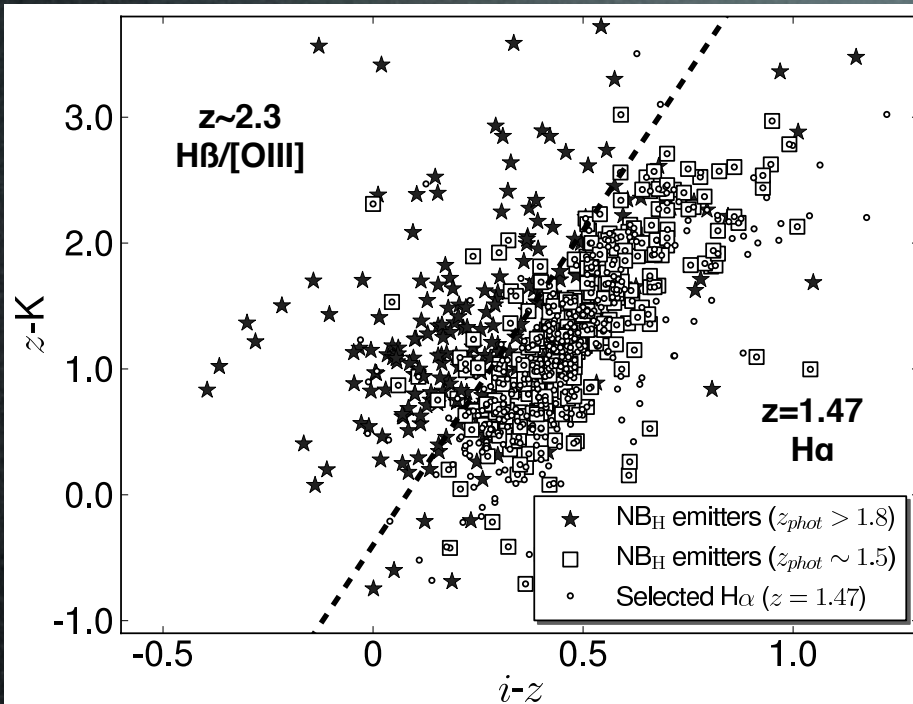
at  $z \sim 1$

Sobral et al. 2011



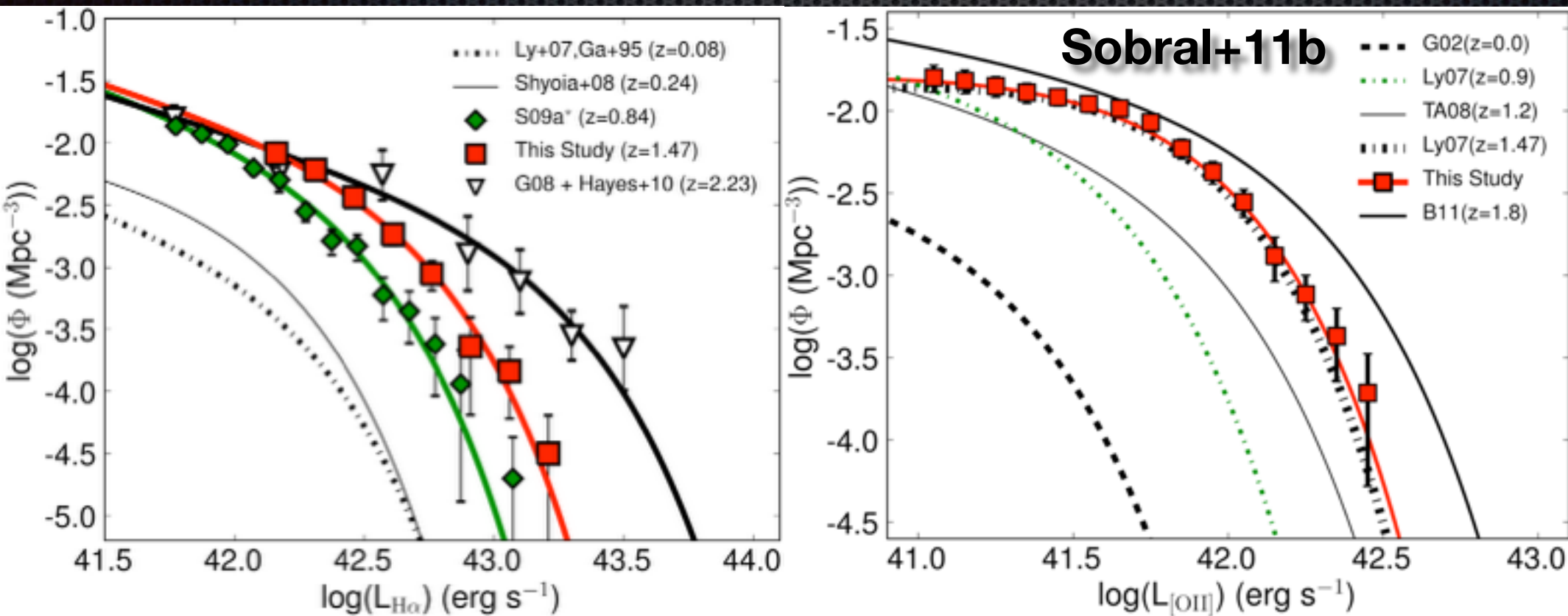
**Merger fraction of star-forming galaxies depends mostly on environment, not mass**

**Stellar mass sets colours of star-forming galaxies, NOT environment**



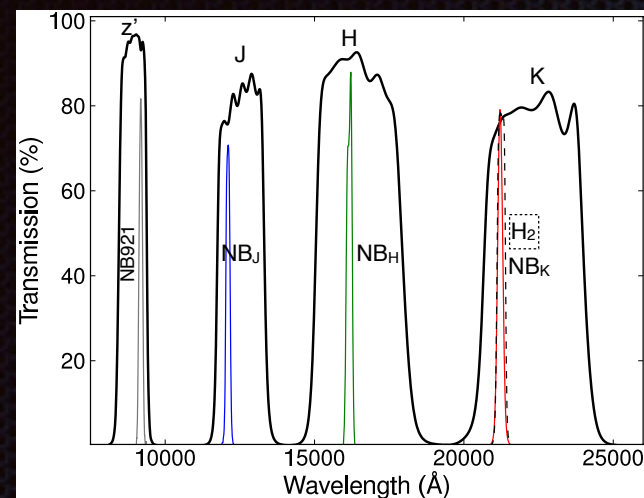
# The H $\alpha$ + [OII] view

- Detailed evolution of the H $\alpha$  LF: strong  $L^*$  evolution to  $z \sim 2.3$



First self-consistent measurement of evolution up to  $z \sim 2.3$

Strong evolution can also be seen using fully consistent measurements of the [OII] luminosity function up to  $z \sim 1.8$



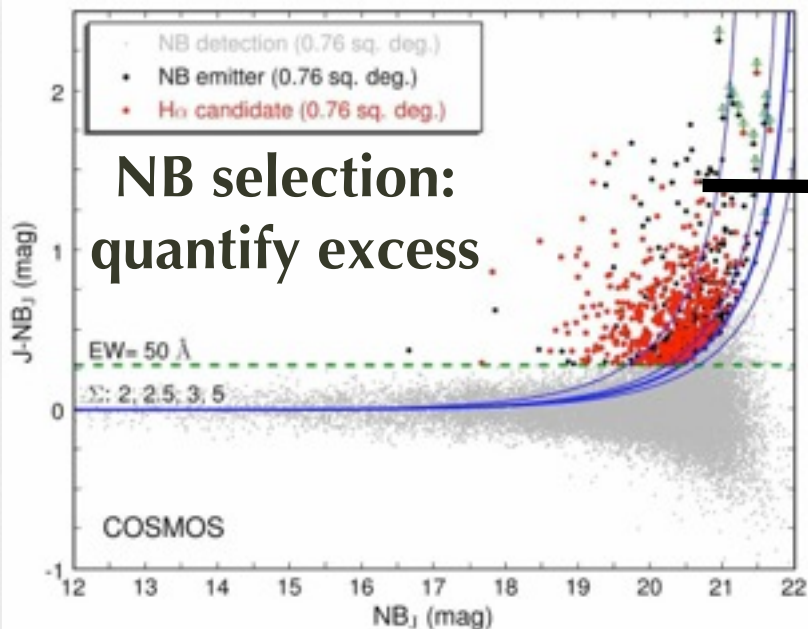
NB filter	$\lambda_c$ ( $\mu\text{m}$ )	FWHM ( $\text{\AA}$ )	$z \text{ H}\alpha$	Volume ( $\text{H}\alpha$ ) ( $10^4 \text{ Mpc}^3 \text{ deg}^{-2}$ )
NB921	0.9196	132	$0.401 \pm 0.010$	5.13
NB <sub>J</sub>	1.211	150	$0.845 \pm 0.015$	14.65
NB <sub>H</sub>	1.617	211	$1.466 \pm 0.016$	33.96
NB <sub>K</sub>	2.121	210	$2.231 \pm 0.016$	38.31
HAWK-I H <sub>2</sub>	2.125	300	$2.237 \pm 0.023$	<b>54.70</b>

**~16 kpc apertures  $z=0.4-2.23$**

Redshift	Limit SFR	Volumes (UDS + COSMOS)
<b><math>0.401 \pm 0.010</math></b>	<b>0.01</b>	<b><math>\sim 1 \times 10^5 \text{ Mpc}^3</math></b>
<b><math>0.845 \pm 0.015</math></b>	<b>1.5</b>	<b><math>\sim 2 \times 10^5 \text{ Mpc}^3</math></b>
<b><math>1.466 \pm 0.016</math></b>	<b>3.0</b>	<b><math>\sim 8 \times 10^5 \text{ Mpc}^3</math></b>
<b><math>2.231 \pm 0.016</math></b>	<b>3.5</b>	<b><math>\sim 7 \times 10^5 \text{ Mpc}^3</math></b>

**$z=0.4-2.23$**

$$\Sigma > 3, EW_{(\text{H}\alpha + [\text{NII}])} > 25 \text{ \AA}$$

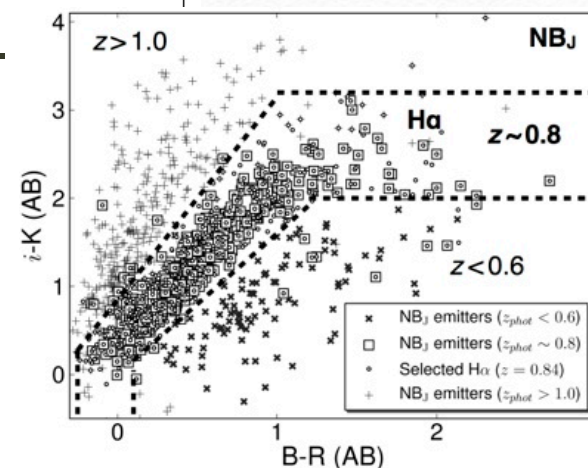
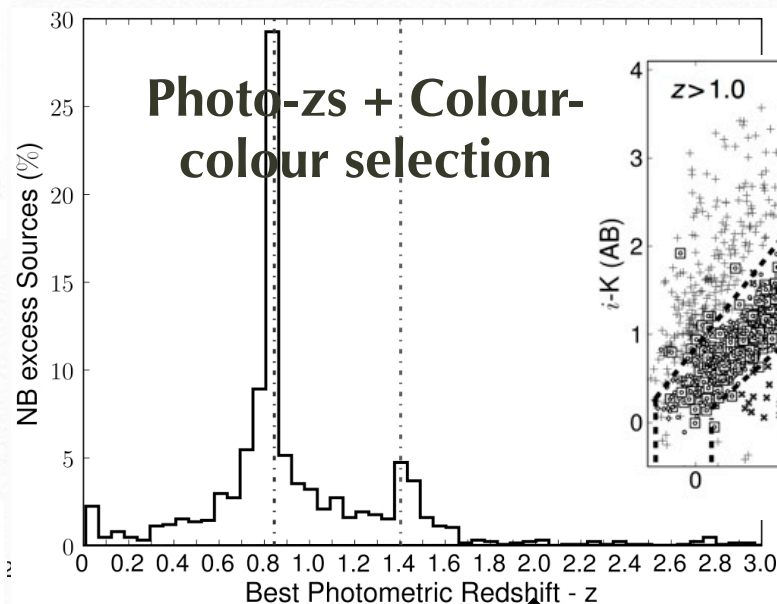


Source extraction

Potential line emitters

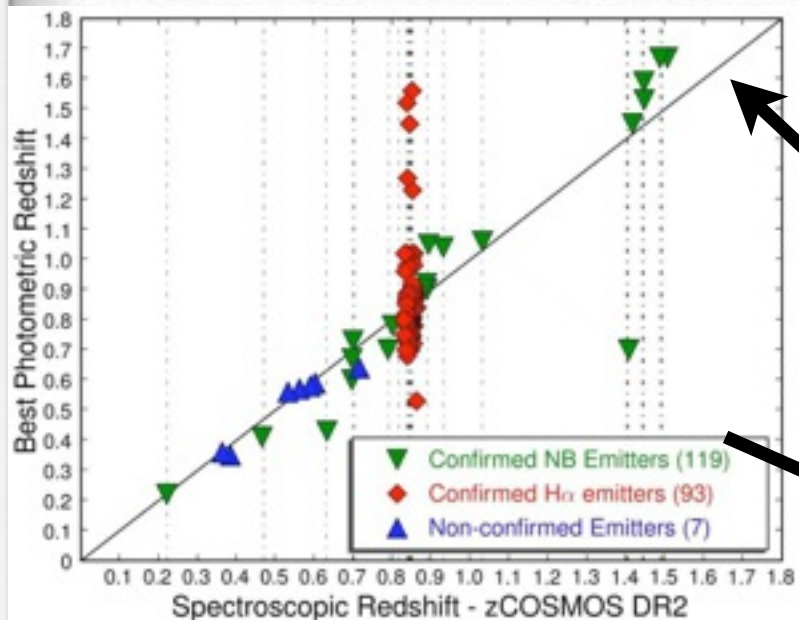
Which emission line?

Probing well-studied fields is fundamental!



Spectro-z confirmation

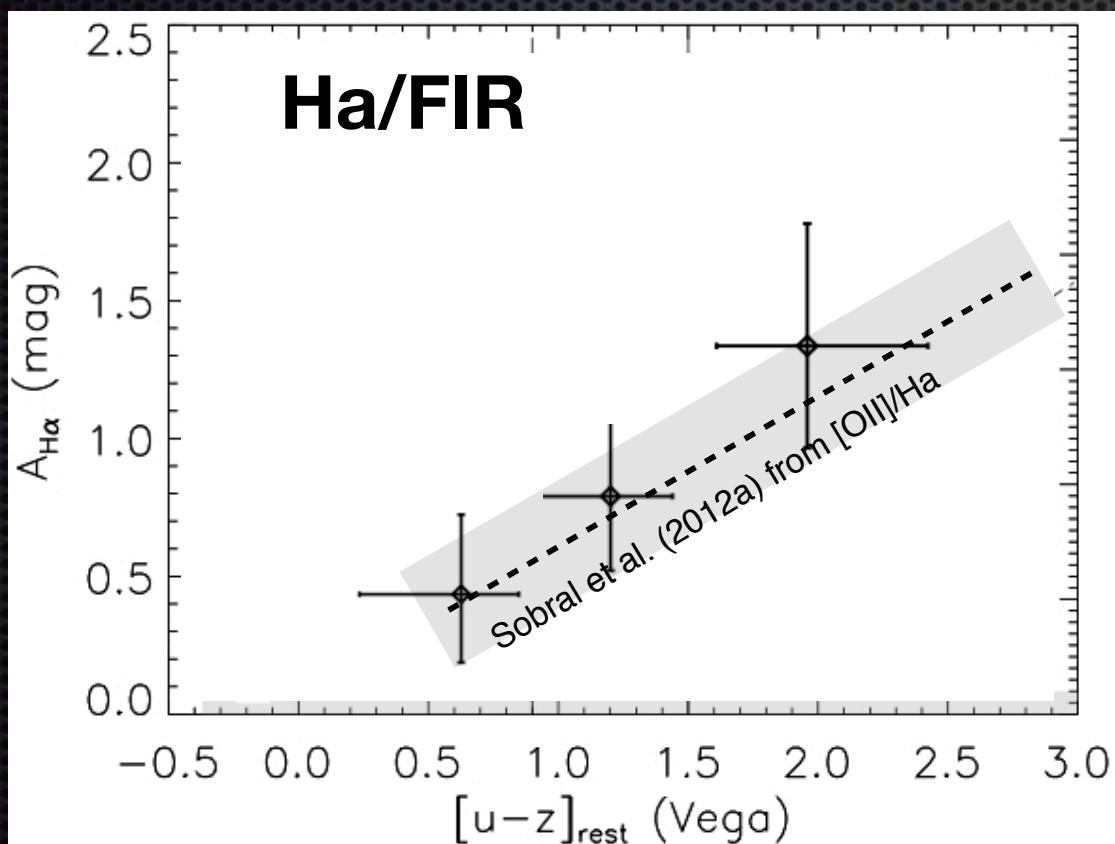
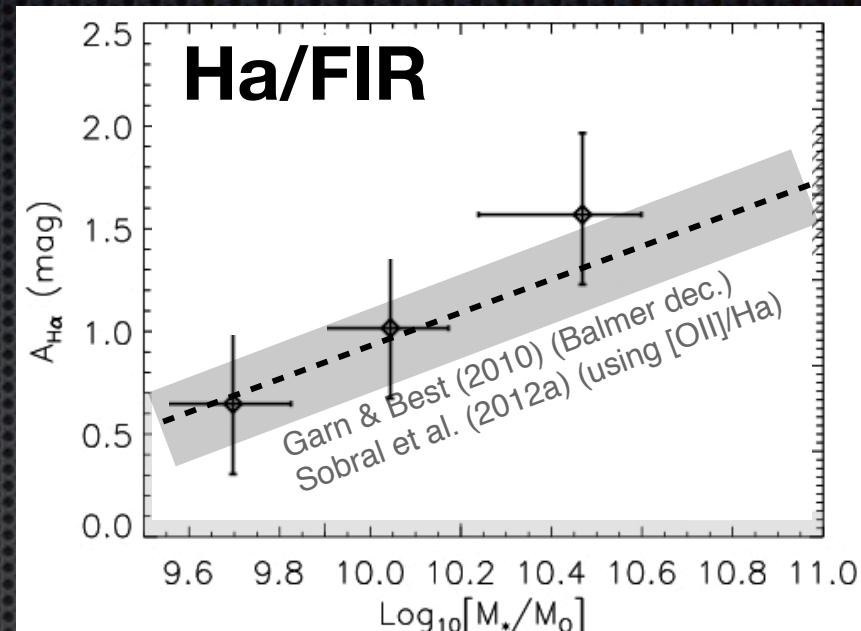
Double-line confirmation



Select H $\alpha$  emitters

Samples >90% reliable  
>90% complete

**Stellar Mass correlates with  
dust extinction in the local  
Universe - (see Garn & Best  
2010)**



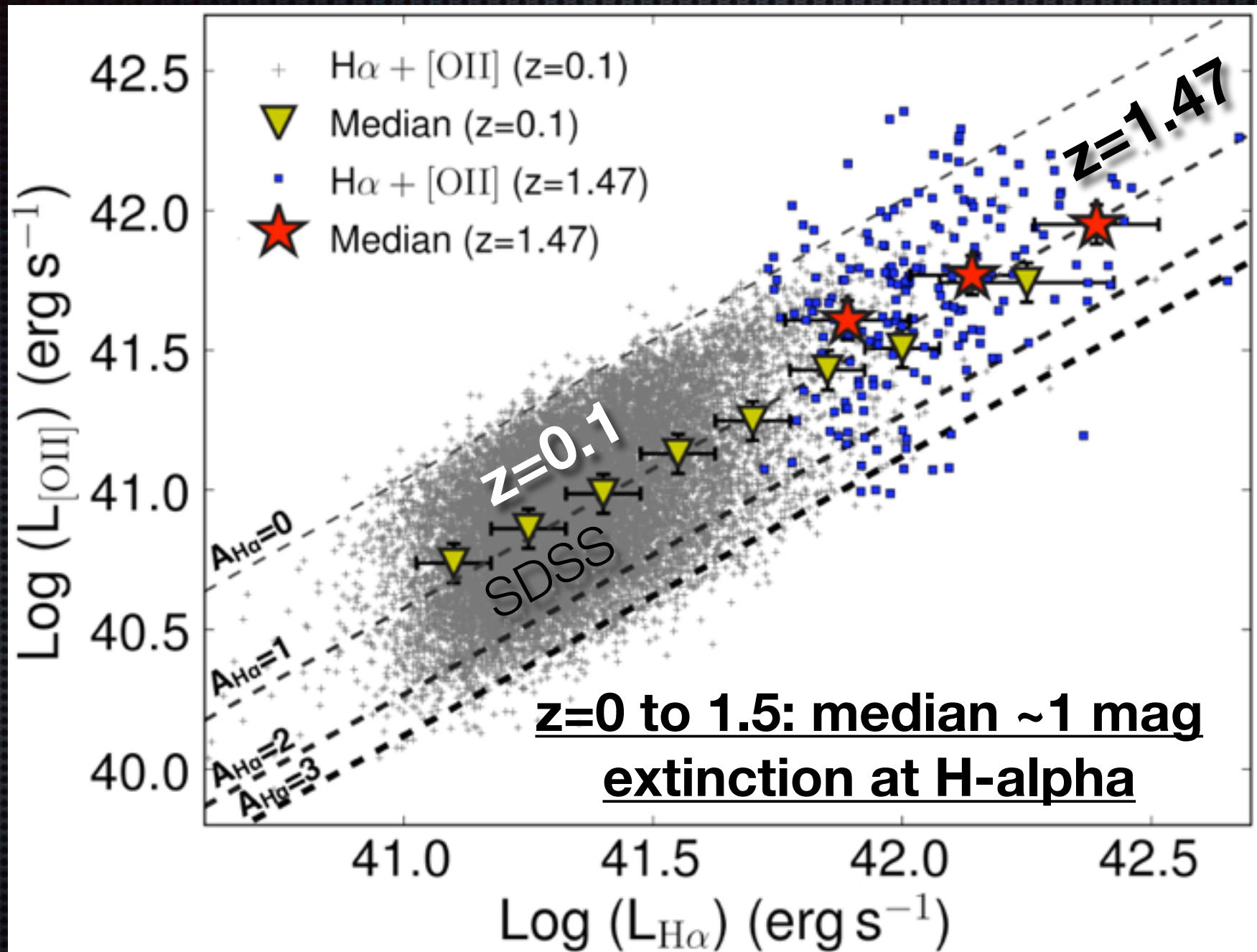
**Simpler way to **predict  
dust extinction with  
observables: optical/UV  
colours - empirical  
relations valid at  $z \sim 0-1.5$****   
**(Sobral et al. 2012)**

## Little evolution in rest-frame R sizes for Star forming galaxies since $z=2.23$

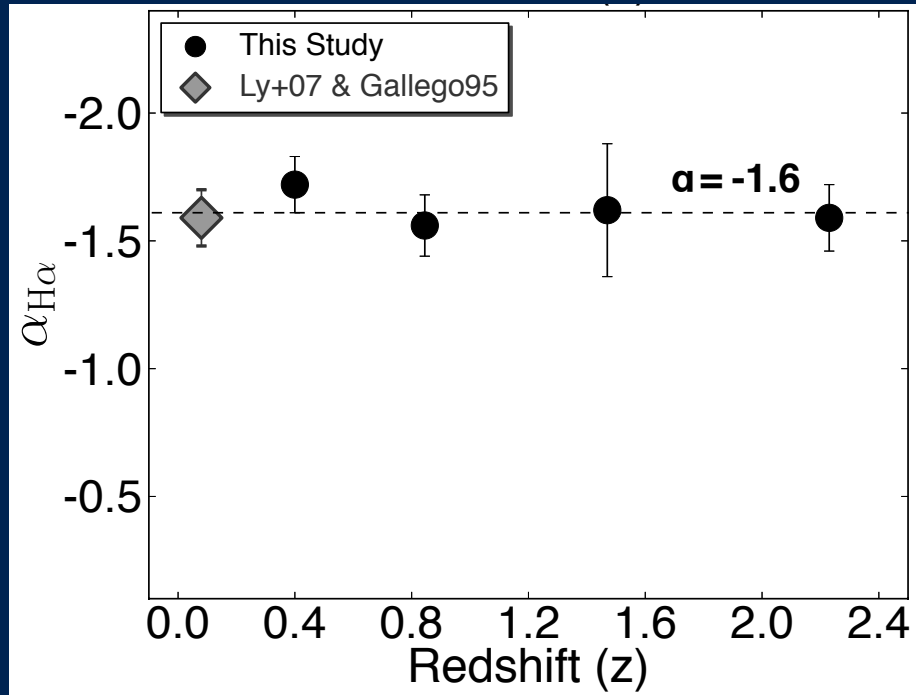
$z$	$a$	$b$	$r_e$ at $\log_{10}(M_*) = 10$ (kpc)
0.40	$0.08 \pm 0.02$	$0.55 \pm 0.03$	$3.6 \pm 0.2$
0.84	$0.03 \pm 0.02$	$0.54 \pm 0.01$	$3.5 \pm 0.1$
1.47	$0.03 \pm 0.02$	$0.59 \pm 0.01$	$3.9 \pm 0.2$
2.23	$0.08 \pm 0.03$	$0.51 \pm 0.02$	$3.3 \pm 0.2$

~Same sizes down to same SFR/SFR\*

# Dust extinction over ~9 Gyrs: evolution?

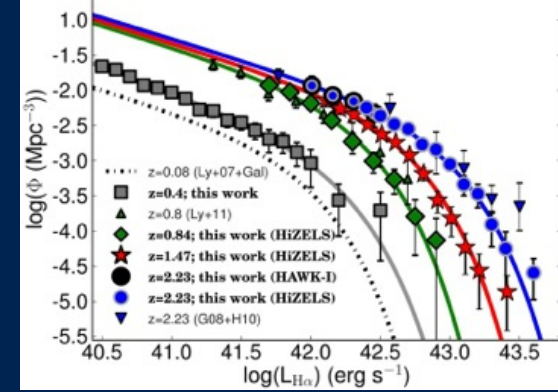


# Faint-end Slope $\alpha$ :

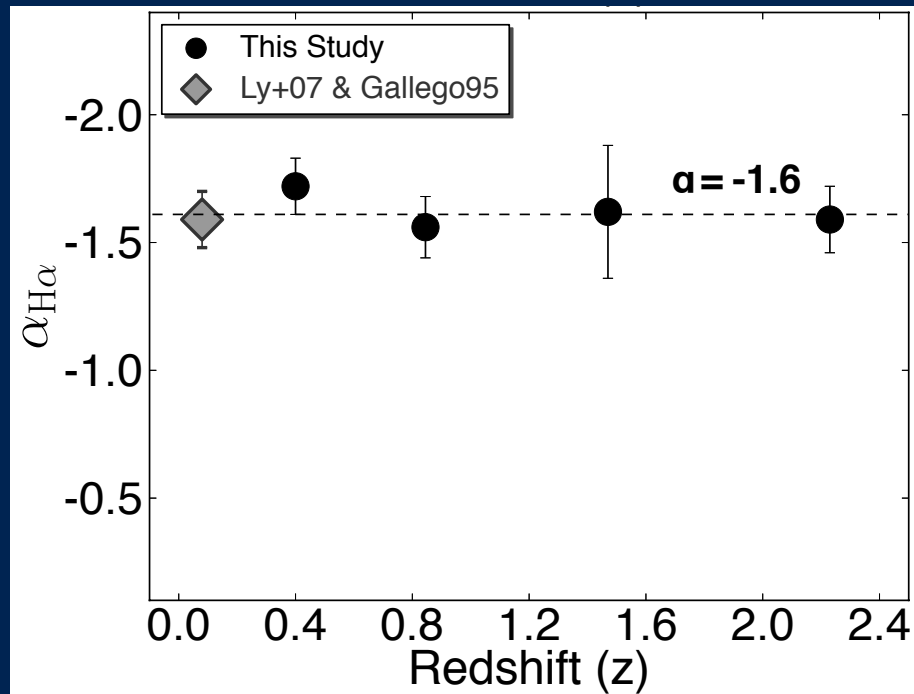


Up to  $z=2.2$ :

$$\alpha = -1.60 \pm 0.08$$

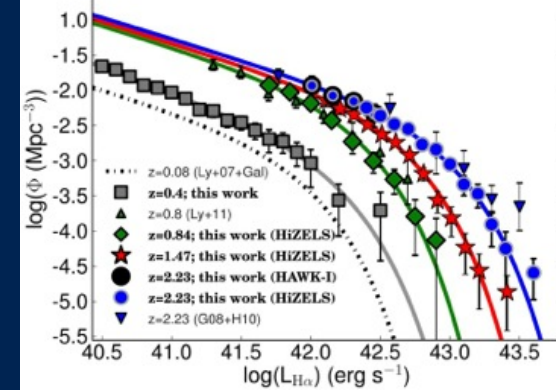


# Faint-end Slope $\alpha$ :

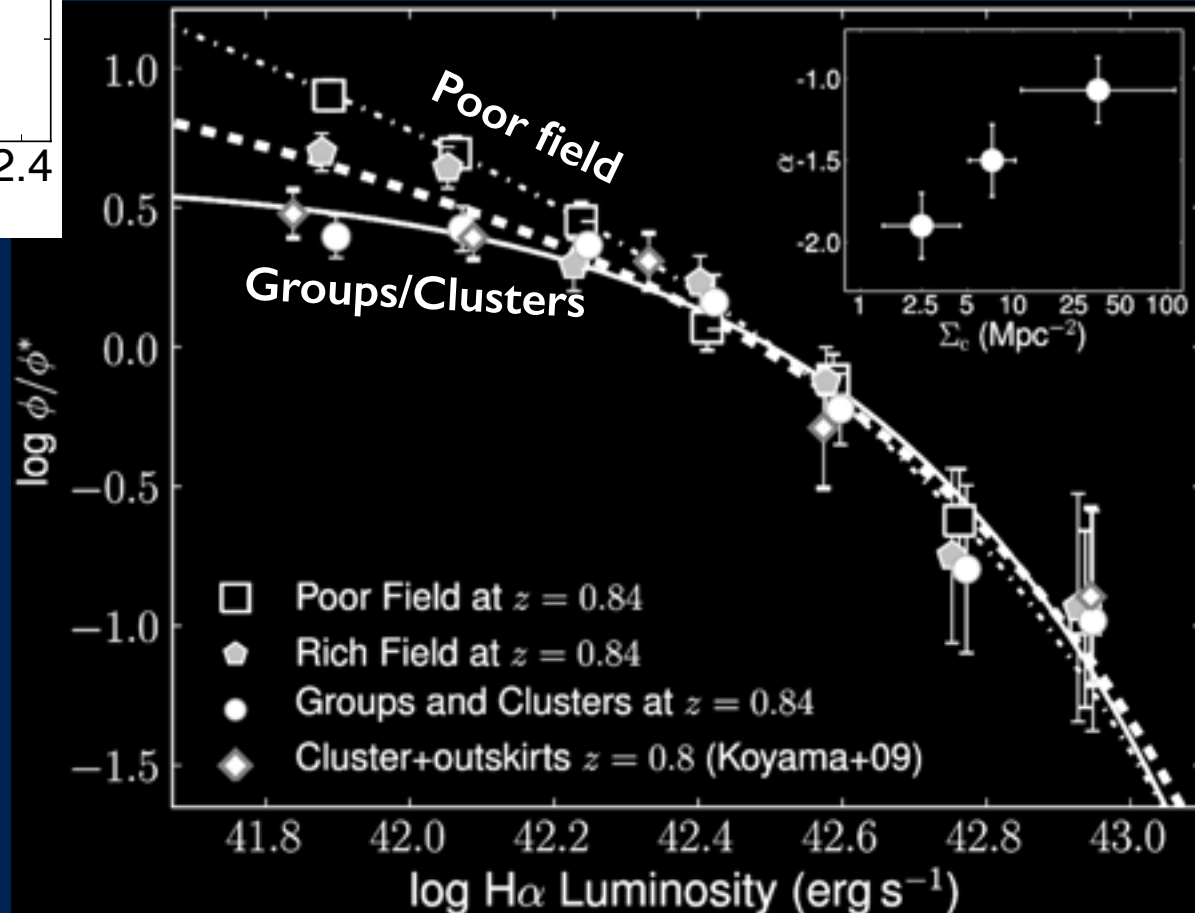


Up to  $z=2.2$ :

$$\alpha = -1.60 \pm 0.08$$



Sobral et al. 2011



Environment sets the faint-end slope of the H $\alpha$  LF:

- steep  $\alpha \sim -2$  for the lowest densities
- shallow  $\alpha \sim -1$  for highest densities

# A simple view: 11 Gyrs of SFGs

- **Strong Evolution: Typical SFR (SFR\*) reduces by 1/10**
- Many statistical properties remain “unchanged”: Dust “extinction”, Mass function ( $M^*$ ,  $\alpha$ )
- Environmental + Mass trends are the same (last  $\sim 9$  Gyrs)
- Same Dark Matter halo masses host the same  $L/L^*$  galaxies
- What changes?  $\Rightarrow$  Concentration of dark matter haloes. Same mass haloes are much more concentrated at high- $z$ : factor 10 increase and SFH?

**More sophisticated dust extinction  
corrections**



**SFR function and its evolution since  
 $z=2.23$**

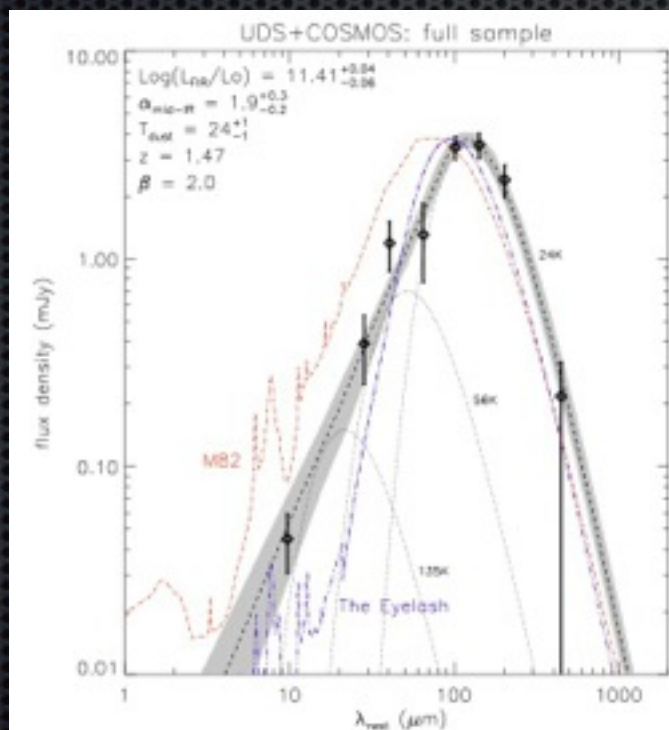


**Compare with the evolution of the Stellar  
Mass Function of Star-forming galaxies**

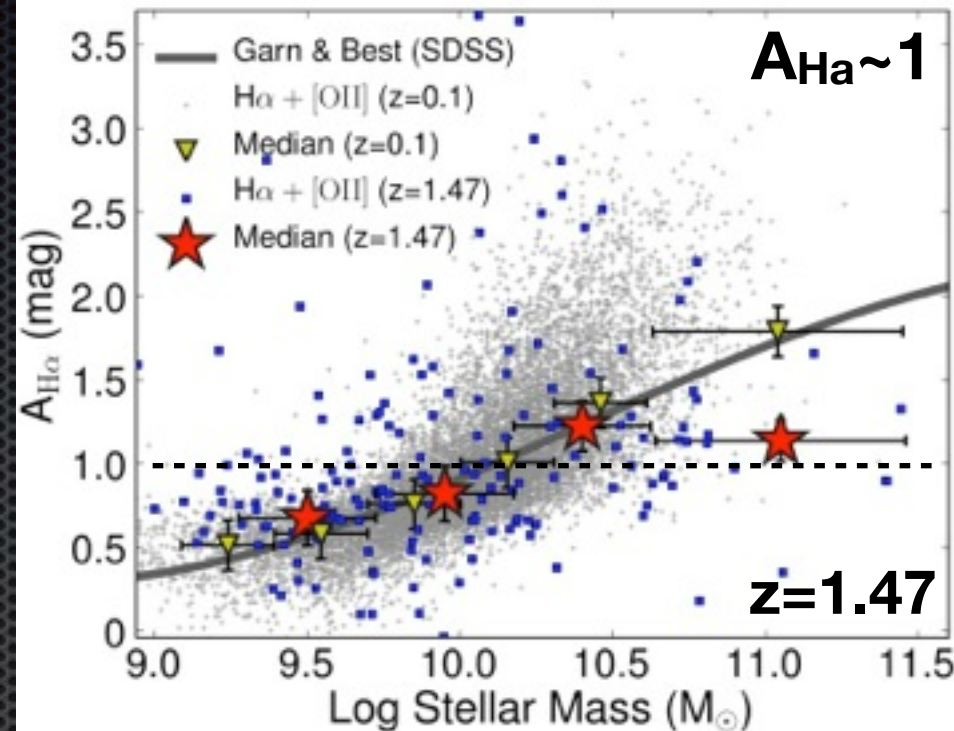
# Extinction-Mass $z \sim 0-1.5$

**Garn & Best 2010:** Stellar Mass correlates with dust extinction in the local Universe

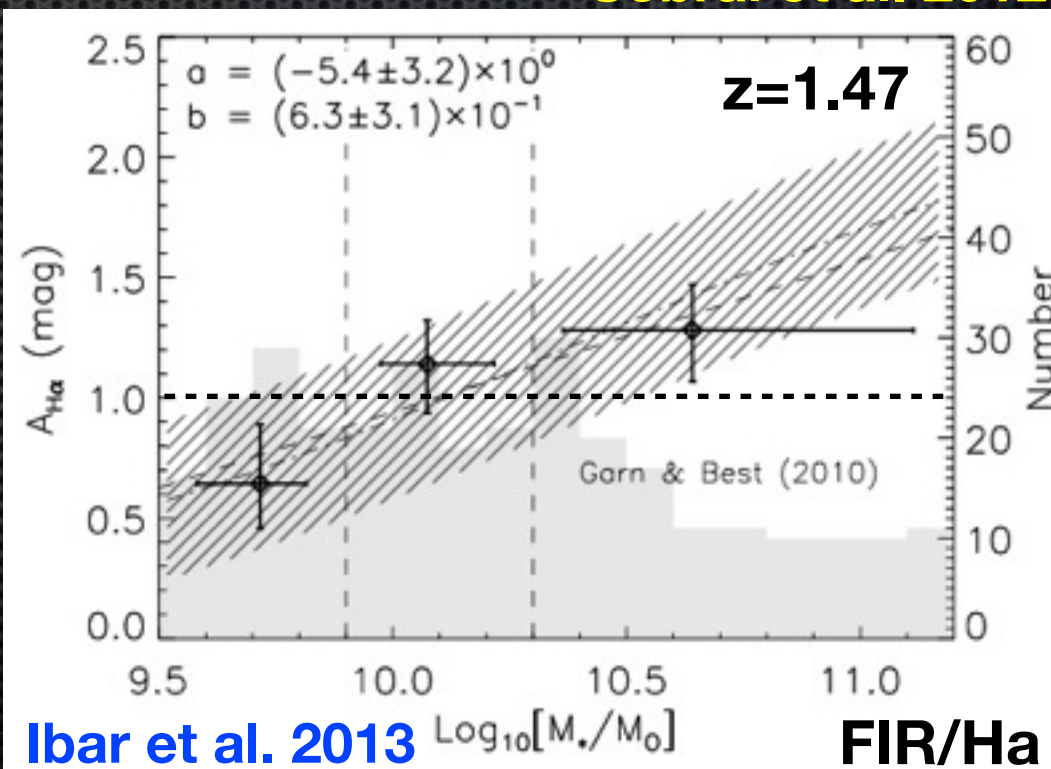
Relation holds up to  $z \sim 1.5-2$



FIR derived  $A_{\text{H}\alpha} = 0.9-1.2$  mag



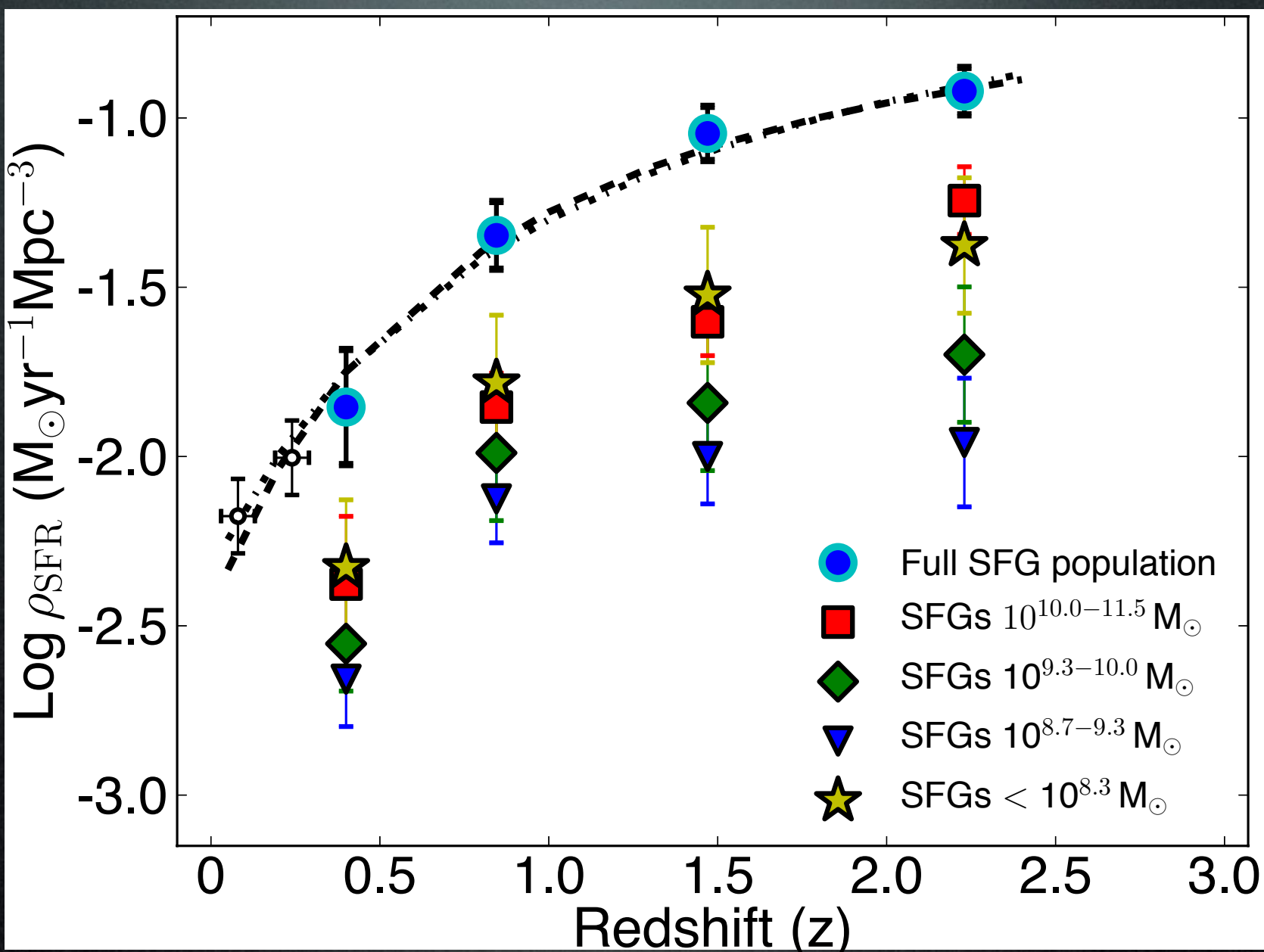
**Sobral et al. 2012**



**Ibar et al. 2013**

**FIR/H $\alpha$**

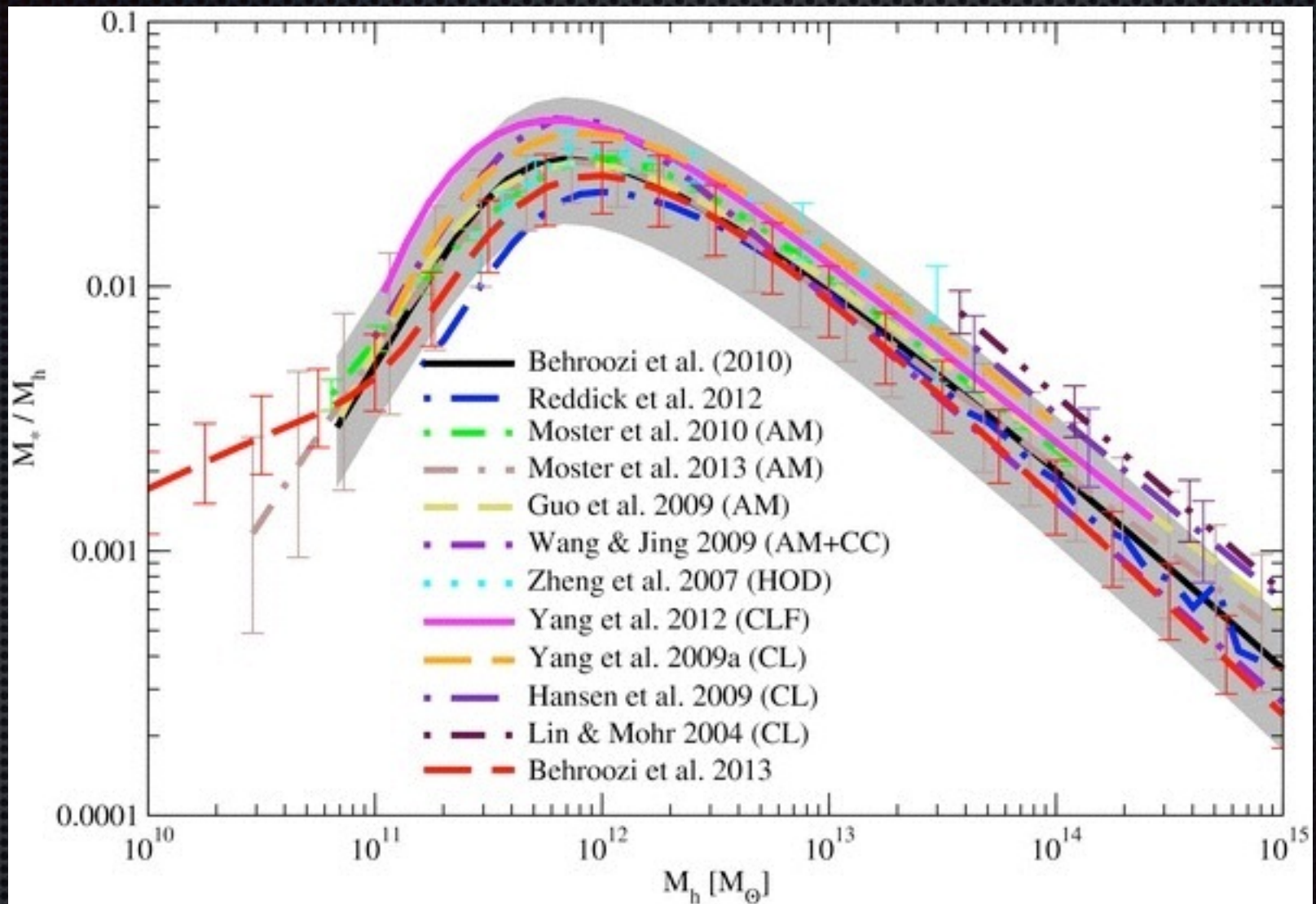
# SF History - Full population and 4 mass bins



Decline at all masses

Sobral et al. (13B)

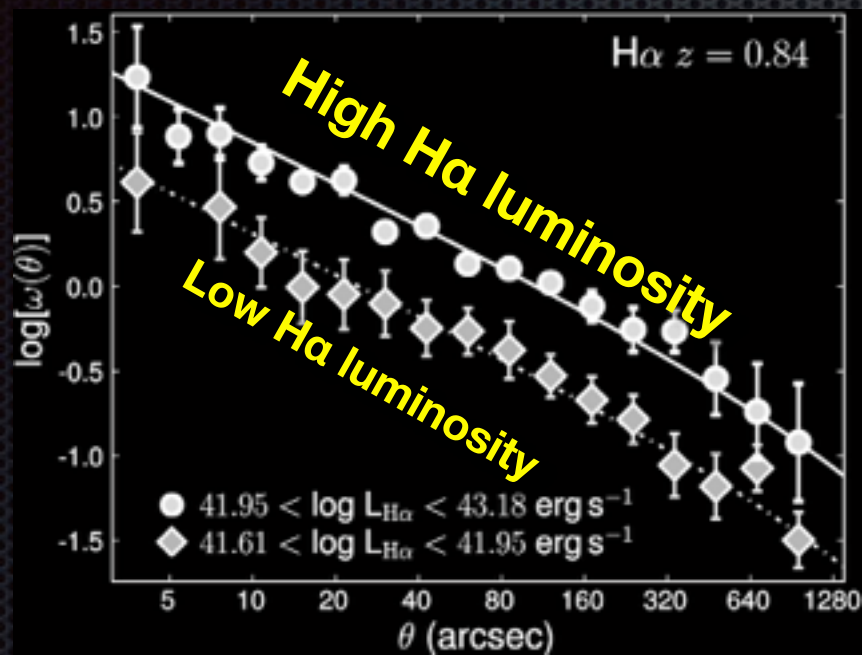
# DM Halo/SF “efficiency”



But what exactly drives this??? Gas? Structure?  
Feedback?

# Clustering of H $\alpha$ emitters

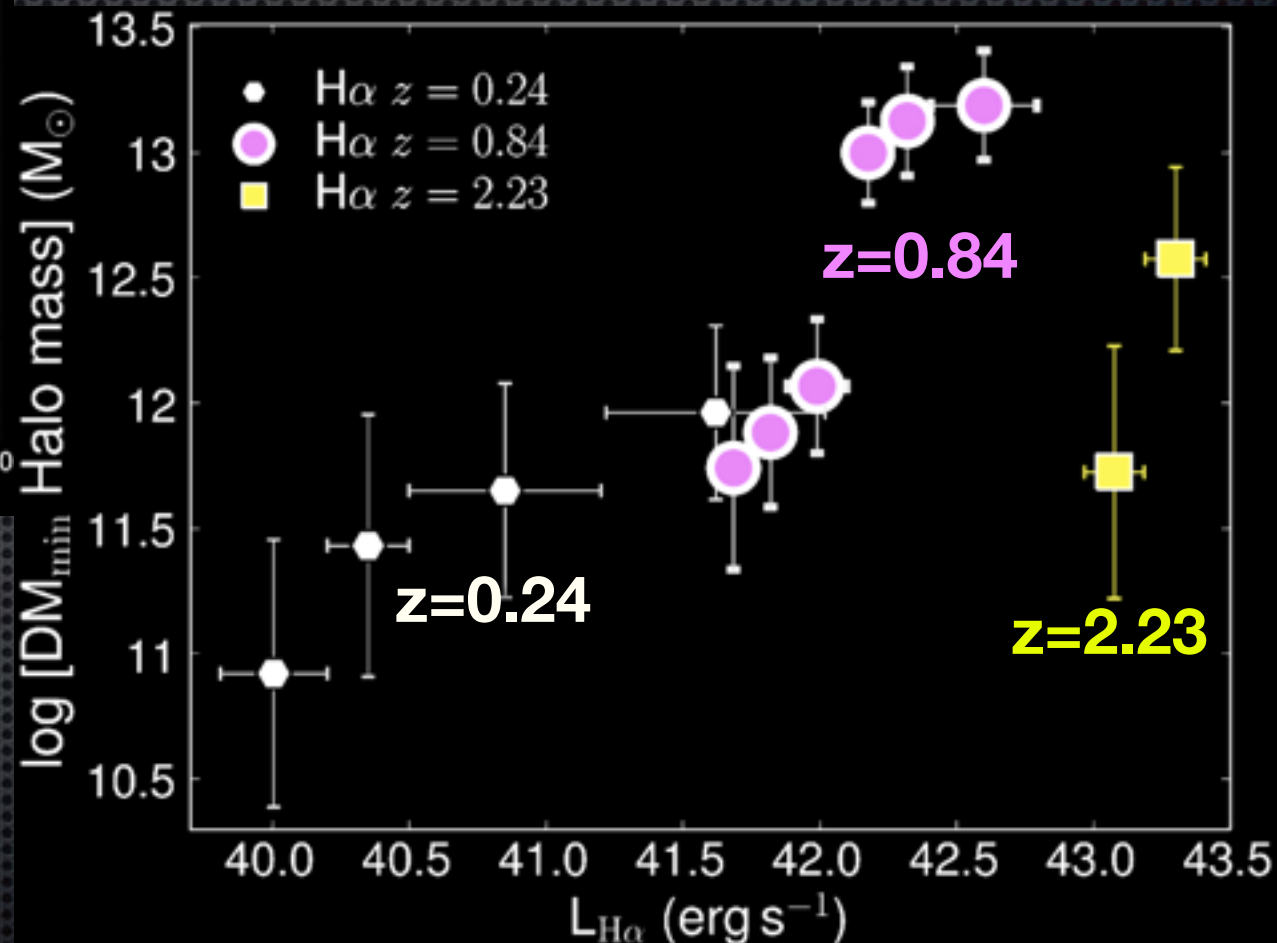
Clustering depends on H $\alpha$  luminosity; galaxies with higher SFRs are more clustered



Clustering-H $\alpha$  relations at 3 very different epochs...

Same DM Halo mass:  
much more efficient at  
High- $z$

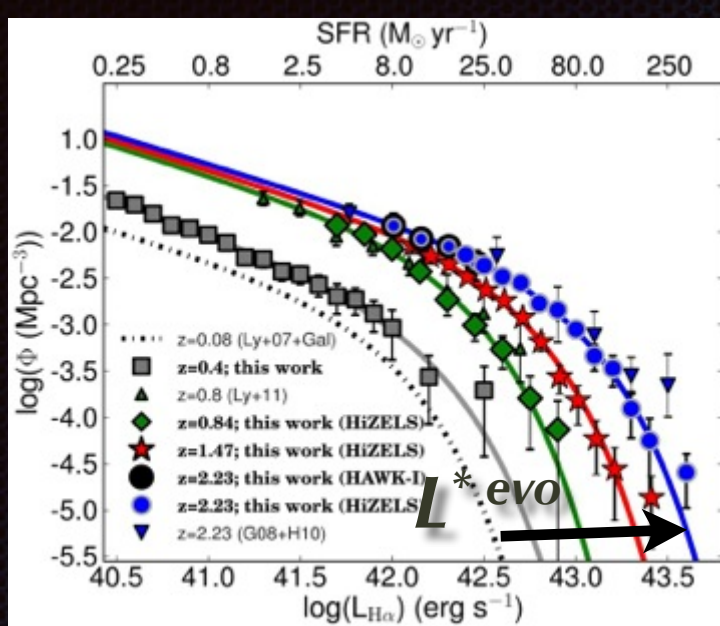
Sobral et al. 2010



# Clustering-Ha

Sobral et al. 2010

Using the Luminosity evolution ( $L^*$ )  
measured before...



Scaling  $H\alpha$  luminosities  
by the break of the  $H\alpha$   
luminosity function  
recovers a **single  
relation**, independent  
of time across the bulk  
of the age of the  
Universe

