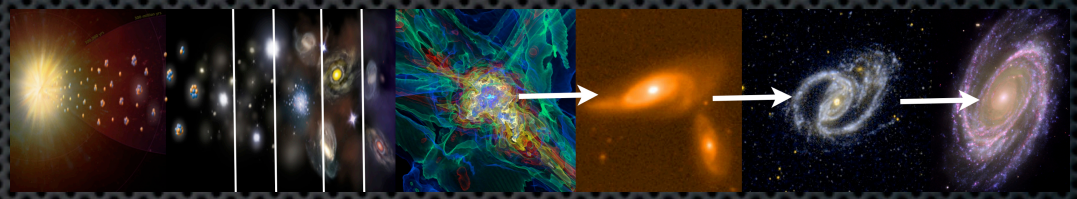
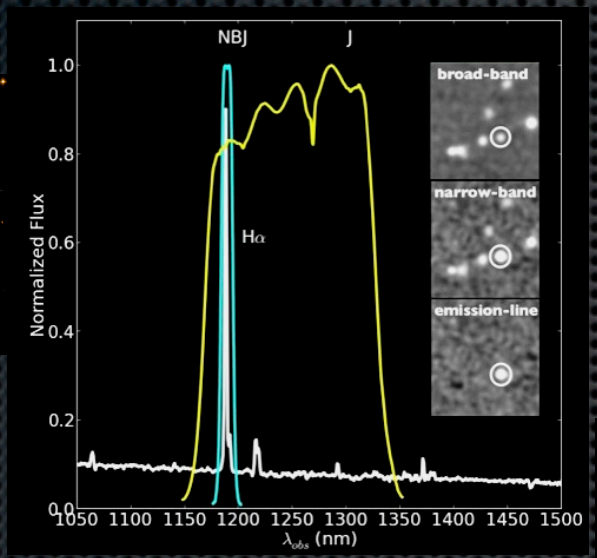
Dynamics, morphologies and evolution of Hα star-forming galaxies since z = 2:23

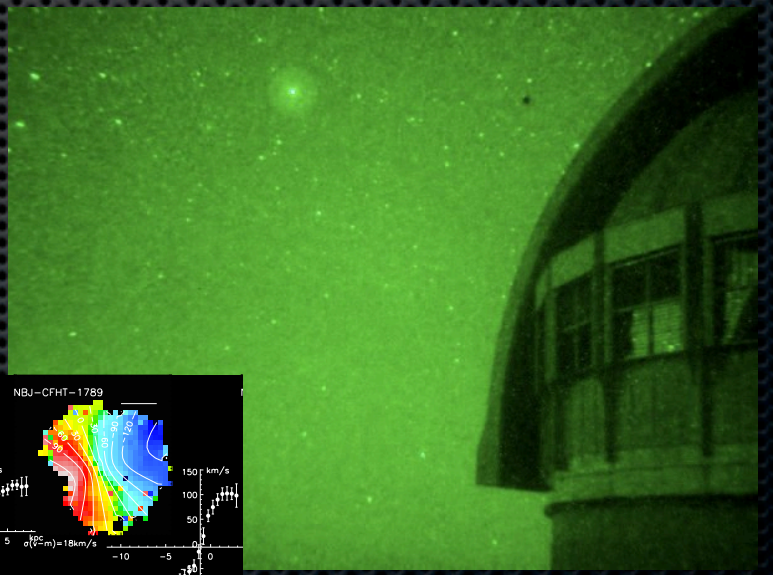
with KMOS, SINFONI & HST

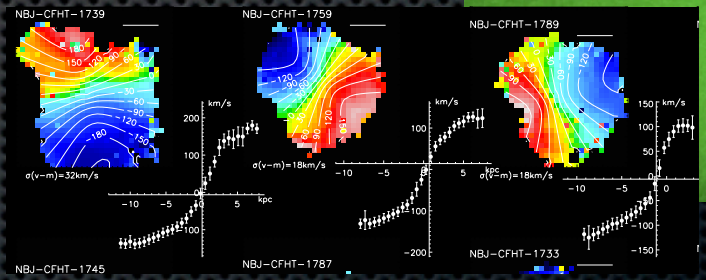
David Sobral

Leiden Observatory









Jorryt Matthee, Mark Swinbank, John Stott,
Richard Bower, Philip Best, Ian Smail, Edo Ibar,
Yusei Koyama, Masao Hayashi, Jim Geach, +

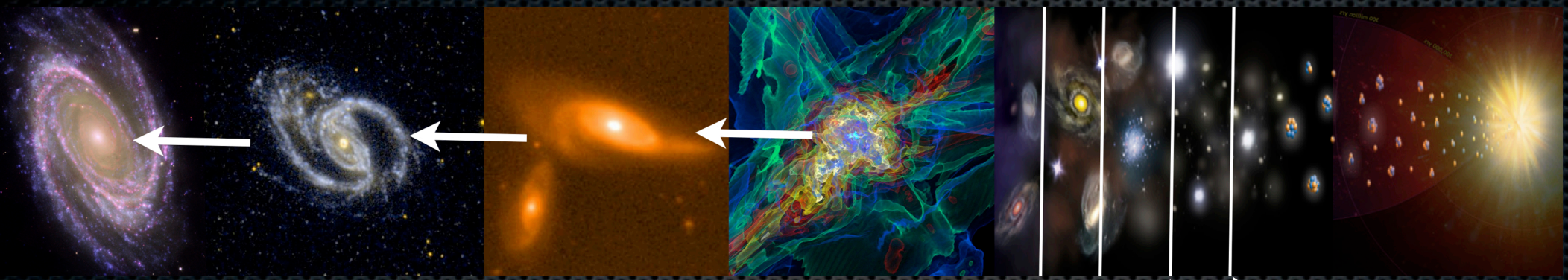
Sterrewacht Leiden

How (and driven by which mechanisms)

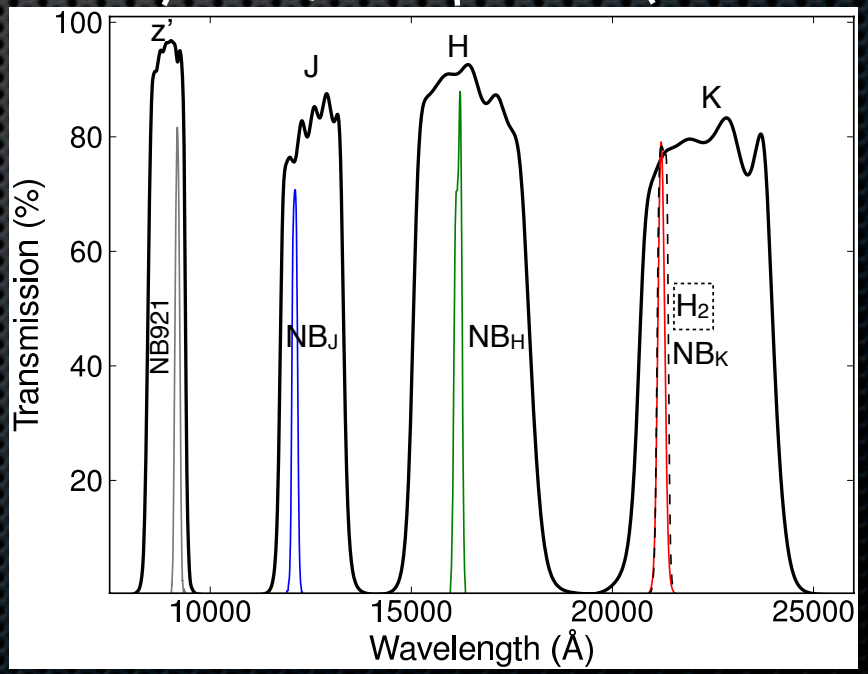
do galaxies form and evolve?

- Morphological change?
- Star formation
- "Quenching"

?

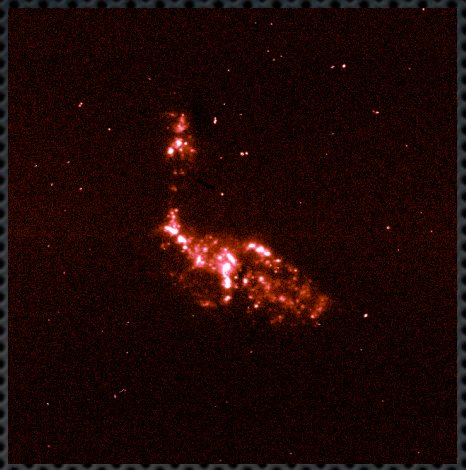


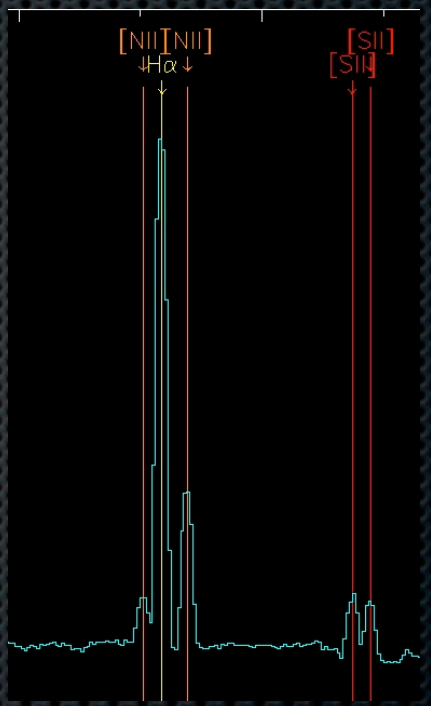
Equally selected "Slices" with >1000 star-forming galaxies in multiple environments and with a range of properties



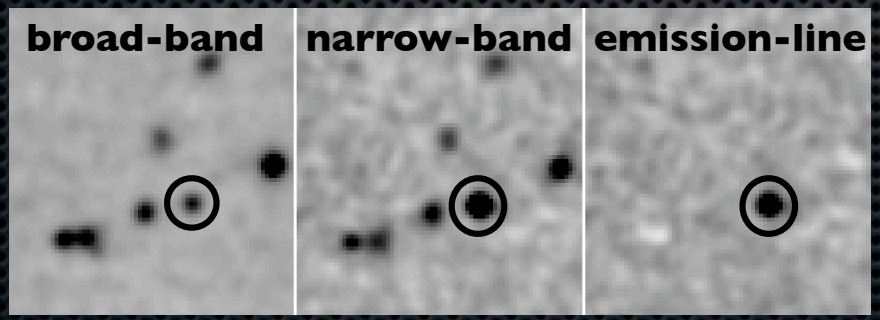
Hα (+NB)

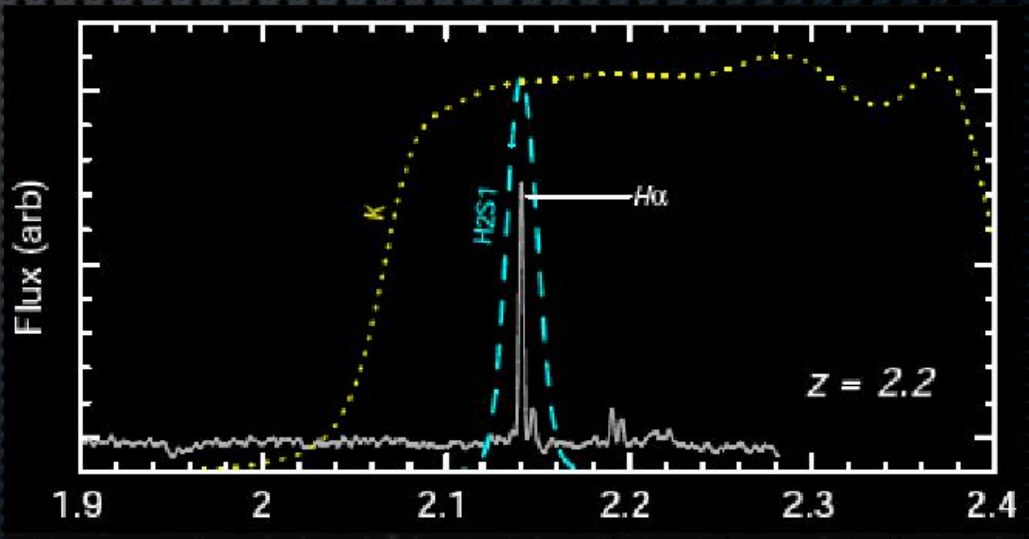
- Sensitive, good selection
- Well-calibrated
- Traditionally for Local Universe
- **Narrow-band technique**





- **Now with Wide Field near-infrared cameras: can be done over large areas**
  - **And traced up to z ~ 3**



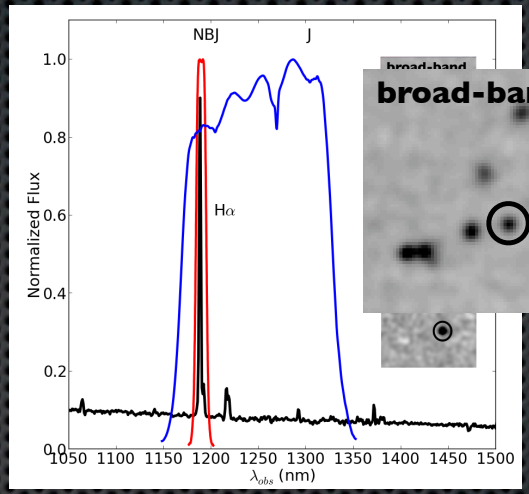


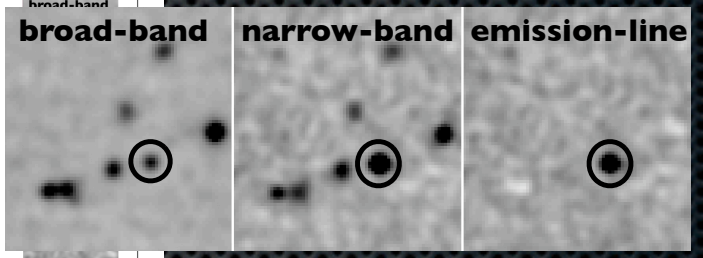
HiZELS

The High Redshift Emission Line Survey

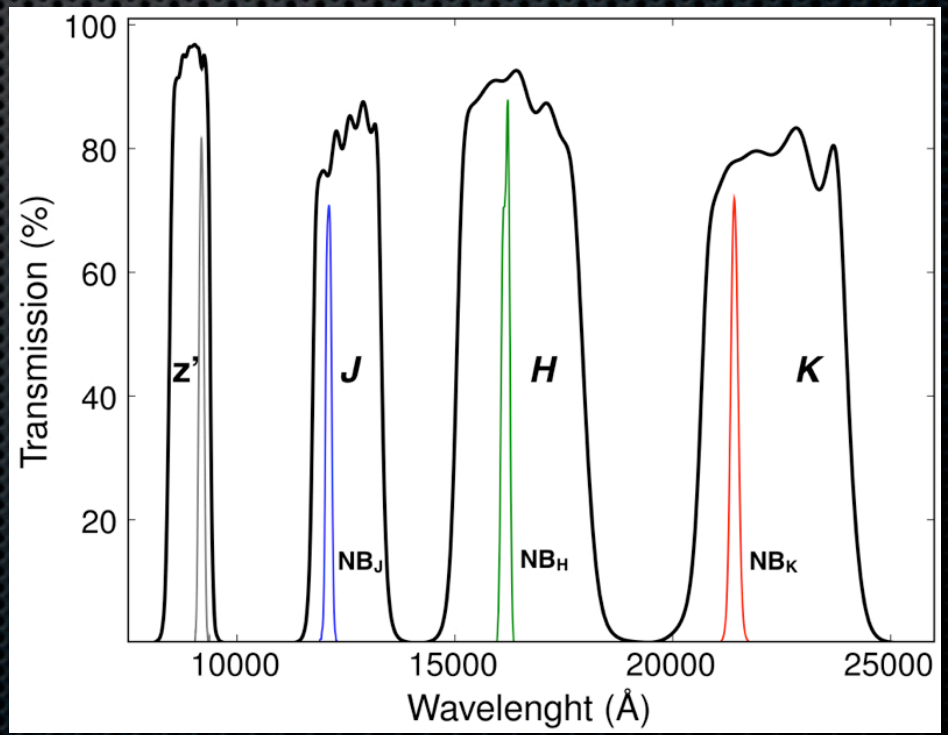
(Geach+08,Sobral+09,12,13a) (+Deep NBH + Subar-HiZELS + HAWK-I)

- **Deep & Panoramic extragalactic survey**, narrow-band imaging (NB921, NB_J, NB_H, NB_K) **over ~ 5-10 deg²**



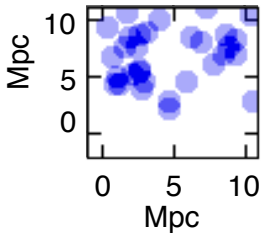


- **~70 Nights UKIRT+Subaru +VLT+CFHT**
- **>1000 galaxies per NB slice**
- Narrow-band Filters target Hα at **z=(0.2), 0.4, 0.8, 0.84, 1.47, 2.23**
- **Same reduction+analysis**
- **Other lines (simultaneously; Sobral+09a,b,Sobral+12,13a,c)**



Sobral et al. 2013a

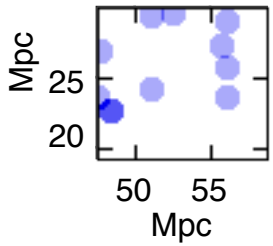
10x10 Mpc~100 arcmin²



Slices of the “Real” Universe

Hα emitters z=0.81+-0.01

10x10 Mpc~100 arcmin²



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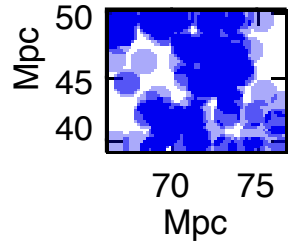

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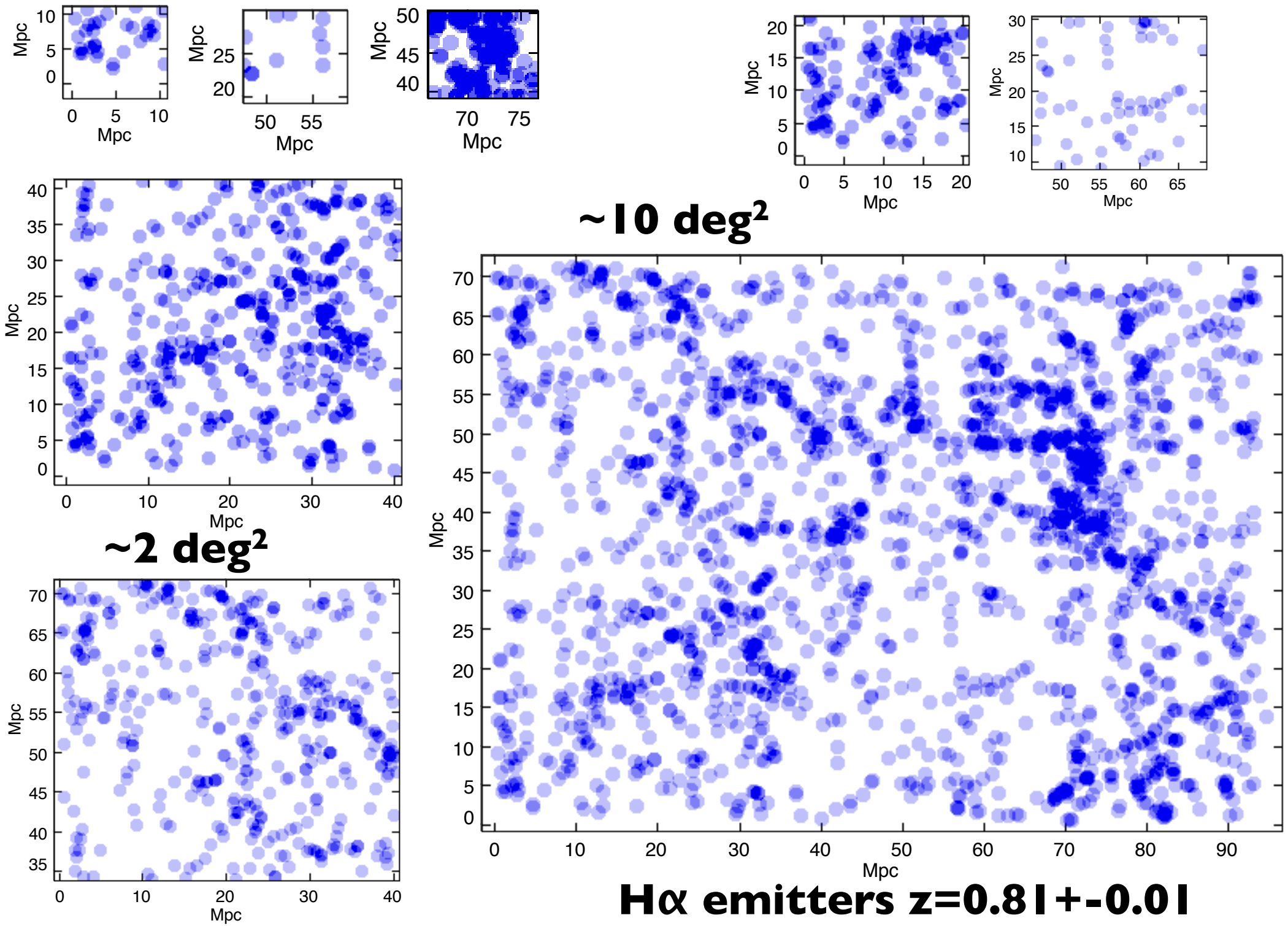
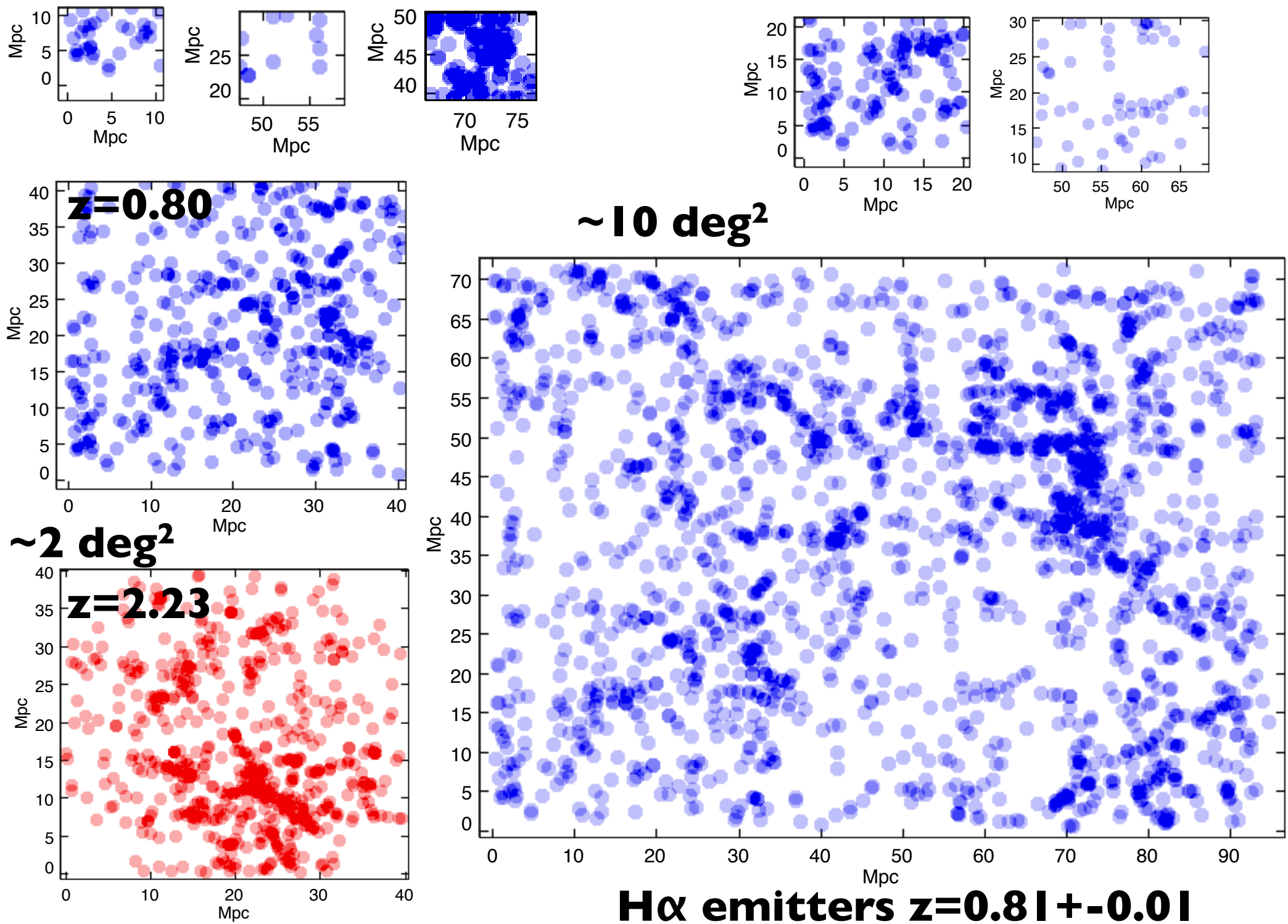
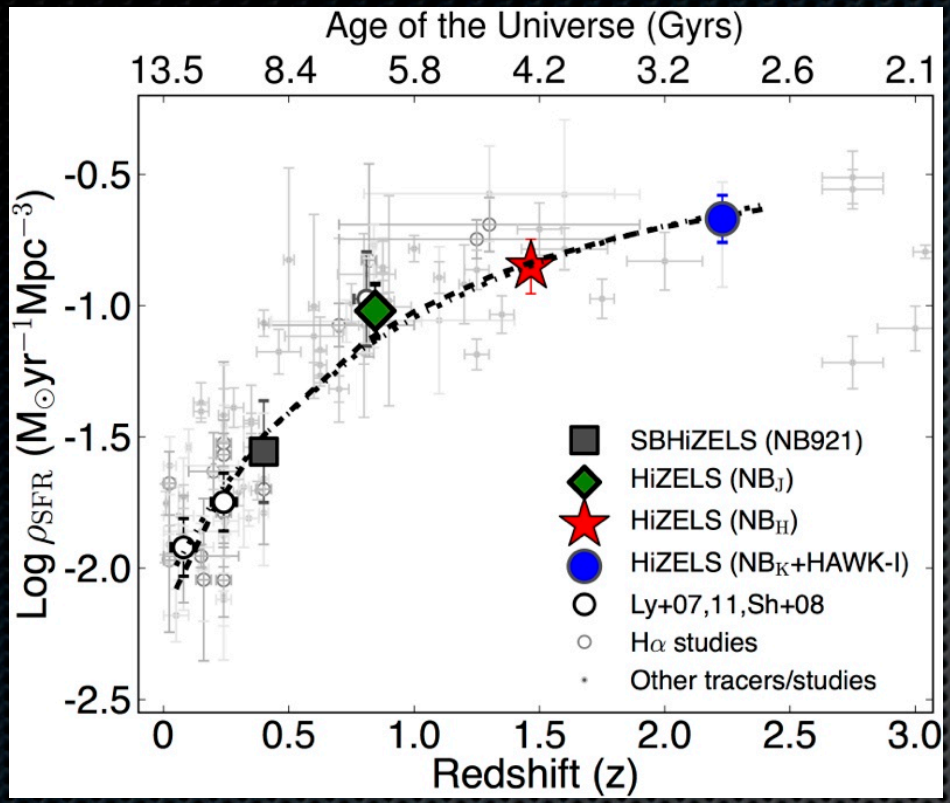

10x10 Mpc~100 arcmin²
20x20 Mpc ~0.7 deg²
~10 deg²
~2 deg²
Hα emitters z=0.81+-0.01
Mpc

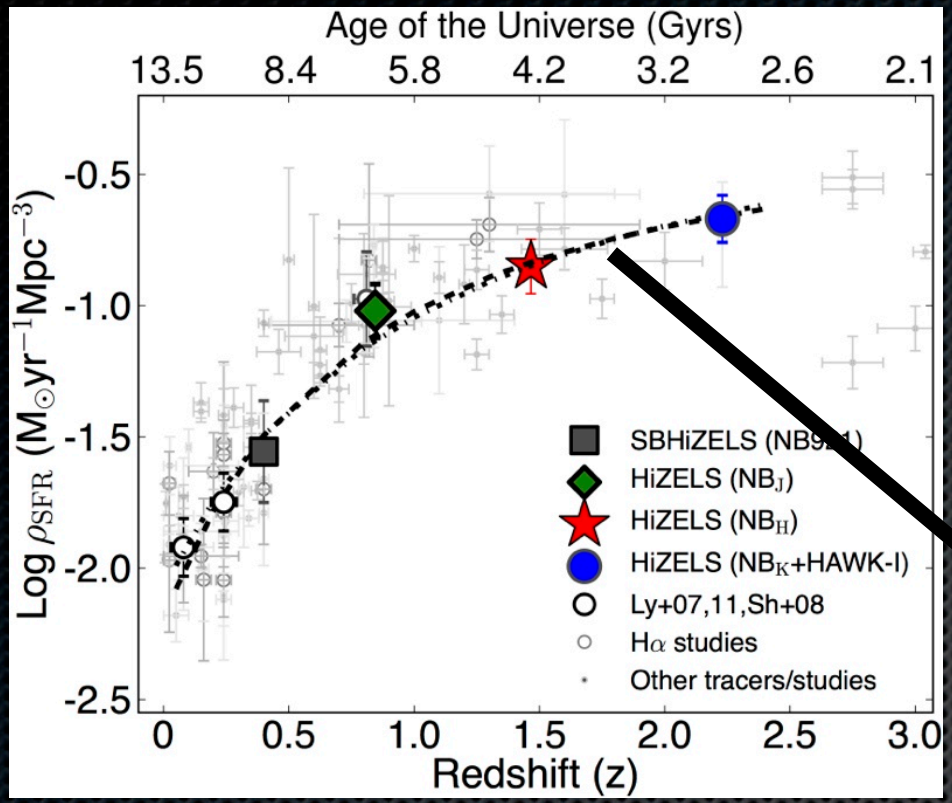

10x10 Mpc~100 arcmin²
20x20 Mpc ~0.7 deg²
z=0.80
~10 deg²
~2 deg²
z=2.23
Hα emitters z=0.81+-0.01
Mpc



Hα Star formation History

Strong decline with cosmic time

Sobral+13a



Hα Star formation History

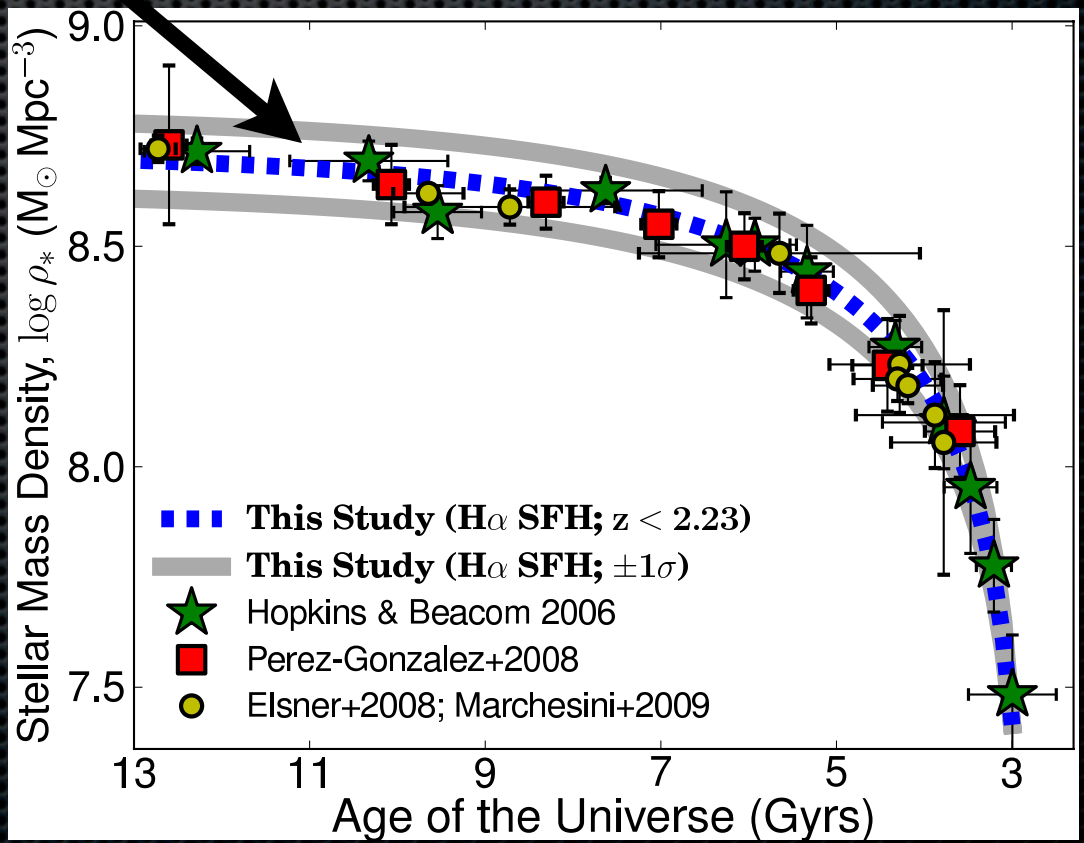
Strong decline with cosmic time

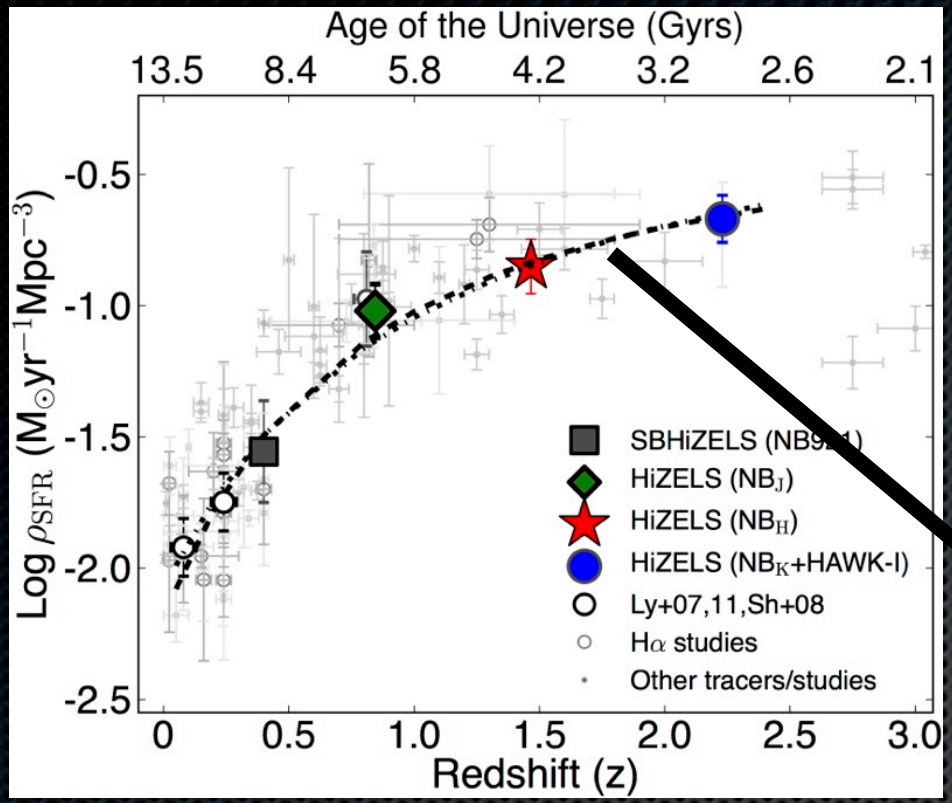
$\log_{10}$(SFRD) = -2.1/(1+z)

Sobral+13a

Stellar Mass density evolution

Star formation history prediction matches observations





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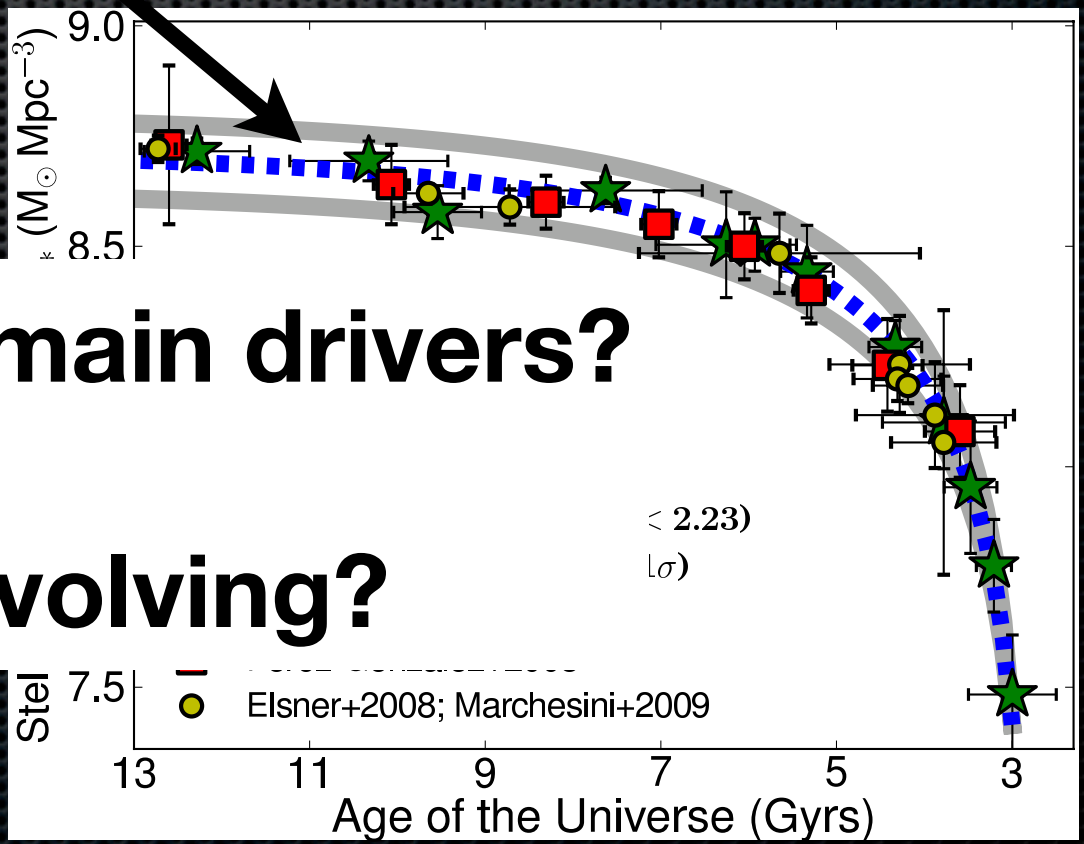


Stellar Mass density evolu

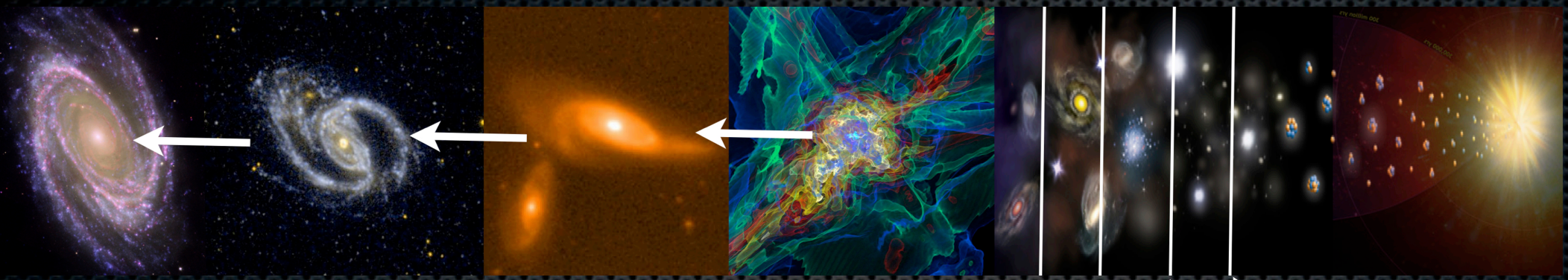
What are the main drivers?

Star f

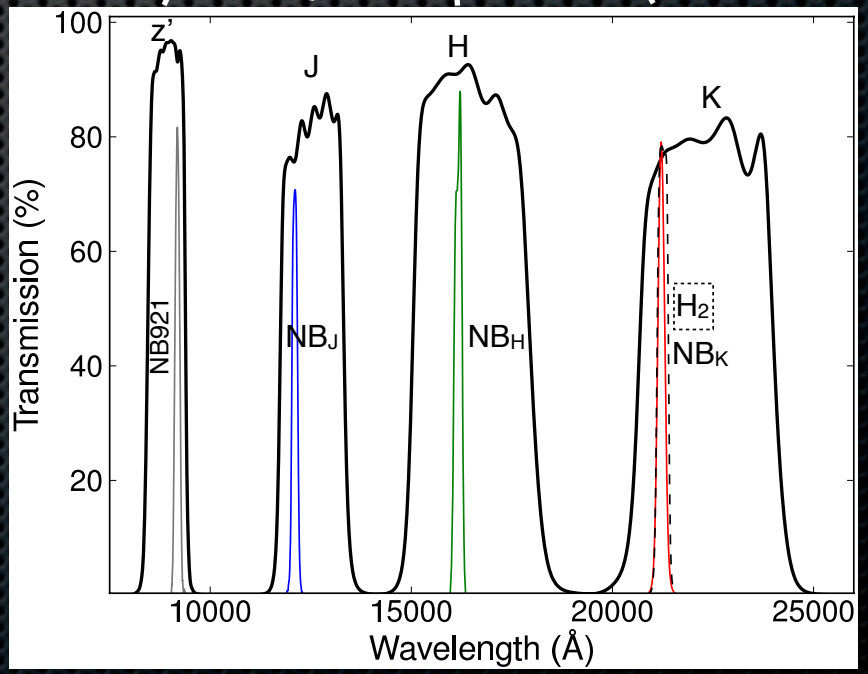
prec

observations

What's evolving?



Equally selected "Slices" with >1000 star-forming galaxies in multiple environments and properties



Sobral+13a

SFR function: Strong SFR* evolution

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

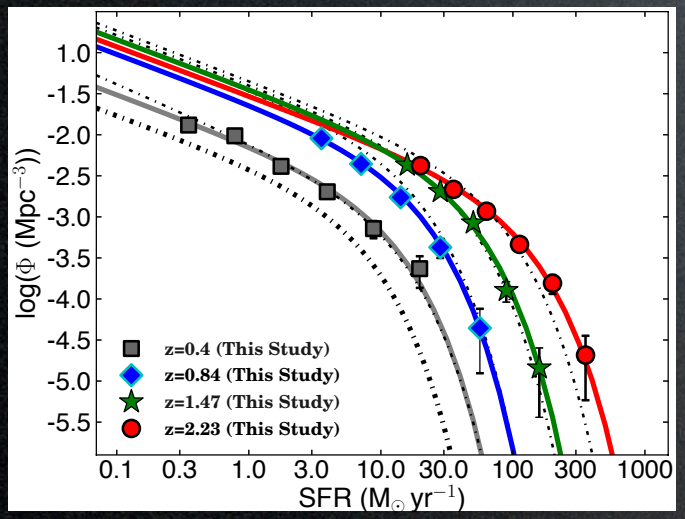
T, Gyrs

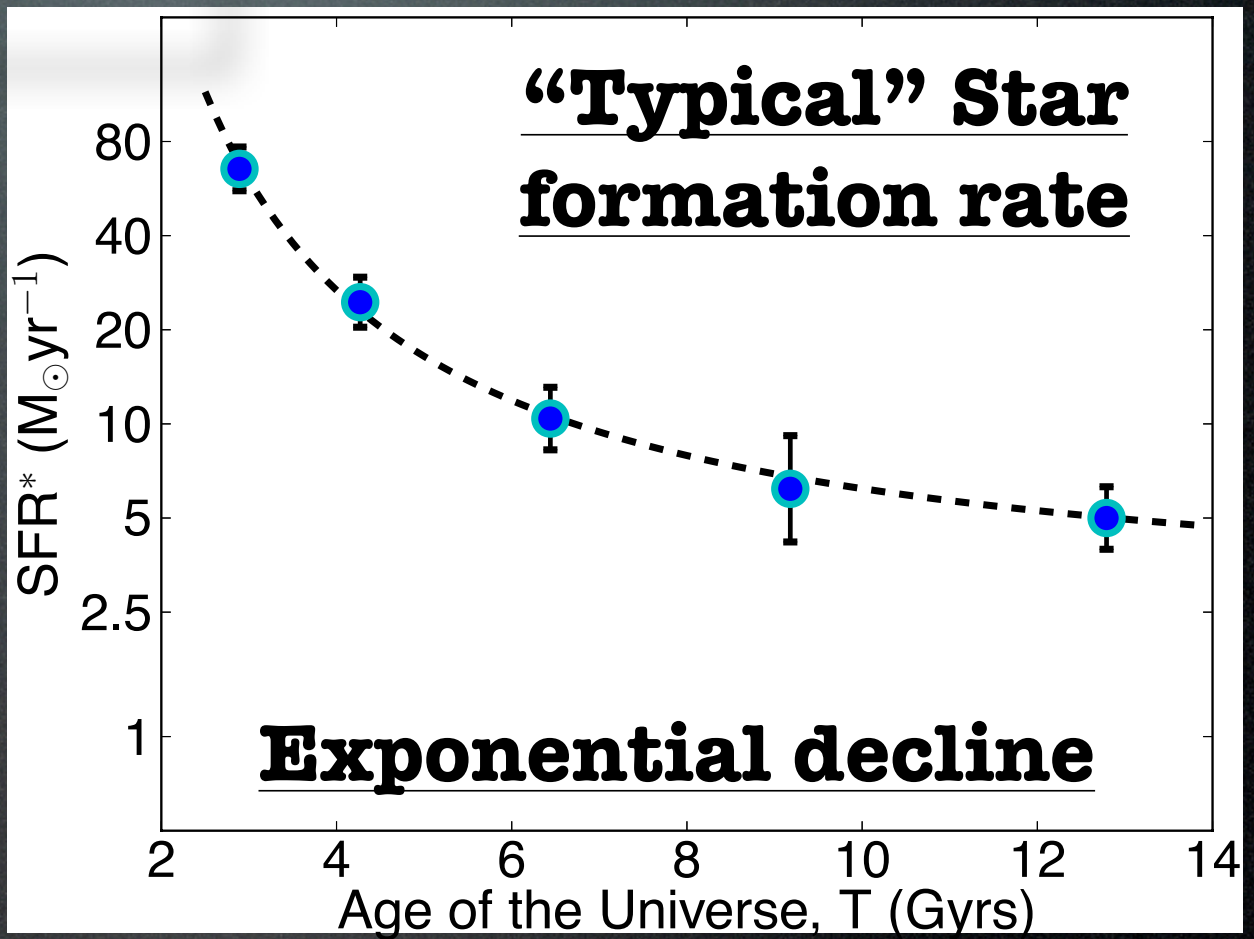
13x decrease over last 11 Gyrs

Sobral+13c, MNRAS

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

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





Φ*: z=1, z=0, z=2

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

T, Gyrs

SFR function: Strong SFR* evolution

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

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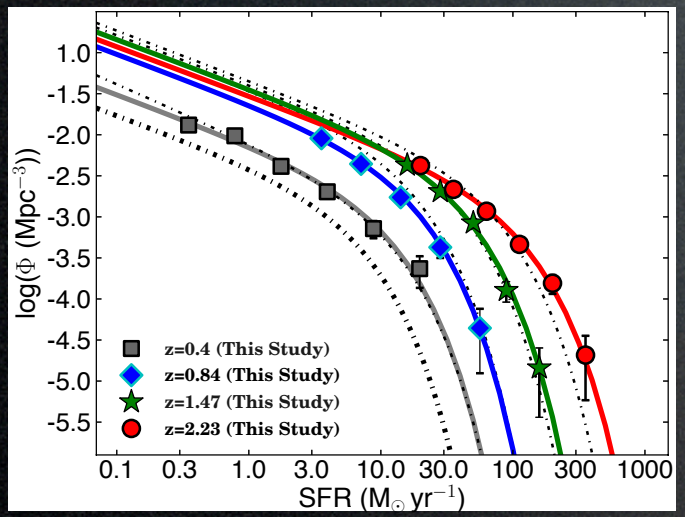

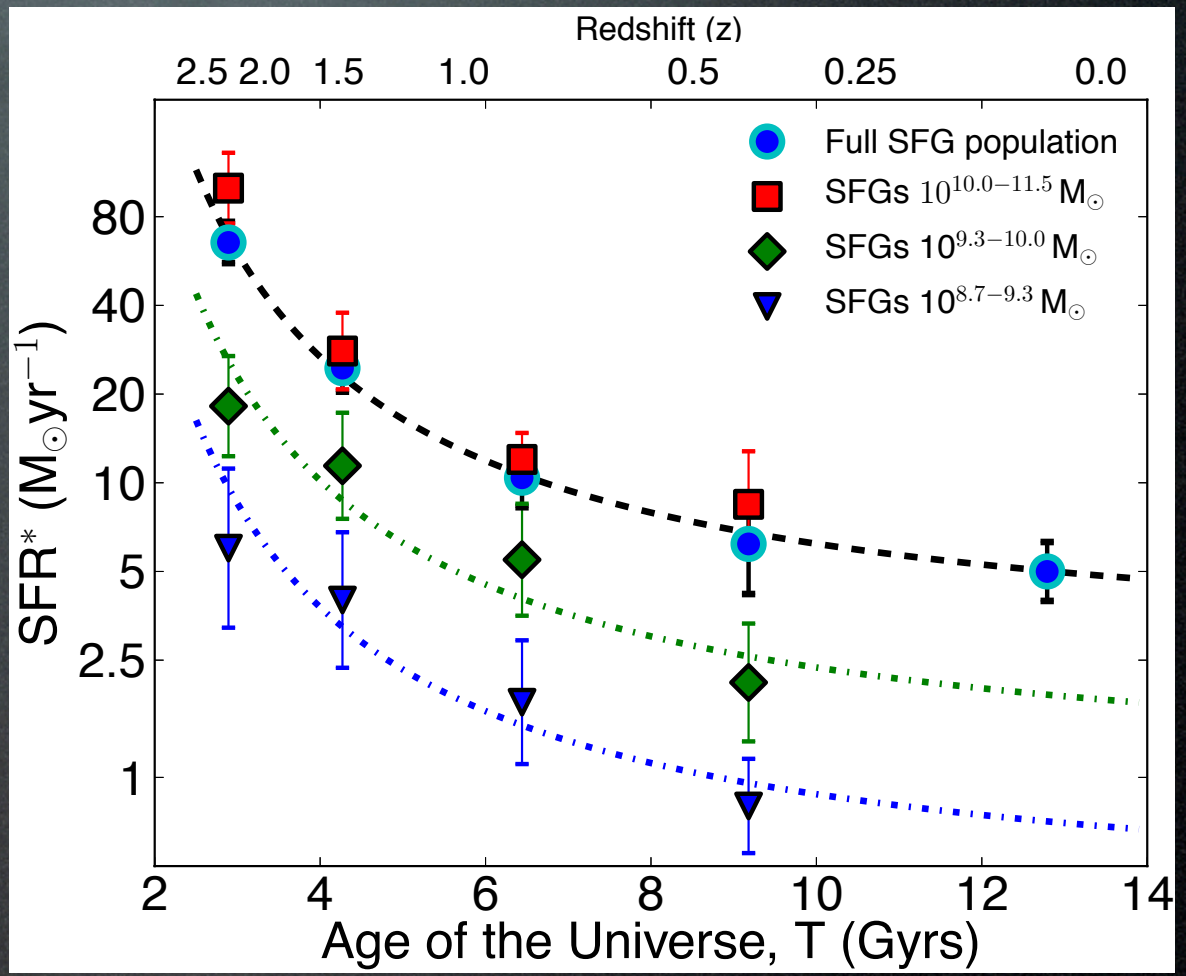

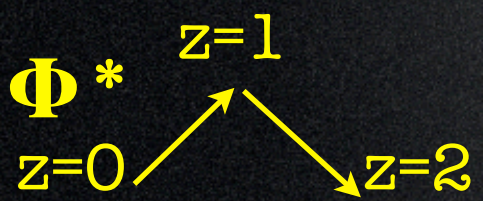

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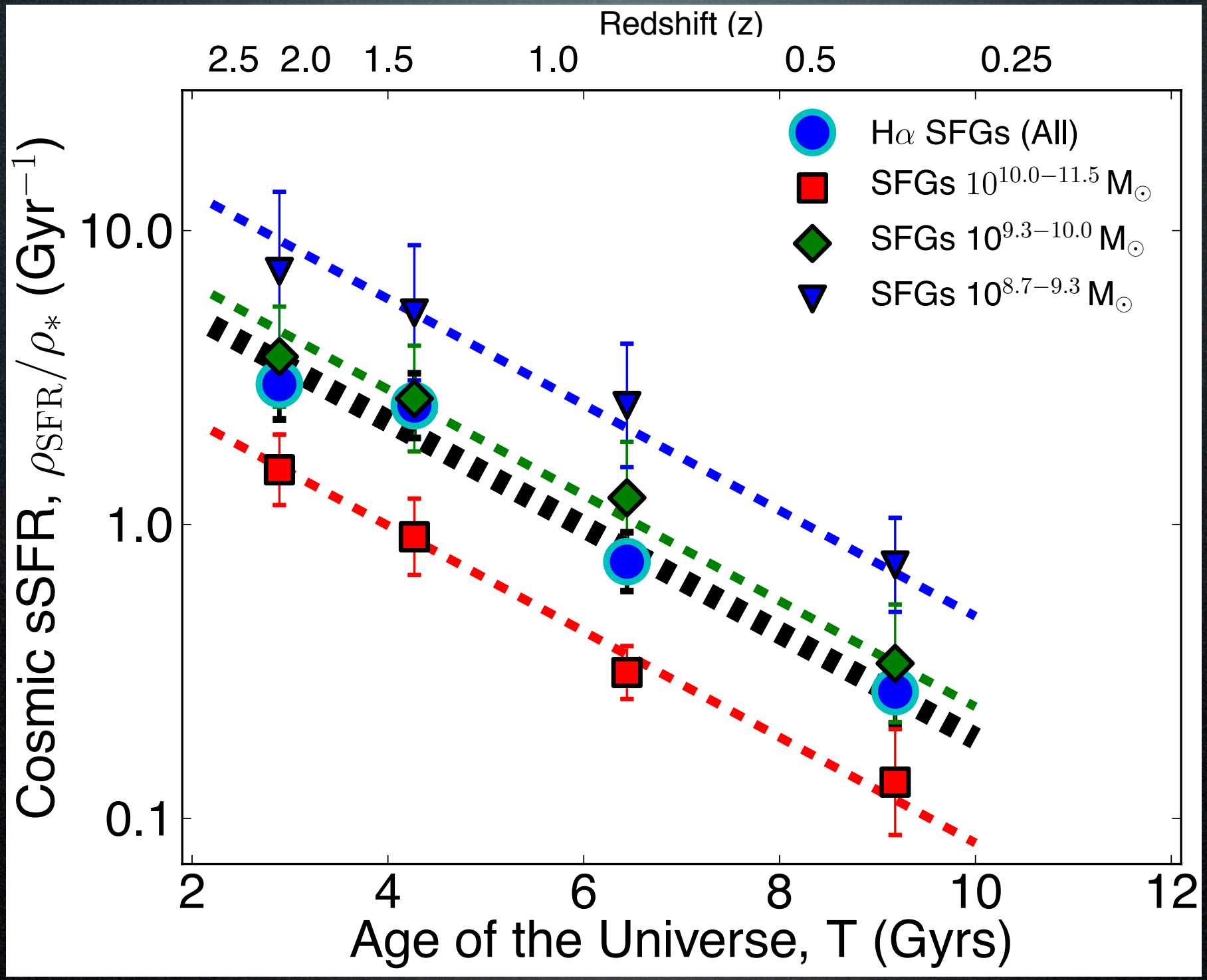
T, Gyrs


Redshift (z)
2.5
2.0
1.5
1.0
0.5
0.25
Hα SFGs (All)
SFGs $10^{10.0-11.5}$ M$_\odot$
SFGs $10^{9.3-10.0}$ M$_\odot$
SFGs $10^{8.7-9.3}$ M$_\odot$
Cosmic sSFR, $\rho_{\rm SFR}/\rho_*$ (Gyr^{-1})
10.0
1.0
0.1
2
4
6
8
10
12
Age of the Universe, T (Gyrs)

Sobral+13c

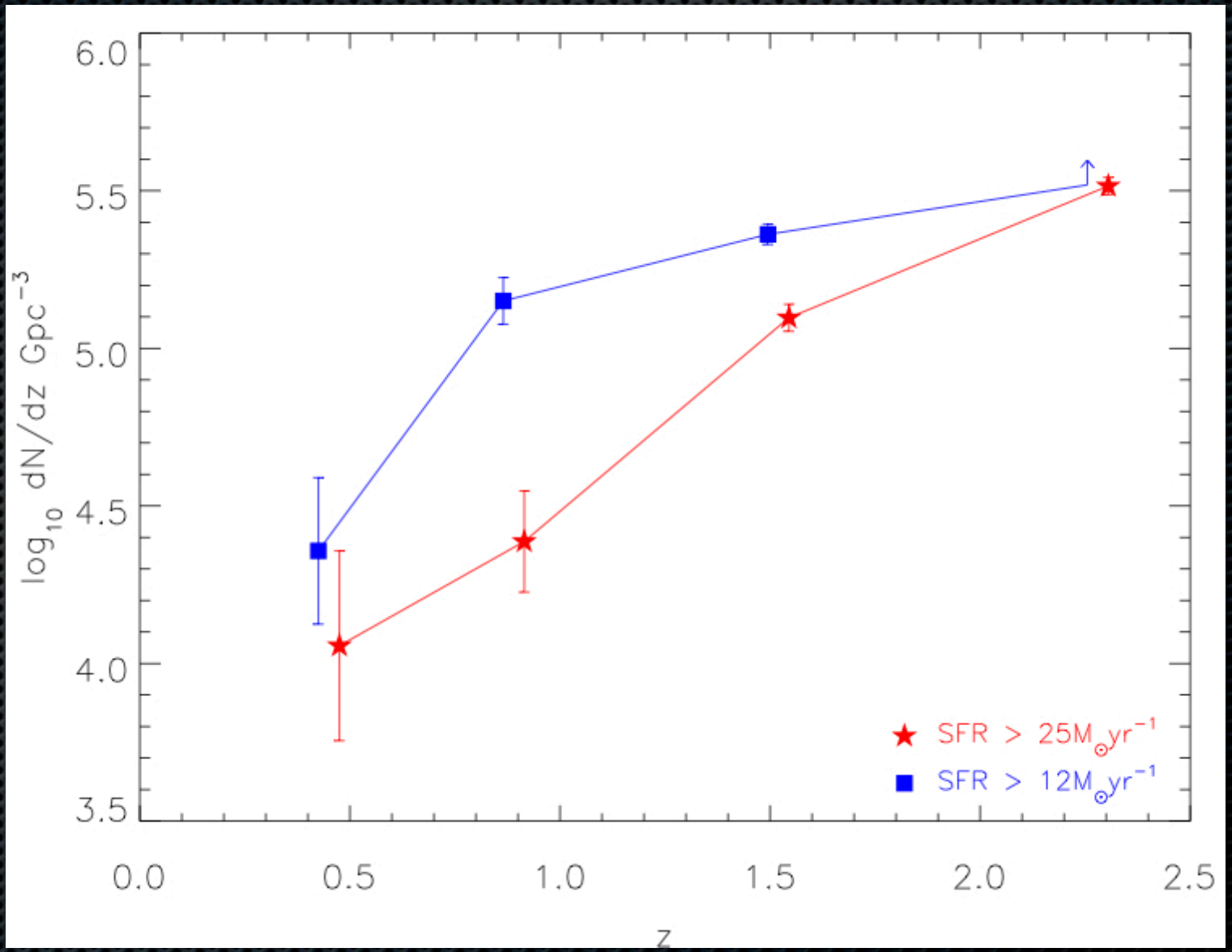
Evolution!?

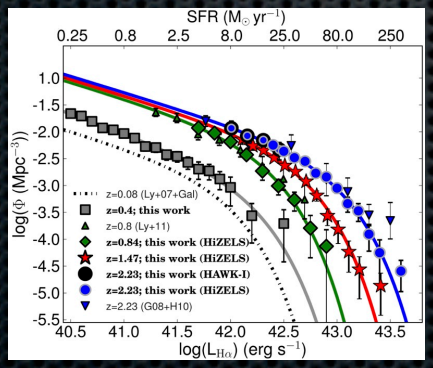
LIRGs & ULIRGs “increase”?

Stott et al. 2013

SFR > 12 M/yr

SFR > 25 M/yr



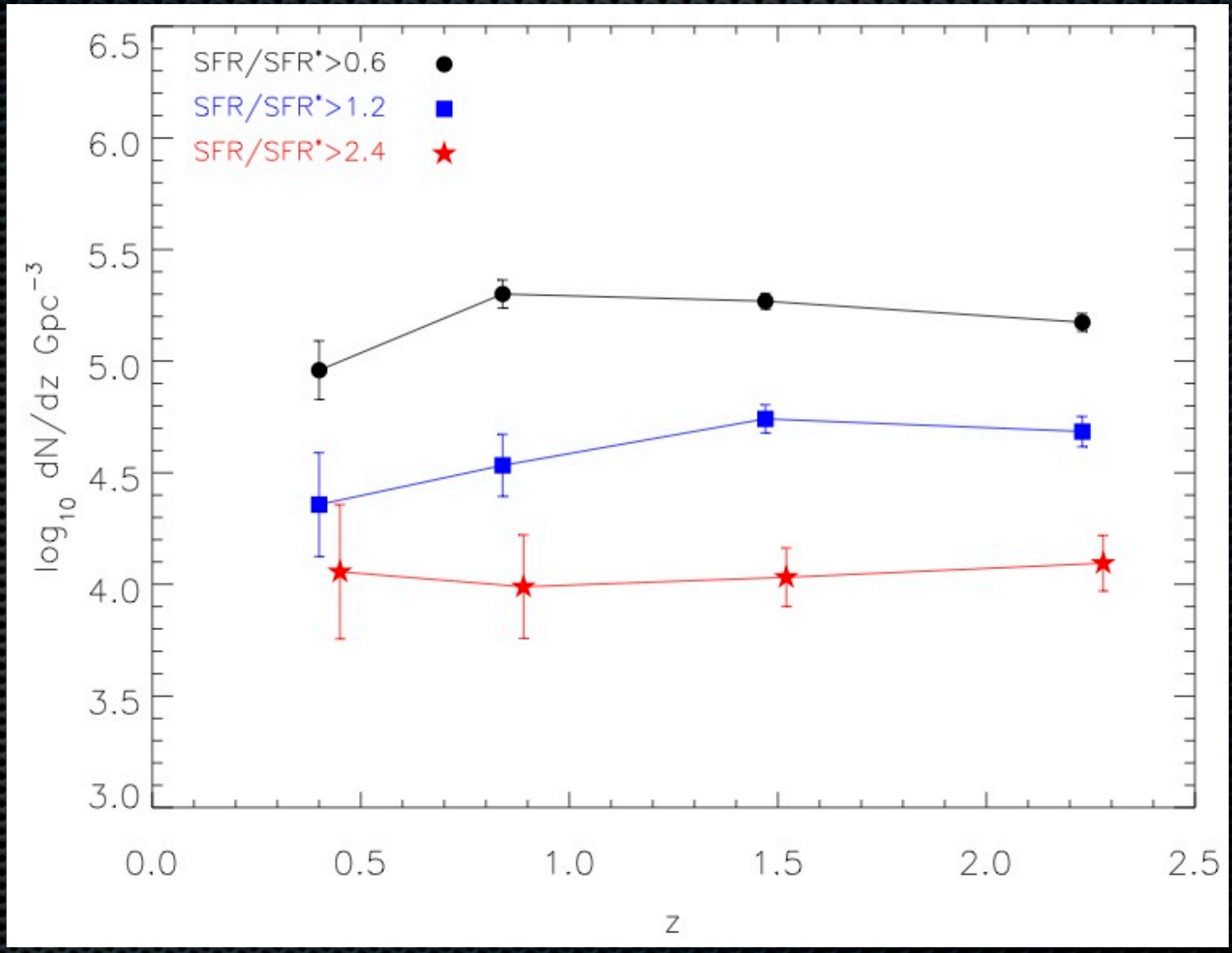


Accounting for evolution of the typical SFR (SFR* or L*):

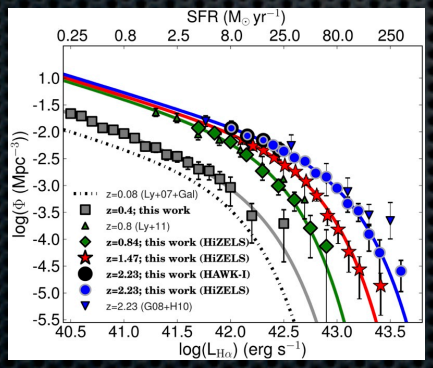
$$\log L^*(z) = 0.45z + \log L^*_{z=0}$$

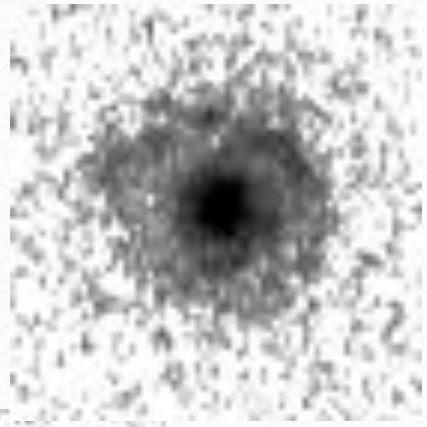
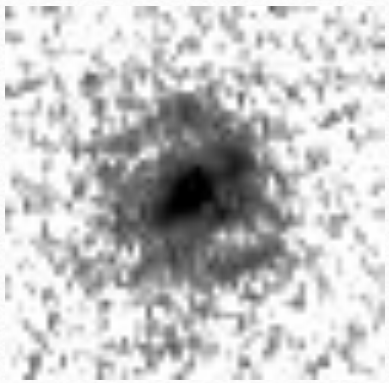
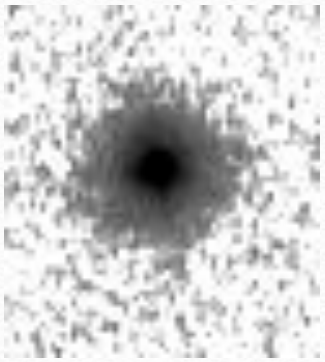
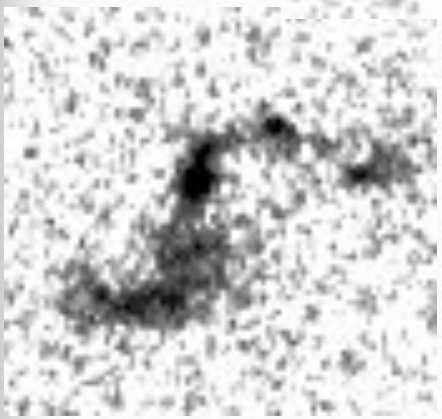
Stott et al. 2013

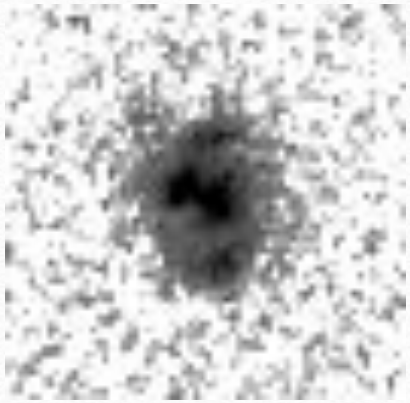
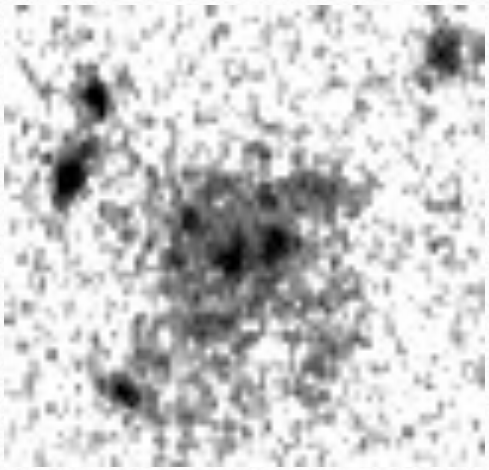
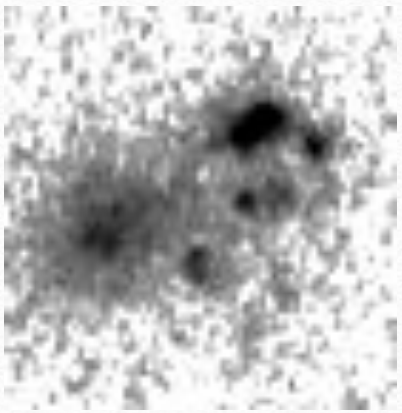
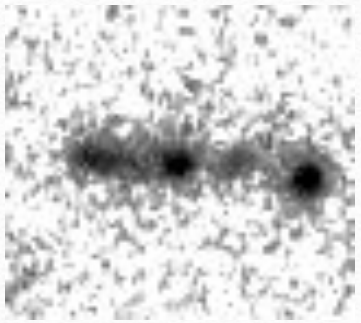
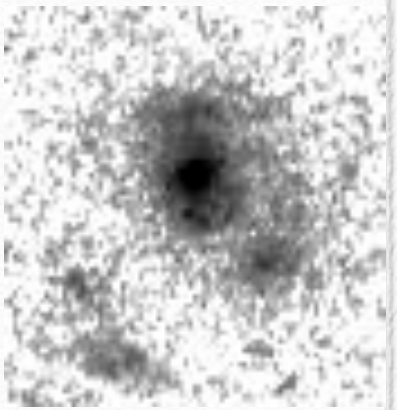
Number density of SF galaxies relative to the typical SFR at their epoch (SFR*(z)) is ~constant over the last 11 Gyrs



After accounting for SFR* evolution



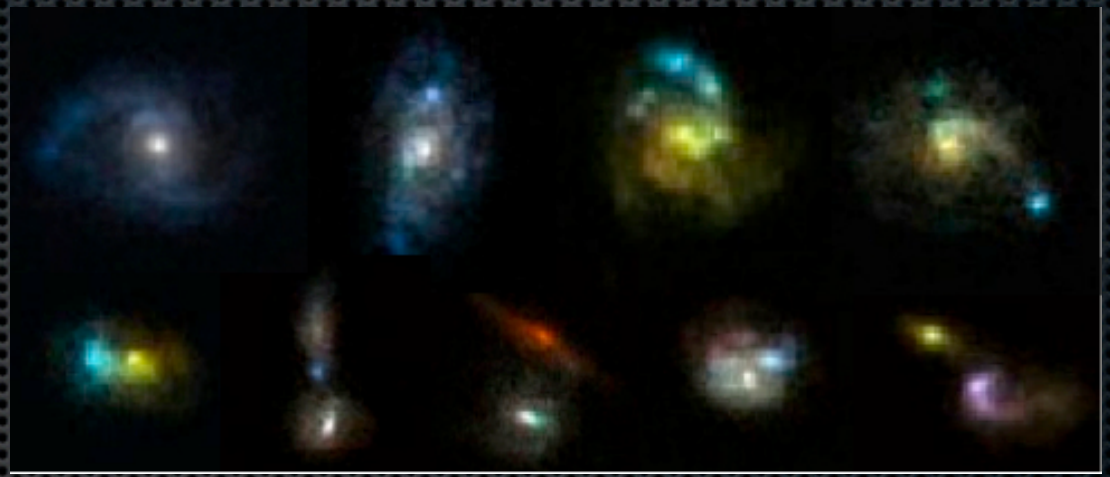






Morphologies: ACS+CANDELS

Hα Star-forming galaxies since z=2.23

Discs/Non-mergers
~75%

Mergers/Irregulars
~25%



Mergers ~
20-30% up to
z=2.23

Sizes (M*):
3.6+-0.2 kpc

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

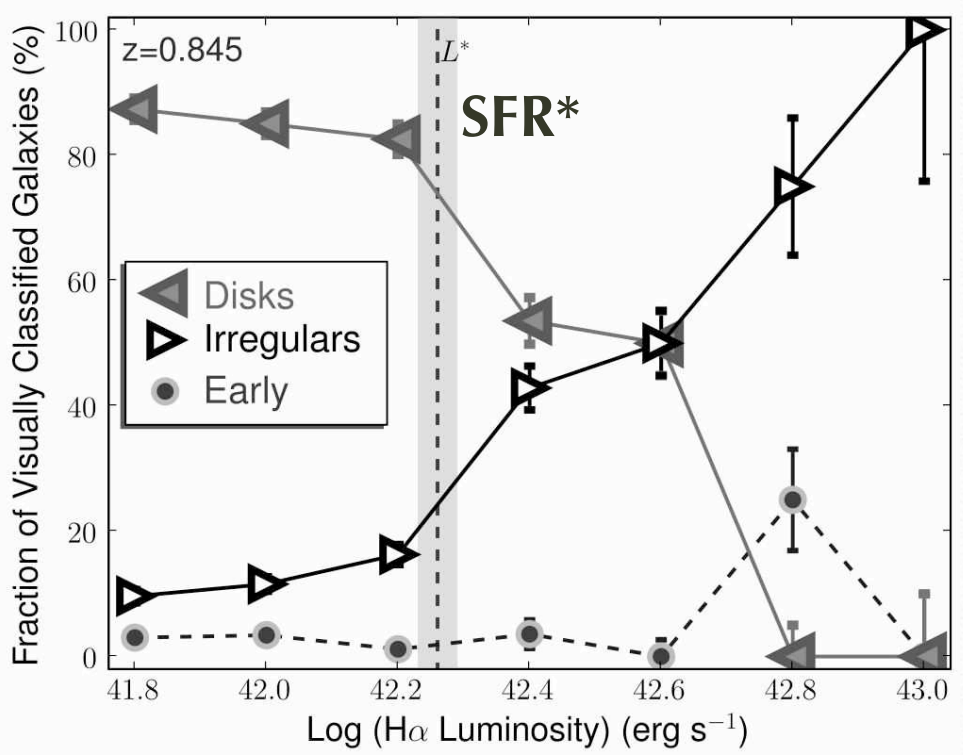
z	a	b	r_e at $\log_{10}(M_\star) = 10$ (kpc)
0.40	0.08±0.02	0.55±0.03	3.6±0.2
0.84	0.03±0.02	0.54±0.01	3.5±0.1
1.47	0.03±0.02	0.59±0.01	3.9±0.2
2.23	0.08±0.03	0.51±0.02	3.3±0.2

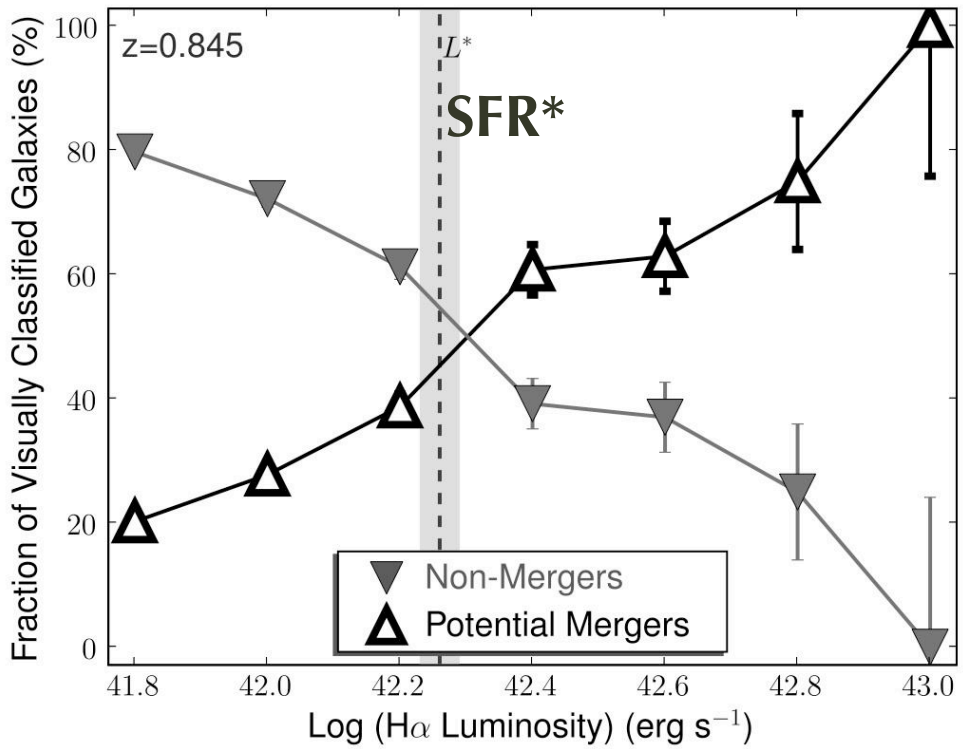
Sobral+09a, Stott+13a

Morphology-SFR relation

at z~1

Sobral et al. 2009a

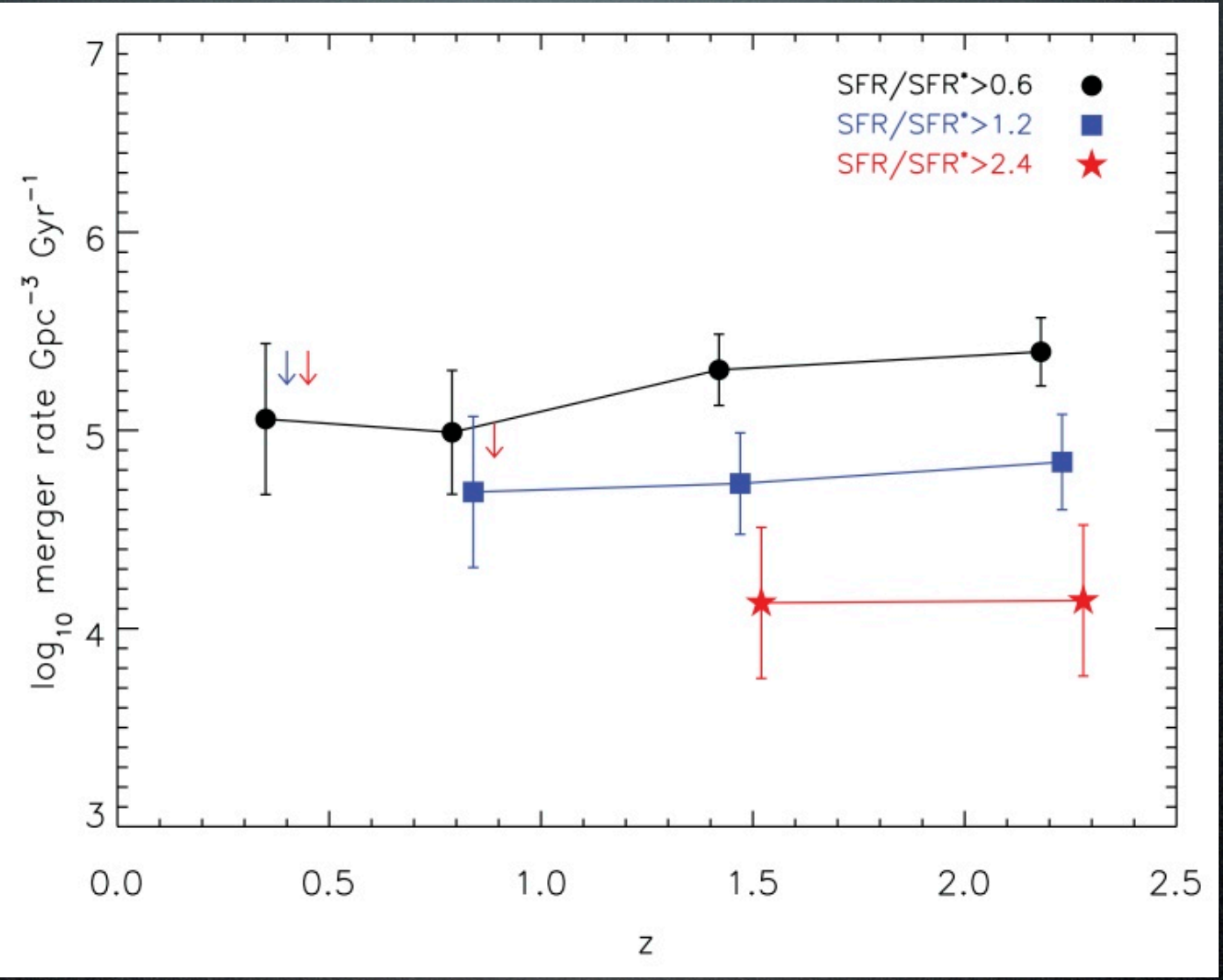




- **Depends on SFR / H-alpha Luminosity**
- Disks/non-mergers completely dominate at **SFR<SFR***, (***L*<*L****)**
- Population "shift" **~*SFR****: **Irr/mergers dominant** (reaching 100%)

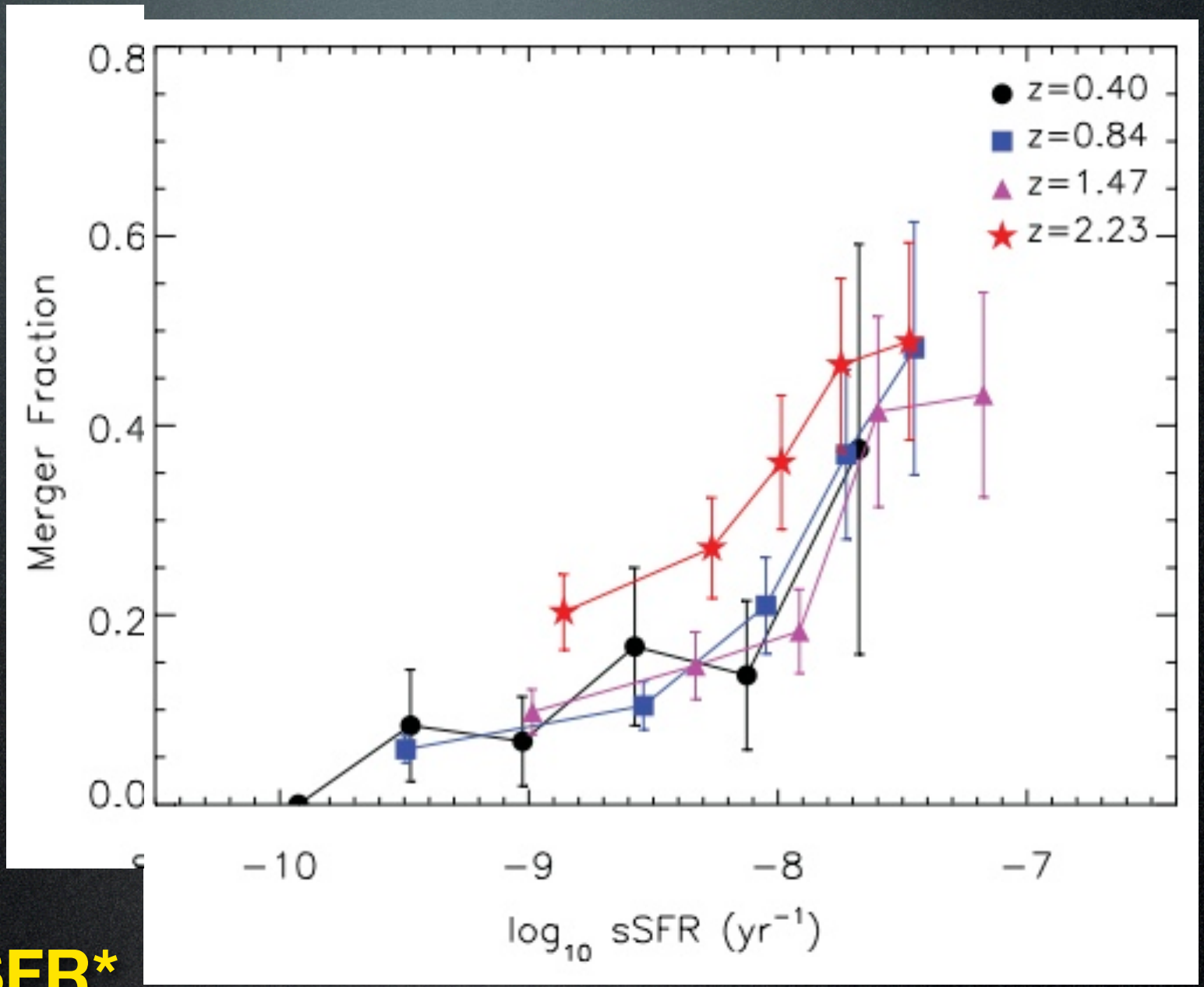
Mergers?

Stott et al. 2013a



Mergers responsible for ~20% SFRD since z=2.2 (S09)

Although:



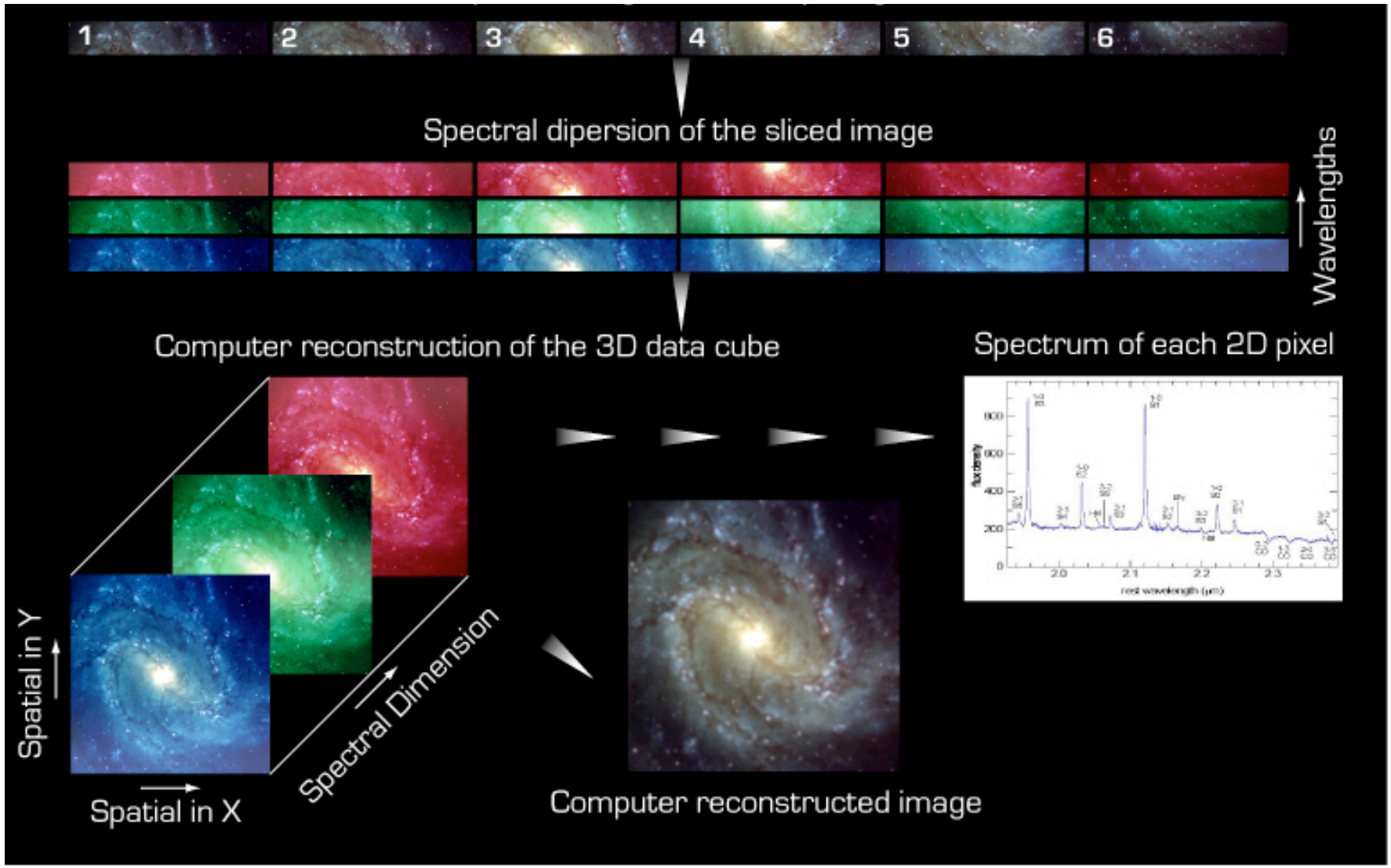
SFR> 0.2 SFR*

Stott et al. 2013a

Galaxy Dynamics at z~0.8-2.2

Integral Field Units, IFUs

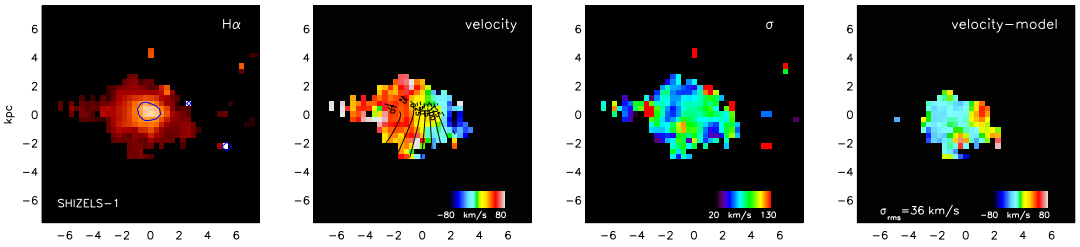
e.g. SINFONI / VLT Hα-selected targets are ideal



Galaxy Dynamics at z~0.8-2.2

Swinbank al. 2012a,b

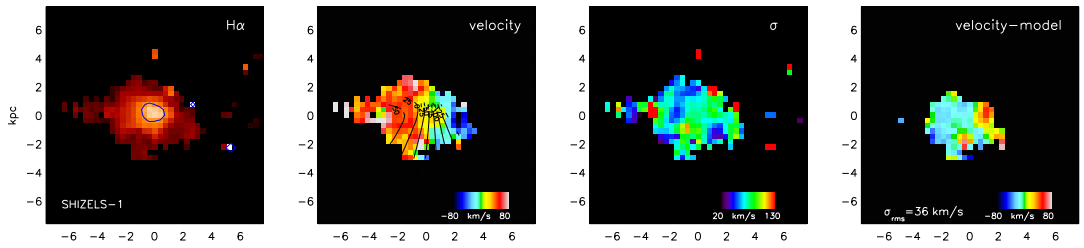
From AO IFU observations



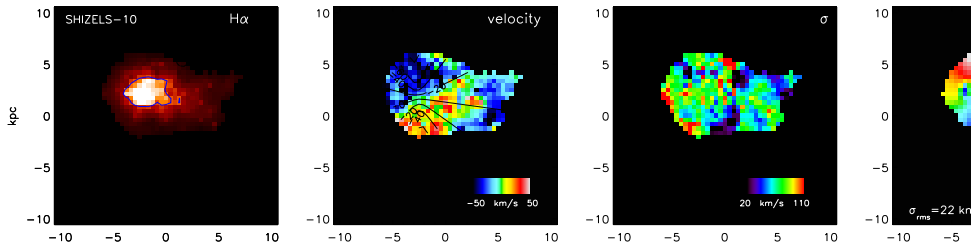
~5 hours of VLT time

Galaxy Dynamics at z~0.8-2.2

Swinbank al. 2012a,b



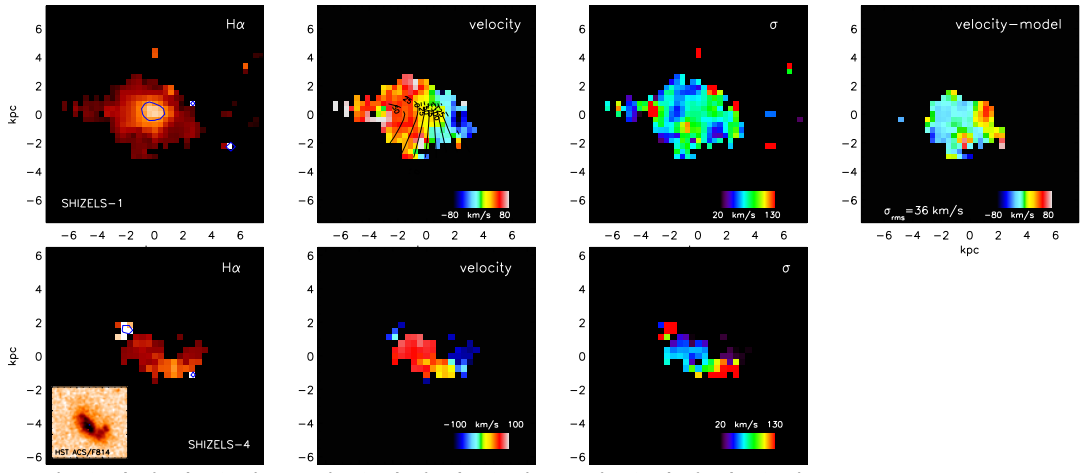
From AO IFU observations



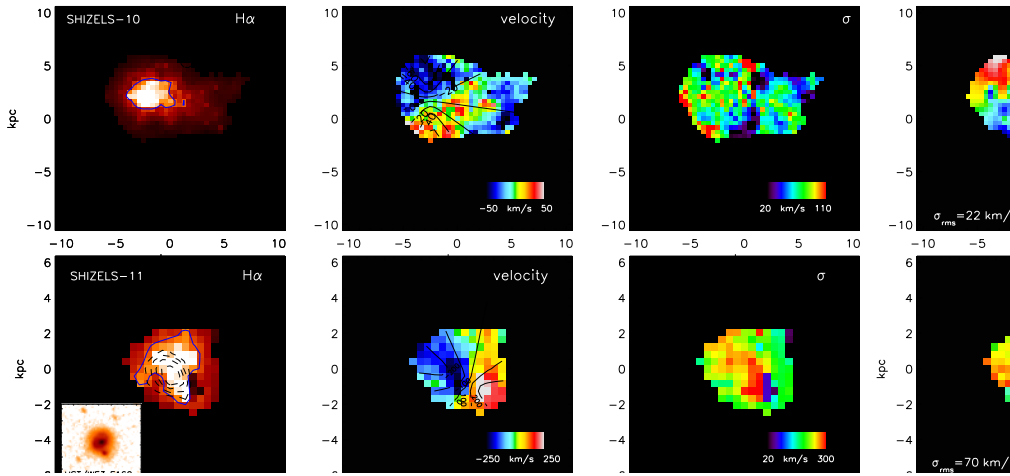
~10 hours of VLT time

Galaxy Dynamics at z~0.8-2.2

Swinbank al. 2012a,b



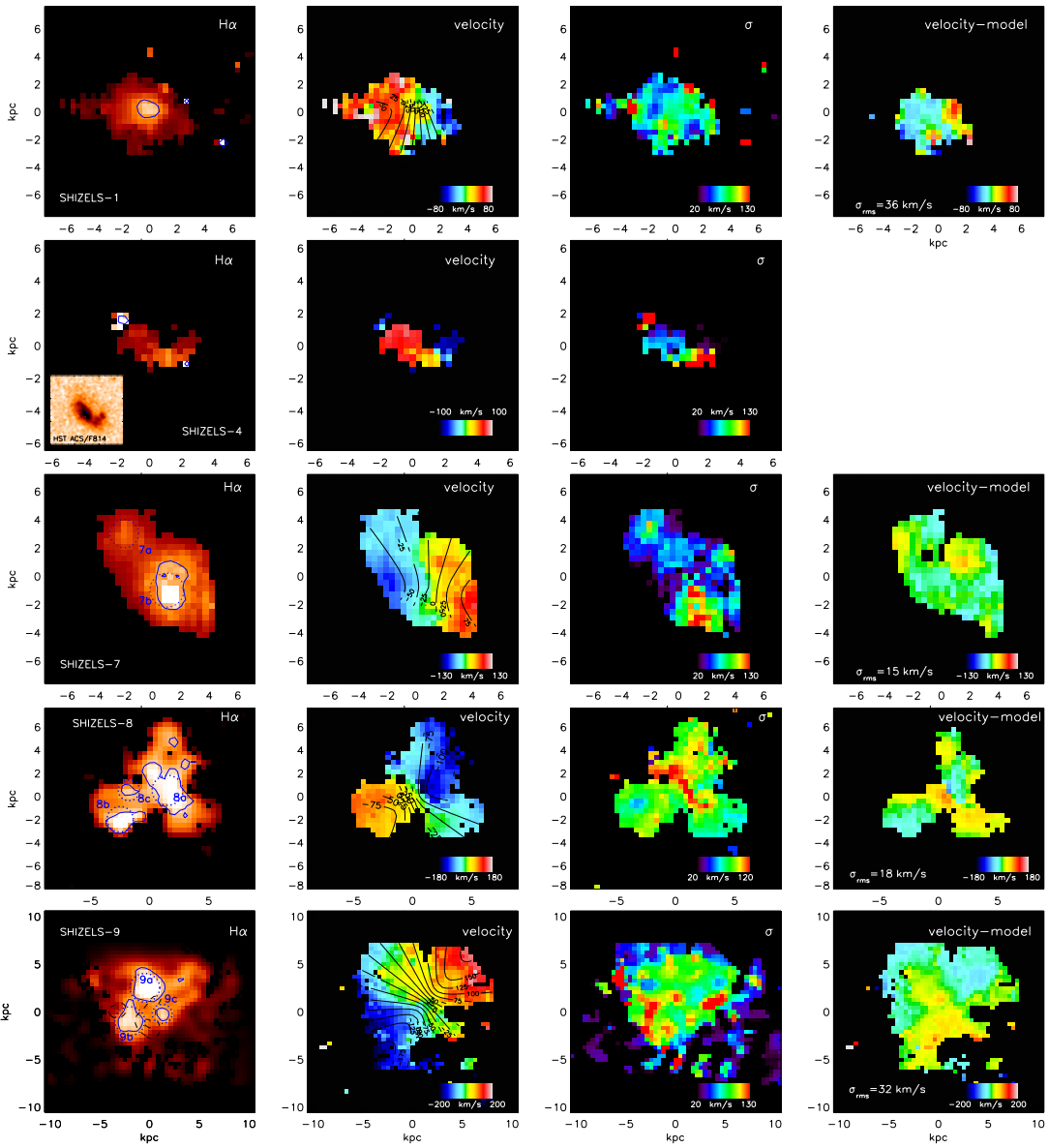
From AO IFU observations



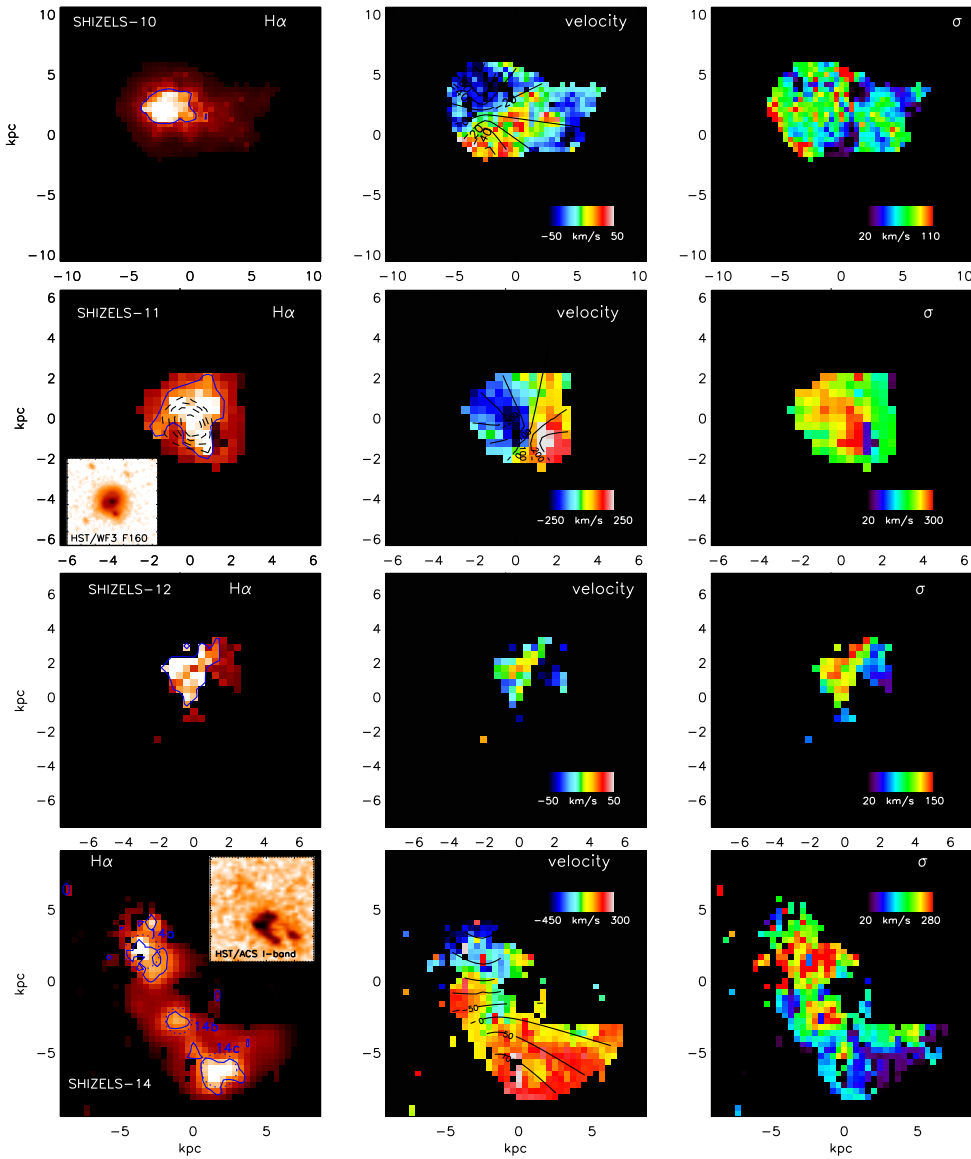
~20 hours of VLT time

Galaxy Dynamics at z~0.8-2.2

Swinbank al. 2012a,b



From AO IFU observations

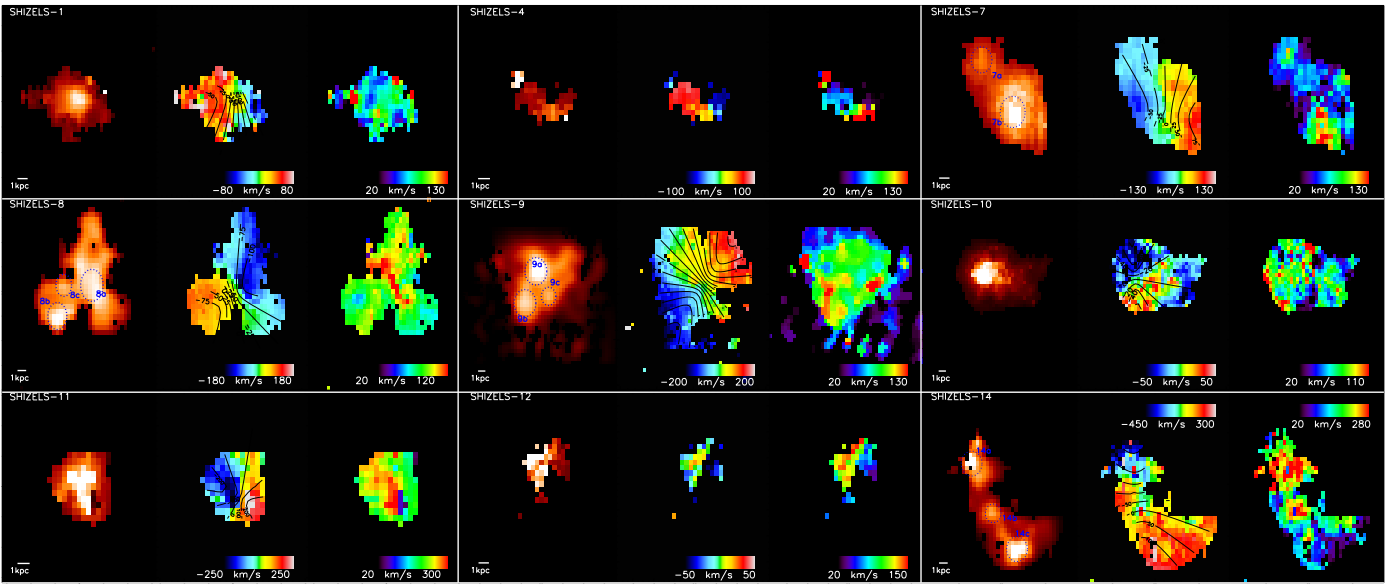


~45 hours of VLT time

Galaxy Dynamics at z~0.8-2.2

Swinbank, Sobral et al. 2012

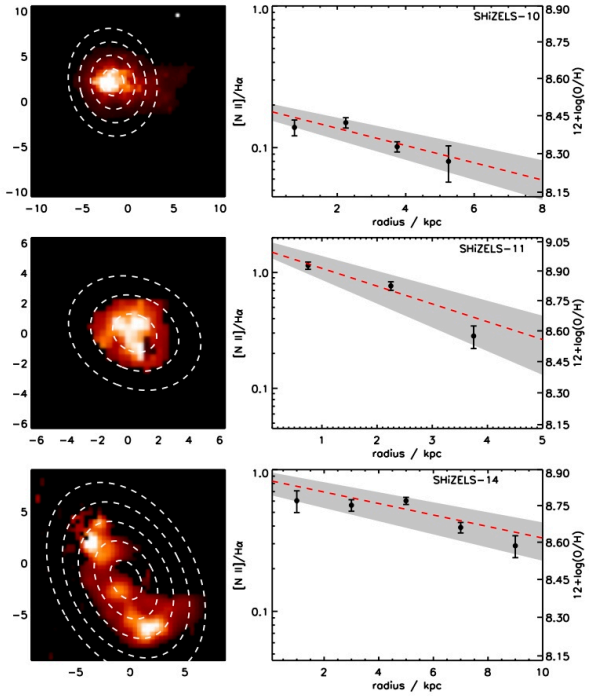
Swinbank, Smail, Sobral et al. 2012

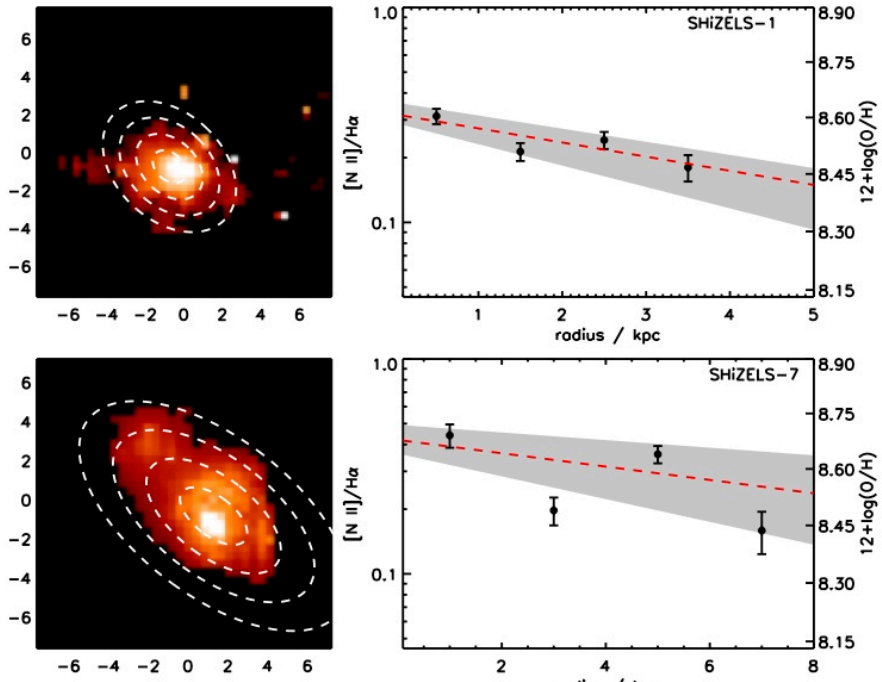


(MNRAS/ApJ):

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

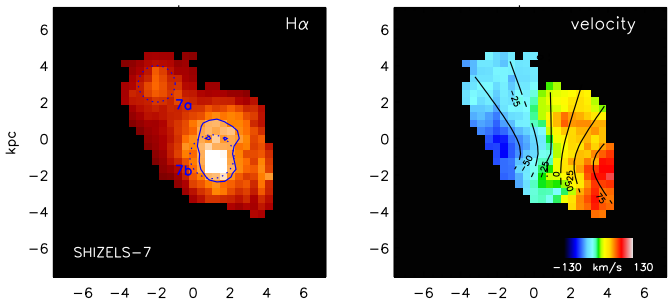
- Negative metallicity gradients: inside-out growth

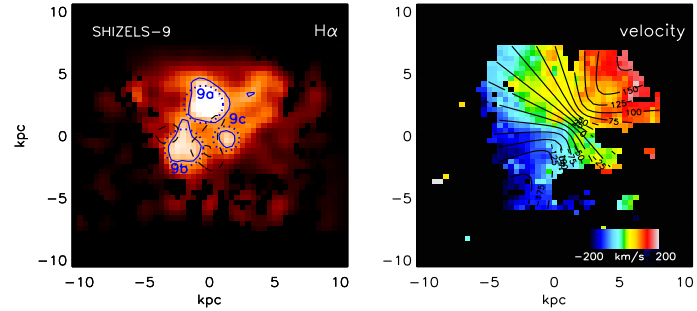




SINFONI

~50 hours of VLT time

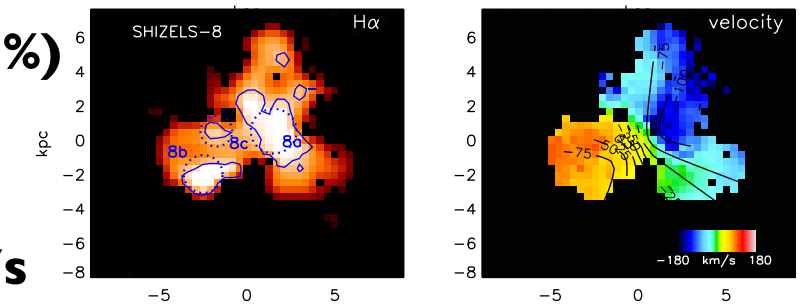




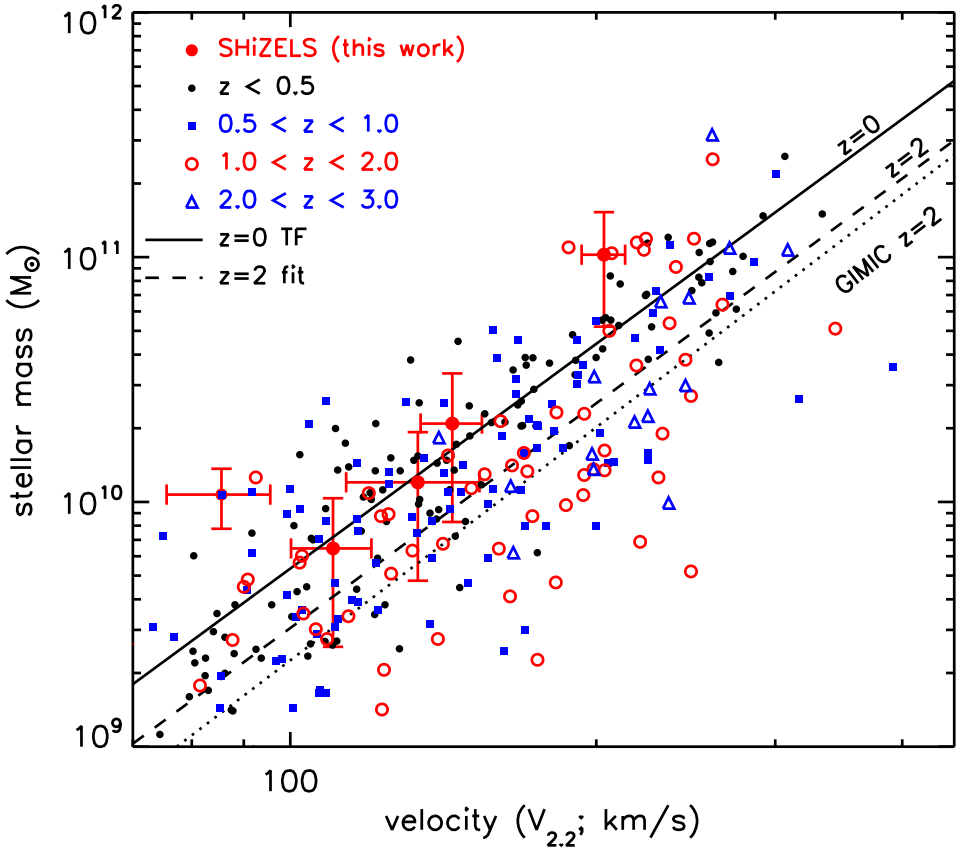
Mostly disks (~70-80%)

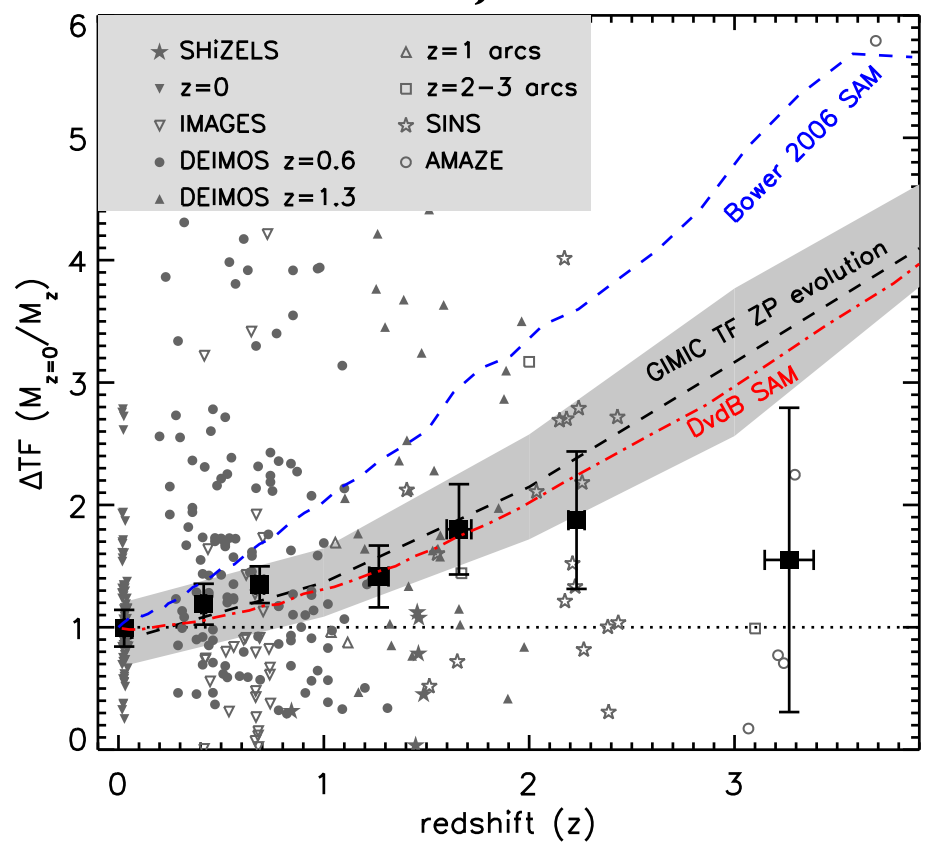
Many "clumpy"

Rotation ~70-200 km/s



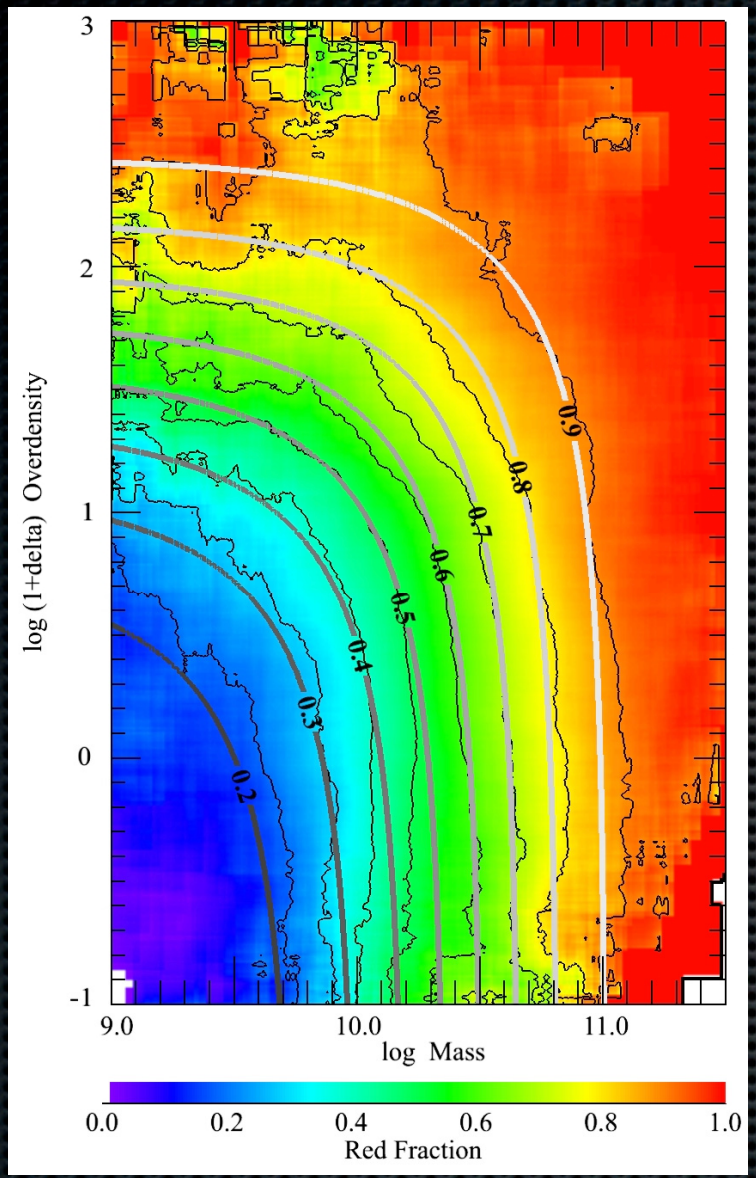
Swinbank, Sobral et al. 2012



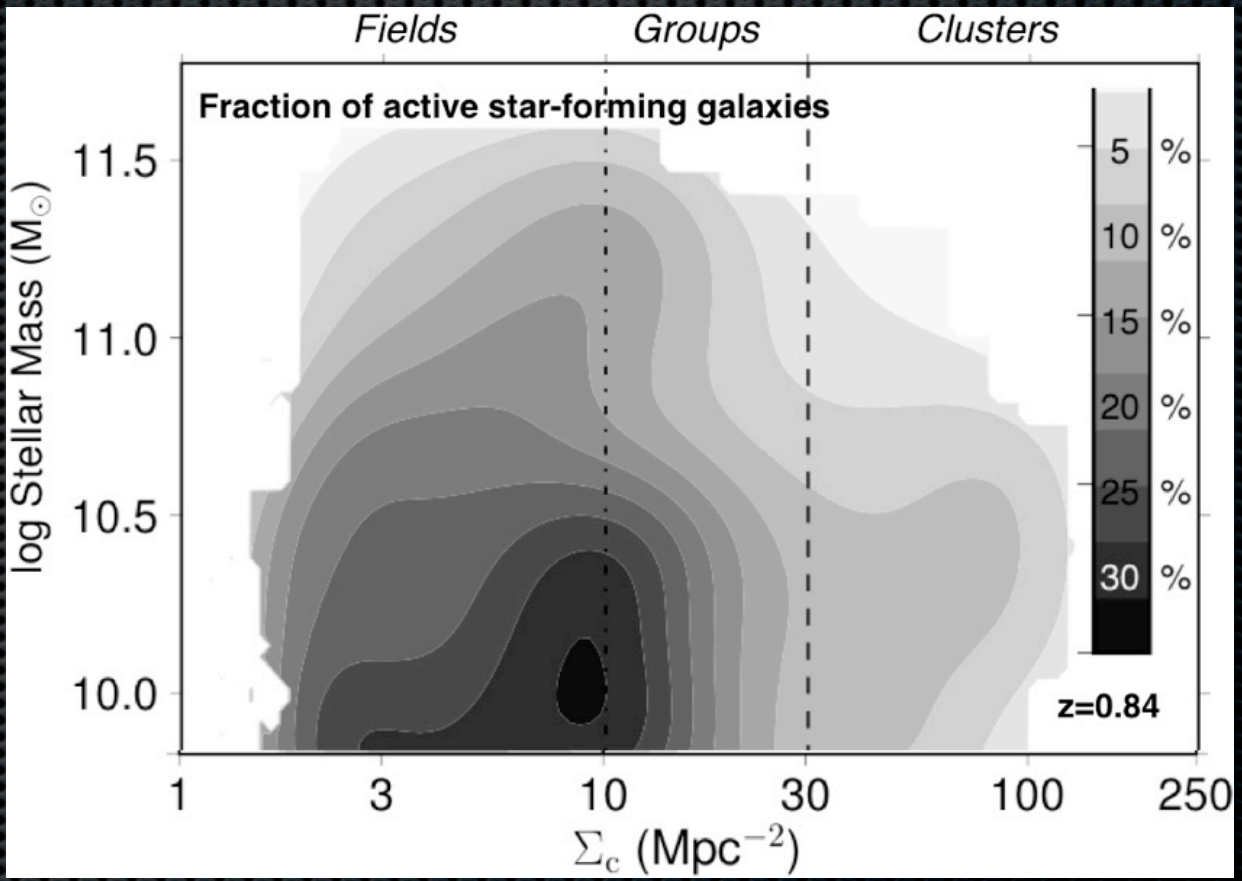


Environment?

z~0 SDSS (Peng+10)

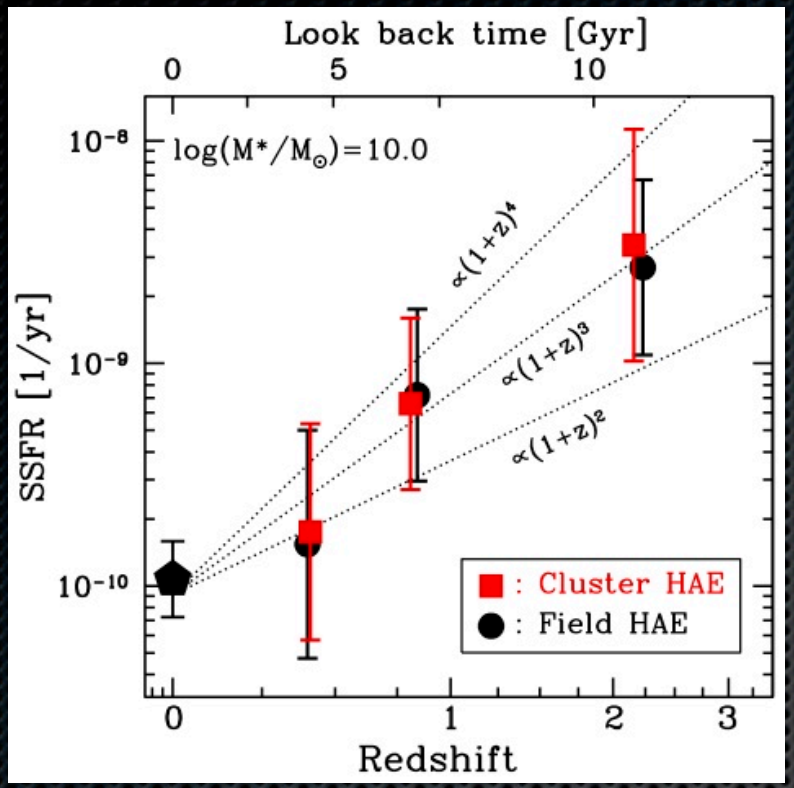


z~1 Sobral et al. 2011



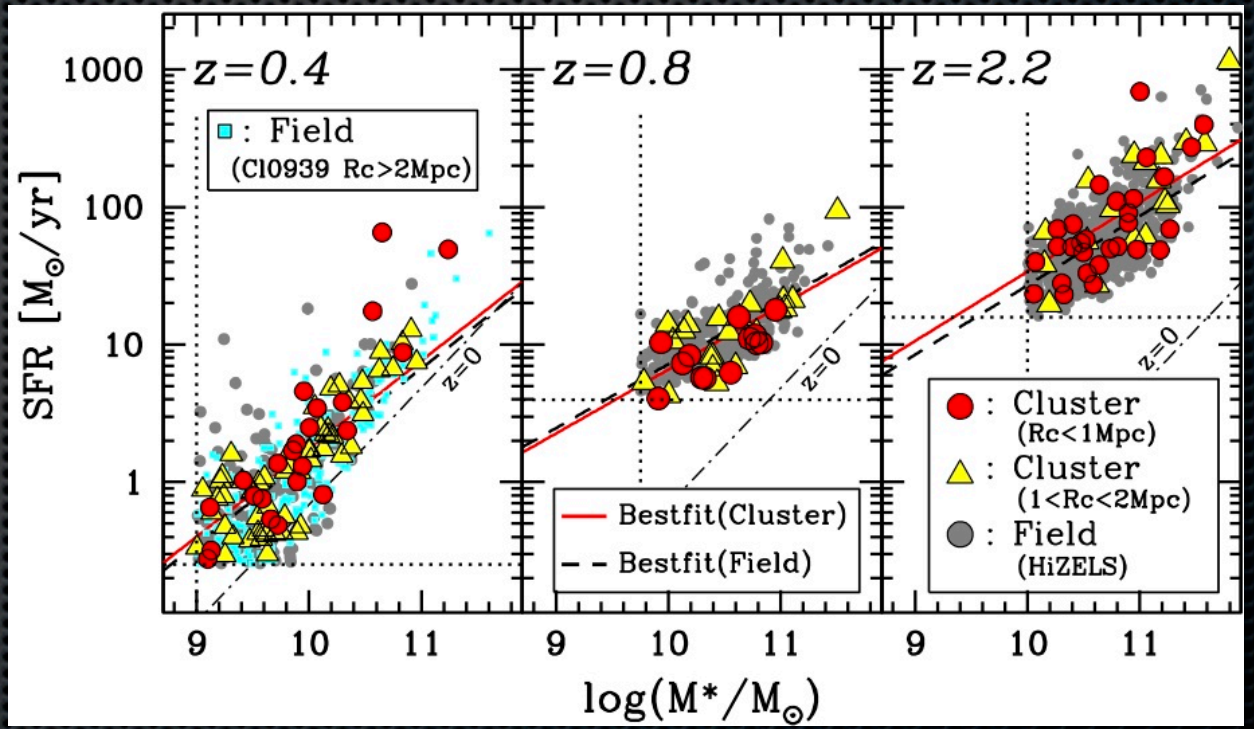
At z~1: Similar to z~0 / SDSS

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



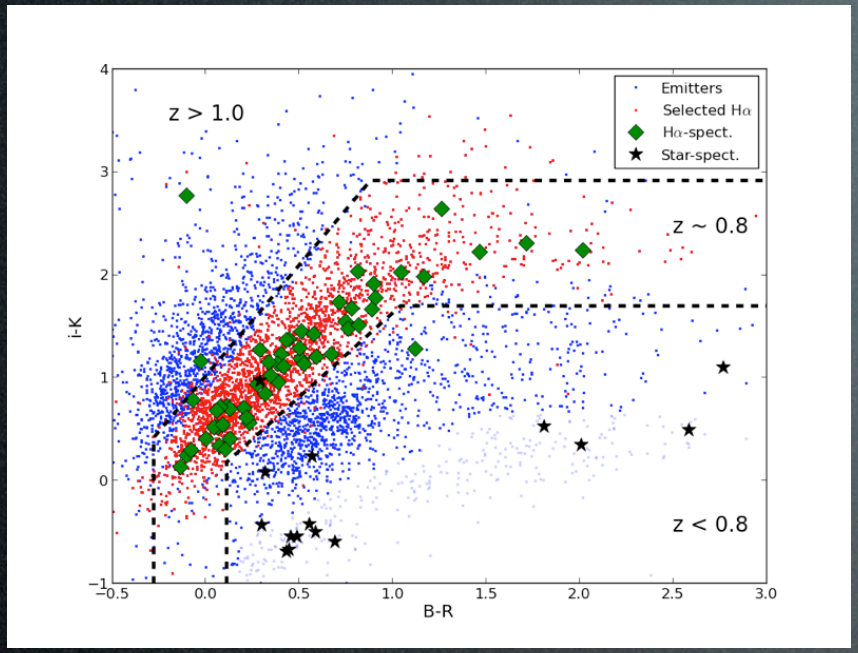
Evolution of SFR* (SSFR) same in fields and clusters since z=2.23

SFR-Mass relation also ~the same in different environments

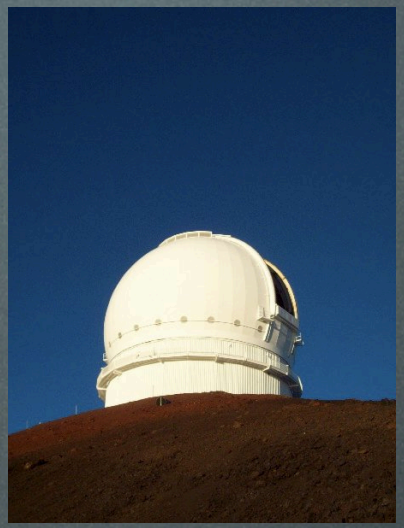


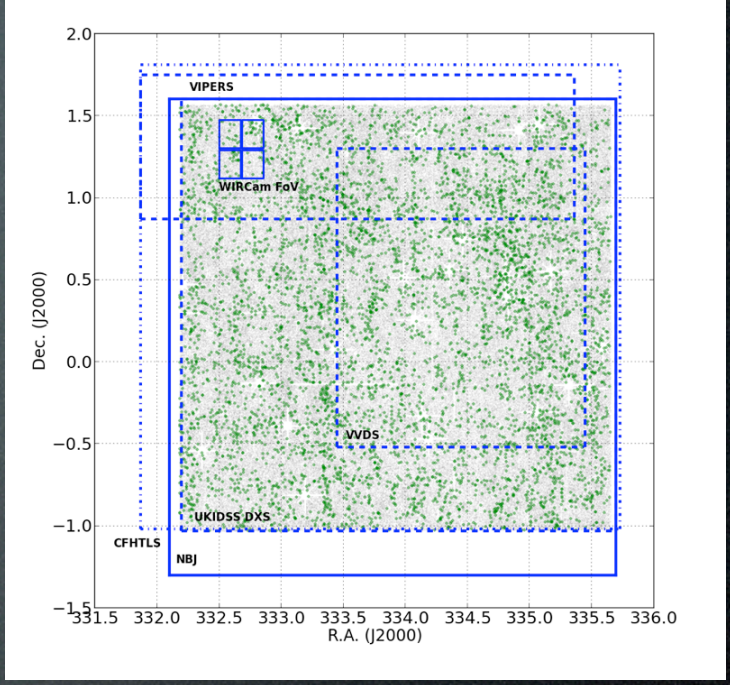
Koyama et al. 2013

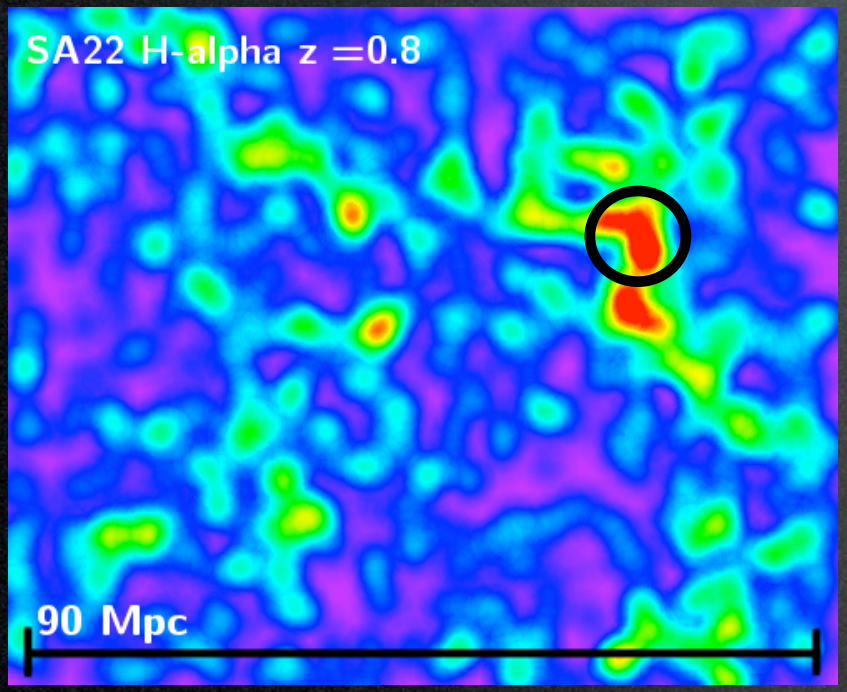
What about their dynamics?



10 sq deg







300 k NB detections

7000 line emitters

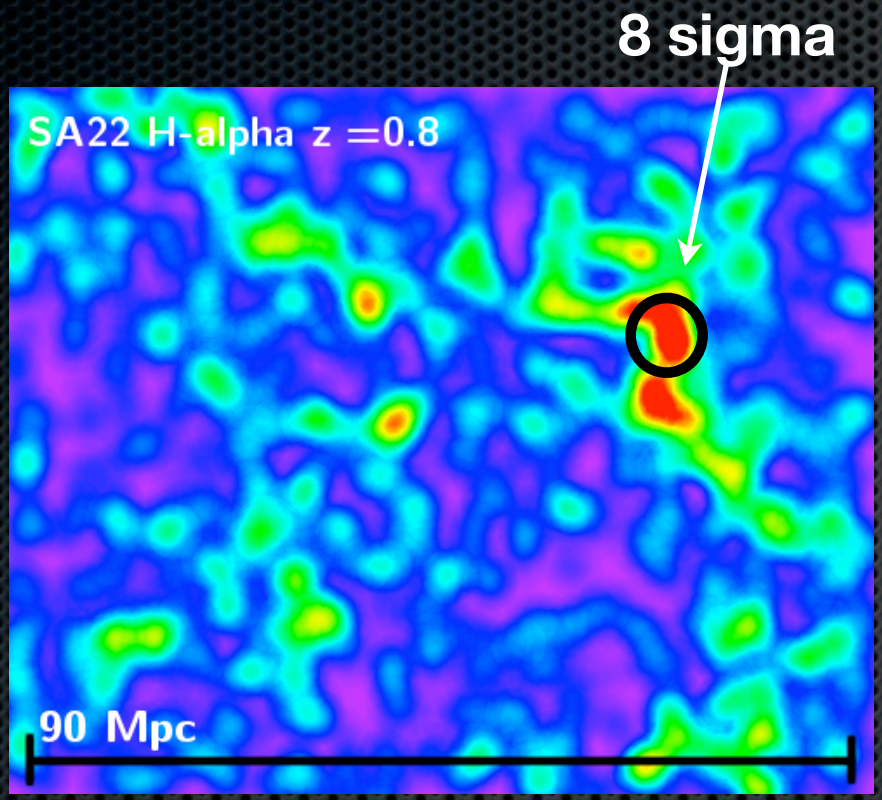
3500 Hα z=0.8

Density of Hα emitters z=0.81+-0.01

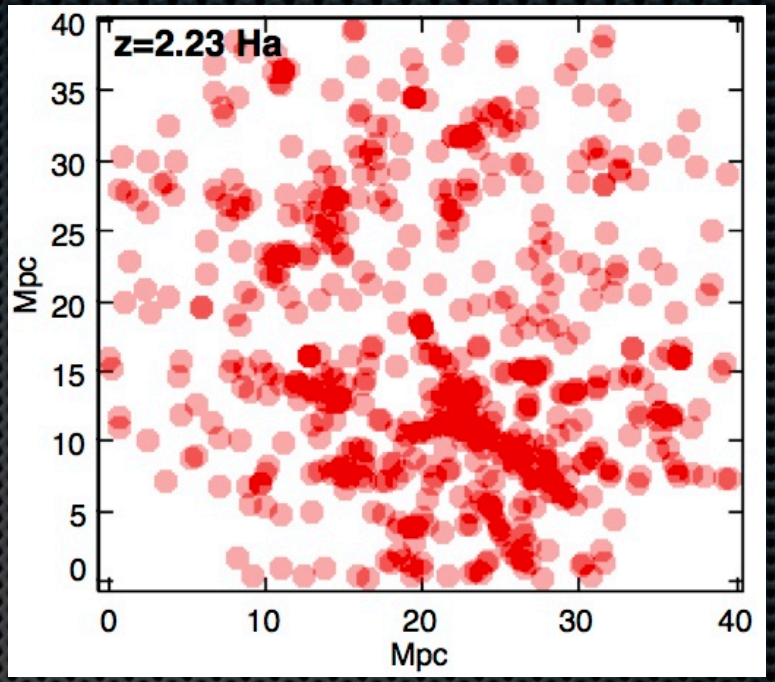
8 sigma over-density

S+13d, Matthee+13

Exploring a wide range of local densities: same selection/survey

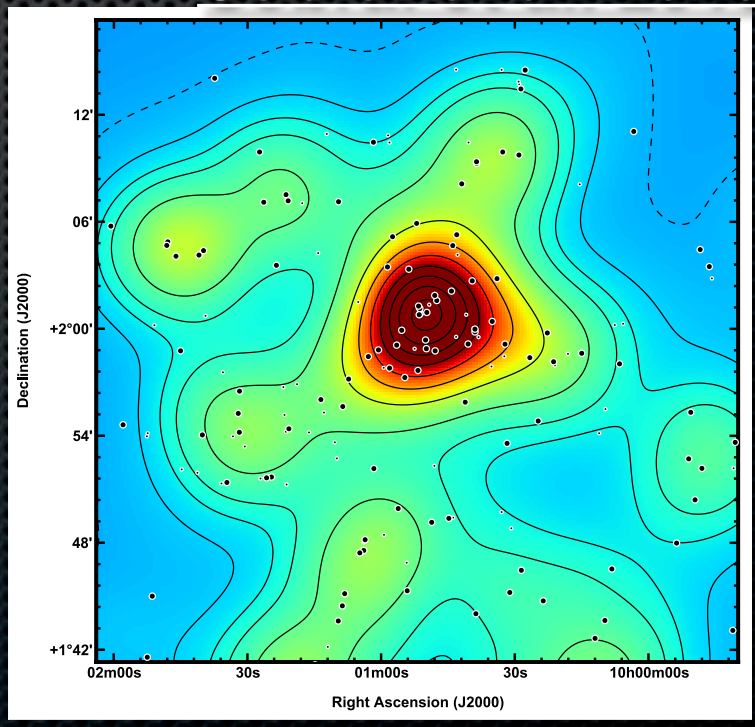


Cluster? Proto-cluster? How special are these galaxies? What are their dynamics?

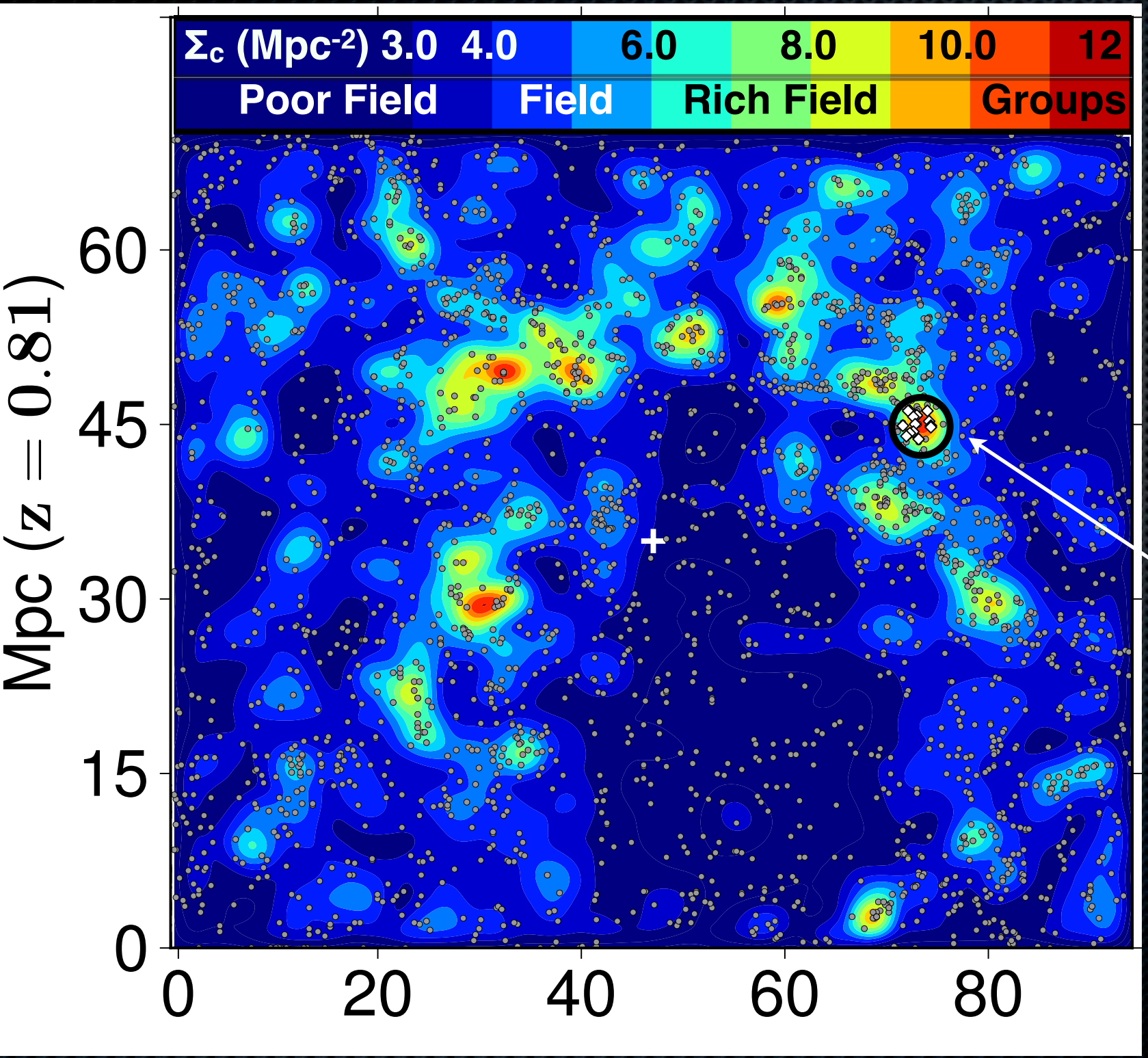


z=2.23

Sobral et al. 2013a



Geach et al. 2012



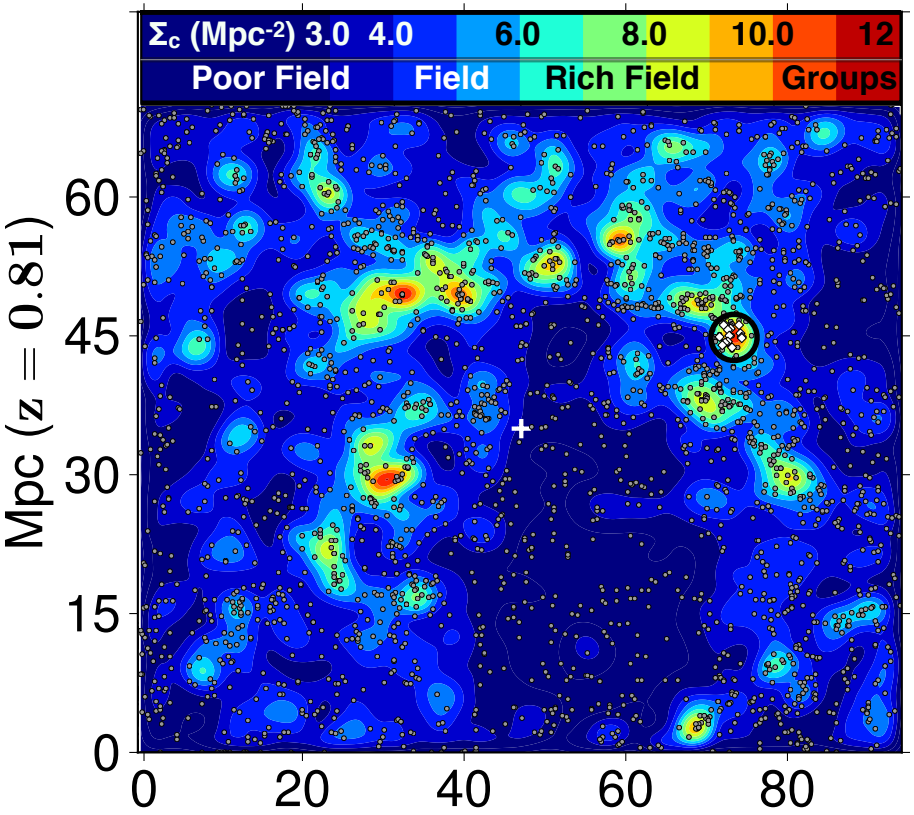
Method: S+11

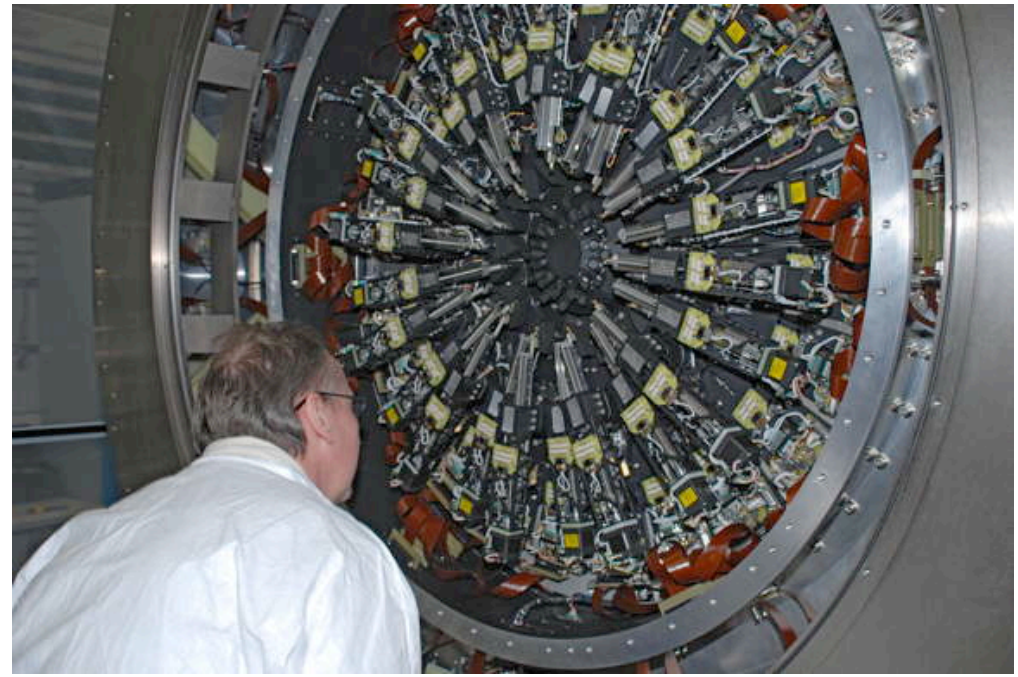
Using *all* galaxies (not just SFGs)

Likely group

30 Hα in 7x7arcmin

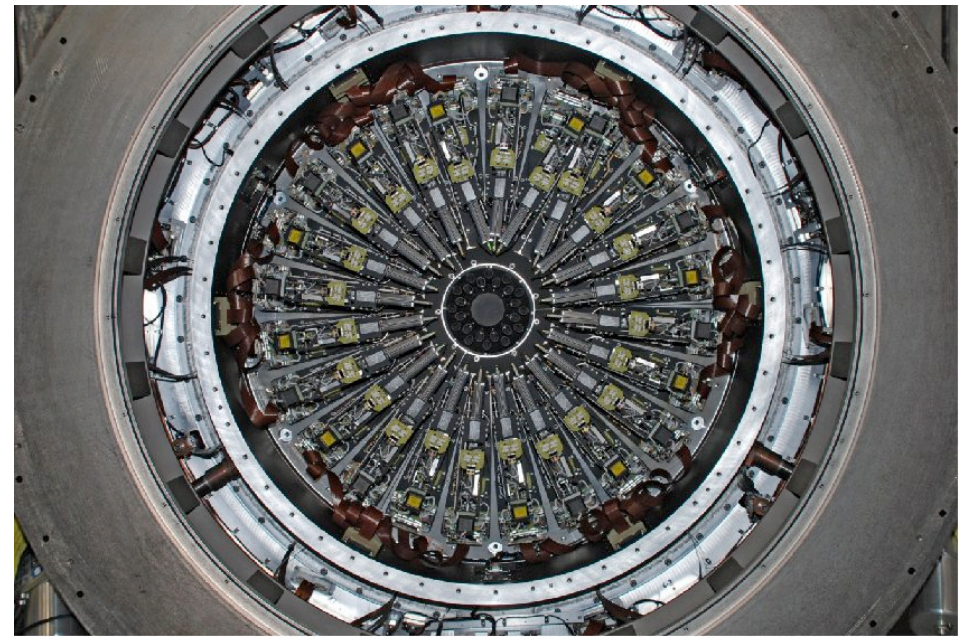
S+13b

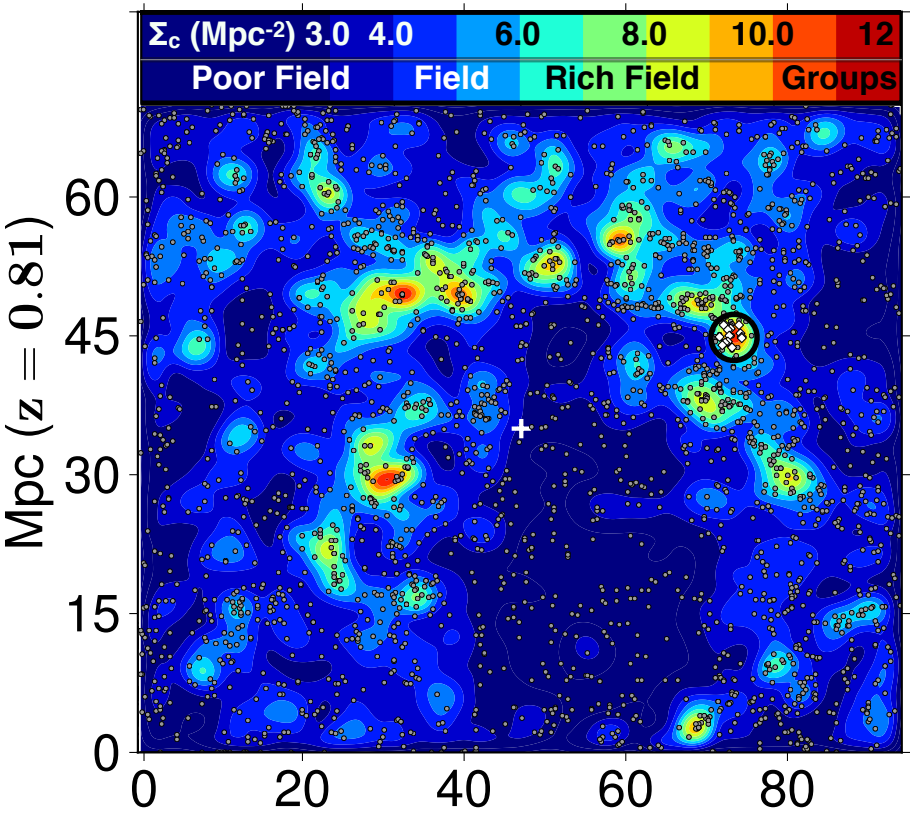




Perfect for Kmos **VLT**

24 IFUs at the same time!



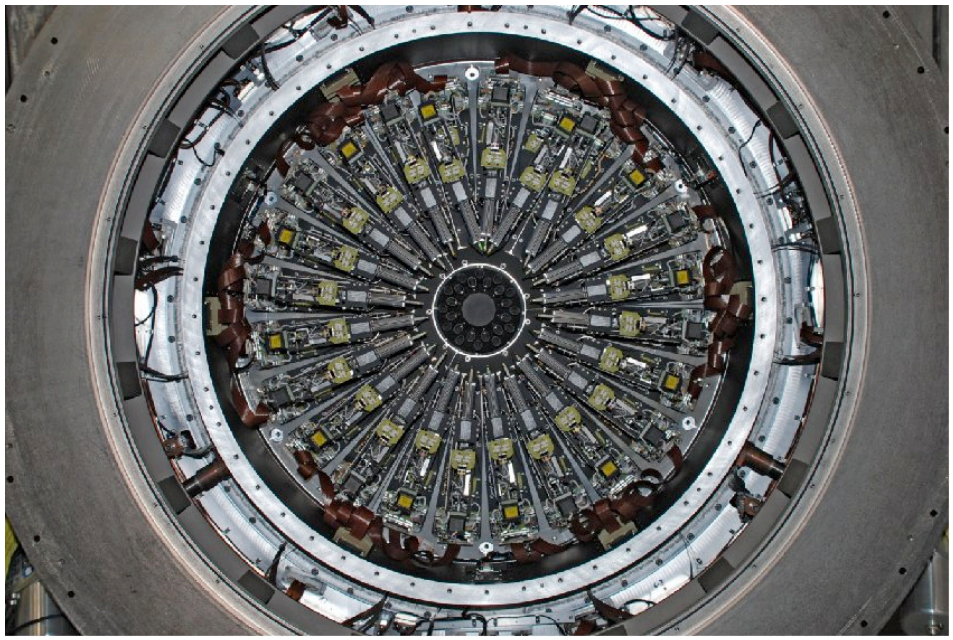


4h PI Science Verification time

Observations June 2013 + (September 2013)

Perfect for Kmos **VLT**

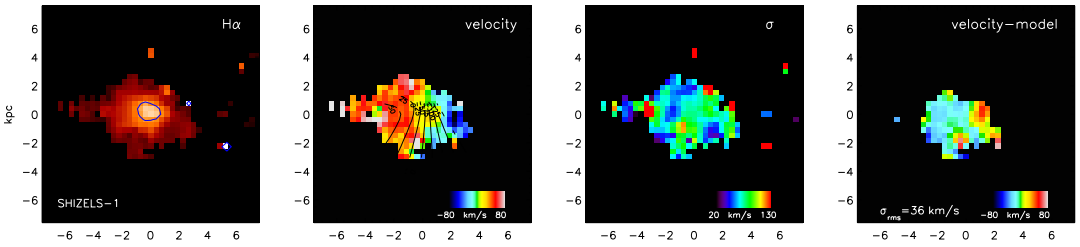
24 IFUs at the same time!



Galaxy Dynamics at z~0.8-2.2

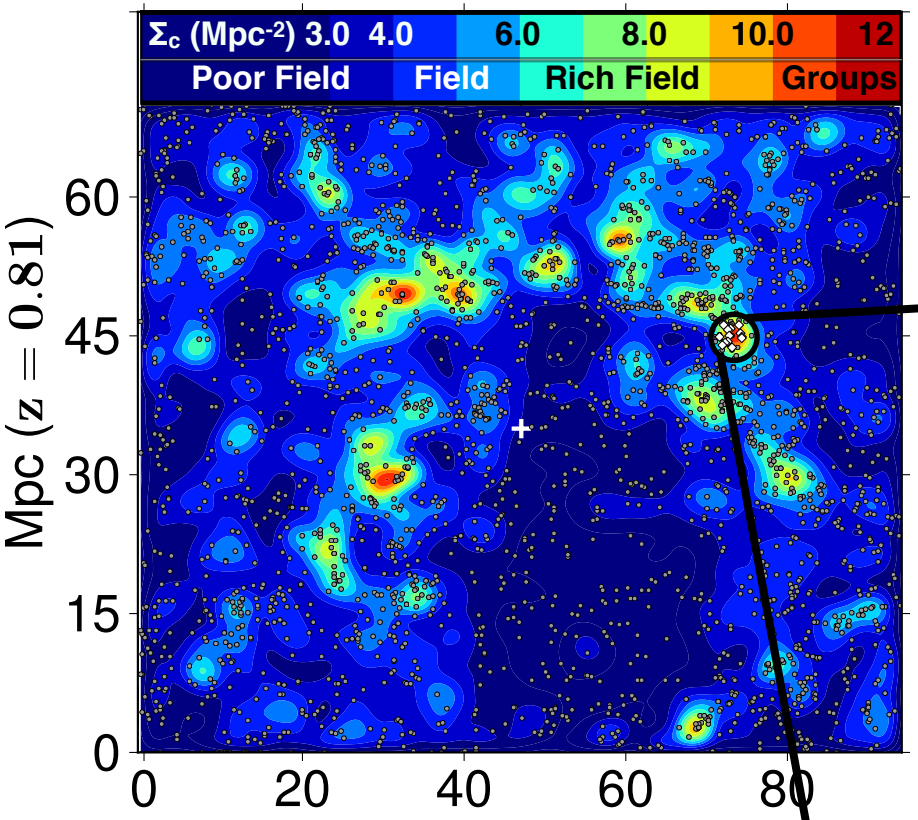
Swinbank al. 2012a

From AO IFU observations

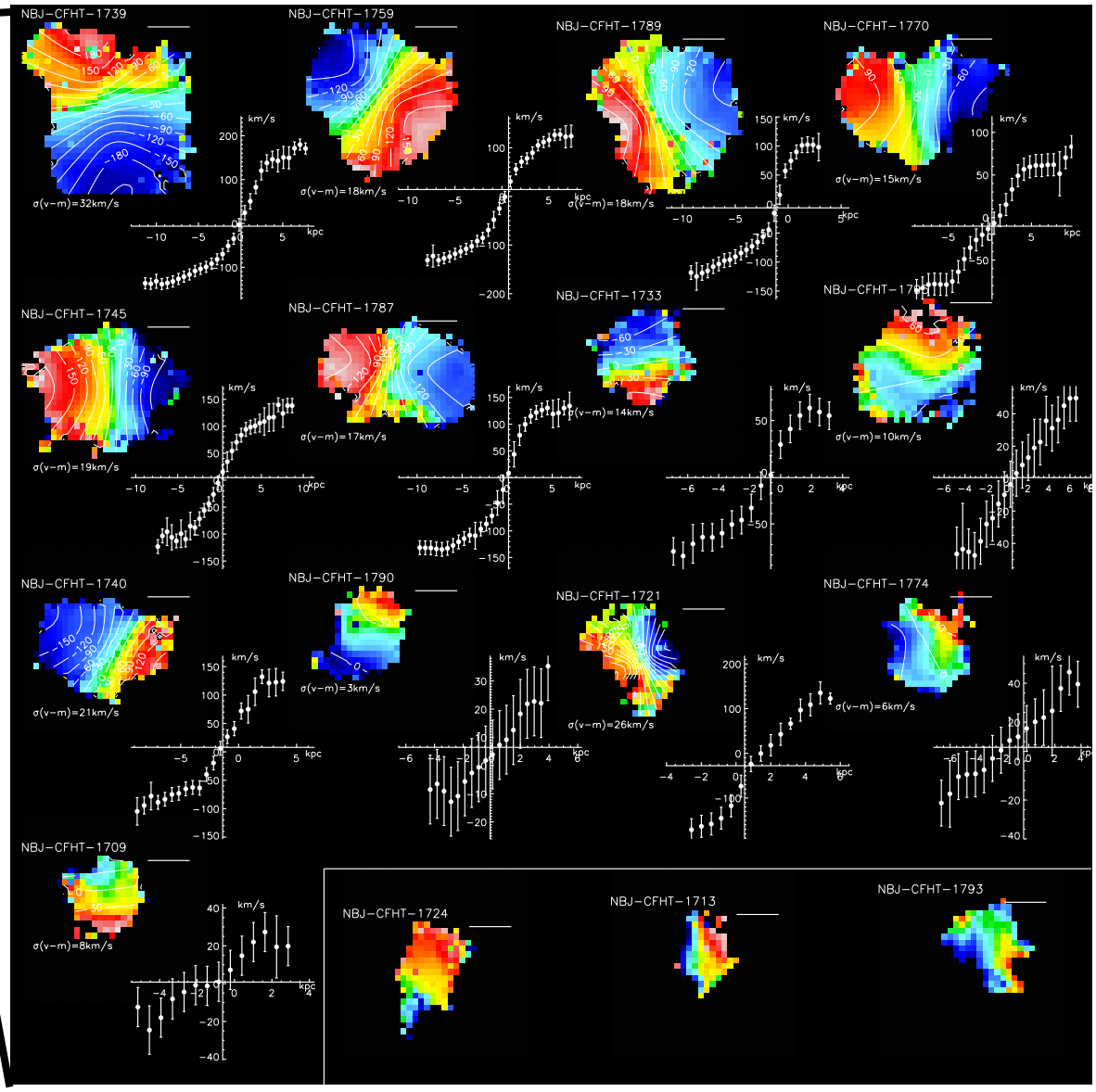


~5 hours of VLT time

CF-HiZELS

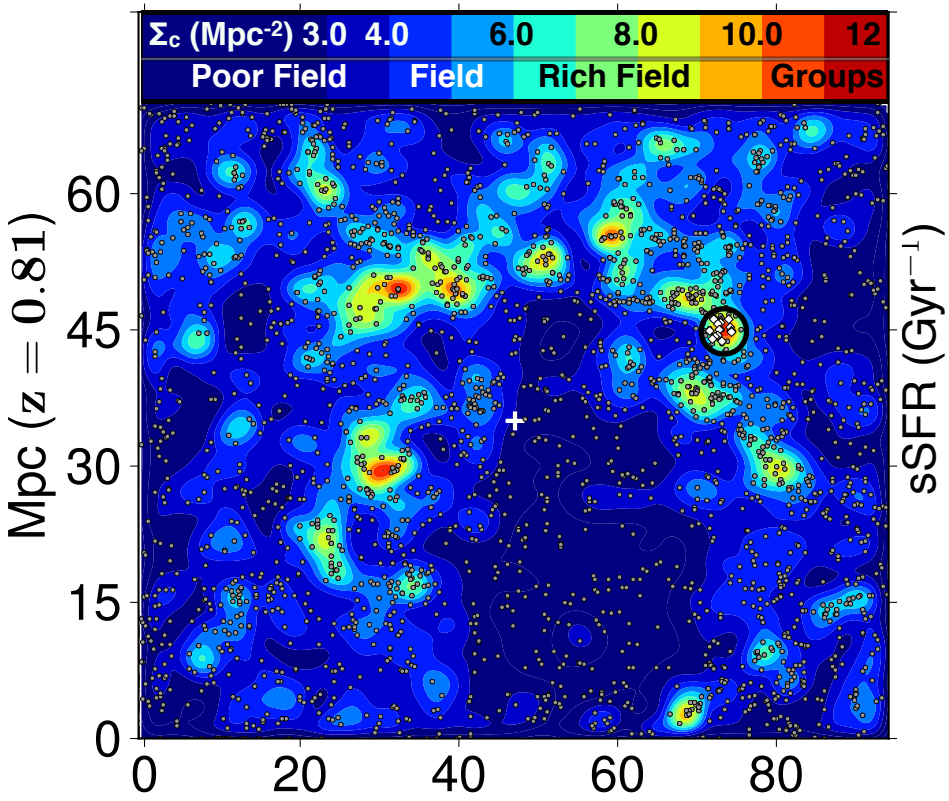


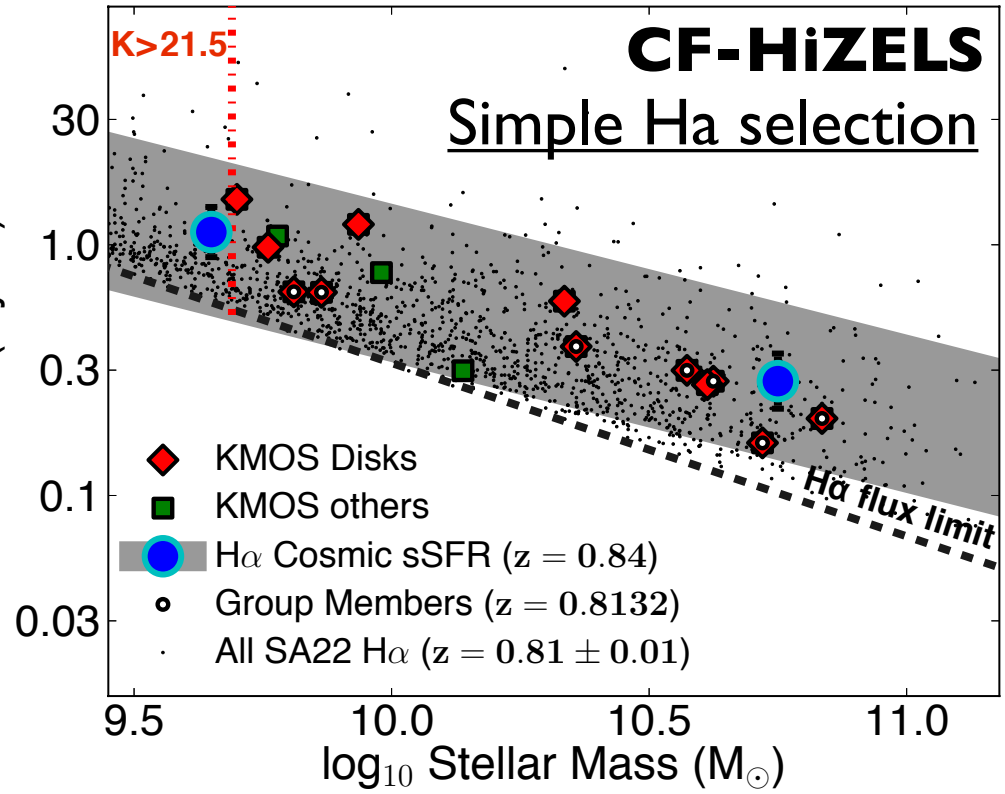
2 hours of VLT time



First results from KMOS

Sobral et al. (2013b), ApJ, in press



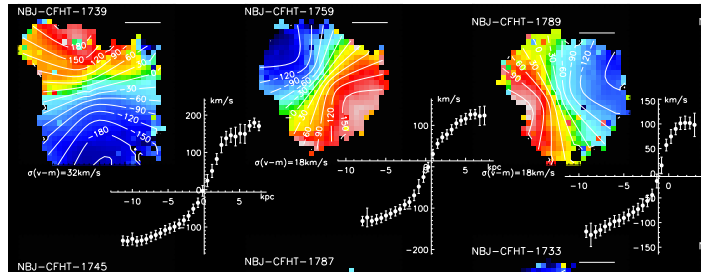


Confirmed group at z=0.813 (13 galaxies)

7 within r=1.5Mpc

Median mass: $10^{10.2}$ $M_\odot$

sSFRs = 0.2-1.1 Gyr^{-1}

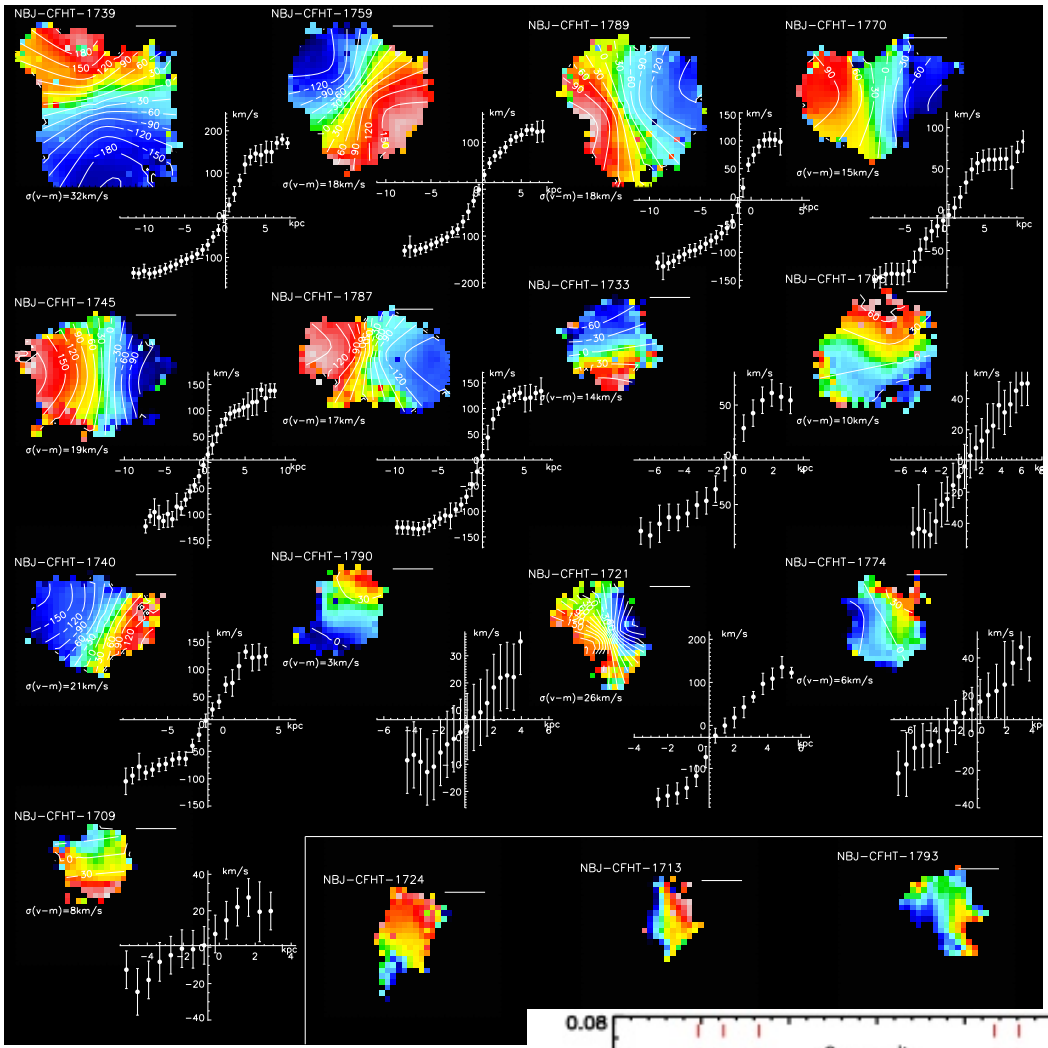


Metallicities

KMOS galaxies z=0.81

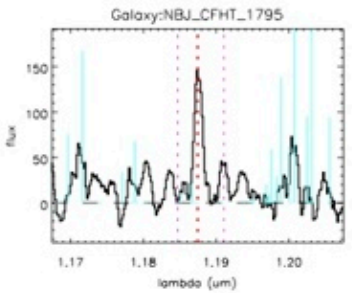
12+log(O/H) = 8.62 +-0.07

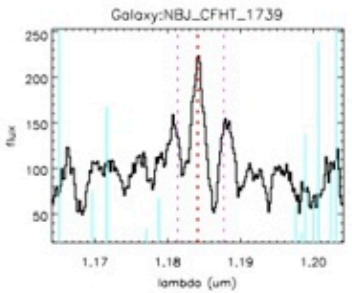
Solar value: 8.66 +-0.07

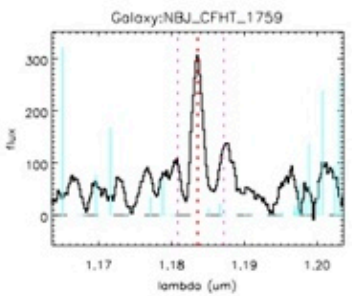


Group galaxies slightly more metal rich

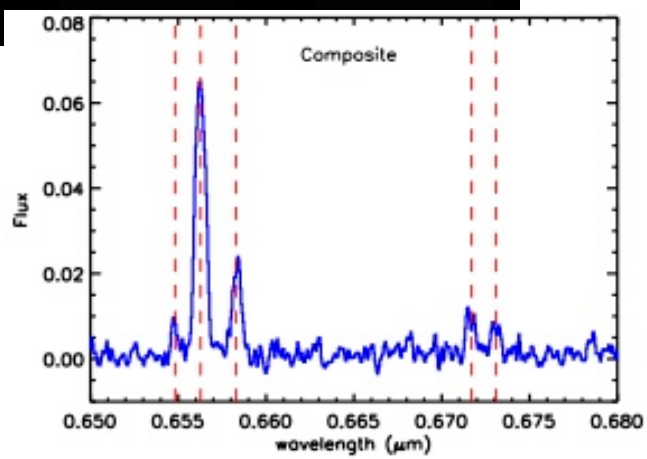
<u>but also more massive</u>



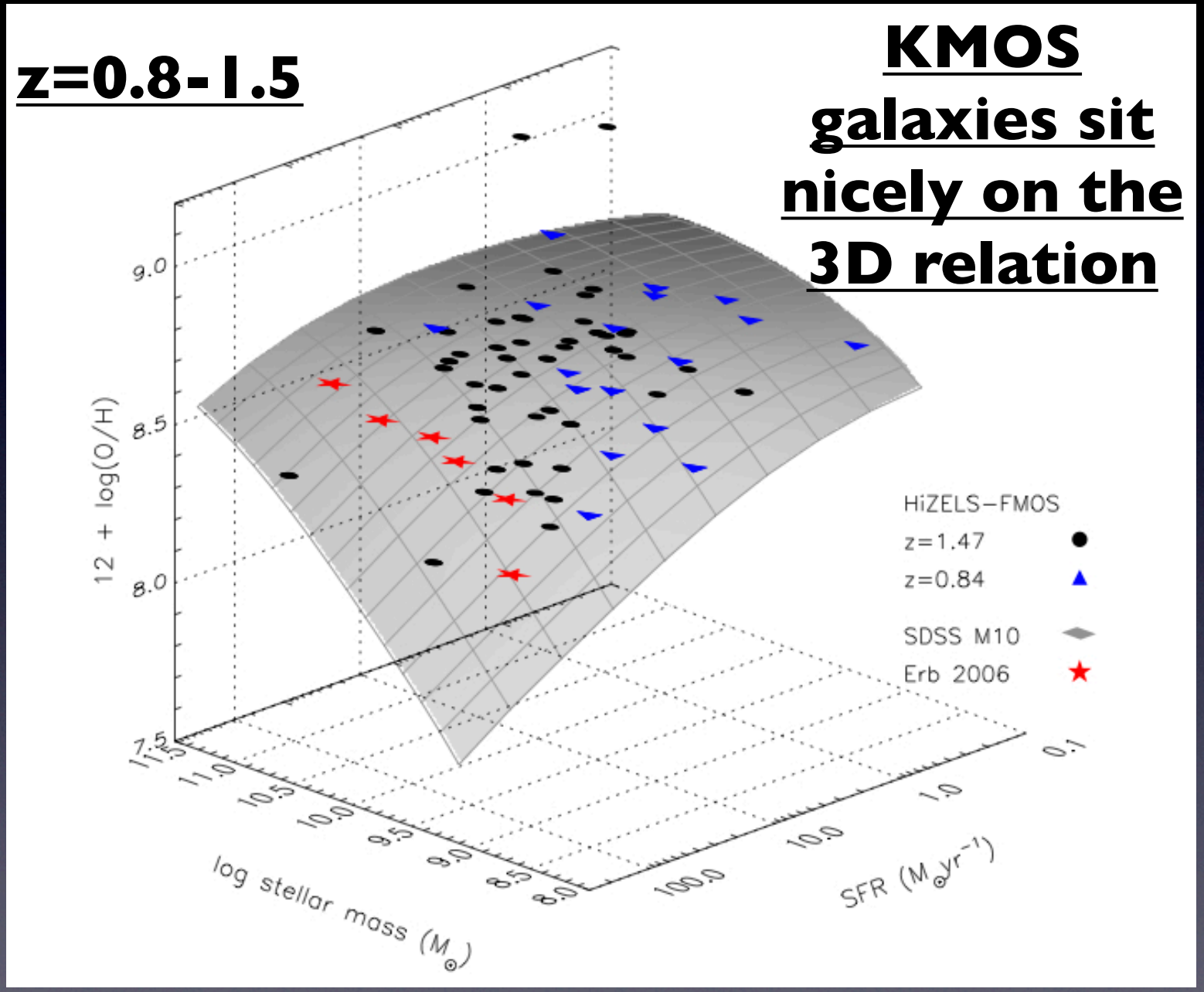




[NII]/Ha =0.32+-0.13



HiZELS "Fundamental" Mass-Metallicity-SFR relation

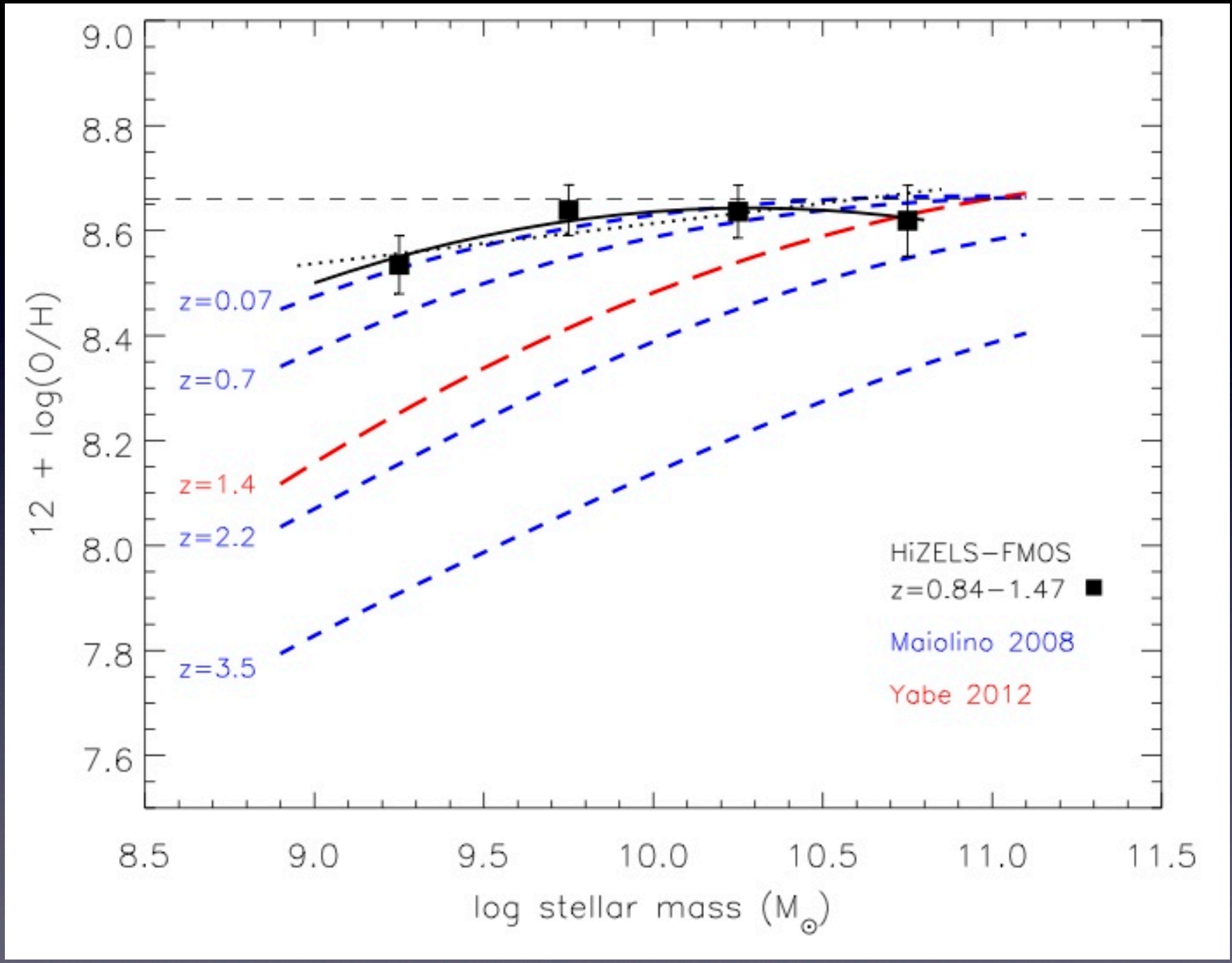


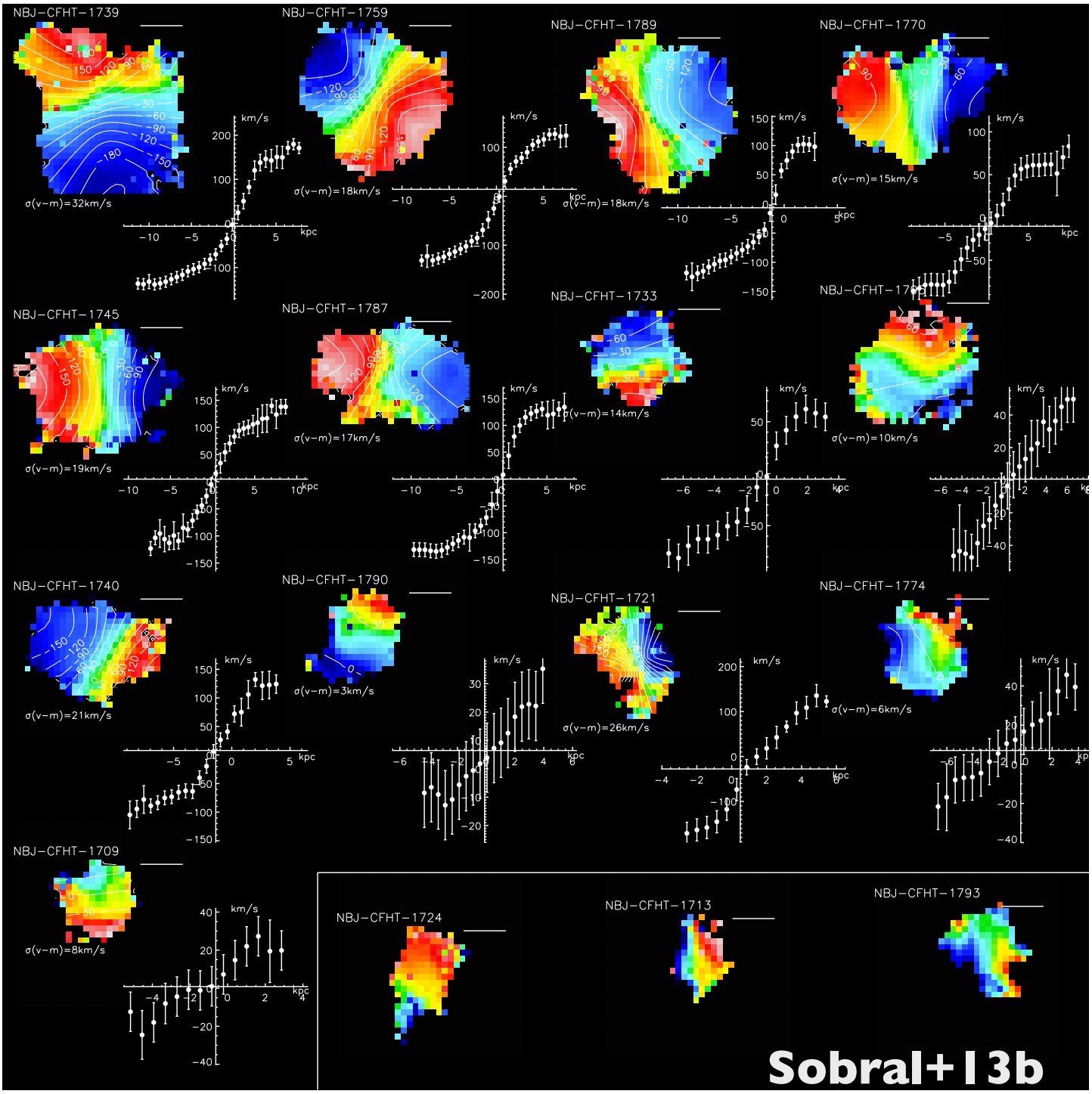
Stott, Sobral et al. 2013b

Stott, Sobral et al. in prep.

Stott, Sobral et al. 2013b

z=0.84 + z=1.47 Ha





75+-8% Disks

Shallow, negative metallicity gradients

Rotation speeds of 50-275 km/s

~solar metallicity

Group galaxies: 100% disks

Evolution of the Tully Fisher relation?

Small Evolution in ZP

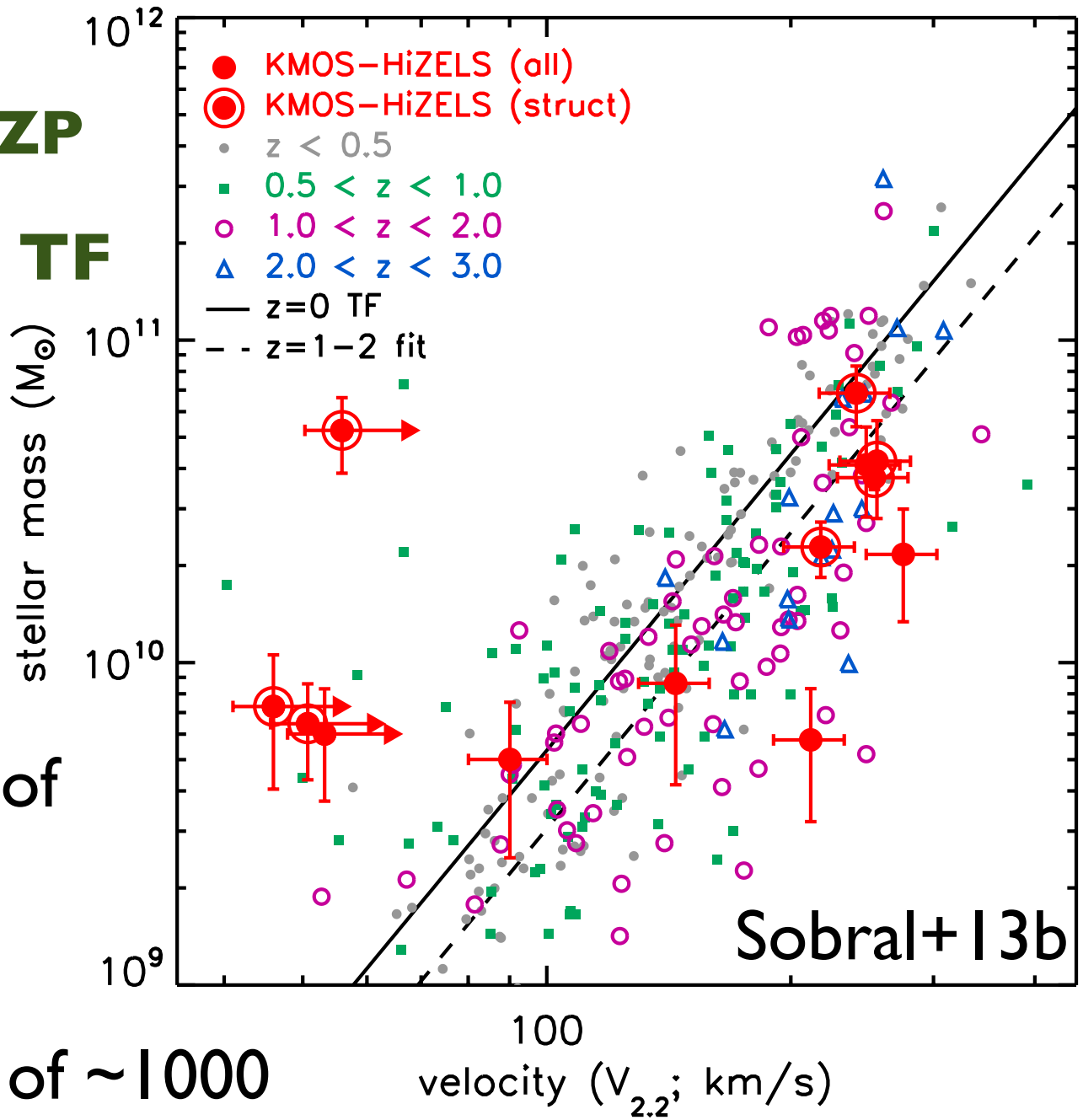
Agrees with z~1-2 TF

<u>No difference</u>
field vs group

With just ~2 hours of VLT time

↓

Future: Build samples of ~1000



Conclusions:

1) Robust, self-consistent SFRH + **Agreement** with the **stellar mass density growth**

2) The **bulk of the evolution** over the **last 11 Gyrs** is in the **typical SFR (SFR*) at all masses: factor ~13x**

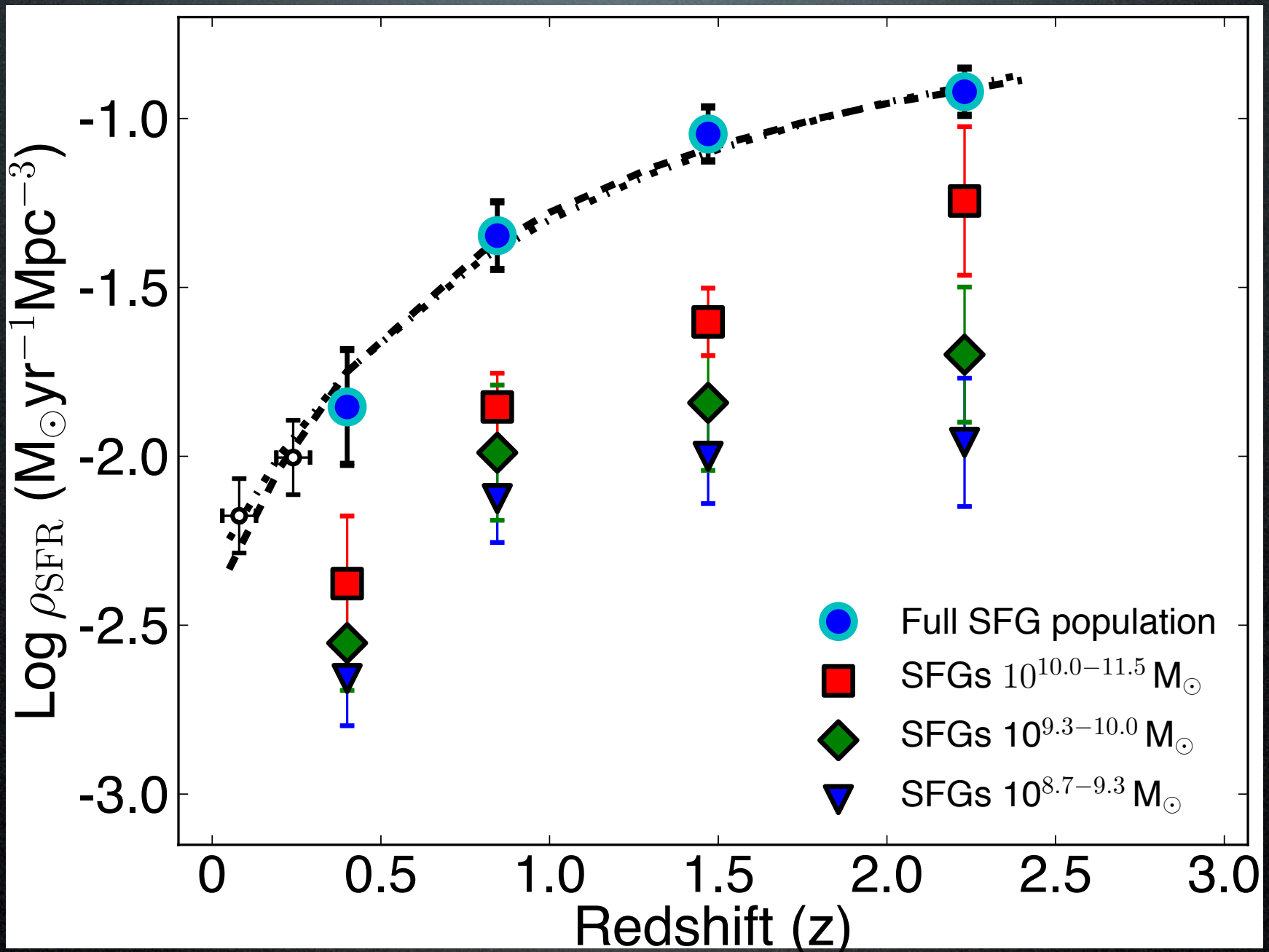
3) Star-forming galaxies since z=2.23: mostly disks, ~20-30% mergers, once SFR* evolution taken into account, little evolution

KMOS+Ha selected works extraordinarily well: resolved dynamics in ~1-2 hours, 75+-8% disks, 50-275km/s

Confirmed a rich group of star-forming galaxies at z=0.813 with ~solar metallicities, typical SFRs, all disks

Group galaxies more massive & slightly lower sSFRs + higher Metallicity, but the same TF and mass-metallicity relations

SF History - Full population and 4 mass bins

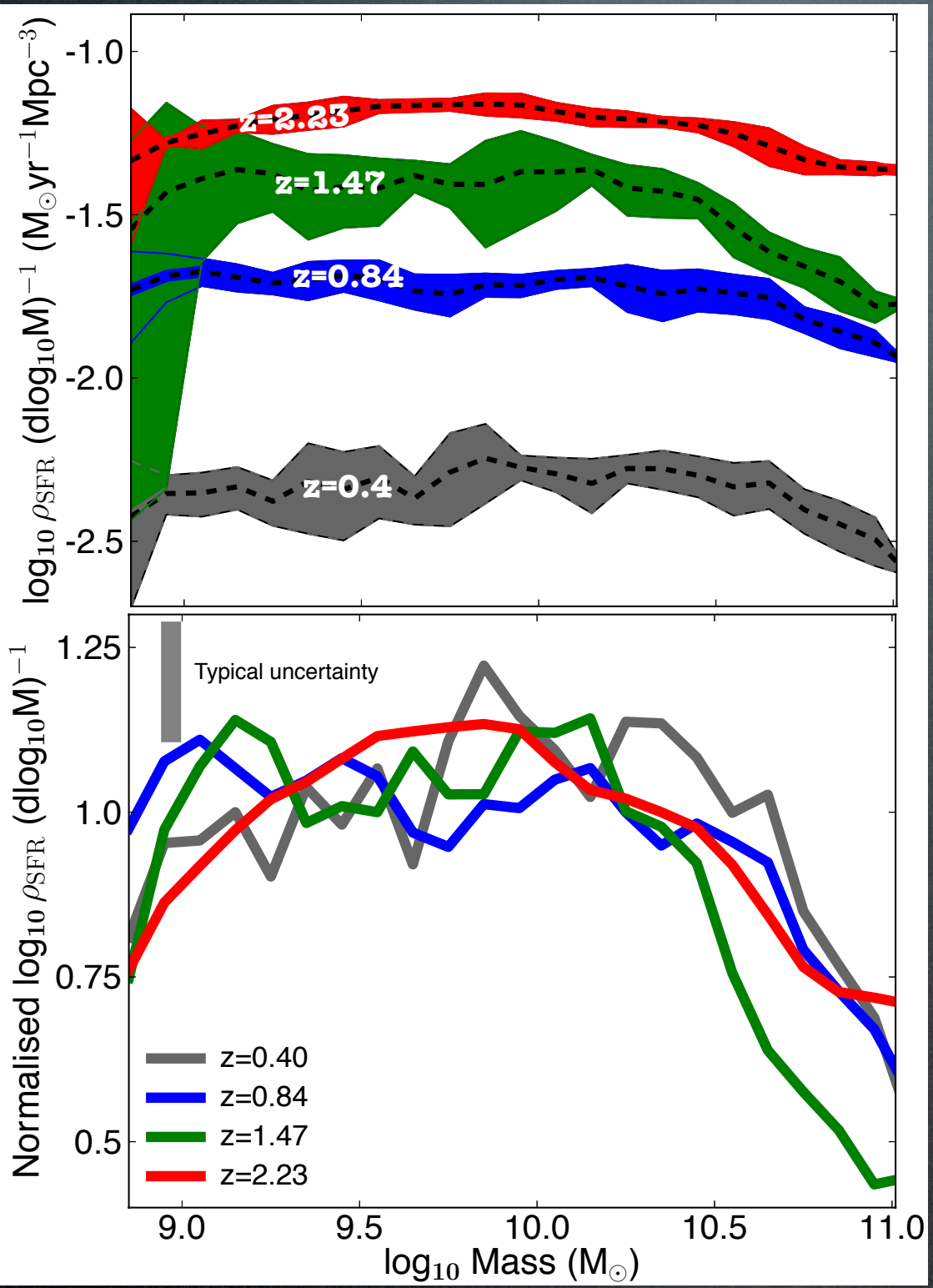


Decline at all masses

Sobral et al. (13C)

SFRD per dLogM

Normalised



Over the last 11 Gyrs

Decrease with time at all masses

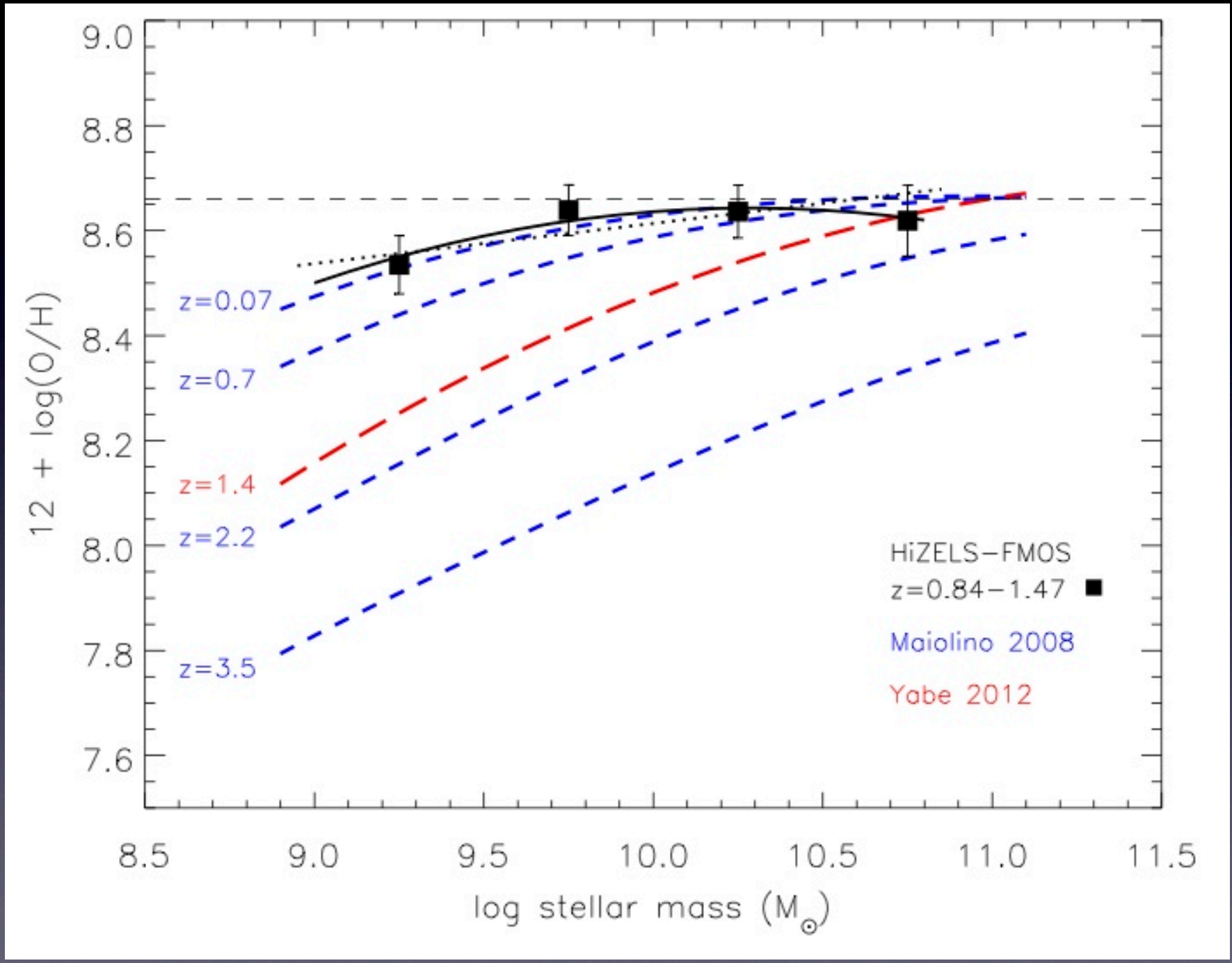
Tentative peak per dLogM at ~10^{10} M_o since z=2.23

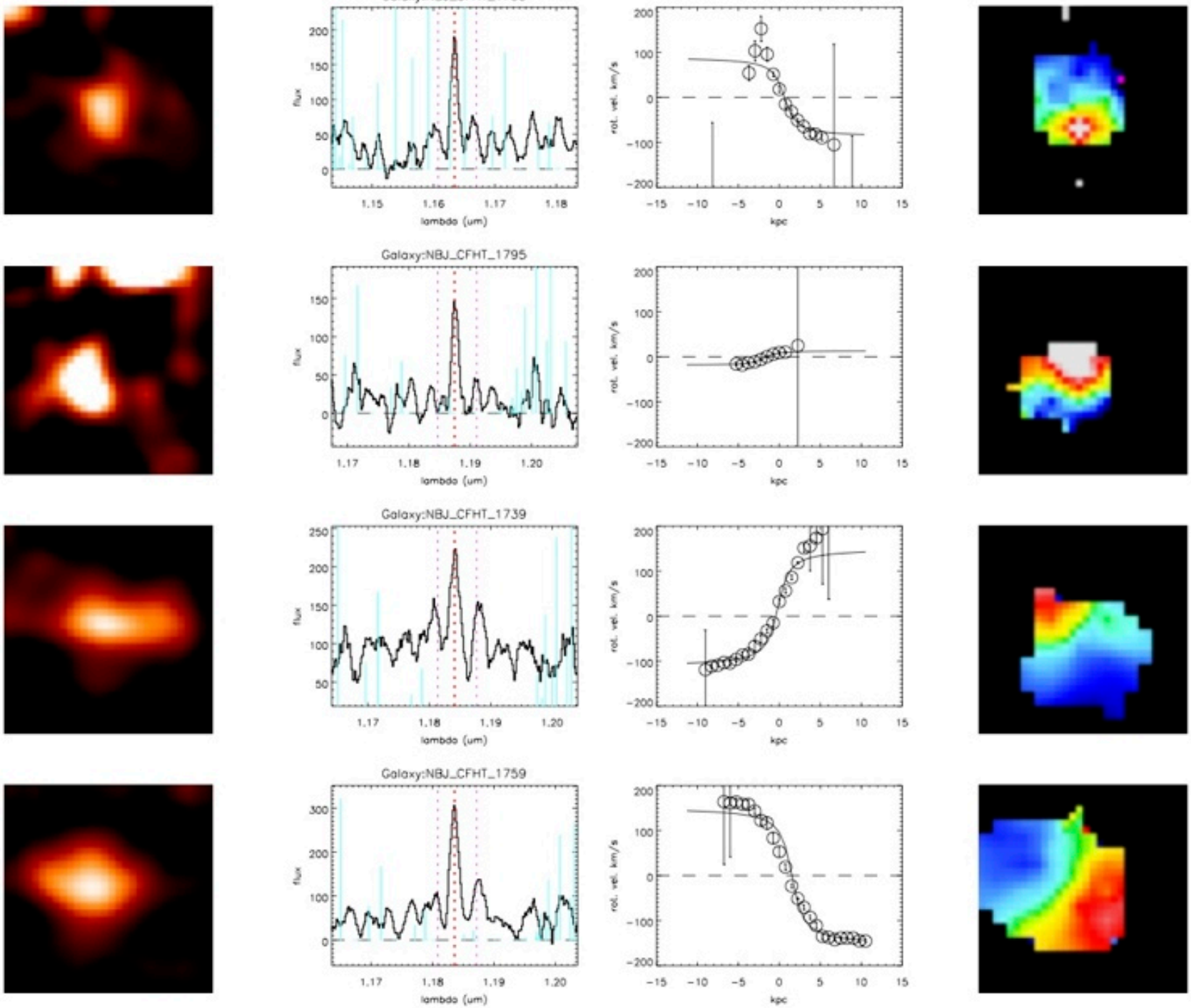
Mostly no evolution apart from normalisation

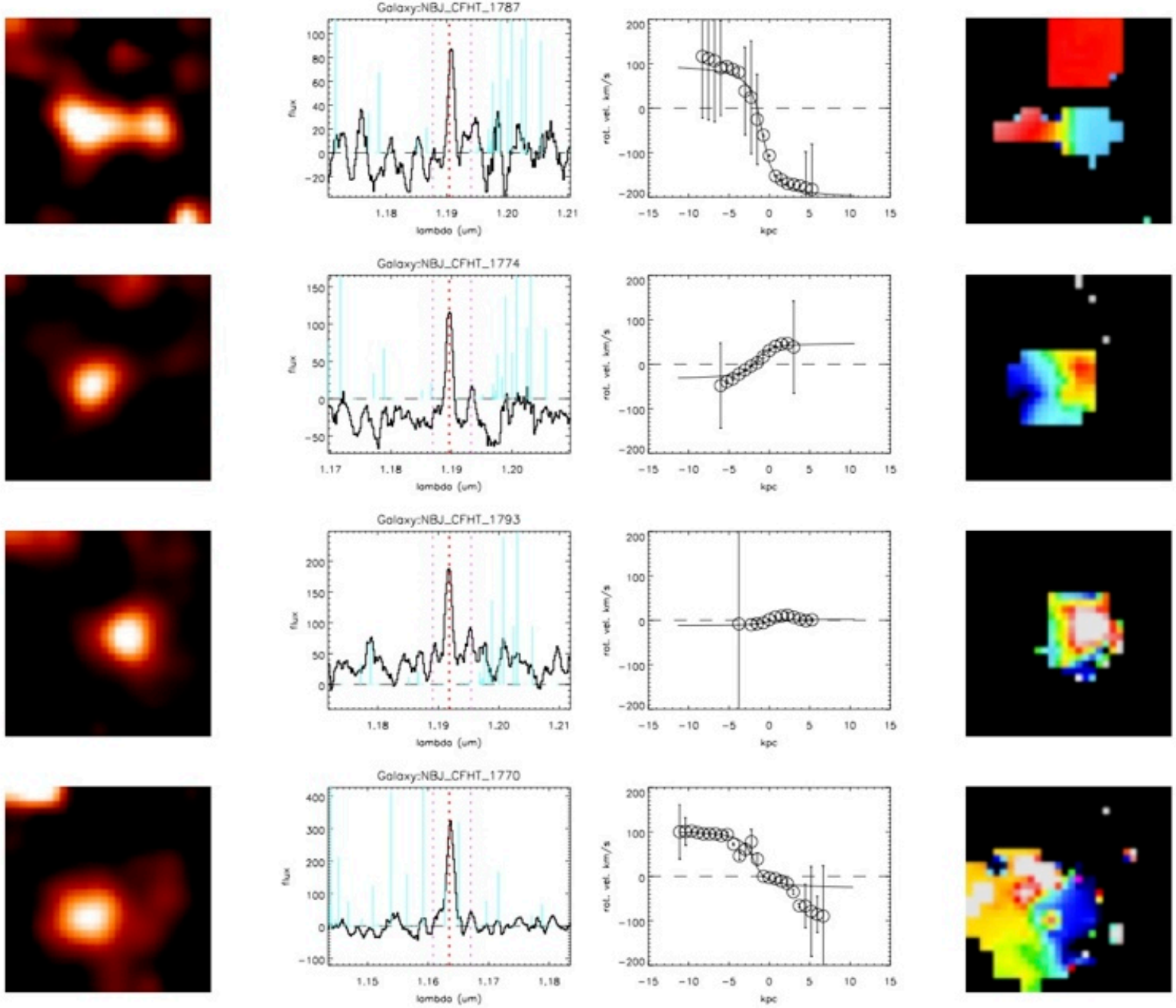
Sobral et al. (13C)

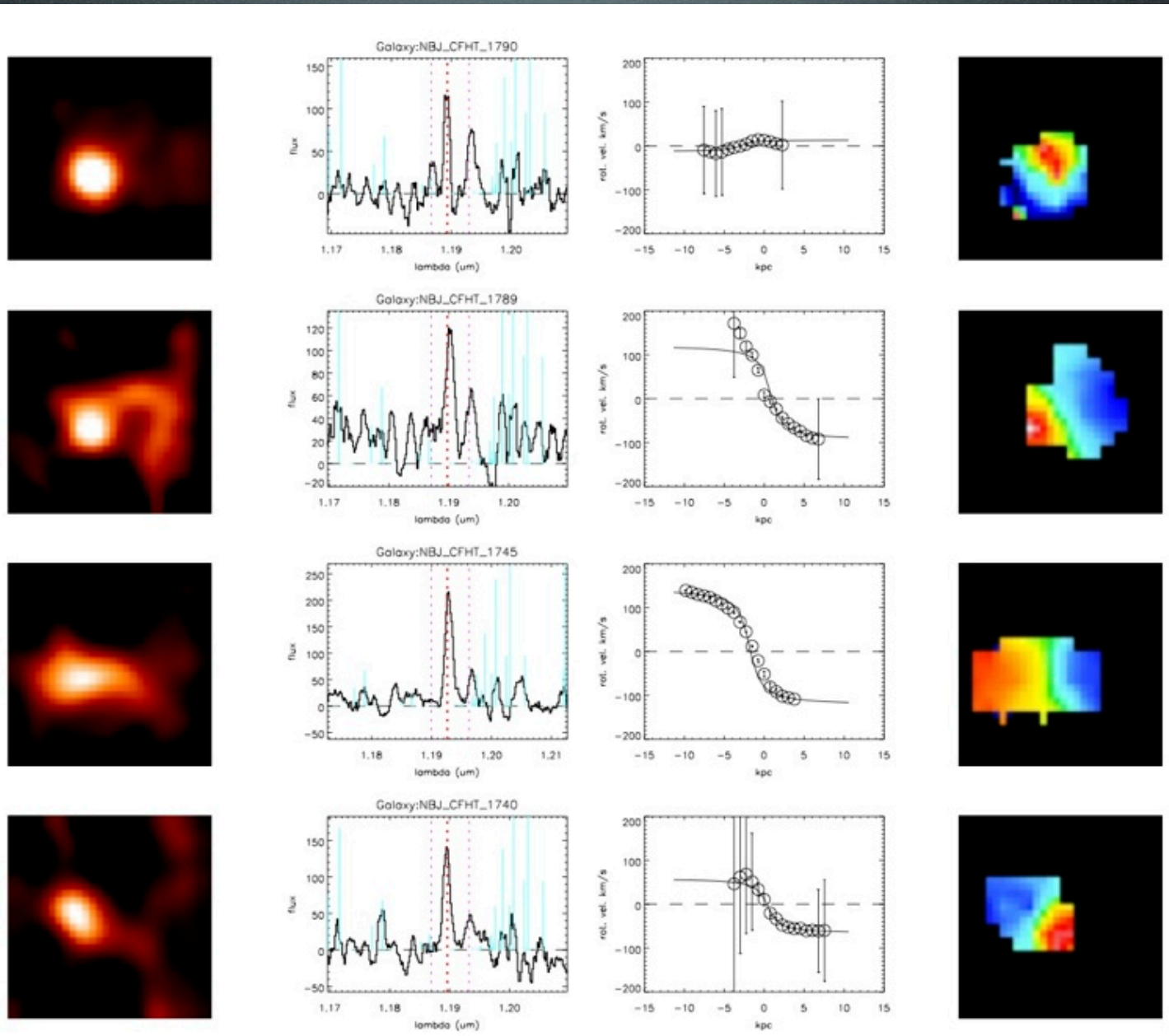
Stott, Sobral et al. 2013b

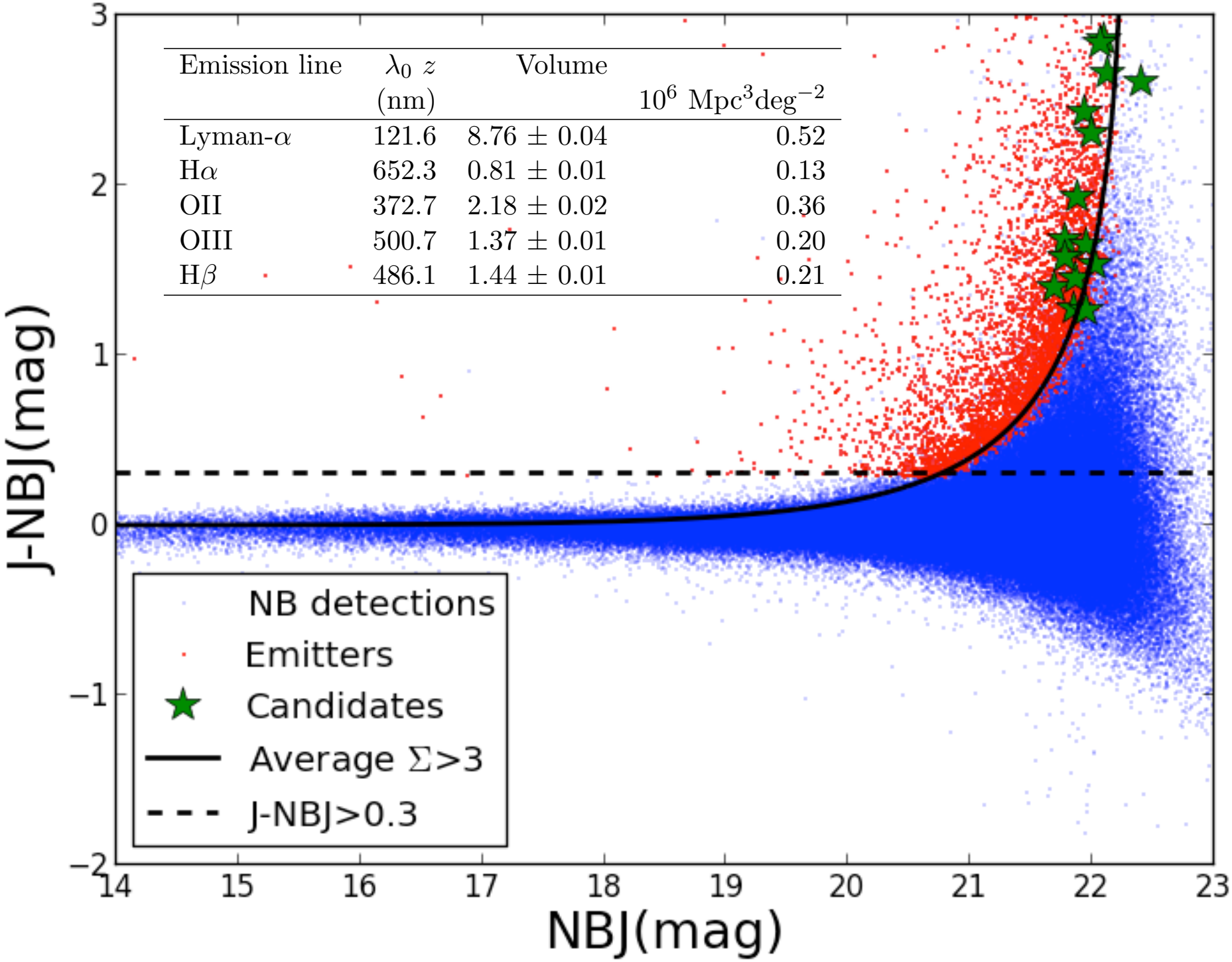
z=0.84 + z=1.47 Ha




Galaxy:NBJ_CFHT_1733
flux
lambda (um)
rot. vel. km/s
kpc
Galaxy:NBJ_CFHT_1795
flux
lambda (um)
rot. vel. km/s
kpc
Galaxy:NBJ_CFHT_1739
flux
lambda (um)
rot. vel. km/s
kpc
Galaxy:NBJ_CFHT_1759
flux
lambda (um)
rot. vel. km/s
kpc

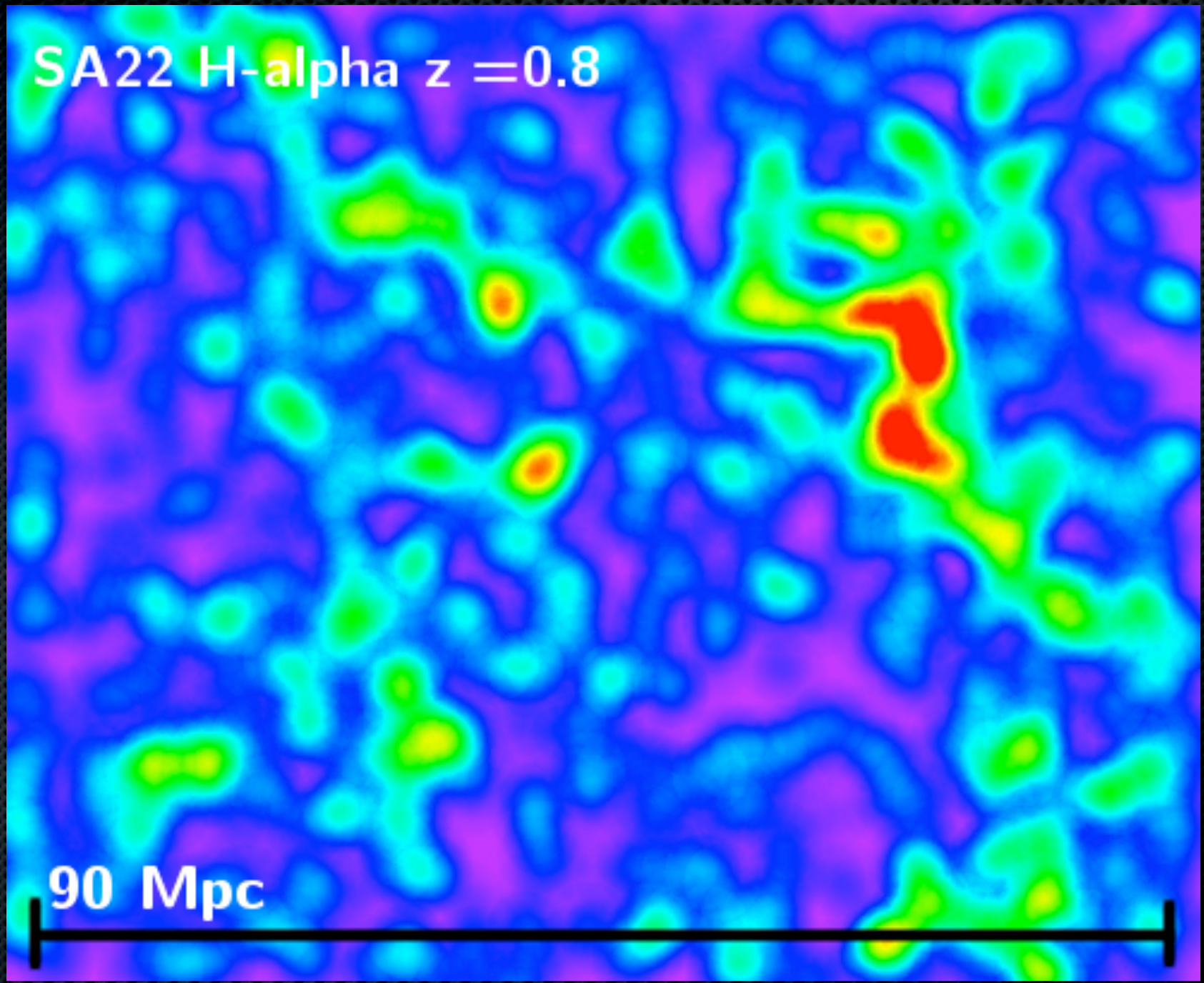

Galaxy:NBJ_CFHT_1787
flux
lambda (um)
rot. vel. km/s
kpc
Galaxy:NBJ_CFHT_1774
flux
lambda (um)
rot. vel. km/s
kpc
Galaxy:NBJ_CFHT_1793
flux
lambda (um)
rot. vel. km/s
kpc
Galaxy:NBJ_CFHT_1770
flux
lambda (um)
rot. vel. km/s
kpc


Galaxy:NBJ_CFHT_1790
Galaxy:NBJ_CFHT_1789
Galaxy:NBJ_CFHT_1745
Galaxy:NBJ_CFHT_1740
flux
lambda (um)
rot. vel. km/s
kpc



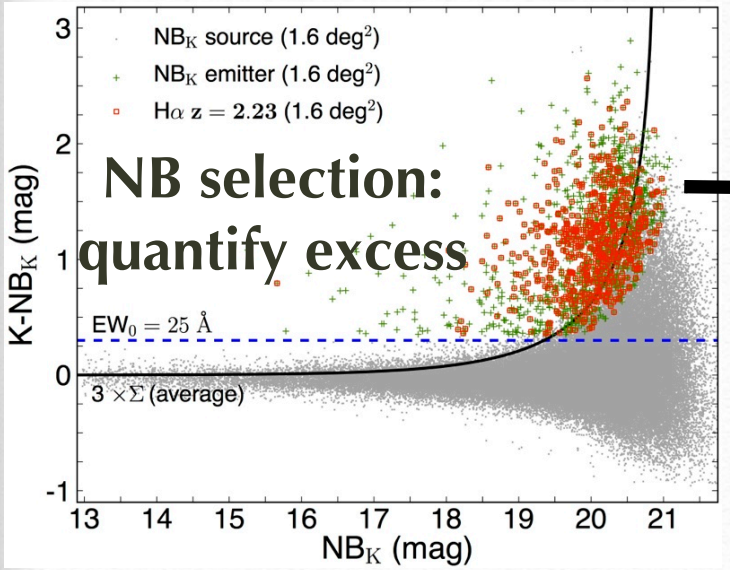
Emission line	λ_0 z (nm)	Volume	10^6 Mpc^{3}deg^{-2}
Lyman-α	121.6	8.76 $\pm$ 0.04	0.52
Hα	652.3	0.81 $\pm$ 0.01	0.13
OII	372.7	2.18 $\pm$ 0.02	0.36
OIII	500.7	1.37 $\pm$ 0.01	0.20
Hβ	486.1	1.44 $\pm$ 0.01	0.21

CFHT/WIRcam survey

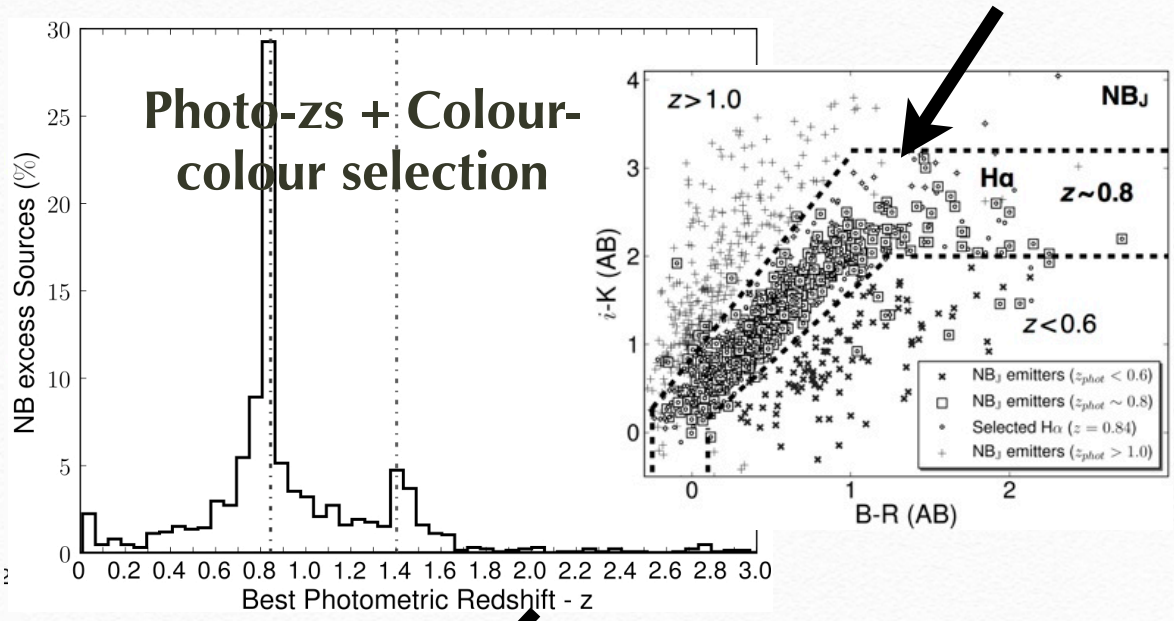


Source extraction

Potential line emitters

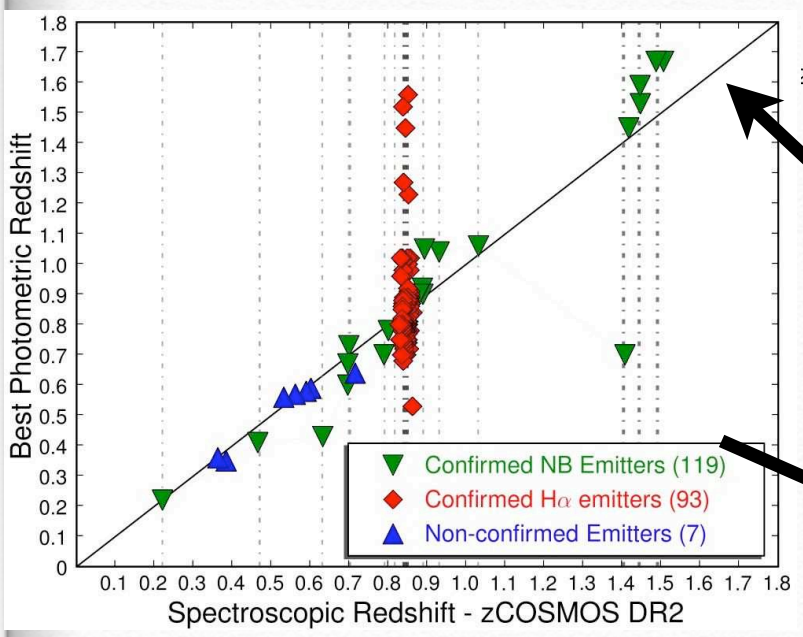


Which emission line?



Spectro-z confirmation

Double-line confirmation



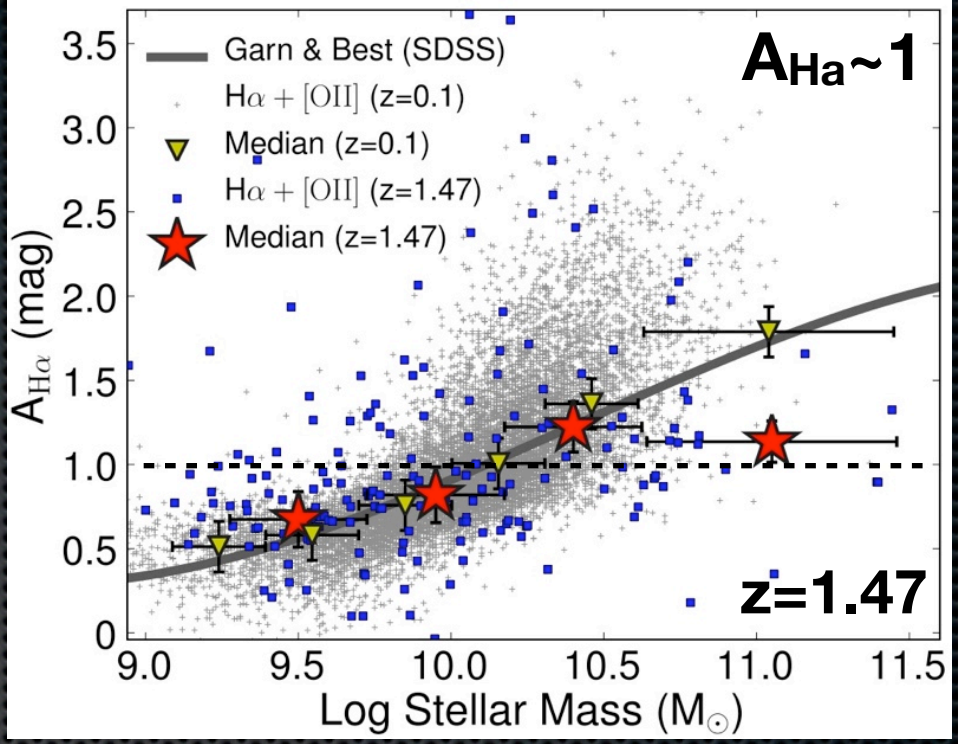
Select Hα emitters

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

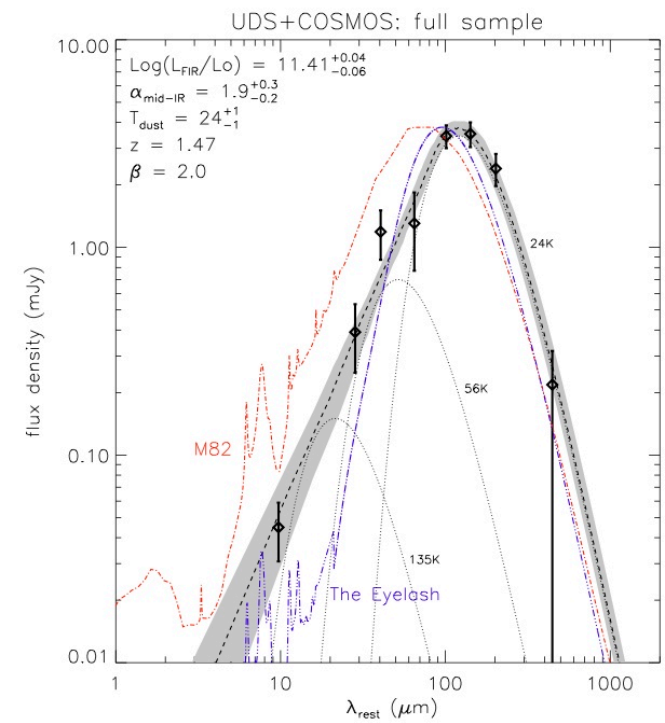
Extinction-Mass z~0-1.5

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

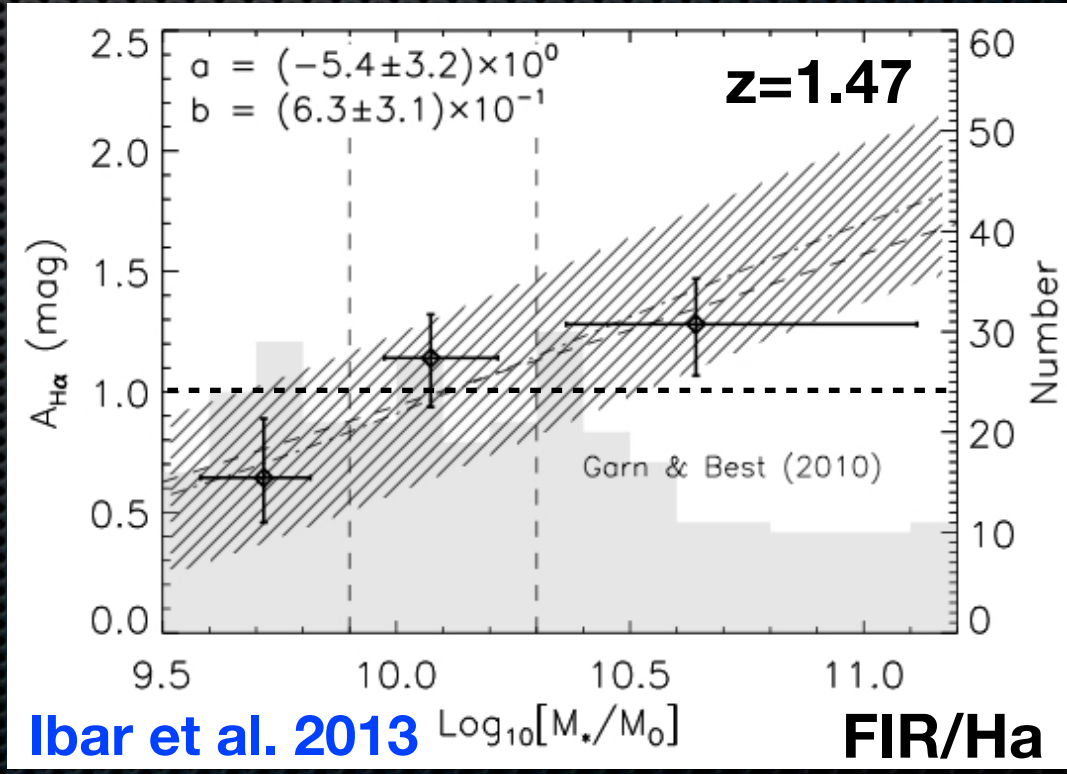
Relation holds up to z~1.5-2



Sobral et al. 2012

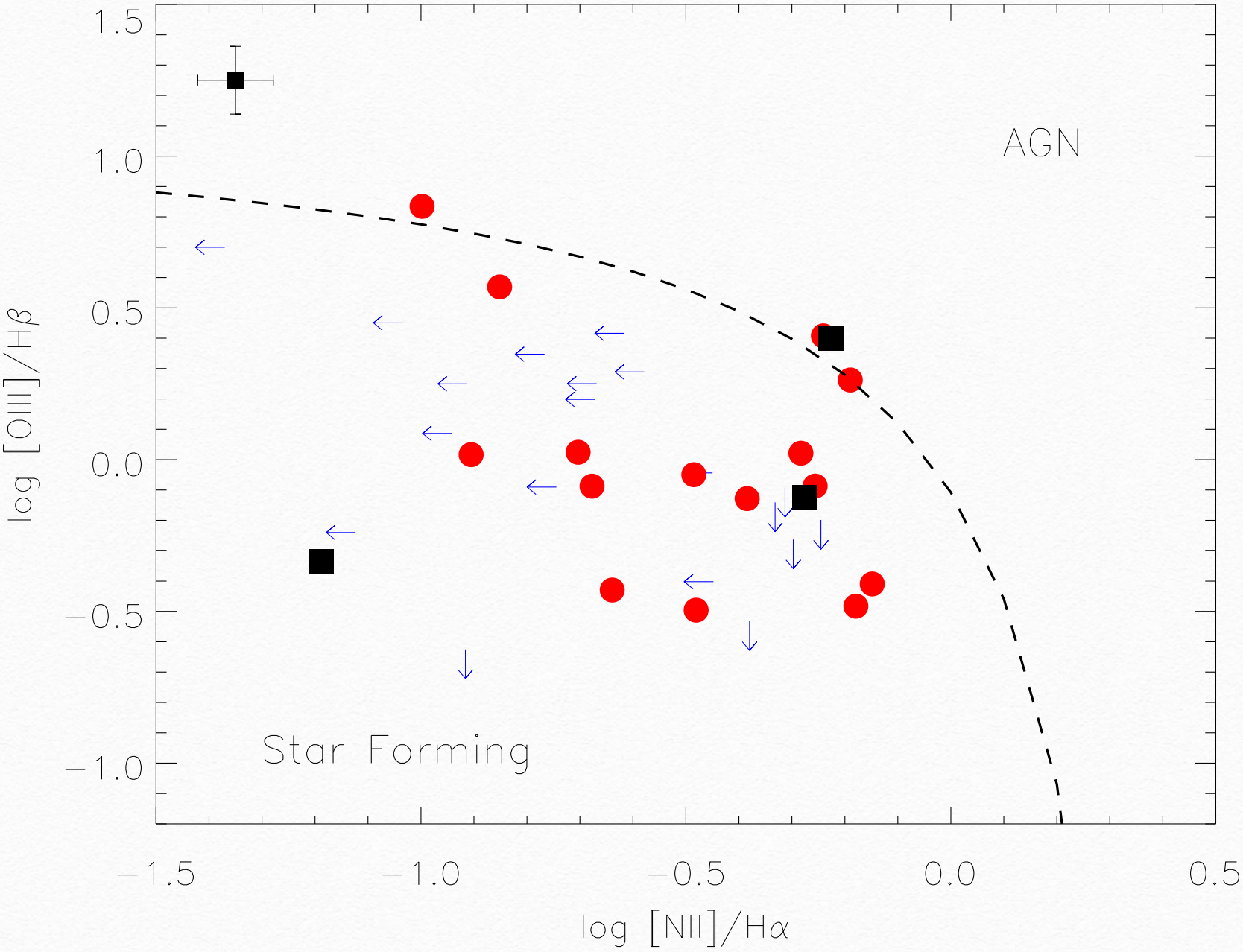


FIR derived A_{Ha} = 0.9-1.2 mag

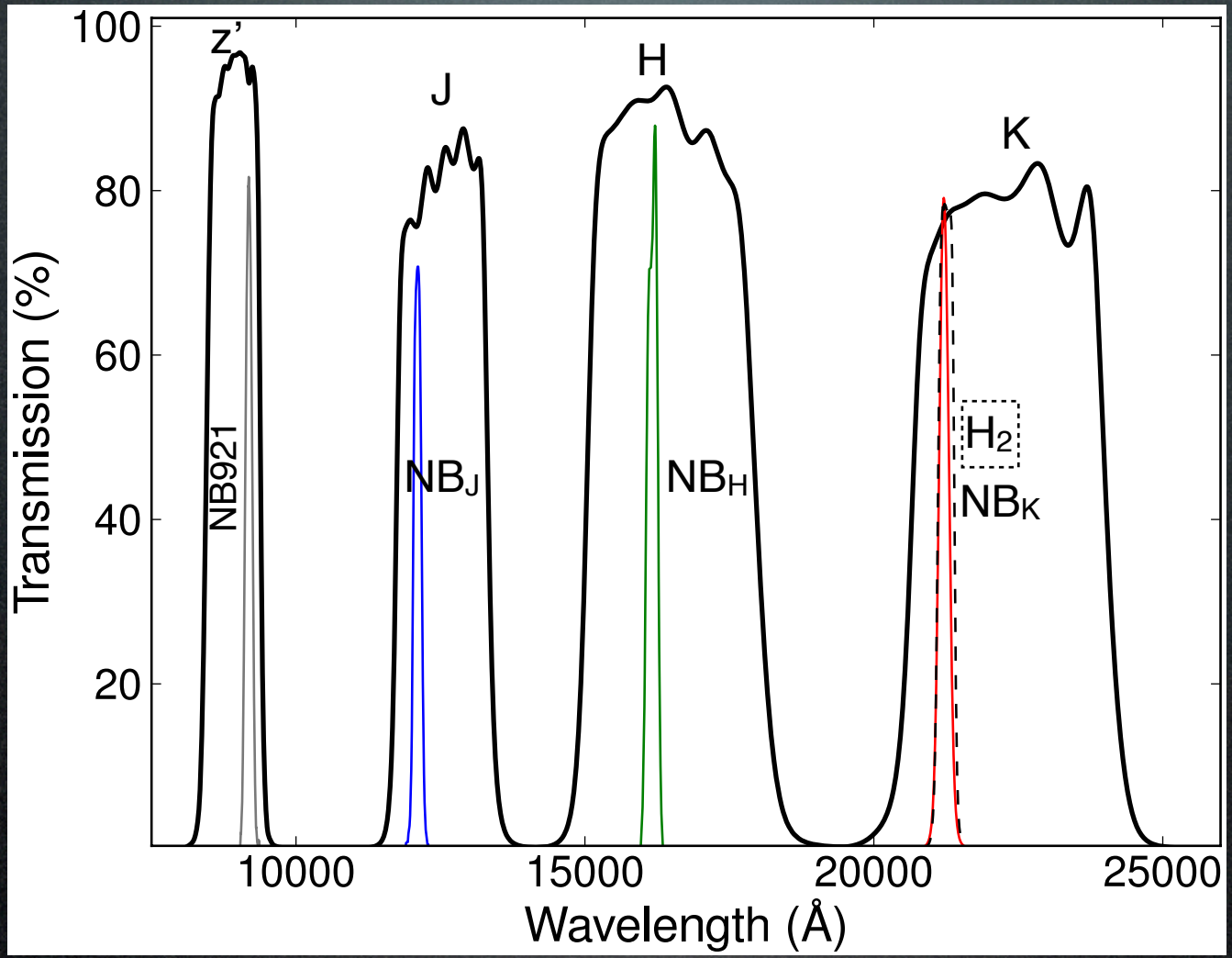


Ibar et al. 2013

FIR/Ha


AGN
Star Forming
log [OIII]/Hβ
log [NII]/Hα
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−1.0
−0.5
0.0
0.5

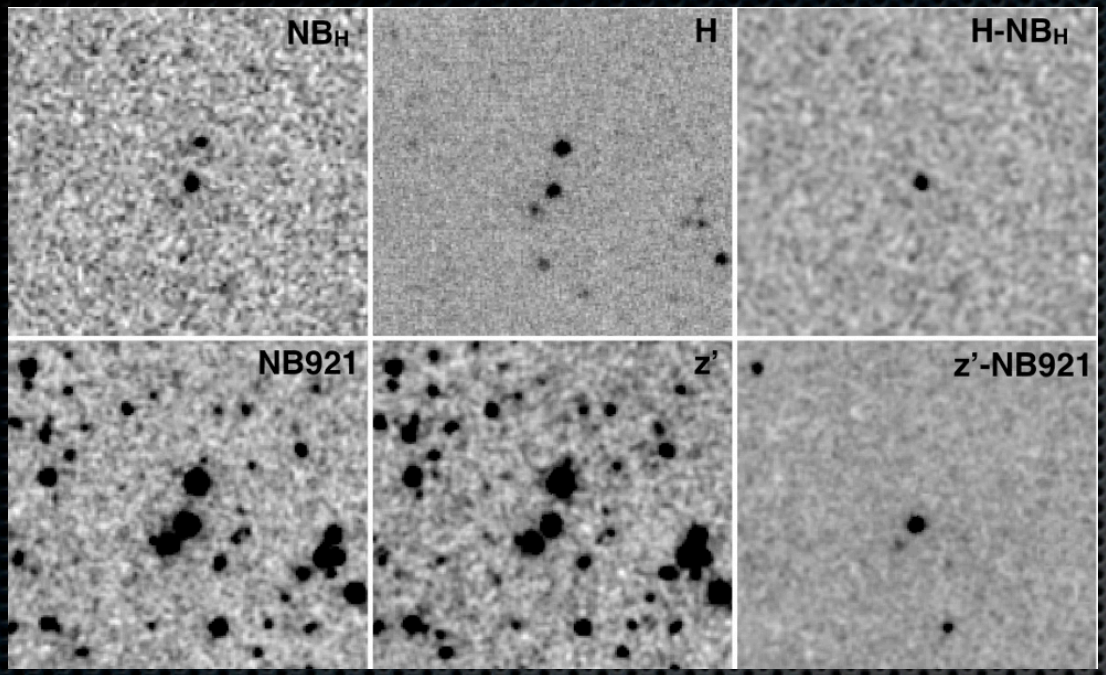
Filters combined to improve selection: double/triple line detections

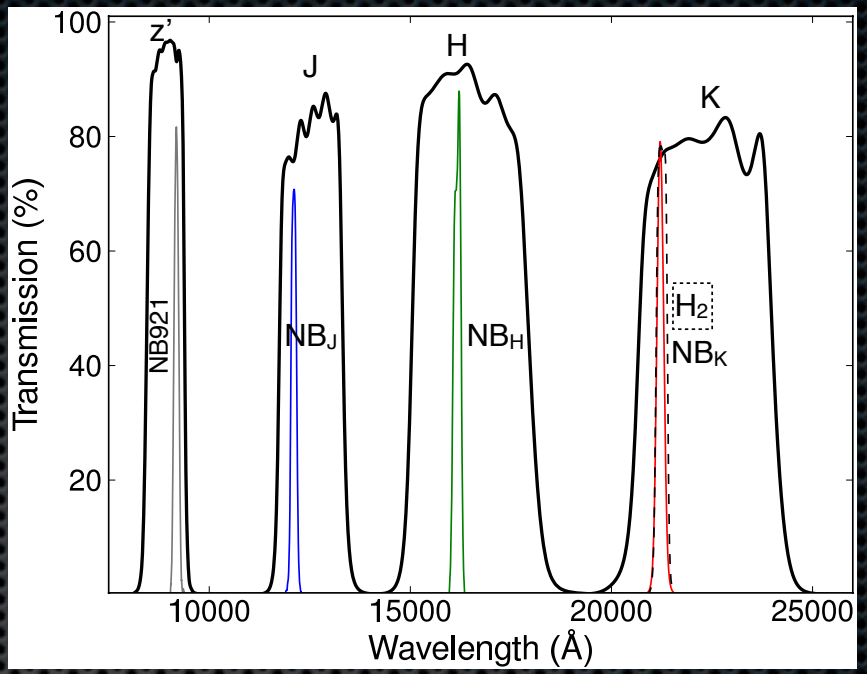


z=2.23 : [OII] (NBJ), [OIII] (NBH), Hα (NBK)

z=1.47 : [OII] (NB921), Hβ (NBJ), Hα (NBH)

z=0.84 : [OIII] (NB921), Hα (NBJ)



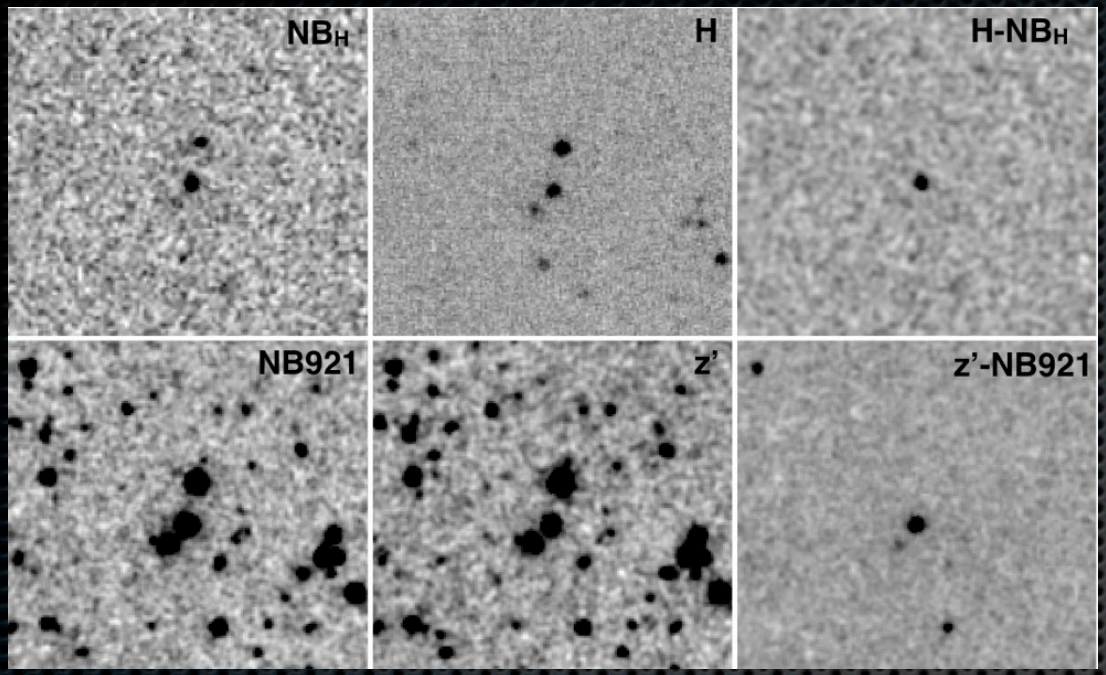


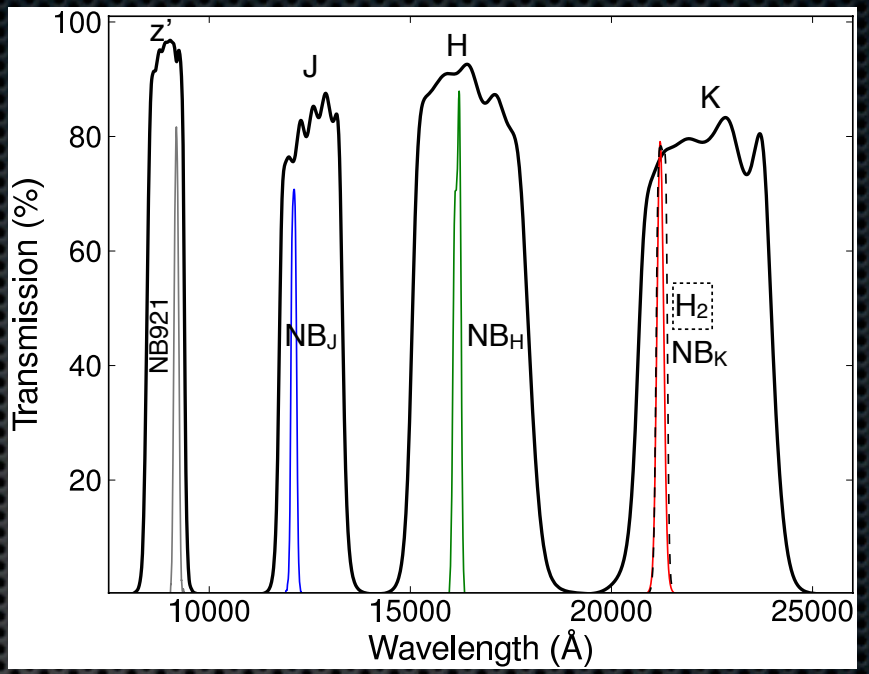
Hα emitters in HiZELS

2 sq deg: COSMOS + UDS

Prior to HiZELS:

~10 sources





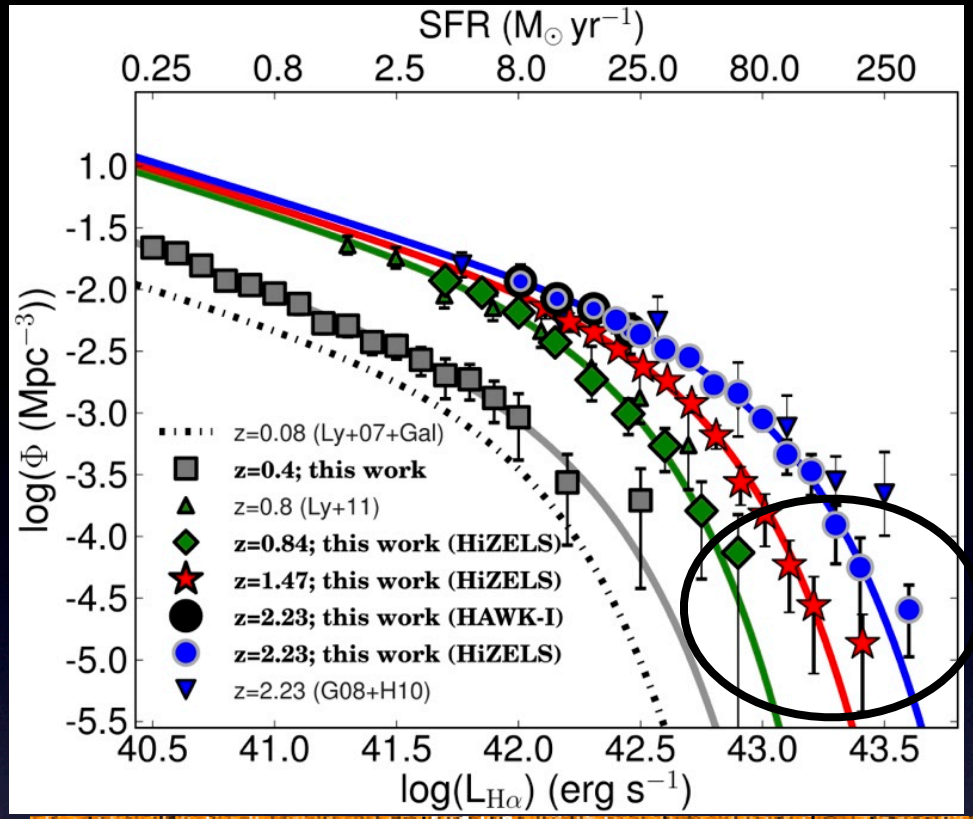
Hα emitters in HiZELS

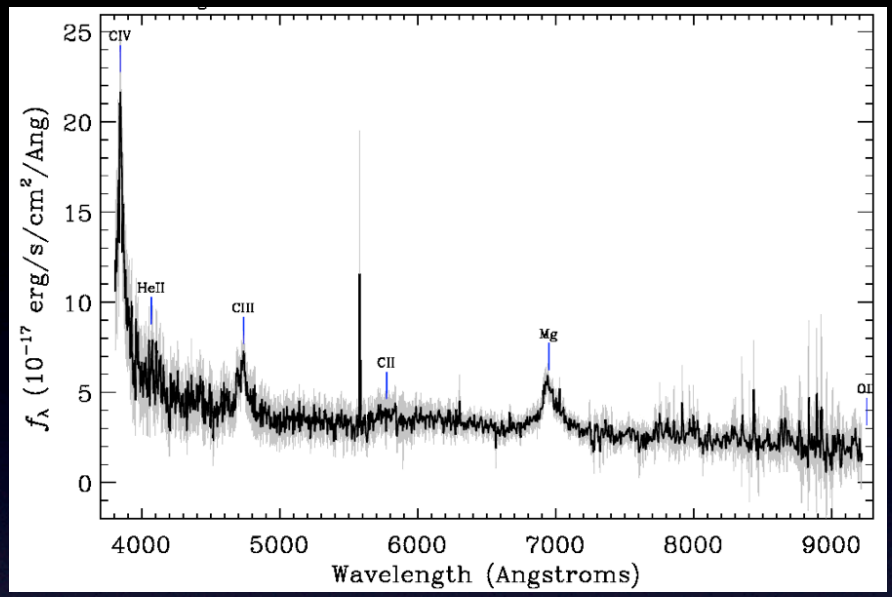
2 sq deg: COSMOS + UDS

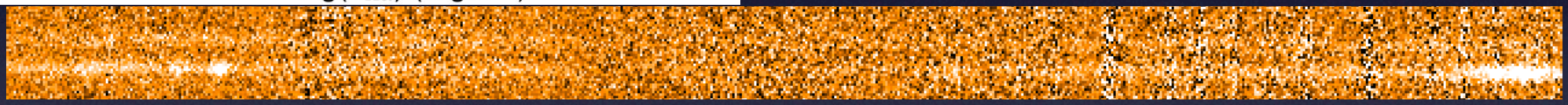
Prior to HiZELS: ~10 sources

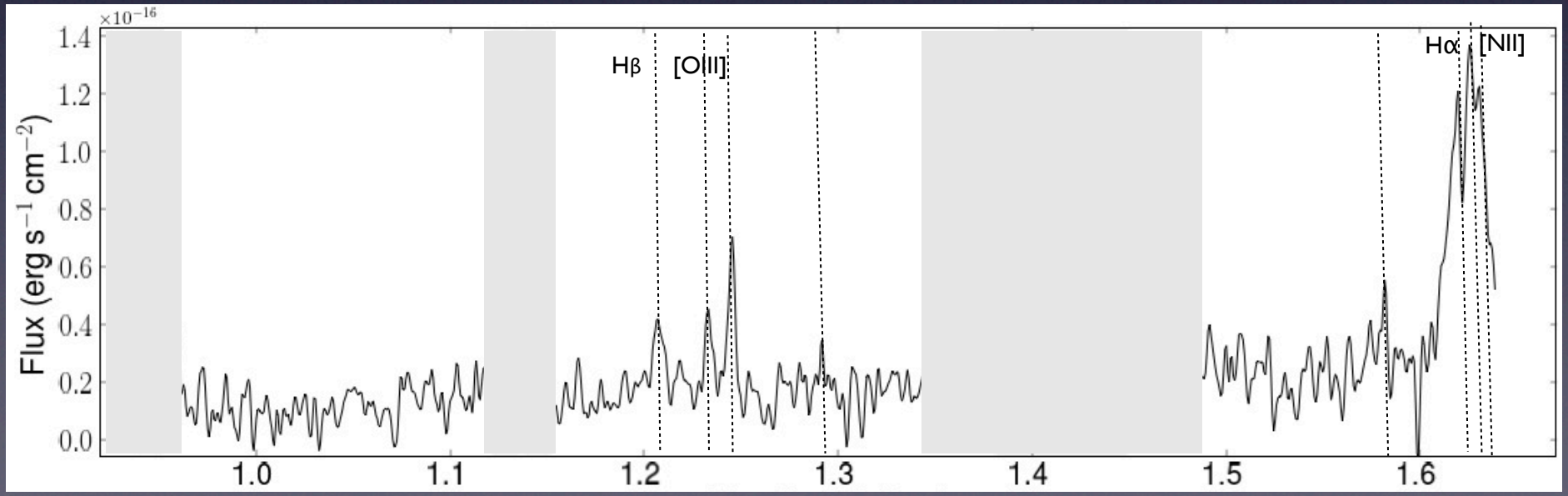
z=0.4: 1122 z=0.8: 637 z=1.47: 515 and z=2.23: 807

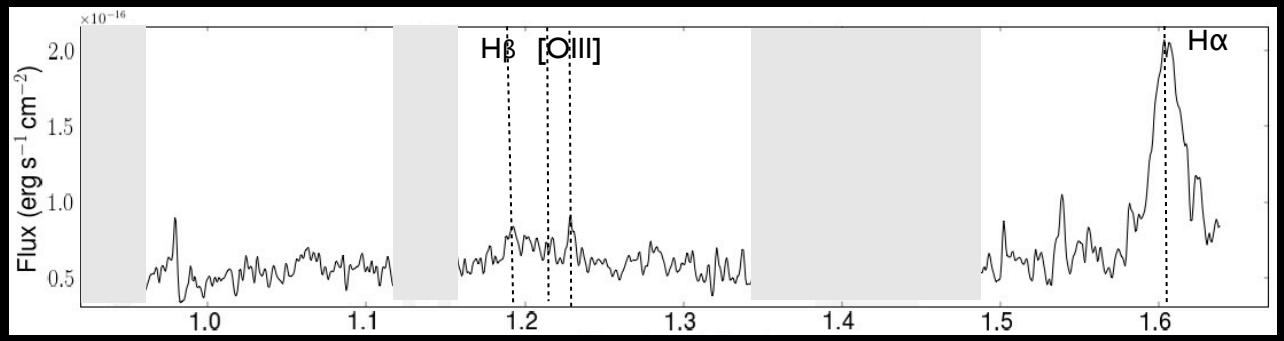
Subaru FMOS + NTT + WHT

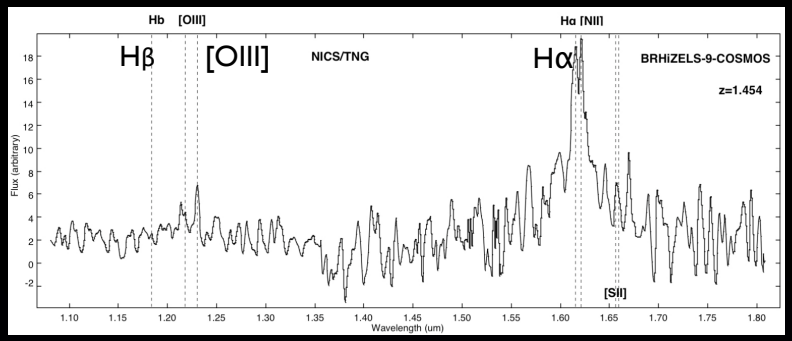


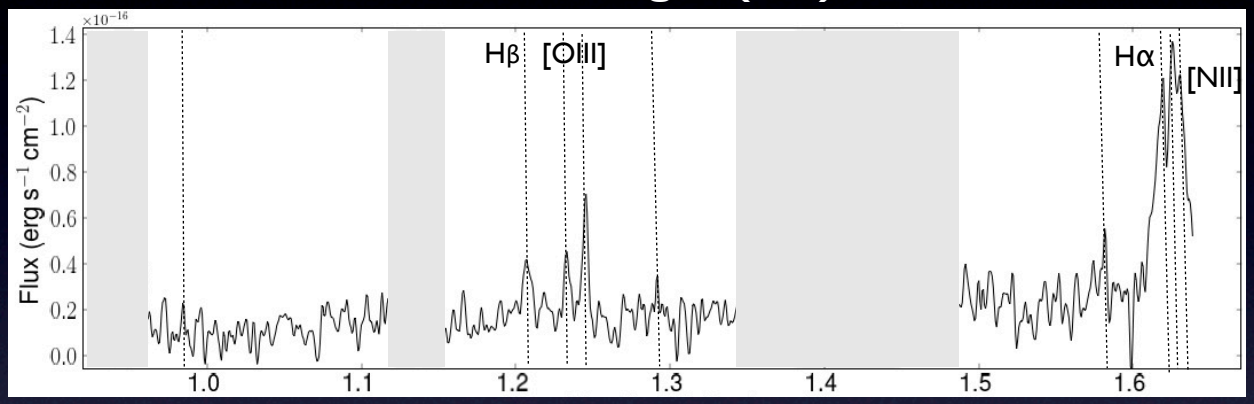


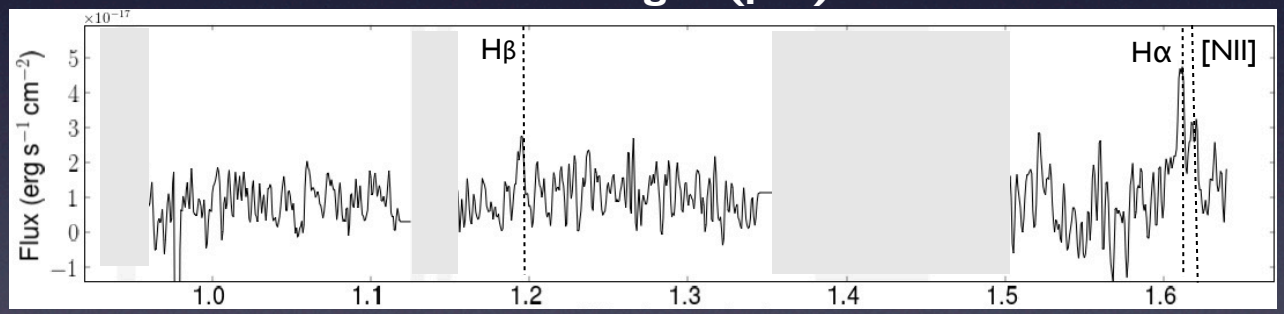


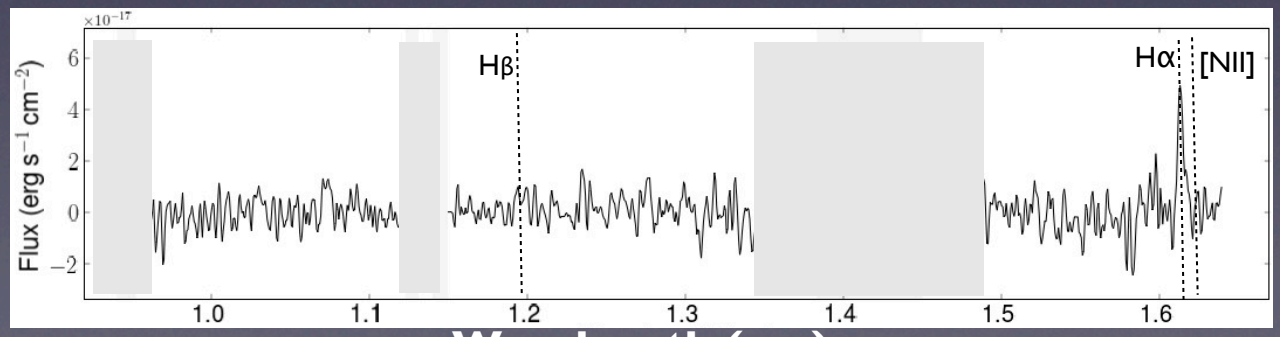












Hα Luminosity

z=1.47

Broad-line AGN

AGN dominated

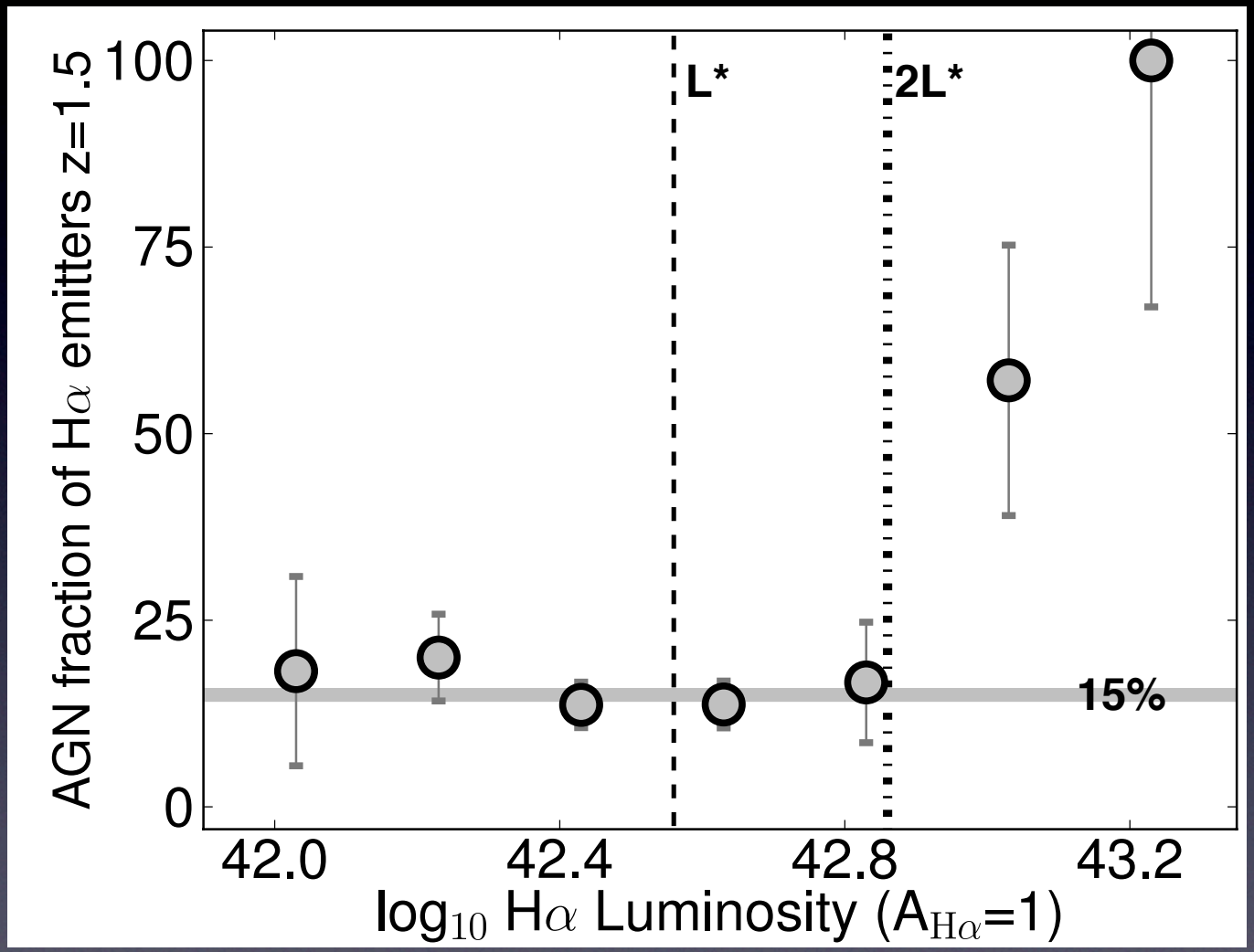
AGN + SF

More Metal-rich

More Metal-poor

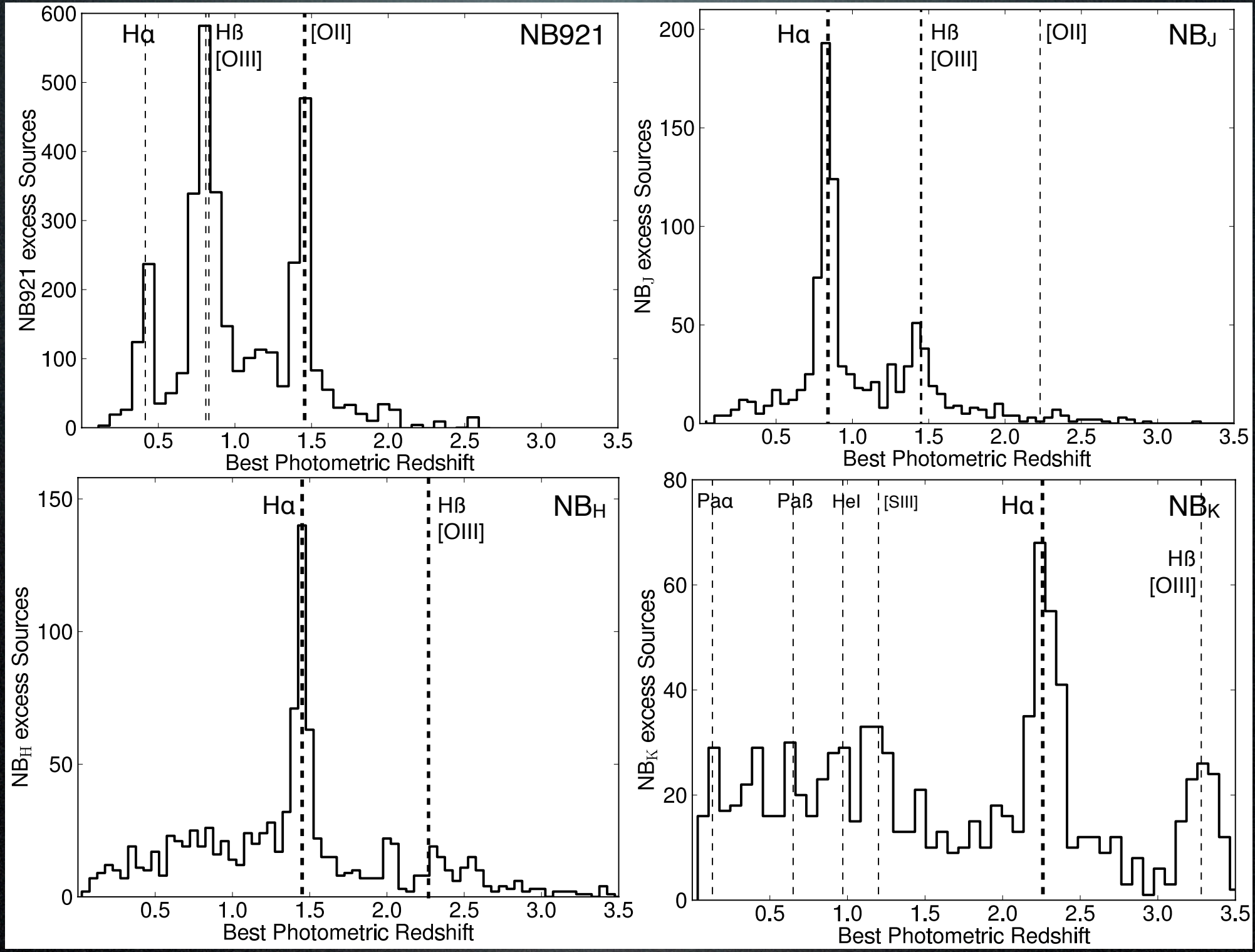
Star-forming

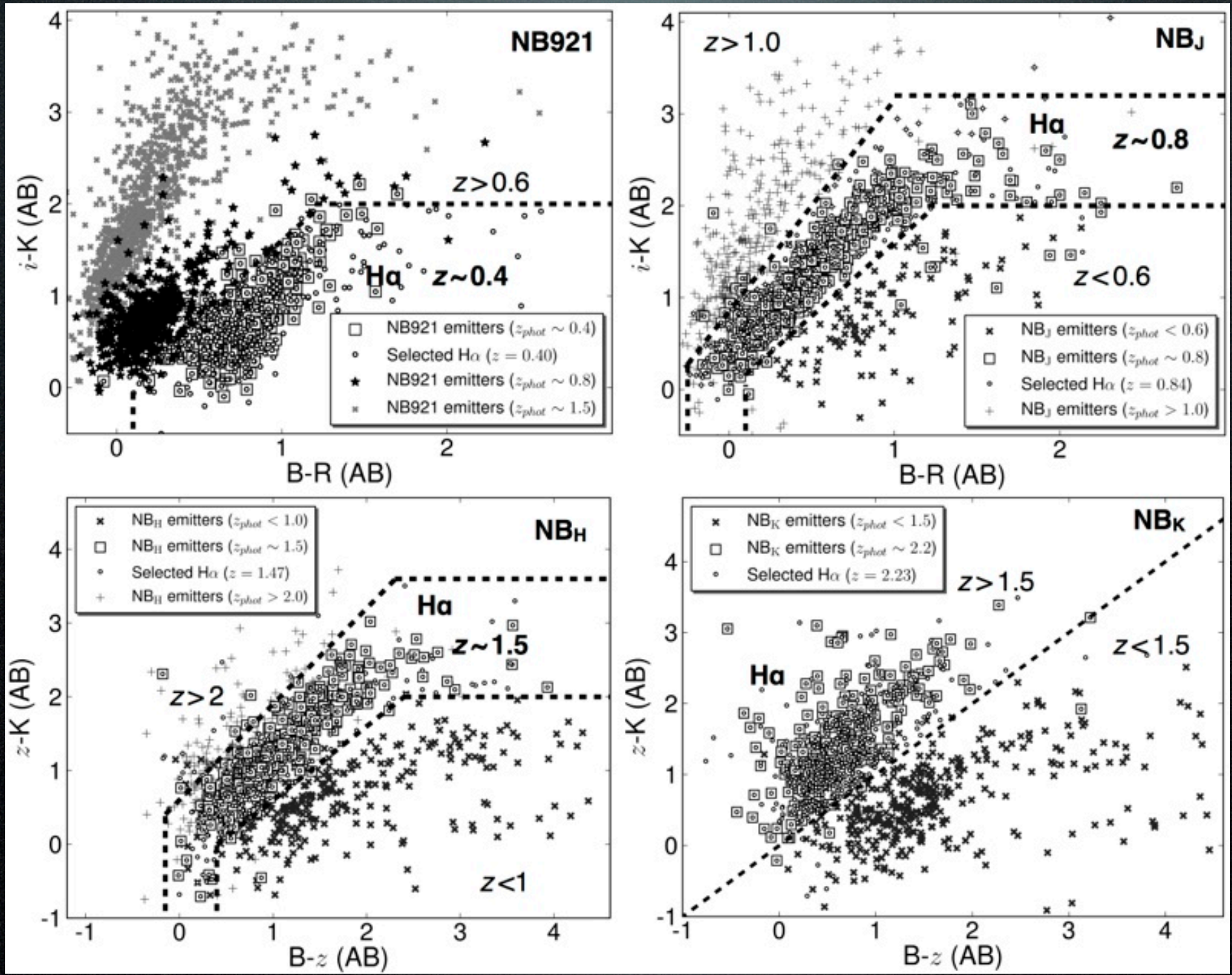
AGN



- ~10 % z~0.8
- ~15 % z~1.47
- ~ Become dominant at L>2L* (H-alpha)

S+ in prep

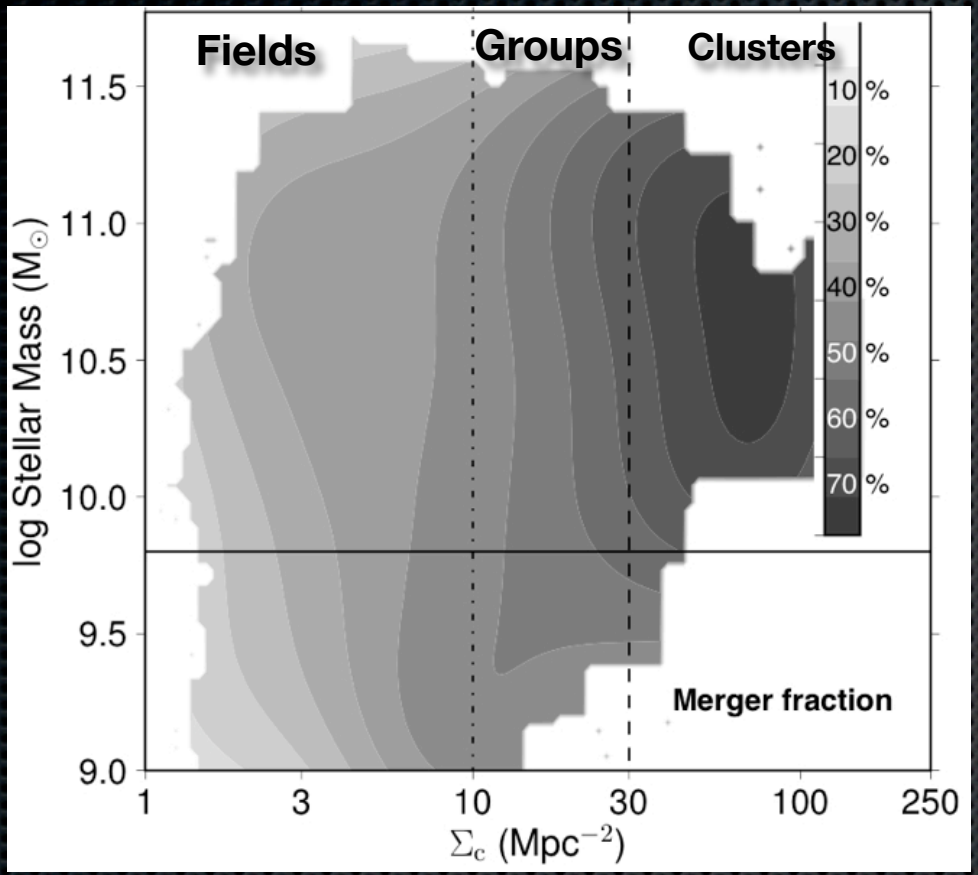

Hα
Hß
[OIII]
[OII]
NB921
NB921 excess Sources
Best Photometric Redshift
NB$_J$
NB$_J$ excess Sources
NB$_H$
NB$_H$ excess Sources
Paα
Paß
HeI
[SIII]
NB$_K$
NB$_K$ excess Sources

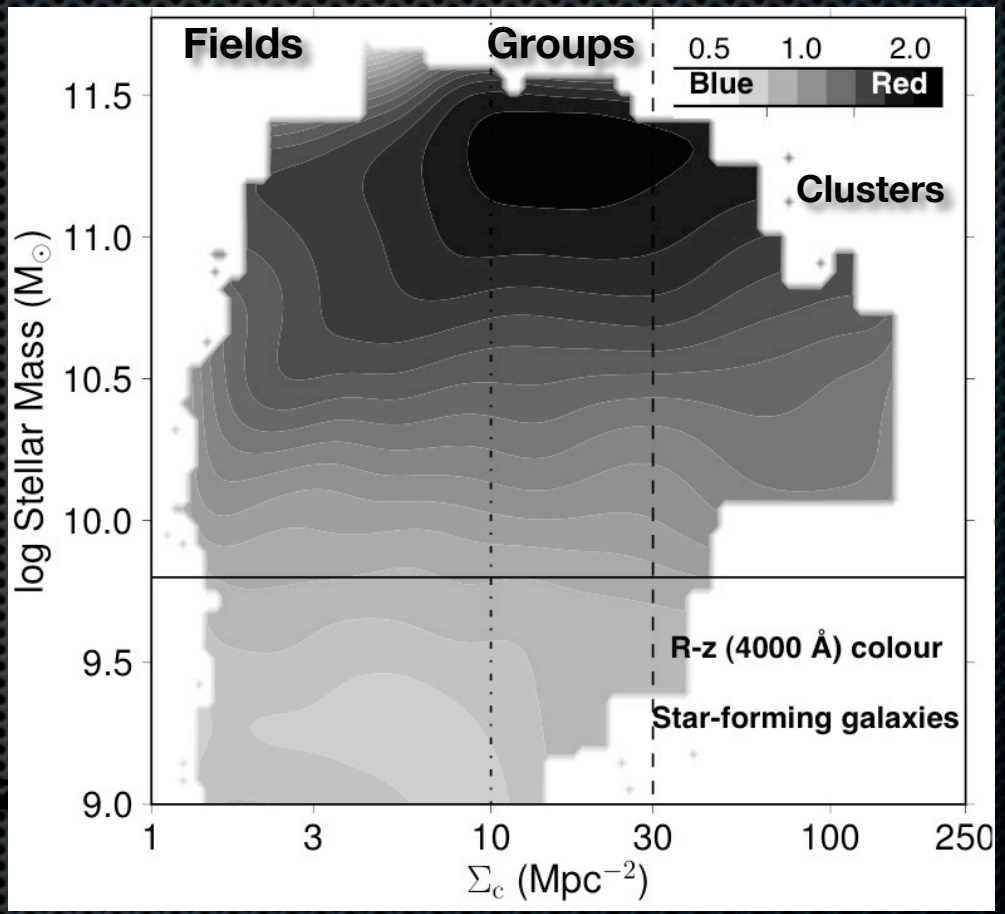

NB921
z>0.6
Hα
z~0.4
NB921 emitters ($z_{phot} \sim 0.4$)
Selected Hα ($z = 0.40$)
NB921 emitters ($z_{phot} \sim 0.8$)
NB921 emitters ($z_{phot} \sim 1.5$)
i-K (AB)
B-R (AB)
z>1.0
NBJ
Hα
z~0.8
z<0.6
NBJ emitters ($z_{phot} < 0.6$)
NBJ emitters ($z_{phot} \sim 0.8$)
Selected Hα ($z = 0.84$)
NBJ emitters ($z_{phot} > 1.0$)
i-K (AB)
B-R (AB)
NBH emitters ($z_{phot} < 1.0$)
NBH emitters ($z_{phot} \sim 1.5$)
Selected Hα ($z = 1.47$)
NBH emitters ($z_{phot} > 2.0$)
NBH
Hα
z~1.5
z>2
z<1
z-K (AB)
B-z (AB)
NBK emitters ($z_{phot} < 1.5$)
NBK emitters ($z_{phot} \sim 2.2$)
Selected Hα ($z = 2.23$)
NBK
z>1.5
z<1.5
Hα
z-K (AB)
B-z (AB)

Mass and/or environment?

at z~1

Sobral et al. 2011

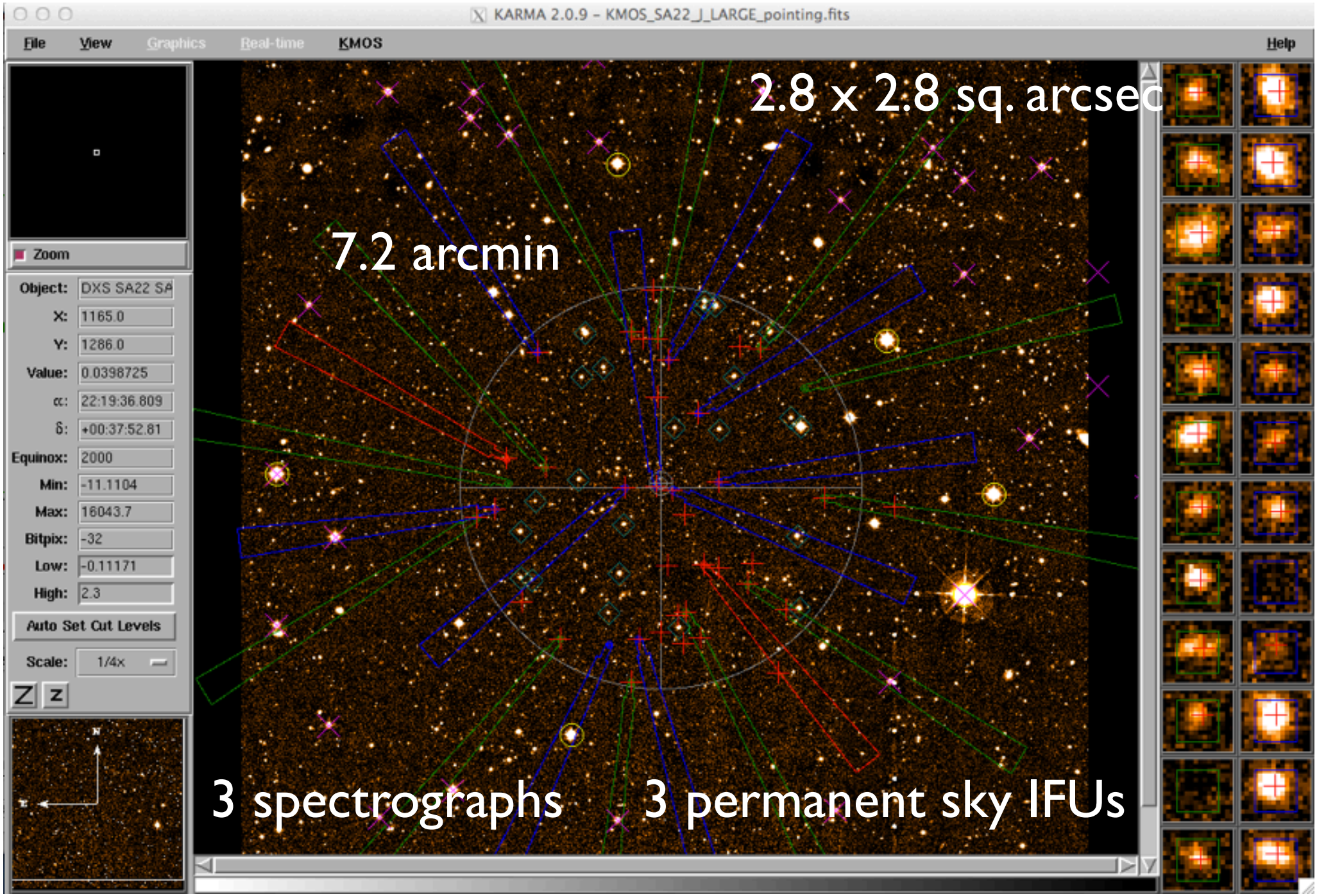


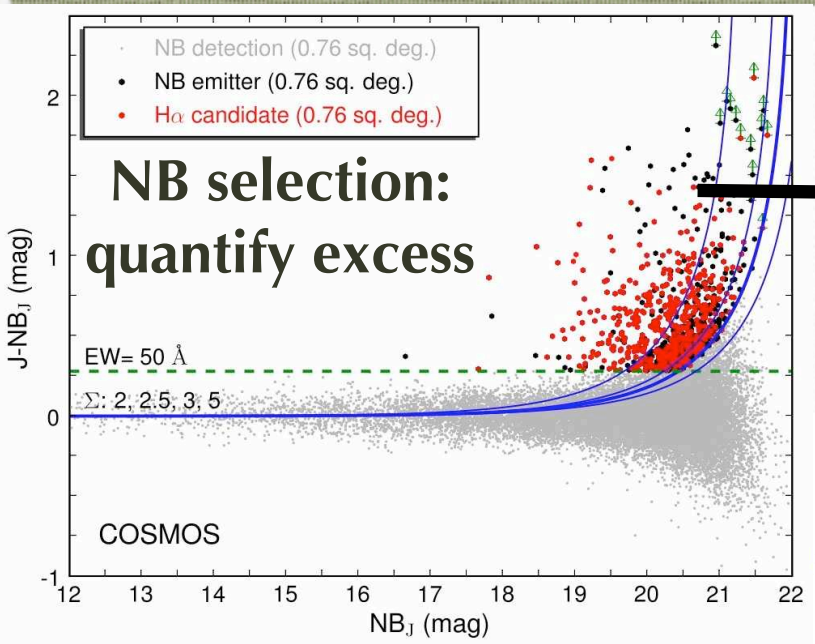


Merger fraction of star-forming galaxies depends mostly on environment, not mass

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

Preparing the OBs for KMOS: KARMA



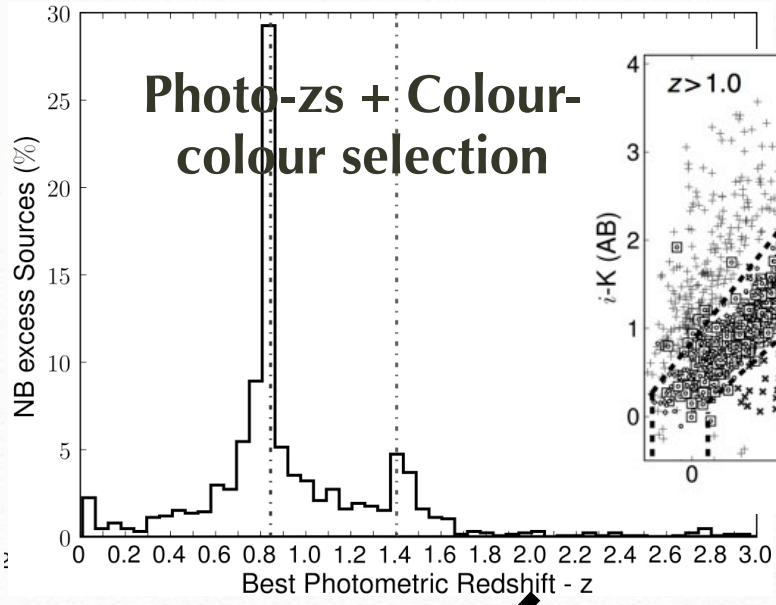


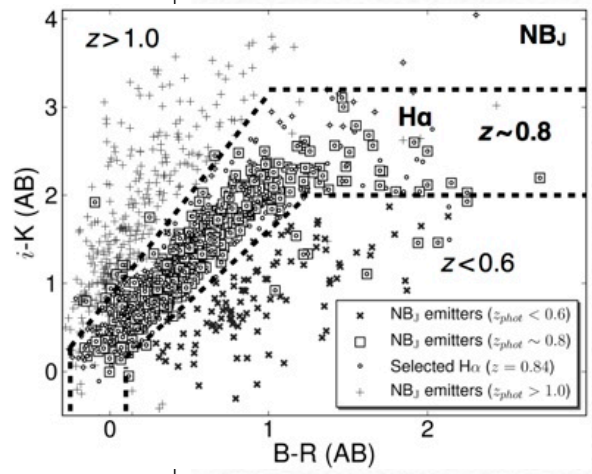
Source extraction

Potential line emitters

Which emission line?

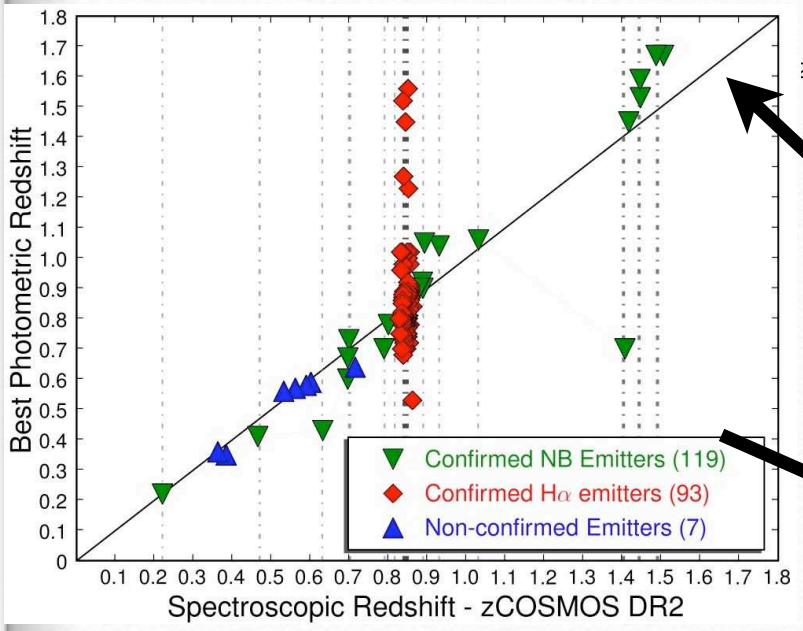
Probing well-studied fields is fundamental!





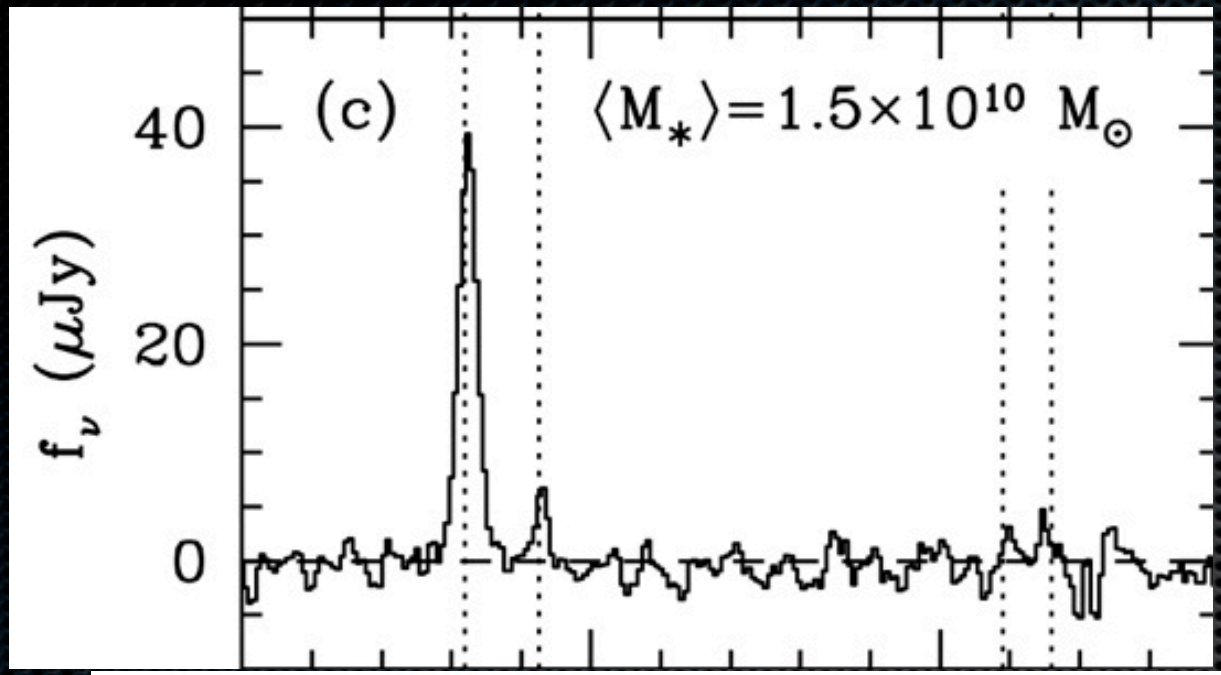
Spectro-z confirmation

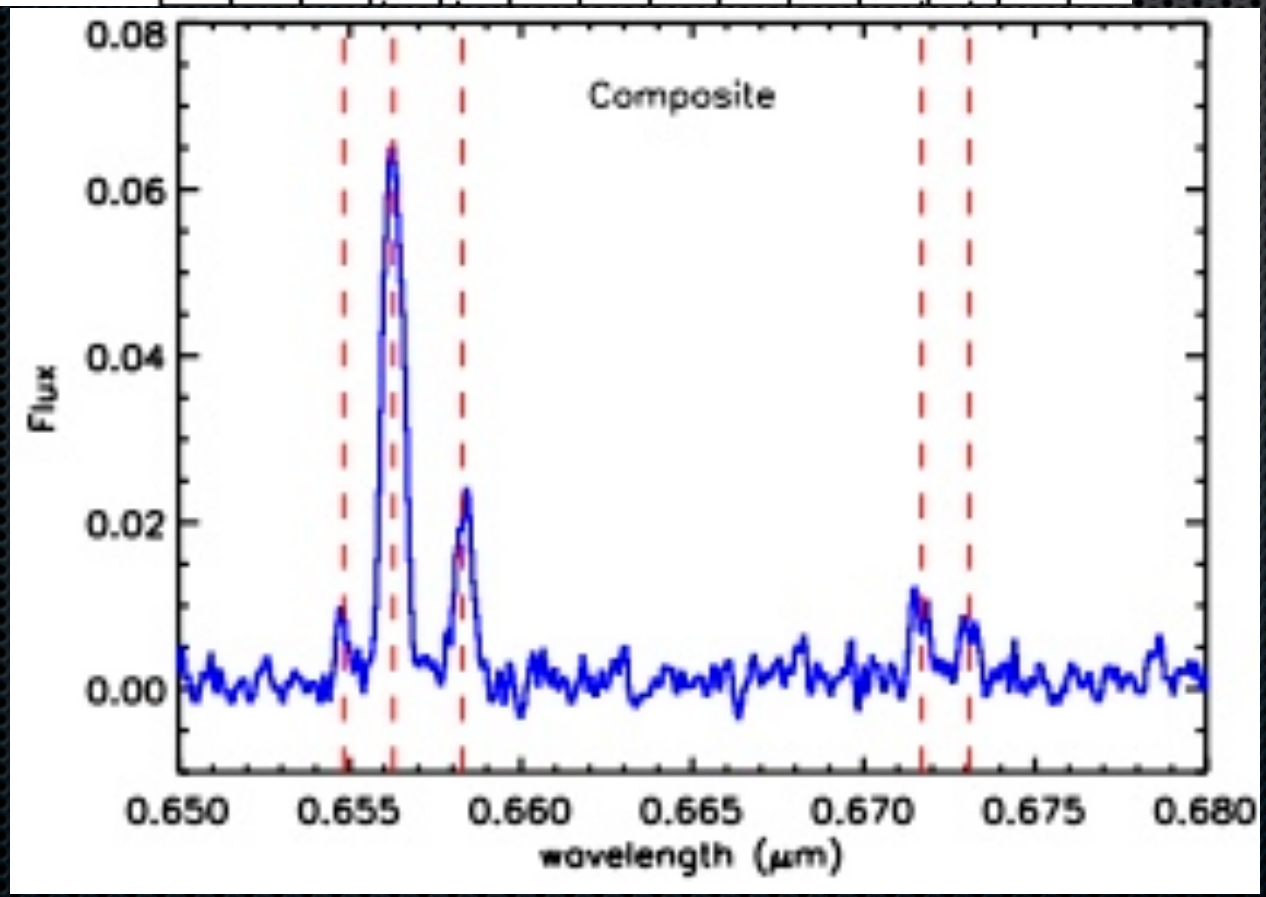
Double-line confirmation



Select Hα emitters

Samples >90% reliable
>90% complete





Selection Matters:

z~1.5-2.23

UV selection: metal-poor

Same masses

Ha selection: only slightly sub-solar

Swinbank+12a

Stott+13b

Conclusions:

KMOS+Ha selected works extraordinarily well: resolved dynamics in ~1-2 hours, 75+-8% disks, 50-275km/s

Confirmed a rich group of star-forming galaxies at z=0.813 with ~solar metallicities, typical SFRs, all disks

Confirmed the weak TF ZP evolution to z~1

Group galaxies more massive & slightly lower sSFRs + higher Metallicity, but the same TF and mass-metallicity relations

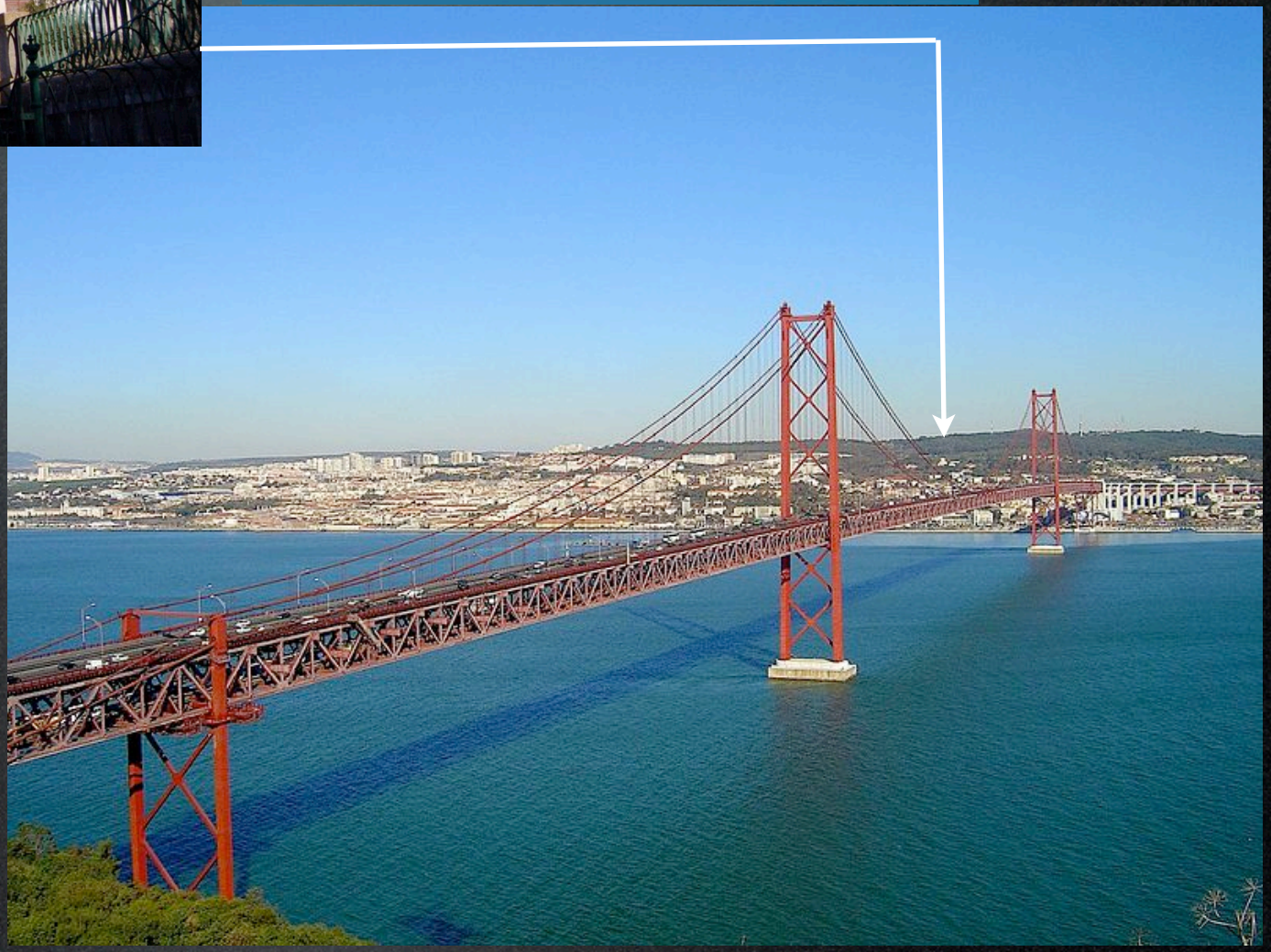
- More data were taken in September - doubles the sample size. Results in ~2 months. Data is public!

Moving to Lisbon

IF
INVESTIGADOR FCT

Lisbon's Observatory

Come visit!



O A L

CENTRO DE ASTRONOMIA E ASTROFÍSICA DA UNIVERSIDADE DE LISBOA
CAAUL

Institute of Astrophysics and Space Sciences