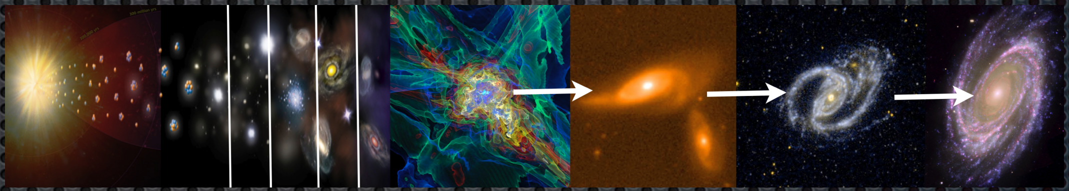
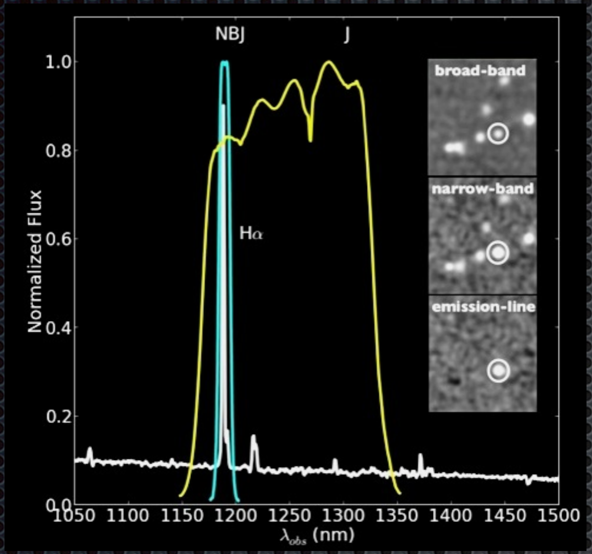
The dynamics and evolution of Hα selected star-forming galaxies since z=2.23

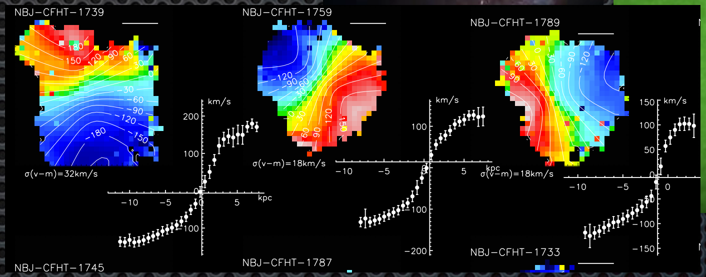
with SINFONI & KMOS

David Sobral

CAAUL Lisbon/Leiden Obs.







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

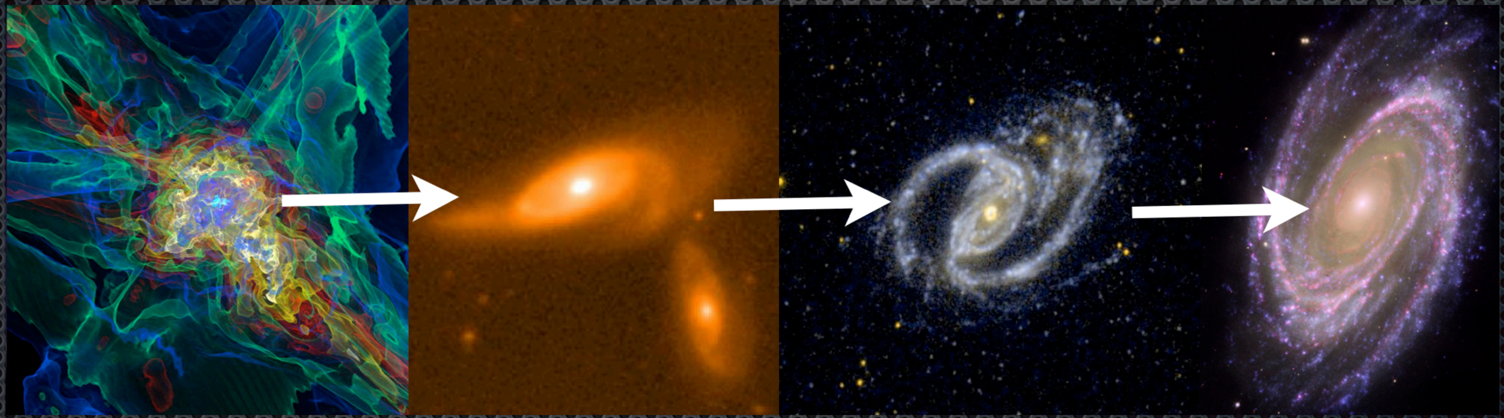
CENTRO DE ASTRONOMIA E ASTROFÍSICA DA UNIVERSIDADE DE LISBOA CAAUL

NWO

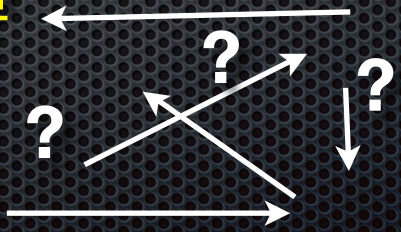
Sterrewacht Leiden

How (and driven by which mechanisms)

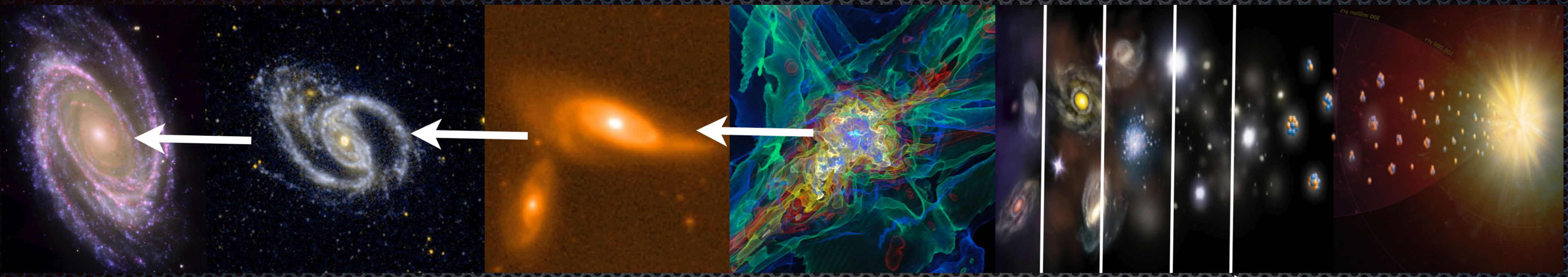
<u>do galaxies form and evolve?</u>



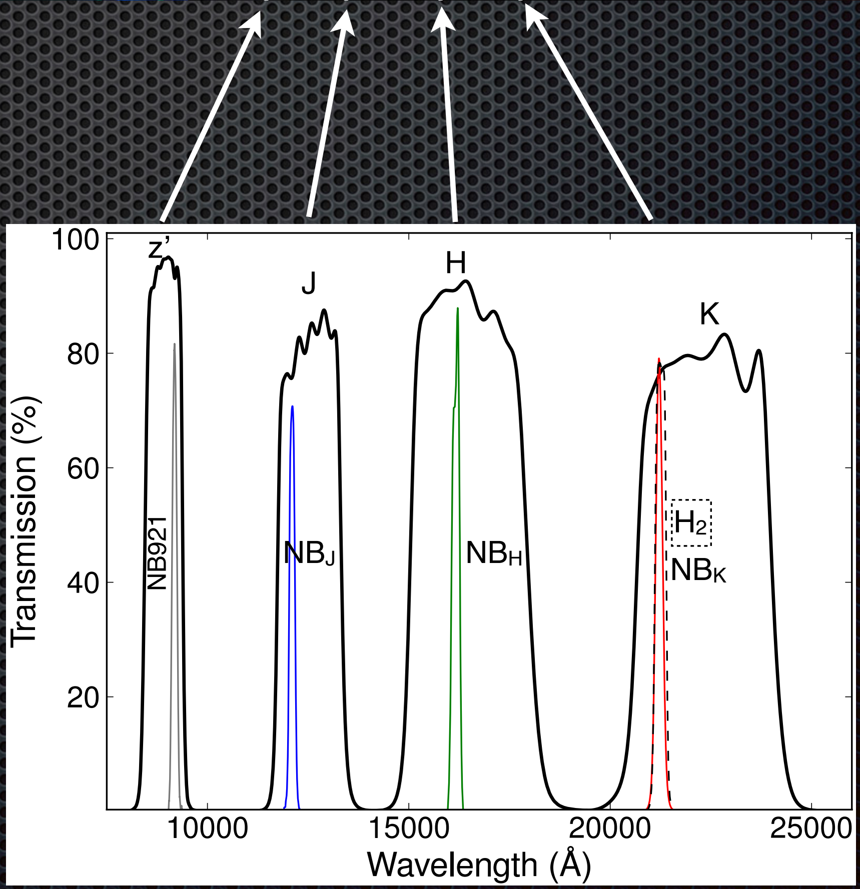
- <u>Morphological change?</u>
- <u>Dynamics</u>



- <u>Star formation</u>
- <u>"Quenching"</u>

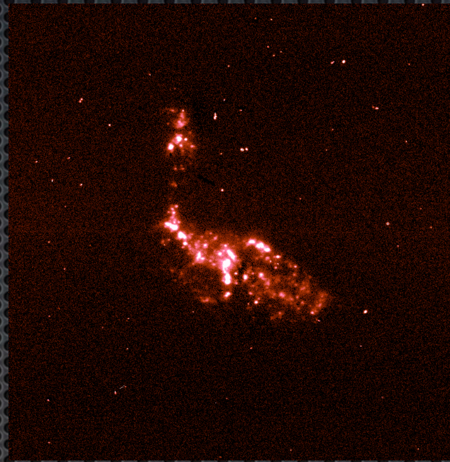


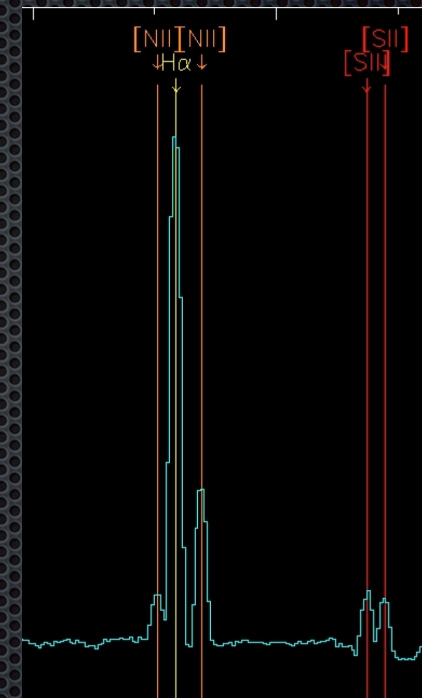
Equally selected "Slices" with >1000 star-forming galaxies in multiple environments and with a range of properties



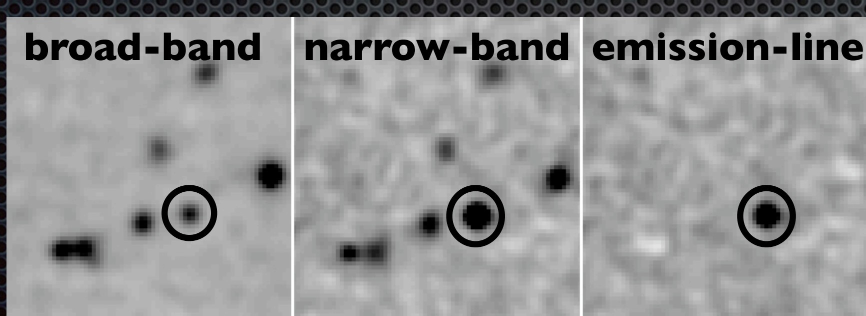
Hα (+NB)

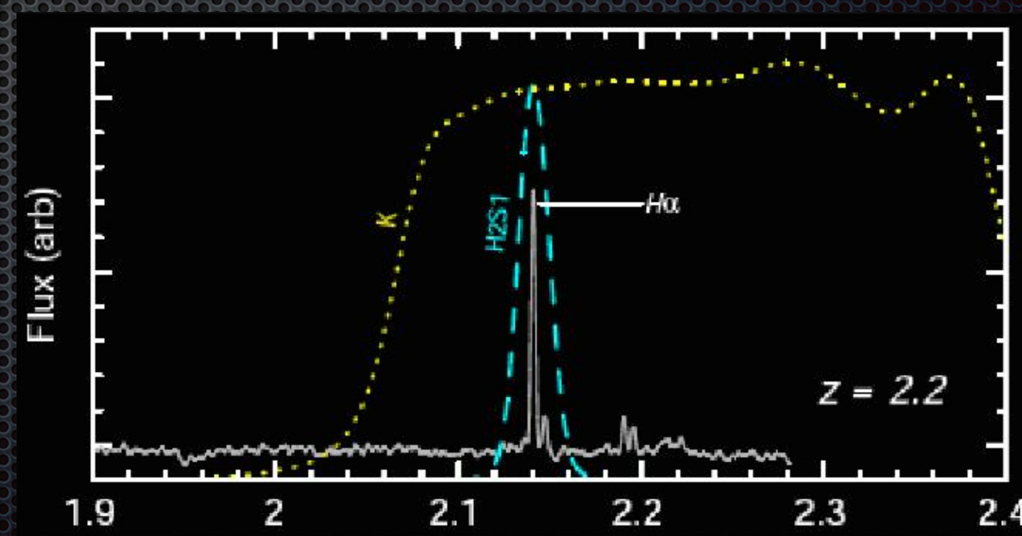
- Sensitive, good selection
- Well-calibrated
- Traditionally for Local Universe
- **<u>Narrow-band technique</u>**





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



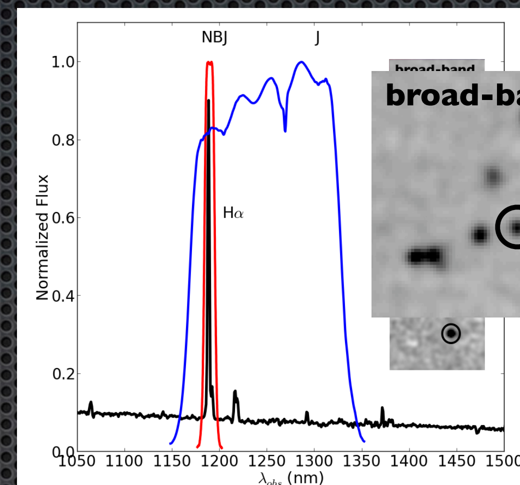


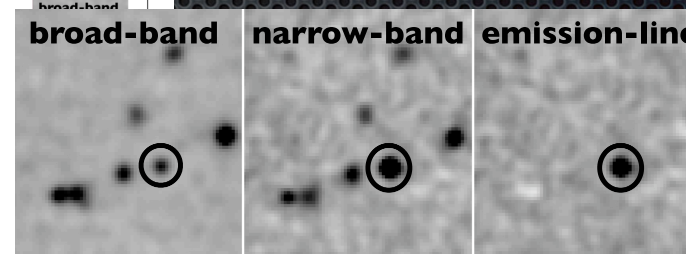
HiZELS

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 deg^2**





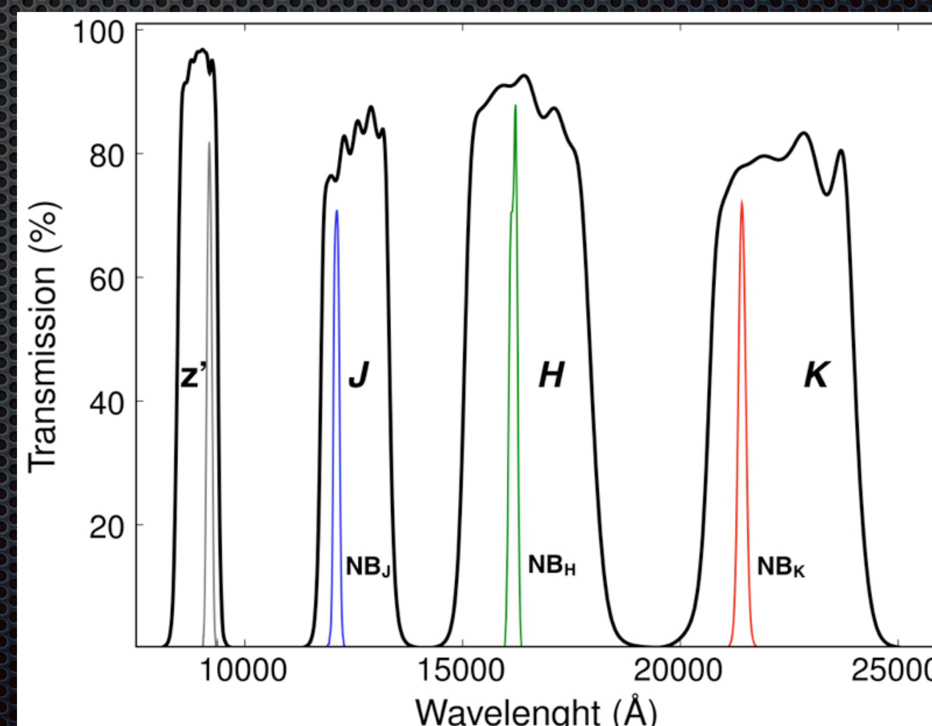
- **~80 Nights UKIRT+Subaru +VLT+CFHT+INT**

- **>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**

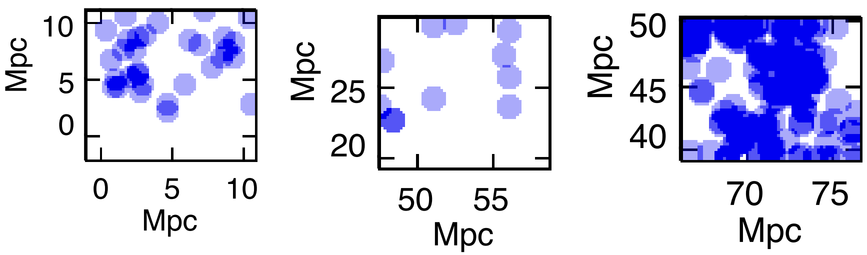
- **Other lines (simultaneously; Sobral+09a,b,Sobral+12,13a,b, Matthee+14)**



<u>Sobral et al. 2013a</u>

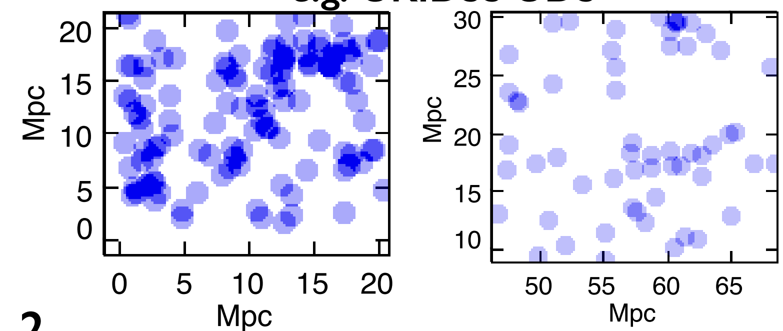
10x10 Mpc~100-300 arcmin^2

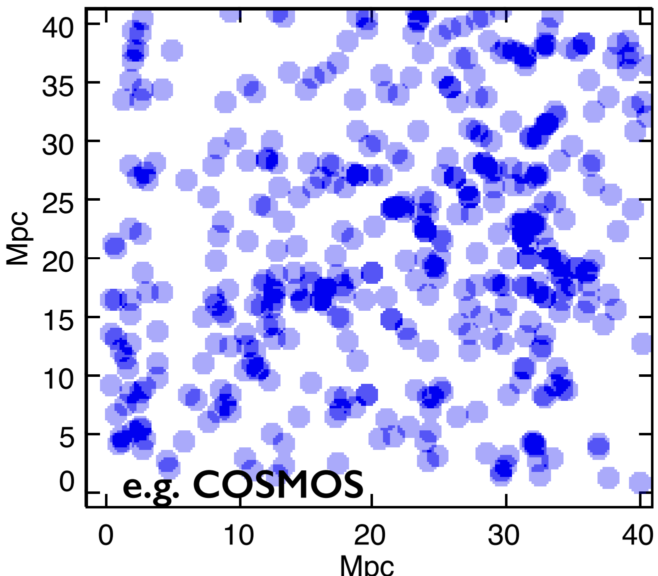
e.g. GOODS-N+S



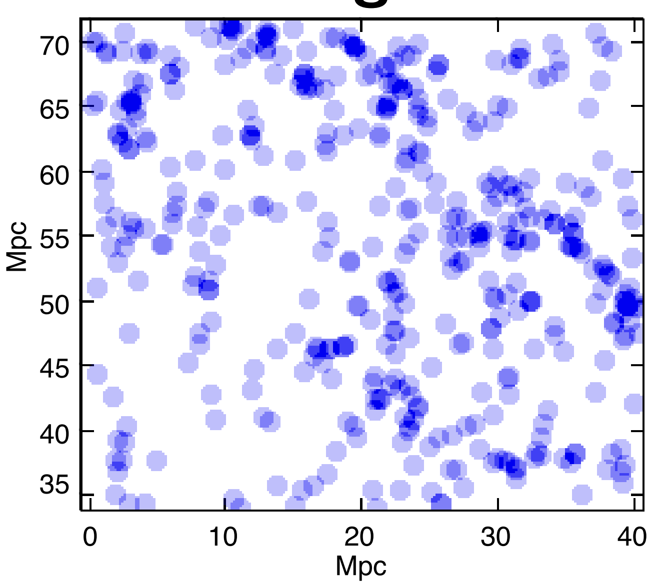
20x20 Mpc ~0.7 deg^2

e.g. UKIDSS UDS

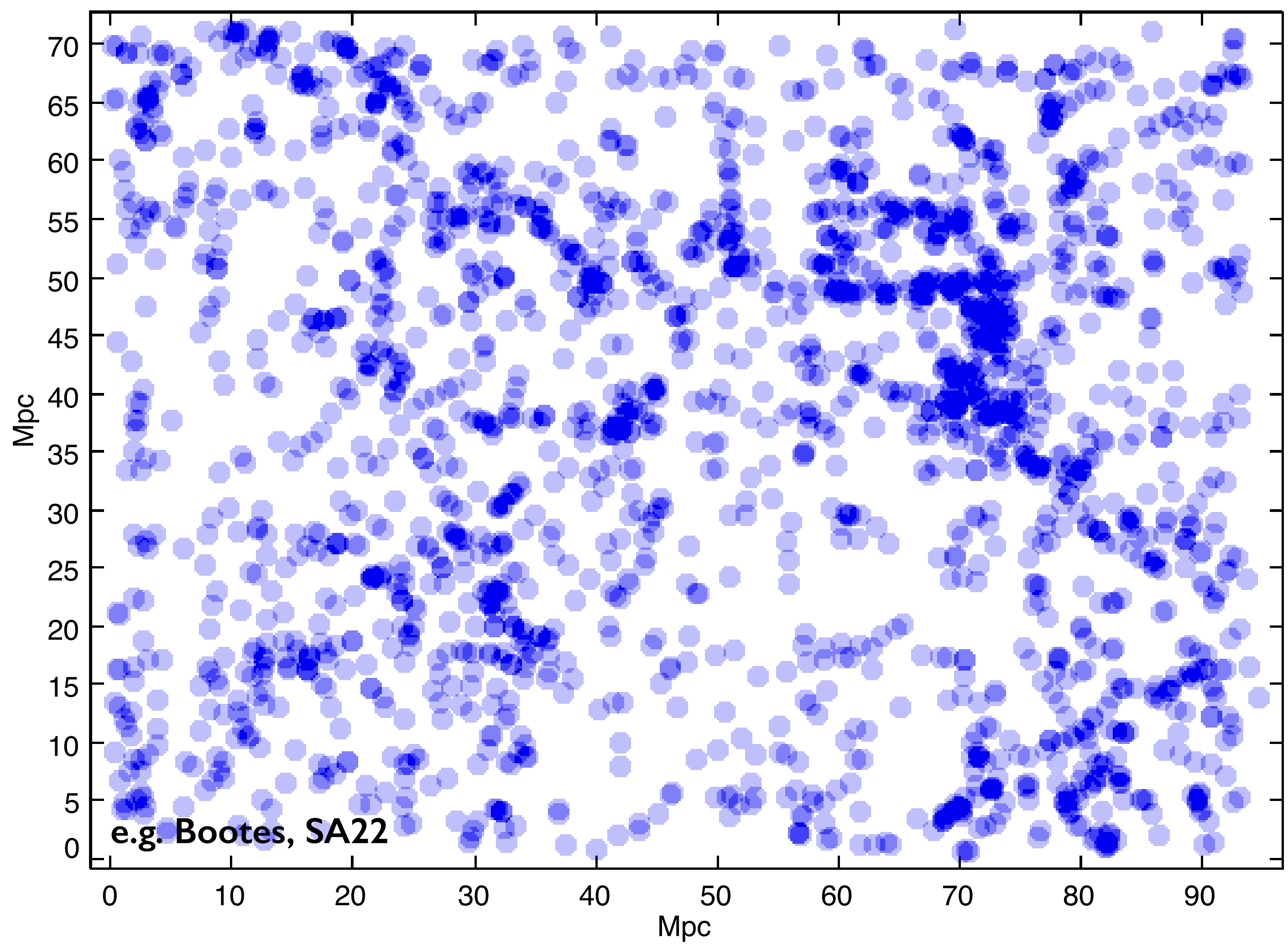




~2 deg^2

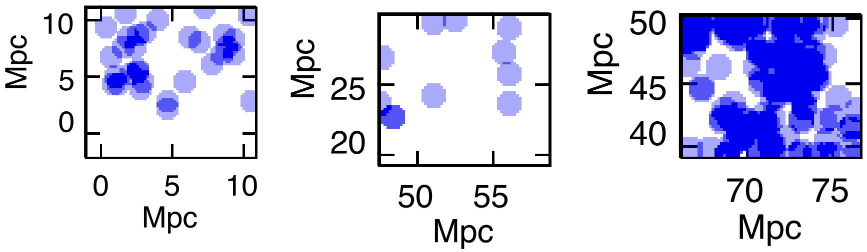


~10 deg^2

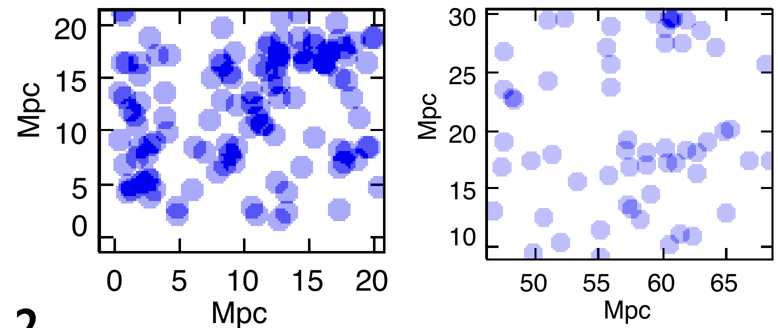


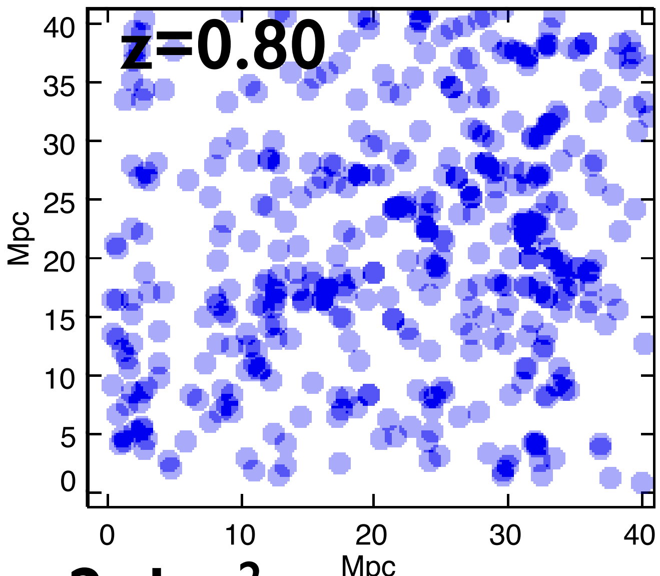
Hα emitters z=0.81+-0.01

10x10 Mpc~100-300 arcmin^2

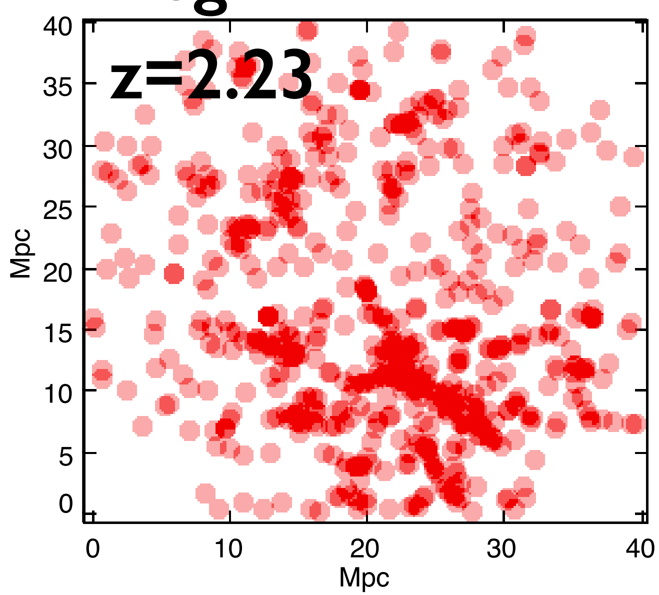


20x20 Mpc ~0.7 deg^2

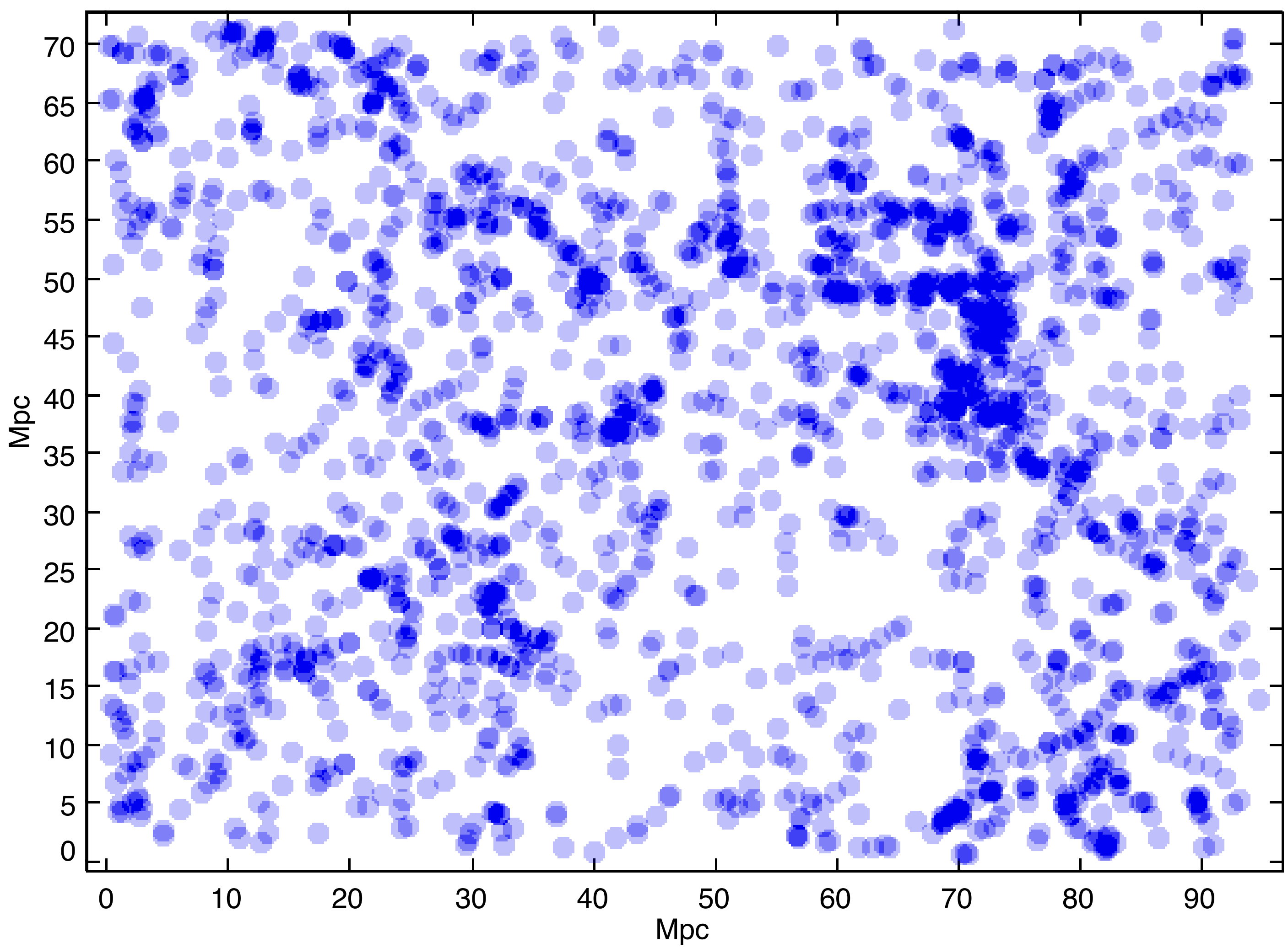




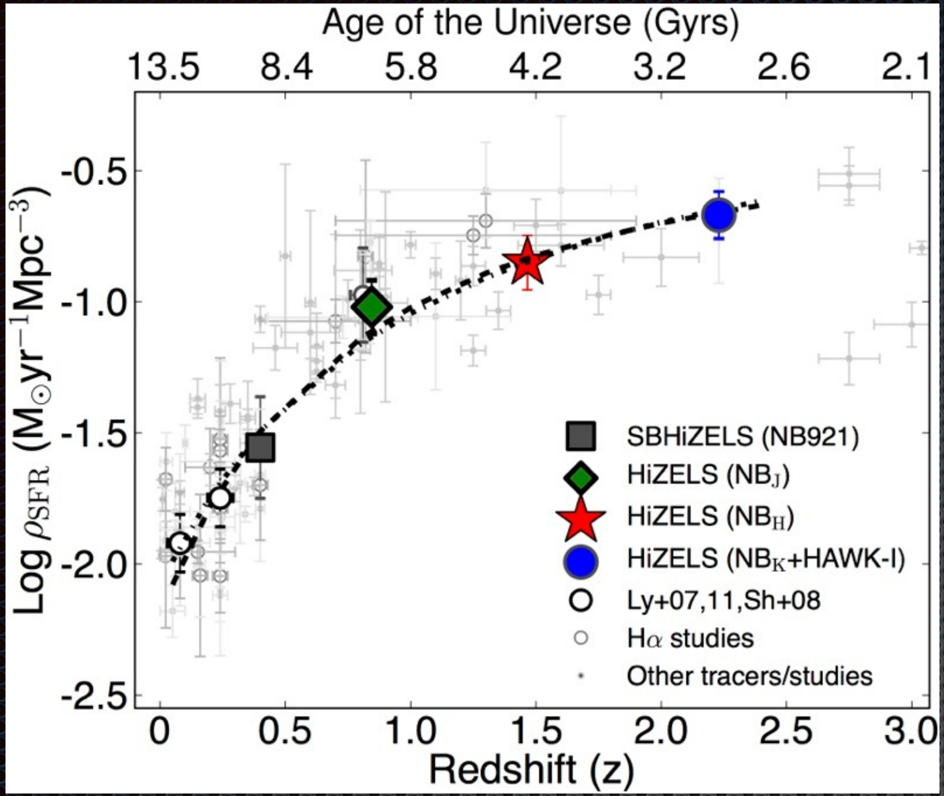
~2 deg^2



~10 deg^2



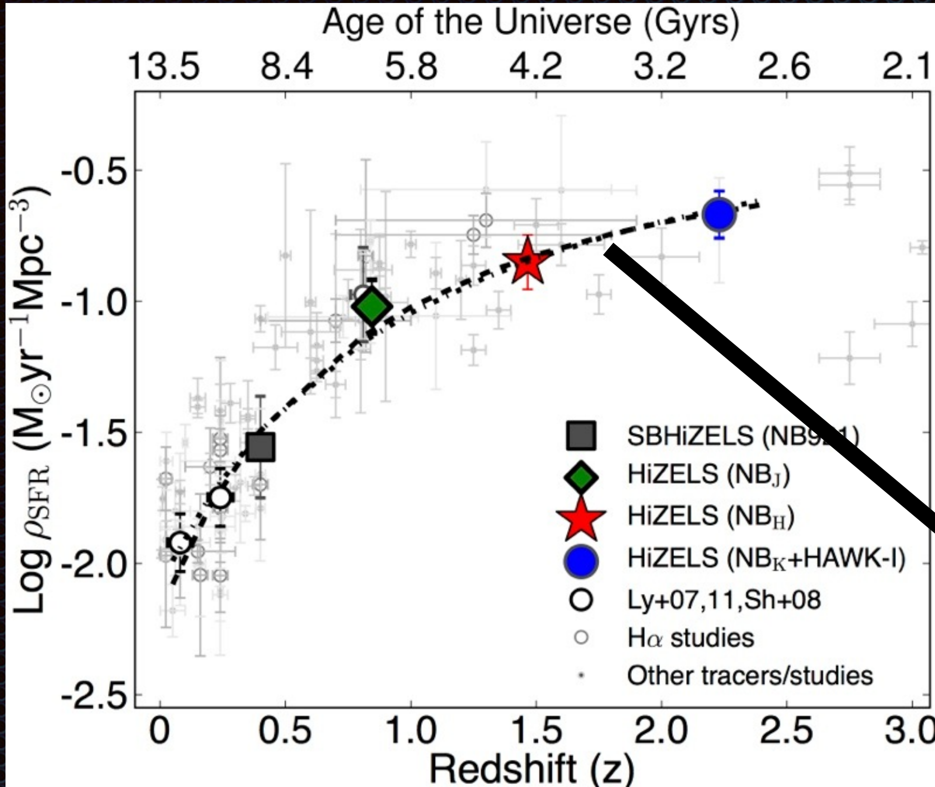
Hα emitters z=0.81+-0.01



Hα Star formation History

Strong decline with cosmic time

Sobral+13a

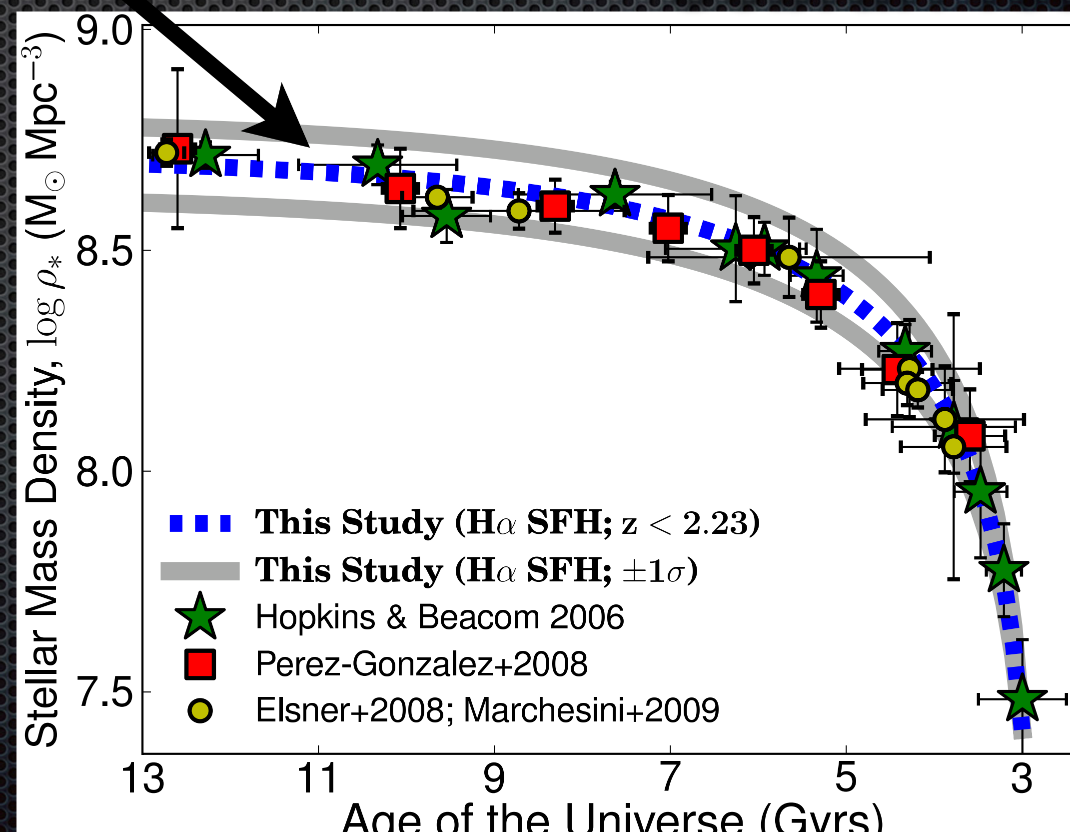


Hα Star formation History

Strong decline with cosmic time

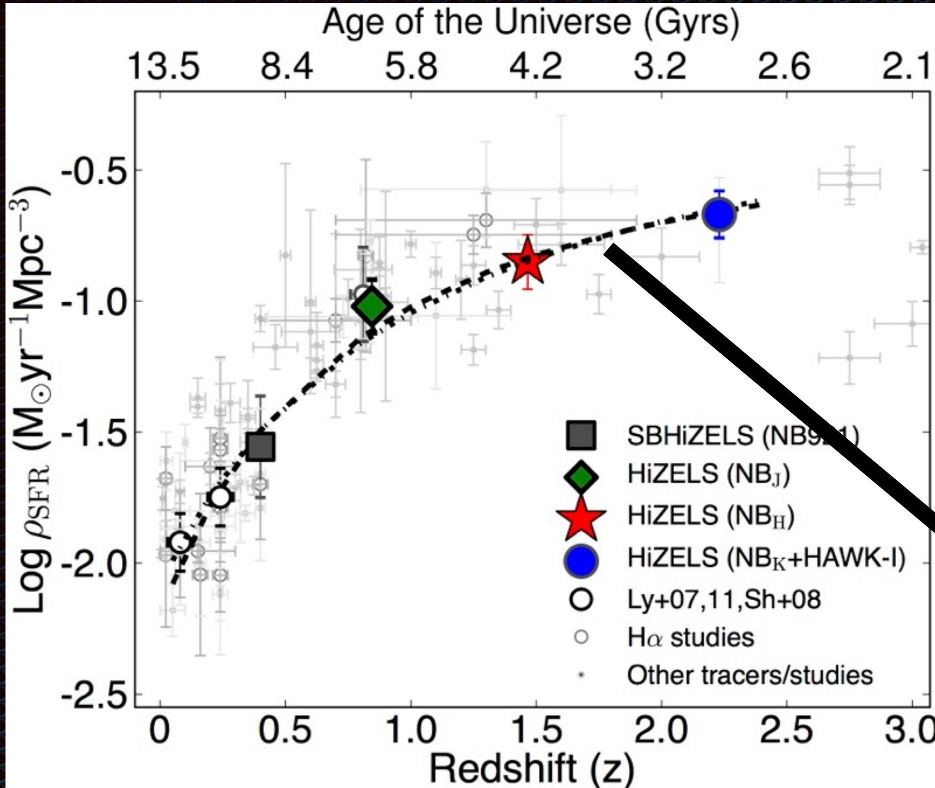
$$\log_{10}(\text{SFRD}) = -2.1/(1+z)$$

Sobral+13a



Stellar Mass density evolution

Star formation history prediction matches observations



Hα Star formation History

Strong decline with cosmic time

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

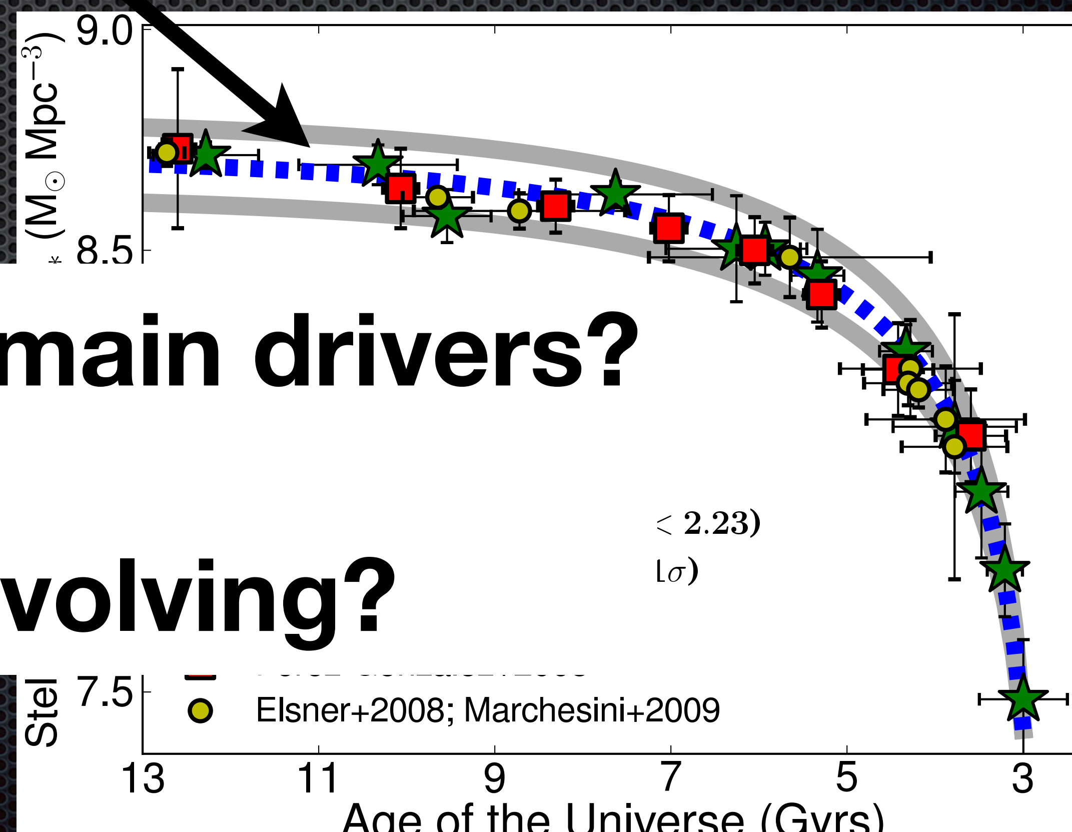
Sobral+13a

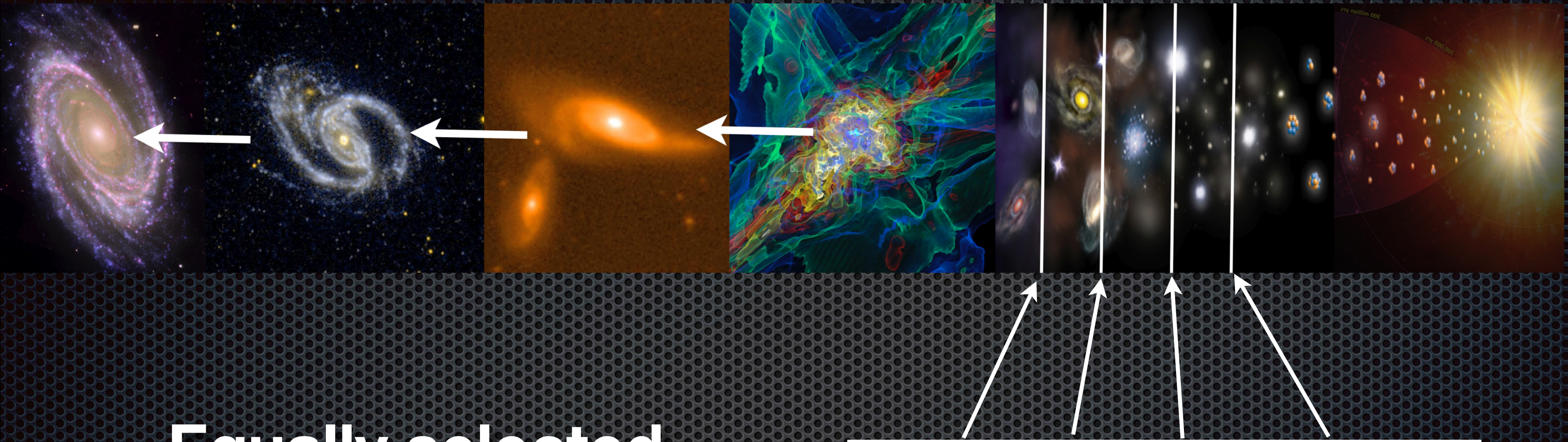
Stellar Mass density evolu

What are the main drivers?

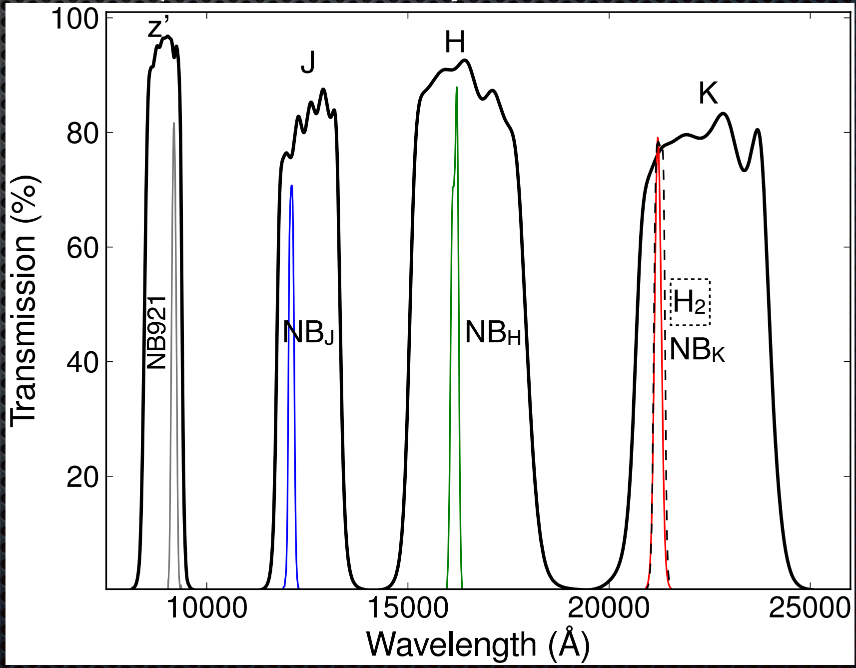
What's evolving?

Star f
prec
observations





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



Sobral+13a

SFR function: Strong SFR* evolution

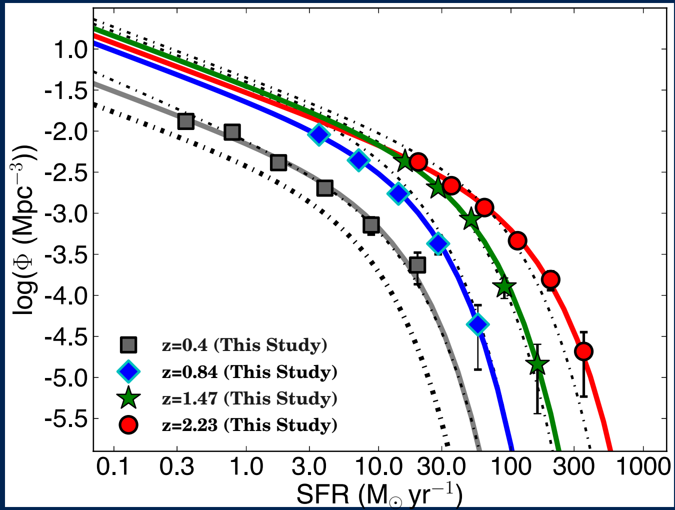
$SFR^*(T)=10^{(4.23/T+0.37)}$ M_o/yr
T, Gyrs

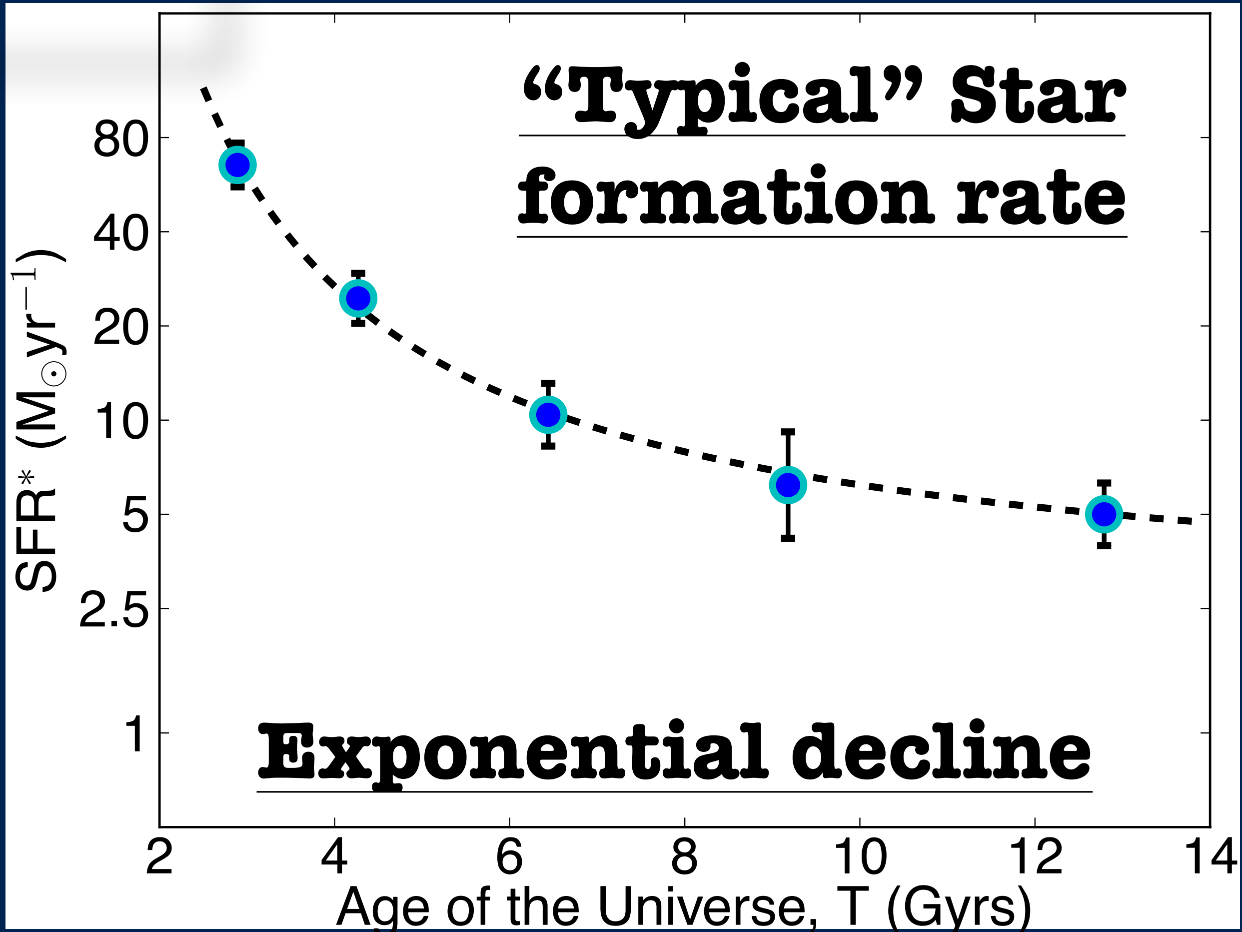
13x decrease over last 11 Gyrs

Sobral+14, MNRAS

Faint-end slope: α = -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

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

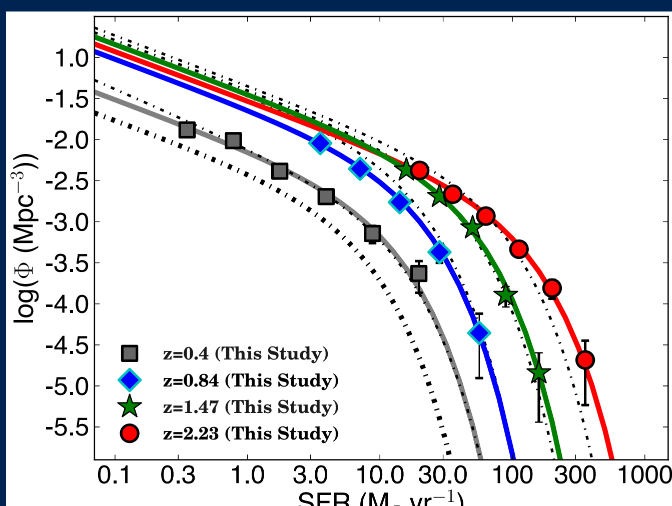
T, Gyrs

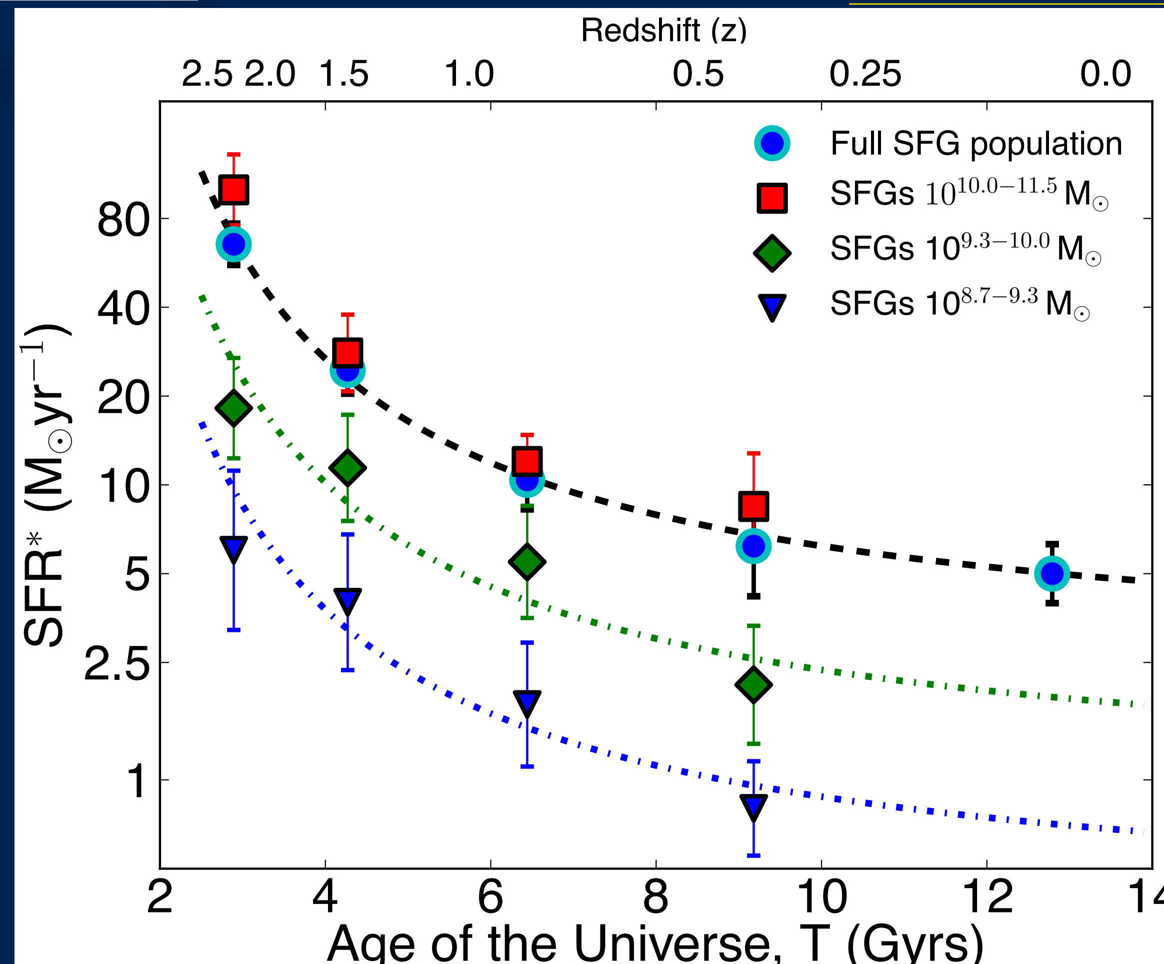
13x decrease over last 11 Gyrs

Sobral+14

Faint-end slope: α = -1.6

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



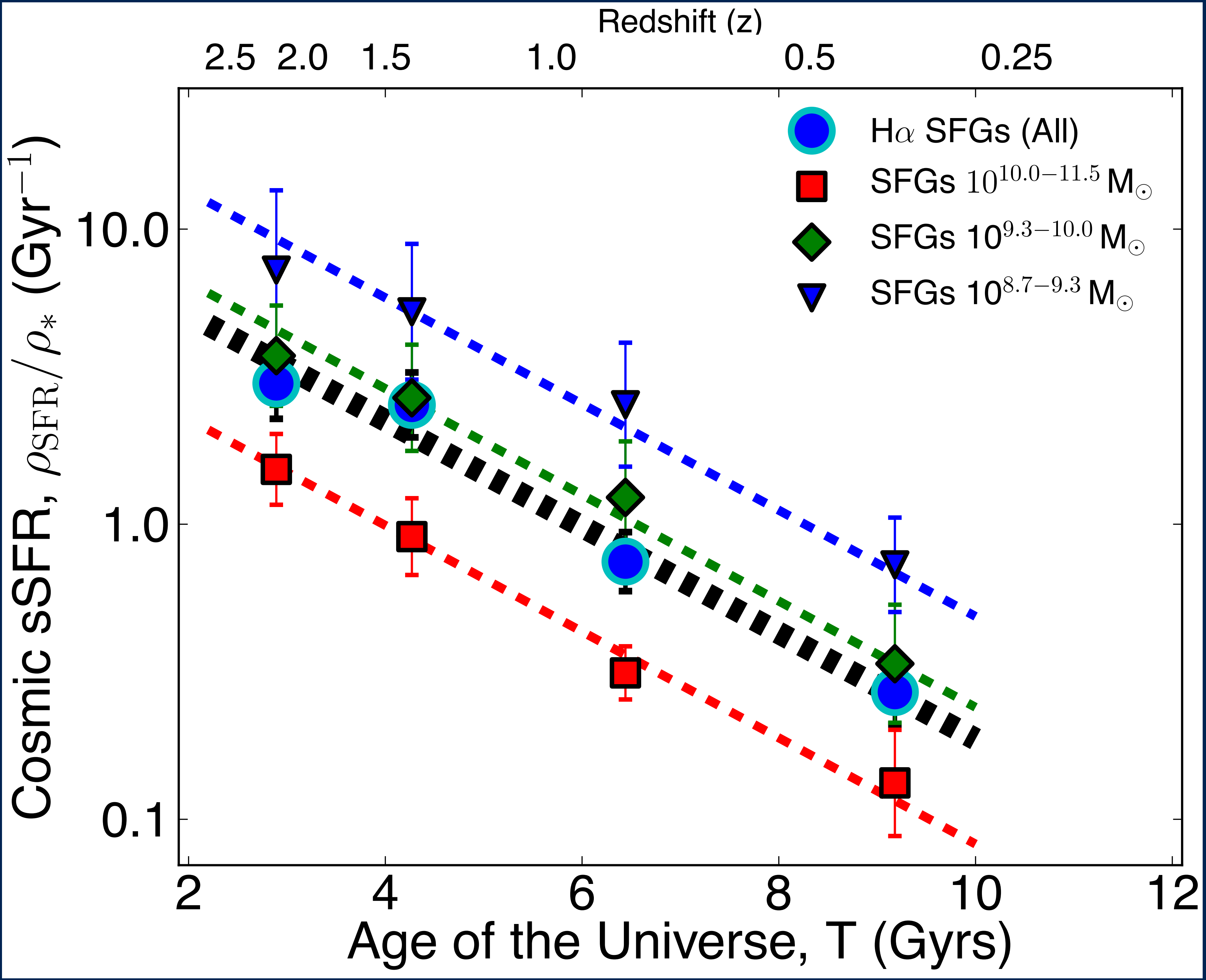


Φ*

z=0 → z=1 → z=2

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

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 $10^{8.7-9.3}$ $M_\odot$
10.0
1.0
0.1
Cosmic sSFR, $\rho_{\rm SFR}/\rho_*$ $(\rm Gyr^{-1})$
2 4 6 8 10 12
Age of the Universe, T (Gyrs)

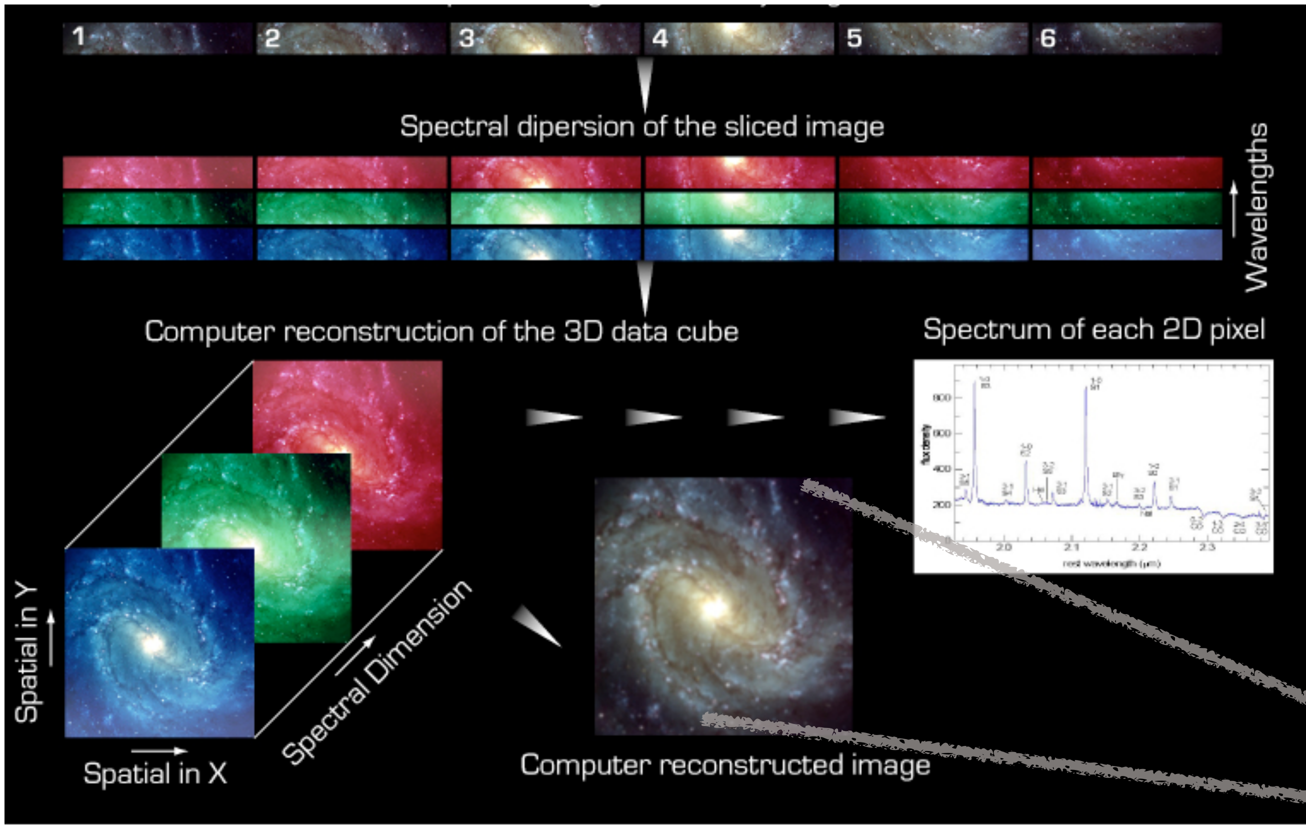
Sobral+14

Galaxy Dynamics at z~0.8-2.2

Integral Field Units, IFUs

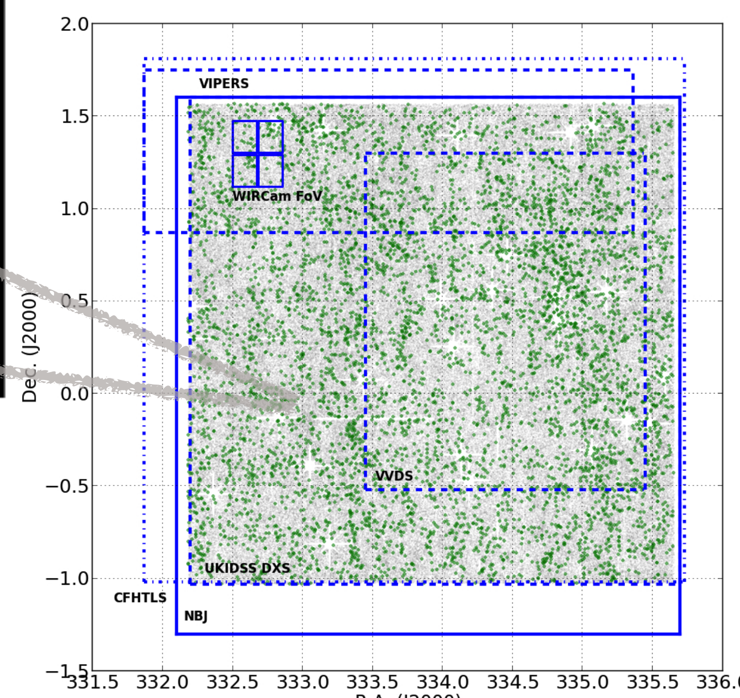
e.g. SINFONI / VLT

Hα-selected targets are ideal



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

Known H-alpha fluxes

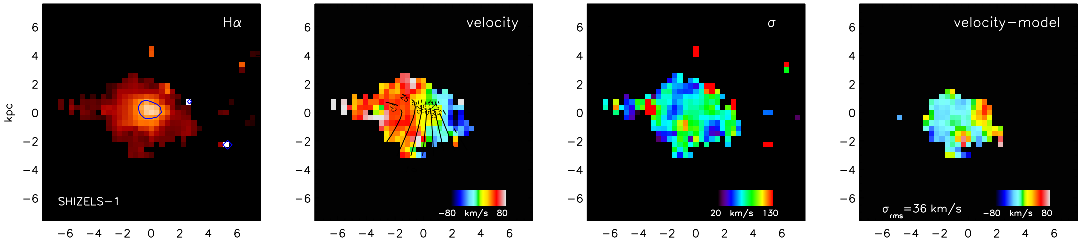


Very efficient combination to get sub-kpc resolution

Galaxy Dynamics at z~0.8-2.2

Swinbank al. 2012a,b

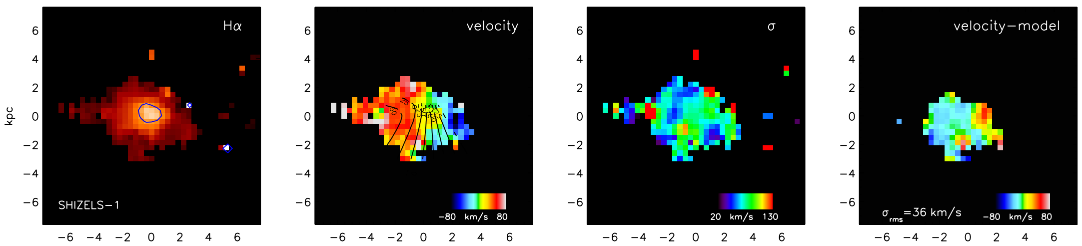
From AO IFU observations



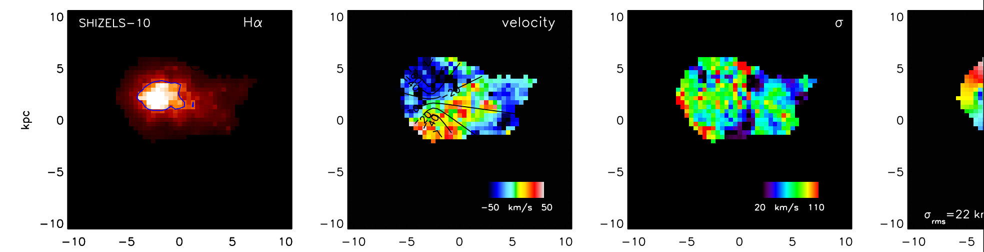
~5 hours of VLT time

Galaxy Dynamics at z~0.8-2.2

Swinbank al. 2012a,b



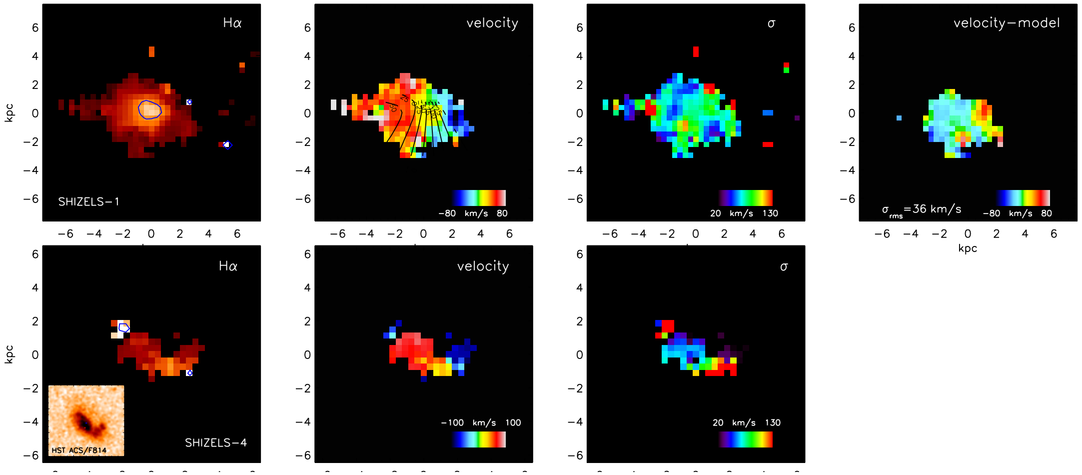
From AO IFU observations



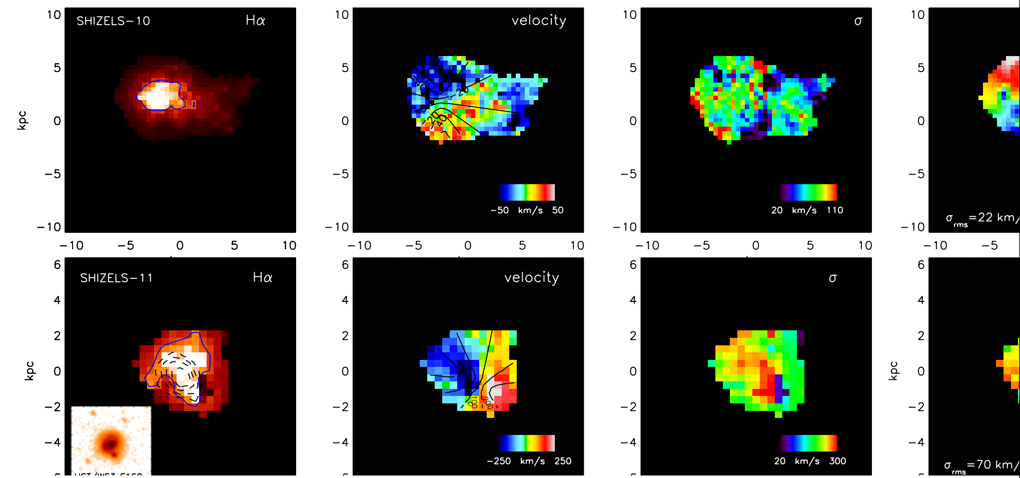
~10 hours of VLT time

Galaxy Dynamics at z~0.8-2.2

Swinbank al. 2012a,b



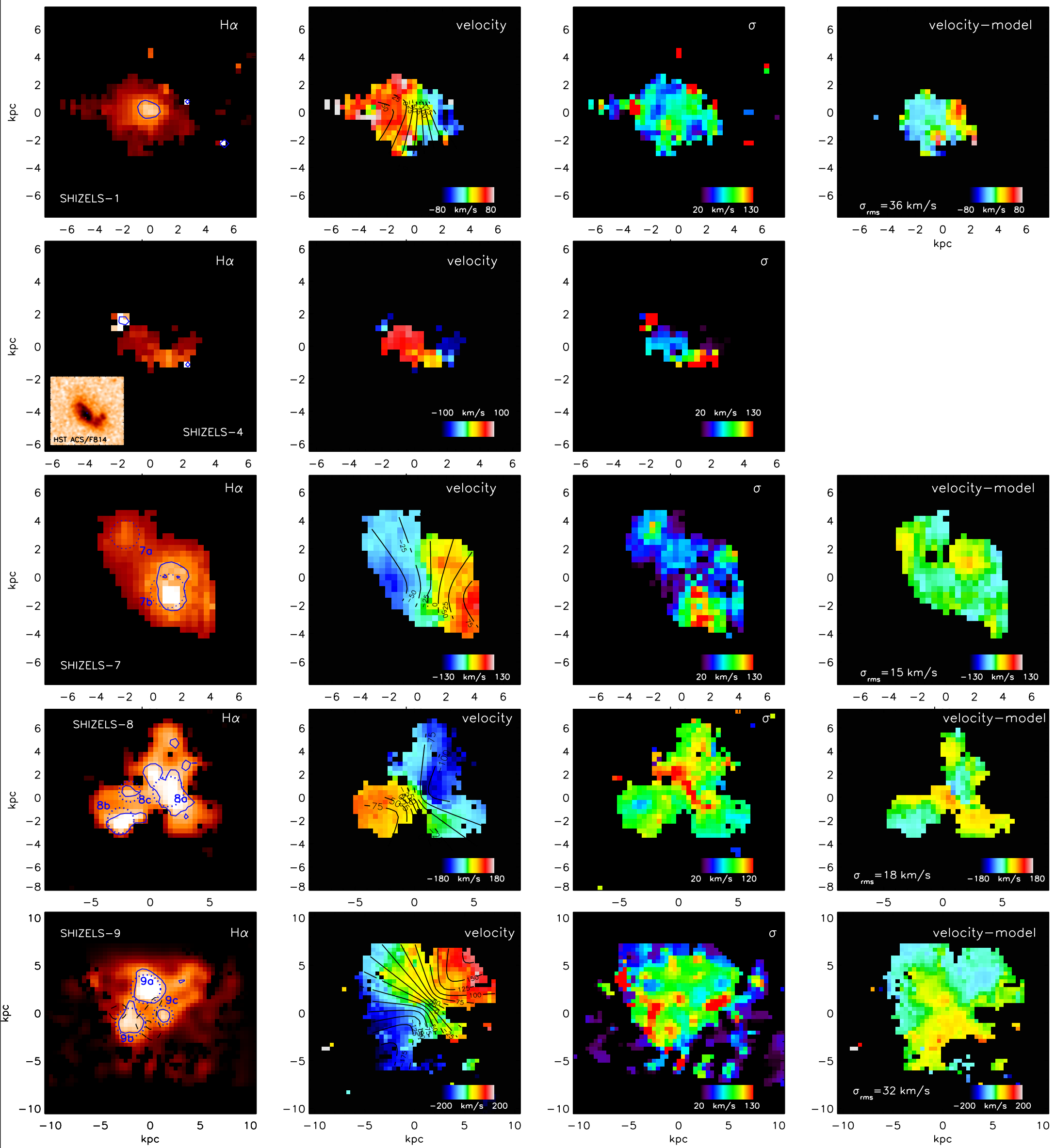
From AO IFU observations



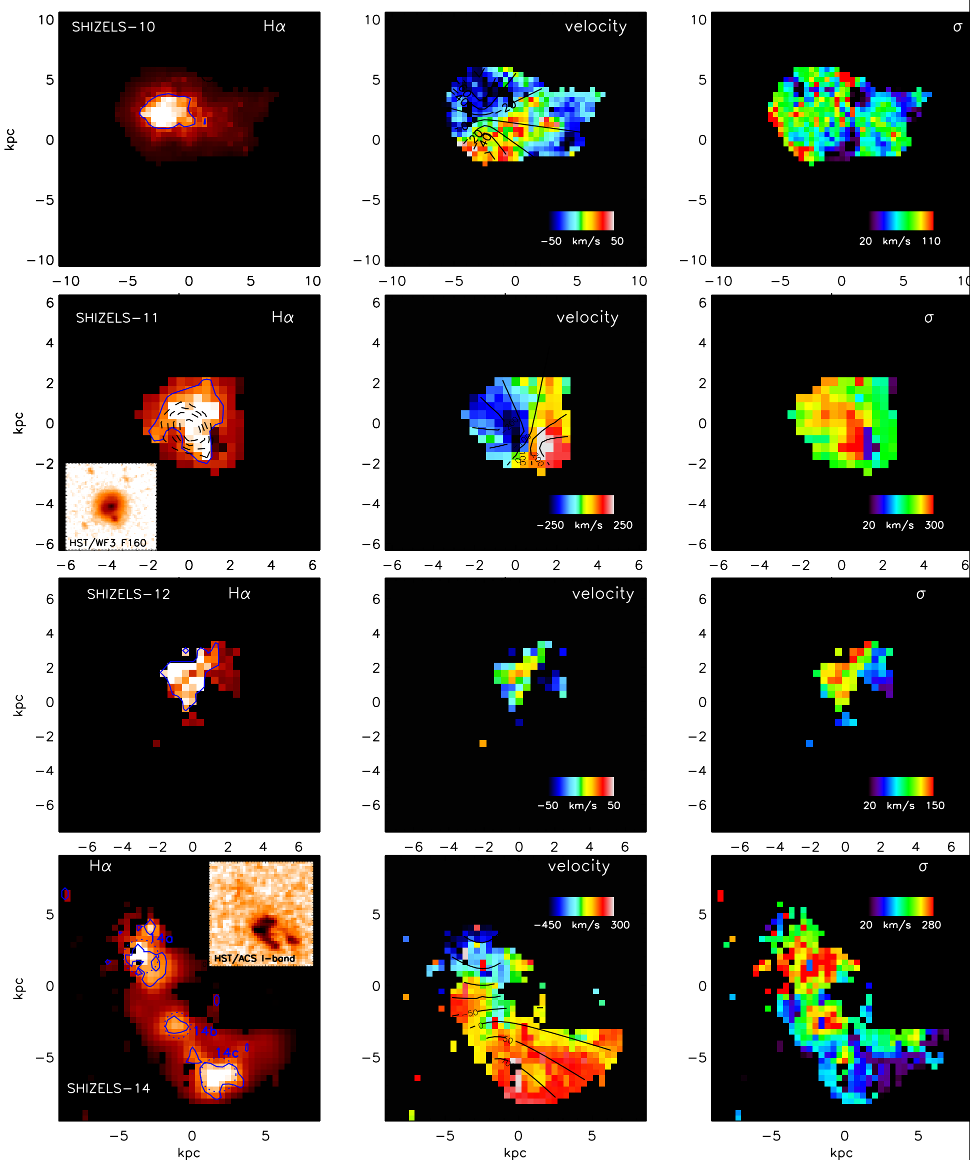
~20 hours of VLT time

Galaxy Dynamics at z~0.8-2.2

Swinbank al. 2012a,b



From AO IFU observations

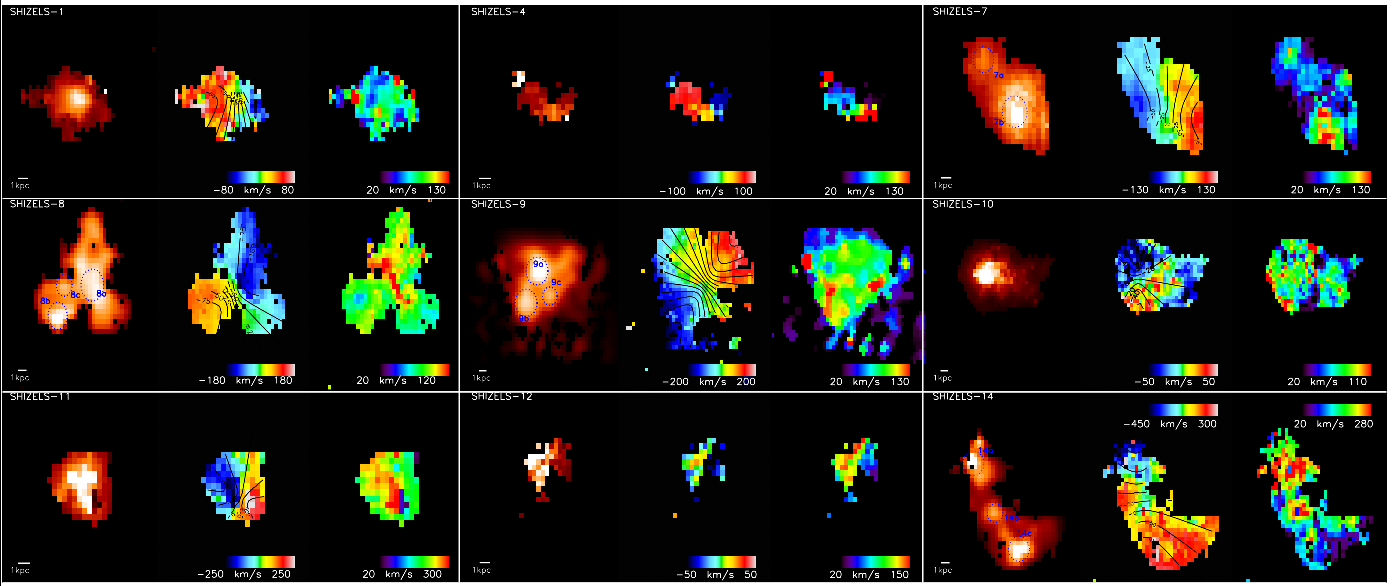


~45 hours of VLT time

Galaxy Dynamics at z~0.8-2.2

Swinbank et al. 2012a

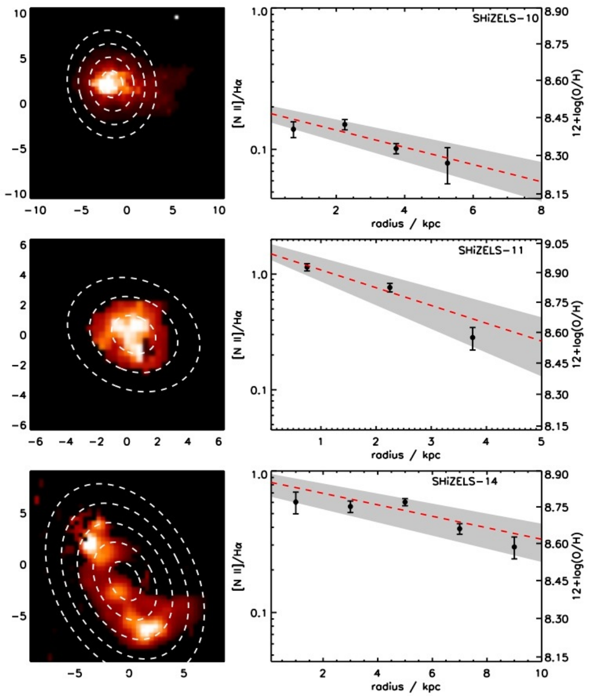
Swinbank al. 2012b

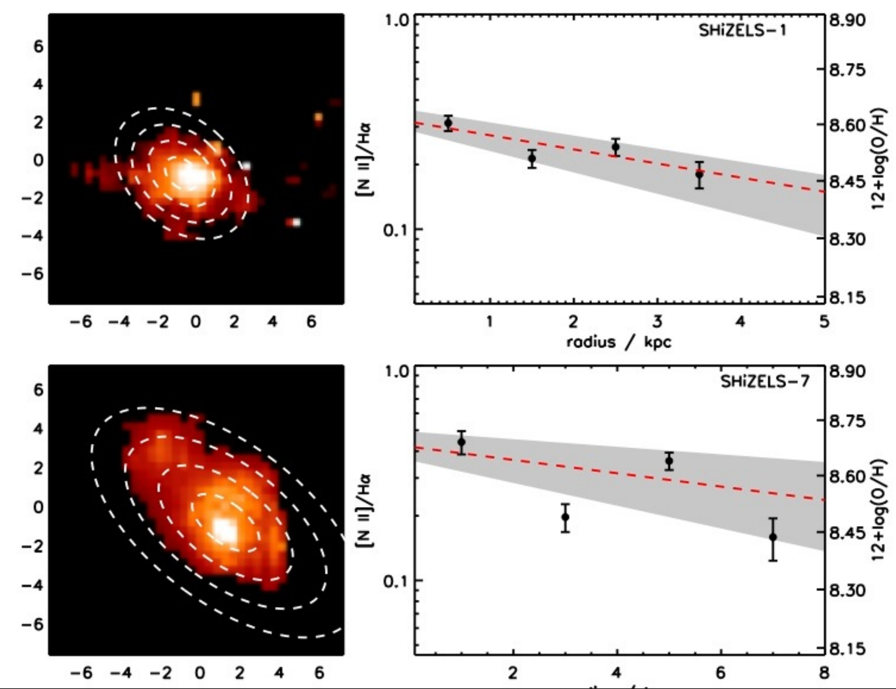


(MNRAS/ApJ):

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

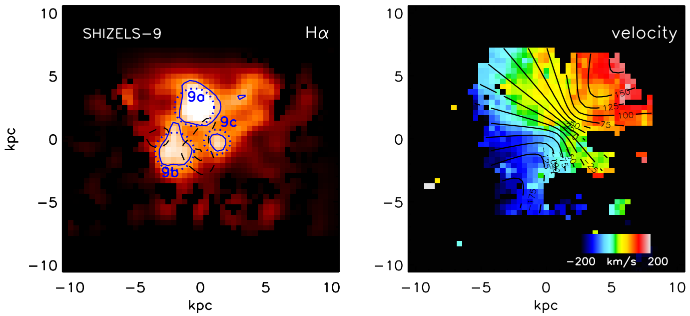
- Negative metallicity gradients: "inside-out" growth

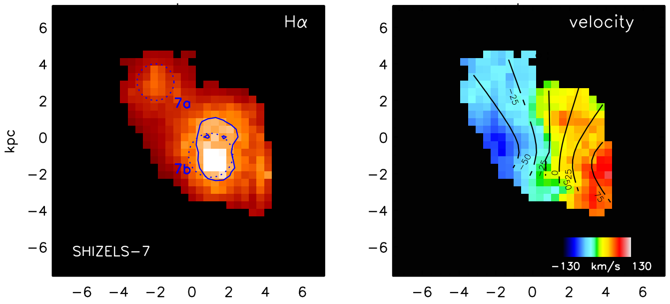




SINFONI

~50 hours of VLT time

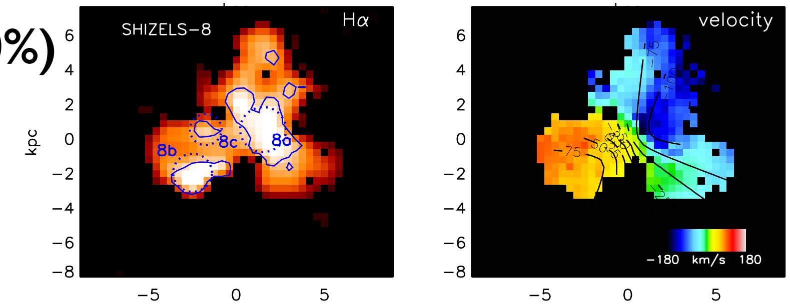




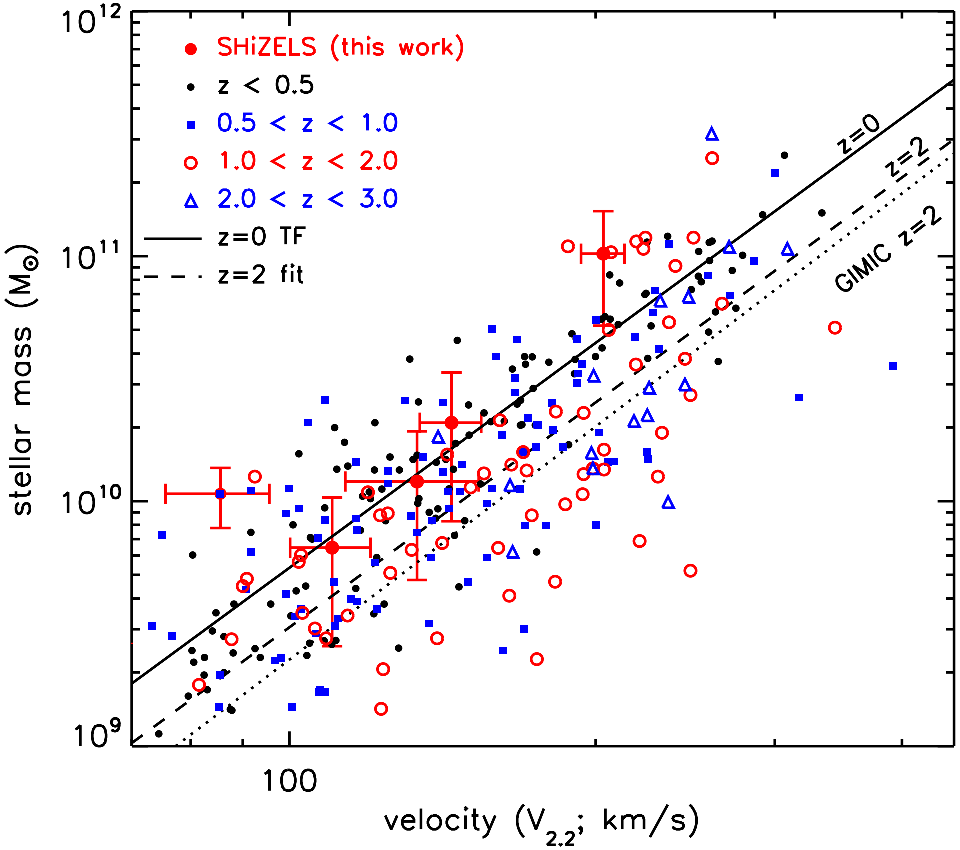
Mostly disks-like (~70-80%)

Many "clumpy" (c.f. Swinbank+12b)

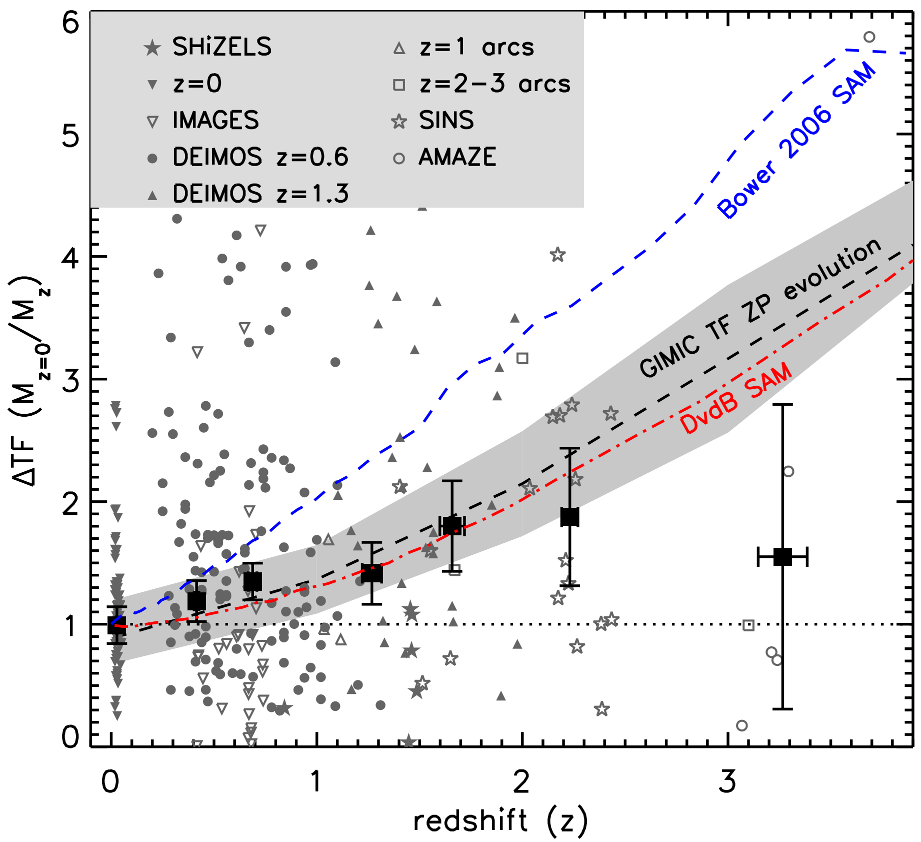
Rotation ~70-200 km/s



Stellar mass TF relation

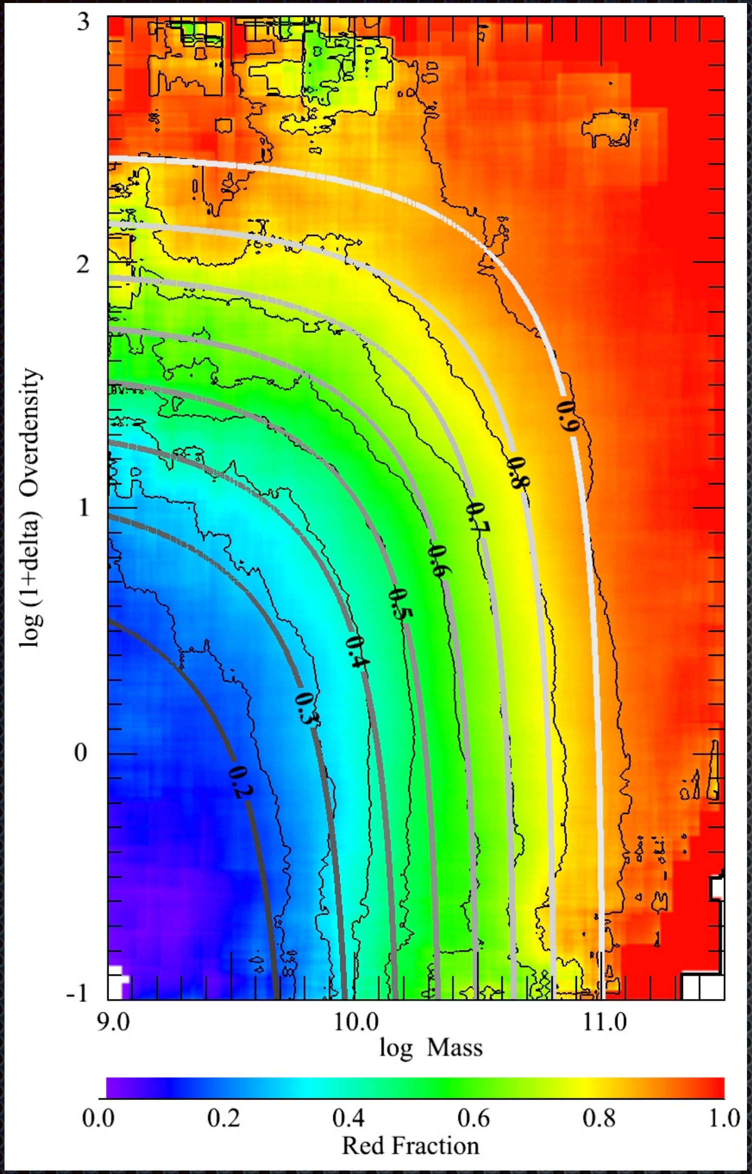


Swinbank, Sobral et al. 2012

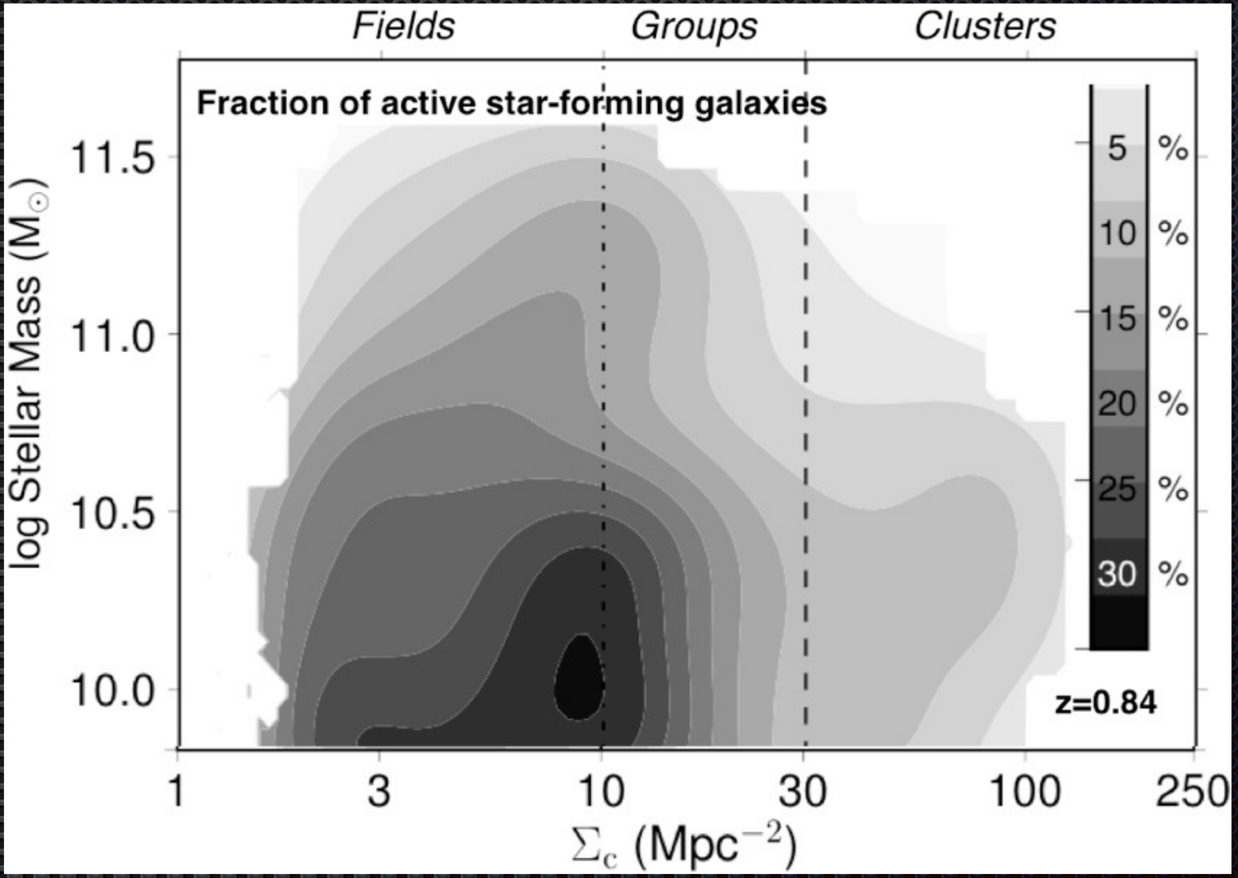


Environment?

z~0 SDSS (Peng+10)

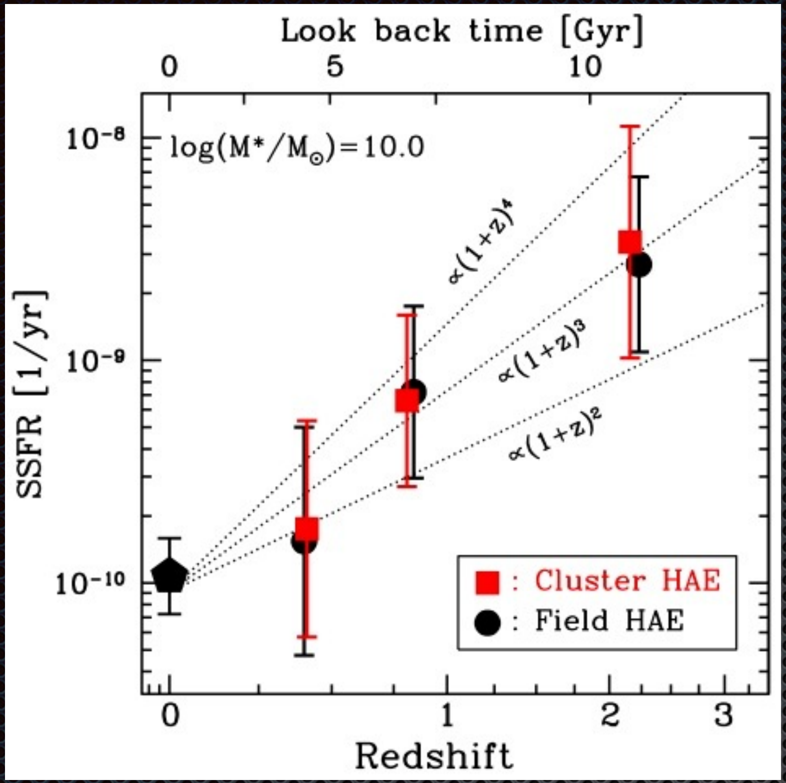


z~1 Sobral et al. 2011

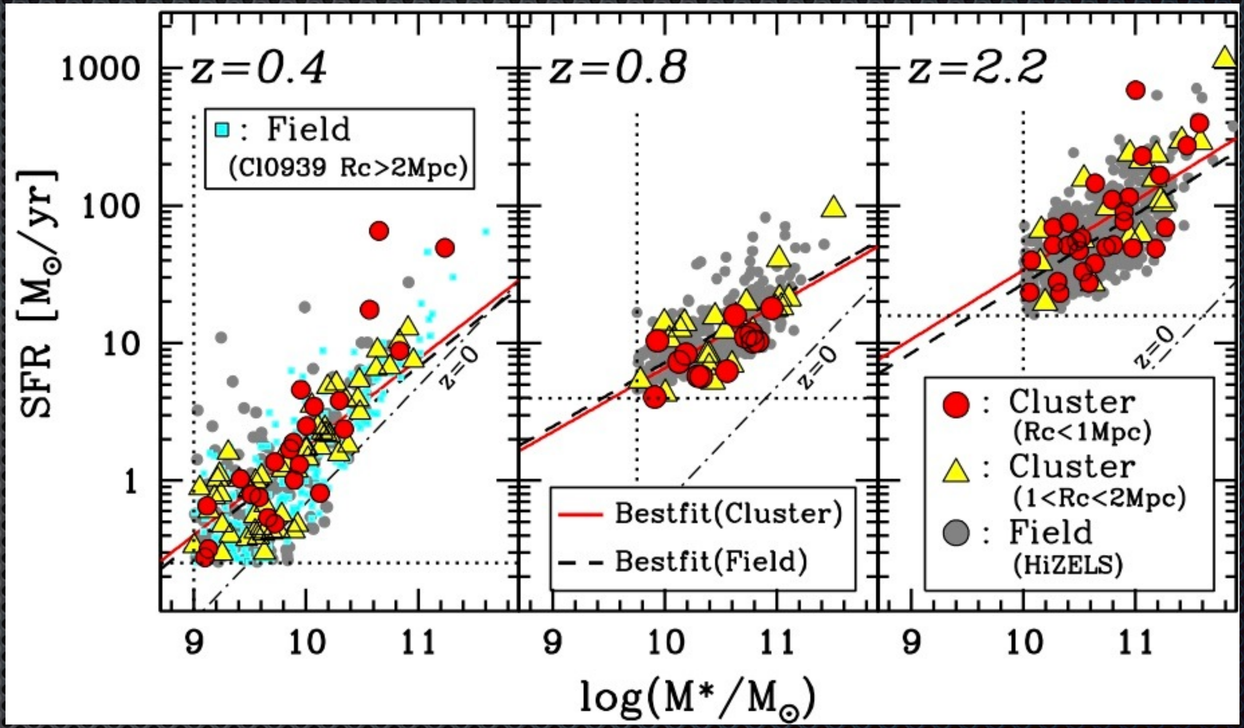


At z~1: Similar to z~0 / SDSS

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

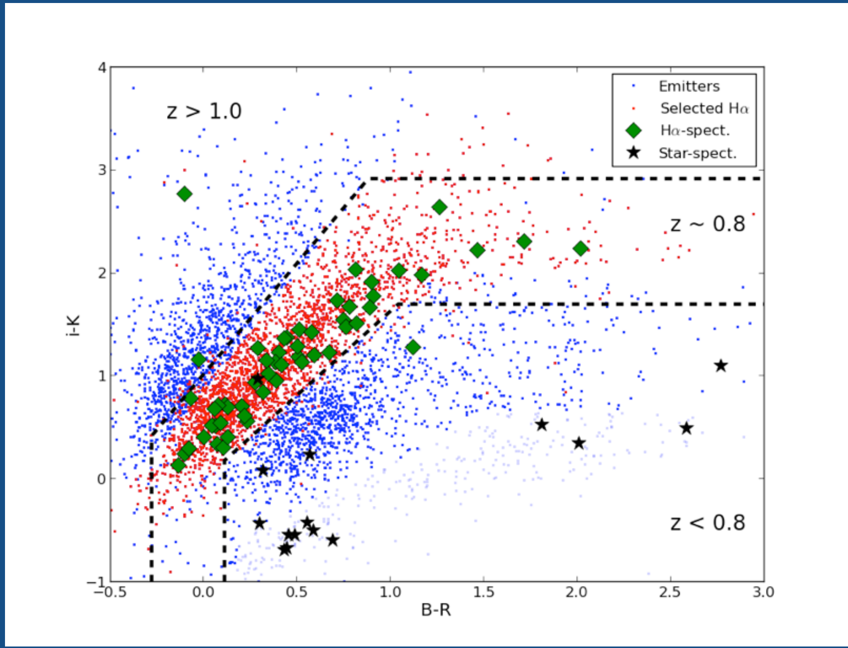


SFR-Mass relation also ~the same in different environments

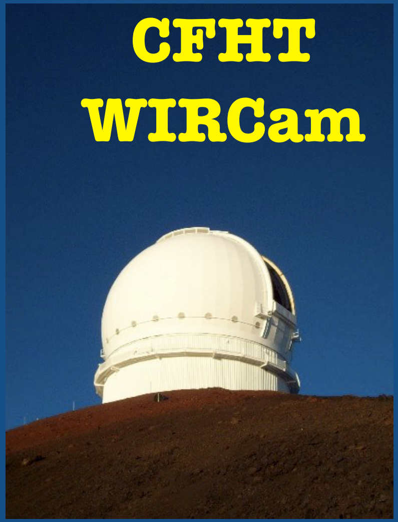
Koyama et al. 2013

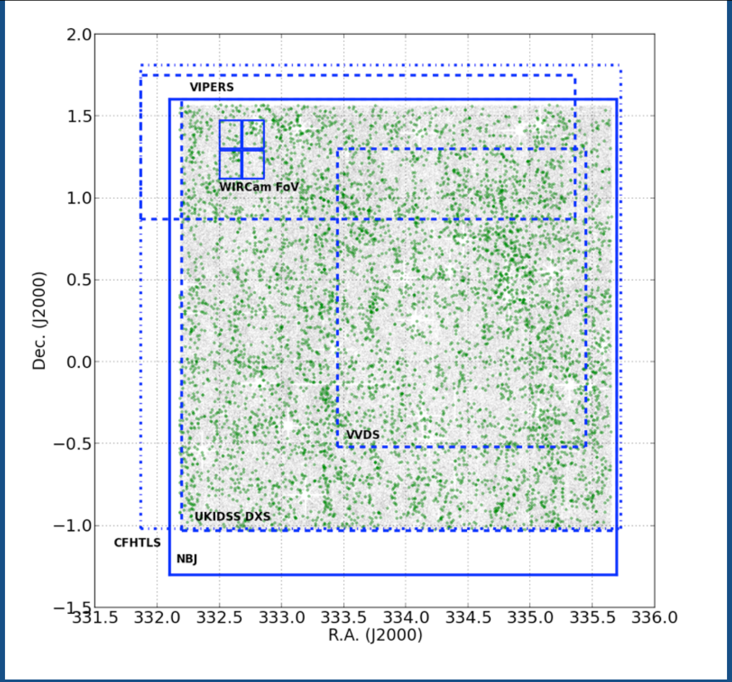
What about their dynamics?

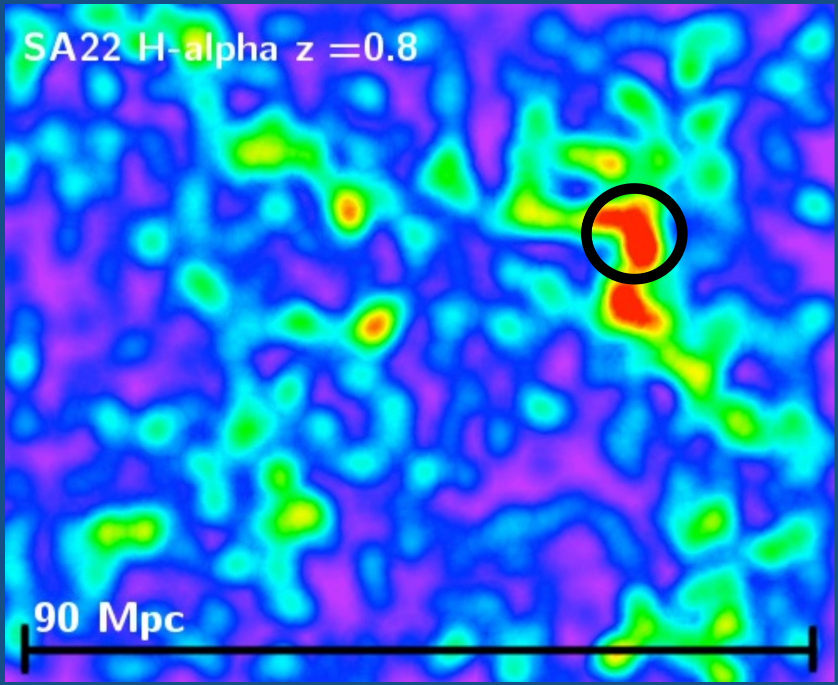
(For "extreme" environmental effects see e.g. Stroe et al. 2014)



10 sq deg







8 sigma over-density

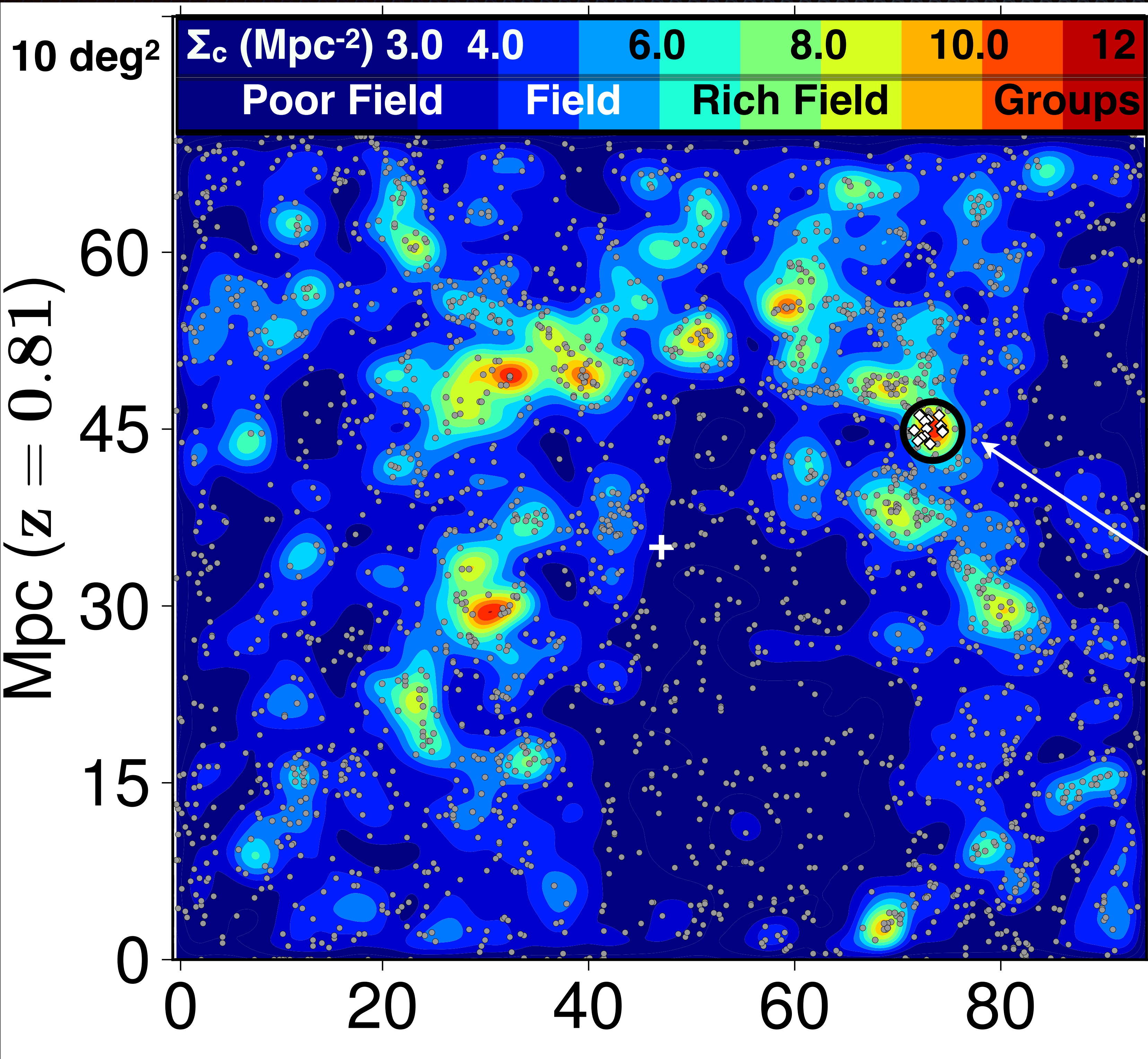
300 k NB detections

6400 line emitters

3500 Hα z=0.8

Density of Hα emitters
z=0.81+-0.01

S+13b, Matthee+14



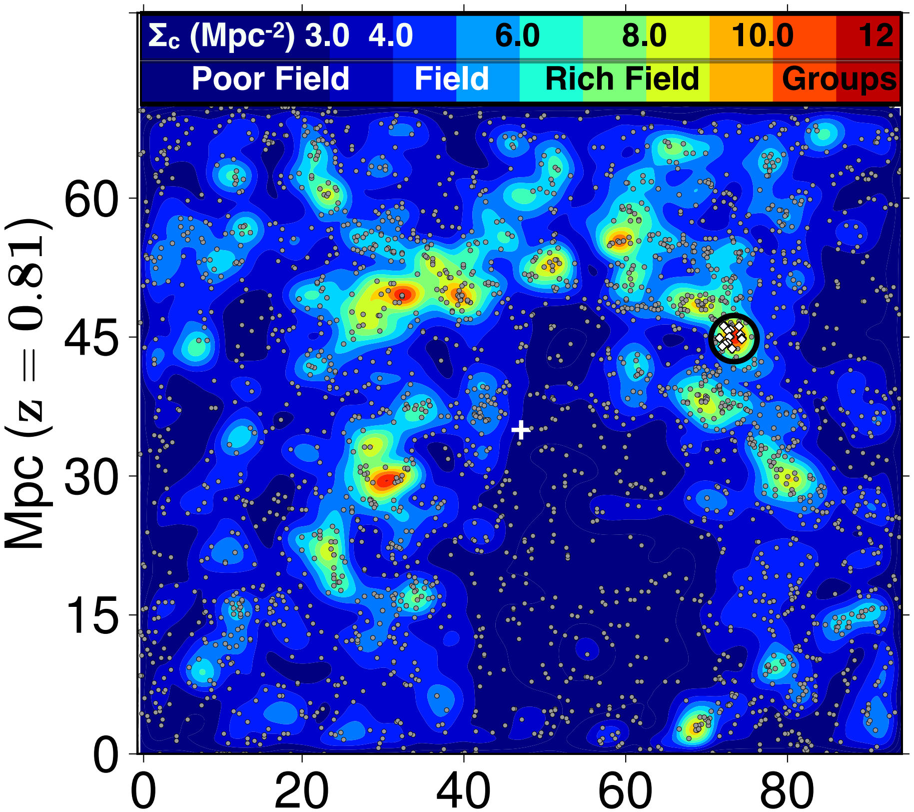
Method: S+11

Using *all* galaxies (not just SFGs)

Likely group

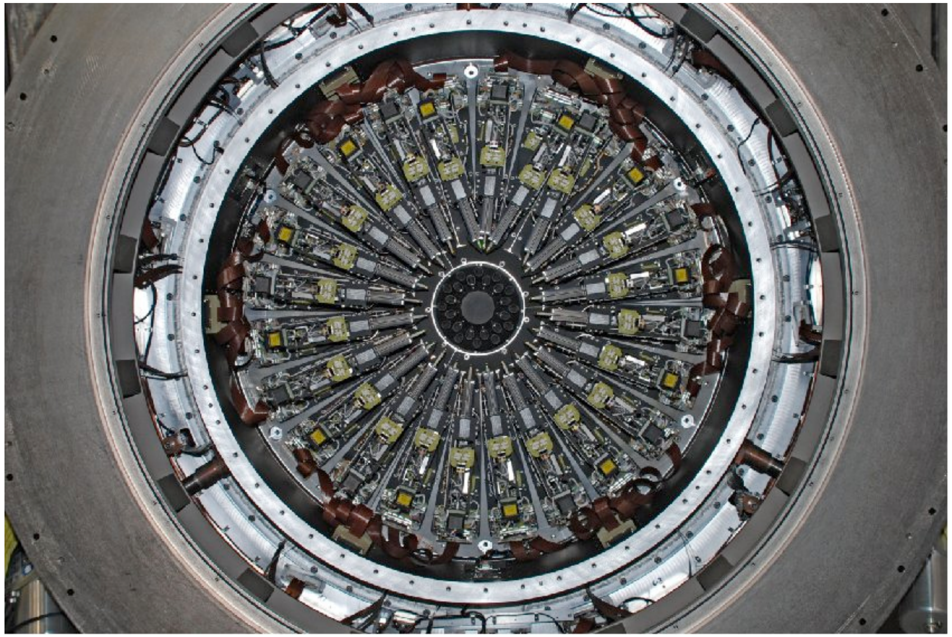
30 Hα in 7x7arcmin

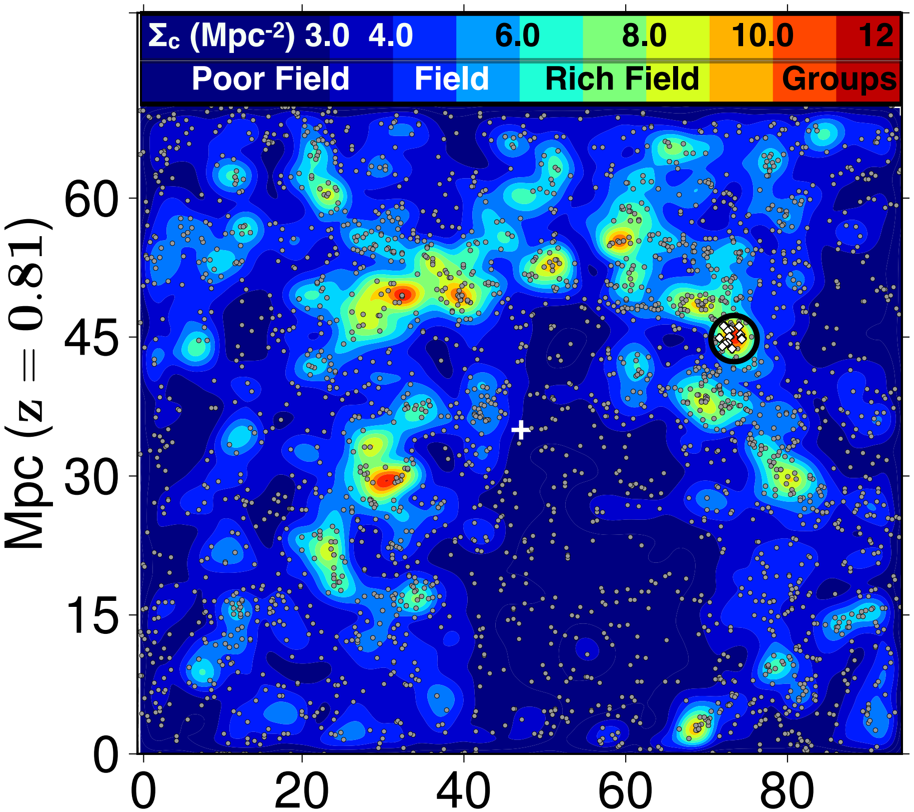
S+13b



Perfect for KMOS VLT

24 IFUs at the same time!



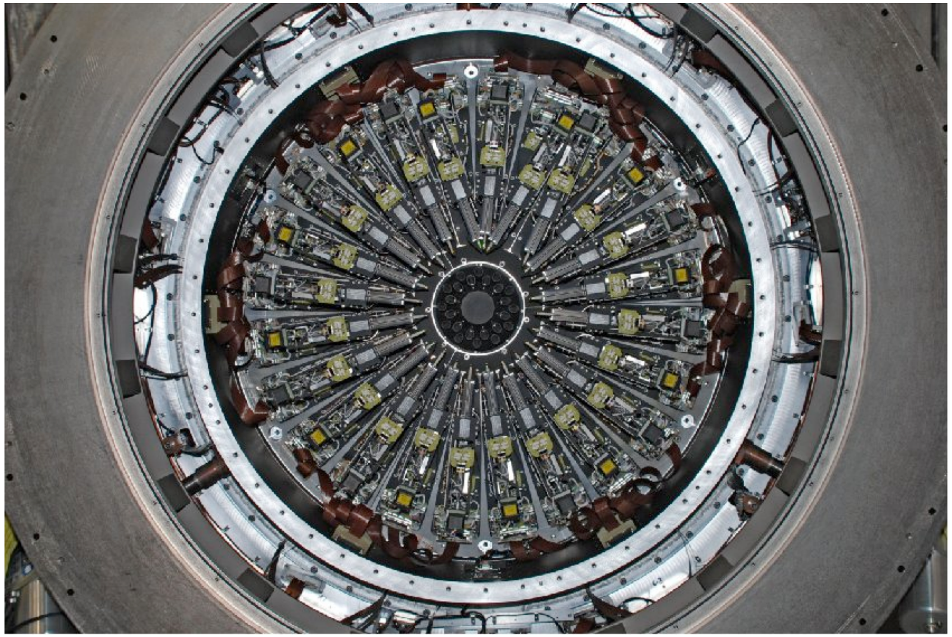


4h Science Verification time

<u>Observations June 2013 + September 2013</u>

<u>Perfect for KMOS VLT</u>

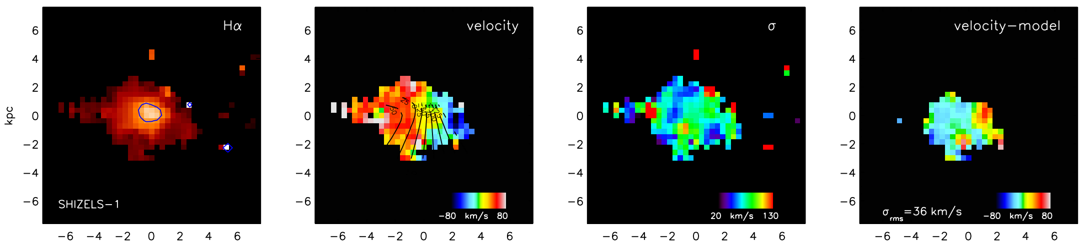
24 IFUs at the same time!



Galaxy Dynamics at z~0.8-2.2

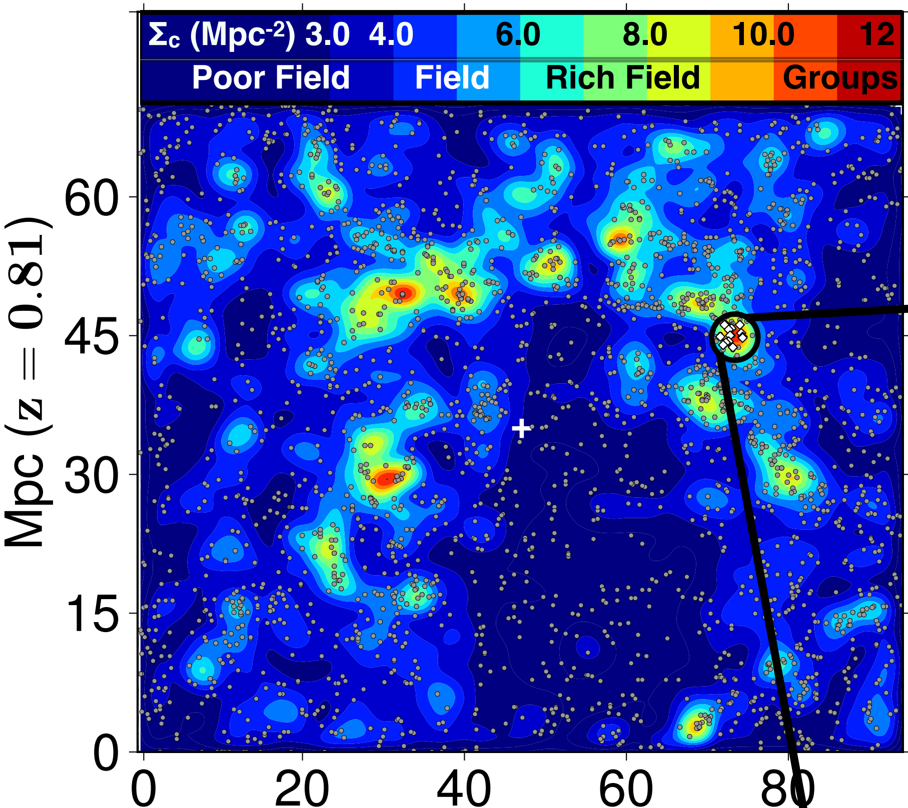
Swinbank al. 2012a

From AO IFU observations

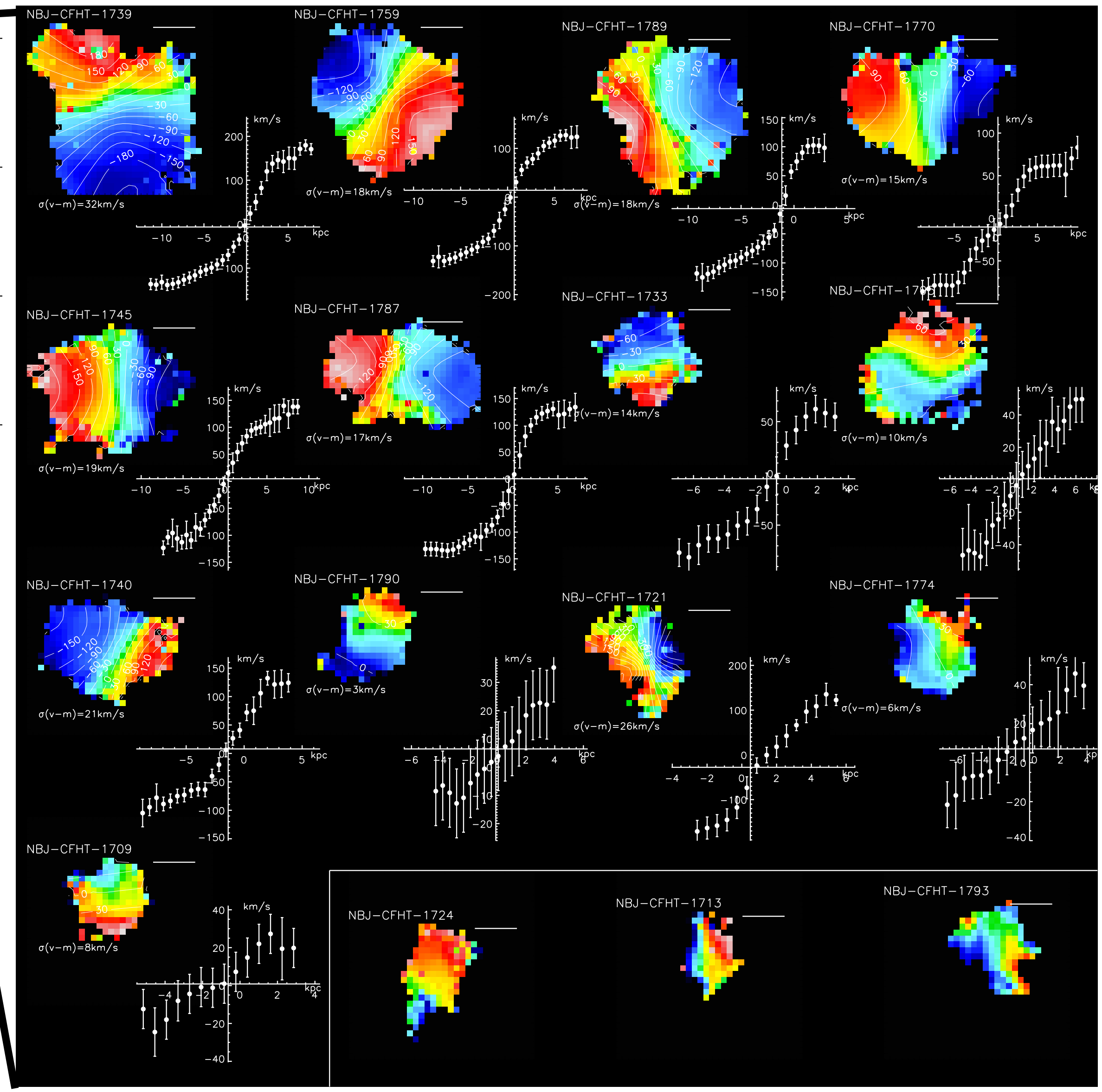


~5 hours of VLT time

CF-HiZELS

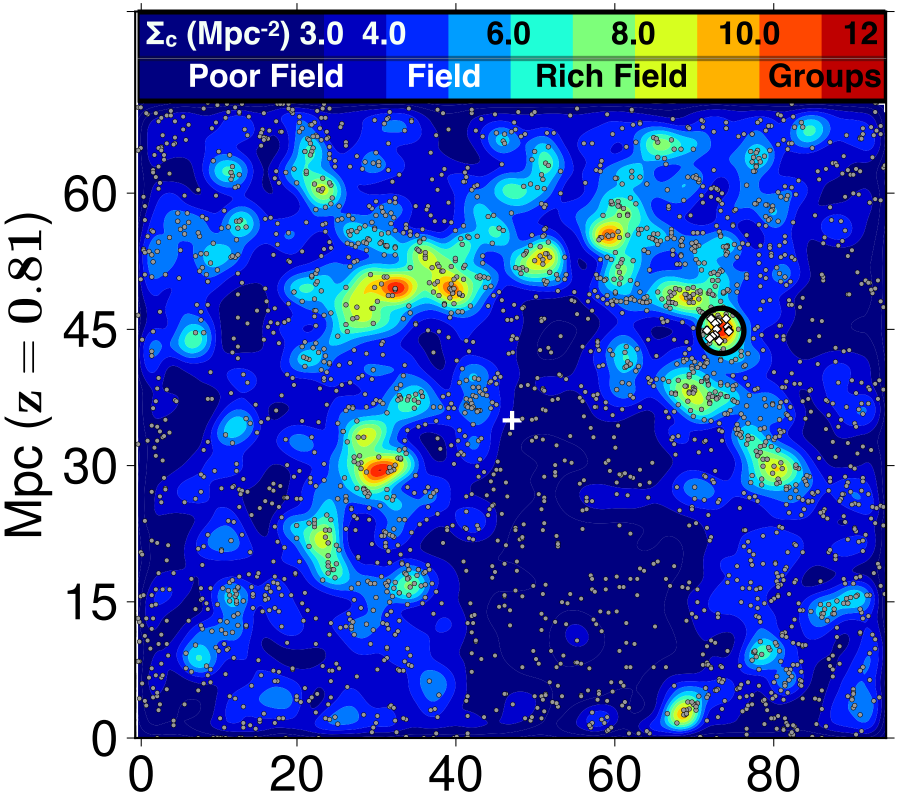


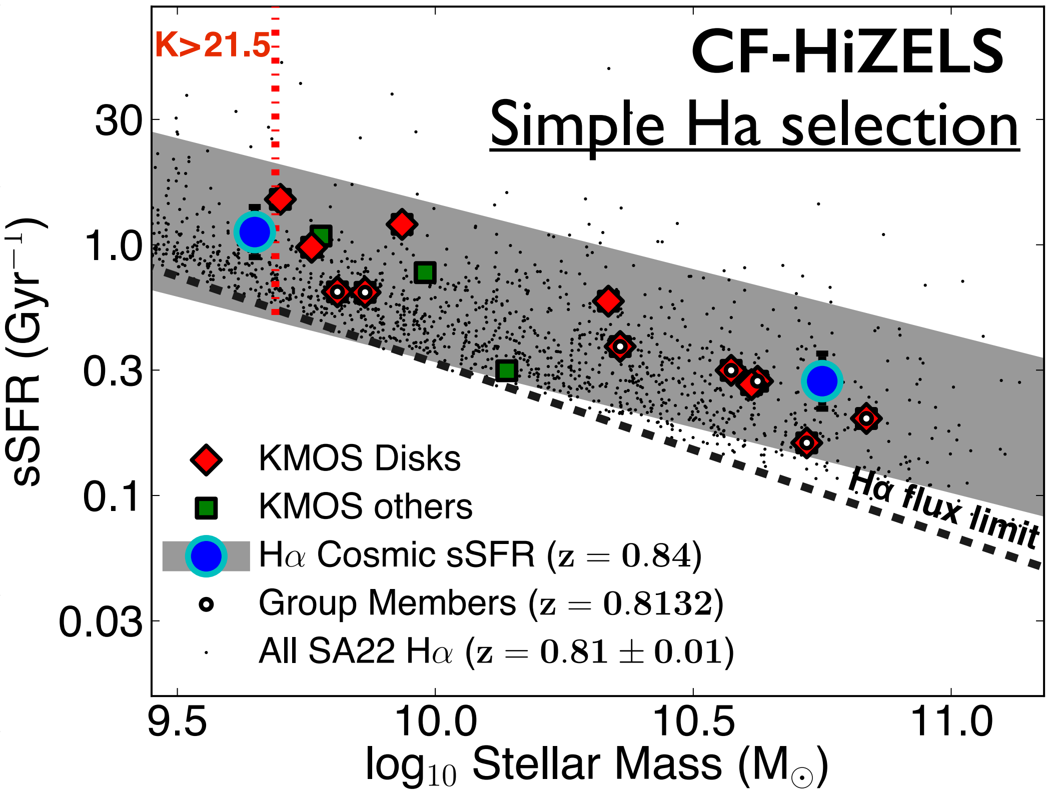
2 hours of VLT time



First Science results from KMOS

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



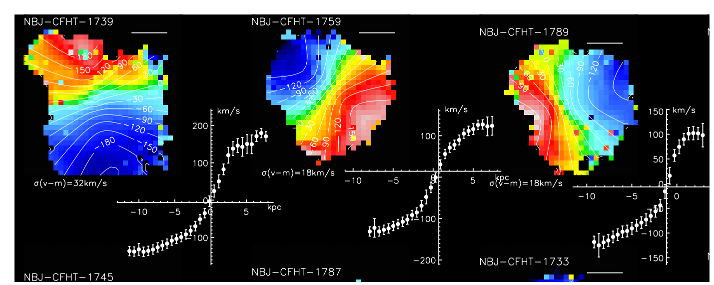


Confirmed <u>group</u> at z=0.813 (13 galaxies)

7 within r=1.5Mpc

Median mass: $10^{10.2}$ M_o

sSFRs = 0.2-1.1 Gyr^{-1}

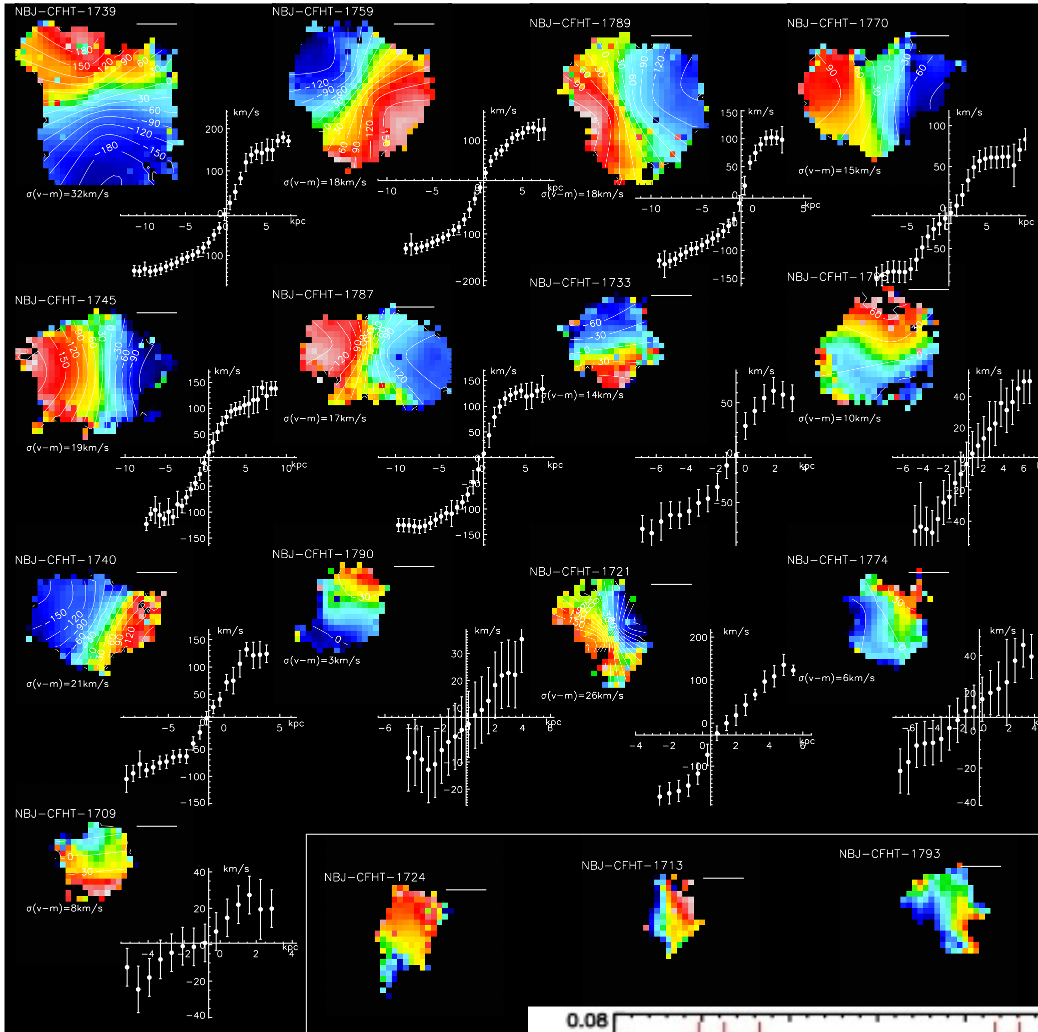


Metallicities

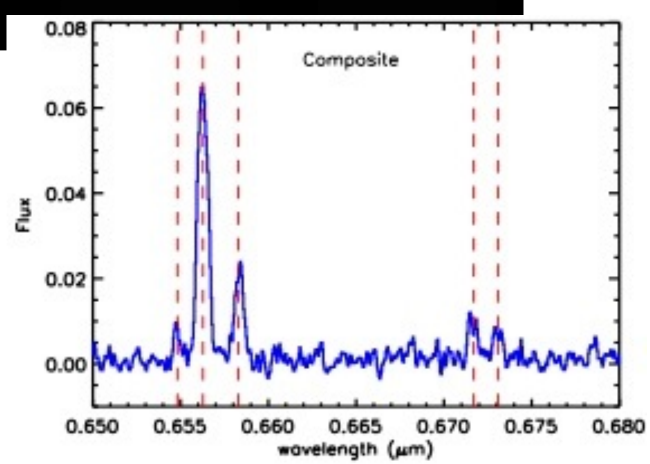
KMOS galaxies z=0.81

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

Solar value: 8.66 +-0.07

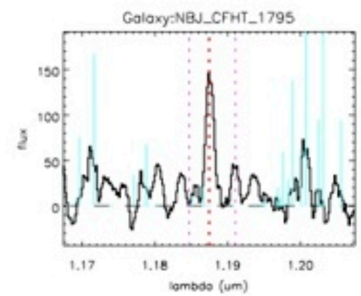


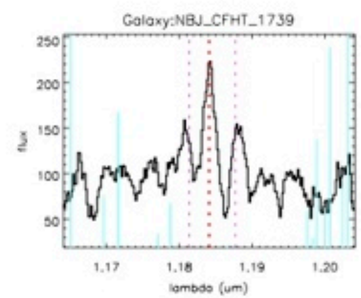
[NII]/Ha
=0.32+-0.13

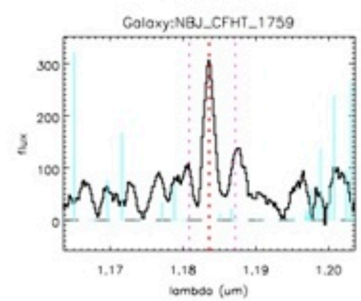


Group galaxies slightly more metal rich

<u>but also more massive</u>

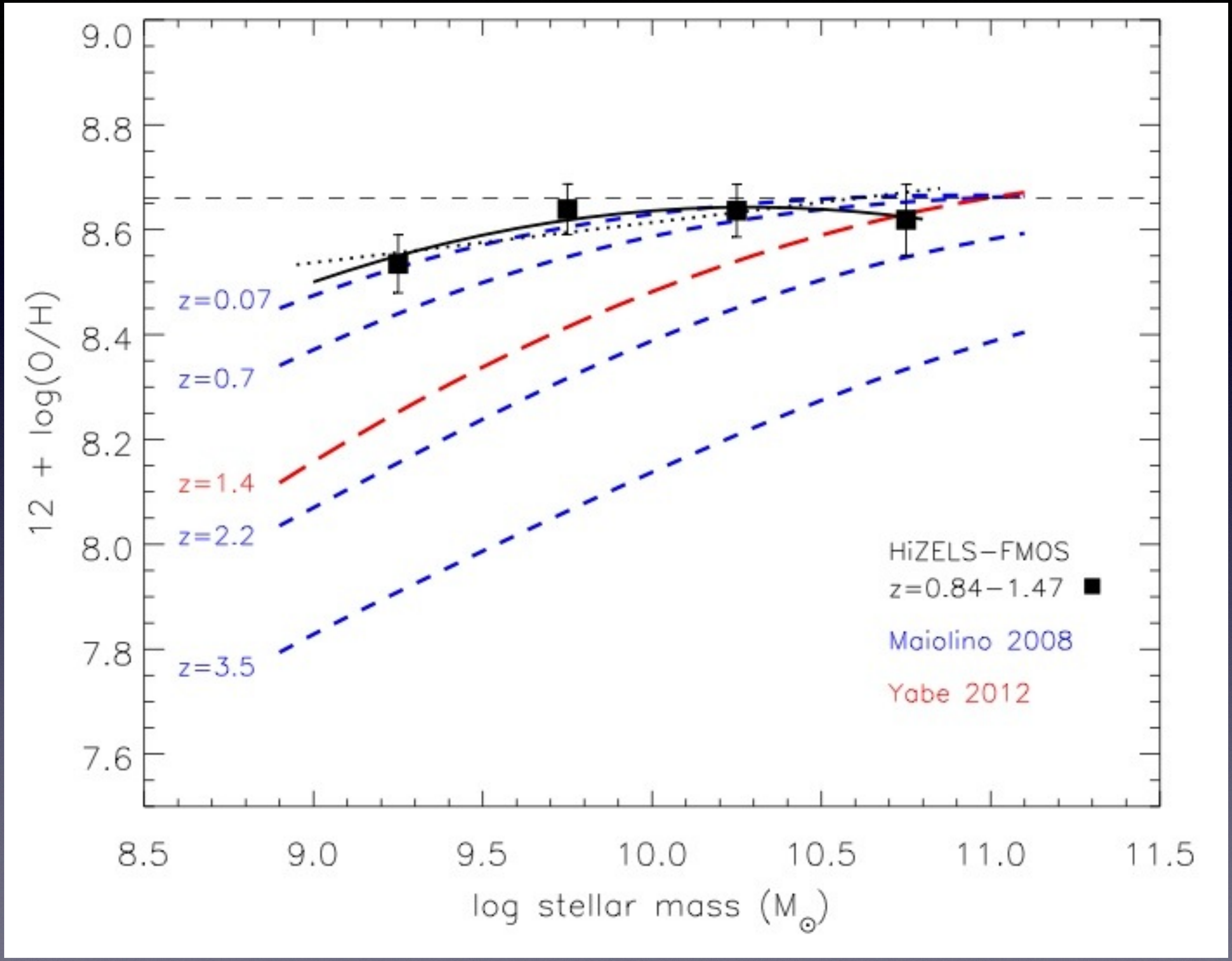




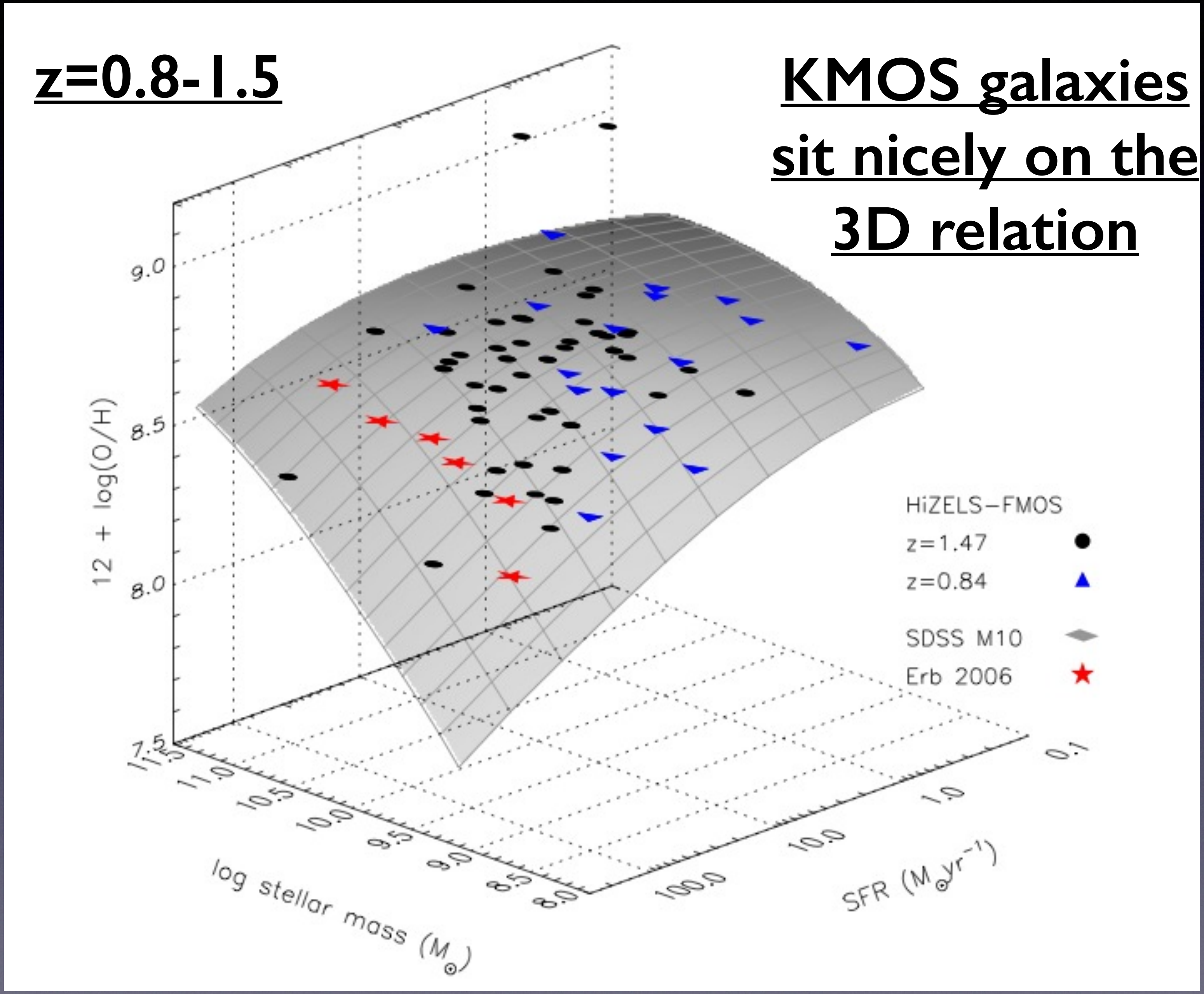


Stott, Sobral et al. 2013b

z=0.84 + z=1.47 Ha



HiZELS "Fundamental" Mass-Metallicity-SFR relation at z~1-2



Stott, Sobral et al. 2013b

Stott, Sobral et al. 2014, submitted

Evolution of the Tully Fisher relation?

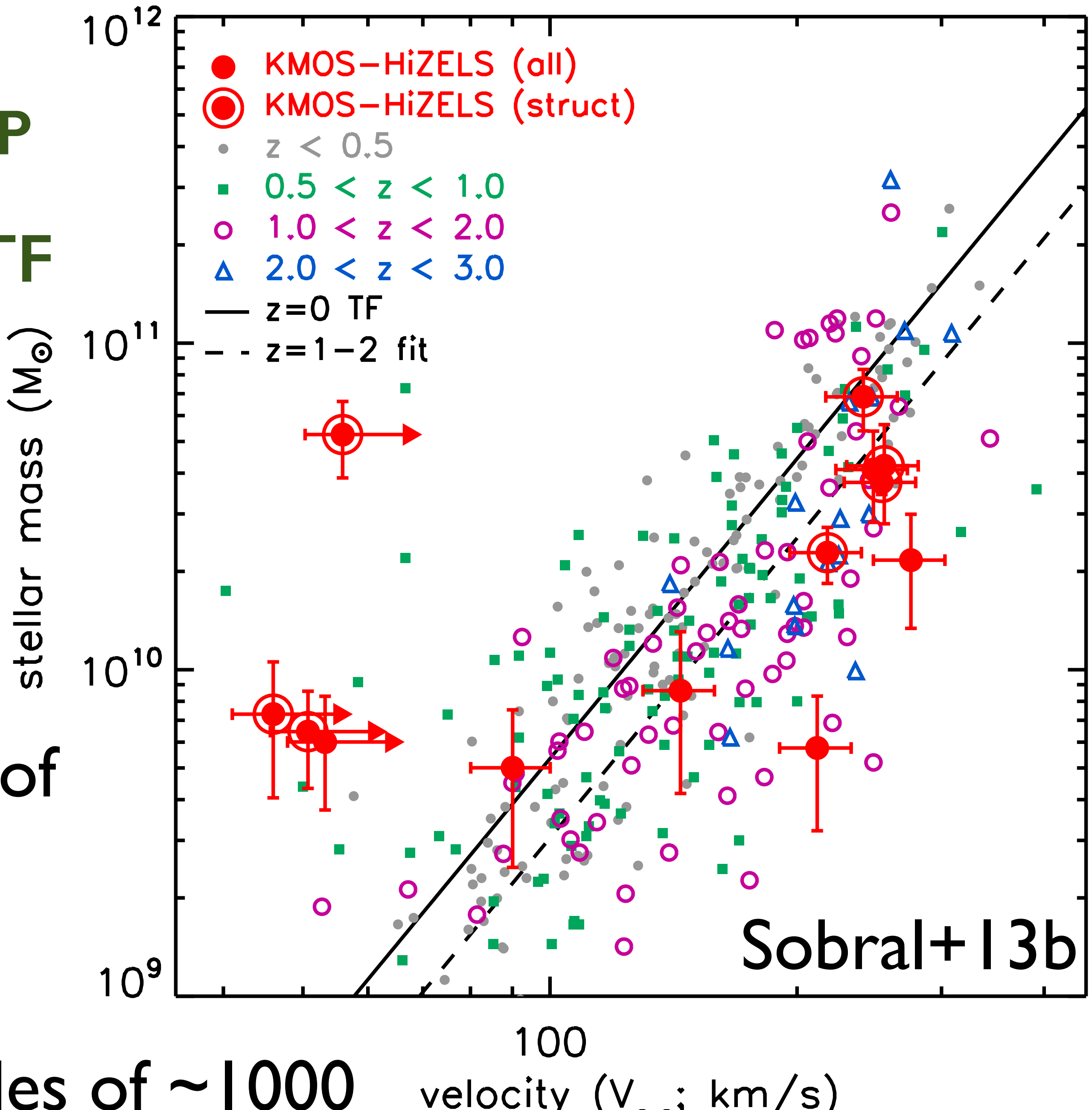
Small Evolution in ZP

Agrees with z~1-2 TF

No difference
field vs group

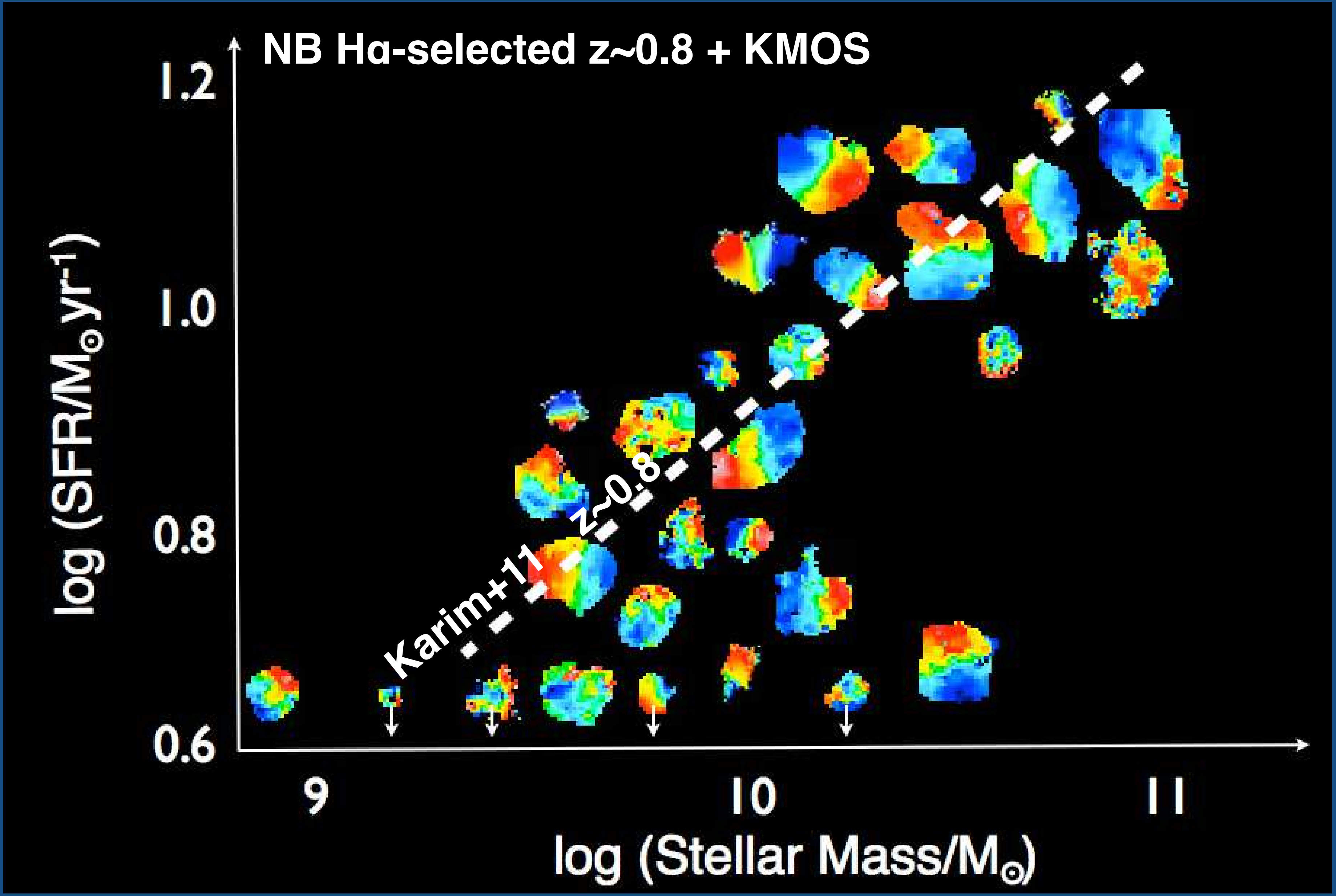
With just ~2 hours of VLT time

"Easy" to build samples of ~1000

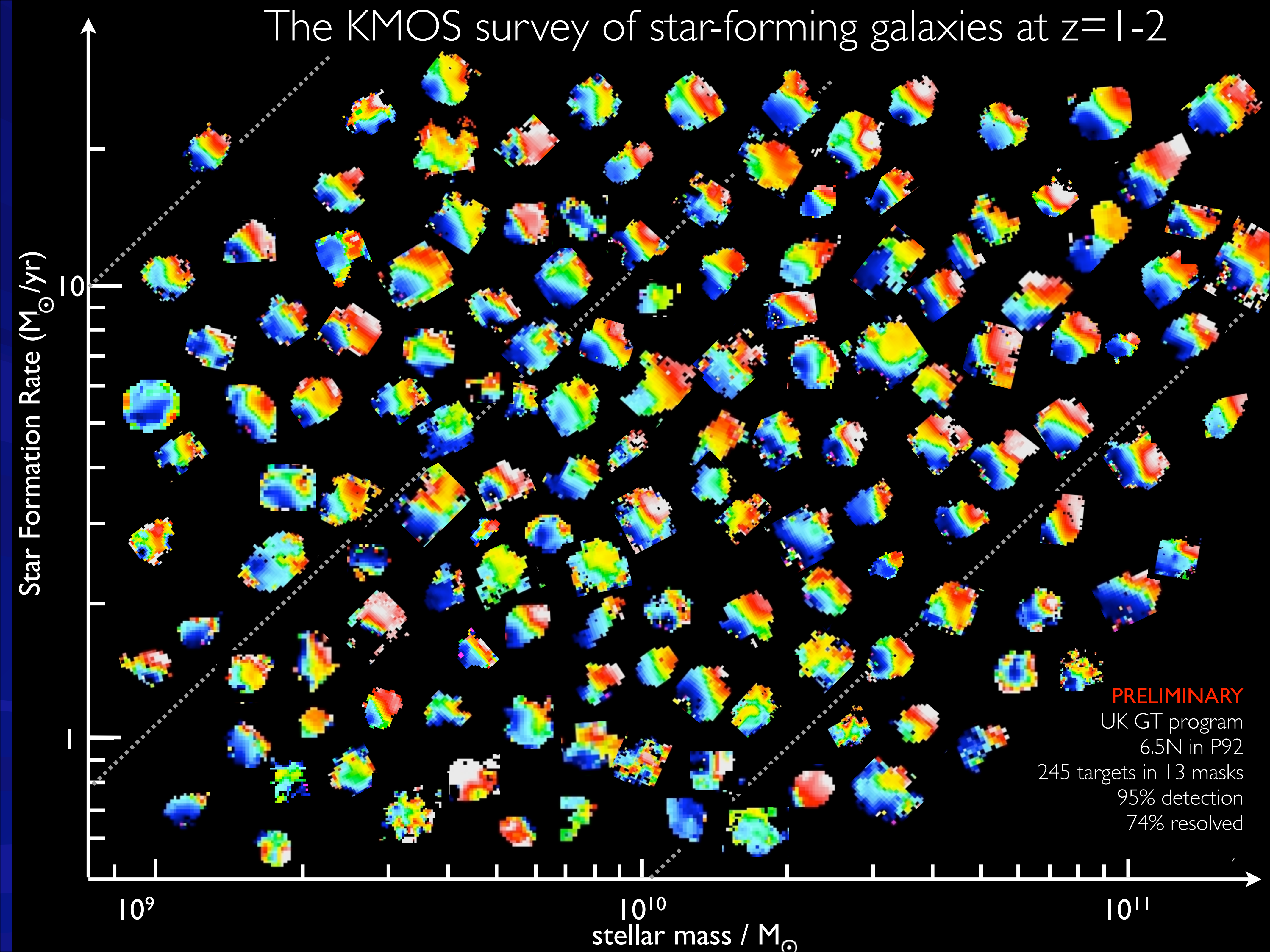


CF-HiZELS KMOS SAMPLE

just 4 hours! (with overheads)

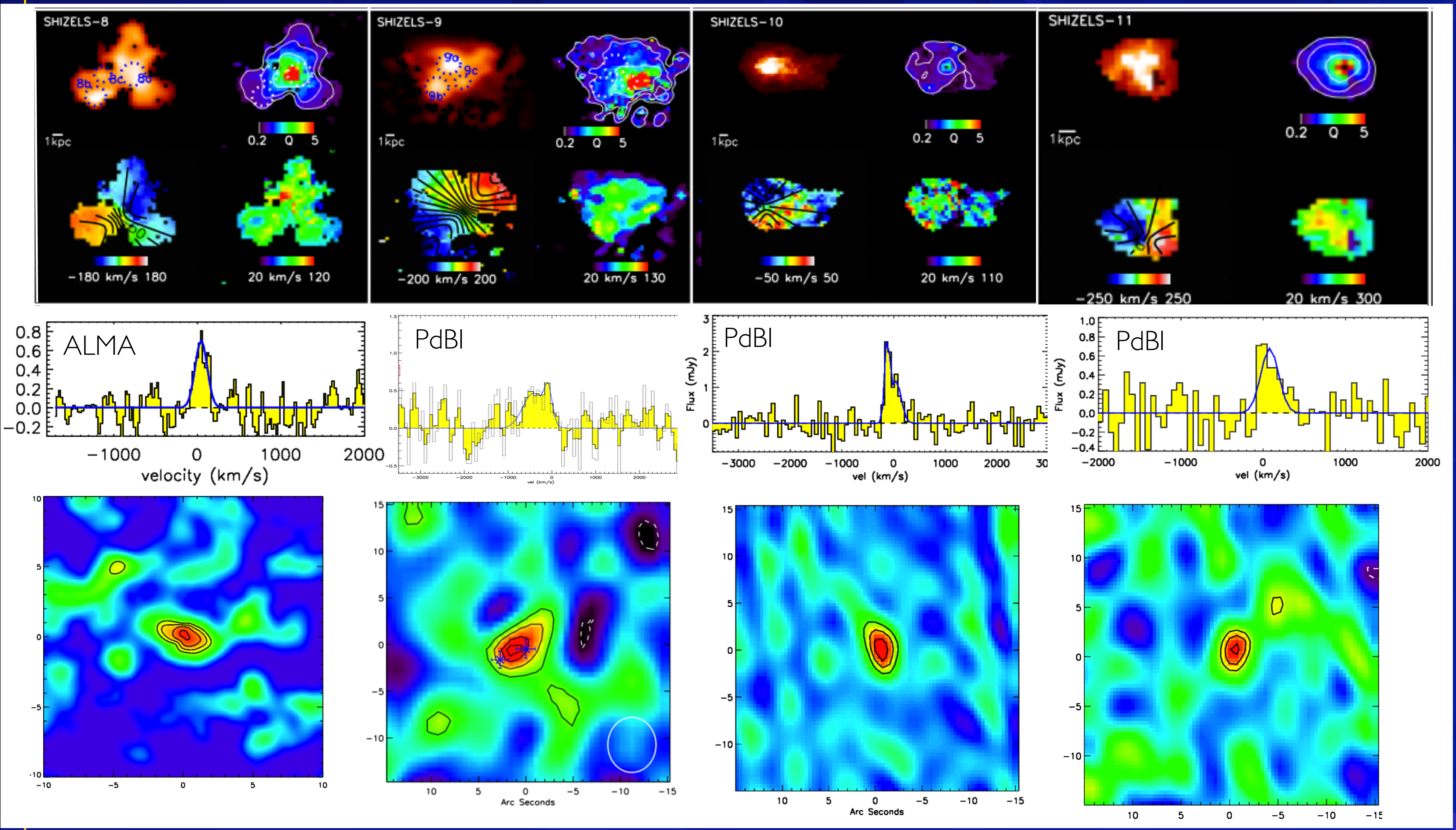


Stott et al. 2014, Sobral, Swinbank et al. 2013

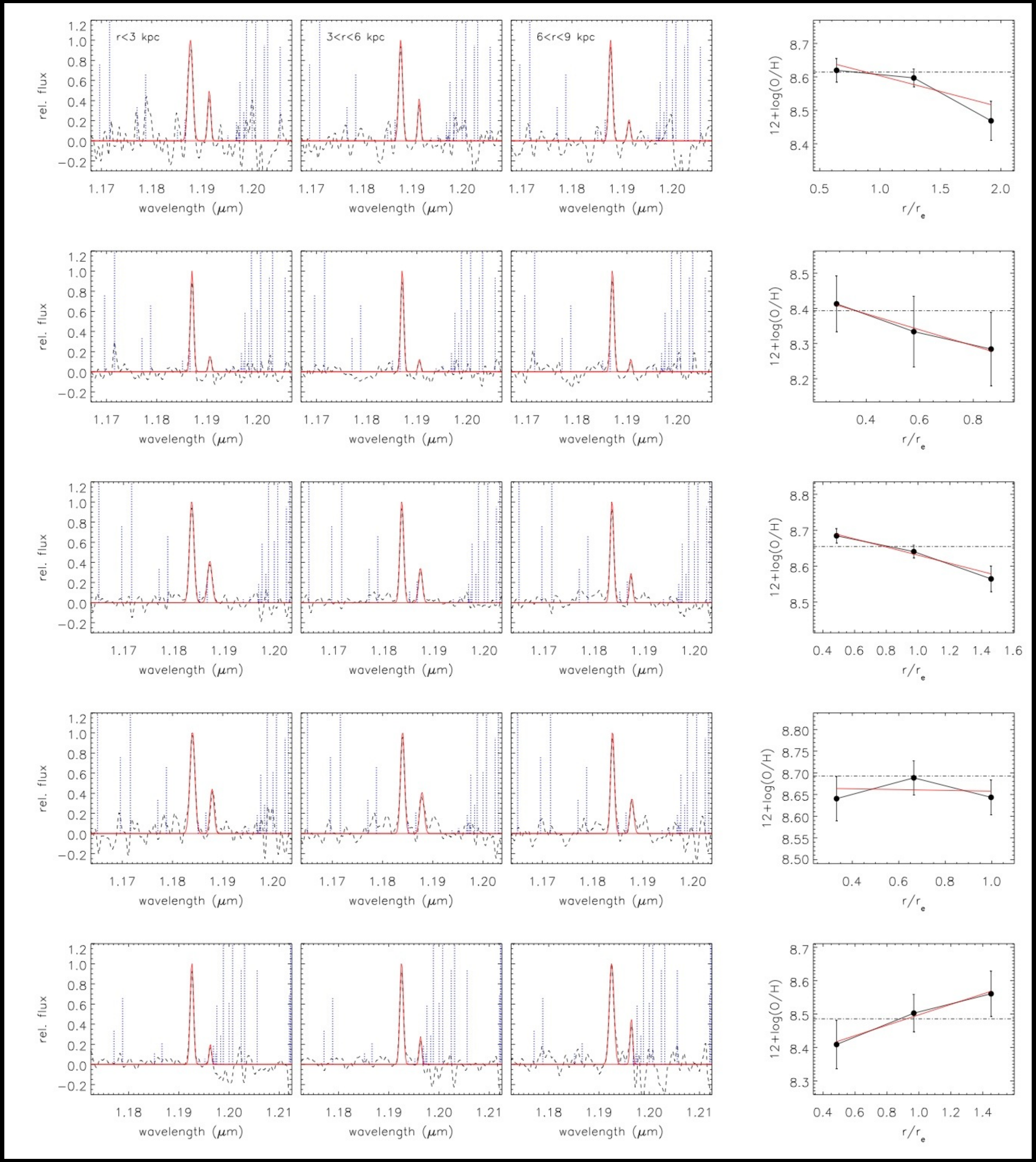


The KMOS survey of star-forming galaxies at z=1-2
Star Formation Rate (M☉/yr)
10
1
10⁹
10¹⁰
10¹¹
stellar mass / M☉
PRELIMINARY
UK GT program
6.5N in P92
245 targets in 13 masks
95% detection
74% resolved

CO follow-up well underway with PdBI and ALMA



M_{gas} = 1-3x$10^{10}M_{\odot}$ (a=2)
M* = 2-4x$10^{10}M_{\odot}$
f_{gas} ~30-50%
M_{gas} / SFR ~ 1Gyr



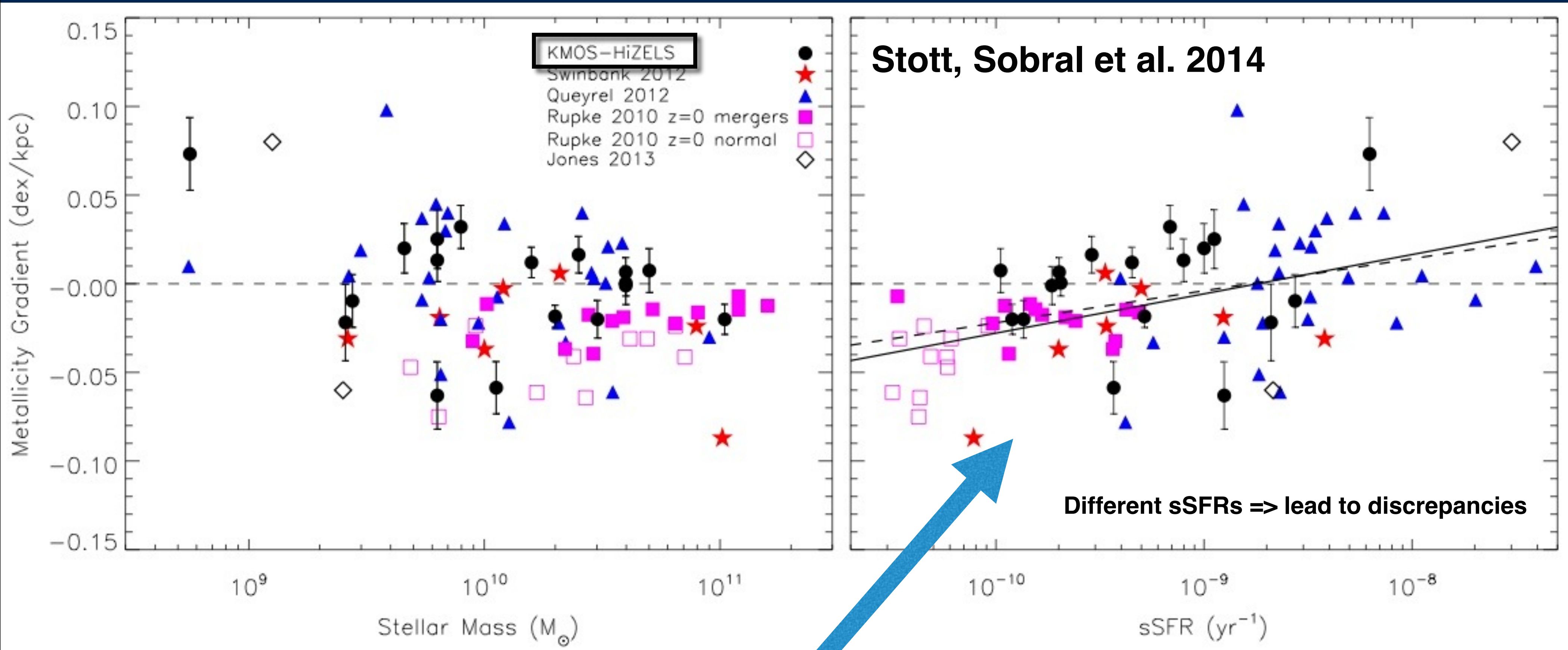
Metallicity gradients for CF-HiZELS KMOS sample

Agreement with SINFONI results (Swinbank+12a)

Mostly negative or flat, very few positive

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

Stott 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)

Conclusions:

- **Hα selection z~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: factor ~13x**

- **SINFONI w/ AO: Star-forming galaxies since z=2.23: ~75% "disks", negative metallicity gradients, many show clumps**

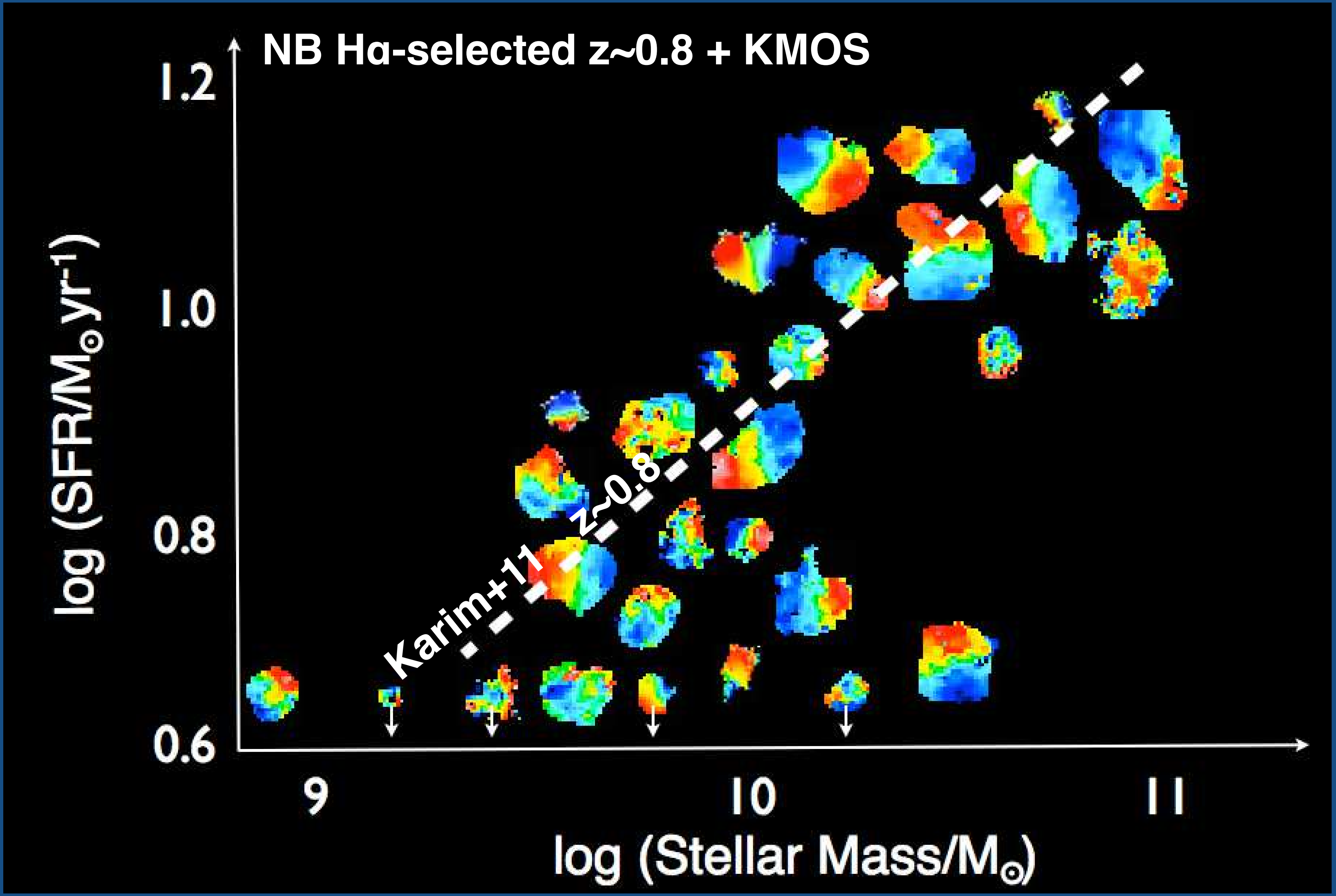
- **KMOS+Hα (NB) selection works extraordinarily well: resolved dynamics of typical SFGs in ~1-2 hours, 75+-8% disks, 50-275km/s**

- **KMOS: 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**

- **KMOS CF-HiZELS: Metallicity gradients correlate with sSFR: FMR & explains discrepancies ?**

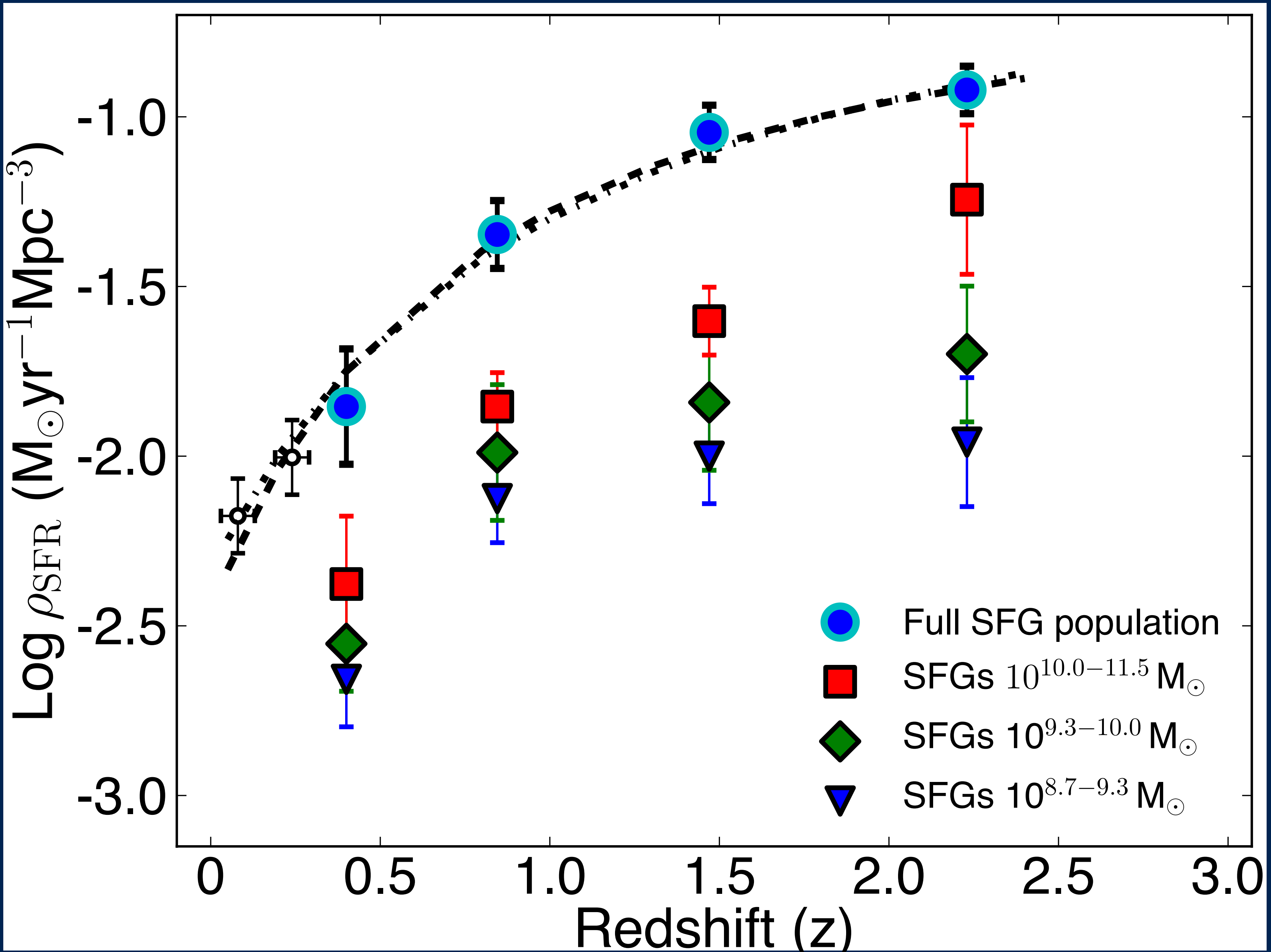
CF-HiZELS KMOS SAMPLE

just 4 hours! (with overheads)



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

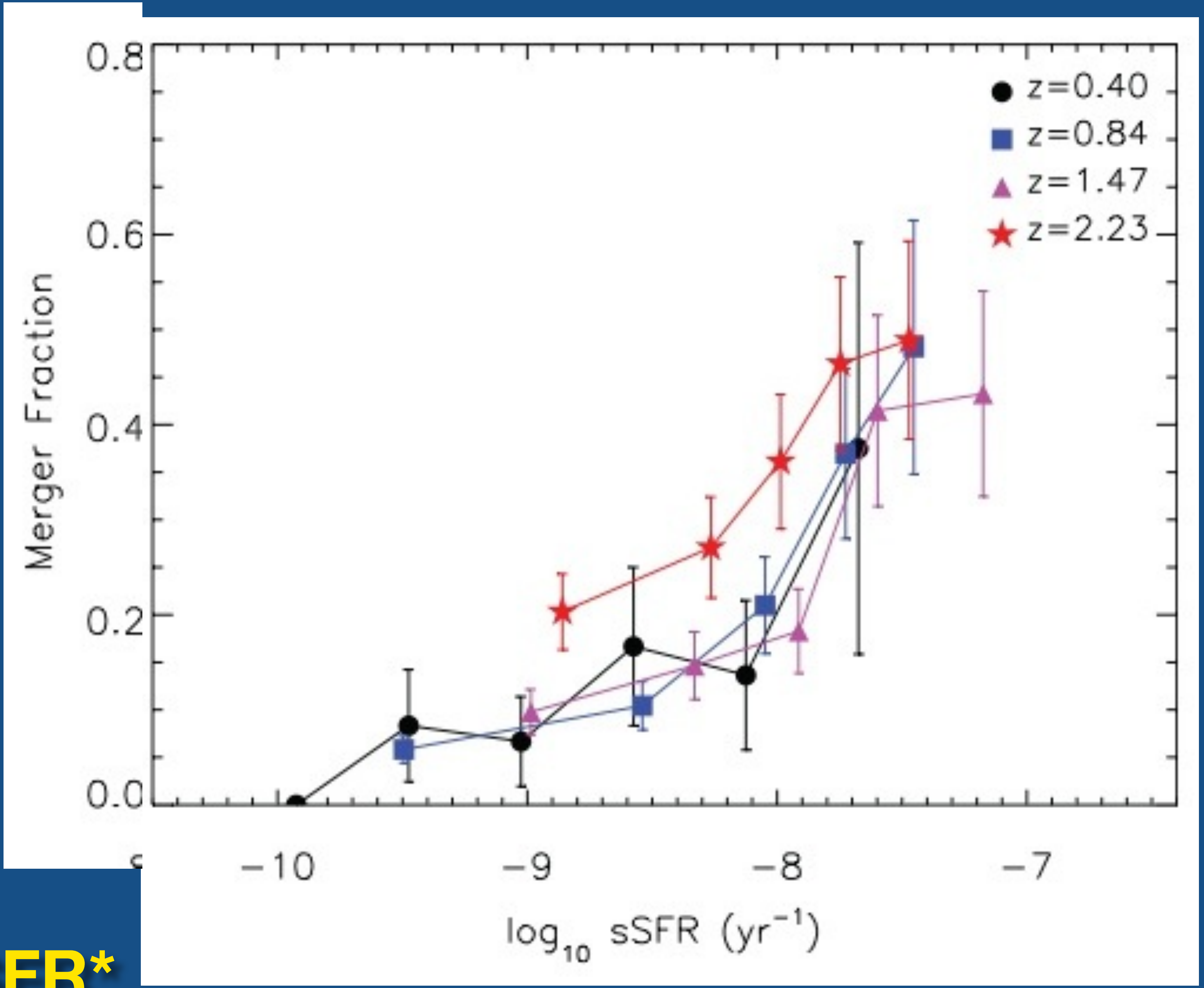
SF History - Full population and 4 mass bins



Decline at all masses

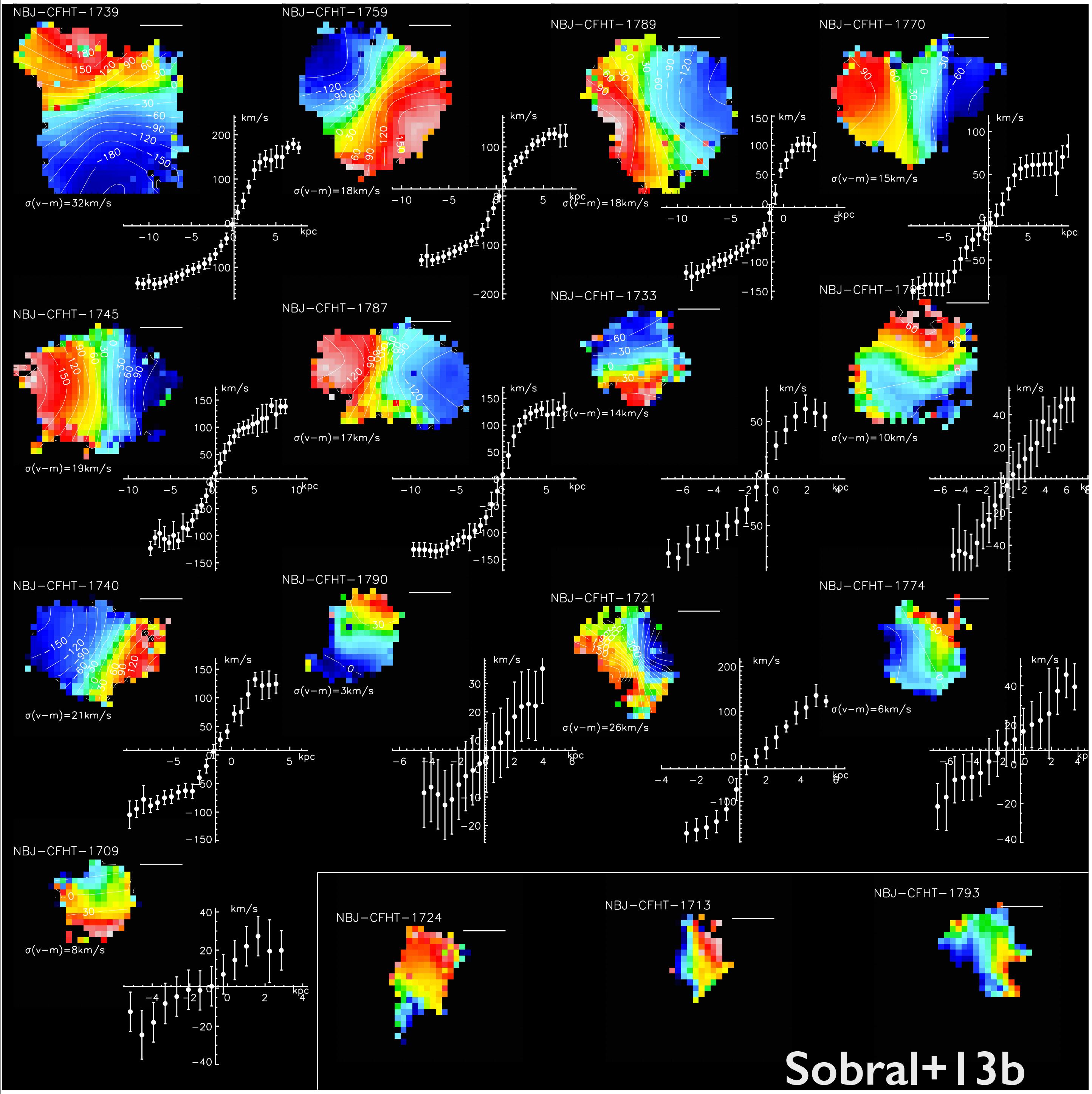
Sobral et al. (13C)

Although:



SFR> 0.2 SFR*

Stott et al. 2013a



75+-8% Disks

Shallow, negative metallicity gradients

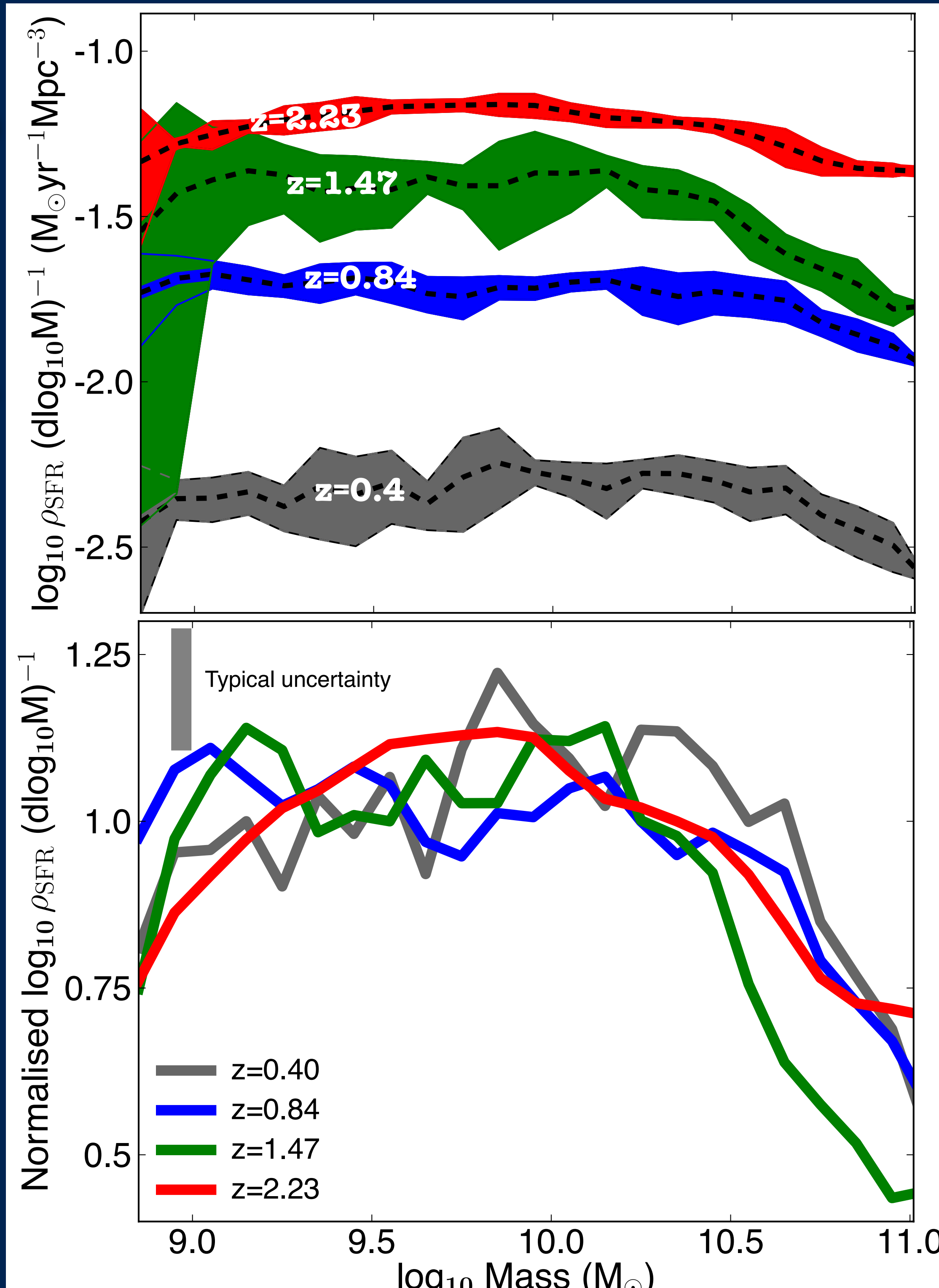
Rotation speeds of 50-275 km/s

~solar metallicity

Group galaxies: 100% disks

SFRD per dLogM

Normalised



Over the last 11 Gyrs

Decrease with time at all masses

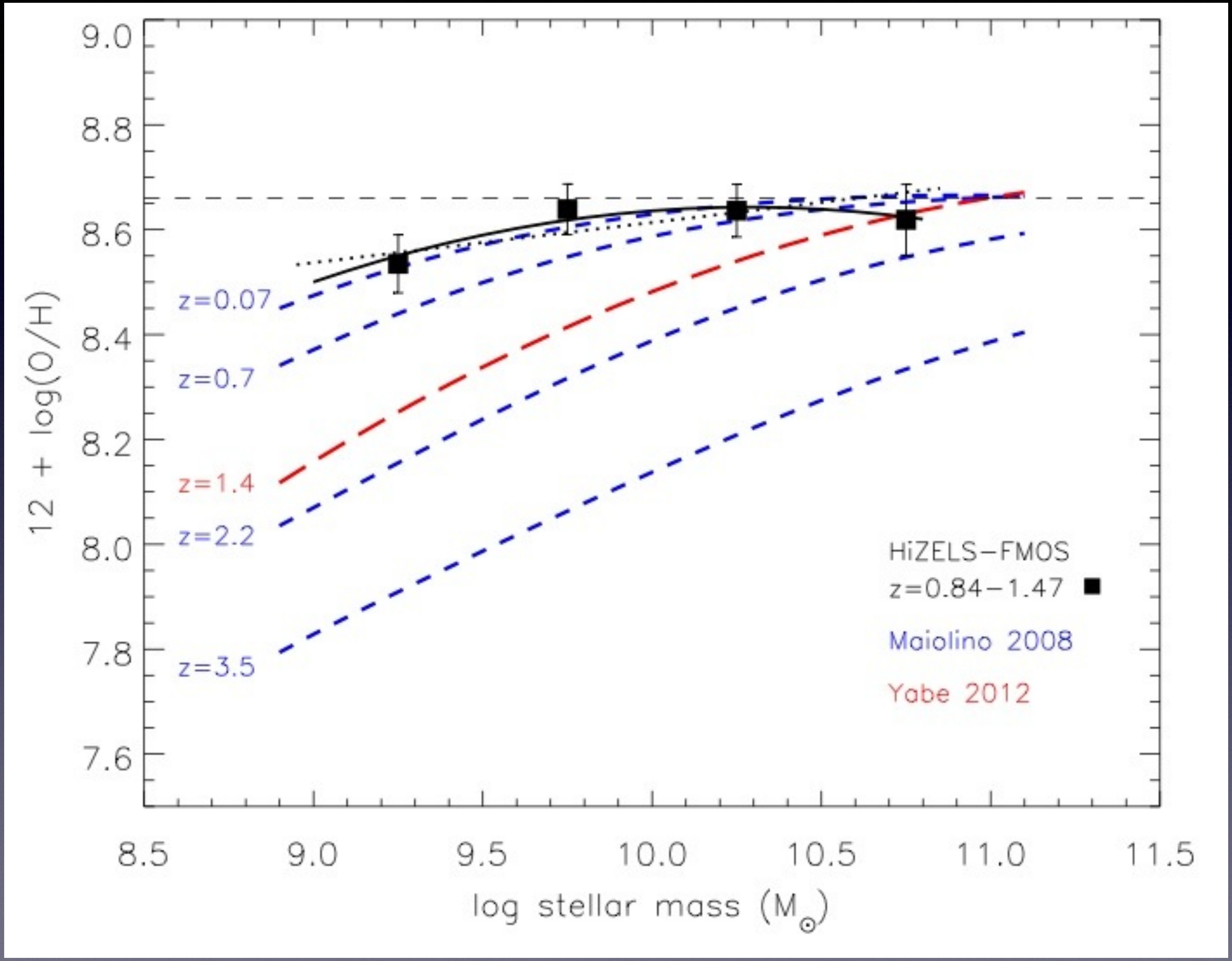
Tentative peak per dLogM at ~10^{10} M_{o} since z=2.23

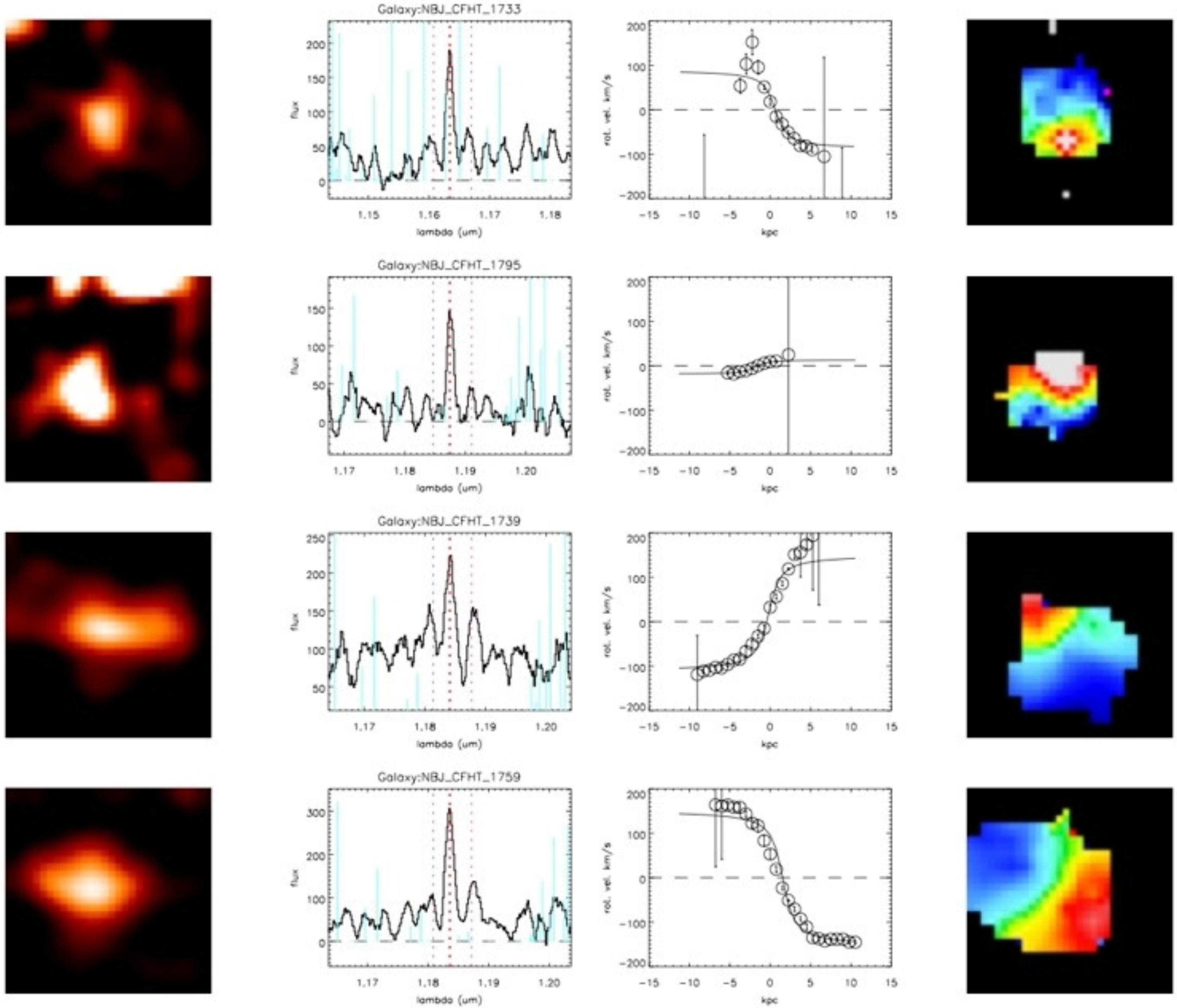
Mostly no evolution apart from normalisation

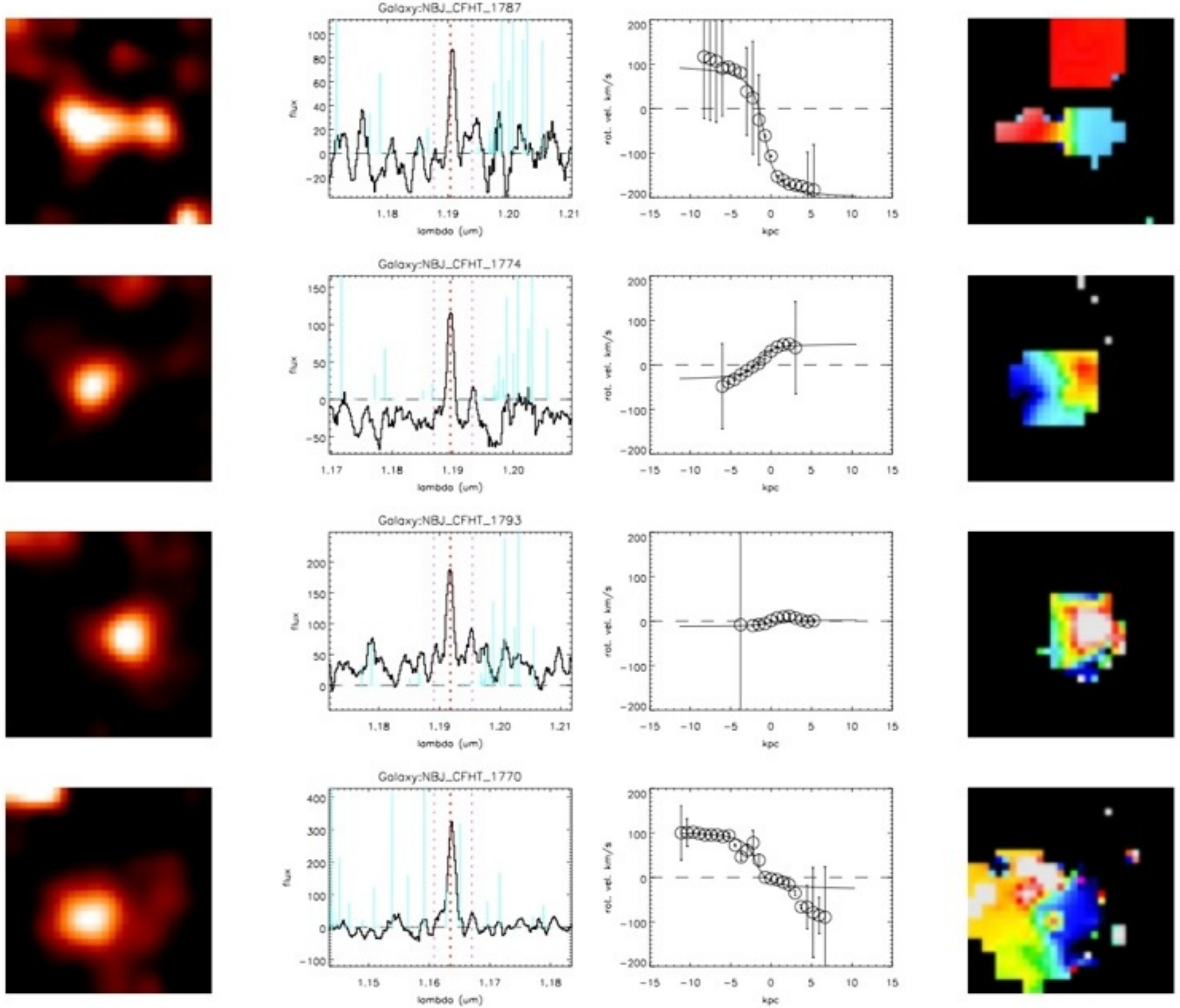
Sobral et al. (13C)

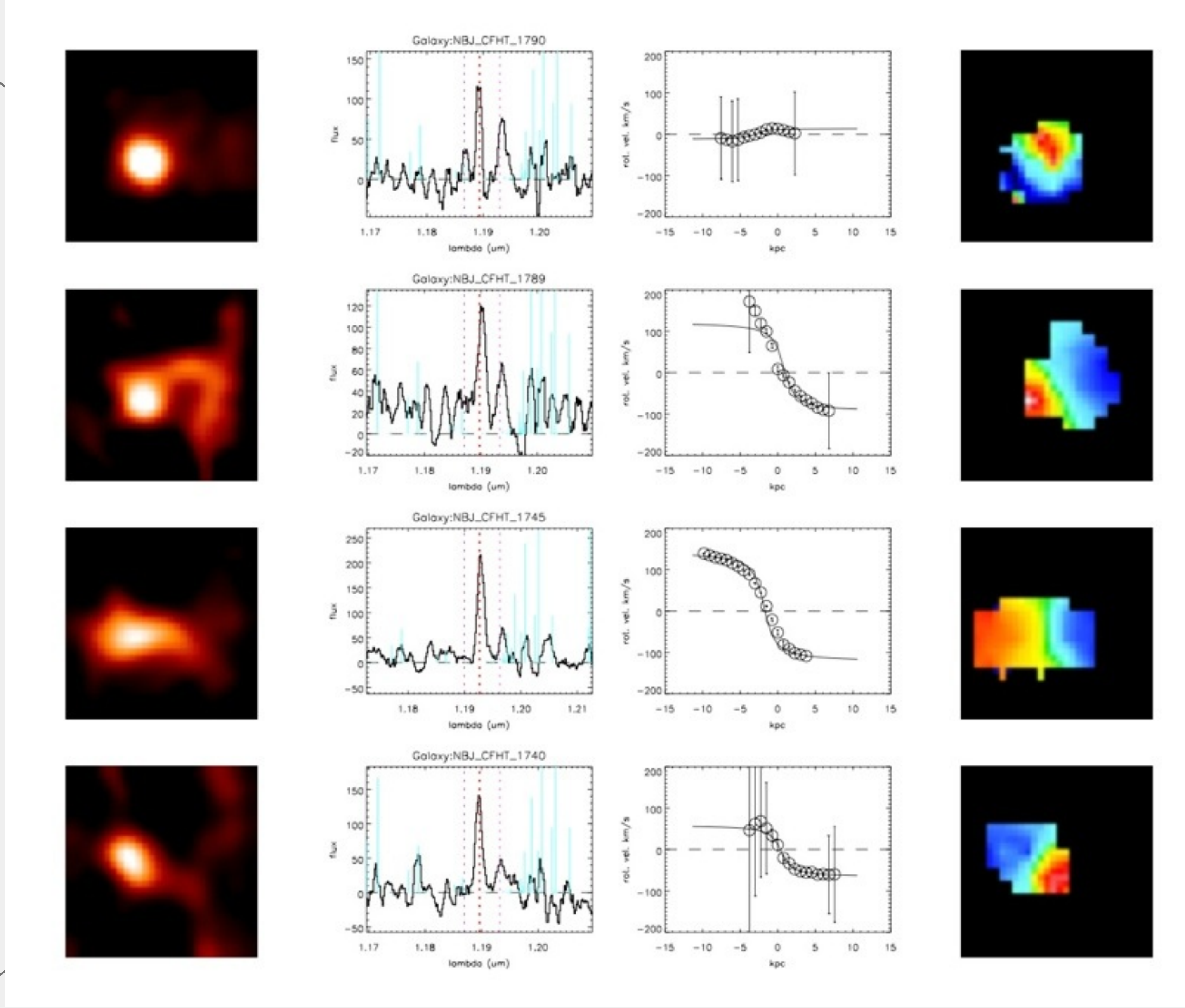
Stott, Sobral et al. 2013b

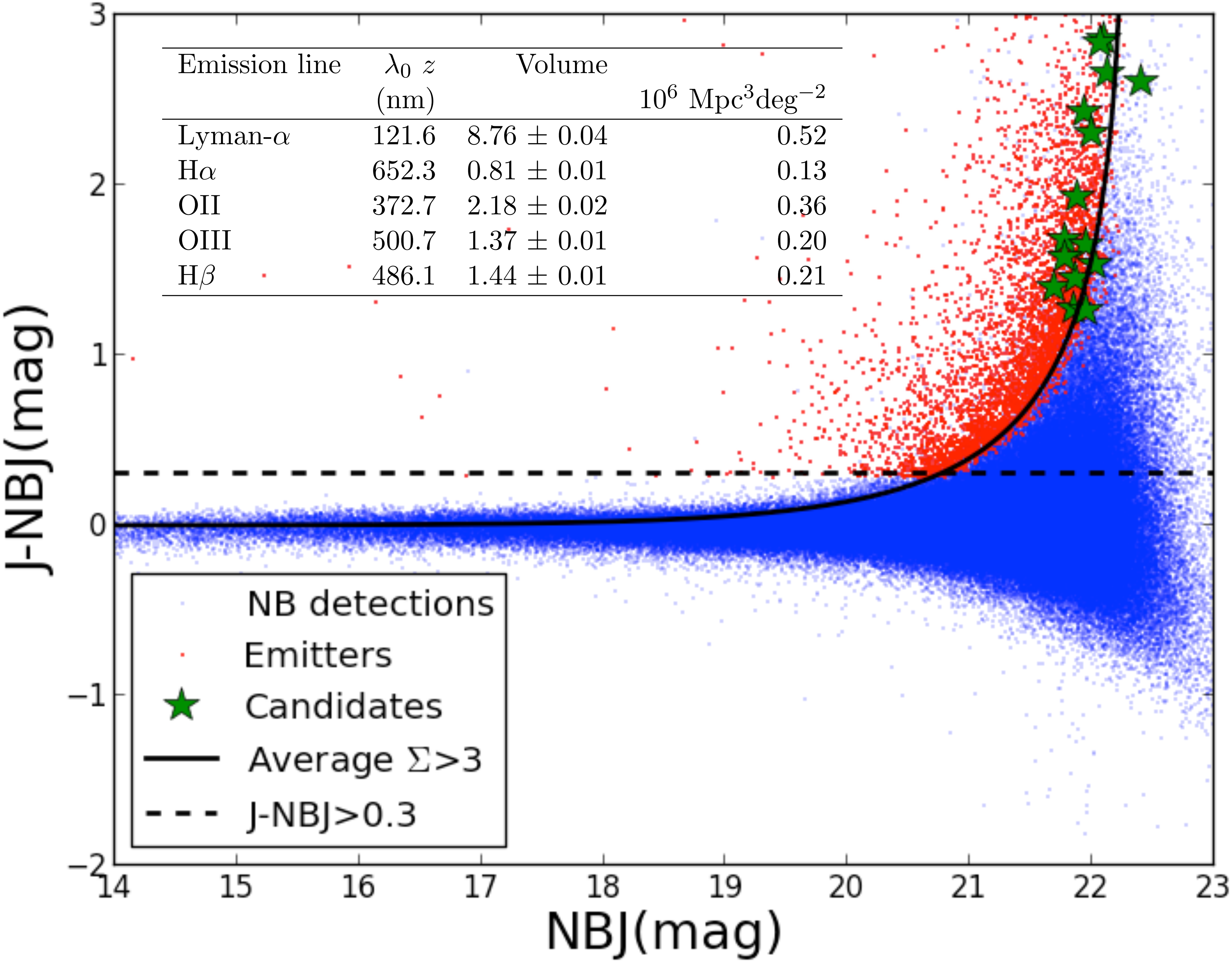
z=0.84 + z=1.47 Ha




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

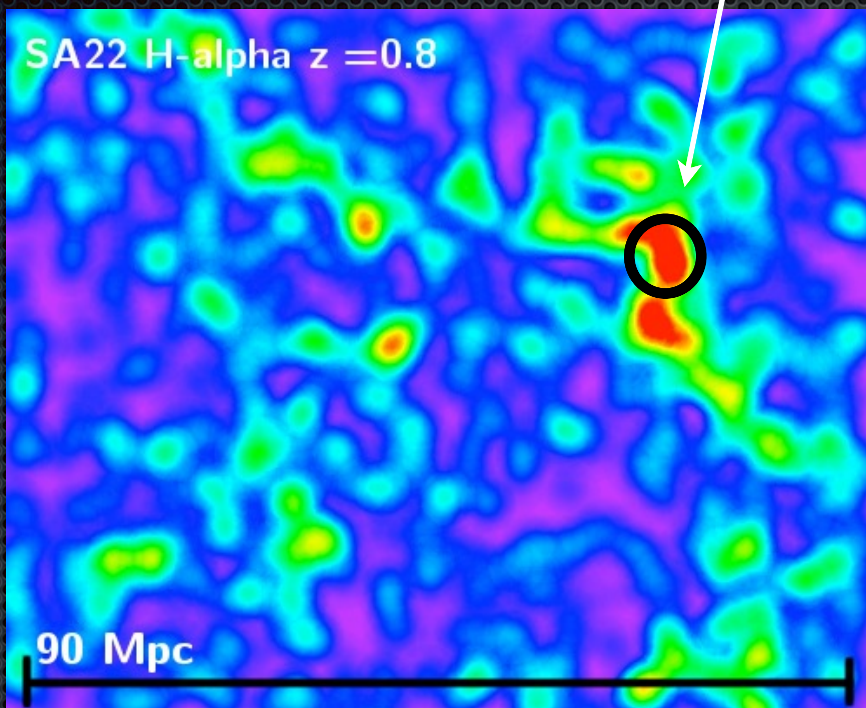

Galaxy:NBJ_CFHT_1787
Galaxy:NBJ_CFHT_1774
Galaxy:NBJ_CFHT_1793
Galaxy:NBJ_CFHT_1770
flux
lambda (um)
rot. vel. km/s
kpc


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

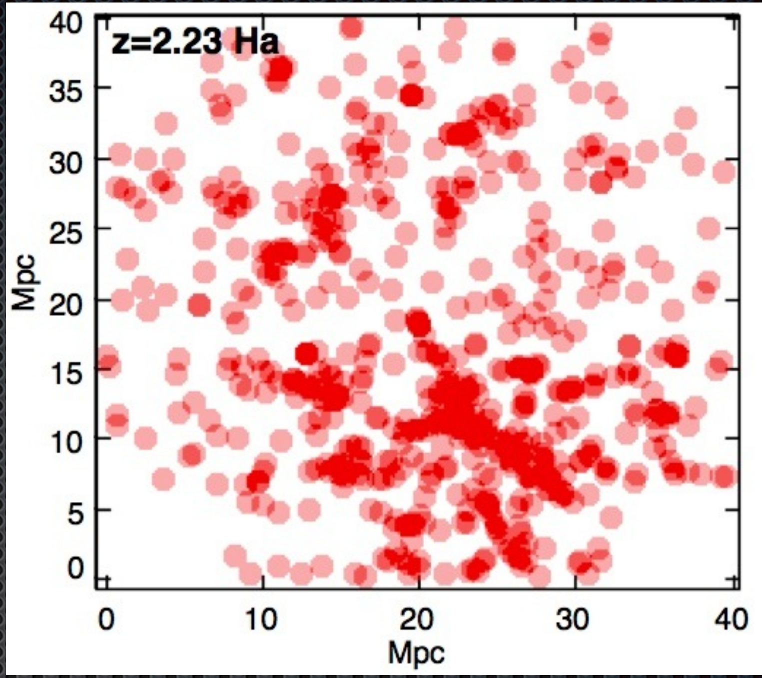

Emission line
λ_0 (nm)
z
Volume
10^6 Mpc^{3}deg^{-2}
Lyman-α 121.6 8.76 ± 0.04 0.52
Hα 652.3 0.81 ± 0.01 0.13
OII 372.7 2.18 ± 0.02 0.36
OIII 500.7 1.37 ± 0.01 0.20
Hβ 486.1 1.44 ± 0.01 0.21
NB detections
Emitters
Candidates
Average Σ>3
J-NBJ>0.3
J-NBJ(mag)
NBJ(mag)
3
2
1
0
−1
−2
14
15
16
17
18
19
20
21
22
23

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

8 sigma

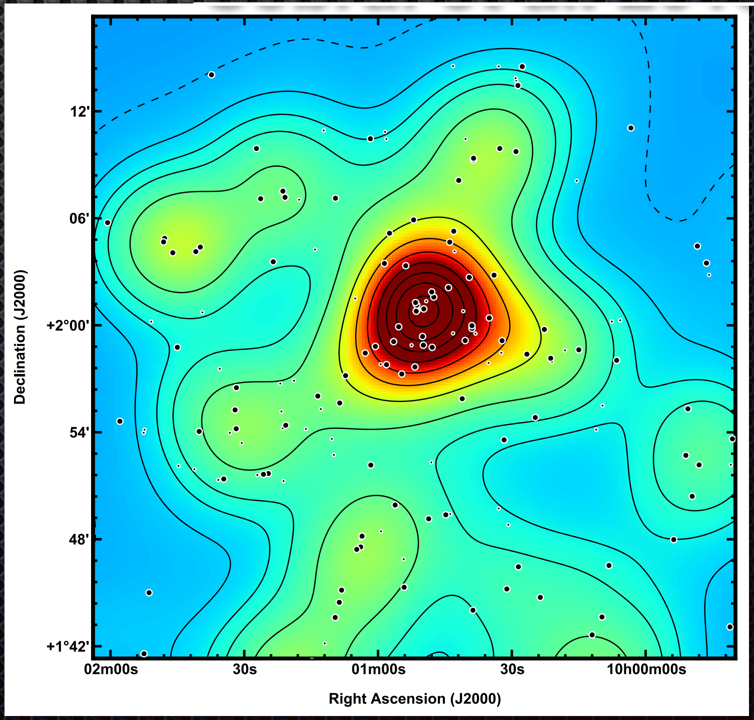


Cluster? Proto-cluster? How special are these galaxies? What are their dynamics?



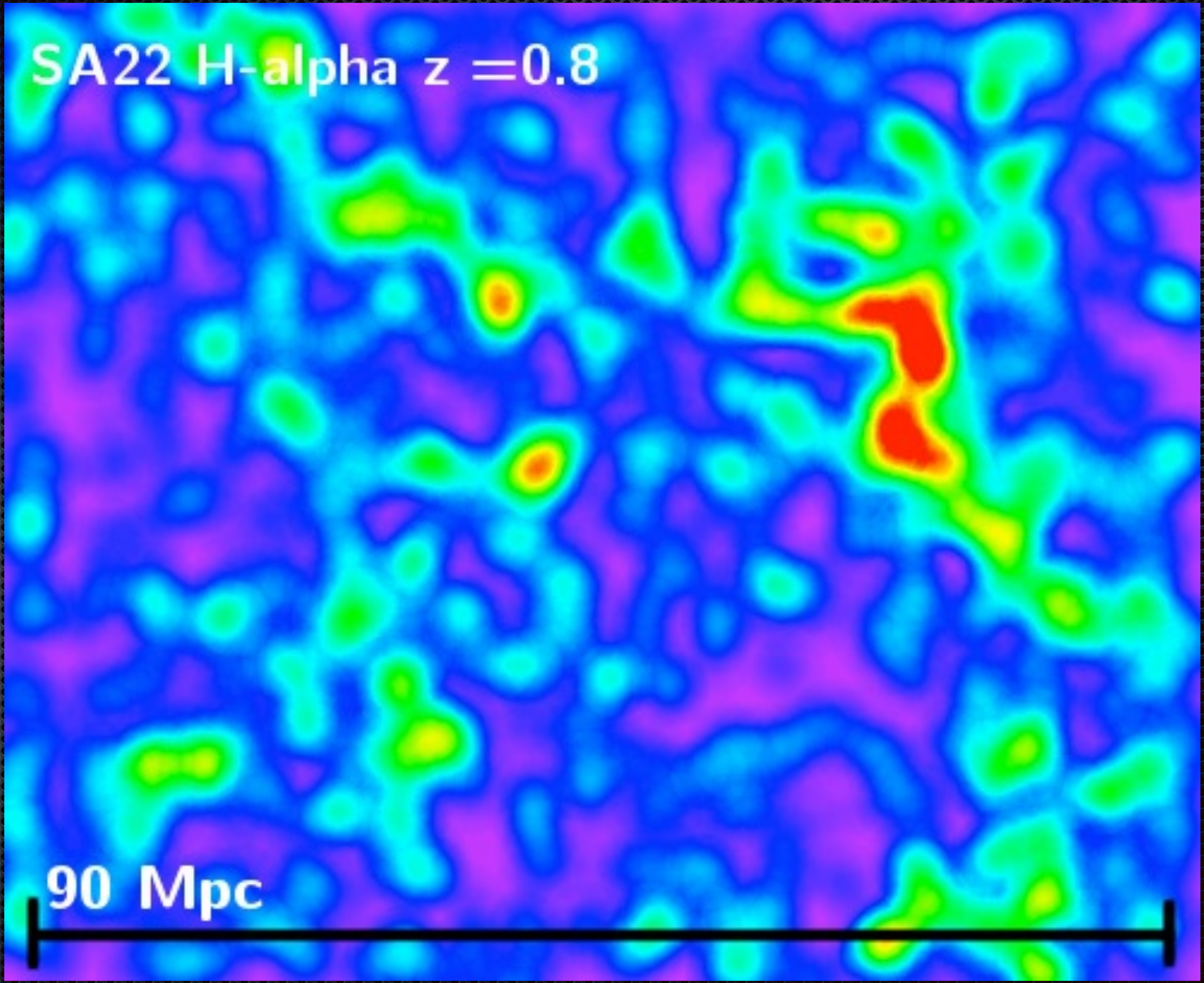
z=2.23

Sobral et al. 2013a



Geach et al. 2012

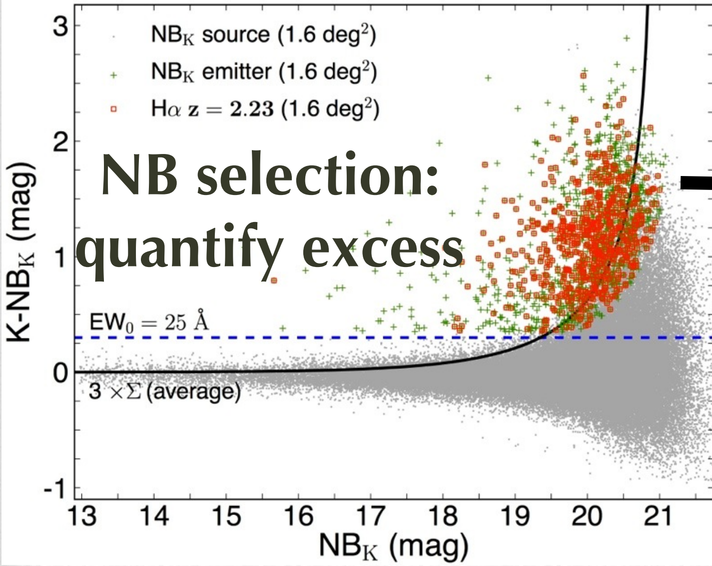
CFHT/WIRcam survey



Source extraction

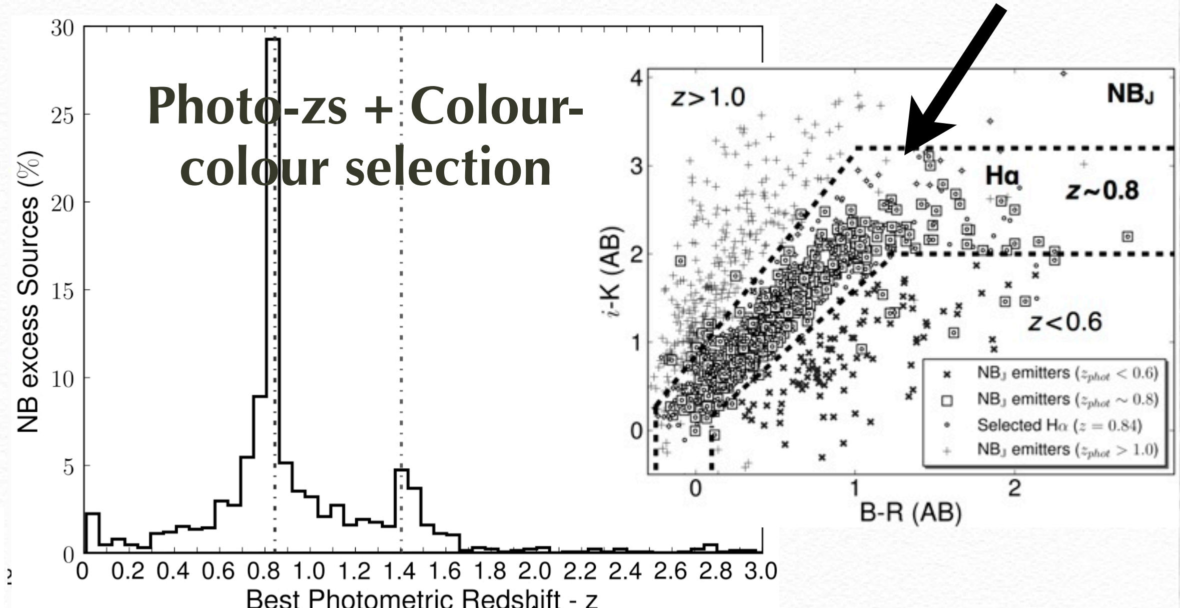
Potential line emitters

NB selection: quantify excess



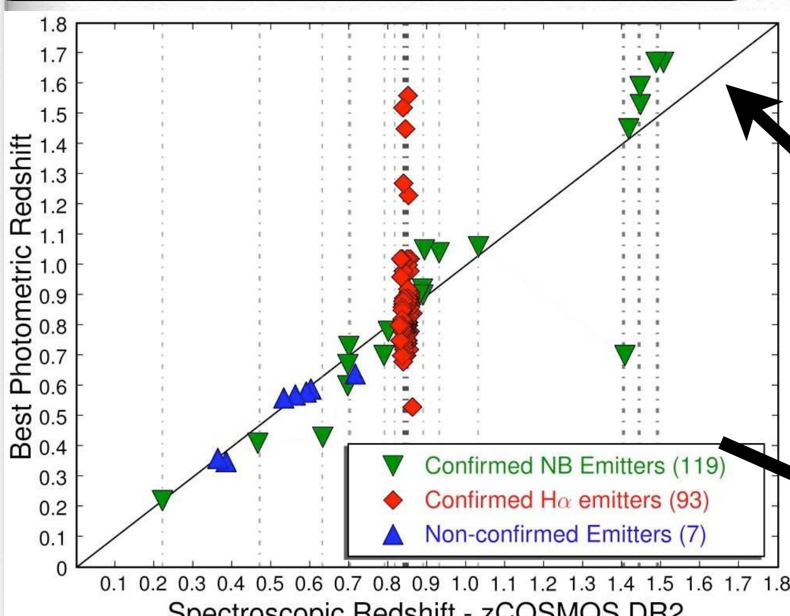
Which emission line?

Photo-zs + Colour-colour selection



Spectro-z confirmation

Double-line confirmation



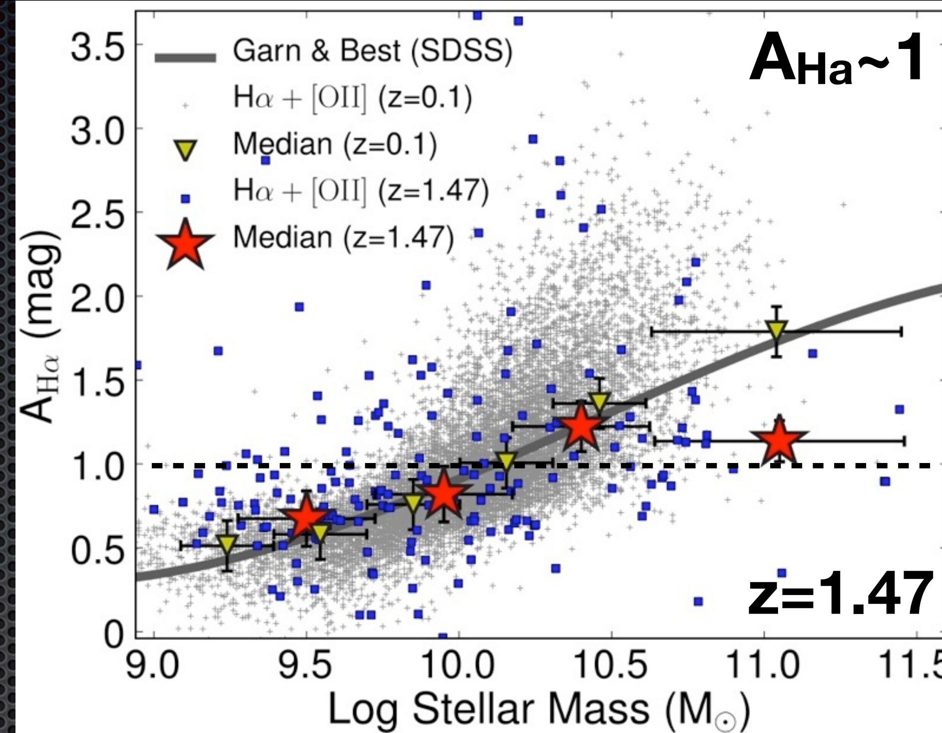
Select Hα emitters

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

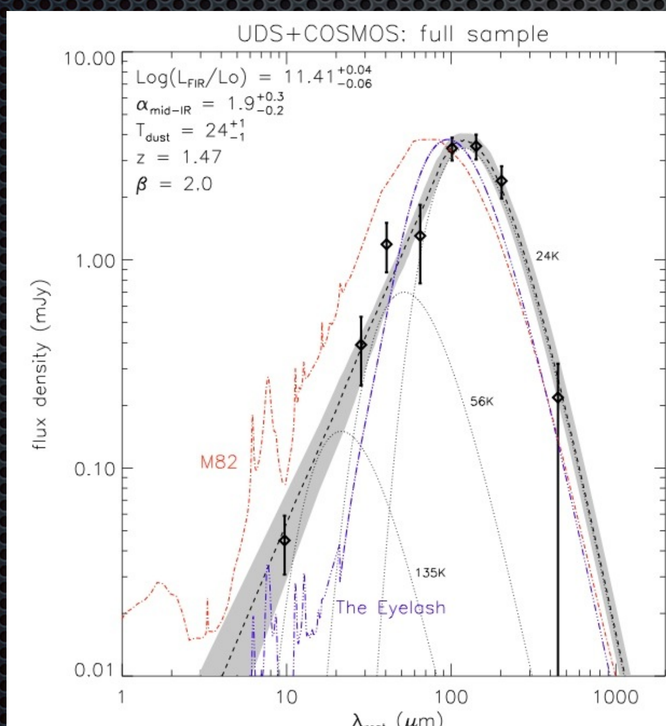
Extinction-Mass z~0-1.5

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

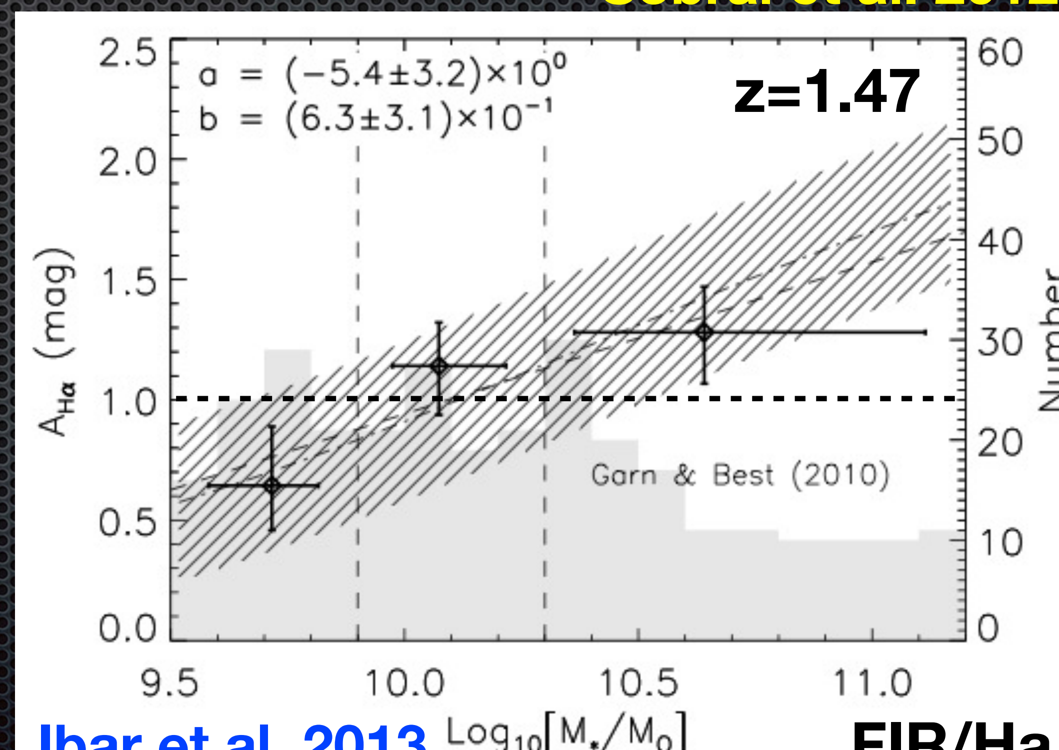
Relation holds up to z~1.5-2



Sobral et al. 2012

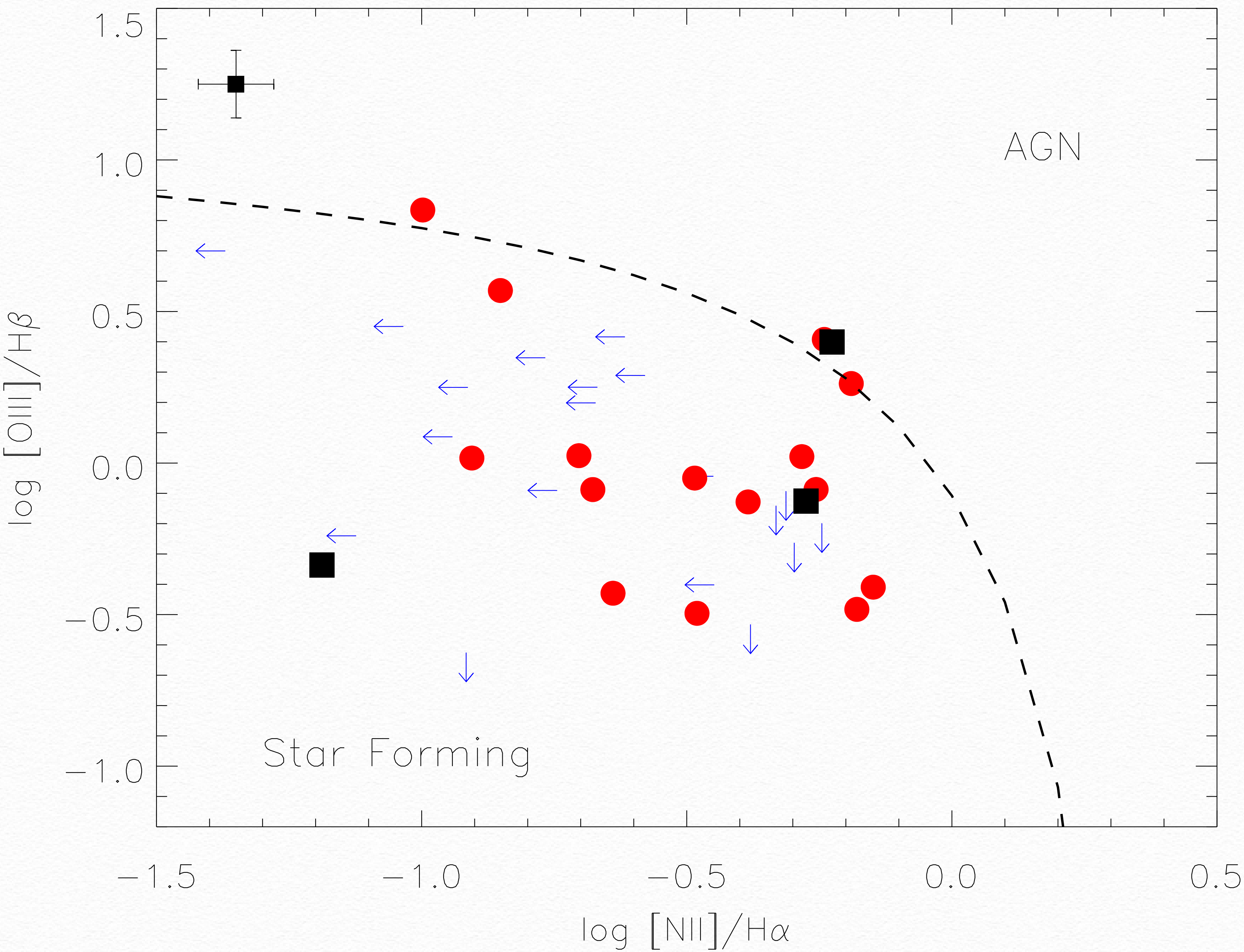


FIR derived A_{Ha} = 0.9-1.2 mag



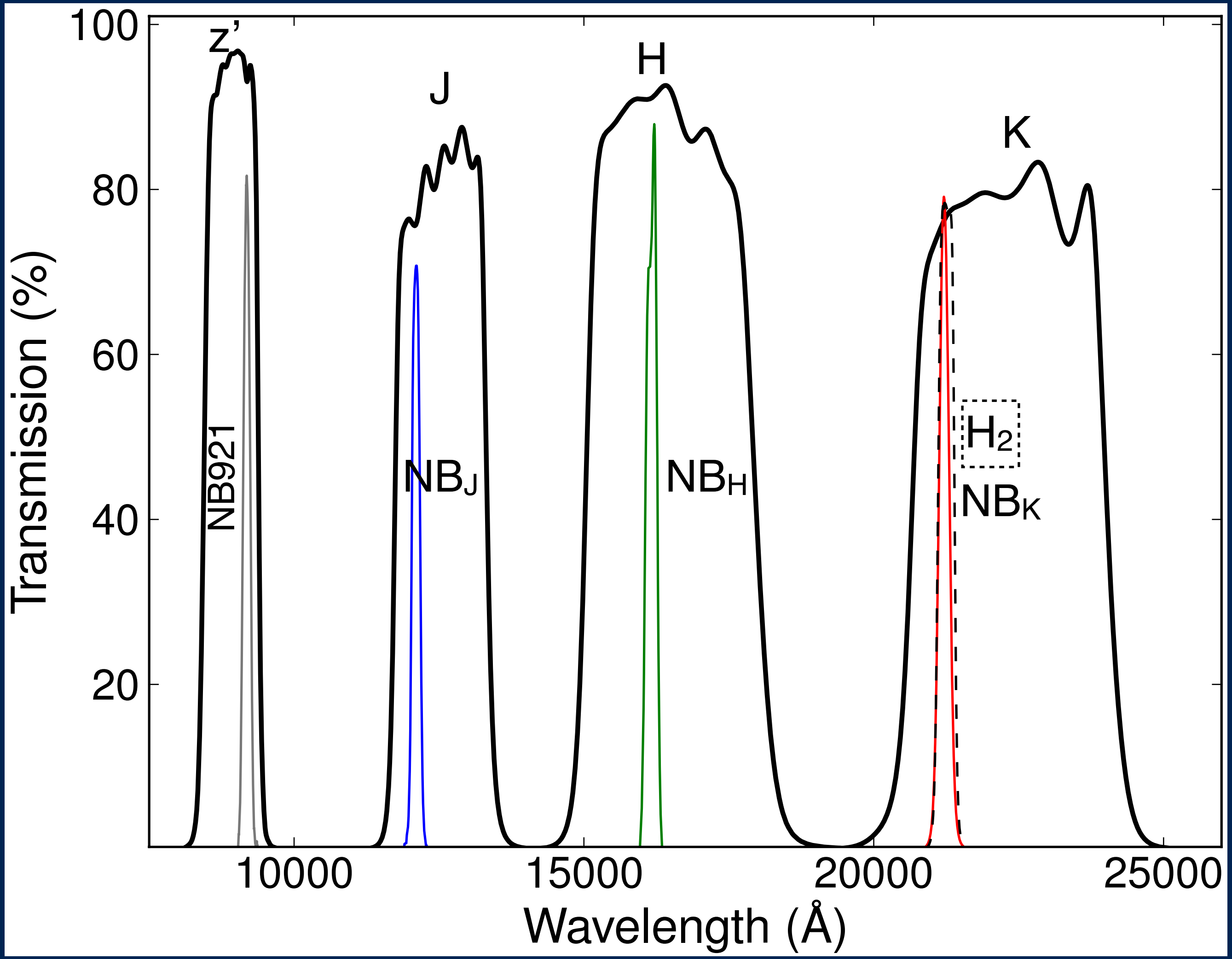
Ibar et al. 2013

FIR/Ha



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

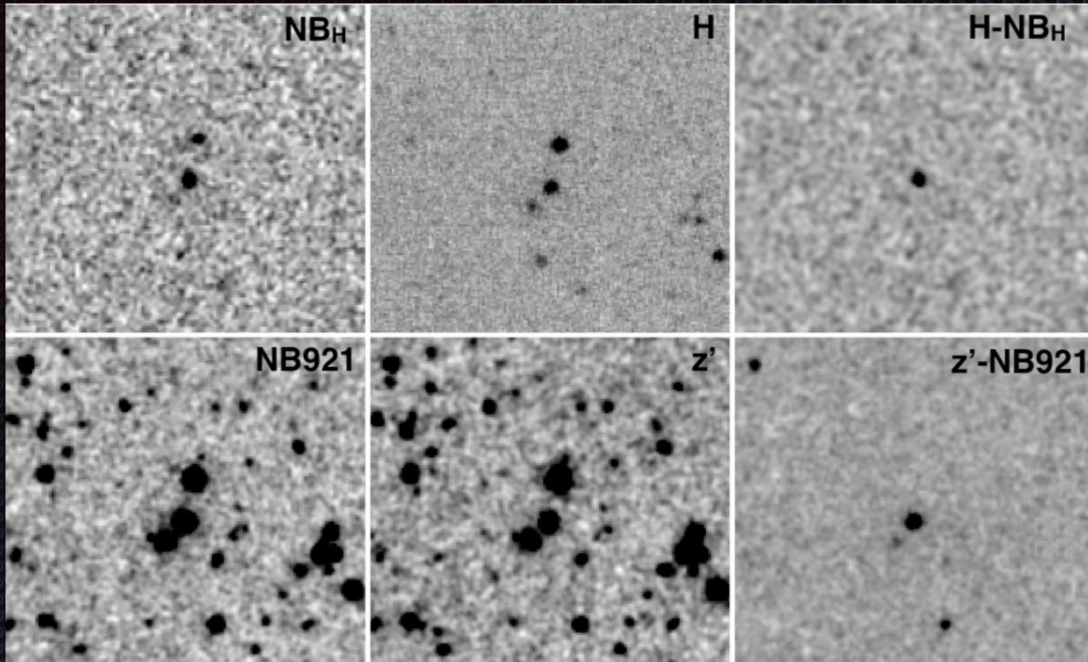
Filters combined to improve selection: double/triple line detections

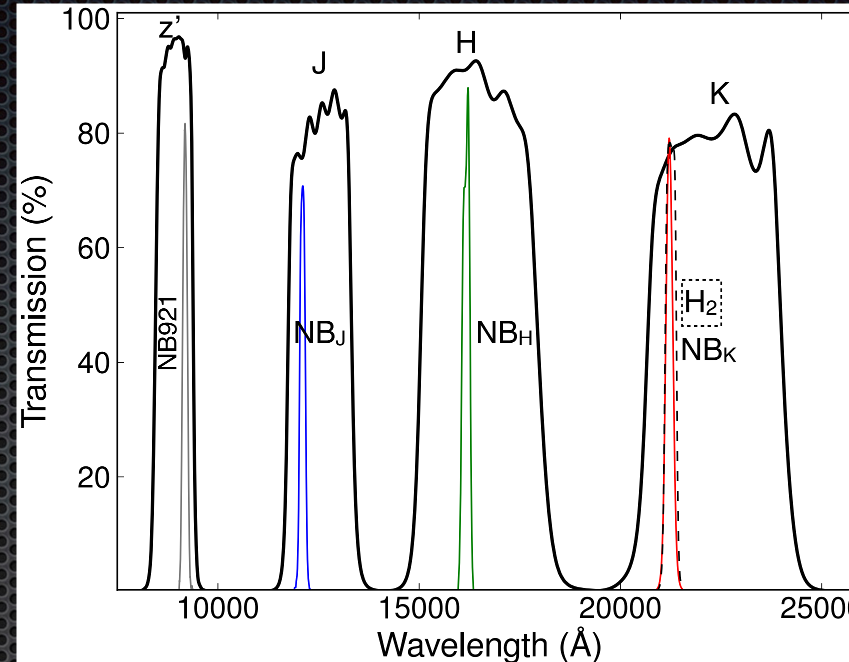


z=2.23 : [OII] (NBJ), [OIII] (NBH), Hα (NBK)

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

z=0.84 : [OIII] (NB921), Hα (NBJ)



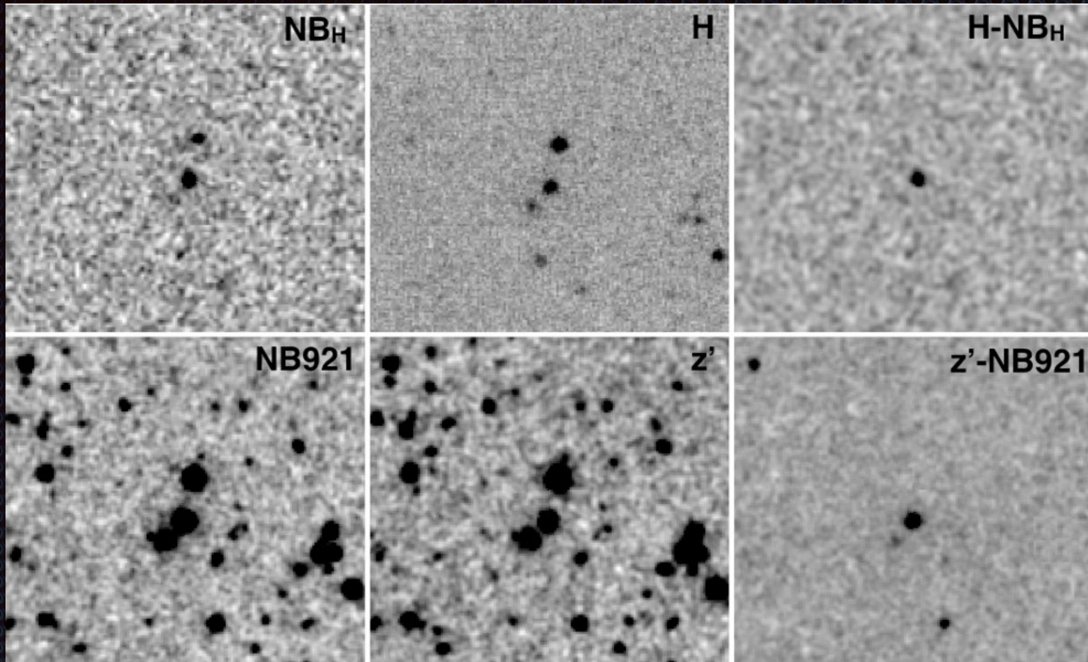


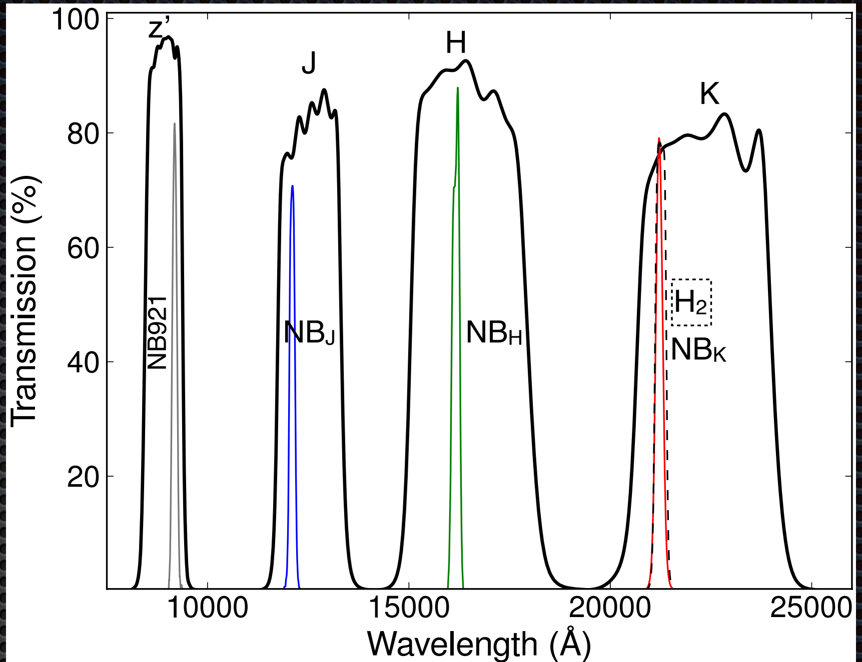
Hα emitters in HiZELS

2 sq deg: COSMOS + UDS

Prior to HiZELS:

~10 sources





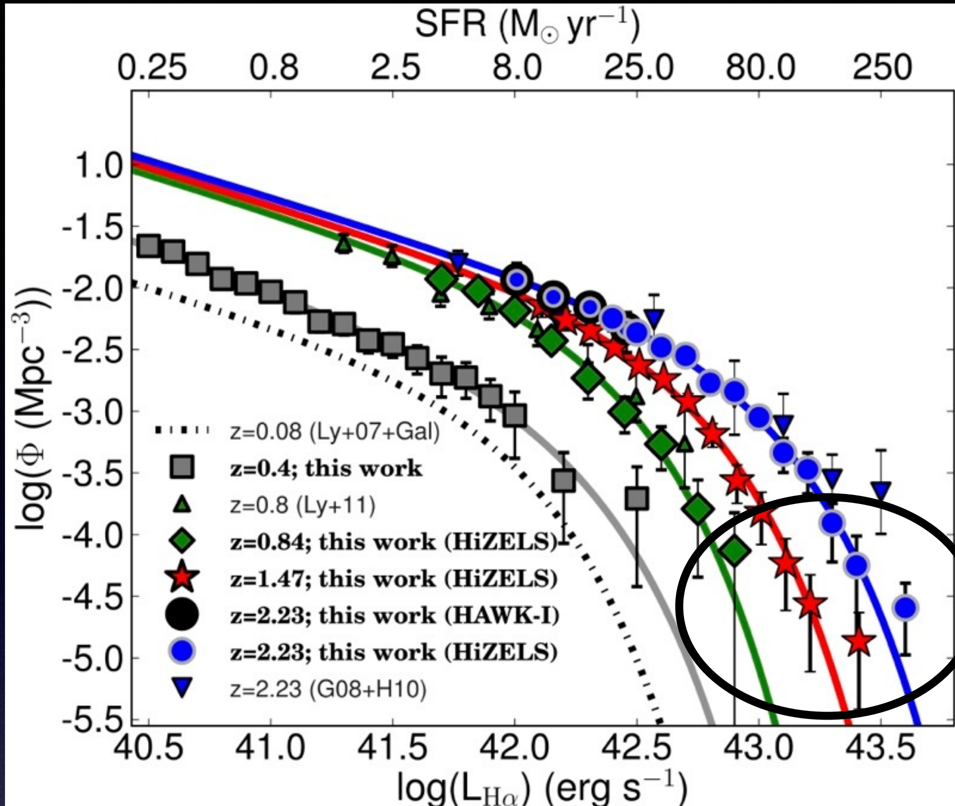
Hα emitters in HiZELS

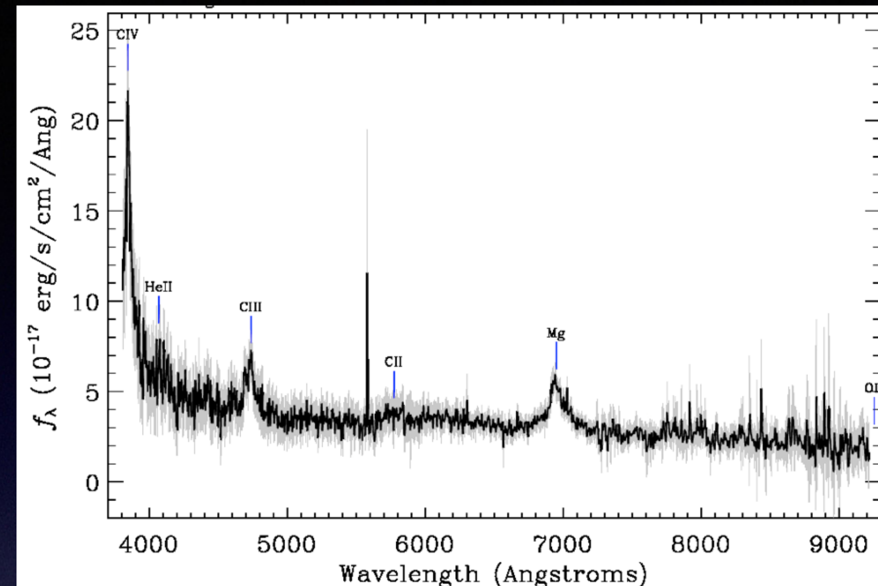
2 sq deg: COSMOS + UDS

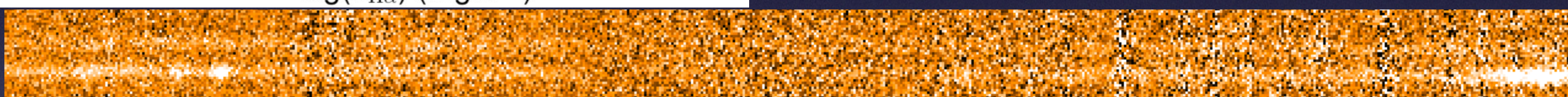
Prior to HiZELS: ~10 sources

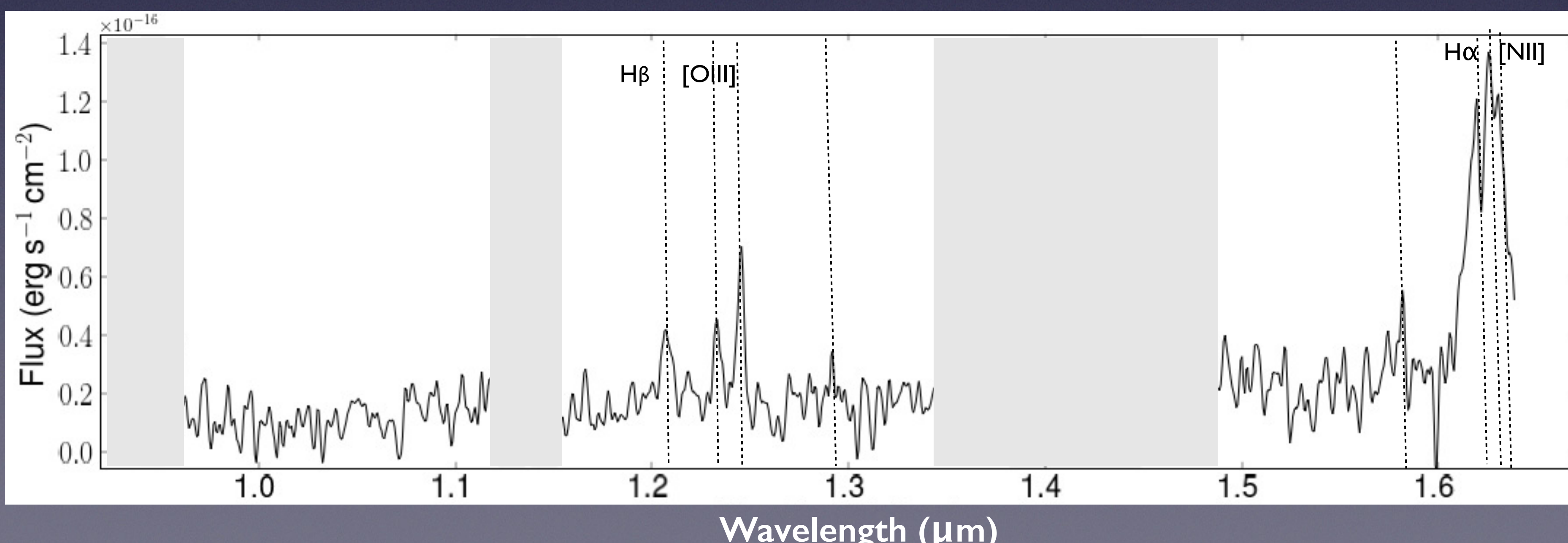
z=0.4: 1122 z=0.8: 637 z=1.47: 515 and z=2.23: 807

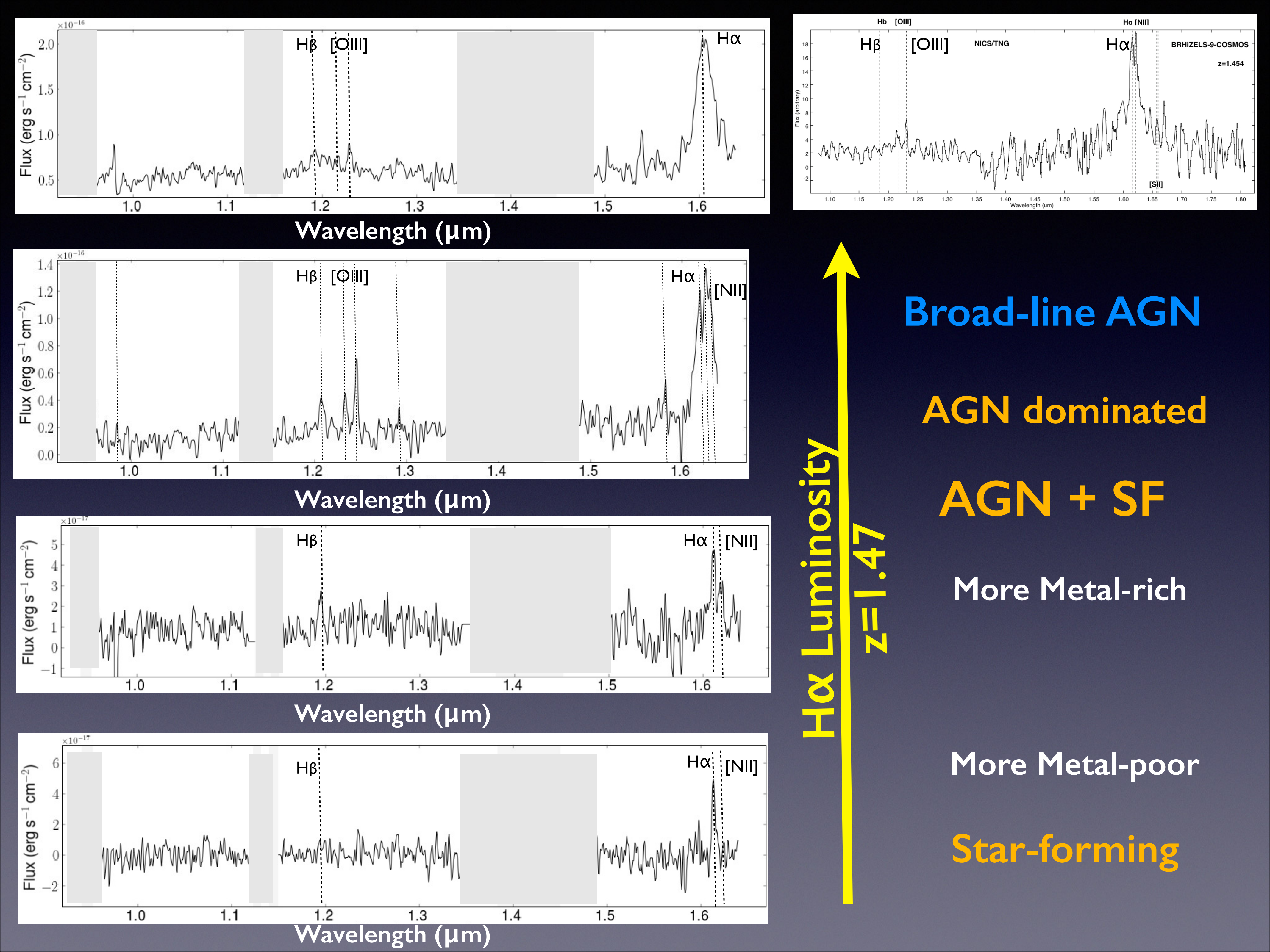
Subaru FMOS + NTT + WHT





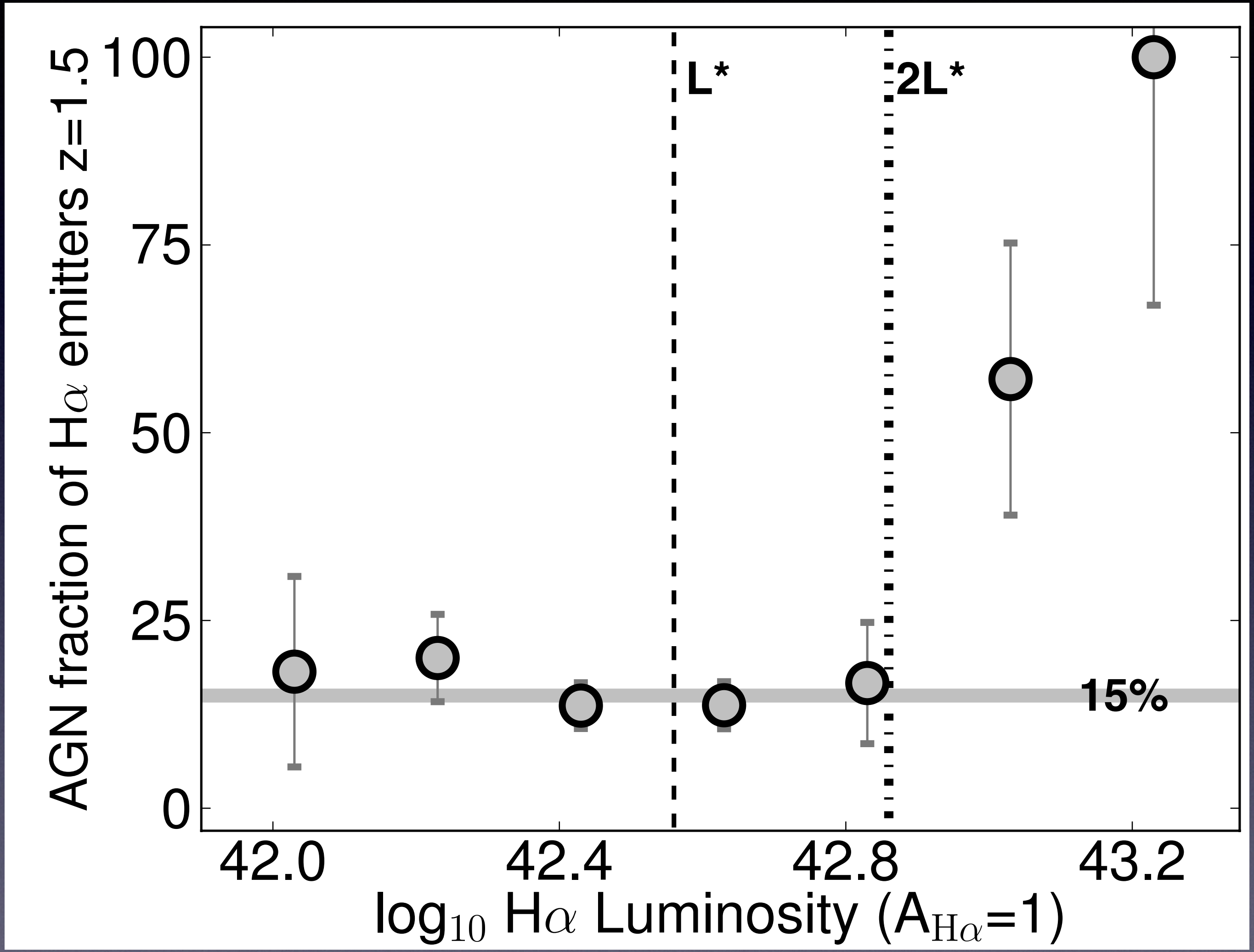






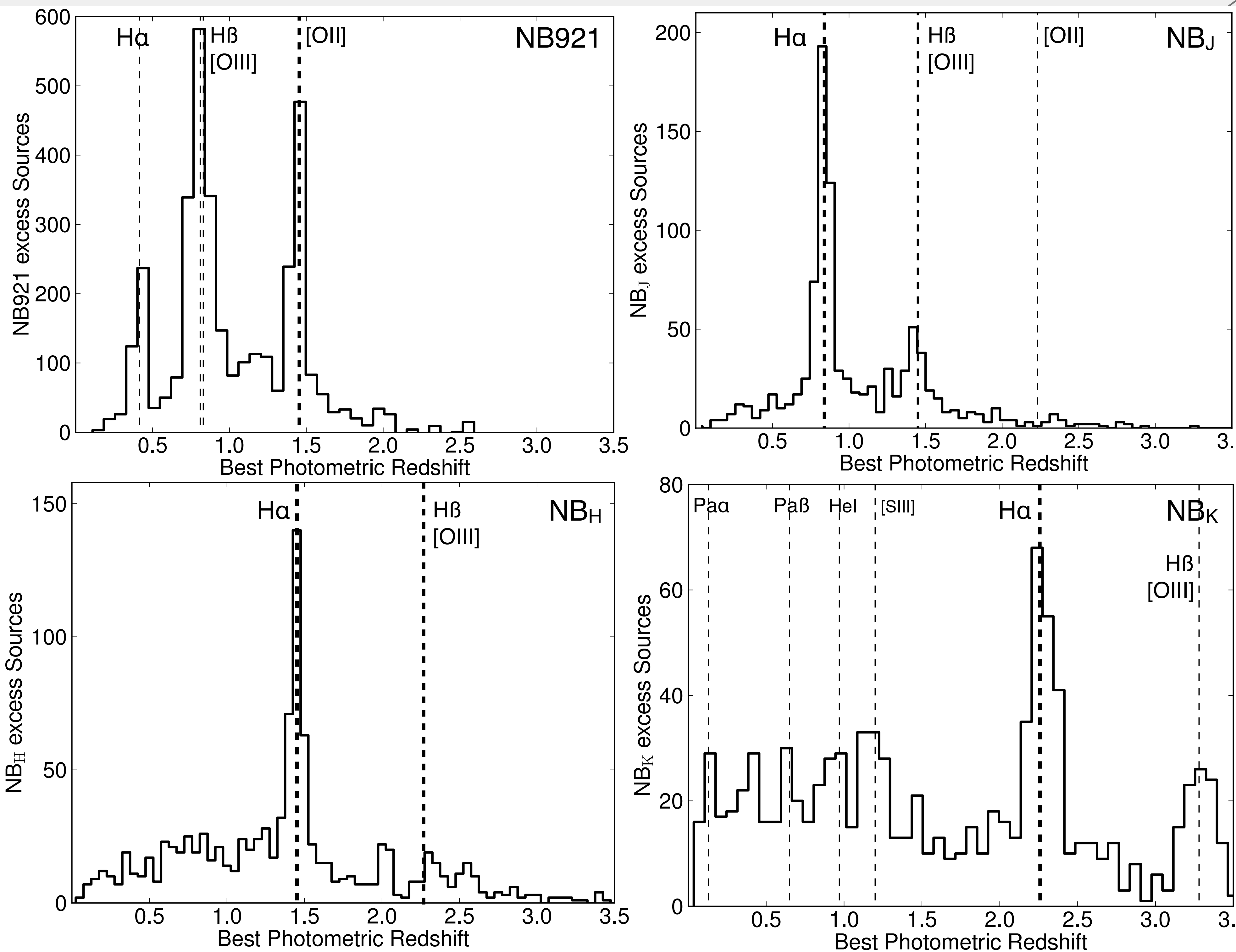
Hβ
[OIII]
Hα
Flux (erg s−1 cm−2)
Wavelength (μm)
Hβ
[OIII]
Hα
[NII]
Flux (erg s−1 cm−2)
Wavelength (μm)
Hβ
Hα
[NII]
Flux (erg s−1 cm−2)
Wavelength (μm)
Hβ
Hα
[NII]
Flux (erg s−1 cm−2)
Wavelength (μm)
Hβ
[OIII]
NICS/TNG
Hα
BRHiZELS-9-COSMOS
z=1.454
[SII]
Hα Luminosity
z=1.47
Broad-line AGN
AGN dominated
AGN + SF
More Metal-rich
More Metal-poor
Star-forming

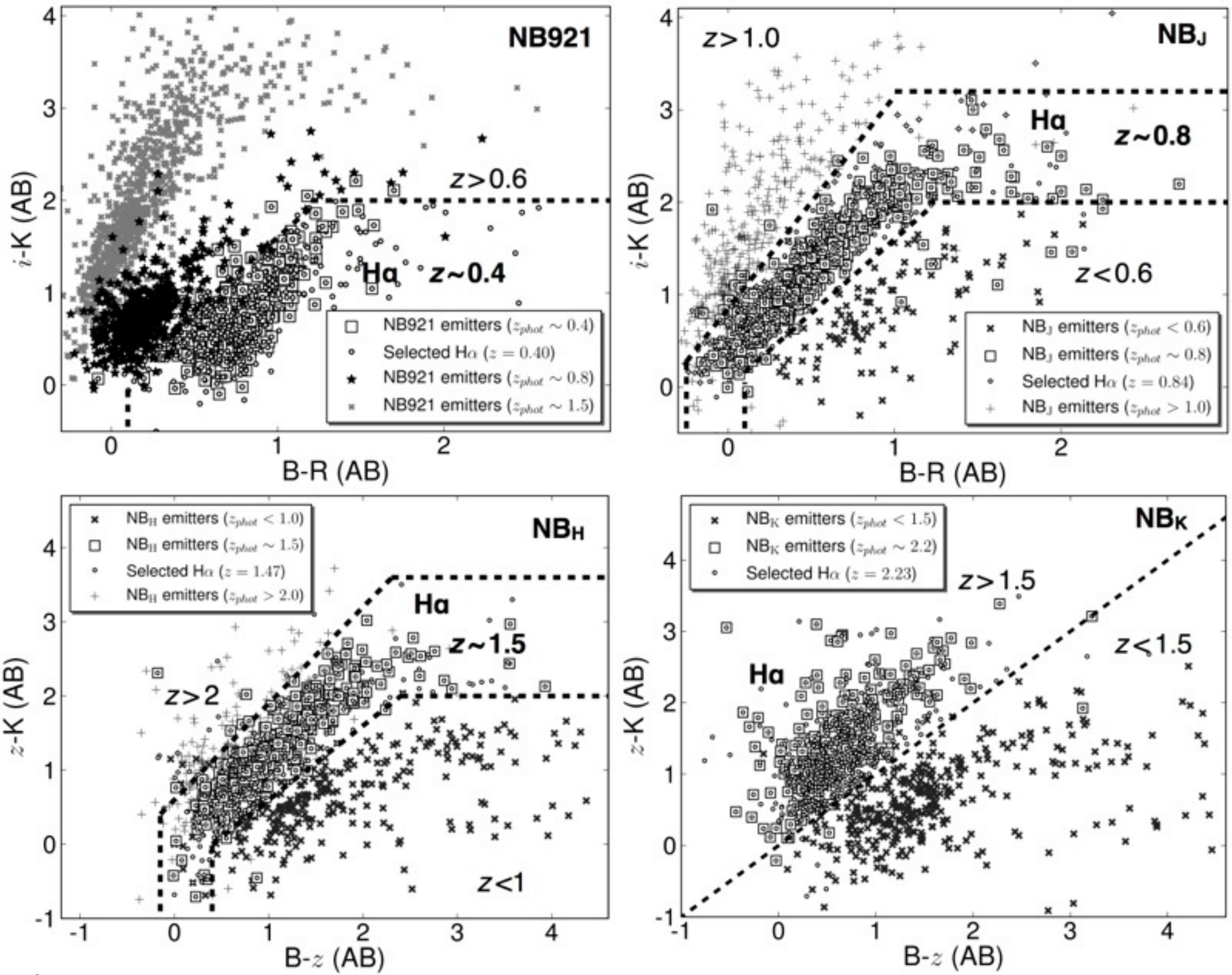
AGN



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

S+ in prep


NB921
Hα
Hβ
[OIII]
[OII]
NB921 excess Sources
Best Photometric Redshift
NBJ
NBJ excess Sources
NBH
NBH excess Sources
NBK
Paα
Paβ
HeI
[SIII]
NBK excess Sources

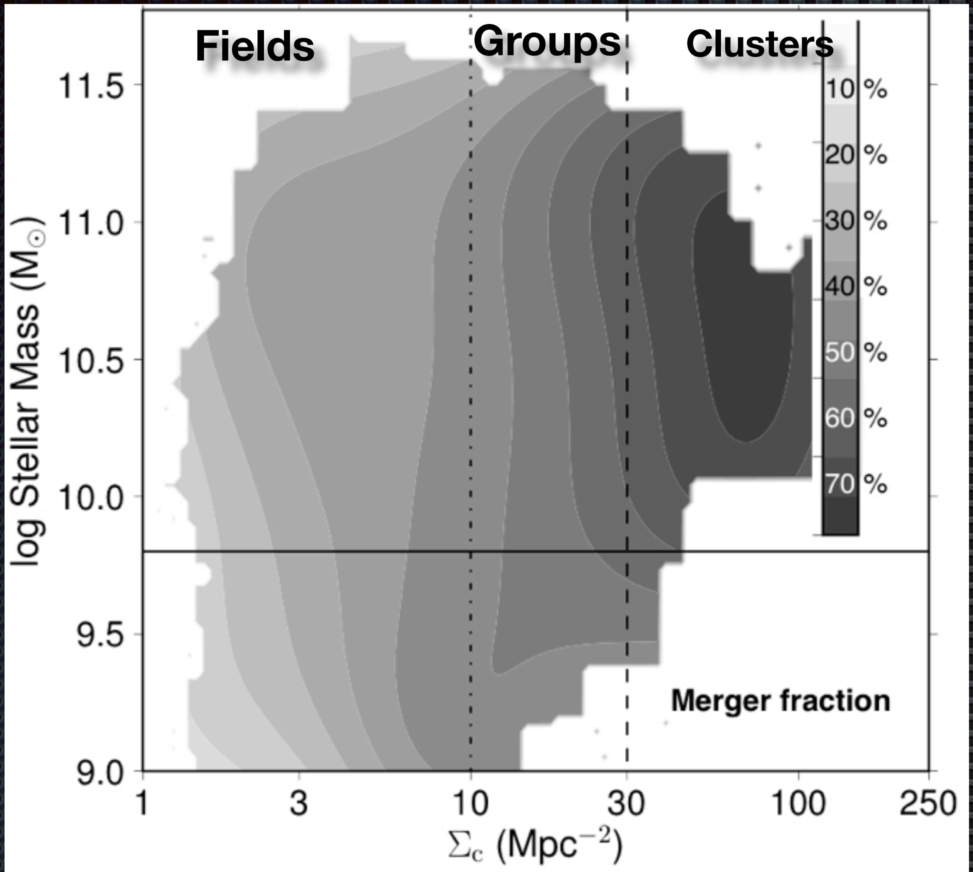


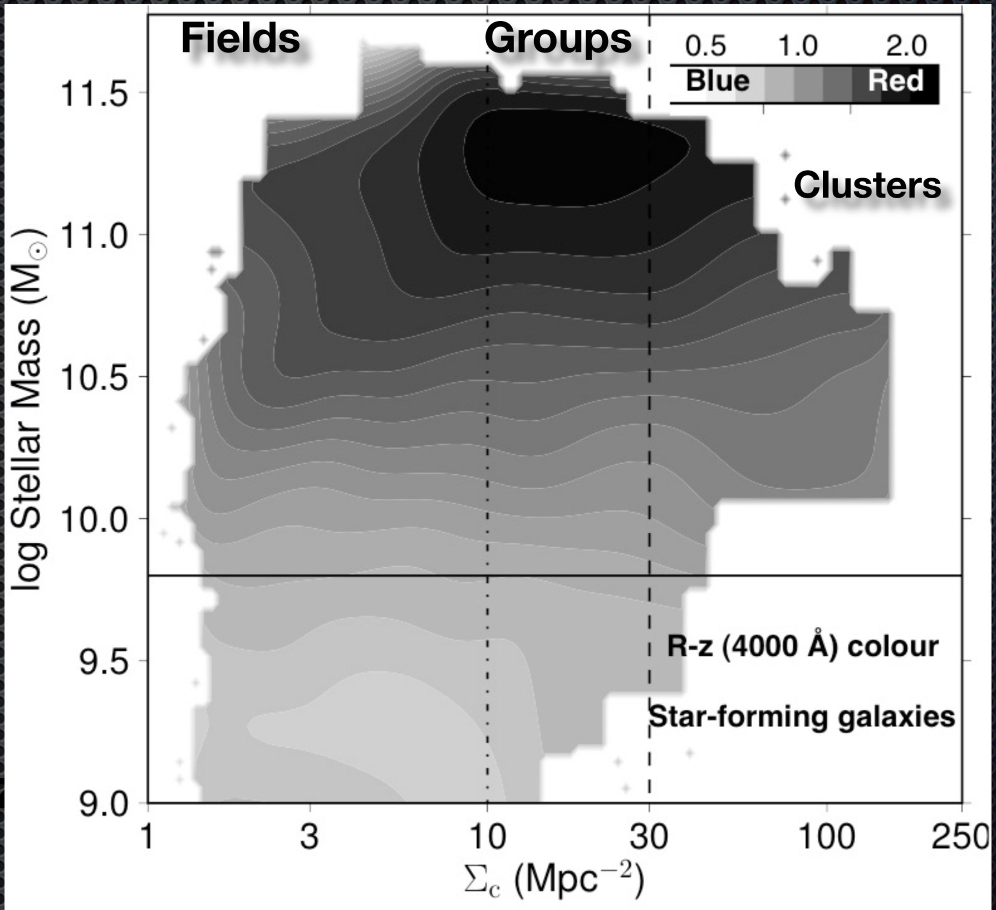
NB921
z>0.6
Hα
z~0.4
i-K (AB)
B-R (AB)
NB921 emitters ($z_{phot} \sim 0.4$)
Selected Hα ($z = 0.40$)
NB921 emitters ($z_{phot} \sim 0.8$)
NB921 emitters ($z_{phot} \sim 1.5$)
NB_J
z>1.0
Hα
z~0.8
z<0.6
i-K (AB)
B-R (AB)
NB_J emitters ($z_{phot} < 0.6$)
NB_J emitters ($z_{phot} \sim 0.8$)
Selected Hα ($z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

Mass and/or environment?

at z~1

Sobral et al. 2011

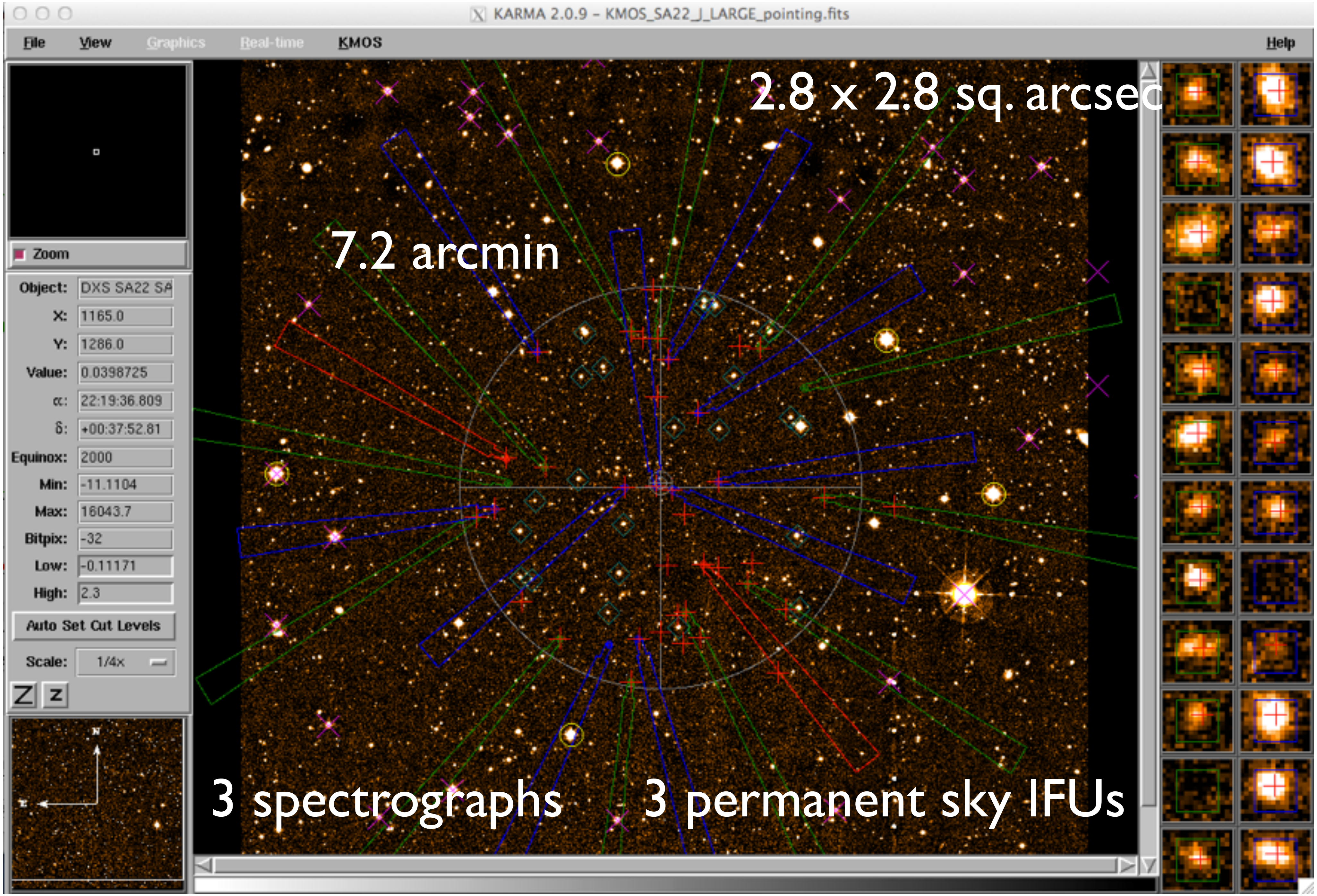


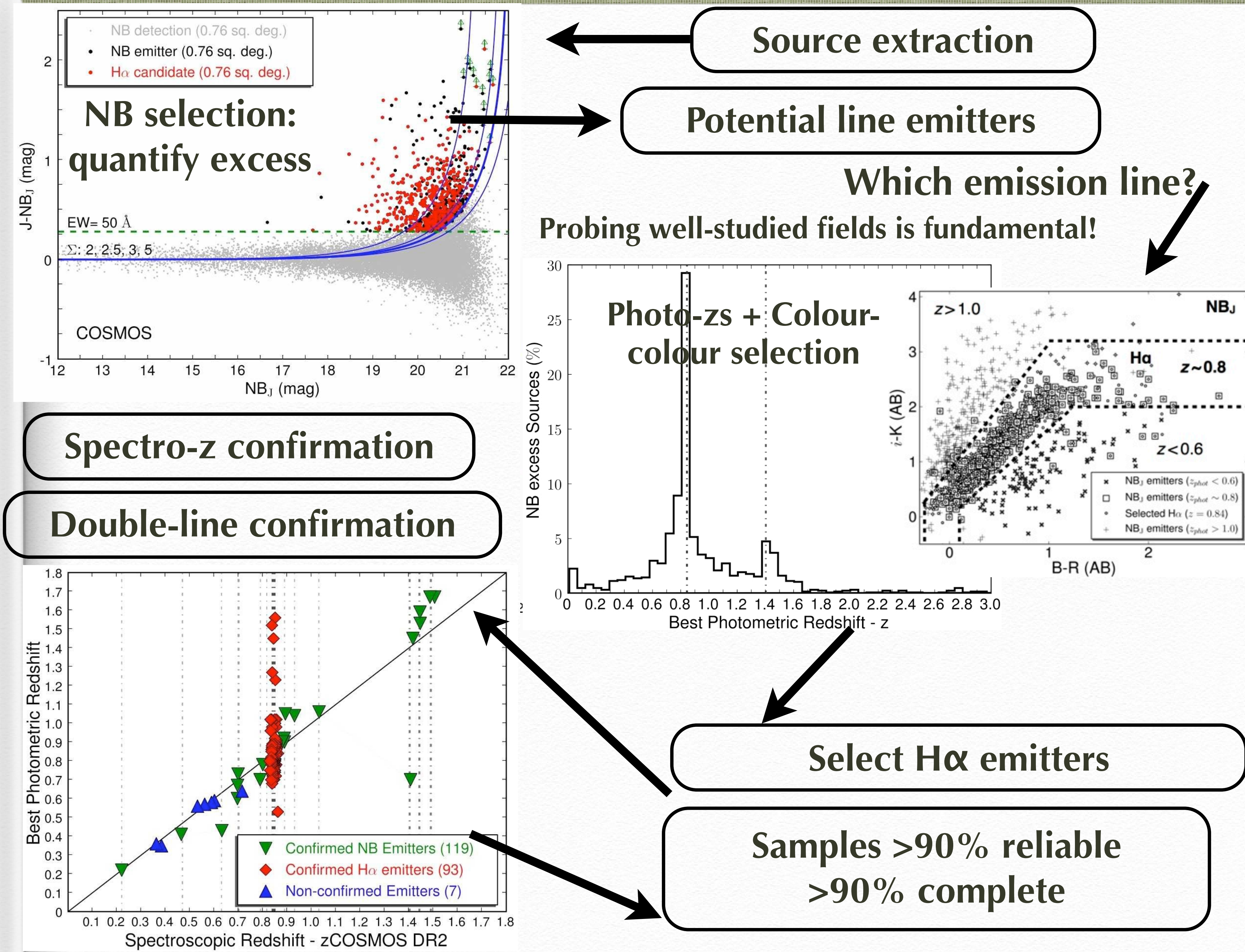


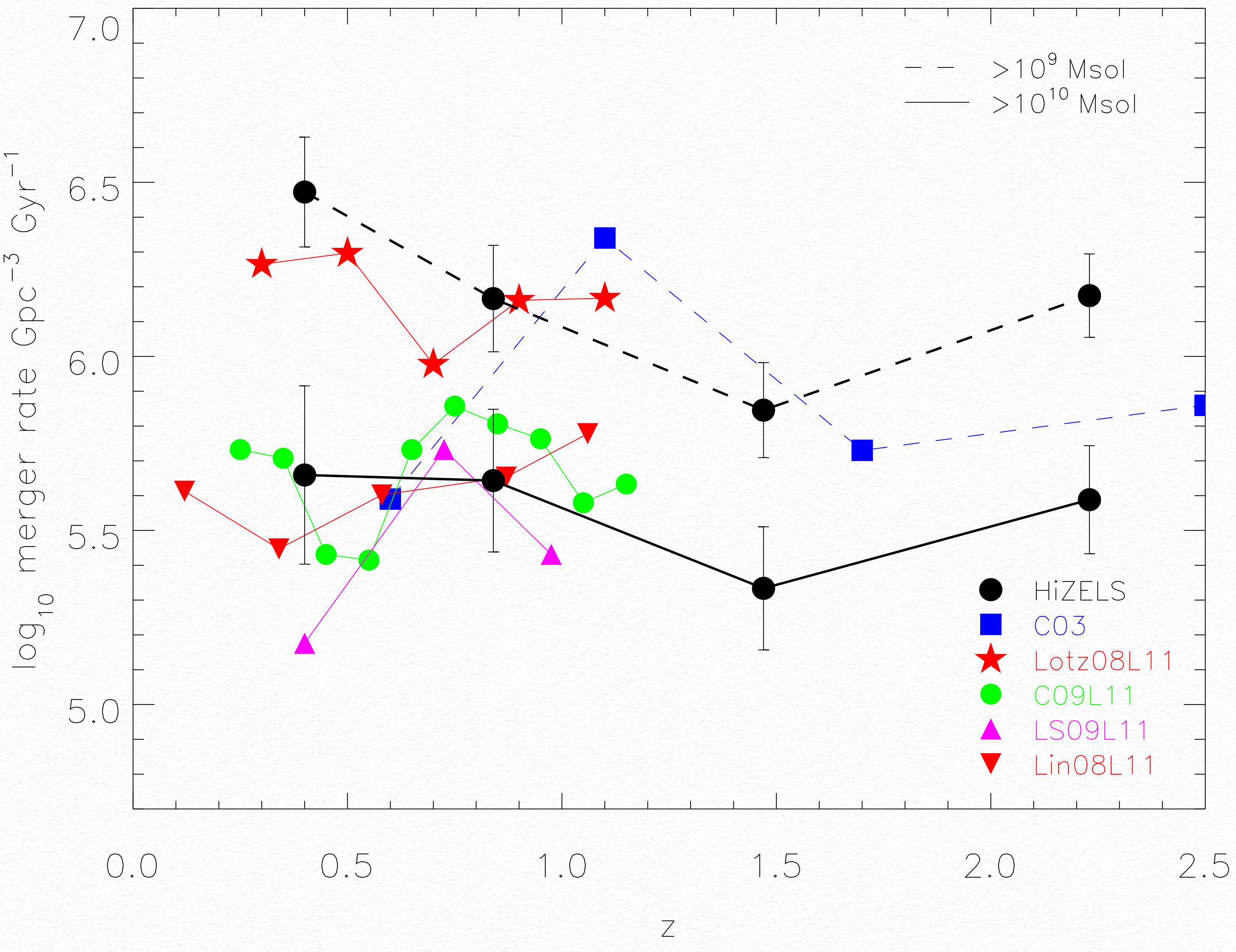
Merger fraction of star-forming galaxies depends mostly on environment, not mass

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

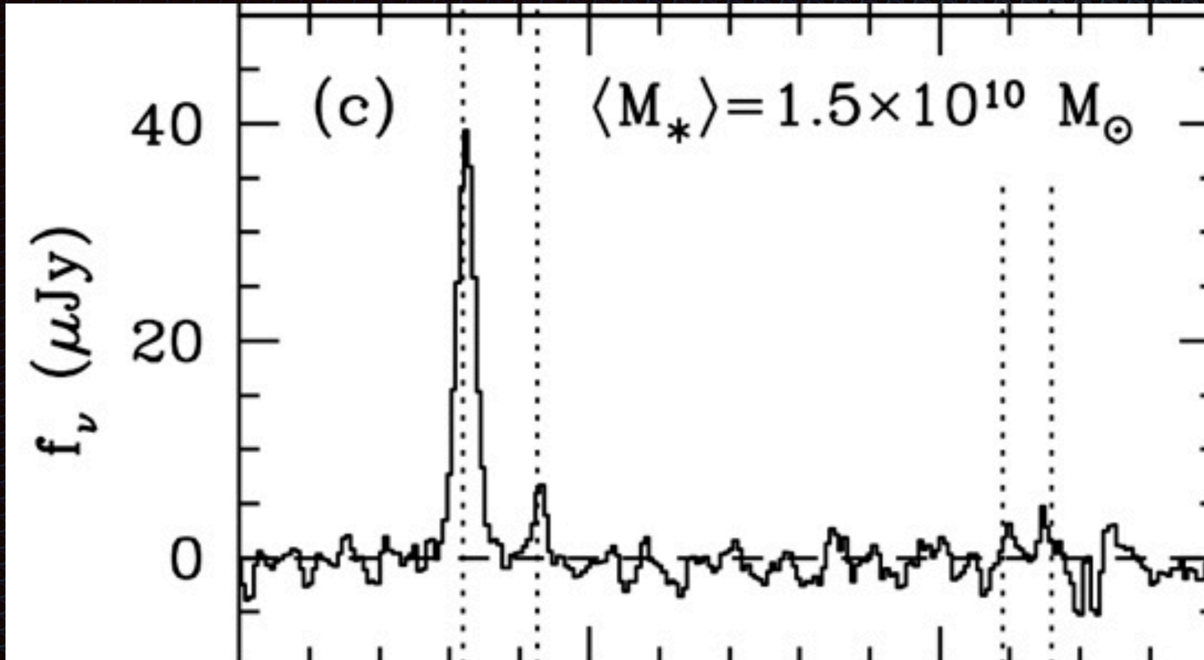
Preparing the OBs for KMOS: KARMA

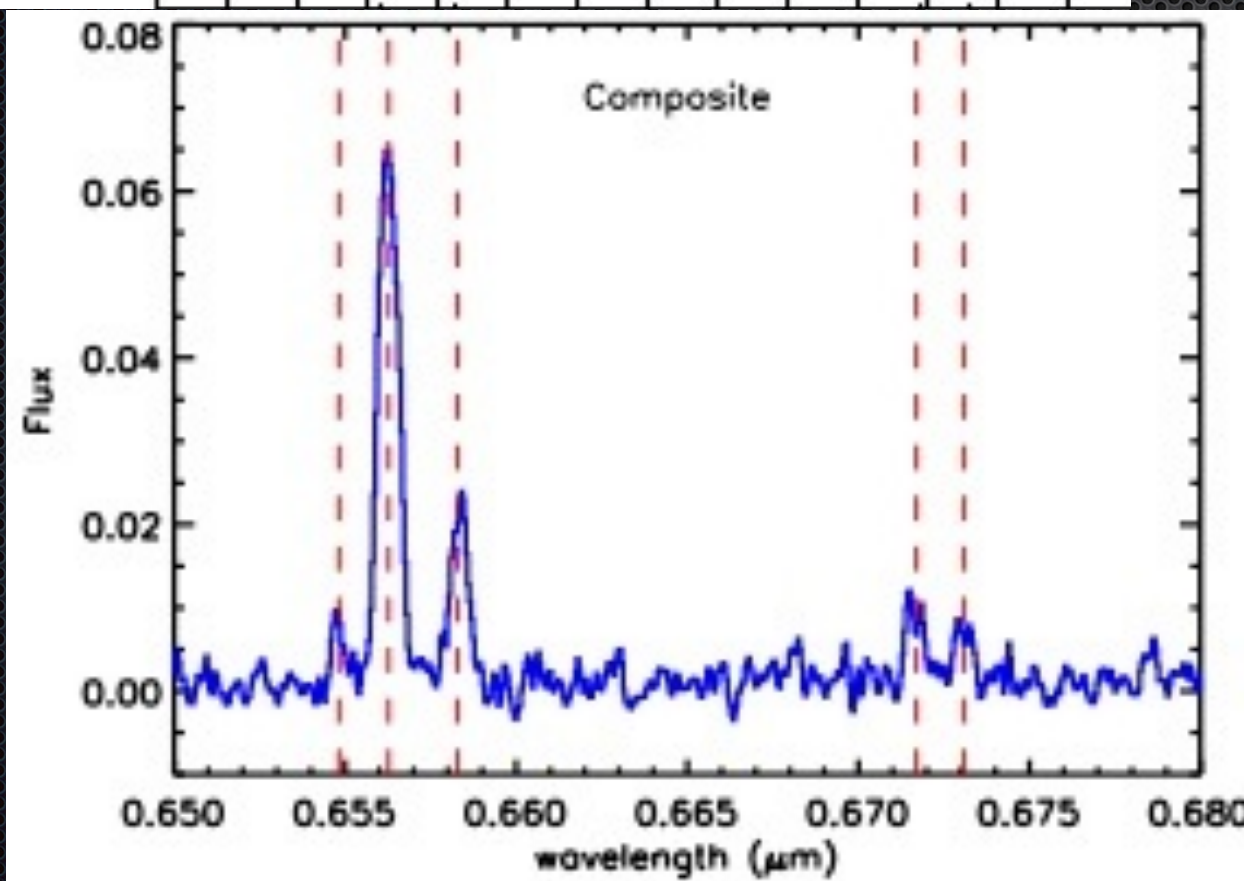



Source extraction
Potential line emitters
NB selection:
quantify excess
Which emission line?
Probing well-studied fields is fundamental!
Photo-zs + Colour-colour selection
Spectro-z confirmation
Double-line confirmation
Select Hα emitters
Samples >90% reliable
>90% complete
NB detection (0.76 sq. deg.)
NB emitter (0.76 sq. deg.)
Hα candidate (0.76 sq. deg.)
EW= 50 Å
Σ: 2, 2.5, 3, 5
COSMOS
J-NB_J (mag)
NB_J (mag)
NB excess Sources (%)
Best Photometric Redshift - z
z>1.0
NB_J
Hα
z~0.8
z<0.6
i-K (AB)
B-R (AB)
NB_J emitters (z_phot < 0.6)
NB_J emitters (z_phot ~ 0.8)
Selected Hα (z = 0.84)
NB_J emitters (z_phot > 1.0)
Best Photometric Redshift
Spectroscopic Redshift - zCOSMOS DR2
Confirmed NB Emitters (119)
Confirmed Hα emitters (93)
Non-confirmed Emitters (7)



7.0
6.5
6.0
5.5
5.0
$\log_{10}$ merger rate Gpc^{-3} Gyr^{-1}
0.0
0.5
1.0
1.5
2.0
2.5
z
$>10^9$ Msol
$>10^{10}$ Msol
HiZELS
C03
Lotz08L11
C09L11
LS09L11
Lin08L11





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

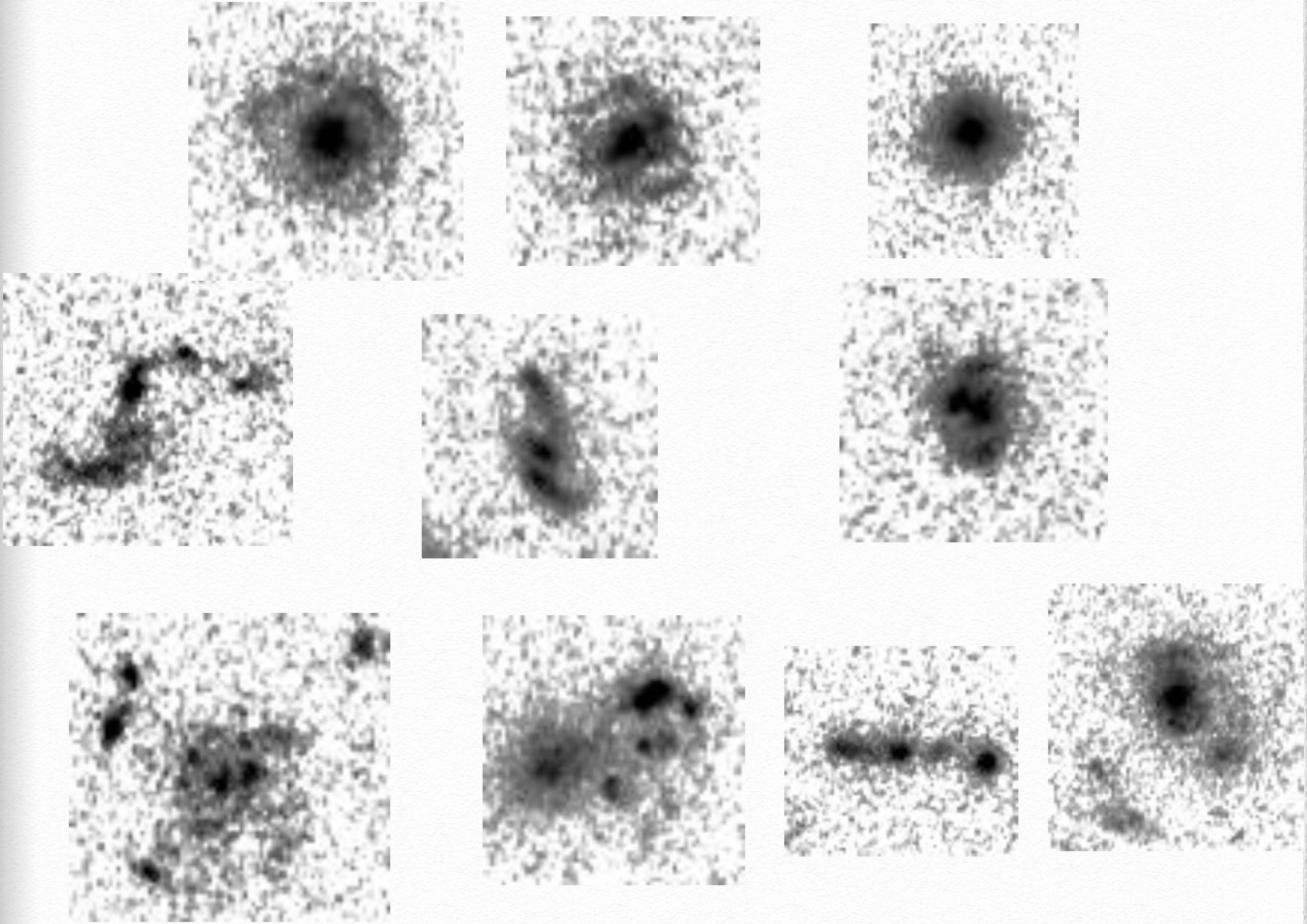
Group galaxies more massive & slightly lower sSFRs + higher Metallicity, but the same TF and mass-metallicity relations

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

Lisbon's Observatory

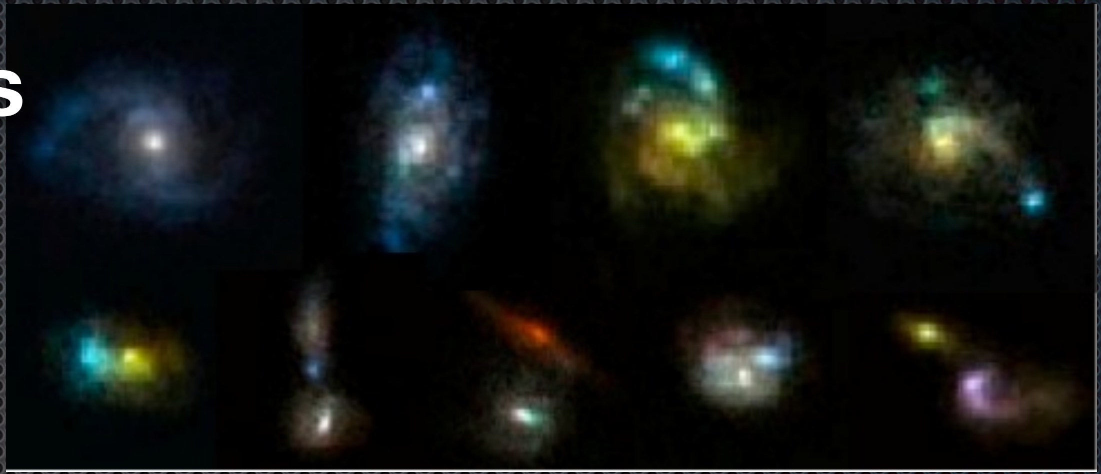
Come visit!

Institute of Astrophysics and Space Sciences



Morphologies: ACS+CANDELS

Hα Star-forming galaxies since z=2.23



Disk-like/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.

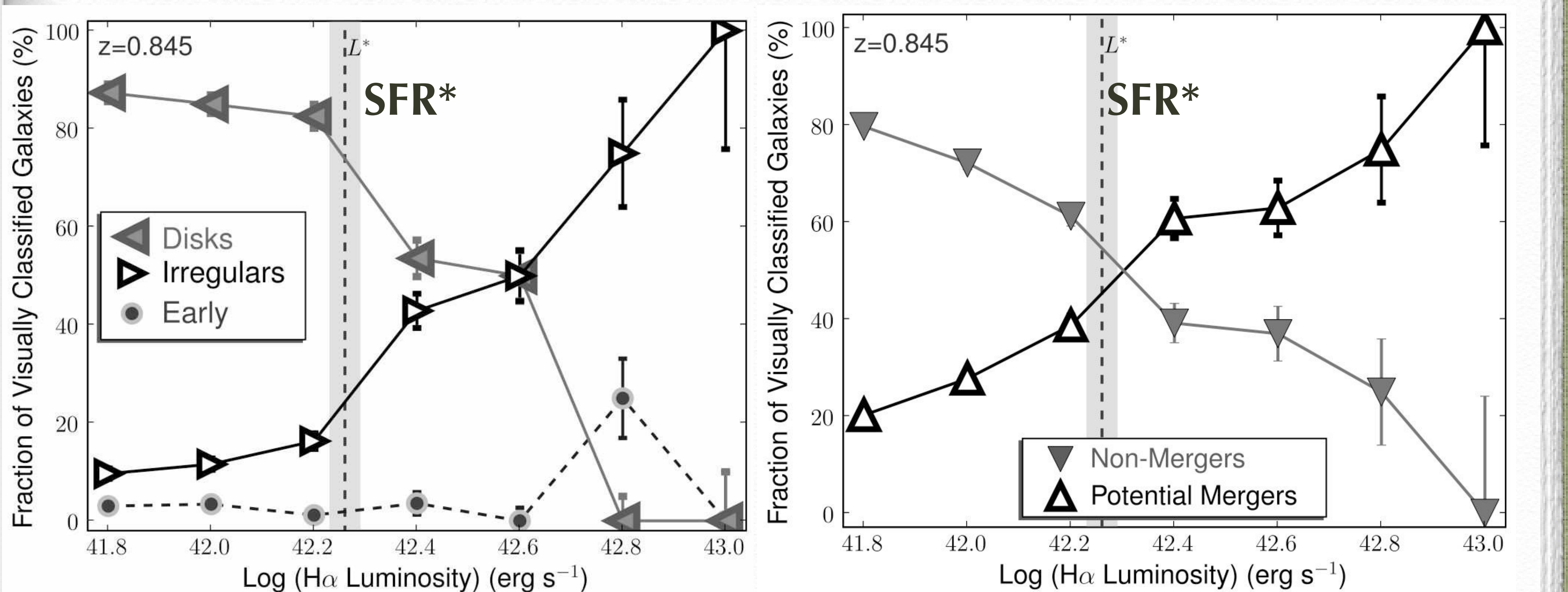
z	a	b	r_e at $\log_{10}(M_\star) = 10$ (kpc)
0.40	0.08±0.02	0.55±0.03	3.6±0.2
0.84	0.03±0.02	0.54±0.01	3.5±0.1
1.47	0.03±0.02	0.59±0.01	3.9±0.2
2.23	0.08±0.03	0.51±0.02	3.3±0.2

Sobral+09a, Stott+13a

Morphology-SFR relation

at z~1

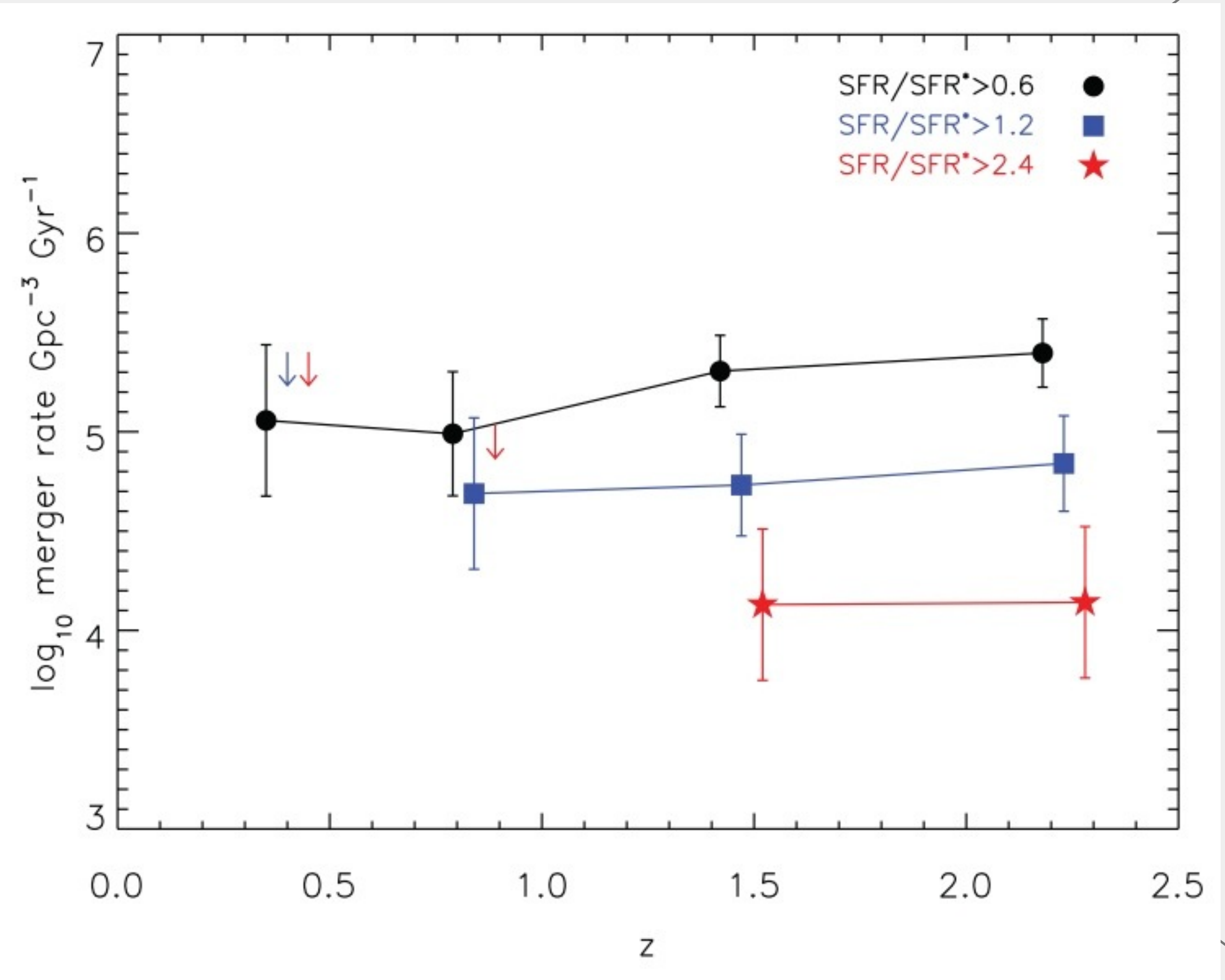
Sobral et al. 2009a



- **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)