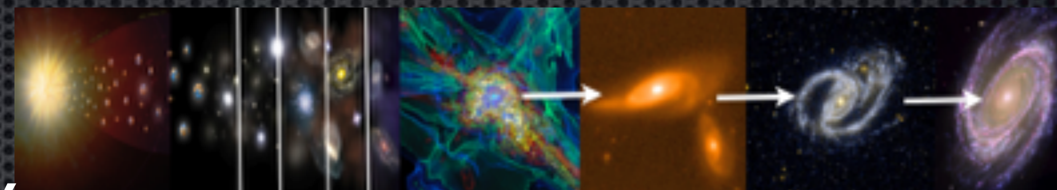
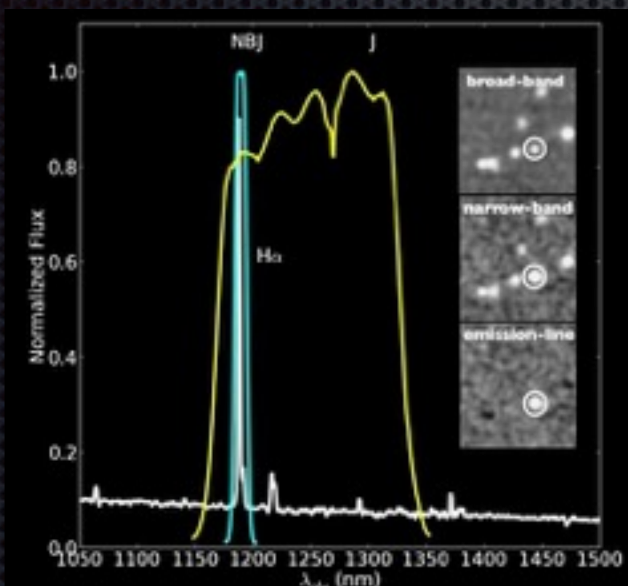
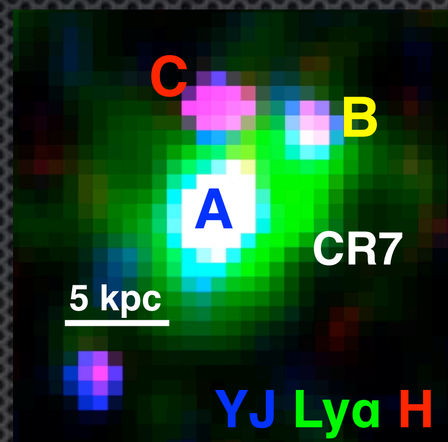
The nature and evolution of star-forming galaxies: 11 Gyrs with a single, homogeneous selection

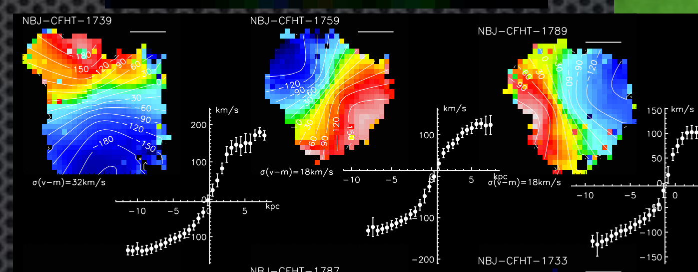


David Sobral

IA-U. Lisbon/Leiden Observatory

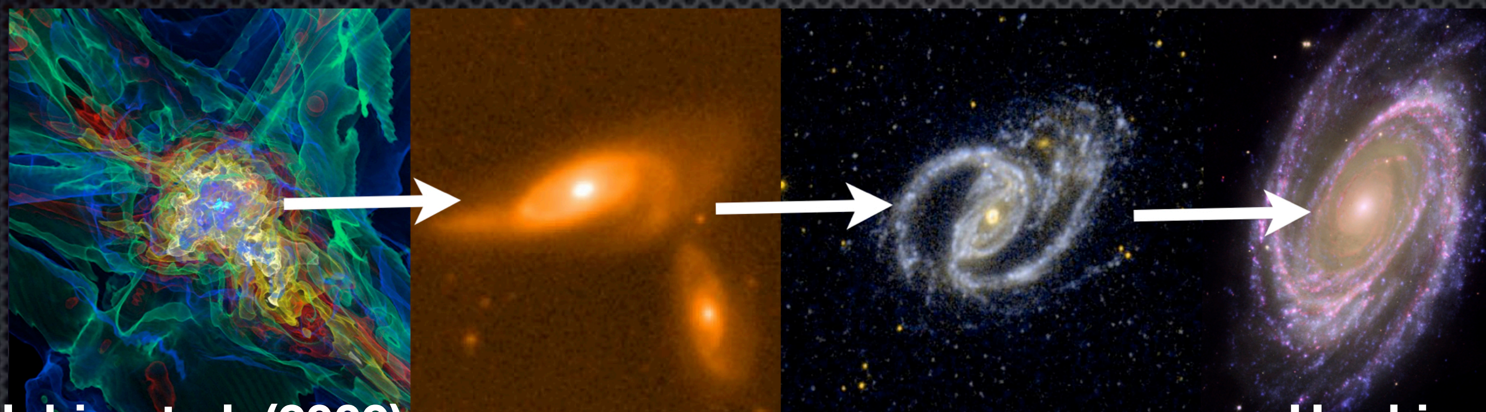




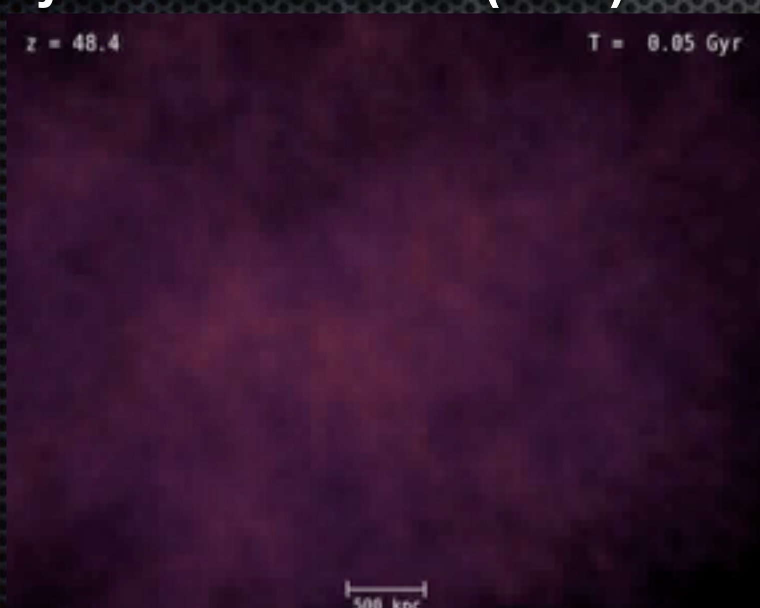


Jorryt Matthee, Ian Smail, Philip Best, Mark Swinbank, John Stott, Ali Khostovan, Iván Oteo, Edo Ibar, Y. Koyama, Behnam Darvish, Bahram Mobasher, Andra Stroe, Sérgio Santos

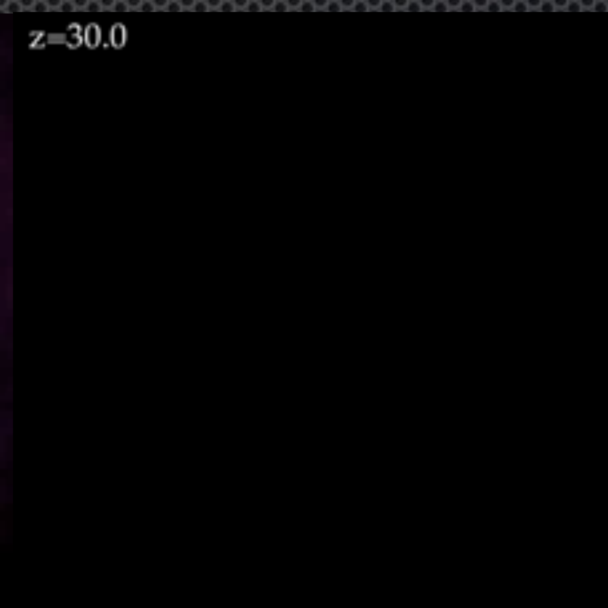
How (and driven by which mechanisms) do galaxies form and evolve?



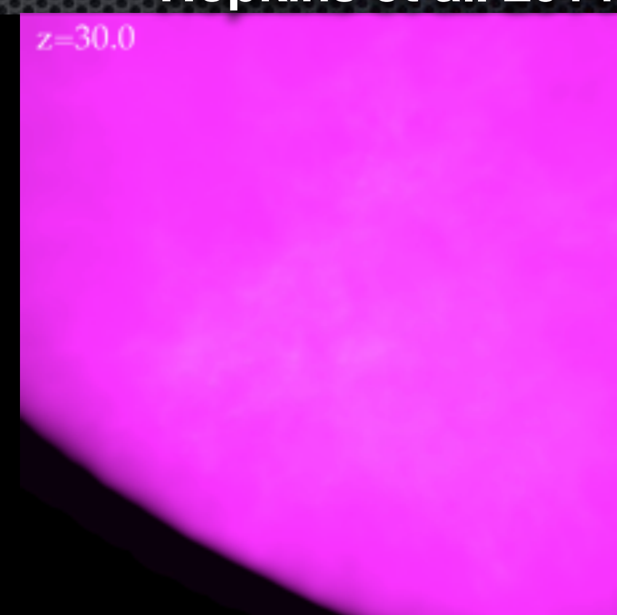
Boylan-Kolchin et al. (2009) Hopkins et al. 2014



Dark Matter (large scale)

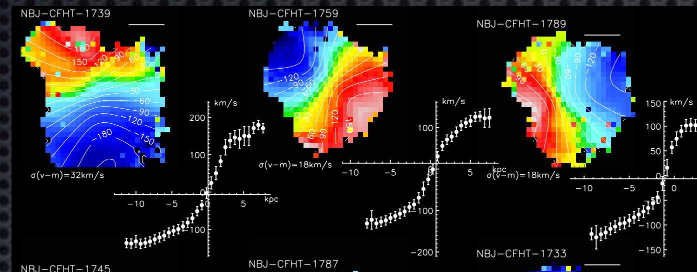


Stars (visible light)



Gas (hot and cold)

Many ways to use the "golden era" telescopes/instrumentation



Sobral+13b: first KMOS Science results

- 1) Take whatever is there (very complicated/biased selection)
- 2) Pick a certain selection that is easy/simple/robust but can't be replicated across cosmic time
- 3) Simple, well-understood selection that can be replicated across cosmic time

Understanding (and minimising/eliminating!) selection biases/ limitations is extremely important

Many ways to use the "golden era" telescopes/instrumentation

- Lots of amazing "follow-up" machines: but we need <u>groundbreaking, large-area, sensitive survey machines</u>

- No point in having S/N~zillion and getting "perfect" measurements if we are "selection-limited"! (Why would we want a perfect measurement of a biased sample?)

- We need to survey with the best possible selection(s) and apply them in the same way across cosmic times

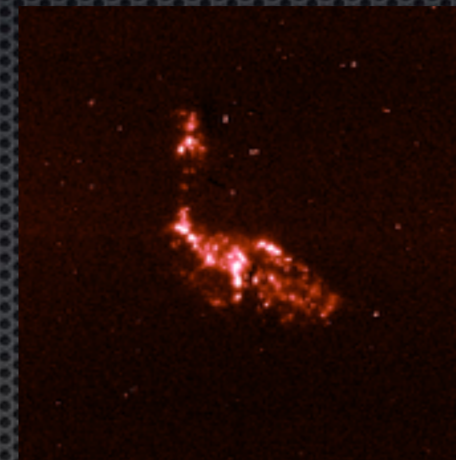
From the "golden era" of follow-up machines to the "Platinum era"

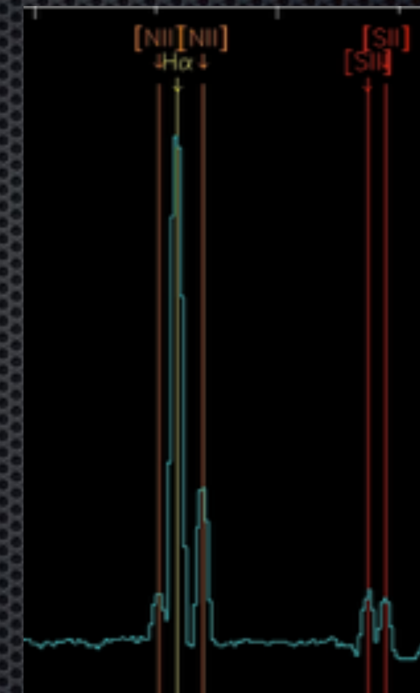
What we need:

- A **good, well-understood** selection that can be applied with current instrumentation
- Well calibrated + sensitive + resulting in a representative population of galaxies
- Able to **uniformly** select large samples
- **Different epochs** + **Large areas + Best-studied fields**

Hα (+NB)

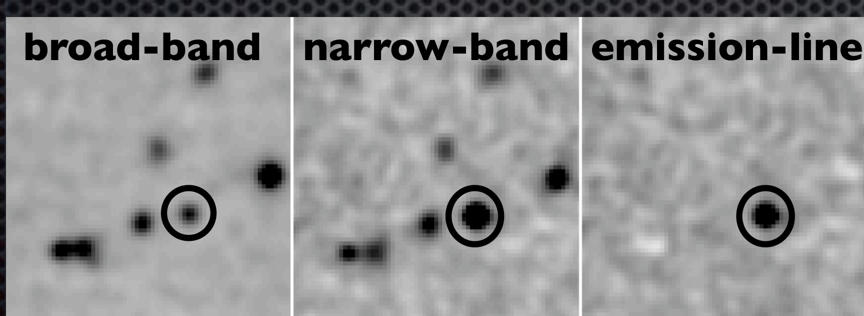
- **MW SFRs up to z~2.5!**

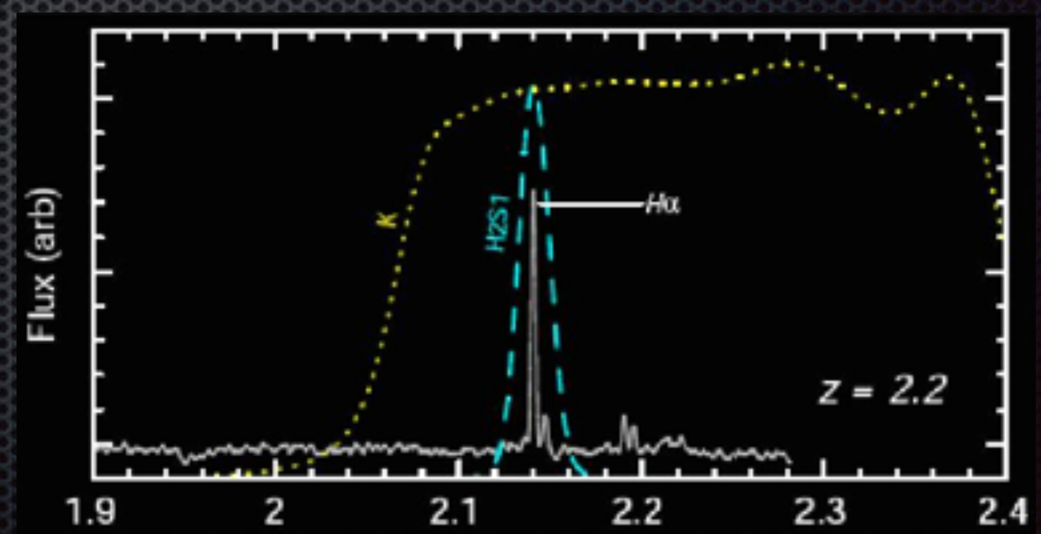




- Sensitive, good selection
- Well-calibrated
- Traditionally for Local Universe
- **Narrow-band technique**

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





Selection really matters

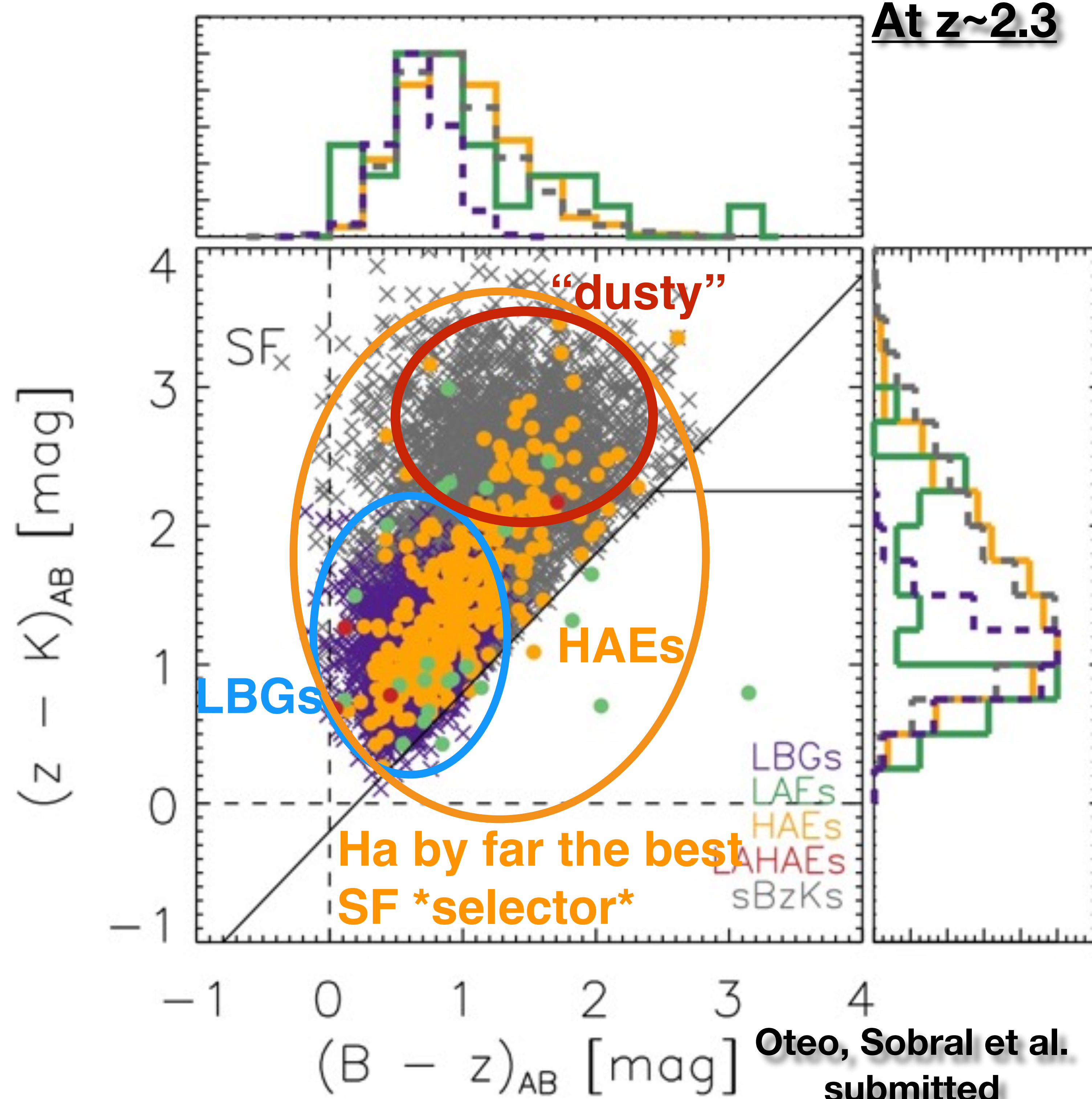
Lyman-break/UV selection: **misses ~65-70%** of star-forming galaxies! (metal-rich, dusty) (+ systematics)

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~2.3



Oteo, Sobral et al. submitted

Selection really matters

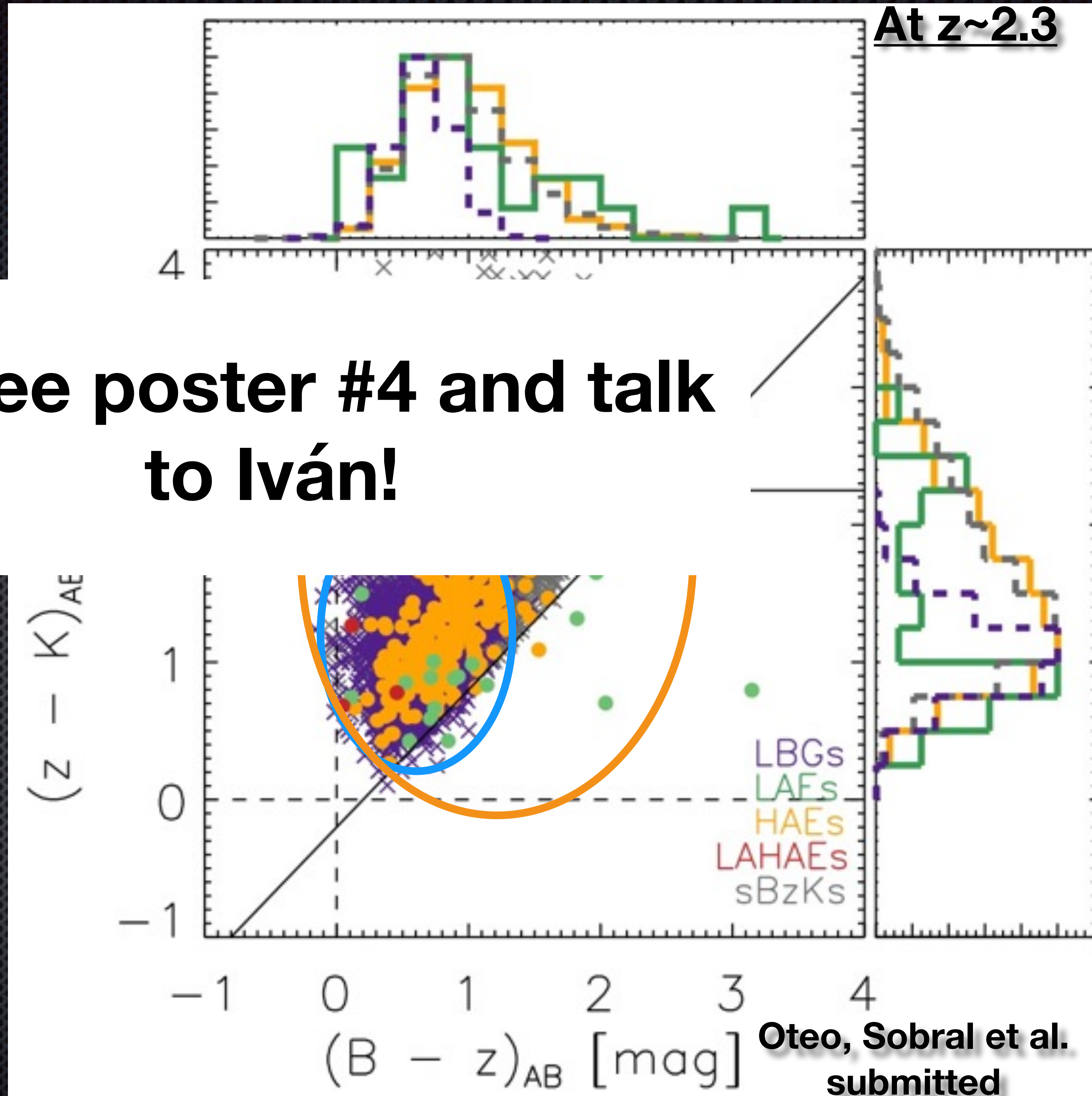
Lyman-break/UV selection: **misses** **~65-70%**
forming g
(metal-rich
(+ syster

LAEs: **miss** ~80% of star-forming galaxies

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

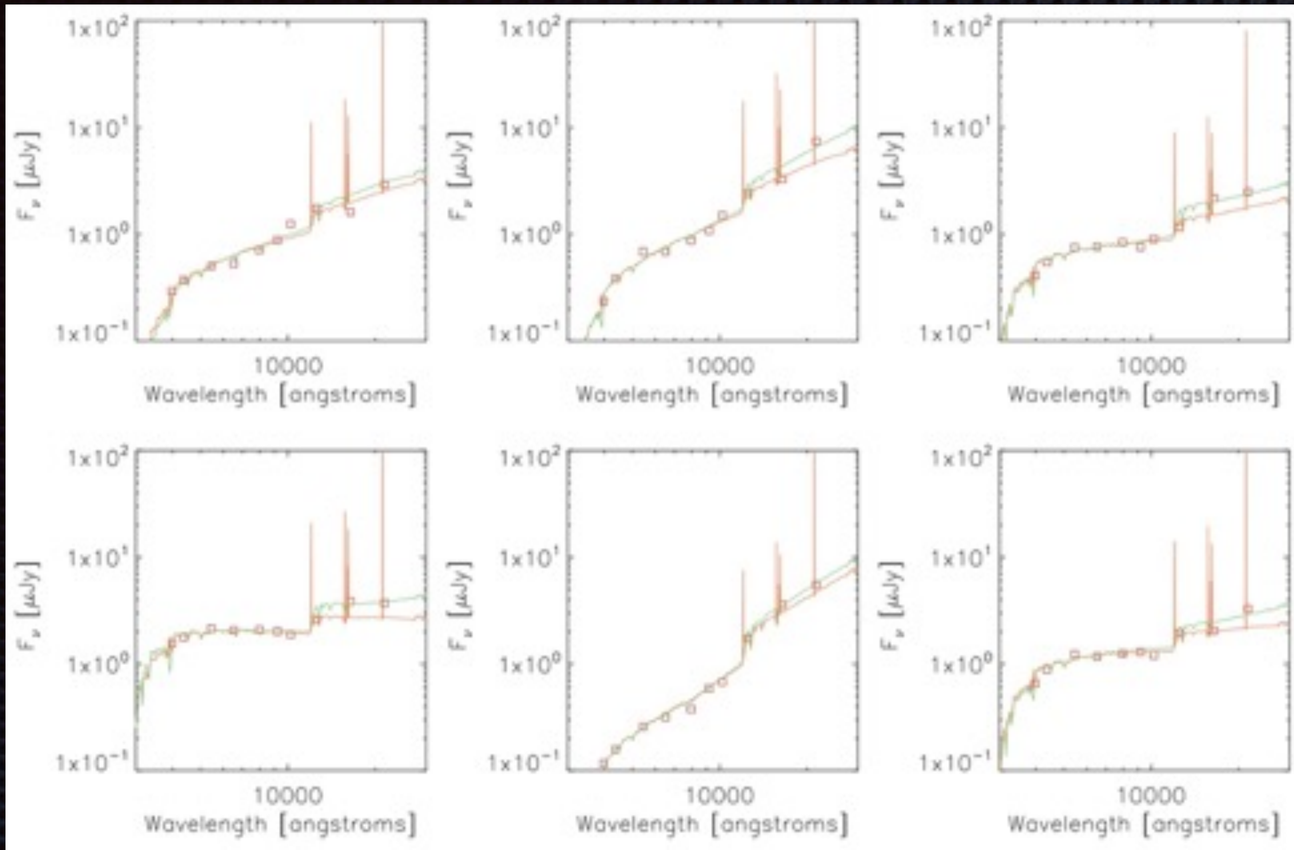
See also Hayashi et al. 2013 for [OII]

At z~2.3



Go see poster #4 and talk to Iván!

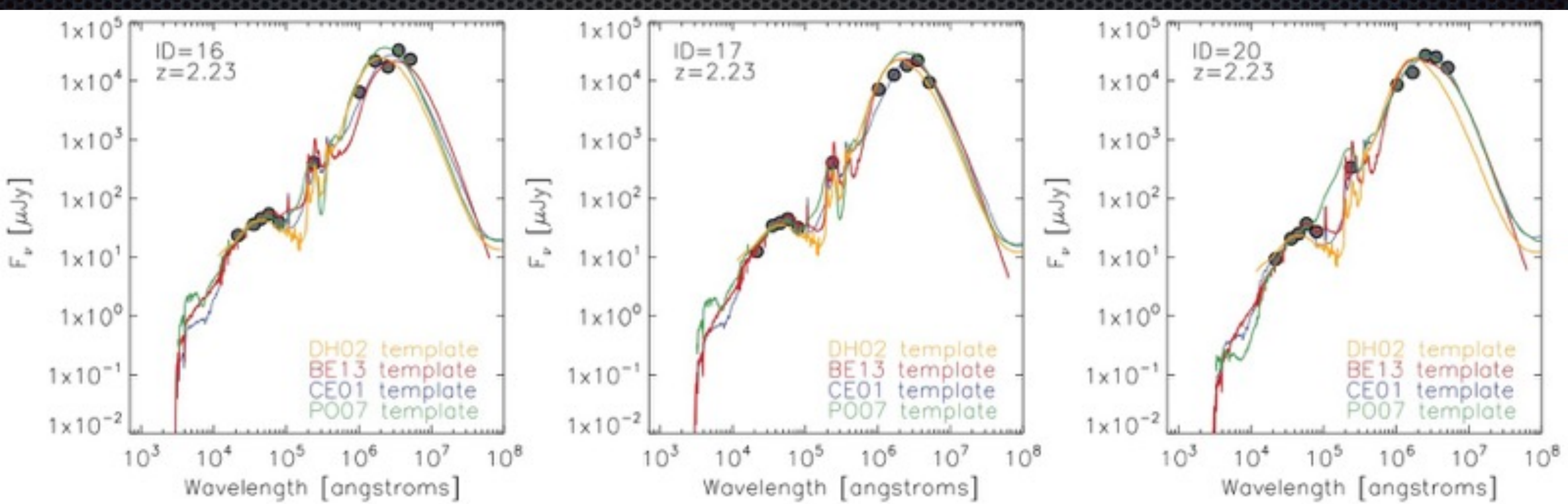
Oteo, Sobral et al. submitted



Selection really matters

Selecting **Star-forming galaxies**: Hα selected samples recover the wide range of Star-forming galaxies + Get robust SFRs

Oteo, Sobral et al. submitted

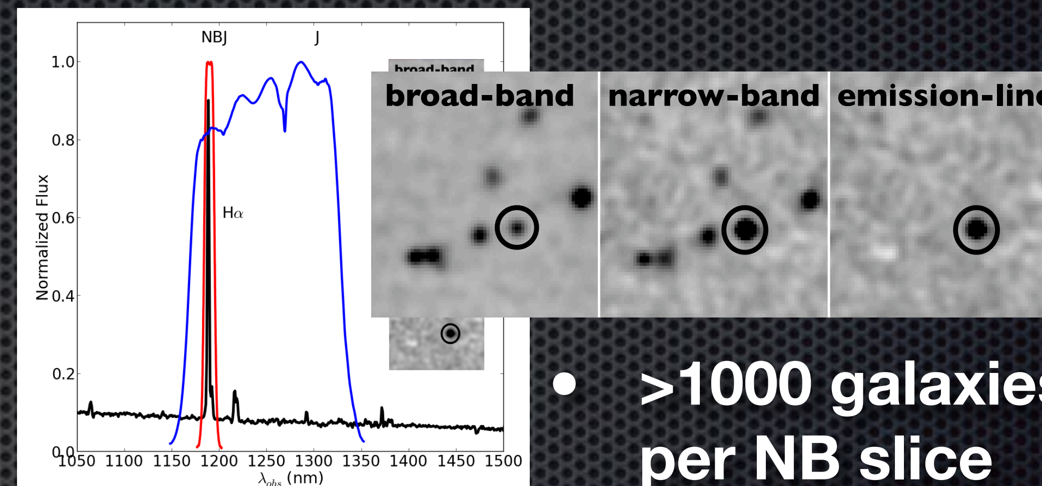


HiZELS

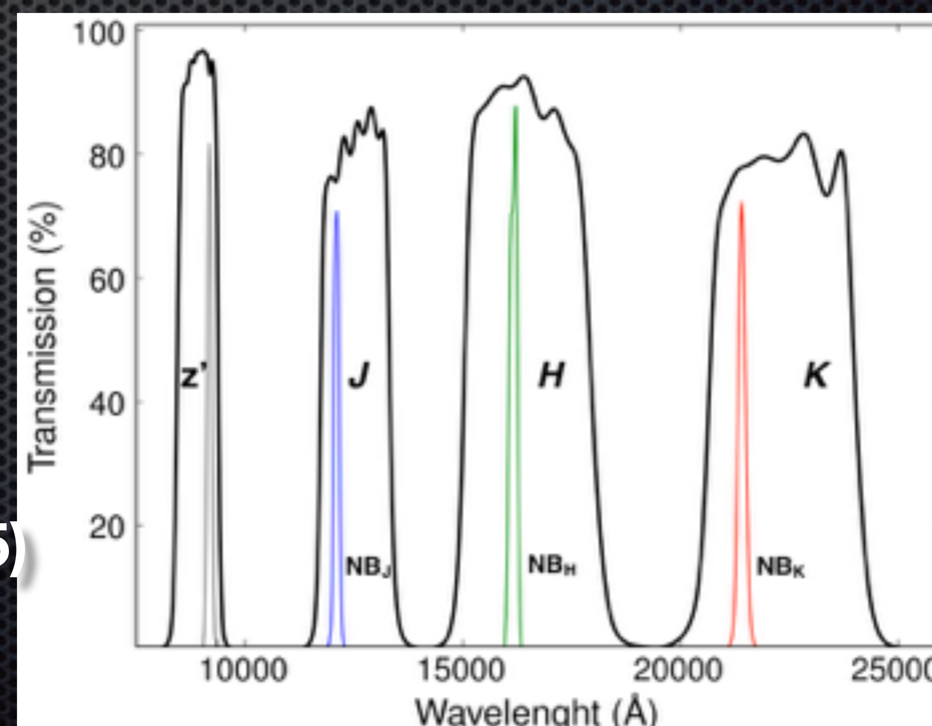
The High Redshift Emission Line Survey

(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**

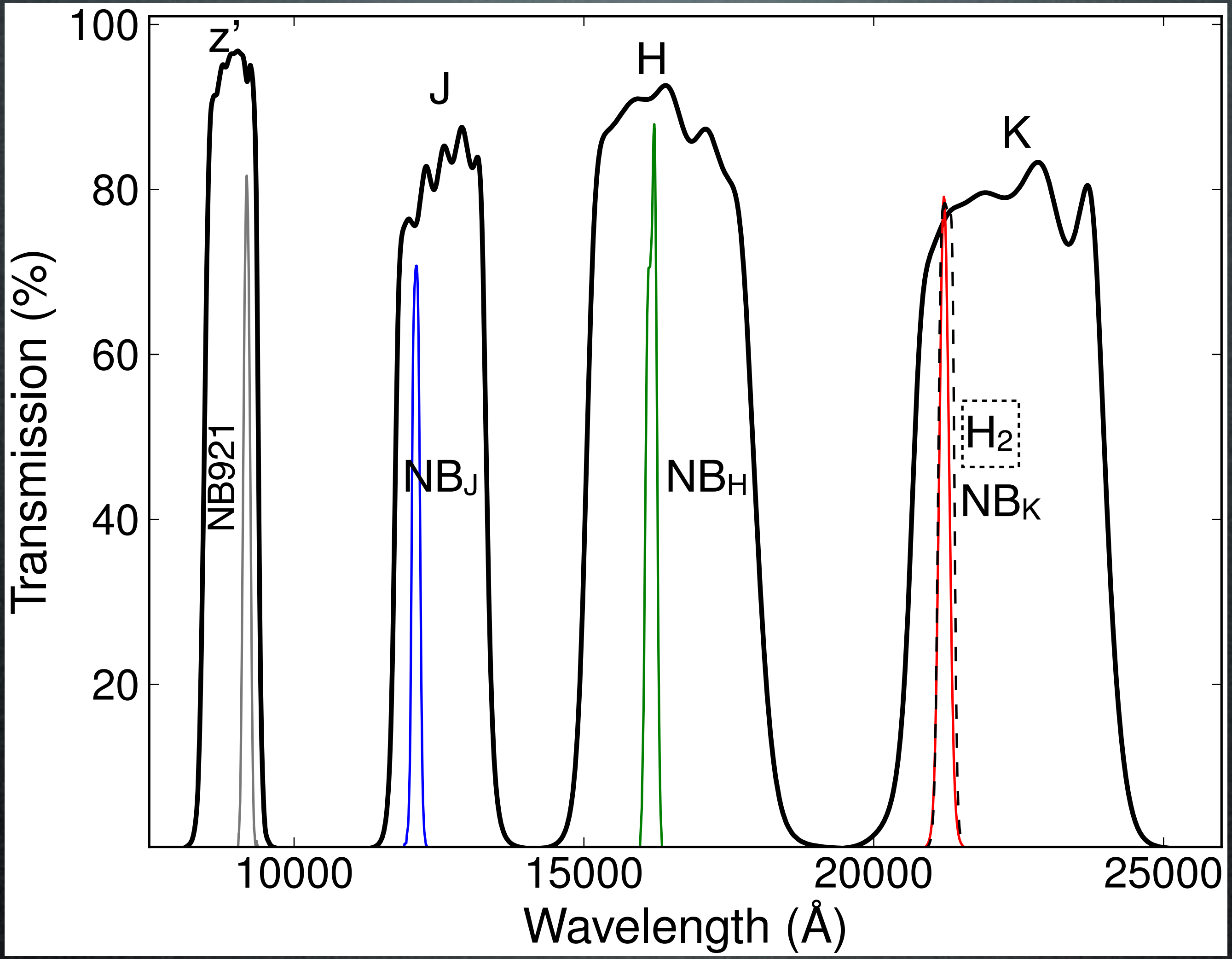


- **~80 Nights UKIRT+Subaru +VLT+CFHT+INT**
- **>1000 galaxies per NB slice**
- Narrow-band Filters target Hα at **z=(0.2), 0.4, 0.8, 0.84, 1.47, 2.23**
- **Same reduction+analysis**
- **Other lines (simultaneously; Sobral +09a,b,Sobral+12,13a,b, 14,15a,c;Matthee+14,Khostovan+15)**



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

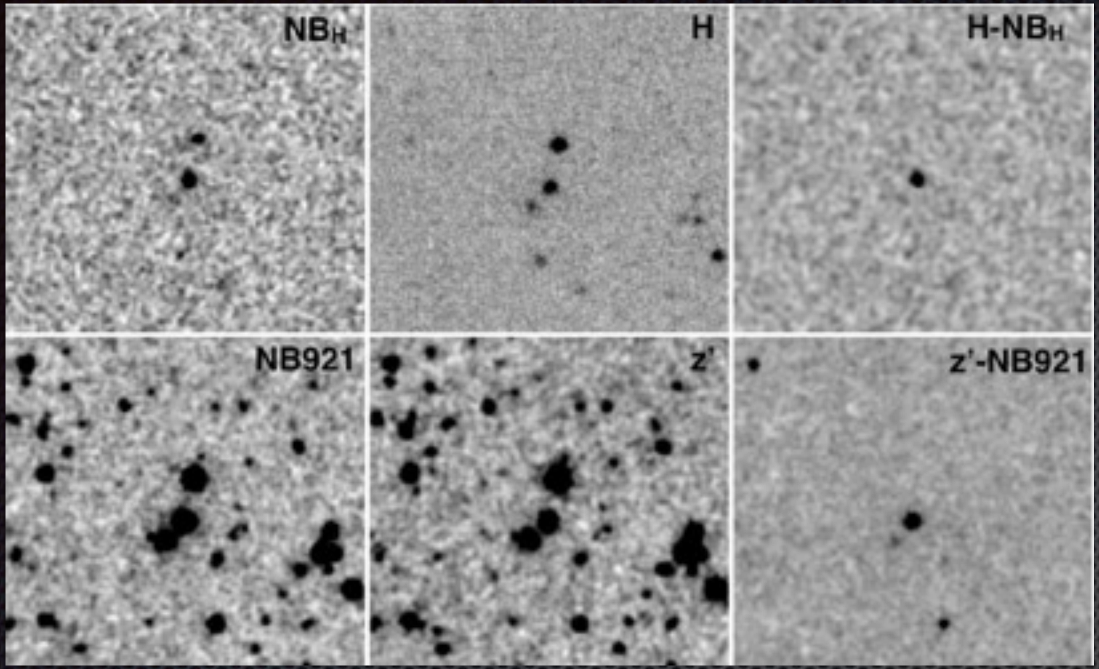
Filters combined to improve selection: double/triple line detections

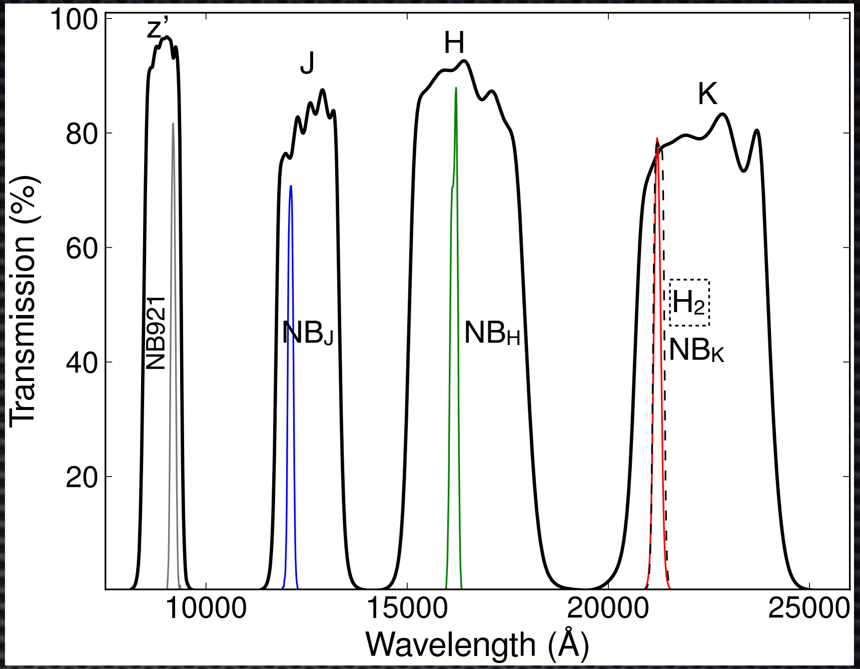


z=2.23 : Lyα (NBU) [OII] (NBJ), [OIII] (NBH), Hα (NBK)

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

z=0.84 : [OIII] (NB921), Hα (NBJ)



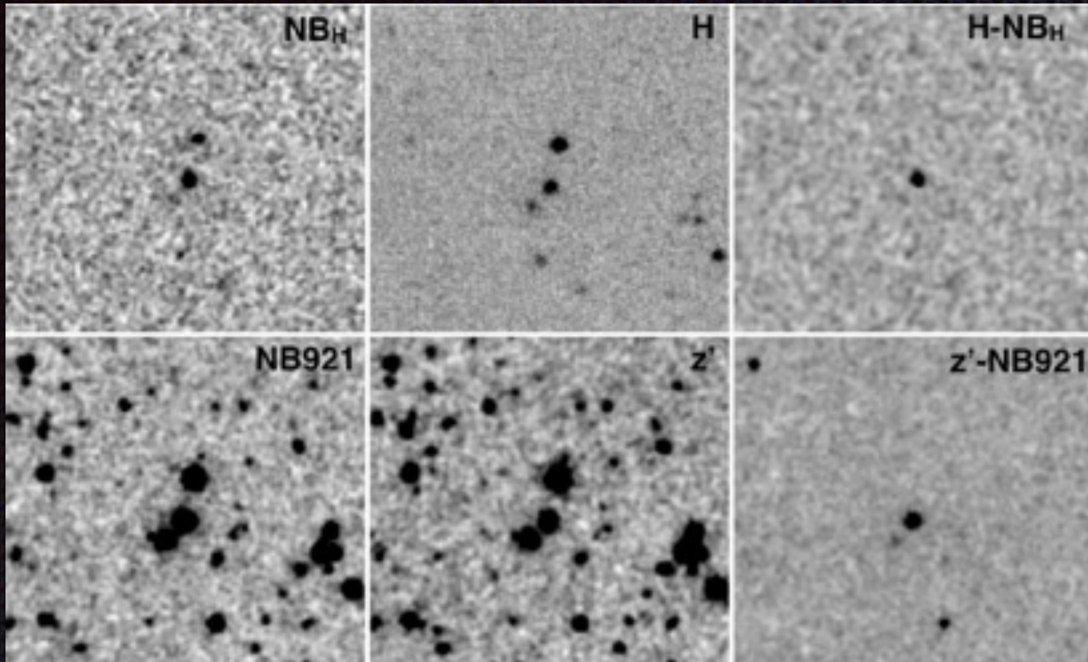


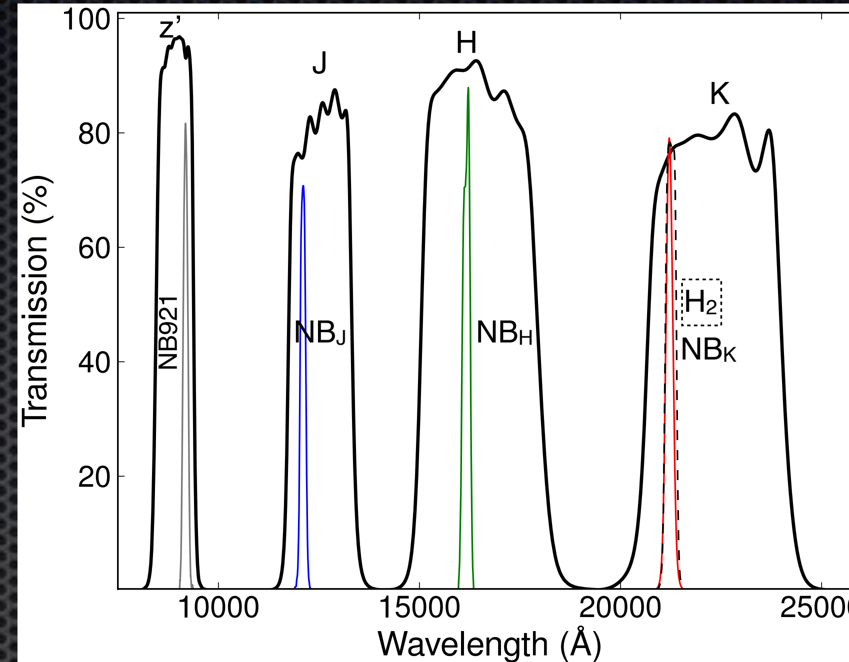
Hα emitters in HiZELS

2 sq deg: COSMOS + UDS

Prior to HiZELS:

~10 sources





Hα emitters in HiZELS

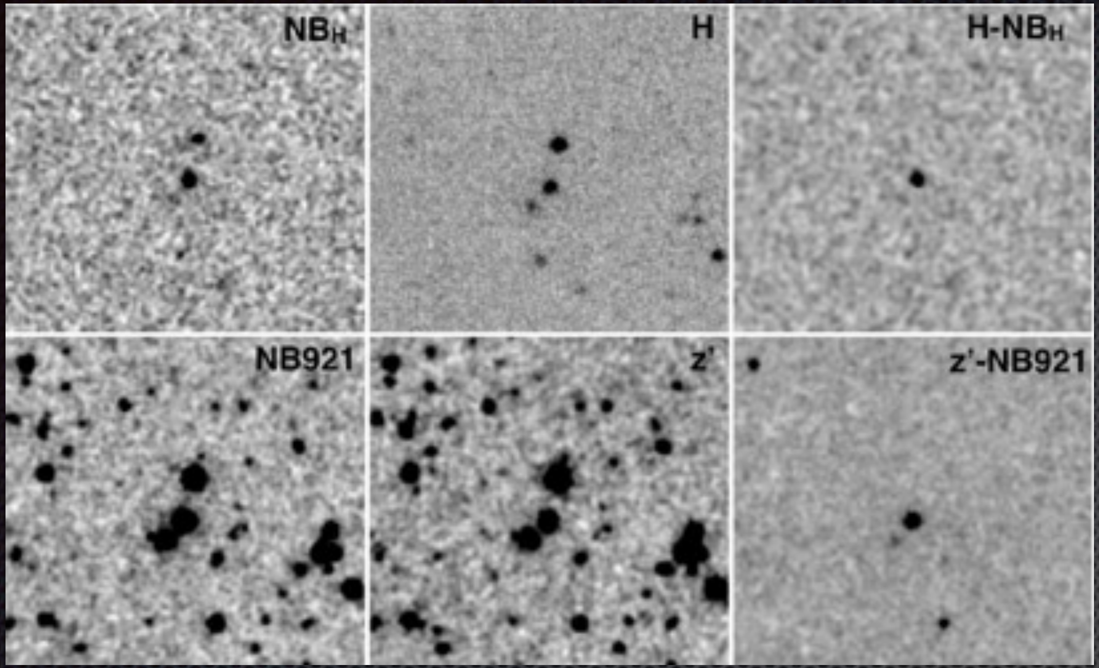
2 sq deg: COSMOS + UDS

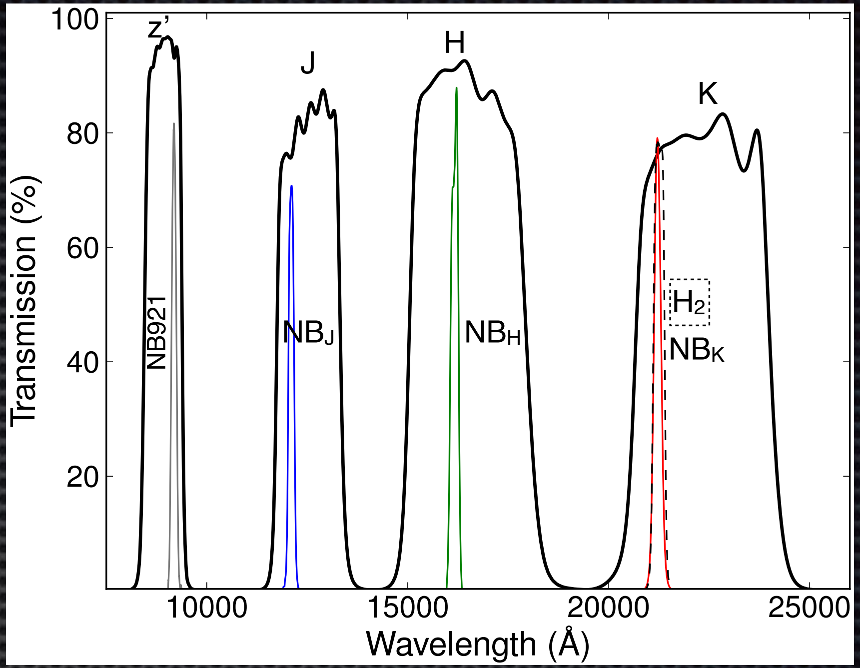
Prior to HiZELS:

~10 sources

Sobral et al. 2013: (catalogues fully public!):

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





Hα emitters in HiZELS

2 sq deg: COSMOS + UDS

Prior to HiZELS:

~10 sources

Sobral et al. 2013: (catalogues fully public!):

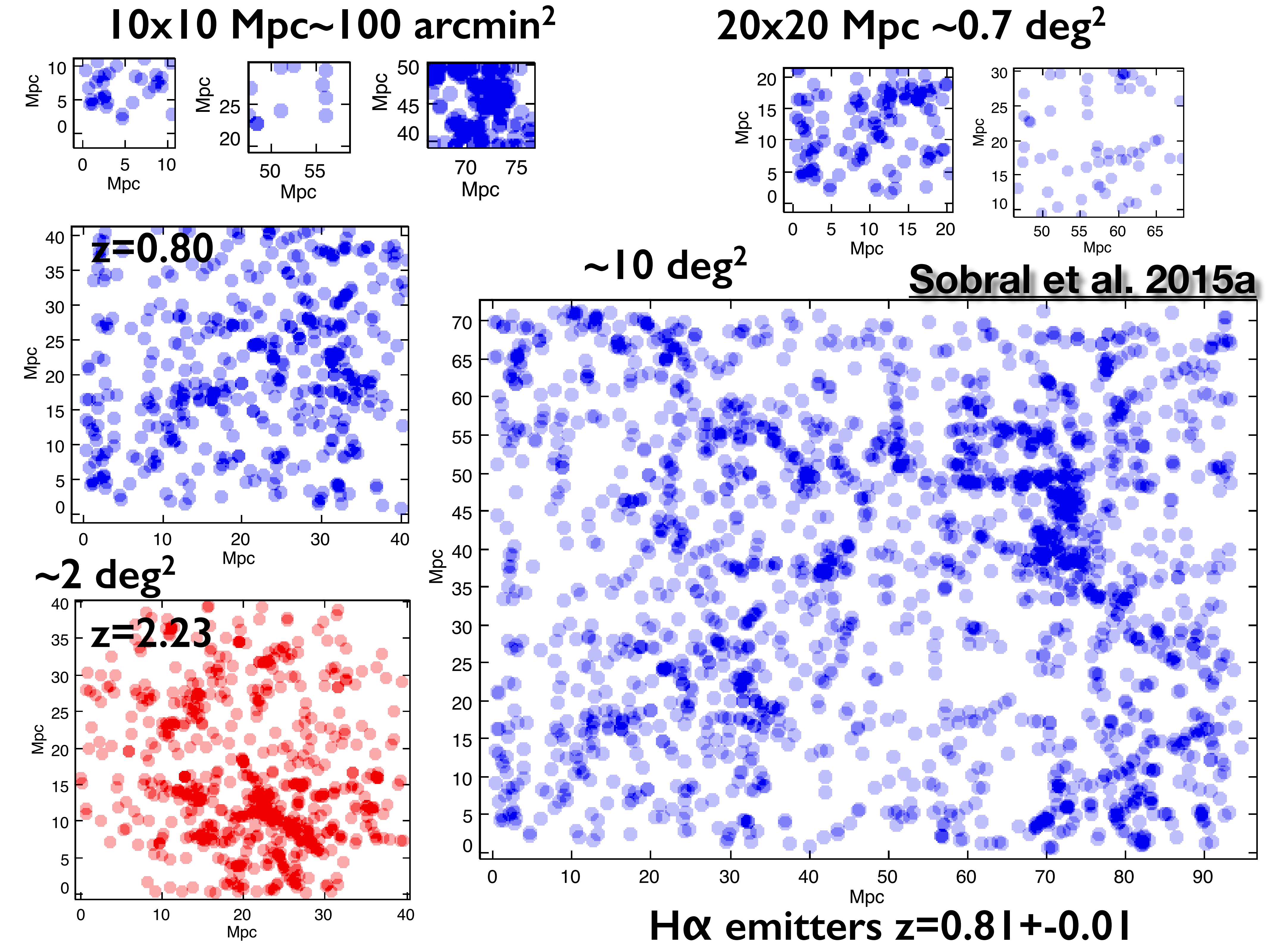
z=0.4: 1122   z=0.8: 637   z=1.47: 515 and z=2.23: 807

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

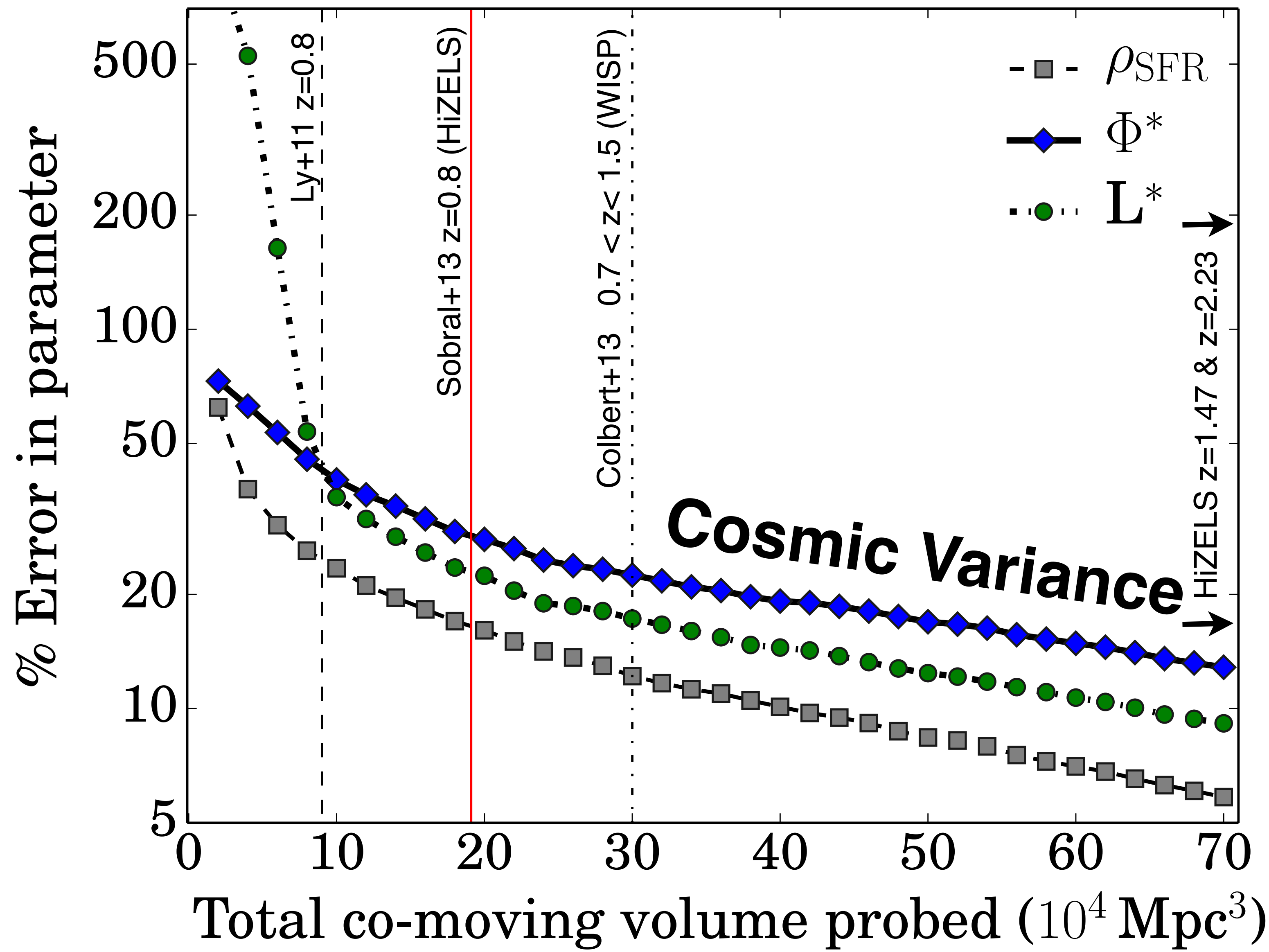
Sobral et al. 2015a


10x10 Mpc~100 arcmin²
20x20 Mpc ~0.7 deg²
z=0.80
~10 deg²
Sobral et al. 2015a
~2 deg²
z=2.23
Mpc
Hα emitters z=0.81+-0.01

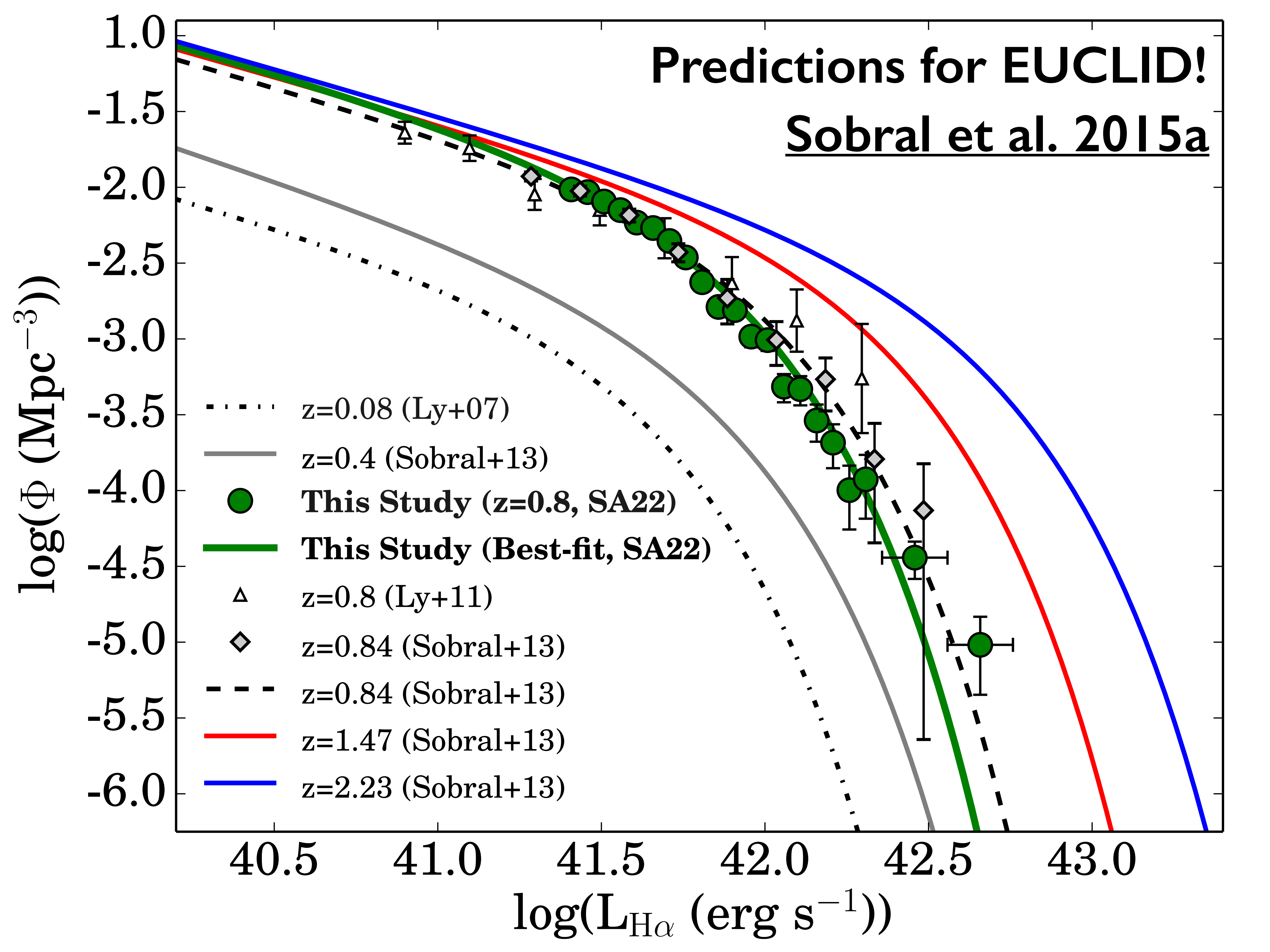
Why we need large, multiple volumes!

Sobral et al. 2015a

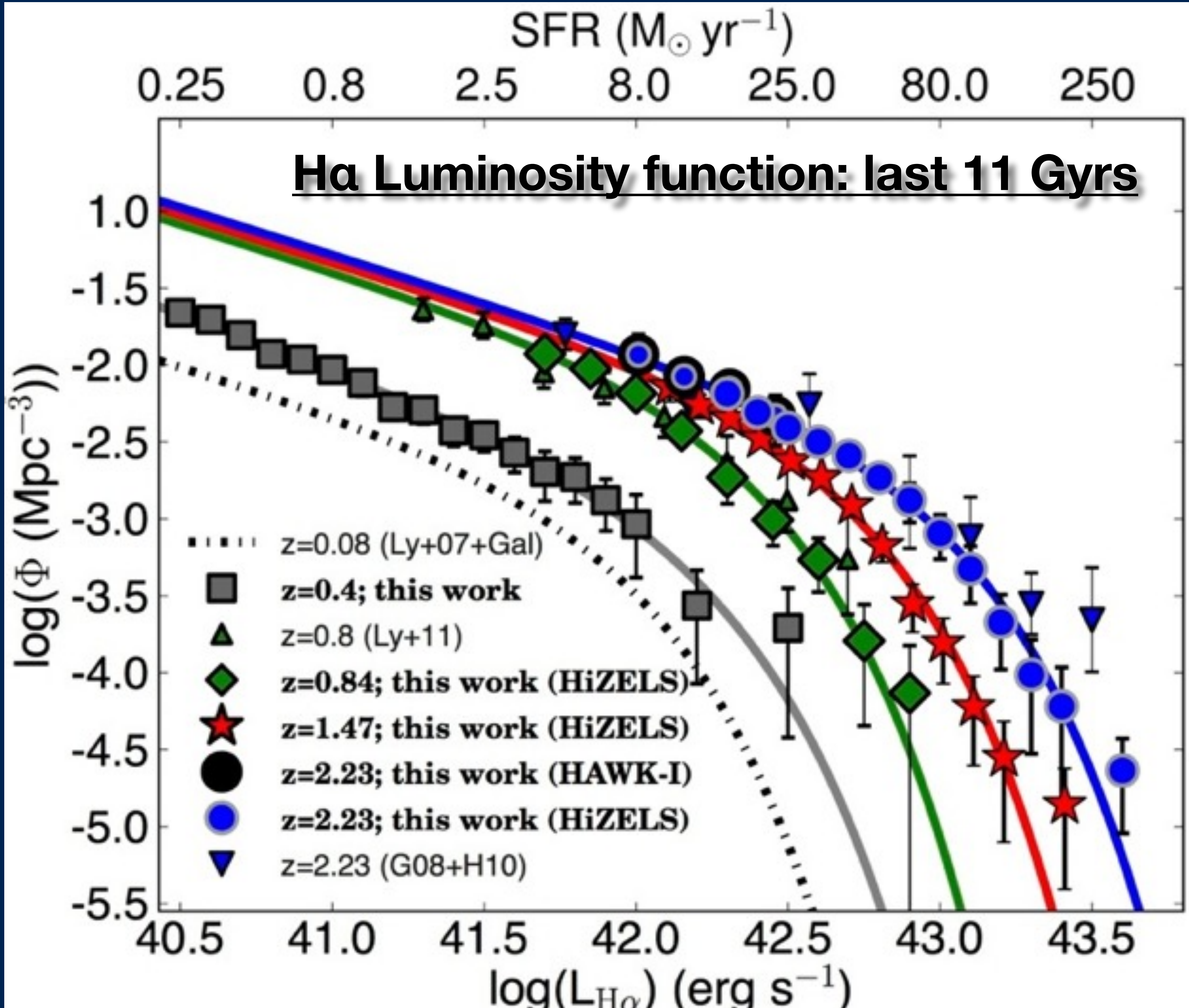
Typical areas **1 deg²** **10 deg²**



With *real* data **Errors < 20%**

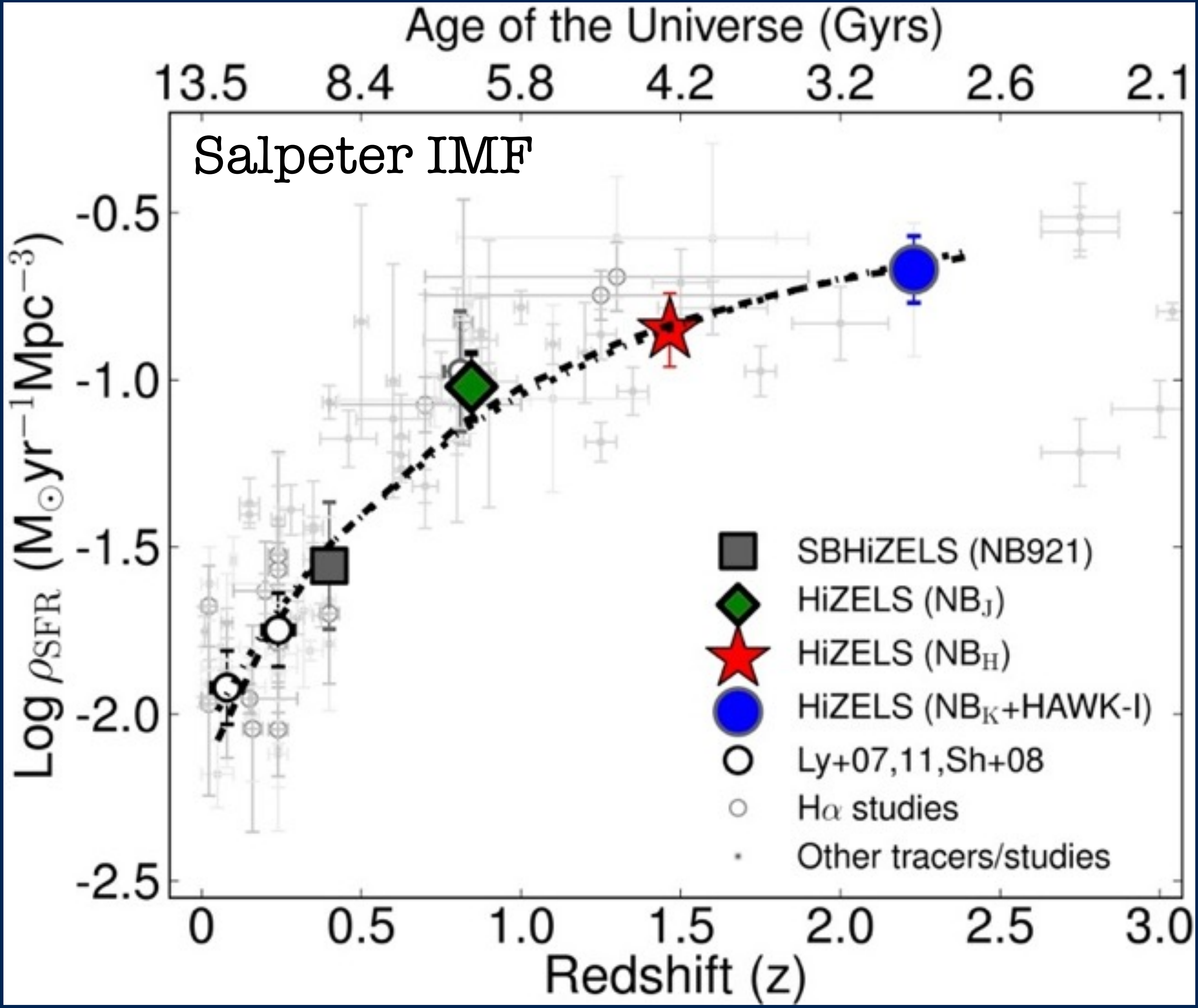


Predictions for EUCLID!
Sobral et al. 2015a
z=0.08 (Ly+07)
z=0.4 (Sobral+13)
This Study (z=0.8, SA22)
This Study (Best-fit, SA22)
z=0.8 (Ly+11)
z=0.84 (Sobral+13)
z=0.84 (Sobral+13)
z=1.47 (Sobral+13)
z=2.23 (Sobral+13)
log(Φ (Mpc^{-3}))
log(L$_{H\alpha}$ (erg s^{-1}))
1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0
-4.5
-5.0
-5.5
-6.0
40.5
41.0
41.5
42.0
42.5
43.0



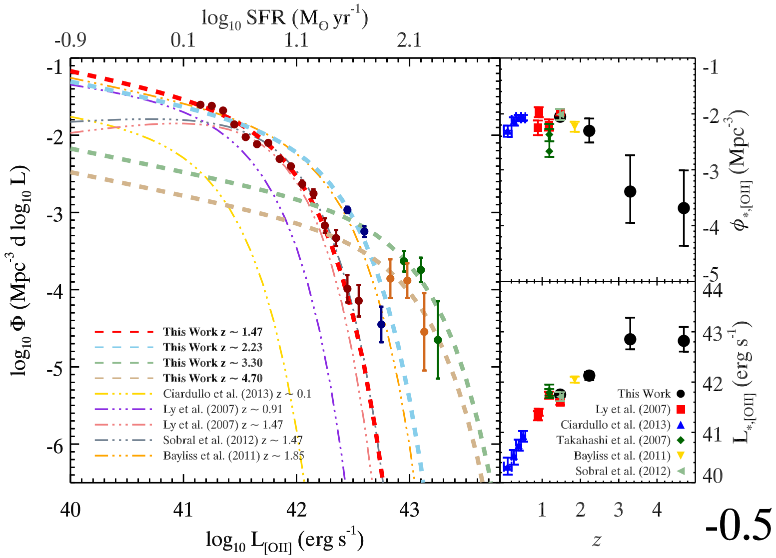
Sobral et al. 2013a

Sobral et al. 2013a Fully self-consistent SFH of the Universe

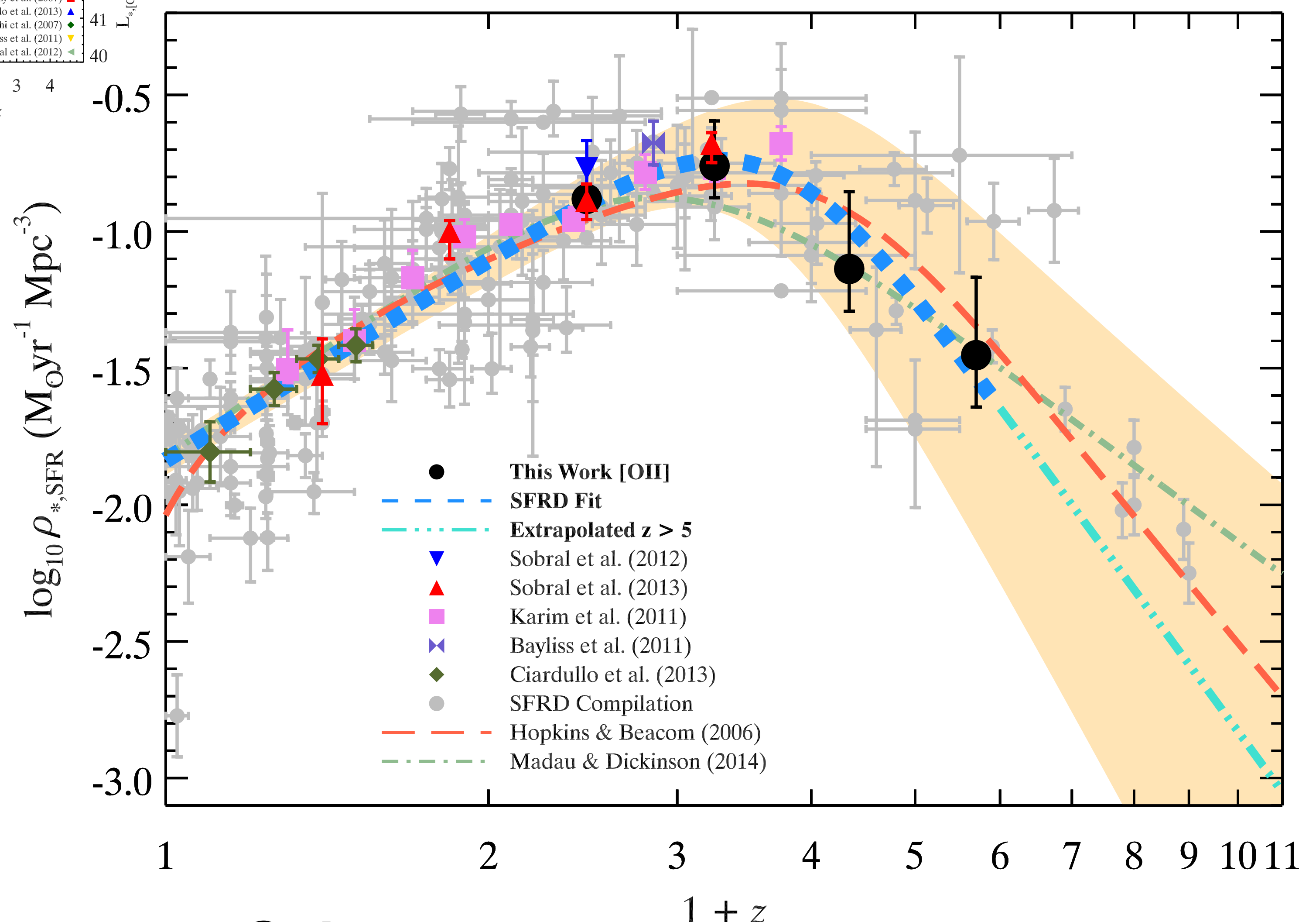


[OII] Star-formation history of the Universe from z=0 to z~5

Khostovan, Sobral et al. 2015

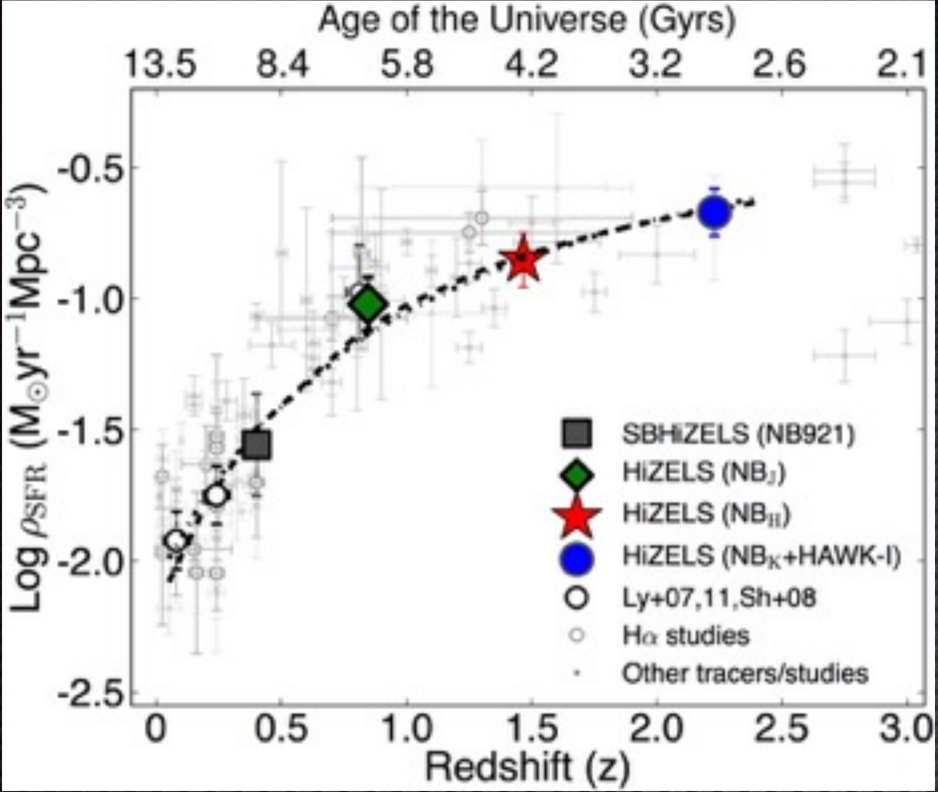


Ali Khostovan



Also [OIII], [OII]: see also Sobral+15a

Hα Star formation History



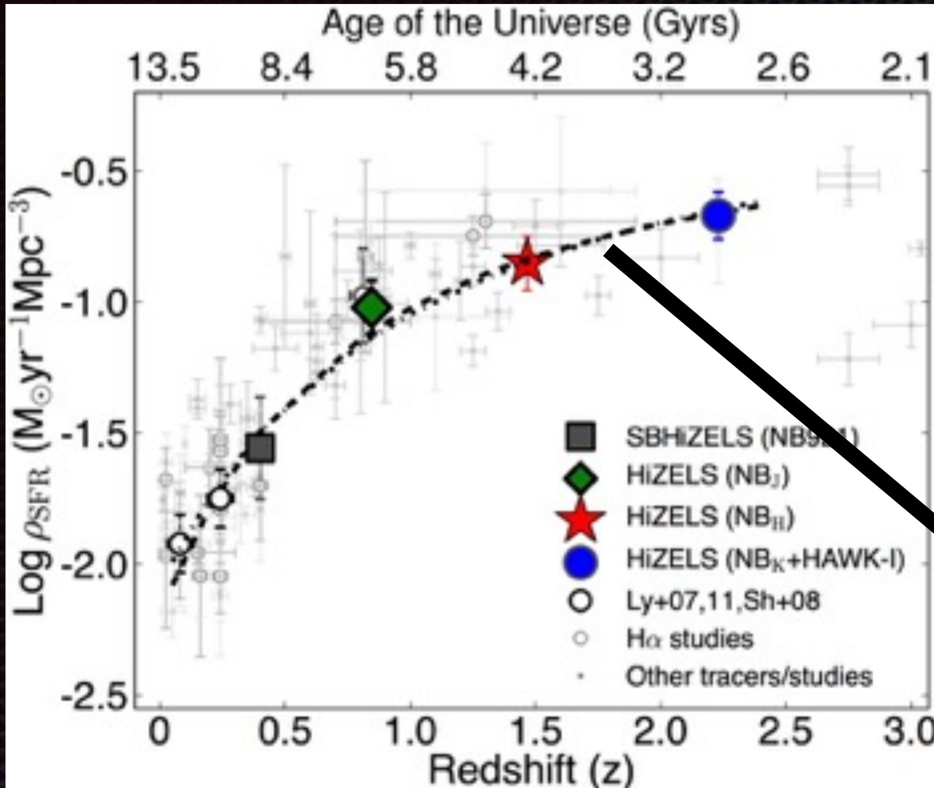
Strong decline with time

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

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

Sobral+13a

Hα Star formation History

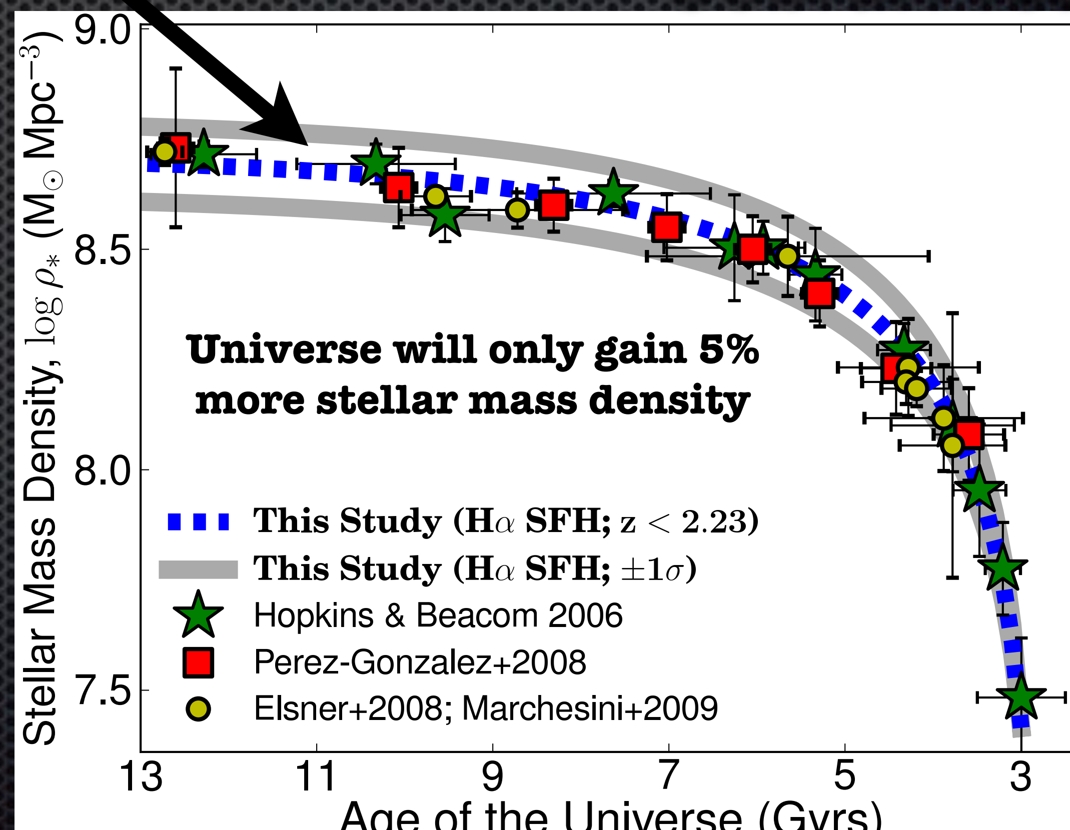


Strong decline with time

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

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

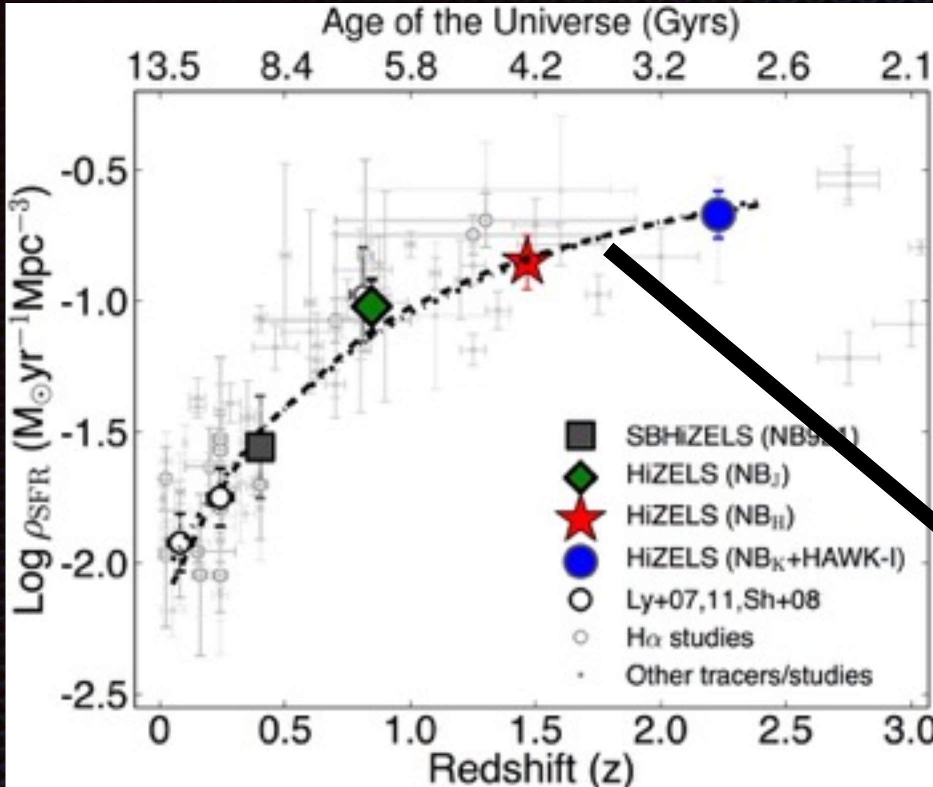
Sobral+13a



Stellar Mass density evolution assembly

Star formation history prediction matches observations

Hα Star formation History

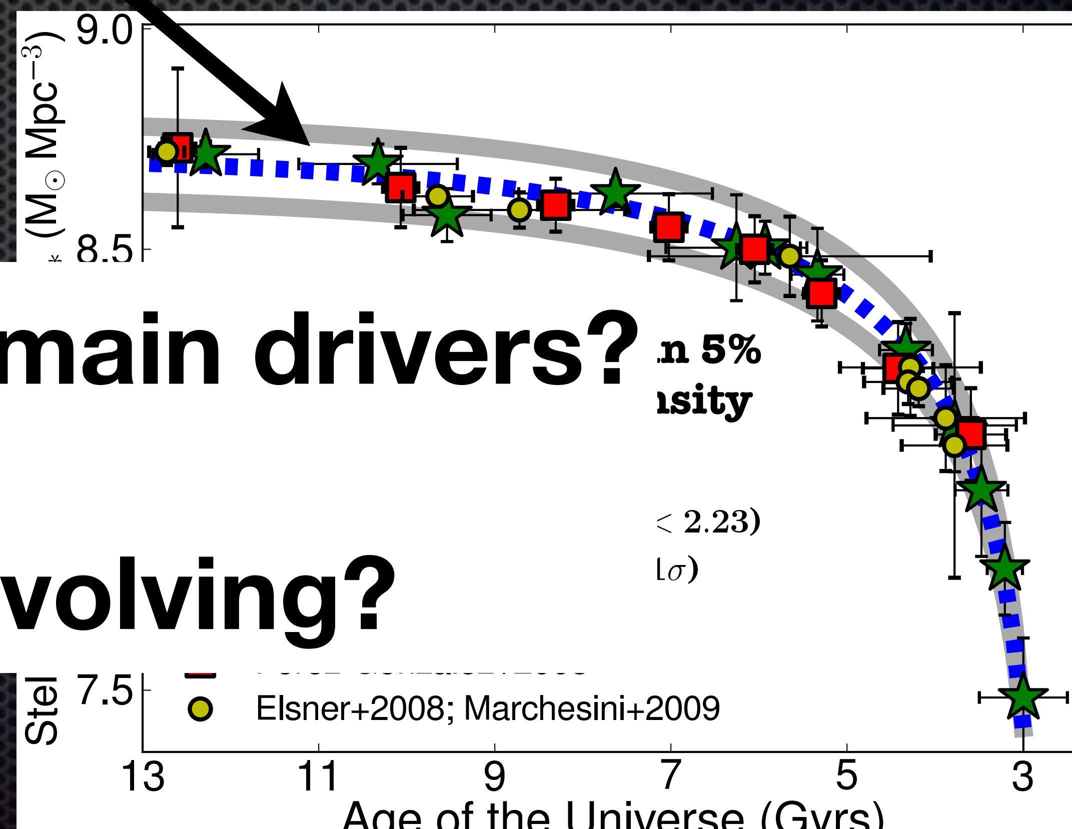


Strong decline with time

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

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

Sobral+13a



Stellar Mass density evolu

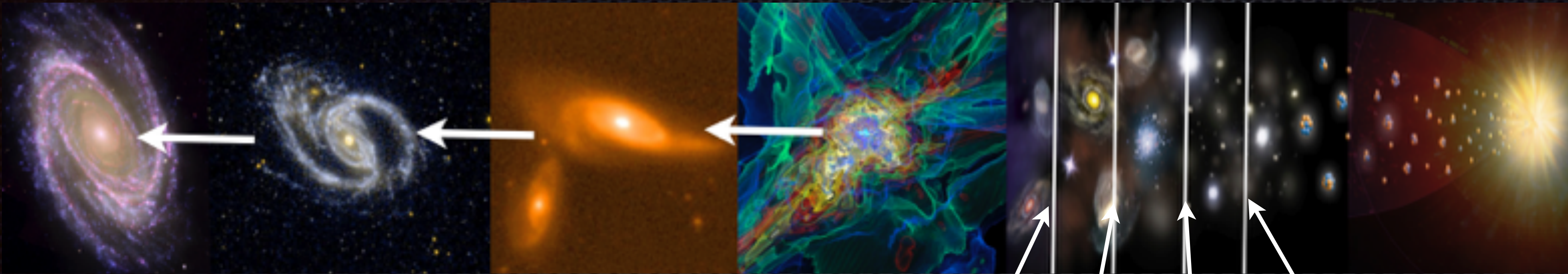
What are the main drivers?

What's evolving?

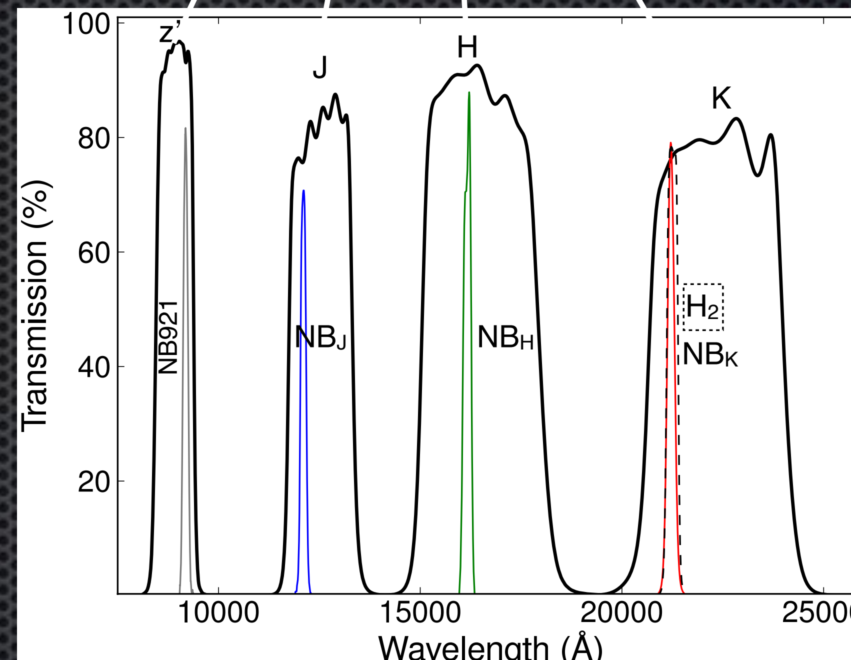
Star f

prec

observations



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



Check out the latest results:

Catalogues, Ha LFs: Sobral+12,13,15a

Size + merger evolution: Stott+13a

Metallicity evolution + FMR: Stott+13b,14

[OII]-Ha at high-z: Sobral+12,Hayashi+13

Dust properties: Garn+10,S+12,Ibar+13

Clustering: Sobral+10, Geach+08,13

[OII]+[OIII] LFs to z~5: Khostovan+15

Dynamics: Swinbank+12a,b, S+13b, Stott+14

Lyman-alpha at z>7: Sobral+09b,Matthee+14

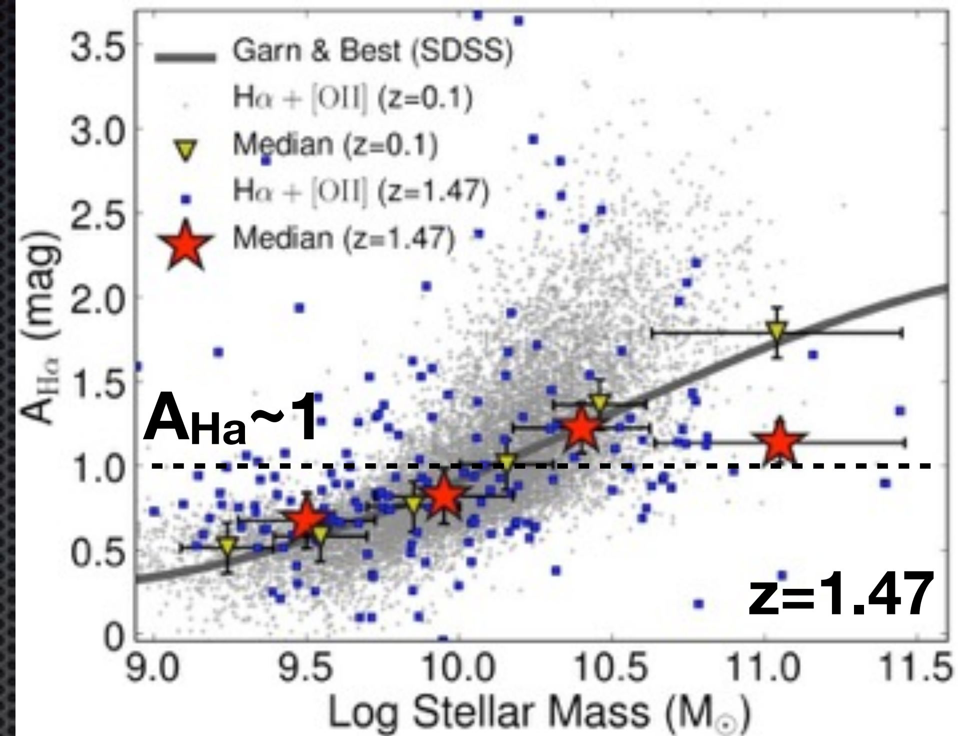
Environment vs Mass: e.g. Sobral+11, Koyama+13, Darvish+14, Sobral+15b, Darvish+15, Stroe+14,15

AGN vs SF: Garn+10, Lehmer+13, Sobral+15d

Extinction-Mass z~0-1.5

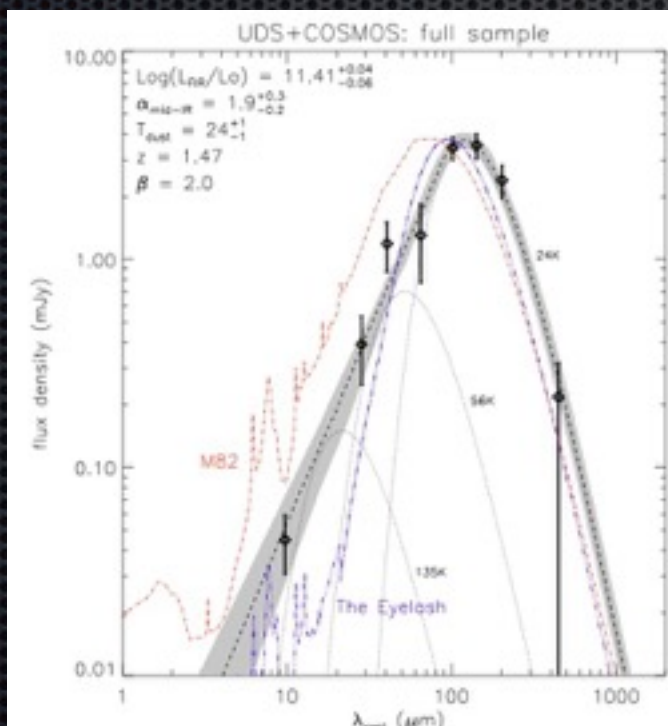
Garn & Best 2010: Stellar Mass correlates with dust extinction (z~0)

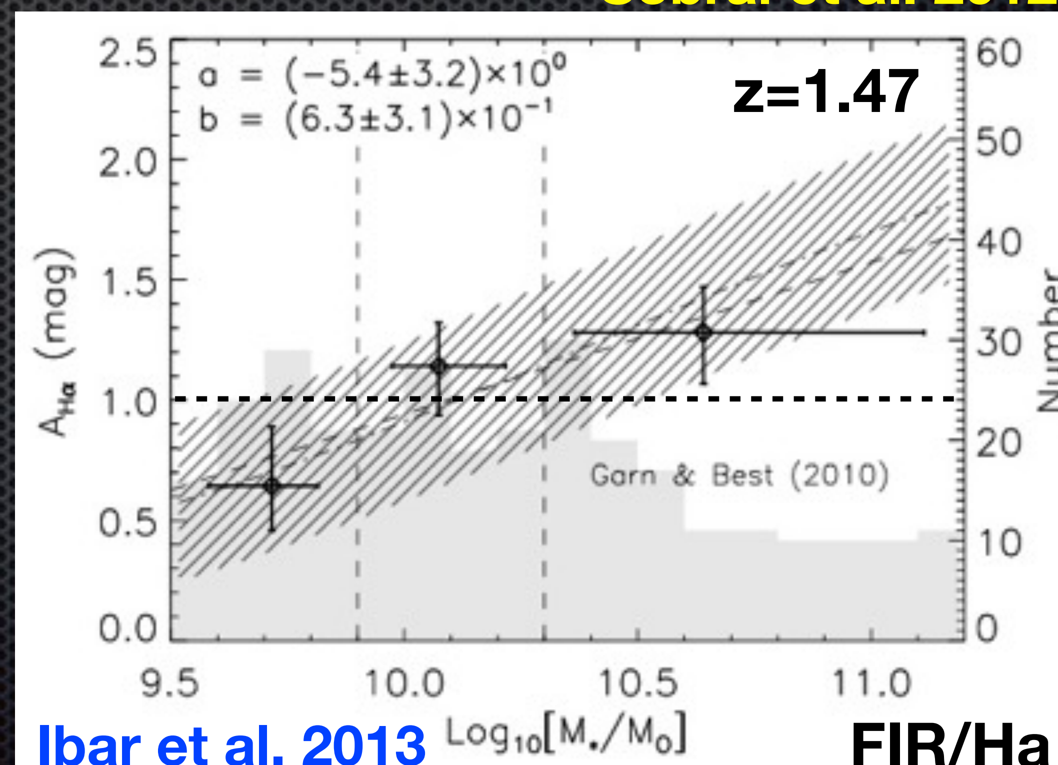
Discovered to be valid up to z~1.5-2! (Sobral+12); discovery further confirmed by e.g. Kashino+14, Ibar+13, Price+13 + many others in many different samples



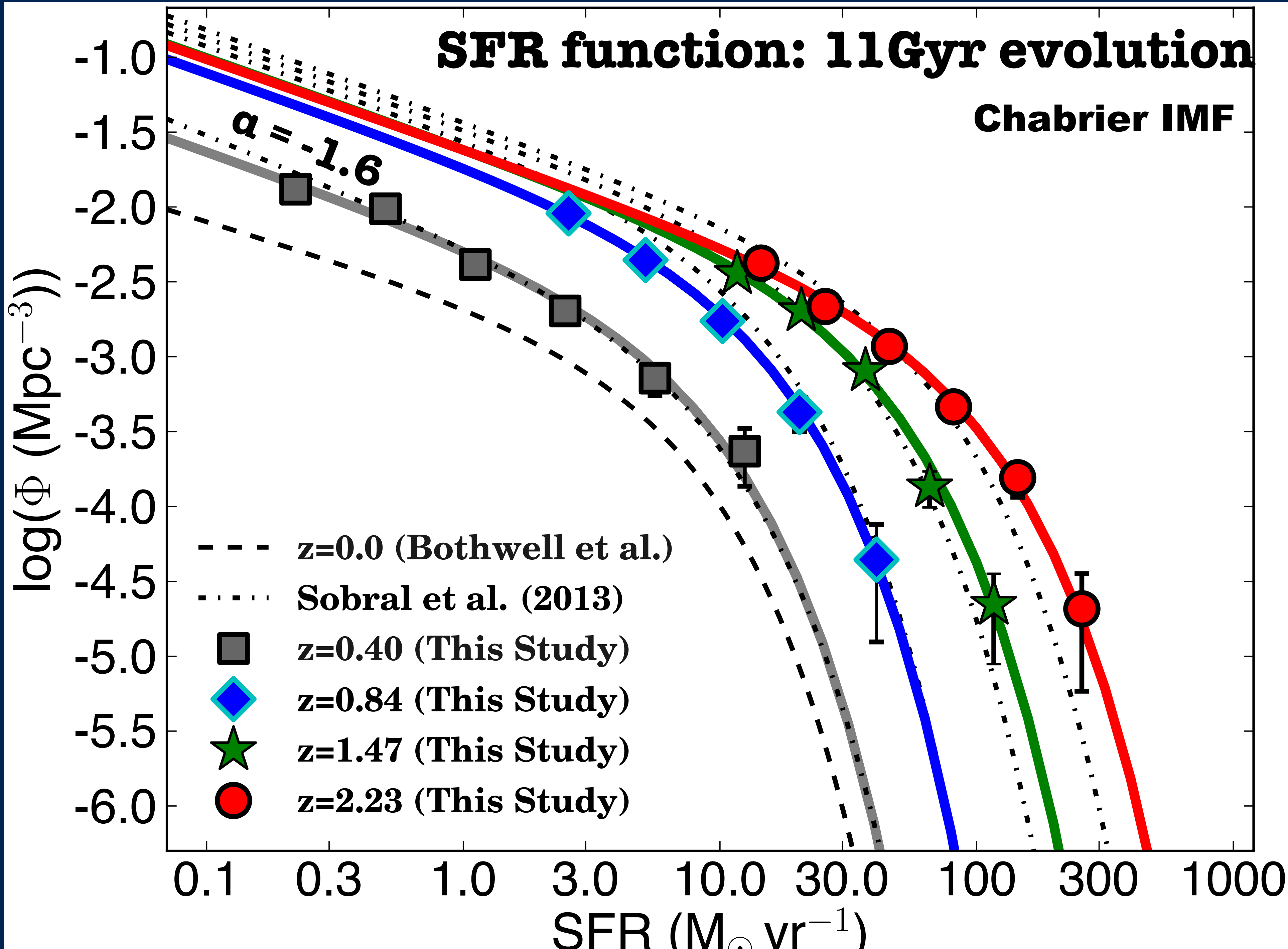
Sobral et al. 2012

Now confirmed by Herschel





FIR derived A_{Ha} = 0.9-1.2 mag



Sobral et al. (2014)

SFR function: Strong SFR* evolution

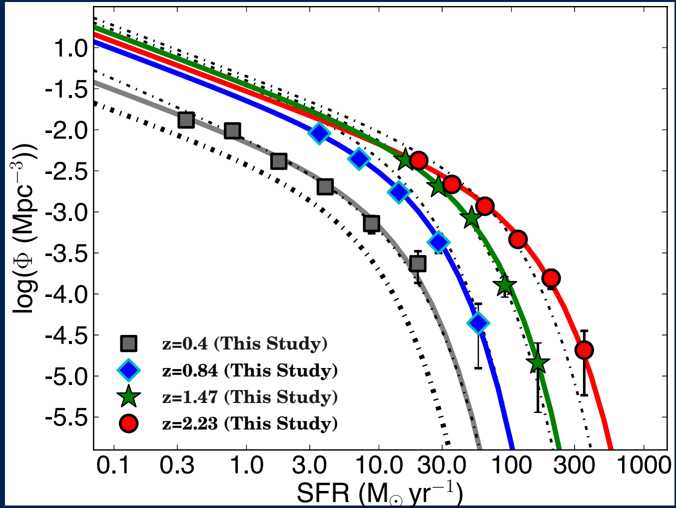
$SFR^*(T)=10^{(4.23/T+0.37)}$ $M_\odot/yr$
T, Gyrs

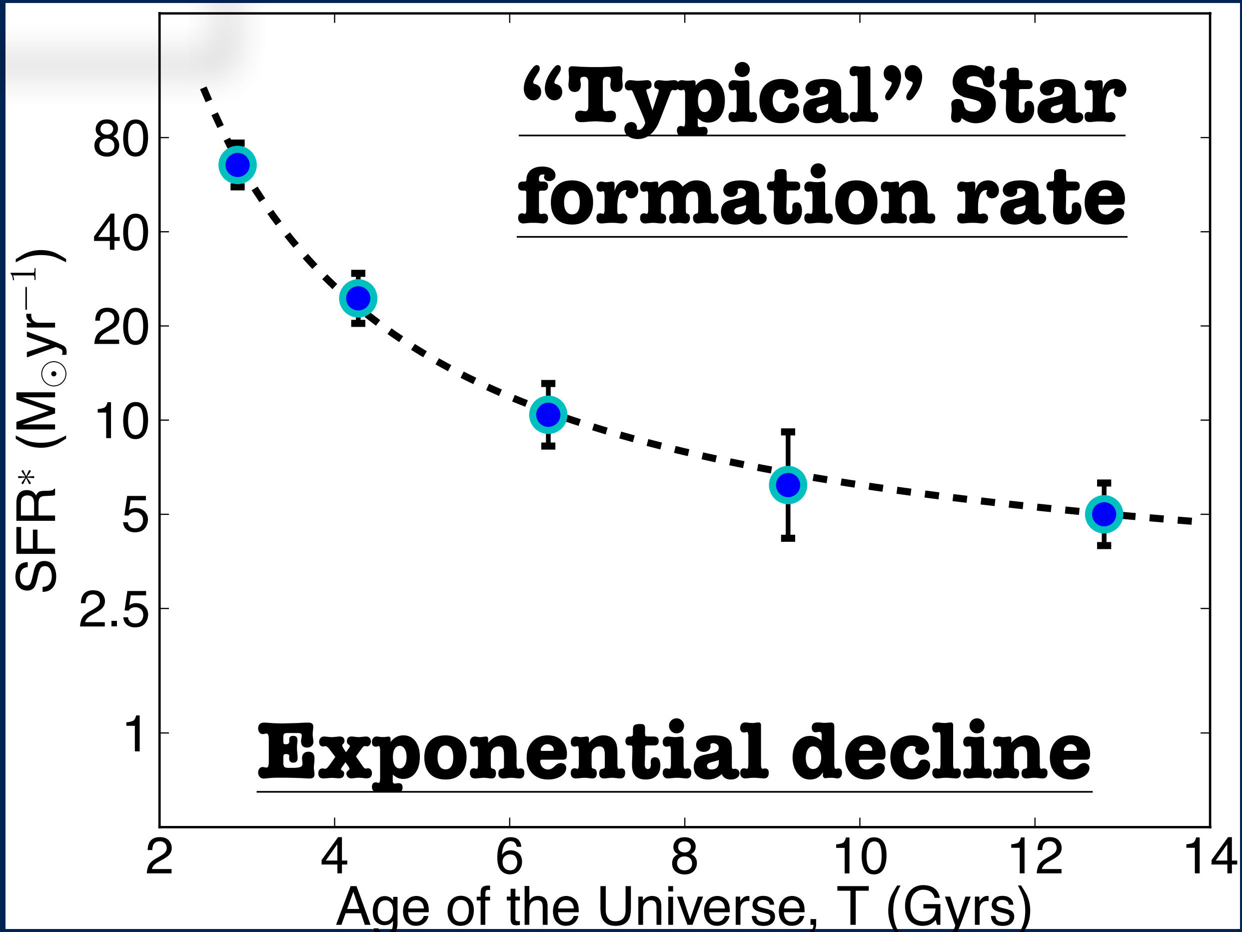
13x decrease over last 11 Gyrs

Sobral+14, MNRAS

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

SFR function: Strong SFR* evolution

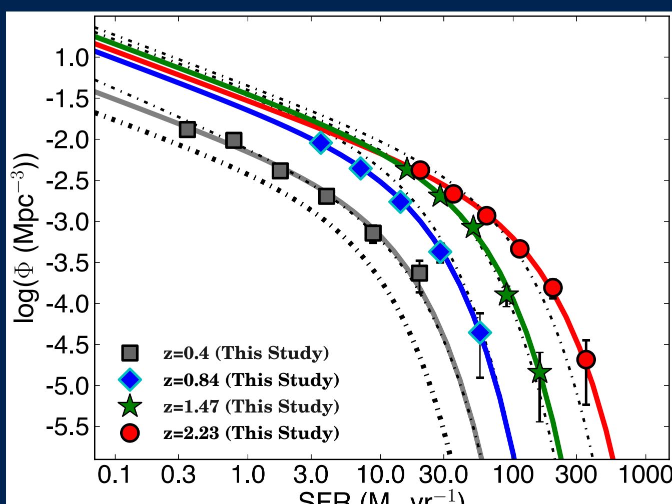
$SFR^*(T)=10^{(4.23/T+0.37)}\ M_o/yr$
T, Gyrs

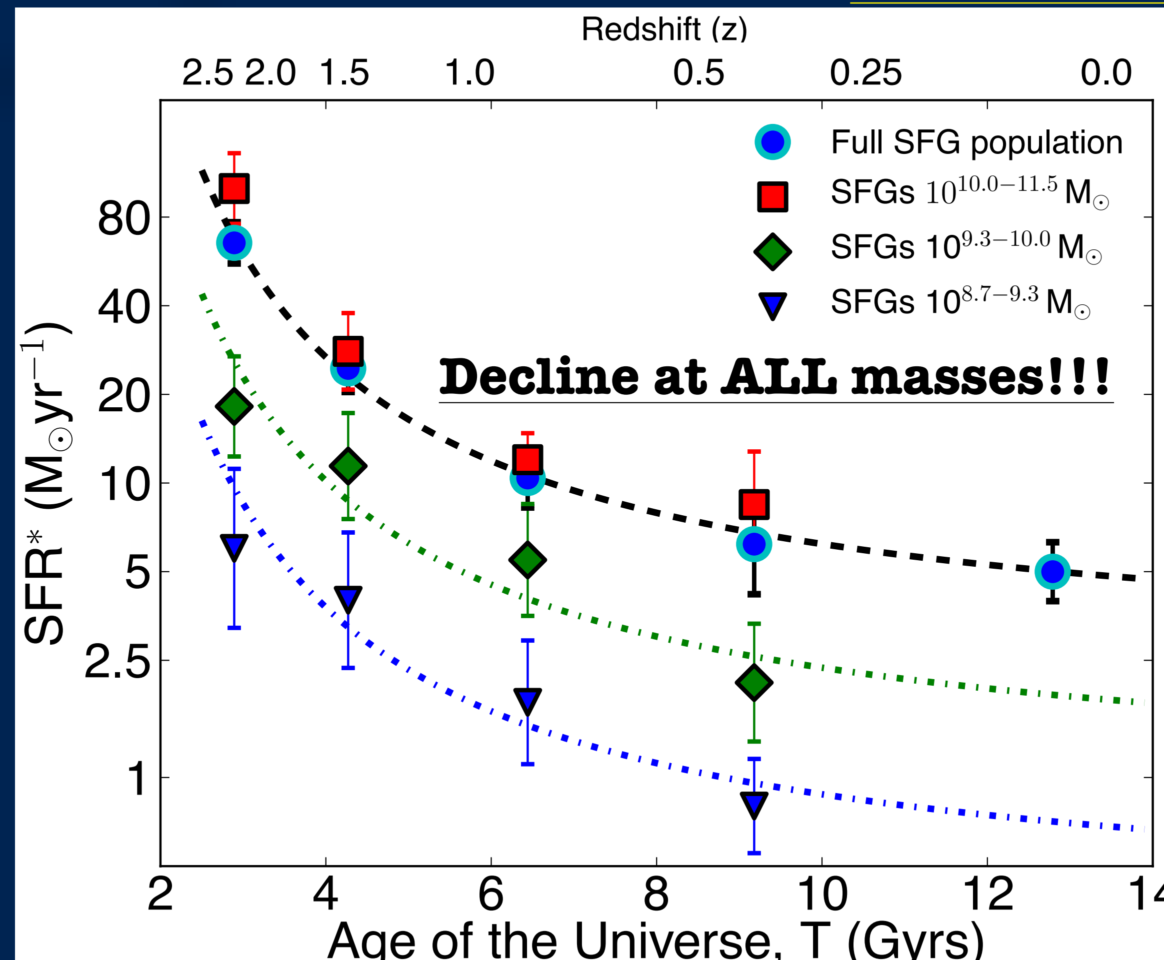
13x decrease over last 11 Gyrs

Sobral+14

Faint-end slope: α = -1.6

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

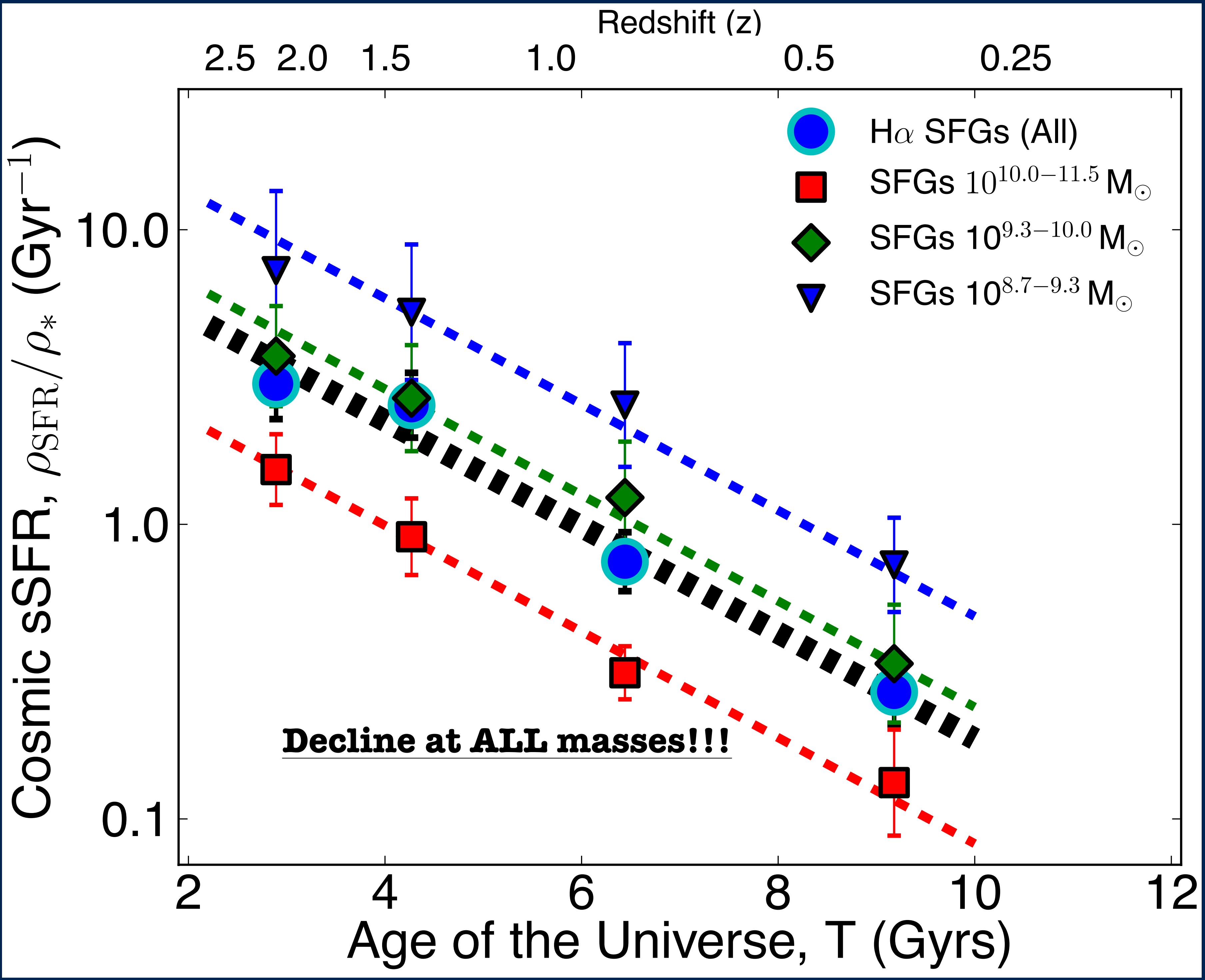




Φ* z=0 → z=1 → z=2

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

T, Gyrs

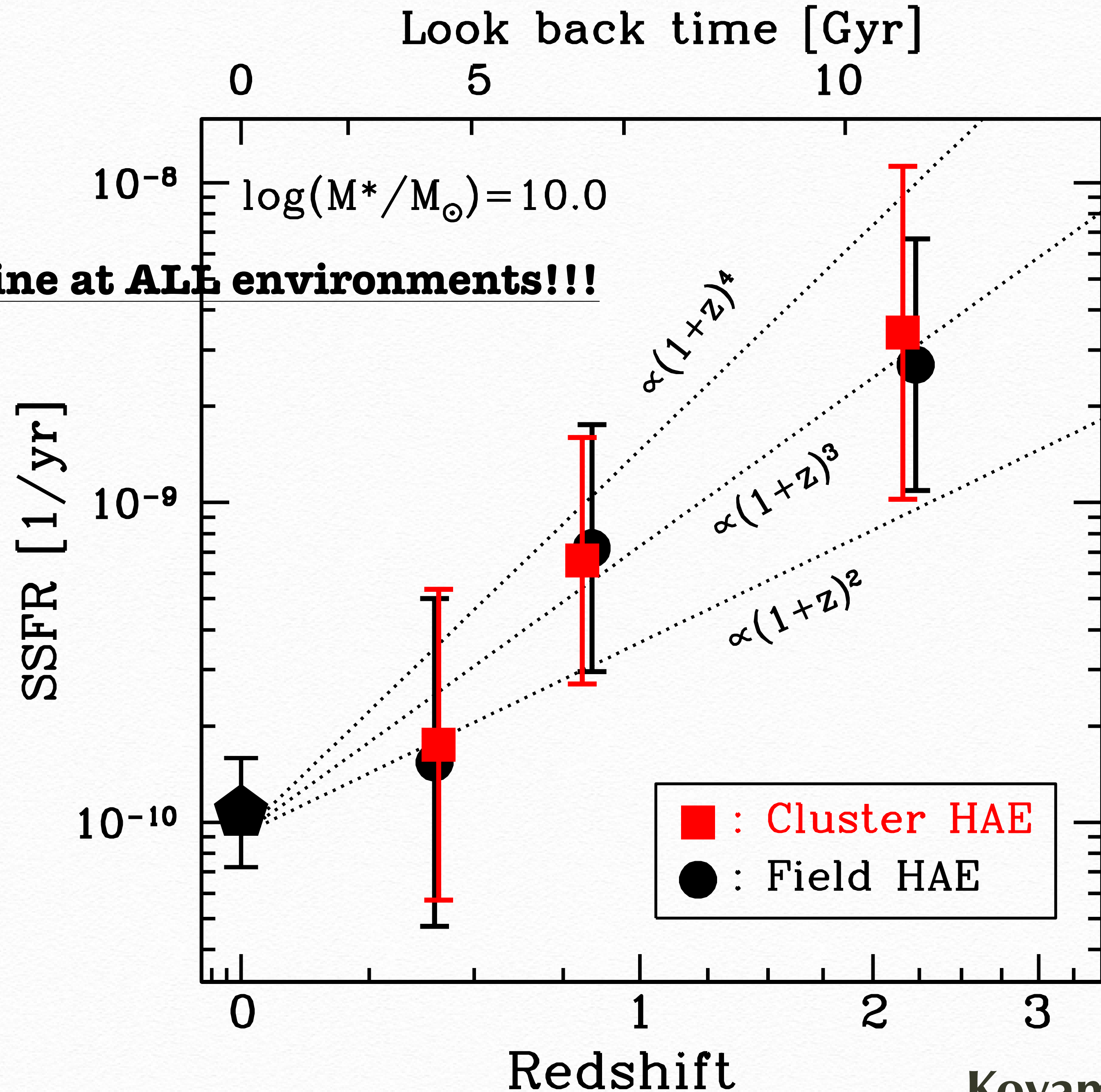


Redshift (z)
2.5
2.0
1.5
1.0
0.5
0.25
Cosmic sSFR, $\rho_{\rm SFR}/\rho_*$ (Gyr^{-1})
10.0
1.0
0.1
Hα SFGs (All)
SFGs $10^{10.0-11.5}$ M$_\odot$
SFGs $10^{9.3-10.0}$ M$_\odot$
SFGs $10^{8.7-9.3}$ M$_\odot$
Decline at ALL masses!!!
2
4
6
8
10
12
Age of the Universe, T (Gyrs)

Sobral+14

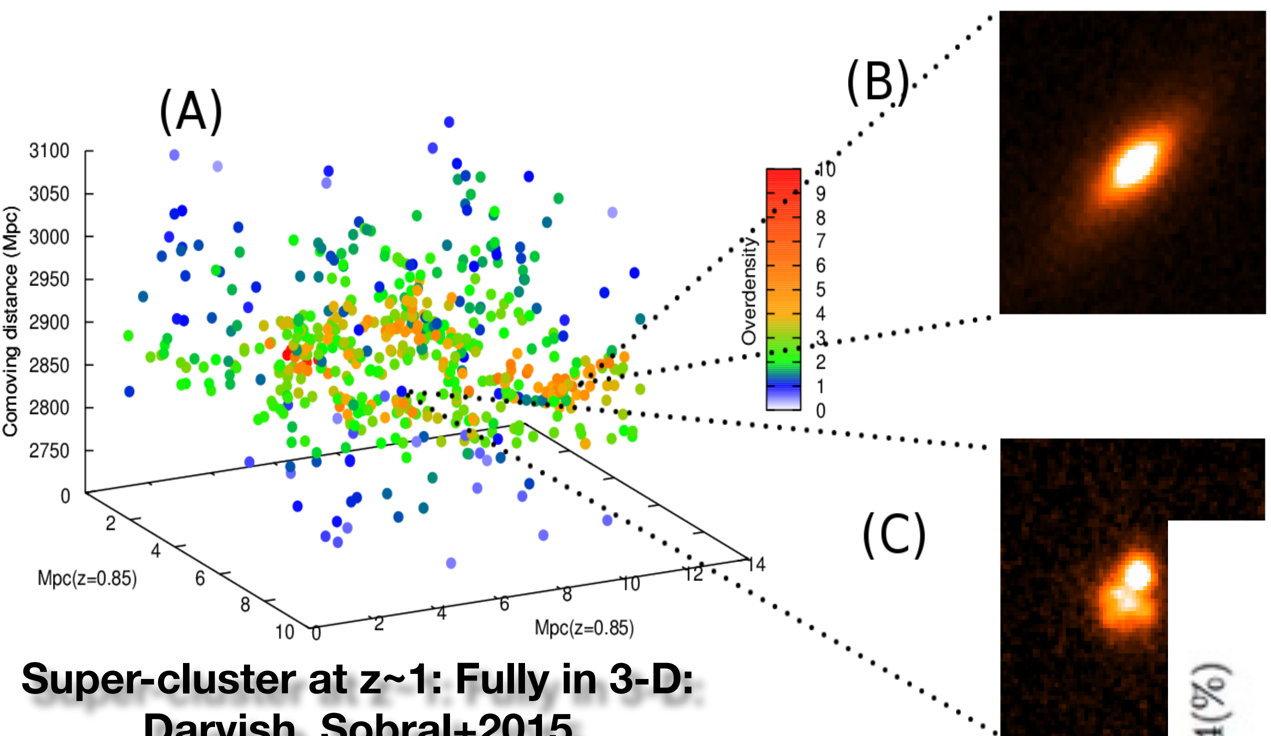
Evolution of SFR* (SSFR) same in fields and clusters since z=2.23

Decline at ALL environments!!!

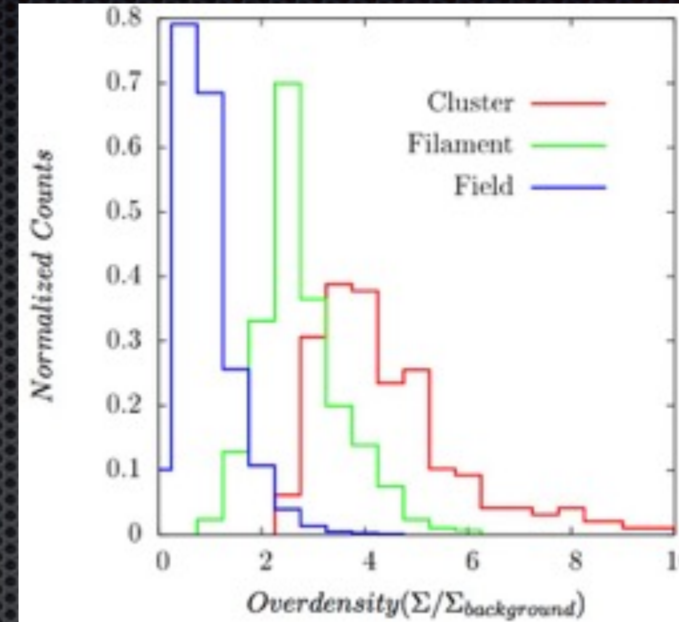


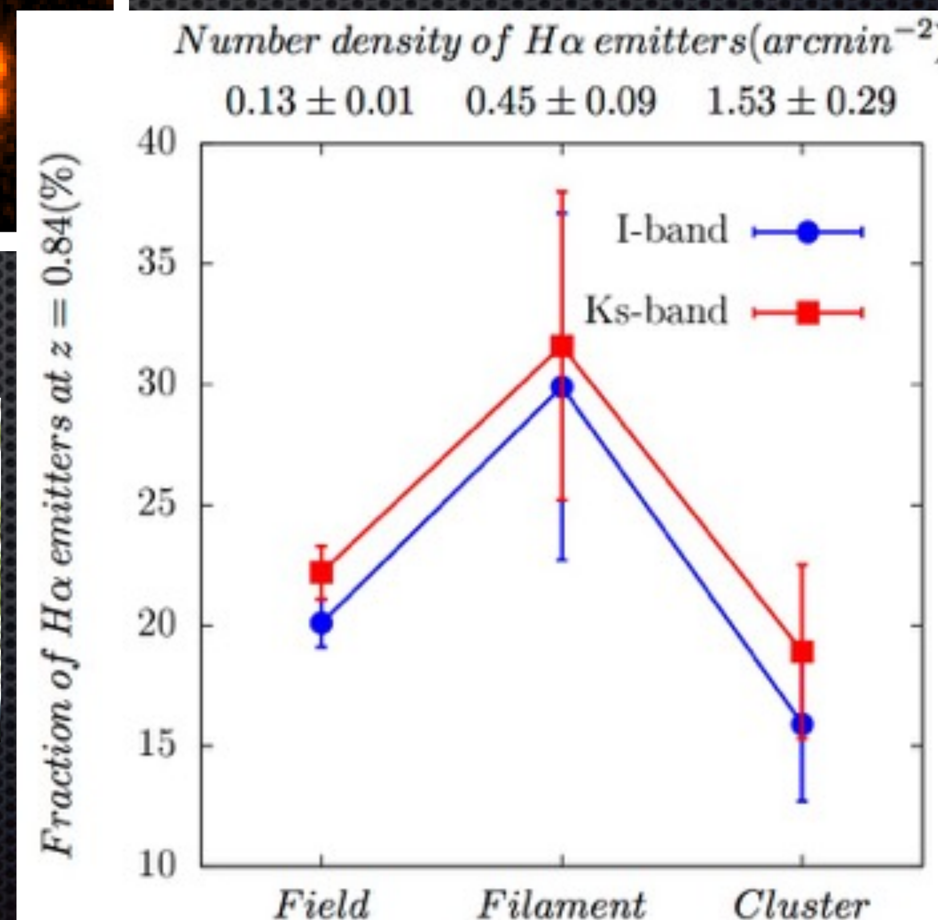
Koyama et al. 2013

Filaments are important!

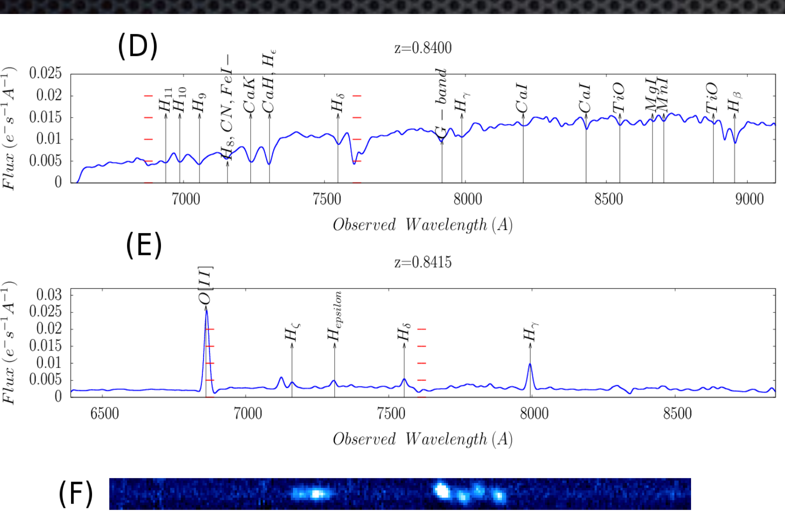


Super-cluster at z~1: Fully in 3-D: Darvish, Sobral+2015

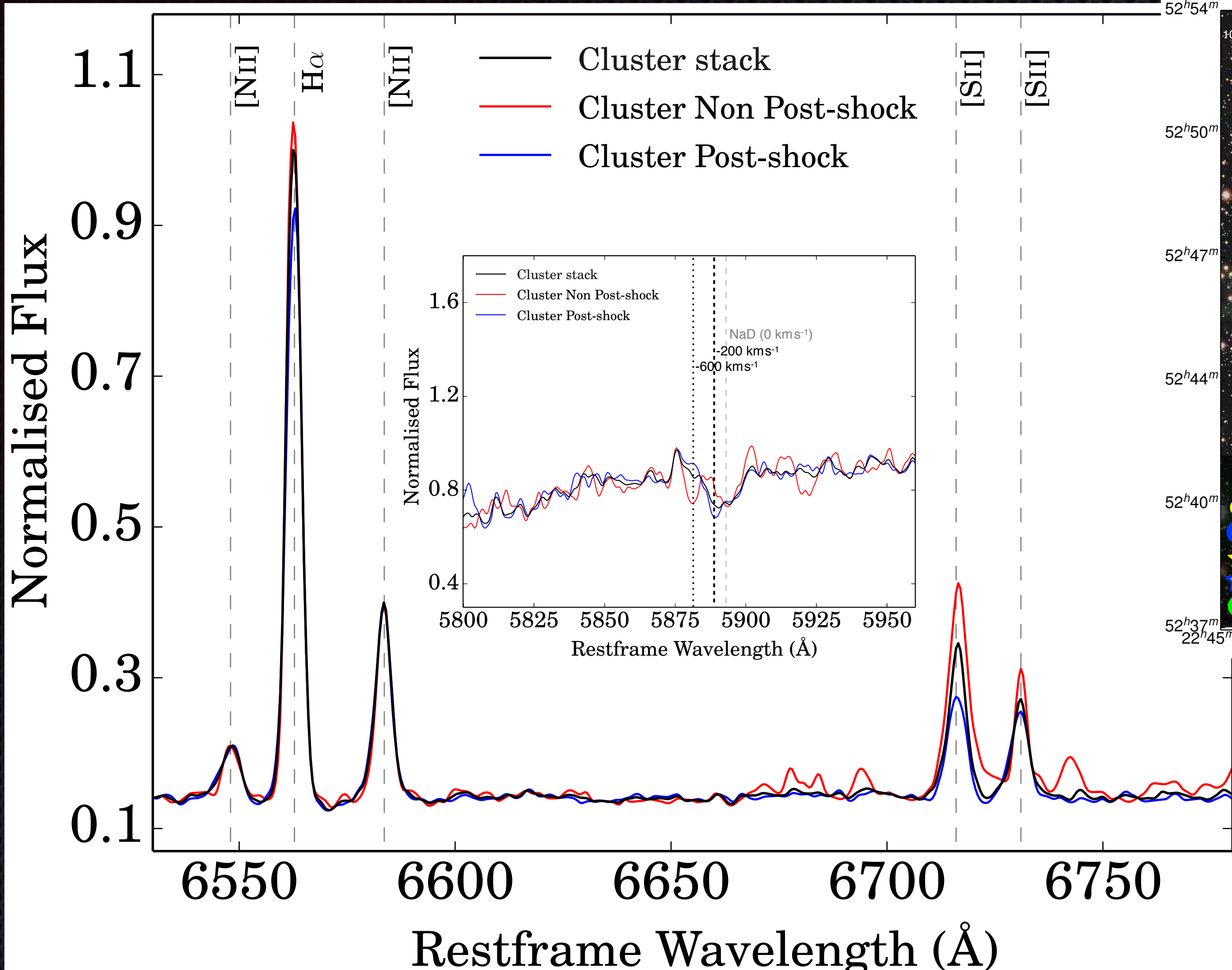


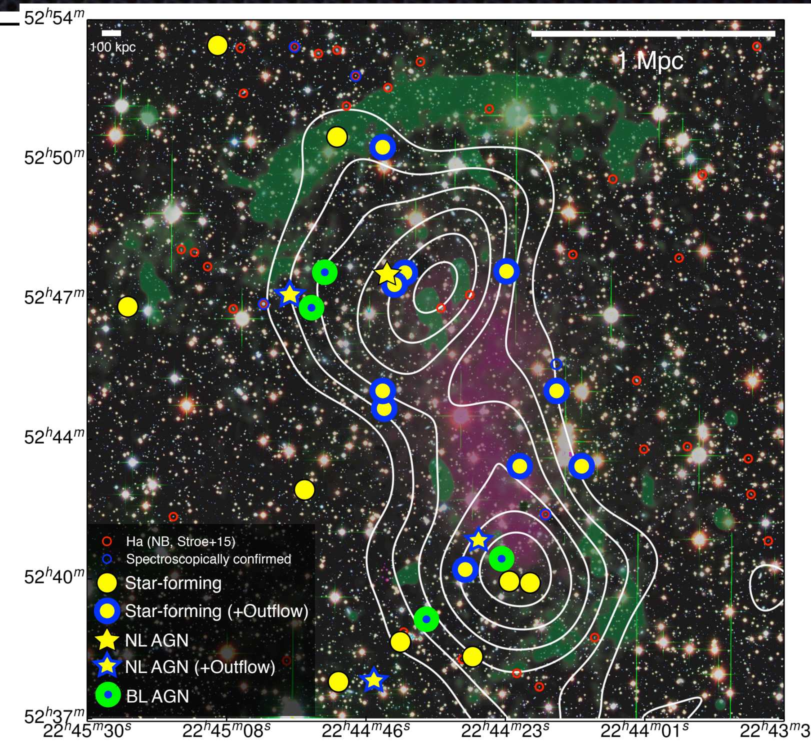


Darvish, Sobral+2014



Behnam Darvish





Merger of >$10^{15}M_{o}$ clusters!

Keck + WHT spectra

Shock waves likely trigger star-formation

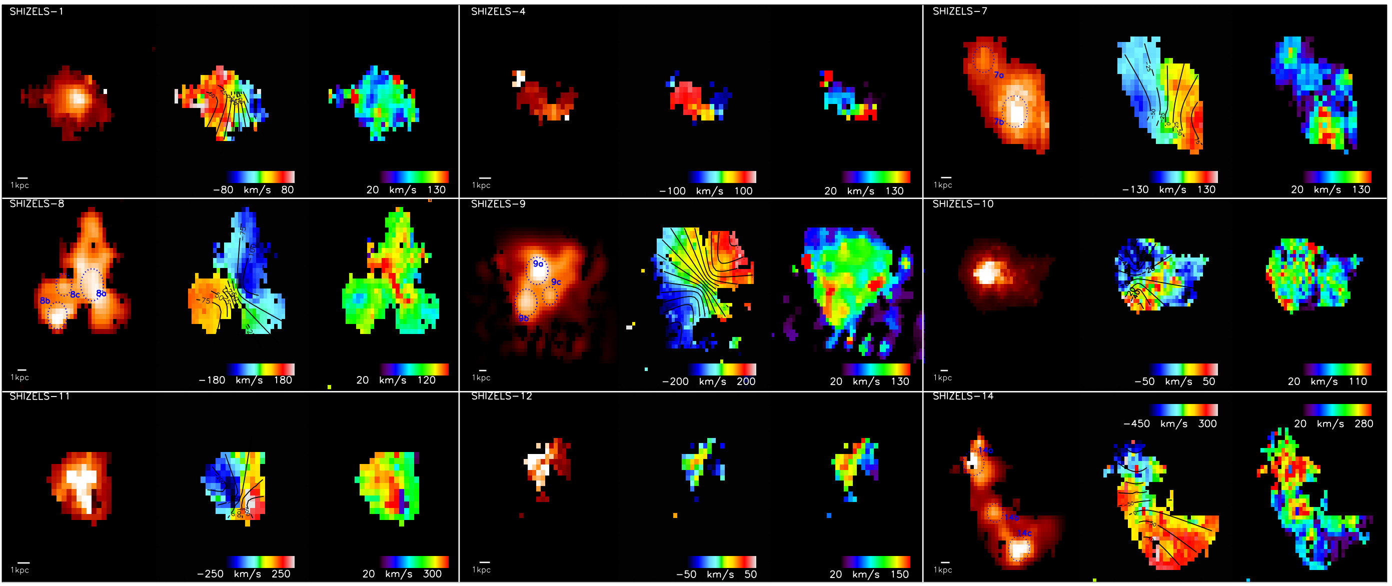
Outflows, supernovae >> will lead to more red +dead galaxies

Cluster mergers are important

Sobral et al. 2015b

Galaxy Dynamics at z~0.8-2.2

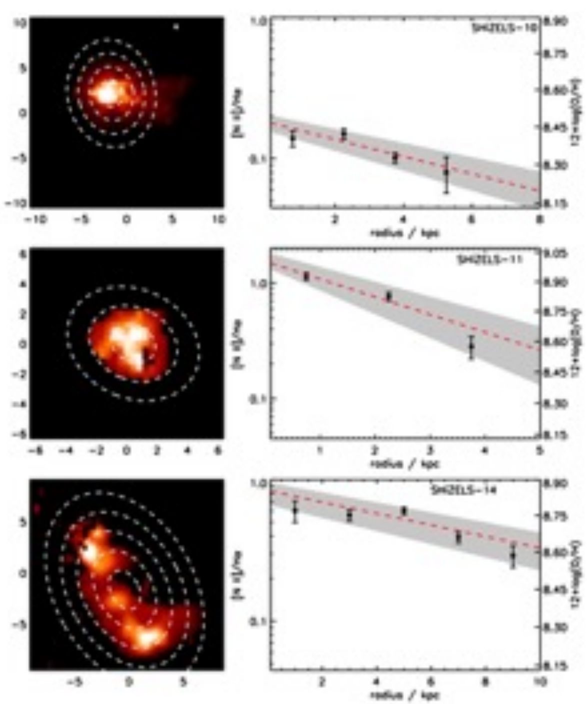
Swinbank, Sobral et al. 2012 **Swinbank al. 2012b**

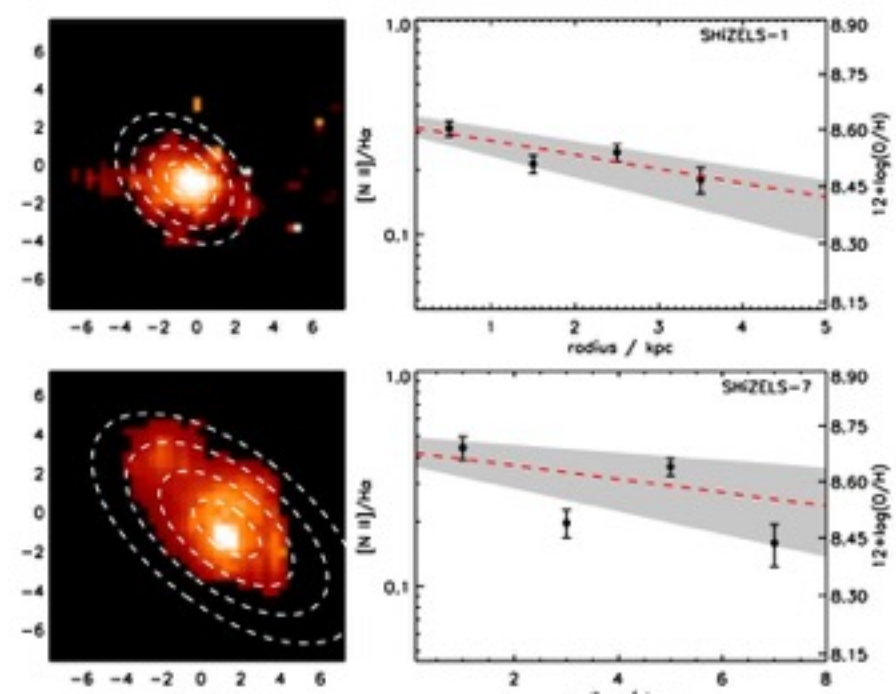


(MNRAS/ApJ):

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

- Negative metallicity gradients: "inside-out" growth

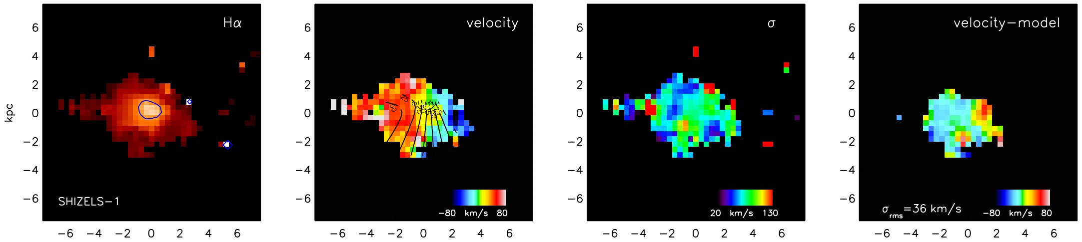




Galaxy Dynamics at z~0.8-2.2

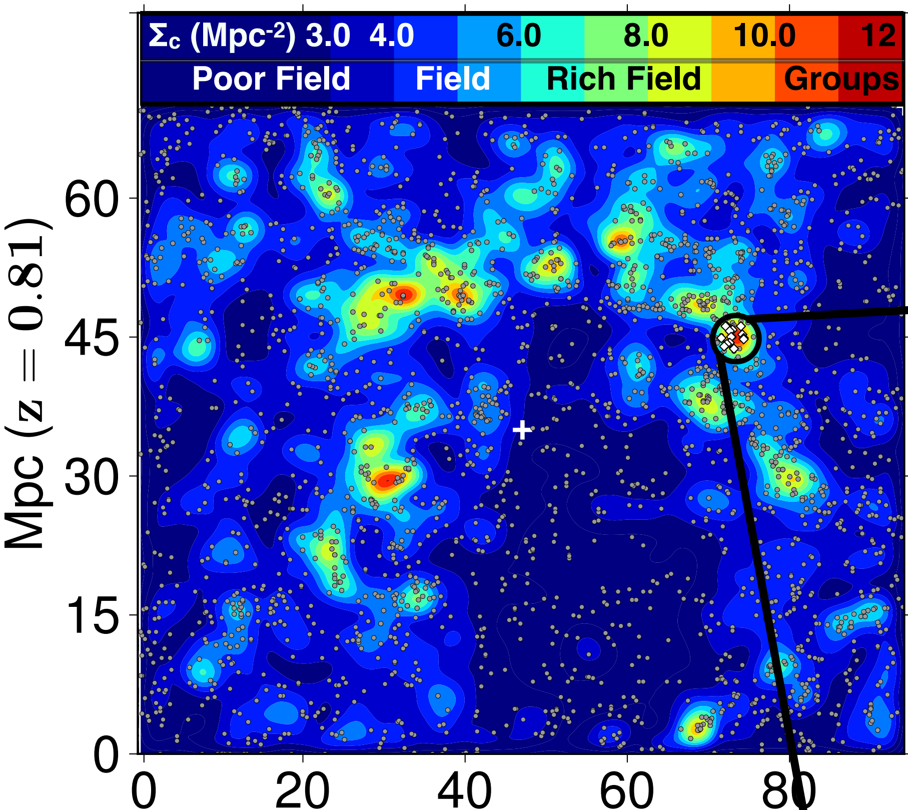
Swinbank al. 2012a

From AO IFU observations

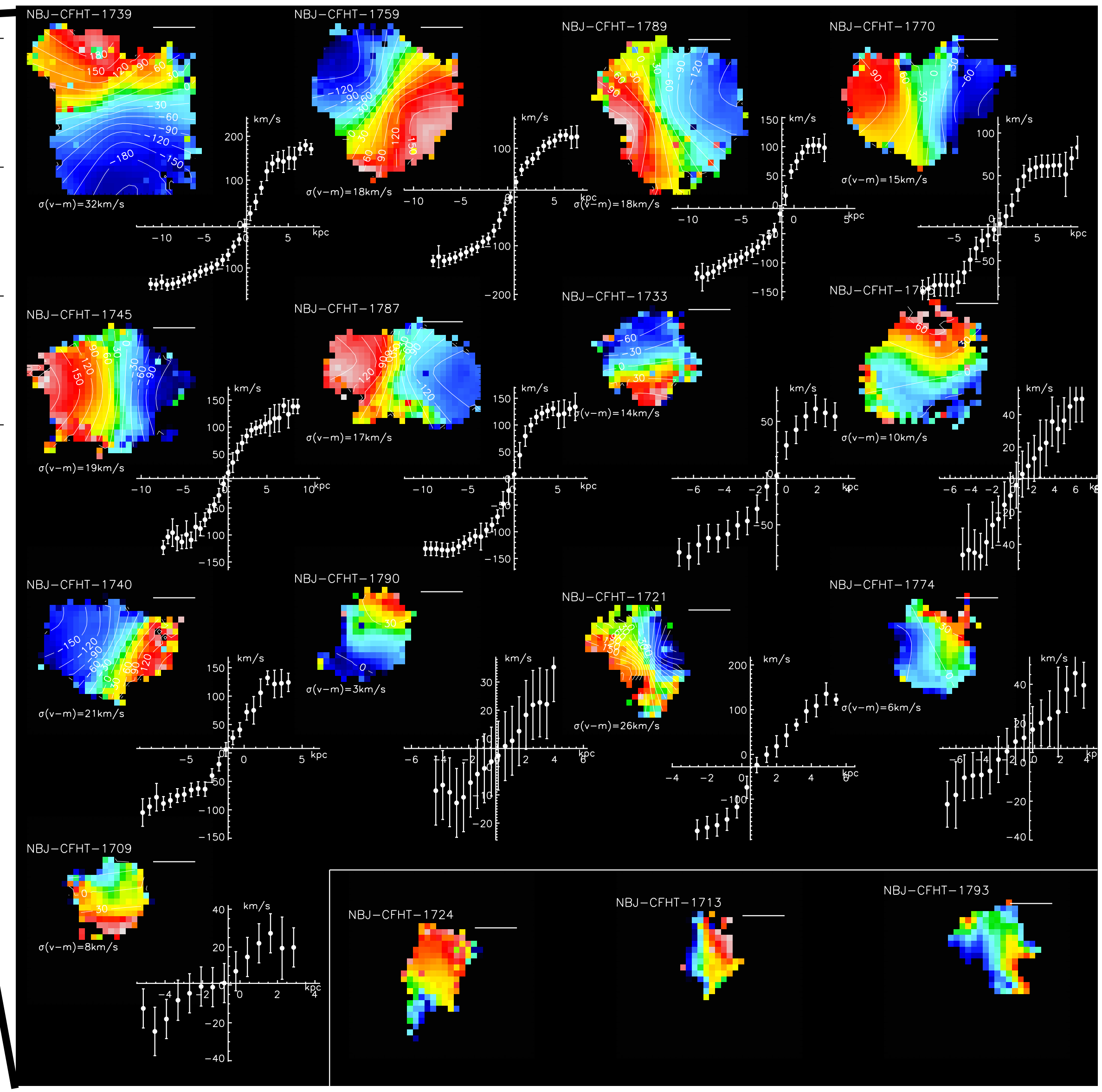


~5 hours of VLT time

CF-HiZELS (Sobral et al. 2015a)



2 hours of VLT time

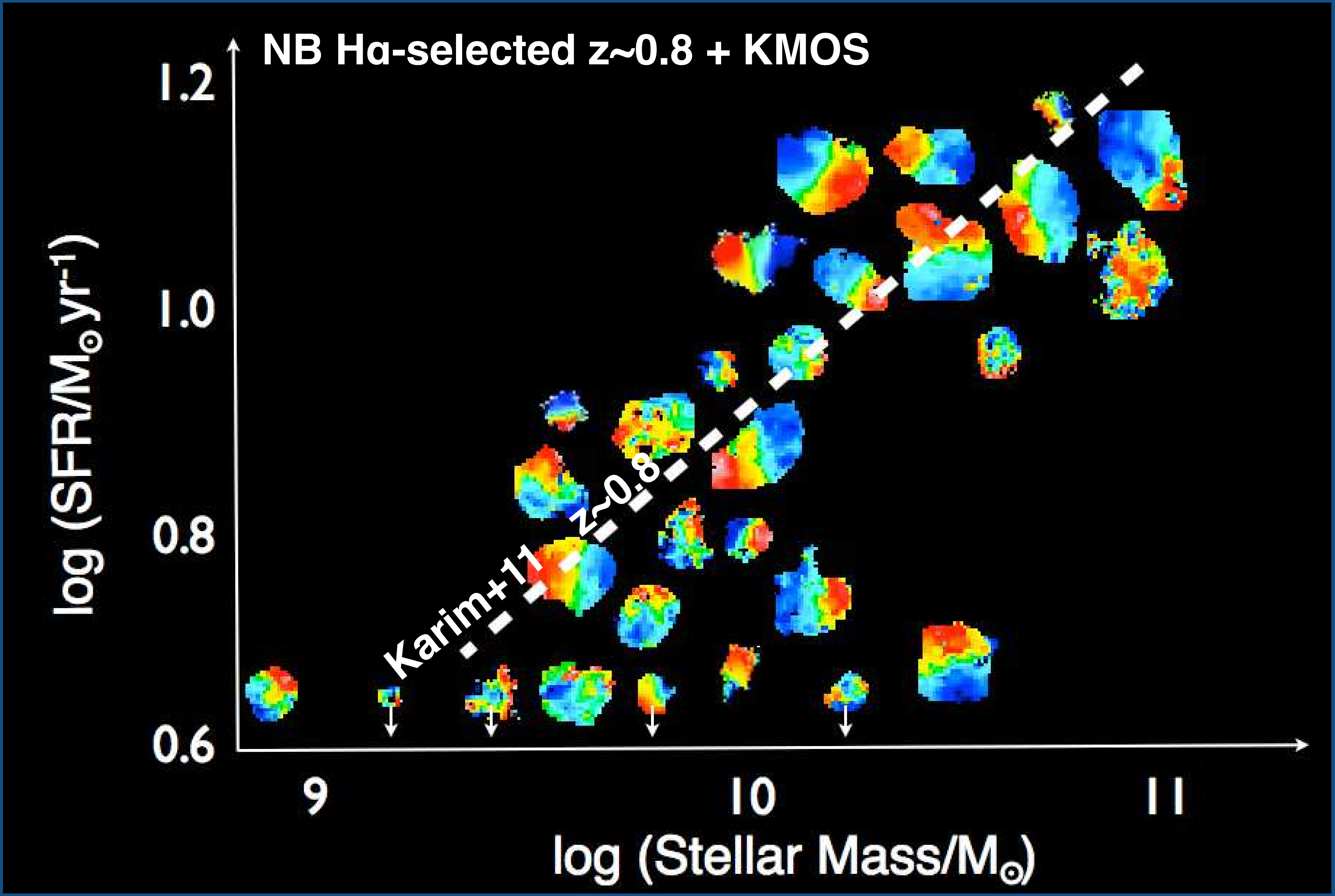


First Science results from KMOS

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

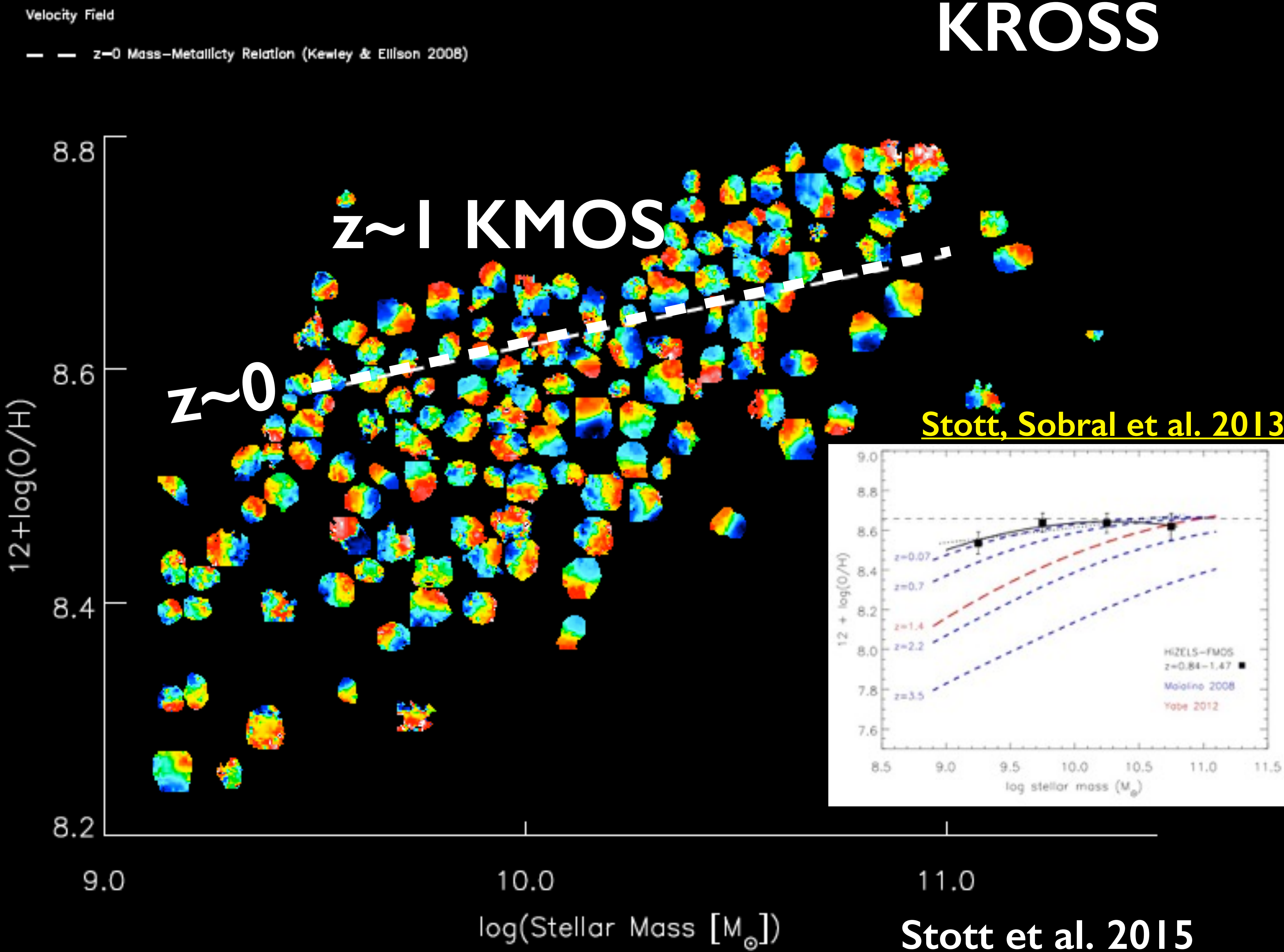
CF-HiZELS KMOS SAMPLE

just 4 hours! (with overheads)



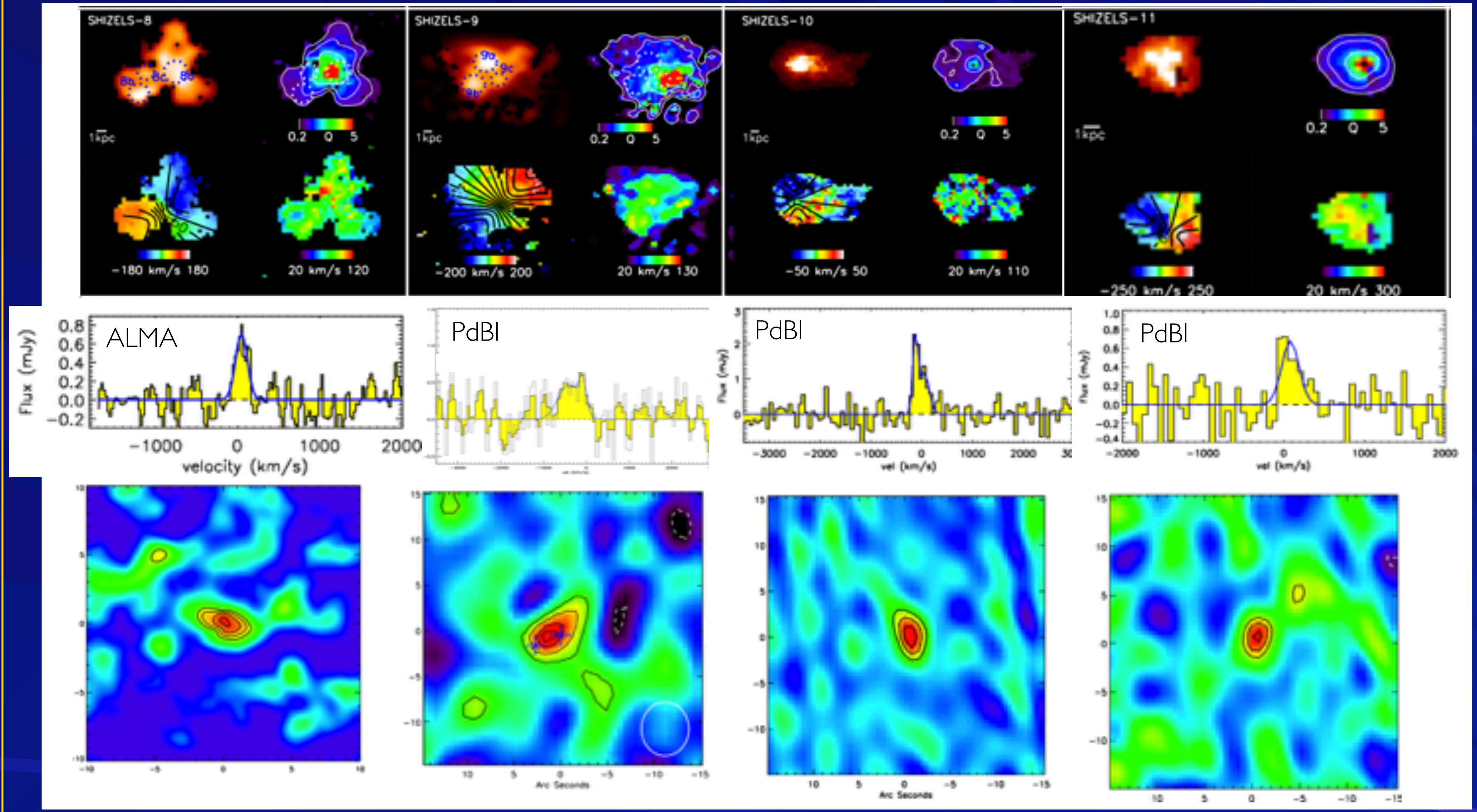
Sobral et al. 2013b, Stott, Sobral et al. 2014

KROSS



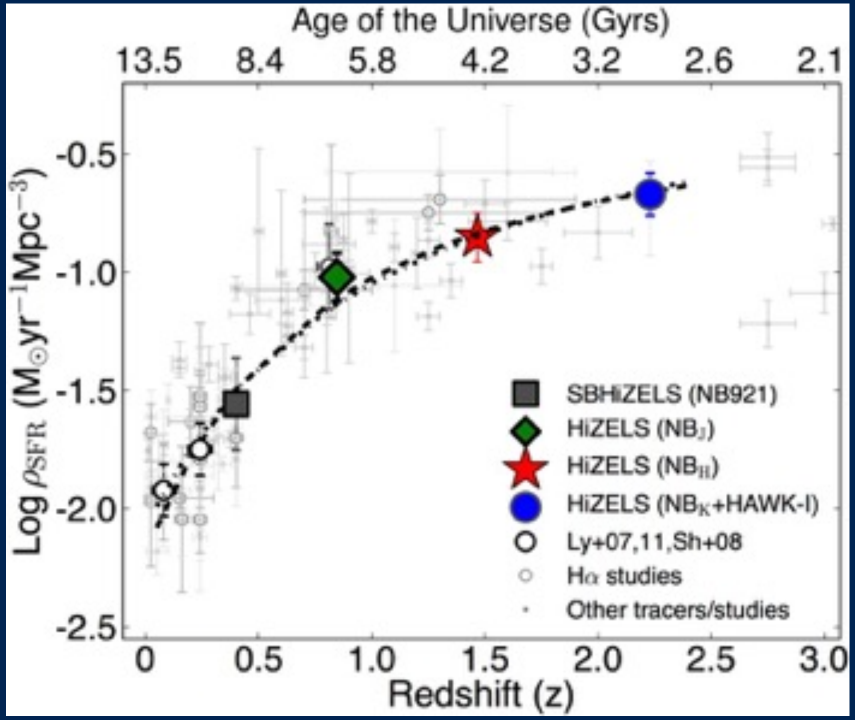
Stott et al. 2015

CO follow-up well underway with ALMA and PdBI



Towards resolved (~sub-kpc) Ha + CO + dust maps and evolution from z~2 to z~0 for "typical" SFGs

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

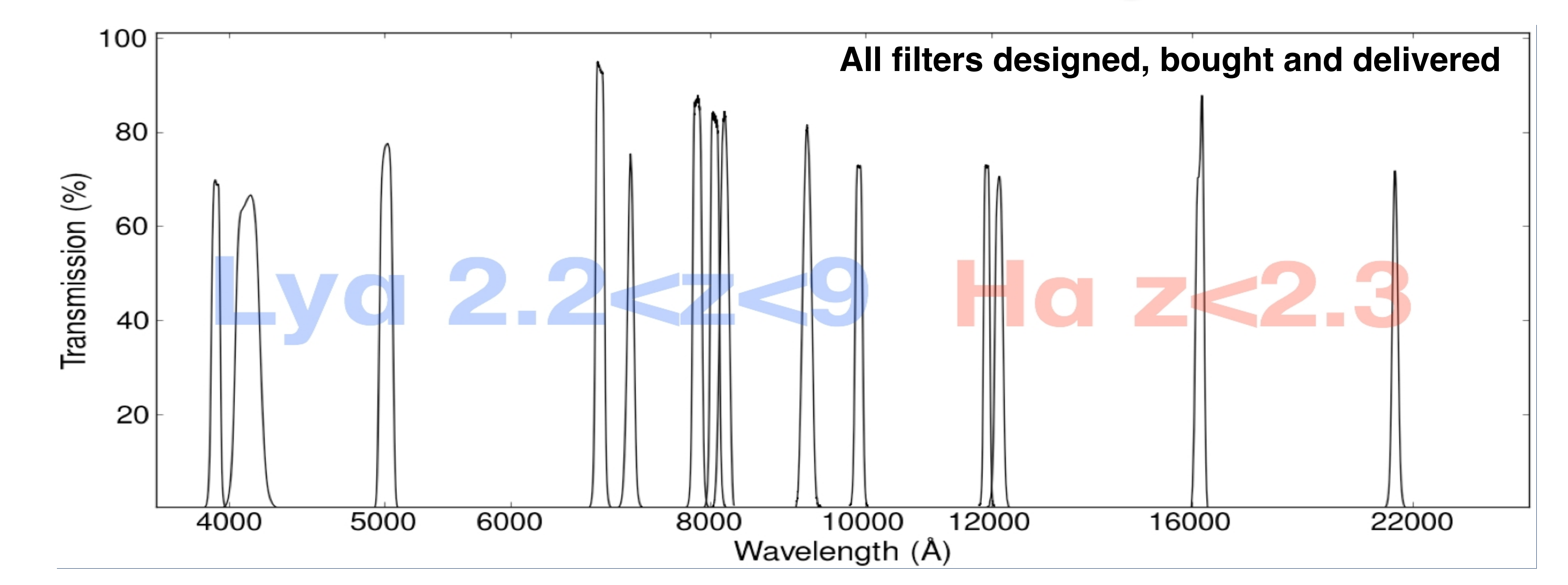


Probe to even earlier times

Calibrate Lyα at z=2.23

Survey areas >20x larger than before

Find and *Study* the most distant galaxies!



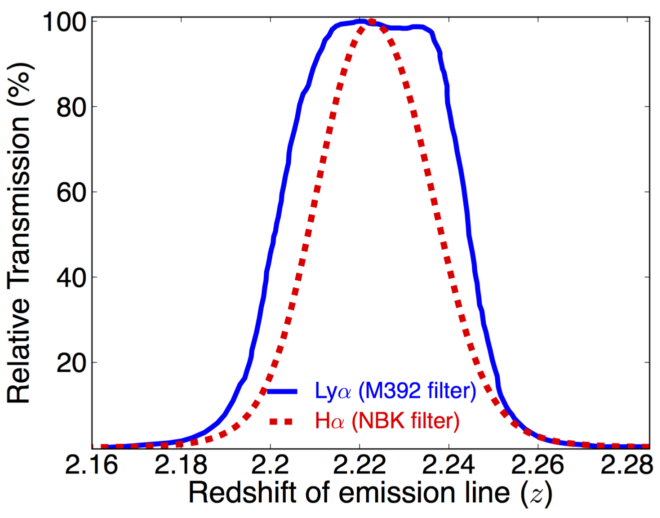
The CALYMHA survey (CAlibrating LYMan-α with Hα)

Custom-made narrow-band filter

Sobral, Matthee, Oteo et al.

A 5 deg^2 deep double-blind matched Lyα-Hα survey z=2.23

55 night survey in total.
Finished on Jan 28 2015



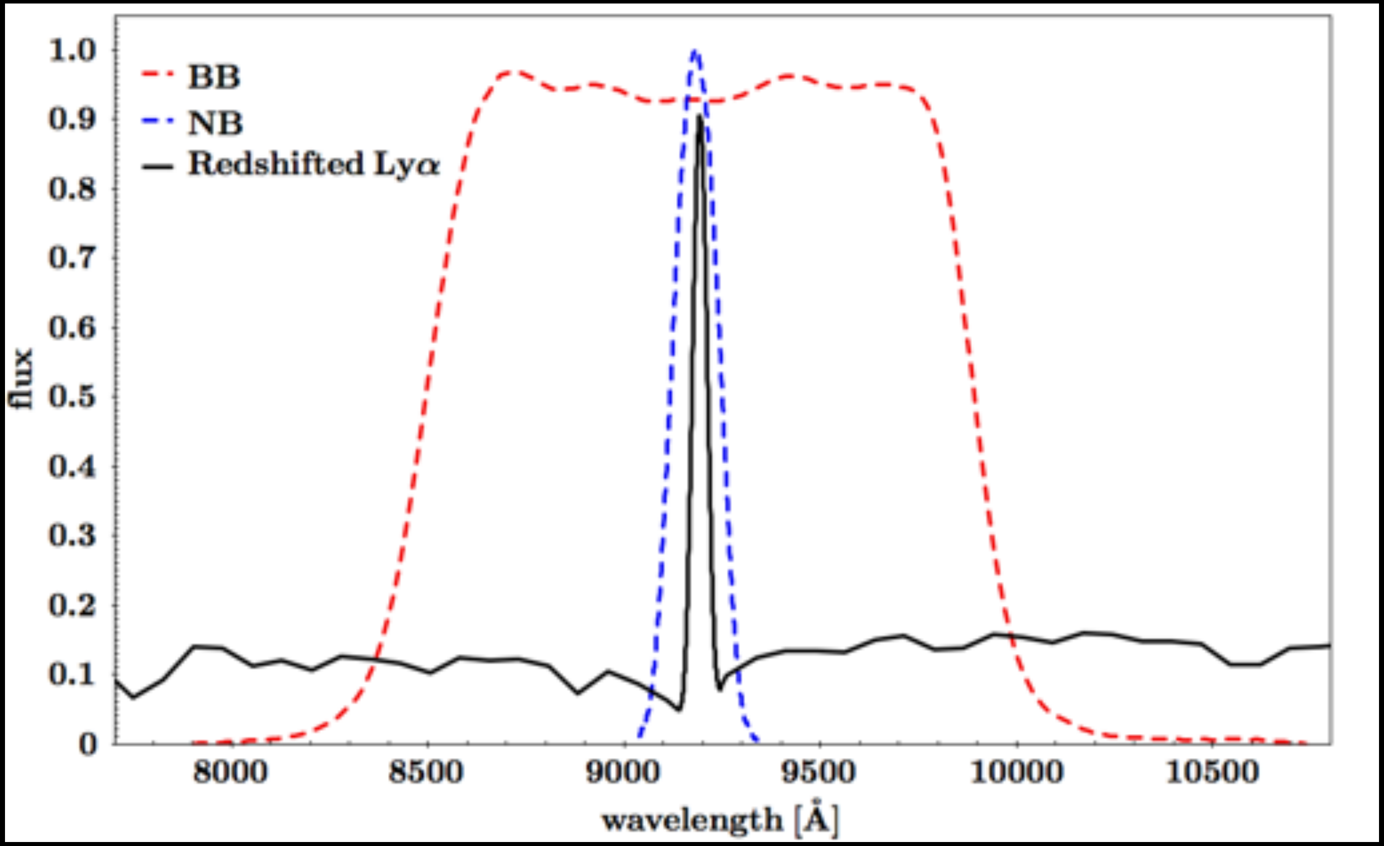
Escape fraction of star-forming galaxies (Lyα): ~4+-2% (consistent with Hayes+)

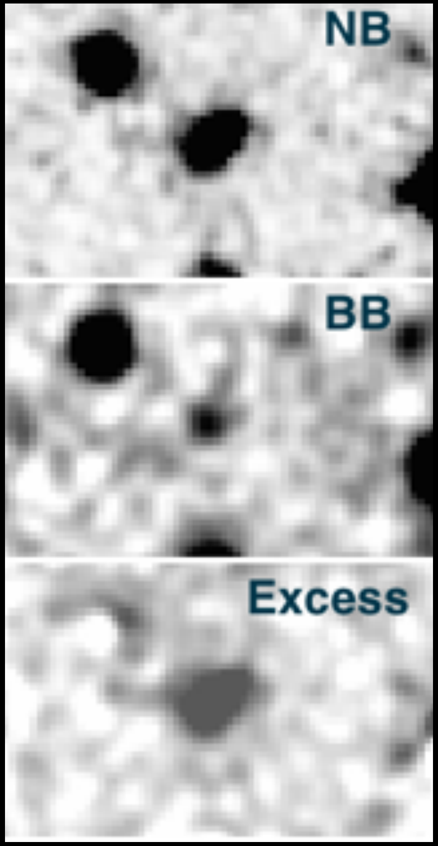
Wide range of properties of matched Lyα-Hα emitters:

Masses: ~10^9 or 10^{11} $M_\odot$ SFRs: ~5-200 Msun/yr
Dust: ~0 to 2 mags Mostly Blue but also Red!

Lyman-α as a tool to study young galaxies and re-ionisation

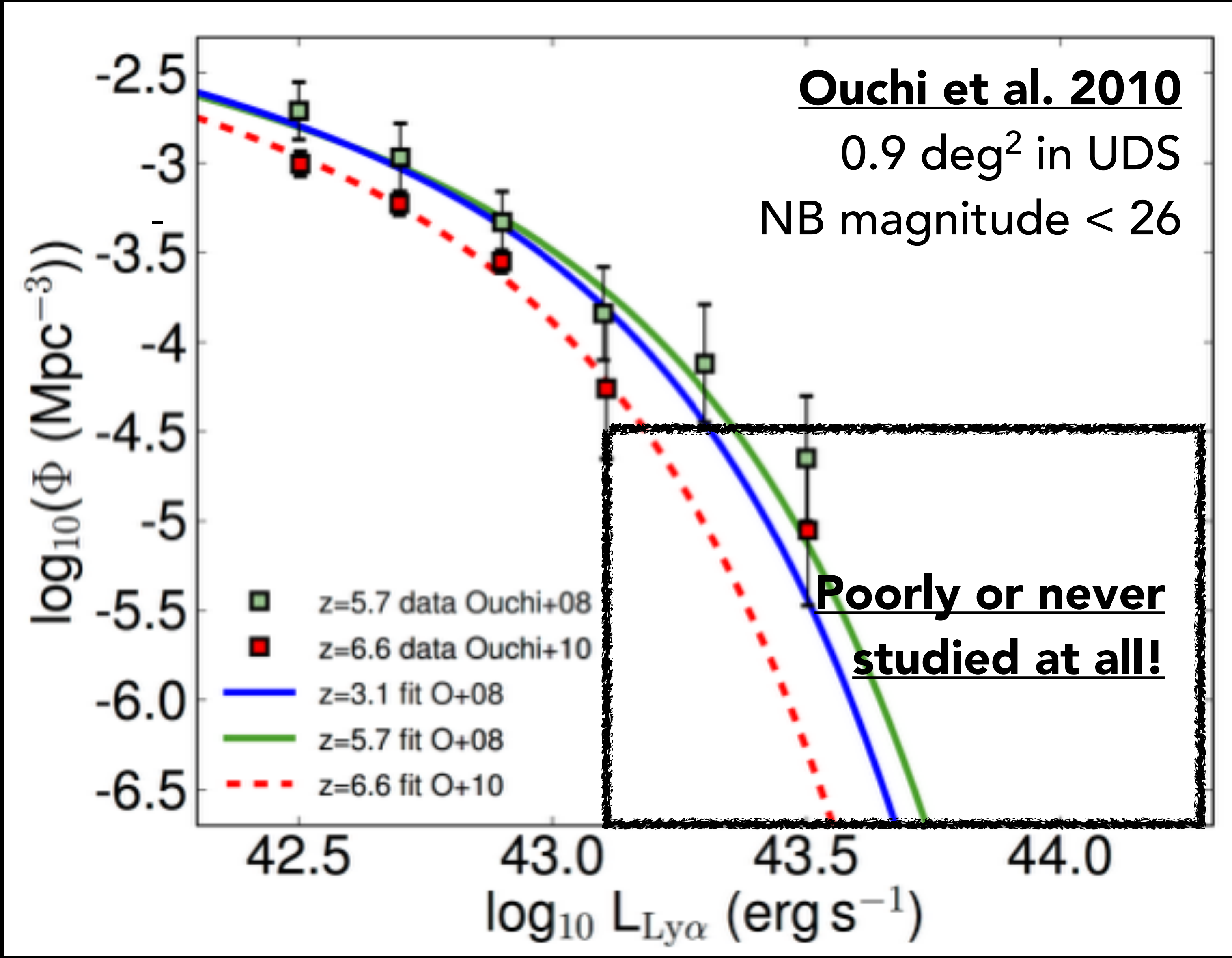
- narrow-band selects redshifted 1216 Å emission (optical at z>2)



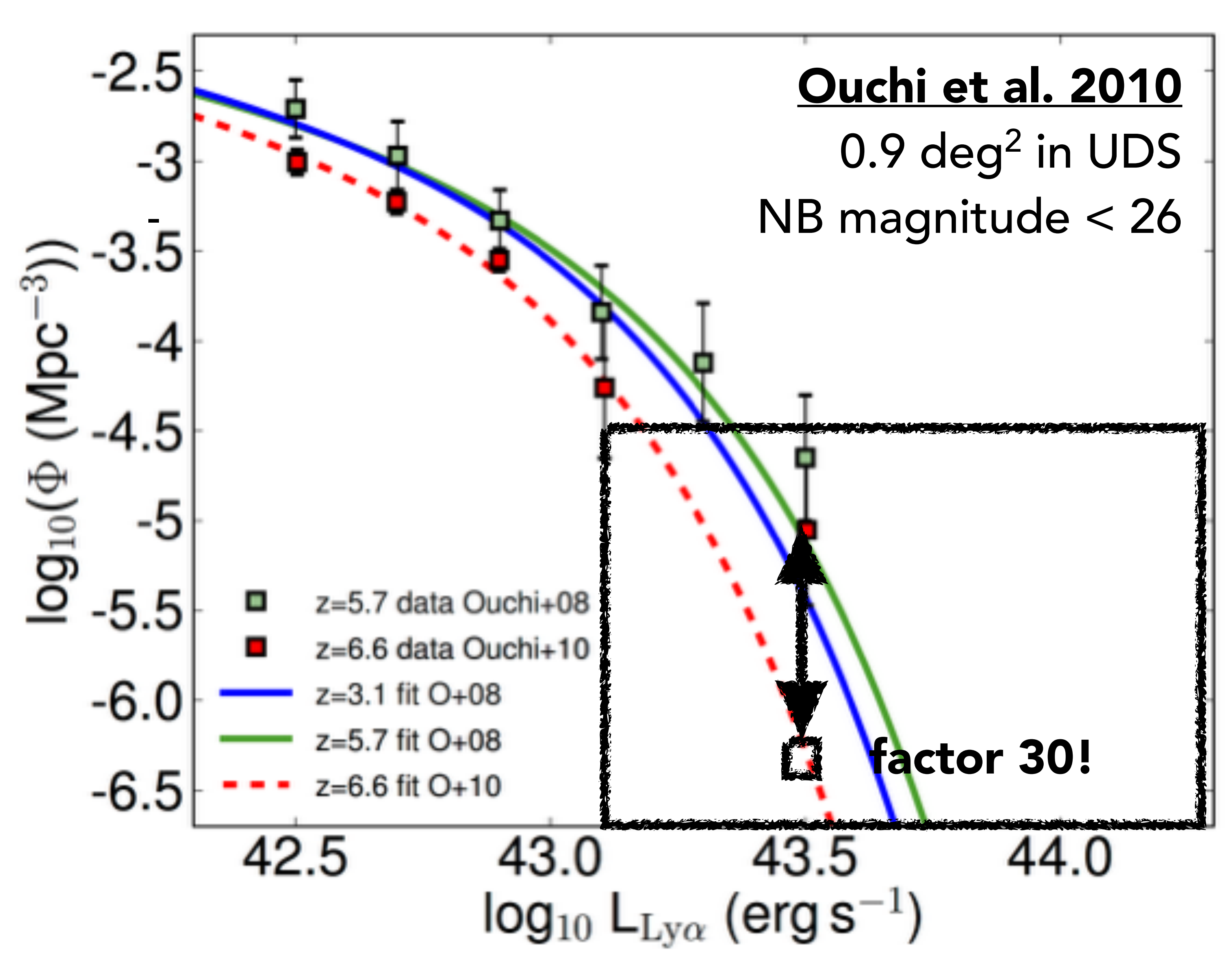


- Lyα emitted by young galaxies (high EW)
- Lyα absorbed in more neutral IGM (test for re-ionisation)

Lyman-α Luminosity function z~3-6 roughly constant -> “decline” at z>6?

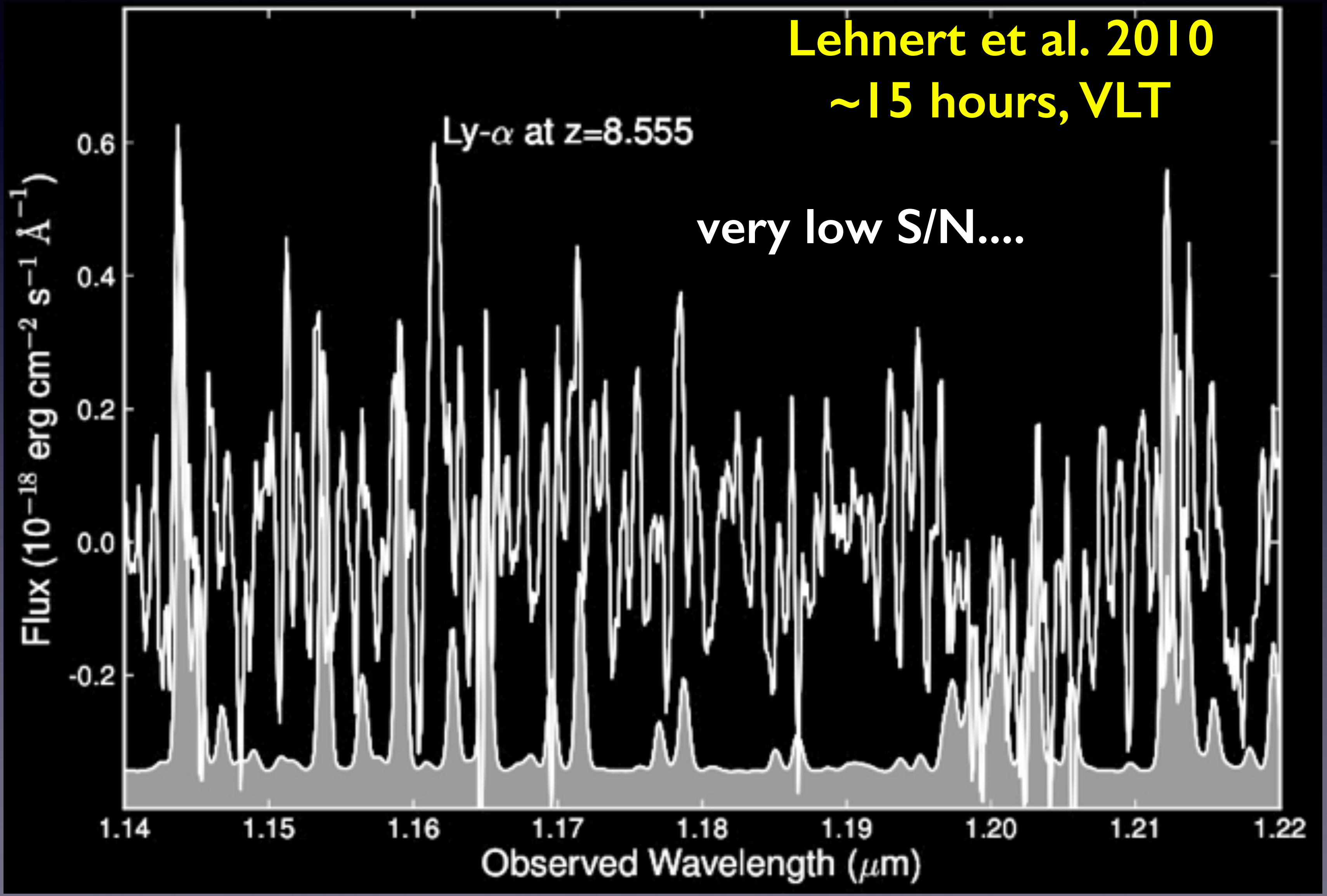


Lyman-α Luminosity function z~3-6 roughly constant -> “decline” at z>6?



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

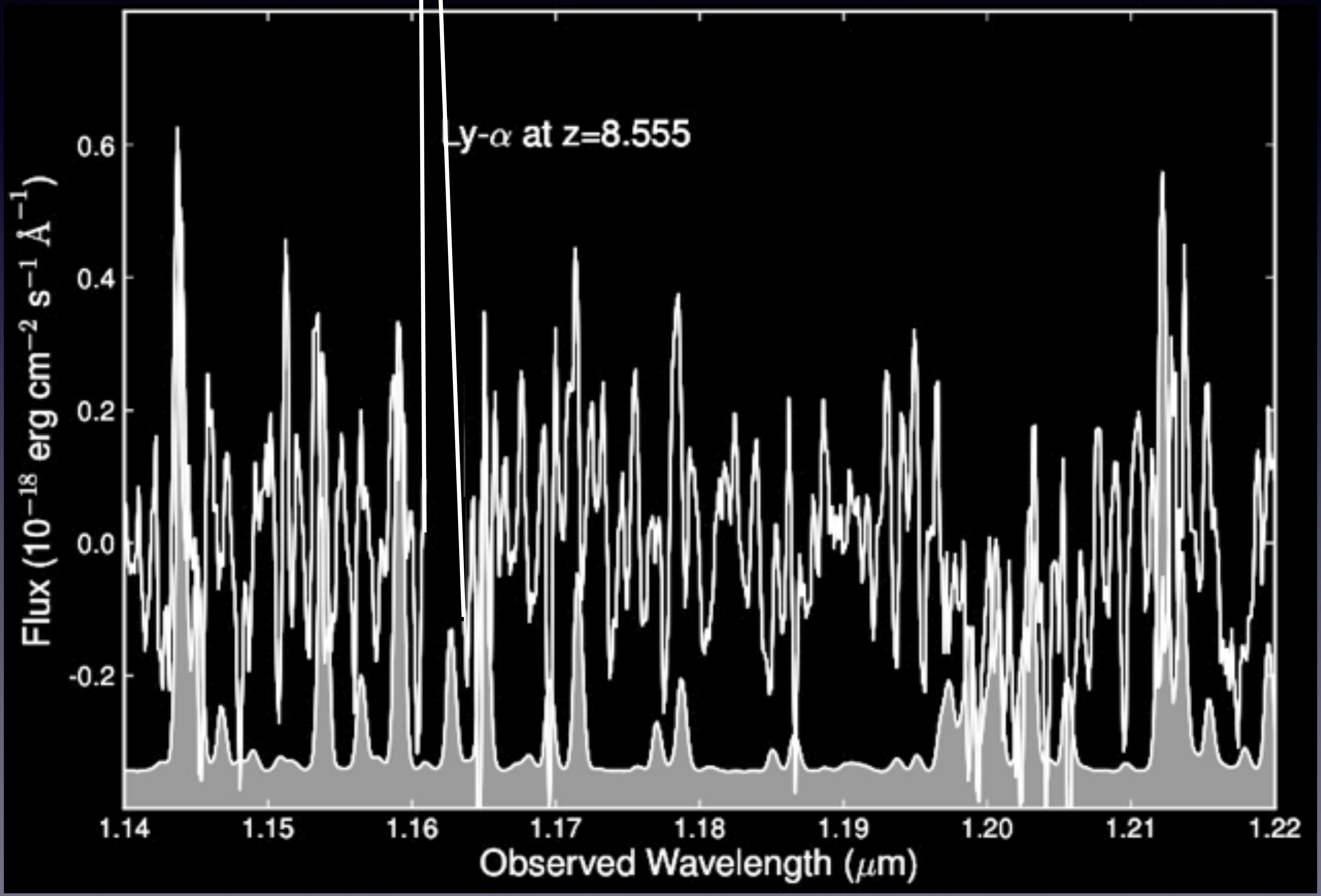
(see Bunker et al. 2013)



In ~ couple of hours

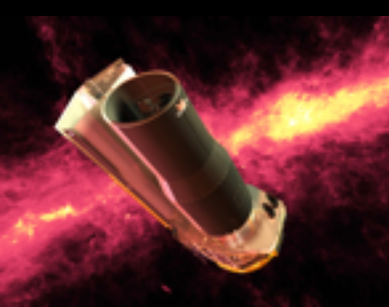
They will look like this!

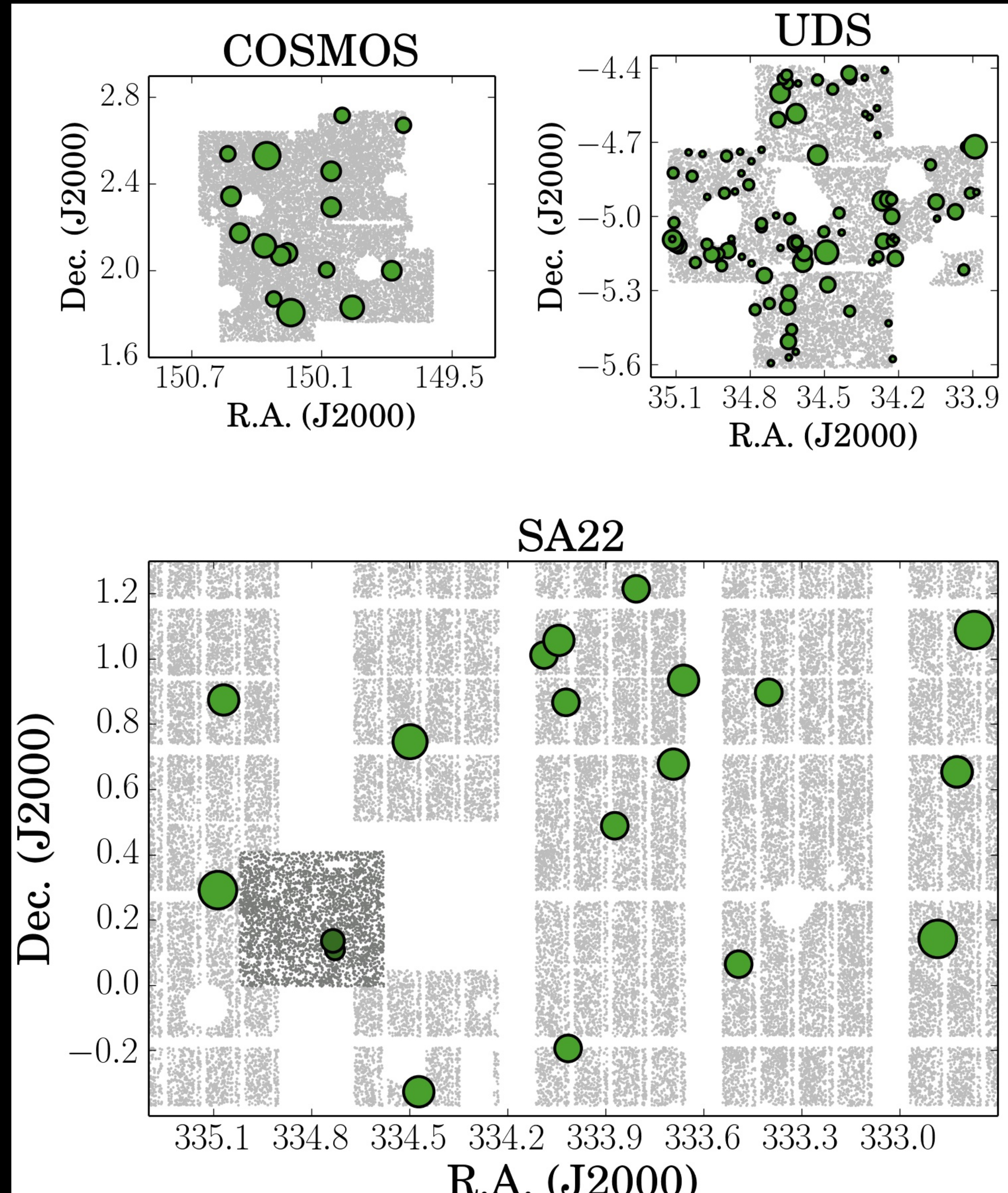
See also: Oesch+2015



Some highlights of the z=6.6 survey (~800 Myr after Big Bang), 1 of 10 different "time slices"

Subaru survey (PI: Sobral)





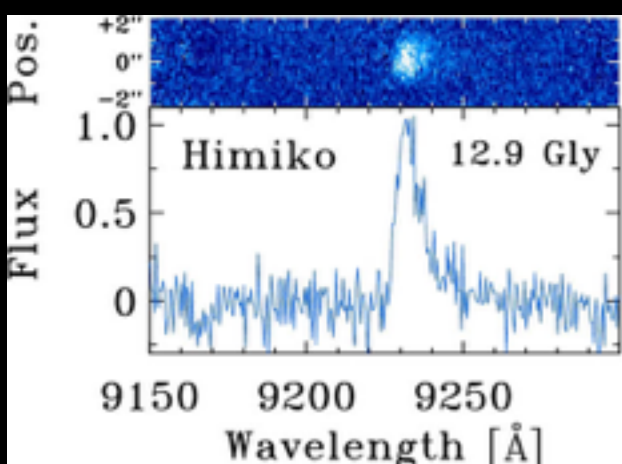
Results:

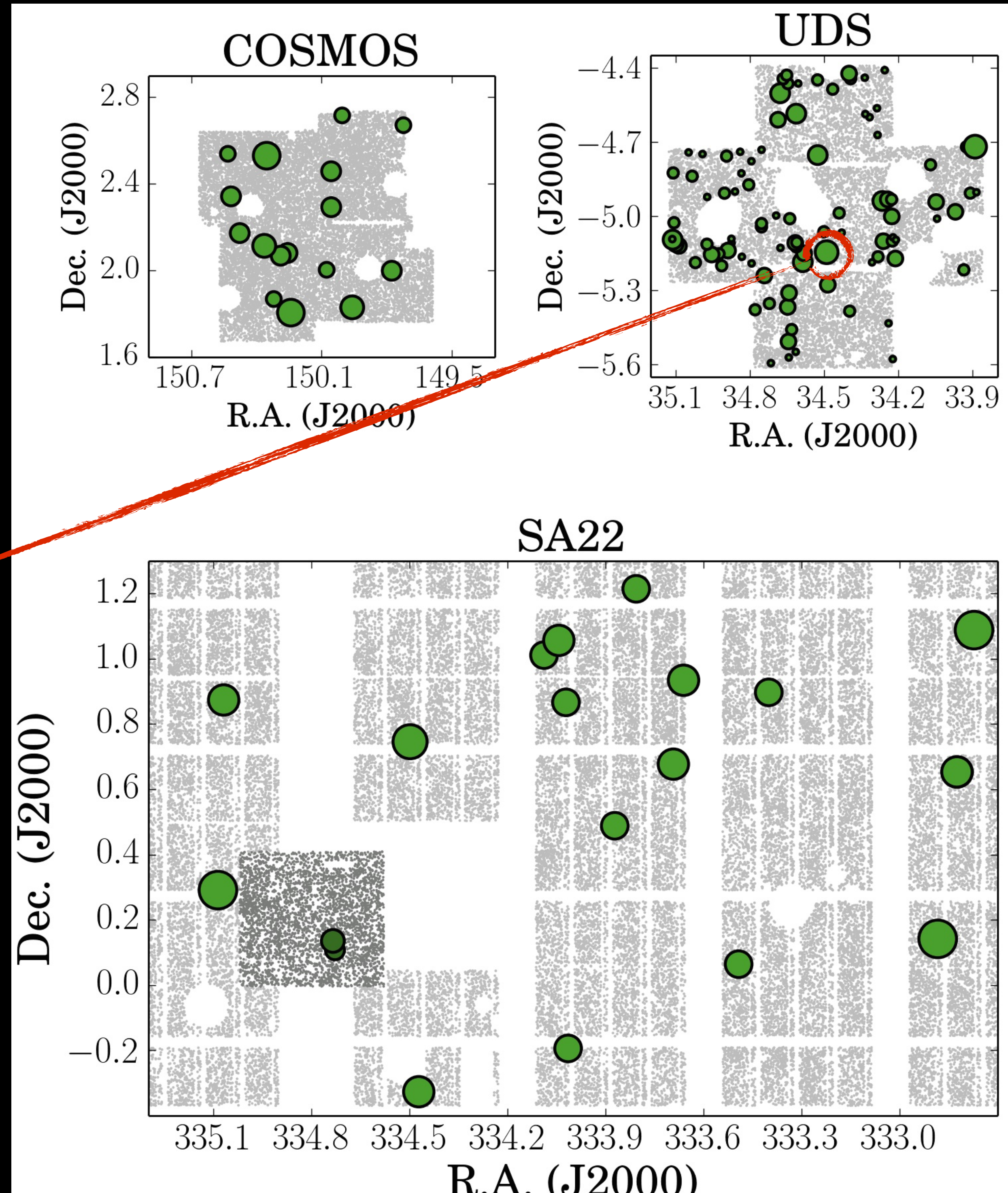
99 LAEs in UDS

15 LAEs in COSMOS

2 LAEs in SA22-Deep

18 LAEs in SA22-Wide





Ouchi et al. 2009, 2013

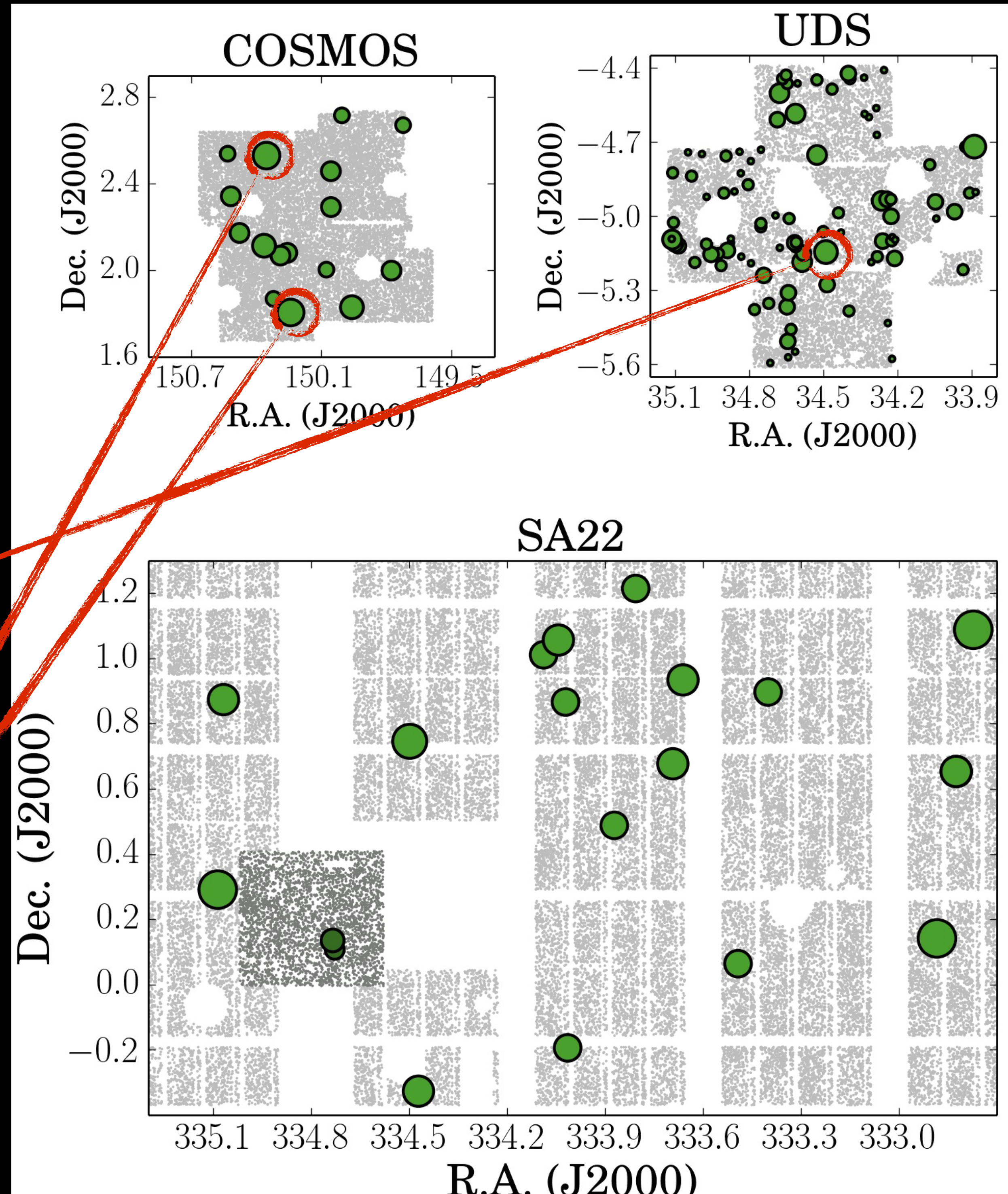
Results:

99 LAEs in UDS

15 LAEs in COSMOS

2 LAEs in SA22-Deep

18 LAEs in SA22-Wide



"Himiko"

Even brighter!

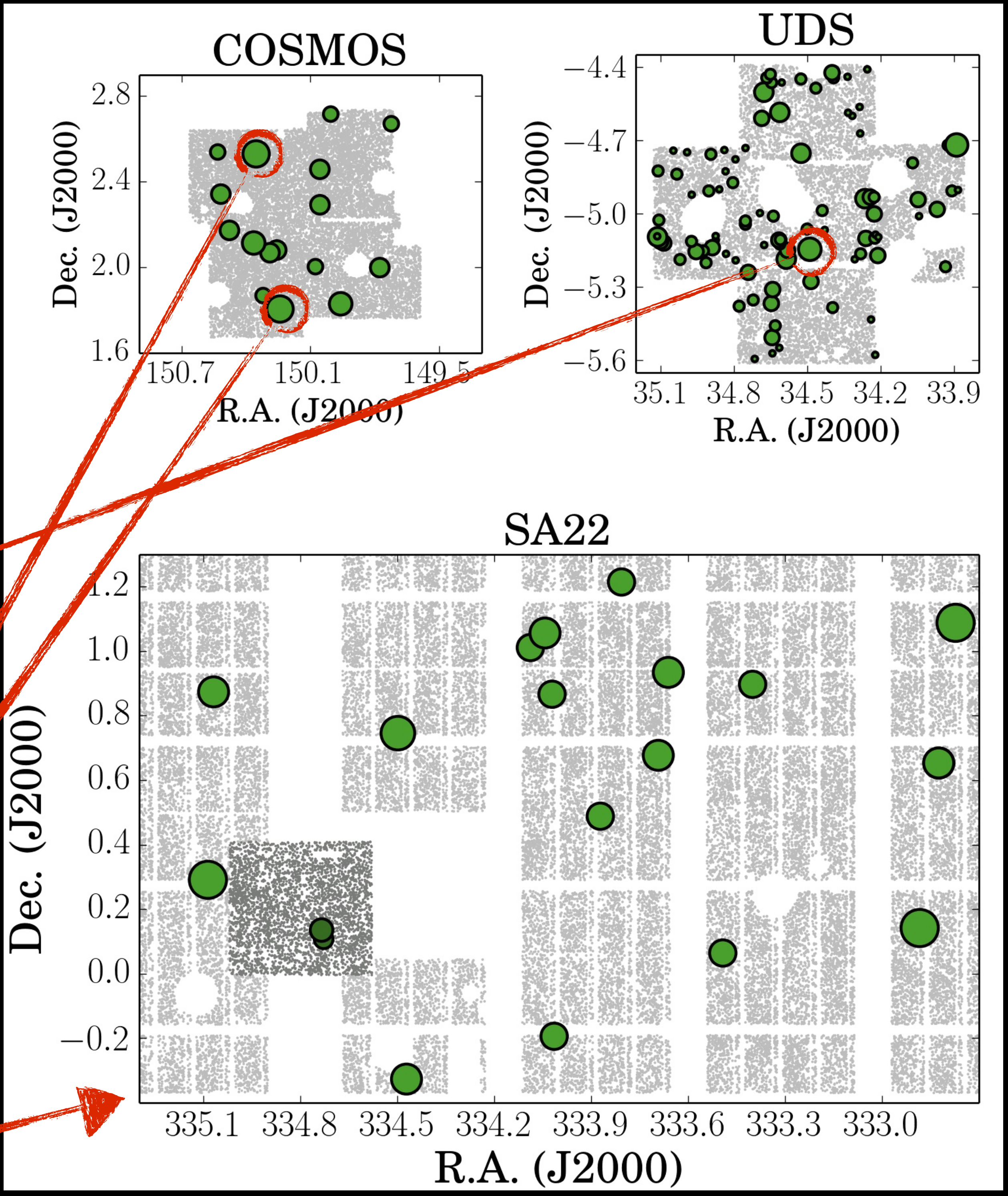
Results:

99 LAEs in UDS

15 LAEs in COSMOS

2 LAEs in SA22-Deep

18 LAEs in SA22-Wide



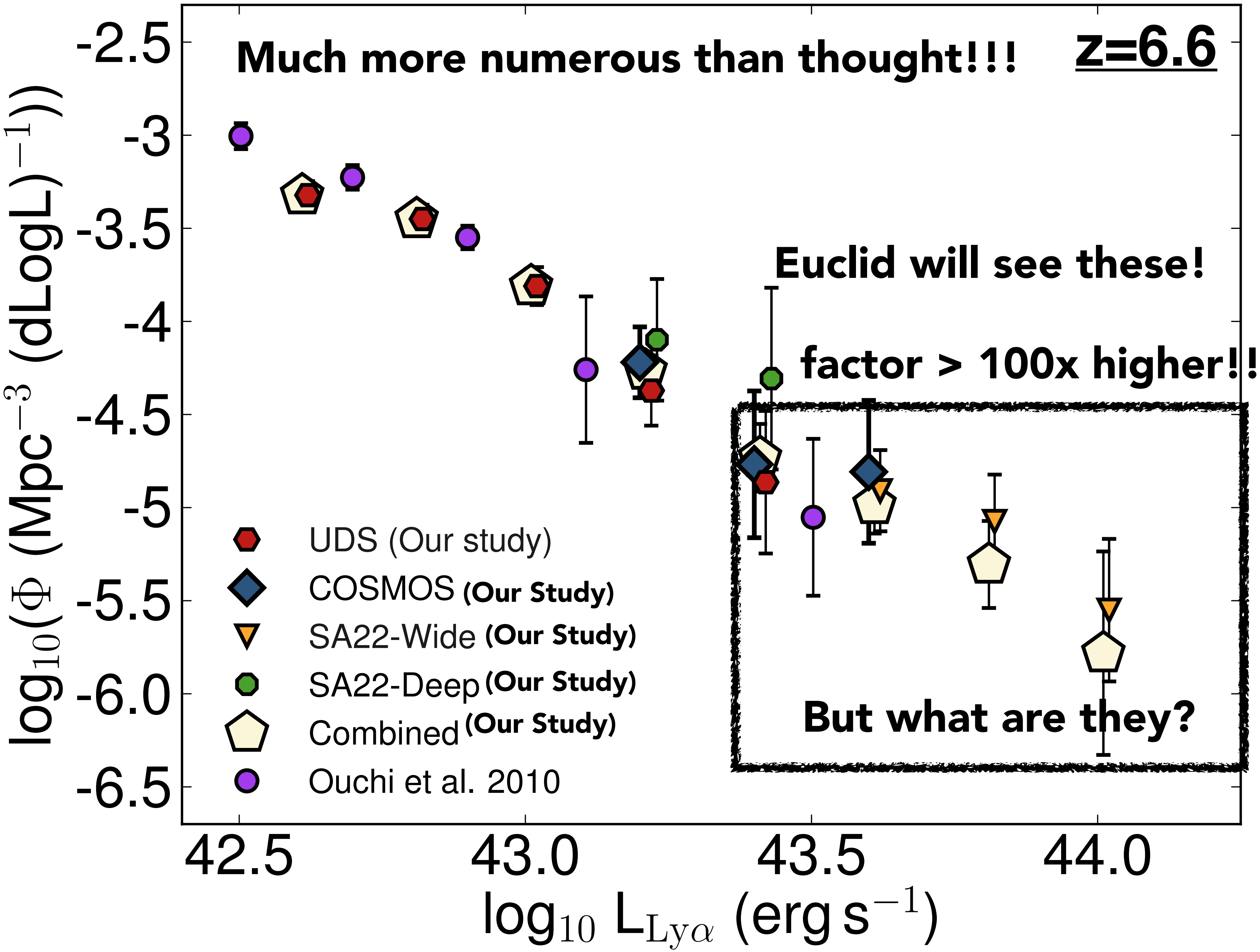
“Himiko”

Even brighter!

EVEN BRIGHTER!!

Lyman-α emitters 12.9 Gyrs ago: number counts

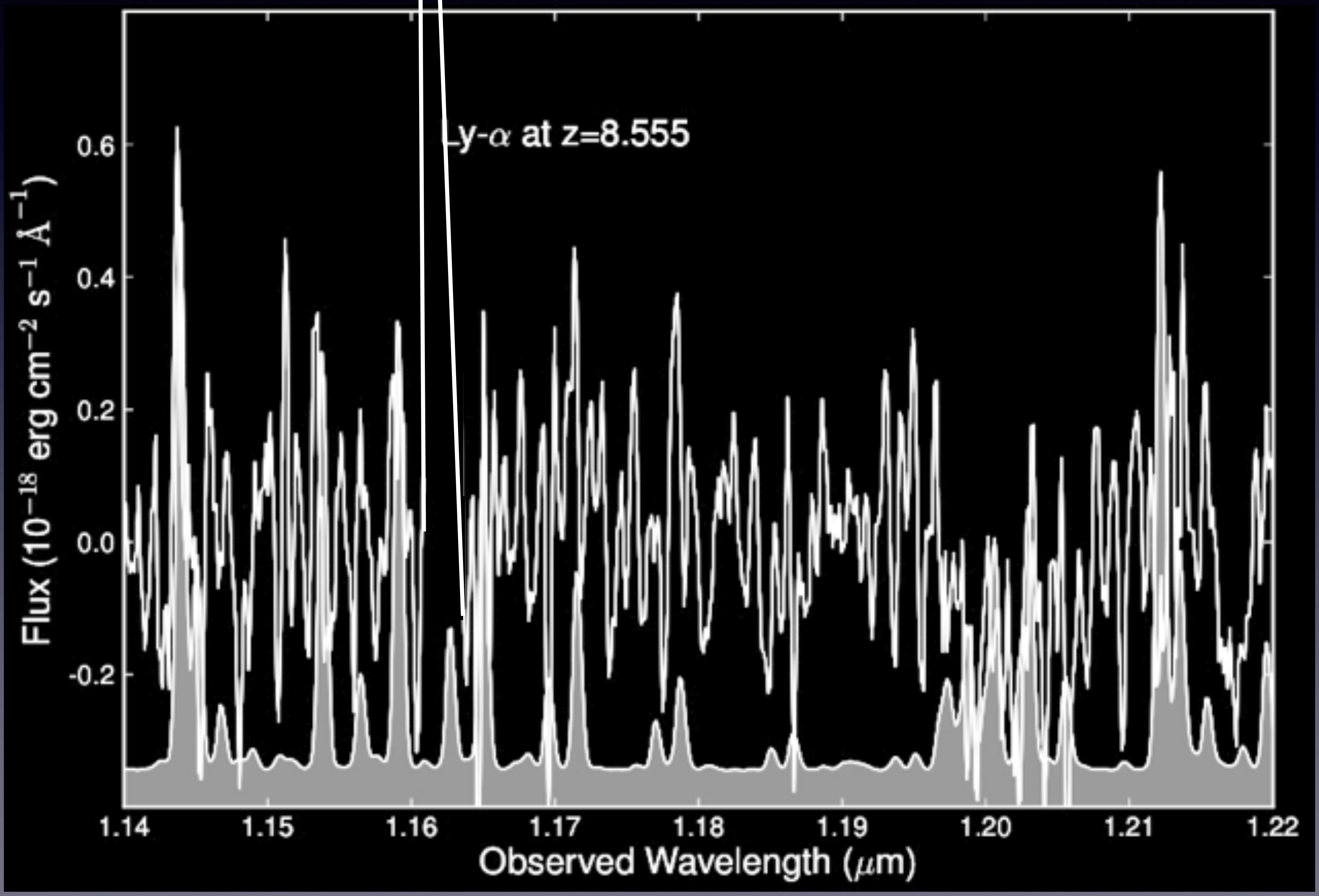
Matthee, Sobral et al. 2015



In ~ couple of hours

So are they like this?

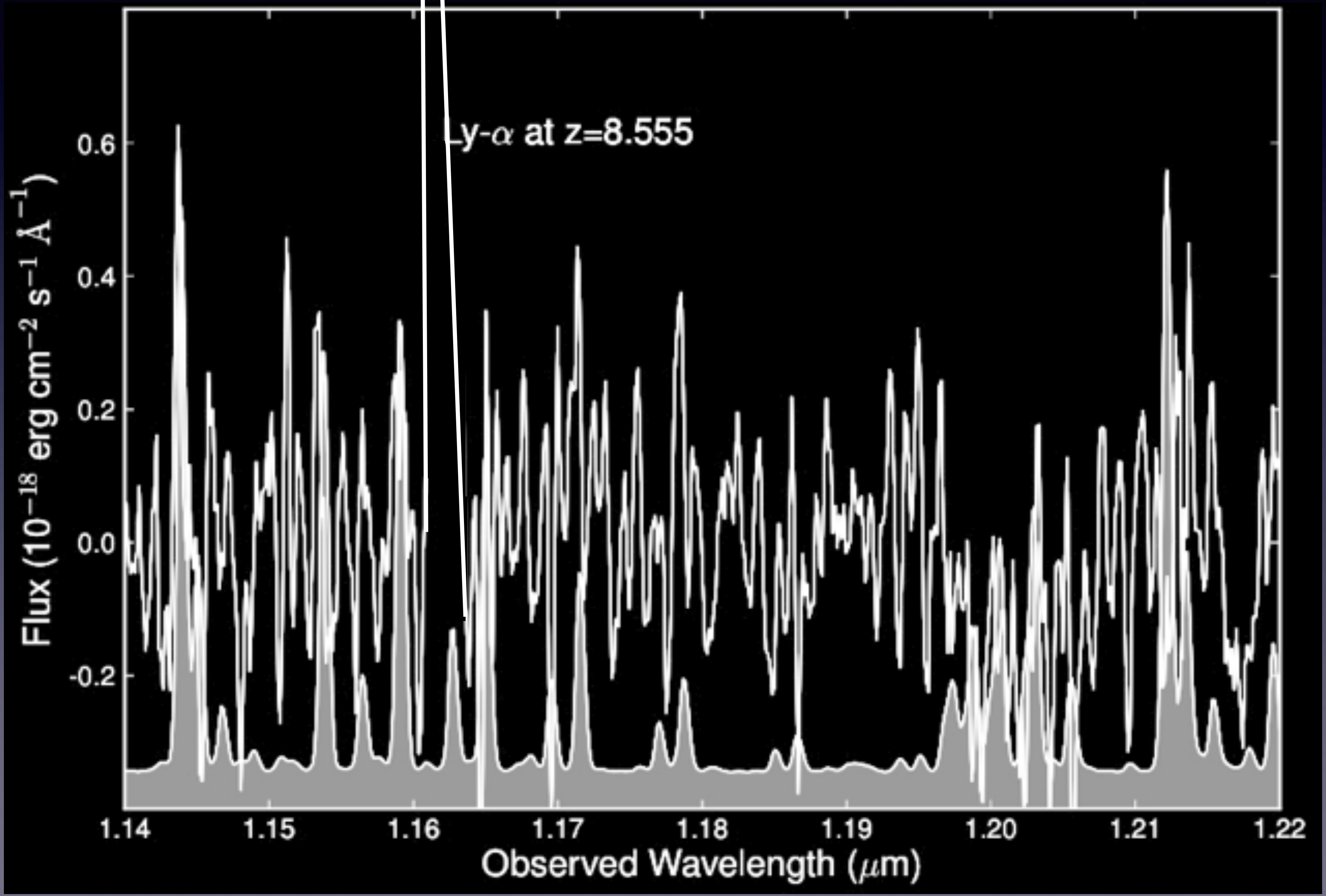
Are they real LAEs?



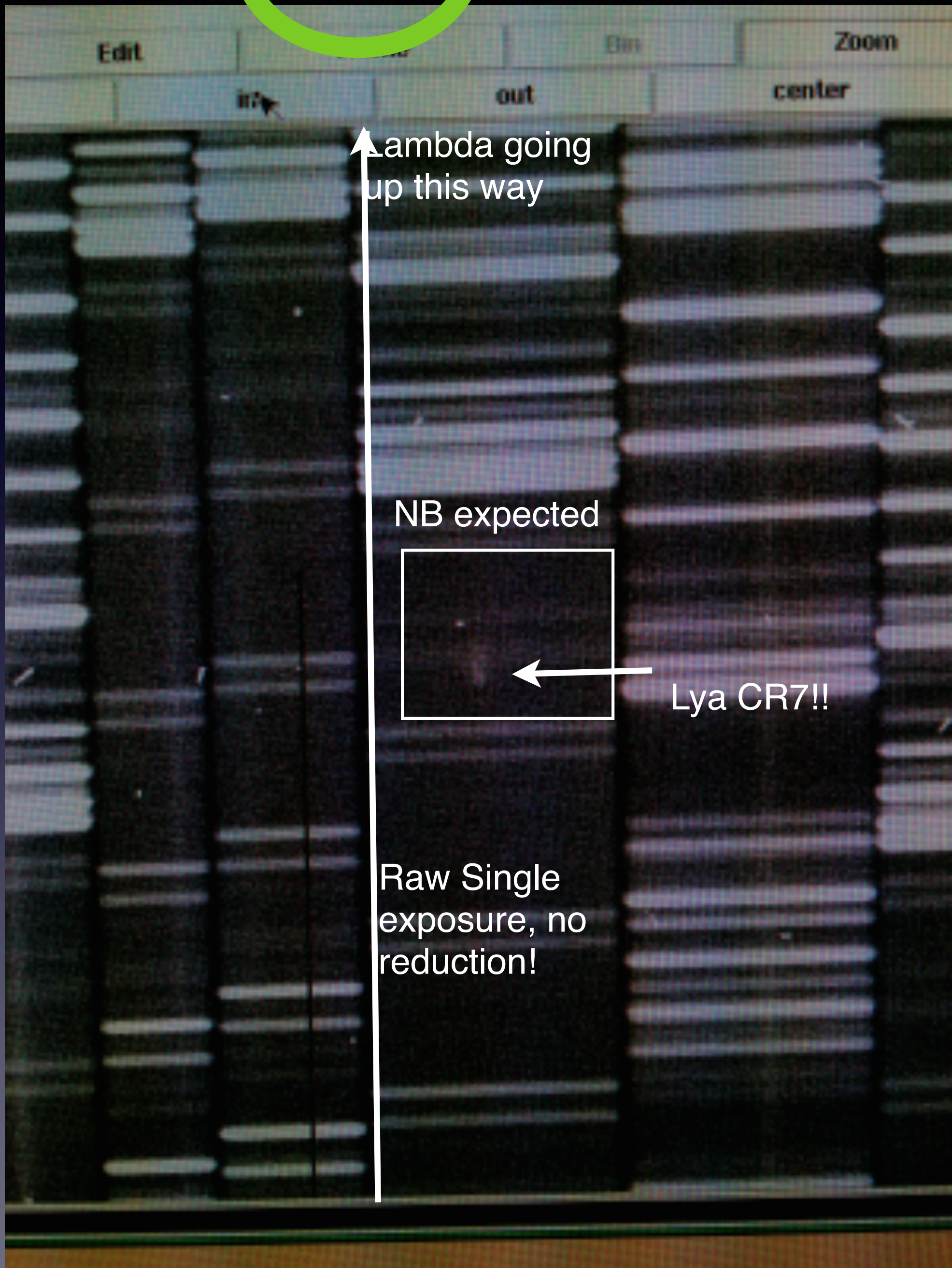
~~In ~ couple of hours~~

So are they like this?

Are they real LAEs?



15 min z=6.6



Spectroscopic confirmation with Keck/DEIMOS

DDT time, PI: Sobral

Spectroscopic confirmation with VLT/X-SHOOTER + FORS2

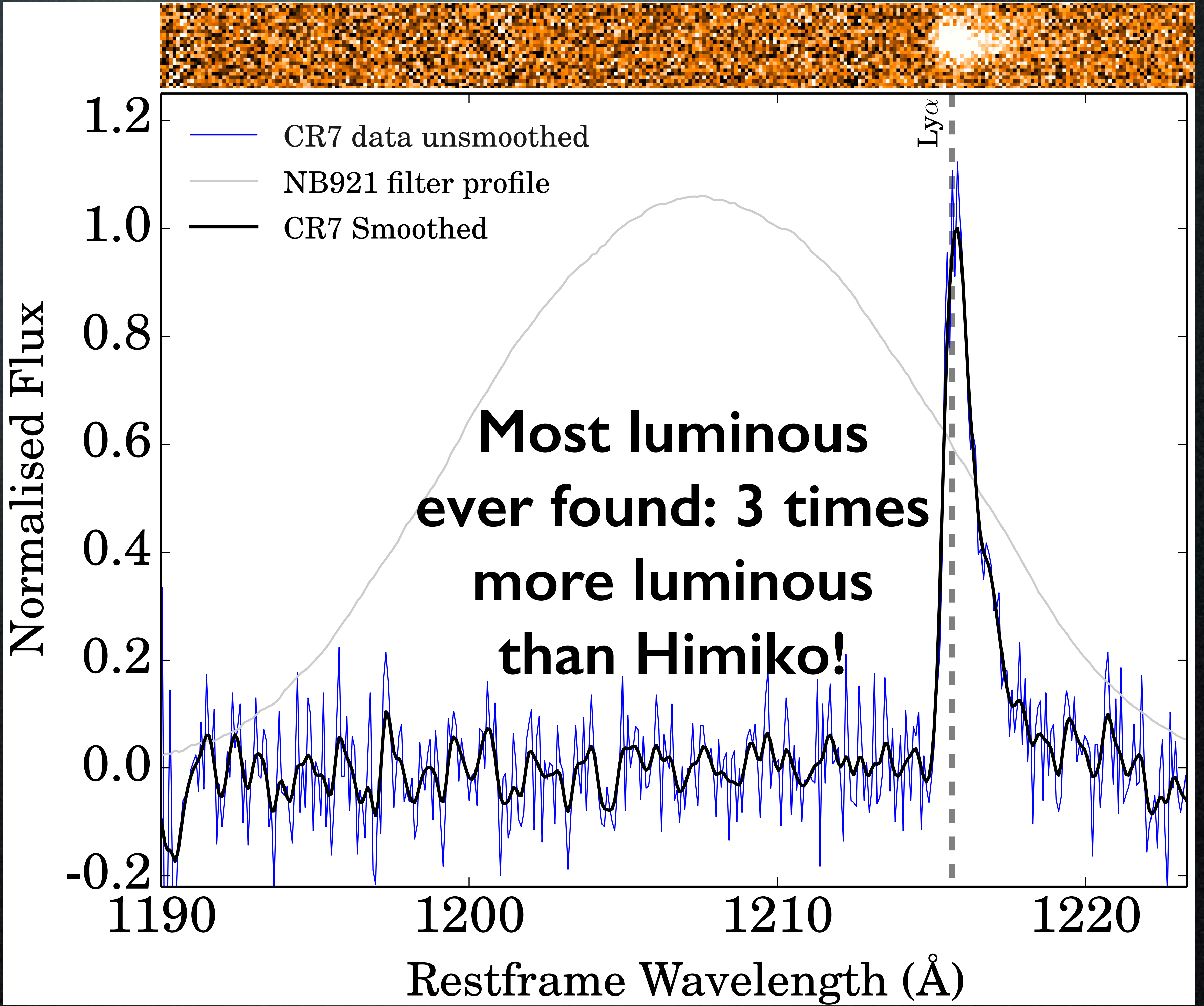
Lyα

Keck/
DEIMOS

1 hour!

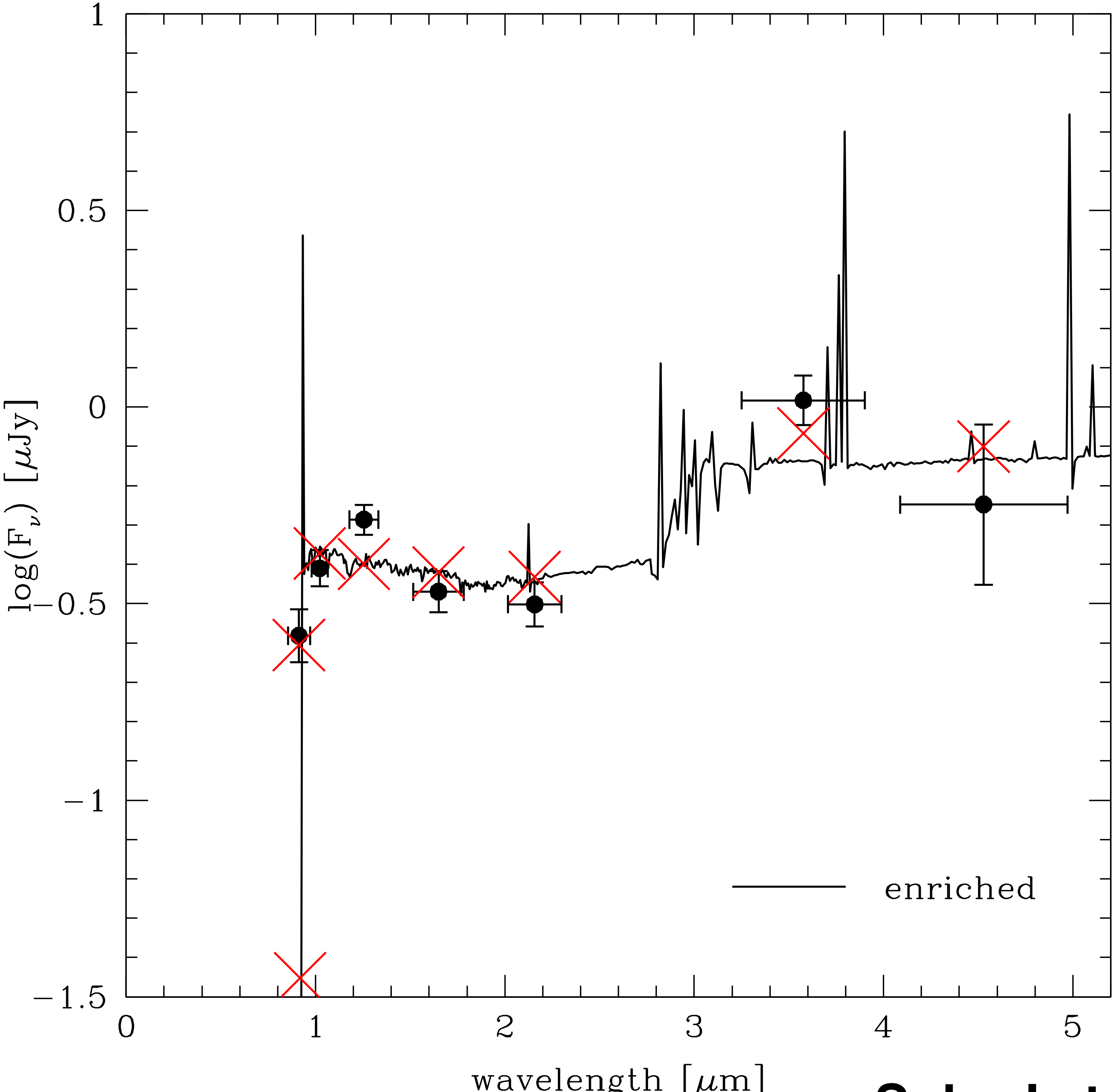
z=6.6

L~10^44 erg/s/cm^2

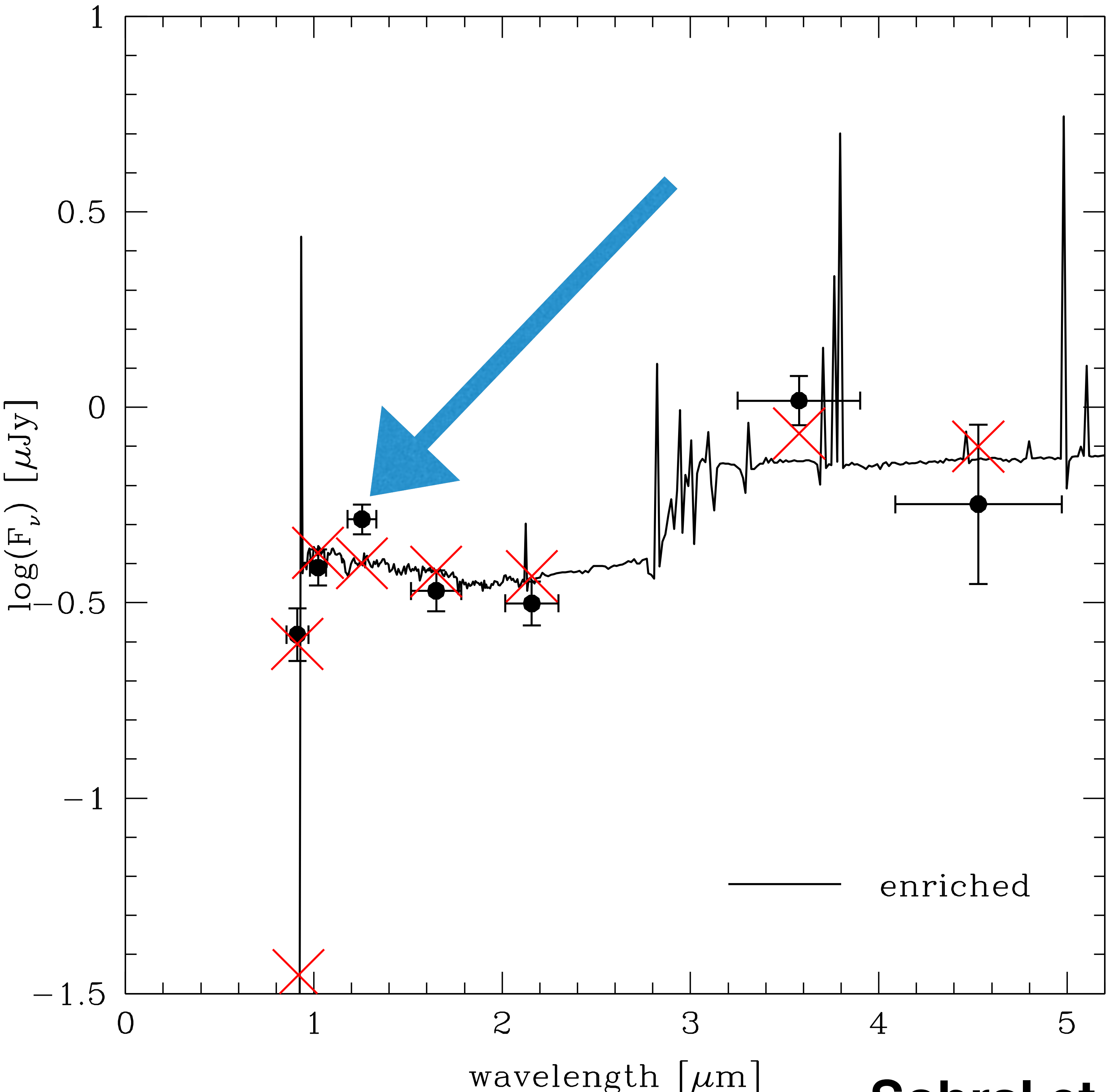


No evidence for AGN

Sobral et al. 2015c.



Sobral et al. 2015c

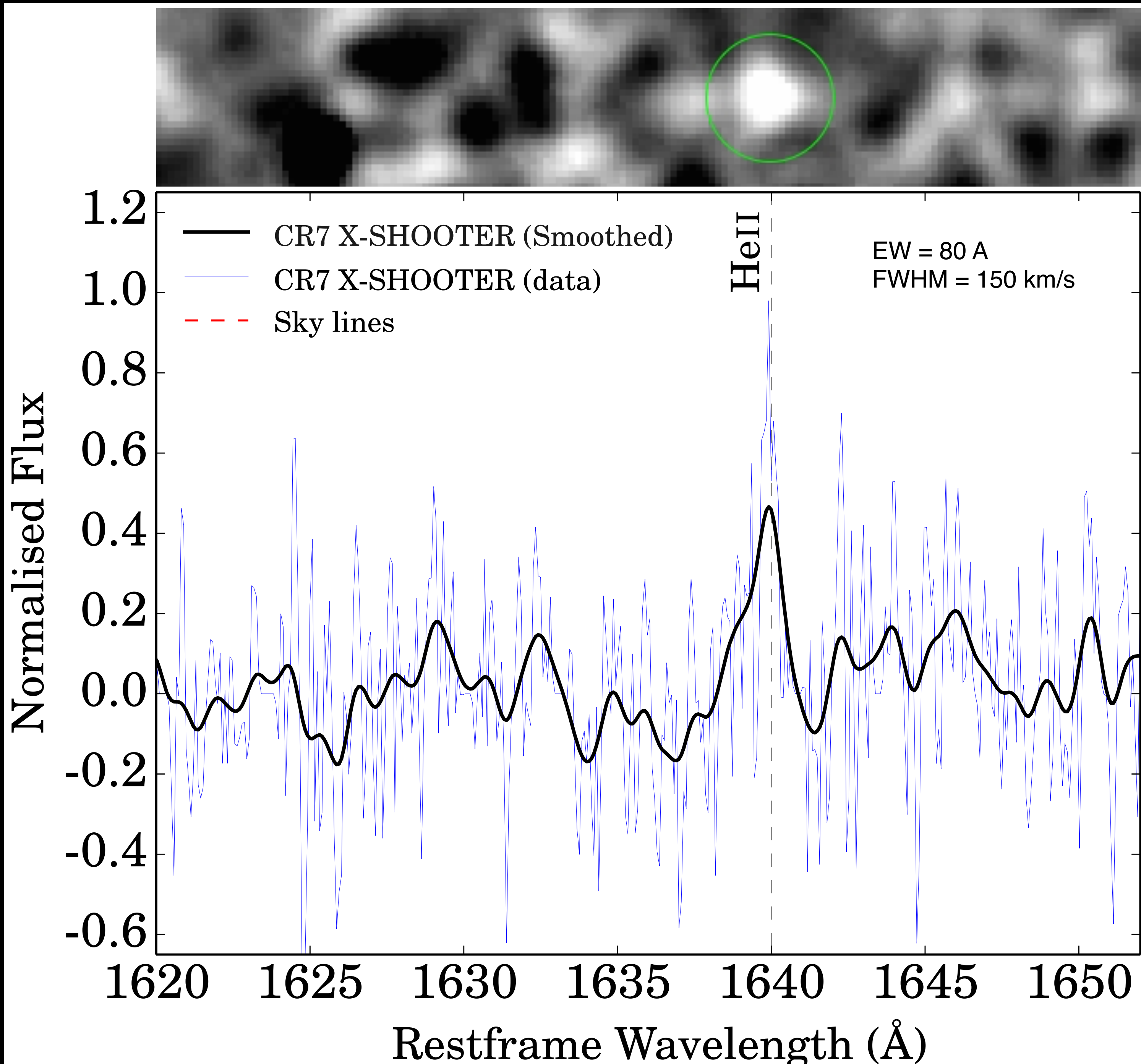


Sobral et al. 2015c

CR7: X-SHOOTER: 2 hours

Anything interesting to explain J excess?

CR7: X-SHOOTER: 2 hours   HeII 1640!

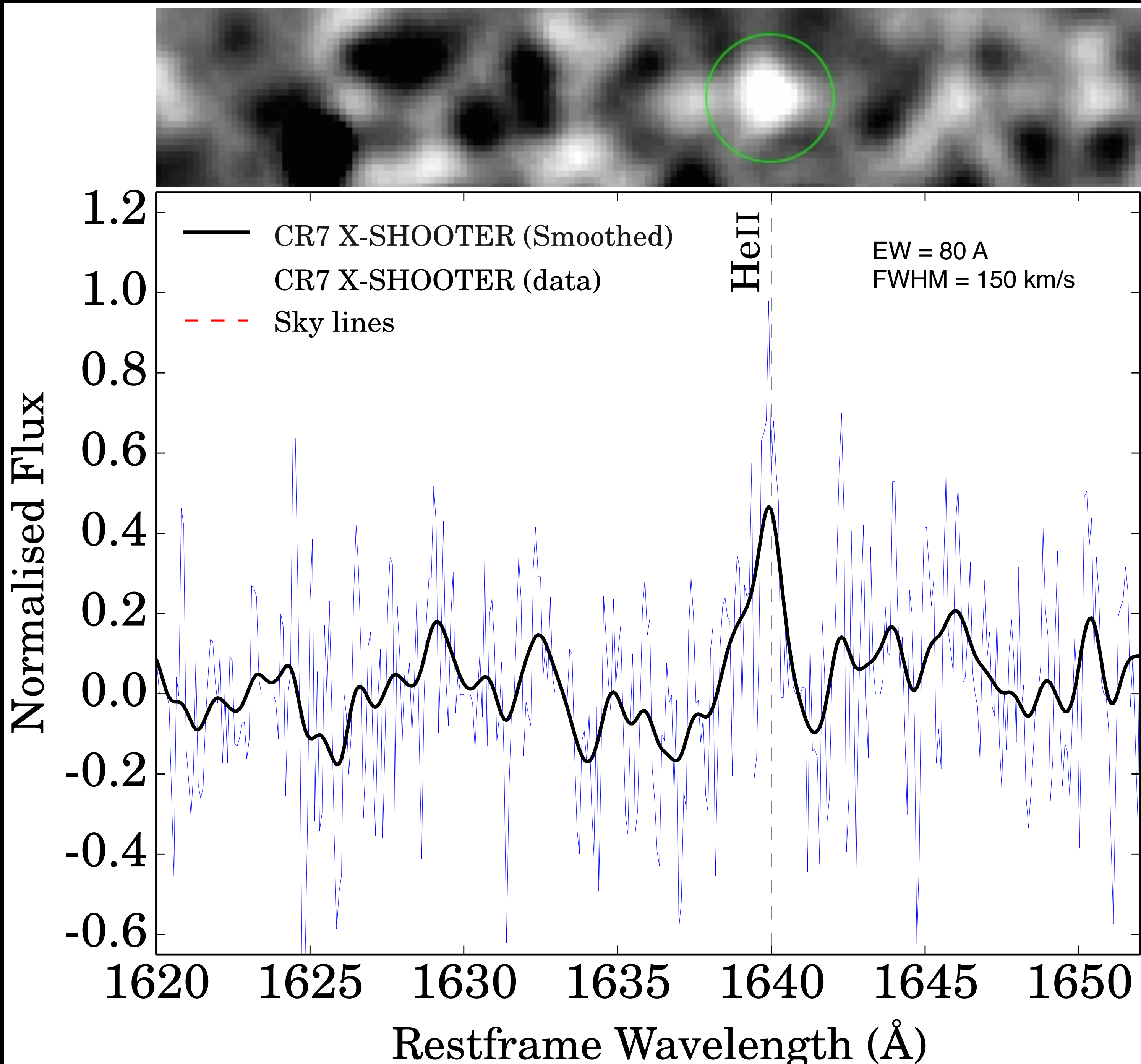


FWHM= 130 km/s

HeII/Lya = 0.27+-0.09

Sobral et al. 2015c

CR7: X-SHOOTER: 2 hours HeII 1640!



FWHM= 130 km/s

HeII/Lya = 0.27+-0.09

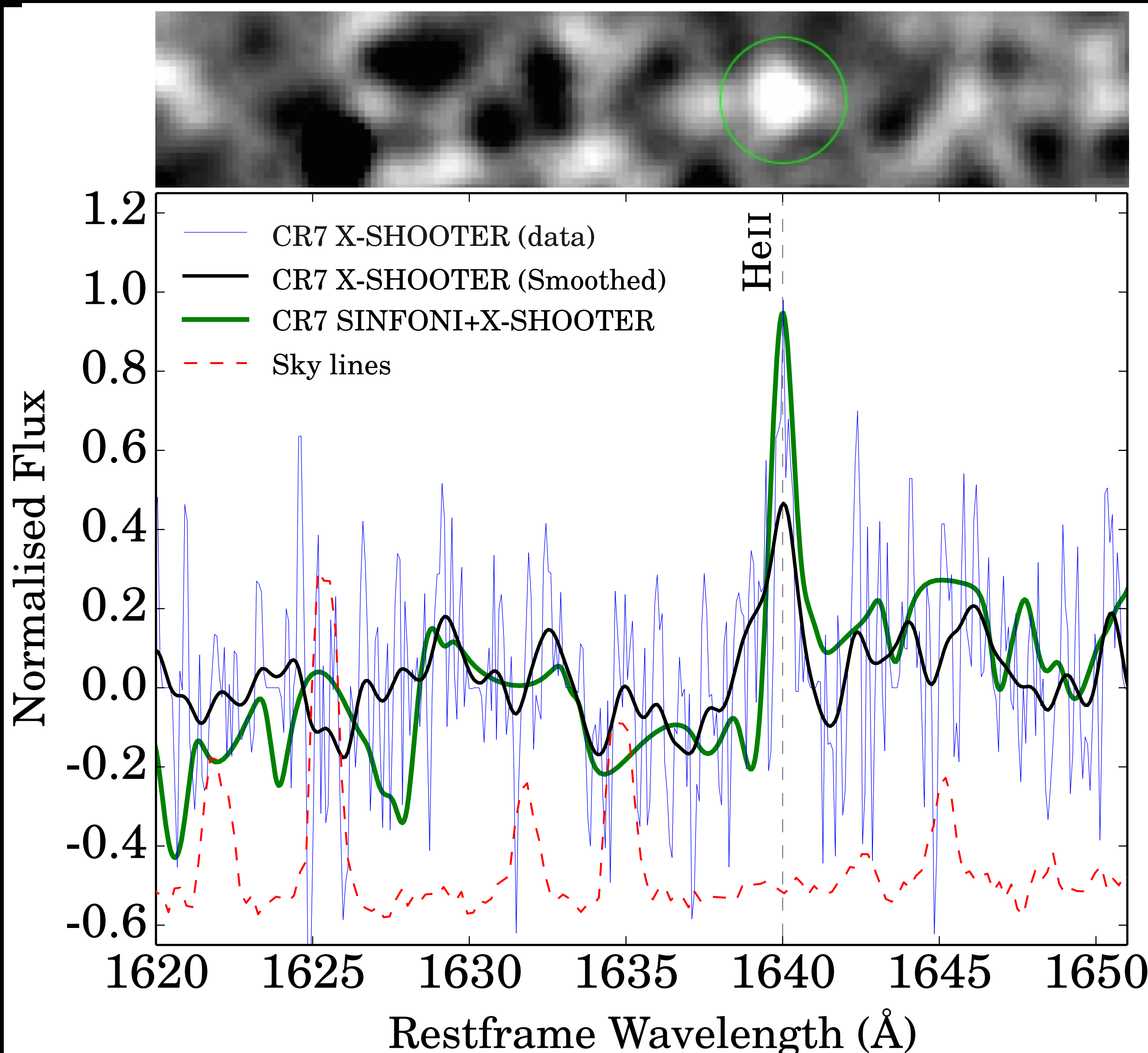
>>> DDT time on SINFONI/VLT to fully confirm

PI: Sobral

Sobral et al. 2015c

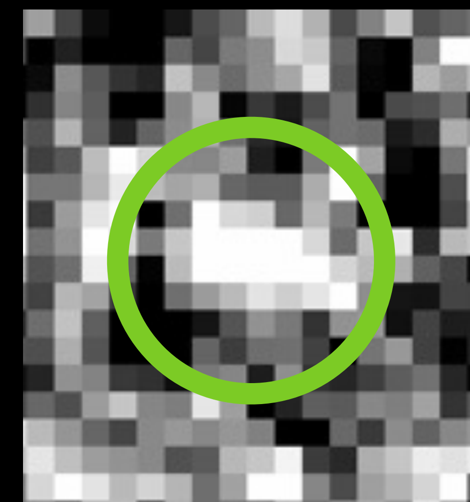
CR7: X-SHOOTER: 2 hours

Sobral, Matthee, Darvish et al. 2015



SINFONI: 3 hours

HeII 1640A in 2D!



~6 sigma!

HeII EW_0>70 A

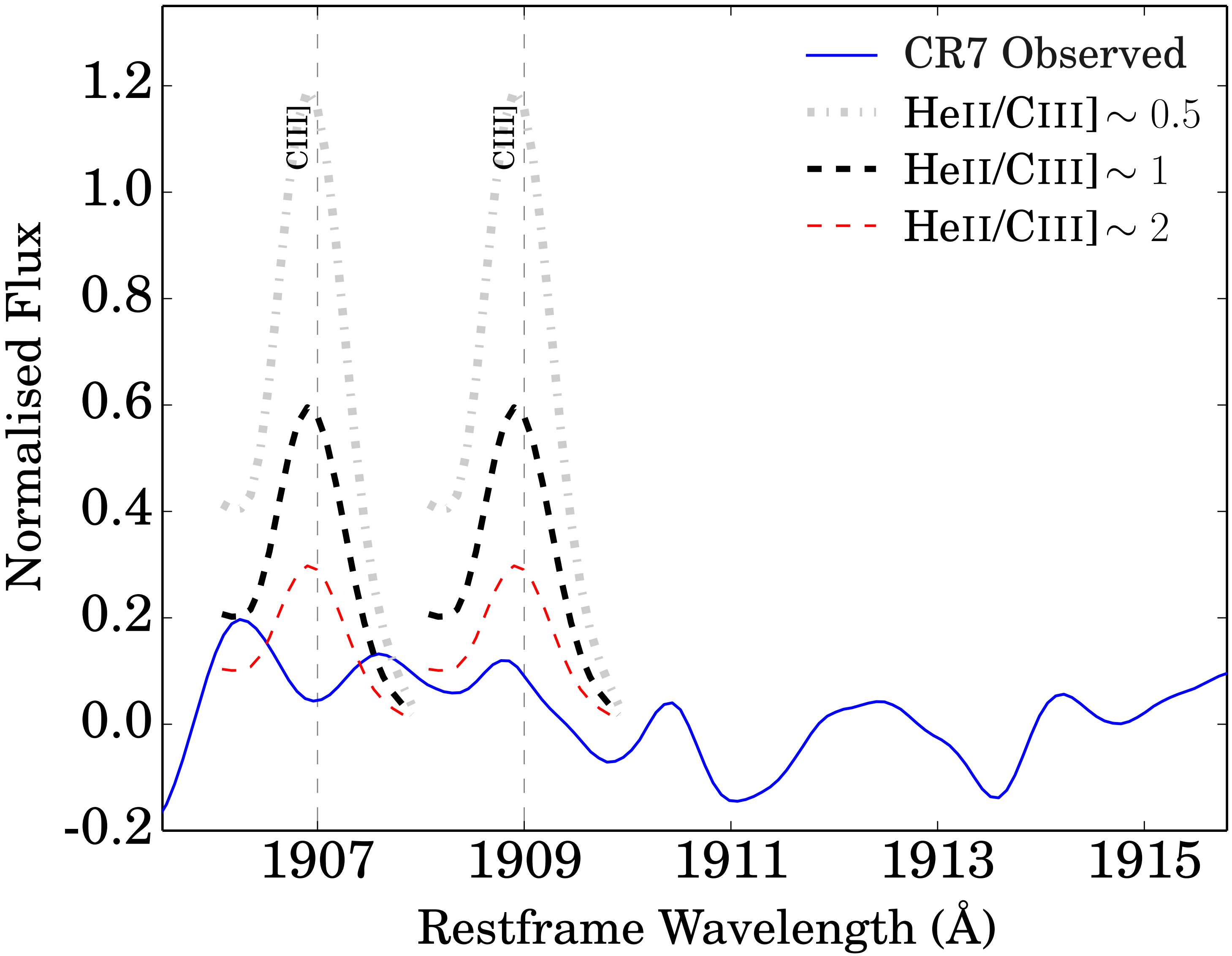
HeII $FWHM_0$= 130 km/s

HeII/Lya = 0.3

Sobral et al. 2015c

Apart from bright narrow Lyα and HeII1640: <u>no other emission lines detected</u>

HeII/Lyα=0.3



No lines except Lyα and HeII

<u>Narrow Lyα and narrow HeII</u>

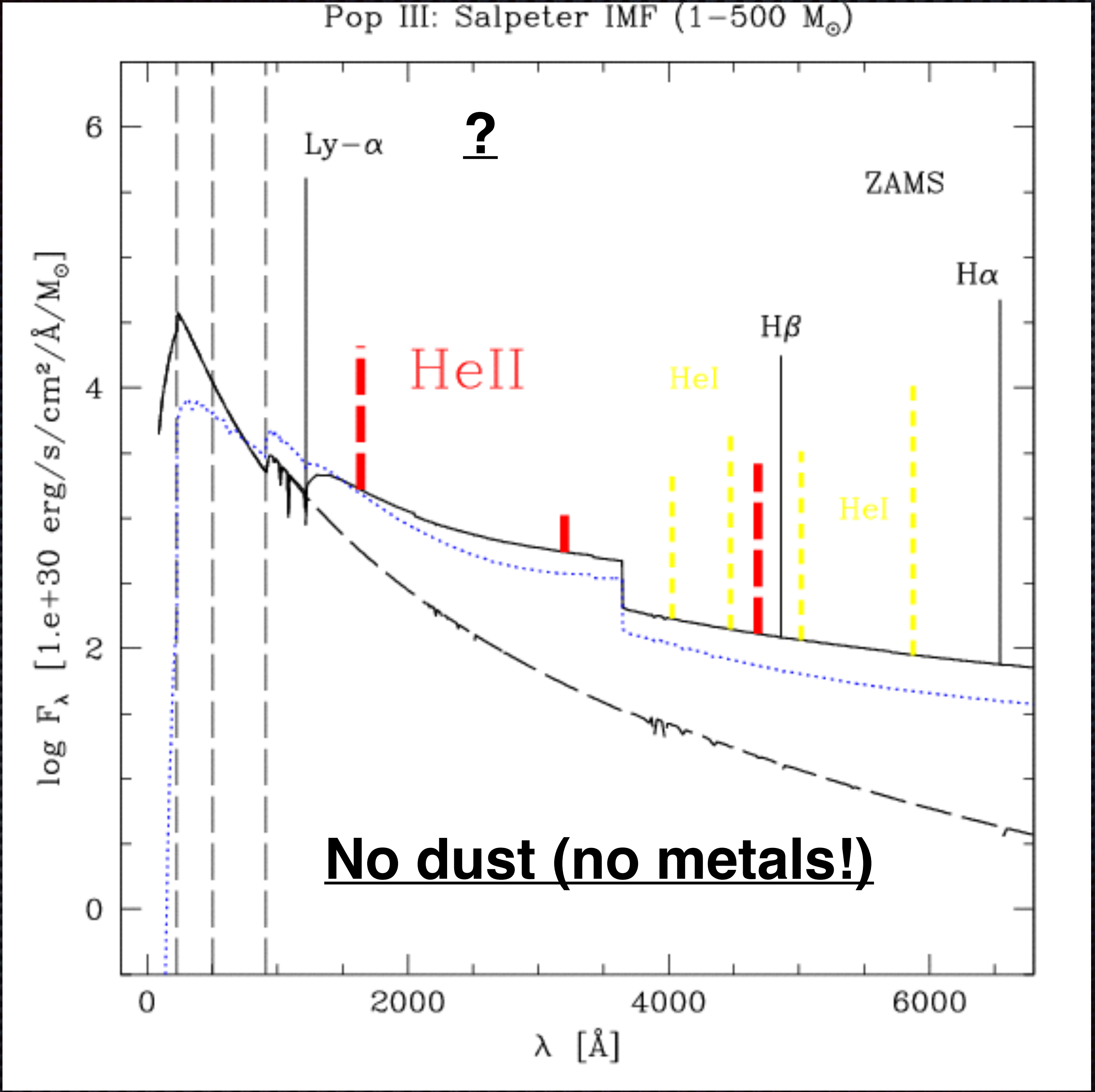
<u>"Talks" like it</u>

<u>"Looks" like it</u>

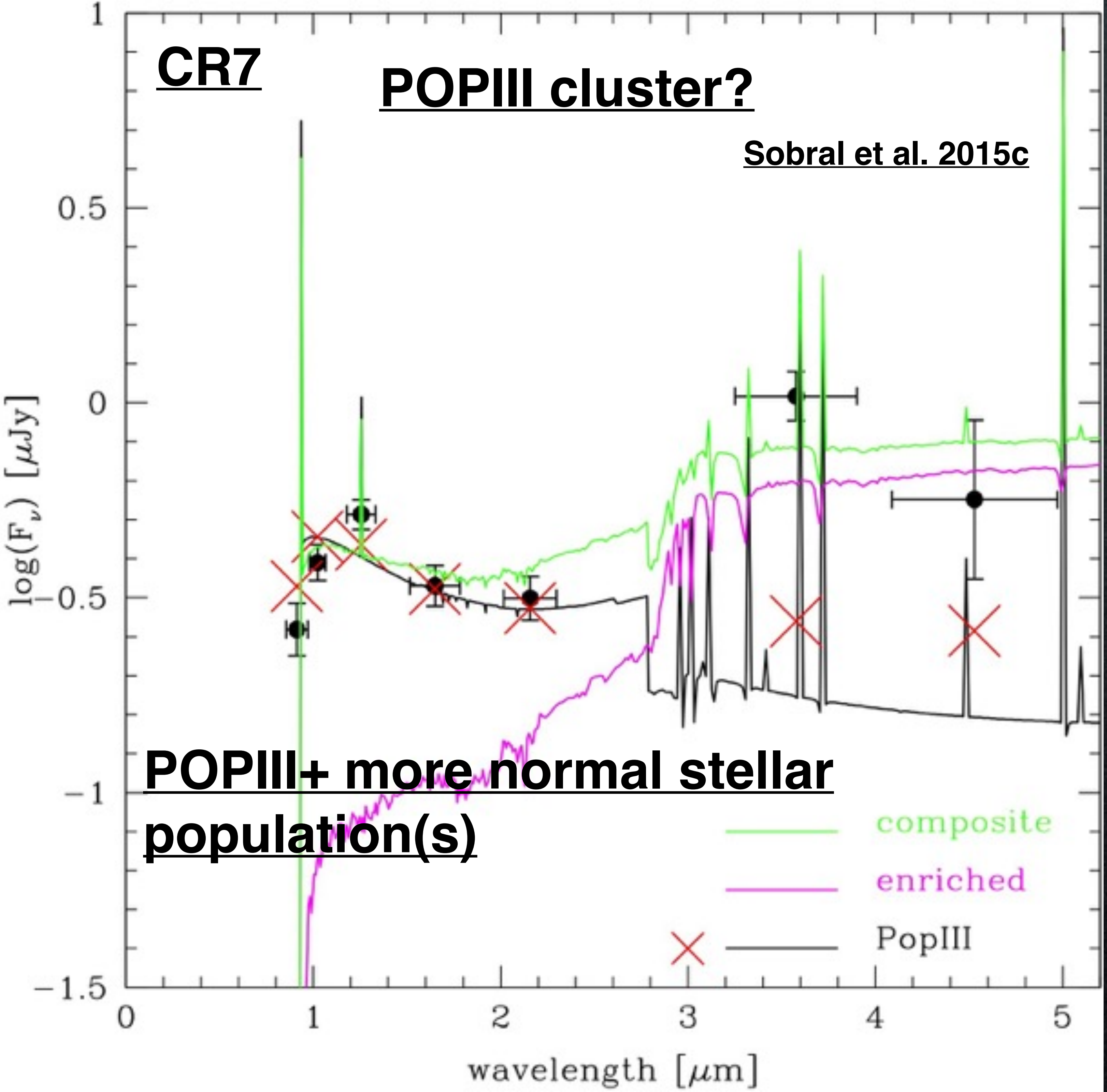
<u>"Moves" like it</u>

<u>"Smells" like it</u>

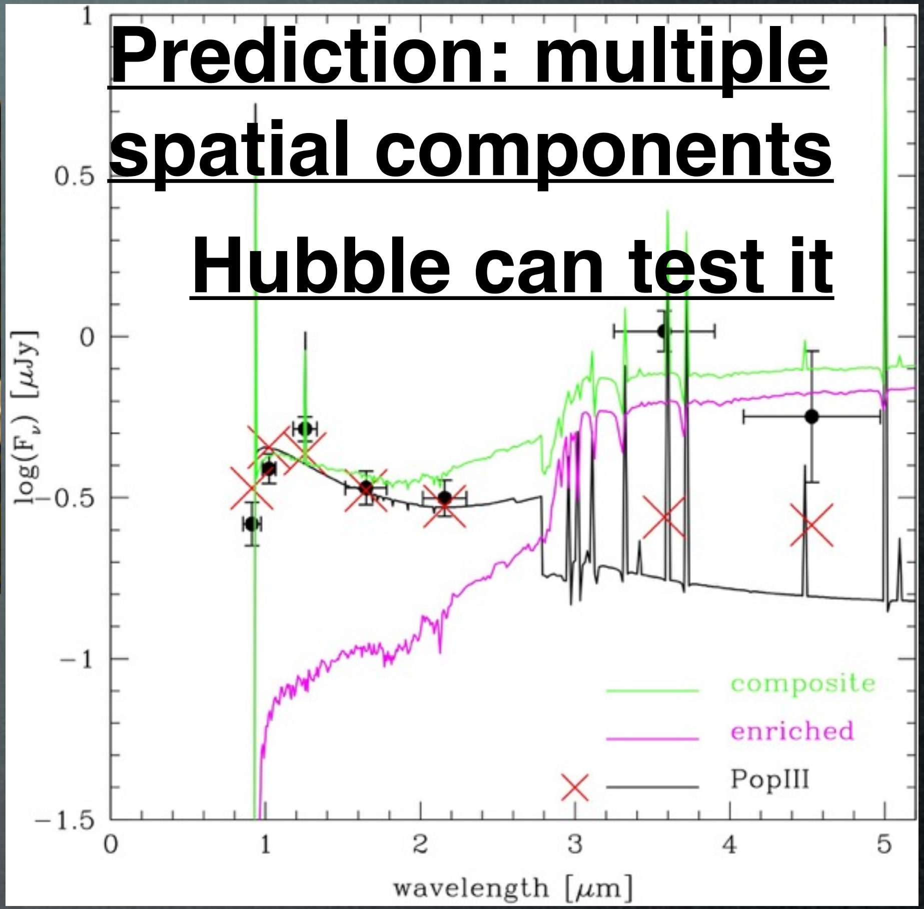
<u>Sobral et al. 2015c</u>



Pop III: Salpeter IMF (1−500 $M_\odot$)
Ly−α
?
ZAMS
Hα
Hβ
HeII
HeI
HeI
No dust (no metals!)
log F_λ [1.e+30 erg/s/cm²/Å/$M_\odot$]
λ [Å]
0
2
4
6
0
2000
4000
6000



CR7
POPIII cluster?
Sobral et al. 2015c
POPIII+ more normal stellar population(s)
composite
enriched
PopIII
log(F_ν) [μJy]
wavelength [μm]
1
0.5
0
−0.5
−1
−1.5
0
1
2
3
4
5

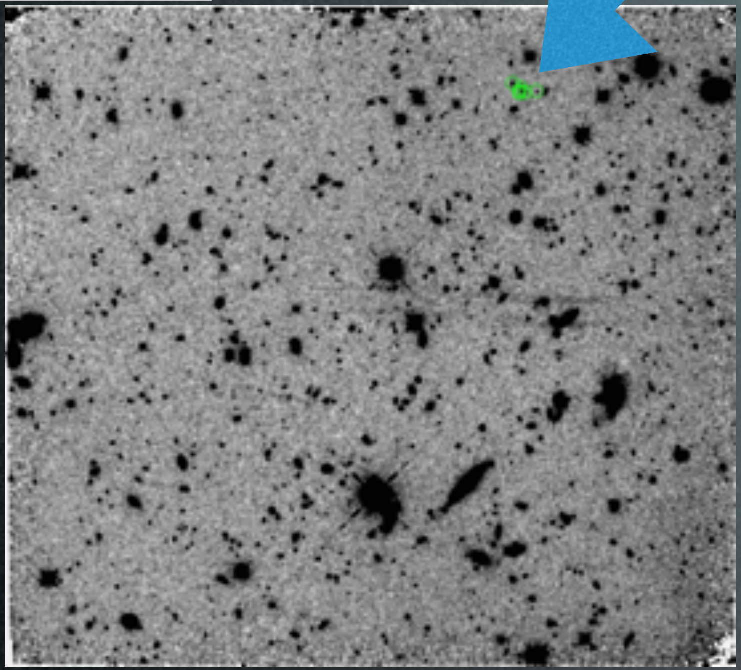


Prediction: multiple spatial components

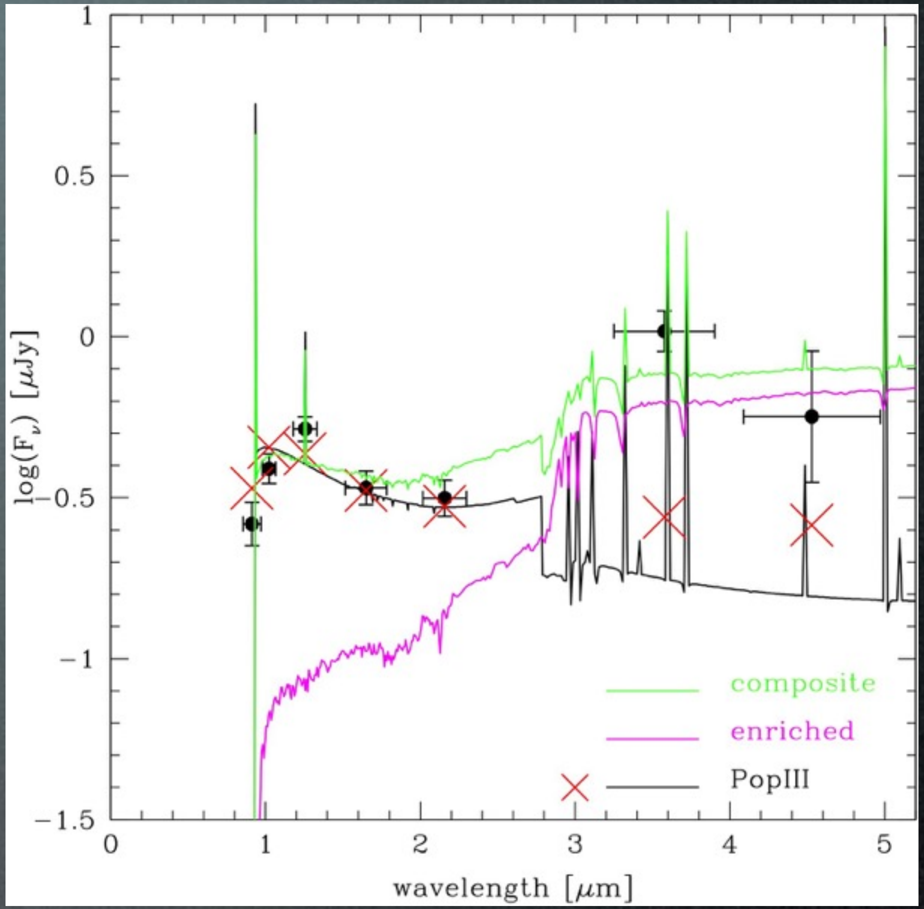
Hubble can test it

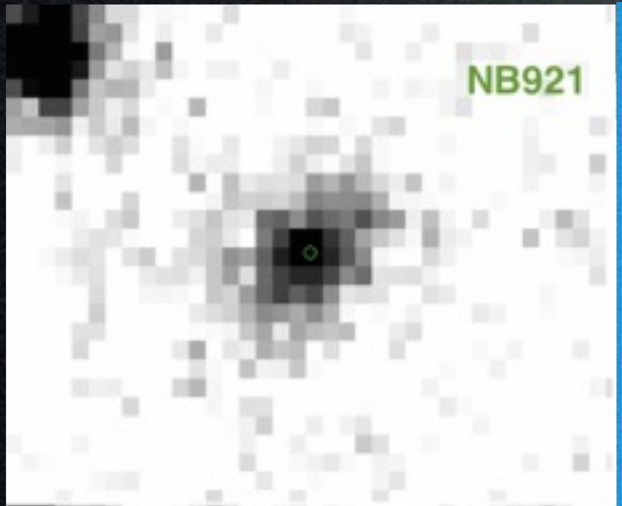
Ok… Submit proposal and wait, right?

WFC3!



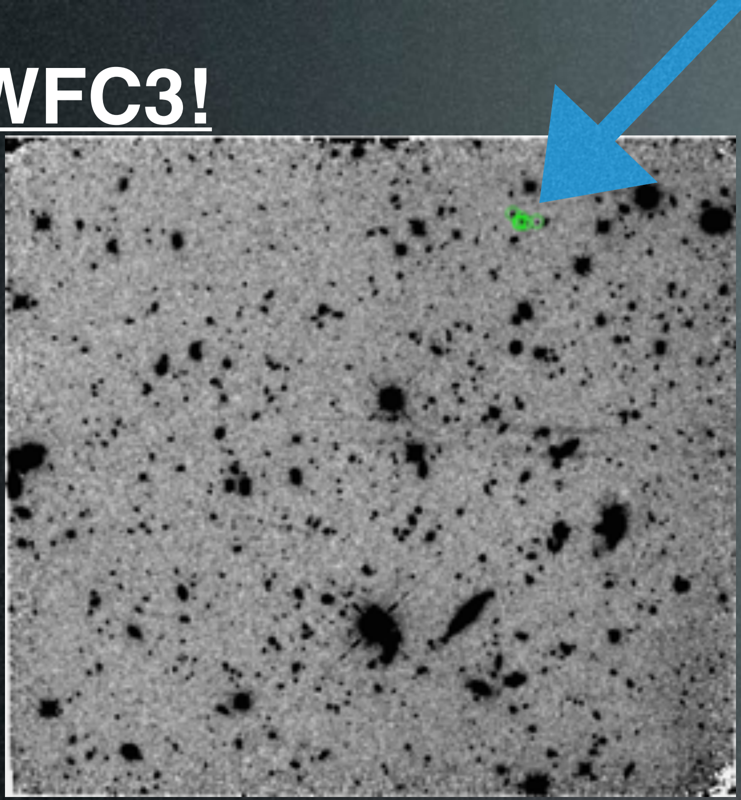
Actually… in the field of view of another target!



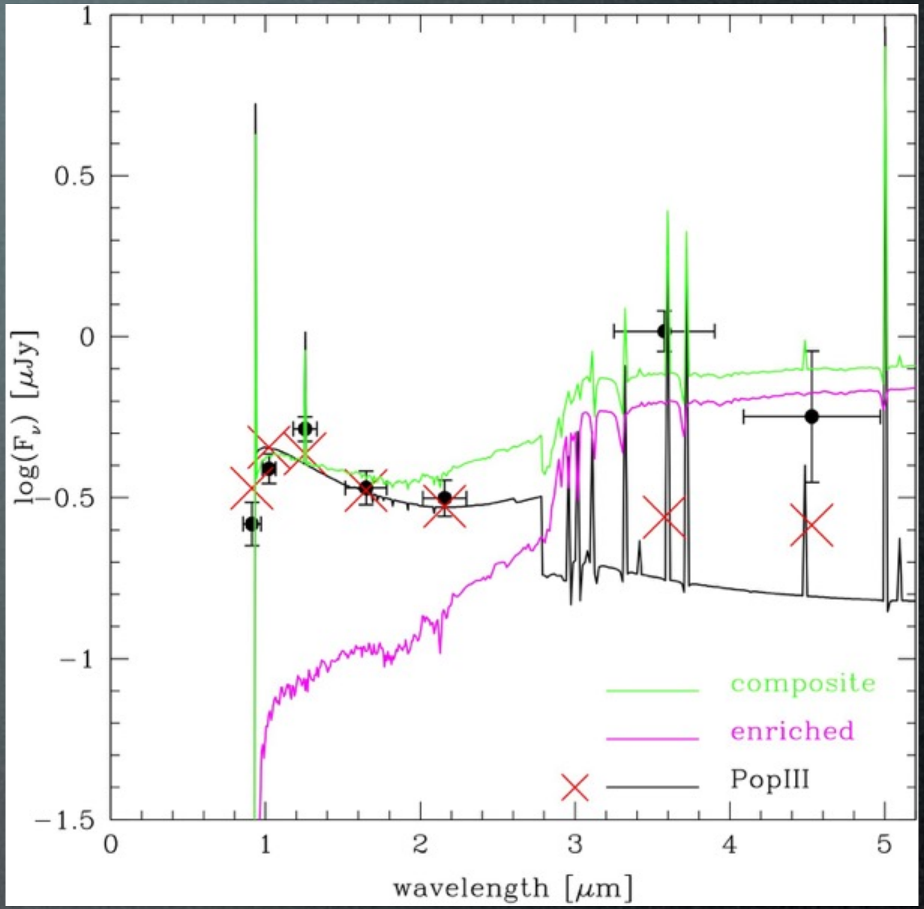


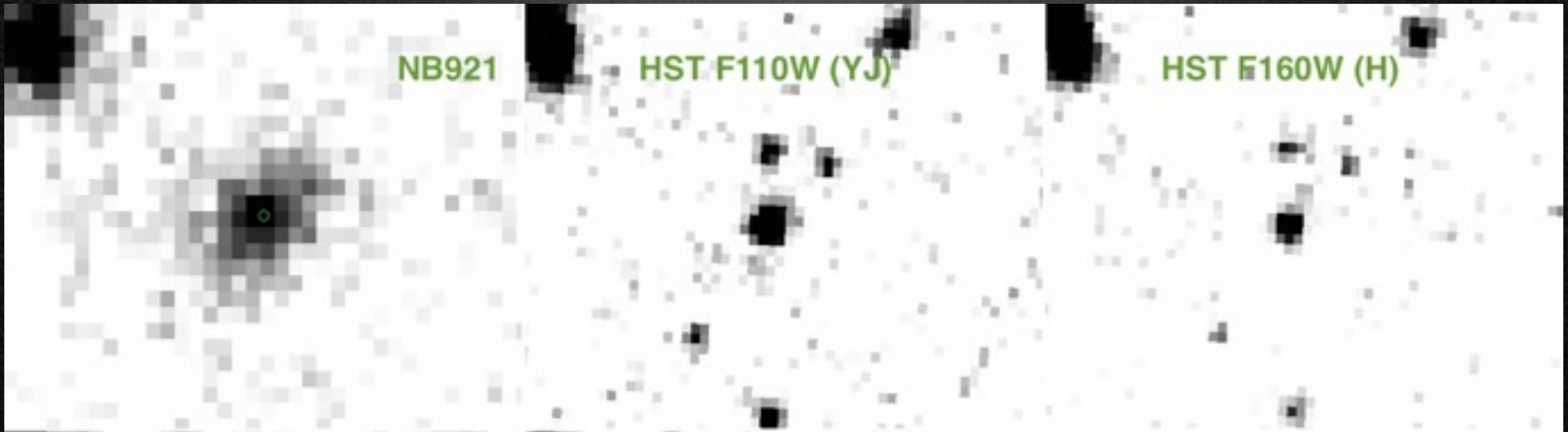
Make your bet: Multiple component (s): right or wrong?

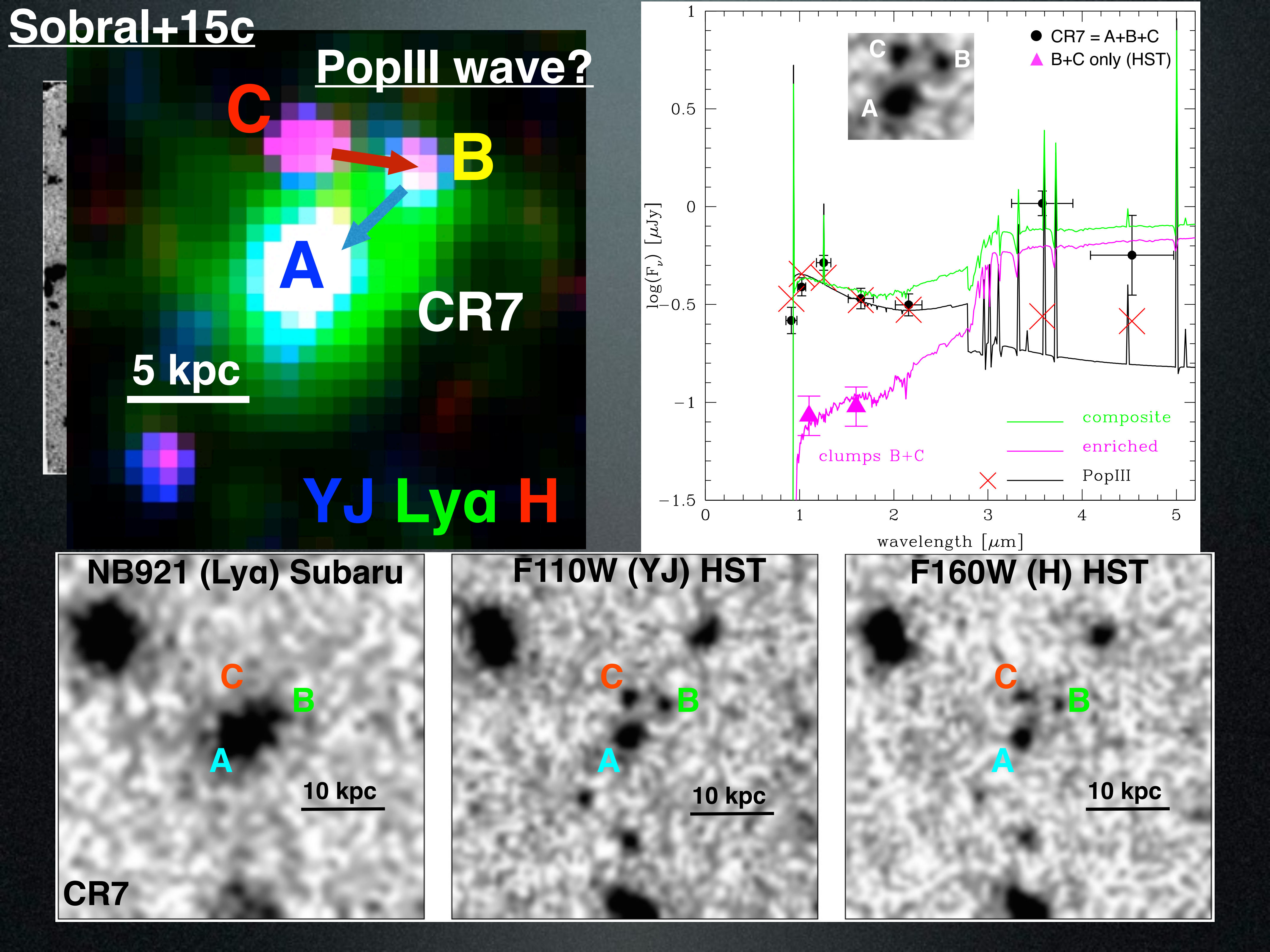
WFC3!



Actually… in the field of view of another target!

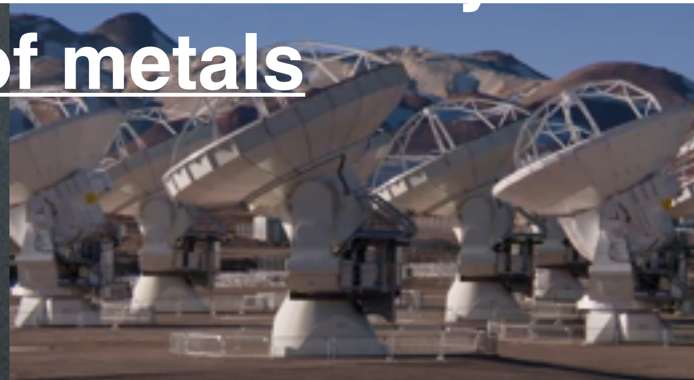


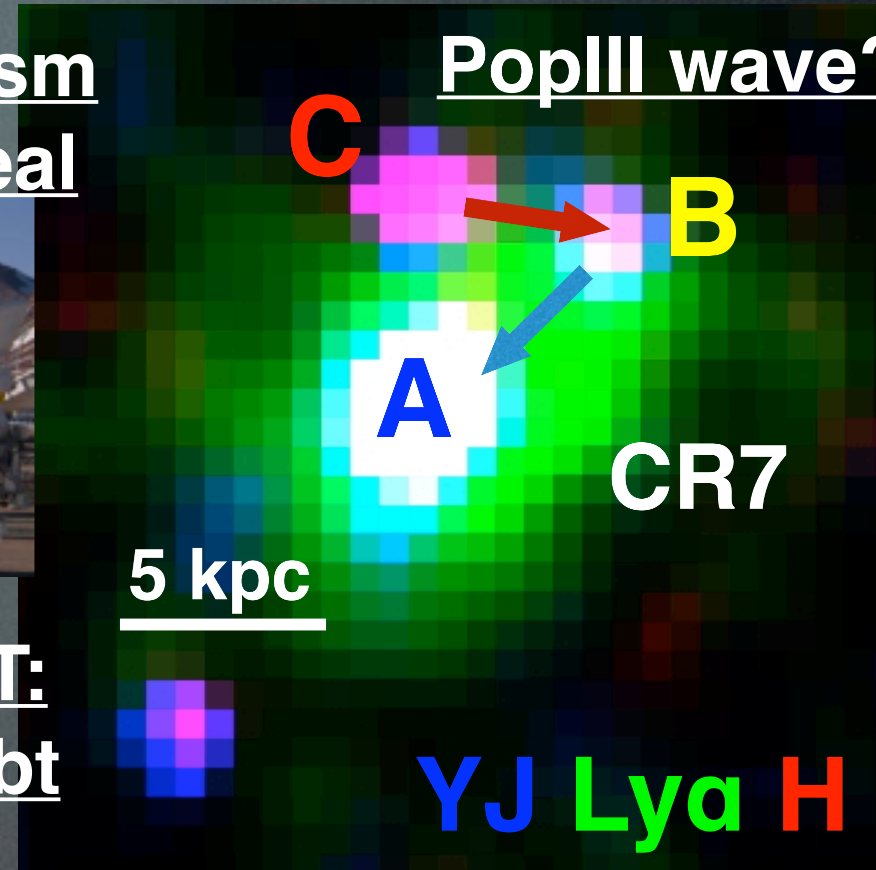




Sobral+15c
PopIII wave?
C
B
A
CR7
5 kpc
YJ Lyα H
CR7 = A+B+C
B+C only (HST)
composite
enriched
PopIII
clumps B+C
log(F_ν) [μJy]
wavelength [μm]
NB921 (Lyα) Subaru
F110W (YJ) HST
F160W (H) HST
10 kpc

Follow-up with HST WFC3 Grism + ALMA needed to clearly reveal any traces of metals





Ideal first-light targets for JWST: confirm PopIII beyond any doubt from day 1!

… and the potential to find and study the most distant galaxies ever found at z~8.8 (current record: z=7.7)

Summary: last 11 Gyrs

- **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 and all environments: factor ~13x**

- Selection effects: selection really matters! Need to compare like with like!

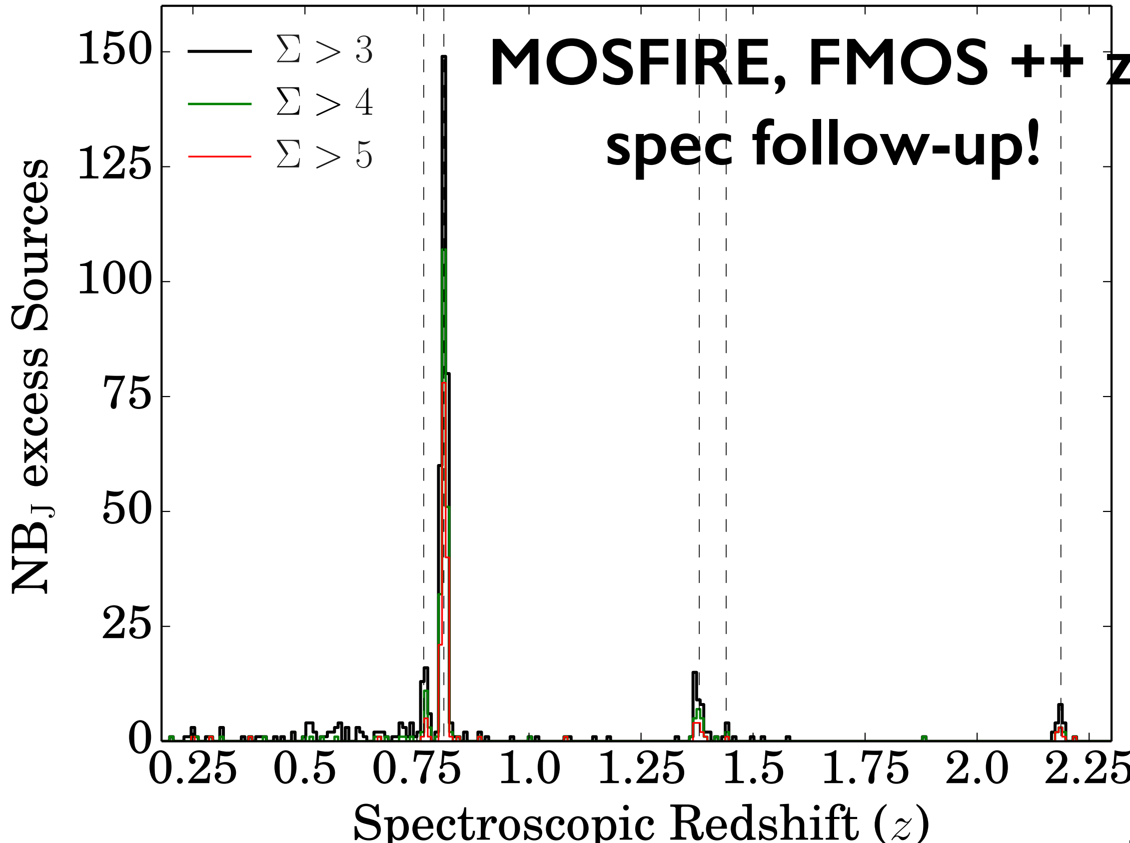
- SINFONI w/ AO: Star-forming galaxies since z=2.23: ~75% "disks", negative metallicity gradients, many show clumps

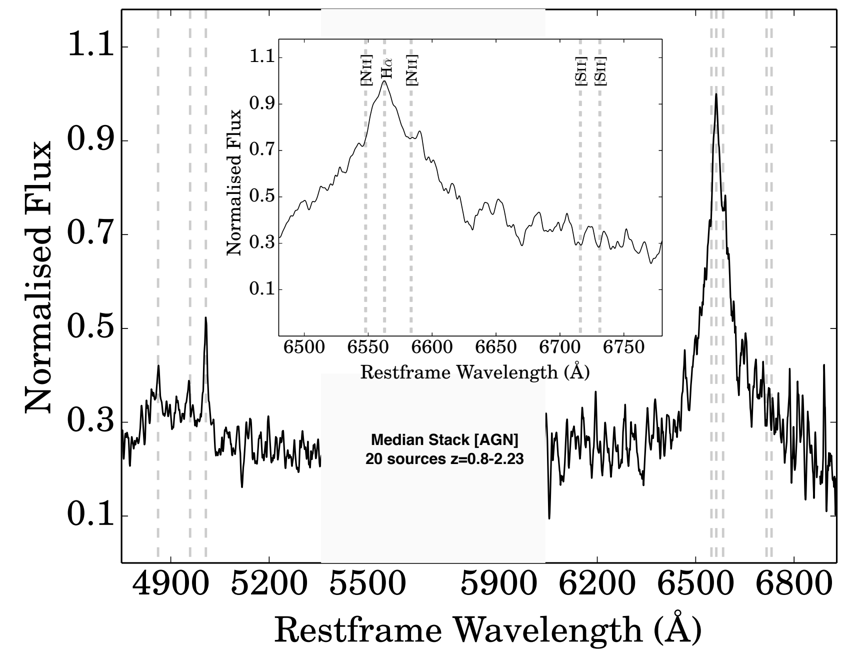
- KMOS+Hα (NB) selection works extraordinarily well: resolved dynamics of typical SFGs in ~1-2 hours, 75+-8% disks, 50-275km/s

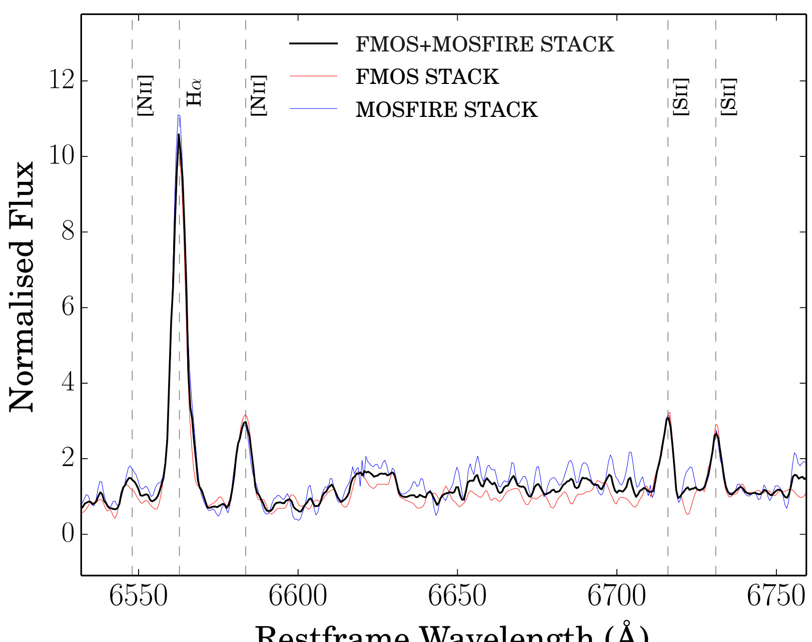
- Largest NB surveys: Hα, [OIII] & [OII]: many lessons learnt, Luminosity functions up to the highest luminosities/volumes

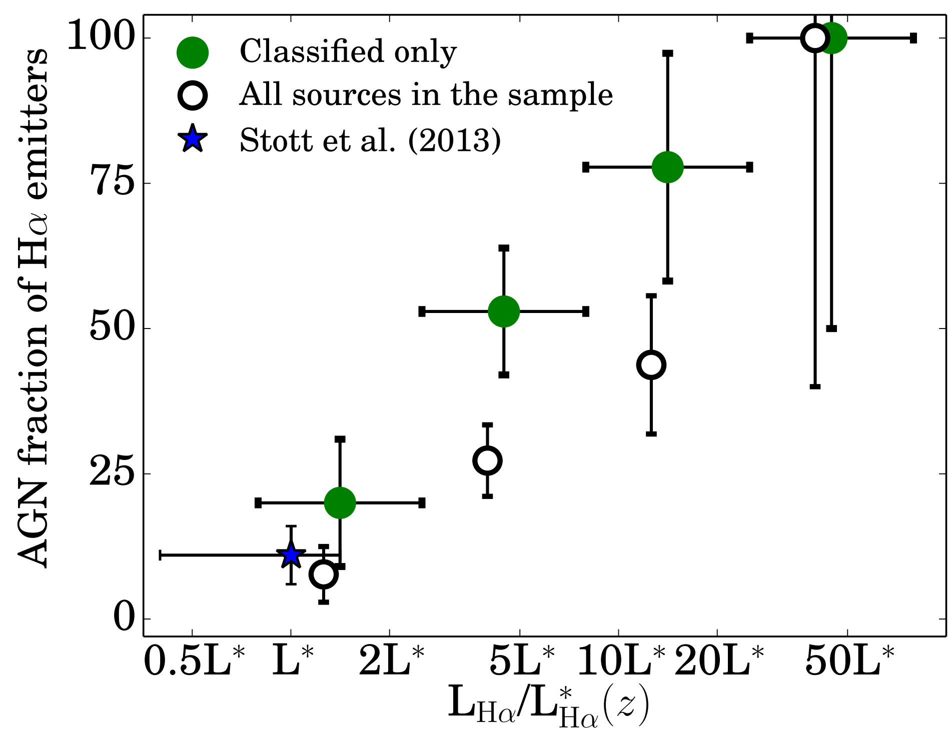
Sobral et al. 2015a,c

MOSFIRE, FMOS ++ z-spec follow-up!

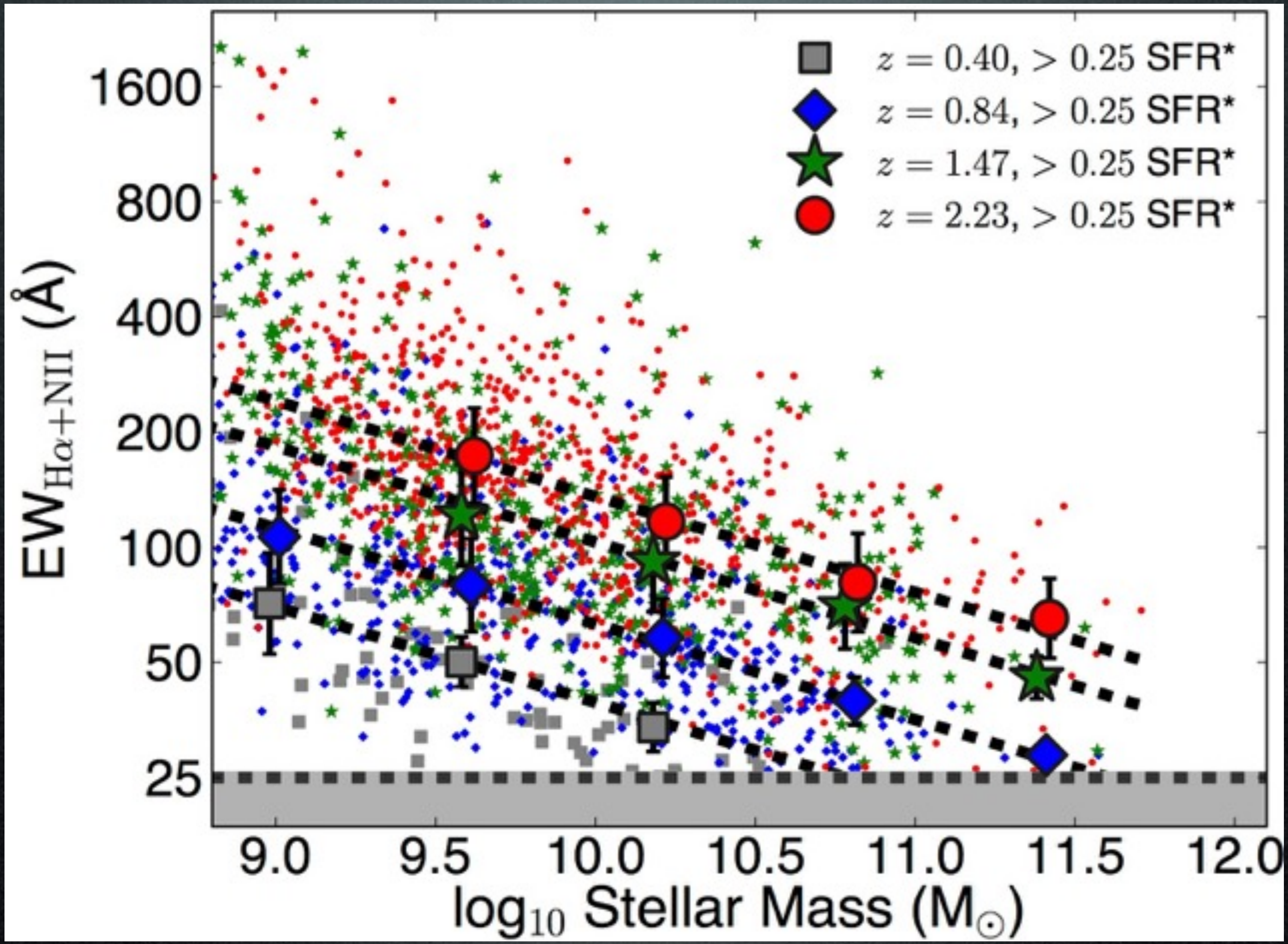




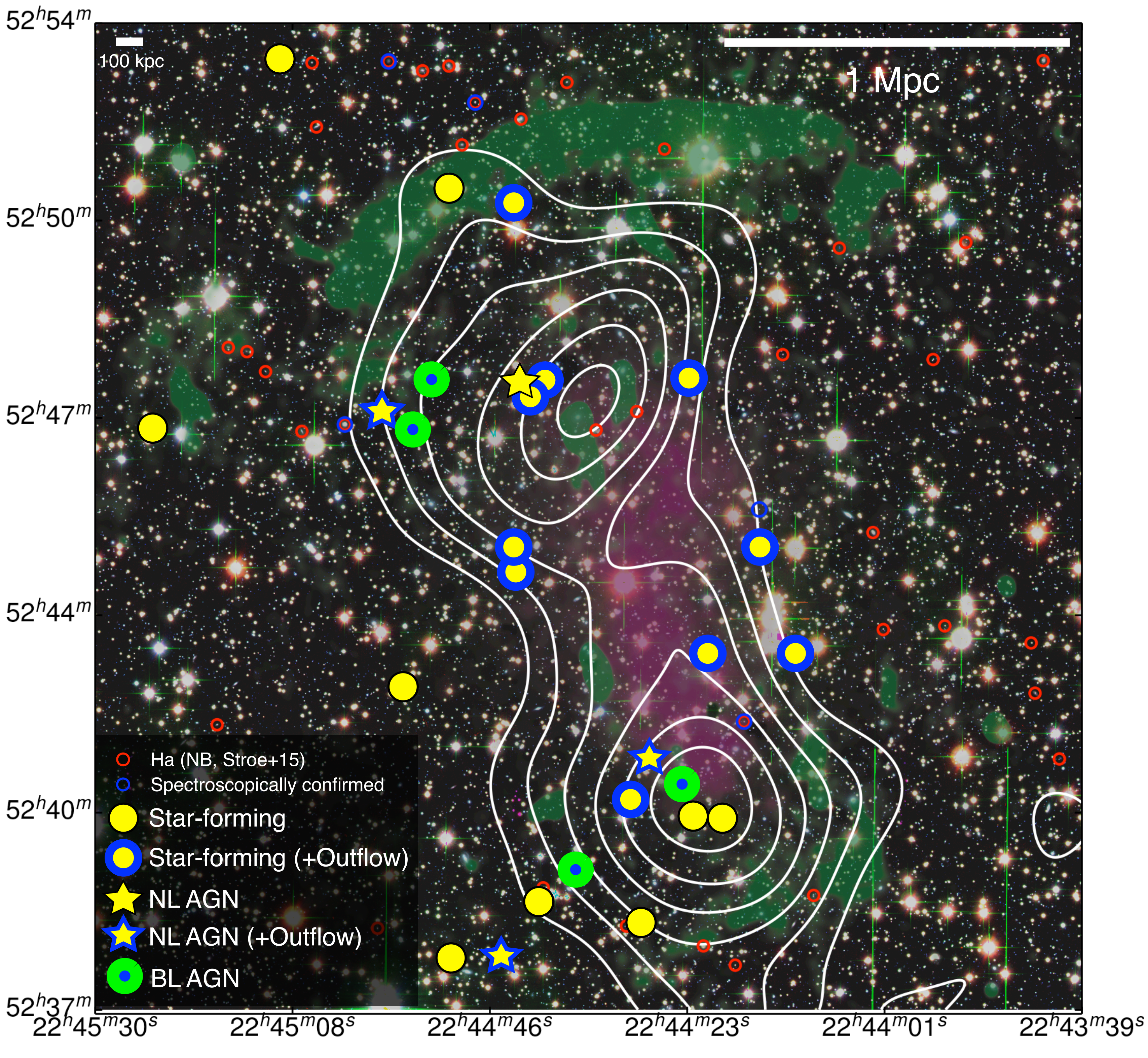




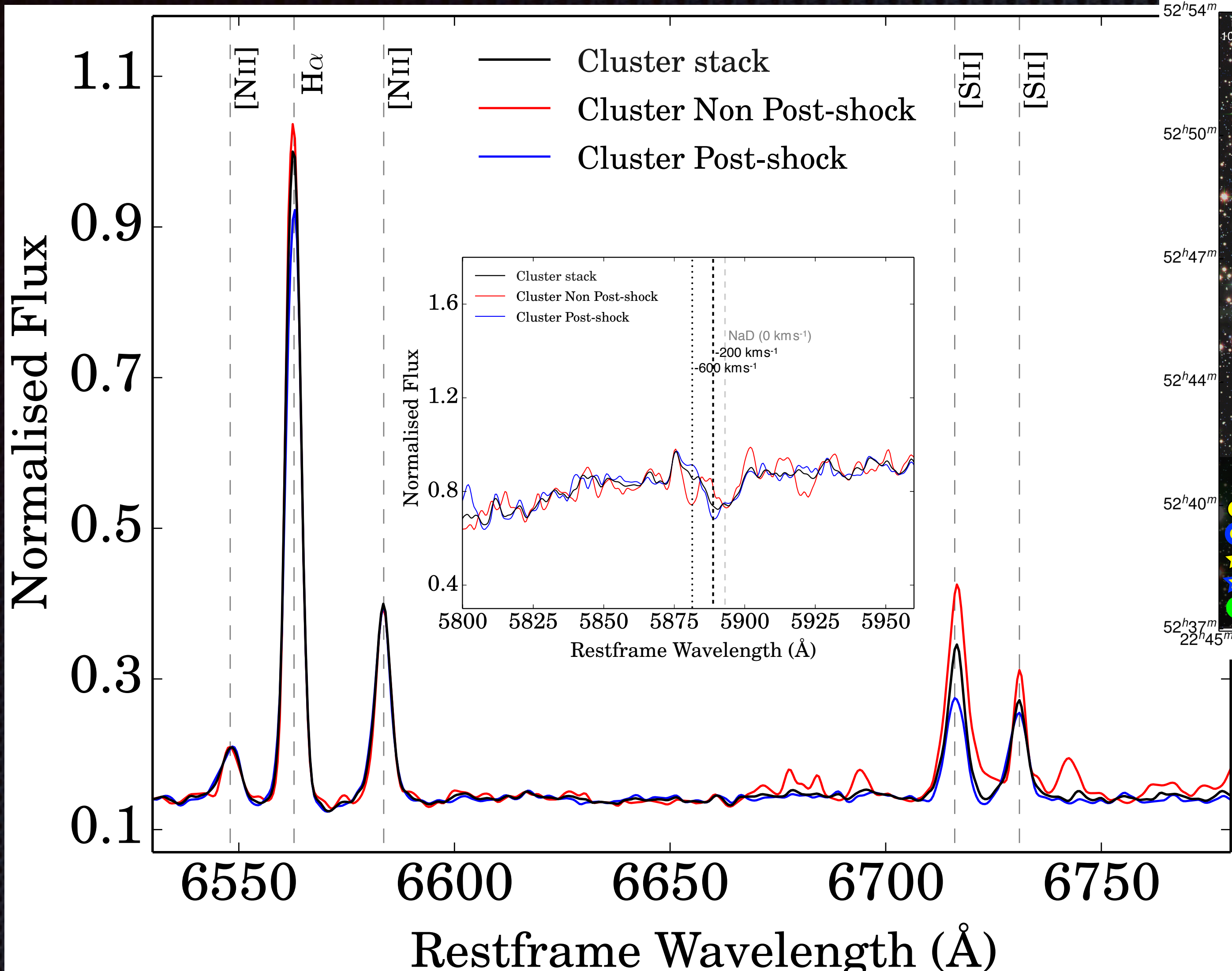
EW Hα rising with increasing redshift at all masses

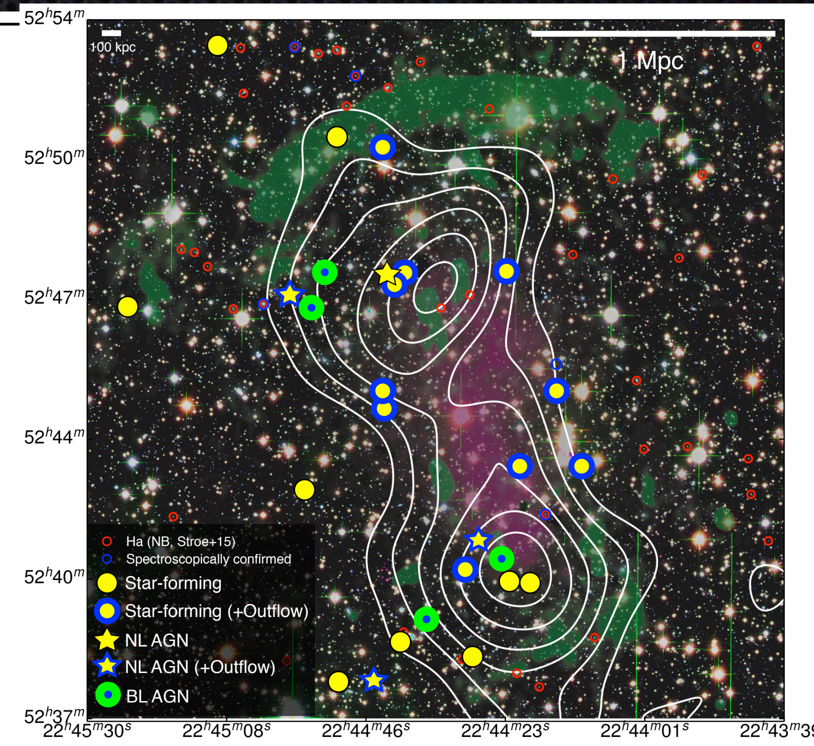


Sobral+14



52^{h}54^m
52^{h}50^m
52^{h}47^m
52^{h}44^m
52^{h}40^m
52^{h}37^m
22^{h}45^{m}30^s
22^{h}45^{m}08^s
22^{h}44^{m}46^s
22^{h}44^{m}23^s
22^{h}44^{m}01^s
22^{h}43^{m}39^s
100 kpc
1 Mpc
Ha (NB, Stroe+15)
Spectroscopically confirmed
Star-forming
Star-forming (+Outflow)
NL AGN
NL AGN (+Outflow)
BL AGN





Keck + WHT spectra

Shock wave likely triggered star-formation

Outflows, supernovae >> will lead to more red +dead galaxies

Cluster mergers are important **Sobral et al. 2015b**

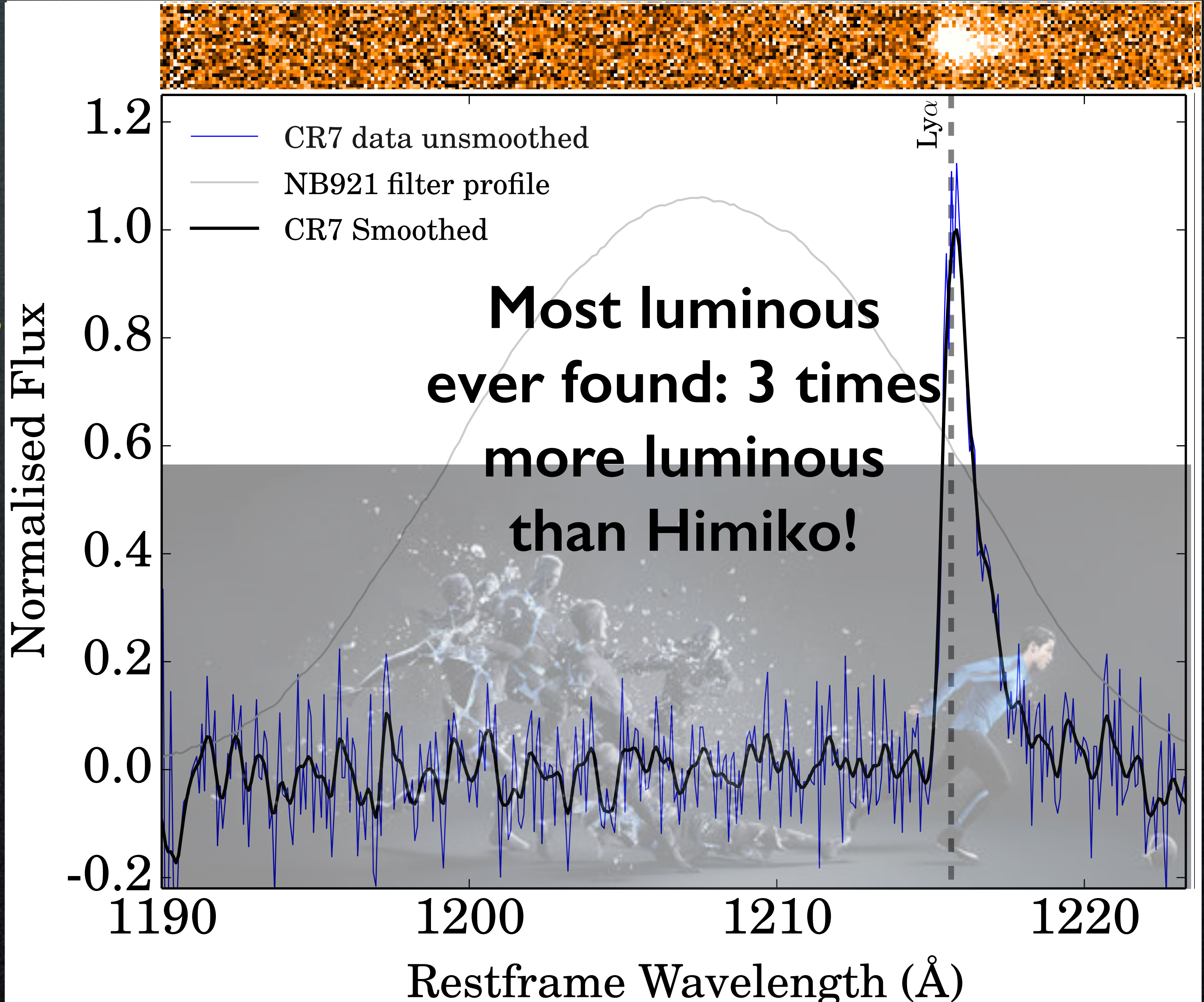
Lyα

Keck/ DEIMOS

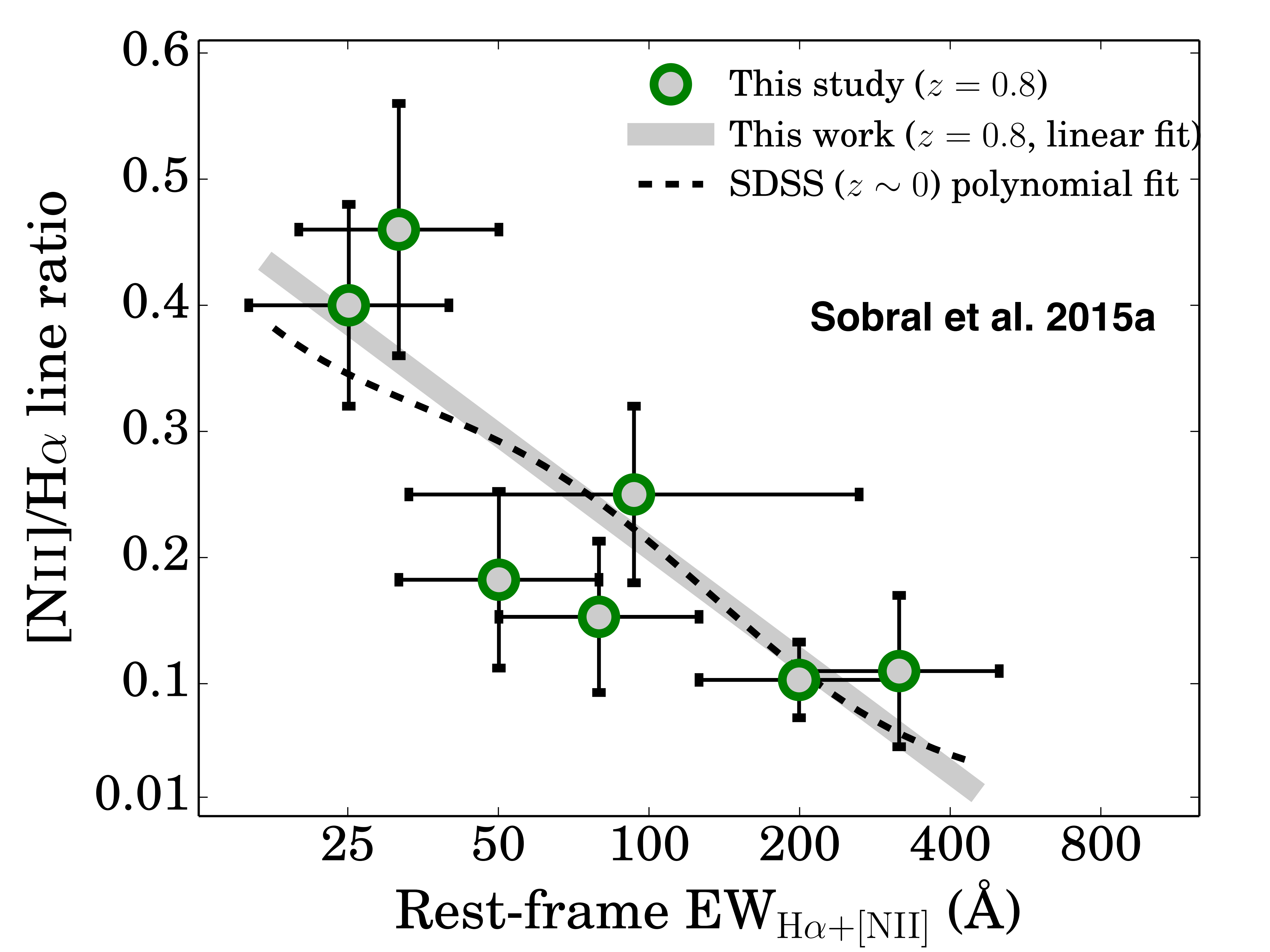
1 hour!

z=6.6

L~10^{44} erg/s/cm^2



No evidence for AGN **Sobral et al. 2015c.**

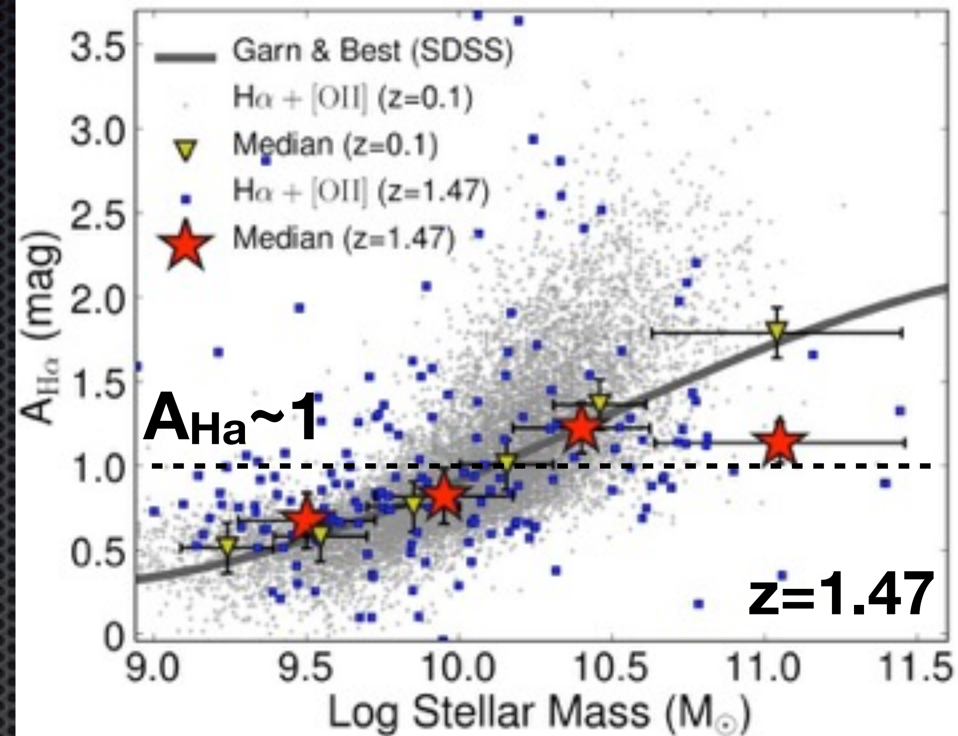


This study ($z = 0.8$)
This work ($z = 0.8$, linear fit)
SDSS ($z \sim 0$) polynomial fit
Sobral et al. 2015a
[NII]/Hα line ratio
0.6
0.5
0.4
0.3
0.2
0.1
0.01
25
50
100
200
400
800
Rest-frame EW$_{H\alpha+[NII]}$ (Å)

Extinction-Mass z~0-1.5

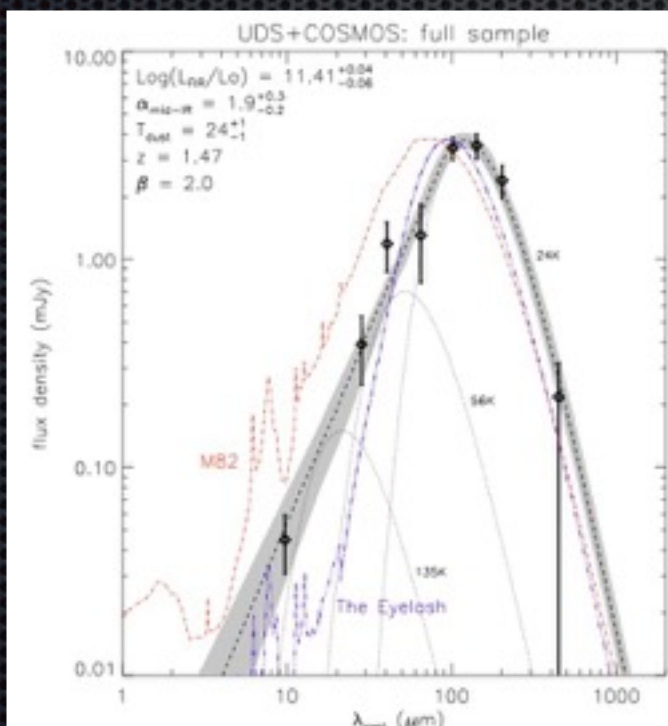
Garn & Best 2010: Stellar Mass correlates with dust extinction (z~0)

Discovered to be valid up to z~1.5-2! (Sobral+12); discovery further confirmed by e.g. Kashino+14, Ibar+13, Price+13 + many others in many different samples

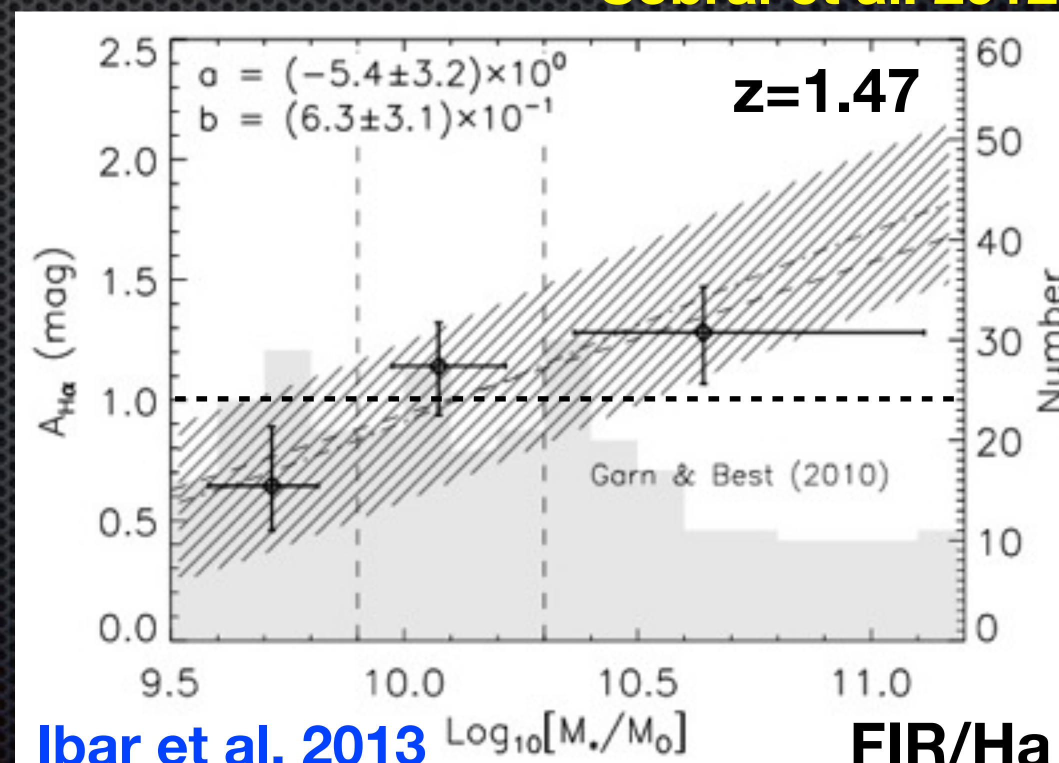


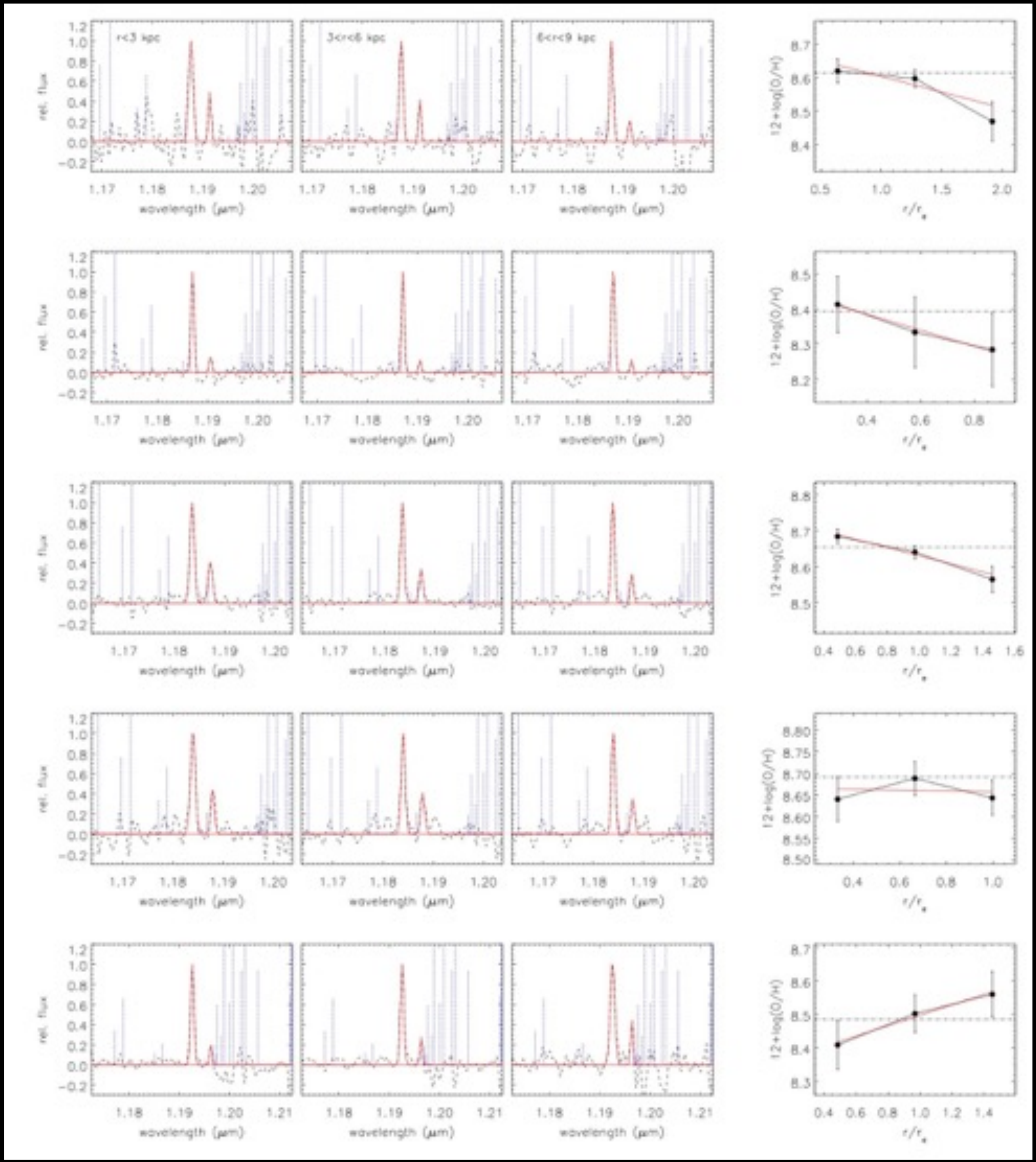
Sobral et al. 2012

Now confirmed by Herschel



FIR derived A_{Ha} = 0.9-1.2 mag





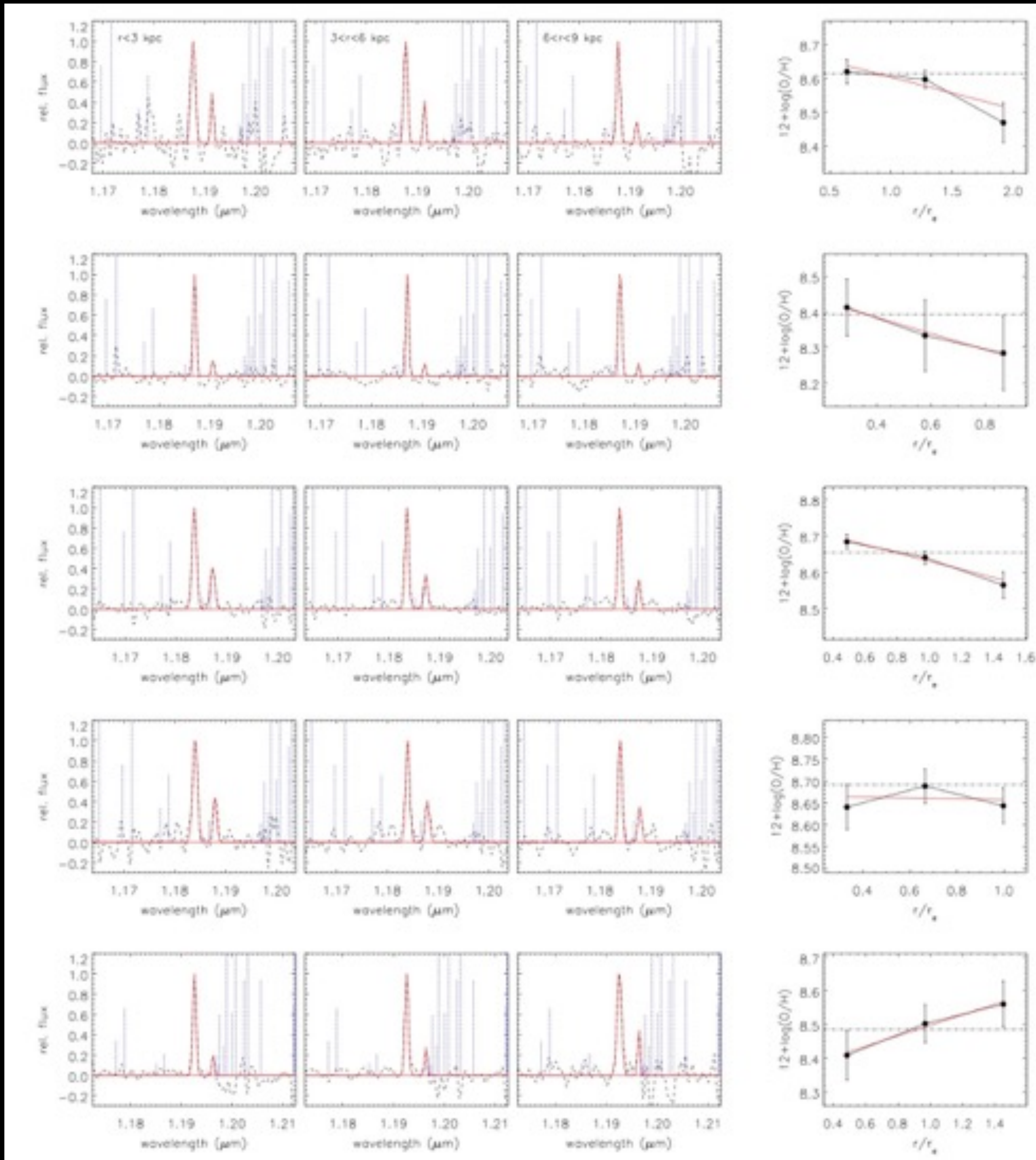
Metallicity gradients for CF-HiZELS KMOS sample

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, Sobral et al. 2014

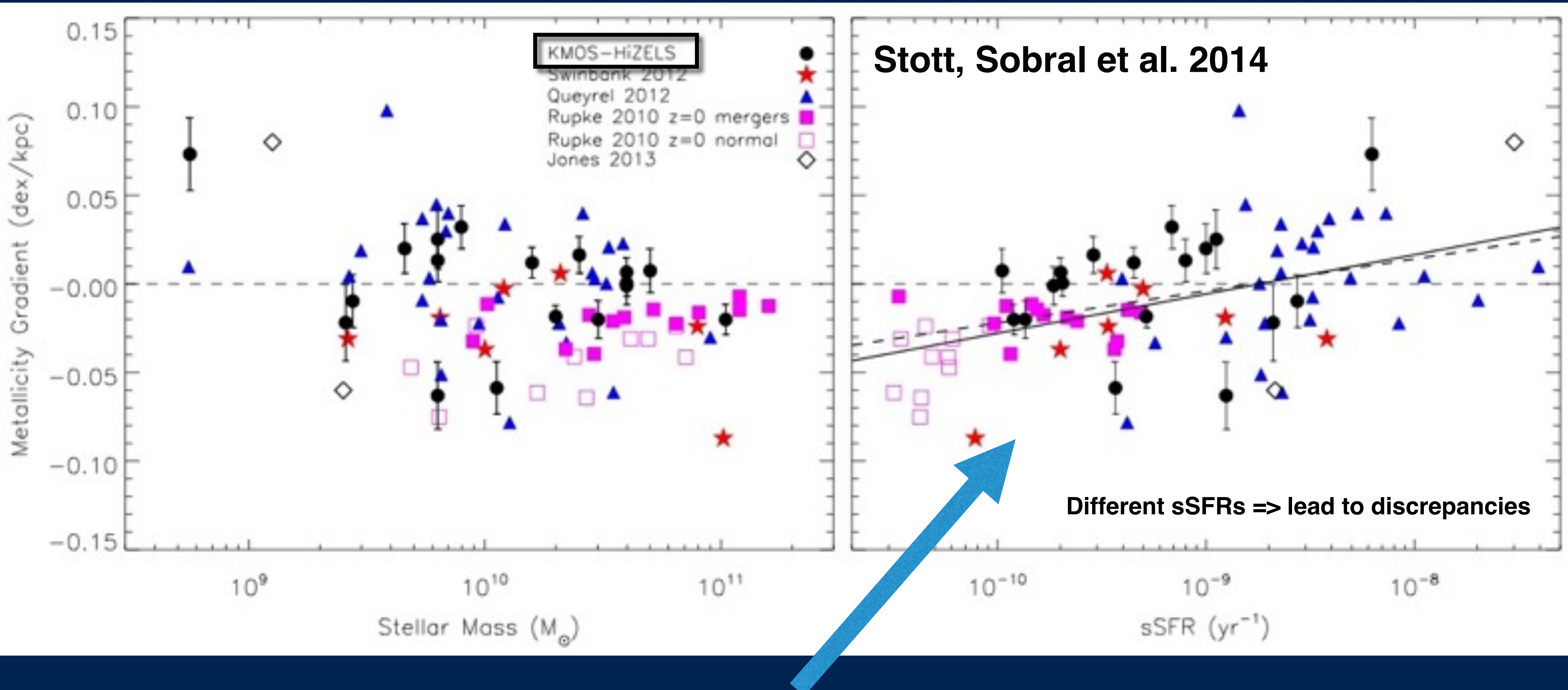


Metallicity gradients for CF-HiZELS KMOS sample

Agreement with SINFONI results (Swinbank+12a)

Mostly negative or flat, very few positive

Stott, Sobral et al. 2014



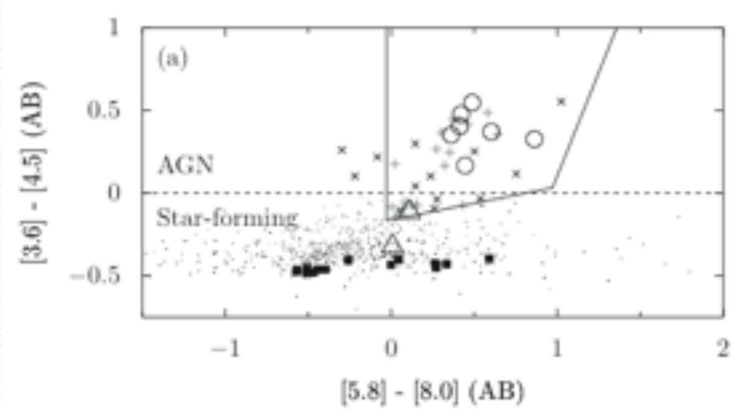
Metallicity Gradients increase with increasing sSFR

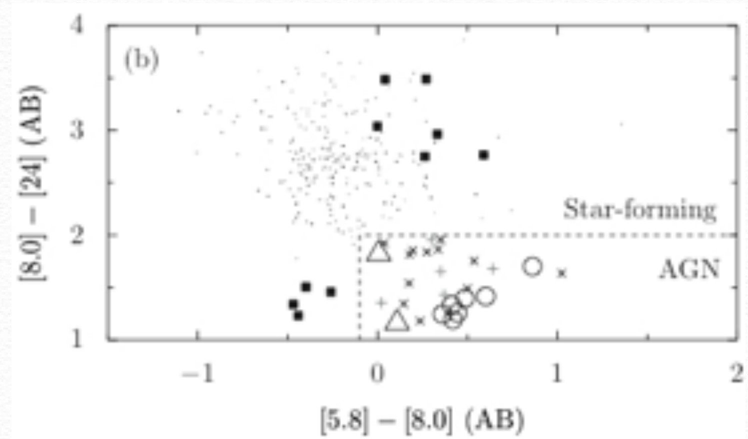
Suggests high sSFRs may be driven by funnelling of "metal poor" gas into their centres

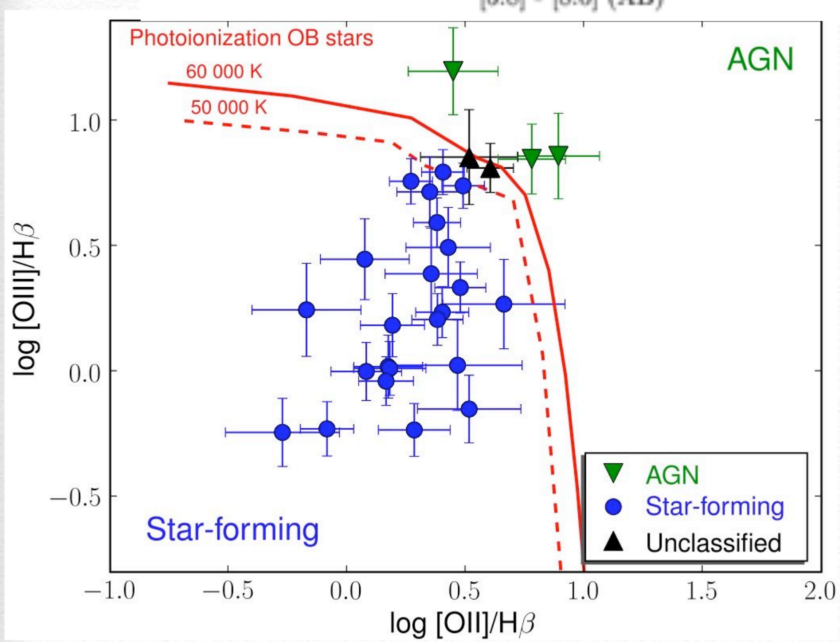
Results may help to explain the FMR (negative correlation between metallicity and SFR at fixed mass)

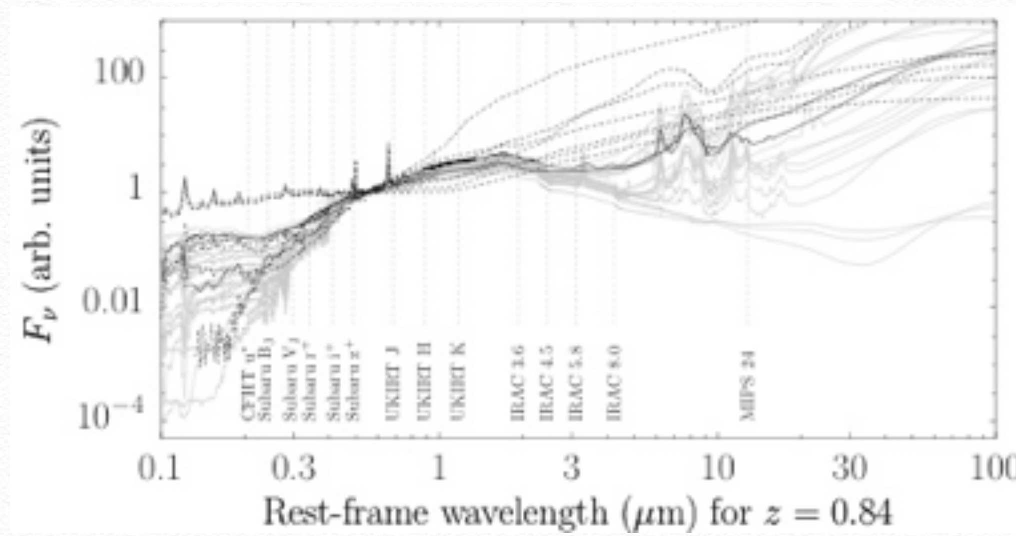
AGN

Garn et al. 2010

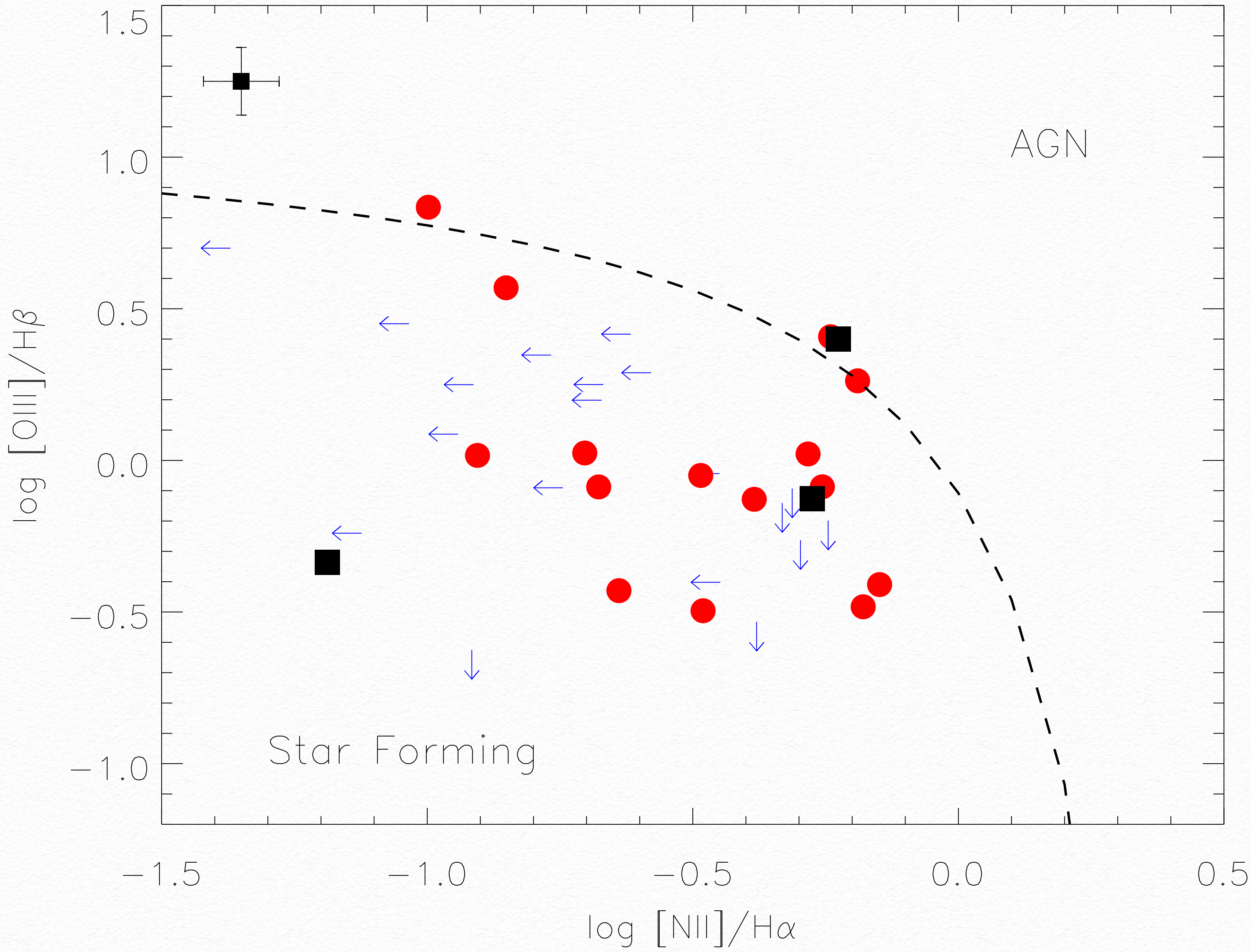






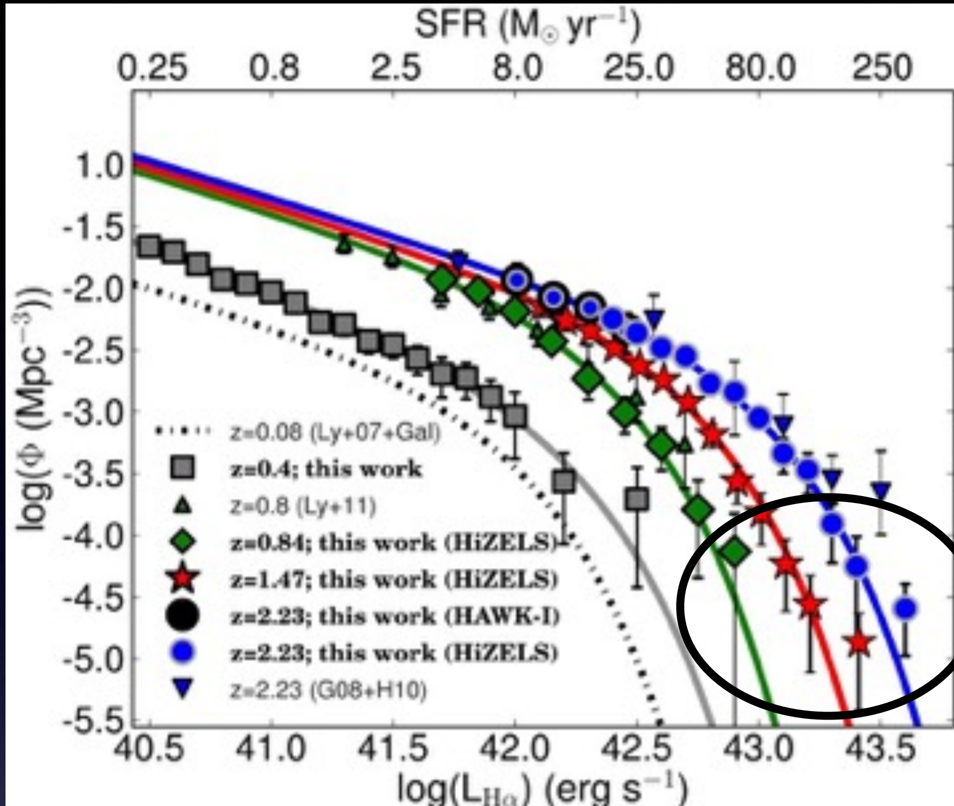


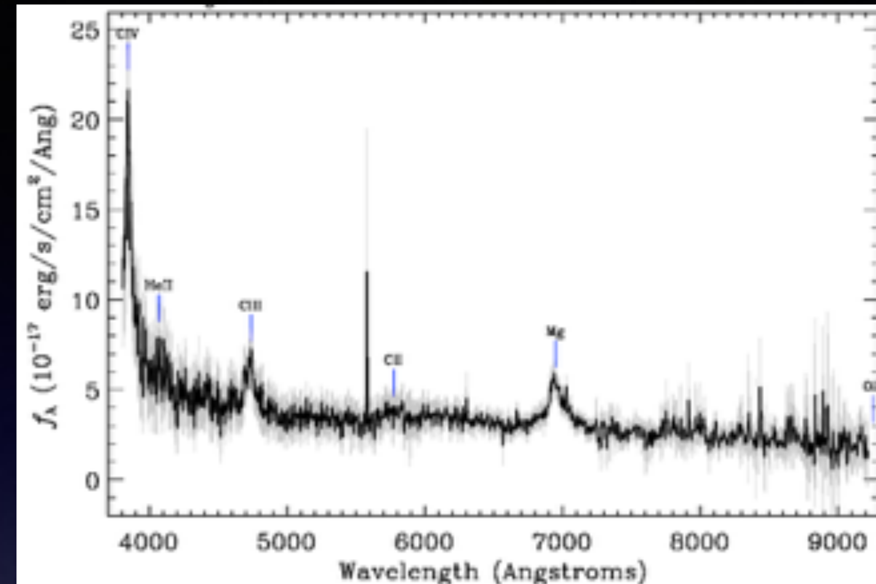
- **Emission-line ratios (optical spectroscopy)+ X-rays+ radio+ mid-infrared colours+ SED fitting: ~10% of Hα emitters at z=0.84 are AGN.**

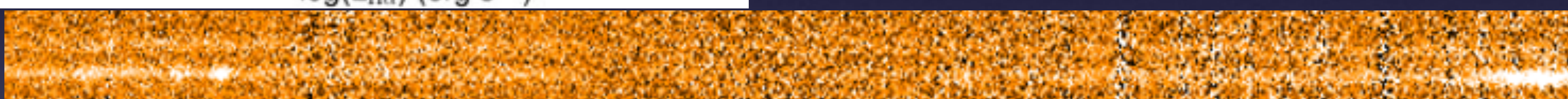


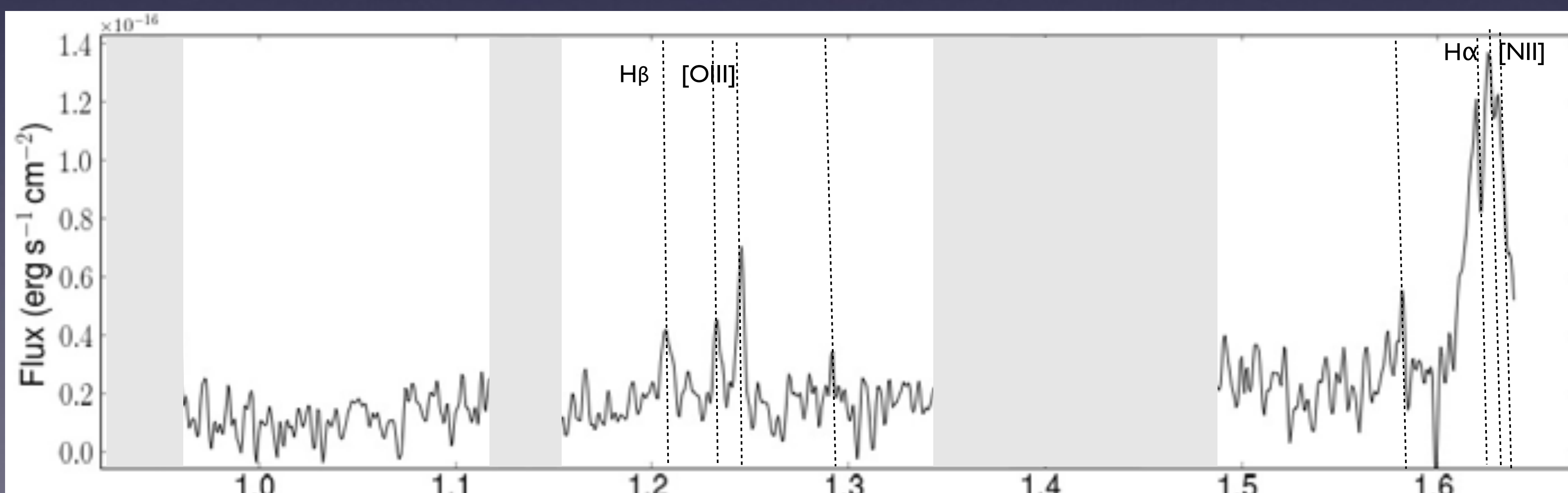
1.5
1.0
0.5
0.0
−0.5
−1.0
AGN
Star Forming
−1.5
−1.0
−0.5
0.0
0.5
log [NII]/Hα
log [OIII]/Hβ

Subaru FMOS + NTT + WHT

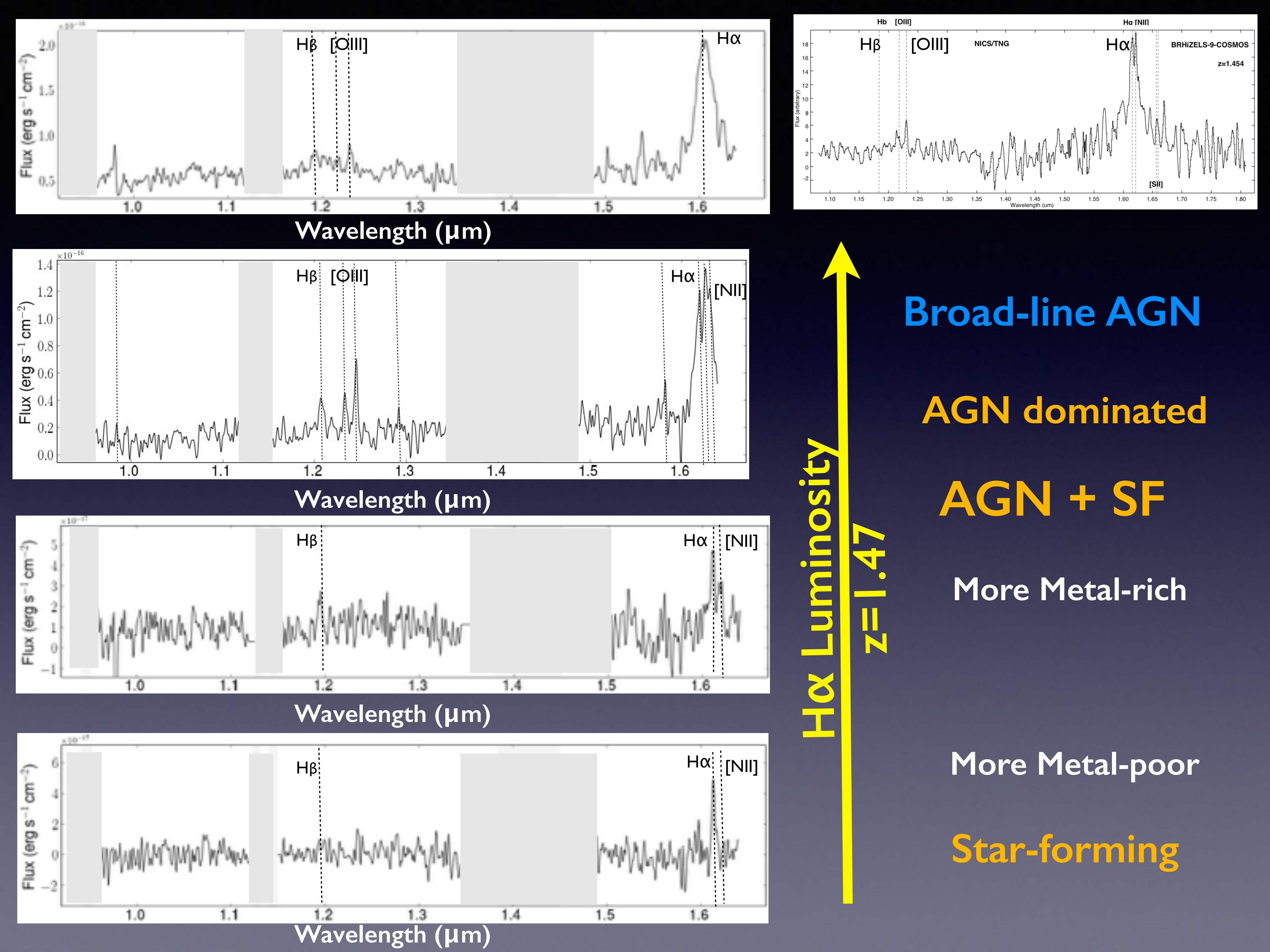




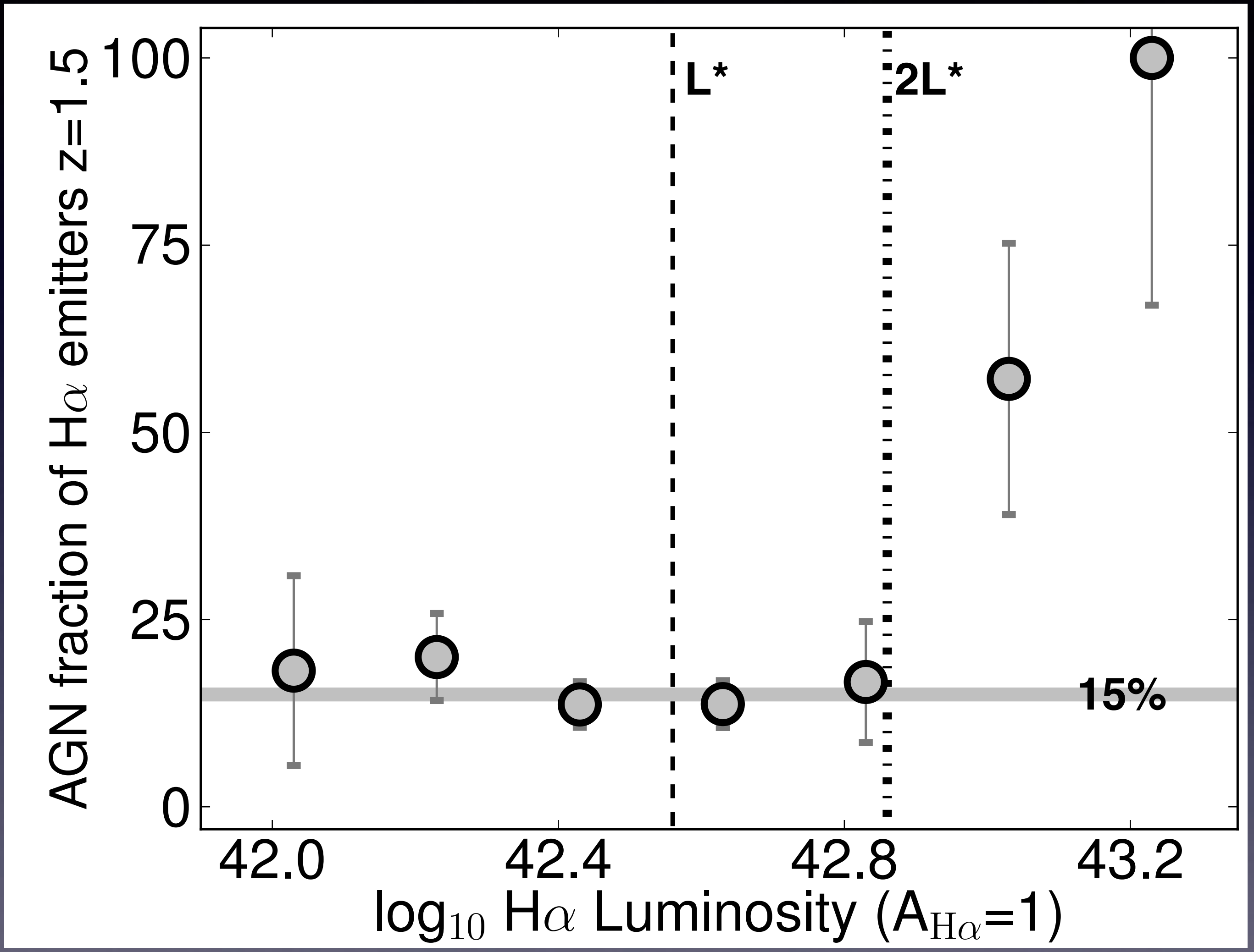




Wavelength (μm)


Hβ
[OIII]
Hα
Flux (erg s⁻¹ cm⁻²)
Wavelength (μm)
Hb [OIII]
Hα [NII]
NICS/TNG
BRHiZELS-9-COSMOS
z=1.454
[SII]
Flux (arbitrary)
Wavelength (um)
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)
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

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

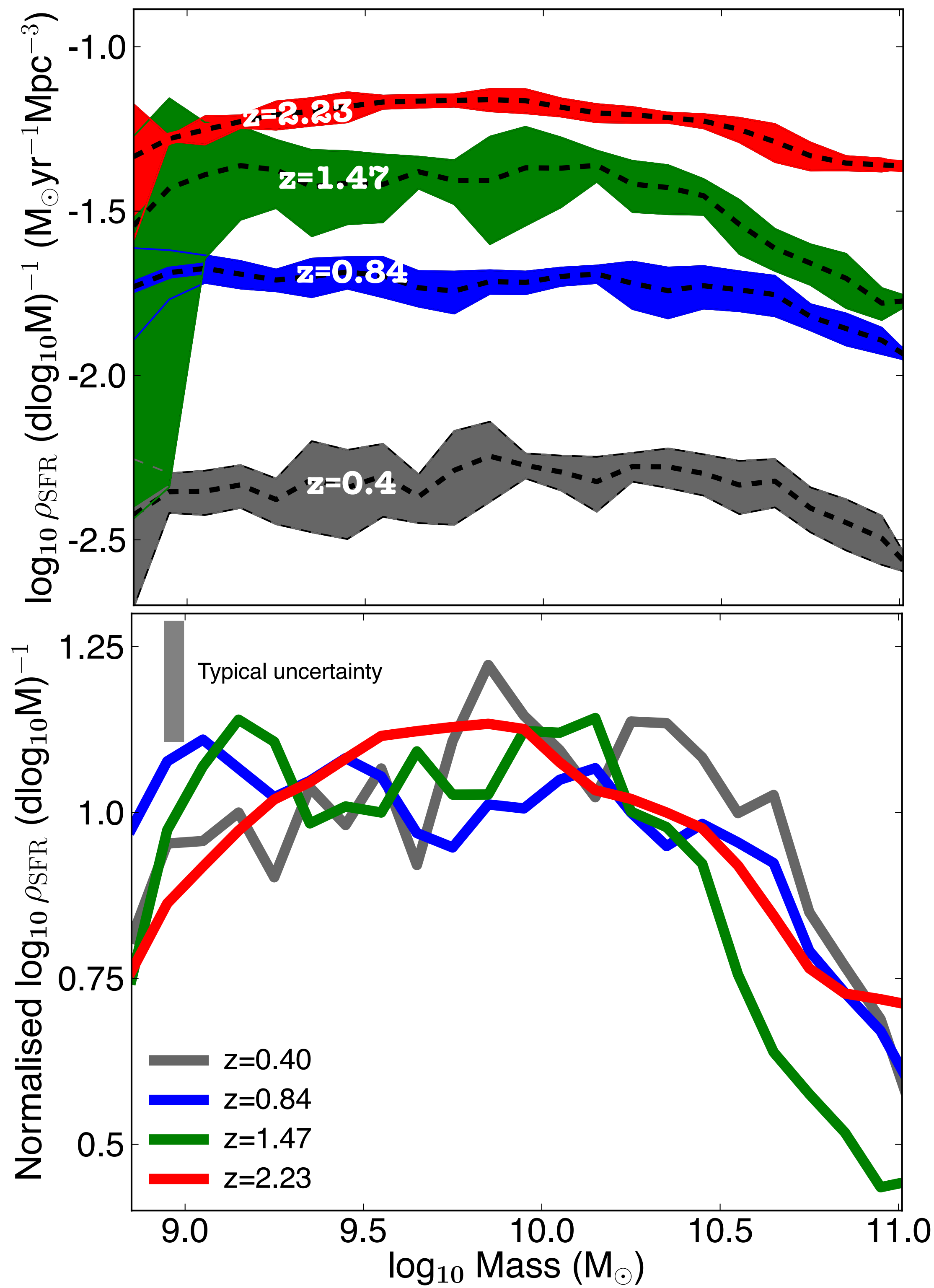
z	a	b	r_e at $\log_{10}(M_*) = 10$ (kpc)
0.40	0.08 ± 0.02	0.55 ± 0.03	3.6 ± 0.2
0.84	0.03 ± 0.02	0.54 ± 0.01	3.5 ± 0.1
1.47	0.03 ± 0.02	0.59 ± 0.01	3.9 ± 0.2
2.23	0.08 ± 0.03	0.51 ± 0.02	3.3 ± 0.2

~Same sizes down to same SFR/SFR*

Stott et al. 2013

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

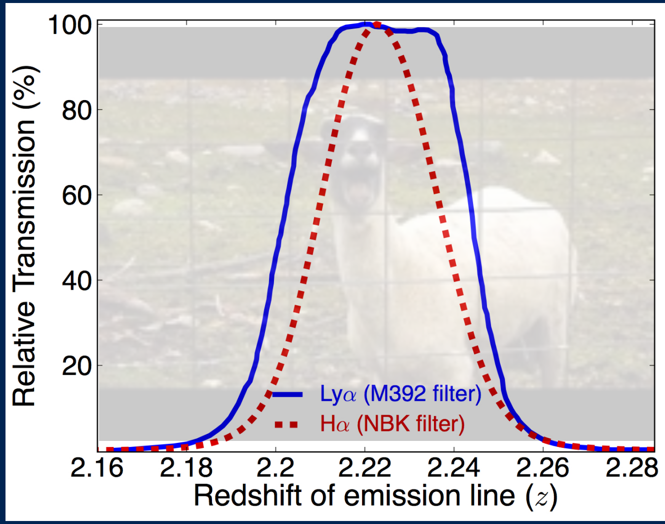
Sobral et al. (2014)

The CALYMHA survey (CAlibrating LYMan-α with Hα)

Custom-made narrow-band filter PI: Sobral

A 5 deg^2 deep double-blind matched Lyα-Hα survey z=2.23

55 night survey in total (but highly weathered out): Finished on Jan 28 2015

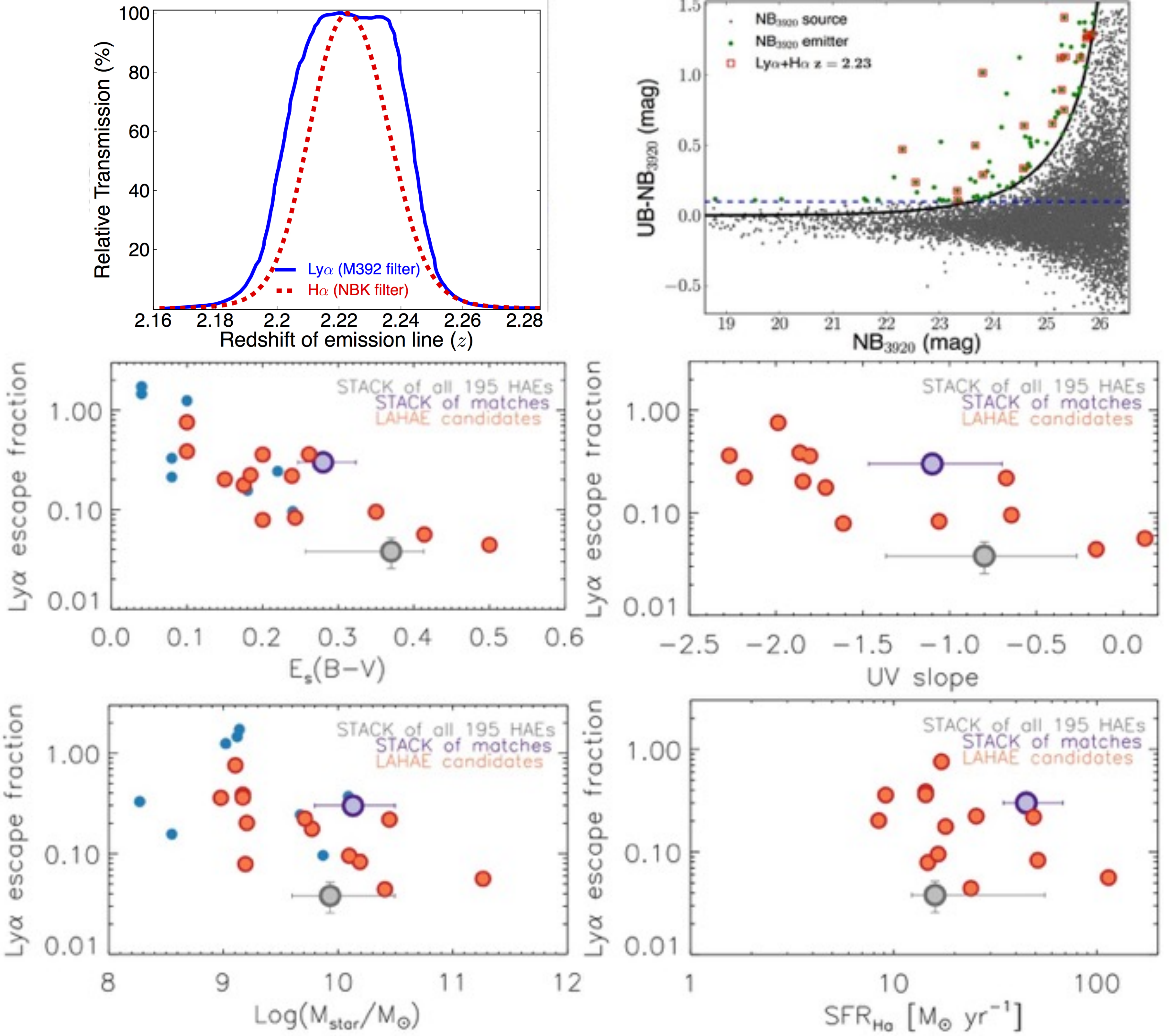


Escape fraction of star-forming galaxies (Lyα): ~4+-2% (consistent with Hayes+)

Wide range of properties of matched Lyα-Hα emitters:

Masses: ~10^9 or 10^{11} M_o SFRs: ~5-200 Msun/yr

Dust: ~0 to 2 mags Mostly Blue but also Red!

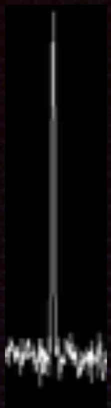


Relative Transmission (%)
Lyα (M392 filter)
Hα (NBK filter)
Redshift of emission line (z)
NB3920 source
NB3920 emitter
Lyα+Hα z = 2.23
UB-NB3920 (mag)
NB3920 (mag)
STACK of all 195 HAEs
STACK of matches
LAHAE candidates
Lyα escape fraction
Es(B−V)
UV slope
Log(Mstar/M⊙)
SFRHα [M⊙ yr−1]

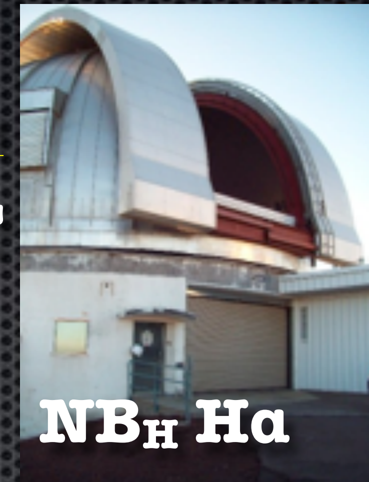
Double-NB survey

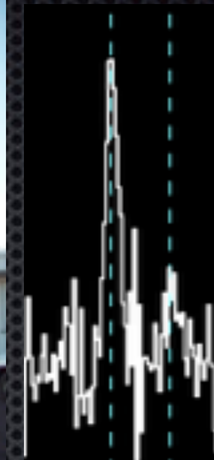
Sobral+12

400 Hα+[OII] / night!



Subaru joins UKIRT to “walk through the desert”

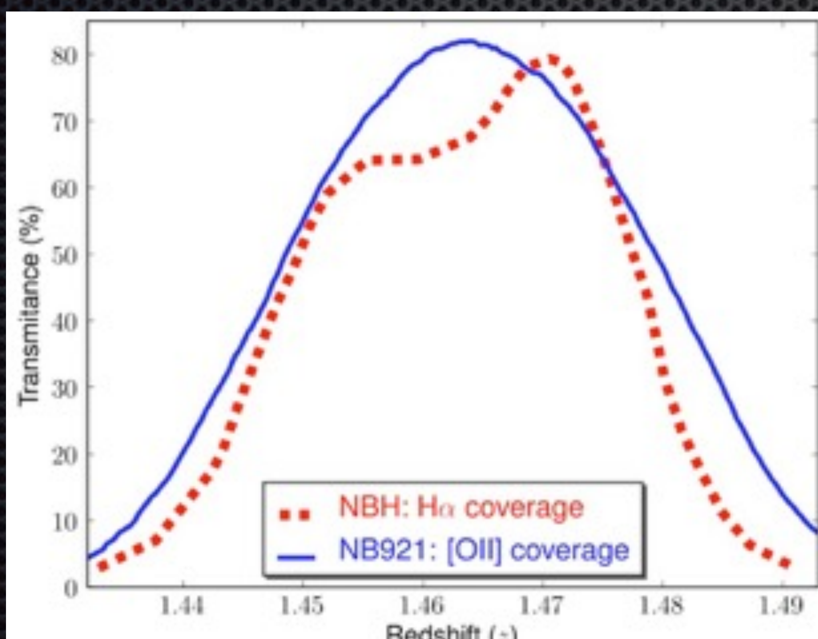


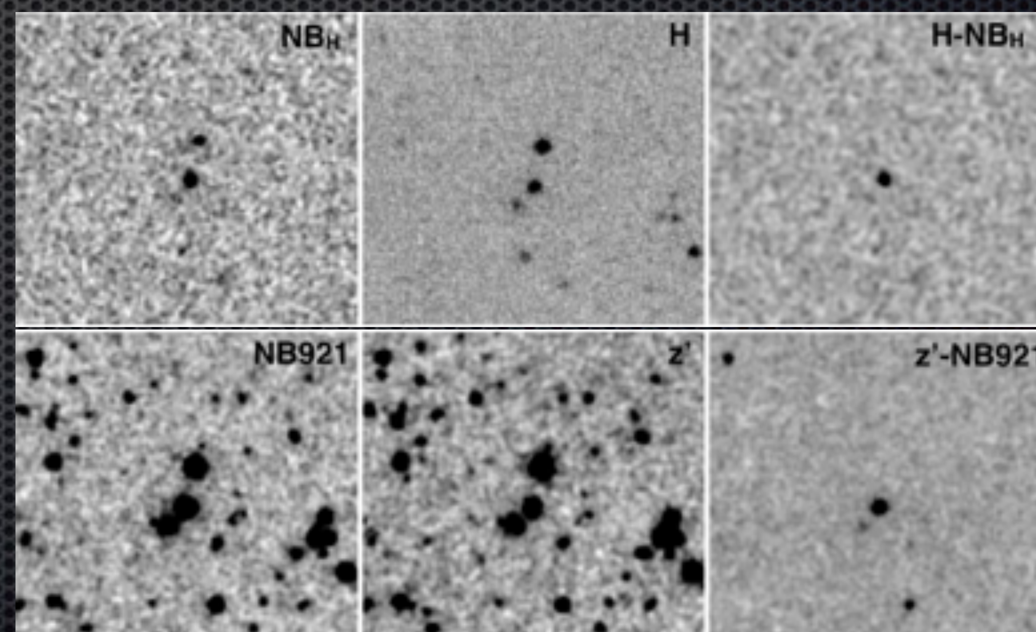


The first Hα-[OII] large double-blind survey at high-z

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