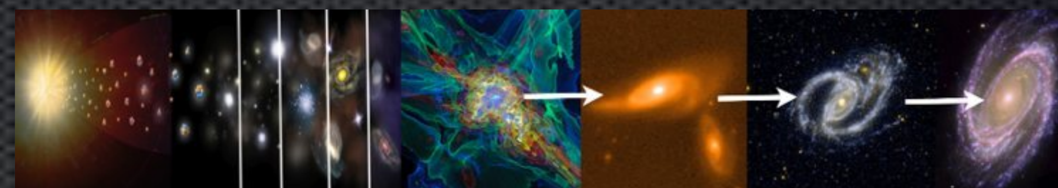
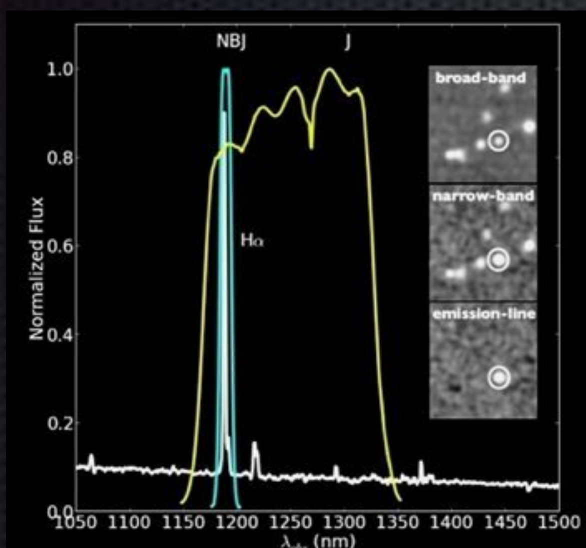
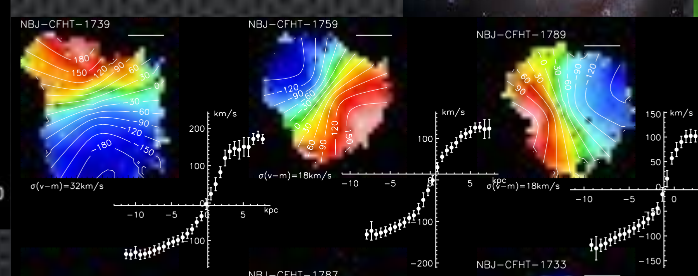
Hα surveys up to z~7: 13 Gyrs, same method

David Sobral

IA-CAAUL Lisbon/Leiden Obs.







Jorryt Matthee, Mark Swinbank, John Stott,
Iván Oteo, Yusei Koyama, Philip Best, Ian Smail

WISH

Wide field Infrared Surveyor for High-redshift

wish

Wide field Infrared Surveyor for Hα

WISH

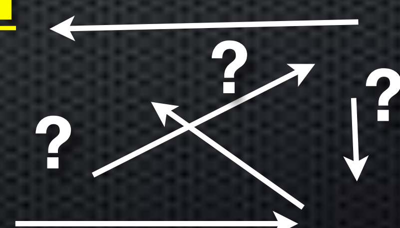
Wide field Infrared Surveyor for Hα

or: how to (potentially) revolutionise our view of $2<z<7$ galaxies and their evolution in just 10 days

How (and driven by which mechanisms)

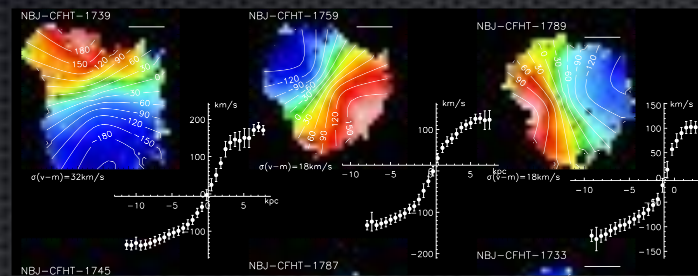
do galaxies form and evolve?

- Morphological change?
- Dynamics



- Star formation
- “Quenching”

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



- 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) A selection that can be replicated but not so robust/simple
- 4) Simple 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 groundbreaking, large-area, sensitive survey machines
- No point in having S/N>zillion and a zillion sources if the samples are completely biased/if we are missing an important part of the population: we will be "selection-limited"
- 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:

Improve SFH

- A **good (single)** star-formation tracer that can be applied from z=0 up to ~13 Gyrs ago (z~7 or more)
- Well calibrated/understood + sensitive

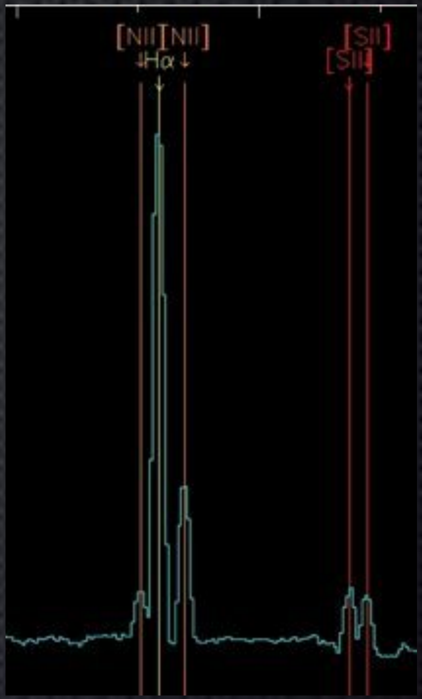
Understand the SFH

- Able to **uniformly** select large samples so you can directly identify/measure evolution
- **Different epochs** + **Large areas + Best-studied fields**
- **Wide parameter range: Masses, Environments, Galaxy properties**

Hα (+NB)

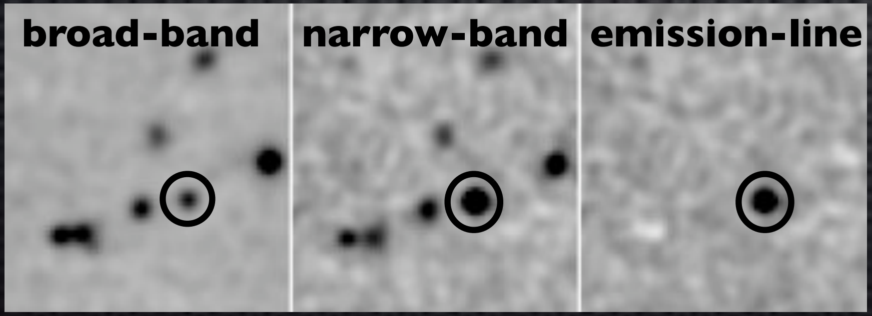
- **To understand the nature and evolution of star-forming galaxies across cosmic time**

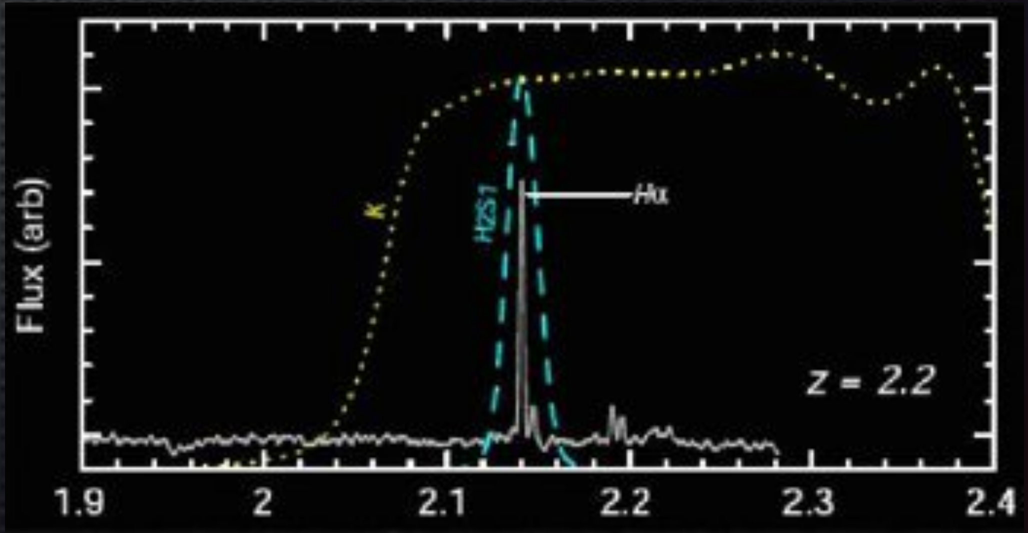
- Sensitive, good selection
- Well-calibrated
- Traditionally for Local Universe
- **<u>Narrow-band technique</u>**



- **Wide Field near-infrared cameras: can be done over large areas**

- **Traced up to z ~ 2.5 (ground)**





Selection really matters

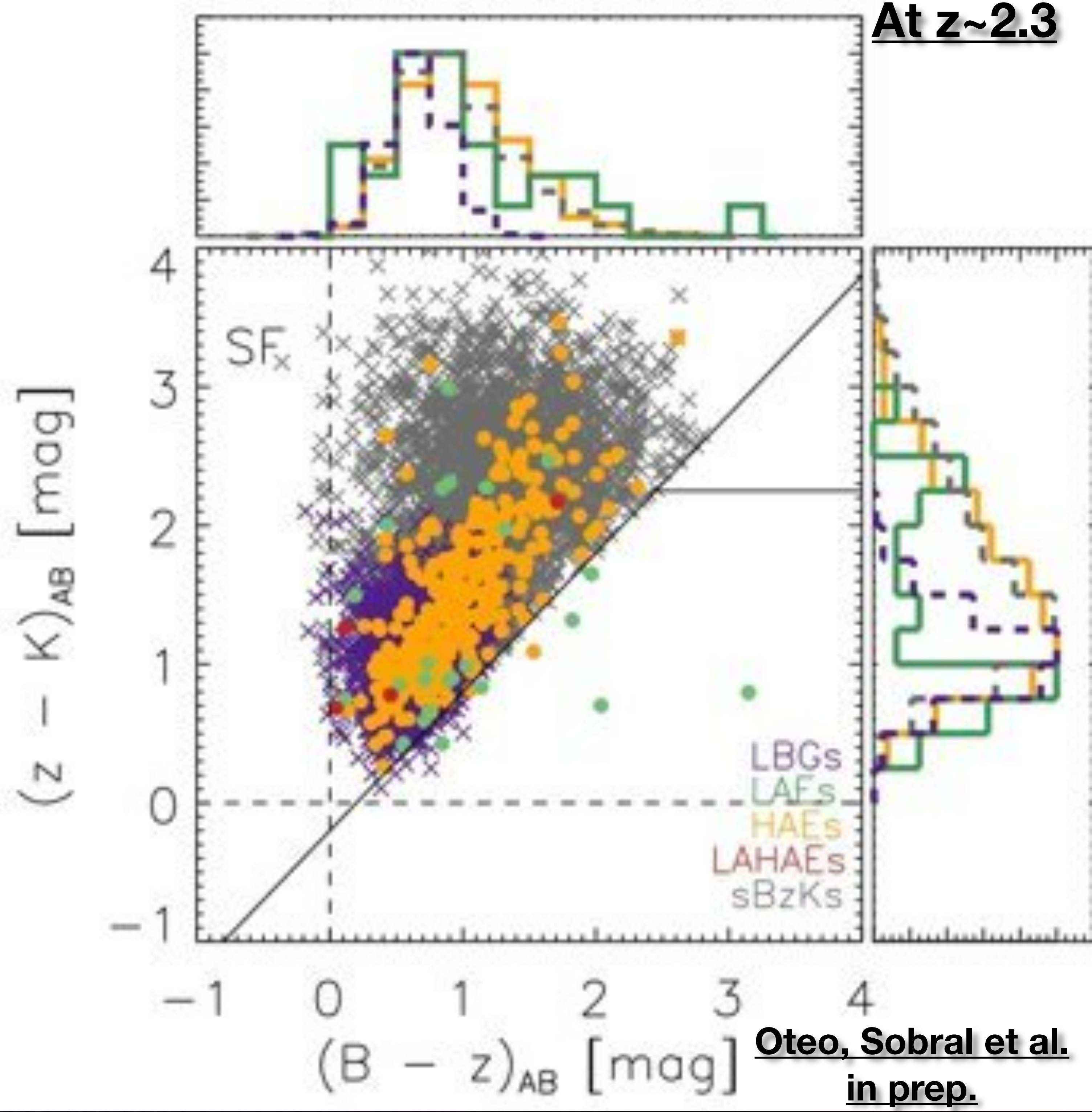
Lyman-break/UV selection: **misses ~65-70%** of star-forming galaxies! (metal-rich, dusty) (+ systematics)

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. in prep.

Selection really matters

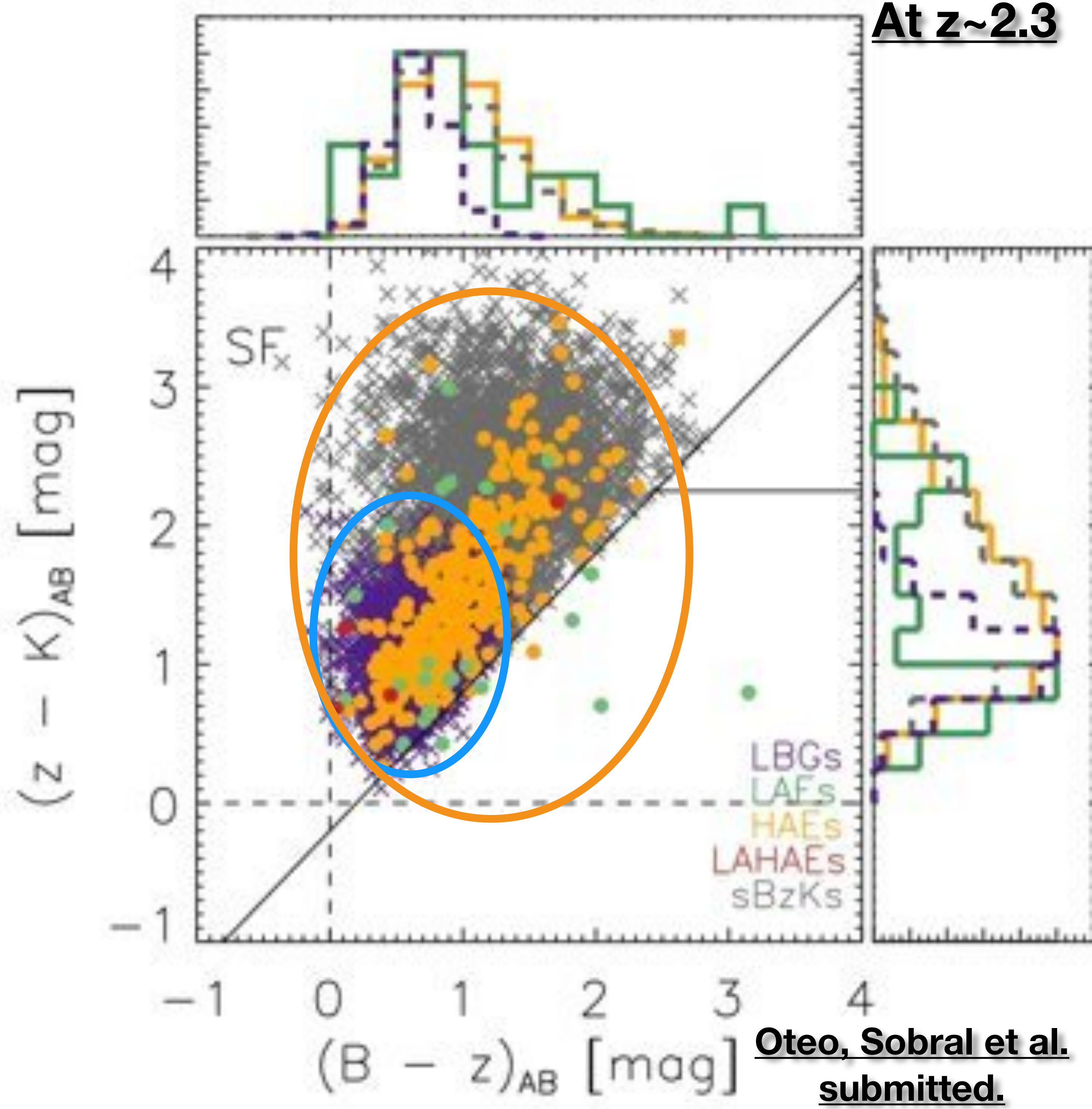
Lyman-break/UV selection: **misses ~65-70%** of star-forming galaxies! (metal-rich, dusty) (+ systematics)

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

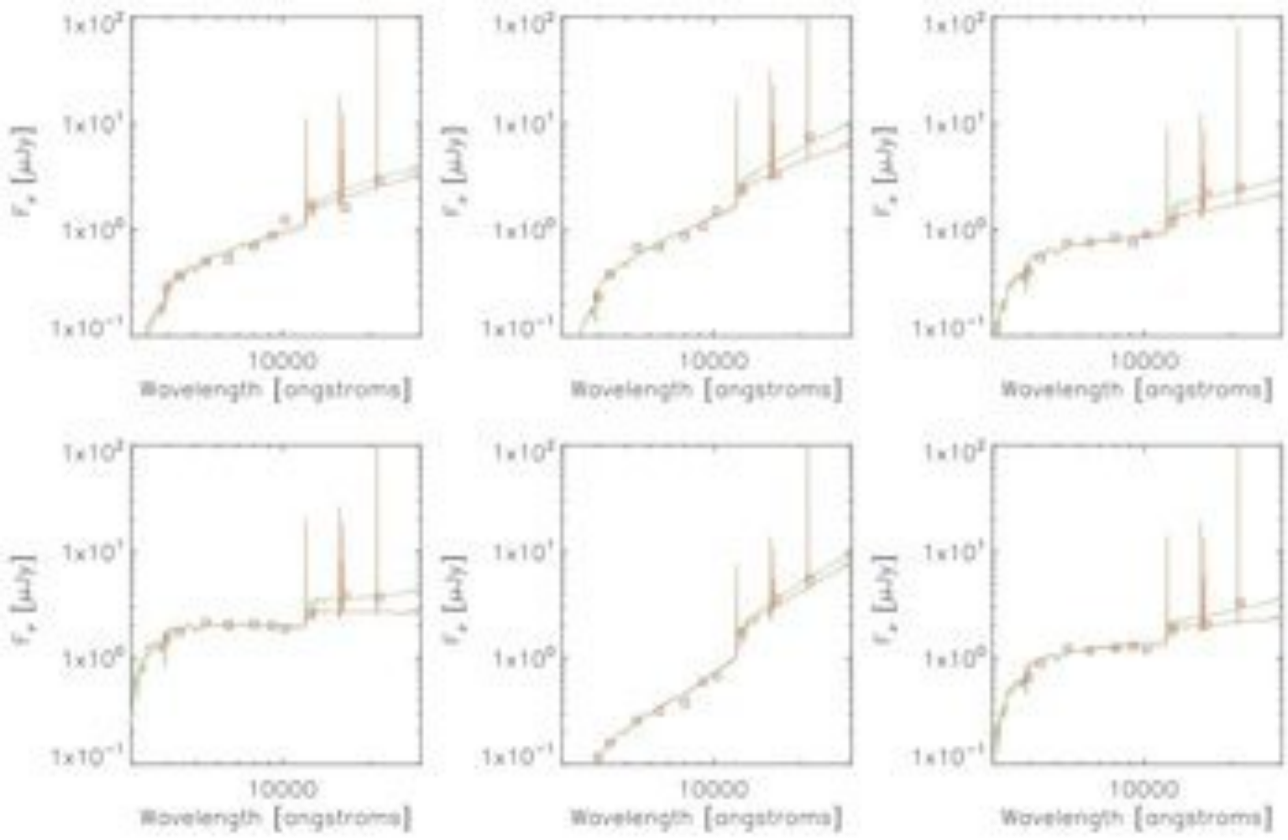
HAEs get ~100% down to the Ha flux limit they sample

See also Hayashi et al. 2013 for [OII]

At z~2.3

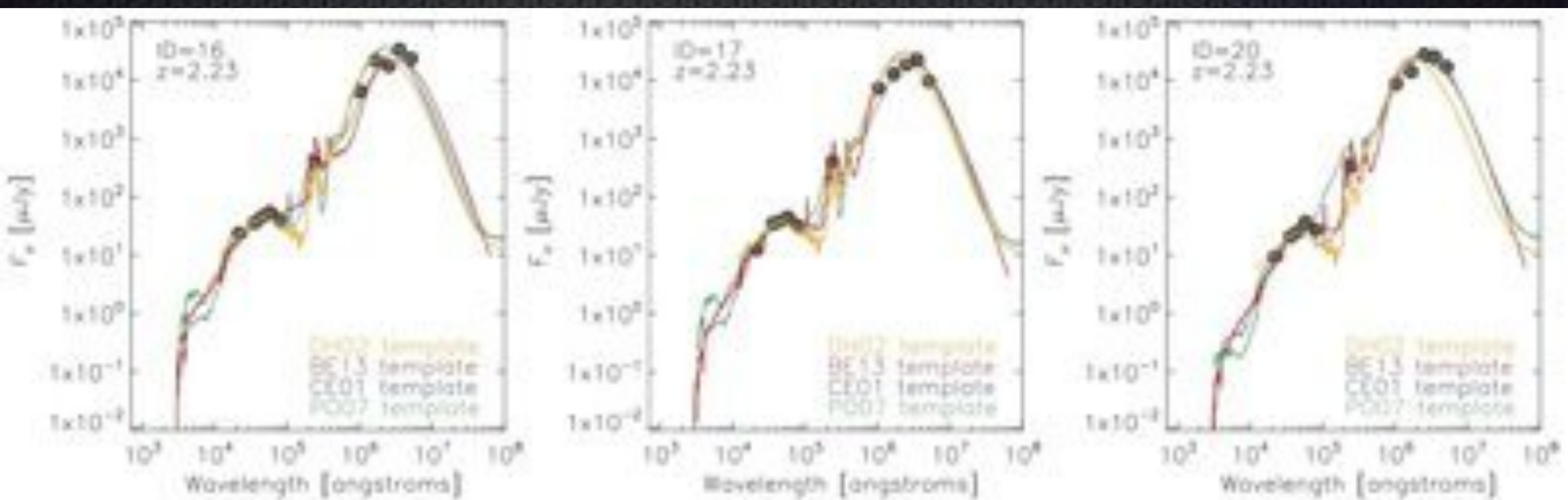


Oteo, Sobral et al. submitted.

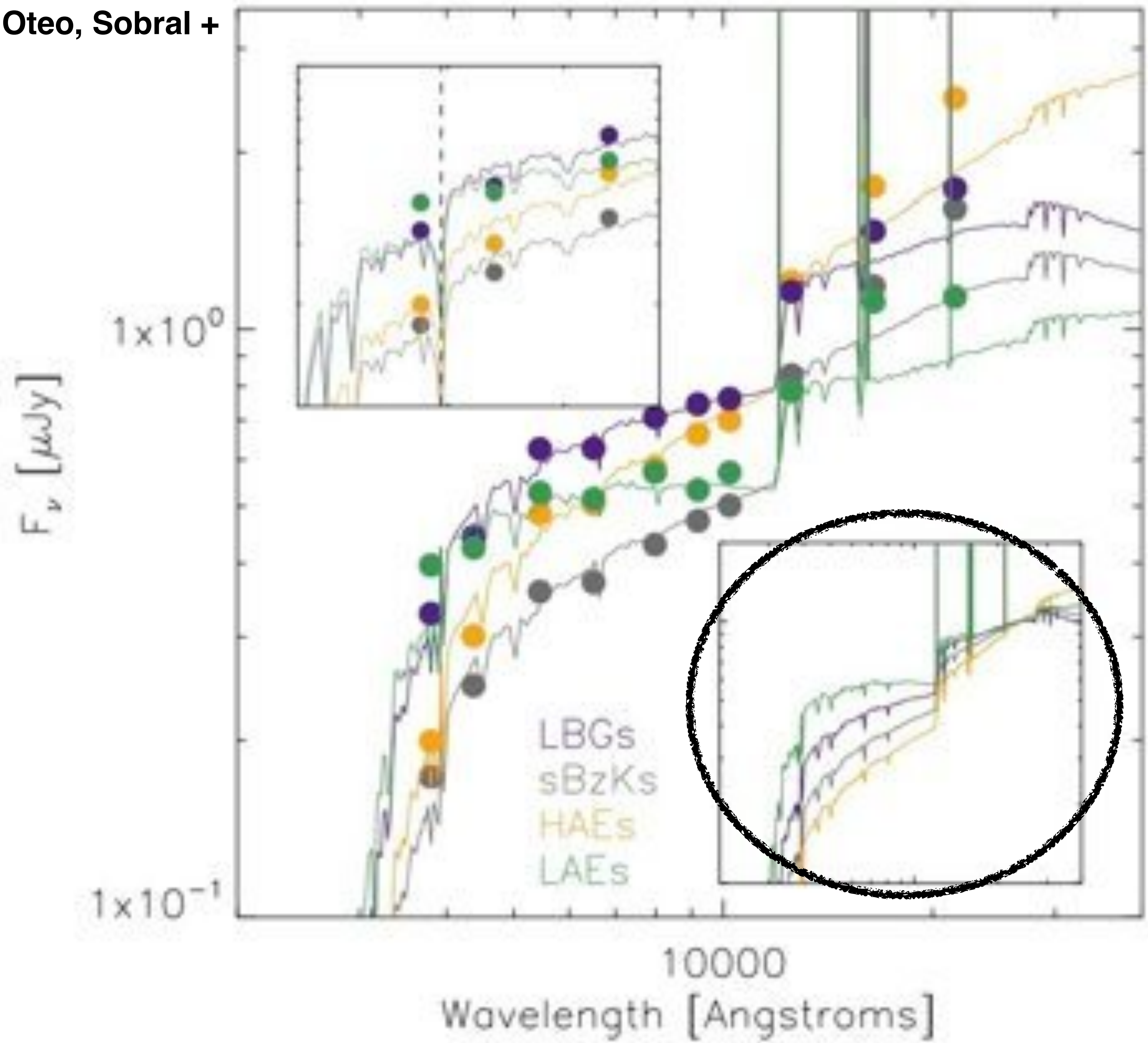


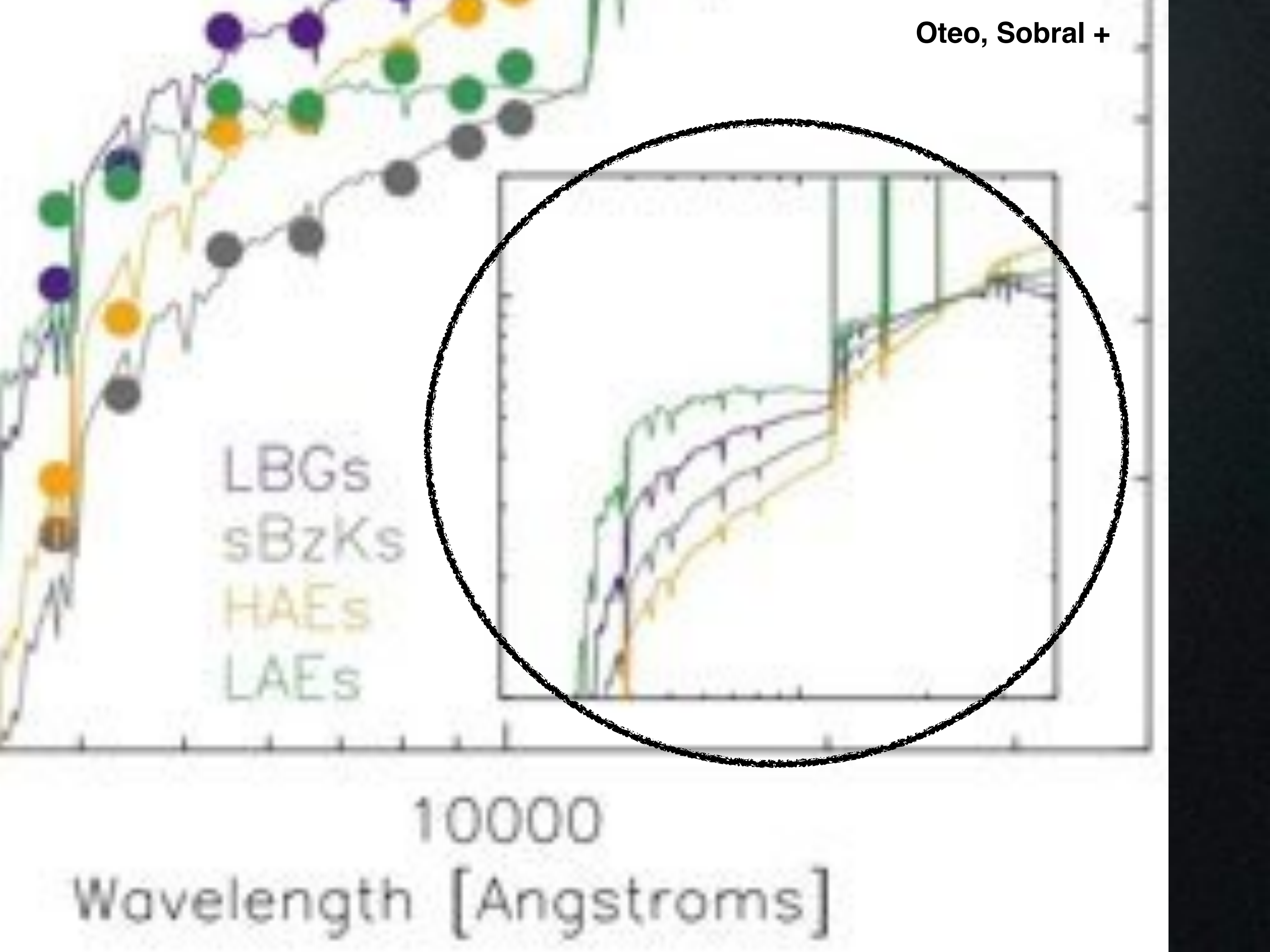
Selection really matters

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



Oteo, Sobral +


1x10^0
1x10^-1
F_ν [μJy]
10000
Wavelength [Angstroms]
LBGs
sBzKs
HAEs
LAEs


Oteo, Sobral +
LBGs
sBzKs
HAEs
LAEs
10000
Wavelength [Angstroms]

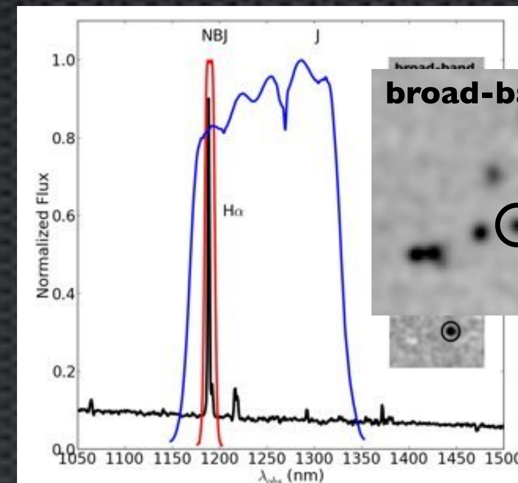
Hα at z<2.5

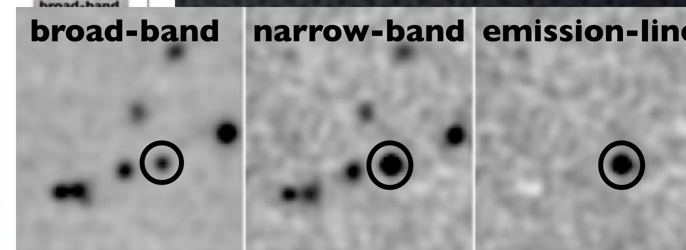
(Geach+08,Sobral+09,12,13a)

HiZELS (+ 3D-HST + WISP)

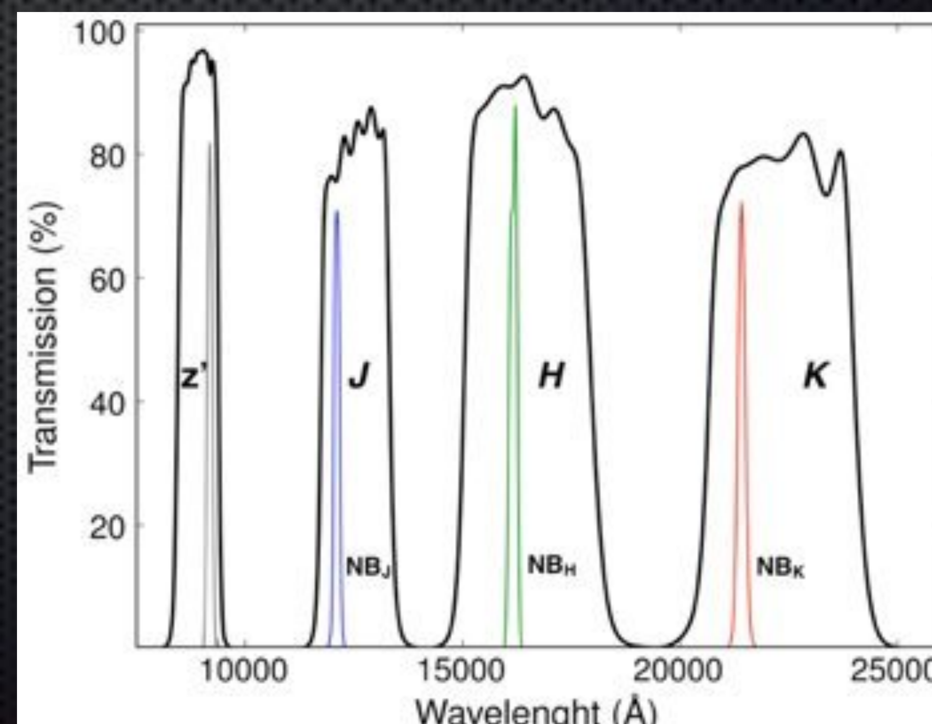
(+Deep NBH + Subar-HiZELS + HAWK-I)

- **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**
- Narrow-band Filters target Hα at **z=0.2, 0.4, 0.6,0.8, 0.84, 1.47, 2.23**
- **Same reduction+analysis**
- **Other lines (simultaneously; Sobral+09a,b,Sobral+12,13a,b, Matthee+14)**

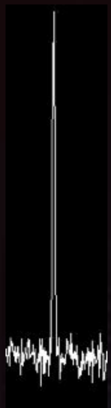




- **>1000 galaxies per NB slice**



Sobral et al. 2013a, 2014

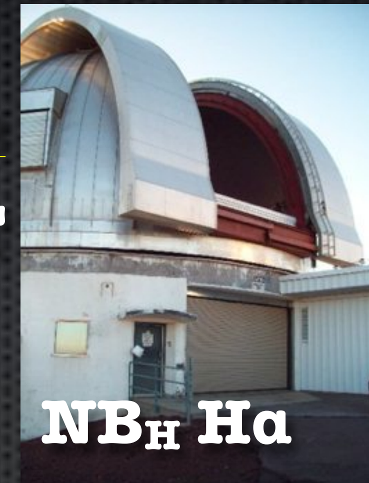


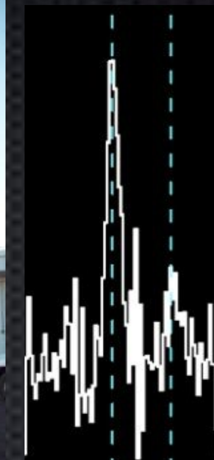
Double-NB survey

Sobral+12

400 Ha+[OII] / night!

Subaru joins UKIRT to "walk through the desert"

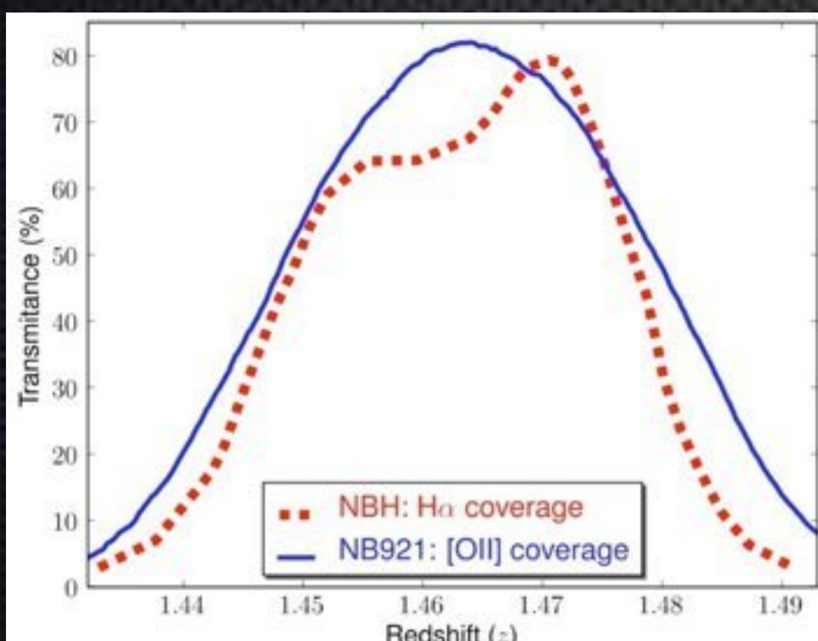


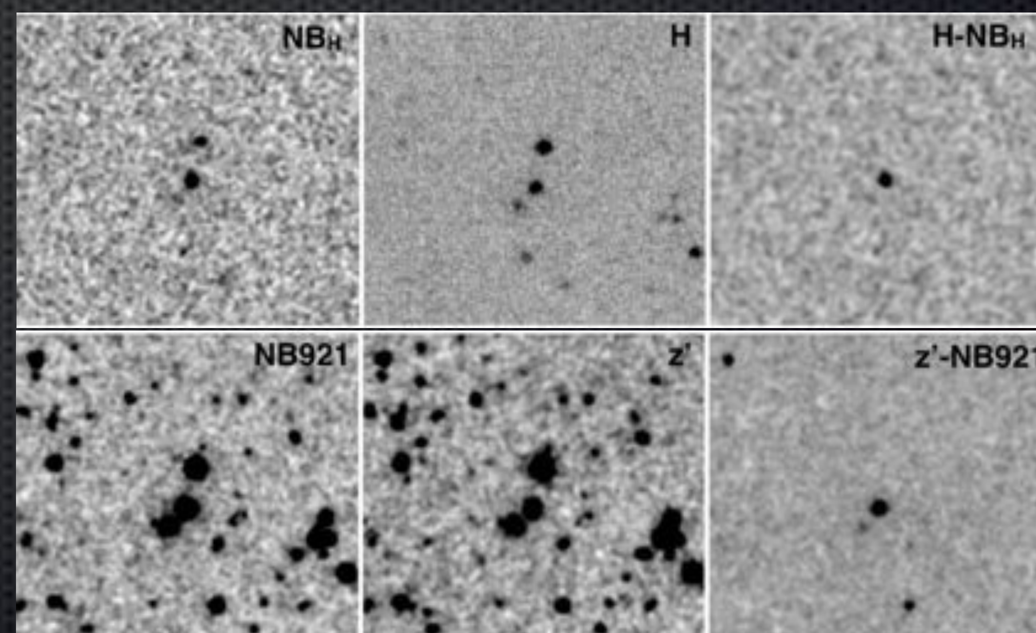


The first Hα-[OII] large double-blind survey at high-z

Sobral et al. 2012

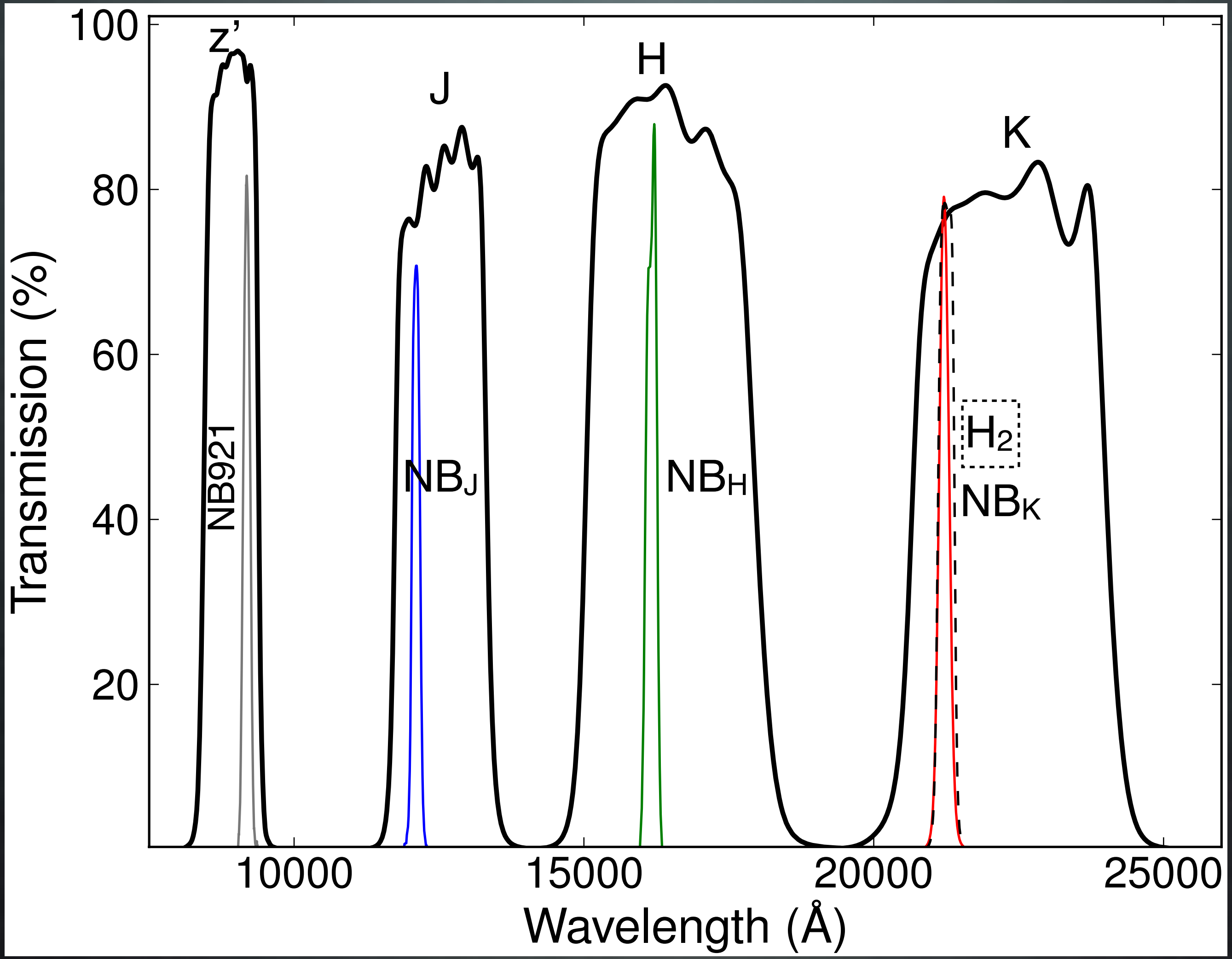
See Hayashi, Sobral et al. 2013: [OII] SFRs at z=1.5





without any need for colour or photometric redshift selections

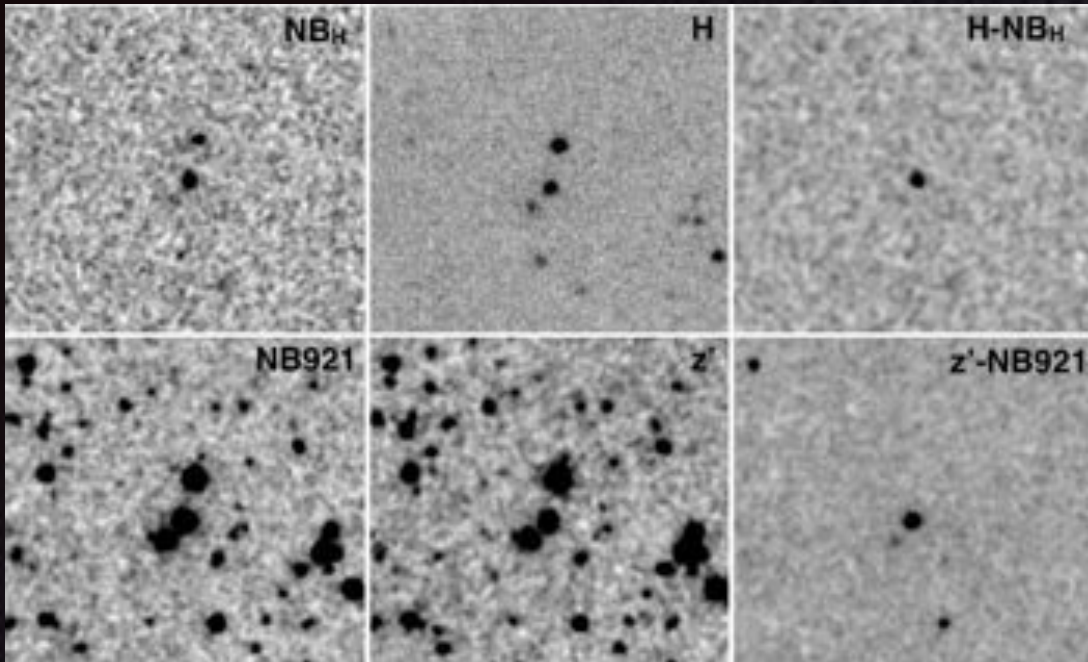
Filters combined to improve selection: double/triple line detections

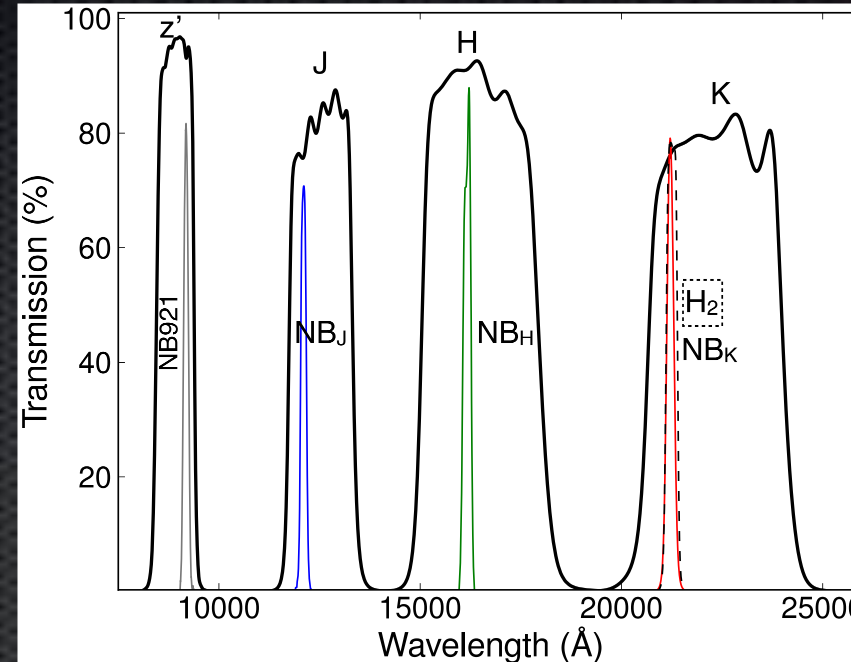


z=2.23 : [OII] (NBJ), [OIII] (NBH), Hα (NBK)

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

z=0.84 : [OIII] (NB921), Hα (NBJ)



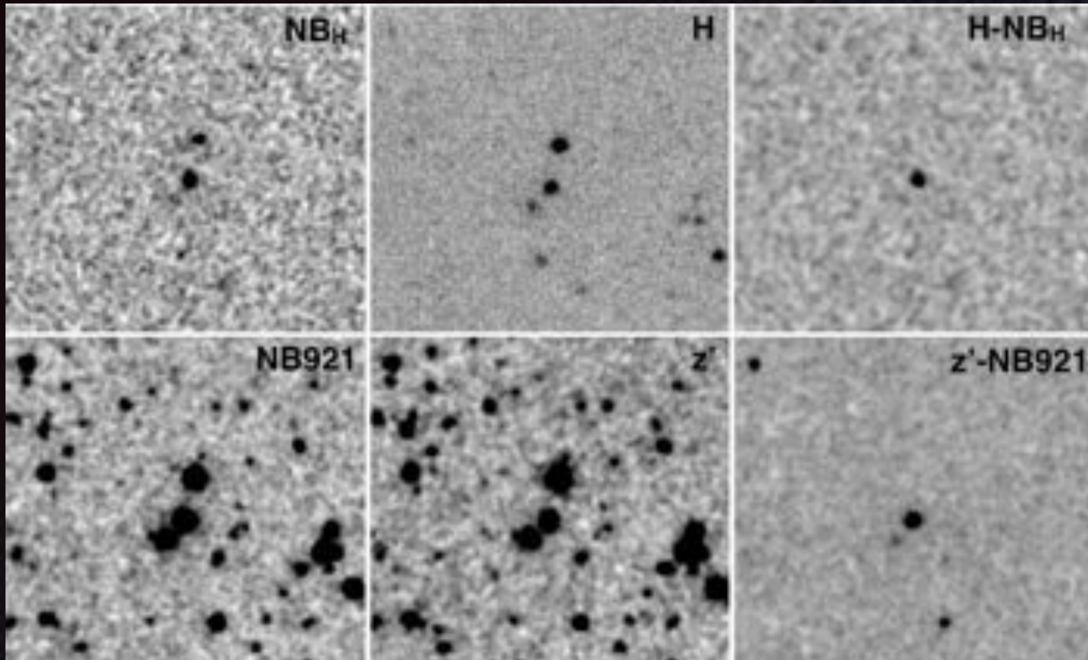


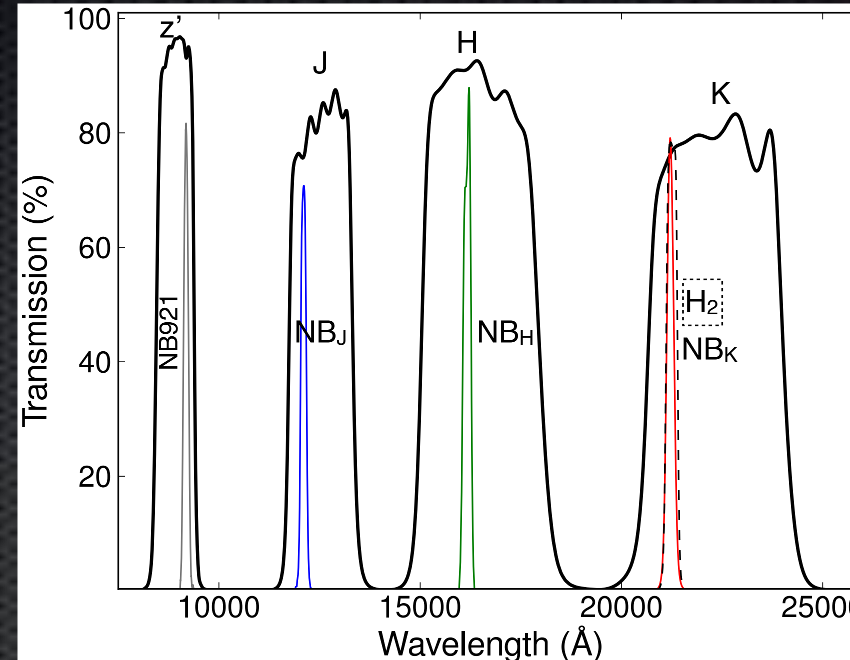
<u>**Hα emitters in HiZELS**</u>

<u>**2 sq deg: COSMOS + UDS**</u>

<u>**Prior to HiZELS:**</u>

<u>**~10 sources**</u>





Hα emitters in HiZELS

2 sq deg: COSMOS + UDS

Prior to HiZELS:

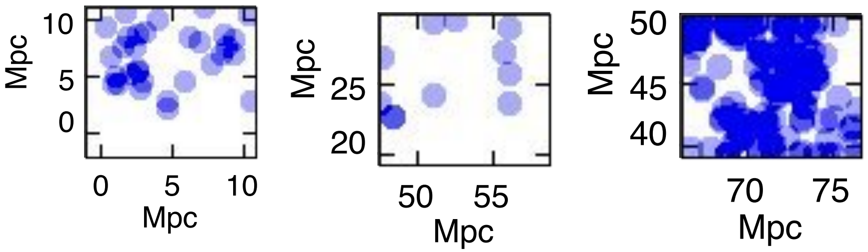
~10 sources

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

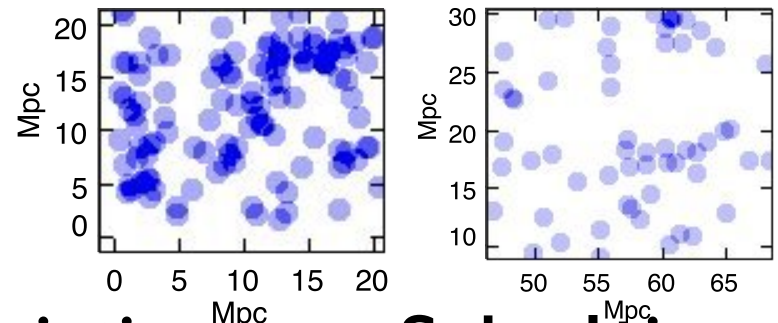
Right now: Full HiZELS (UKIDSS DXS fields) + CFHT (SA22):

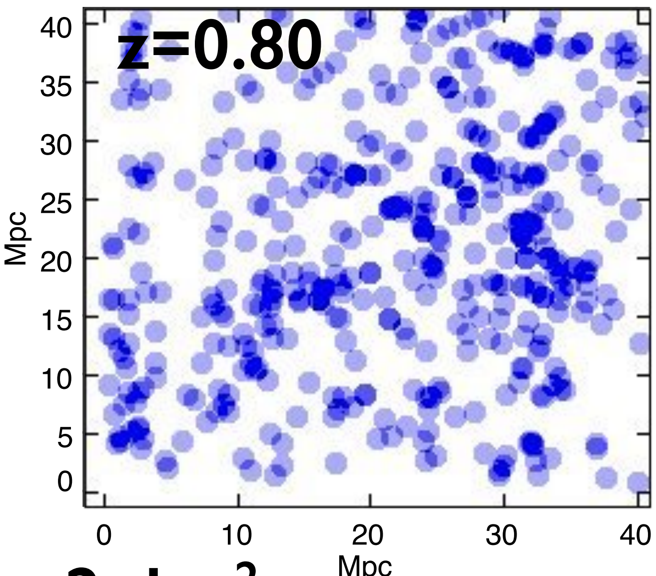
z=0.8: 6000 z=1.47: 1200 and z=2.23: 1500
along with 1000s of other z~0.1-9 emission line selected galaxies

10x10 Mpc~100 arcmin^2

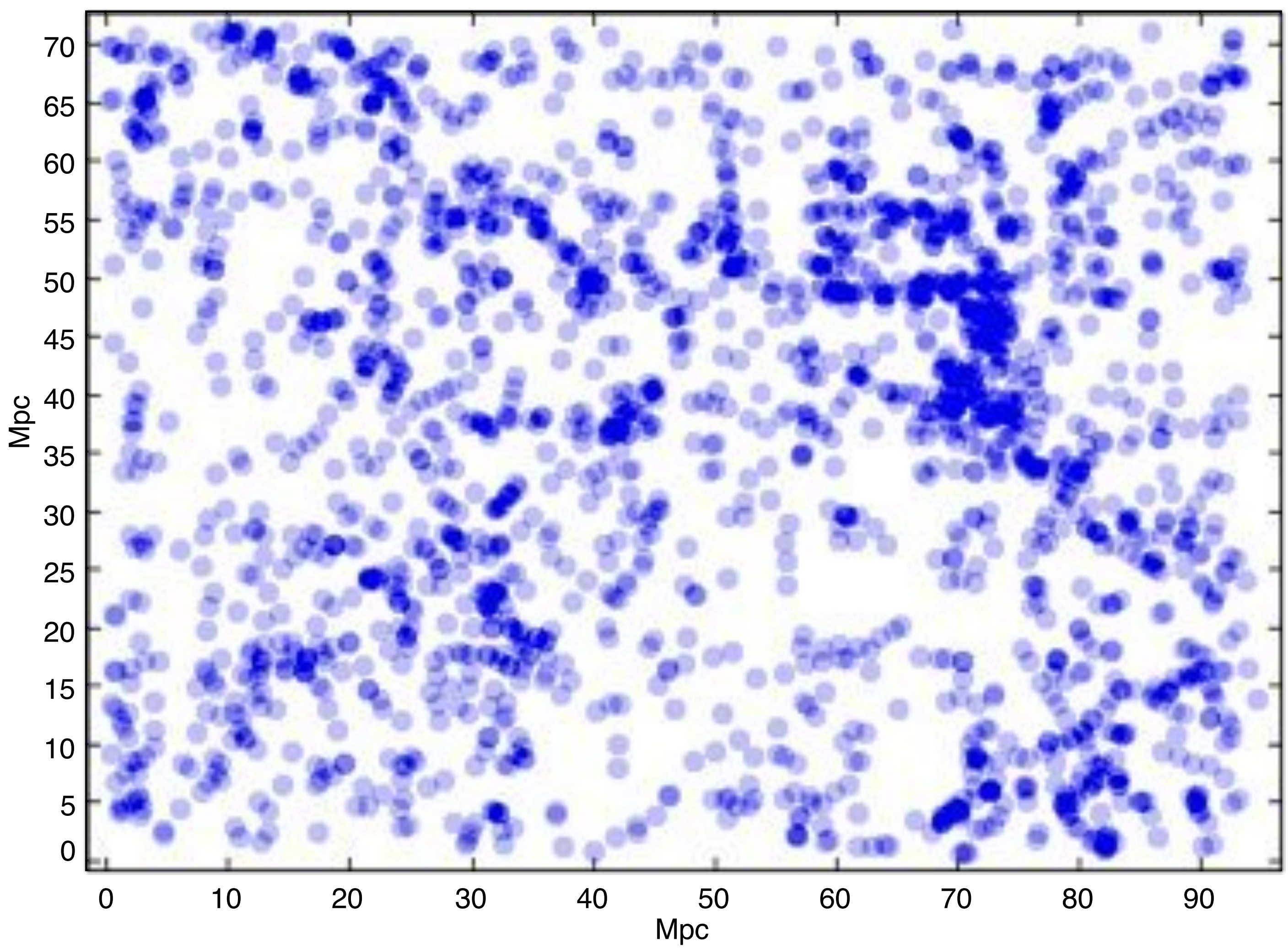


20x20 Mpc ~0.7 deg^2

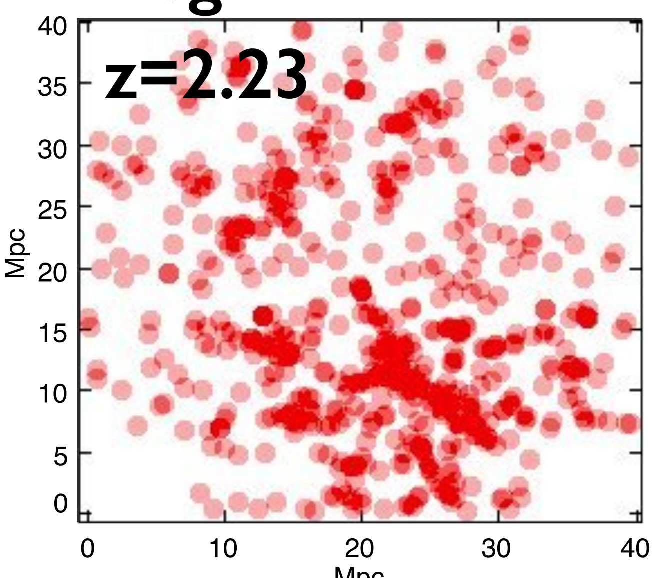




10 deg^2 80 pointings Sobral+in prep.

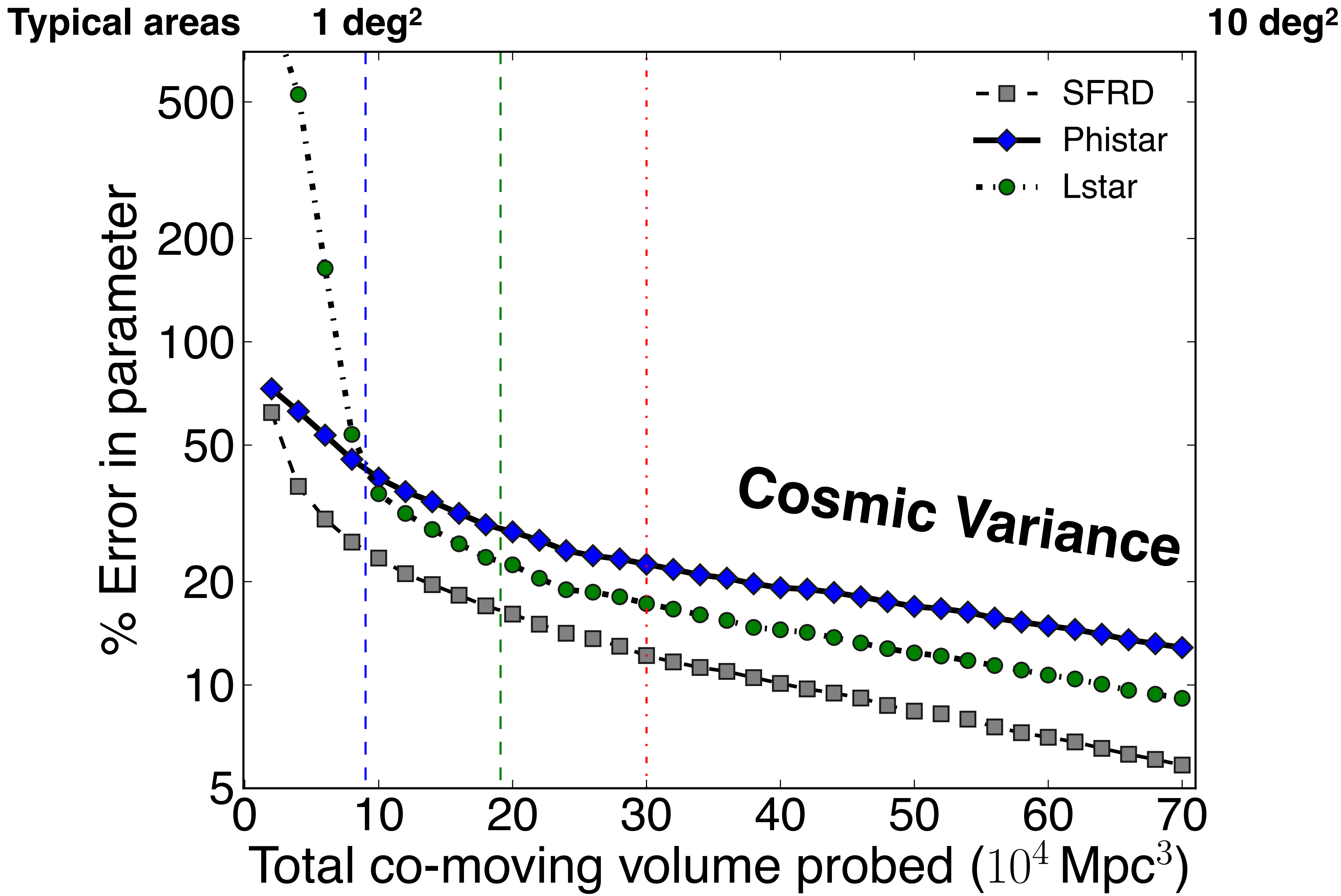


~2 deg^2



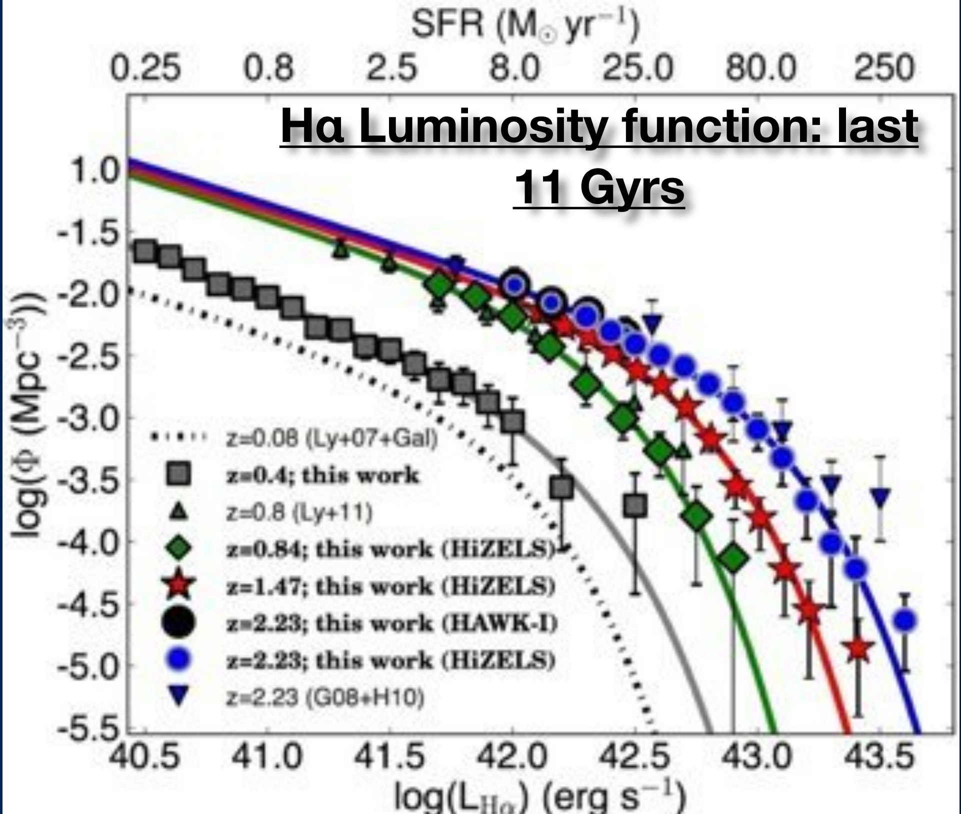
Hα emitters z=0.81+-0.01

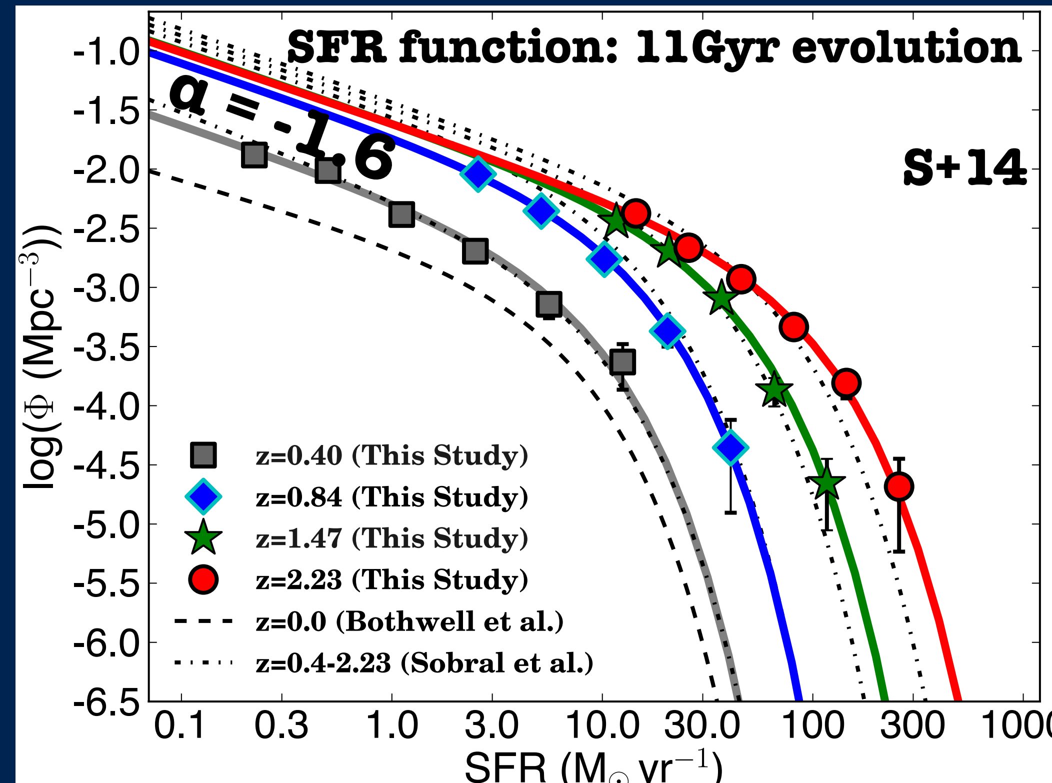
Why we need large, multiple volumes!



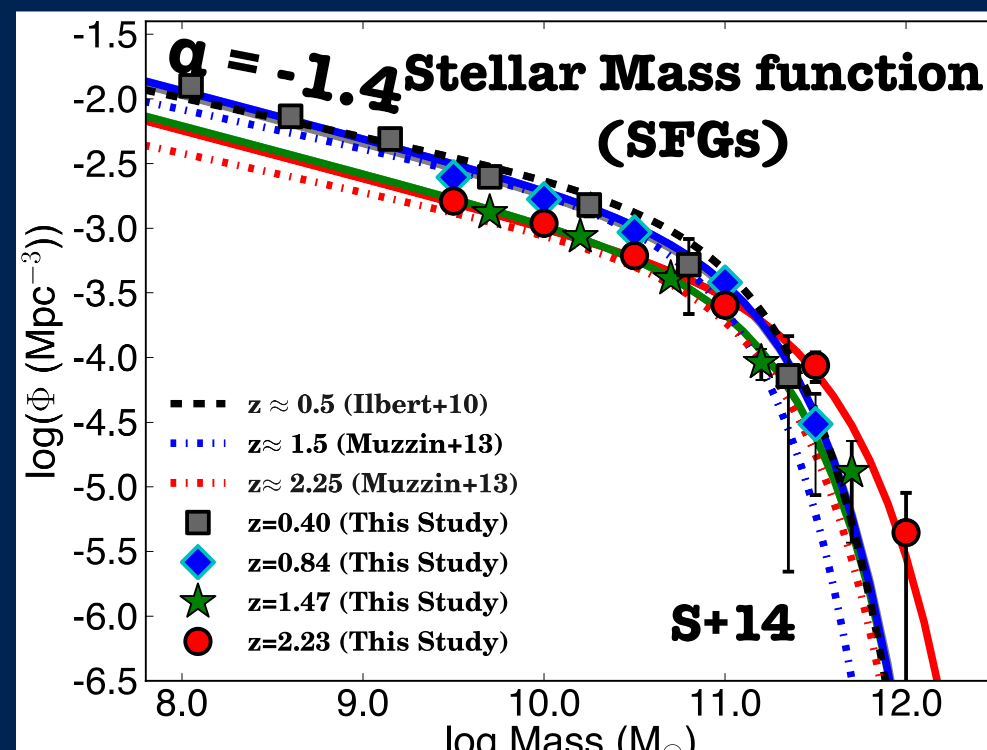
With *real* data

Errors < 20%



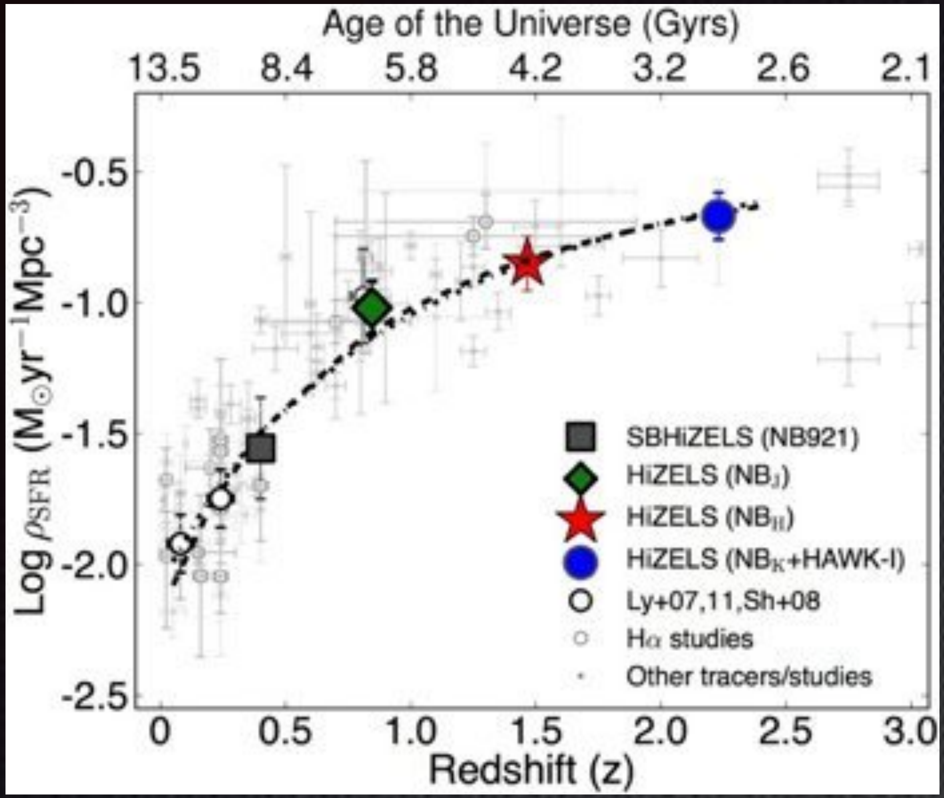


Sobral et al. 2013a, 2014



Same selection: evolution of LF, SFR function, Mass function

Up to z~2.5 OK

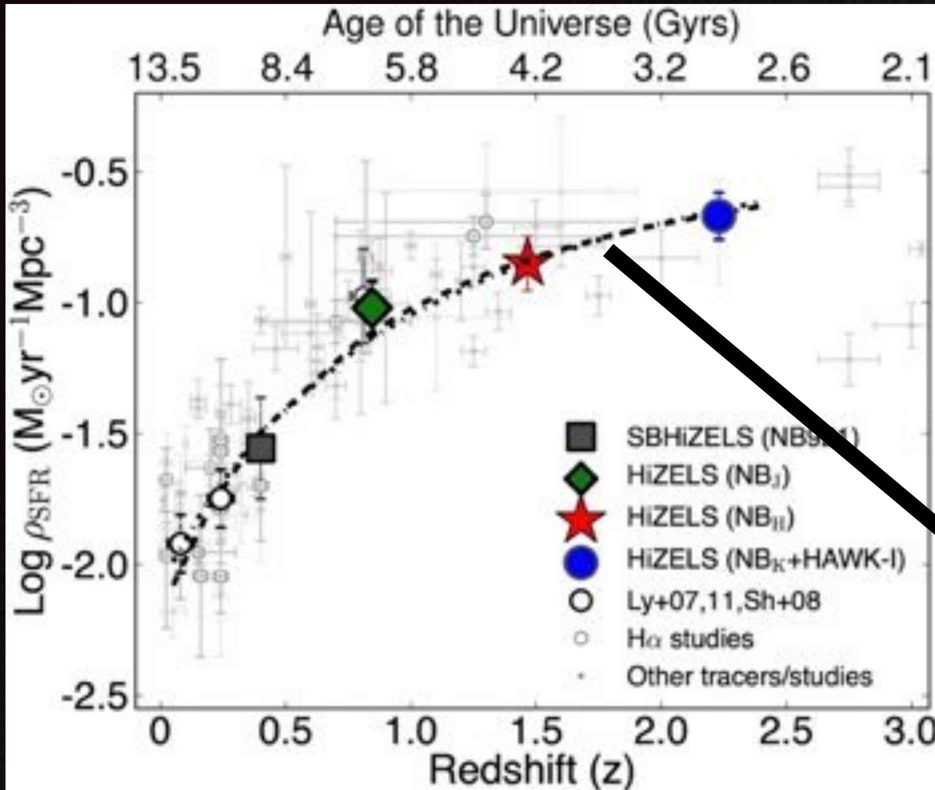


+ e.g. Lilly+96, Hopkins04, Karim+11

Star formation History

Strong decline with cosmic time

Sobral+13a



+ e.g. Lilly+96, Hopkins04, Karim+11

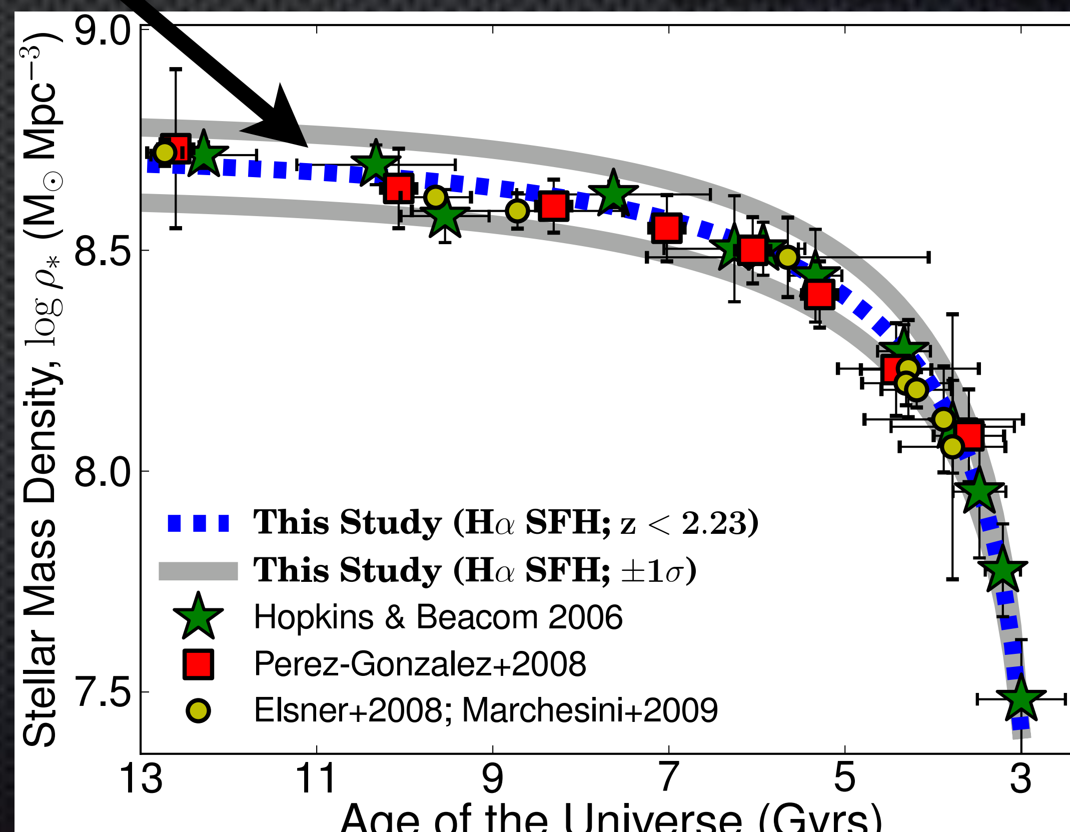
Star formation History

Strong decline with cosmic time

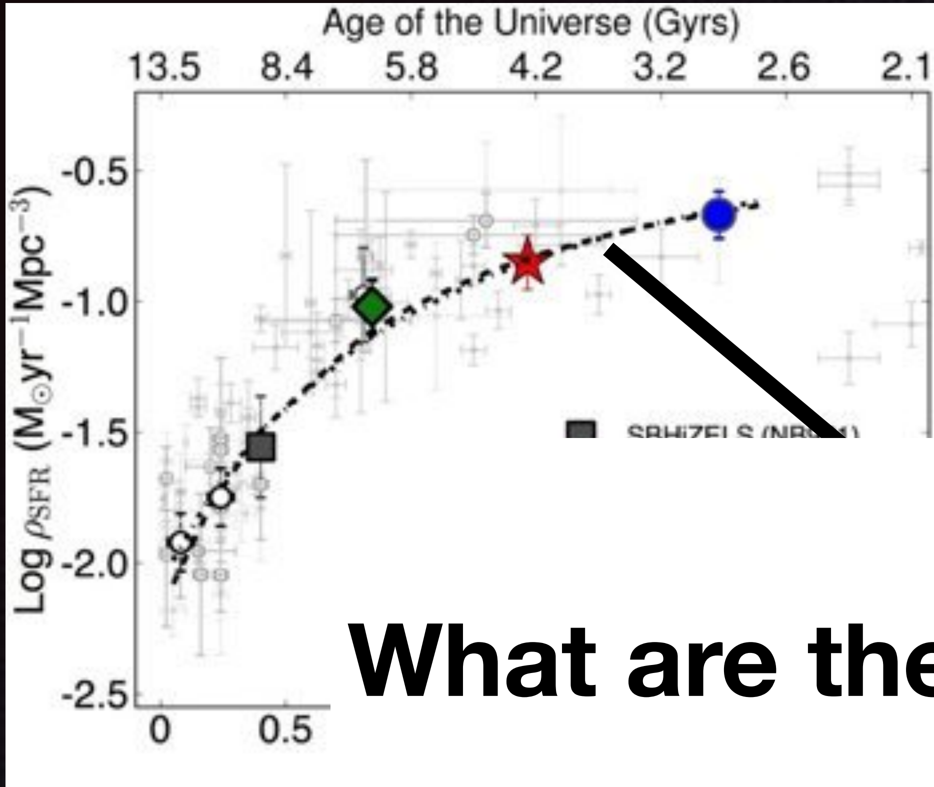
$\log_{10}(\mathrm{SFRD}) = -2.1/(1+z)$

Sobral+13a

Stellar Mass density evolution



Star formation history from Hα matches observations!!



Star formation History

Strong decline with cosmic time

-2.1/(1+z)

Sobral+13a

+ e.g. Lilly+9

What are the main drivers?

What's evolving?

And what about z>2-3??

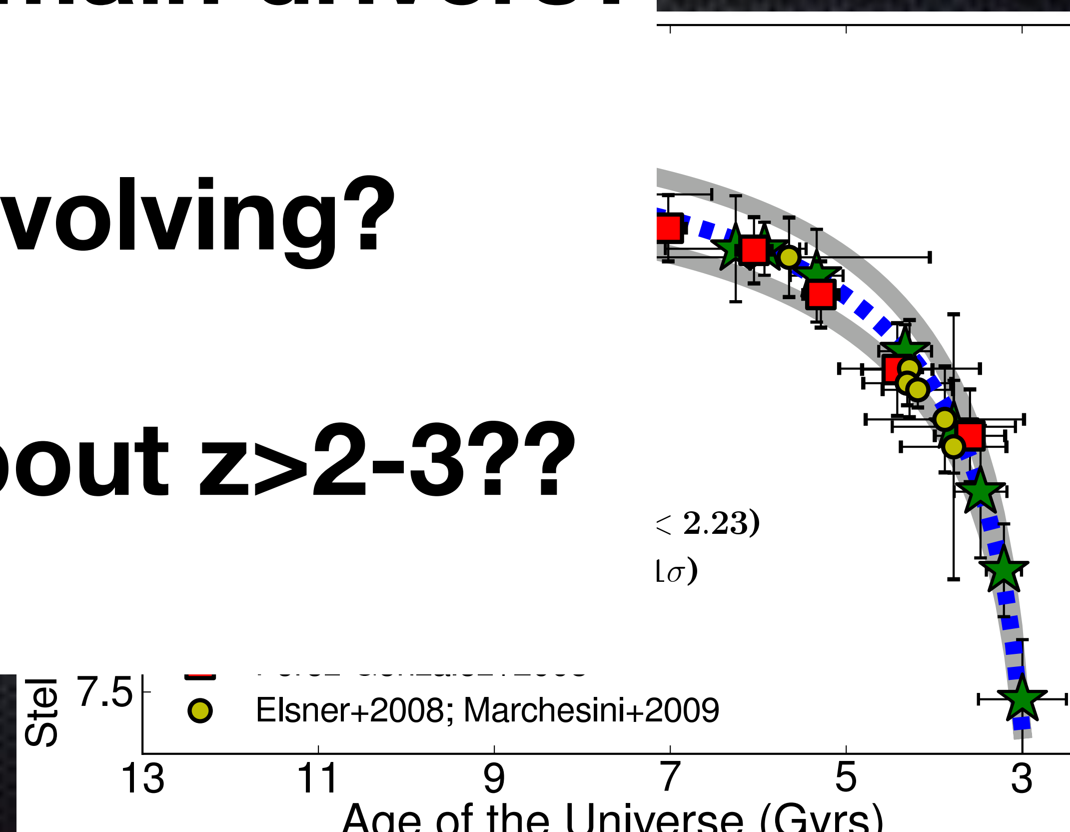
Stellar

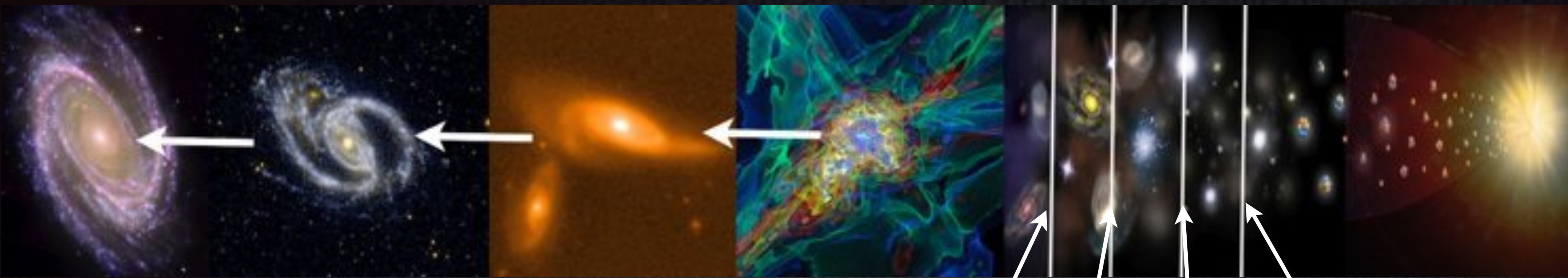
e

Star fo

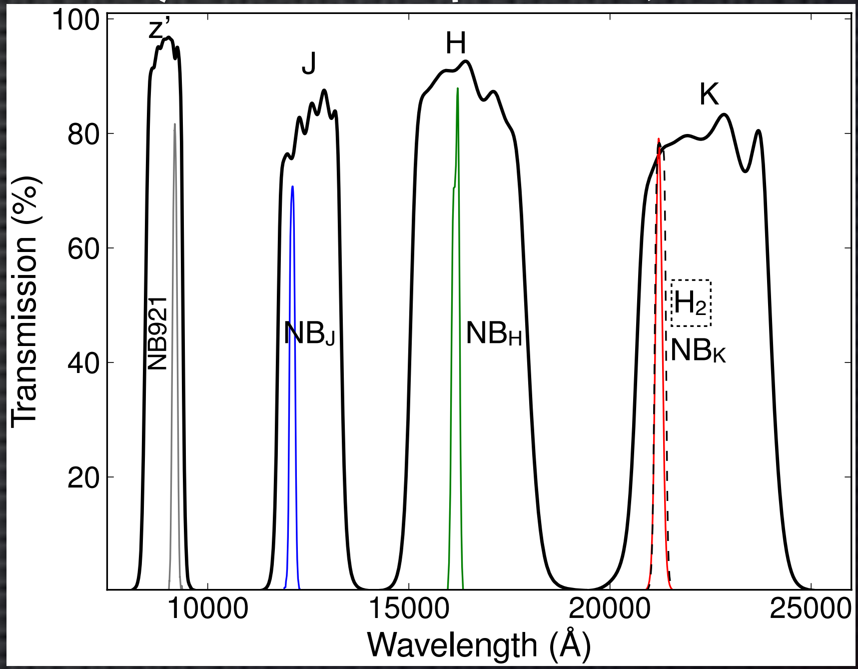
from

observations!!





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

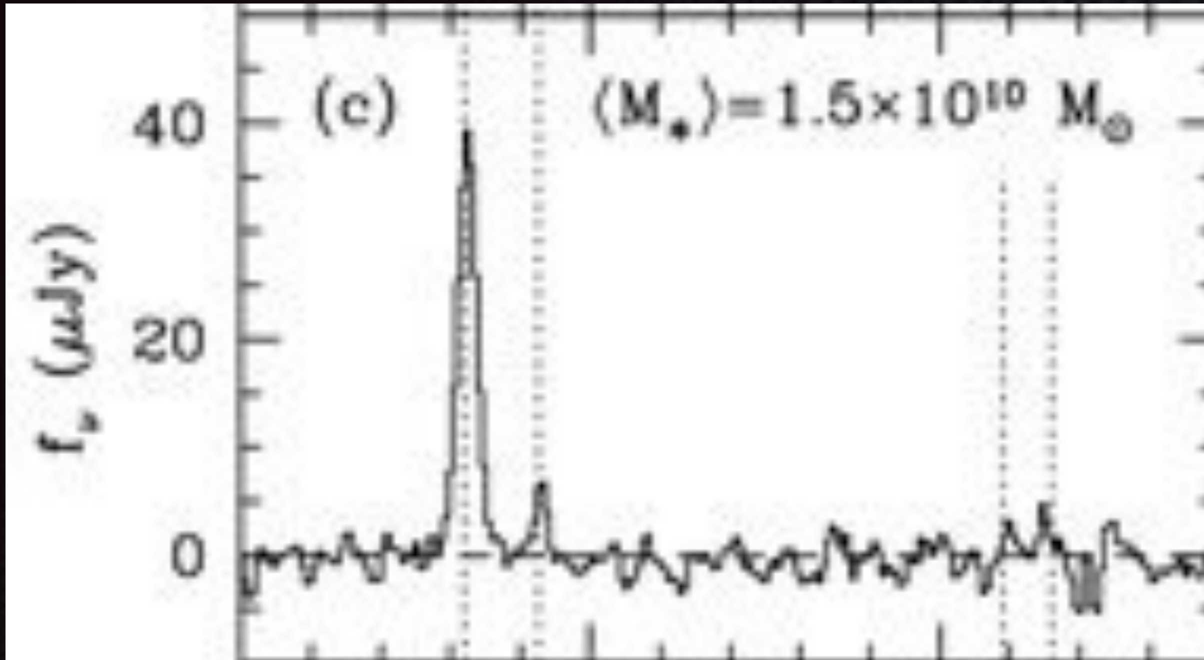


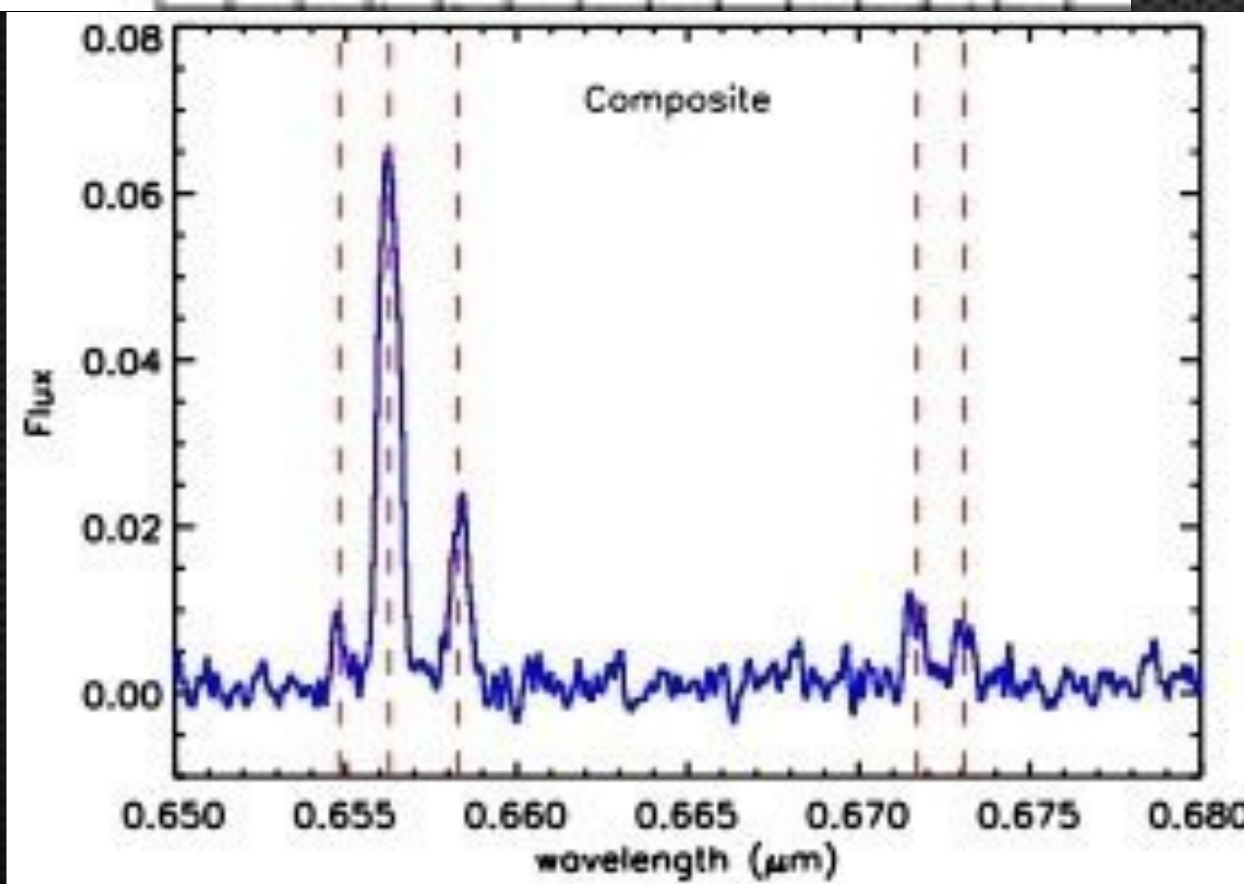
Catalogues are public (Sobral+13a)!

Check out the latest results:

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

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





Selection Matters:

z~1.5-2.23

UV selection: metal-poor, misses dusty galaxies

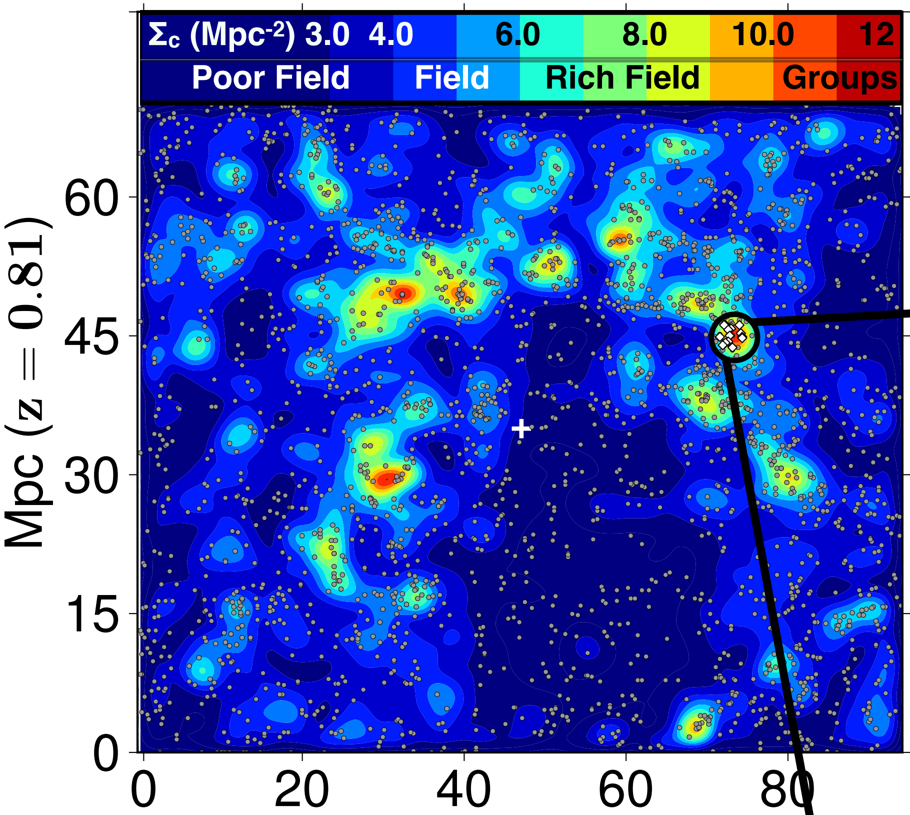
Same masses

Ha selection: only slightly sub-solar, much more representative

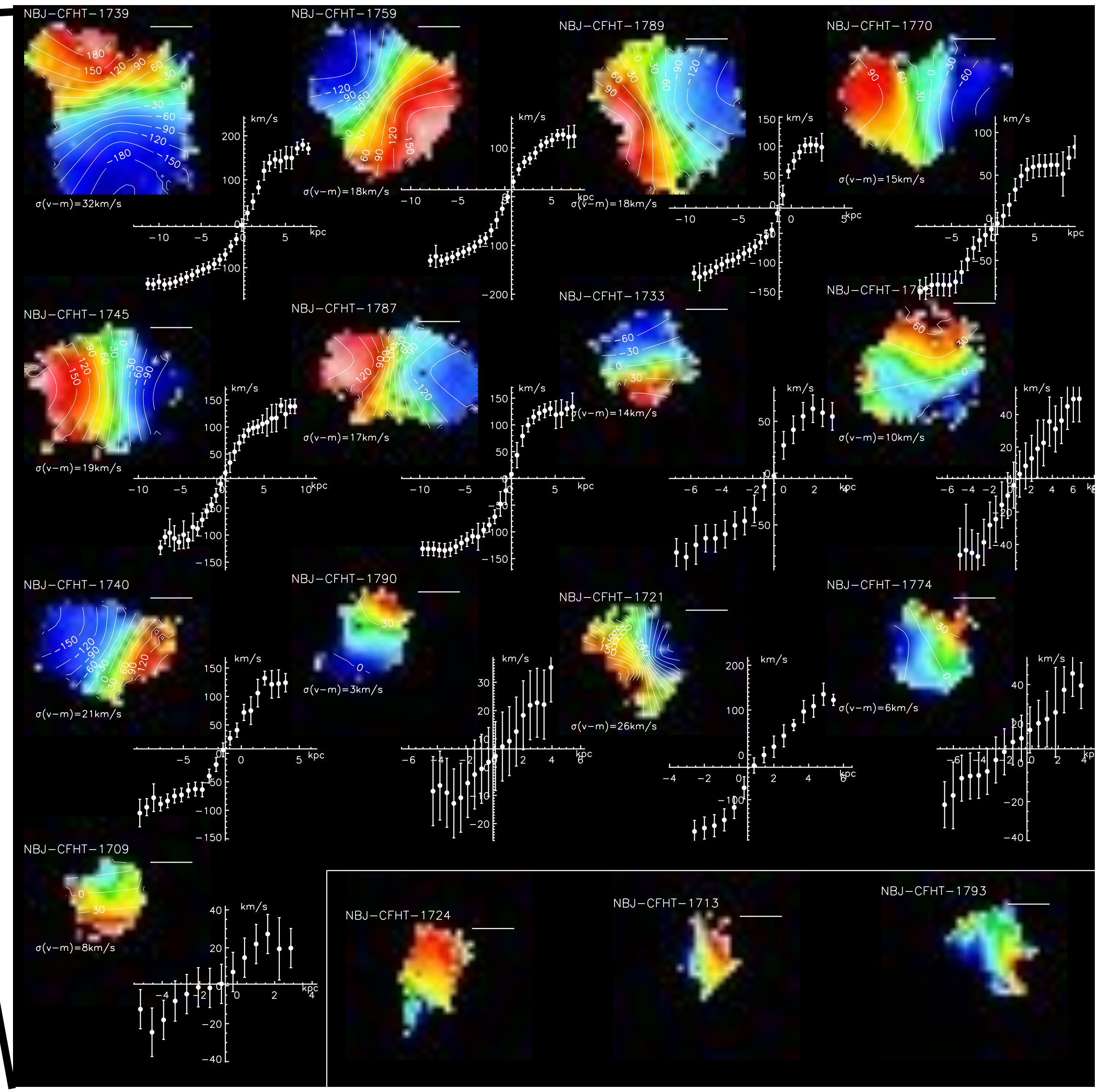
Swinbank+12a

Stott+13b

KMOS CF-HiZELS: SA22



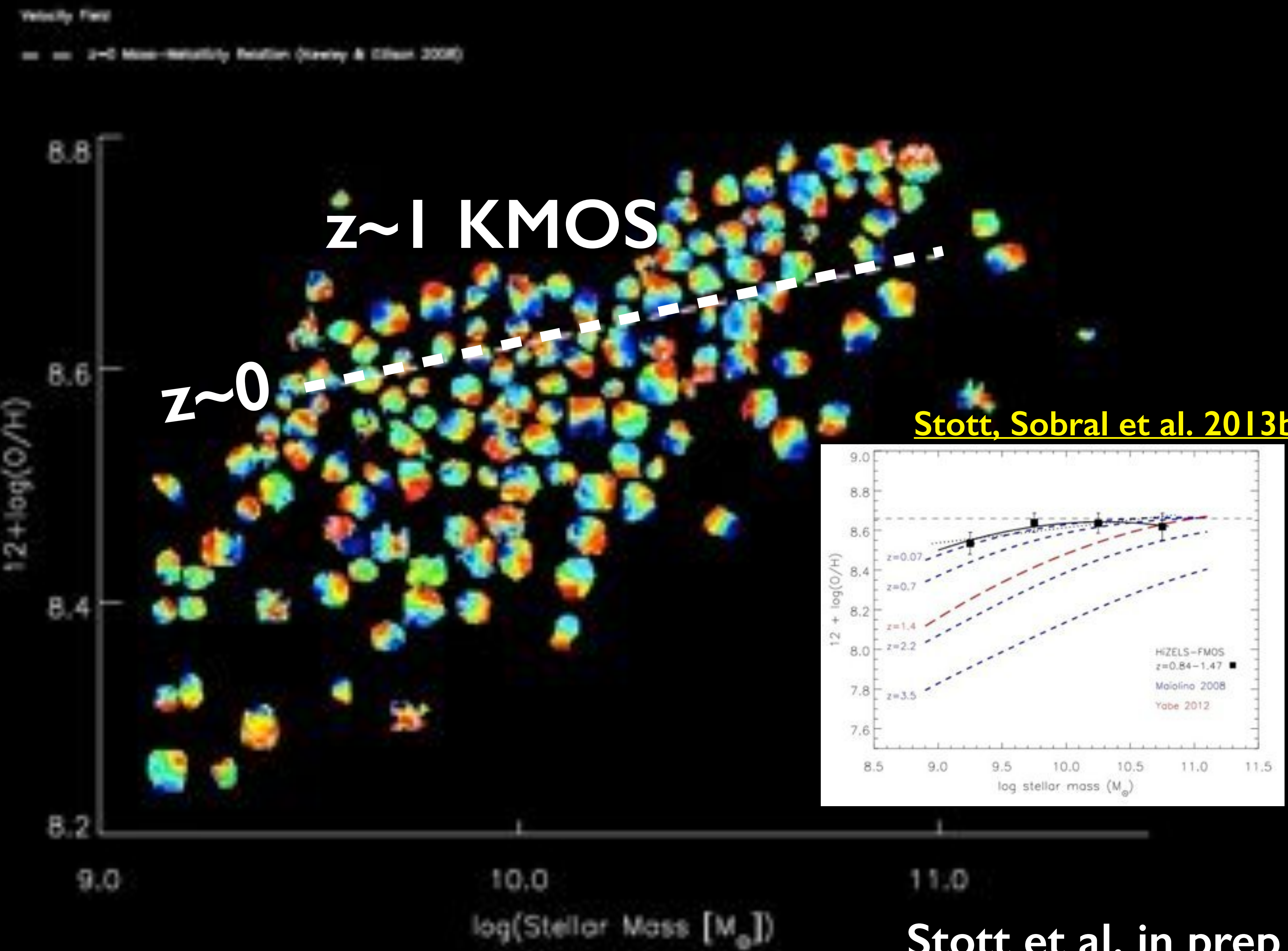
2 hours of VLT-KMOS time



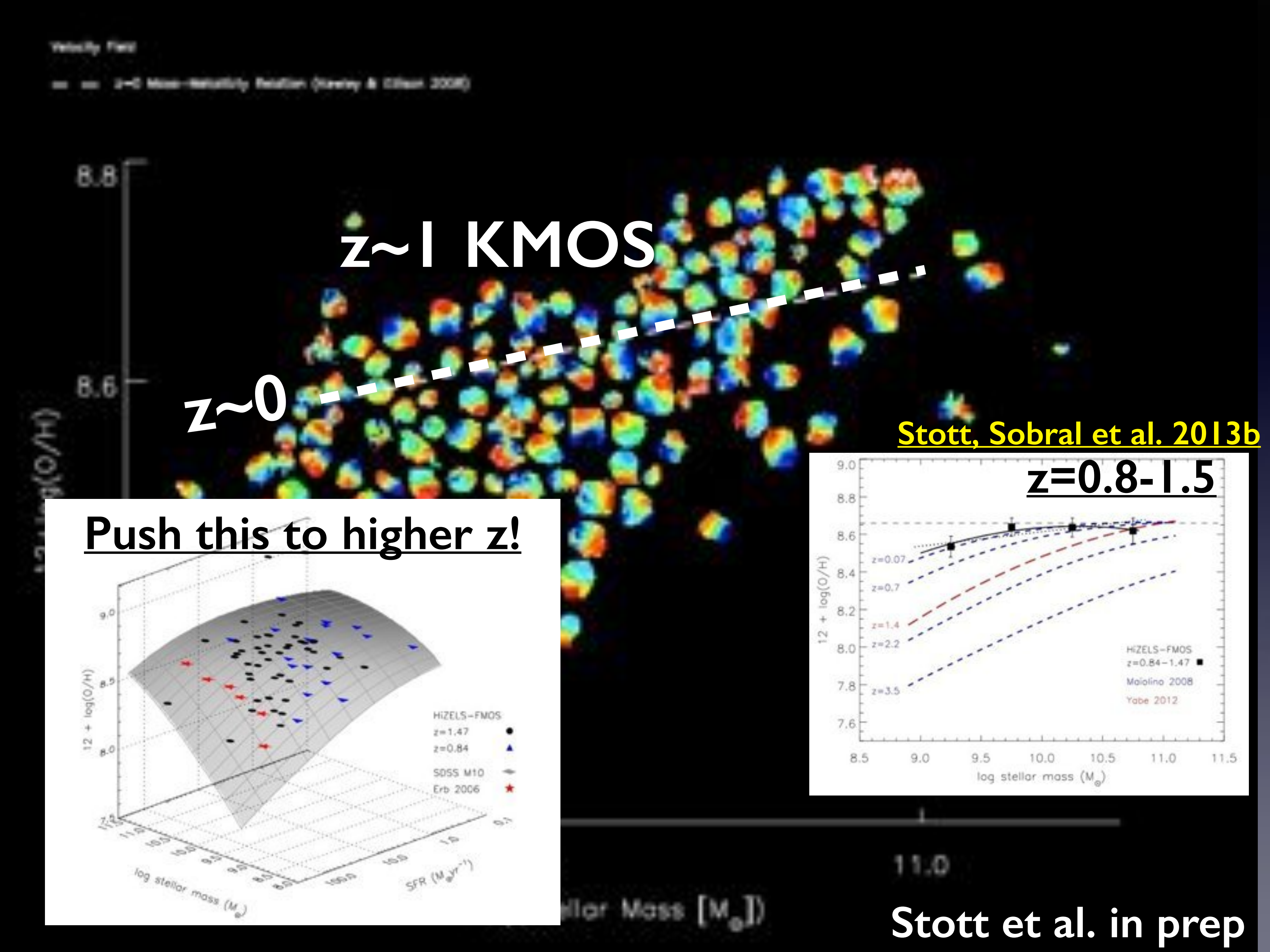
First KMOS Science results

75+-8% Disk-like. Very good agreement with AO results + HST

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

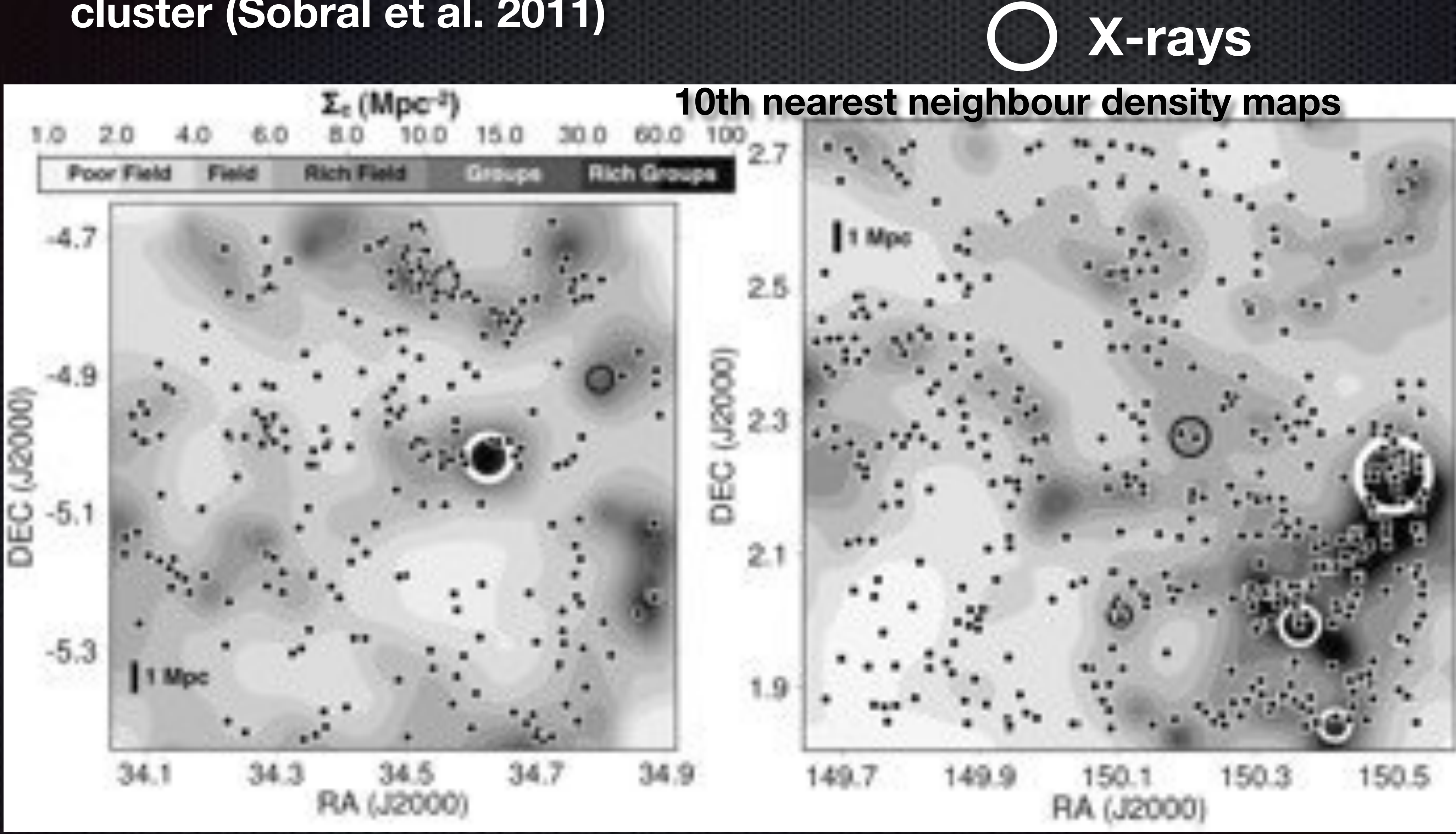


z~1 KMOS
z~0
Stott, Sobral et al. 2013b
8.8
8.6
8.4
8.2
12+log(O/H)
9.0
10.0
11.0
log(Stellar Mass [M☉])
9.0
8.8
8.6
8.4
8.2
8.0
7.8
7.6
z=0.07
z=0.7
z=1.4
z=2.2
z=3.5
12 + log(O/H)
HiZELS-FMOS
z=0.84-1.47
Maiolino 2008
Yabe 2012
8.5
9.0
9.5
10.0
10.5
11.0
11.5
log stellar mass (M☉)
Stott et al. in prep


z~1 KMOS
z~0
8.8
8.6
11.0
Push this to higher z!
HiZELS-FMOS
z=1.47
z=0.84
SDSS M10
Erb 2006
12 + log(O/H)
log stellar mass (M⊙)
Stott, Sobral et al. 2013b
z=0.8-1.5
z=0.07
z=0.7
z=1.4
z=2.2
z=3.5
HiZELS-FMOS
z=0.84-1.47
Maiolino 2008
Yabe 2012
log stellar mass (M⊙)
Stott et al. in prep

The role of the Environment

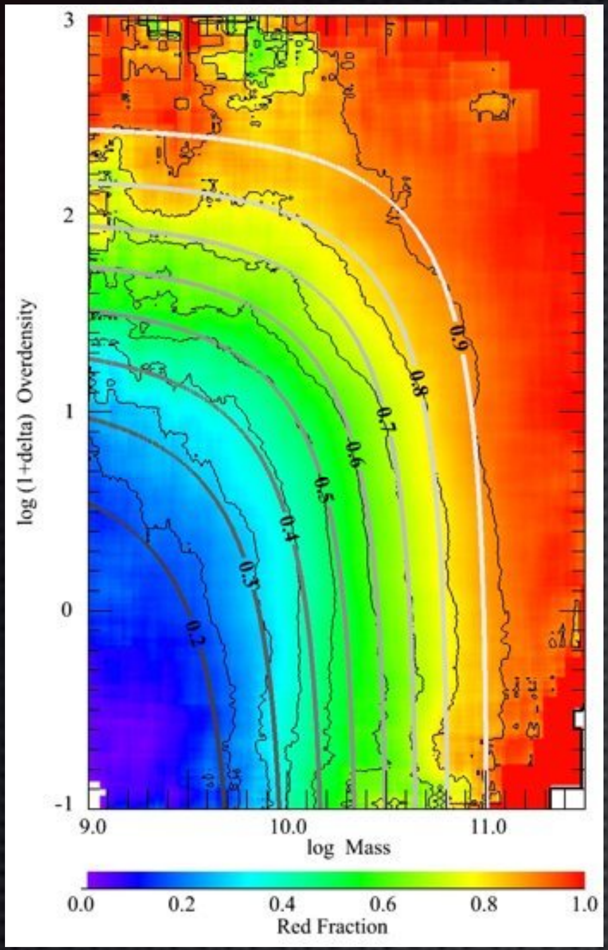
- A very wide range of environments - from the fields to a super-cluster (Sobral et al. 2011)



- UKIDSS UDS z=0.84
- COSMOS z=0.84

Mass and Environment

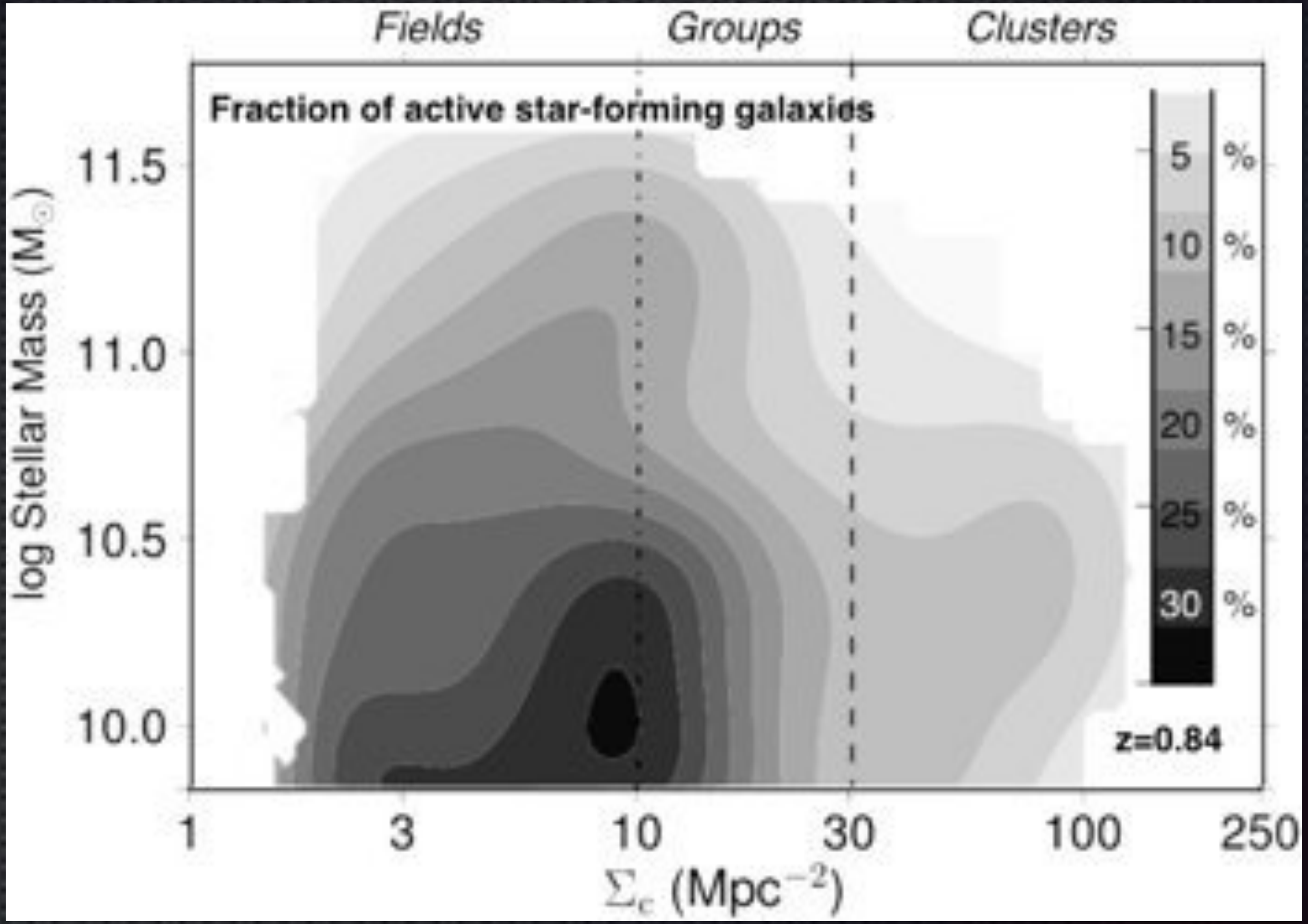
z~0



SDSS (Peng+10)

z~1

Sobral et al. 2011

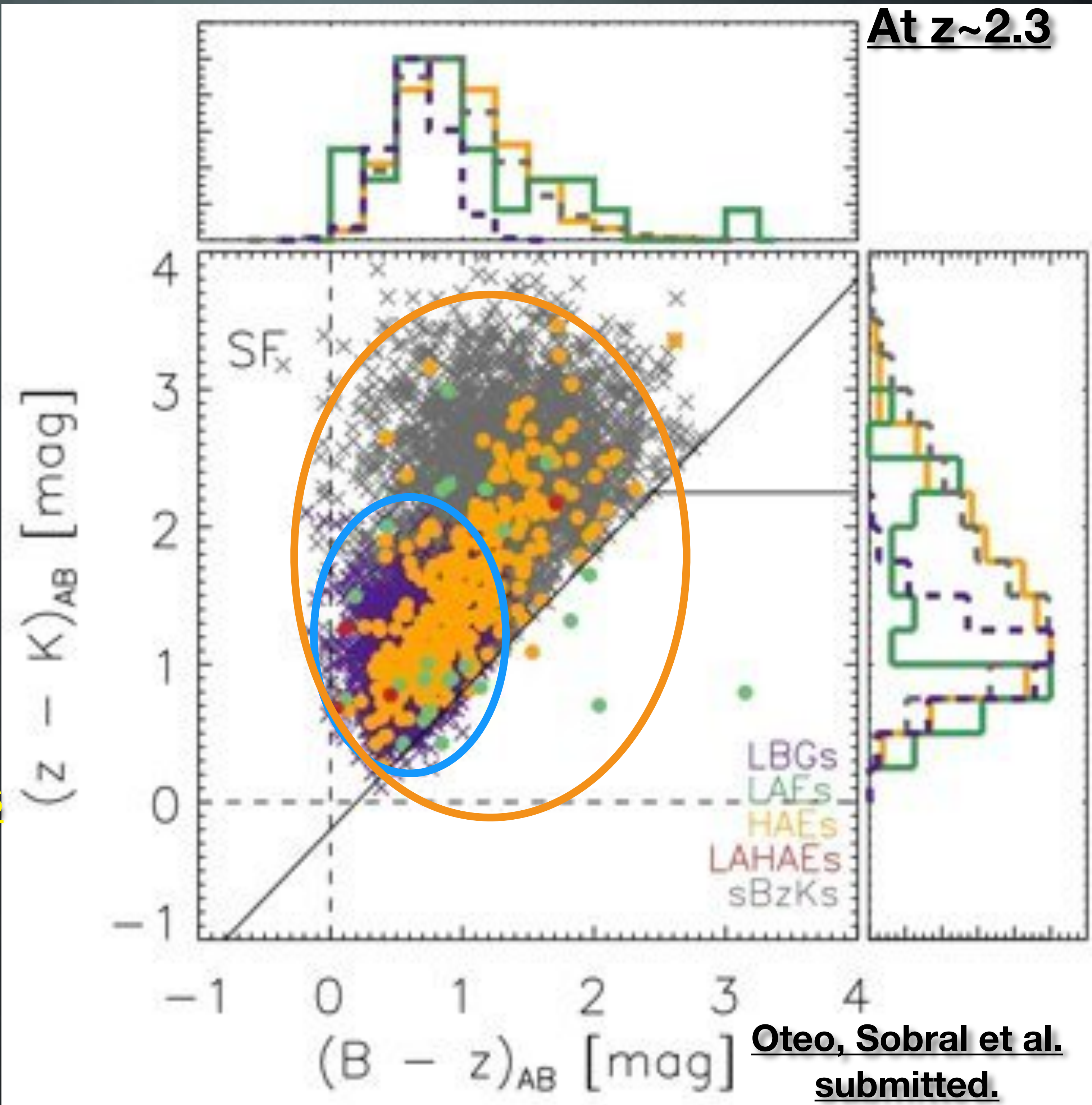


Mass trend at least up to z~1.5

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

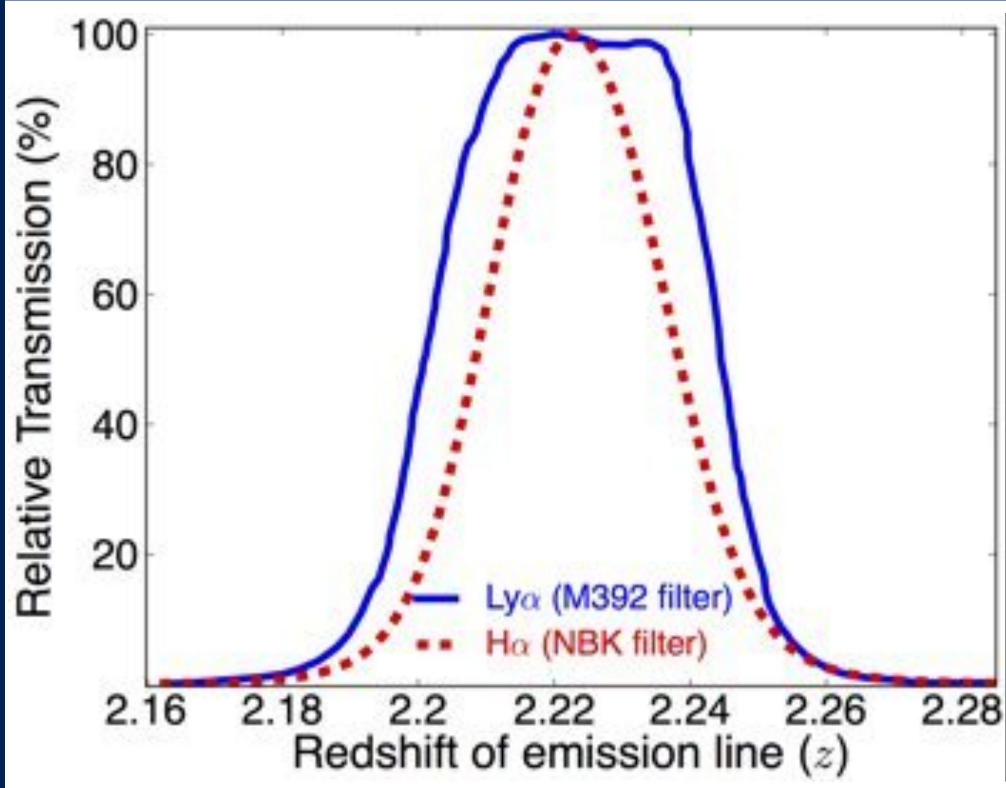
At z>2.5: Lyman-alpha + UV? Is this all we are going to have?

How much are we missing? Can measurements be biased?



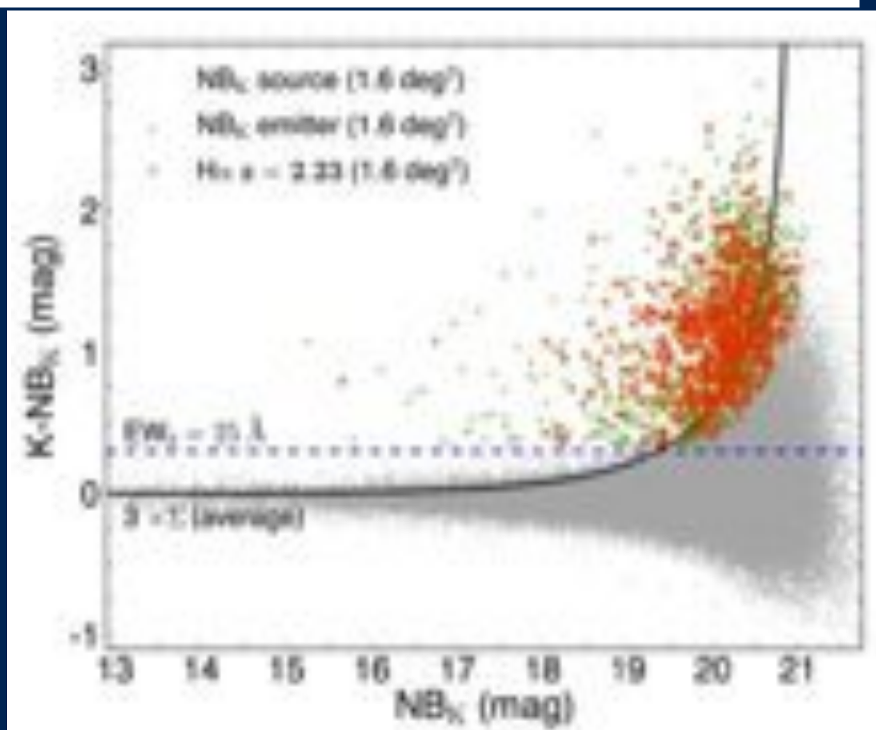
See also Hayashi et al. 2013 for [OII]

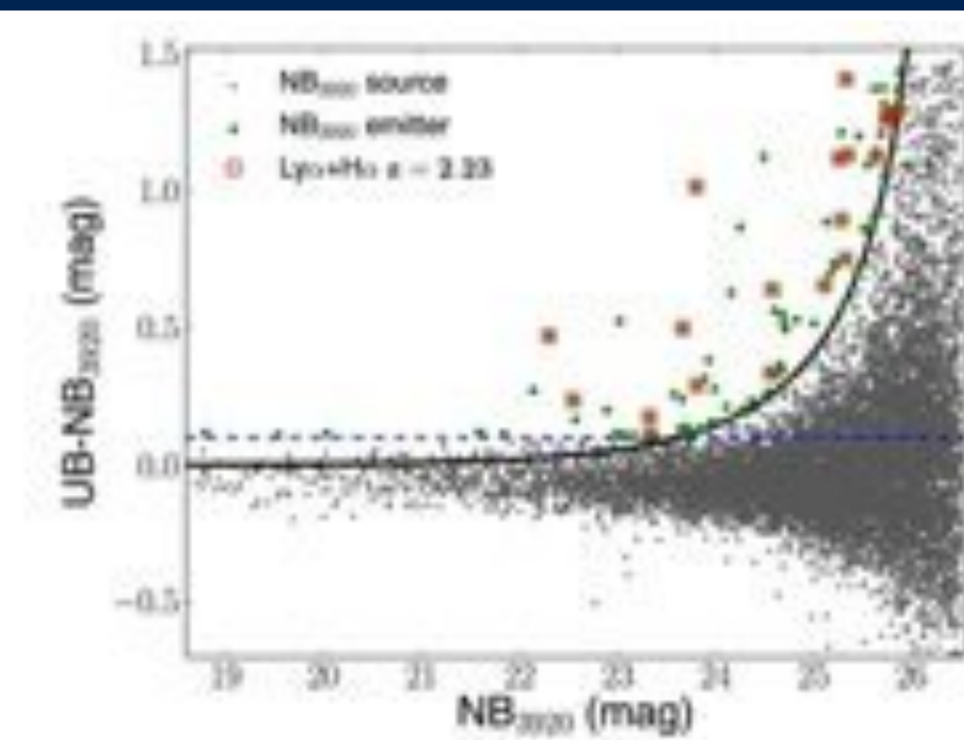
Oteo, Sobral et al. submitted.



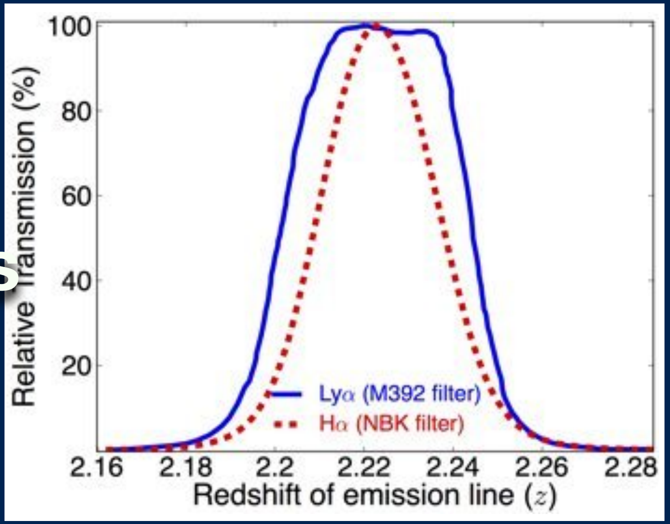
Calibrate Lyα at z=2.23

5 deg² deep double-blind matched Lyα-Hα survey. Pilot survey: INT => CFHT





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



~50 night pilot (but highly weathered out so far): >70% of data to come in 4 months

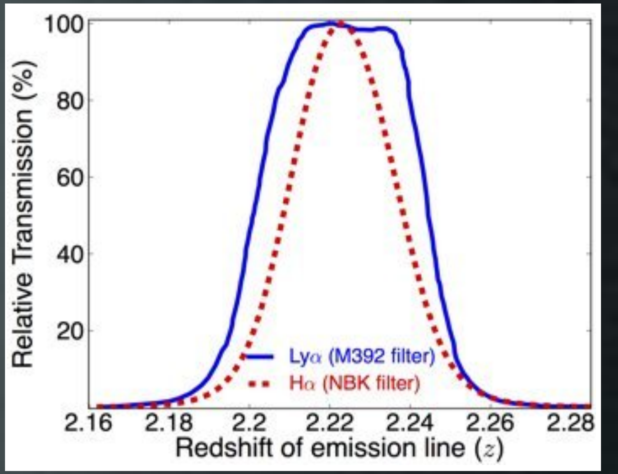
Preliminary espace fraction (Lyα): ~7% (consistent with Hayes+)

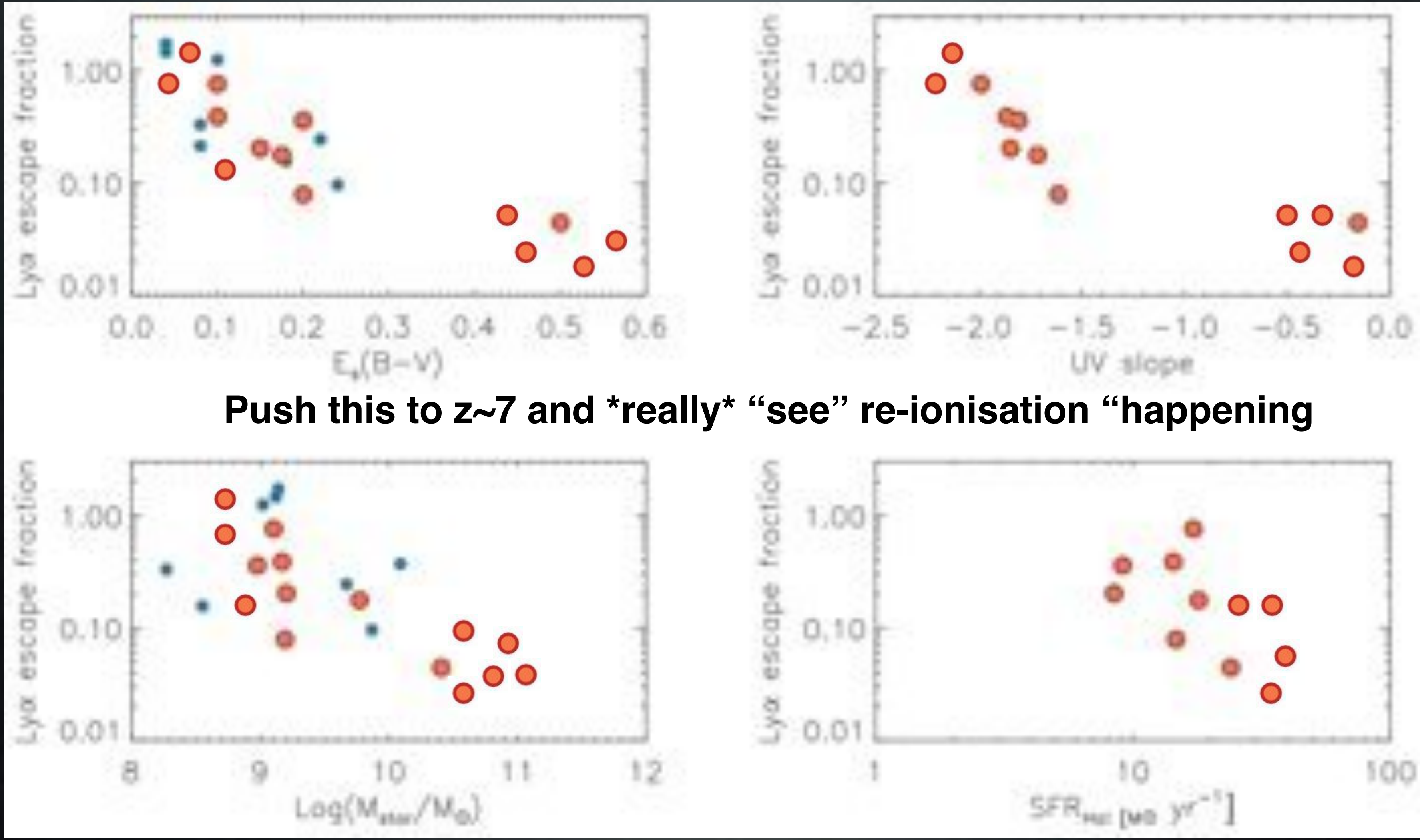
Wide range of properties of matched Lyα-Hα emitters:

Masses: ~10^9 or 10^{11} M_o SFRs: ~5-200 Msun/yr
Dust: ~0 to 2 mags Mostly Blue but also red

Not easy to calibrate Lyα using Hα for range of masses, SFRs, extinction, colour, etc

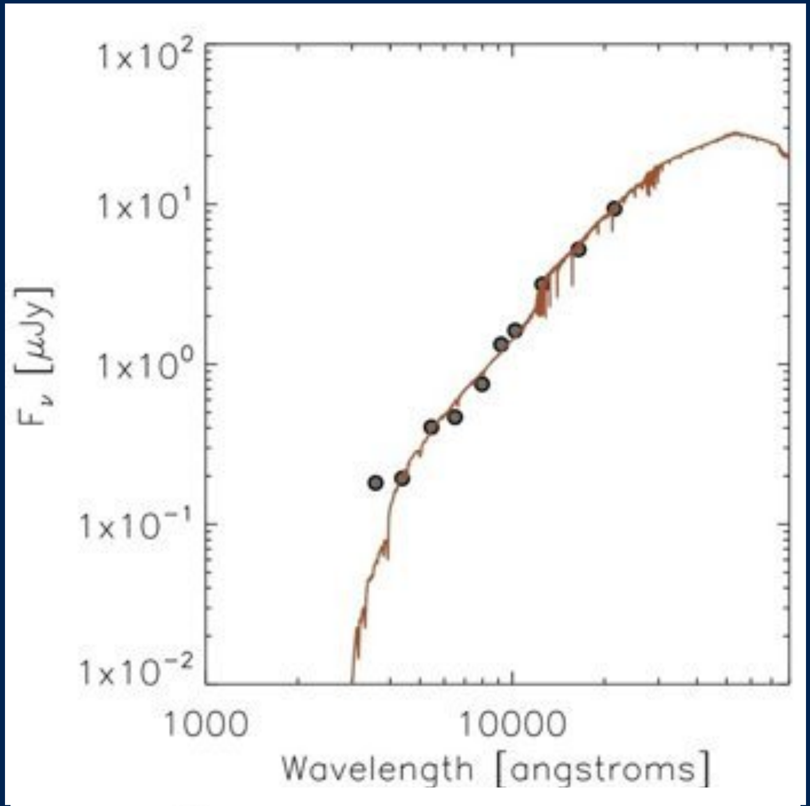
Lyman-alpha escape fraction at z=2.23 (push it to z~7 in multiple redshifts)

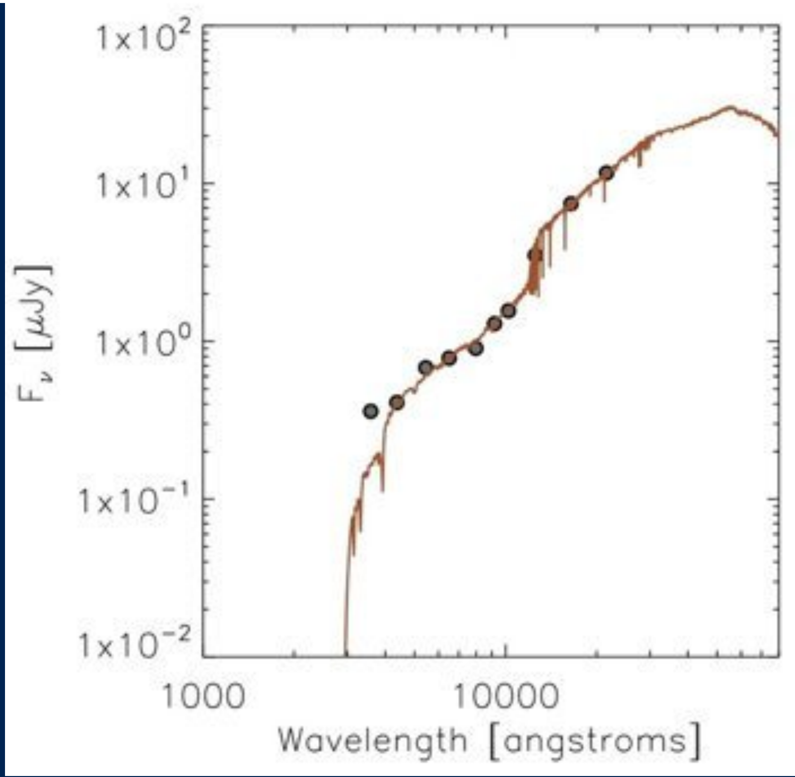




Push this to z~7 and *really* "see" re-ionisation "happening

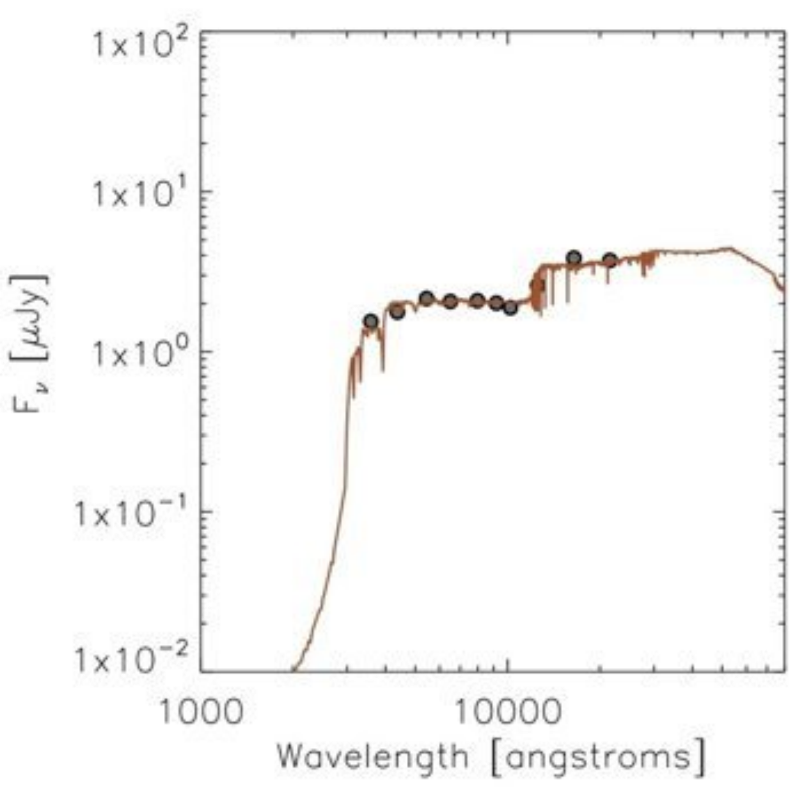
Oteo, Sobral et al. , Matthee, Sobral et al.

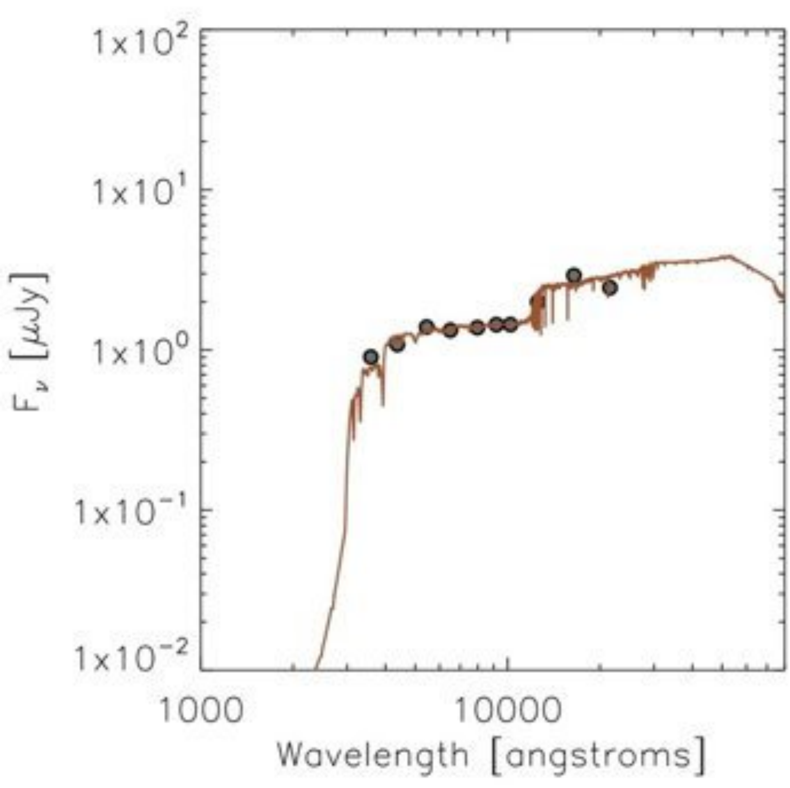


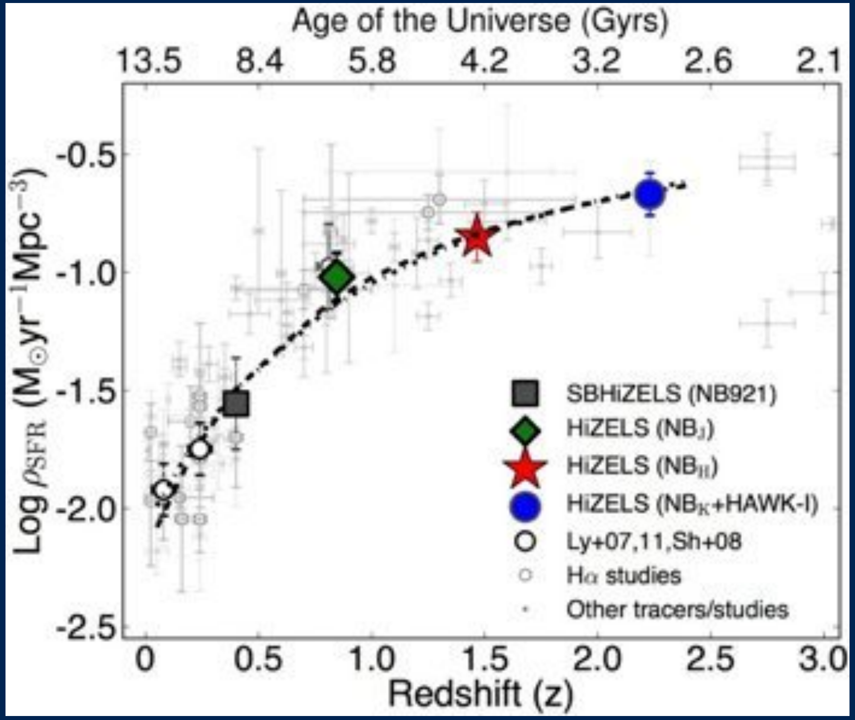


Lyα-Hα emitters

Strong emission lines… But some very red (dusty!) SEDs





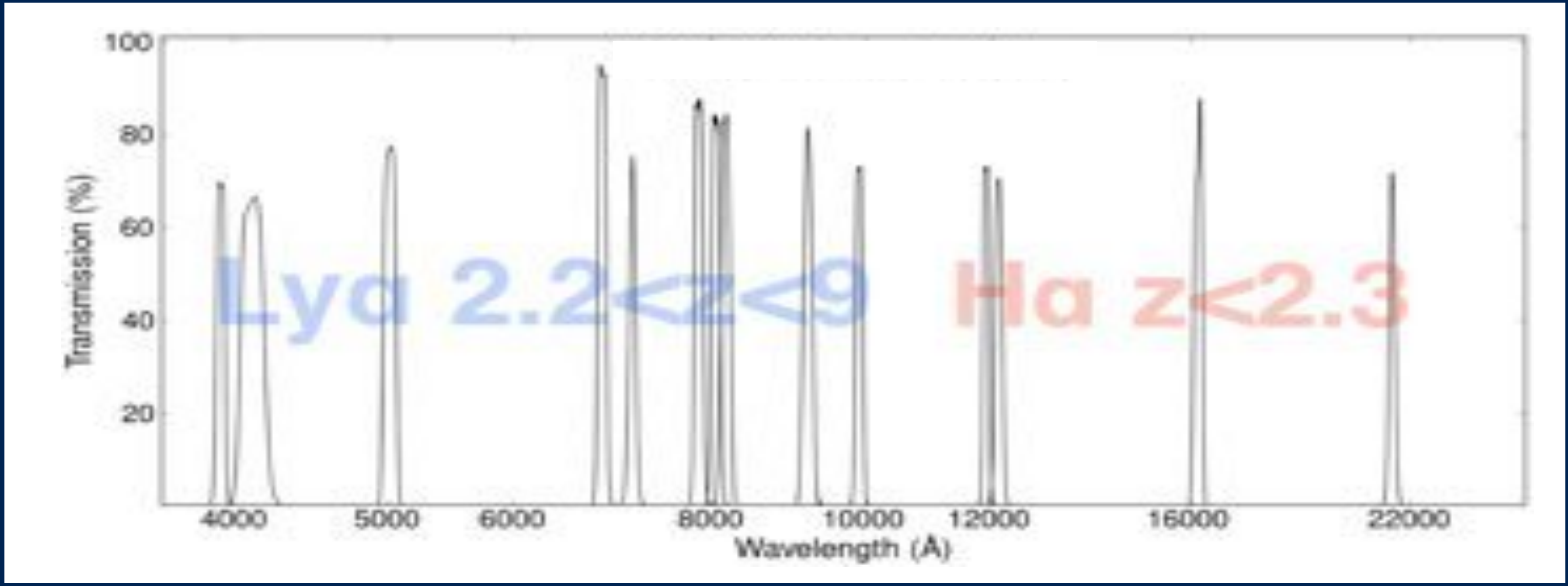


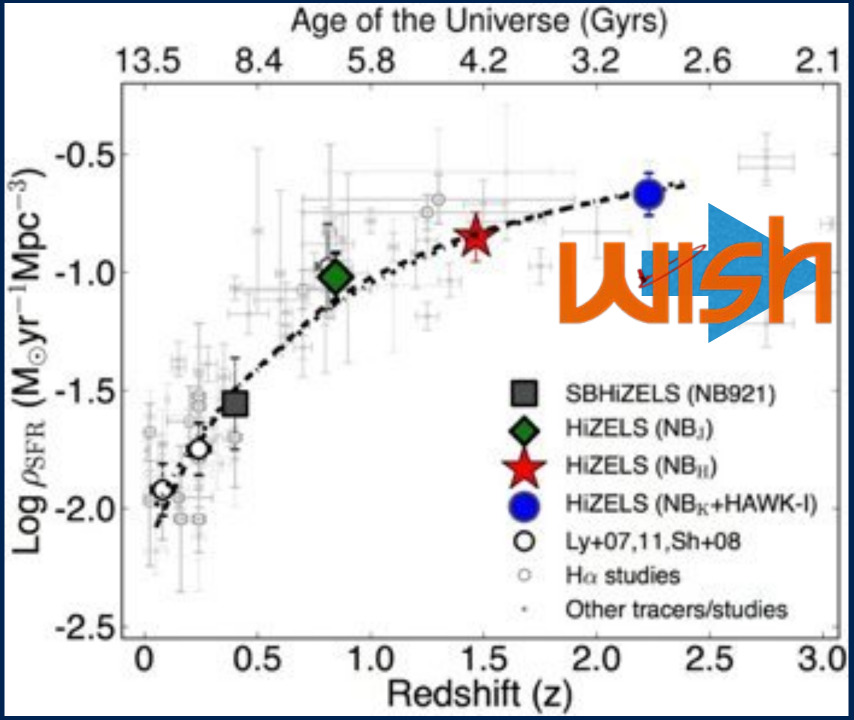
Probe to even earlier times

Probe large volumes

Complement LBG/UV studies

e.g. Bouwens+, Trenti+, Atek+





Probe to even earlier times

Probe large volumes

Complement LBG/UV studies

e.g. Bouwens+, Trenti+, Atek+

A Big step forward :

Beyond K band

Many issues/questions raised by e.g. Kiyoto Yabé, Médéric Boquien, Daniel Shaerer etc

A Big step forward :

Beyond K band

Let's really solve the biggest problems in a completely alternative, very robust way:

SFRs, sSFRs, EWs, Complete self-consistent samples across 13 Gyrs
Evolution in: metallicities, environment, masses, dust extinction, clustering + re-ionisation

+ ideal follow-up samples!

A Big step forward :

Beyond K band

wish

Wide field **I**nfrared **S**urveyor for **H**α

A Big step forward :

Beyond K band

Wide field Infrared Surveyor for Hα

Hα star-forming galaxies $2<z<7$

Same robust selection

Full galaxy population: 13 Gyrs!

A Big step forward :

Beyond K band

Wide field Infrared Surveyor for Hα

Hα s ... <z<7

Sam ...

Is it realistic? Why would you need to do it?

Full galaxy population: 13 Gyrs!

Wide field Infrared Surveyor for Hα

~5 NB filters to image the unexplored: >2.5 um to 5 um

Same redshifts as Lyman-α/Hyper-Suprime cam surveys

SFH and full census of *star-forming* galaxies (Hα selected)

Direct comparison to UV and Lyman-α: re-ionization

Clustering, metallicity evolution, mass function

Morphologies, size evolution

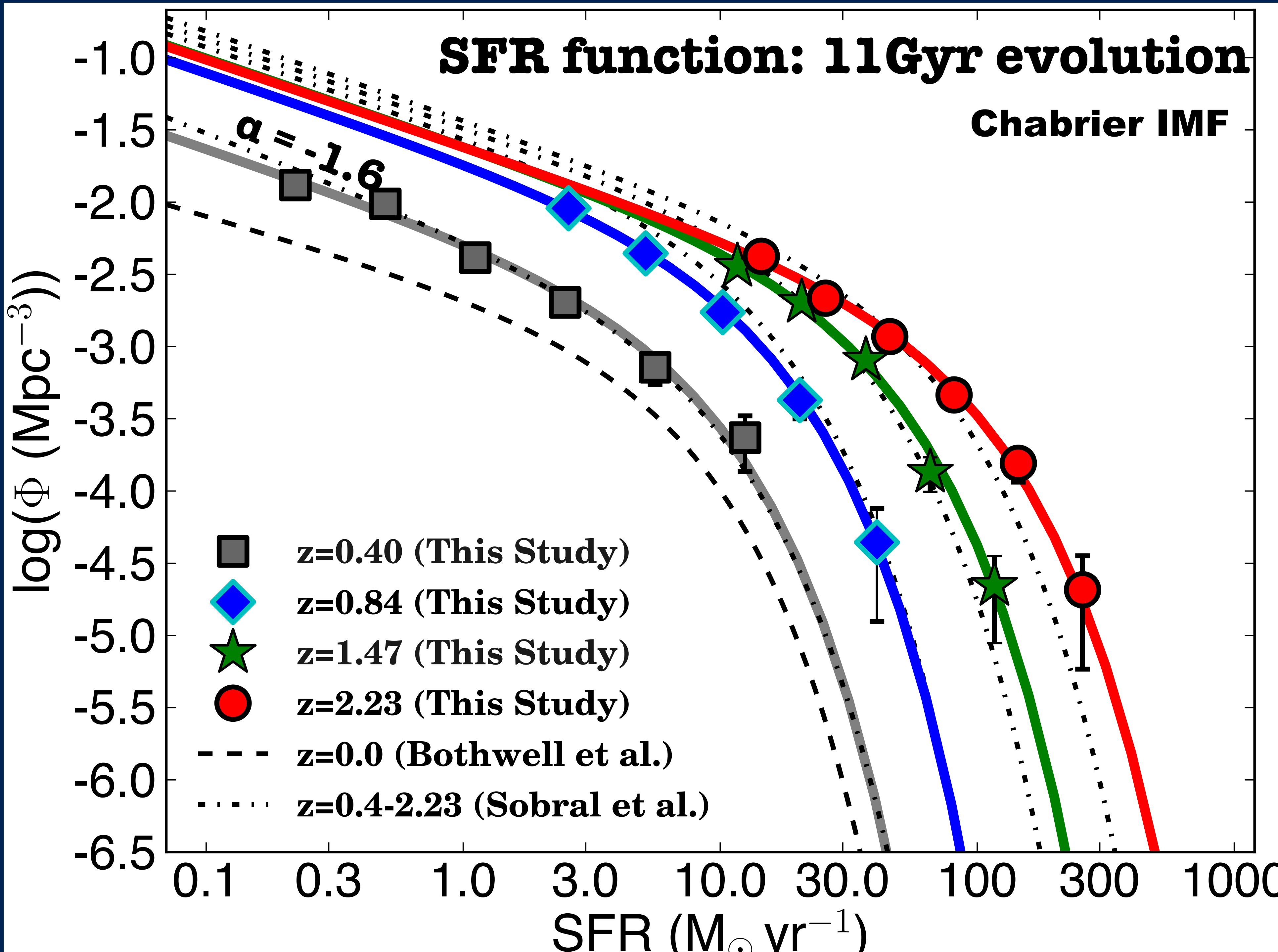
Wide field Infrared Surveyor for Hα

<u>We know this will be unique and will work</u>. So very high gain/very low risk.

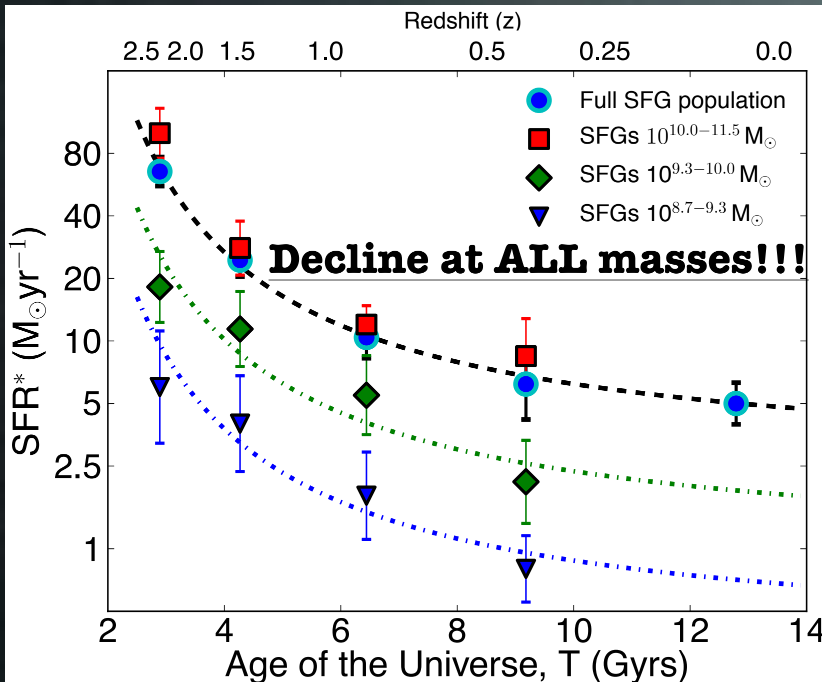
<u>We know we can do it</u> - the selection and exploration of the sample is very mature and can completely mimic the selection done for $z<2.5$ samples to directly compare

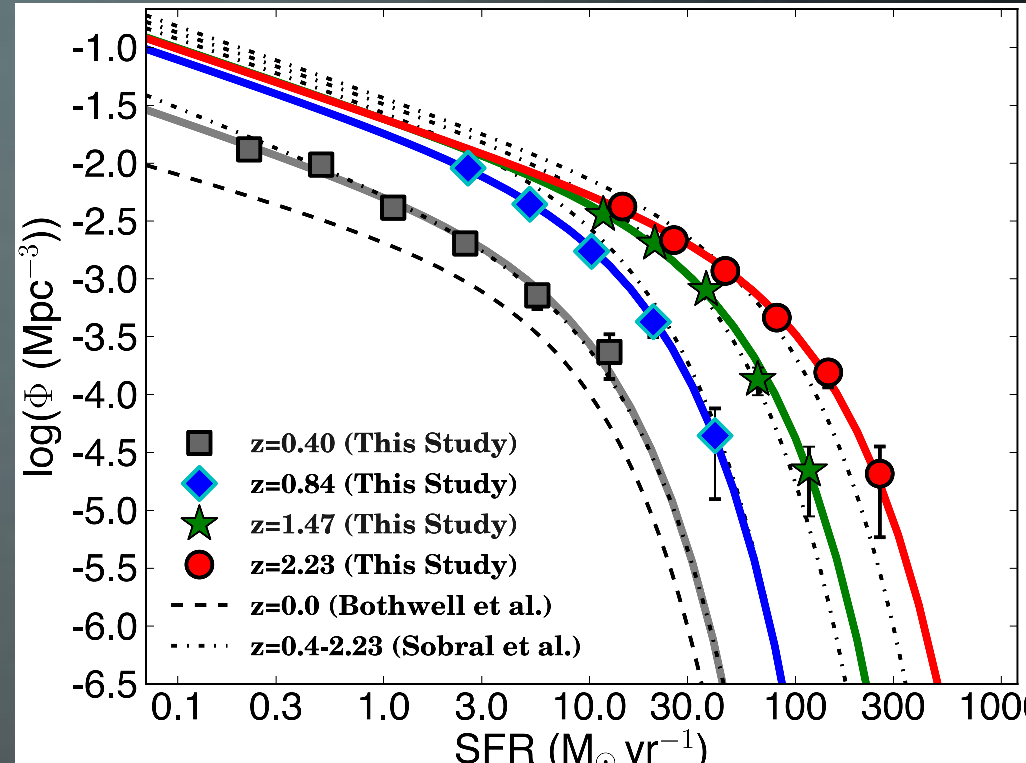
Perfect use of the WISH BB survey (SED fitting), direct comparison with UV, only modest time investment

Perfect targets for detailed follow-up: Physics!



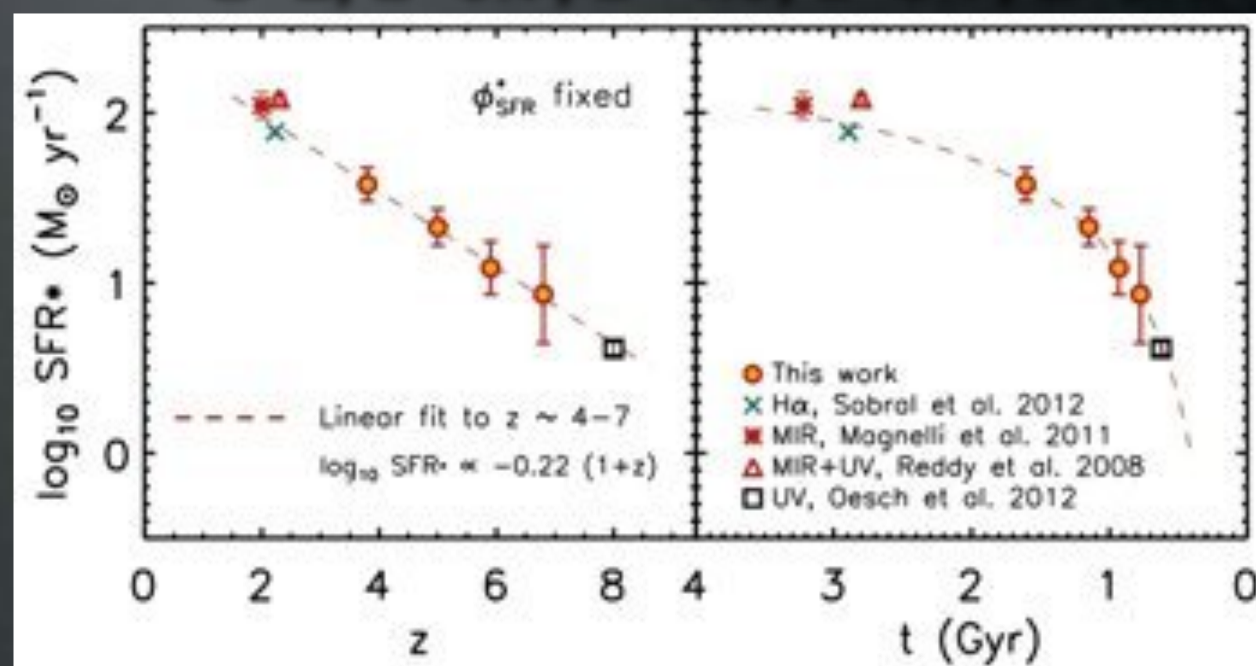
Sobral et al. (2014)





Smit+11; Sobral+13a,14

z~2, z~3.7, z~4.5, z~5.7, z~6.6



Realistic predictions: Hα emitters

NB limit 25: f>3x10^{18} erg/s/cm^2

L(Hα) limit ~**10^{41} erg/s**

SFRs (Hα) >**0.5 M_o/yr**

WISH α 100k/1M Hα

5 NB filters: All matched to Lyα HSC surveys

100k

Wide field **I**nfrared **S**urvey for **H**α

wishα 100k/1M Hα

5 NB filters: All matched to Lyα HSC surveys

10 deg^2: 1-5x10^6 Mpc^3

WISH: 100 k Hα SFGs

@z=2.2: 25,000 Hα emitters
@z=3.7: 20,000 Hα emitters
@z=4.5: 10,000 Hα emitters
@z=5.7: 8,500 Hα emitters
@z=6.6: 4,500 Hα emitters

3h/pix (50%Oh) x 46 p =210h
<10 days!

100k

Wide field Infrared Survey for Hα

wishα 100k/1M Hα

5 NB filters: All matched to Lyα HSC surveys

Mega

Wide field Infrared Survey for Hα

100 deg^2: 1-3x10^7 Mpc^3

WISH: 1 million Hα SFGs

@z=2.2: 250,000 Hα emitters
@z=3.7: 200,000 Hα emitters
@z=4.5: 100,000 Hα emitters
@z=5.7: 85,000 Hα emitters
@z=6.6: 45,000 Hα emitters

3h/pix (50%Oh) x 460 p =2100h
<100 days

WISH α 100k/1M Hα

5 NB filters: All matched to Lyα HSC surveys

10 deg^2: 1-5x10^6 Mpc^3

WISH: 100 k Hα SFGs

@z=2.2: 25,000 Hα emitters
@z=3.7: 20,000 Hα emitters
@z=4.5: 10,000 Hα emitters
@z=5.7: 8,500 Hα emitters
@z=6.6: 4,500 Hα emitters

3h/pix (50%Oh) x 46 p =210h
<10 days!

100 deg^2: 1-3x10^7 Mpc^3

WISH: 1 million Hα SFGs

@z=2.2: 250,000 Hα emitters
@z=3.7: 200,000 Hα emitters
@z=4.5: 100,000 Hα emitters
@z=5.7: 85,000 Hα emitters
@z=6.6: 45,000 Hα emitters

3h/pix (50%Oh) x 460 p =2100h
<100 days

wishα 100k Hα

5 NB filters: All matched to Lyα HSC surveys

All matched to Lyα SC/HSC surveys and in the WISH UDS

Science goals:

- Robust Star formation history of the Universe in multiple slices (spaced by <1Gyr) in the last 13 Gyrs
- Evolution of: SFR-Mass, Mass Function
- Role of Environment up to z~7 in the same way
- Clustering and evolution: DM halo masses - evolution
- Morphologies, sizes, dynamics (follow-up)
- Metallicity evolution with the same, robust selection
- Comparison/calibration with UV to better extend to z>7
- Re-ionisation: (Ha-Lya matched surveys z=2.2 to 6.6)

WISH α

100k Hα

5 NB filters: All matched to Lyα HSC surveys

All matched to Lyα SC/HSC surveys and in the WISH UDS

Science goals:

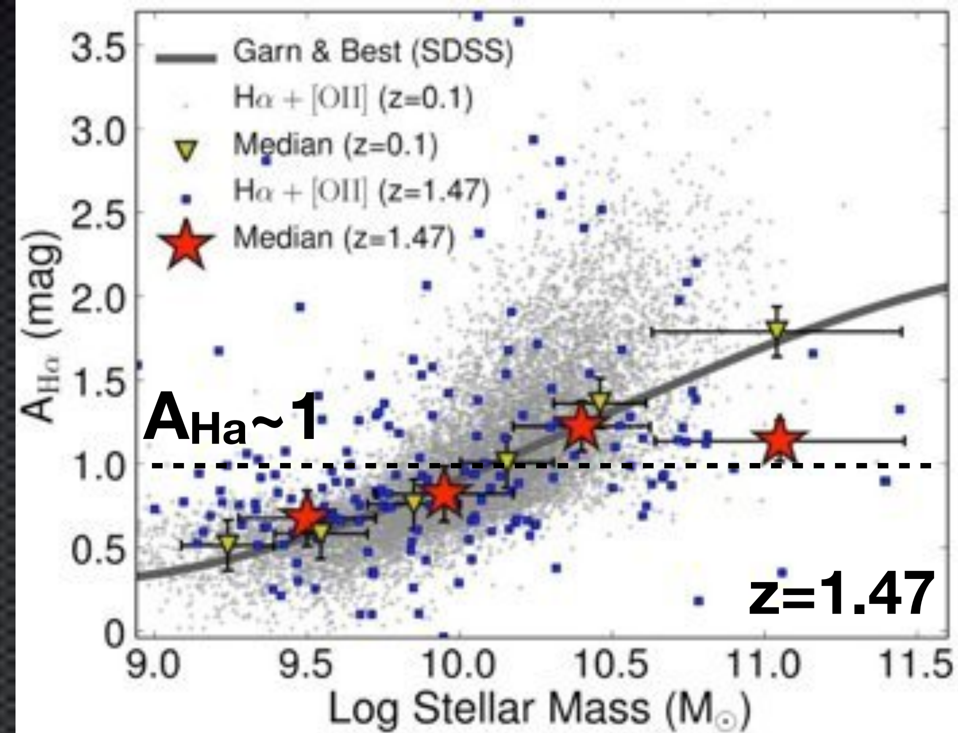
- Robust Star formation history of the Universe in multiple slices (spaced by <1Gyr) in the last 13 Gyrs
- Evolution of: SFR-Mass, Mass Function
- Role o … y
- Cluste … volution
- Morph
- Metal … ection
- Comp … nd to z>7
- Re-ionisation: (Ha-Lya matched surveys z=2.2 to 6.6)

+ [OIII] + [OII] NB surveys up to z~12! ++ much more

Extinction-Mass z~0-7?

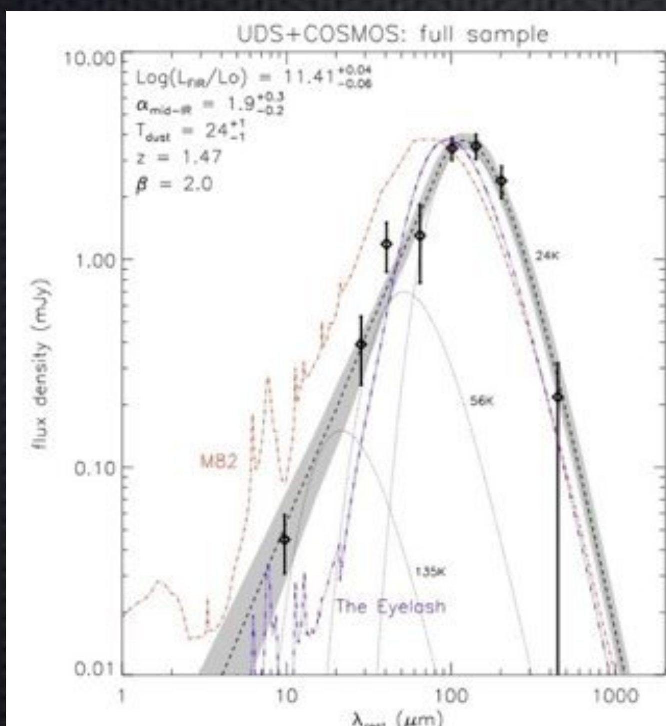
Garn & Best 2010: Stellar Mass correlates with dust extinction (z~0)

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**)**

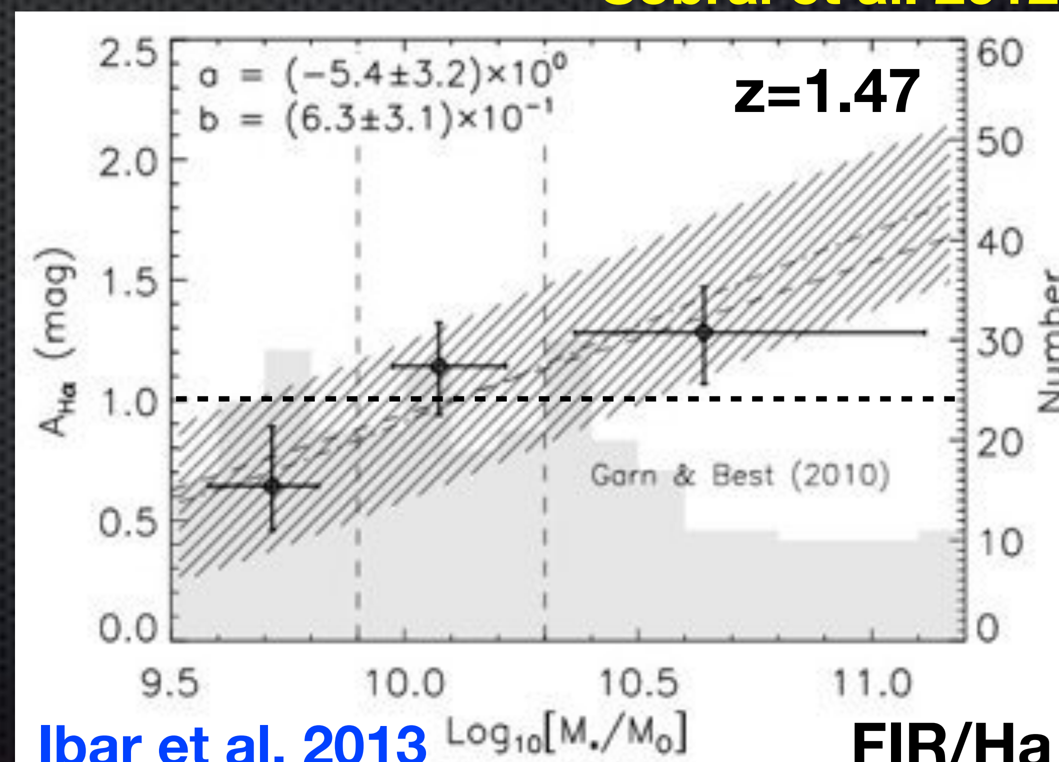


Sobral et al. 2012

Now confirmed by Herschel

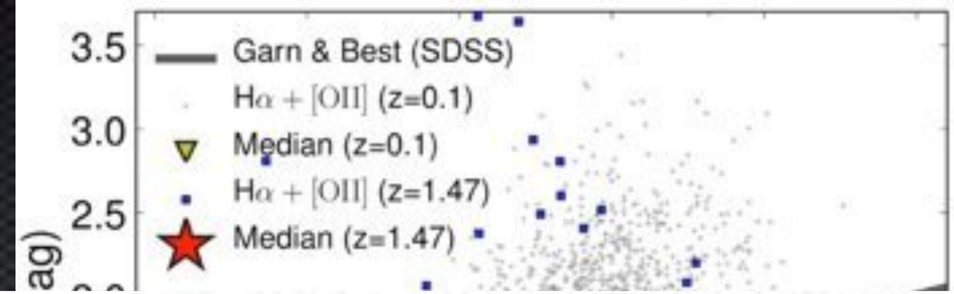


FIR derived A_{Ha} = 0.9-1.2 mag



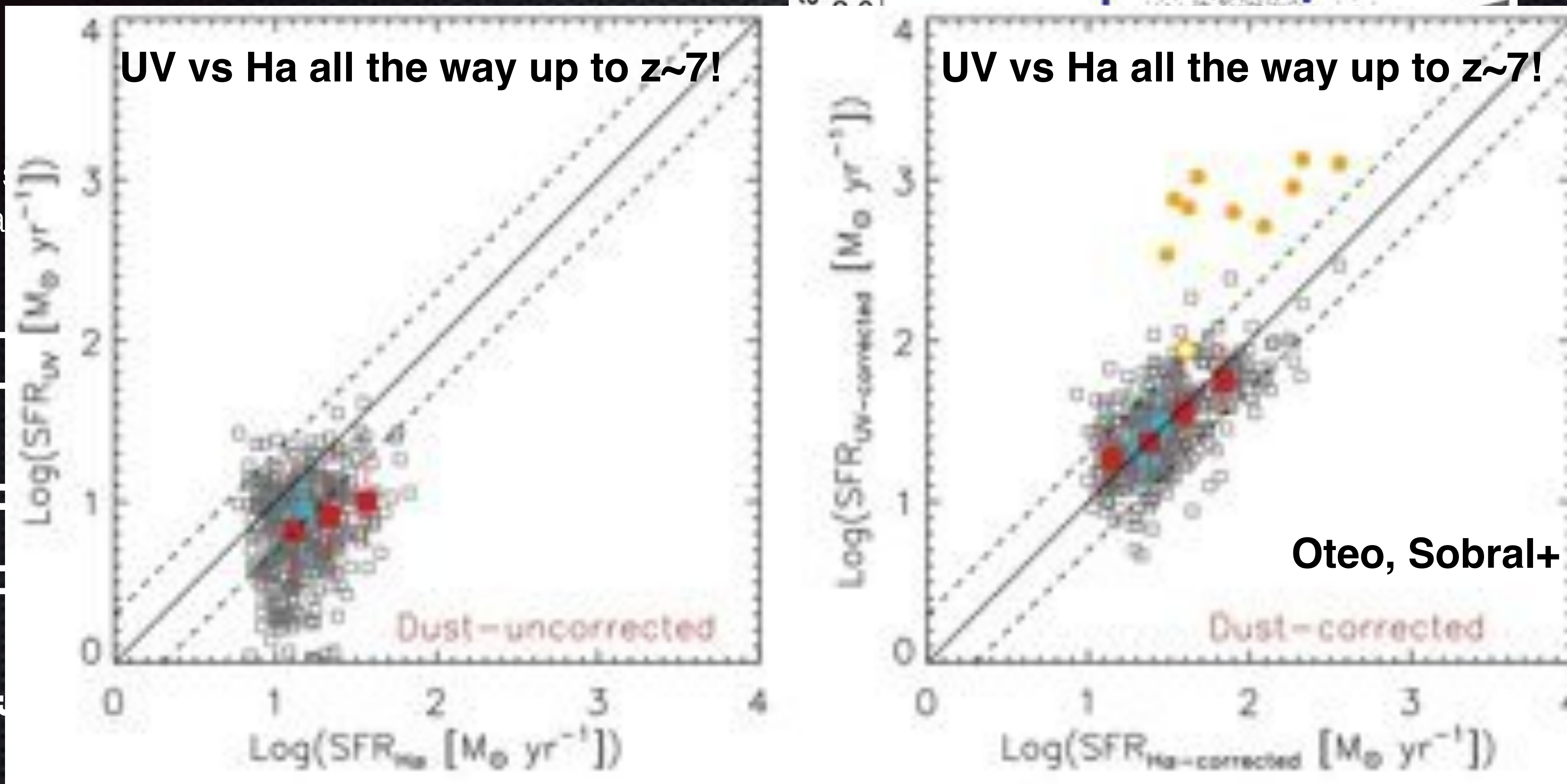
Extinction-Mass z~0-7?

Garn & Best 2010: Stellar Mass correlates



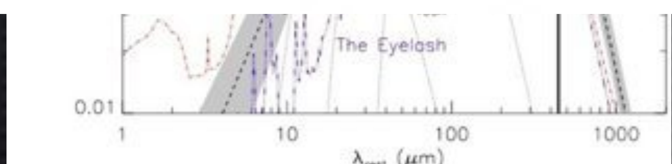
di

Iba

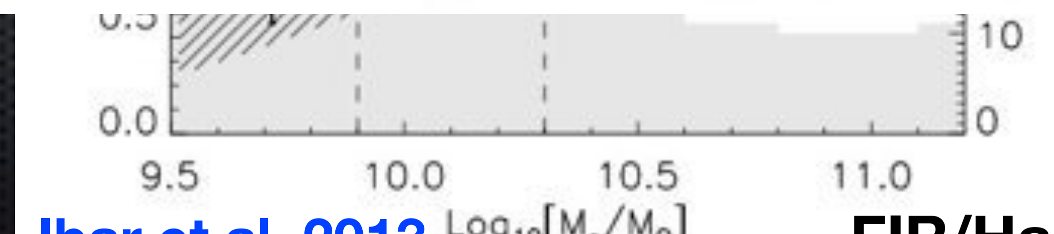


Oteo, Sobral+

Now



FIR derived A_{Ha} = 0.9-1.2 mag



Ibar et al. 2013

FIR/Ha

SFR function: Strong SFR* evolution

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

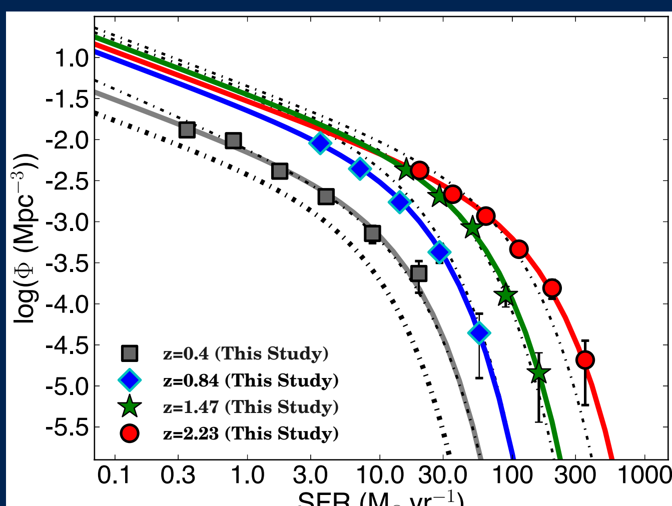
T, Gyrs

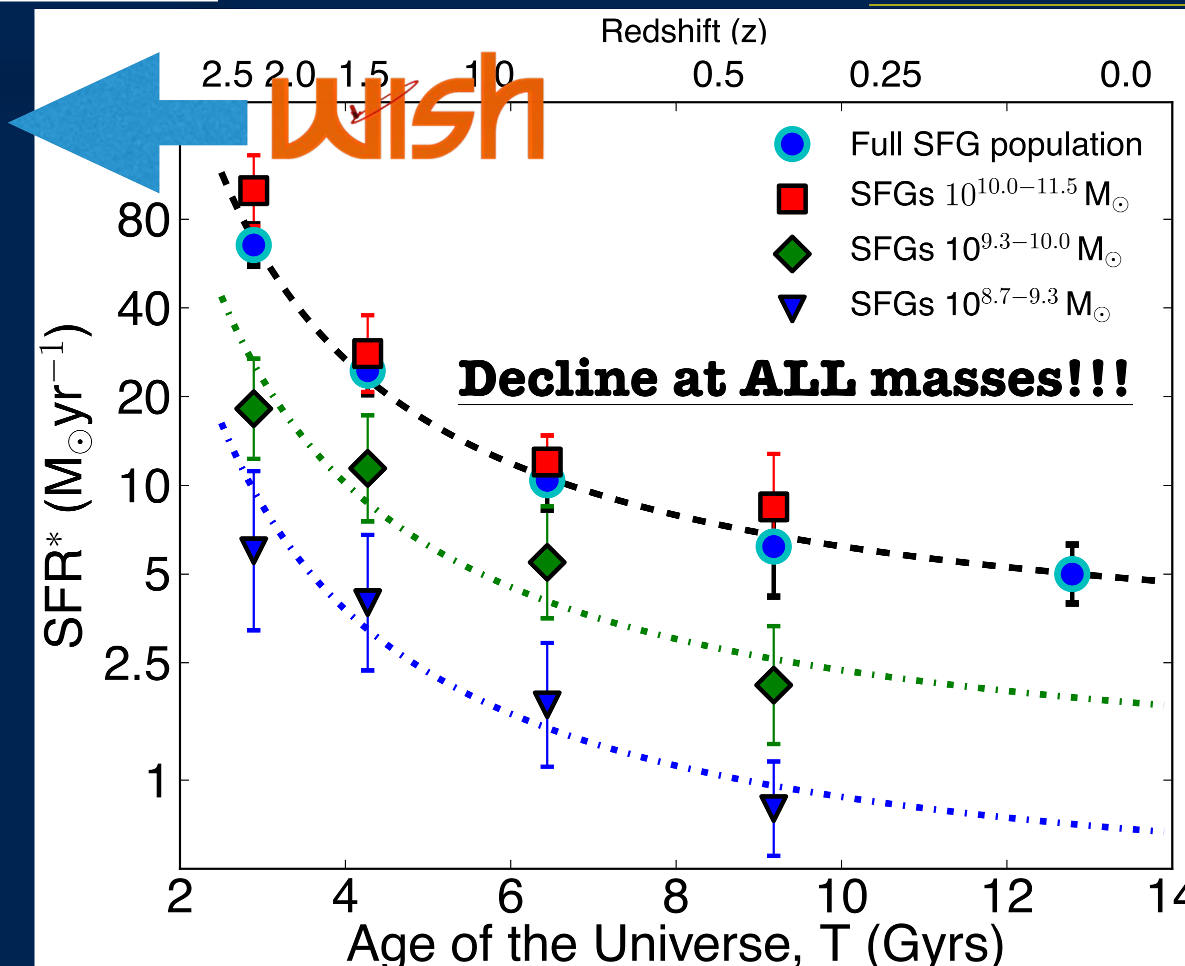
13x decrease over last 11 Gyrs

Sobral+14

Faint-end slope: α = -1.6

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



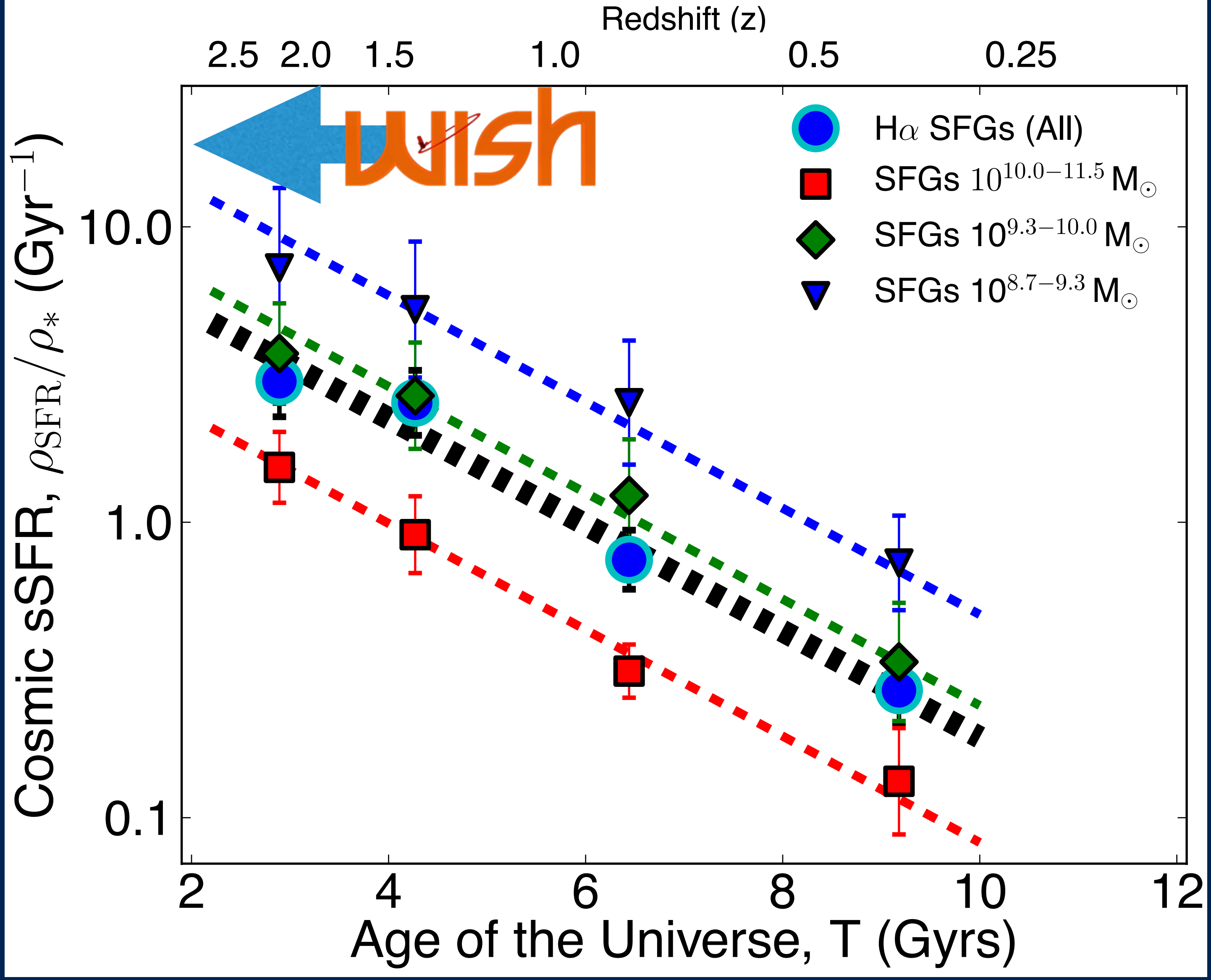


Φ*

z=0 → z=1 → z=2

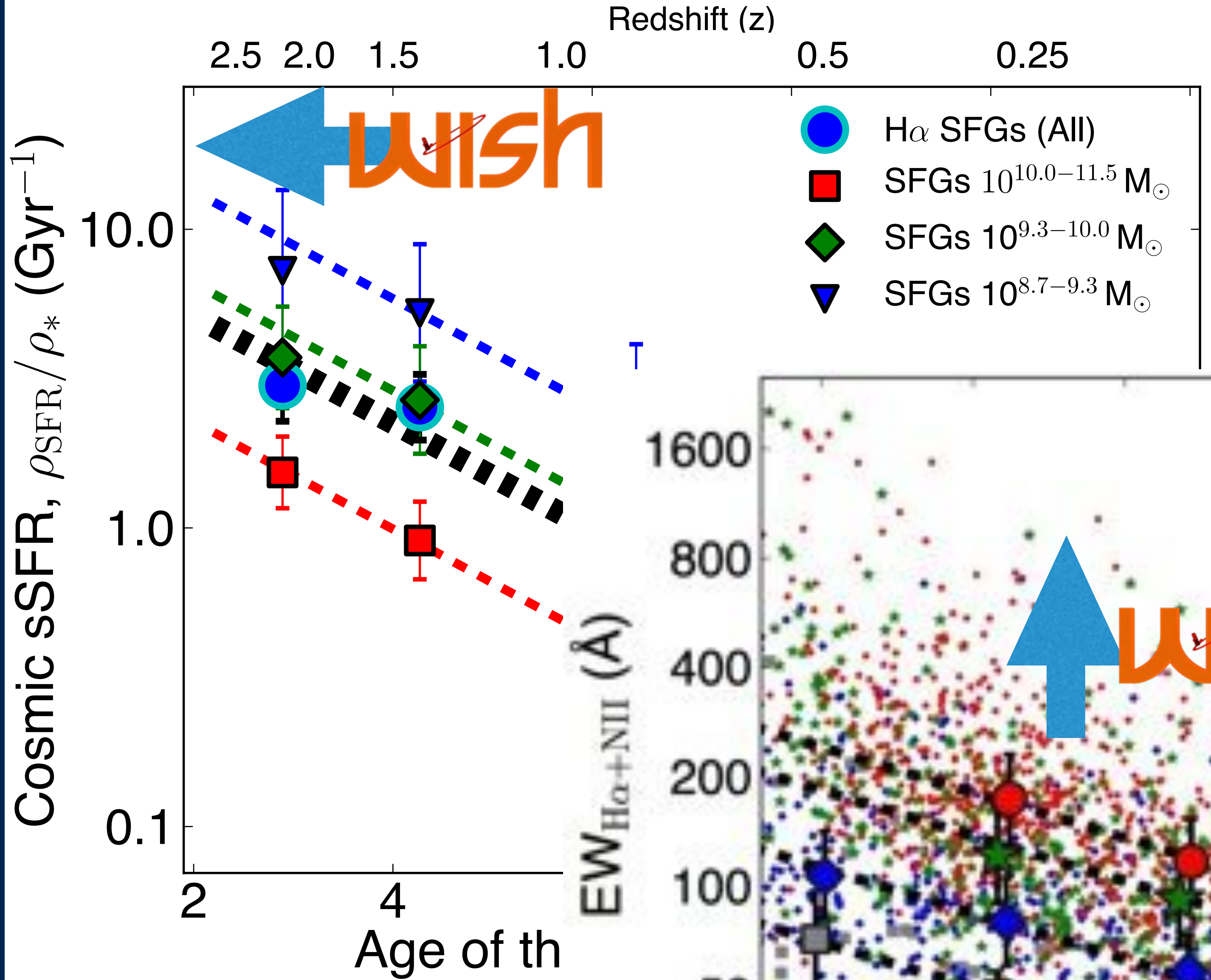
$$\log_{10}(\phi^*) = 0.004231T^3 - 0.1122T^2 + 0.858T - 4.659$$

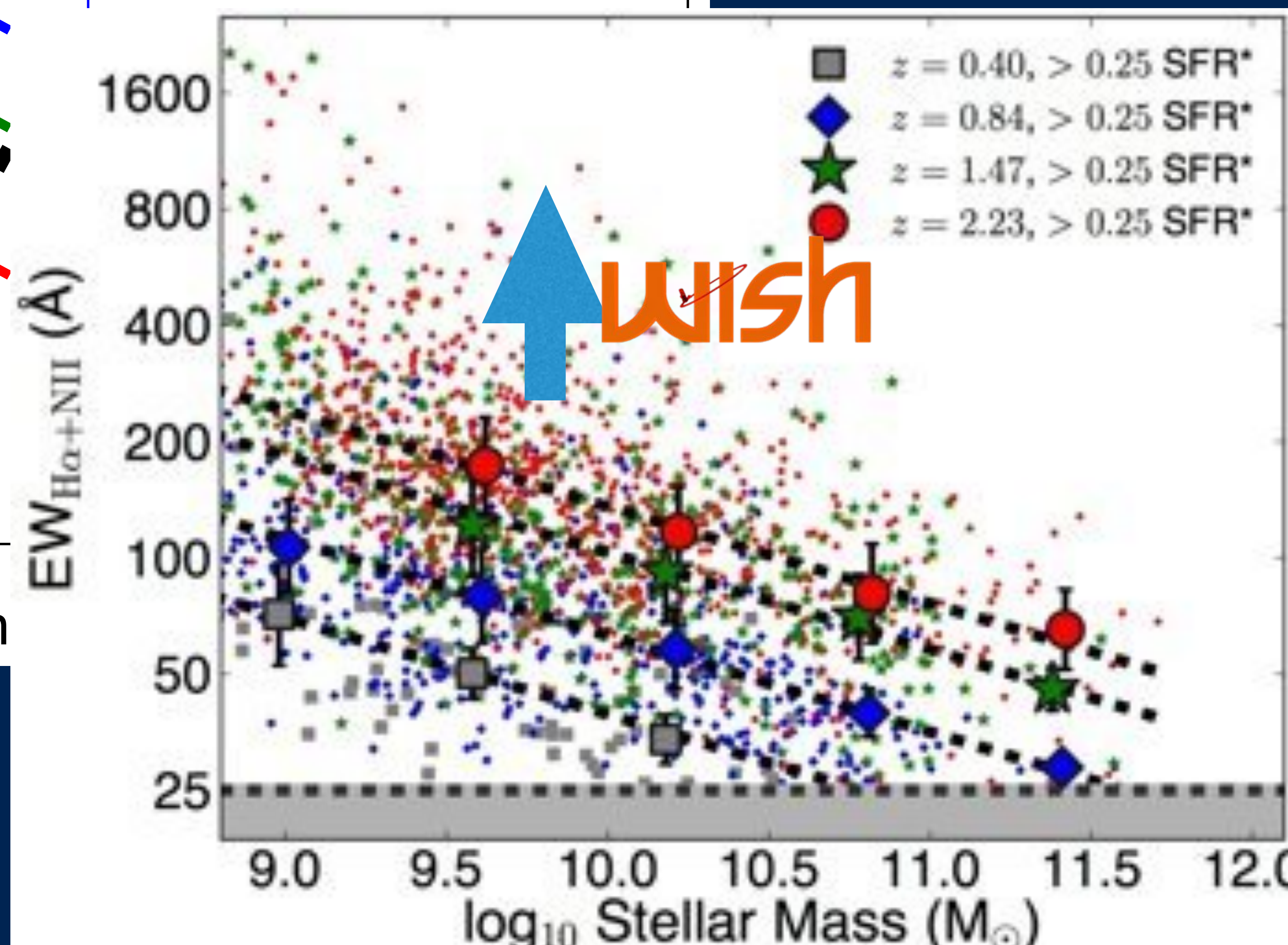
T, Gyrs



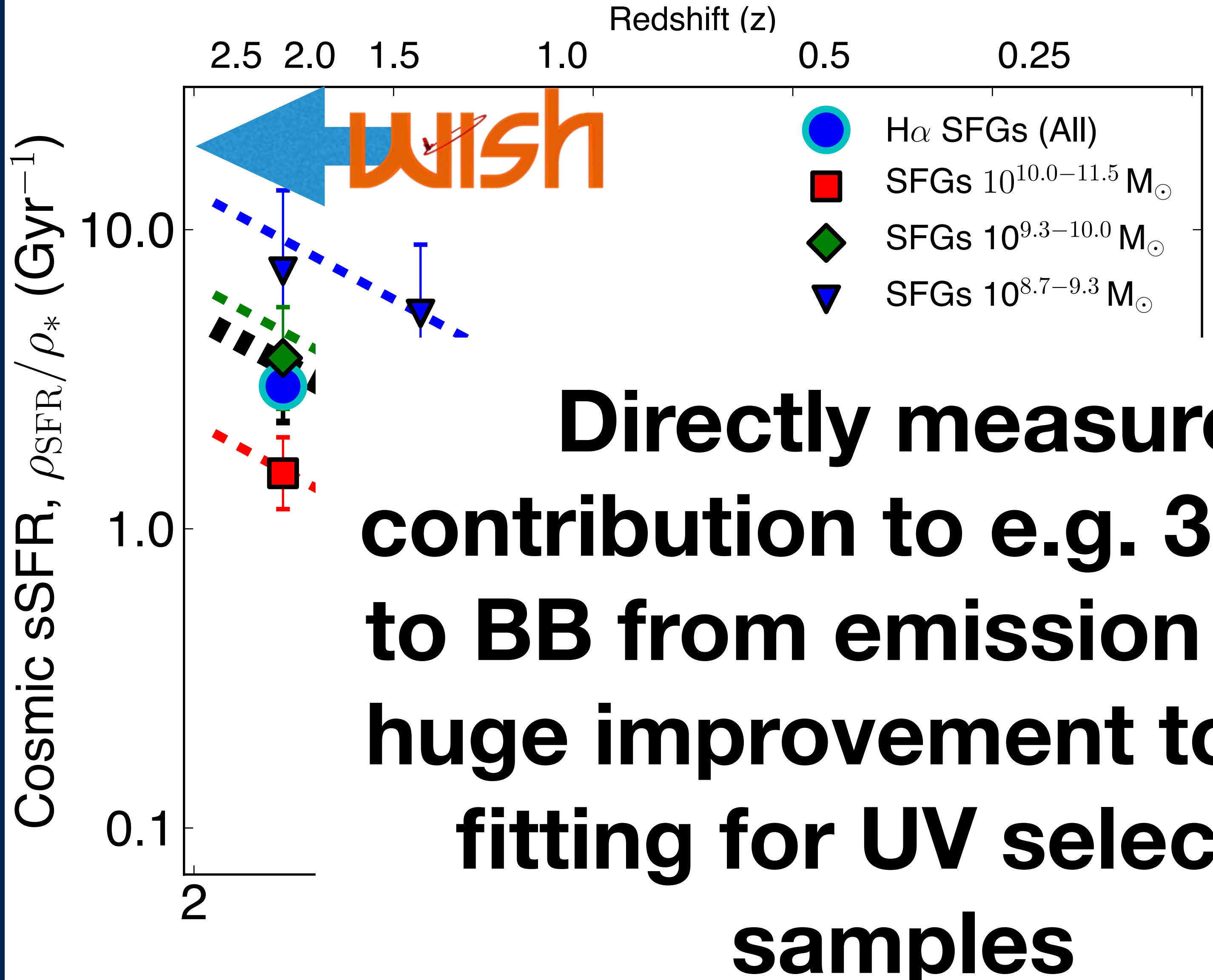
Redshift (z)
2.5 2.0 1.5 1.0 0.5 0.25
wish
Hα SFGs (All)
SFGs $10^{10.0-11.5}$ M$_\odot$
SFGs $10^{9.3-10.0}$ M$_\odot$
SFGs $10^{8.7-9.3}$ M$_\odot$
Cosmic sSFR, $\rho_{\rm SFR}/\rho_*$ (Gyr^{-1})
10.0
1.0
0.1
2 4 6 8 10 12
Age of the Universe, T (Gyrs)

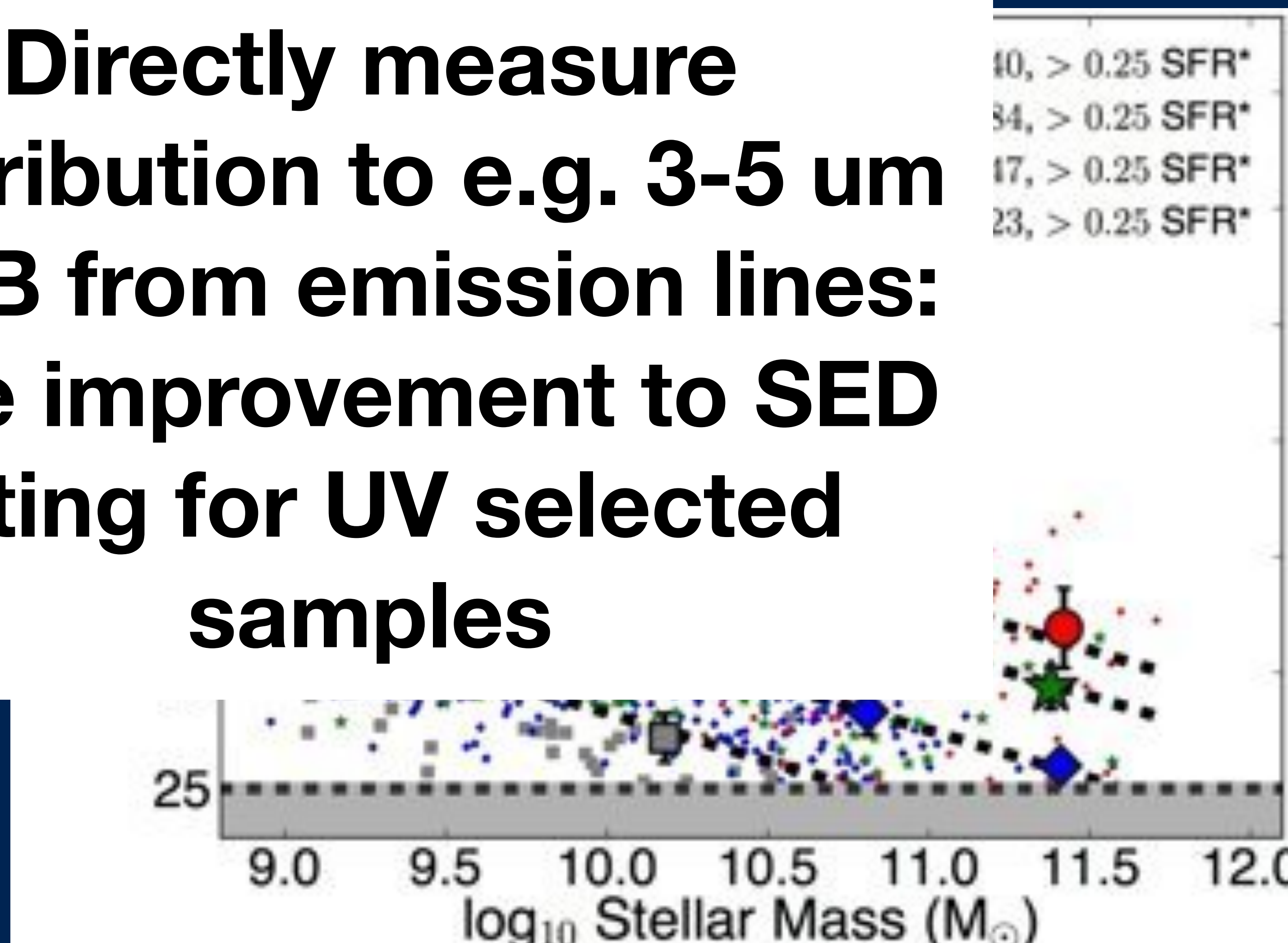
Sobral+14


Redshift (z)
2.5
2.0
1.5
1.0
0.5
0.25
wish
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, ρ_{SFR}/ρ_* (Gyr^{-1})
10.0
1.0
0.1
2
4
Age of th


wish
$z = 0.40$, > 0.25 SFR*
$z = 0.84$, > 0.25 SFR*
$z = 1.47$, > 0.25 SFR*
$z = 2.23$, > 0.25 SFR*
EW$_{H\alpha+NII}$ (Å)
1600
800
400
200
100
50
25
9.0
9.5
10.0
10.5
11.0
11.5
12.0
log$_{10}$ Stellar Mass (M$_\odot$)

Sobral+14



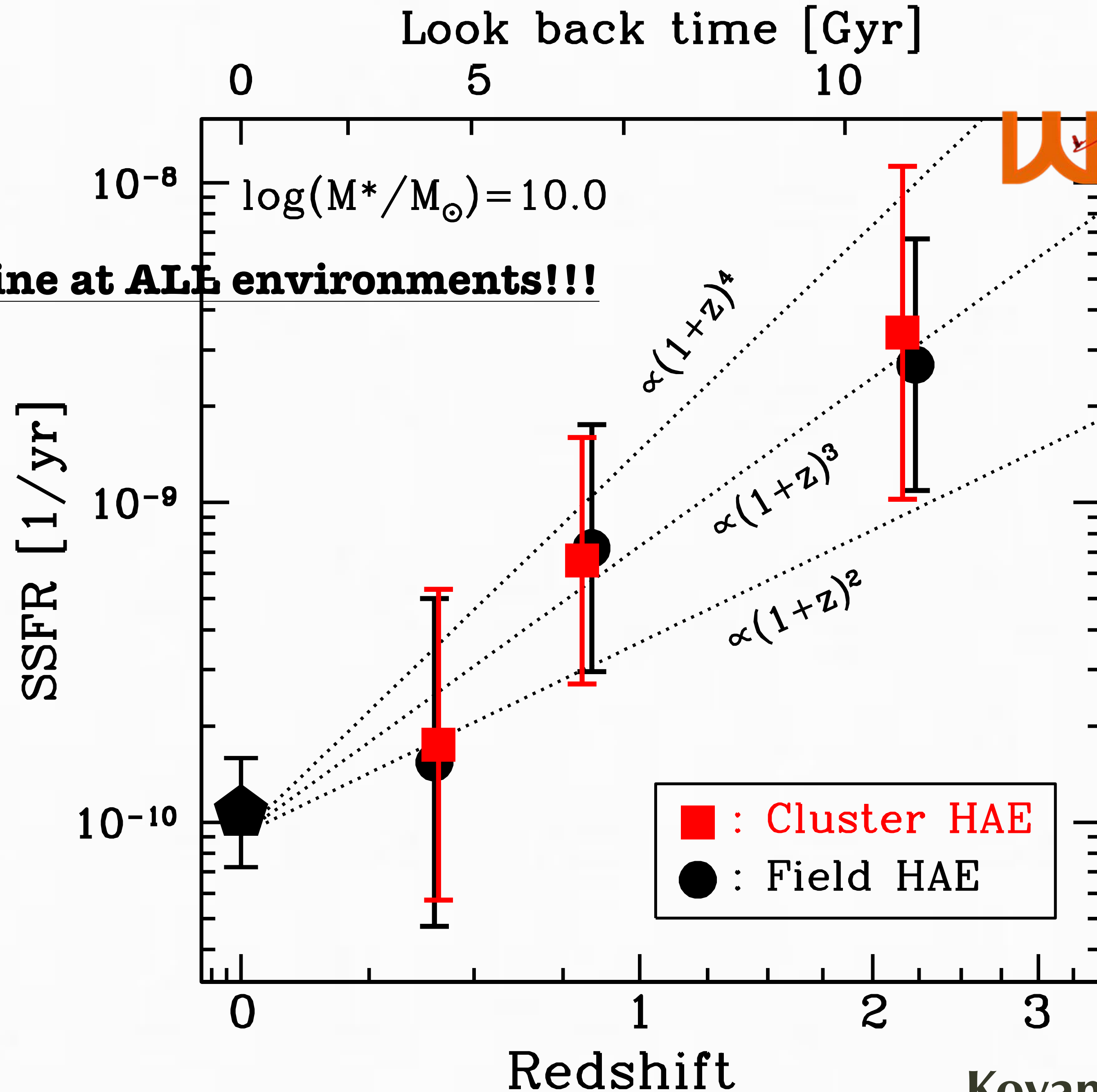


Directly measure contribution to e.g. 3-5 um to BB from emission lines: huge improvement to SED fitting for UV selected samples

Sobral+14

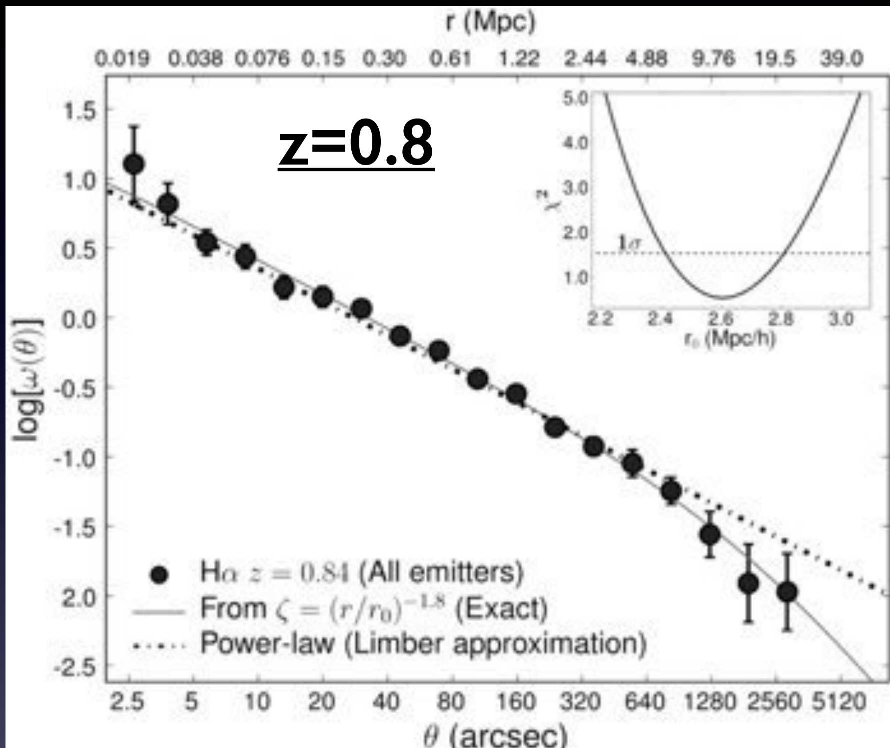
Evolution of SFR* (SSFR) same in fields and clusters since z=2.23

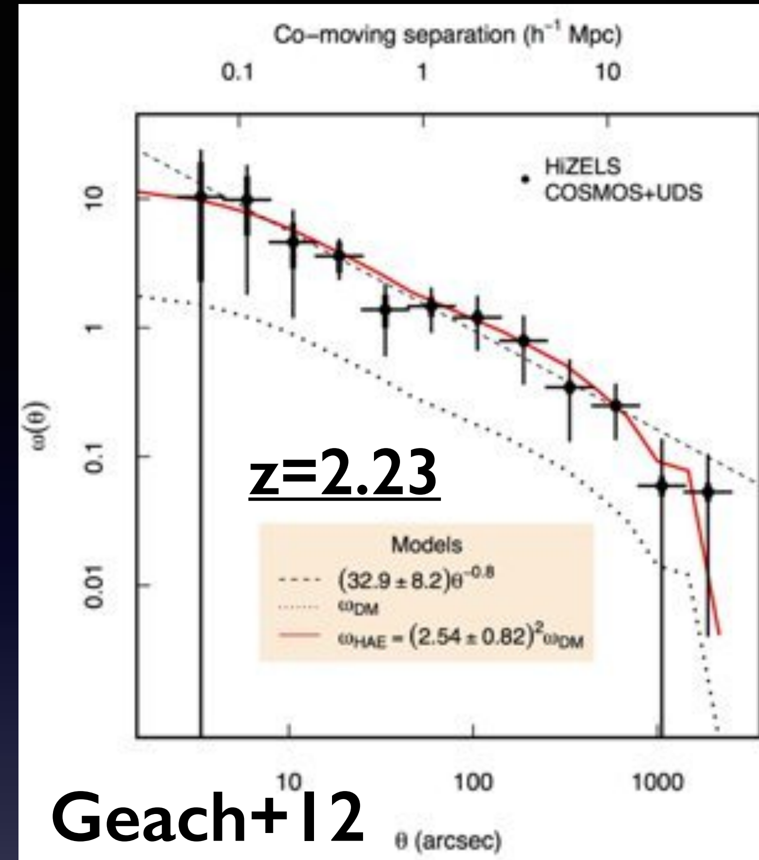
Decline at ALL environments!!!



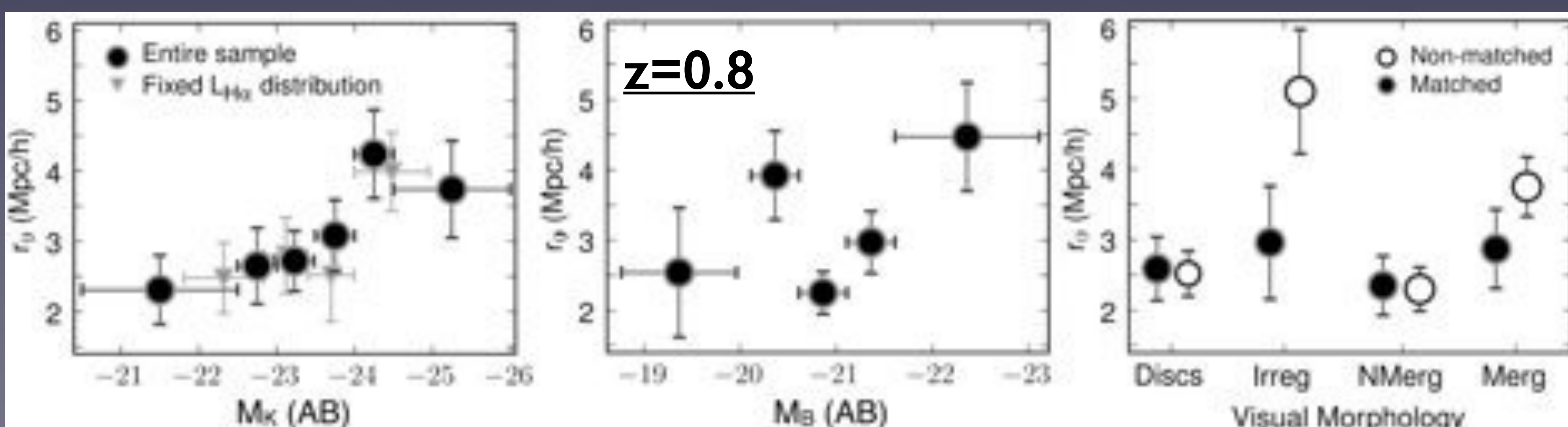
Koyama et al. 2013

Clustering



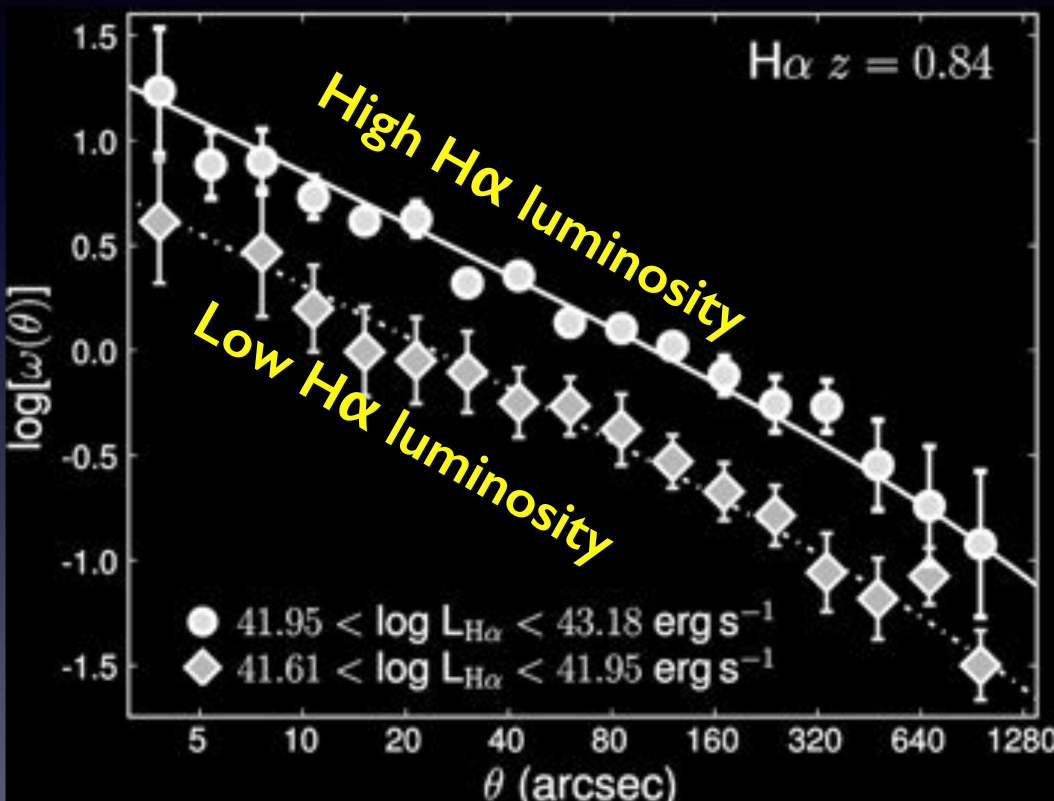


Sobral et al. 2010

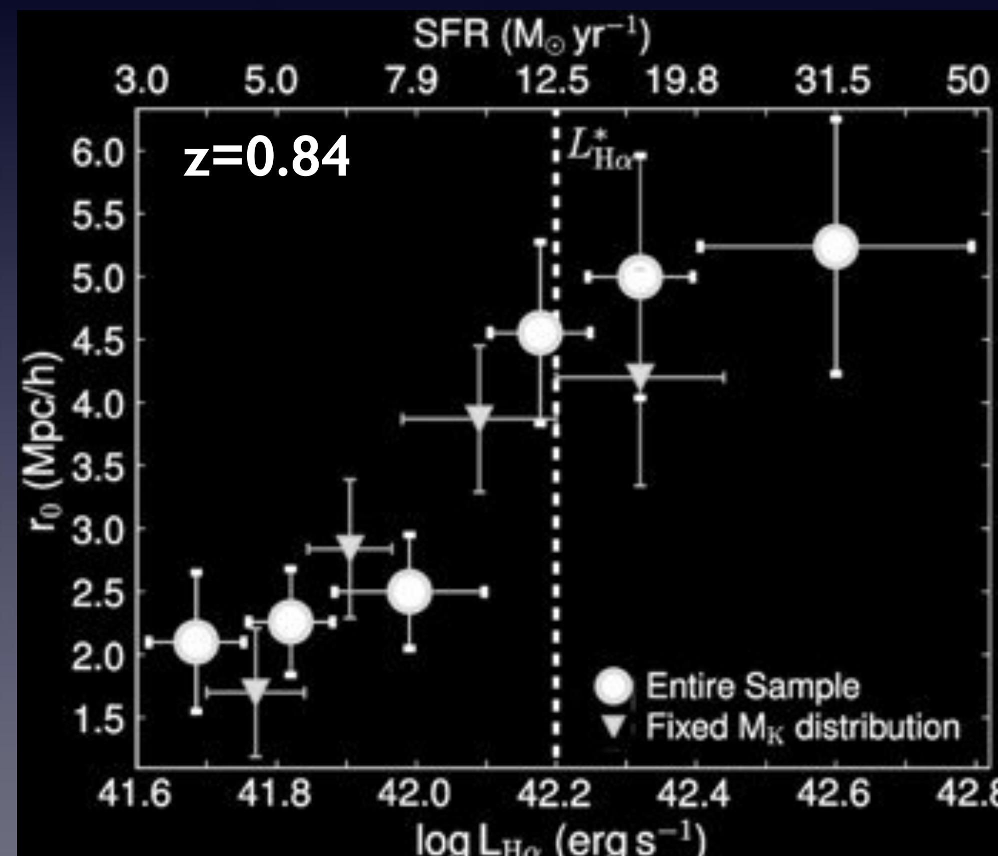


Clustering of Hα at z~1

<u>Clustering depends on Hα luminosity</u>; galaxies with higher SFRs are more clustered

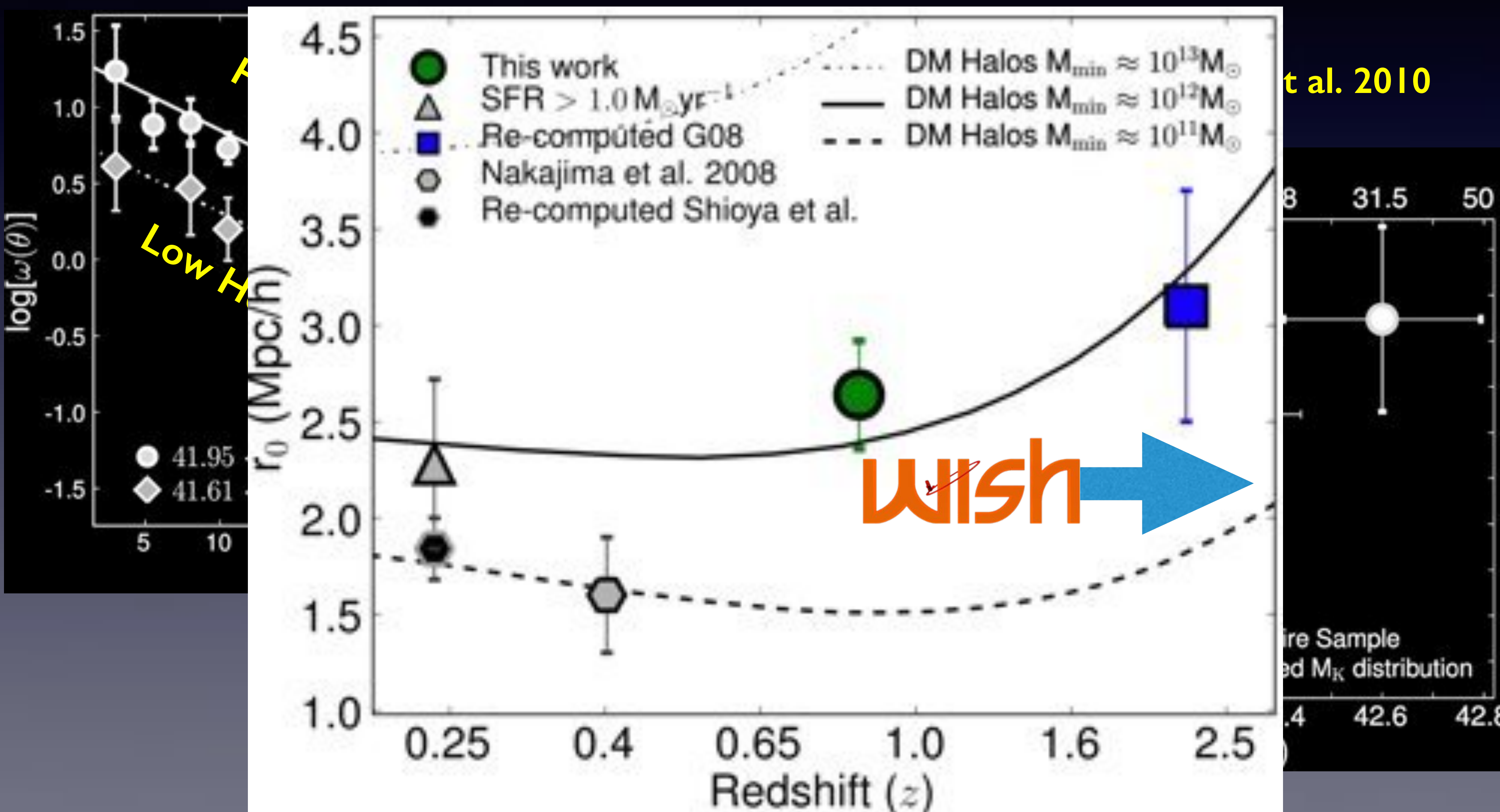


Sobral et al. 2010



Clustering of Hα at z>2

Clustering depends on Hα luminosity; galaxies with higher SFRs are more clustered

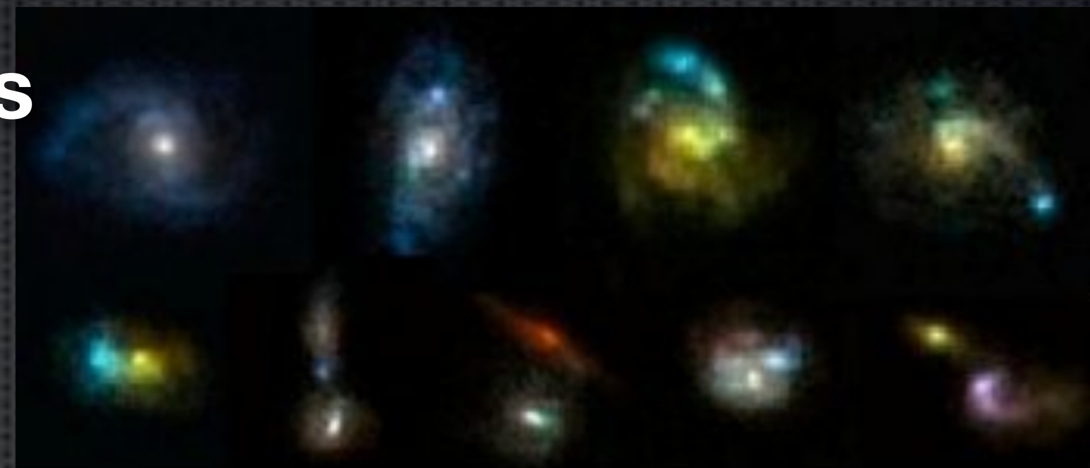


Sizes (and morphologies)

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 $\log_{10} r_e = a(\log_{10}(M_*) - 10) + b$. Where r_e and M_* are in units of kpc and $M_\odot$ respectively.

z	a	b	r_e at $\log_{10}(M_*) = 10$ (kpc)
0.40	0.08±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

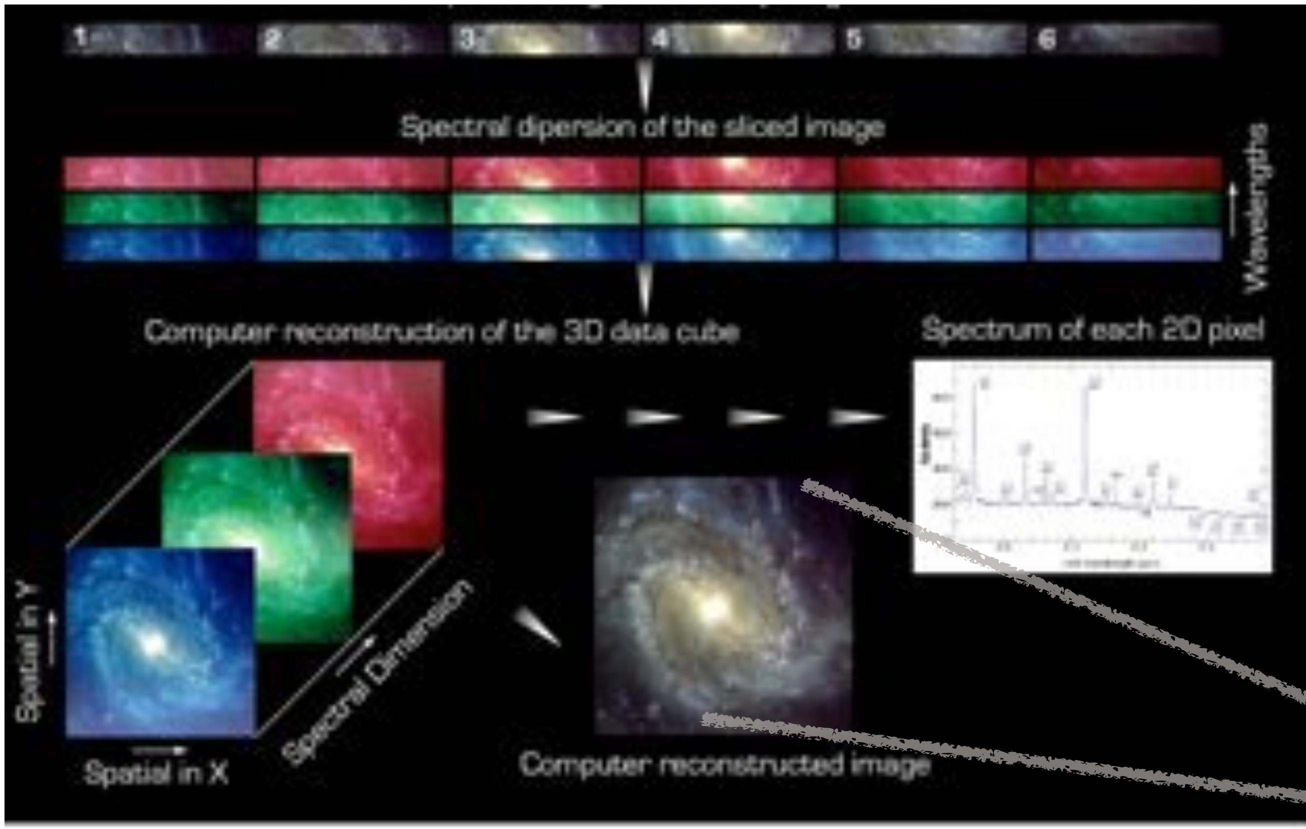
Sobral+09a, Stott+13a

Galaxy Dynamics at z~0.8-2.2 => to z~7?

Integral Field Units, IFUs

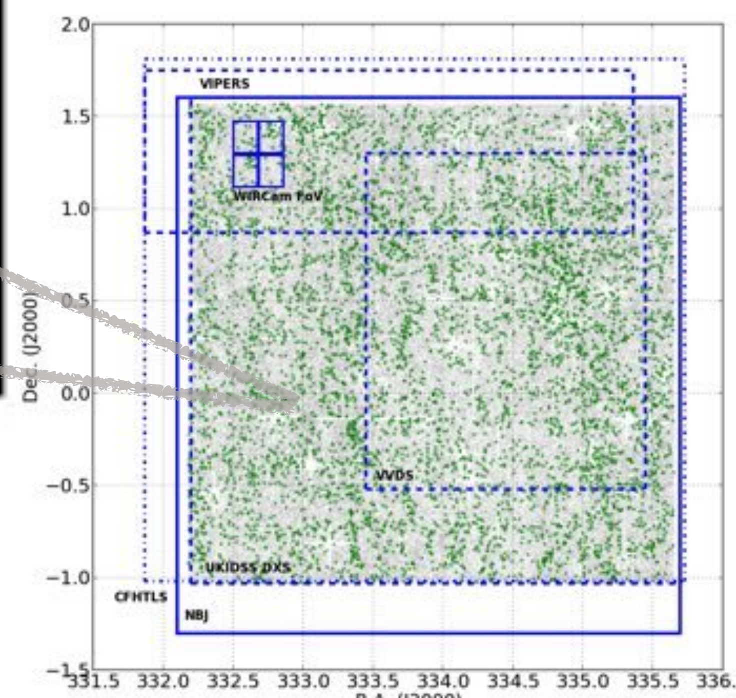
e.g. SINFONI / VLT

Hα-selected targets are ideal



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

Known Hα fluxes

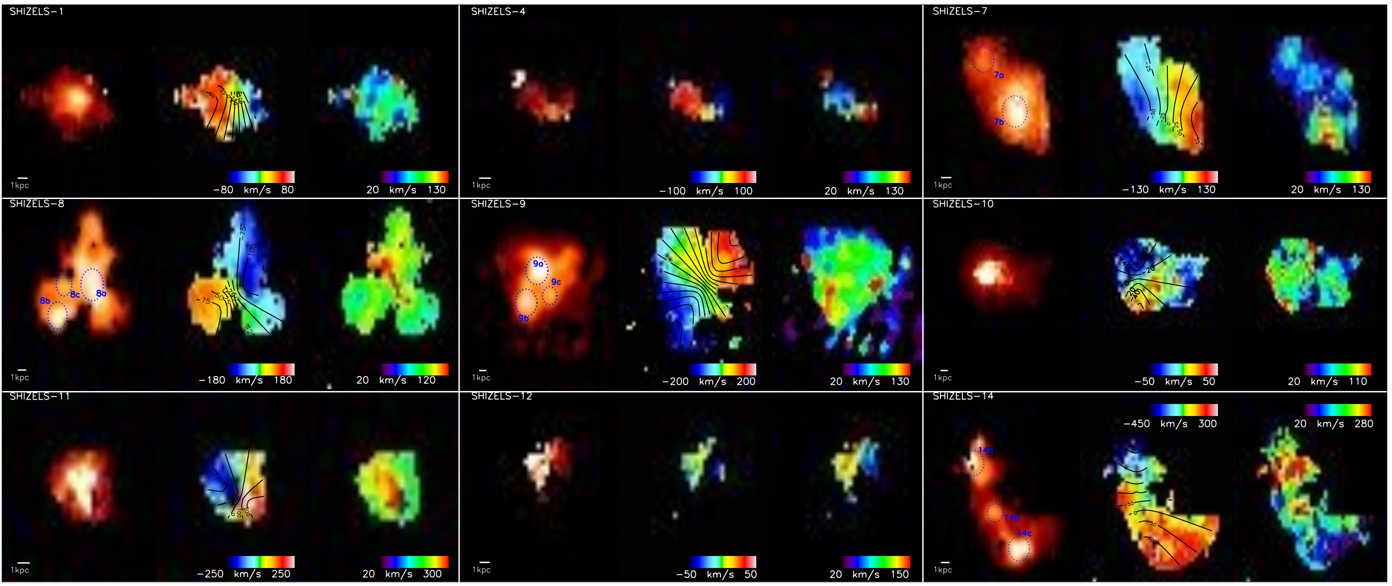


Very efficient combination to get sub-kpc resolution

Galaxy Dynamics at z~0.8-2.2

Swinbank et al. 2012a

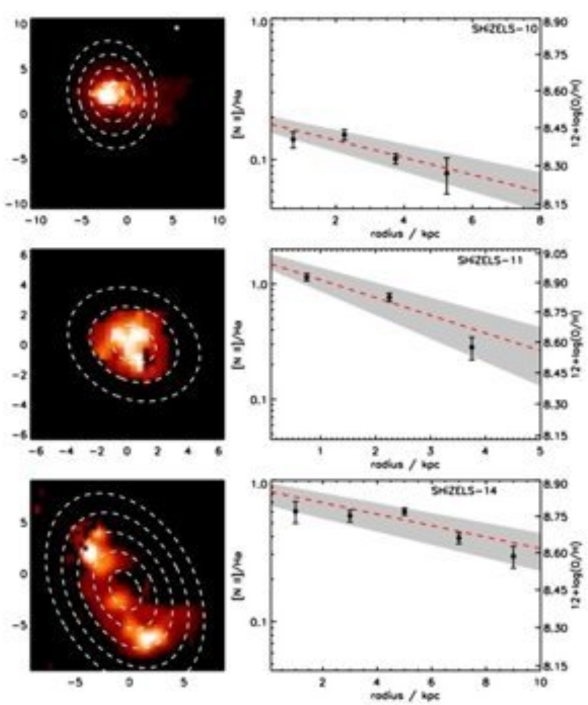
Swinbank al. 2012b

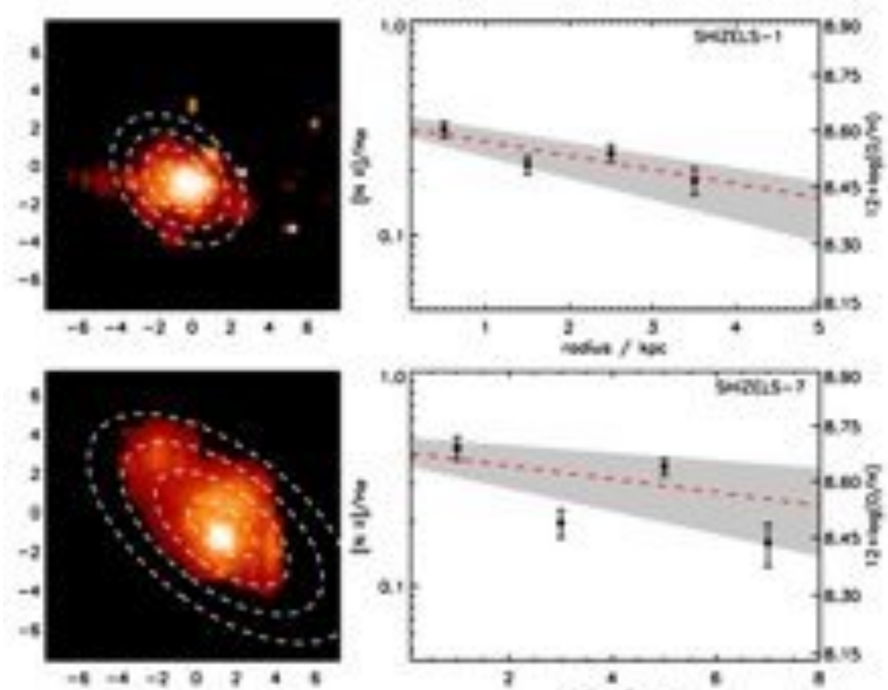


(MNRAS/ApJ):

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

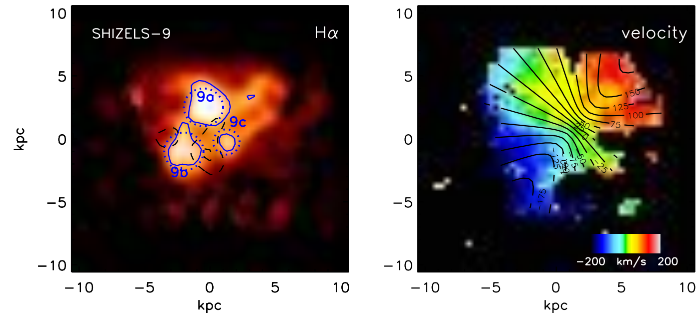
- Negative metallicity gradients: "inside-out" growth

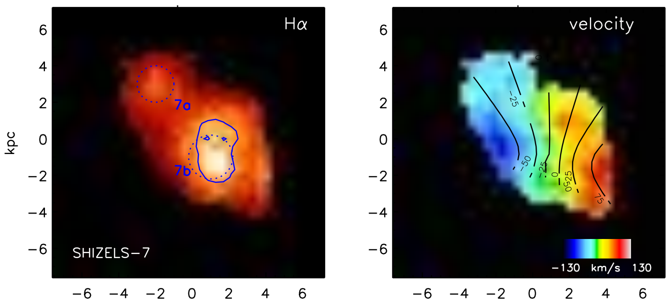




SINFONI

~50 hours of VLT time

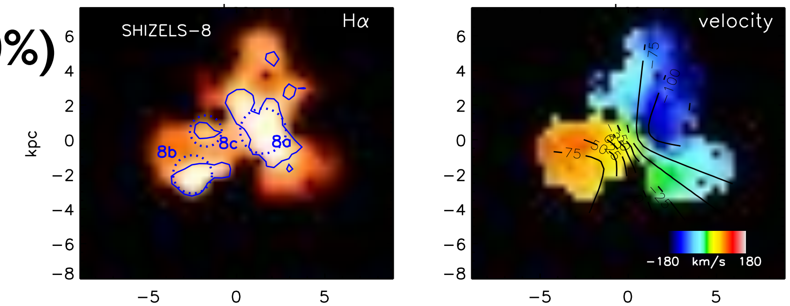




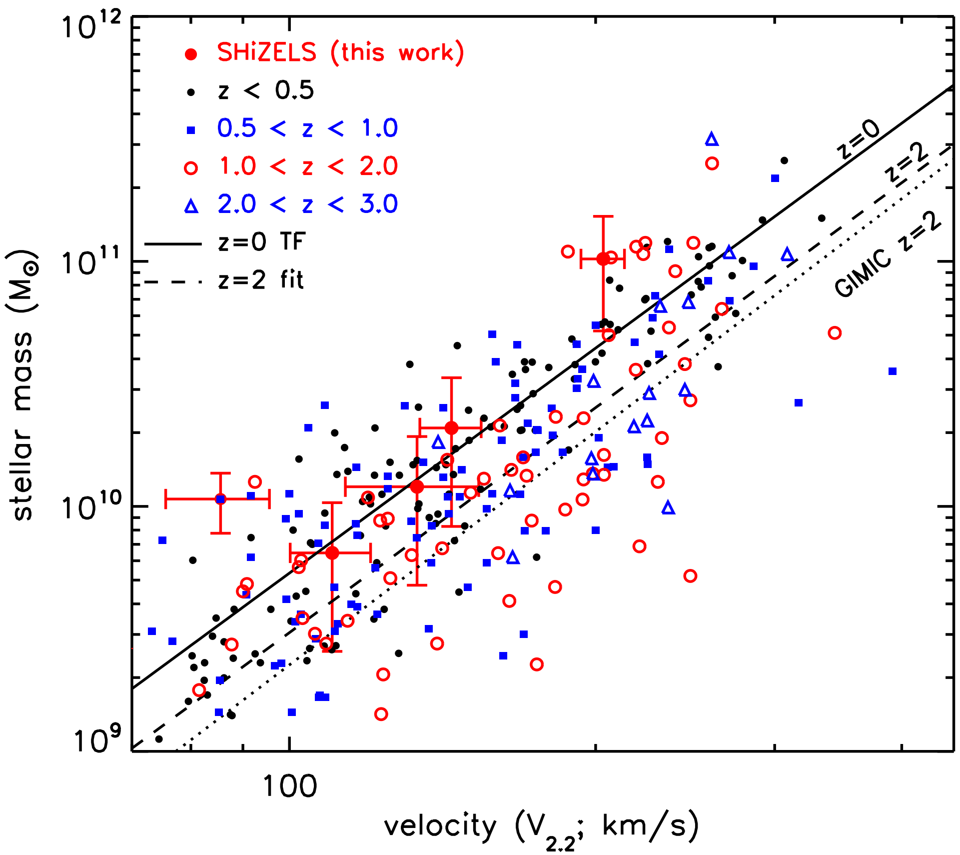
Mostly disks-like (~70-80%)

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

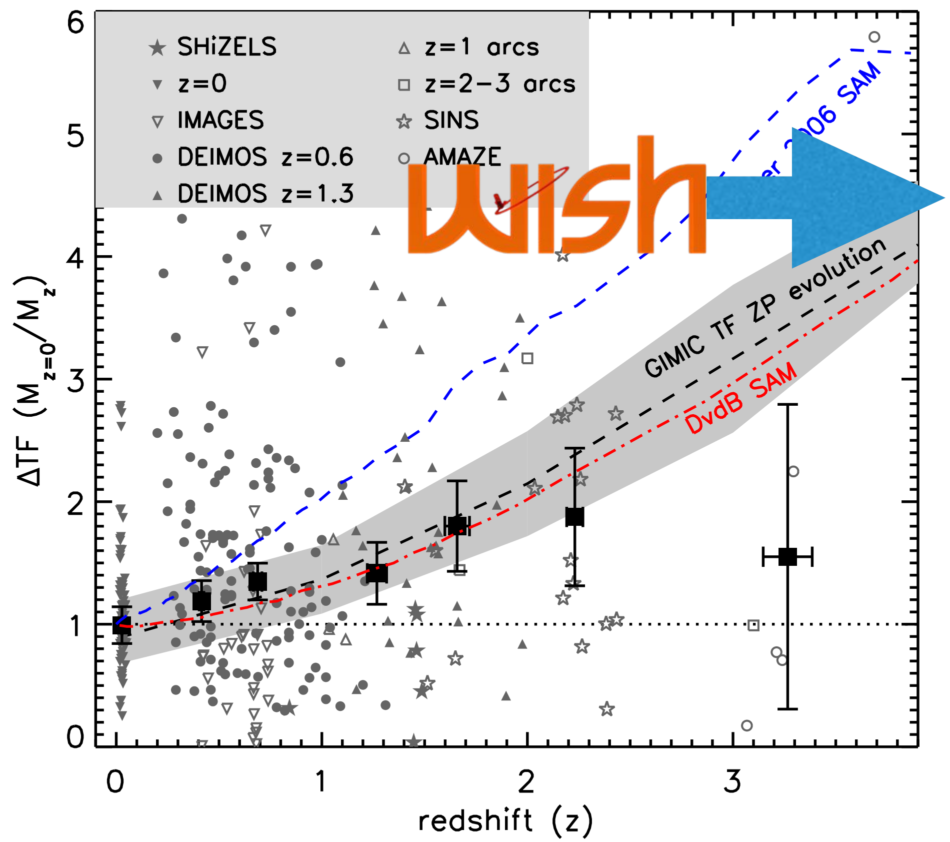
Rotation ~70-200 km/s



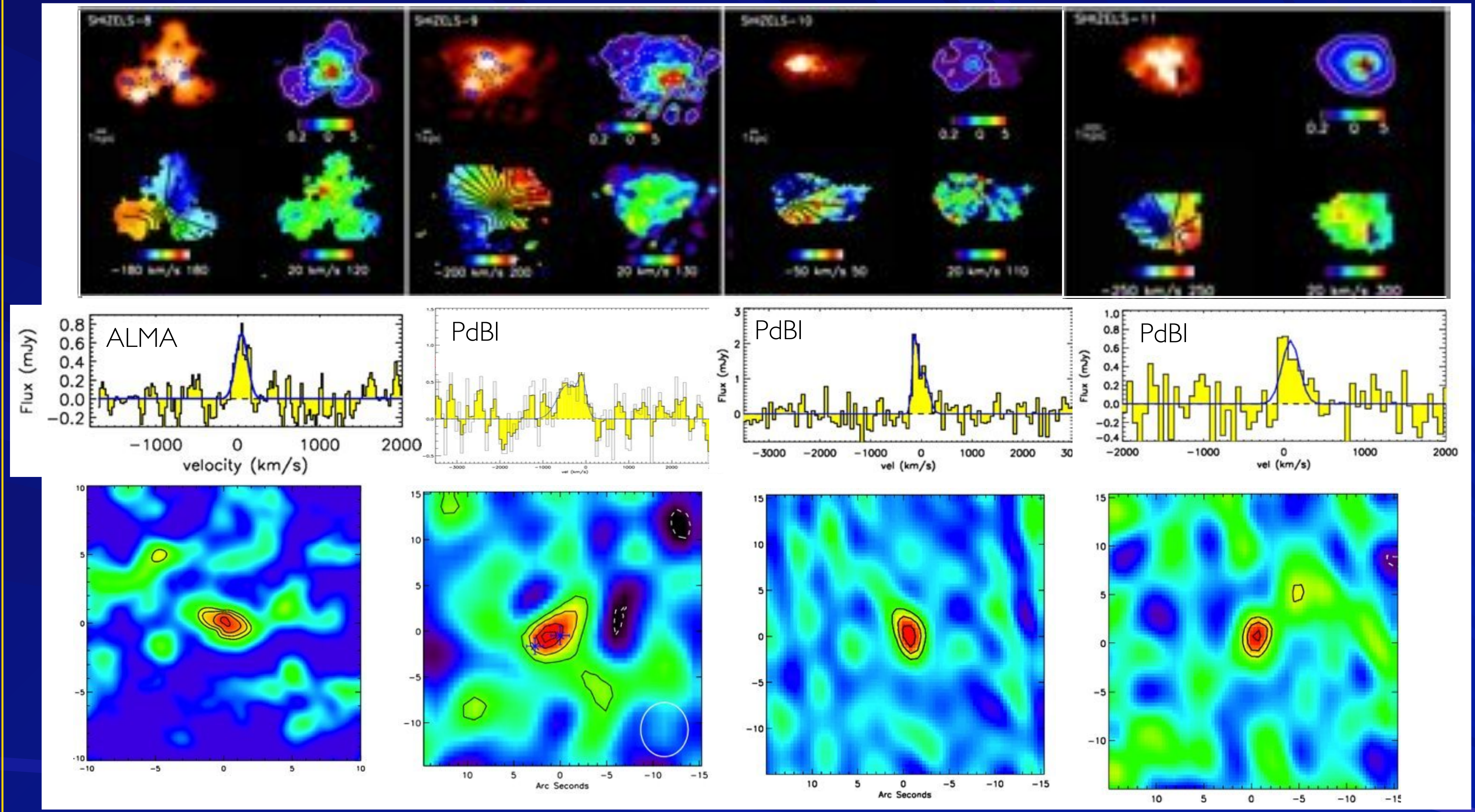
Stellar mass TF relation



Swinbank, Sobral et al. 2012



Push to z~7 CO+dust follow-up with ALMA vs UV selected



Towards resolved (~sub-kpc) Ha + CO + dust maps and evolution from z~2 (~7!) to z~0 for "typical" SFGs

$M_{gas} = 1\text{-}3\times10^{10} M_\odot$ (a=2)
$M^* = 2\text{-}4\times^{10} M_\odot$
f_{gas} ~30-50%
M_{gas} / SFR ~ 1Gyr

The Big step forward we need :

Beyond K band

wish

100K/MEGA

Wide field Infrared Surveyor for Hα

100k Hα emitters: z~2.2, 3.5, 4.5, 5.7, 6.6

Same selection over 13 Gyrs

SFH, evolution of all galaxy properties

Direct comparison with UV + Lya

deep15.oal.ul.pt

Join us now on Facebook + Twitter: @deepconf

Back at the Edge of the Universe

Latest results from the deepest astronomical surveys

Sintra, Portugal, 15-19 March 2015

Home | The Conference | The People | Sintra

An international conference organised by the

Centro de Astronomia e Astrofísica da Universidade de Lisboa

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

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

The Big step forward we need :

Beyond K band

WISH

100K/MEGA

Wide field Infrared Surveyor for Hα

100k Hα emitters: z~2.2, 3.5, 4.5, 5.7, 6.6

Same selection over 13 Gyrs

SFH, evolution of all galaxy properties

Direct comparison with UV + Lya

Conclusions: **last 11 Gyrs**

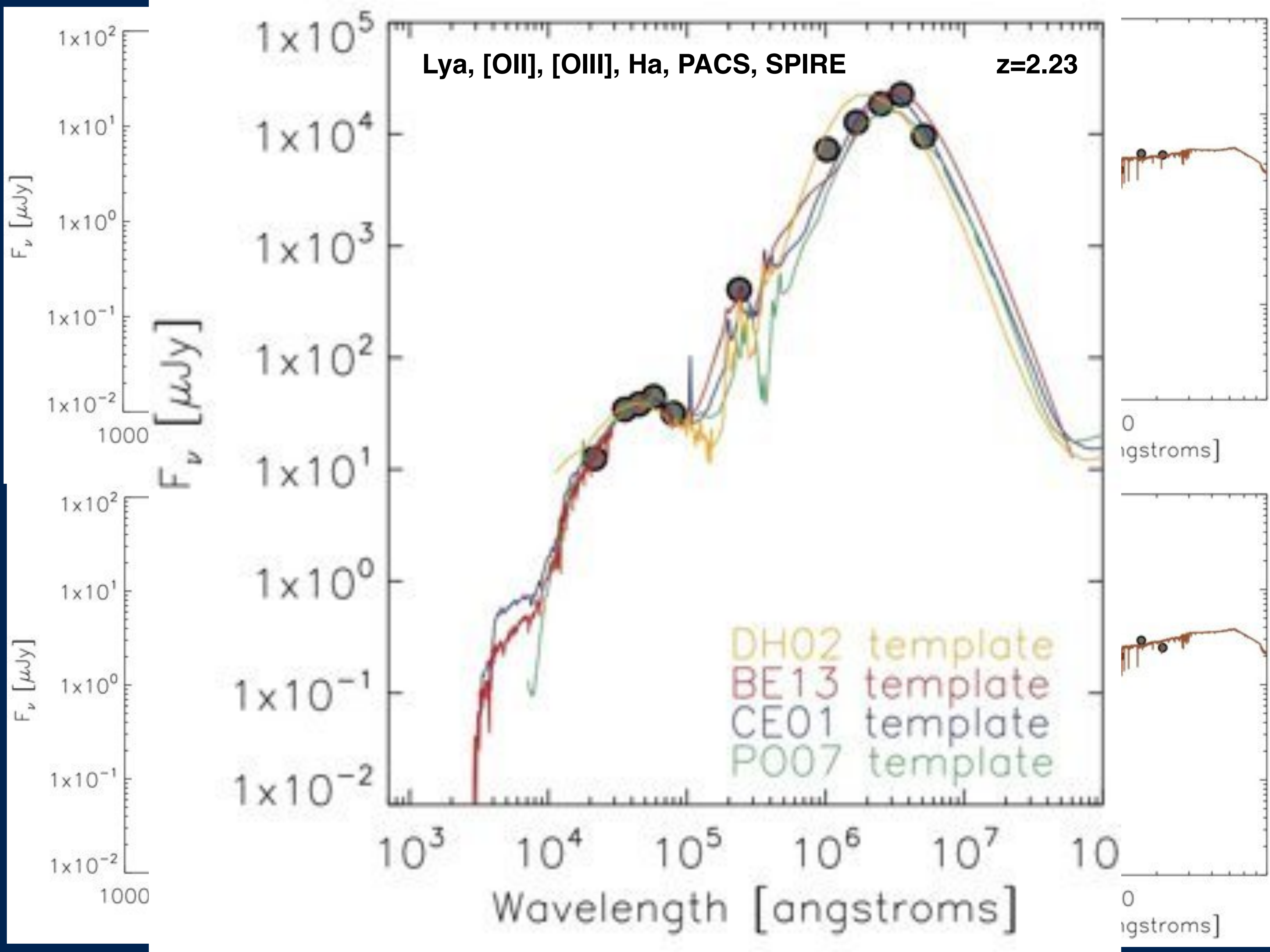
- **Hα selection z~0.2-2.2: Robust**, self-consistent SFRH + **Agreement** with the **stellar mass density growth**

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

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

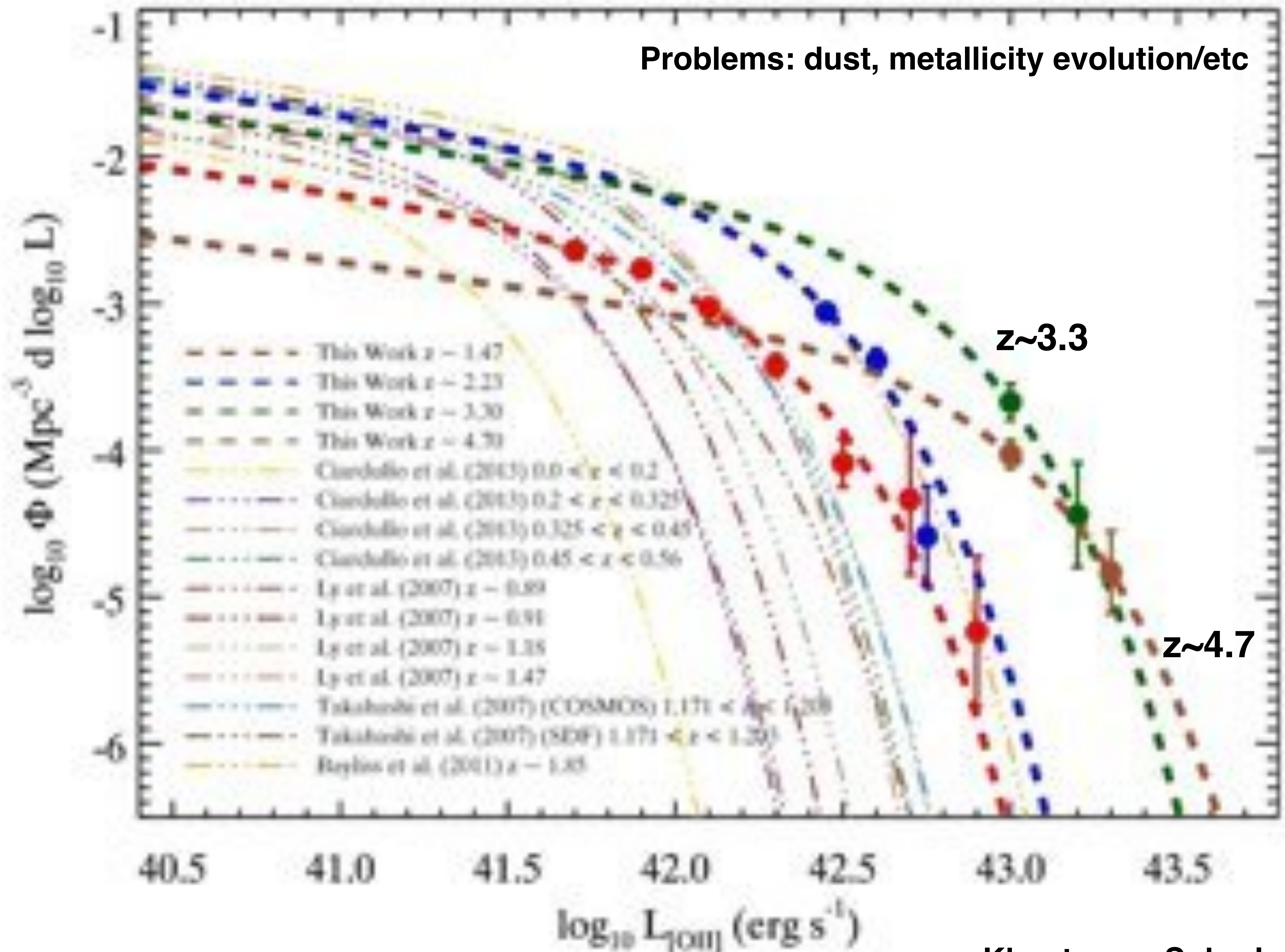
- **KMOS+Hα (NB) selection works extraordinarily well: resolved dynamics of typical SFGs in ~1-2 hours, 75+-8% disks, 50-275km/s**

Most of claimed "evolution" with redshift is driven by:
- **The evolution of SFR* (typical SFR(z))**
- **Selection effects: selection really matters! Need to compare like with like!**



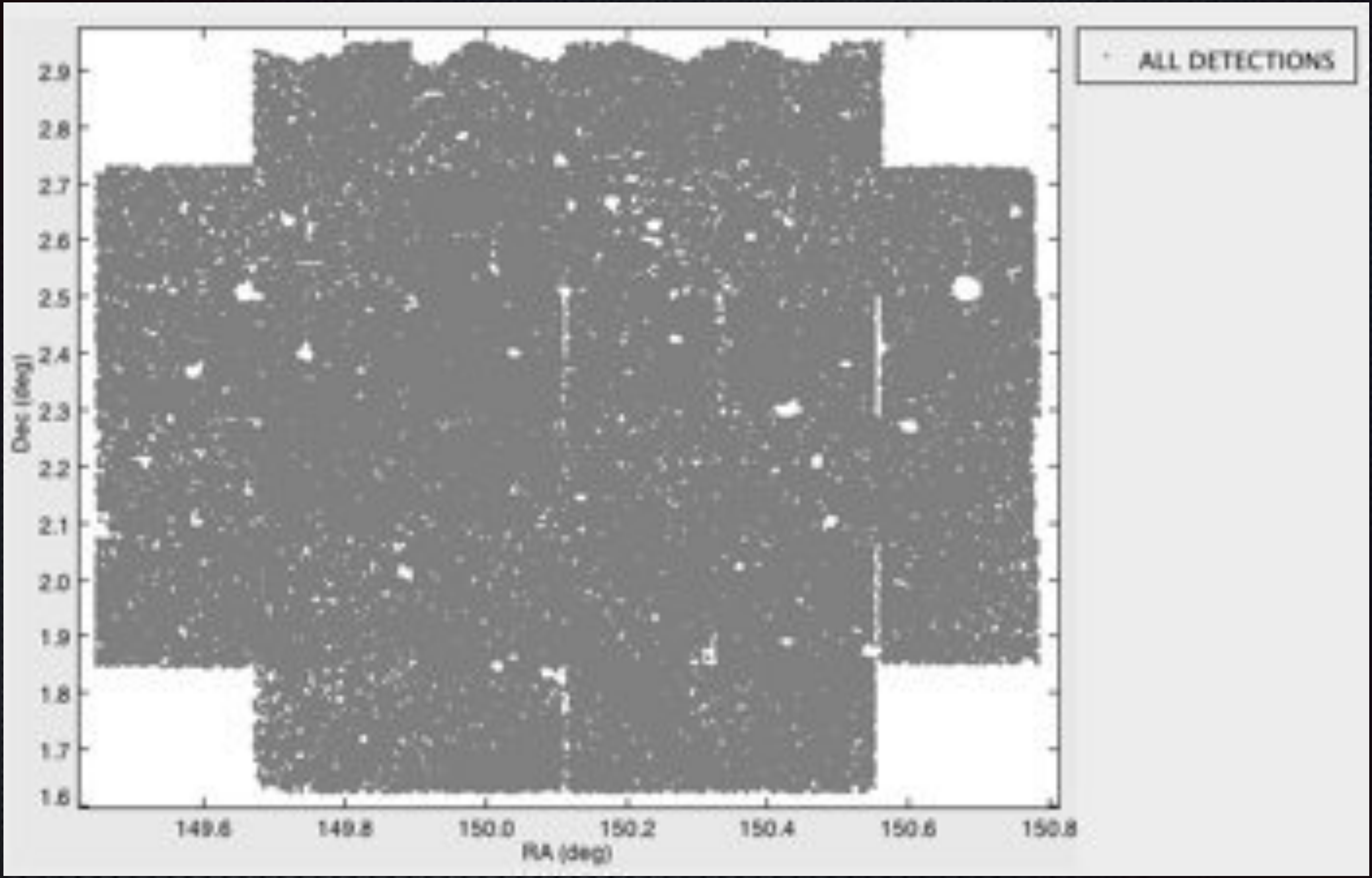
Lya, [OII], [OIII], Ha, PACS, SPIRE
z=2.23
F_ν [μJy]
1x10^5
1x10^4
1x10^3
1x10^2
1x10^1
1x10^0
1x10^-1
1x10^-2
10^3
10^4
10^5
10^6
10^7
Wavelength [angstroms]
DH02 template
BE13 template
CE01 template
P007 template

Using [OII] try to go beyond z~2.5?



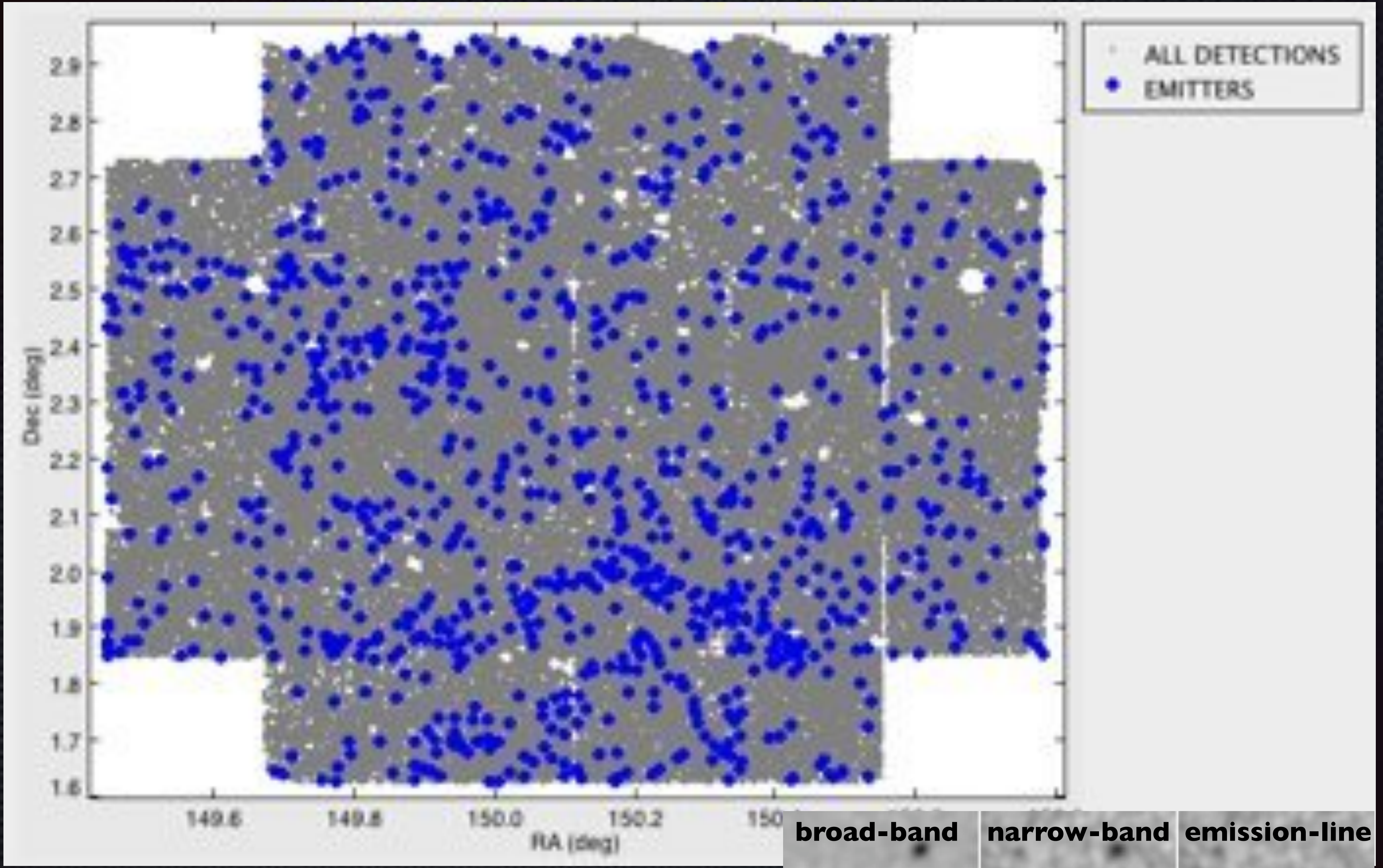
Khostovan, Sobral et al.

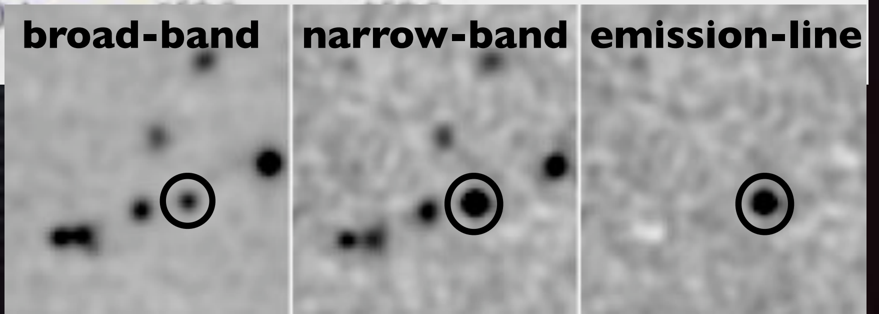
All sources K band



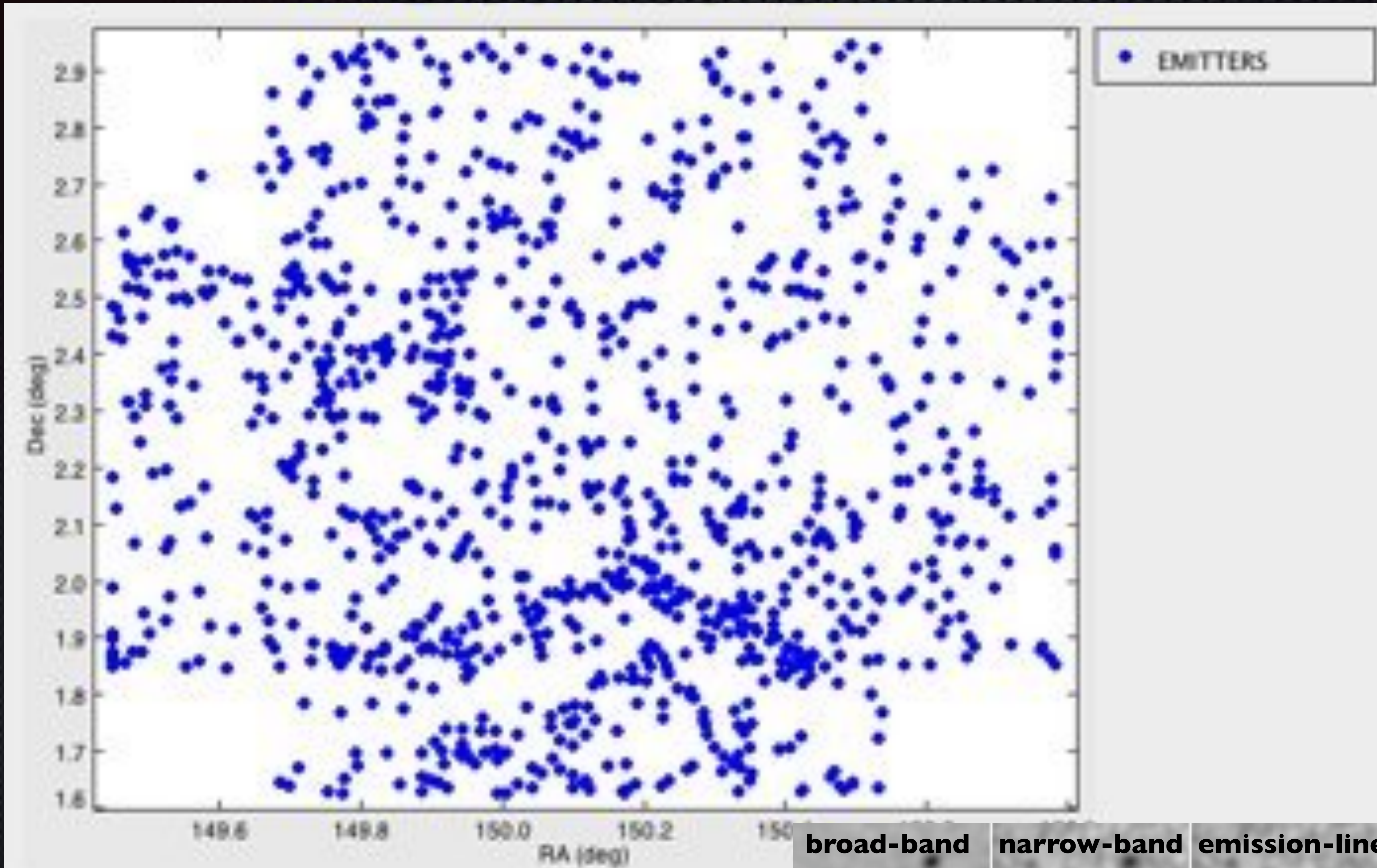
E.g. COSMOS field from the ground

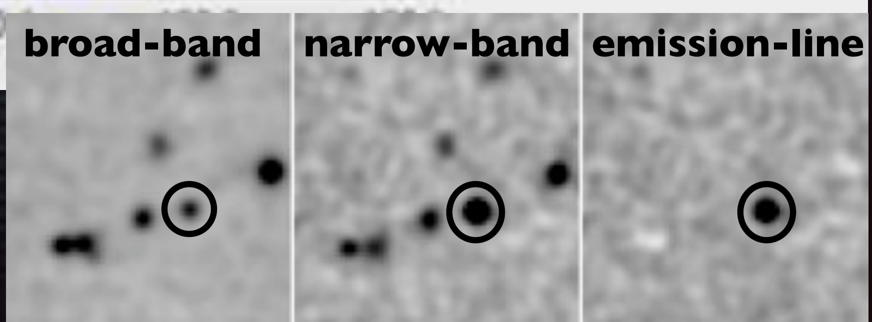
All sources K band => Line emitters NBK



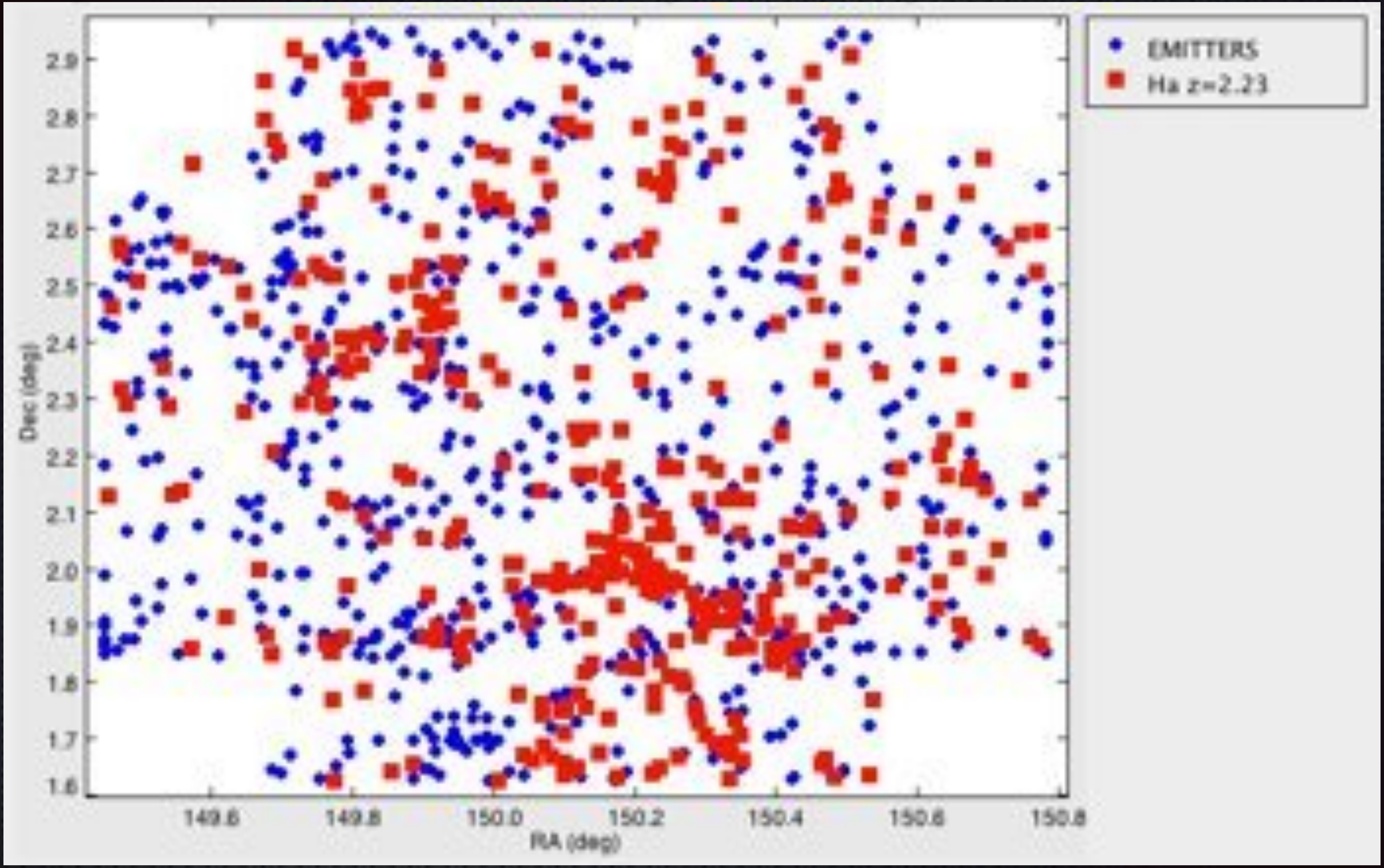


Line emitters NBK

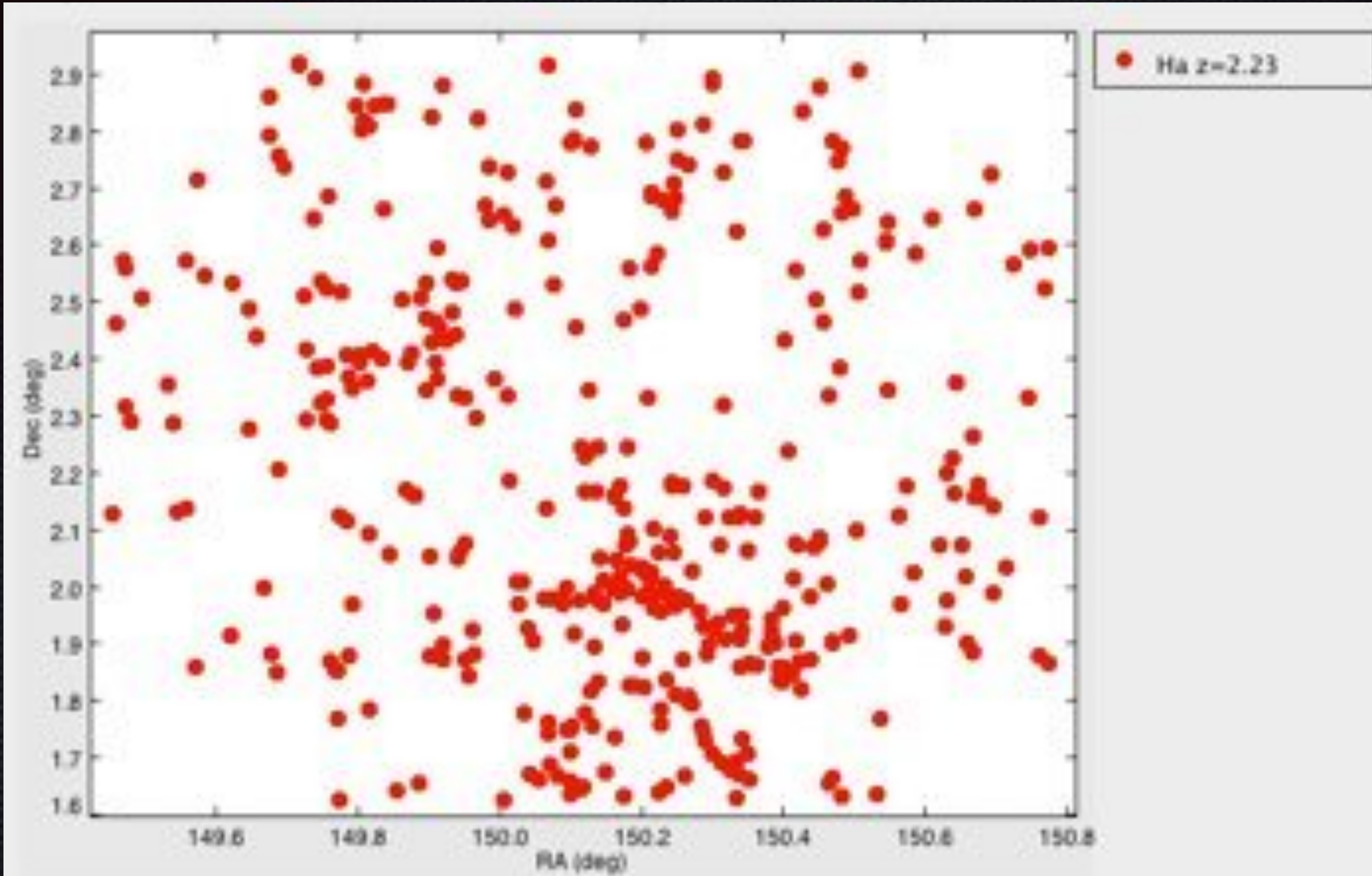




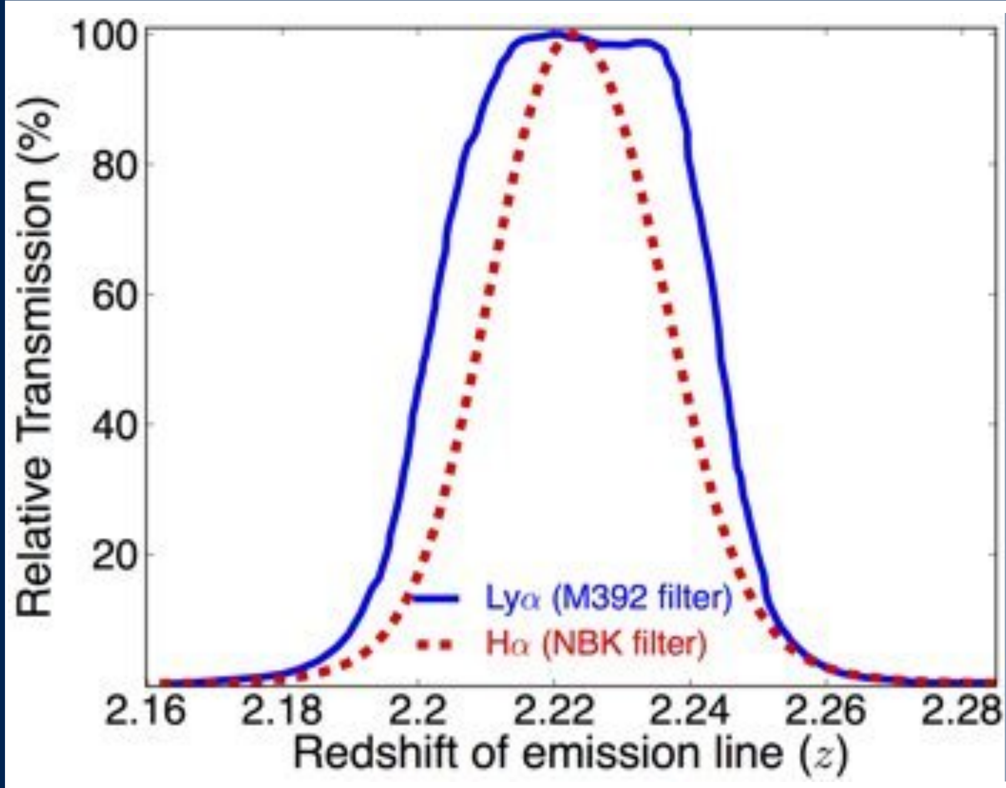
H-alpha sources: Double/triple NB + photo-zs + colours



H-alpha sources: Double/triple NB + photo-zs + colours

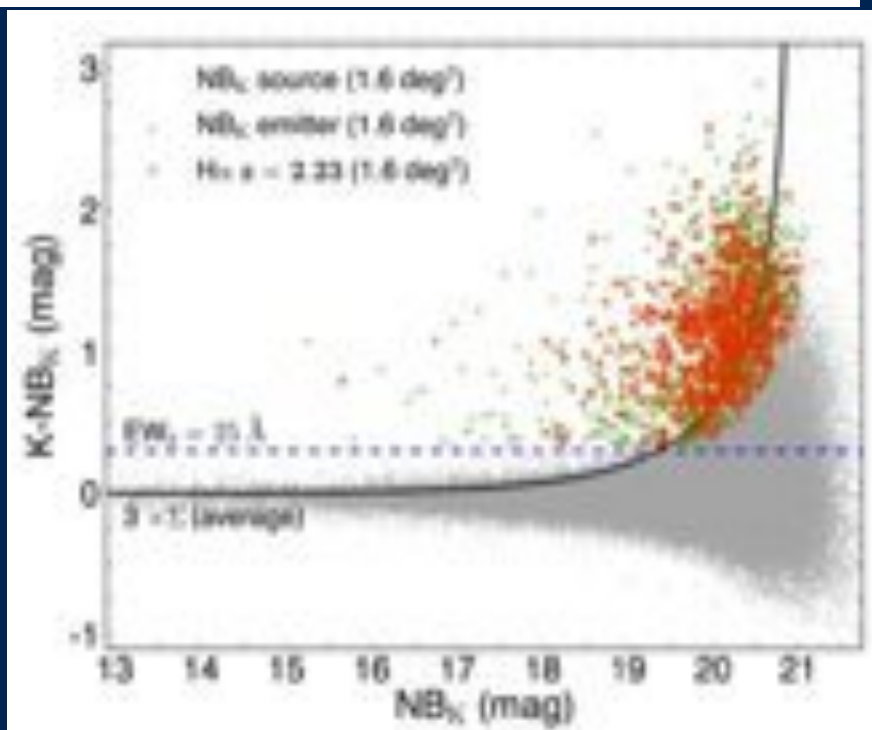


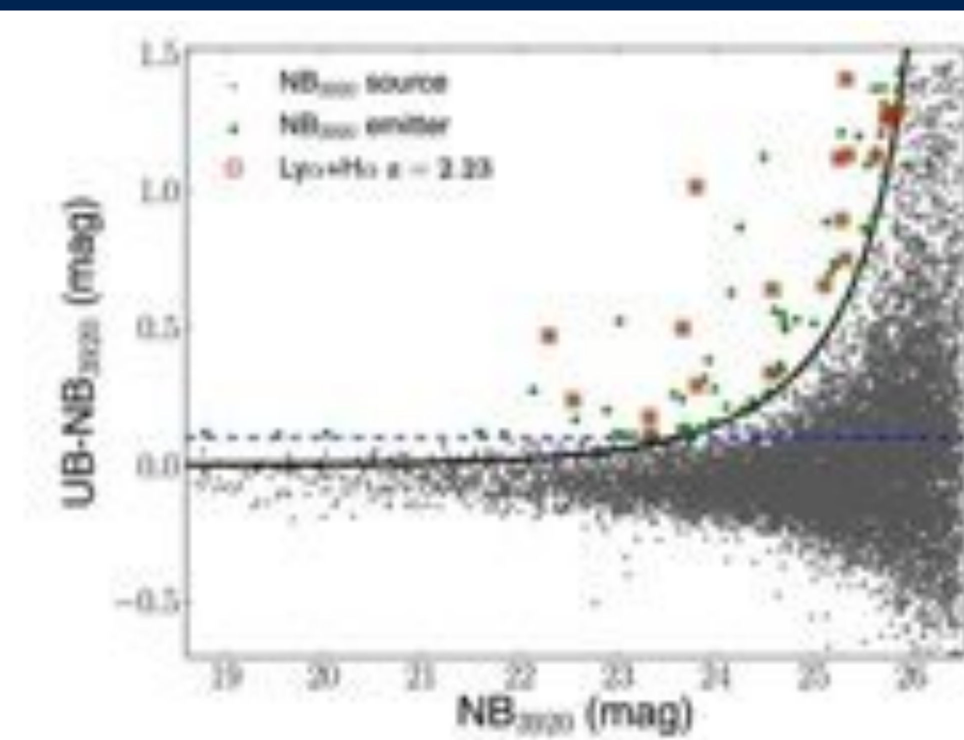
Clean, complete "slices" of 1000s of H-alpha selected galaxies in the last 11 Gyrs



Calibrate Lyα at z=2.23

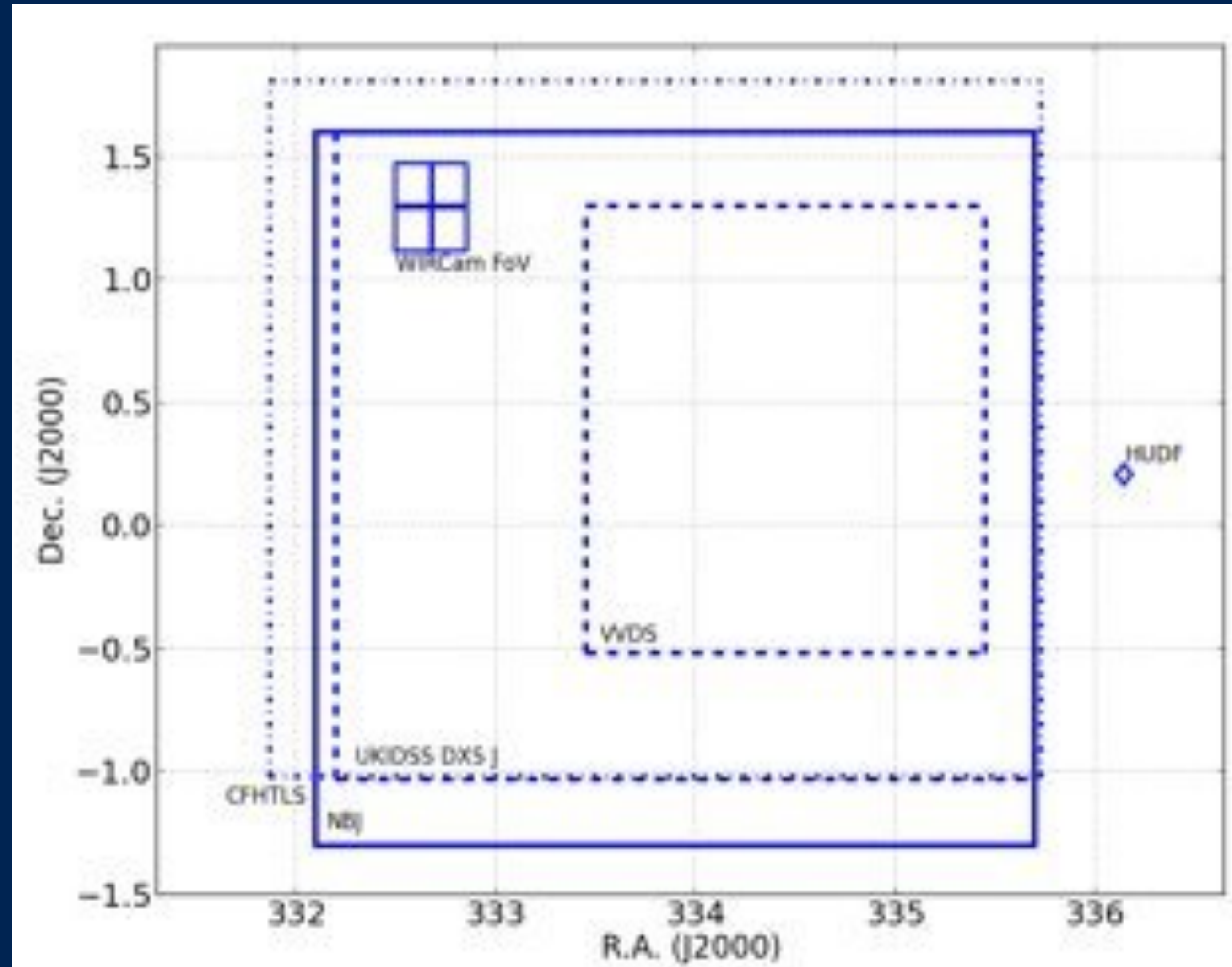
5 deg² deep double-blind matched Lyα-Hα survey.
Pilot survey: INT => CFHT





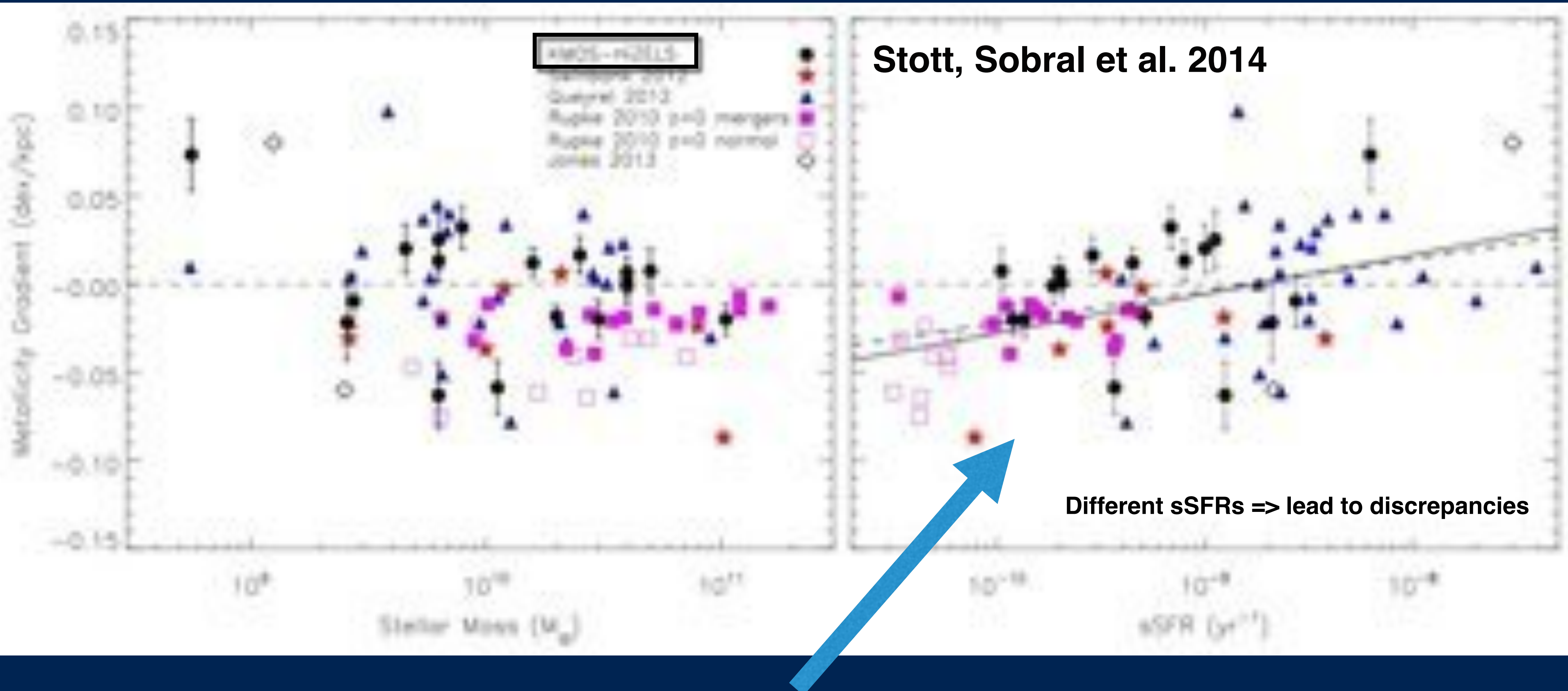
WIRCam/ LowOH2

Down to about 1Mo/yr z=0.8



10 sq deg. SA22

S+13b, Matthee+14



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)

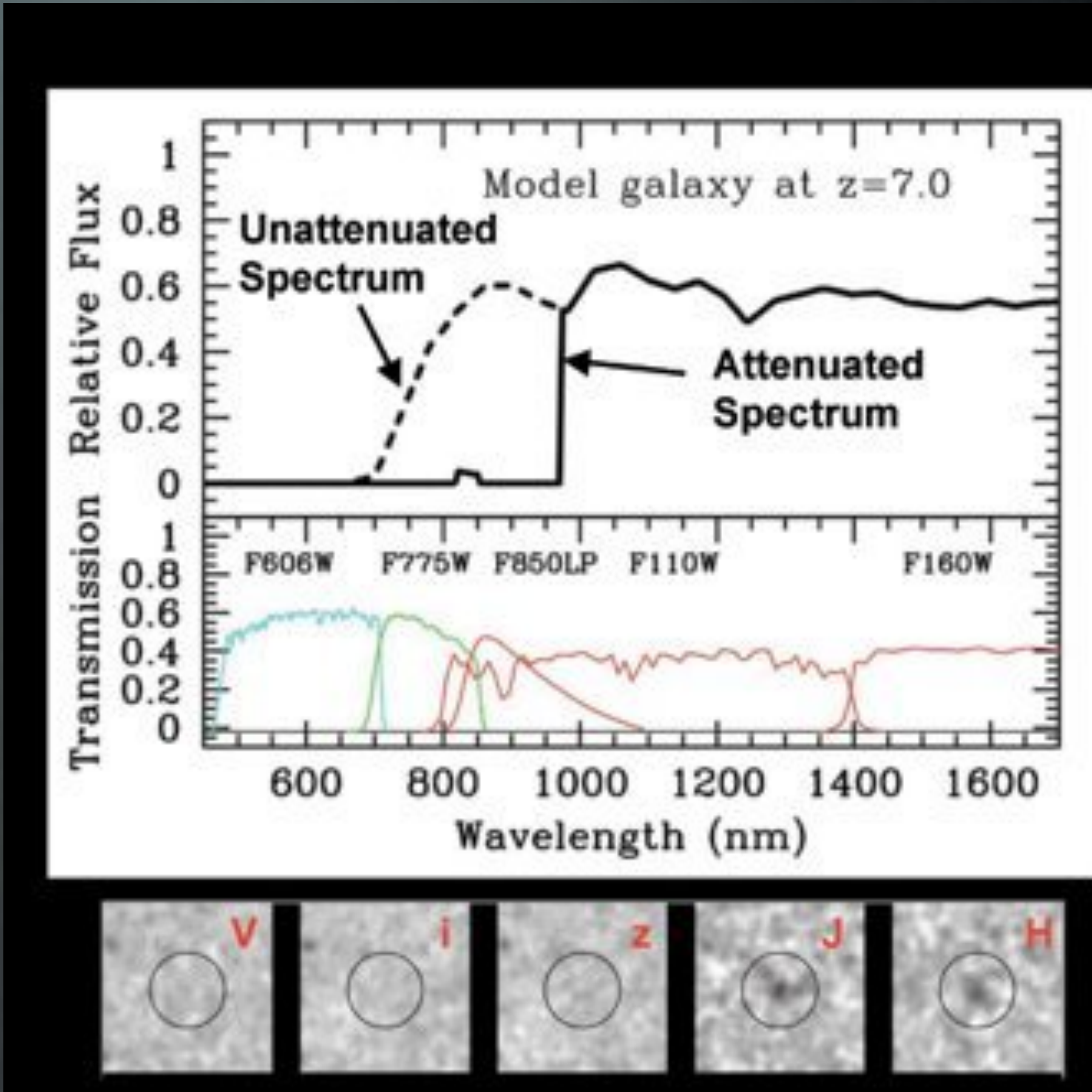
Looking for z=8.8 Lya emitters: CFHTLS + UKIDSS

- No detection in optical individual bands

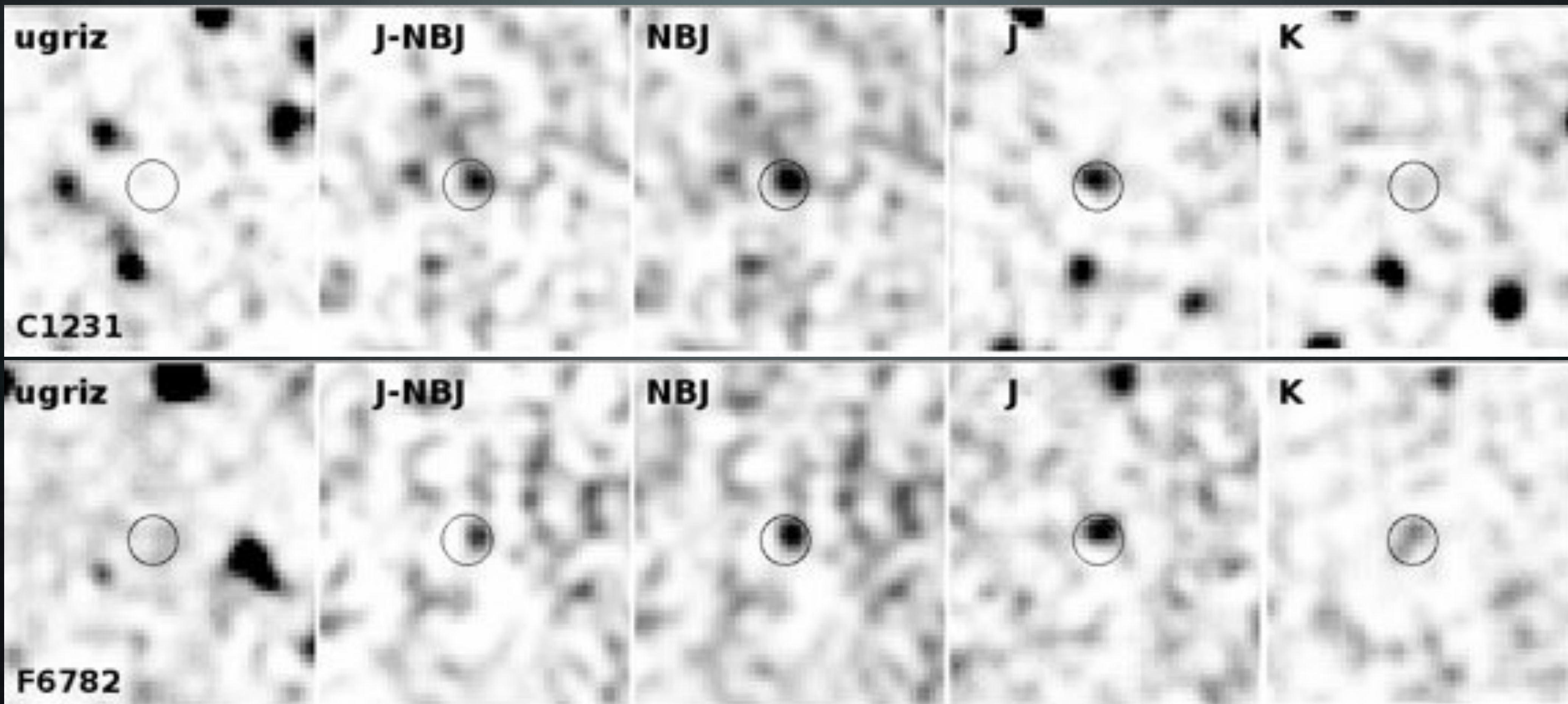
- No detection in CFHTLS optical stack

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

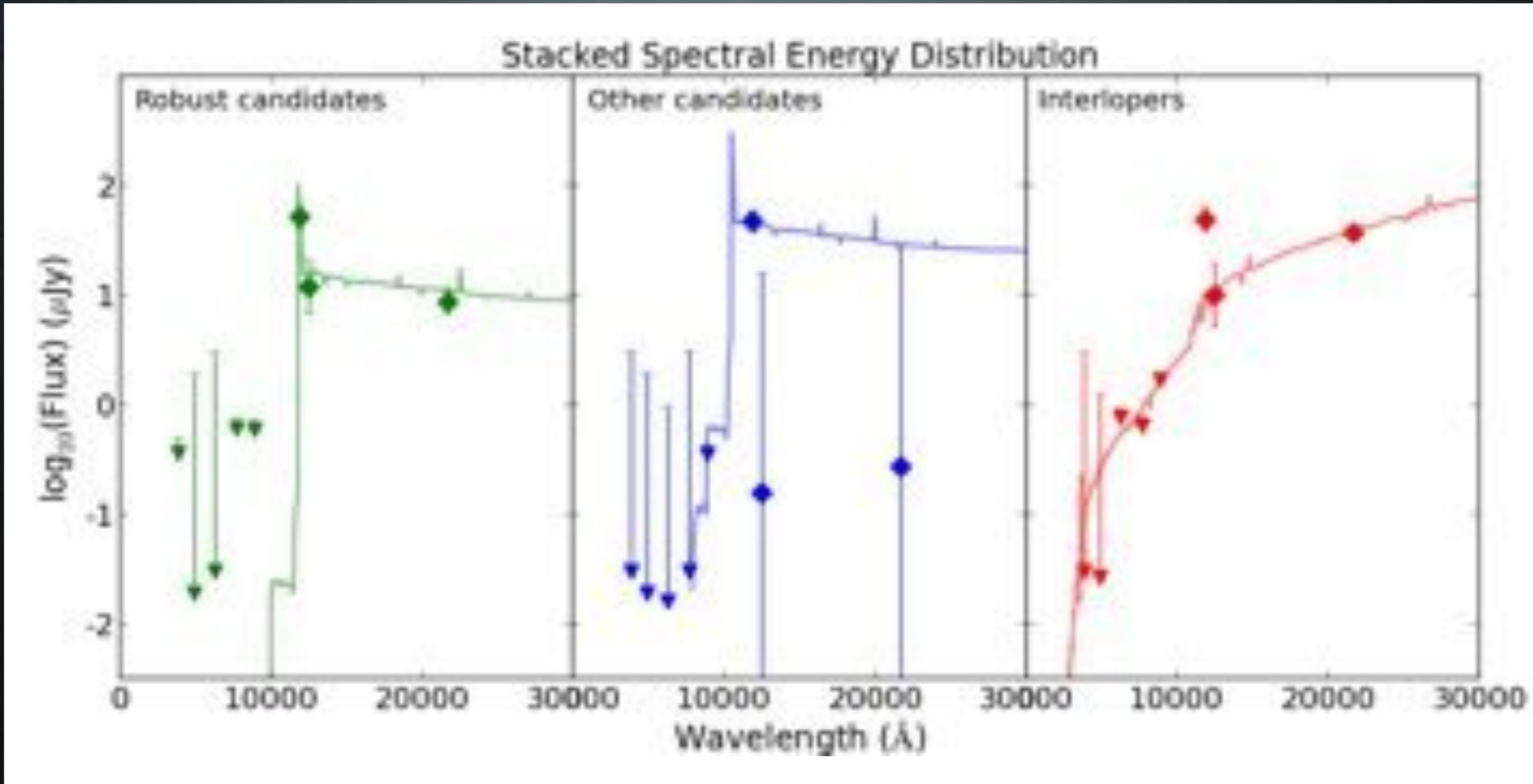
- Results in 6 good candidates



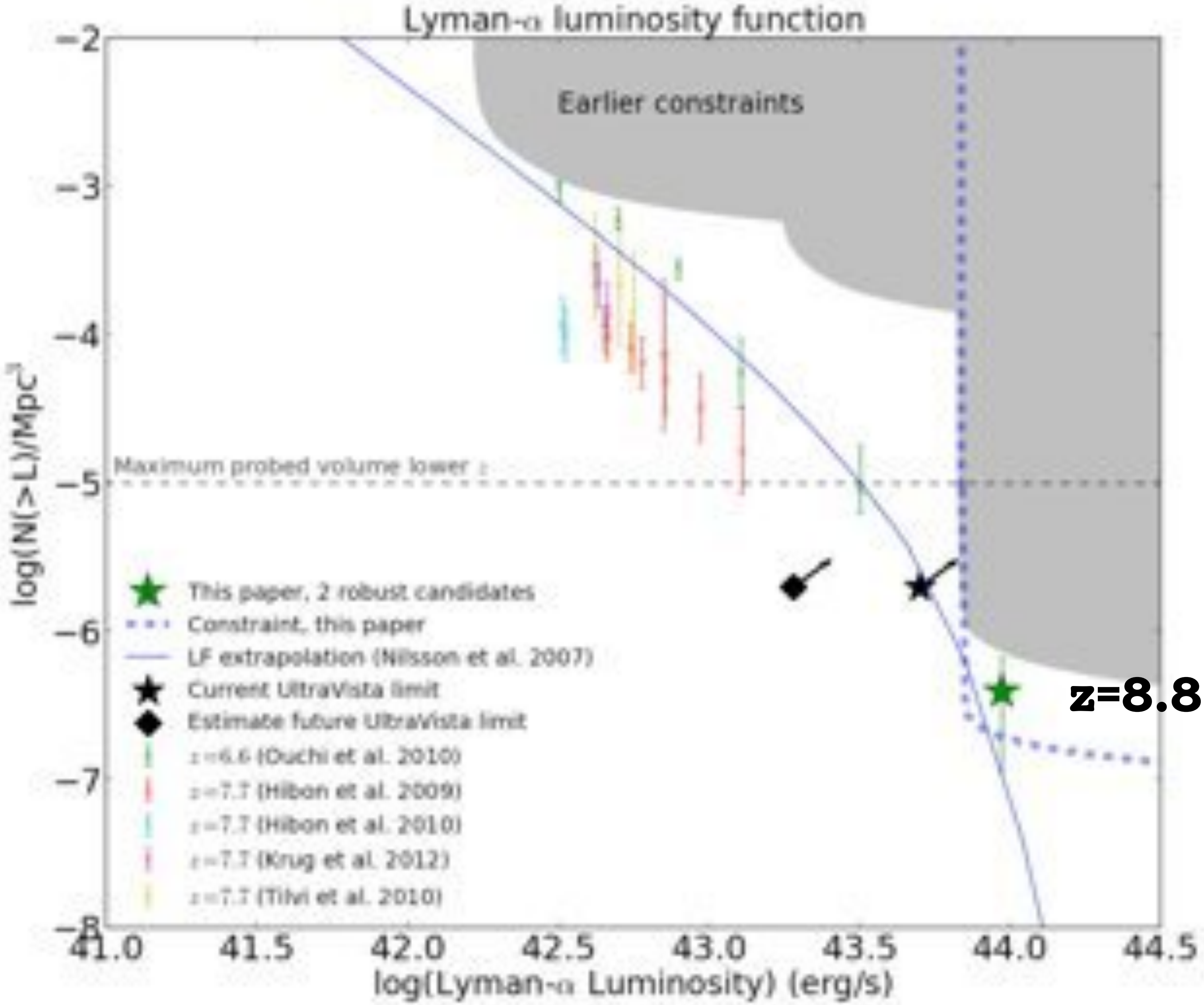
2 out of 6 Lyman-alpha candidates z=8.8



Matthee, Sobral et al. 2014

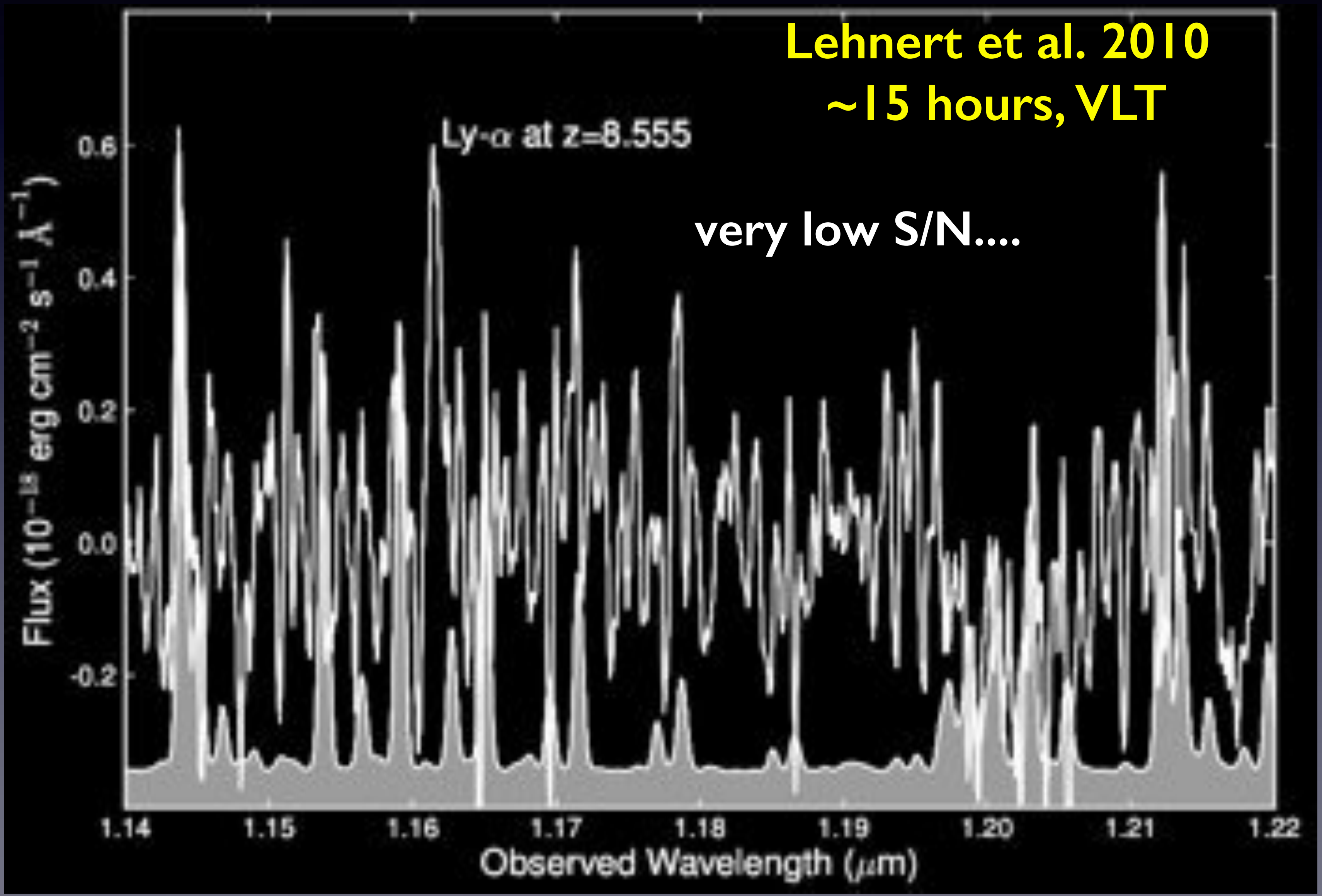

Stacked Spectral Energy Distribution
Robust candidates
Other candidates
Interlopers
log10(Flux) (μJy)
Wavelength (Å)
0
10000
20000
30000
2
1
0
-1
-2

Matthee, Sobral et al. 2014



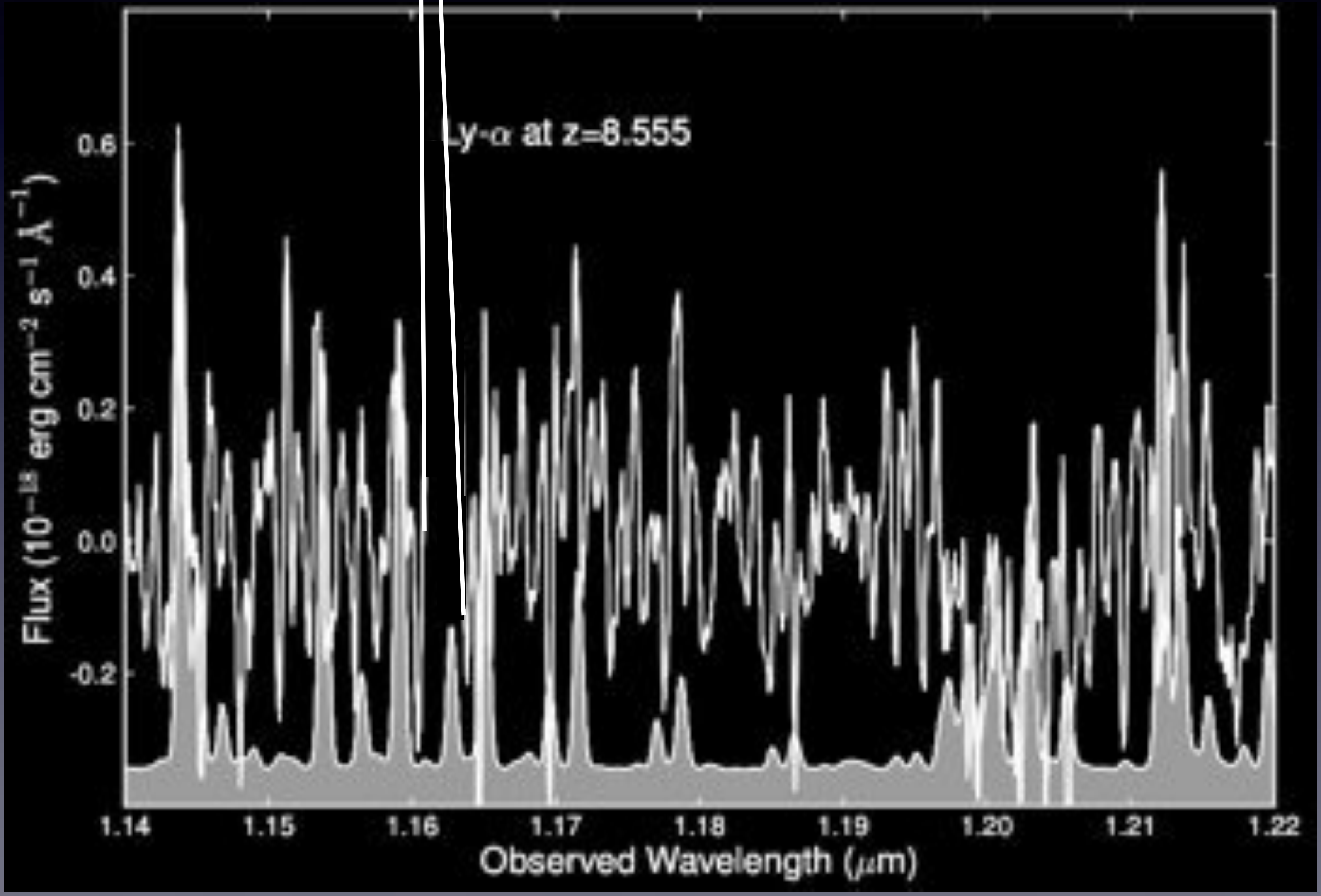
The big advantage for spectroscopic follow-up is that they will *not* look like this:

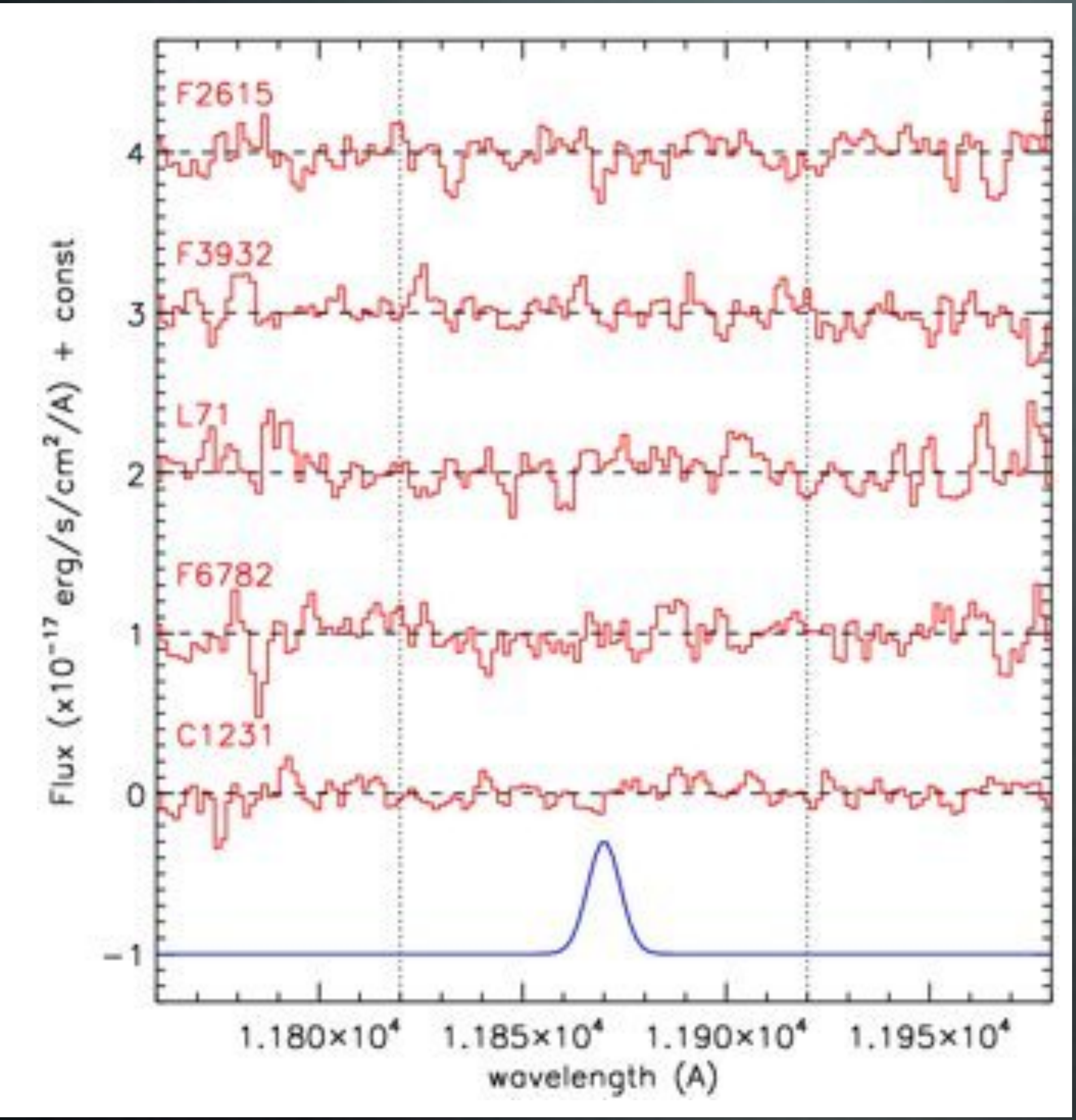
(see Bunker et al. 2013)



In ~ couple of hours

They will look like this!





SINFONI/VLT

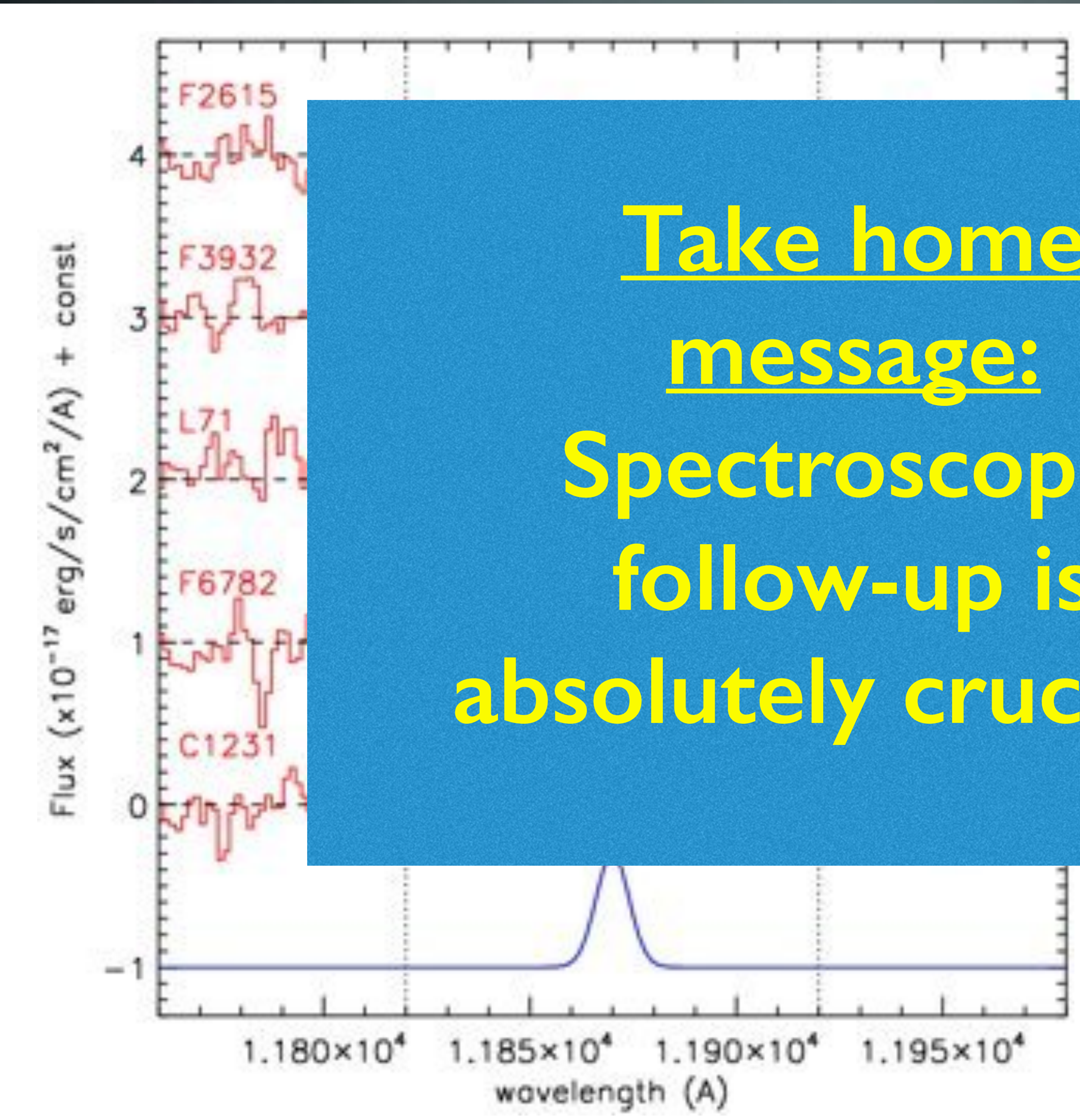
5 best candidates: 1 hour per source

All shown not to be at z=8.8

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

Matthee et al. 2014

SINFONI/VLT



Take home message:

Spectroscopic follow-up is absolutely crucial!!!

candidates:
per source

n not to be
z=8.8

w the little
up of other
idates” is
g the same
(e.g. Faisst et al. 2014)

Matthee et al. 2014

Conclusions:

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: factor ~13x**

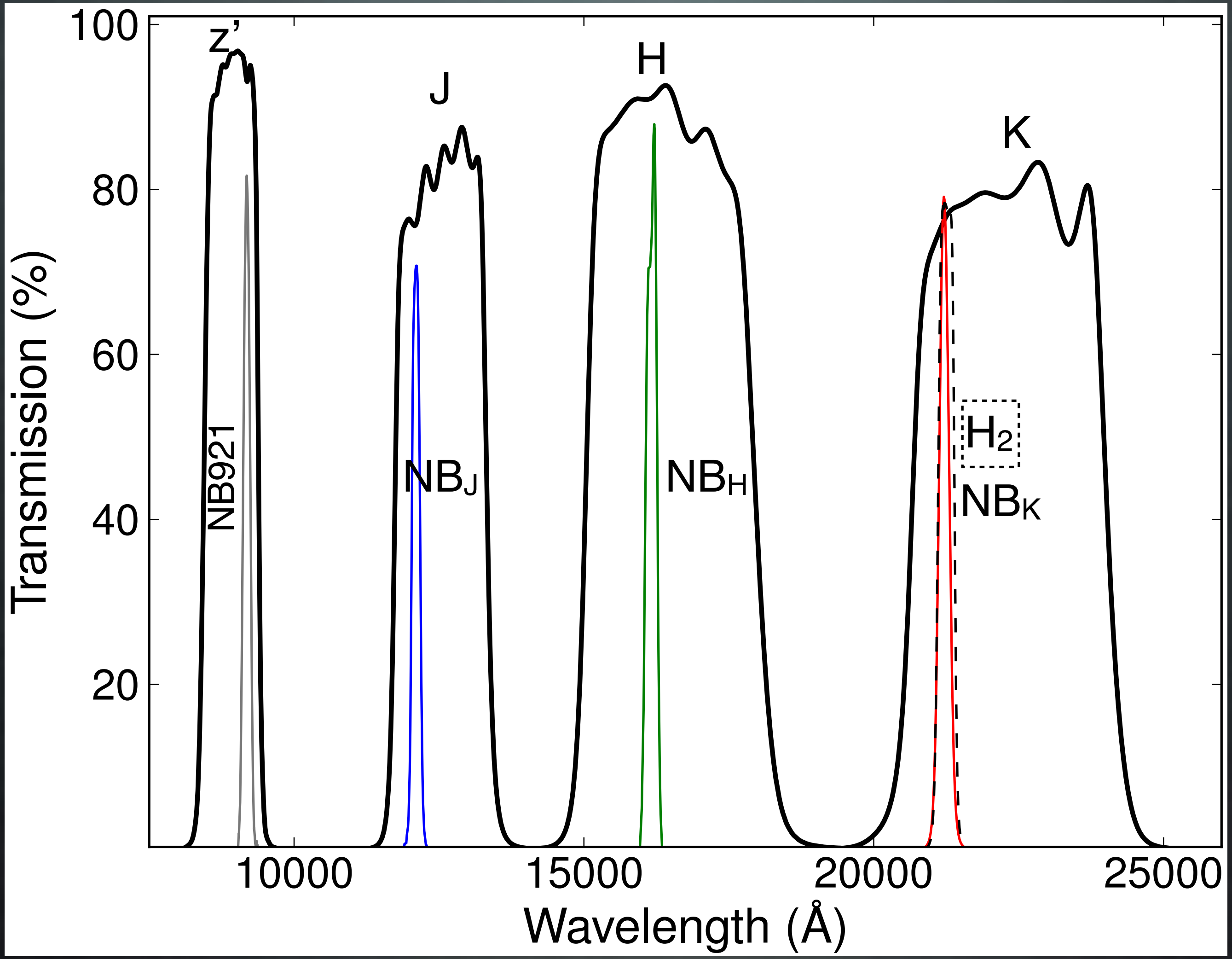
- **SINFONI w/ AO: Star-forming galaxies since z=2.23: ~75% "disks", negative metallicity gradients, many show clumps**

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

Most of claimed "evolution" with redshift is driven by:

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

Filters combined to improve selection: double/triple line detections

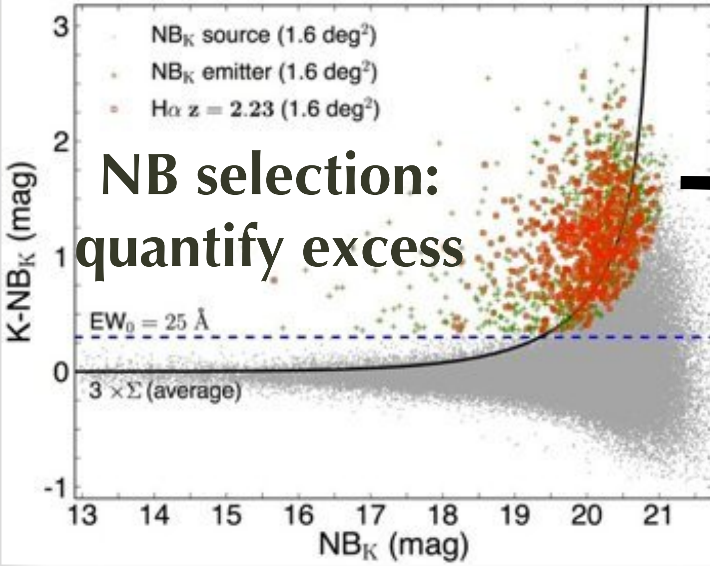


z=2.23 : **Lya** (NBm*) [OII] (NBJ), [OIII] (NBH), Hα (NBK)

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

z=0.84 : [OIII] (NB921), Hα (NBJ)

Source extraction



NB selection: quantify excess

Potential line emitters

Which emission line?

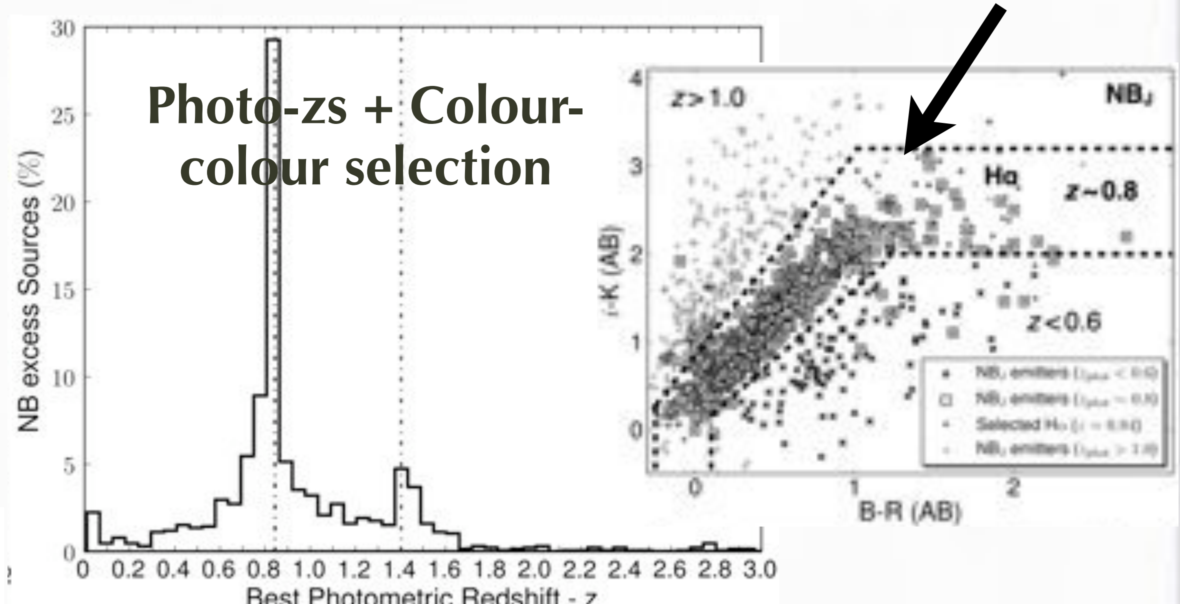
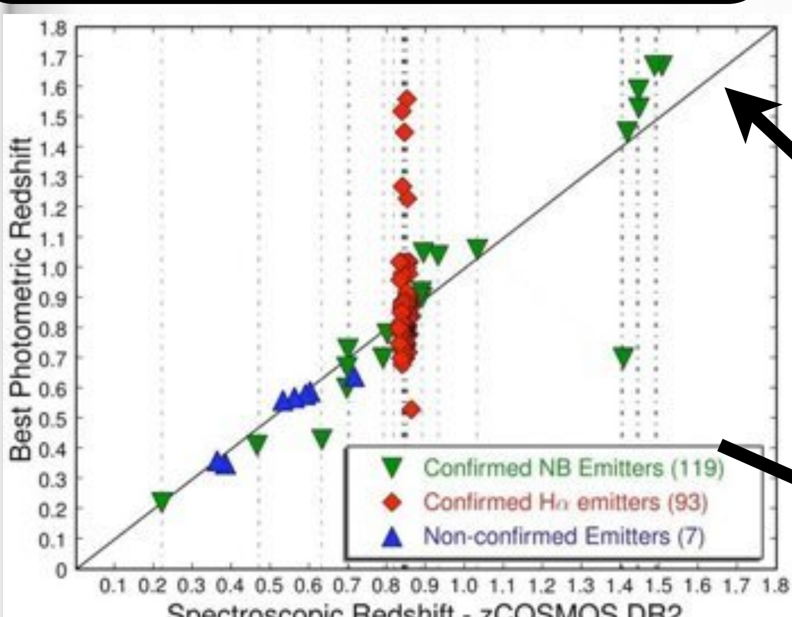


Photo-zs + Colour-colour selection

Spectro-z confirmation

Double-line confirmation



Select Hα emitters

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

Observations

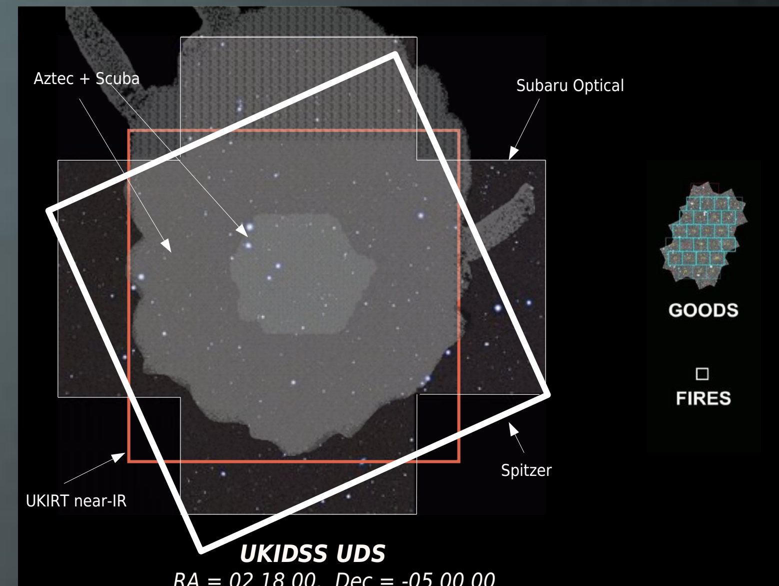
COSMOS + UDS

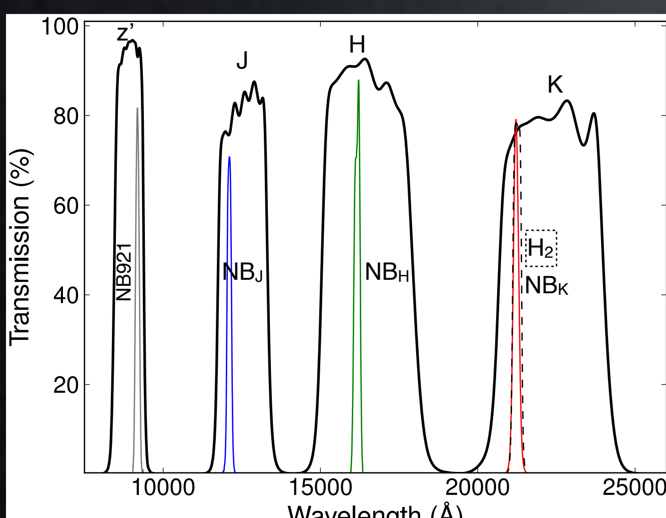
2 deg^2

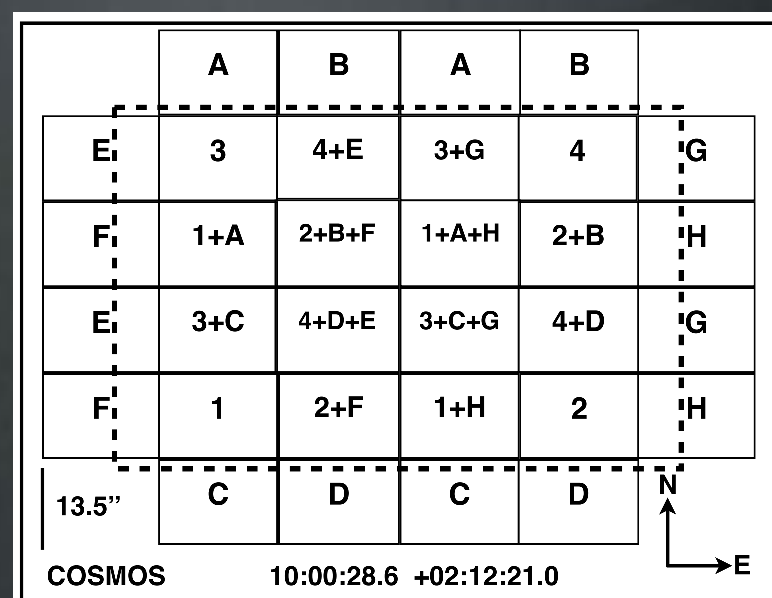
UKIRT/WFCAM: 25 nights

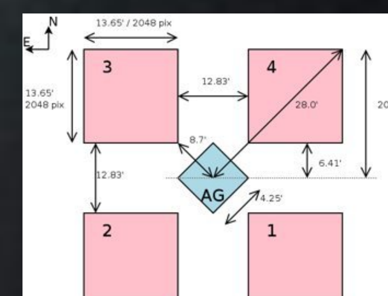
VLT/HAWK-I: 3 nights

Subaru/Suprime-cam: 5 nights

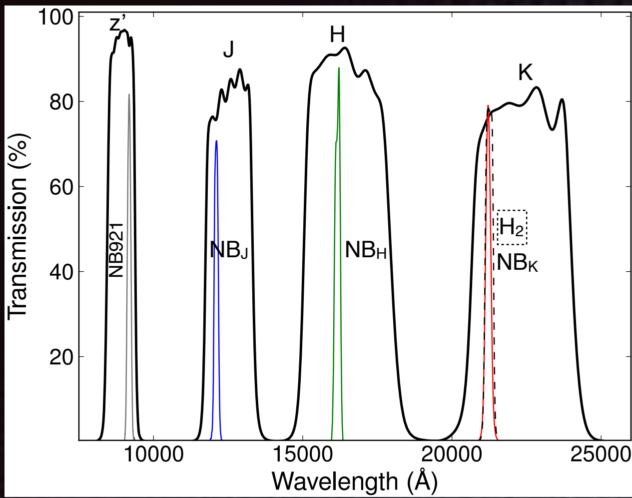








Sobral et al. 2013



NB filter	λ_c (μm)	FWHM (Å)	z Hα	Volume (Hα) (10^4 Mpc^3 deg^{-2})
NB921	0.9196	132	0.401±0.010	5.13
NB_J	1.211	150	0.845±0.015	14.65
NB_H	1.617	211	1.466±0.016	33.96
NB_K	2.121	210	2.231±0.016	38.31
HAWK-I H_2	2.125	300	2.237±0.023	54.70

~16 kpc apertures z=0.4-2.23

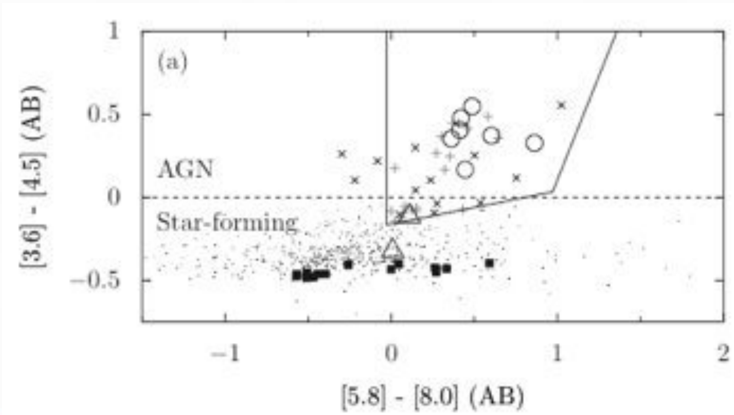
Redshift	Limit SFR	Volumes (UDS + COSMOS)
0.401±0.010	0.01	~1x10^5 Mpc^3
0.845±0.015	1.5	~2x10^5 Mpc^3
1.466±0.016	3.0	~8x10^5 Mpc^3
2.231±0.016	3.5	~7x10^5 Mpc^3

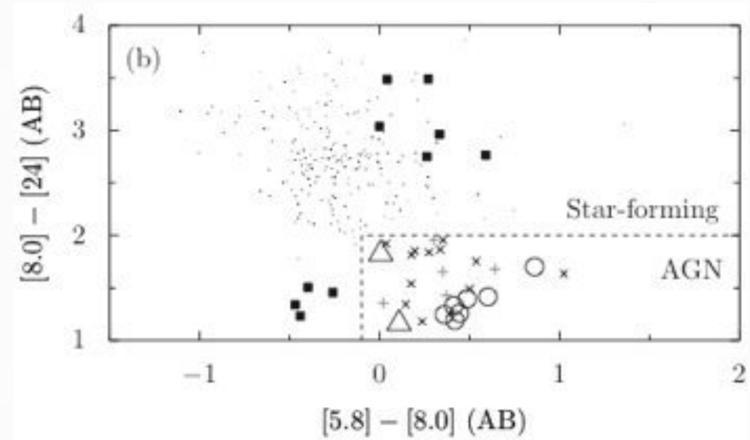
z=0.4-2.23

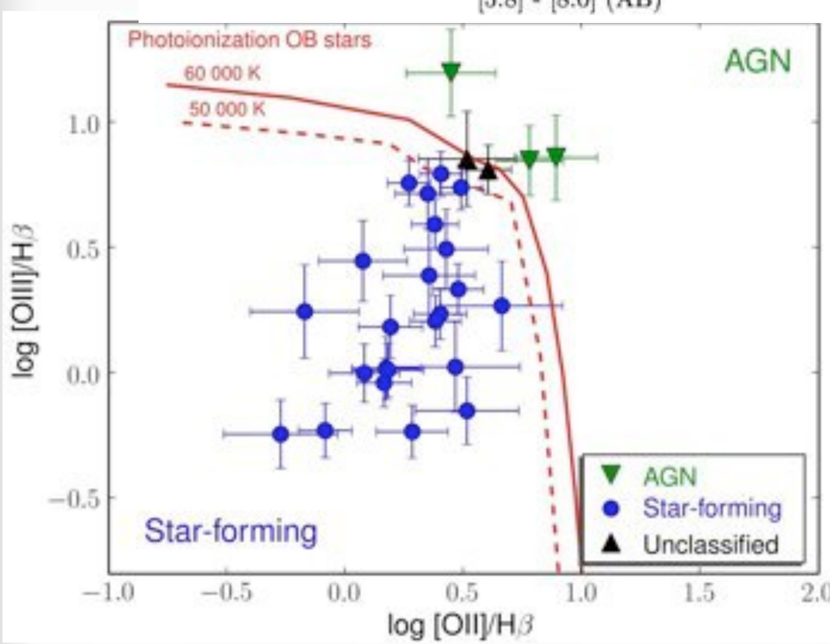
$\Sigma > 3$, $EW_{(Ha+[NII])} > 25$ Å

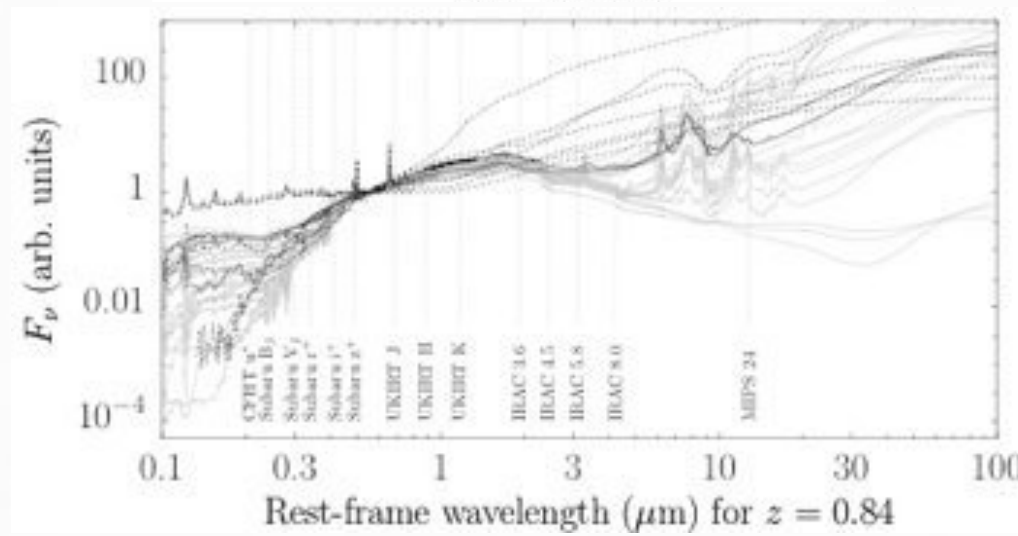
AGN

Garn et al. 2010

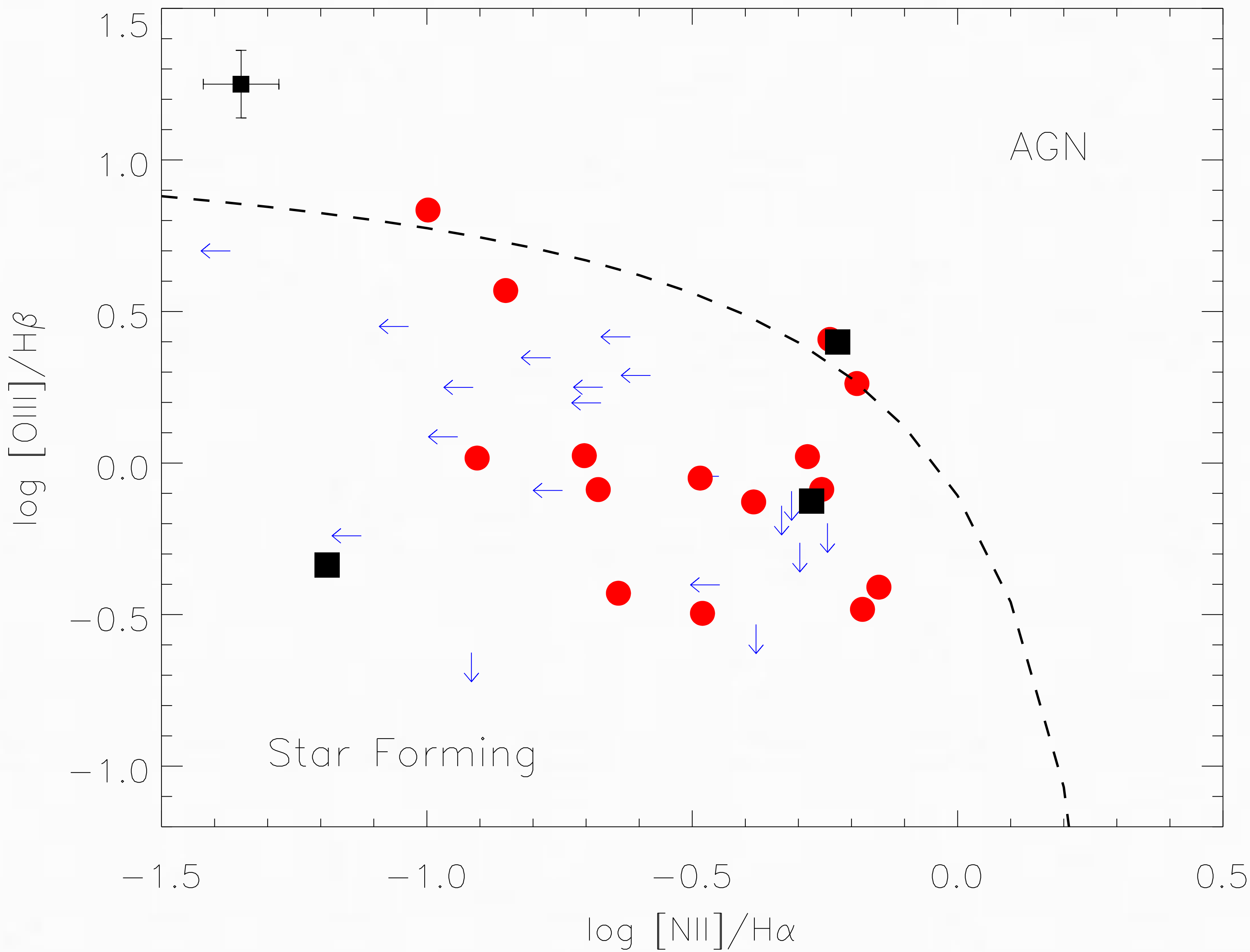






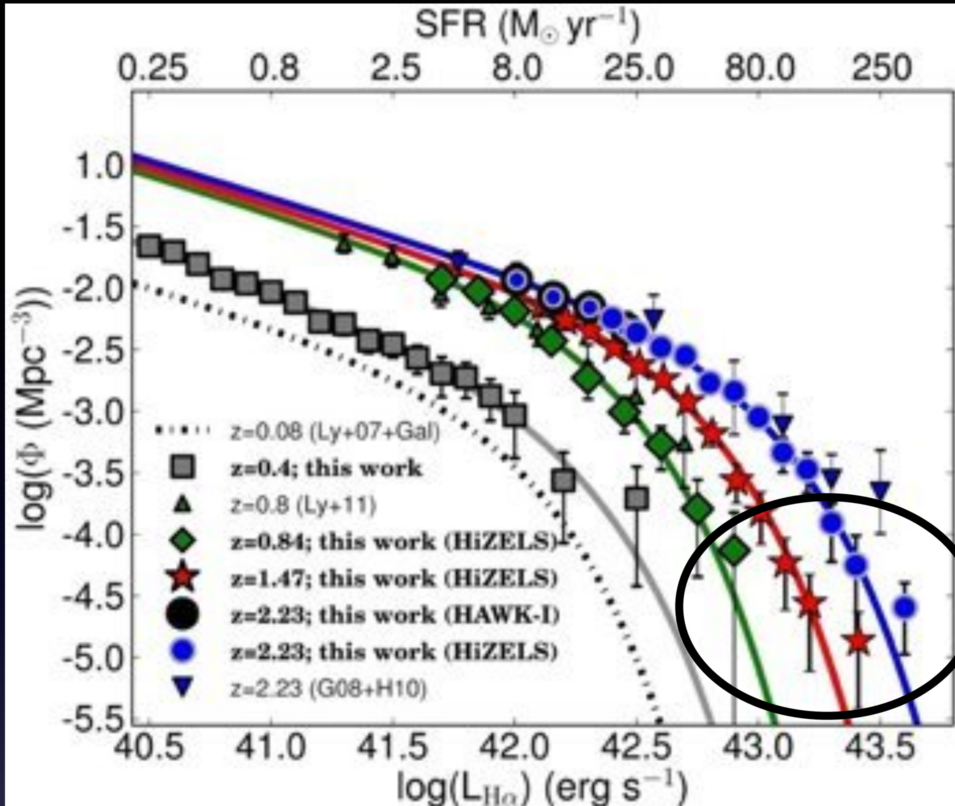


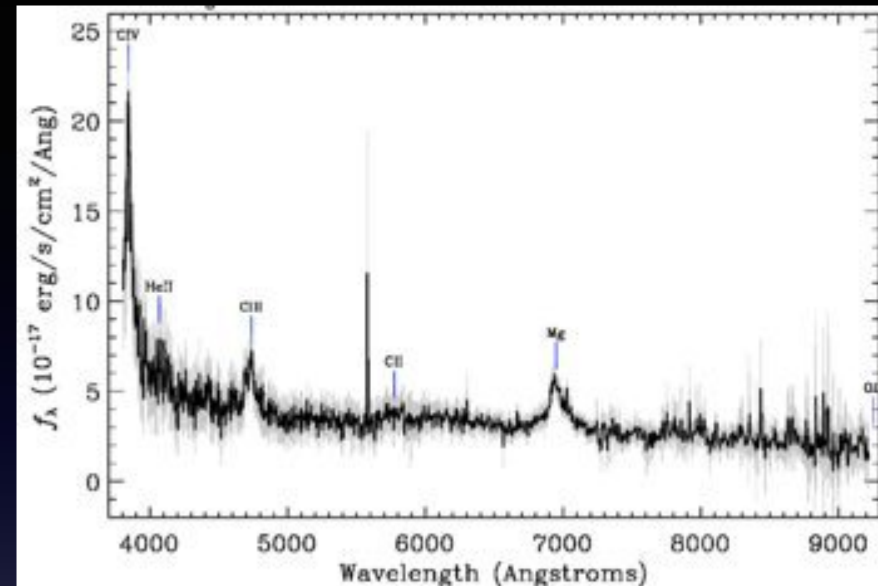
- **Emission-line ratios (optical spectroscopy)+ X-rays+ radio+ mid-infrared colours+ SED fitting: ~10% of Hα emitters at z=0.84 are AGN.**

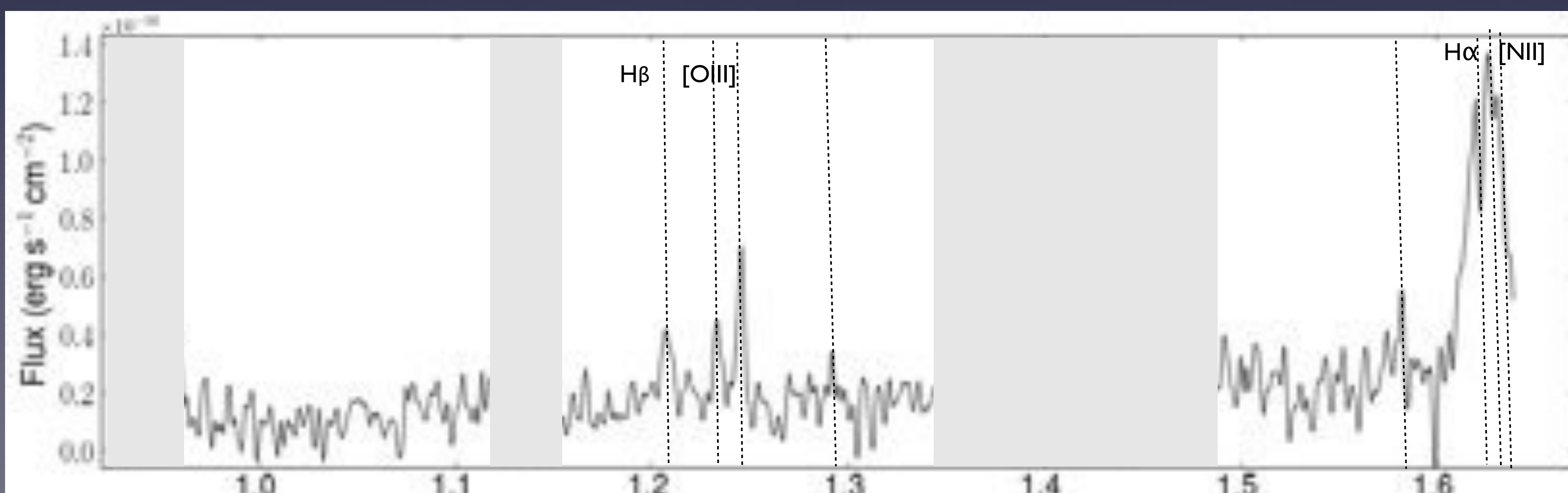


AGN
Star Forming
log [OIII]/Hβ
log [NII]/Hα
1.5
1.0
0.5
0.0
−0.5
−1.0
−1.5
−1.0
−0.5
0.0
0.5

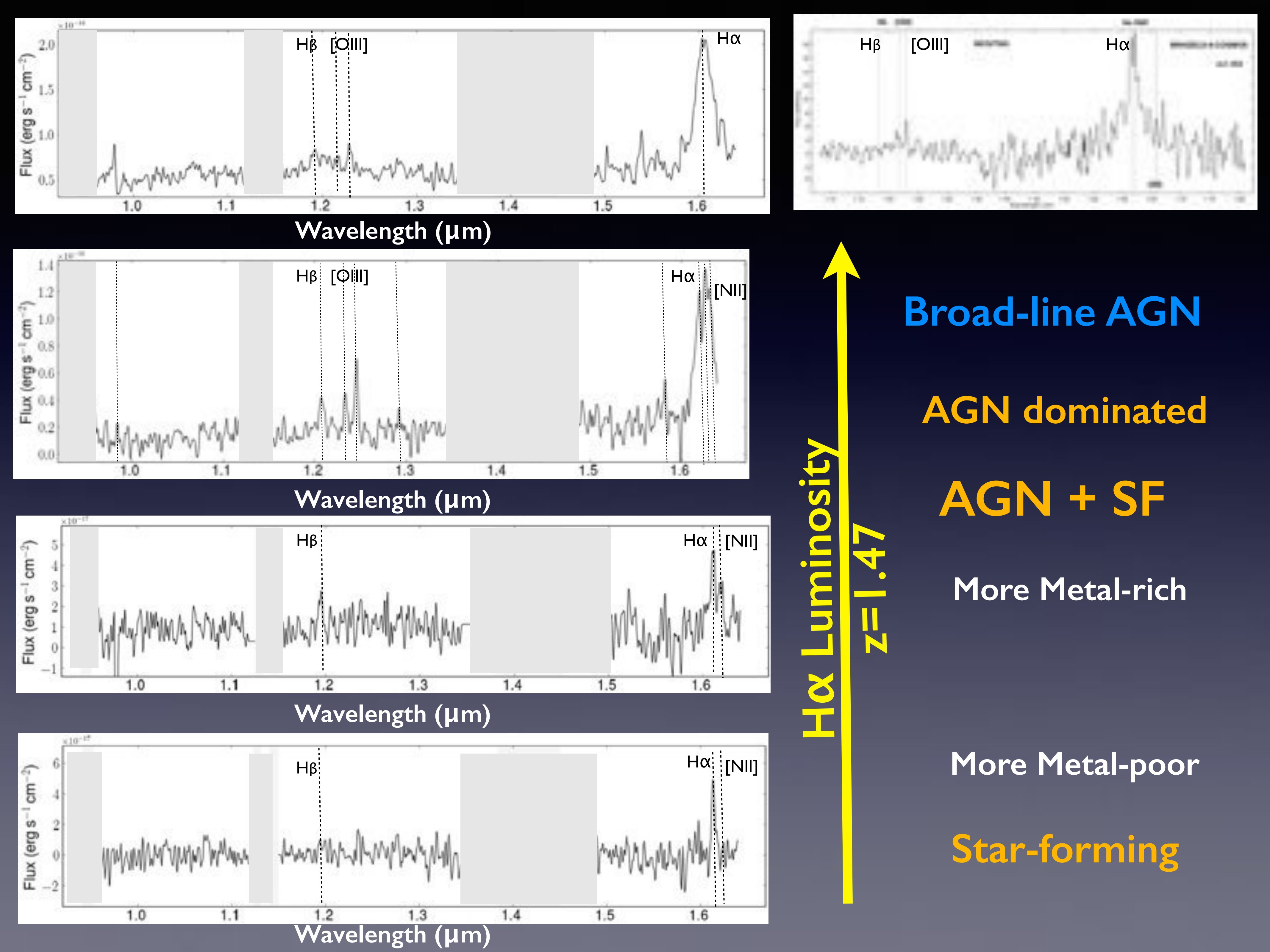
Subaru FMOS + NTT + WHT



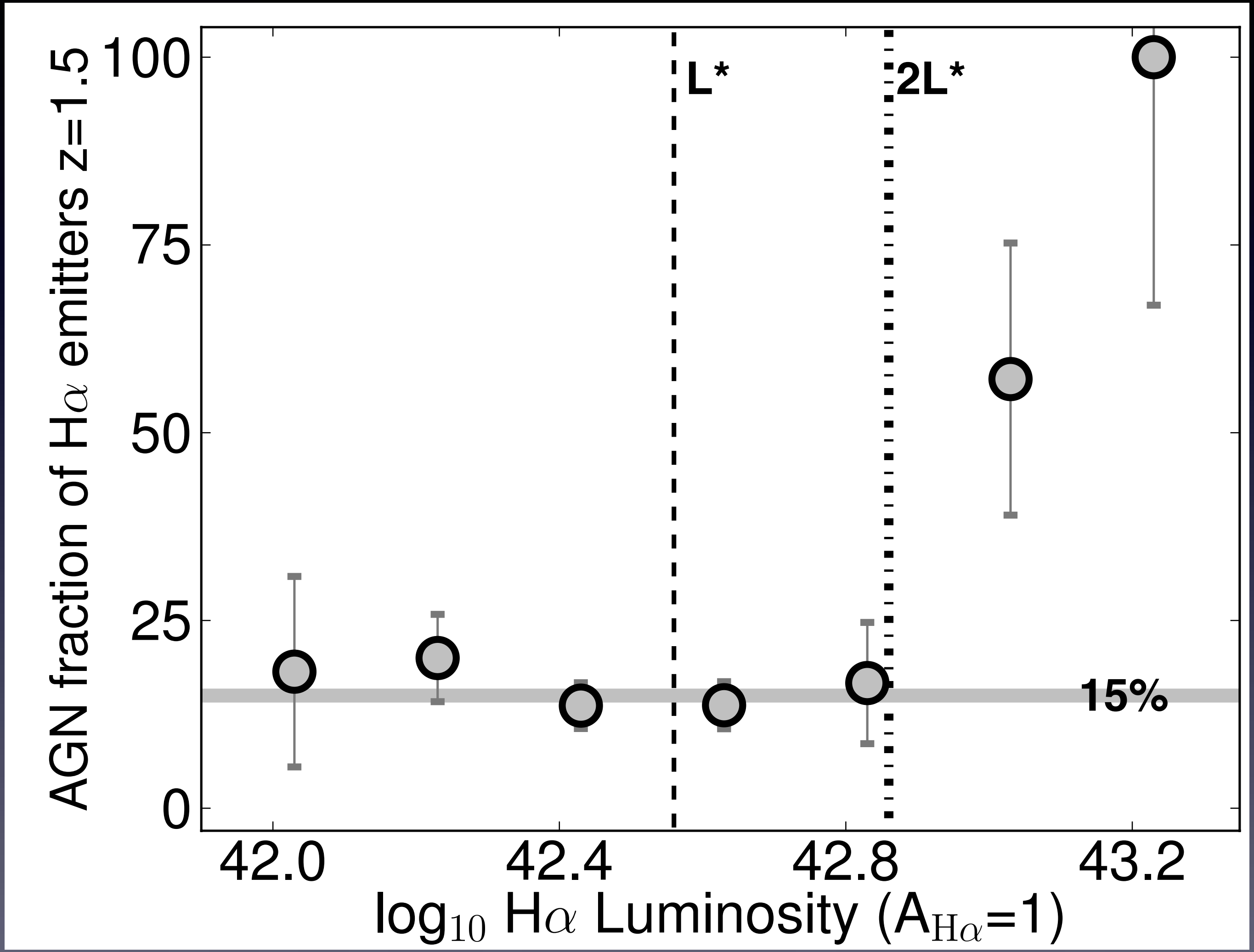




Wavelength (μm)


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]
Hα
Hα Luminosity
z=1.47
Broad-line AGN
AGN dominated
AGN + SF
More Metal-rich
More Metal-poor
Star-forming

AGN

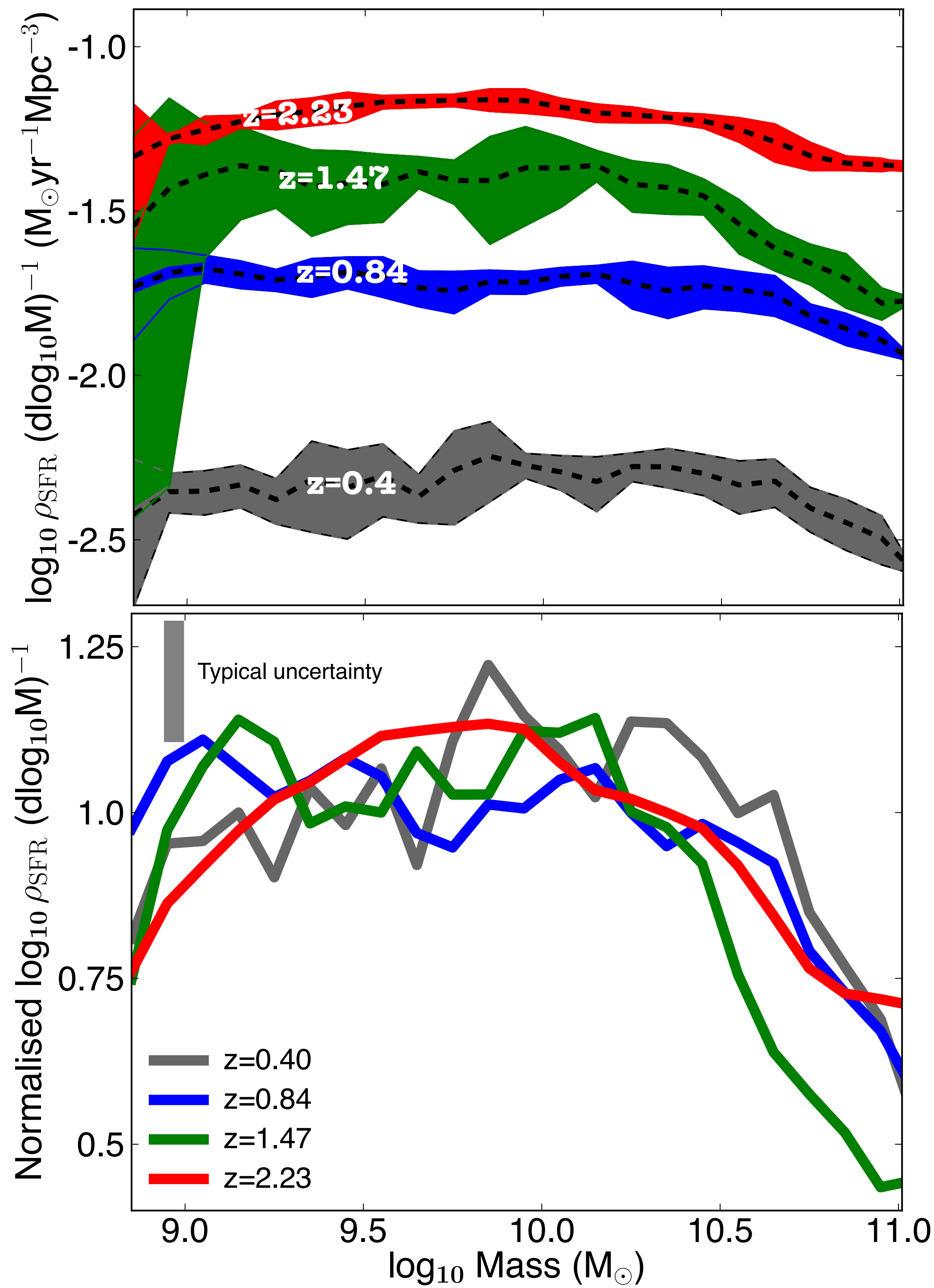


- ~10 % z~0.8
- ~15 % z~1.47
- ~ Become dominant at L>2L* (H-alpha)

S+ in prep

SFRD per dLogM

Normalised



Over the last 11 Gyrs

Decrease with time at all masses

Tentative peak per dLogM at ~10^{10} $M_\odot$ since z=2.23

Mostly no evolution apart from normalisation

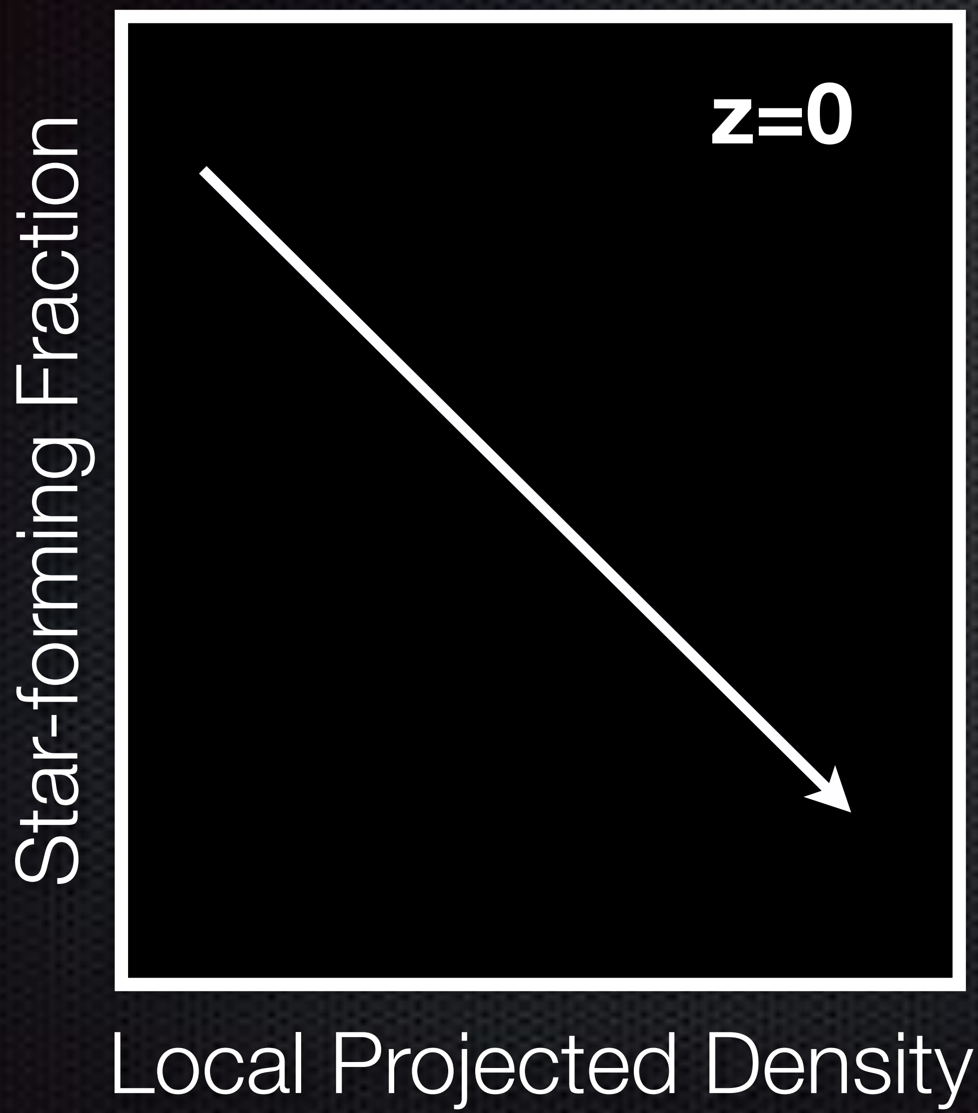
Sobral et al. (2014)

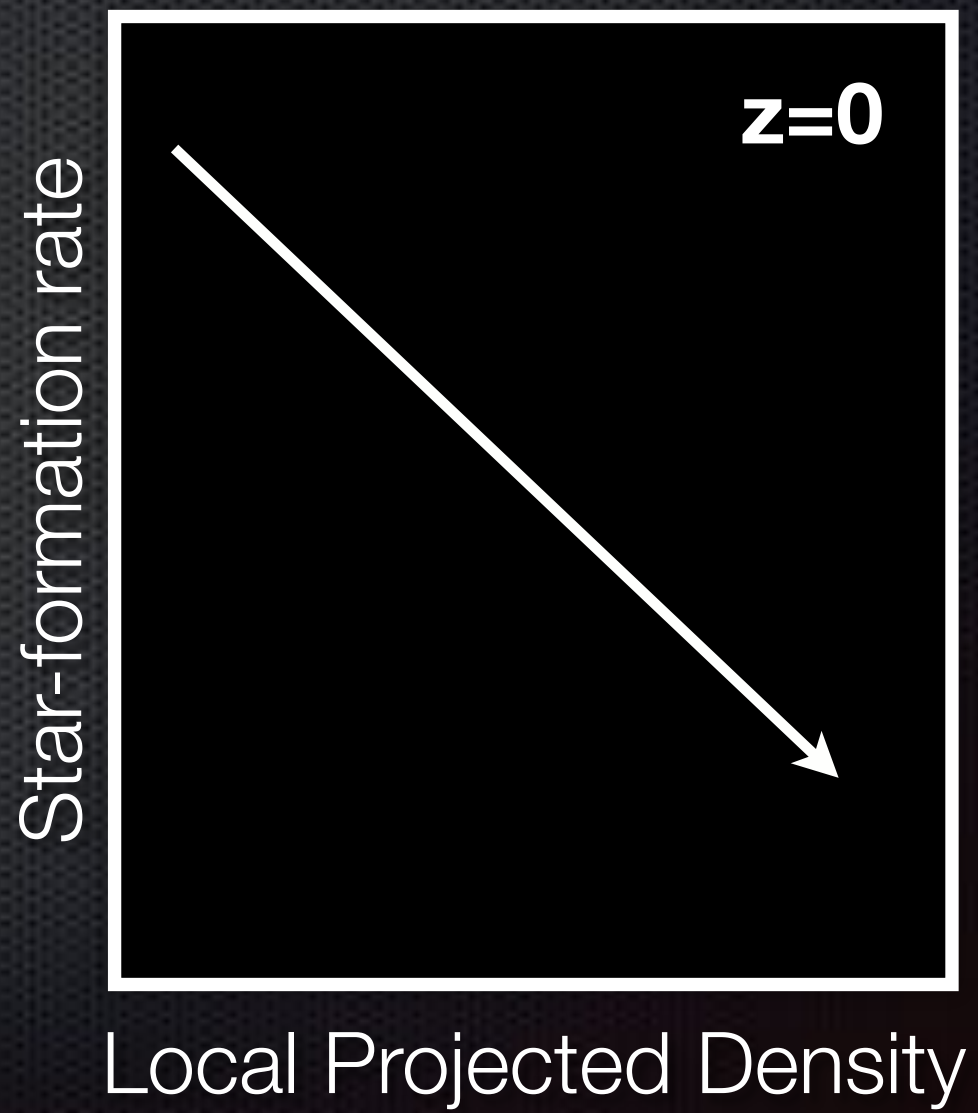
The Environment at z~1

~Field Studies

Cluster+outskirts

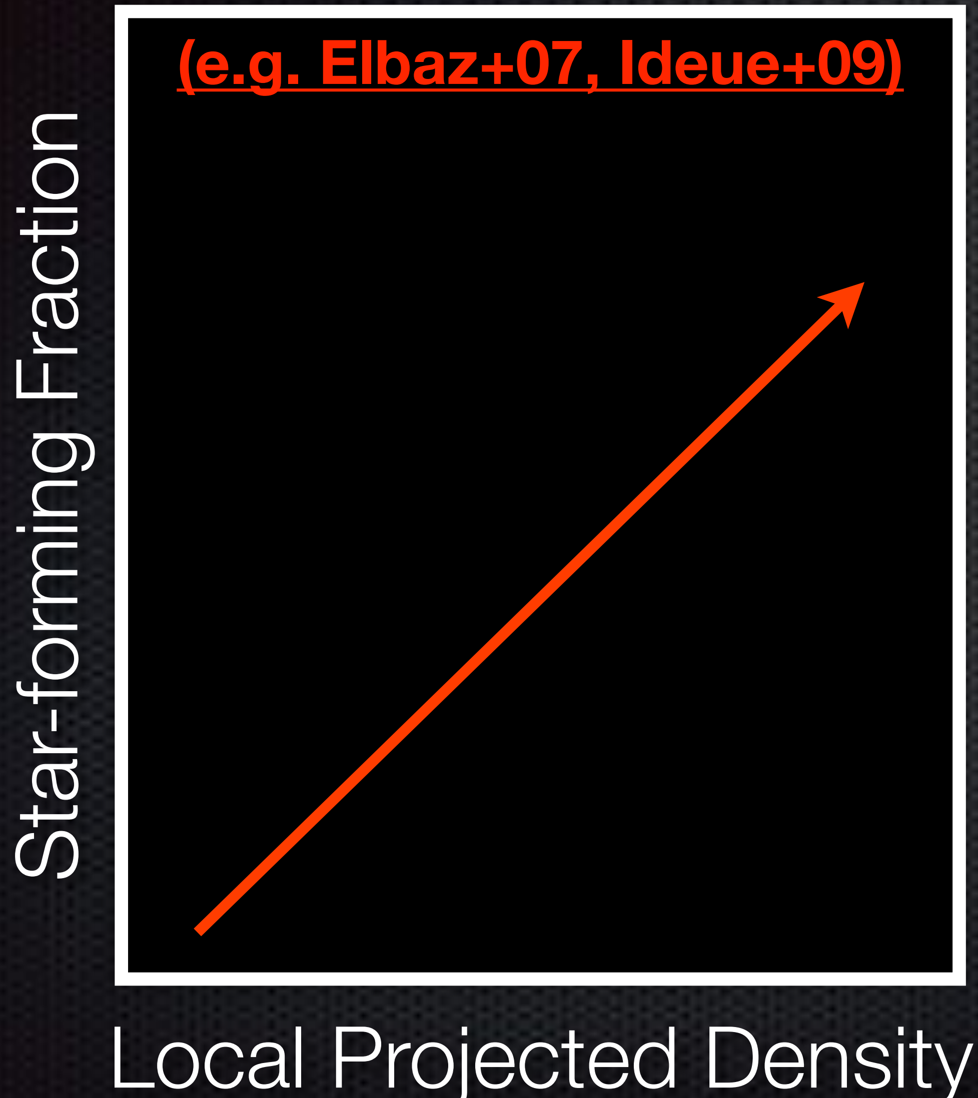
Rich Clusters

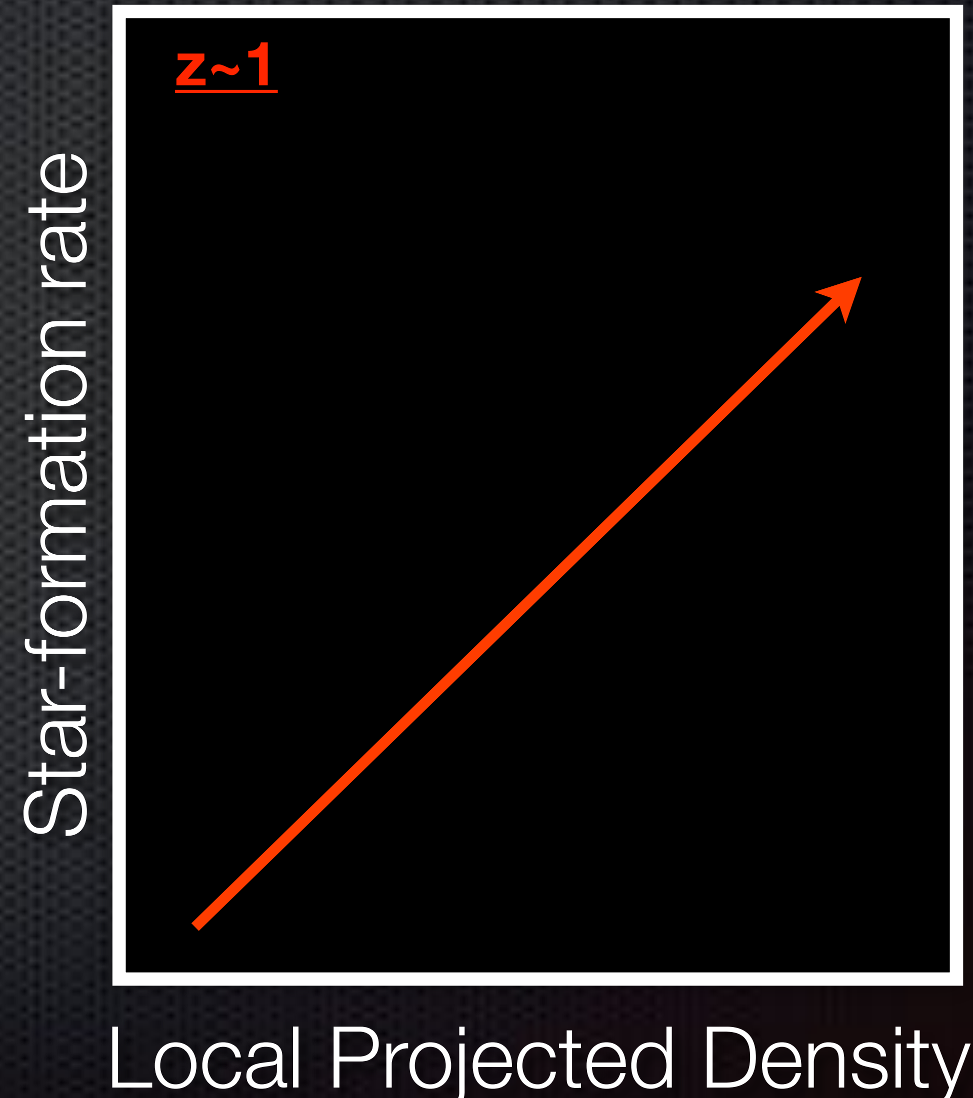




The Environment at z~1

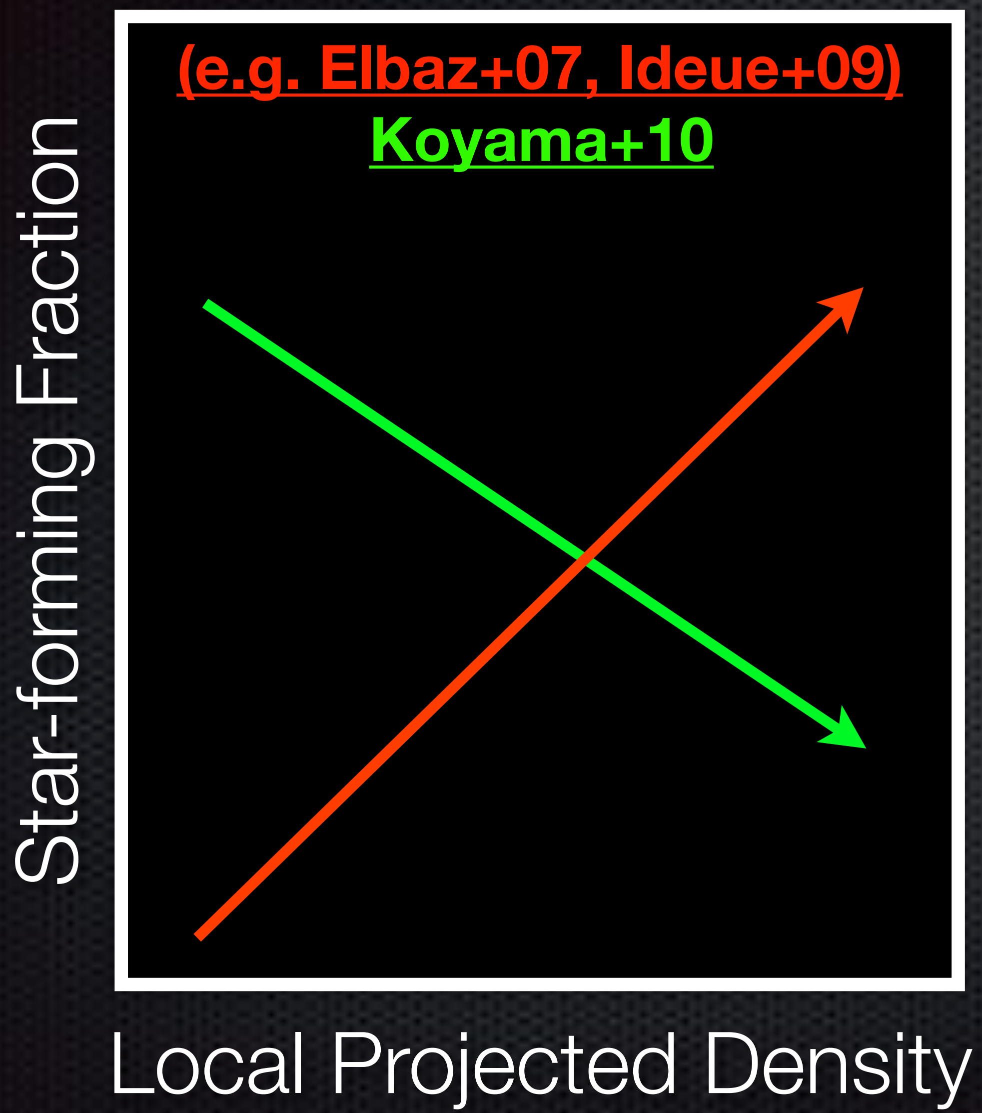
~Field Studies | **Cluster+outskirts** | **Rich Clusters**

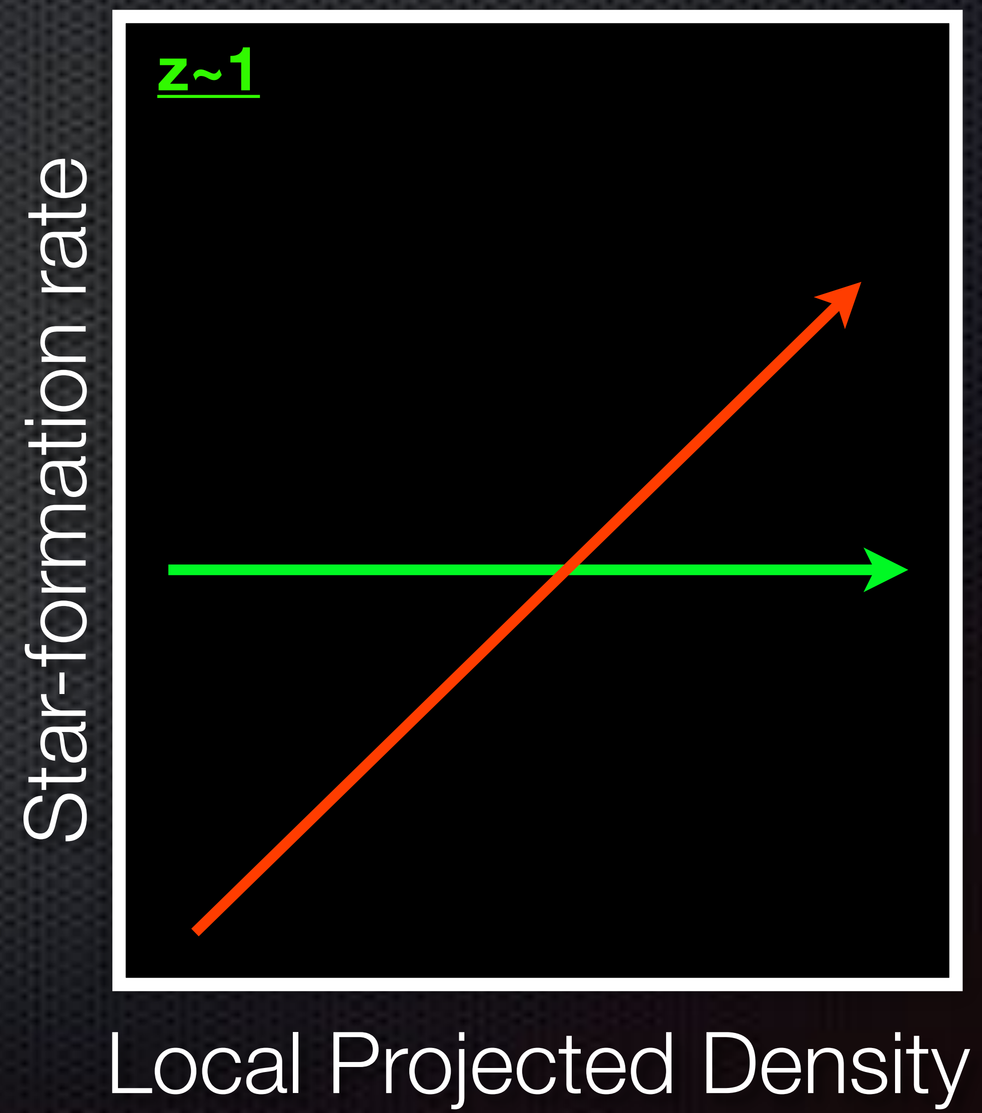




The Environment at z~1

~Field Studies | Cluster+outskirts | Rich Clusters

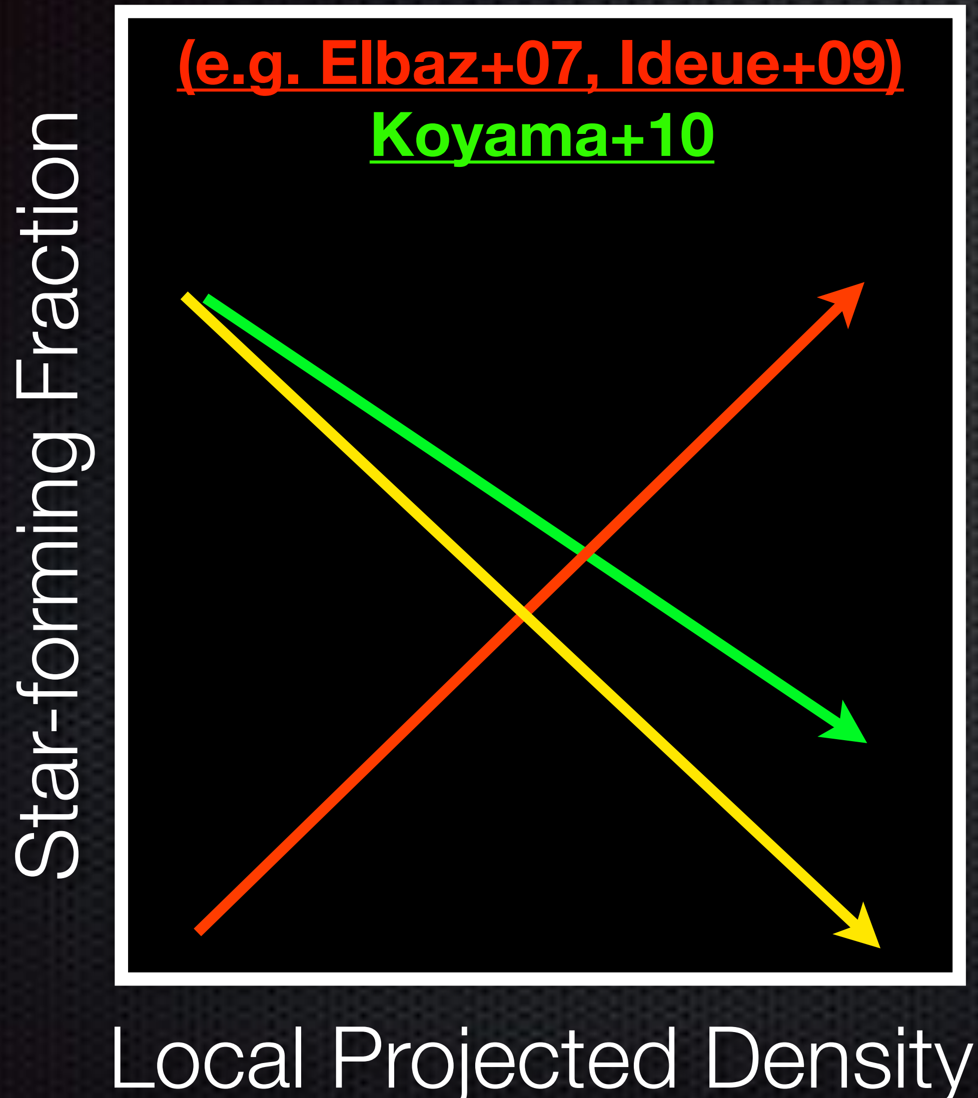


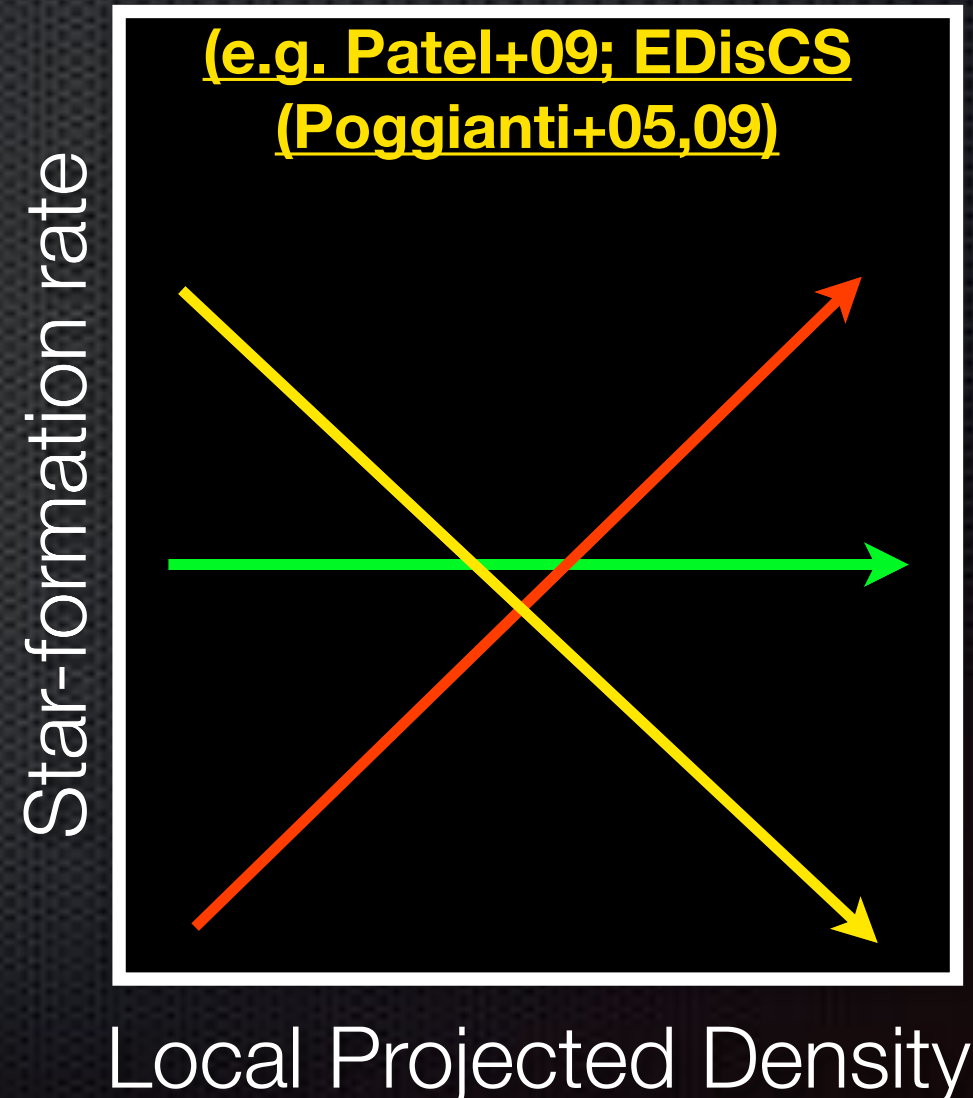


The Environment at z~1

~Field Studies — Cluster+outskirts — Rich Clusters

Can we reconcile the apparent contradictions?

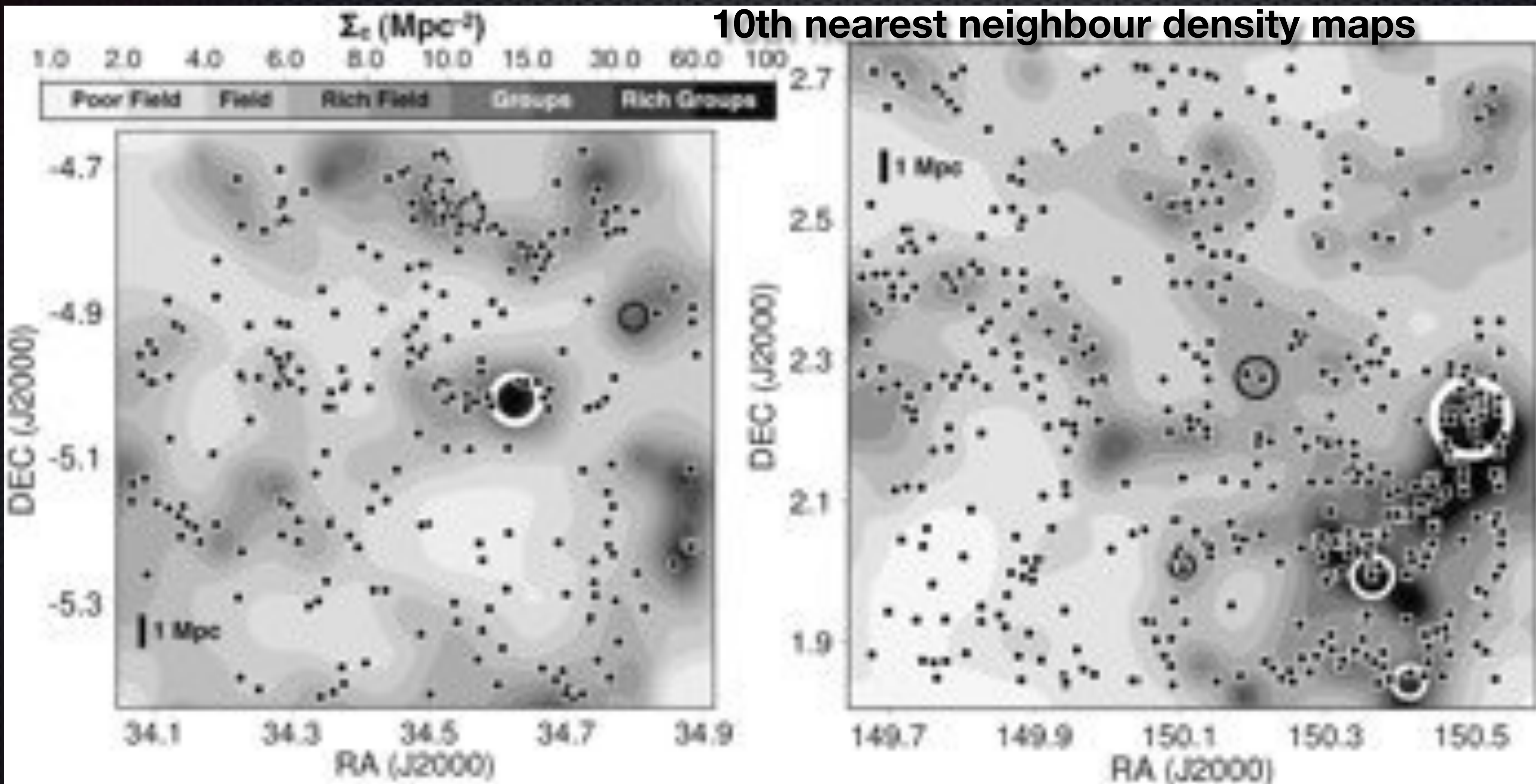




The role of the Environment

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

◯ X-rays

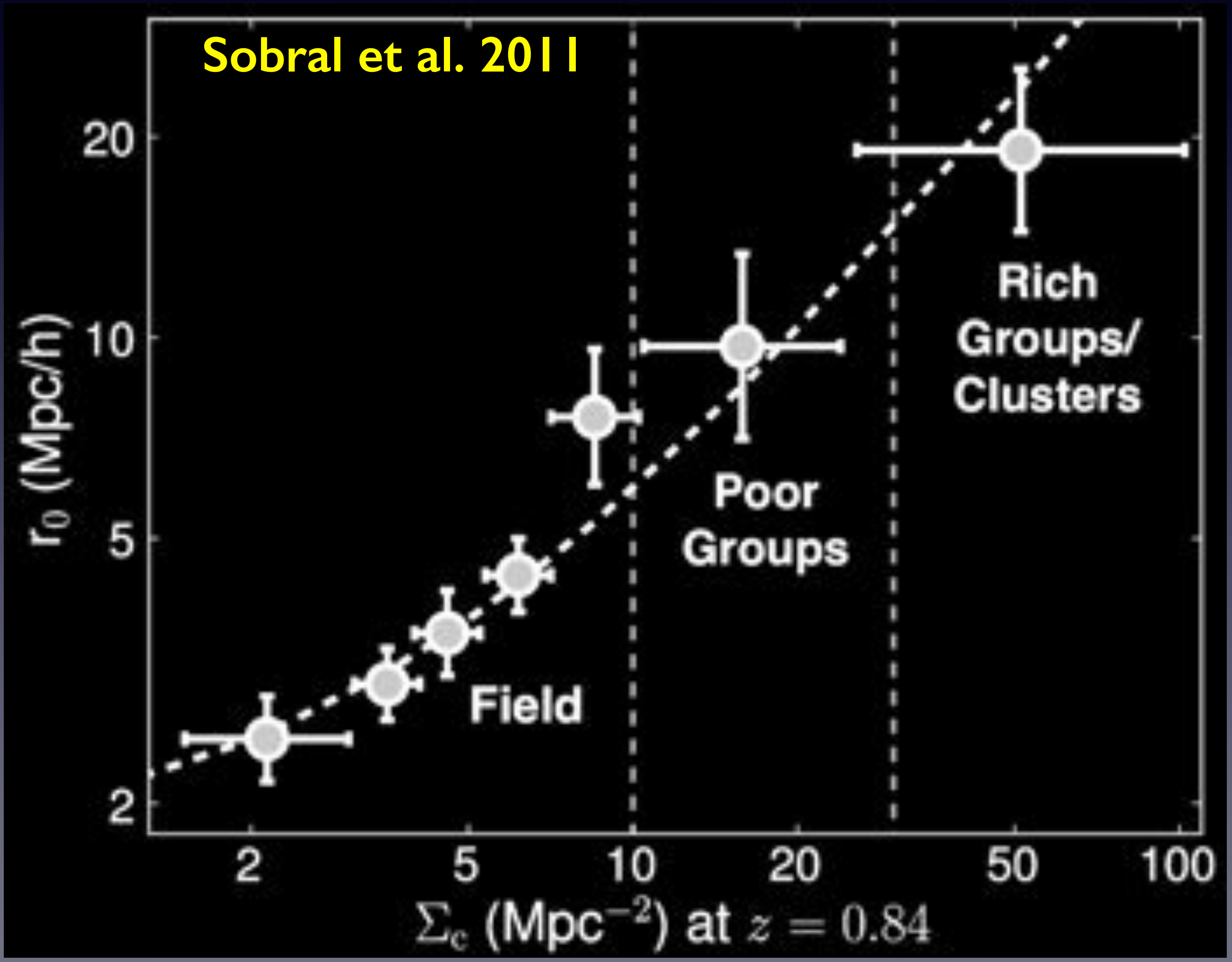


- UKIDSS UDS z=0.84
- COSMOS z=0.84

The role of the Environment

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

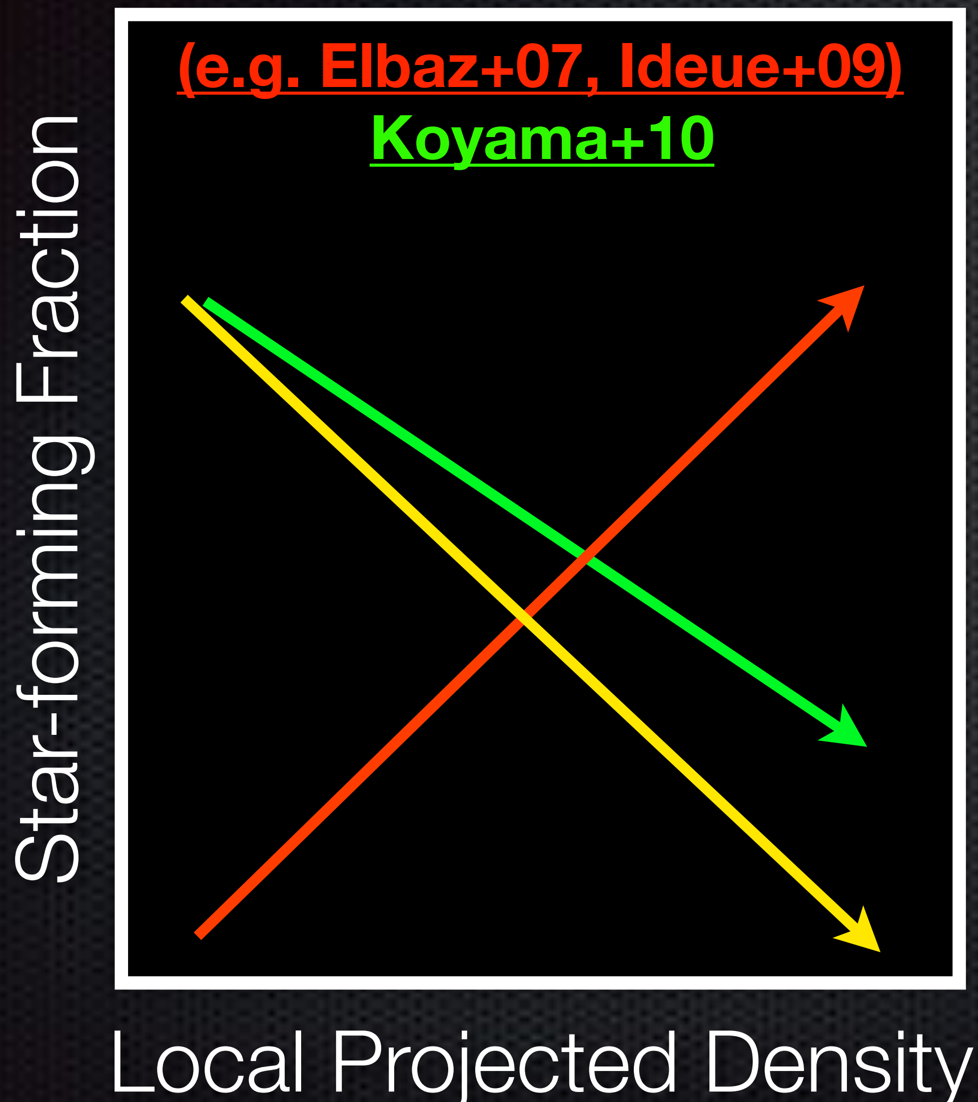
"Calibrate" environments in a reliable way using the accurate clustering analysis and real-space correlation lengths of field, groups and clusters

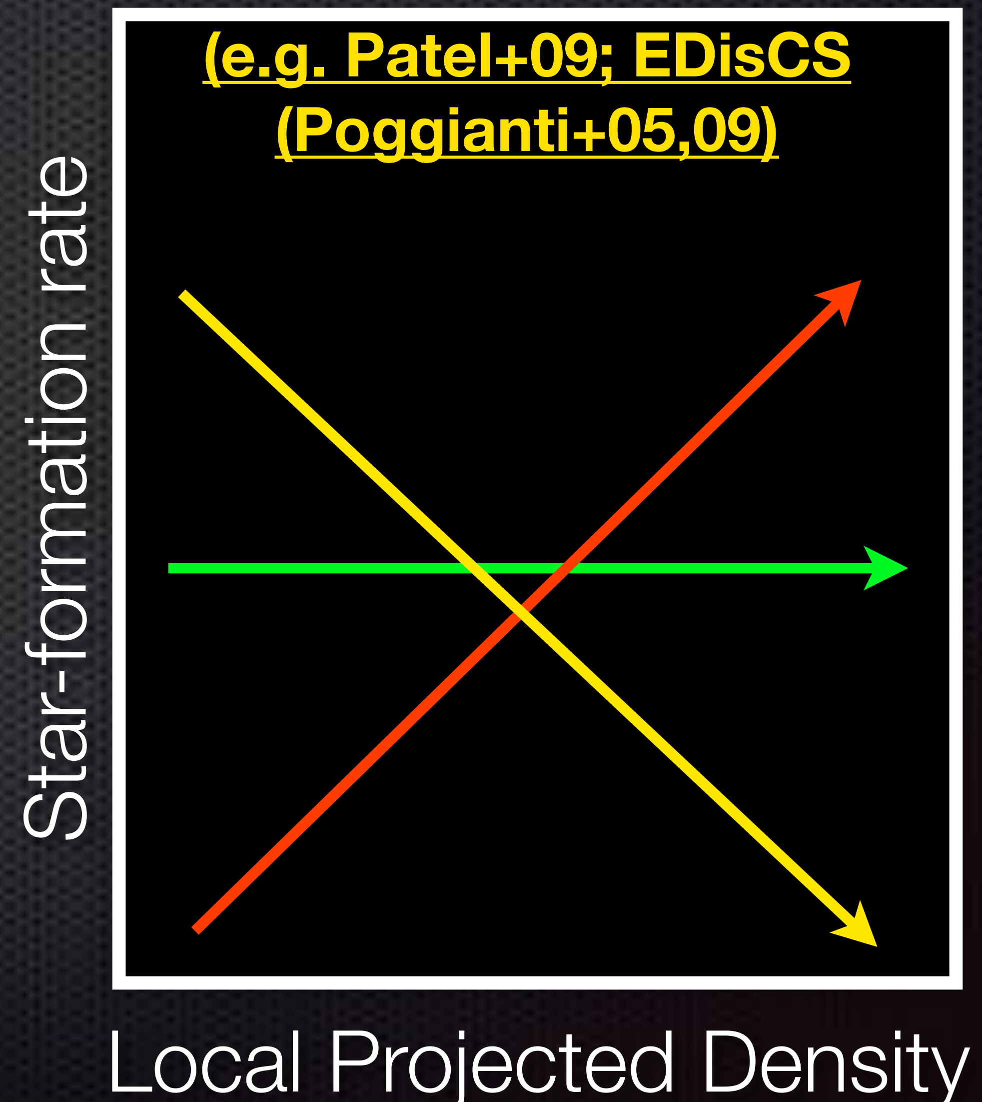


The Environment at z~1

~Field Studies | Cluster+outskirts | Rich Clusters

Can we reconcile the apparent contradictions?

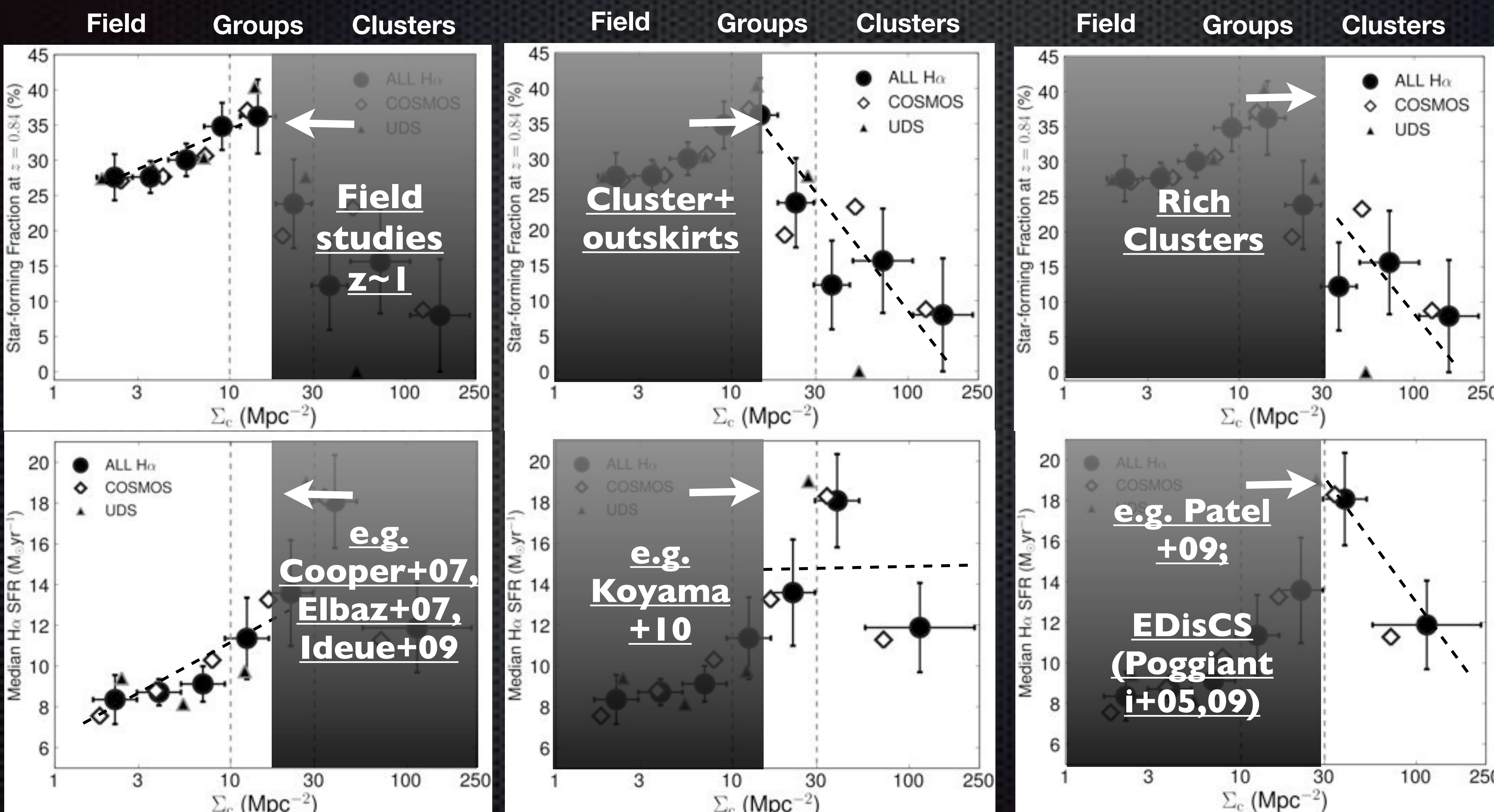


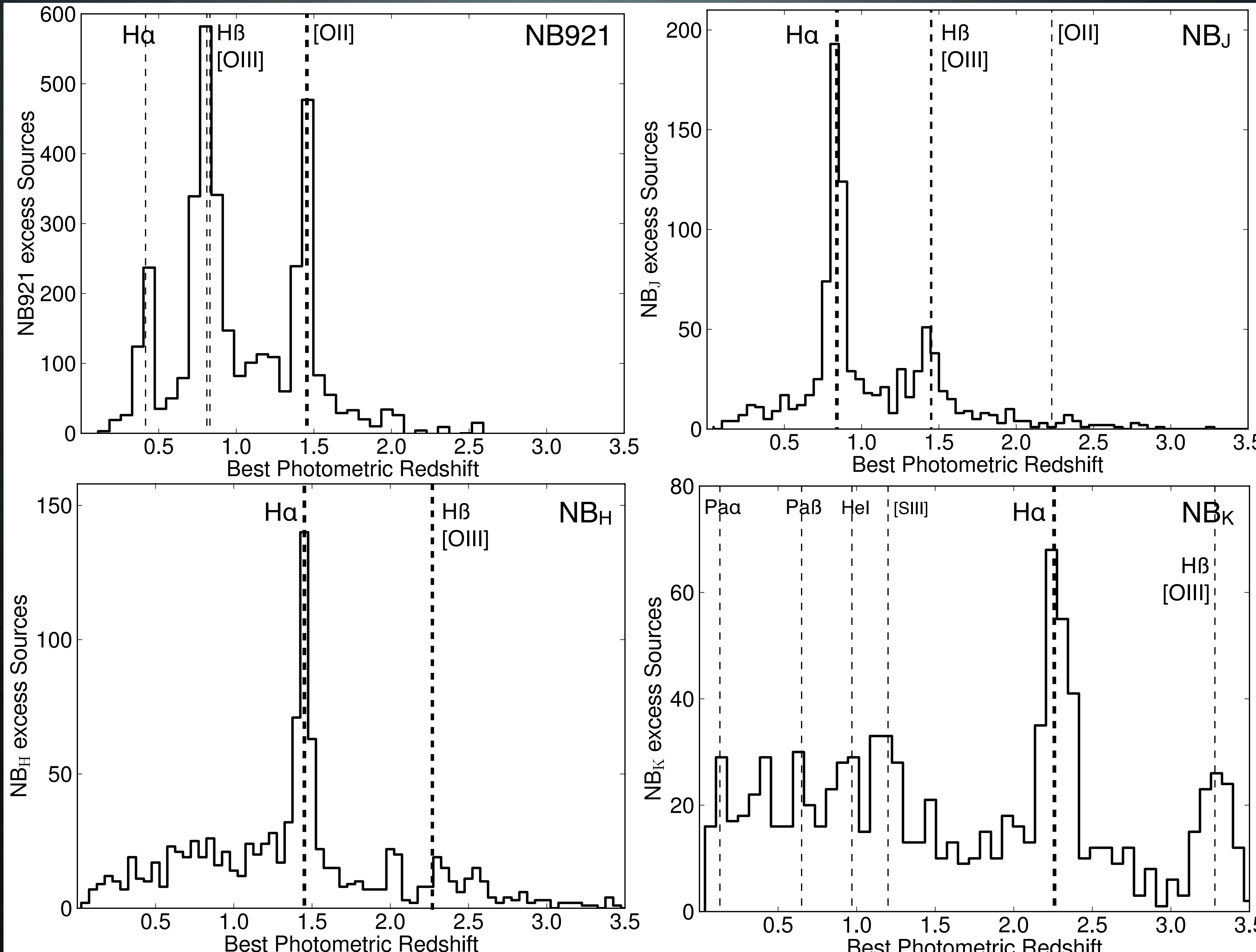


Environment at z~1

Sobral et al. (2011)

Results reconcile previous apparent contradictions

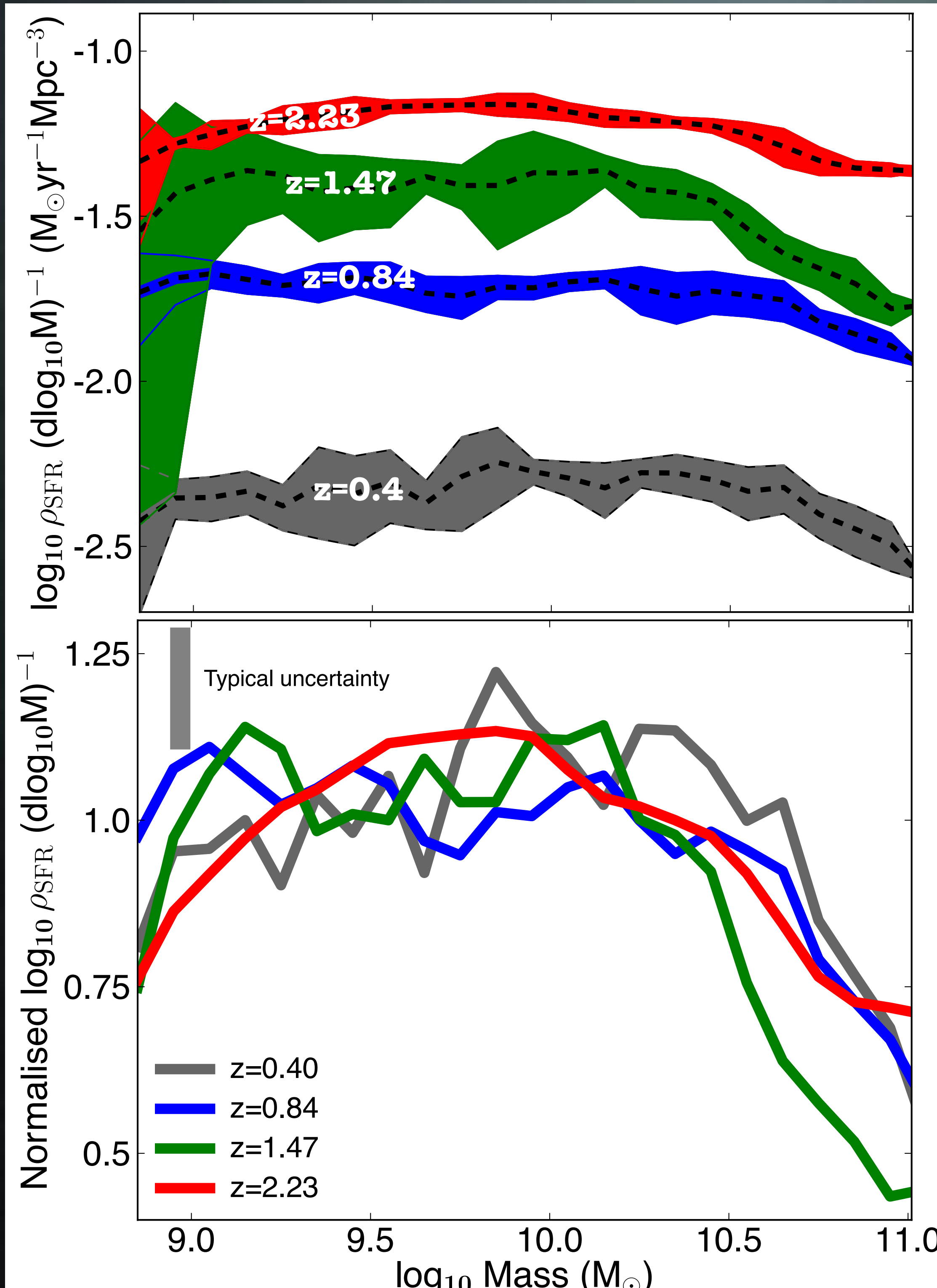




NB921
Hα
Hβ
[OIII]
[OII]
NB921 excess Sources
Best Photometric Redshift
NB_J
NB_J excess Sources
NB_H
NB_H excess Sources
NB_K
Paα
Paβ
HeI
[SIII]
NB_K excess Sources

SFRD per dLogM

Normalised



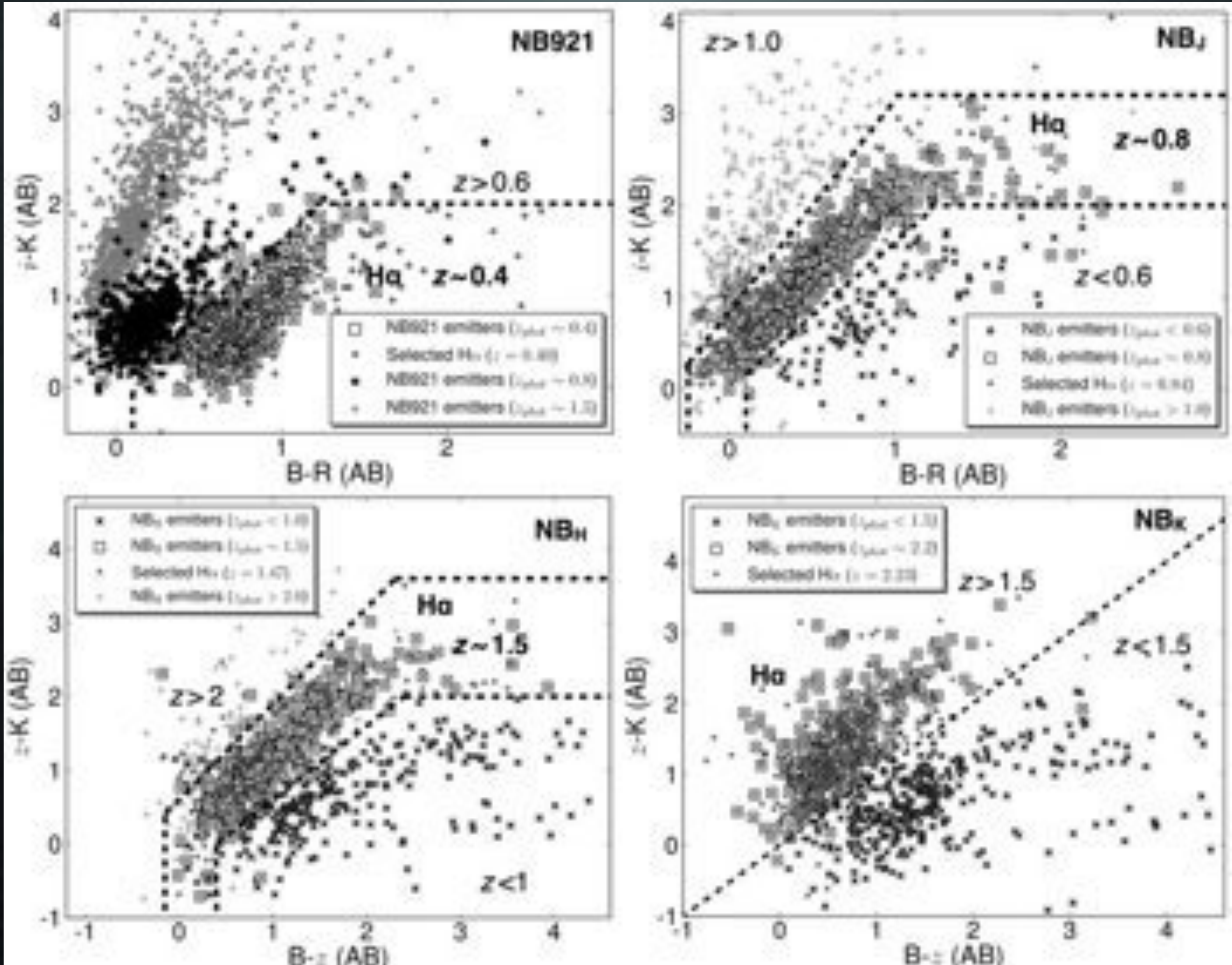
Over the last 11 Gyrs

Decrease with time at all masses

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

Mostly no evolution apart from normalisation

Sobral et al. (14)

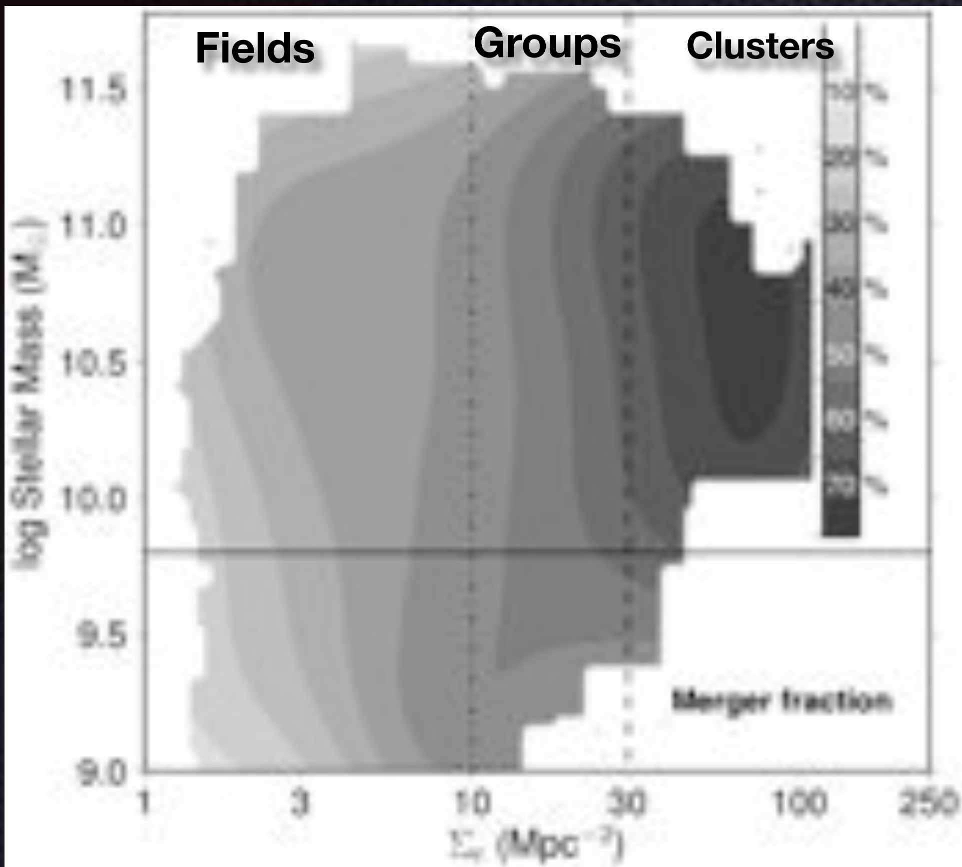


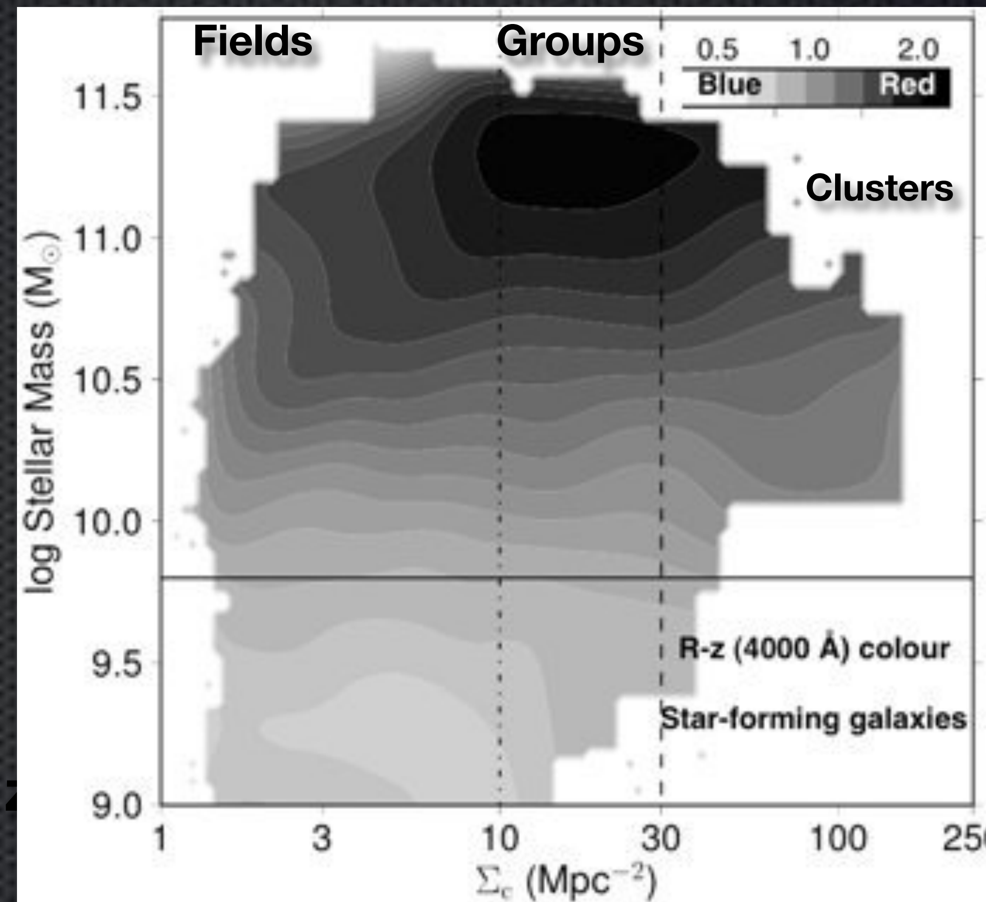
NB921
z>0.6
Hα
z~0.4
i-K (AB)
B-R (AB)
NB921 emitters
Selected Hα
NB921 emitters
NB921 emitters
z>1.0
NBJ
Hα
z~0.8
z<0.6
i-K (AB)
B-R (AB)
NBH
Hα
z~1.5
z>2
z<1
z-K (AB)
B-z (AB)
NBK
z>1.5
z<1.5
Hα
z-K (AB)
B-z (AB)

Mass and/or environment?

at z~1

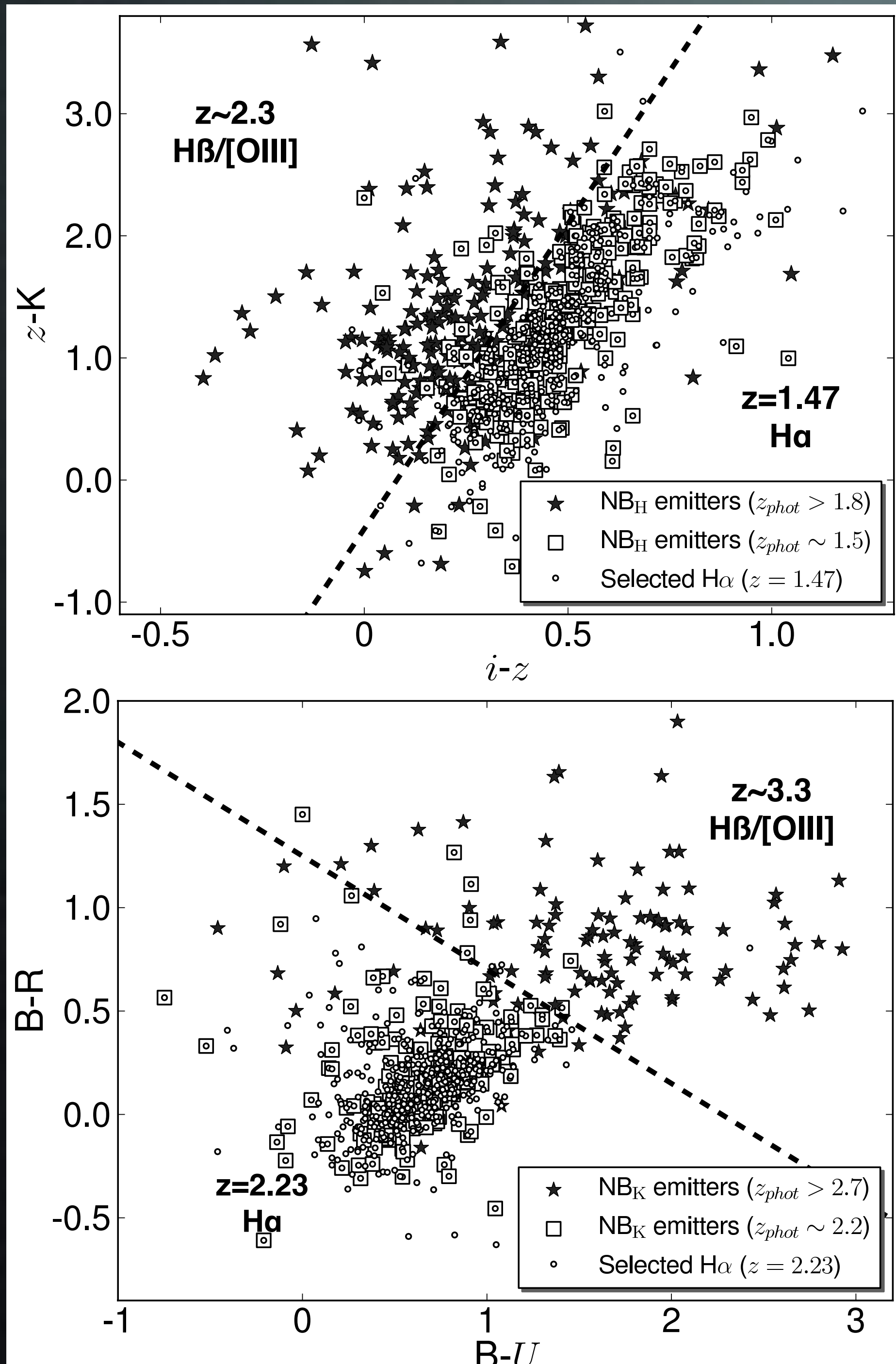
Sobral et al. 2011

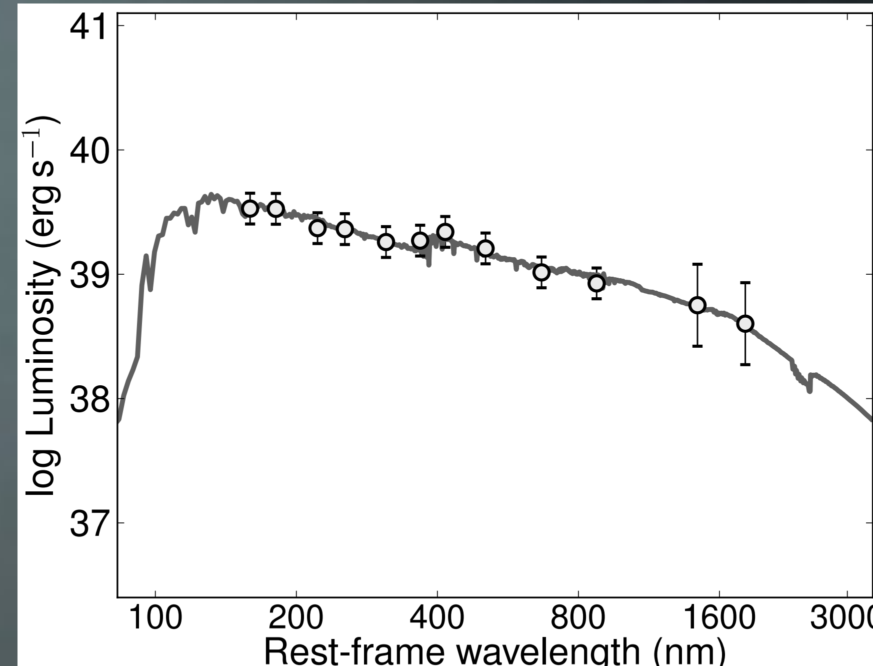


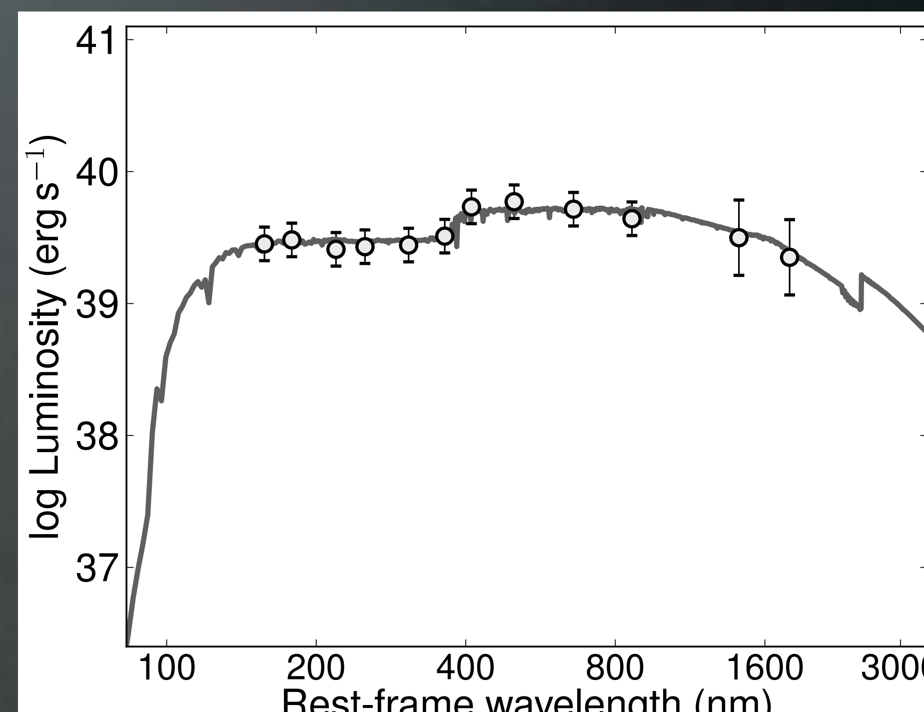


Merger fraction of star-forming galaxies depends mostly on environment, not mass

Stellar mass sets colours of <u>star-forming</u> galaxies, NOT environment

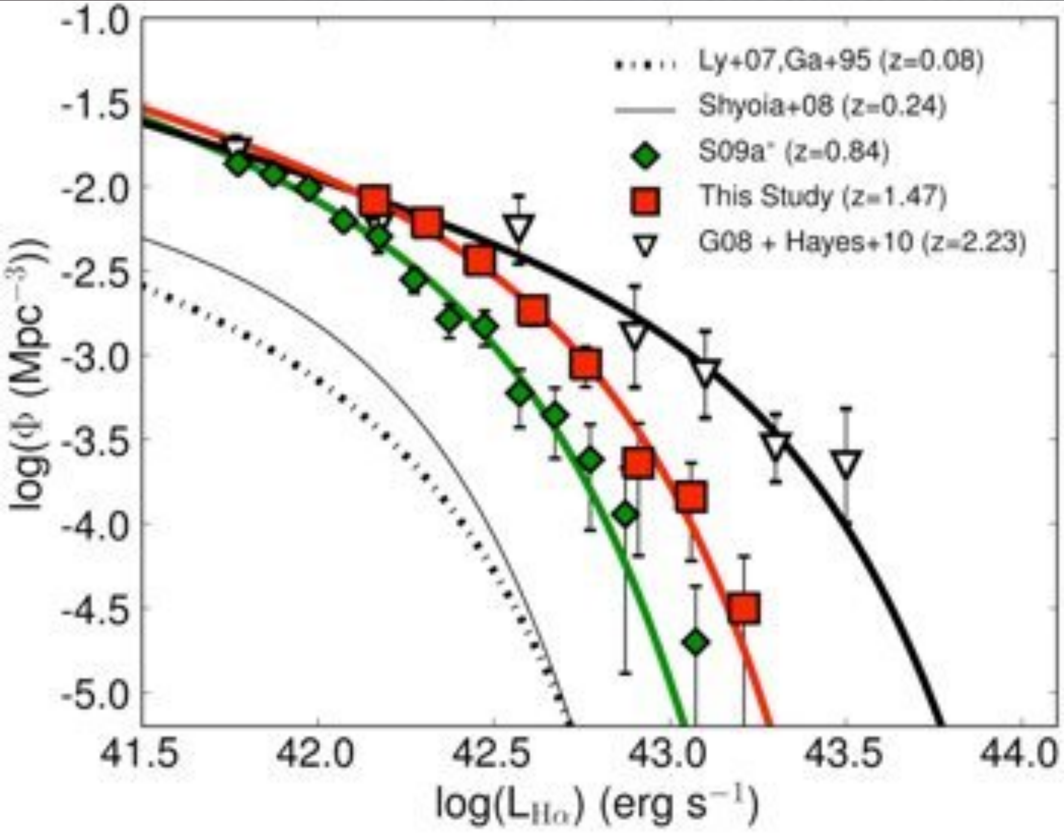

z~2.3
Hß/[OIII]
z=1.47
Hα
z-K
i-z
NB$_H$ emitters ($z_{phot} > 1.8$)
NB$_H$ emitters ($z_{phot} \sim 1.5$)
Selected Hα ($z = 1.47$)
z~3.3
Hß/[OIII]
z=2.23
Hα
B-R
B-U
NB$_K$ emitters ($z_{phot} > 2.7$)
NB$_K$ emitters ($z_{phot} \sim 2.2$)
Selected Hα ($z = 2.23$)

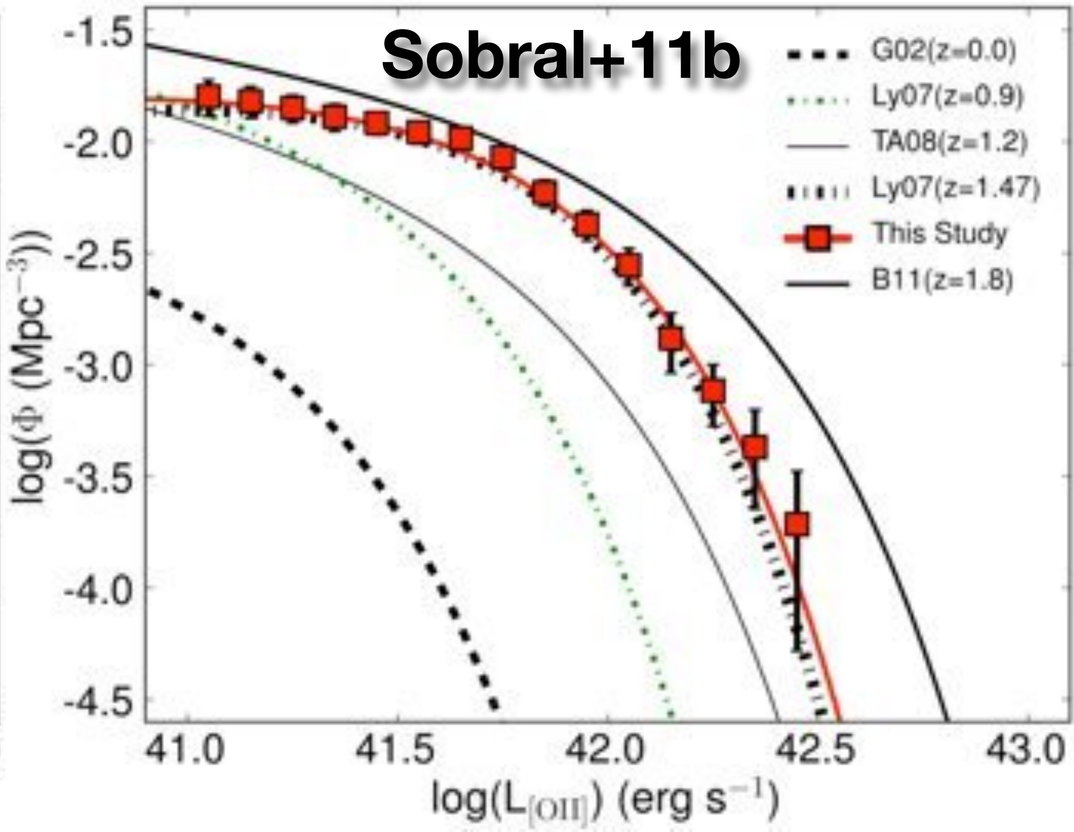

log Luminosity (erg s^{-1})
Rest-frame wavelength (nm)


log Luminosity (erg s^{-1})
Rest-frame wavelength (nm)

The Hα + [OII] view

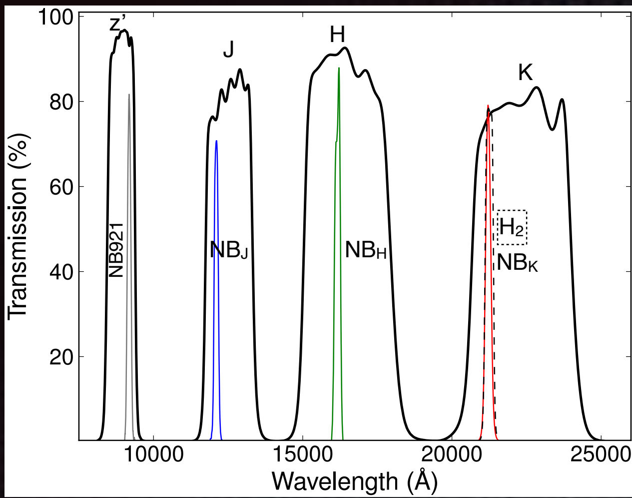
- Detailed evolution of the Hα LF: strong L^* evolution to z~2.3





First self-consistent measurement of evolution up to z~2.3

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



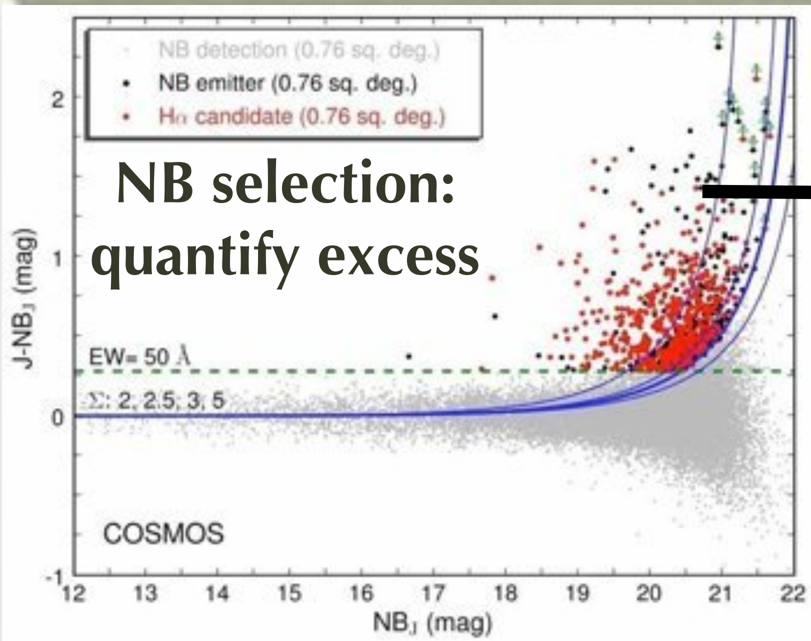
NB filter	λ_c (μm)	FWHM (Å)	z Hα	Volume (Hα) (10^4 Mpc^3 deg^{-2})
NB921	0.9196	132	0.401±0.010	5.13
NB$_J$	1.211	150	0.845±0.015	14.65
NB$_H$	1.617	211	1.466±0.016	33.96
NB$_K$	2.121	210	2.231±0.016	38.31
HAWK-I H$_2$	2.125	300	2.237±0.023	54.70

~16 kpc apertures z=0.4-2.23

Redshift	Limit SFR	Volumes (UDS + COSMOS)
0.401±0.010	0.01	~1x10^5 Mpc^3
0.845±0.015	1.5	~2x10^5 Mpc^3
1.466±0.016	3.0	~8x10^5 Mpc^3
2.231±0.016	3.5	~7x10^5 Mpc^3

z=0.4-2.23

$\Sigma > 3$, EW$_{(Ha+[NII])} > 25$ Å



NB selection: quantify excess

Source extraction

Potential line emitters

Which emission line?

Probing well-studied fields is fundamental!

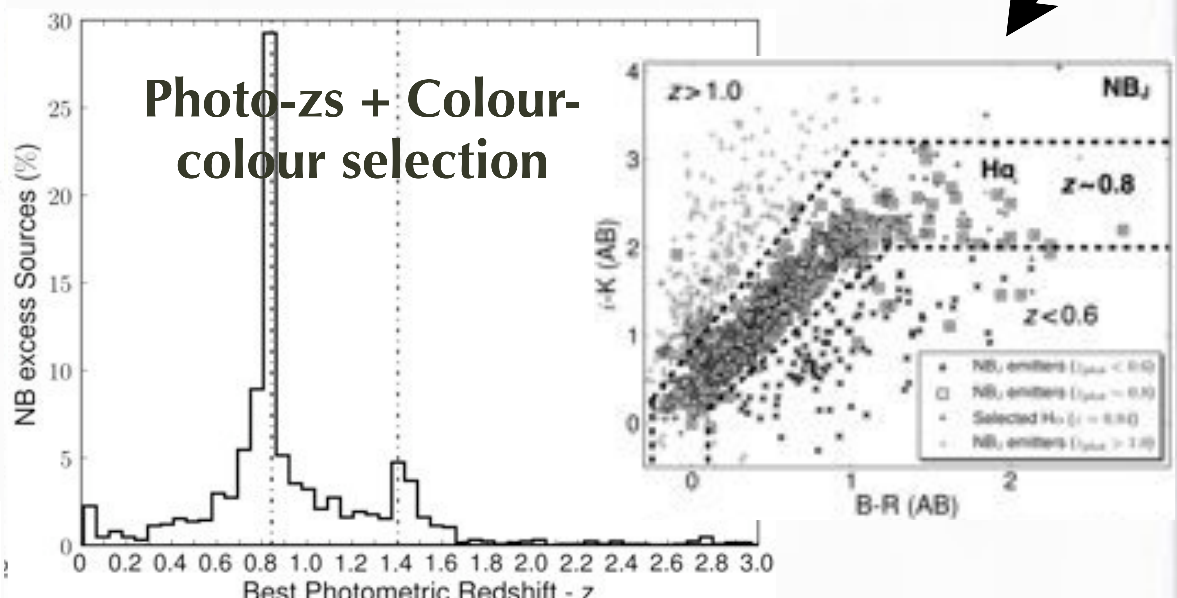
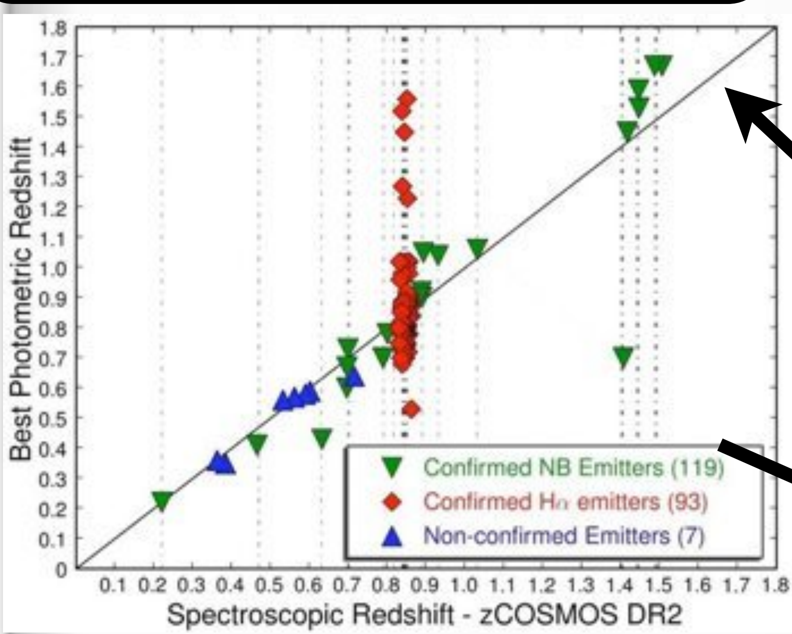


Photo-zs + Colour-colour selection

Spectro-z confirmation

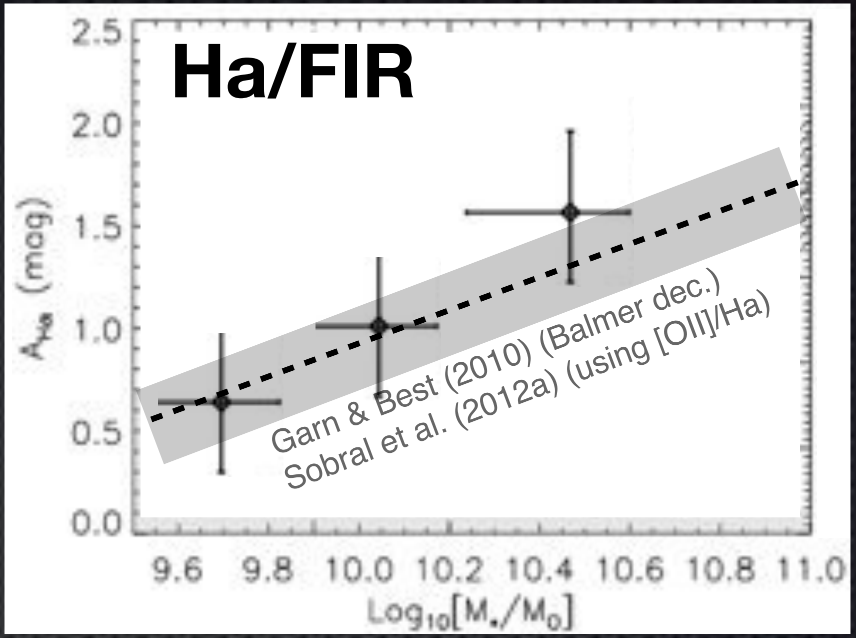
Double-line confirmation

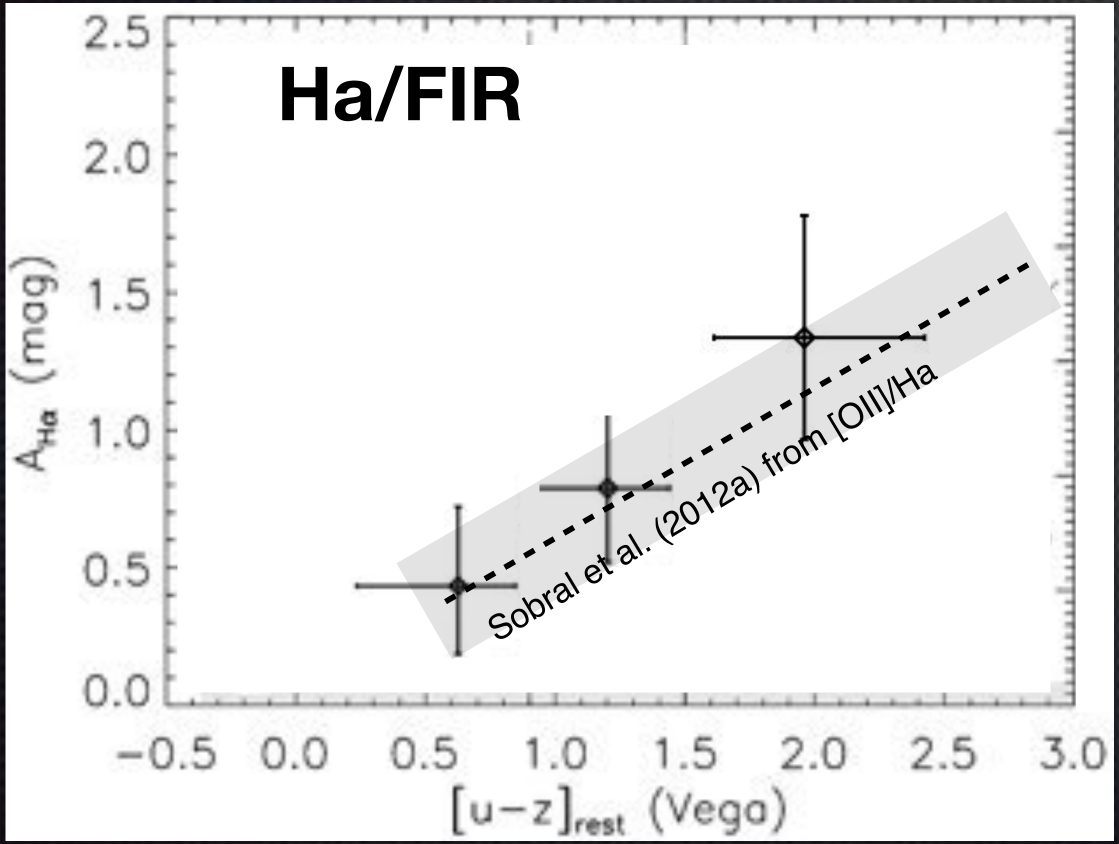


Select Hα emitters

Samples >90% reliable
>90% complete

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





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

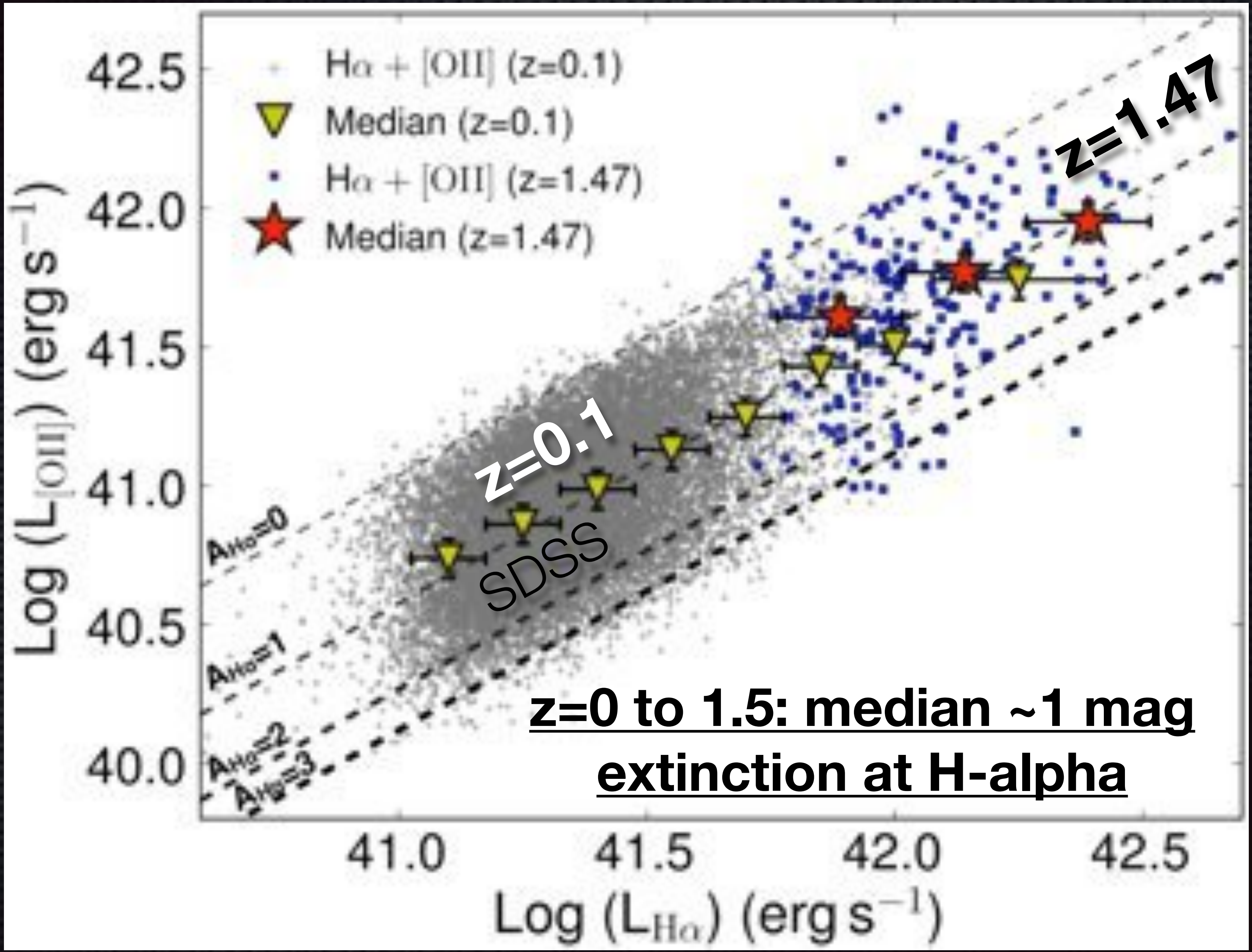
Little evolution in rest-frame R sizes for Star forming galaxies since z=2.23

z	a	b	r_e at $\log_{10}(M_*) = 10$ (kpc)
0.40	0.08 ± 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

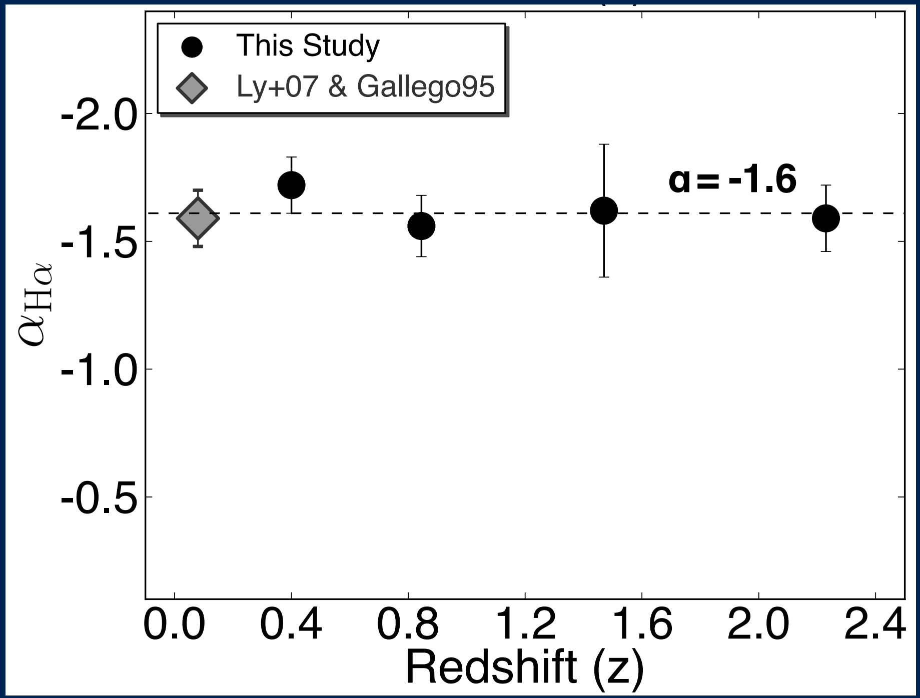
~Same sizes down to same SFR/SFR*

Stott et al. 2013

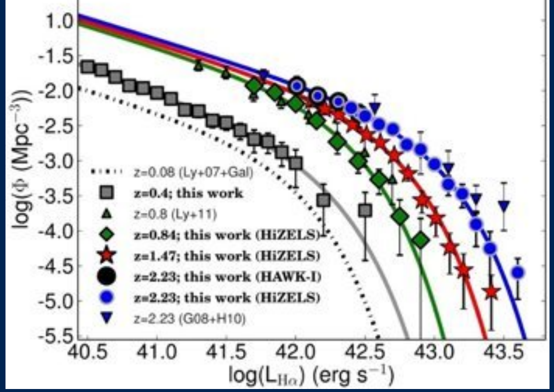
Dust extinction over ~9 Gyrs: evolution?



Faint-end Slope α:



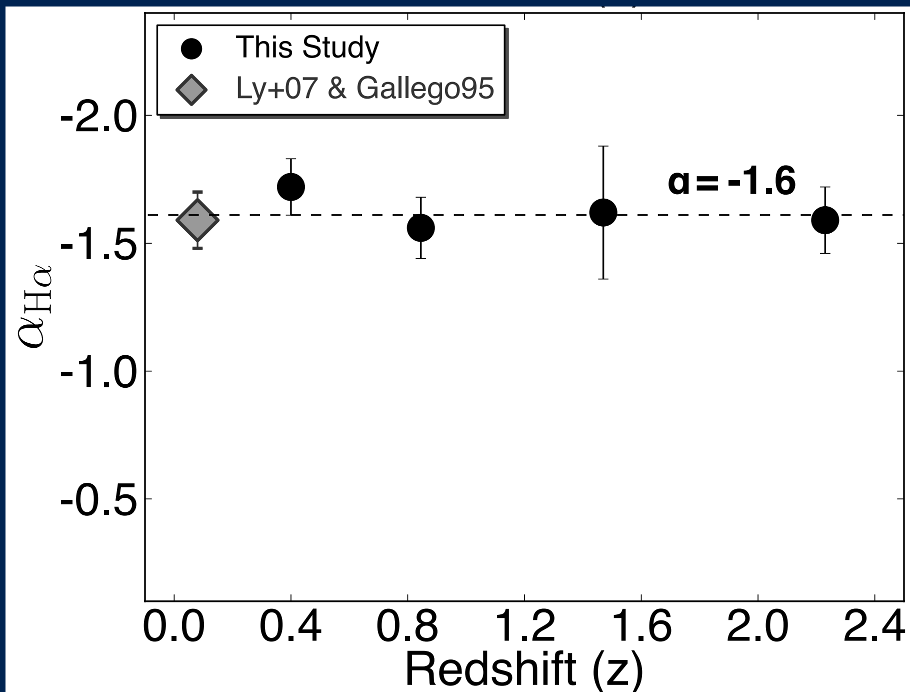
Up to z=2.2:



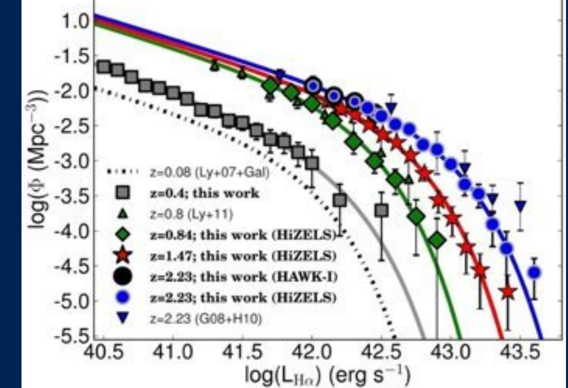
$$\alpha = -1.60 \pm 0.08$$

Sobral et al. 2013a

Faint-end Slope α:

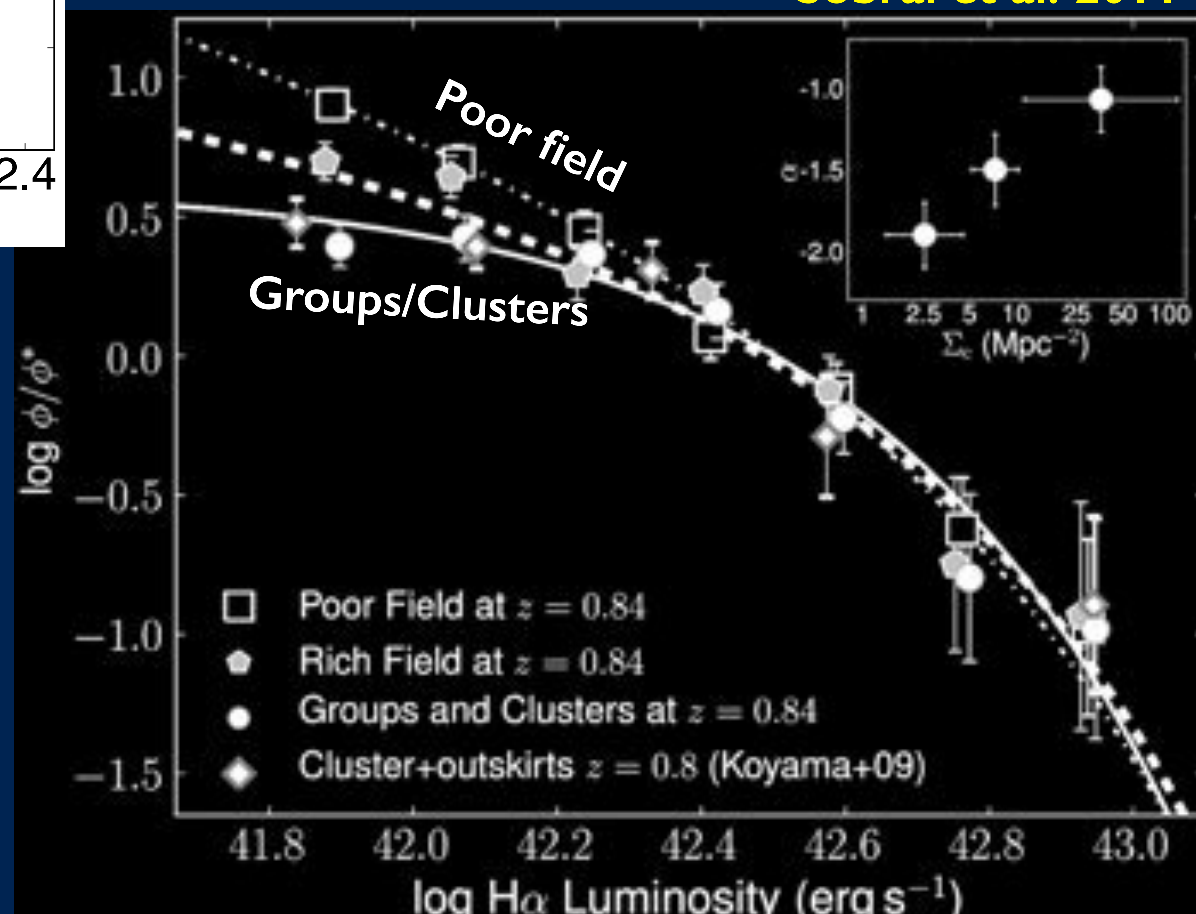


Up to z=2.2:



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

Sobral et al. 2011



Environment sets the faint-end slope of the Hα LF:

-<u>steep</u> α~-2 for the lowest densities

- <u>shallow</u> α~-1 for highest densities

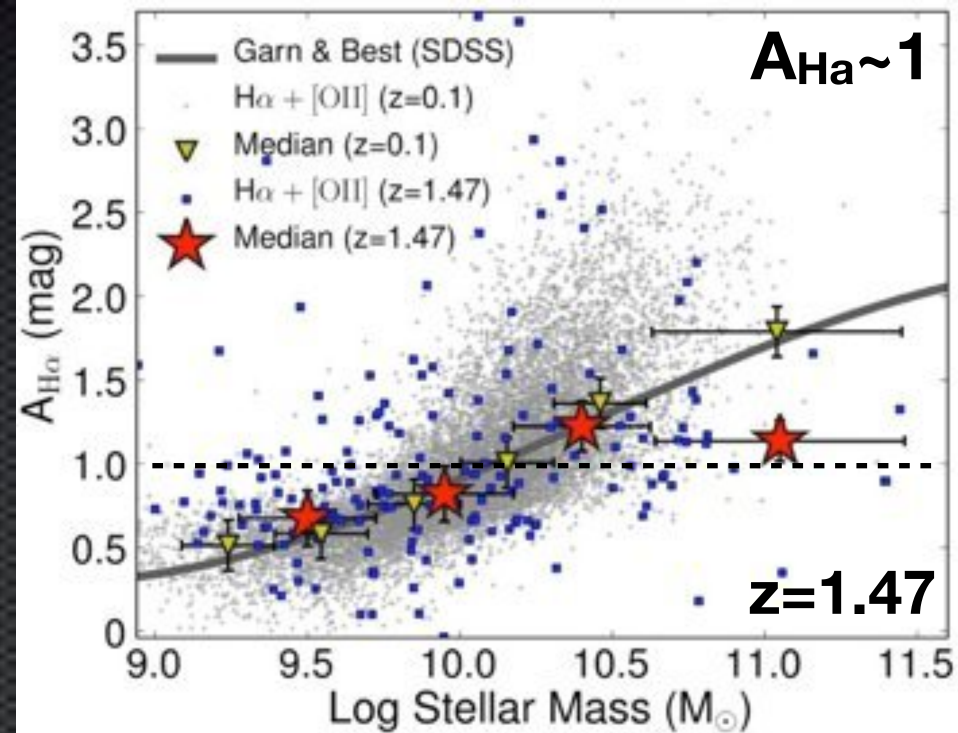
A simple view: 11 Gyrs of SFGs

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

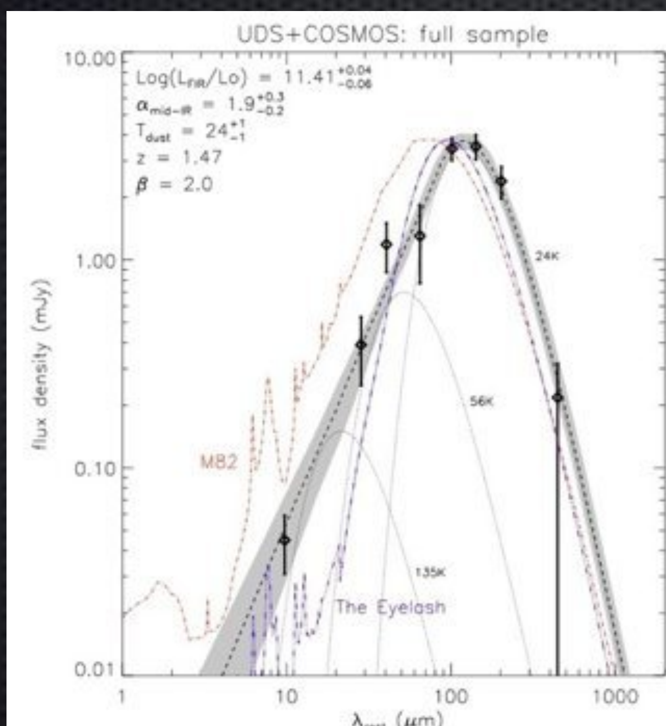
Extinction-Mass z~0-1.5

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

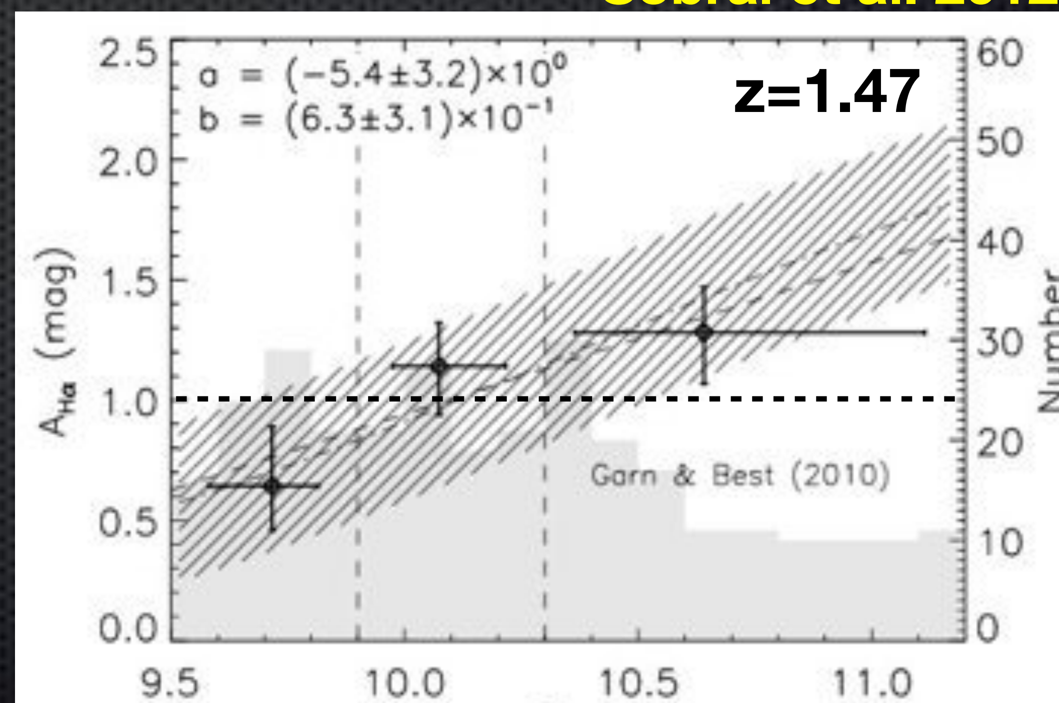
Relation holds up to z~1.5-2



Sobral et al. 2012



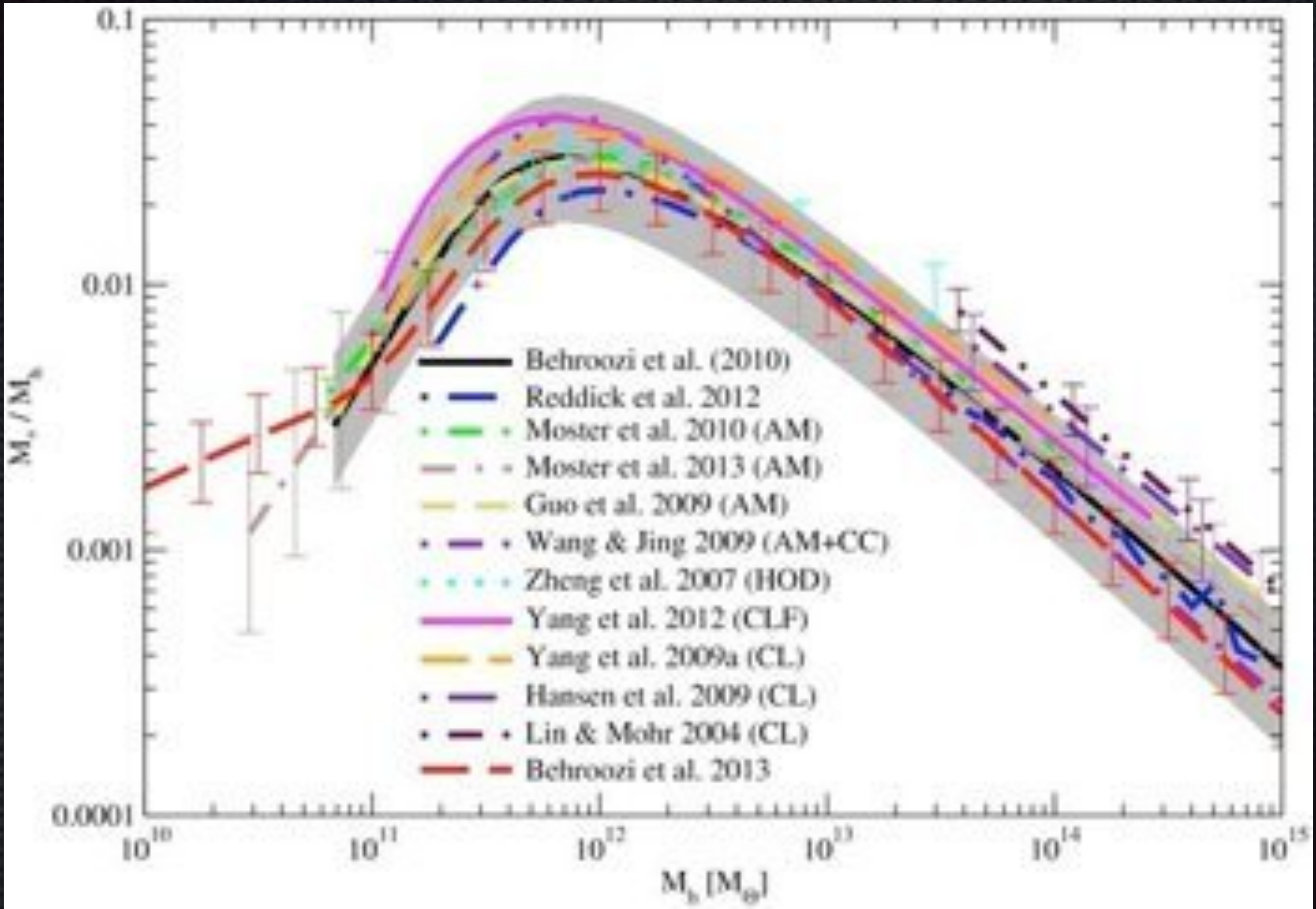
FIR derived A_{Ha} = 0.9-1.2 mag



Ibar et al. 2013

FIR/Ha

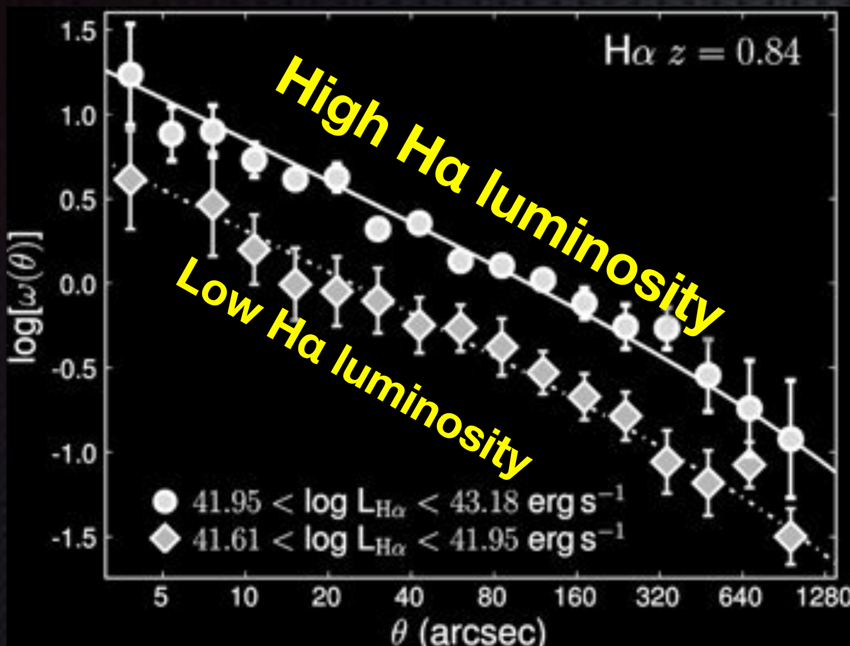
DM Halo/SF “efficiency”



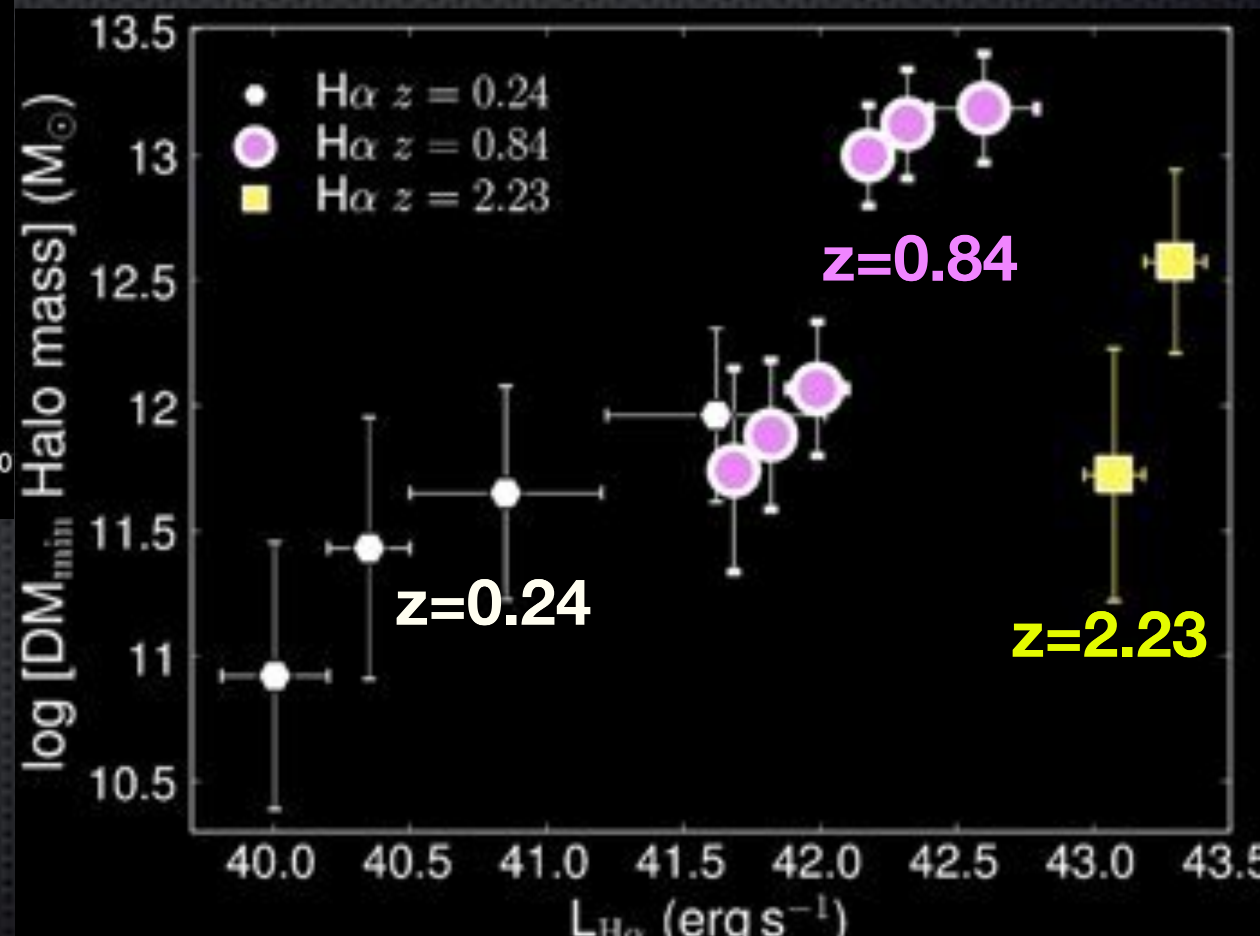
But what exactly drives this??? Gas? Structure? Feedback?

Clustering of Hα emitters

<u>Clustering depends on Hα luminosity;</u> galaxies with higher SFRs are more clustered



Sobral et al. 2010

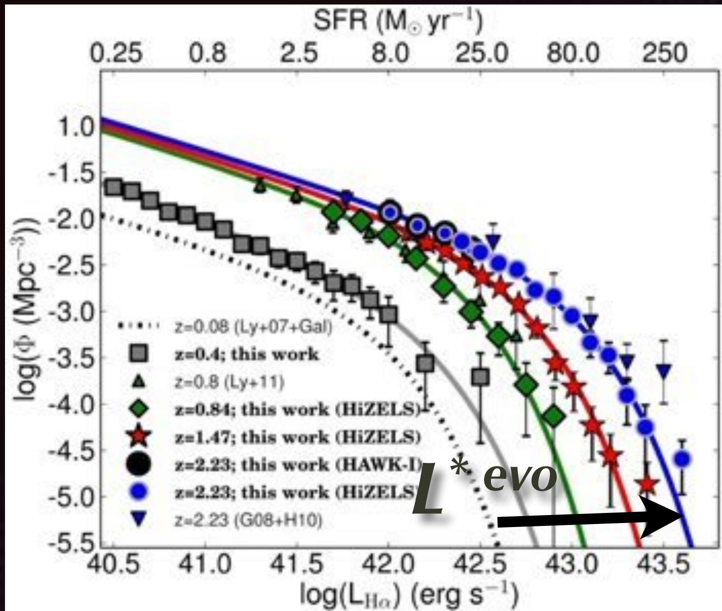


Clustering-Hα relations at 3 very different epochs...

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

Clustering-Hα

Sobral et al. 2010



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

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