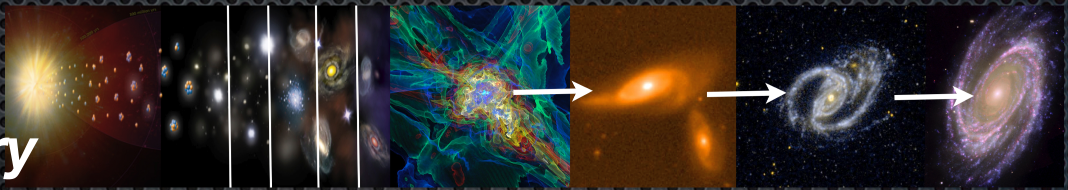
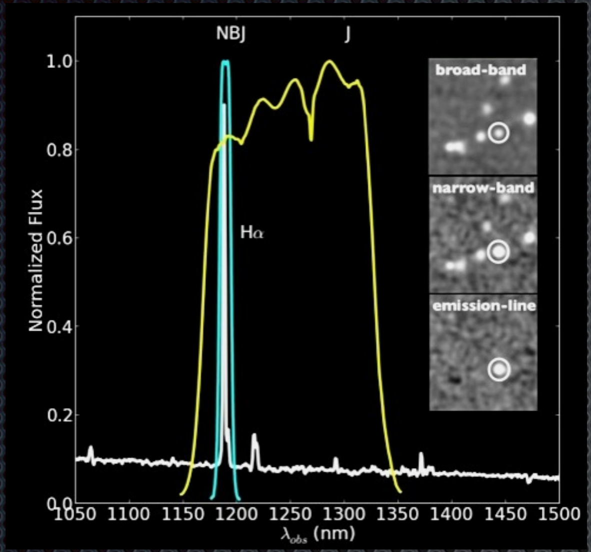
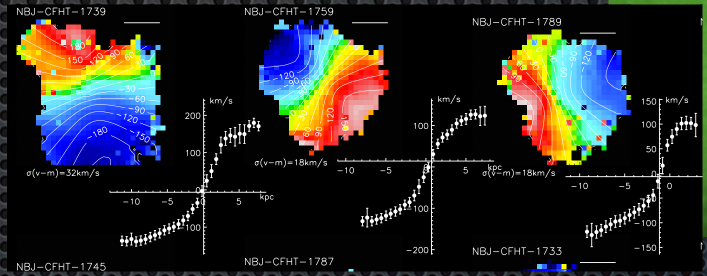
The nature and evolution of star-forming galaxies: 11 Gyrs with a single, homogeneous selection

David Sobral

IA-U. Lisbon/Leiden Observatory







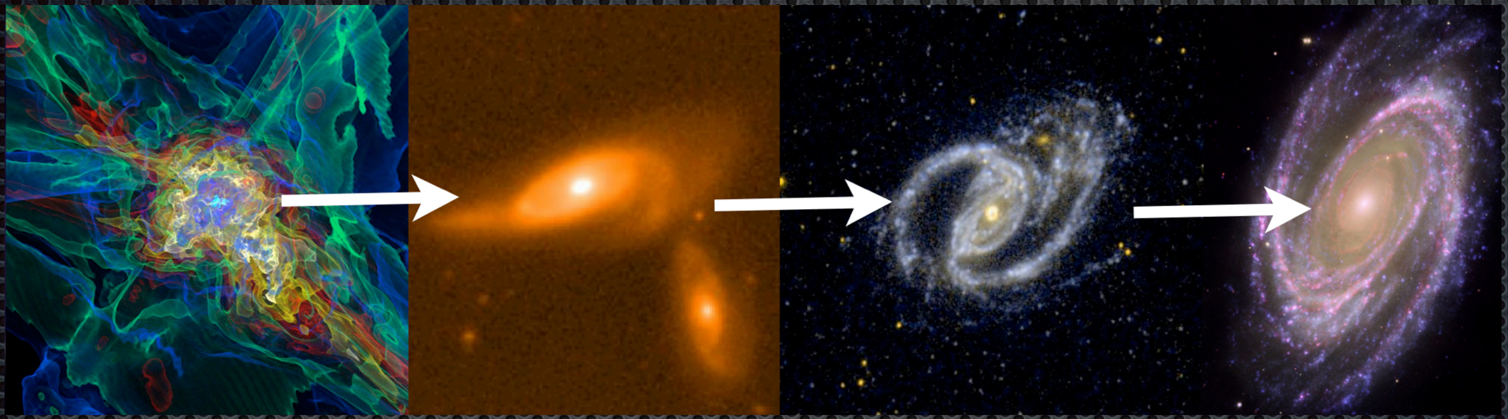
Jorryt Matthee, Ian Smail, Philip Best, Mark Swinbank, John Stott, Ali Khostovan, Iván Oteo, Edo Ibar, Y. Koyama, Ana Afonso, João Calhau, Behnam Darvish, Bahram Mobasher, Andra Stroe, Sérgio Santos

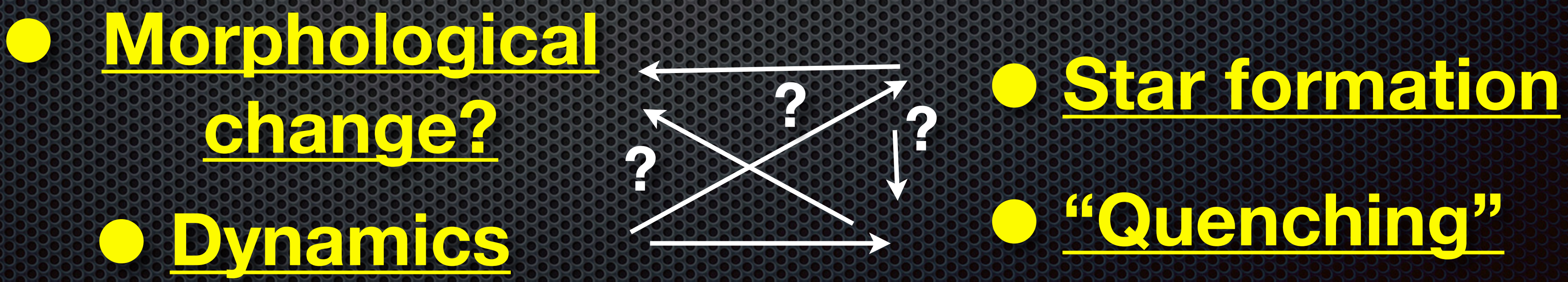
NWO

Sterrewacht Leiden

How (and driven by which mechanisms)

do galaxies form and evolve?





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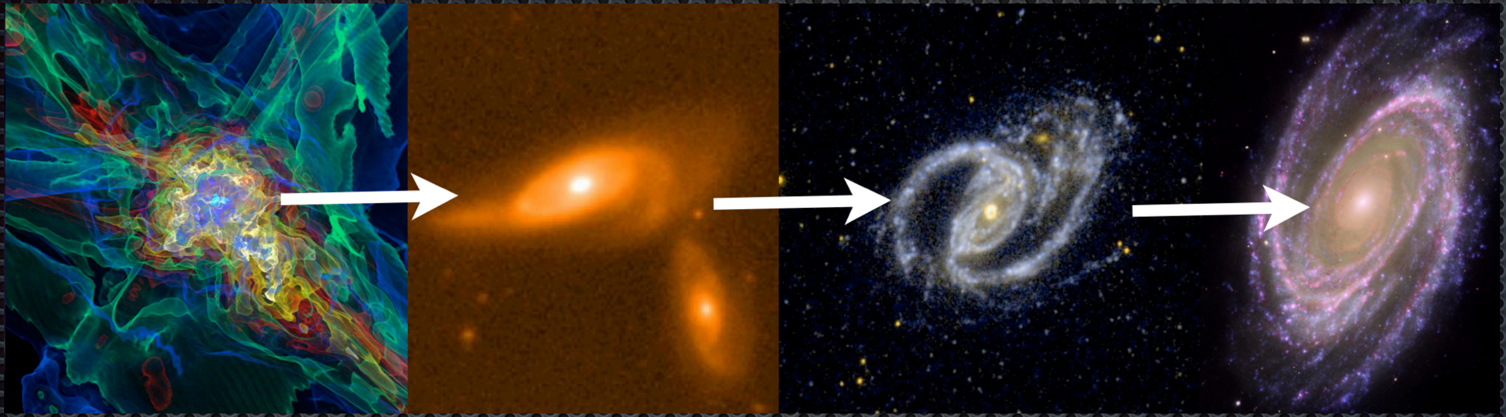


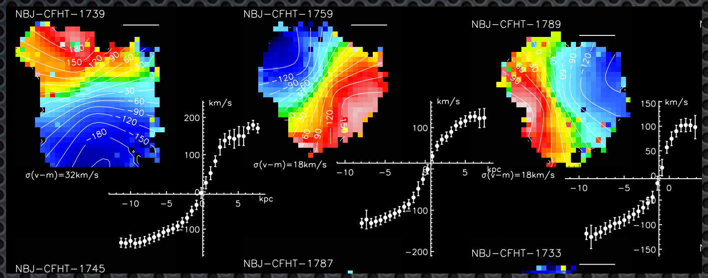
Complicated:

- 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 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:

Improve SFH/ Part I

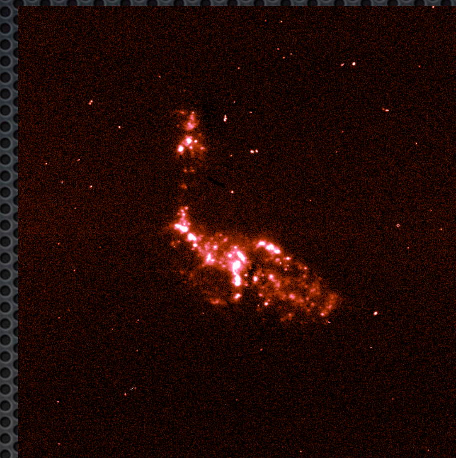
- A **good (single)** star-formation tracer that can be applied with current instrumentation
- Well calibrated + sensitive

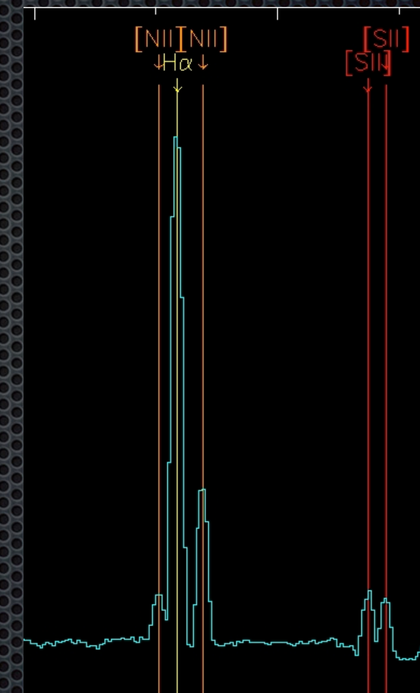
Understand the SFH/ Part II

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

Hα (+NB)

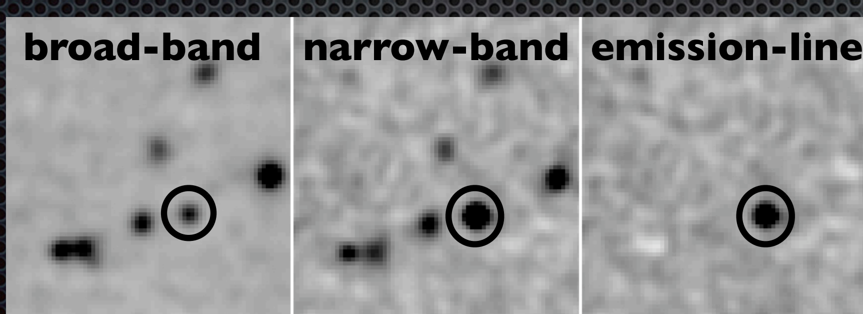
- MW SFRs up to z~2.5!

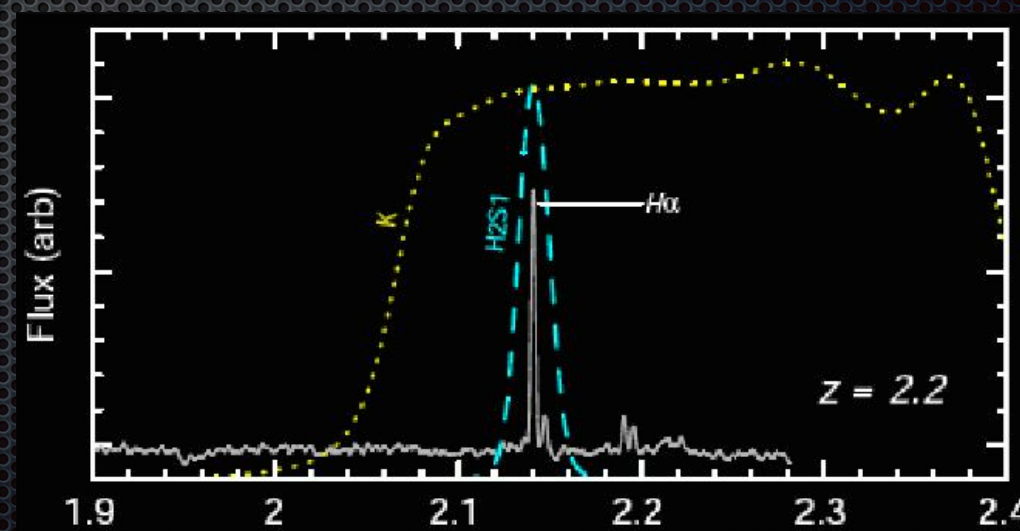




- Sensitive, good selection
- Well-calibrated
- Traditionally for Local Universe
- **<u>Narrow-band technique</u>**

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





Selection really matters

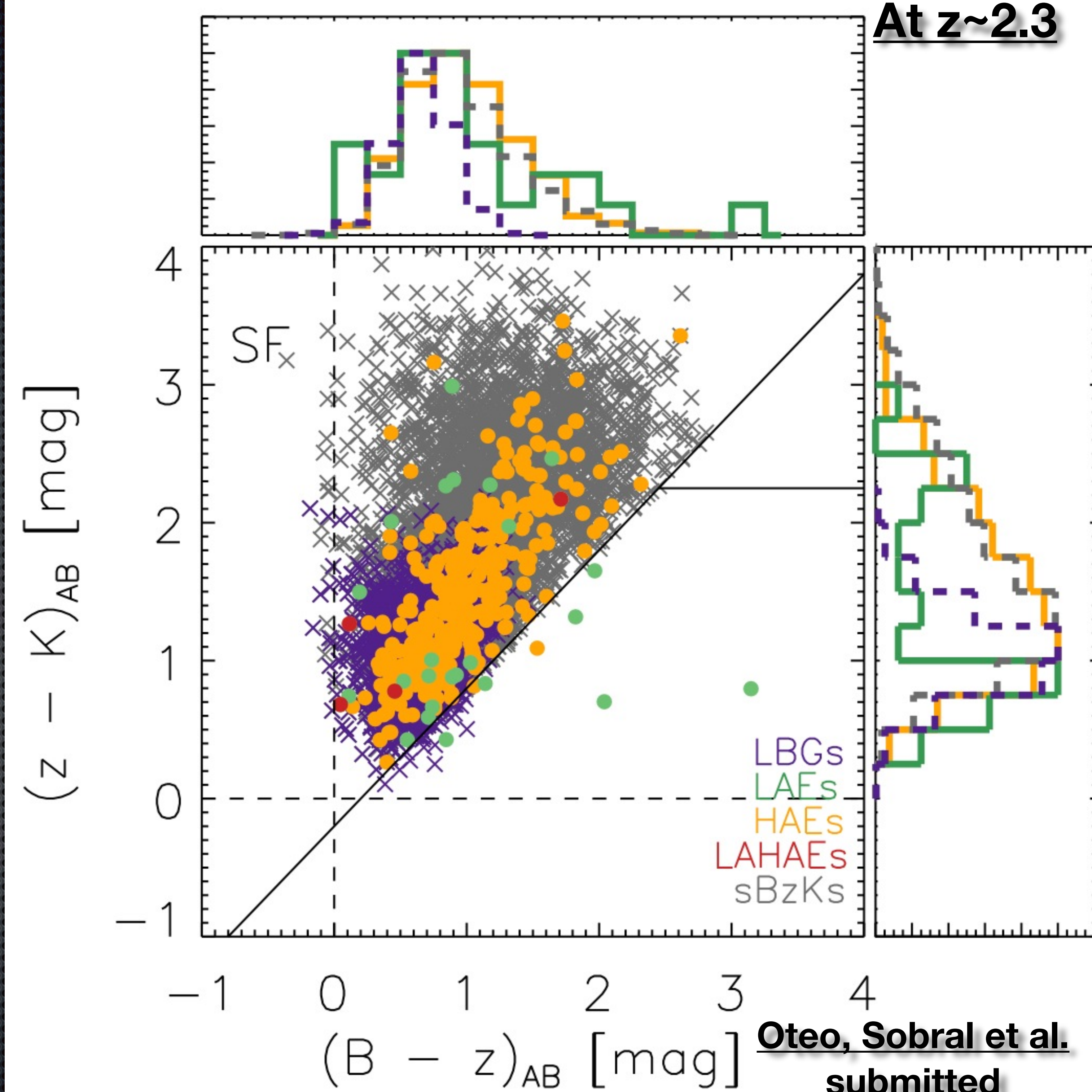
Lyman-break/UV selection: **misses ~65-70%** of star-forming galaxies! (metal-rich, dusty) (+ systematics)

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

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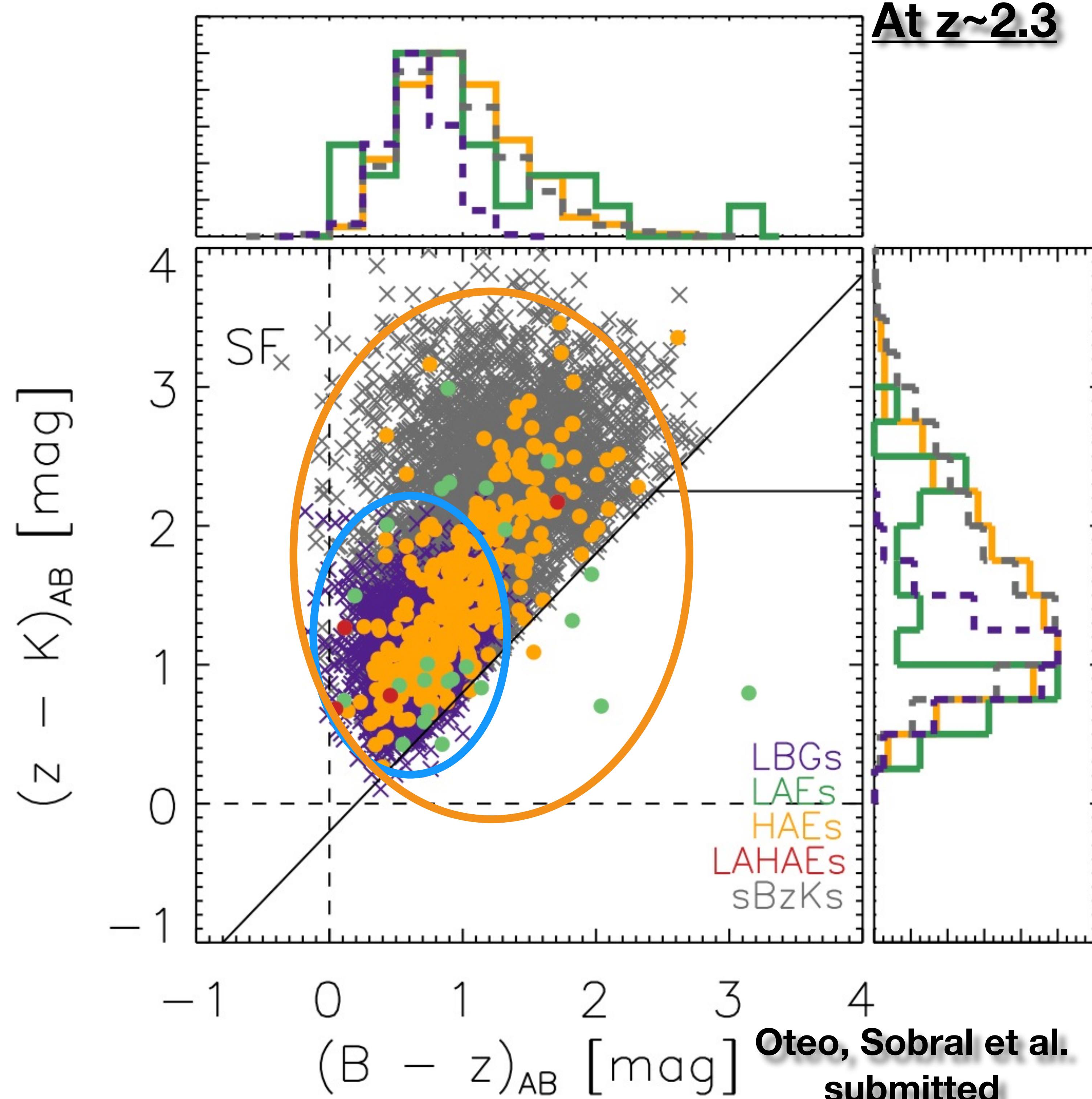

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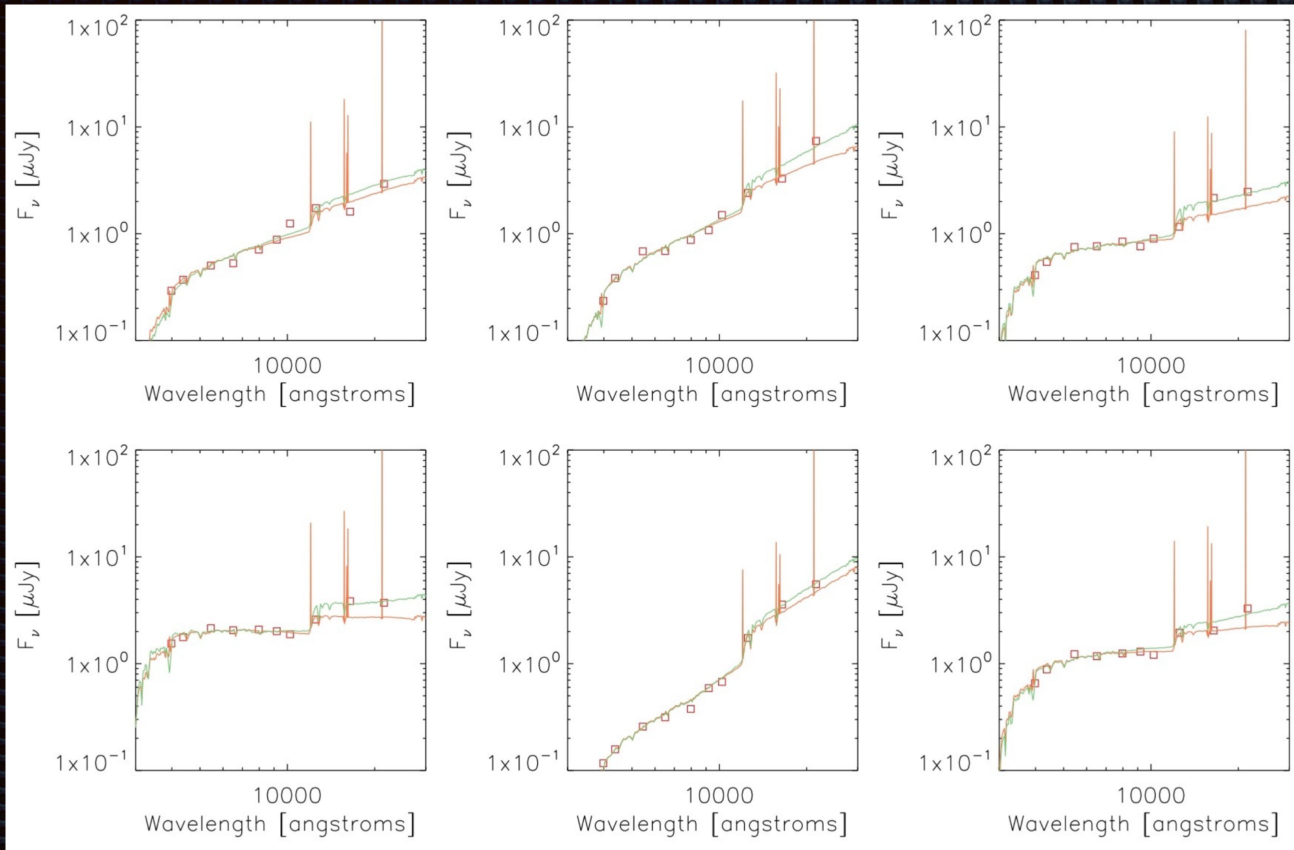
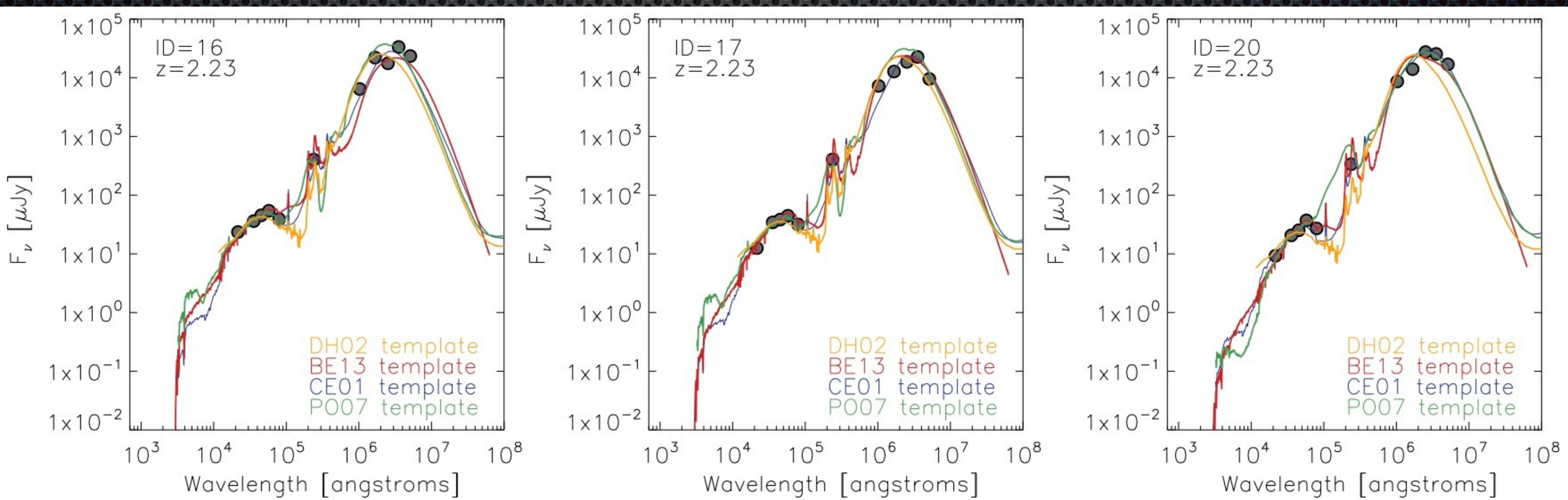


Selection really matters

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



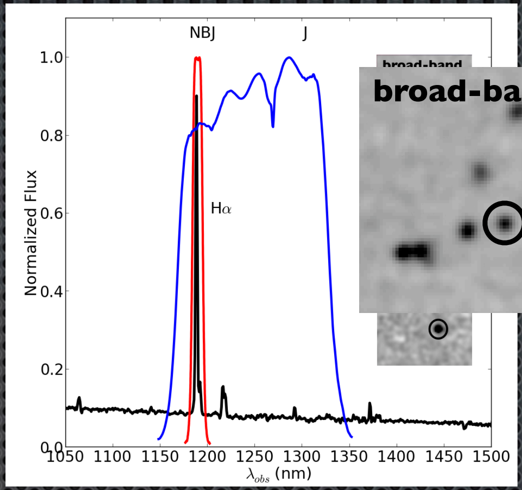
HiZELS

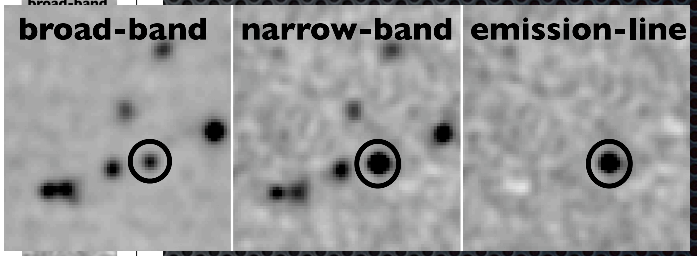
The High Redshift Emission Line Survey

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

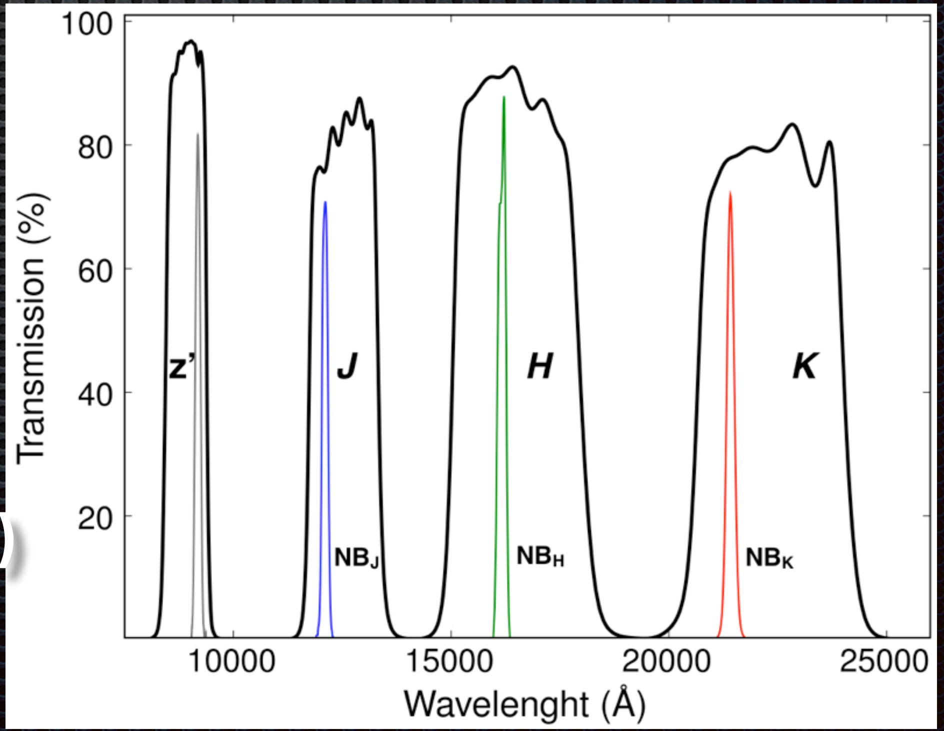
(+Deep NBH + Subar-HiZELS + HAWK-I)

- **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**
- 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)**





- **>1000 galaxies per NB slice**

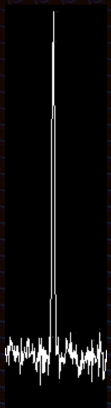


<u>Sobral et al. 2013a</u>

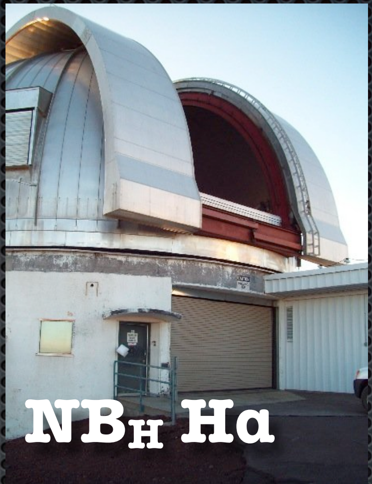
Double-NB survey

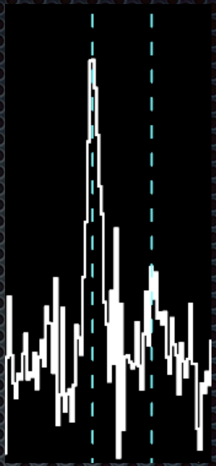
Sobral+12

400 Ha+[OII] / night!



Subaru joins UKIRT to "walk through the desert"

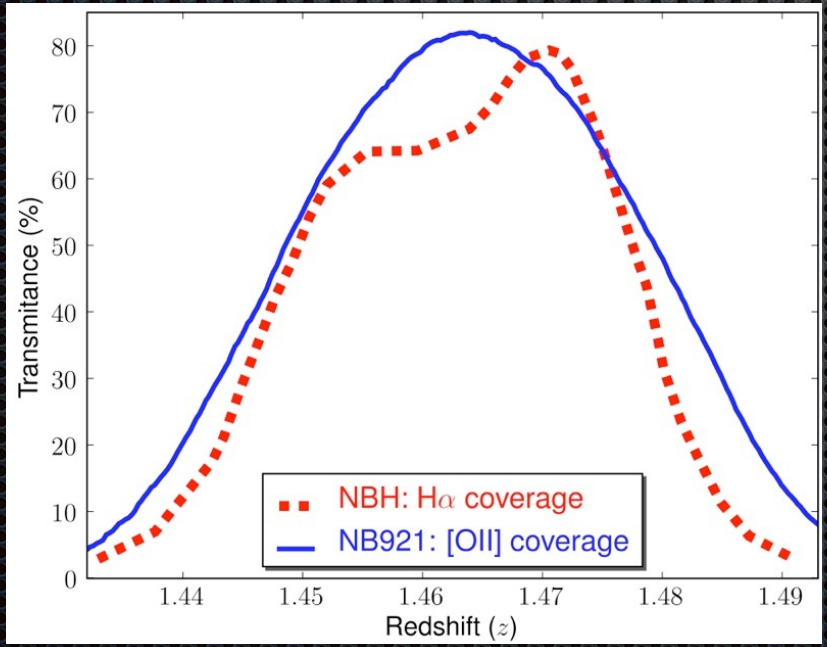


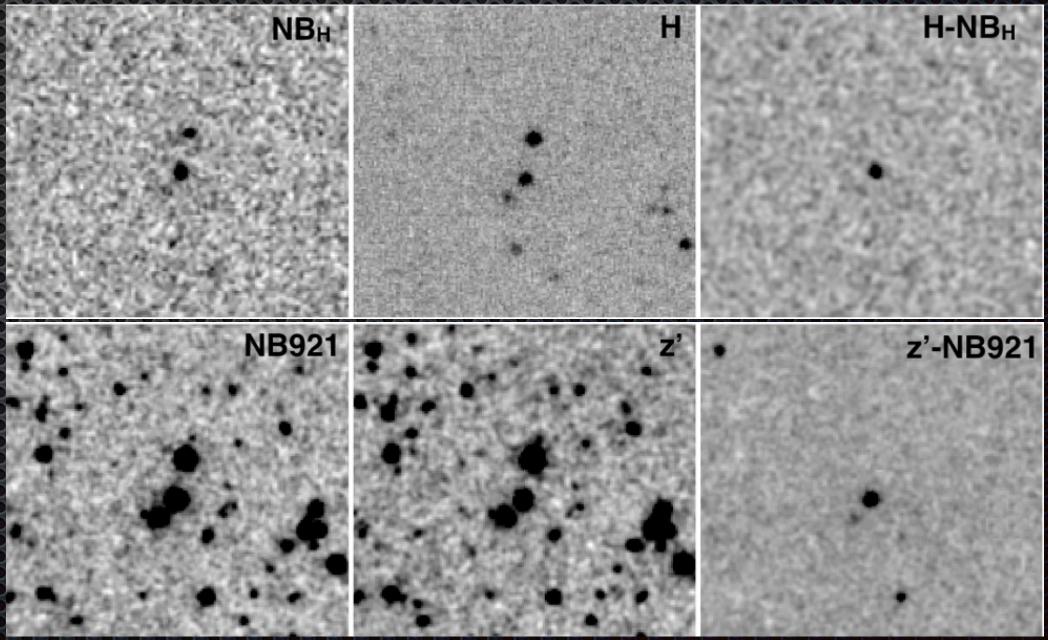


The first Hα-[OII] large double-blind survey at high-z

Sobral et al. 2012

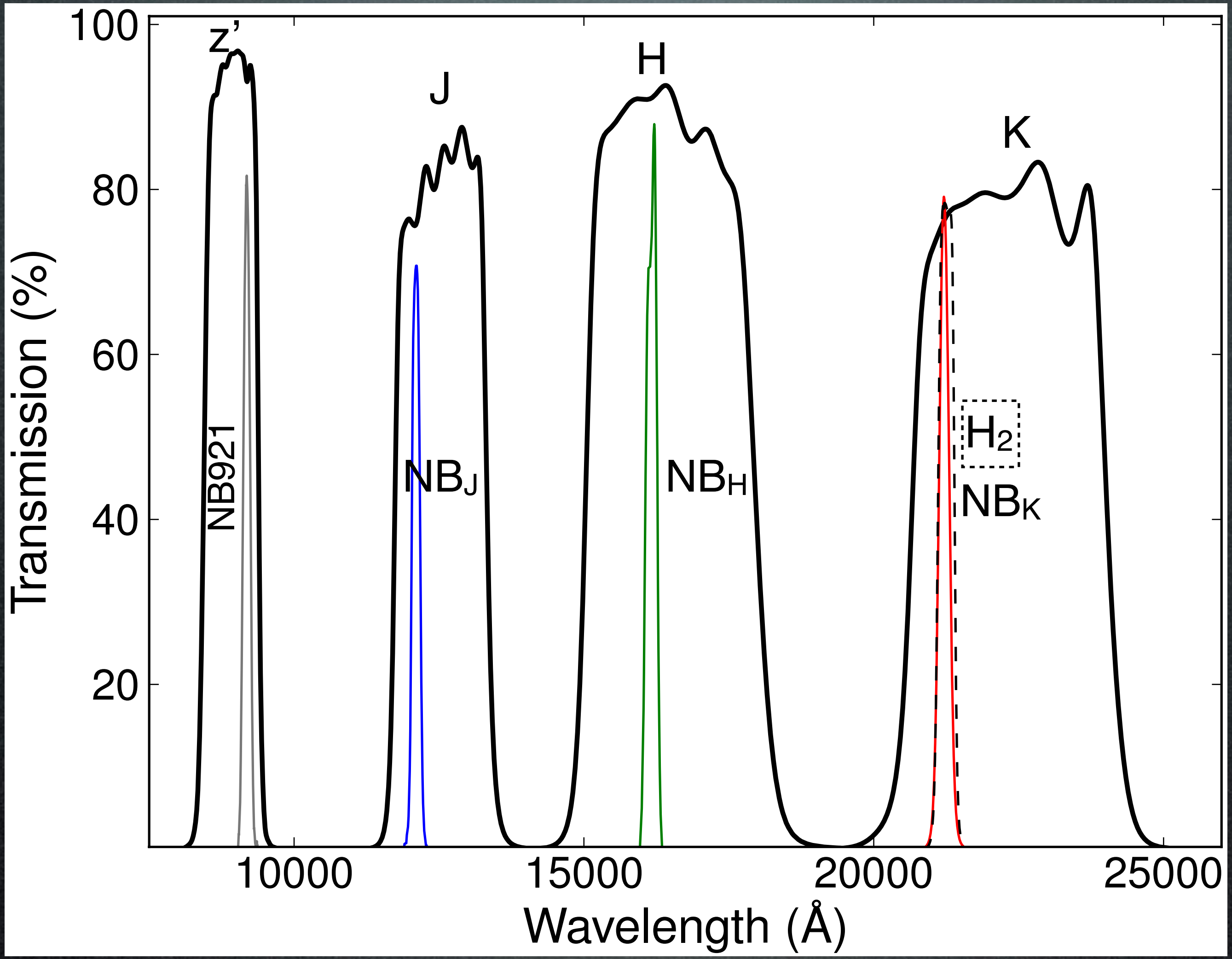
See Hayashi, Sobral et al. 2013: [OII] SFRs at z=1.5





without any need for colour or photometric redshift selections

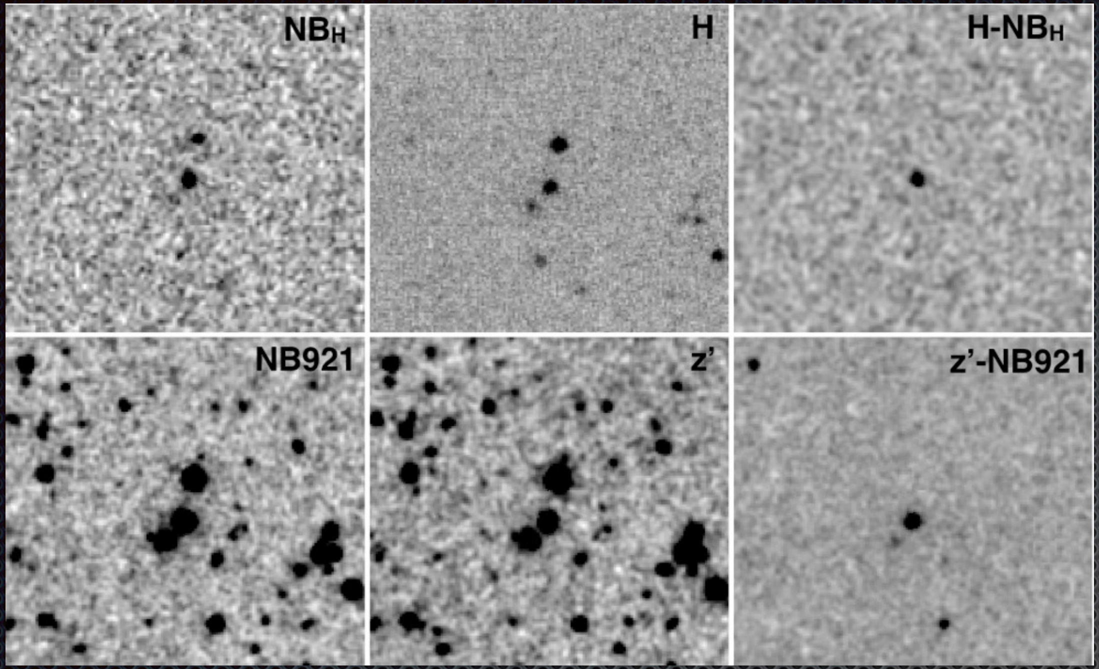
Filters combined to improve selection: double/triple line detections

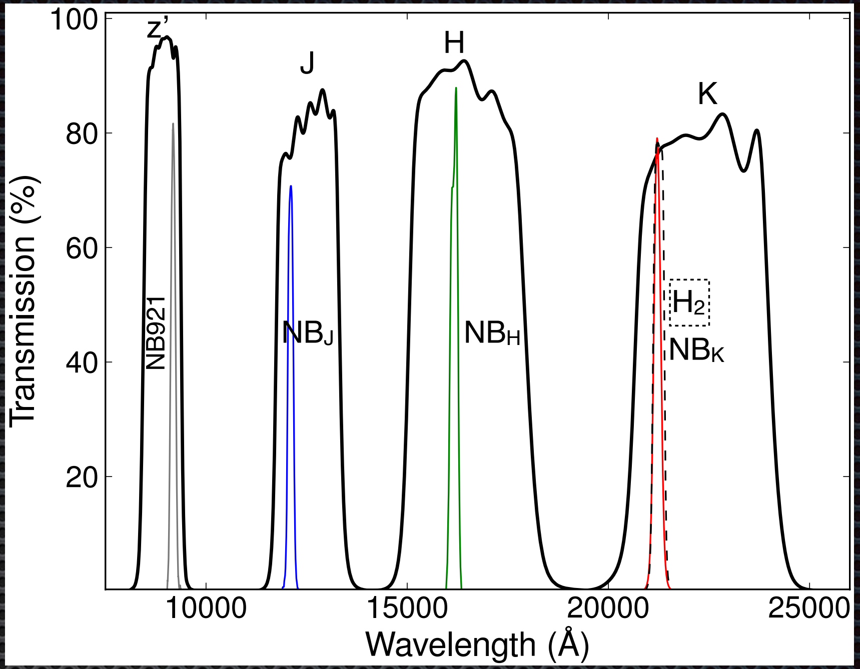


z=2.23 : [OII] (NBJ), [OIII] (NBH), Hα (NBK)

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

z=0.84 : [OIII] (NB921), Hα (NBJ)





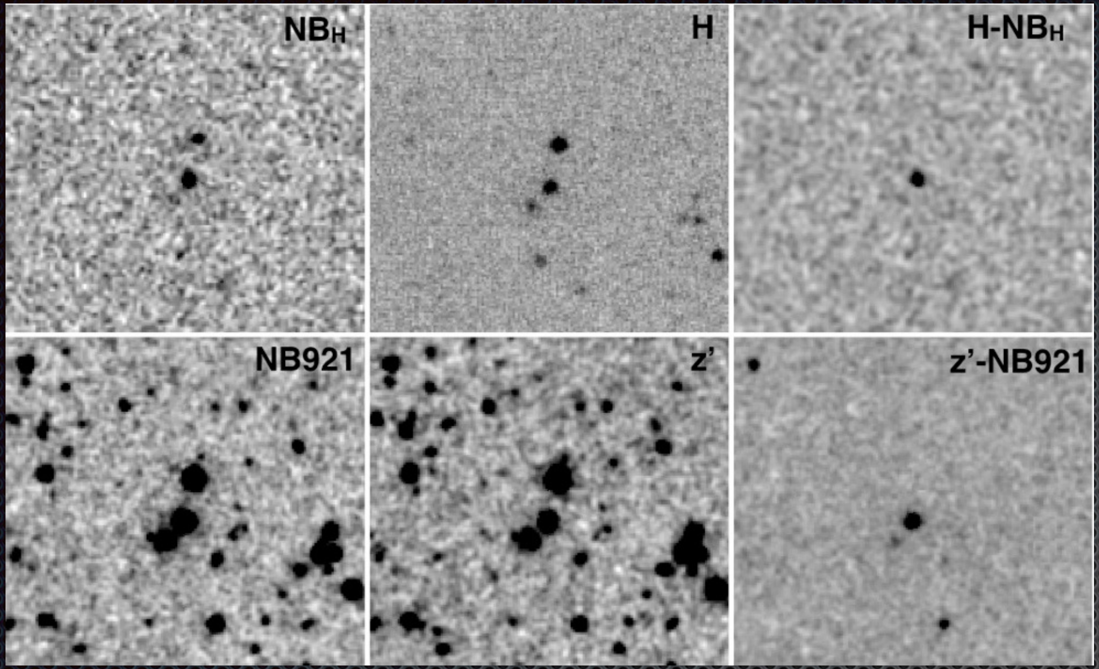
Hα emitters in HiZELS

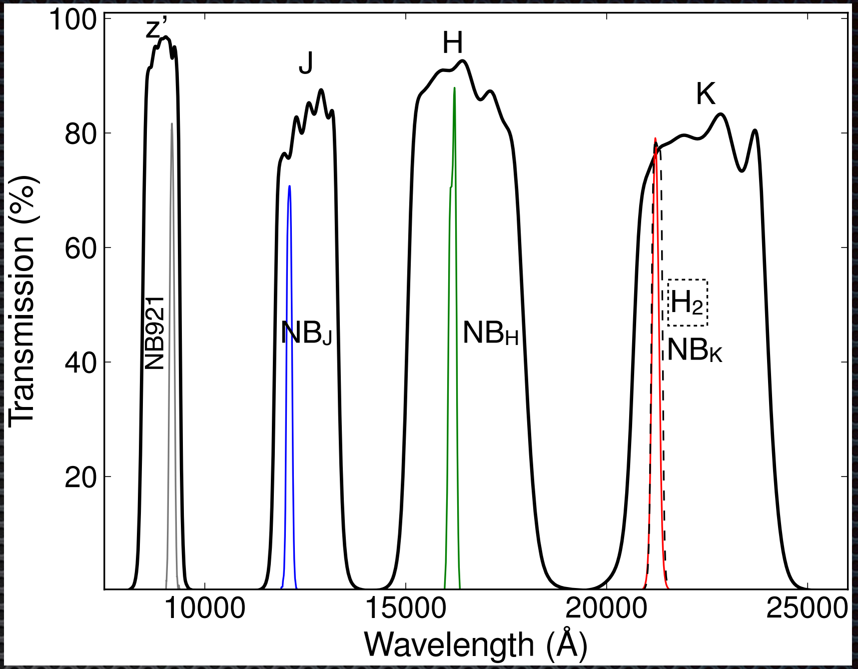
2 sq deg: COSMOS + UDS

Prior to HiZELS:

~10 sources

In DEEP2006





Hα emitters in HiZELS

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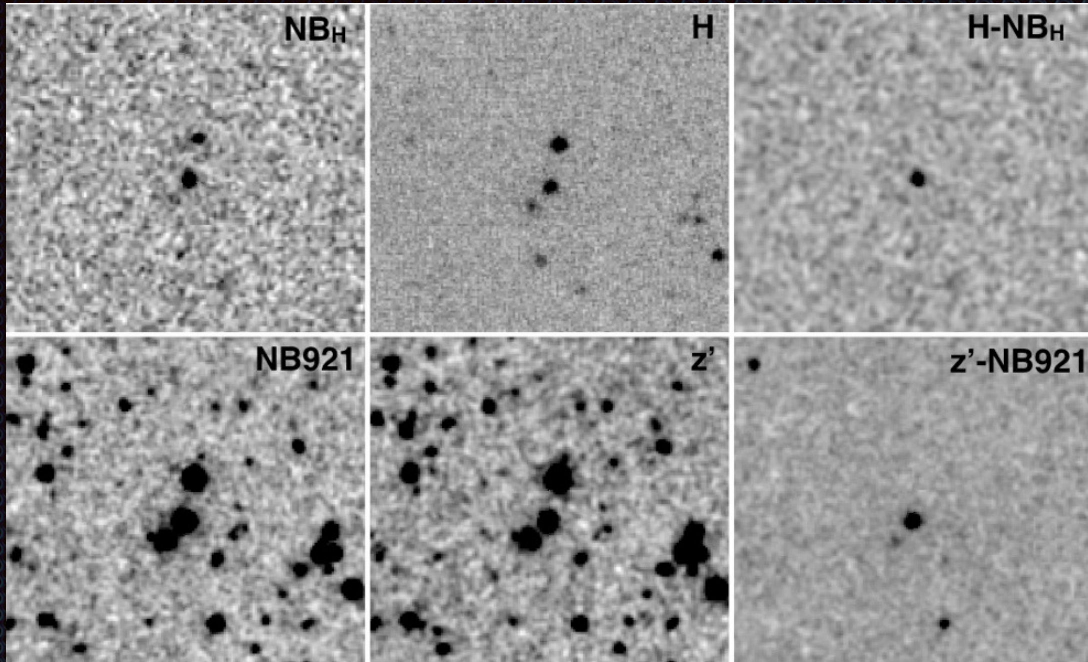
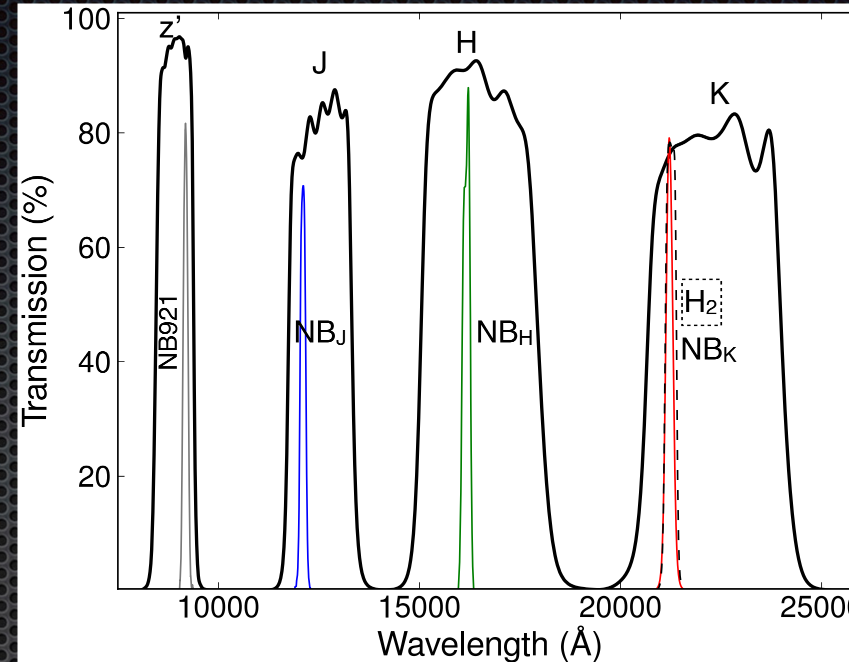
Sobral et al. 2013: (catalogues fully public!):

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





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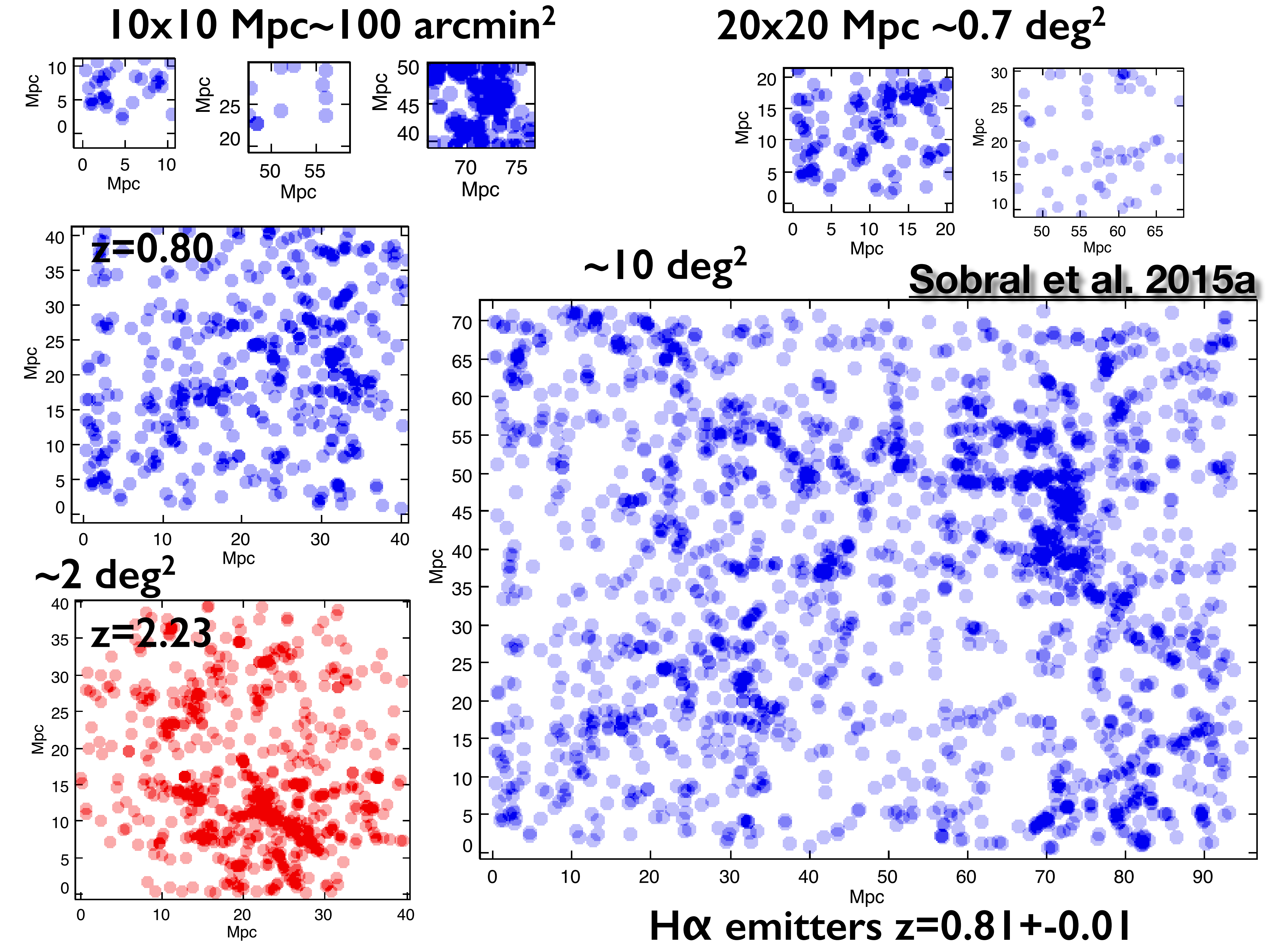
z=0.4: 1122 z=0.8: 637 z=1.47: 515 and z=2.23: 807

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

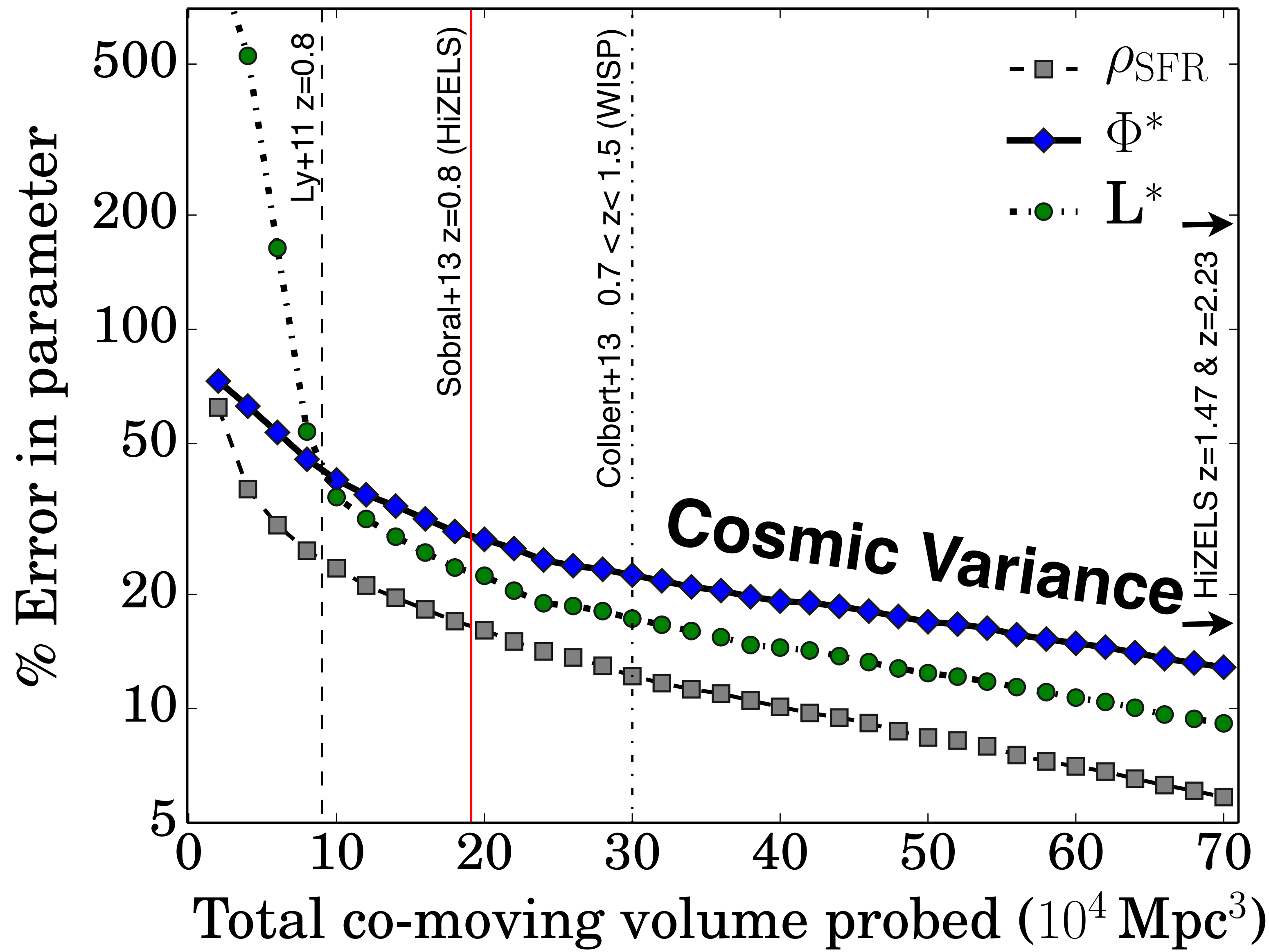
Sobral et al. 2015a


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

Why we need large, multiple volumes!

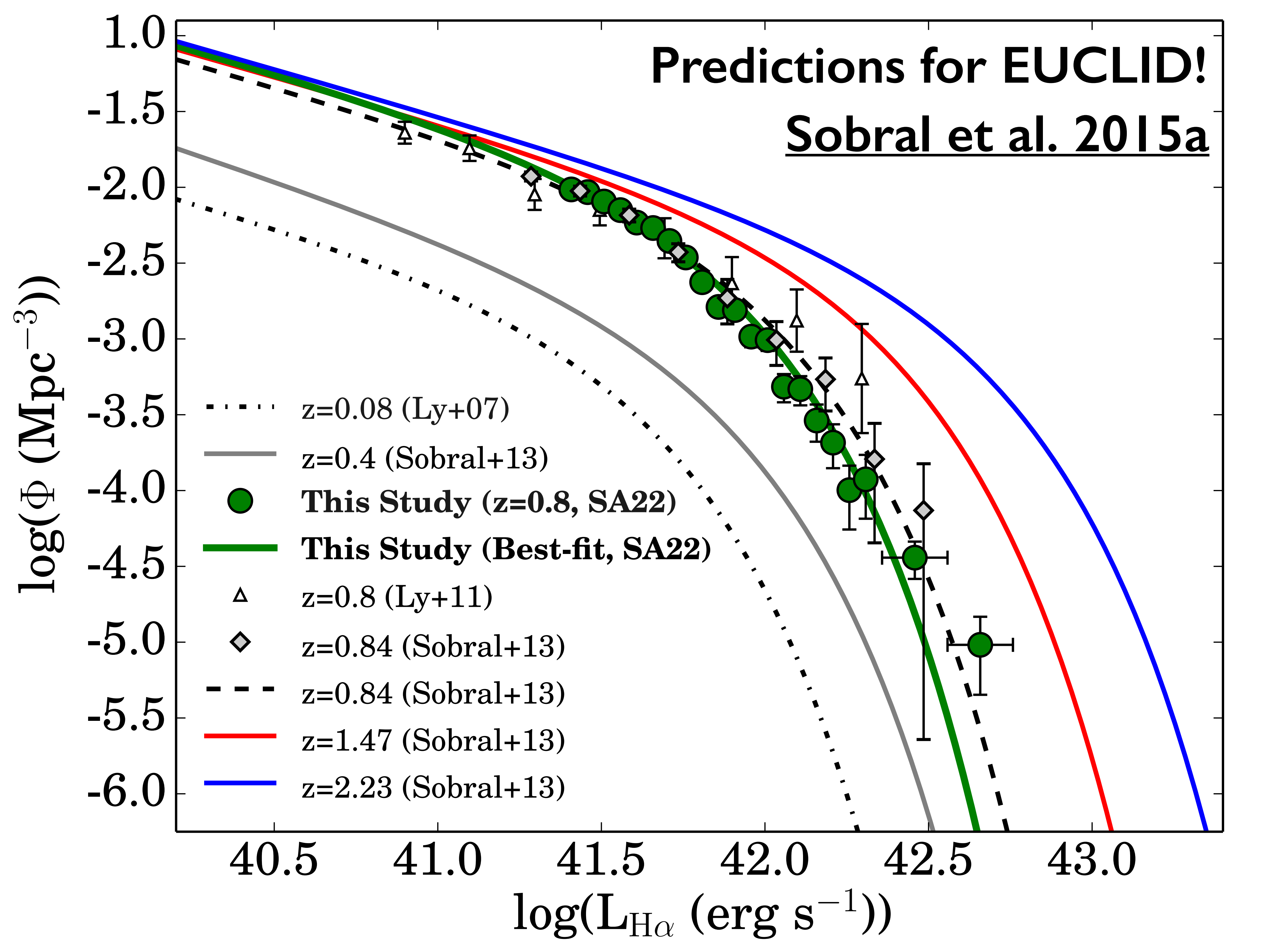
Sobral et al. 2015a

Typical areas **1 deg²** **10 deg²**

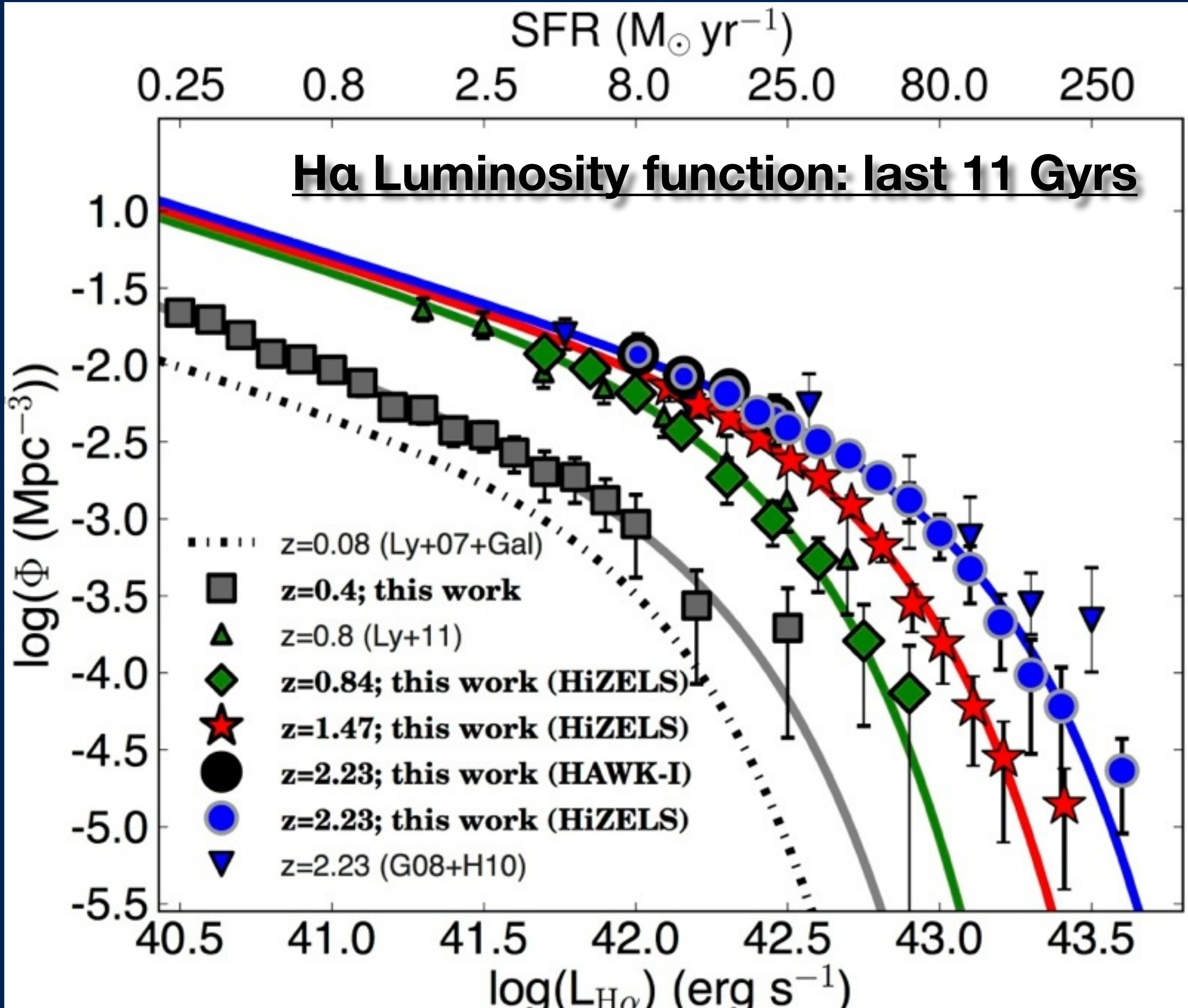


With *real* data

Errors < 20%

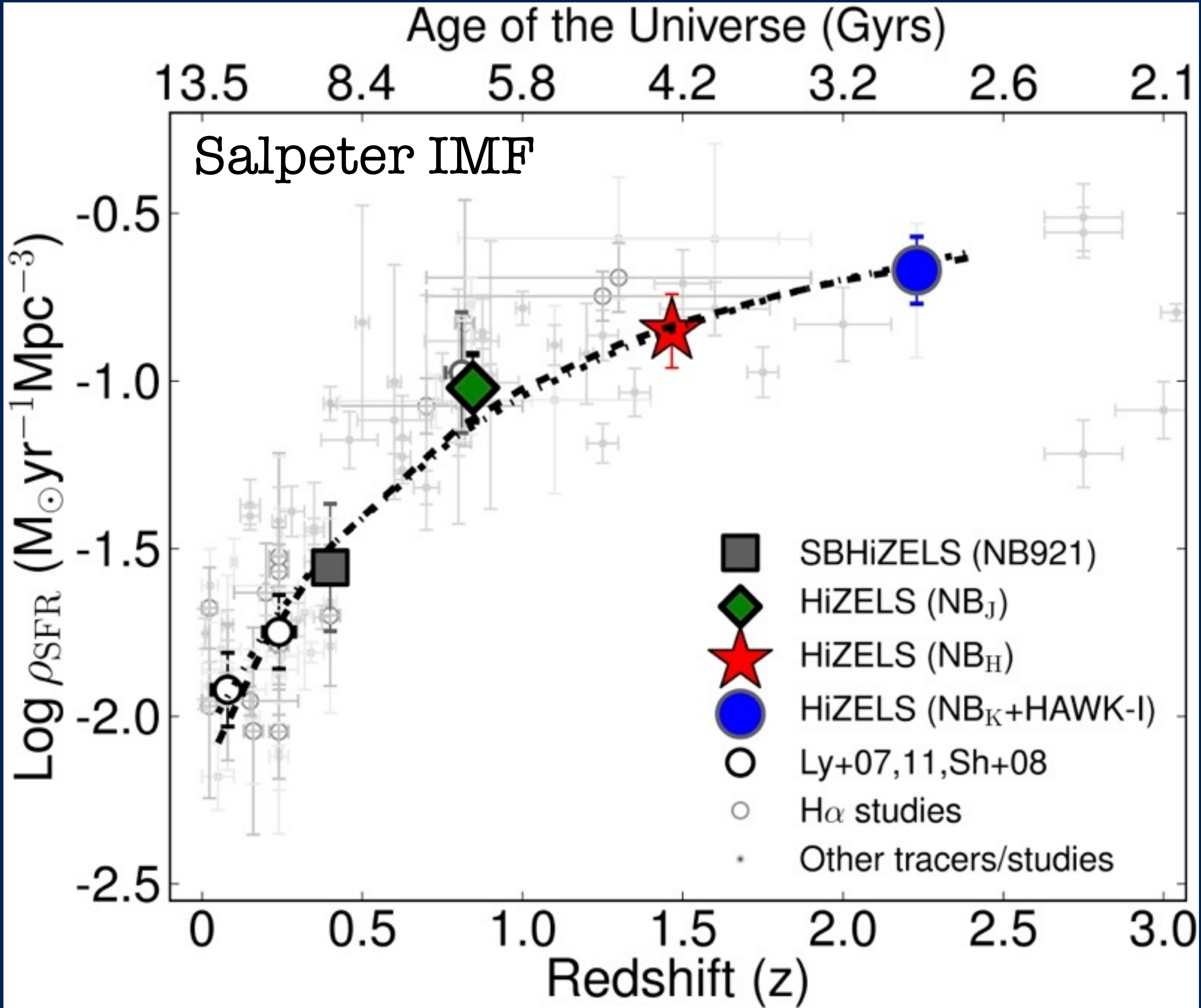


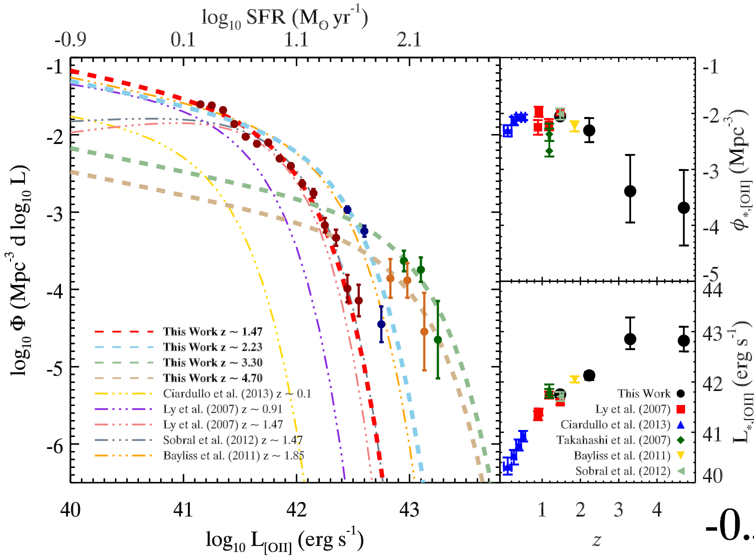
Predictions for EUCLID!
Sobral et al. 2015a
z=0.08 (Ly+07)
z=0.4 (Sobral+13)
This Study (z=0.8, SA22)
This Study (Best-fit, SA22)
z=0.8 (Ly+11)
z=0.84 (Sobral+13)
z=0.84 (Sobral+13)
z=1.47 (Sobral+13)
z=2.23 (Sobral+13)
log(Φ (Mpc^{-3}))
log(L$_{H\alpha}$ (erg s^{-1}))
1.0
-1.5
-2.0
-2.5
-3.0
-3.5
-4.0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



Sobral et al. 2013a

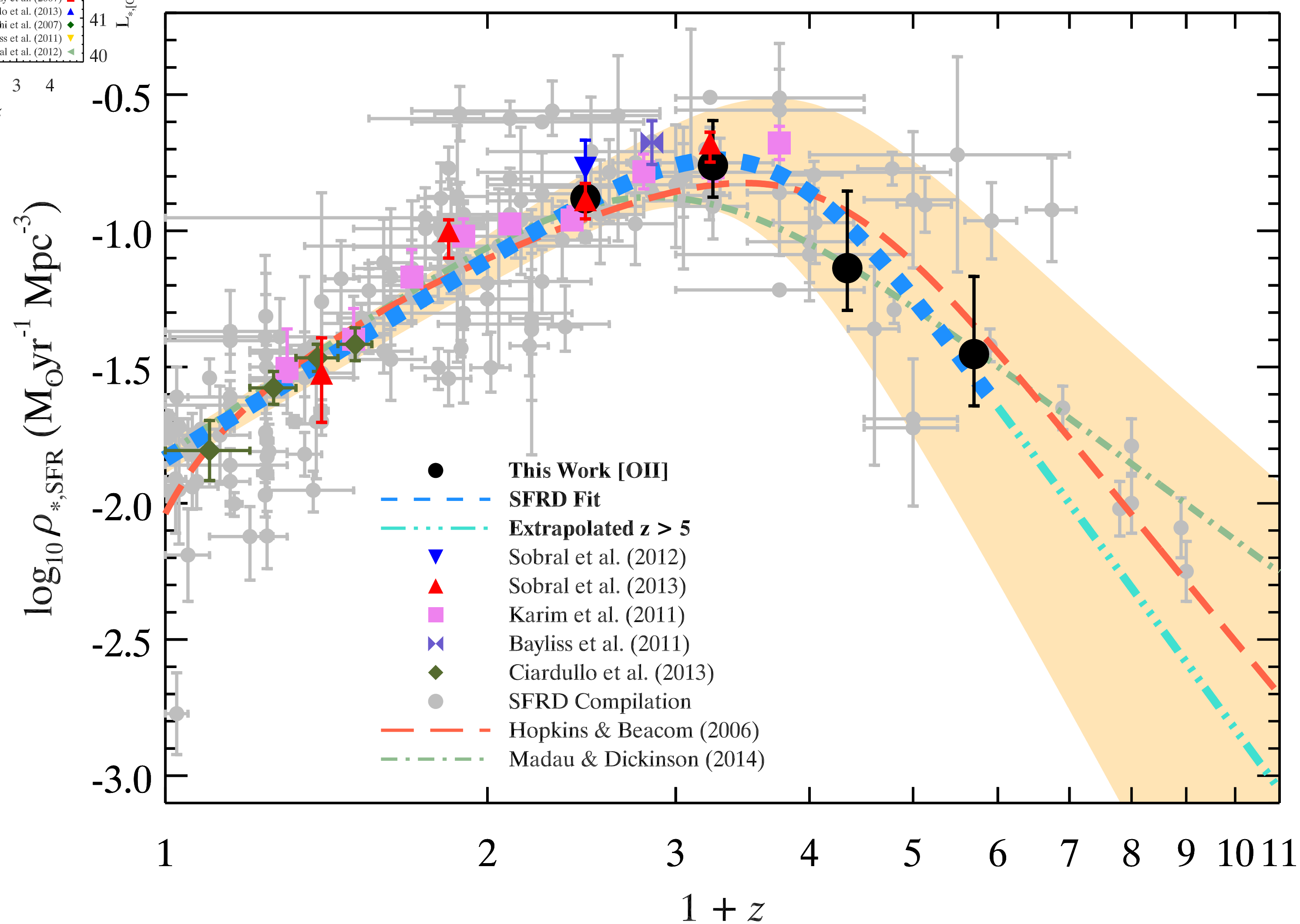
Sobral et al. 2013a Fully self-consistent SFH of the Universe





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

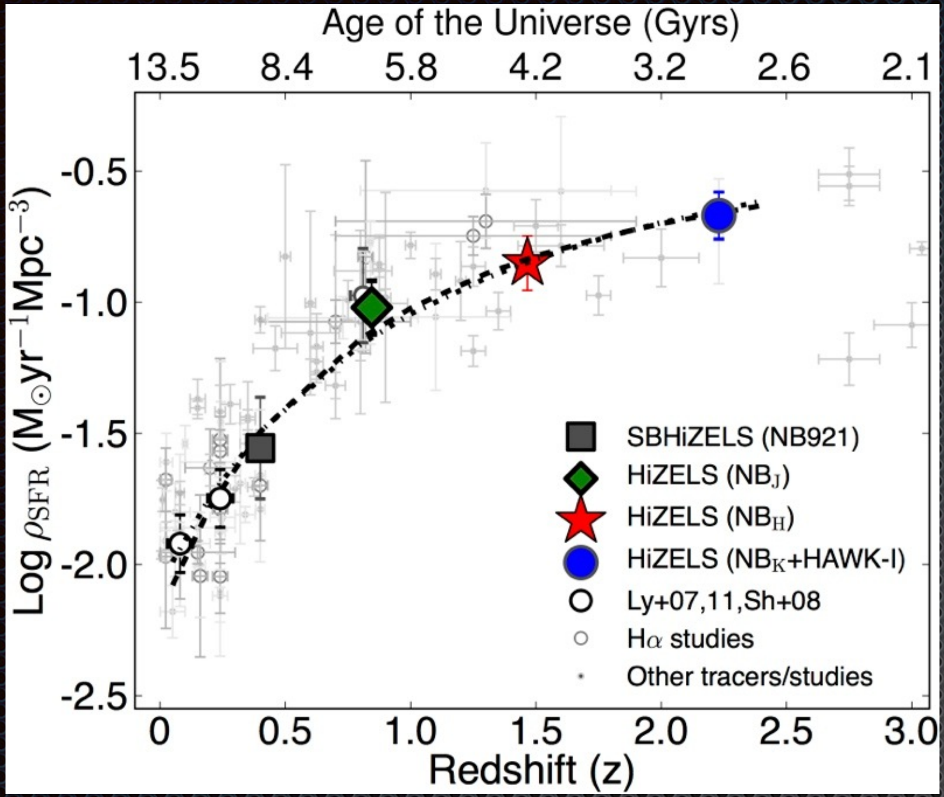
Khostovan, Sobral, Mobasher et al. 2015



Ali Khostovan

Go see his poster!

See also Tomoko Suzuki's talk



Hα Star formation History

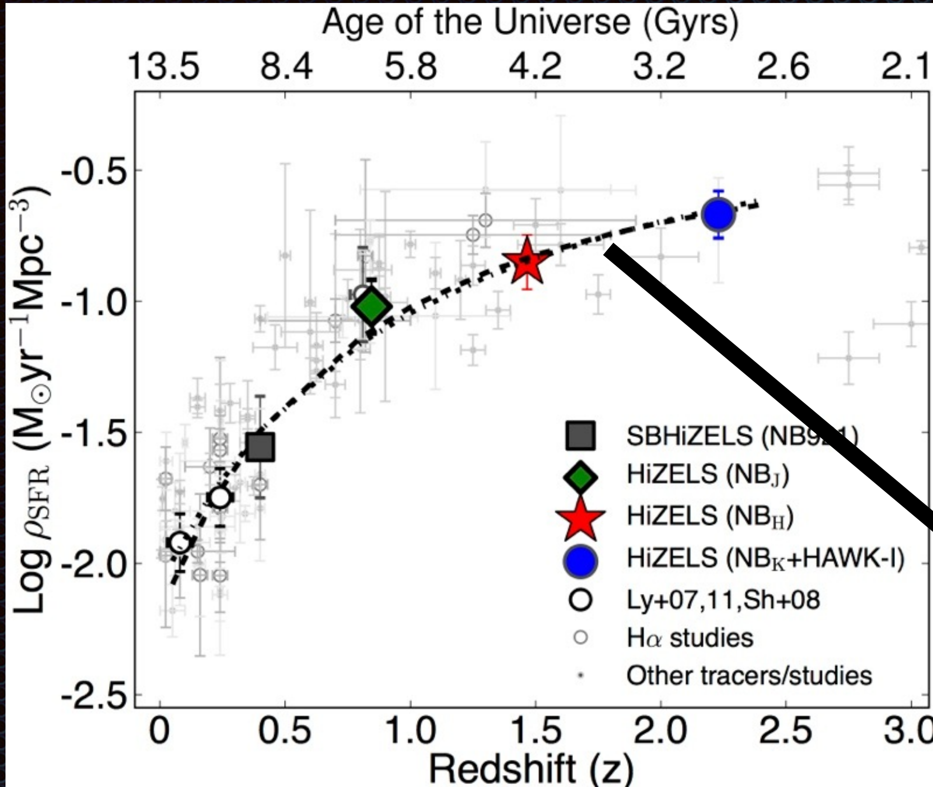
Strong decline with time

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

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

Sobral+13a

Hα Star formation History



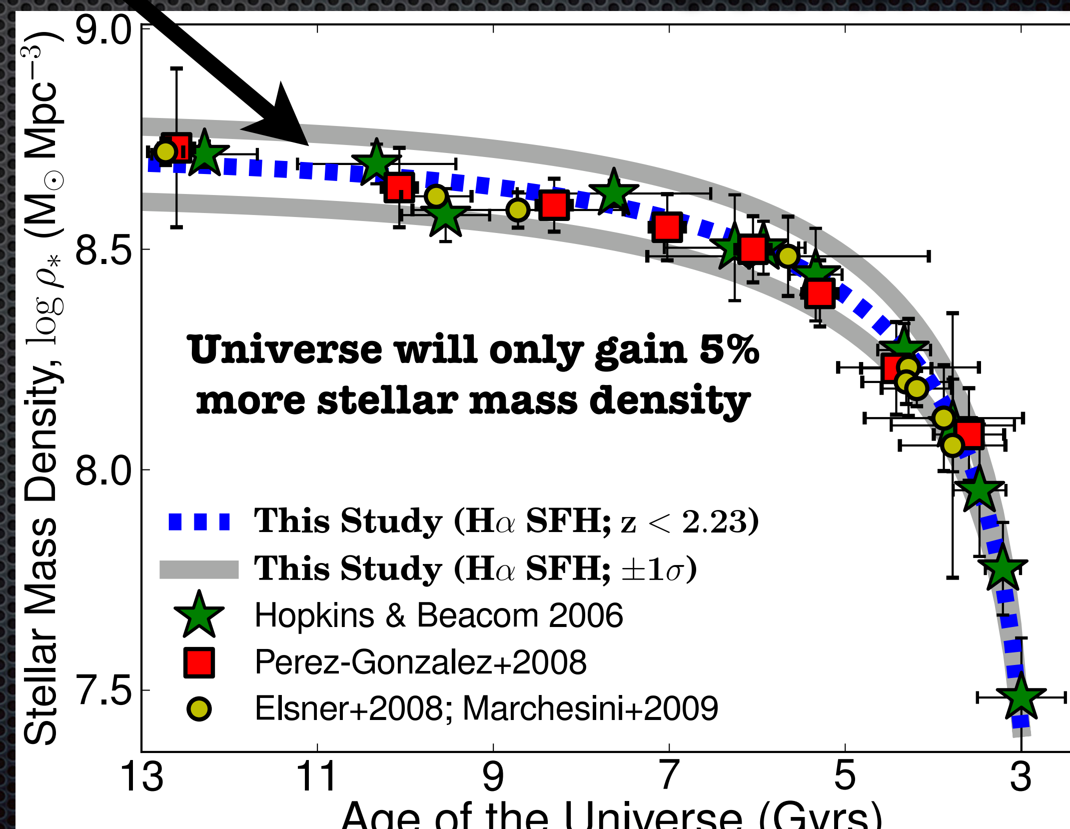
Strong decline with time

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

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

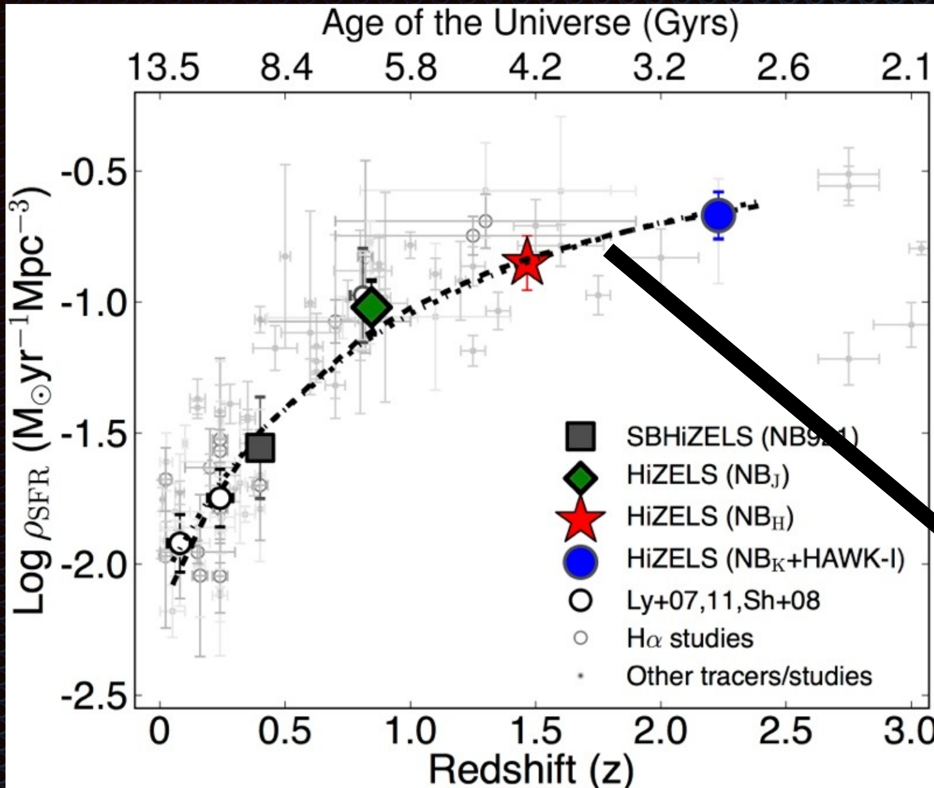
Sobral+13a

Stellar Mass density evolution assembly



Star formation history prediction matches observations

Hα Star formation History



Strong decline with time

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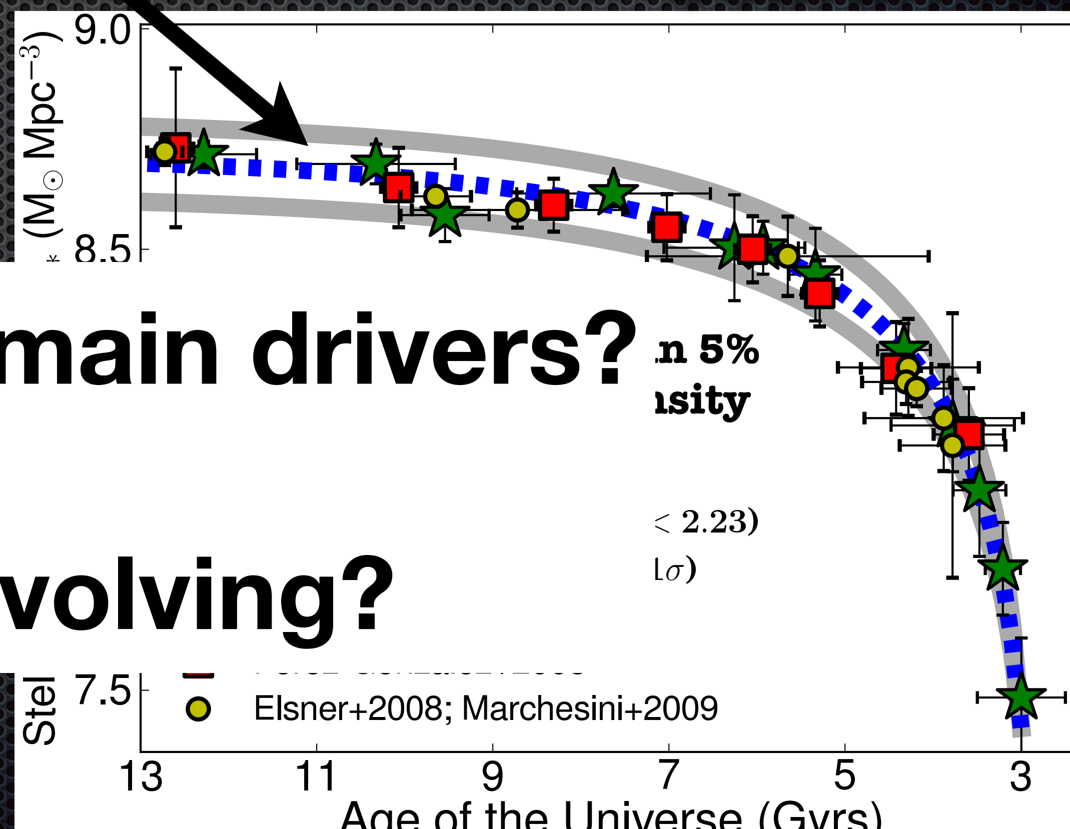
$\log_{10}$(SFRD) = -2.1/(1+z)

Sobral+13a



Stellar Mass density evol

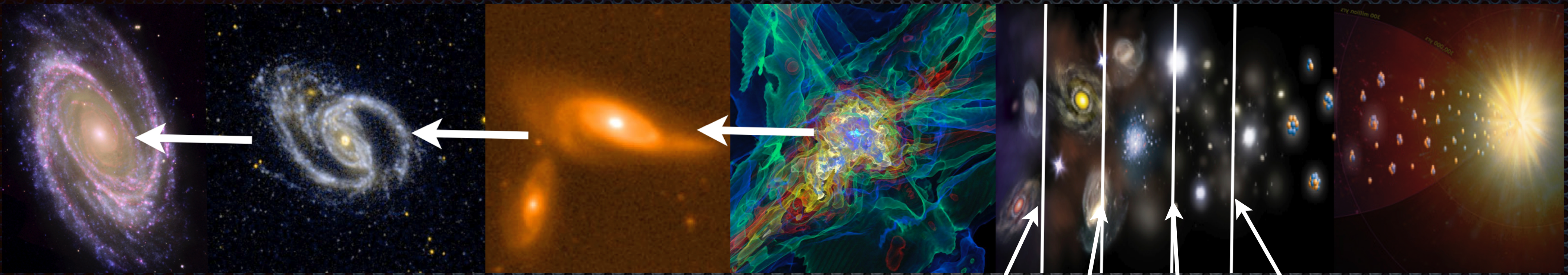
Star f

prec

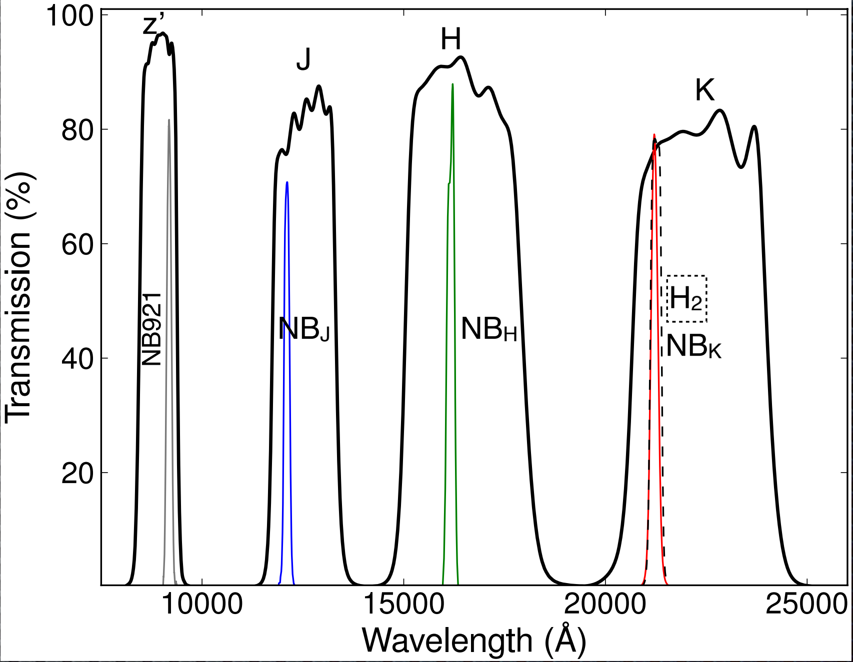
observations

What are the main drivers?

What's evolving?



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

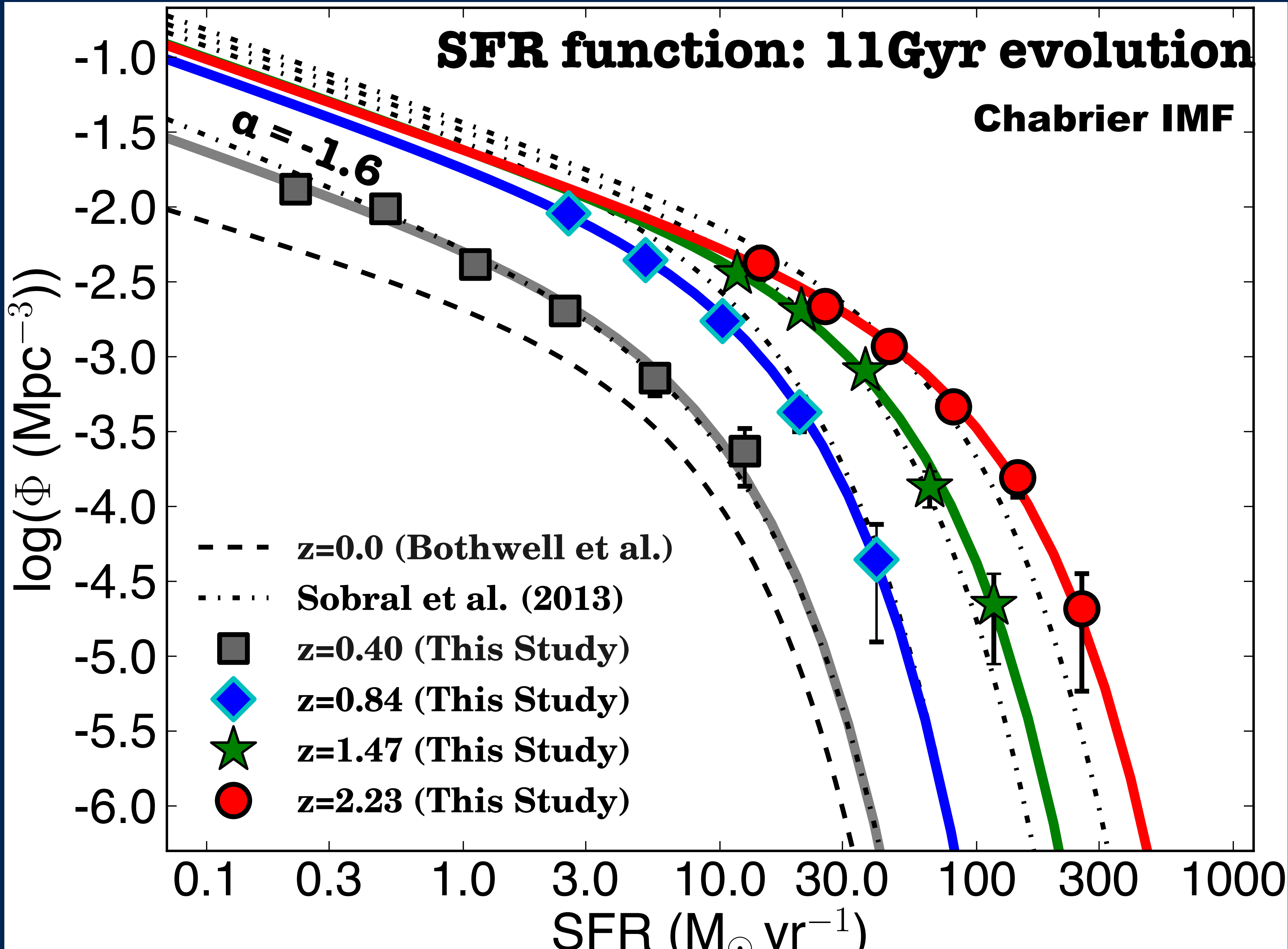


Check out the latest results:

Size + merger evolution: Stott+13a
Metallicity evolution + FMR: Stott+13b,14
[OII]-Ha at high-z: Hayashi+13,Sobral+12
Dust properties: Garn+10,S+12,Ibar+13
Clustering: Geach+08,13, Sobral+10
[OII]+[OIII] LFs to z~5: Khostovan+15

Catalogues are public!

Dynamics: e.g. Swinbank+12a,b, Sobral+13b
Lyman-alpha at z>7: Sobral+09b,Matthee+14
Environment vs Mass: e.g. Sobral+11, Koyama+13
AGN vs SF: Garn+10, Lehmer+13, Sobral+15c



Sobral et al. (2014)

SFR function: Strong SFR* evolution

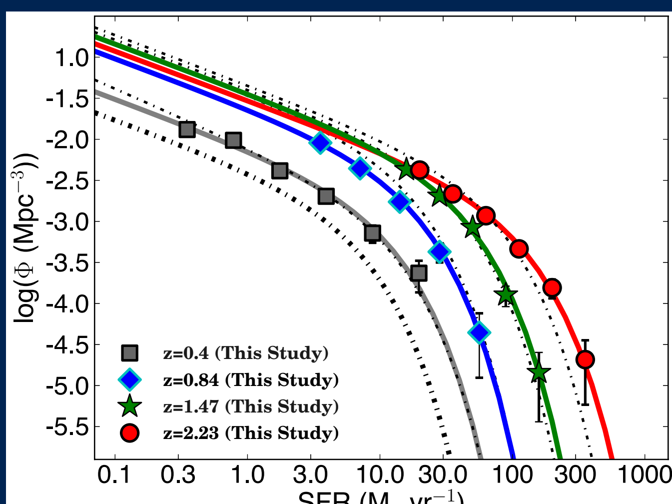
$\mathbf{SFR^*(T)=10^{(4.23/T+0.37)}\ M_{\odot}/yr}$
T, Gyrs

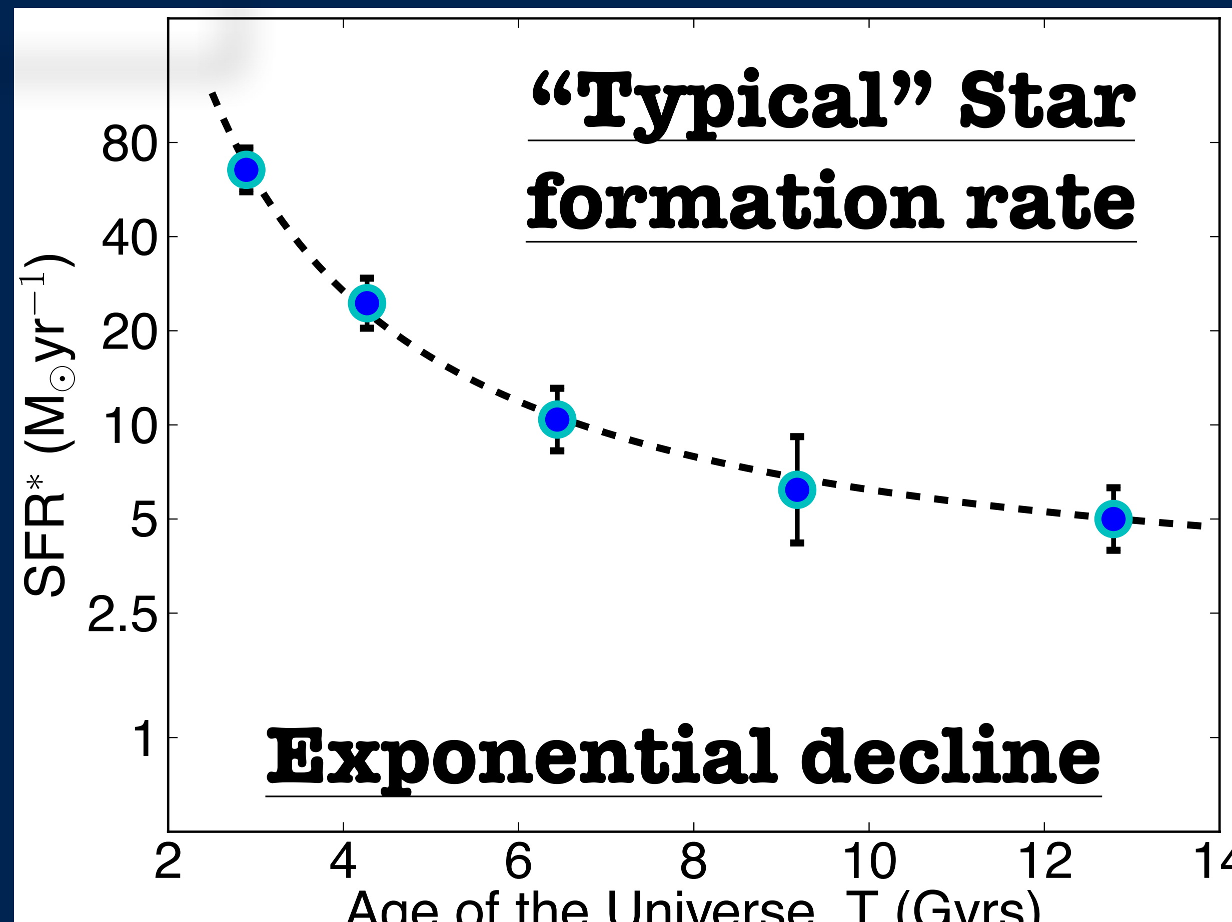
13x decrease over last 11 Gyrs

Sobral+14, MNRAS

Faint-end slope: α = -1.6

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





Φ^*

z=1

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

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

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Sobral+14

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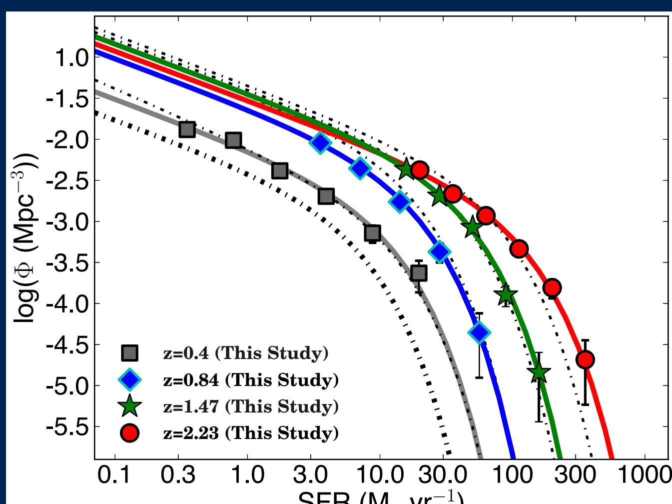

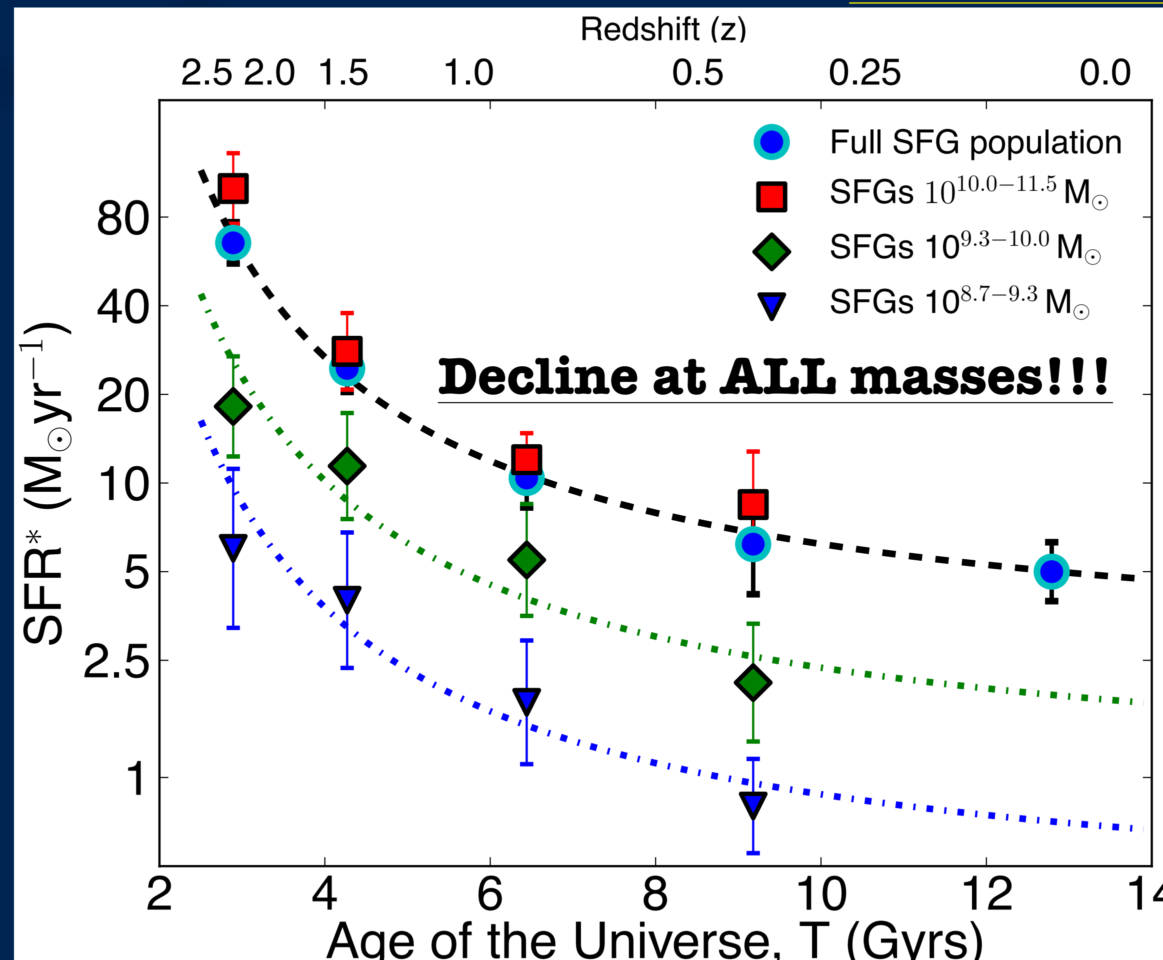

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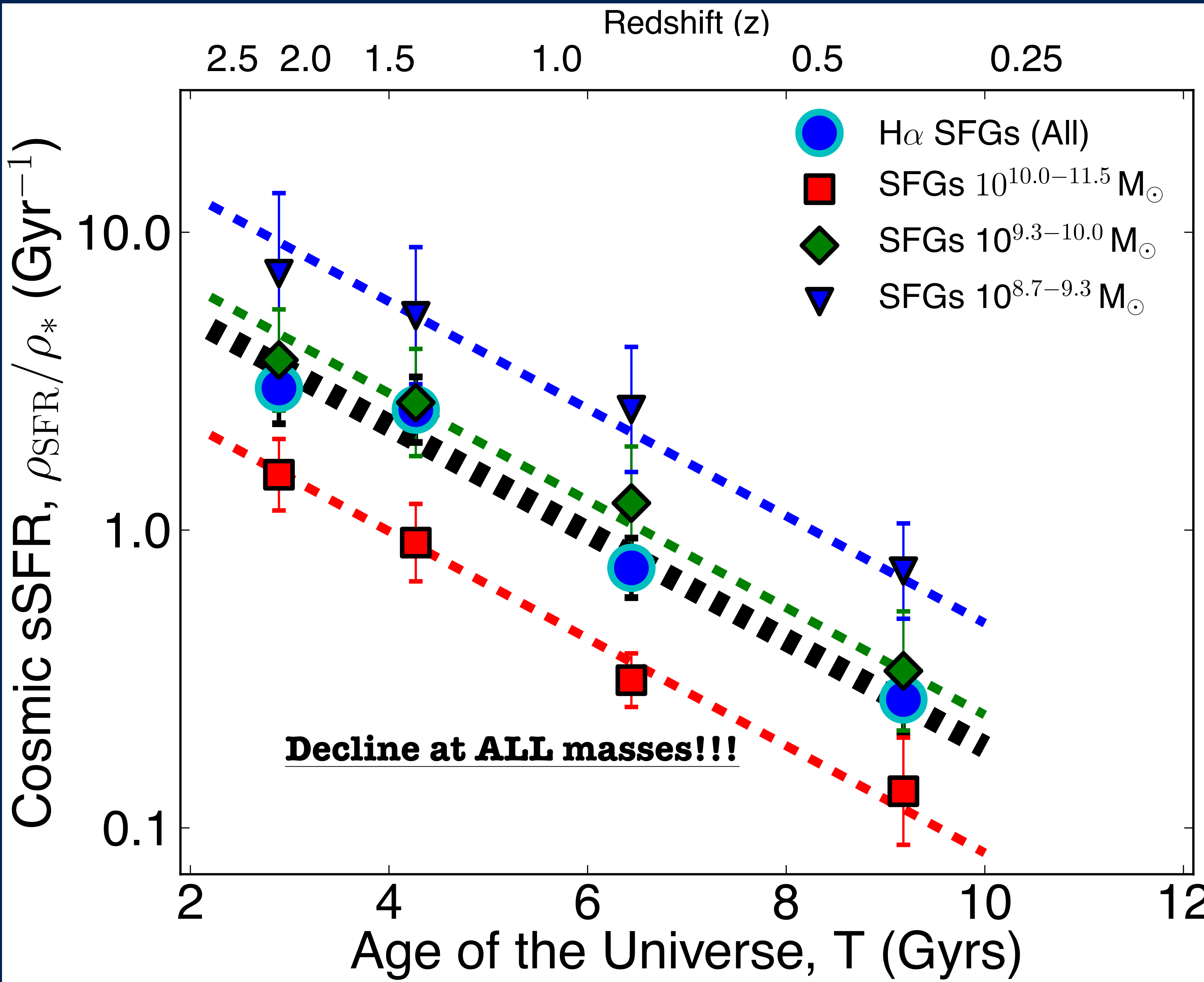
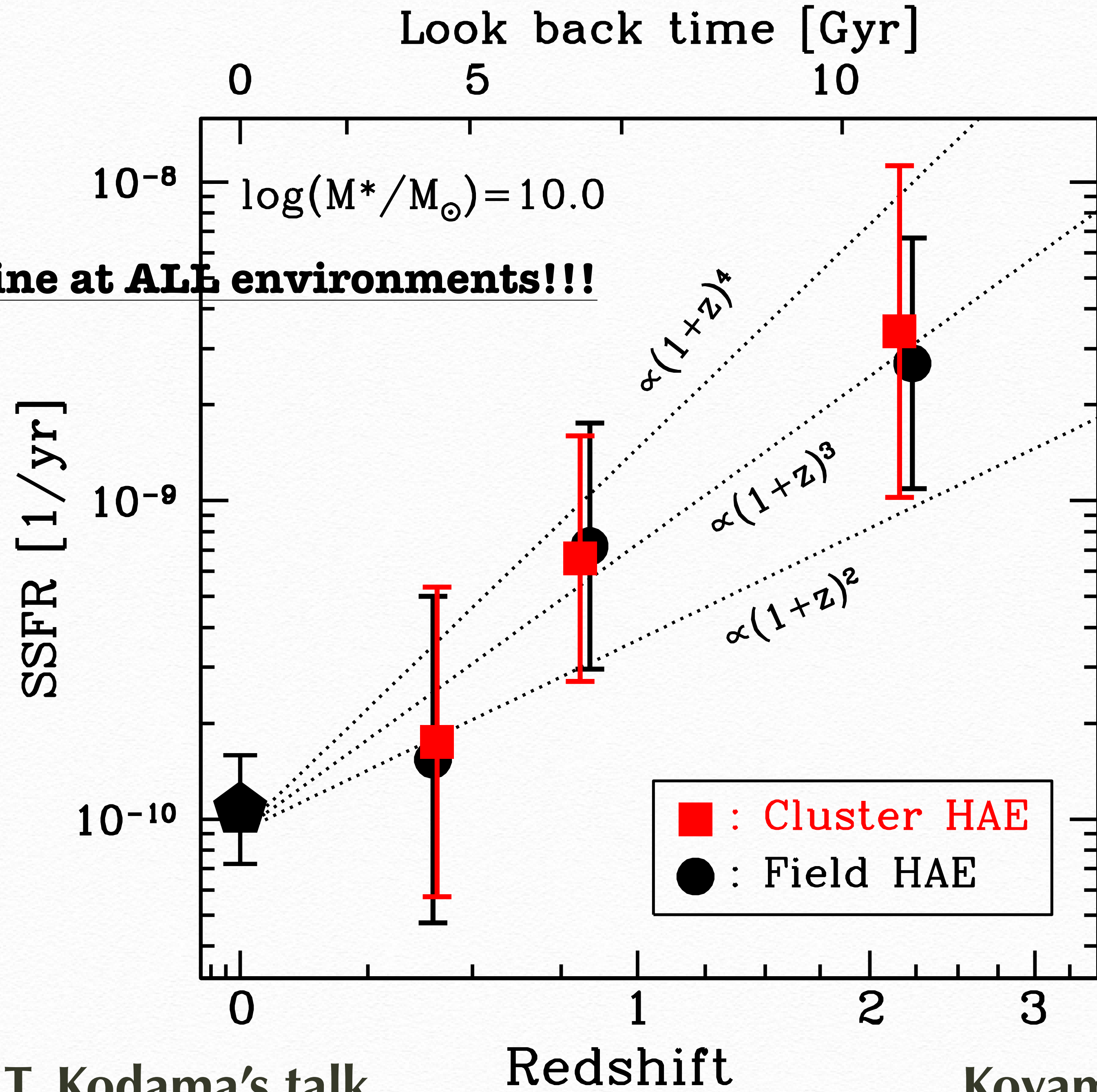
T, Gyrs


Redshift (z)
2.5 2.0 1.5 1.0 0.5 0.25
Hα SFGs (All)
SFGs $10^{10.0-11.5}$ $M_\odot$
SFGs $10^{9.3-10.0}$ $M_\odot$
SFGs $10^{8.7-9.3}$ $M_\odot$
Cosmic sSFR, $\rho_{\rm SFR}/\rho_*$ (Gyr^{-1})
10.0
1.0
0.1
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!!!



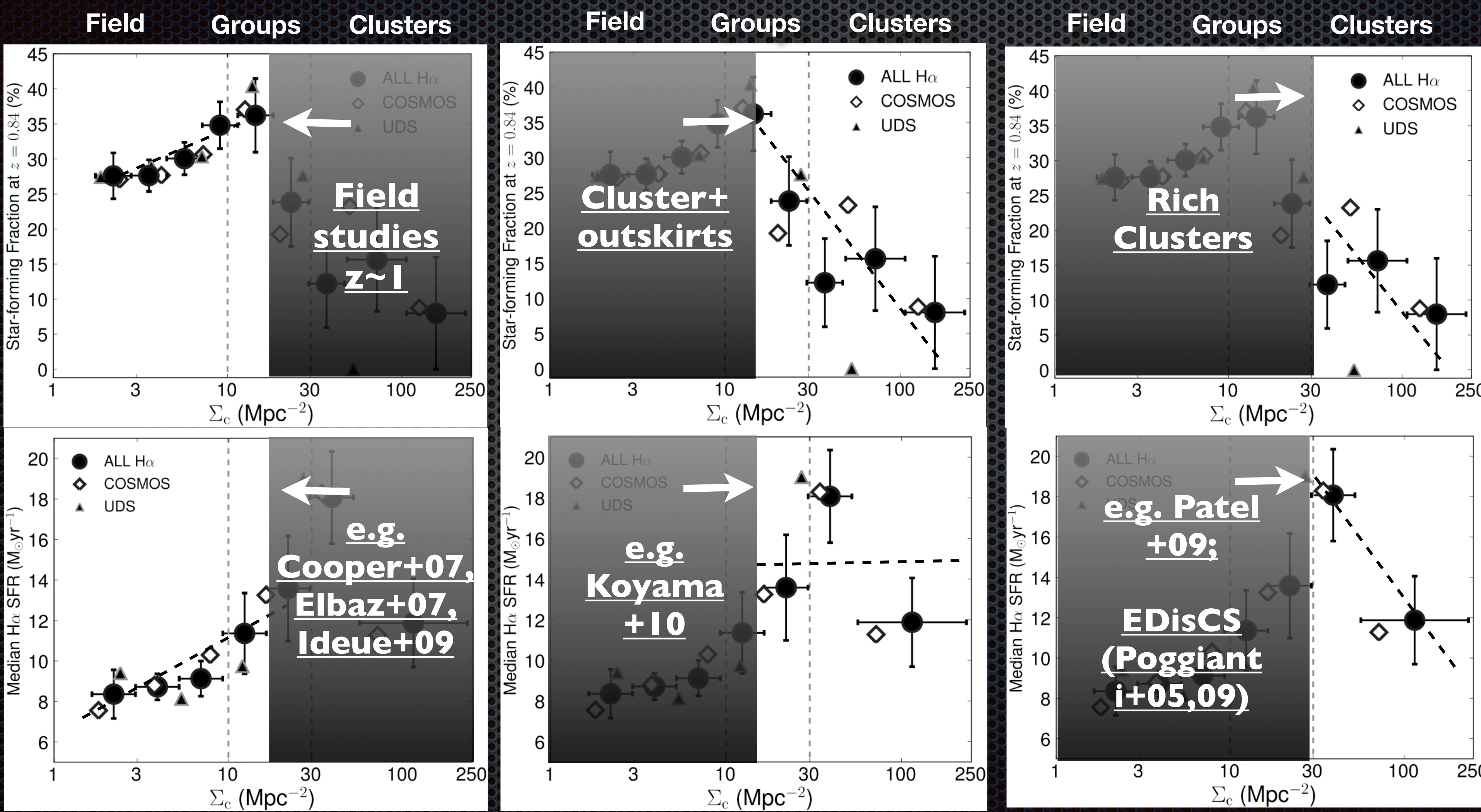
see T. Kodama's talk

Koyama et al. 2013

Environment at z~1

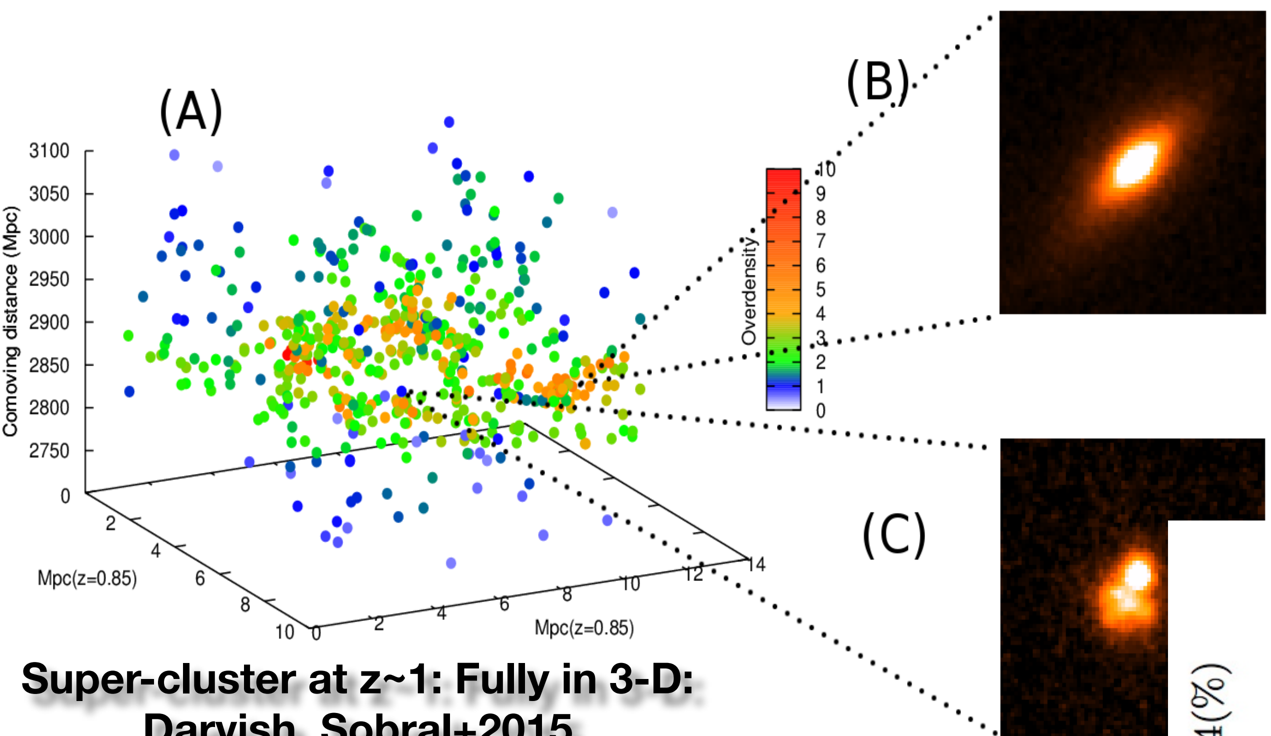
Sobral et al. (2011)

Results reconcile previous apparent contradictions

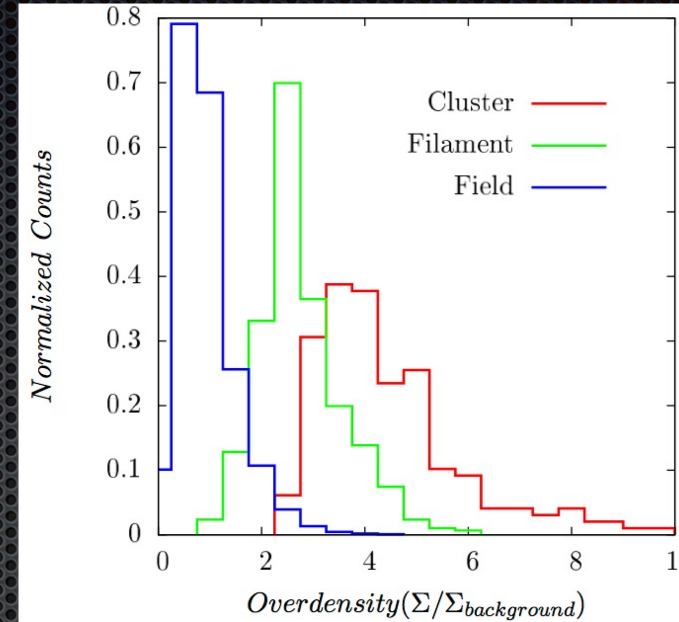


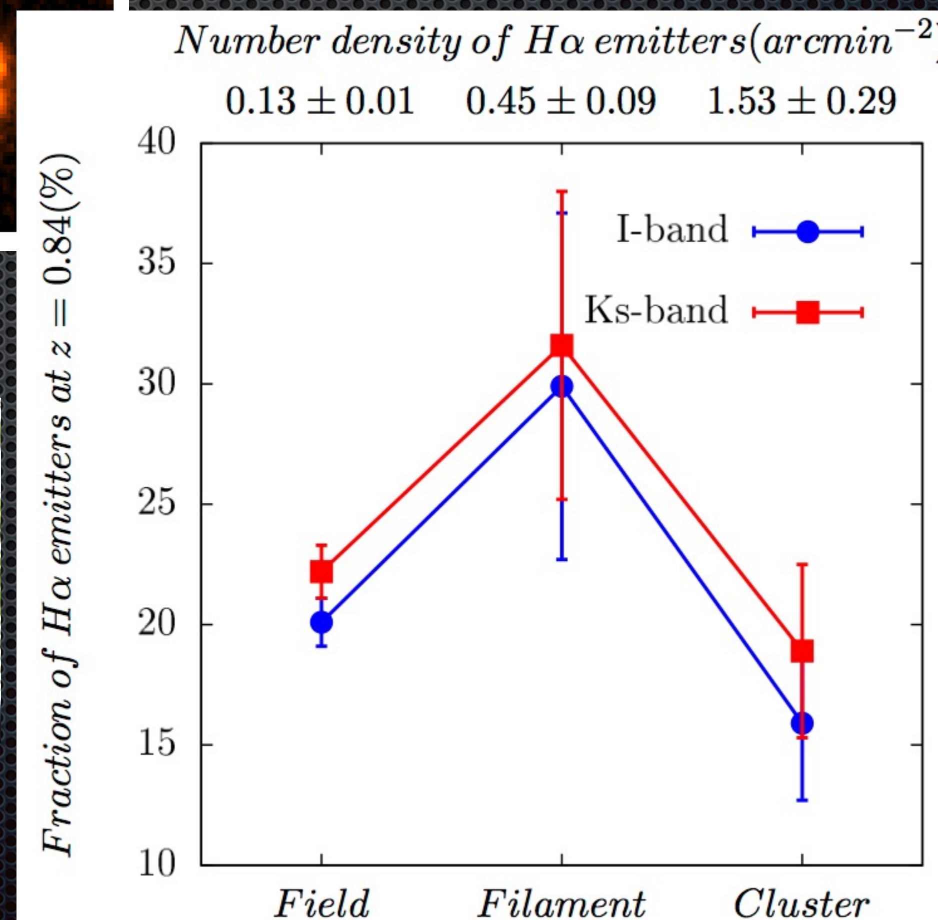
see T. Kodama's talk

Filaments are important!

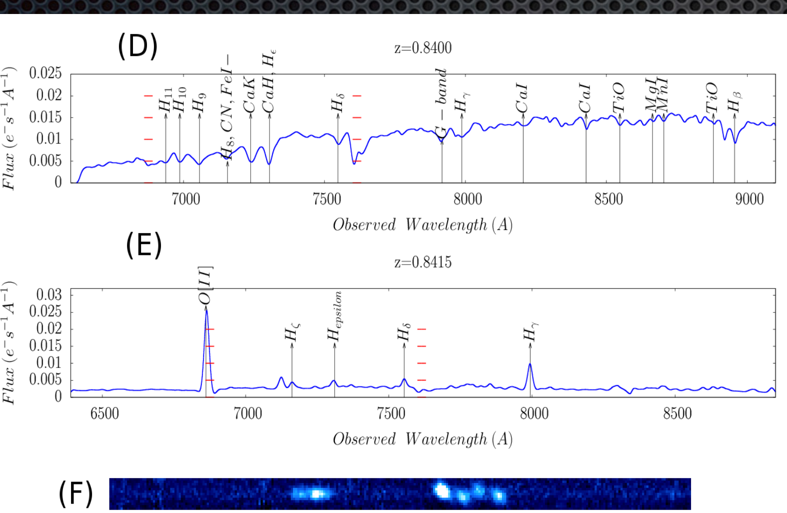


Super-cluster at z~1: Fully in 3-D: Darvish, Sobral+2015





Darvish, Sobral+2014

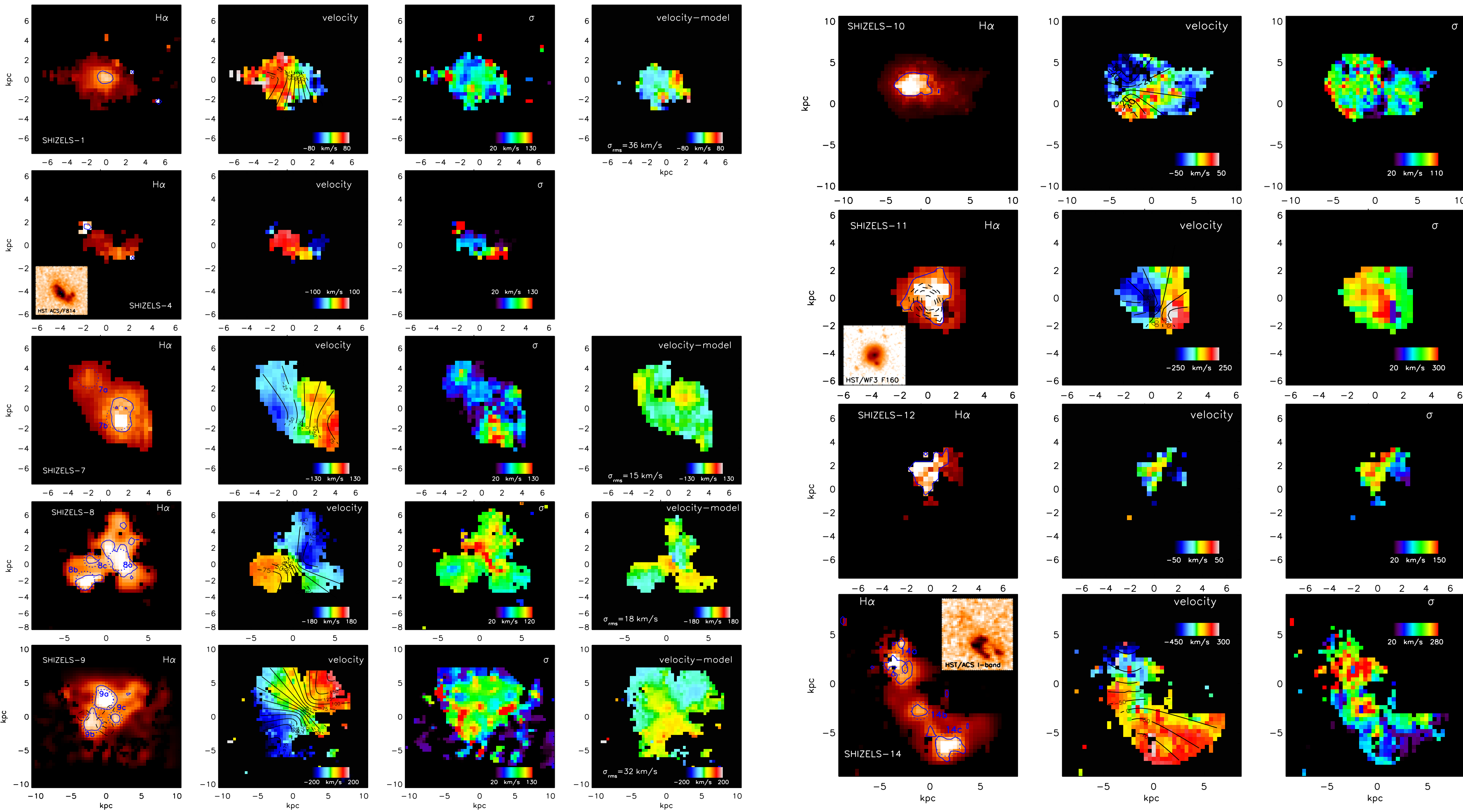


Behnam Darvish

Galaxy Dynamics at z~0.8-2.2

Swinbank, Sobral al. 2012

From AO IFU observations



~45 hours of VLT time

Galaxy Dynamics at z~0.8-2.2

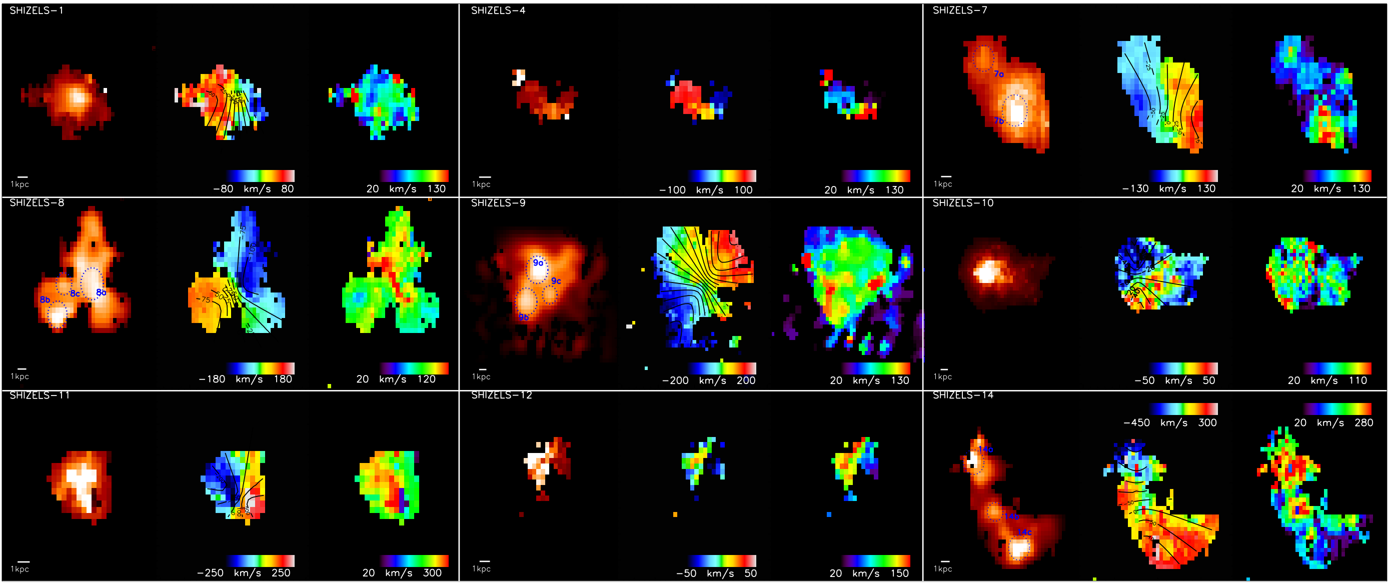
Swinbank, Sobral et al. 2012

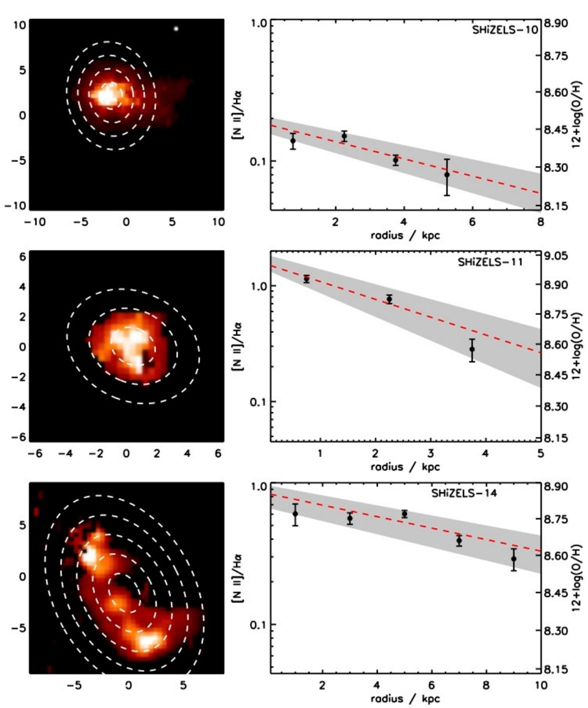
Swinbank al. 2012b

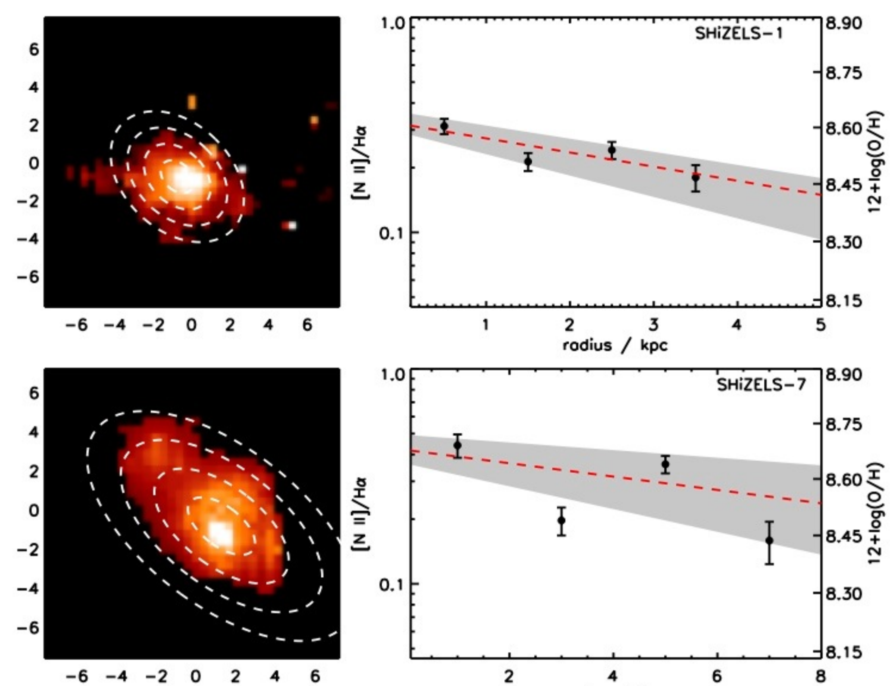
(MNRAS/ApJ):

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

- Negative metallicity gradients: “inside-out” growth

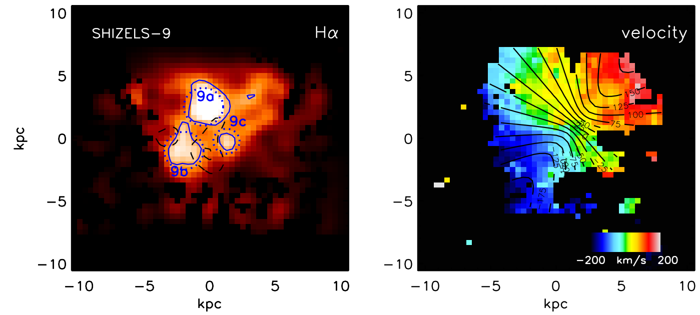


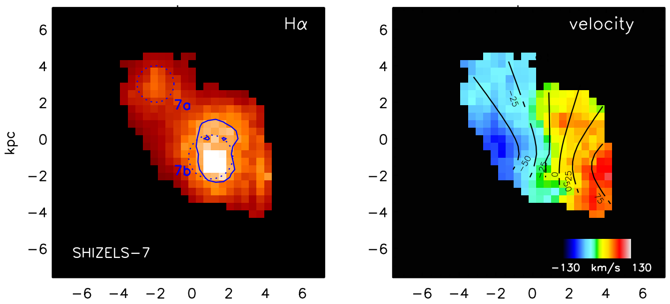




SINFONI

~50 hours of VLT time

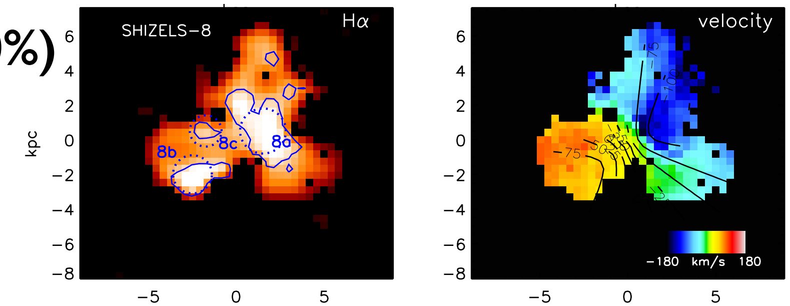




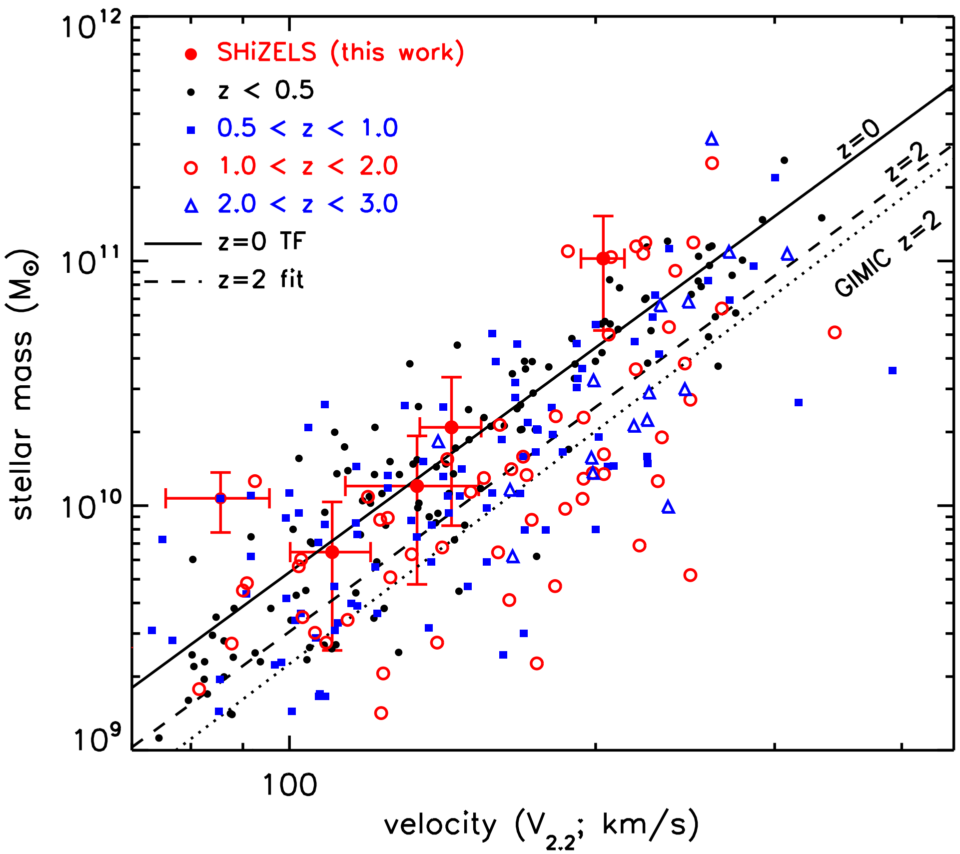
Mostly disks-like (~70-80%)

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

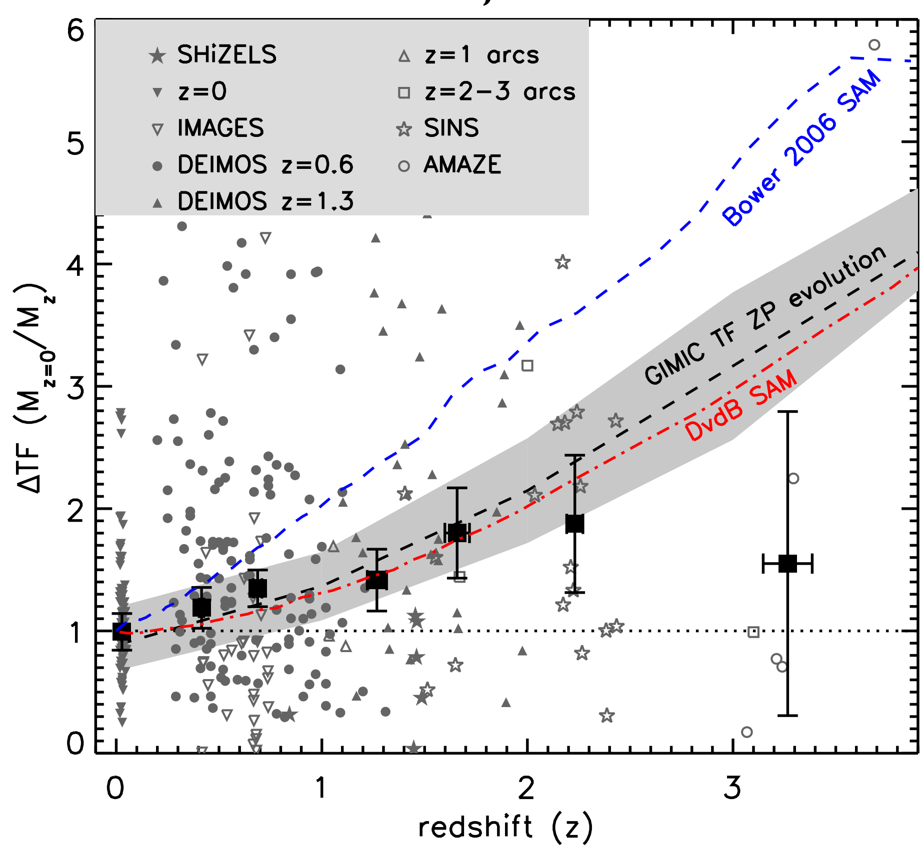
Rotation ~70-200 km/s



Stellar mass TF relation



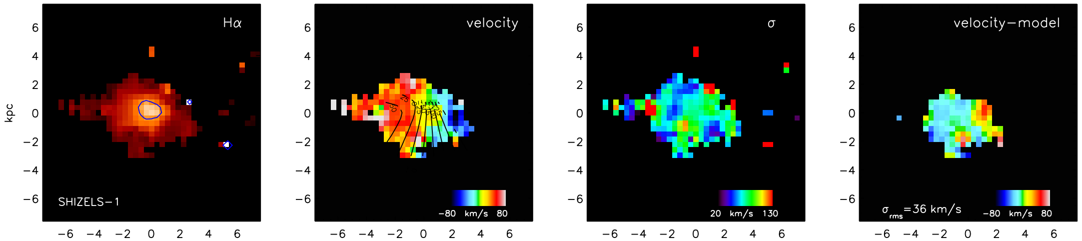
Swinbank, Sobral et al. 2012



Galaxy Dynamics at z~0.8-2.2

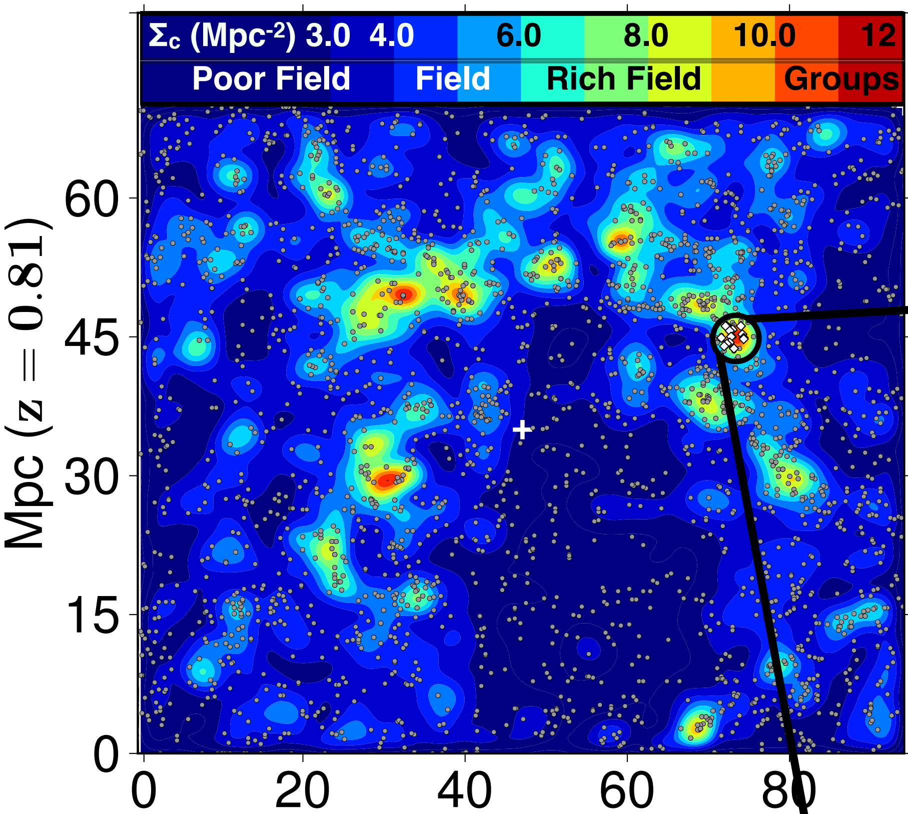
Swinbank al. 2012a

From AO IFU observations

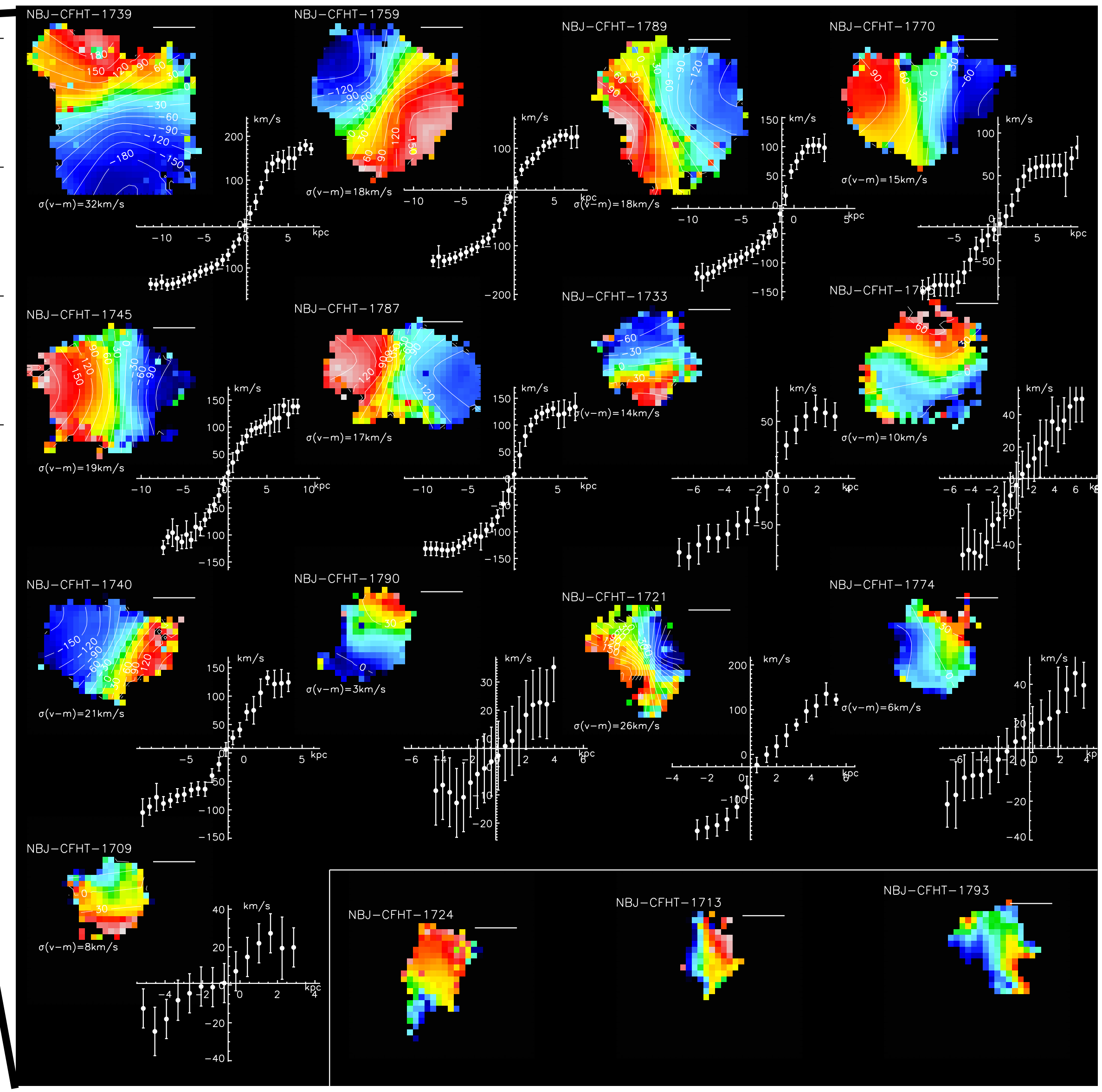


~5 hours of VLT time

CF-HiZELS (Sobral et al. 2015a)



2 hours of VLT time



First Science results from KMOS

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

Evolution of the Tully Fisher relation?

Small Evolution in ZP

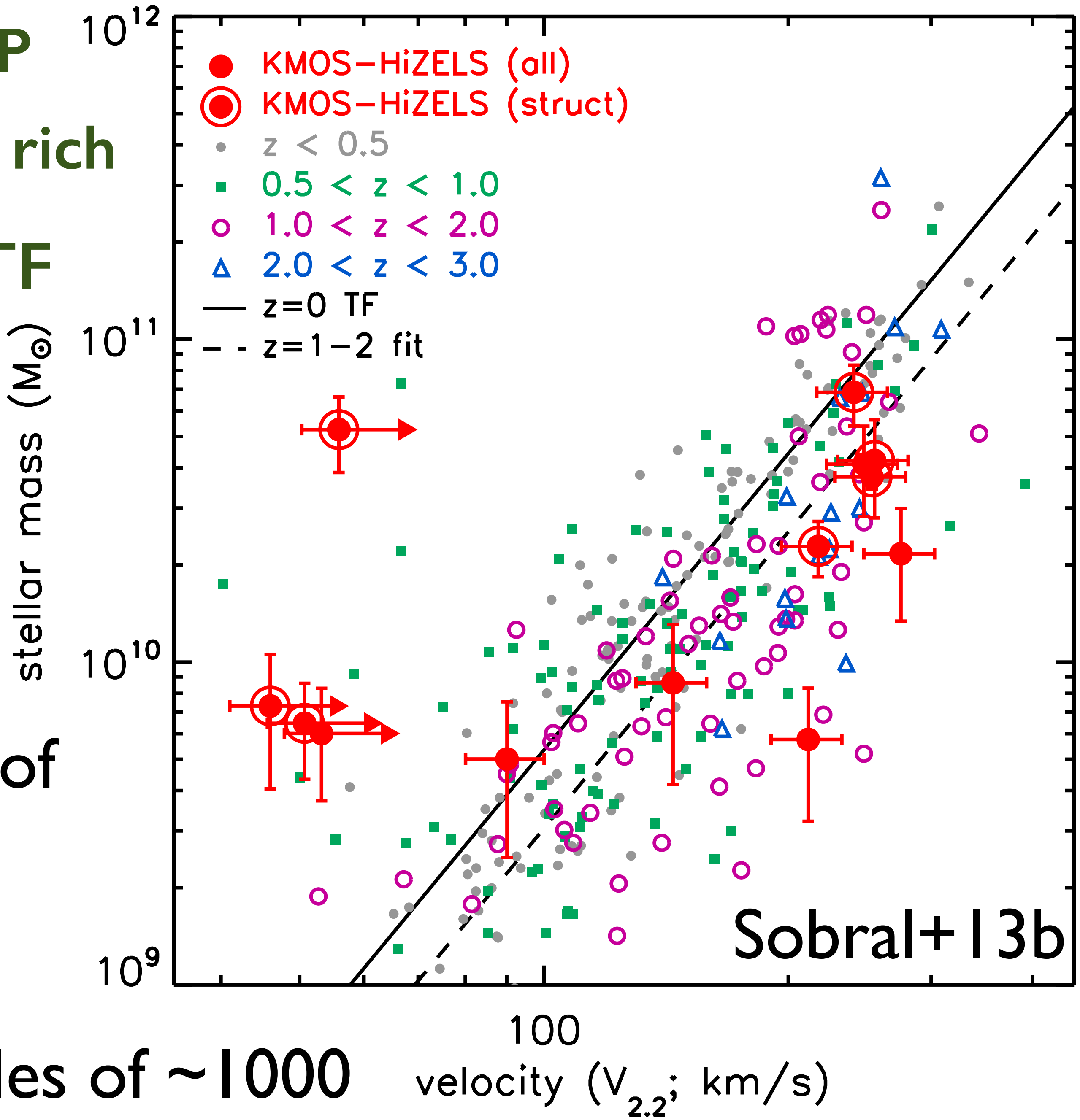
SFGs likely more gas rich

Agrees with z~1-2 TF

<u>**No difference**</u>

field vs group

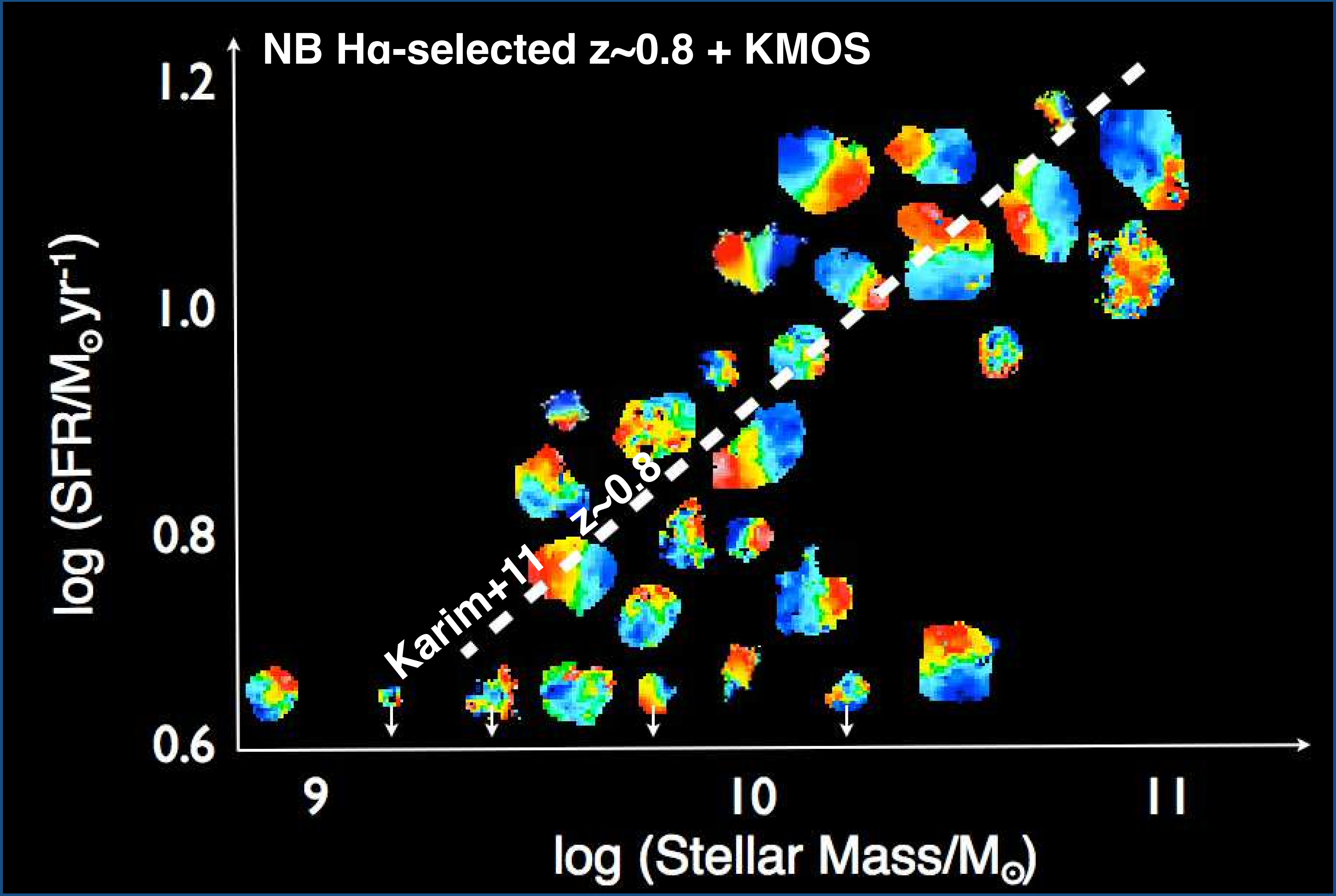
With just ~2 hours of VLT time



"Easy" to build samples of ~1000

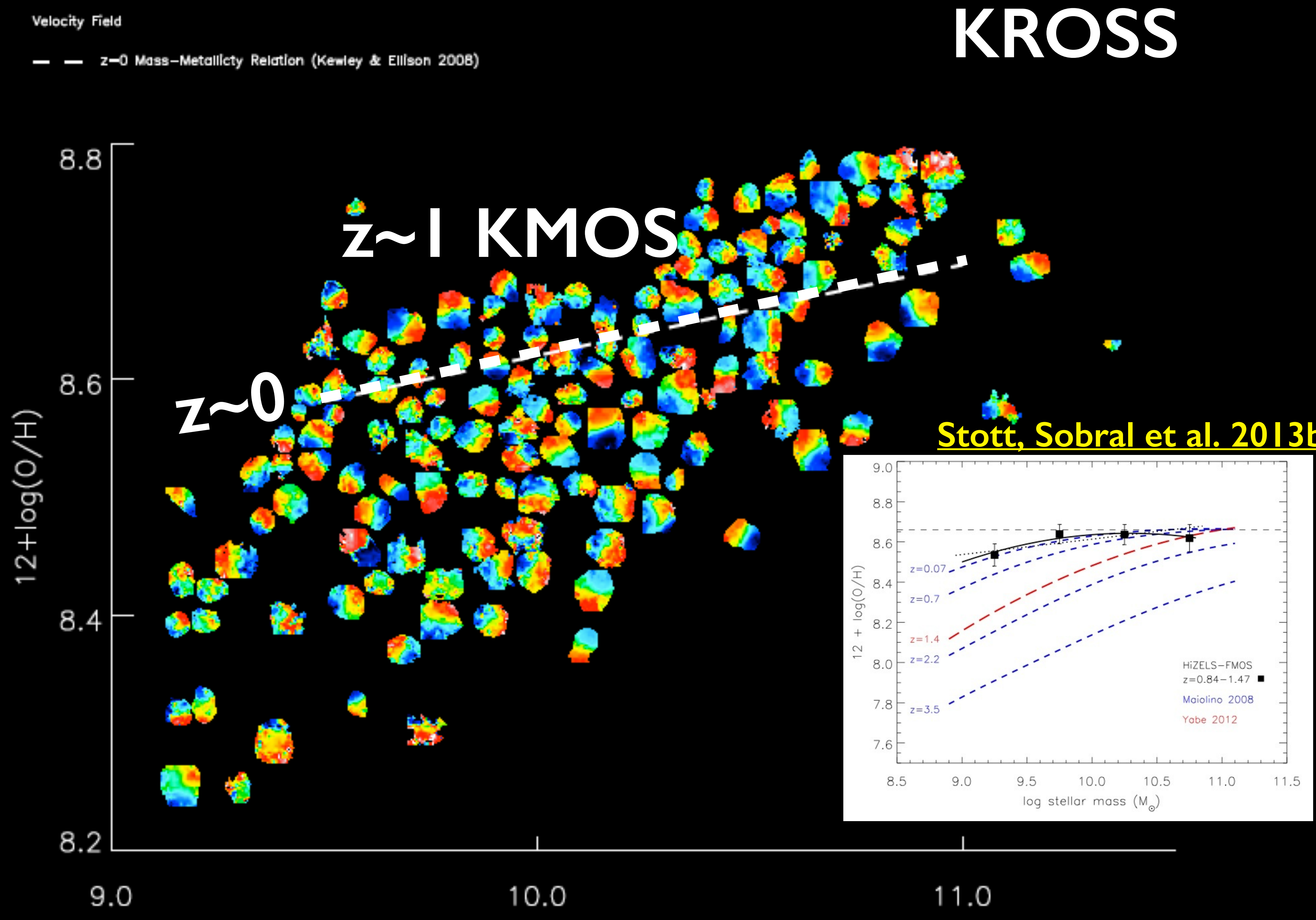
CF-HiZELS KMOS SAMPLE

just 4 hours! (with overheads)



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

KROSS



Stott et al. 2015

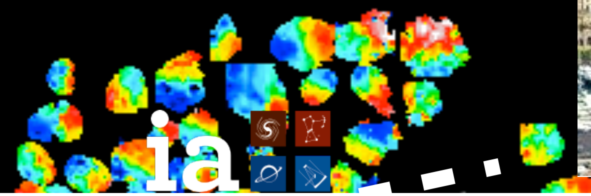
Velocity Field

— — z~0 Mass–Metallicty Relation (Kewley & Ellison 2008)

8.8

Evolution from z~2.23 to z~0

Go see Ana's poster!



Structural evolution of Hα-selected galaxies from z$\sim$0 to z$\sim$2.3

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[1] Instituto de Astrofísica e Ciências do Espaço, Universidade de Lisboa, OAL, Tapada da Ajuda, PT1349-018 Lisboa, Portugal

[2] Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Edifício C8, Campo Grande, PT1749-016, Lisboa, Portugal

[3] Leiden Observatory, Leiden University, P.O. Box 9513, NL-2300 RA Leiden, The Netherlands

instituto de astrofísica e ciências do espaço

A sample of hundreds of Hα-selected galaxies

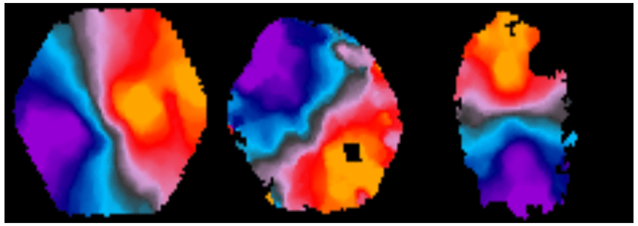
Using Hα narrow-band imaging over very large areas through the HiZELS survey [4], we have obtained samples of thousands of galaxies selected in a consistent way since z$\sim$2.5 until today. Here we present the structural analysis of the CALIFA DR2 sample together with the KMOS followed-up sample.

GALFIT: a parametric galaxy fitting code

GALFIT [3] is a public available 2D parametric image-fitting algorithm designed to study the structural components of galaxies using well-known parametrized models from the literature. For the purpose of this work single Sérsic profiles were applied. Masking of bright neighbours and proper PSFs were taken into account during the fitting process. Highly irregular galaxies are excluded from the final sample.

The Calar Alto legacy integral field area survey

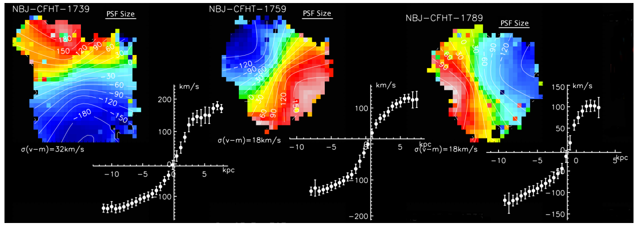
Being one of the best local IFU surveys, CALIFA was designed to obtain spatially resolved spectroscopy of a diameter selected sample of $\sim$600 galaxies. The 2^{nd} Data Release [2] contains data for $\sim$200 sources spanning redshifts between 0.005 and 0.03, which enable us to characterize observationally a wide range of properties such as stellar masses, ionization conditions and morphological types.



Three typical velocity maps from the CALIFA website [7].

The KMOS redshift one spectroscopic survey

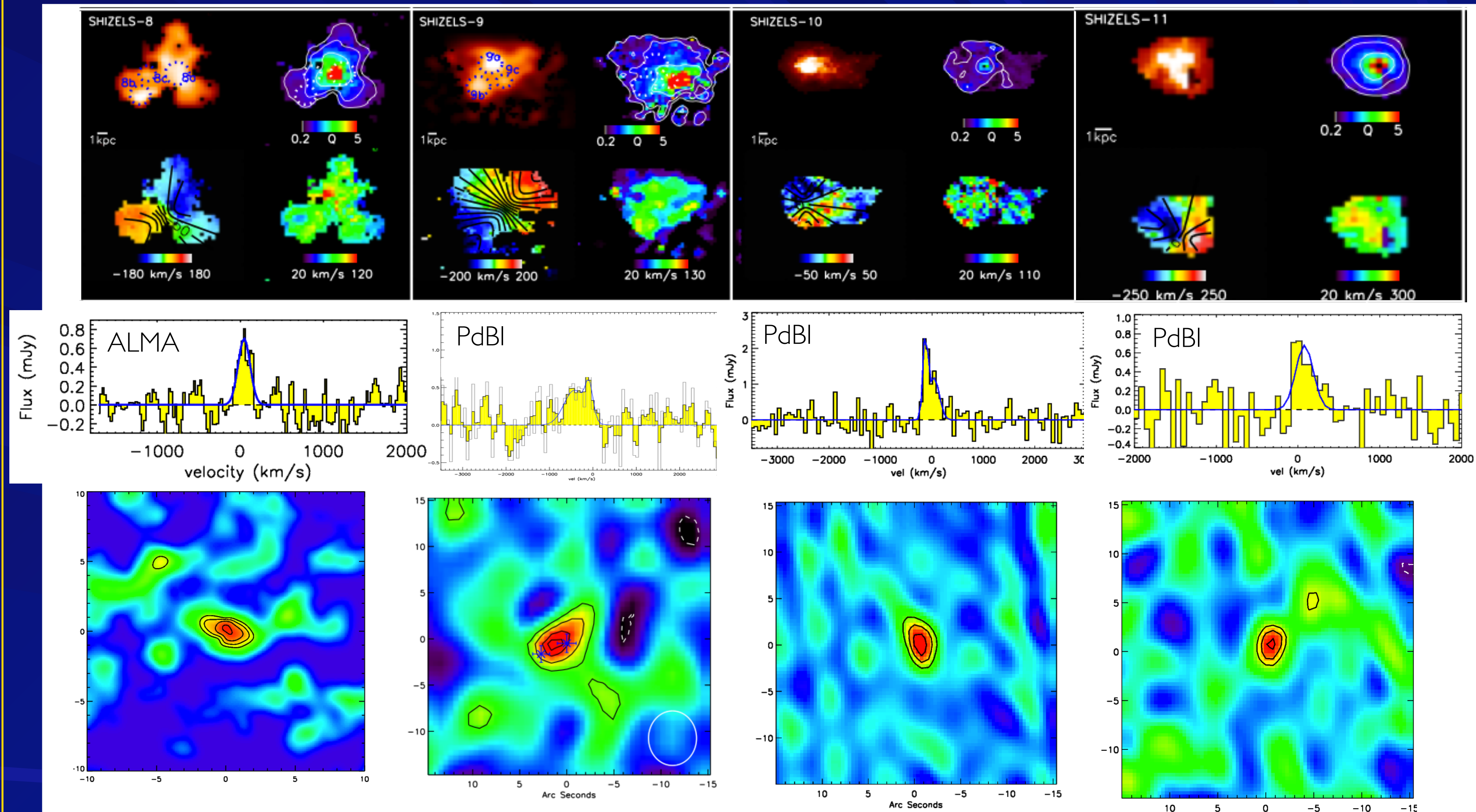
KROSS is a large programme at VLT that aims to resolve spatially the dynamics, metal content and star formation of 1000 galaxies at z$\sim$1. With such a large sample, one will be able to compare different bins of stellar mass, star formations, rotational speeds and quantify trends from galaxy scaling relations and investigate the role of nature and nurture in galaxy evolution since z$\sim$2.5.



Examples of H-α velocity maps shown in [5].

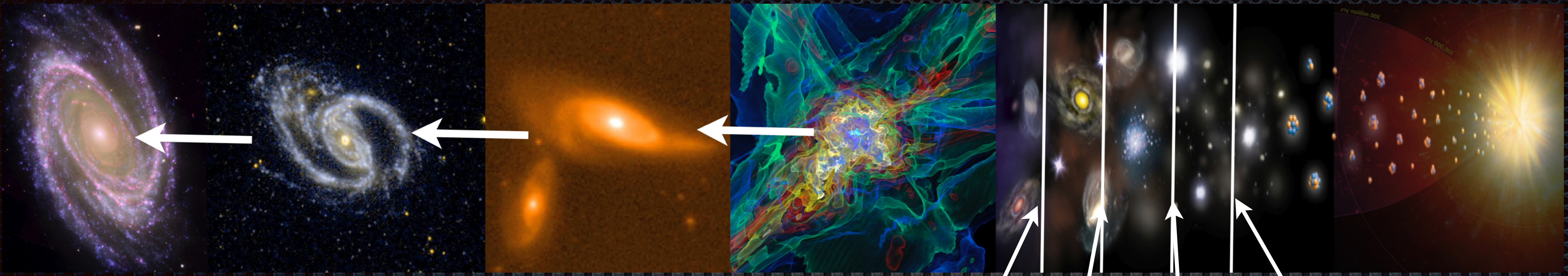
The evolution of sizes and Sérsic indices from the peak of the star-formation history till today

CO follow-up well underway with ALMA and PdBI

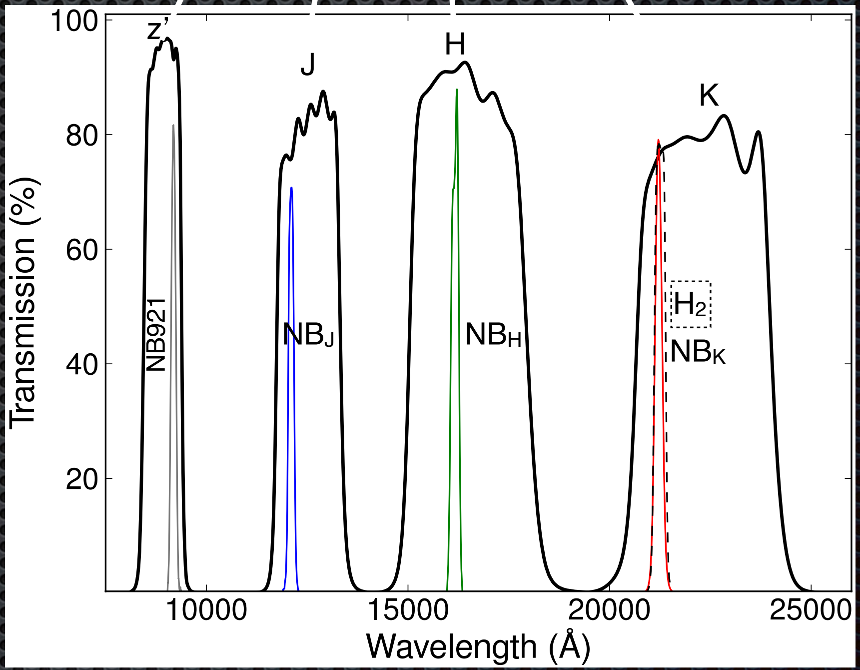


Towards resolved (~sub-kpc) Ha + CO + dust maps and evolution from z~2 to z~0 for "typical" SFGs

M_{gas} = 1-3x10^{10}M$_{\odot}$ (a=2)
M* = 2-4x^{10}M$_{\odot}$
f_{gas} ~30-50%
M_{gas} / SFR ~ 1Gyr



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: Hayashi+13,Sobral+12

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

Clustering: Geach+08,13, Sobral+10

[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

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

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**