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

David Sobral

IA-CAAUL Lisbon/Leiden Obs.

Mark Swinbank, John Stott, Jorryt Matthee, Richard Bower, Philip Best, Ian Smail, Ray Sharples, Jim Geach

Stott+14a, arXiv:1407.1047
How (and driven by which mechanisms) do galaxies form and evolve?

- Morphological change?
- Dynamics
- Star formation
- “Quenching”
Star formation History

Strong decline with cosmic time

Sobral+13a

+ e.g. Lilly+96, Hopkins04, Karim+11
Stellar Mass density evolution
Star formation history prediction matches observations

Star formation History
Strong decline with cosmic time

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

+ e.g. Lilly+96, Hopkins04, Karim+11
Star formation History

Strong decline with cosmic time

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

+Sobral+13a

What are the main drivers?

What’s evolving?

Stellar Mass density evolution

Star formation history prediction matches observations + e.g. Lilly+96, Hopkins04, Karim+11

Age of the Universe (Gyrs)

Log $\rho_{\text{SFR}}$ ($M_\odot$ yr$^{-1}$ Mpc$^{-3}$)

Redshift ($z$)

$M_\odot$ Mpc$^{-3}$

< 2.23

$\sigma$

Ellsner+2008; Marchesini+2009

Age of the Universe (Gyrs)
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
**Hα (+NB)**

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

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

- To understand the nature and evolution of star-forming galaxies across cosmic time
Selection really matters

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

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
Selection really matters

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

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]
Selection Matters:

$z \sim 1.5-2.23$

UV selection: metal-poor, misses dusty galaxies

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

Swinbank+12a
Stott+13b
HiZELS
(Geach+08,Sobral+09,12,13a)

The High Redshift Emission Line Survey
(+Deep NBH + Subar-HiZELS + HAWK-I)

- Deep & Panoramic extragalactic survey, narrow-band imaging (NB921, NB\text{J}, NB\text{H}, NB\text{K}) over \sim 5-10 deg$^2$
- \sim 80 Nights UKIRT+Subaru +VLT+CFHT+INT
- Narrow-band Filters target H\alpha at $z=$(0.2), 0.4, 0.8, 0.84, 1.47, 2.23
- Same reduction+analysis
- Other lines (simultaneously; Sobral+09a,b,Sobral+12,13a,b, Matthee+14)

Sobral et al. 2013a
10x10 Mpc~100-300 arcmin$^2$

20x20 Mpc ~0.7 deg$^2$

5-7 independent large fields

Up to ~10 deg$^2$ contiguous

H$\alpha$ emitters $z=0.81\pm0.01$
Catalogues of all line emitters are publicly available

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

Sobral+13a
SFR function: Strong SFR* evolution

\[ \text{SFR}^*(T) = 10^{(4.23/T + 0.37)} \text{M}_\odot/\text{yr} \]

Faint-end slope: \( \alpha = -1.6 \)

\[ \alpha = -1.60 \pm 0.08 \]

13x decrease over last 11 Gyrs

\( \Phi^* \) at

\( z = 0 \)
\( z = 1 \)
\( z = 2 \)

Sobral+14, MNRAS

“Typical” Star formation rate

Expontial decline

\[ \log_{10}(\phi^*) = 0.004231T^3 - 0.1122T^2 + 0.858T - 4.659 \]
**SFR function: Strong SFR* evolution**

\[
\text{SFR}^*(T) = 10^{(4.23/T + 0.37)} \text{ M}_\odot/\text{yr}
\]

**Faint-end slope:** \( \alpha = -1.6 \)

\[\alpha = -1.60 \pm 0.08\]

\[\Phi^*\]

**13x decrease over last 11 Gyrs**

**Sobral+14**

\[\log_{10}(\phi^*) = 0.004231T^3 - 0.1122T^2 + 0.858T - 4.659\]
Cosmic sSFR, $\rho_{\text{sSFR}}/\rho_*$ (Gyr$^{-1}$)

Age of the Universe, $T$ (Gyrs)

- H$\alpha$ SFGs (All)
- SFGs $10^{10.0-11.5} M_\odot$
- SFGs $10^{9.3-10.0} M_\odot$
- SFGs $10^{8.7-9.3} M_\odot$

Sobral+14
~5 hours of VLT time
Galaxy Dynamics at z~0.8-2.2

Swinbank al. 2012a,b

From AO IFU observations

~45 hours of VLT time
Galaxy Dynamics at $z\sim0.8$-2.2

Swinbank et al. 2012a  Swinbank al. 2012b  see also e.g. Jones+10, Yuan+11

- Star-forming clumps: scaled-up version of local HII regions
- Negative metallicity gradients: “inside-out” growth
Mostly disk-like (~70-80%)
similar to HST (Sobral et al. 2009)

Many “clumpy” (c.f. Swinbank+12b)

Rotation ~70-200 km/s

SINFONI
~50 hours of VLT time
SINFONI
~50 hours of VLT time

High resolution is extremely important (we are getting a sample ~3x larger with SINFONI AO [+ ALMA follow-up])

But... need (much) larger samples!

Can we do better?
Mostly disk-like ($\sim$70-80%)

Also see talks by: R. Genzel, N. Förster Schreiber, J. Stott, E. Wuyts
300 k NB detections

6400 line emitters

3000 Hα z=0.8

Density of Hα emitters
z=0.81±0.01

S+13b, Matthee+14

8 sigma over-density
Method: S+11

Using *all* galaxies (not just SFGs)

Likely group

30 Hα in 7x7arcmin

S+13b
Perfect for KMOS ‘LT
24 IFUs at the same time!

4h Science Verification time
Observations June 2013 + September 2013
Galaxy Dynamics at $z \sim 0.8-2.2$

Swinbank al. 2012a

From AO IFU observations

~5 hours of VLT time
First KMOS Science results

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

KMOS: Evolution of the Tully Fisher relation?

Small Evolution in ZP
Agrees with $z \sim 1$-2 TF
Higher gas fractions at $z \sim 1$ (J. Stott’s talk)
No difference field vs group

With just $\sim 2$ hours of VLT time
“Easy” to build samples of $\sim 1000$
Figure 1. The SFR plotted against stellar mass for the 29 resolved galaxies in the CF-HiZELS KMOS sample. The KMOS-HiZELS sample includes both "MS" galaxies AND blue galaxies, not biased towards blue galaxies.

The KMOS-HiZELS-SV2 sample data are presented in Sobral et al. (2013b). The average value of the metallicity gradient for our sample is just 4 hours! (with overheads).

The details of the KMOS-HiZELS-SV2 sample. The CF-HiZELS galaxies are named CFHT-NBJ and the VVDS galaxies are numbered just 4 hours! (with overheads). (following Stott et al. 2013a). Examples of the spectra in each field. Note, positions are approximate to avoid galaxy velocity contamination.
Metallicities

KMOS galaxies z=0.81

$12 + \log(O/H) = 8.62 \pm 0.07$

Solar value: $8.66 \pm 0.07$

Group galaxies slightly more metal rich

but also more massive

$[\text{NII}] / \text{Ha} = 0.32 \pm 0.13$
Stott et al. in prep

see J. Stott’s talk

Stott, Sobral et al. 2013b

Stott et al. in prep
HiZELS “Fundamental” Mass-Metallicity-SFR relation at z~1-2

z=0.8-1.5

KMOS galaxies sit nicely on the 3D relation

See also results from e.g. CALIFA
Metallicity gradients for CF-HiZELS KMOS sample

Agreement with SINFONI results (Swinbank+12a)

Mostly negative or flat, very few positive

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

Metallicity Gradients increase with increasing sSFR. 

Suggests high sSFRs may be driven by funnelling of “metal poor(er)” gas into their centres.

Results may help to explain the FMR (negative correlation between metallicity and SFR at fixed mass).
Stott et al. 2014
Stay tuned for John Stott’s talk in the afternoon! Stott et al. 2014
Conclusions:

- **Ha 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 +HST** 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

- **CF-HIZELS KMOS**: ~solar metallicities, typical SFRs, all disks. Group galaxies more massive & slightly lower sSFRs + higher Metallicity, but the same TF and mass-metallicity relations

- **KMOS CF-HiZELS**: Metallicity gradients correlate with sSFR: FMR & explains discrepancies?
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 KMOS survey of star-forming galaxies at z=1-2

Ray Sharples, John Stott, Mark Swinbank, Richard Bower, Martin Bureau

PRELIMINARY

UK GT program
6.5N in P92
245 targets in 13 masks
95% detection
74% resolved
Evolution of SFR* (SSFR) same in fields and clusters since $z=2.23$

SFR-Mass relation also ~the same in different environments

Koyama et al. 2013

(For “extreme” environmental effects see e.g. Stroe et al. 2014)
M_{gas} = 1 - 3 \times 10^{10} M_{\odot} \ (a=2) \\
M_{*} = 2 - 4 \times 10^{10} M_{\odot} \\
f_{\text{gas}} \sim 30 - 50\% \\
M_{\text{gas}} / \text{SFR} \sim 1 \text{Gyr} \\
CO follow-up well underway with PdBI and ALMA
The SFR plotted against stellar mass for the 29 resolved galaxies is presented in Sobral et al. (2013b). The KMOS-HiZELS sample data are just 4 hours! (with overheads) to extract the best fitting dynamical disc model, found in the data cube so that the radii:

- VVDS-944 22:19:39.73 0:24:02.45 0.8970 22.31 2.1
- VVDS-942 22:19:39.44 0:25:29.30 0.8095 23.41 4.0
- VVDS-888 22:19:38.00 0:20:07.41 0.8331 22.10 1.3
- VVDS-503 22:19:51.16 0:25:42.21 0.9925 21.82 4.2
- VVDS-432 22:19:46.70 0:21:35.44 0.8095 21.24 4.8
- CFHT-NBJ-2048 22:19:51.67 0:21:00.90 0.8155 22.90 5.8
- CFHT-NBJ-1209 22:19:40.16 0:22:38.52 0.8085 21.76 10.4
- CFHT-NBJ-956 22:19:27.05 0:23:42.44 0.8095 21.43 4.5
- CFHT-NBJ-C339 22:19:46.96 0:25:02.53 0.8135 20.12 3.0

The SFR plotted against stellar mass for the 29 resolved galaxies is presented in Sobral et al. (2013b). The CF-HiZELS galaxy catalogue system.

The details of the KMOS-HiZELS-SV2 sample. The CF-HiZELS galaxies...
SF History - Full population and 4 mass bins

Decline at all masses

- Log $\rho_{SFR}$ ($M_\odot$ yr$^{-1}$ Mpc$^{-3}$)

- Redshift ($z$)

Full SFG population

SFGs $10^{10.0-11.5} M_\odot$

SFGs $10^{9.3-10.0} M_\odot$

SFGs $10^{8.7-9.3} M_\odot$

Sobral et al. (13C)
Lya, [OII], [OIII], Ha, PACS, SPIRE

$z=2.23$
Although:

\[ SFR > 0.2 \text{ SFR}^* \]

Stott et al. 2013a
The KMOS Kinematic Survey of $z \sim 1$ Galaxies

Fig. 2.— Two dimensional velocity fields for the sixteen galaxies in our KMOS sample. The contours denote the dynamics of the best-fit two dimensional disk model. From these velocity fields, thirteen galaxies have dynamics that resemble rotating systems, and we extract one dimensional rotation curves (shown as insets for each galaxy) extracted from the dynamical center and position angle from the best-fit dynamical model. In these plots, the error bars for the velocities are derived from the formal 1σ uncertainty in the velocity arising from the Gaussian profile fits to the Hα emission. The final three galaxies in this plot do not resemble rotating systems.

We therefore measure the velocity field and velocity dispersion asymmetry for all of the galaxies in our sample, defining the velocity asymmetry ($K_V$) and the velocity dispersion asymmetry ($K_\sigma$) as in Sobral+13b. For an ideal disk, the values of $K_V$ and $K_\sigma$ will be zero. In contrast, in a merging system, strong deviations from the idealised case causes large values of $K_V$ and $K_\sigma$ (which can reach $K_V \sim K_\sigma \sim 10$ for very disturbed systems). For the KMOS galaxies in our sample, we measure the velocity and velocity dispersion asymmetry and report their values in Table 1, (NBJ-CFHT 1724, 1713 and 1793 have too few independent spatial resolution elements across the galaxy so we omit these from the kinemetry analysis). Although the errors bars on $K_TOT$ are large (these errors are found by bootstrap resampling for the errors in the velocities, velocity dispersions and dynamical centers of each galaxy), the average $K_TOT = 0.40 \pm 0.07$ suggests that the majority of these galaxies are dominated by disk-like dynamics (indeed, twelve of the thirteen galaxies in our KMOS sample).

75+-8% Disks
Shallow, negative metallicity gradients
Rotation speeds of 50-275 km/s
~solar metallicity

Group galaxies: 100% disks

Sobral+13b
Over the last 11 Gyrs

- Decrease with time at all masses

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

- Mostly no evolution apart from normalisation

Sobral et al. (13C)
Stott, Sobral et al. 2013b

$z=0.84 + z=1.47$ Ha
Table 2.1: Observation log for the NBJ (LowOH2) observations on CFHT WIRCam.

<table>
<thead>
<tr>
<th>Emission line</th>
<th>λ₀ ( (\text{nm}) )</th>
<th>Volume ( 10^6 \text{Mpc}^3\text{deg}^{-2} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lyman-α</td>
<td>121.6</td>
<td>8.76 ( \pm 0.04 )</td>
</tr>
<tr>
<td>Hα</td>
<td>652.3</td>
<td>0.81 ( \pm 0.01 )</td>
</tr>
<tr>
<td>OII</td>
<td>372.7</td>
<td>2.18 ( \pm 0.02 )</td>
</tr>
<tr>
<td>OIII</td>
<td>500.7</td>
<td>1.37 ( \pm 0.01 )</td>
</tr>
<tr>
<td>Hβ</td>
<td>486.1</td>
<td>1.44 ( \pm 0.01 )</td>
</tr>
</tbody>
</table>

Table 2.2: Redshifts at which the LowOH-2 filter (\( \lambda = 1187\text{nm}, \Delta\lambda = 10\text{nm} \)), targets emission lines.

- 1. Dark substraction
- 2. Create skyflat
- 3. Create mask for bad pixels
- 4. Improve skyflat
- 5. Match coordinate system
- 6. Stack individual frames

1. Dark exposures measure the intrinsic noise of the detector (so called dark current) and therefore the first step is to substract the dark exposures from the raw exposures. For each field ten individual exposures were made in a jitter pattern with small (but certainly not negligible) difference in the pointings. WIRCam has four camera's and the following steps are done for each camera (and each field) separately.

2. To create first pass skyflat, which is made to correct for the different sensitivities across the detectors and to detect bad and warm pixels, ten exposures of different pointings taken at roughly the same time are used. This meant that for the fields which had ten valid exposures in the 2011
Exploring a wide range of local densities: same selection/survey

Cluster? Proto-cluster? How special are these galaxies? What are their dynamics?
CFHT/WIRcam survey

SA22 H-alpha z = 0.8

90 Mpc
NB selection: quantify excess

Source extraction
Potential line emitters
Which emission line?

Spectro-z confirmation
Double-line confirmation

Photo-zs + Colour-colour selection

Select Hα emitters
Samples >90-95% complete, <5-10% contamination
Extinction-Mass $z \sim 0-1.5$

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

Relation holds up to $z \sim 1.5-2$

FIR derived $A_{\text{Ha}} = 0.9-1.2$ mag

$A_{\text{Ha}} \sim 1$

$Ibar$ et al. 2013

FIR/Ha
The BPT diagram (Baldwin et al. 1981) for the galaxies in the HiZELS dataset, showing the fraction of HiZELS galaxies that occupy the same region of the diagram as AGN is. The filled red circles are those with detected [NII], and the filled black squares are those missing upper limits. The dashed line is the demarcation between star-forming and AGN galaxies.

The median value of N2 for our sample (including the upper-limits) is found to be $\alpha_H = 8.5$. The median metallicity of the HiZELS-FMOS sample, for those with detected [NII], is found to be $\alpha_N = 8.0$. This is often referred to as the N2 method, where the metallicity of a galaxy can be estimated from the ratio of the [NII] to H$\beta$ flux, assuming $\tau = 1$. The typical error is shown in the top left corner of the plot. The mass-metallicity relation for our combined sample of HiZELS-FMOS sources is $\alpha_M = -0.5$. This is in remarkable agreement with the results of Savaglio et al. (2005); Erb et al. (2006). The BPT diagram as AGN is...
Filters combined to improve selection: double/triple line detections

$z=2.23$: $[\text{OII}]$ (NBJ), $[\text{OIII}]$ (NBH), H$\alpha$ (NBK)

$z=1.47$: $[\text{OII}]$ (NB921), H$\beta$ (NBJ), H$\alpha$ (NBH)

$z=0.84$: $[\text{OIII}]$ (NB921), H$\alpha$ (NBJ)
Ha emitters in HiZELS
2 sq deg: COSMOS + UDS

Prior to HiZELS:
~10 sources
**Ha emitters in HiZELS**

2 sq deg: COSMOS + UDS

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

**Prior to HiZELS:**

~10 sources
Sobral+11b,12a

**Subaru FMOS + NTT + WHT**
The nature and evolution of luminous line emission in galaxies observed at $z=1.47$. The spectra show a range of emission lines, including $H\beta$, [OIII], $H\alpha$, $H\beta$, [NII], and [OIII]. The emission lines are indicative of different stellar populations and activities, with broad-line AGN, AGN + SF, more metal-rich, and more metal-poor environments.

- **AGN dominated**: Emission lines are strong and broad, indicating a powerful AGN component.
- **AGN + SF**: Emission lines from both AGN and star-forming regions are observed.
- **More Metal-rich**: Stronger emission lines of [NII] and [OIII] indicate a higher metallicity.
- **More Metal-poor**: Emission lines are weaker, suggesting a lower metallicity.
- **Star-forming**: Emission lines from young stars, such as $H\beta$ and [OIII], are prominent.

The wavelength range varies from $1.0$ to $1.6$ μm, showing the flux distribution across these wavelengths.
AGN

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

S+ in prep
Merger fraction of star-forming galaxies depends mostly on environment, not mass

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

Sobral et al. 2011

Mass and/or environment?

at z~1
Preparing the OBs for KMOS: KARMA

- 2.8 x 2.8 sq. arcsec
- 7.2 arcmin
- 3 spectrographs
- 3 permanent sky IFUs

**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**

**NB selection: quantify excess**

**Select Hα emitters**

Samples >90% reliable >90% complete
Figure 8. Left: Fraction of $M_{20}$ identified mergers versus stellar mass for the four HiZELS redshift slices. Centre: Fraction of $M_{20}$ identified mergers versus SFR for the four HiZELS redshift slices. From these plots we can see that the merger fraction depends on mass and perhaps SFR with the most massive and most star-forming galaxies having the lowest merger fractions. Right: Fraction of $M_{20}$ identified mergers versus sSFR for galaxies with $\text{ENSFR} > 0.2$ for the four HiZELS redshift slices. This suggests that major mergers can lead to galaxies having unusually high sSFR compared to the typical value at a given mass and redshift.

Figure 9. Left: Mergers rate for the HiZELS sample above a given mass against redshift. For comparison, we include merger rates derived from: close pairs (Lin et al. 2008, Lin08L11); Gini/$M_{20}$ (Lotz et al. 2008, Lotz08L11); and galaxy asymmetry, (Conselice et al. 2003, 2009; L´opez-Sanjuan et al. 2009, labelled C03, C09L11 and LS09L11 respectively). The L11 denotes that these merger rates were originally sourced from their respective papers but have been corrected to the timescales calculated by Lotz et al. (2011) using the galaxy evolution models of Somerville et al. (2008). The samples of Lin08L11, Lotz08L11, C09L11 and LS09L11 are all at $M_\star > 10^{10} M_\odot$ while C03 is $M_\star > 10^{9} M_\odot$. Right: The merger rate for HiZELS galaxies with $M_\star > 10^{10} M_\odot$ above a given epoch normalised star formation rate ($\text{ENSFR} = \text{SFR}/\text{SFR}_\star(z)$). The points are offset by $\Delta z$ for clarity. From these plots one can see that there is no evidence for a significant evolution in merger rate when both the mass and the ENSFR of the galaxies are accounted for in the selection.

By defining the epoch-normalised star-formation rate ($\text{ENSFR} = \text{SFR}/\text{SFR}_\star(z)$) we account for the increase in the typical star-formation rate of galaxies with redshift. In §2 we demonstrate that the number of galaxies above a given mass and ENSFR does not evolve significantly over the 6 Gyr from $z = 0$ to 2.23. We also note that the HiZELS sample has already been shown to accurately trace the increase of the SFRD with redshift and that there is no strong evolution in the normalisation of the H$\alpha$ luminosity function (Sobral et al. 2013). Taken, in combination this means the increase in the SFRD with redshift is not due to an increase in the number of star-forming galaxies of a given mass but instead must result from an increase in the amount of star formation in these galaxies. This can be described as an increase in the average sSFR for star-forming galaxies (Rodighiero et al. 2010; Elbaz et al. 2011) without a significant increase in the number density. Also, we note that the $\text{SFR}_\star$ (derived from $L_\star$ H$\alpha$) evolves in the same way as the typical sSFR for star forming galaxies (Elbaz et al. 2011), which implies that the luminosity of the knee in the H$\alpha$ luminosity function is evolving significantly more rapidly than the characteristic mass of the stellar mass function.

The size–mass relation for galaxies is assessed in §3.1. In order to do this for a large sample we need to use wide-field ground-based imaging. Hence we confirm that we can reliably recover the galaxy size determined from the HST CANDELS imaging by deconvolving the affect of atmospheric seeing from the ground-based imaging. We find that the size–mass relation is surprisingly constant out to $z = 2.23$, in agreement with the findings...
Lisbon’s Observatory

Come visit!

Institute of Astrophysics and Space Sciences
$z \sim 2.2$

~Age

~UV slope
Morphologies: ACS+CANDELS

Ha 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.

<table>
<thead>
<tr>
<th>( z )</th>
<th>( a )</th>
<th>( b )</th>
<th>( r_e ) at ( \log_{10} (M_*) = 10 ) (kpc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.40</td>
<td>0.08±0.02</td>
<td>0.55±0.03</td>
<td>3.6±0.2</td>
</tr>
<tr>
<td>0.84</td>
<td>0.03±0.02</td>
<td>0.54±0.01</td>
<td>3.5±0.1</td>
</tr>
<tr>
<td>1.47</td>
<td>0.03±0.02</td>
<td>0.59±0.01</td>
<td>3.9±0.2</td>
</tr>
<tr>
<td>2.23</td>
<td>0.08±0.03</td>
<td>0.51±0.02</td>
<td>3.3±0.2</td>
</tr>
</tbody>
</table>

Sobral+09a, Stott+13a
Morphology-SFR relation

- Depends on SFR / H-alpha Luminosity
- Disks/non-mergers completely dominate at \( SFR < SFR^* \), \( (L < L^*) \)

- Population “shift” \( \sim SFR^* \): Irr/mergers dominant (reaching 100%)

Sobral et al. 2009a
Mergers?

Mergers responsible for $\sim 20\%$ SFRD since $z=2.2$ (S09)

Stott et al. 2013a