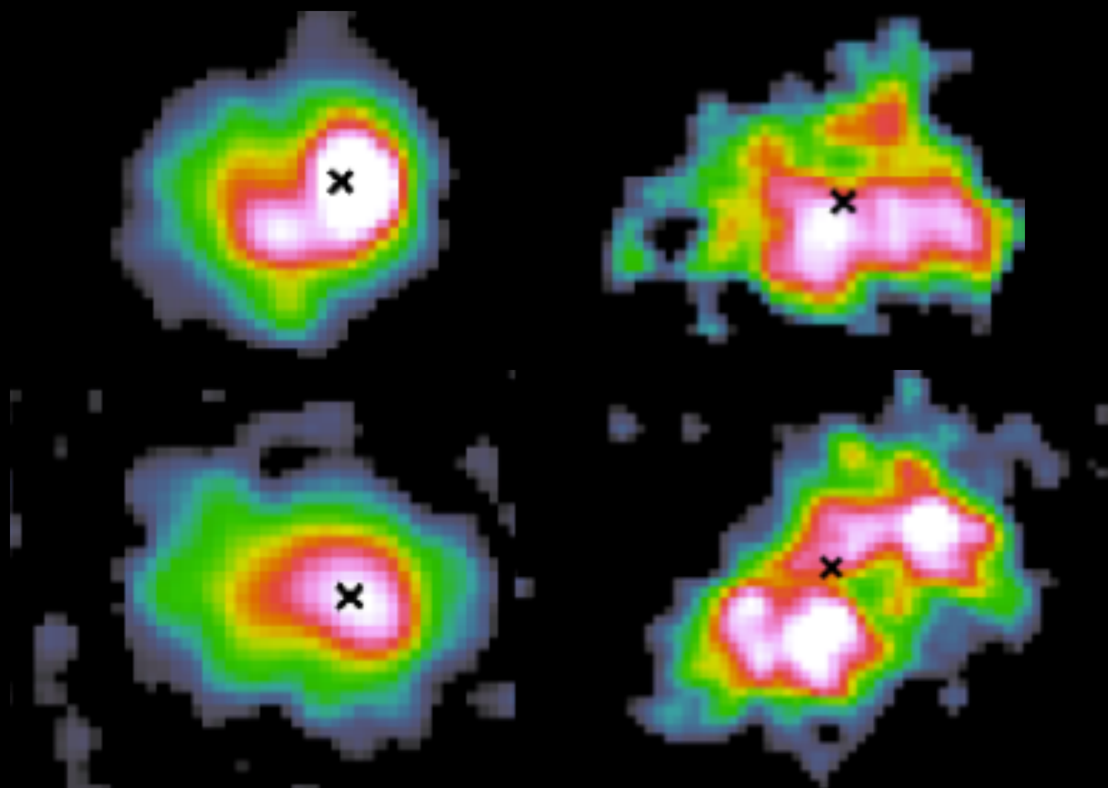
Spatially resolved emission line maps: studying star-forming clumps at high-z

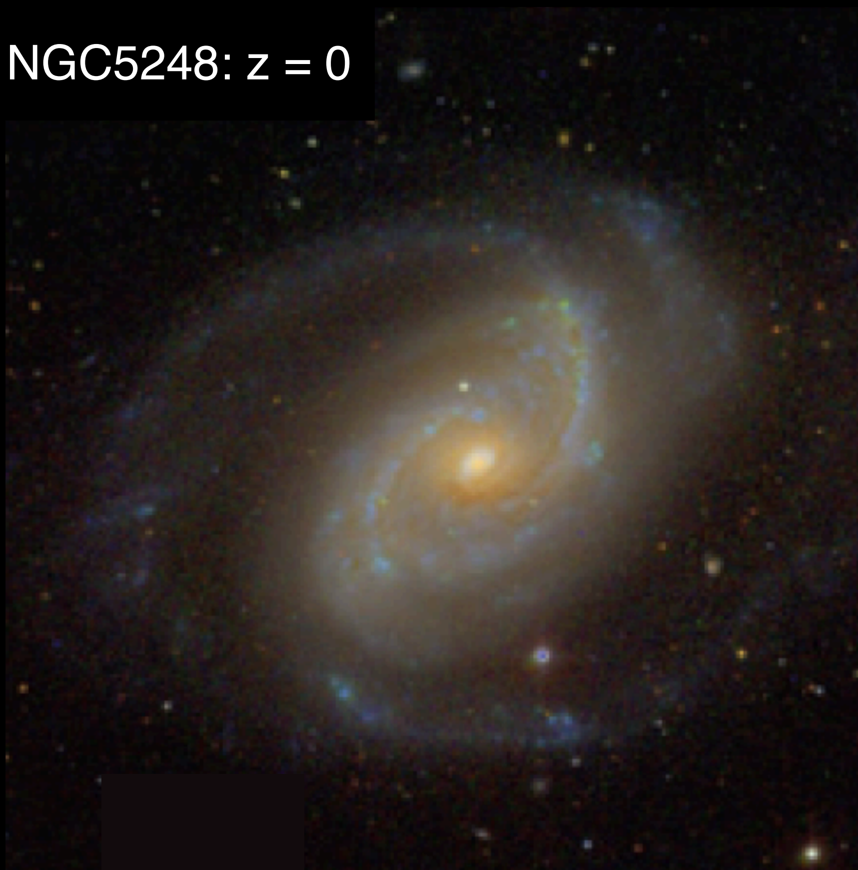


Anita Zanella

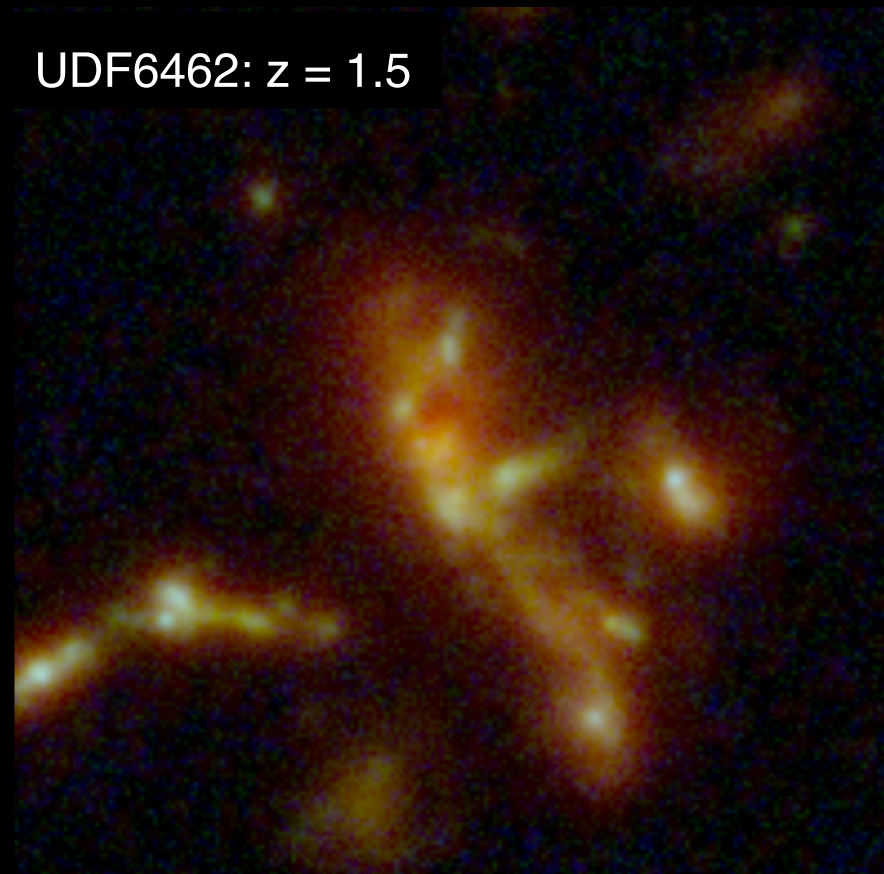
in collaboration with: E. Le Floc'h, E. Daddi, F. Bournaud et al.

18th September 2017 – KICC workshop

How do high-z galaxies look like?



Elmegreen+13

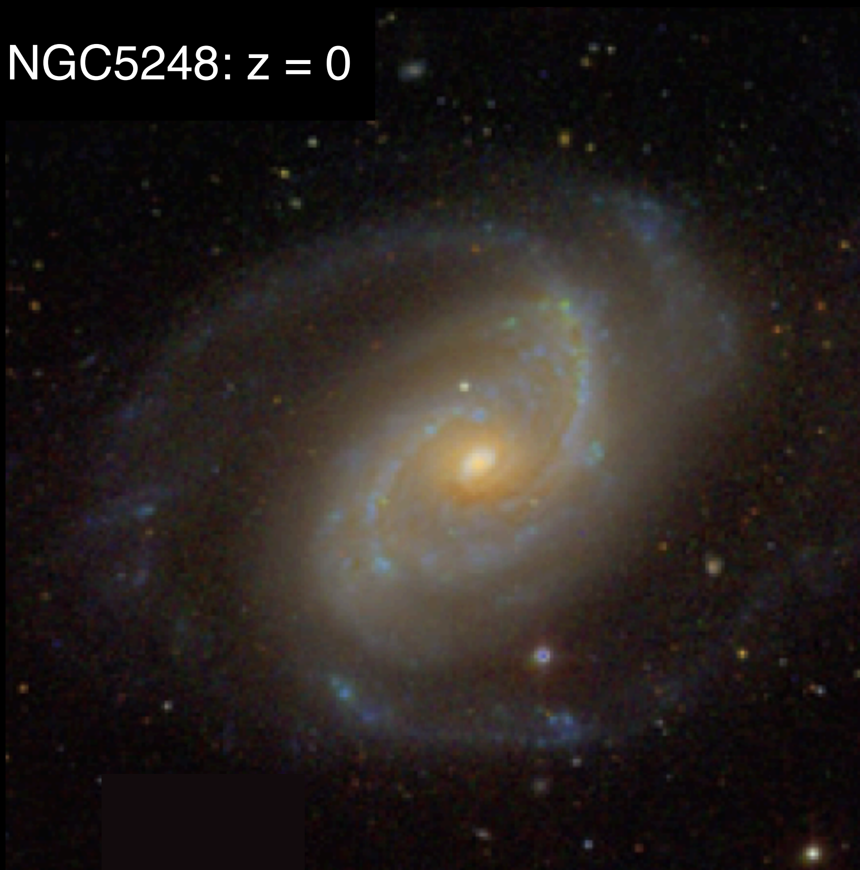


Bournaud+15

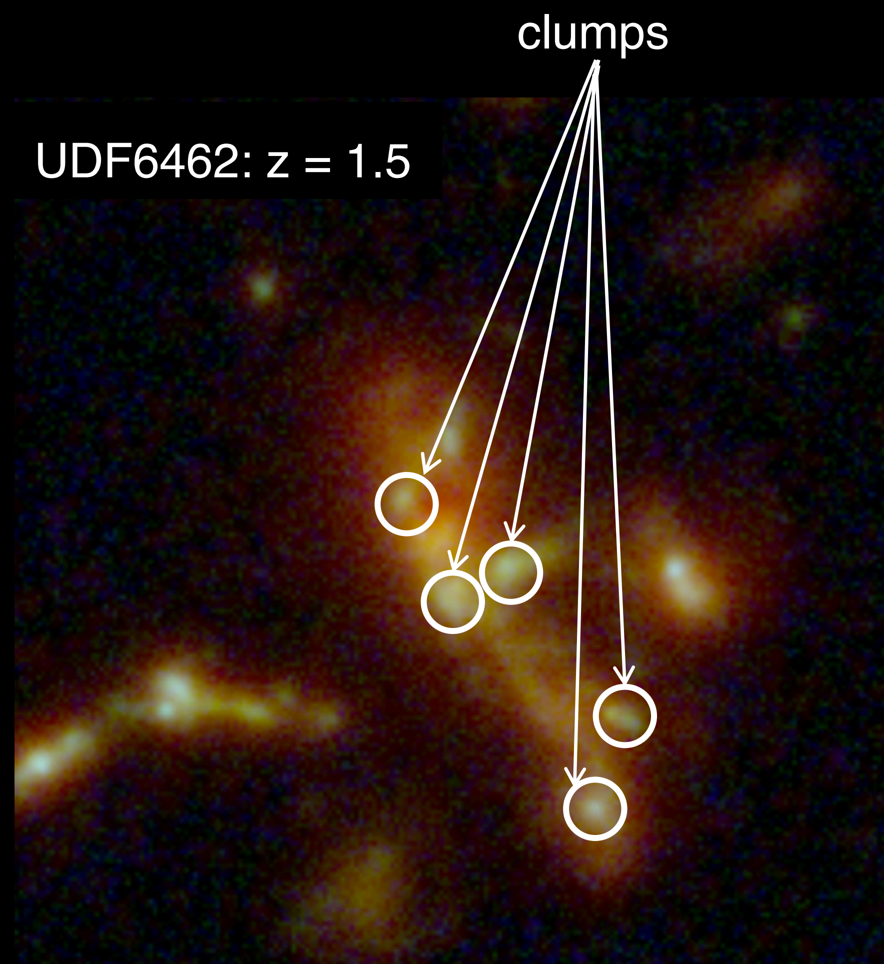
Local galaxy: f_{gas} ~ 5 - 10%

High-z galaxy: f_{gas} ~ 50%

How do high-z galaxies look like?



Elmegreen+13



Bournaud+15

Local galaxy: f_{gas} ~ 5 - 10%

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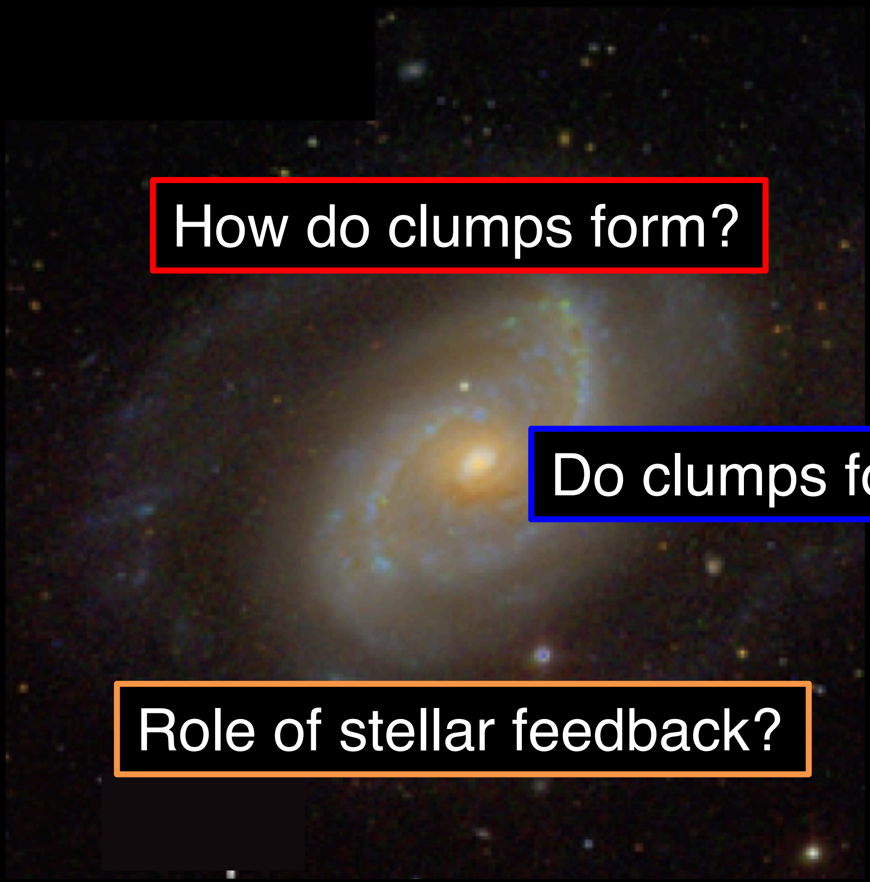
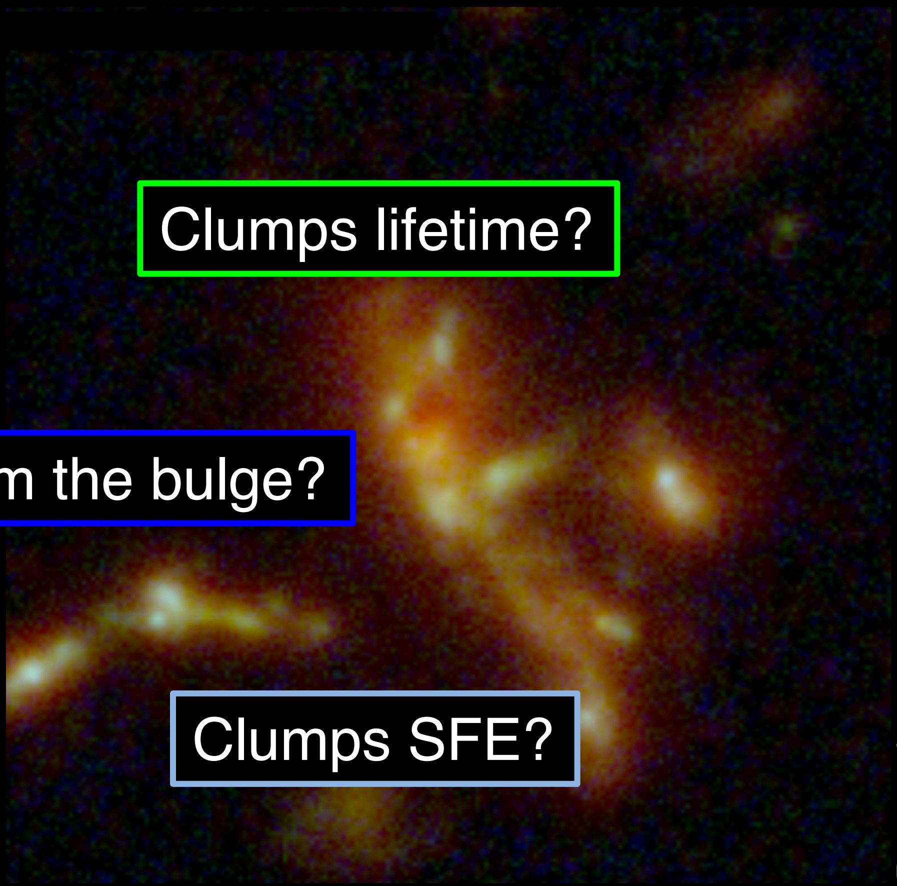
How do high-z galaxies look like?

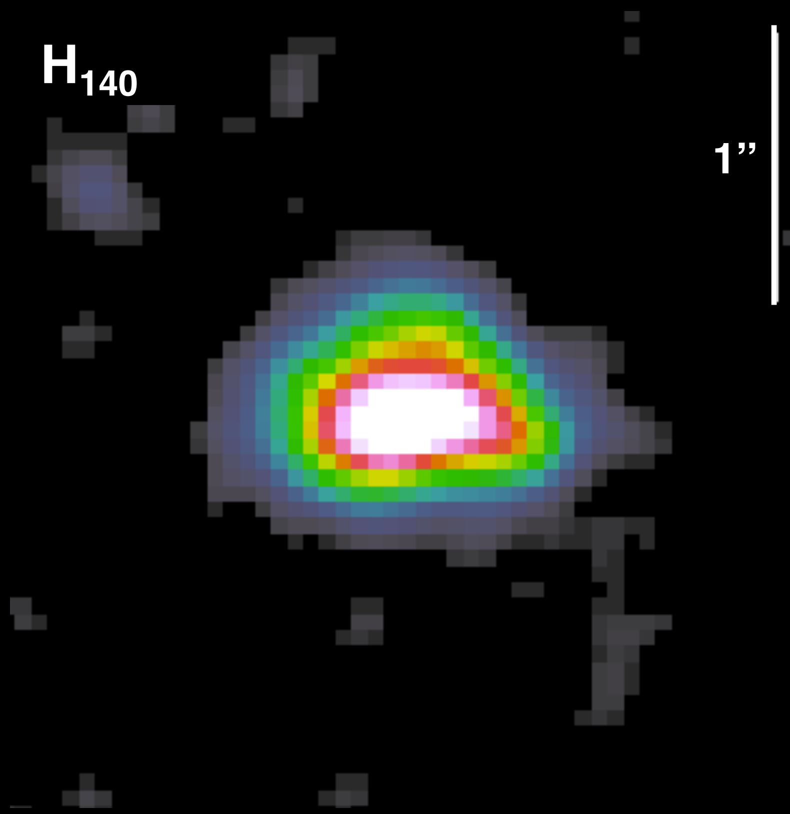




Do clumps form the bulge?

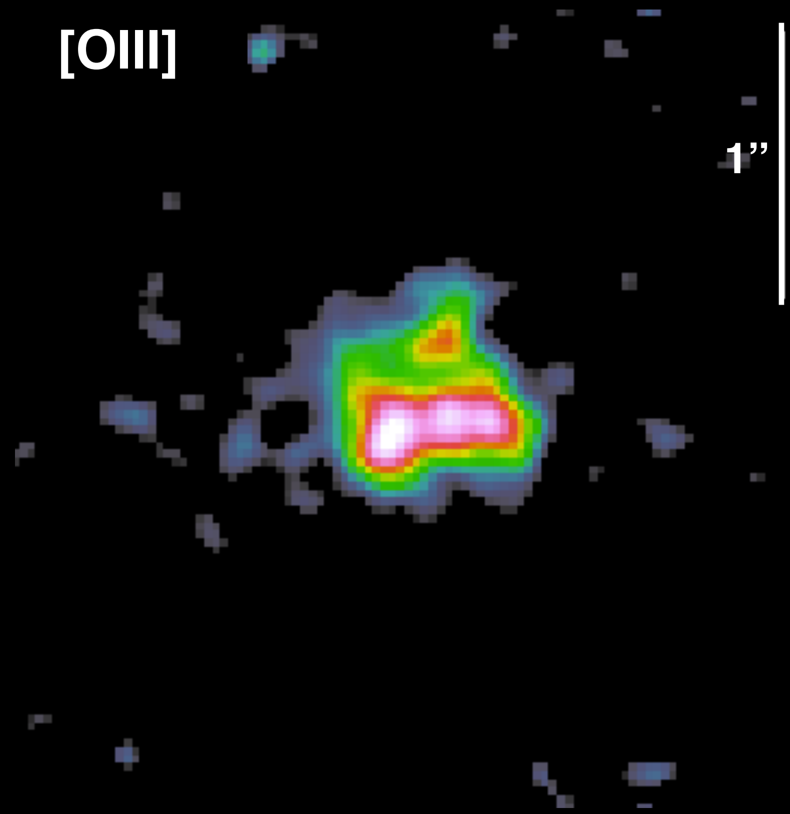
Key needed ingredients

Rest-frame optical imaging



Spatially resolved probe of
stellar mass distribution

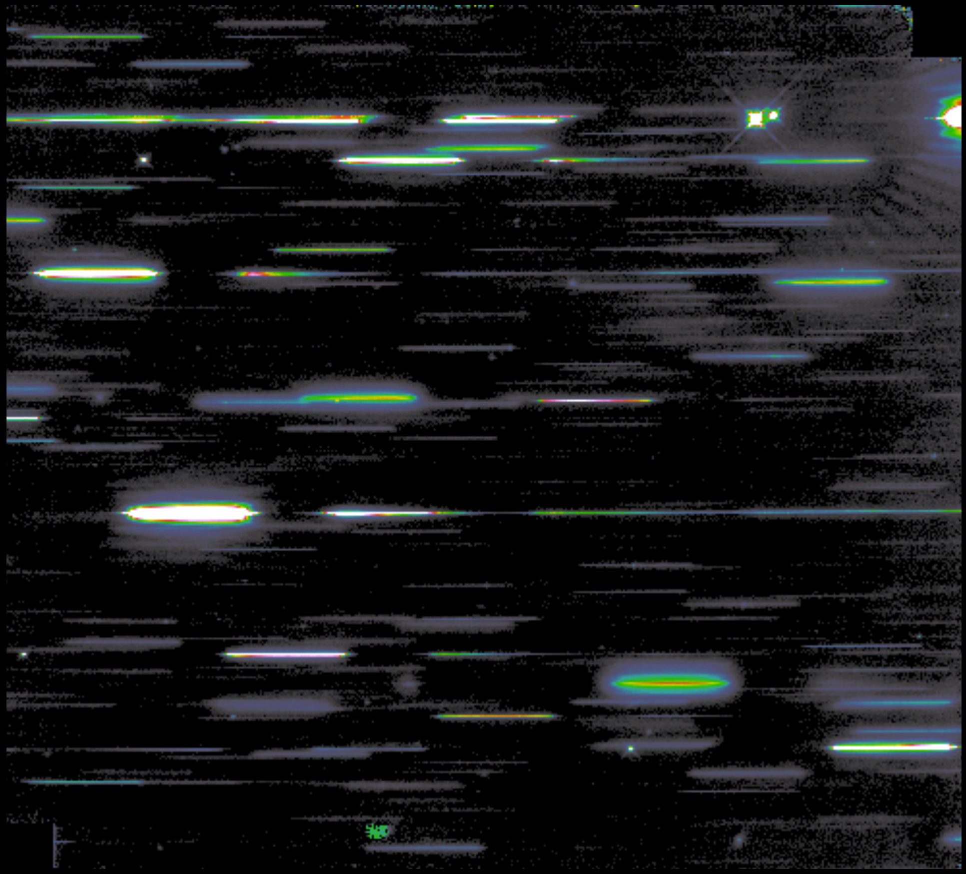
Rest-frame UV imaging or
spectroscopy (for young ages)



Spatially resolved probe of
star formation distribution

Our sample

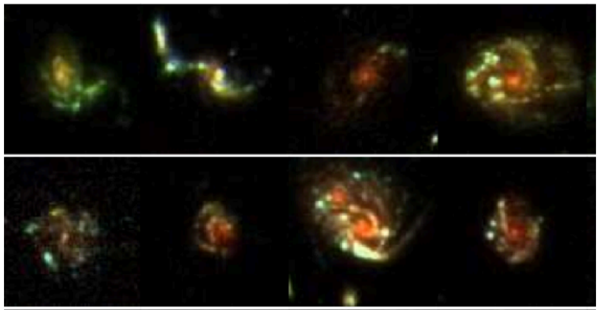
HST/WFC3:
Slitless spectroscopy (18 orbits)
Imaging: near-IR (F140W, F105W)
UVIS (F606W)



Pointed at CL J1449+0856 cluster (Gobat+ 13)

Exploring a new parameter space

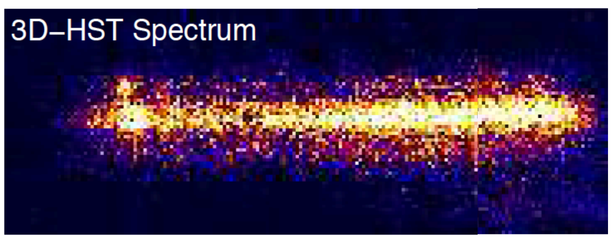
Guo+12



- **CANDELS-like surveys**:
  broad-band photometry only

  cannot identify young clumps
  (age > 100 Myr)

Nelson+15



- **3DHST-like surveys**:
  2 – 4 orbits slitless spectroscopy

  only anomalously bright clumps

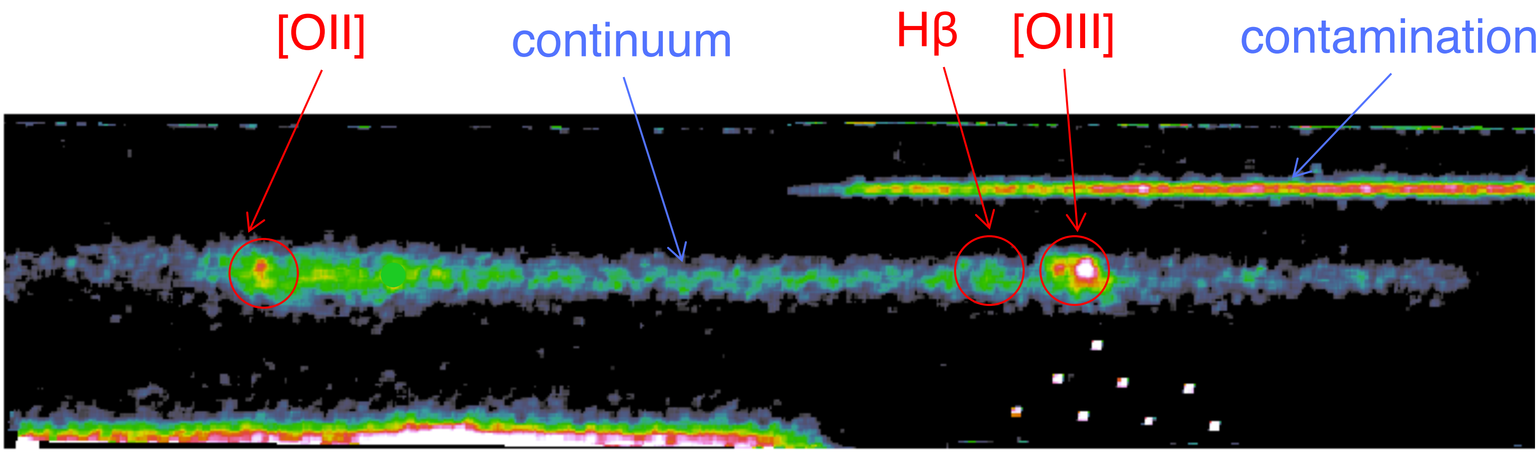
Treu+16

- **FRONTIER FIELDS dataset**
  pointing at local clusters

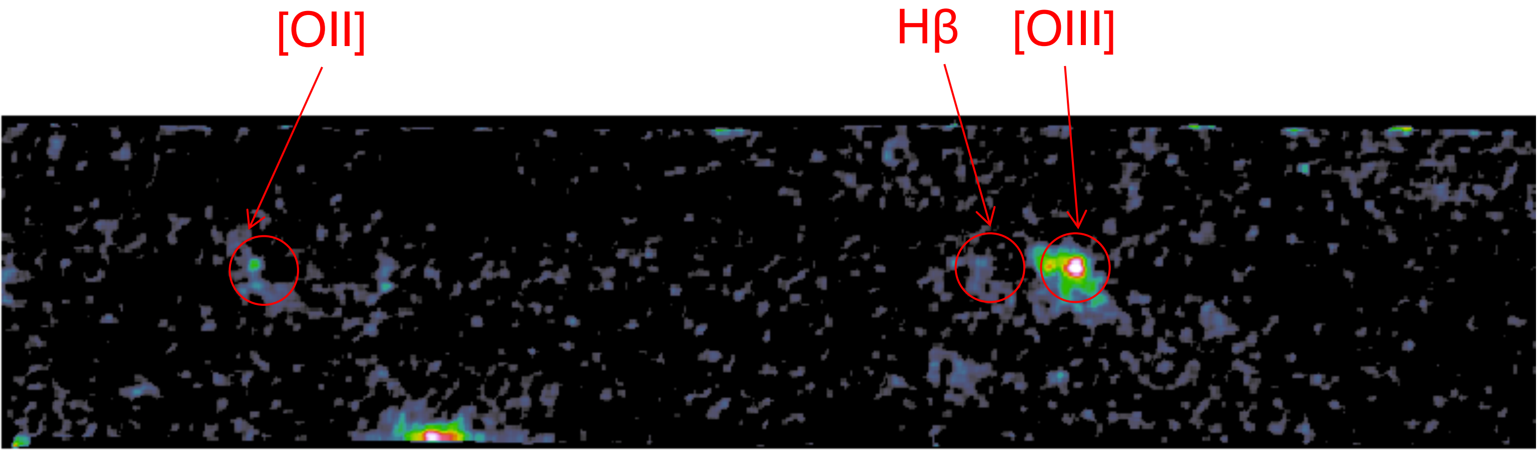
- **HUDF dataset** (18 orbits)

With our data set we can explore the young clumps regime

Creating emission line maps

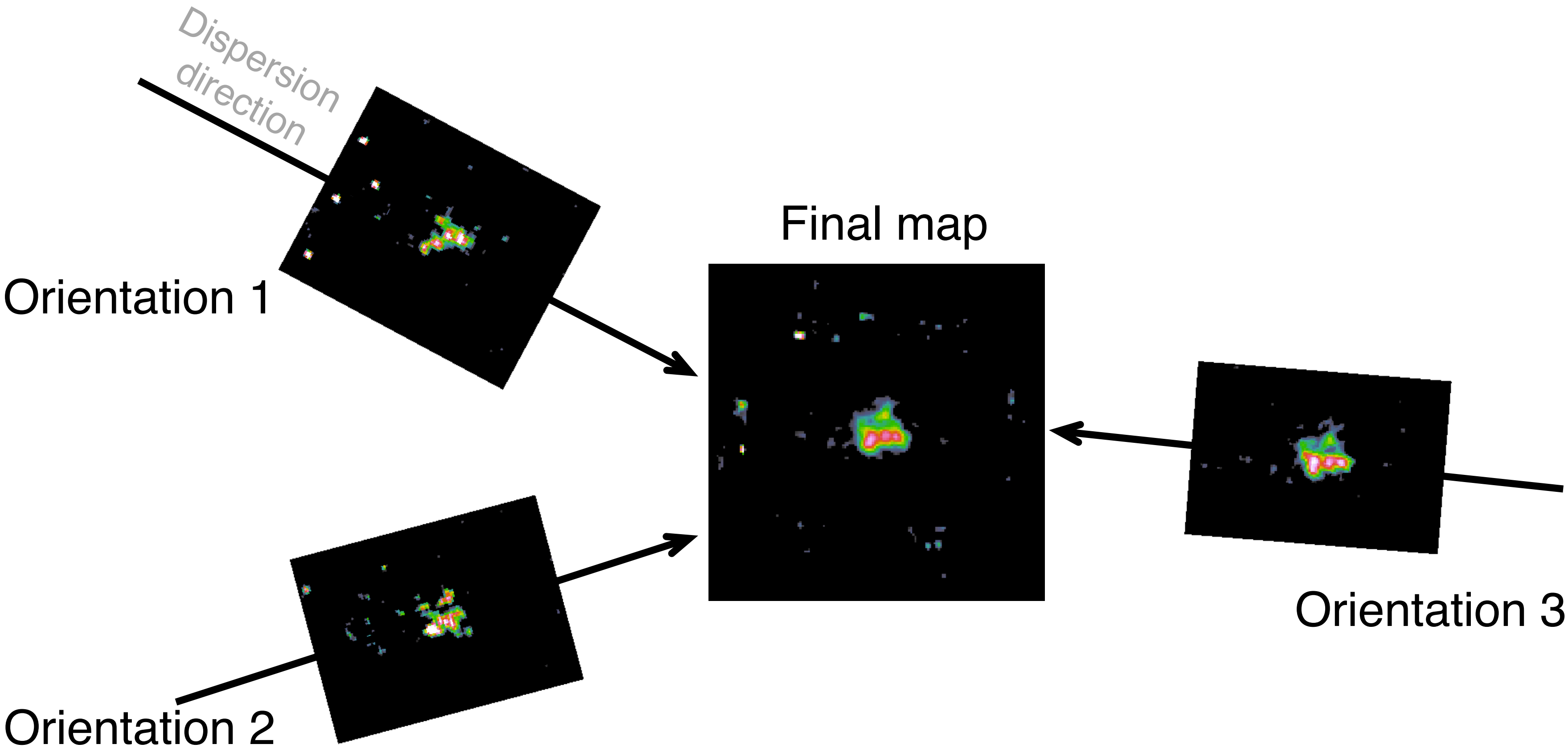


spectrum



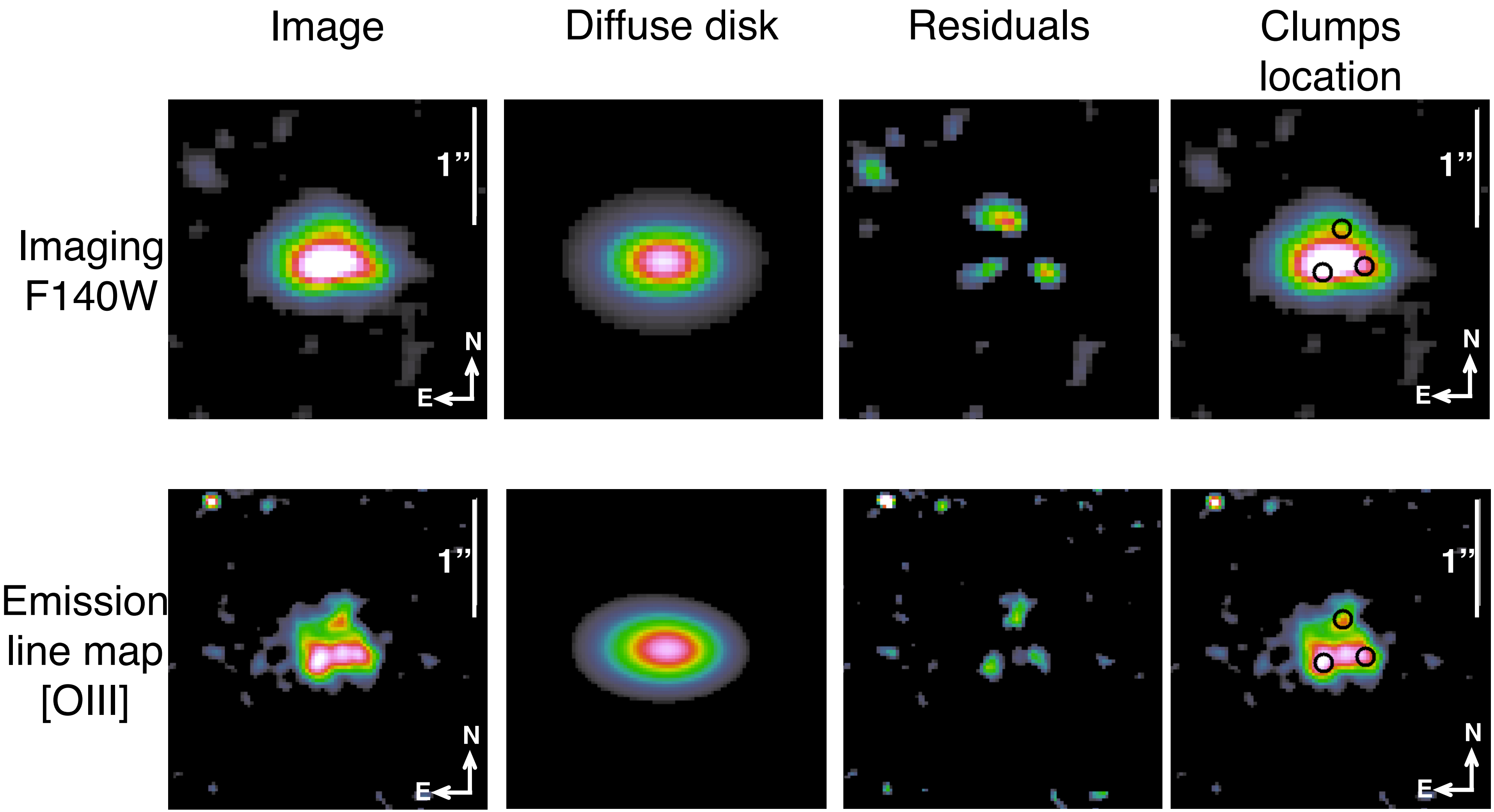
spectrum - continuum - contamination

Creating emission line maps

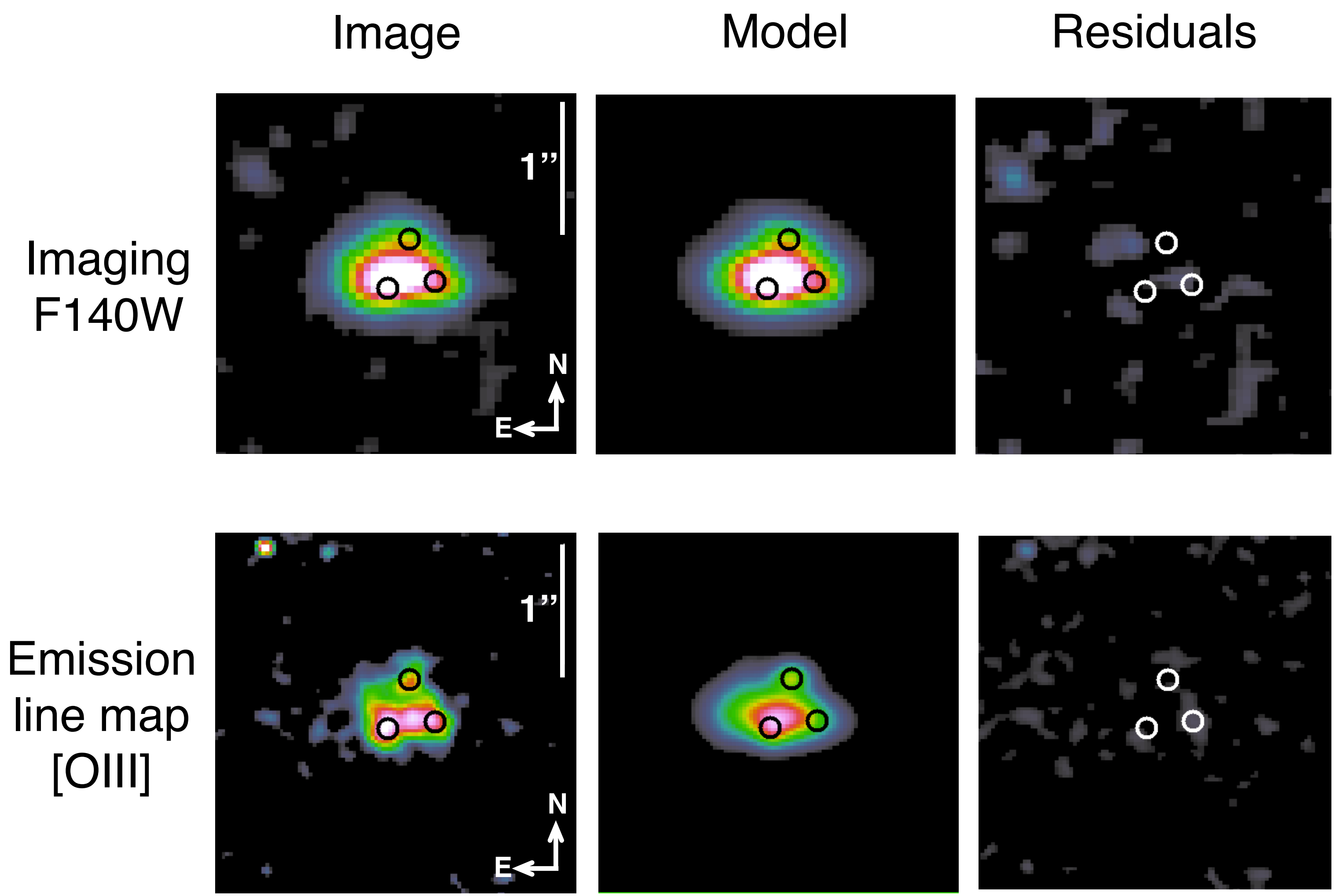


$\boxed{\text{Cross correlation}}$ $$CC = \sum_{i}^{N_{\text{width}}} \sum_{j}^{N_{\text{width}}} f_{i,j} \times f'_{i,j}$$

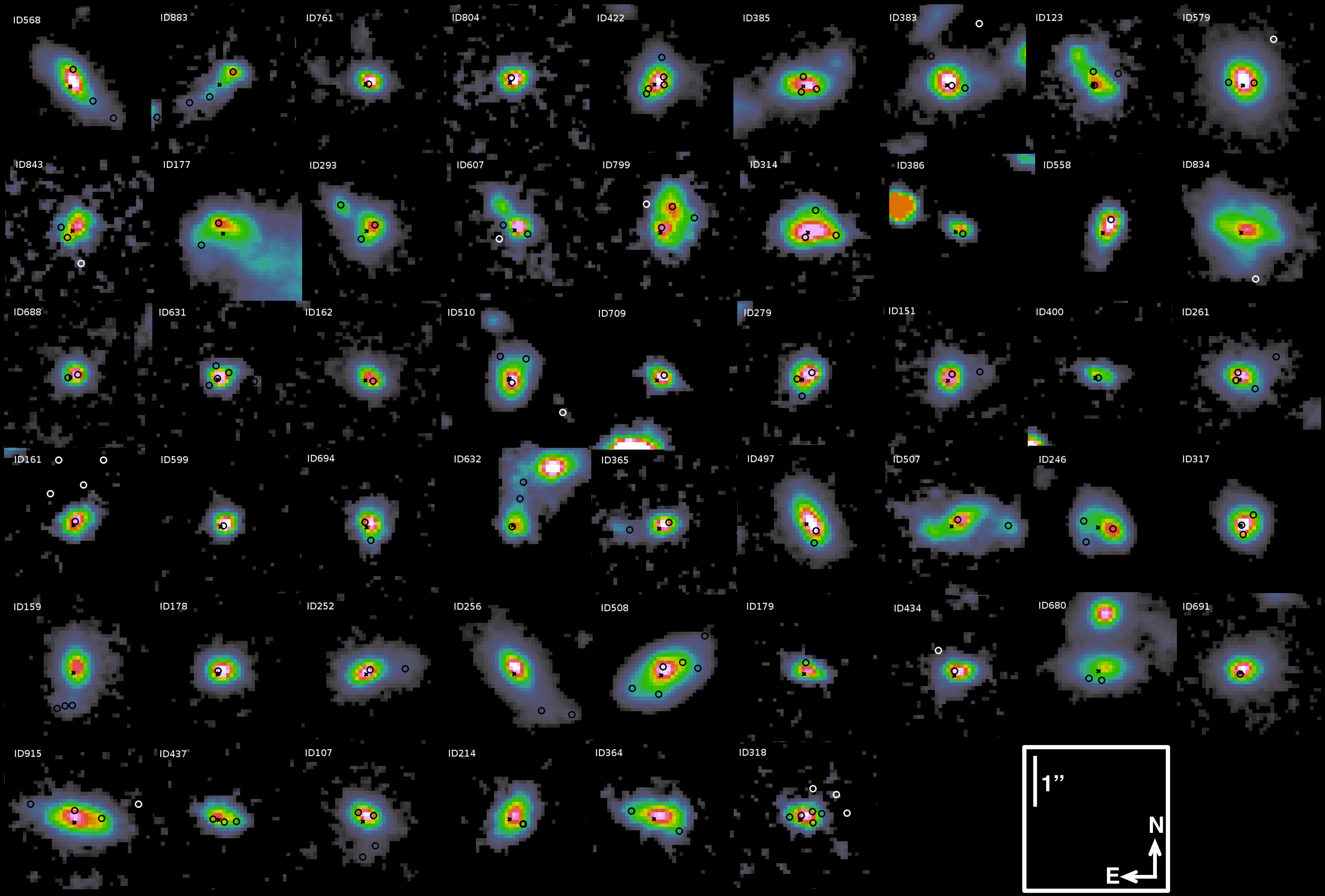
Finding clumps



Modelling light profiles



Imaging



ID568
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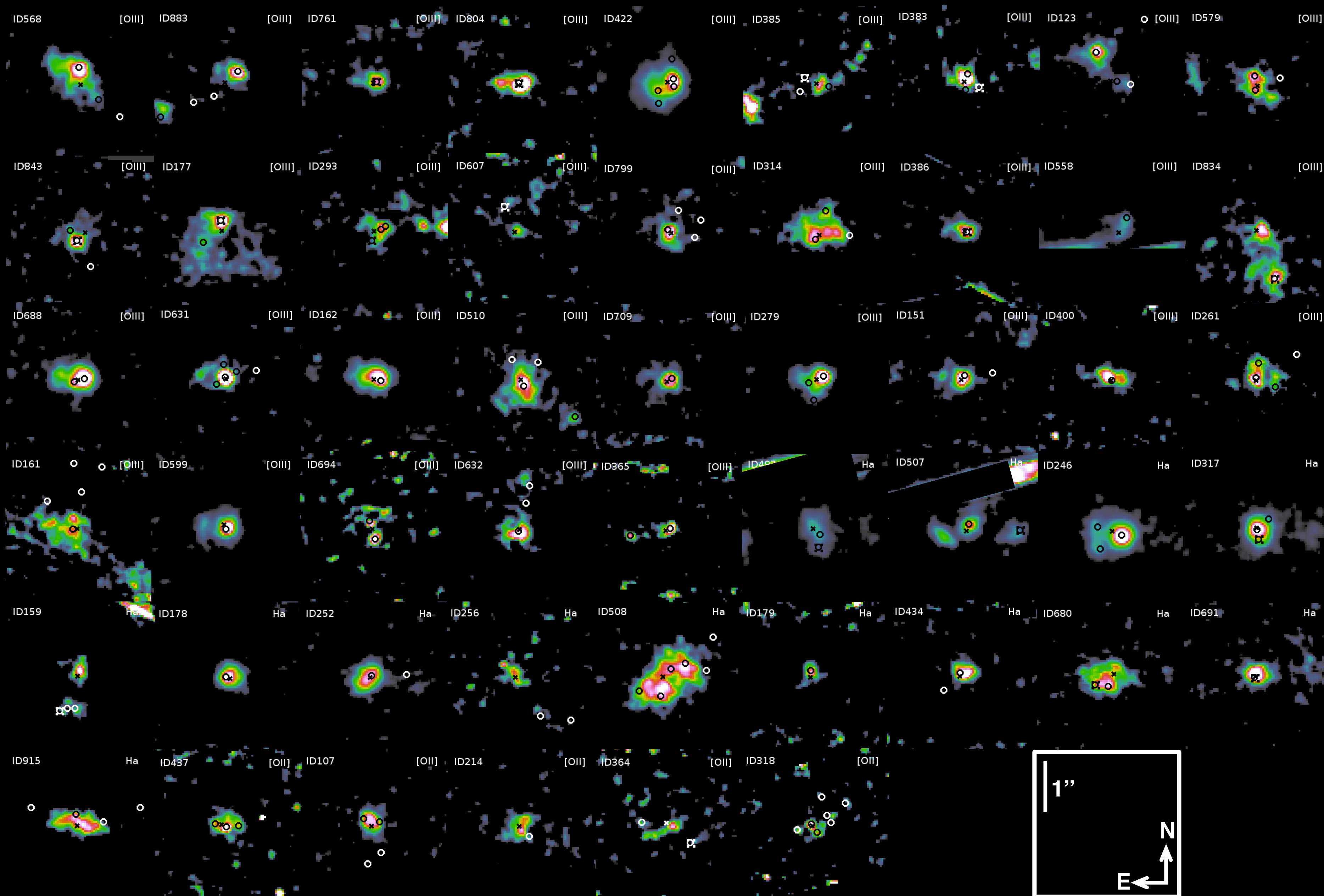
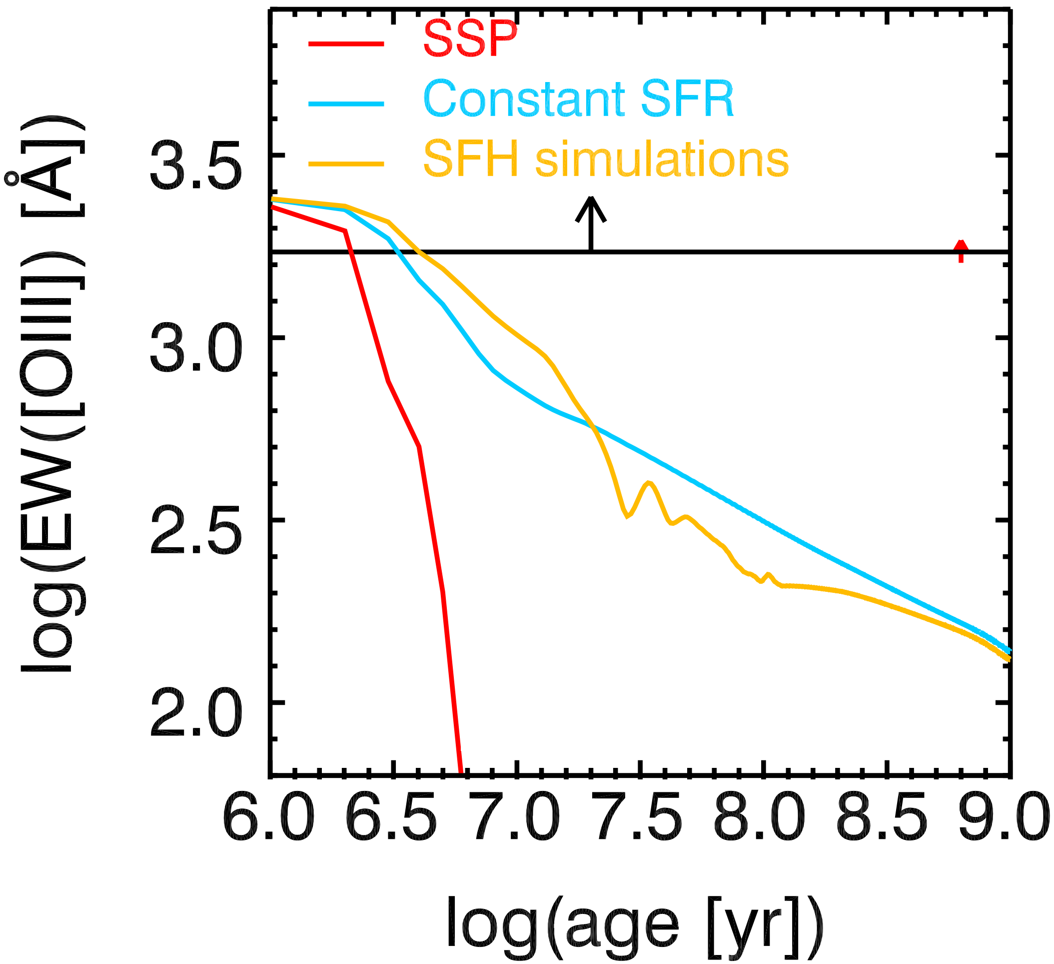
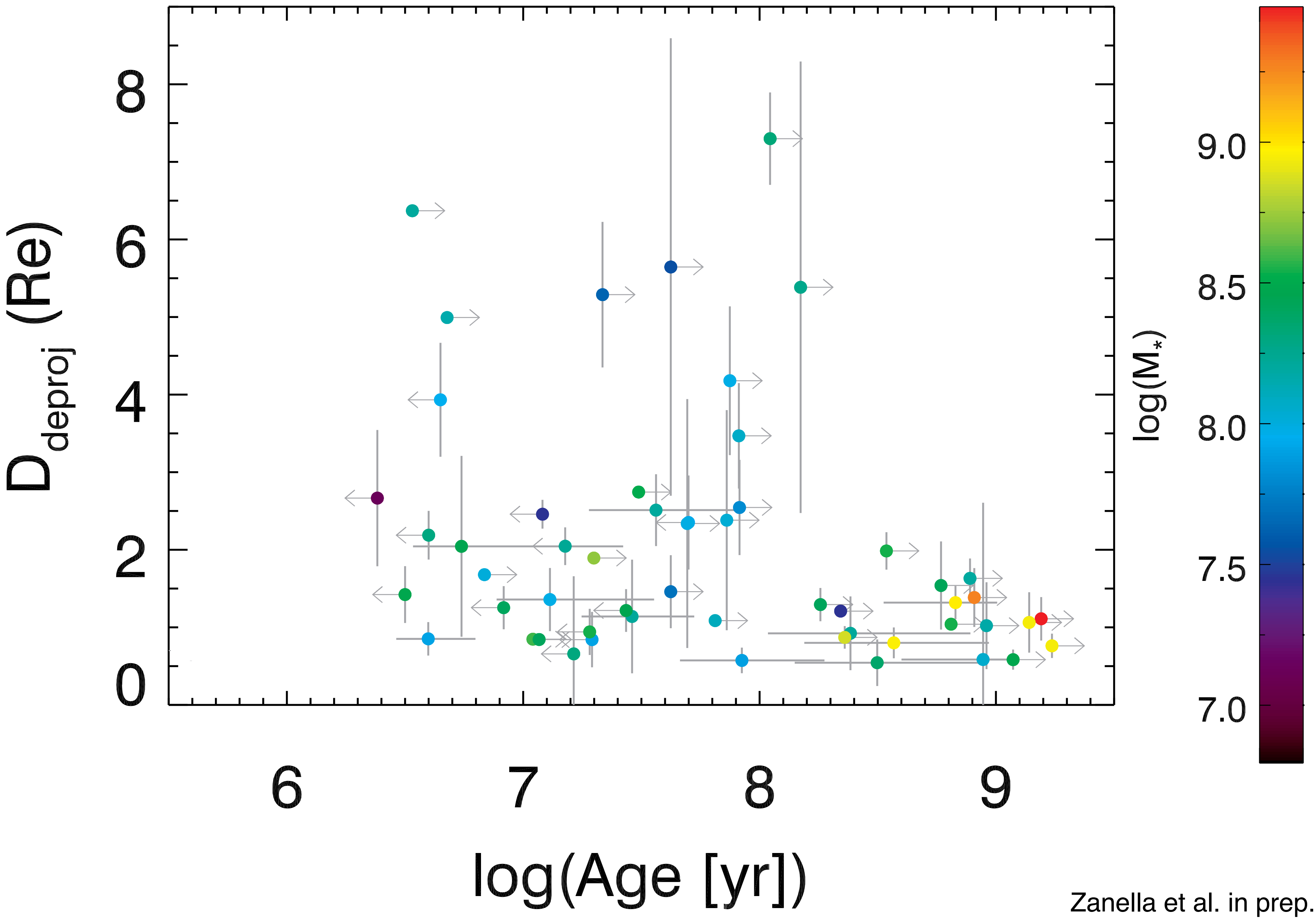
Emission line maps

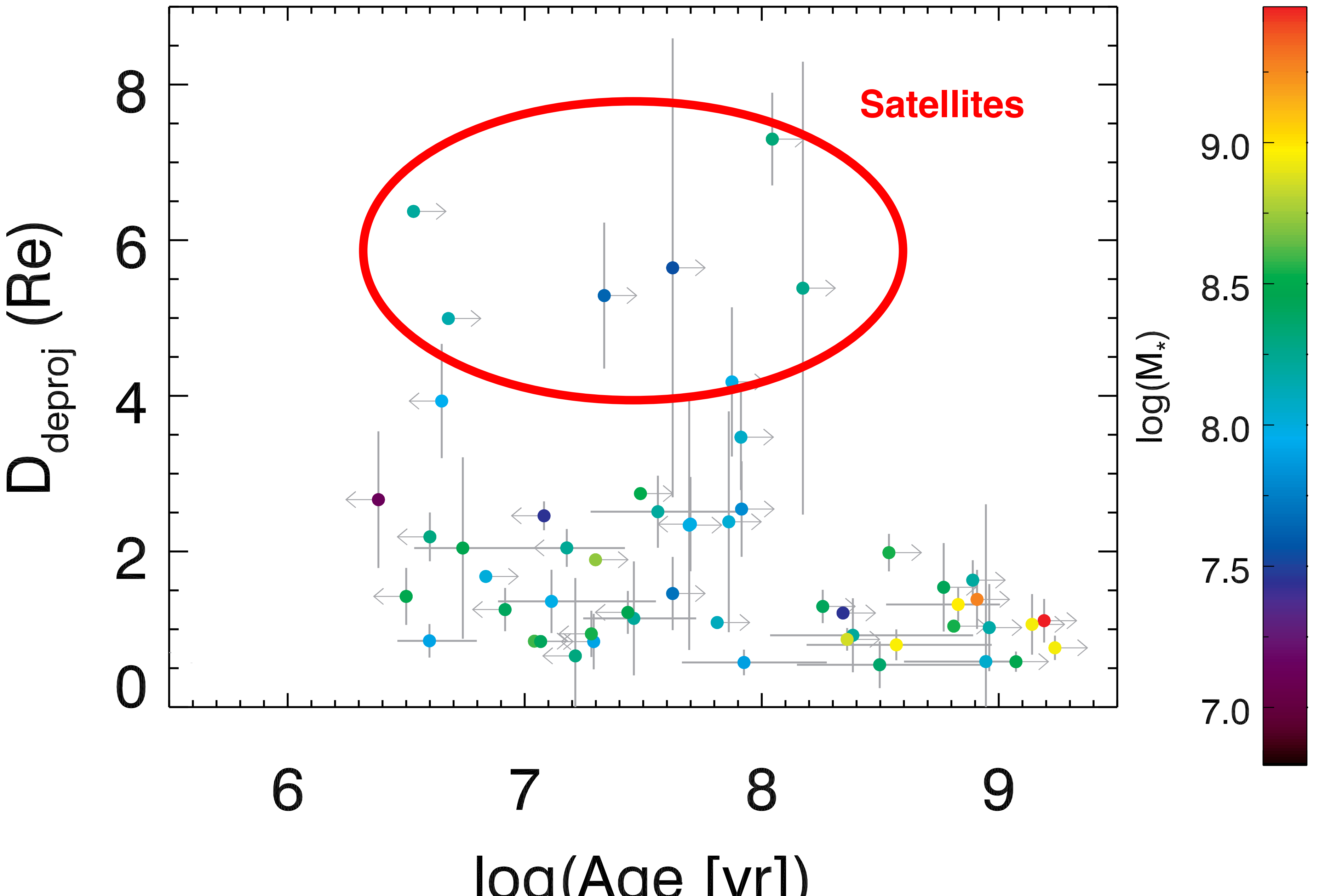


Age estimate for young clumps

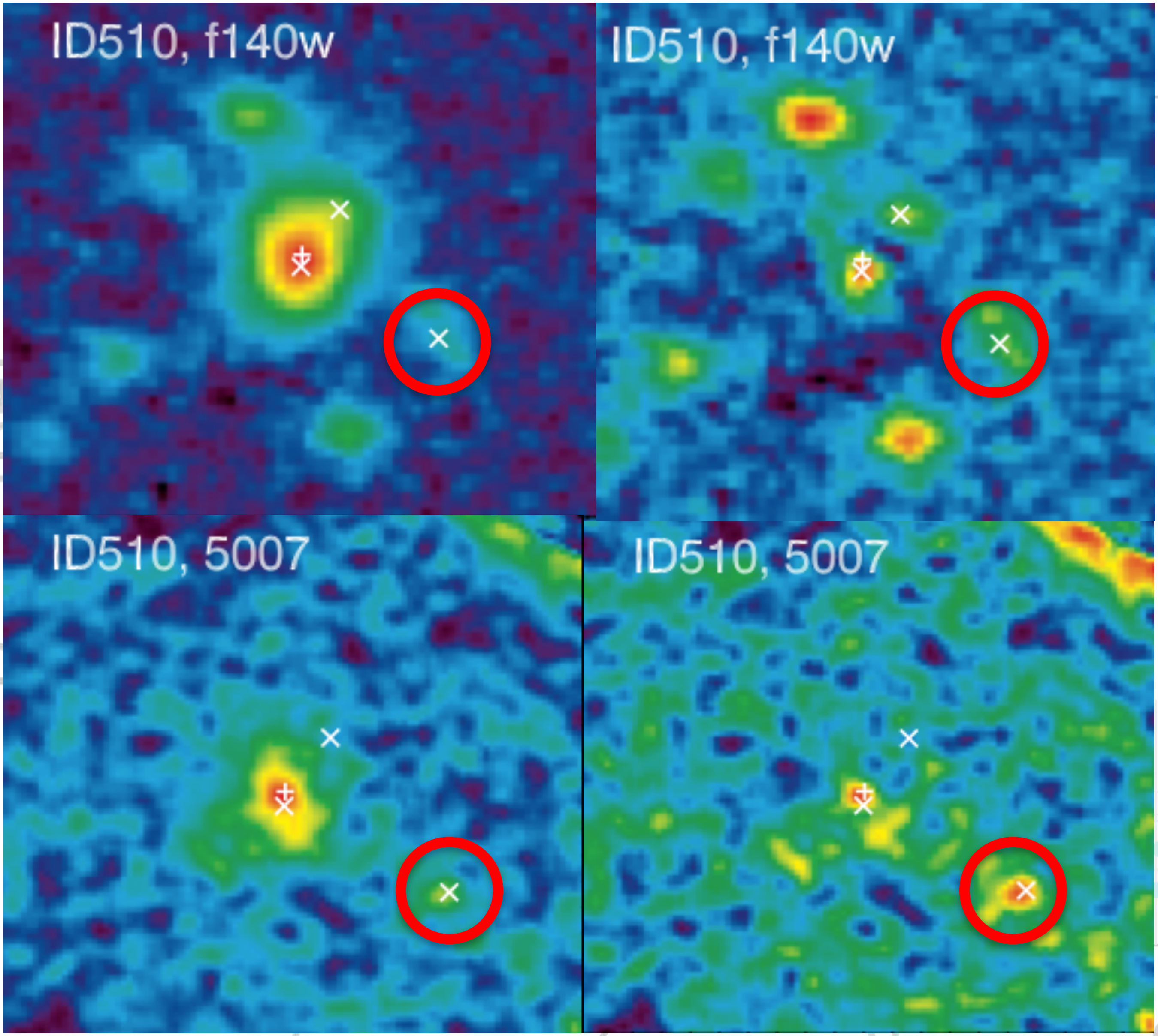




D_deproj (Re)
log(Age [yr])
log(M*)
8
6
4
2
0
6
7
8
9
9.0
8.5
8.0
7.5
7.0
Zanella et al. in prep.



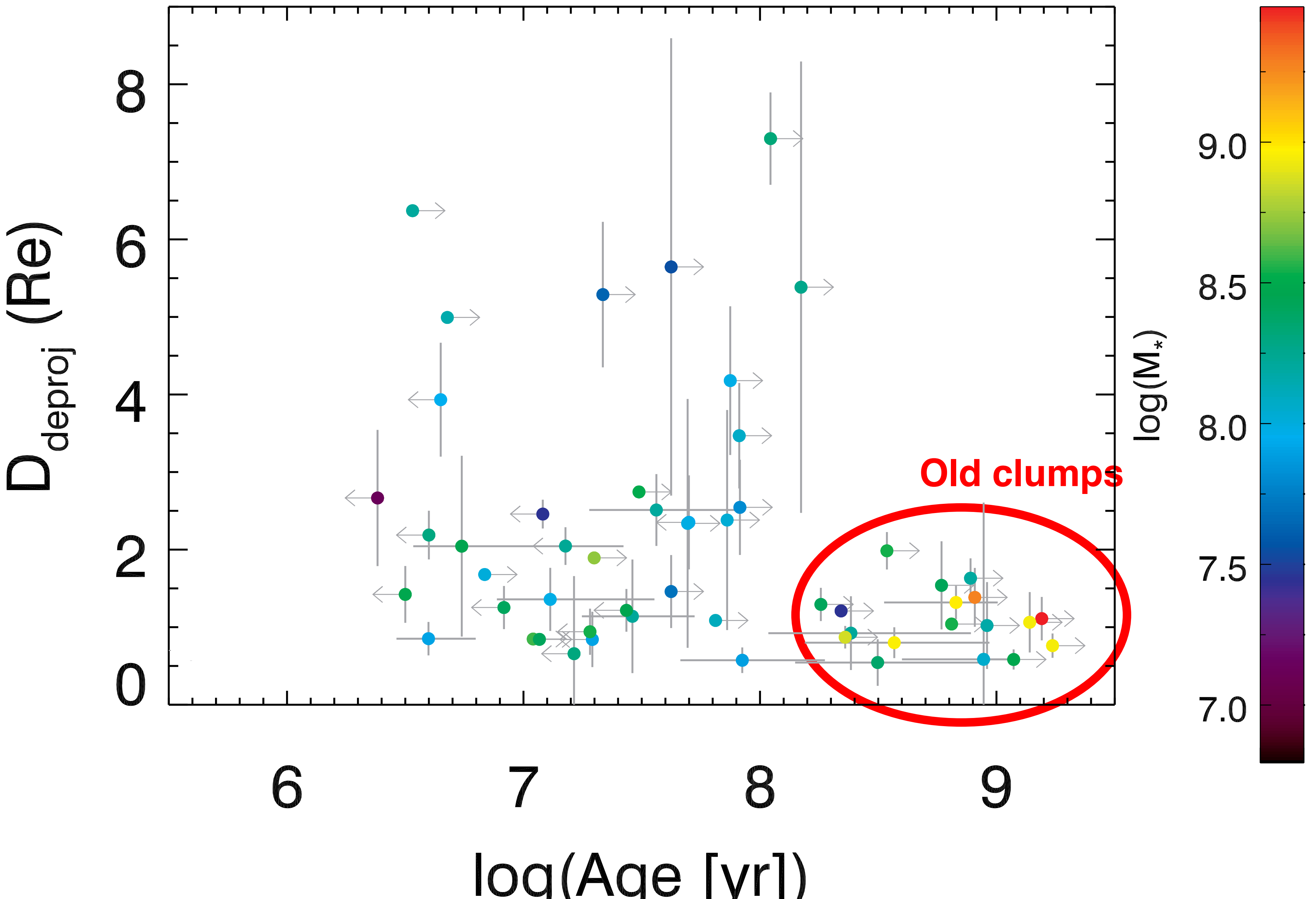
Satellites
D_{deproj} (Re)
log(Age [yr])
log(M_*)
0
2
4
6
8
6
7
8
9
7.0
7.5
8.0
8.5
9.0



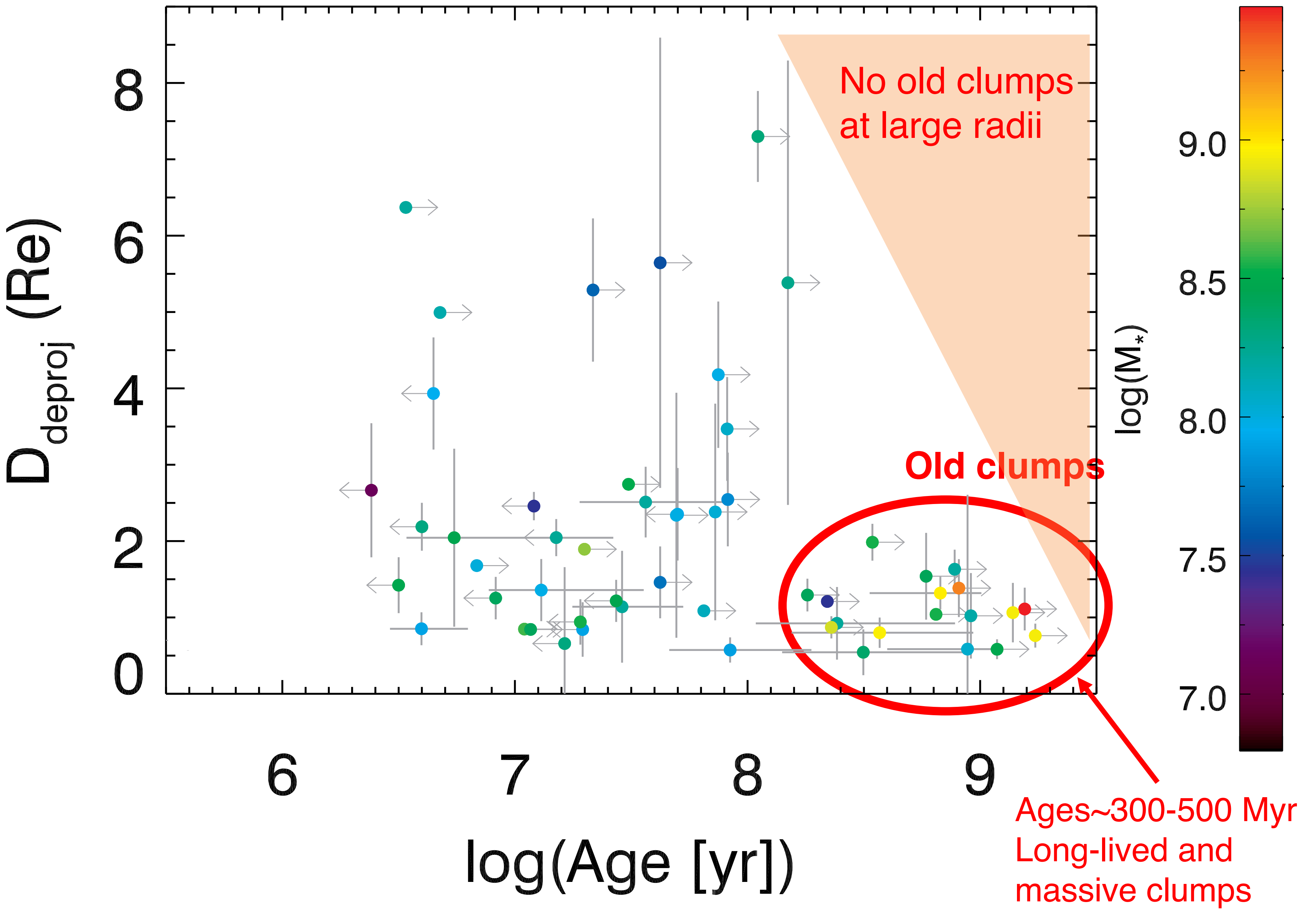
Imaging (rest-frame optical)

[OIII] emission line map

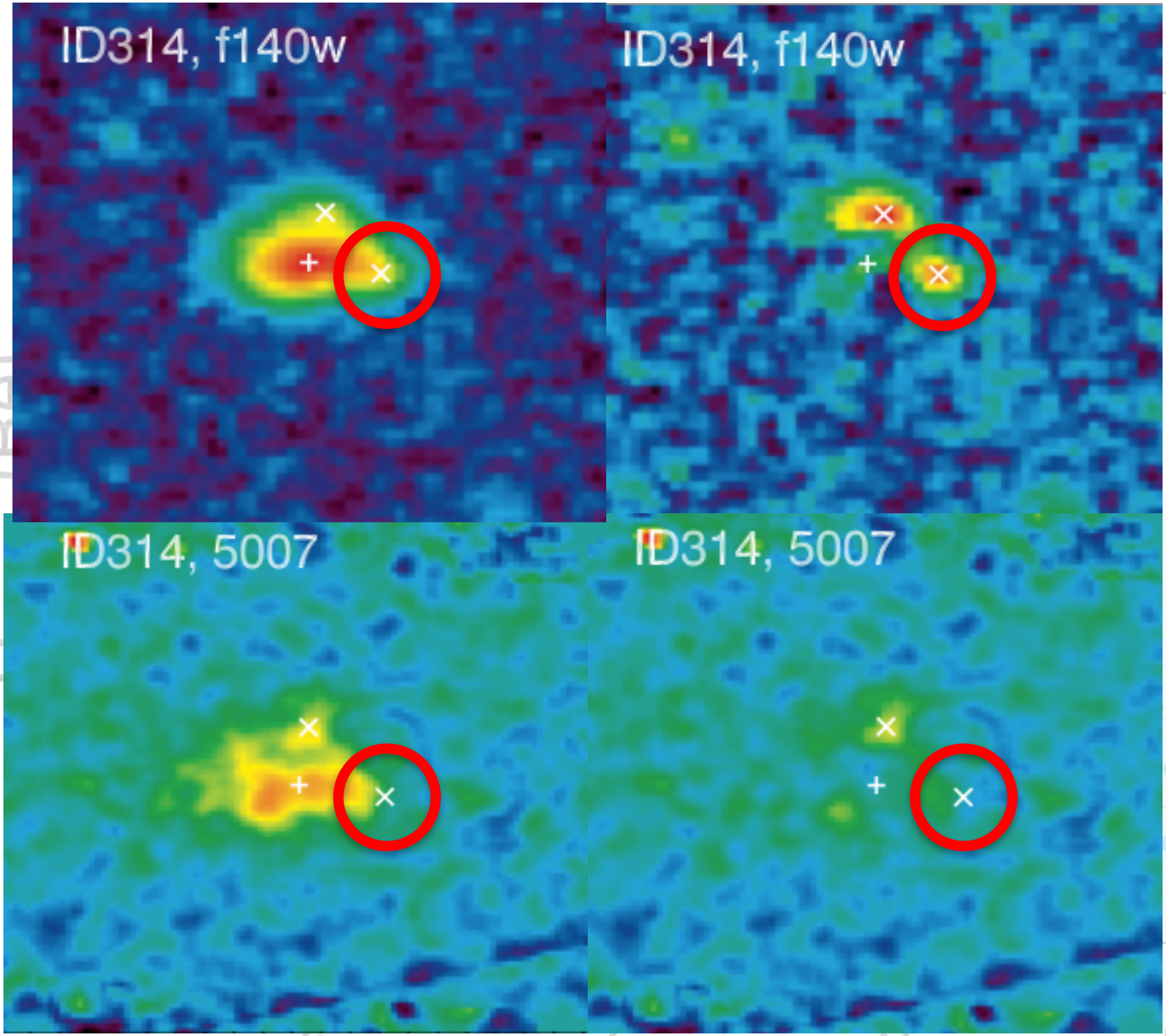
Close pairs selection through emission line maps



Old clumps
D_{deproj} (Re)
log(Age [yr])
log(M_*)
0
2
4
6
8
6
7
8
9
7.0
7.5
8.0
8.5
9.0



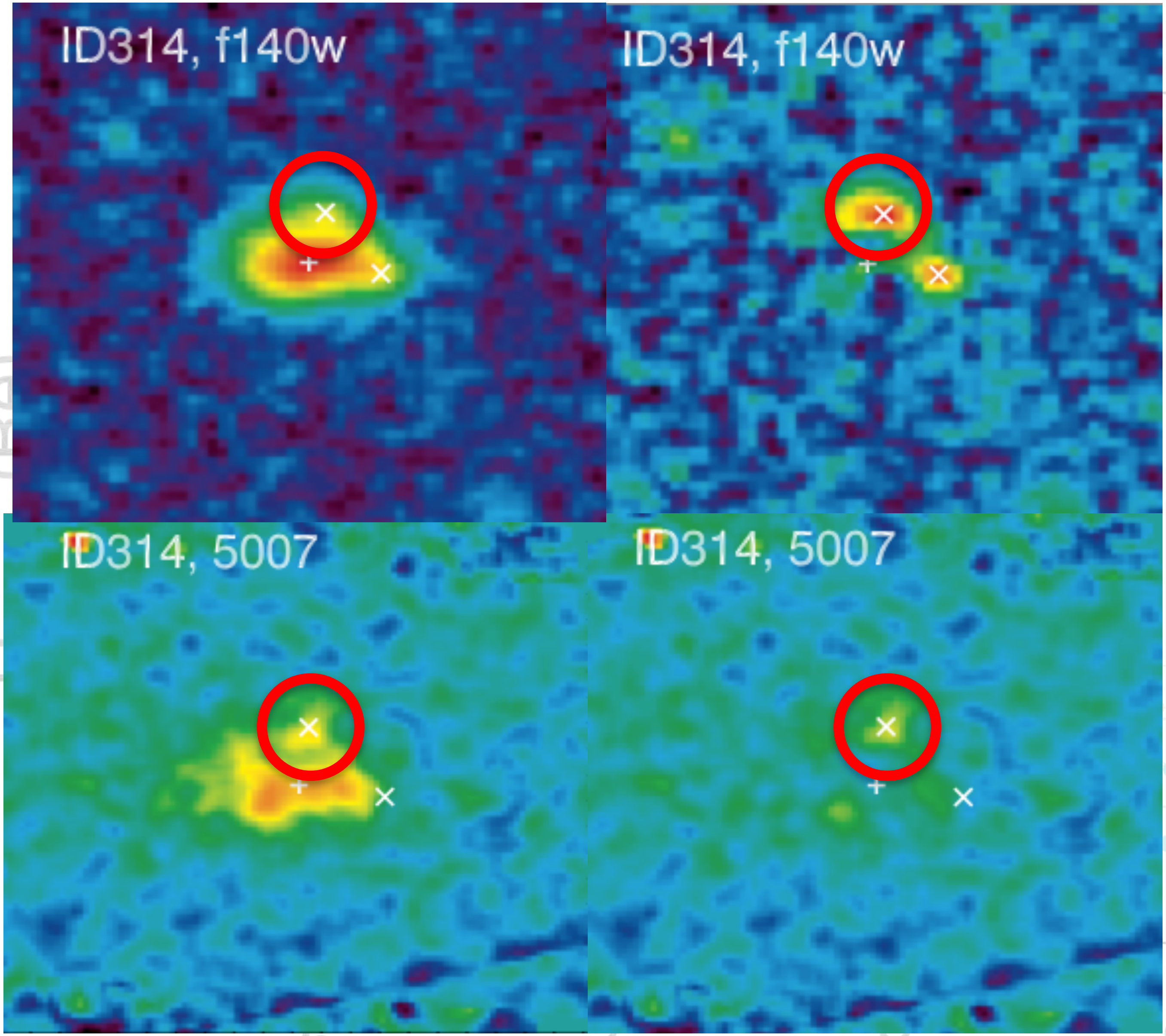
No old clumps
at large radii
Old clumps
Ages~300-500 Myr
Long-lived and
massive clumps
D_{deproj} (Re)
log(Age [yr])
log(M_*)
8
6
4
2
0
6
7
8
9
9.0
8.5
8.0
7.5
7.0



Imaging (rest-frame optical)

[OIII] emission line map

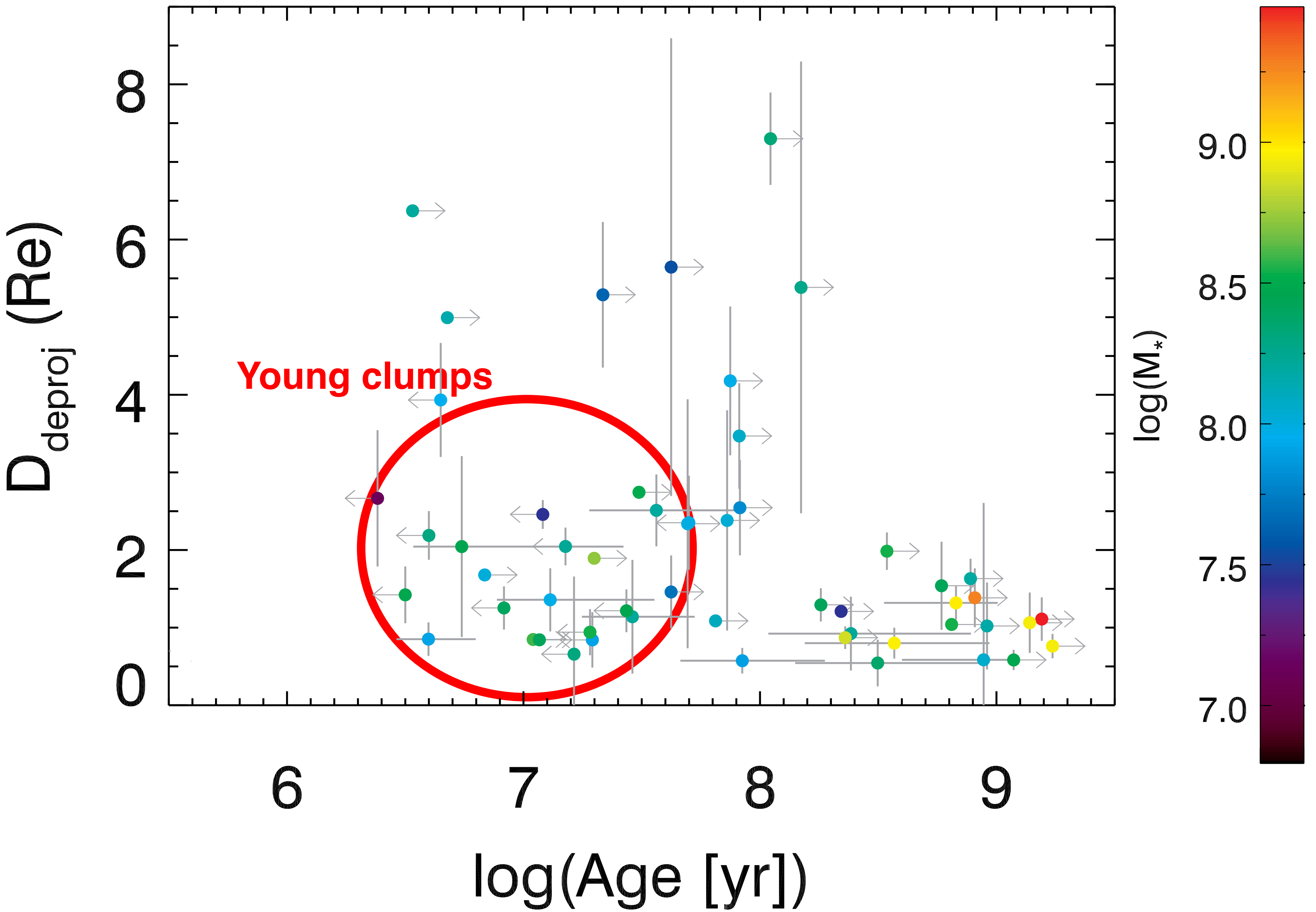
Old clumps: detected in continuum, but not in emission line maps



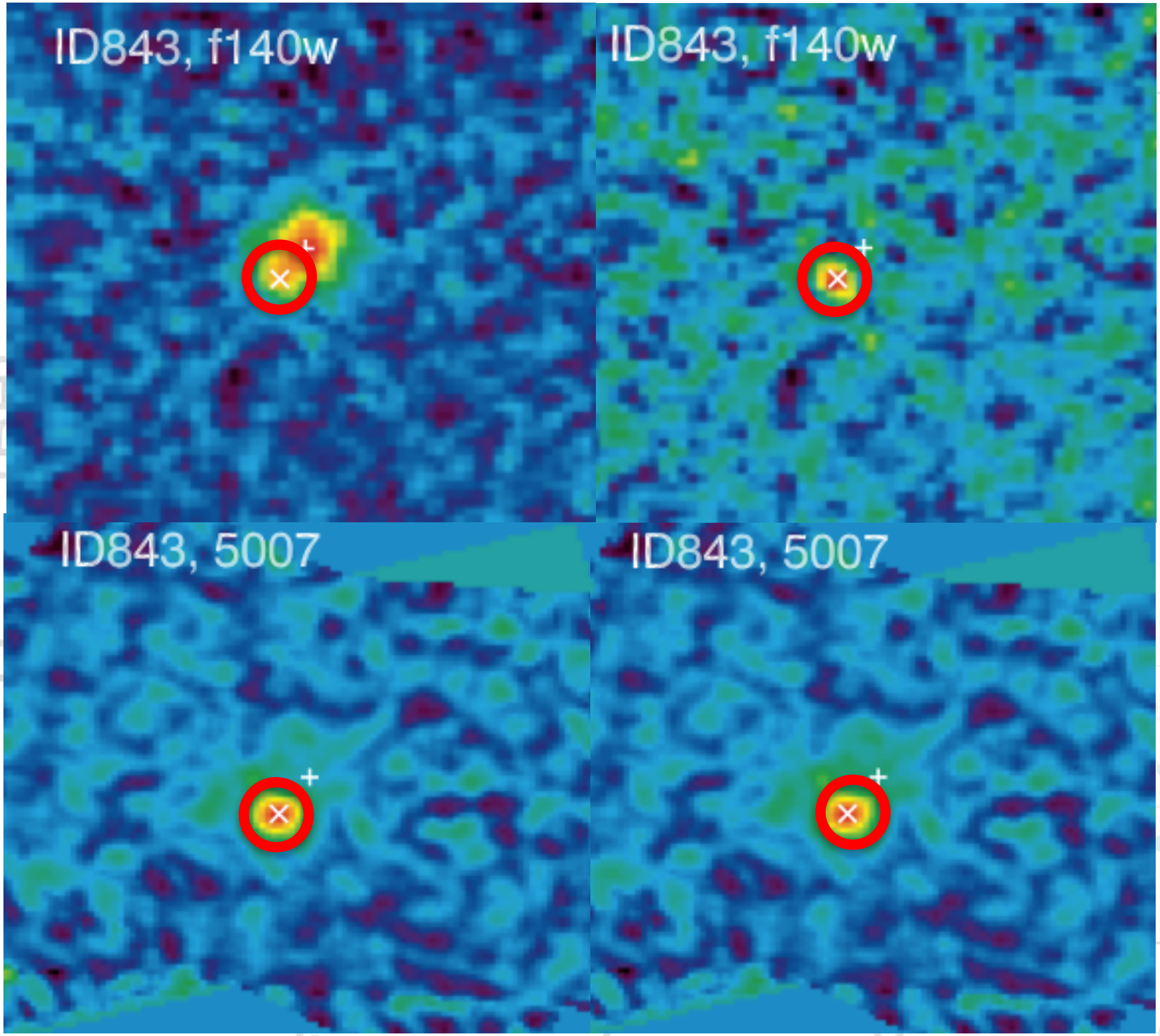
Imaging (rest-frame optical)

[OIII] emission line map

Intermediate-age clumps: continuum and emission lines detected



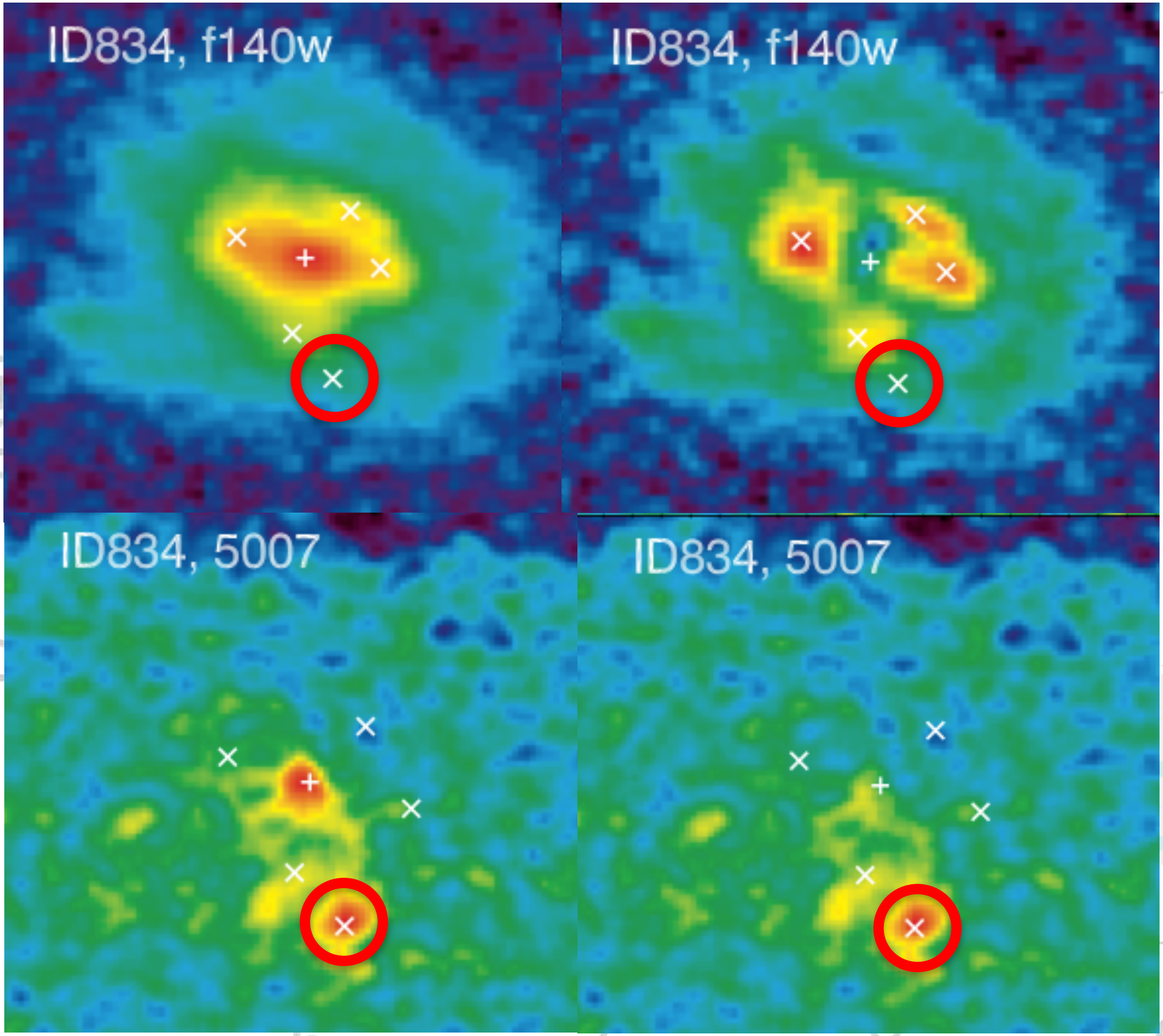
Young clumps
D_{deproj} (Re)
log(Age [yr])
log(M_*)
0
2
4
6
8
6
7
8
9
7.0
7.5
8.0
8.5
9.0



Imaging (rest-frame optical)

[OIII] emission line map

Contribution of emission lines in broad-band observations is important

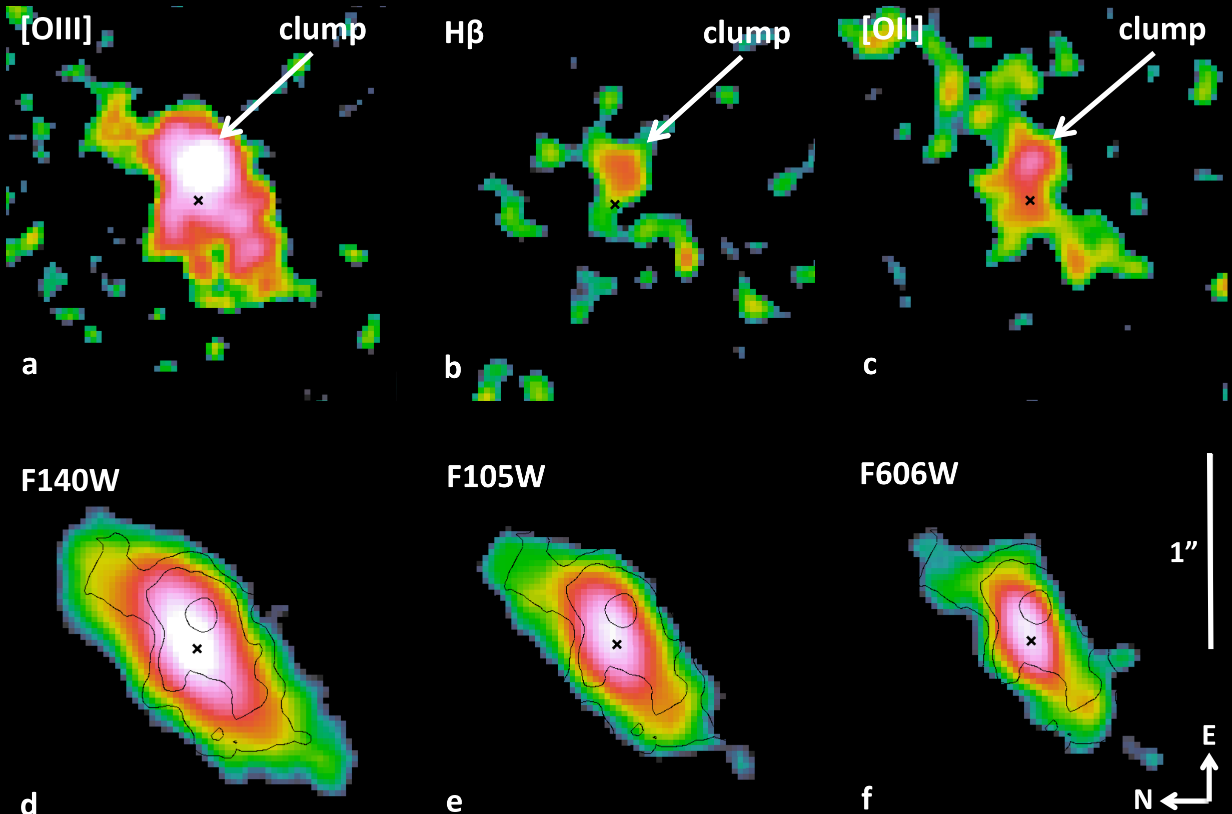


Imaging (rest-frame optical)

[OIII] emission line map

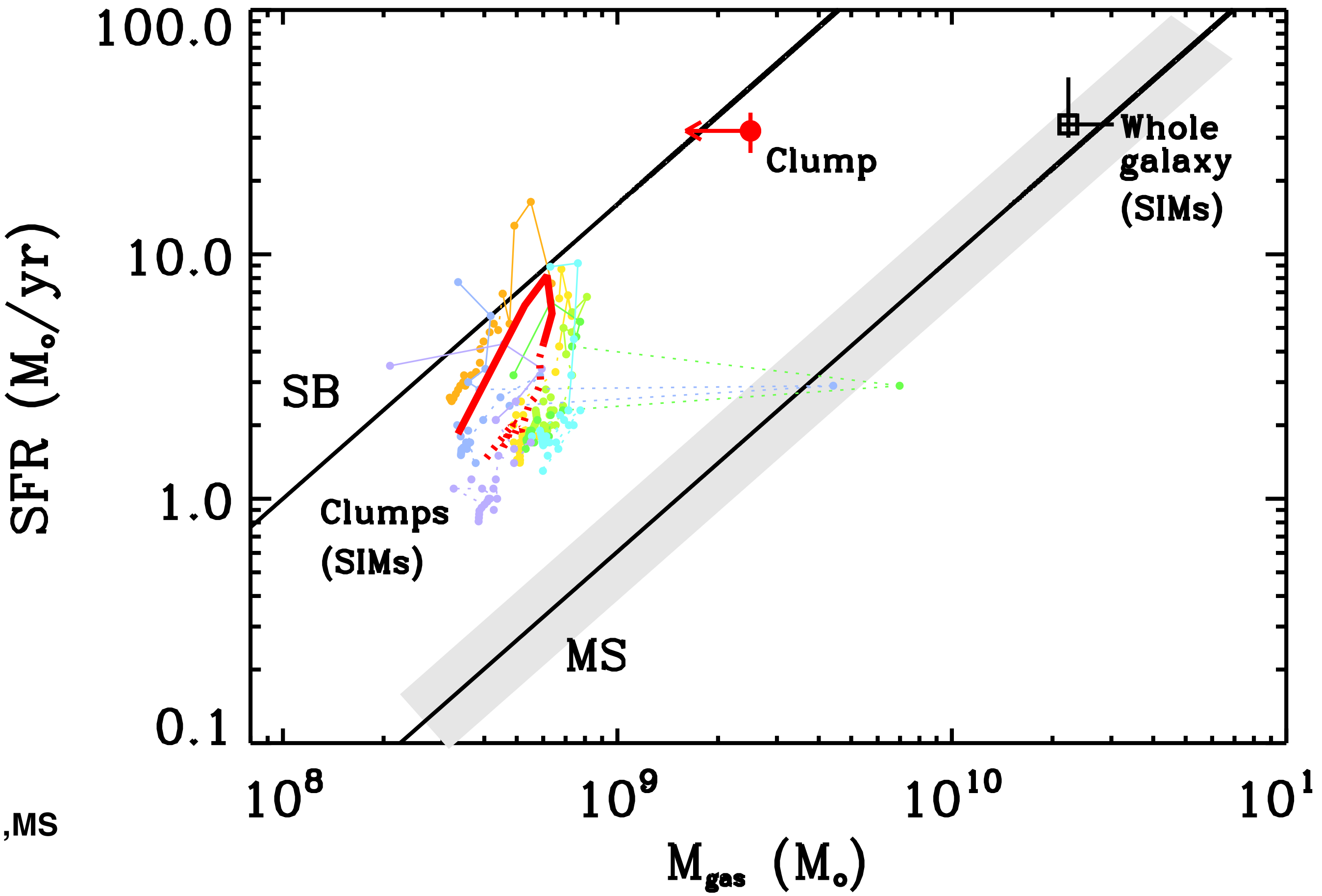
Bona fide young clump

An extremely young clump



Age < 10 Myr

Newly born clumps behave like mini-starbursts



sSFR > 30x sSFR$_{gal,MS}$

SFE > 10x SFE$_{gal,MS}$

Zanella et al. 2015, **Nature**, 521, 54

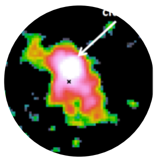
Clumps formation rate

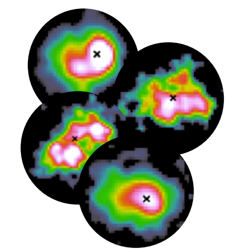
$$\mathrm{CFR} = \frac{\boxed{N_{\mathrm{young}}}}{\boxed{t_V}\boxed{N_{\mathrm{gal}}}}$$

# of young clumps

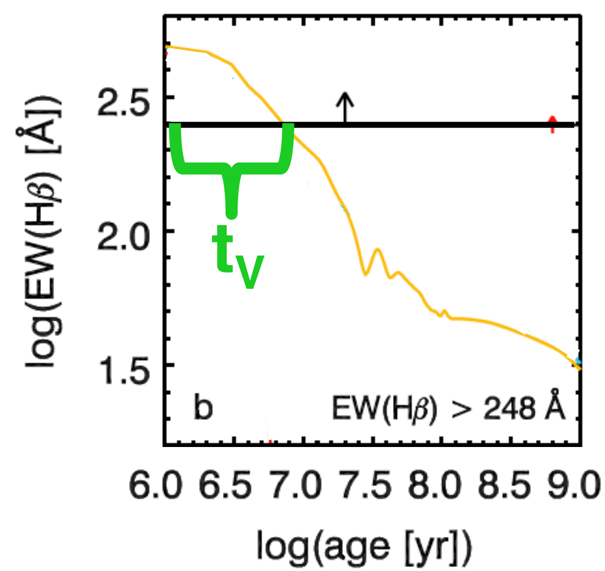
# of sample galaxies

Visibility window



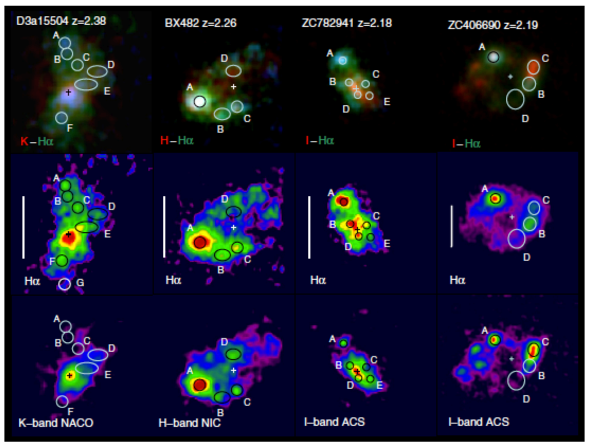


CFR ~ 2.5 clumps/galaxy/Gyr

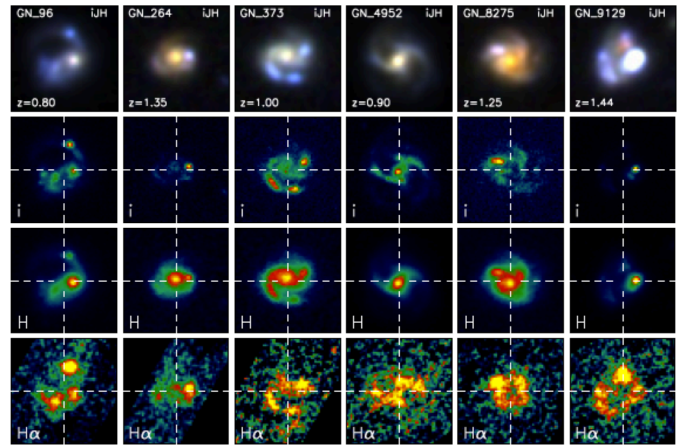


Clumps lifetime

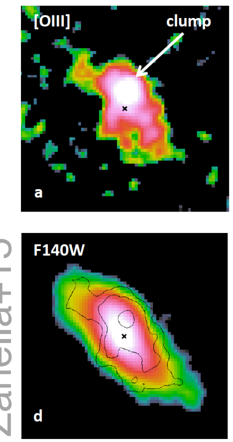
Genzel+11



Wuyts+13



Zanella+15



$$\mathrm{LT} = \frac{\boxed{N_{\mathrm{cl/gal}}}}{\mathrm{CFR}}$$

→ # of clumps/galaxy with $M_{tot} \geq 2.5 \times 10^9 M_\odot$

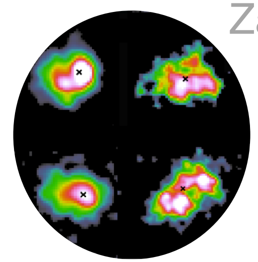
LT ~ 500 Myr → clumps likely survive stellar feedback

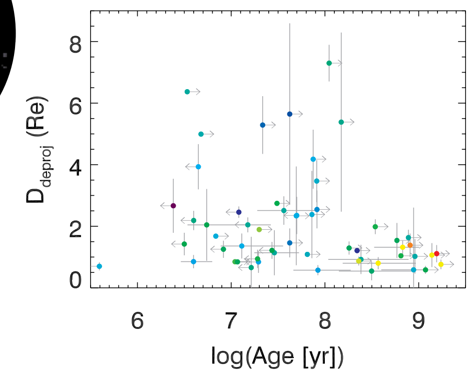
Summary

- Simultaneously analyzing continuum and emission line maps allows us to:

  detect **close pairs** and **gas-rich mergers**
  properly **age star-forming clumps**
  old clumps (**300 – 500 Myr**) close to center

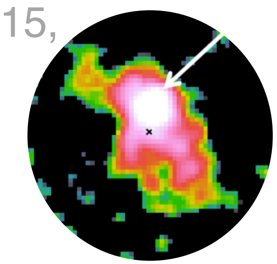
Zanella et al. in prep.

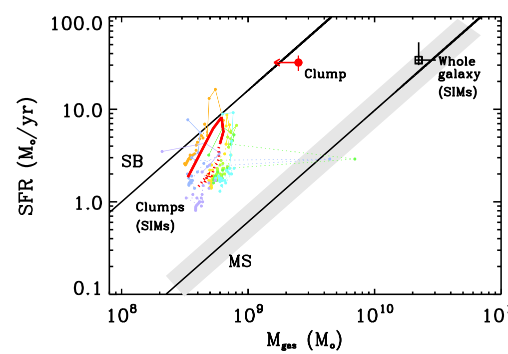




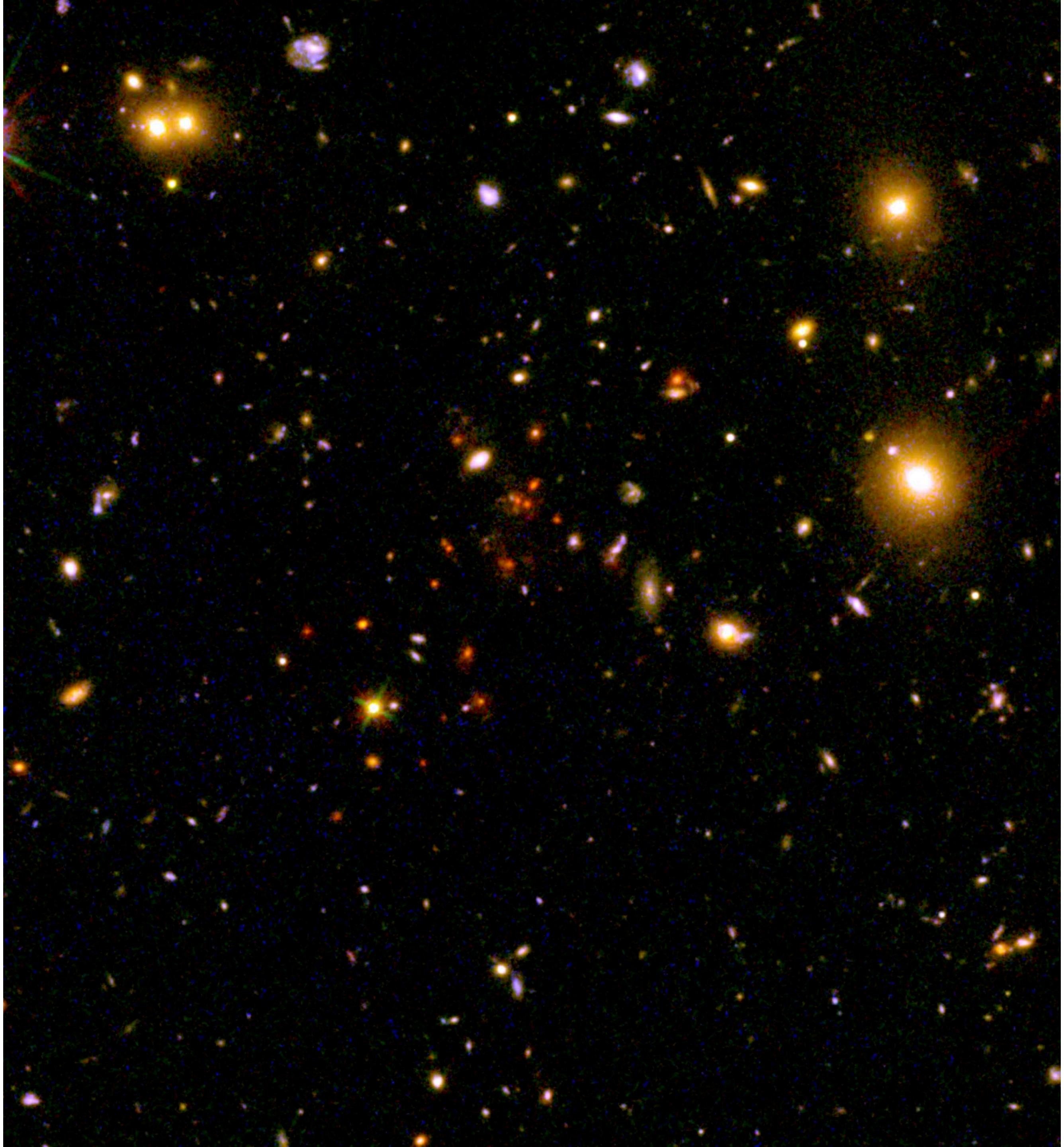
- **Young clumps**:
  at young ages have **starburst-like SFE**;
  likely live ~ 500 Myr: **survive feedback**;
  play a role in **bulge growth**

Zanella et al. 2015, Nature, 521, 54





Backup



Gobat+13

Table 1. Photometric and spectroscopic coverage of CL J1449+0856.

Filter	Central wavelength (μm)	Exposure (s)	Instrument	Telescope	Observation date	References[a]
0.5-10 keV	-	80000	EPIC-MOS	XMM-Newton	2001-2003	B05, G11
0.5-8 keV	-	188000	ACIS	Chandra	2004 Jun, 7th-13th, 2014 May, 21st	C09, G11, V16
U	0.36	14700	FORS2	VLT	2011 May, 3rd	S13
NB3640	0.36	12890	LRIS	Keck	2014 Mar, 27th	V16
OII/4000+45	0.37	28800	FORS2	VLT	2011 May, 3rd	Gobat in prep.
V	0.55	12130	FORS2+LRIS	VLT+Keck	2011 May, 3rd, 2014 Mar, 27th	S13, V16
B	0.44	1500	Suprime-Cam	Subaru	2003 Mar, 5th	K06
F606W	0.59	1080	WFC3	*HST*	2013 May, 20th	Z15
R	0.65	3600	Prime Focus Camera	WHT	1998 May, 19th-21st	D00
I	0.80	5400	Suprime-Cam+LRIS	Subaru+Keck	2003 Mar, 5th, 2014 Mar, 27th	K06
z	0.91	2610	Suprime-Cam	Subaru	2003 Mar, 4th-5th	K06
Y	1.02	17780	MOIRCS	Subaru	2009 Mar, 15th, 2010 Feb, 7th-8th, 21st	G11
F105W	1.06	11880	WFC3	*HST*	2013 May, 20th	Z15
J	1.26	9360	MOIRCS+ISAAC	Subaru+VLT	2007 Mar, 10th, Apr 5th	G11
F140W	1.40	4320	WFC3	*HST*	2010 Jun, 6th, 26th, Jul, 1st 9th	G13, Z15
F160W	1.60	17920	NIC3	*HST*	2008 May, 11th	G11
H	1.65	2380	MOIRCS	Subaru	2007 Apr, 8th	G11
K	2.15	1890	NIRC2	Keck	2009 Apr, 4th	G11
K_s	2.20	7800	MOIRCS+ISAAC	Subaru+VLT	2007 Mar, 8th, Apr, 5th	G11
IRAC 1	3.6	65640	IRAC	*Spitzer*	2004 Jul, 22nd, 2011 Sep 8th-9th, 11th	G11, G13, S13
IRAC 2	4.5	65640	IRAC	*Spitzer*	2004 Jul, 22nd, 2011 Sep 8th-9th, 11th	G11, G13, S13
IRAC 3	5.8	65640	IRAC	*Spitzer*	2004 Jul, 22nd, 2011 Sep 8th-9th, 11th	G11, G13, S13
IRAC 4	8.0	65640	IRAC	*Spitzer*	2004 Jul, 22nd, 2011 Sep 8th-9th, 11th	G11, G13, S13
MIPS 24	24	480	MIPS	*Spitzer*	2004 Aug, 5th	G11, G13, S13
PACS Bands	100, 160	63720	PACS	Herschel	2011 Jul, 19th-20th	Strazzullo in prep.
SPIRE Bands	250, 350, 500	14400	SPIRE	Herschel	2013 Apr, 1st	Strazzullo in prep.
345 GHz	870	108000	LABOCA	APEX	2011 Aug - Sep	Dannerbauer in prep.
Band 7	870	14728	-	ALMA	2013 Jun - 2014 Dec	V16, Strazzullo in prep.
S	1.3×10^5	75600	-	JVLA	2012 Feb - Nov	Coogan in prep.
L	2×10^5	57600	-	e-MERLIN	2012 May	Béthermin in prep.
325 MHz	9.2×10^5	14400	-	GMRT	2013 Jan - May	Sargent in prep.
GRIS-300V+10	0.45-0.87	36000	FORS2	VLT	2008 Apr - Jul	G11
GRIS-300V+10	0.45-0.87	41400	FORS2	VLT	2012 Apr, 16th-17th	Gobat in prep.
LR-BLUE	0.37-0.67	9000	VIMOS	VLT	2004 Mar, 29th	G11
Optical	0.47-0.93	5400	MUSE	VLT	2015 Jun, 20th	Valentino in prep.
HK500	1.30-2.30	50400	MOIRCS	Subaru	2013 Apr, 7th-9th	V15
K	1.93-2.46	73800	KMOS	VLT	2015 Apr - 2016 Mar	Valentino in prep.
G141	1.40	44640	WFC3	*HST*	2010 Jun, 6th, 26th, Jul, 1st 9th	G13, Z15
Band 3	CO(3-2)	13794	-	ALMA	2014 May - 2015 June	Strazzullo in prep.
Band 4	CO(4-3)	13819	-	ALMA	2016 Apr - May	(Ongoing reduction)
Ka	CO(1-0)	75600	-	JVLA	2012 Feb - Mar	Coogan in prep.

[a]References: D00: Daddi et al. 2000; B05: Brusa et al. 2005; K06: Kong et al. 2006; C09: Campisi et al. 2009; G11: Gobat et al. 2011; G13: Gobat et al. 2013; S13: Strazzullo et al. 2013; V15: Valentino et al. 2015; Z15: Zanella et al. 2015; V16: Valentino et al. 2016.

Emission line maps creation

1. Background subtraction (SExtractor)
2. Continuum + contamination subtraction (renormalization of each aXe model)
3. Cross correlation as a function of the shift along dispersion direction (redshift)
4. Uncertainties on cross-correlation: error propagation on the fit parameters
5. Weighted image combination (WDRIZZLE)
6. Computation of the average redshift of the combined map (and uncertainty obtained propagating the error on the cross-correlation)
7. Quantify effects of distorsions (wavelength calibration, astrometric calibration of the input image, misalignment in the cross-dispersion direction)
8. To estimate the average distorsion affecting the maps (= accuracy of the procedure) we forced the chi square to 1

$$\chi^2_{\rm red} = \frac{1}{N}\Sigma_{i=0}^{N}\frac{(D_{\rm i} - D_{\rm aver})^2}{\epsilon^2_{\rm z,i} + \epsilon^2_{\rm z,aver} + \sigma^2_{\rm D}}$$

with: $D_i = z_{map,i,j} - z_{aver,i}$

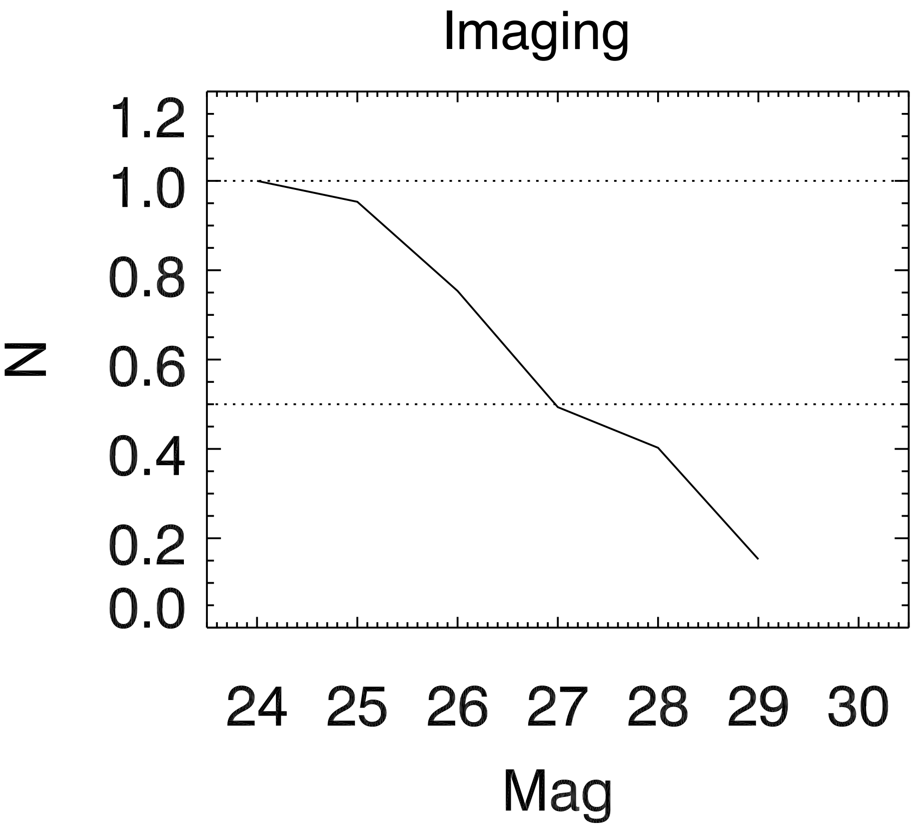
D_{aver} = average D_i over the whole sample of galaxies for the j-th orientation

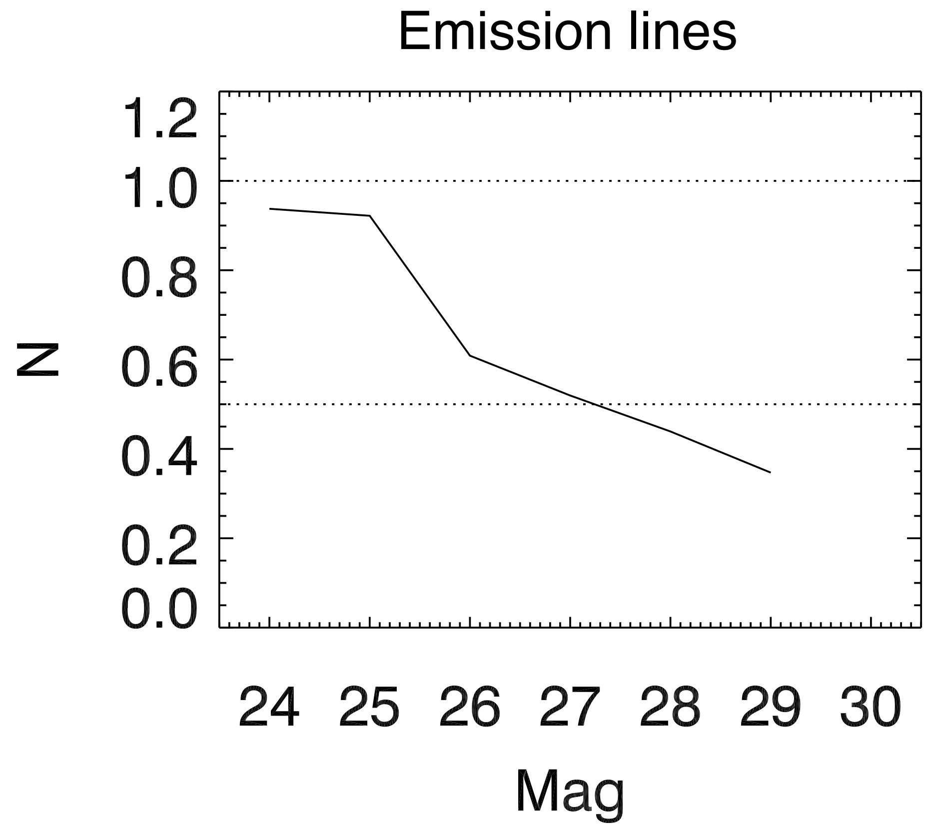
Distorsions < 0.06”

Emission line maps creation

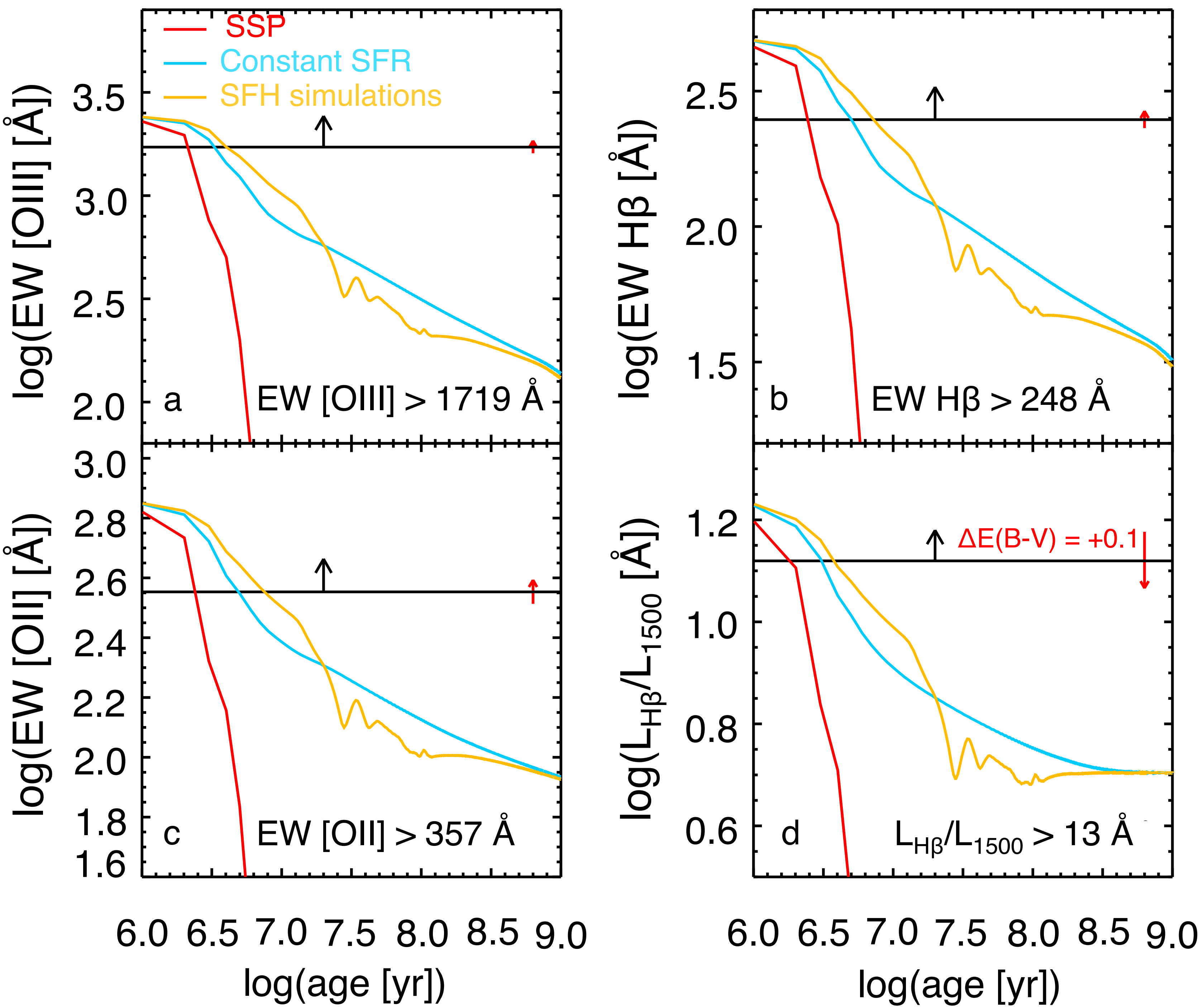
9. Check for the alignment when multiple clumps are present
10. Bestfit model allowed to rigidly shift to correct further small misalignments
11. Check obtained redshifts with MOIRCS redshifts

Completeness





Vyc1



SSP
Constant SFR
SFH simulations
log(EW [OIII] [Å])
a
EW [OIII] > 1719 Å
log(EW Hβ [Å])
b
EW Hβ > 248 Å
log(EW [OII] [Å])
c
EW [OII] > 357 Å
log(L_Hβ/L_1500 [Å])
ΔE(B-V) = +0.1
d
L_Hβ/L_1500 > 13 Å
log(age [yr])

Vyc1 is point-like

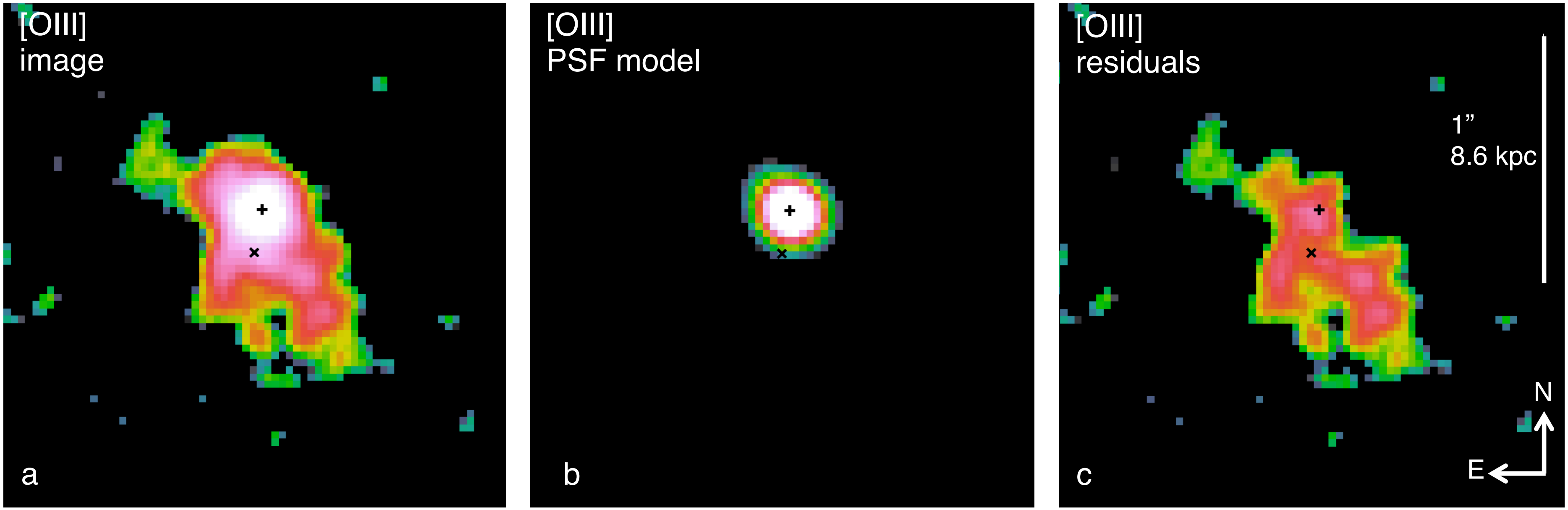
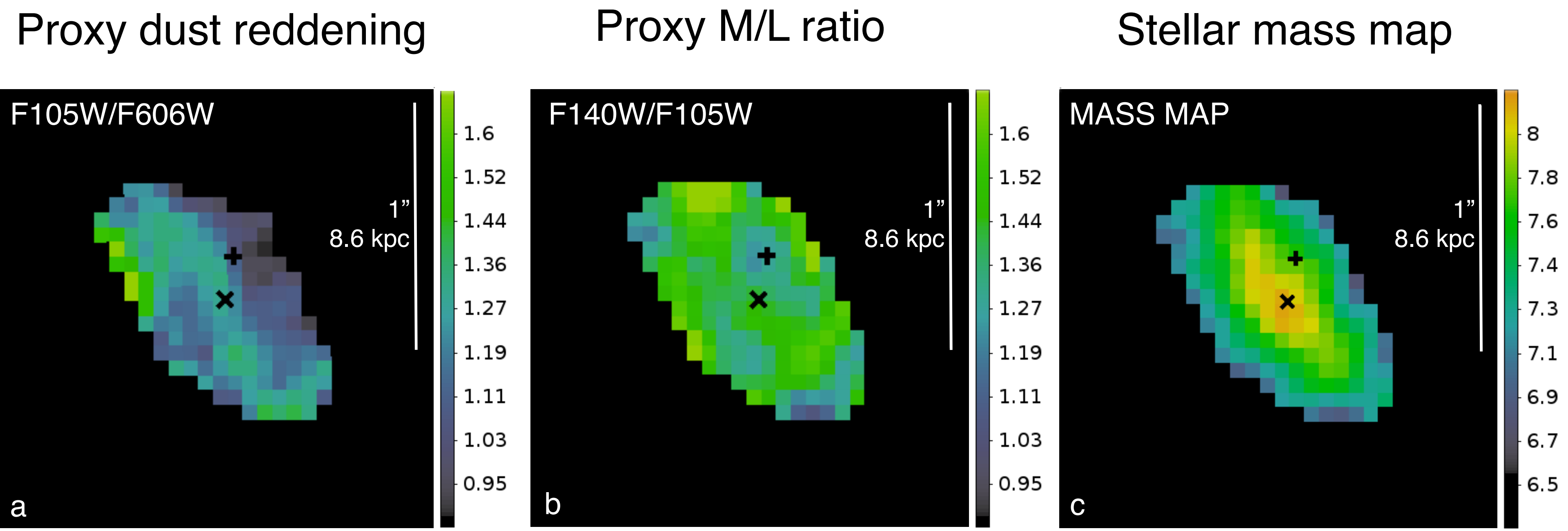
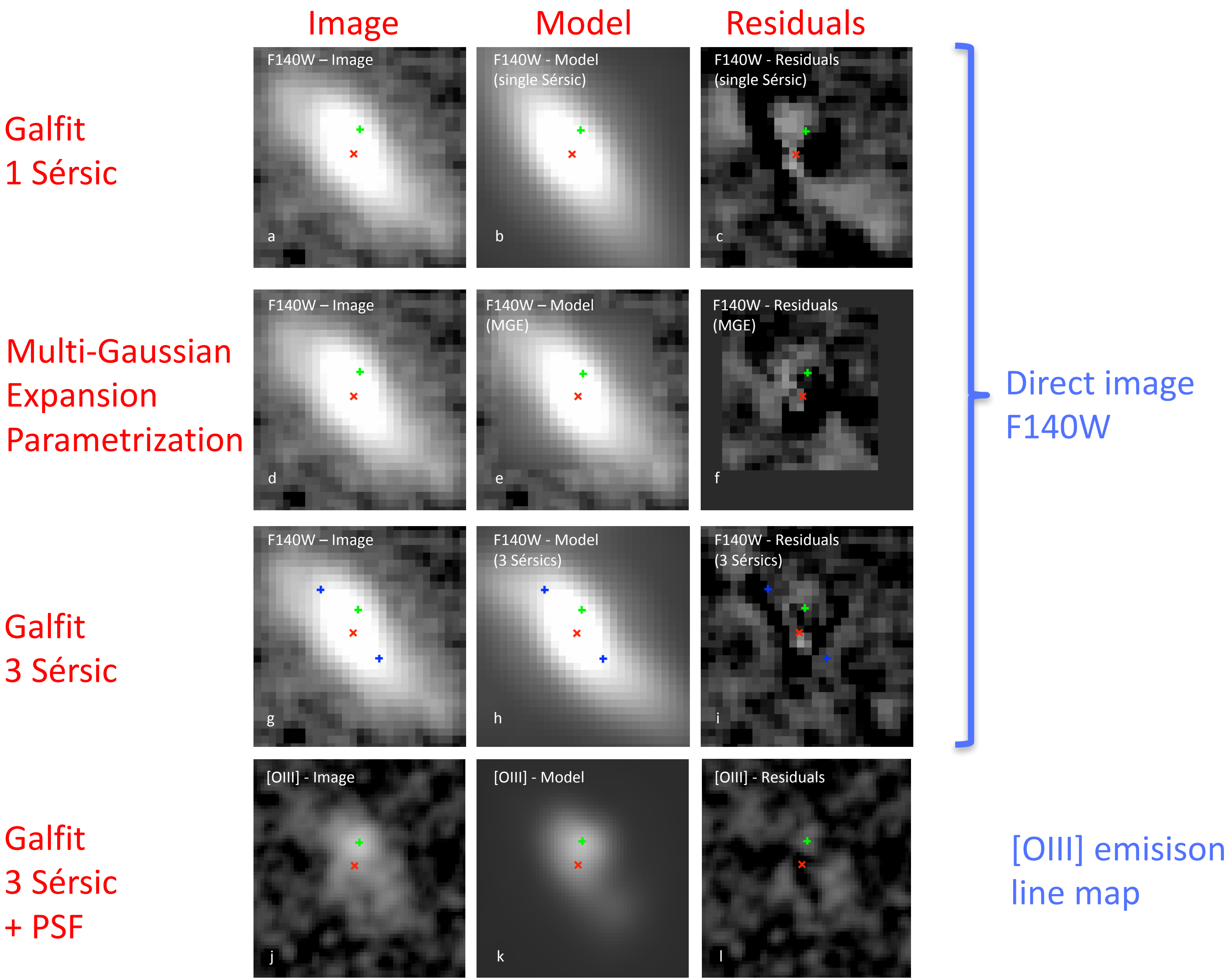
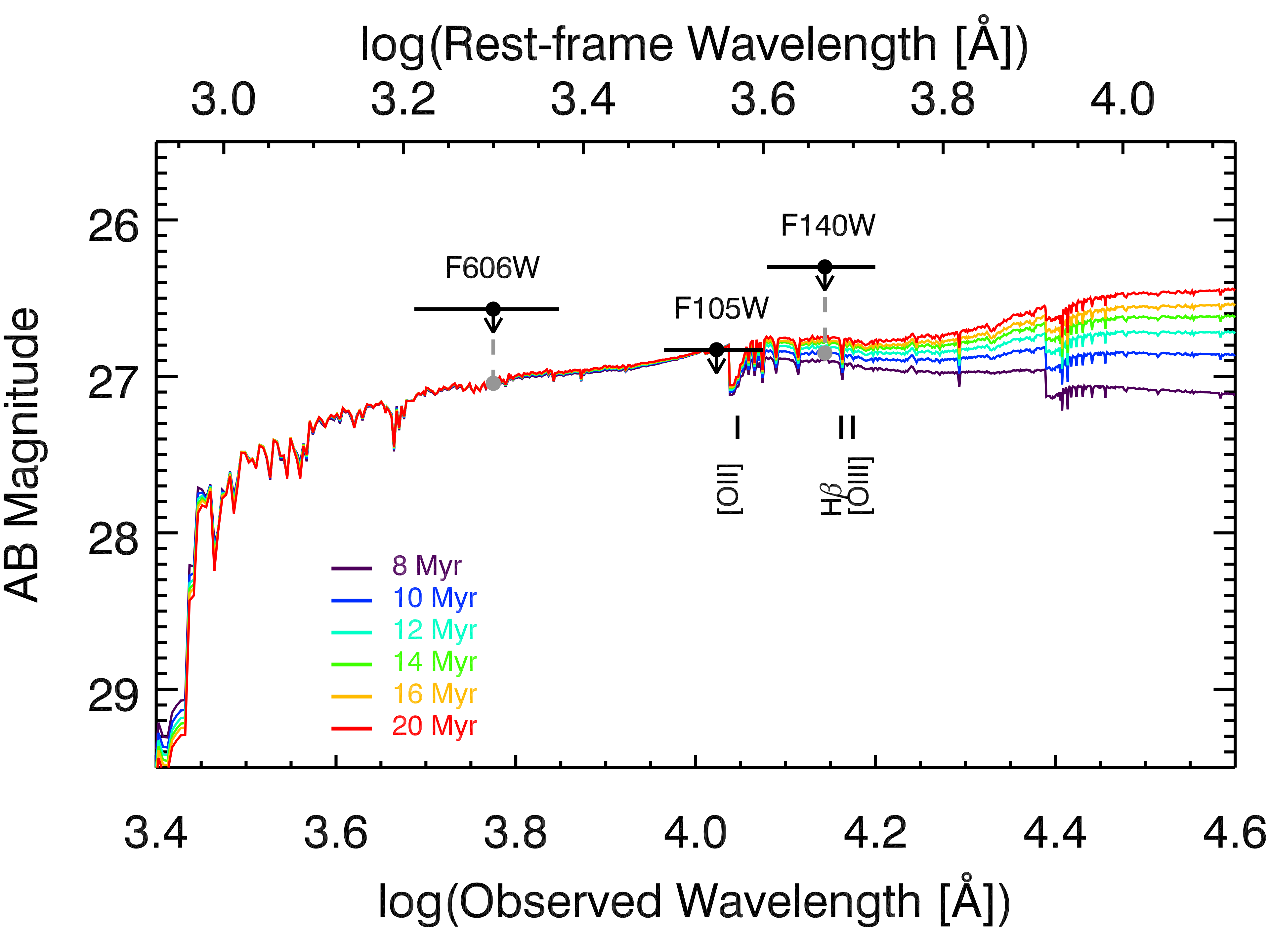


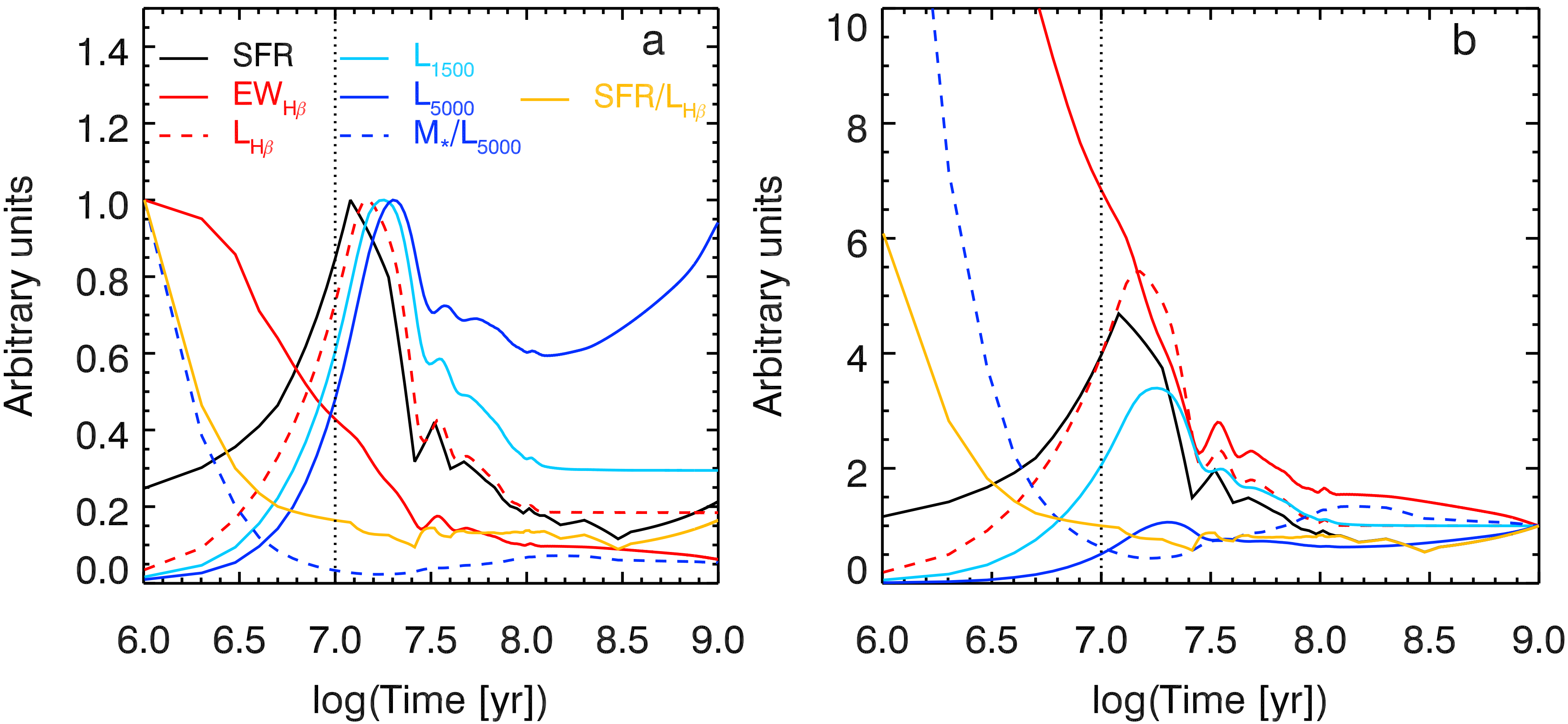
Image ratios and mass map



Galfit decomposition




log(Rest-frame Wavelength [Å])
3.0
3.2
3.4
3.6
3.8
4.0
26
27
28
29
AB Magnitude
F606W
F105W
F140W
[OII]
Hβ
[OIII]
8 Myr
10 Myr
12 Myr
14 Myr
16 Myr
20 Myr
3.4
3.6
3.8
4.0
4.2
4.4
4.6
log(Observed Wavelength [Å])


a
b
SFR
$EW_{H\beta}$
$L_{H\beta}$
L_{1500}
L_{5000}
M_*/L_{5000}
$SFR/L_{H\beta}$
Arbitrary units
log(Time [yr])
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0
2
4
6
8
10
6.0
6.5
7.0
7.5
8.0
8.5
9.0

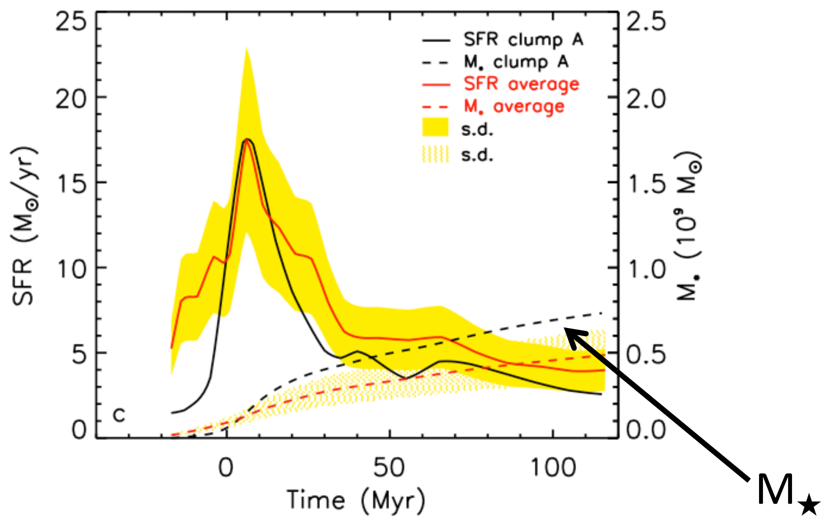
	Galaxy	Clump
$\mathbf{R_e}$ [kpc]	2.8 ± 0.4^a	< 0.5
SFR $[\mathrm{M}_\odot/\mathrm{yr}]$	77 ± 9	32 ± 6
$\mathbf{log(M_\star/}\mathrm{M}_\odot\mathbf{)}$	$10.3^{+0.2}_{-0.3}$	$\lesssim 8.5$
$\mathbf{log(M_{\mathrm{gas}}/}\mathrm{M}_\odot\mathbf{)}$	10.7 ± 0.2^b	$\lesssim 9.4$
$\mathbf{Z}$ $[\mathrm{Z}_\odot]$	0.6 ± 0.2	0.4 ± 0.2
$\mathbf{F^{obs}_{[OIII]}}$ $[10^{-17}\mathrm{erg\,s^{-1}cm^{-2}}]$	10.4 ± 0.7	4.3 ± 0.2
$\mathbf{F^{obs}_{H\beta}}$ $[10^{-17}\mathrm{erg\,s^{-1}cm^{-2}}]$	1.5 ± 0.8	0.9 ± 0.3
$\mathbf{F^{obs}_{[OII]}}$ $[10^{-17}\mathrm{erg\,s^{-1}cm^{-2}}]$	6.5 ± 1.7	1.9 ± 0.6
$\mathbf{F^{obs}_{F140W}}$ $[10^{-20}\mathrm{erg\,s^{-1}cm^{-2}\,\AA^{-1}}]$	67.5 ± 3.4^c	< 1.1
$\mathbf{F^{obs}_{F105W}}$ $[10^{-20}\mathrm{erg\,s^{-1}cm^{-2}\,\AA^{-1}}]$	89.2 ± 4.6^c	< 1.8
$\mathbf{F^{obs}_{F606W}}$ $[10^{-20}\mathrm{erg\,s^{-1}cm^{-2}\,\AA^{-1}}]$	212.3 ± 10.6^c	< 4.5

Instrument	Date	Time (direct imaging) (hr)	Time (spectroscopy) (hr)
HST/WFC3	2010, 6$^{\mathrm{th}}$ June	0.3 (F140W)	2.7
HST/WFC3	2010, 25$^{\mathrm{th}}$ June, 1$^{\mathrm{st}}$ July	0.6 (F140W)	7
HST/WFC3	2010, 9$^{\mathrm{th}}$ July	0.3 (F140W)	2.7
HST/WFC3	2013, 20$^{\mathrm{th}}$ May	3.3 (F105W)	-
HST/WFC3	2013, 20$^{\mathrm{th}}$ May	0.3 (F606W)	-
Subaru/MOIRCS	2013, 7$^{\mathrm{th}}$ - 9$^{\mathrm{th}}$ April	-	7.3

Mass estimate of Vyc1

Stellar mass estimate: $M_\star \leq 3 \times 10^8 M_\odot$

1) Average M/L ratio of host galaxy
2) M/L ratio at young ages from simulations
3) Simulations (normalizing to observed Hβ)



Gas mass estimate: $M_{gas} < 2.5 \times 10^9 M_\odot$

1) Jeans mass → $\boxed{M_J \sim \frac{\sigma^4 R_d^2}{M_d}}$
2) Simulations (normalizing to obs Hβ)
3) Comparison with older clumps using our simulations to relate properties at peak and later phases →

$$\boxed{M_{gas,clump} = \frac{SFR_{clump}}{SFR_{lit}} \cdot M_{\star,lit} \cdot \left(\frac{M_{gas,young}}{M_{\star,old}}\right)_{sim} \cdot \left(\frac{SFR_{young}}{SFR_{old}}\right)_{sim}^{-1}}$$

Do massive clumps exist?

Masses of observed giant clumps are overestimated due to blending caused by insufficient resolution?

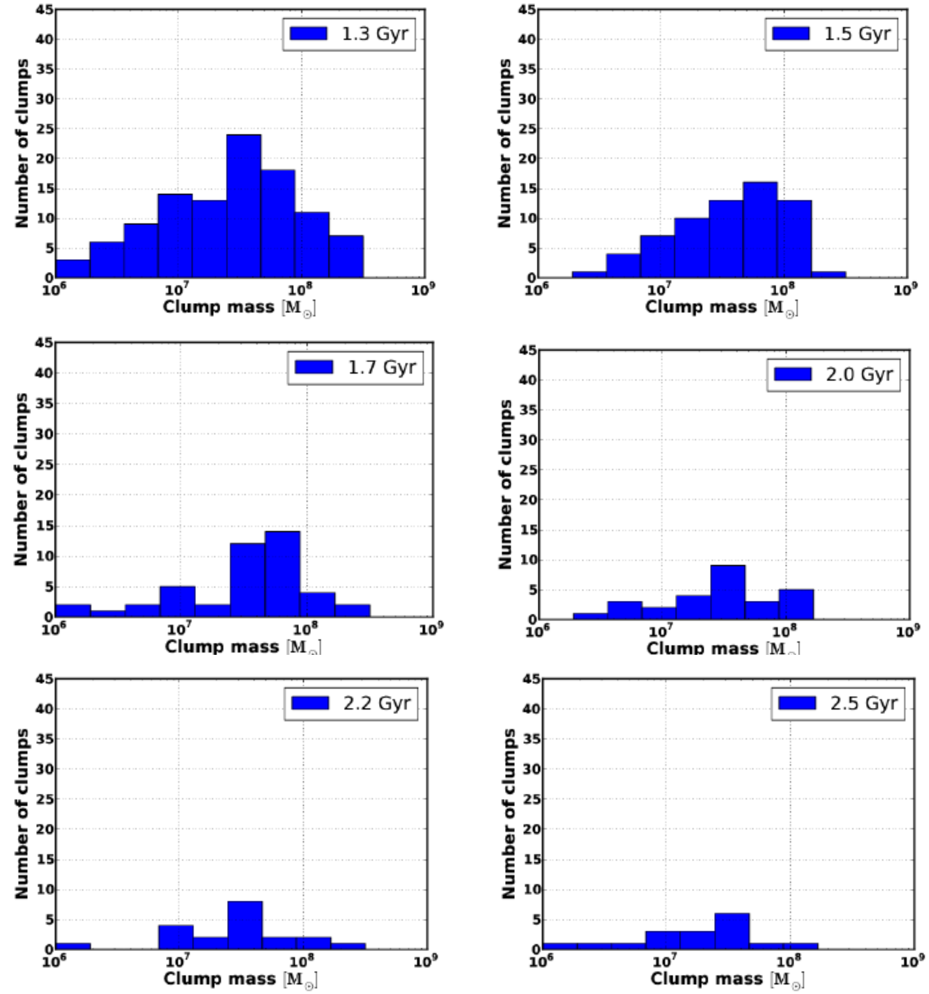
For our young clump:

Stellar mass: $M_\star \leq 3 \times 10^8 M_\odot$

from M/L ratio and simulations

Gas mass estimate: $M_{gas} \leq 2.5 \times 10^9 M_\odot$

from Jeans mass and simulations → $\boxed{M_J \sim \frac{\sigma^4 R_d^2}{M_d}}$



Tamburello+ 14

Could the clump mass be much lower?

Jeans mass:

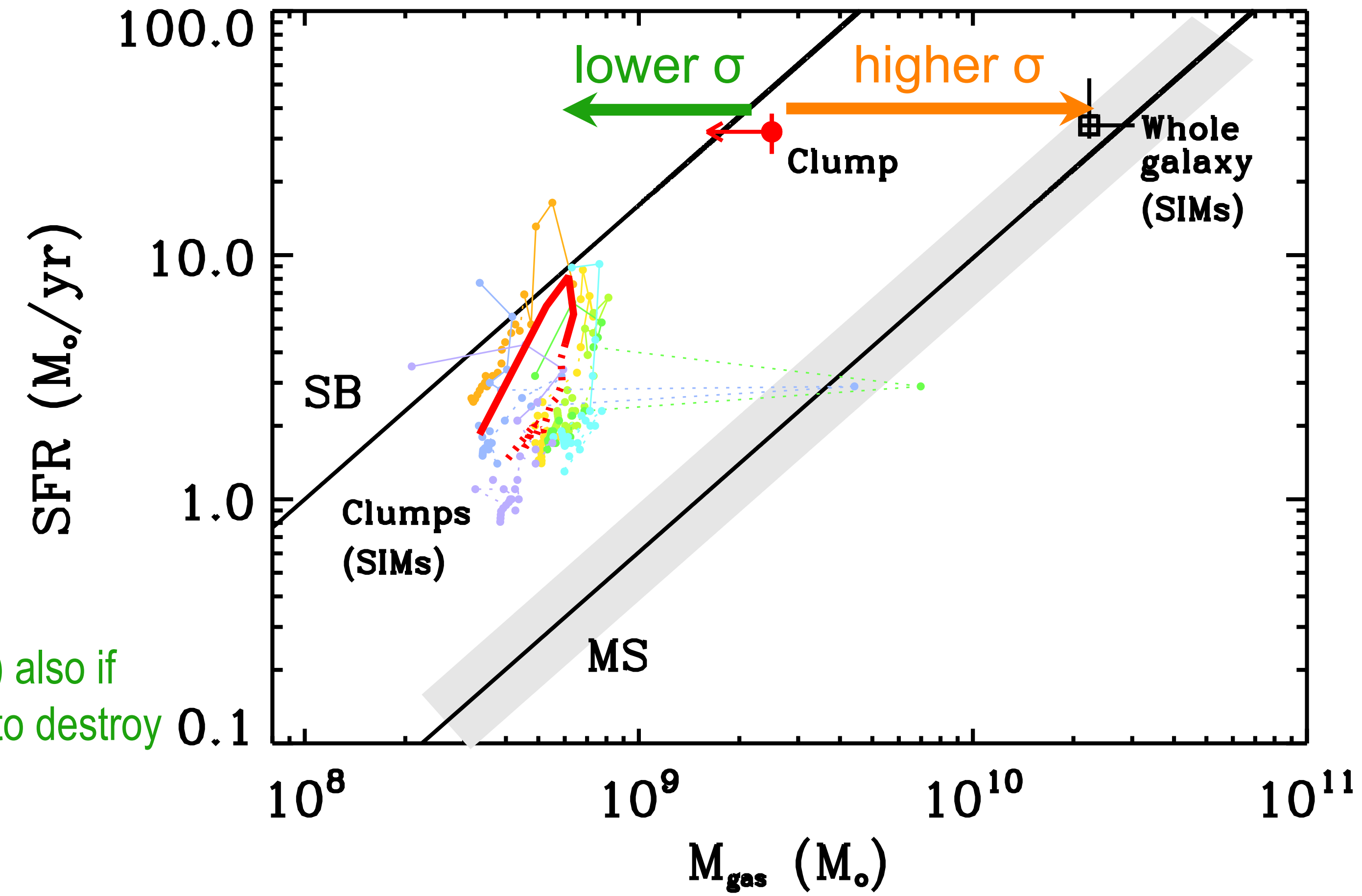
$$M_J \sim \frac{\boxed{\sigma^4} R_d^2}{M_d}$$

Lifetime:

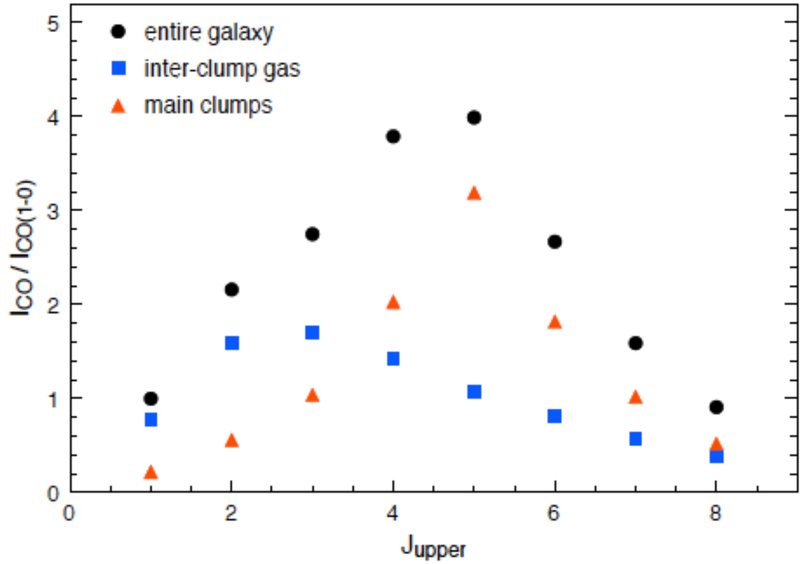
$$LT = \frac{\boxed{f_{cl/gal}}}{CFR} \rightarrow \sim M^{-2}$$

> σ : all M_{gas} of the host concentrated in the clump

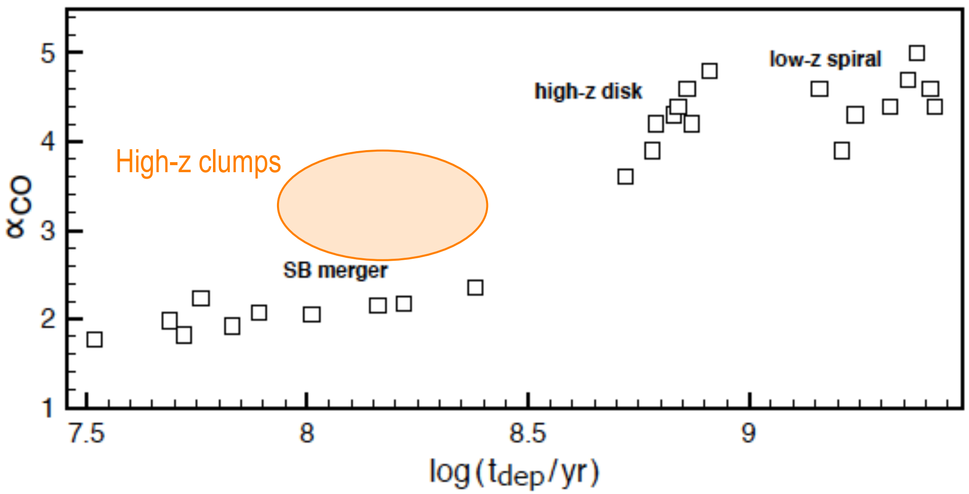
< σ : too long lifetimes (Gyrs) also if low mass clumps are easier to destroy



Clumps drive high SFE and CO excitation

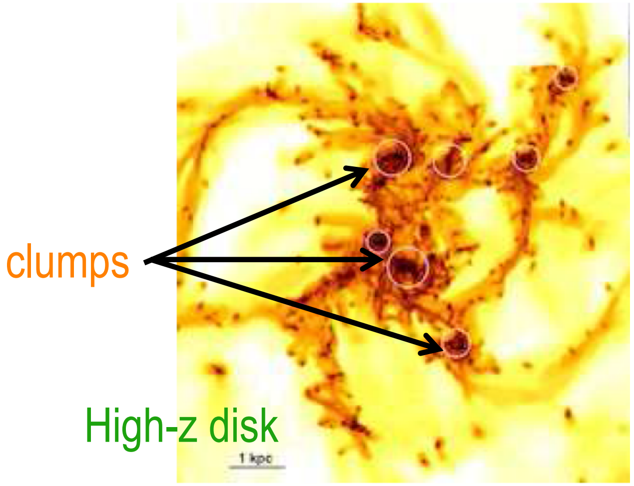


Bournaud et al. 2015



α_{CO} clump < α_{CO} host galaxy:
consistent with **clumps starburst-like behaviour**
→ clumps have **shorter gas depletion timescales** than their host

Observations:
clumps have higher CO excitation than the host (Daddi+15)



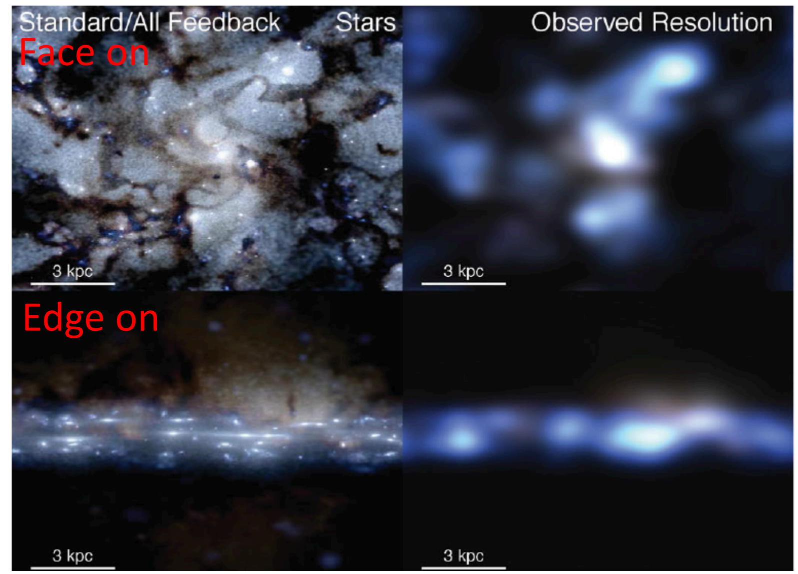
Where do young clumps form?

Offset observed clump = 1.6 ± 0.3 kpc

Estimate of galaxy inclination
clump PA

→ Deprojected distance

HST-like resolution



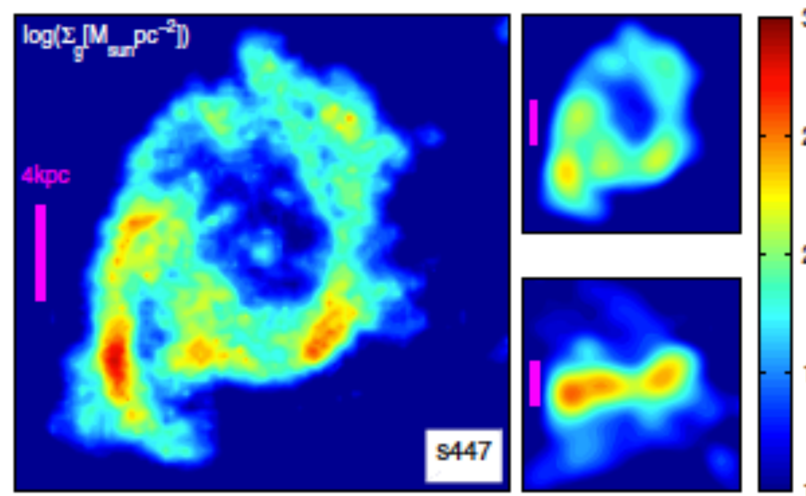
Hopkins+ 12

Deprojected distance from the galaxy nucleus:

1) Observed clump: $3.6 \leq d \leq 6.2$ kpc

2) Our simulations: $2.1 \leq d \leq 7.0$ kpc

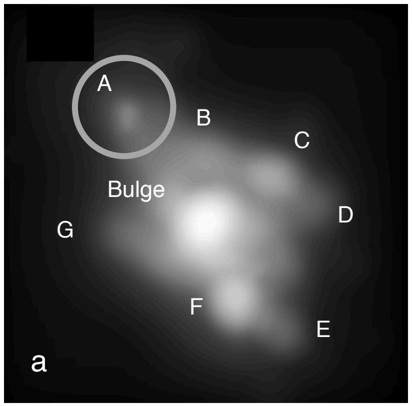
3) Other simulations: $2.0 \leq d \leq 10.0$ kpc
(e.g., Mandelker+14, Genel+12, Hopkins+12)



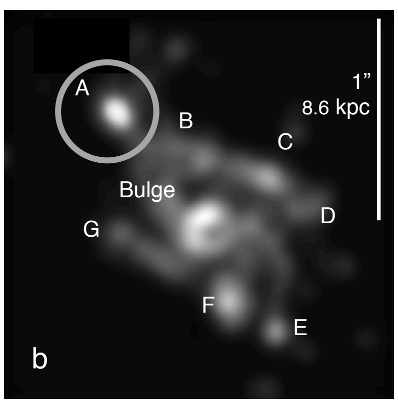
Genel+ 12

Our simulations

M$_\star$ map



SFR map



AMR code RAMSES (Teyssier 2002)

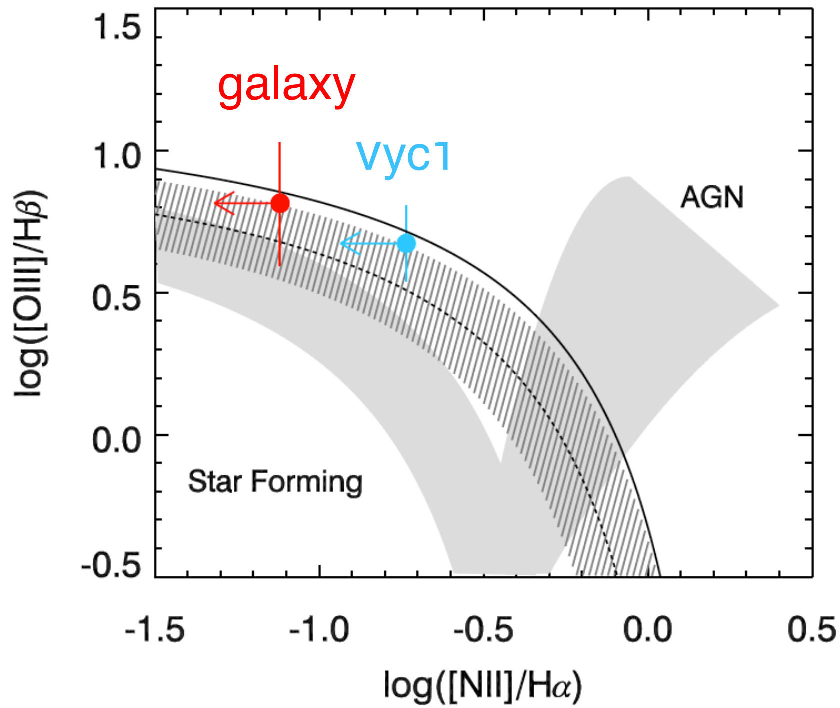
Resolution: 3.5 pc

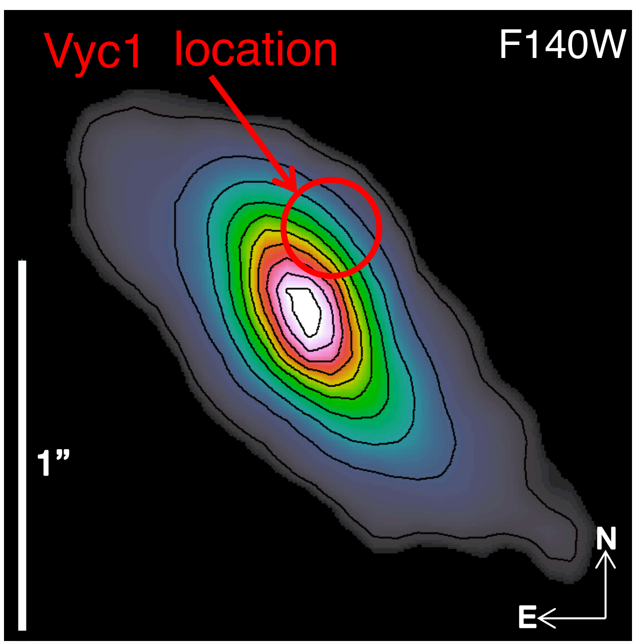
Feedback from young stars:
- photo-ionization
- radiation pressure
- supernova explosions

Gas fraction: 50%

Bulge/Disk: 30%

1% of gas is converted into stars per free fall time



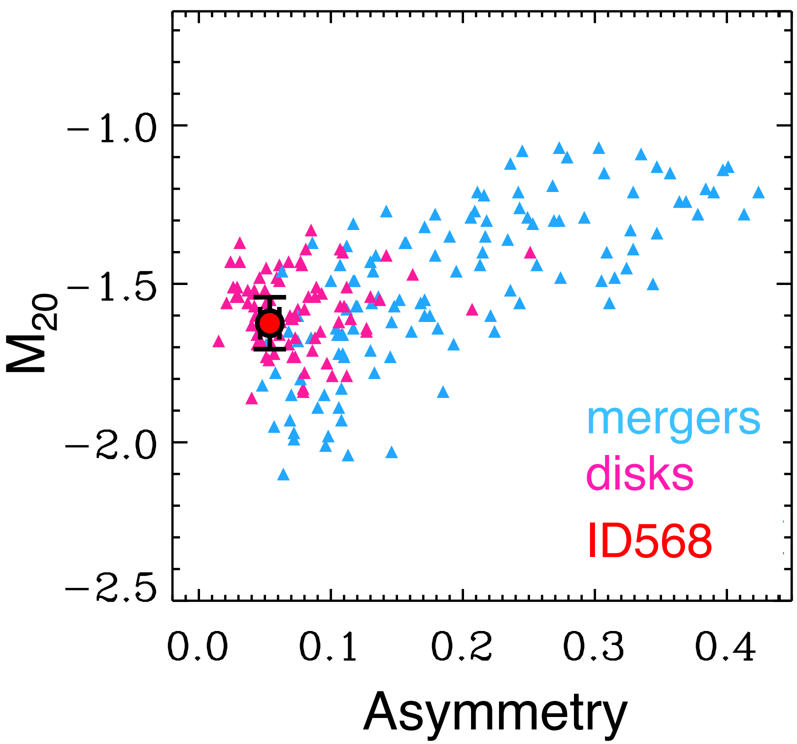


- **AGN hypothesis**

  X rays: no XMM and Chandra detection
  IR, RADIO: no detection
  BPT: in the SF region
  $EW_{[OIII]} > 1700$ Å

- **Shock hypothesis**

  $L_{[OIII]} \sim 50 - 500$x brighter than
  shock ionization from wind outflows



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  $EW_{[OIII]} > 1700$ Å

- **Shock hypothesis**

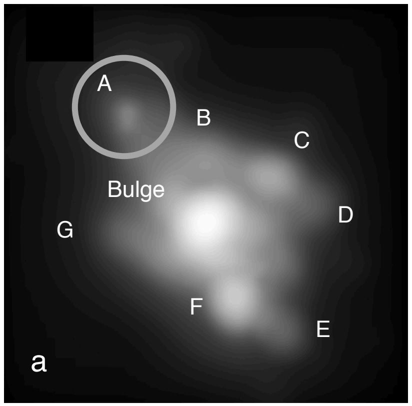
  $L_{[OIII]} \sim 50 - 500$x brighter than
  shock ionization from wind outflows

- **Merger hypothesis**

  Asymmetry– M_{20} diagnostics
  No detected continuum

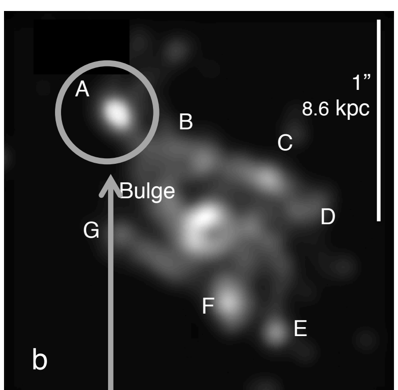
Simulations

$M_\star$ map

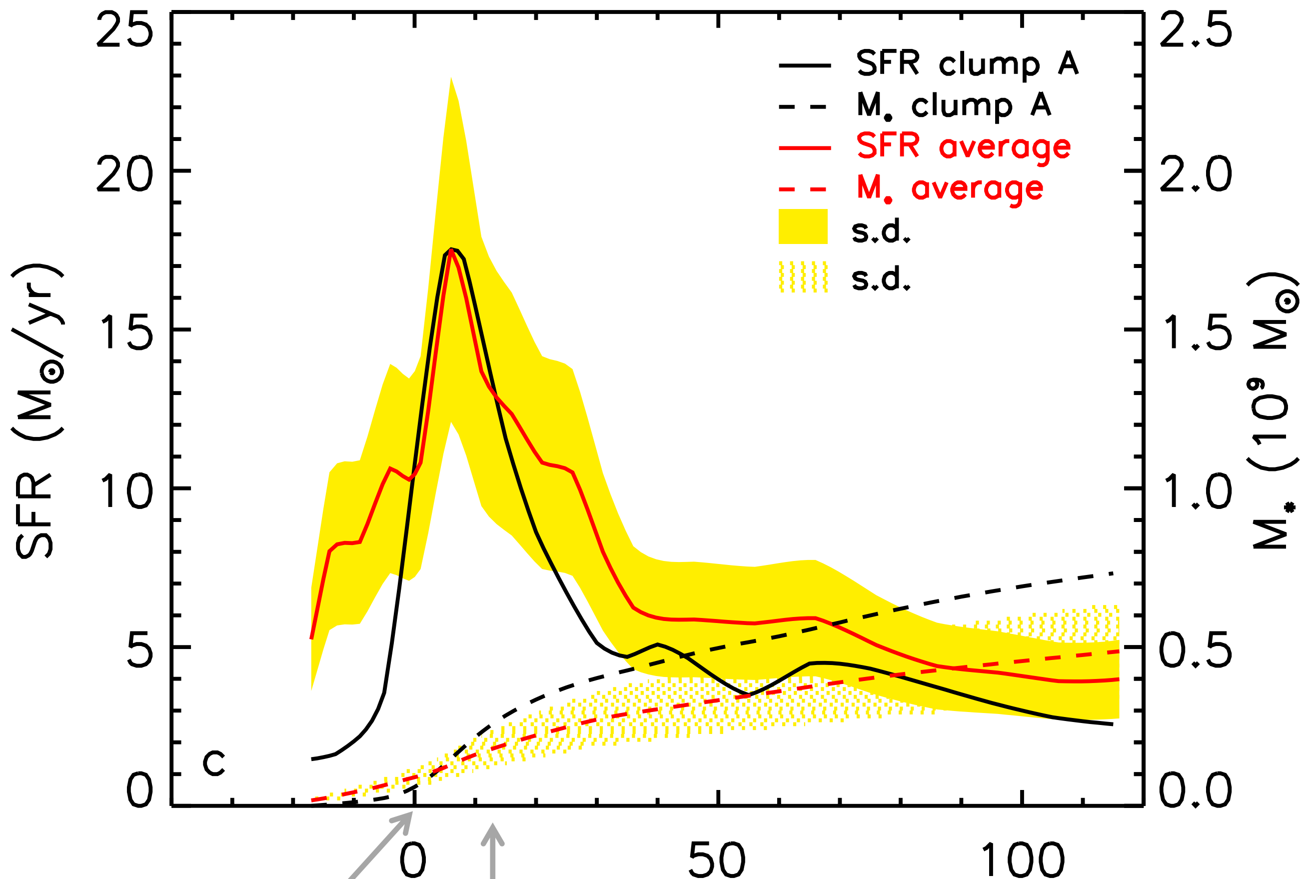


Bournaud+14

SFR map



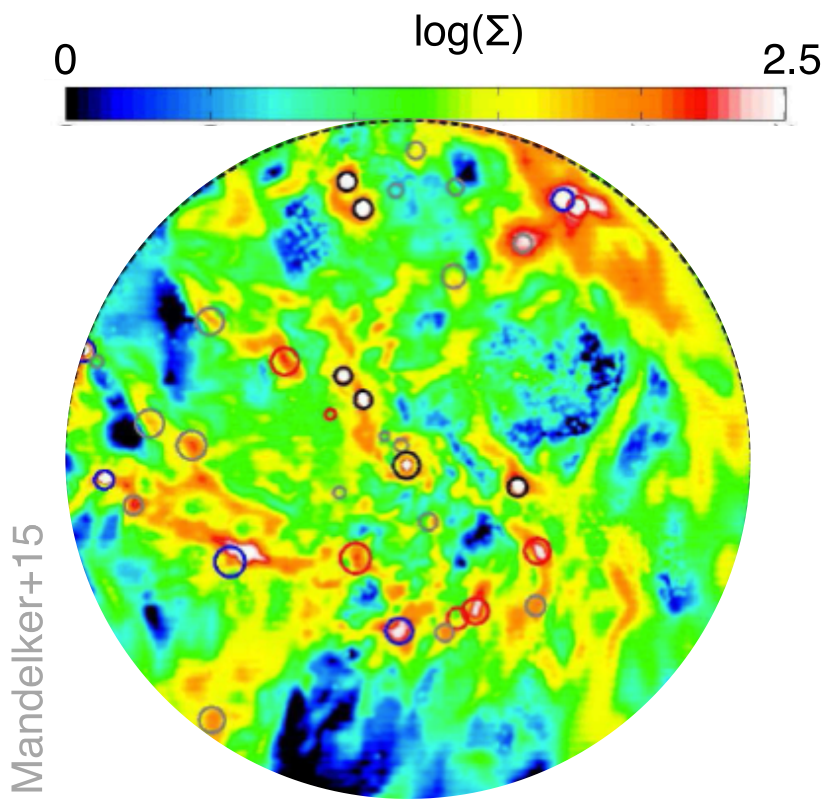
age = 12 Myr

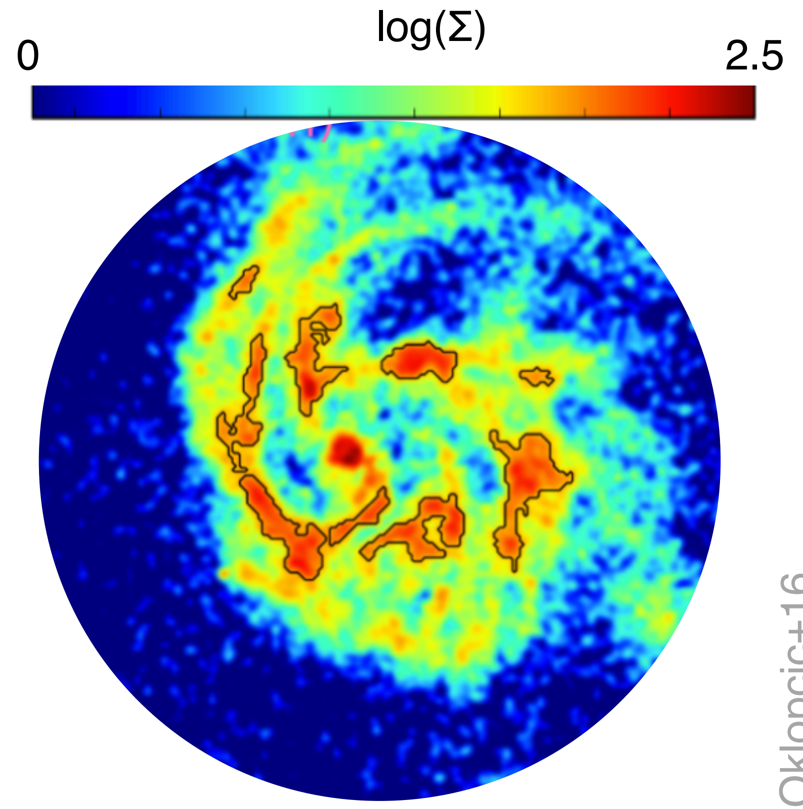


Birthtime clump A

Observed time $M_\star$, SFR maps

Giant clumps: simulations





Long-lived clumps (~ 500 Myr)

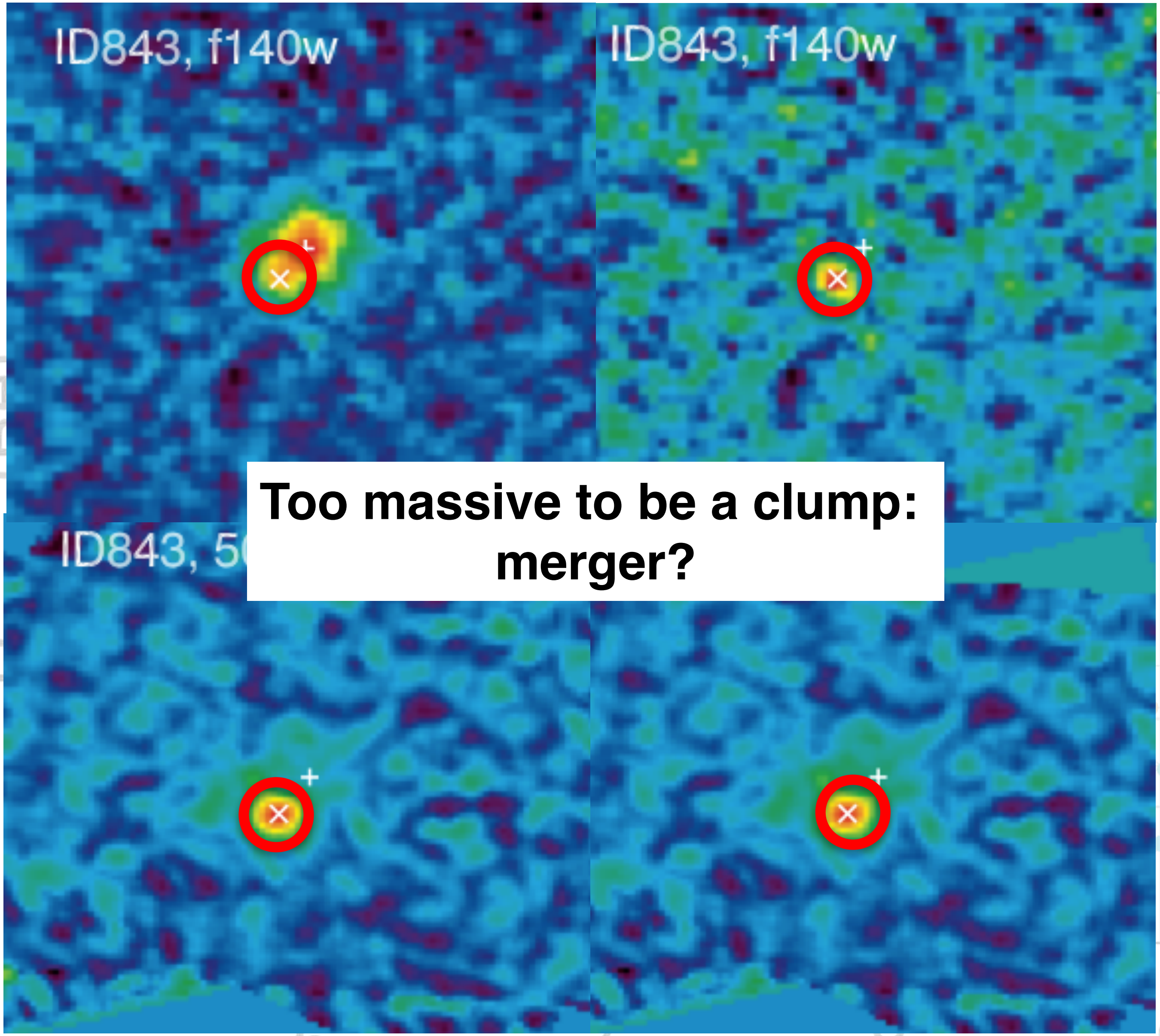
Inward migration → bulge formation

(Dekel+11, Bournaud+14, Mandelker+15)

Short-lived clumps (~ 50 Myr)

Strong feedback → disruption

(Genel+12, Murray+10, Oklopcic+16)



Too massive to be a clump: merger?

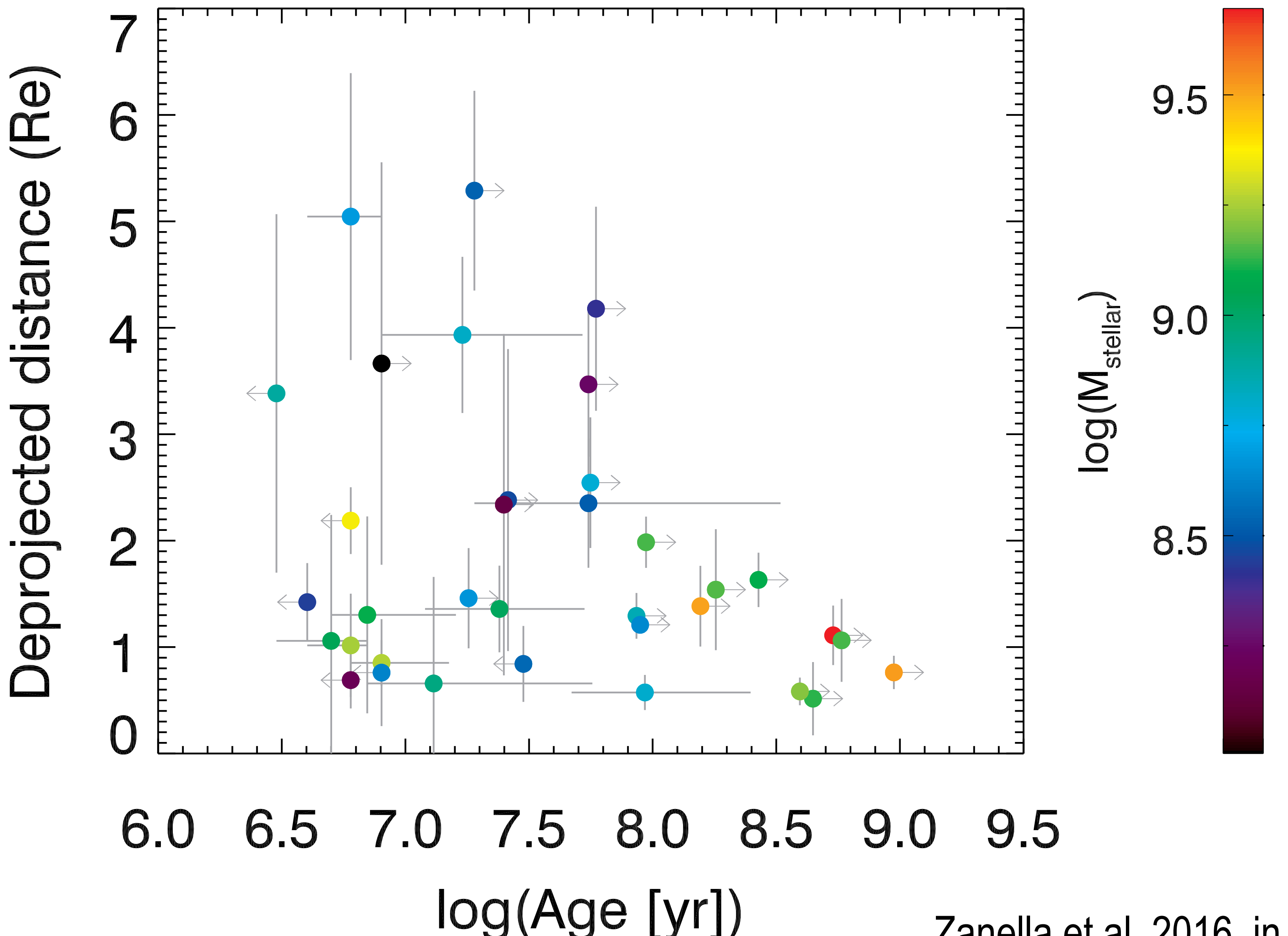
Imaging (rest-frame optical)

[OIII] emission line map

Emission line maps allow to identify very gas rich mergers

A statistical sample

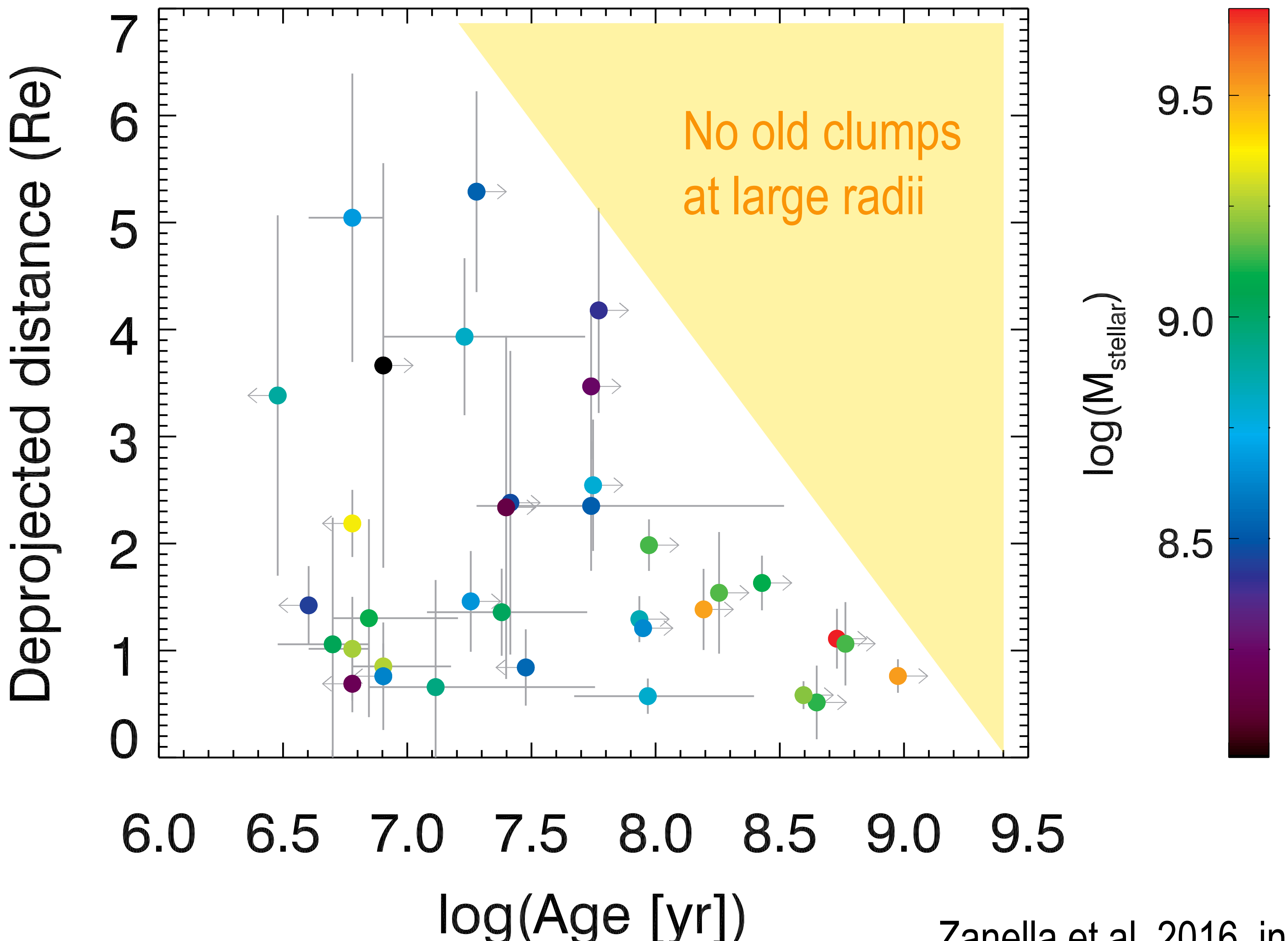
Ongoing analysis!



Zanella et al. 2016, in prep.

Ongoing analysis!

A statistical sample



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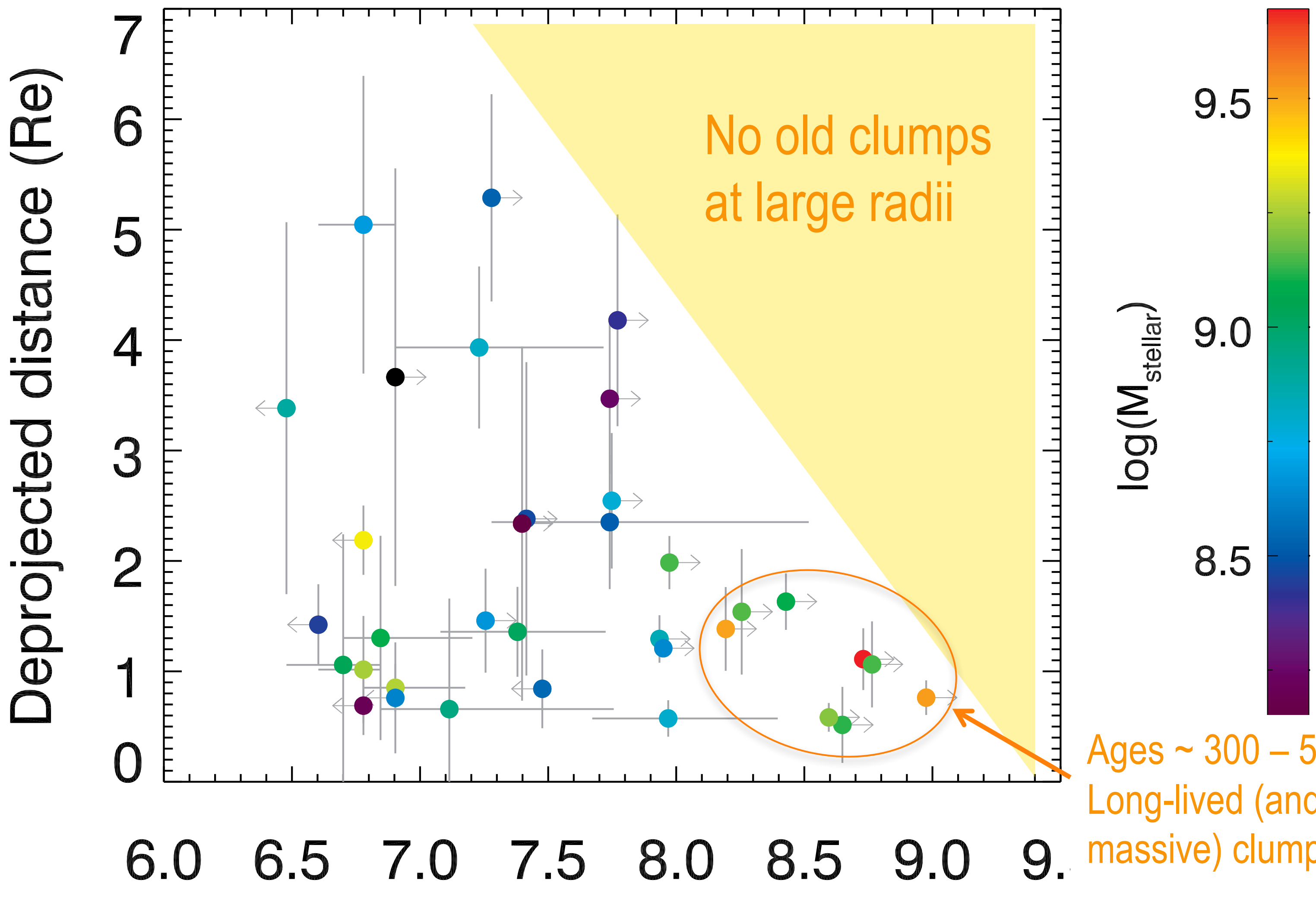
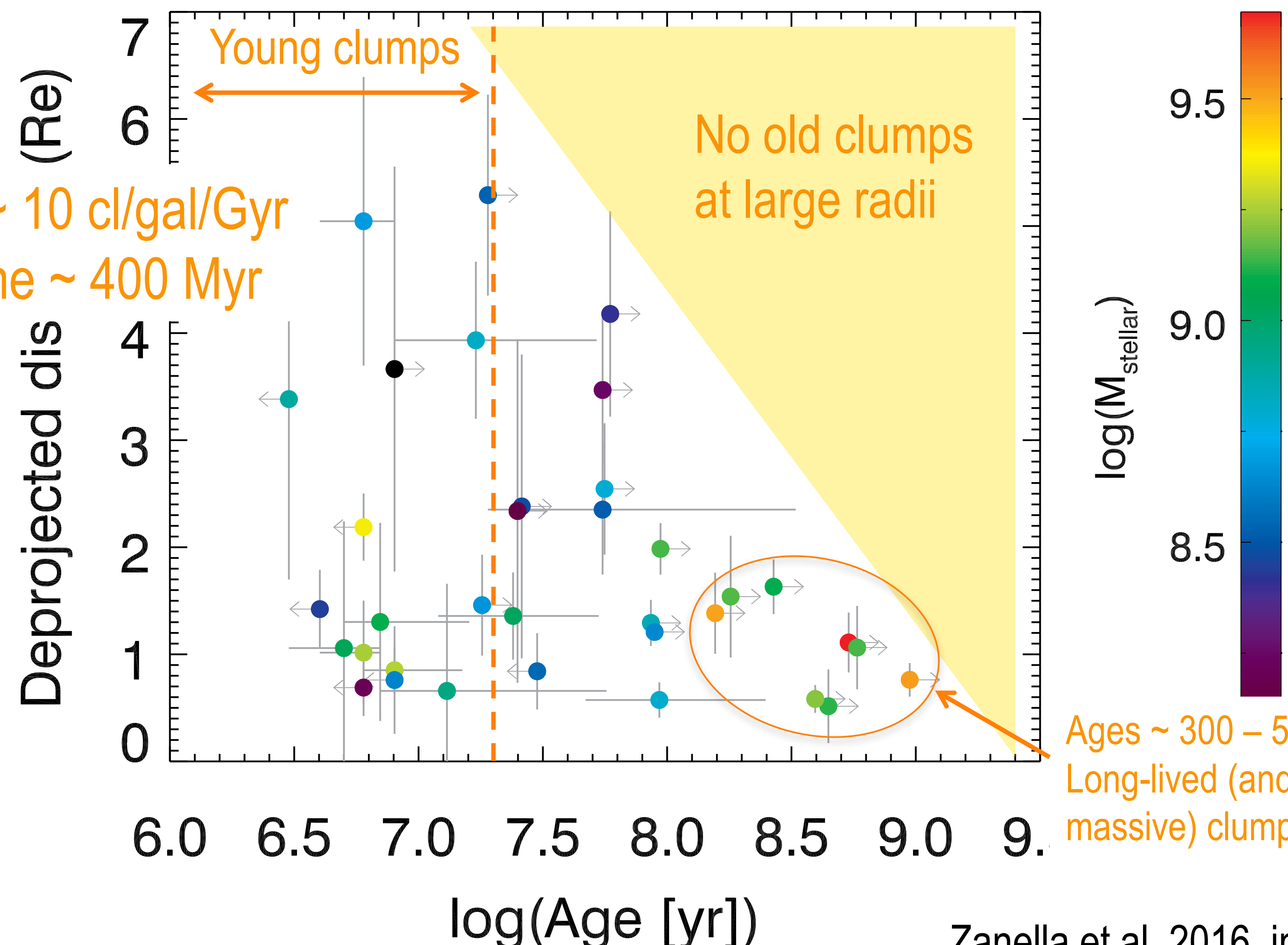


Ages ~ 300 – 500 Myr
Long-lived (and more massive) clumps

Zanella et al. 2016, in prep.

A statistical sample

Ongoing analysis!



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