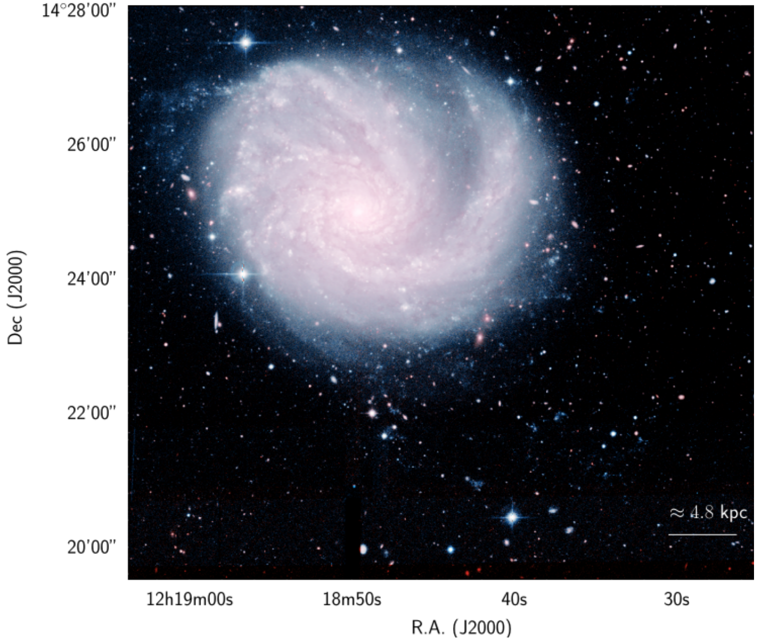
Lyman continuum escape from intergalactic star clusters – around NGC 4254

Gerhard Hensler, Yannick Hein, Alessandro Boselli + VESTIGE team

Composite SDSS *gri*-image of the grand-design spiral North is up; east is left. The image size is $7' \times 6.3'$.



from NGVS data (Boselli et al. 2018).

Examples for f_{esc} from observations scatter

- Izotov+ (2016): for 4 compact sf DGs f_{esc}≈4.6-13.2%
- Izotov+ (2016, Nature, 529): f_{esc}≈8% from 1 compact sf DG
- Izotov+ (2018): z=0.369 galaxy with f_{esc}≈50%
- Izotov et al. (2018), Vanzella et al. (2018), Rivera-Thorsen et al. (2019): 4 $\log(M/M_{\odot})\sim 9$ galaxies at z~4 with f_{esc}>50%
- Atak_et al. (2024, Nature, 626), LzLCS: f_{esc}≈4.5-15.6% for 8 UFDs [$\log(M/M_{\odot})$ =4-10]
- Schaerer et al. (2025, A&A,693): models with diff. IMFs

Conditions for LyC production and escape

- *Interesting only*: Sufficiently large Lyman cont. fluxes
- *Sources*: massive stars > 15 $M_\odot$ (short lifetimes), high SFRs (starbursts), AGNs
- *Conditions for galaxies*: Holes/chimneys in the surrounding ISM

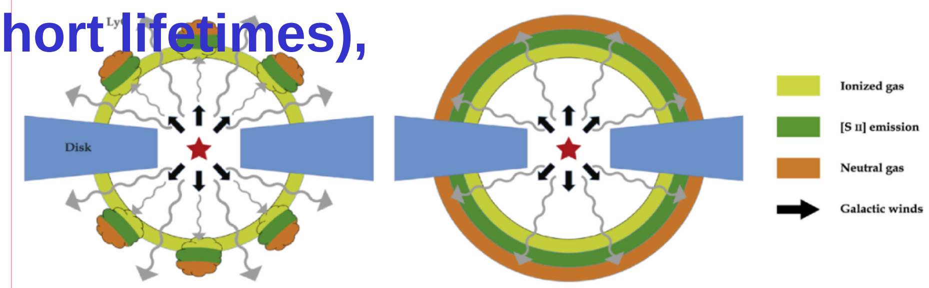


Figure 3: Outflow schematic depicting a LyC emitter on left and non-emitter on the right. From (Wang et al. 2021)

Model of Star-forming DGs

(Melekh et al. (GH) 2015, MN, 451, 111)

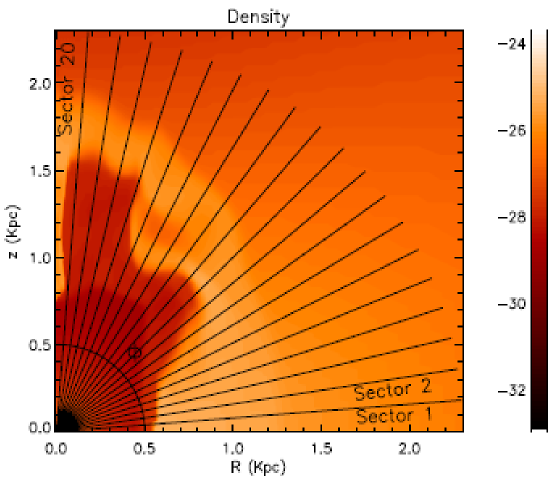
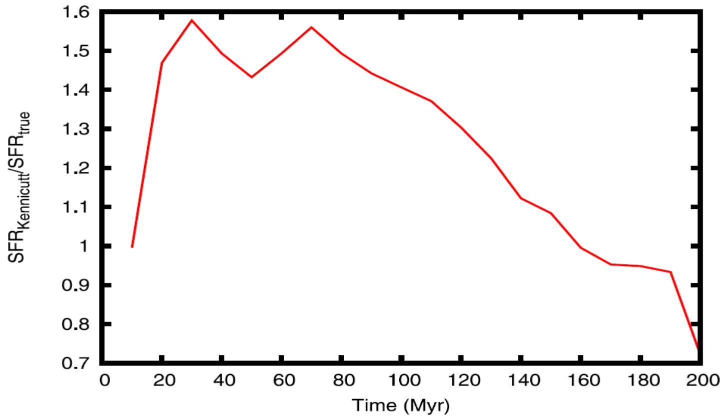
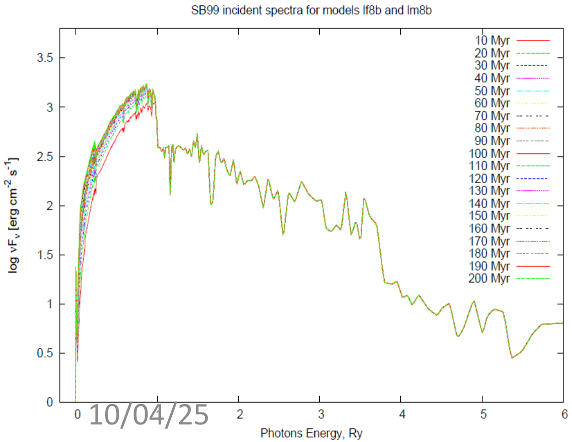
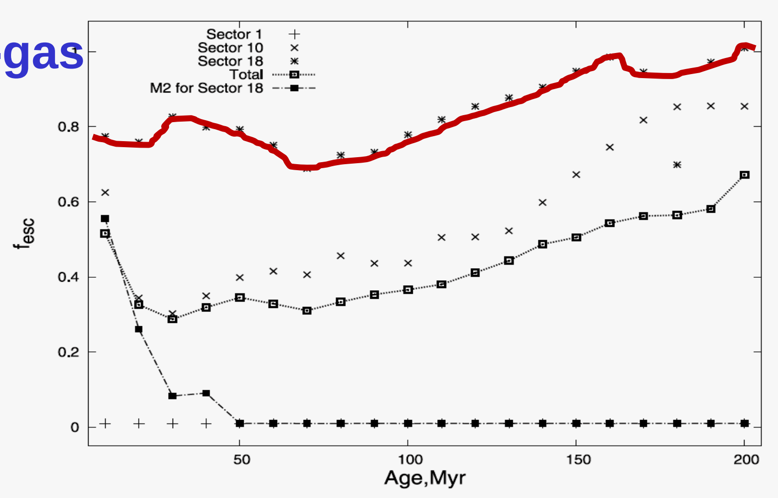


Photo-ion. analysis of a chemo-dyn. DG model with self-regul. SF (no starburst!) by ***Recchi & Hensler (2013, A&A, 551).*** Irradiation by ionizing spectral en. distribution from central SF region (Starburst99) + the hot-gas wind bubble.







<u>Result:</u> *1. Stronger H→*

2. Thru the HWB (sect. 18) 80-100% of the LyC photons are lost.

The galactic mean as f_{esc}(t) is 30-60%.

Conditions for LyC production and escape

- *Interesting only*: Sufficiently large Lyman cont. fluxes
- *Sources*: massive stars > 15 $M_\odot$ (short lifetimes), high SFRs (starbursts), AGNs
- *Conditions for galaxies*: Holes/chimneys in the surrounding ISM

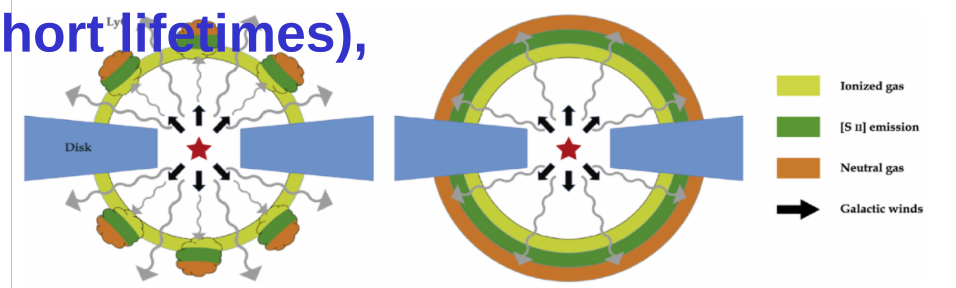
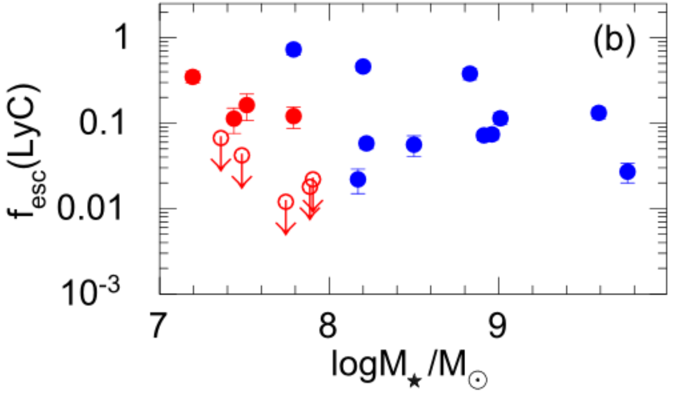
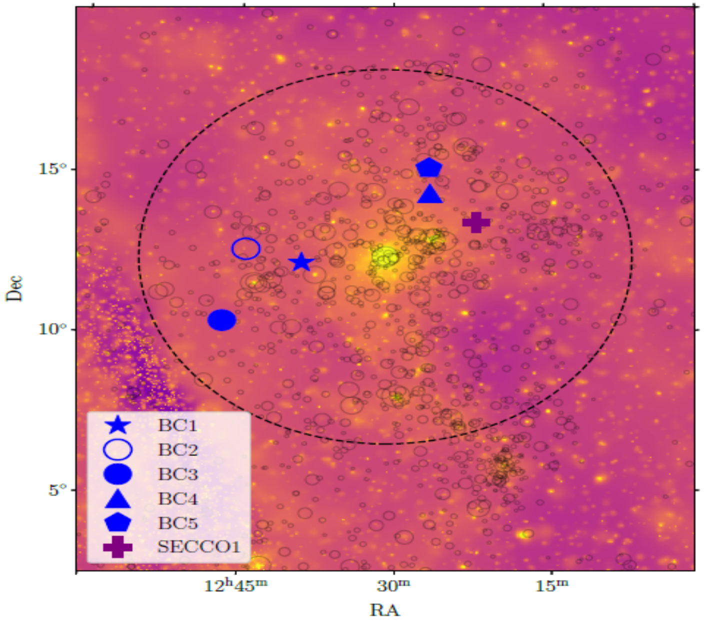


Figure 3: Outflow schematic depicting a LyC emitter on left and non-emitter on the right. From (Wang et al. 2021)

- *Possible sites of SBs and dilute ISM*: Dwarf galaxies, but also naked star clusters: TDGs?, extra-/intergalactic SCs

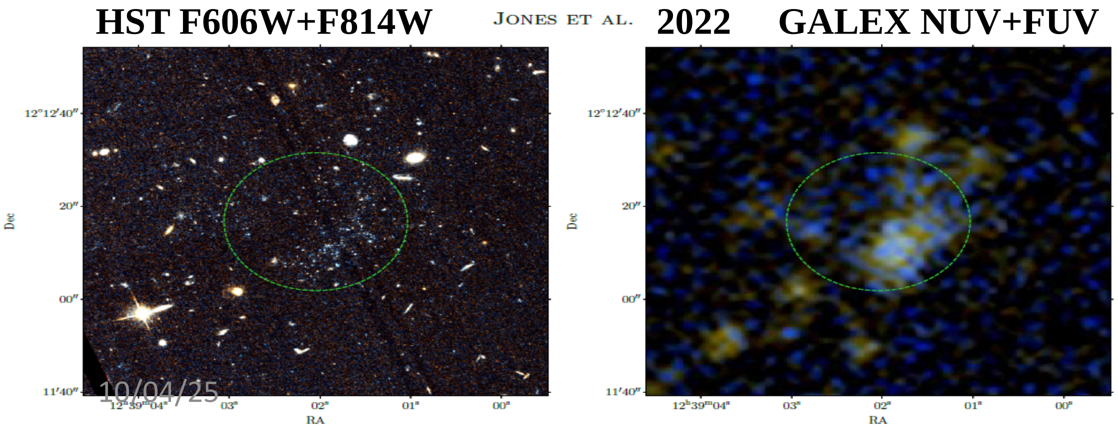


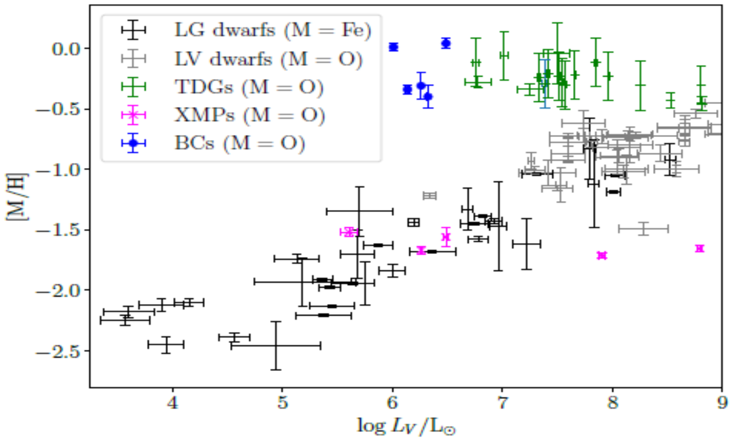
Isolated IG Star Clusters



Recent detections of absolutely isolated young star clusters rise problems:

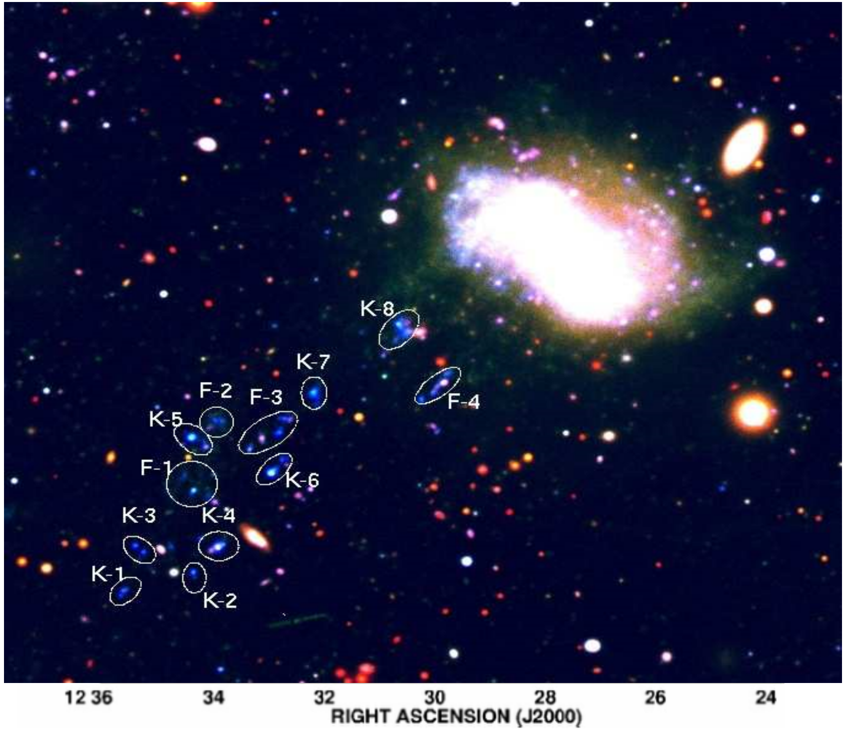
- How do gas clouds survive in hot ICM?
- What is there origin? Timescales?
- SFRs: well below 10^{-3} $M_\odot$/yr
- Gas consumpt. time: ~ few Gyr
- Z much higher than M-Z relation

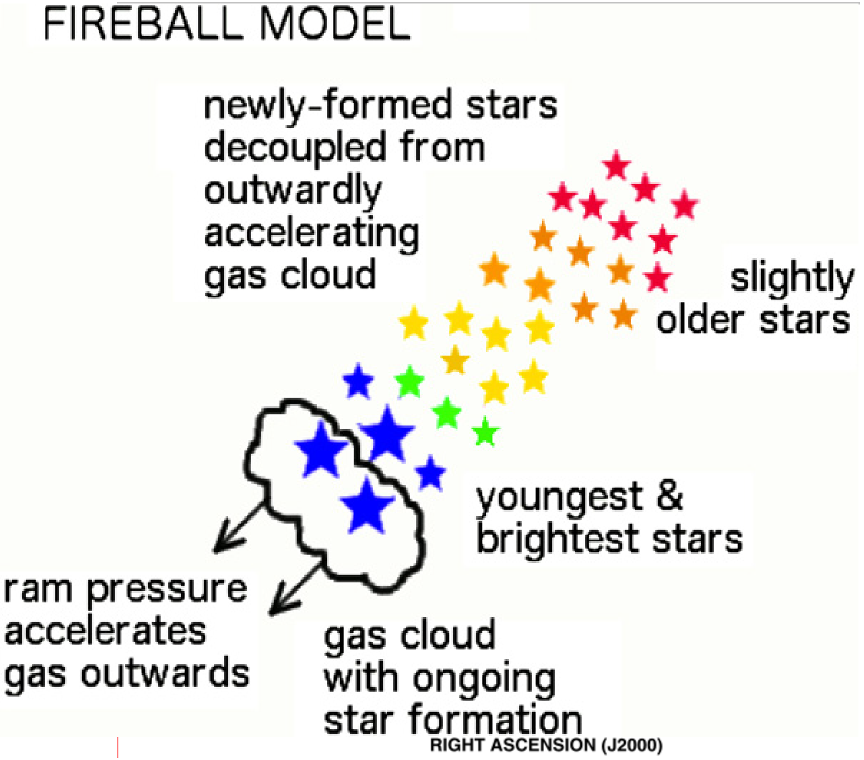




Dwarf Galaxies lose gas at cluster infall already by the low-density ICM ram pressure

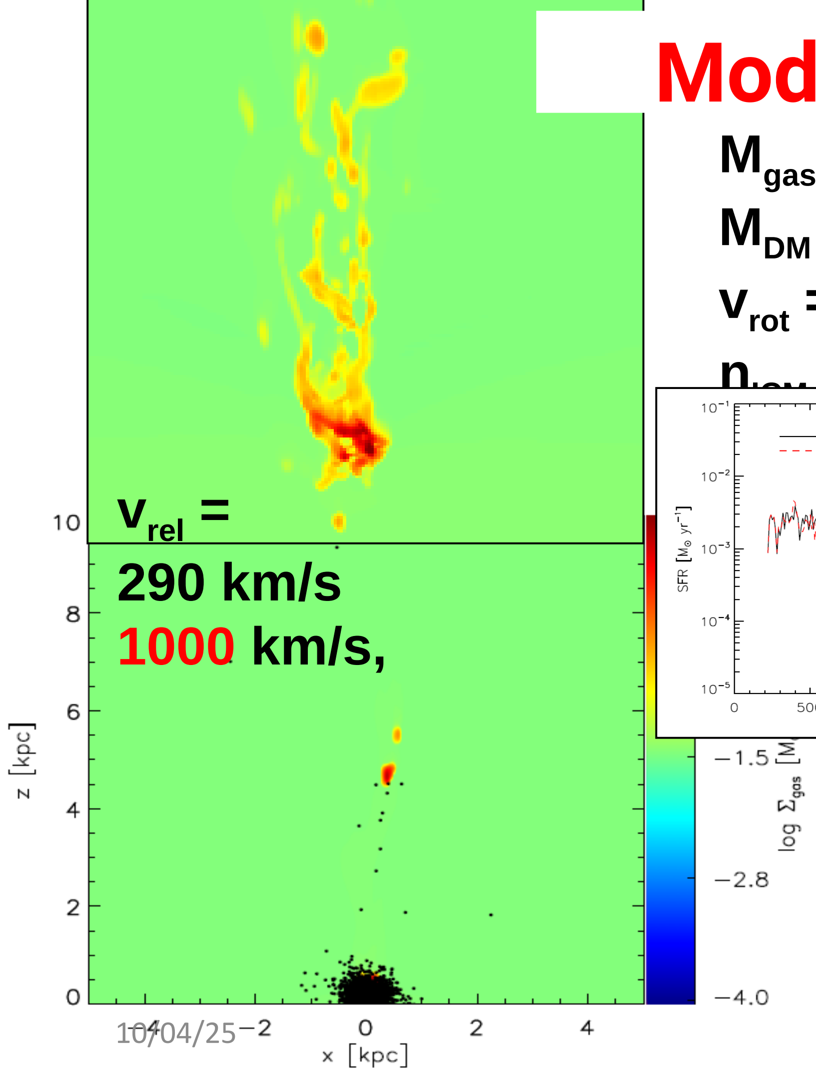
THE ASTROPHYSICAL JOURNAL, 780:119 (20pp), 2014 January 10





LBT image from Fumagalli et al., 2010

Models: slow vs. fast RPS DGs



v_{rel} =
290 km/s
1000 km/s,

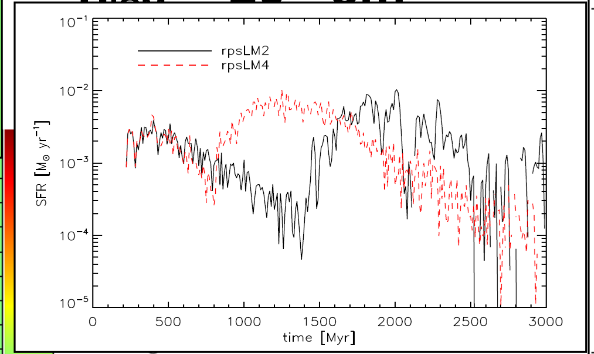
$M_{gas,i} = 6.3 \times 10^6 M_\odot$; $M_{s,i} = 0$

$M_{DM} = 1.2 \times 10^8 M_\odot$

$v_{rot} = 2$ km/s

$n_{ICM} = 10^{-4}$ cm^{-3}

Steyrleithner, Hensler, Boselli (2020) MNRAS, 494



Blob	N_{part}	M_* [$M_\odot$]	Δt [Myr]	SFR [$M_\odot$ yr^{-1}]
B3	2	2392	1	2.4×10^{-3}
B4	3	2536	1	2.6×10^{-3}
B4	3	3110	3	1.0×10^{-3}
B4	6	3096	10	3.1×10^{-4}
B4	2	1935	4	4.8×10^{-4}
B4	1	948	1	9.5×10^{-4}
B4	2	2445	1	2.4×10^{-3}
B4	2	1737	1	1.7×10^{-3}
B4	3	1408	3	4.7×10^{-4}

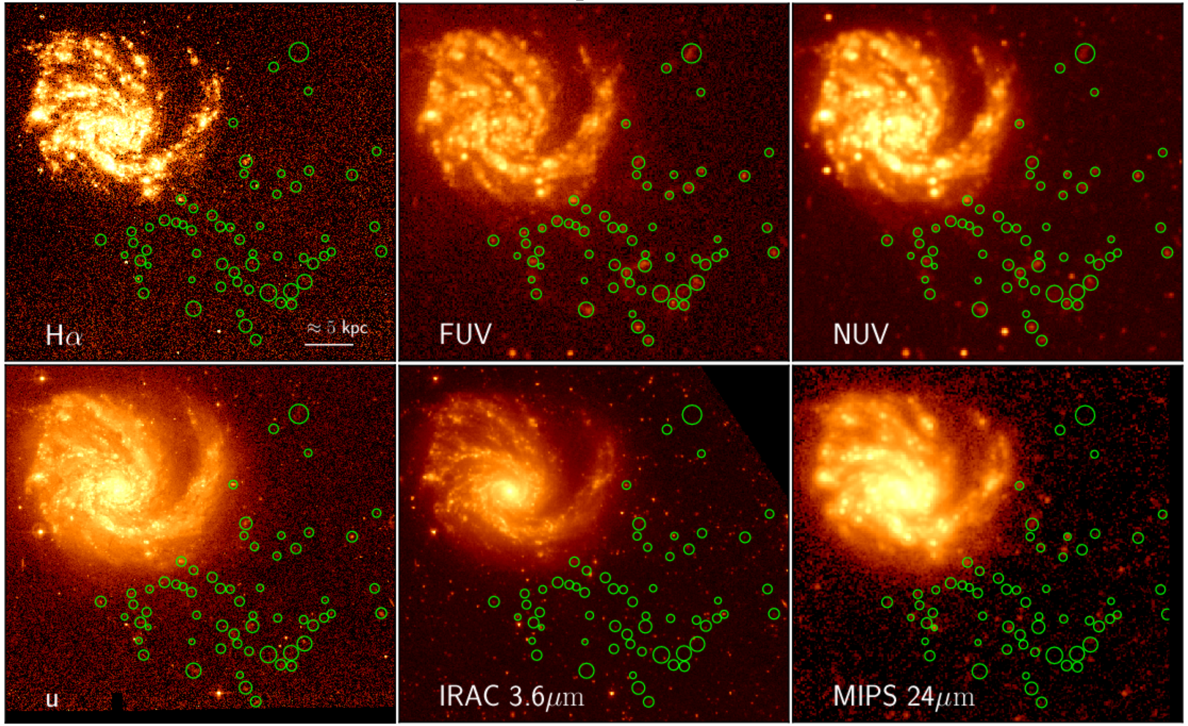
- ✓ Gas stripping by ram pressure.
- ✓ Clouds are self-gravitating,
- ✓ SF in massive clumps only at large v_{rel}; multiple star clusters form: low SFRs!
- ✓ Star clusters get gas-free: no H→, only UV

LyC escape

Ram-pressure stripping in NGC 4254

NGC 4254 moves with v_{rad}□1400 km/s ▲ heavy RPS happens.

NE motion leads to separation of RP clouds out to 30 kpc.



green: FUV knots

Boselli et al. (GH) 2018, A&A, 615, A114

VESTIGE:

A Virgo Environmental Survey Tracing Ionised Gas Emission

(Boselli et al. (GH) 2018, A&A, 614)

<u>*NGC 4254*</u>: 60 extragalactic star clusters in UV to one side, 30 with H→ emission ▲ embedded in gas clouds

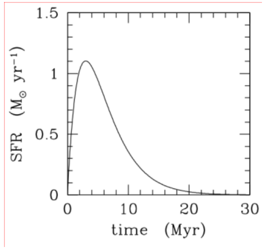
<u>*Question*</u>: timescale ⤨$_{cl}$ of gas cleaning, H→ vanishes, LyC photons escape?

<u>*Advantage*</u>: dust free

Age overlay

Age determination from SED

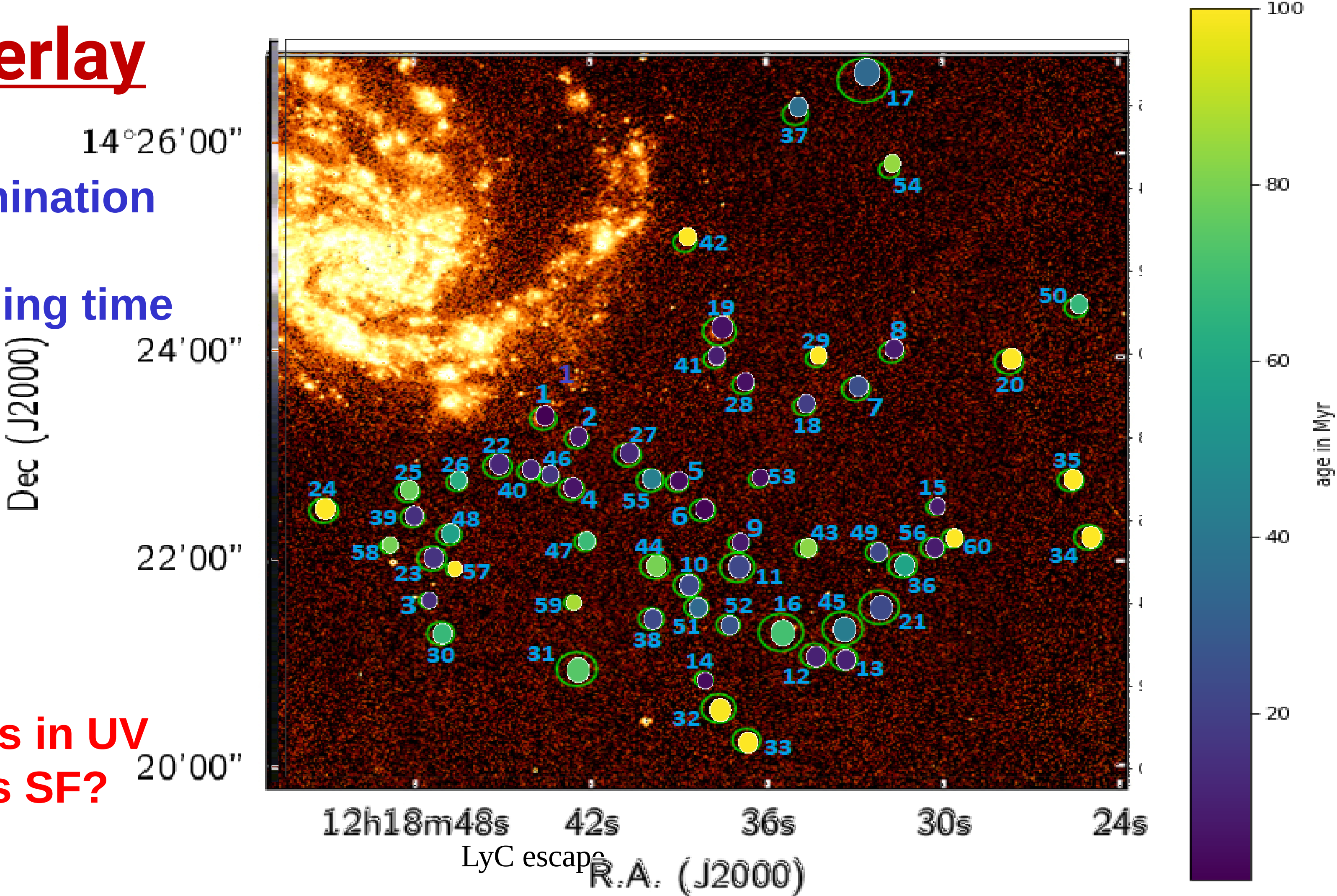
SFR: e-folding time with 3 Myr



Surprise:

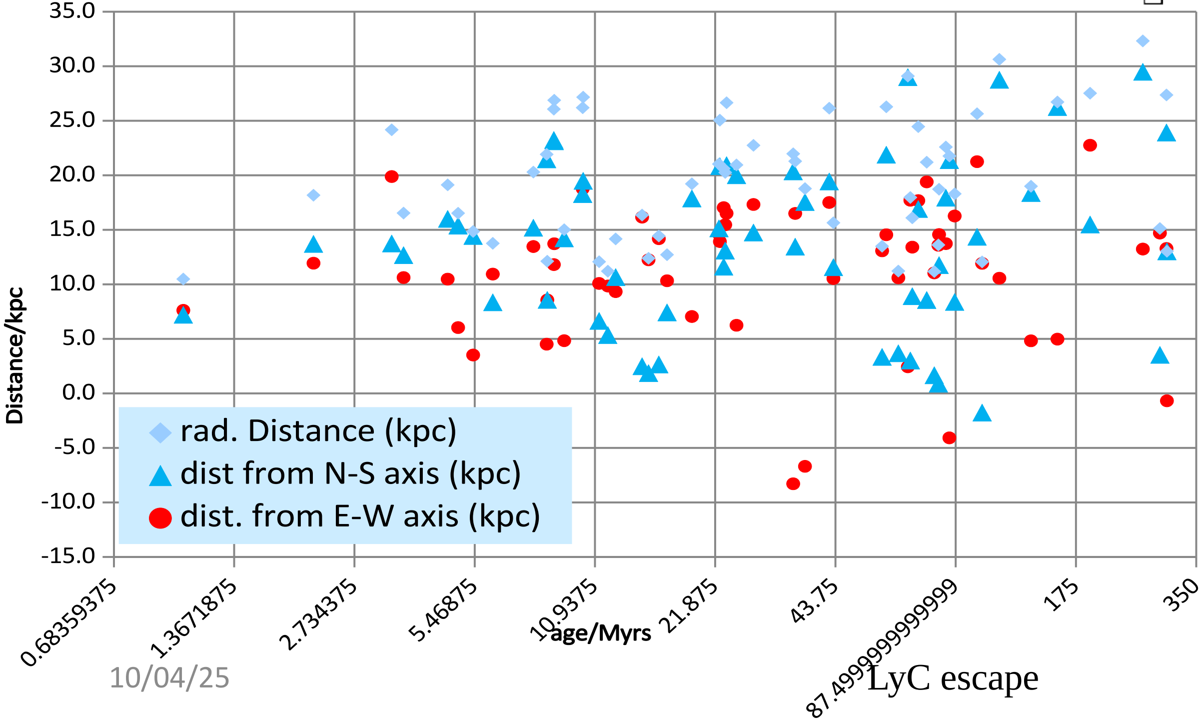
Old clusters in UV

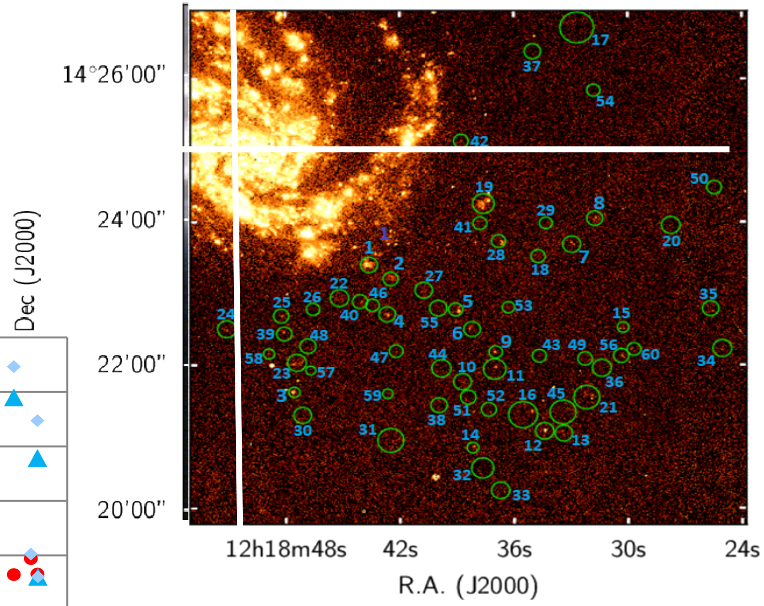
Continuous SF?



LyC escape

Distances of star clusters





LyC derived from H→:

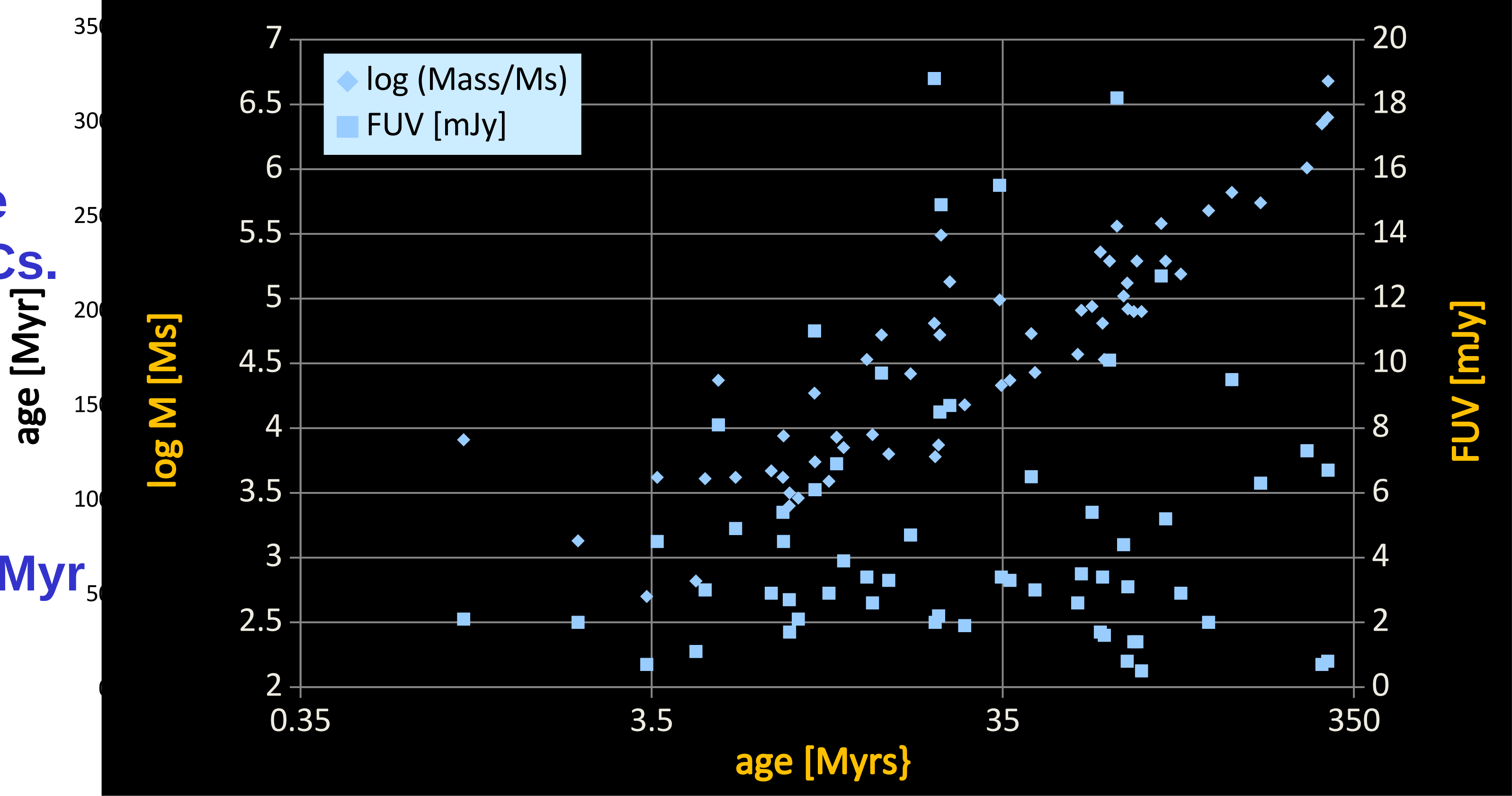
filter PSEUDO$_{LyC}$ derived as described in Boselli et al. (2016b):

$$\mathrm{LyC\,[mJy]} = \frac{1.07\times10^{-37}\times \mathrm{L(H\alpha)\,[erg\,s^{-1}]}}{D^2\,\mathrm{[Mpc]}}. \quad (1)$$

The more massive the older the SCs.

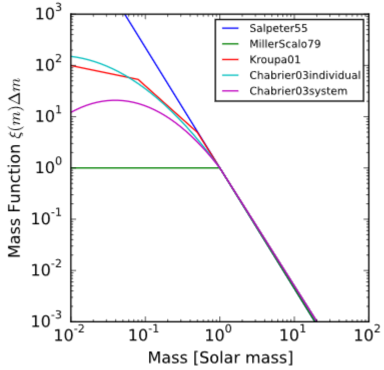
LyC for $M/M_{\odot}<10^{5.5}$, and ages mostly <50 Myr

FUV exists for all SCs!



Finding the SC IMF + LyC emission

- ✓ Taking the SC age from SED fit and the observed FUV
- ✓ Tracing back to the initial cluster mass
- ✓ IMF (Kroupa) stochasticly sampled (1000 runs) with upper mass truncation and for a 3 Myr SF e-folding time according to Boselli+ (2018)
- ✓ Forward calculations of existing LyC photon fluxes to present day from Sternberg+ (2003) models
- ✓ Calculat. of H→ with Calzetti+ 2013, recalc. of $PSEUDO_{LyC}$
- ✓ Comparison with observationally derived $PSEUDO_{LyC}$ from H→ emission
- ✓ LyC escape fraction: f_{esc}=1- LyC_{obs}/LyC_{mod}
- ✓ GALEX FUV and NUV magnitudes provided by Luciana Bianchi
- ✓ Conversion of UV magn.s to fluxes
- ✓ Normalization of model fluxes to obs. FUV



filter $PSEUDO_{LyC}$ derived as described in Boselli et al. (

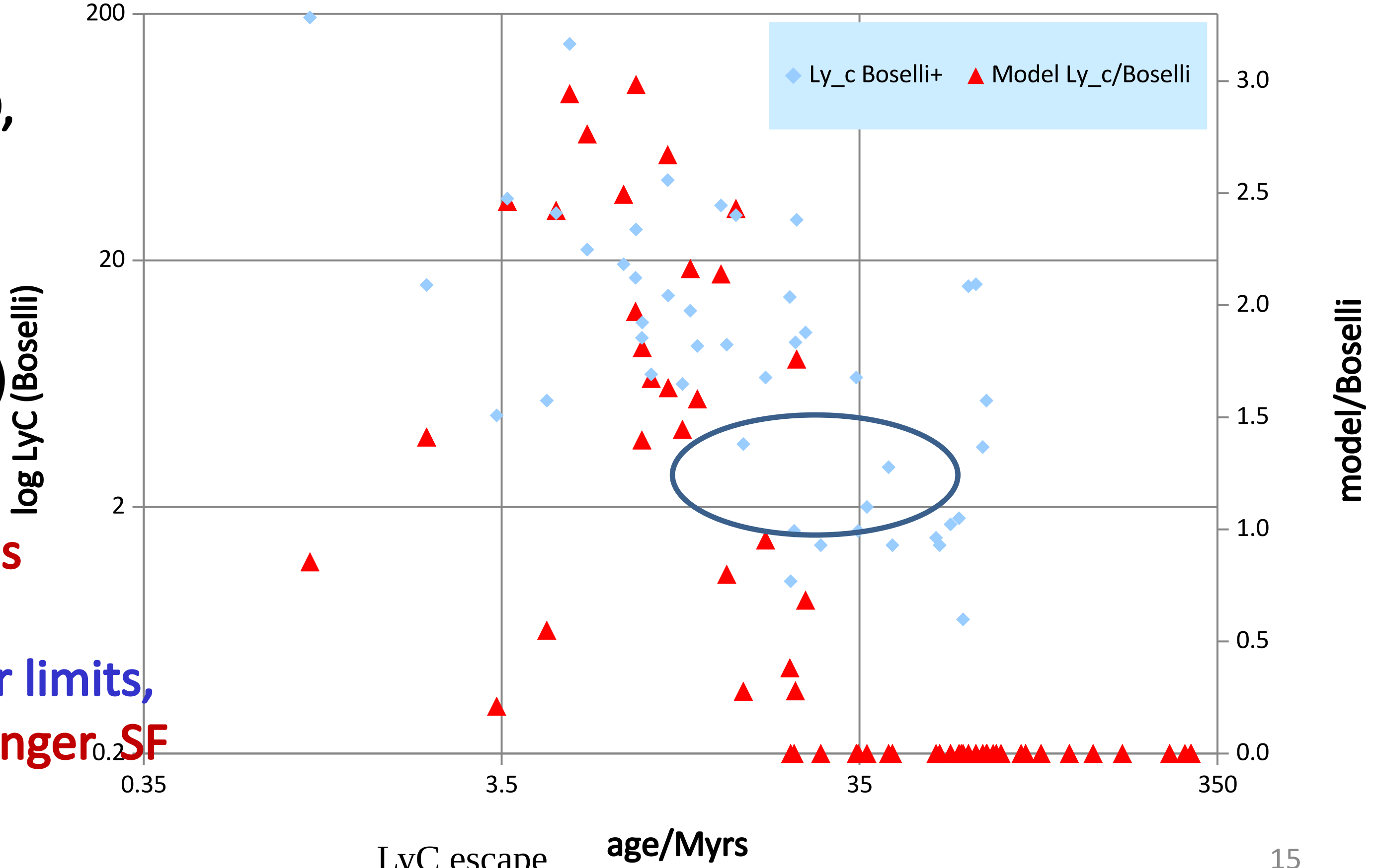
$$\mathrm{LyC\,[mJy]} = \frac{1.07 \times 10^{-37} \times L(H\alpha)\ [\mathrm{erg\ s^{-1}}]}{D^2\ [\mathrm{Mpc}]}.$$

Yannick et al. (GH) 2025, in prep.

Obs. LyC flux vs. cluster age + LyC model/obs. vs. age

Assumption:
SSP and age from SED,
Present-day M_*,
Obs. LyC from H→,
M_* projected to t=0,
Theor. LyC ($M_*(0)$,age)
[Sternberg+ 2003]

Result:
Theor. LyC flux vanishes after ~<20 Myrs,
"obs." LyC from upper limits,
older SCs with LyC: longer SF episode?



Yannick et al. (GH) 2025, in prep.

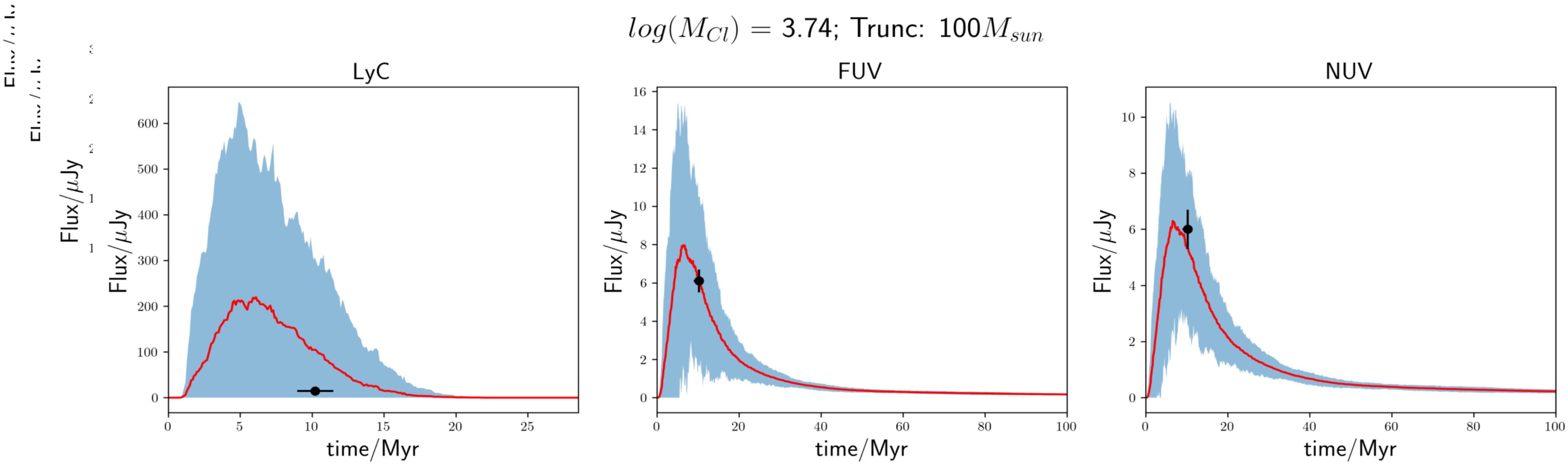
$log(M_{Cl}) = 3.74$; Trunc: $15 M_{sun}$

$log(M_{Cl}) = 3.74$; Trunc: $25 M_{sun}$

$log(M_{Cl}) = 3.74$; Trunc: $40 M_{sun}$

$log(M_{Cl}) = 3.74$; Trunc: $60 M_{sun}$

$log(M_{Cl}) = 3.74$; Trunc: $100 M_{sun}$



Results for model age ~10 Myr:

Best fits to FUV and NUV fluxes for upper mass limit at 60 -100 $M_{\odot}$

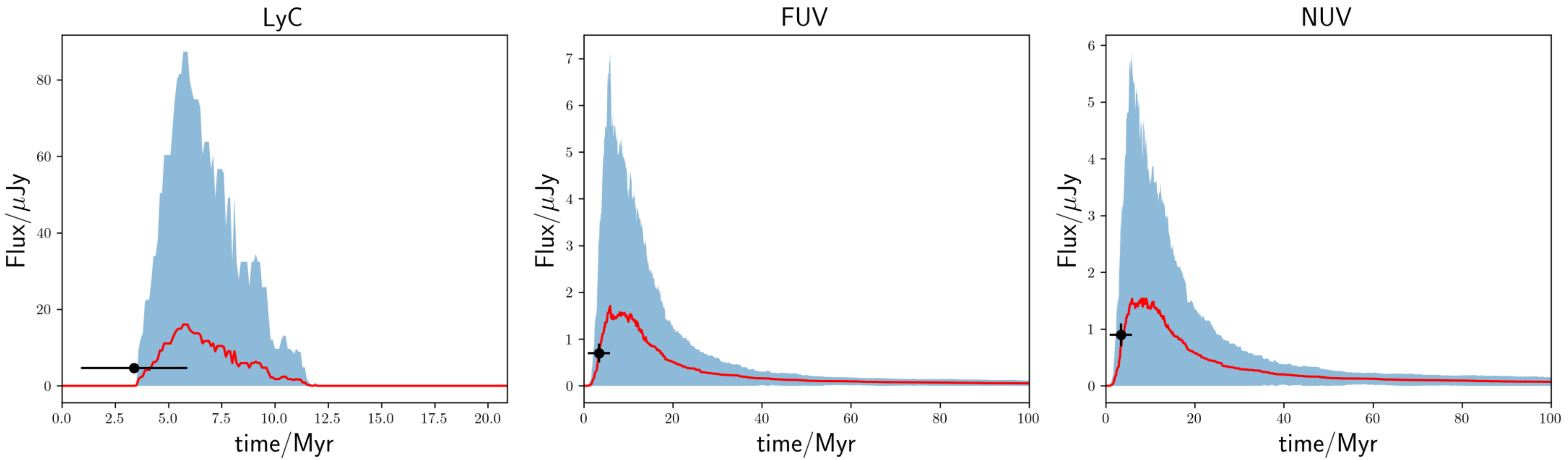
Clear deficit of obs. LyC flux compared to model

Filled vs incomplete IMF

$log(M_{Cl}) = 2.7$; Trunc: $25 M_{sun}$

$log(M_{Cl}) = 2.7$; Trunc: $40 M_{sun}$

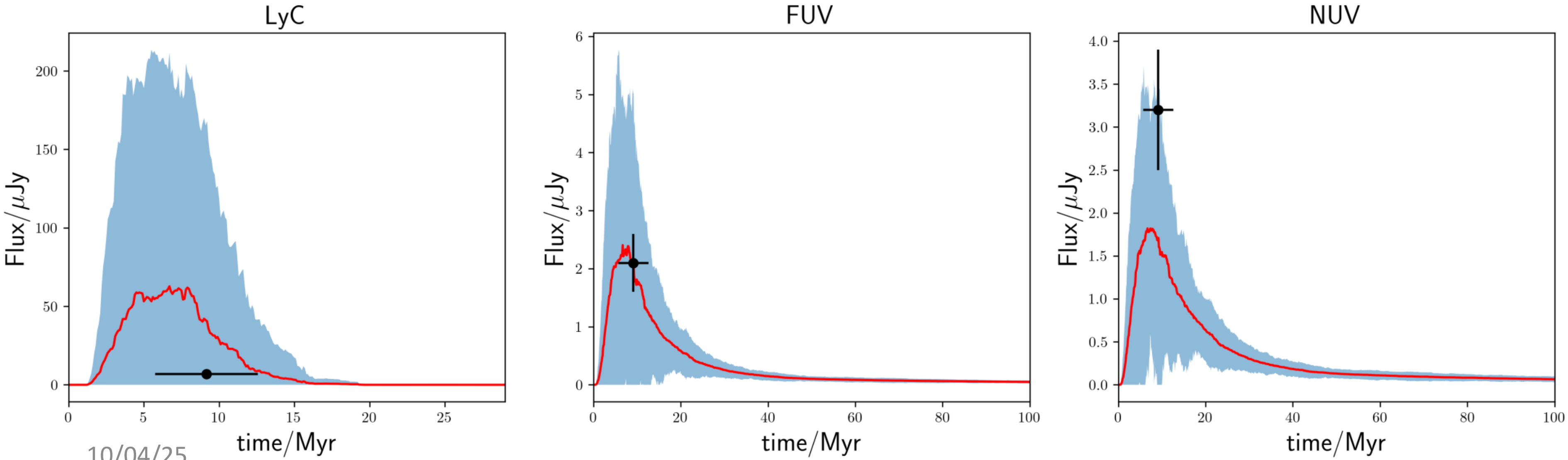
$log(M_{Cl}) = 2.7$; Trunc: $100 M_{sun}$



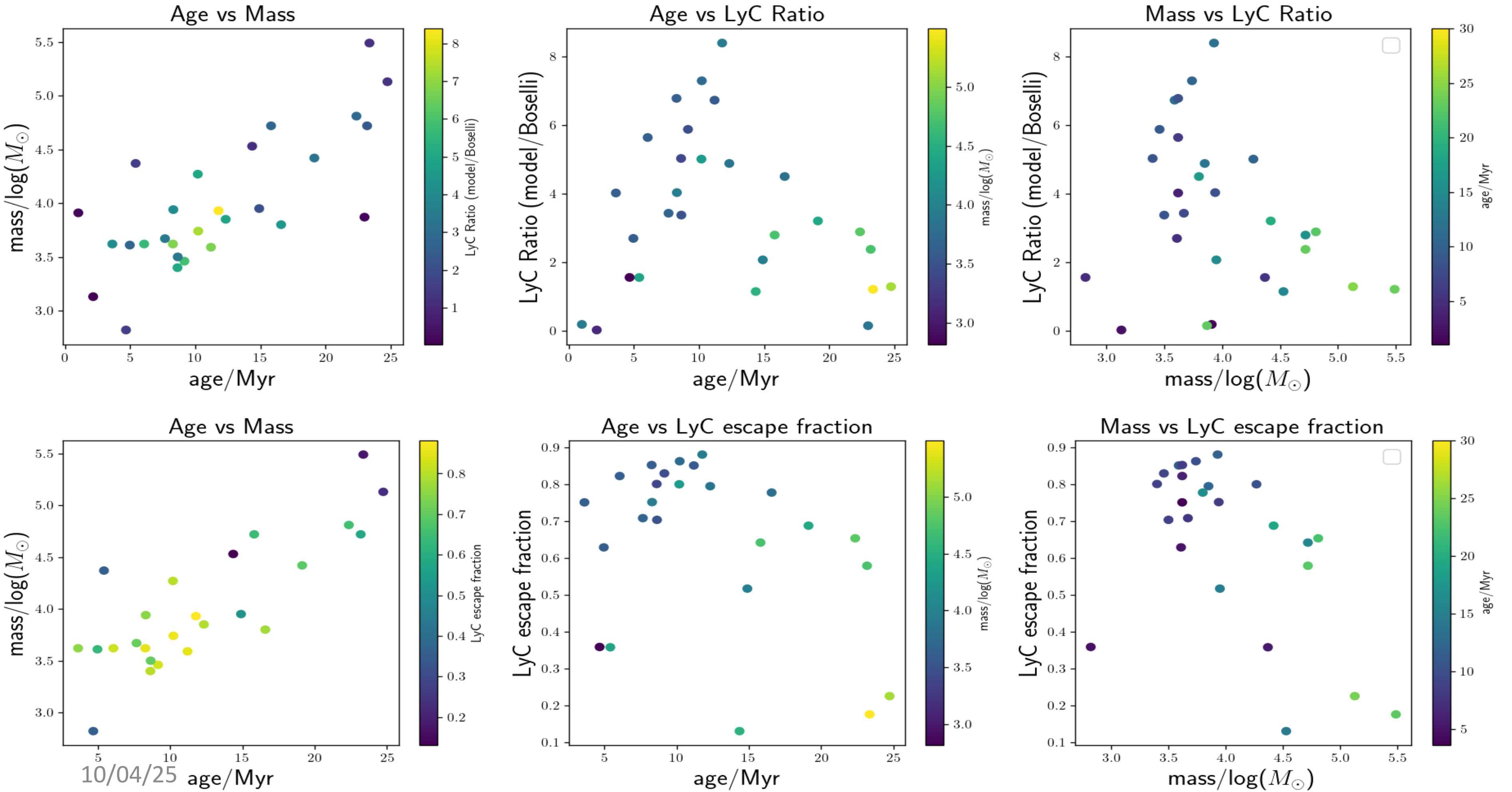
Takeaway: **low-mass SCs cannot fill the IMF; massive star are formed even with stochastic sampling but low probability**

Filled vs incomplete IMF

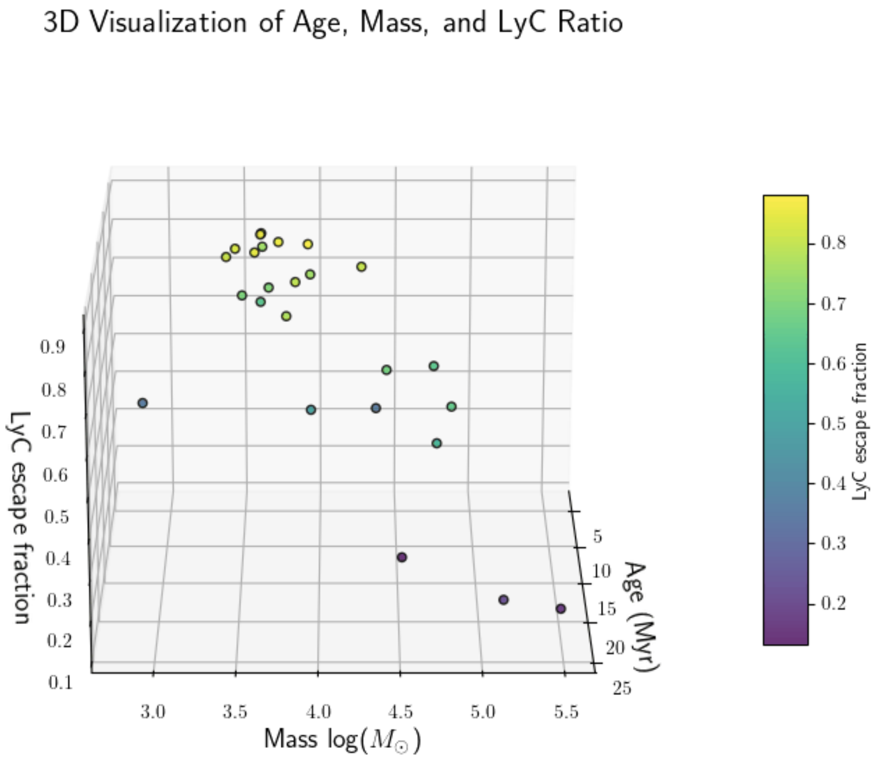
$log(M_{Cl}) = 3.46$; Trunc: $15 M_{sun}$
$log(M_{Cl}) = 3.46$; Trunc: $40 M_{sun}$
$log(M_{Cl}) = 3.46$; Trunc: $60 M_{sun}$
$log(M_{Cl}) = 3.46$; Trunc: $100 M_{sun}$



Scatter Plots of Age, Mass, and LyC Ratio



f_{esc}=1 - LyC_{obs}/LyC_{mod}



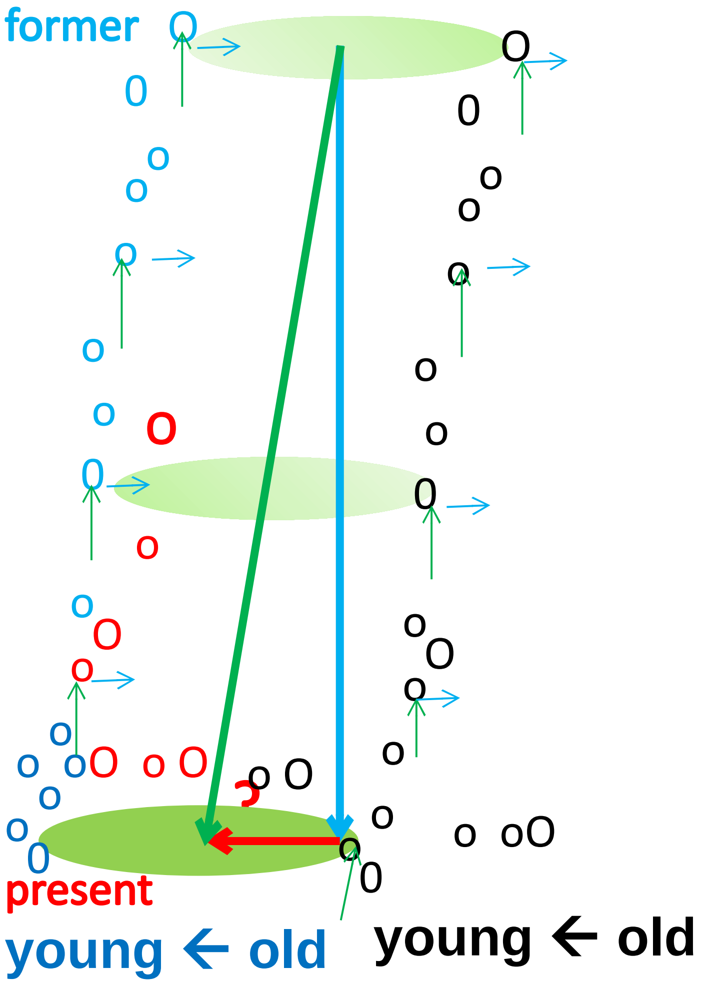
Conclusions

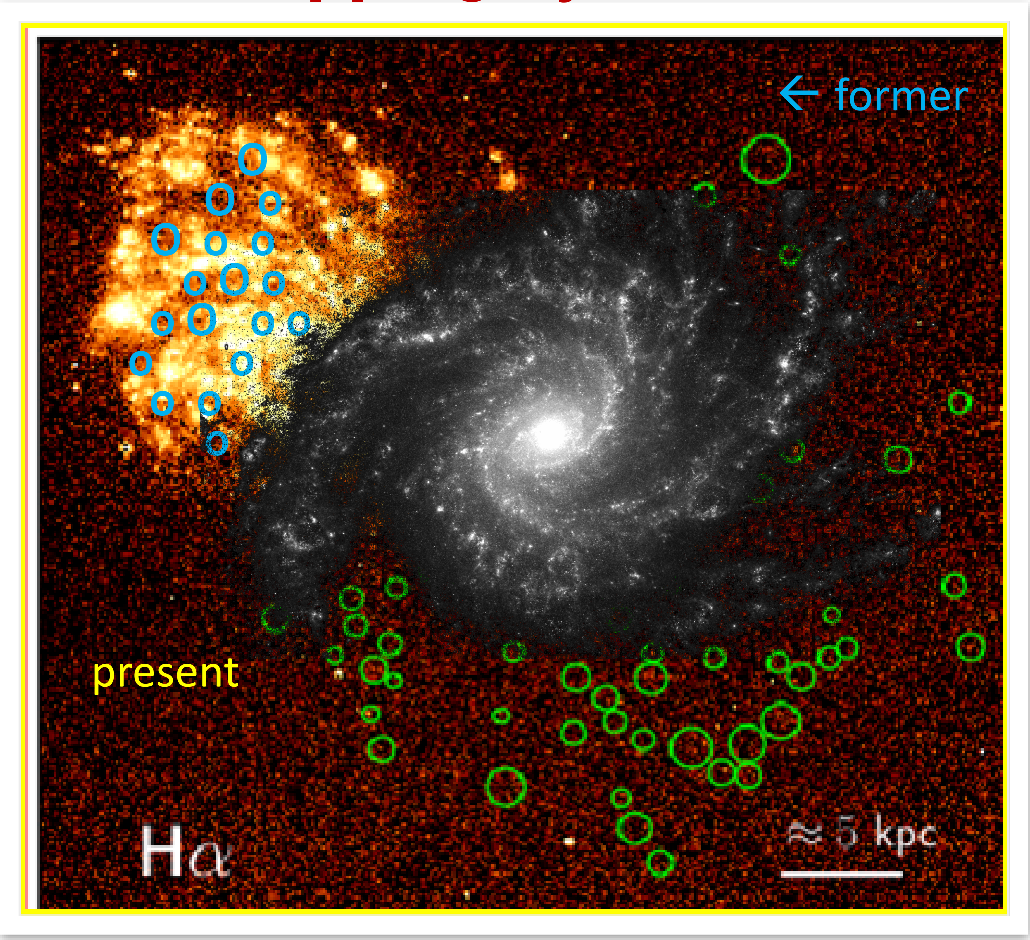
- Intra-cluster star clusters formed from RPS gas are easily freed from their gas and can freely release their available LyC.
- LyC photons as long as the massive stars of > 15 $M_{\odot}$ exist.
- Low-mass clusters lose their gas rapidly!
- Yet soft X-ray photons from SNII bubbles are not considered.

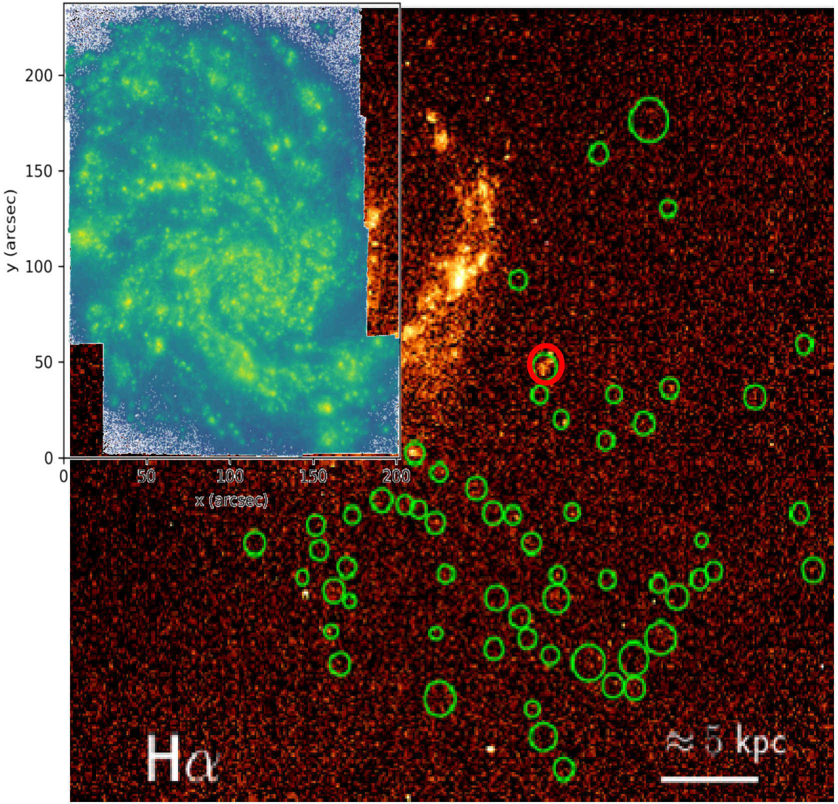
Next steps

- Tracing back the LyC to the initial cluster mass
- Explore, when the gas envelop is pushed off and the star cluster extricated
- Study the frequency of isolated intergalactic star clusters (Globular Clusters, RPS clusters, TDG?)
- Develop a consistent picture of the NGC 4254 motion

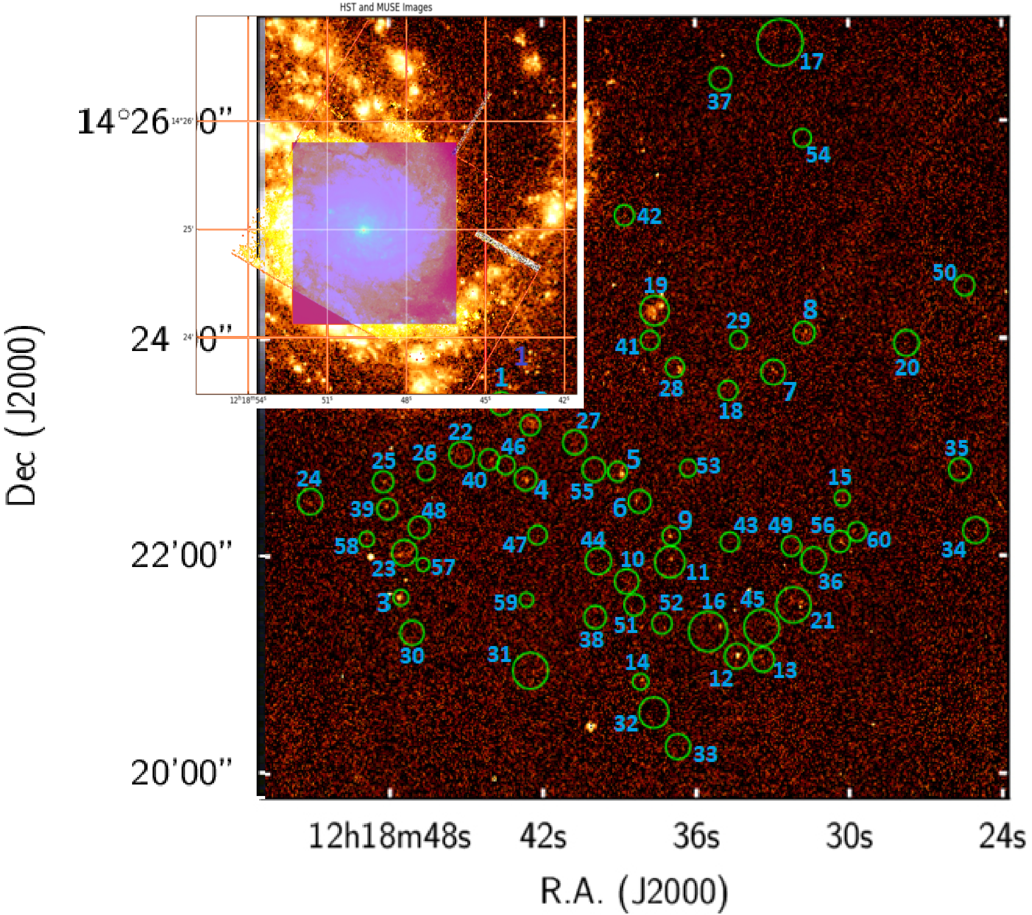
The stripping dynamics





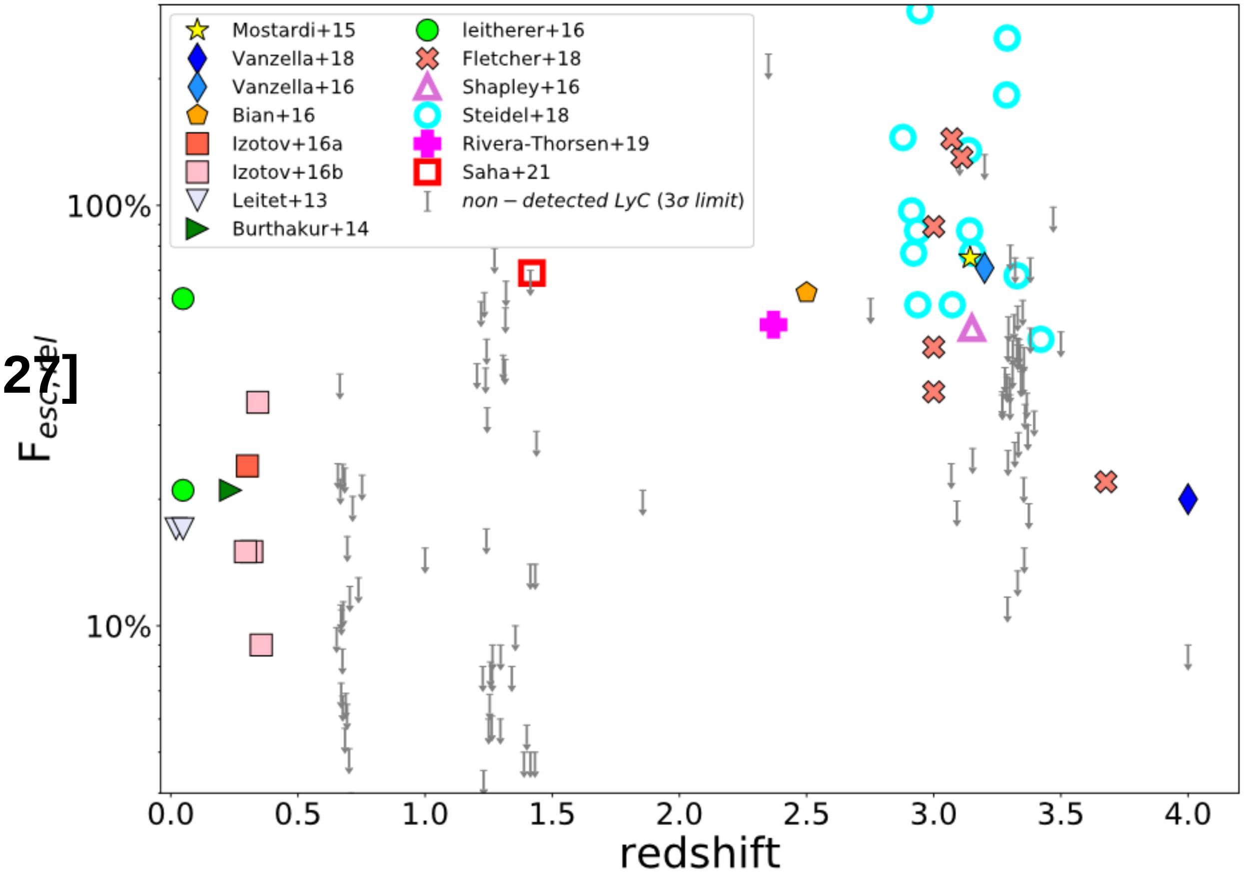


y (arcsec)
x (arcsec)
0
50
100
150
200
Hα
≈ 5 kpc



HST and MUSE Images
Dec (J2000)
14°26'0"
24'0"
22'00"
20'00"
12h18m48s
42s
36s
30s
24s
R.A. (J2000)

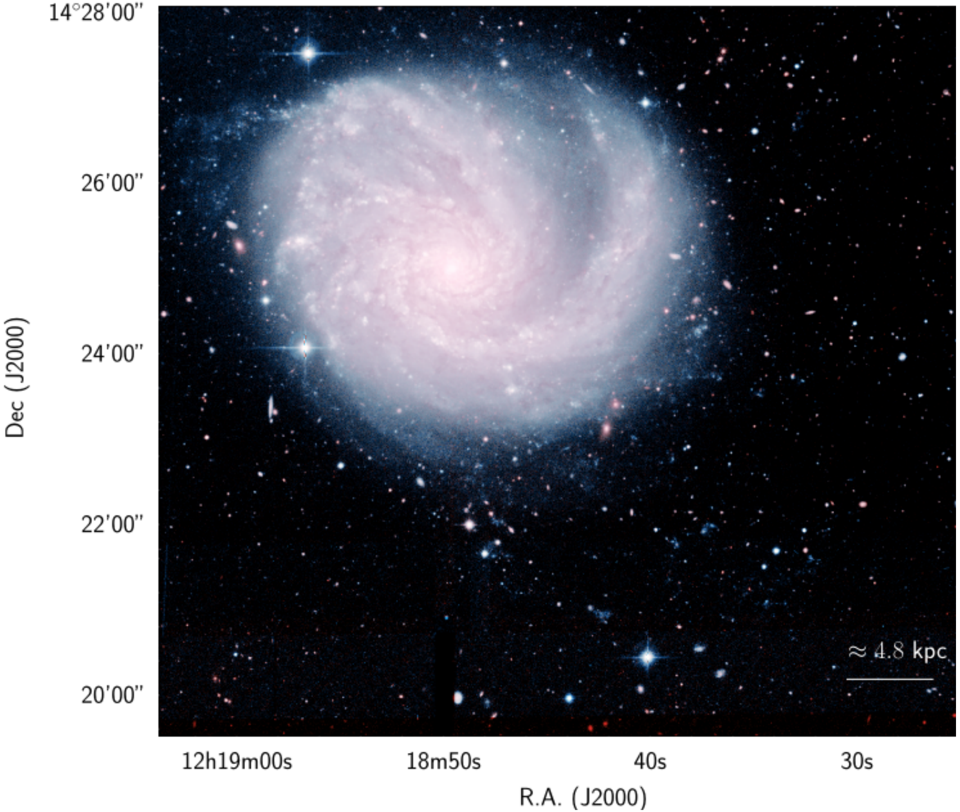
Finding measure are:
Ly→ emission,
MgII emission,
High [OIII 5007]/[OII 3727] EL ratio,
Strong CIV 1550

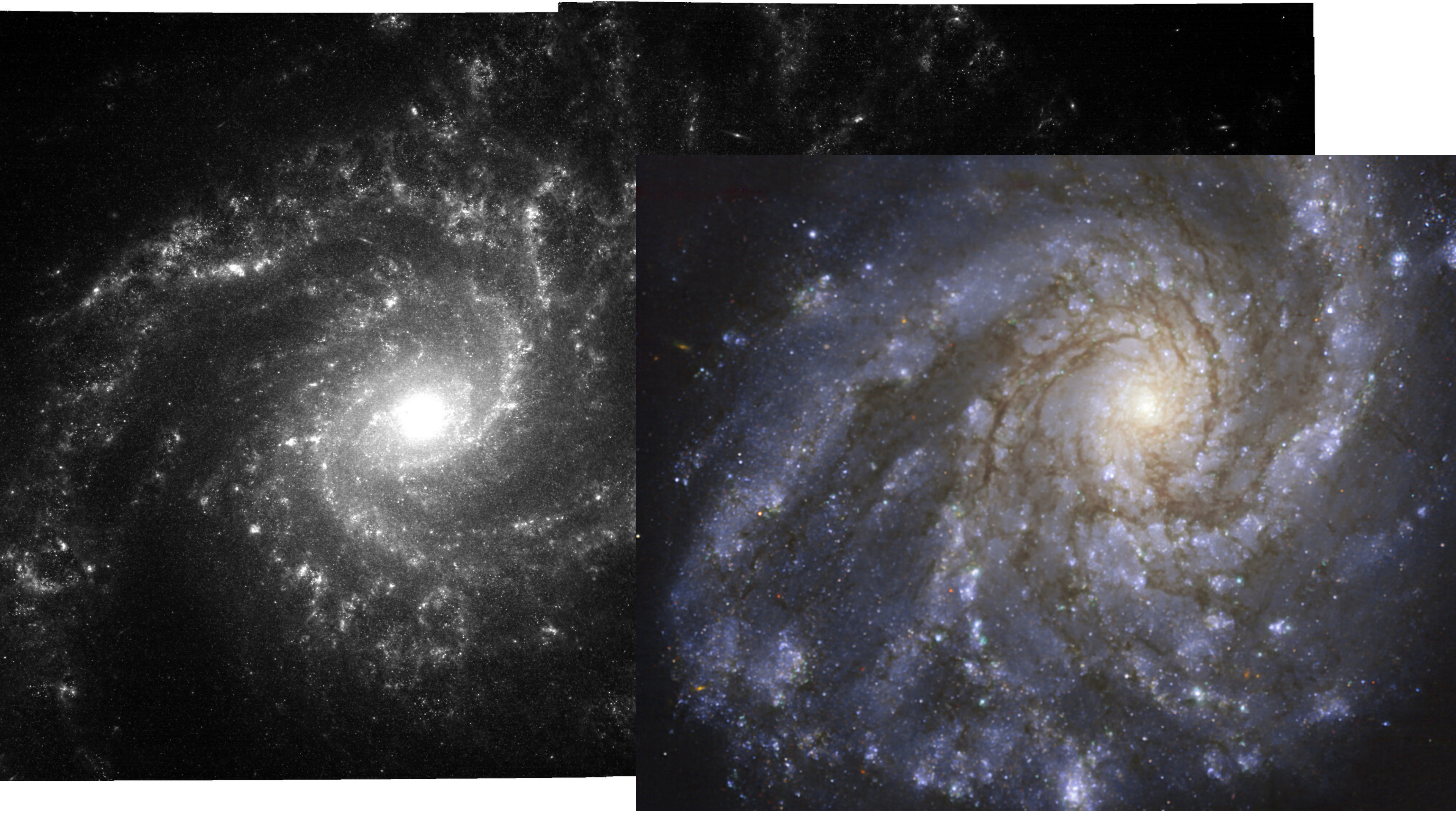


NGC 4254 – orientation and RPS star cluster analysis

Gerhard Hensler & Yannick Hein

Composite SDSS *gri*-image of the grand-design spiral North is up; east is left. The image size is 7′ × 6.3′.

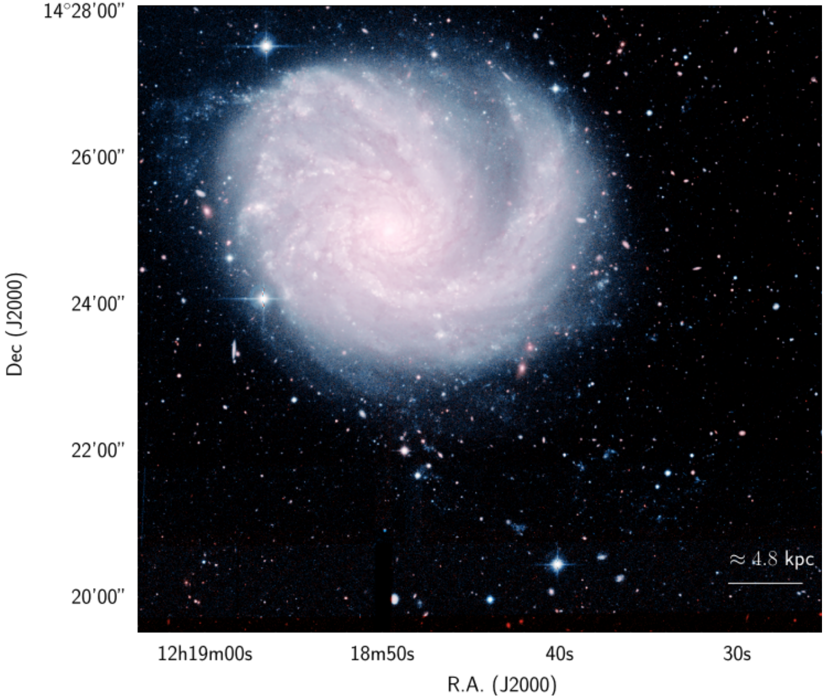




NGC 4254 – orientation and RPS star cluster analysis

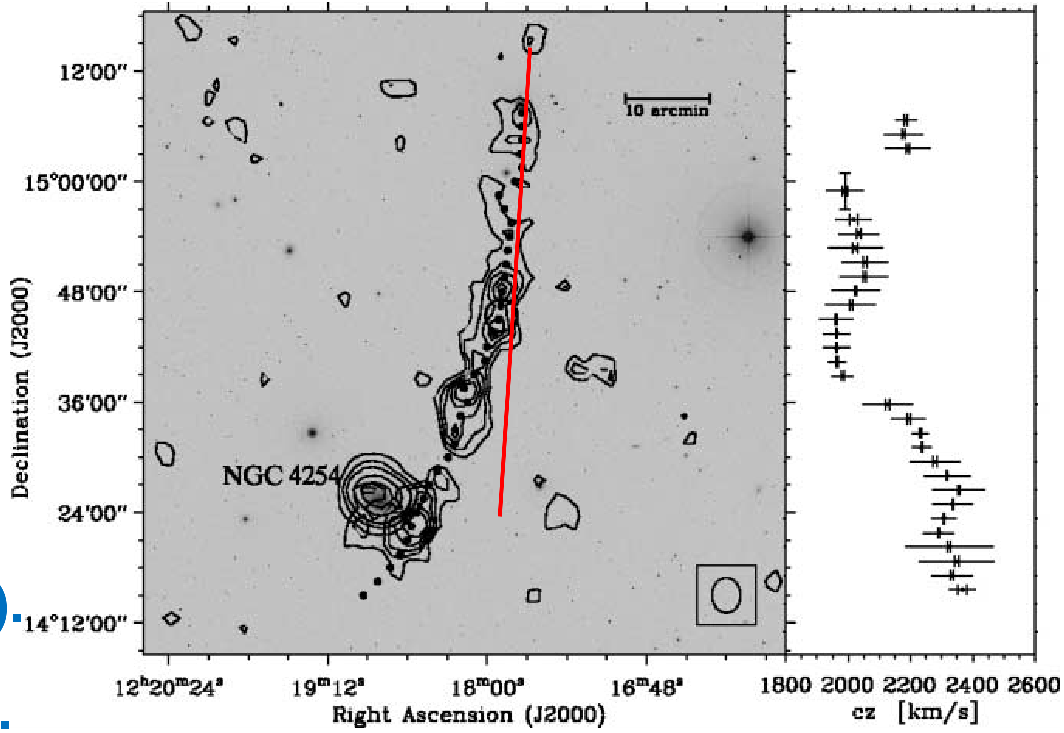
Gerhard Hensler, Yannick Hein, Alessandro Boselli + VESTIGE team

Composite SDSS *gri*-image of the grand-design spiral
North is up; east is left. The image size is $7' \times 6.3'$.



The VIRGOHI21 tail?

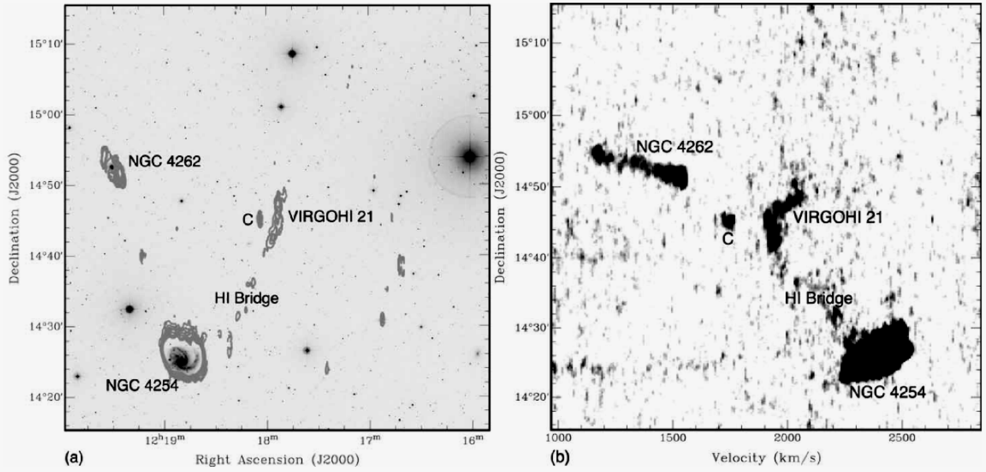
✓The velocity curve is representative of an edge-on dark disk galaxy (+- 200 km/s).
✓NGC 4254 moves with a relative radial vel. of +1300 km/s. From virial arguments the azimuthal vel. should be lower (not 800 km/s). Is VIRGOHI a tidally disrupted rotating dark galaxy (Minchin et al. 2007; Davies et al., 2004)?
✓The total length stretchs from NGC 4254 to a distance of ~ 48´ 288 kpc.
✓NGC 4254 deviates from the straight line of first tidal occur. by ~10‘ (48 kpc).
✓Due to the rotation curve a stripping scenario is unlikely (not by ram-pressure nor tidally). Only the S end corresponds with the radial vel. of NGC 4254.

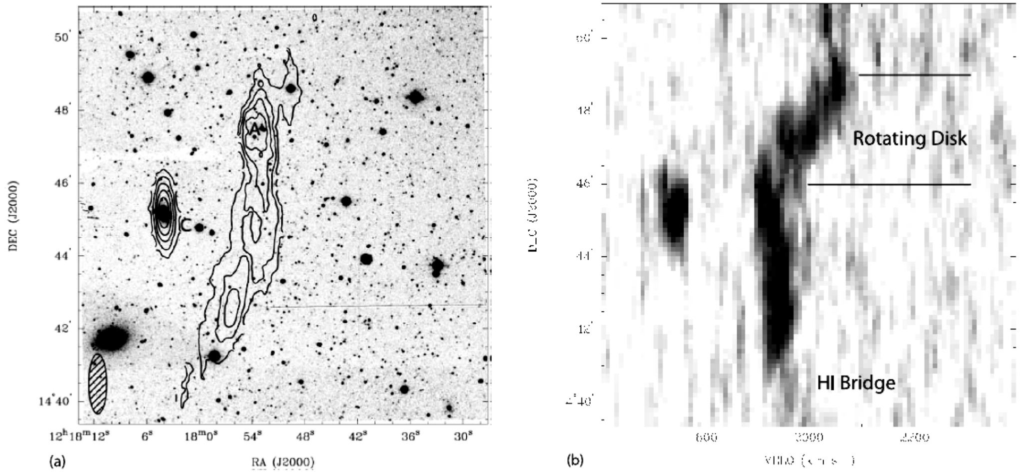


The whole system is seen 2D in projection on the sky. The radial velocity measurements help to get a 3D impression.

VIRGOHI21 is located between ➦=14°40´-14°50´ and l=$12^h17^m50^s$ – 18^m0^s (lower density: ➦=14°35´-15°05´) and has therefore a projected length of 600“x80pc = 48 kpc (~144 kpc).
Its mean radial vel. is 2100 km/s with a rotational velocity of 💼100 km/s.

NGC 4254 is displaced from VIRGOHI21 by 📝➦15´~ 72 kpc (at minimum) and 📝$v_{r,rel}$□+300 km/s.





The VIRGOHI 21 tail?

NGC 4254 moves with a rel. radial vel. of +1300 km/s and any perturber has passed to the N with ~1000 km/s. From virial vel. arguments the azimuthal vel. should be lower than in Boselli et al. 2014 (not 800 km/s).

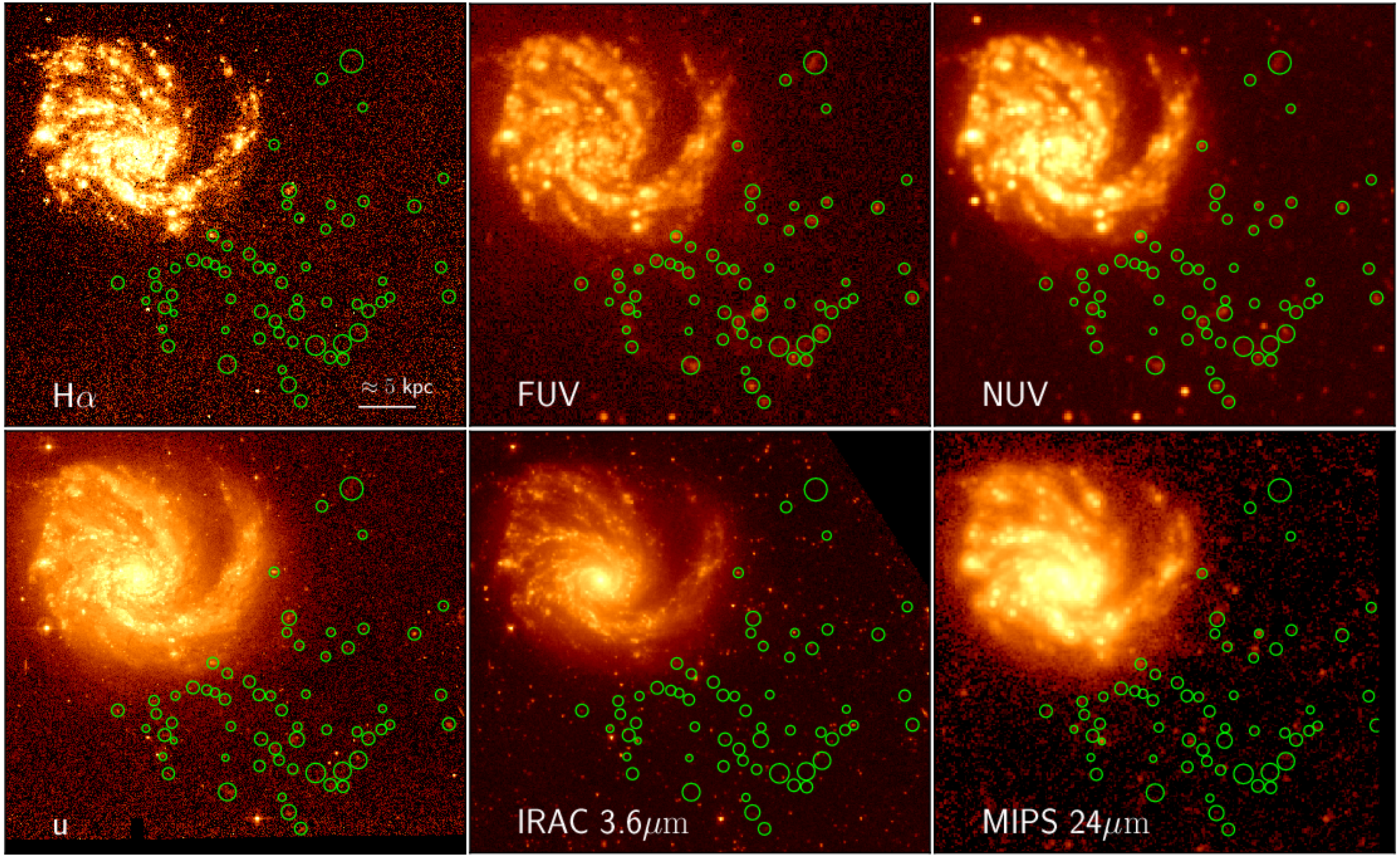
For the tail length of ~36´, this would mean a length of 2160´´x 80pc/´´ = 172.8 kpc.
Is the tail a tidally disrupted totating dark intra-cluster cloud/galaxy?

The NGC 4254 motion

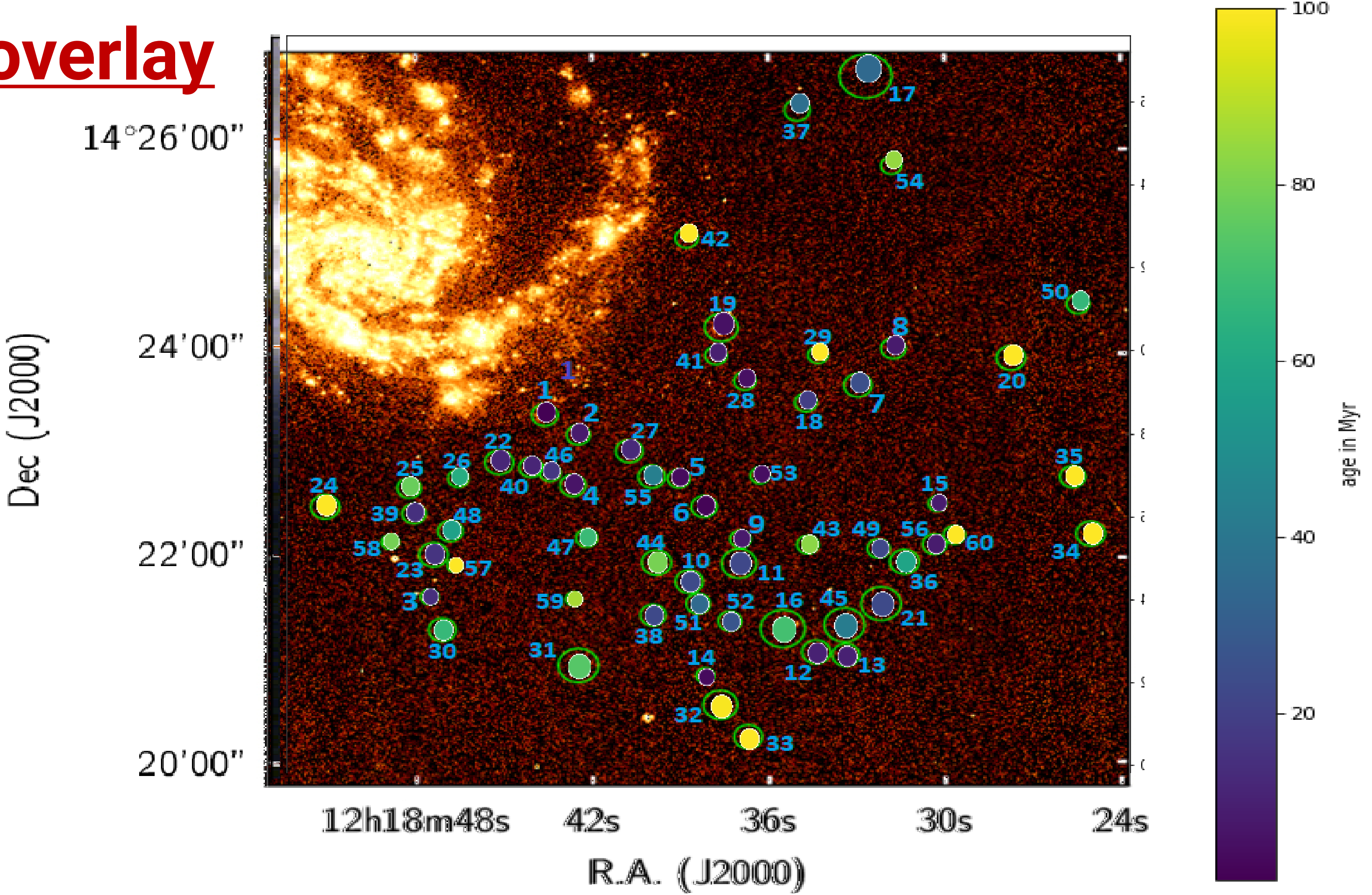
NGC 4254 moves with a radial rel. vel. of +1400 km/s and must experience RPS in radial direction. Where are the already stripped gas clouds and possible formed young star clusters at the disk edge changing with time?

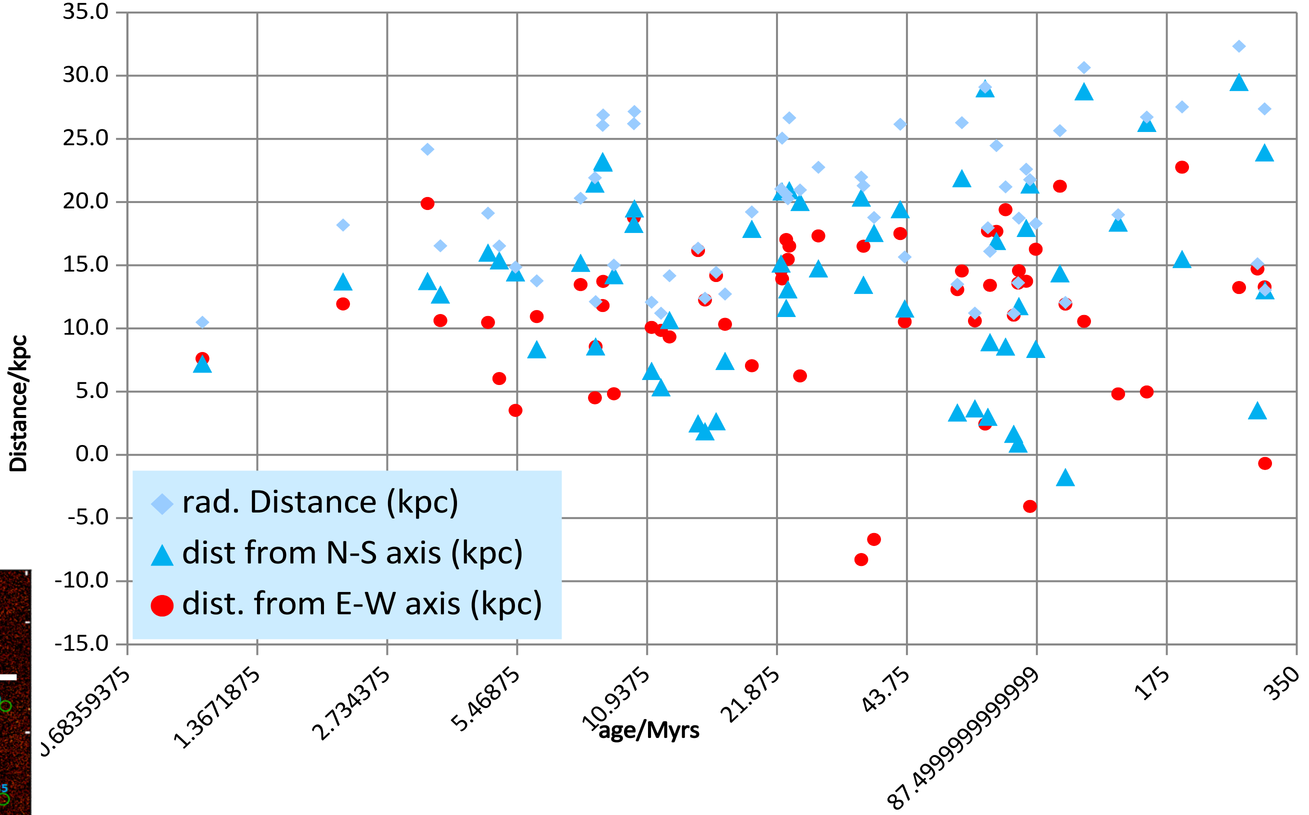
If the perturber moves to the N with 1000 km/s, for the tail length of ~36‘ , this would need:
172,8 kpc/1000 pc/Myr 175 Myr

In the same time NGC4254 has moved to the NE by ~50 kpc, what means with a velocity of ~ 285 km/s

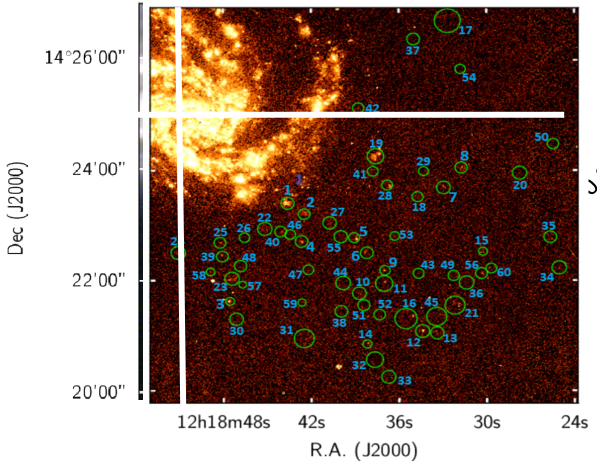

Hα
≈ 5 kpc
FUV
NUV
u
IRAC 3.6μm
MIPS 24μm

Age overlay


14°26'00"
24'00"
22'00"
20'00"
Dec (J2000)
12h18m48s
42s
36s
30s
24s
R.A. (J2000)
age in Myr
100
80
60
40
20

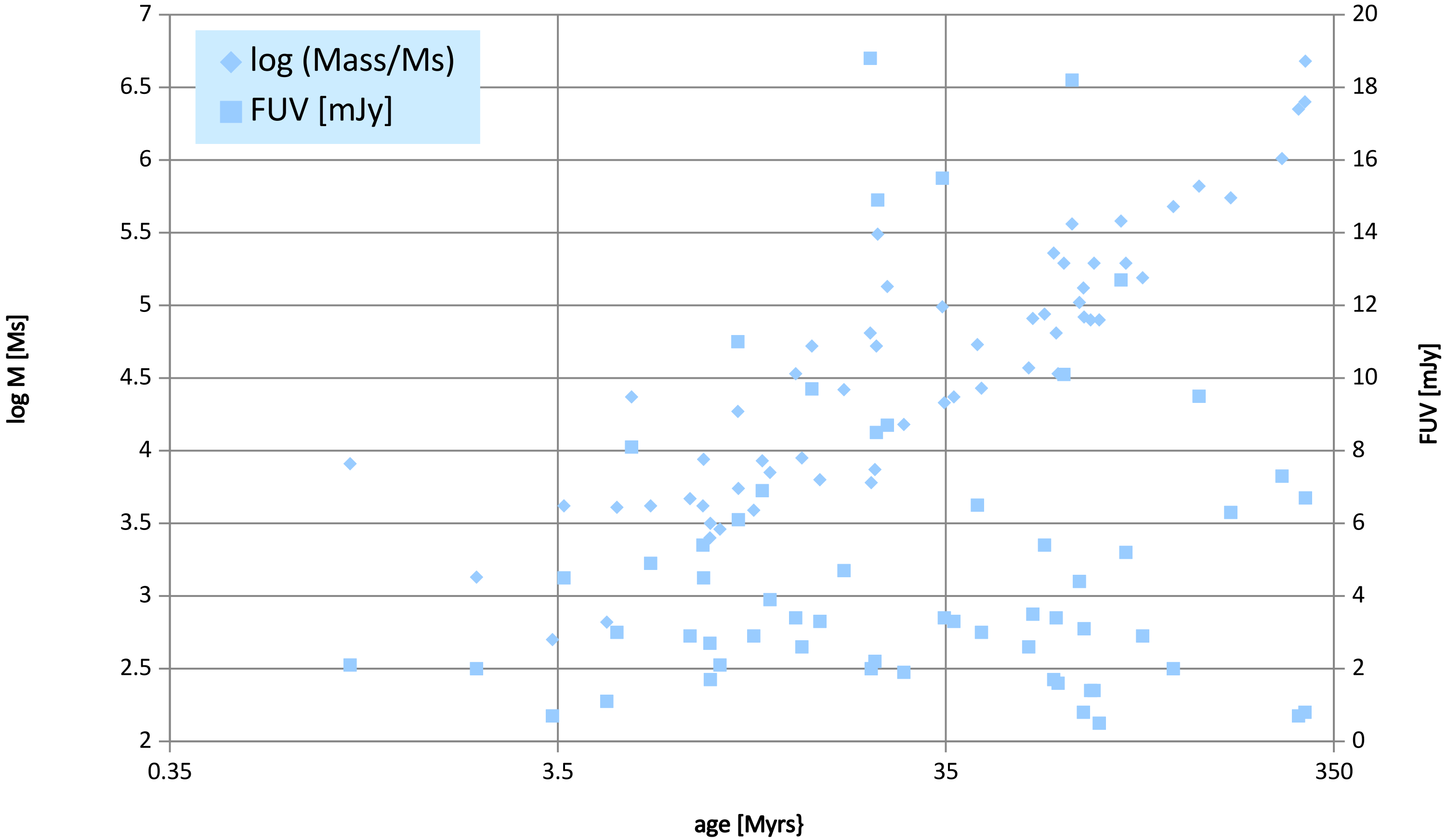


35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
-5.0
-10.0
-15.0
Distance/kpc
rad. Distance (kpc)
dist from N-S axis (kpc)
dist. from E-W axis (kpc)
1.3671875
2.734375
5.46875
10.9375
21.875
43.75
87.499999999999
175
350
age/Myrs

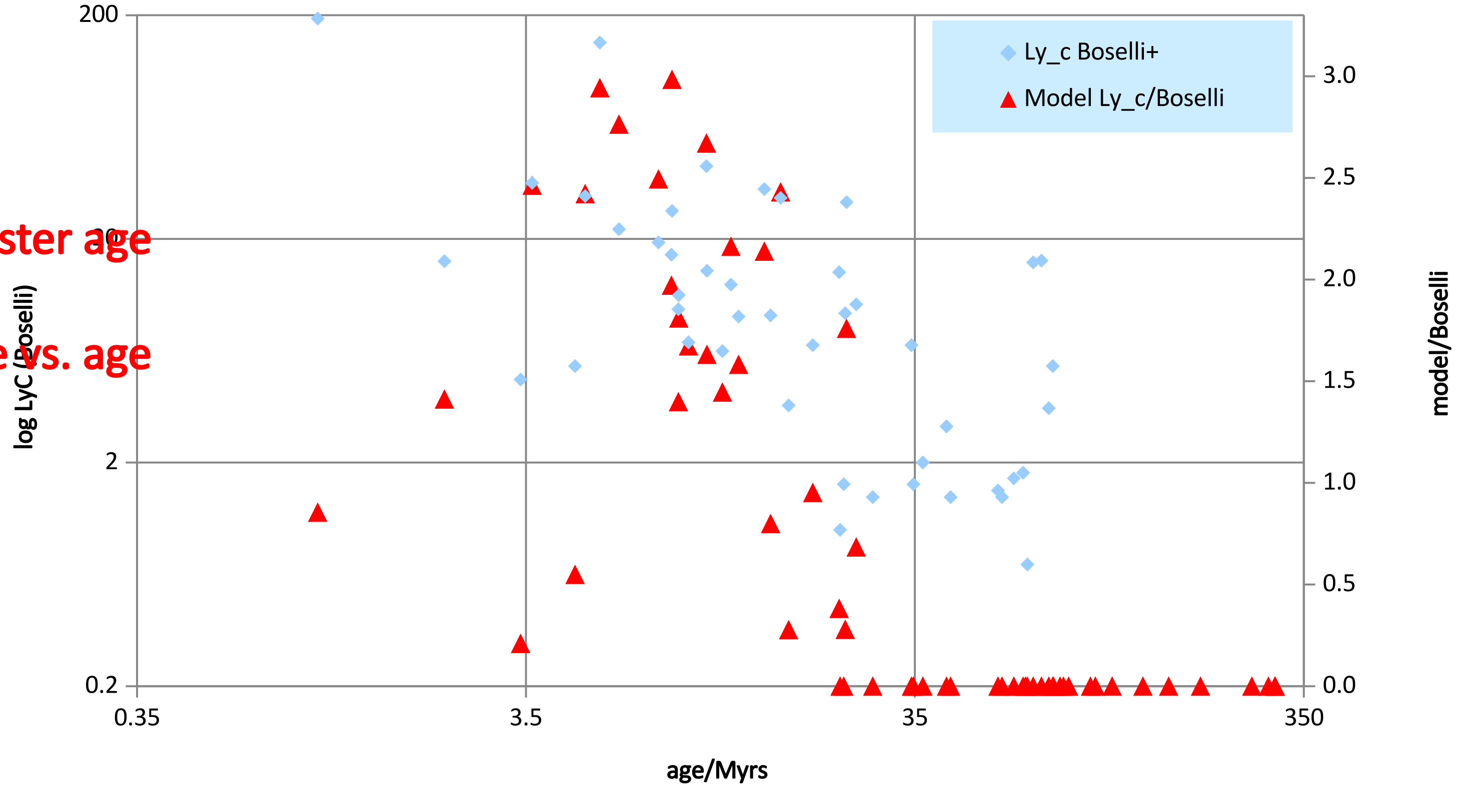


14°26'00"
24'00"
22'00"
20'00"
Dec (J2000)
12h18m48s
42s
36s
30s
24s
R.A. (J2000)

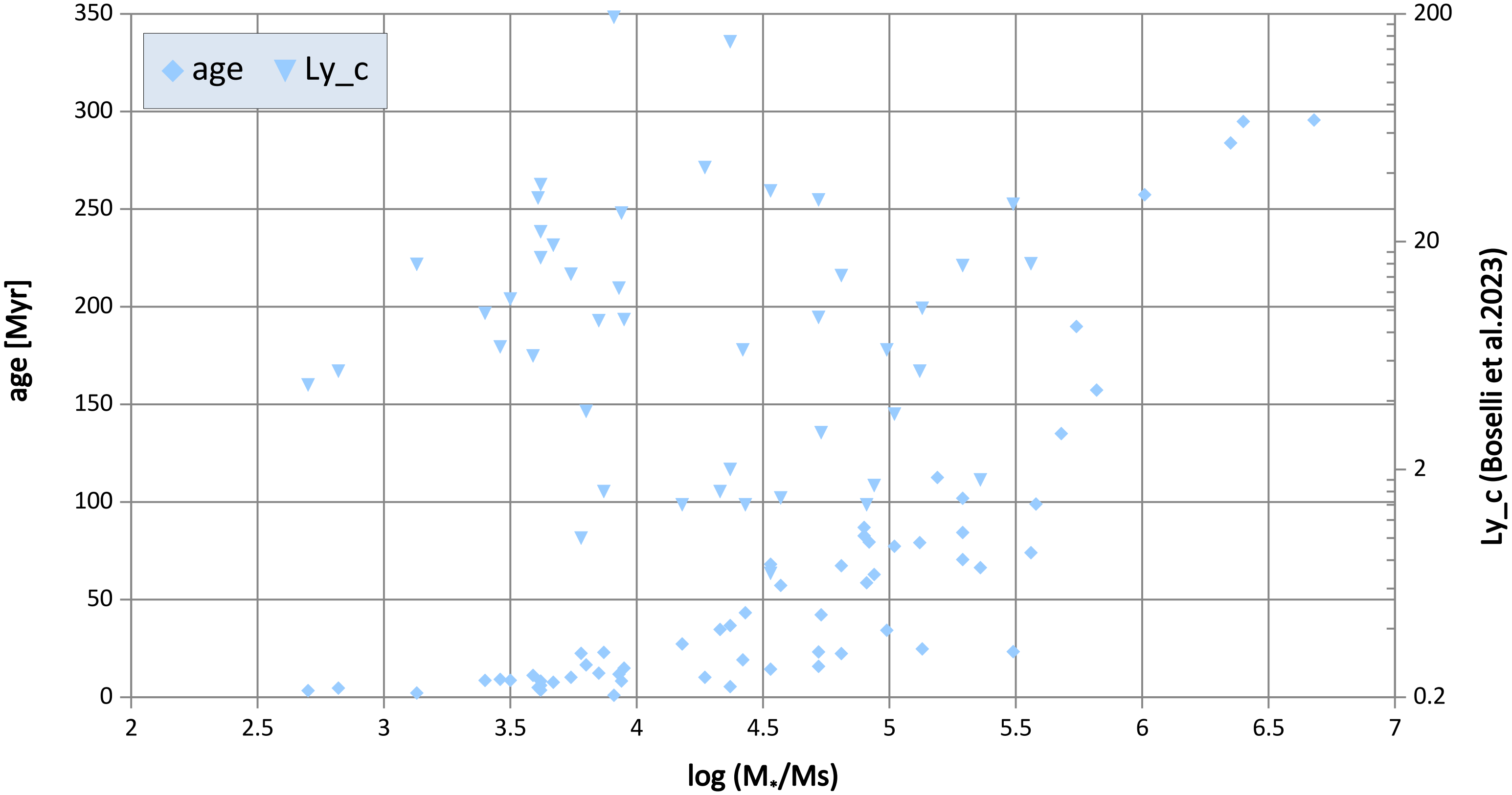
Mass vs. age and FUV vs. age



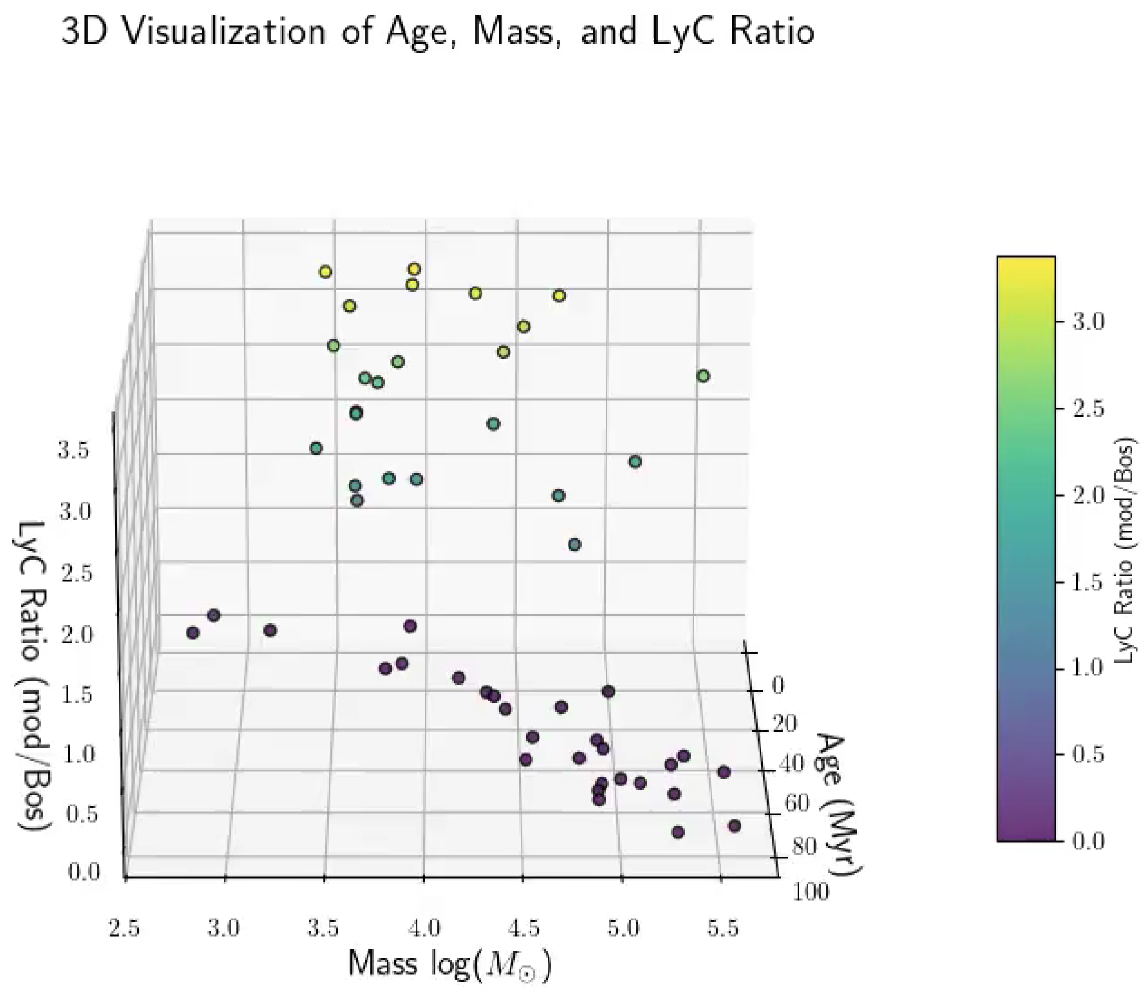
Obs. LyC flux vs. cluster age and
LyC model/measure vs. age



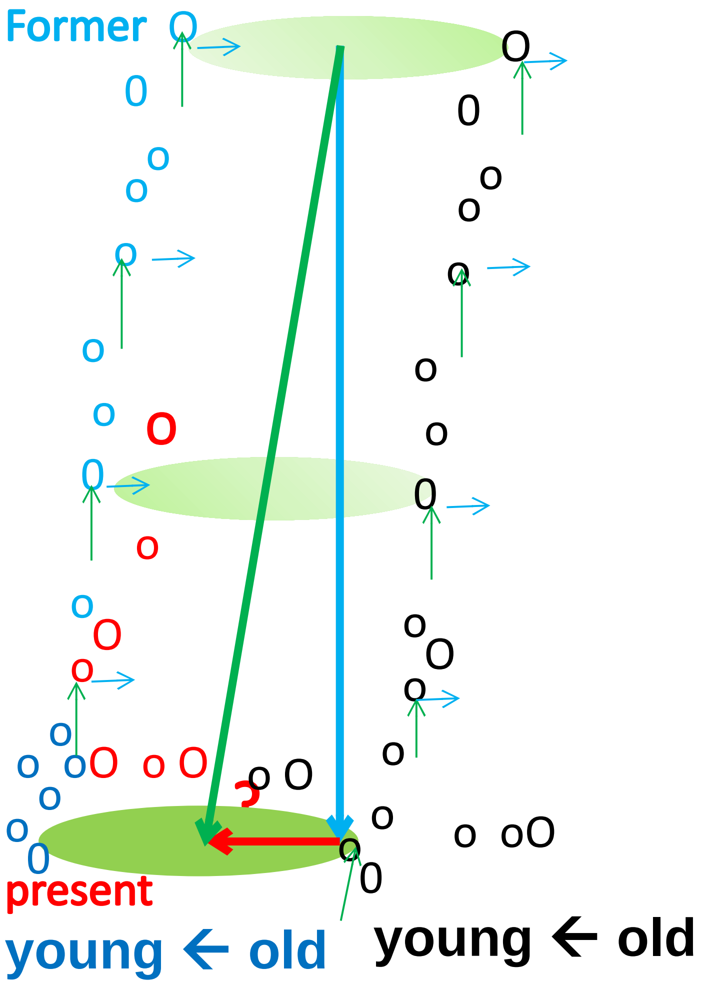
Result:
The Ly_C flux vanishes after ~<20 Myrs

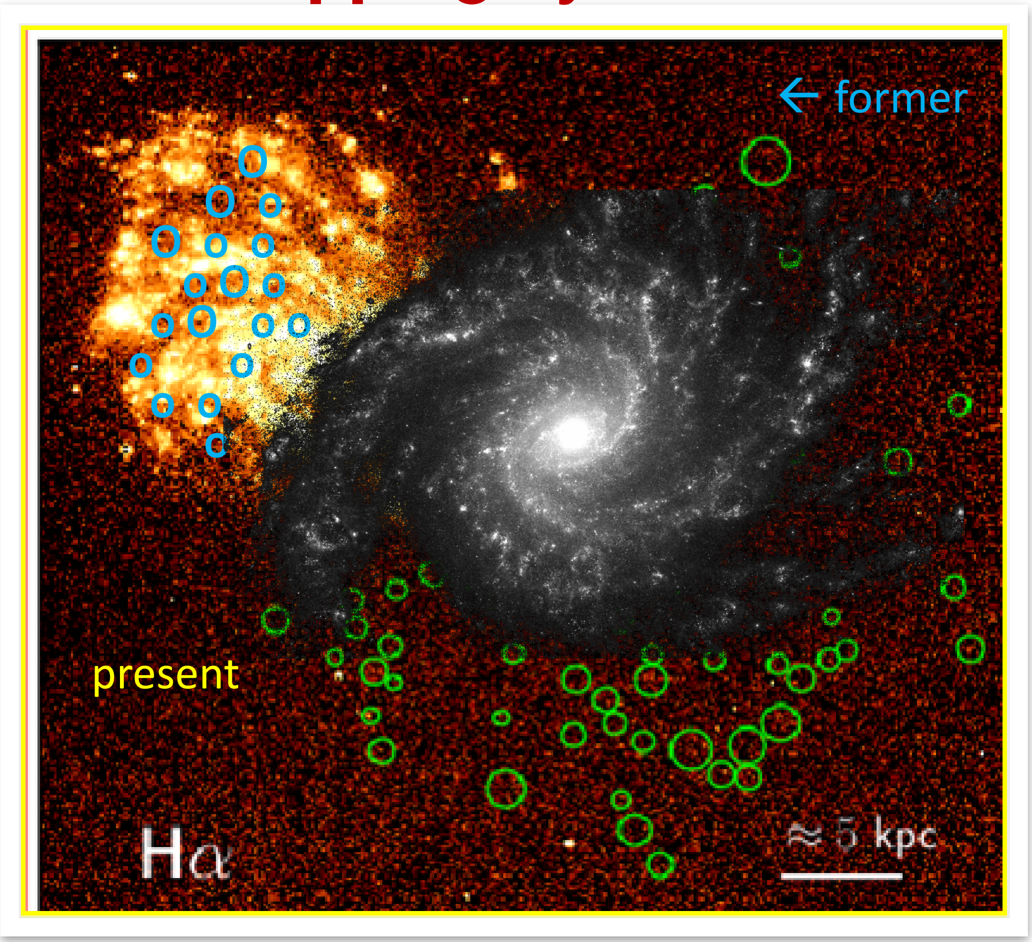


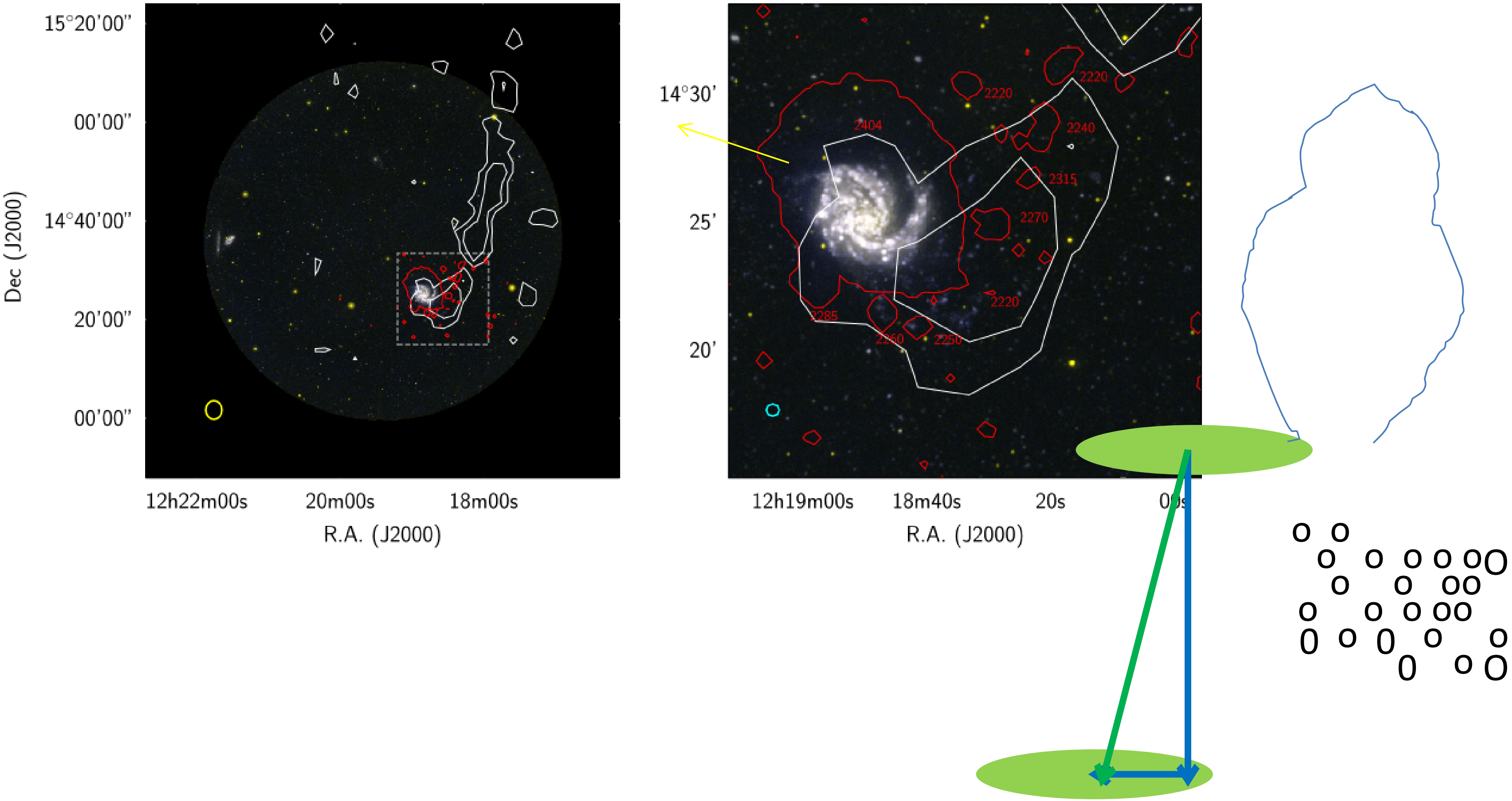
age
Ly_c
age [Myr]
Ly_c (Boselli et al.2023)
log (M*/Ms)
350
300
250
200
150
100
50
0
200
20
2
0.2
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7


3D Visualization of Age, Mass, and LyC Ratio
LyC Ratio (mod/Bos)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Mass log($M_\odot$)
2.5
3.0
3.5
4.0
4.5
5.0
5.5
Age (Myr)
0
20
40
60
80
100
LyC Ratio (mod/Bos)
0.0
0.5
1.0
1.5
2.0
2.5
3.0

The stripping dynamics






15°20'00"
00'00"
14°40'00"
20'00"
00'00"
Dec (J2000)
12h22m00s
20m00s
18m00s
R.A. (J2000)
14°30'
25'
20'
2404
2220
2220
2240
2315
2270
2220
2285
2260
2250
12h19m00s
18m40s
20s
R.A. (J2000)

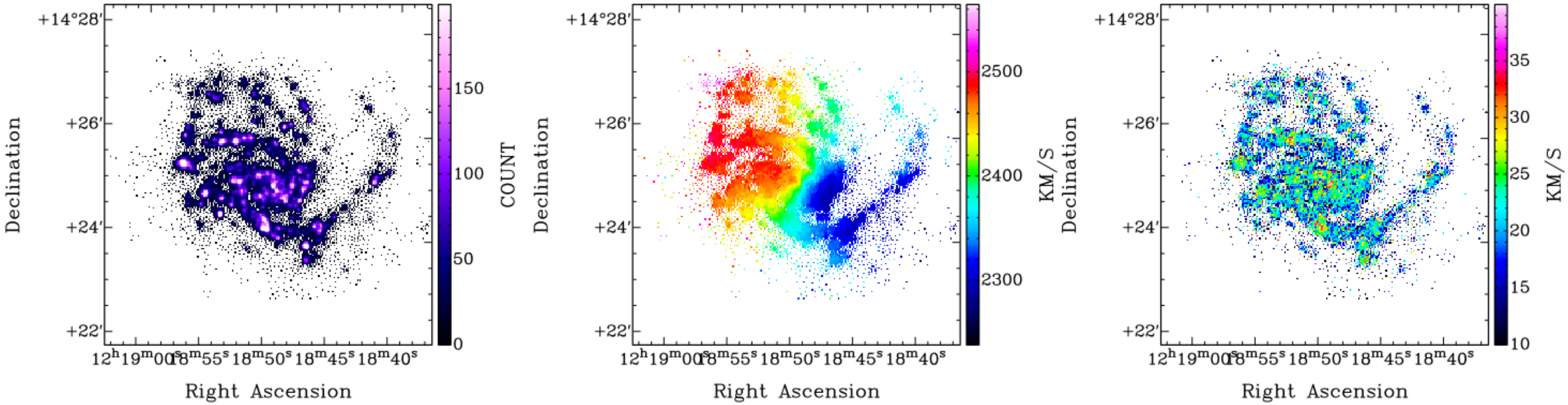
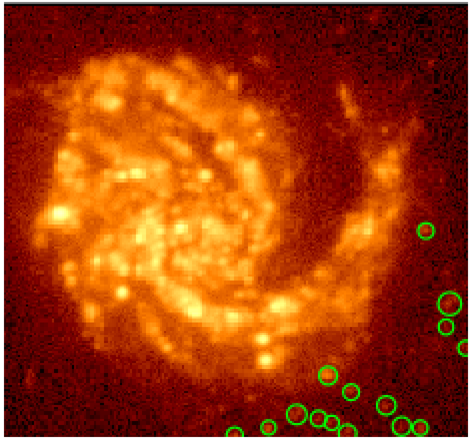
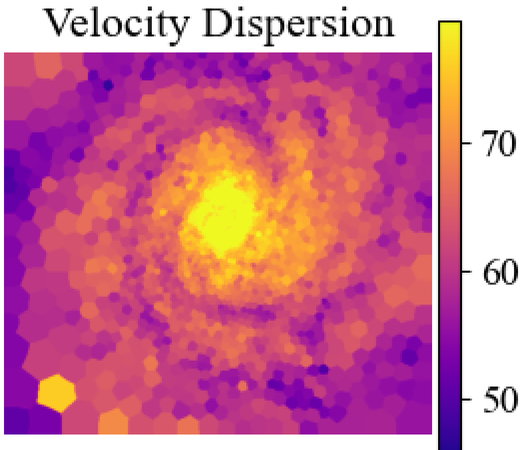
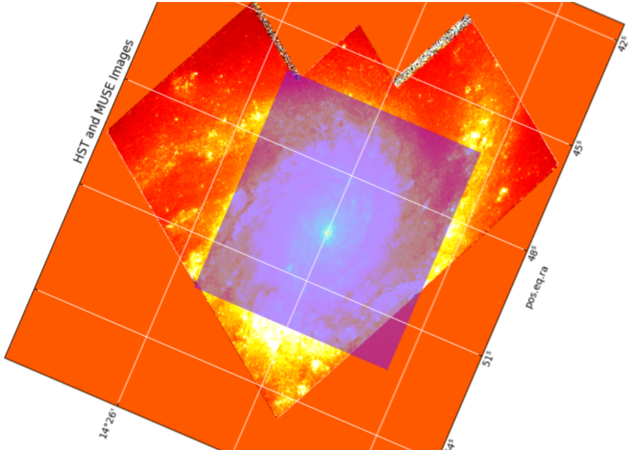
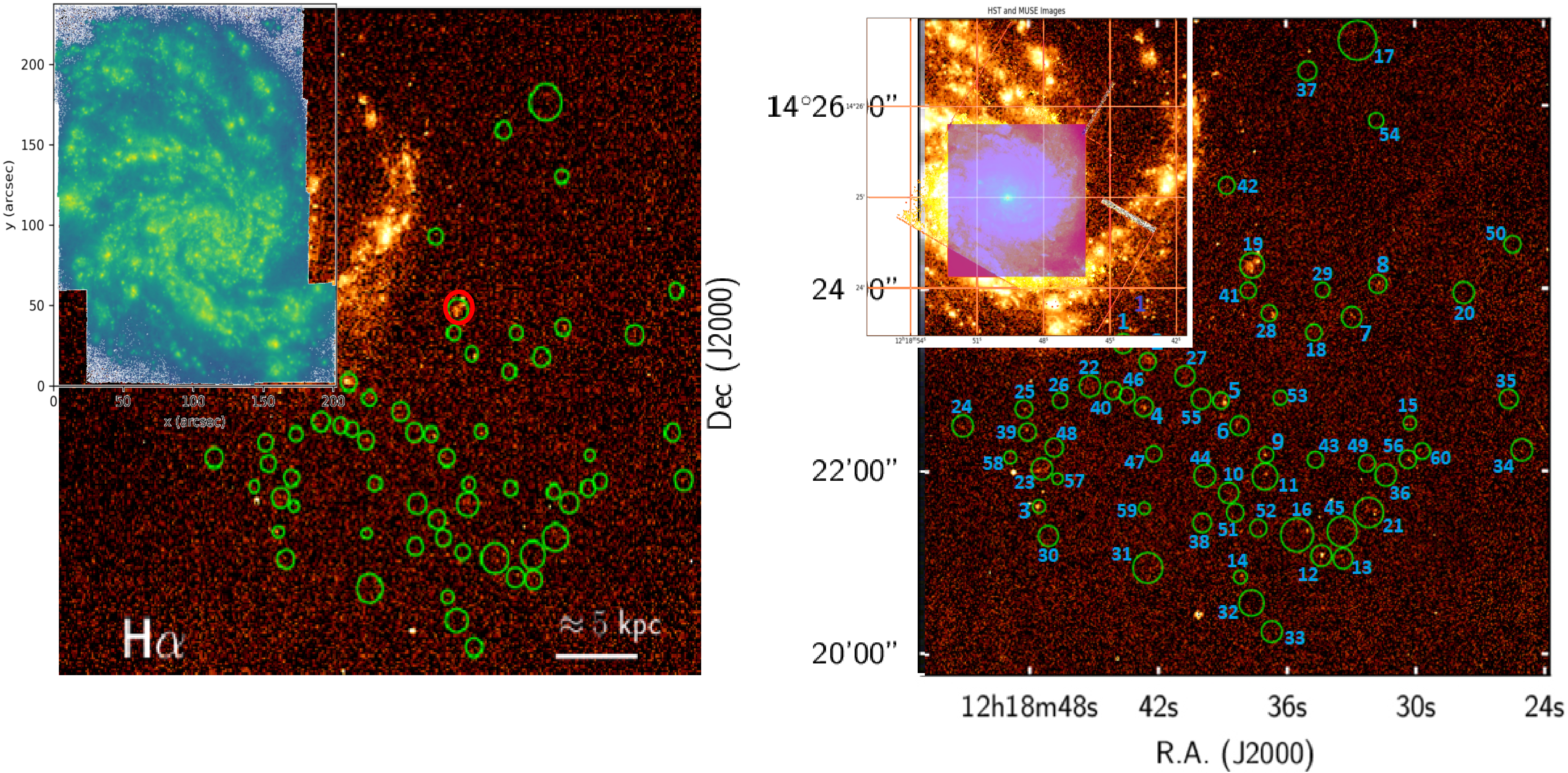


Fig. 2. Hα integrated emission, velocity field, and velocity dispersion map of M 99 (*from left to right*, respectively).



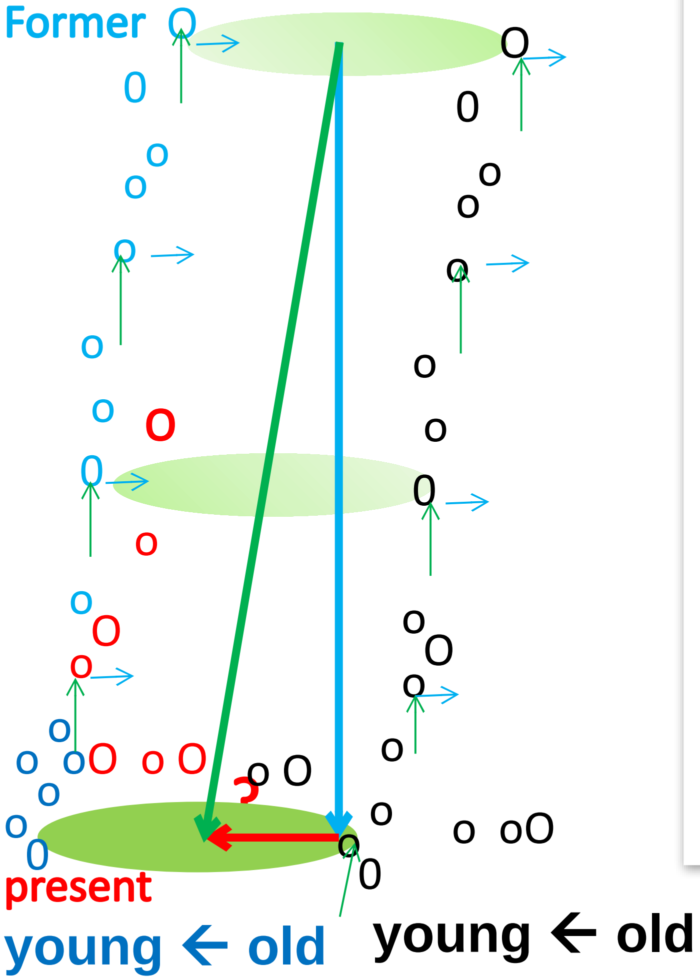


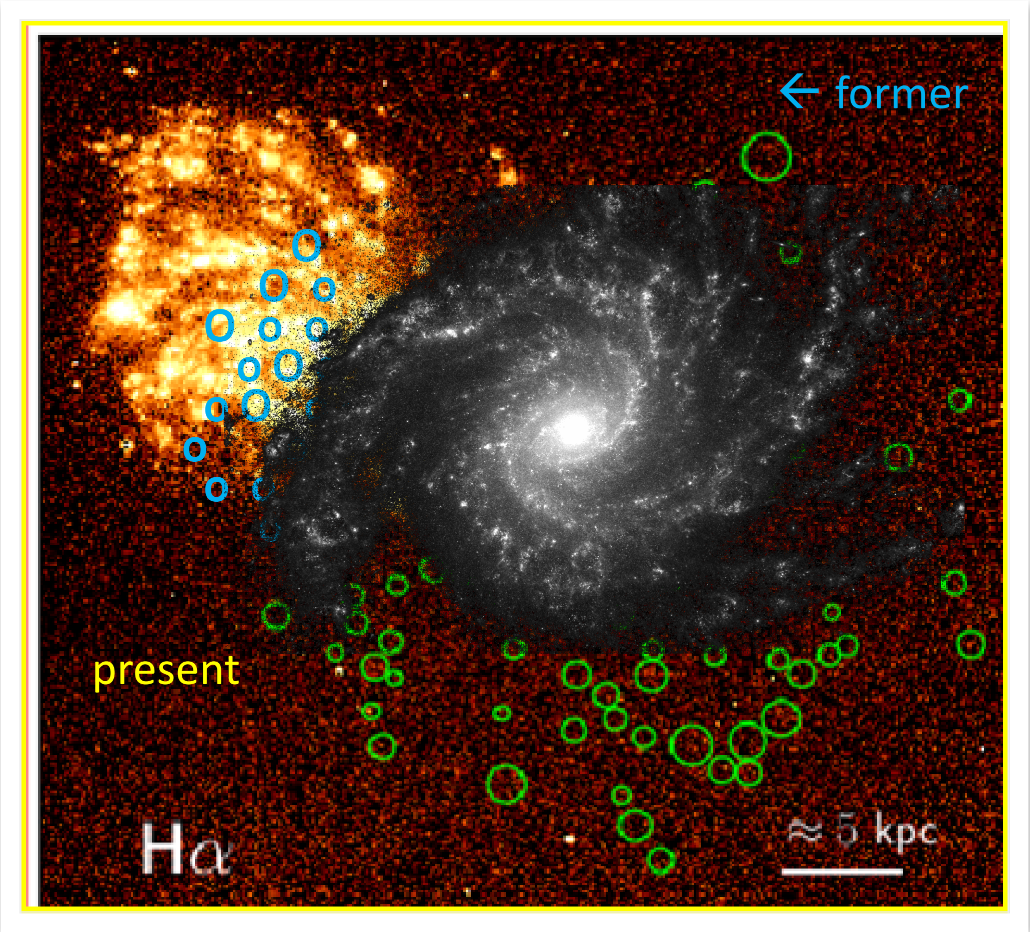




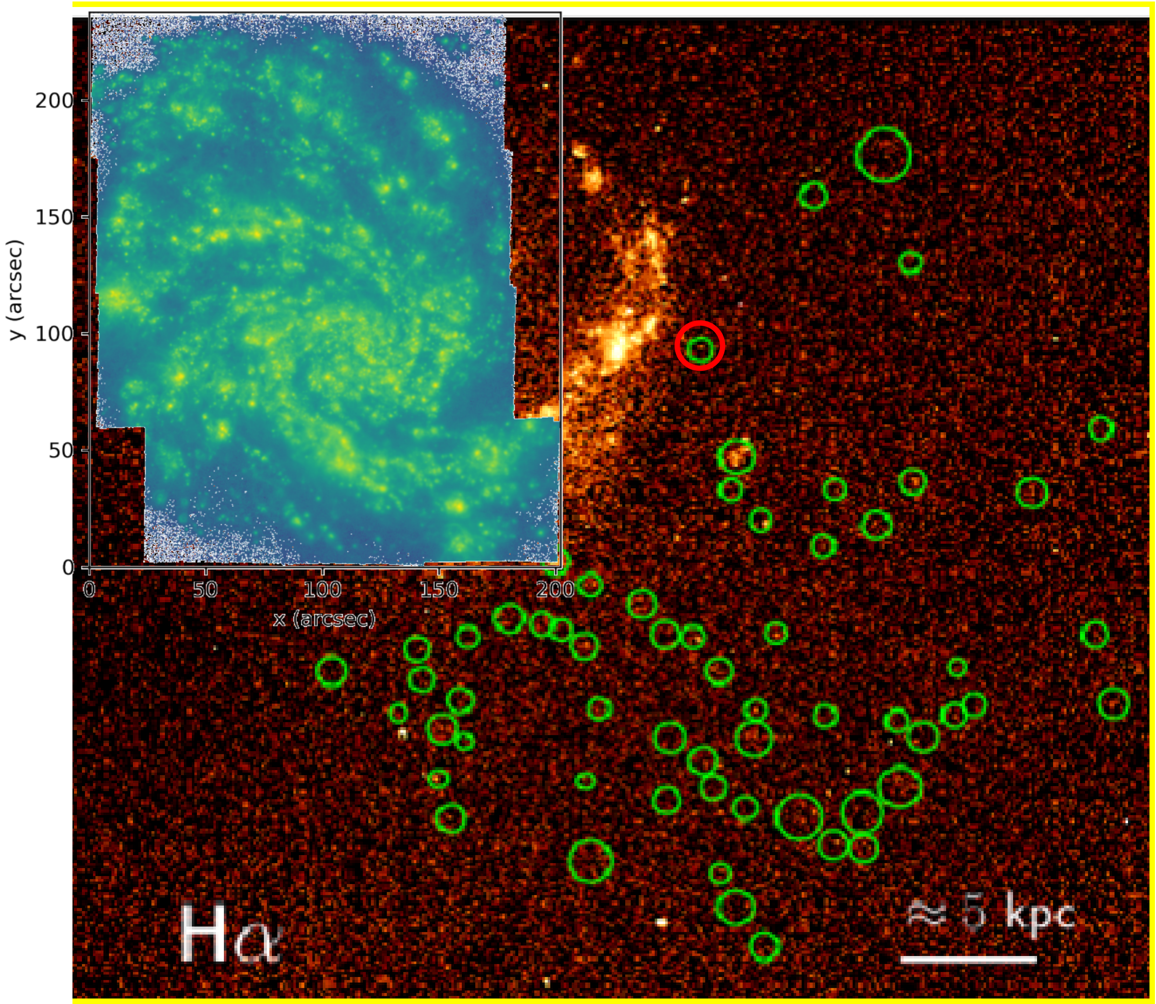
y (arcsec)
x (arcsec)
Hα
≈ 5 kpc
HST and MUSE Images
14°26'0''
24'0''
22'00''
20'00''
Dec (J2000)
12h18m48s
42s
36s
30s
24s
R.A. (J2000)

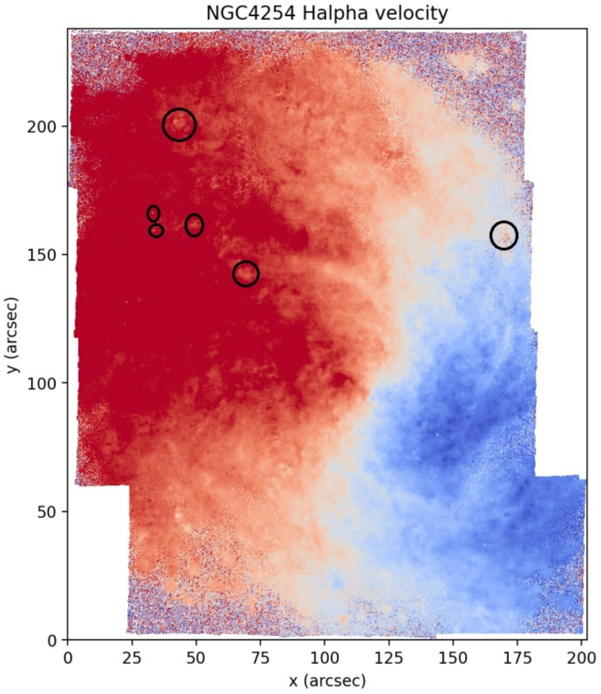
The stripping dynamics



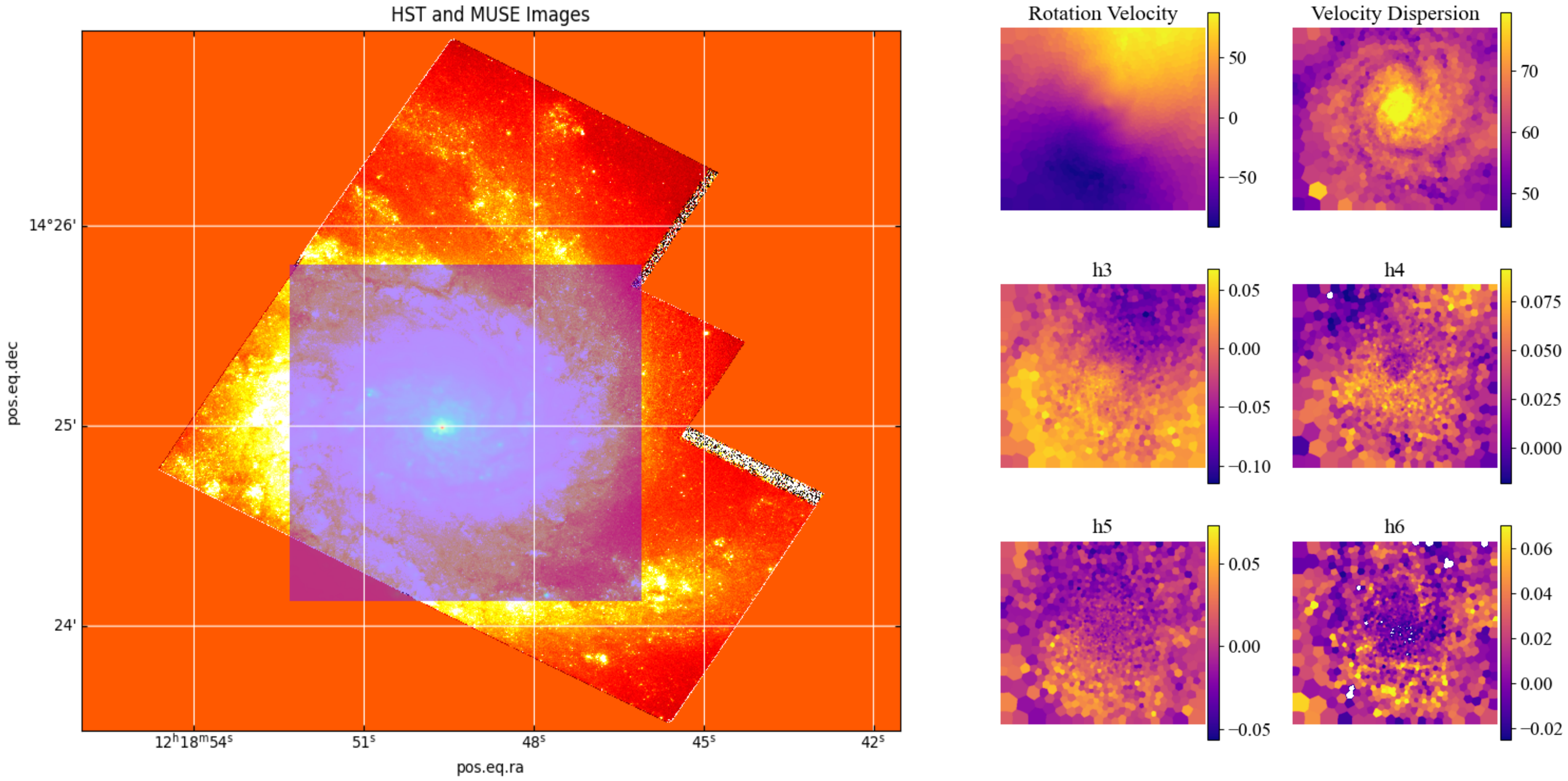


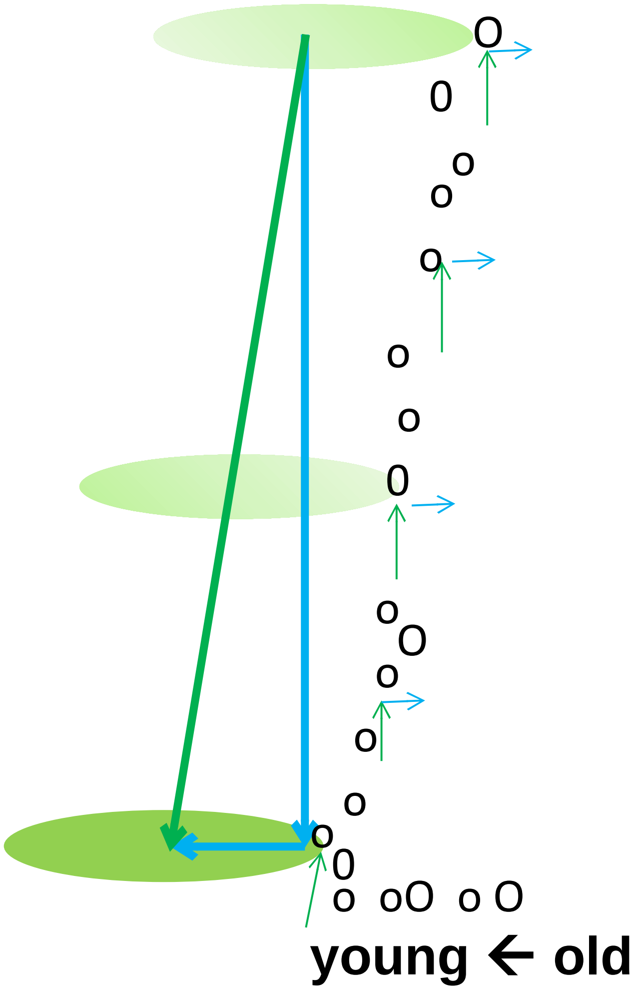
NGC 4254 - VESTIGE overlaid with MUSE/Phangs

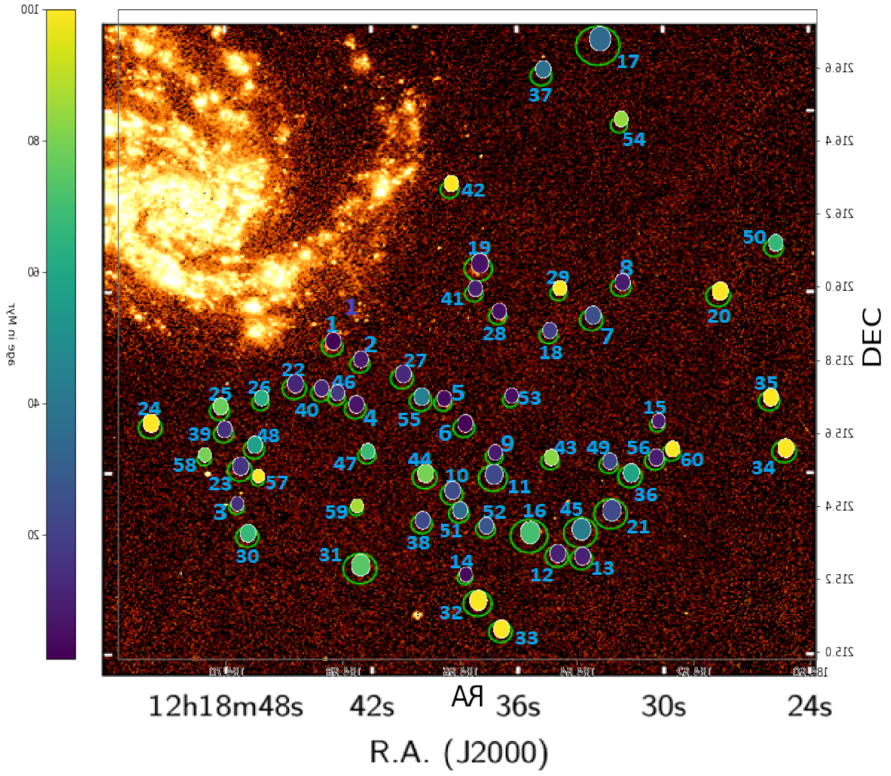




NGC4254 : Purelly stellar







no.	log M*/Ms	age/ Myrs	D (kpc)	v_E (km/s)
20	5,82	157,3	26,73	169,91
32	5,58	98,98	25,65	259,14
33	5,74	189,87	27,53	144,99
34	6,01	257,35	32,33	125,63
35	5,19	112,56	30,64	272,21

<u>Model approach</u>: The measured radial velocity is only one, but the dominant component. Now the aim is at deriving the azimuthal velocity component.

1. From the present-day cluster mass we derive the initial stellar cluster mass depending on the cluster age.
2. We assume, that 10% of the cloud mass are forming stars and derive the initial cloud mass.
3. With Virial equilibrium and a sound speed of $T=10^4$ K, the clouds size is calculated.
4. From cloud mass and size the free-fall time is derived.
5. The stripped gas clouds are accelerated as long as the stars are formed, i.e. times the free-fall time.
6. A) The cloud are accelerated during x ff times until the remaining cloud is pushed off.
   B) The cloud is dissolved when the ram pressure exceeds the binding energy
7. This

Assumptions:

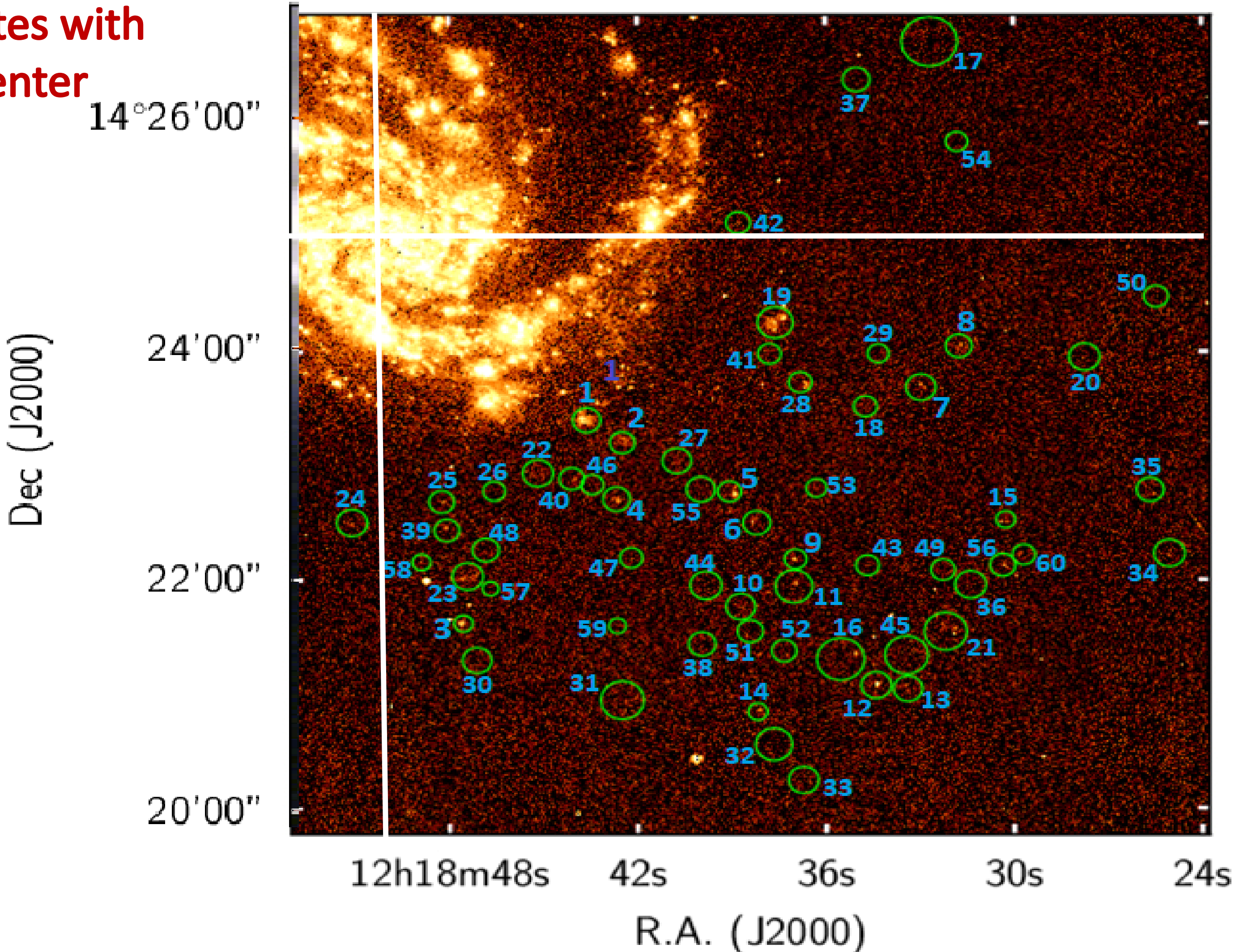
$M_*(t)=f(t)$
M_{*i}

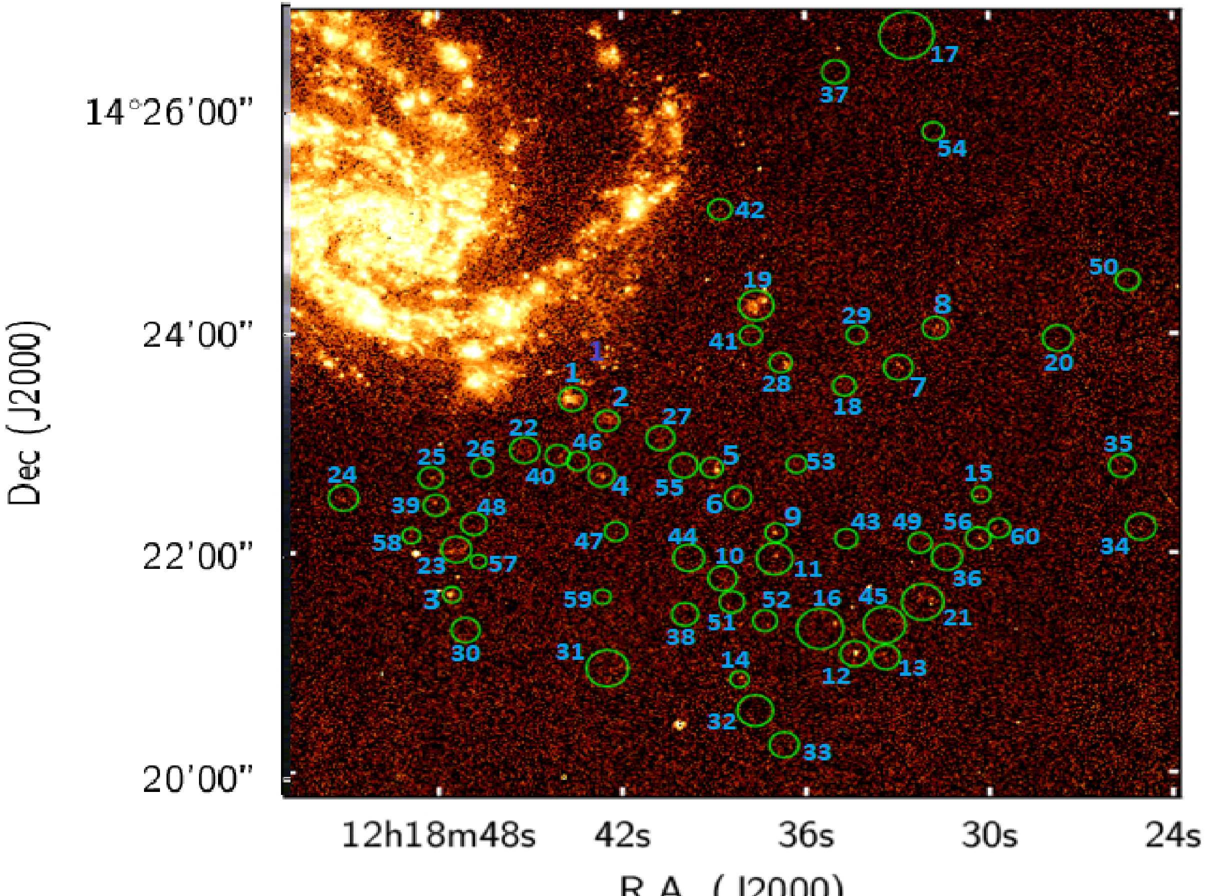
SFE = 0,1

$M_*=0.1\ M_{cl}$

							2T+V=0			SF(t) = 10 * t_{ff}
							$2T=M\ c_s^2$			$P_{ram} = r_{ICM}\ v^2_{rel}$
							$V=3/5\ GM^2/R;\ r\sim r^{-2}$	t_{ff}=sqrt(3p/(32G r)		$a = P_{ram}/S_{cl}$
no.	log $M_*(t)$/M	age/Myrs	log M_{*i}/M	$M_{i,cl}$/M	D (kpc)	$r_{cl} = M_{i,cl}/(4p/3\ R^3)$ [g/cm³]	$R_{cl}=3/5\ G\ M_{cl}/c_s^2$ [pc]	t_{ff}=66430/sqrt(r_{cl}) [s]	$S_{cl} = M_{cl}/2p\ R^2$ [M/pc²]	v_{rel} = sqrt[D S_{cl}/ (r_{ICM} 10t_{ff} (10t_{ff}+age)/2)] [km/s]
34	6,01	257,35	6,12E+00	1,33E+07	32,33	5,04E-24	3,50E+02	2,96E+16	1,73E+01	1,09E+01
33	5,74	189,87	5,84E+00	6,87E+06	27,53	1,89E-23	1,80E+02	1,53E+16	3,36E+01	2,71E+01
20	5,82	157,3	5,92E+00	8,26E+06	26,73	1,31E-23	2,17E+02	1,84E+16	2,79E+01	2,04E+01
32	5,58	98,98	5,66E+00	4,56E+06	25,65	4,28E-23	1,20E+02	1,02E+16	5,05E+01	4,85E+01
35	5,19	112,56	5,27E+00	1,86E+06	30,64	2,58E-22	4,88E+01	4,14E+15	1,24E+02	1,99E+02

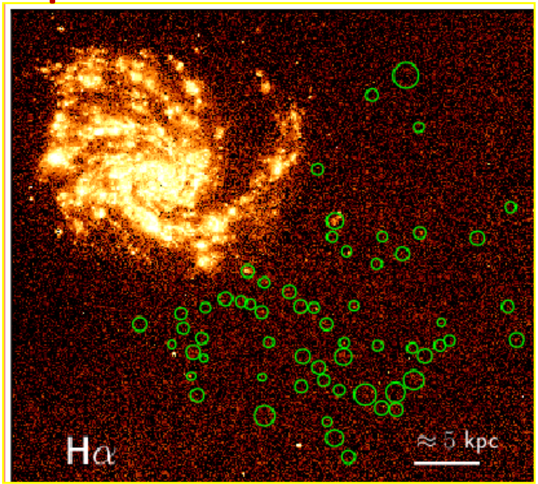
Separation of coordinates with respect to the galaxy center

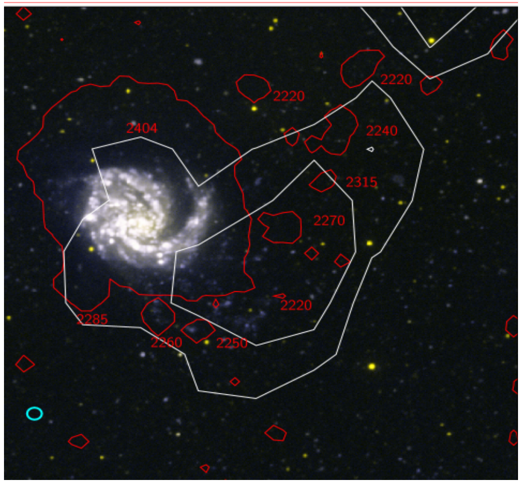


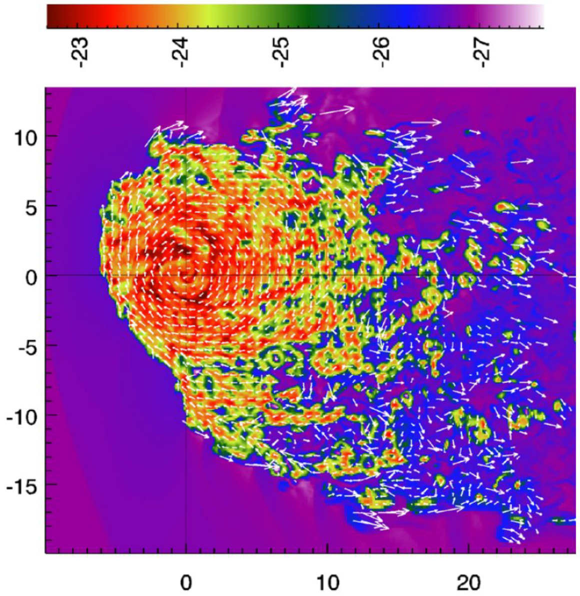


Region	log (M* /Ms)	log (SFR [Ms/yr])	age/ Myrs	diam./ pc	D_radial (kpc)	D_ra (kpc) N-S	D_dec (kpc)W-E	Boselli+
1	3,91	-2,09	1,02	–	10,49	7,21	7,62	193,3
2	3,94	-3,23	8,31	–	12,12	8,58	8,57	26,7
3	4,53	-3,3	14,36	483	16,35	2,49	16,16	33,4
4	3,62	-3,28	6,07	508,7	13,76	8,35	10,94	22,1
5	3,62	-2,79	3,63	327,1	16,54	12,68	10,62	35,6
6	3,13	-3,06	2,16	129,9	18,18	13,71	11,94	15,9
7	5,13	-3,95	24,74	171,1	20,95	20,00	6,25	10,2
8	3,62	-3,49	8,28	934,1	21,93	21,46	4,51	17
9	3,67	-3,38	7,67	75,8	20,30	15,19	13,47	19,3
10	4,72	-3,93	23,18	–	20,26	13,09	15,47	9,3
11	4,81	-3,8	22,36	239,6	21,04	15,13	14,62	14,2
12	4,27	-3,12	10,19	295,2	26,20	18,27	18,78	42,3
13	3,74	-3,6	10,22	–	27,17	19,49	18,93	14,4
14	2,7	-3,69	3,39	–	24,17	13,74	19,89	4,7
15	3,4	-3,77	8,63	–	26,07	23,24	11,81	9,7
16	5,29	-4,51	70,54	–	24,47	16,91	17,68	15,7
17	4,99	-4,43	34,3	–	21,98	20,35	-8,29	6,7
18	4,42	-4,03	19,13	–	19,22	17,88	7,05	6,7
19	4,37	-2,33	5,42	–	14,85	14,43	3,52	151
20	5,82	–	157,3		26,73	26,26	4,98	-
21	5,49	-3,43	23,36	–	26,66	20,93	16,51	29,2
22	3,93	-3,66	11,78	–	11,21	5,35	9,85	12,5
23	4,72	-3,33	15,81	–	14,43	2,65	14,19	30,5
24	5,29	-5,71	101,9	460,9	12,06	-1,76	11,93	-
25	5,02	-5,29	77,34	302,6	11,18	1,66	11,05	3,5
26	4,94	-5,47	62,88	–	11,22	3,67	10,60	1,7
27	3,85	-3,82	12,33	–	14,17	10,66	9,33	9
28	3,61	-3,09	4,97	–	16,53	15,39	6,04	31,1
29	5,68	–	135,04		19,00	18,37	4,82	-
30	4,81	–	67,38		17,97	3,01	17,72	-
31	5,56	-4,55	74,04	–	21,20	8,56	19,40	16
32	5,58	–	98,98		25,65	14,36	21,25	-
33	5,74	–	189,87		27,53	15,49	22,76	-
34	6,01	–	257,35		32,33	29,49	13,24	-
35	5,19	–	112,56		30,64	28,76	10,56	-
36	4,91	-5,88	58,65	–	26,28	21,89	14,55	1,4
37	4,37	-5,02	36,71	–	18,78	17,55	-6,69	2
38	3,87	-4,73	22,98	–	20,62	11,62	17,04	1,6
39	3,95	-3,75	14,9	96,1	12,39	1,86	12,25	9,1
40	3,59	-3,95	11,2	–	12,07	6,64	10,08	6,3
41	3,46	-3,87	9,16	–	15,01	14,21	4,83	6,9
42	6,68	–	295,63		13,04	13,02	-0,68	
43	4,9	–	82,68		22,60	17,95	13,73	
44	4,92	–	79,51		18,73	11,76	14,57	
45	4,73	-4,91	42,22	–	26,16	19,44	17,51	2,9
46	3,8	-4,26	16,58	–	12,72	7,43	10,33	3,6
47	4,53	-6	68,15	–	16,10	8,91	13,41	0,7
48	4,57	-5,42	57,26	–	13,49	3,34	13,07	1,5
49	3,78	-4,85	22,48	–	25,06	20,83	13,92	1
50	5,36	-5,92	66,41	–	29,10	29,00	2,44	1,8
51	4,33	-5,21	34,7	–	21,29	13,45	16,50	1,6
52	4,18	-4,88	27,28	–	22,75	14,75	17,32	1,4
53	2,82	-3,74	4,68	77	19,12	16,00	10,48	5,4
54	5,29	–	84,37		21,78	21,39	-4,08	-
55	4,43	-5,27	43,25	–	15,65	11,57	10,53	1,4
56	3,5	-3,65	8,65	281,6	26,89	23,12	13,73	11,2
57	6,35	–	283,92		15,12	3,53	14,70	-
58	5,12	-4,4	79,2	–	13,62	0,89	13,59	5,4
59	4,9	–	86,99		18,30	8,38	16,27	
60	6,4	–	294,89		27,37	23,93	13,29	-

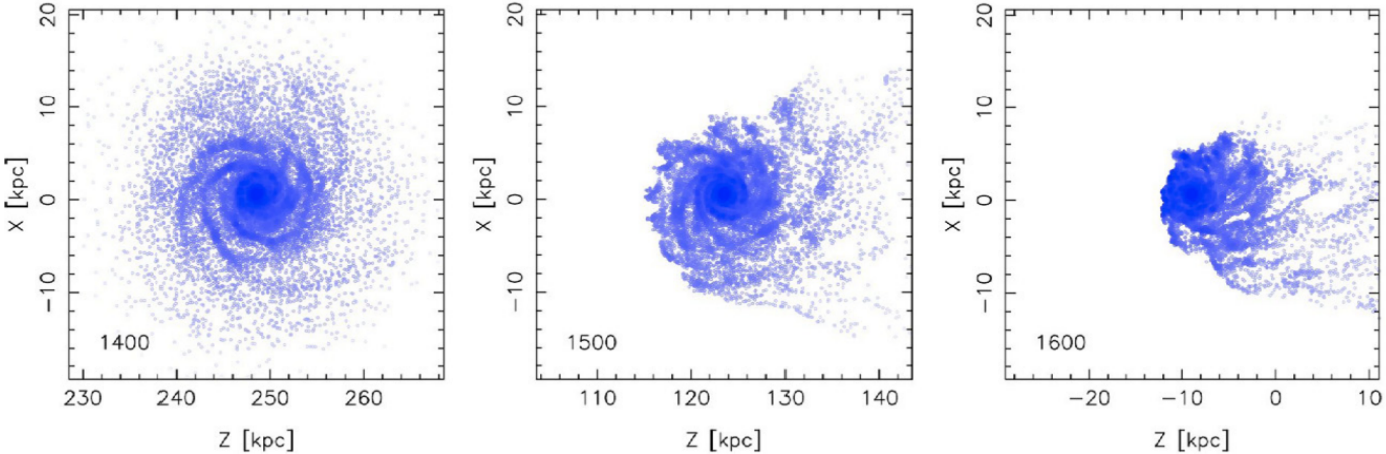
Ram-pressure direction from simulations

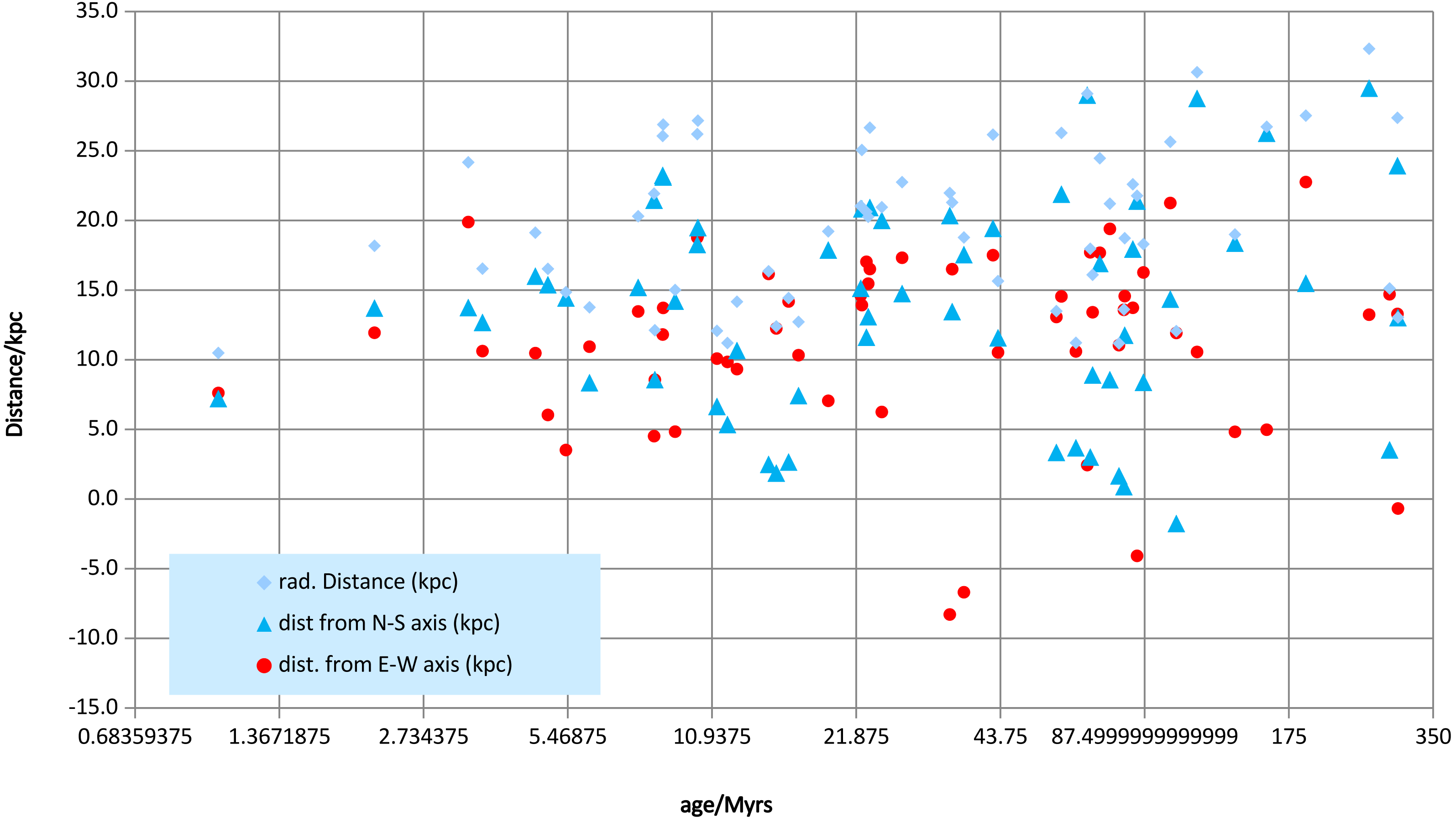




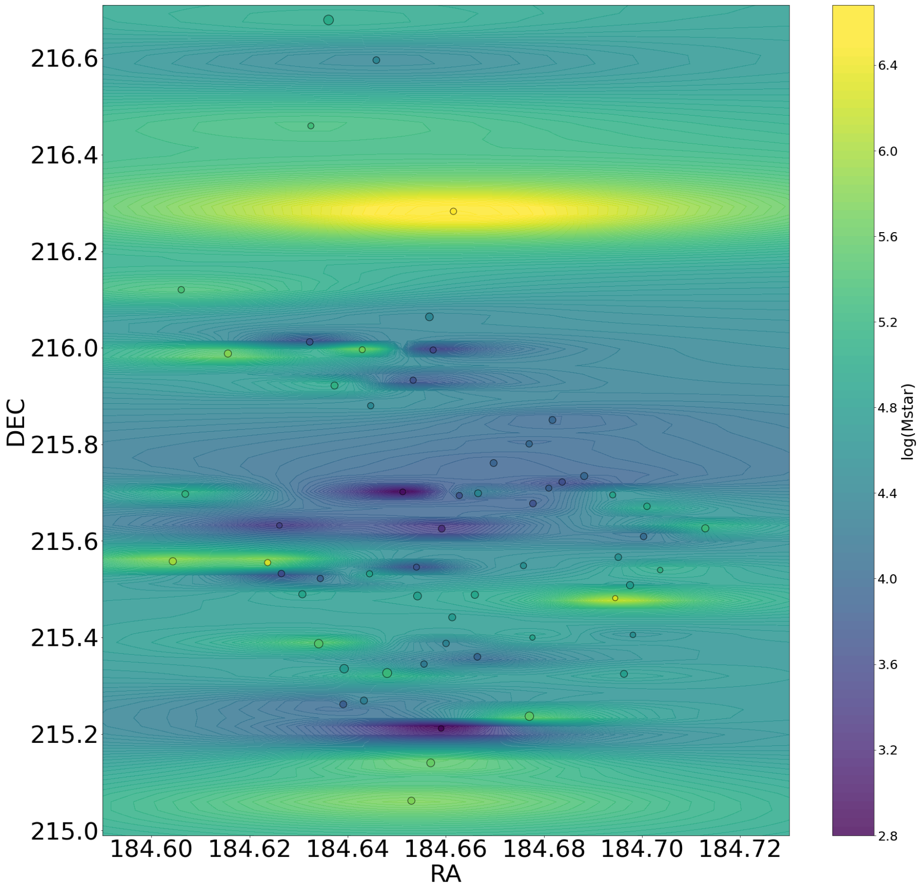


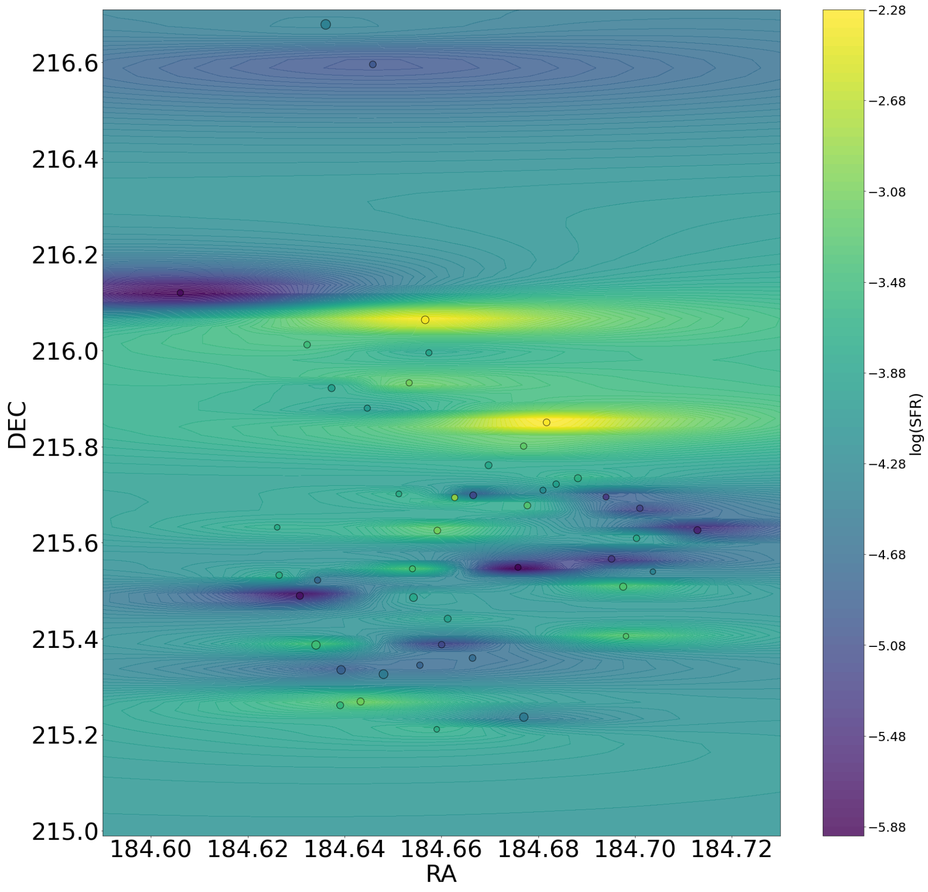
tangential on-stream →



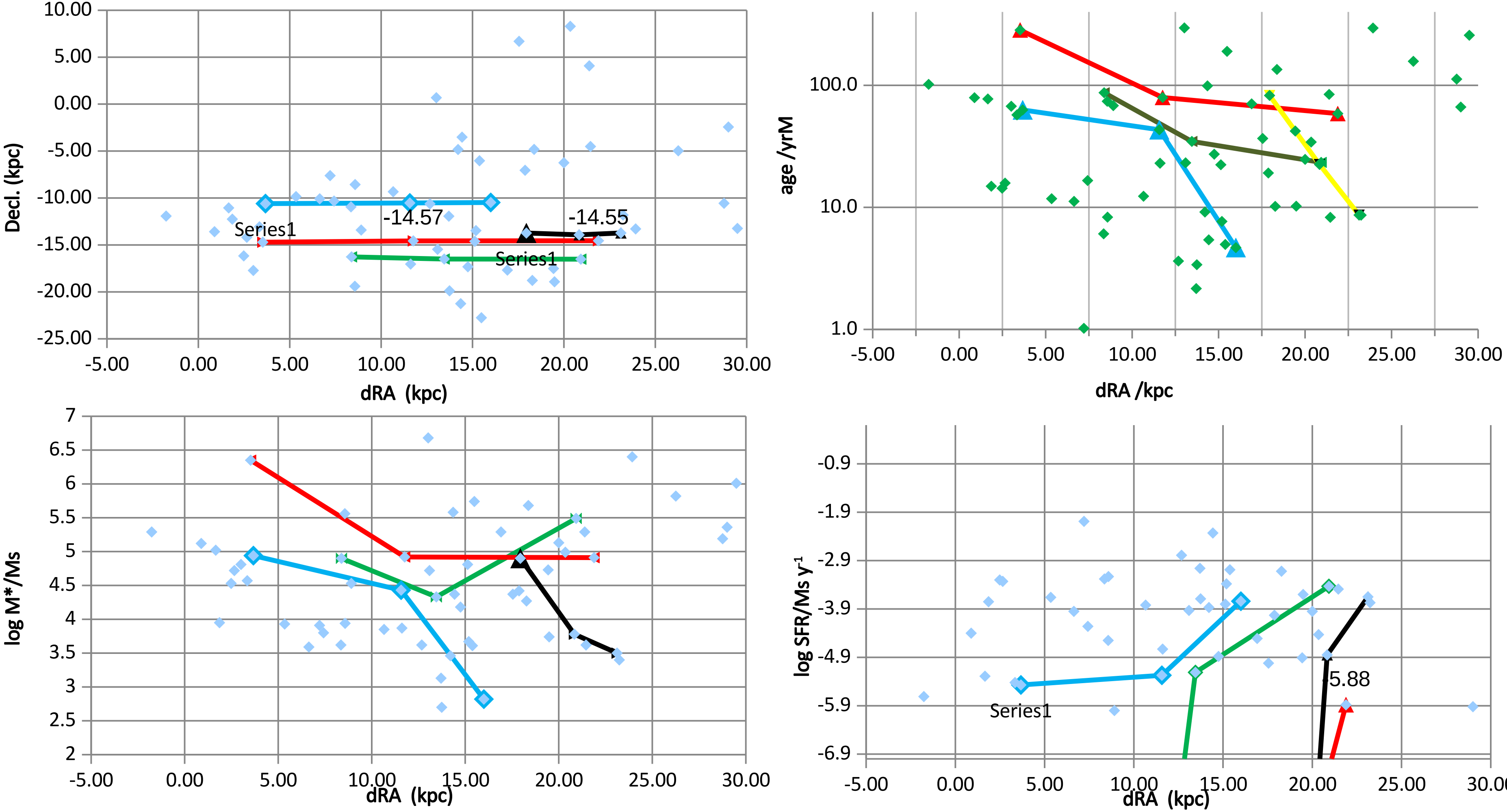

Distance/kpc
35.0
30.0
25.0
20.0
15.0
10.0
5.0
0.0
-5.0
-10.0
-15.0
0.68359375
1.3671875
2.734375
5.46875
10.9375
21.875
43.75
87.4999999999999
175
350
age/Myrs
rad. Distance (kpc)
dist from N-S axis (kpc)
dist. from E-W axis (kpc)

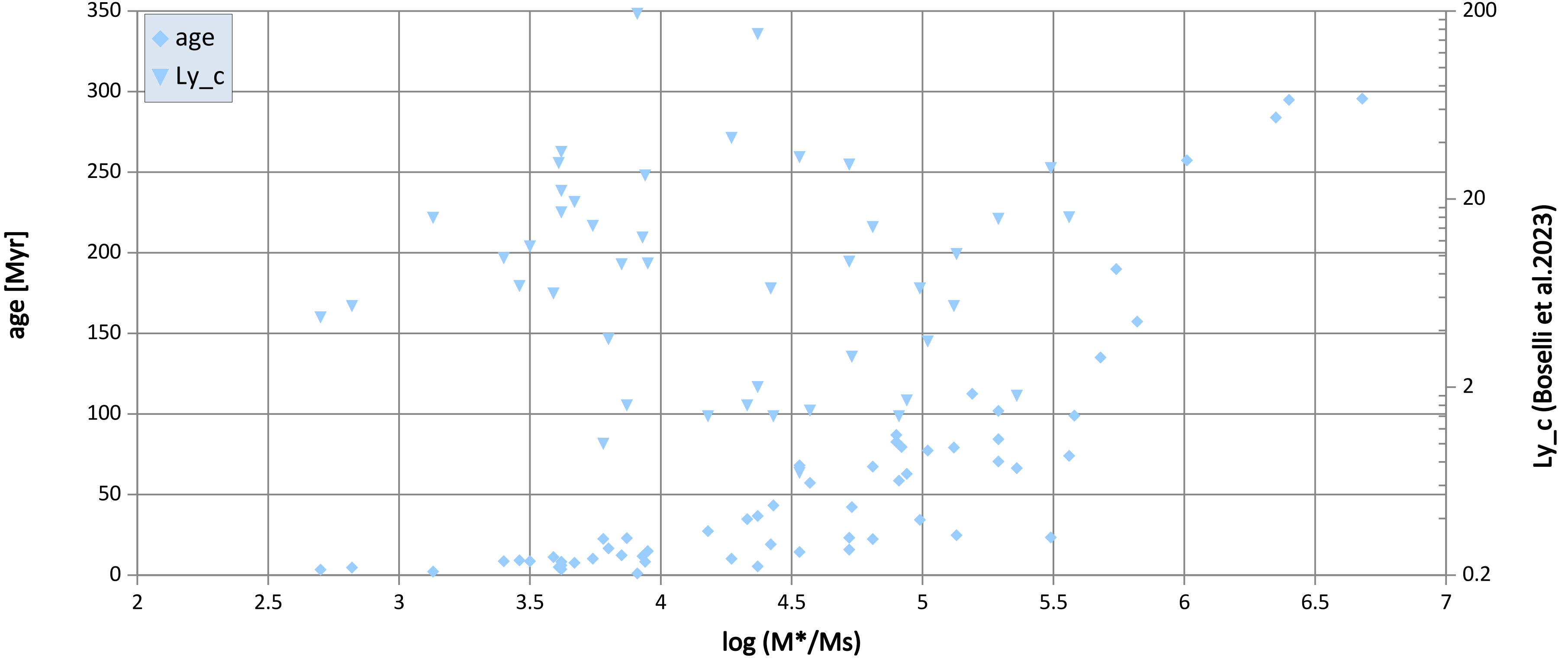
Probability distributions



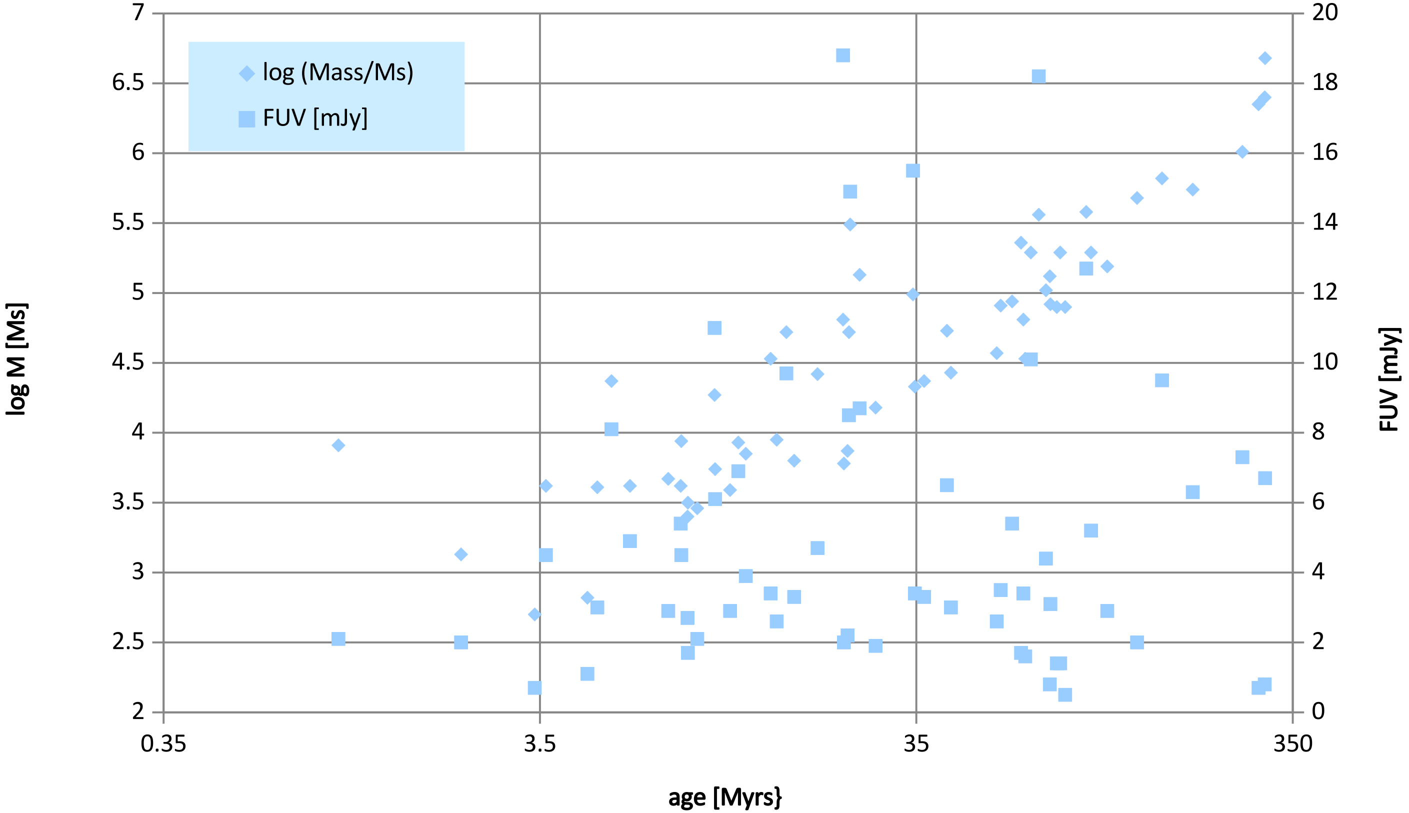


possible RPS stream with subsequent SF in E-W direction

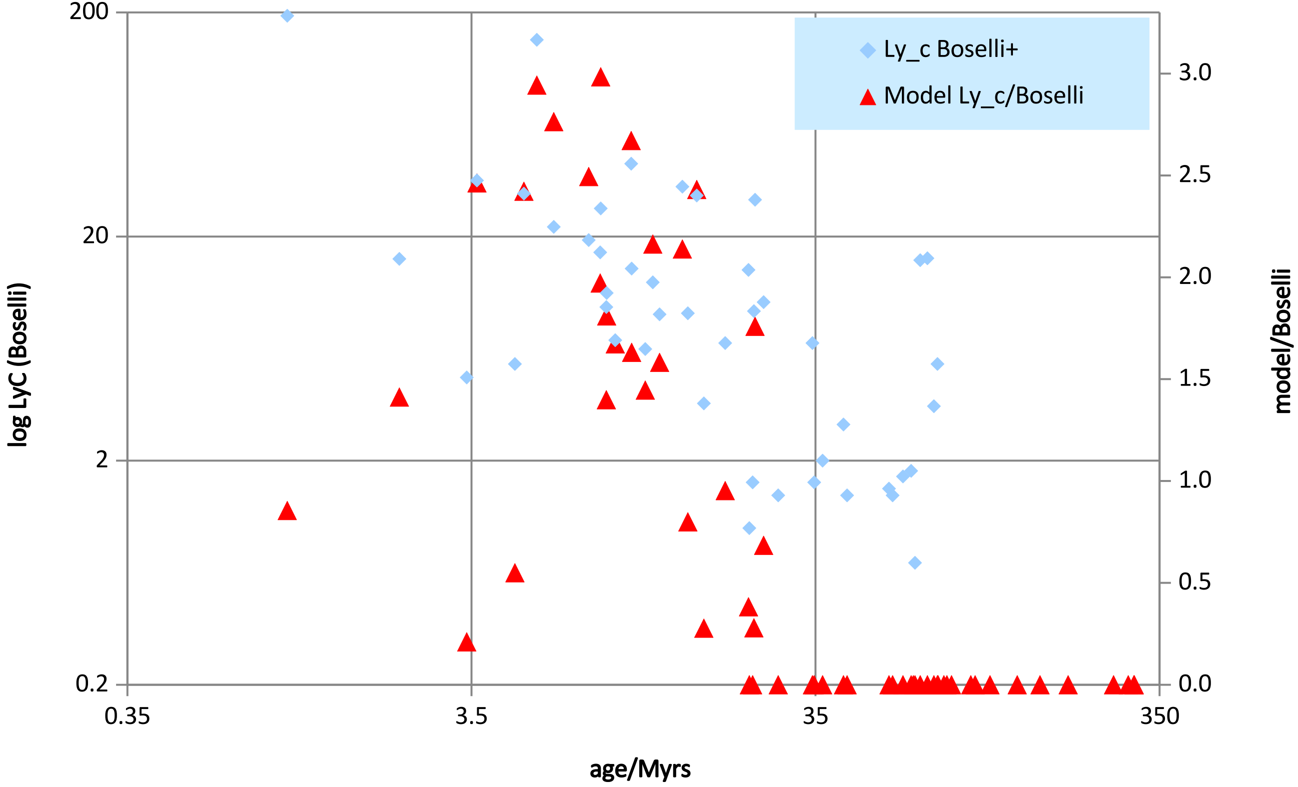




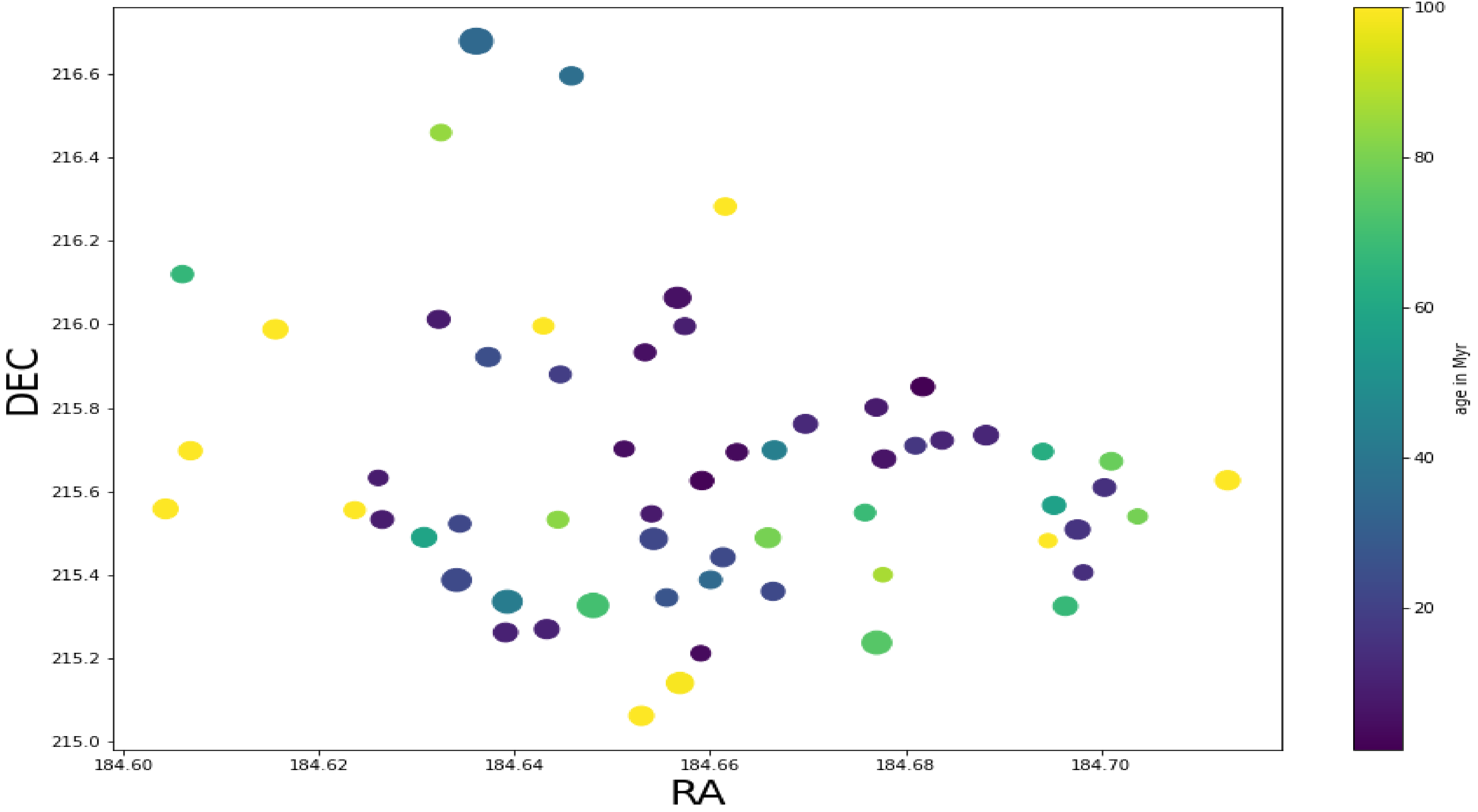
age
Ly_c
age [Myr]
350
300
250
200
150
100
50
0
2
2.5
3
3.5
4
4.5
5
5.5
6
6.5
7
log (M*/Ms)
200
20
2
0.2
Ly_c (Boselli et al.2023)



log (Mass/Ms)
FUV [mJy]
log M [Ms]
FUV [mJy]
age [Myrs}
7
6.5
6
5.5
5
4.5
4
3.5
3
2.5
2
20
18
16
14
12
10
8
6
4
2
0
0.35
3.5
35
350



Ly_c Boselli+
Model Ly_c/Boselli
200
20
2
0.2
log LyC (Boselli)
3.0
2.5
2.0
1.5
1.0
0.5
0.0
model/Boselli
0.35
3.5
35
350
age/Myrs



216.6
216.4
216.2
216.0
215.8
215.6
215.4
215.2
215.0
DEC
184.60
184.62
184.64
184.66
184.68
184.70
RA
100
80
60
40
20
age in Myr