Tow ionised bubbles in the BDF, at z~7

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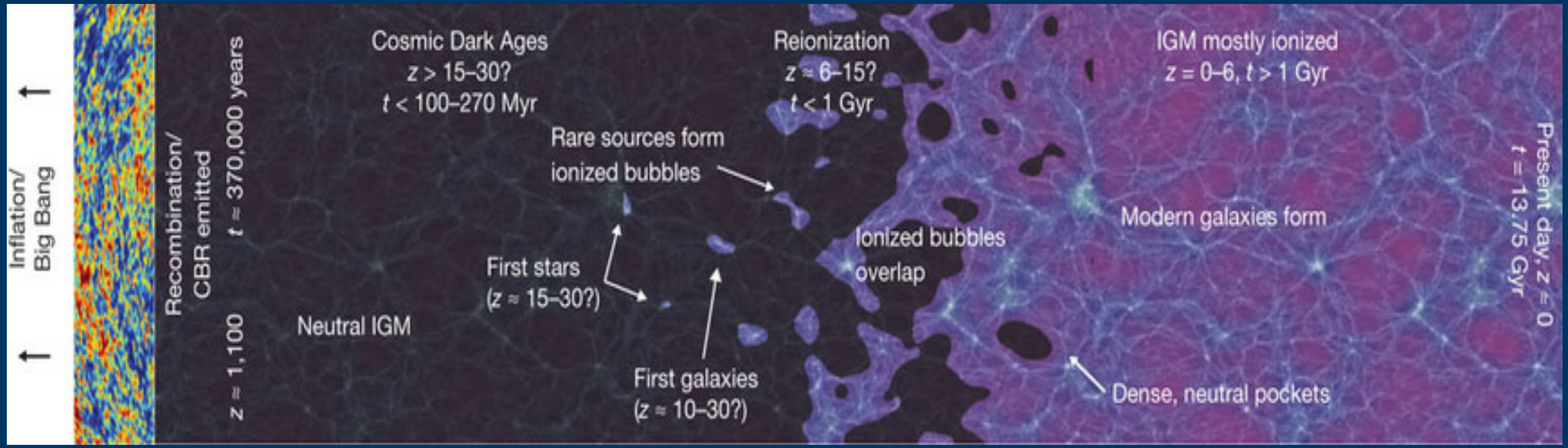
Reionisation of the Universe



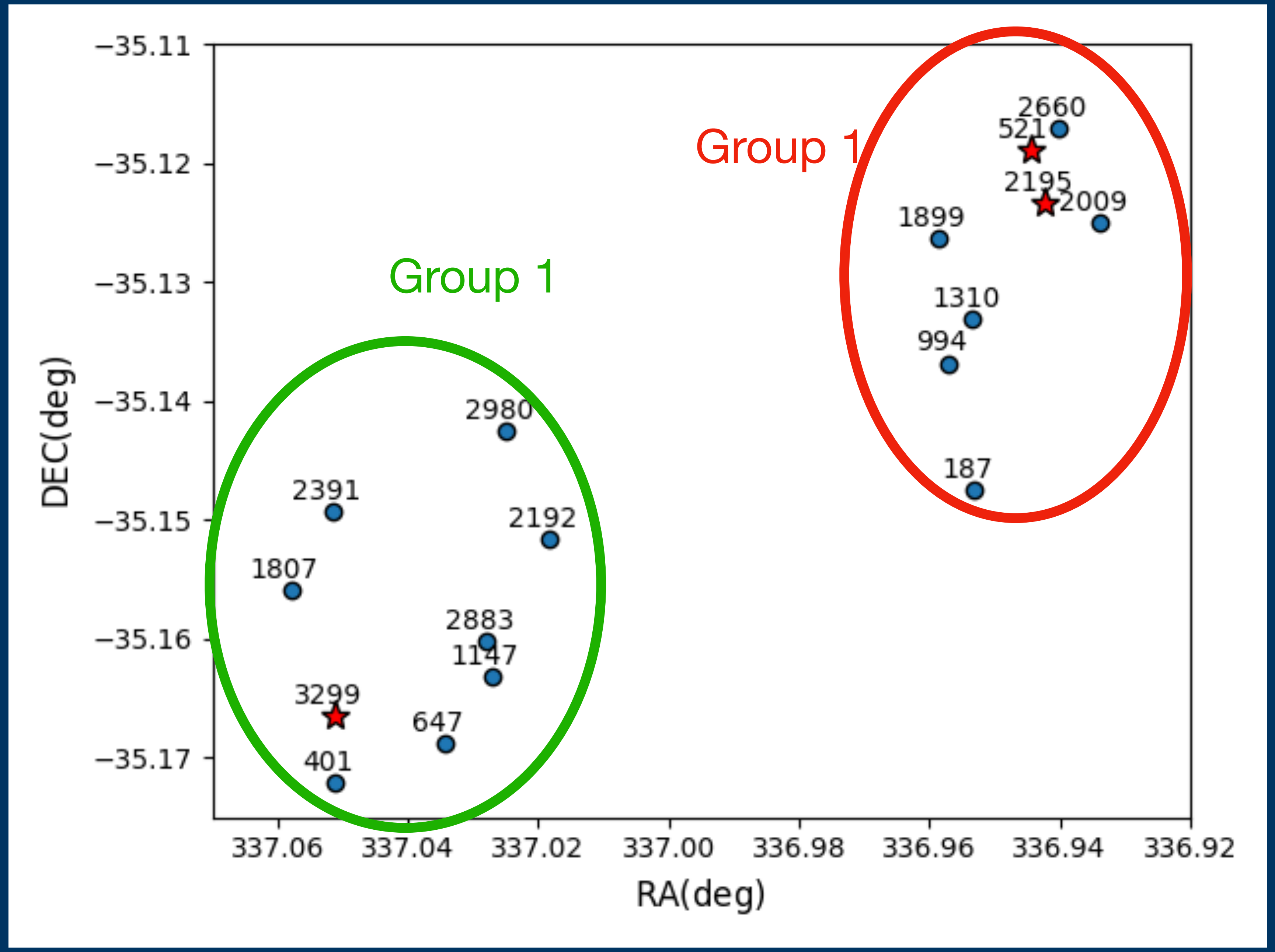
Reionisation occurred through ionised bubbles that merge into each other, thus getting bigger, and finally completing the reionisation by z ~ 6

The Bremer Deep Field

- Vanzella et al (2011) & Castellano et al. (2018) discovered three Lyα emitters in the BDF

- The pointings were guided by the three LAEs discovered by Vanzella (2011)

- They also discovered 14 LBG



What they did not do

- Consider the LBGs
- Consider any low luminosity sources
- So we did considered all these sources, namely:
  - The three LAEs discovered by Vanzella
  - The LBGs they discovered
  - Plus the Low Luminosity sources

THE ASTROPHYSICAL JOURNAL, 803:34 (49pp), 2015 April 10 BOUWENS ET AL.

Table A1
Observed Surface Densities of $z \sim 4$, $z \sim 5$, $z \sim 6$, $z \sim 7$, $z \sim 8$, and $z \sim 10$ Galaxy Candidates from All Fields[a]

Magnitude	Surface Density[c] (arcmin^{-2})	Magnitude	Surface Density[c] (arcmin^{-2})	Magnitude	Surface Density[c] (arcmin^{-2})
$z \sim 4$		$z \sim 6$		$z \sim 8$	
$22.50 < i_{775} < 23.00$	< 0.0039[b]	$22.40 < Y_{105} < 22.90$	< 0.0015[b]	$22.50 < H_{160} < 23.00$	< 0.0015[b]
$23.00 < i_{775} < 23.50$	0.0106 ± 0.0061	$22.90 < Y_{105} < 23.40$	< 0.0015[b]	$23.00 < H_{160} < 23.50$	< 0.0015[b]
$23.50 < i_{775} < 24.00$	0.0354 ± 0.0112	$23.40 < Y_{105} < 23.90$	< 0.0015[b]	$23.50 < H_{160} < 24.00$	< 0.0015[b]
$24.00 < i_{775} < 24.50$	0.2376 ± 0.0290	$23.90 < Y_{105} < 24.40$	0.0014 ± 0.0014	$24.00 < H_{160} < 24.50$	< 0.0015[b]
$24.50 < i_{775} < 25.00$	0.6494 ± 0.0480	$24.40 < Y_{105} < 24.90$	0.0081 ± 0.0033	$24.50 < H_{160} < 25.00$	< 0.0015[b]
$25.00 < i_{775} < 25.50$	1.4575 ± 0.0718	$24.90 < Y_{105} < 25.40$	0.0350 ± 0.0069	$25.00 < H_{160} < 25.50$	0.0041 ± 0.0023
$25.50 < i_{775} < 26.00$	2.4695 ± 0.0935	$25.40 < Y_{105} < 25.90$	0.0981 ± 0.0115	$25.50 < H_{160} < 26.00$	0.0081 ± 0.0033
$26.00 < i_{775} < 26.50$	3.7300 ± 0.1627	$25.90 < Y_{105} < 26.40$	0.2584 ± 0.0419	$26.00 < H_{160} < 26.50$	0.0527 ± 0.0190
$26.50 < i_{775} < 27.00$	4.7275 ± 0.7609	$26.40 < Y_{105} < 26.90$	0.3806 ± 0.1638	$26.50 < H_{160} < 27.00$	0.1441 ± 0.1019
$27.00 < i_{775} < 27.50$	6.6043 ± 0.8993	$26.90 < Y_{105} < 27.40$	1.0717 ± 0.2749	$27.00 < H_{160} < 27.50$	0.4270 ± 0.1754
$27.50 < i_{775} < 28.00$	6.5582 ± 0.8962	$27.40 < Y_{105} < 27.90$	1.2049 ± 0.2915	$27.50 < H_{160} < 28.00$	0.4992 ± 0.1897
$28.00 < i_{775} < 28.50$	8.3582 ± 1.0117	$27.90 < Y_{105} < 28.40$	1.8070 ± 0.3570	$28.00 < H_{160} < 28.50$	0.6403 ± 0.2148
$28.50 < i_{775} < 29.00$	10.4910 ± 1.4912	$28.40 < Y_{105} < 28.90$	2.9412 ± 0.7896	$28.50 < H_{160} < 29.00$	1.0643 ± 0.4908
$29.00 < i_{775} < 29.50$	16.8280 ± 1.8886	$28.90 < Y_{105} < 29.40$	5.8268 ± 1.1113	$29.00 < H_{160} < 29.50$	1.3466 ± 0.5520
$29.50 < i_{775} < 30.00$	10.7412 ± 1.5089	$29.40 < Y_{105} < 29.90$	4.5725 ± 0.9845	$29.50 < H_{160} < 30.00$	1.6986 ± 0.6200
$z \sim 5$		$29.90 < Y_{105} < 30.40$	2.0457 ± 0.6585	$z \sim 10$	
$22.50 < Y_{105} < 23.00$	< 0.0015[b]	$z \sim 7$		$22.20 < H_{160} < 23.20$	< 0.0014[b]
$23.00 < Y_{105} < 23.50$	0.0014 ± 0.0014	$22.95 < J_{125} < 23.45$	< 0.0015[b]	$22.70 < H_{160} < 23.70$	< 0.0014[b]
$23.50 < Y_{105} < 24.00$	0.0041 ± 0.0023	$23.45 < J_{125} < 23.95$	< 0.0015[b]	$23.70 < H_{160} < 24.70$	< 0.0014[b]
$24.00 < Y_{105} < 24.50$	0.0231 ± 0.0055	$23.95 < J_{125} < 24.45$	< 0.0015[b]	$24.70 < H_{160} < 25.70$	< 0.0014[b]
$24.50 < Y_{105} < 25.00$	0.0893 ± 0.0110	$24.45 < J_{125} < 24.95$	0.0014 ± 0.0014	$25.70 < H_{160} < 26.70$	0.0070 ± 0.0070
$25.00 < Y_{105} < 25.50$	0.2771 ± 0.0194	$24.95 < J_{125} < 25.45$	0.0215 ± 0.0054	$26.70 < H_{160} < 27.70$	< 0.0792[b]
$25.50 < Y_{105} < 26.00$	0.5549 ± 0.0274	$25.45 < J_{125} < 25.95$	0.0333 ± 0.0067	$27.70 < H_{160} < 28.70$	< 0.2488[b]
$26.00 < Y_{105} < 26.50$	1.1366 ± 0.0884	$25.95 < J_{125} < 26.45$	0.1569 ± 0.0327	$28.70 < H_{160} < 29.70$	0.4523 ± 0.3198
$26.50 < Y_{105} < 27.00$	1.9991 ± 0.3950	$26.45 < J_{125} < 26.95$	0.2821 ± 0.1411	...	...
$27.00 < Y_{105} < 27.50$	2.2056 ± 0.4149	$26.95 < J_{125} < 27.45$	0.3527 ± 0.1577	...	...
$27.50 < Y_{105} < 28.00$	3.1493 ± 0.4958	$27.45 < J_{125} < 27.95$	0.8306 ± 0.2420	...	...
$28.00 < Y_{105} < 28.50$	4.3133 ± 0.5802	$27.95 < J_{125} < 28.45$	1.2726 ± 0.2996	...	...
$28.50 < Y_{105} < 29.00$	4.6413 ± 0.9919	$28.45 < J_{125} < 28.95$	1.2638 ± 0.5176	...	...
$29.00 < Y_{105} < 29.50$	6.3116 ± 1.1566	$28.95 < J_{125} < 29.45$	4.2857 ± 0.9531	...	...
$29.50 < Y_{105} < 30.00$	5.2184 ± 1.0517	$29.45 < J_{125} < 29.95$	3.4843 ± 0.8594	...	...

The three LAEs

Derived from the EWo (Sobral & Matthee 2019)

Lyα,intr=Lyα/fesc,lyα

Group 1

Name	Group	EW_o Å	$Flux_{Ly\alpha}$ 10^{-17} erg s^{-1}	$f_{esc,Ly\alpha}$	$L_{Ly\alpha}$ 10^{42} erg s^{-1}	$L_{Ly\alpha,intr}$ 10^{43} erg s^{-1}	Q_{ion} 10^{54}s^{-1}
BDF521	1	64±6	1.62±0.16	0.32±0.03	9.14±0.91	2.98±0.41	2.53 ± 0.35
BDF2195	1	50±12	1.85±0.46	0.24±0.06	10.56 ± 2.63	4.40 ± 1.52	3.73 ± 1.29
BDF3299	2	50±6	1.21±0.14	0.24±0.24	7.08±0.83	2.95±0.49	2.50 ± 0.42

- **Total for Group 1 = 6.26 10^{54} s^{-1}**
- **Total for Group 2 = 2.50 10^{54} s^{-1}**

The medium luminosity LBGs

- We derived the Q^*_{ion} in the following way:
- First we found the fluxes from the AB Magnitudes
- Then we derived the Luminosity at λ 1500Å

Name	Group	M_{AB}	$f_{\lambda 1320}$ 10^{-20} erg s^{-1} cm^{-2} $Å^{-1}$	L_{1500} 10^{40} erg s^{-1} $Å^{-1}$	Q^*_{ion} 10^{54} s^{-1}
BDF2009	1	26.89±0.08	13.75±12.78	6.89±5.61	0.65±0.50
BDF994	1	27.11±0.19	11.23±9.43	5.69±4.19	0.53±0.39
BDF2660	1	27.27±0.10	9.69±8.84	4.91±3.93	0.46±0.34
BDF1310	1	27.32±0.16	9.26±7.99	4.69±3.55	0.44±0.31
BDF187	1	27.33±0.10	9.17±8.37	4.65±3.72	0.43±0.33
BDF1899	1	27.35±0.15	9.00±7.84	4.56±3.49	0.42±0.31
				Total Group 1	**2.93±0.15**
BDF2883	2	25.97± 0.08	32.10±29.82	16.08±14.94	1.51±1.32
BDF401	2	26.43± 0.08	21.01±19.52	10.53±9.78	0.99±0.87
BDF1147	2	27.26±0.11	9.78±8.84	4.72±4.23	0.46±0.39
BDF2980	2	27.30±0.12	9.43±8.44	4.72±4.23	0.44±0.38
BDF647	2	27.31±0.15	9.34±8.14	4.68±4.08	0.44±0.36
BDF2391	2	27.33±0.17	9.17±7.84	4.59±3.93	0.43±0.35
BDF1807	2	27.36±0.09	8.92±8.21	4.47±4.11	0.42±0.36
BDF2192	2	27.40±0.10	8.60±7.84	4.31±3.93	0.41±0.35
				Total Group 2	**5.11±0.64**

Finally we derived the Q^*_{ion} using the expression:

$L(1500) = 1.18 \times 10^{-11} \times Q^*_{ion}$ erg s^{-1} (Osterbrock 1989)

The Low Luminosity LBGs

M_{AB} range	Surface Density arcmin^{-2}	# Group 1 3.94 arcmin^2	# Group 2 3.82 arcmin^2	# Corrected 1 overdensity	# Corrected 2 overdensity
27.45 - 27.95	0.831 ± 0.242	3.27 ± 0.95	3.17 ± 0.92	11.46 ± 0.85	11.11 ± 0.85
27.95 - 28.45	1.273 ± 0.300	5.02 ± 1.18	4.86 ± 1.15	17.55 ± 1.05	17.01 ± 1.05
28.45 - 28.95	1.264 ± 0.518	4.98 ± 2.04	4.83 ± 1.98	17.43 ± 1.81	16.90 ± 1.81
28.95 - 29.45	4.286 ± 0.953	16.89 ± 3.75	16.37 ± 3.64	59.10 ± 3.34	57.30 ± 3.34
29.45 - 29.95	3.484 ± 0.859	13.73 ± 3.38	13.31 ± 3.28	48.05 ± 3.01	46.59 ± 3.01

Once we knew how many sources we could derive the Q^*_{ion} in the same way as for the LBGs

M_{AB}	$f_{\lambda 1320}$ $\times 10^{-20}$ erg s^{-1} cm^{-2} Å^{-1}	L_{1500} $\times 10^{40}$ erg s^{-1}	$Q^*_{ion,G1}$ $\times 10^{54}$ s^{-1}	$Q^*_{ion,G2}$ $\times 10^{54}$ s^{-1}
27.70	6.74	3.38	3.64 ± 0.38	3.53 ± 0.27
28.20	4.25	2.13	3.52 ± 0.30	3.41 ± 0.21
28.70	2.68	1.34	2.20 ± 0.33	2.14 ± 0.23
29.20	1.69	0.85	4.72 ± 0.38	4.57 ± 0.27
29.70	1.07	0.54	2.42 ± 0.22	2.35 ± 0.15
Total			16.49 ± 0.39	15.99 ± 0.27

Putting everything together

	$Q^*_{ion,G1}$ $\times 10^{54}\,s^{-1}$	$Q^*_{ion,G2}$ $\times 10^{54}\,s^{-1}$
LAEs	$\gtrsim 6.26 \pm 0.94$	$\gtrsim 2.50 \pm 0.42$
Mid Luminosity	2.93±0.15	5.11±0.64
Low Luminosity	16.49±0.39	15.99±0.27

Table 5. The number of intrinsic ionising continuum photons produced by the medium and low luminosity LBGs in each of the Groups. The values listed for the LAEs are just lower limits as they should be corrected by the corresponding Lyman continuum escape fraction as discussed in the text.

Note that for the LAEs we do not yet know their total output, as we do not know the $f_{esc,LyC}$

Deriving the $f_{esc,LyC}$

- Finally, we compare the number of photons required to reionise Group1 and Group2 with the number of photons available from the sources in the BDF

- There is an ingredient missing, which is the $f_{esc,LyC}$

- We get this value solving the following equation:

$$[\![Q^*_{ion} + Q_{LAEs}/(1-f_{esc,LyC})]\!] \times f_{esc,LyC} = \dot{N}_{ion}$$

Where $\dot{N}_{ion}$ comes from the AMIGA code

The results are

	$\dot{N}^{S}_{min,corr}$ $\times 10^{54}$ s^{-1}	$\dot{N}^{D}_{min,corr}$ $\times 10^{54}$ s^{-1}	$f_{esc,S}$	$f_{esc,D}$
Group 1	2.20 ± 0.09	3.01 ± 0.09	0.09	0.11
Group 2	2.12 ± 0.08	2.91 ± 0.08	0.13	0.15

- These are the $f_{esc,LyC}$ obtained. Note they are fairly small in agreement with many authors
- These are the values that produce a bubble that fills the volume of either Groups
- Increasing the value of $f_{esc,LyC}$ we increase the volume of the ionised bubbles

Summary

- We have found two large ionised bubbles in the BDF
- The ionising photons required have been provided by three types of sources: LAEs, Medium Luminosity LBGs and low luminosity LBGs
- We have derived the $f_{esc,LyC}$ required, that it is relatively small, in line with many authors
- We note that the low luminosity galaxies are the stronger contributors to provide ionising photons to ionise these bubbles
- This in agreement with the current reionisation scenarios