

Using Ly α to probe LyC escape from galaxies

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MUSE: Mieke Paalvast, Peter Weilbacher, Lutz Wisotzki, Josie Kerutt, Hanae Inami, Johan Richard and the GTO consortium



European Research Council
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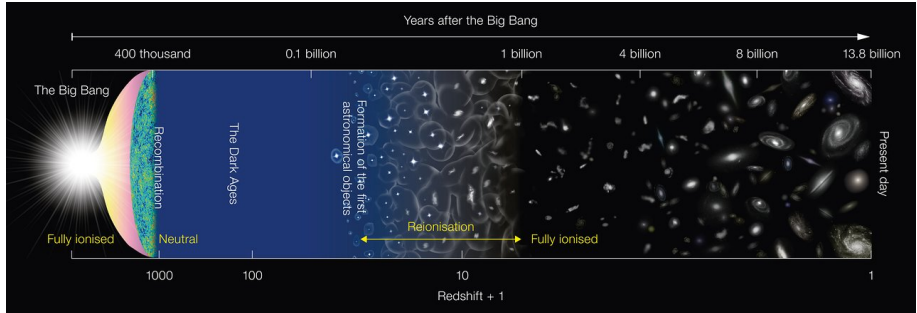
UNIVERSITÉ
DE GENÈVE



CENTRE DE RECHERCHE ASTROPHYSIQUE DE LYON

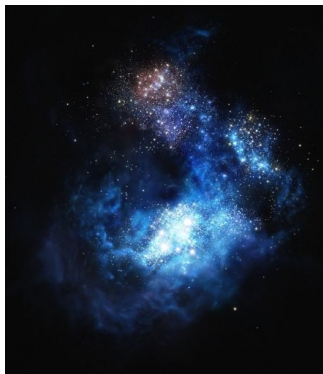
- * recent results on the escape of LyC from galaxies
- * using Ly α to trace LyC escape
- * Ly α properties of a virtual LyC emitter

What is Cosmic Reionization ? Why is it important ?



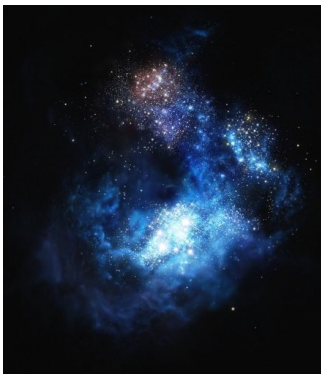
- * major phase transition in the history of the Universe
- * strong impact on galaxy formation and evolution
- * **main unknown** : the nature of the sources of Reionization

Can stars in galaxies reionize the Universe ?



- * produce a lot of ionising radiation, forming the Lyman continuum (LyC $\lambda < 912\text{\AA}$)
- * **main unknown** : LyC escape fraction
- * Numerous studies reporting non-detections :
 - * at $z < 1$ *Leitherer+95, Deharveng+97, Heckman+01, Deharveng+01, Malkan+03, Bergvall+06, Grimes+09, Bridge+10, Siana+10, Leitet+13, Bergvall+13, Rutkowski+16*
 - * at $2 < z < 4$ *Vanzella+10,12, Siana+15, Mostardy+15, Sandberg+15, Grazian+16, Vasei+16, Grazian+17, Rutkowski+17, Japel+17, Marchi+17*
- * before 2016, only 3-4 detections :
 - * at $z < 0.3$: *Bergvall+06, Leitet+13, Borthakur+14*

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- * before 2016, only 3-4 detections :
 - * at $z < 0.3$: *Bergvall+06, Leitet+13, Borthakur+14*

Several detections reported over the last two years

- * 14 objects at $z < 0.4$ (*Izotov+16ab, Leitherer+16, Izotov+18ab*)
- * 4 objects at $z \sim 2 - 4$ (*deBarros+16, Vanzella+16, Shapley+16, Bian+17, Vanzella+18*),
+15 direct detections in Steidel+18

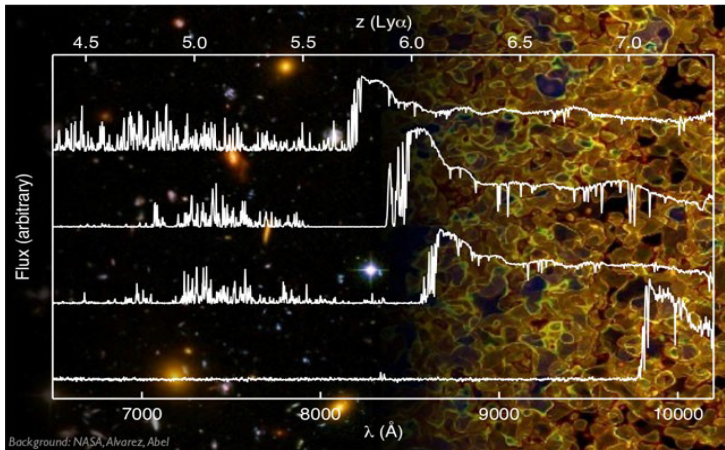
Observing the sources of cosmic Reionization in LyC ?

$z \sim 5.7$

$z \sim 5.9$

$z \sim 6.1$

$z \sim 7.1$



- * Intergalactic medium (IGM) opacity increases with redshift
- * direct detection of LyC impossible from galaxies at $z > 6$

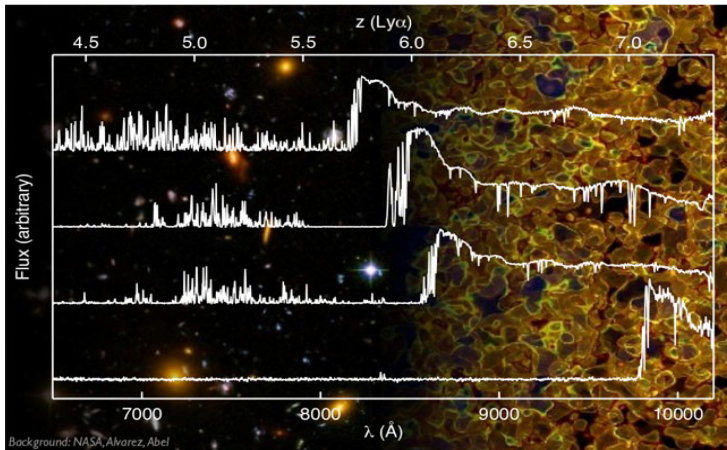
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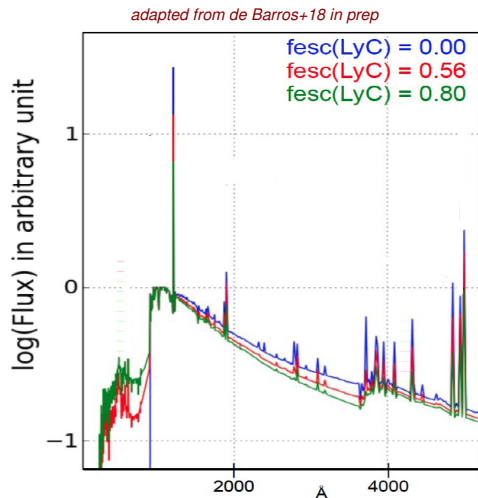
$z \sim 7.1$



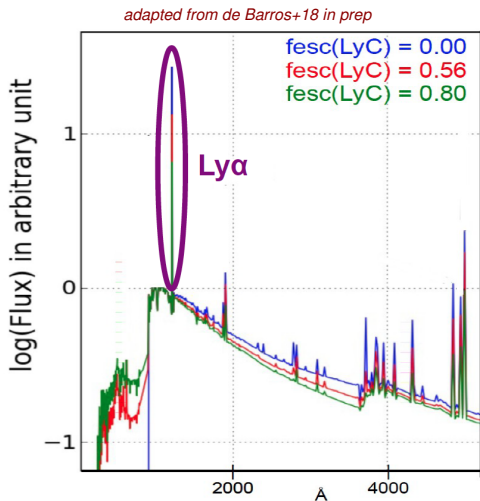
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→ need for indirect diagnostics of LyC leakage from galaxies

Three Indirect Probes of LyC Leakage



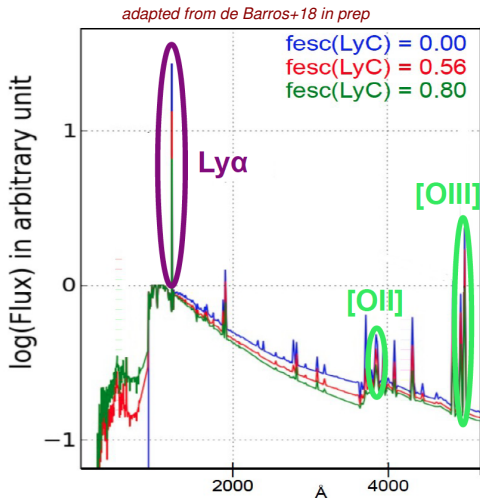
Three Indirect Probes of LyC Leakage



Probe I $\text{Ly}\alpha$ emission

Verhamme+15, Dijkstra&Gronke16

Three Indirect Probes of LyC Leakage



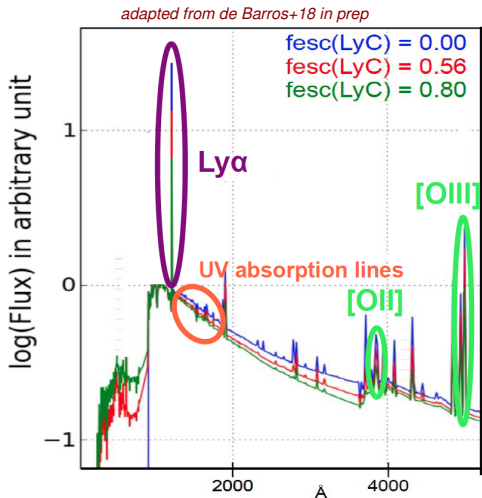
Probe I $\text{Ly}\alpha$ emission

Verhamme+15, Dijkstra&Gronke16

Probe II high $[\text{OIII}]/[\text{OII}]$ ratio

Jaskot+13, Nakajima+14

Three Indirect Probes of LyC Leakage



Probe I $\text{Ly}\alpha$ emission

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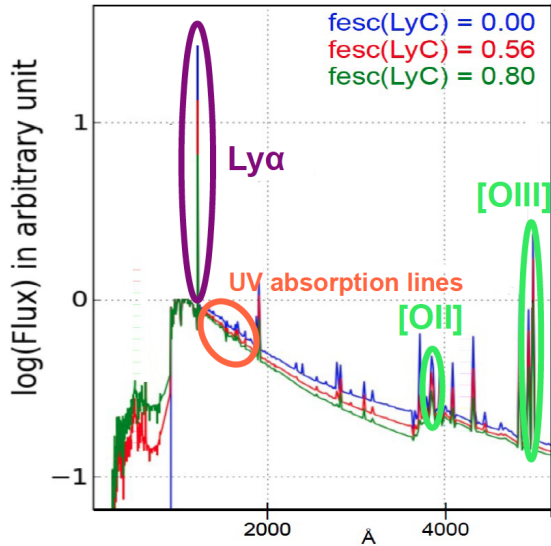
Probe II high [OIII]/[OII] ratio

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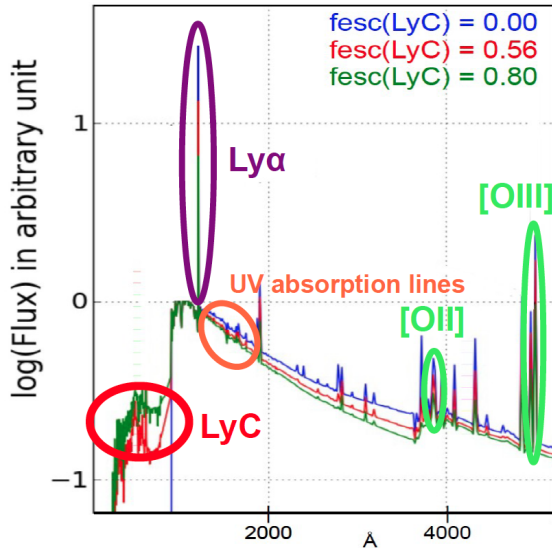
Probe III UV absorption lines

Heckman+11

Towards an observational confirmation ? $\rightarrow z \sim 0.3$



Towards an observational confirmation ? $\rightarrow z \sim 0.3$



Green Peas : unique benchmark sample

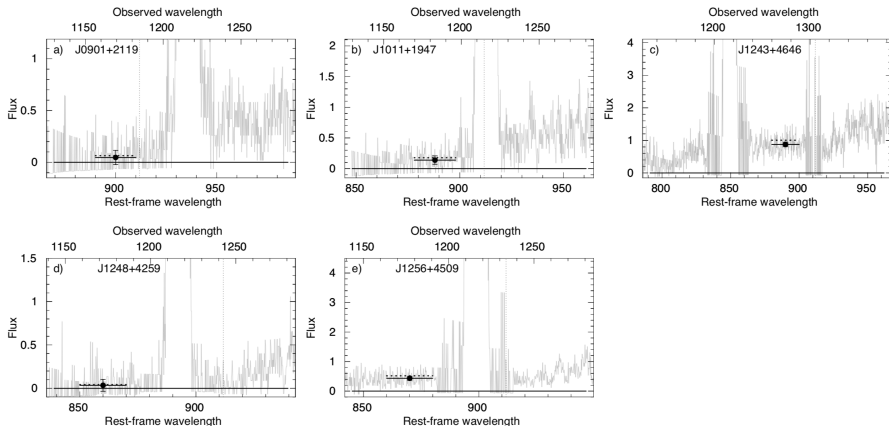
Izotov+16*ab*, Schaerer+16, Verhamme+17, Chisholm+17, Izotov+18*ab*

Name	R.A.(2000.0)	Dec.(2000.0)	z	D_L^a	D_A^b	O ₃₂
J0901+2119	09:01:45.61	+21:19:27.78	0.2993	1562	925	8.0
J1011+1947	10:11:38.28	+19:47:20.94	0.3322	1763	994	27.1
J1243+4646	12:43:00.63	+46:46:50.40	0.4317	2401	1172	13.5
J1248+4259	12:48:10.48	+42:59:53.60	0.3629	1956	1053	11.8
J1256+4509	12:56:44.15	+45:09:17.01	0.3530	1893	1034	16.3



Green Peas : 11/11 LyC emitters, fesc(LyC) 2-73%

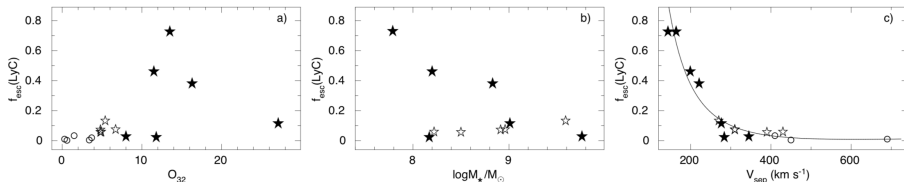
Izotov+16ab, Schaerer+16, Verhamme+17, Chisholm+17, Izotov+18ab



see Daniel's talk tomorrow, John's talk on Friday, Simon's poster

Green Peas : indirect probes vs LyC escape

Izotov+16ab, Schaerer+16, Verhamme+17, Chisholm+17, Izotov+18ab



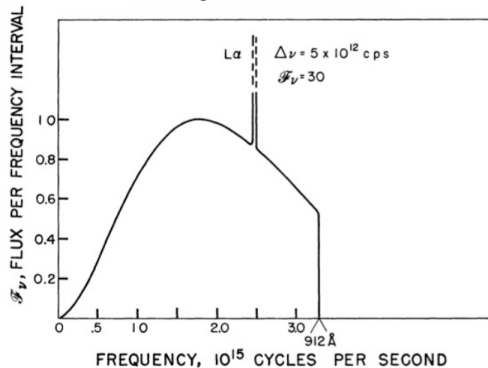
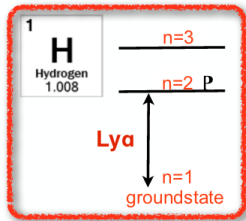
- * no correlation between O32 and $f_{\text{esc}}(\text{LyC})$
- * strongest leakers have lower masses
- * tight correlation between Ly α peaks separation and $f_{\text{esc}}(\text{LyC})$, as expected!! *Verhamme+15, Dijkstra+16*

$\text{Ly}\alpha$ - LyC interconnexions

Ly α escape from galaxies : strong line

M. Dijkstra, Saas Fee Advanced School 2016

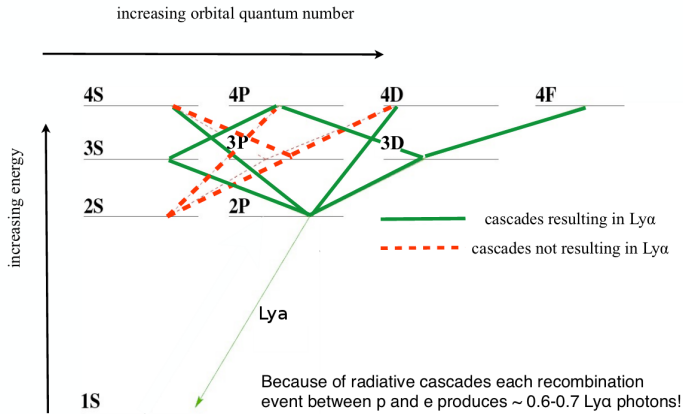
Partridge & Peebles 1967



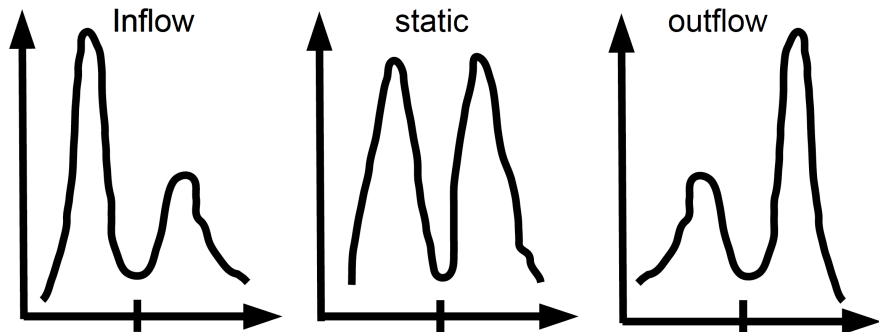
~7-40% (!) of bolometric luminosity of young galaxies in Ly α emission line

$\text{Ly}\alpha$ escape from galaxies : resonant line

M. Dijkstra, Saas Fee Advanced School 2016

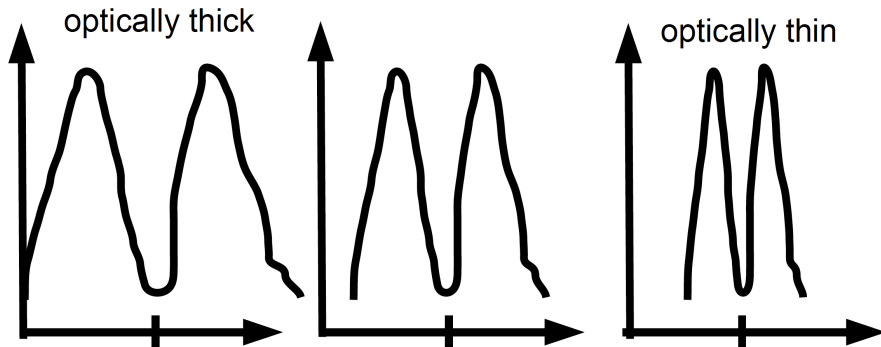


The basics of $\text{Ly}\alpha$ RT : kinematics



- * $\text{Ly}\alpha$ is never tracing line of sight velocity, as an absorption line would do, but the bulk velocity of the scattering medium with respect to the $\text{Ly}\alpha$ source

The basics of $\text{Ly}\alpha$ RT : density

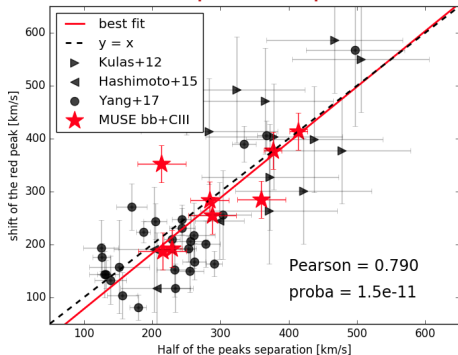


- * $\text{Ly}\alpha$ spectrum = distribution of the minimum necessary shifts for escape : always follows/traces the path of least opacity

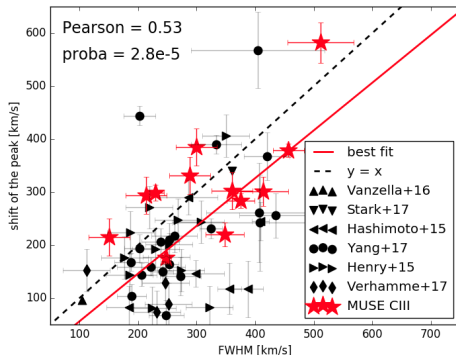
Recovering systemic redshift from the Ly α line

Verhamme+18

half of the peaks separation



FWHM as proxy for peak shift



$\text{Ly}\alpha$ as indirect probe of LyC escape from galaxies

Theoretical Expectations

- spectral shape : narrow profiles, small Δ_V
- escape fraction : high, higher than LyC escape fraction
- spatial extent : steep slopes, most of the $\text{Ly}\alpha$ flux from the center

$\text{Ly}\alpha$ as indirect probe of LyC escape from galaxies

Theoretical Expectations

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Observations, today

- 14 LyC emitters at $z < 0.4$

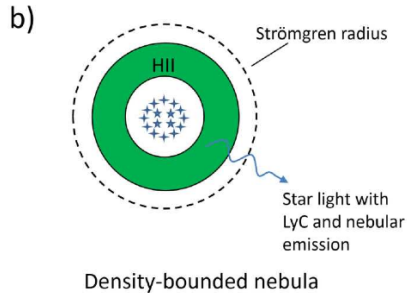
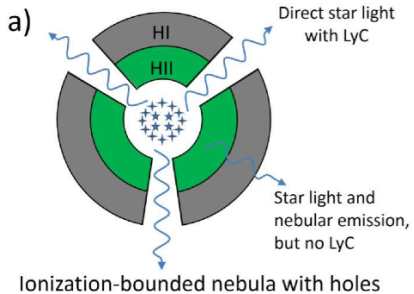
Bergvall+06, Leitet+13, Borthakur+14, Leitherer+16, Izotov+16a,b,18a,b

- 4 LyC emitters at $2 < z < 4$ *Vanzella+16, Shapley+16, Bian+17, Vanzella+18*
plus several new candidates from Steidel+18, Fletcher+18, Naidu+18...
- see kanak and Emil's talks for very new detections

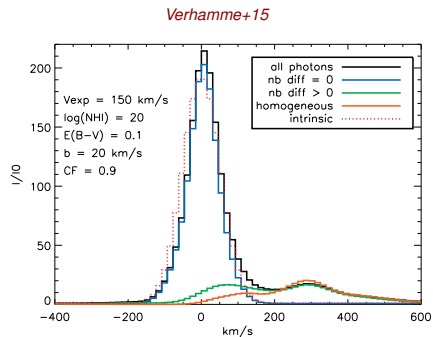
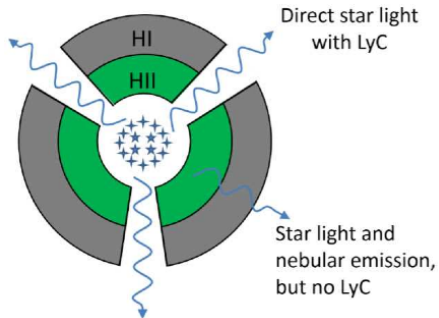
$\text{Ly}\alpha$ spectra

$\text{Ly}\alpha$ spectra of LyC Emitters : two possible geometries

Zackrisson+13

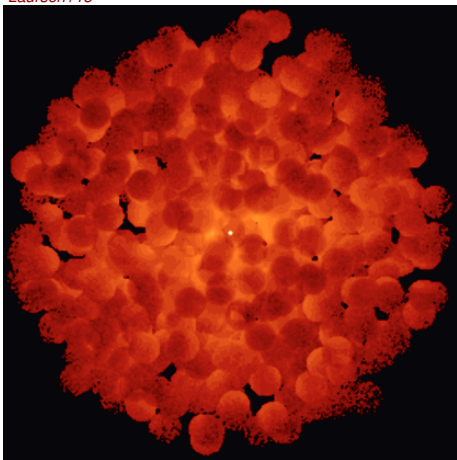


Ly α spectra of LyC Emitters – Triple peaks from holes

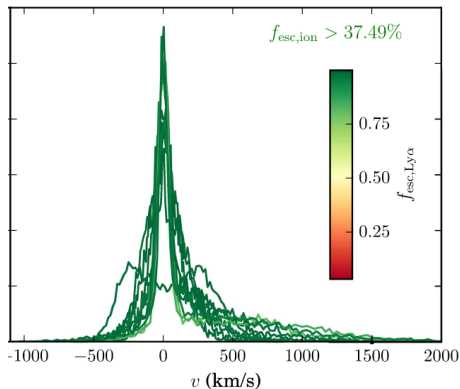


Ly α spectra of LyC Emitters – Triple peaks from holes

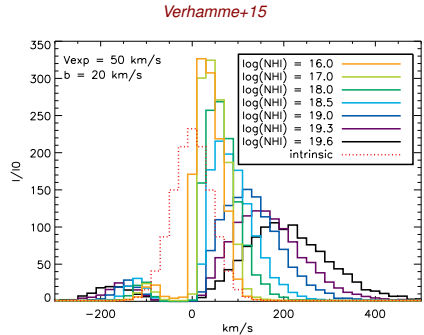
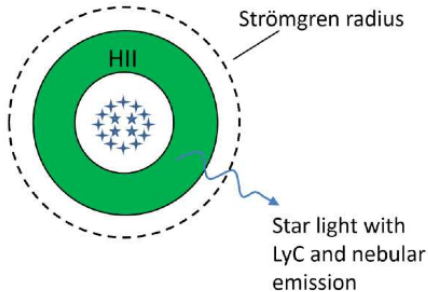
Laursen+13



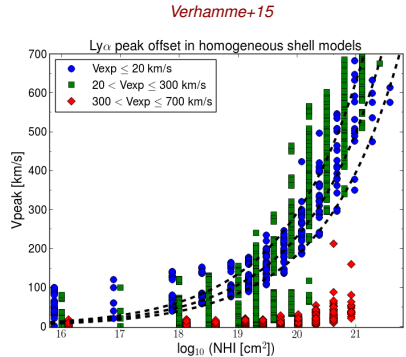
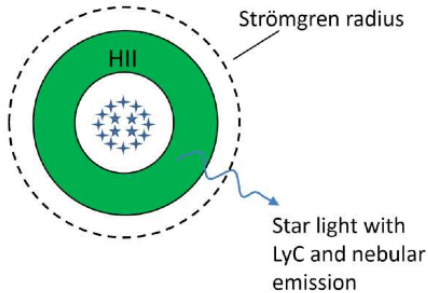
Dijkstra & Grönke 2016



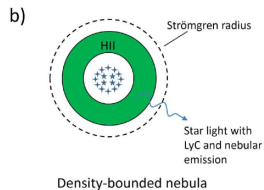
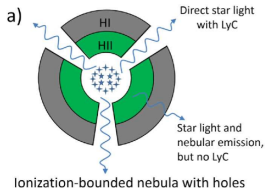
Ly α spectra of LyC Emitters – small Δ_V from optically thin H II regions



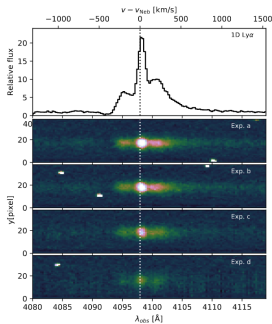
$\text{Ly}\alpha$ spectra of LyC Emitters – small Δ_V from optically thin H II regions



Ly α spectra of LyC Emitters : observations

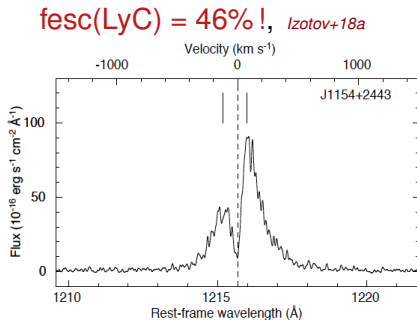
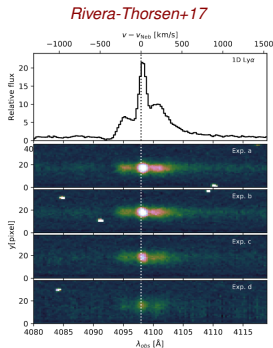
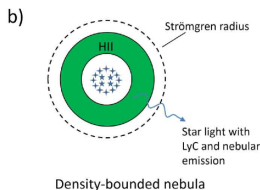
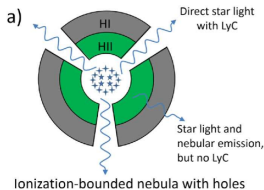


Rivera-Thorsen+17

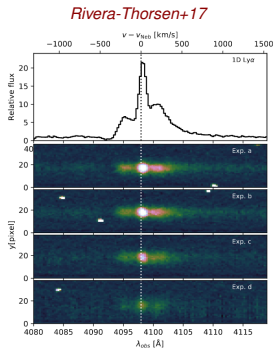
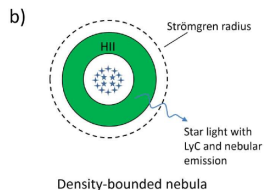
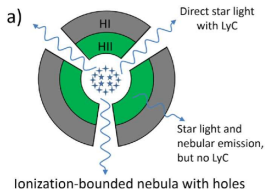


Verhamme+17

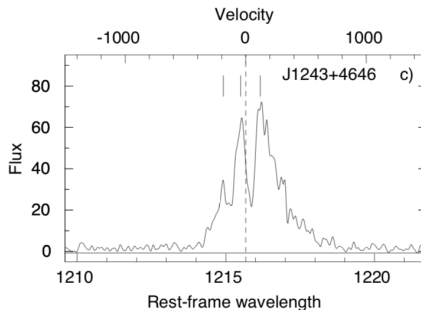
Ly α spectra of LyC Emitters : observations



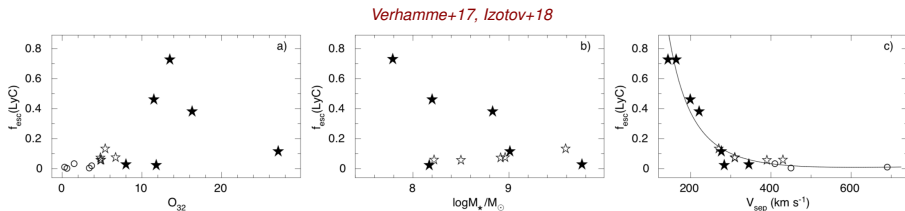
Ly α spectra of LyC Emitters : observations



$$f_{\text{esc}}(\text{LyC}) = 73\%!, \text{ Izotov+18b}$$



Ly α spectra of LyC Emitters : observations

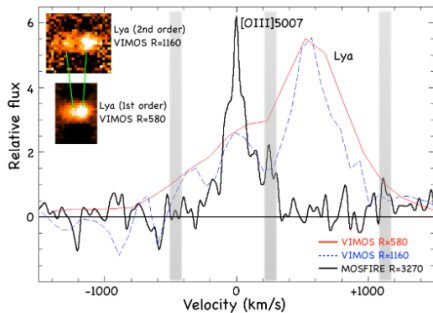


Lessons from local LyC Emitters

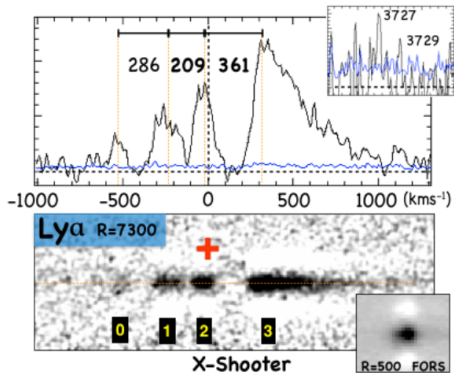
- * $[\text{OIII}]/[\text{OII}]$ ratios does not always correlate with $f_{\text{esc}}(\text{LyC})$
- * stronger LyC emitters are the least massive
- * Ly α peaks separation decreases with increasing $f_{\text{esc}}(\text{LyC})$

Ly α spectra of LyC Emitters : more observations...

ION 2, *de Barros+16*

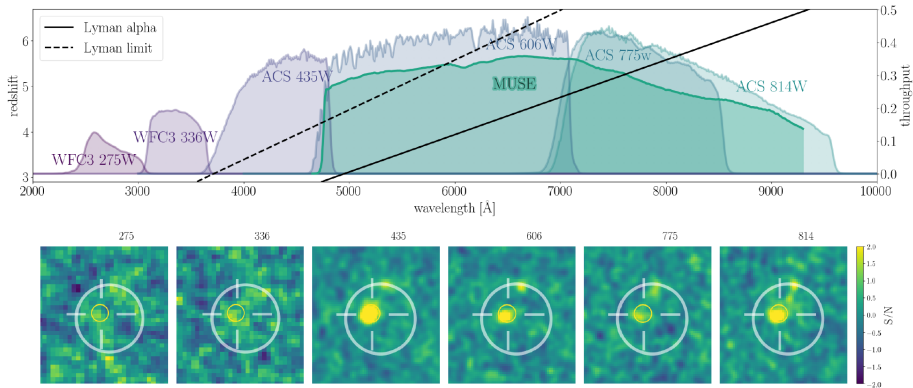


ION 3, *Vanzella+18*

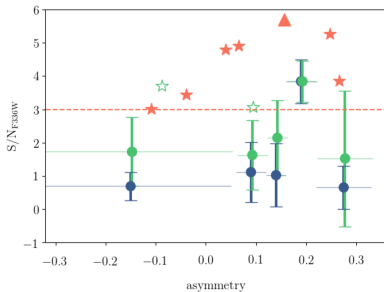
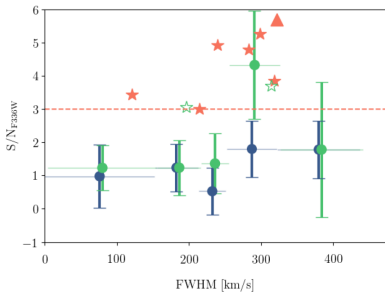
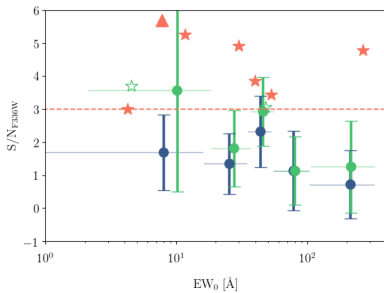
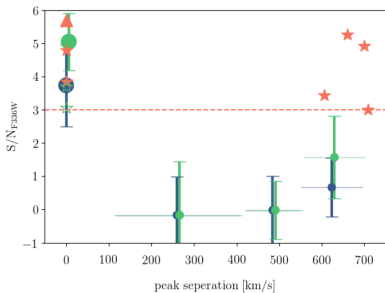


Ly α spectra of LyC Emitters : more observations...

Kerutt, Wisotzki et al, in prep



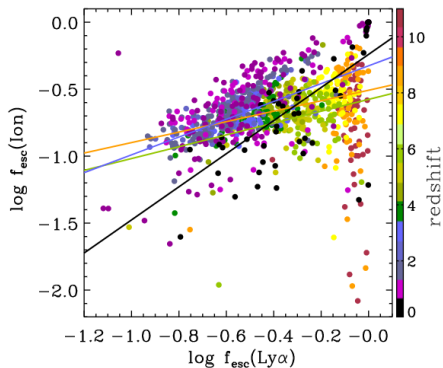
Ly α spectra of LyC Emitters : more observations...



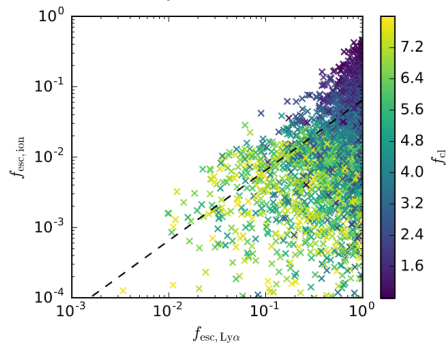
$\text{Ly}\alpha$ escape fractions

$\text{Ly}\alpha$ vs LyC escape fractions : predictions

Yajima+14

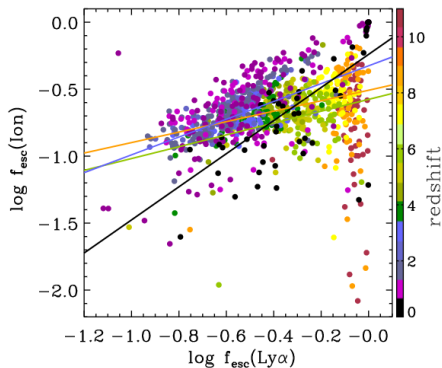


Dijkstra&Grönke, 2016

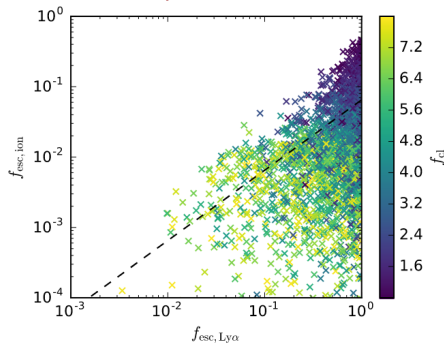


$\text{Ly}\alpha$ vs LyC escape fractions : predictions

Yajima+14

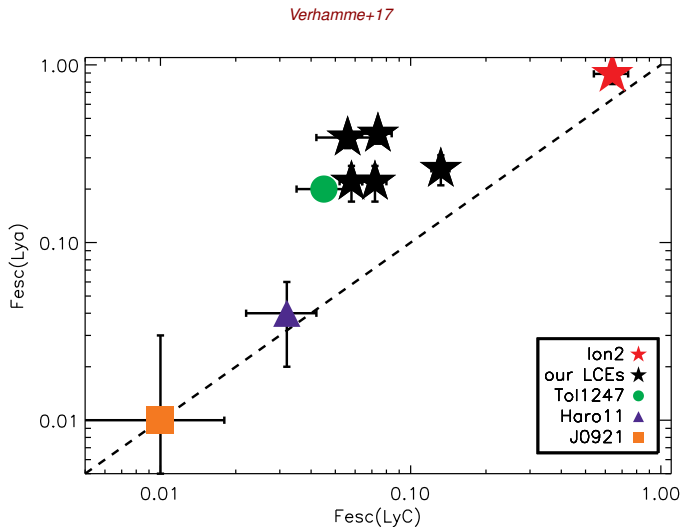


Dijkstra&Grönke, 2016

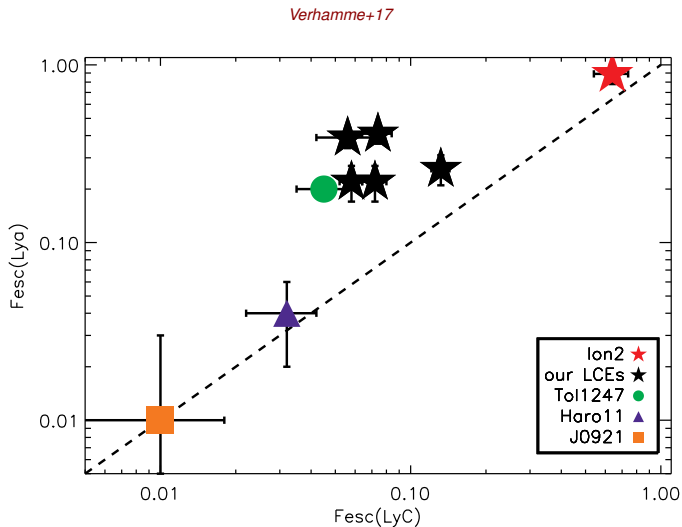


$\text{Ly}\alpha$ escape fraction > LyC escape fraction

$\text{Ly}\alpha$ vs LyC escape fractions : observations



$\text{Ly}\alpha$ vs LyC escape fractions : observations

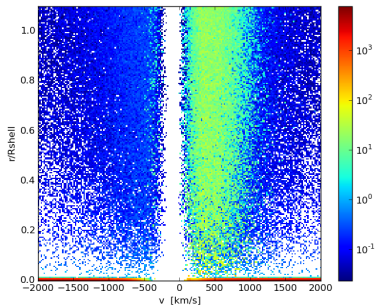


Lyman-alpha escape fractions are high in LyC emitters.

$\text{Ly}\alpha$ spatial distribution

Ly α spatial vs spectral escape from expanding shells

Verhamme, Garel et al, in prep
 $\log(\text{NHI}) = 20.2$, $V_{\text{exp}} = 150 \text{ km/s}$

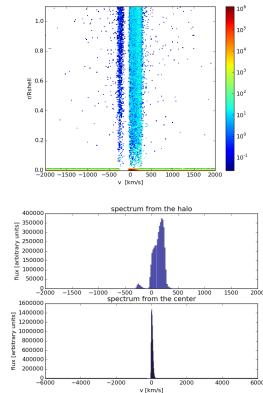
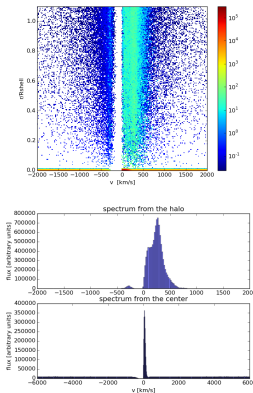
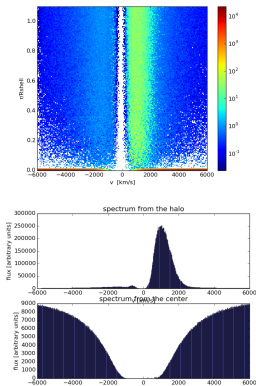


LCEs have no/faint halos

$\log(\text{NHI}) = 21.1$
(LBG)

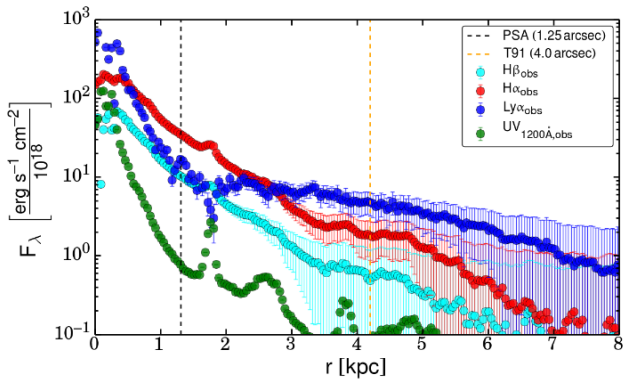
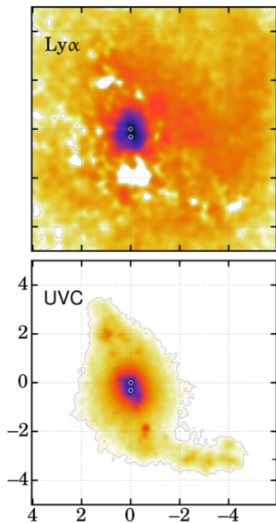
$\log(\text{NHI}) = 19.2$
(LAE)

$\log(\text{NHI}) = 17.2$
(LCE)



Ly α halos of LyC Emitters : insights from observations ?

Puschnig+18, $f_{\text{esc}}(\text{LyC}) \sim 1 - 4\%$



Ly α halos of LyC Emitters : insights from observations ?

Marchi+17, see also Yang+16

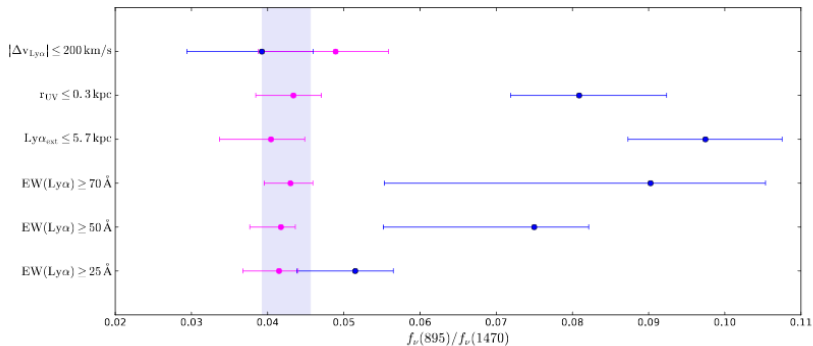
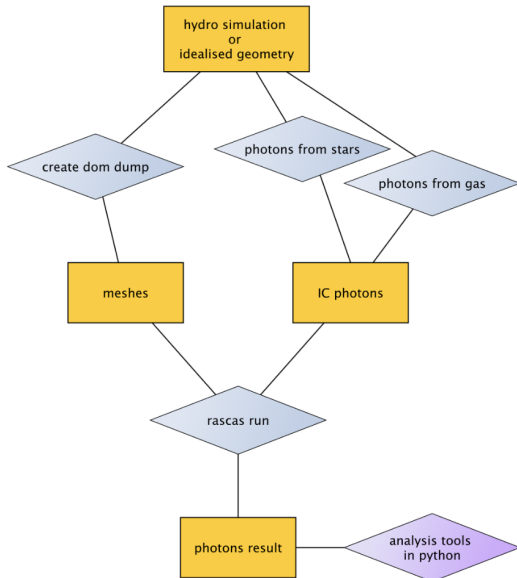


Fig. 3. Flux density ratios evaluated from the stacks of the samples in the y-axis (blue dots) and from the complementary samples (magenta dots) as indicated in Table 1. The lavender vertical band is the 1σ confidence interval evaluated for the total sample of 201 galaxies.

$\text{Ly}\alpha$ properties of a virtual LyC emitter

RASCAS : Radiation Scattering in Simulations

A massively parallel Monte Carlo code for line transfer in AMR simulations



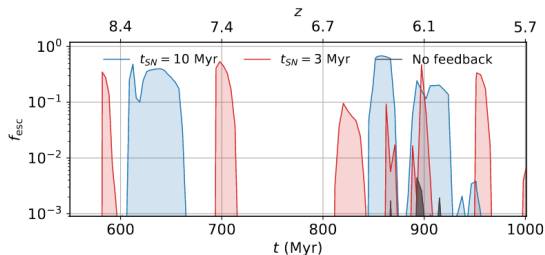
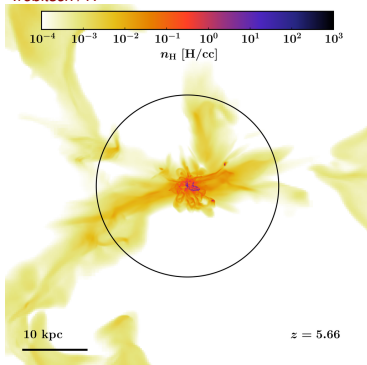
Several applications :

- * $\text{Ly}\alpha$ (+D +dust) scattering
- * metallic resonance lines (SiII, MgII, FeII)
- * dust scattering of stellar light
- * LyC escape fraction
- * **public release... soon**

Michel-Dansac+18 in prep /w Verhamme

Ly α emission from a virtual $z \sim 6$ LyC Emitter

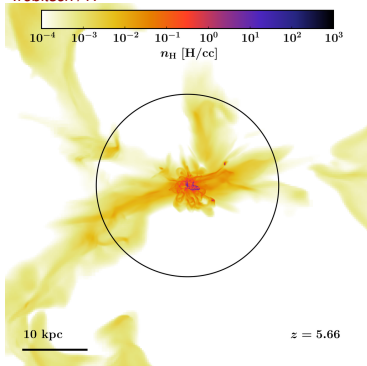
Trebitsch+17



$\text{Ly}\alpha$ emission from a virtual $z \sim 6$ LyC Emitter

LyC

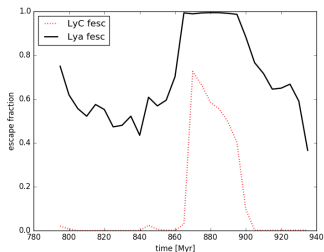
Trebitsch+17



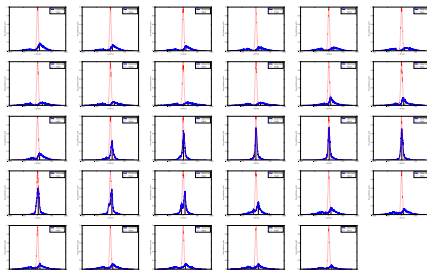
$\text{Ly}\alpha$

$\text{Ly}\alpha$ emission from a virtual $z \sim 6$ LyC Emitter

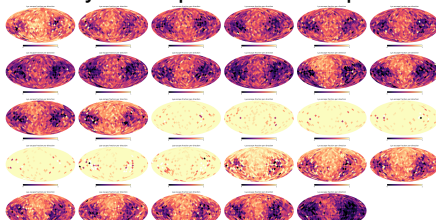
$\text{Ly}\alpha$ and LyC escape fractions vs time



$\text{Ly}\alpha$ spectra

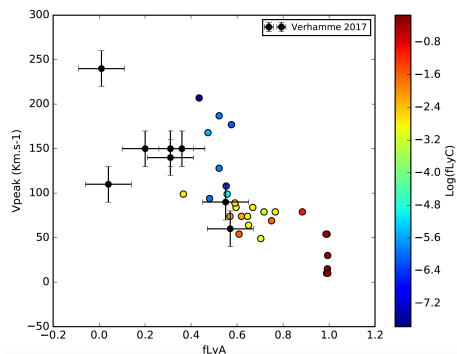
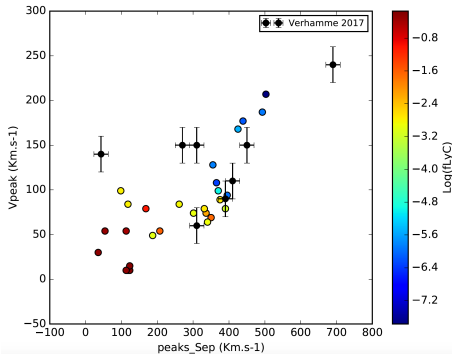


$\text{Ly}\alpha$ escape fraction maps



$\text{Ly}\alpha$ emission from a virtual $z \sim 6$ LyC Emitter

Verhamme+18 in prep



Conclusions

- * we have discovered a class of galaxies of the local Universe which are leaking ionising radiation
- * they share many properties of high-redshift galaxies (low mass, low metallicity, high SFR, young ages...)
- * among indirect indicators of LyC escape, $\text{Ly}\alpha$ is confirmed, O32 disregarded
- * on going : calibrate the indirect probes on simulations
- * future : understand why these galaxies are leaking, be ready for JWST