Lyman-alpha – Lyman continuum interconnexions

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

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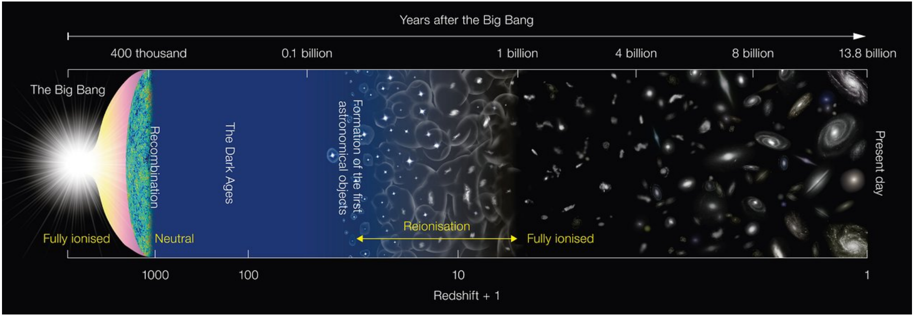
Outline

* recent results on the escape of LyC from galaxies
* using Lyα to trace LyC escape
* New RT code : RaSCaS (aka MCLya v.2.0)



- * 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 $\lambda < 912$Å)
- 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, Japeli+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*), see Steidel+18, Flechter+18

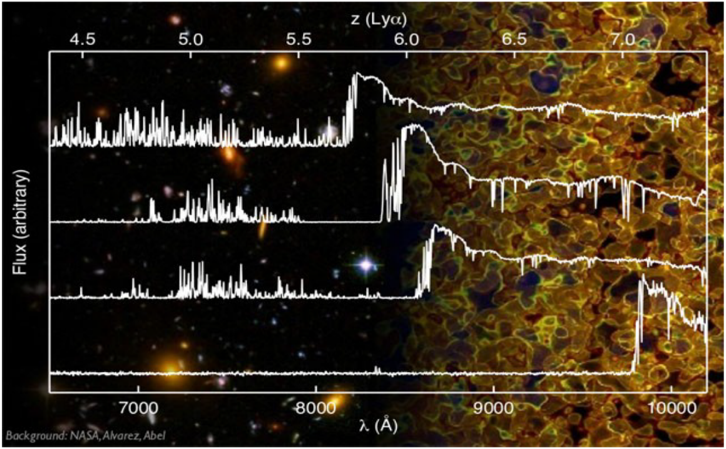
Observing the sources of cosmic Reionization in LyC ?

z ~ 5.7

z ~ 5.9

z ~ 6.1

z ~ 7.1



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

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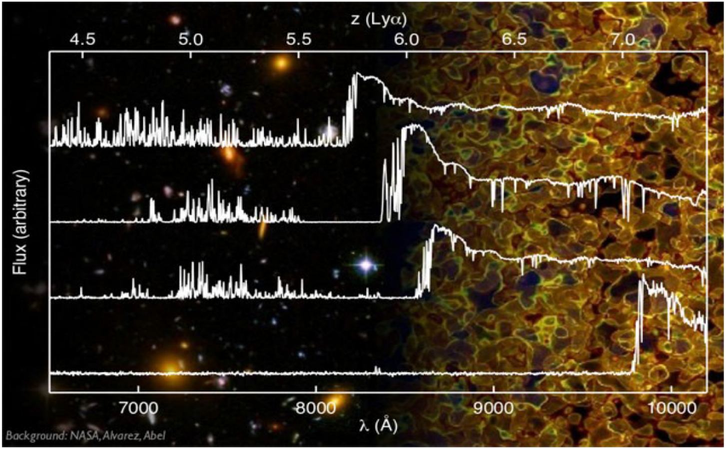

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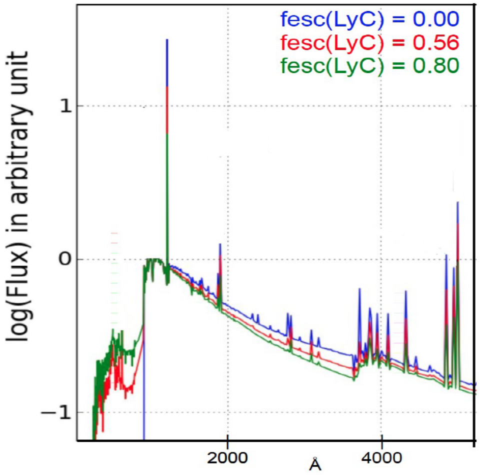
* direct detection of LyC impossible from galaxies at $z > 6$

$\longrightarrow$ need for indirect diagnostics of LyC leakage from galaxies

Three Indirect Probes of LyC Leakage

adapted from de Barros+18 in prep



Three Indirect Probes of LyC Leakage

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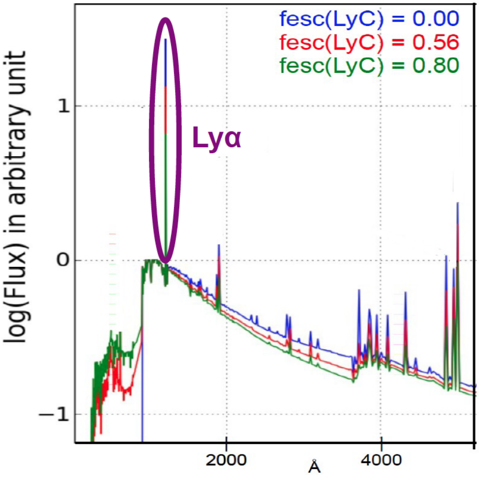
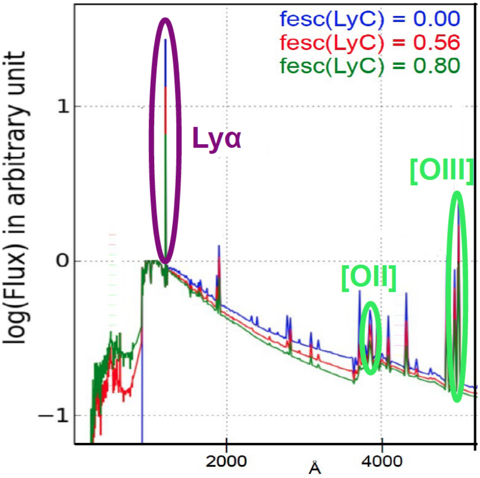


Probe I Lyα emission

Verhamme+15, Dijkstra&Gronke16

adapted from de Barros+18 in prep



Probe I Lyα emission

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Probe II high [OIII]/[OII] ratio

Jaskot+13, Nakajima+14

Three Indirect Probes of LyC Leakage

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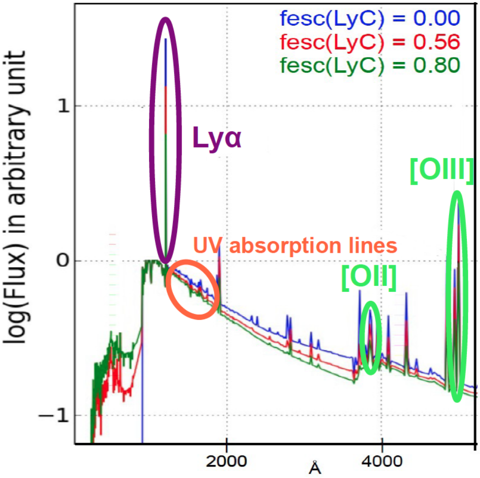

Probe I Lyα emission

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Probe II high [OIII]/[OII] ratio

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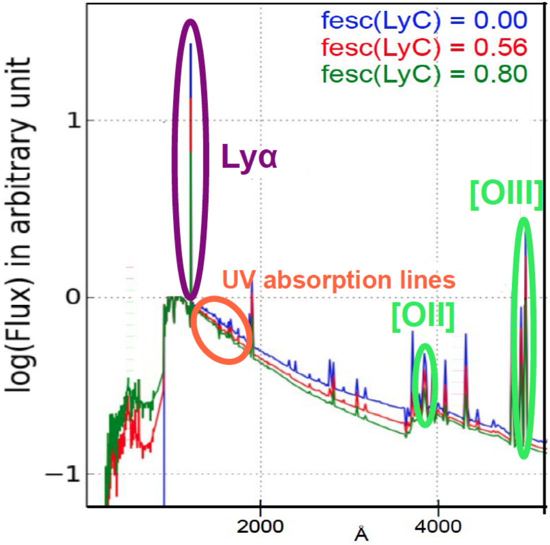
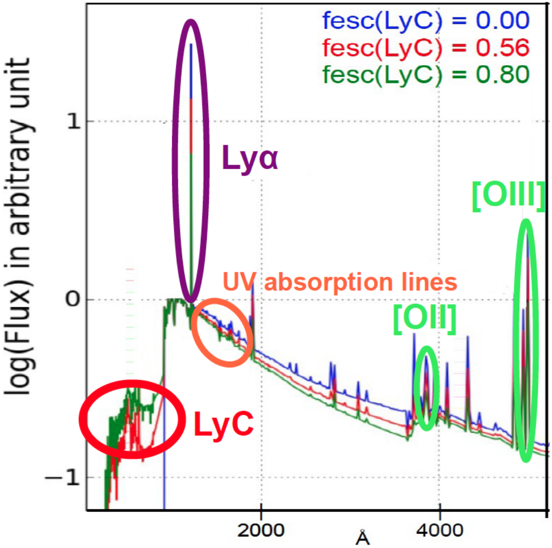
Probe III UV absorption lines

Heckman+11


fesc(LyC) = 0.00
fesc(LyC) = 0.56
fesc(LyC) = 0.80
Lyα
UV absorption lines
[OII]
[OIII]
log(Flux) in arbitrary unit
1
0
−1
2000
4000
Å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UV absorption lines
[OIII]
[OII]
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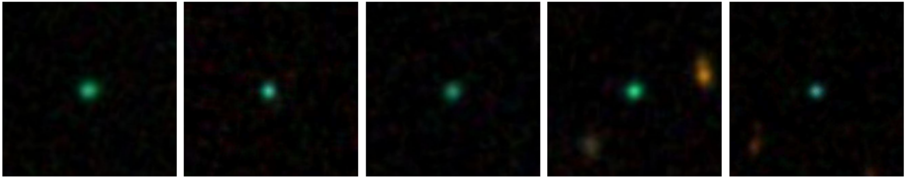
Å
4000

Green Peas : unique benchmark sample

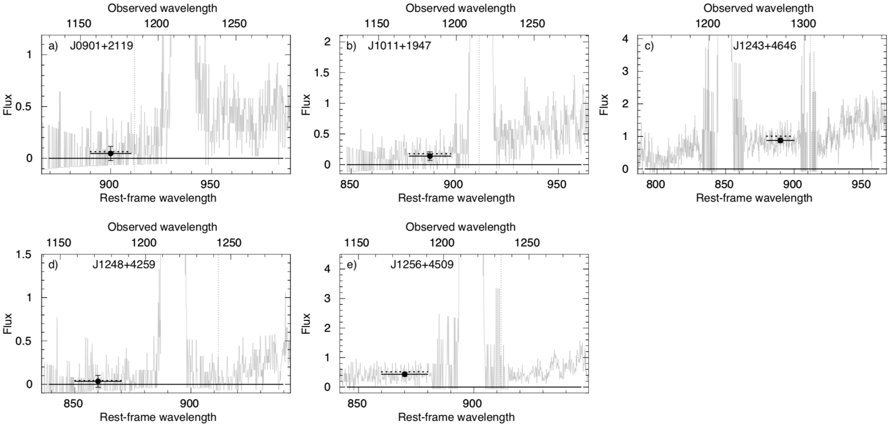
Izotov+16ab, Schaerer+16, Verhamme+17, Chisholm+17, Izotov+18ab, with Gabor Worseck

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



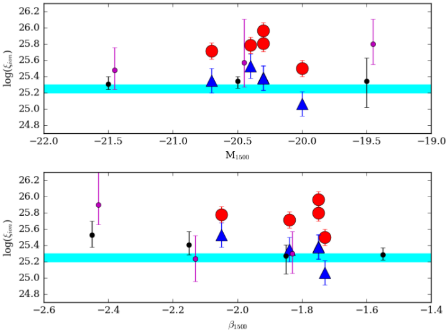
Green Peas : 11/11 LyC emitters, fesc(Lyc) 2-73%

Izotov+16ab, Schaerer+16, Verhamme+17, Chisholm+17, Izotov+18ab, with Gabor Worseck

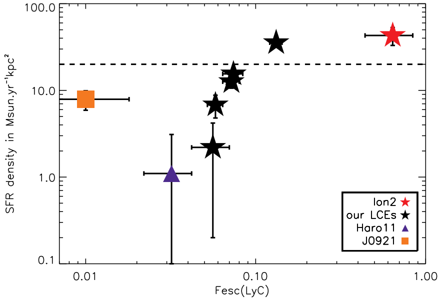


Green Peas : local analogues of the sources of reionisation ?

$\xi_{\rm ion}$, *Schaerer+16, Izotov+17*

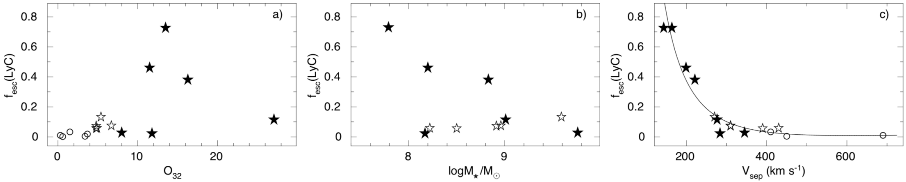


SFR density, *Verhamme+17*



Green Peas : indirect probes vs LyC escape

Izotov+16ab, Schaerer+16, Verhamme+17, Chisholm+17, Izotov+18ab, with Gabor Worseck

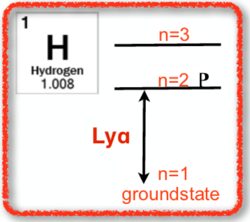


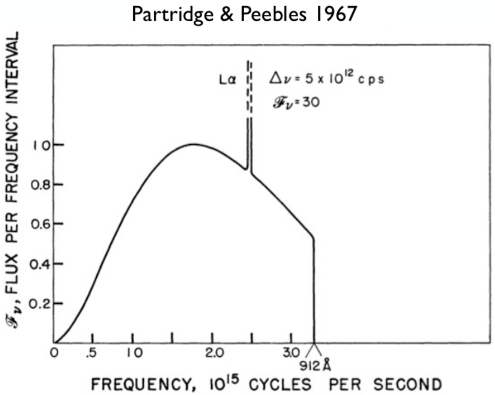
- no correlation between O32 and fesc(LyC)
- strongest leakers have lower masses
- tight correlation between Lyα peaks separation and fesc(LyC), as expected ! ! *Verhamme+15, Dijkstra+16*

Lyα - LyC interconnexions

Lyα escape from galaxies : strong line

M. Dijkstra, Saas Fee Advanced School 2016

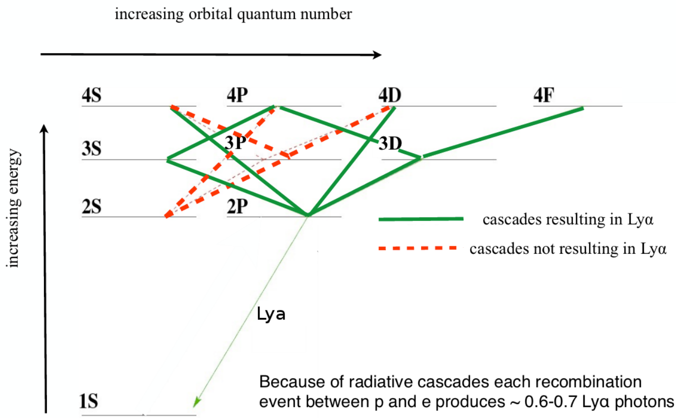




~7-40% (!) of bolometric luminosity of young galaxies in Lyα emission line

Lyα escape from galaxies : resonant line

M. Dijkstra, Saas Fee Advanced School 2016

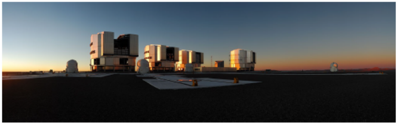


Because of radiative cascades each recombination event between p and e produces ~ 0.6-0.7 Lyα photons!

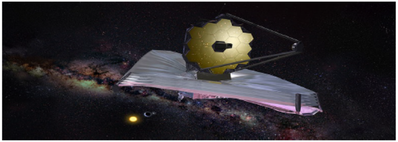
Lyα escape from galaxies : to the highest redshifts

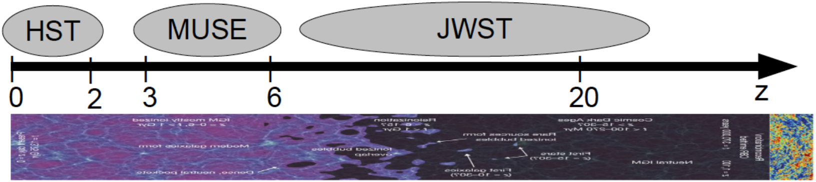
Lya in UV with HST

Lya in optical from the ground

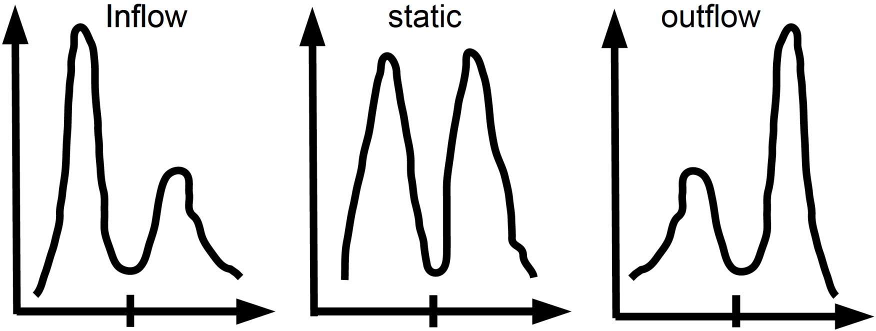


Lya in IR with JWST



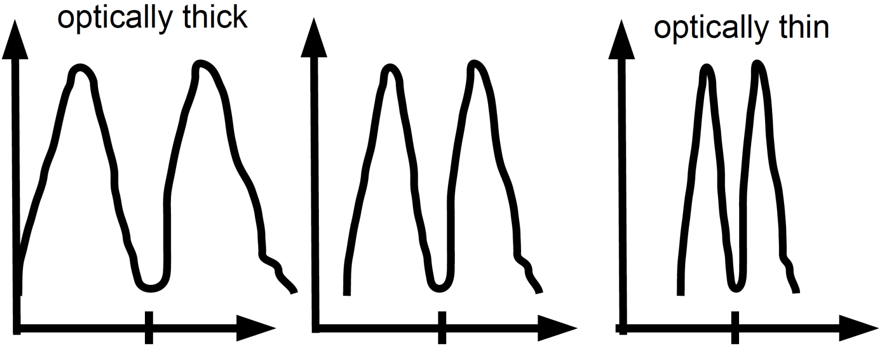


The basics of Lyα RT : kinematics



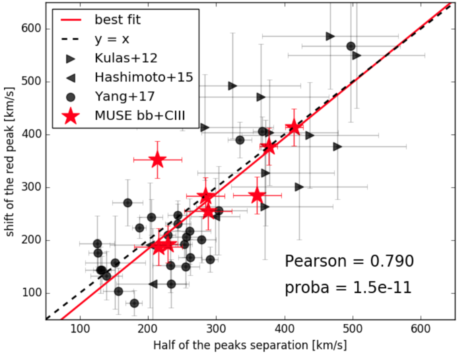
* Lyα is never tracing line of sight velocity, as an absorption line would do, but the bulk velocity of the scattering medium with respect to the Lyα source

The basics of Lyα RT : density

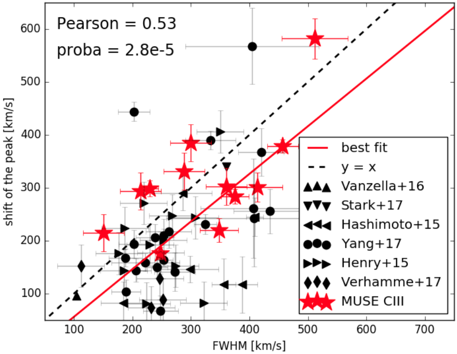


* Lyα spectrum= distribution of the minimun necessary shifts for escape : always follows/traces the path of least opacity

half of the peaks separation



FWHM as proxi for peak shift



Lyα 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 Lyα flux from the center

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Observations, today

- 14 LyC emitters at z < 0.4

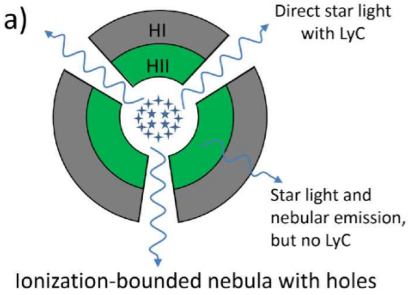
  Bergvall+06, Leitet+13, Borthakur+14, Leitherer+16, Izotov+16a,b,18a,b
- 4 LyC emitters at 2 < z < 4 plus several new candidates from Steidel+18, Fletcher+18, + see Rob's highlight talks *Vanzella+16, Shapley+16, Bian+17, Vanzella+18*
- upper limits on the escape fraction from galaxy populations

  Rutkowski+16,17, Grazian+17

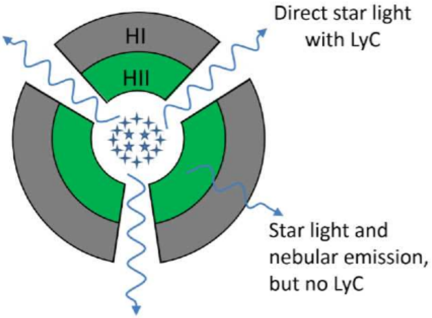
Lyα spectra

Lyα spectra of LyC Emitters : two possible geometries

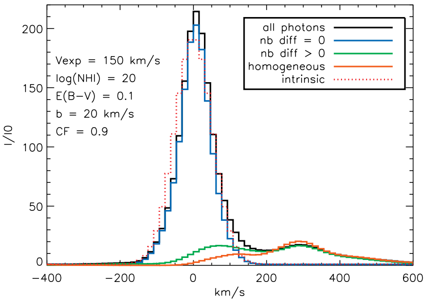
Zackrisson+13



Lyα spectra of LyC Emitters – Triple peaks from holes

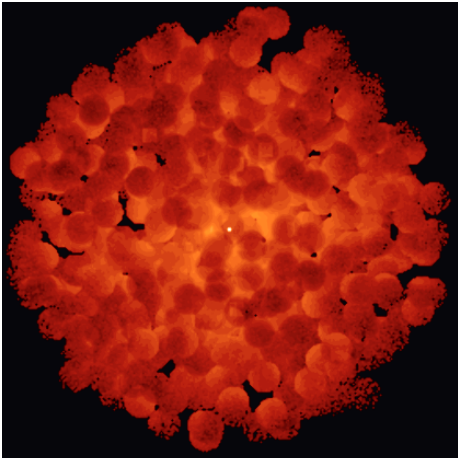


Verhamme+15

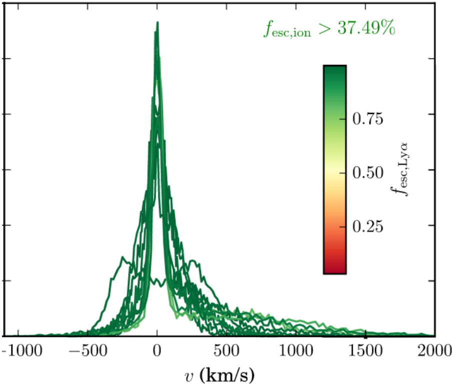


Lyα spectra of LyC Emitters – Triple peaks from holes

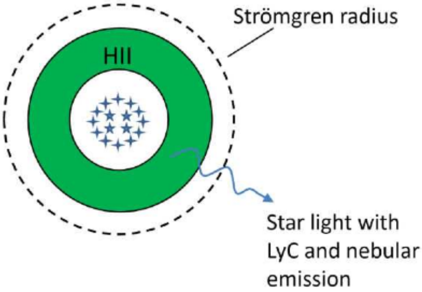
Laursen+13



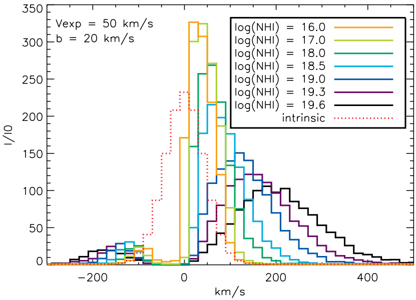
Dijkstra & Grönke 2016



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



Verhamme+15



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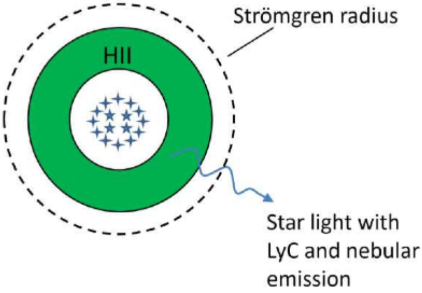
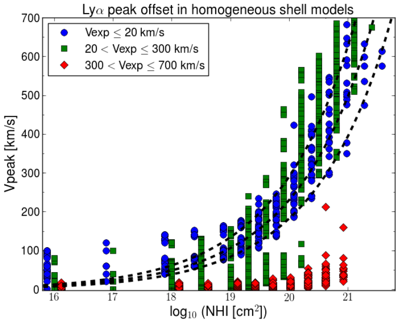
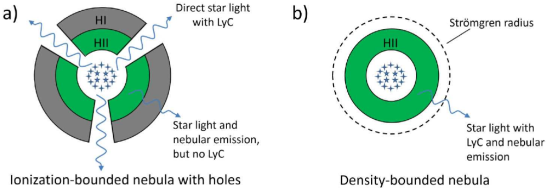


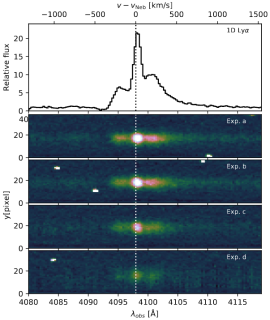
Verhamme+15



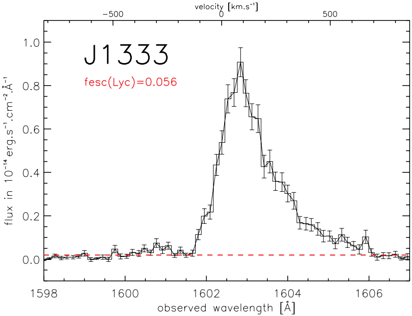
Lyα spectra of LyC Emitters : observations

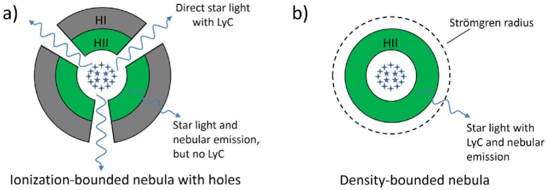


Rivera-Thorsen+17

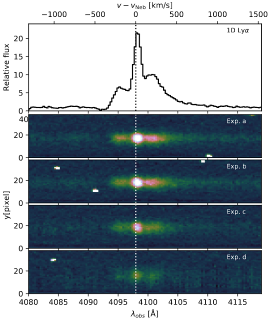


Verhamme+17

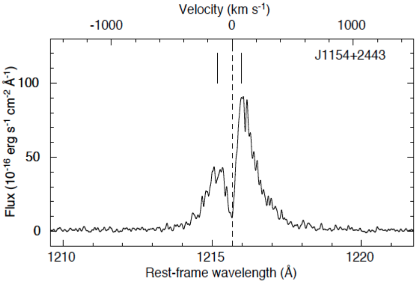




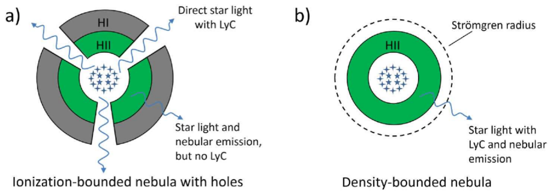
Rivera-Thorsen+17



fesc(LyC) = 46% !, *Izotov+18a*



Lyα spectra of LyC Emitters : observations



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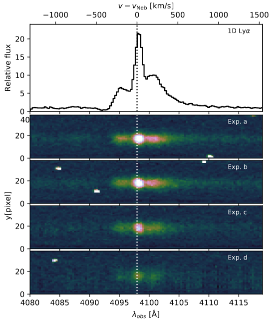
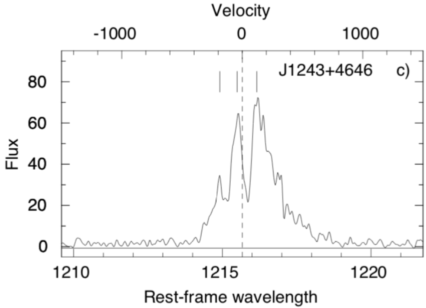
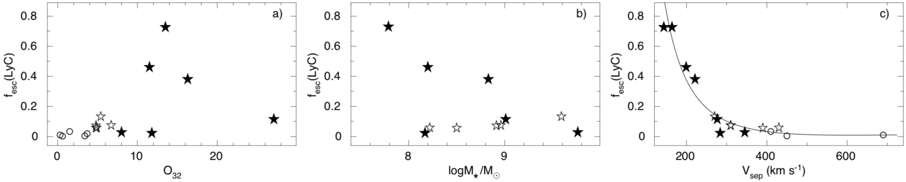


fesc(LyC) = 73% !, *Izotov+18b*



Verhamme+17, Izotov+18

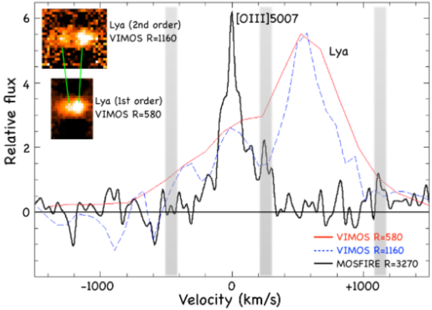


Lessons from local LyC Emitters

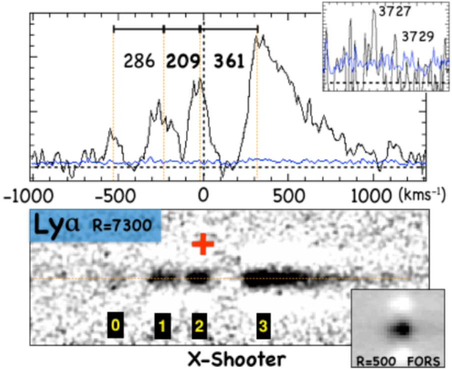
- [OIII]/[OII] ratios does not always correlate with fesc(LyC)
- stronger LyC emitters are the least massive
- Lyα peaks separation decreases with increasing fesc(LyC)

Lyα spectra of LyC Emitters : more observations...

ION 2, *de Barros+16*



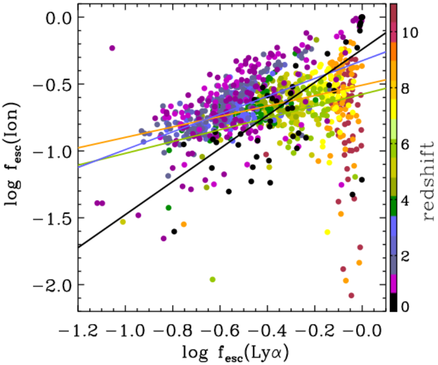
ION 3, *Vanzella+18*



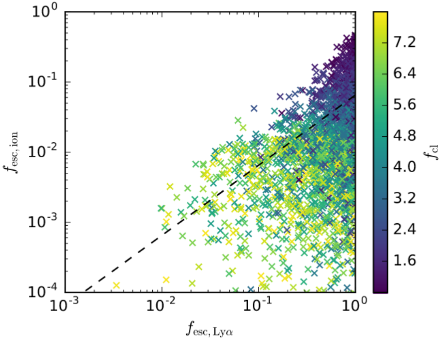
Lyα escape fractions

Lyα vs LyC escape fractions : predictions

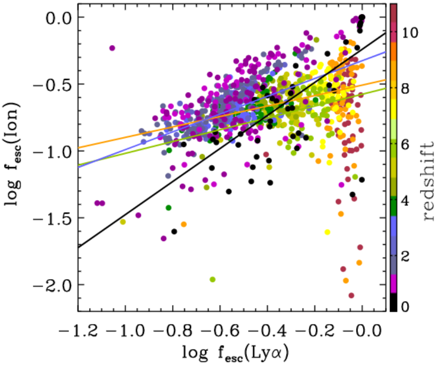
Yajima+14



Dijkstra&Grönke, 2016



Yajima+14



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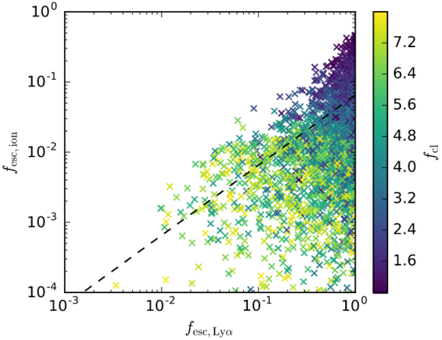
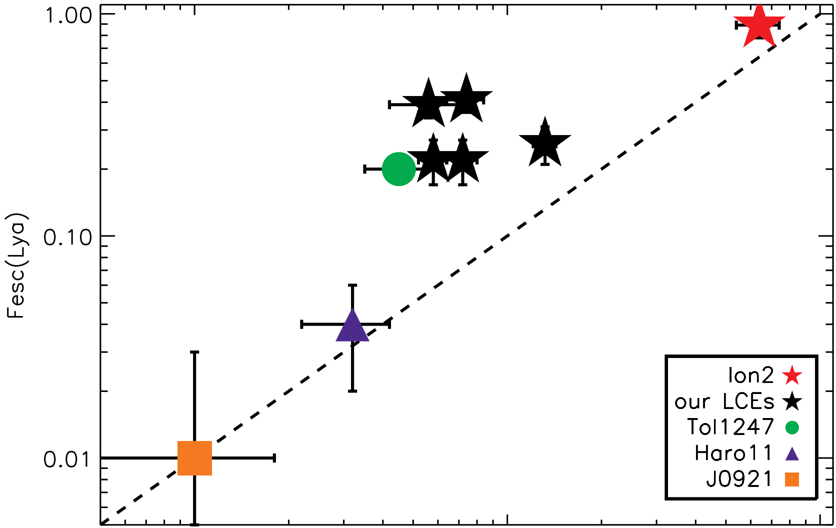


Lyα escape fraction > LyC escape fraction

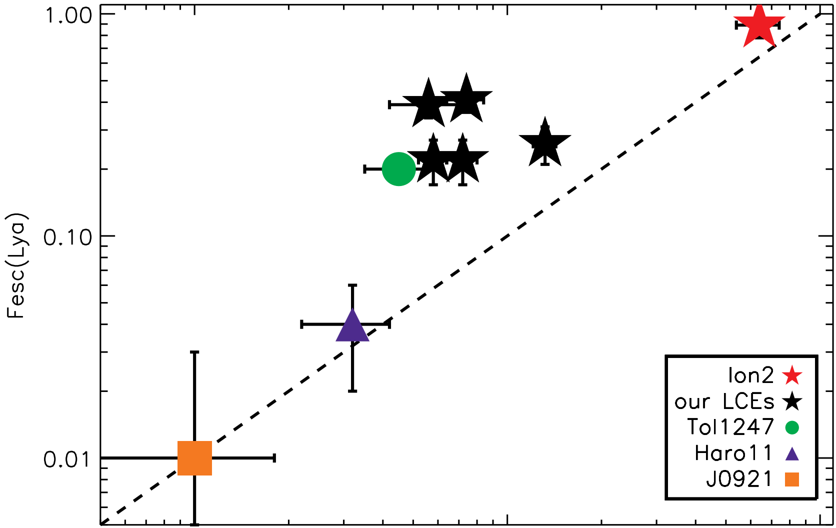
Lyα vs LyC escape fractions : observations

Verhamme+17



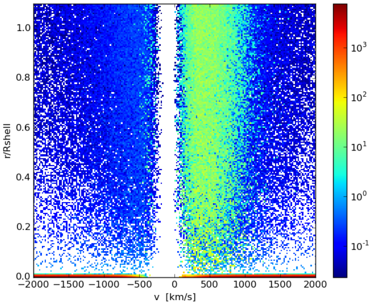
Lyα vs LyC escape fractions : observations

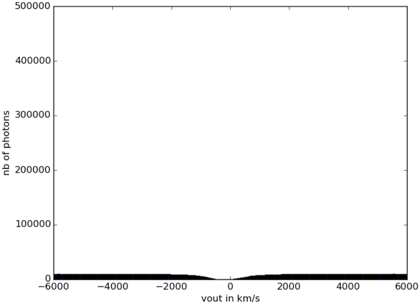
Verhamme+17



Lyα spatial distribution

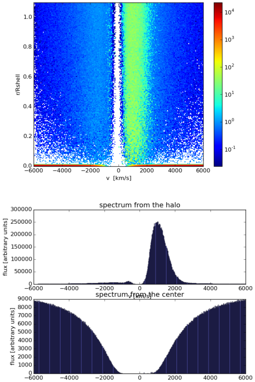
Verhamme, Garel et al, in prep
log(NHI) = 20.2, Vexp = 150 km/s



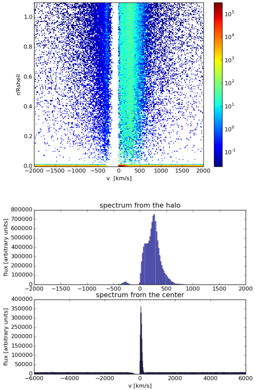


LCEs have no/faint halos

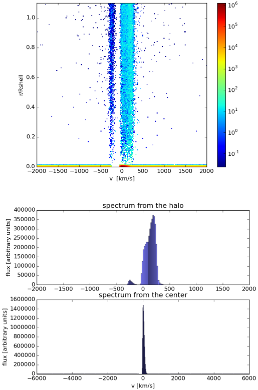
log(NHI) = 21.1
(LBG)



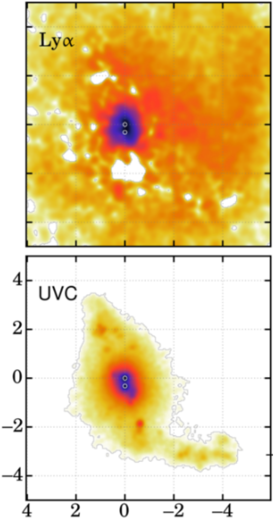
log(NHI) = 19.2
(LAE)

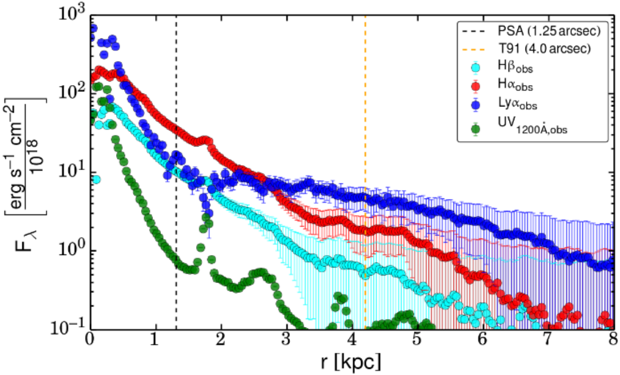


log(NHI) = 17.2
(LCE)



Puschnig+18, fesc(LyC) $\sim 1 - 4\%$





Lya halos of LyC Emitters : insights from observations ?

Marchi+17, see also Yang+16

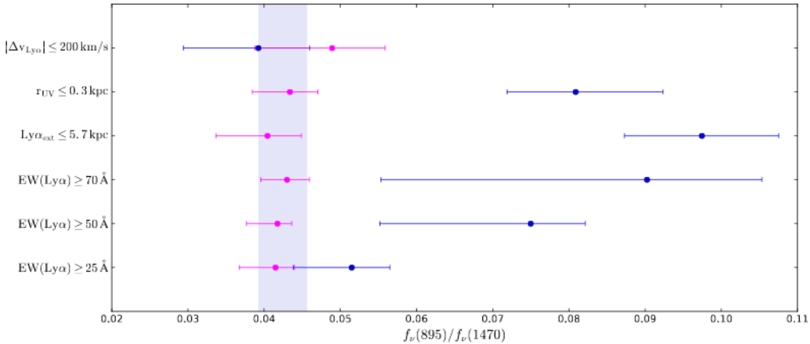
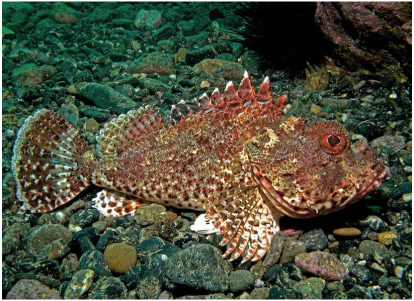


Fig. 3. Flux density ratios evaluated from the stacks of the samples in the y-axis (blue dots) and from the complementary samples (magenta dots) as indicated in Table 1. The lavender vertical band is the 1σ confidence interval evaluated for the total sample of 201 galaxies.

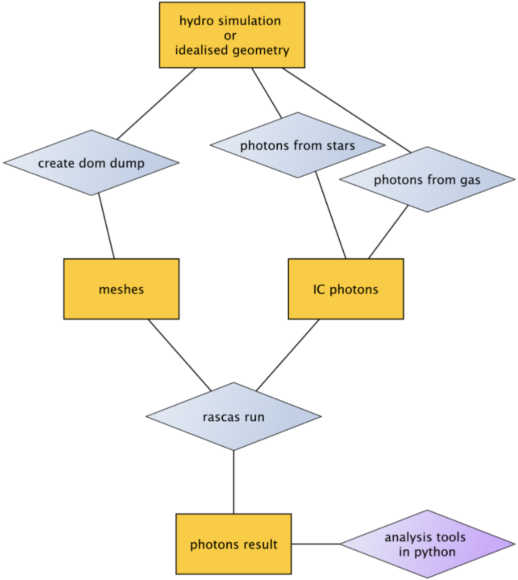
Lyα properties of a virtual LyC emitter

New RT code : RaSCaS (aka MCLya v.2.0)

la rascasse



la bouillabaisse de Marseille



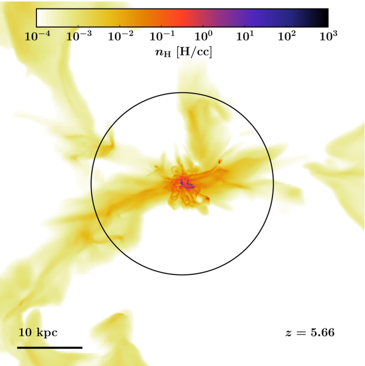
Several applications :

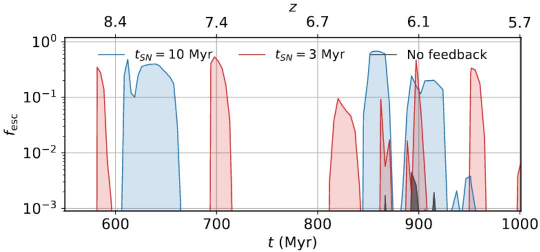
- $\mathrm{Ly}\alpha$(+D +dust) scattering
- metallic resonance lines (SiII, MgII, FeII)
- dust scattering of stellar light
- LyC escape fraction
- public release... soon

Michel-Dansac+18 in prep /w Verhamme

Lyα emission from a virtual $z \sim 6$ LyC Emitter

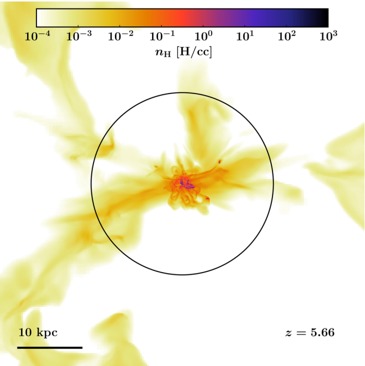
Trebitsch+17



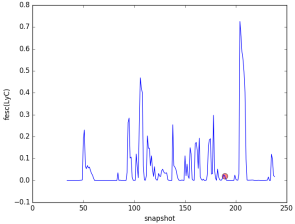


Lyα emission from a virtual $z \sim 6$ LyC Emitter

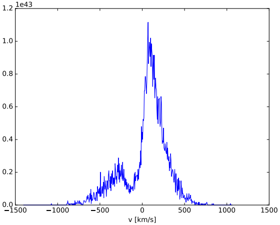
Trebitsch+17



LyC

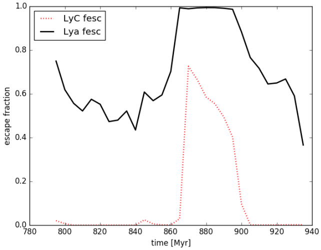


Lyα

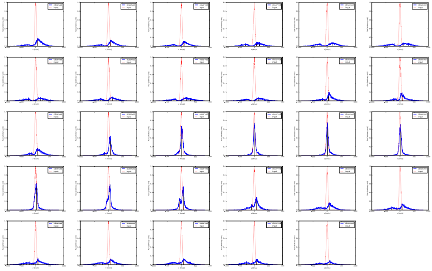


Lyα emission from a virtual $z \sim 6$ LyC Emitter

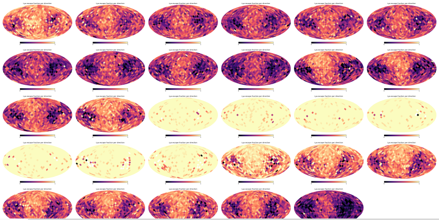
Lyα and LyC escape fractions vs time



Lyα spectra

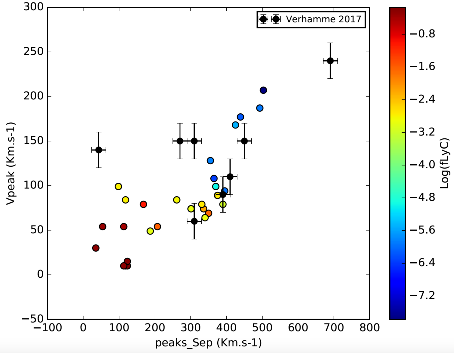


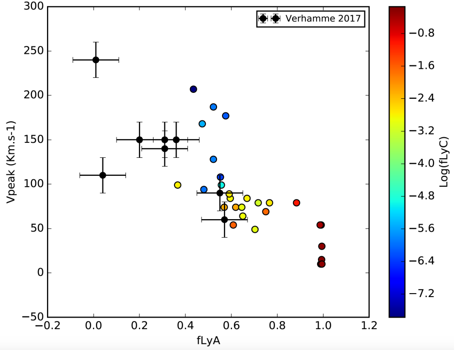
Lyα escape fraction maps



Lyα 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, Lyα is confirmed, O32 disgarded
* on going : calibrate the indirect probes on simulations
* future : understand why these galaxies are leaking, be ready for JWST