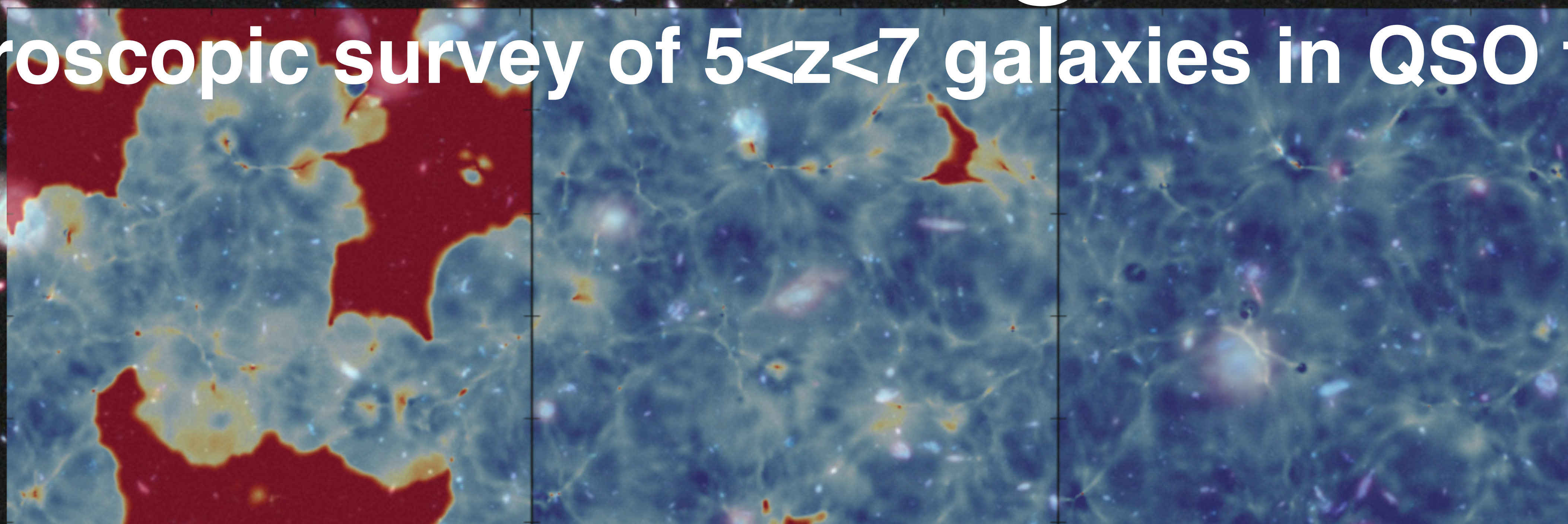
On the Role of Galaxies and AGN in Reionising the IGM:

spectroscopic survey of $5<z<7$ galaxies in QSO fields



Koki Kakiichi

University College London

With Richard Ellis, Nicolas Laporte, Adi Zitrin, Anna-Christina Eilers, Emma Ryan-Weber, Romain Meyer, Brant Robertson, Dan Stark, Sarah Bosman

Marseille 2018

What reionized the Universe?

Gunn & Peterson (1965) paper

NOTES

ON THE DENSITY OF NEUTRAL HYDROGEN IN INTERGALACTIC SPACE

The flux can come from three sources; normal galaxies, radiogalaxies, and QSS's, and the intergalactic medium itself. The contribution from the first two sources can be estimated roughly, and almost certainly does not exceed 3×10^{-24} units at $z = 2$, of which about 10 per cent is from quasi-stellar sources (assuming that one can extrapolate the visual radiation into the UV with a spectral index of -0.7, and assuming a present space density of $[600\ \mathrm{Mpc}]^{-3}$).

50 years old problem!

What reionized the universe?

Problem 1 “escape fraction”

COSMIC REIONIZATION AFTER PLANCK: COULD QUASARS DO IT ALL?

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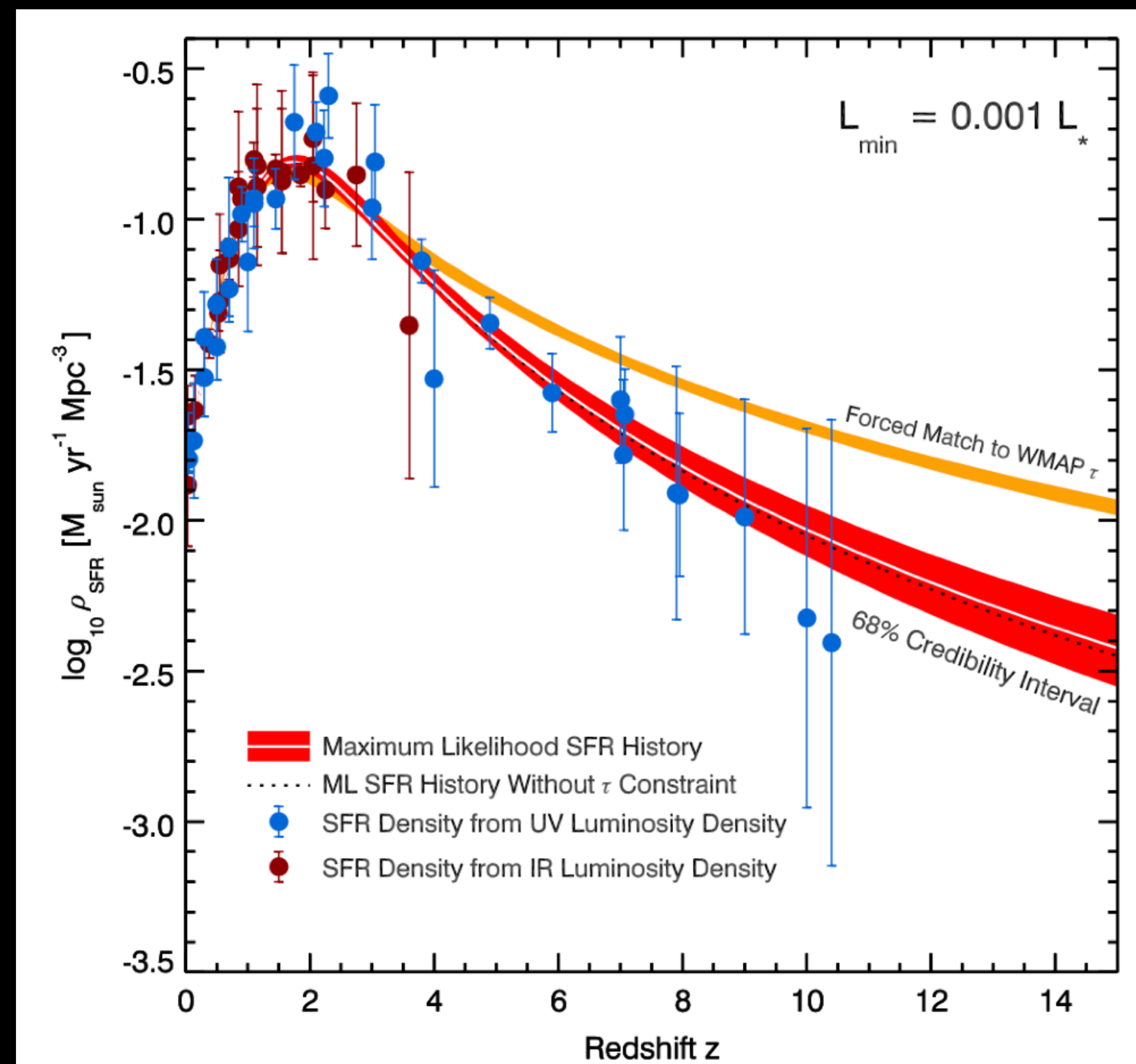
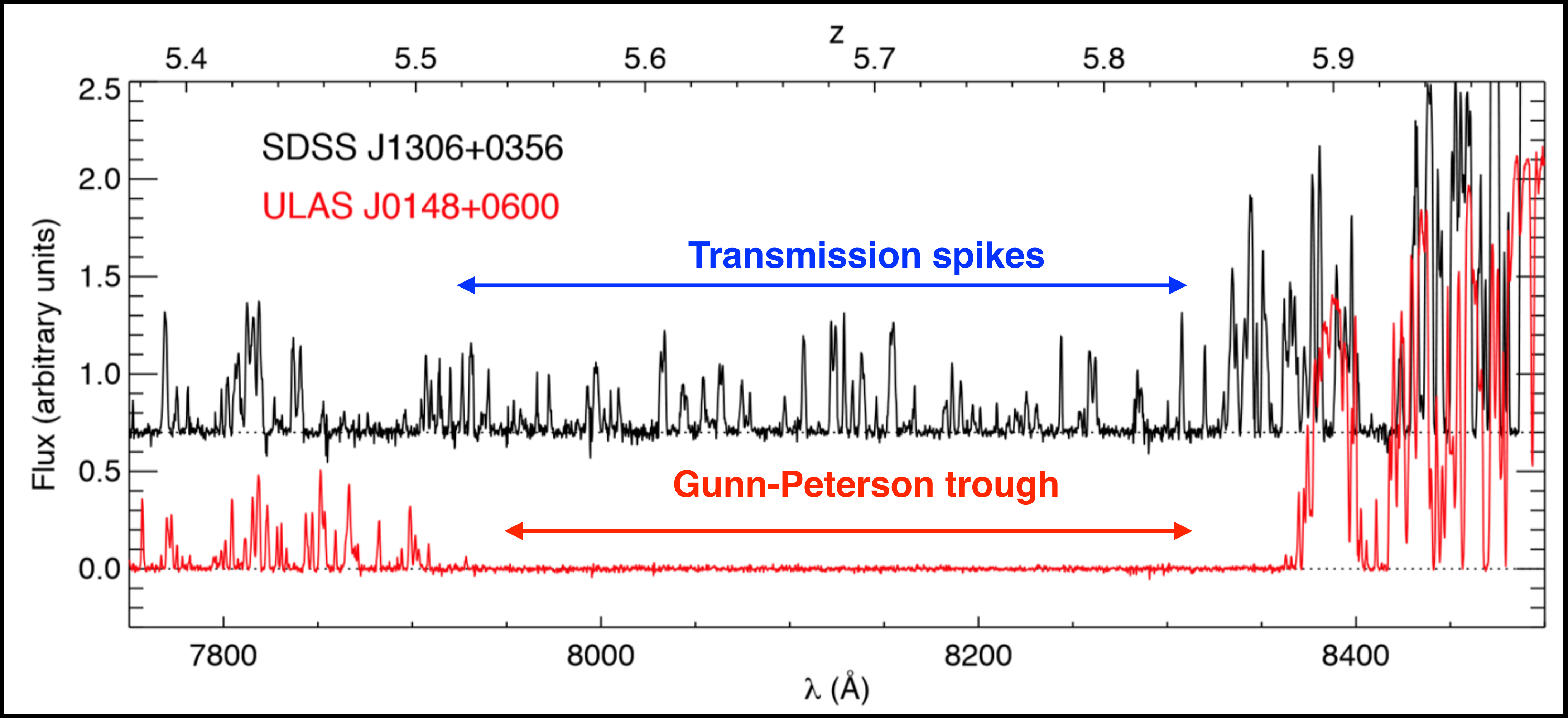


Robertson+15

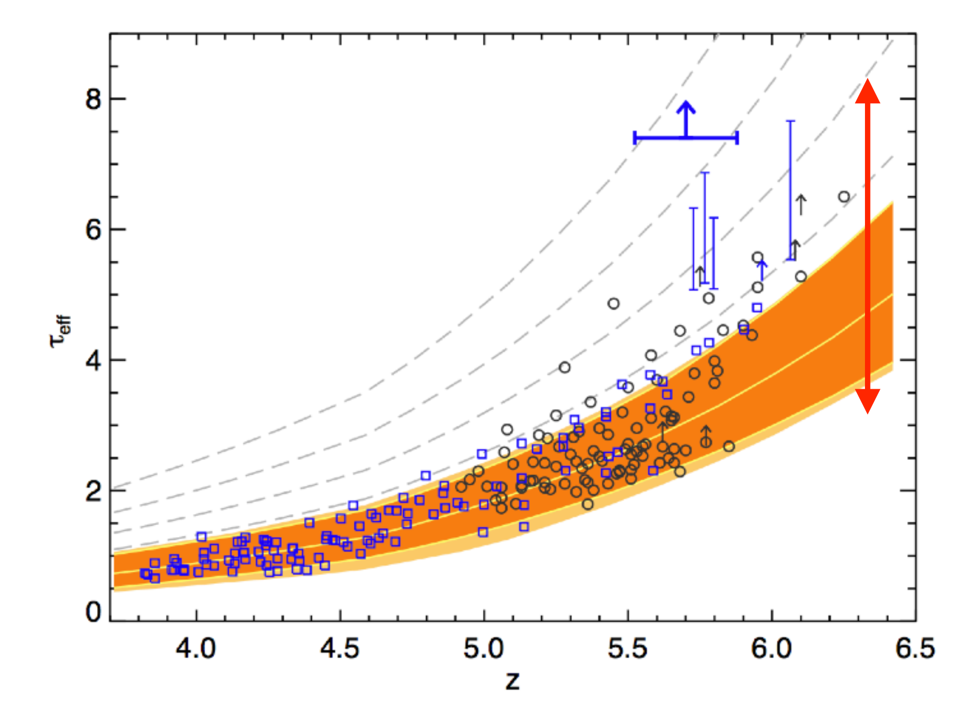
1.
HST galaxy demographics can drive reionisation but “Unknown f_{esc}”

What reionized the universe?

Problem 2 "Faint vs Luminous systems"



Becker+15
also Bosman+18



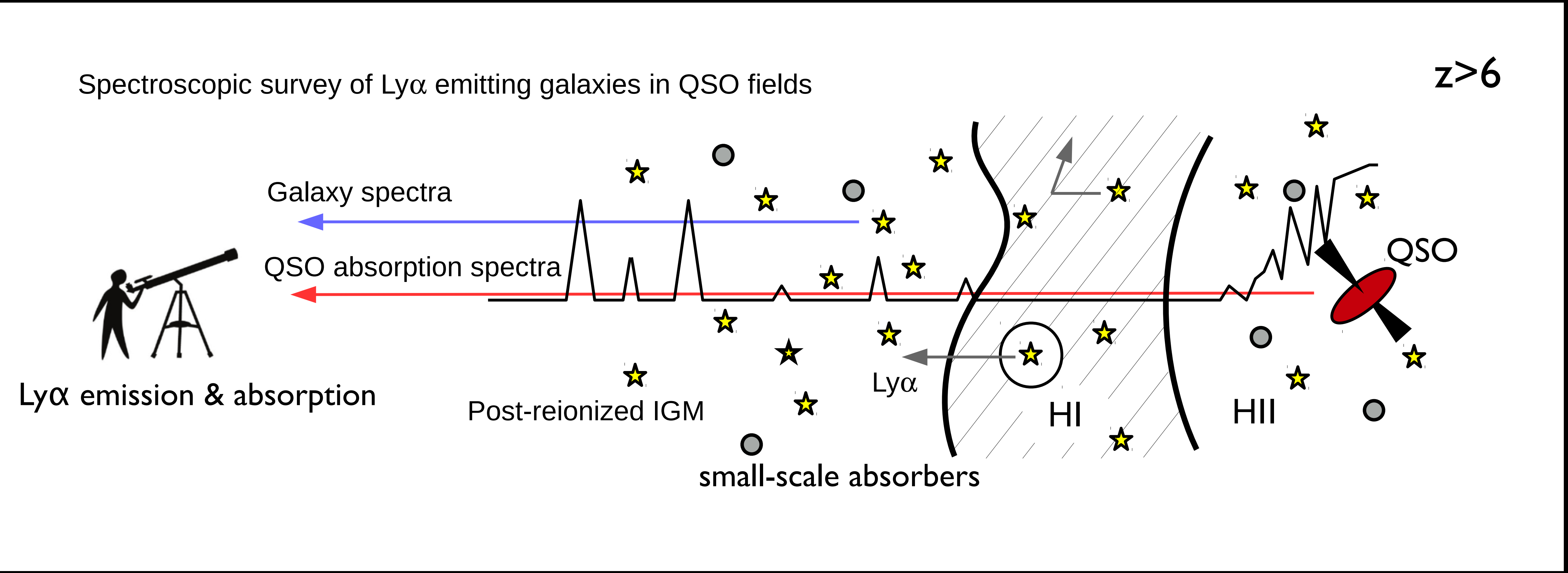
2.
Huge variation of the intergalactic Lyman alpha optical depth at z>5.5

Difficult with faint galaxies..
Need of luminous systems, e.g. AGN?
thermal fluctuations? mean free path?

e.g. Chardin+16, D'Aloisio+16, Davies+16

Testing what reionized the universe:

Probing the direct influence of galaxies on the Lyα forest at z>5



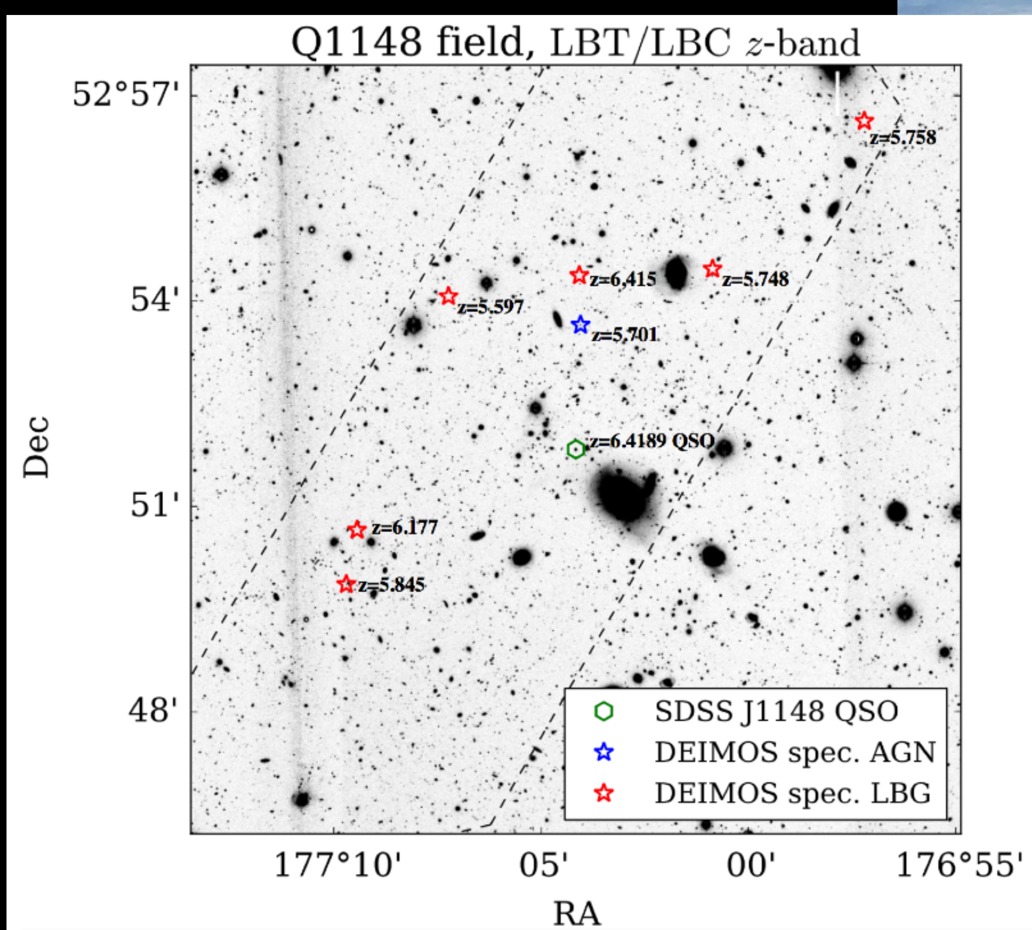
"Lyα probing Lyα"

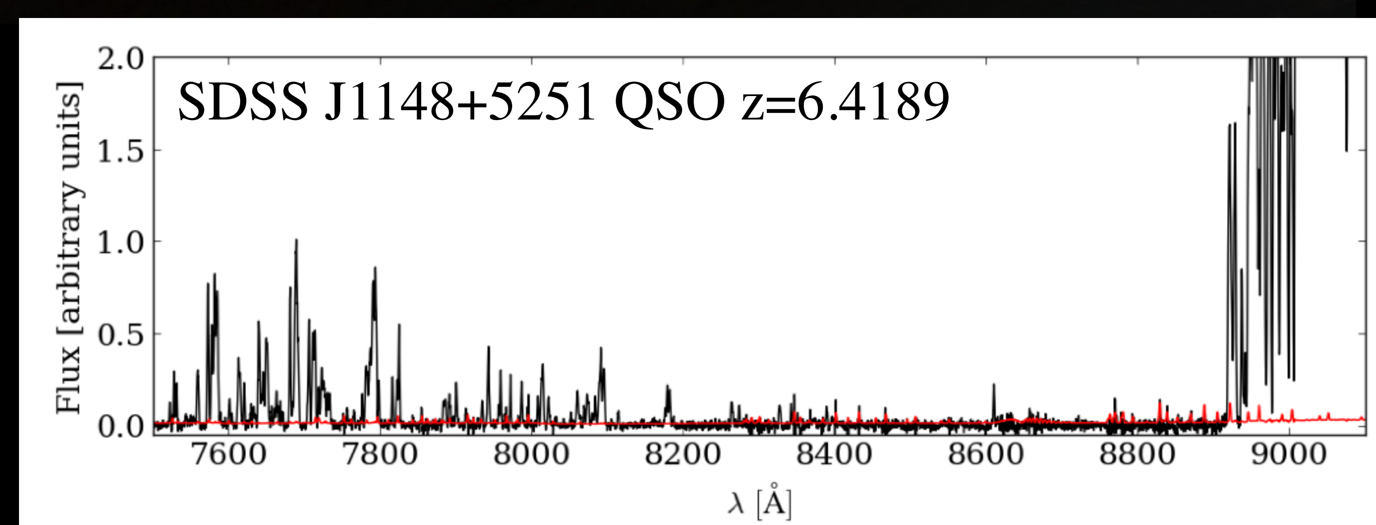
A reionisation-era extension of idea in
COS-halos (Tumlinson et al 2013 etc)
Keck Baryonic Structure Survey (Steidel et al) e.g. Rudie+12, Turner+14
and Quasar Probing Quasar Survey (Hennawi & Prochaska et al) e.g. Prochaska+13, Schmidt+17

Keck spectroscopy of 5<z<7 galaxies around the Lyα forest of a background QSO field

Survey design:

DEIMOS spectroscopy of bright LBGs
(r- and i-dropouts, z mag < 25.5)
in the foreground of well-known QSO z~6
(Keck/ESI QSO spectra)

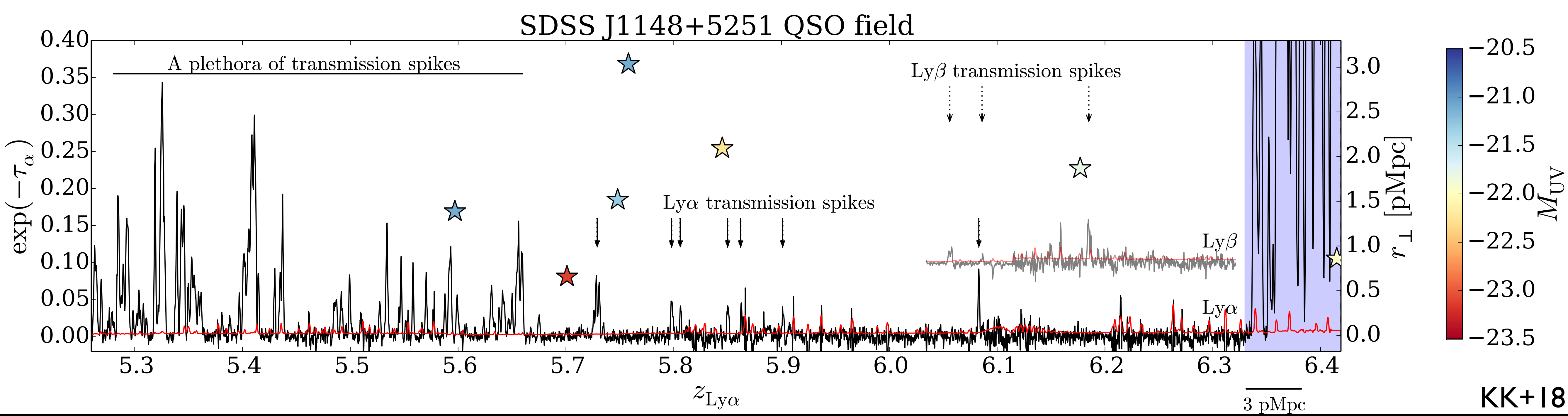




Kakiichi+2018 (arXiv:1803.02981)

Lyα emitting Lyman-break galaxies in J1148+5251 QSO field

"Direct mapping of the physical state of the IGM around galaxies at z~6"



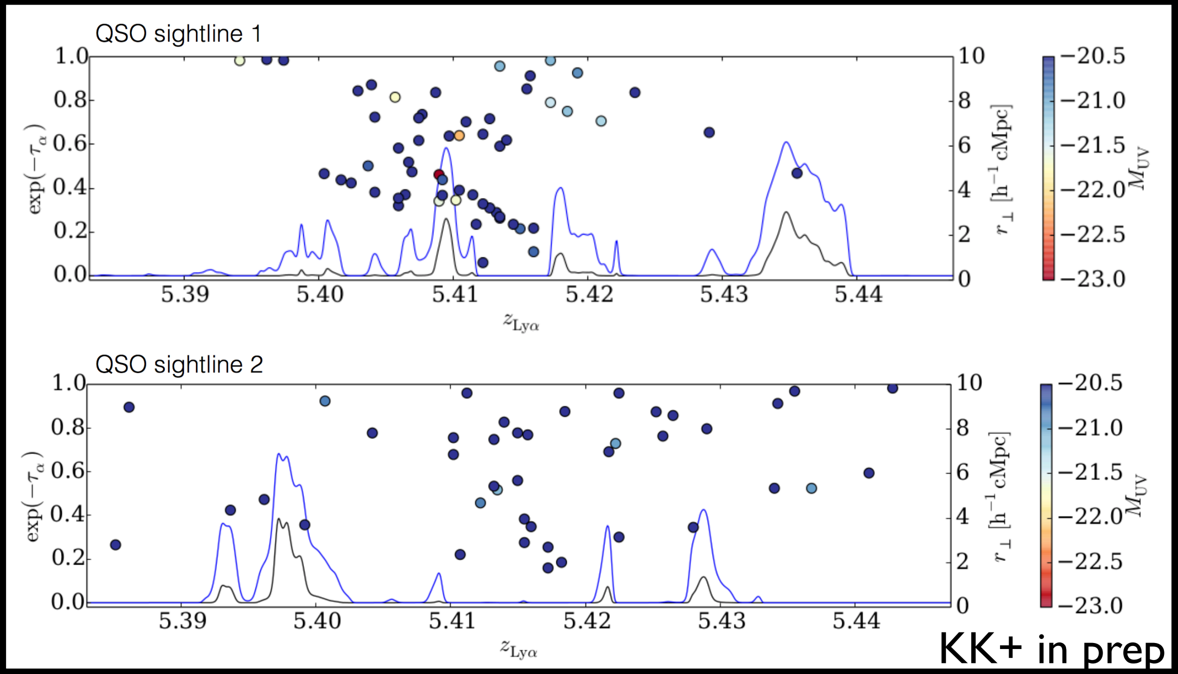
Cosmological hydrodynamic simulation
+ simple radiative transfer

Ionising UV radiation from galaxies →
more Lyα transmission spikes around galaxies
but the individual associations are "*stochastic*"

Lyα optical depth

$$\tau_\alpha \simeq 11(1+\delta_m)^2 \left(\frac{\Gamma_{\rm HI}}{10^{-12}\ {\rm s}^{-1}}\right)^{-1} \left(\frac{T}{10^4\ {\rm K}}\right)^{-0.72} \left(\frac{1+z}{7}\right)^{9/2}$$

Gas density   UV background   Temperature



Lya emitting Lyman-break galaxies in J1148+5251 QSO field

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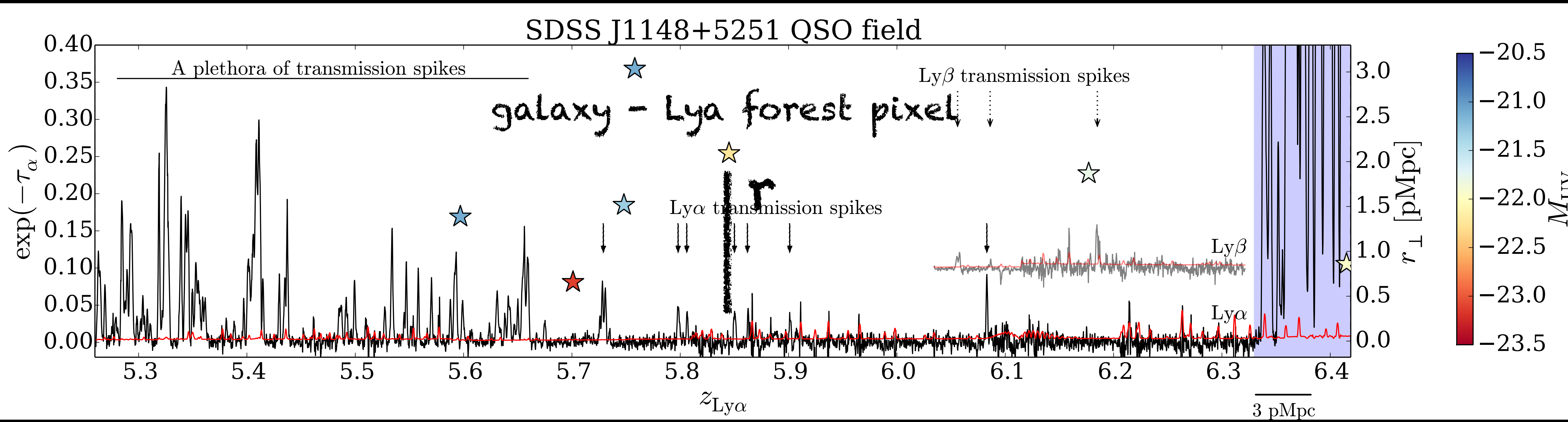

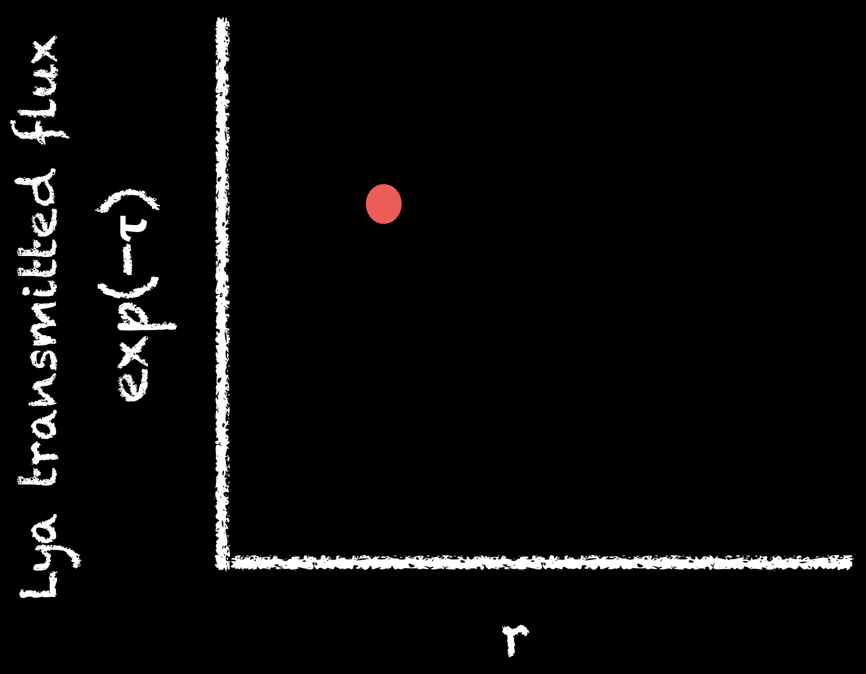

Cross-correlate… ?

Lyα emitting Lyman-break galaxies in J1148+5251 QSO field

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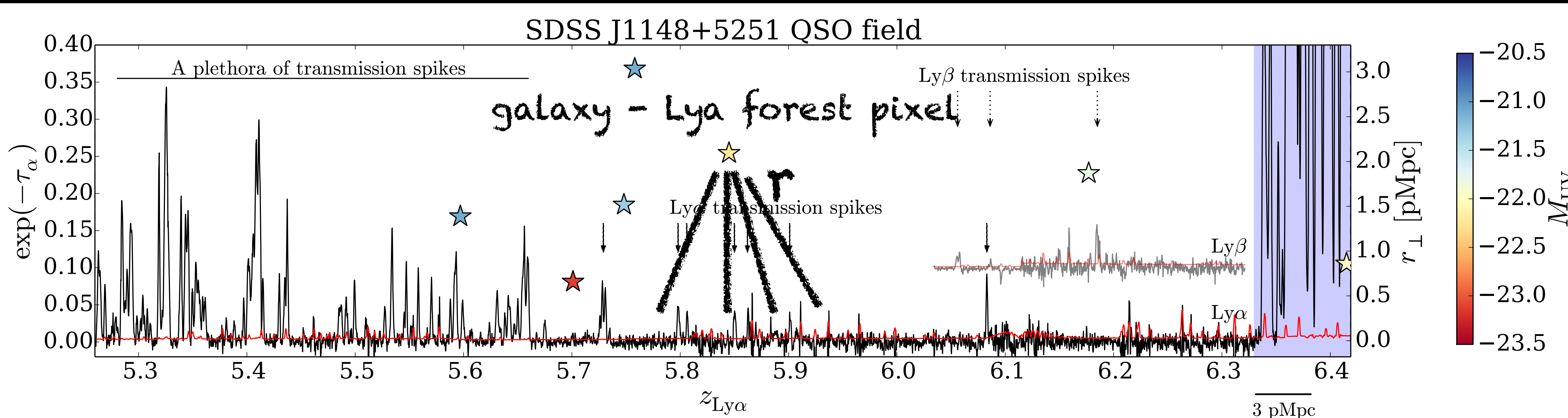

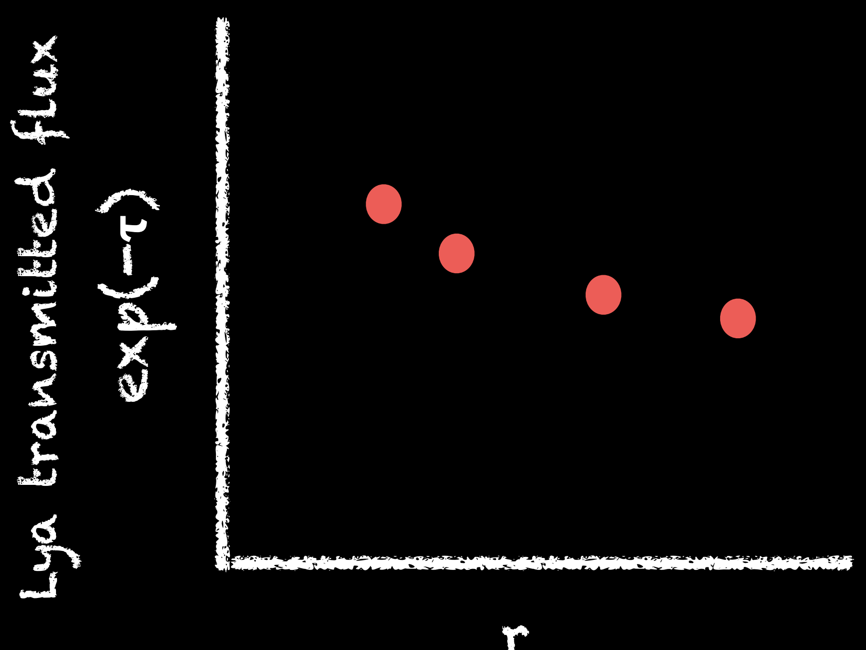

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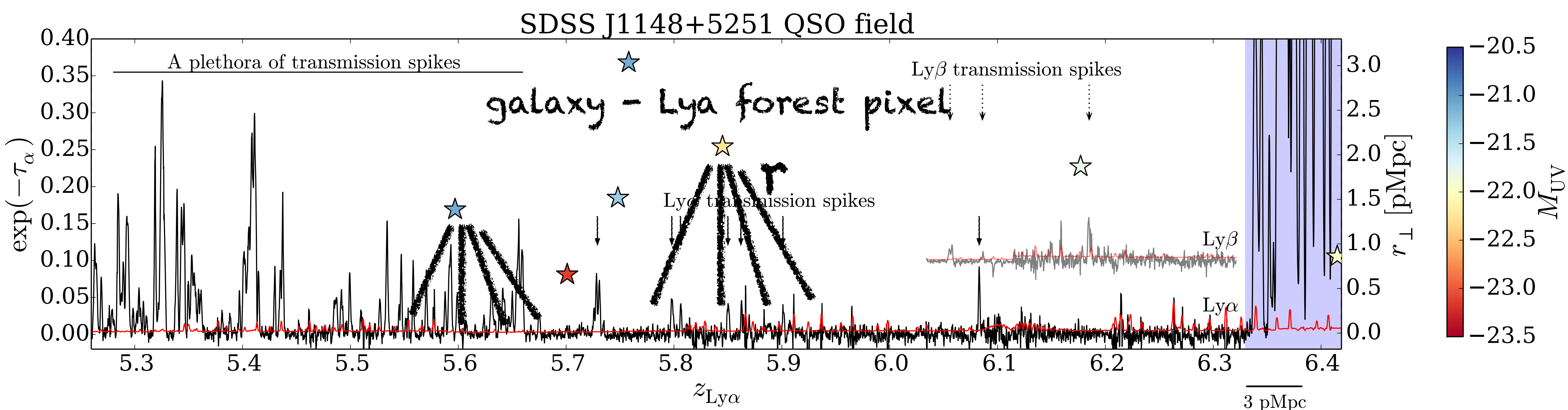

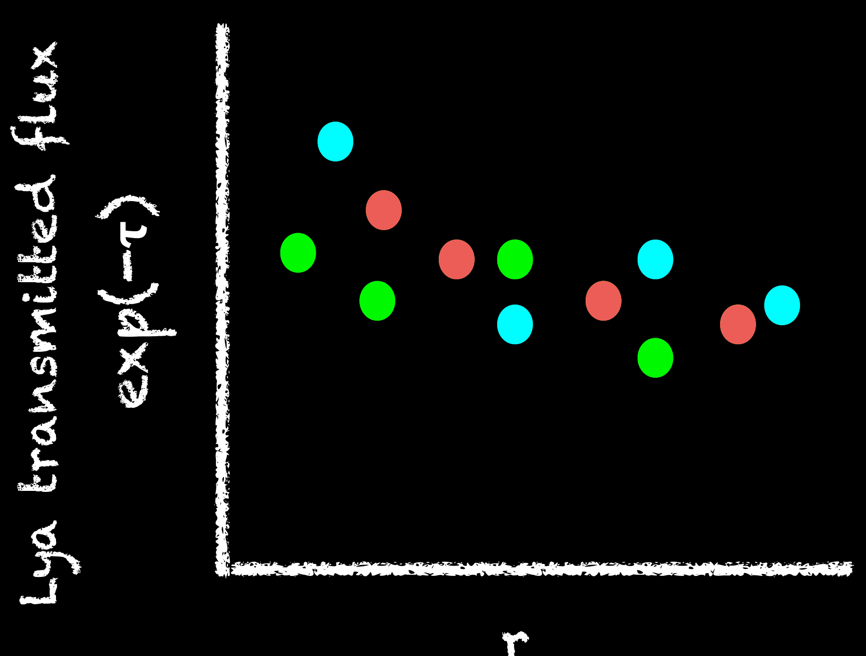

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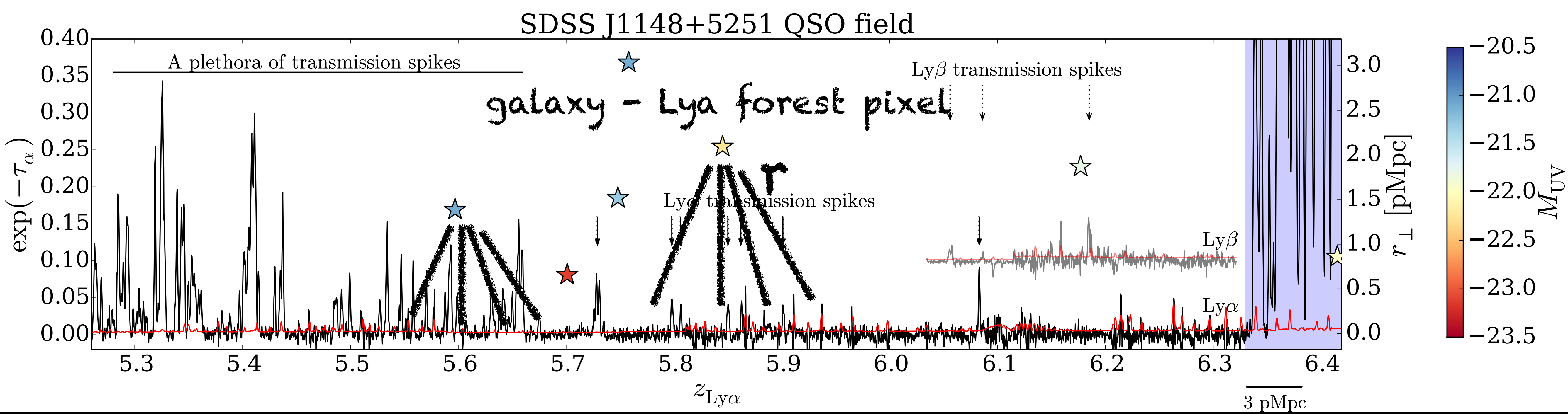
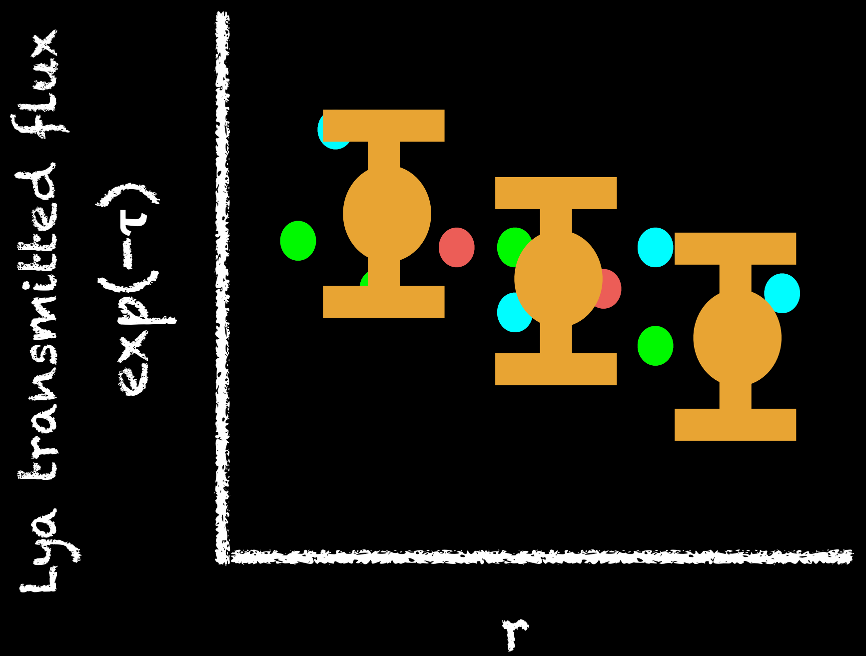
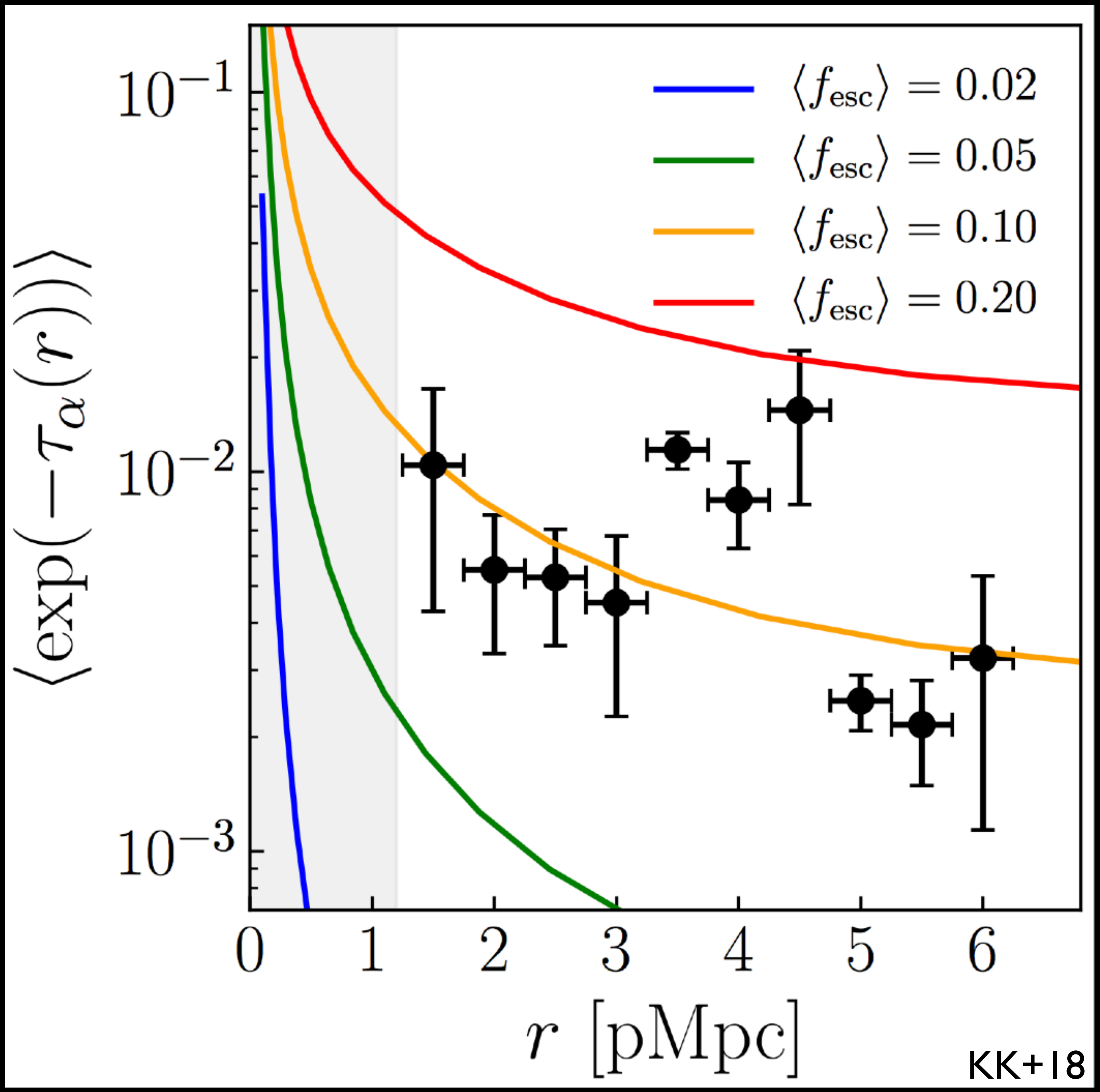




Cross-correlate... well, just take the MEAN Lya transmitted flux around LBGs

Mean Lyα transmitted flux around LBGs at z~5.8

More Lyα forest transmission
(=IGM more ionised)



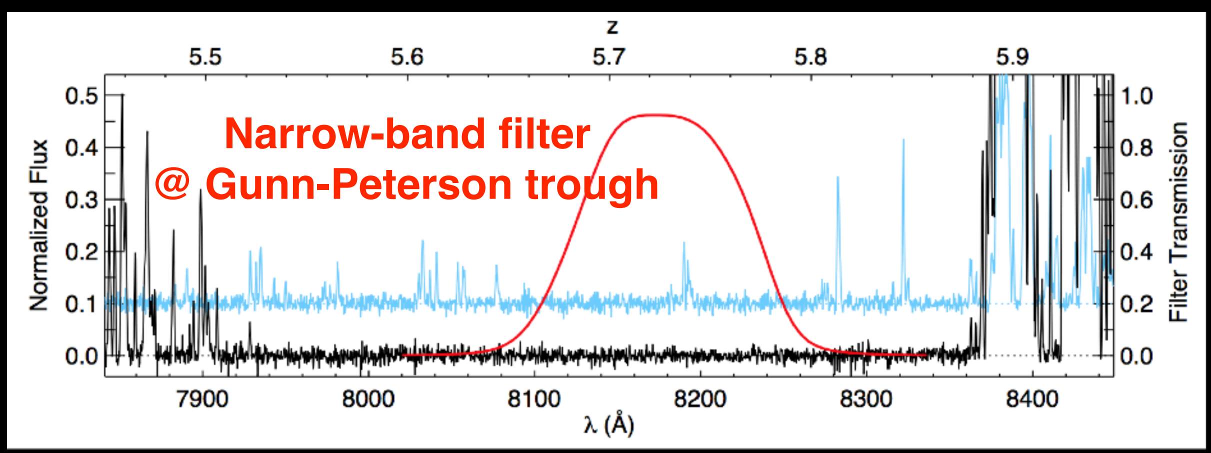
Closer to galaxies

*"**Tentative**", but promising, evidence of*
*"**Statistical HI proximity effect**" ?*

More QSO field observations are on-going and now being analysed to secure this!!

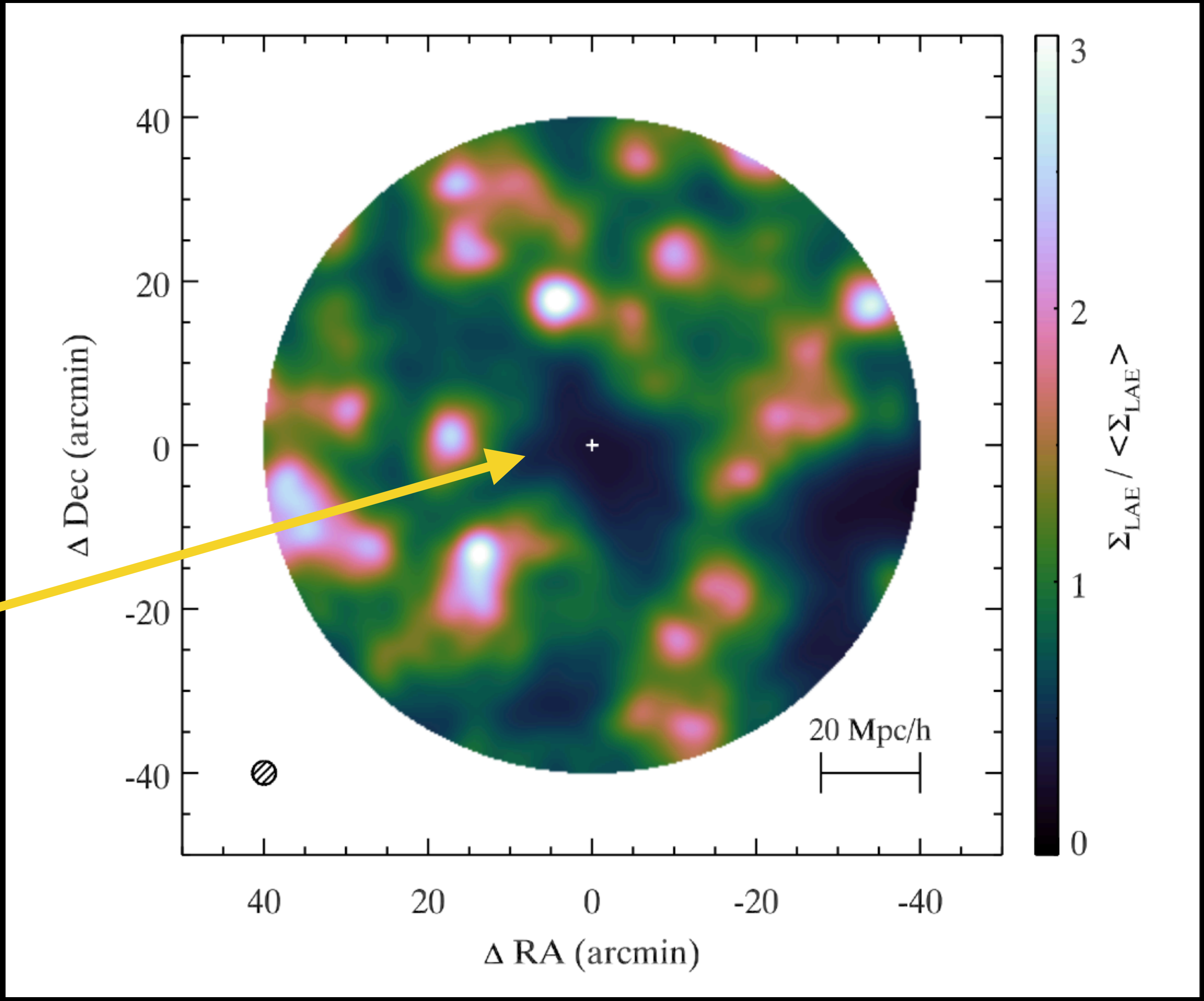
Independent test of statistical HI proximity effect

Statistical HI proximity effect →
more galaxies around high Lyα forest transmission
⬍
"less galaxies around Gunn-Peterson troughs"



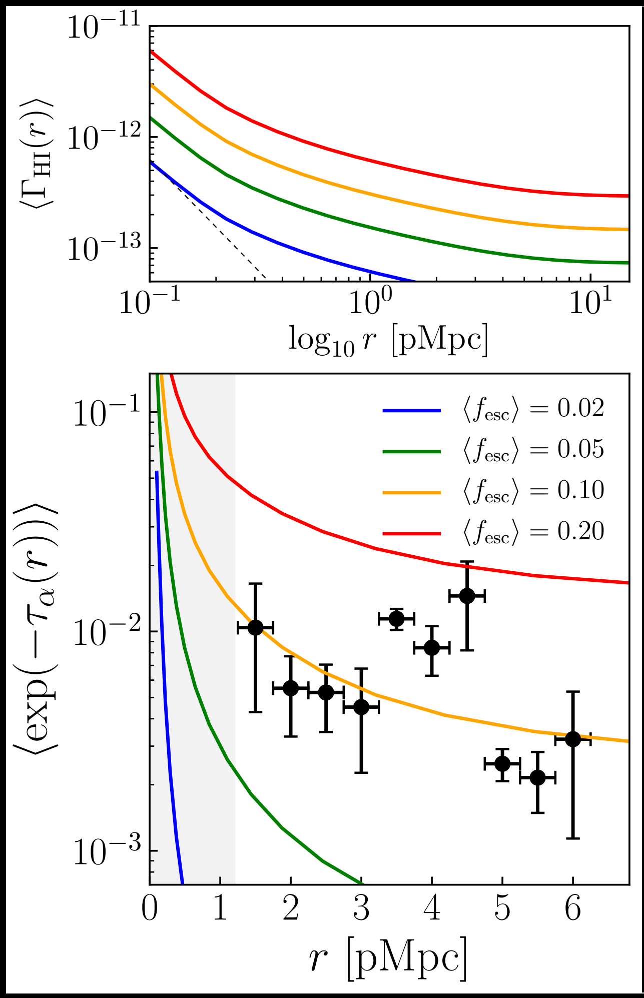
Becker+18

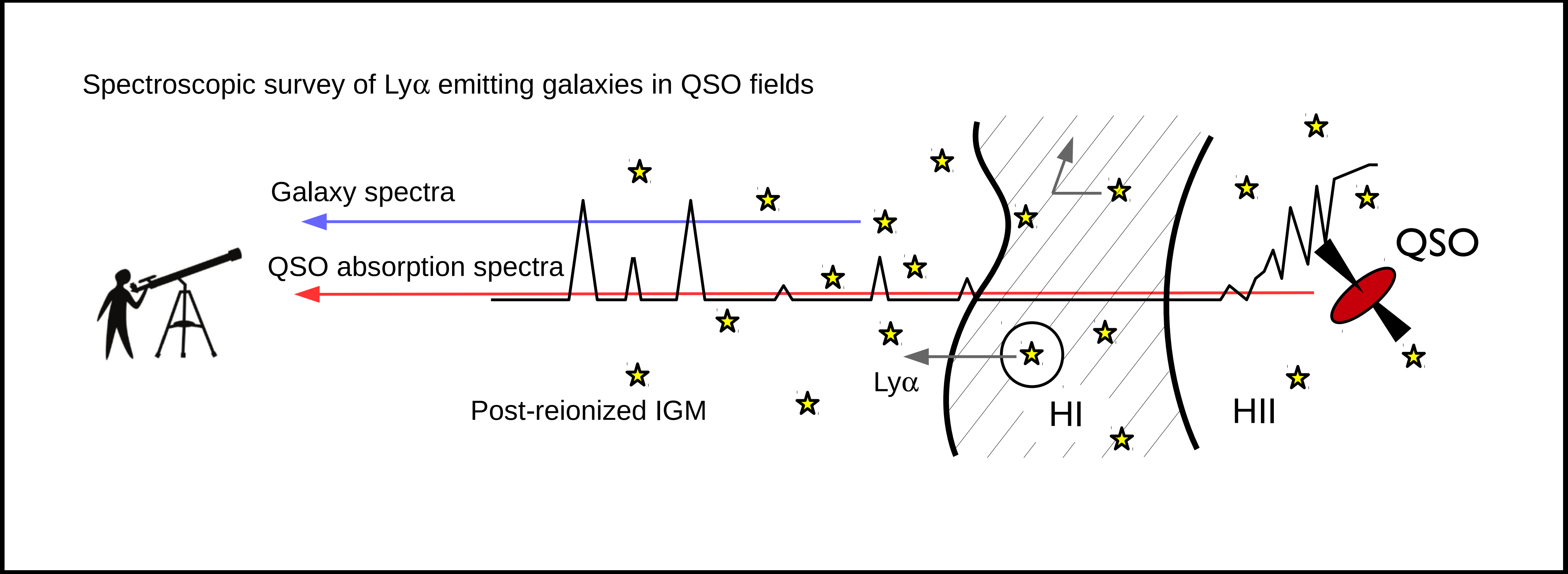
Subaru/HSC narrow-band observation of z~5.7 LAEs around the large Gunn-Peterson trough finds a *'deficit' of LAEs.*



→ **Independent confirmation of the proximity effect around galaxies**

Interpretation:
Mean Lyα transmitted flux around LBGs at z~5.8





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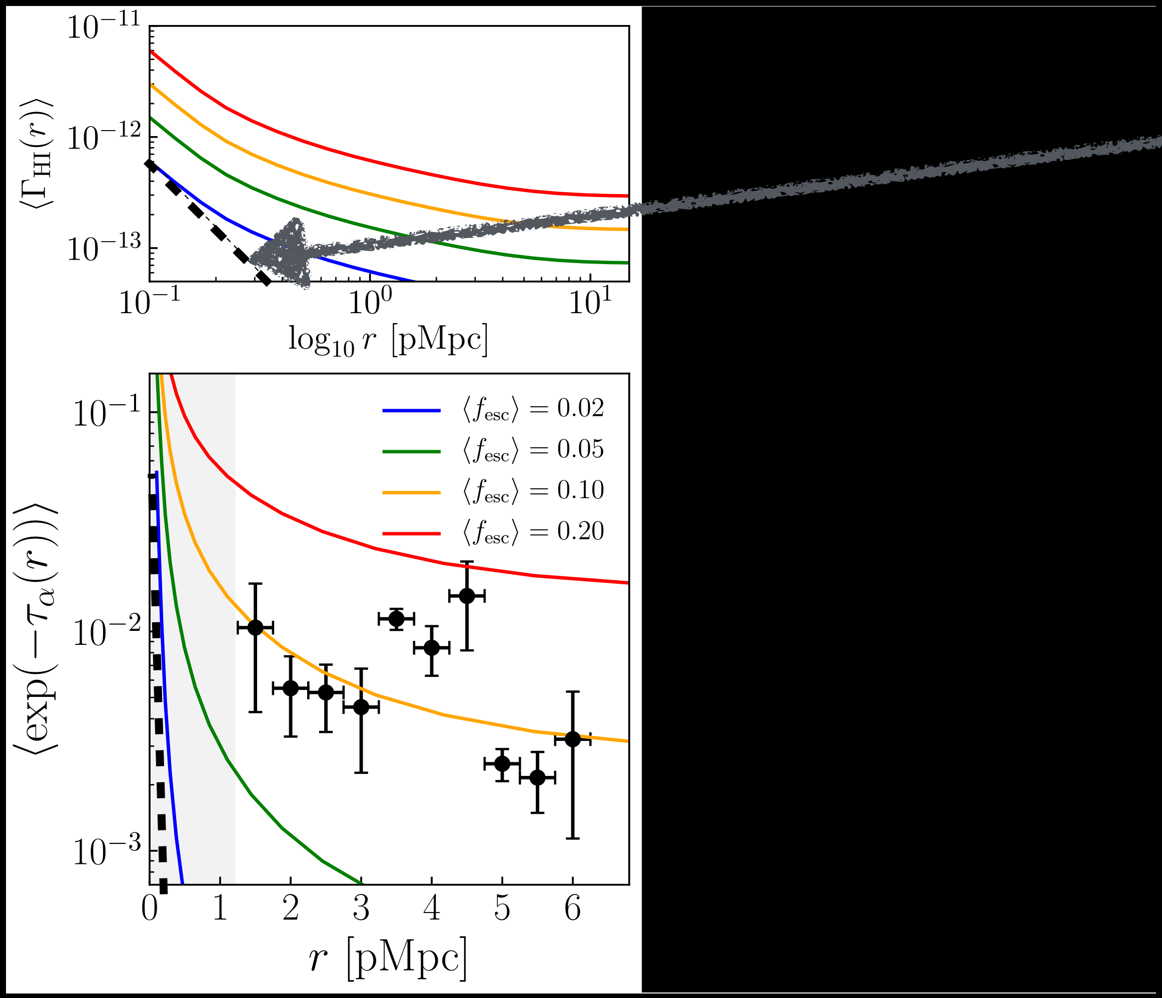
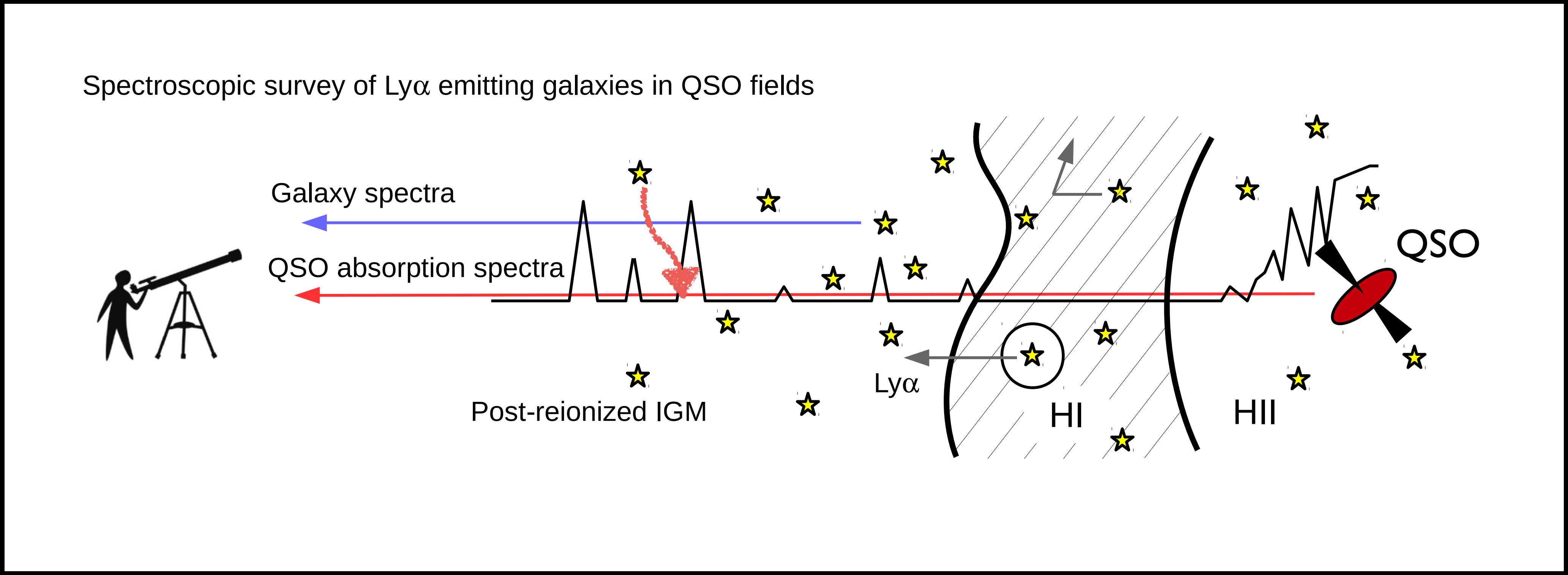


Ionising radiation from the 'detected' galaxies is too small to explain the observation (statistical HI proximity effect)



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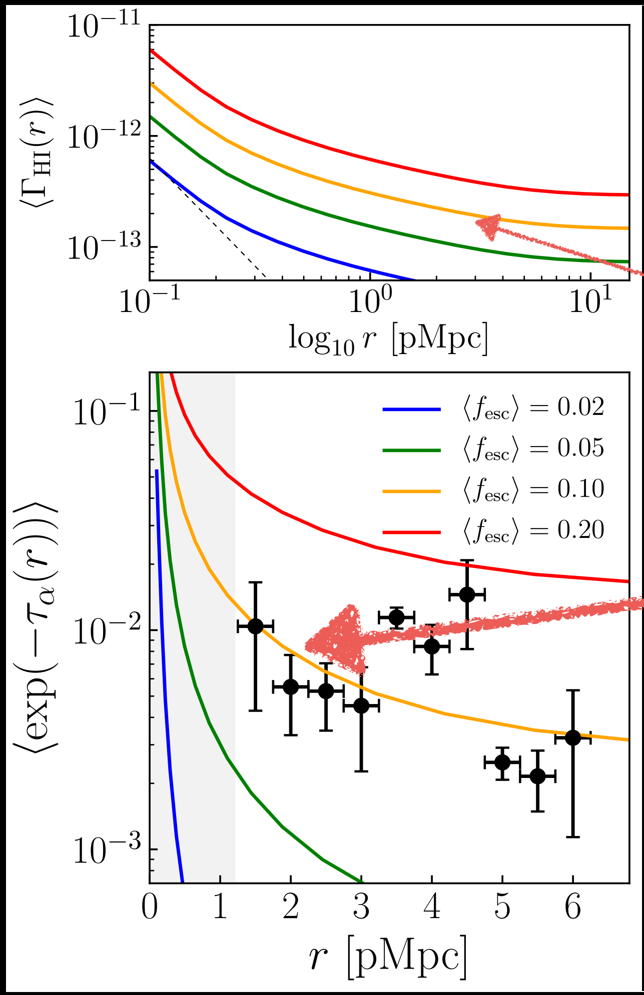
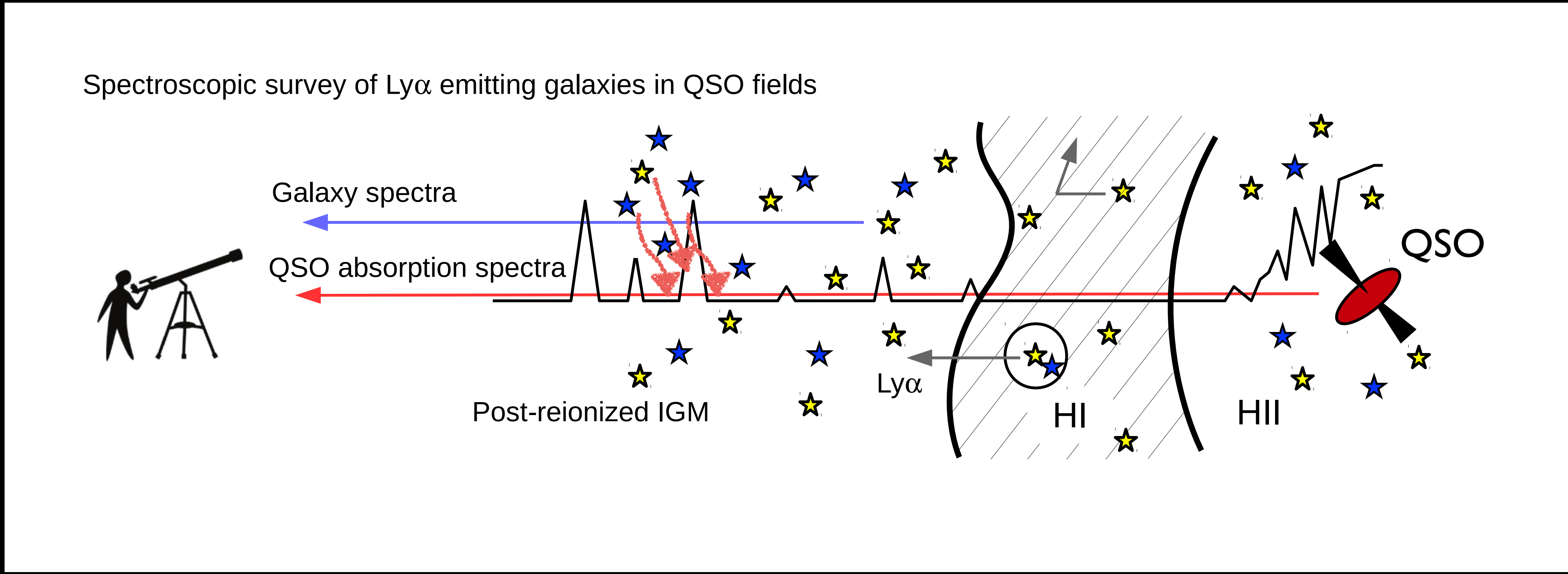


Ionising radiation from the 'detected' galaxies is too small to explain the observation (statistical HI proximity effect)

Need "*faint unseen galaxies clustering around the detected galaxies*" & their collective ionising radiation

(modelled by CLF/HOD framework and joint analysis of luminosity function and angular galaxy clustering, then do RT)



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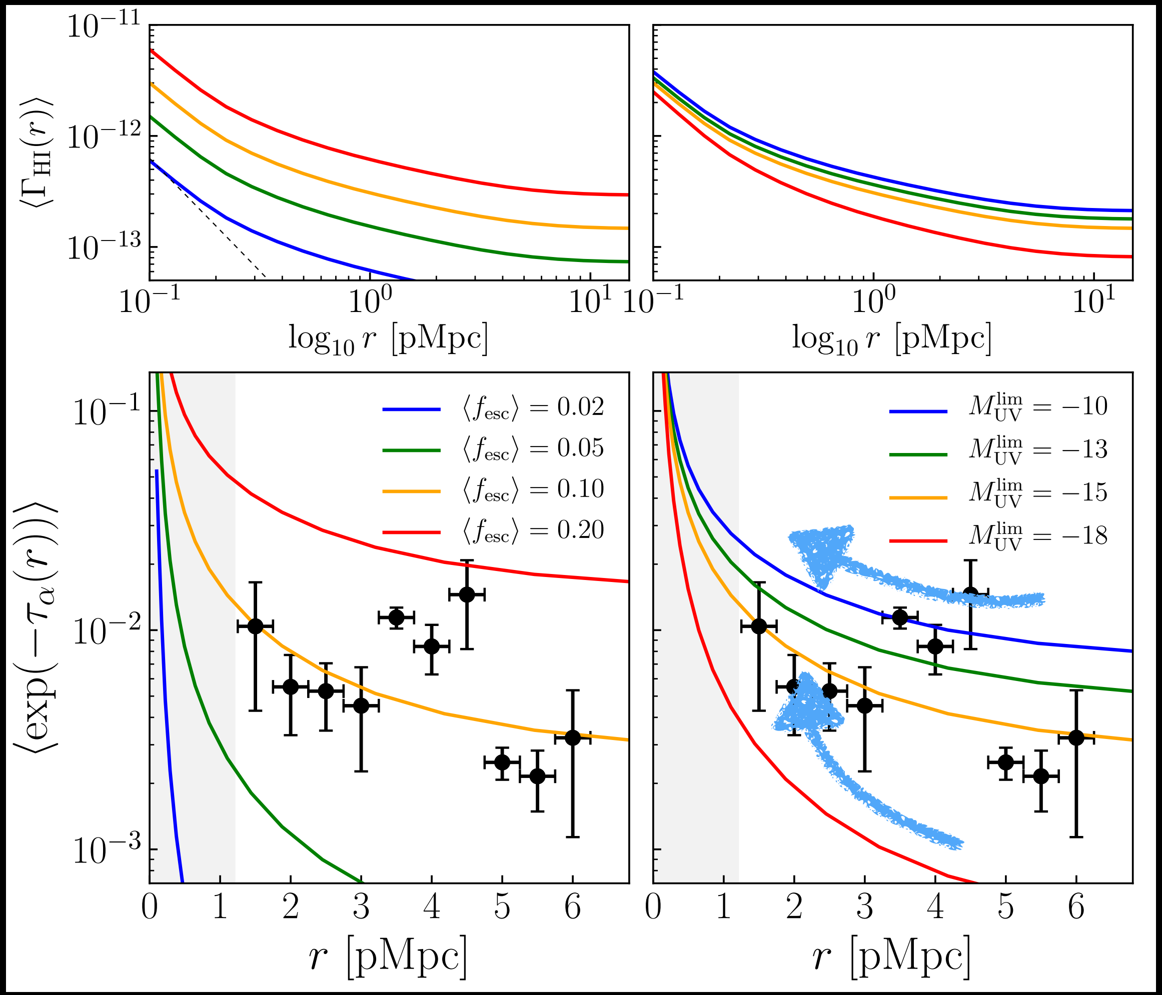

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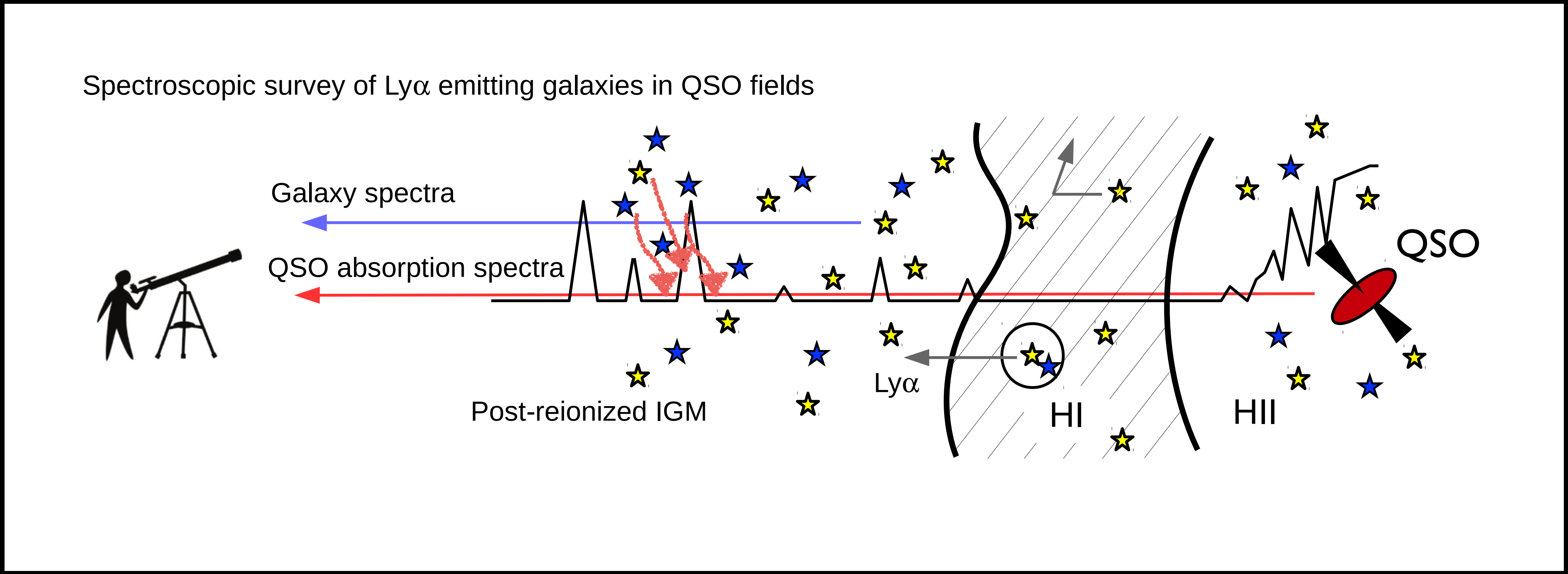
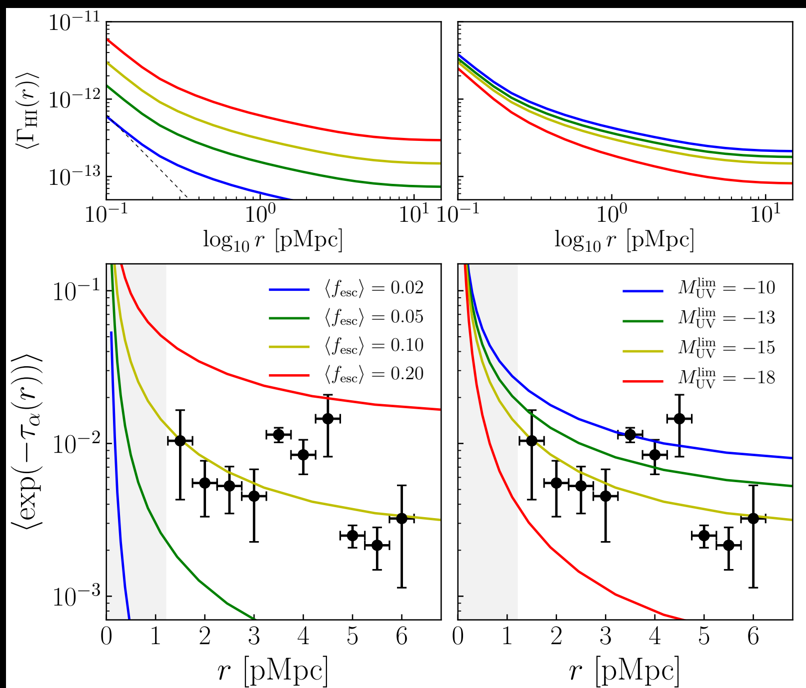
Slope is shallower if the IGM is ionised by even fainter galaxies '*clustering bias of ionising sources*'



From the mean Lyα transmitted flux around LBGs to the average LyC escape fraction



$$\langle \Gamma_{\rm HI}(r) \rangle \propto \langle f_{\rm esc} \rangle \times \frac{\alpha_g \langle \xi_{\rm ion} \rangle}{\alpha_g + 3} \times \left[\begin{array}{c} \textit{Galaxy abundance:} \\ \textit{LBG + galaxy clustering } P_g(k) \end{array} \right]$$

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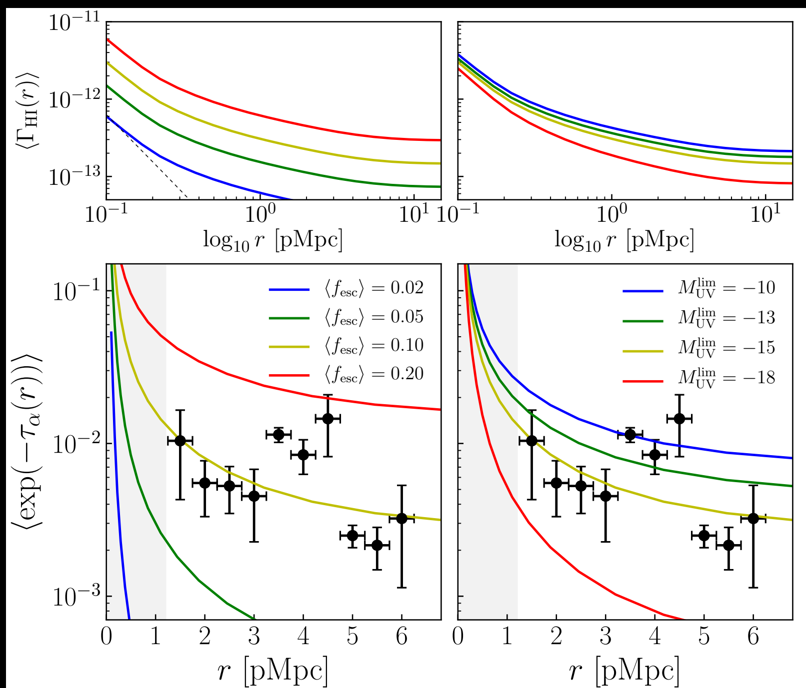
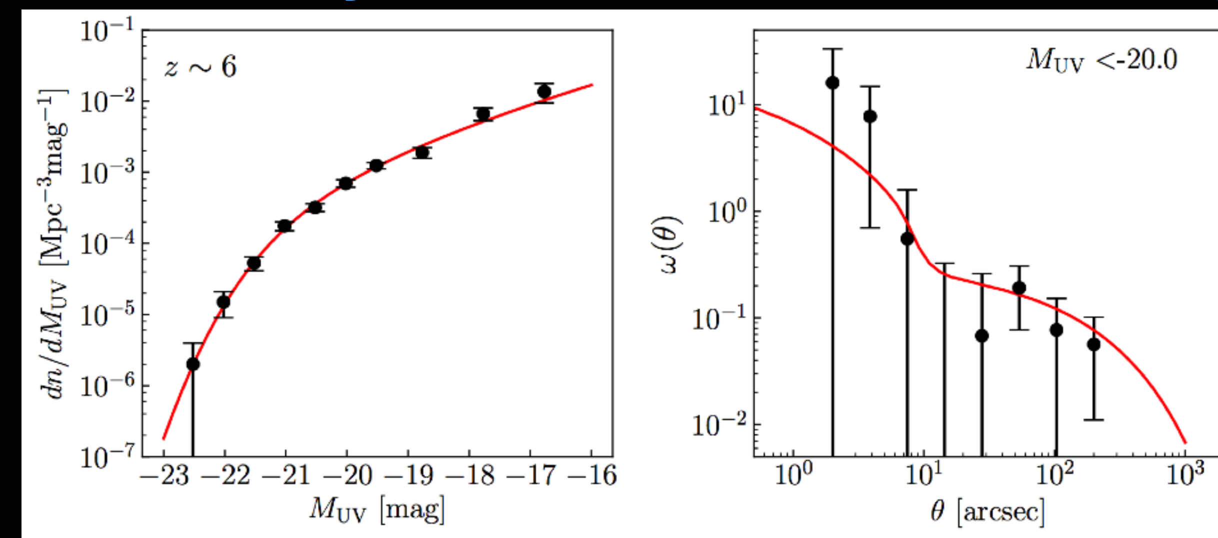


Luminosity function + LBG clustering



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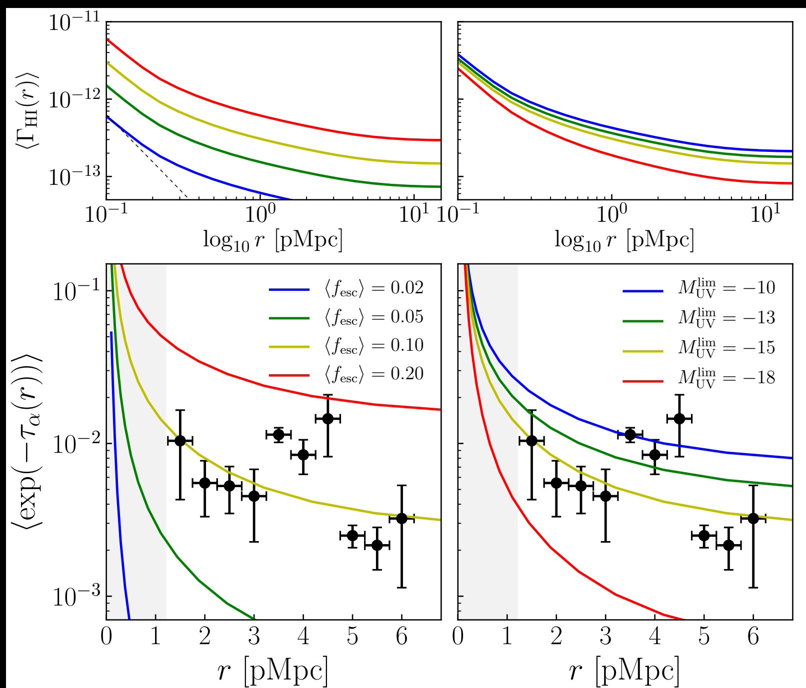

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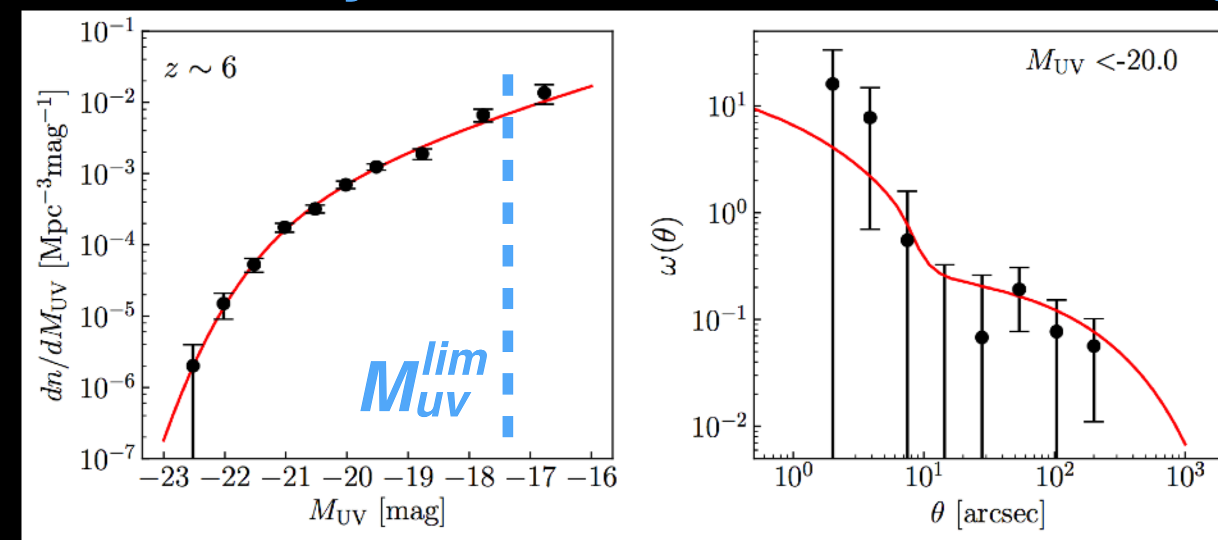

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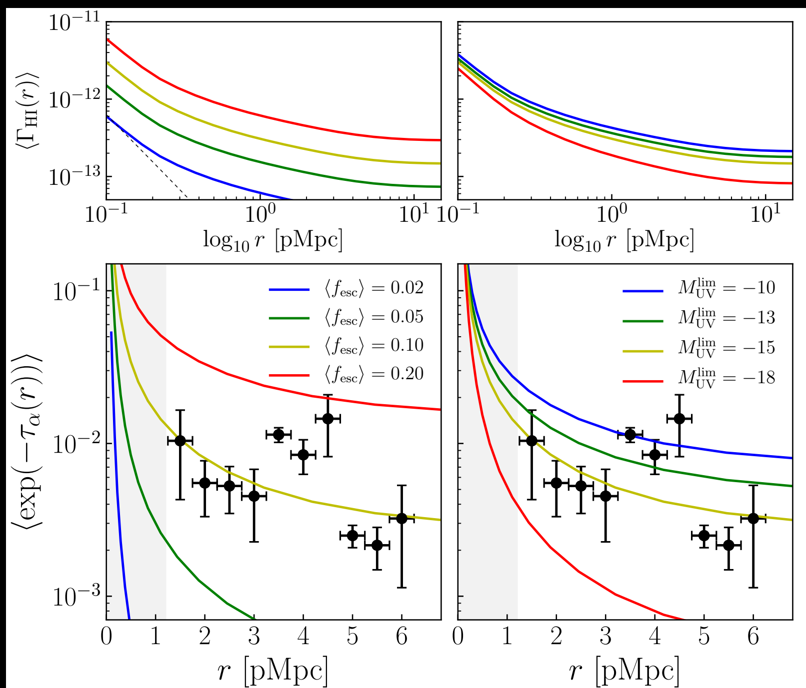

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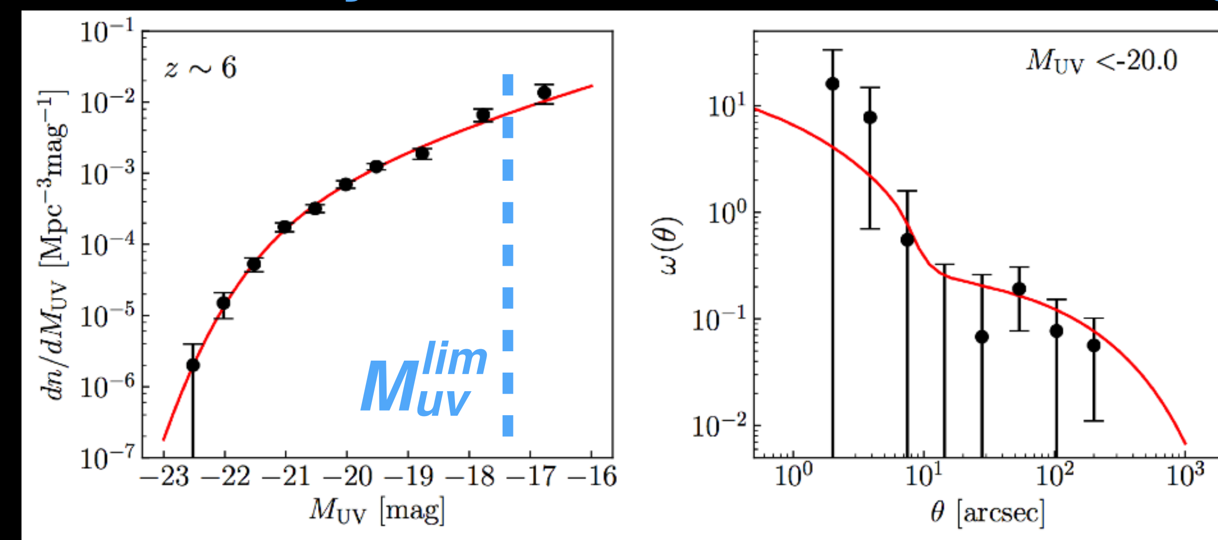

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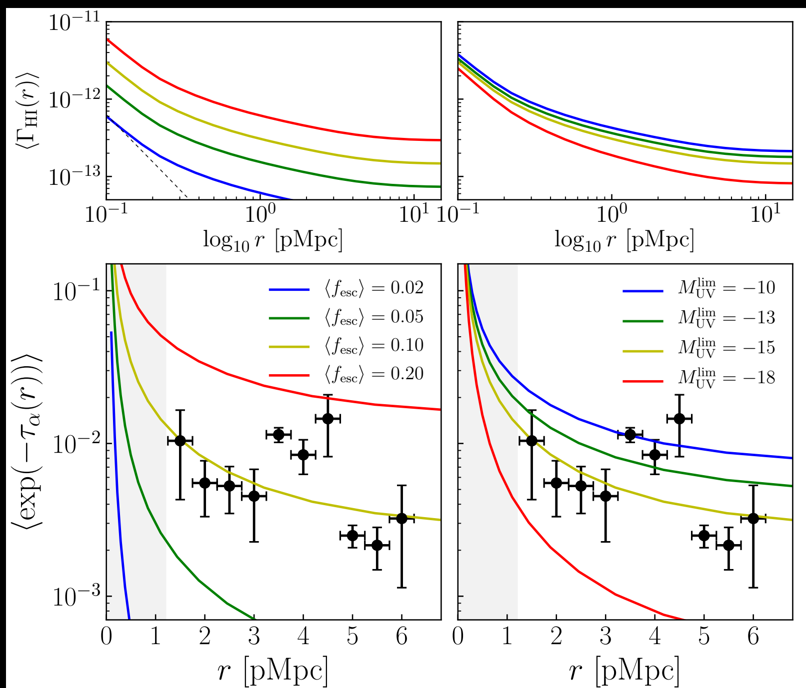
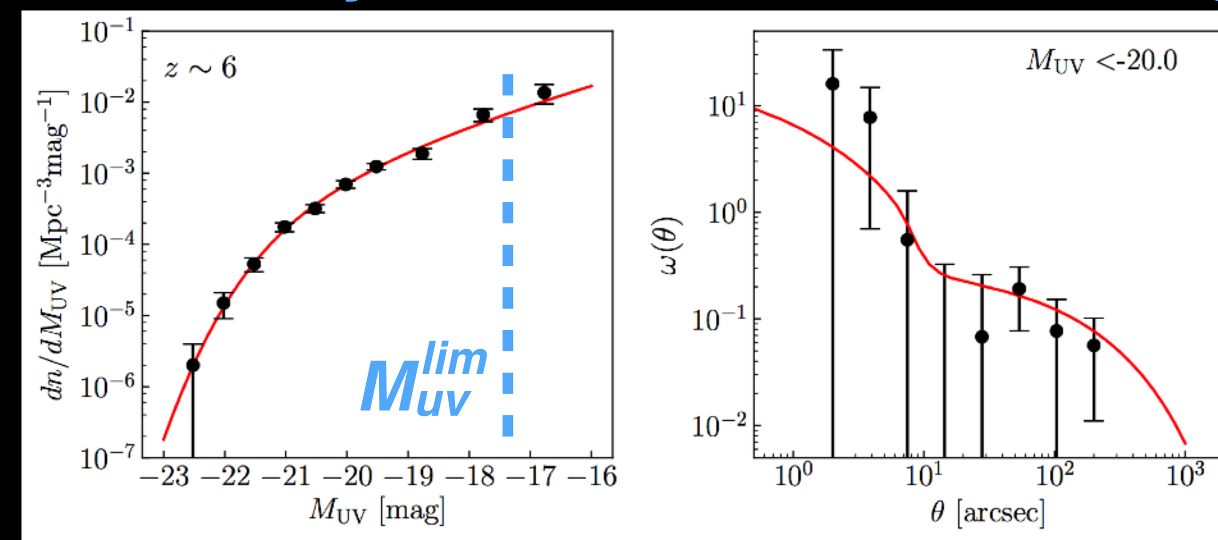
Spectral hardness of sources

From the mean Lyα transmitted flux around LBGs to the average LyC escape fraction



Luminosity function + LBG clustering



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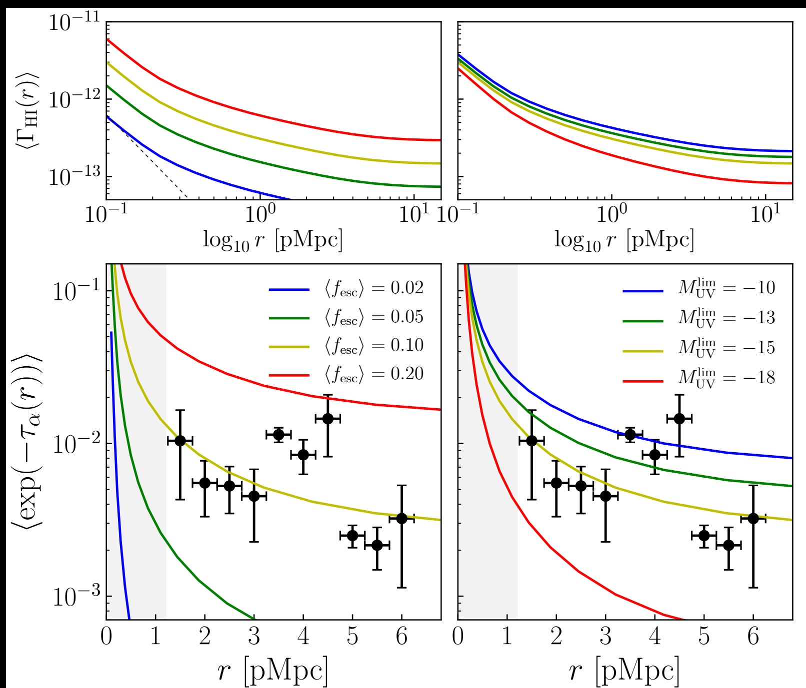
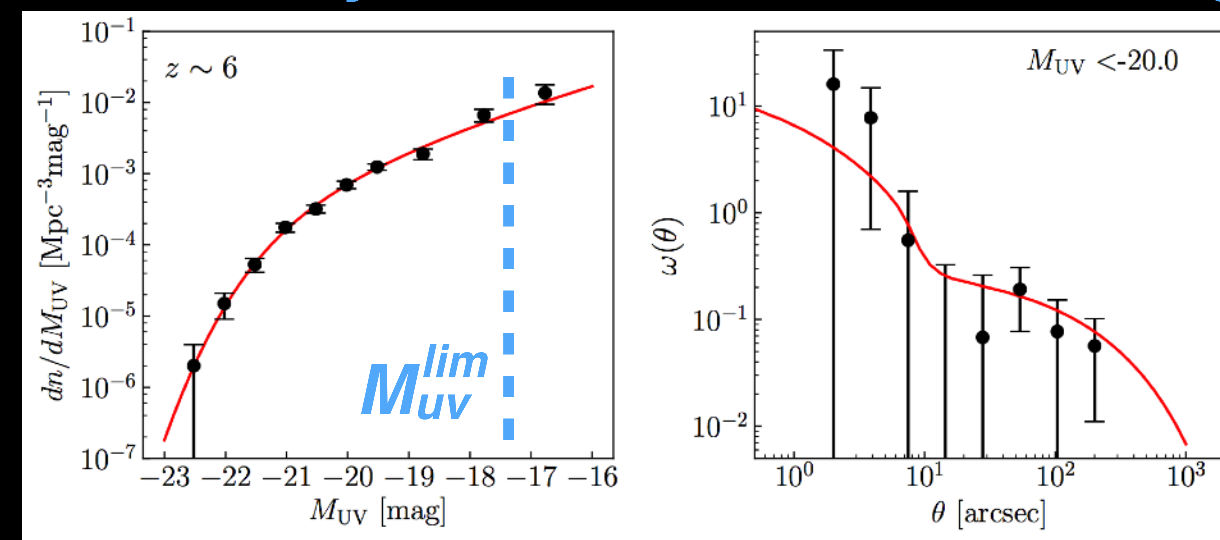
Spectral hardness of sources

Do radiative transfer calculation…

From the mean Lyα transmitted flux around LBGs to the average LyC escape fraction



Luminosity function + LBG clustering



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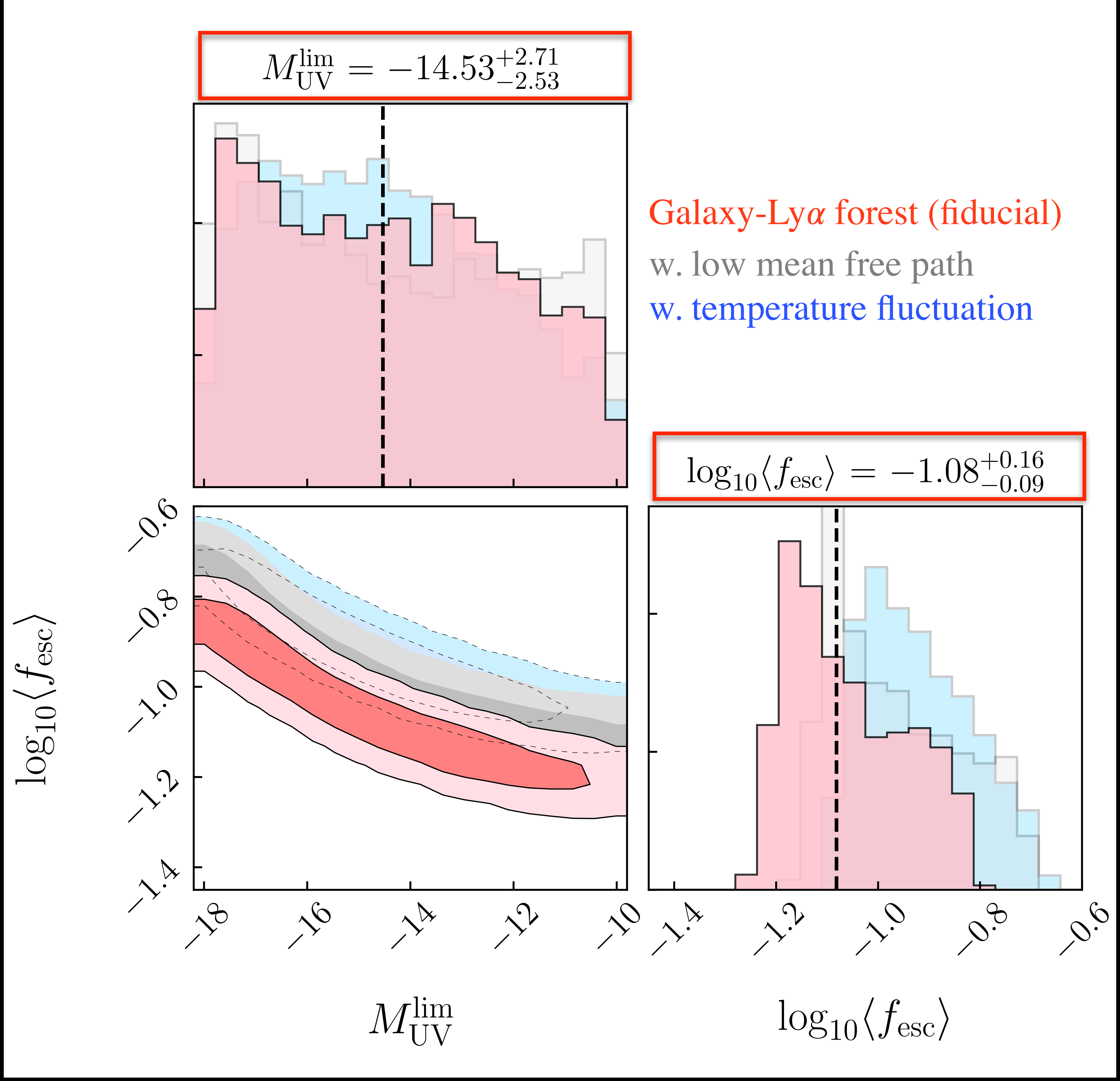
Spectral hardness of sources

Do radiative transfer calculation…

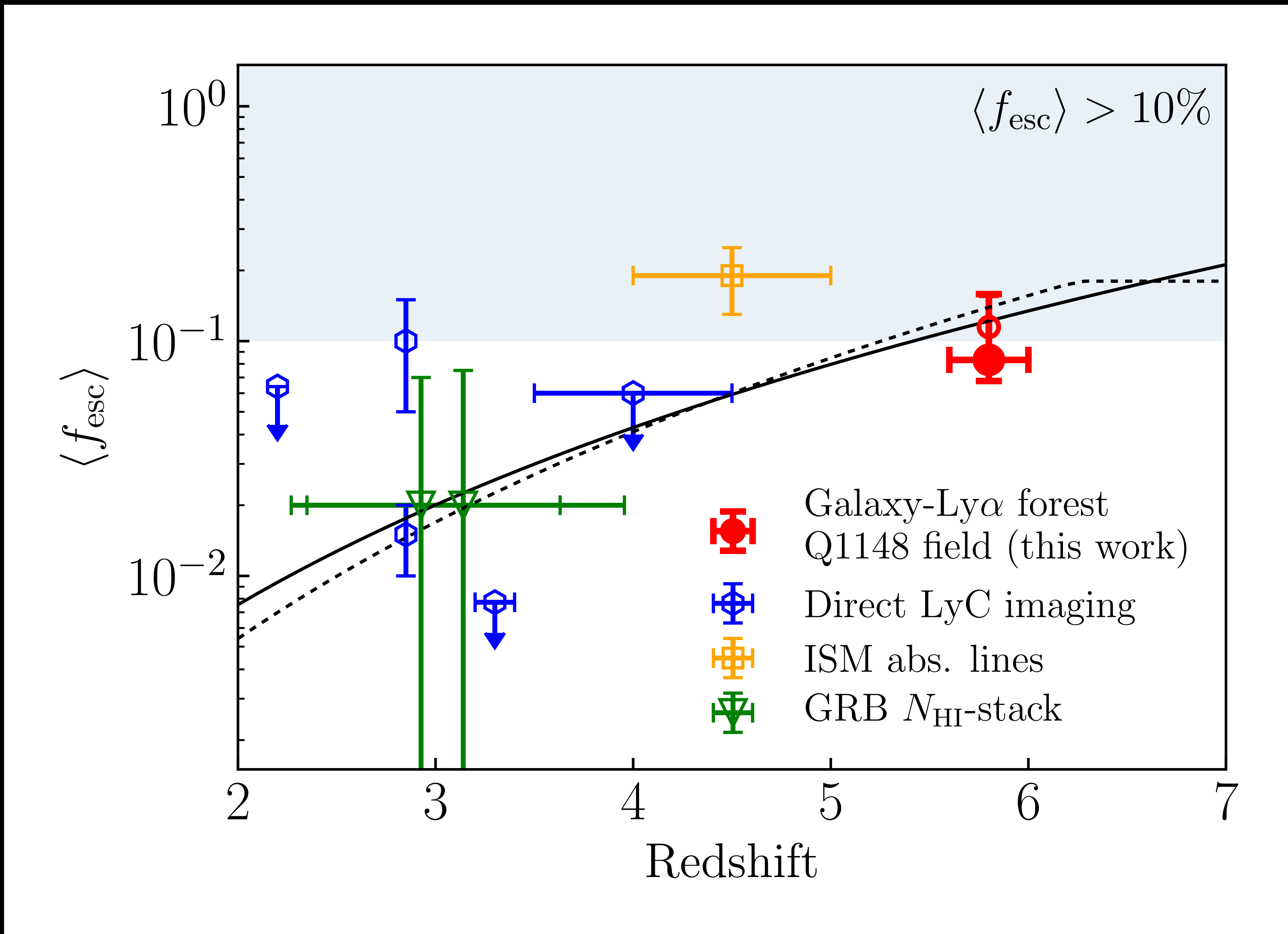
Measurement of the population-averaged escape fraction!!

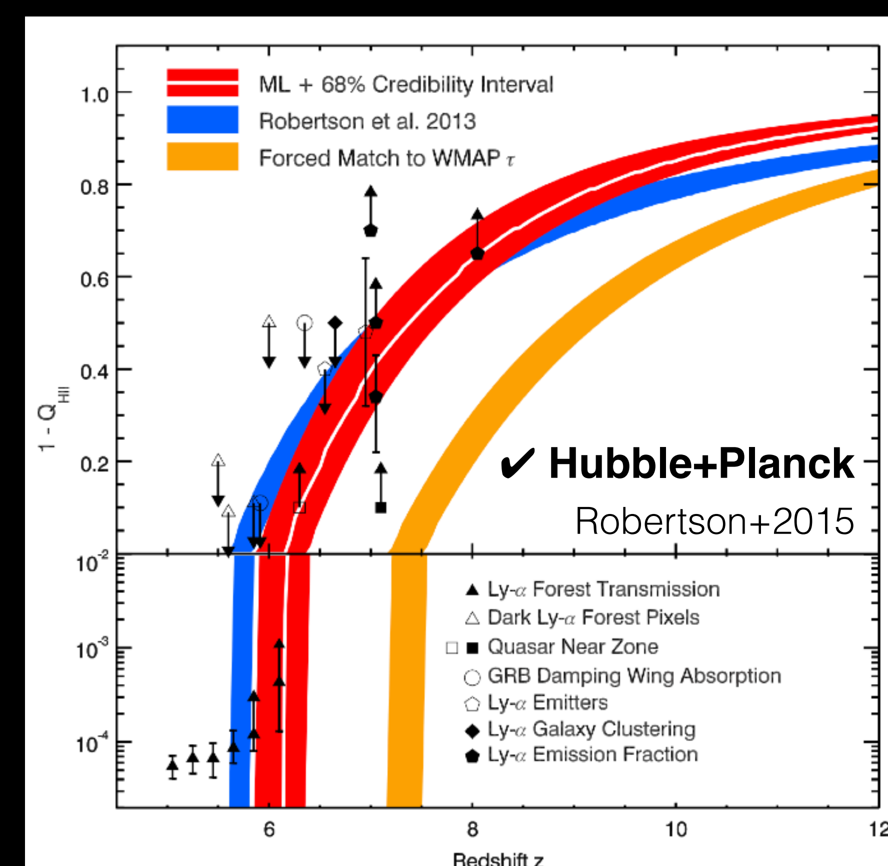
Constraint on the average escape fraction at z~5.8



$$\langle f_{esc}\rangle = 0.08^{+0.08}_{-0.02}\left(\frac{\langle\xi_{ion}\rangle}{10^{25.2}\,\mathrm{erg^{-1}\,Hz}}\right)^{-1}$$

Constraint on the average escape fraction at z~5.8



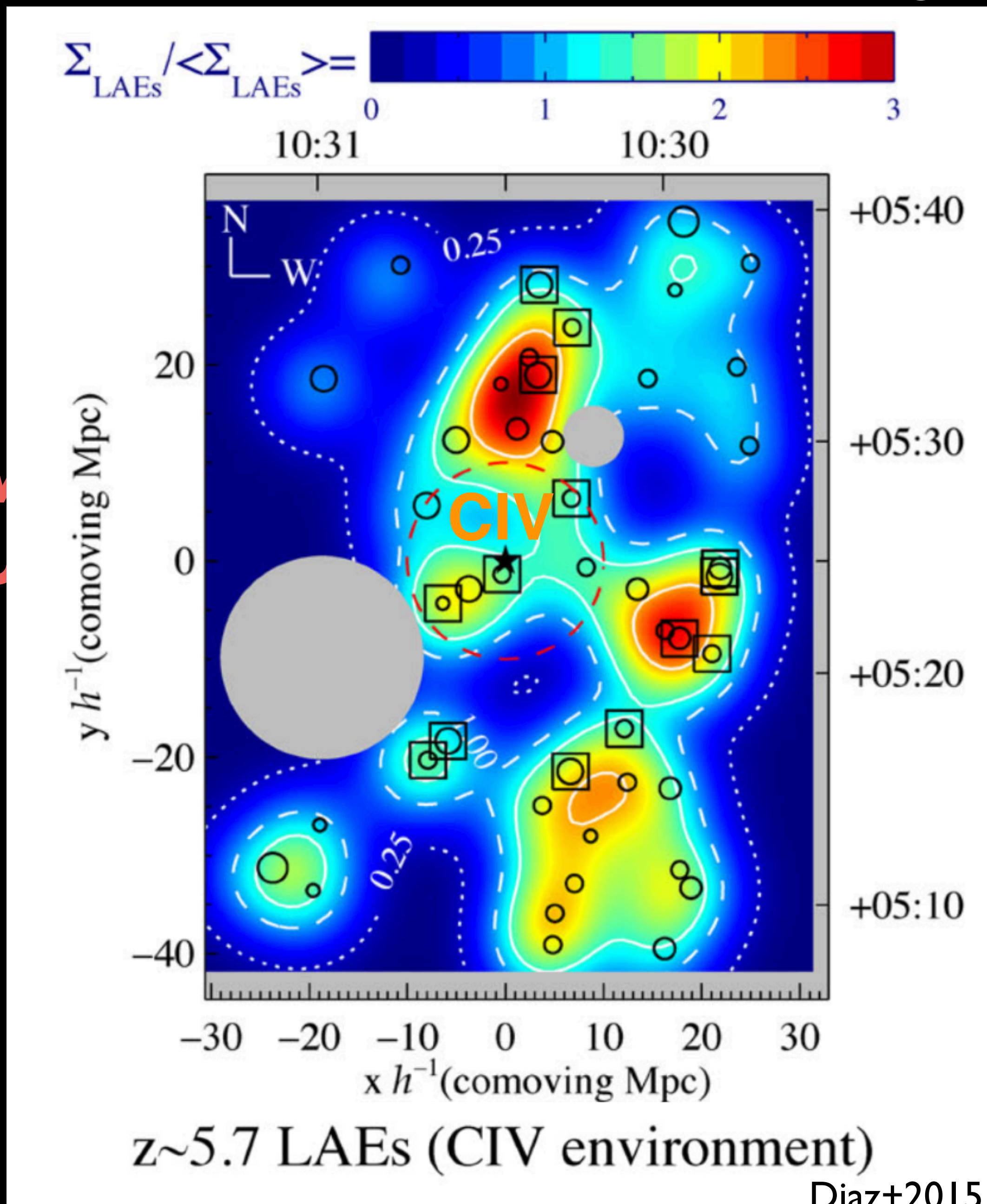


What reionised the Universe?

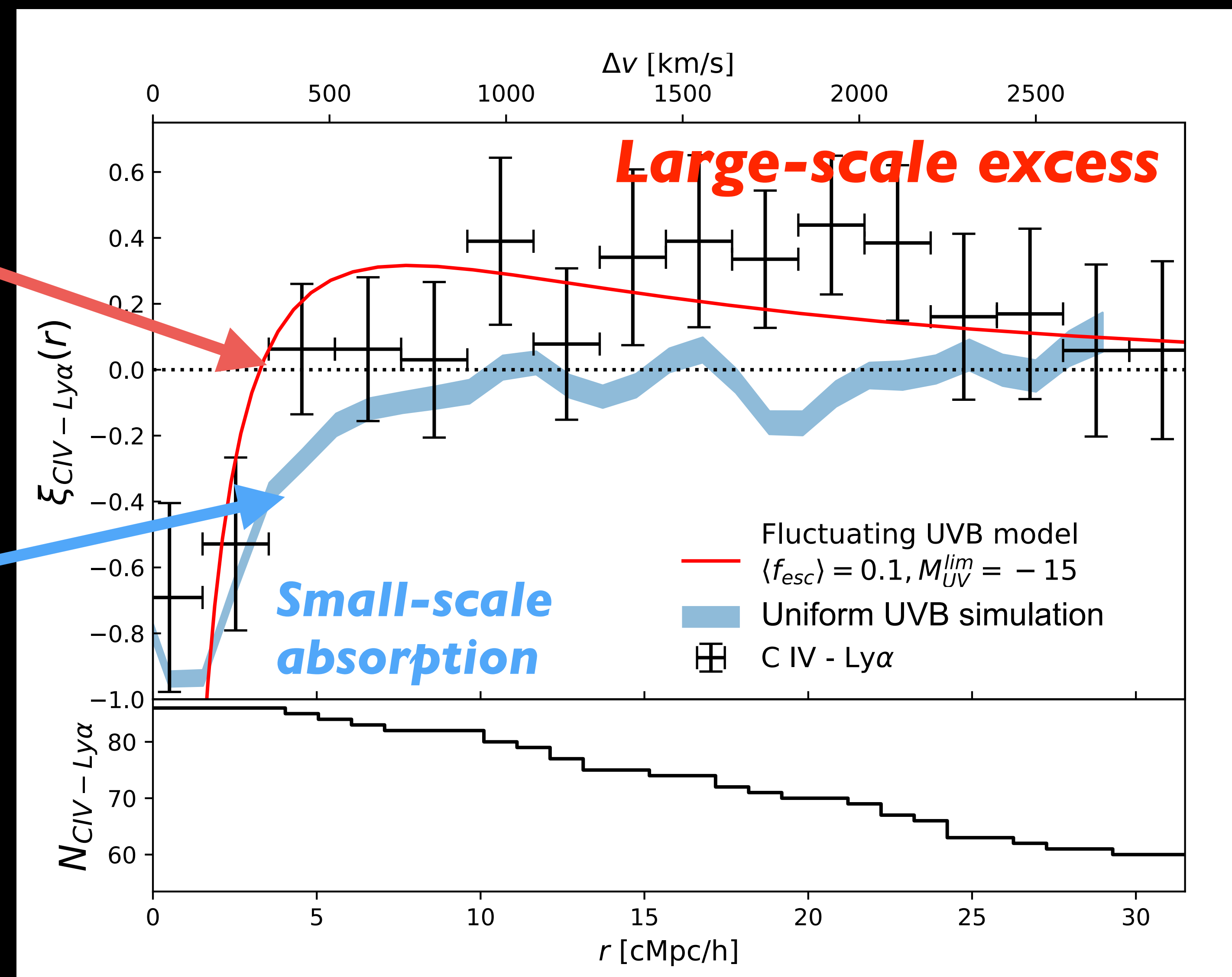
Faint galaxies (M_{uv}<-15) deposit enough ionising radiation to the IGM to drive HI reionisation (f_{esc}>10%)

Gaseous environment of faint low-mass galaxies

Insight from CIV



ross-correlation measurement at <z>=5.2



Need for the enhanced UV background by clustered galaxies around CIV-host galaxies

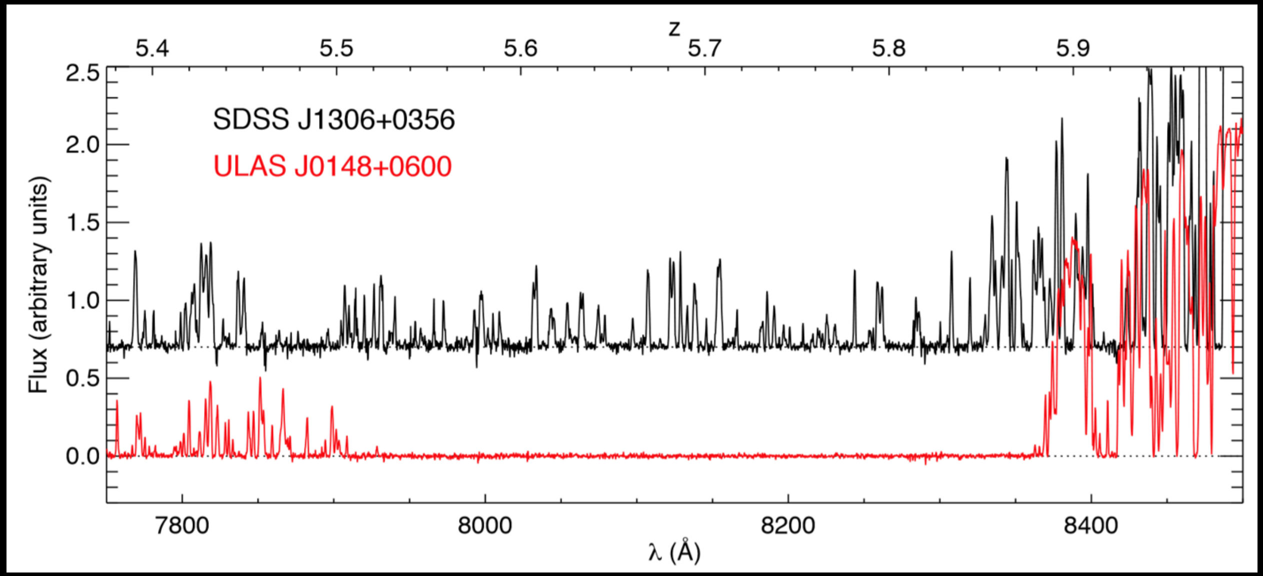
Consistent with reionisation by faint galaxies with fesc=10% (work in progress)

Romain Meyer, Bosman, Kakiichi, Ellis (in prep)

What reionised the Universe?

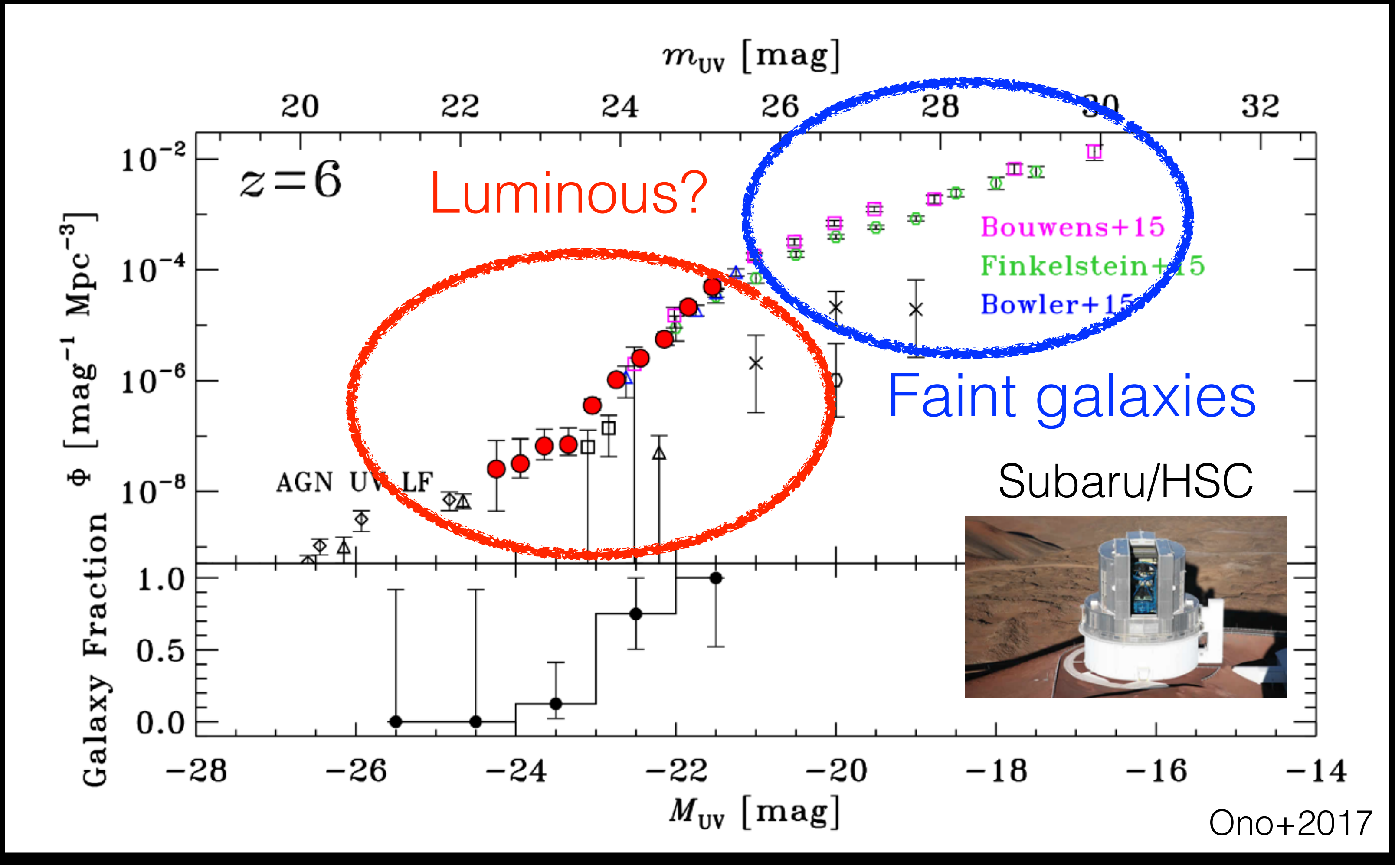
Faint galaxies f_{esc}>10% …

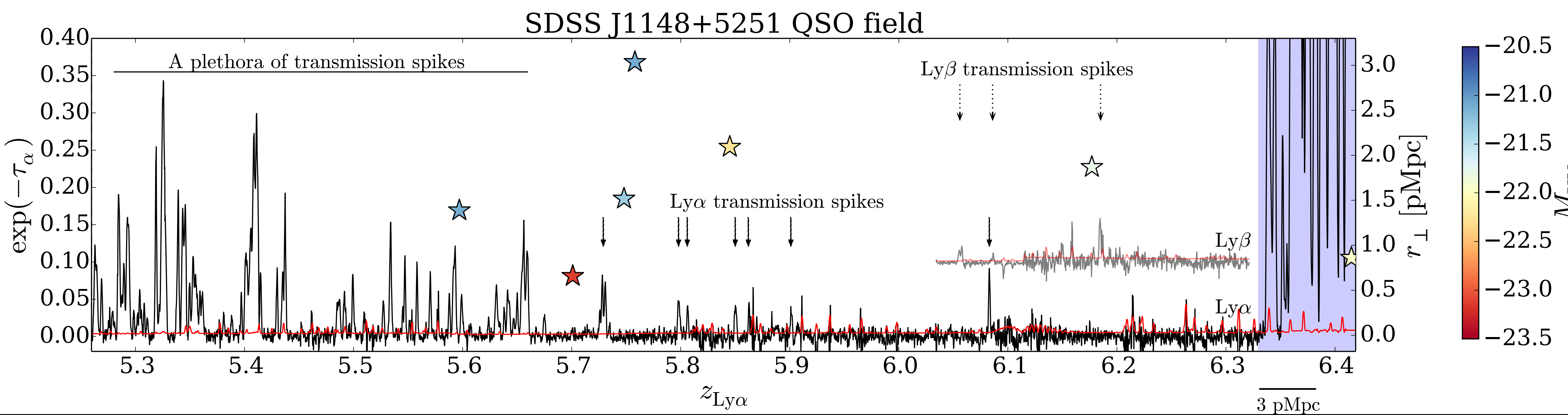
What about this then?



Twist in a story: luminous systems

bright galaxies & faint AGN





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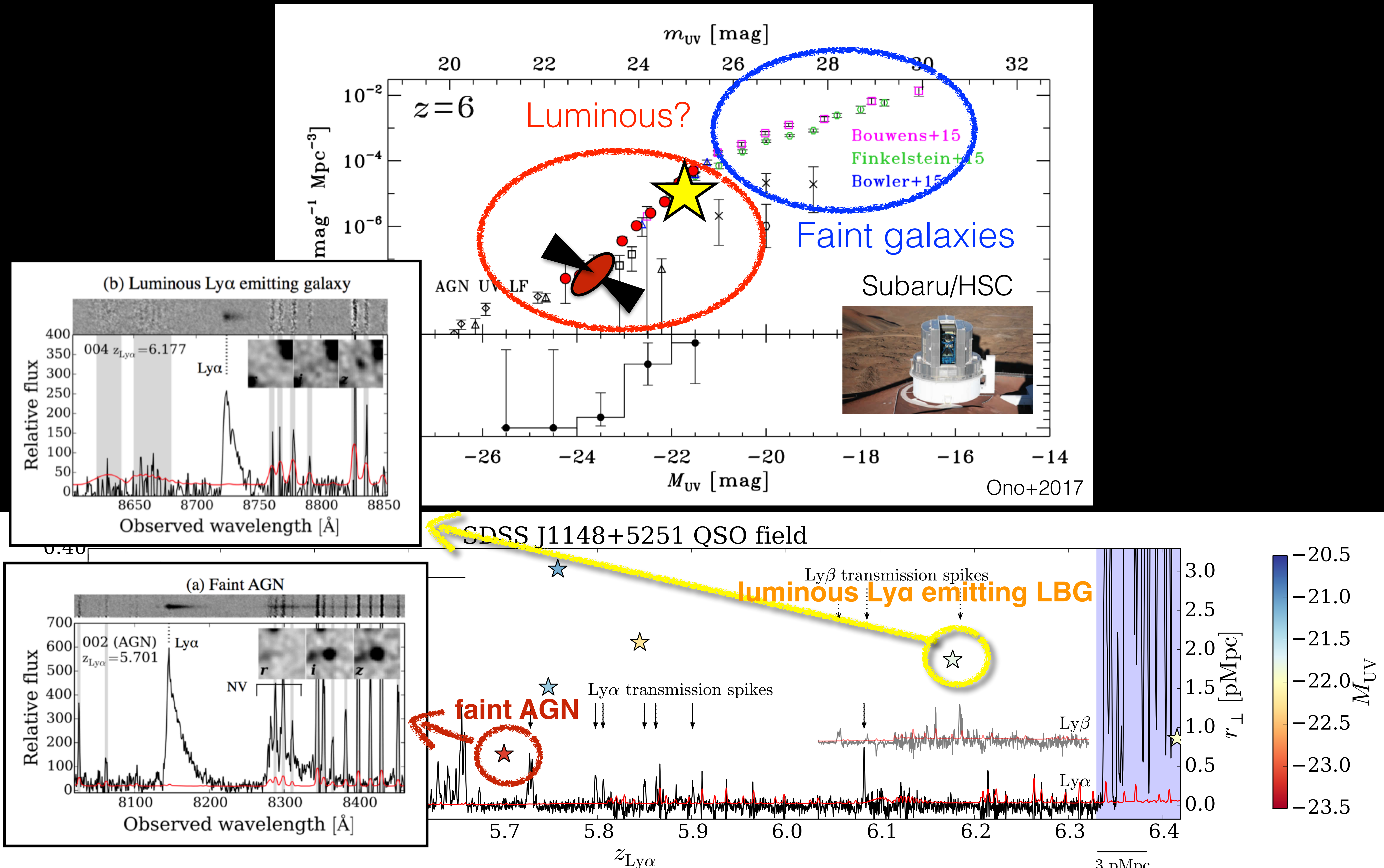
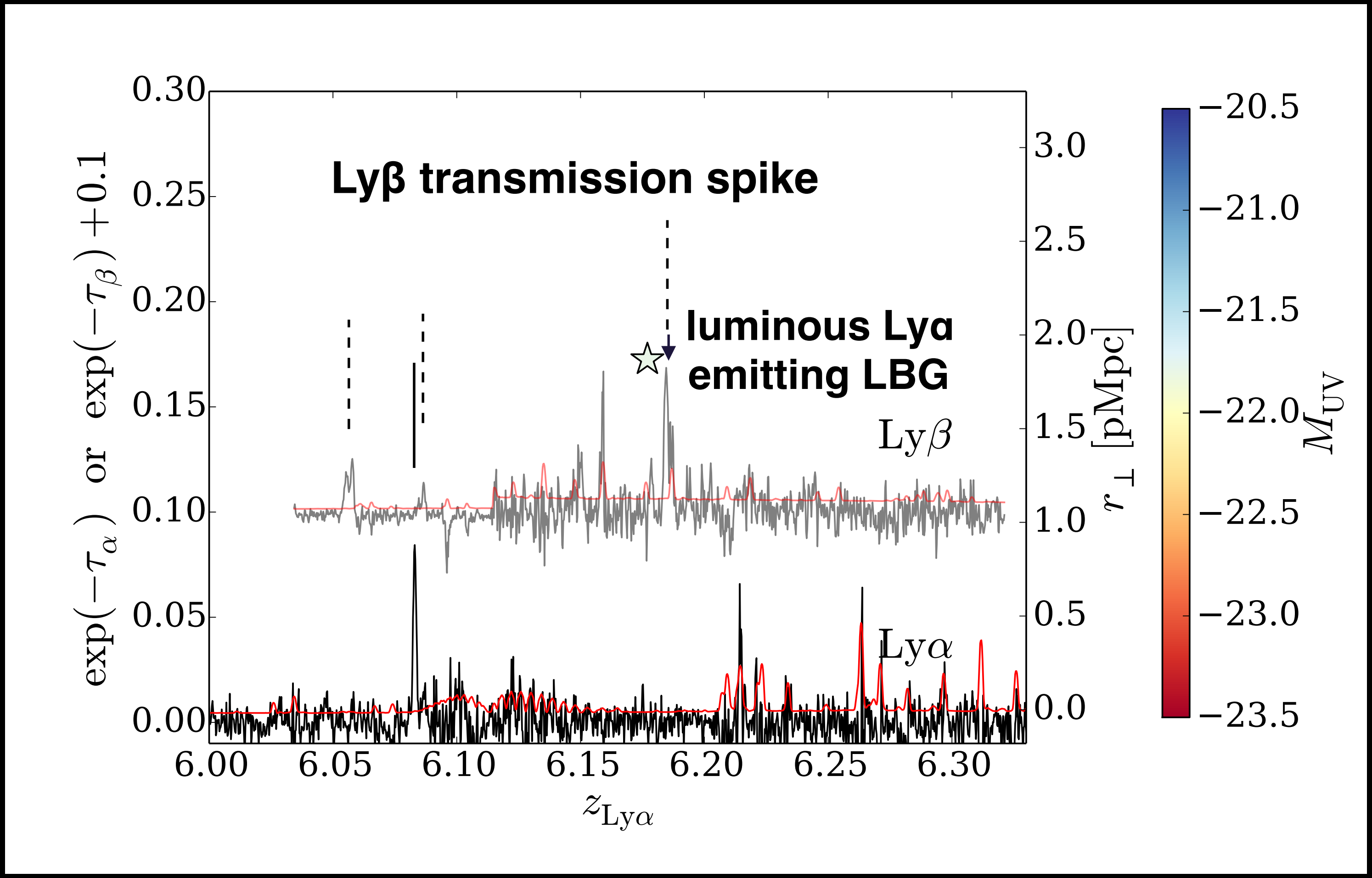


A discovery of an individual transverse proximity effect around z=6.177 luminous LBG



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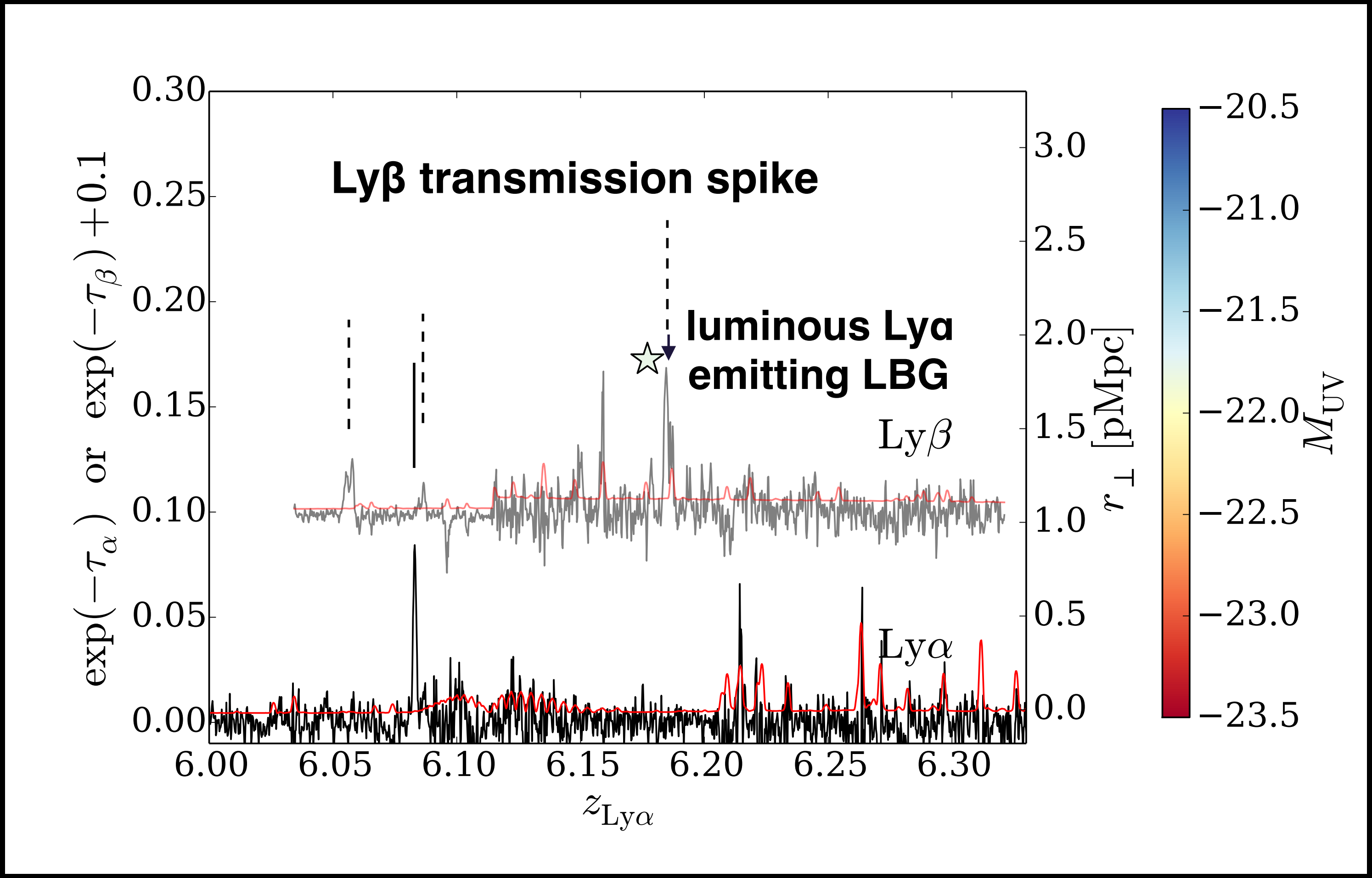
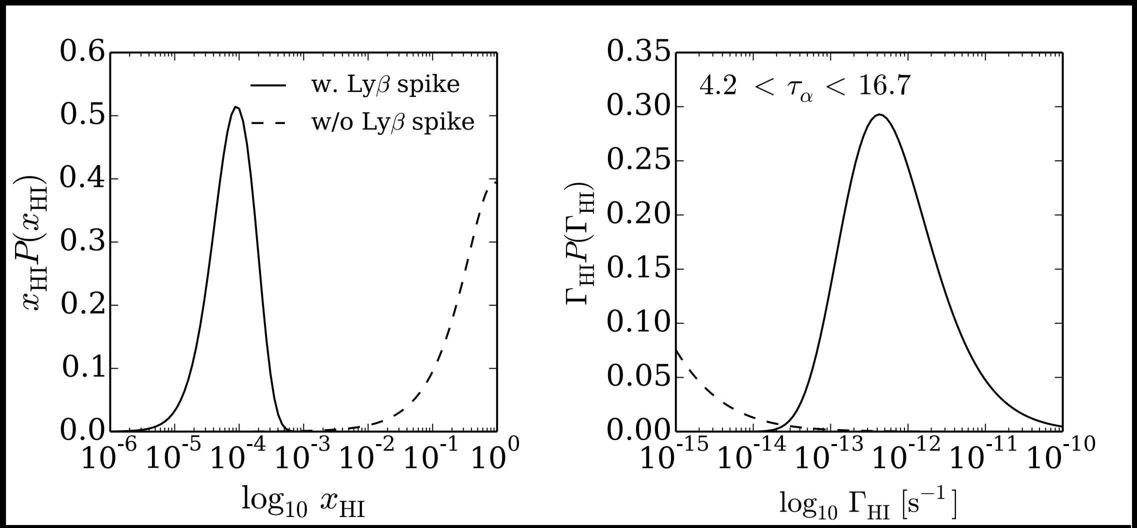
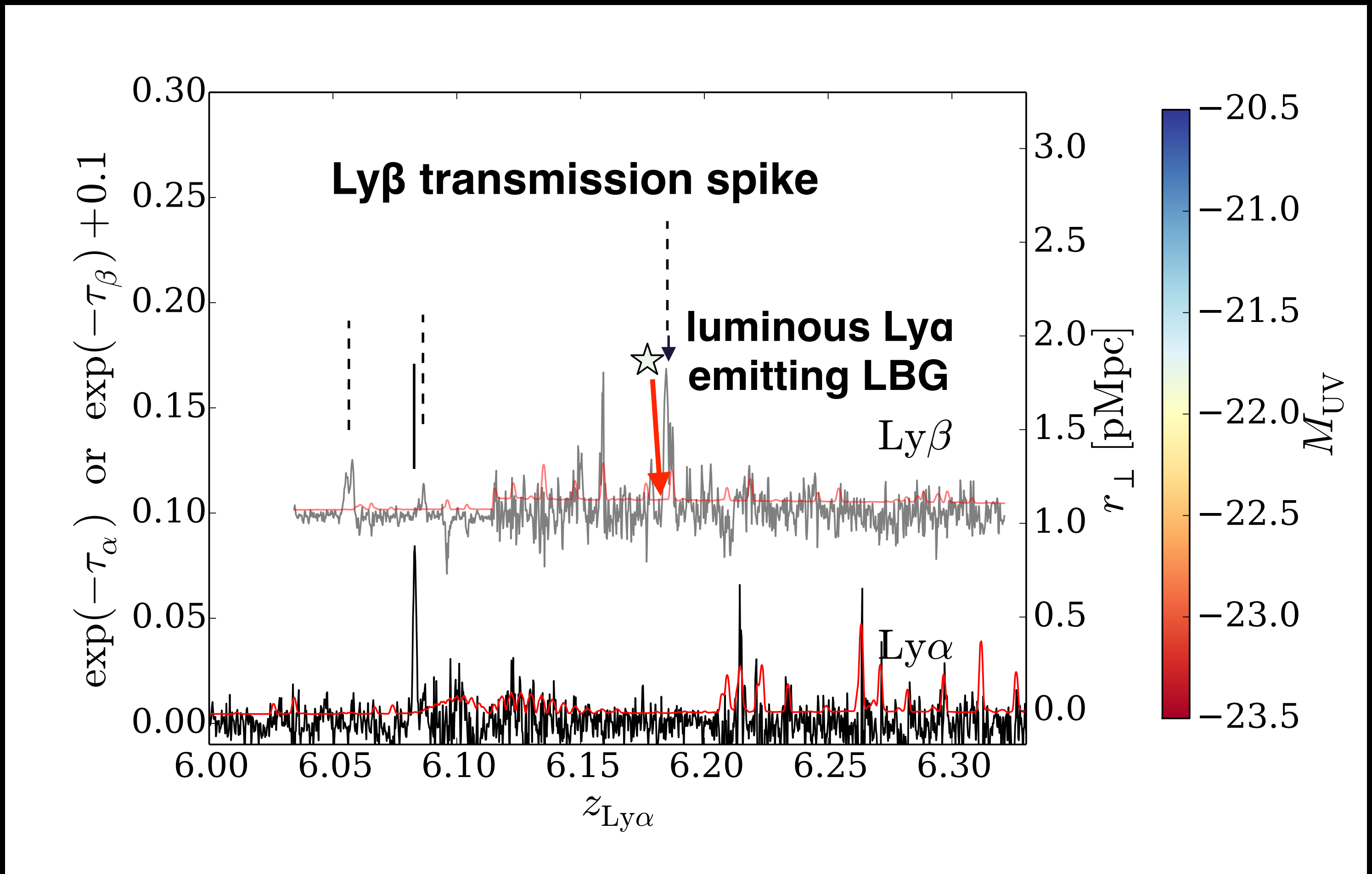


Evidence that **z>6 luminous galaxies preferentially reside in highly ionized environment**,



With cosmo. hydrodynamical simulations

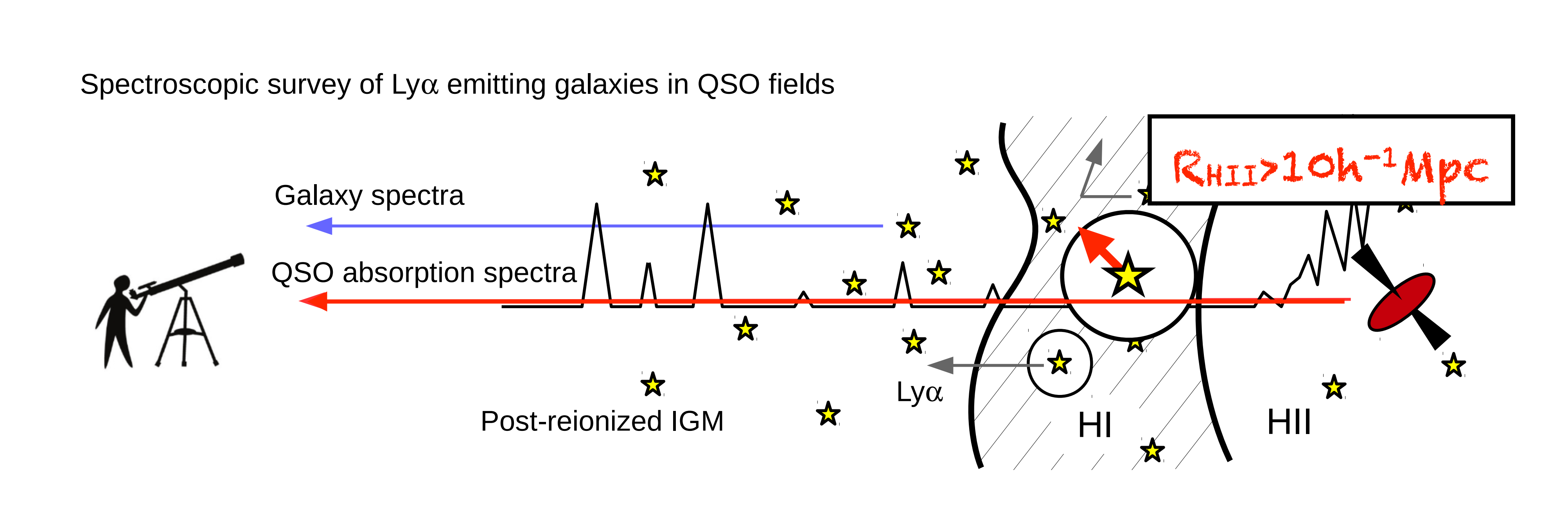
A discovery of an individual transverse proximity effect around z=6.177 luminous LBG



Evidence that **z>6 luminous galaxies preferentially reside in highly ionized environment**,

A lower limit to the size of cosmological HII region

$R_{HII}>d_{spike} \simeq 10h^{-1}$Mpc @ z≃6.2



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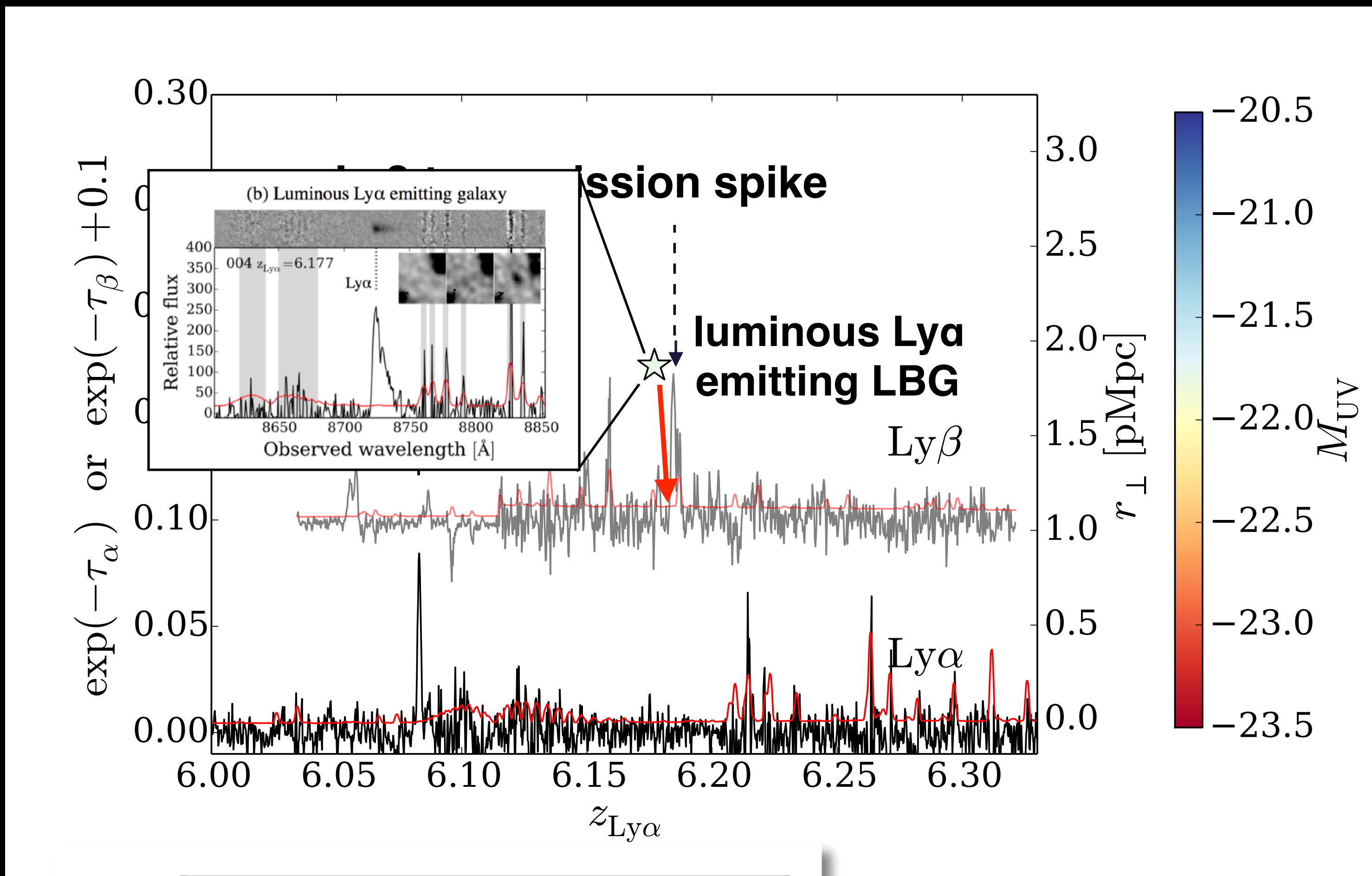

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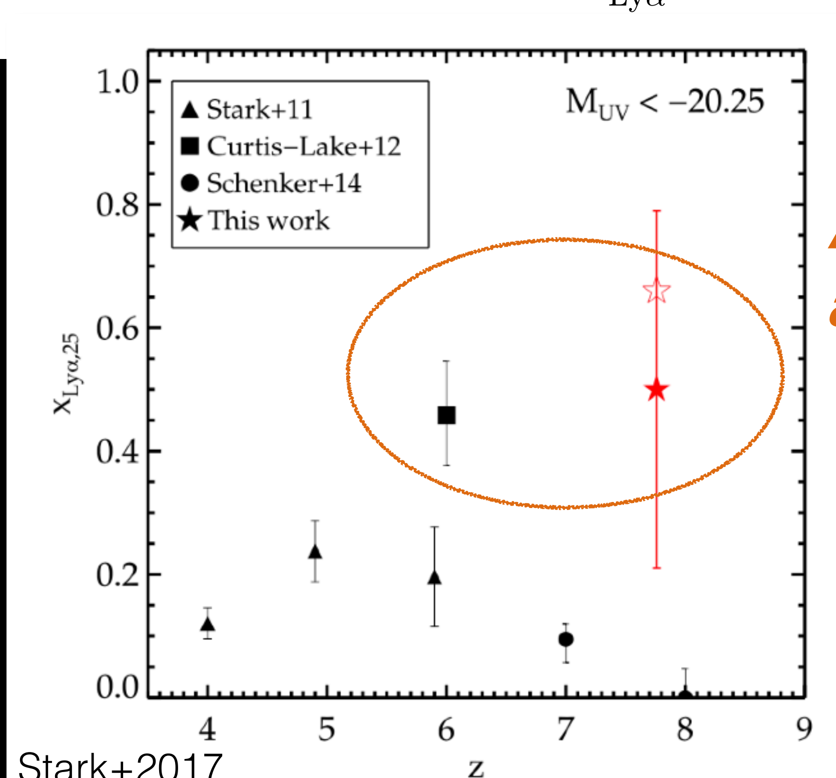
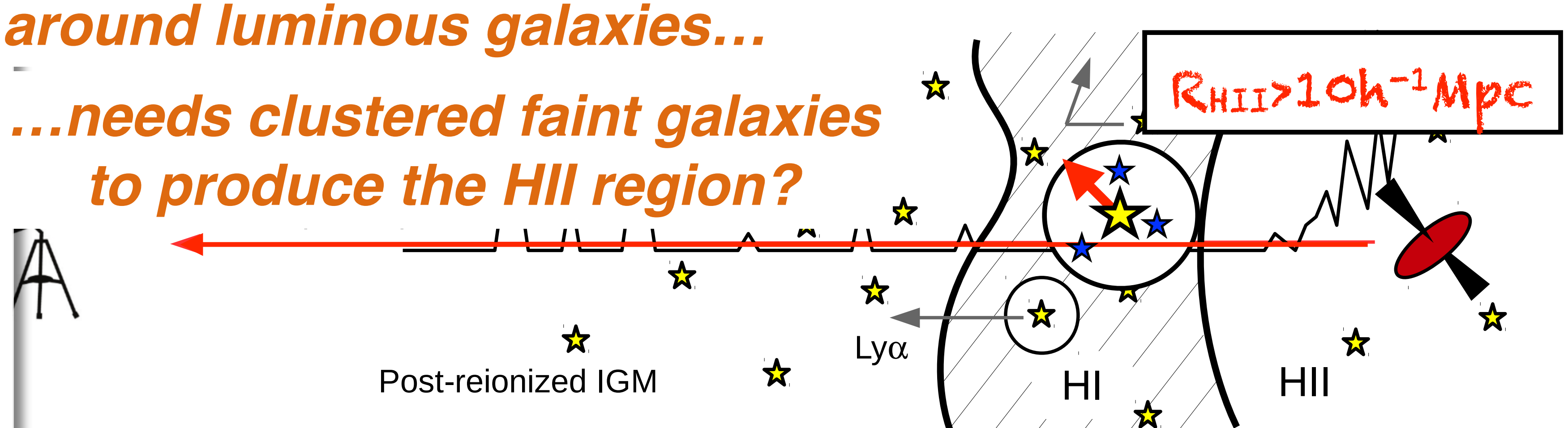


Accelerated reionization around luminous galaxies…

…needs clustered faint galaxies to produce the HII region?



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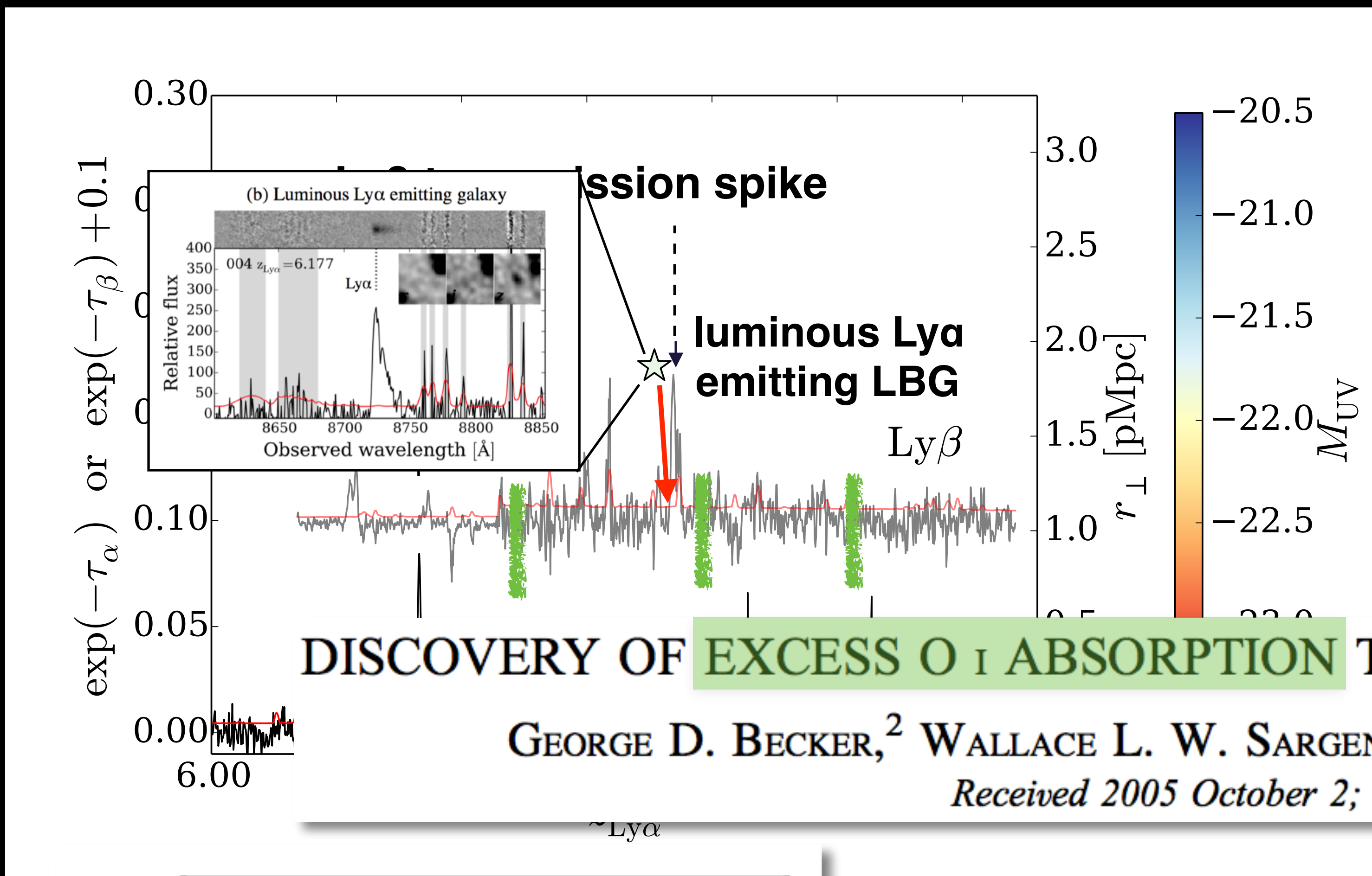


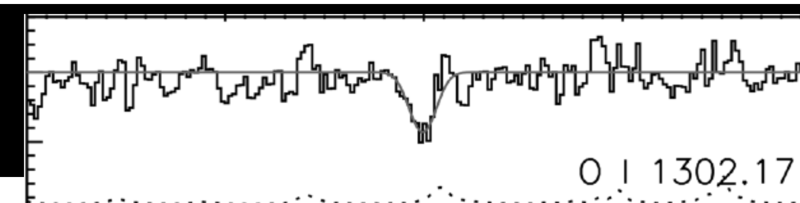
Evidence that **z>6 luminous galaxies preferentially reside in highly ionized environment**,

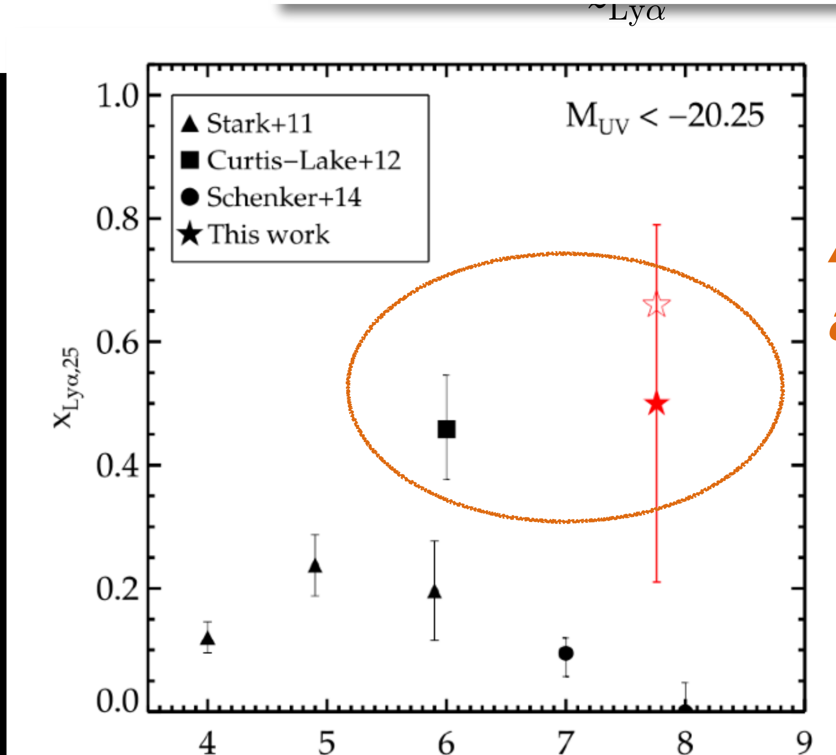
A lower limit to the size of cosmological HII region

DISCOVERY OF EXCESS O I ABSORPTION TOWARD THE $z = 6.42$ QSO SDSS J1148+5251

George D. Becker,[2] Wallace L. W. Sargent,[2] Michael Rauch,[3] and Robert A. Simcoe[4]

Received 2005 October 2; accepted 2005 November 22





Stark+2017

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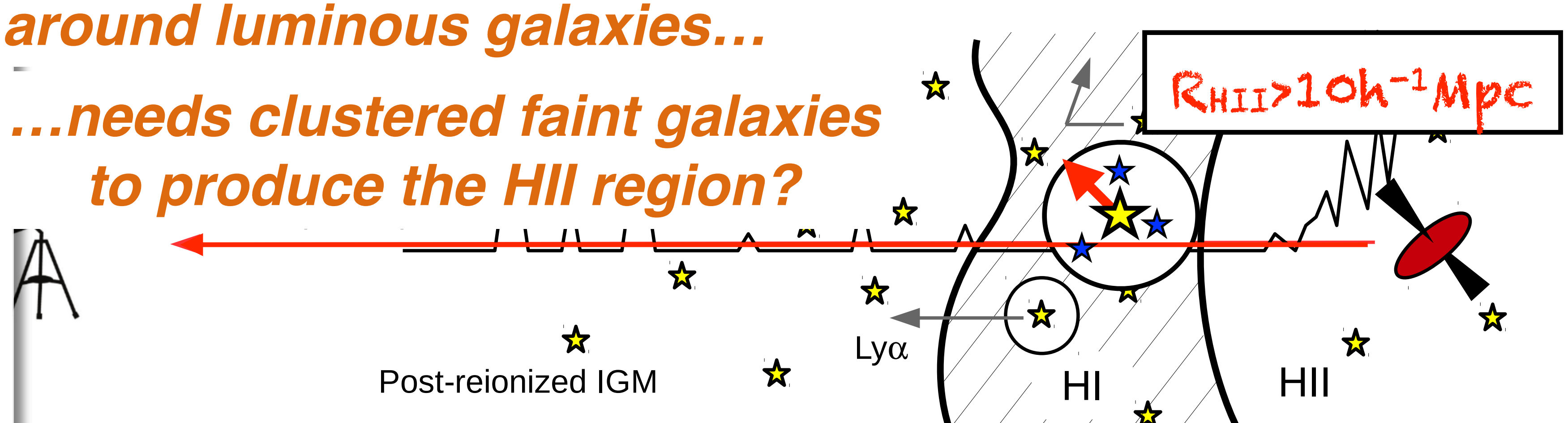

The role of AGN: reionization of hydrogen & helium

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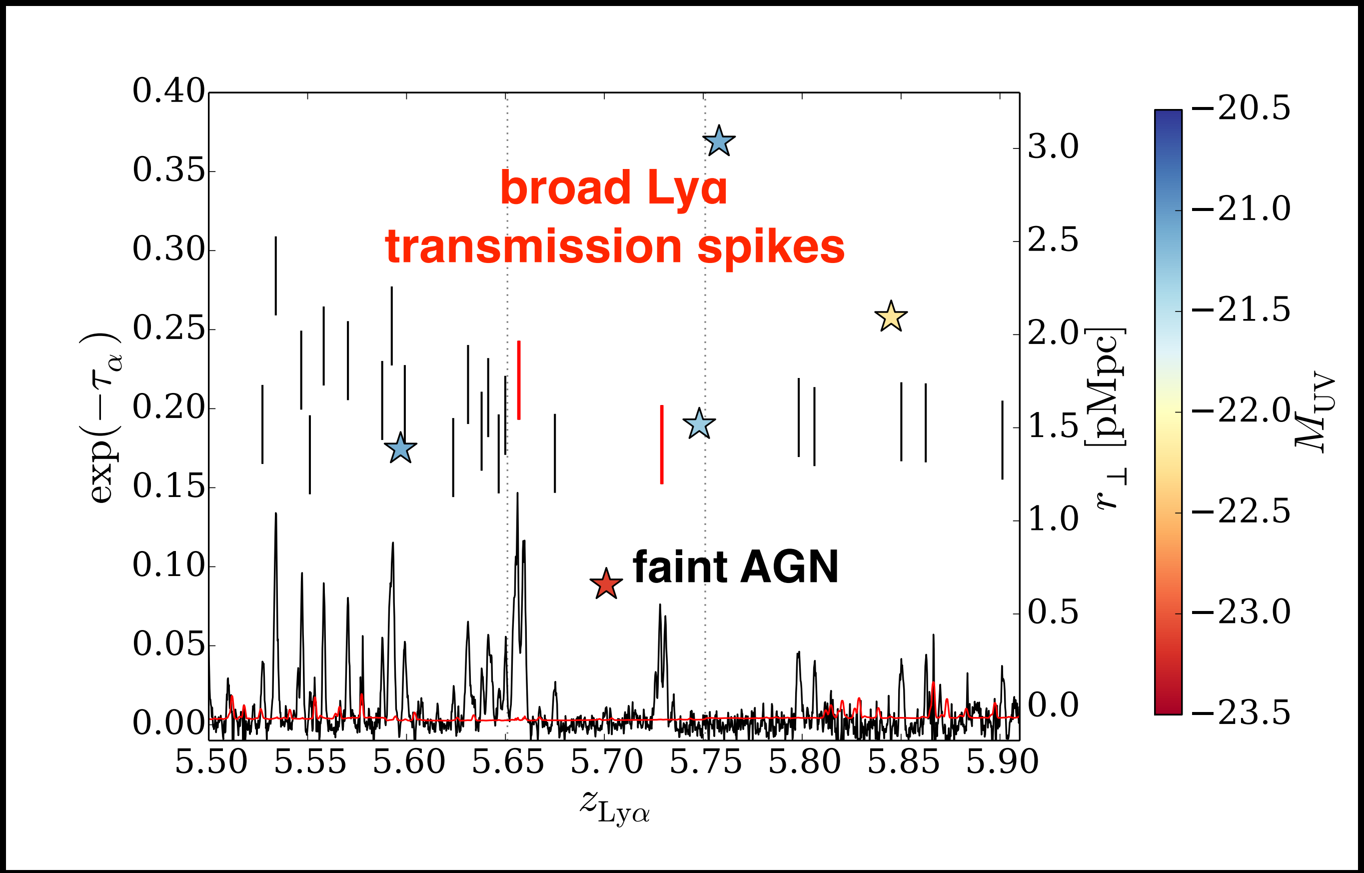
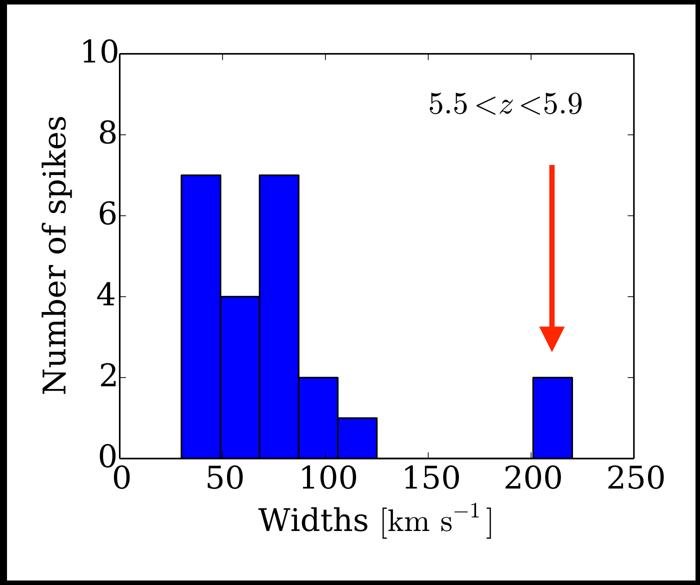


Unusually(?) broad Lyα transmission spikes near faint AGN…



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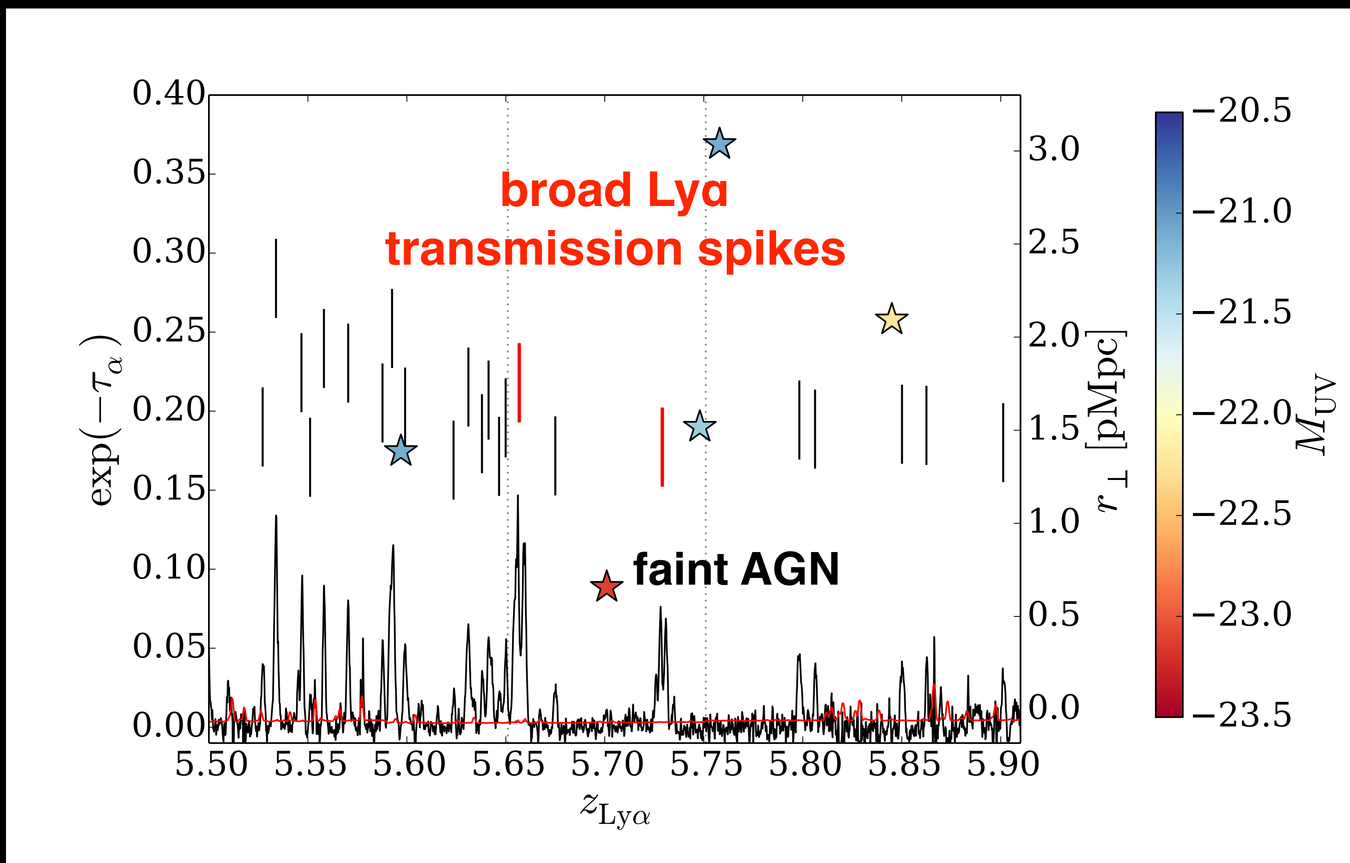

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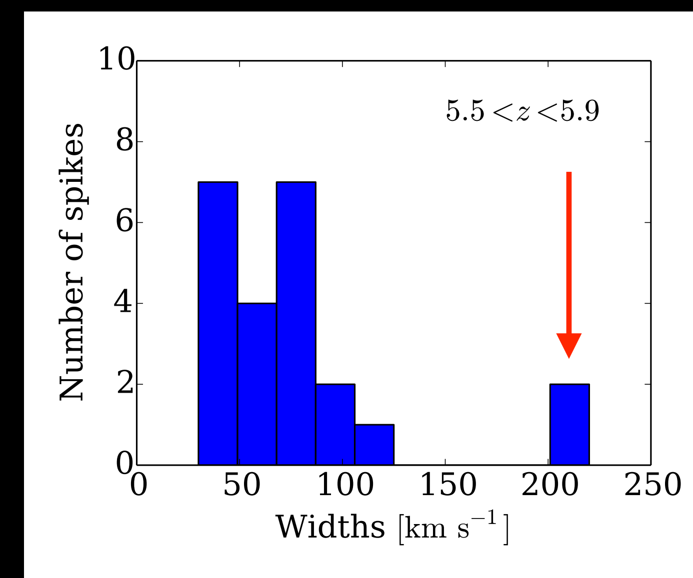
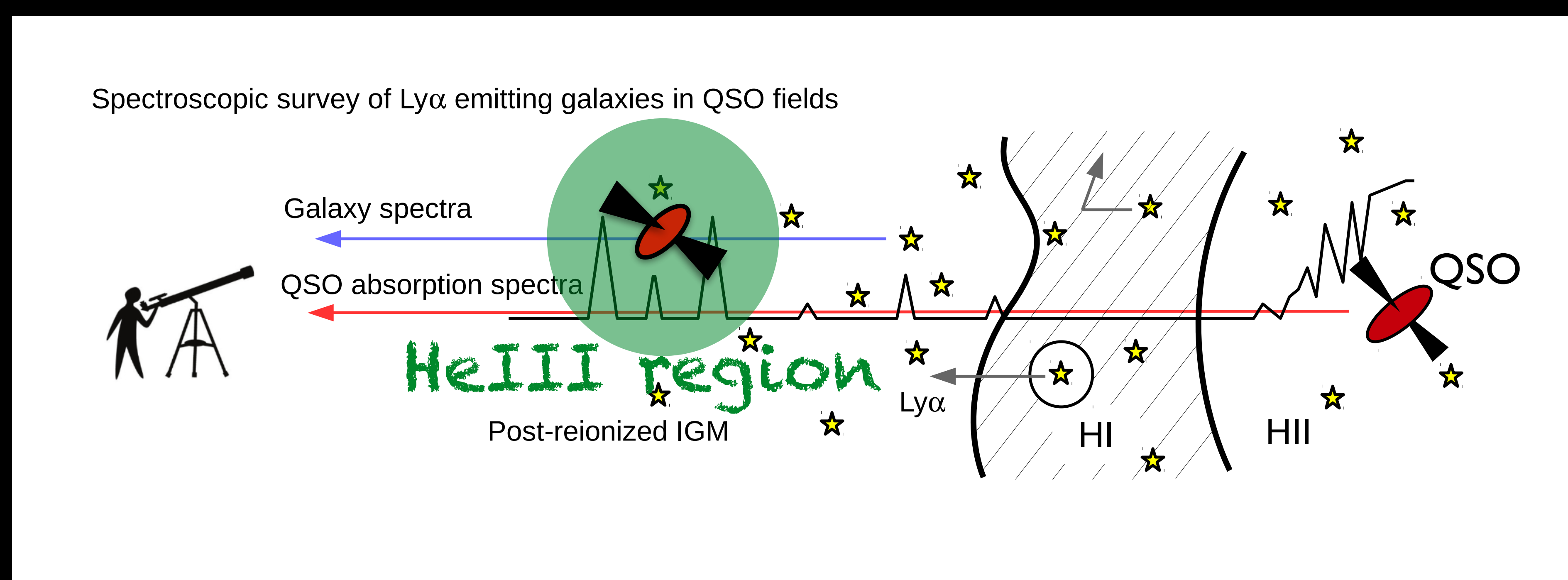
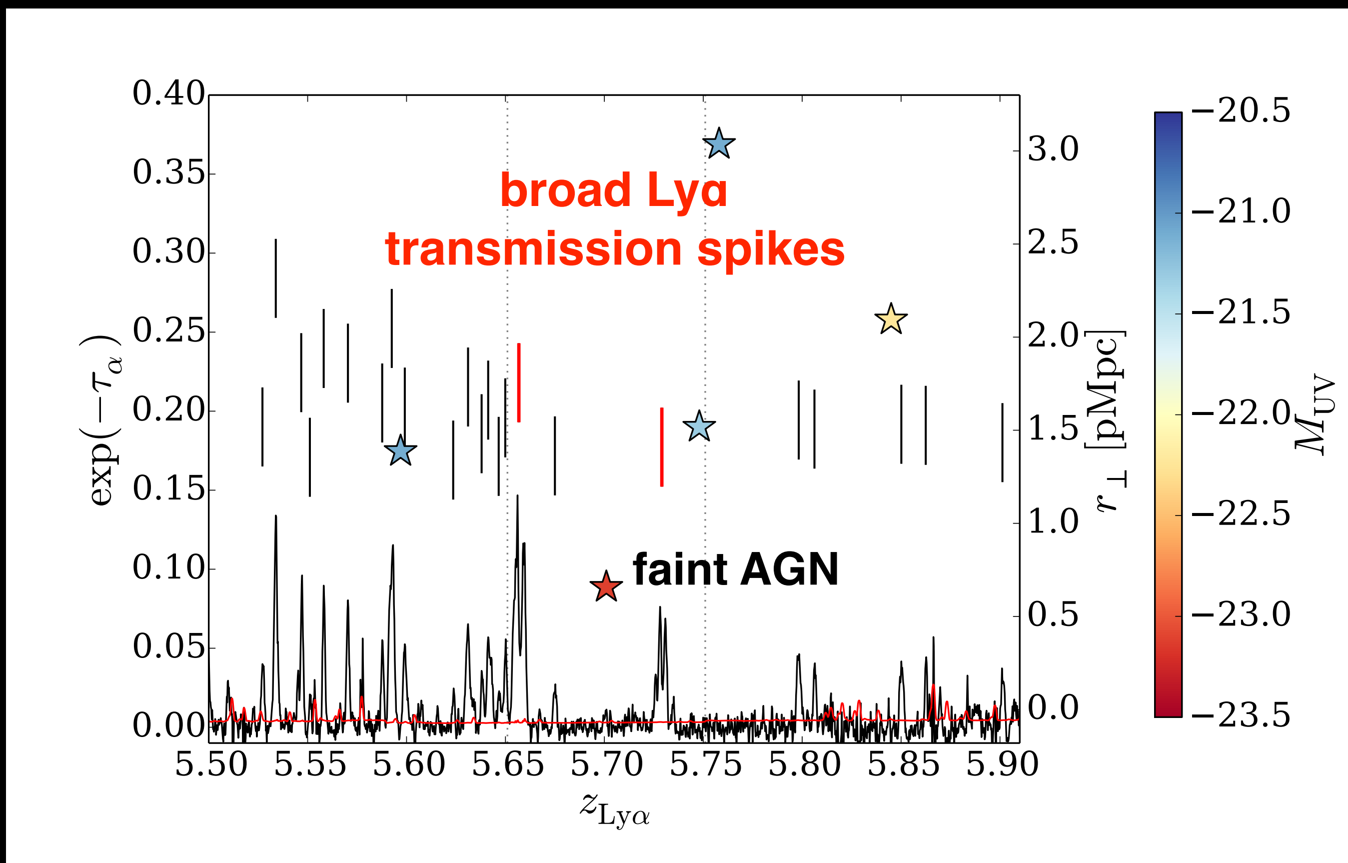


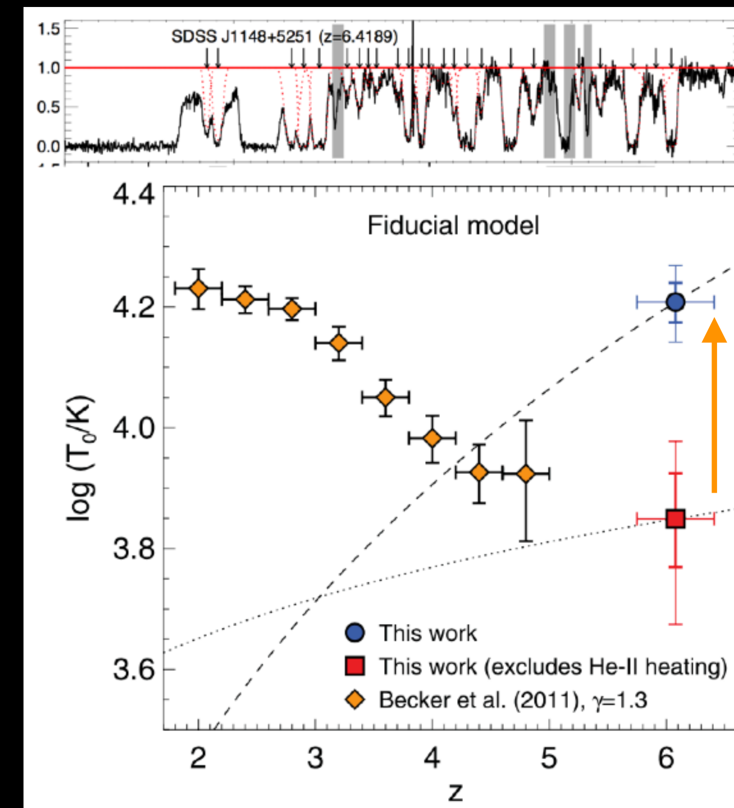
AGN may heat up the IGM through HeII photo-heating across HeIII ionization front

Early z>5 patchy onset of HeII reionization?



The role of AGN: reionization of hydrogen & helium





Bolton+2012

Evidence of early onset of HeII reionziation
The effect of HeII heating in the proximity zone of bright QSOs

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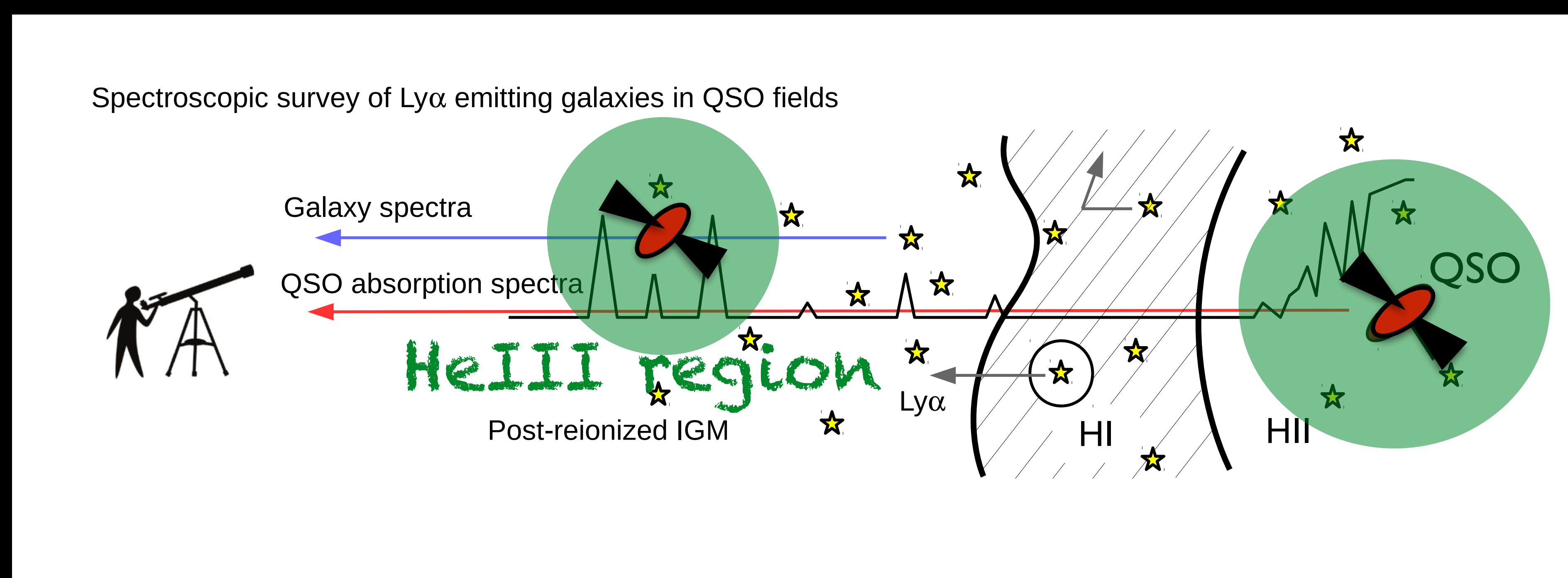
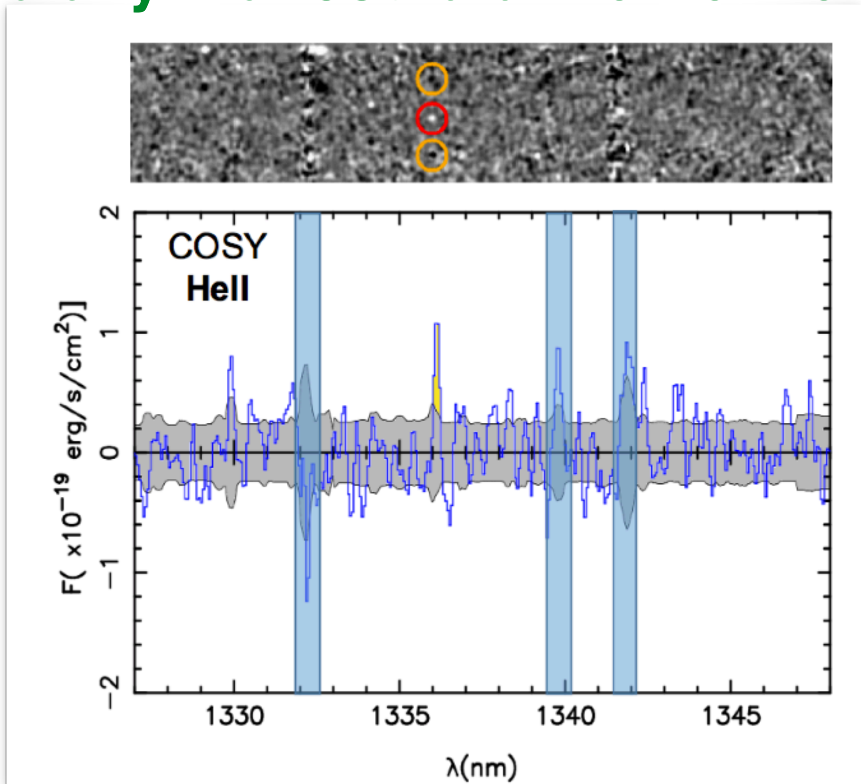
Early z>5 patchy onset of HeII reionization?

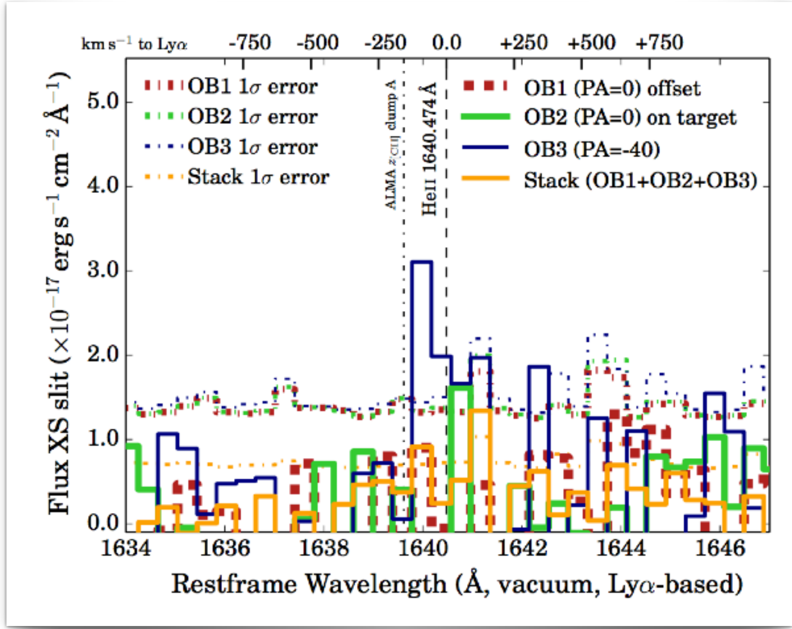


The role of AGN: reionization of hydrogen & helium

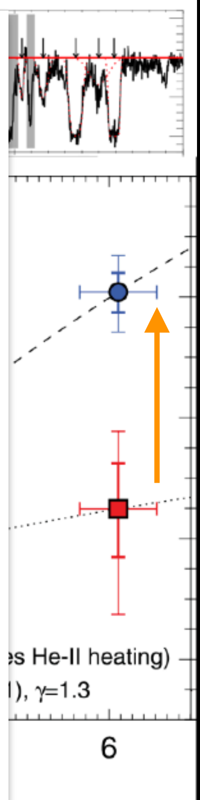
Galaxy that could drive HeII reionization in its local environment



z=7.15 galaxy with AGN activity (Laporte+2017)



and z=6.6 CR7? (Sobral+2018, but Shibuya+2018)



Bolton+2012

ell reionziation the proximity Os

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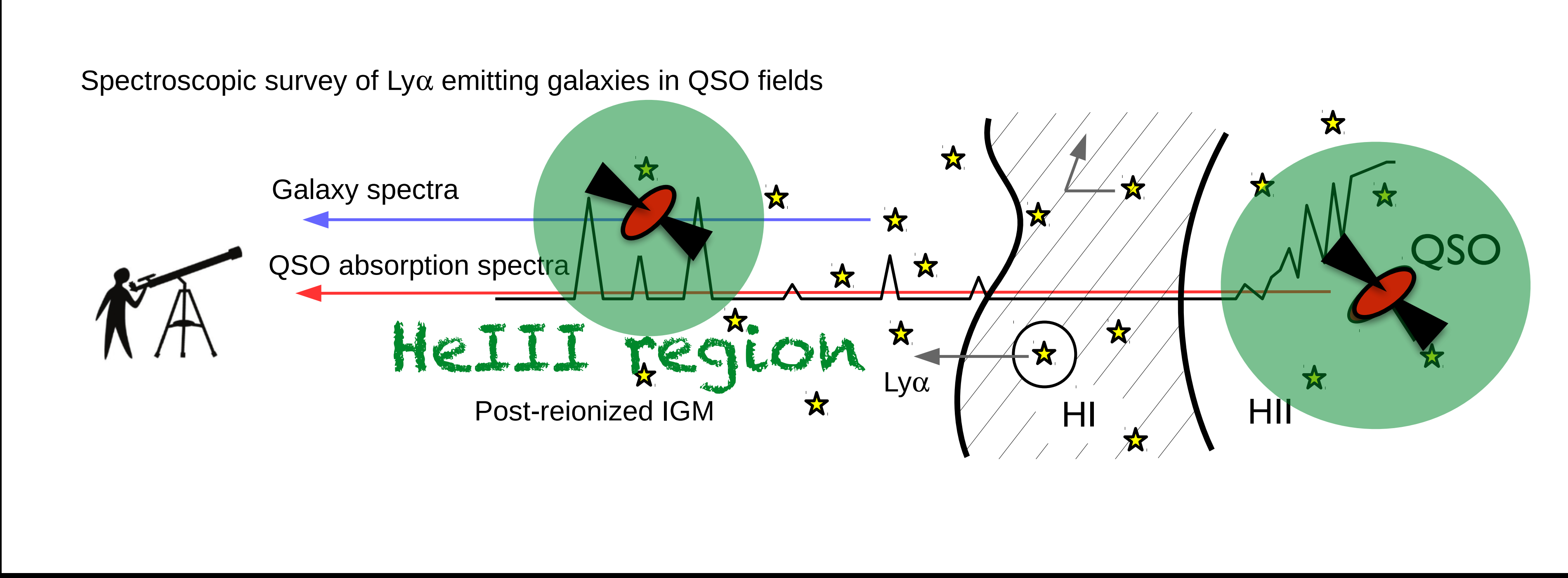
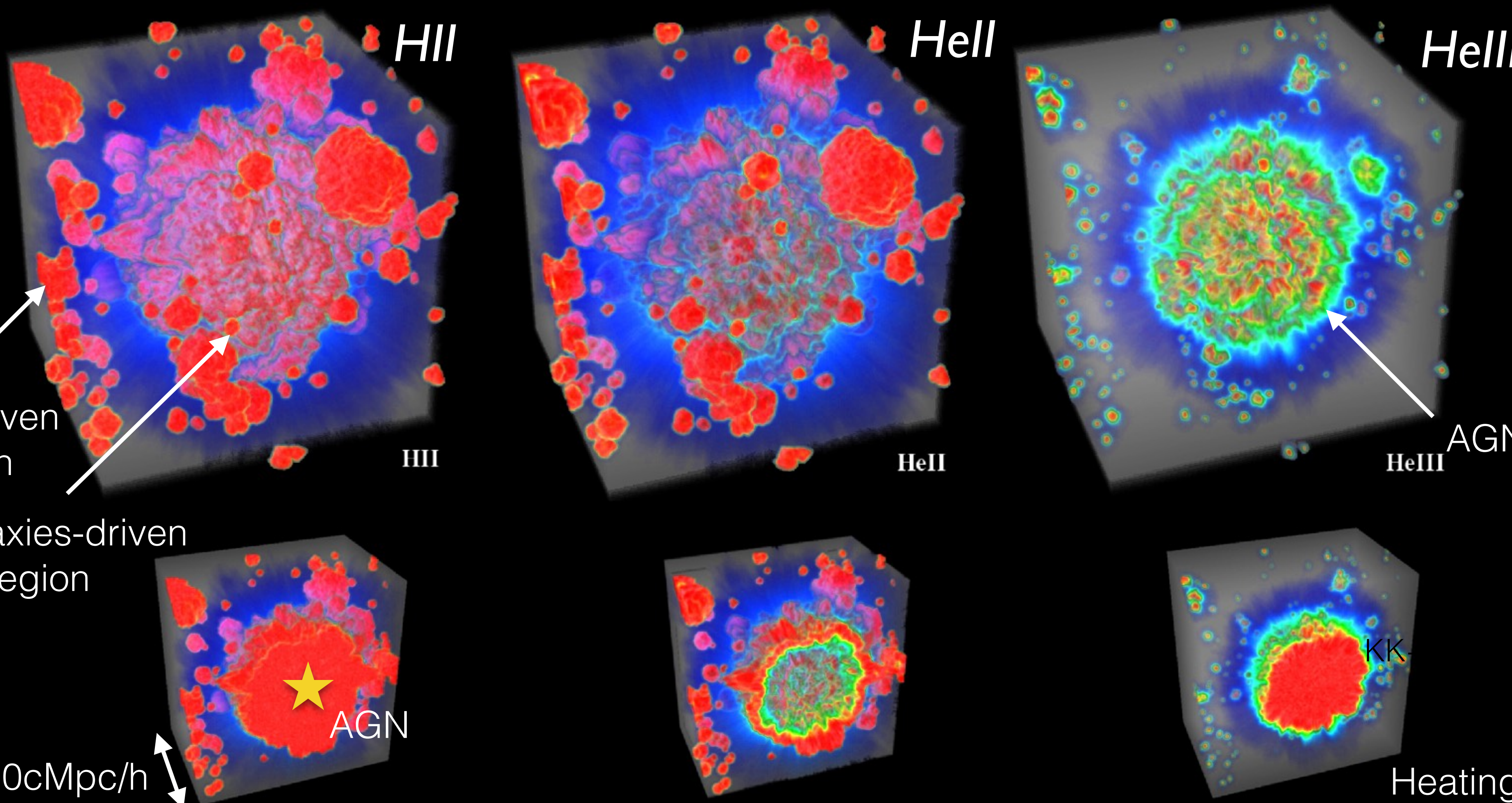


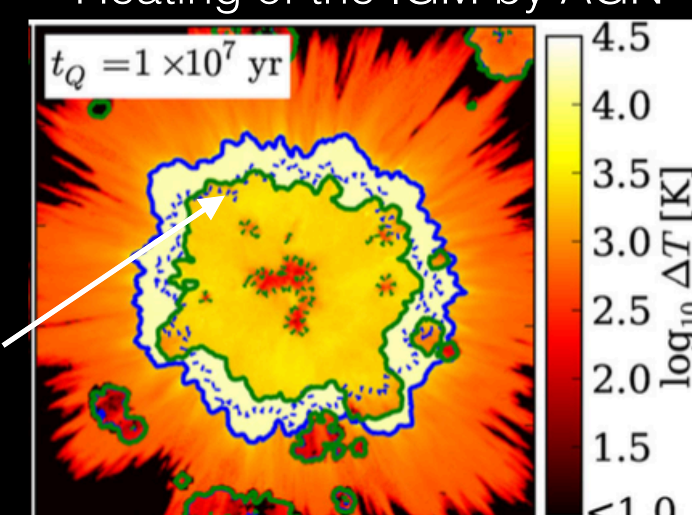
The role of AGN: reionization of hydrogen & helium

Multi-frequency radiative transfer simulation of hydrogen & helium reionization with galaxies and AGN

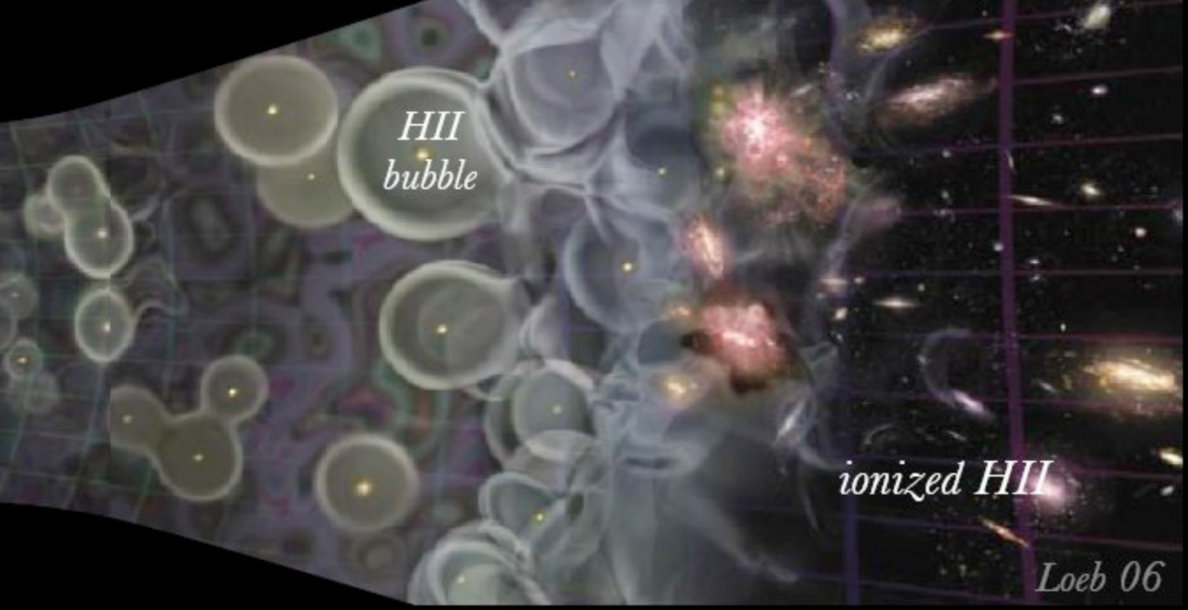
Kakiichi+2017



Heating of the IGM by AGN



The 'concerted' impact of galaxies & AGN on the ionization and thermal state of the IGM in its local ennvironment?



Hypothesis emerging from J1148+5251 QSO field

What reionised the Universe?

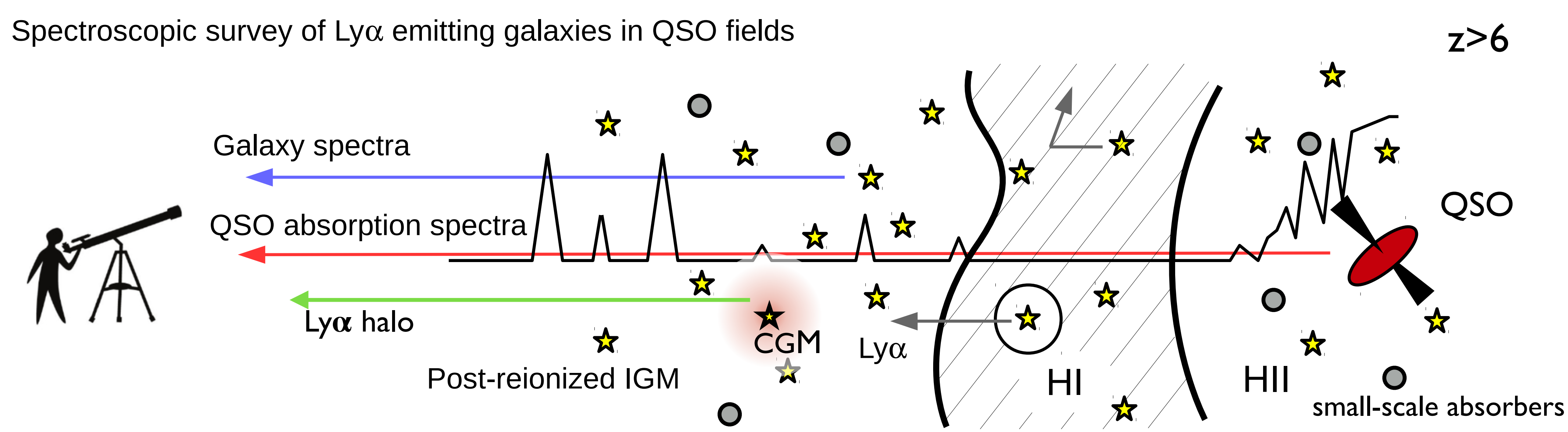
*While **faint galaxies** with high escape fraction (>10%) primarily **drive reionisation**, **luminous galaxies and AGN** may play an increasingly important role in sourcing the **large-scale fluctuations of the UV background and thermal state of the IGM** towards the tail end of reionisation, possibly via their hard ionising spectra.*

Summary "*Lyα probing Lyα*"

What reionised the Universe?

We are mapping ***a full 3D distribution of galaxies*** *×* ***the intergalactic medium*** *(using "Lya in emission and absorption") to understand the Epoch of Reionization.*

"While ***faint galaxies*** *(M_{UV}<-15) with high escape fraction (>10%) primarily* ***drive reionization****,* ***luminous galaxies and AGN*** *may play an increasingly important role in sourcing the* ***large-scale fluctuations of the UV background and thermal state of the IGM*** *towards the tail end of reionisation"*



1) A new route to escape fraction. 2) Role of luminous galaxies and AGN. 3) … more!

Kakiichi+2018 (arXiv:1803.02981)