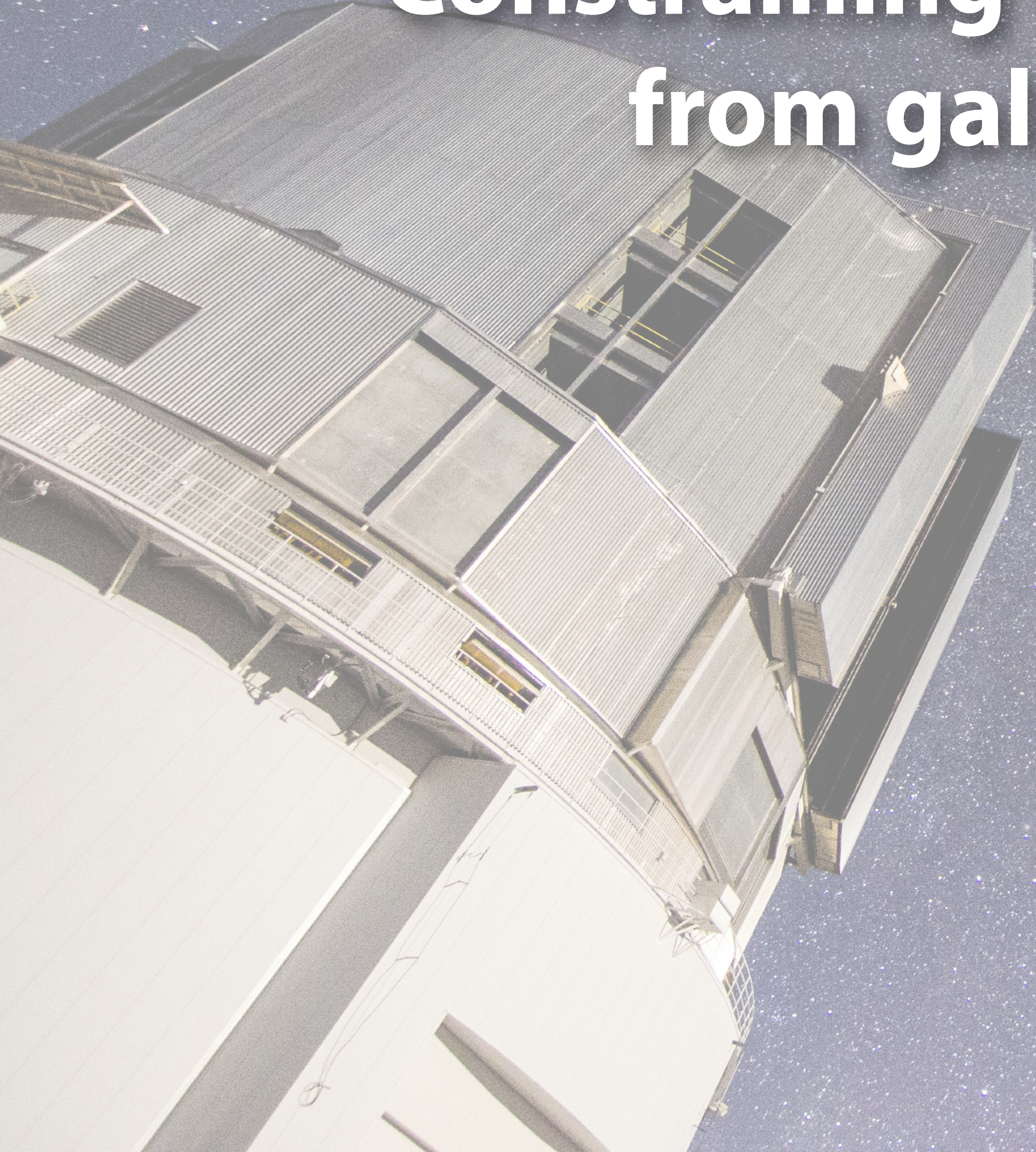


Constraining the reionization scenario from galaxy surveys at the end of Epoch of Reionization

see *Kashino+2020, ApJ, 888, 6* for full details

Daichi Kashino (ETH Zurich)

Collaboration with
S. Lilly, T. Shibuya, M. Ouchi
N. Kashikawa, R. Ishimoto

Aim of our research

Reveal the origin of highly inhomogeneous reionization?

➡ **Large sightline variations in the HI optical depth at the end of reionization**

- ❖ **Introduction**
  Observations of the HI optical depth and models

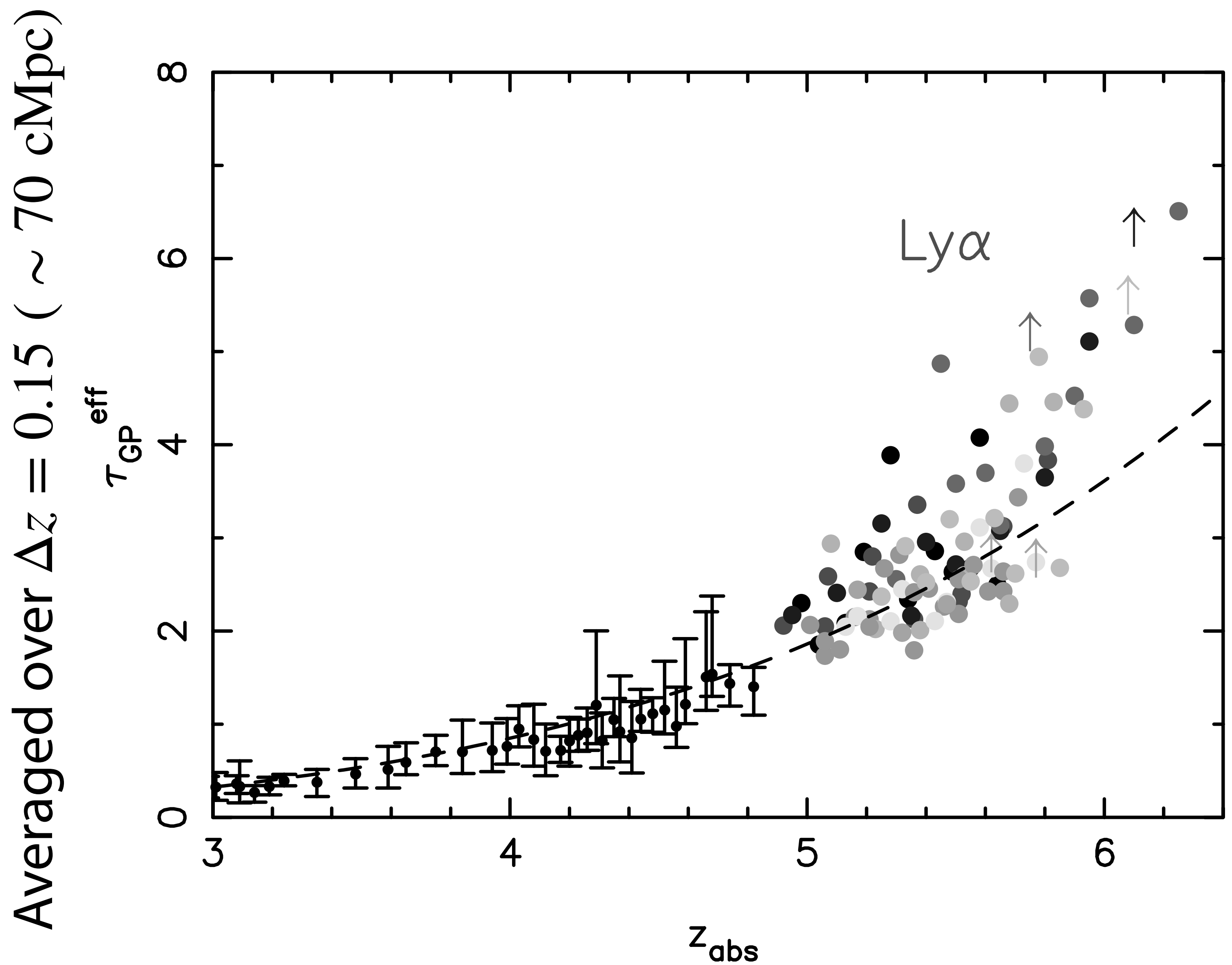
- ❖ **Testing the models — our observations**
  LBG surveys with HSC in the field of bright $z>6$ quasars

- ❖ **First result**
  Evidence that an exceptional Lyα trough (i.e., highly opaque region) is associated to a galaxy underdensity.

  → Constraints on the models

Gunn-Peterson test — increasing scatter of $\tau_{\rm eff}$

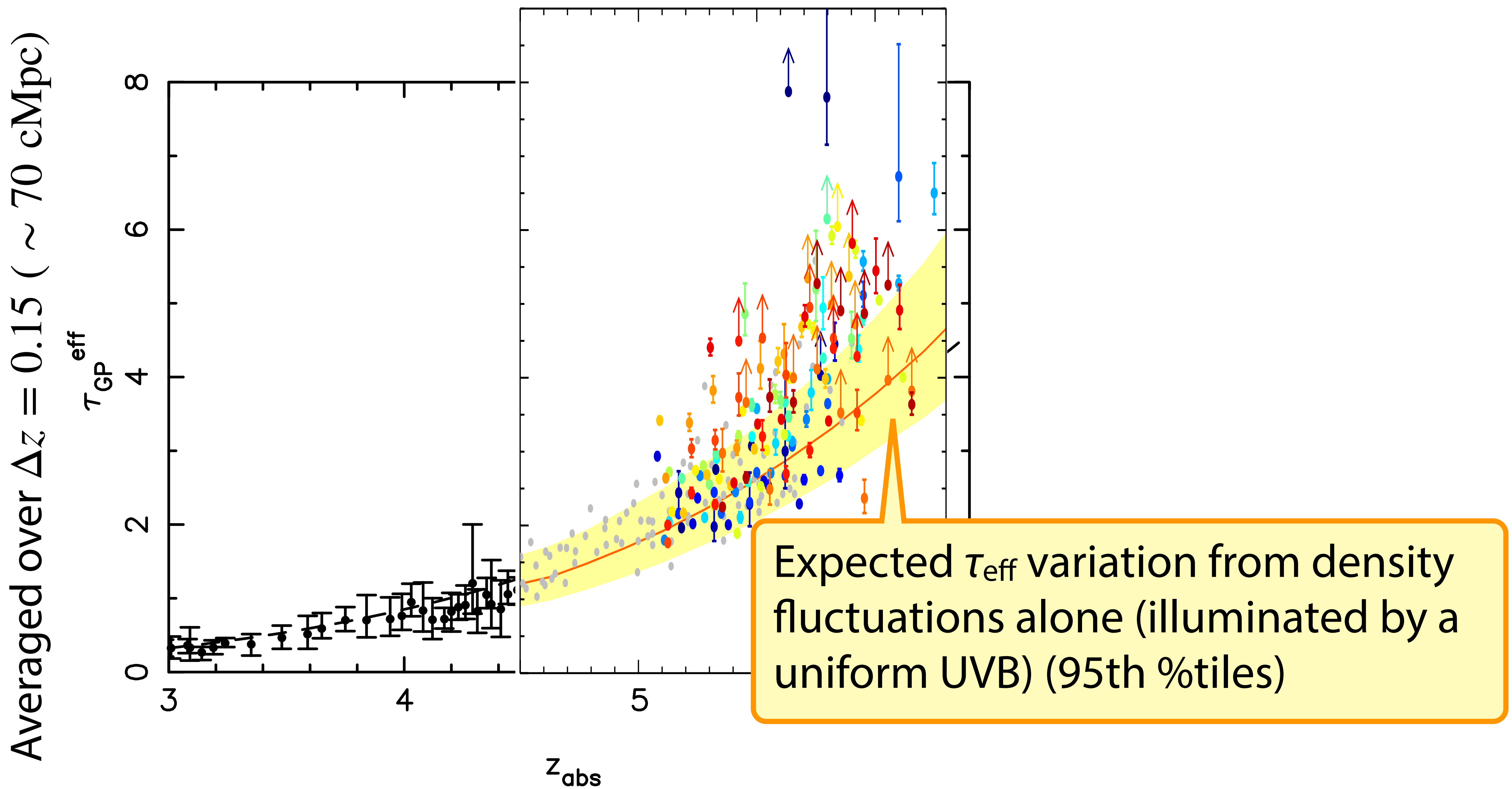
The scatter appears to rapidly grow up at z~5–5.5,
much beyond the range predicted with a uniform UV background.



Gunn-Peterson test — increasing scatter of τ_{eff}

The scatter appears to rapidly grow up at z~5–5.5,
much beyond the range predicted with a uniform UV background.

➡ what do the large optical depth variations mean?



What do the large $\tau_{\rm eff}$ variations mean?

In photoionization-recombination equilibrium,
the optical depth $\tau_{\rm eff}$ scales as

observationally

coming from the T-dependence of
the recombination coefficient $\alpha_{\rm HI}$

$$\tau_{\rm eff} = -\ln\langle F_\lambda^{\rm obs}/F_\lambda^{\rm int}\rangle \propto \left\langle N_{\rm HI}\right\rangle \propto \Delta^2\ \Gamma^{-1}\ T^{-0.72}$$

Underlying density UV background IGM temperature

The large $\tau_{\rm eff}$ fluctuations require additional fluctuations
either in **Γ (UV background)** or ***T* (IGM temperature)**.

The density field **Δ (density)** is well established by the theory of
structure formation, thus no room to more fluctuate it.

Possible scenarios

$$\tau_{\rm eff} = -\ln\langle F_\lambda^{\rm obs}/F_\lambda^{\rm int}\rangle \propto N_{\rm HI} \propto \Delta^2\ \Gamma^{-1}\ T^{-0.72}$$

UV background ↗ ↖ IGM temperature

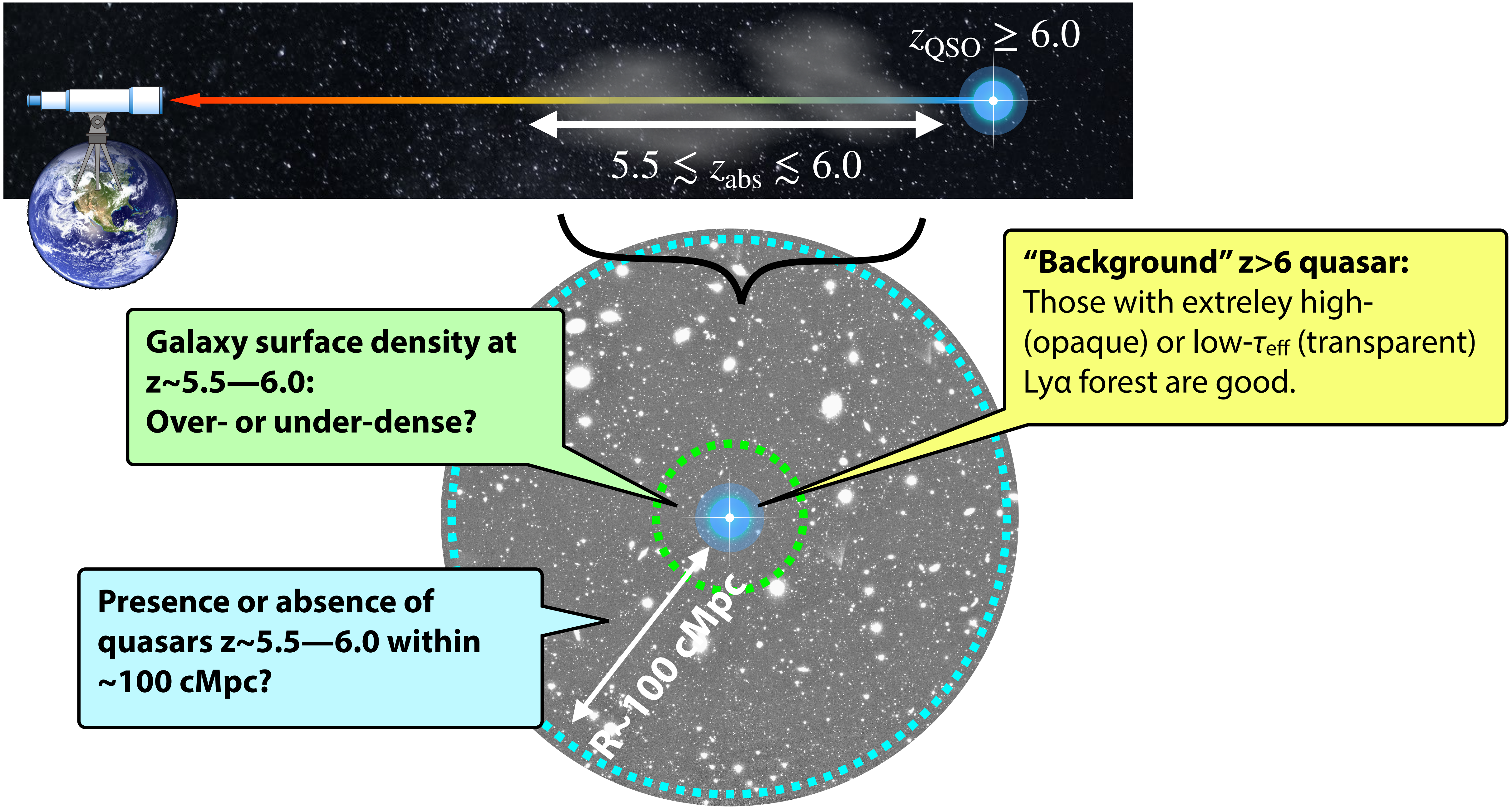
Model	What fluctuate?	Source of fluctuation	Predicted $\tau_{\rm eff}$-ρ relation and/or observation
fluctuating-$\lambda_{\rm mfp}$ Davies & Furlanetto '16	Γ	Galaxy distribution and spatially-varying $\lambda_{\rm mfp}$	Negative correlation: high-$\tau_{\rm eff}$ ⇔ low-ρ low-$\tau_{\rm eff}$ ⇔ high-ρ
rare-source Chardin+15, 17	Γ	Significant contribution of rare bright sources, i.e., quasars	Not clear, but we should always find >1 quasars in high-$\tau_{\rm eff}$ region, but no in low-$\tau_{\rm eff}$ regions
fluctuating-$T_{\rm IGM}$ D'Aloisio+15	T	Time-lags of reionization b/w over- and underdensities	Positive correlation: high-$\tau_{\rm eff}$ ⇔ high-ρ low-$\tau_{\rm eff}$ ⇔ low-ρ
Late-reionization Kulkurni+19 Keating+19	Γ (and T)	Residual neutral islands ($x_{\rm HI}$~1) in reionization that ended at z~5.2	high-$\tau_{\rm eff}$ ⟹ low-ρ low-$\tau_{\rm eff}$ ⟹ wide variation in ρ

Daichi Kashino | ETH Zürich | kashinod@phys.ethz.ch

Testing the models

Testing the models

Correlate **galaxy distribution** with **the HI optical depth** across 5.5<z<6.0.



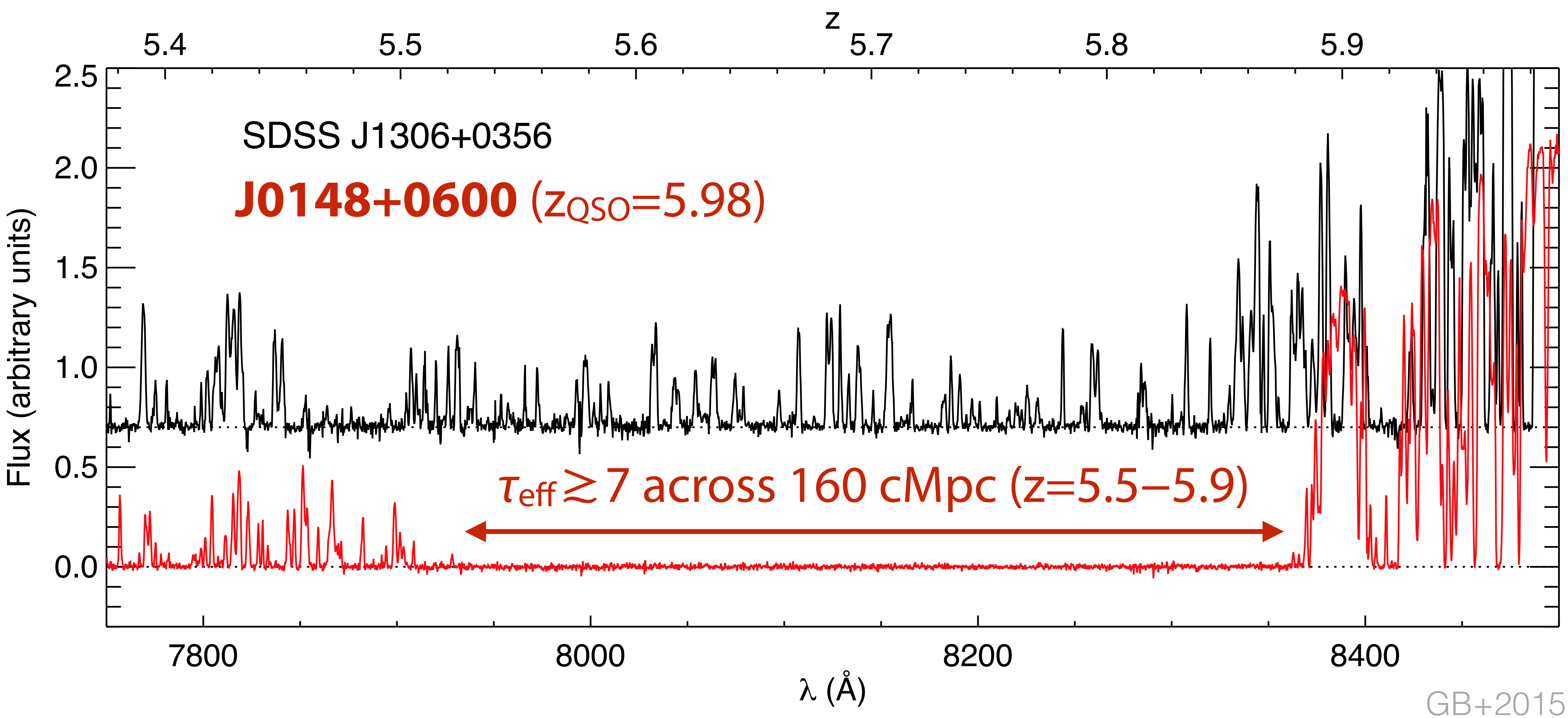
Subaru/HSC matches perfectly to carry out this experiment!

Daichi Kashino | ETH Zürich | kashinod@phys.ethz.ch

A surprisingly opaque and long trough

Unusually **opaque** ($\tau_{\rm eff} \gtrsim 7$) and **long** (~160 cMpc) Lyα trough at z=5.5–5.9

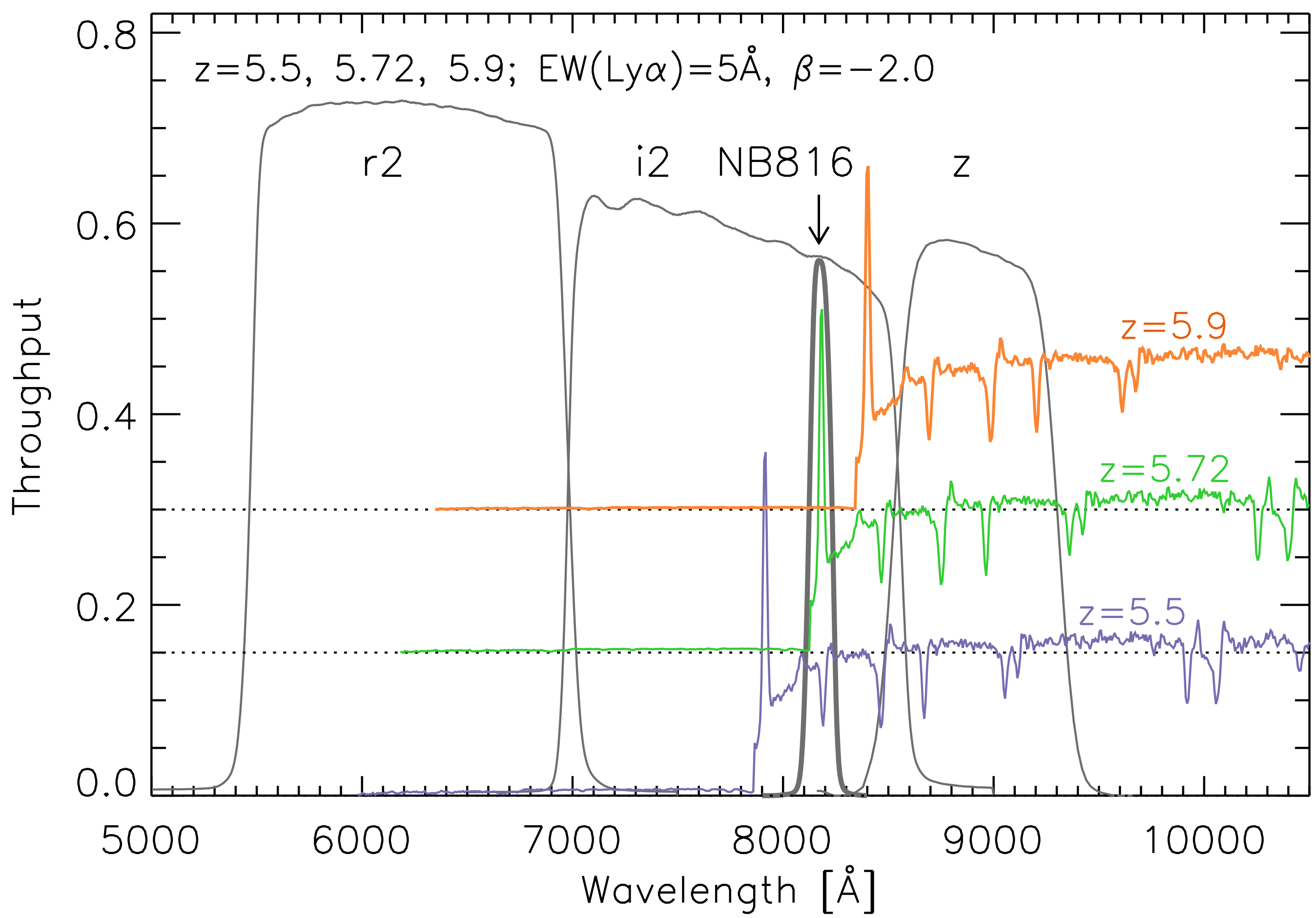
➡ **Good target field for distinguishing the models**

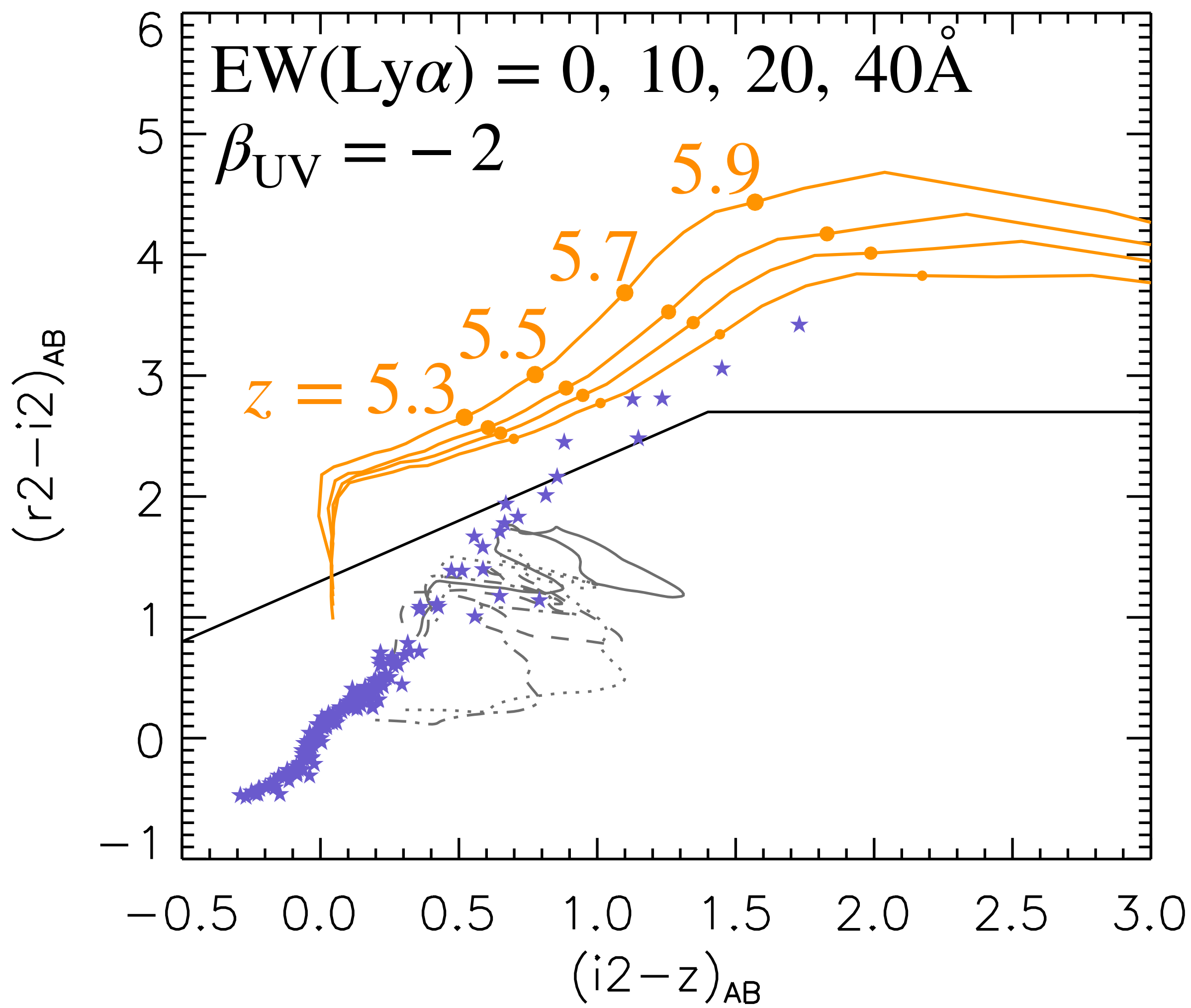


Becker et al. (2015) (Figure taken from G. Becker's slide, 2016)

LBG surveys with HSC in multiple quasar fields

- ✓ Good density tracers which are not impacted by local HI optical depth.
- ✓ Color (i-z) is sensitive to redshift ($\delta z \simeq 0.25$, FWHM).





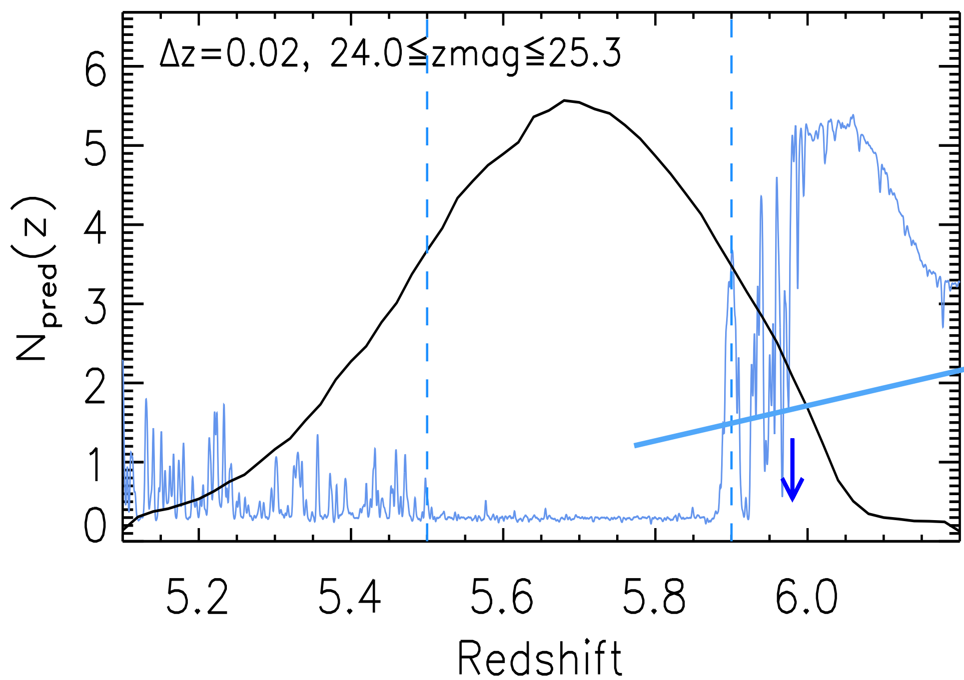
First result — QSO J0148+0600

Result: LBG candidates

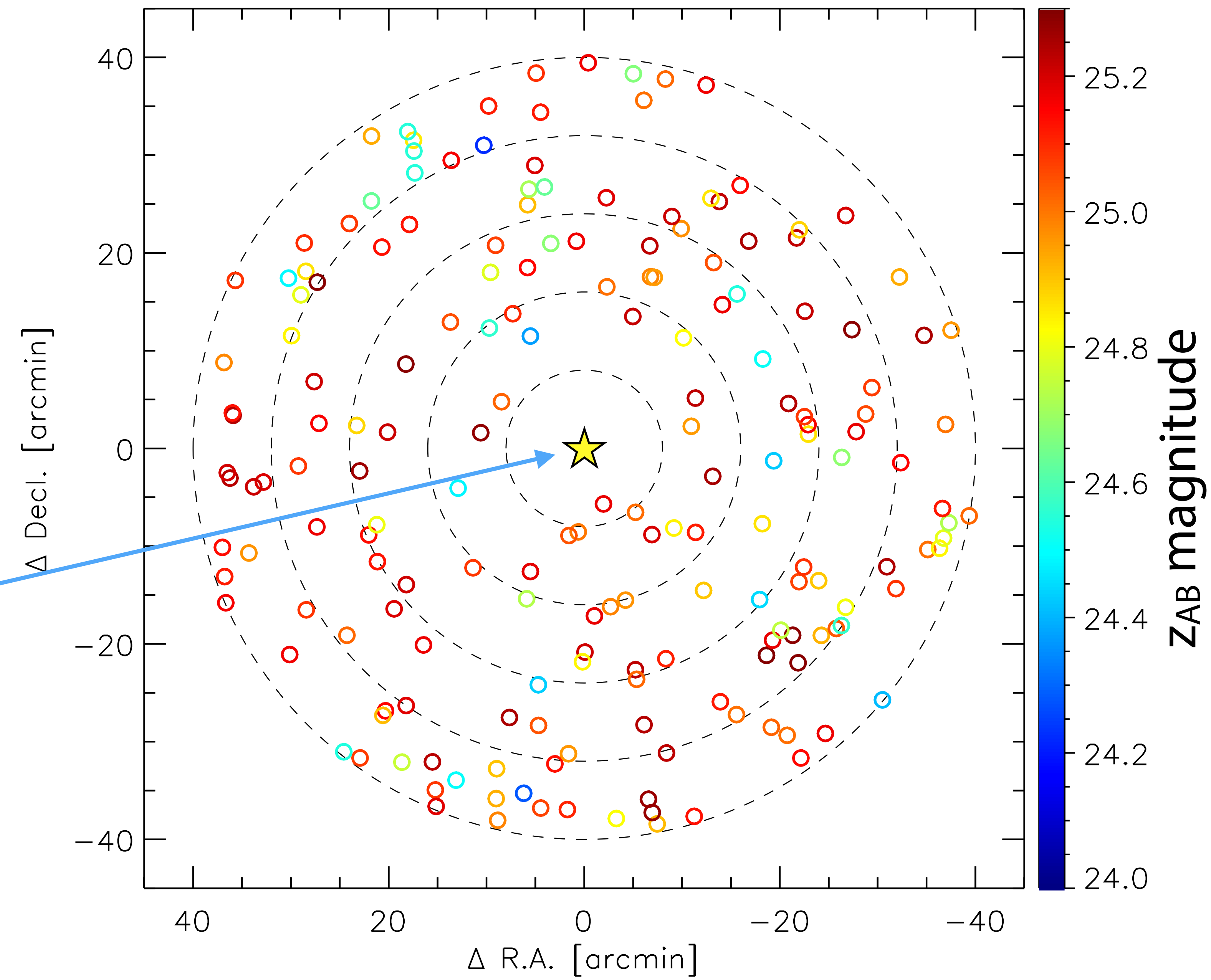
The spatial distribution of 185 LBG candidates (z_{AB}<25.3) within 40 arcmin
➡ “**deficit**” at the quasar position

Predicted *N*(z)

covers the full length of the trough

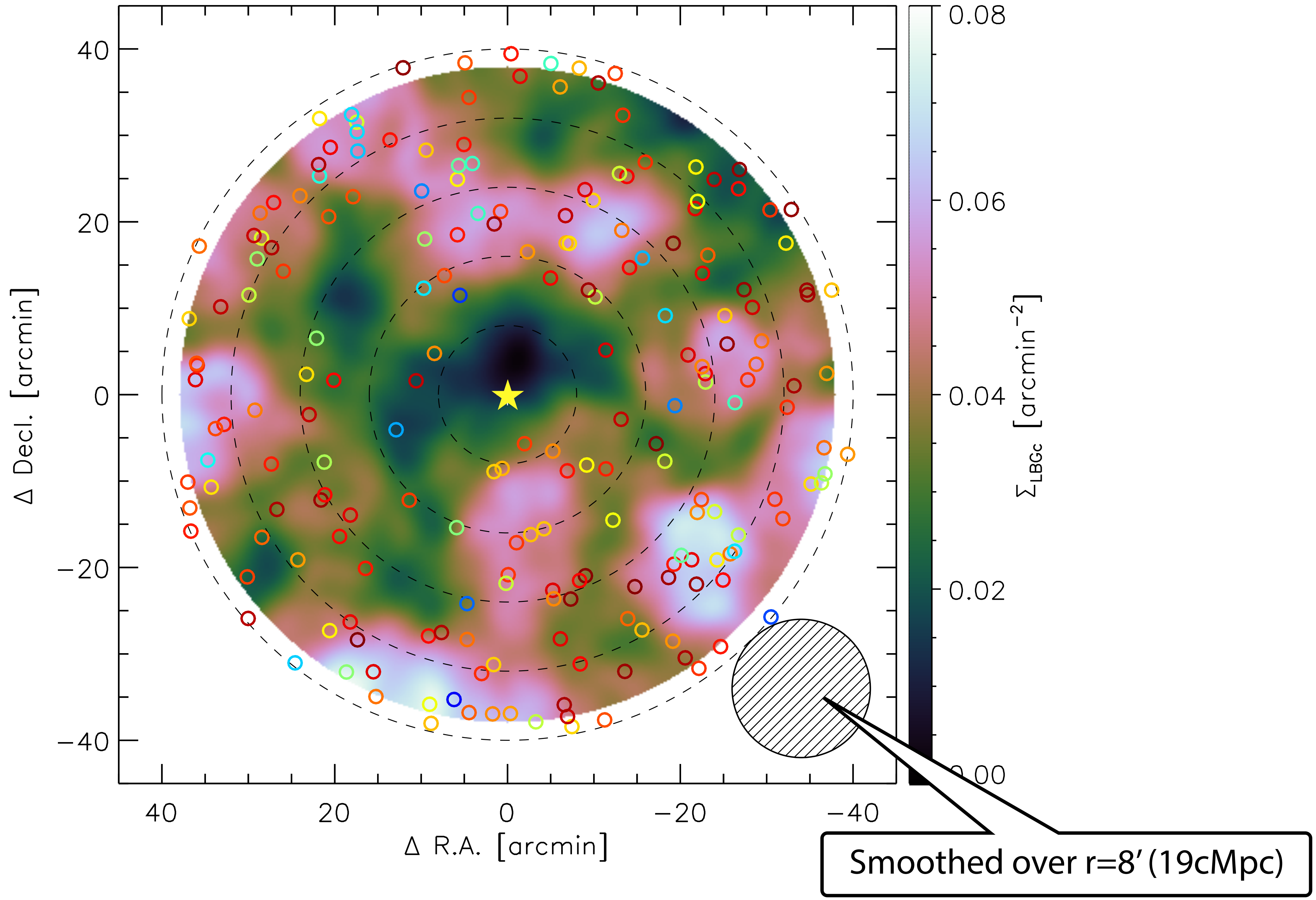


Blue: J0148+0600 spectrum (z_{QSO}=5.98)



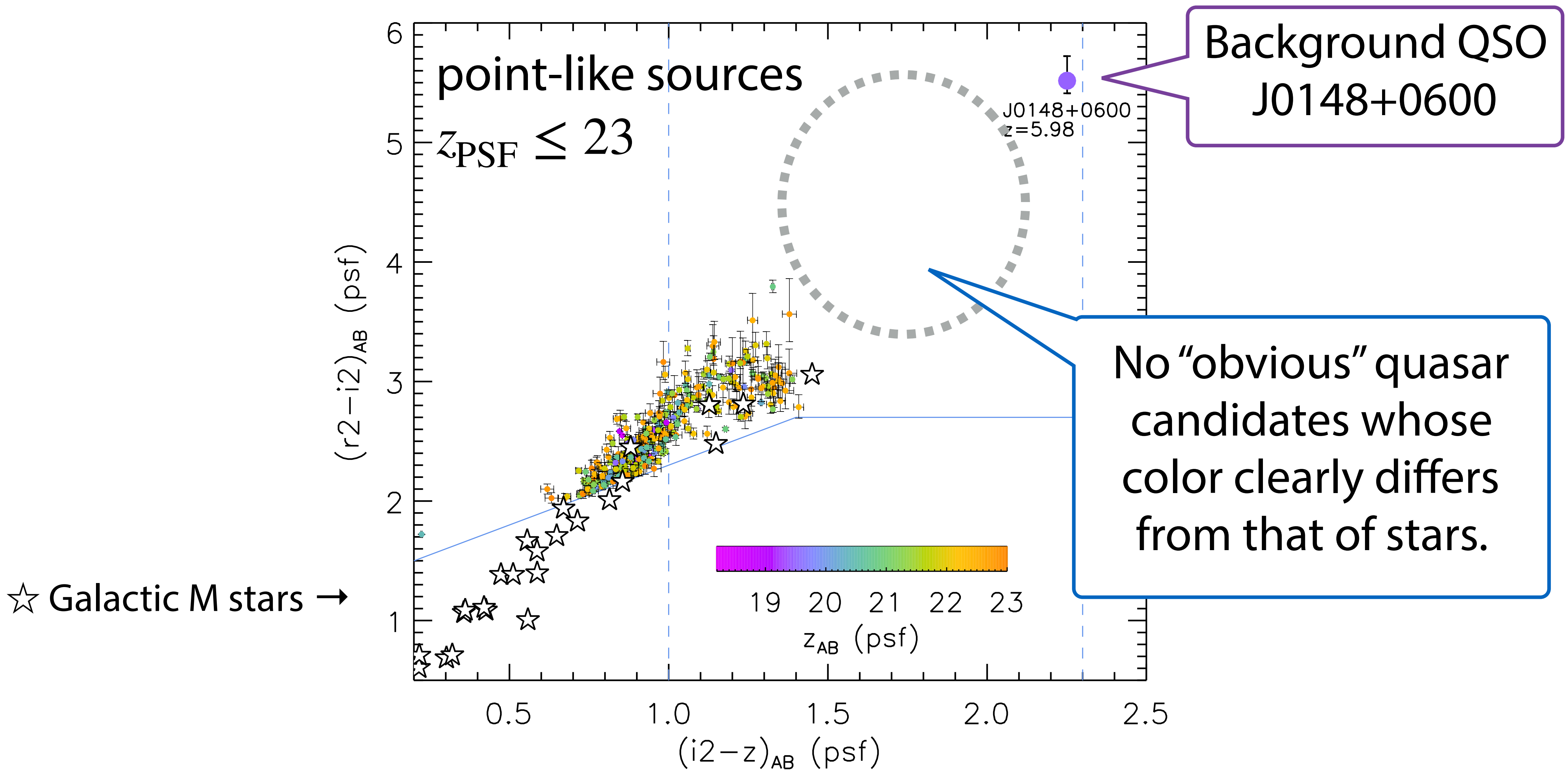
Result: LBG surface density map

Σ_{LBG} is the lowest at the center among the independent r=8′ apertures across the field.



Test for the rare-source model:
No "obvious" bright quasars in the field

➡ consistent with the rare-source model (no quasars in high-τ_{eff} region)



But, it is challenging to distinguish quasars which are fainter and/or similar to stars in colors because of their similar light profile..

Summary

An LBG underdensity is associated to an extremely opaque Lyα trough.
This is a complementary confirmation of a pre-indication via an LAE survey.

Model	What fluctuate?	Source of fluctuation	Predicted τ_{eff} -ρ relation and/or observation
fluctuating-λ_{mfp}	Γ	Galaxy distribution and spatially-varying λ_{mfp}	Negative correlation: high-τ_{eff} $\Leftrightarrow$ low-ρ low-τ_{eff} $\Leftrightarrow$ high-ρ
rare-source	Γ	Significant contribution of rare bright sources, i.e., quasars	Not clear, but we should always find >1 quasars in low-τ_{eff} region, but no in high-τ_{eff} regions
fluctuating-T_{IGM}	T	Time-lags of reionization b/w over- and underdensities	Positive correlation: high-τ_{eff} $\Leftrightarrow$ high-ρ low-τ_{eff} $\Leftrightarrow$ low-ρ
Late-reionization	Γ (and T)	Residual neutral islands (x_{HI}~1) in reionization that ended at z~5.2	high-τ_{eff} $\Longrightarrow$ low-ρ low-τ_{eff} $\Longrightarrow$ wide variation in ρ

Stay tuned for further results!

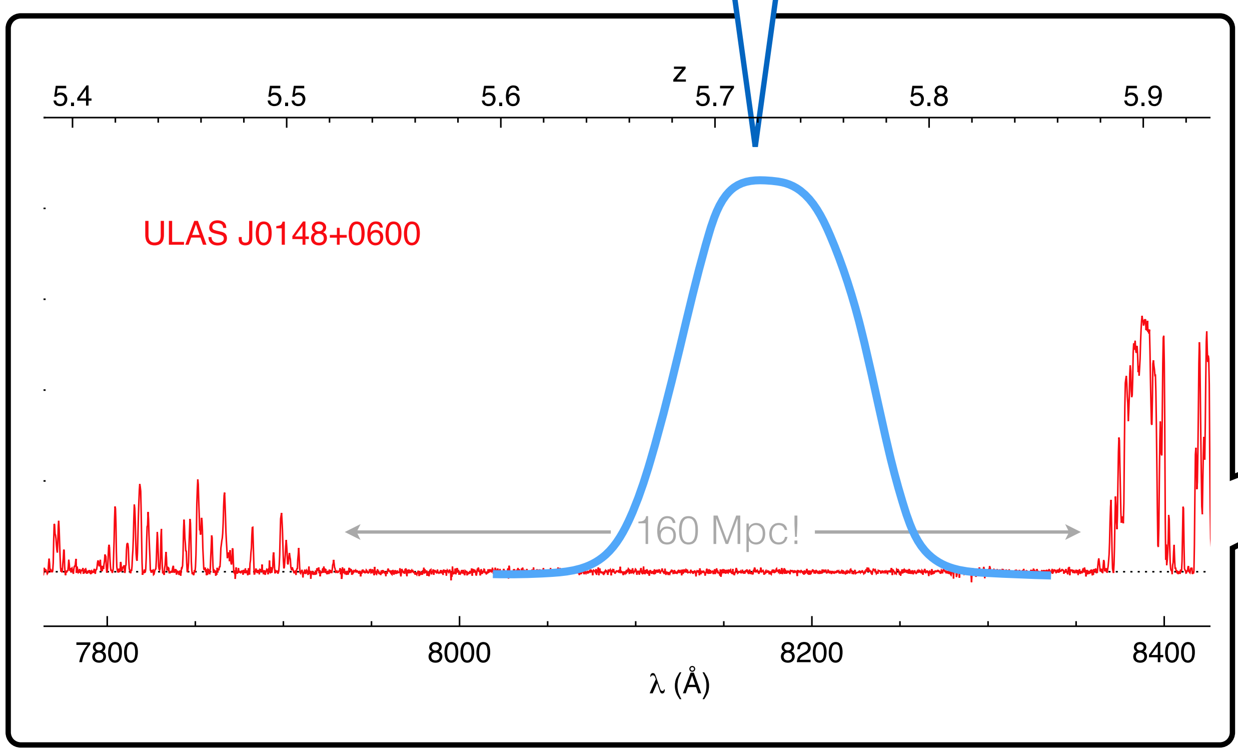
Backup slides

Past result with HSC LAE survey

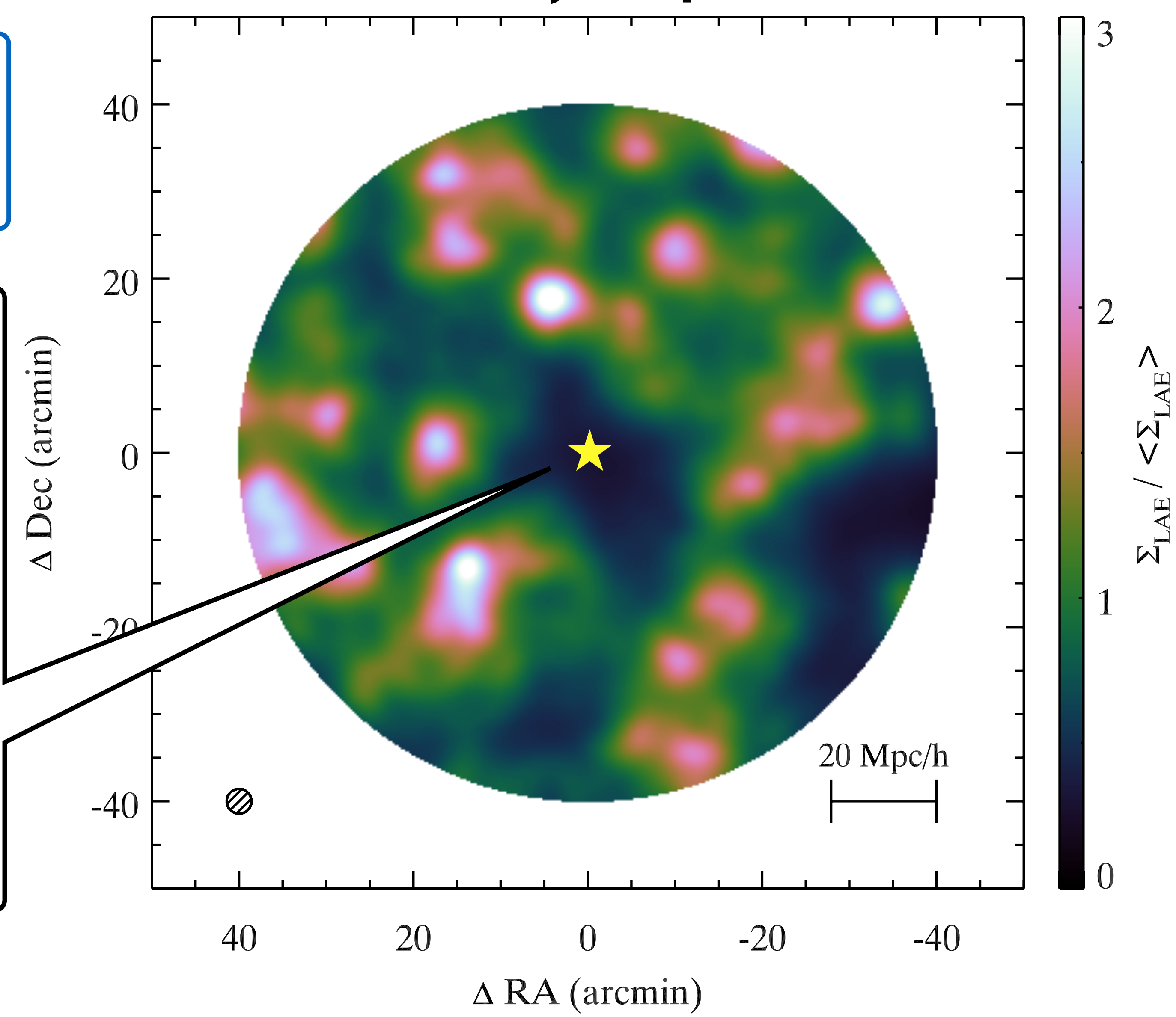
An LAE survey with HSC/NB816 (z=5.7) in the QSO J0148+0600 field

➡ the extremely high-τ_{eff} trough is associated with an LAE underdensity.

LAEs identified with NB816 fall into the center of the trough



Surface density map of ~800 LAEs



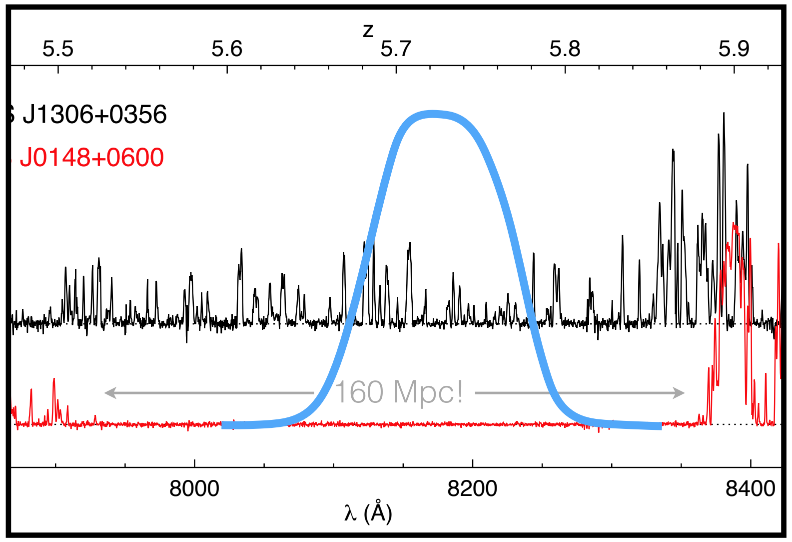
Becker et al. (2018)

Caveats…

Is this really the evidence of a negative Σ_{gal}-τ_{eff} correlation?

Are LAEs really suited to this kind of study?
Detection of LAEs may be suppressed in such high τ_{eff} regions due to absorption of Lyα.
Complimentary surveys of other types of galaxies are required.

For J0148,
NB816 does not cover the full length of the trough.
Does the galaxy underdensity holds across the entire range of the Lyα trough?



More (Σ_{gal}, τ_{eff}) for establishing the correlation.
Need to observe more fields of quasars across a wide range of τ_{eff} to establish the relation between Σ_{gal} and τ_{eff}.

Need further and complementary observations!

Data and LBG selection

Filter	Exposure time (hr)	Seeing (arcsec)	Typical 5σ-lim. mag (2″.0 aperture)
r2	1.5	0.61	26.82
i2	2.4	0.63	26.34
z	1.33	0.78	25.40

Criteria of LBGs at 5.5<z<5.9:

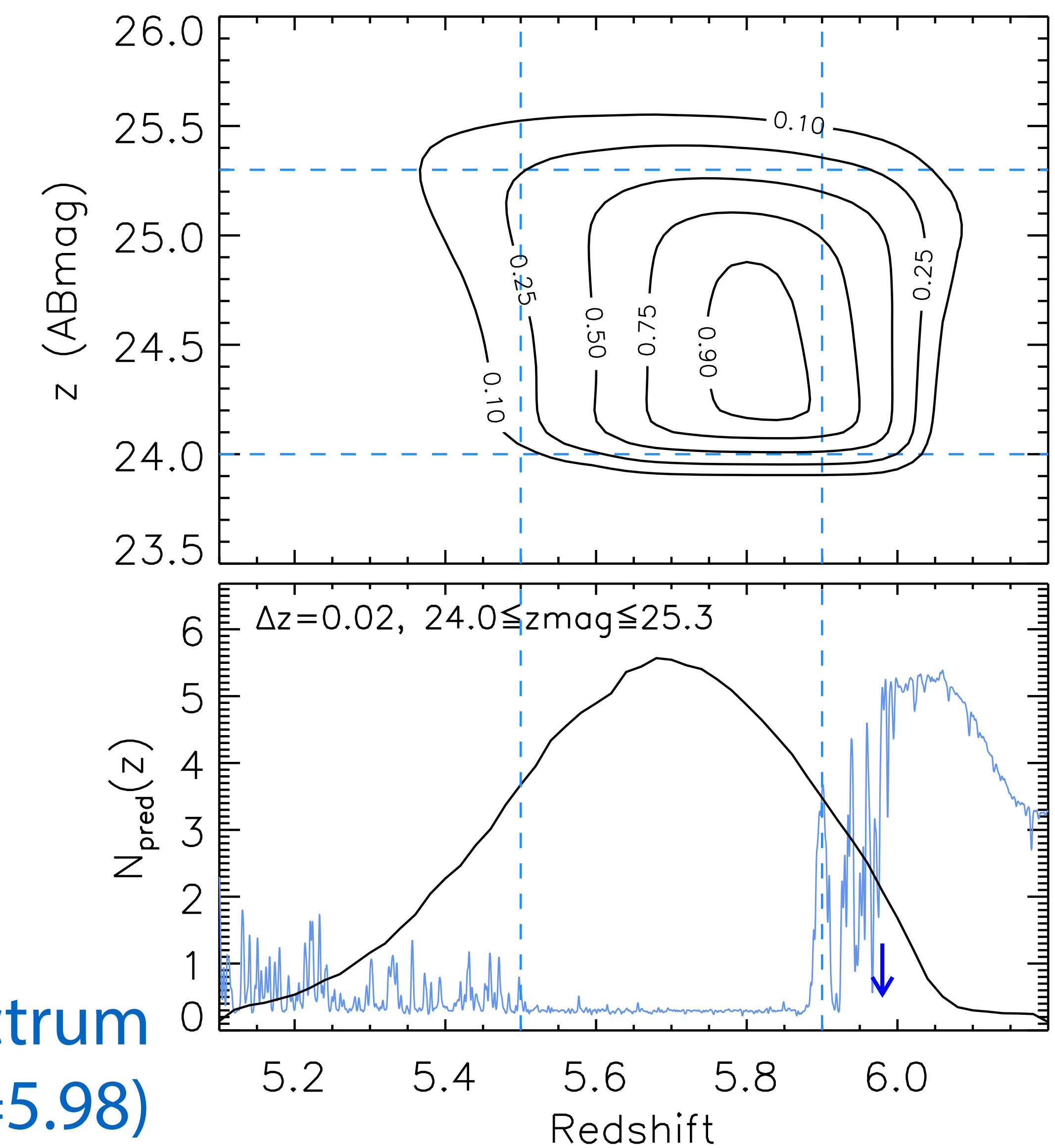
$\mathrm{S/N}(z) \geq 5 \quad \& \quad 24.0 \leq z_{\mathrm{AB}} \leq 25.3$

$\& \quad 1.0 \leq (i2 - z)_{\mathrm{AB}} \leq 2.3$

$\& \quad r2_{\mathrm{AB}} \geq 27.8 \quad \& \quad \mathrm{S/N}(r2) < 2.0$

Completeness & Predicted *N*(z) ▶

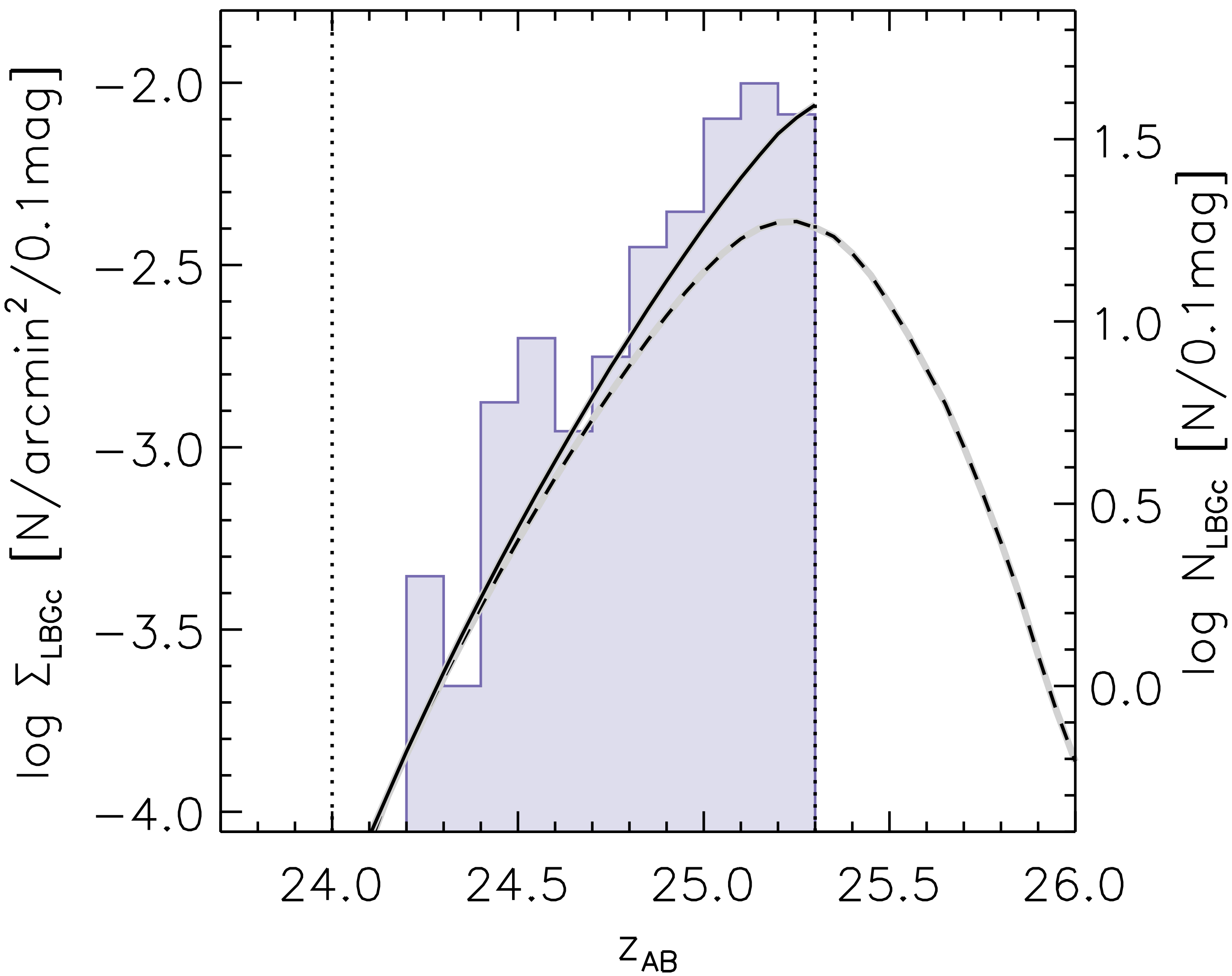
Expected *N*(z) has the peak at z~5.7 and covers the whole length of the Lyα trough.



Blue: J0148+0600 spectrum (z_{QSO}=5.98)

Results: LBG candidates

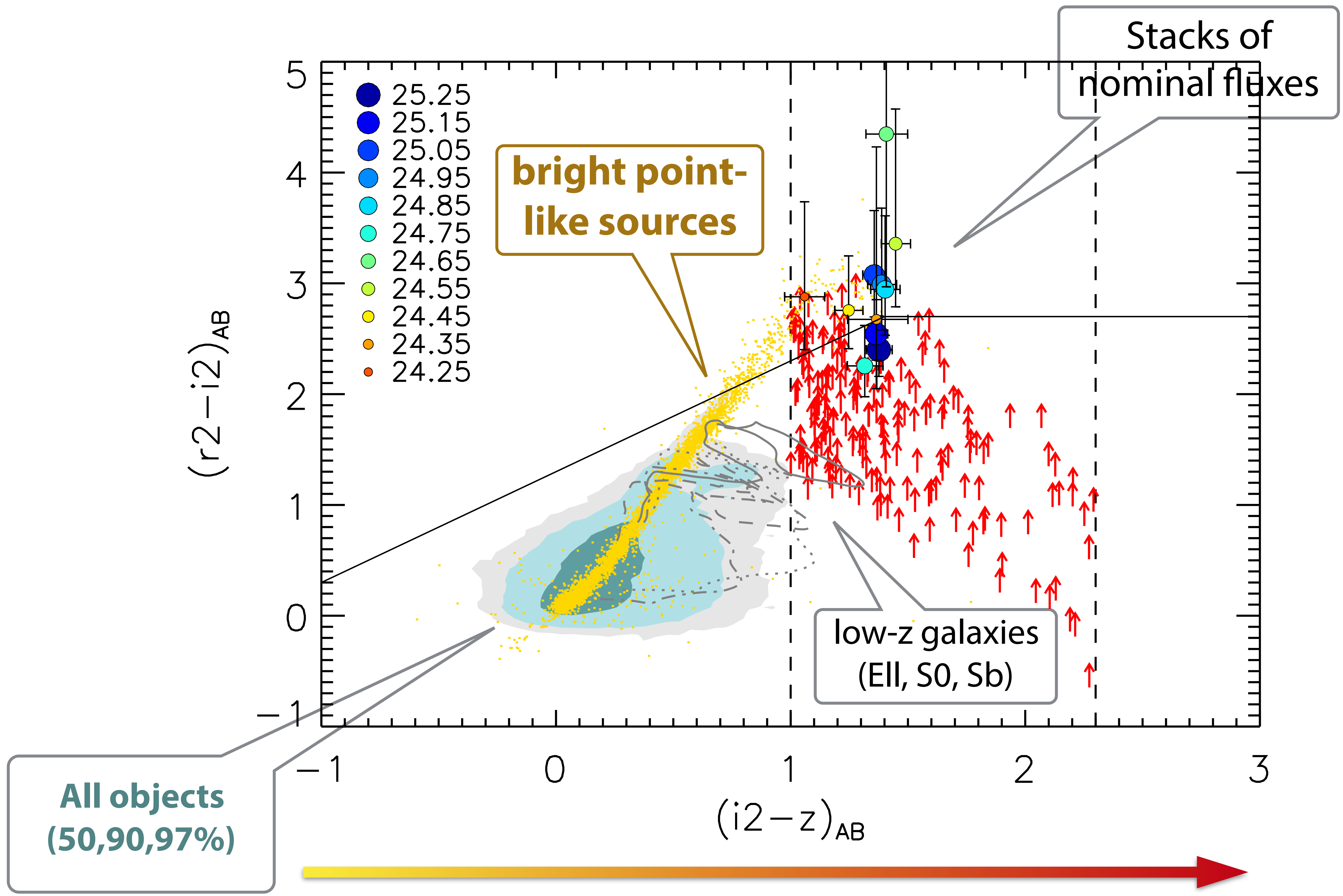
The z_{AB} magnitude distribution is in good agreement with that expected from completeness calculations and luminosity function.



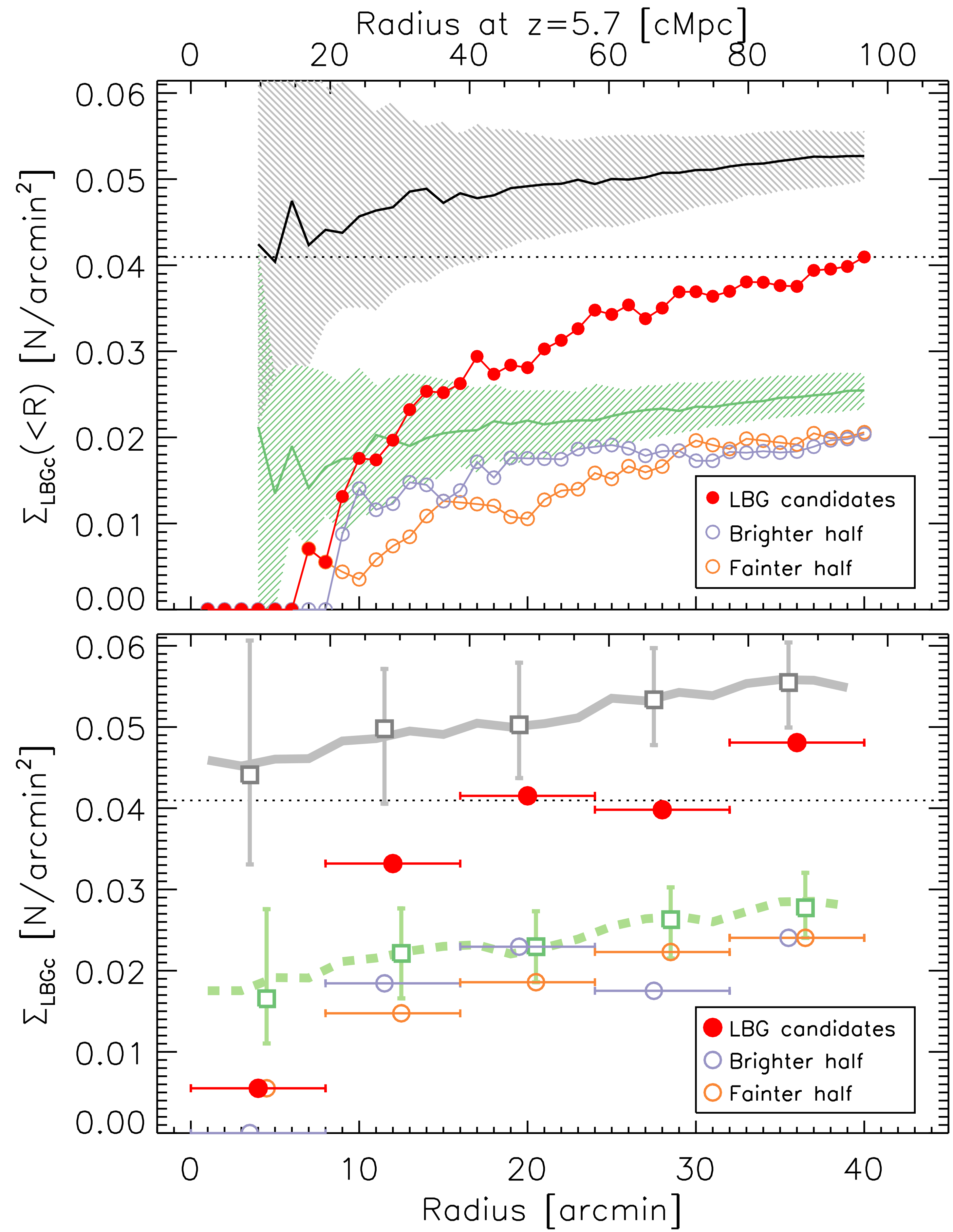
observed z_{AB} mags disturbed by photometric errors (to be compared with the result)

the same, but for true z_{AB} magnitude.

LBG candidates on the color-color diagram

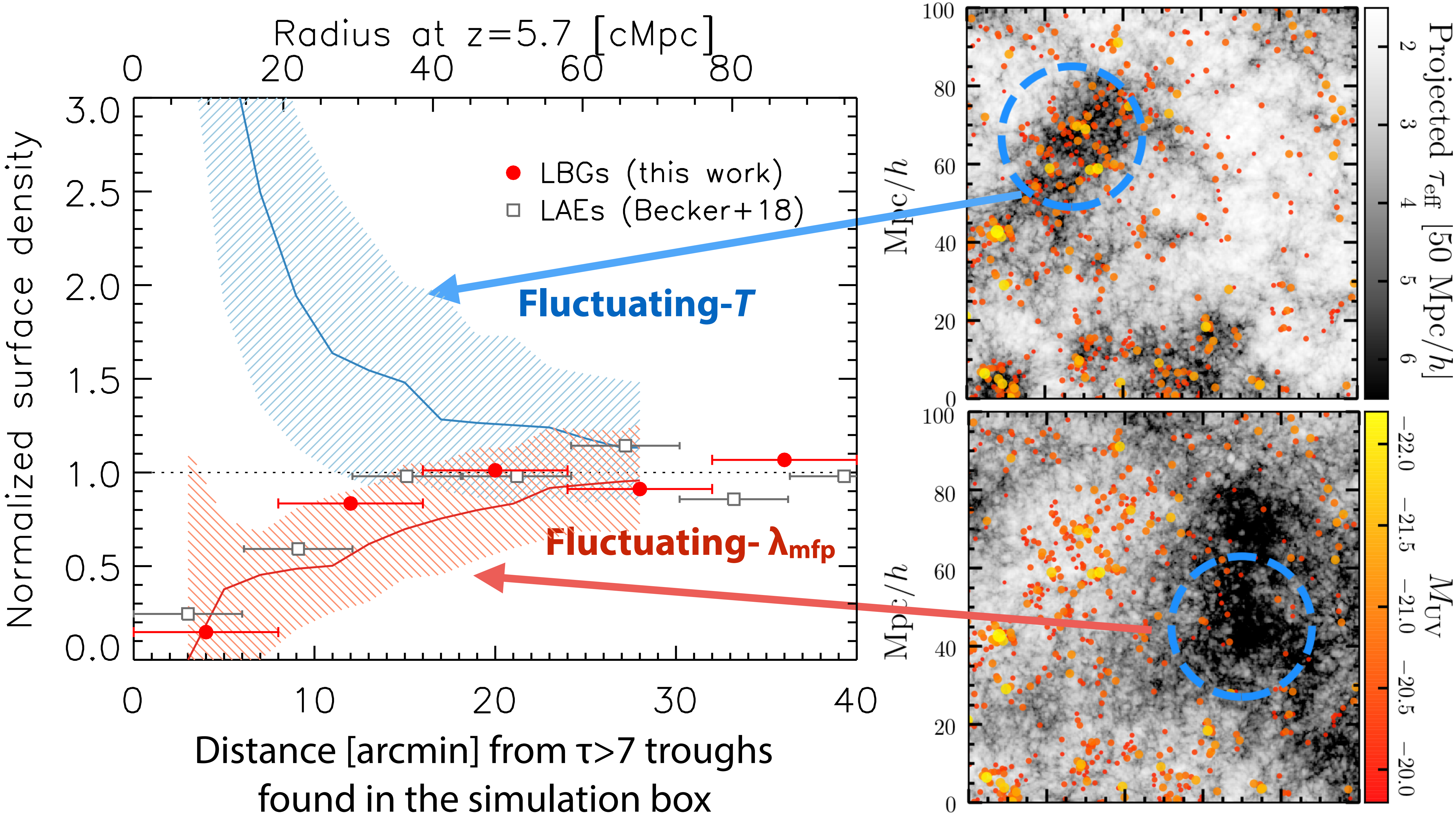


Radial profiles



Comparisons to models

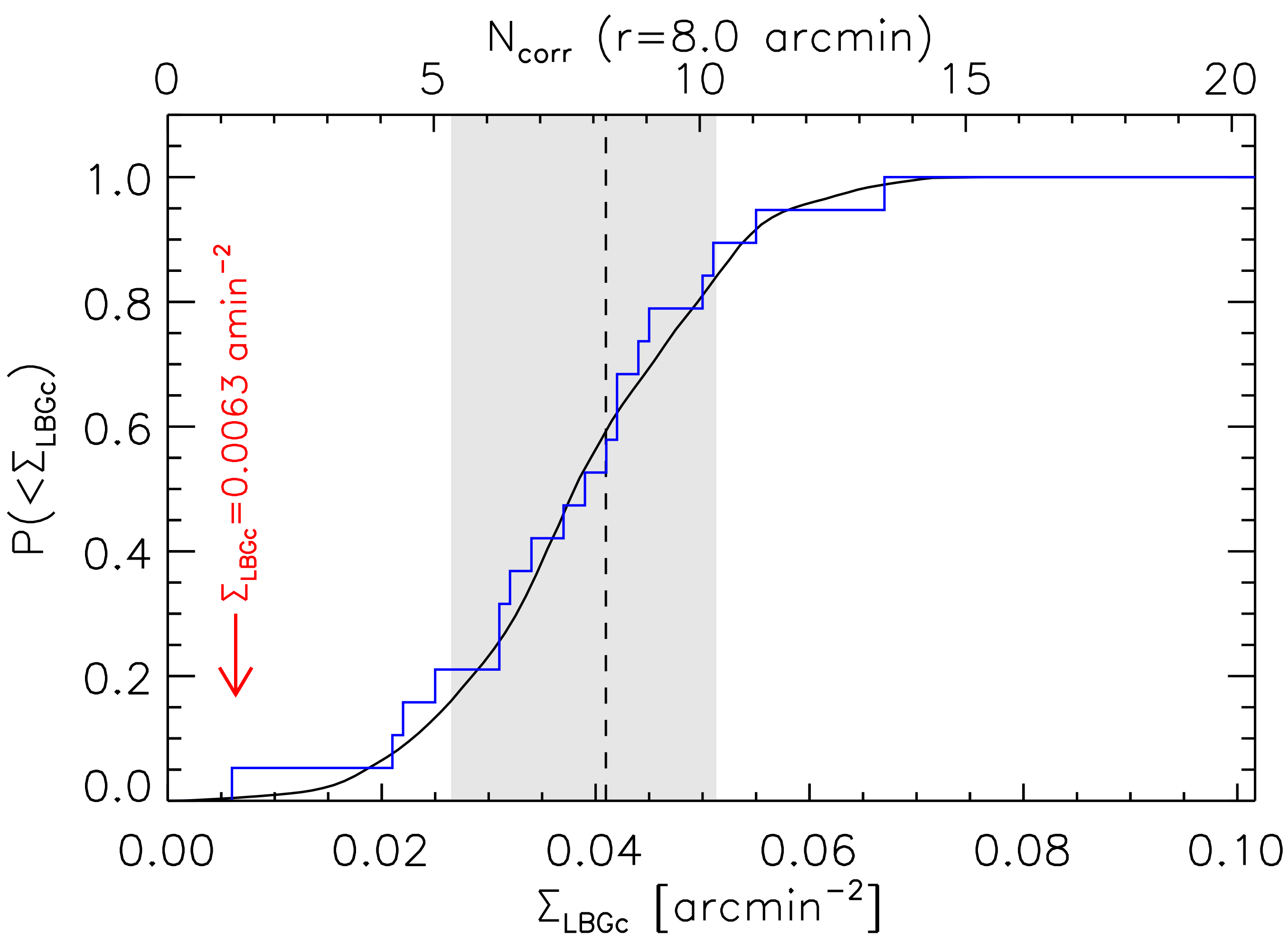
LBG surface density map (r_{fix} = 8′, limited within R_{max}=38′):
A clear underdensity near the center of the field (quasar position).

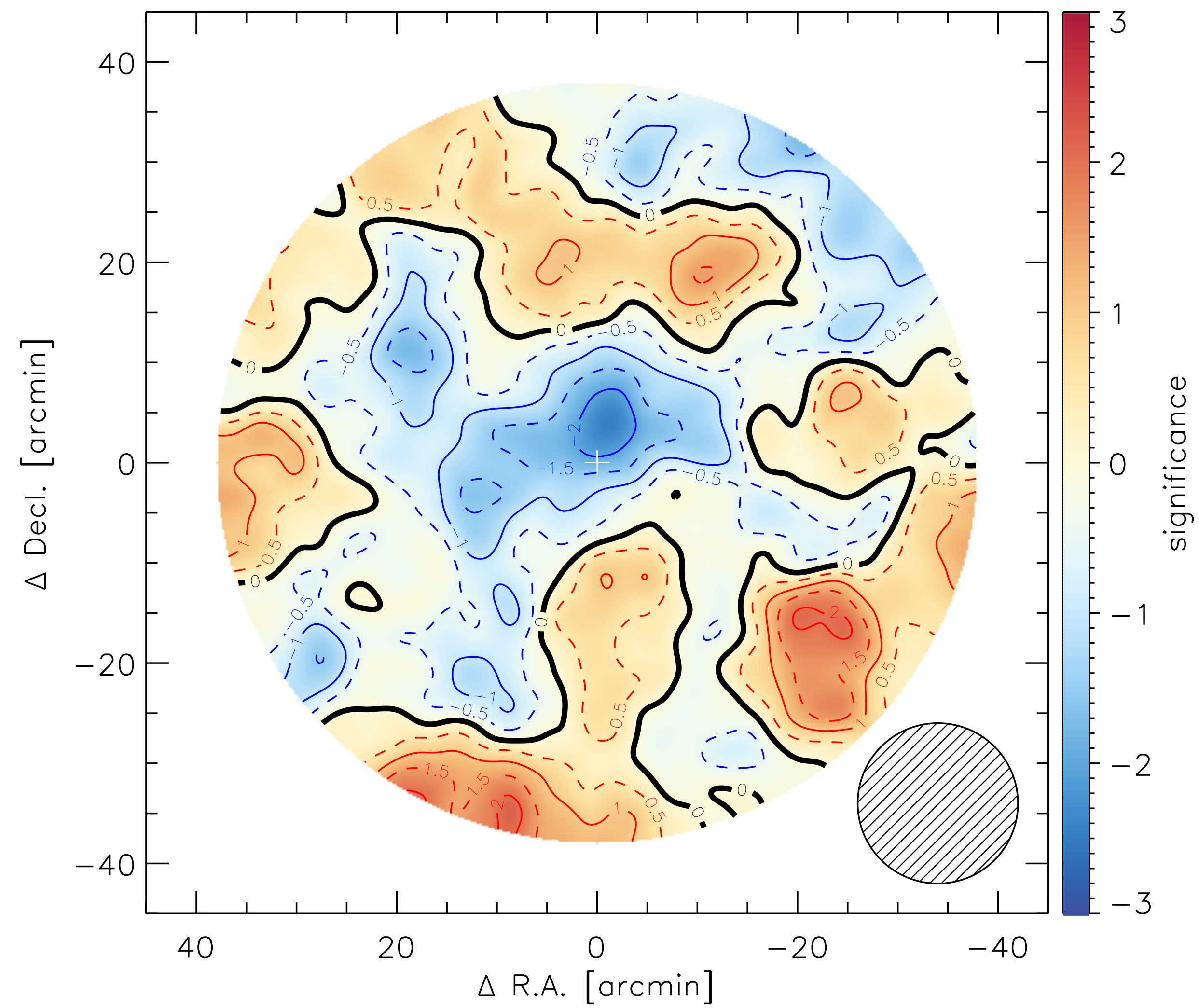


Simulations by Davies et al. (2018)

How rare is the underdensity as observed at the field center?

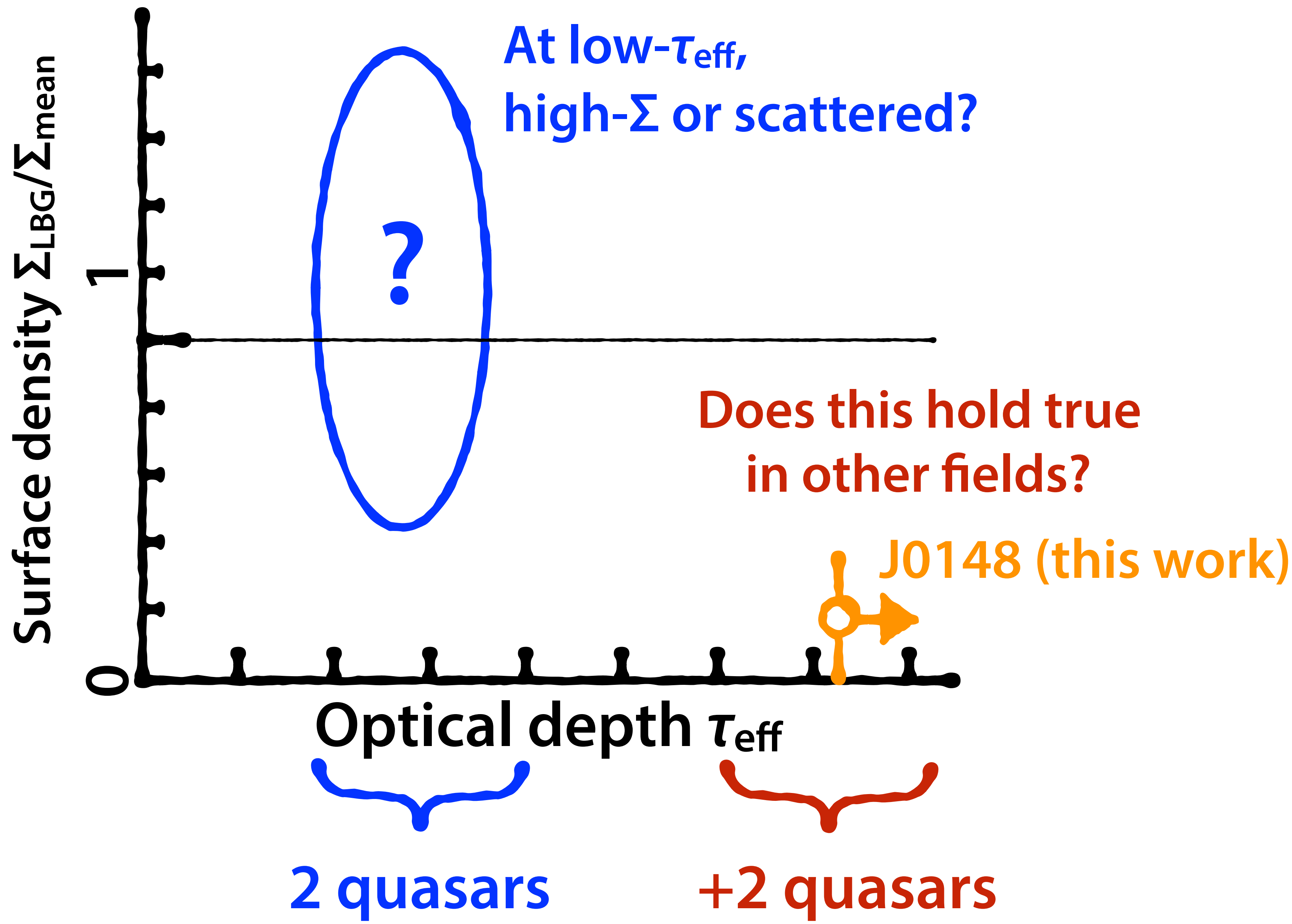
Probability of measuring lower or equal Σ_{LBG} is <1%.
In terms of Poisson statistics, 2σ at the quasar position and 2.5σ at the center of the "hole" which is slightly off from the quasar position.





w/ Poisson statistics

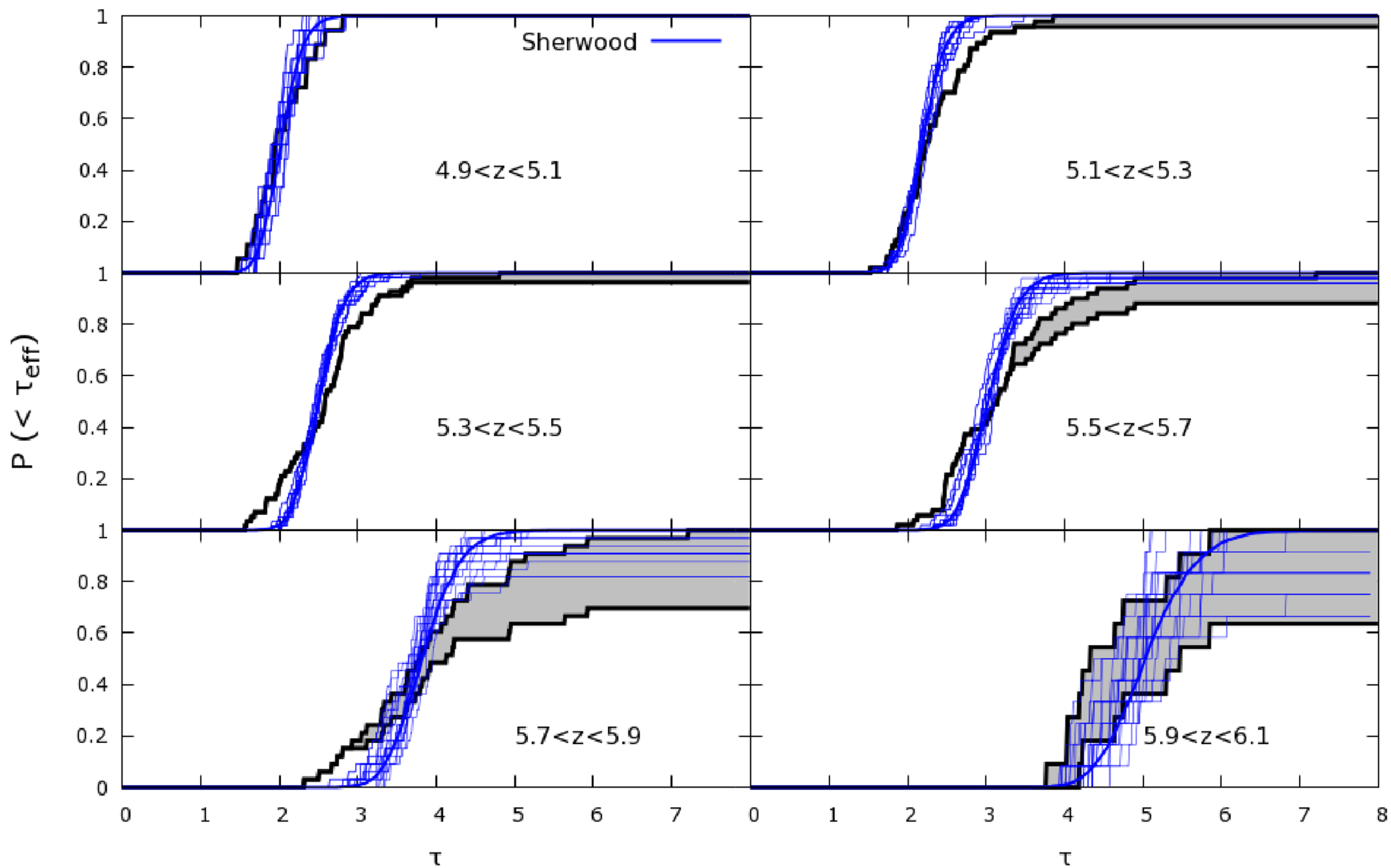
Upcoming observations



~(2–3) x N_{QSO} points of (τ_{eff}, Σ) in total

Latest constraints of the variations in $\tau_{\rm eff}$

Bosman et al. 2018



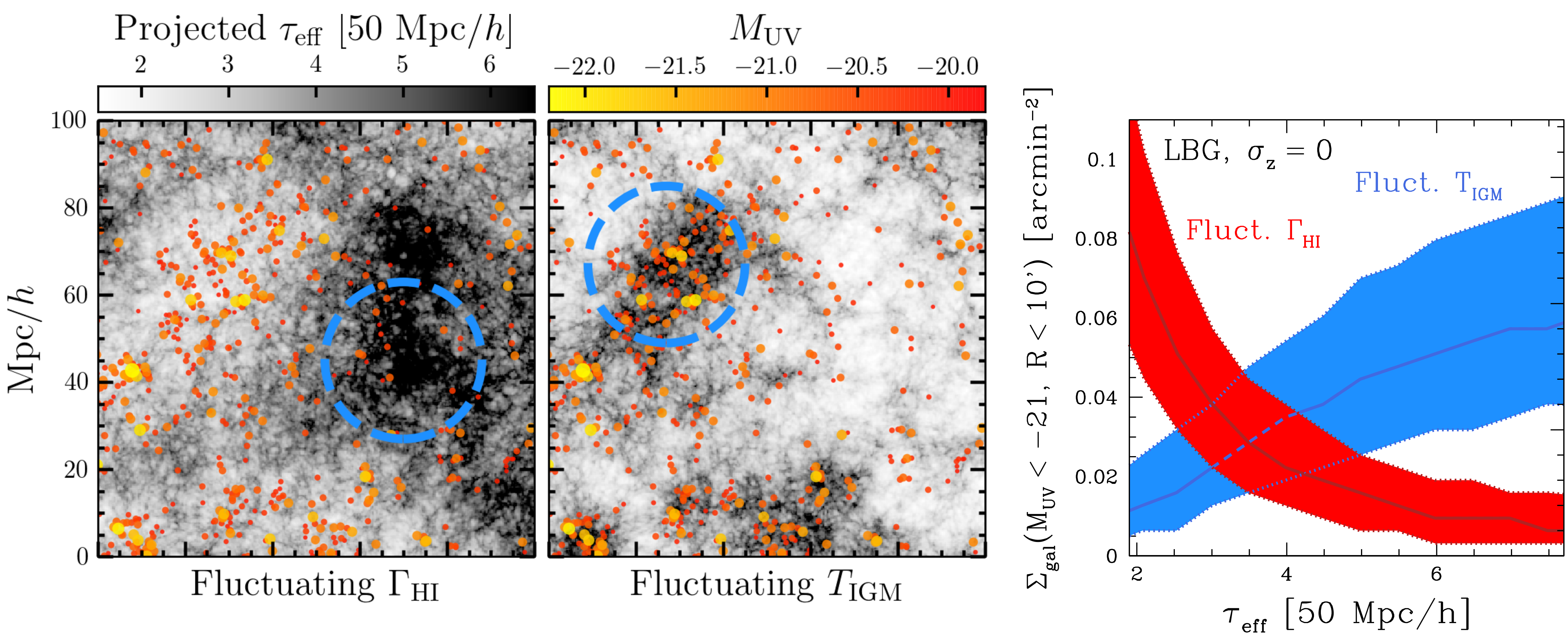
Blue: random realization from simulations with a uniform UV background

Fluctuating λ_{mfp} UVB and Fluctuating T_{IGM}

expect different correlations between Δ (or galaxy density) and τ.

Fluct.- λ_{mfp}: underdensities are protected from ionization → high-τ_{eff}

Fluct.-*T*: overdensities are ionized earlier then have enough time to cool → high-τ_{eff}



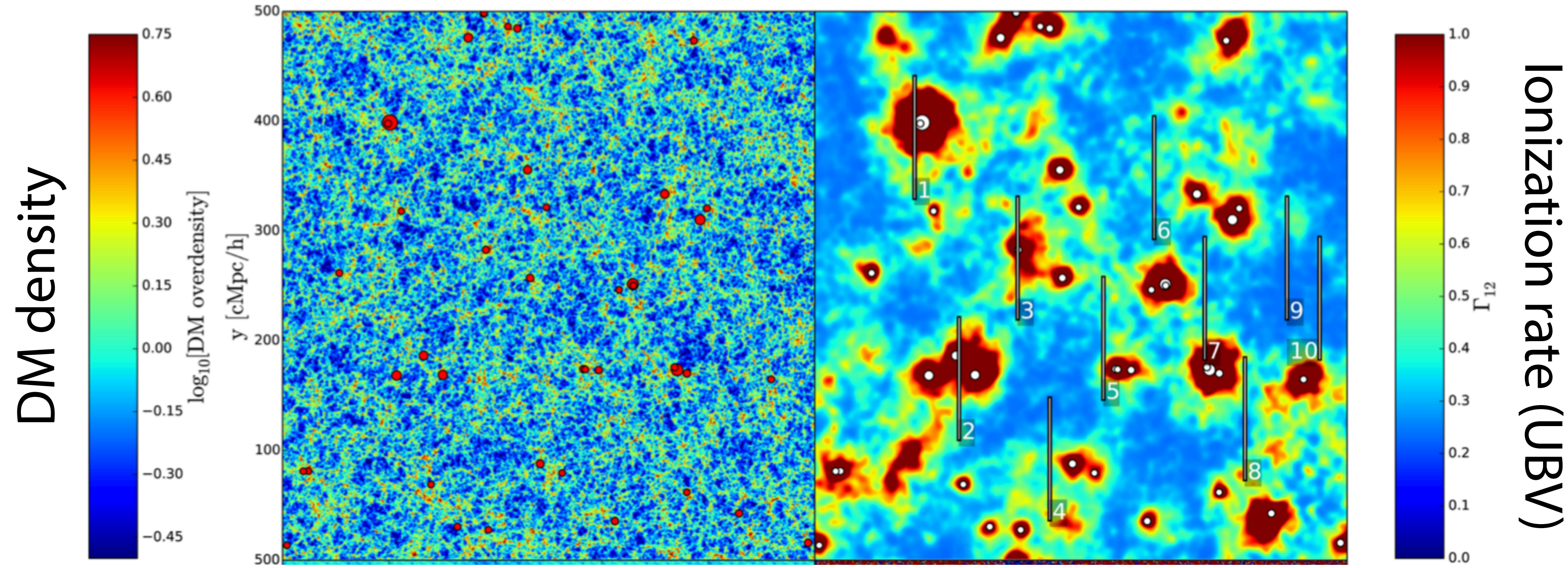
Semi-numerical simulations by Davies et al. (2018)

Rare-source (quasar) model

The presence or absence of rare, bright sources enhance fluctuations in the UVB.

➡ We expect to always find bright quasar(s) (M_{UV}<-22) within ~100 cMpc of low-τ_{eff} regions, but not around high-τ_{eff} regions.

➡ HSC's wide field is very much to test this model.



Box size: 500 cMpc/h

But this model is getting more unlikely…

The model needs a number of bright quasars as measured by Giallongo et al. (2015), which was highly overestimated compared to recent measures.
The quasar-dominated UVB may also cause too-early HeII reionization.

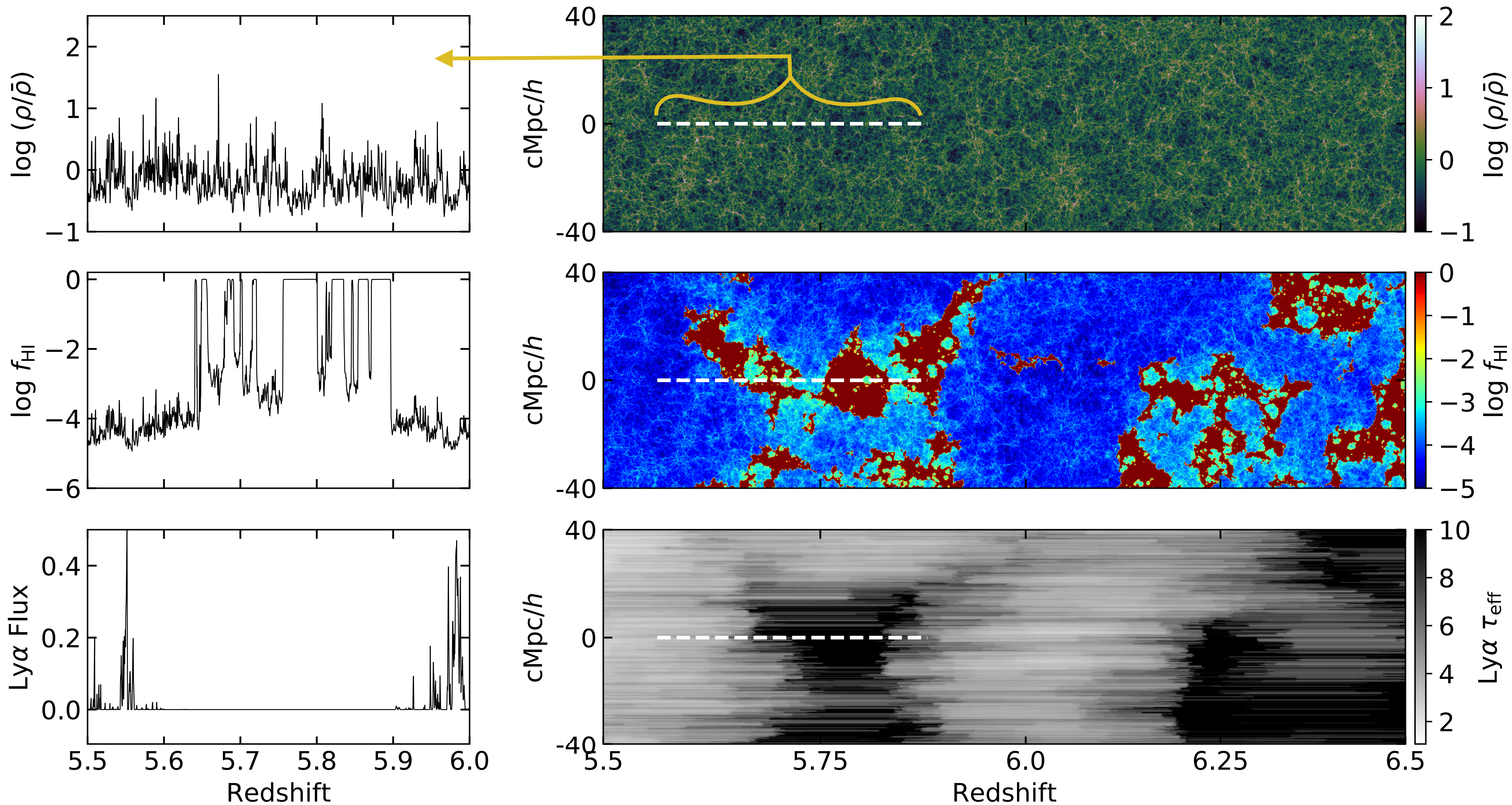
Chardin et al. 2015, 2017

Late-reionization model: Residual neutral “islands” for late-reionization

Given reionization ended relatively later, residual islands of neutral hydrogen could exist until $z \lesssim 5.5$.

➡ A very high-$\tau_{\rm eff}$ Lyα trough could be reproduced in underdense regions.

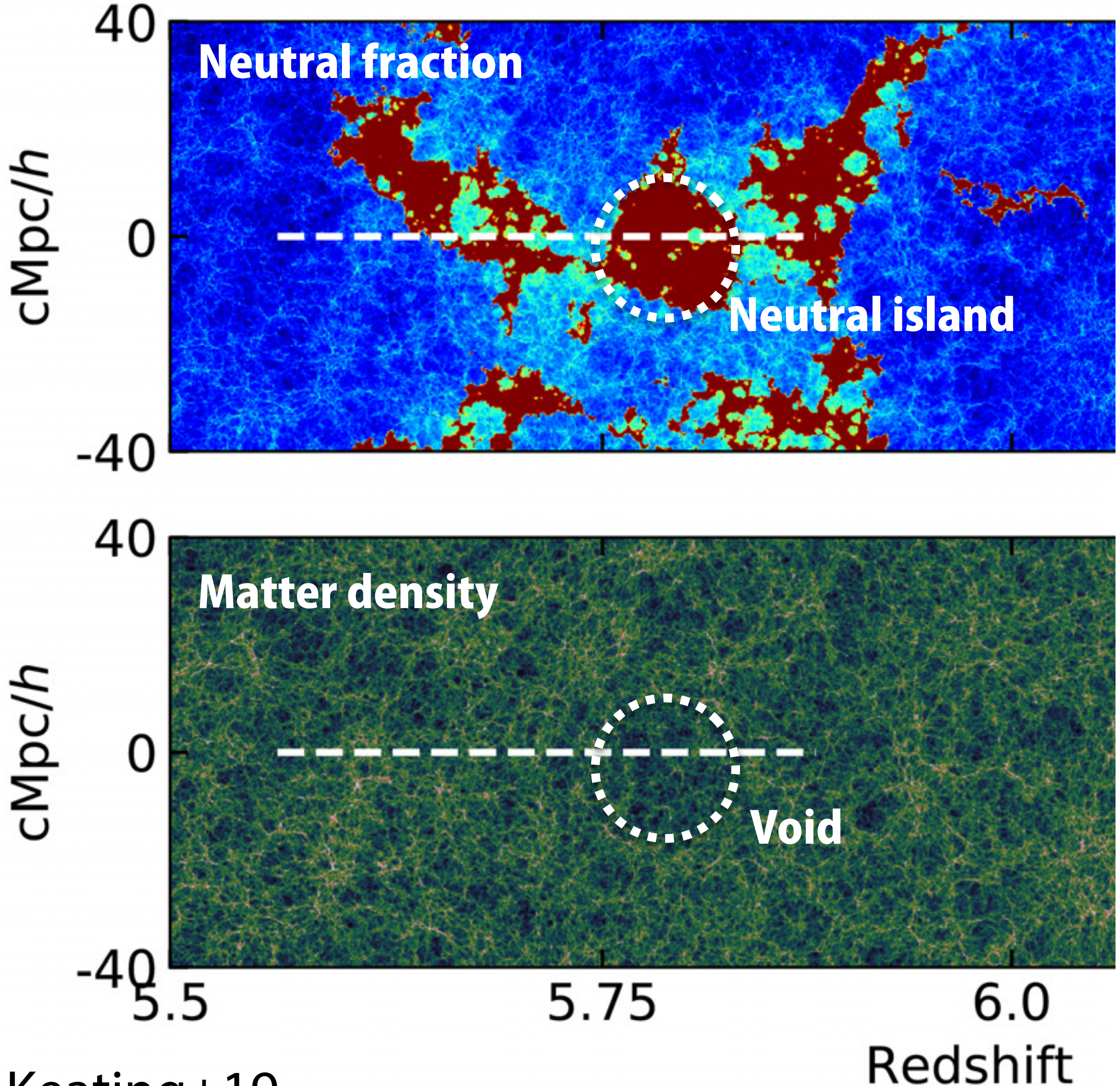
➡ But, underdense regions are not necessarily always high-$\tau_{\rm eff}$.



Kulkarni et al. 2019, Keating et al. 2019

Late-reionization scenario (as an example)

Late-reionization model in which the scatter is driven by residual neutral islands from ongoing reionization that ends as late as z<~5.5



Keating+19

Neutral islands may persist down to z~5.5 in underdense regions which are far from the regions where the space density of ionizing sources are high.