Subaru UM FY2020

Exploring the tail end of reionization with deep HSC surveys

see *Kashino+2020, ApJ, 888, 6*
for the first results

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Collaboration with
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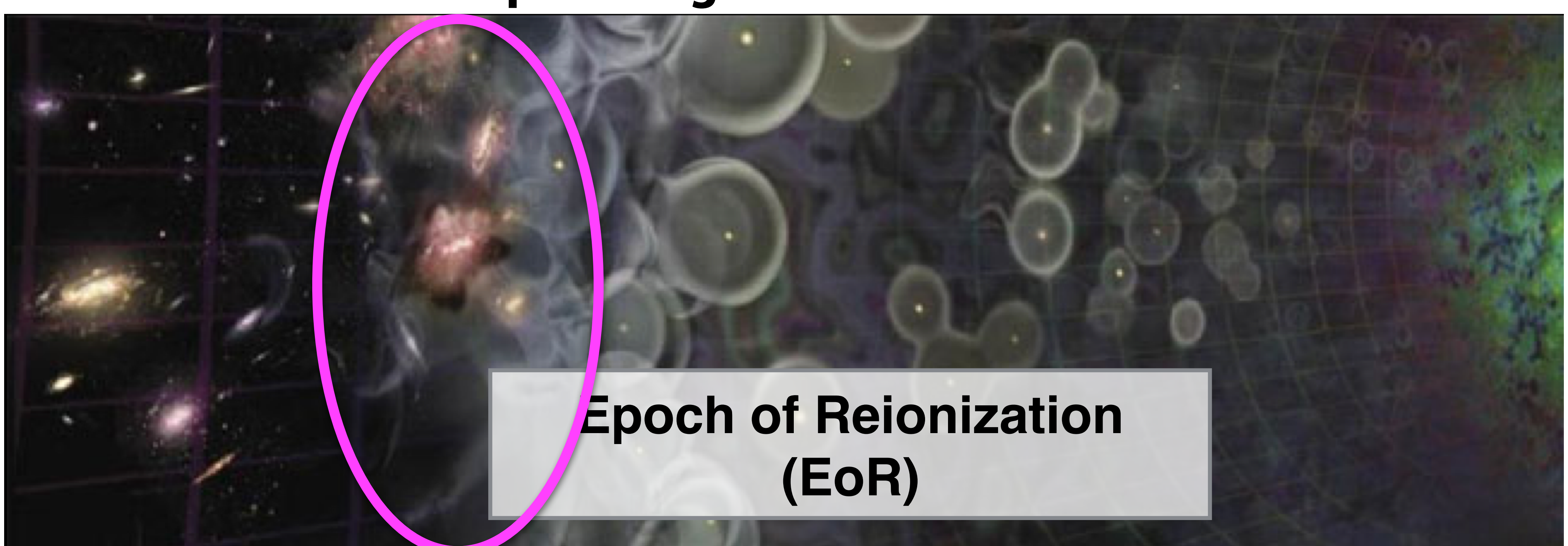
Aim of our Subaru/HSC project

How was the Universe reionized?

Reveal the origin of **highly inhomogeneous spatial structuresHI optical depth of the IGM at the end of reionization**, which must telling us about processes at earlier times.



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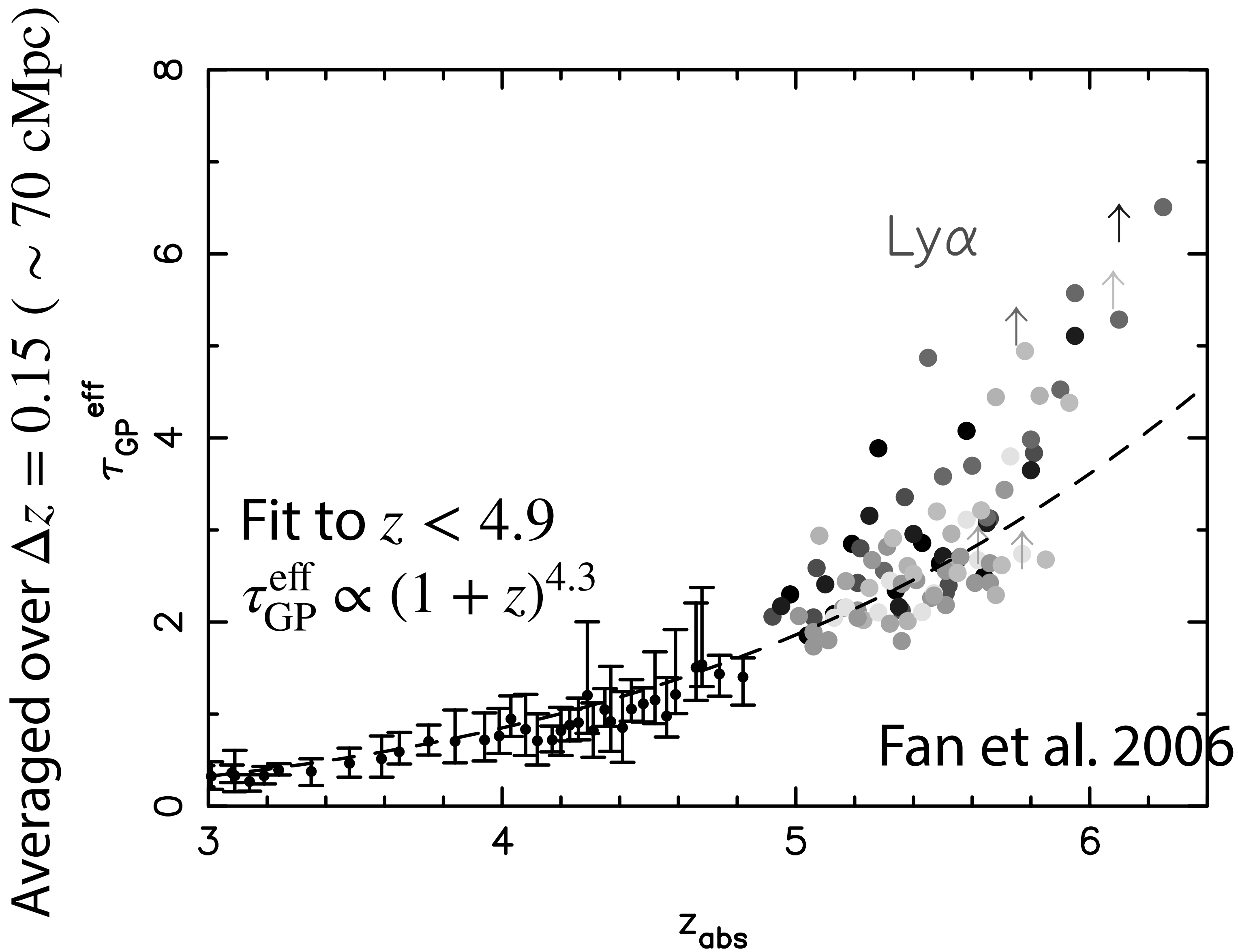
Gunn-Peterson test

Effective optical depth $\tau_{\rm eff} = -\ln\langle F_\lambda^{\rm obs}/F_\lambda^{\rm int}\rangle$
(averaged over ~70 cMpc, or Δz=0.15)

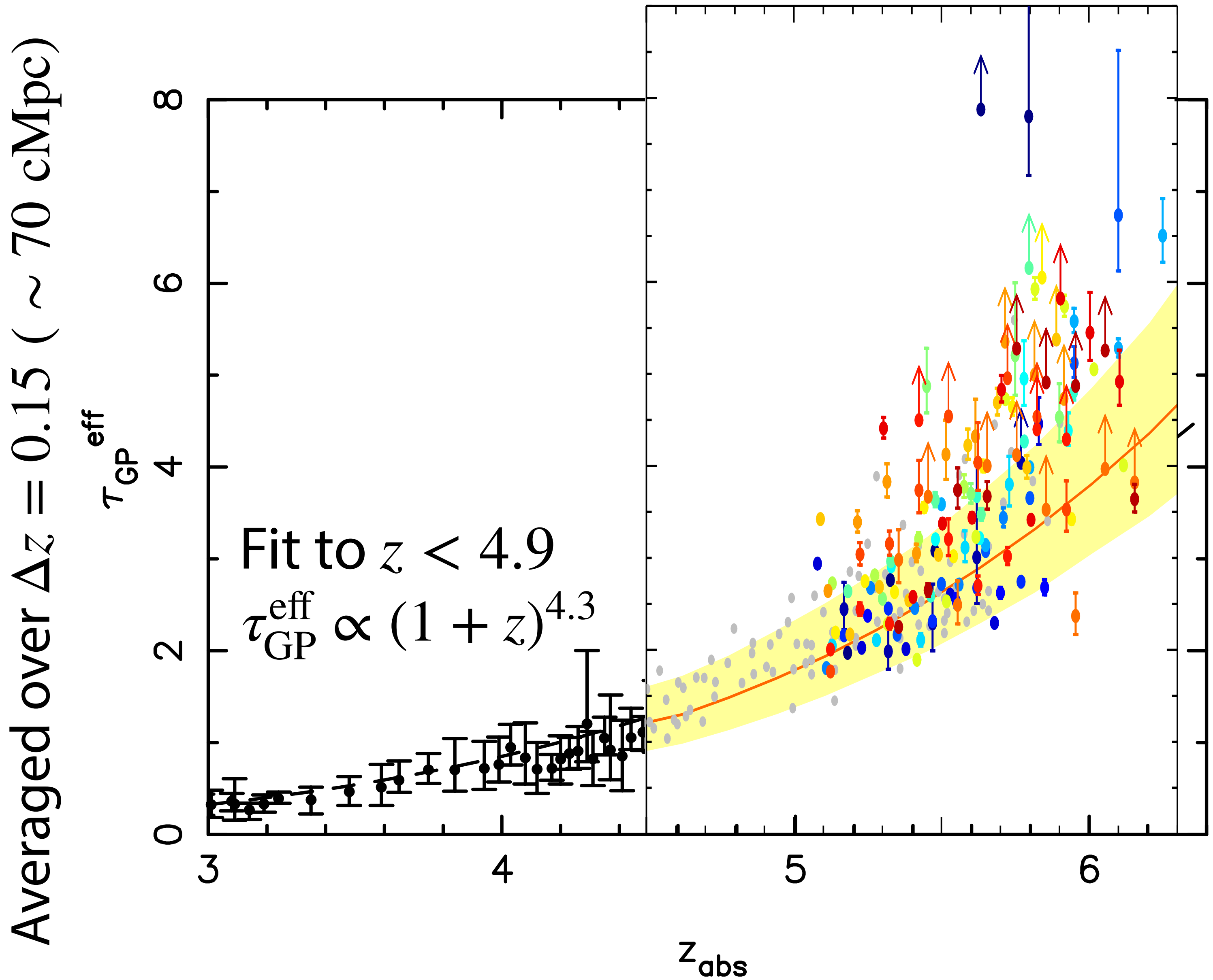


The rapid increase of optical depth marks the end of reionization at z~6.

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

Effective optical depth $\tau_{\rm eff} = -\ln\langle F_\lambda^{\rm obs}/F_\lambda^{\rm int}\rangle$

(averaged over ~70 cMpc, or Δz=0.15)



The sighline-to-sightline variations in the optical depth also increases at z>5.5.

This suggests a highly inhomogeneous "patchy-reionization".

Competing 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 ↗ (Γ^{-1})   ↖ IGM temperature ($T^{-0.72}$)

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

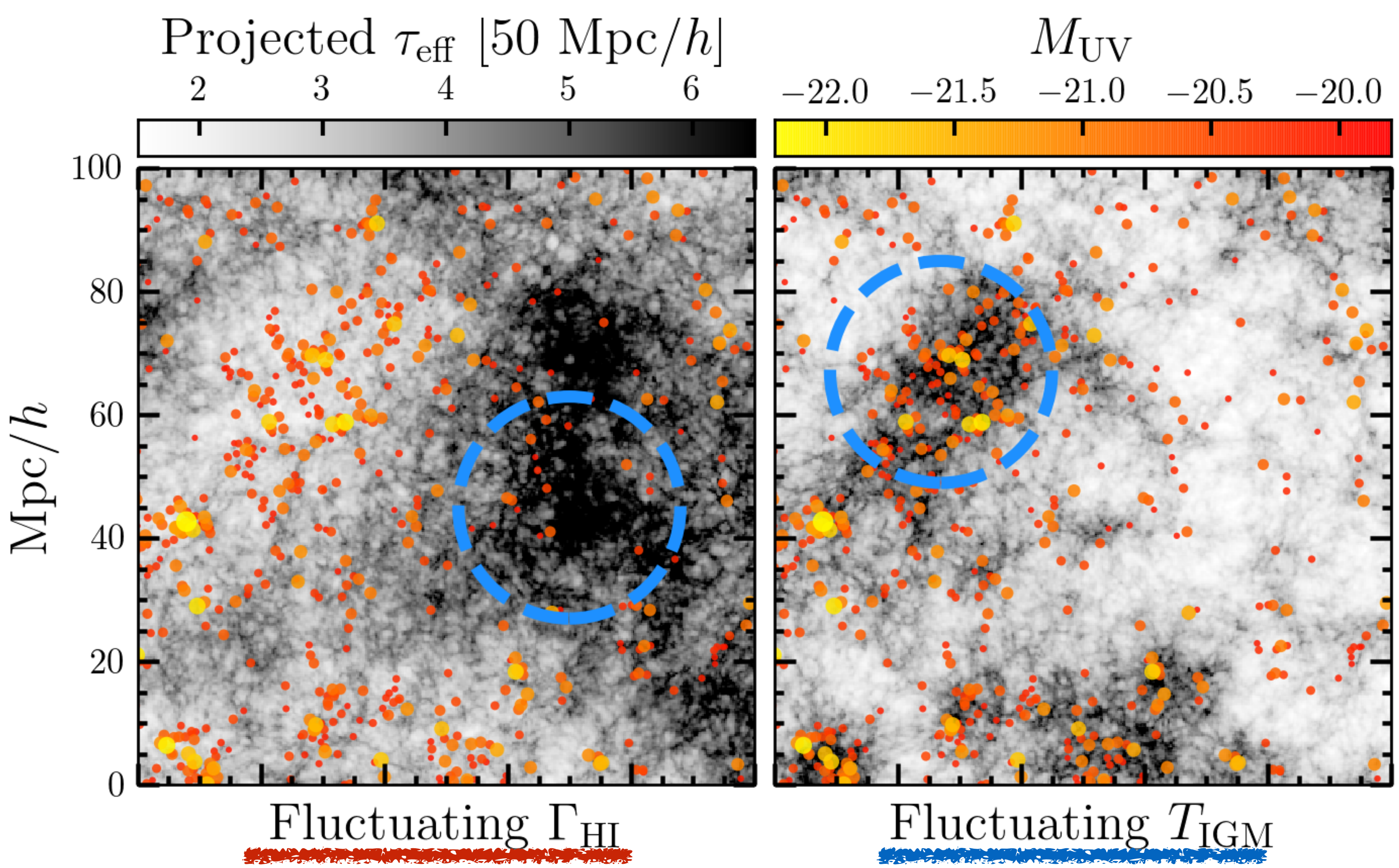
Competing scenarios

Fluctuating Γ_{HI} (UVB) vs. Fluctuating T_{IGM}

expect different correlations between DM (or galaxy) density and optical depth τ_{HI}.

Fluct-Γ: underdensities are protected from ionization → high-τ_{HI}

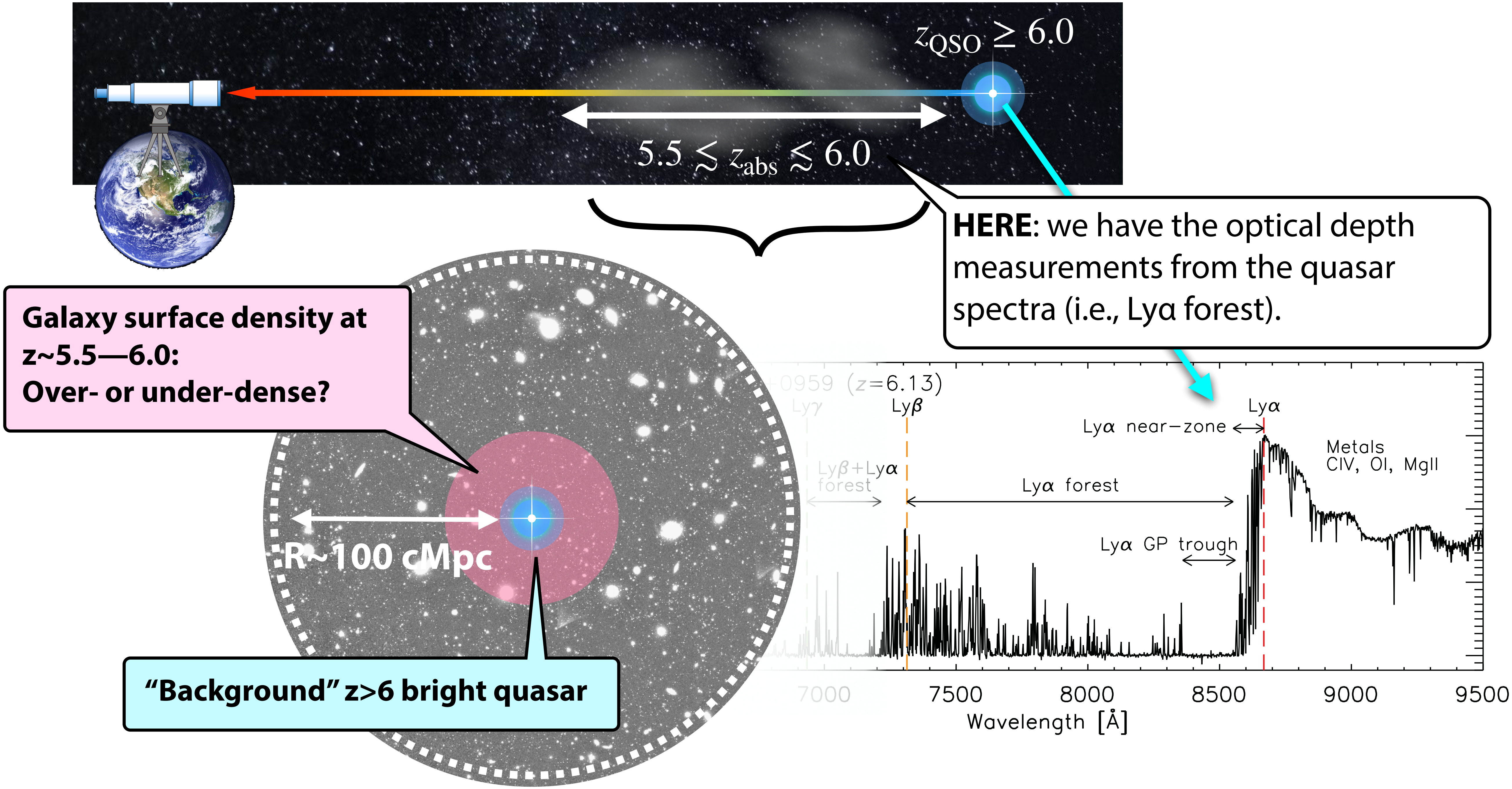
Fluct-*T*: overdensities are ionized earlier then have enough time to cool → high-τ_{HI}



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

Testing the models

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

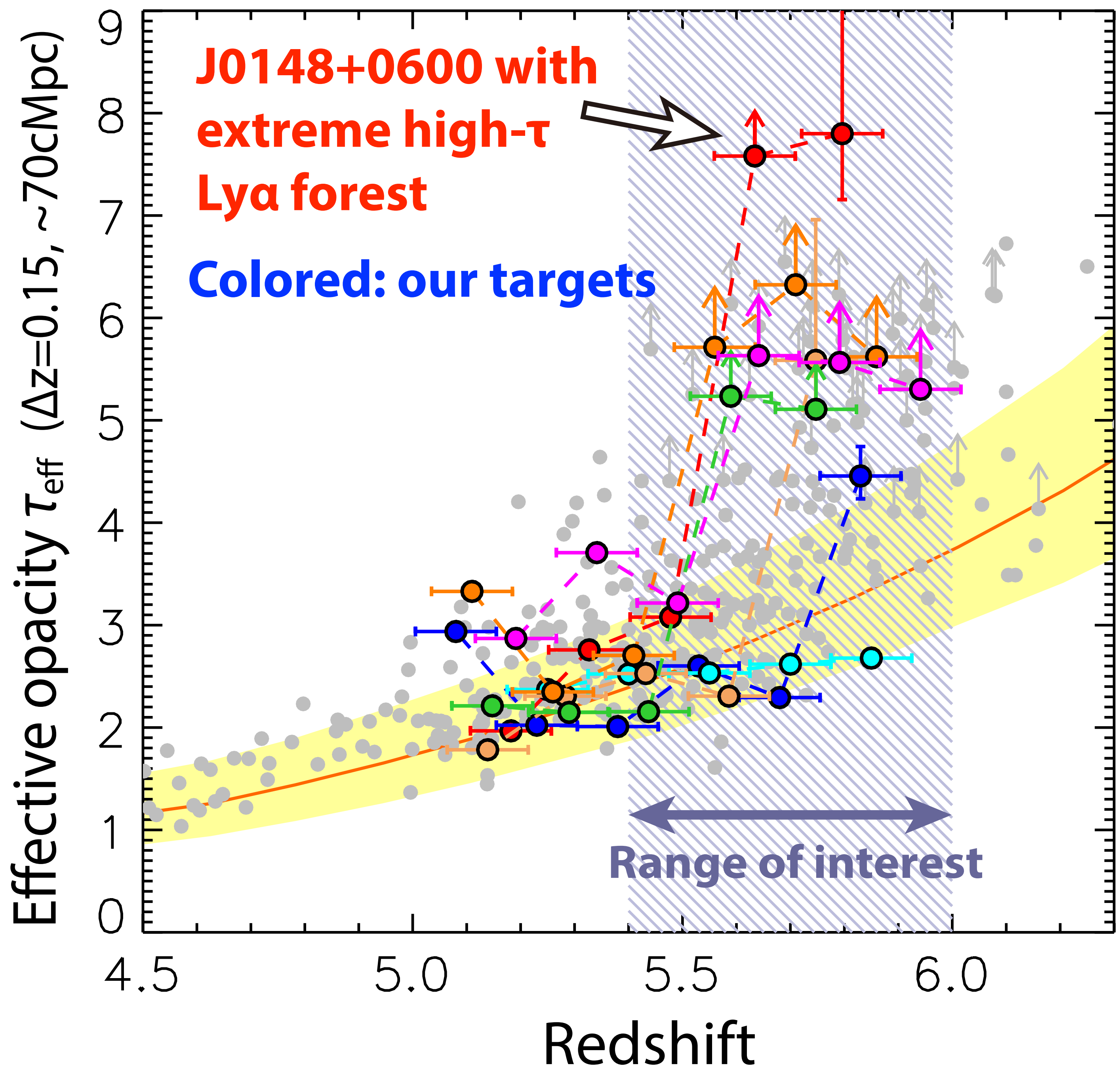


Subaru/HSC matches perfectly to carry out this experiment!

Target fields

z>6 bright quasars showing extremely high- or low-optical depth Lyα forest are good.

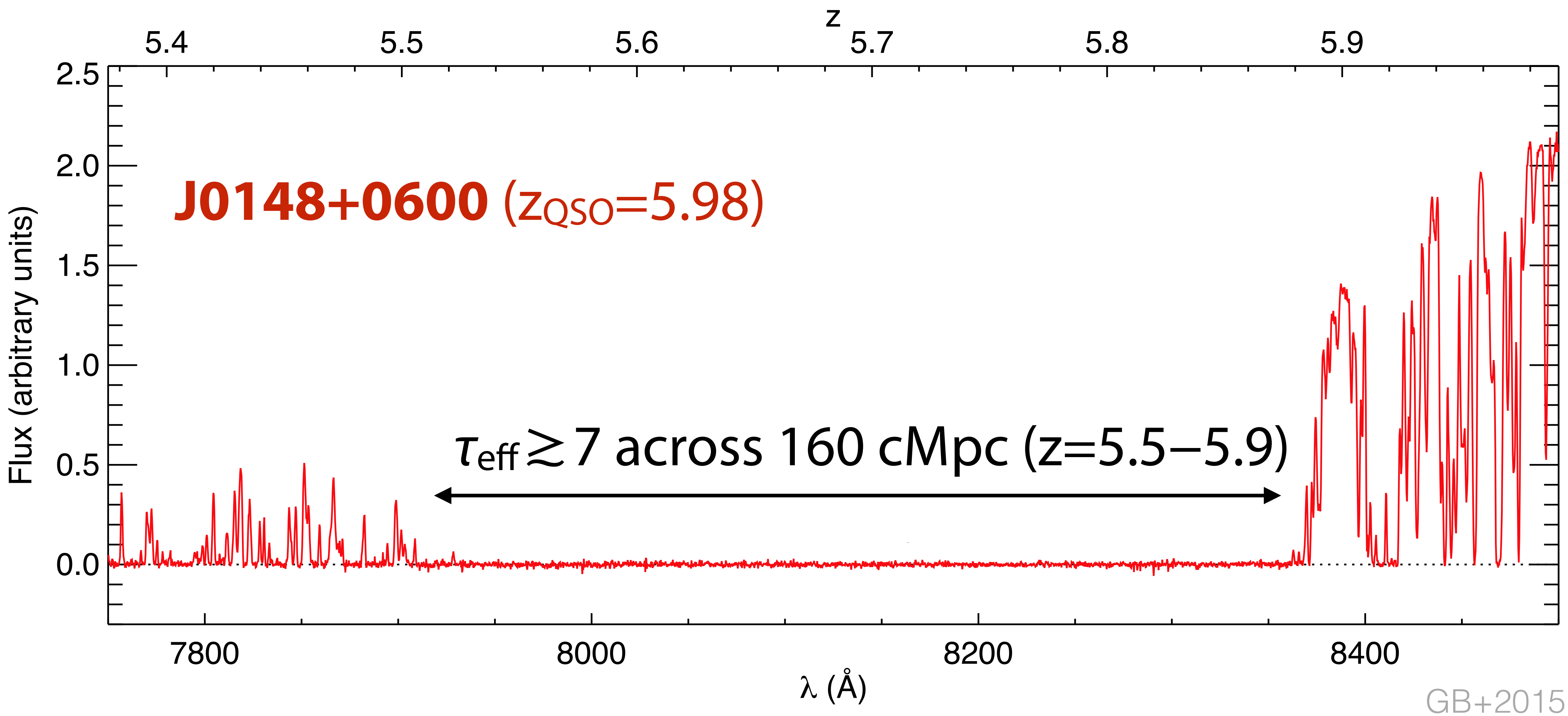
J0148+0600
J0422-1927
J0842+1218
J1137+3549
J1602+4228
J1630+4012
J2054-0005



A surprisingly opaque and long trough

A remarkably **opaque** ($\tau_{eff} \gtrsim 7$) and **long** (~160 cMpc) Lyα trough has been discovered at z=5.5–5.9 towards **J0148+0600** (z=5.98)

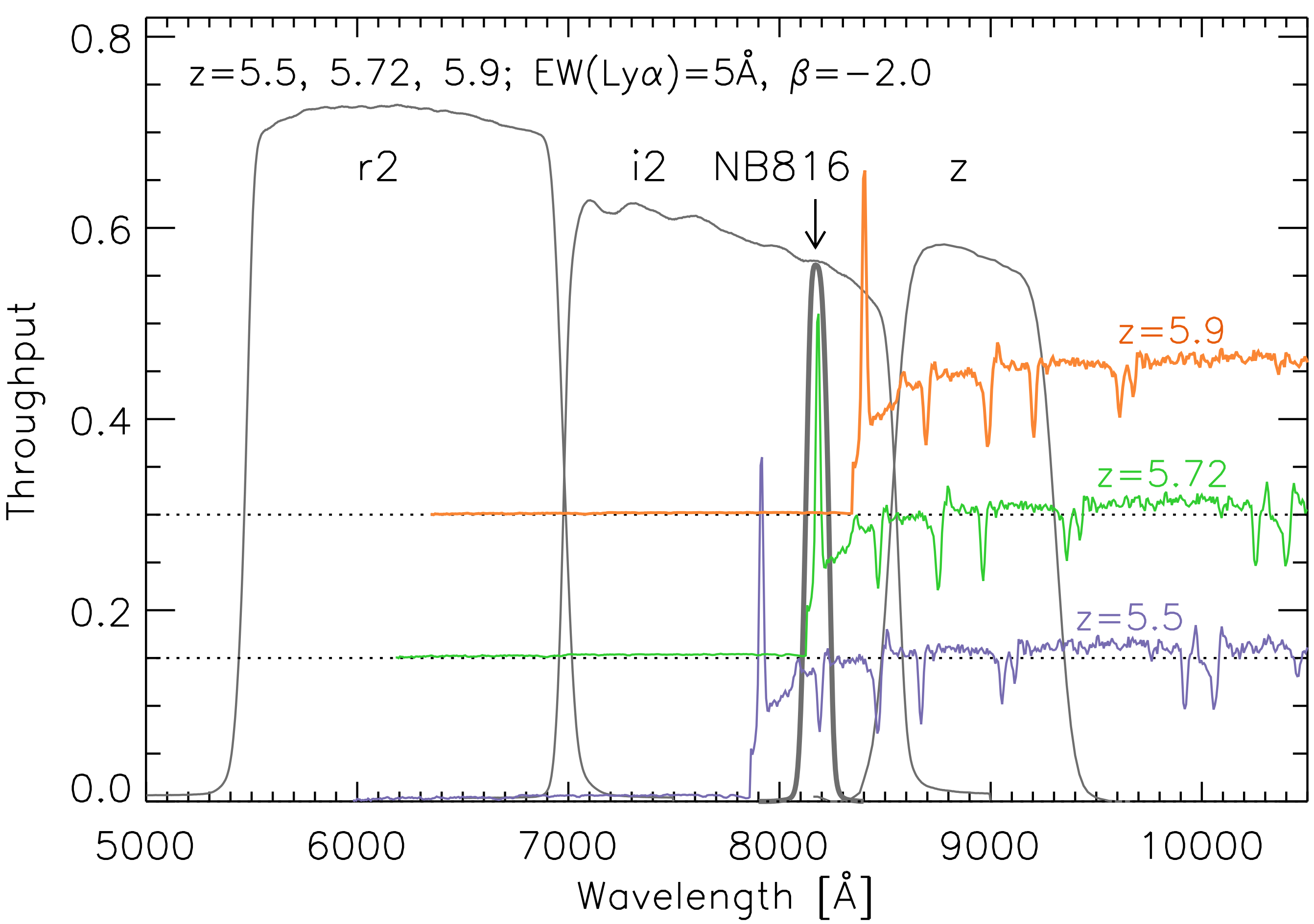
➡ **Very good target field for distinguishing the models**

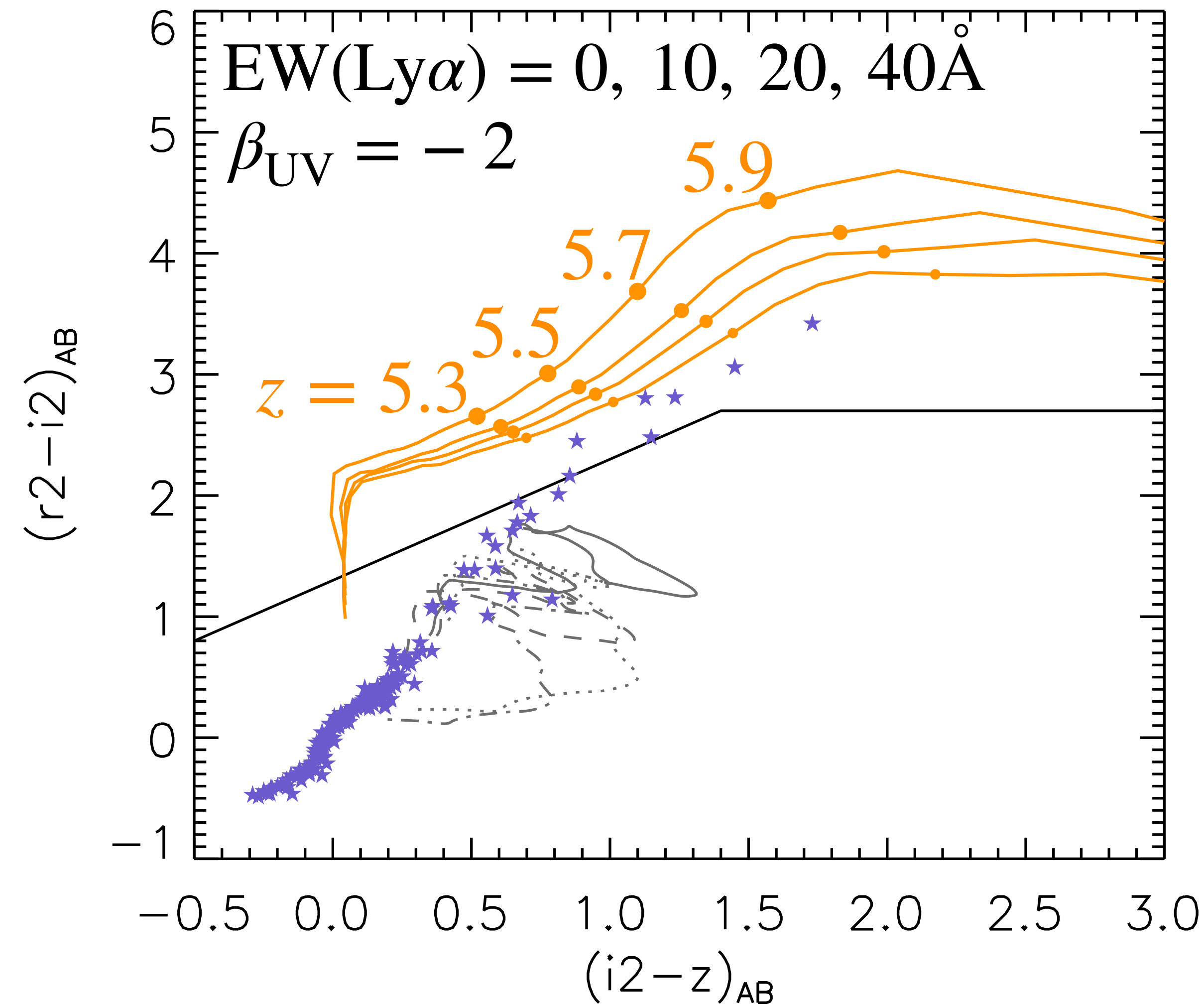


Becker et al. (2015) (Figure taken from G. Becker's slide, 2016)

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).





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Observations

- Observations through S18B—S20A (additional times approved in S21A).
- HSC r2, i2, and z images at SSP-deep-like depths (~2 hrs) in seven fields.
- Complementary z=5.7 LAE surveys (using NB0816) in some of our fields are carried out by R. Ishimoto and N. Kashikawa.
- We have mostly obtained the requested images and are now performing scientific analysis.
- All data are now reduced with hscpipe8.4

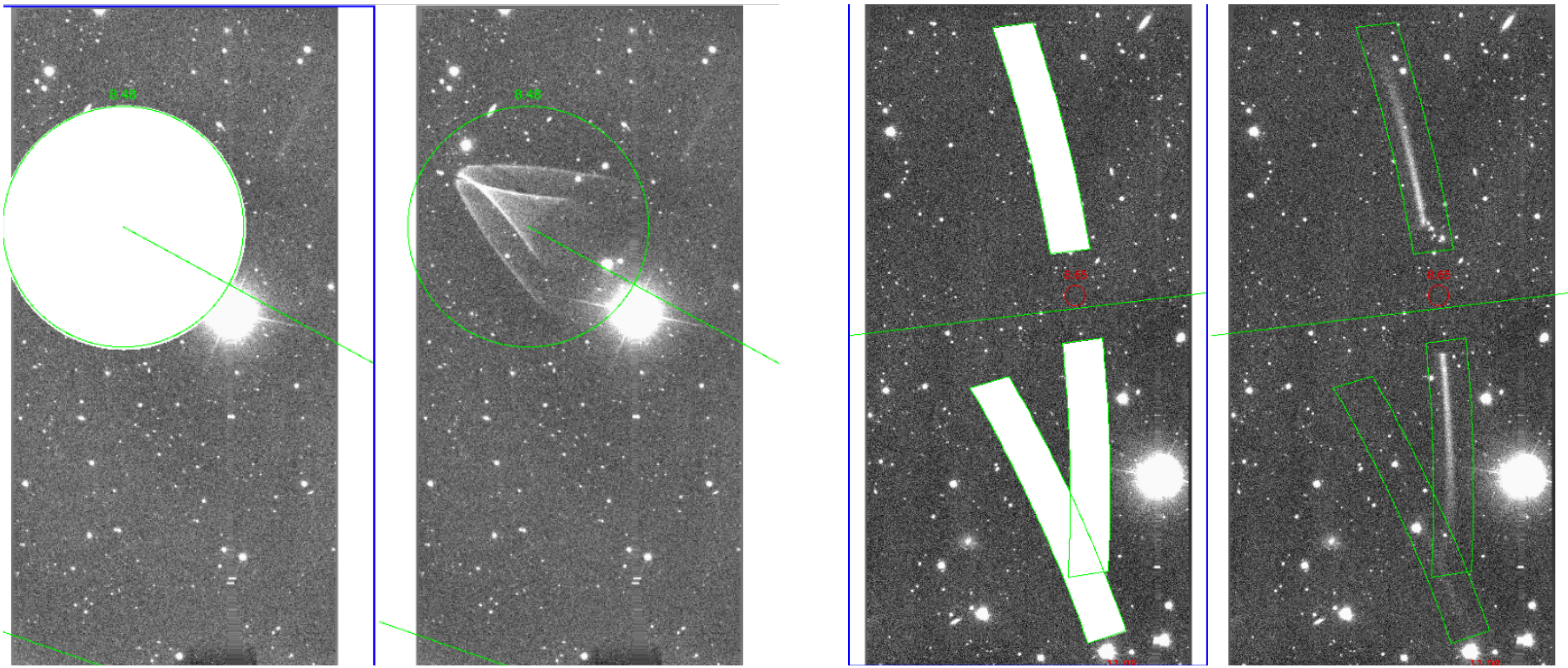
Field	r2	i2	z
J0148+0600*	27.20	26.35	26.06
J0422–1927	27.35	26.60	25.79
J0842+1218	27.20	26.80	26.16
J1137+3549	26.81**	26.28**	25.85
J1602+4228	27.16	26.57	25.88
J1630+4012	27.30	26.65**	25.96**
J2054–0005	under analysis		**

* combined with archival data

** further observations are scheduled

Masking ghosts

With a custom code based on “hscGhost" (Komiyama, Kawanomoto et al.)



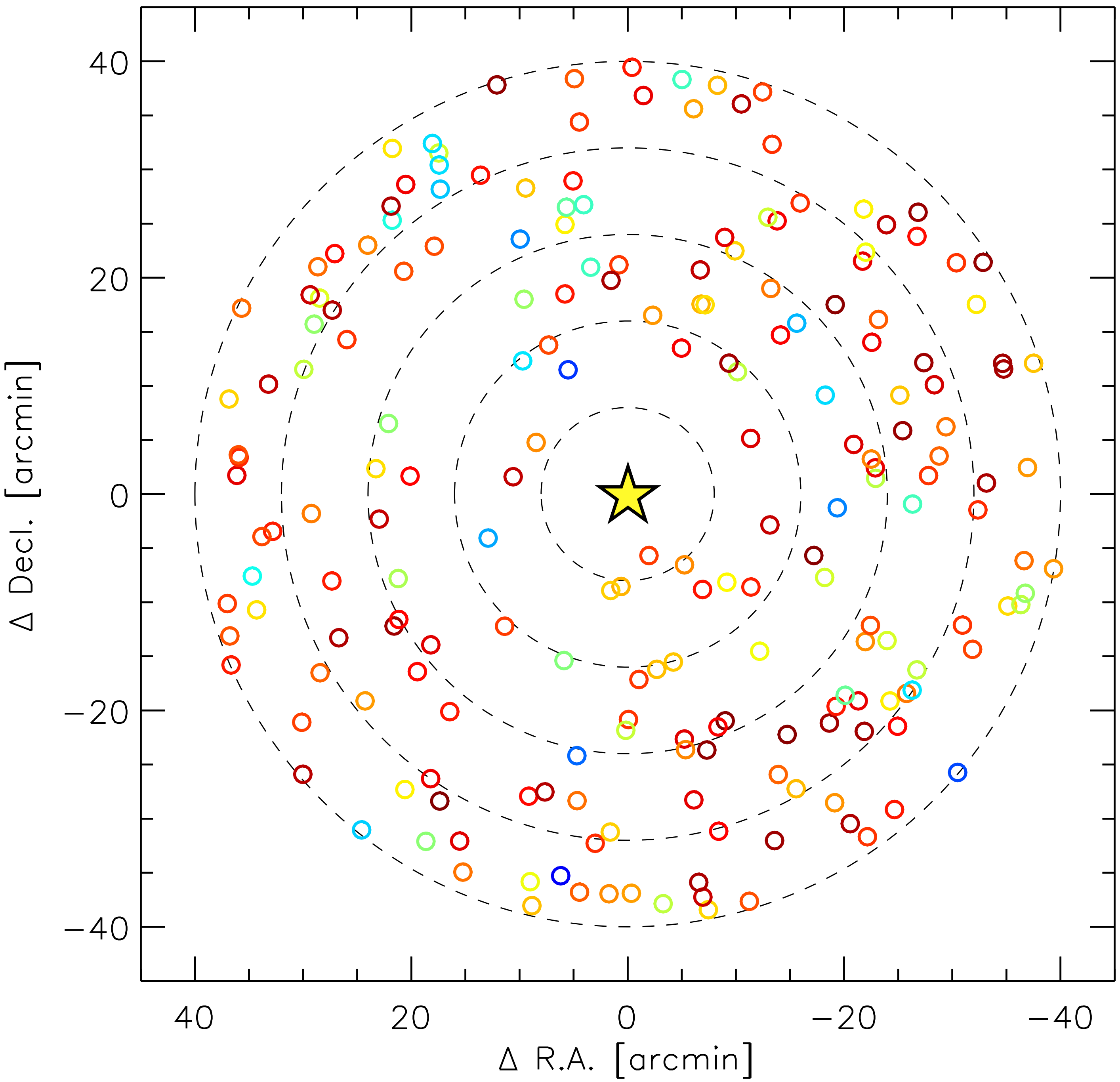
This makes significant improvement of the final coadded images.

(with 0.6-mag shallower z-band image)

First result in the J0148+0600 field

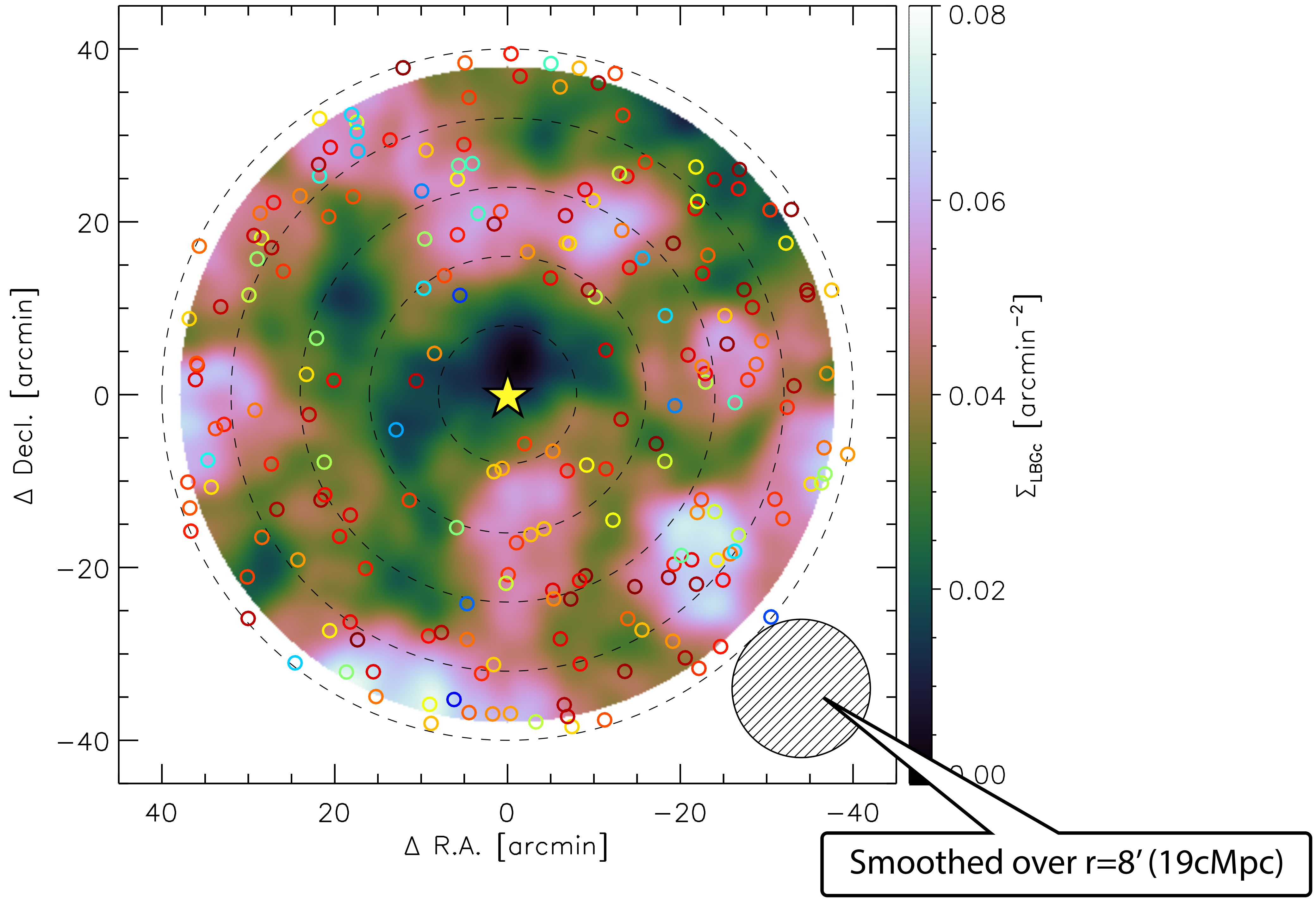
The spatial distribution of 185 LBG candidates ($z\sim5.5$—5.9; $z_{AB}<25.3$)

➡ "**deficit**" at the quasar position



First result in the J0148+0600 field

The extremely high-τ_{eff} region is found to be associated to an underdensity of LBGs!



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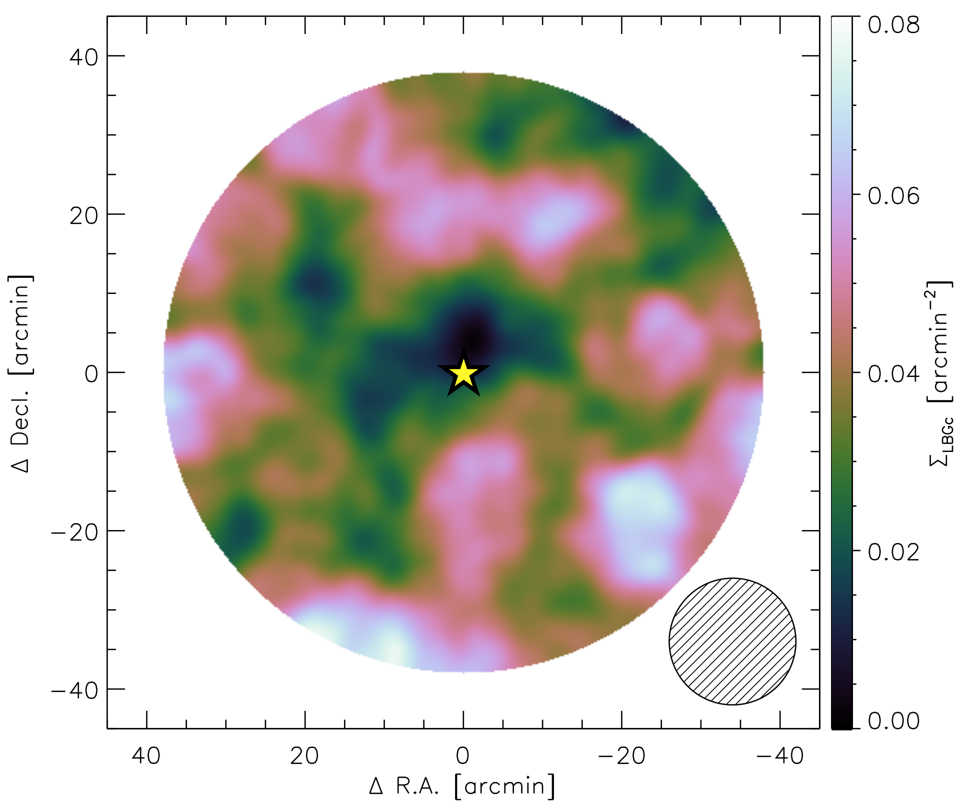
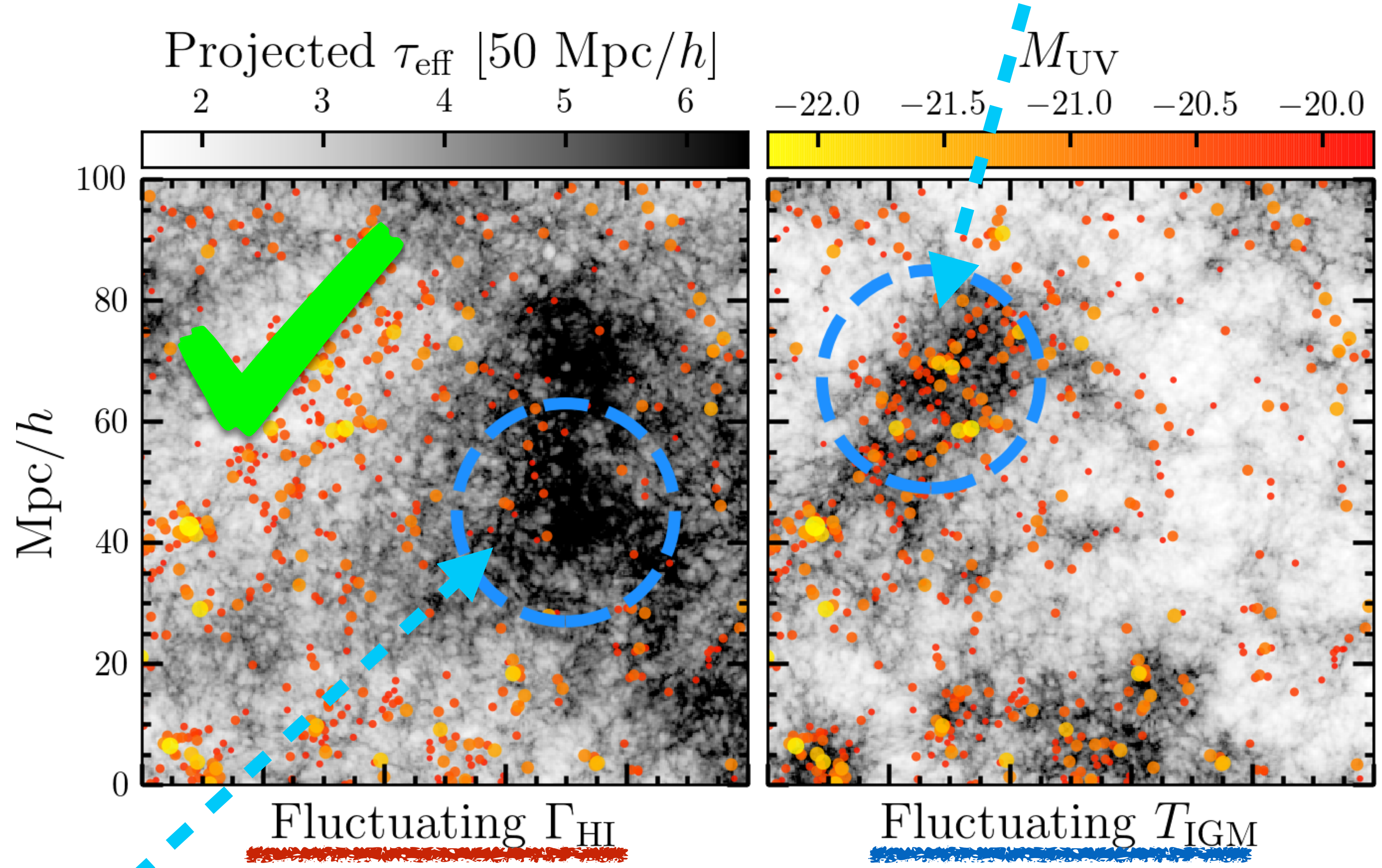
Comparisons to models

Our result is consistent with the prediction of the fluctuating-Γ model, but appears to disfavor the fluctuating-T_{IGM} model that predicts an overdensity in a high-τ region.





low galaxy density in
a high optical depth region

Simulations by Davies et al. (2018)

Summary

- We are carrying out LBG surveys with HSC around seven quasar fields.
- The first result: evidence of a highly opaque void, giving some constraints on the reionization models.
- Almost all the required data are now under analysis. We will be able to achieve a conclusive statement soon.