Understanding the first billion years with Lyman alpha and 21-cm

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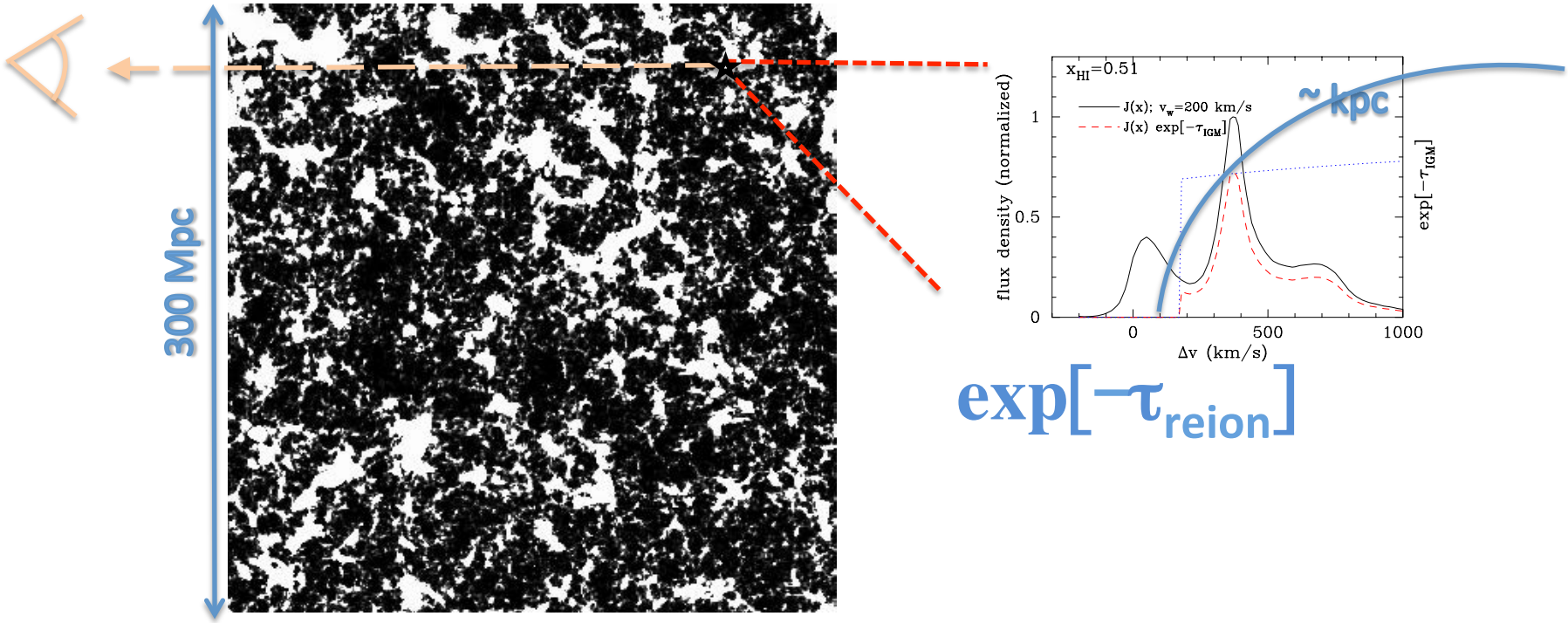
AIDA

European Research Council

Galactic Lyα is modulated by the EoR

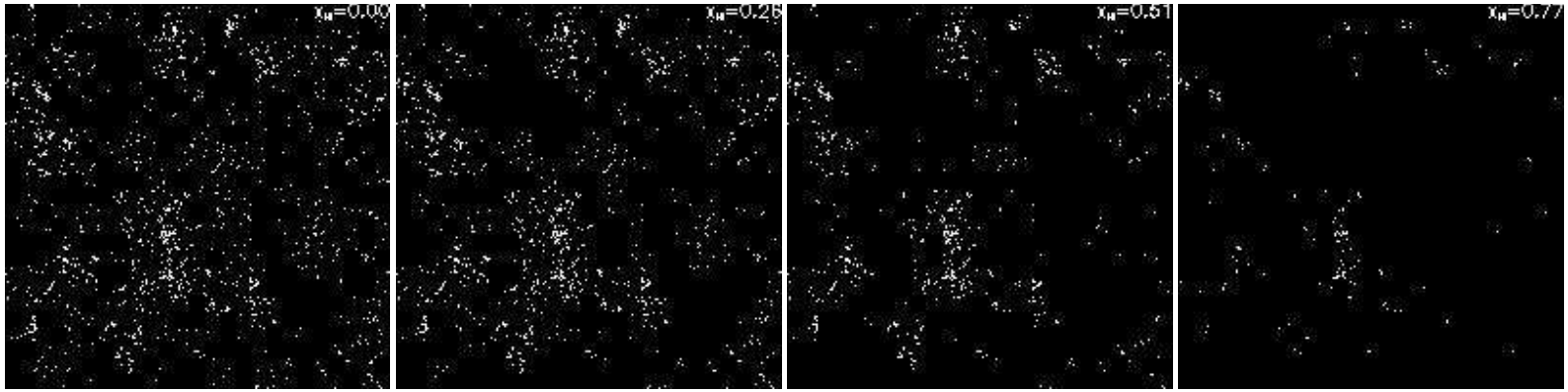


The EoR modulates:

1. the observability of Lyman alpha emission (talks by TT, Laura…)
2. **the observed clustering of LAEs**

LAE clustering as a signature of reionization

x_{HI} →



AM & Furlanetto (2008)

- The distribution of observed LAEs is modulated by the cosmic HII regions on large-scales → clustering increases during reionization (e.g. Furlanetto+2006; McQuinn+2007, AM & Furlanetto 2008; Jensen+2013)

LAE clustering is a **more robust** probe than evolution in number density

- Clustering of DM halos is well-understood: the intrinsic correlation function of the host halos only varies by a factor of ~few, making the additional contribution from reionization easier to identify
- The uncertain galactic environment has a much weaker signature on large-scale clustering, than on the observed Lyα emission

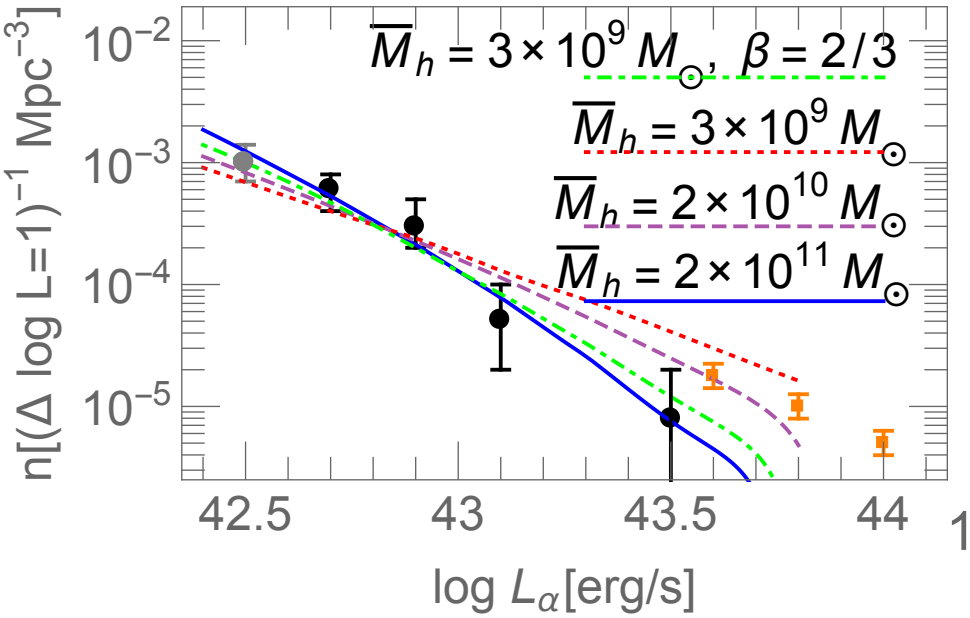
LAE clustering during the EoR

Two ingredients:

i) $L_{\alpha}^{intr} \rightarrow M_{halo}$ relation

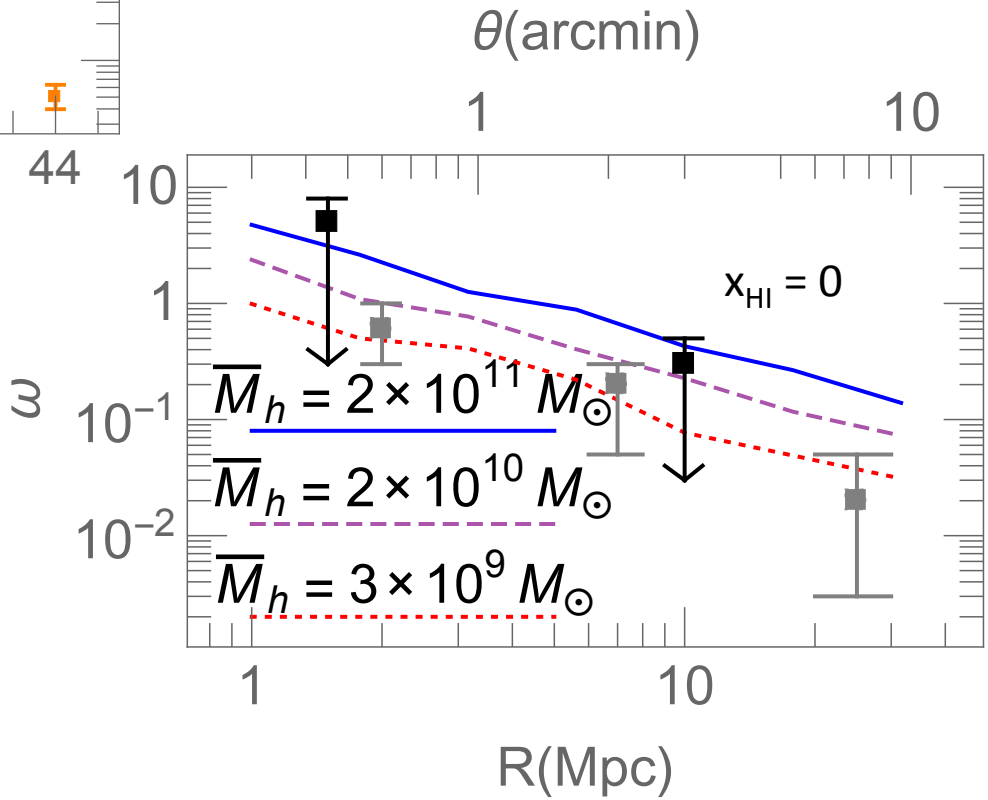
ii) EoR topology for a given $\langle x_{HI} \rangle$

Extreme L^{intr} <-> M_h



$$L_\alpha^{\rm intr} = L_\alpha^{\rm min}\left(\frac{M_{\rm h}}{M_\alpha^{\rm min}}\right)^\beta \chi$$

χ is a random variable ($\chi = 1$ with probability $f_{\rm duty}$



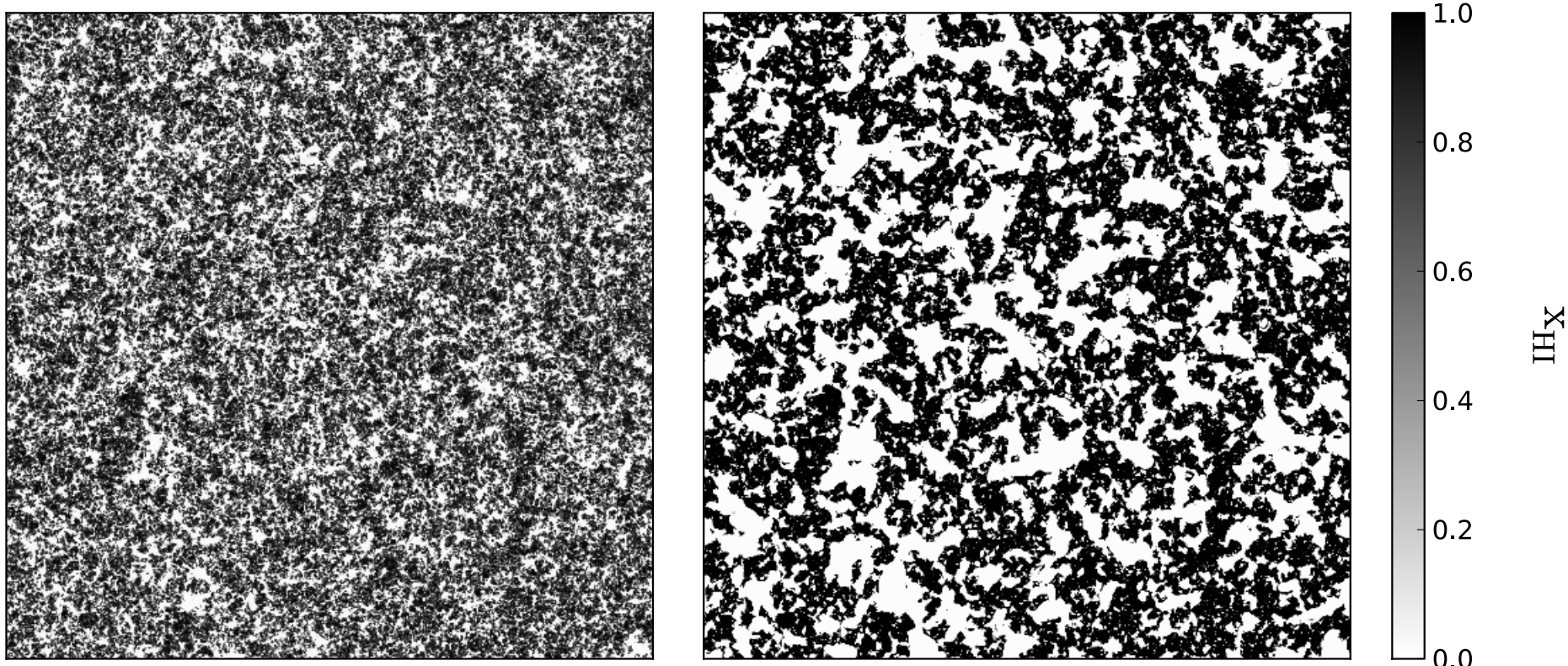
$n_{LAE}(z\sim7) = 4.1\times10^{-4}$ Mpc^{-3} (Ouchi+2010)

Sobacchi & AM (2015)

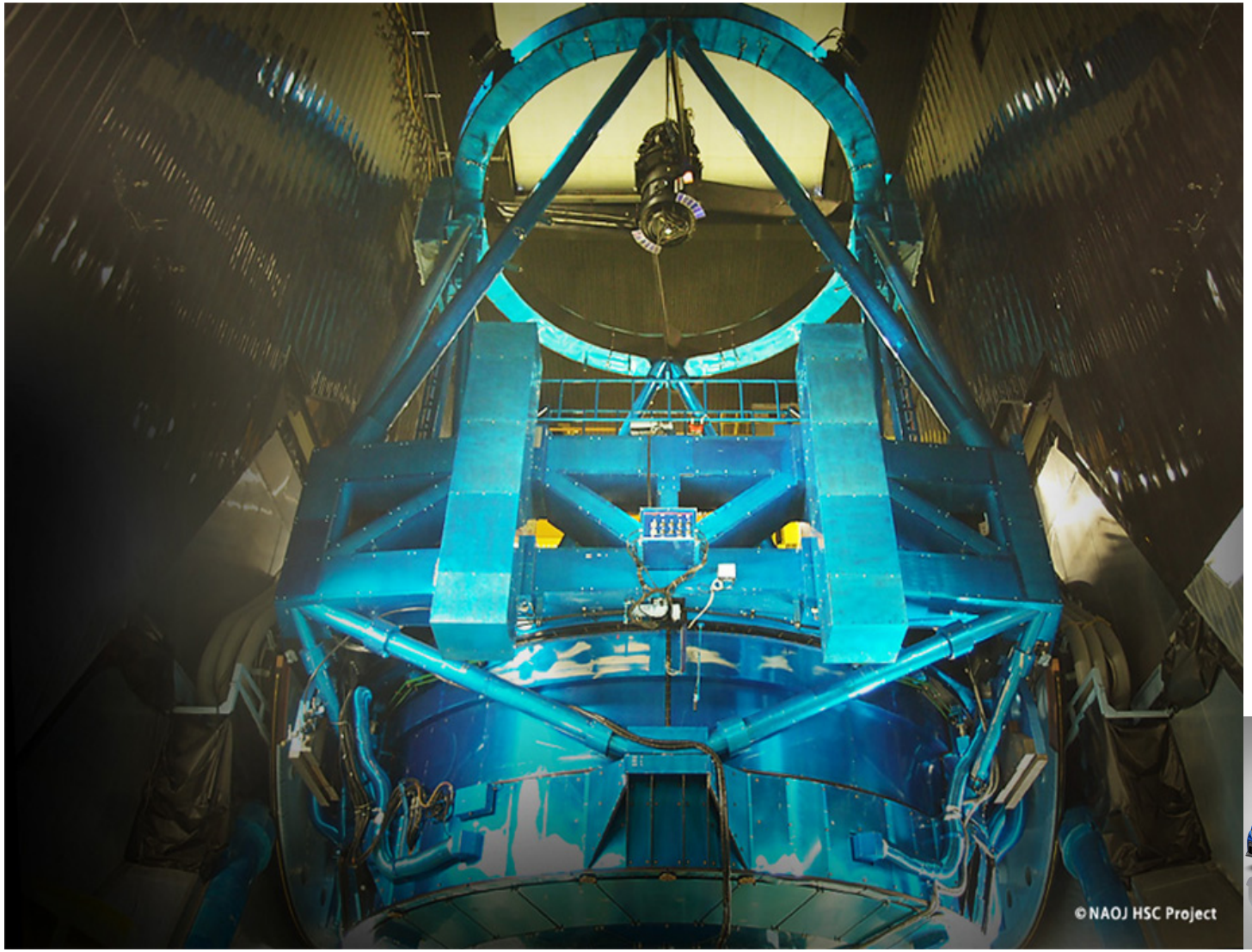
Extreme reionization morphologies

Faint galaxies dominate
(Small HII morphology)

Bright galaxies dominate
(Large HII morphology)

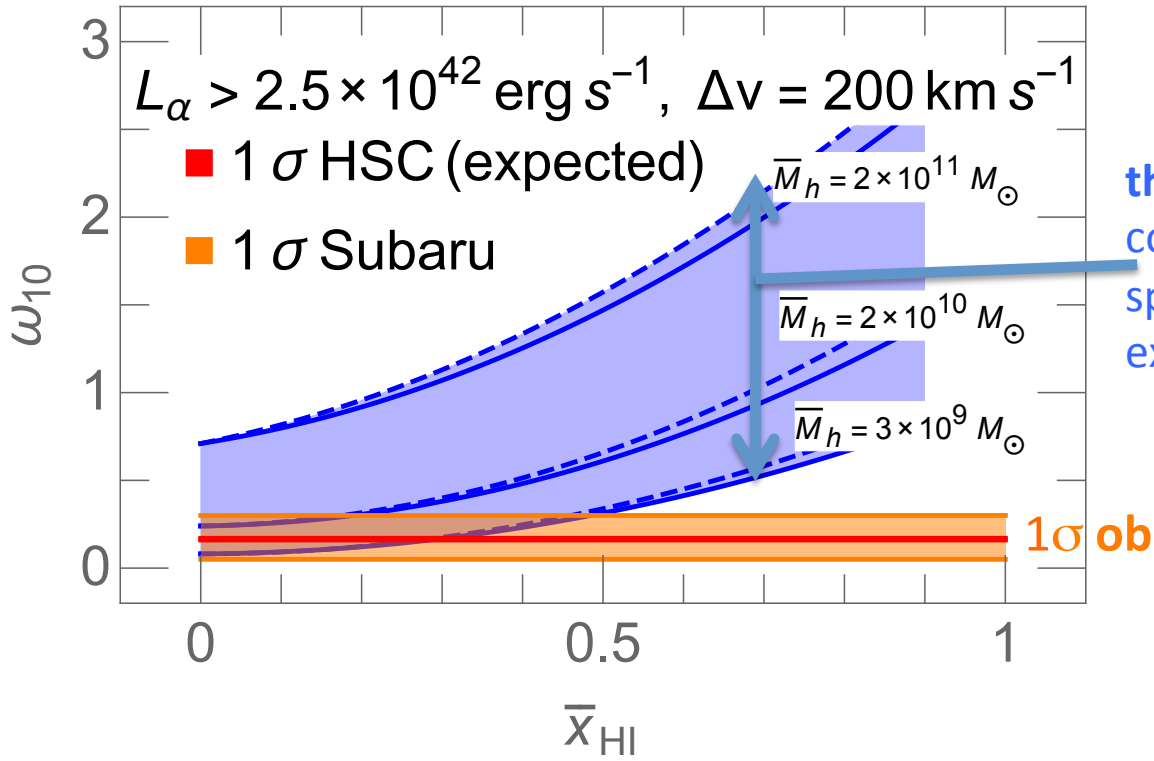


Subaru…



Subaru current and upcoming constraints on LAE clustering

Sobacchi & AM (2015)



theoretically allowed correlation function, spanned by most extreme models

1σ **observations** Ouchi+2010

- systematic approach taking the most extreme models for reionization morphology and for L^{intr} <->M_{halo}
- comparison done *at fixed* $n_{LAE}(z\sim7)$ (see also, e.g. Jensen+2014)

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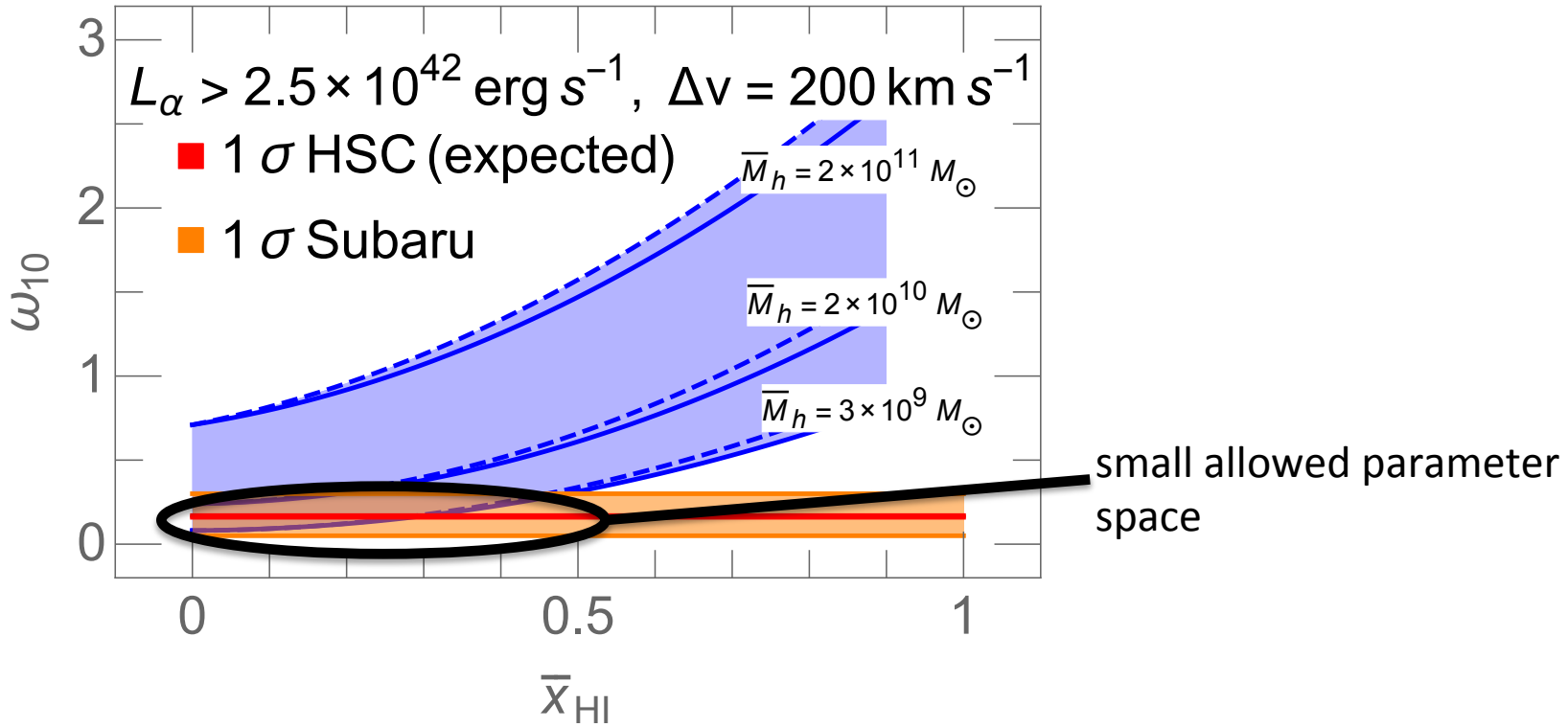

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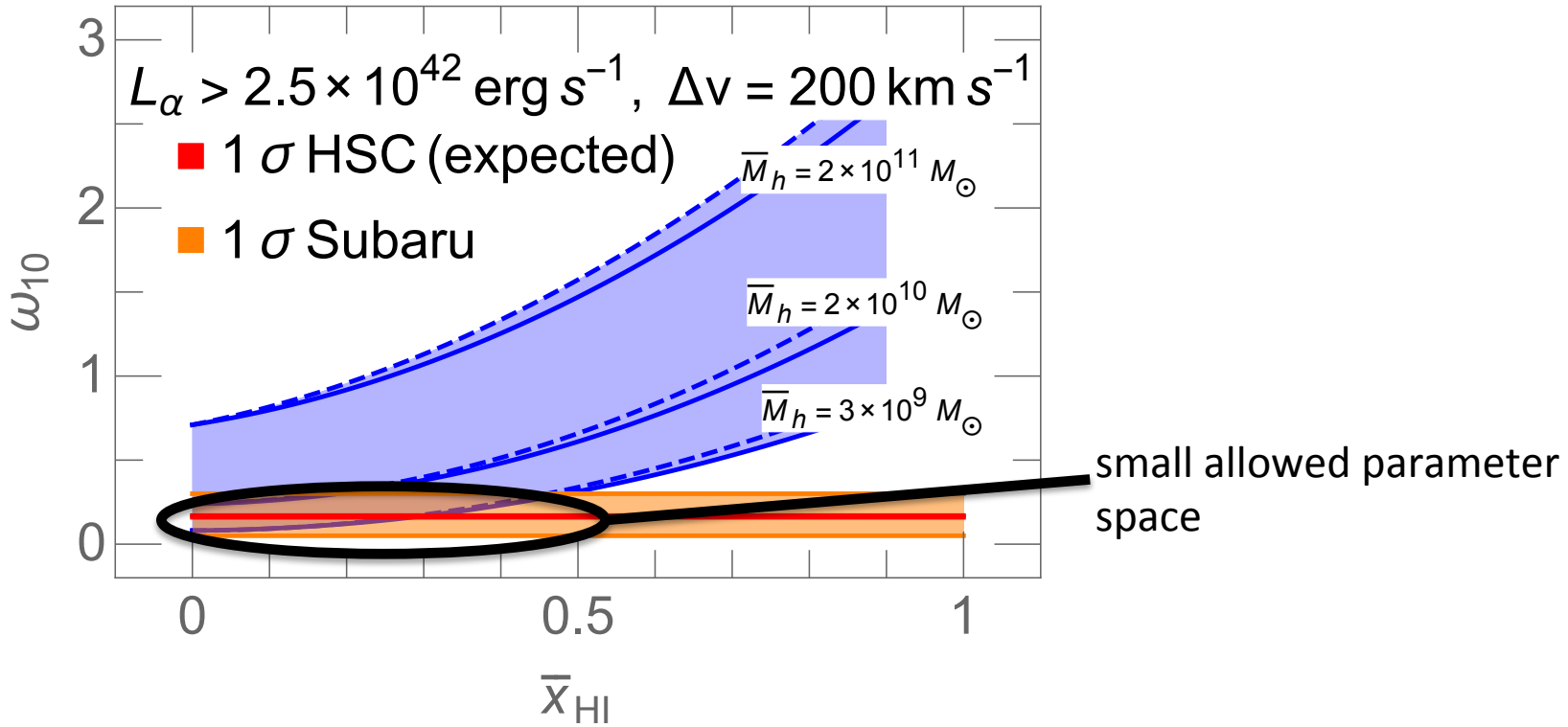
Sobacchi & AM (2015)



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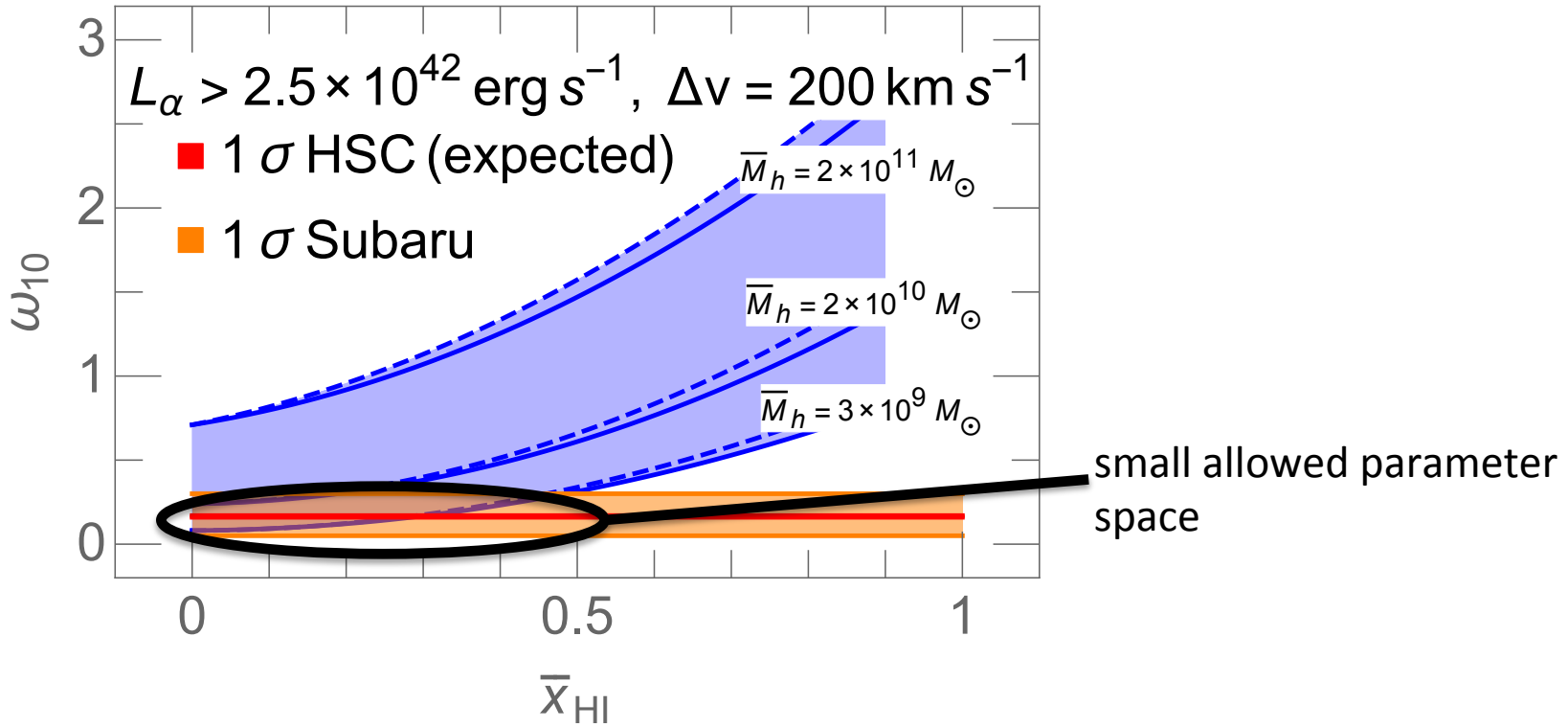

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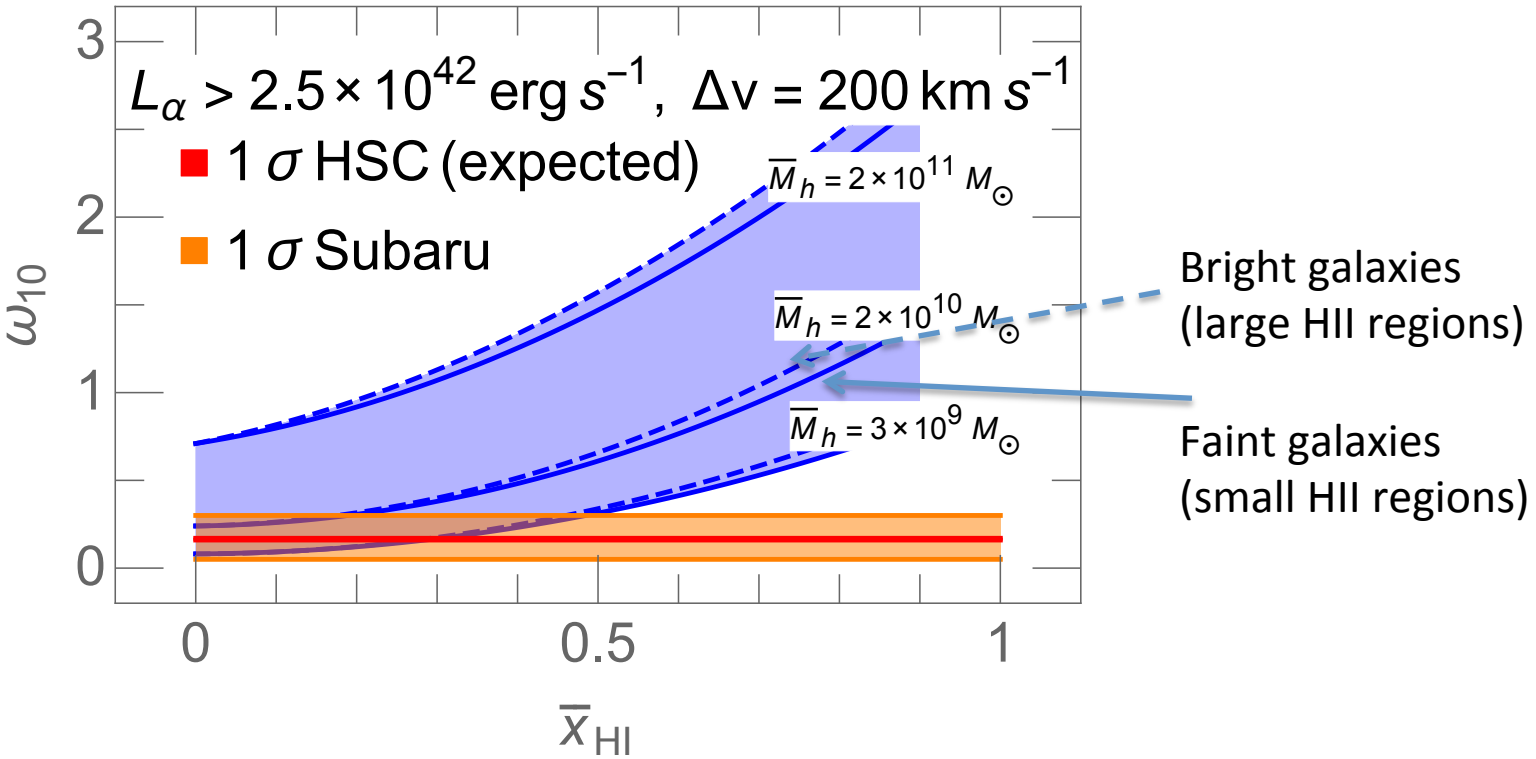

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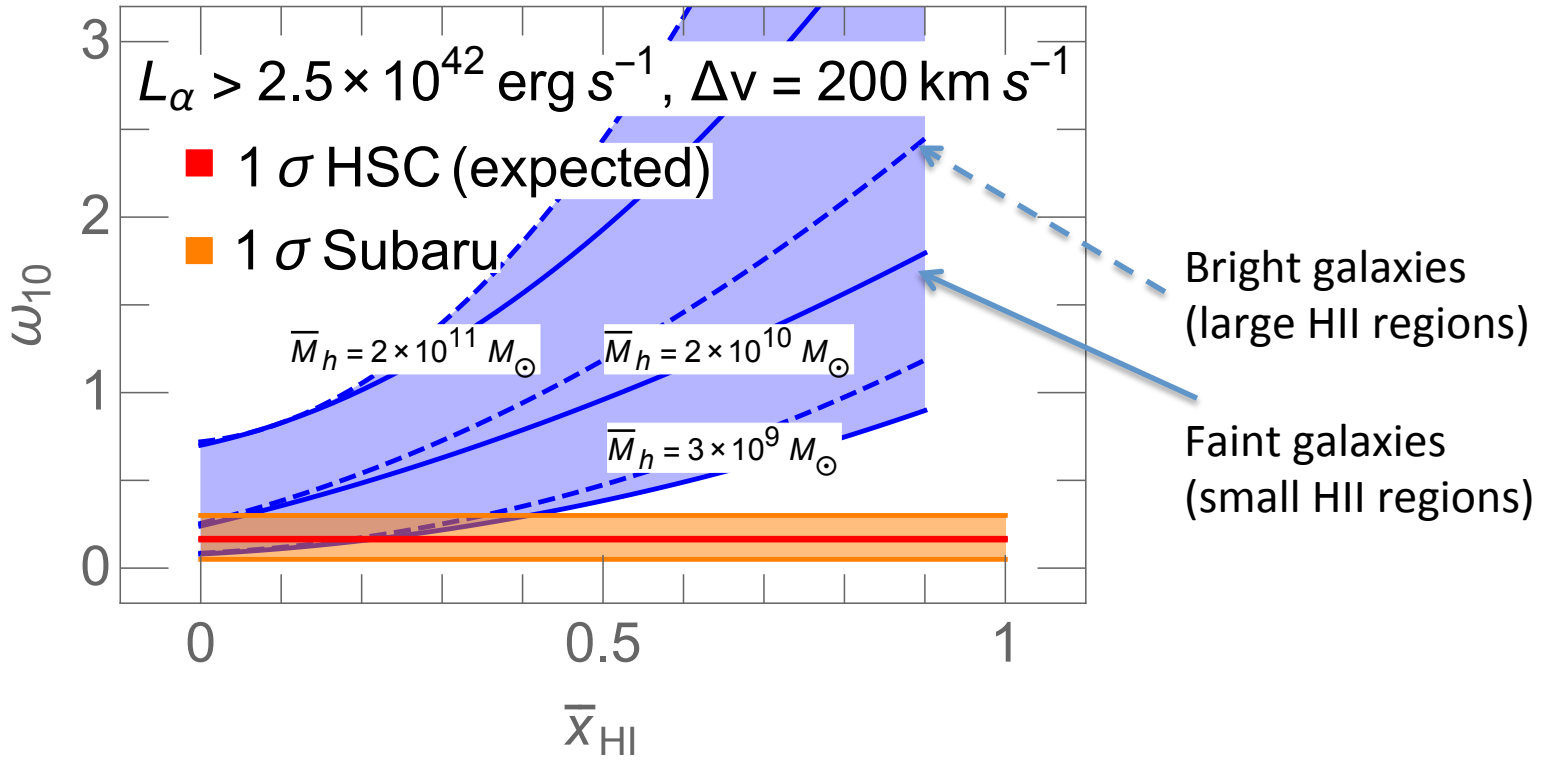
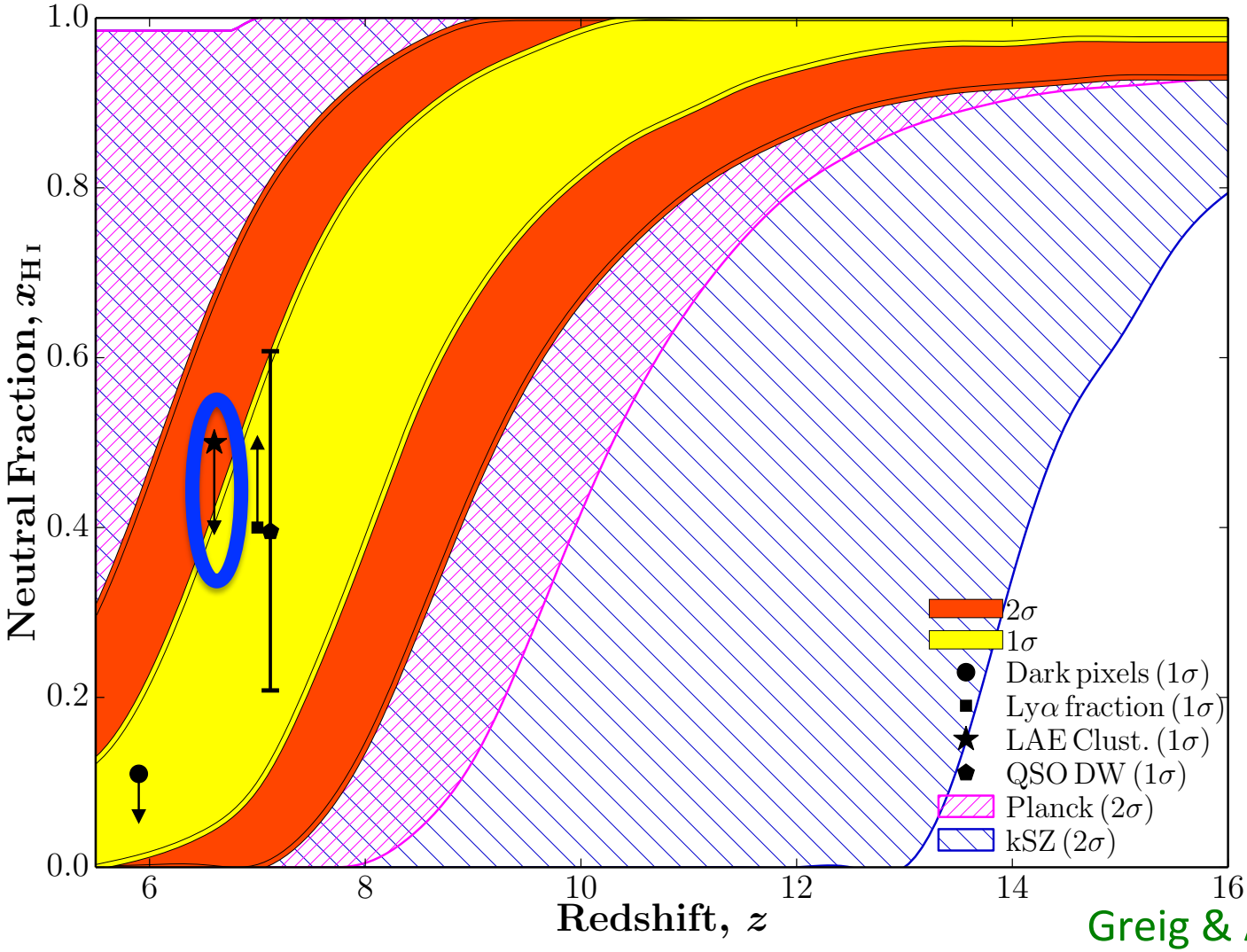


If we have two redshift measurements with PFS, we can isolate the EoR model/ topology from the evolution of the angular correlation function.

Current status of EoR timing



Greig & AM (2017)

see also Planck 2016; Price+2016; Mitra+2017

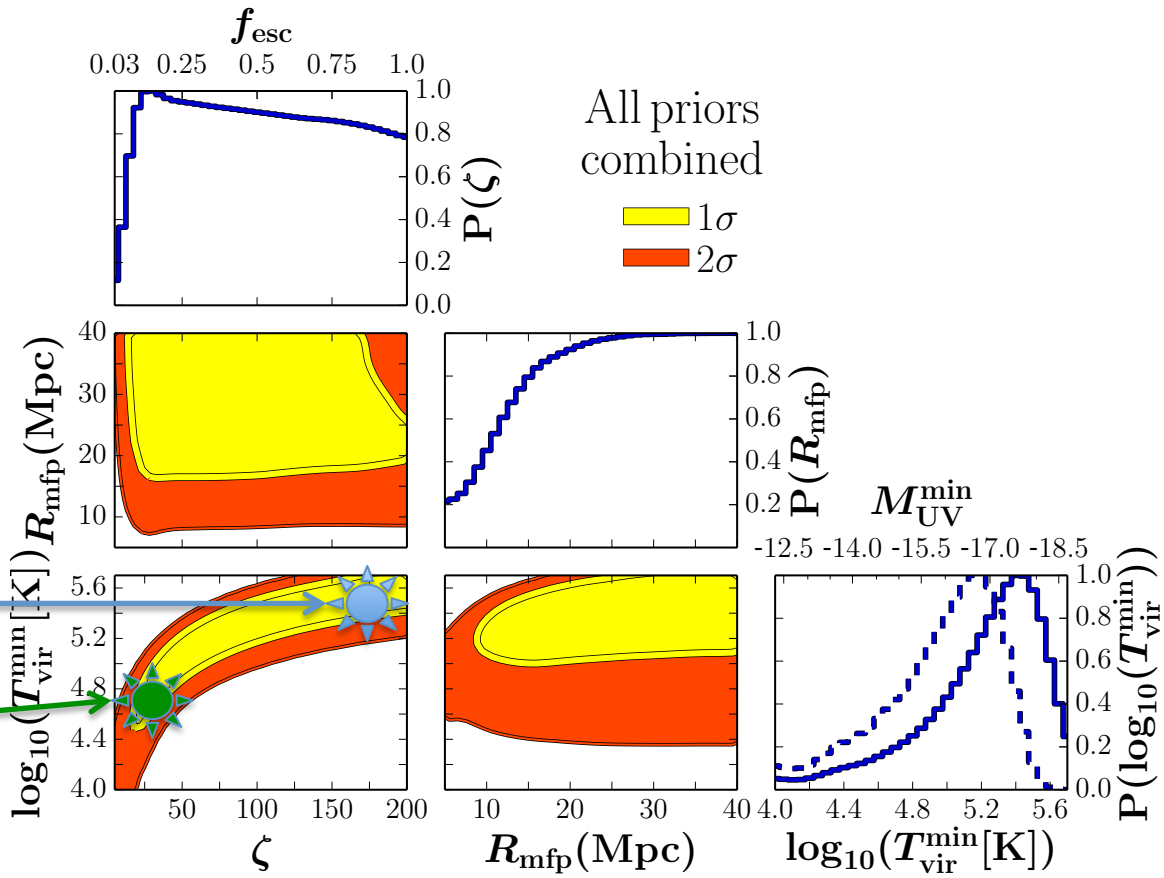
But what do we know about the underlying astrophysics?

Strong degeneracies

rare, bright galaxies

vs

abundant, faint galaxies



Greig & AM (2017)

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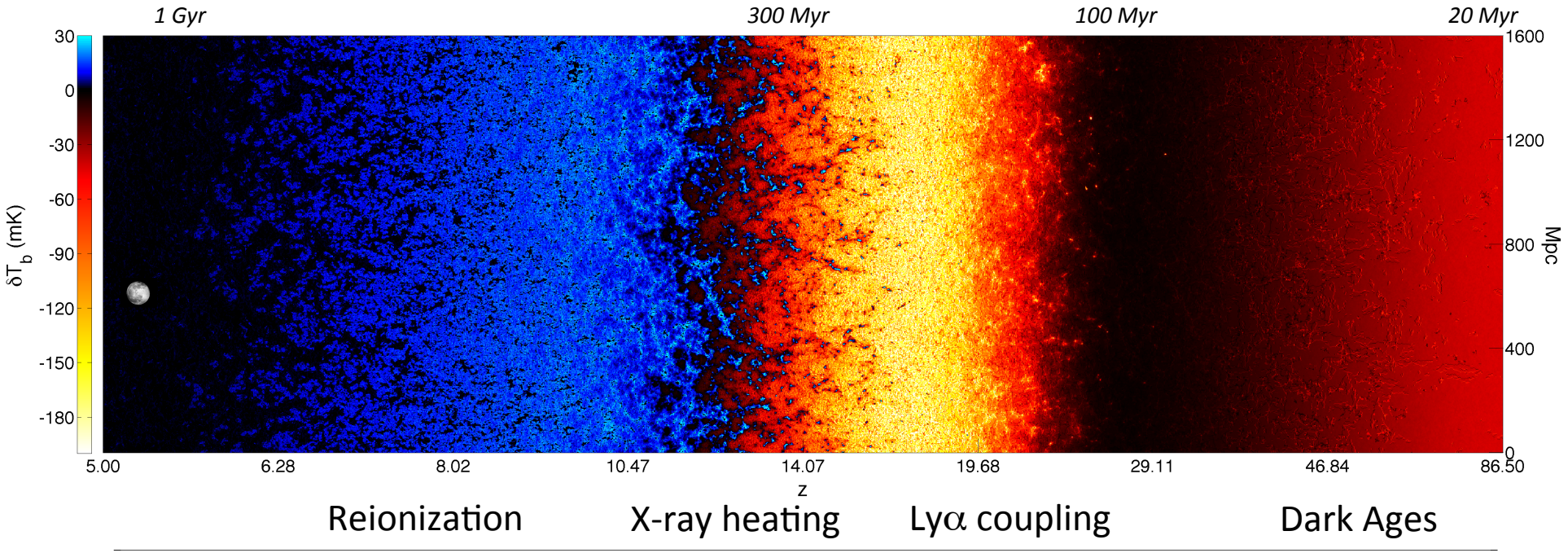
Upcoming revolution: 21-cm tomography

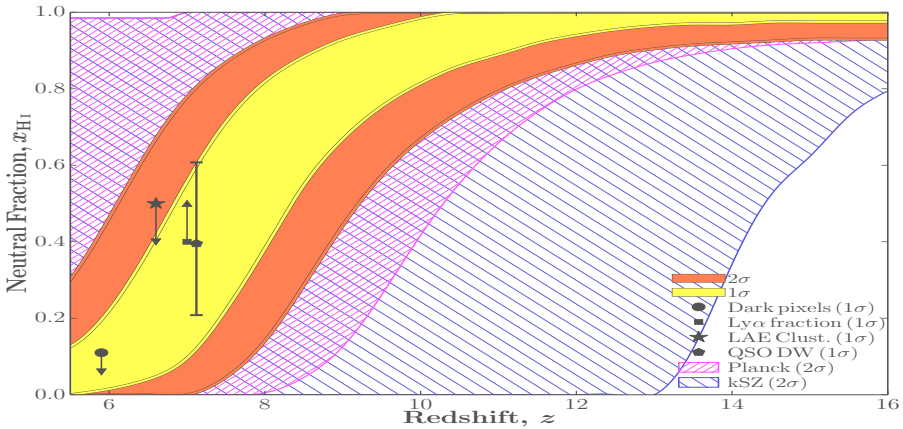


- **Sensitive to the thermal and ionization state of the IGM**
- **The timing and patterns of the signal tell us about source properties and IGM structures!!!**

Evolution of 21cm Structure (EOS; Mesinger+ 2016)

Unlocking properties of early galaxies:

going beyond $\langle x_H \rangle$ vs z



Greig & AM (2017)

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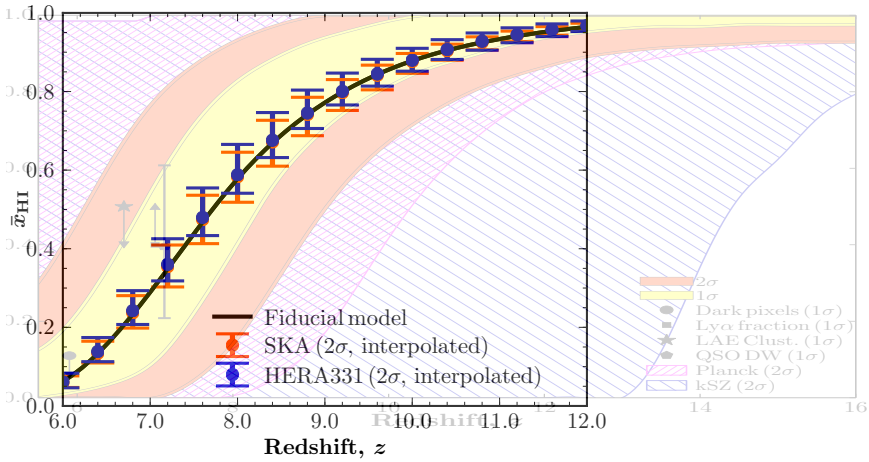

Greig & AM (2017)

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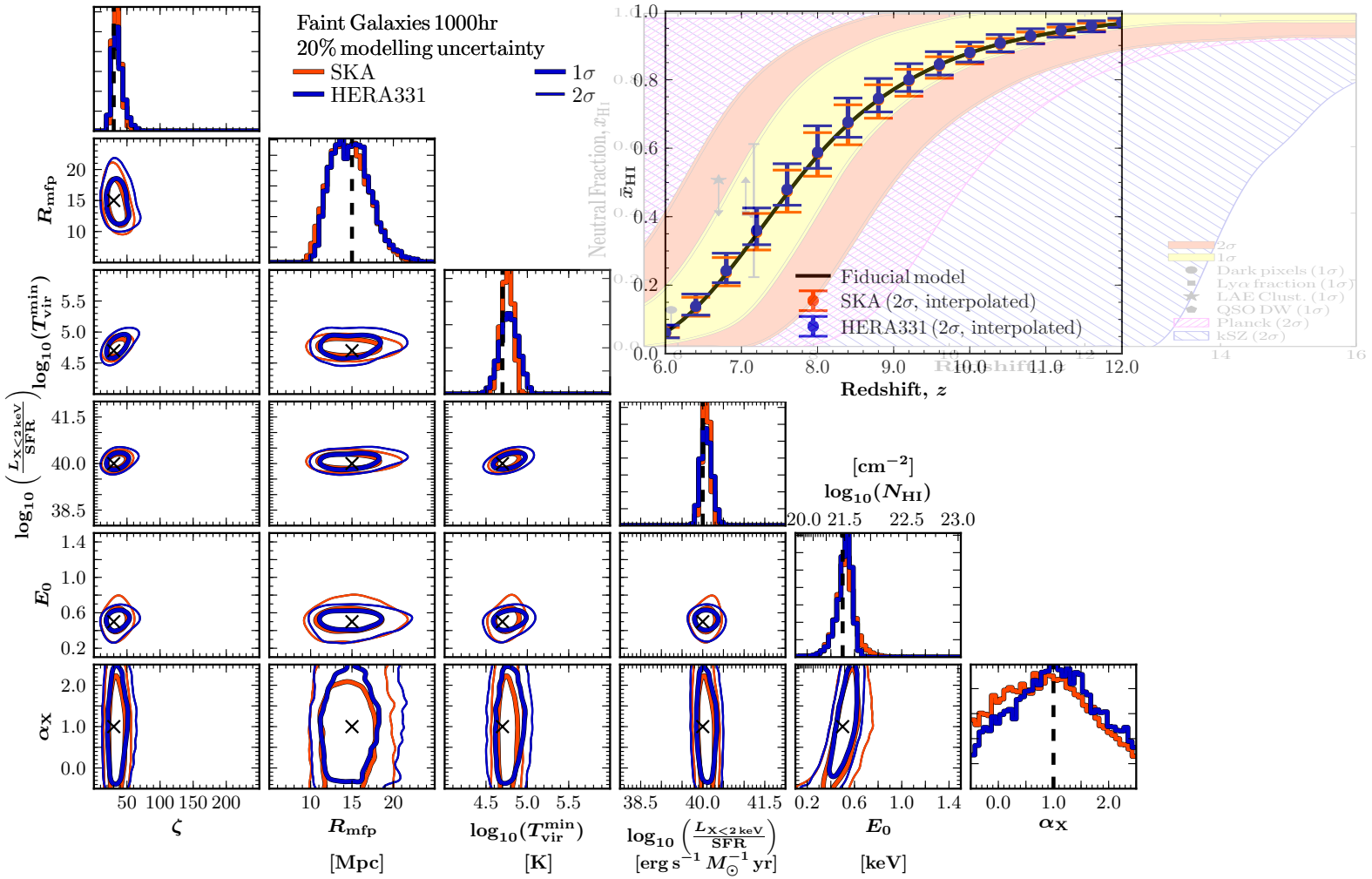
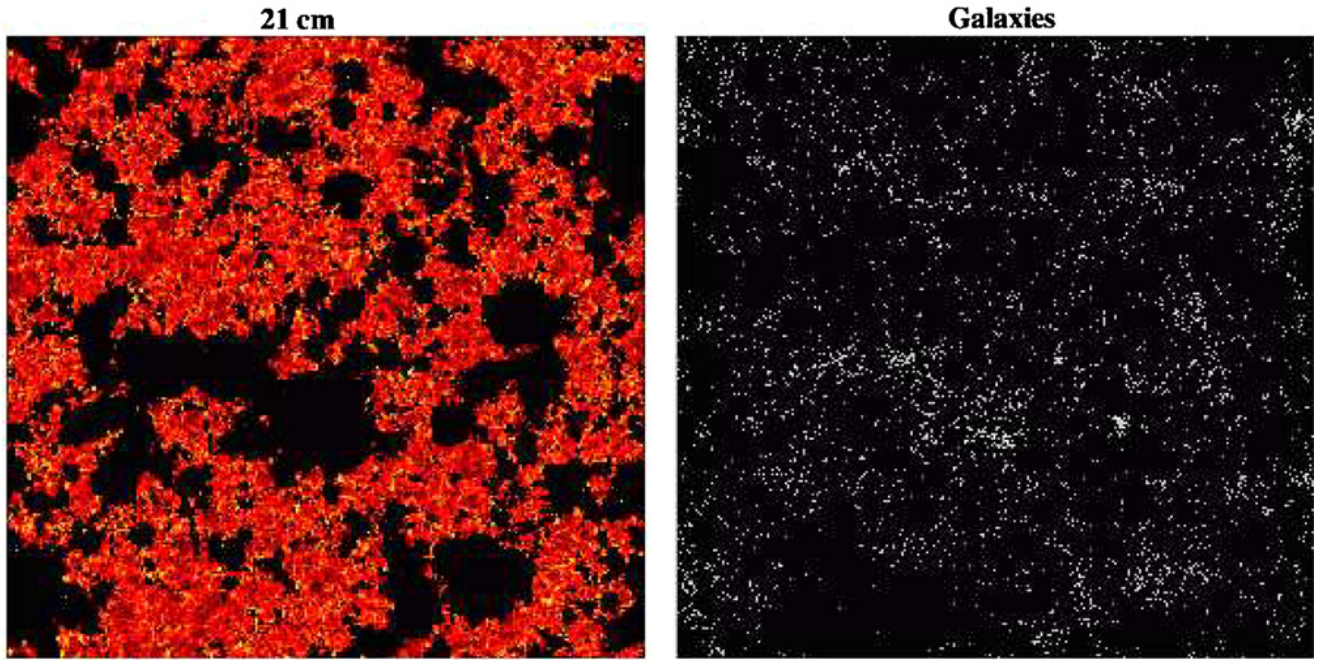


Greig & AM (2017)

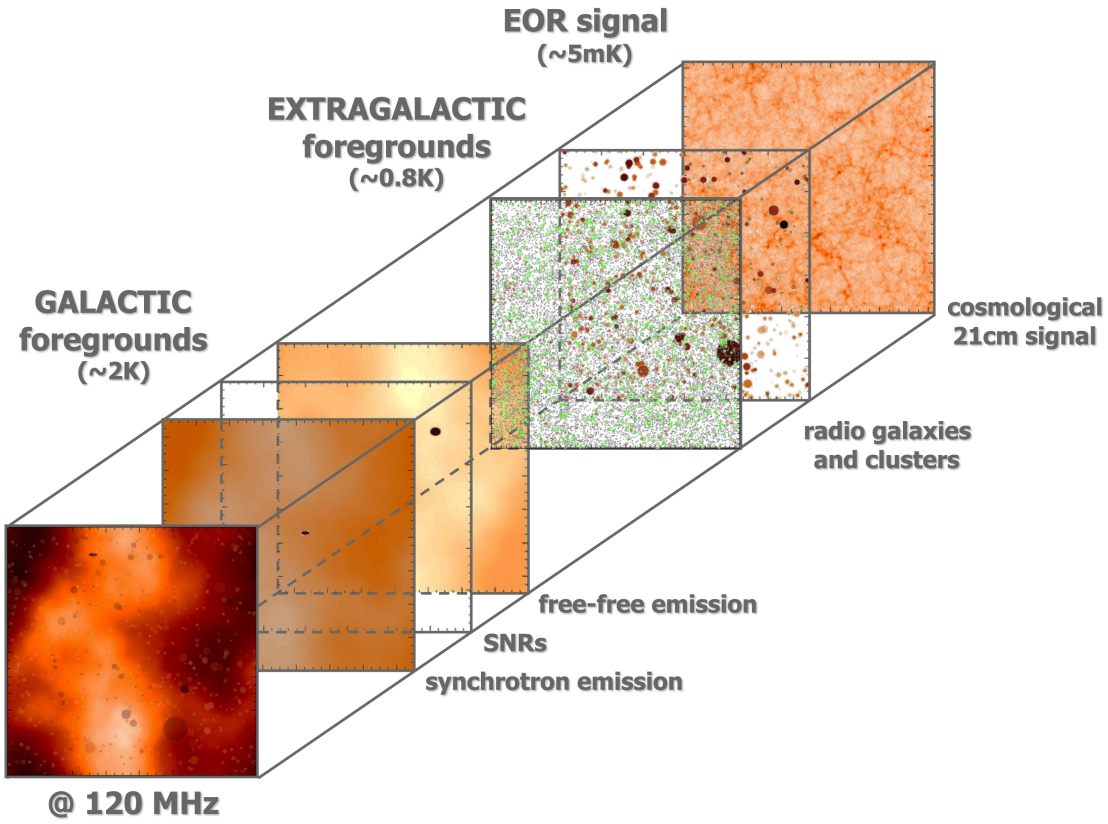
Why am I talking about 21-cm at a Lyα conference?

- During the EoR, galaxies preferentially reside in cosmic HII regions, with ~zero 21cm emission. Thus a LAE map should **anti-correlate** with the corresponding 21cm map (e.g. Lidz+2009)



Why is this important???

Zaroubi+ (2009)



- **The 21-cm signal is out there!!!!**
- **BUT it is a very difficult measurement!**

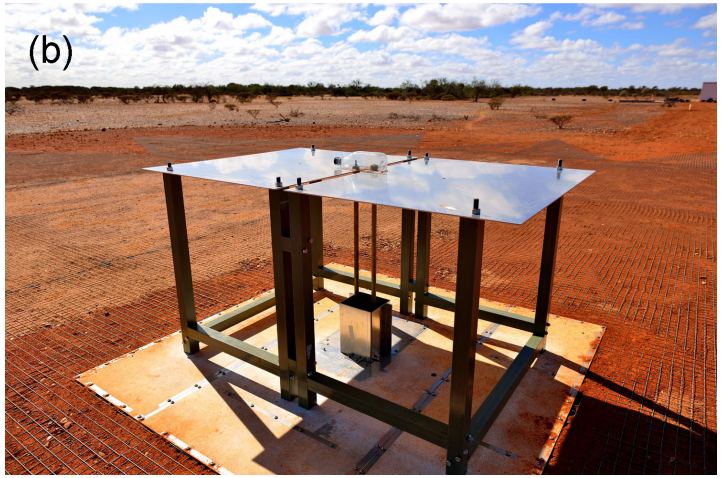
Why is this important???

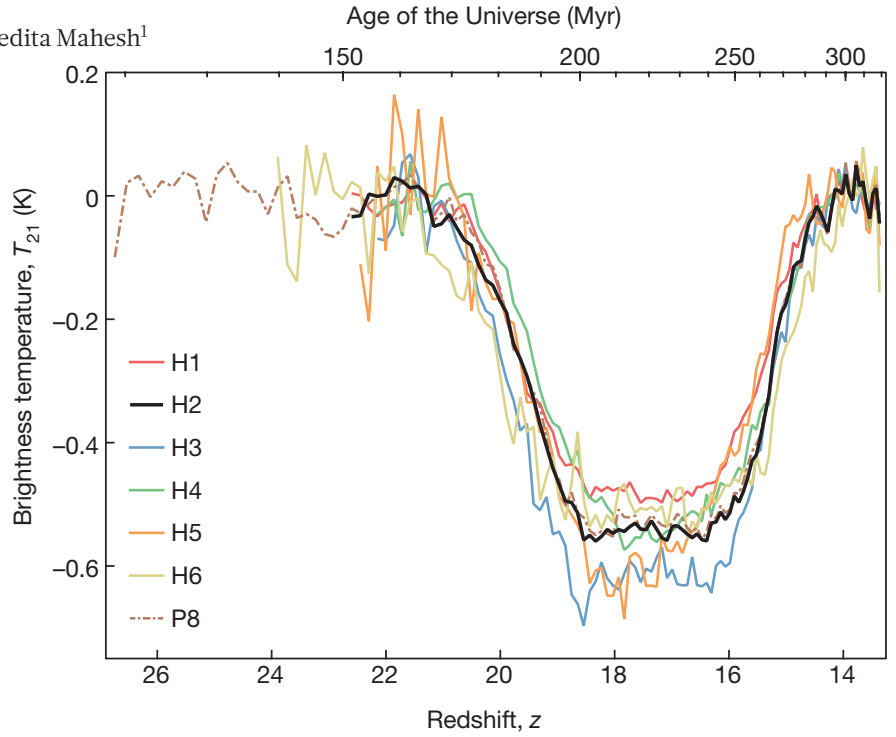
LETTER

doi:10.1038/nature25792

An absorption profile centred at 78 megahertz in the sky–averaged spectrum

Judd D. Bowman[1], Alan E. E. Rogers[2], Raul A. Monsalve[1,3,4], Thomas J. Mozdzen[1] & Nivedita Mahesh[1]



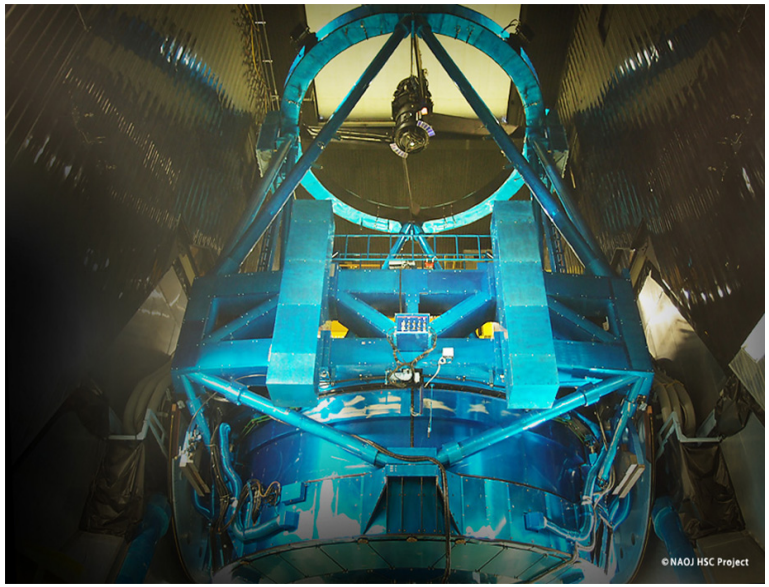


Bowman et al. 2018

Why is this important???

- It’s a slow march to 21-cm tomography!
- We will desperately need “sanity checks” that our signal is **real (cosmological origin)** and that our analysis pipeline is **working!**

LAE – 21cm cross-correlation forecast:
Subaru HSC UDF + LOFAR 1000h



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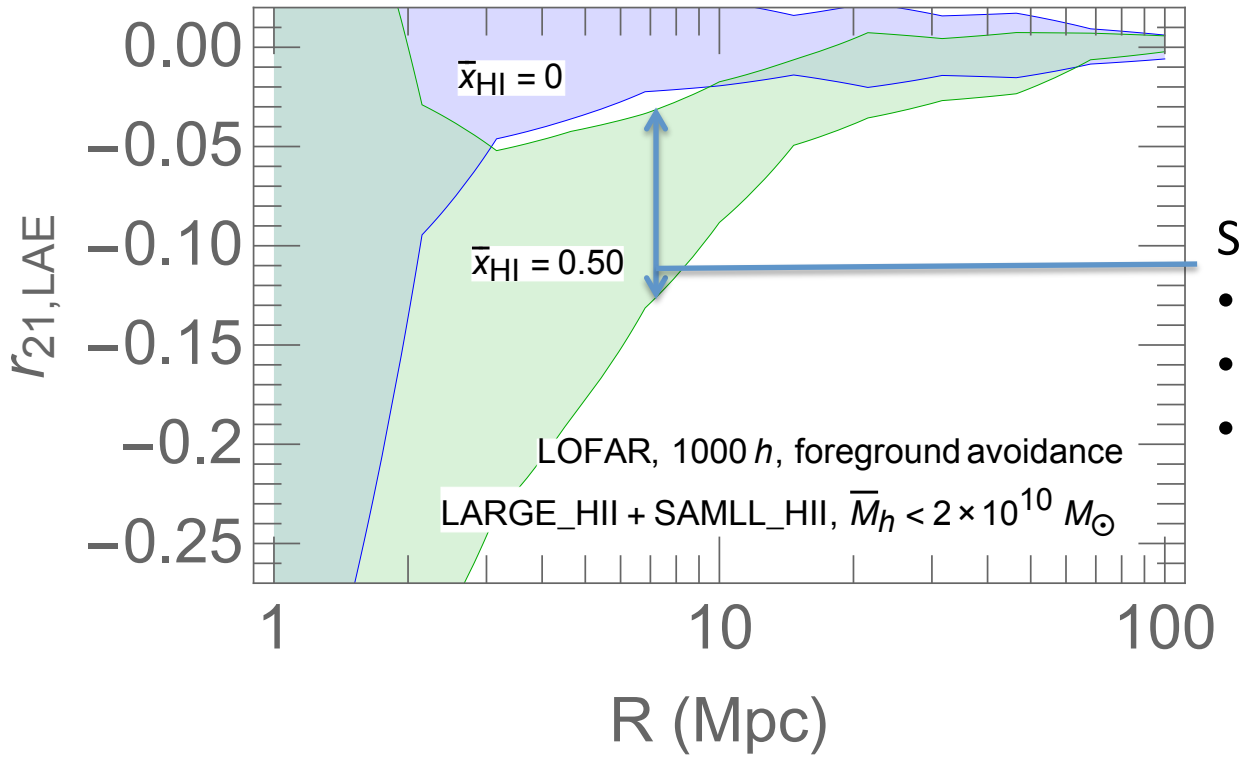


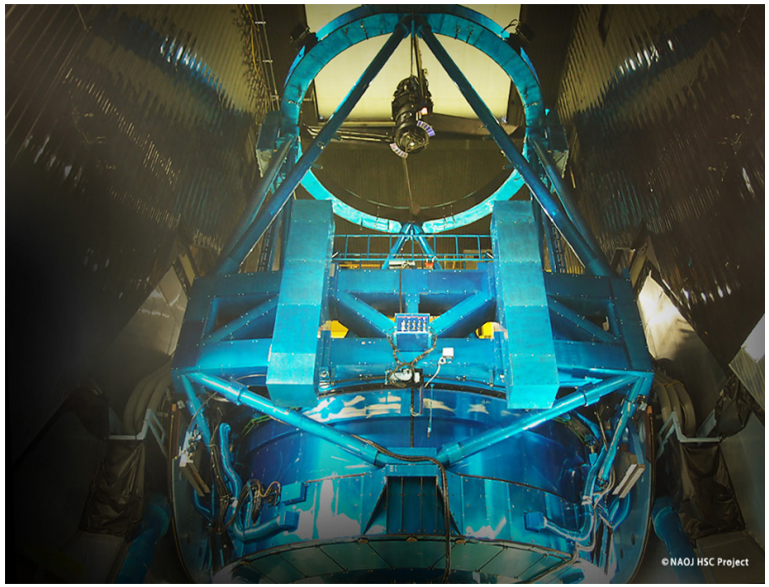
Span includes:

- foreground noise
- EoR topology
- LAE model

The cross-correlation will only be detectable at ~1 sigma, unless the EoR is characterized by large HII regions

Sobacchi, AM, Greig (2016)
see also Vrbanec+2015;
Hasegawa+2017; Yoshiura+2017

LAE – 21cm cross-correlation forecast:
Subaru HSC UDF + SKA 1000h



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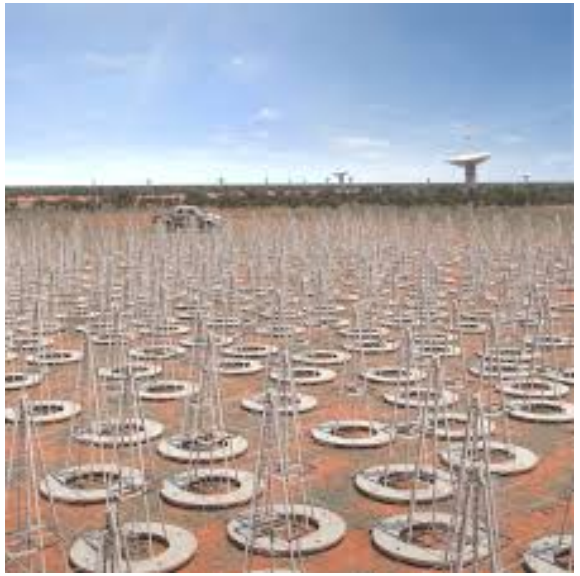

LAE – 21cm cross-correlation forecast:
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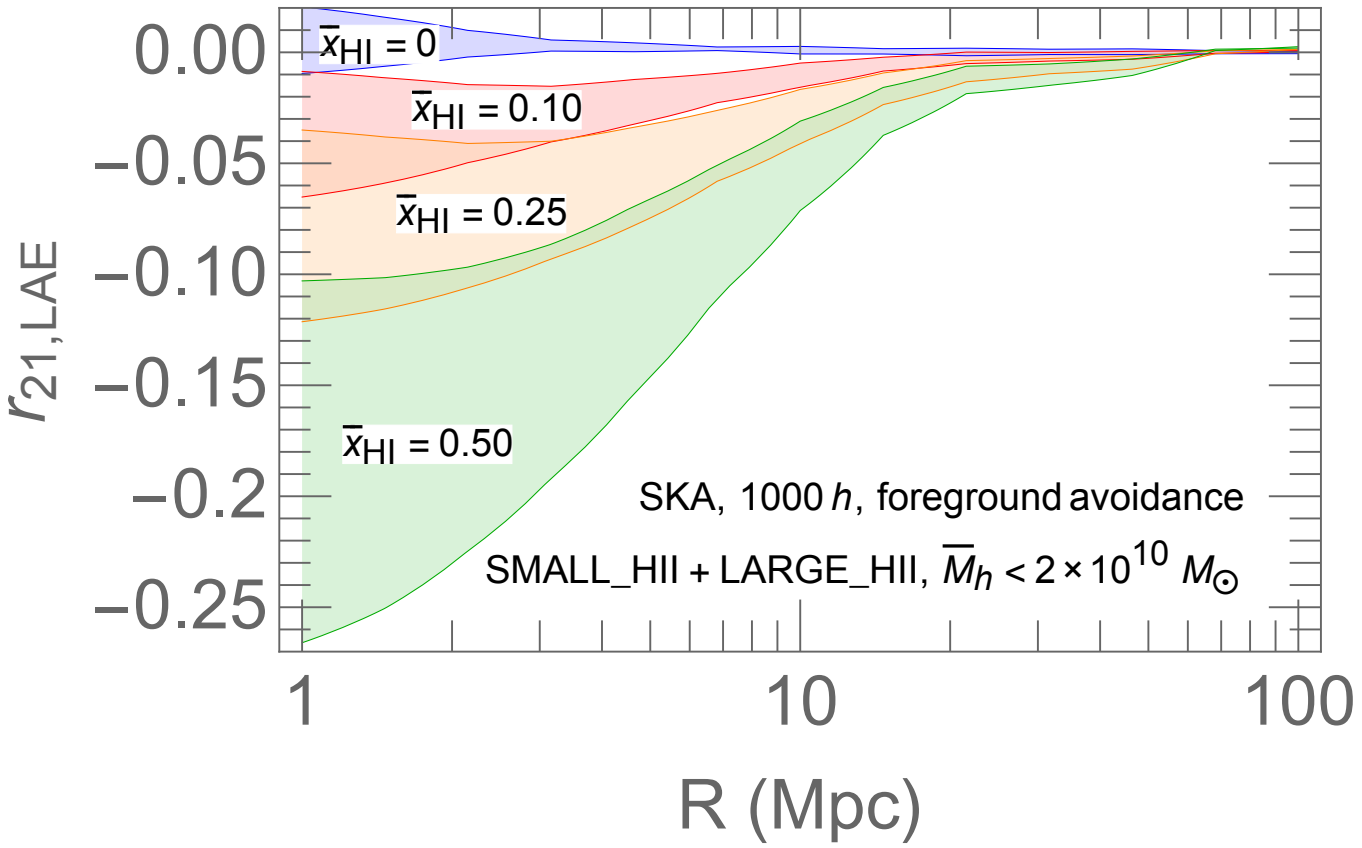


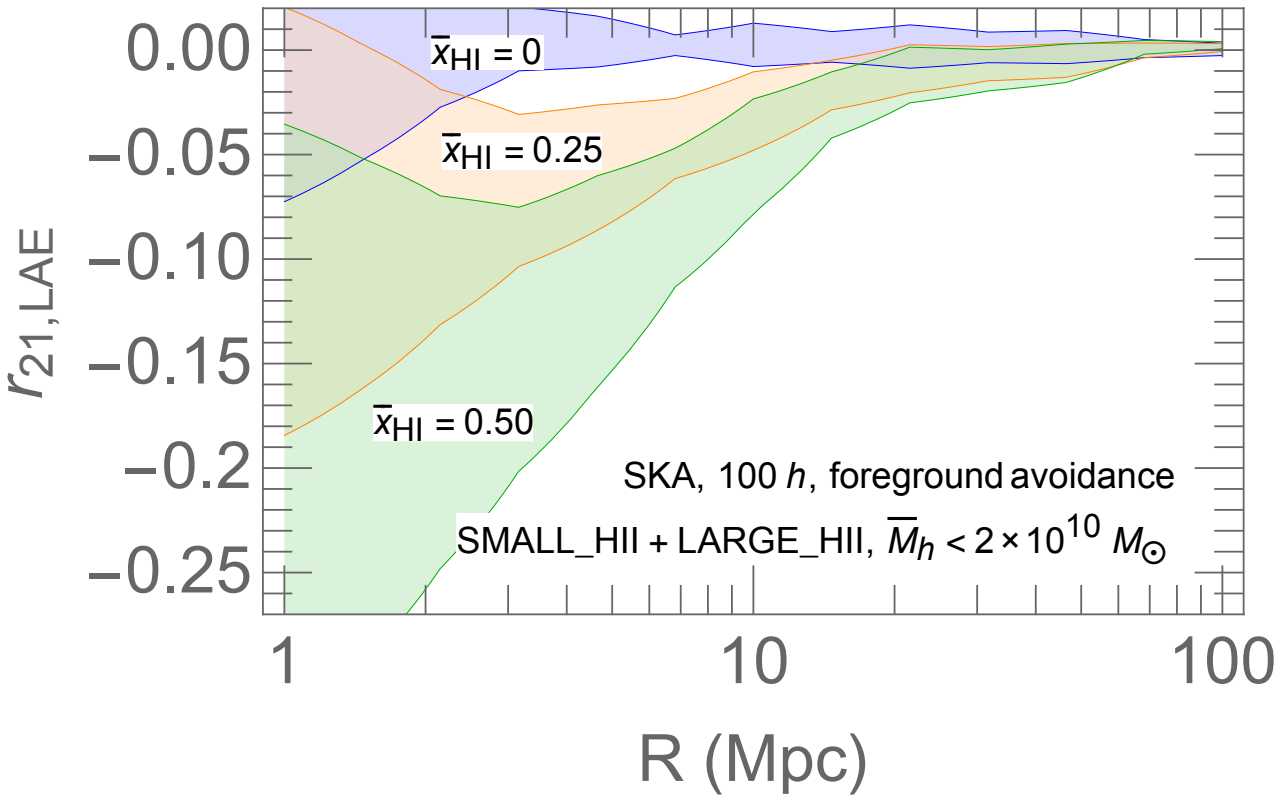
The cross-correlation is easily detectable, even if $\langle x_{HI} \rangle < 0.1$!!!

Sobacchi, AM, Greig (2016)

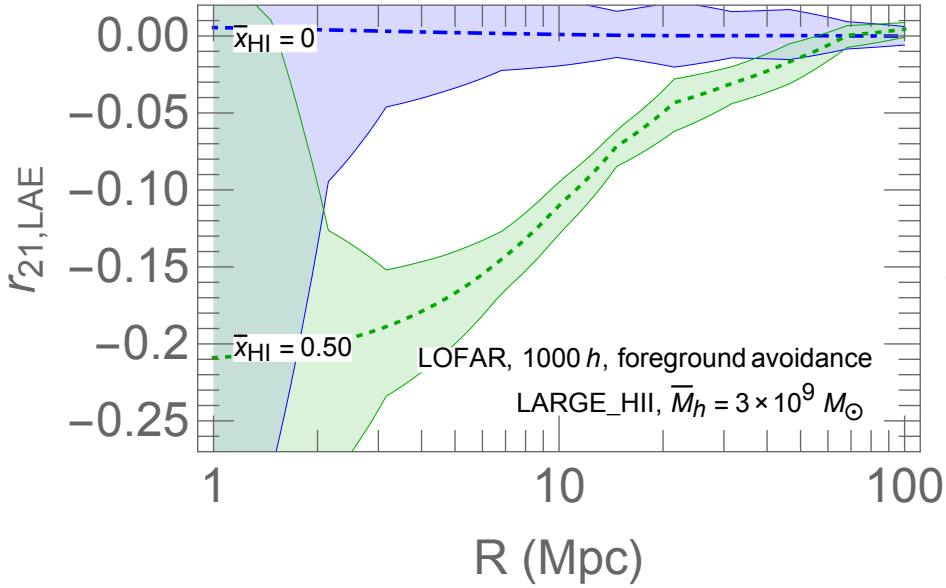
Conclusions

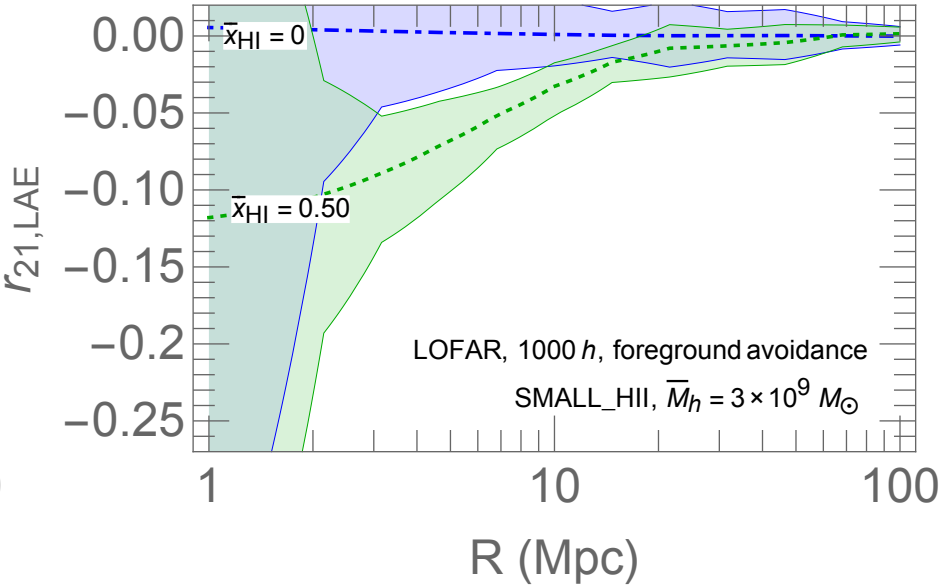
- LAE clustering measurements with Subaru SC constrain $x_{HI,z7} < 0.5$ (68% C.L.), with limits improving by ~ 50% with upcoming HSC UDF survey.
- Redshift info with the PFS can distinguish between reionization models
- DM halos hosting LAEs with $L_\alpha > 10^{42.4}$ erg/s at z~7 typically have small masses, $<\sim 10^{10}$ M_{sun} , duty cycles of < per cent → narrow-band selected LAEs preferentially trace young, bursty galaxies
- cross-correlation with 21cm provides an important sanity check for 21cm data reduction efforts:
  - Detection with Subaru HSC + LOFAR will be challenging unless we get lucky and the EoR is characterized by large HII regions, and is ~50% neutral at z~7
  - Detection with Subaru HSC + SKA1 will be easy, even if the IGM is only 10% neutral

SKA 100h

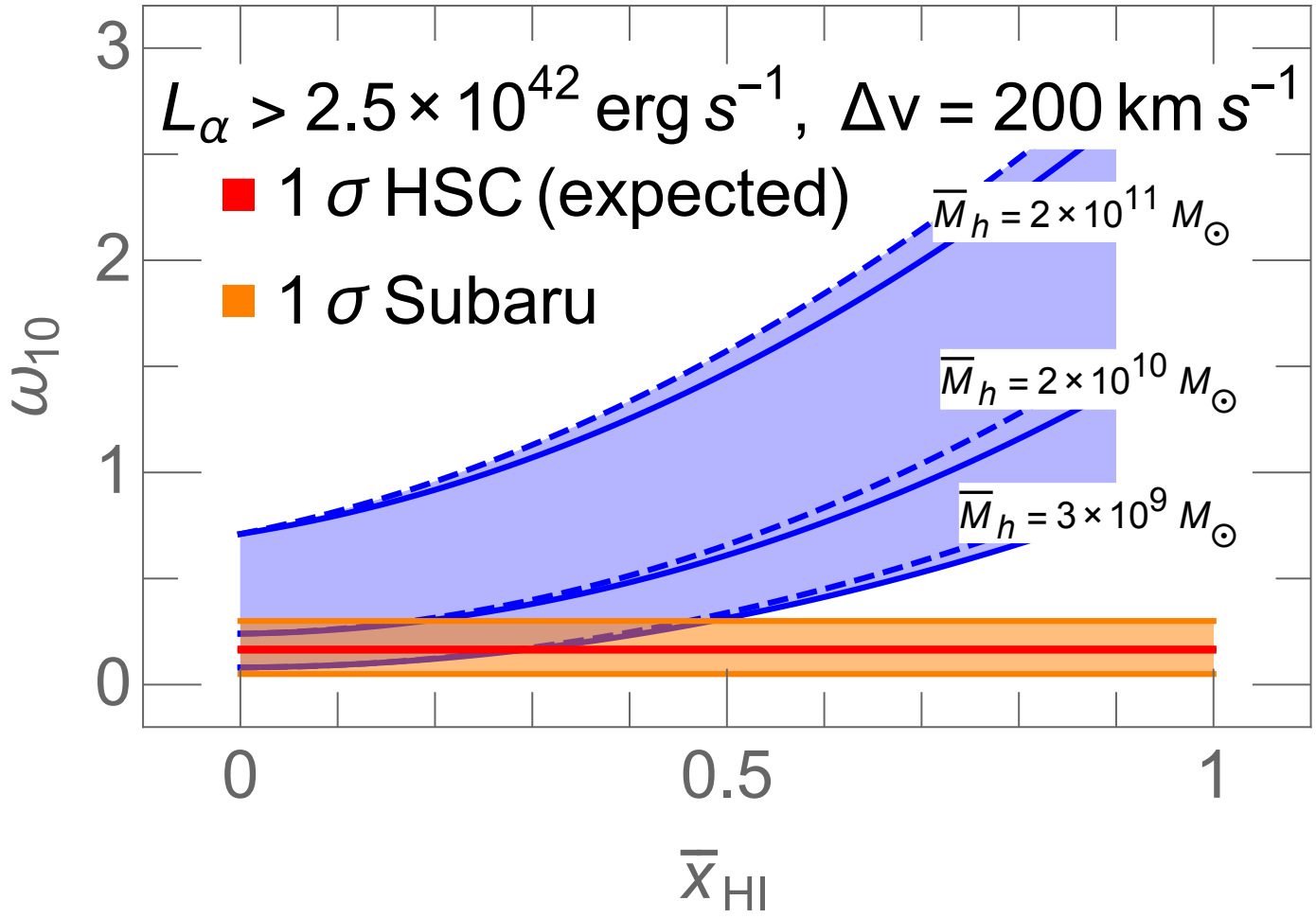

0.00
−0.05
−0.10
−0.15
−0.2
−0.25
$r_{21,\mathrm{LAE}}$
$\bar{x}_{\mathrm{HI}} = 0$
$\bar{x}_{\mathrm{HI}} = 0.25$
$\bar{x}_{\mathrm{HI}} = 0.50$
SKA, 100 h, foreground avoidance
SMALL_HII + LARGE_HII, $\bar{M}_h < 2 \times 10^{10}\ M_\odot$
1
10
100
R (Mpc)

LOFAR diff EoR

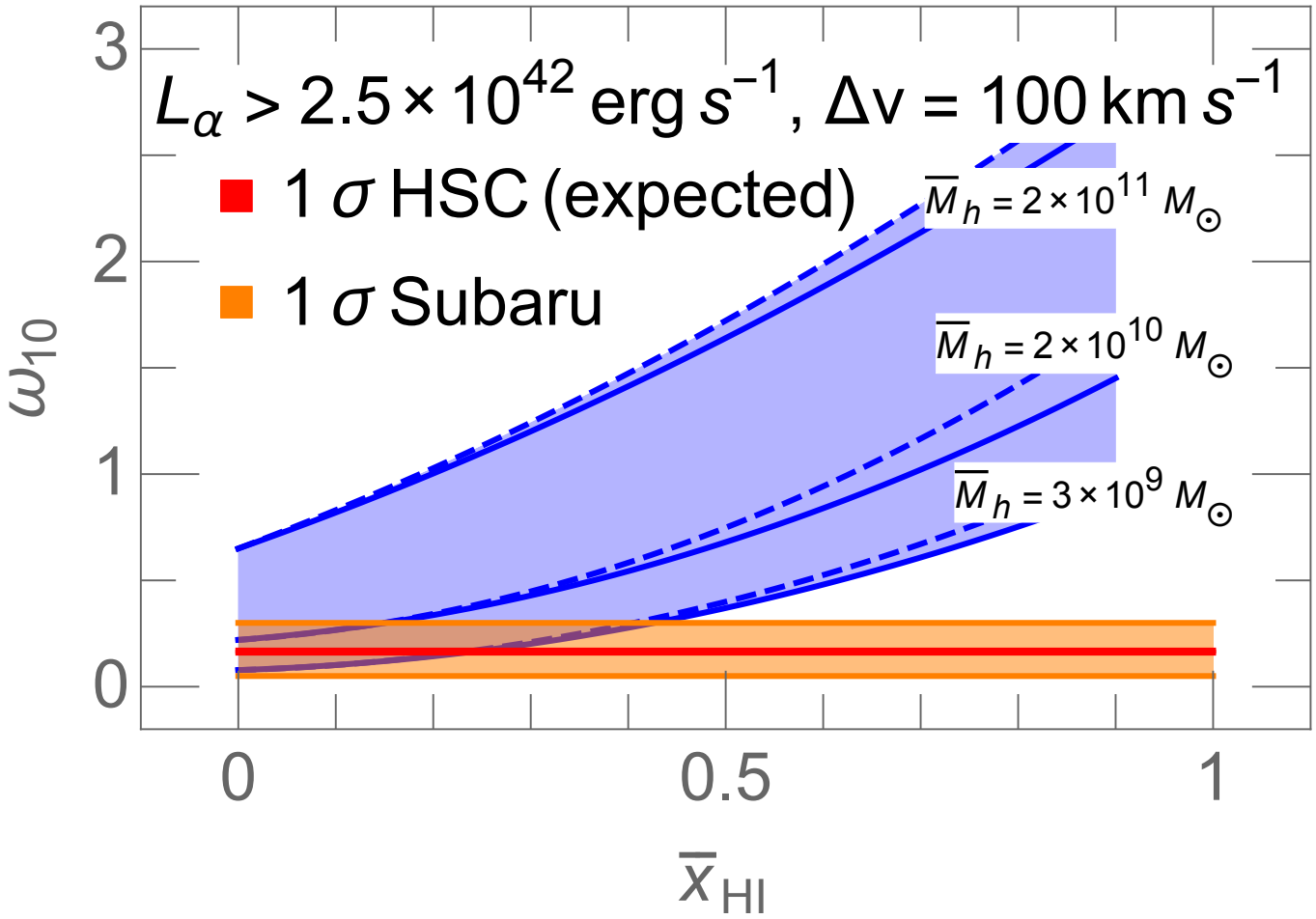




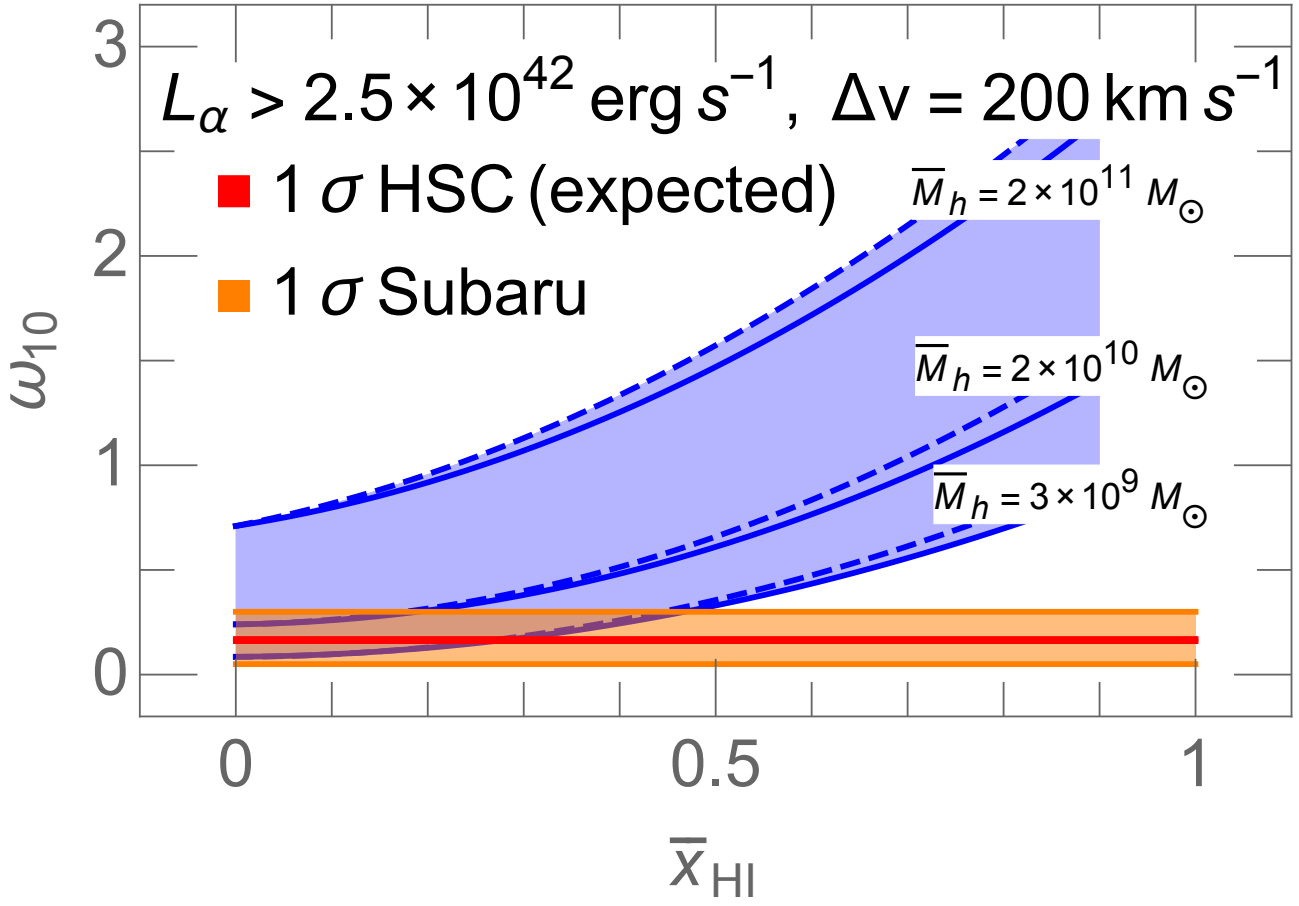
fiducial


$L_\alpha > 2.5 \times 10^{42}\,\mathrm{erg\,s^{-1}},\ \Delta v = 200\,\mathrm{km\,s^{-1}}$
1 σ HSC (expected)
1 σ Subaru
$\overline{M}_h = 2 \times 10^{11}\,M_\odot$
$\overline{M}_h = 2 \times 10^{10}\,M_\odot$
$\overline{M}_h = 3 \times 10^{9}\,M_\odot$
ω_{10}
$\overline{x}_{\mathrm{HI}}$
0
1
2
3
0
0.5
1

low systemic v offset



beta = 2/3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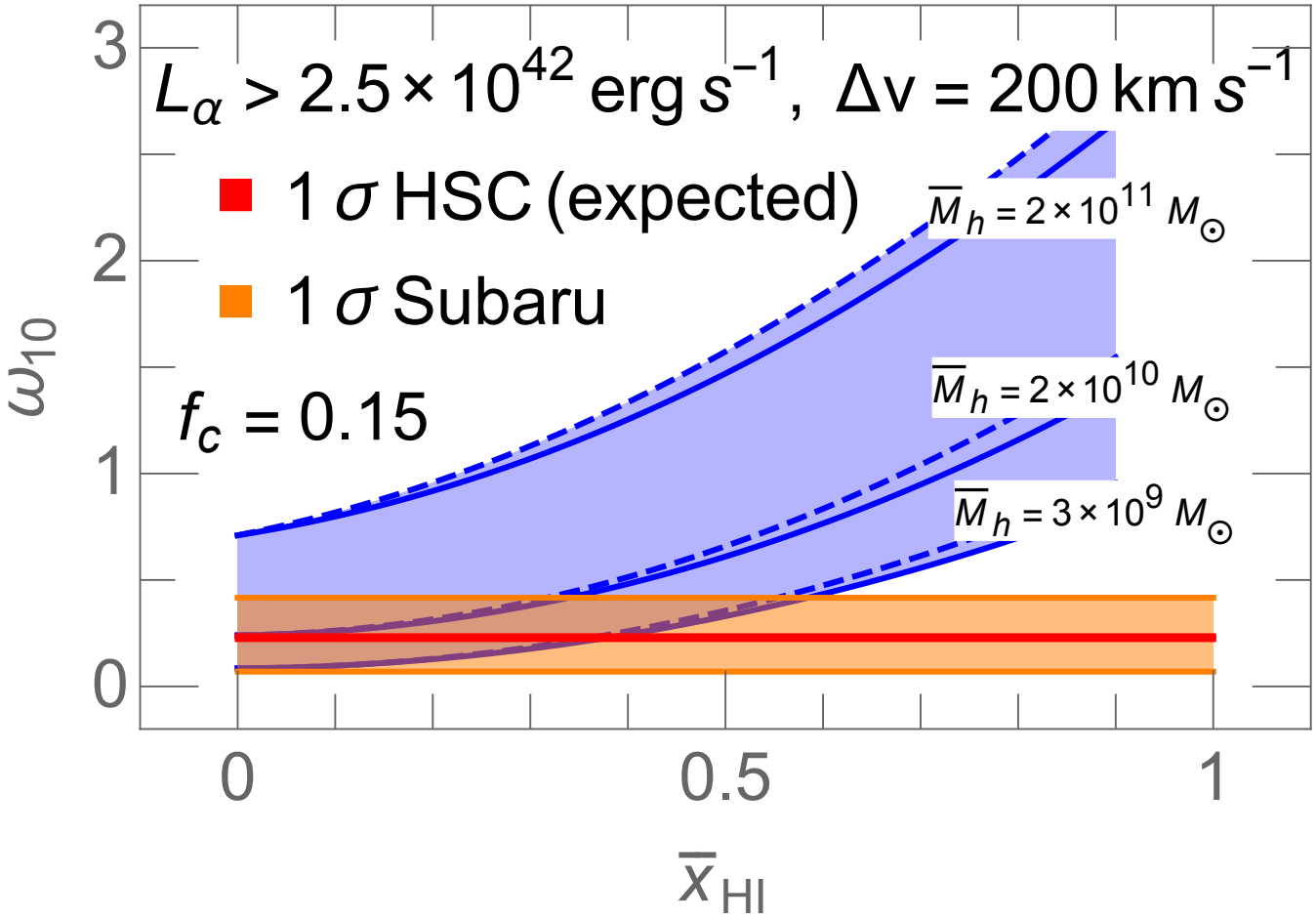
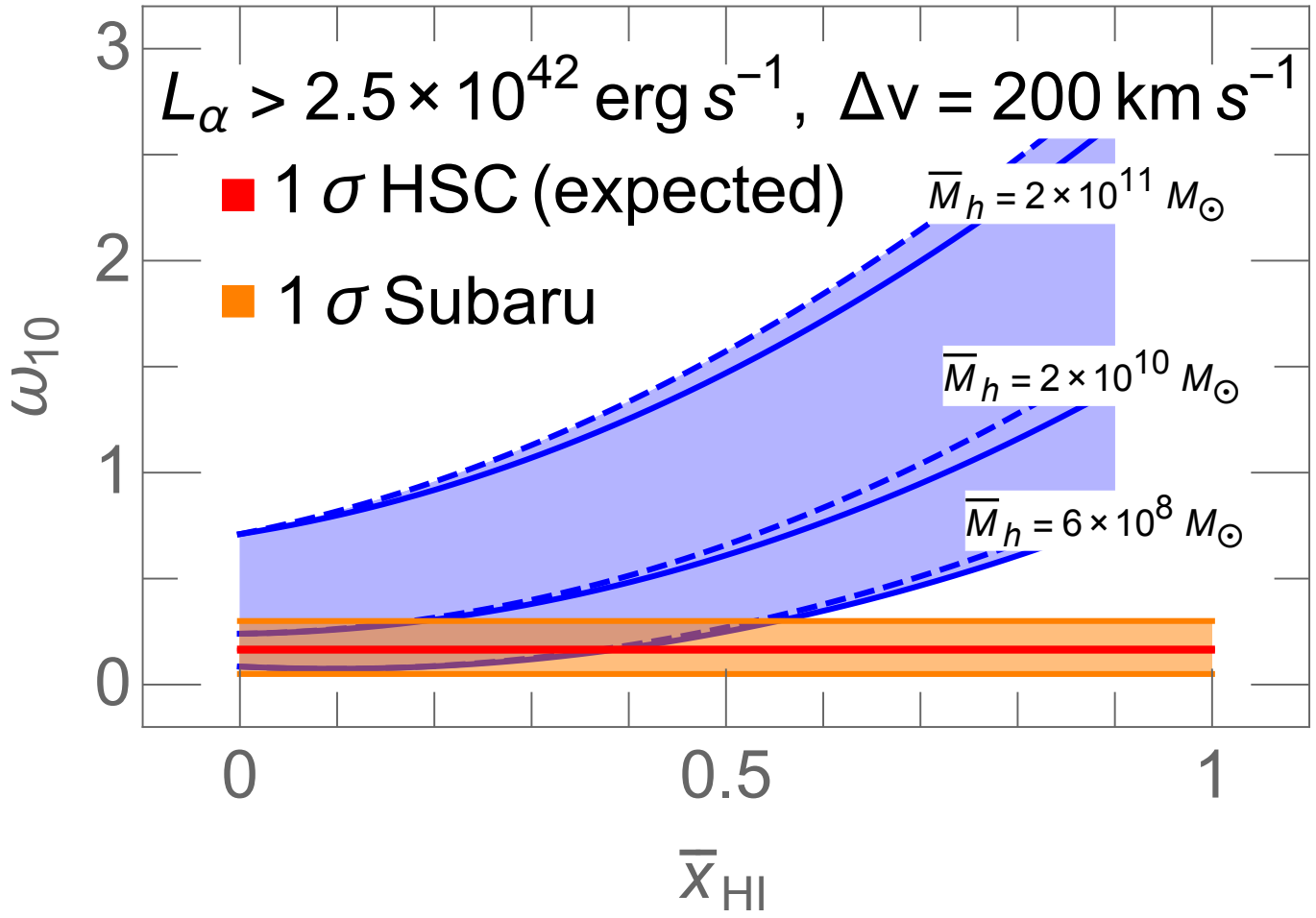
1 σ HSC (expected)
1 σ Subaru
$\overline{M}_h = 2 \times 10^{11}\ M_\odot$
$\overline{M}_h = 2 \times 10^{10}\ M_\odot$
$\overline{M}_h = 3 \times 10^{9}\ M_\odot$
ω_{10}
$\overline{x}_{\mathrm{HI}}$
0
1
2
3
0
0.5
1

15% interlopers



down to atomic-cooling thresh.



bright sub-sample