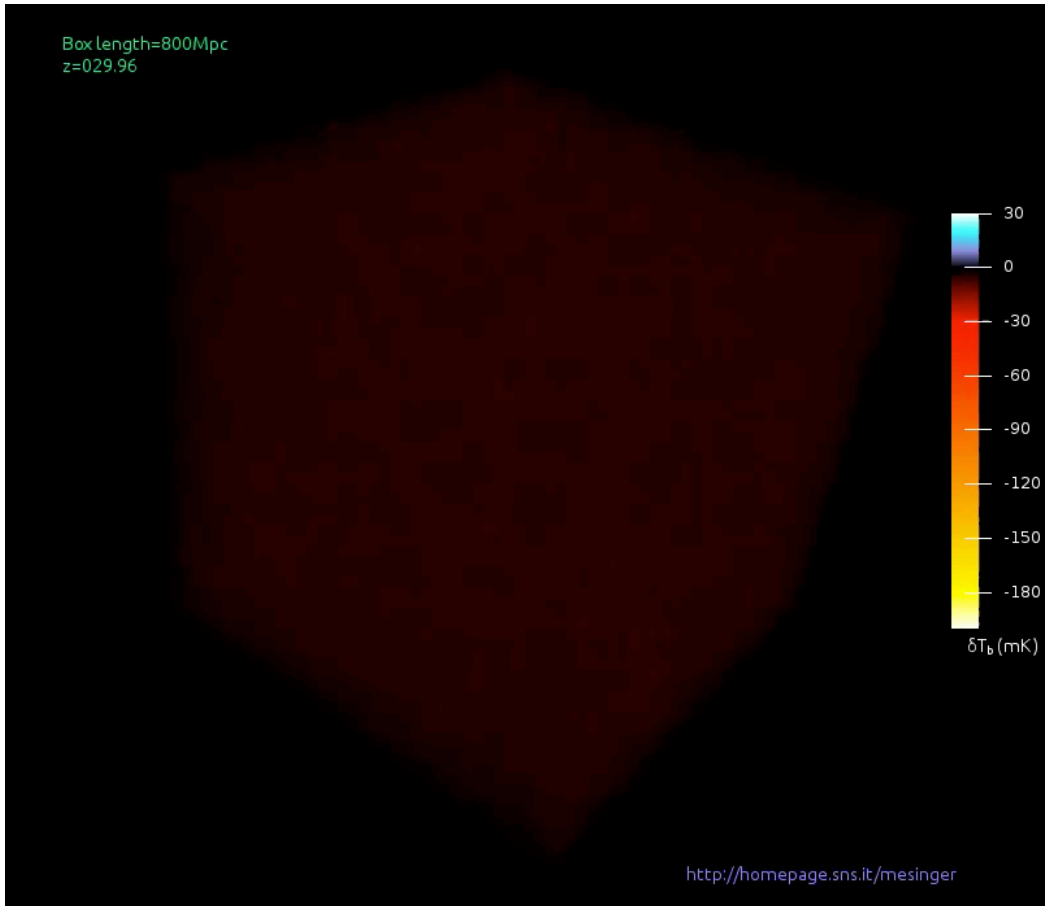
Cosmic Dawn and Reionization: Theory and Simulations



http://*homepage.sns.it/*
mesinger/EOS.html

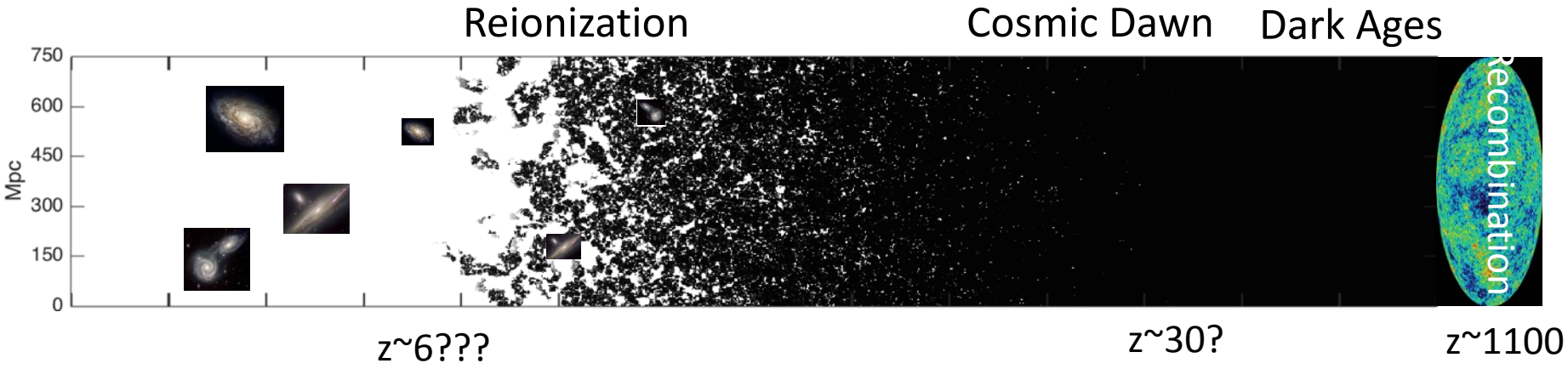
Andrei Mesinger

AiDA

SCUOLA NORMALE SUPERIORE

European Research Council

Why Cosmic Dawn?



Potentially some fundamental questions: ***When*** *did the first generations of galaxies form?* ***What*** *were their properties?* ***How*** *did they interact with each other and the intergalactic medium? What is the structure of the intergalactic medium? What is the thermal and ionization history of the baryons?*

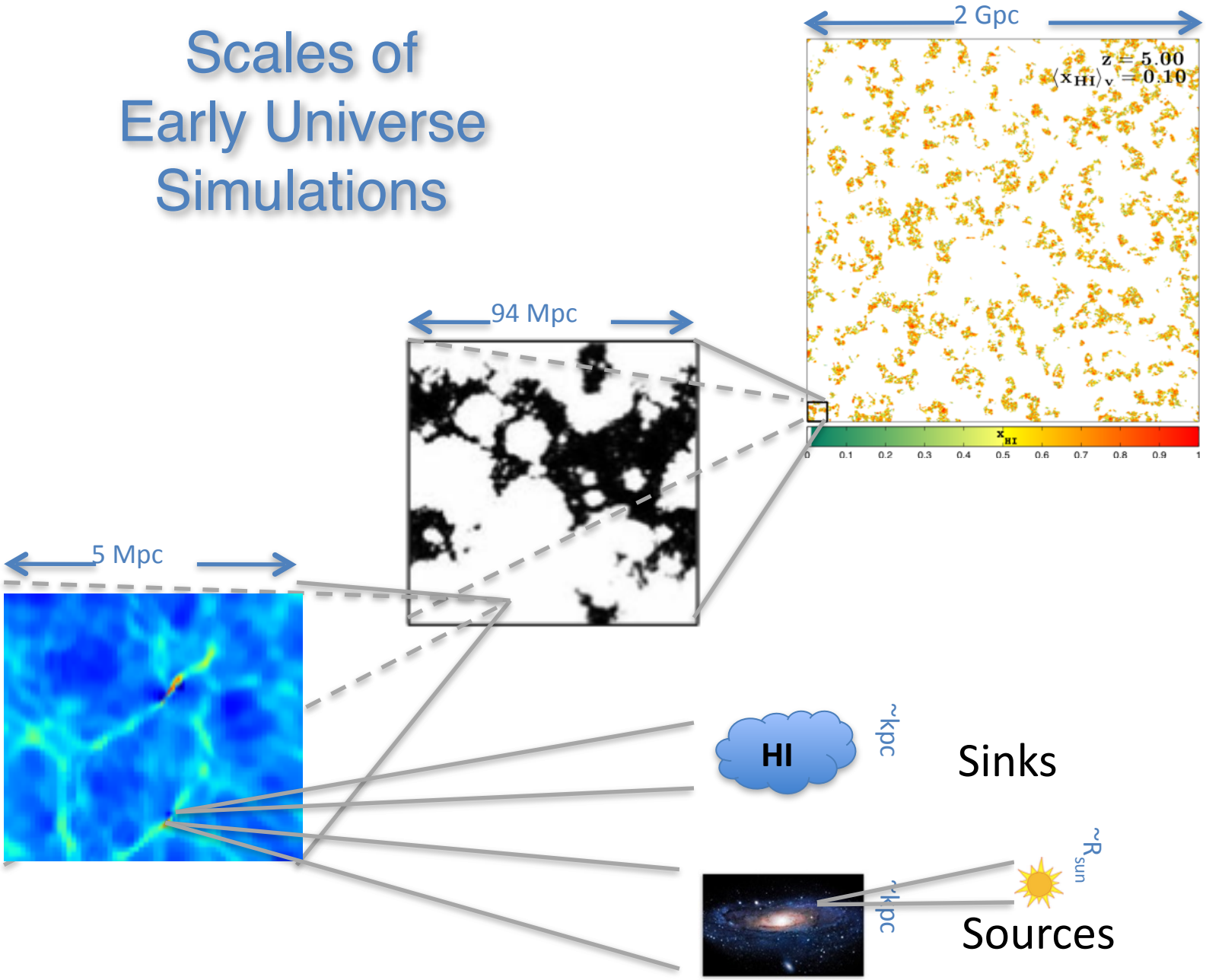
Robust **conclusions require:**

- **accurate models**
- **statistics**
- **exploration of astrophysical parameter space**

Outline

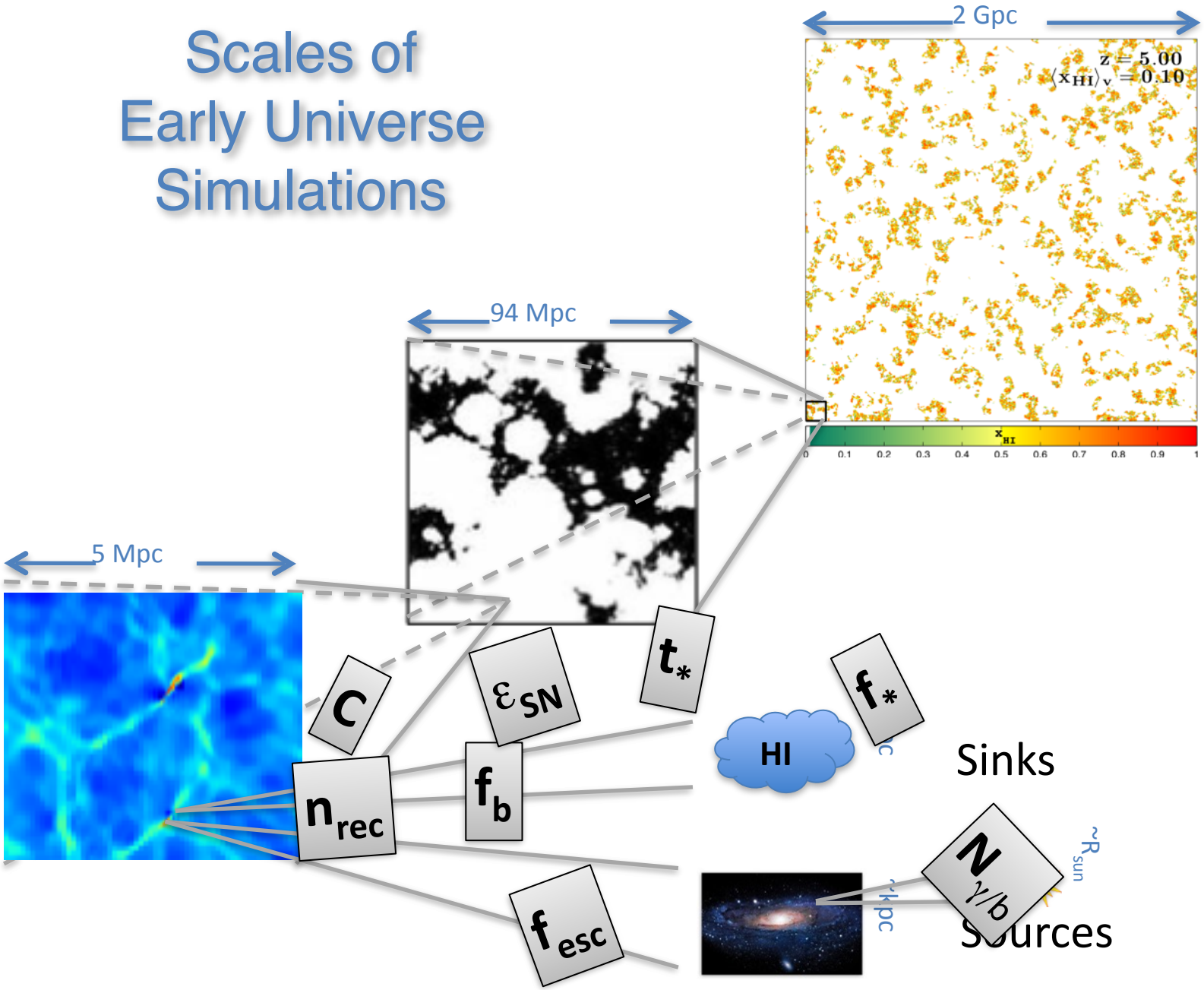
- Challenges for EoR/CD modeling
- Reionization Simulation “toolkit” (hydro-numeric, numeric, semi-numeric, tiered)
- Interpreting EoR/CD observations
  - current state of knowledge
  - the future is bright with 21-cm

Scales of Early Universe Simulations



Astrophysical (known) unknowns

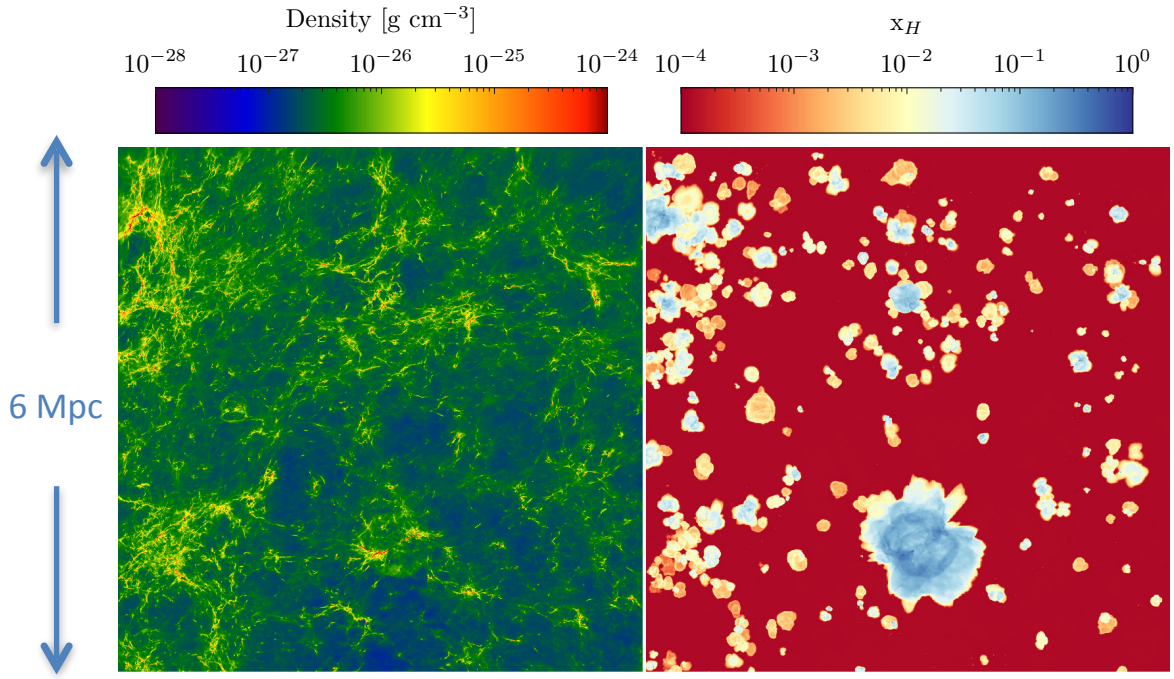
Scales of Early Universe Simulations



Cosmo Sim toolkit: hydrodynamic+RT
small boxes (~1 - 10s Mpc)

Uses:

- "resolve" the very first, molecularly-cooled galaxies. can be used to study resulting radiative feedback, metal pollution, stochastic star-formation…
- resolve recombinations in the IGM (e.g. Rahmati et al. 2014)
- encapsulate relevant processes and use them in larger simulations



e.g. Hu et al. 2016

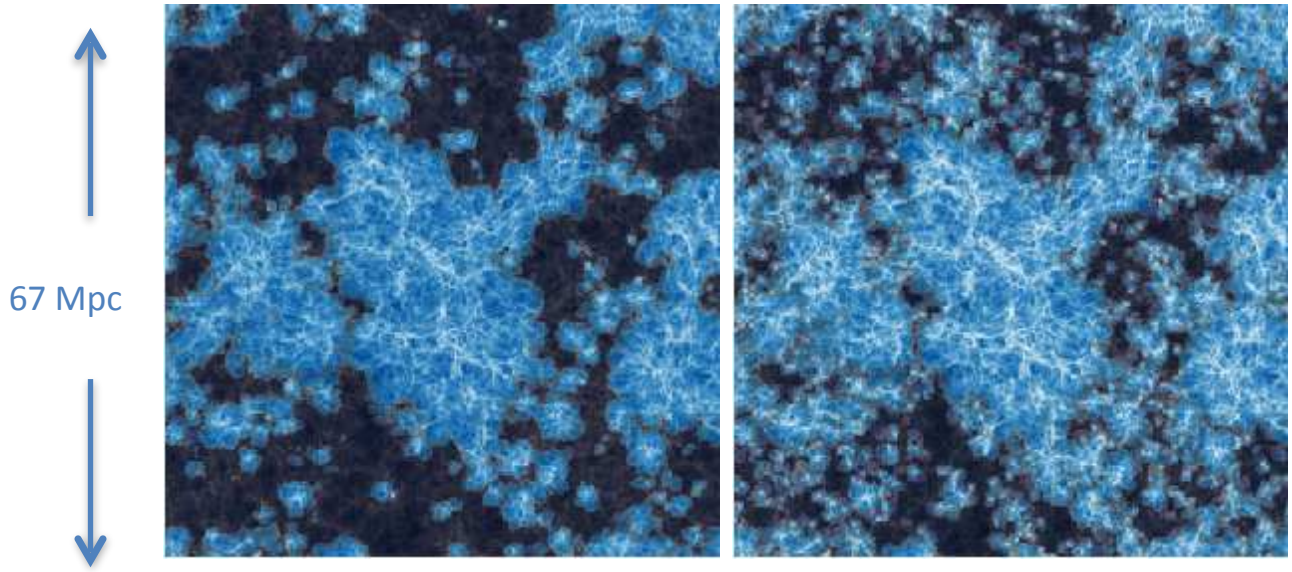
Caution:

- still not resolving sub-structure of stellar environments, turbulence, SNe, etc. —> results still depend on sub-grid prescriptions, with "tuning" done on smaller scales (fewer "knobs")
- box-size modes become non-linear at early times + few halos large enough to be observable —> challenging to compare/calibrate to observations

Cosmo Sim toolkit: N-body+RT
medium - large boxes (~10s - 100Mpc)

Uses:

- "resolve" the DM halos hosting the bulk of the reionizing galaxies (atomically-cooled)
- capture medium-large scale distributions of the DM halos, and the resulting ionization fields



e.g. Dixon+ 2016

Caution:

- missing hydro affects accuracy on small-scales
- galaxy properties (e.g. SFR and ionizing luminosity) must be assigned to DM halos —> not predictive

Cosmo Sim toolkit: semi-numeric simulations

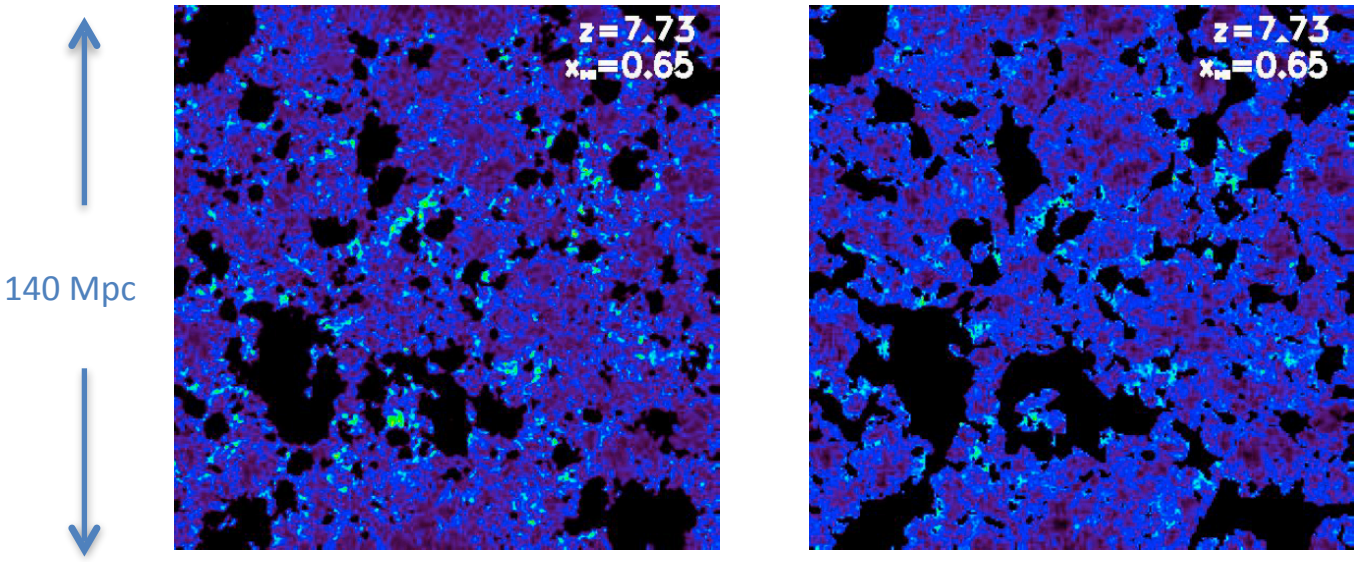
large - ultra large boxes (~100s - 1Gpc)

Uses:

- quickly explore the large astrophysical parameter space
- easily create mock data-sets for large FoV cosmological observations (e.g. 21-cm)

hydro+DM+RT

21cmFAST



~ 1 week on 1536 cores

~ few min on 1 core

e.g. Mesinger+2011 (also Zahn+2007; Furlanetto&AM2007; Santos+2011)

Caution:

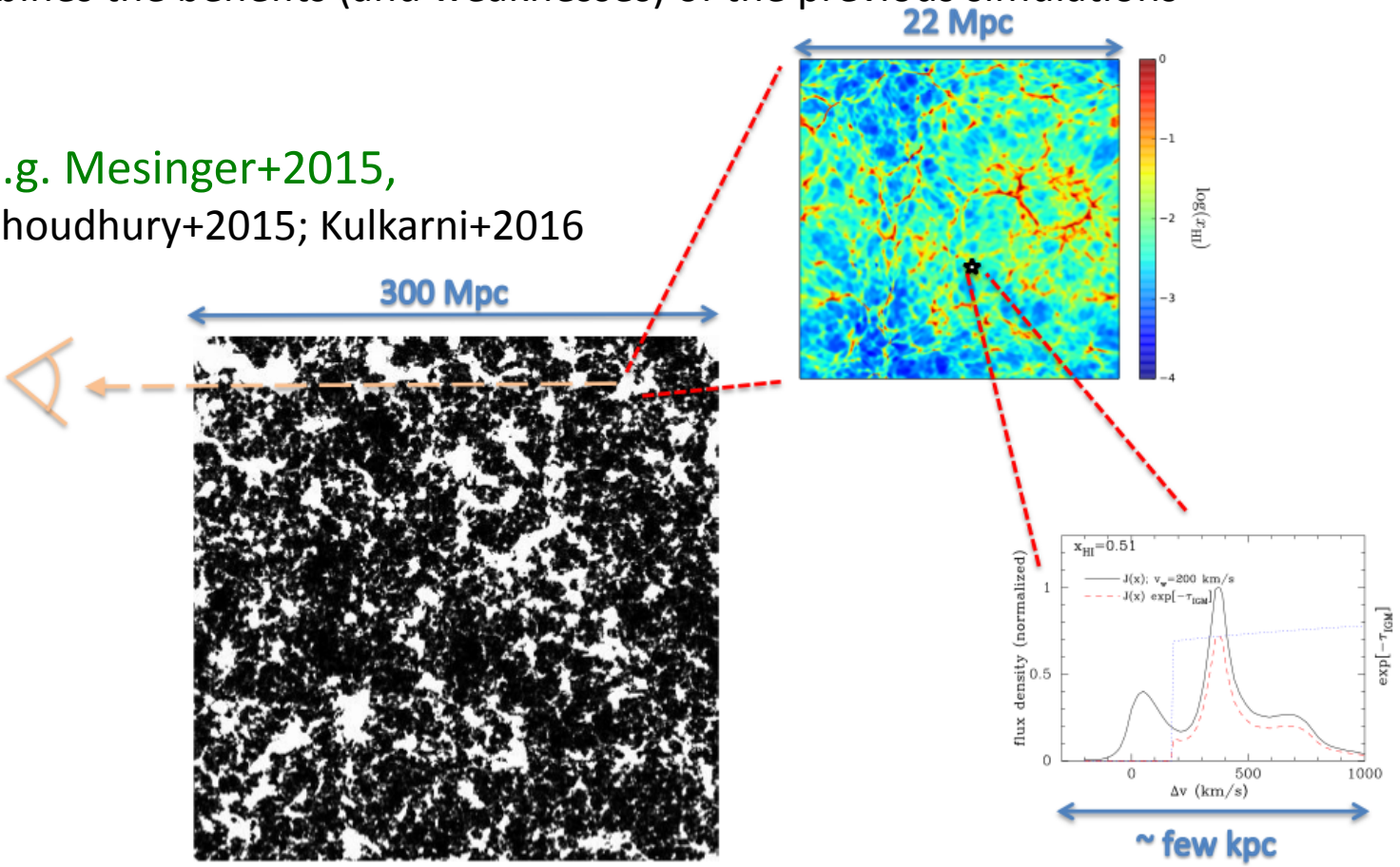
- RT treatment is simplistic —> fails on small scales (~1Mpc)
- inputed galaxy properties are parametric —> direct physical insight on star formation/ feedback physics needs to be done posteriori w. analytic models or small hydro sims

Cosmo Sim toolkit: “tiered” simulations

Uses:

- combines the benefits (and weaknesses) of the previous simulations

e.g. Mesinger+2015,
Choudhury+2015; Kulkarni+2016



Multi-scale approach

Caution:

- requires care when combining small into big… difficult to just add the missing modes
- is mostly done “post-processing” —> small-scales have limited impact on the large-scales

***Moral*:**

Think about the question you wish to answer, and then pick the most appropriate tool(s)

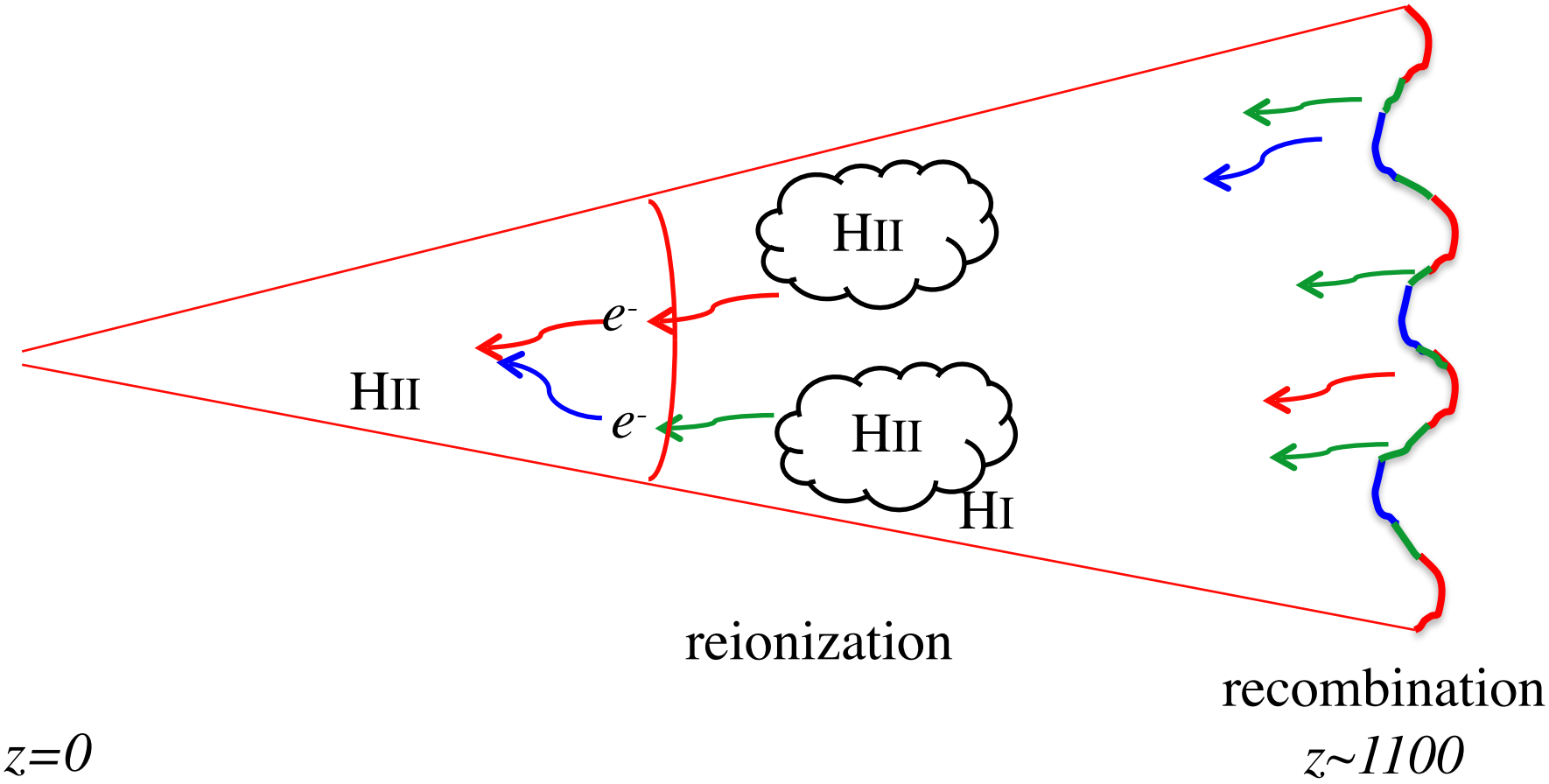
(there is no "one size fits all" EoR simulation)

Interpreting Observations

- What we know now…
  - Clues to the timing of reionization from galaxies, QSOs and the CMB

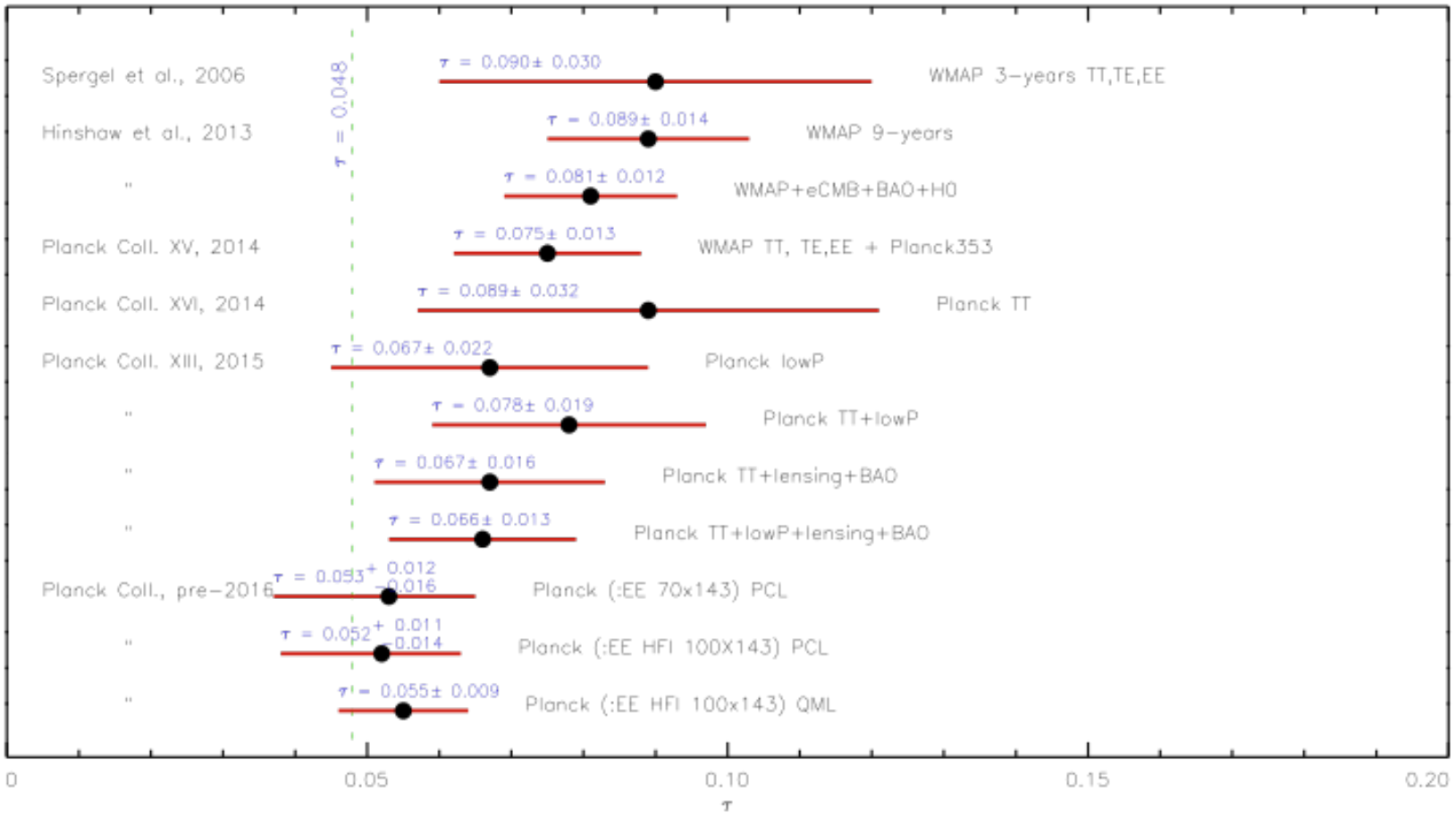
When?

- Two main classes of probes
  1. **Integral CMB constraints (e.g. τ_e, kinetic SZ)**



History of Thompson scattering optical depth measurements

WMAP1 2003



Planck 2016

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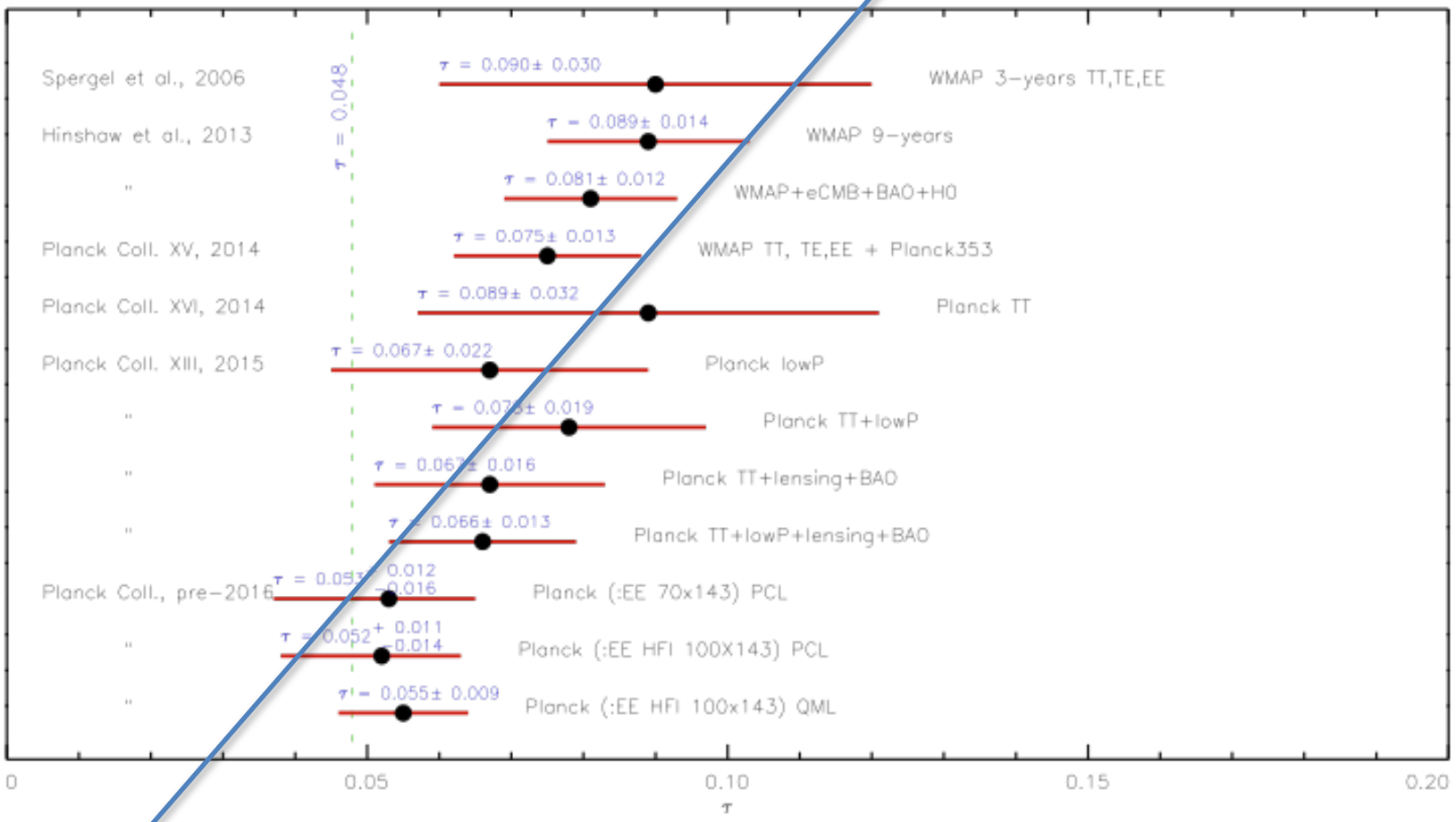

Planck 2016

~2020 – negative tau: Reionization never happened!

History of Thompson scattering optical depth measurements

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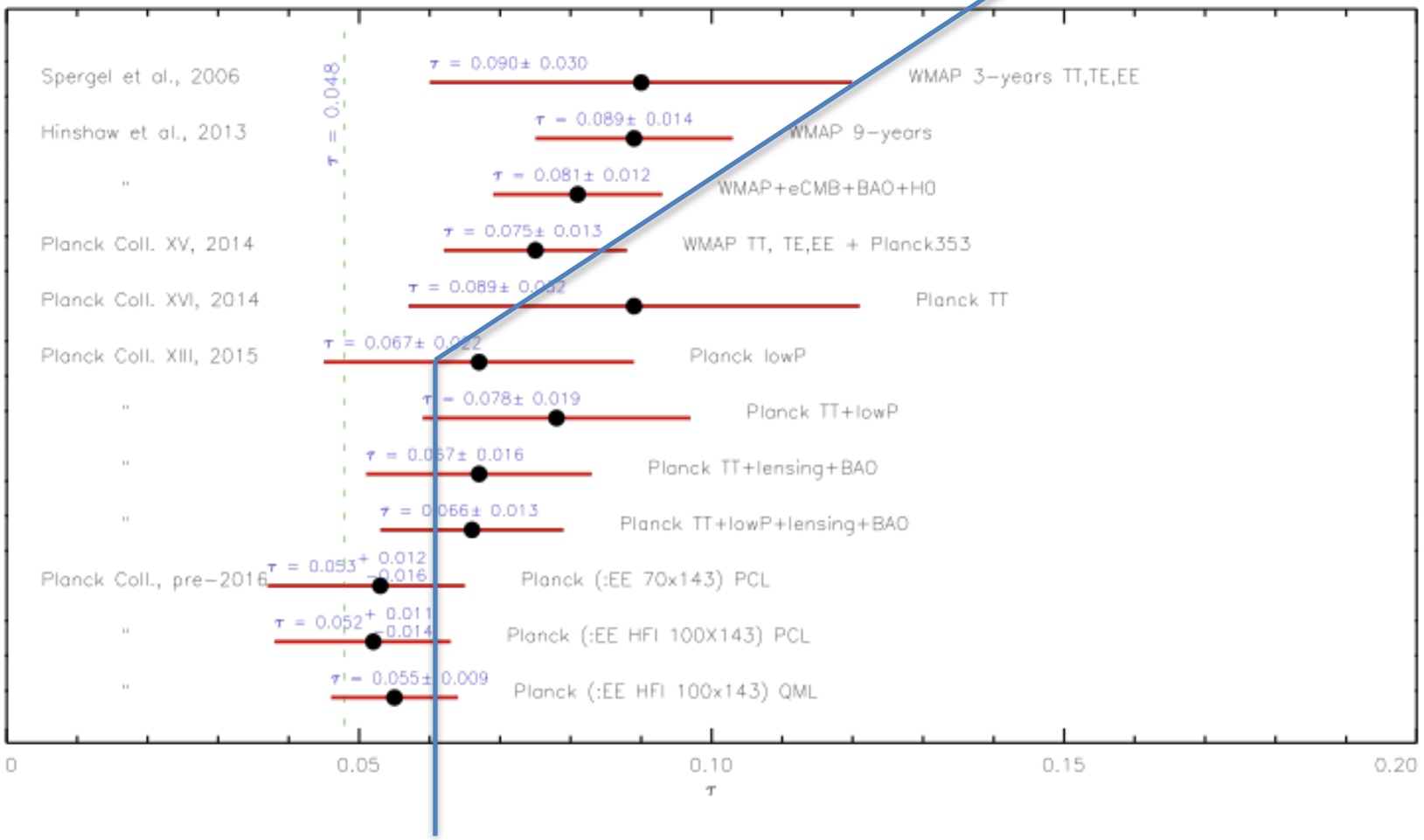
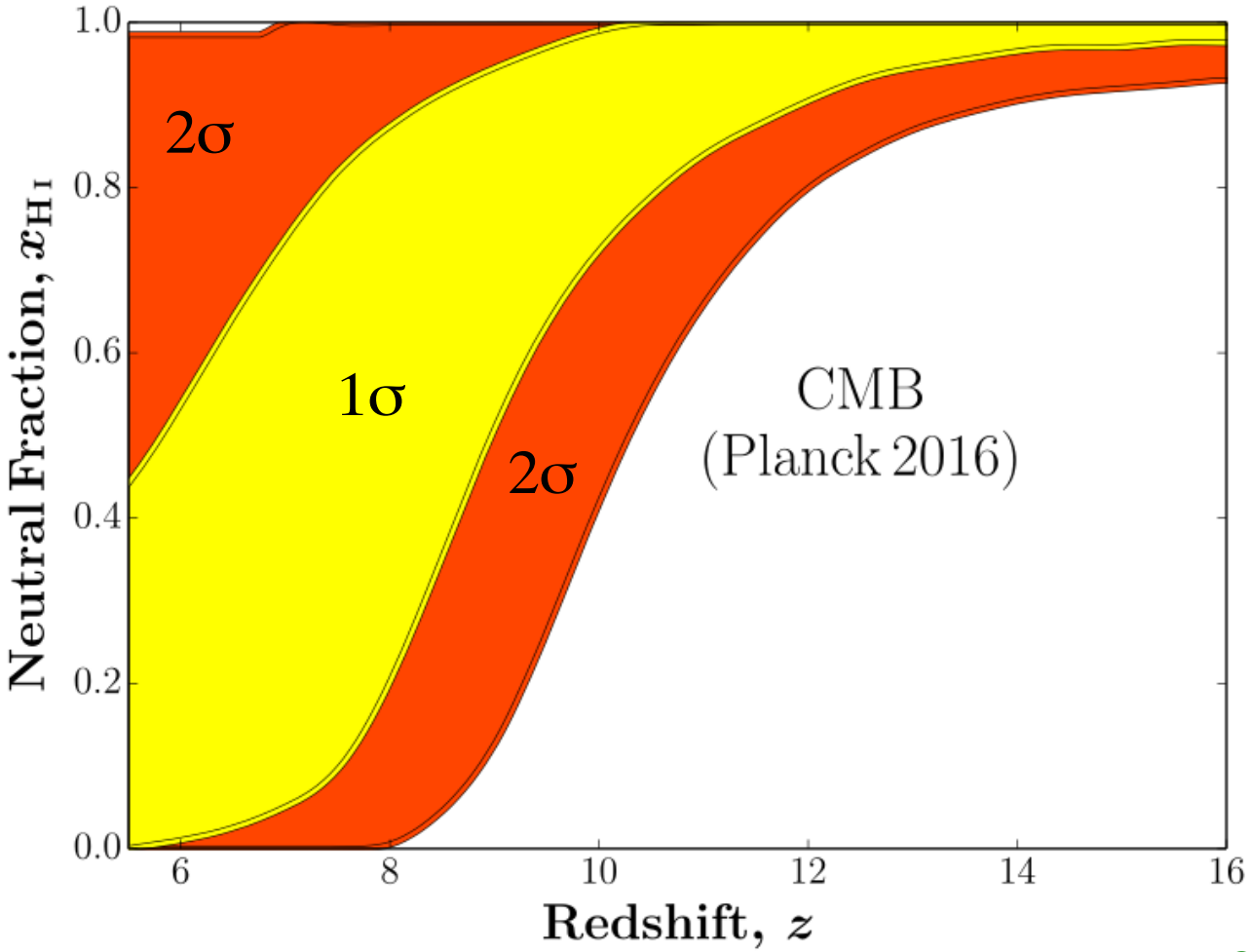


Planck 2016

What does this tell us about *when* reionization occurred?



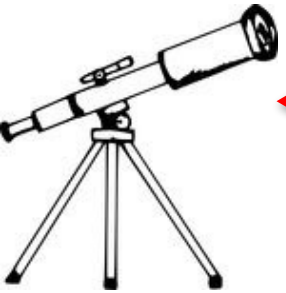
Greig & AM 2017

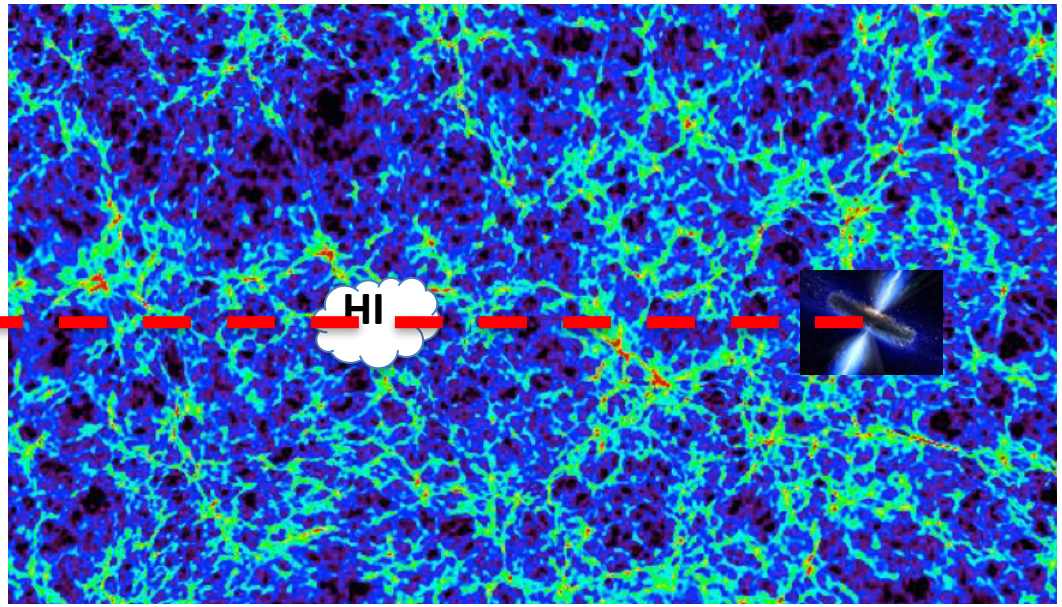
When?

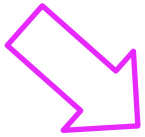
- Two main classes of probes
  1. Integral CMB constraints (e.g. τ_e, kinetic SZ)
  2. **Astrophysical 'flashlights' (e.g. high-z galaxies, QSOs)**

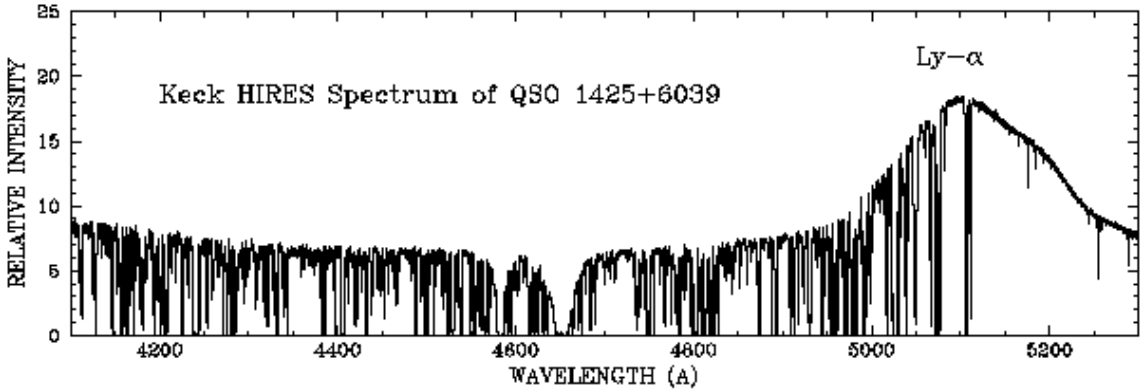
Astrophysical flashlights: Lyα

Post-reionization IGM

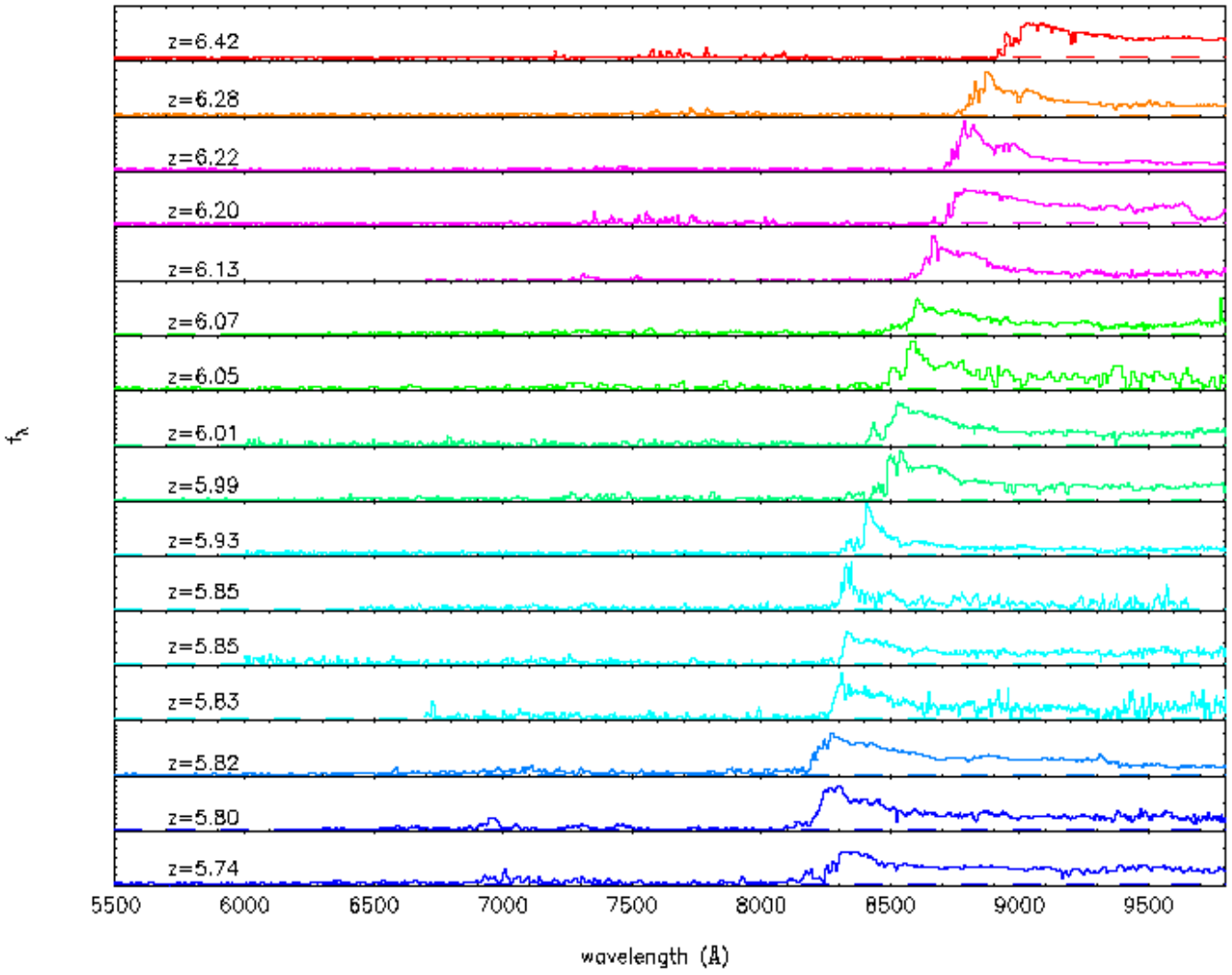








We can't directly observe the EoR in Lyα

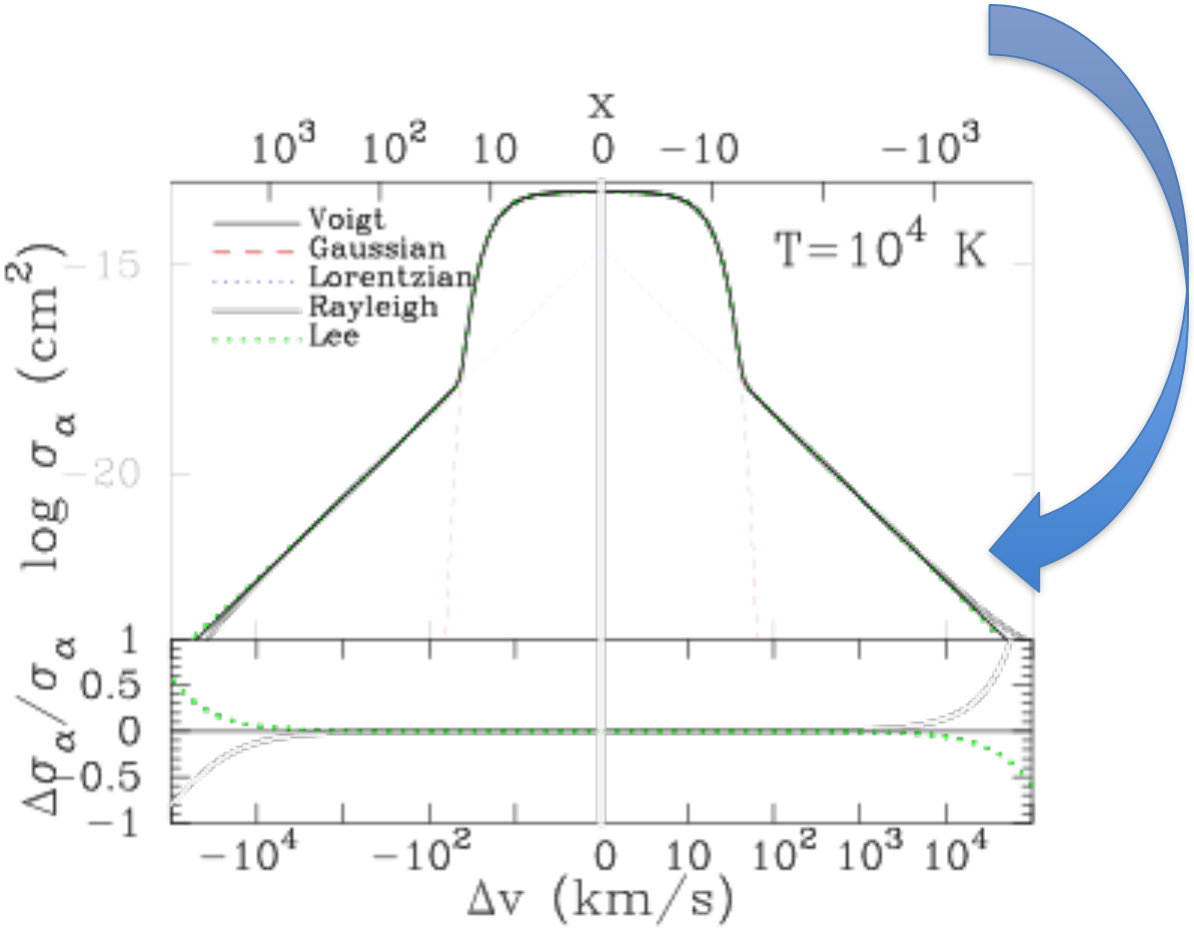


Fan+ (2006)

Lyα forest saturates at z>5, when the Universe becomes too dense.

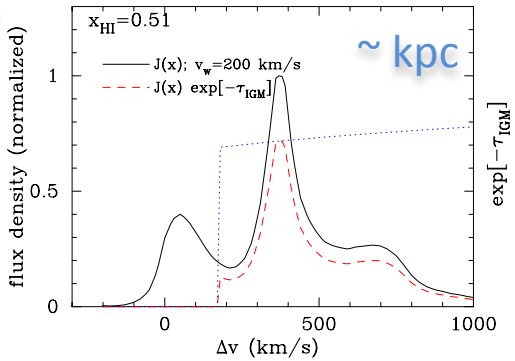
Even trace amounts of HI, x_{HI} ~> 10^{-5} result in no flux being detected in the forest.

But… *damping wing*!



Dijkstra 2014

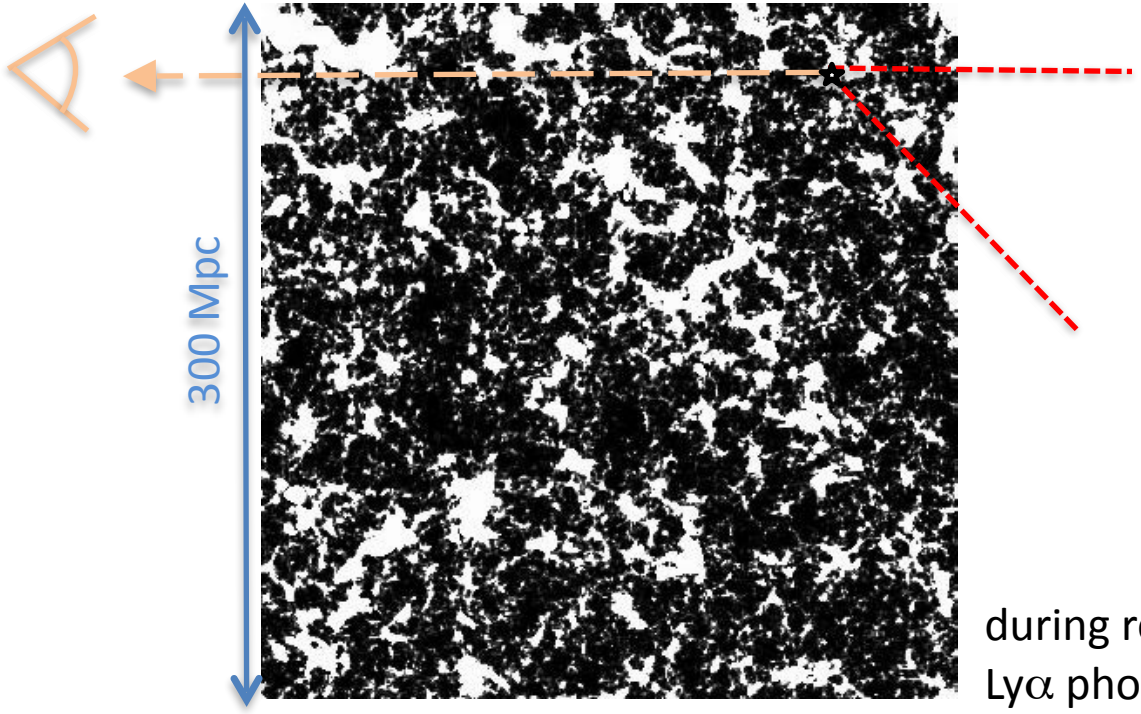
Lyα damping wing absorption as a probe of the EoR

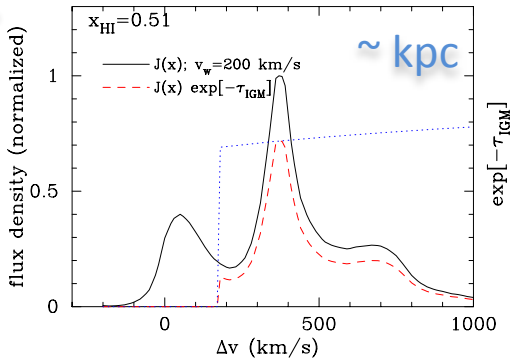


e.g. Dijkstra, AM+2011

Lyman alpha line emerging from galaxies is shaped by the ISM/CGM (winds, infall, dust, geometry..)

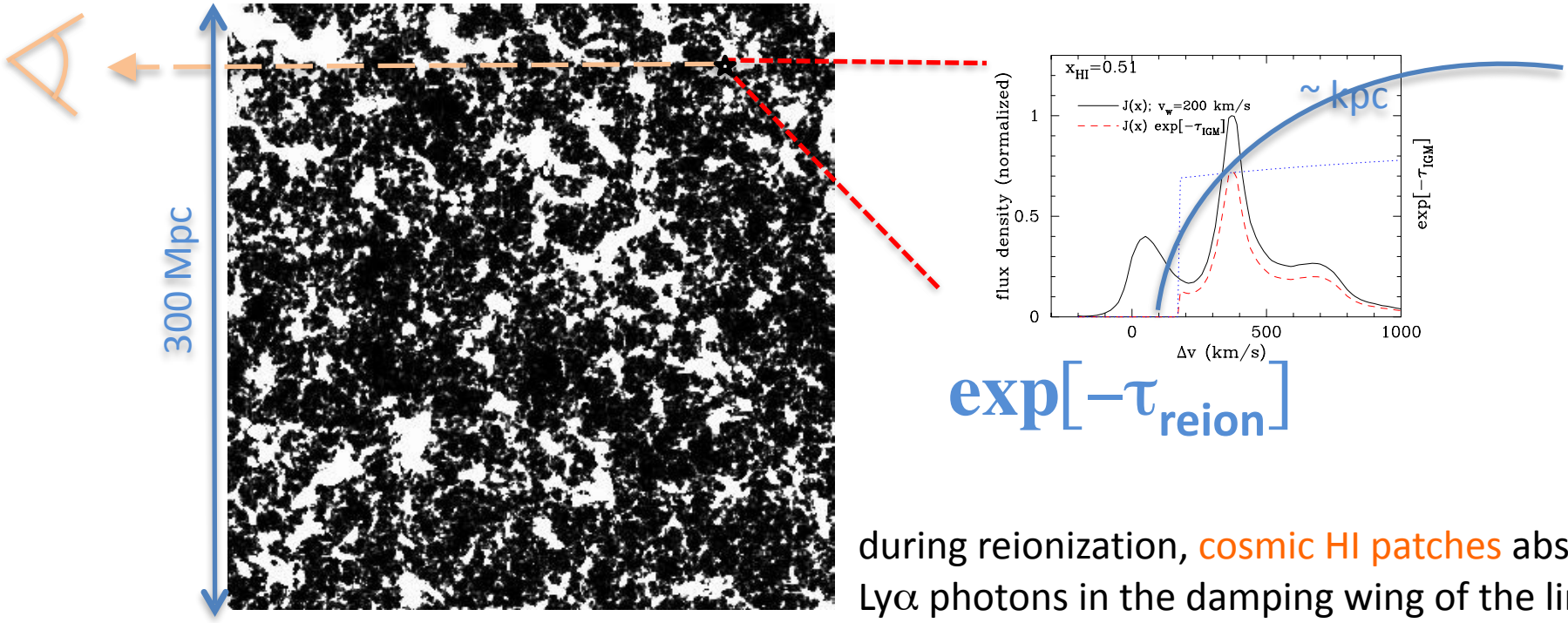
Lyα damping wing absorption as a probe of the EoR





during reionization, cosmic HI patches absorb Lyα photons in the damping wing of the line

Lyα damping wing absorption as a probe of the EoR



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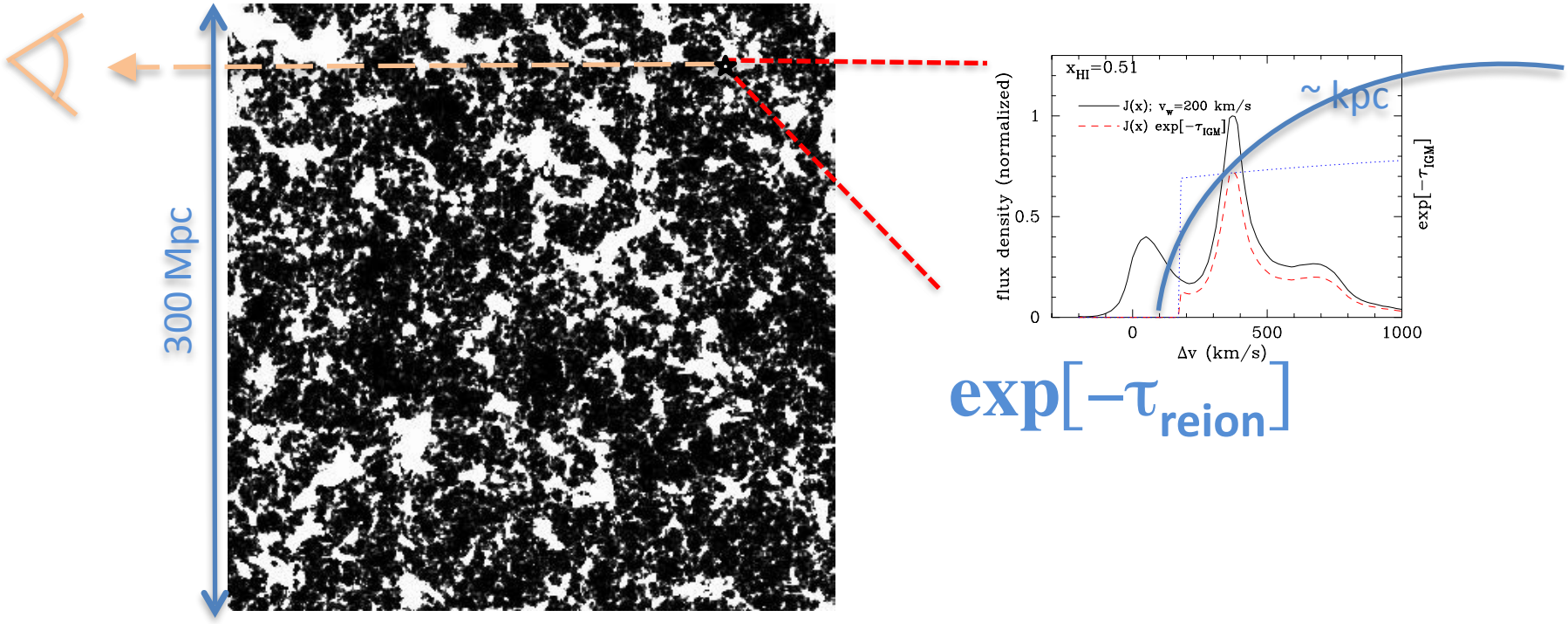
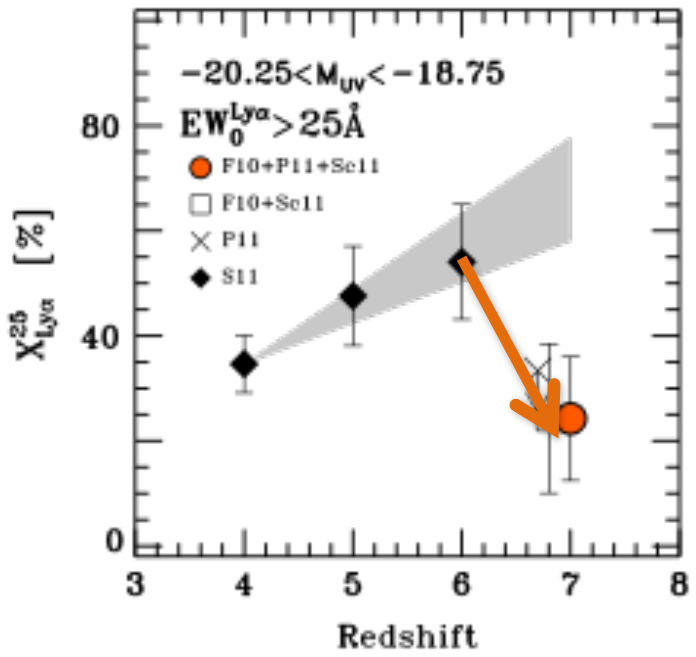
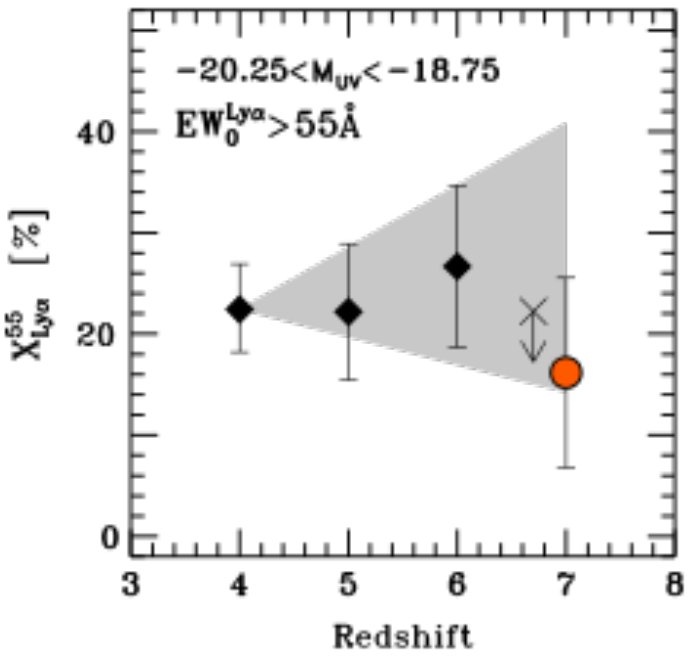


The Lyα damping wing impacts:

1. **the observability of Lyman alpha emission**
2. **the observed clustering of Lyα emitting galaxies**
3. **the Lyα emission profile of high-z QSOs**

Strong drop in the number of Lya emitting galaxies beyond z~>6





Drop in the fraction of UV faint galaxies with REW>25 A from z=6→7

Ono+2012 (see also, e.g. Stark+2010; Pentericci+2011; Caruana+2013; Schenker+2014…)

What does this mean?

- Evolution in the IGM neutral fraction from an incomplete reionization (e.g. Dijkstra, AM+2011)
- Evolution in the ionizing background:
  - the abundance of self-shielded systems, (e.g. Bolton & Haehnelt 2011)
  - flattening out the galaxy's surface brightness due to increased Lyα scattering (Sadoun+2016)
- Evolution in galaxy properties (e.g. Jones+2012; Dayal & Ferrara 2012; Finkelstein+2012)
- Co-evolution (e.g. Dijkstra+2014)

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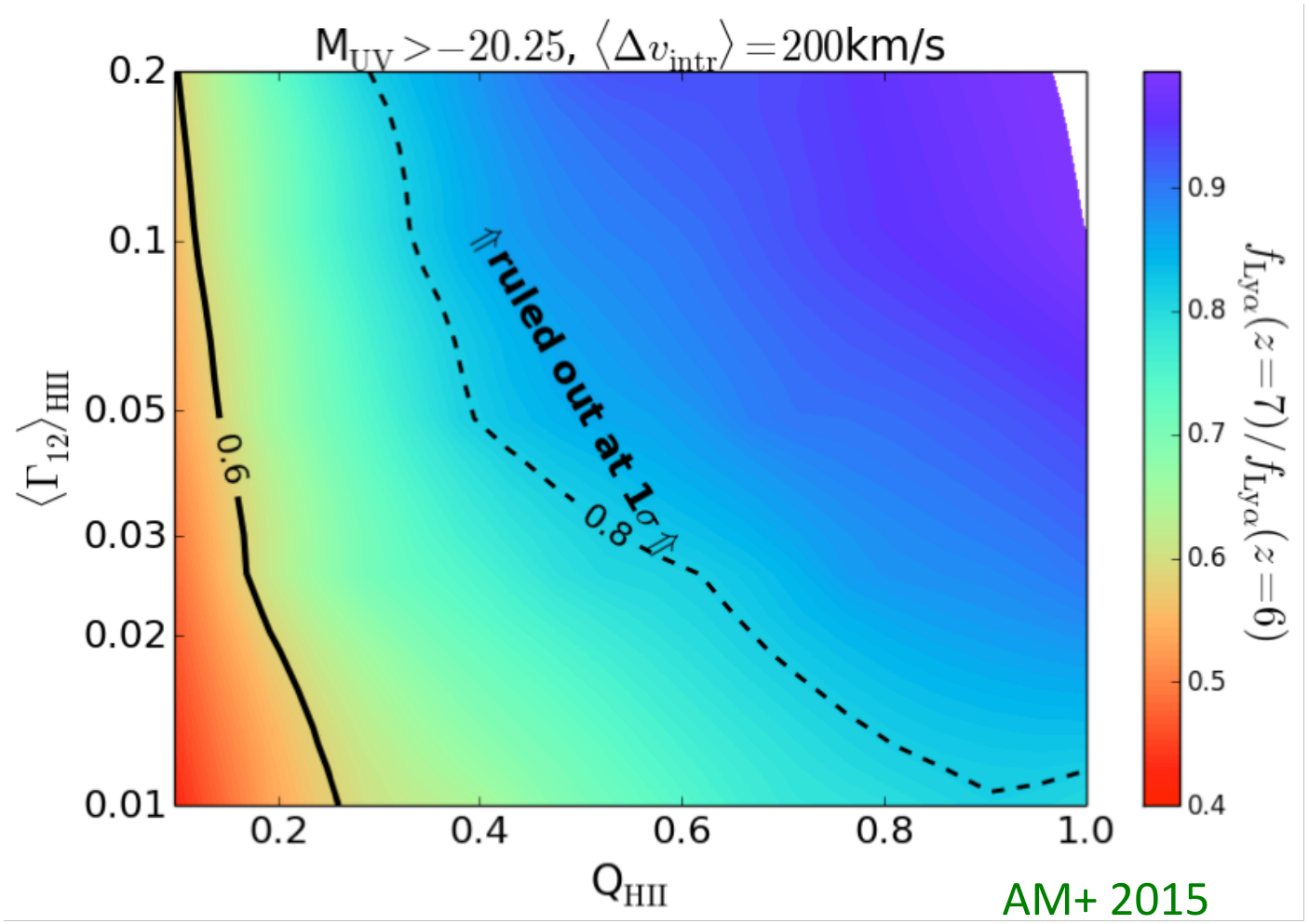
- *Extreme evolution required to fit the data.*
- *Degeneracies are difficult to quantify…*

z=7/z=6 Lyα fractions

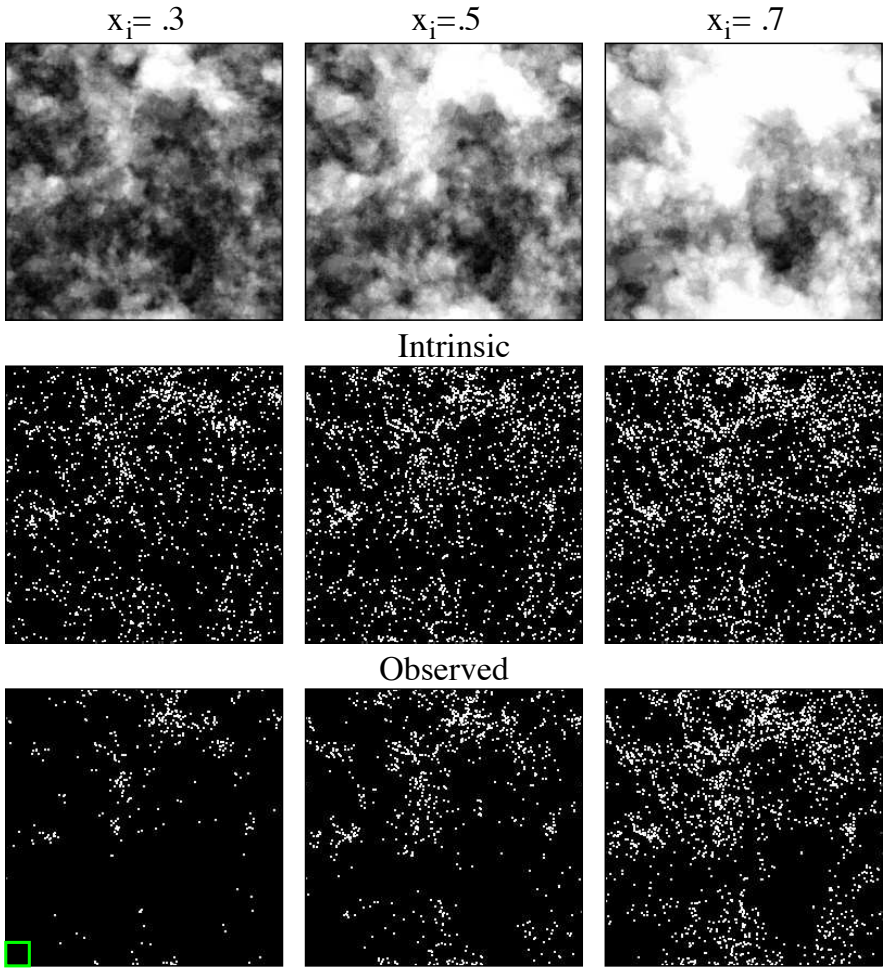


AM+ 2015

(see also Choudhury+2015)

- Marginalizing over Γ, we get $\langle x_{HI} \rangle > 0.4$ (68% C.L.)
- Recent work by **Mason+2017** *using the full Lya flux distribution*, obtains even stronger constraints $\langle x_{HI} \rangle = 0.59^{+0.11}_{-0.15}$ (68% C.L.)

LAE clustering as a signature of reionization



McQuinn+2007

- 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)

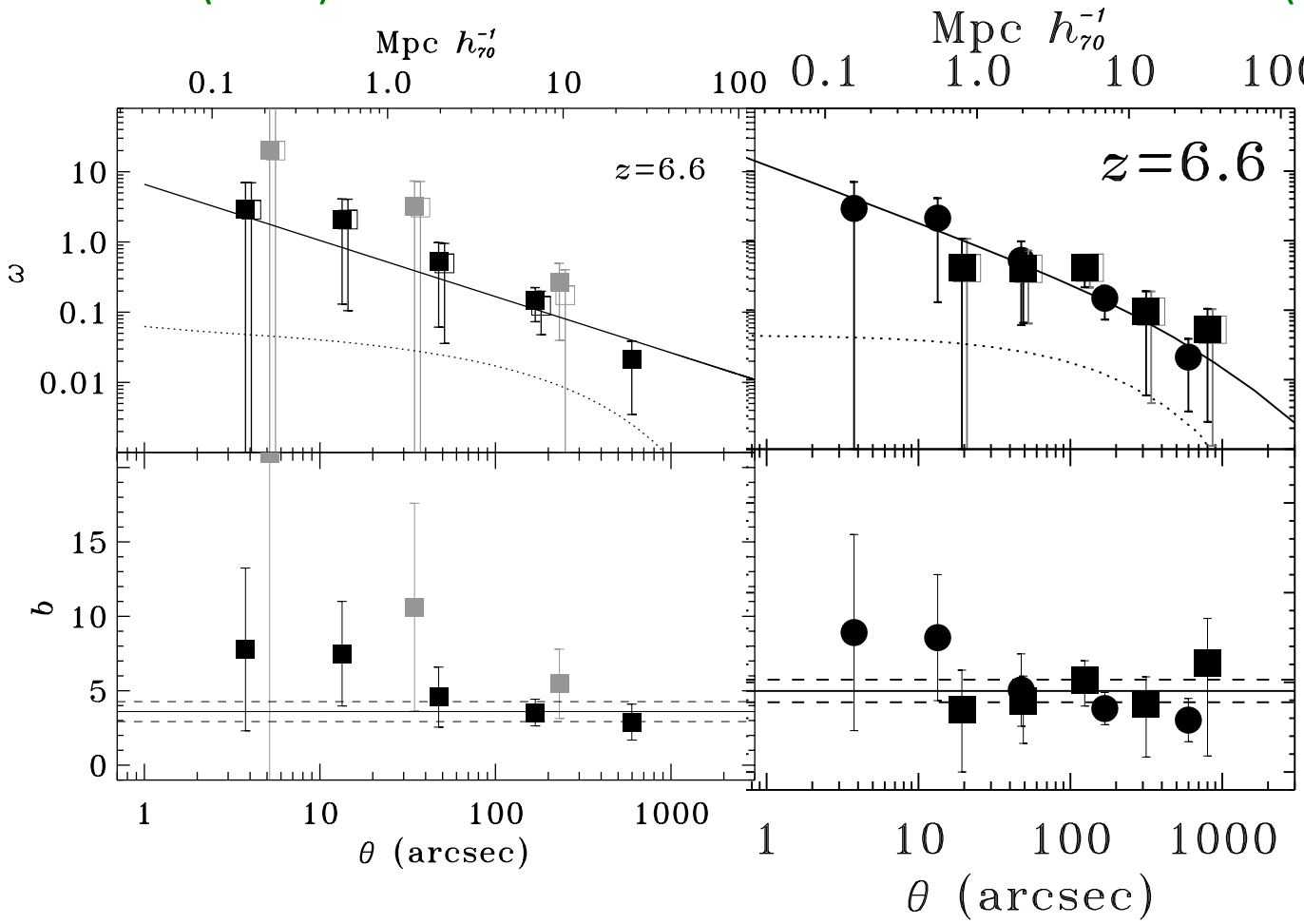
LAE clustering is a **more robust** probe than evolution in number density

- 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

z=6.6 LAE Clustering with SUBARU

Ouchi+ (2010)

Ouchi+ (2017)

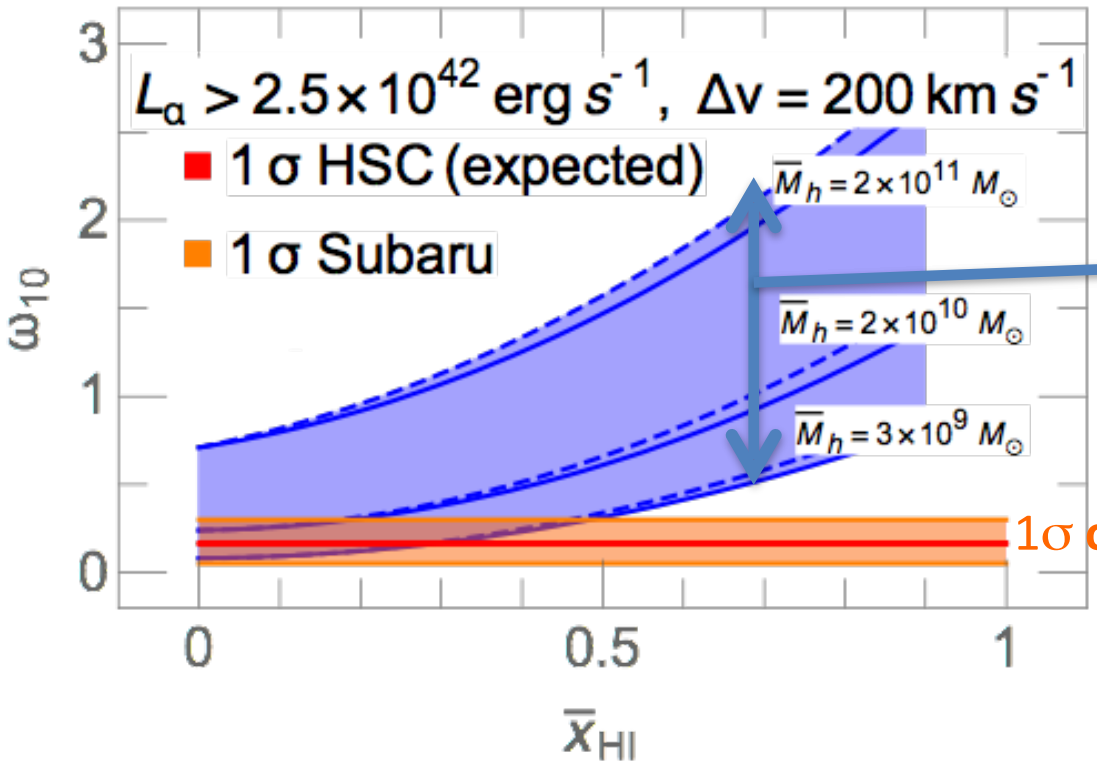


black squares:
L > 2.5 x 10^{42} erg/s

black squares:
L > 7.9 x 10^{42} erg/s

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)

Subaru current and upcoming constraints on LAE clustering

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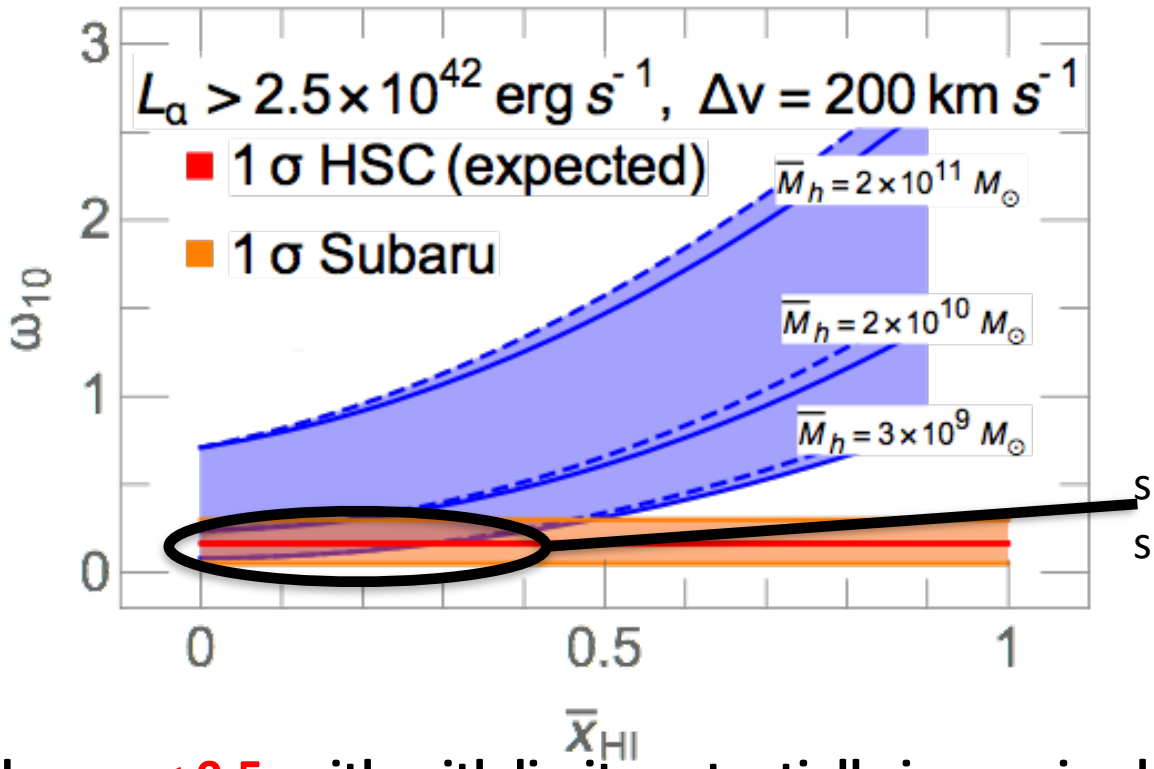
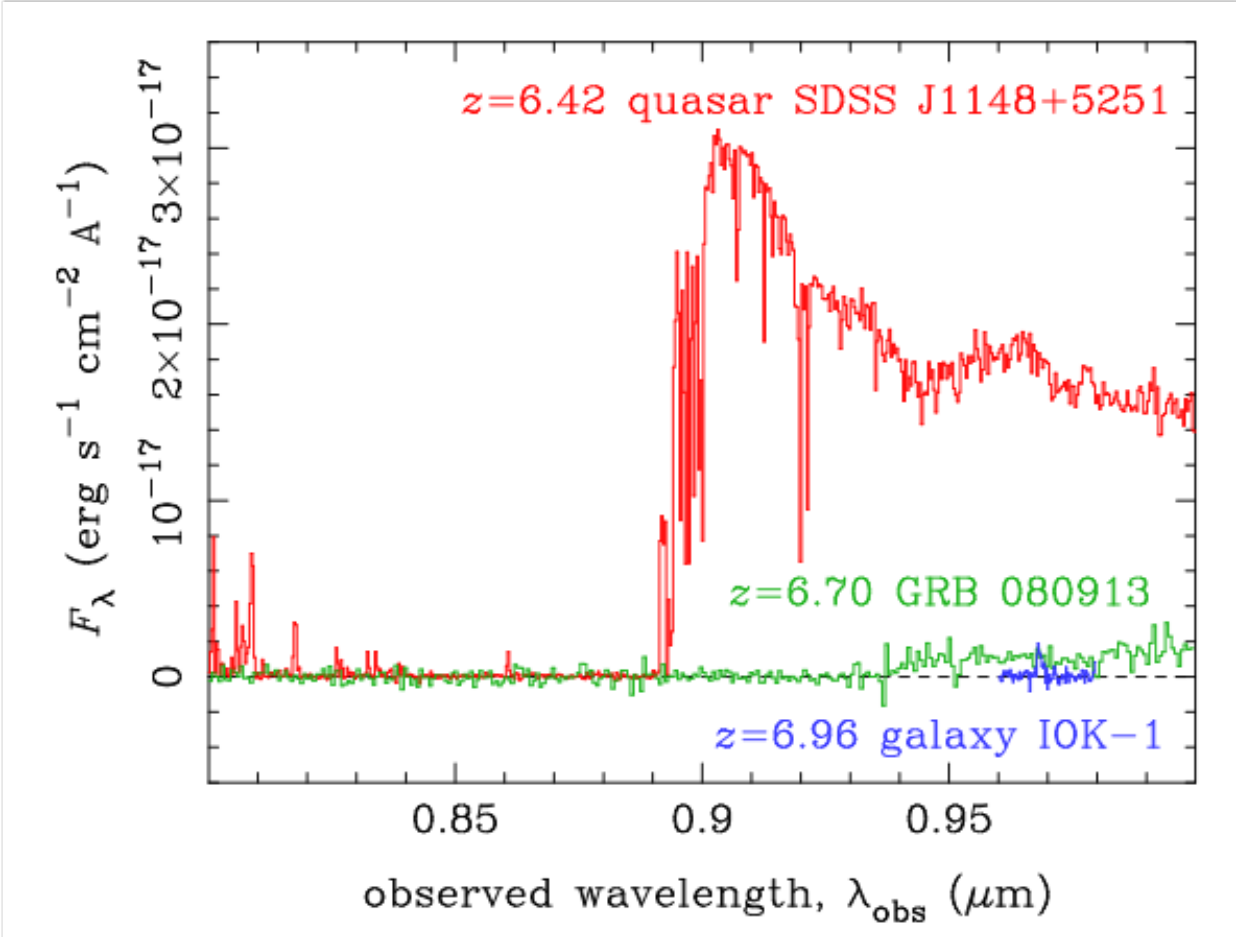


small allowed parameter space

1. **already $x_{HI,z7} < 0.5$, with with limits potentially improving by ~ 50% with HSC.**
2. signal is not sensitive to EoR morphology. need spectroscopy…
3. observed LAEs are hosted by much smaller DM halos than LBGs, $M<10^{10}M_{sun}$

QSOs: the brightest cosmic flashlights

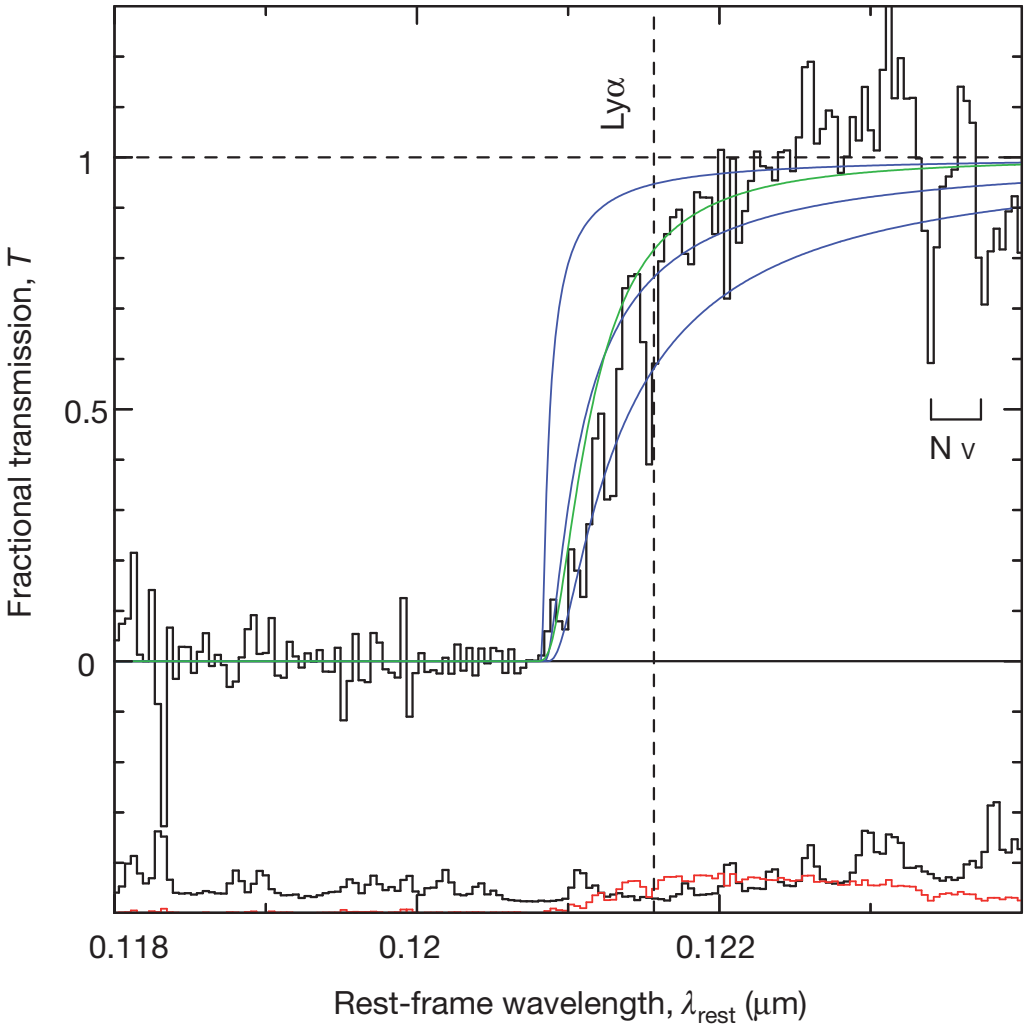
$f = A\, e^{-\tau}$



QSO spectra can be analyzed ***individually***, unlike galaxies which require a statistically significant sample

figure courtesy of D. Mortlock

z=7.1 QSO shows evidence of an EoR damping wing?

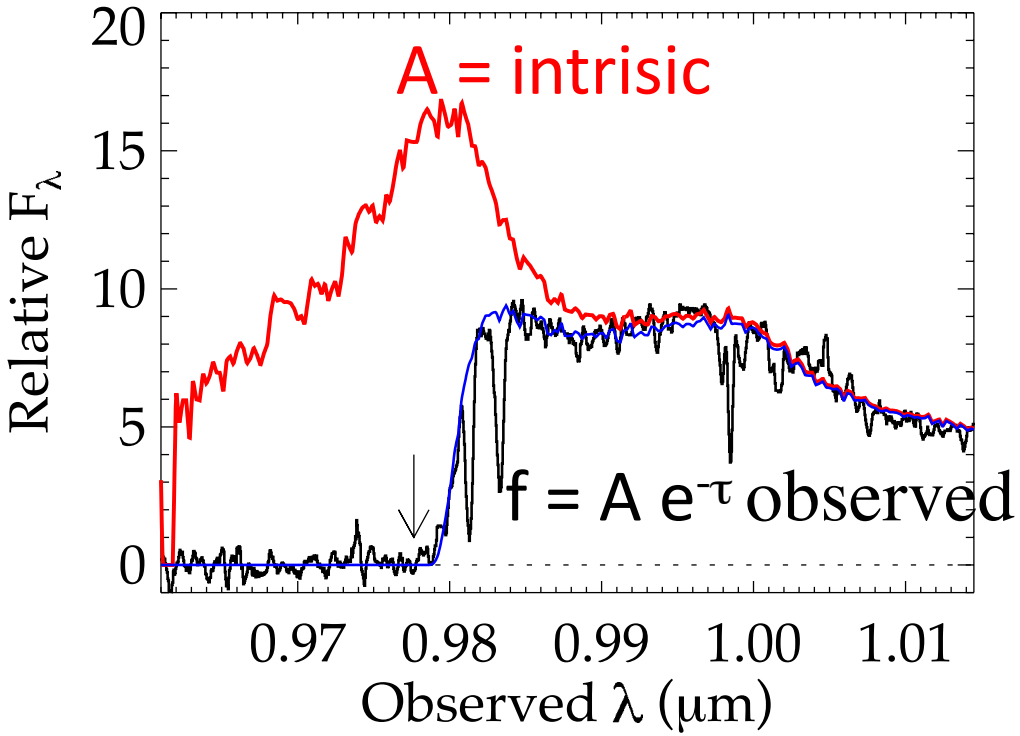


Mortlock+ (2011)

Damping wing in QSO spectra

- *Caution:* We must *jointly* sample the uncertainties in the **intrinsic (pre IGM absorption) QSO emission** together with the **sightline to sightline scatter of the EoR**

z=7.1 spectra



Simcoe+2012

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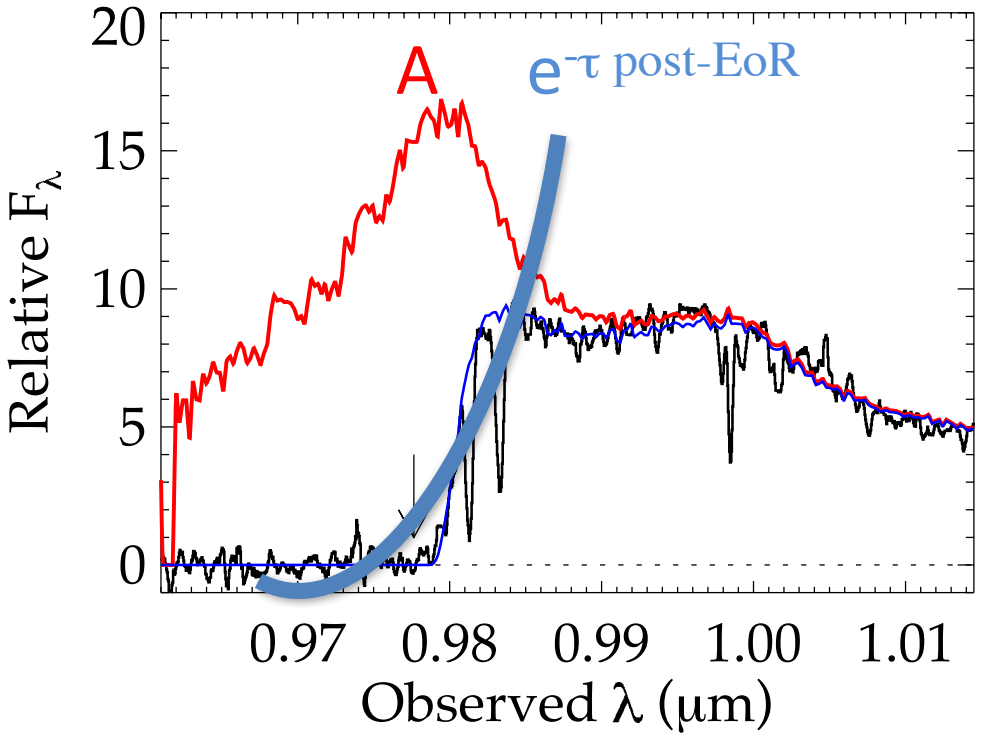

z=7.1 spectra

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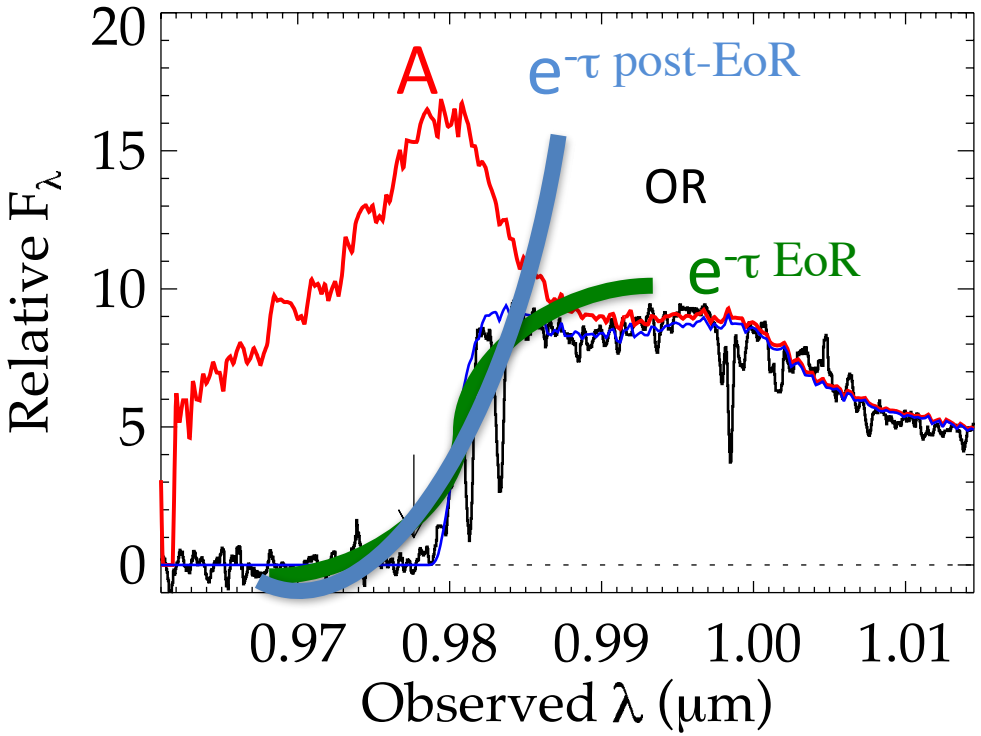
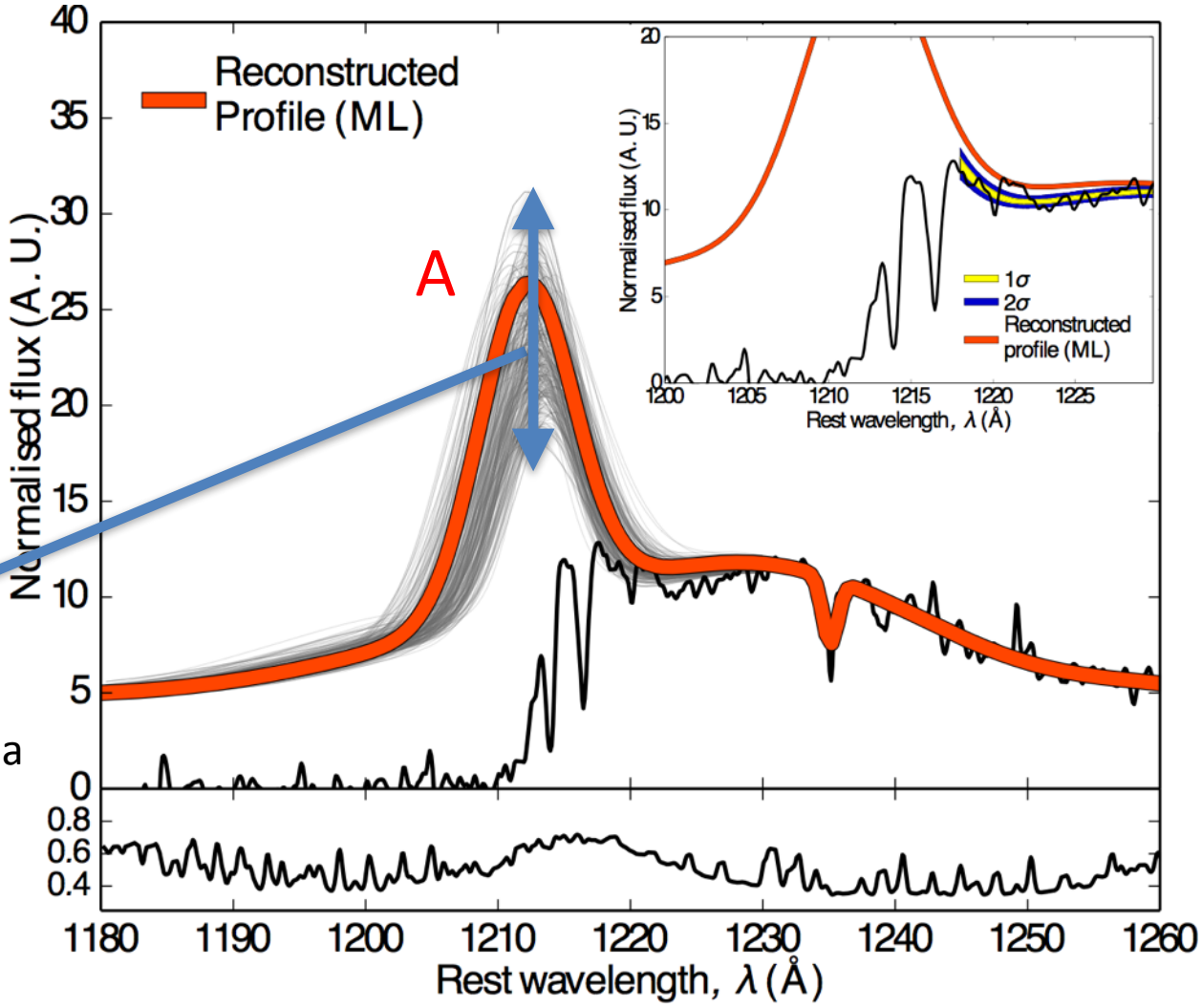


z=7.1 spectra

Simcoe+2012

Analysis of z=7.1 QSO ULASJ1120

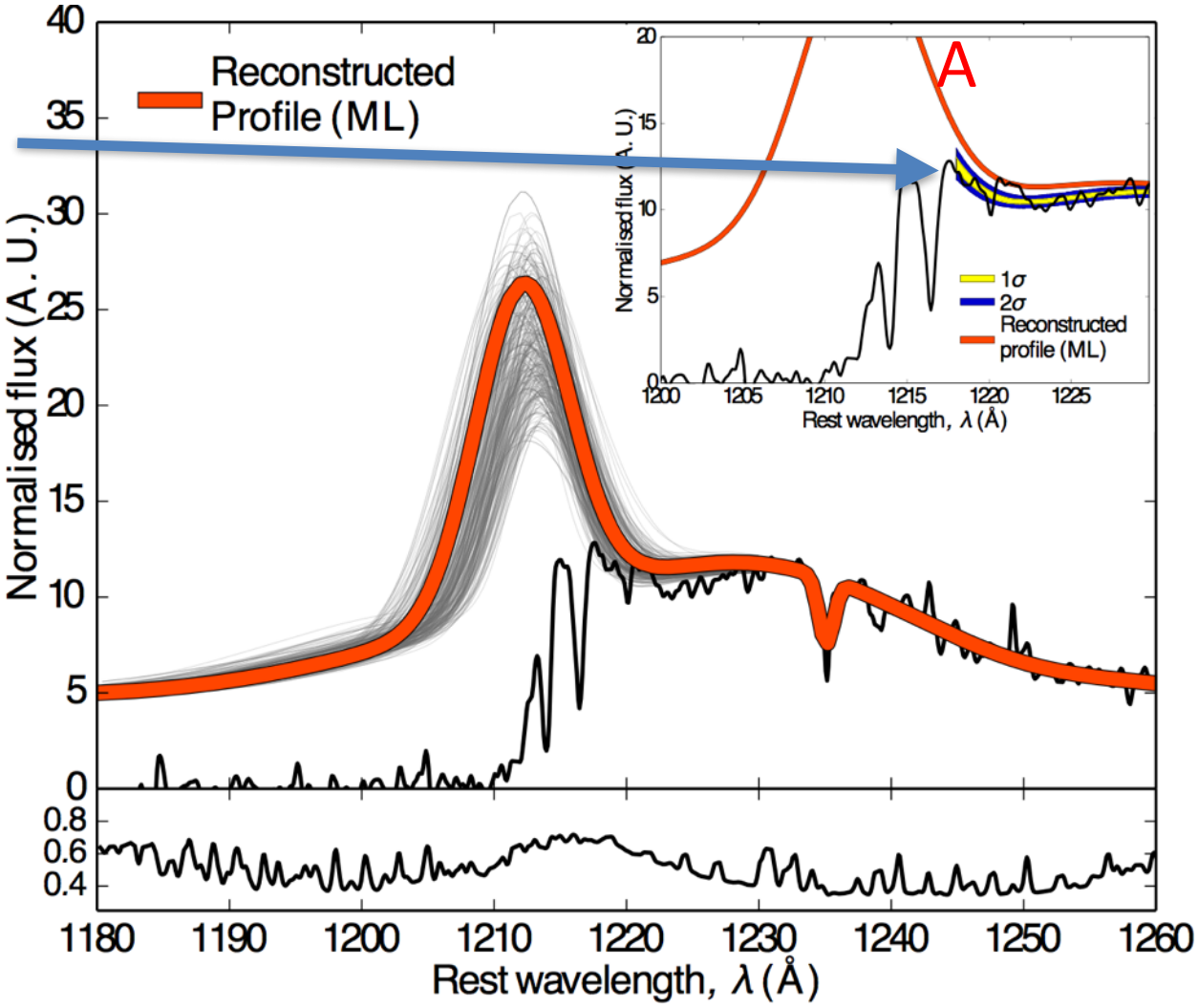


Posterior samples of **intrinsic Lya profiles** constructed from a database of ~2000 moderate redshift QSOs

Greig, AM+ 2017

Analysis of z=7.1 QSO ULASJ1120

$A\ e^{-\tau}$



Greig, AM+ 2017

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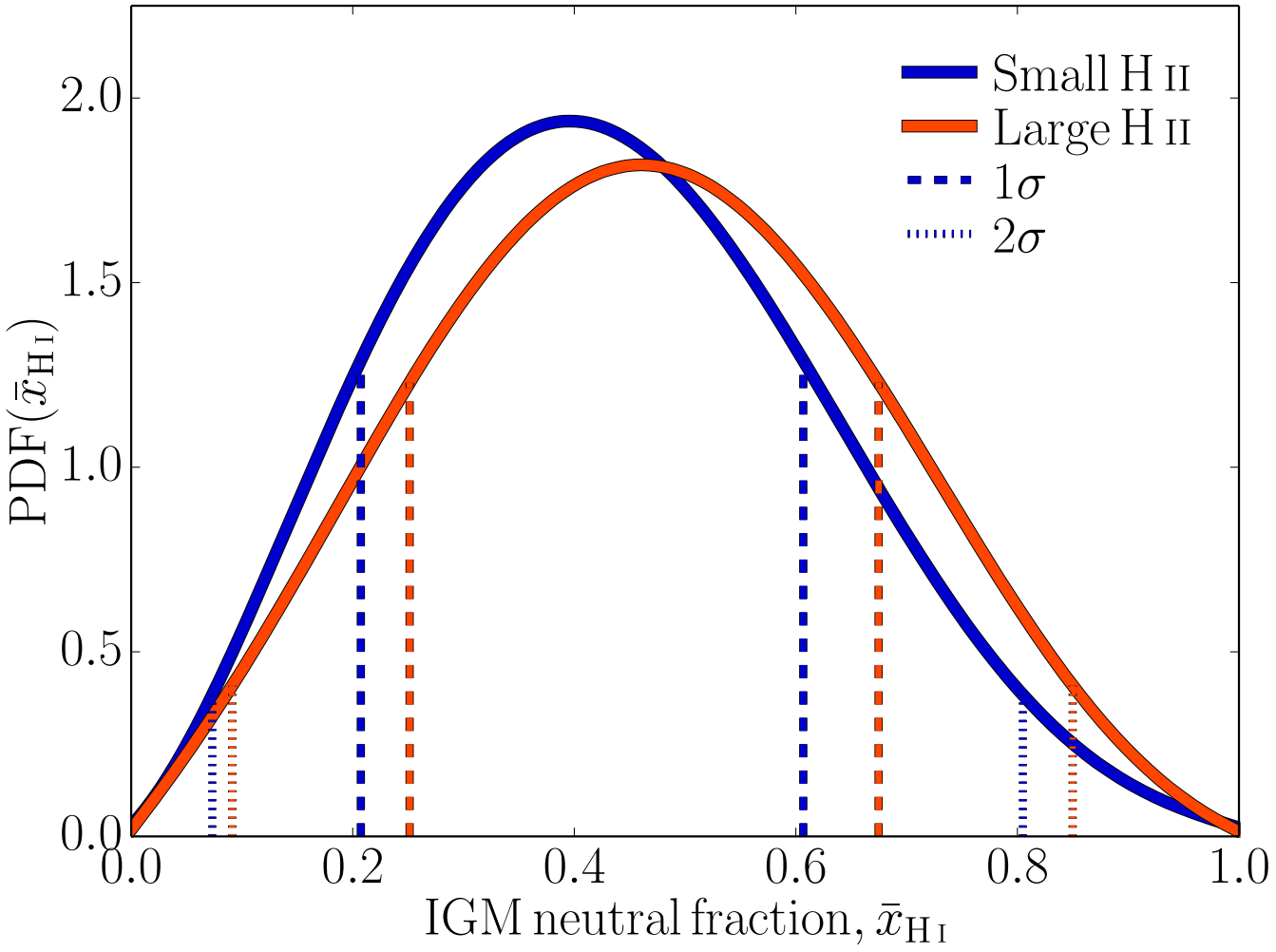


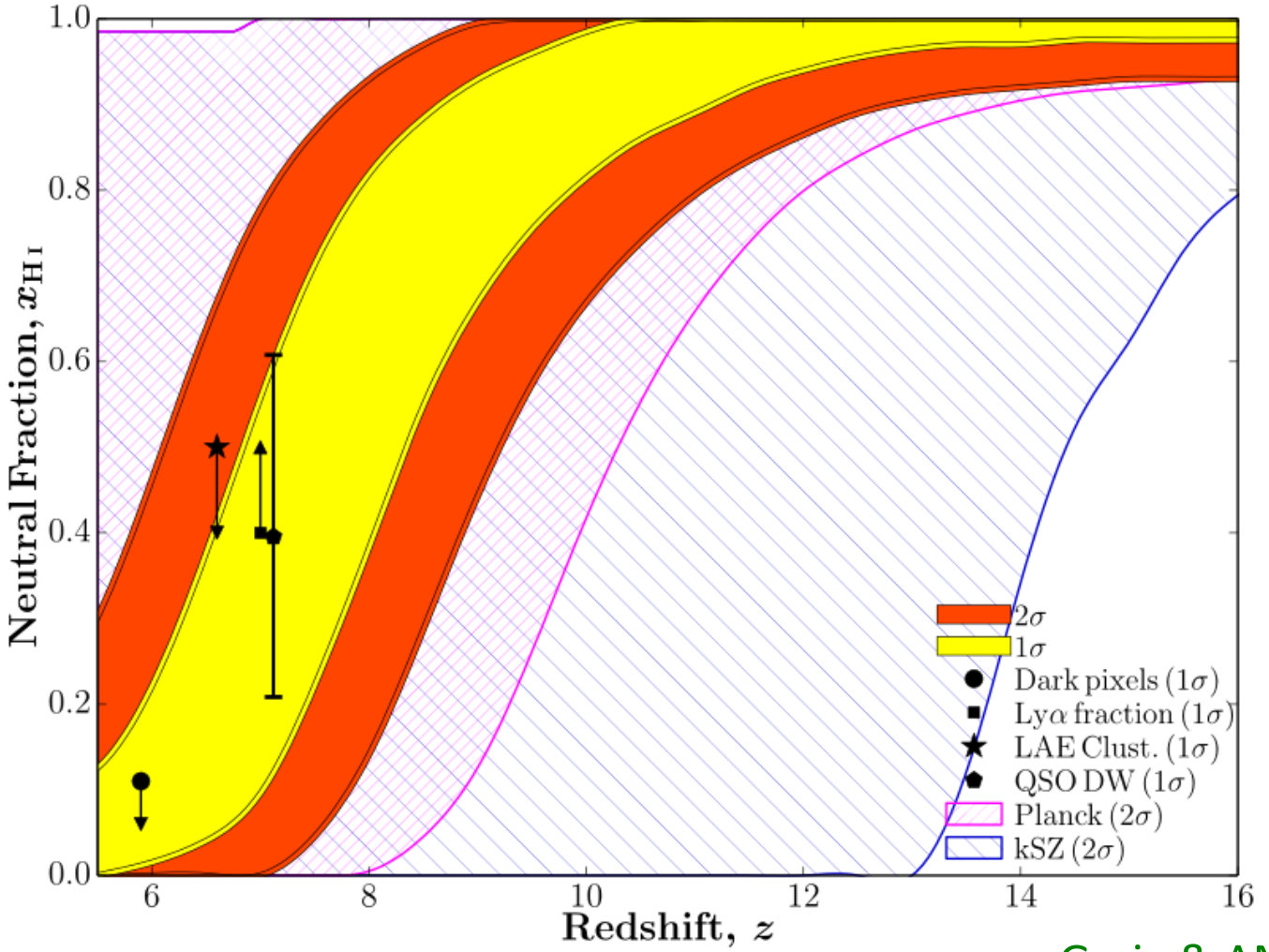
First detection of ongoing reionization!!!

$\langle x_{HI} \rangle = 0.40^{+0.41}_{-0.32}$ ($2\,\sigma$)

Greig, AM+ 2017

putting it all together…

When did the Universe reionize?



We now have a reasonable handle on when…

Greig & AM (2017)
see also Planck 2016;
Price+2016; Mitra+2016

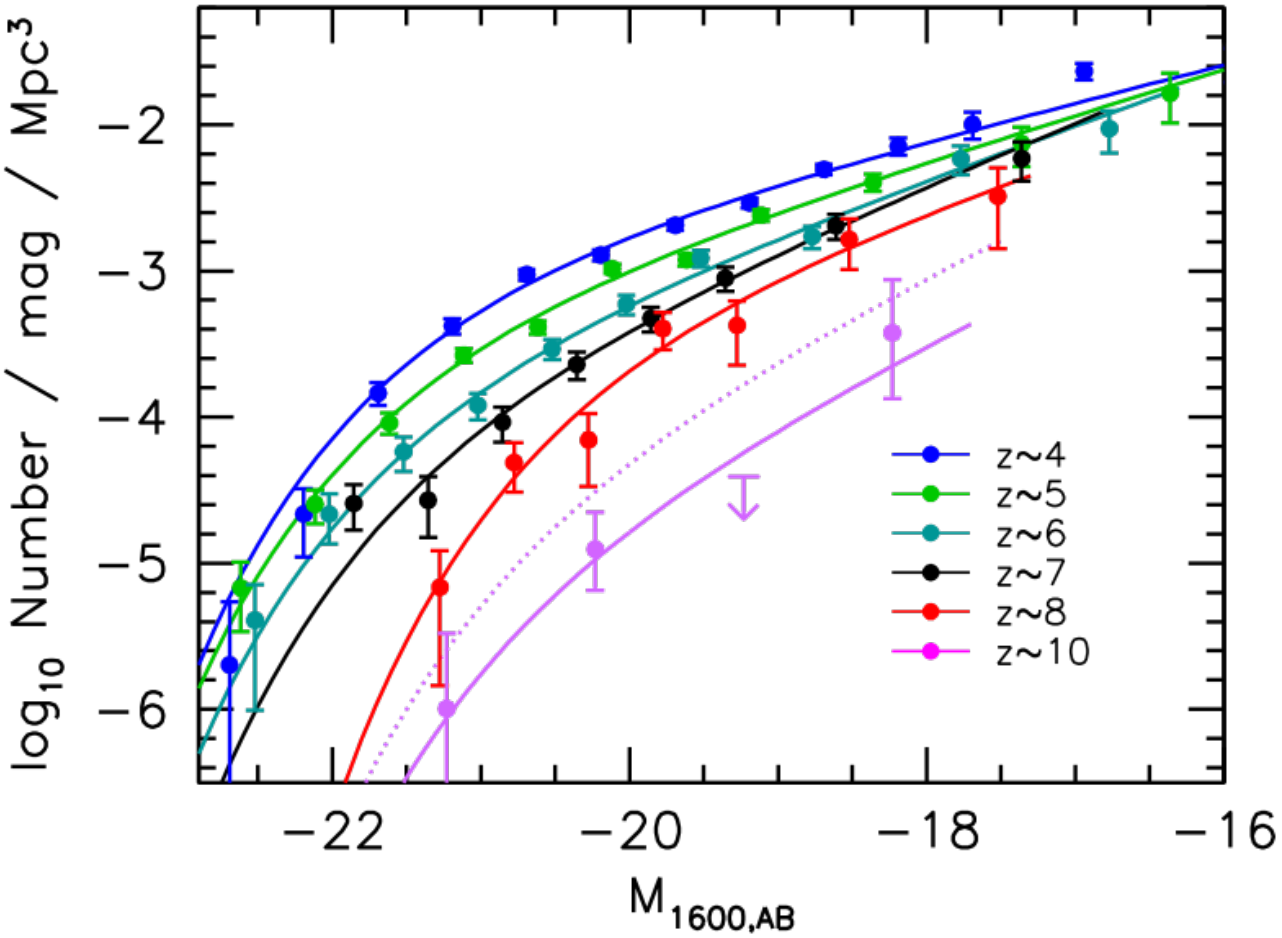
What and how??

stellar populations vs AGN, IMF in first galaxies, role of SNe and radiative feedback, metal pollution, efficiency of star formation, IGM structures, UVB evolution etc..

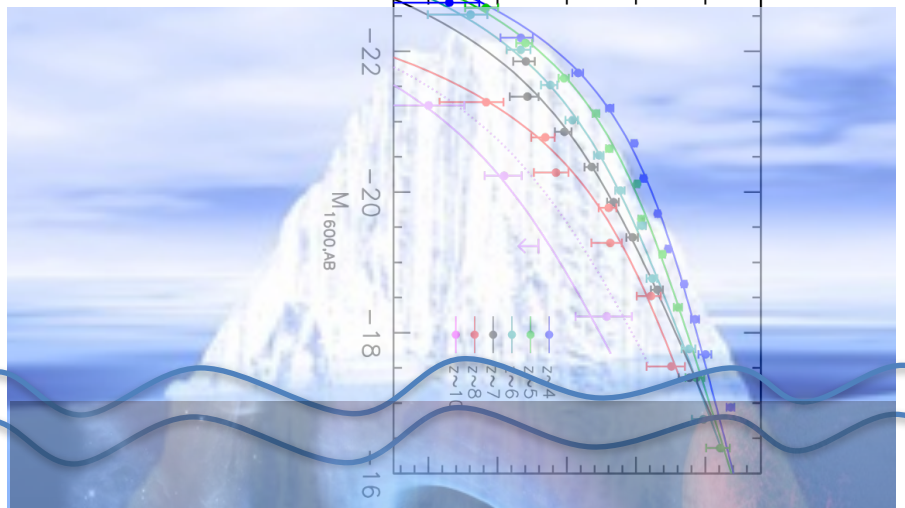
we don't really know…

What and how?

- Galaxy candidates have been found out to z~10. Are these the stellar populations responsible for the Cosmic Dawn and reionization? Estimates suggest they are too few…



Bouwens+ (2015)



Hubble limit

JWST limit

HERE THERE BE MONSTERS!

H-cooling threshold

H_2 cooling

M_{AB}= -22

M_{AB}= -18

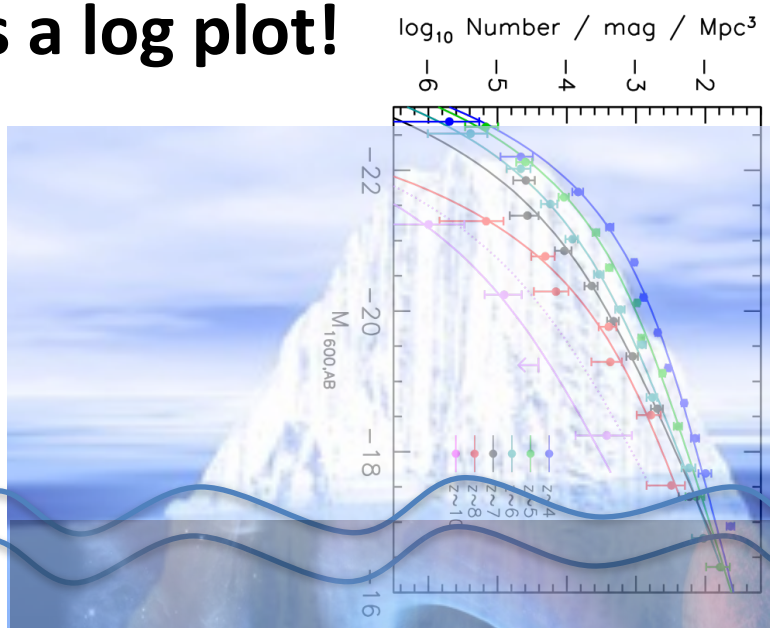
M_{AB}= -14

M_{AB}= -10

M_{AB}= - 6

hidden population of abundant ,faint galaxies??

Note: this is a log plot!



Hubble limit

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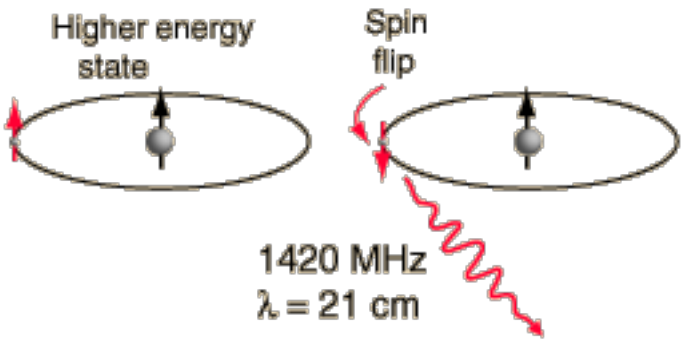
hidden population of abundant ,faint galaxies??

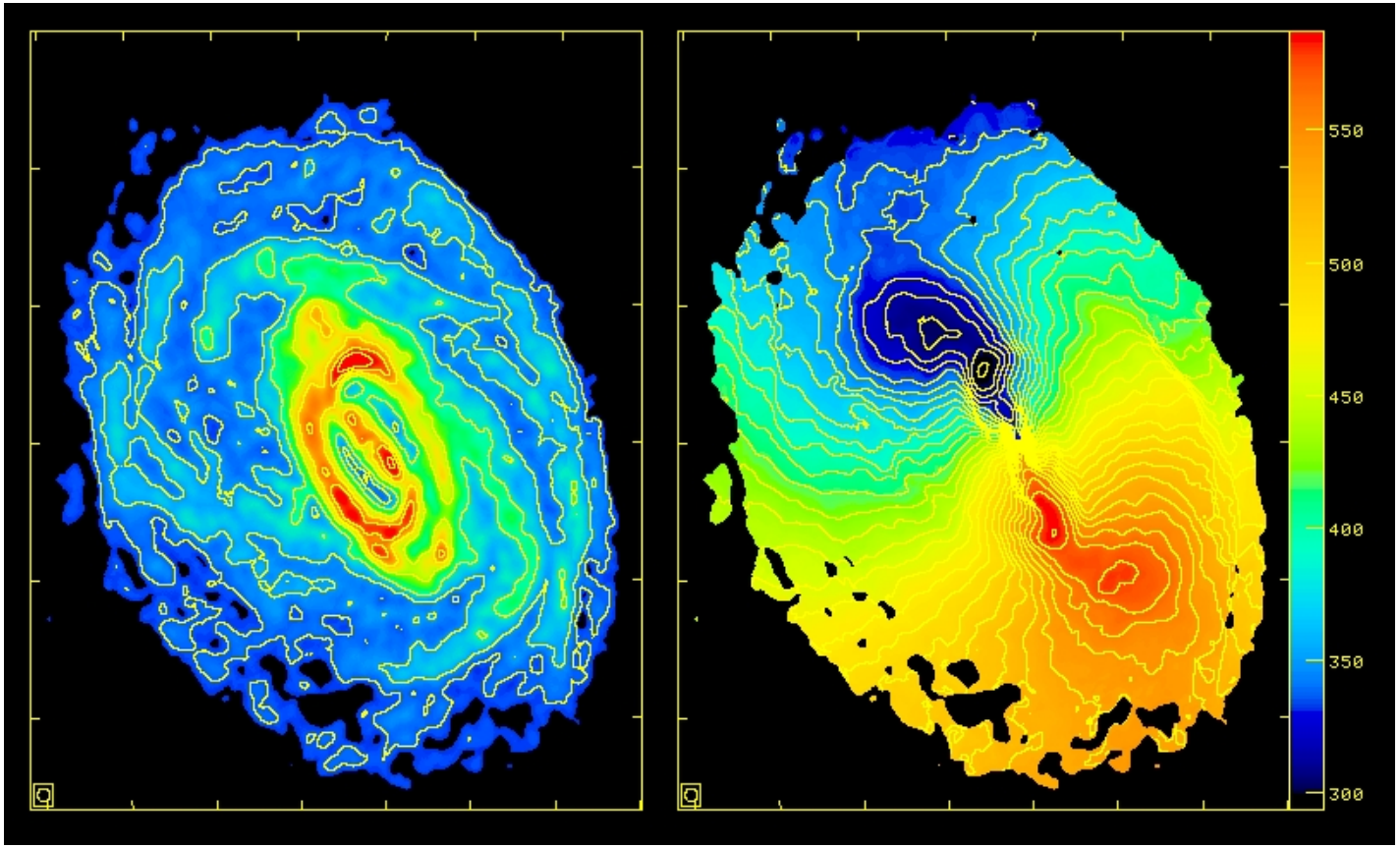
Get ready for the revolution: the cosmic 21 cm signal

21 cm line from neutral hydrogen



Hyperfine transition in the ground state of neutral hydrogen produces the 21cm line.

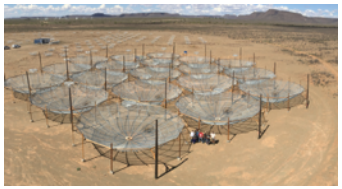
Widely used to map the HI content of our galaxy and nearby galaxies



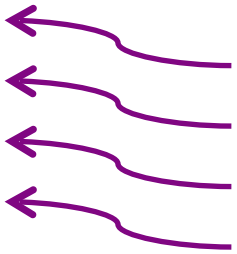
Circinus Galaxy

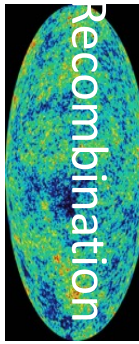
ATCA HI image by B. Koribalski (ATNF, CSIRO), K. Jones, M. Elmouttie (University of Queensland) and R. Haynes (ATNF, CSIRO).

Cosmic 21-cm signal



z = 0





z~1100

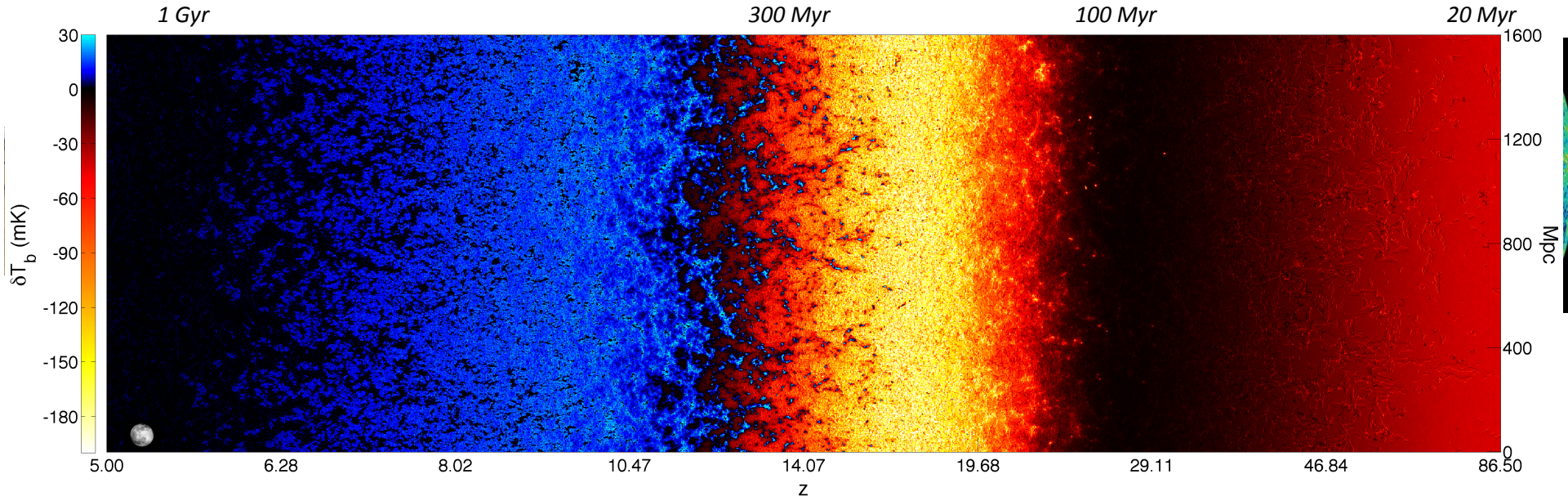
use the CMB as a background. measure the difference in intensities of the CMB and the cosmic HI, the so-called brightness temperature offset from the CMB:

$$\delta T_b(\nu) \approx 27 x_{\rm HI}(1+\delta_{\rm nl}) \left(\frac{H}{dv_r/dr + H}\right)\left(1-\frac{T_\gamma}{T_S}\right)\left(\frac{1+z}{10}\frac{0.15}{\Omega_M h^2}\right)^{1/2}\left(\frac{\Omega_b h^2}{0.023}\right) {\rm mK}$$

Signal contains both **ASTROPHYSICAL** and **COSMOLOGICAL** terms

Cosmic 21-cm signal

AM+ 2016



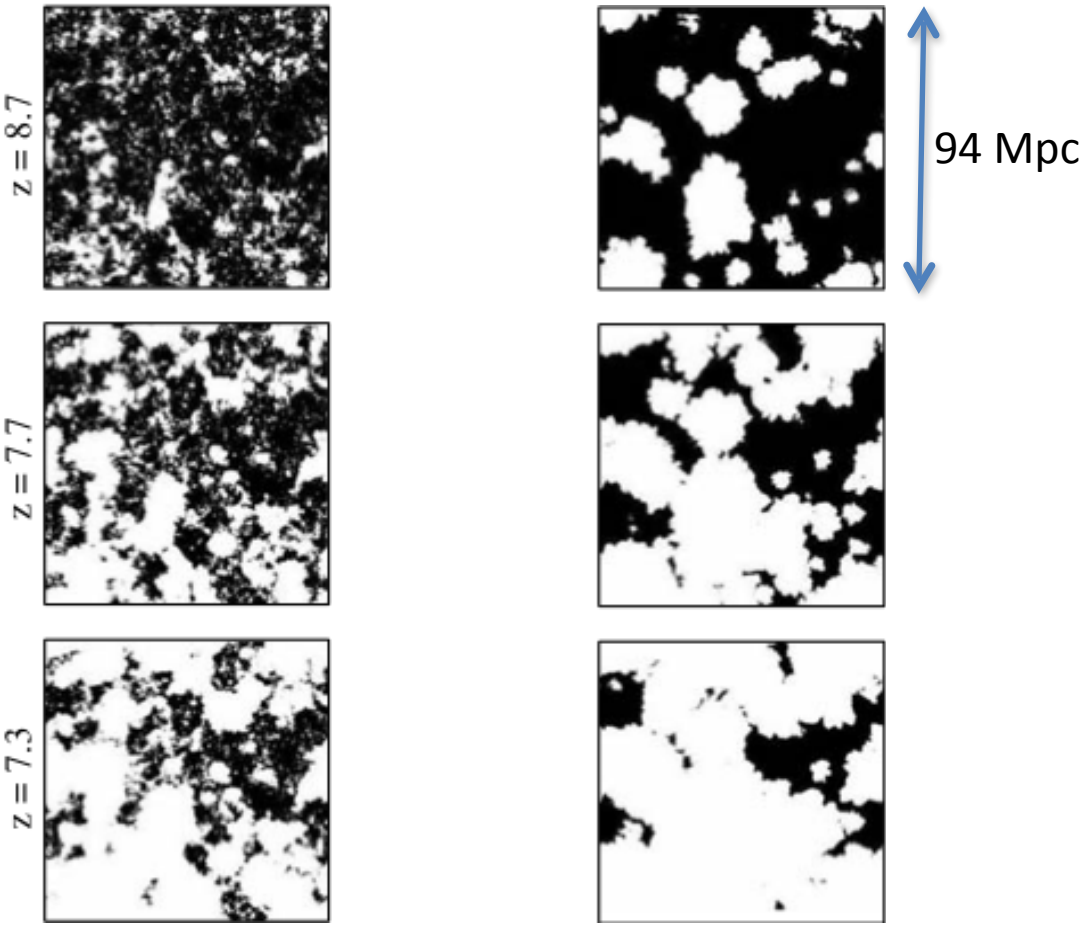
Reionization X-ray heating Lyα coupling Dark Ages

$$\delta T_b(\nu) \approx 27 x_{\rm HI}(1+\delta_{\rm nl}) \left(\frac{H}{dv_r/dr + H}\right) \left(1 - \frac{T_\gamma}{T_S}\right) \left(\frac{1+z}{10}\frac{0.15}{\Omega_M h^2}\right)^{1/2} \left(\frac{\Omega_b h^2}{0.023}\right) \text{mK}$$

Signal contains both **ASTROPHYSICAL** and **COSMOLOGICAL** terms

How do we learn about the hidden sources?

- Galaxy clustering + stellar properties → *evolution of large-scale EoR/CD structures*

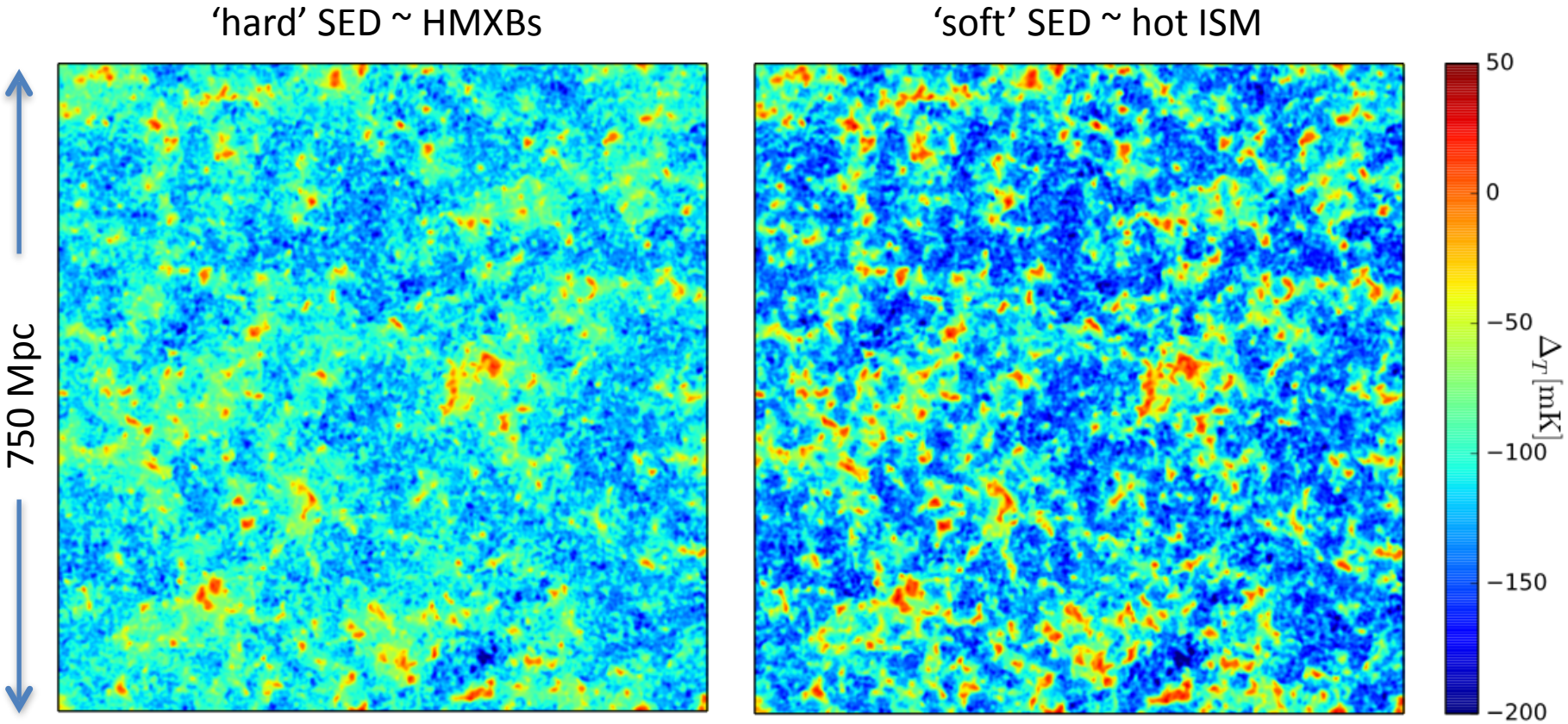


McQuinn+ 2007

Abundant, faint galaxies vs **Rare, bright galaxies**

Patterns in the Epoch of Heating

High-energy processes in the first galaxies are also encoded in the cosmic 21-cm signal



differences are easily detectable with HERA and the SKA

Pacucci+ 2014

Roadmap to 21-cm treasure trove

Roadmap to 21-cm treasure trove

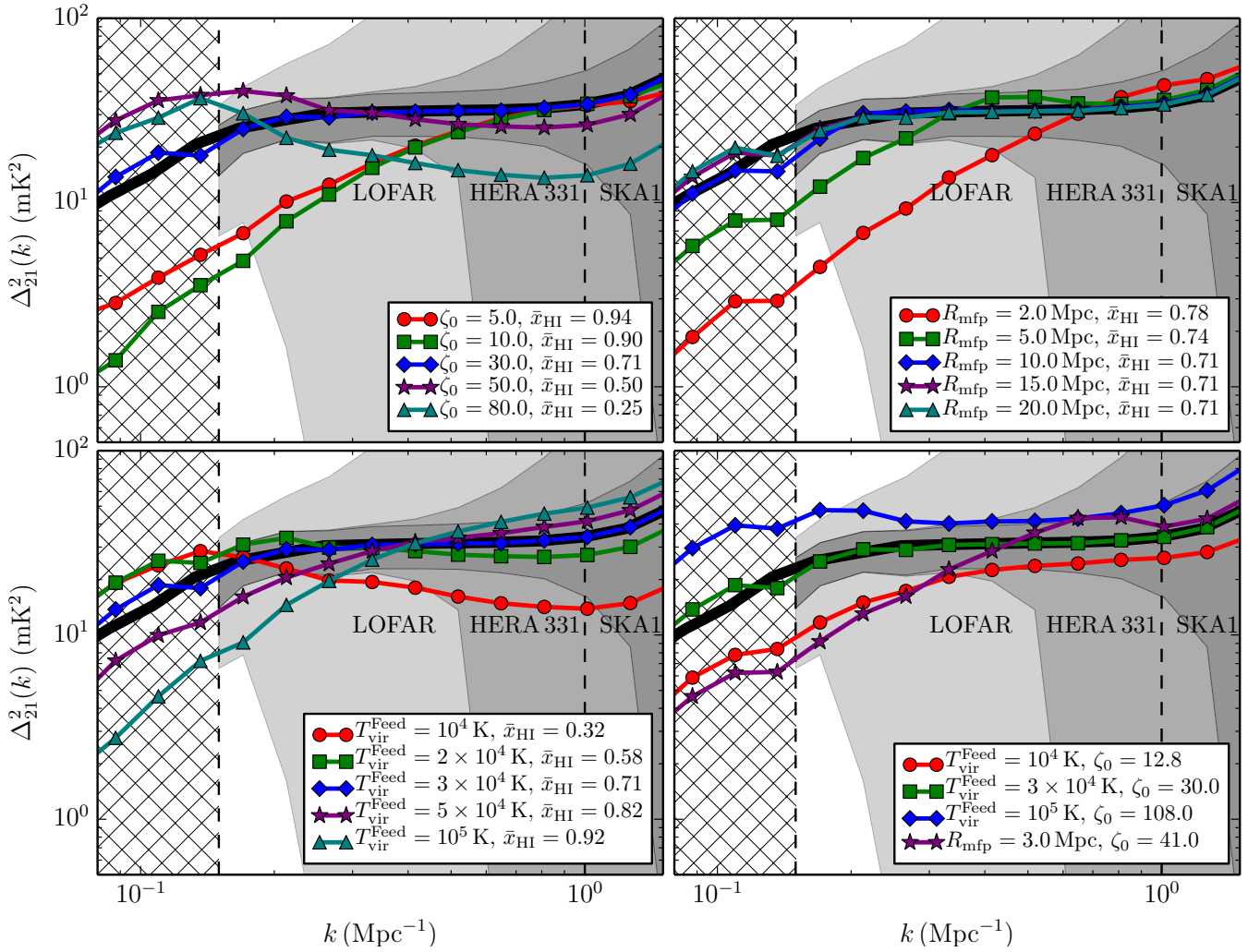
1) Observe the signal *(some smart observers will take care of this…)*

Roadmap to 21-cm treasure trove

1) Observe the signal *(some smart observers will take care of this…)*

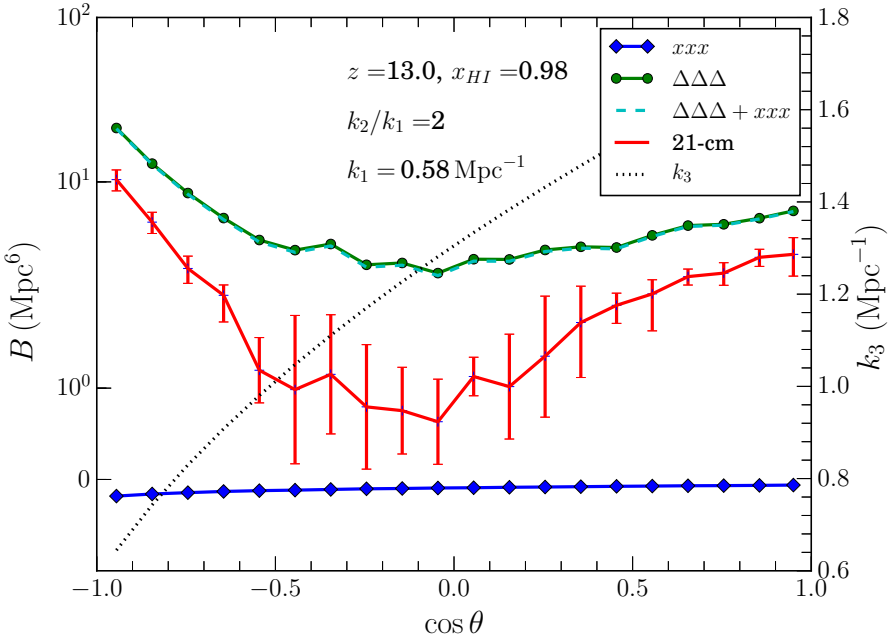
2) Characterize the observed signal

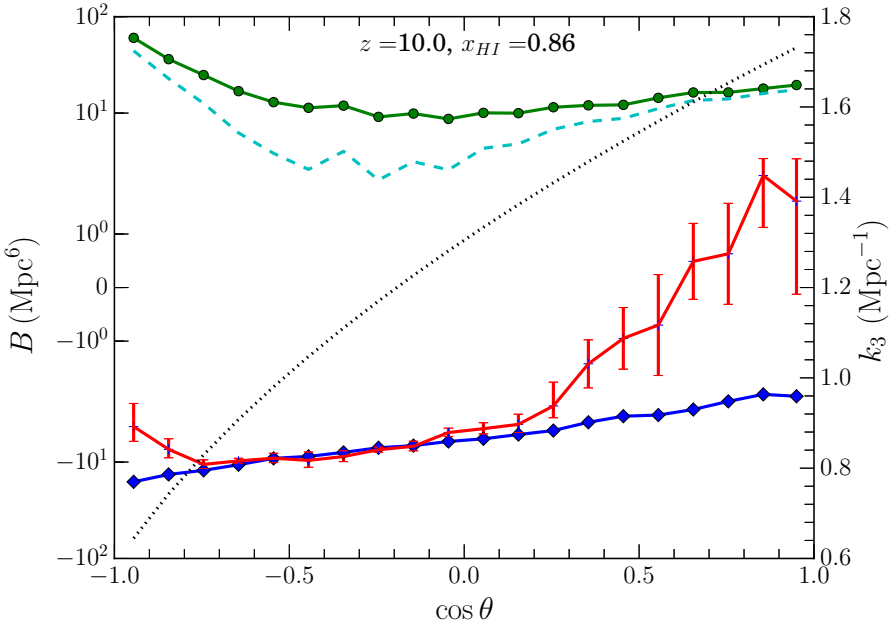
Power spectrum: most common statistic



- **Different astrophysical models of galaxies and the IGM show different 21-cm power spectra**
- **Variation is up to a factor of ~10, at a fixed cosmic epoch…**

Bispectrum…



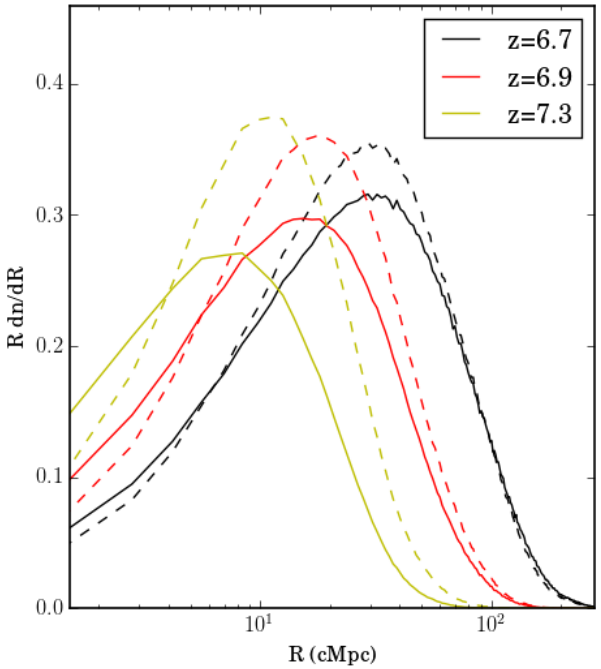


Majumdar+2017
(see also Bharadwaj & Pandey 2005; Yoshiura+2015; Shimabukuro+2016)

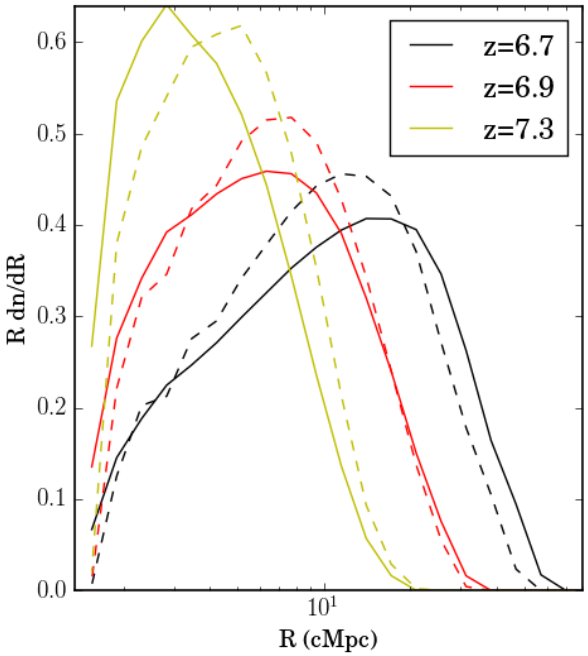
- **dominated by ionization and density fields at different stages and configurations…**
- **also a powerful discriminant for astrophysics?**

HII region size characterizations

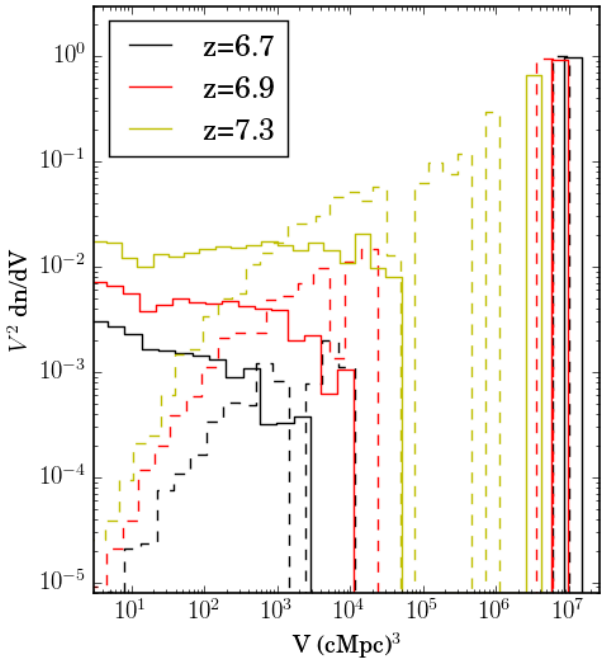
"mean free path" measure



spherical average



Friends of friends



Giri+2017

- **bubble size distributions should be measurable from SKA maps, and can be an additional check on the progress of reionization**

Roadmap to 21-cm treasure trove

1) Observe the signal *(some smart observers will take care of this…)*

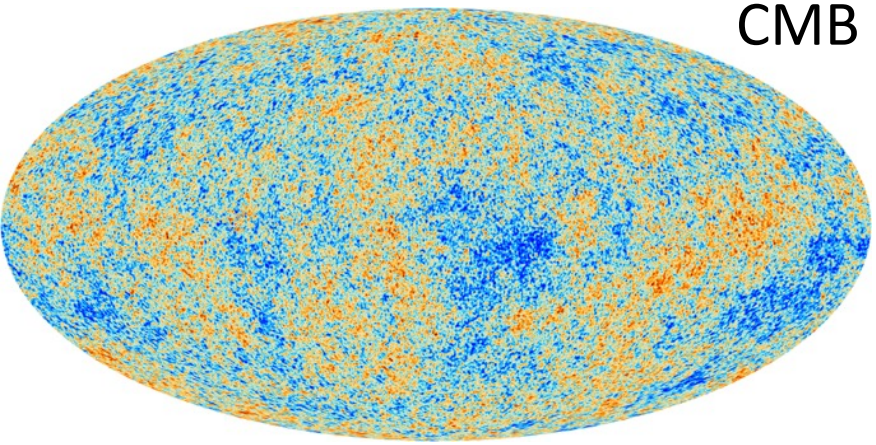
2) Characterize the observed signal

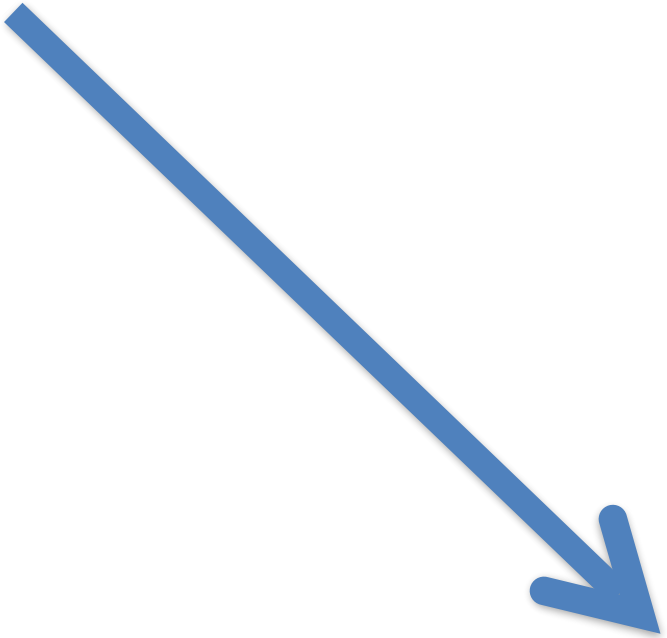
3) Interpret

How efficient was star formation? What role did feedback play? On what scales? What where the dominant stellar populations? What are the high-energy processes in the first galaxies? What were their environments? etc…

Physical cosmology

CMB map

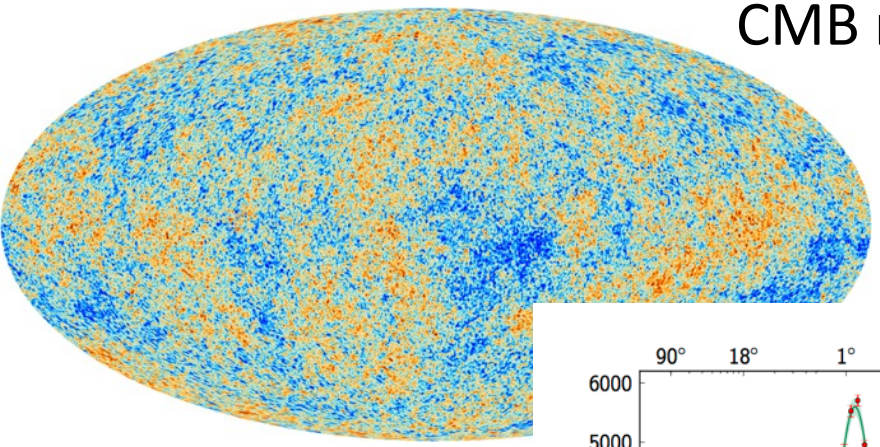




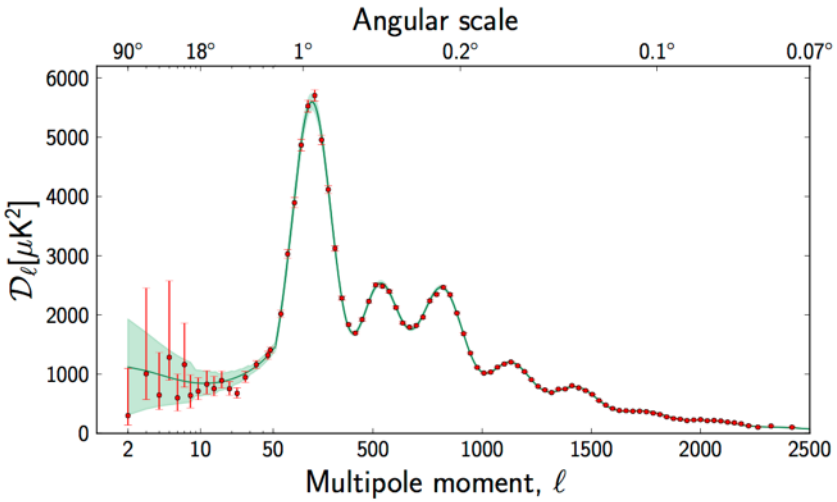
Planck 2013; 2015

Physical cosmology

CMB map



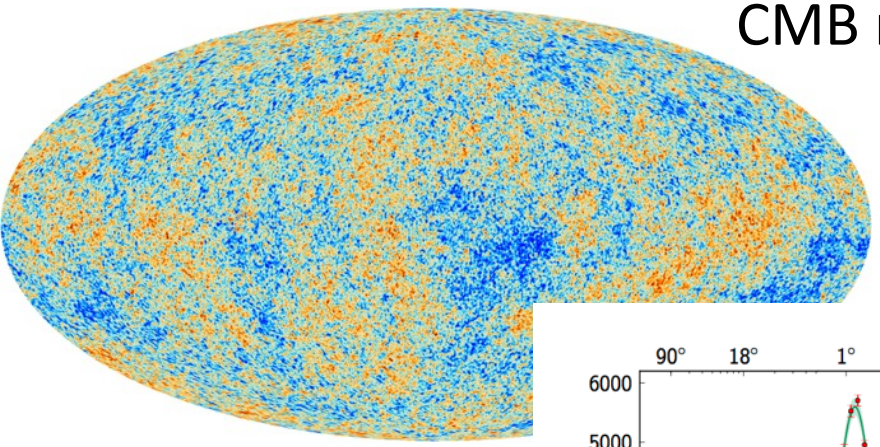
power spectrum



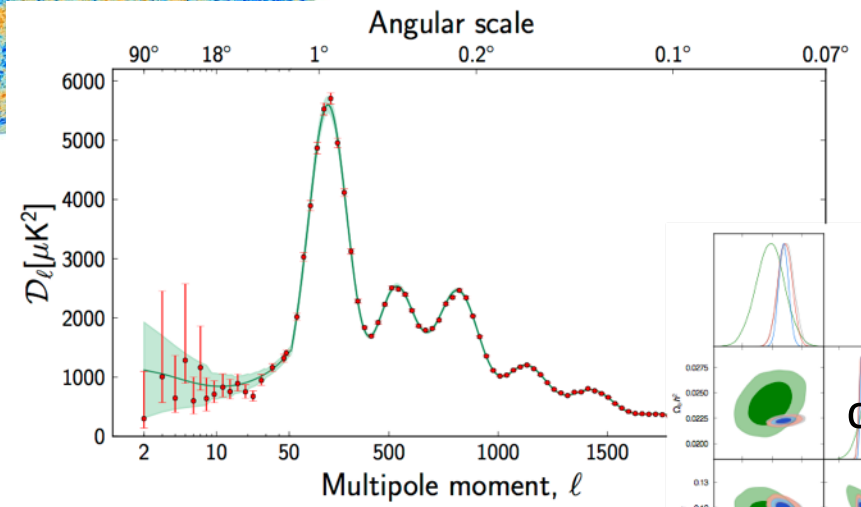
Planck 2013; 2015

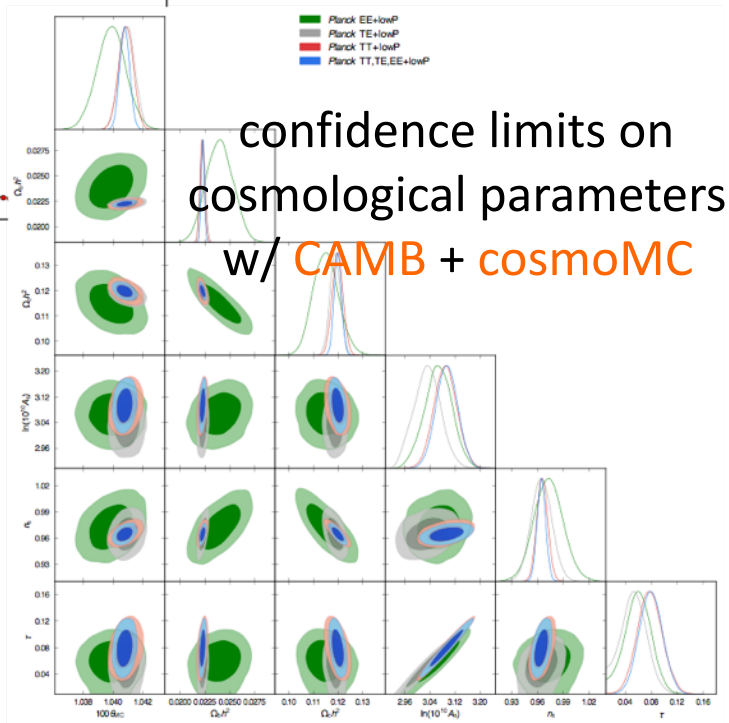
Physical cosmology

CMB map



power spectrum



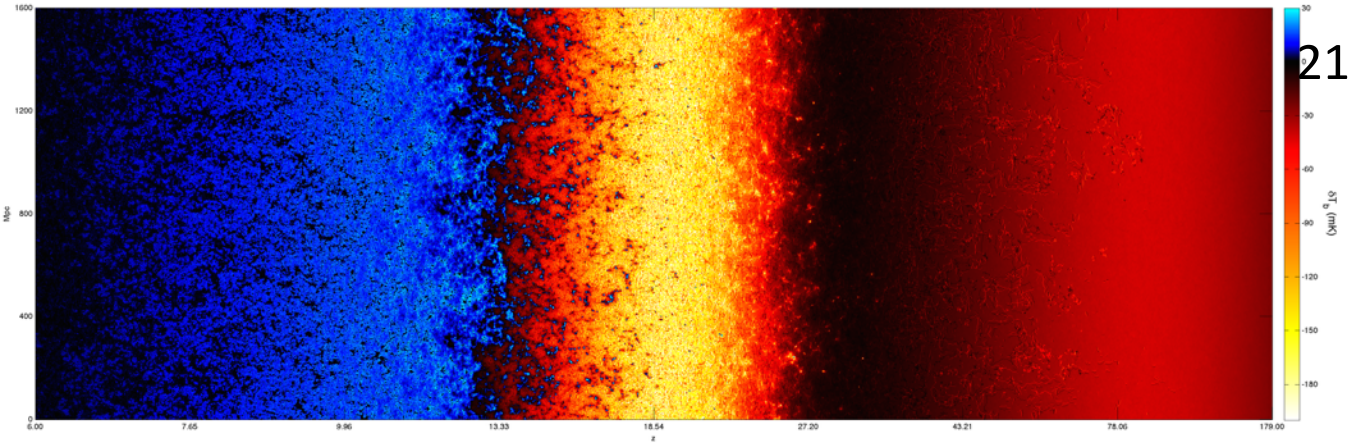


confidence limits on cosmological parameters w/ CAMB + cosmoMC

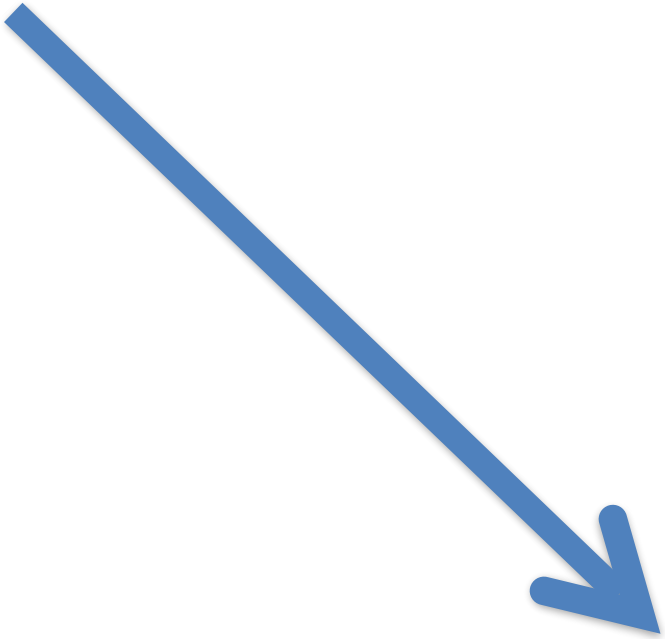
Planck 2013; 2015

*Astro*physical cosmology

← time

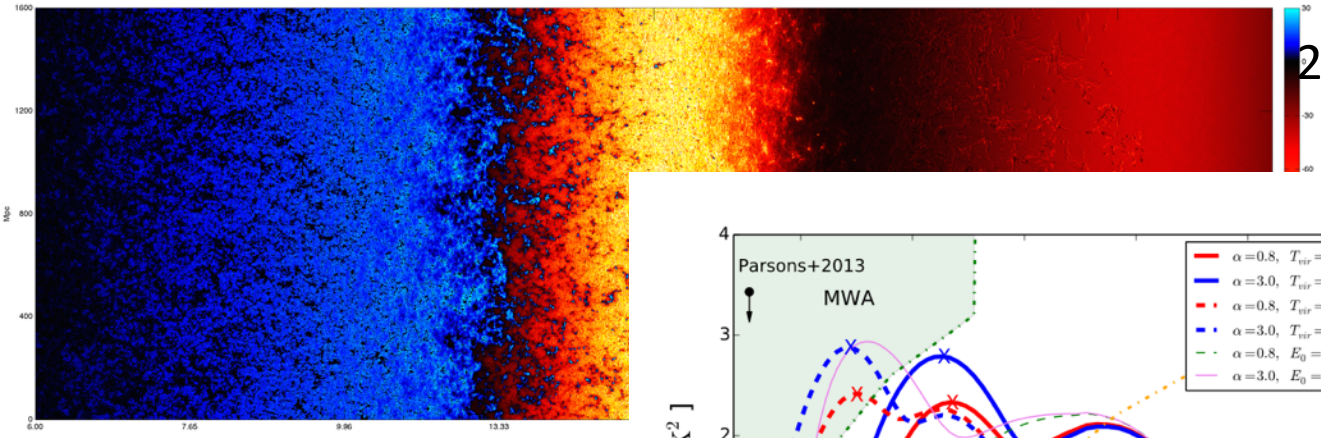


21cm **3D!!!** map



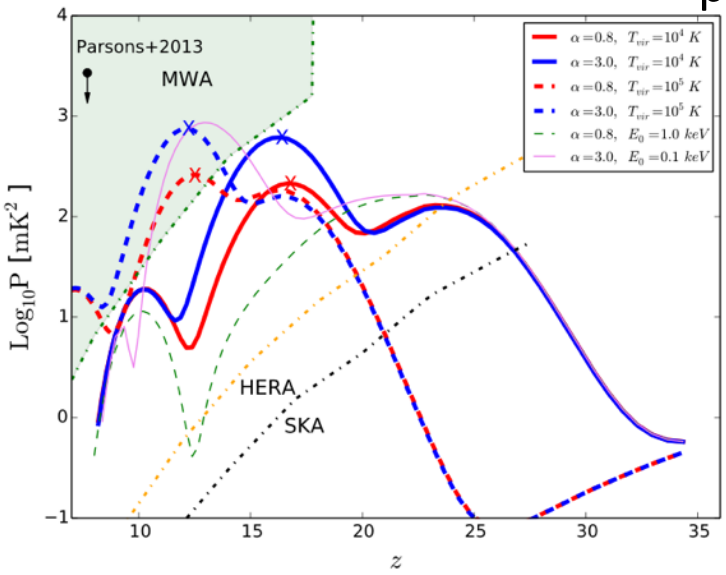
*Astro*physical cosmology

← time



21cm **3D!!!** map

power spectrum**??**



*Astro*physical cosmology

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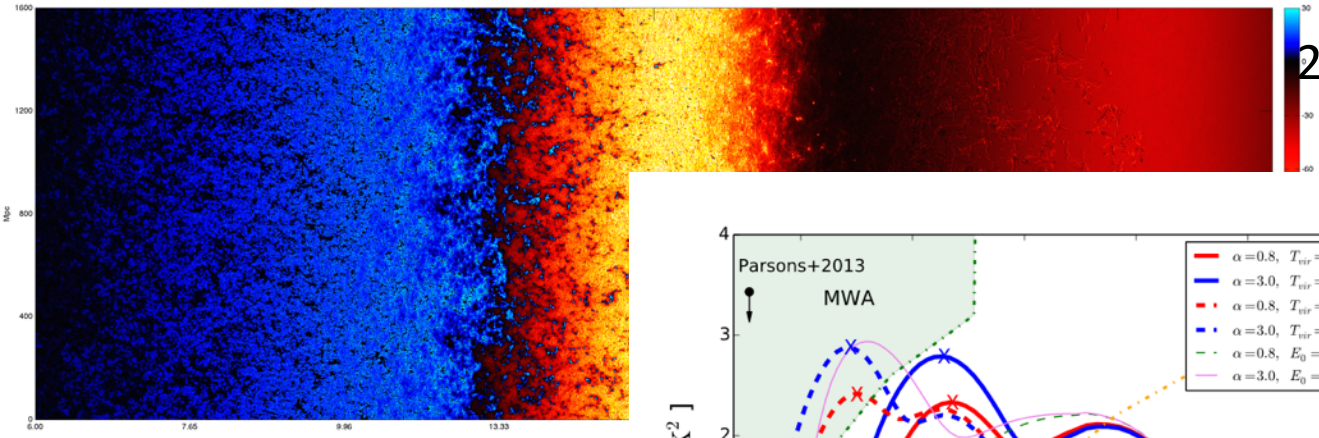
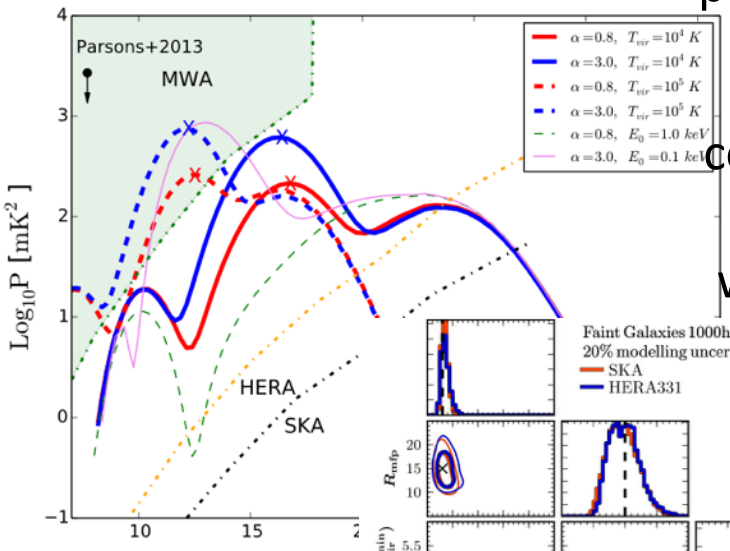


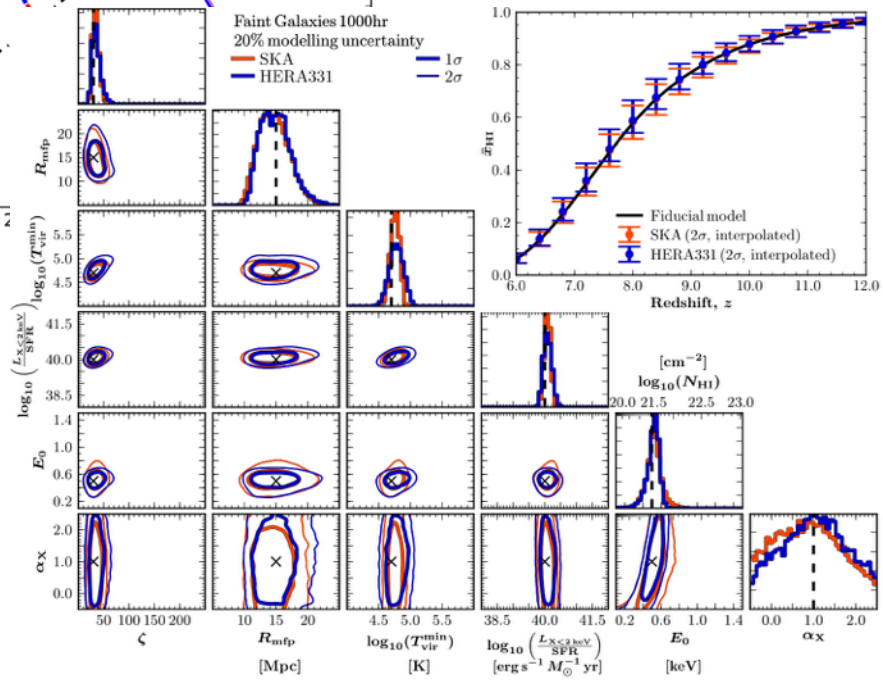
21cm **3D!!!** map

power spectrum**??**



confidence limits on ***astro*** parameters

w/ 21cmFAST+ 21CMMC



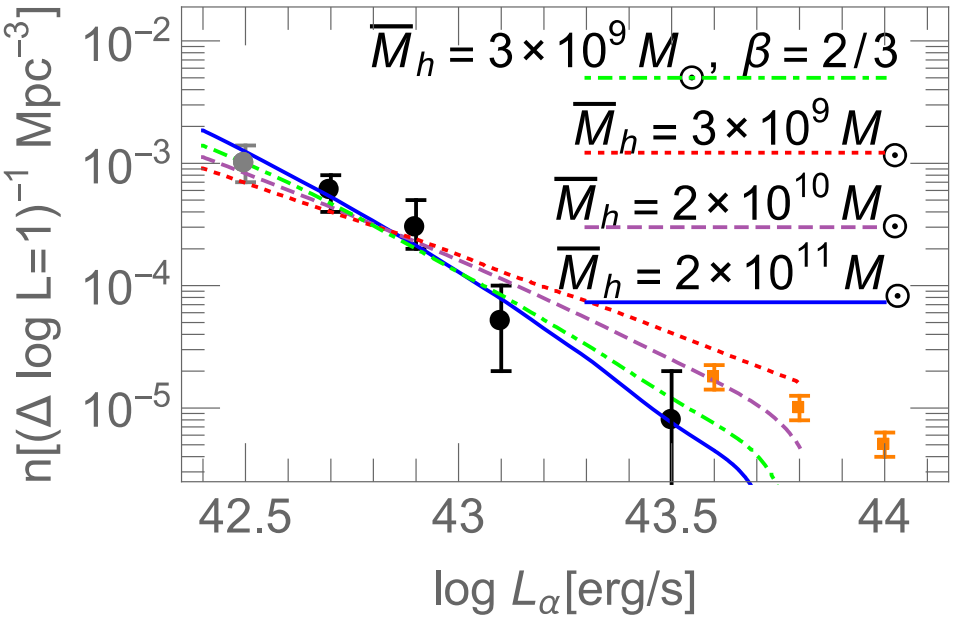
Greig & AM (2015; 2017)

percent level constraints on most parameters w. **HERA** and **SKA-low**

Conclusions

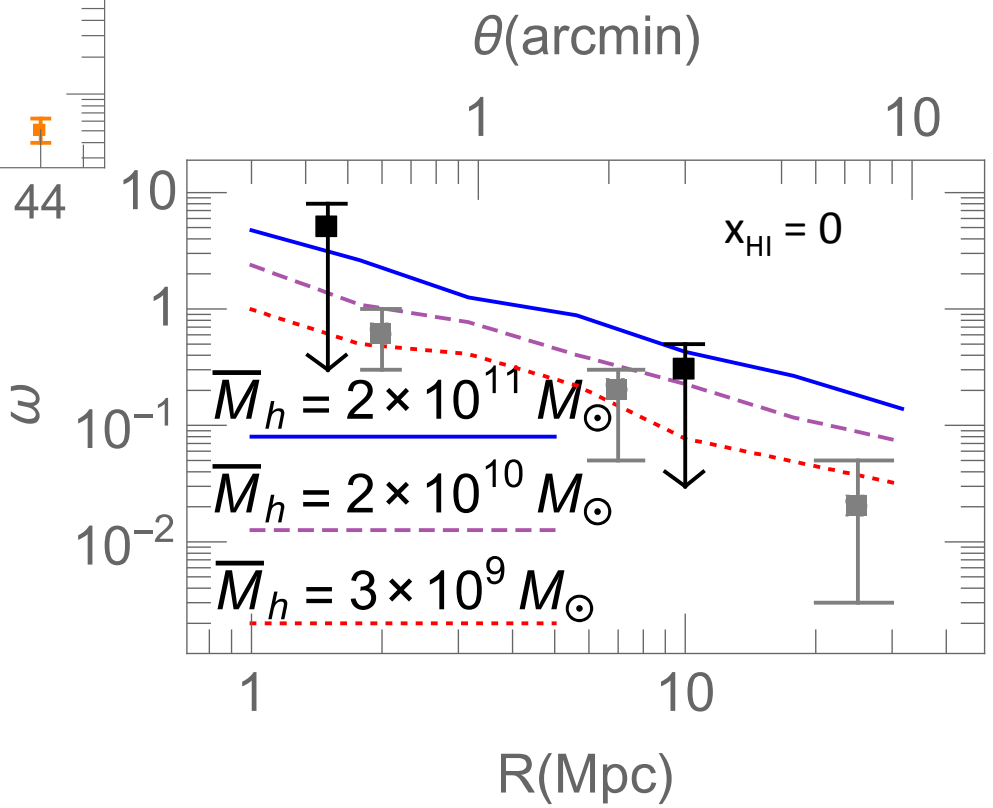
- The past few years have seen substantial progress in modeling reionization, with many techniques available: hydro+RT, N-body+RT, semi-numerical, tiered, etc…
- Applying these tools to current observations tells us roughly when reionization occurred, e.g. midpoint around $z = 7.6_{-0.7}^{+0.8}$ ($1\,\sigma$). The strongest constraints come from Planck 2016 (integral constraints), and the first detection from QSO ULASJ1120: $\langle x_{HI} \rangle = 0.40_{-0.32}^{+0.41}$ ($2\,\sigma$) at $z \sim 7$.
- However, we do not know anything about the astrophysical sources and sinks. The properties of sources and sinks are encoded in the 3D structure of the 21-cm signal
- To quantify what we can learn, we have a Bayesian framework for astrophysical parameter estimation, capable of on-the-fly MCMC sampling of 3D simulations.
- Upcoming 21-cm interferometers will constrain astrophysical parameters to per cent level precision
- What more can we learn??

Extreme L^{intr} <-> M_h



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

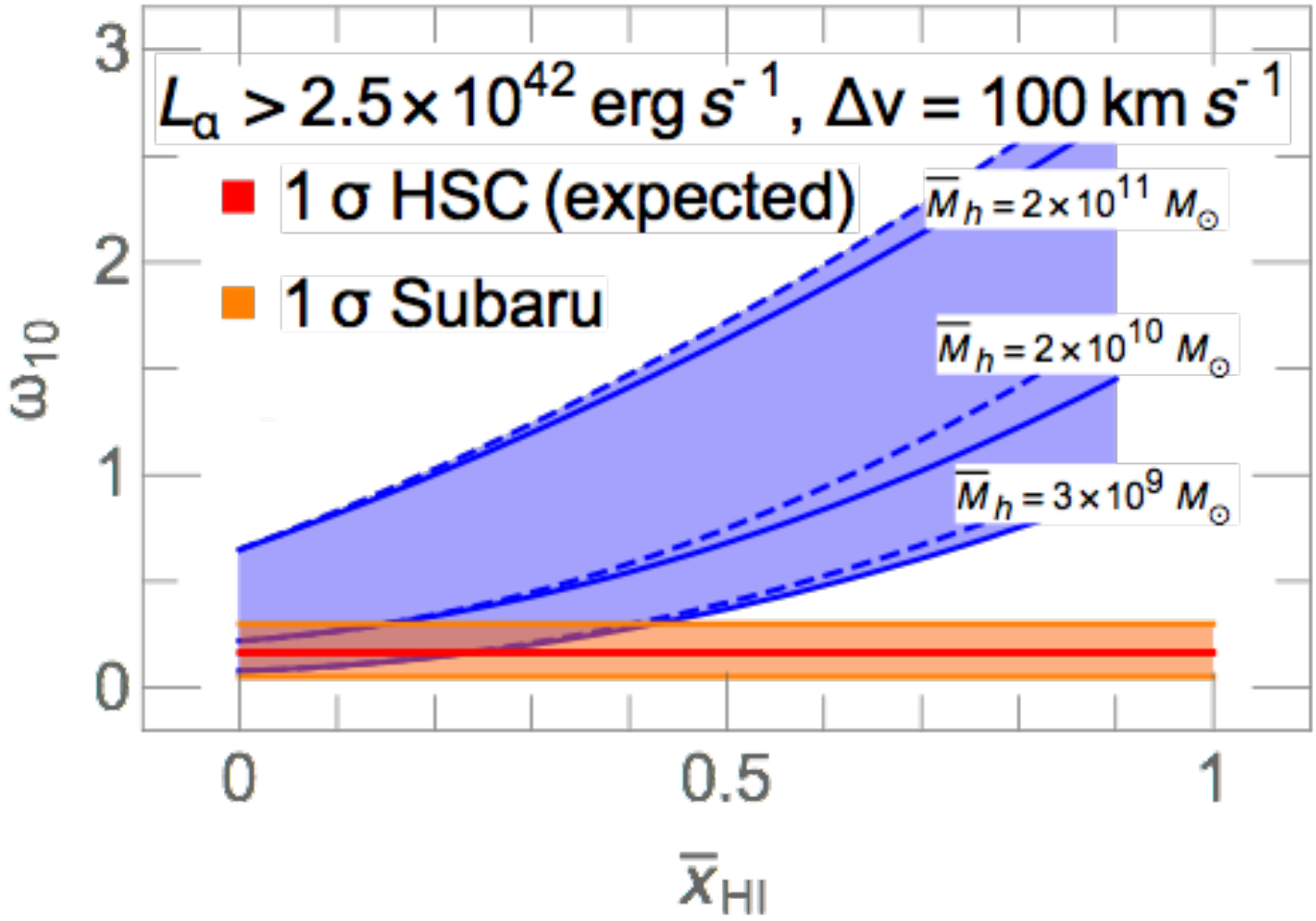
χ is a random variable ($\chi = 1$ with probability $f_{\rm duty}$



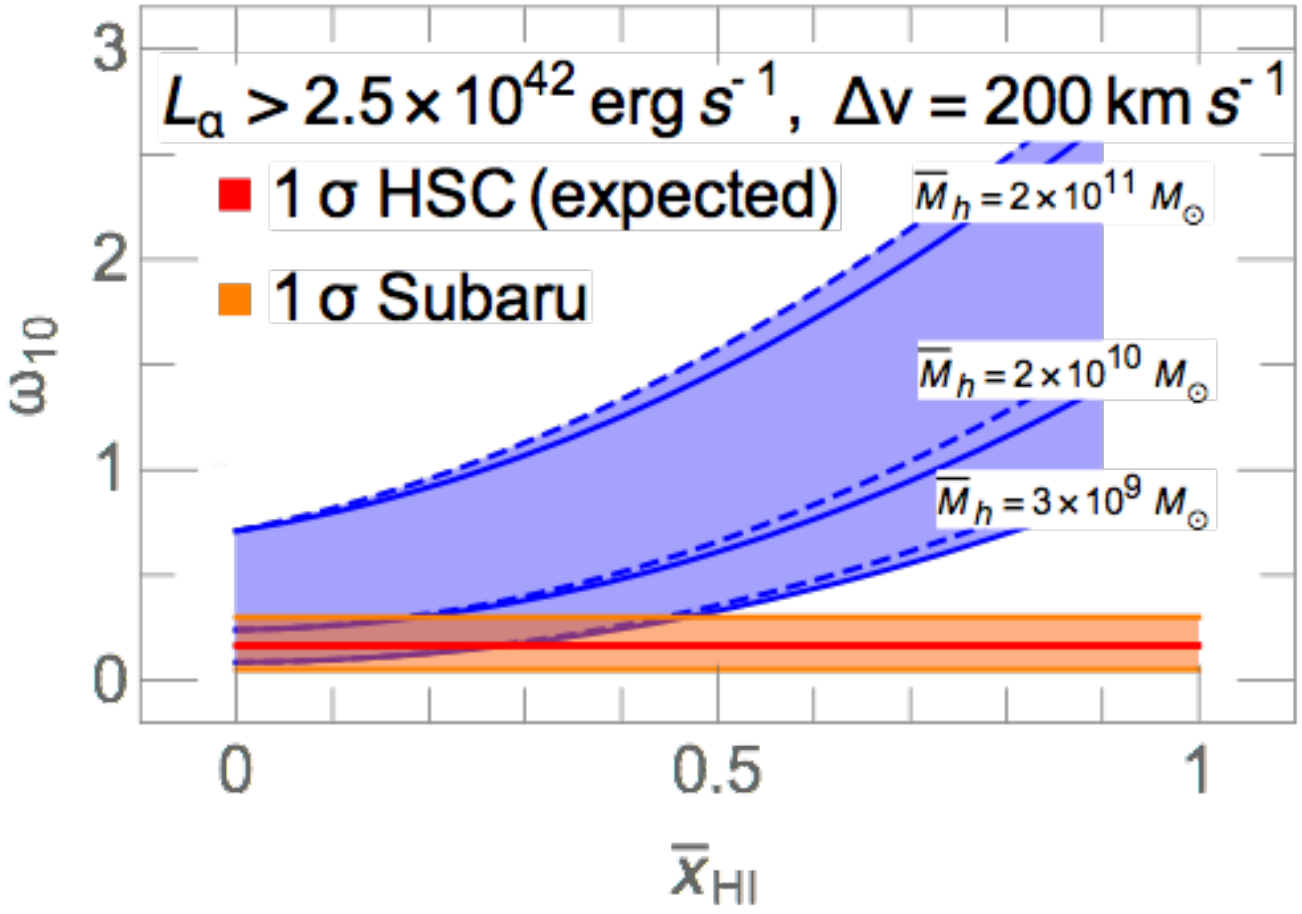
$n_{LAE}(z\sim7) = 4.1\times10^{-4}$ Mpc^{-3} (Ouchi+2010)

Sobacchi & AM (2015)

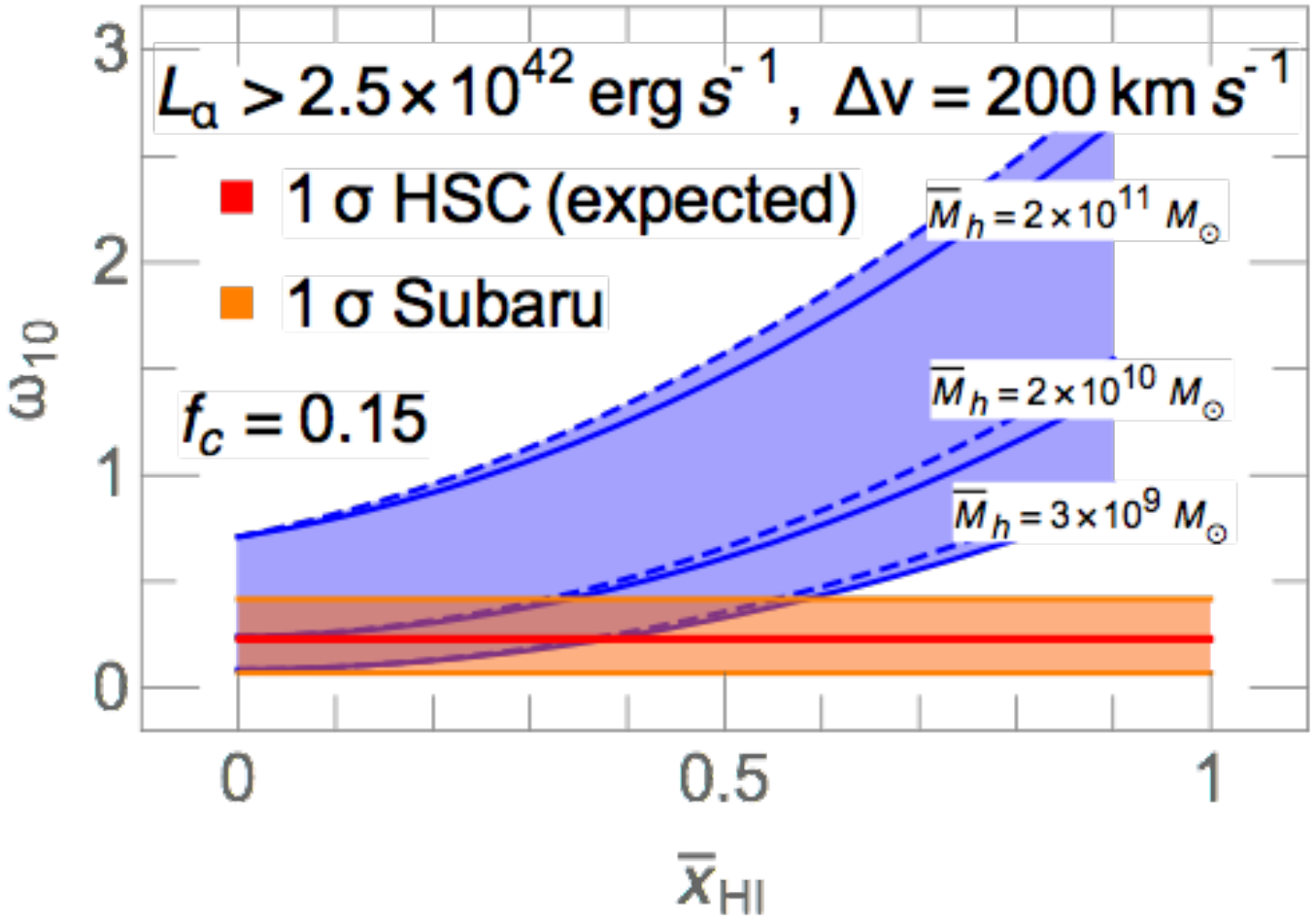
low systemic v offset



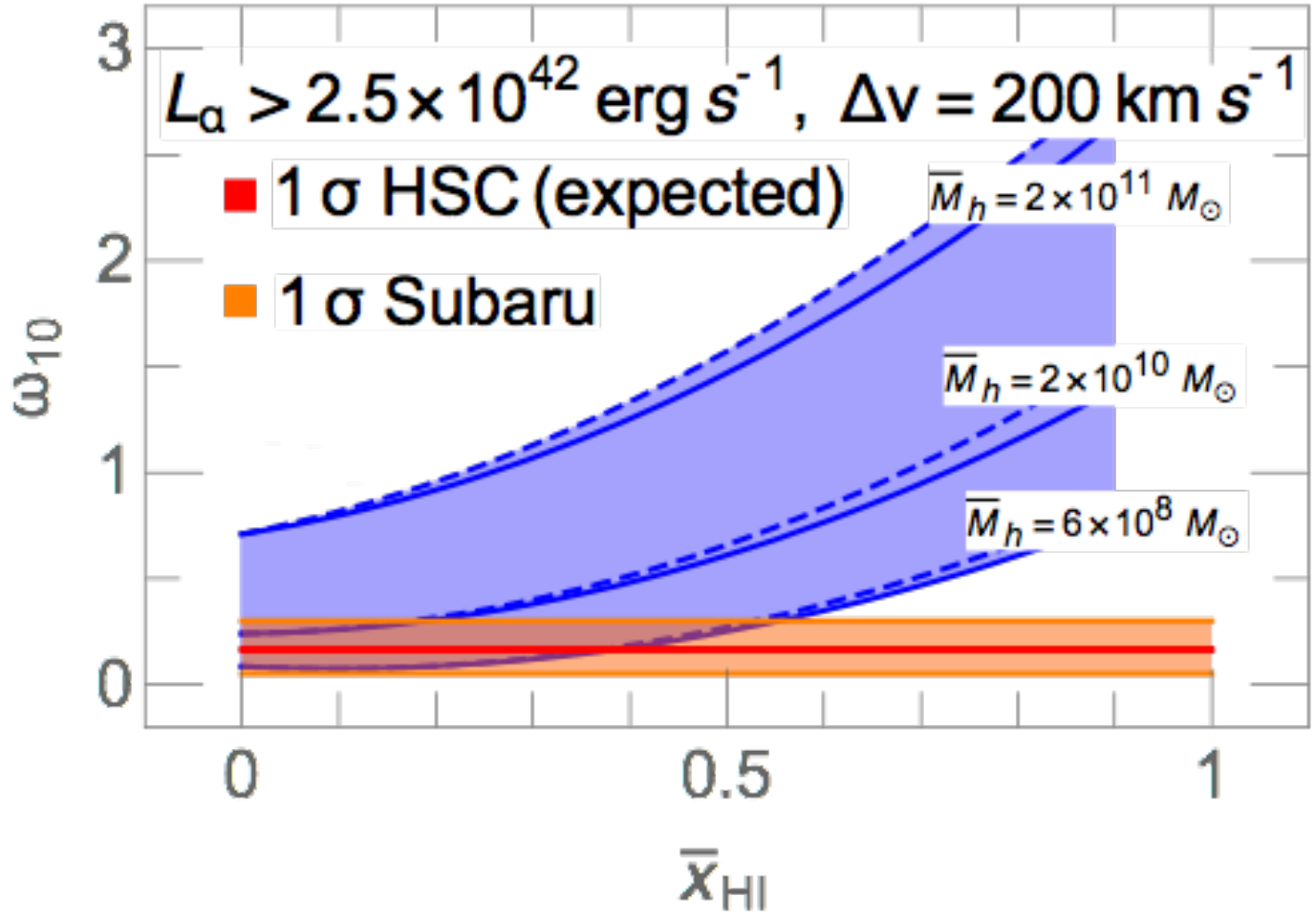
beta = 2/3


$L_\alpha > 2.5\times10^{42}$ erg s^{-1}, $\Delta v = 200$ km s^{-1}
1 σ HSC (expected)
1 σ Subaru
$\overline{M}_h = 2\times10^{11}\ M_\odot$
$\overline{M}_h = 2\times10^{10}\ M_\odot$
$\overline{M}_h = 3\times10^{9}\ M_\odot$
ω_{10}
$\overline{x}_{HI}$
0
1
2
3
0
0.5
1

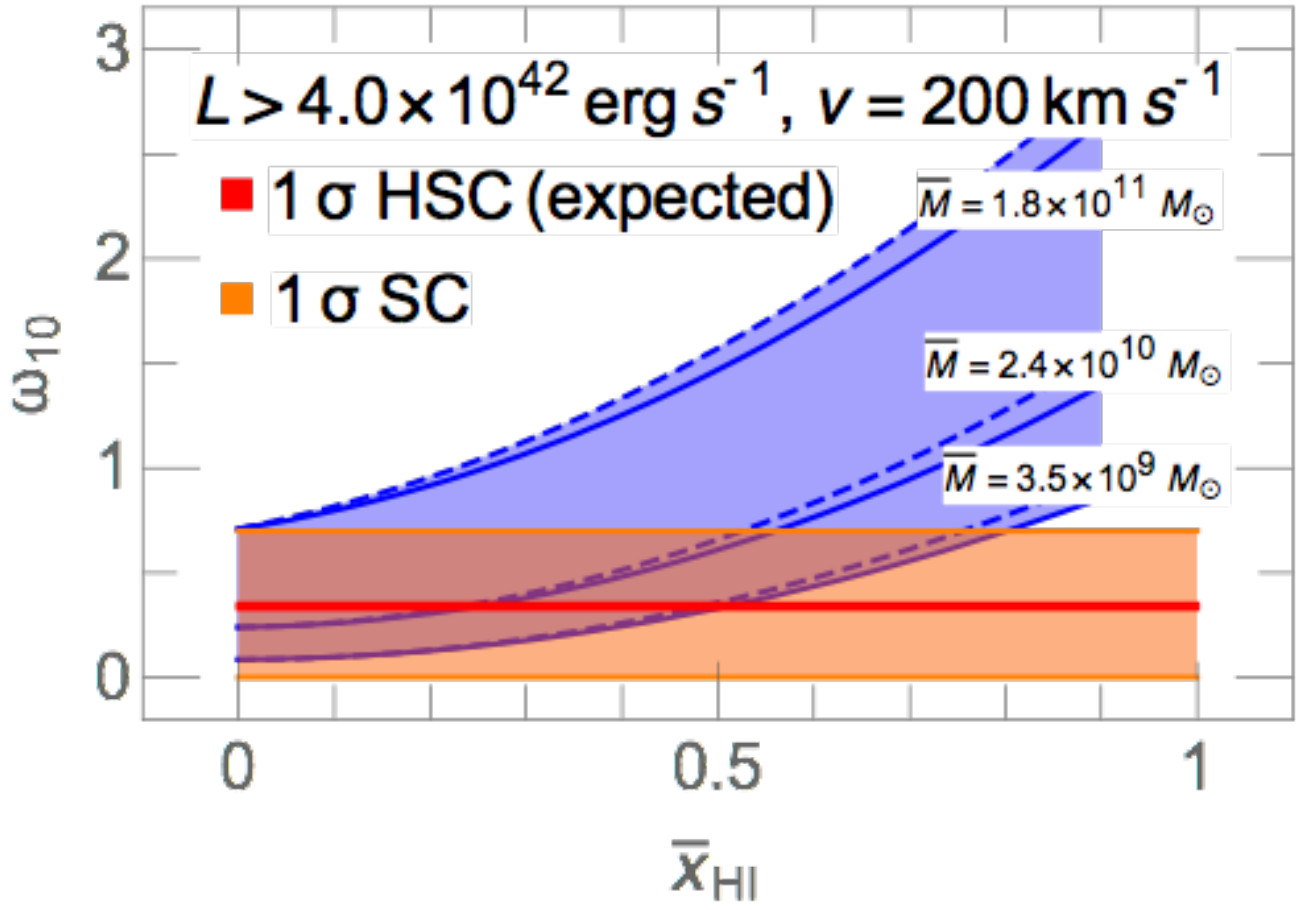
15% interlopers



down to atomic-cooling thresh.

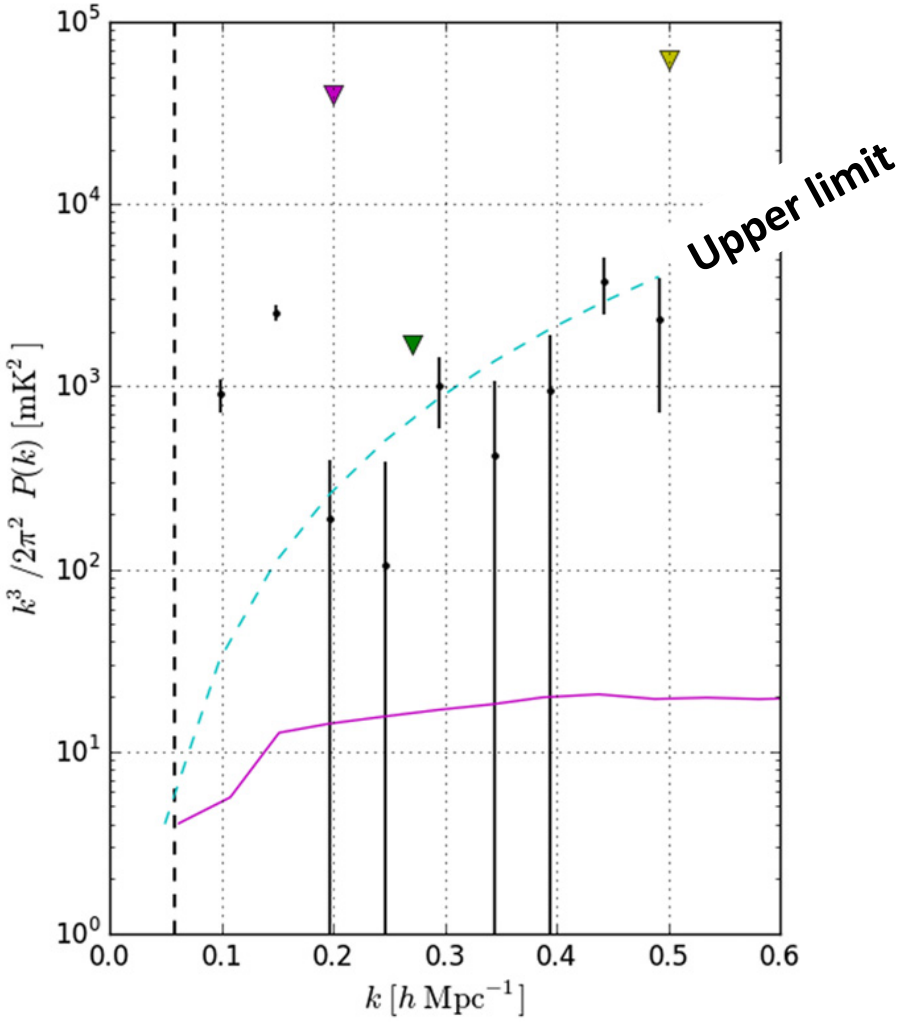


bright sub-sample



The time is now!

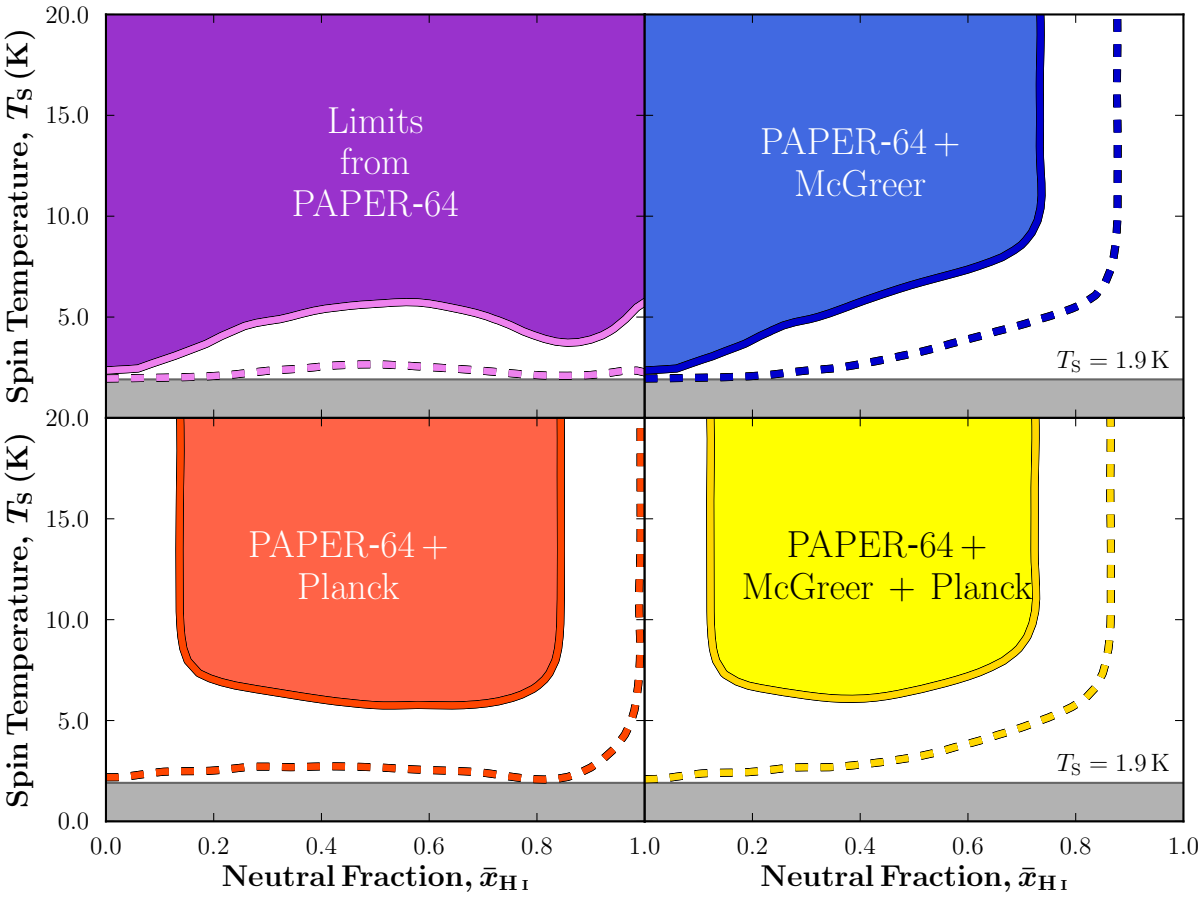
- 1st gen. interferometers are already taking data, ruling-out extreme models with no heating



Ali+ (2015)

The time is now!

- 1st gen. interferometers are already taking data, ruling-out extreme models with no heating



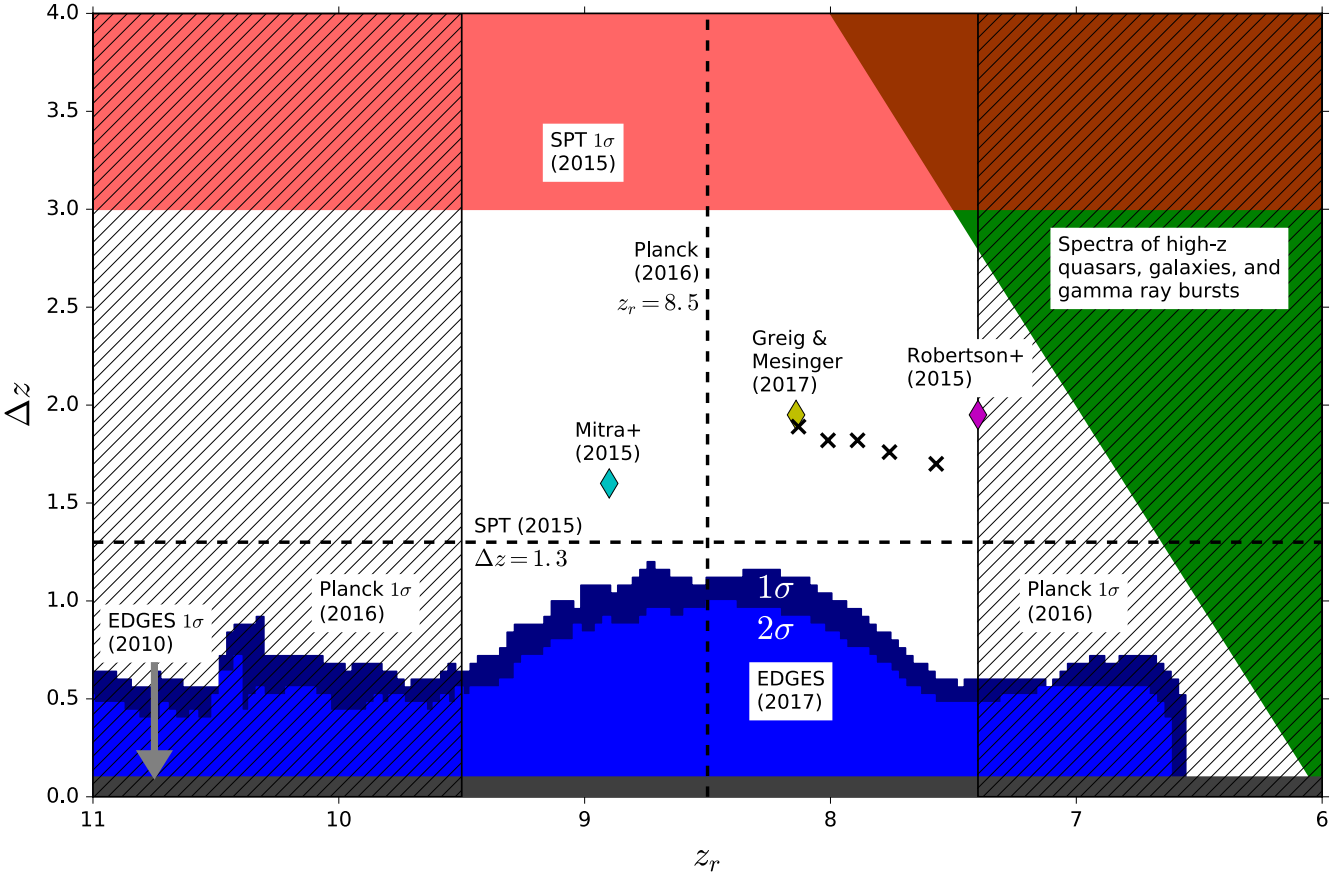
$\langle T_{HI} \rangle > 6$ K @ z=8.4

← adiabatically-cooled IGM

Greig, AM, Pober (2016)
(see also Pober+2015)

The time is now!

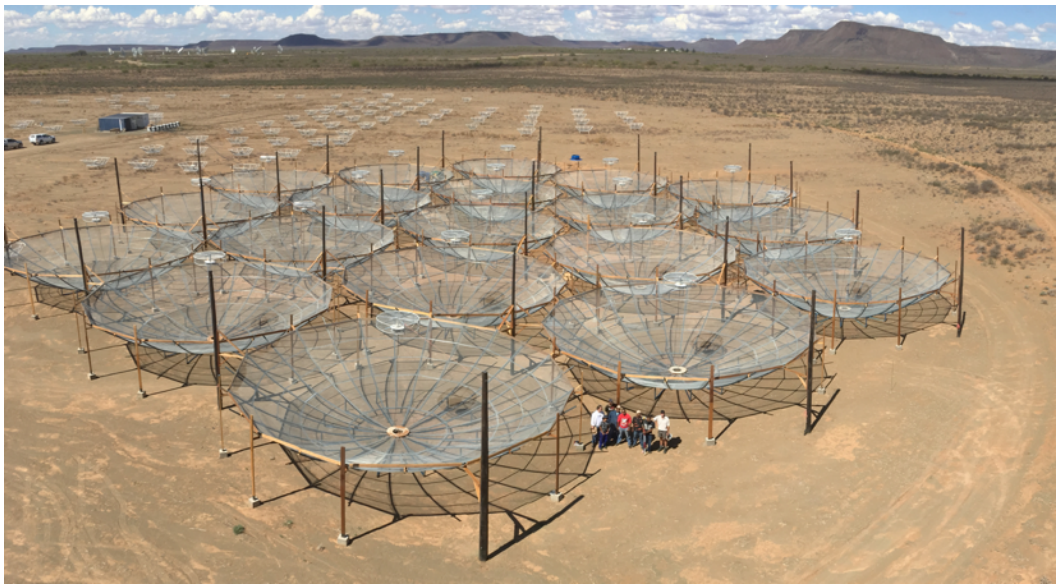
- 1st gen. single-antenna instruments are ruling-out extreme models with a rapid reionization



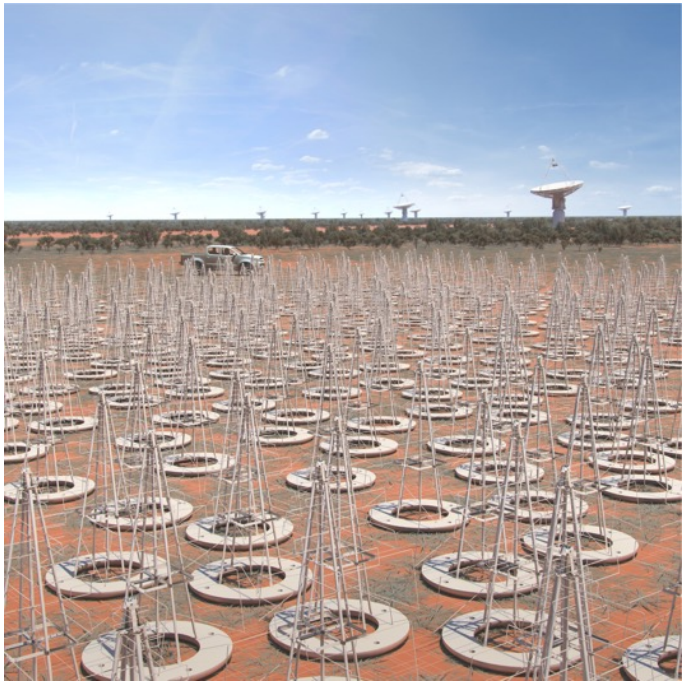
Monsalve+ (2017)

The time is now!

- 2nd gen. interferometers, HERA & SKA1, are coming in the next few years, bringing high S/N detections throughout the Cosmic Dawn

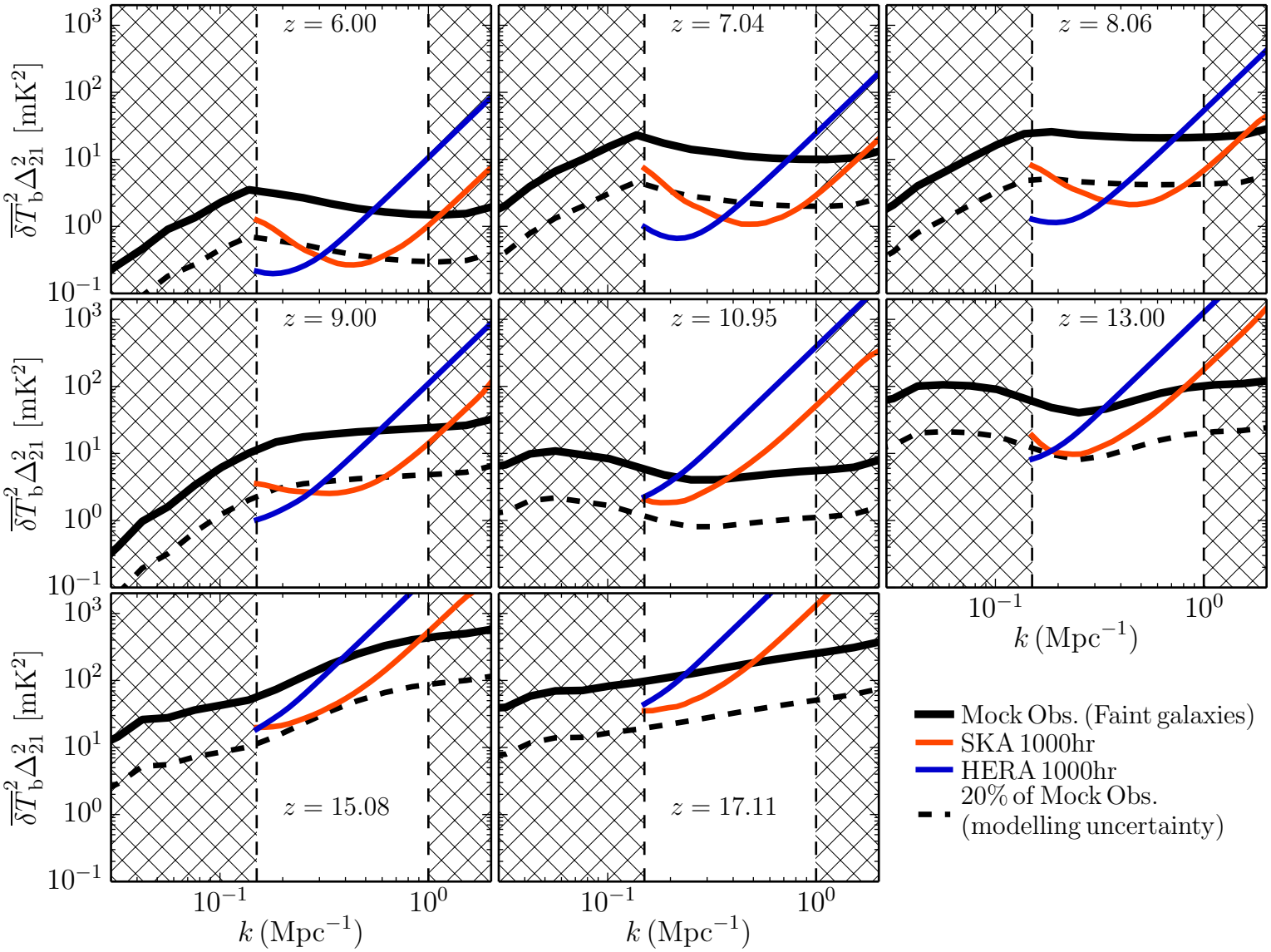


first 19 of planned 350 HERA dishes



rendering of SKA1-Low

Sensitivities



Simulation slice