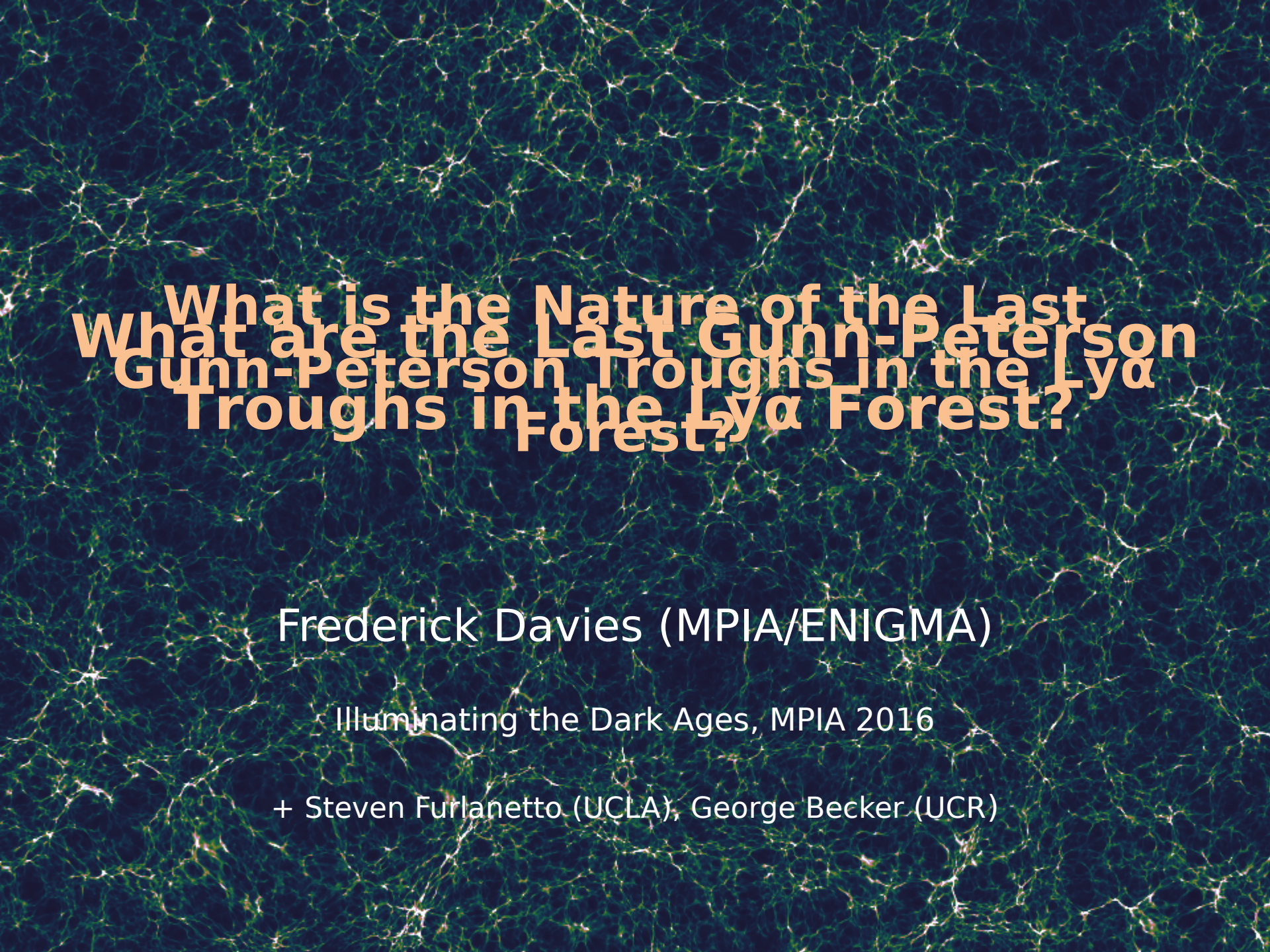


What is the Nature of the Last Gunn-Peterson Troughs in the Lyα Forest?

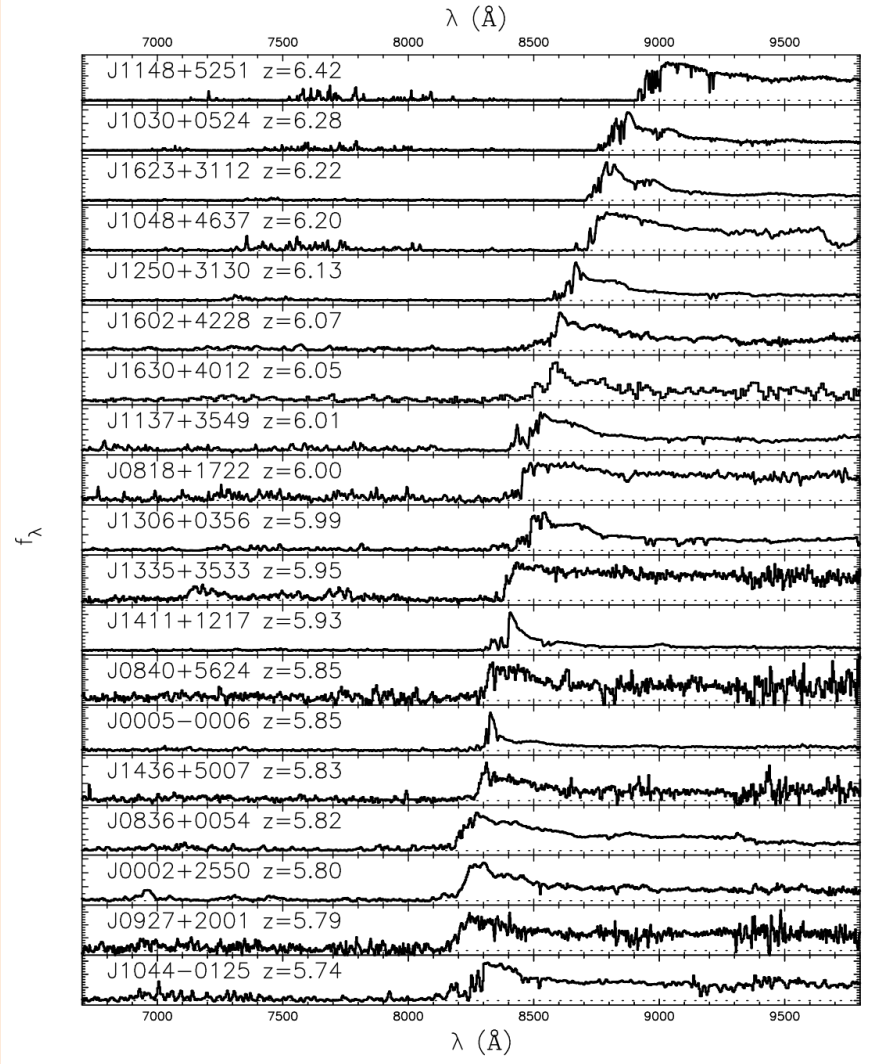
What are the Last Gunn-Peterson Troughs in the Lyα Forest?

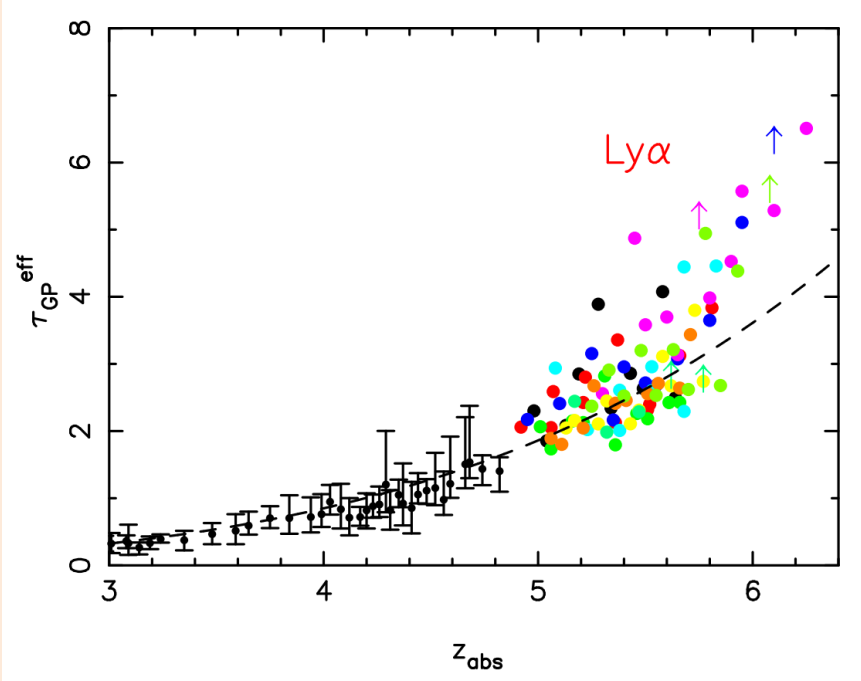
Frederick Davies (MPIA/ENIGMA)

Illuminating the Dark Ages, MPIA 2016

+ Steven Furlanetto (UCLA), George Becker (UCR)

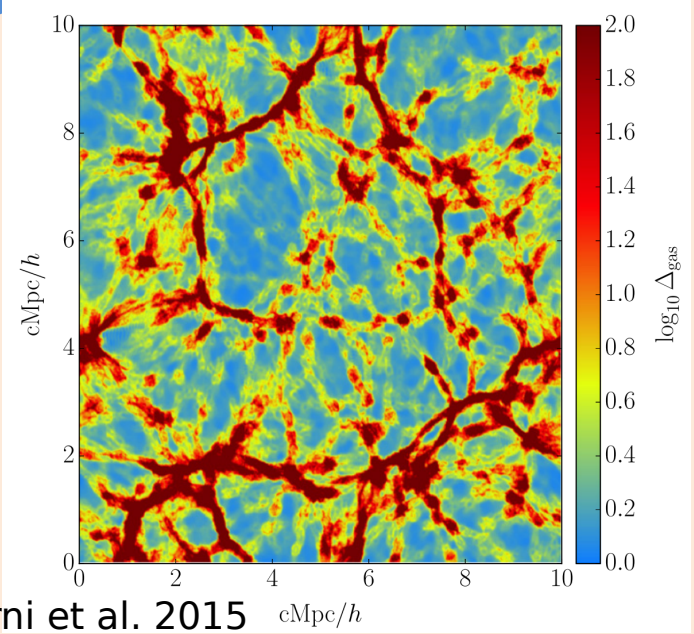
Lyα forest transmission constrains the end of the reionization epoch





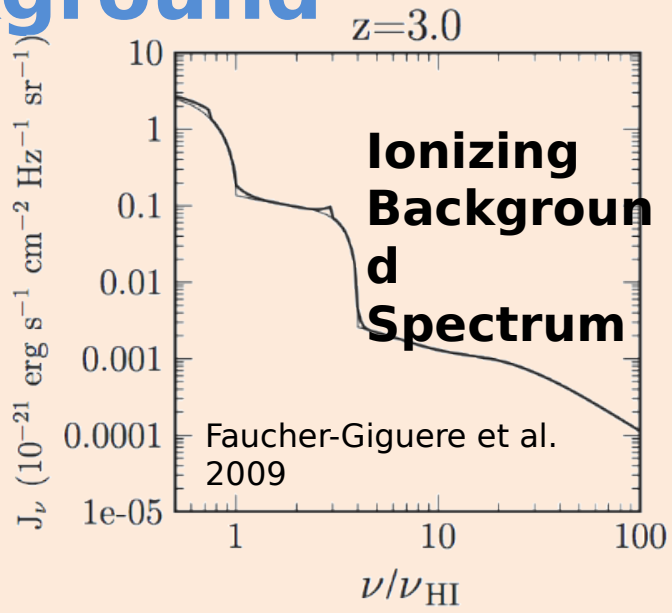
Fan et al. 2006

At “low” redshift, the Lyα forest represents the cosmic web processed by a uniform UV background

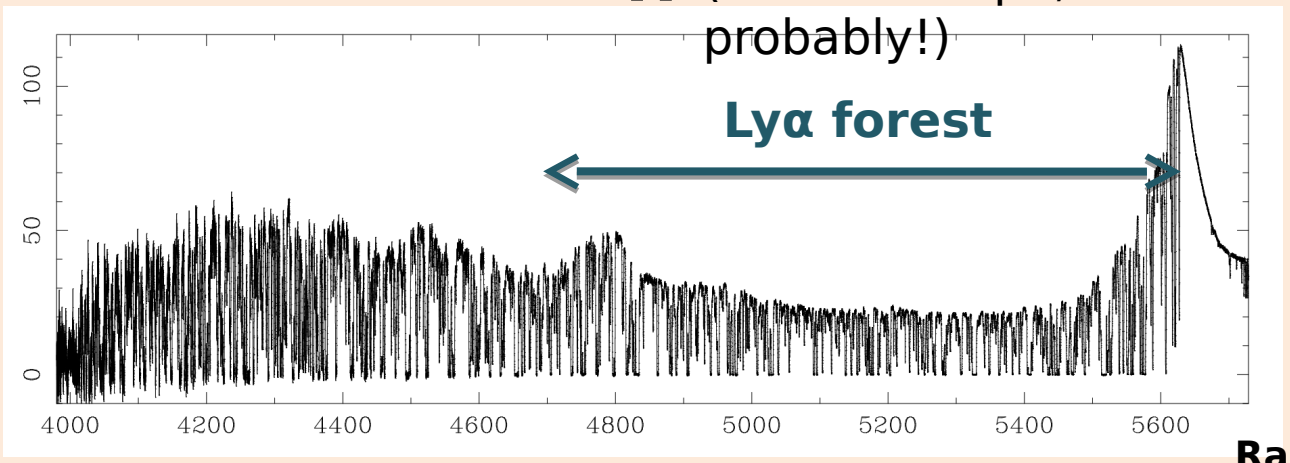


Kulkarni et al. 2015

+

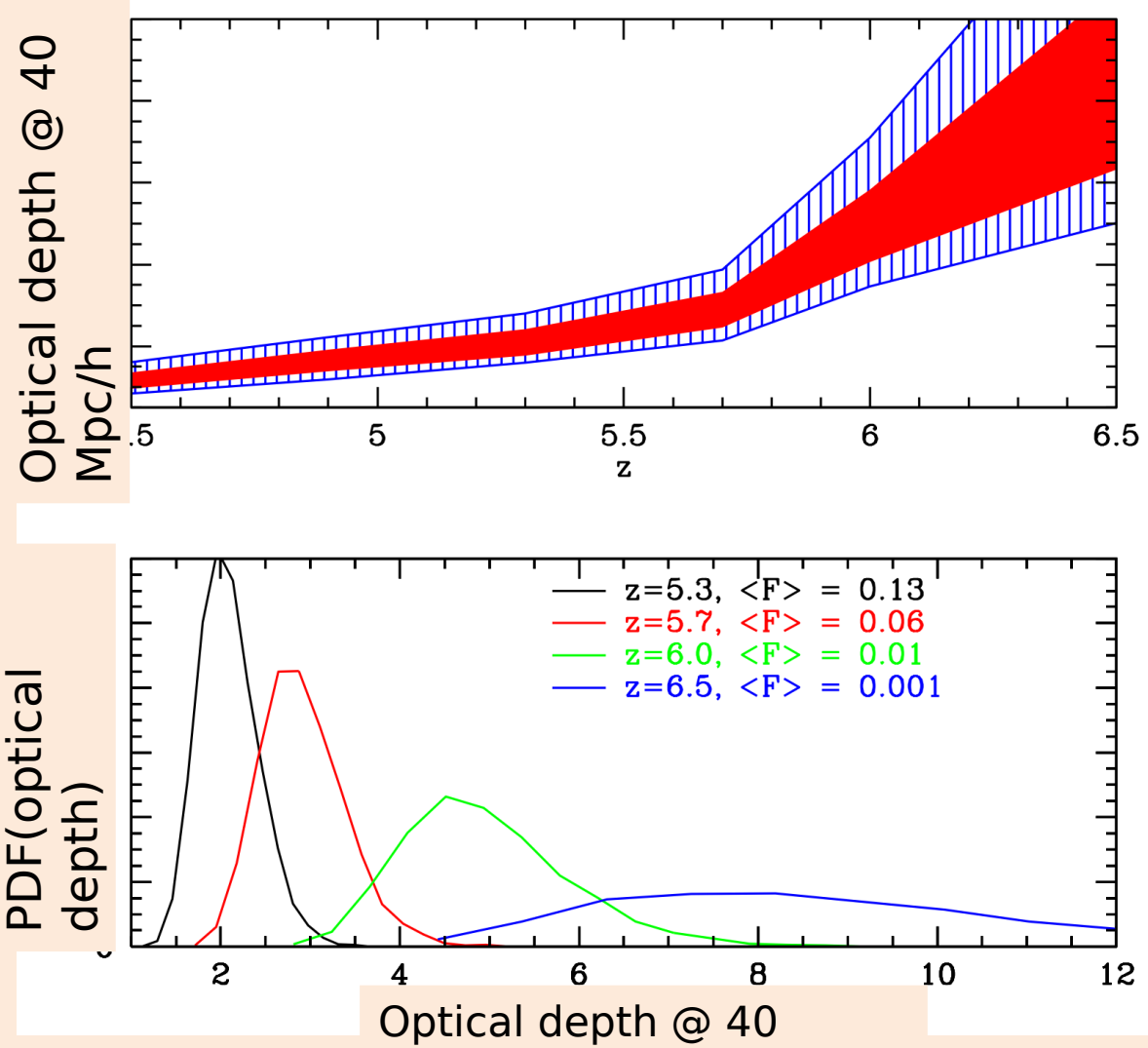


= (+ a telescope, probably!)



Rauch 1998

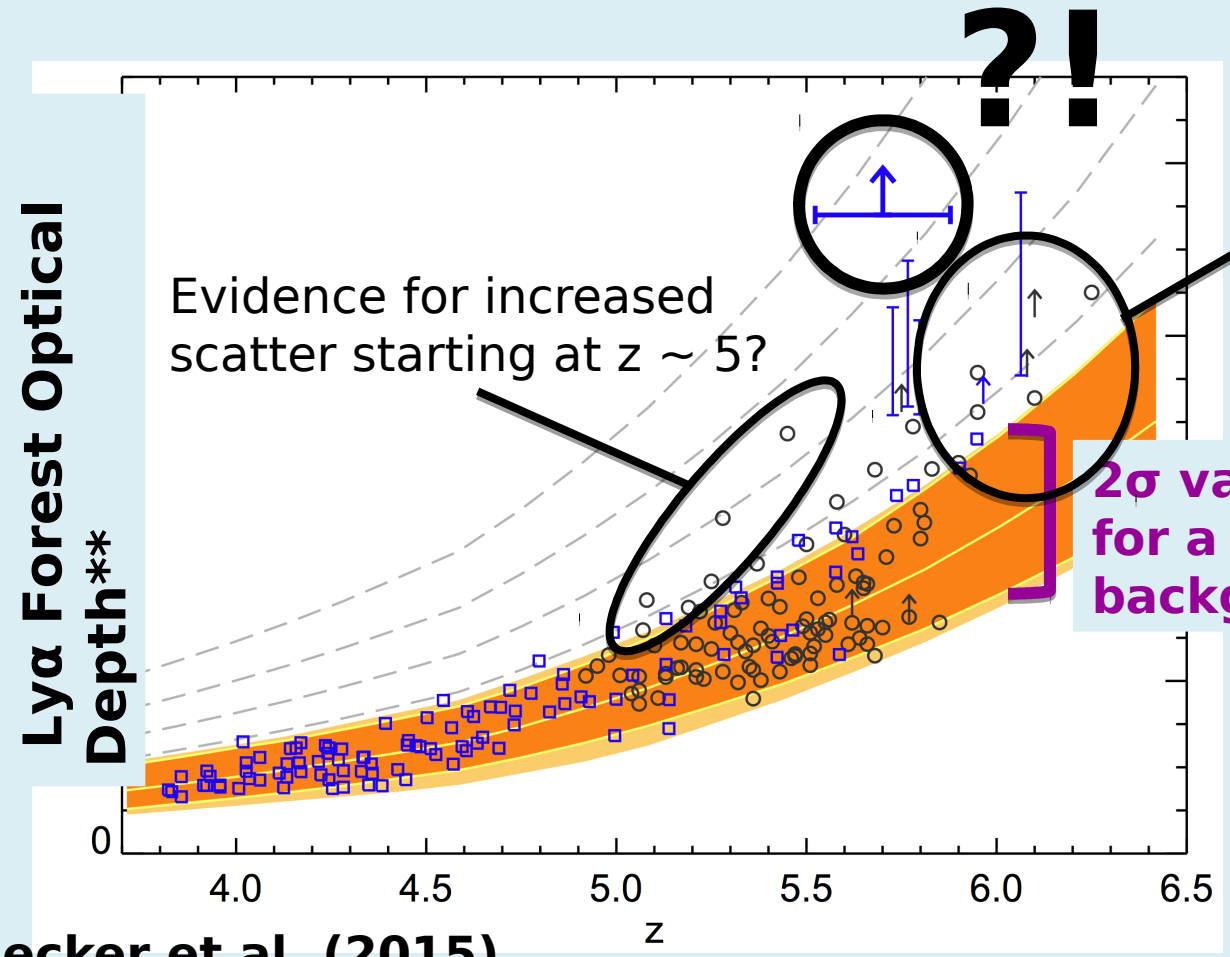
Formation of cosmic structure predicts scatter in optical depth



At high optical depths, the scatter increases

Lidz et al. 2006

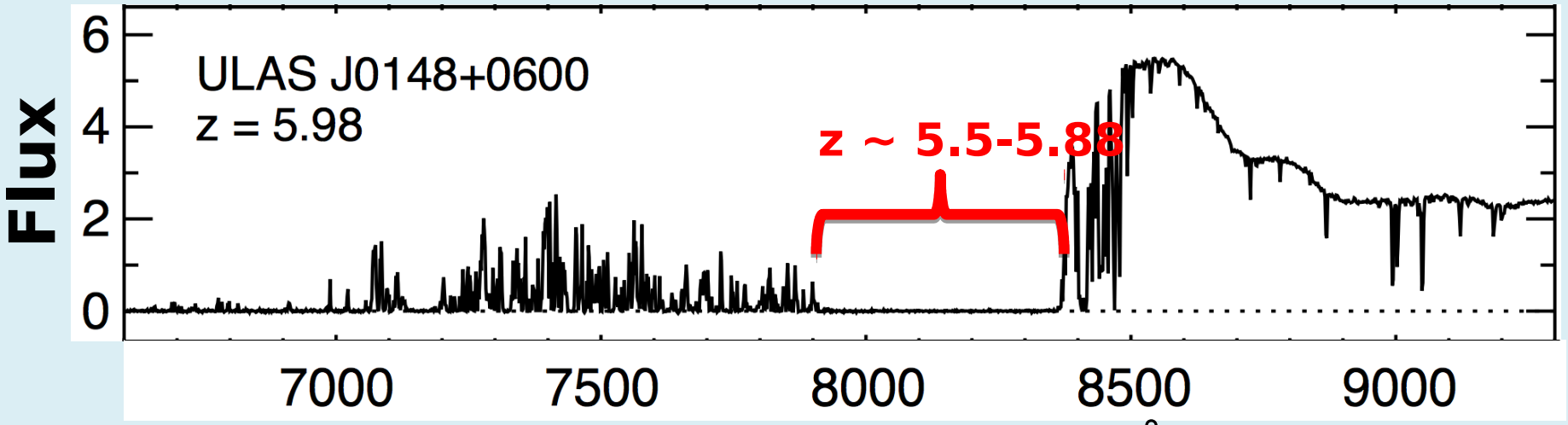
Above z ~ 5.5, variation in Lyα forest opacity increases above the density field expectation



Becker et al. (2015)

**Optical depth measured in (roughly) 50 Mpc/h bins of the

Observation: ~100 Mpc/h Lyα GP trough at z ~ 5.7
Theorists: ??????????

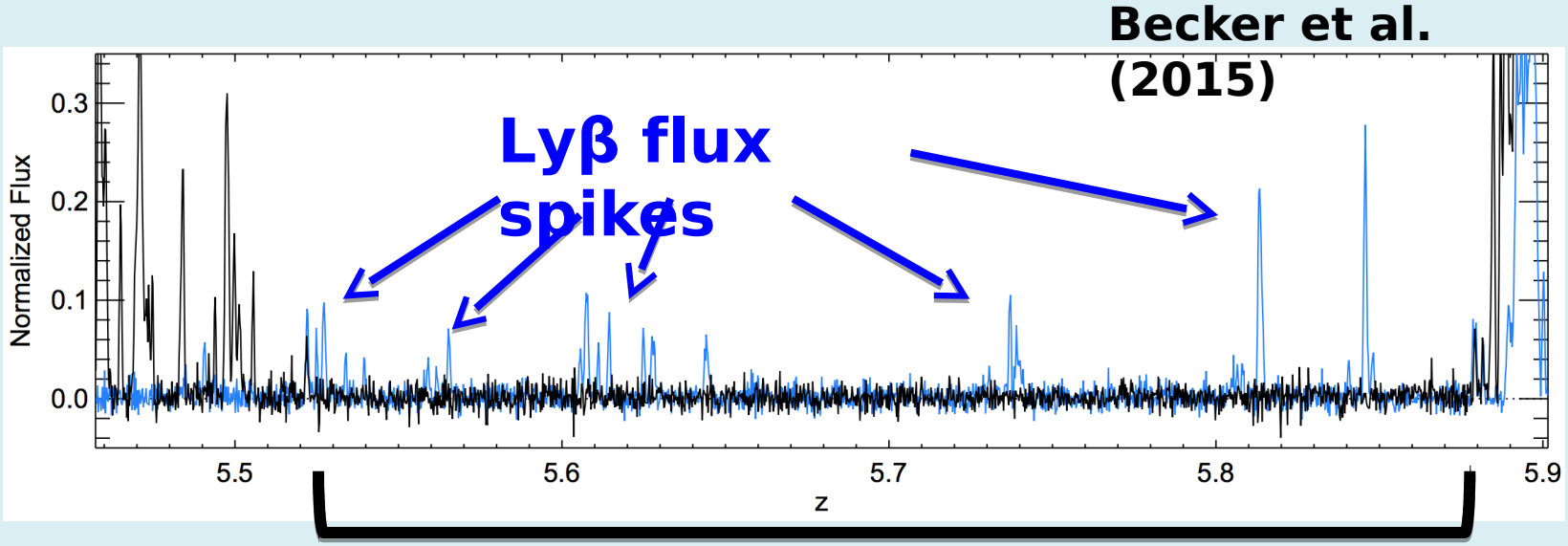


Becker et al. (2015)

Median Lyα optical depth at z ~ 5.7 is ~2.5

ULAS J0148+0600 Lyα trough optical depth > **7.4!**

But: there is substantial Lyβ transmission, probably not incomplete reionization!



Some physical property of the *ionized* IGM must be responsible…

What is required to reproduce the J0148+0600 trough?

Lyα forest opacity

Fraction of neutral hydrogen

$$\tau_{\rm eff}(\text{large scale}) \propto x_{\rm HI}^{\approx 0.6}$$

$$x_{\rm HI} \propto \Gamma^{-1} T^{-0.7}$$

Ionizing background strength

IGM temperature

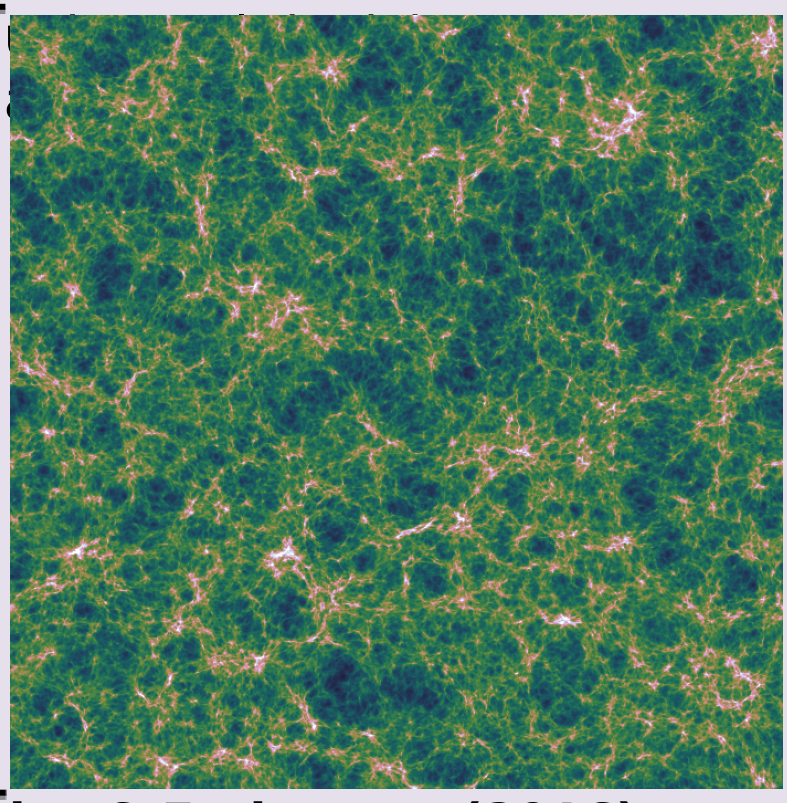
Two possible scenarios to account for the observed trough (within scatter!):

factor of ~3-4 weaker ionizing background than average (Davies & Furlanetto 2016)

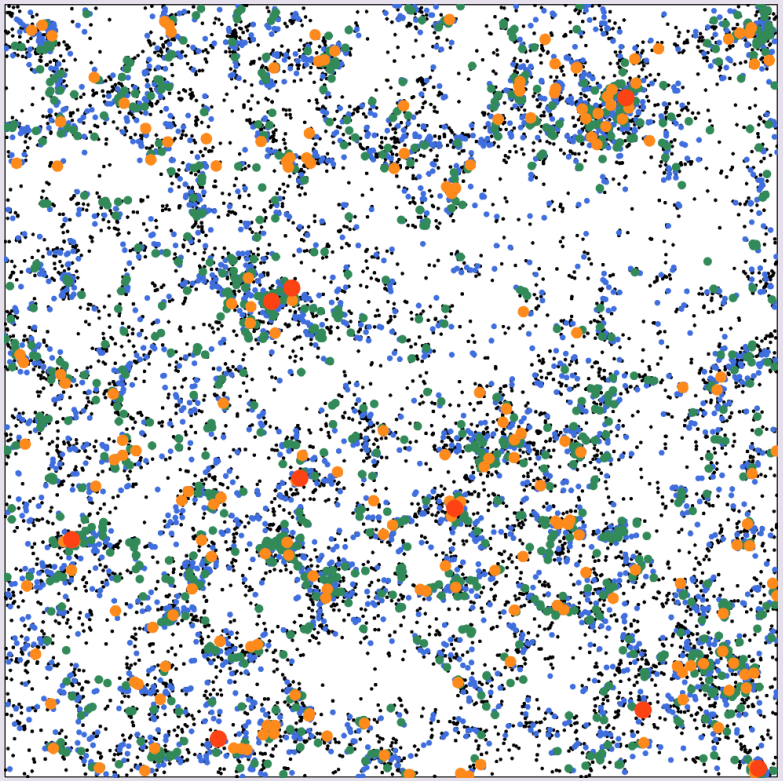
OR

"Semi-numerical" cosmological simulation: cheap, easy, large-volume

Quasi-linear density field @ z = 5.6



Semi-numerical halo field



Davies & Furlanetto (2016)

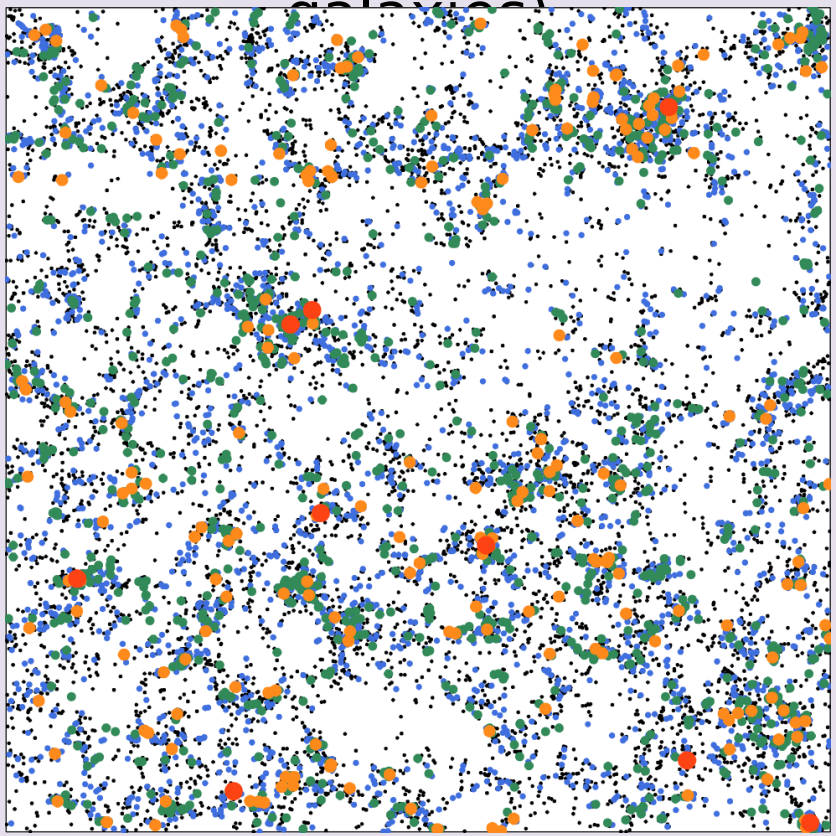
Semi-num code: DexM

Mesinger & Furlanetto (2007)

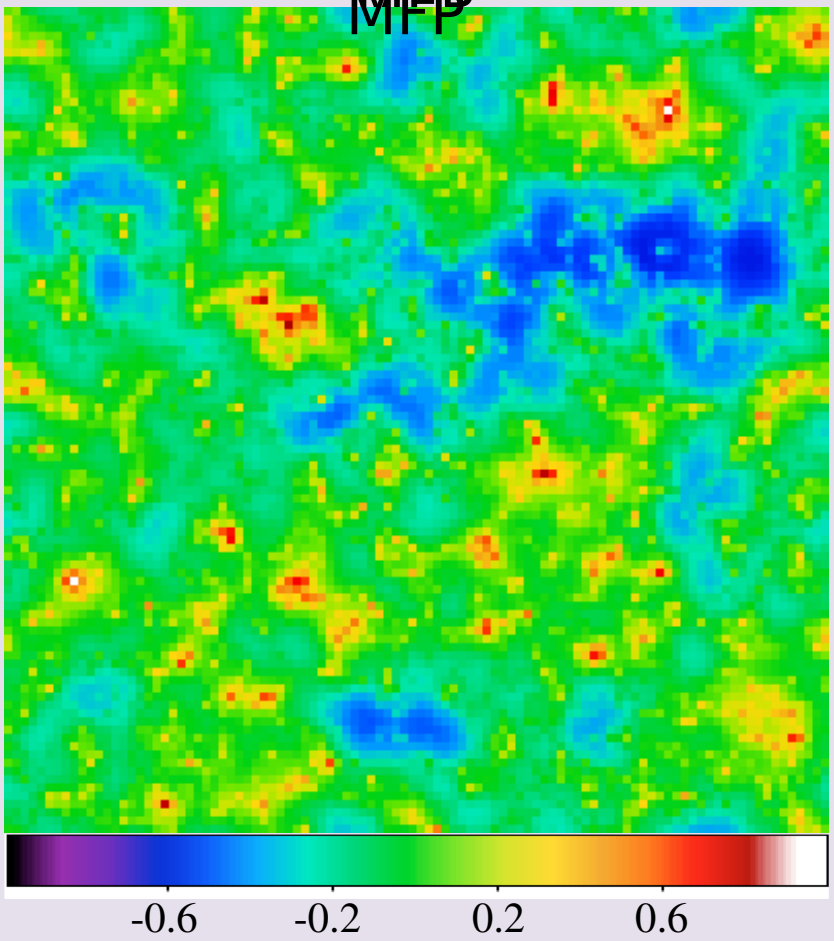
~25 million galaxies with $-12.9 < M_{UV} < -23.4$

Mean free path fluctuations can greatly increase ionizing background fluctuations

Halo field (M_{UV} < -18 galaxies)



Ionization rate, fluctuating MFP

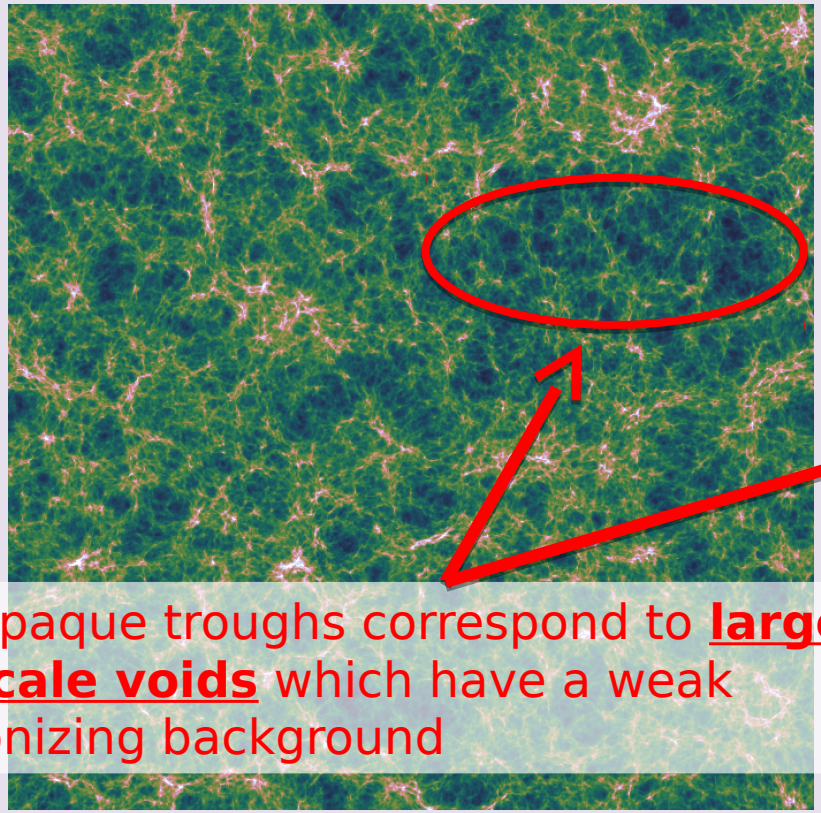


log Ionization Rate (relative to

Davies & Furlanetto (2016)

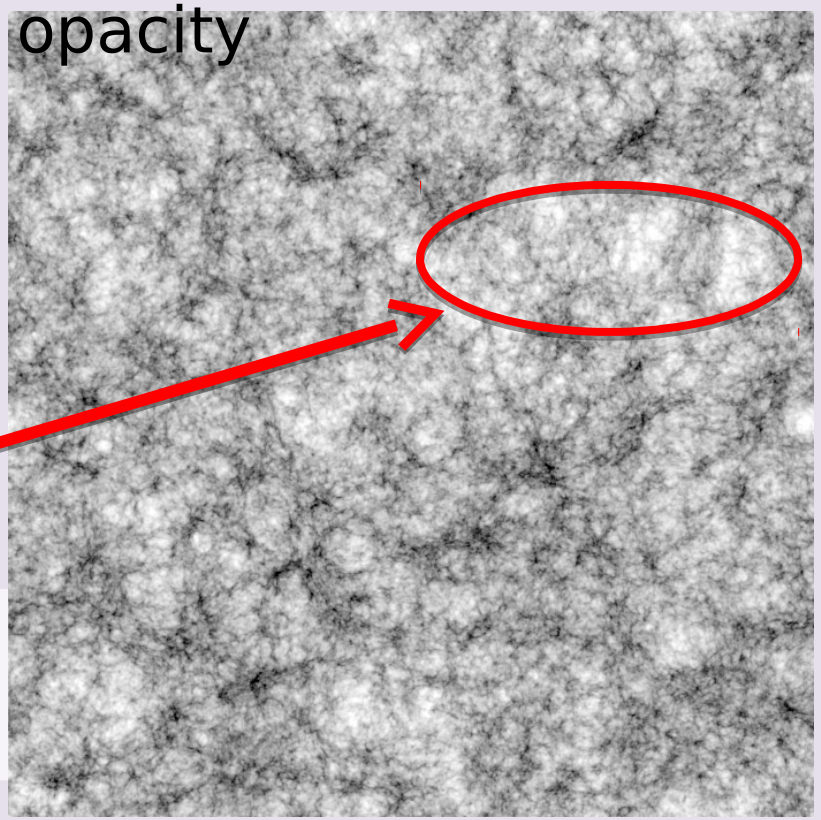
Relationship between Lyα forest opacity and density field is reversed vs low-z

Density field @ z = 5.6



50 Mpc/h Lyα forest opacity

Black = opaque
White = transparent



Opaque troughs correspond to **large-scale voids** which have a weak ionizing background

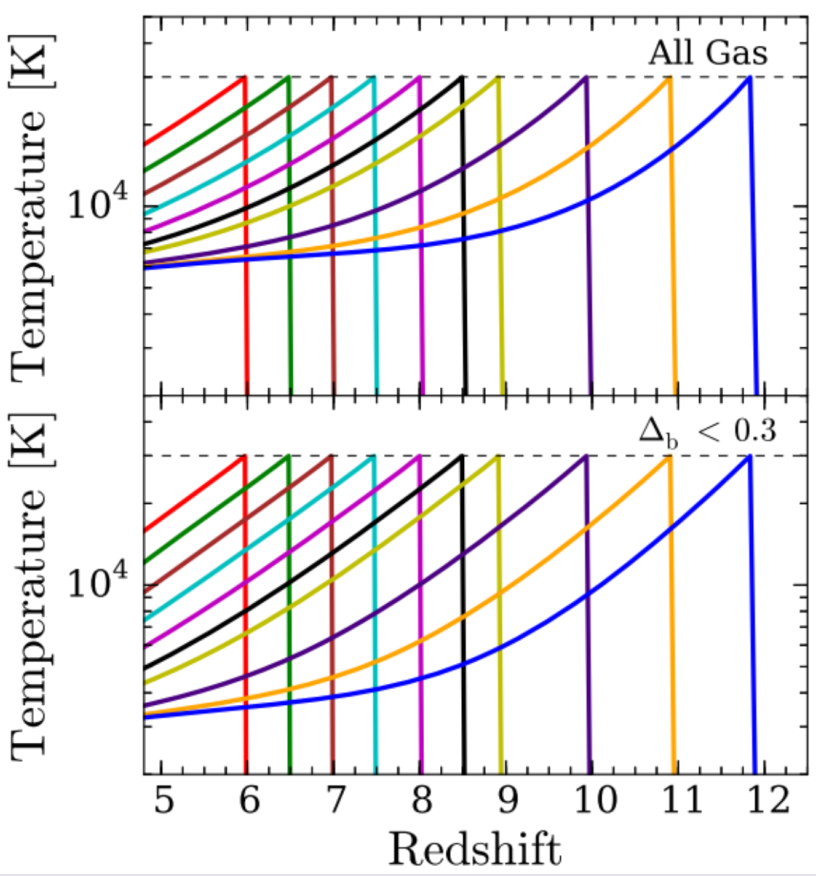
Davies & Furlanetto (2016)

Fluctuating ionizing background

Could it be temperature instead?

D'Aloisio et al. 2015:

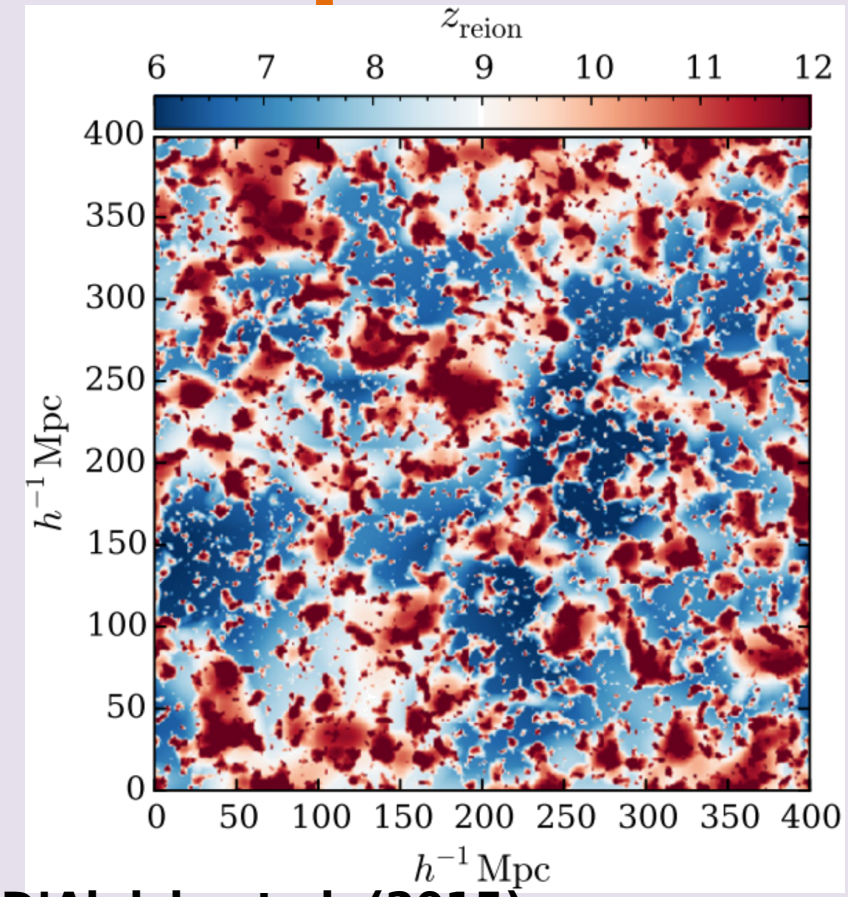
Temperature variations due to an extended reionization process

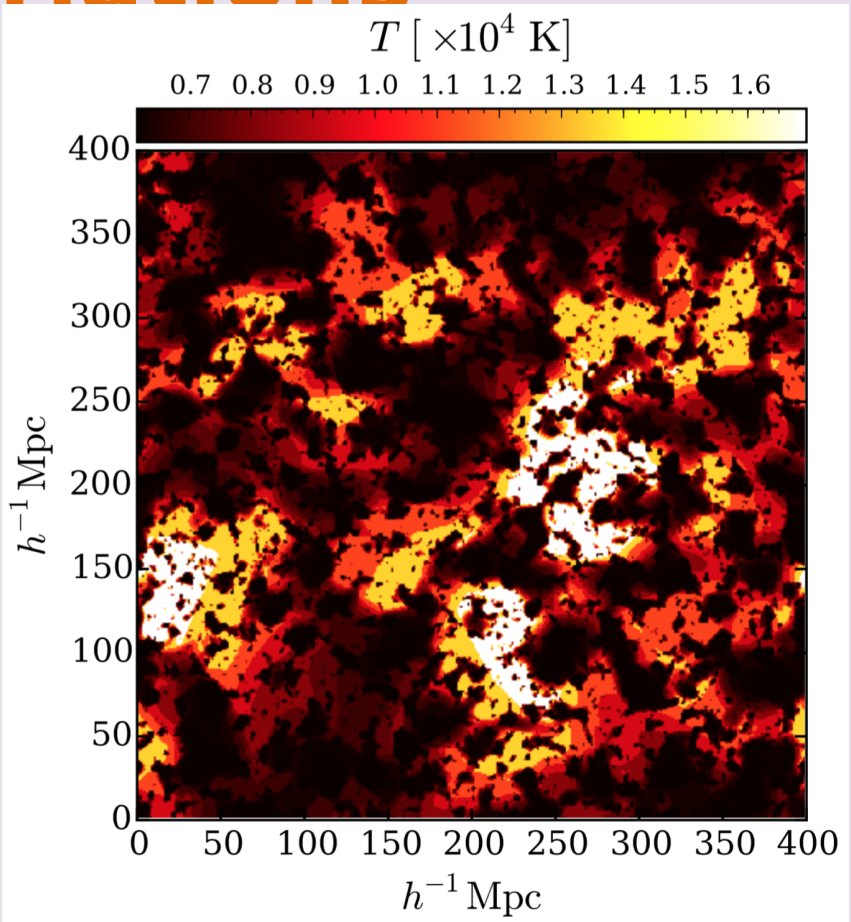


Gas instantaneously heated to a few times 10^4 K (e.g. Abel & Haehnelt 1999)

Colors ✉ reionization redshift

Extended reionization leads to strong large-scale temperature variations





D'Aloisio et al. (2015)

Opaque regions are **large-scale overdense regions** which reionized early

Open question: what is the nature of the last large opaque troughs in the Lyα forest?

<u>If it's the ionizing background:</u>

Large voids, far away from sources

<u>If it's the gas temperature:</u>

Large cold overdensities, which were ionized early (z>8? 9?)

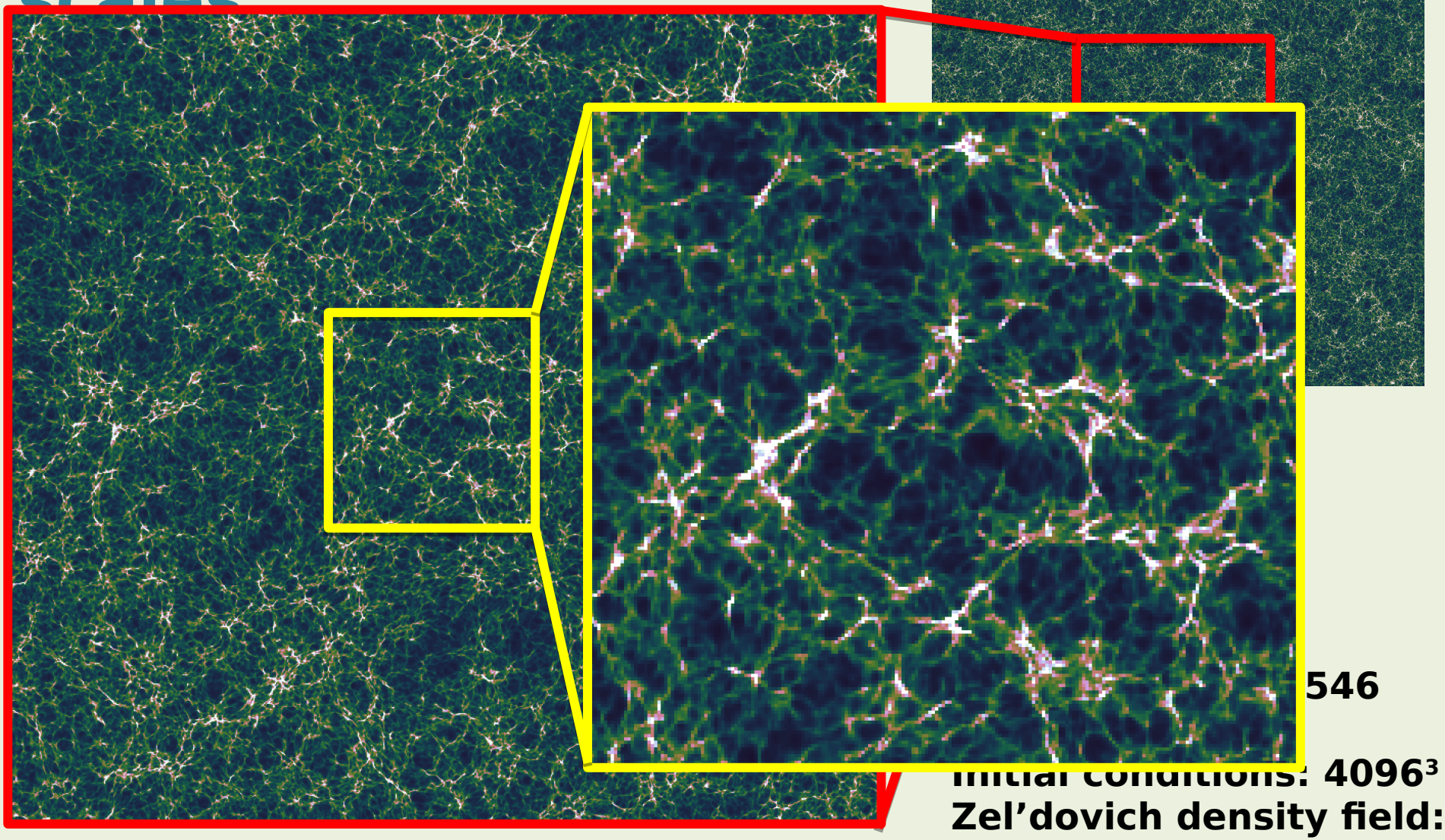
The two effects oppose each other, one has to dominate!

Is there another way to distinguish the models?

How about using galaxies to detect the large-scale density?

**Need to simulate distribution of galaxies in *rare*

simulation to probe ~100 Mpc/h scales

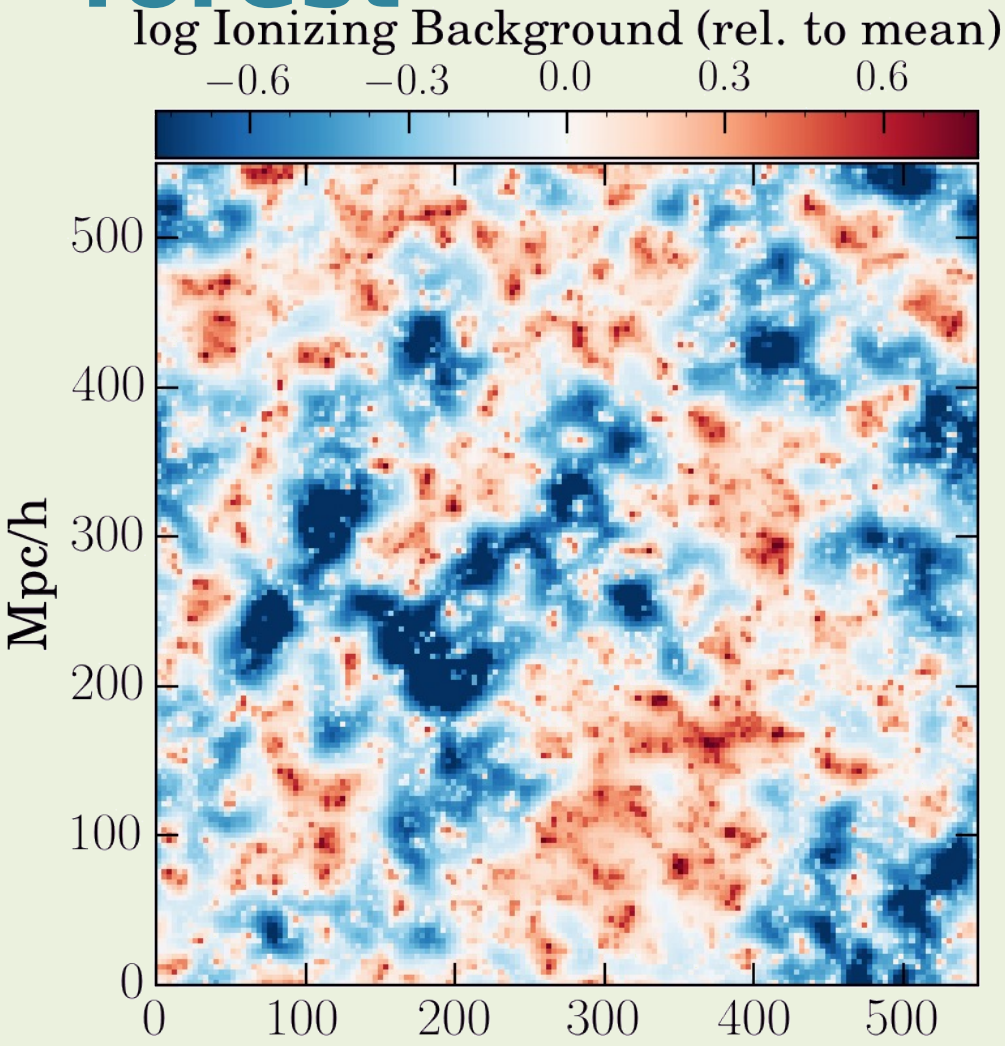


546

Initial conditions: 4096^3
Zel'dovich density field: 2048^3

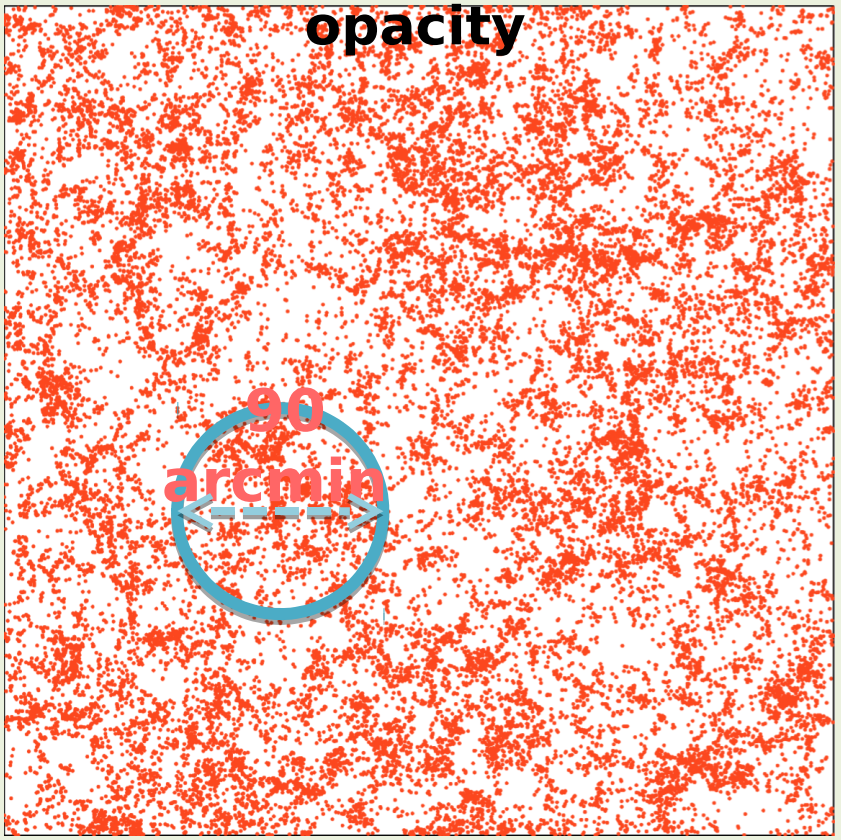
1-pixel-thick (~380 ckpc) density field slice

~100 Mpc-scale features in the ionizing background and Lyα forest



Davies et al., in prep

50 Mpc/h Lyα forest opacity

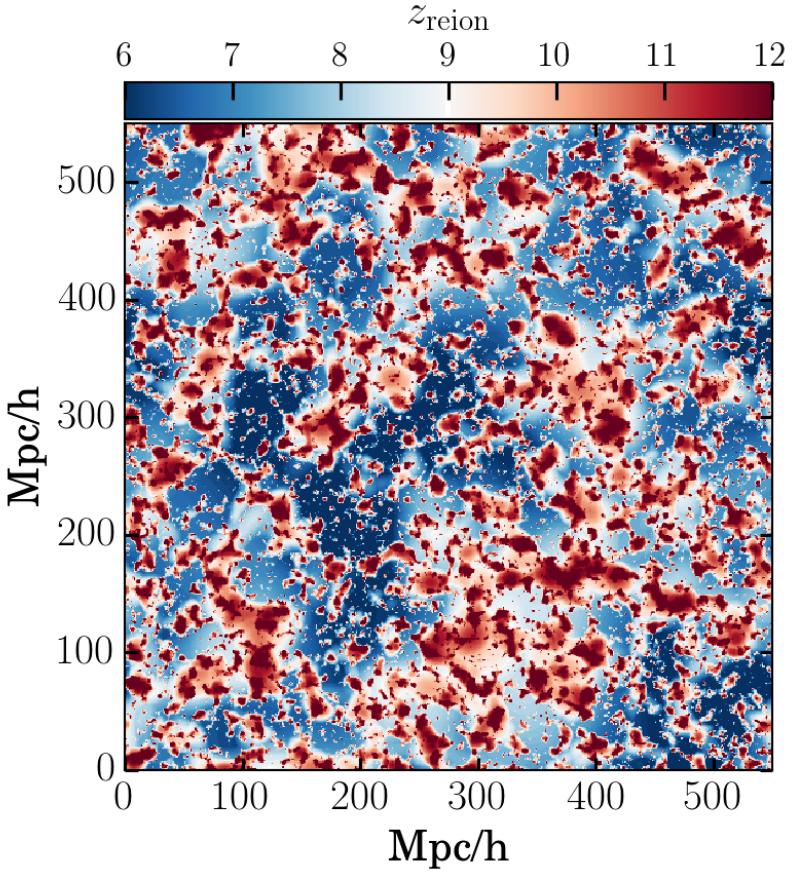


"Bright" M_{UV} < -19 galaxies

Adding temperature fluctuations to the semi-numerical model

Need to include two more calculations:

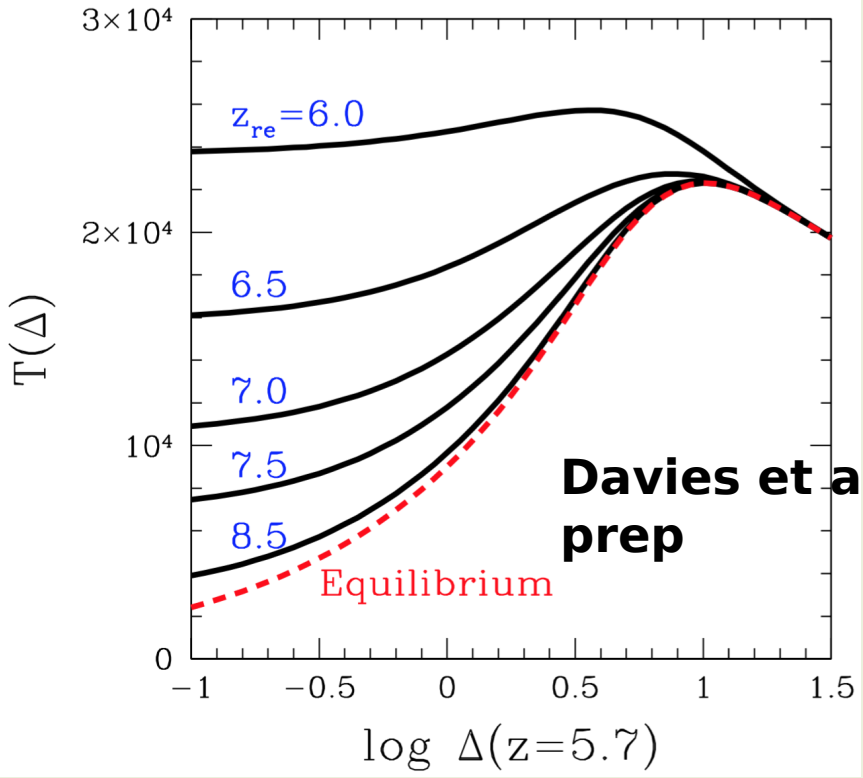
Inhomogeneous



(Computed via excursion set,

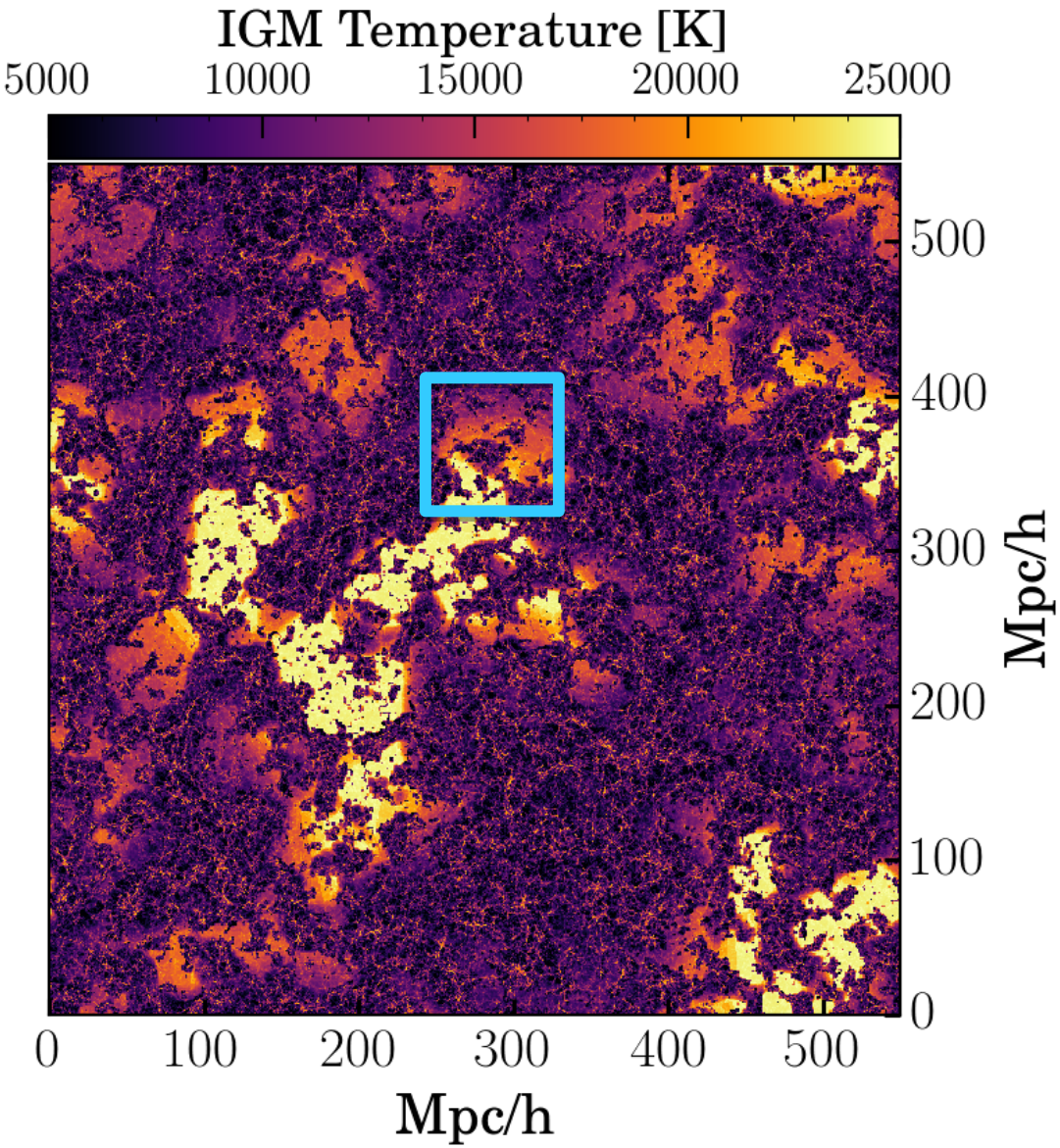
Temperature evolution

$$\frac{dT}{dt} = -2HT + \frac{2T}{3\,\Delta}\frac{d\Delta}{dt} - \frac{T}{n_{\rm tot}}\frac{dn_{\rm tot}}{dt} + \frac{2}{3k_B n_{\rm tot}}\frac{dQ}{dt}$$



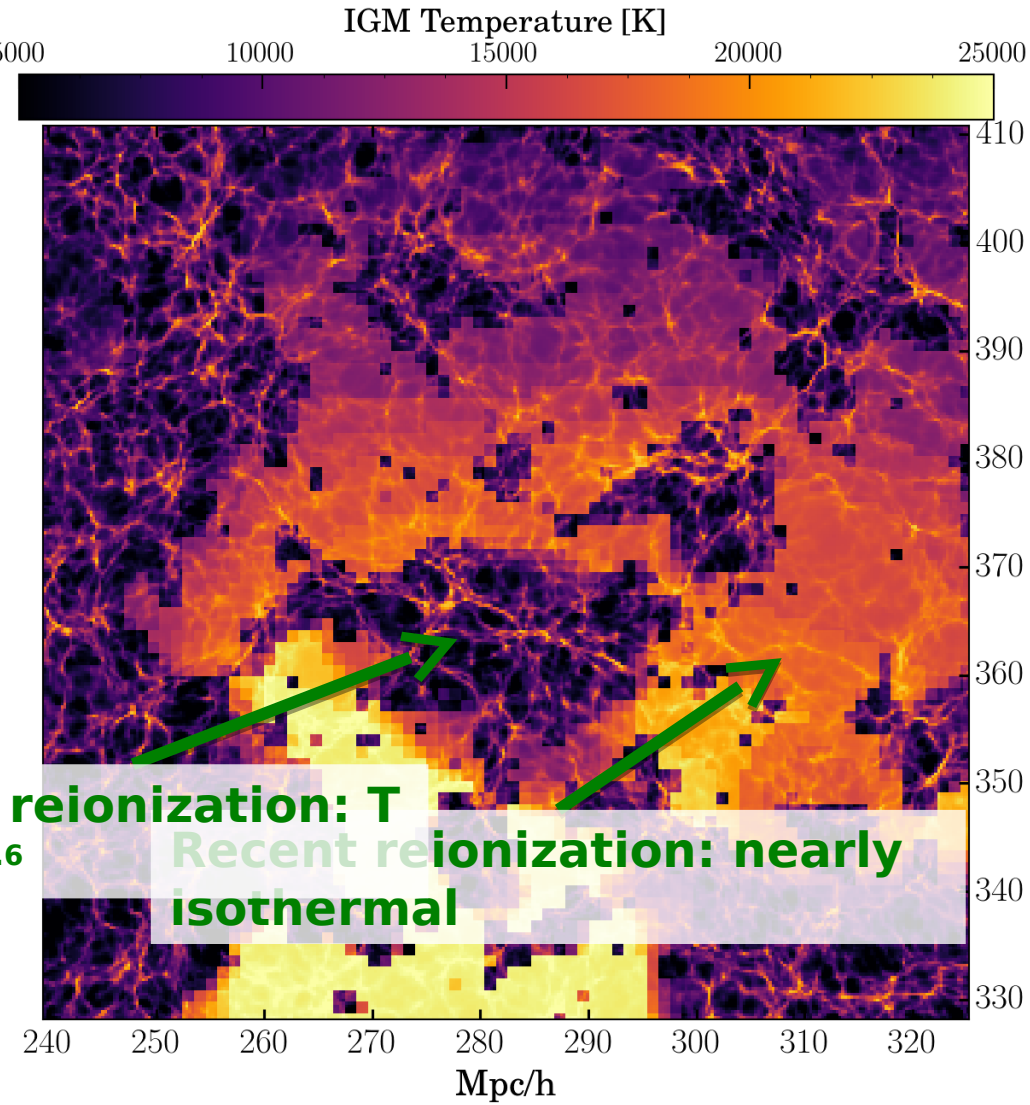
Davies et al., in prep

Inhomogeneous IGM temperature model



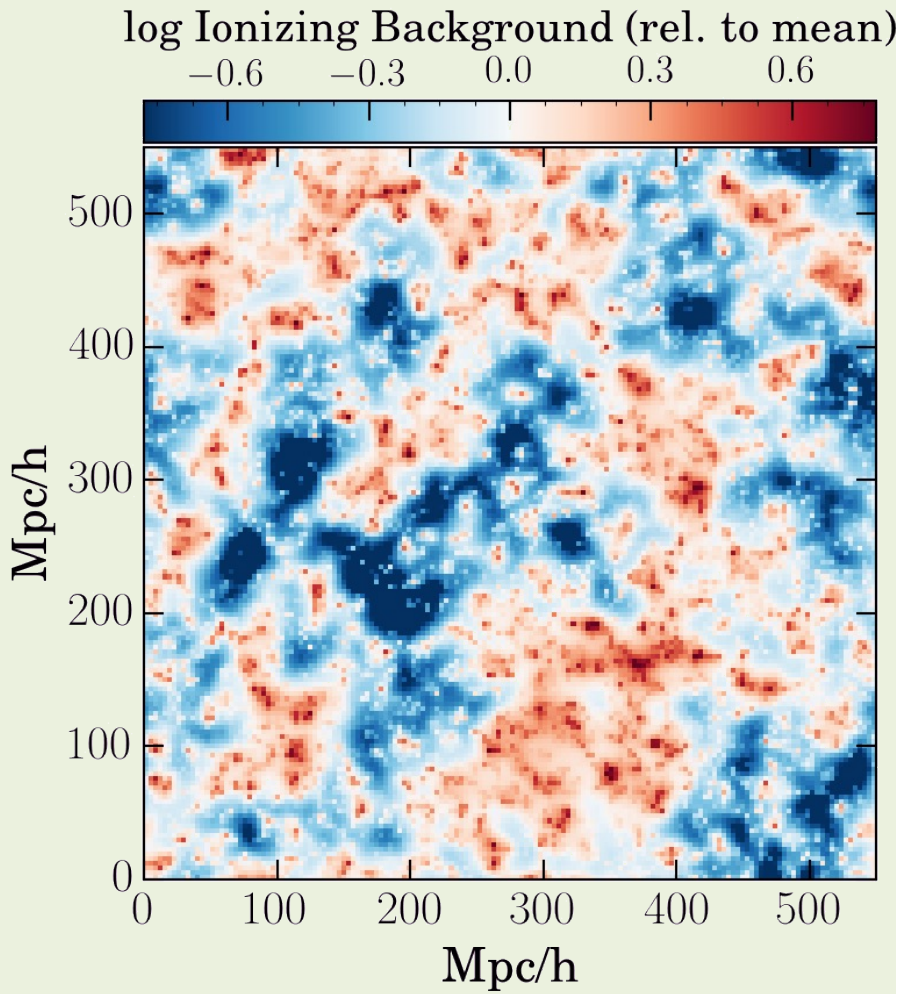
See also:
Trac et al. 2008
Lidz & Malloy 2014

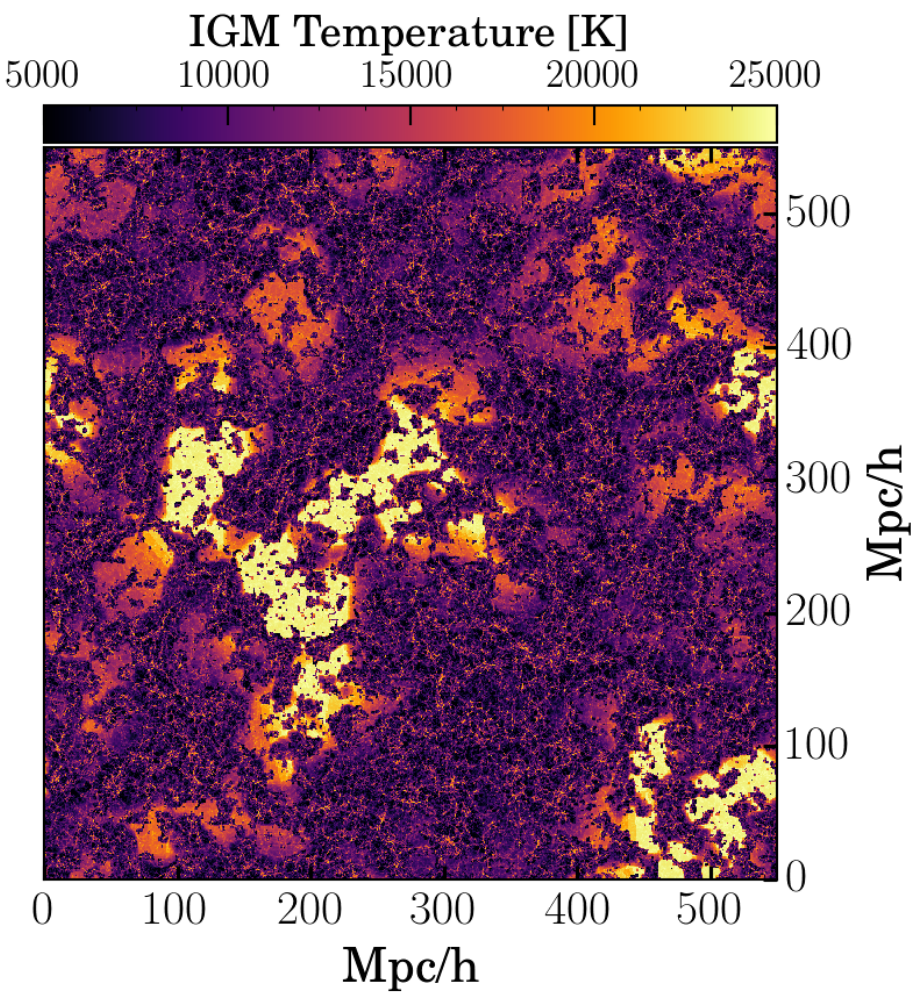
Inhomogeneous IGM temperature model



Note: reionization map is only 512^3, dz=0.1, but this will improve!

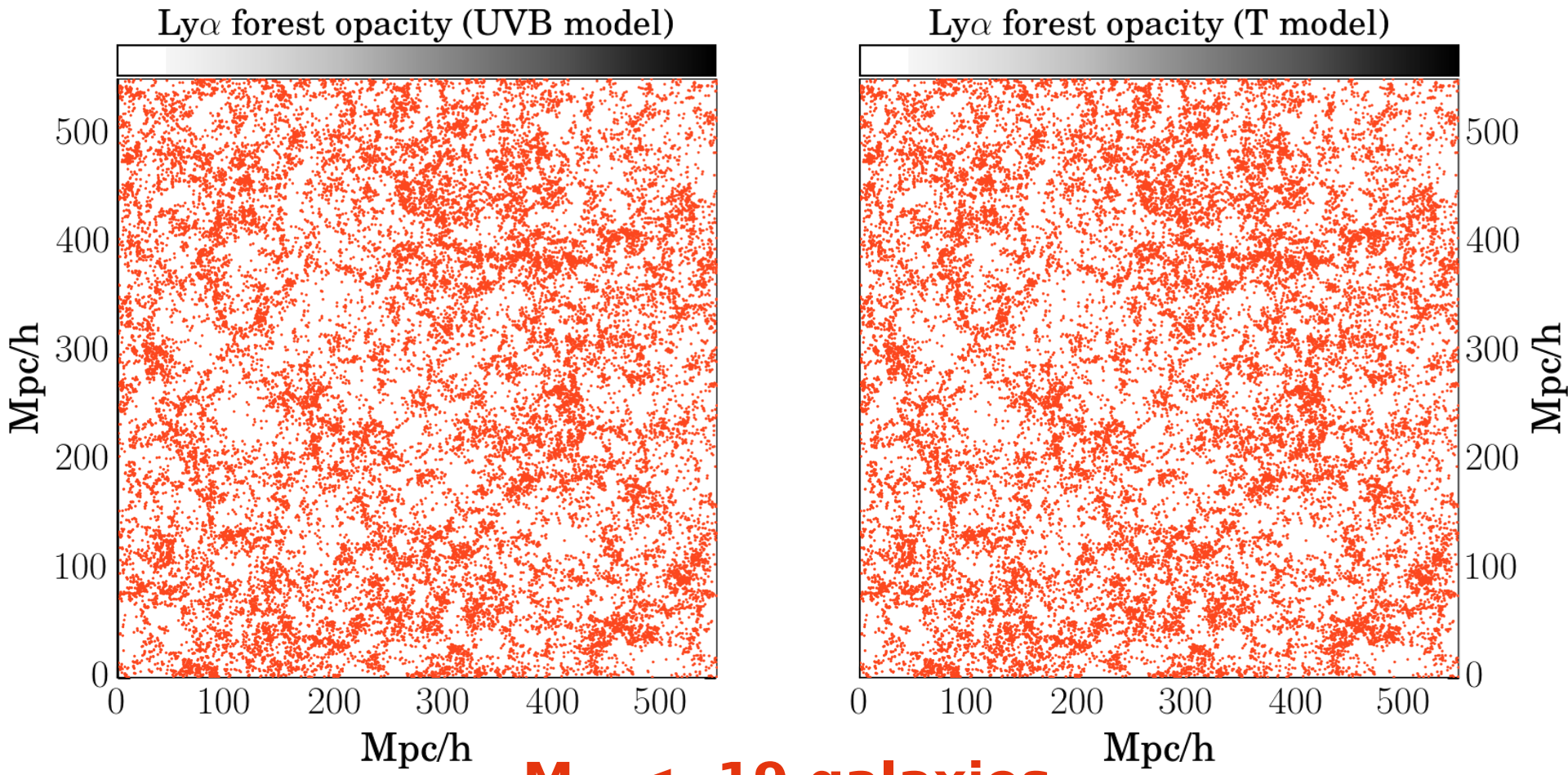
Relationship between density and Lyα forest opacity is opposite between the two models





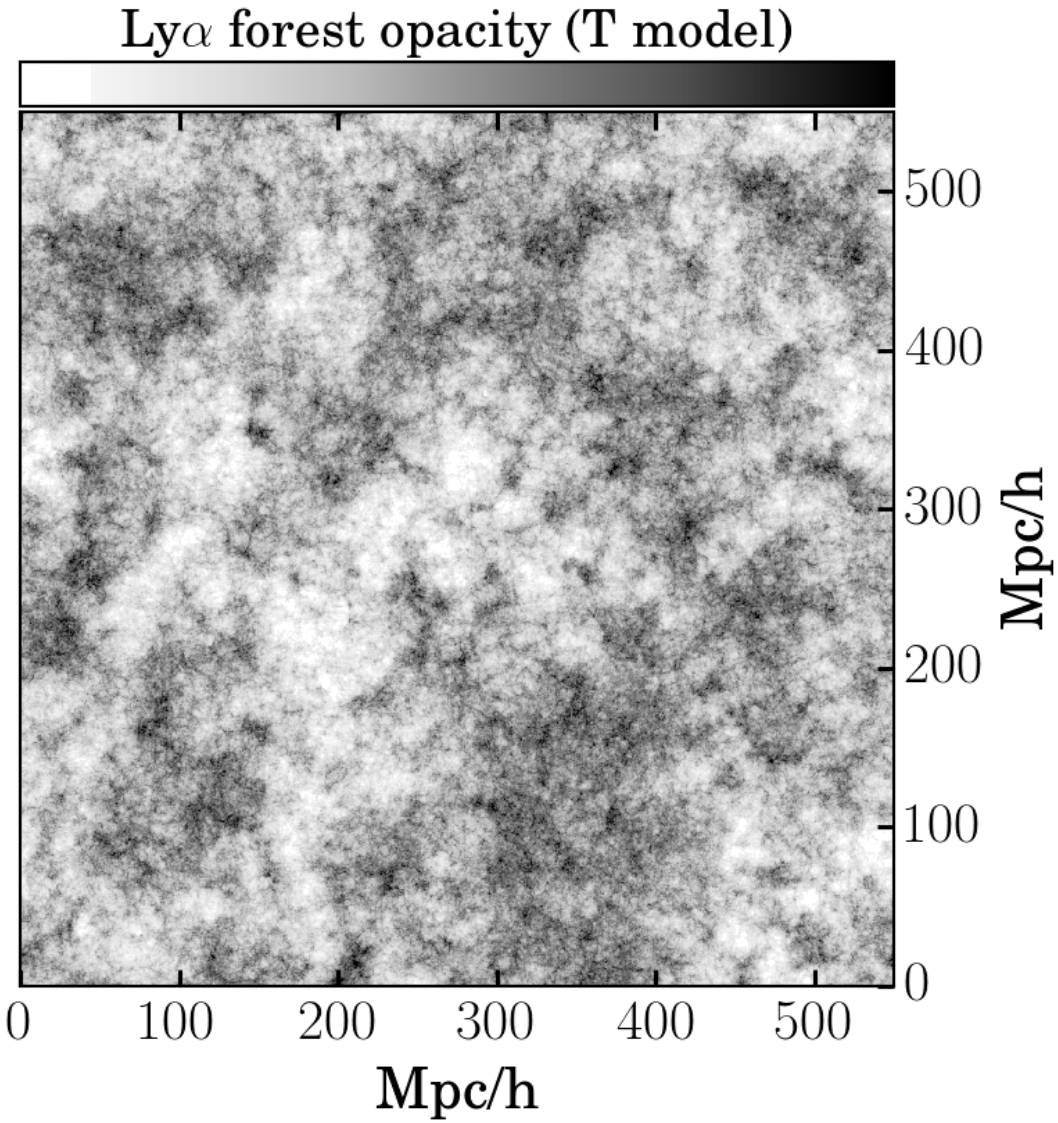
Davies et al., in prep

Relationship between density and Lyα forest opacity is opposite between the two models



$M_{UV} < -19$ galaxies

Davies et al., in prep

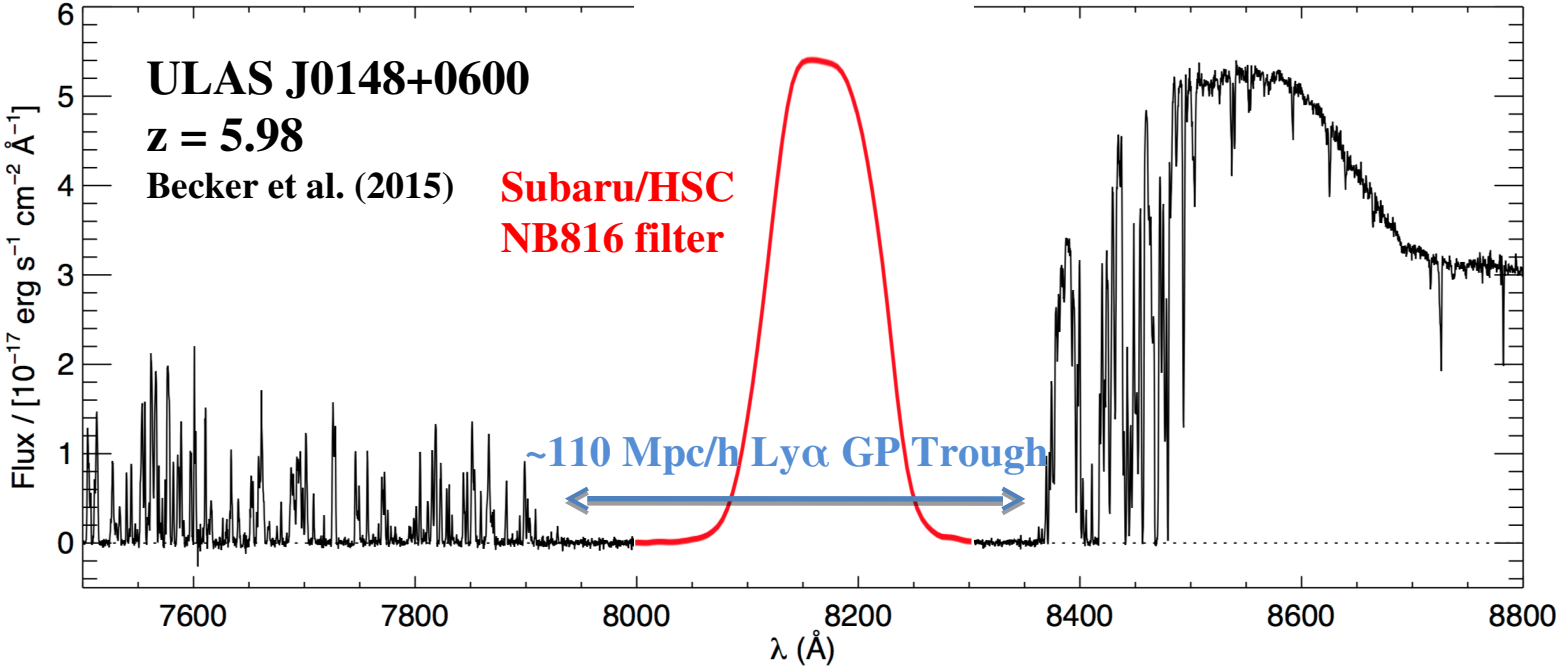

Lyα forest opacity (T model)
0
100
200
300
400
500
Mpc/h
0
100
200
300
400
500
Mpc/h

Can we distinguish between models with a galaxy survey?

ULAS J0148+0600 GP trough covers z~5.52-5.88

LBG redshifts accurate to dz~1 (photo-z)

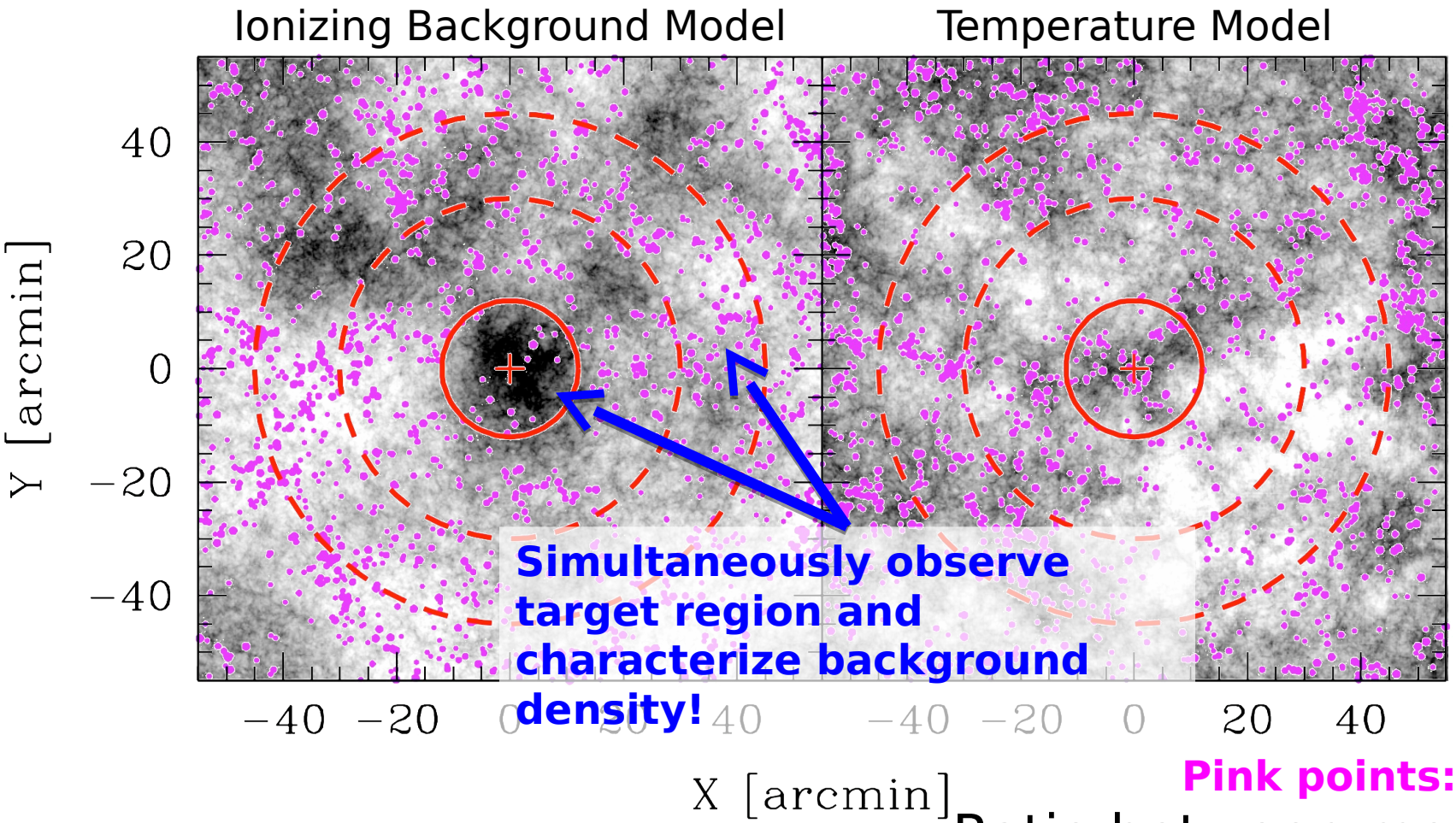
LAE redshifts accurate to dz~0.1



The void or overdensity is weak, but large scale, need a very large field of view for statistical sample

Subaru Hyper Suprime-C

How many galaxies (LAEs) should we see around a giant Gunn-Peterson trough?



Pink points: Lyα em

Ratio between models is ~4x

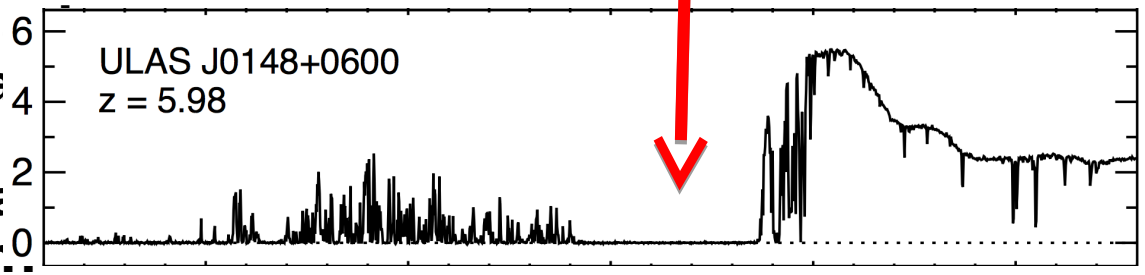
Outer dashed circle:
Subaru Hyper Suprime-Cam field of view

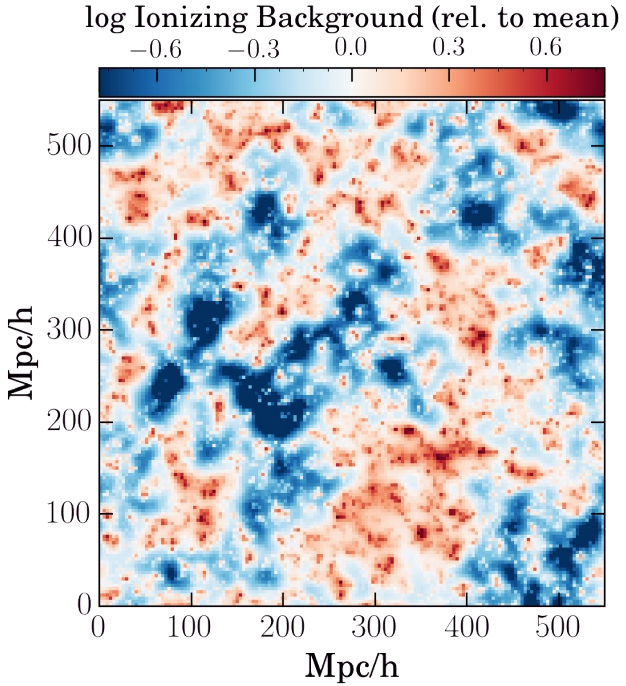
The nature of observed Gunn-Peterson troughs is unknown!

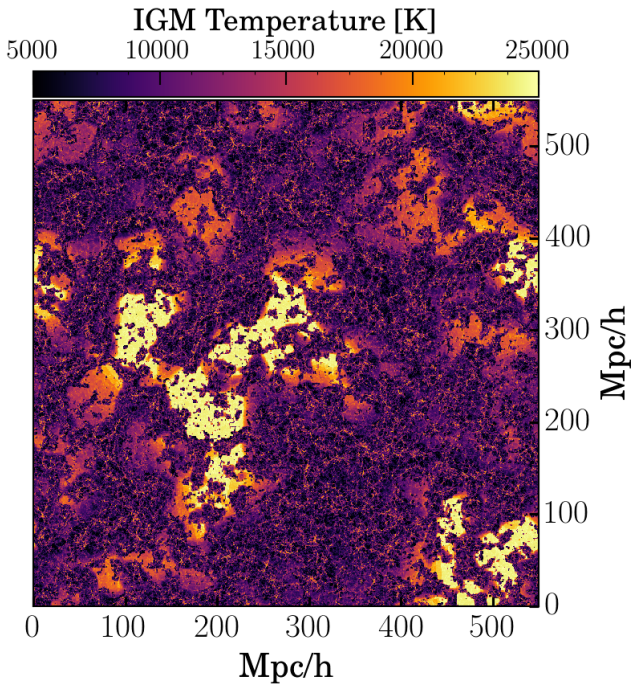
Are they underdense, overdense, or neither? ????

Ionizing background fluctu
fluctuating MFP and/or qua

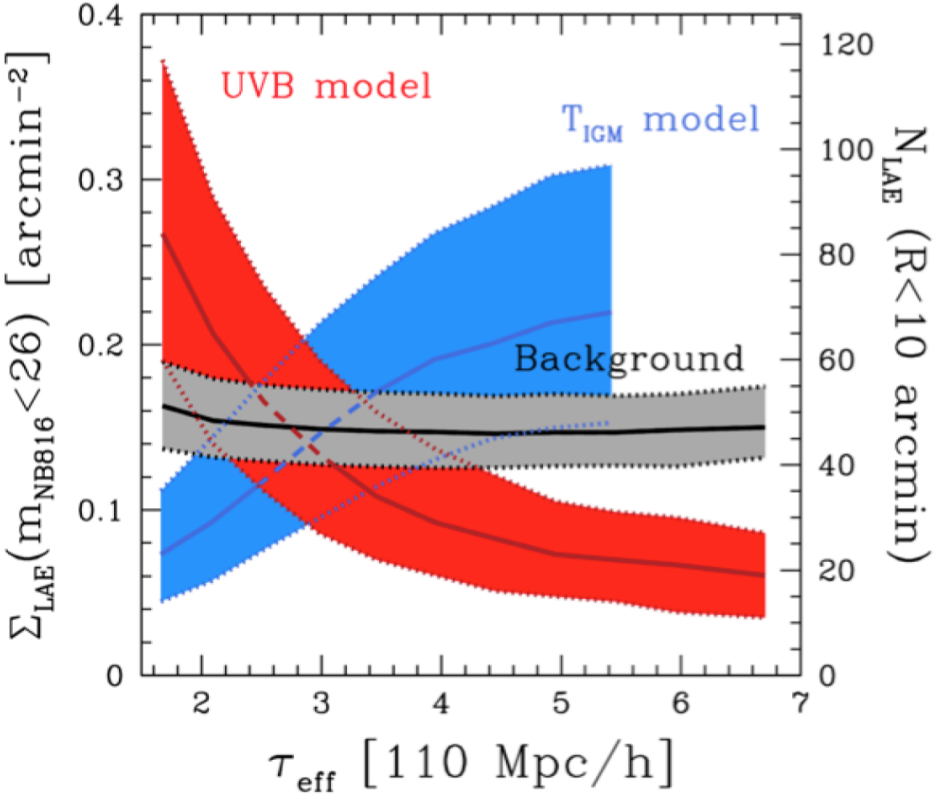
Residual temperature varia
from extended reionizatior

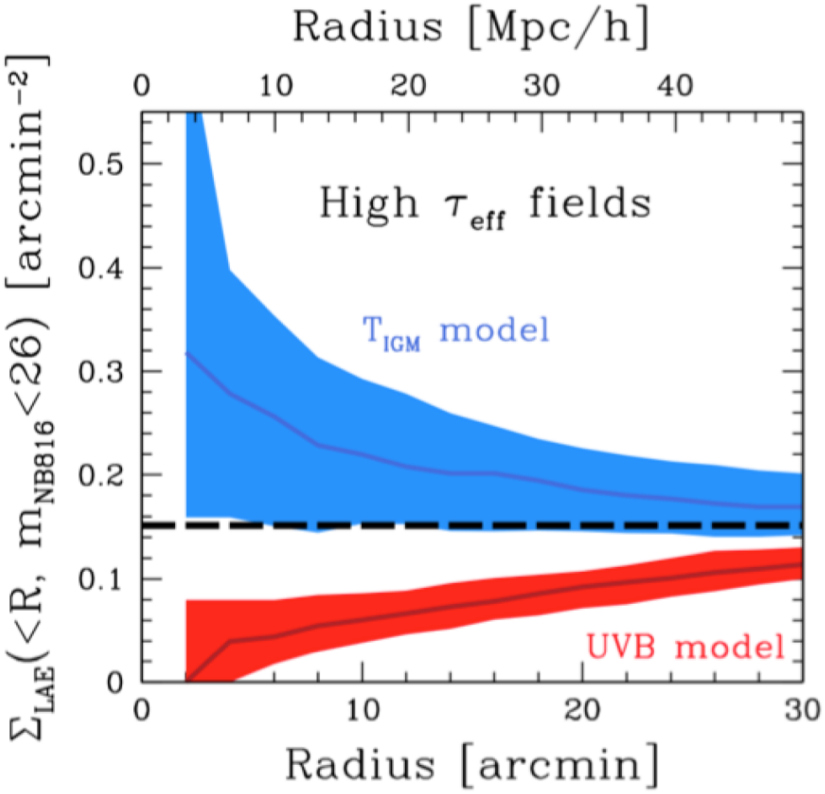






Extra: Subaru predictions





Your name tags are a “real” semi-numerical reionization simulation!