Simulations of H Reionization

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Contents

- Ingredients for simulations
- Some results and observables
- Sizes of HII regions
- Topology
- Effects of small scale clumping
- Effects of suppression

Ingredients for Simulations

- For simulating cosmic H reionization we need the following three ingredients
  - Evolving intergalactic baryonic density field
  - Distribution of sources
  - UV luminosity of sources
- We need these ingredients in a large enough volume to capture scales relevant for reionization.
- Consensus: ≥ 100 h^{-1}Mpc. This is based on HII bubble sizes and cosmic variance considerations.
- Future 21cm observations will cover scales 0.5 – 1 h^{-1}Gpc

The IGM Density Field

- To derive the IGM density field, we use a cosmological dark matter simulation:
  - Code: **cubep3m** (Merz et al. 2005)
  - Cube of 114 h^{-1}Mpc=163 Mpc on each side
  - $M_{particle}$=5 10^6 $M_\odot$
  - Mesh: 6144^3, reduced to 256^3 for radiative transfer.
  - Cosmology: WMAP5
- Use dark matter as a proxy for baryonic matter: on the largest scales (> Mpc) baryons should follow the DM.
- Option to include small scale structure through clumping factors ($C=\langle n^2\rangle/\langle n\rangle^2$).

Sources of Reionization

- At the fundamental level, we do not know the nature of the sources of reionization.
- Observed galaxy/QSO population at redshift 6 – 7 → sources connected to the collapsed DM halos at that epoch.
- Different halo types:
  1. $M < 10^8 M_\odot$: need H_2 to cool.
  2. $10^8 < M < 10^9 M_\odot$: cool via H, growth affected by reionization.
  3. $M > 10^9 M_\odot$: cool via H, growth unaffected by reionization.
- Cubep3m simulation ($M_{particle}$=5 $10^6 M_\odot$) gives us *all* halos of type 2 and 3.
- Assumption: type 1 halos unimportant (H_2 is destroyed by Lyman-Werner radiation, hν< 13.6 eV), but see Ahn et al. (2009).

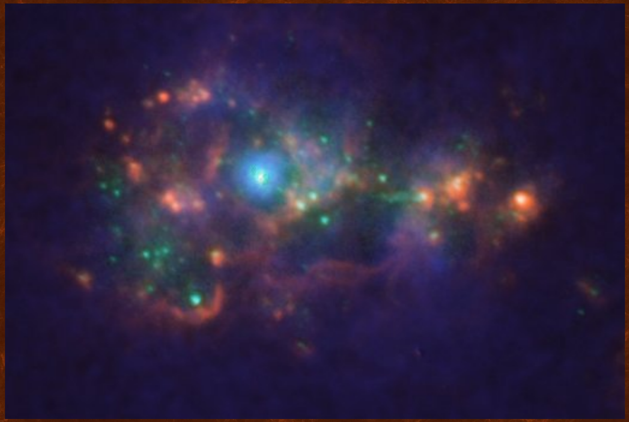
Negative Feedback on Sources

- Type 2 halos are affected by reionization: in ionized & heated region ($T \sim 10^4$ K) accretion of baryons is stopped/reduced.
- Also known as "Jeans mass filtering".
- Different studies show different results (Thoul & Weinberg 1996; Gnedin 2000; Okamota et al. 2008; Mesinger & Dijkstra 2008).
- Our source suppression model:
  - Type 2 halos ($M<10^9$ $M_\odot$) cease to be sources once inside an ionized region.
- This leads to "self-regulated reionization" as rapid reionization will result in many suppressed type 2 sources (Iliev et al. 2007).

Ionizing Photon Flux

- We assume stellar populations as sources of EUV radiation.

- Parameters:
  - Initial Mass Function (IMF)
  - Star formation rate (SFR)
  - EUV escape efficiency (f_{esc})



ESO338-IG04

- Options (in general):
  - Simple parametrization ($L \propto f(M_{DM})$, #photons per baryon).
  - Galaxy evolution models (DM + hydro, semi-analytical models): GADGET, GALFORM.
  - Imposed global SFH.

Simple Source Parametrization

- Photon production:
  - For a halo $N_{halo} \propto g\, M_{halo}$ in 10^7 yr, with
  - $g = f_{SF} \times f_{esc} \times N_{photon}$.
- N_{photon} EUV photons per baryon (IMF dependent):
  - Top-heavy/PopIII: N_{photon}=50,000
  - Top-heavy/PopII: N_{photon}=10,000
  - Salpeter: N_{Ph}=5,000
- So g=8.7 means for for Salpeter IMF and f_{esc}=5% that f_{SF}≈3.5%.
- Spectrum: 50 kK Black body.
- Type 2 and 3 halos typically are given different values of g.
- (Note: old f parameter: f ≈ 2g).

Radiative Transfer

- We solve for the evolution of the ionized hydrogen by tracing the EUV radiation from the sources through the evolving IGM density field.
- The code C^2-Ray (Conservative Causal RAY-tracing) was developed for use inside hydrodynamic simulations, and is therefore extremely efficient when used on its own (Mellema et al. 2006).
- It uses short-characteristic ray-tracing on a regular grid.
- It deals with multiple sources.
- It can use both shared and distributed memory parallelization, scales well up to 10,000 cores.

Notation

- Our simulations are characterized by

Suppression of type 2 sources

163Mpc_g8.7_130S_256

Density fields and halo sources from 163 Mpc cubep3m simulation

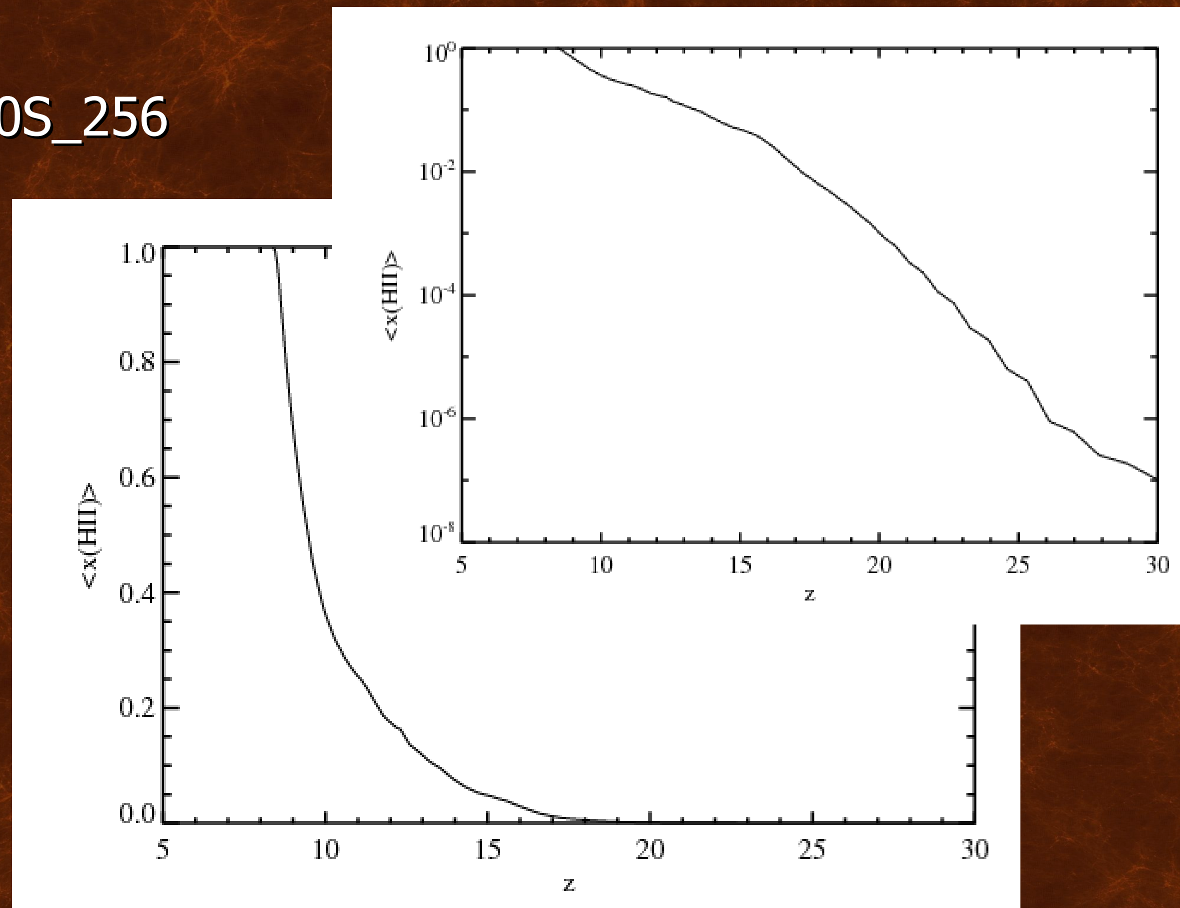
Efficiency of type 3 (high mass) sources

Efficiency of type 2 (low mass) sources

RT mesh = 256^3

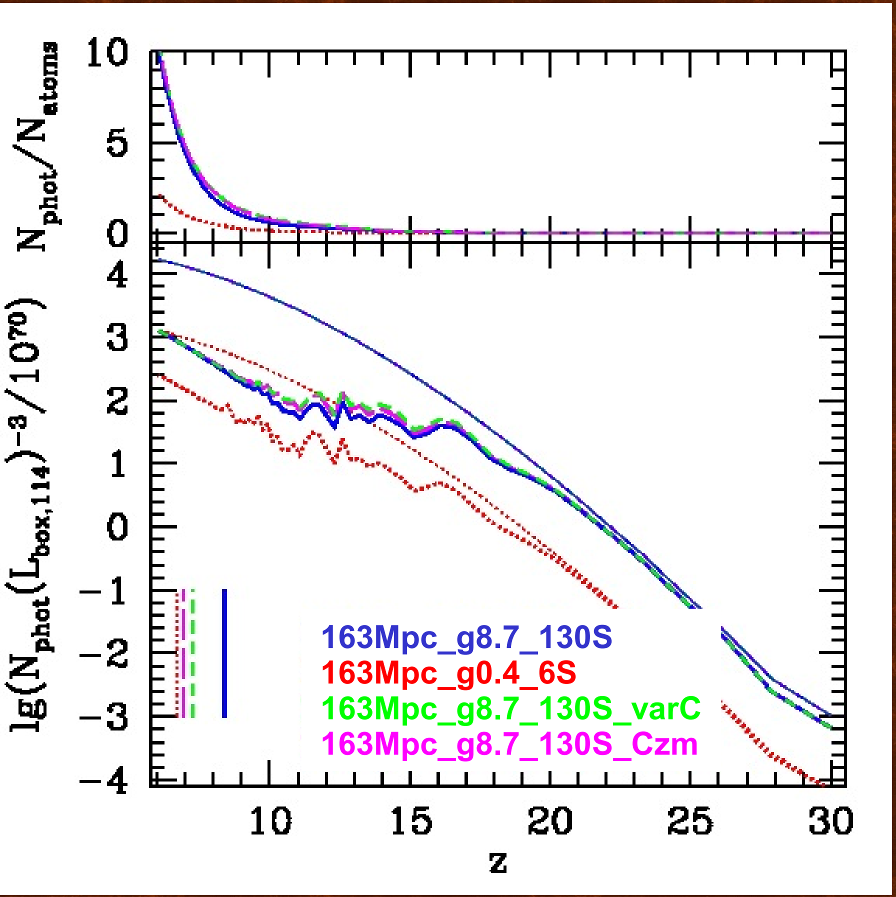
Reionization History

- Simulation: 163Mpc_g8.7_130S_256
- z(50%)=9.46
- z(99%)=8.45
- τ= 0.082



Photon Budget

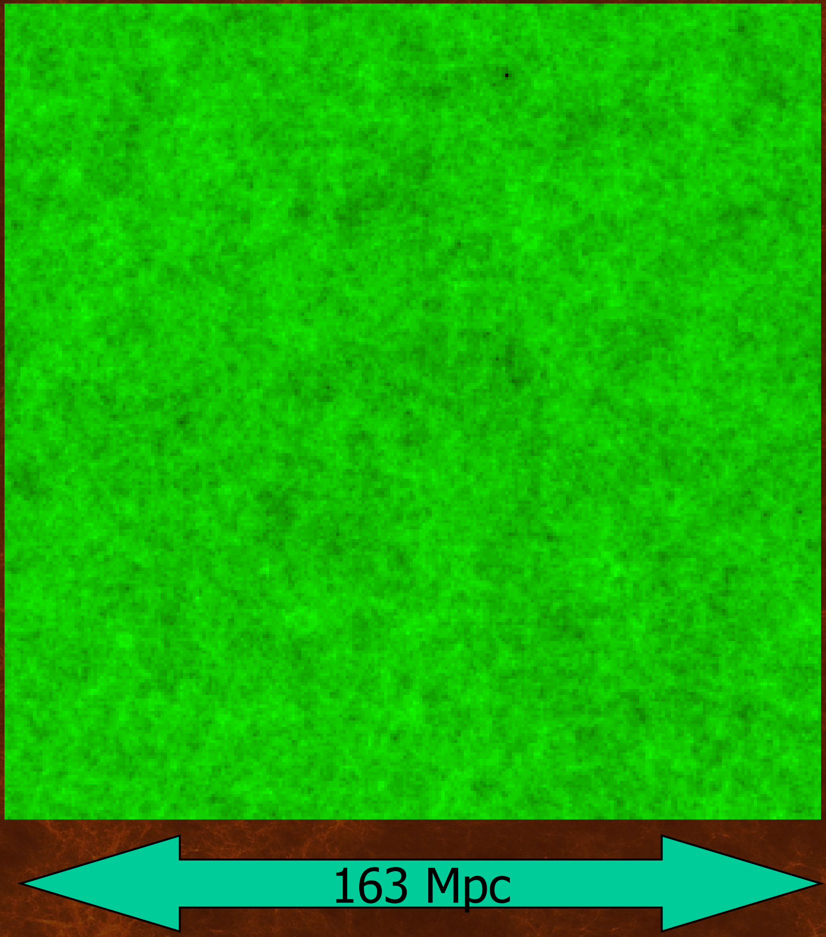
- Photon budget:
- ~2 photons per atom needed for reionization.
- Due to self-regulation, ~80% of those are provided by type 3 halos.
- The g=8.7 choice gives about 10 photons/baryon produced by z=6 (NB: not the same as UVB).



Growing HII Regions (2D)

- Movie of (slice of) density field and HII regions.
- Green: neutral
- Orange: ionized
- Blue dots: sources (stellar population).

- Note: high source density.
- Inside-out reionization.
- Complex morphologies.



Growing HII Regions (3D)

Movie produced with VAPOR software from NCAR

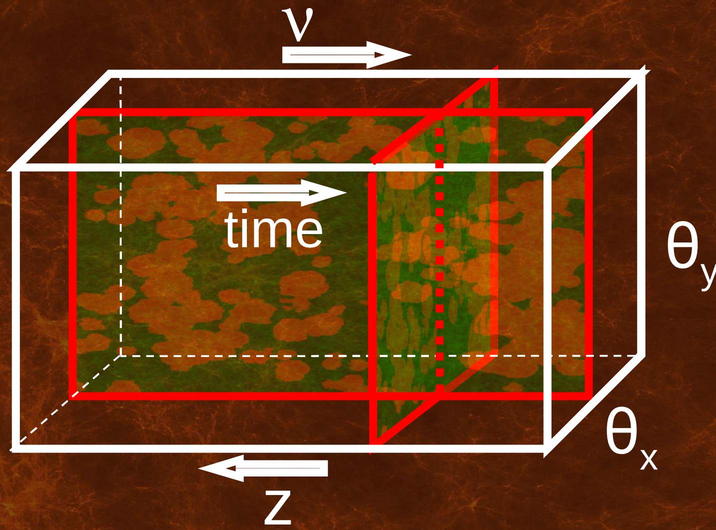
The Redshifted 21cm Signal

- The measured signal is the differential brightness temperature

$$\delta T_b \approx 28\mathrm{mK}\,(1+\delta)x_{HI}\frac{T_s - T_{CMB}}{T_s}\frac{\Omega_b h^2}{0.02}\left[\frac{0.24}{\Omega_m}\left(\frac{1+z}{10}\right)\right]^{\frac{1}{2}}$$

- Depends on:
  - x_{HI}: neutral fraction
  - δ: overdensity
  - T_s: spin temperature
- For $T_s \gg T_{CMB}$, the dependence on T_s drops out.
- The signal is *line* emission: carries spatial, temporal, and velocity information.

The image cube: images stacked in frequency space



Growing HII Regions (2D)

- Movie of the time evolution of **δT_b** in a slice through the simulation volume.
- Neutral regions are yellow, red and green.
- Ionized regions are black.

- Note: drop in δT_b due to z-term and small HII regions.
- Complex morphology.

Flying through Time and Space

- Movie of the LOS evolution of δT_b (flying through the 21cm image cube)
- Neutral regions are yellow, red and green.
- Ionized regions are black.
- Movie generated by using the periodicity of the volume, but rotating it to avoid passing through the same structures.

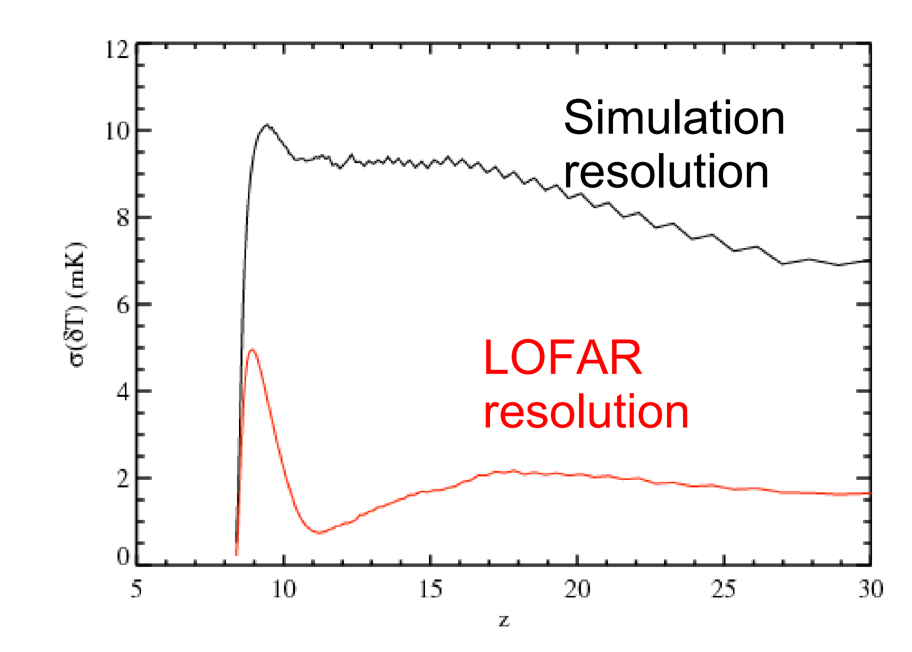
Statistical Measurements

- The sensitivity of the upcoming EoR experiments will be too low to image 21cm from reionization pixel by pixel: Statistical measurements needed.

- Luckily, the 21cm line signal is rich in properties:
  - Global signals: rms fluctuations.
  - Angular properties: power spectra
  - Frequency properties: Kaiser effect
  - Non-Gaussianity: skewness, PDFs

RMS Fluctuations & Resolution

- The simplest statistic measured by an interferometer is the 'global' rms of the 21cm signal.
- This signal shows a characteristic peak.
- At the resolution of the simulation this peak falls at $\langle x_{HII} \rangle \sim 0.5$.
- For the upcoming experiments, this peak may fall at higher $\langle x_{HII} \rangle$!



"LOFAR" resolution: 3' and 440 MHz.

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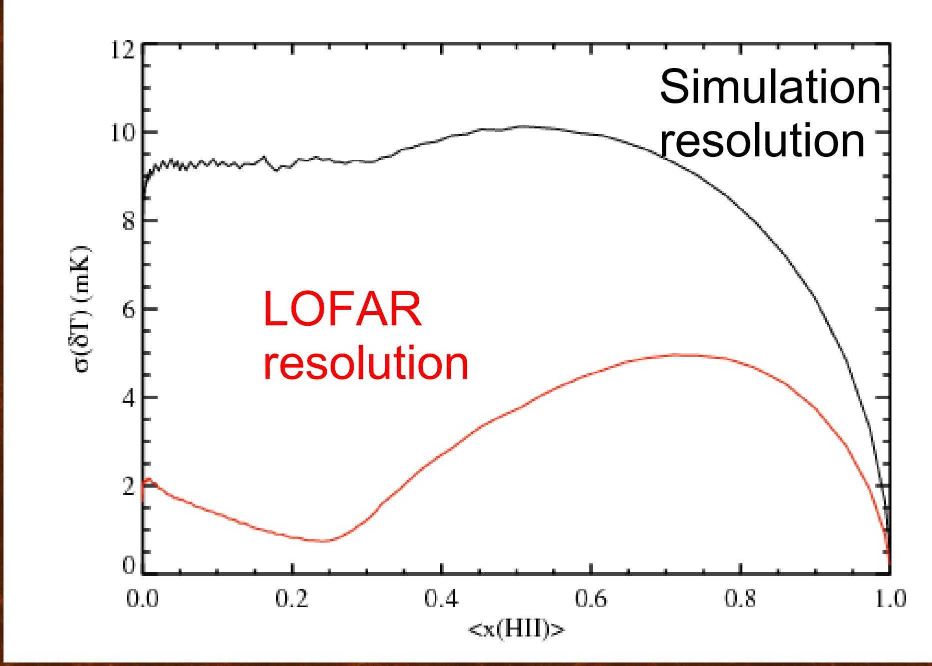
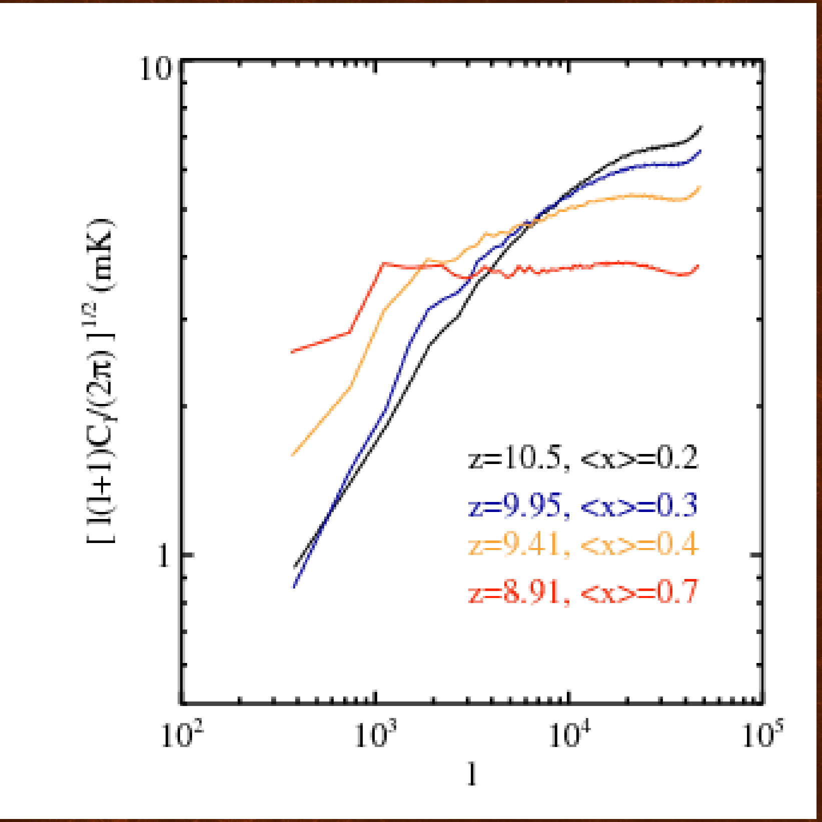


"LOFAR" resolution: 3' and 440 MHz.

Power Spectra

- Information about the size scales can be obtained from the power spectra.
- Simulations show clear trends of shifting power to larger scales as reionization progresses, and a flattening of the power spectra.
- Note that the angular power spectrum is measured directly by an interferometer, the multipole l is equivalent to $\sqrt{(u^2+v^2)}$ in a visibility map.

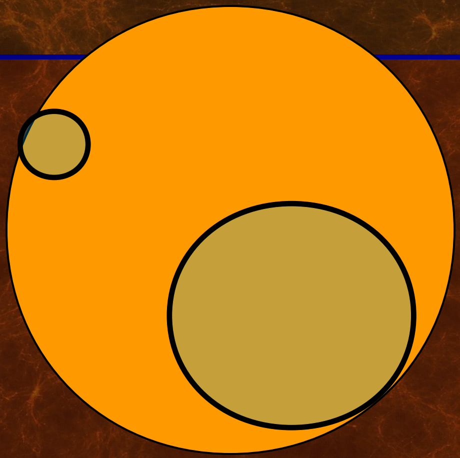
Angular Power Spectra

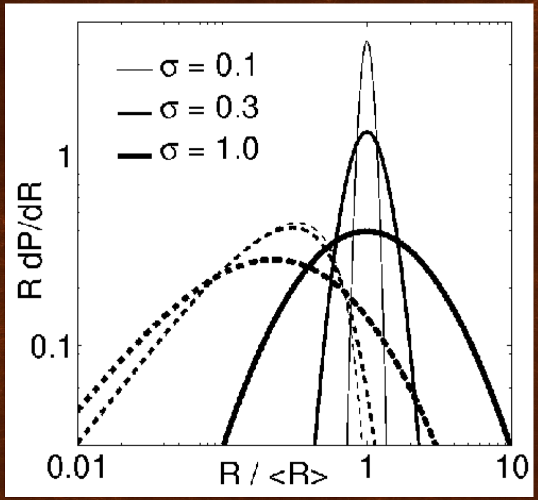


163 Mpc volume

Characterizing the Sizes

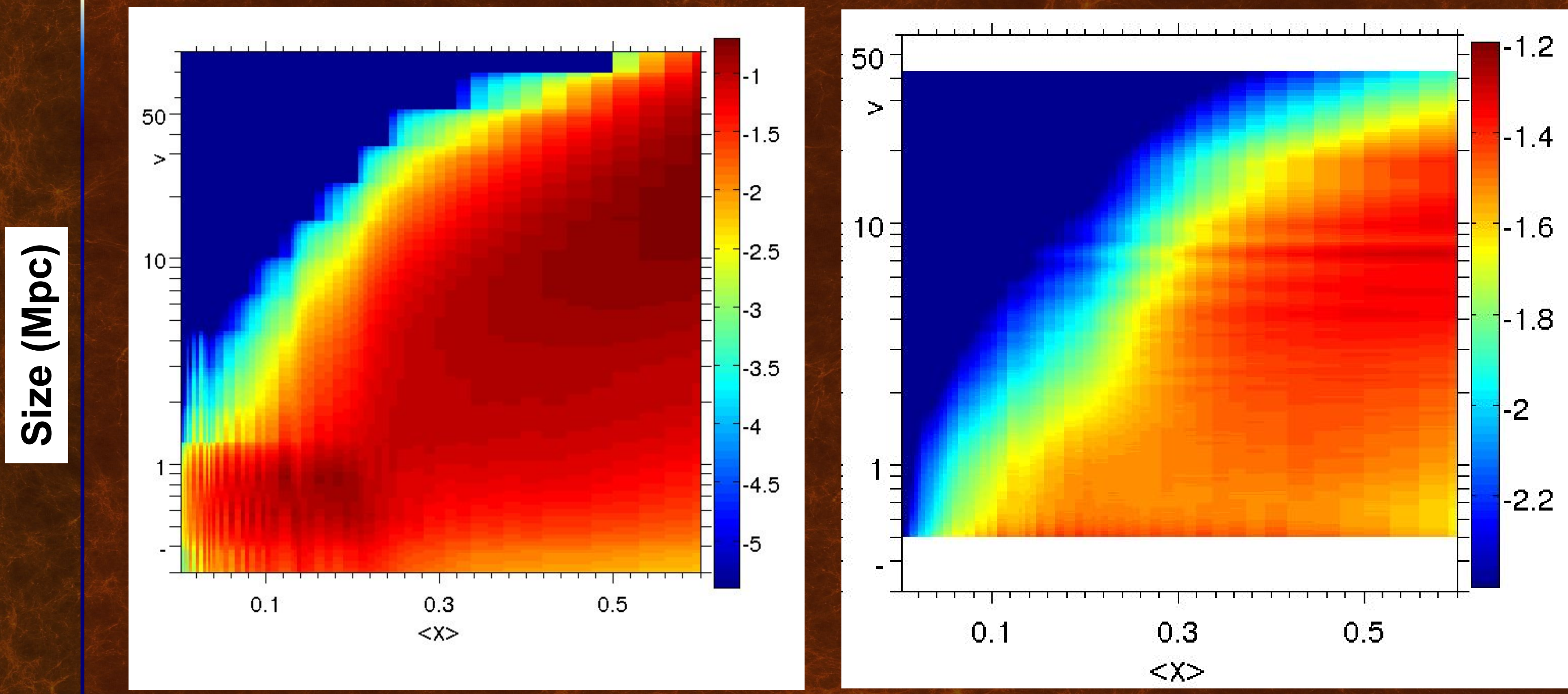
- How to characterize the size of HII regions given the complex shapes?
- We are exploring a combination of methods (on x_{HII}):
  - Friends of Friends (Iliev et al. 2006)
  - Spherical average (Zahn et al. 2007)
  - Power spectra
  - 3V/A (Minkowski functionals V_0, V_1)
- Complex non-spherical geometry and non-gaussian pdfs, so all imperfect.
- We use $S_{SA}=4R_{SA}$, $S_{PS}=2.46/k$





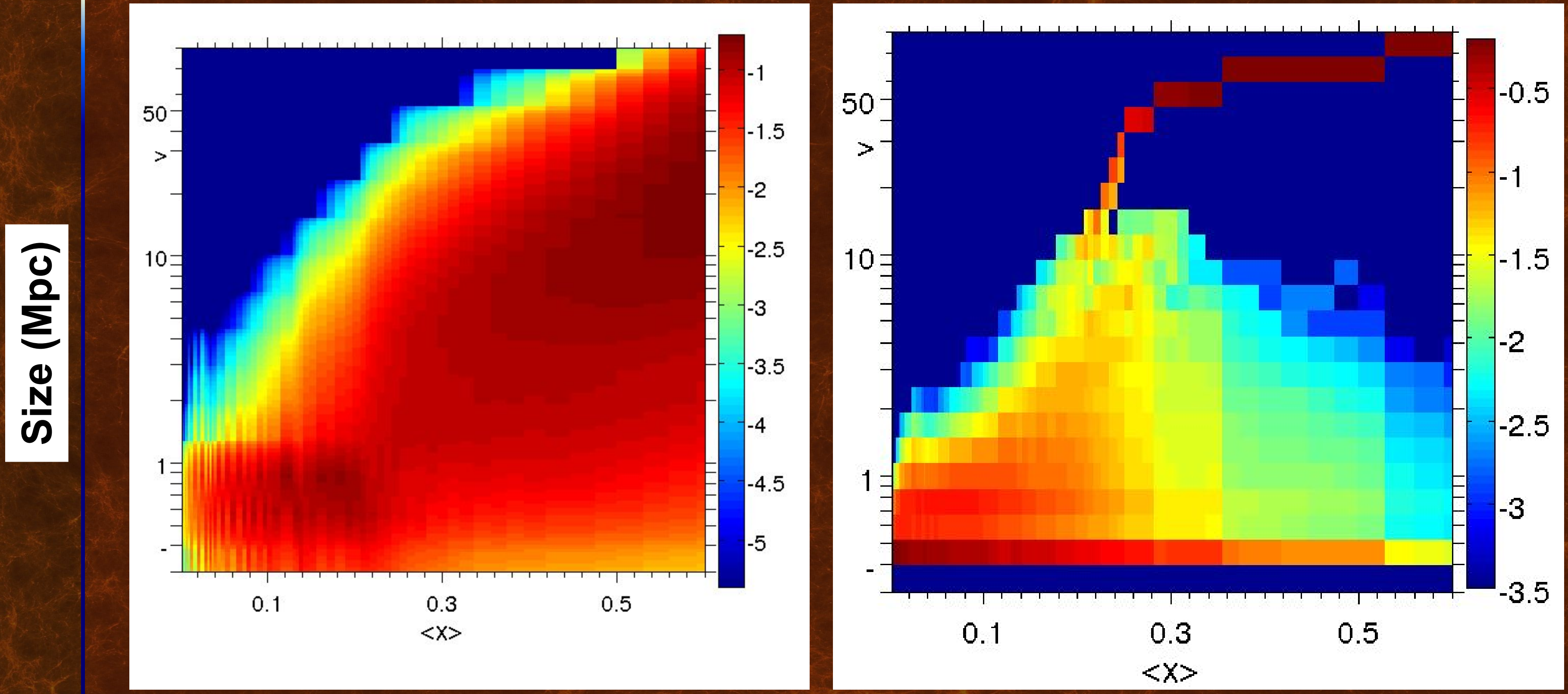
Spherical Average

Sizes: SA versus PS



Friedrich et al. (2010)

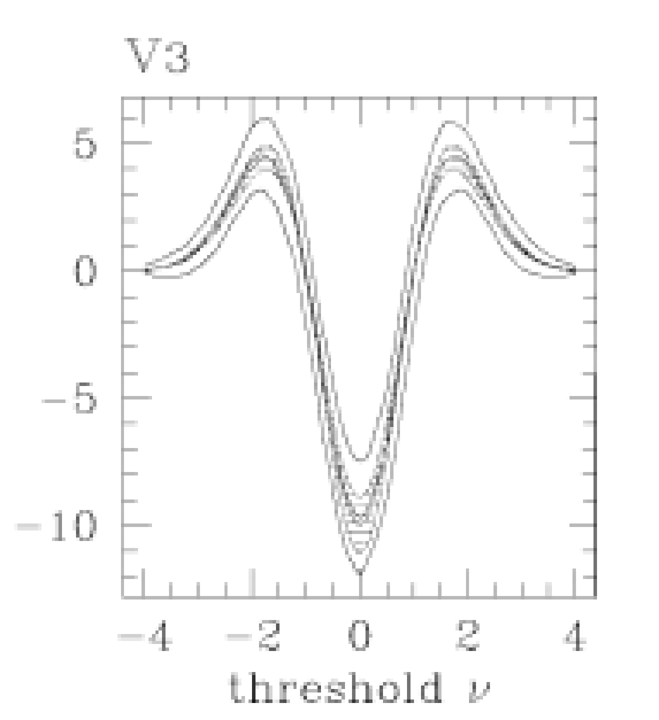
Sizes: SA versus FoF



Friedrich et al. (2010)

Topology

- Euler characteristic: number of objects + number of cavities – number of tunnels. Equal to 1- genus.
- Minkowski functionals:
  - Volume V_0
  - Surface V_1
  - Curvature V_2
  - Euler characteristic V_3
- V_3 for Gaussian field:

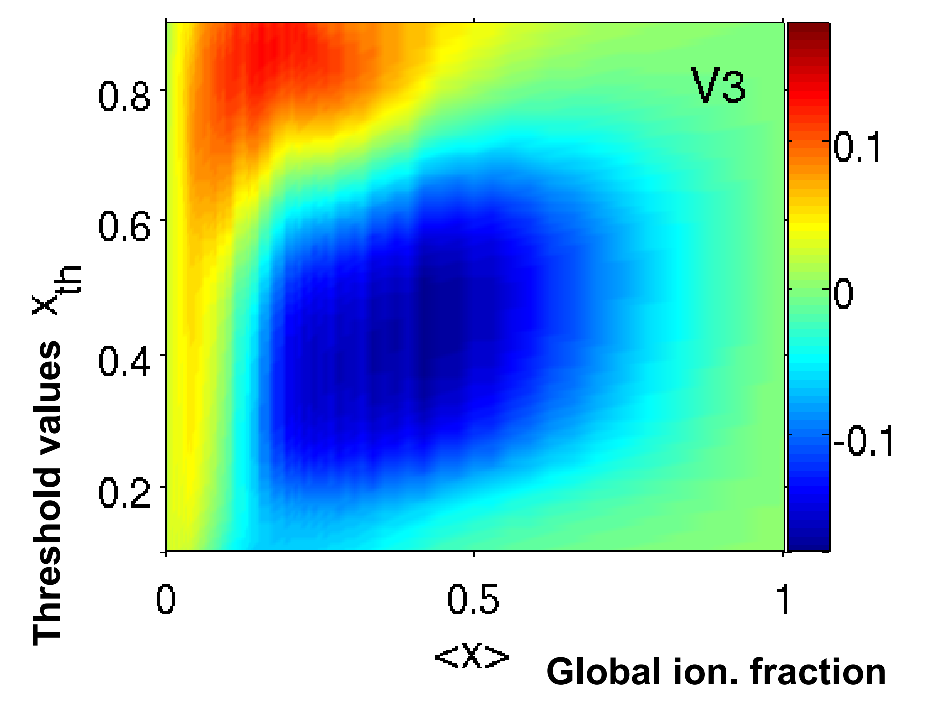


Schmaltzing & Buchert (1997)

See also Gleser et al. (2006) and Lee et al. (2008)

Euler Characteristic for Ionization Fraction

- Result depends on threshold value chosen for the local ionization fraction x_{HII} (due to resolution effects).
- At x_{HII}~0.5: Initially V3 follows that of a Gaussian field: inside out reionization!
- But: no second peak; reionization ends when ionization fronts move into the voids.



163Mpc_g8.7_130S_256

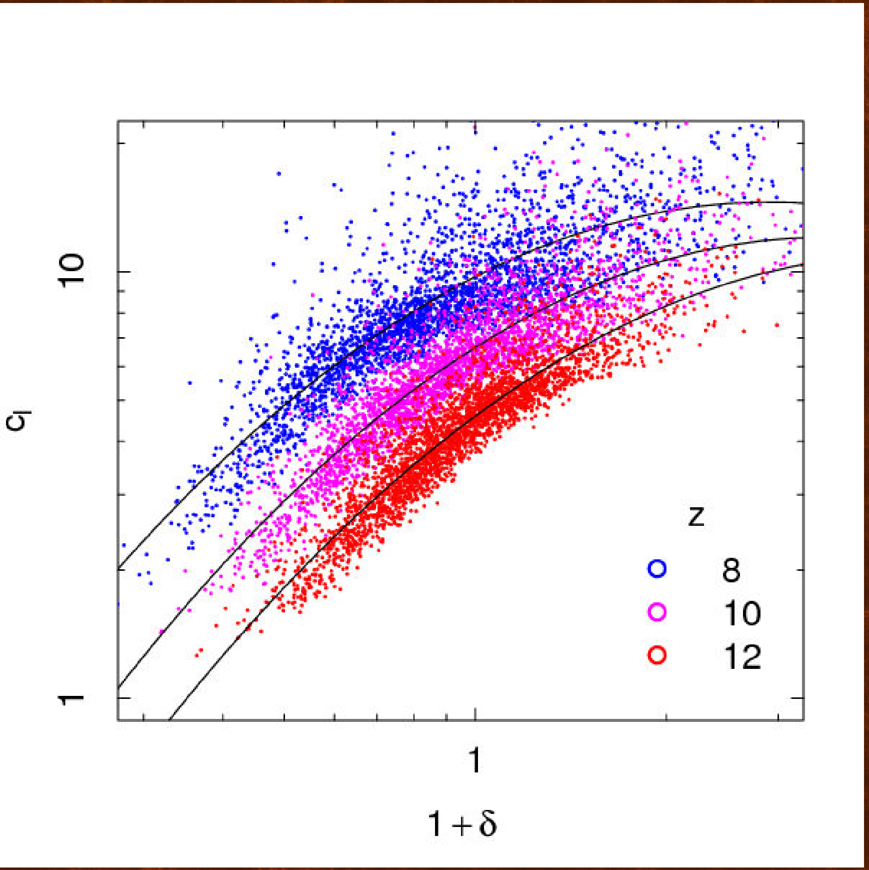
Friedrich et al. (2010)

Exploring Assumptions

- The model presented by necessity has many assumptions.
- We will now briefly explore two aspects:
  - Effects of small scale density variations
  - Effects of source suppression
- Both are work in progress...

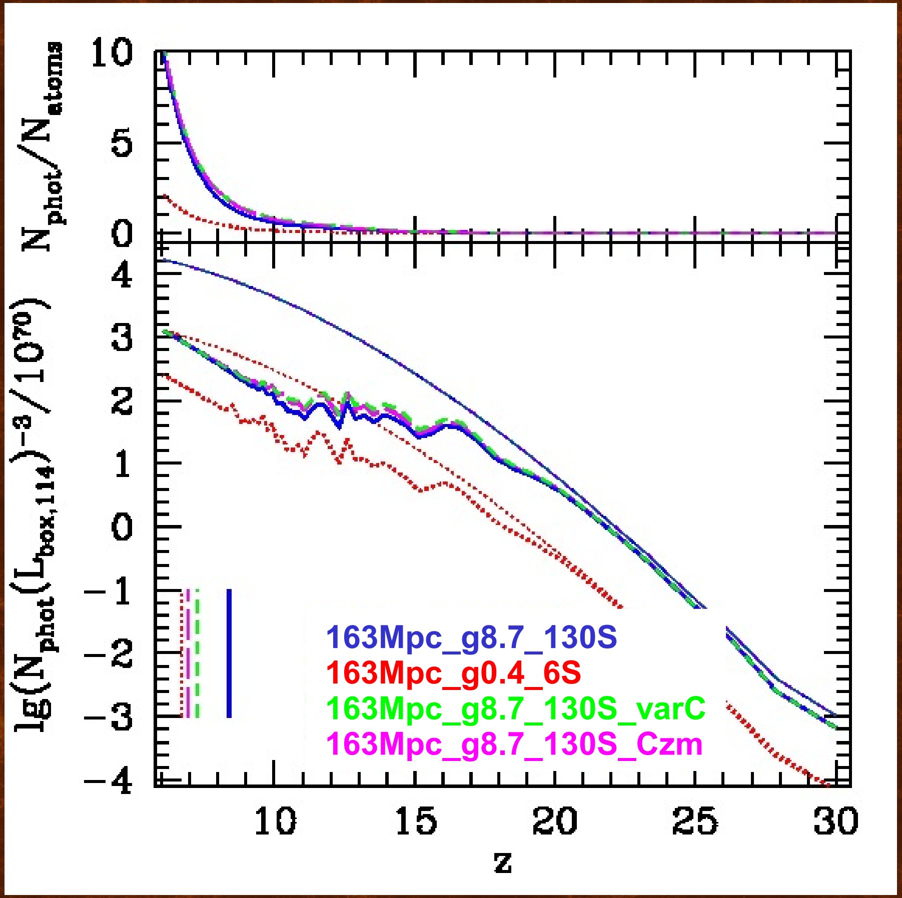
IGM Density Variations

- To test the effects of density variations below our spatial resolution, we apply a density and redshift dependent fit of the clumping C to every position.
- Fit derived from 29 Mpc simulation resolving $10^5\ M_\odot$ halos and scales ~300 pc.
- As reionization progresses DM clumping becomes an overestimate. Clumping and non-clumping cases bracket the possible behaviour.



Reionization Histories

	No clumping	Clumping
z(50%)	9.46	8.17
z(99%)	8.45	7.26
τ	0.082	0.069
N_{phot} per atom	~2	~4



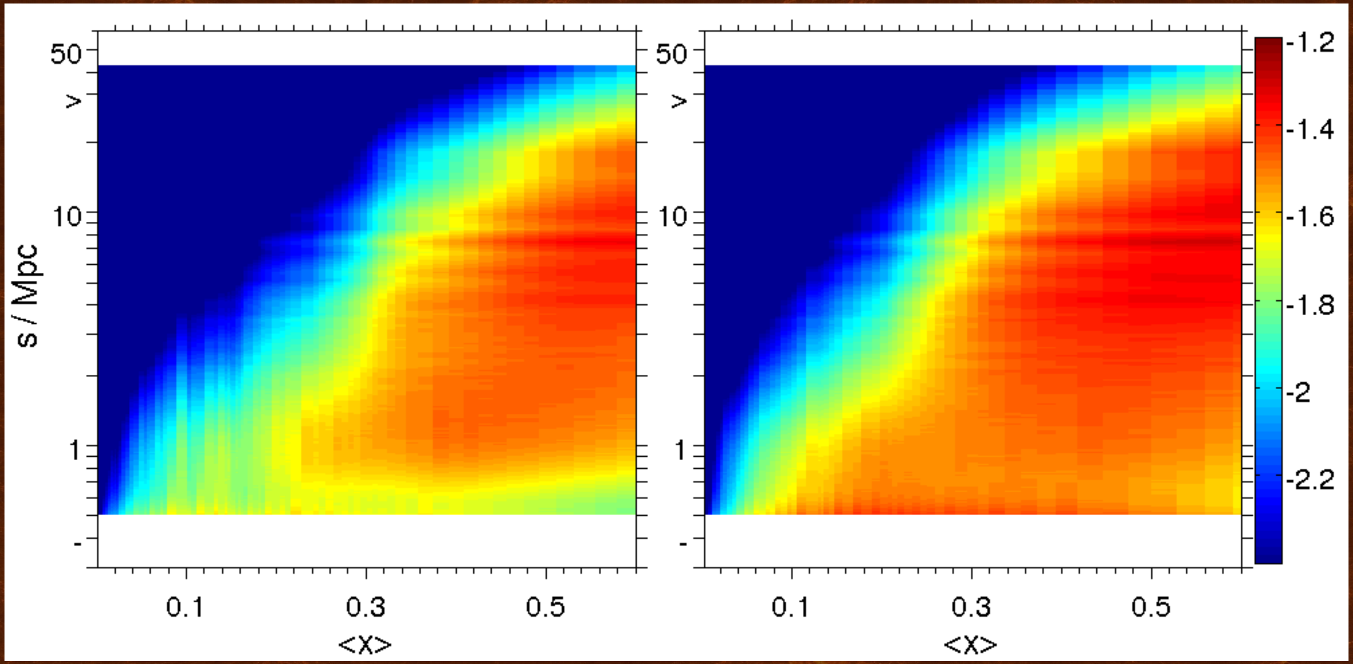
Size Scales

- Comparison of evolution of PS (x_{HII}): suppression of small scale HII regions due to recombinations (also seen in SA).

Power Spectra

Clumping

No clumping



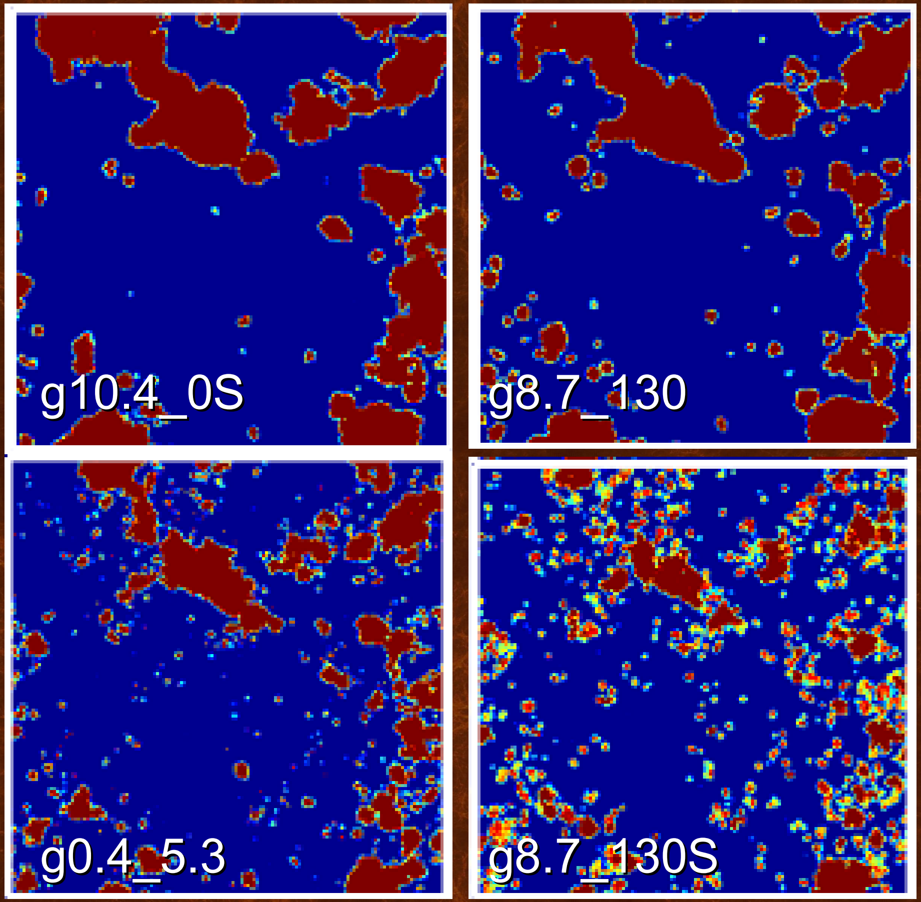
Different Source Populations

- Since we do not know how suppression works in reality, it is interesting to explore its effects on reionization.
- Also the effects of a higher mass cut off for our source population need exploration.

- Comparison in 53 Mpc volume:
  - Standard g8.7_130S [z(99%)=8.5, τ= 0.08]
  - Always suppression g10.4_0 (20% increase)
  - No suppression, weak sources g0.4_5.3 (20x weaker)
  - No suppression g8.7_130 [z(99%)=12.9,τ= 0.13]

Ionization Maps at z(30%)

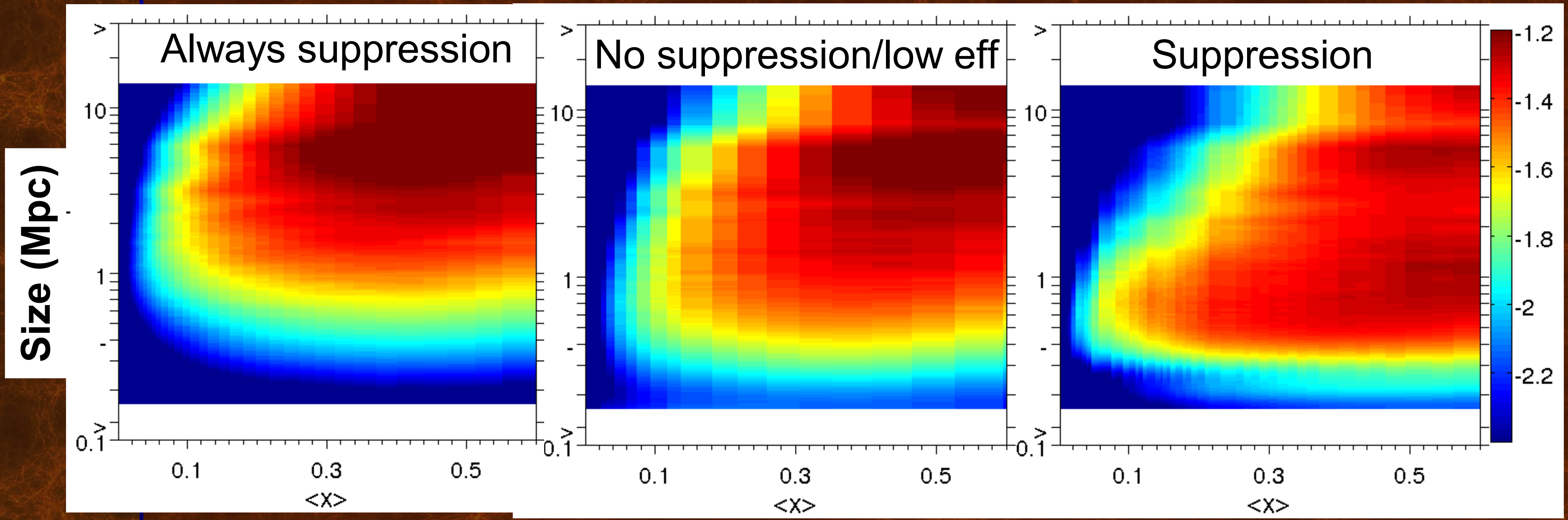
- Slices of the distribution of ionized fraction between these four show
- ”No suppression/high eff” and ”always suppression” similar.
- ”No suppression/low eff” and ”suppression” somewhat similar.



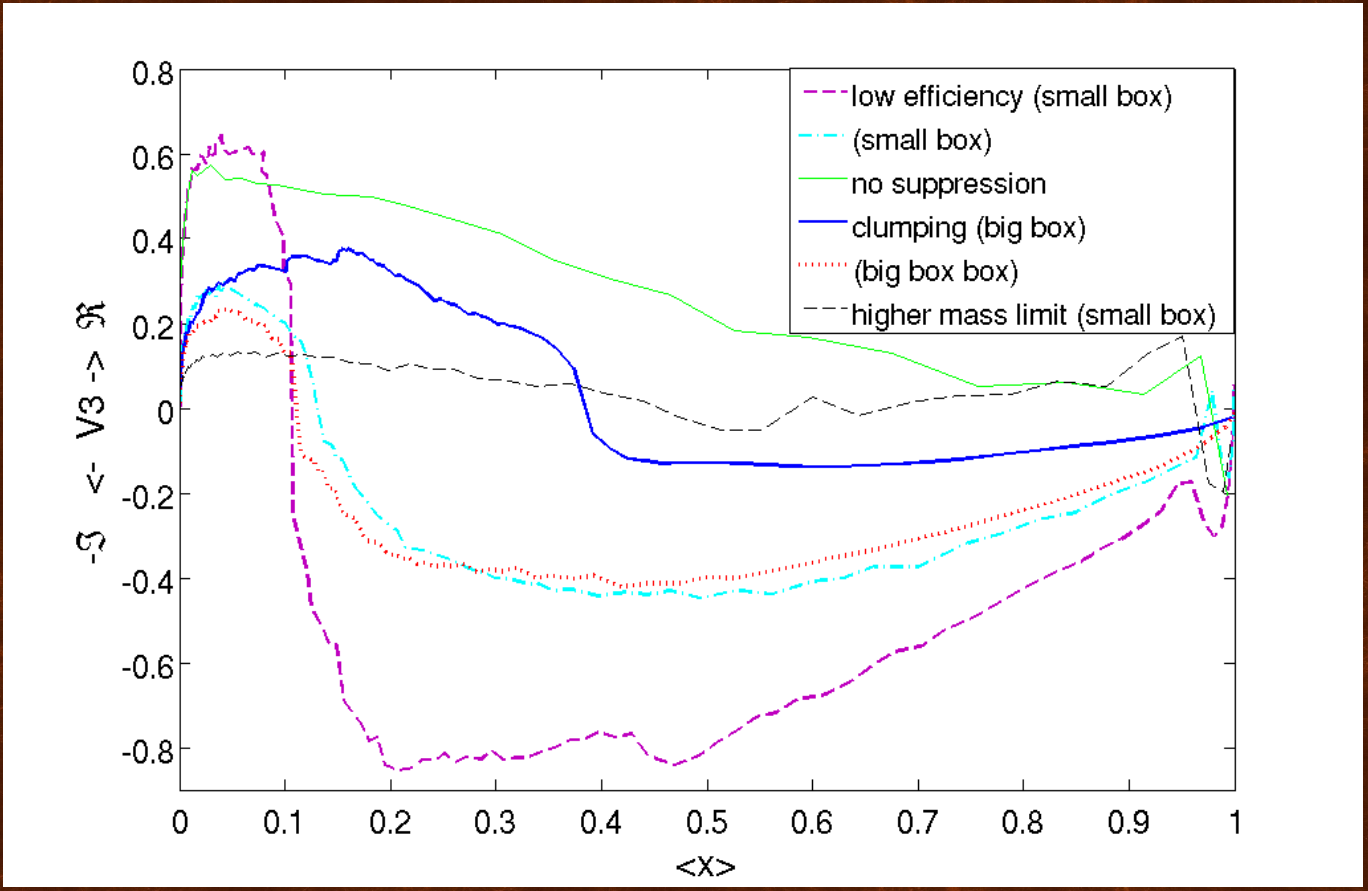
Sizes

- PS for the "no suppression" and "always suppression" cases appear to be quite similar, at least for the larger scales.

Power Spectra (for x_{HII})



Topology



low efficiency (small box)
(small box)
no suppression
clumping (big box)
(big box box)
higher mass limit (small box)
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
<X>

Conclusions

- Simulations can be used to gain better understanding of the complex process of reionization and the interpretation of the observations.
- Different size measurements address different aspects.
- The Euler characteristic provides a useful analysis tool for the topology of simulation results.
- The 21cm signal has a rich set of properties which should help in recognizing it in the data of upcoming EoR experiments.
- The later stages of the EoR show a peak in the 21cm rms fluctuations, but peak is not necessarily at 50% ionized.
- Small scale clumping can shift evolution by max $\Delta z=1$ and doubles number of photons needed; it suppresses small scale structure.

Thank You for Your Attention