

Early Large-scale Structure Formation and Reionization

Ilian T. Iliev

University of Sussex

with

**Garrelt Mellema (Stockholm), Paul Shapiro (Austin),
Ue-Li Pen (CITA), Kyungjin Ahn (Chosun), Uros Seljak
(Zurich/Berkeley) and others**

Progress of reionization: 3D view

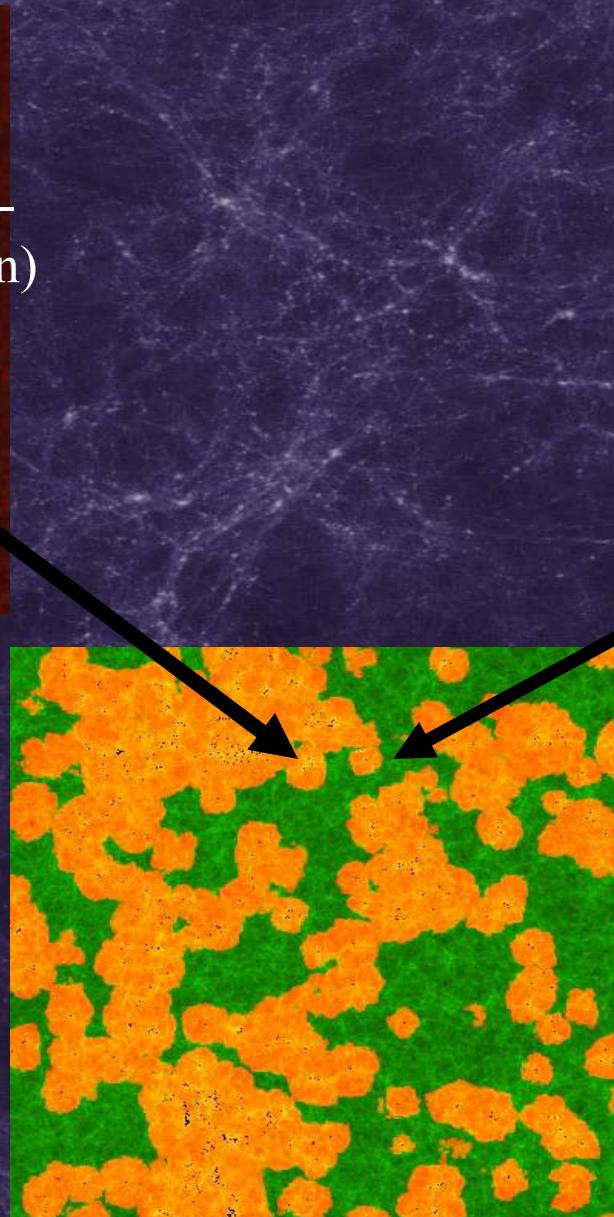


Large-Scale Simulations of Reionization

[Iliev et al. 2006a, 2007a; Mellema, Iliev, et al. 2006; and in prep.]

- N-body: CubeP³M
1728³-3072³ part.
(5.2 to 29 billion) or more -
4000³-5488³ (64-165 billion)
- density slices
- velocity slices
- halo catalogues-sources
- Scales well at least up to
21,952 cores

35-114/h Mpc (CubeP³M)
resolving 10^8 M_{\odot} halos
up to 21×10^6 sources
50-100 dens. snapshots
simple source models
sub-grid clumping
no hydro – large scales.



- C²-Ray code
(Mellema, Iliev, et al. 2006)
- radiative transfer
 - noneq. chemistry
 - precise
 - highly efficient
- coupled to gasdynamics
 - massively parallel
(scales well up to
10,240 cores).

Coupled to hydro

N-body code

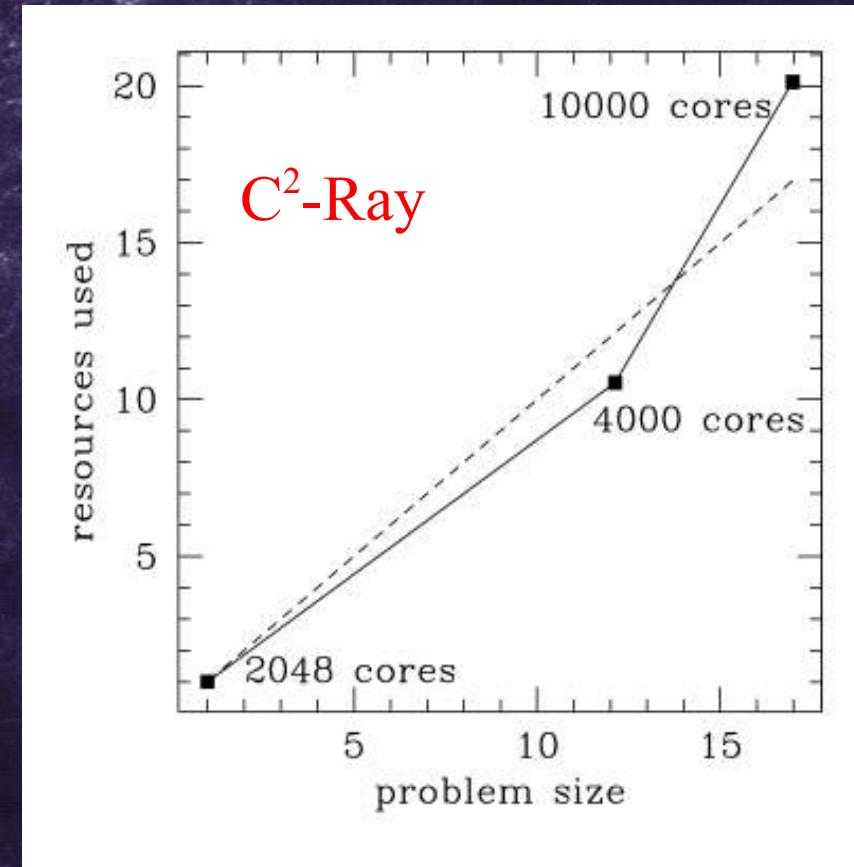
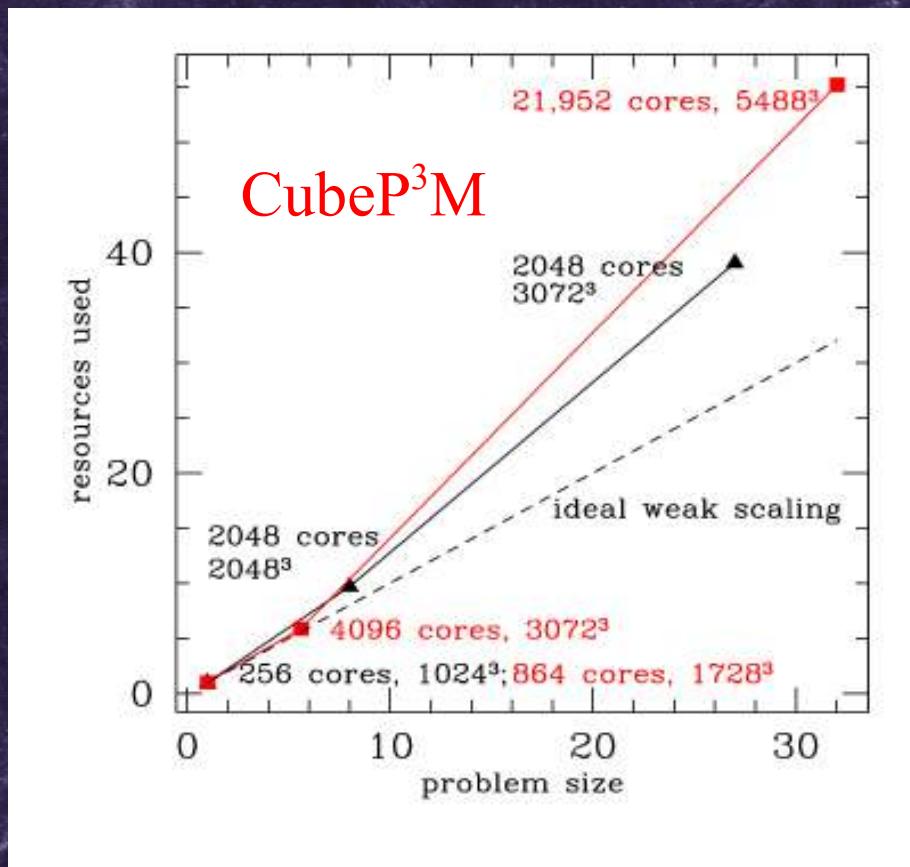
(Merz, Pen and Trac 2005; Iliev, et al., TeraGrid08 and Moriond 2010)

- CubeP³M, massively parallel, particle-particle-particle-mesh code:
www.cita.utoronto.ca/mediawiki/index.php/CubePM
- Regular (cubical) domain decomposition
- Hybrid MPI+OpenMP parallelization
- High scalability (tested up to 22,000 cores)
- Fairly lean and efficient in terms of memory and CPU usage

Code Scaling

(Iliev, et al. 2008 in TeraGrid08 and Moriond 2010)

Both N-body and radiative transfer codes are massively parallel and scale (weakly) up to thousands of processors.



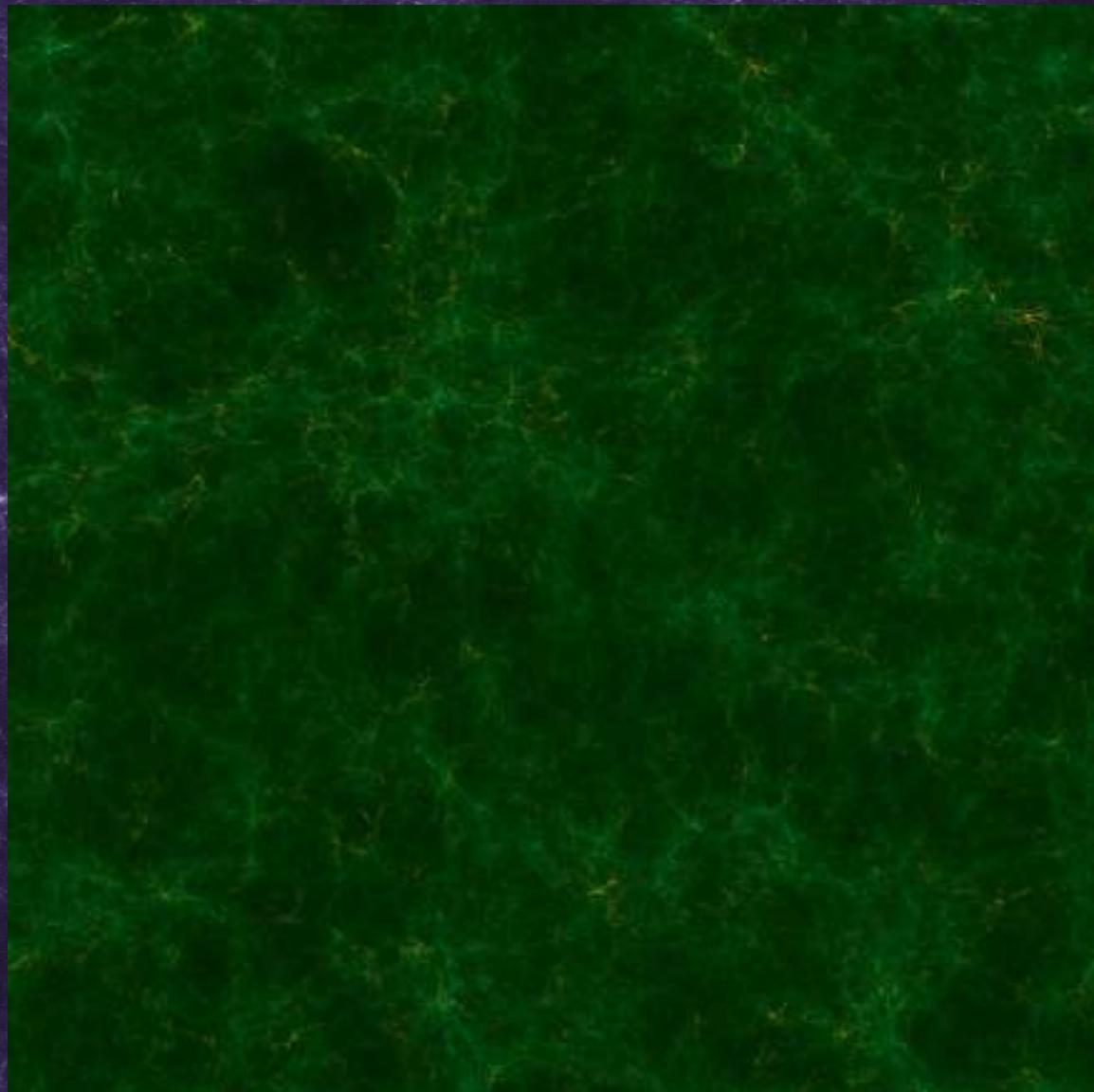
The Formation of Early Cosmic Structures

Iliev, Mellema, Pen, Merz, Shapiro, Alvarez 2006a, MNRAS, 369, 1885, and in progress)

114/h Mpc box @ z=6
3072³ particles (29 billion),
6144³ cells, P³M simulation
density=green, halos=orange

We have now ran simulations
With 1024³-3072³ particles in
boxes of 37/h-114/h Mpc.

These sizes allow us to
Resolve all halos down to
the atomically-cooling limit
($10^8 M_{\text{star}}$) in 100-150/h Mpc
boxes - the typical goal for
this type of simulations.



Simulation ran at Texas Advanced
Computing Facility on 2,048 cores.

The Formation of Early Cosmic Structures

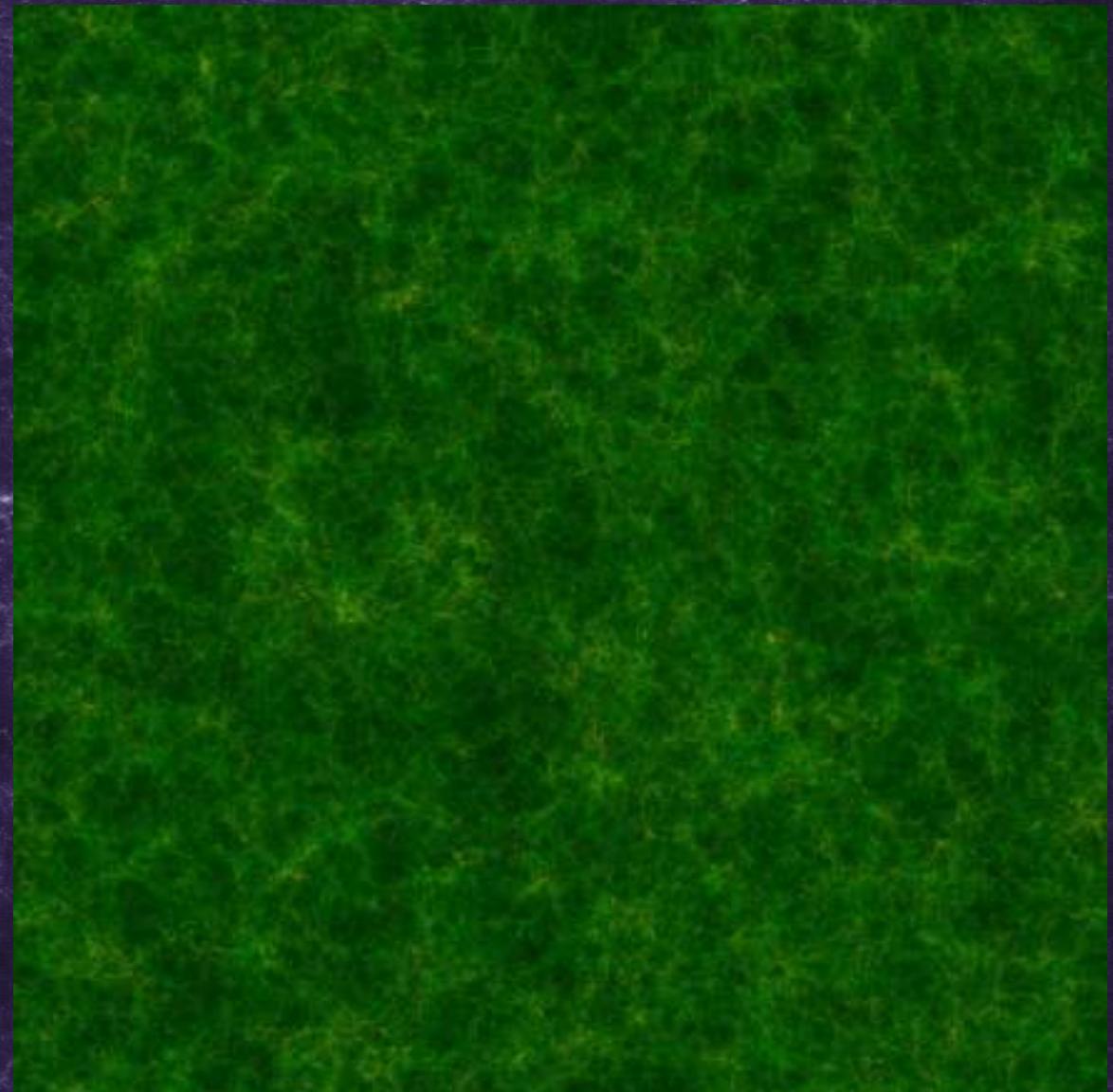
(Iliev, et al., work in progress)

425/h Mpc box @ z=6
5488³ particles (165 billion),
10976³ cells, P³M simulation
density=green, halos=orange

Resolves 10⁹ solar mass
halos and up
First halos form at z~26
~90 million halos by z=6

Simulation to be used to
simulate full RT the (nearly)
complete volume of EoR
radio surveys like LOFAR

Still larger simulations are
Possible on current or
near-future hardware, with
up to few trillion particles



Simulation ran at Texas Advanced
Computing Facility on 10,976 cores.

The Formation of Early Cosmic Structures: The Very Small Scales

20/h Mpc box @ z=8

5488³ particles (165 billion),
10,976³ cells, P³M simulation

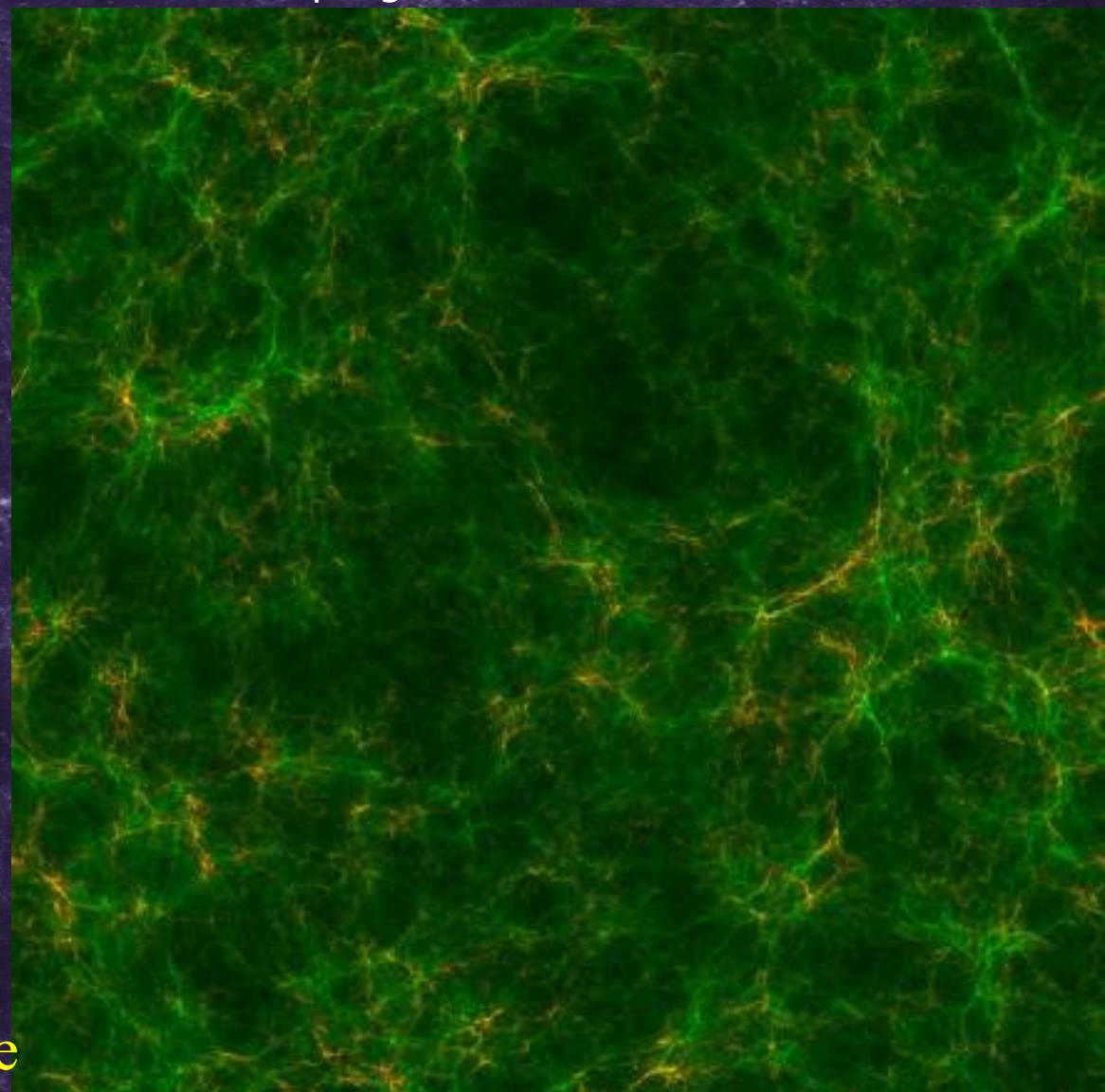
(Iliev, et al., work in progress)

Resolves all halos down to small minihalos ($10^5 M_{\odot}$). We also ran 11.4/h Mpc and 6.3/h Mpc boxes with same min resolution.

Structures are highly biased. Extend to extremely small scales (resolution of this simulation is 182 pc!)

First halos form at z=43.
112+ million halos at z=8.

Very useful for modelling the effects of small-scale structure and 21-cm absorption.



Simulations ran at Texas Advanced Computing Center on 864-21,952 cores.

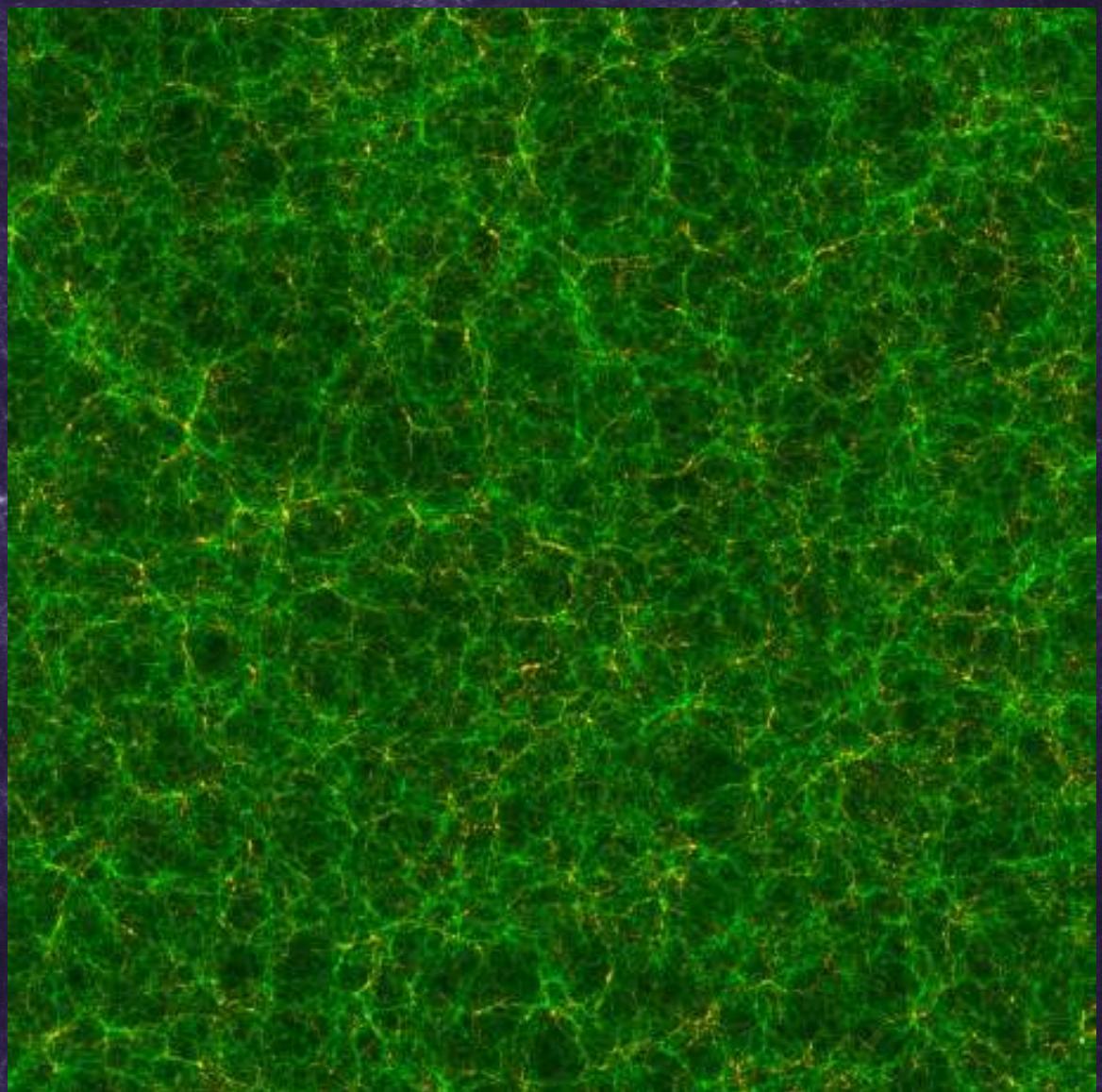
The Formation of Large-scale structure (Iliev, et al., work in progress)

1/h Gpc box @ z=0
3456³ particles (41 billion),
6912³ cells, P³M simulation
Resolves all halos down to
 $5 \times 10^{10} M_{\text{dm}}$).

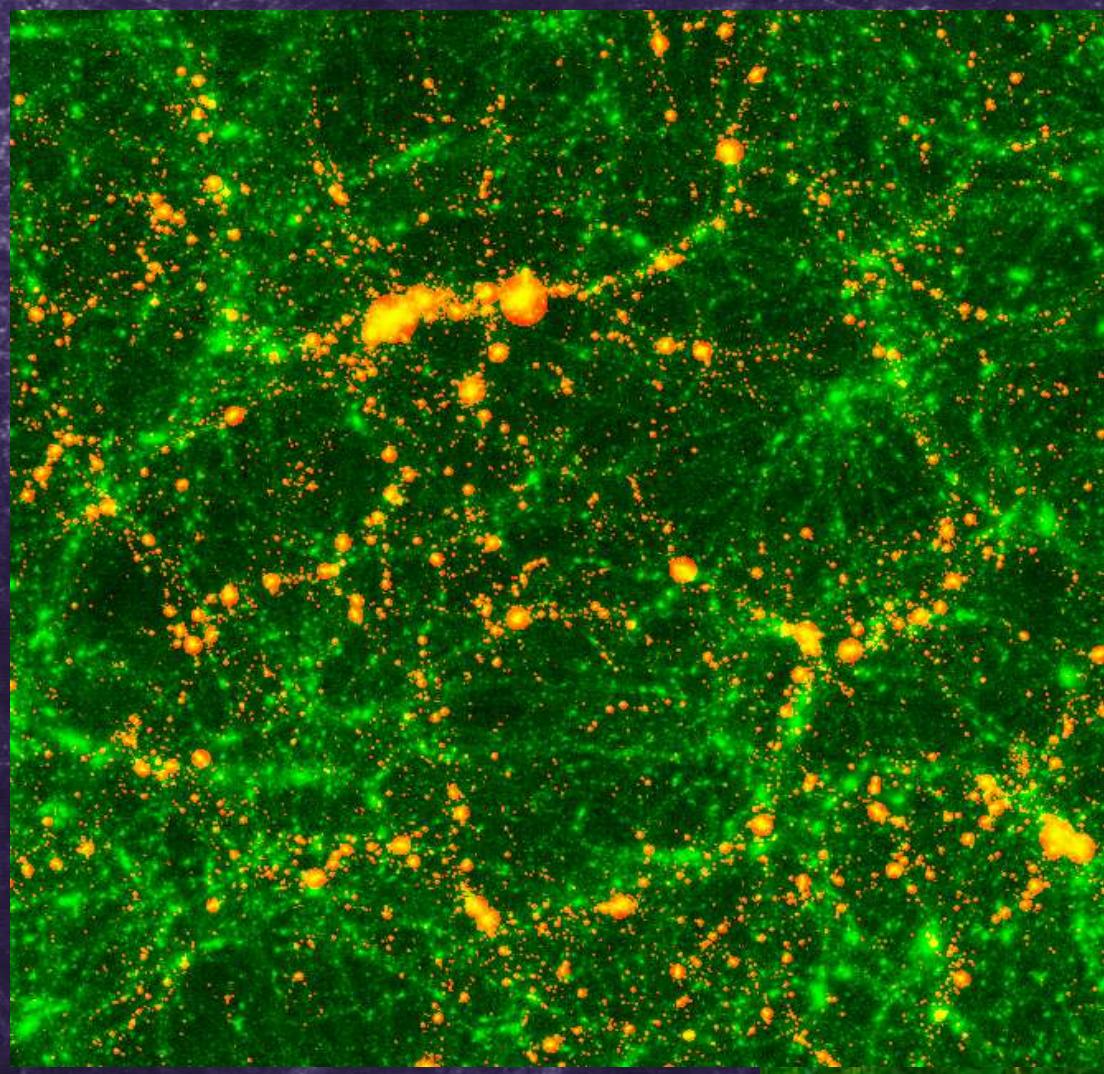
Resolution is similar to
Millenium sim (but in
8x the volume)

First halos form at z=16.6.
47+ million halos at z=0.

Part of a suite of sims
for modelling galaxy
surveys, BAO,
cosmological
parameter estimations.



Simulation ran at Texas Advanced
Computing Center on 6,912 cores.



scale structure
(in progress)

Part of a suite of sims
for modelling galaxy
surveys, BAO,
cosmological
parameter estimations.

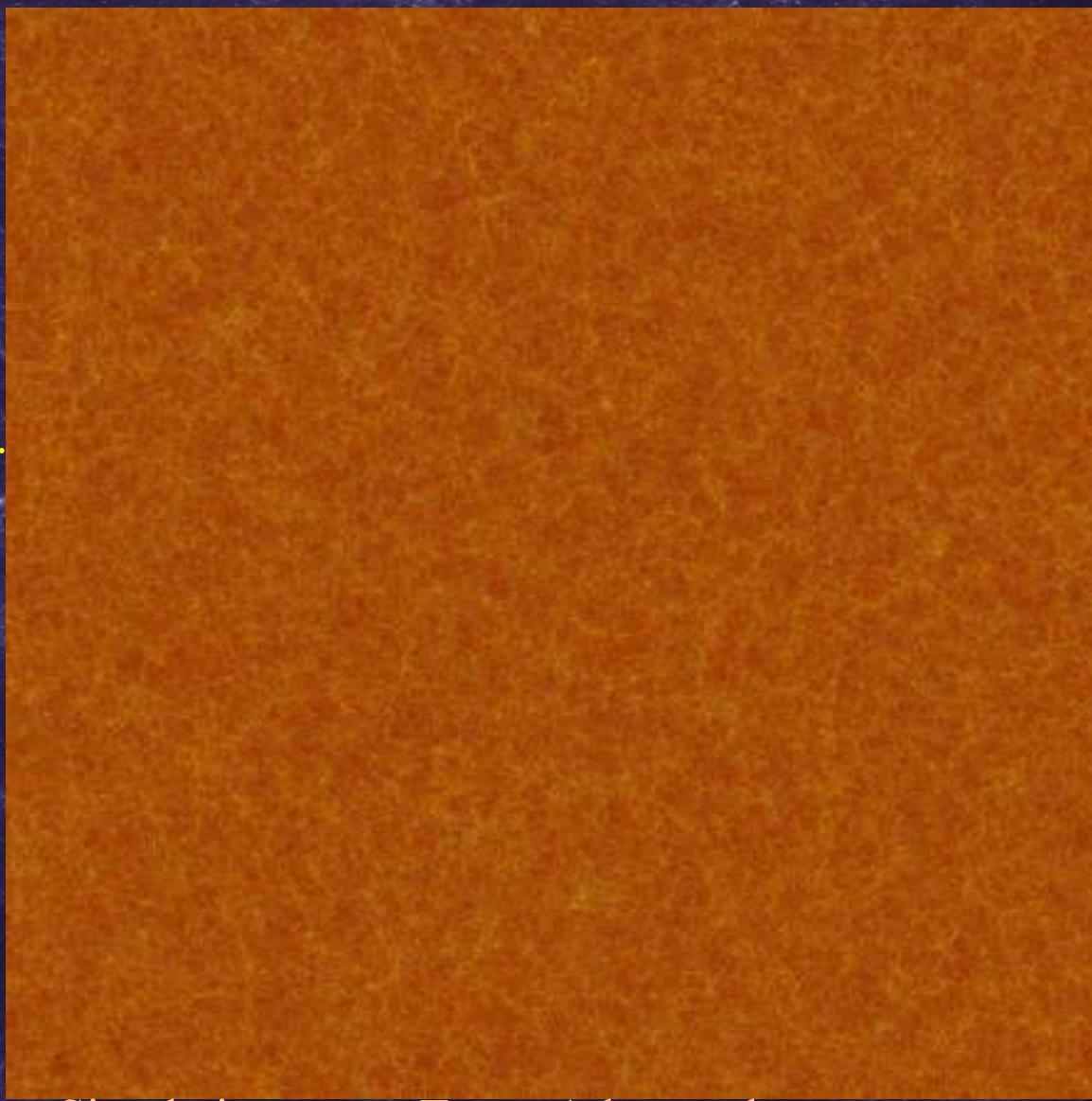
Simulation ran at Texas Advanced
Computing Center on 6,912 cores.

The very large-scale structure (in prep.)

3.2/h Gpc box @ z=0
4000³ particles (64 billion),
8000³ cells, P³M simulation
over 100 million halos at low z's,
~1 million clusters

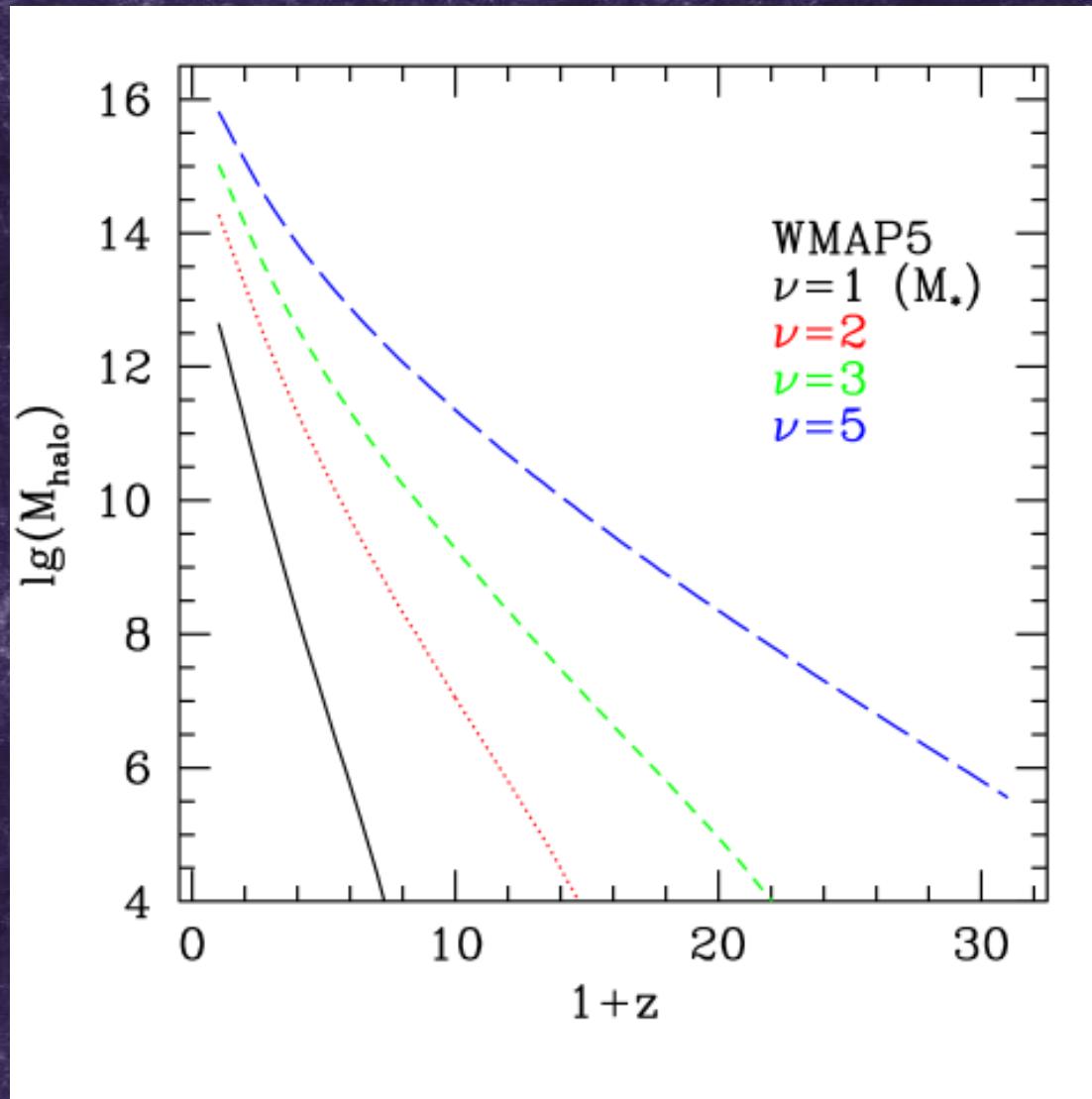
Suite of sims with 64 billion
(4000³) particles (on 4000 cores).

These sizes allow simulating
the whole volume of a large
galaxy survey (multiple Gpc³)
with the appropriate resolution
(i.e. resolving L* or better) – up
to 1 billion galaxies! Ideal for
LOFAR/SKA HI surveys (BAO,
nonlinear bias, non-gaussianity).



Simulation ran at Texas Advanced
Computing Facility on 4000 cores.

How rare are halos?



The high-z halo mass function

(work in progress)

Rich statistics ($z=8$):

20/h Mpc box: 114 million halos

2/h Mpc box: 5M+ (mini)halos

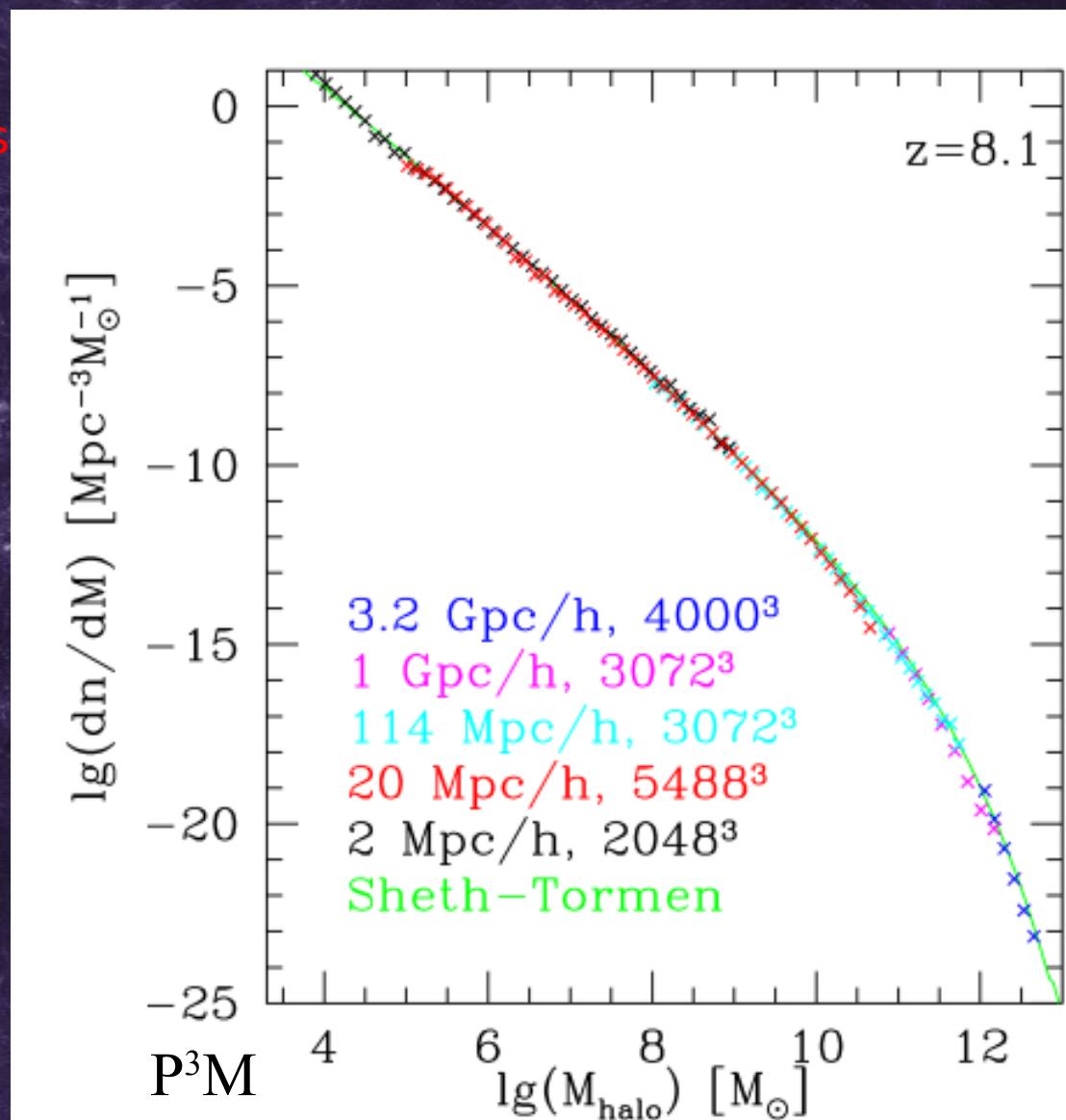
114/h Mpc box: 12M+ halos

1 Gpc/h box: 330k+ halos

3.2 Gpc/h box: 3600+ halos

(MW-sized or larger!)

Results show good agreement with each other, but differ from the Sheth-Tormen mass function (green) at the high-mass end.



The high-z halo mass function

(work in progress)

Rich statistics ($z=8$):

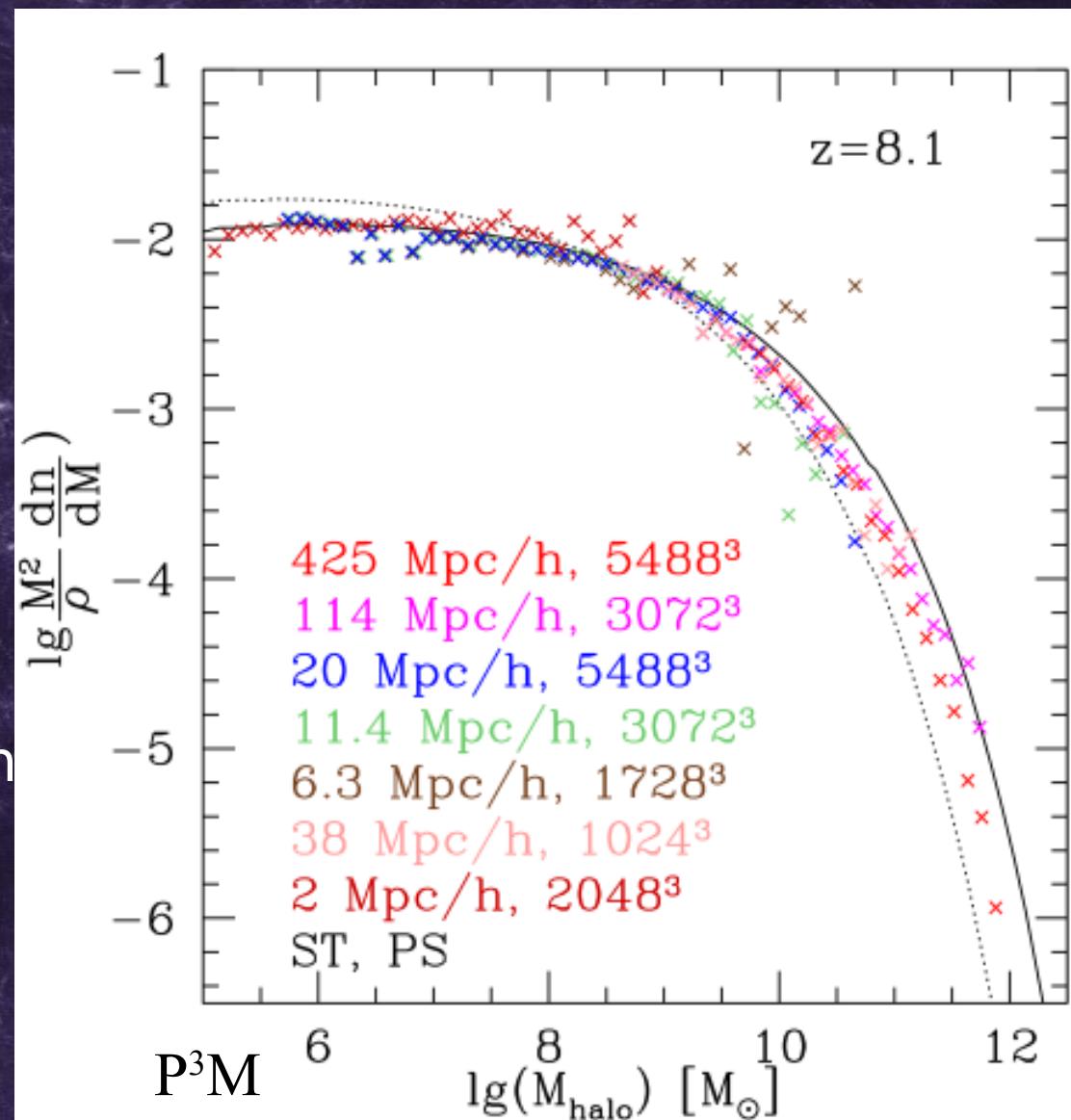
425 Mpc/h: 39 million halos

20 Mpc/h: 114 million halos

2 Mpc/h: 5M+ (mini)halos

114 Mpc/h: 12M+ halos

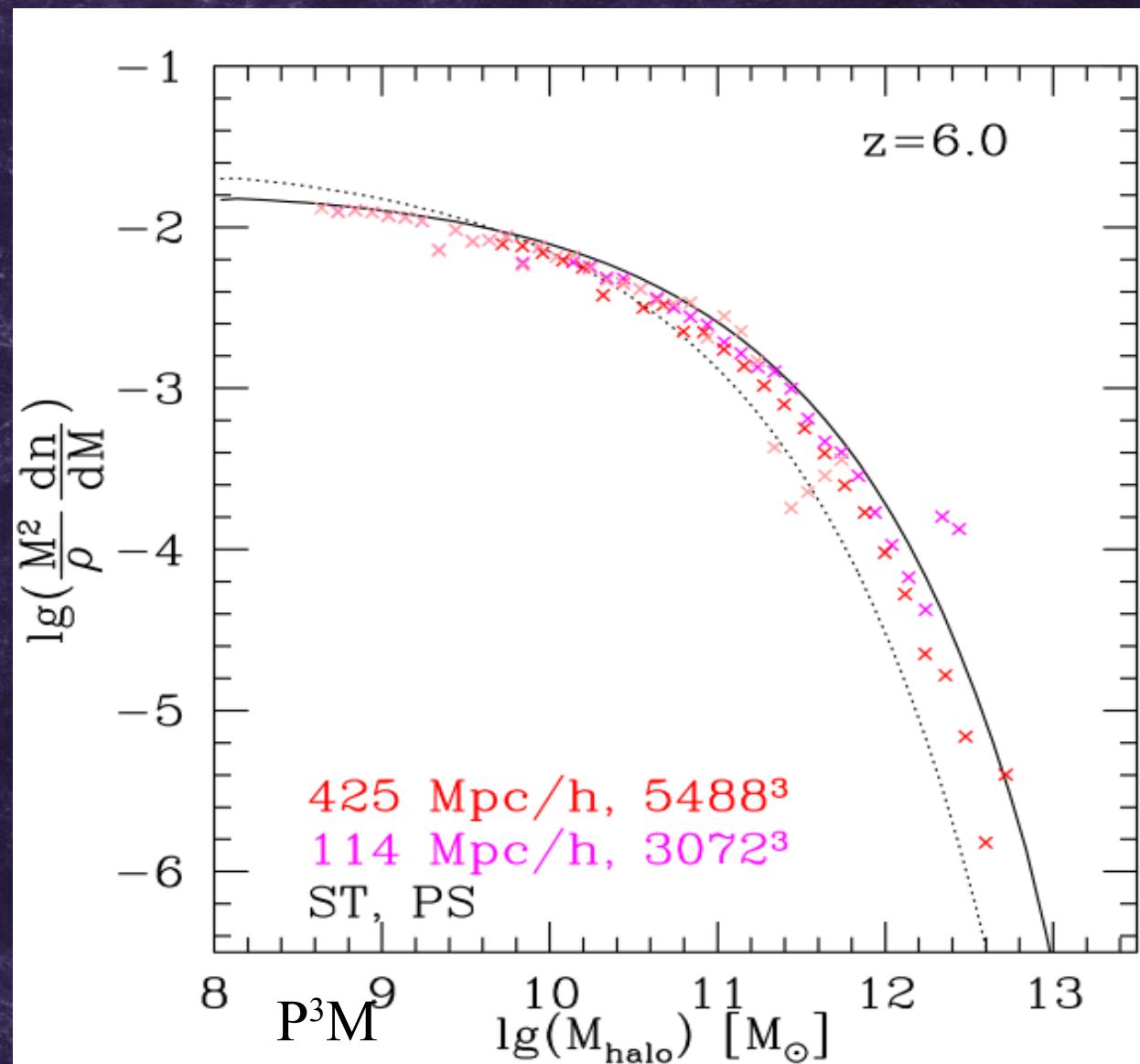
Results show good agreement with each other (within cosmic variance), but differ from the Sheth-Tormen mass function at the high-mass end.



The high-z halo mass function

(work in progress)

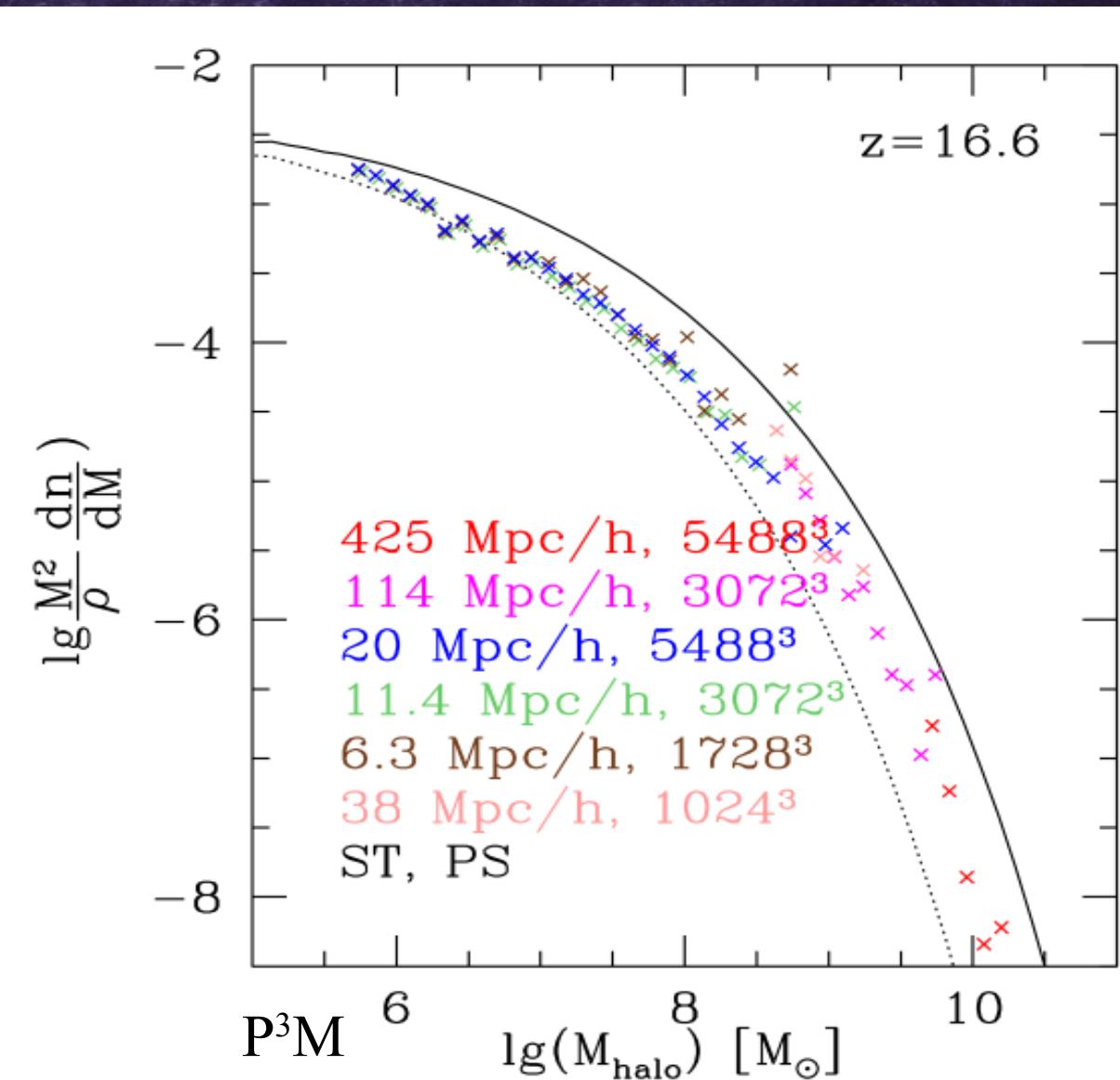
$z=6$,
100+ particles/halo



The high-z halo mass function

(work in progress)

$z=16.6$,
100+ particles/halo

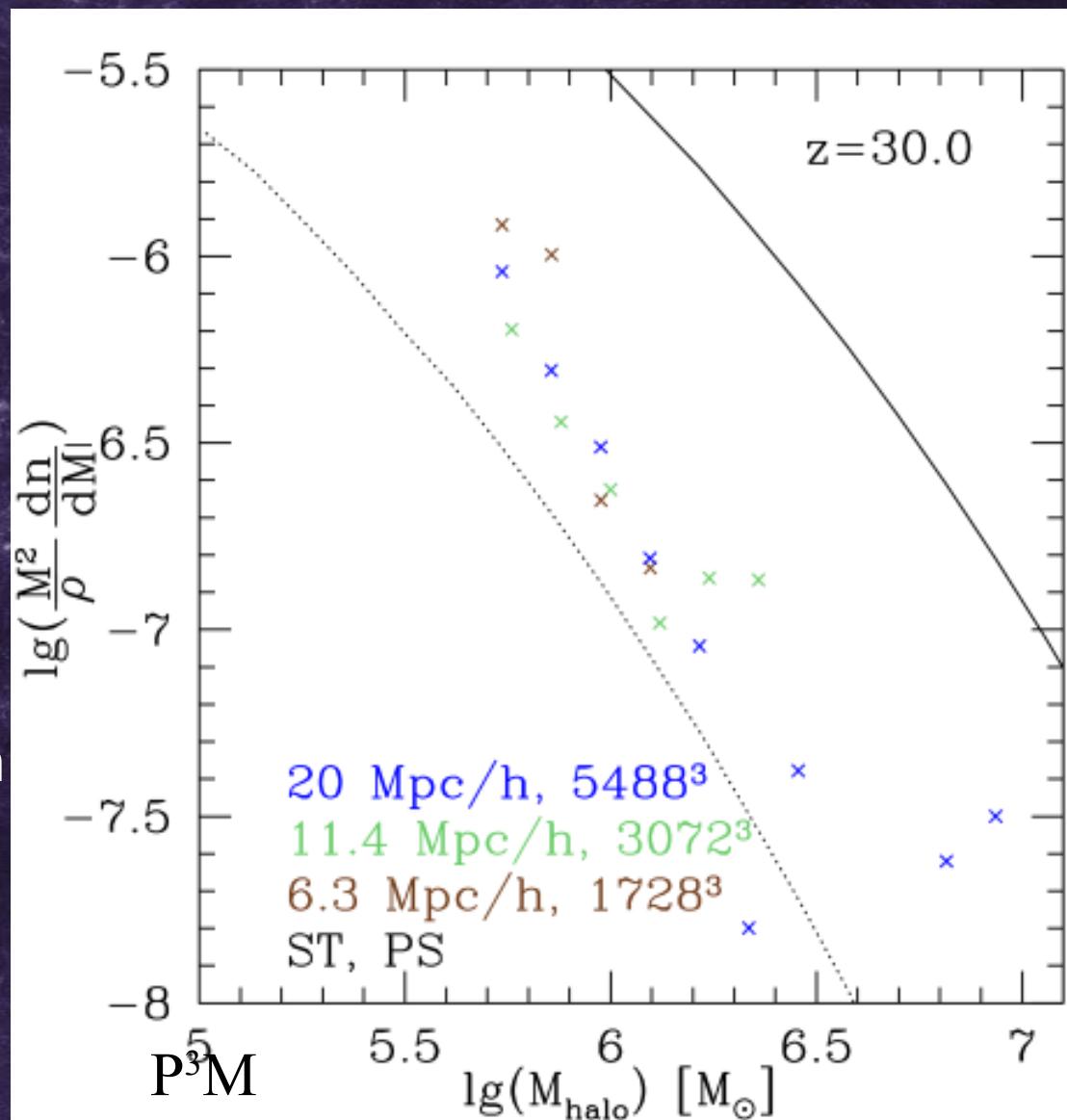


The high-z halo mass function

(work in progress)

Z=30, 100+ particles/halo
20 Mpc/h box: ~100k halos
11.4 Mpc/ box: 18k+ halos
6.3 Mpc/h box: 3k+ halos

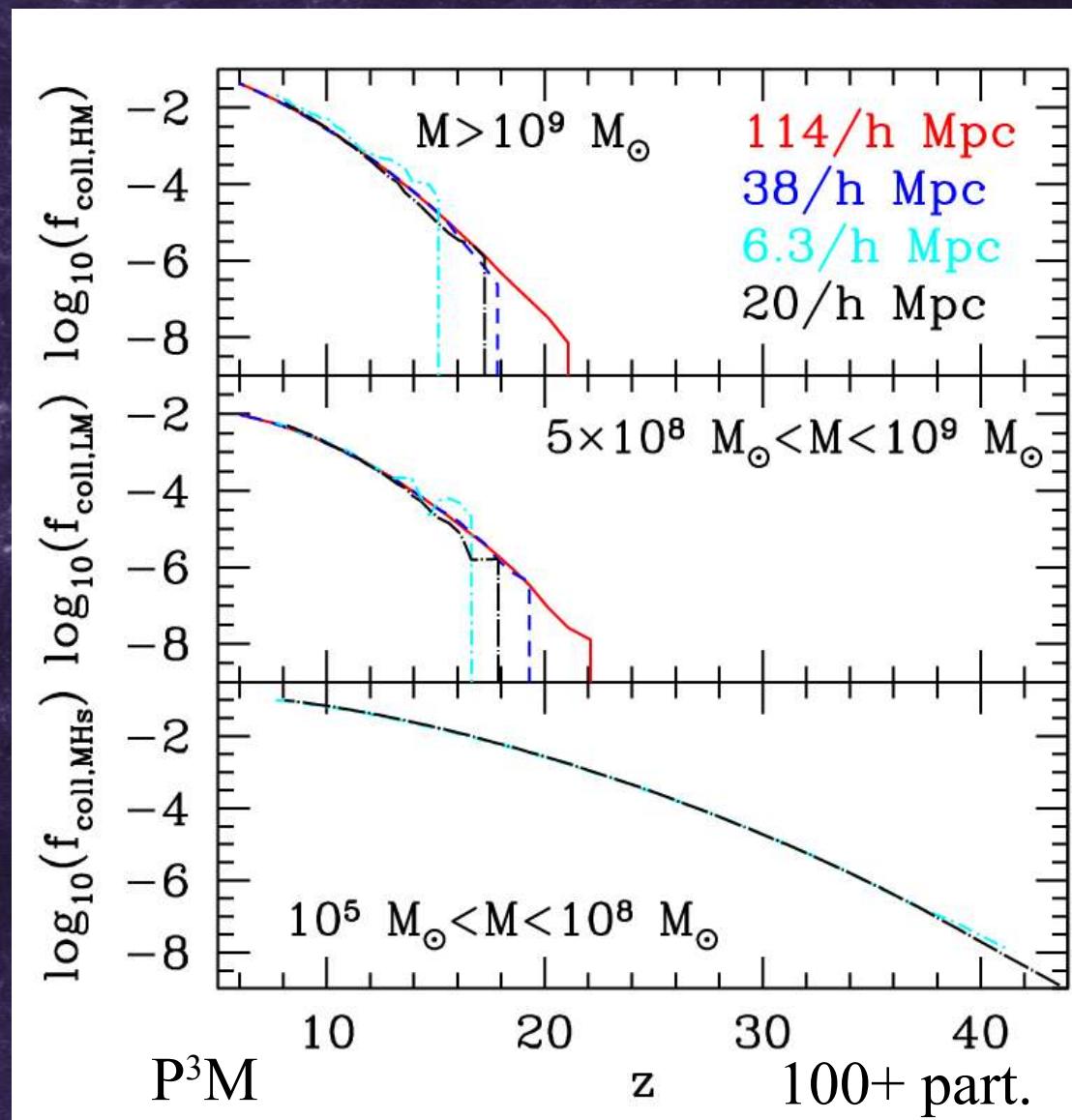
Results show good agreement with each other, but differ by an order of magnitude from the Sheth-Tormen mass function for all halos.



The high-z collapsed fractions

(work in progress)

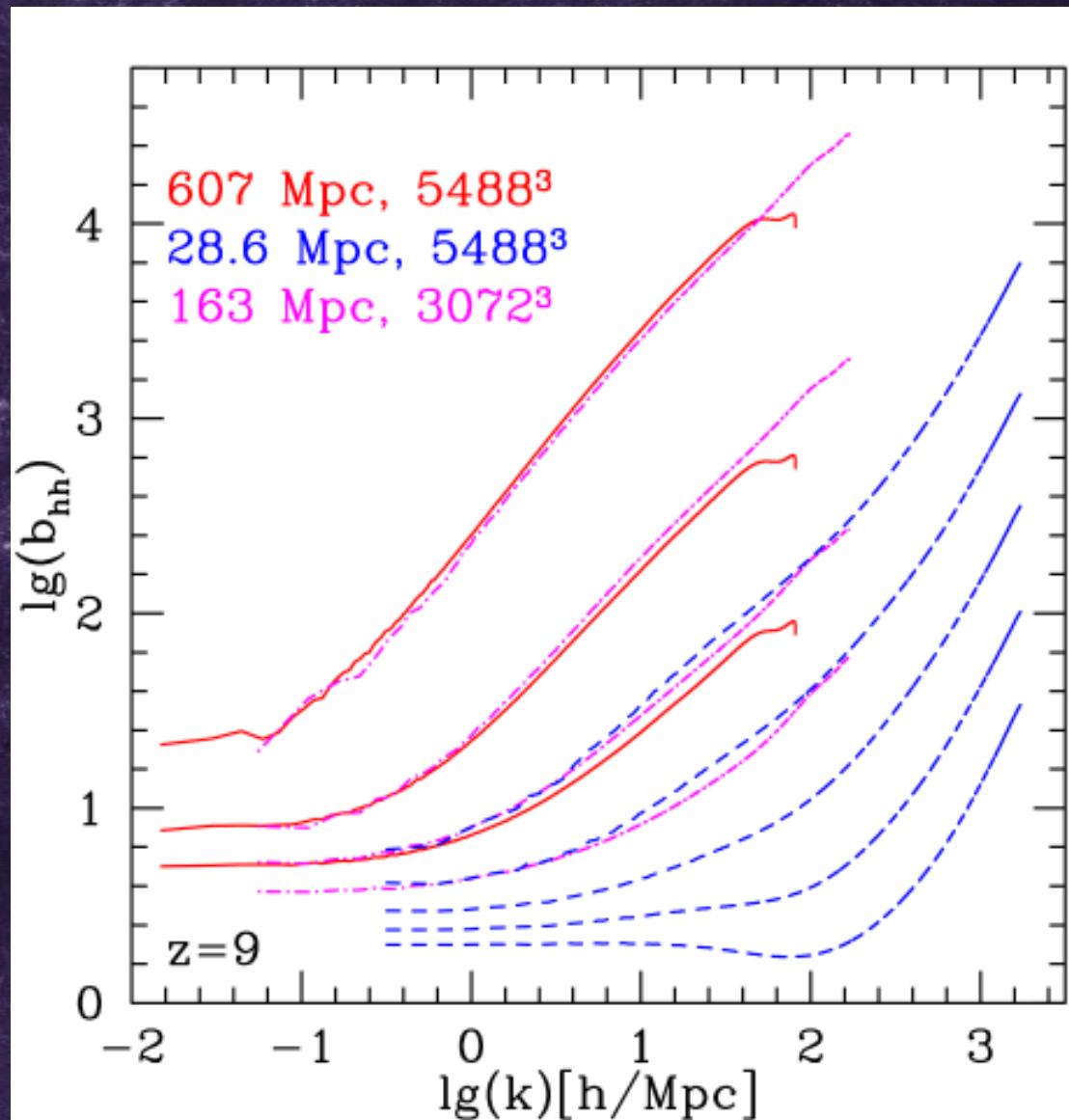
Halo collapsed fractions agree quite well for a range of box sizes from 114 Mpc/h to 6.3 Mpc/h. Cut-off and noise at high mass is due to poor statistics (i.e. cosmic variance).



The high-z halo bias

(work in progress)

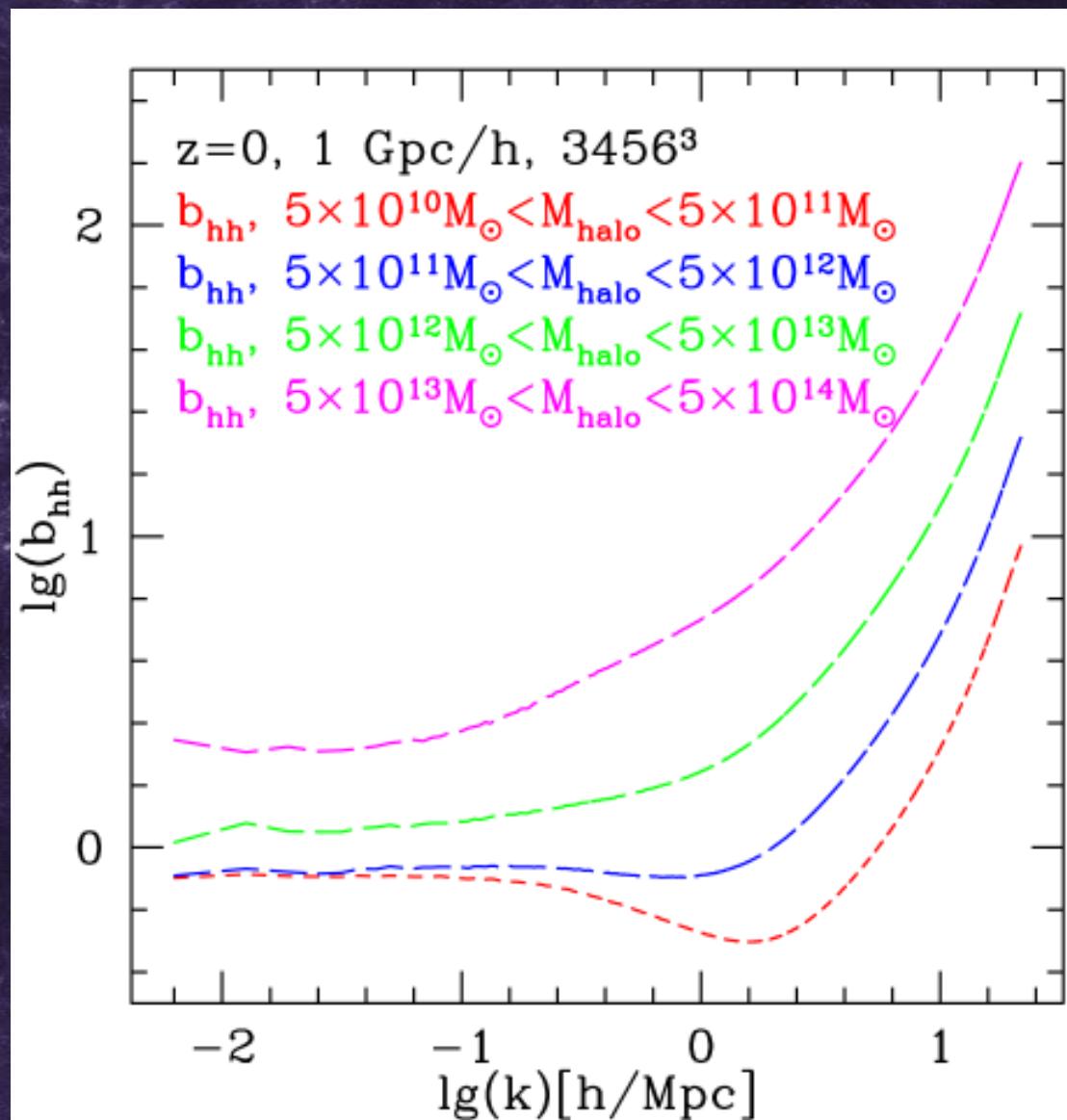
- Halos at high-z are strongly clustered.
- Bias increases fast with halo mass and can reach a thousands in the nonlinear regime.
- Scale at which bias becomes linear varies significantly with halo mass.
- Simulations with different resolutions agree fairly well in the overlapping mass ranges.



$z=0$ halo bias

(work in progress)

- Halos at $z=0$ are much less clustered.
- Scale at which bias becomes linear varies significantly with halo mass.
- Smallest halos (below M_* ~ $5 \times 10^{12} M_\odot$) are anti-biased ($b < 1$), as expected.



The high-z halo mass functions: effect of primordial non-Gaussianity

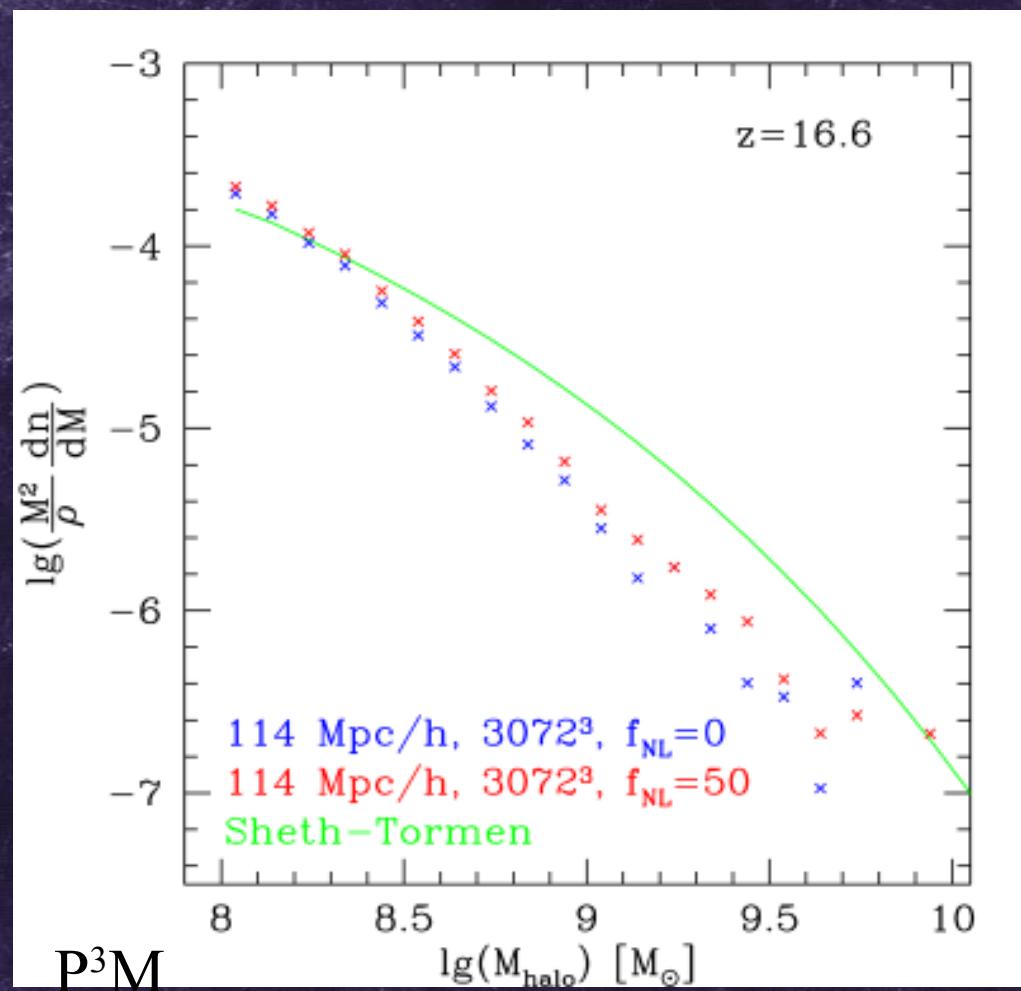
(work in progress)

Many inflationary theories predict the possibility of non-Gaussianity in the primordial density fluctuations.

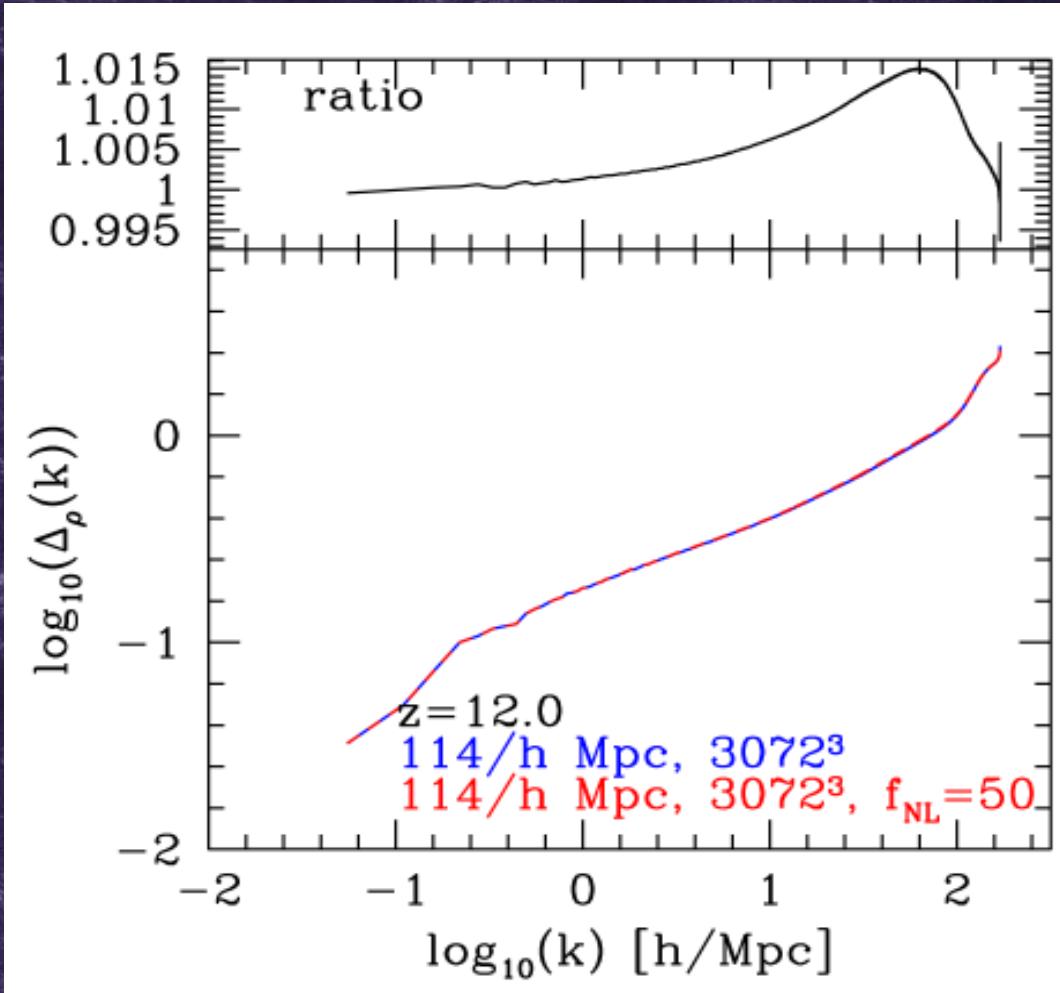
Usually characterized by parameter f_{NL} (quadratic term in potential). Current observational limits suggest $0 < f_{NL} < 50$.

Important effects on very large scales at $z=0$ (e.g. Dalal et al 2008, Desjacques et al. 2009, Pillepich et al., 2009)

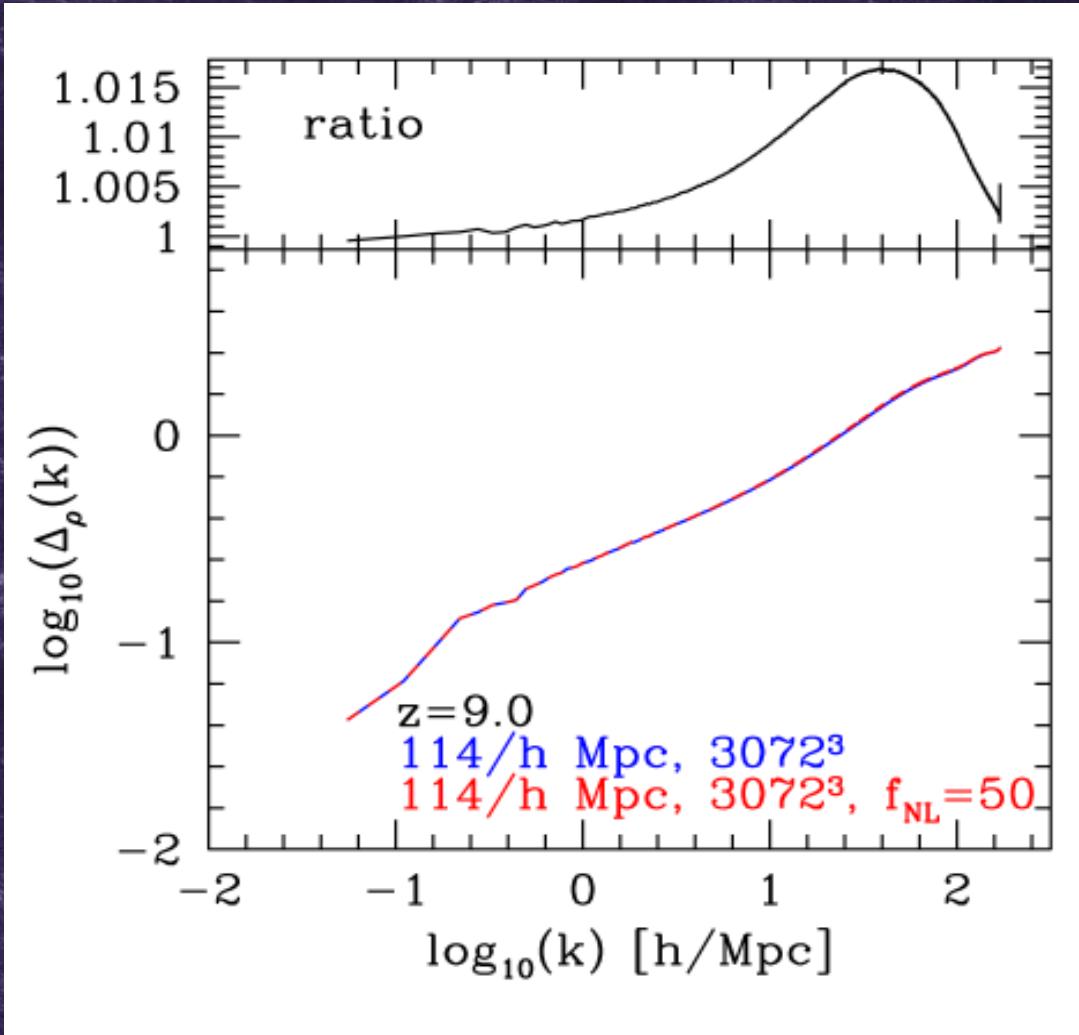
Can it also affect reionization?



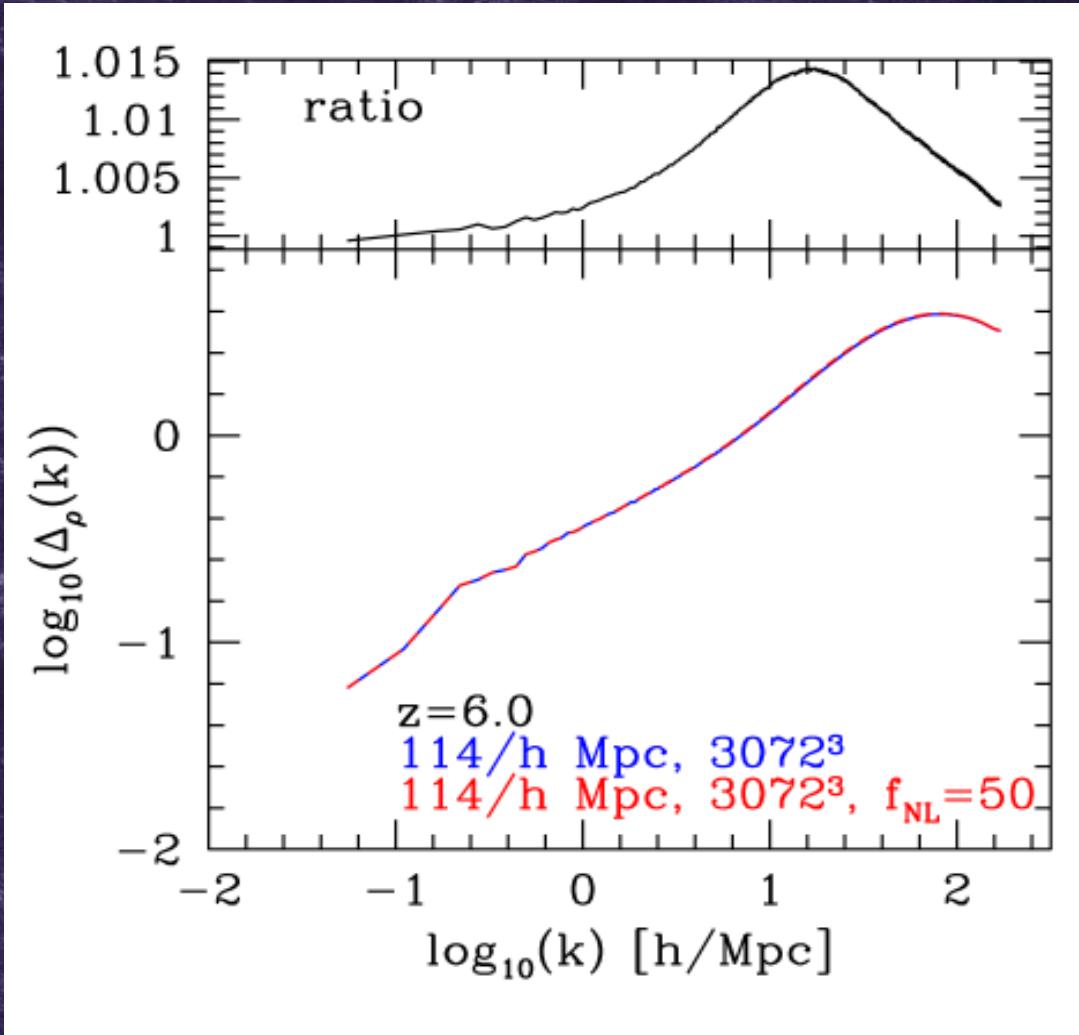
$f_{NL} \neq 0$: power spectra



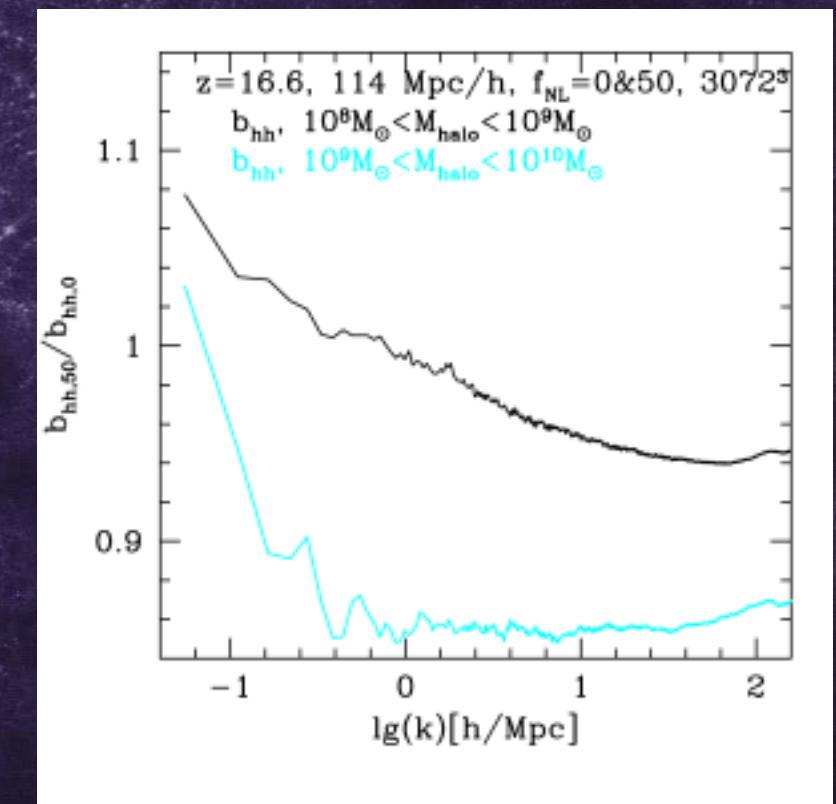
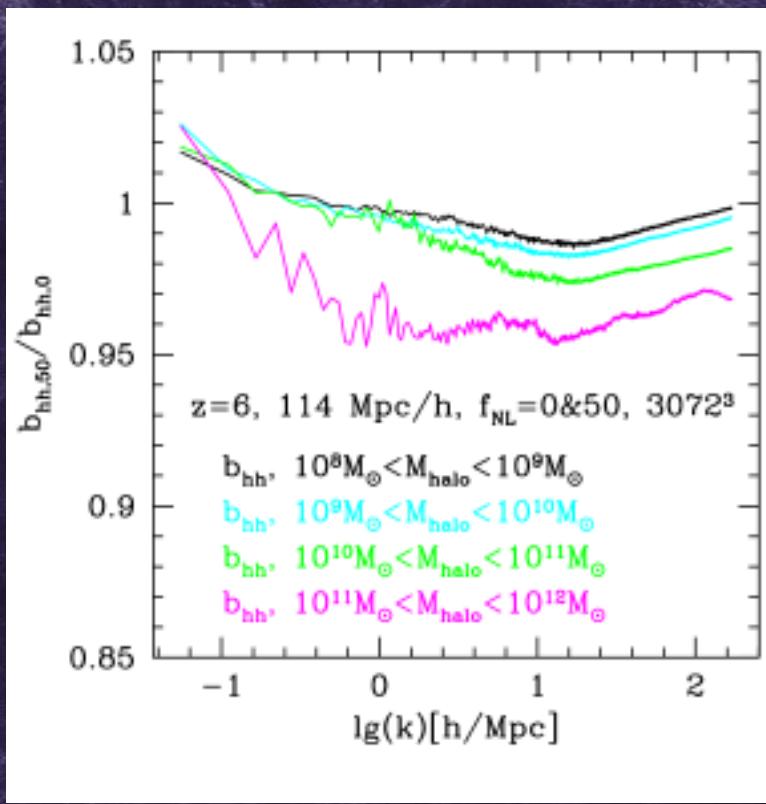
$f_{NL} \neq 0$: power spectra



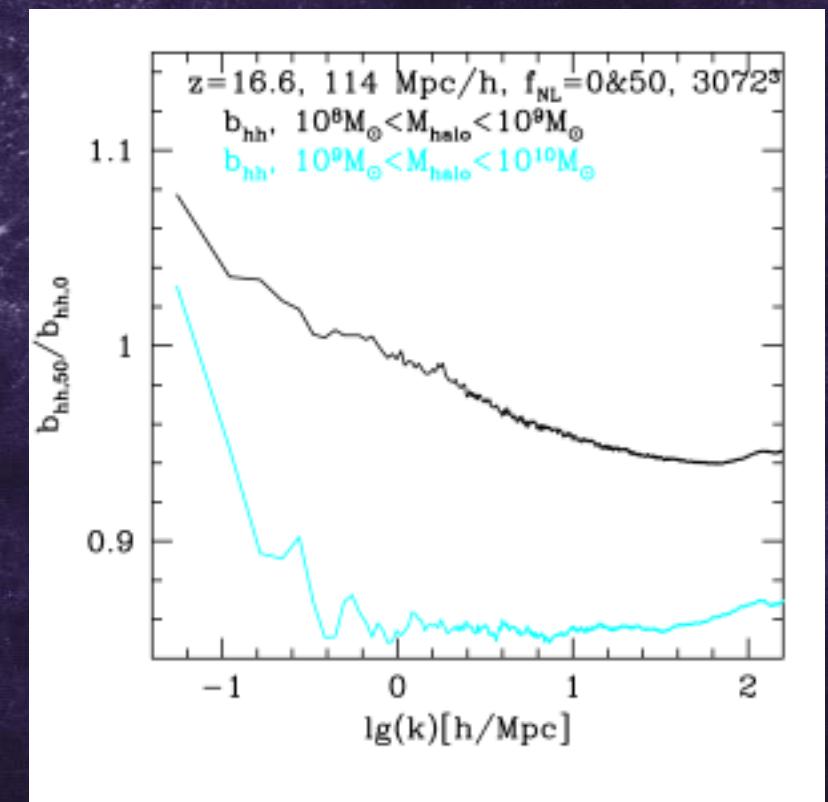
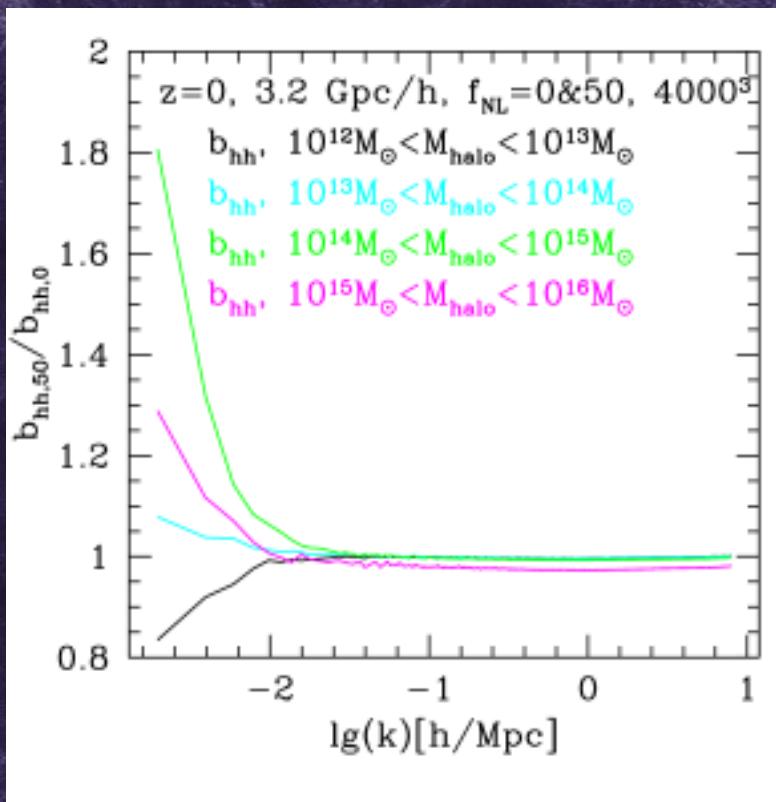
$f_{NL} \neq 0$: power spectra



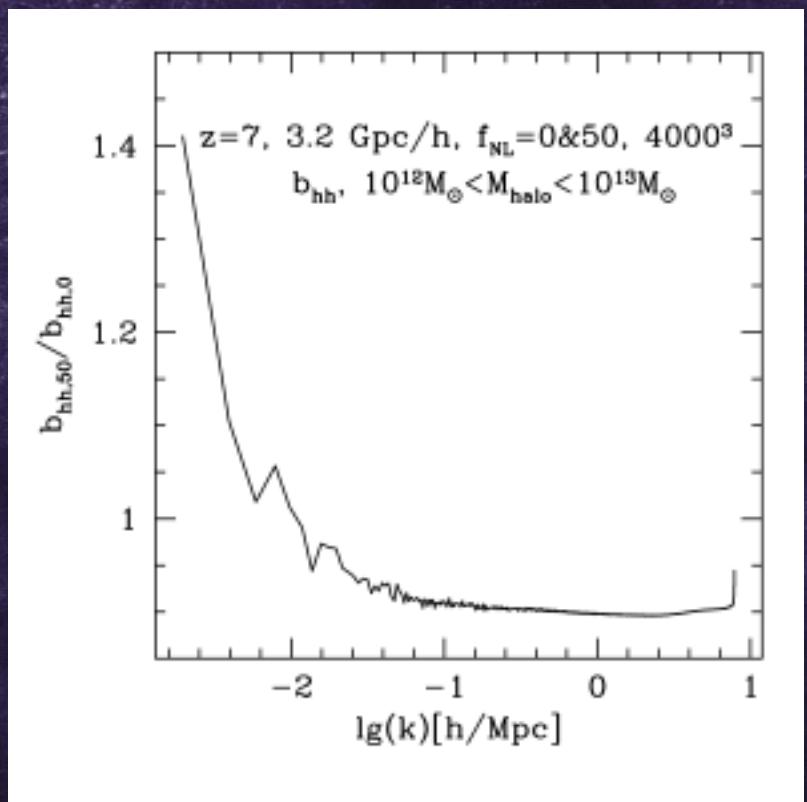
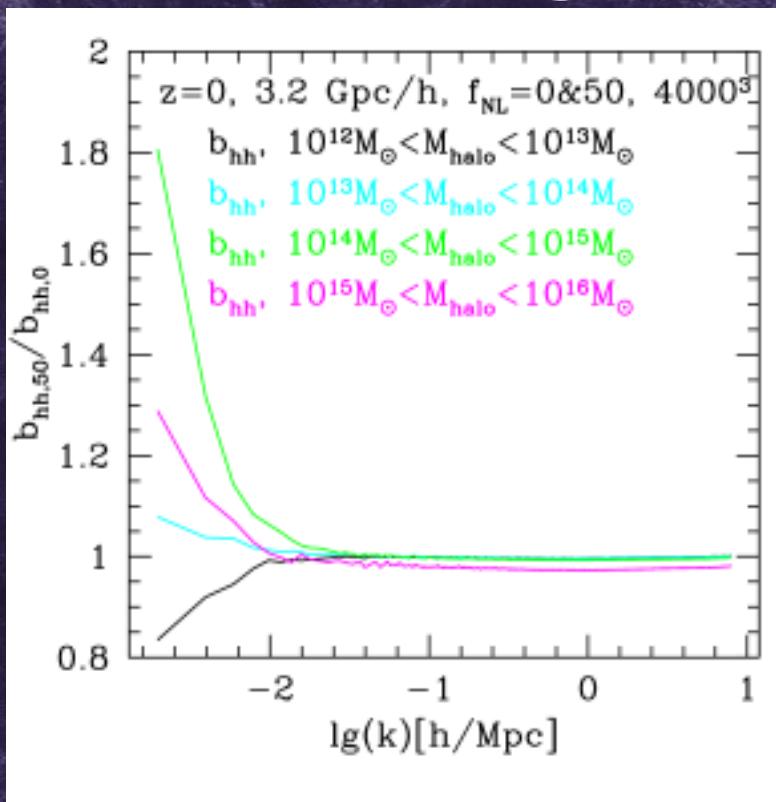
$f_{NL} \neq 0$: halo bias ratio



$f_{NL} \neq 0$: halo bias ratio, high- vs. low-z



$f_{\text{NL}} \neq 0$: halo bias ratio, high- vs. low-z II

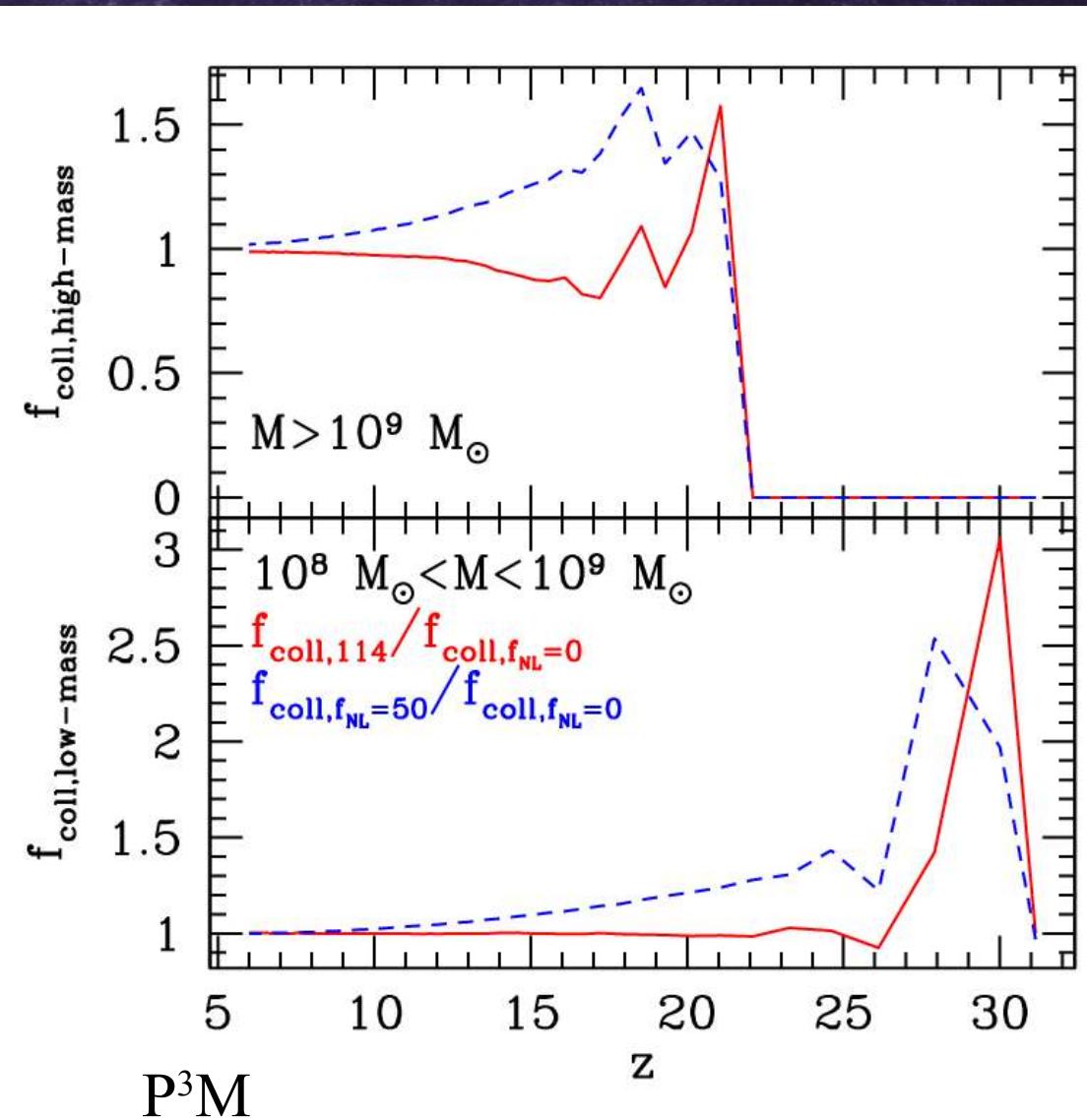


The high- z collapsed fractions: effect of primordial non-Gaussianity

(work in progress)

Effect of non-Gaussianity is largest at for very rare halos and gradually diminishes as halos become more common (blue).

Initial 'peak' is in fact due to cosmic variance (present also for 2 random realizations without Non-Gaussianity (red)).

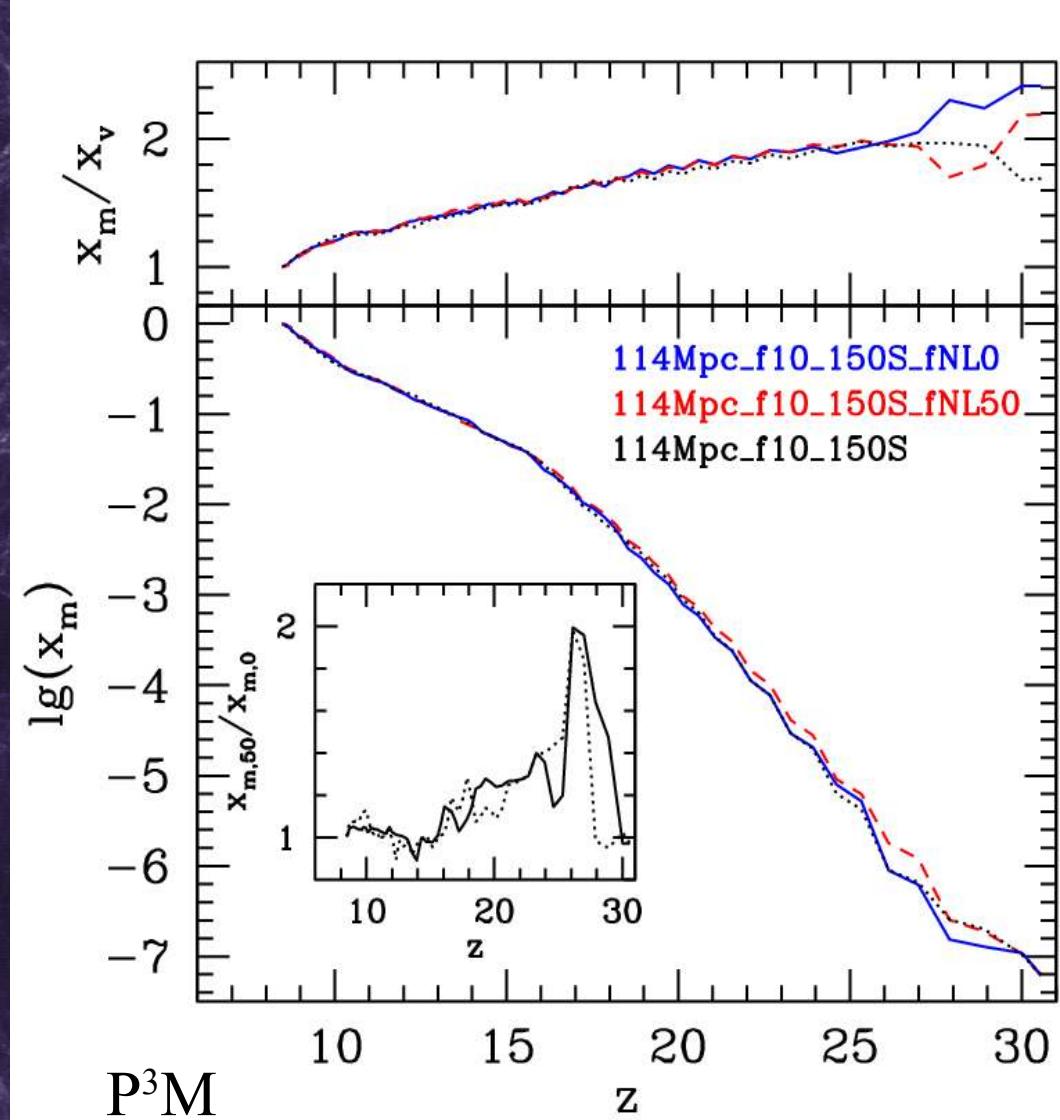


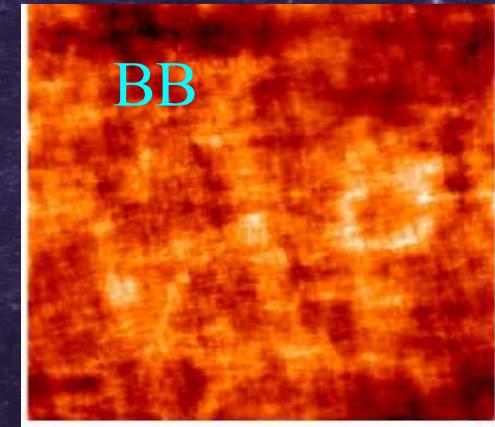
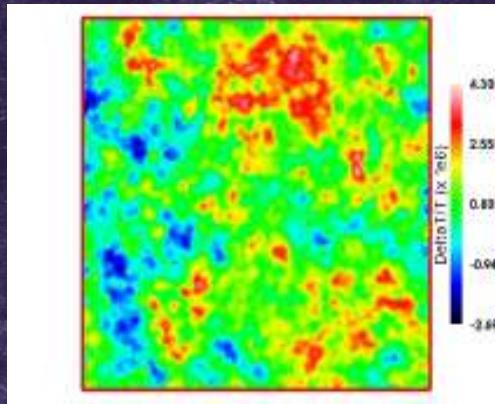
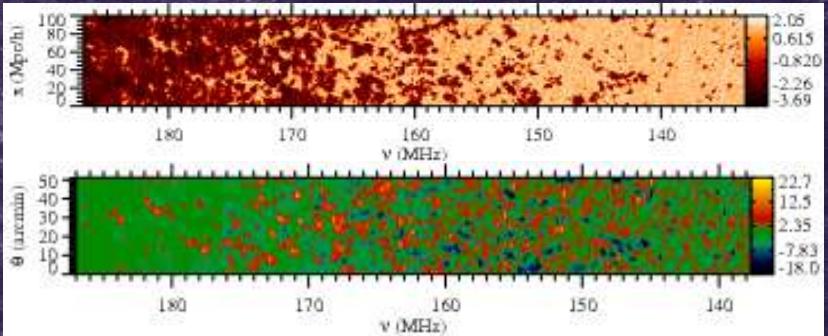
Effect of primordial non-Gaussianity: reionization history

(work in progress)

Effect on mean reionization history is significant (>20%) at high-z ($z > 16$), when reionization is dominated by rare sources and largely disappears at lower redshifts.

Non-Gaussianity affects the halo clustering and abundances and thus will affect HII region sizes, 21-cm fluctuations, etc. Stay tuned...





redshifted 21-cm

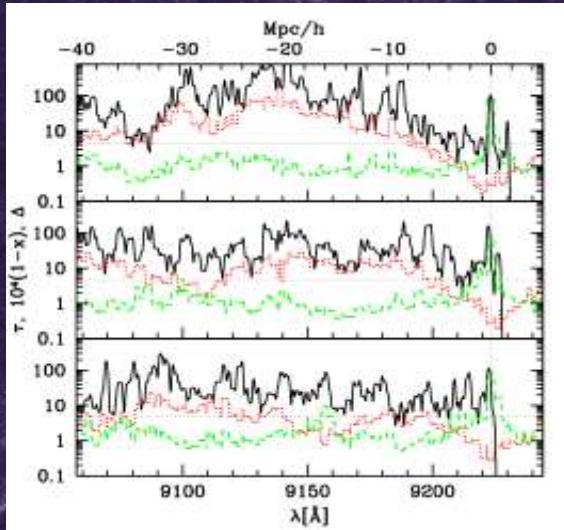
kinetic Sunyaev-Zeldovich
effect (kSZ)

CMB polarization

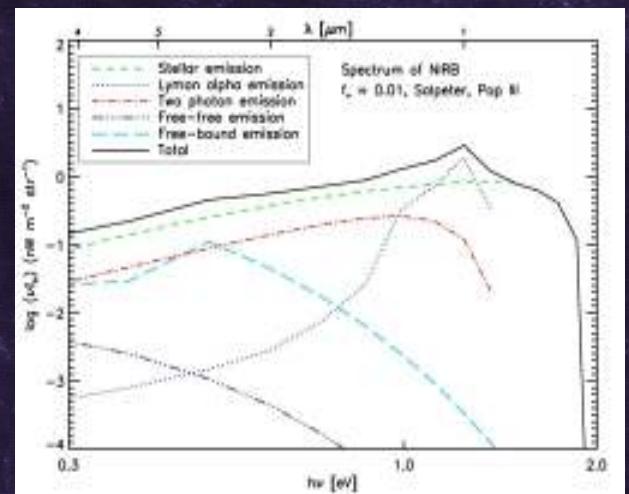
Ly- α sources

Observing the Reionization Epoch

NIR fluctuations

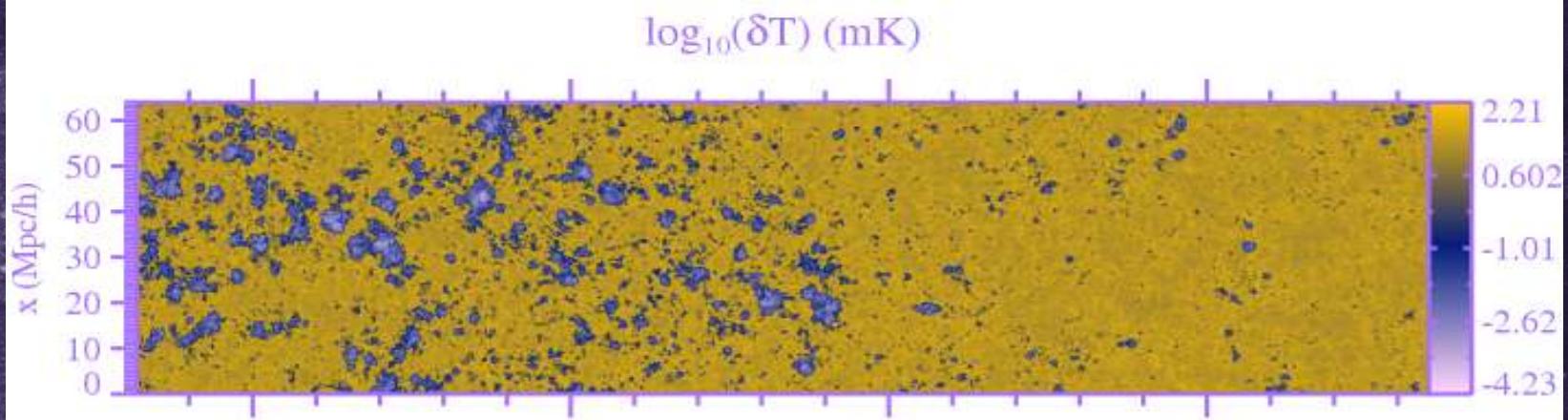


Iliev et al. 2006a, MNRAS;
2007(a,b,c,d), 2008 MNRAS,
ApJ, Mellema et al. 2006,
MNRAS; Dore et al., 2006,
Phys. Rev. D; Holder, Iliev
& Mellema 2006 ApJ,
Fernandez et al. 2010, ApJ
Tilvi et al. 2010, ApJ

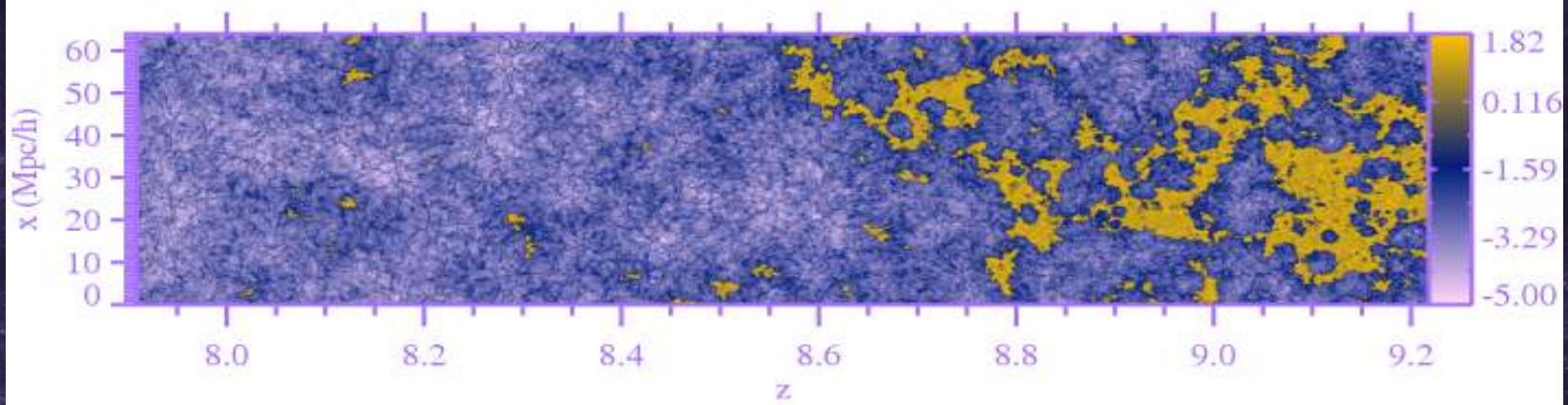
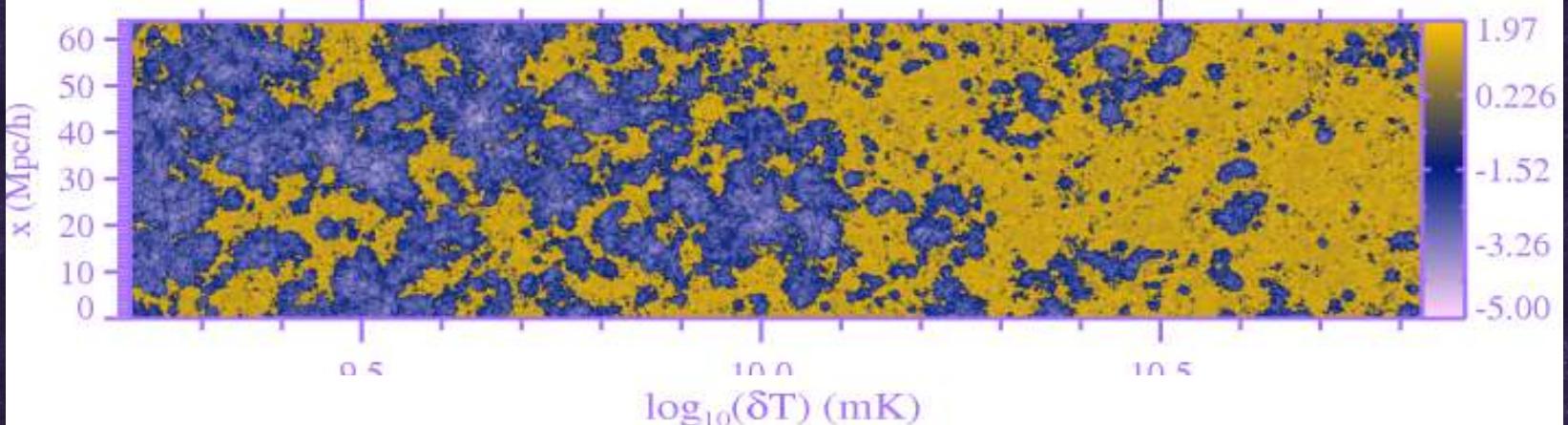


21-cm observations: flying through the image cube

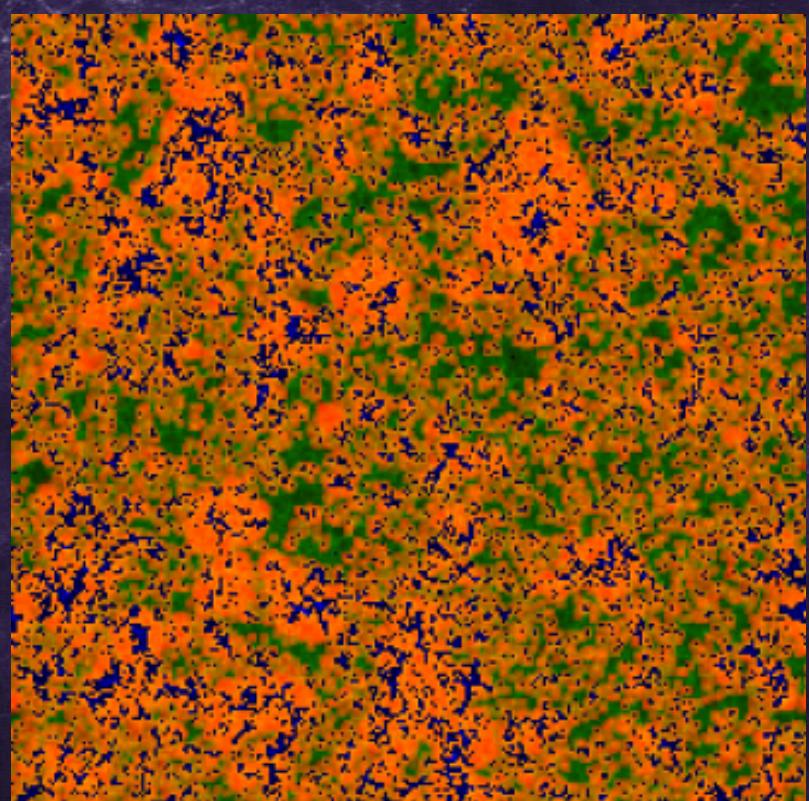
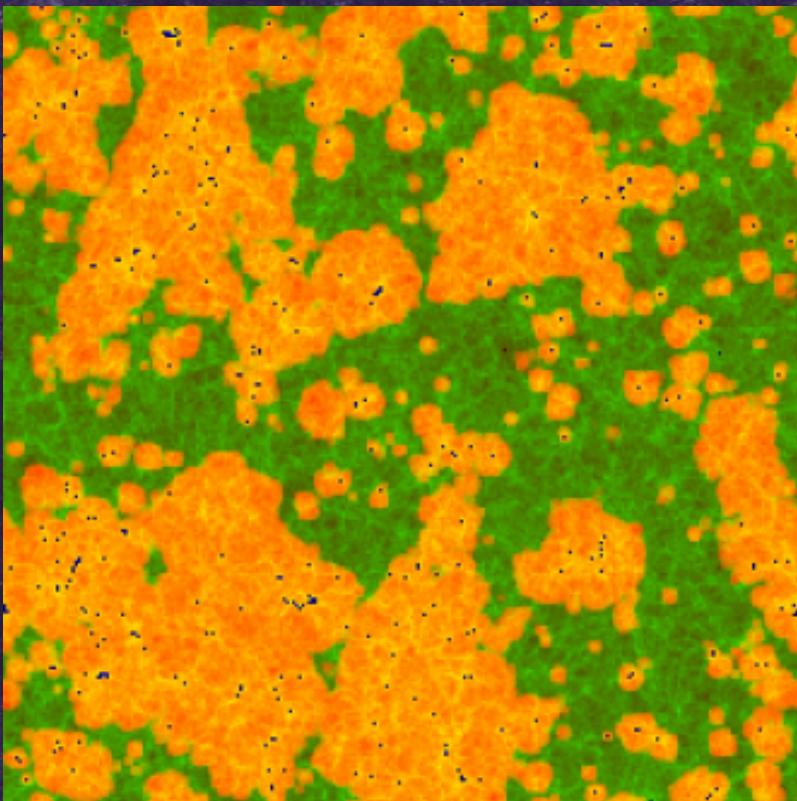




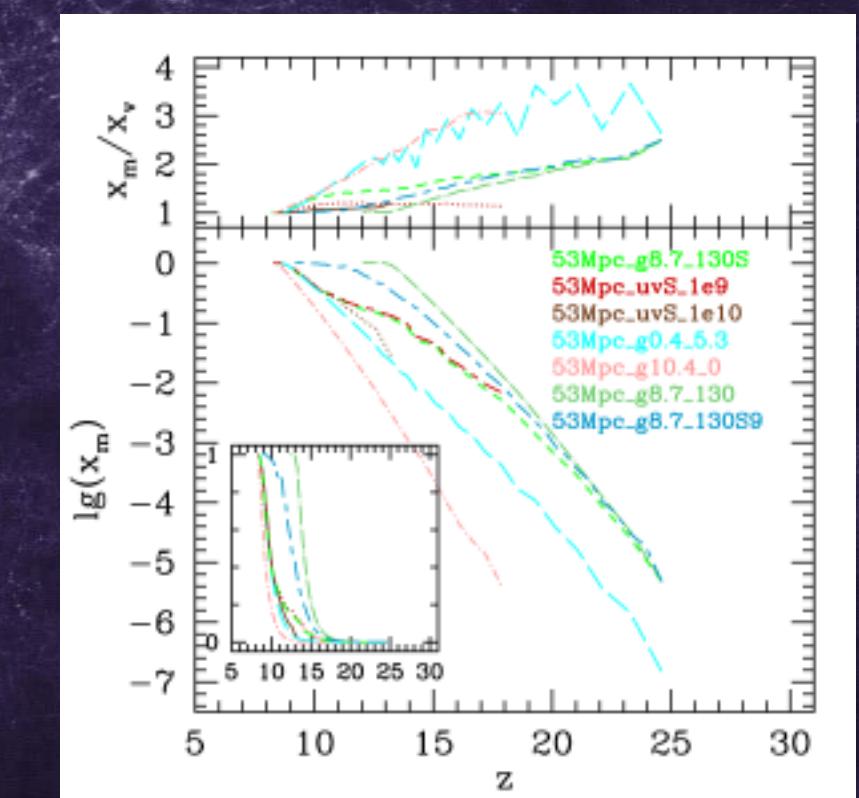
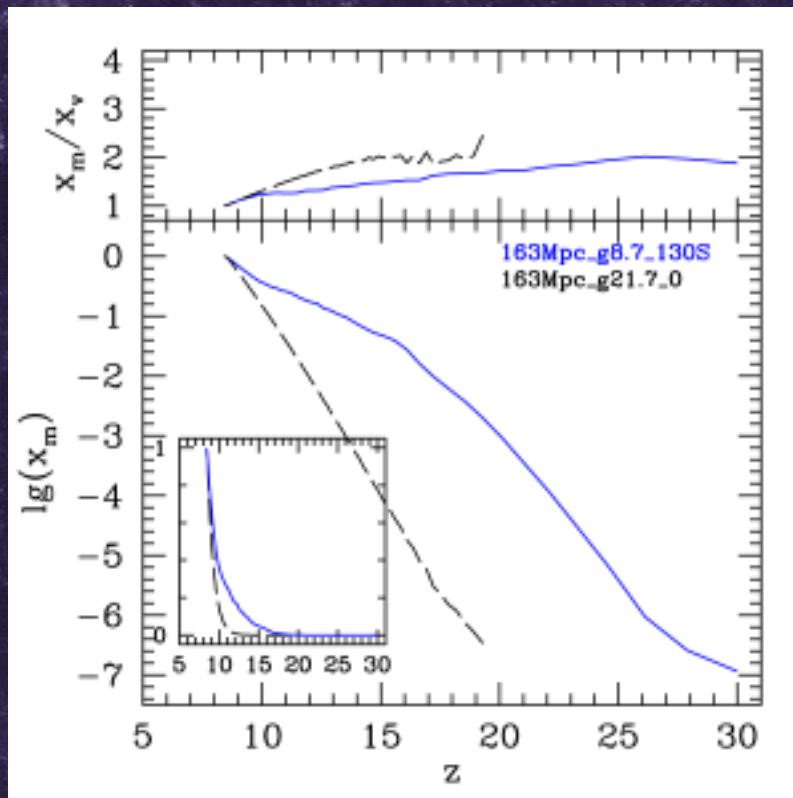
f100_250S_64Mpc WMAP3+



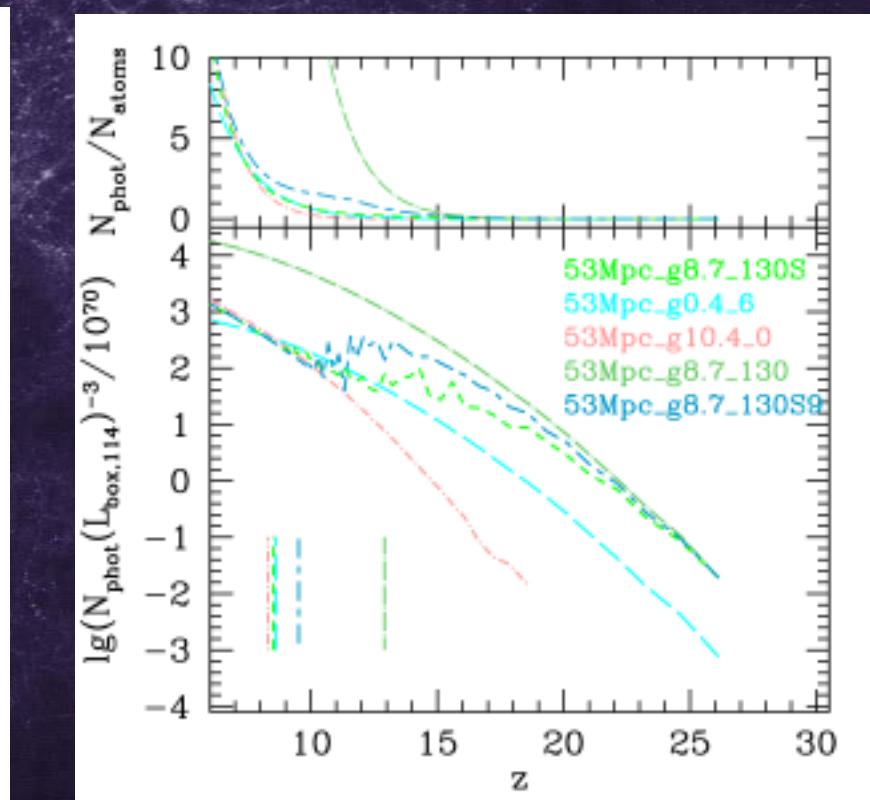
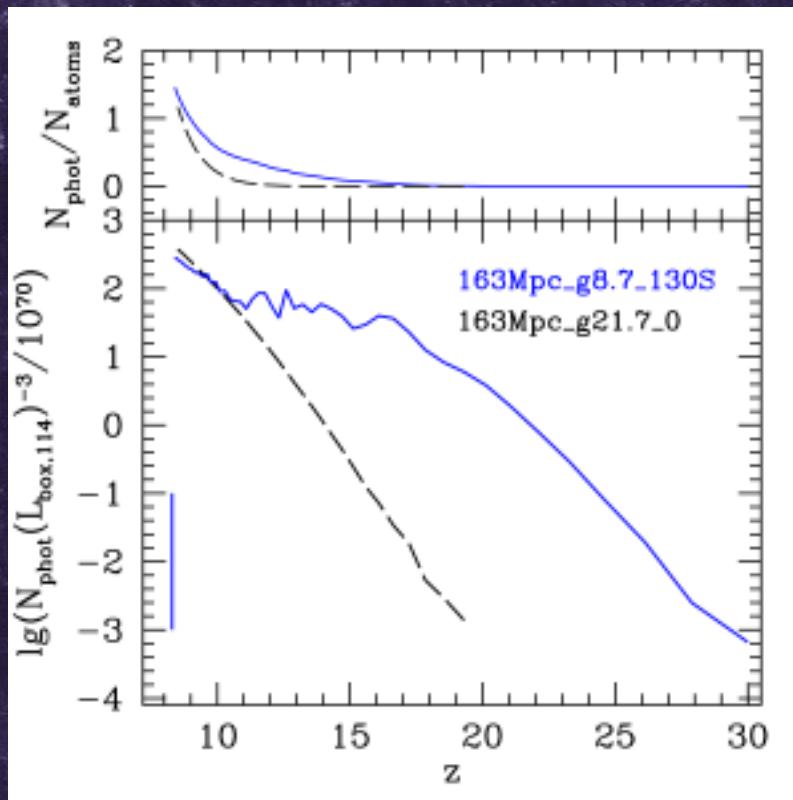
Effects of self-regulation (Jeans-mass filtering) on reionization



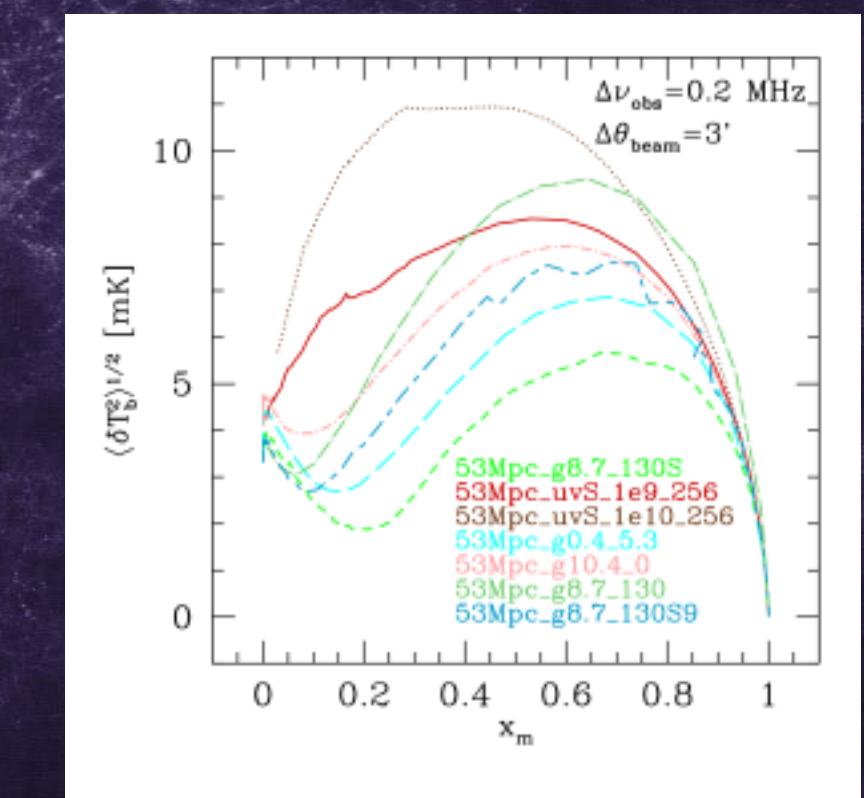
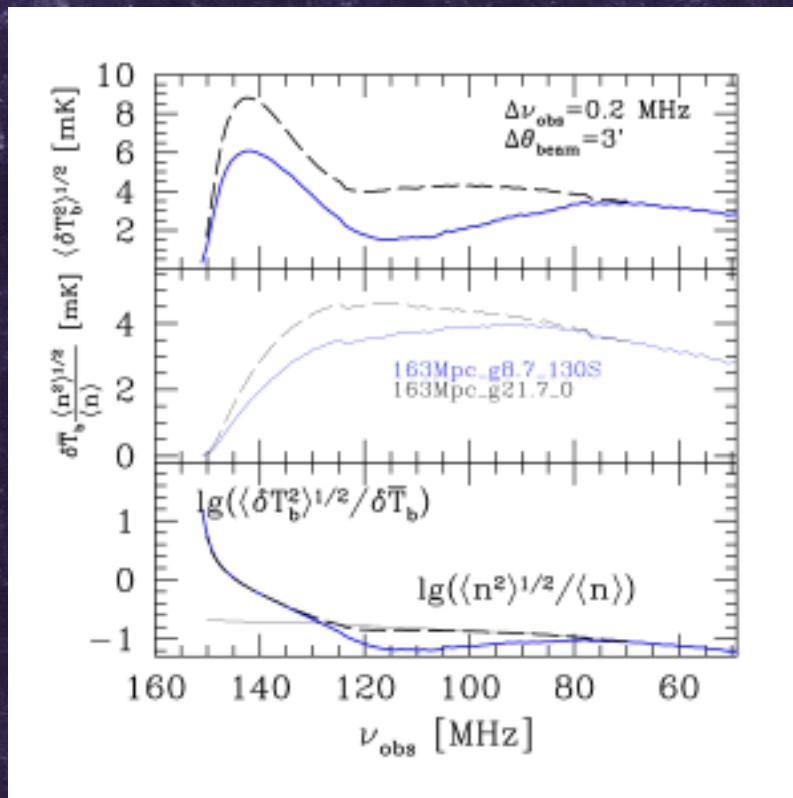
Reionization history: self-regulation and source models



Photon emissivity: self-regulation and source models



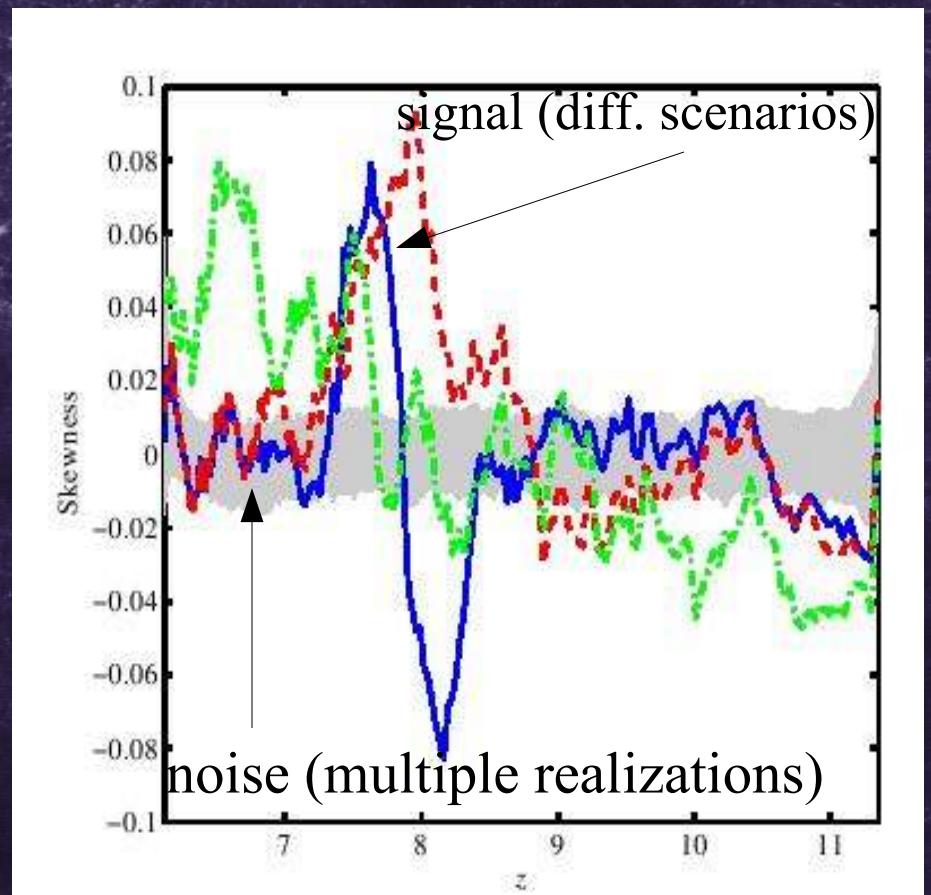
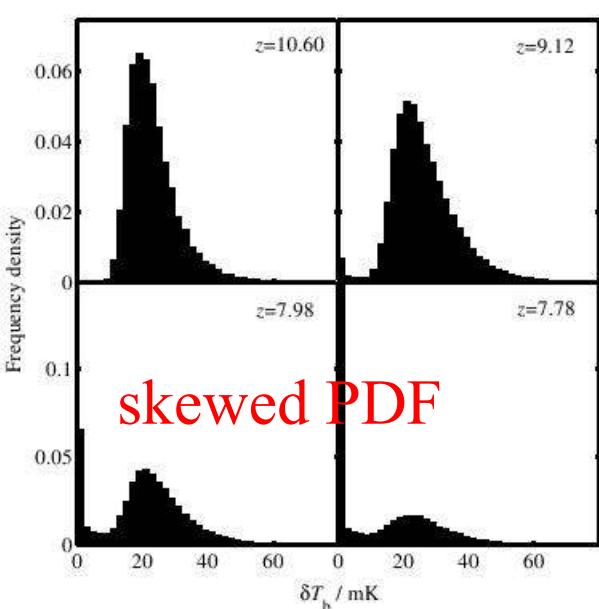
21-cm rms fluctuations



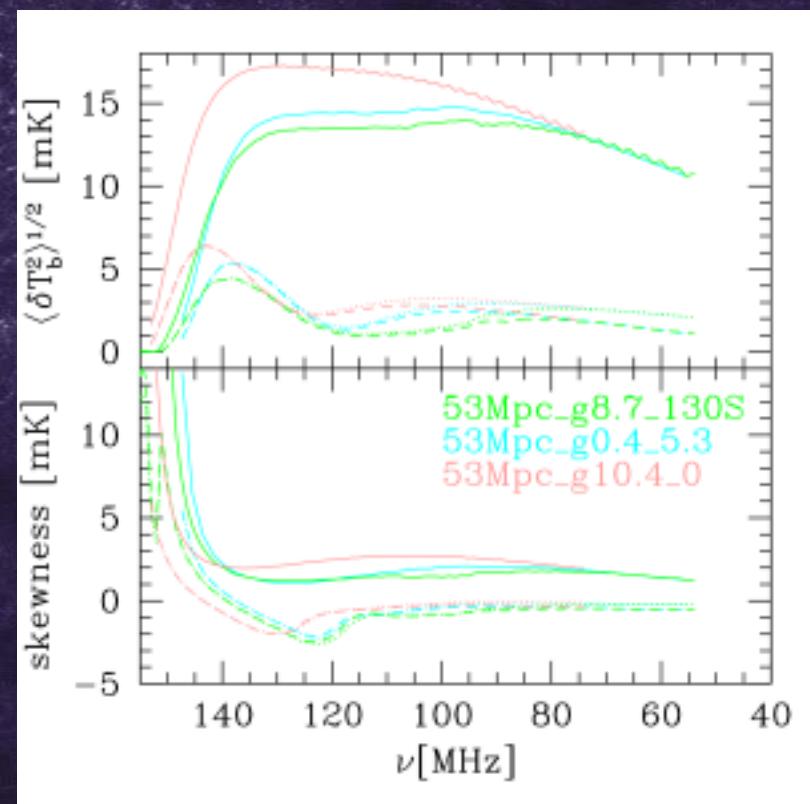
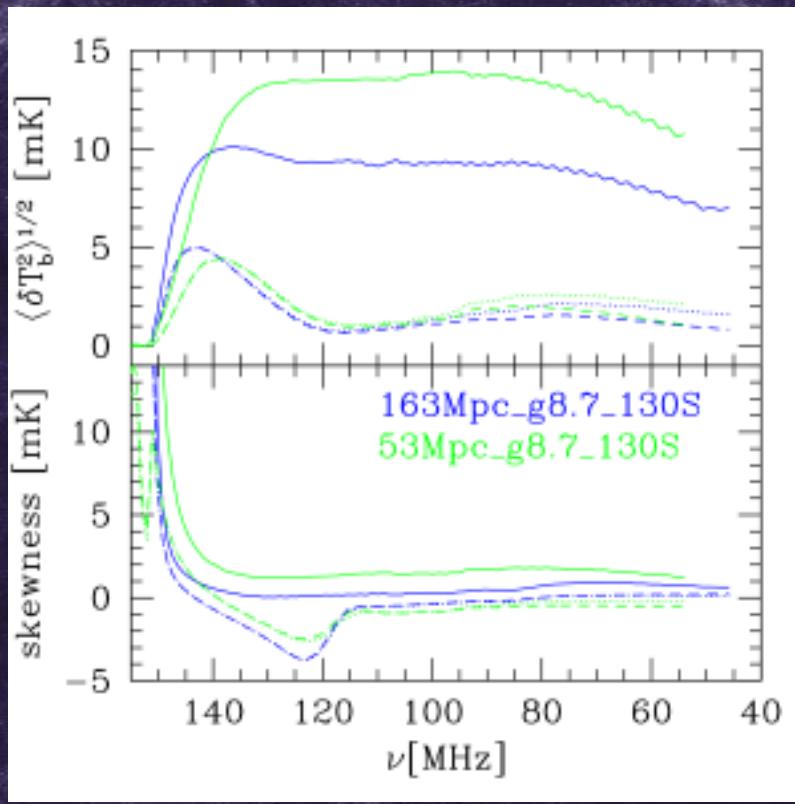
Using higher-order statistics to extract the EoR signal

(LOFAR EoR team; Harker et al, 2009, MNRAS)

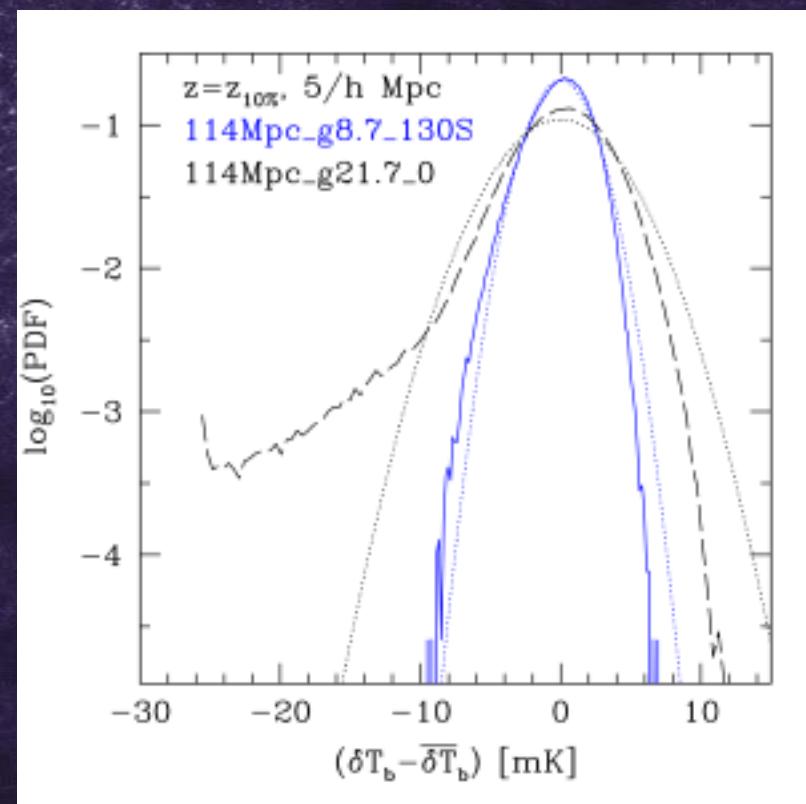
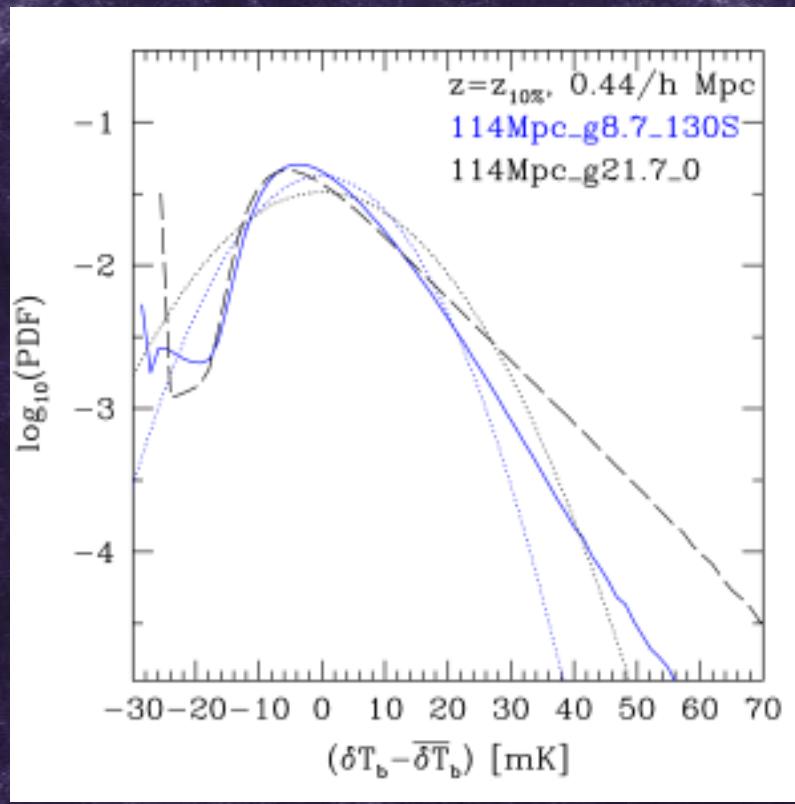
We might be able to use the non-Gaussianity of the EoR signal and its characteristic evolution to extract it from the very strong foregrounds.



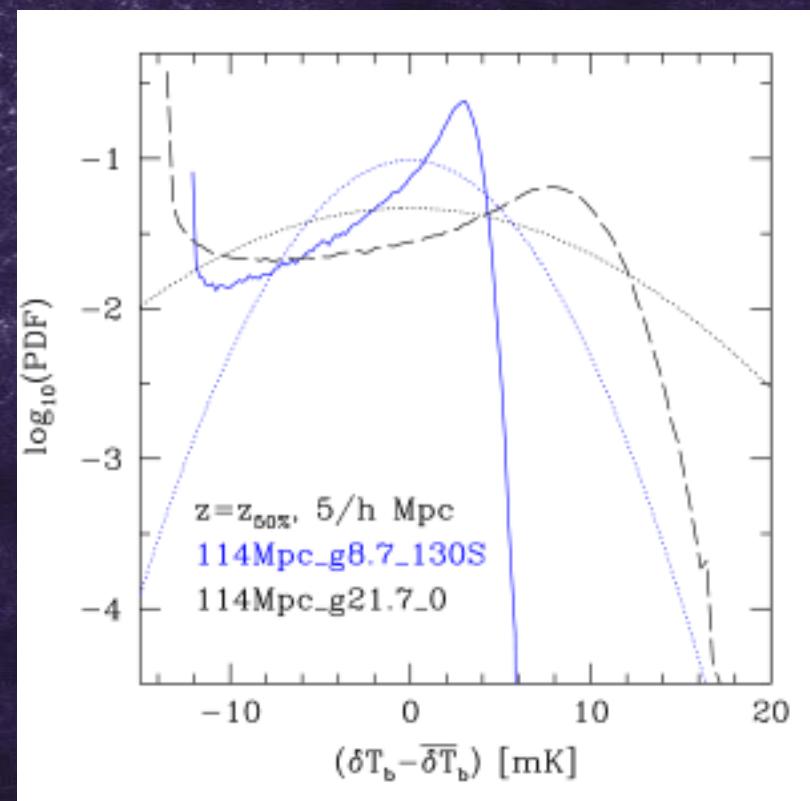
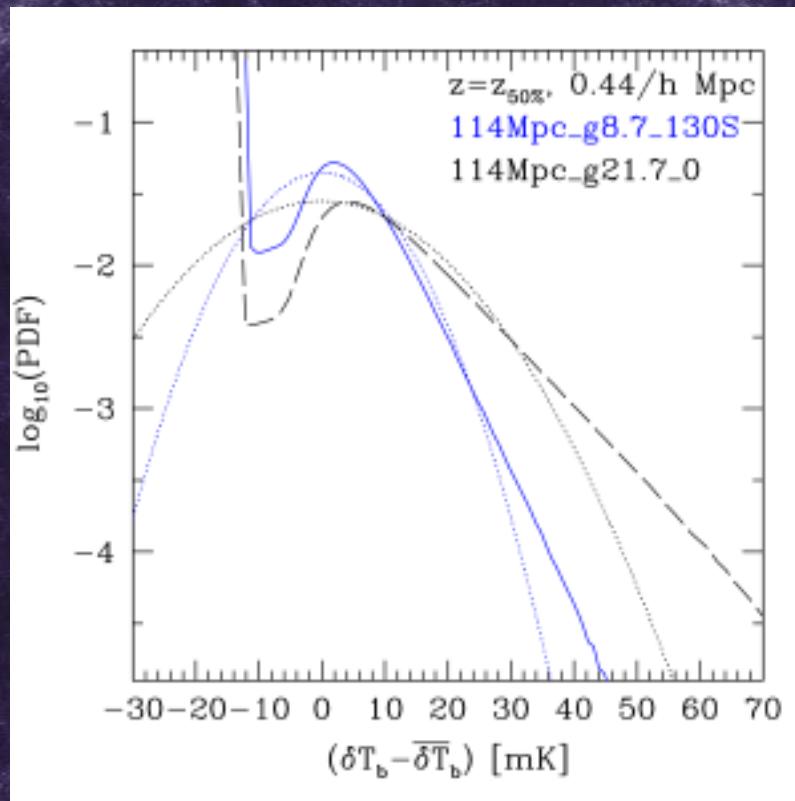
Evolution of the skewness



21-cm PDFs: effect of self-regulation, $x=0.1$



21-cm PDFs: effect of self-regulation, $x=0.5$



21-cm PDFs: effect of self-regulation, $x=0.9$

