Title: Reionization of the Universe: Character and Observable Signatures

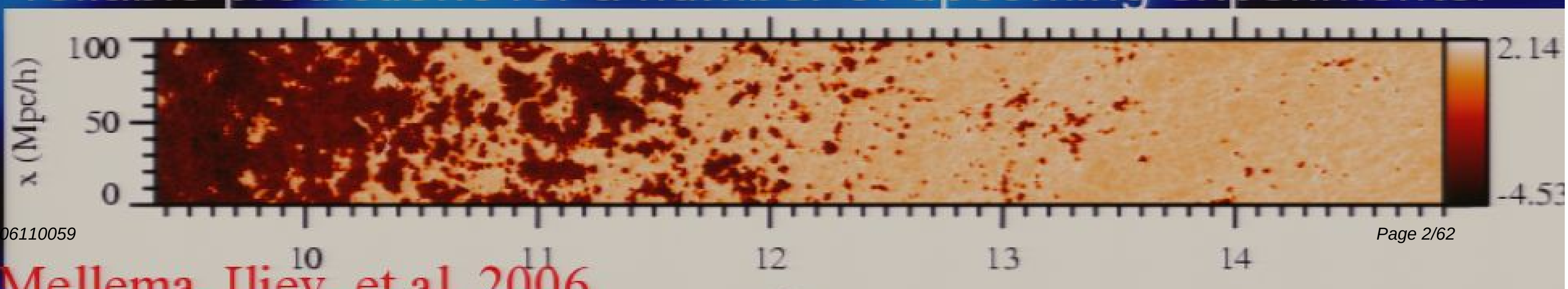
Date: Nov 10, 2006 03:00 PM

URL: http://pirsa.org/06110059

Abstract:

The importance of Reionization

- Reionization: global transition of the IGM from neutral to highly-ionized which occurred by z~6 due to the ionizing radiation from the first galaxies.
- Significant and important period in the history of the Universe (from age ~100 Myr to 1 Gyr). Complex, patchy evolution.
- Primordial fluctuations grow and first nonlinear structues form.
- It has profound effects on the state of the IGM and the subsequent galaxy formation.
- Currently very little observational data is available: difficult to constrain models of reionization and important to make reliable predictions for a number of upcoming experiments.



Mellema, Iliev, et al 2006

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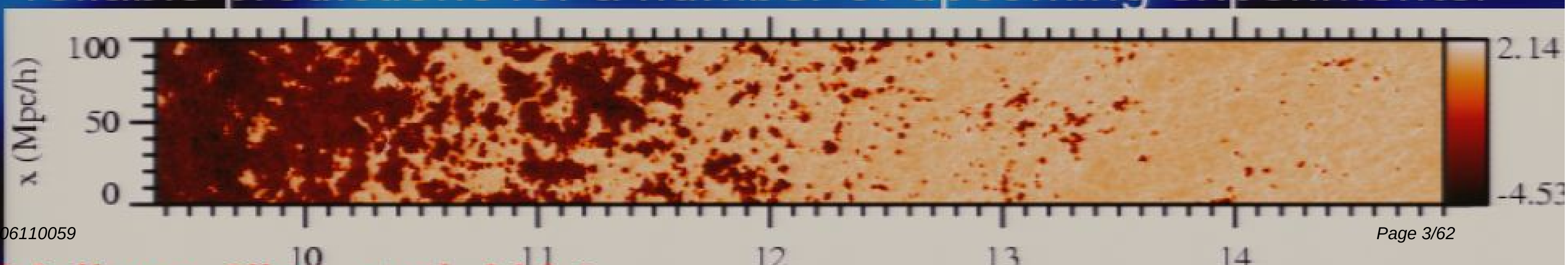
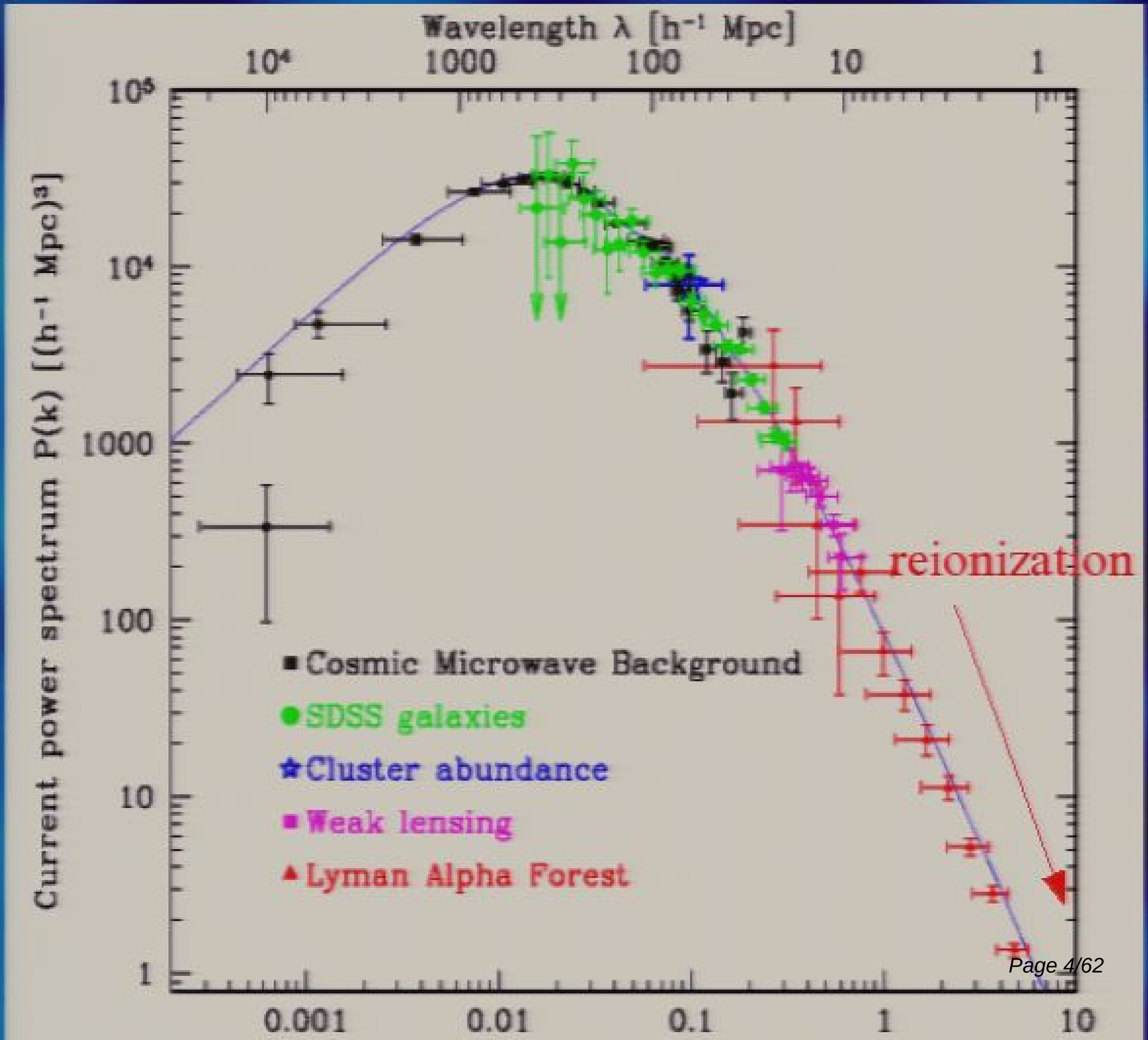


Mellema, Iliev, et al 2006

Primordial power spectrum of density fluctuations

Reionization depends mostly on scales k>>1/Mpc, a part of the P(k) density power spectrum well below the scales currently probed by other methods



Simulations of Global Reionization

[Iliev et al. 2006 (a,b); Mellema, Iliev, et al. 2006]

- Large computational boxes needed, both fundamentally - due to strong bias of the sources the HII regions are large; and observationally - degree scale on the sky and multiple MHz in bandwidth are required.
- Physical models for the ionizing sources (photon production, star-formation efficiencies, escape fractions).
- Precise, high-resolution radiative transfer.
- Detailed knowledge of structures forming at high-z:
  - number and distribution of sources – down to dwarf galaxies of $\sim 10^8 M_{solar}$ (need up to 100 billion particles for 100/h Mpc box!)
  - density fluctuations (photon sinks) – self-shielded or not.

Done by: -large N-body simulations + radiative transfer post-processing

-tracking the radiation from all sources ($\sim 10^4$-10^5) + subgrid models for local gas clumping and Jeans-mass filtering of small sources.

The first and only radiative transfer simulations at such scales by a large factor, crucial for steering current/planned observations!

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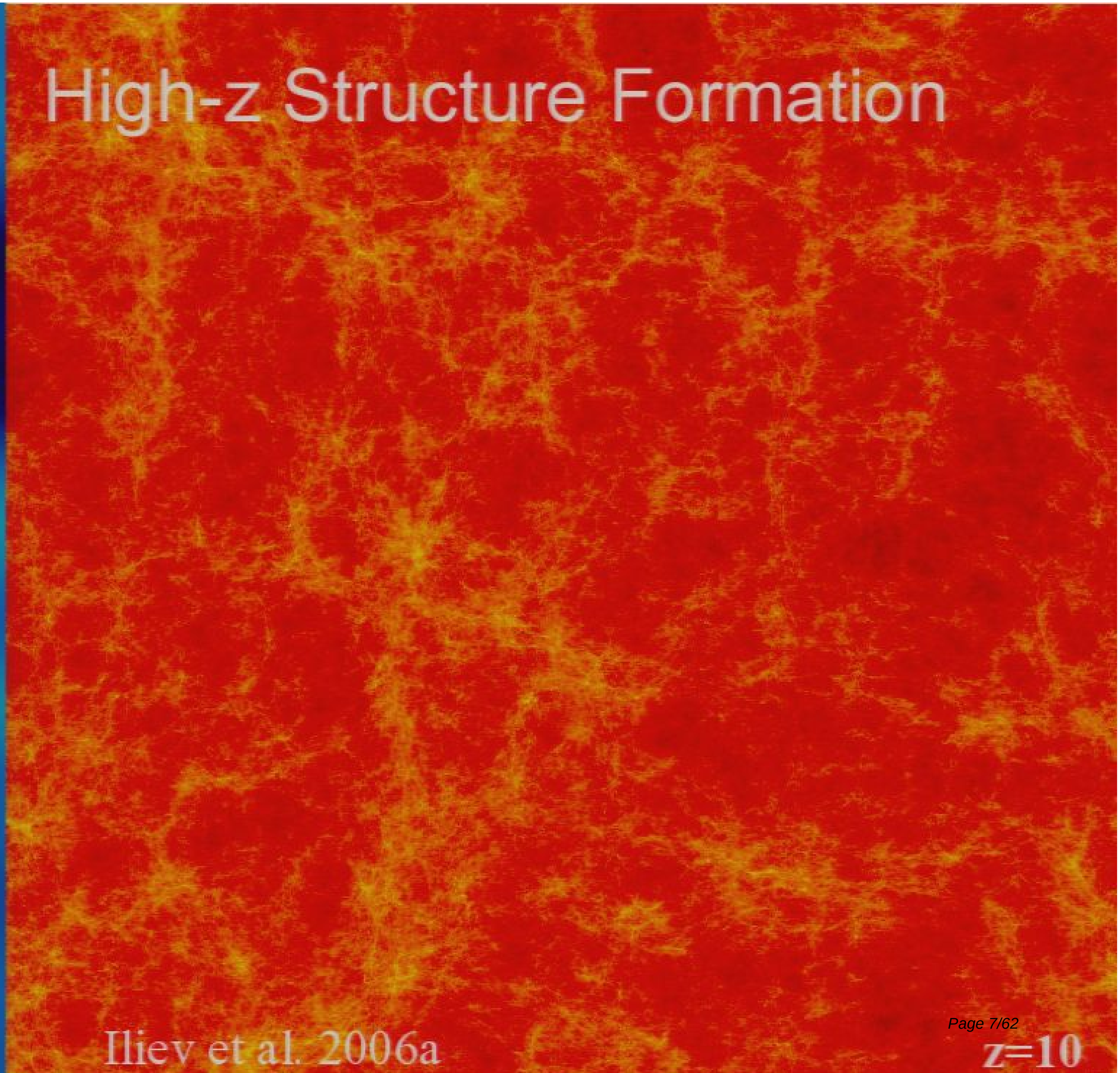
High-z Structure Formation

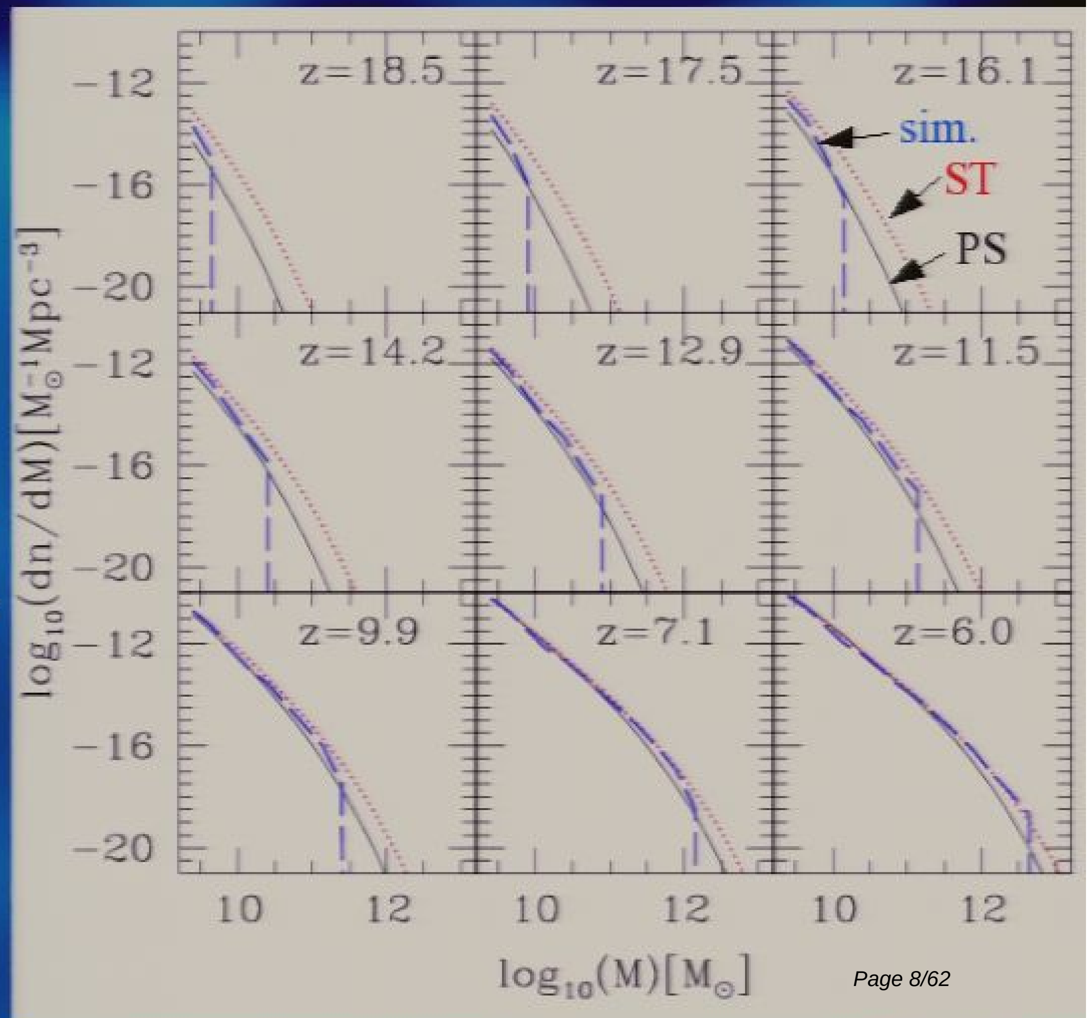
- Very high resolution N-body simulations of structure formation using PMFAST code developed at CITA (Merz, Pen & Trac 2004)
- 100/h, 35/h and 3.5/h Mpc boxes, 1624^3 particles (4.3 billion), 3248^3 cells. Up to 1-2 million halos identified (with >100 particles/halo $=2.5\times10^9 M_{solar}$, $10^8 M_{solar}$ and $10^5 M_{solar}$)



The high-z halo mass function

(Iliev et al., 2006a, MNRAS, 369,1625)

- Up to ~2 million halos identified.
- The simulated halo mass function at high z (z>10) is not matched well by either Sheth-Tormen (ST), or Press-Schechter analytical models.
- However, below z~10 ST is a fairly good fit.



Simulations

(Iliev et al., 2006a,b; Mellema et al. 2006)

- Photon efficiency $f = f_{SF} \times f_{esc} \times N_{photon}$

Sim	f	clumping	z(50%)	z_{ov}	τ_{es}
f2000	2000	1	13.6	11.3	0.13
f2000C	2000	C(z)	12.6	10.15	0.121
f250	250	1	11.7	9.3	0.109
f250C	250	C(z)	10.8	8.2	0.098

+ 8 more simulations with a smaller (50 Mpc) box, which allowes us to resolve $\sim 10^8 M_{solar}$ halos; + 8 more with WMAP 3-year parameters

Reionization history of sub-regions

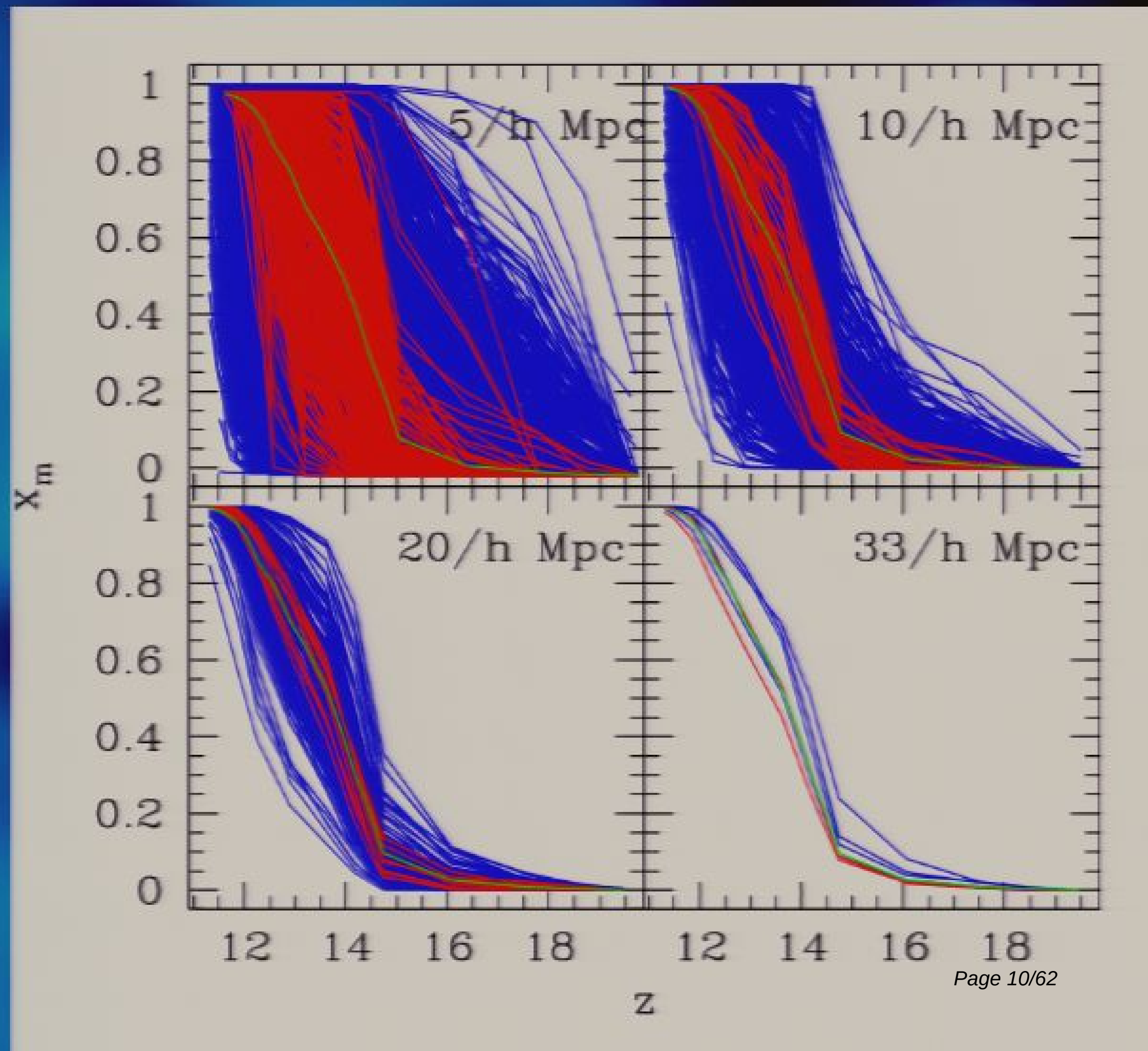
(Iliev et al., 2006a, MNRAS, 369,1625)

green = total mean

red = mean-density subregions

blue = all sub-regions

For small regions there is huge scatter and overlap epoch cannot be determined well. Only sufficiently large regions (>20 Mpc) describe the mean evolution well (though still larger volumes needed for e.g. HII regions size distribution).



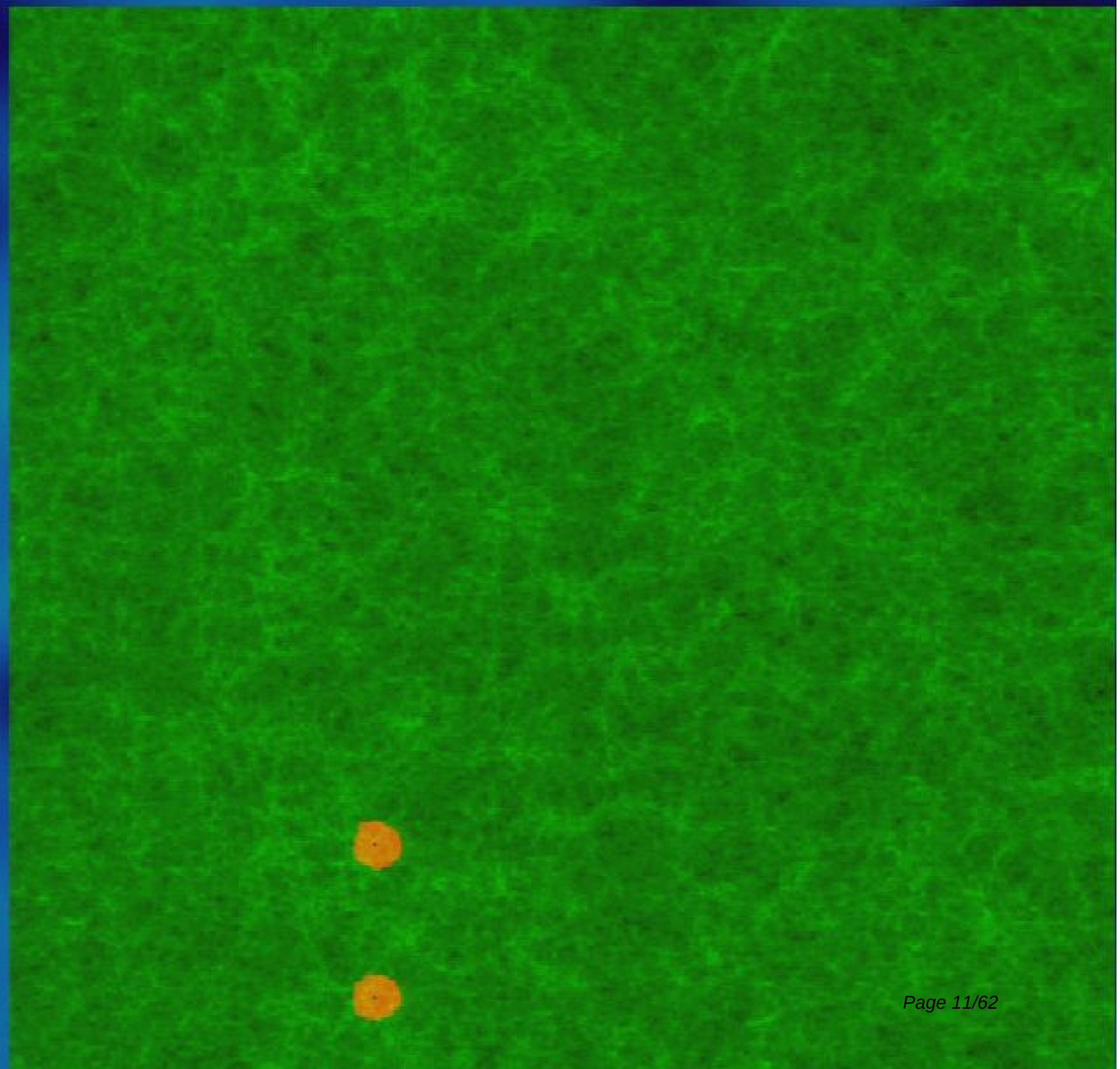
Large-Scale Topology of Reionization: Animation

(see also **www.cita.utoronto.ca/~iliev/dokuwiki/doku.php?id=research**)

(Iliev et al. 2006a)

100/h Mpc box, 406^3 radiative transfer simulation

- Evolution: Cosmic web (green) and HII regions (red/orange) of individual sources and groups (dark blue).
- The topology of the ionized / neutral regions is complex. Strong bias leads to clustering and large ionized regions.



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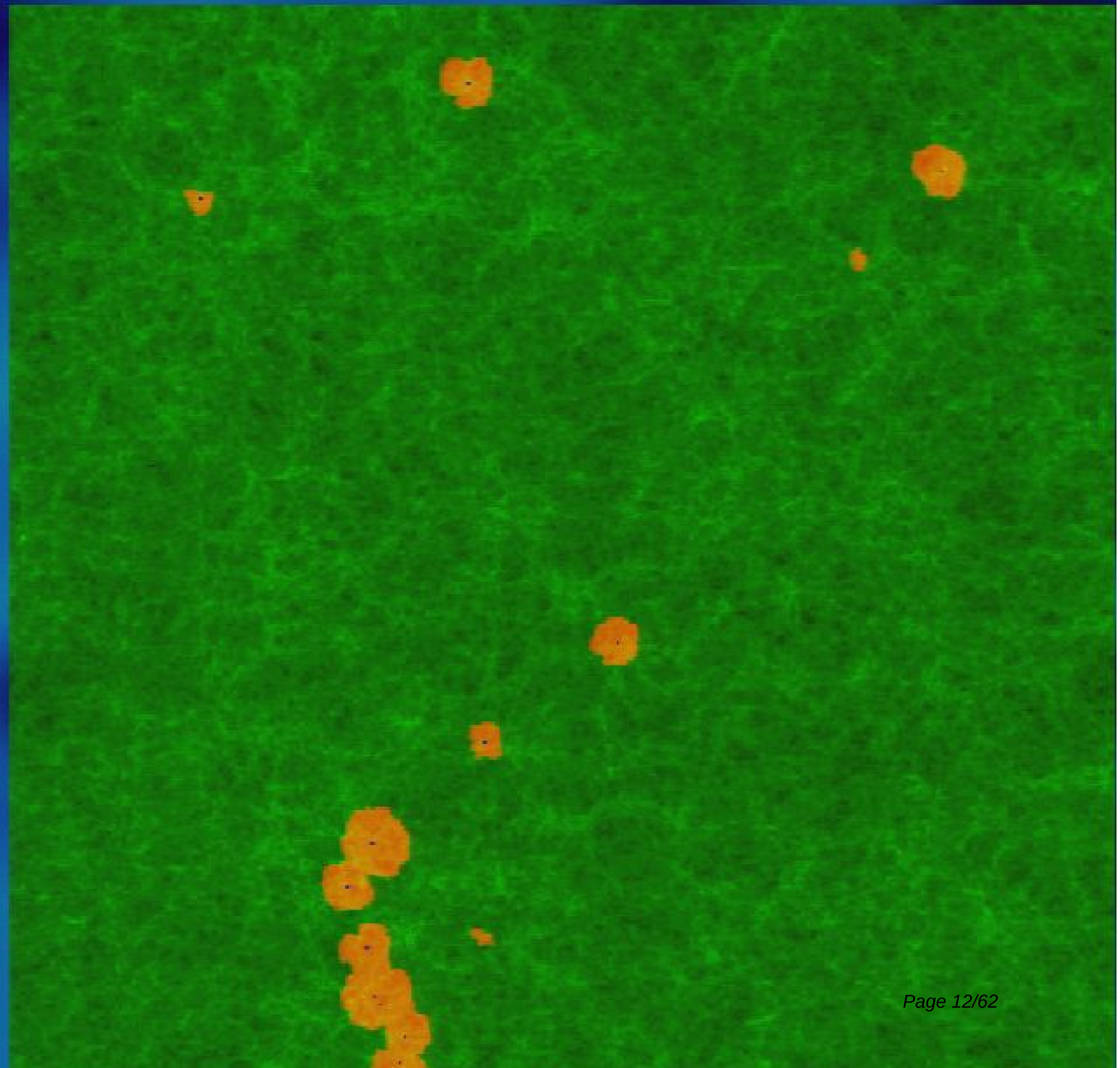

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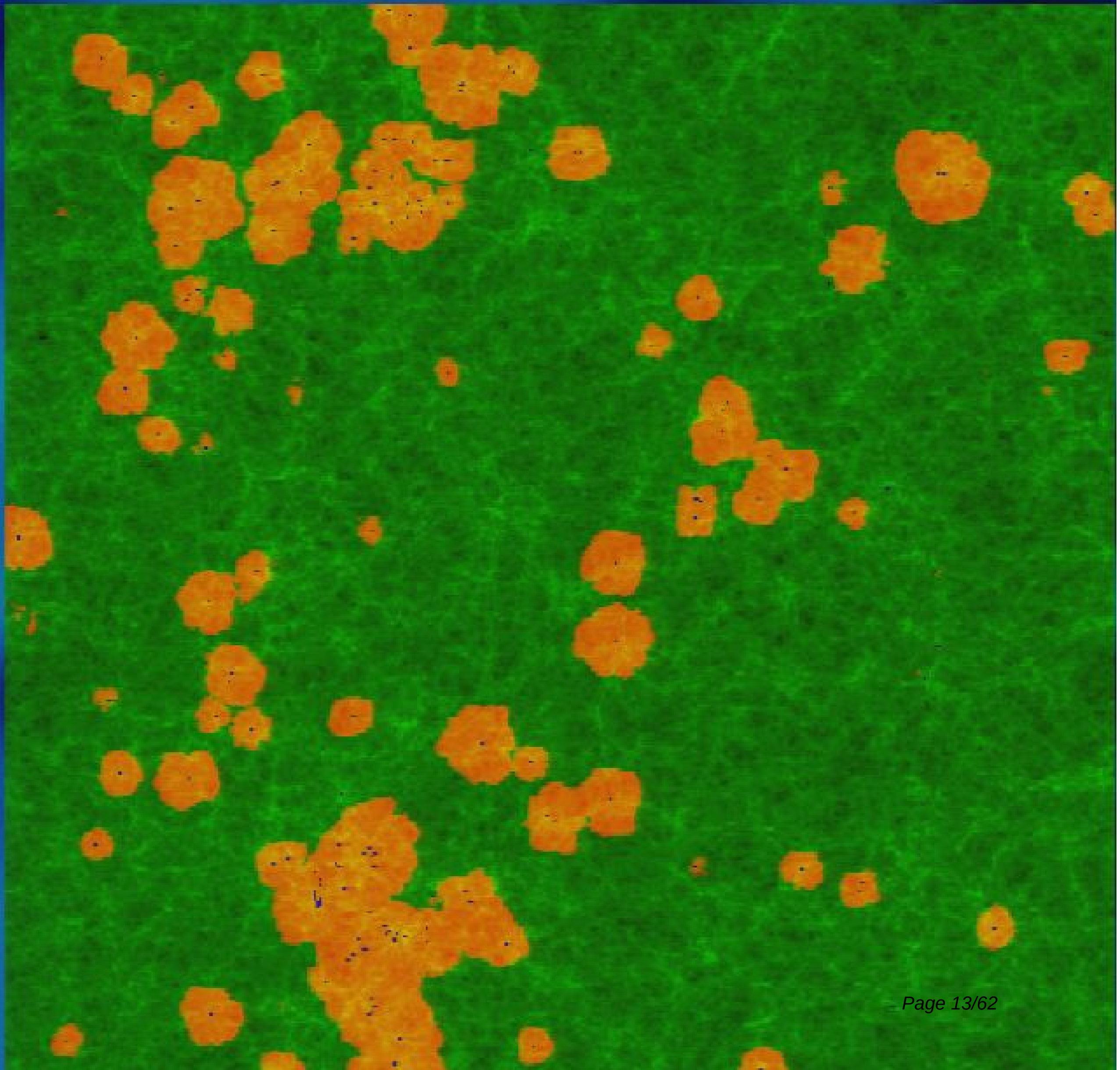

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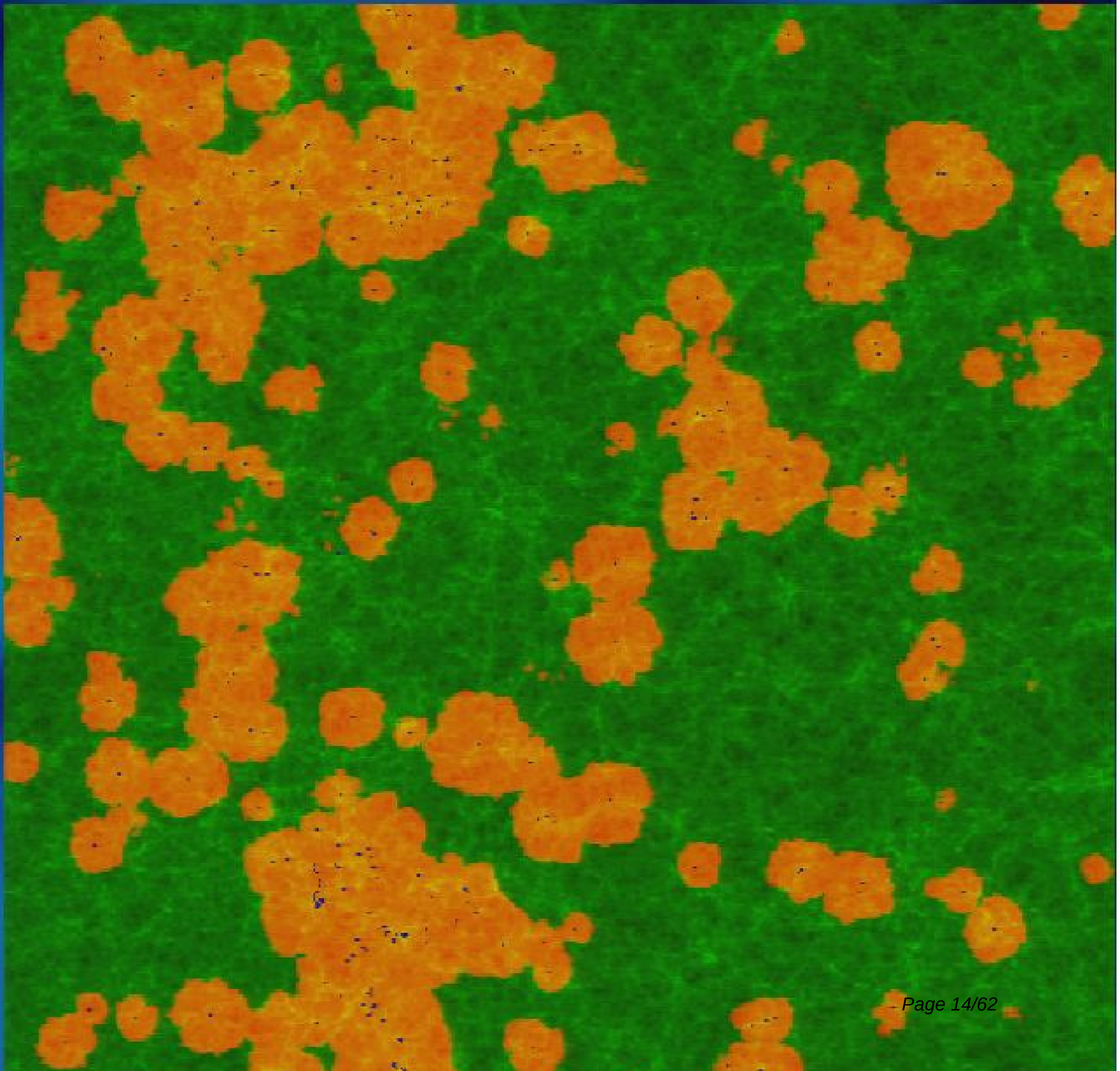

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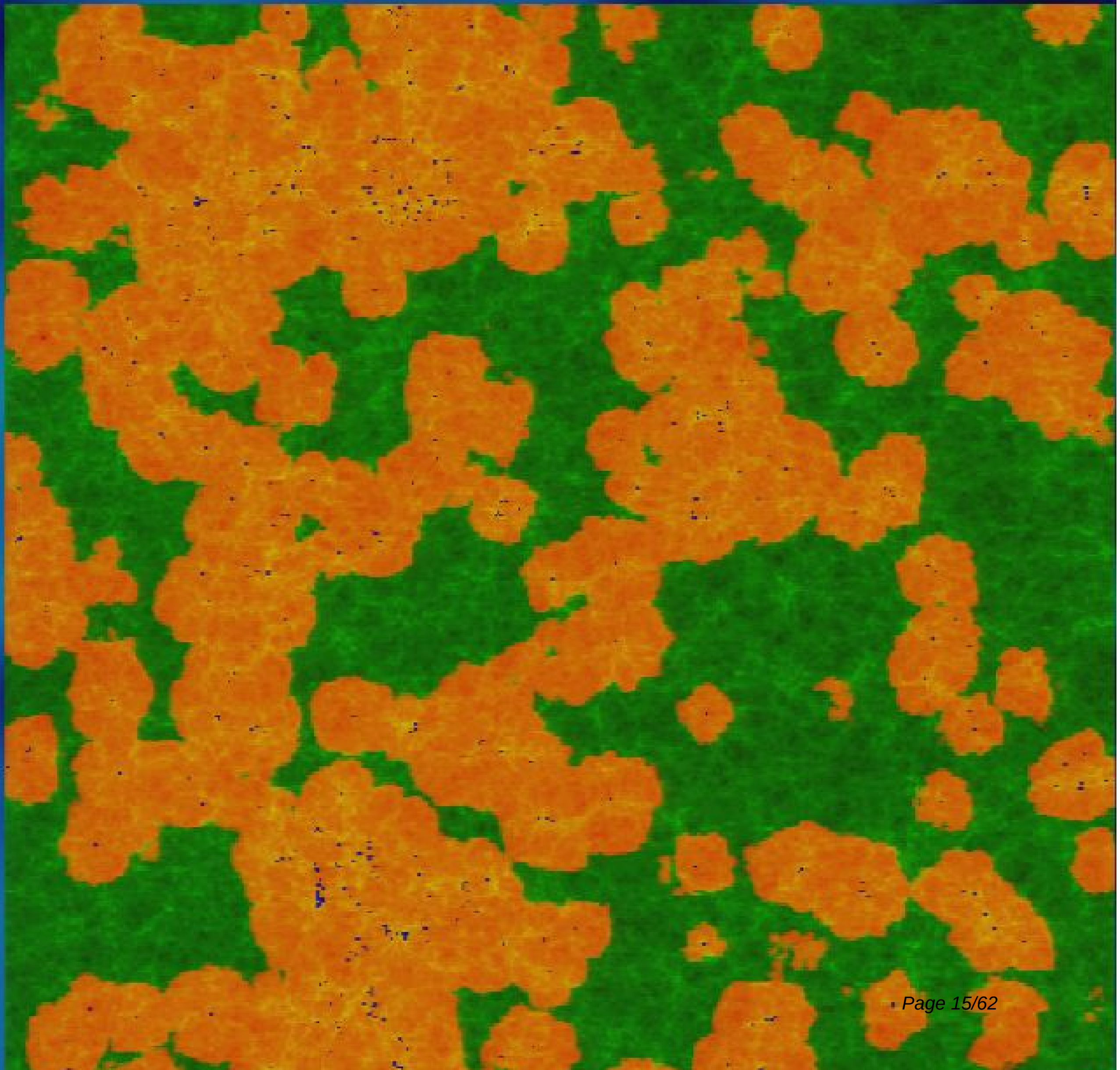

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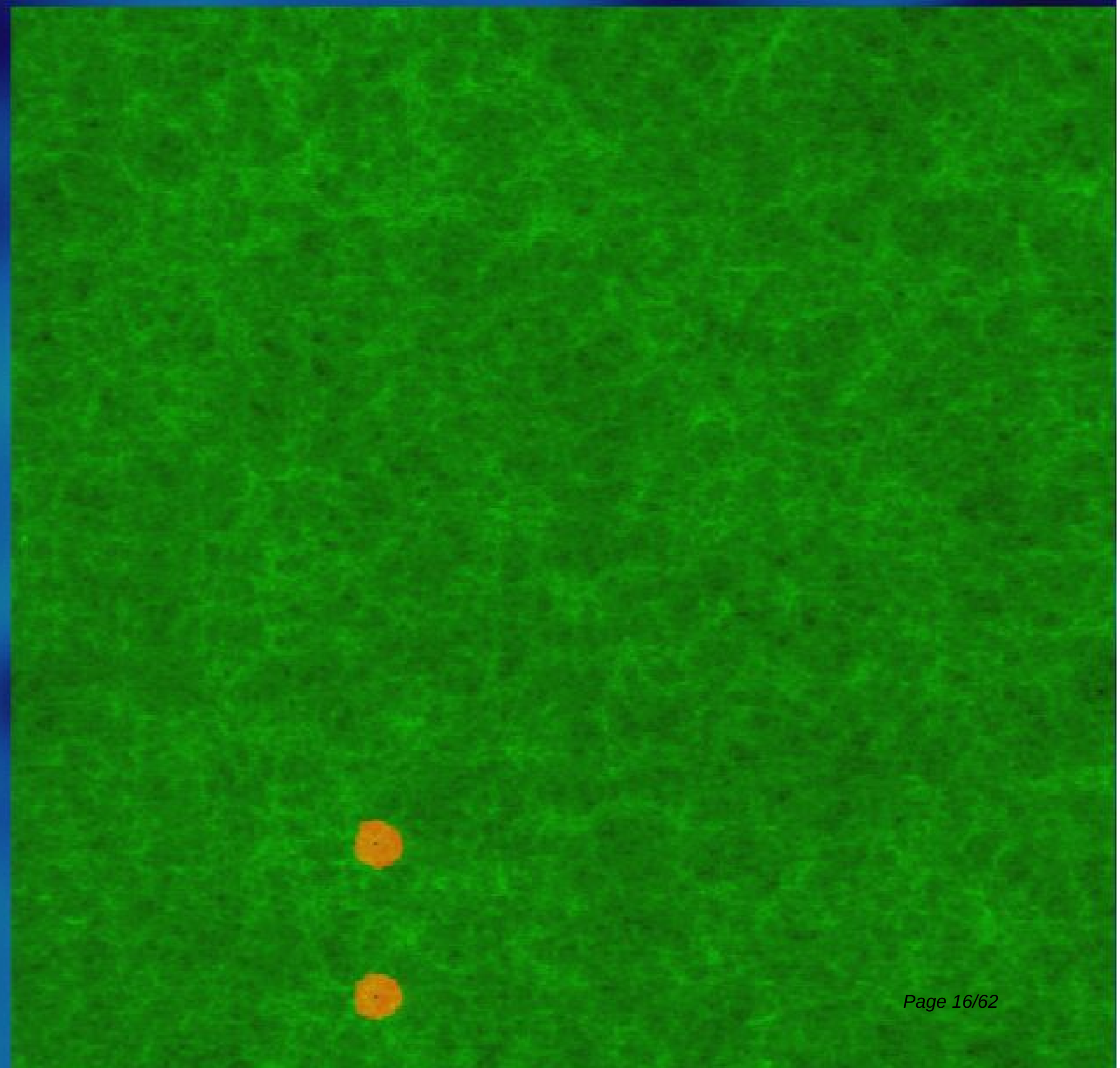


Large-Scale Topology of Reionization: Animations

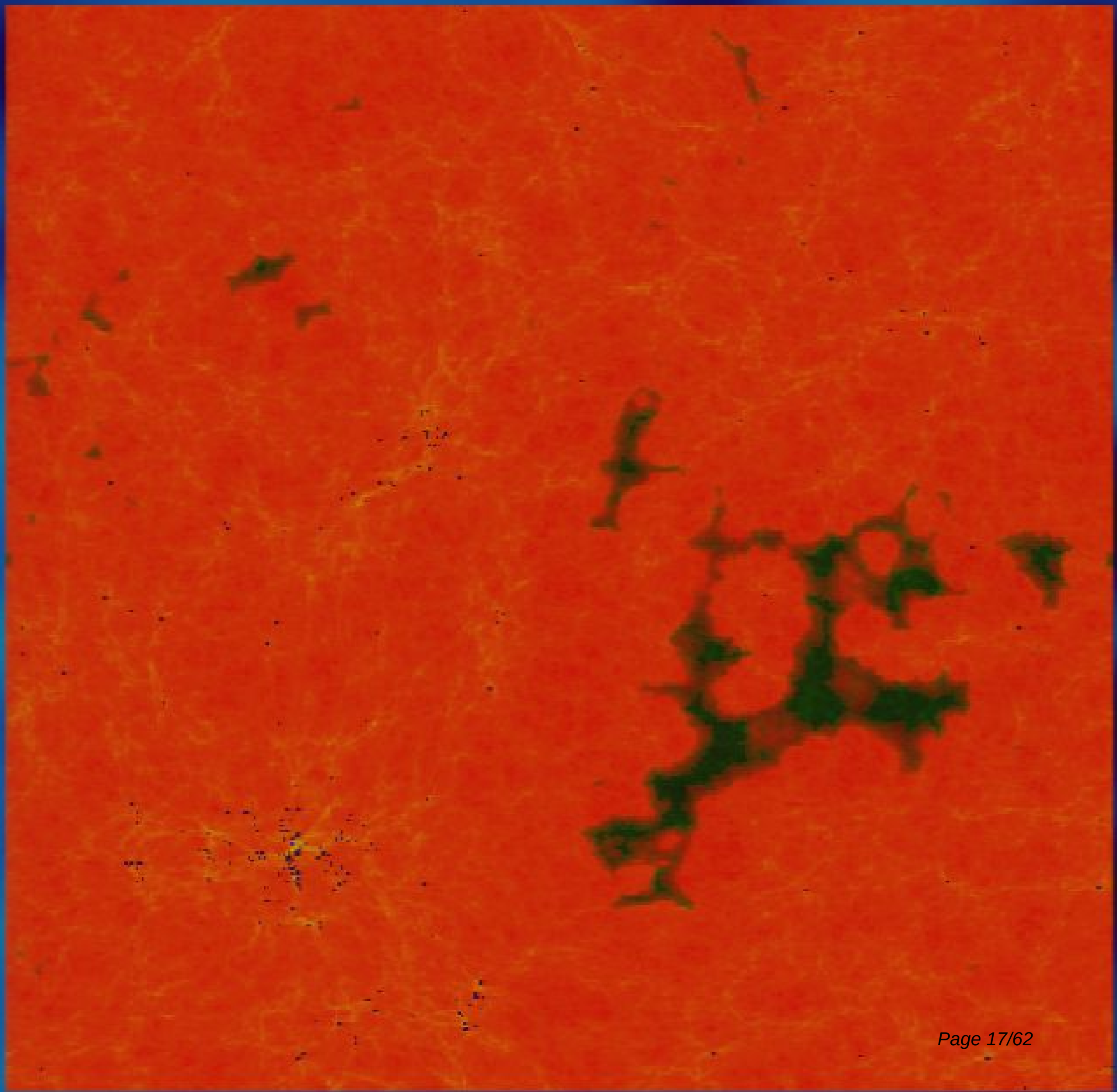
(Iliev et al. 2006b, astro-ph/0607517)

35/h Mpc box, 406^3 radiative transfer simulation, WMAP3

Evolution: z=21 to 7.5.

$>10^8$ solar mass halos resolved (i.e. all atomically-cooling halos)

Jeans mass filtering included



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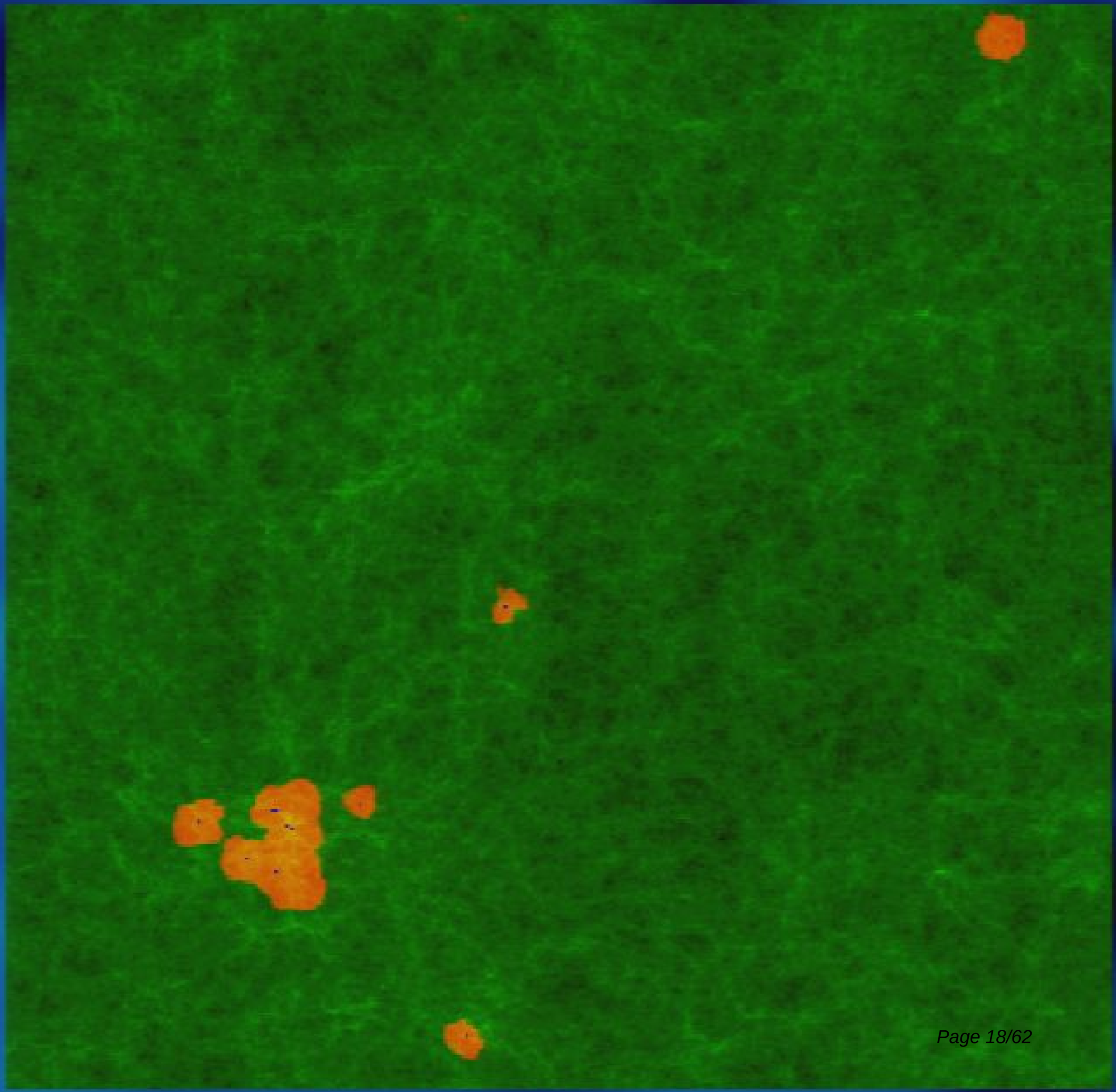

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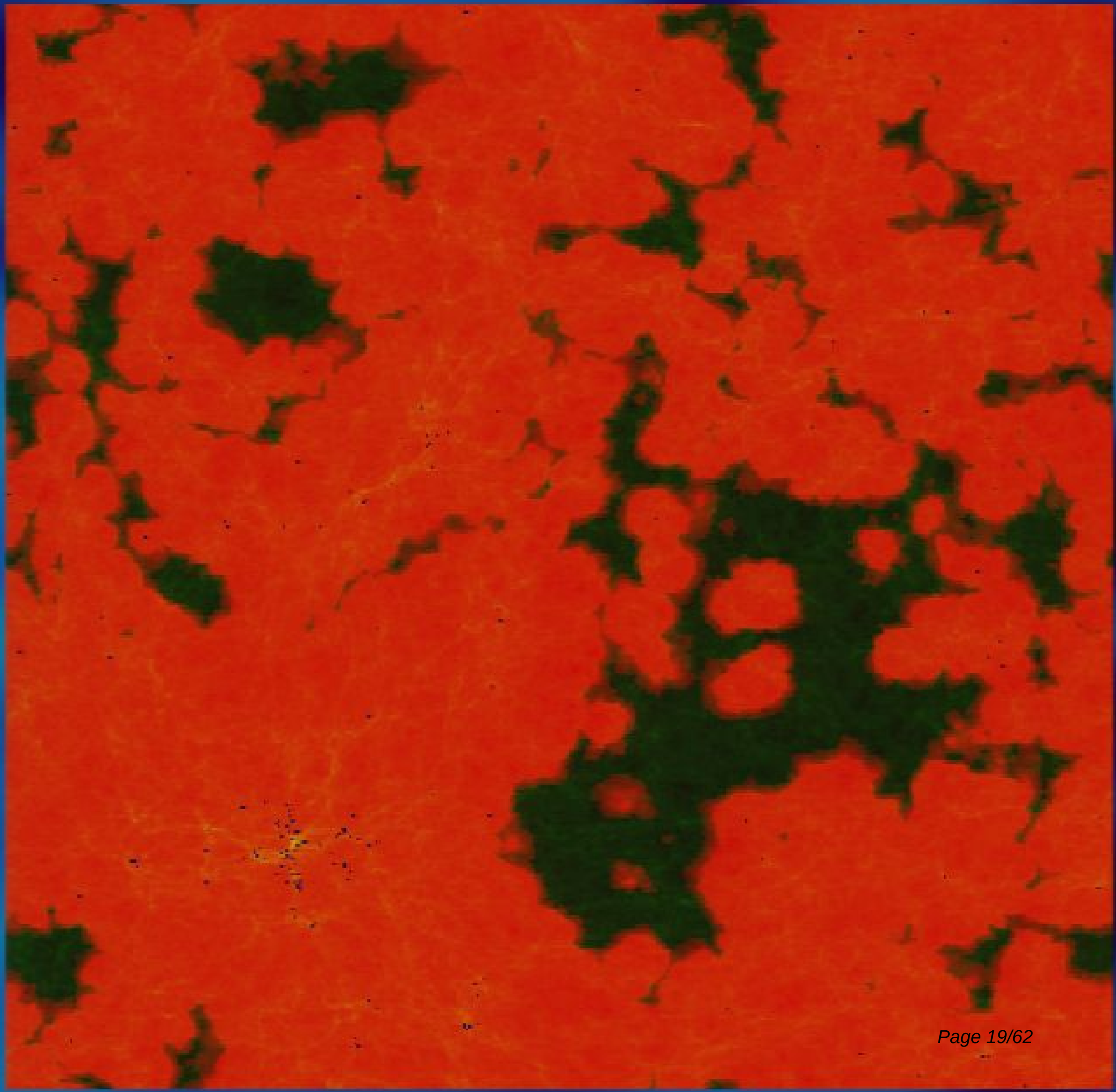

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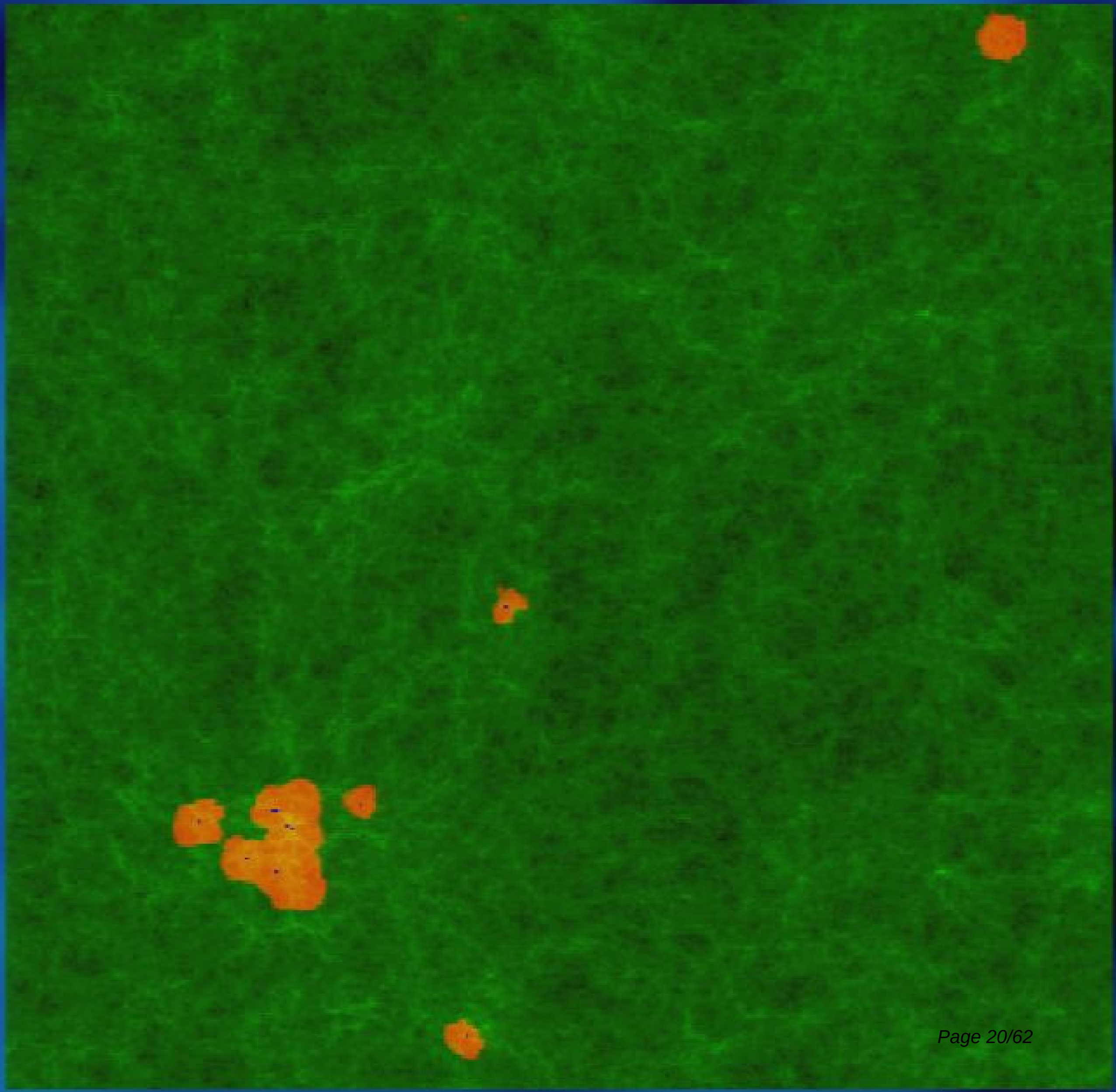


Self-Regulated Reionization

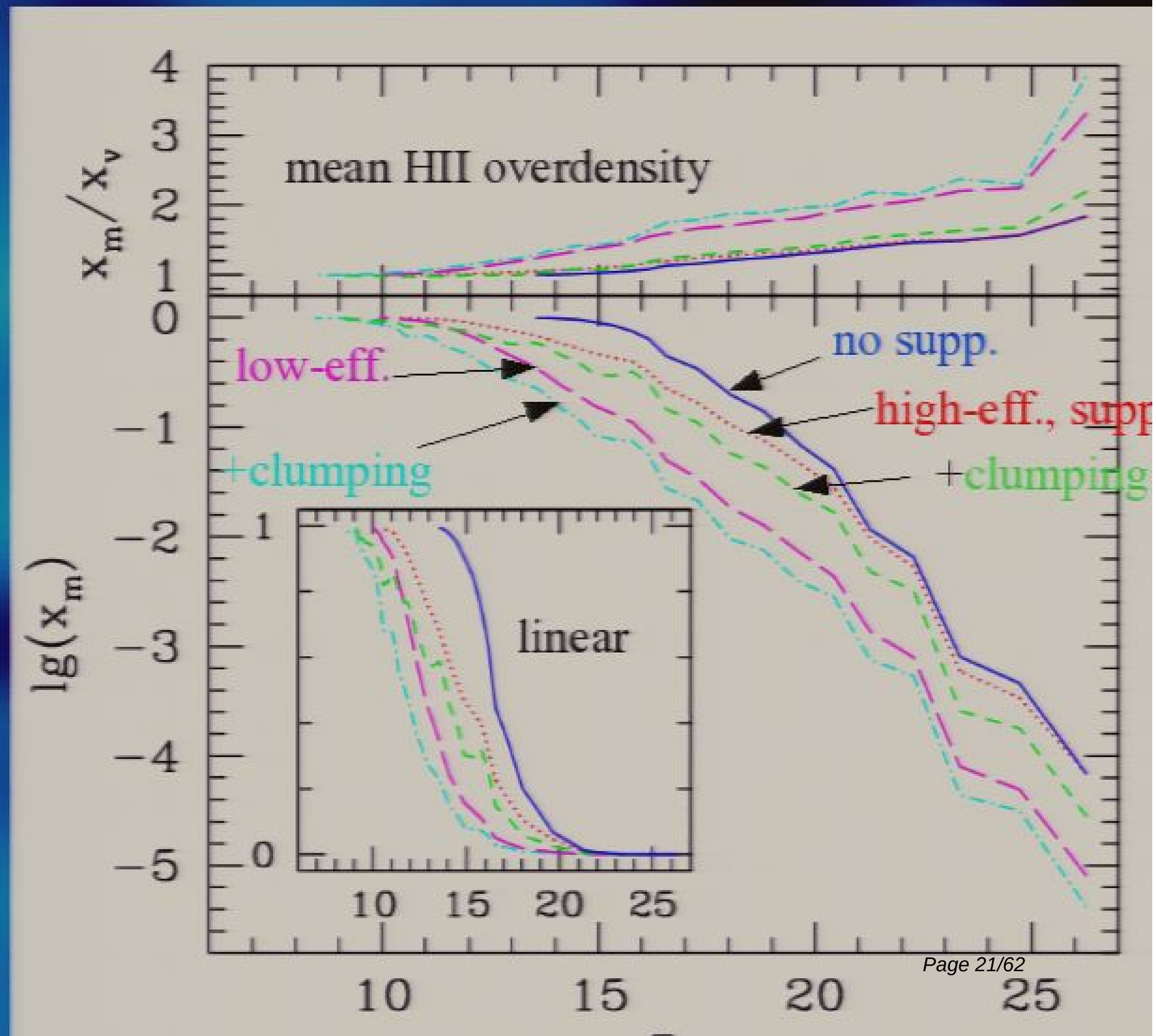
(Iliev et al., 2006b, astro-ph/0607517; MNRAS, submitted)

Lower large-source efficiencies, Jeans-mass filtering of small sources and time-increasing sub-grid gas clumping all extend reionization and delay overlap.

However:

Lower small-source efficiency does not extend reionization appreciably (but decreases τ).

Reionization is self-regulated.

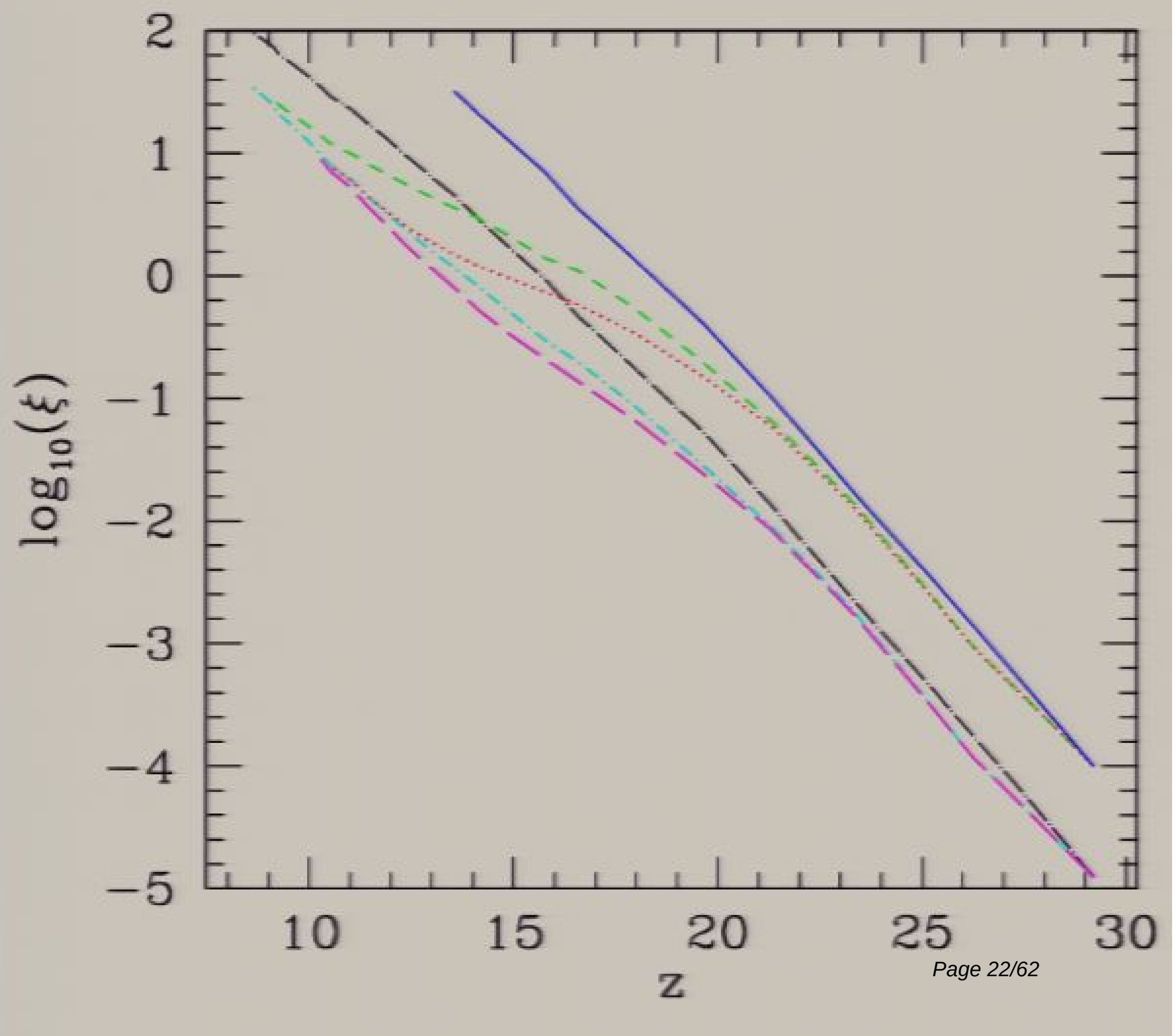


Self-Regulated Reionization II

Jeans-mass filtering of small sources suppresses the total emissivity by order of magnitude or more.

However:

The epoch overlap is determined by the level of sub-grid clumping and the large, unsuppressed sources alone.



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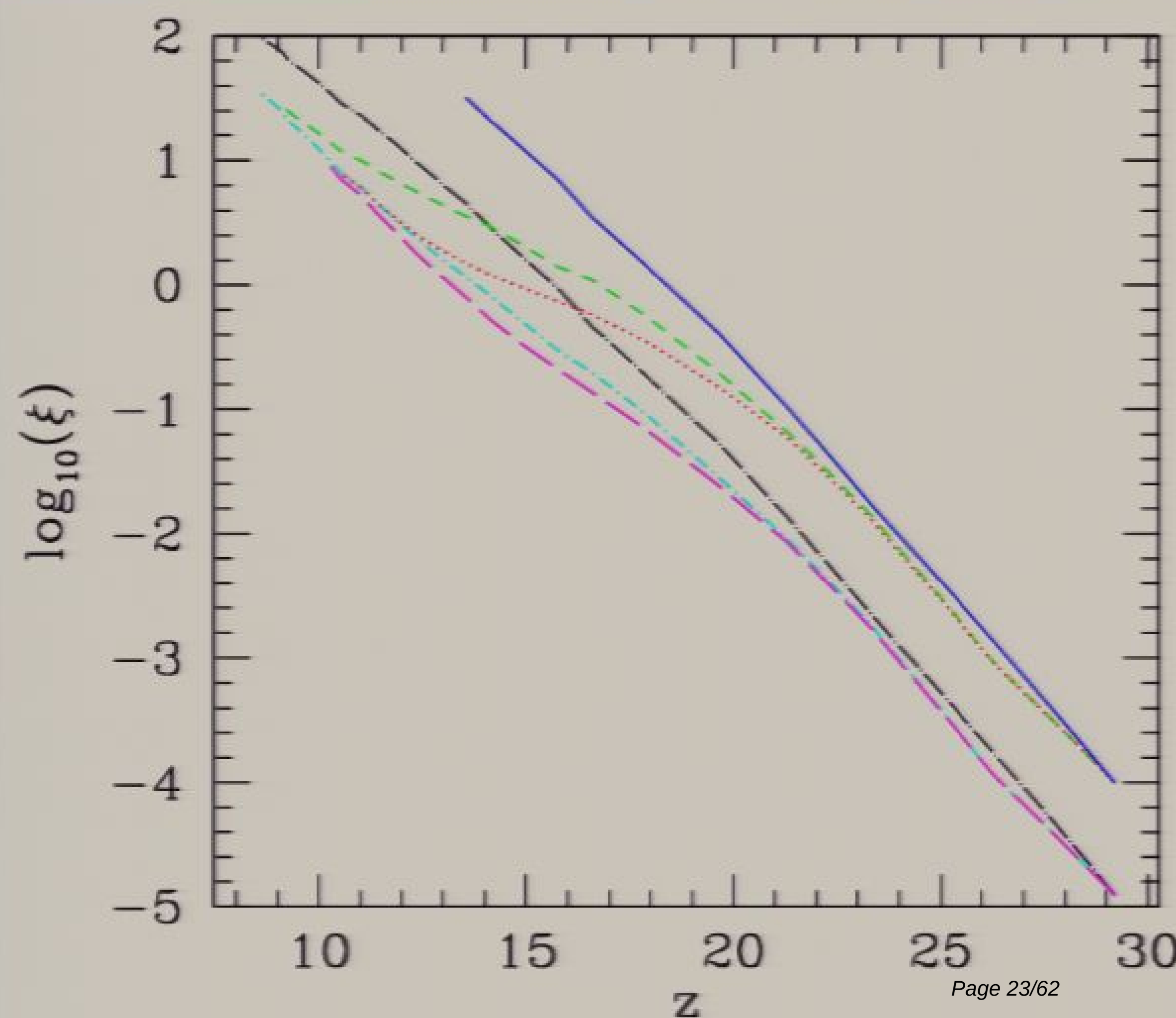
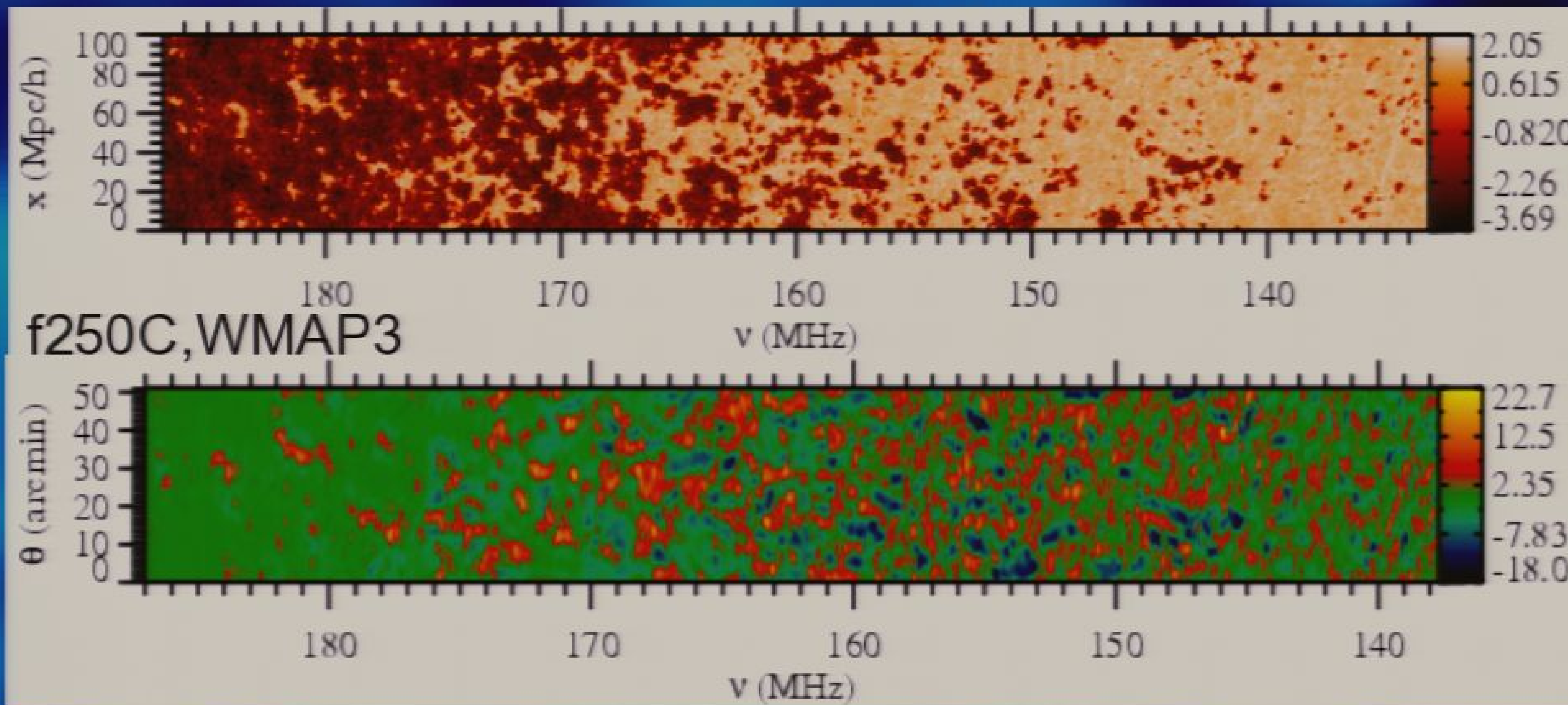


Evolution Slices at 21-cm line

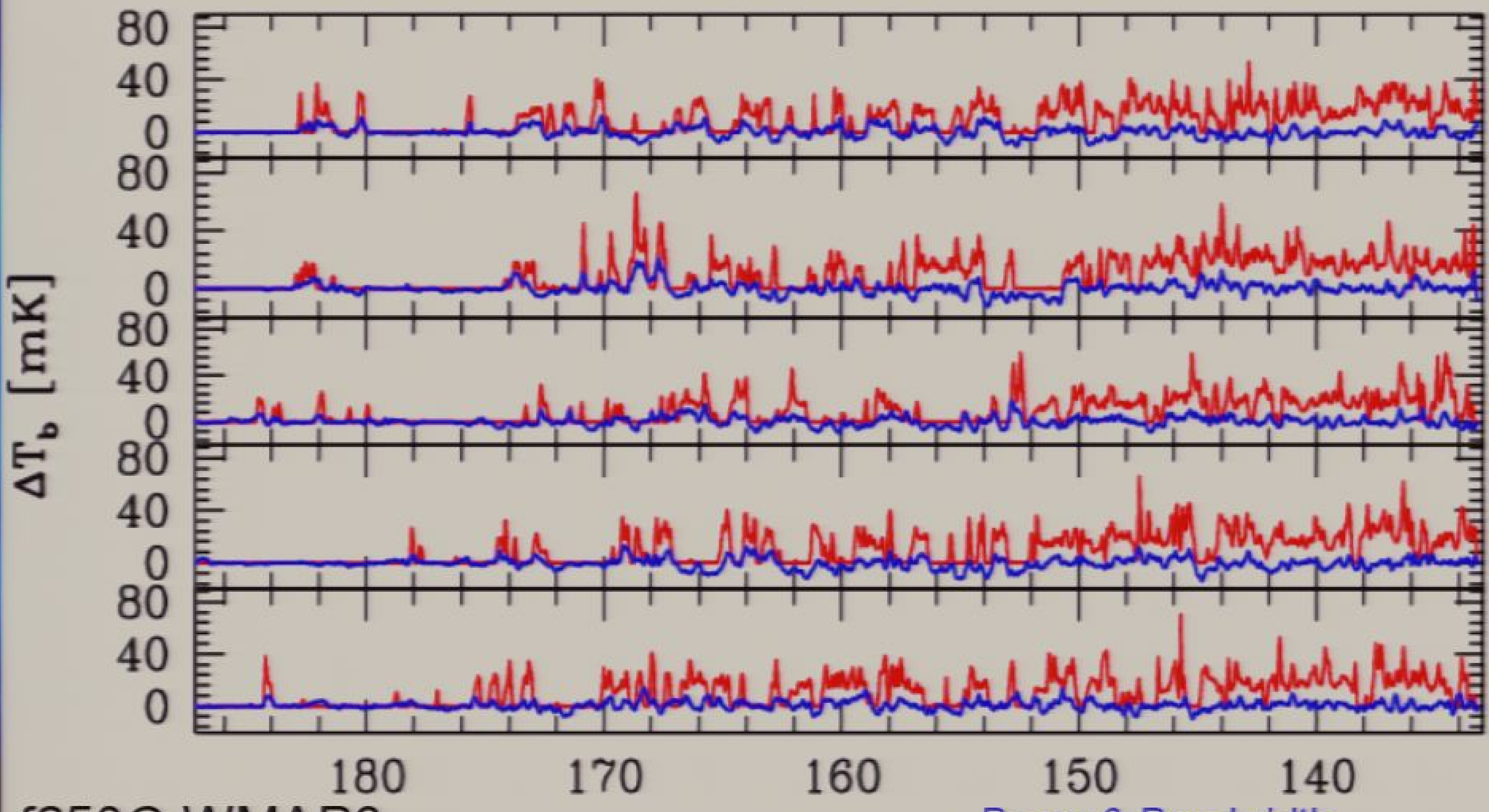
(Mellema, Iliev, et al. 2006, MNRAS in press; Iliev et al. in prep.)



21-cm line is due to spin-flip transition of H atoms decoupled from CMB by collisions and/or Ly-alpha photons. Shown is (log/linear) differential (to CMB) brightness temperature: top: high-res; bottom: beam- and bandwidth-smoothed (LOFAR: will see large ion. bubbles!)

LOS spectra: 21-cm emission

(Mellema, Iliev, et al.2006; Iliev et al. in prep.)

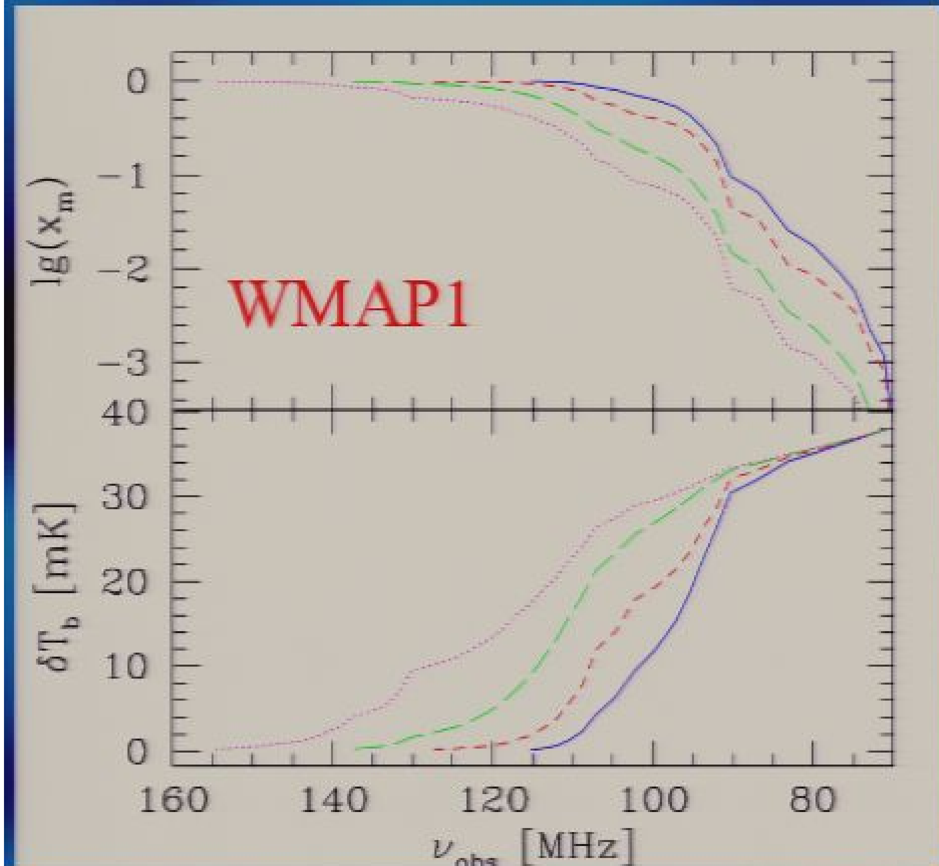


f250C,WMAP3

Full resolution

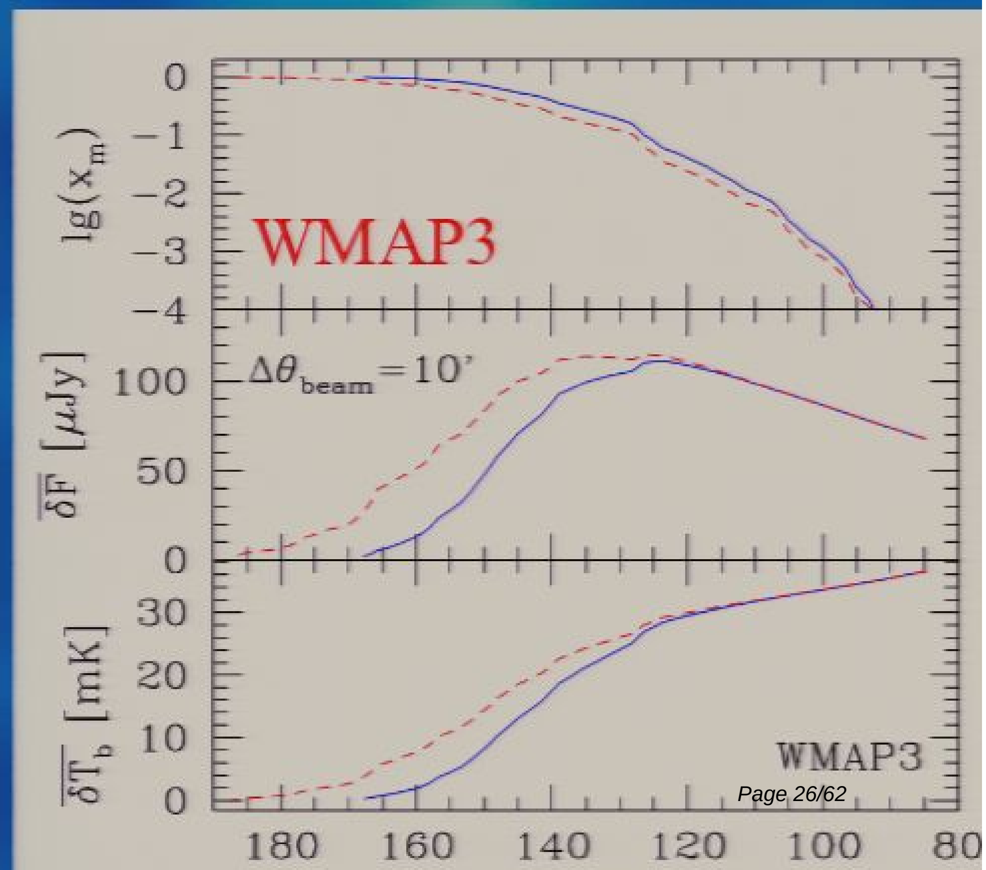
Beam & Bandwidth smoothed: 3', 0.2 MHz

Global Step



WMAP1: left to right: f250C, f250, f2000C,f2000)

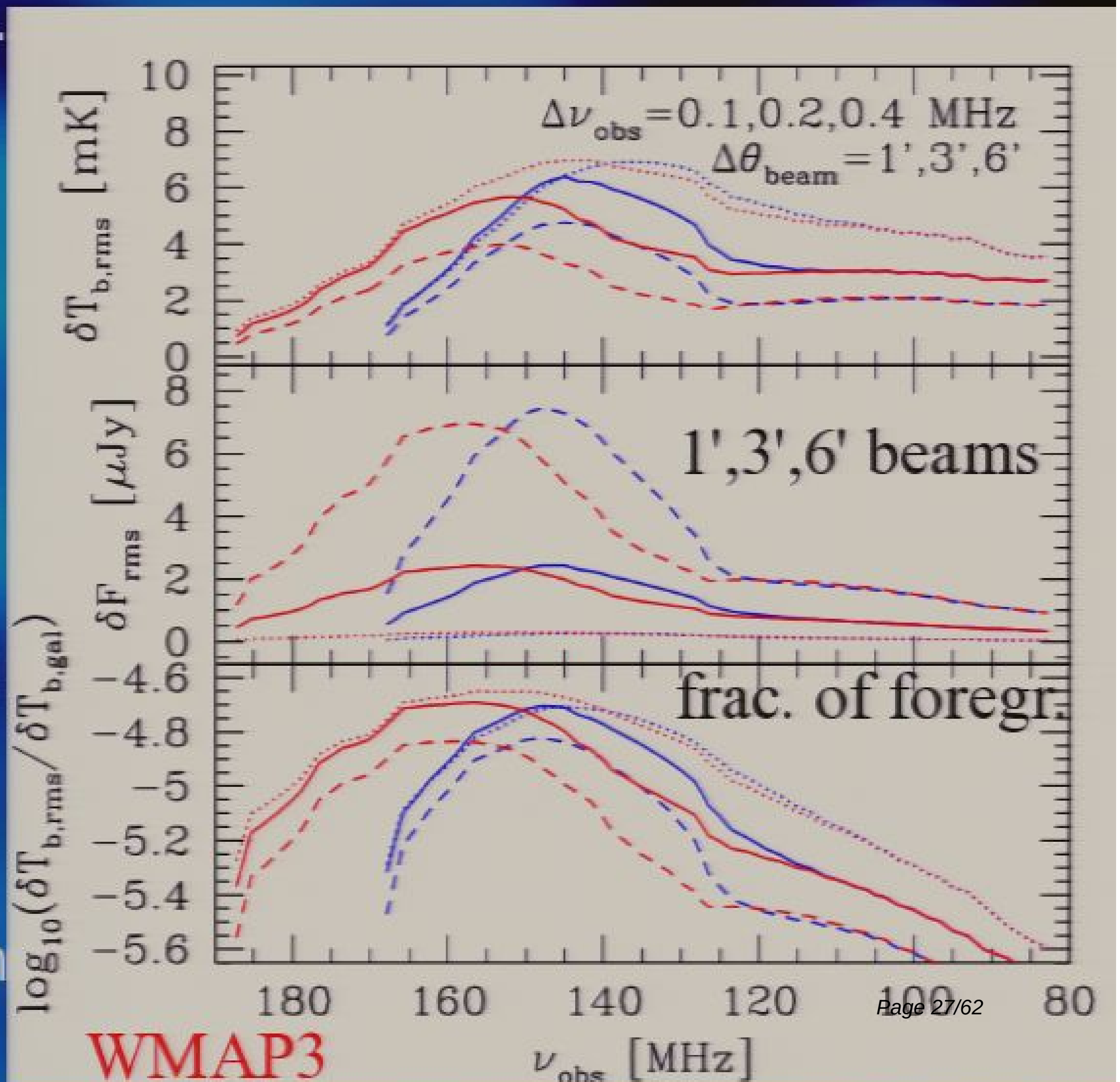
WMAP3: left to right: f250C, f250)



- Average signal over all lines of sight: global step (Shaver et al. 1999). Sharp change with frequency.
- Instead, simulations show gradual transition:~20 mK over ~20 Mhz.
- Mean flux peaks at ~140 Mhz (WMAP3)

RMS Fluctuations

- Interferometers measure differential temperatures, expressed as one number: rms fluctuations.
- All large-beam dTb fluctuations peak at ~50% ionization, at ~140-160 MHz!
- The flux and dTb fluct. as fraction of foregrounds both peak later than dTb!
- Max amplitude changes depending on how well the beam and bandwidth match the typical patch sizes.

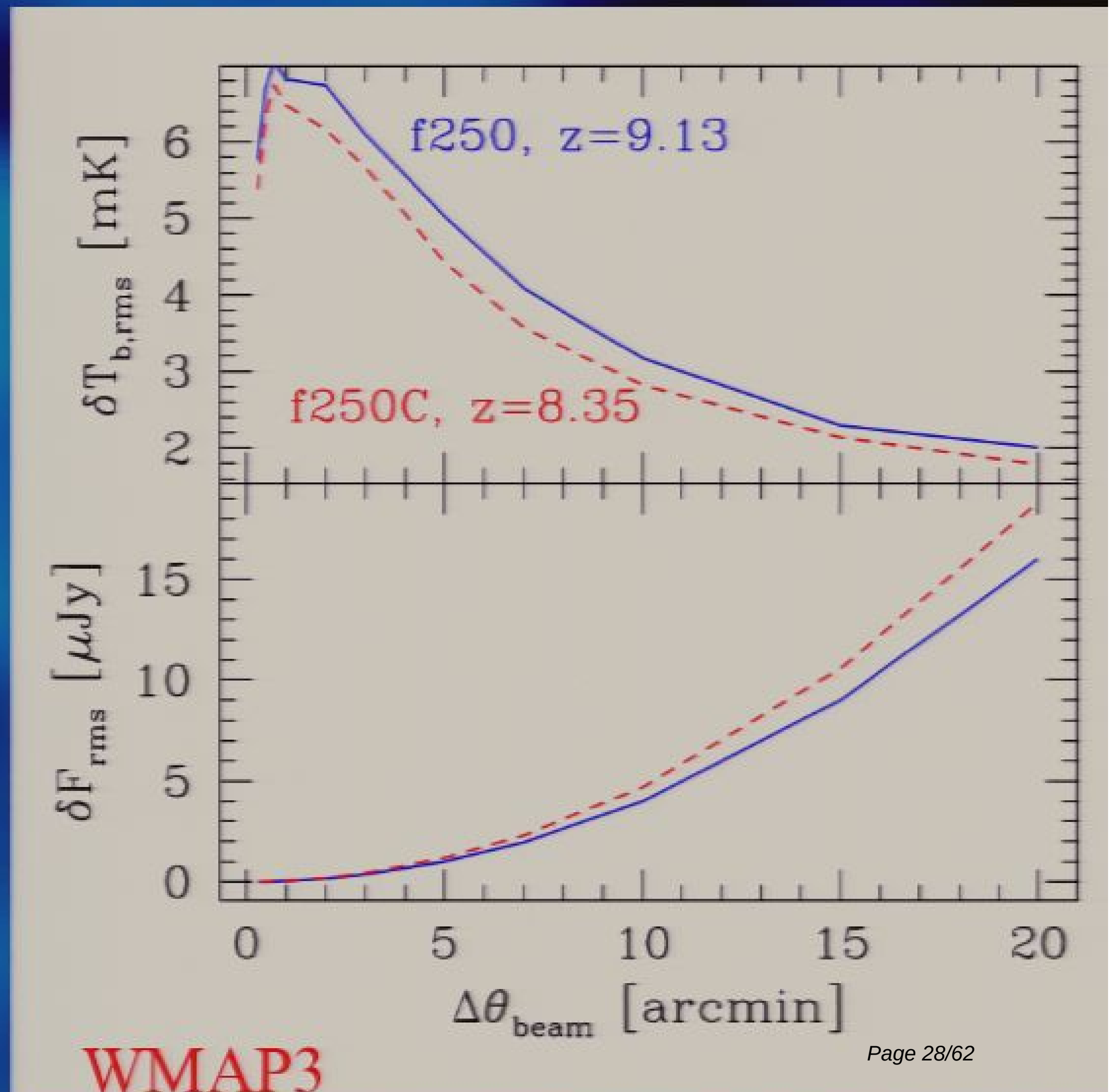


RMS Fluctuations vs. resolution

(Iliev, et al. in prep.)

Higher interferometer resolution -> higher temperature fluctuations, but lower flux – tradeoff!

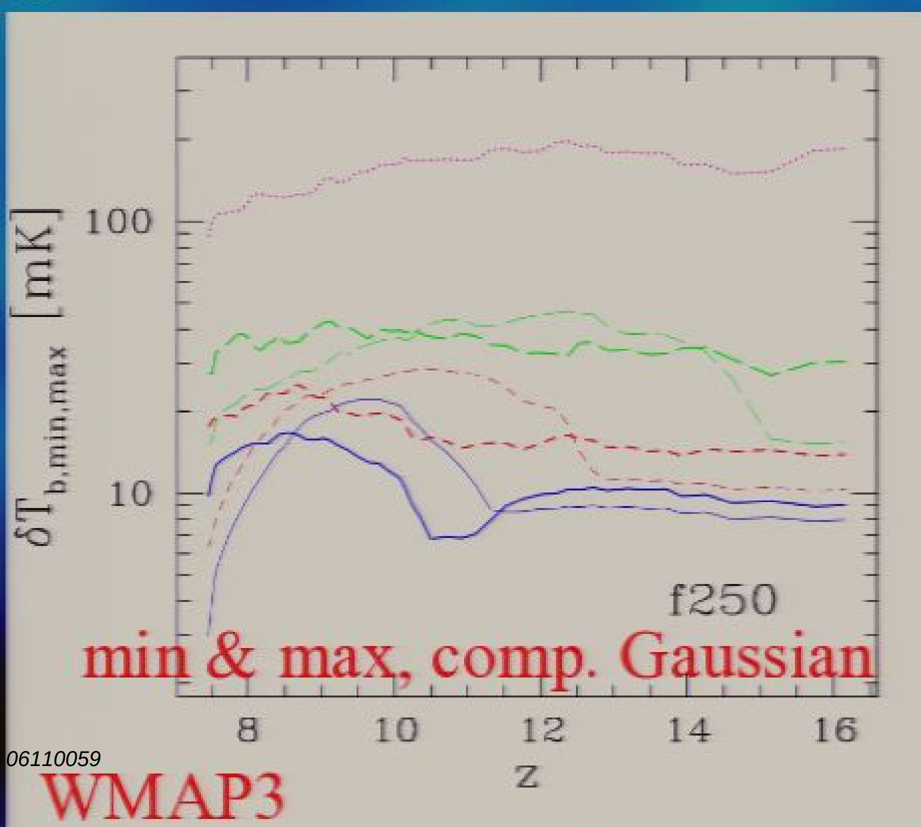
Compact interferometer cores are required for sensitivity. ~10' could be optimal.

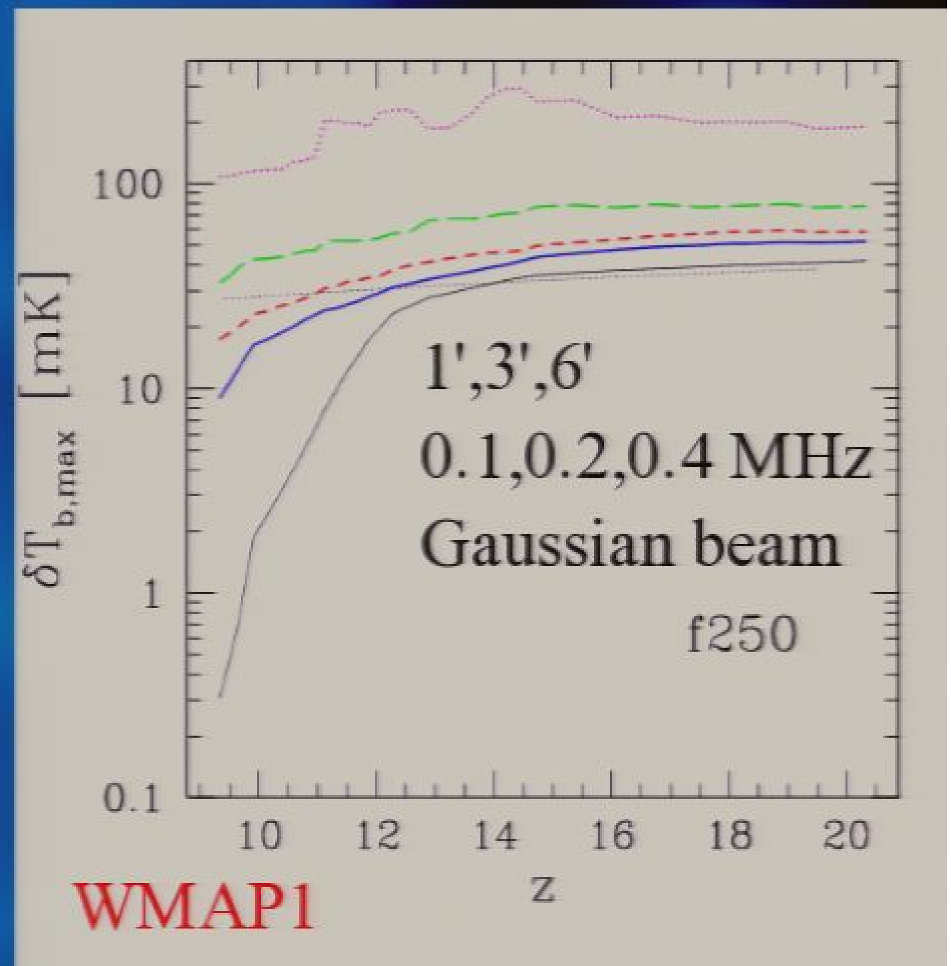


Beyond Gaussian statistics

(Mellema, Iliev, et al. 2006)

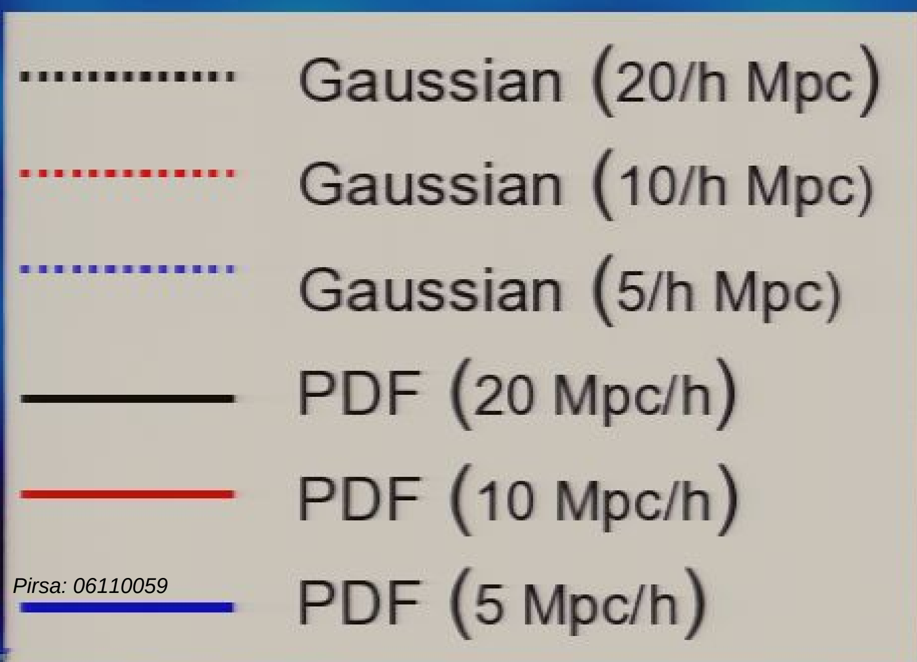
- What is the brightest point in our volume at a given redshift?

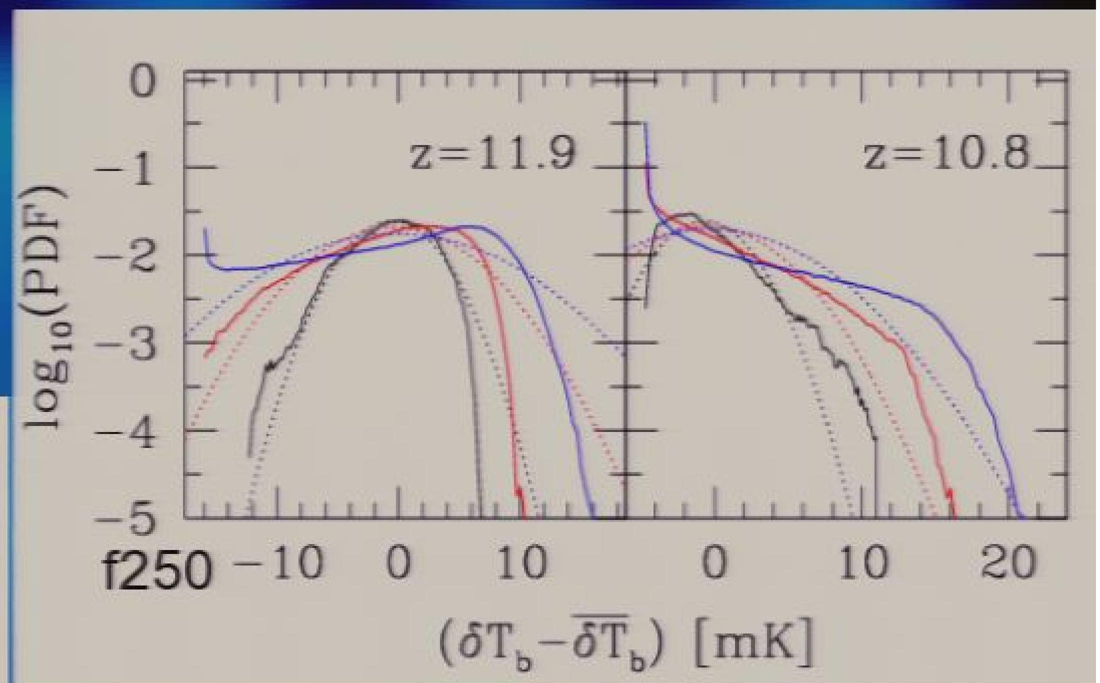




Probability Distribution Functions

Distribution of δ T is highly non-Gaussian, especially at late times.



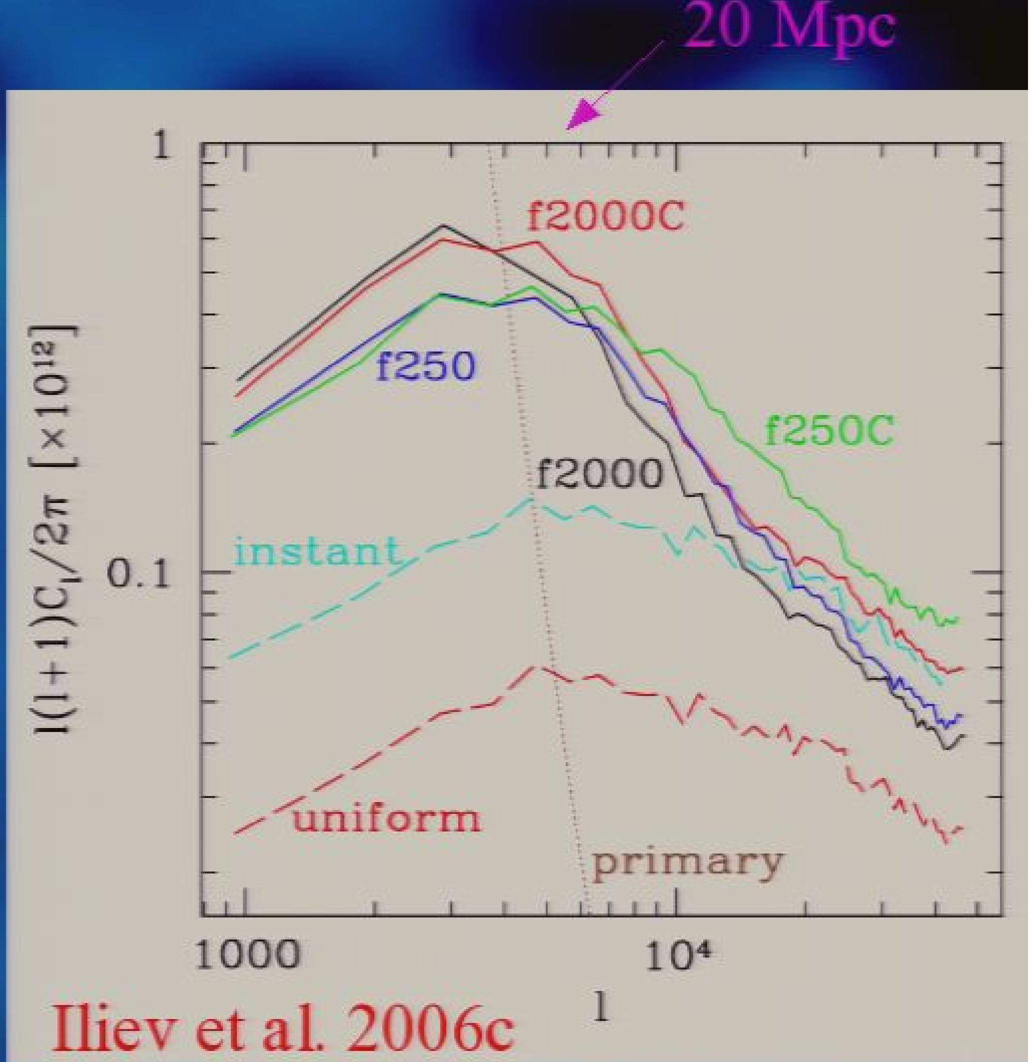


kSZ effect from patchy reionization: sky power spectra

(Iliev et al., 2006c, ApJ, submitted)

kSZ effect is due to Compton scattering of CMB photons on moving electrons. Several upcoming experiments: ACT, SPT aim to detect this signal.

- Power spectra peak at l~3000-5000, with a peak value of a few μK
- Homogeneous reionization scenarios (same τ as f250) has much less power, less clear characteristic scale.



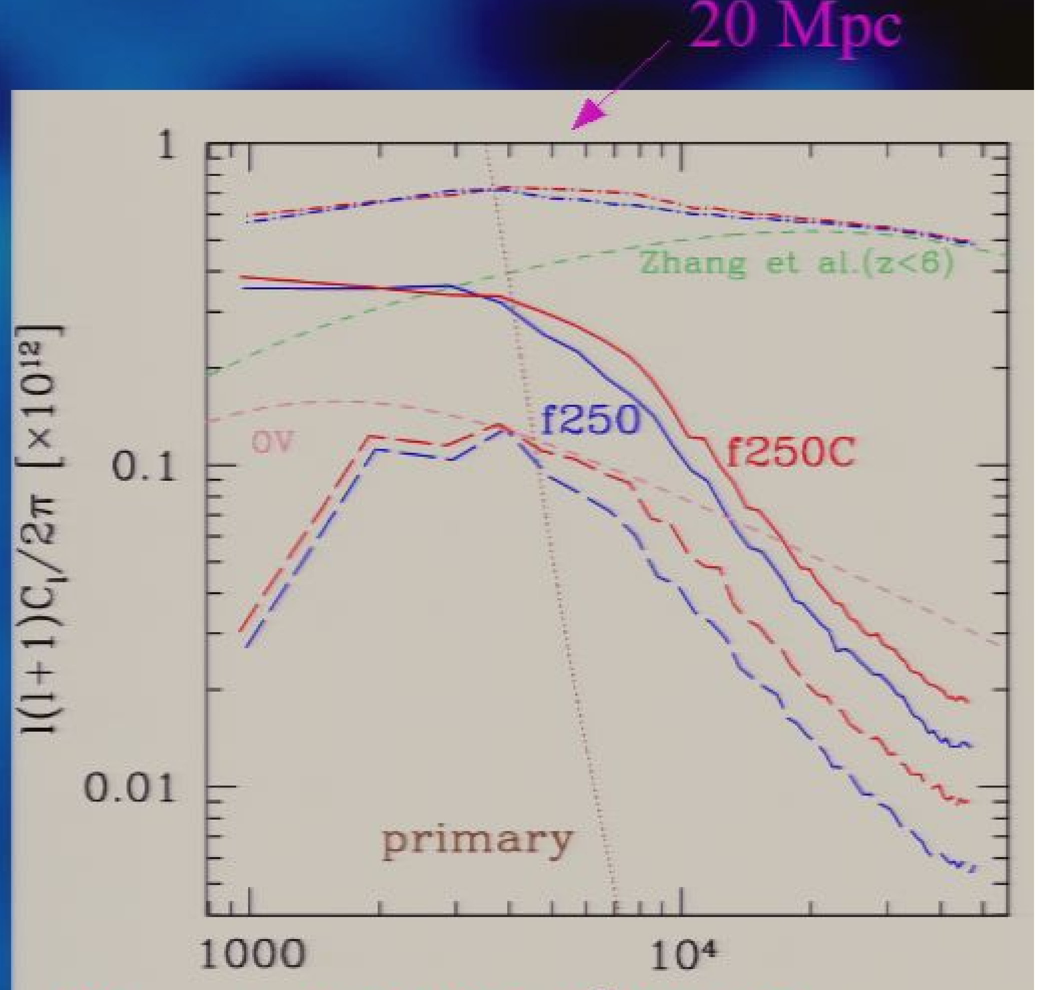
kSZ effect from patchy reionization: sky power spectra

(Iliev et al., 2006c, submitted, Iliev et al., 2006d, in prep.)

In WMAP3 cosmlogy signals are somewhat lower, but still detectable, peak at similar scales as WMAP1 (long-dashed).

Similar magnitude to the predicted post-reionization signals (short-dashed).

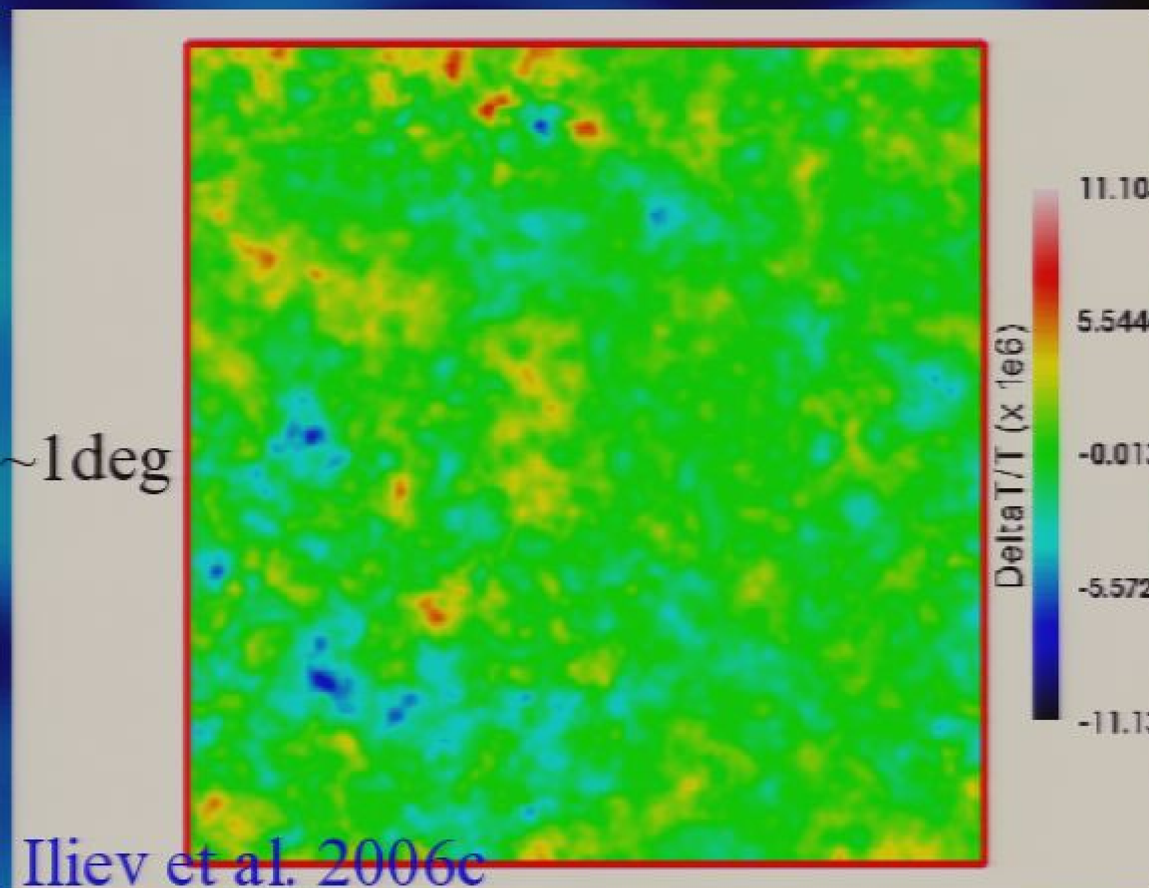
Correcting for large-scale velocity power missing from the box brings signal further up (solid lines).



Iliev et al. 2006d, WMAP3

Sample kSZ map from patchy reionization

- Sample kSZ map (run f250C).
- range of pixel values is $\Delta T/T = -10^{-5}$ to 10^{-5}, i.e. ΔT max/min are in the tens of μK at ~ arcmin scales.

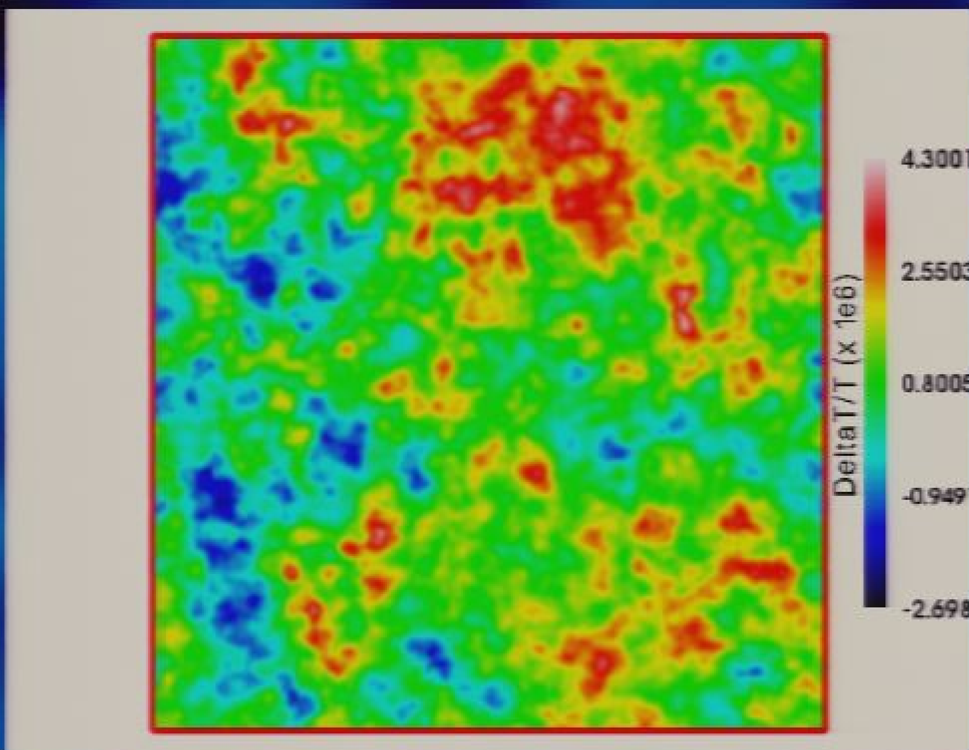


~1deg

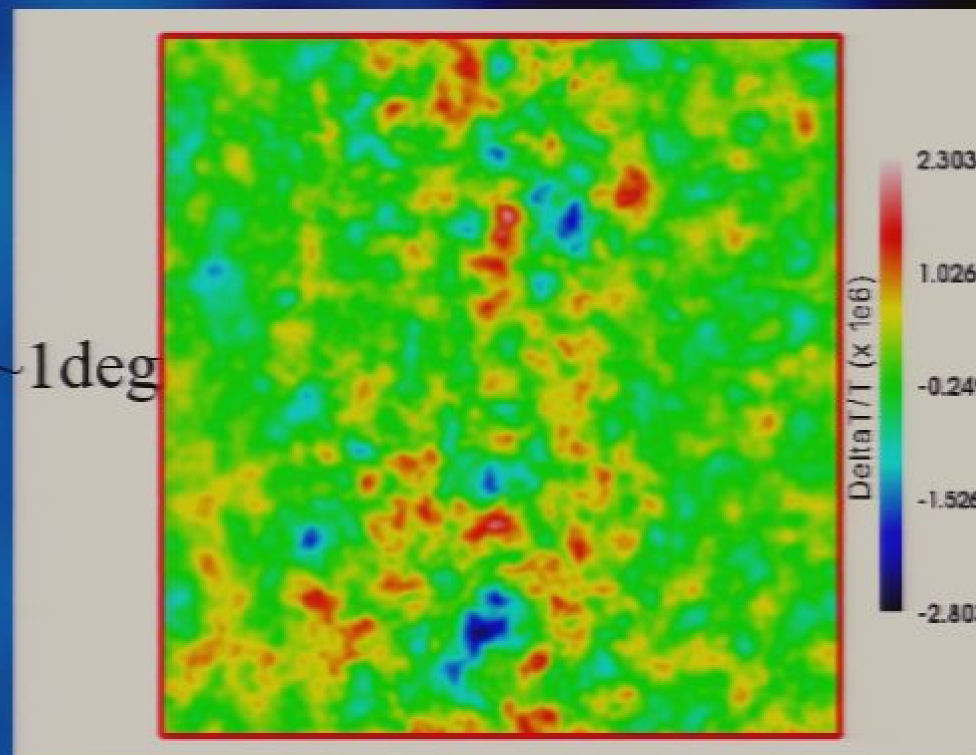
~1 deg

(images produced using Ifrit package of N. Gnedin)

Sample kSZ map from patchy reionization: WMAP3



~1deg



~1 deg

with large-scale velocity corrections

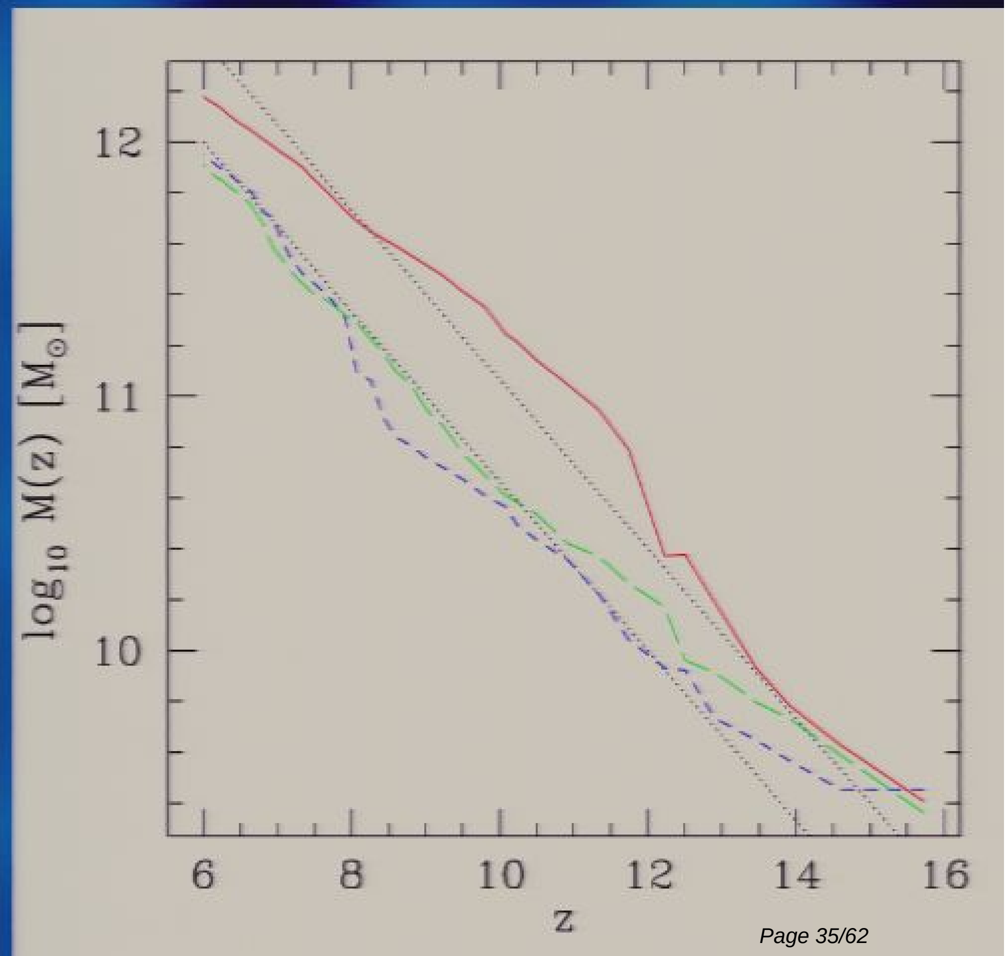
Iliev et al. 2006e

(images produced using Ifrit package of N. Gnedin)

Luminous sources at the end of reionization

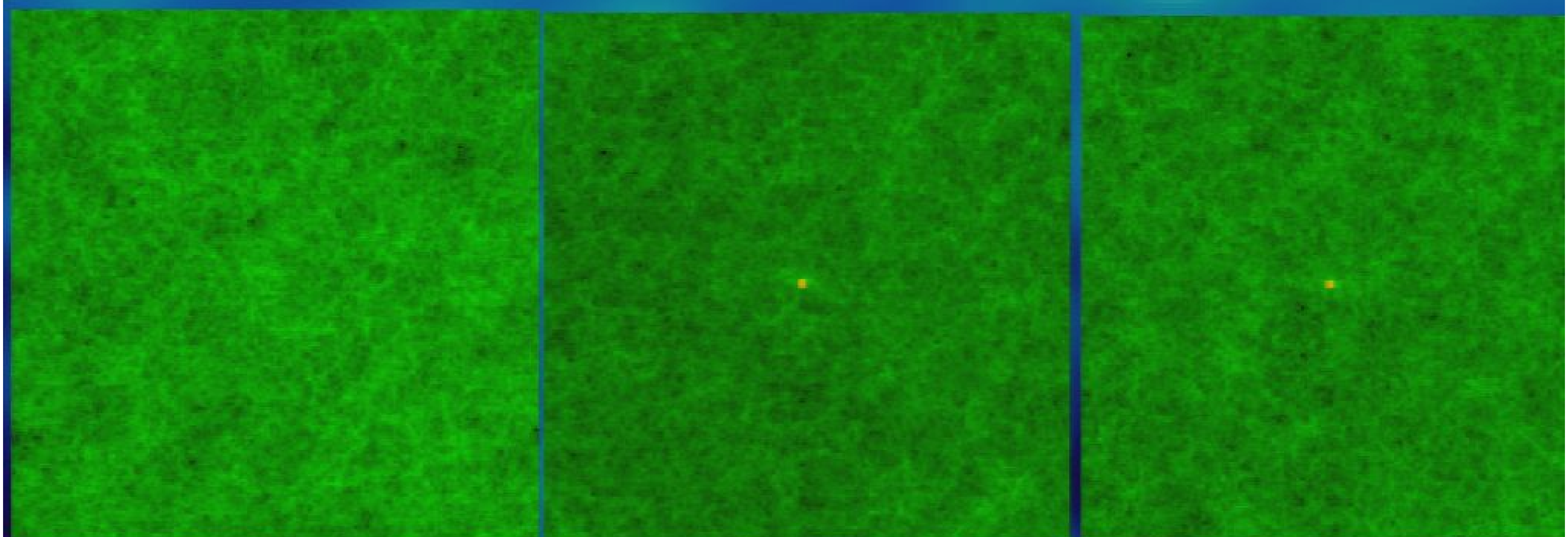
(work in progress!)

- The first sources detected at the reionization tail-end (z~6) are among the brightest galaxies and QSOs (e.g. in SDSS)
- Rare, high peaks of the density
- Strongly clustered sources
- Most massive galaxies in our box ~1e12 M_{solar} at z=6, mass accretion history of the 3 most massive shown.



Luminous sources at the end of reionization: animations

- The most massive source at z~6 is in the center
- HII region around it forms early (z~16) and grows quite large
- ... but even at the end (z~6.6) many neutral patches still exist.



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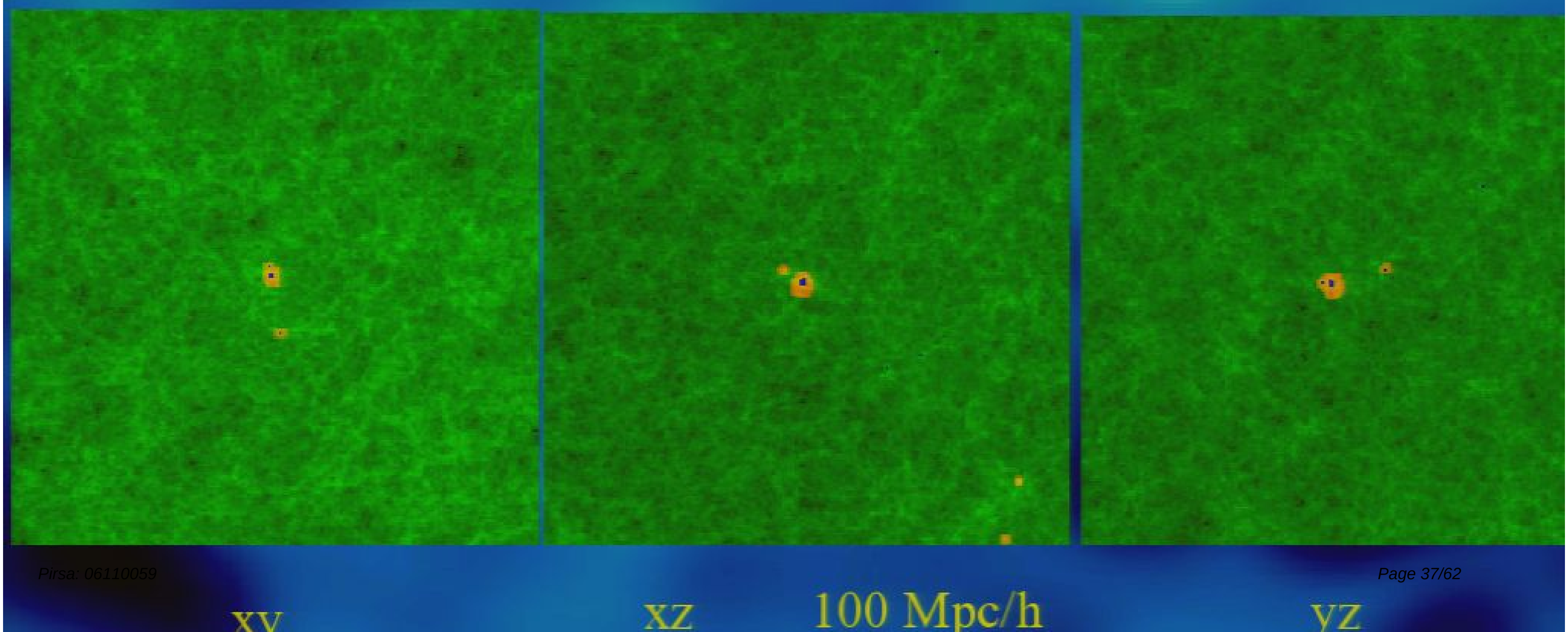

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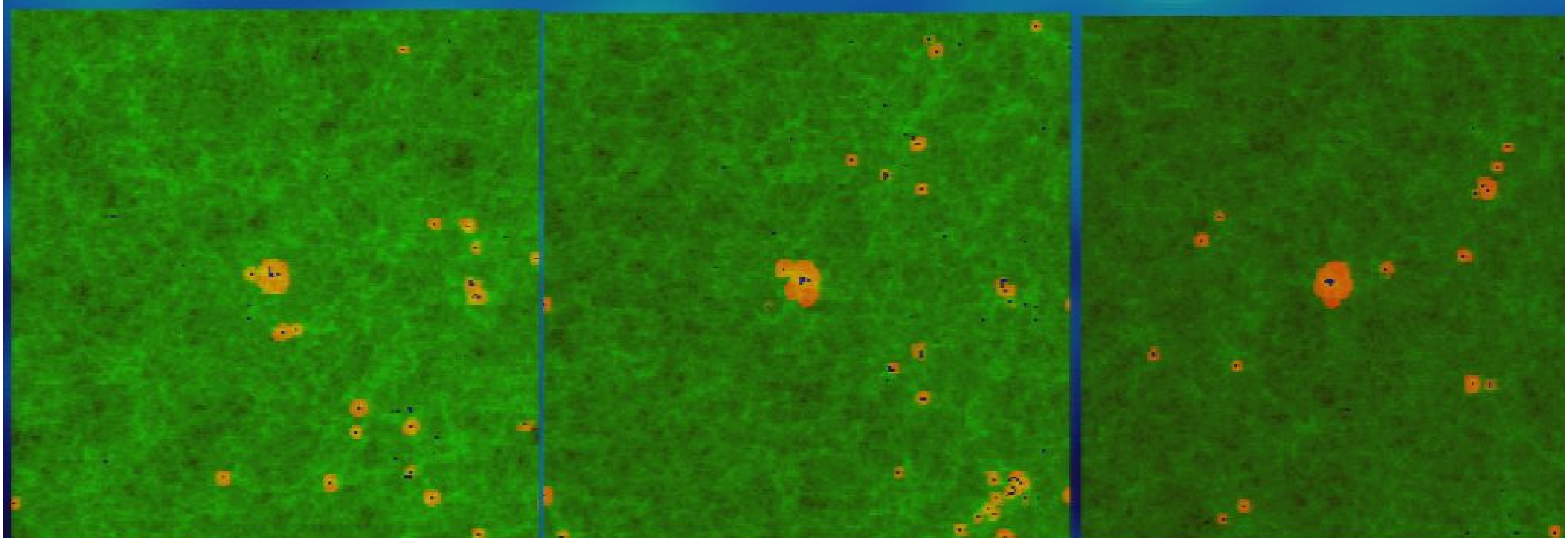

xy xz 100 Mpc/h yz

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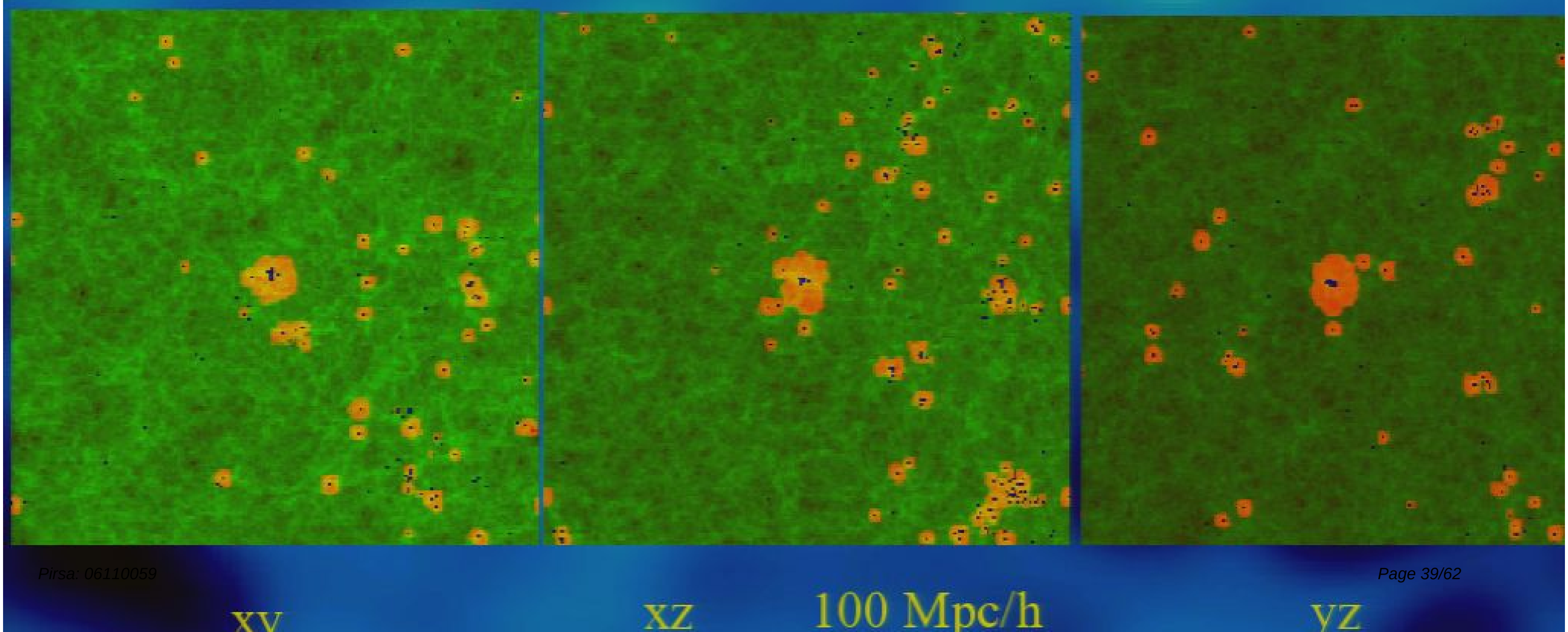

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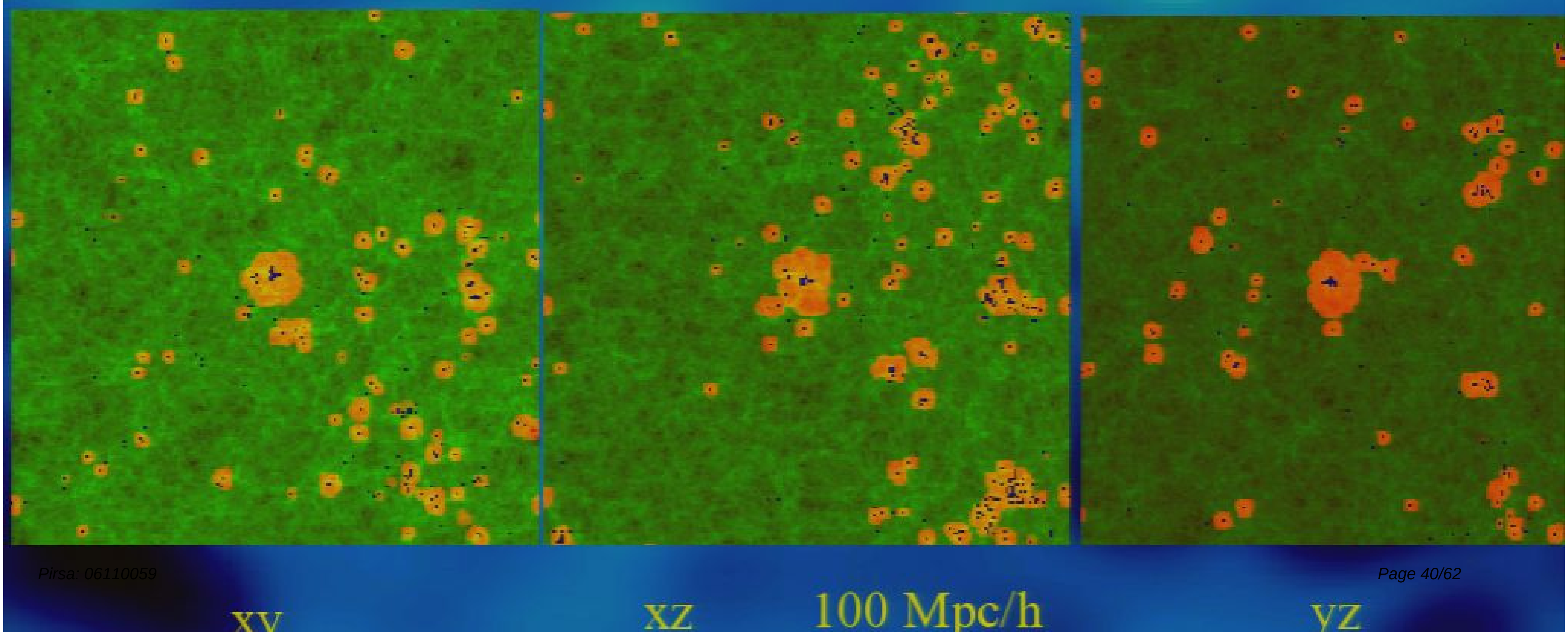

Luminous sources at the end of reionization: animations

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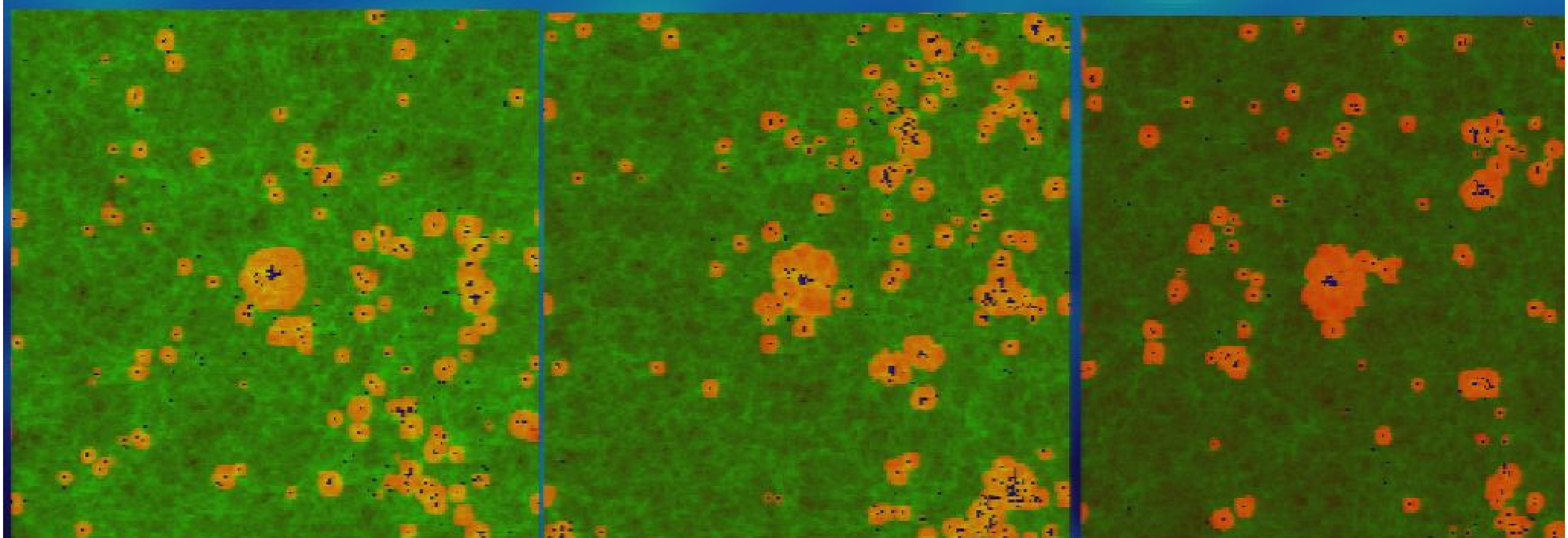

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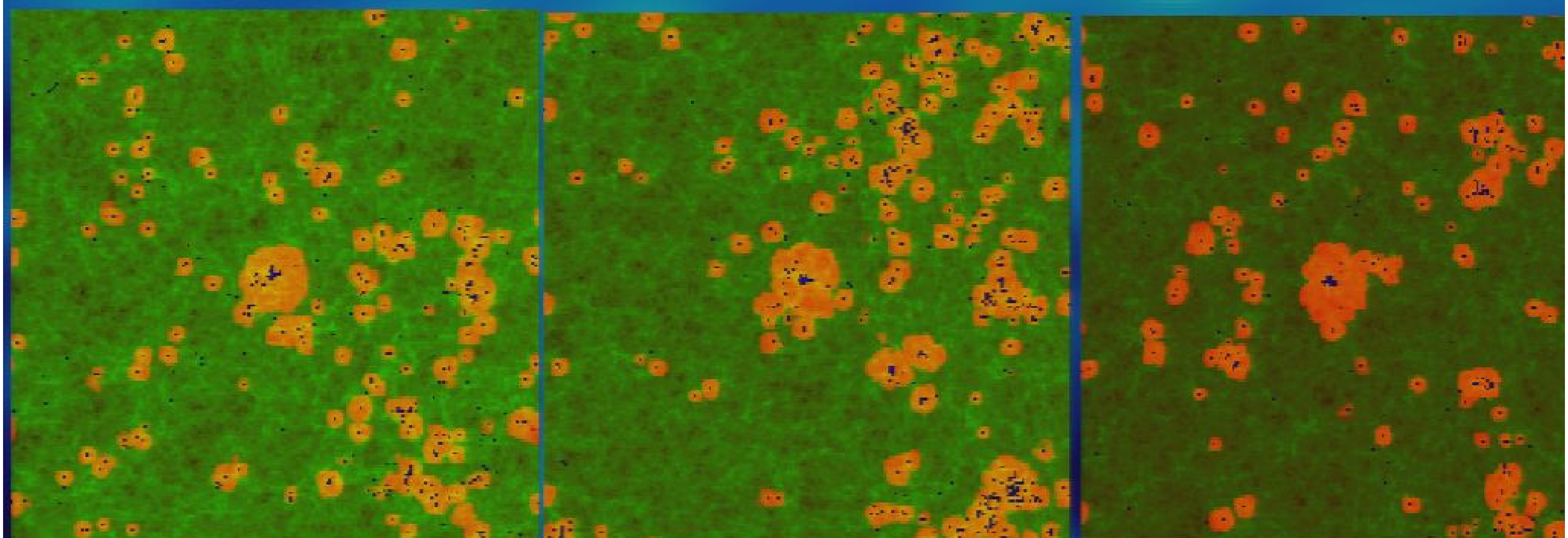

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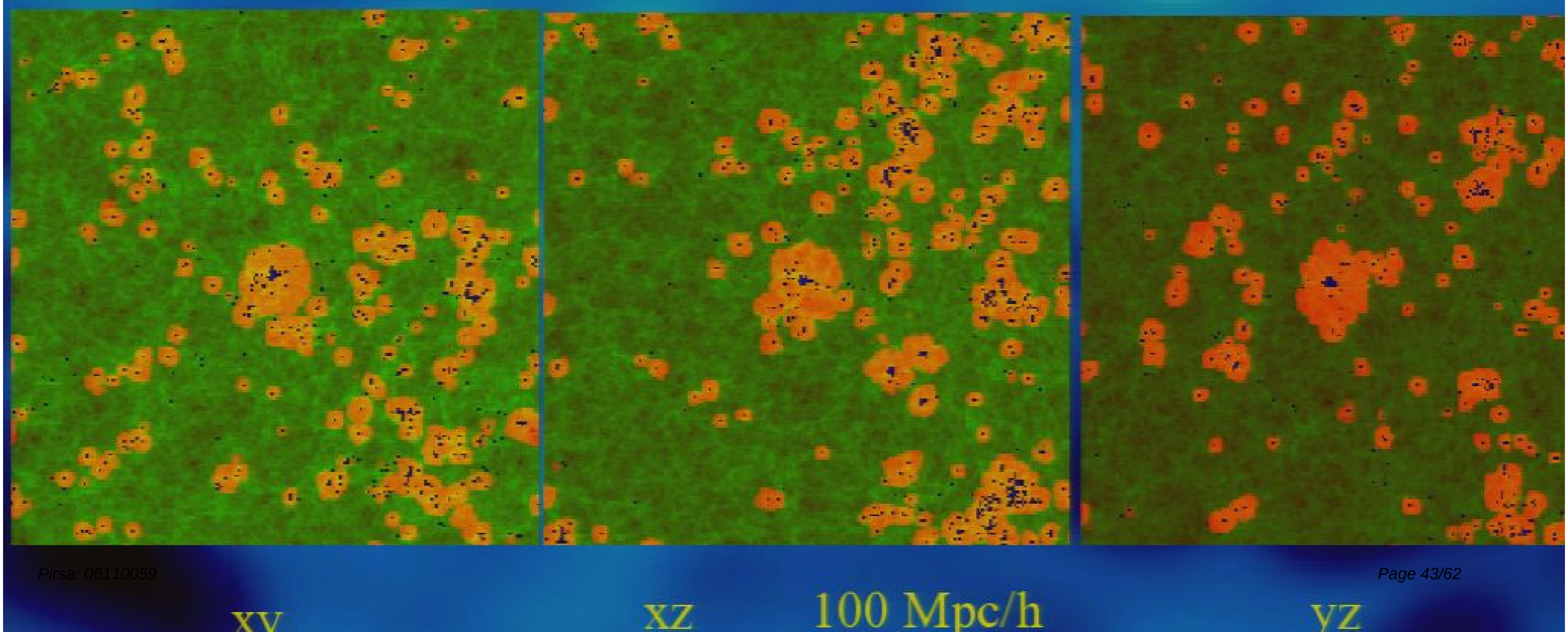

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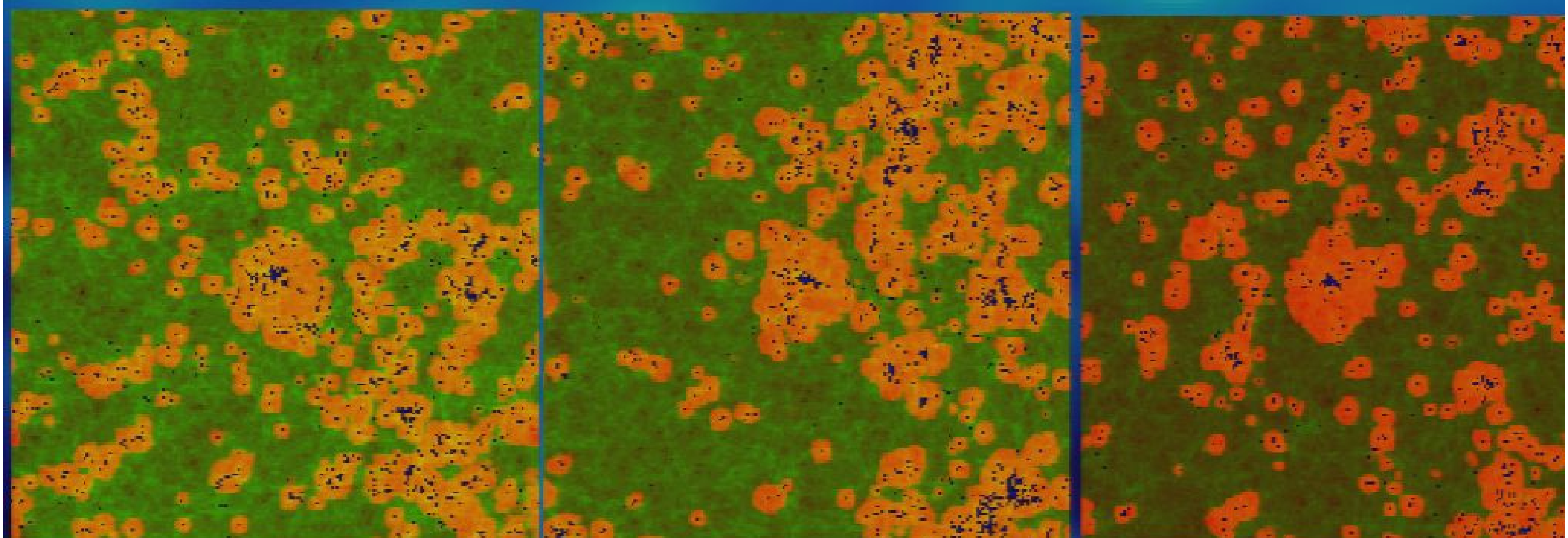

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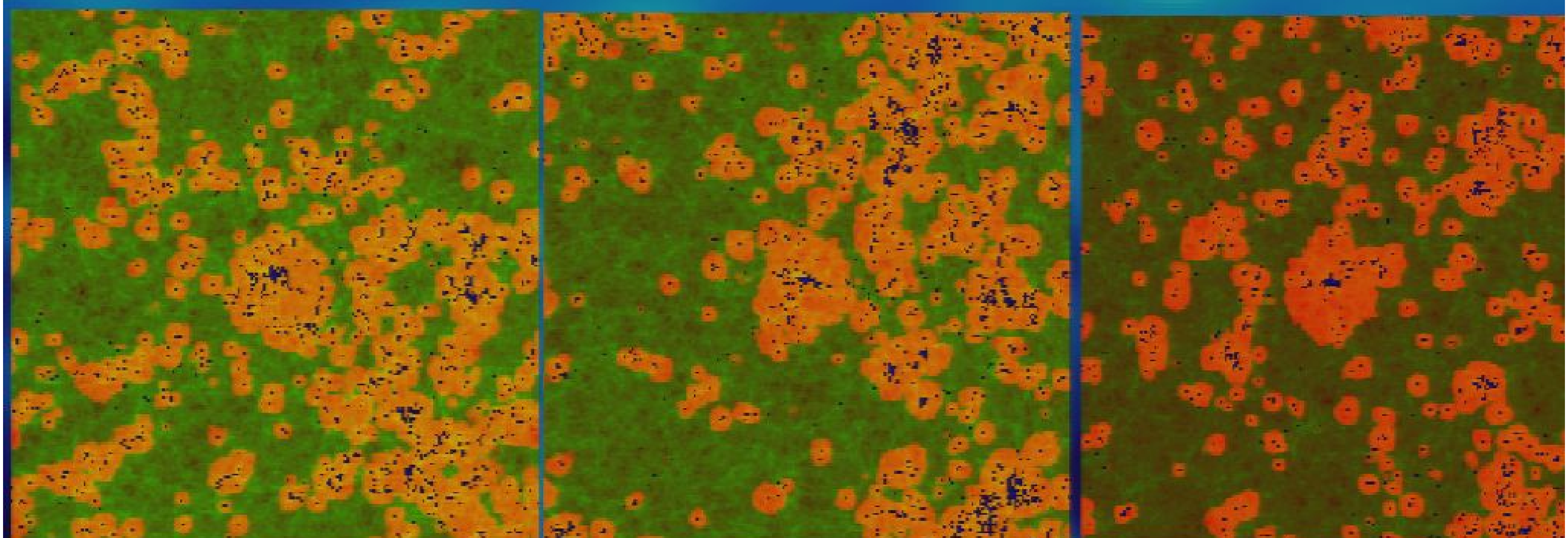

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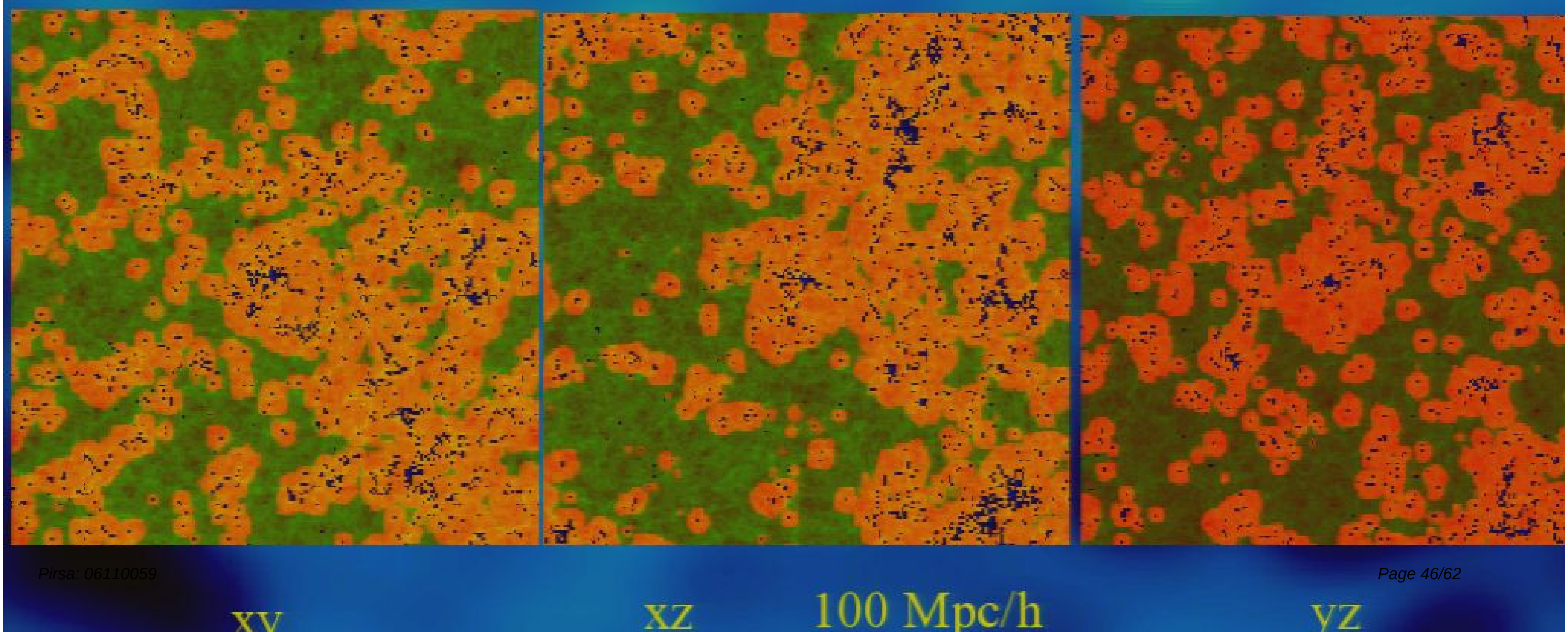

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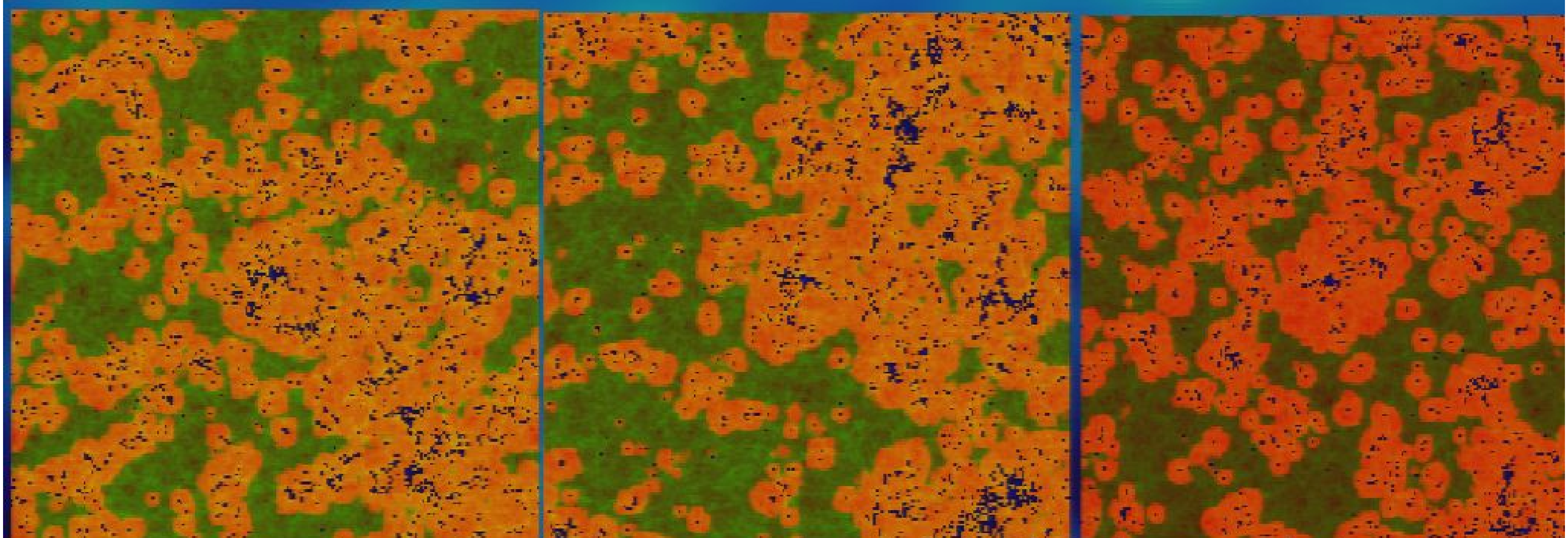

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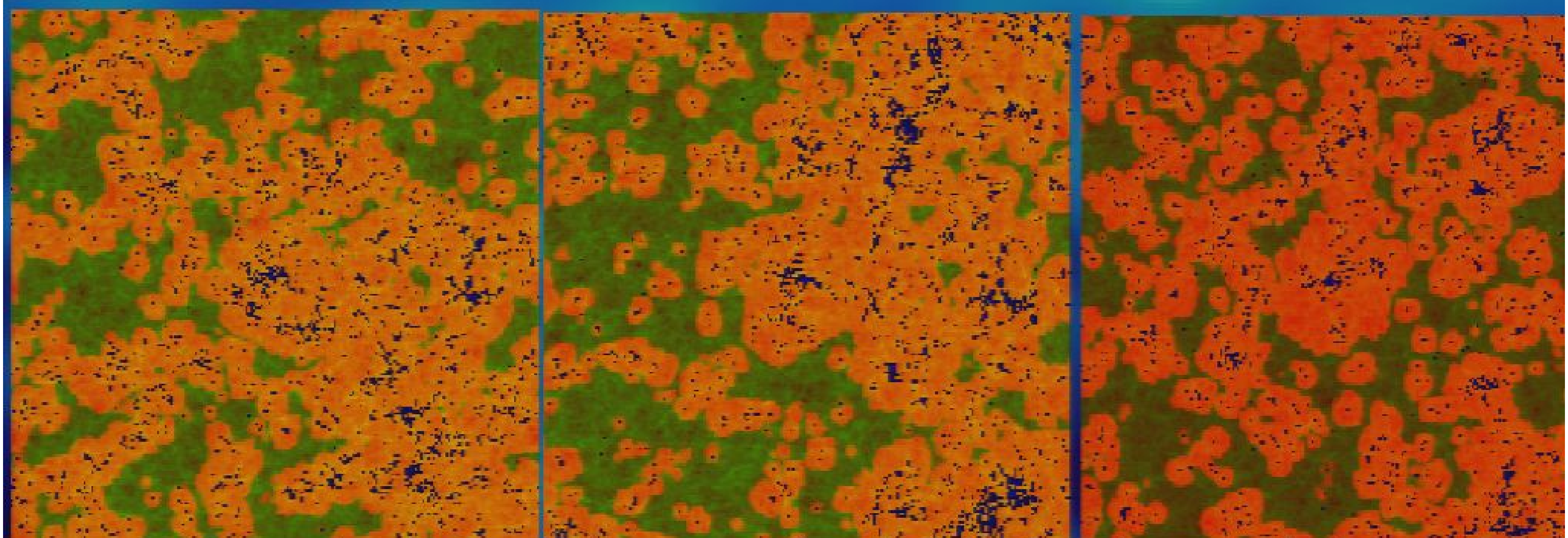

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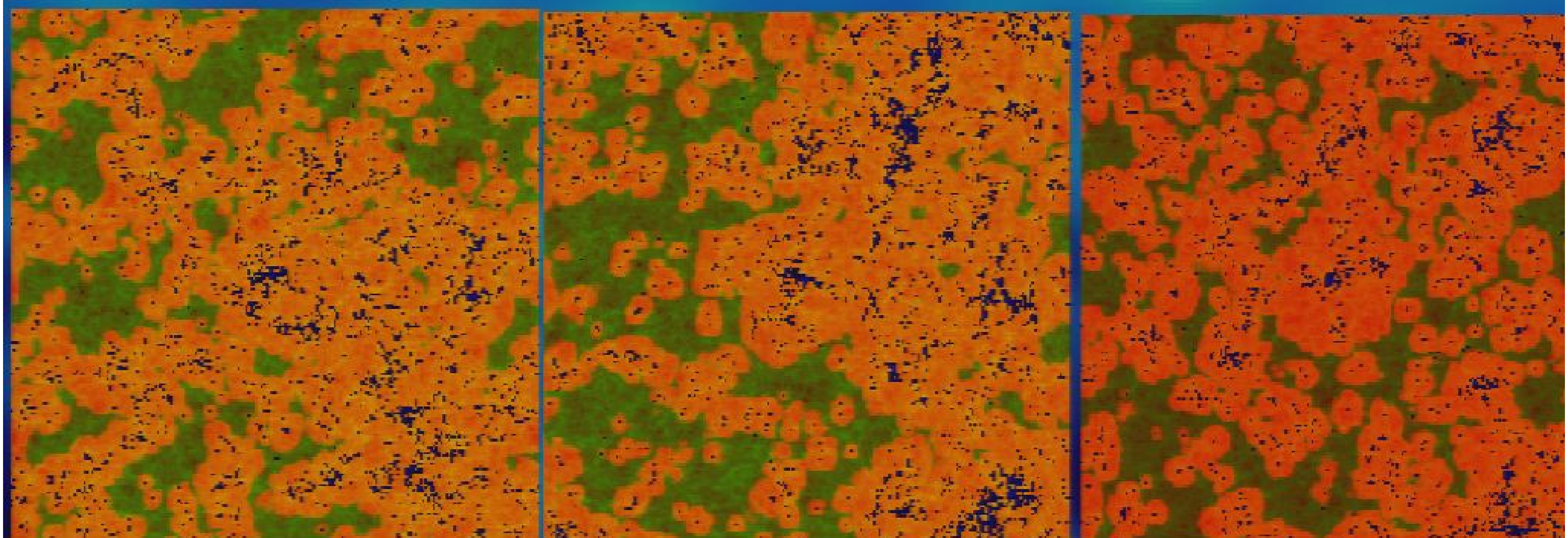

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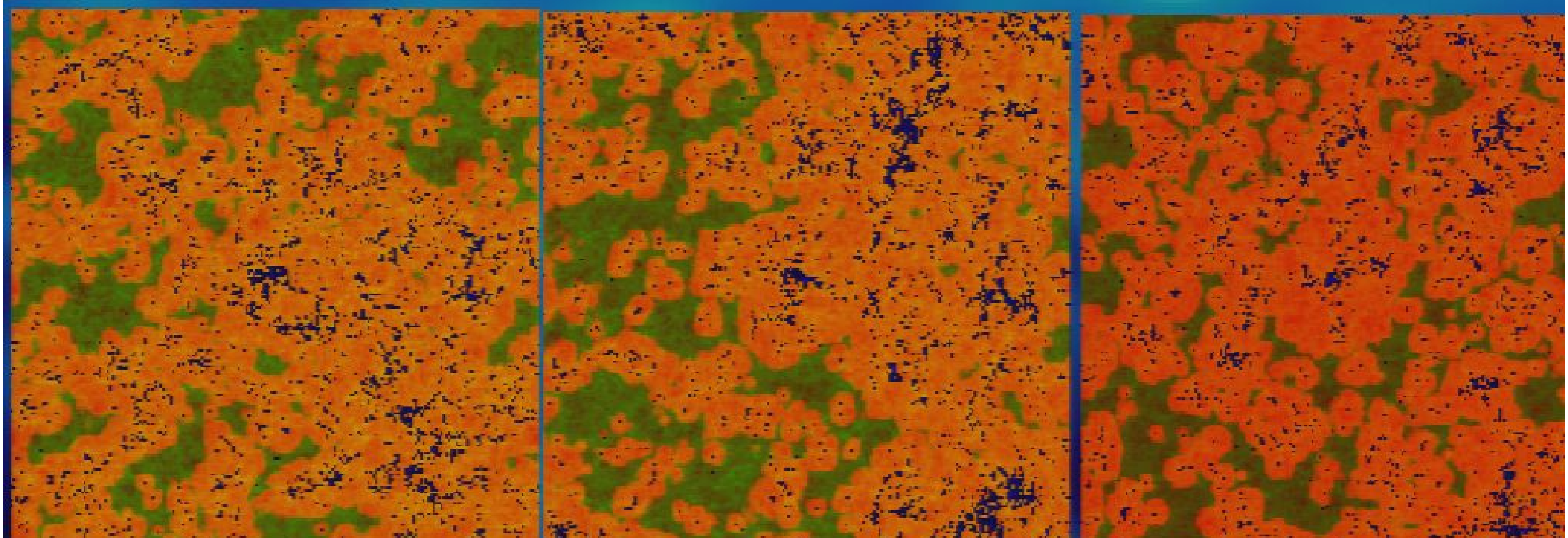

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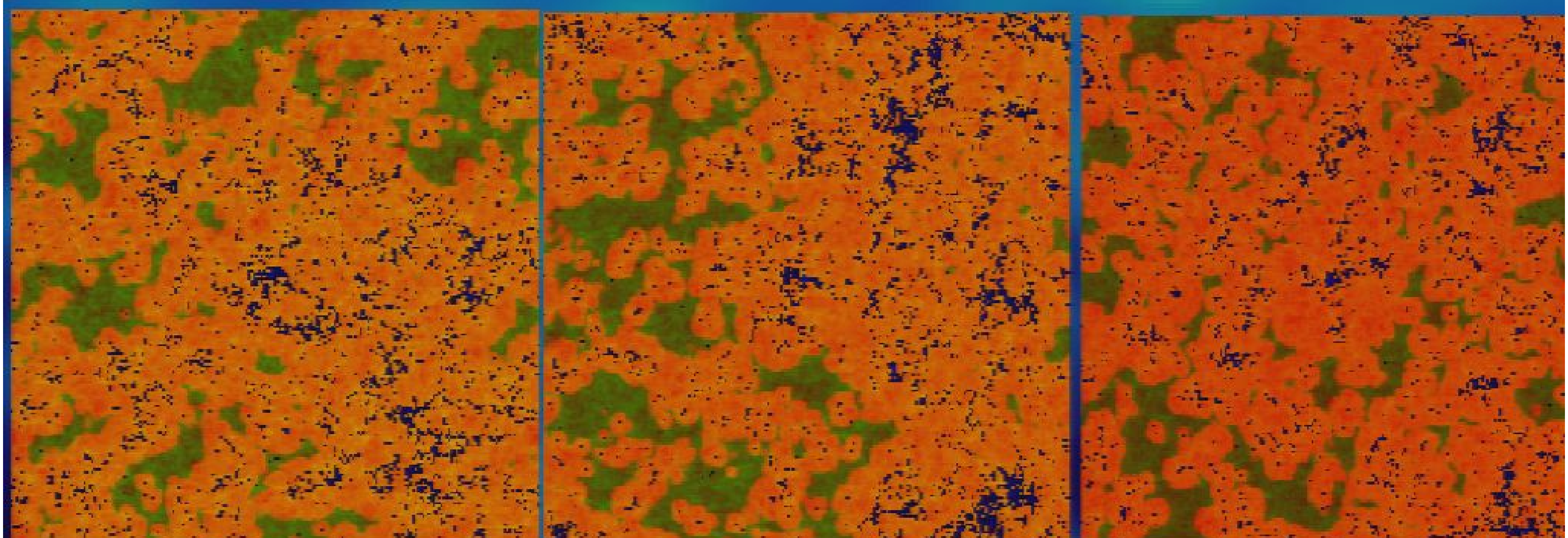

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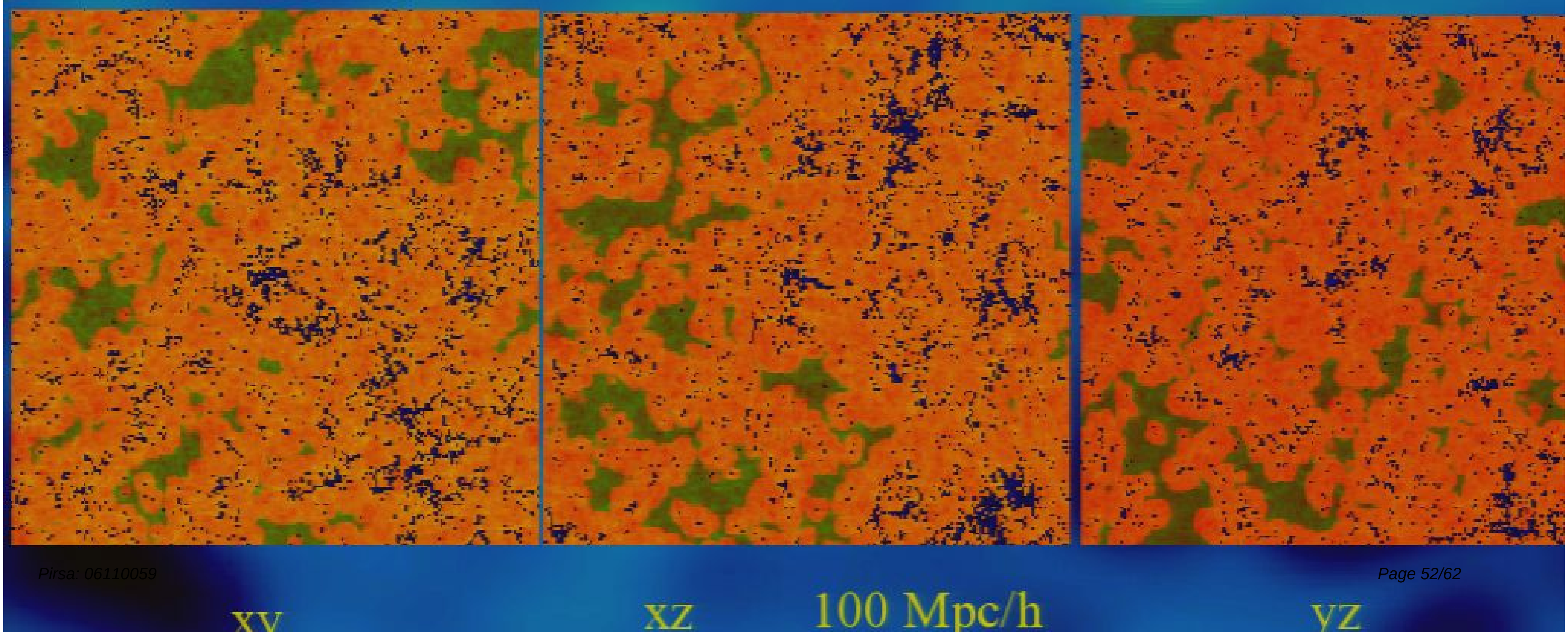

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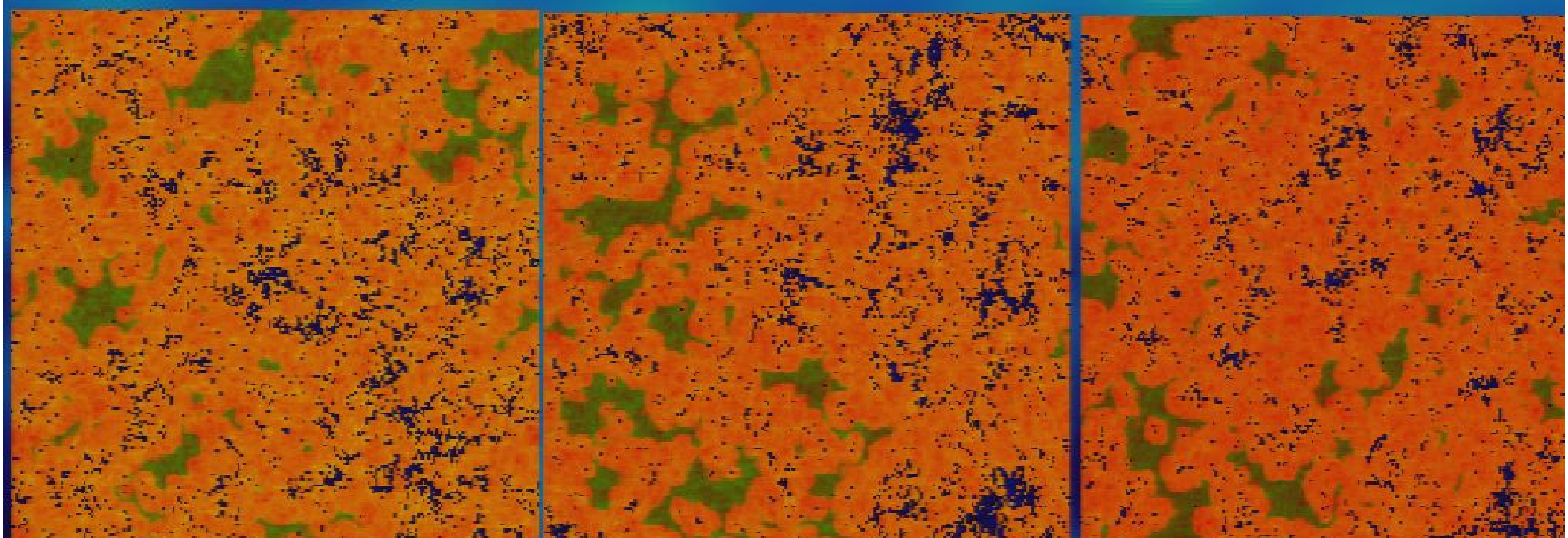

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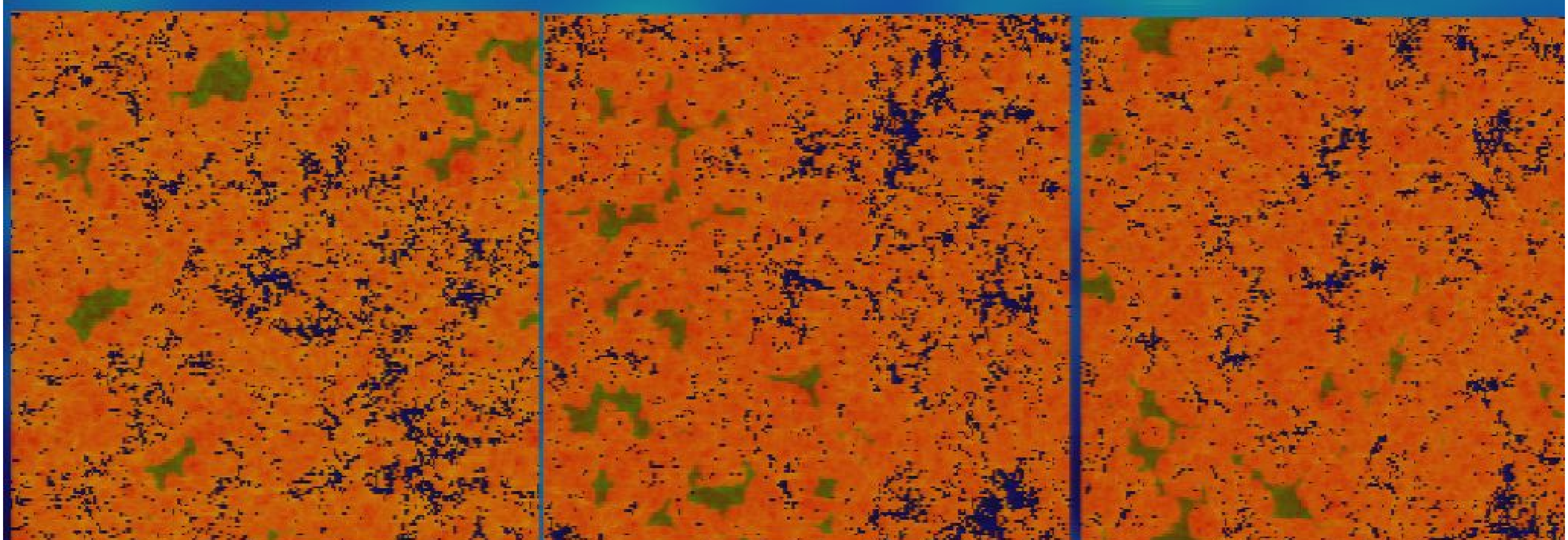

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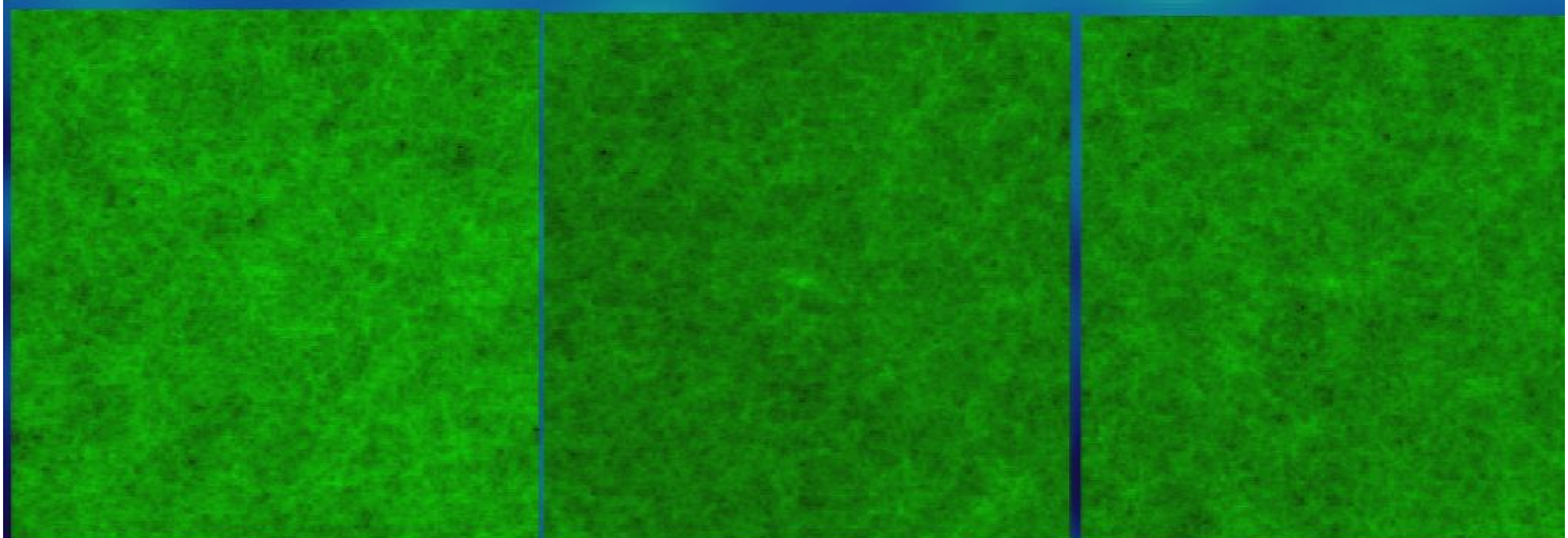
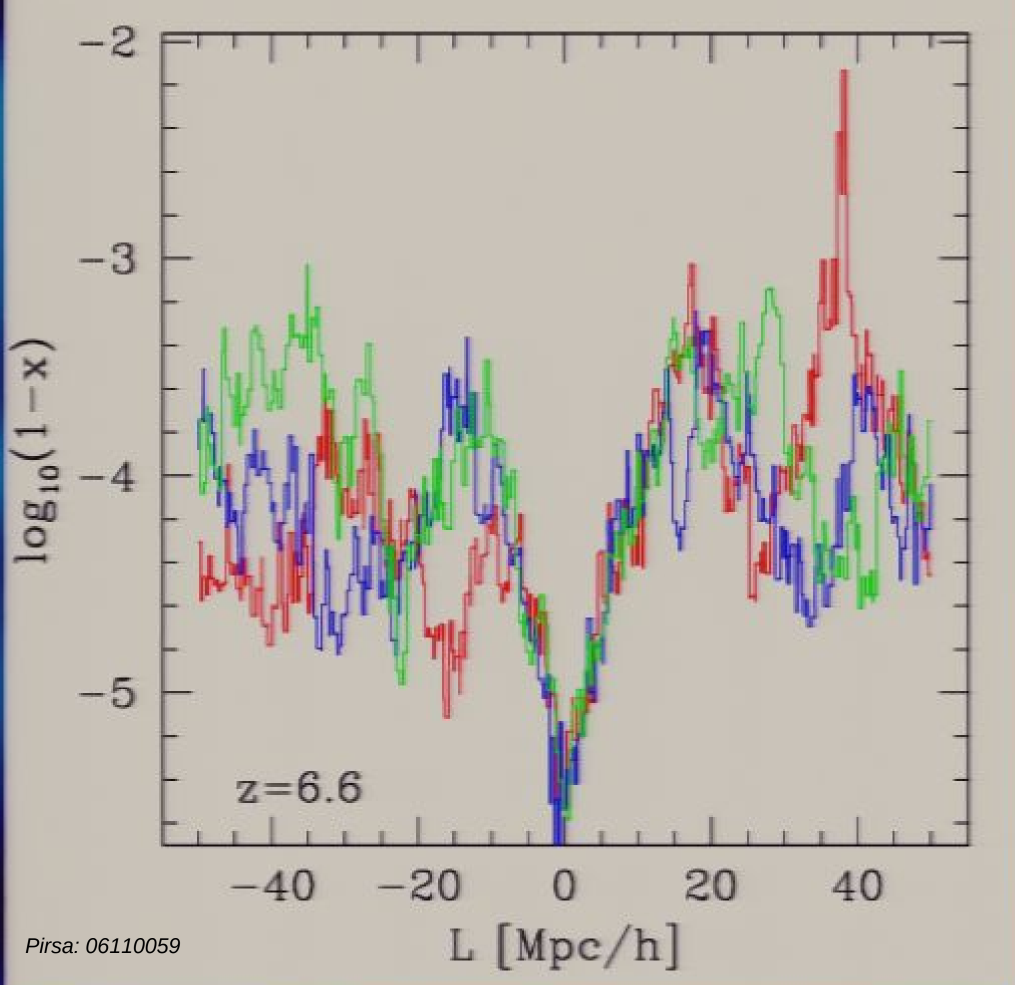
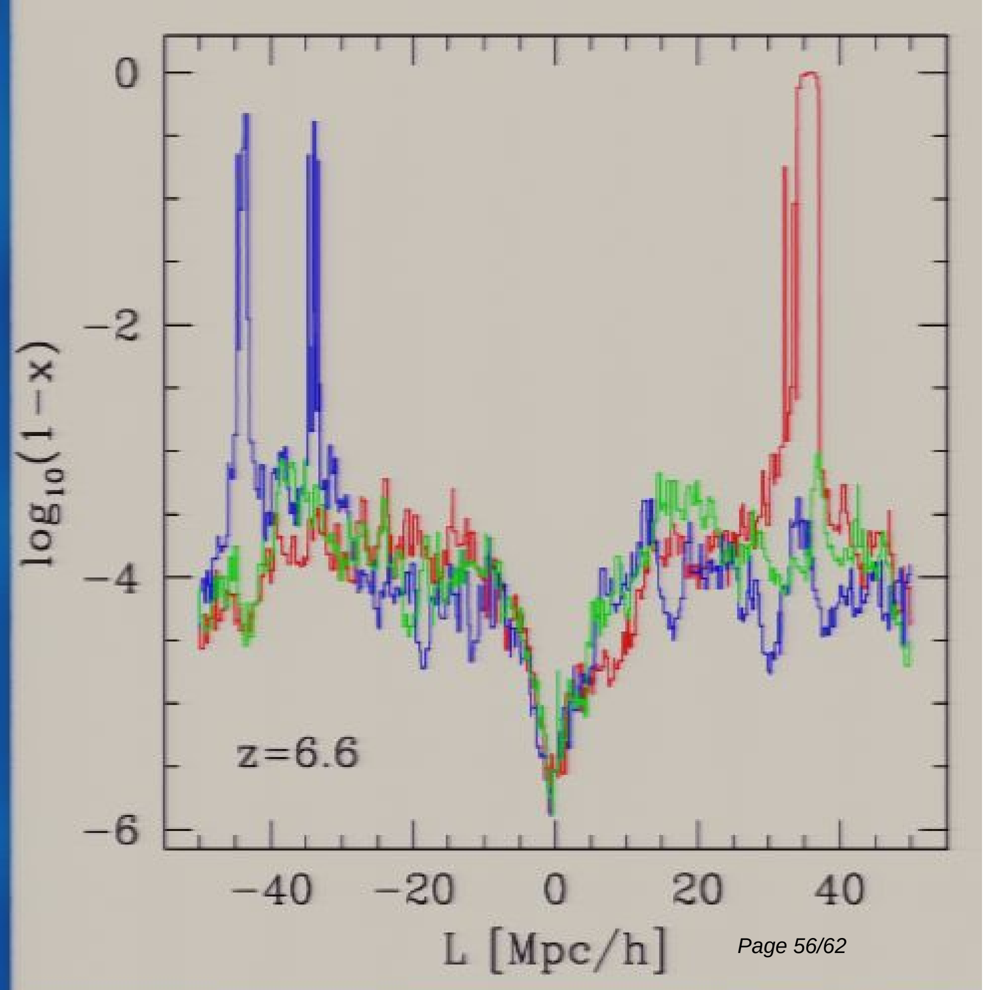


xy xz 100 Mpc/h yz

Luminous sources at the end of reionization: LOS variations





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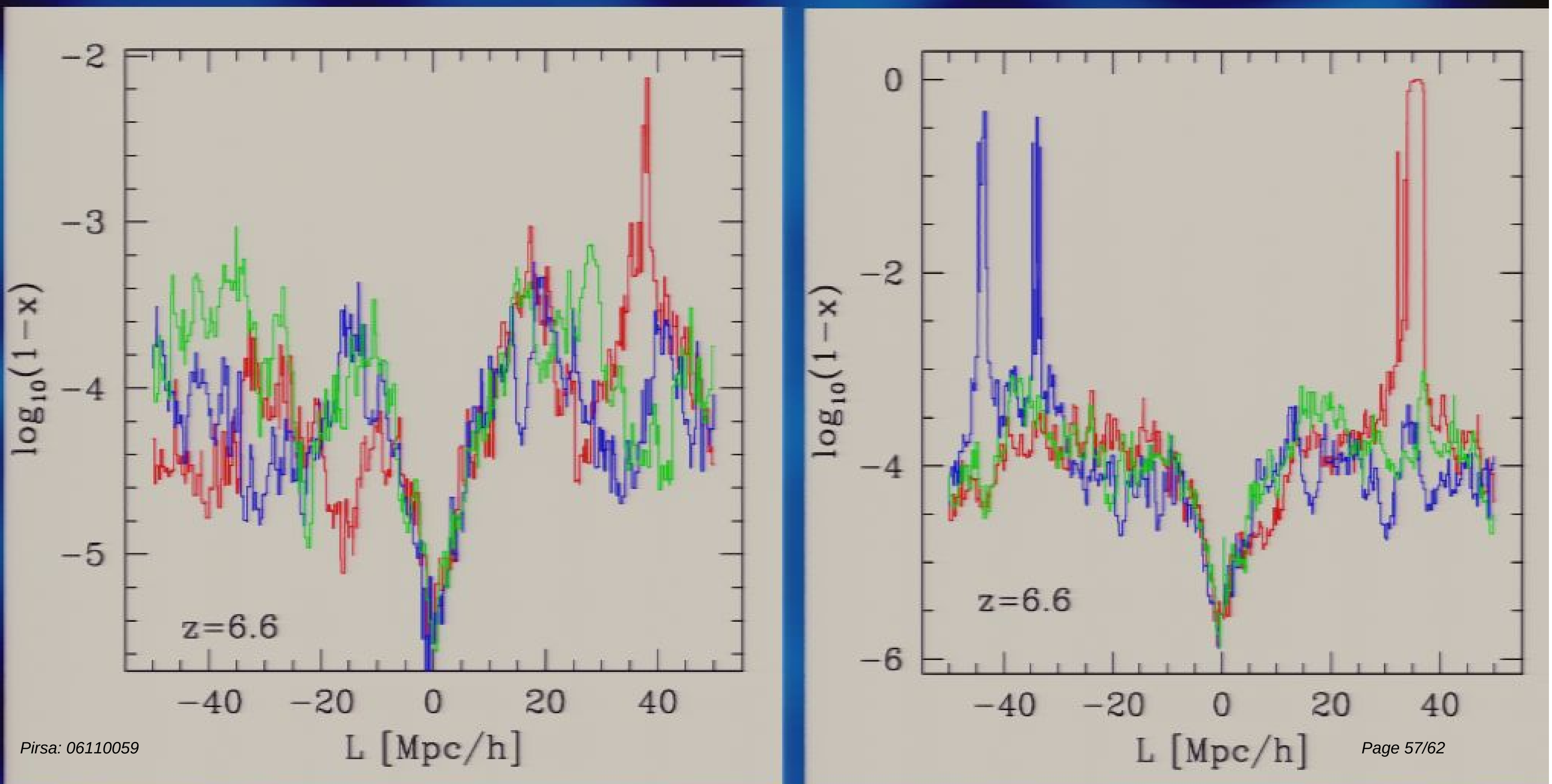
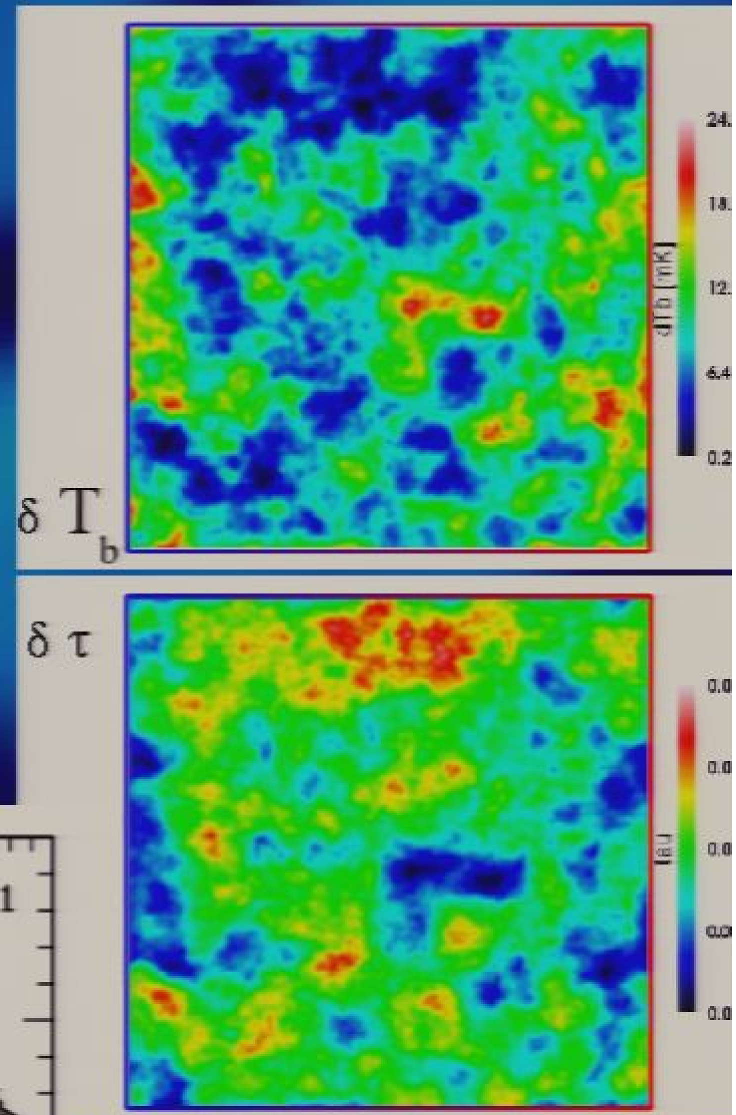
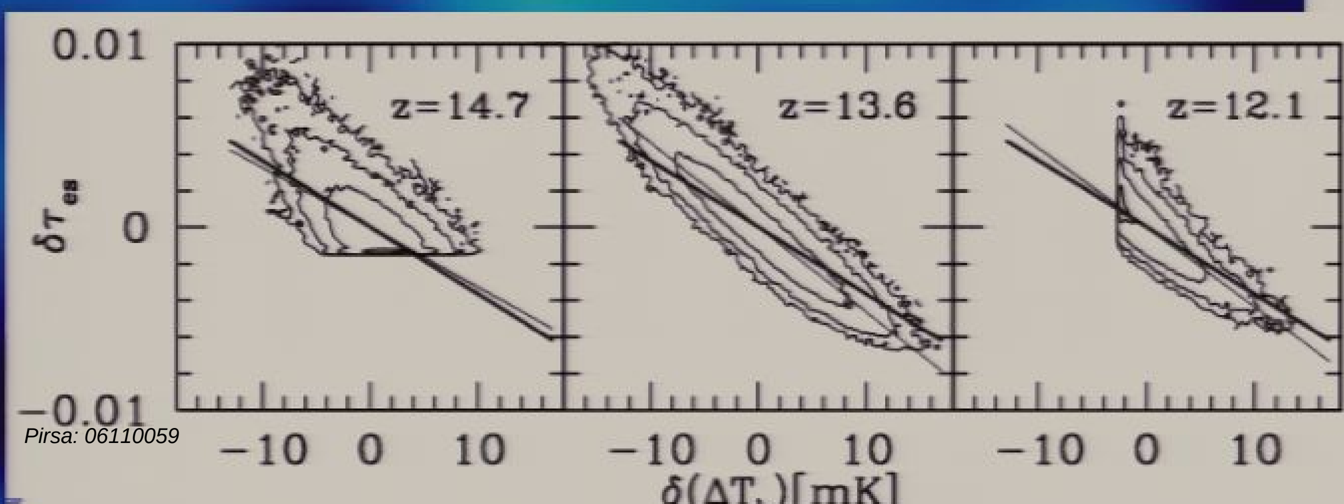


Reconstructing the Thomson Optical Depth due to Patchy Reionization with 21-cm Fluctuation Maps

(Holder, Iliev, Mellema, ApJL, submitted)

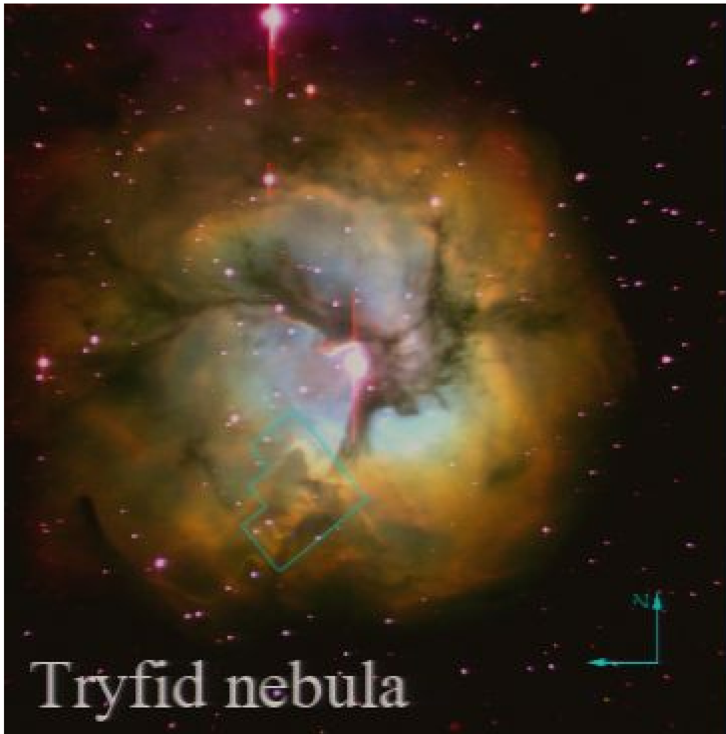
21-cm maps are an almost perfect negative image of Thomson optical depth, small-scale CMB polarization features could be derived

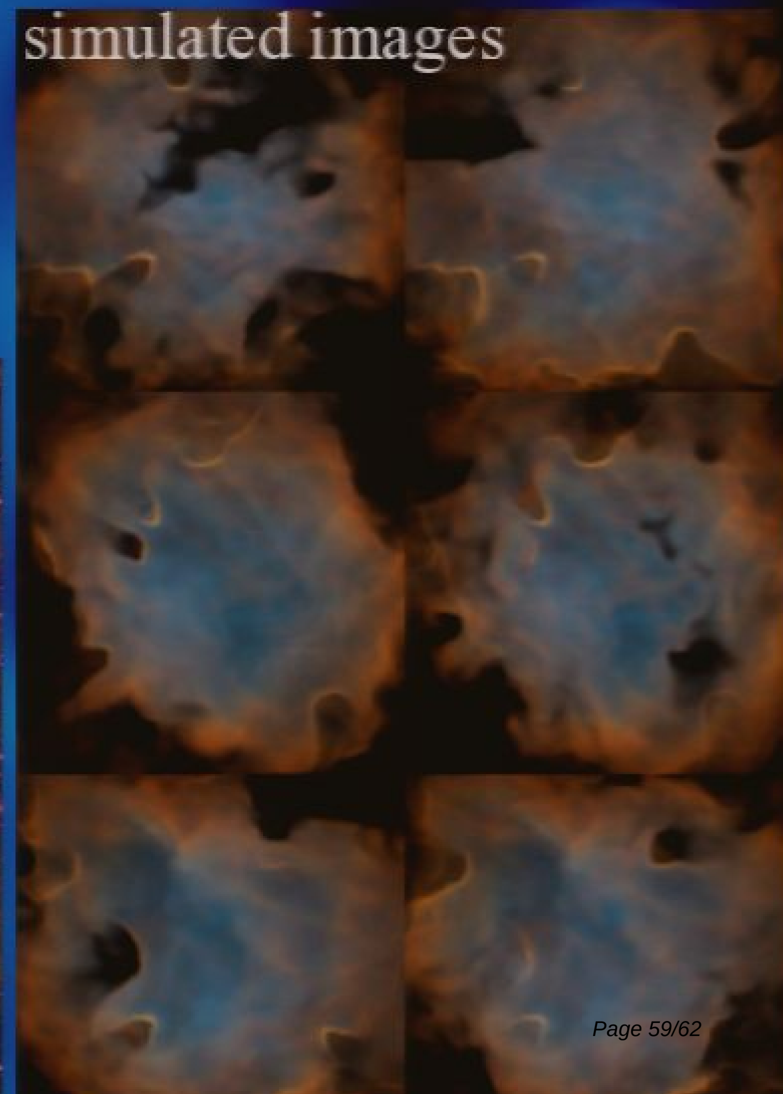




A bit of ISM: Dynamical HII Region Evolution in Turbulent Molecular Clouds

(Mellema, Arthur, Henney, Iliev, Shapiro, ApJ, 647, 397)





How reliable are the radiative transfer codes? :

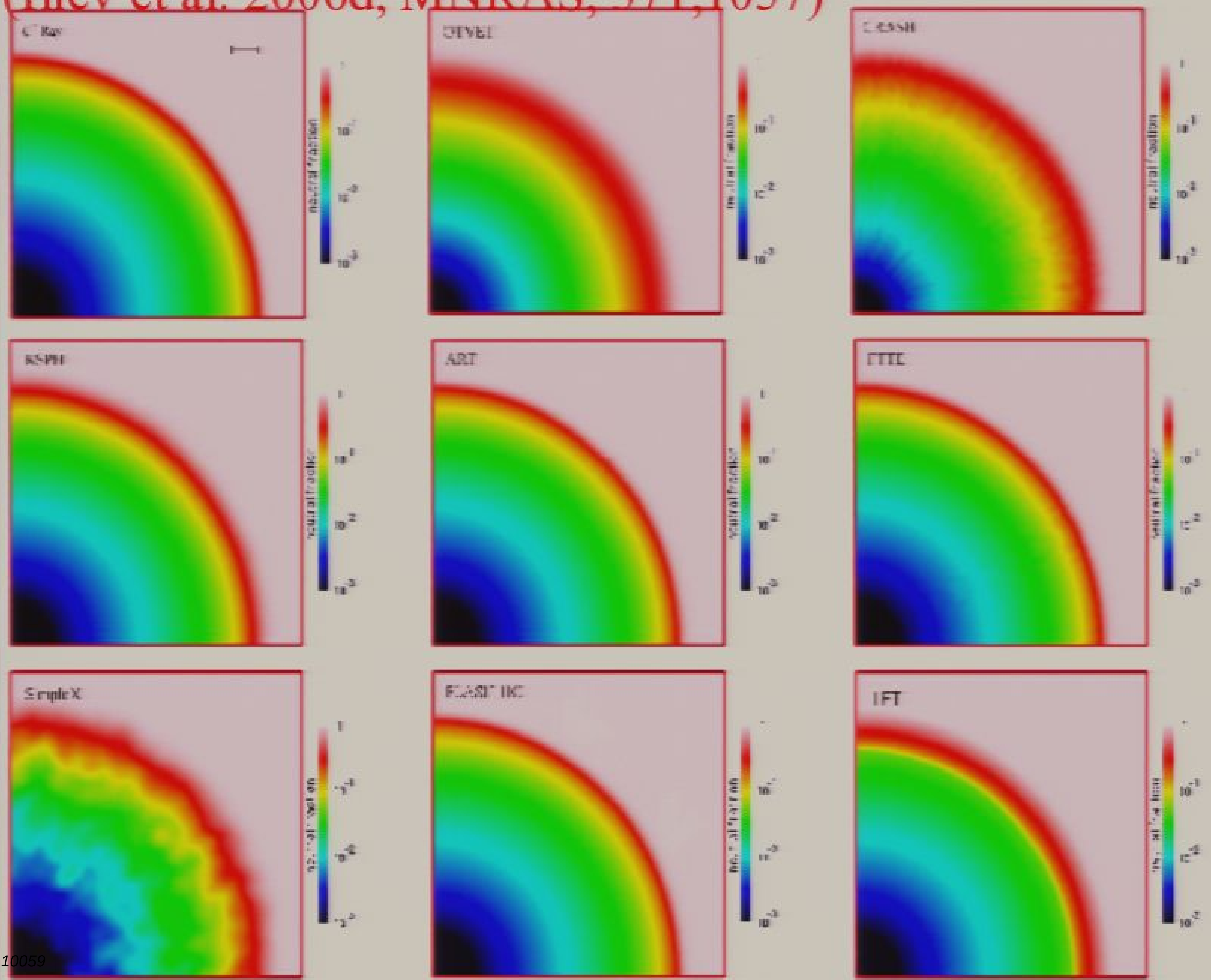
Cosmological radiative transfer code comparison project

http://www.cita.utoronto.ca/~iliev/rtwiki/doku.php

- Verification of current codes
- Testbed for future radiative transfer code development
- 13 codes (7 coupled to hydrodynamics)
- 8 tests, 5 pure RT and 3 with gas-dynamics
- Paper I (pure radiative transfer, static density fields) completed (Iliev et al. 2006d, MNRAS, 371,1057)
- results with gasdynamics still being collected and studied, to be completed in the next few months (Iliev et al., in prep.).

Cosmological Radiative Transfer Codes Comparison Project 11

(Iliev et al. 2006d, MNRAS, 371,1057)



Conclusions

- Now we can do sufficiently large (100/h Mpc size) radiative transfer simulations of reionization to reliably derive the global reionization history, HII region size distributions, redshifted 21-cm signal, patchy kSZ effect, etc.
- Reionization proceeds inside-out and is strongly self-regulated.
- Small-volume simulations can give very incorrect results for global process and significantly underpredict 21-cm and kSZ signals..
- The kSZ power spectra peak strongly to $l(l+1)C_l/2\pi > 10\ (\mu K)^2$ at l~3-9000.
- The patchy kSZ signal is much stronger than under a homogeneous scenario
- Global 21-cm step is gradual, difficult to observe. Fluctuations should be observable and peak at ~50% ionization. Redshift spectral distortions are important. Late-time PDFs are strongly non-Gaussian.
- Luminous sources at the end of reionization are in high density peaks and surrounded by large clusters of smaller sources, HII regions around them are highly anisotropic. More detailed studies are under way ...
- Radiative transfer codes are reaching maturity, provide fairly reliable results in terms of I-front tracking, less so in temperature and spectral hardening