# Reionization of the Universe

**Paul Shapiro**
**The University of Texas at Austin**

Collaborators in the new work described today include:

**Pierre Ocvirk[3], Dominique Aubert[3], Nicolas Gillet[3], Ilian Iliev[2],
Romain Teyssier[4], Gustavo Yepes[5], Stefan Gottloeber[6],
Junhwan Choi[1], Hyunbae Park[1], Anson D'Aloisio[1], David Sullivan[2],
Yehuda Hoffman[7], Alexander Knebe[5], Timothy Stranex[4]**
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(5) U Madrid (6) AIP Potsdam (7) Hebrew U

*XIth Rencontres Du Vietnam : Cosmology 50 Years After CMB Discovery*,
ICISE – Quy Nhon, August 21, 2015

# Simulating C ic Reionization and Its O ervable Consequences

## Part I: Some Background

**Paul Shapiro**
**The University of Texas at Austin**

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**Ilian Iliev[2], Garrelt Mellema[3], Kyungjin Ahn[4], Yi Mao[1,12], Jun Koda[1,5], Ue-Li Pen[6], Martina Friedrich[3], Kanan Datta[3], Hyunbae Park[1], Eiichiro Komatsu[1,13] Elizabeth Fernandez[7,14], Anson D'Aloisio[1], Hannes Jensen[3], Pierre Ocvirk[8], Dominique Aubert[8], Romain Teyssier[9], Gustavo Yepes[10], Stefan Gottloeber[12], Junhwan Choi[1]**

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# Simulating Cosmic Reionization and Its Observable Consequences

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# Reionization of the Local Universe

**Part II**

**Paul Shapiro**
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Collaborators in the new work described today include:

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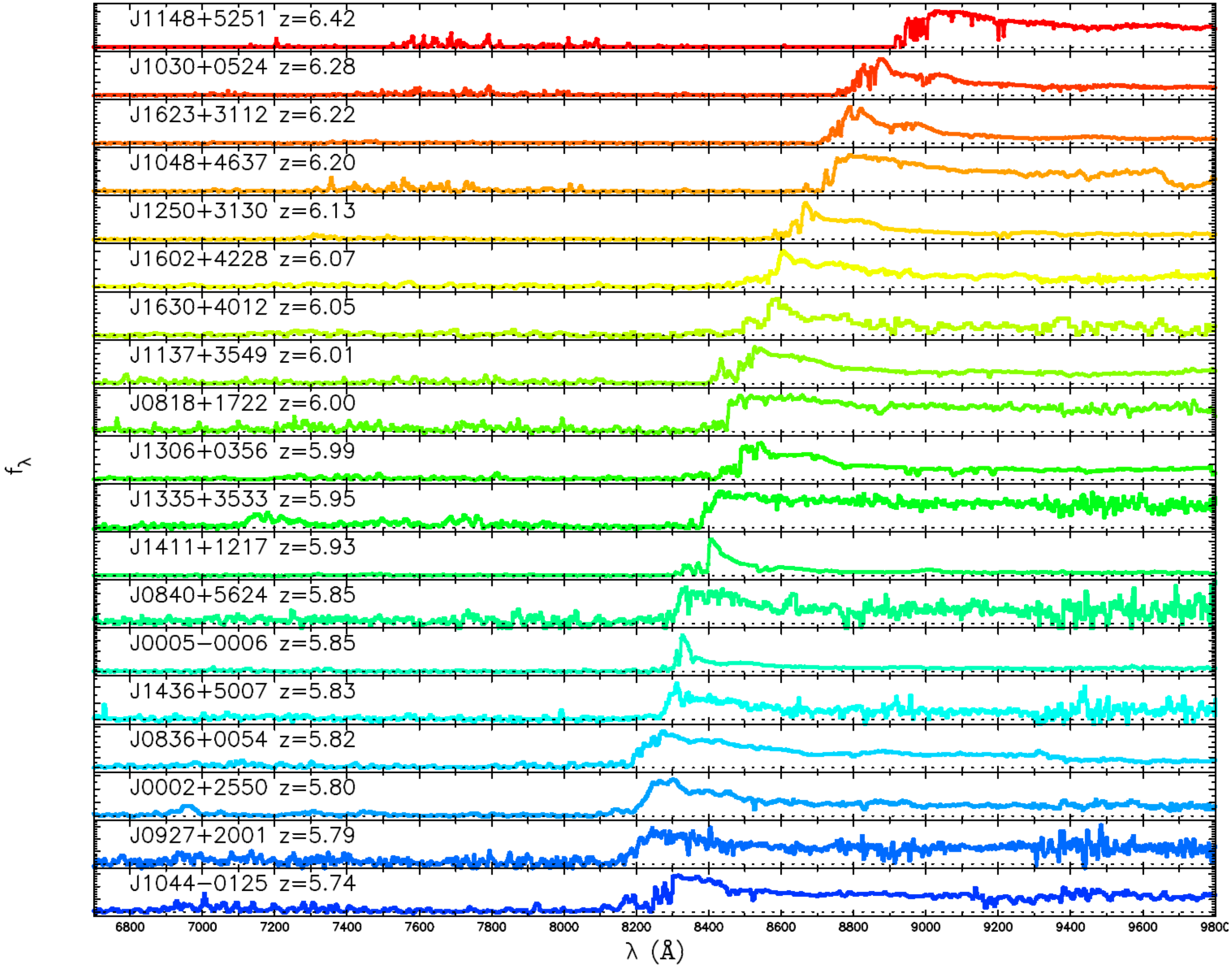
# The Epoch of Reionization

- Absorption spectra of quasars have long shown that the intergalactic medium at redshifts $z < 6$ is highly ionized, with a residual neutral H atom concentration of less than 1 atom in $10^4$ .

  ===> universe experienced an “epoch of reionization” before this.
- Sloan Digital Sky Survey quasars have been observed at $z > 6$ whose absorption spectra show dramatic increase in the H I fraction at this epoch as we look back in time.

  ===> epoch of reionization only just ended at $z \gtrsim 6$.

# SDSS quasars show Lyman α opacity of intergalactic medium rises with increasing redshift at z = 6 ➔ IGM more neutral ➔ reionization just ending?



Fan et al (2005)

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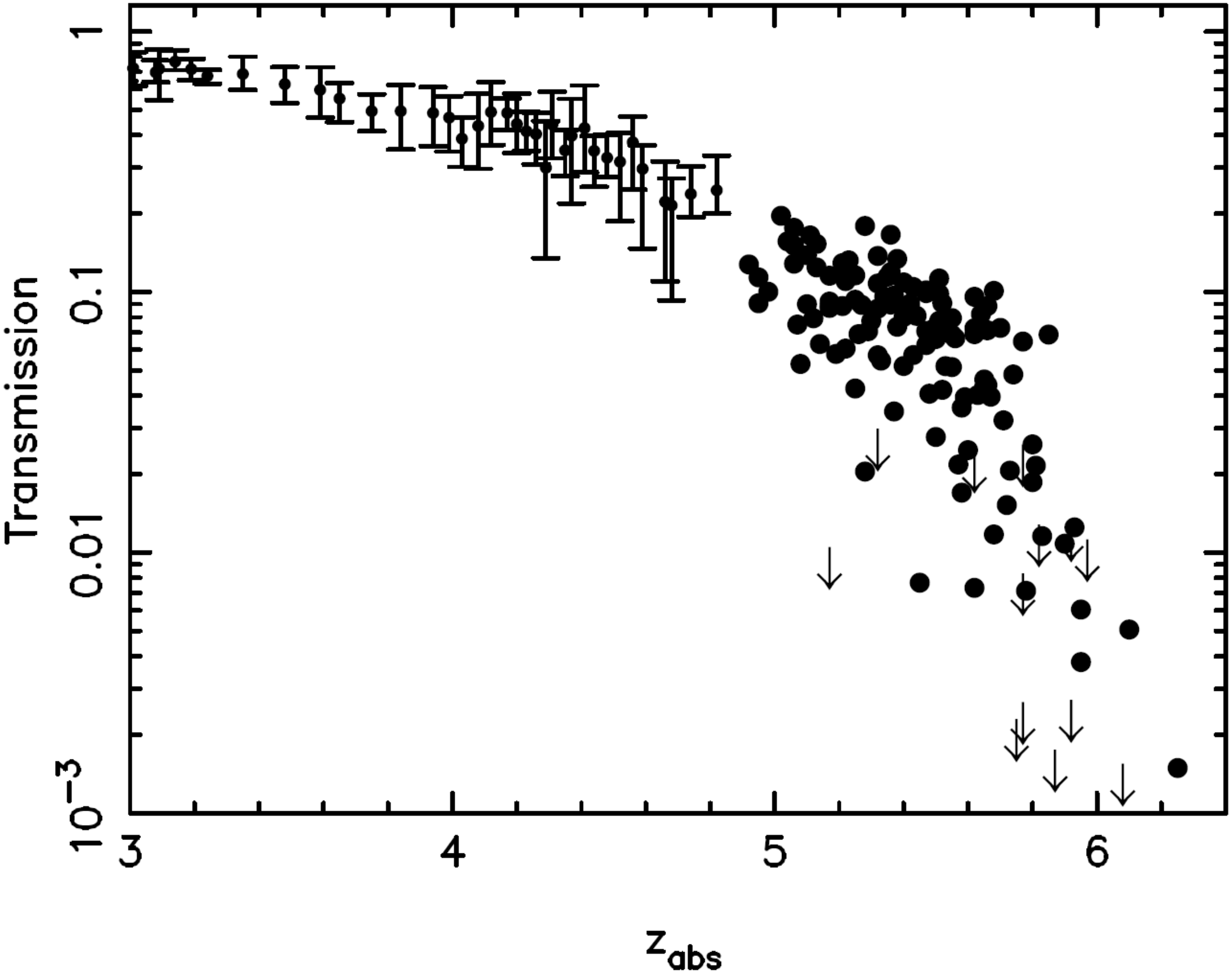
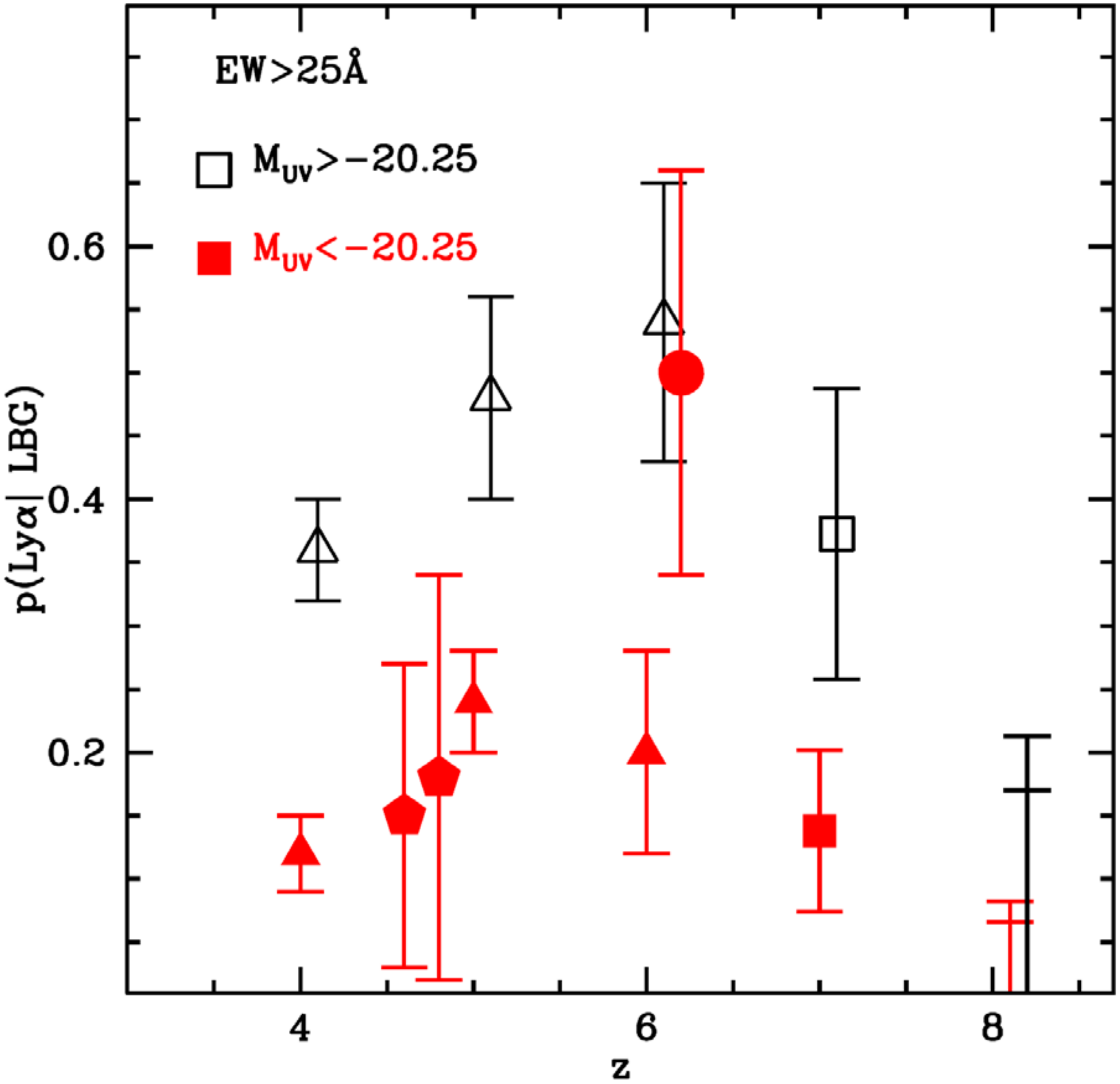


Fan et al (2006)

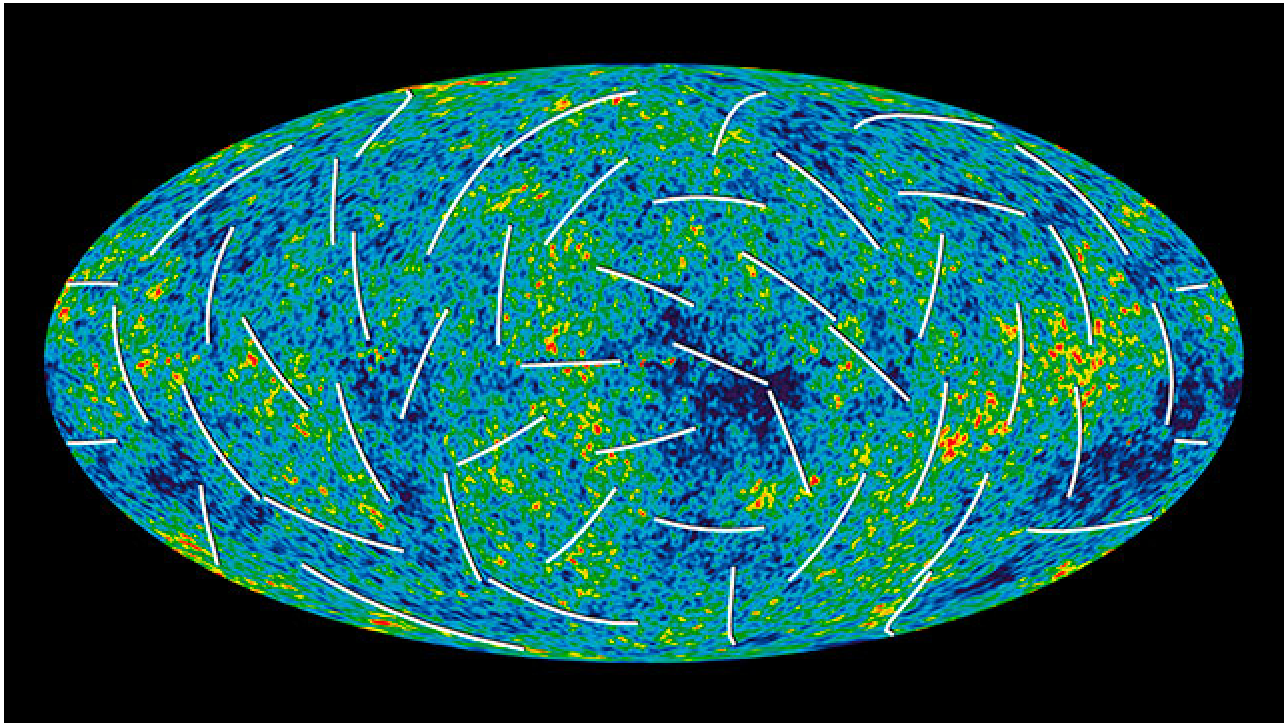
Fraction of Lyman-Break Galaxies (LBGs) which are Lyman α emitters (LAEs) decreases from z = 6 to 8 ➔ Lyman α opacity of intergalactic medium rises with increasing redshift at z = 6 ➔ IGM more neutral ➔ reionization just ending?

**The changing Lya optical depth in the range 6<z<9 from MOSFIRE spectroscopy of Y-dropouts**

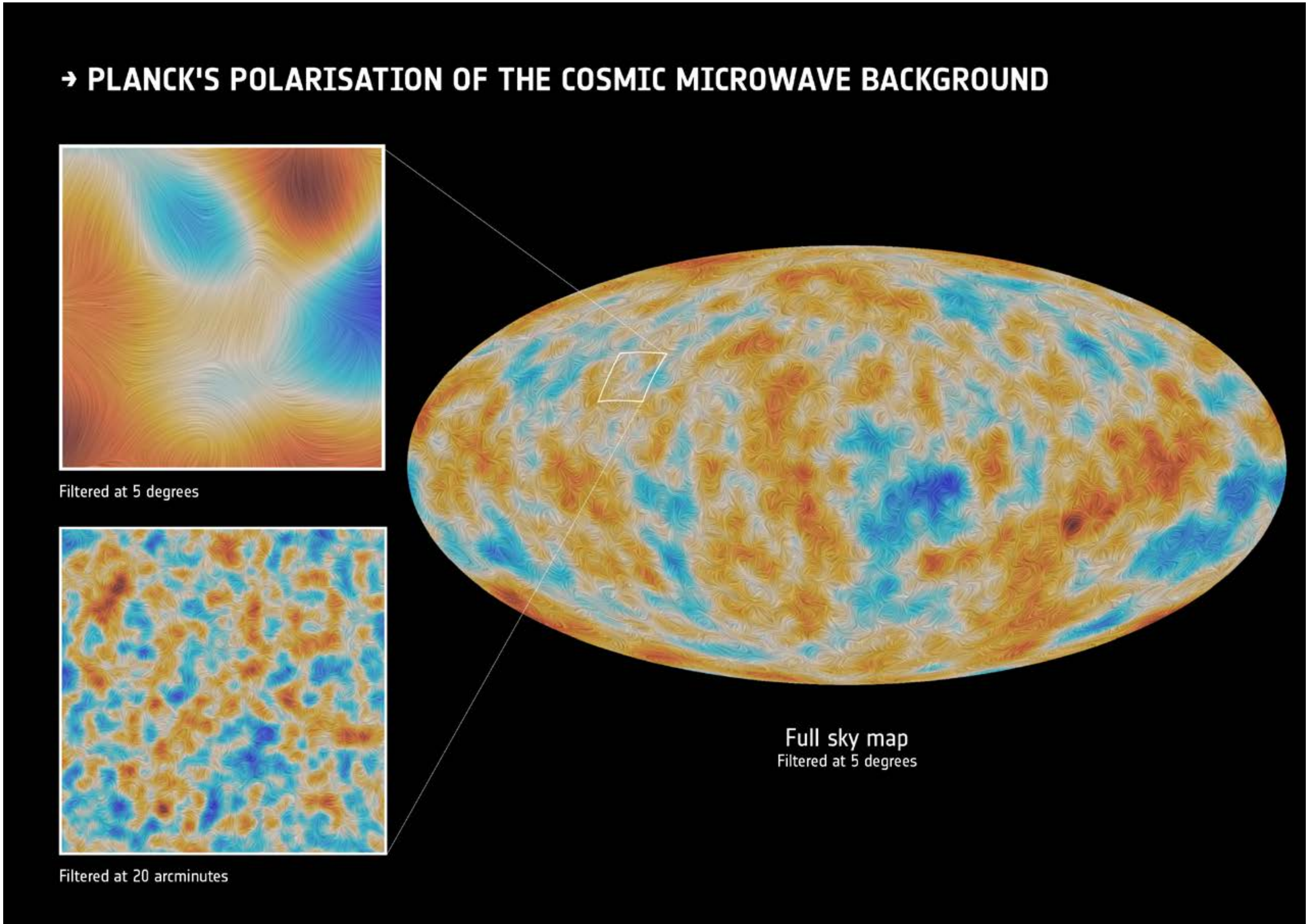


Treu etal.(2013) arXiv:1308.595

***WMAP*** satellite mapped the pattern of polarization of the cosmic microwave background radiation across the sky ←→ light was scattered as it travelled across the universe, by intergalactic electrons



# ***Planck*** satellite mapped the pattern of polarization of the cosmic microwave background radiation across the sky ←→ light was scattered as it travelled across the universe, by intergalactic electrons



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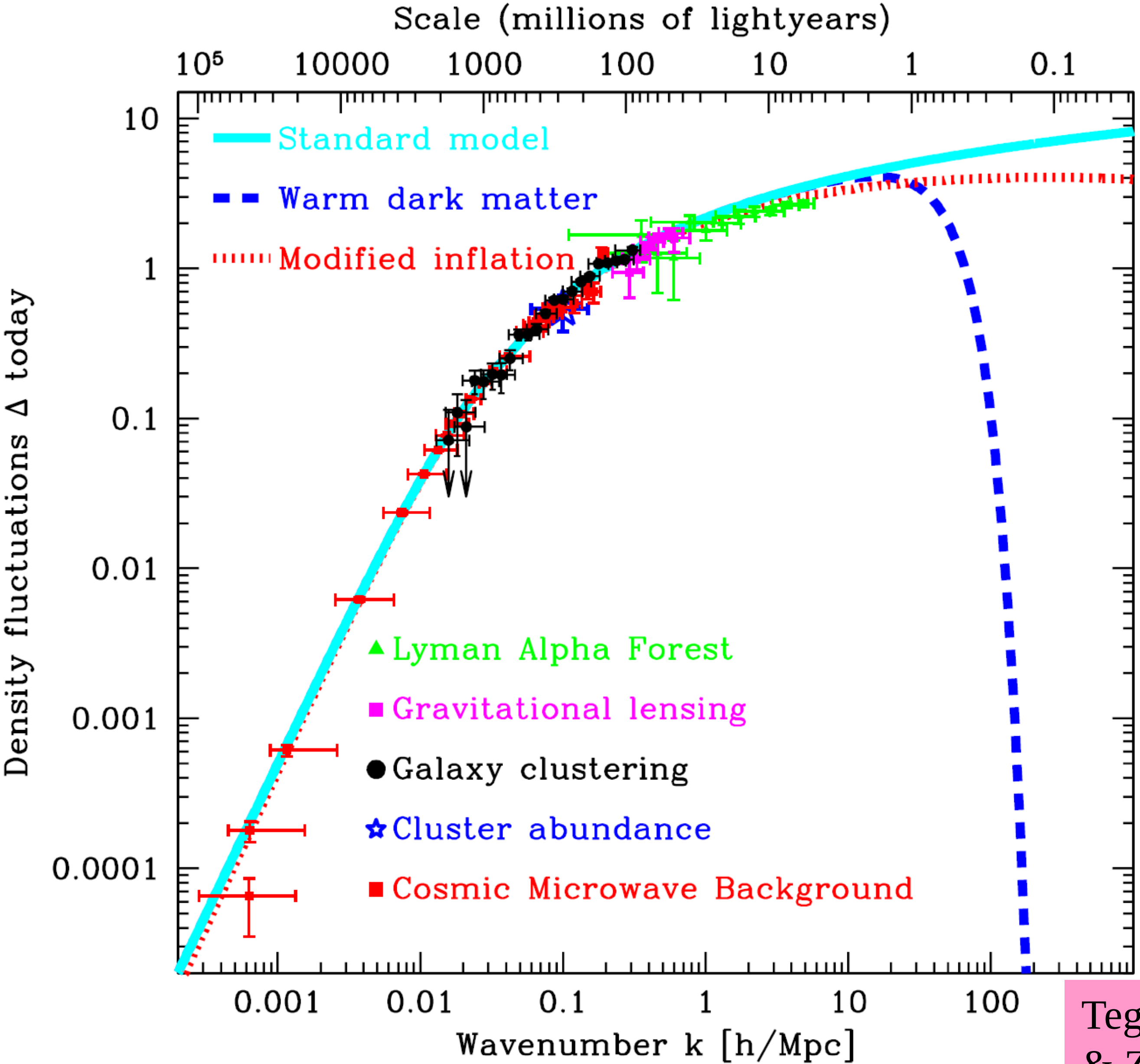
- Sloan Digital Sky Survey quasars have been observed at z > 6 whose absorption spectra show dramatic increase in the H I fraction at this epoch as we look back in time.

  ===> epoch of reionization only just ended at $z \gtrsim 6$ .
- **The cosmic microwave background (CMB ) exhibits polarization which fluctuates on large angular scales; *Planck* finds that almost 7% of the CMB photons were scattered by free electrons in the IGM, but only 4% could have been scattered by the IGM at z < 6.**

  **===> IGM must have been ionized earlier than z = 6 to supply enough electron scattering optical depth**

  **===> reionization already substantial by $z \gtrsim 9$**

# EoR Probes the Primordial Power Spectrum Down to Very Small Scales



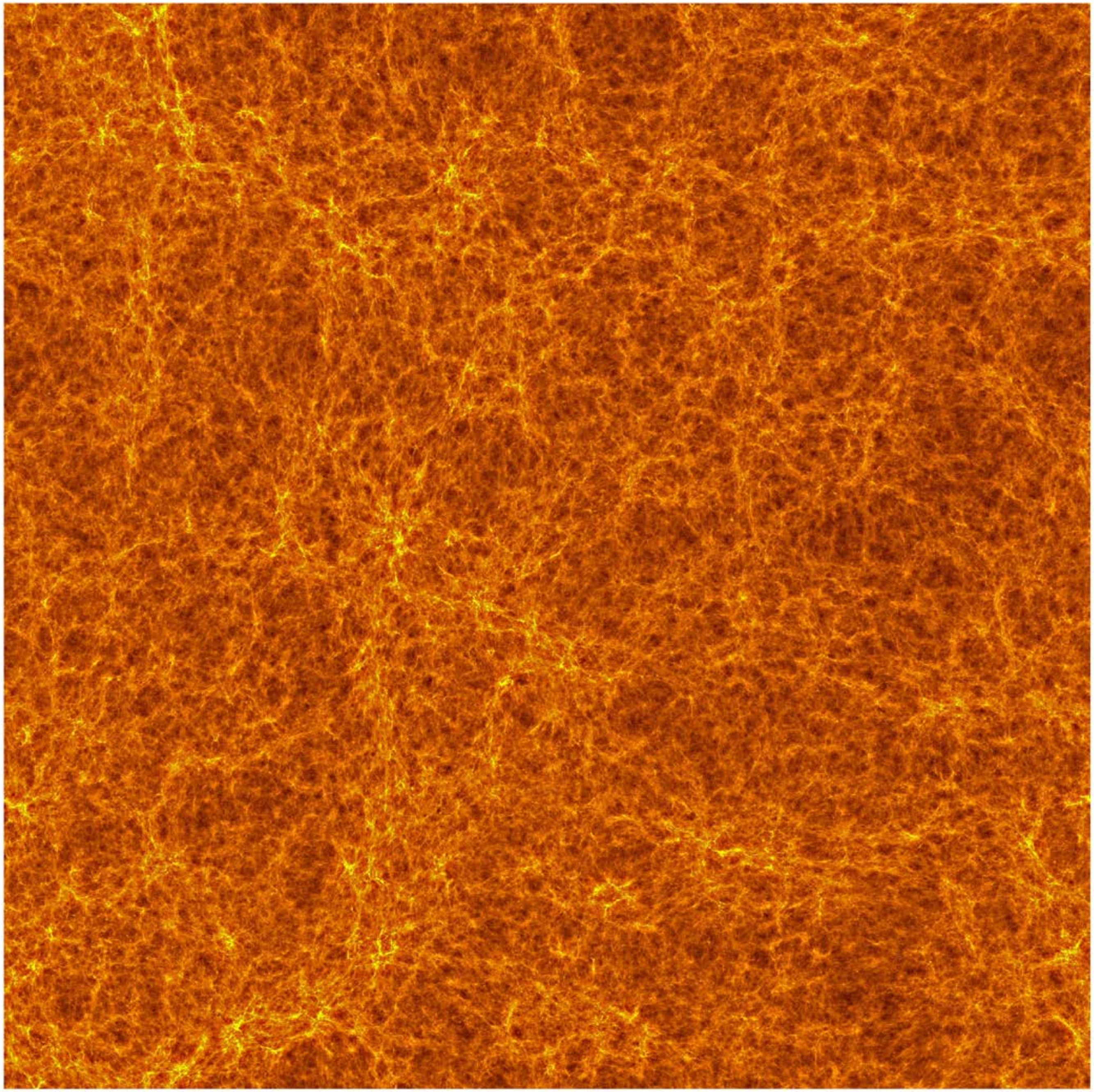
Tegmark
& Zaldarriaga (2008)

# Structure formation in ΛCDM at $z = 10$

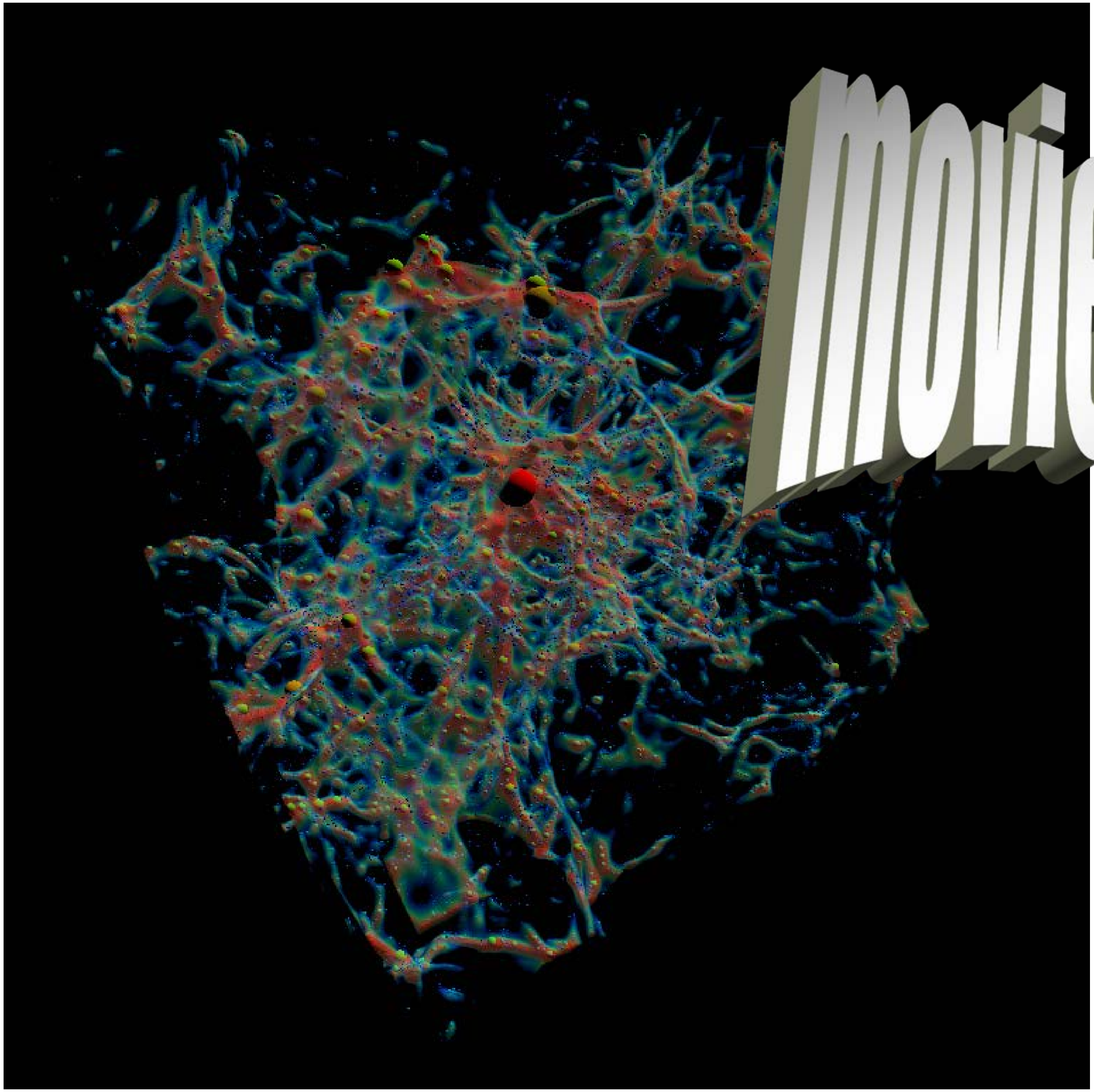
simulation volume
=
$(100\ h^{-1}\mathrm{Mpc})^3$,
comoving

$1624^3$ particles on
$3248^3$ cells

Projection of
cloud-in-cell
densities of 20
Mpc slice



# A Dwarf Galaxy Turns on at z=9



movie slide

# N-body + Radiative Transfer → Reionization simulation

- *N-body simulation* yields the density field and sources of ionizing radiation

  - **New**: 2nd generation N-body code *CUBEP³M*,

    a P³M code, massively paralleled (MPI+Open MP),

    $3072^3$ = 29 billion particles, $6{,}144^3$ cells,

    particle mass = 5 x $10^6$ $M_{solar}$ (163 Mpc box),

    \+

    $5488^3$ = 165 billion particles, $10{,}976^3$ cells,

    particle mass = 5 x $10^3$ $M_{solar}$ (30 Mpc box),

    \+

    particle mass = 5 x $10^7$ $M_{solar}$ (607 Mpc box),

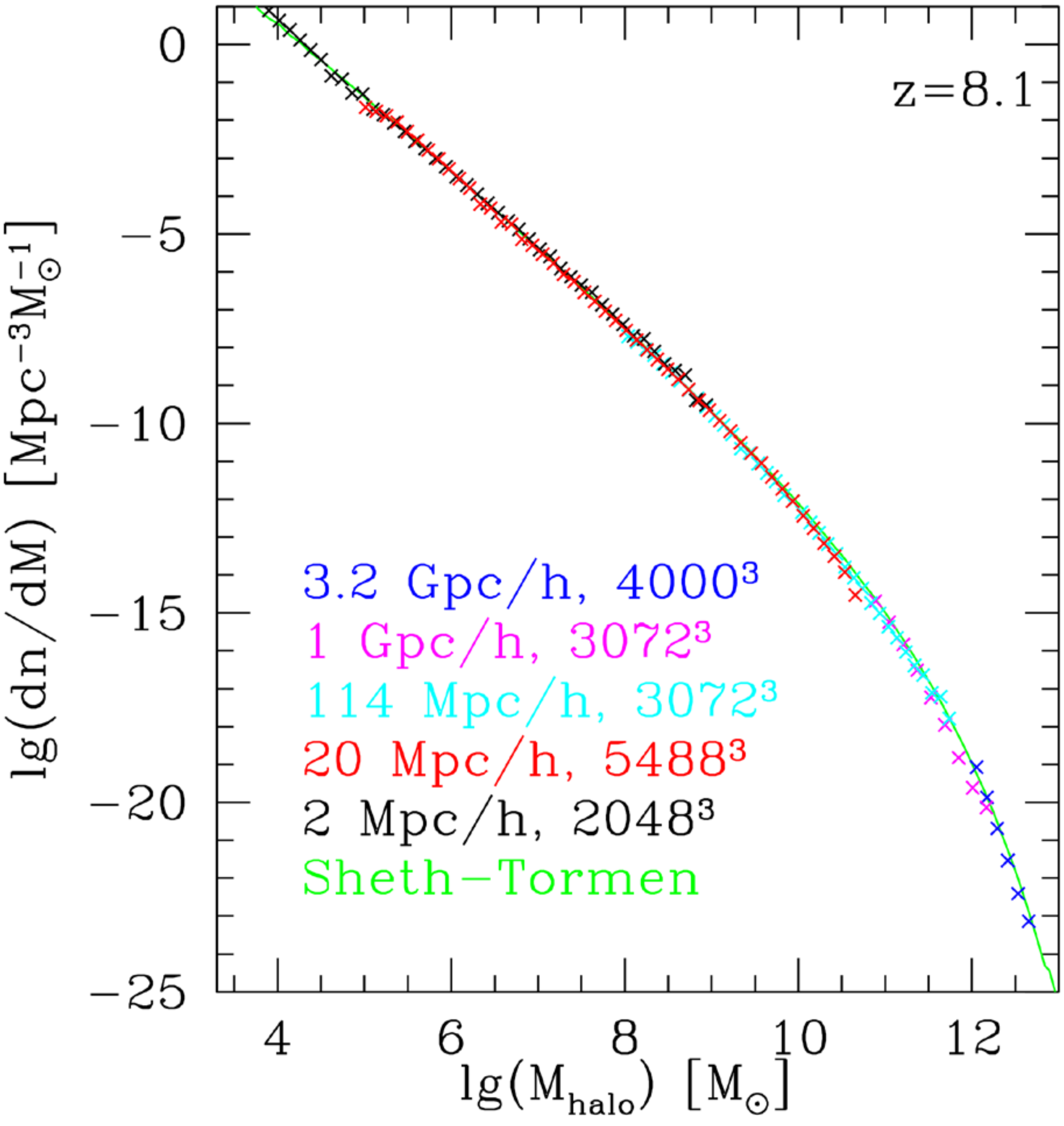
  - Halo finder “on-the-fly” yields location, mass, other properties of all galaxies,

    M $\geq 10^5$ $M_{solar}$ (30 Mpc box), $10^8$ $M_{solar}$ (163 Mpc box),

    $10^9$ $M_{solar}$ (607 Mpc box)

- **Halo mass function** now simulated for LCDM

  over full mass range from IGM Jeans mass before EOR to the largest halos that form during the EOR

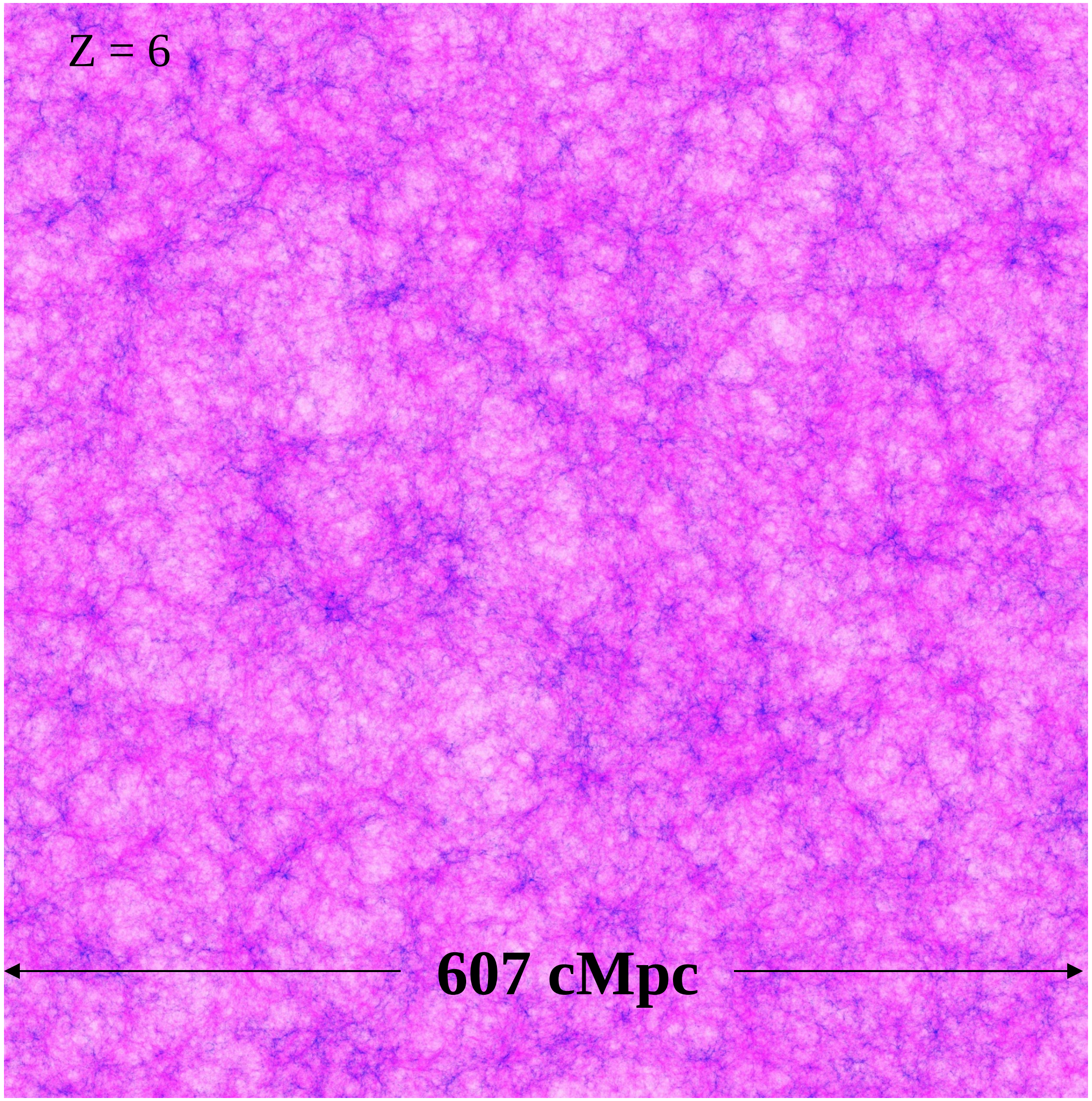


# Largest Volume N-body Simulation for Reionization : (607 cMpc)$^3$

- **CUBEP$^3$M**
  **5488$^3$ = 165 billion particles**
  **10, 976$^3$ cells**

- **Resolves all halos with**
  **$M \geq 10^9 M_{sun}$**
- **First halos form at**
  **z = 26**
- **4 x 10$^7$ halos by**
  **z = 8**
- **~ 2 x 10$^8$ halos by**
  **z = 2.5**

- IGM density = violet
  halos = blue



Box size ~ volume of the LOFAR EOR 21cm background survey

# N-body + Radiative Transfer ➔ Reionization simulation

- *Radiative transfer* simulations evolve the radiation field and nonequilibrium ionization state of the gas

  \- New, fast, efficient *$C^2$-Ray* code (*Conservative, Causal Ray-Tracing*) (Mellema, Iliev, Alvarez, & Shapiro 2006, *New Astronomy*, 11, 374) uses short-characteristics to propagate radiation throughout the evolving gas density field provided by the N-body results, on coarser grid of ~ $(256)^3$ to $(512)^3$ cells, for different resolution runs, from each and every galaxy halo source in the box.

e.g. $N_{halo} \sim 4 \times 10^5$ by $z \sim 8$ (WMAP1) ( > $2 \times 10^9\ M_{sun}$)

$\sim 3 \times 10^5$ by $z \sim 6$ (WMAP3) ( > $2 \times 10^9\ M_{sun}$)

$\sim 10^7$ by $z \sim 8$ (WMAP5) ( > $10^8\ M_{sun}$)

for simulation volumes ~ $(100\ h^{-1}\ \mathrm{Mpc})^3$

# Every galaxy in the simulation volume emits ionizing radiation

- We assume a constant mass-to-light ratio for simplicity:

$f_\gamma$= # ionizing photons released by each galaxy per halo baryon

➔ $f_\gamma = f_* \ f_{esc} \ N_i$ ,

where

$f_*$ = star-forming fraction of halo baryons,

$f_{esc}$ = ionizing photon escape fraction,

$N_i$ = # ionizing photons emitted per stellar baryon over stellar lifetime

e.g.

$N_i$ = 50,000 (top-heavy IMF), $f_*$ = 0.2, $f_{esc}$ = 0.2 ➔ $f_\gamma = 2000$

or

$N_i$ = 4,000 (Salpeter IMF), $f_*$ = 0.1, $f_{esc}$ = 0.1 ➔ $f_\gamma = 40$

- This yields source luminosity: $dN_\gamma/dt = f_\gamma M_{bary} /(\mu m_H \Delta t_*)$ ,

$\Delta t_*$ = source lifetime (e.g. $2 \times 10^7$ yrs),

$M_{bary}$ = halo baryonic mass = $M_{halo} * (\Omega_{bary}/ \Omega_m)$

➔halo star formation rate: $SFR = (f_\gamma / \Delta t_*)(M_{bary} / f_{esc} \ N_i )$

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→halo star formation rate: $SFR = (f_\gamma / \Delta t_*)(M_{bary} / f_{esc} \; N_i )$

$\mathbf{SFR \cong 1.7\ (f_\gamma/40)\ (0.1/f_{esc})\ (4000/N_i)\ (10\ Myr/\ \Delta t_*\ )\ (M_{halo}/10^9\ M_{solar})\quad M_{solar}/\ yr}$

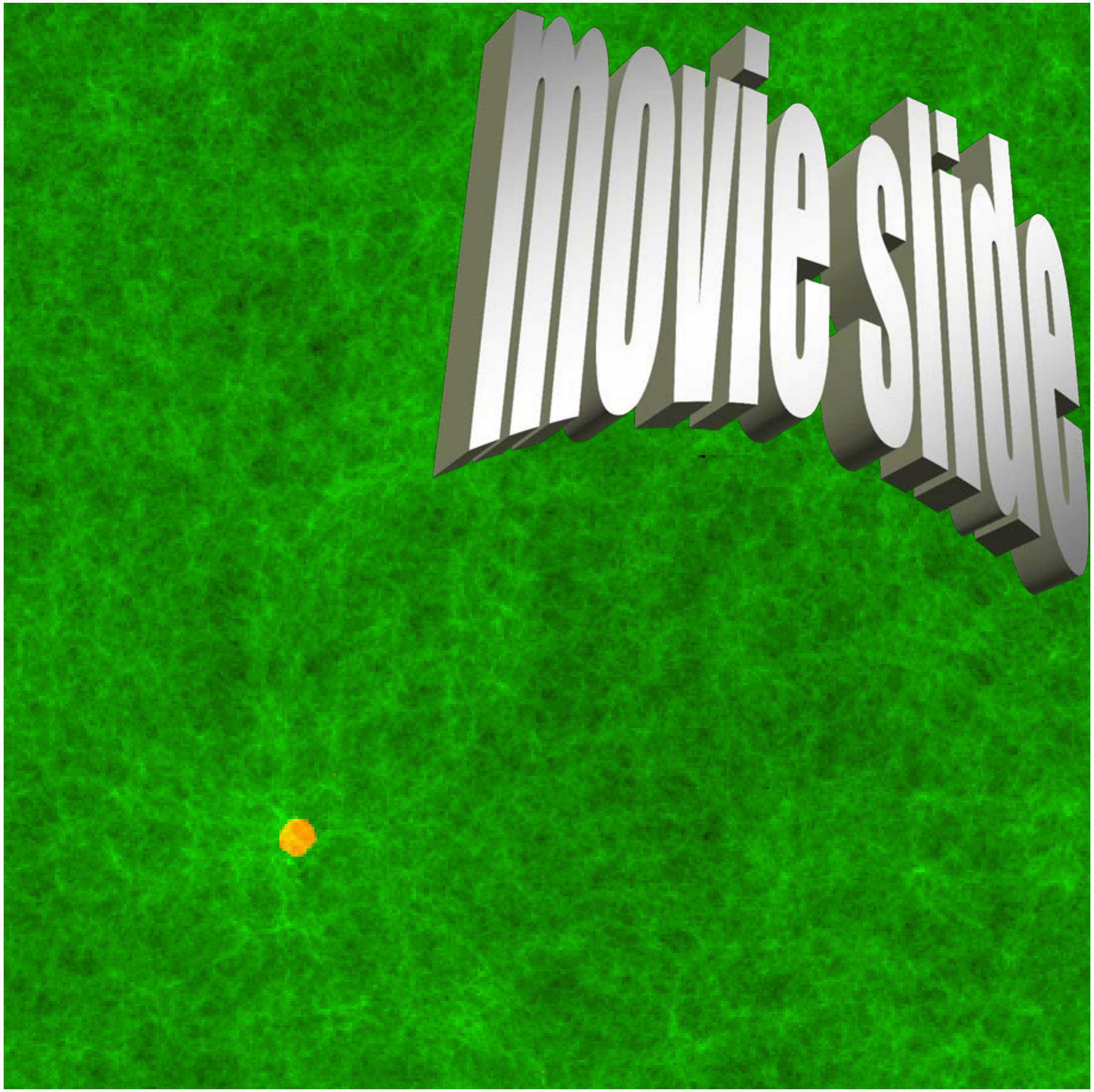
e.g. $f_\gamma = 40$, $f_{esc}$ = 0.1, $f_*$ = 0.1, $\Delta t_* = 2 \times 10^7$ yrs →

$SFR \cong (0.8\ M_{solar}/yr) * (M_{halo}/10^9\ M_{solar})$

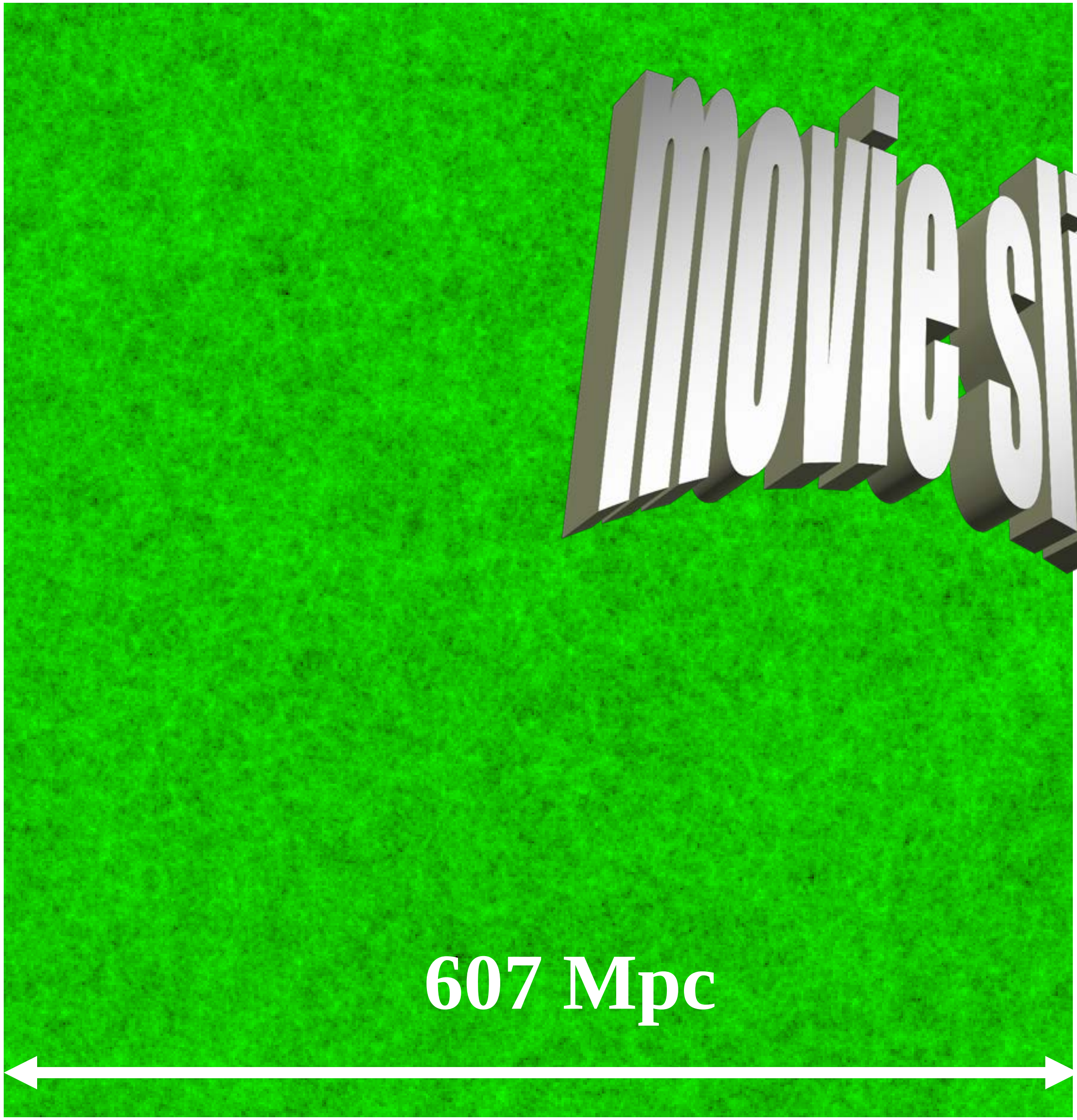
# Self-Regulated Reionization

Iliev, Mellema, Shapiro, & Pen (2007), MNRAS, 376, 534; (astro-ph/0607517)

- Jeans-mass filtering ➔ low-mass source halos ($M < 10^9\ M_{solar}$) cannot form inside H II regions ;
- 35/h Mpc box, $406^3$ radiative transfer simulation, WMAP3, $f_\gamma = 250$;
- resolved all halos with $M > 10^8\ M_{solar}$ (i.e. all atomically-cooling halos), (blue dots = source cells);
- Evolution: $z=21$ to $z_{ov} = 7.5$.



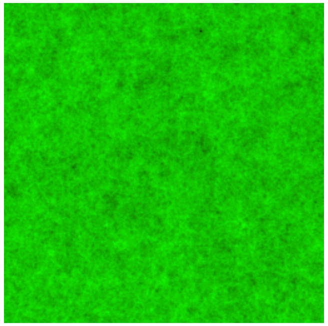
# Large-scale, self-regulated reionization by atomic-cooling halos



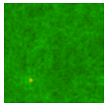
**movie slide**

Three generations of simulation

**163 Mpc**



**50 Mpc**



- white4.wmv

Movie Slide

Q: Are there observable consequences of reionization we can predict which will allow us to determine which of these sources contribute most significantly to reionization?

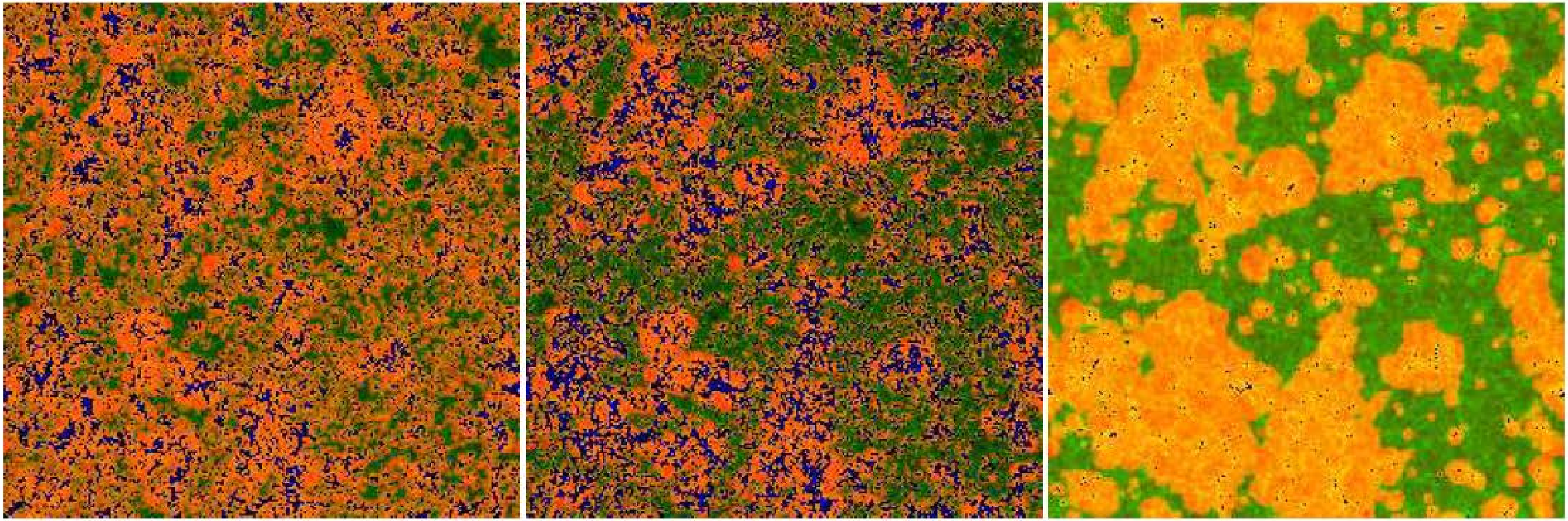
A : Radiation backgrounds from the EoR, including:

1. 21cm
2. Near-IR
3. CMB (polarization & kinetic Sunyaev-Zel'dovich)

# Can 21-cm Observations Discriminate Between High-Mass and Low-Mass Galaxies as Reionization Sources?

Iliev, Mellema, Shapiro, Pen, Mao, Koda, & Ahn 2012, MNRAS, 423, 2222 (arXiv: 1107.4772)

163 Mpc boxes at the 50% ionized epoch



High efficiency = early reionization

Low efficiency = late reionization

High efficiency = early reionization

HMACHs + LMACHs

HMACHs only

**Low-Mass Atomic Cooling Halos, or *LMACHs***

**→ $10^8 < M < 10^9\ M_{solar}$**

**(suppressed inside H II regions by photoheating)**

**High-Mass Atomic Cooling Halos, or *HMACHs***

**→ $M > 10^9\ M_{solar}$**

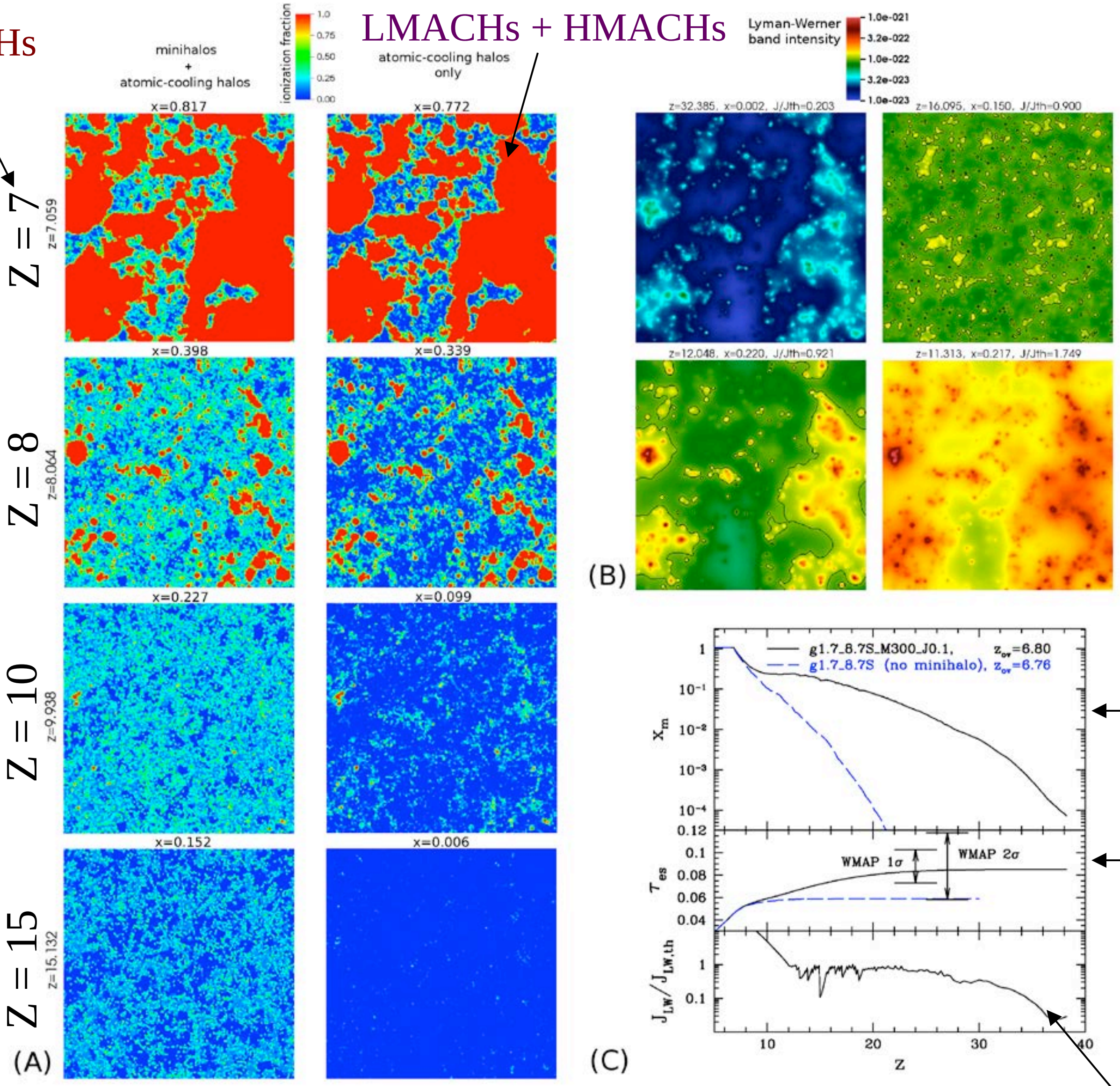
# Effects of the First Stars and Minihalos on Reionization

## Ahn, Iliev, Shapiro, Mellema, Koda, and Mao (2012) ApJL, 756, L16

Minihalos + LMACHs + HMACHs

LMACHs + HMACHs

- 163 Mpc box, with and without minihalo sources
- Minihalos suppressed in H II regions and when LW intensity exceeds $J_{LW,th}$



Lyman-Werner Background Intensity Field at z = 32, 16, 12, 11 (with minihalos)

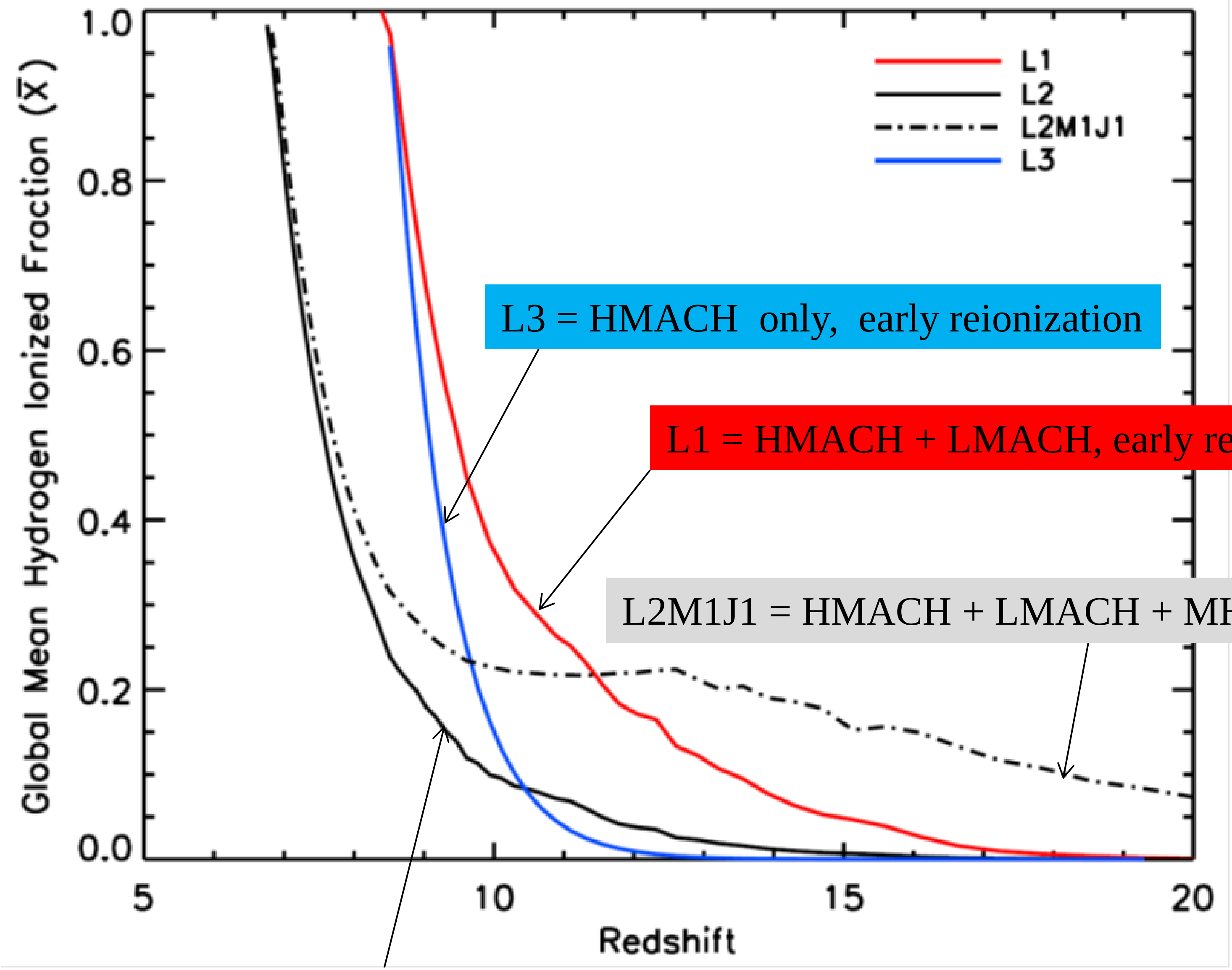
Global ionization history

Electron Scattering Optical depth

Mean Lyman-Werner Intensity

Ionized Fraction Field of IGM

# Four reionization simulation cases for comparison

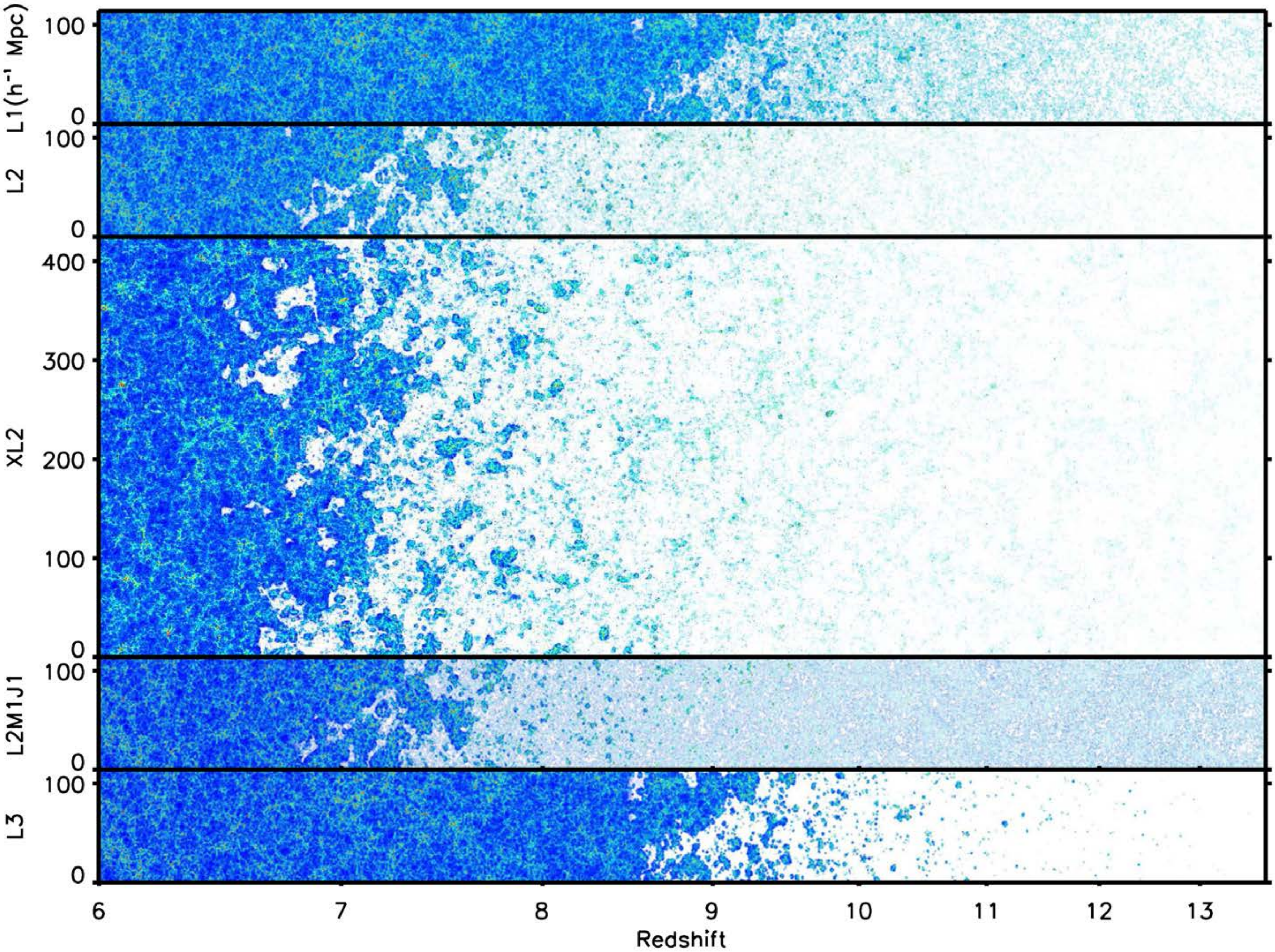


L3 = HMACH only, early reionization

L1 = HMACH + LMACH, early reionization

L2M1J1 = HMACH + LMACH + MHs, late reionization

L2 = HMACH + LMACH, late reionization

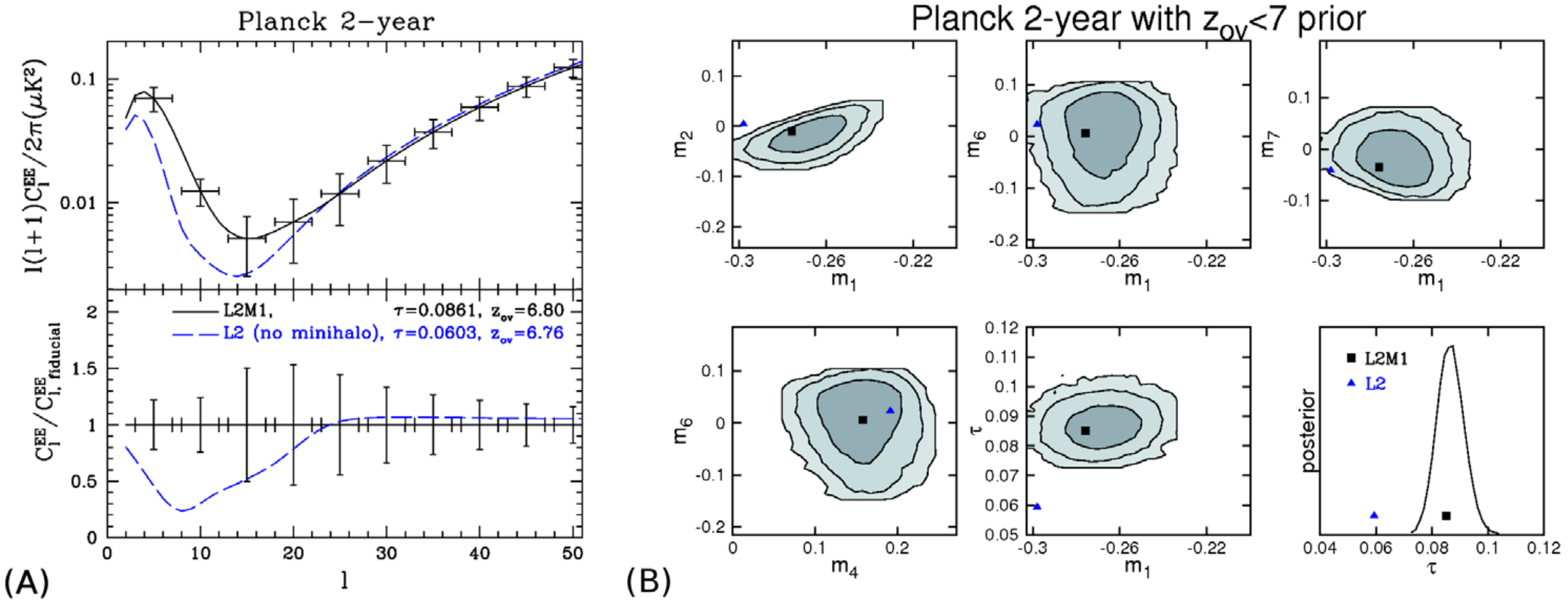

L1 (h⁻¹ Mpc)
100
0
L2
100
0
XL2
400
300
200
100
0
L2M1J1
100
0
L3
100
0
6
7
8
9
10
11
12
13
Redshift

# CMB polarization fluctuations at large angular scales may probe the effects of the first stars and minihalos on reionization

**Ahn, Iliev, Shapiro, Mellema, Koda, and Mao (2012) ApJL, 756, L16**

**Prediction:**

- With minihalo sources, reionization began much earlier and was greatly extended, which boosts the intergalactic electron-scattering optical depth and large-angle polarization fluctuations of the CMB significantly.
- If reionization ended as late as z ~ 7, as suggested by other observations, *Planck* will thereby see the signature of the first stars at high redshift, currently undetectable by any other probe



# The Kinetic Sunyaev-Zel’dovich Effect from Patchy Reionization as a Cosmological Probe

**Park, Shapiro, Komatsu, Iliev, Ahn, Mellema (2013), ApJ, 769, 93**

- kSZ effect is the CMB temperature anisotropy induced by electron scattering by free electrons moving along the line-of-sight:

$$\frac{\Delta T}{T_{\rm CMB}} = \int d\eta e^{-\tau_{\rm es}(\eta)} a n_e \sigma_T \mathbf{n} \cdot \mathbf{v},$$

where η is conformal time,

$$\eta = \int_0^t dt' / a(t')$$

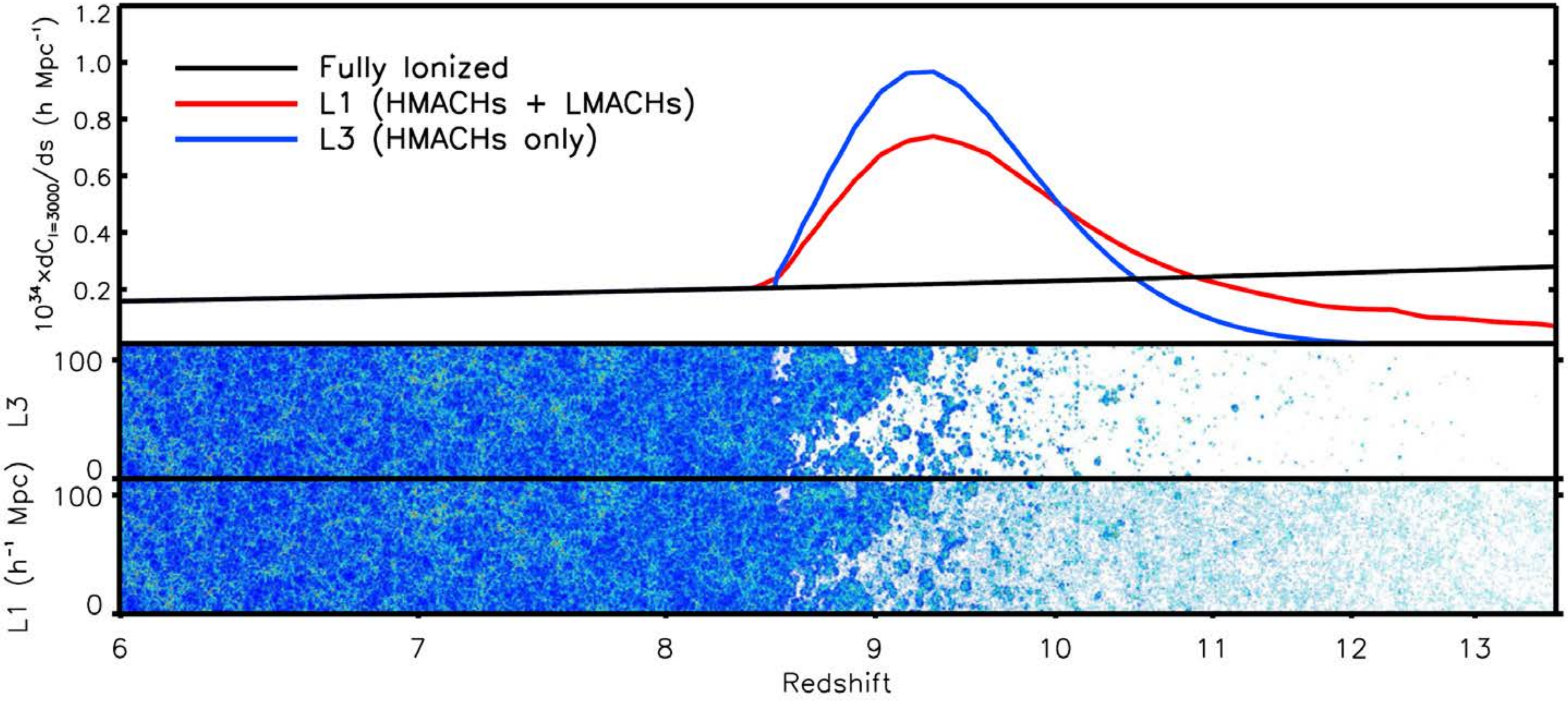
# Contributions to kSZ from different redshifts: post-reionization + patchy reionization ➔ different source models distinguishable?

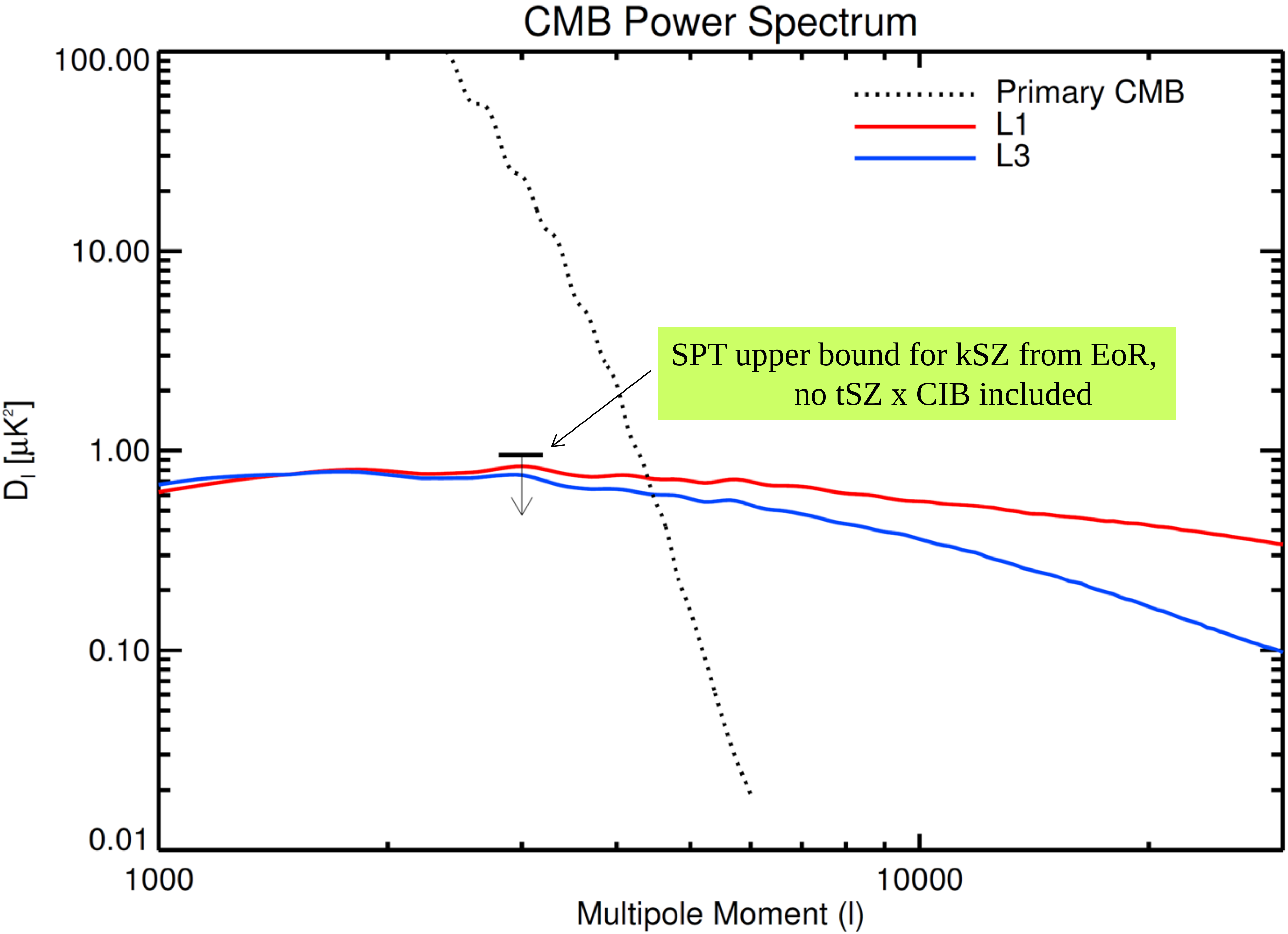
Park, Shapiro, Komatsu, Iliev, Mellema, Mao, Ahn (2013), ApJ, 769, 93

Global Reionization History and kSZ Signal

| Label | $z_{50\%}$ | $z_{99\%} - z_{20\%}$ | $z_{75\%} - z_{25\%}$ | $z_{\rm ov}$ | $D_{l=3000}^{\rm kSZ, z>5.5}$ | $D_{l=3000}^{\rm kSZ, z<z_{ov}}$ [a] | $D_{l=3000}^{\rm kSZ, z>z_{ov}}$ | $D_{l=3000}^{\rm kSZ, total}$ |
|---|---|---|---|---|---|---|---|---|
| L1 | 9.5 | 3.2 | 2.2 | 8.3 | 1.27 | 1.94 | 0.83 | 2.77 |
| L2 | 7.6 | 2.1 | 1.4 | 6.8 | 0.87 | 1.69 | 0.66 | 2.35 |
| L2M1J1 | 7.7 | 6.5 | 2.1 | 6.8 | 0.90 | 1.69 | 0.69 | 2.38 |
| L3 | 9.1 | 1.3 | 0.9 | 8.4 | 1.20 | 1.96 | 0.75 | 2.71 |

**Note.** [a] From the scaling relation of Shaw et al. (2012).





SPT upper bound for kSZ from EoR,
no tSZ x CIB included

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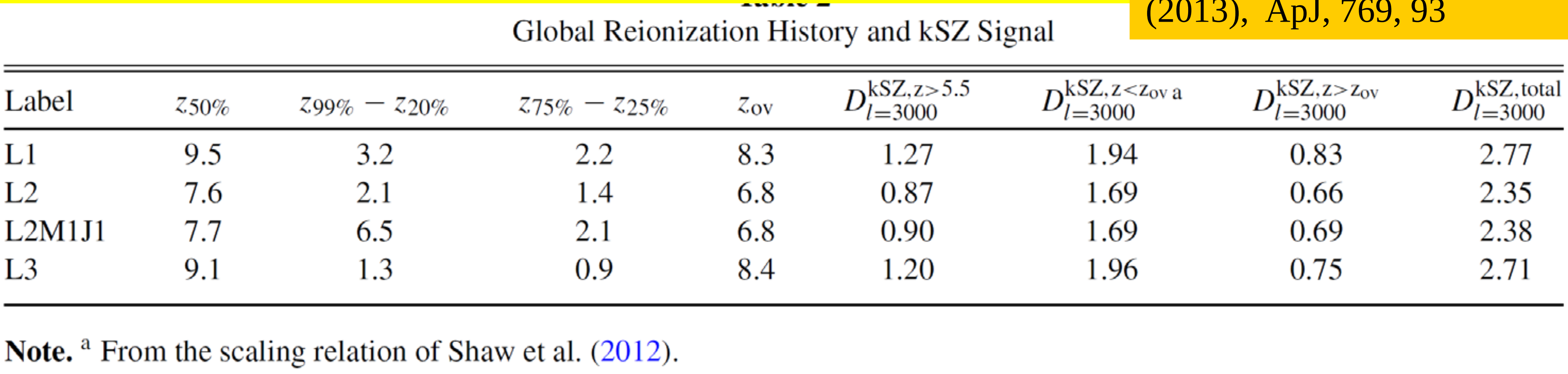
Park, Shapiro, Komatsu, Iliev, Mellema, Mao, Ahn (2013), ApJ, 769, 93



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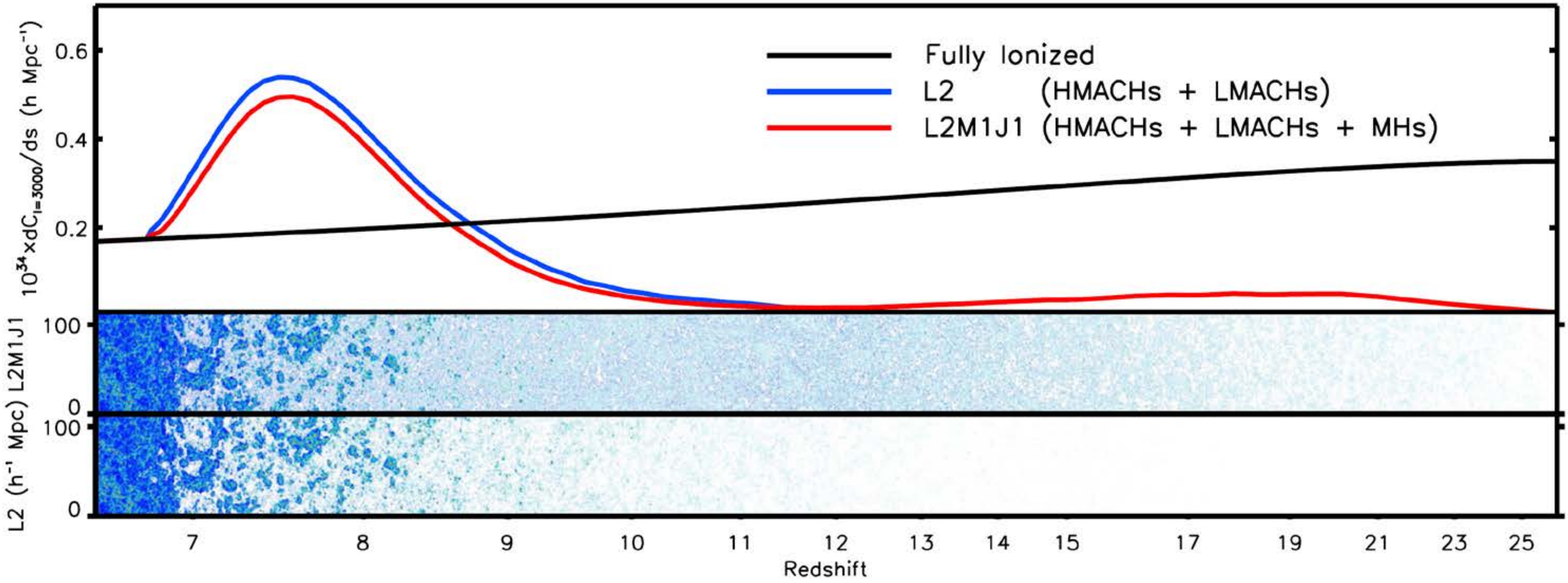
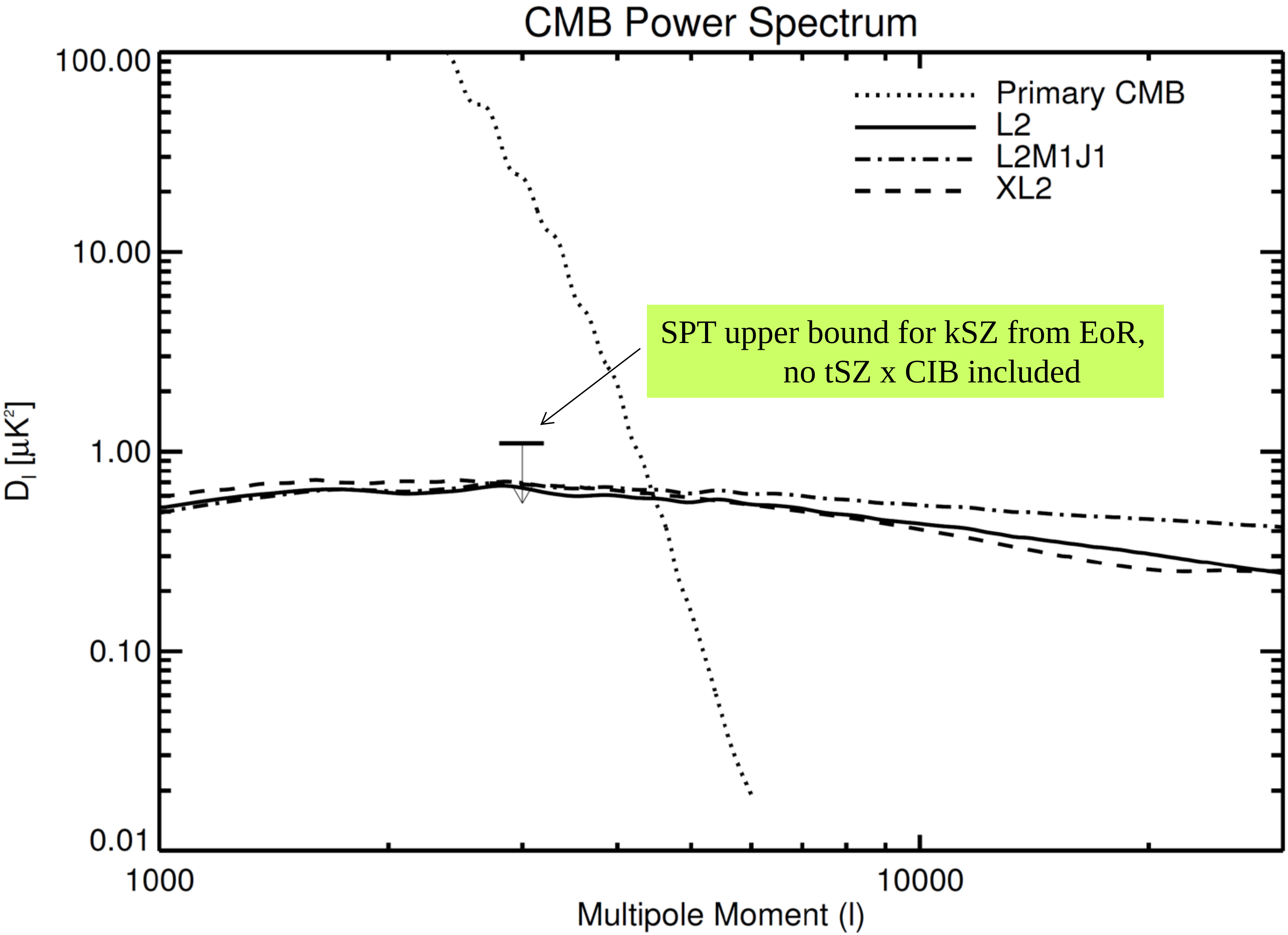


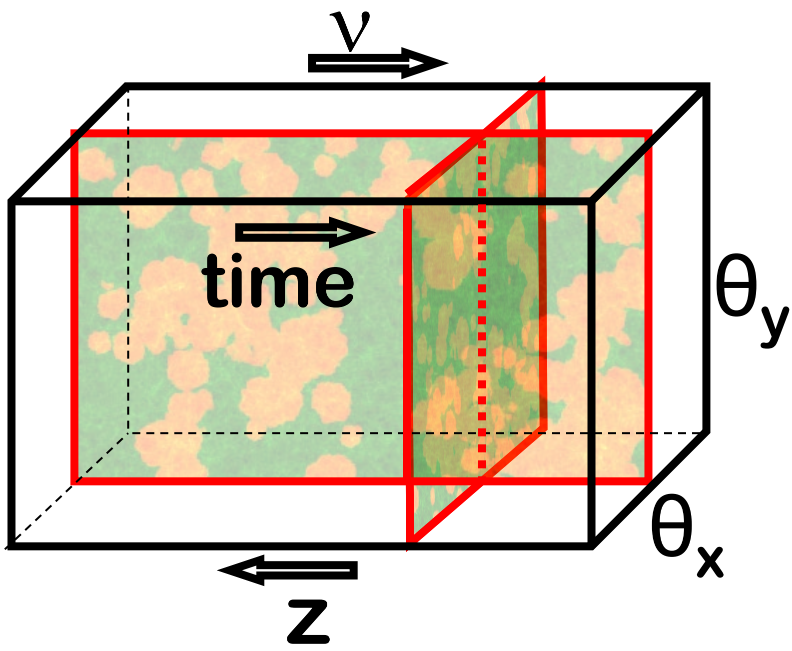


SPT upper bound for kSZ from EoR,
no tSZ x CIB included

# The Redshifted 21cm Signal From the EoR

- The measured radio signal is the differential brightness temperature
- $\delta T_b = T_b - T_{CMB}$: $\delta T_b = 28.74\, x_{\rm HI}(1+\delta)\left(\frac{1+z}{10}\right)^{1/2}\left[1-\frac{T_{\rm CMB}(z)}{T_s}\right]\left[1+\left(\frac{1+z}{H(z)}\right)\frac{dv_\parallel}{dr_\parallel}\right]^{-1}$ mK

  (for WMAP7 cosmological parameters).
- 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 a spectral *line*: carries spatial, temporal, and velocity information.



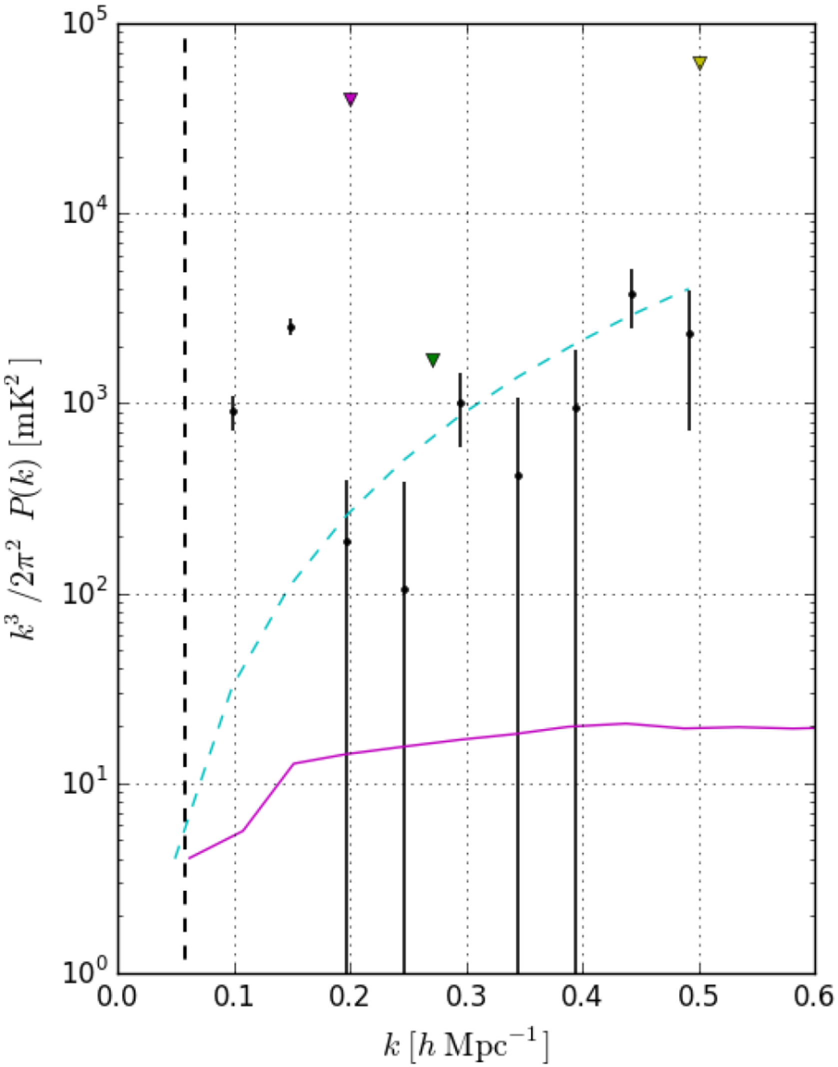
The image cube: images stacked in frequency space

$$\nu = \frac{\nu_0}{1+z_{\rm obs}} \qquad \text{and} \qquad z_{\rm obs} = (1+z)(1+\frac{v_\parallel}{c}) - 1$$

# New limit on 21cm power spectrum at z = 8.4 from the Paper-64 EoR Experiment

Ali et al. (2015) arXiv:1502.06016

135 days of data ➔



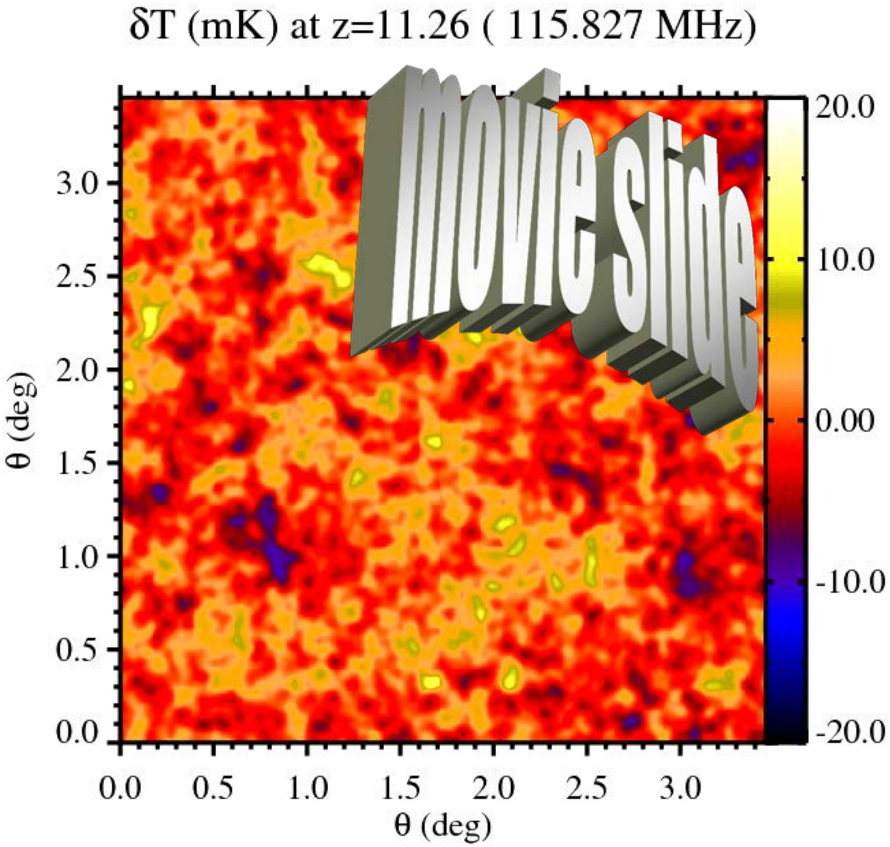
Consistent with IGM at z = 8.4 either fully ionized or else heated where still neutral (e.g. as if by X-rays) so $T_{spin} >> T_{CMB}$

New 2σ upper limit $(22\ \mathrm{mK})^2$ for $k = 0.15\ h\ \mathrm{Mpc}^{-1}$ To $k = 0.5\ h\ \mathrm{Mpc}^{-1}$

# Sky Maps of 21cm Background Brightness Temperature Fluctuations During Epoch of Reionization : Travel through Time

**Iliev, Mellema, Ahn, Shapiro, Mao & Pen 2014, *MNRAS,* 439, 725 (arXiv:1310.7463)**

- Reionization has a complex geometry of growing and overlapping HII regions.
- Here illustrated evolving redshifted 21cm signal:
  - High density neutral regions are yellow
  - Ionized regions are **blue/black**.
- LOFAR-like beam: 3' resolution & average signal is zero.



607 cMpc box

# Reionization of the Universe

**Paul Shapiro**
**The University of Texas at Austin**

Collaborators in the new work described today include:

**Pierre Ocvirk[3], Dominique Aubert[3], Nicolas Gillet[3], Ilian Iliev[2], Romain Teyssier[4], Gustavo Yepes[5], Stefan Gottloeber[6], Junhwan Choi[1], Hyunbae Park[1], Anson D'Aloisio[1], David Sullivan[2], Yehuda Hoffman[7], Alexander Knebe[5], Timothy Stranex[4]**

(1)U Texas at Austin (2)U Sussex (3)U Strasbourg (4) U Zurich
(5) U Madrid (6) AIP Potsdam (7) Hebrew U

*XIth Rencontres Du Vietnam : Cosmology 50 Years After CMB Discovery*,
ICISE – Quy Nhon, August 21, 2015

# Reionization of the Local Universe

**Part II**

**Paul Shapiro**
**The University of Texas at Austin**

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*XIth Rencontres Du Vietnam : Cosmology 50 Years After CMB Discovery*,
ICISE – Quy Nhon, August 21, 2015

# Reionization of the Local Universe: Witnessing our Own Cosmic Dawn

**Shapiro, Ocvirk, Aubert, Iliev, Teyssier, Gillet, Yepes, Gottloeber, Choi, Park, D'Aloisio, Sullivan +**

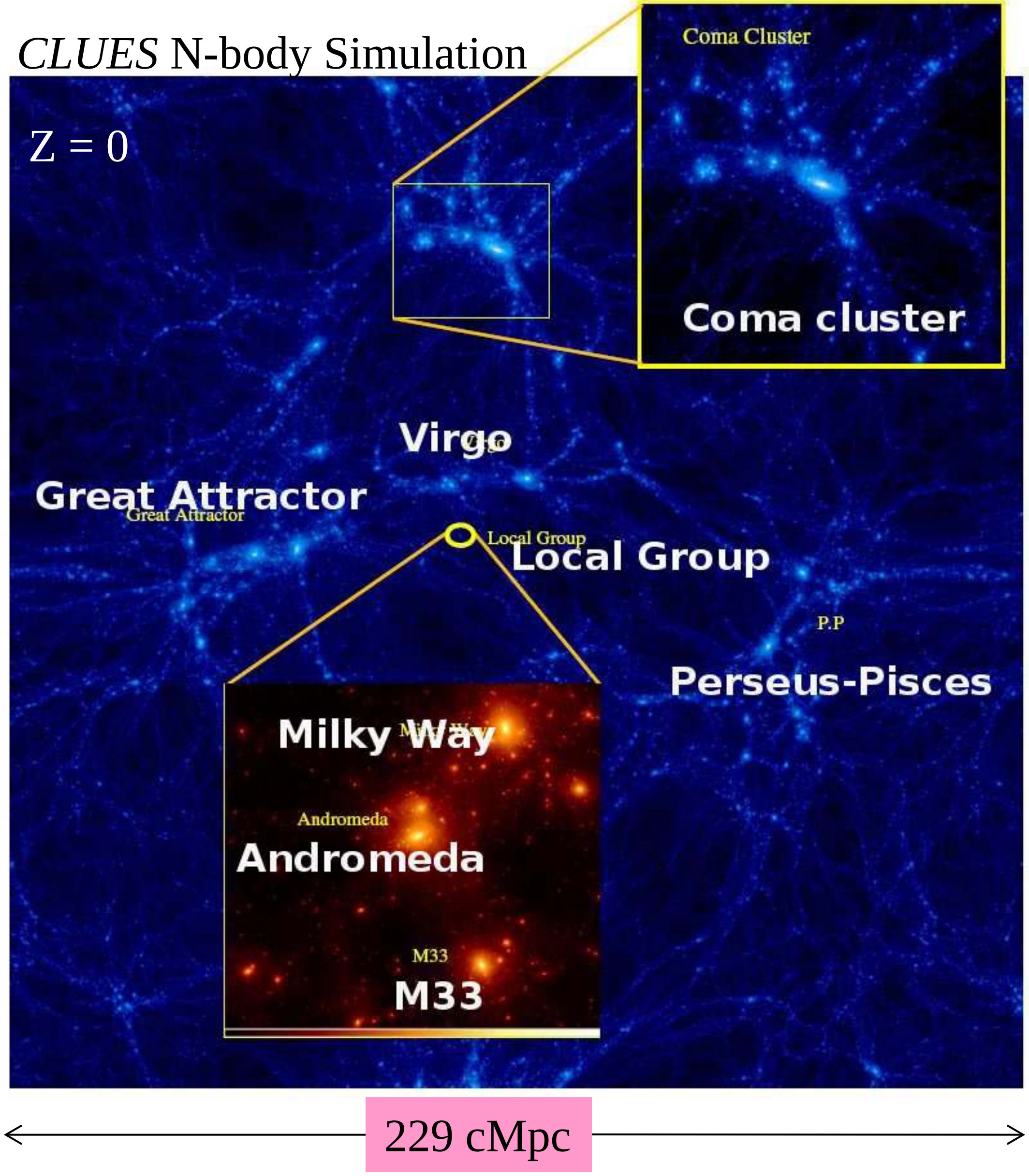
**Q**: Did reionization leave an imprint on the Local Group galaxies we can observe today?

**Q**: Does reionization help explain why the observed number of dwarf galaxies in the Local Group is far smaller than the number of small halos predicted by ΛCDM N-body simulations?

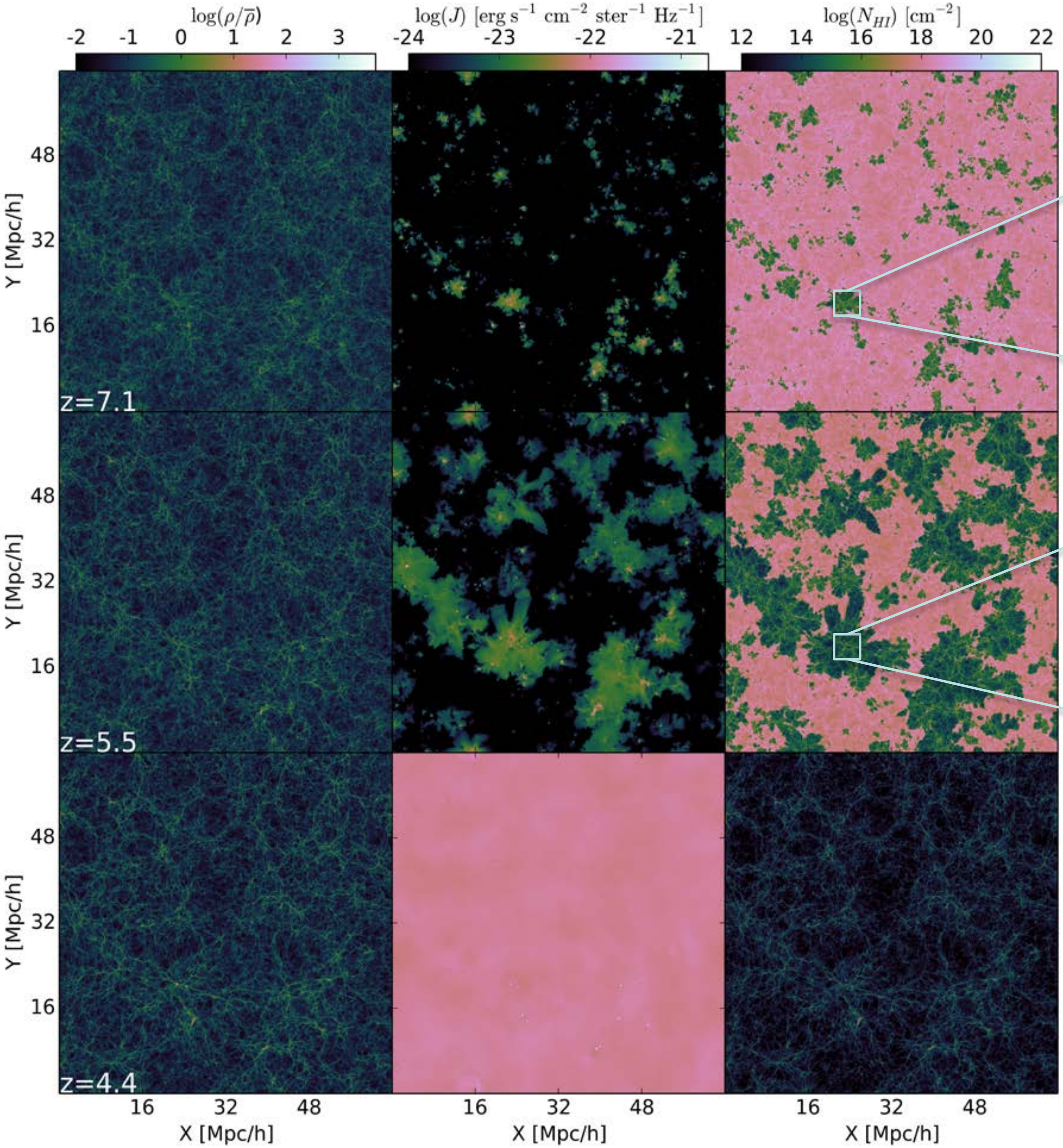
**Q**: Was the Local Group ionized from within or without?

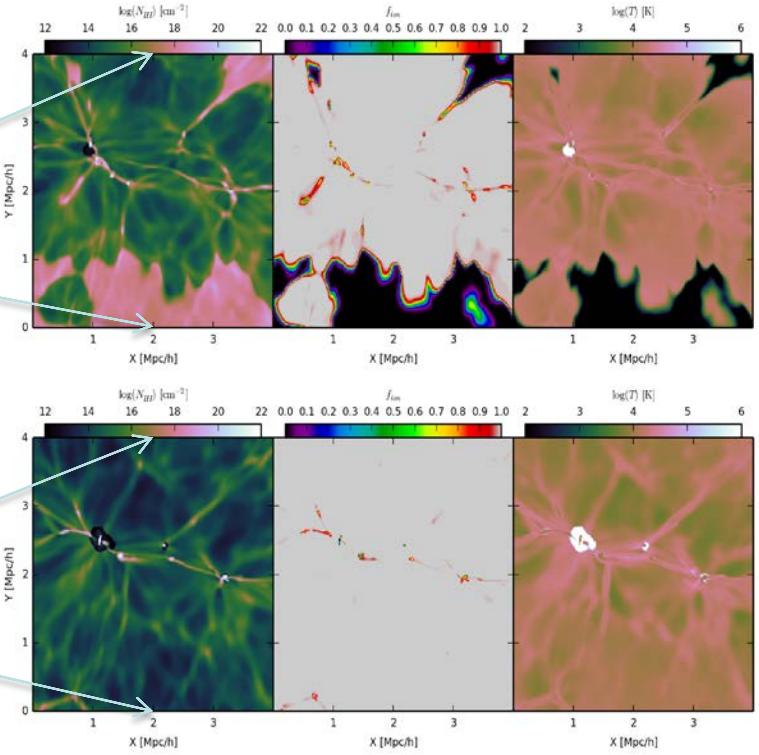
**A**: Simulate the coupled radiation-hydro-N-body problem of reionization ➔ galaxy formation with ionization fronts that swept across the IGM in the first billion years of cosmic time, in a volume 91 Mpc on a side centered on the Local Group.

*CLUES* N-body Simulation



# Introducing the CoDa (COsmic DAwn) Simulation: Reionization of the Local Universe with Fully-Coupled Radiation + Hydro + N-body Dynamics





**Shapiro, Ocvirk, Aubert, Iliev, Gillet, Teyssier, Yepes, Choi, Park, D'Aloisio, Sullivan, Gottloeber, Hoffman, Stranex, Knebe, Libeskind**

# Reionization of the Local Universe: Witnessing our Own Cosmic Dawn

**Shapiro, Ocvirk, Aubert, Iliev, Teyssier, Gillet, Yepes, Gottloeber, Choi, Park, D’Aloisio, Sullivan +**

*What makes this possible now?*

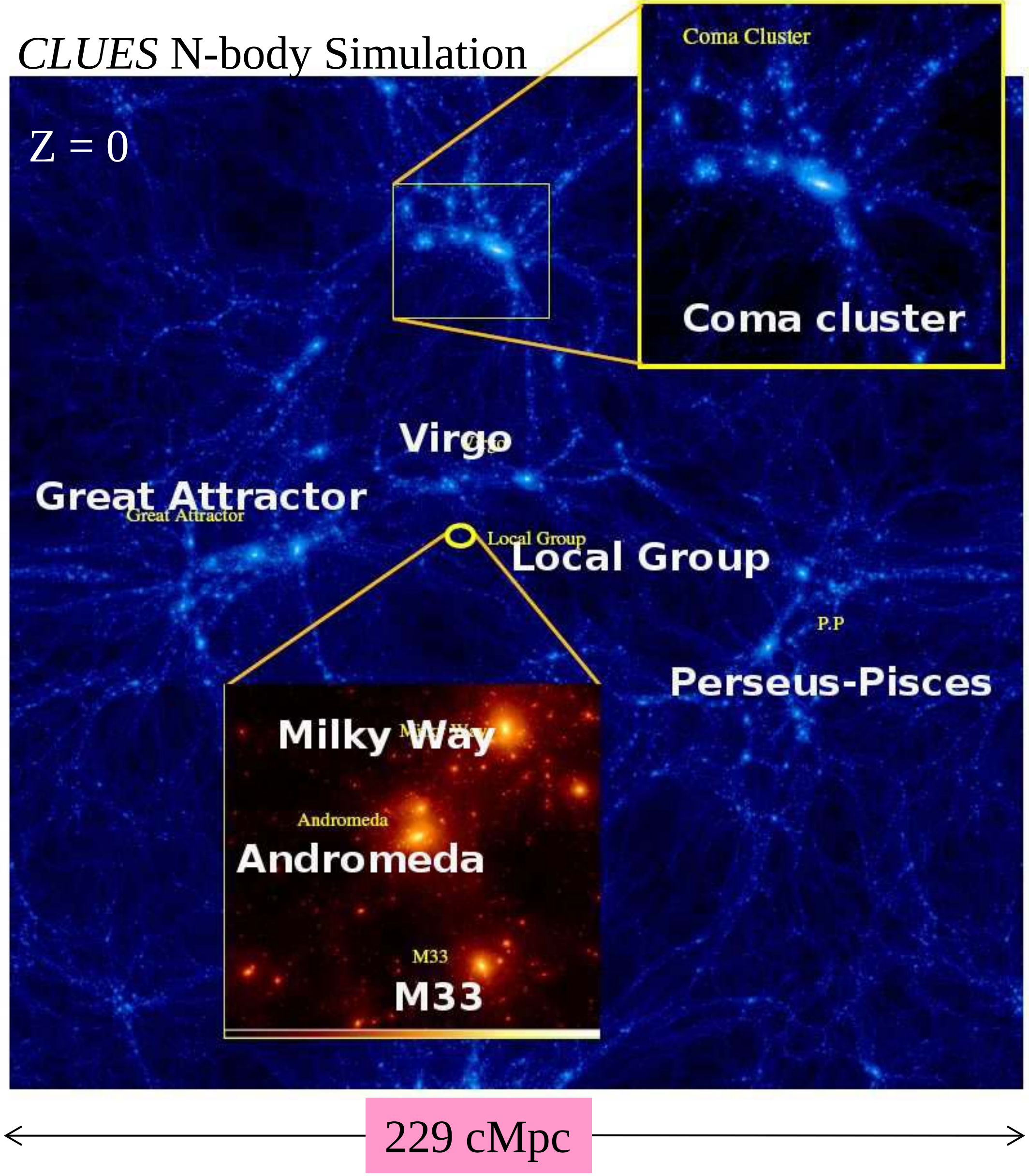
1) <u>Initial Conditions</u>:

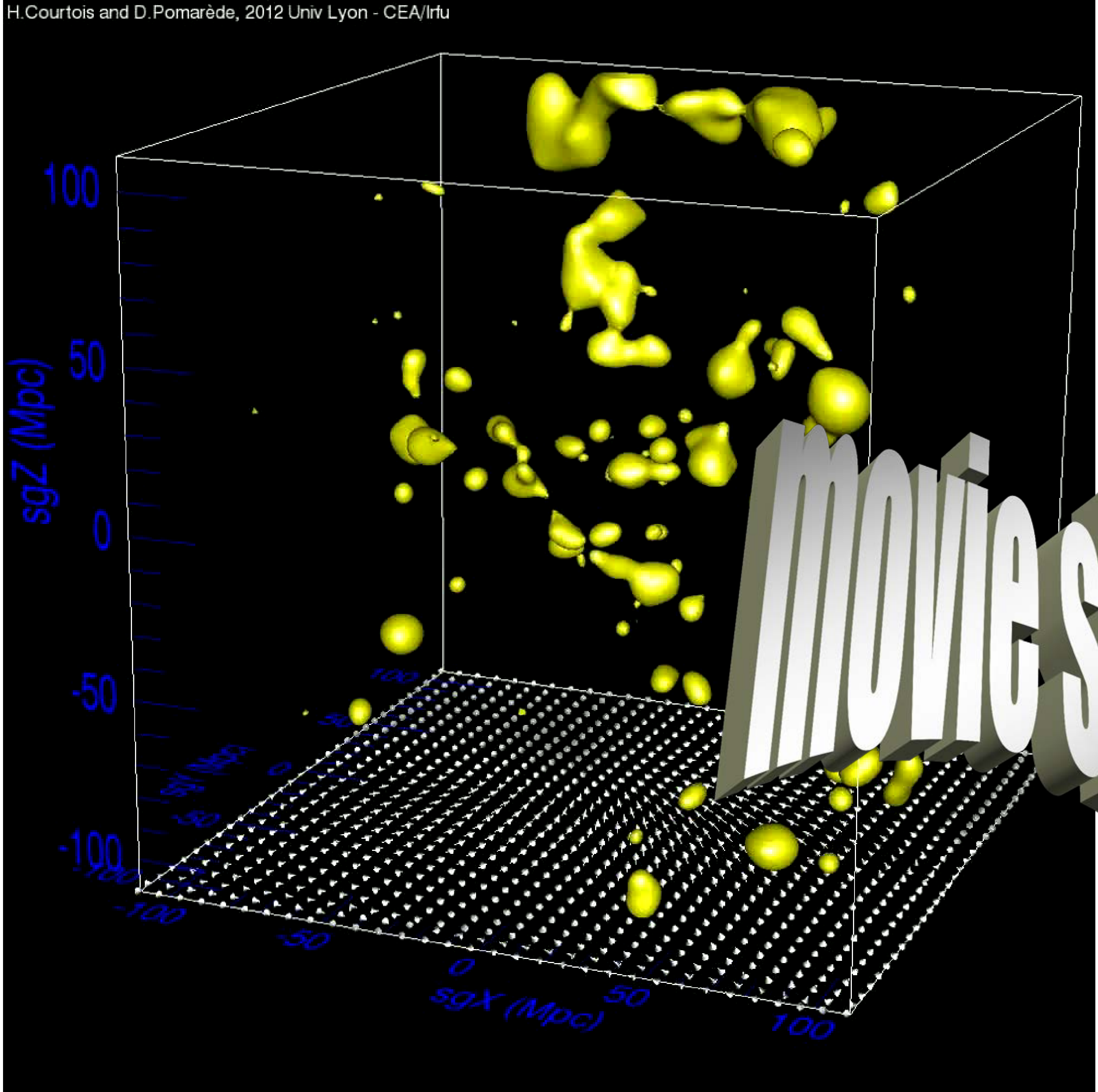
- Start from “constrained realization” of Gaussian-random-noise initial conditions, provided by our collaborators in the *CLUES* (**C**onstrained **L**ocal **U**nivers**E** **S**imulations) consortium

- This reproduces observed features of our local Universe, including the Local Group and nearby galaxy clusters.

- Add higher frequency modes for small-scale structure

*CLUES* N-body Simulation





H.Courtois and D.Pomarède, 2012 Univ Lyon - CEA/Irfu

movie slide

# Reionization of the Local Universe: Witnessing our Own Cosmic Dawn

**Shapiro, Ocvirk, Aubert, Iliev, Teyssier, Gillet, Yepes, Gottloeber, Choi, Park, D'Aloisio, Sullivan +**

*What makes this possible now?*

2) New Hybrid (CPU + GPU) numerical method + New Hybrid (CPU + GPU) supercomputer

N-body + Hydro = **RAMSES** (Teyssier 2002)

- Gravity solver is Particle - Mesh code with Multi-Grid Poisson solver
- Hydro solver is shock-capturing, second-order Godunov scheme on Eulerian grid

Radiative Transfer + Ionization Rate Solver = **ATON** (Aubert & Teyssier 2008)

- RT is by a moment method with M1 closure
- Explicit time integration, time-step size limited by CFL condition ➔

$$\Delta t < \Delta x / c\ ,$$

where $c$ = speed of light

**ATON ➔ (ATON) x (GPUs) = CUDATON** (Aubert & Teyssier 2010)

•GPU acceleration by factor **~ 100**

**RAMSES + CUDATON = RAMSES-CUDATON**

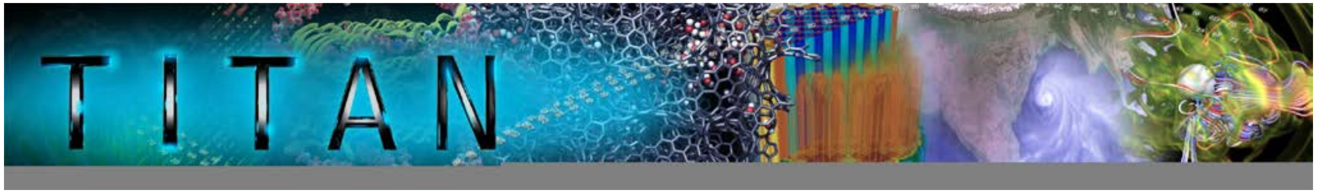
•RT on the GPUs @ CFL condition set by speed of light

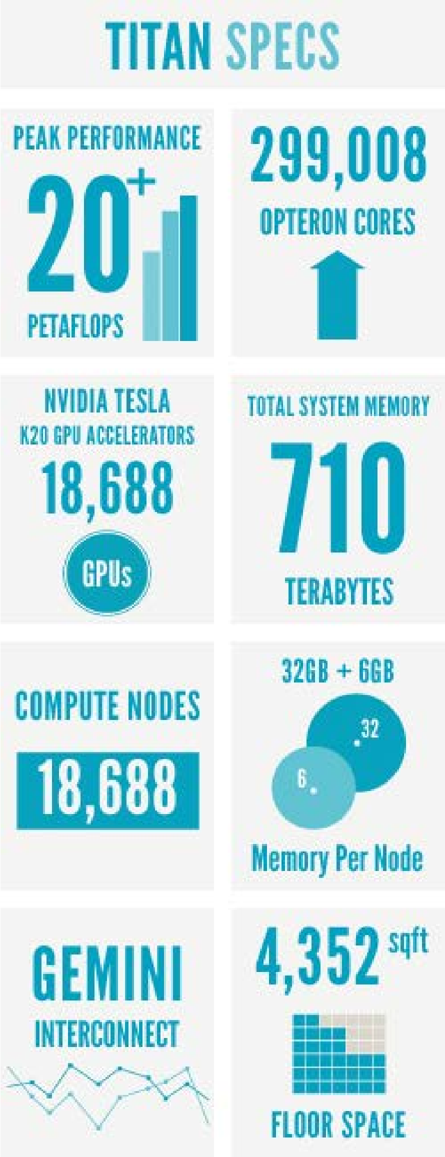
•(hydro + gravity) on the CPUs @ CFL condition set by sound speed

• (# RT steps)/(# hydro-gravity steps) > 1000 will not slow hydro-gravity calculation

# Reionization of the Local Universe: Witnessing our Own Cosmic Dawn

**Shapiro, Ocvirk, Aubert, Iliev, Teyssier, Gillet, Yepes, Gottloeber, Choi, Park, D’Aloisio, Sullivan +**





TITAN by the numbers:

- 20 Petaflops peak
- 18,688 compute nodes
- 299,008 cores
- Each node consists of an AMD 16-Core Opteron 6200 Series processor and an NVIDIA Tesla K20 GPU Accelerator
- Gemini interconnect

# Introducing the CoDa (COsmic DAwn) Simulation: Reionization of the Local Universe with Fully-Coupled Radiation + Hydro + N-body Dynamics

**Shapiro, Ocvirk, Aubert, Iliev, Teyssier, Gillet, Yepes, Gottloeber, Choi, Park, D’Aloisio, Sullivan +**

RAMSES-CUDATON simulation

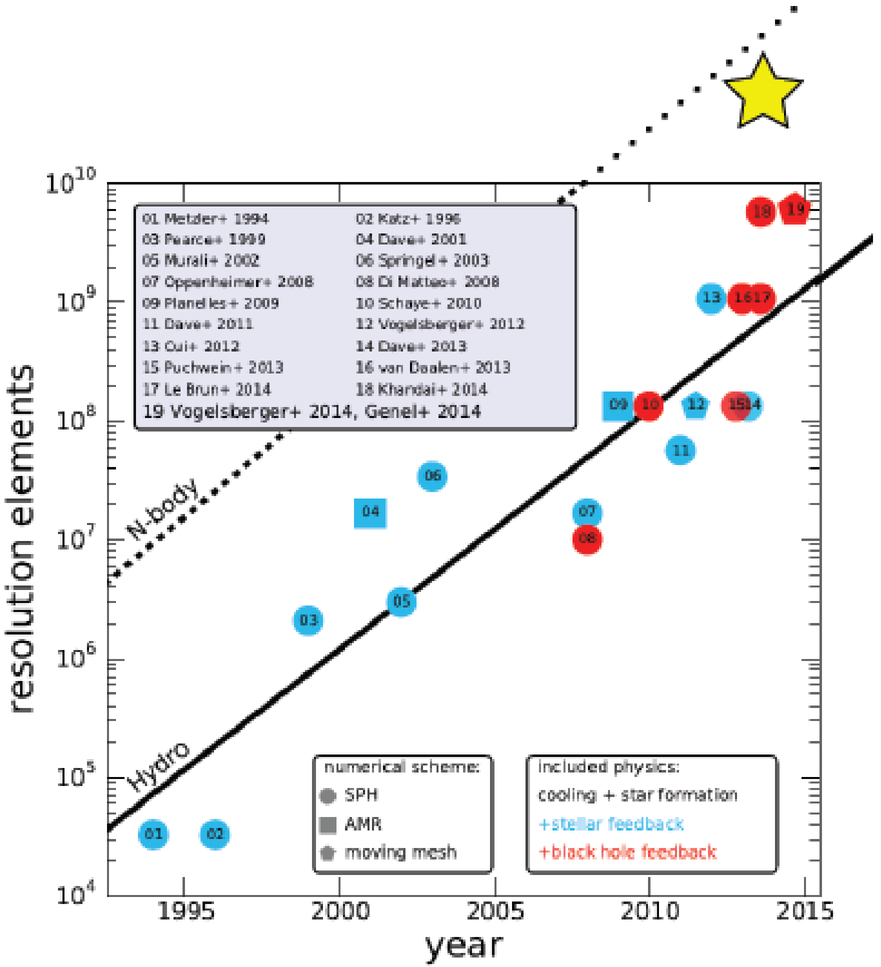
- Box size = 91 cMpc
- Grid size = $(4096)^3$ cells, $\Delta x \sim 20$ cKpc
- N-body particles = $(4096)^3 \sim 64$ billion
- Min halo mass ~ $10^8$ M_solar ~300 particles

TITAN Supercomputer requirements

- # steps/run = 2000 CPU (+800,000 GPU)
- # CPU cores (+ # GPUs) = 131,072 (+ 8192)
- # CPU hrs = 2.1 million node hrs ~ 11 days

- Largest fully-coupled radiation-hydro simulation to-date of the reionization of the Local Universe.

- Large enough volume to simulate global reionization and its impact on the Local Group simultaneously, while resolving the masses of dwarf satellites of the MW and M31.



(taken from illustris website)

# Reionization of the Local Universe: Witnessing our Own Cosmic Dawn

**Shapiro, Ocvirk, Aubert, Iliev, Teyssier, Gillet, Yepes, Gottloeber, Choi, Park, D'Aloisio, Sullivan +**

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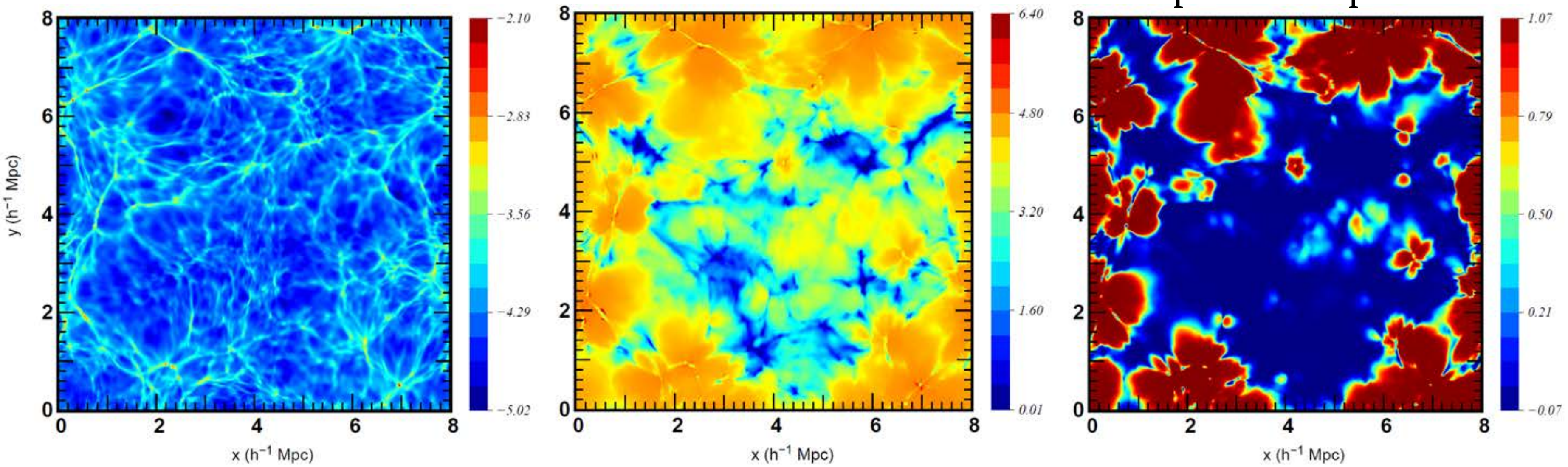
- # CPU cores (+ # GPUs) = 131,072 (+ 8192)
- # CPU hrs = 2.1 million node hrs ~ 11 days

TEST RUN: 11 cMpc box: a spatial slice



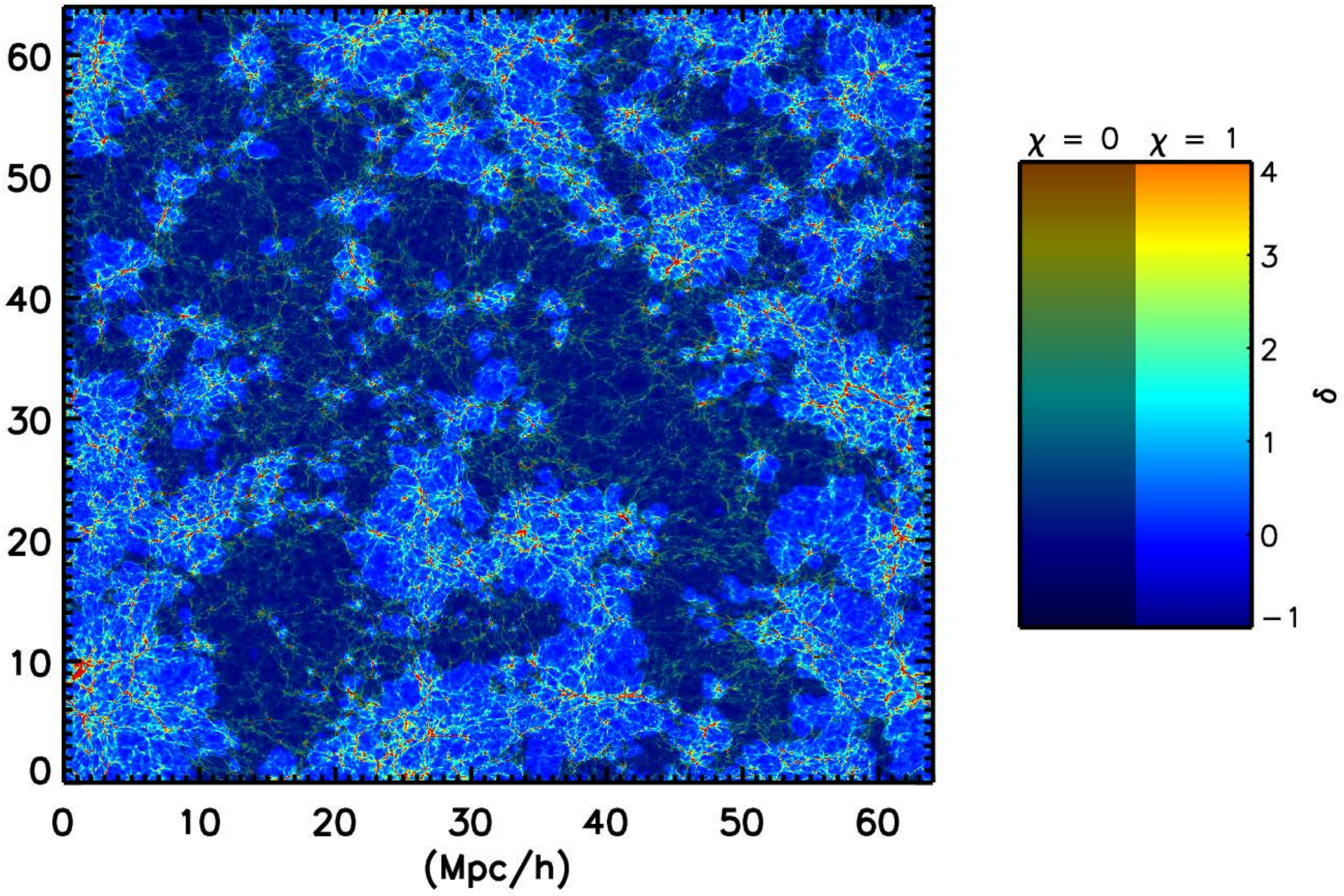
log10(density) log10(temperature) ionized hydrogen fraction

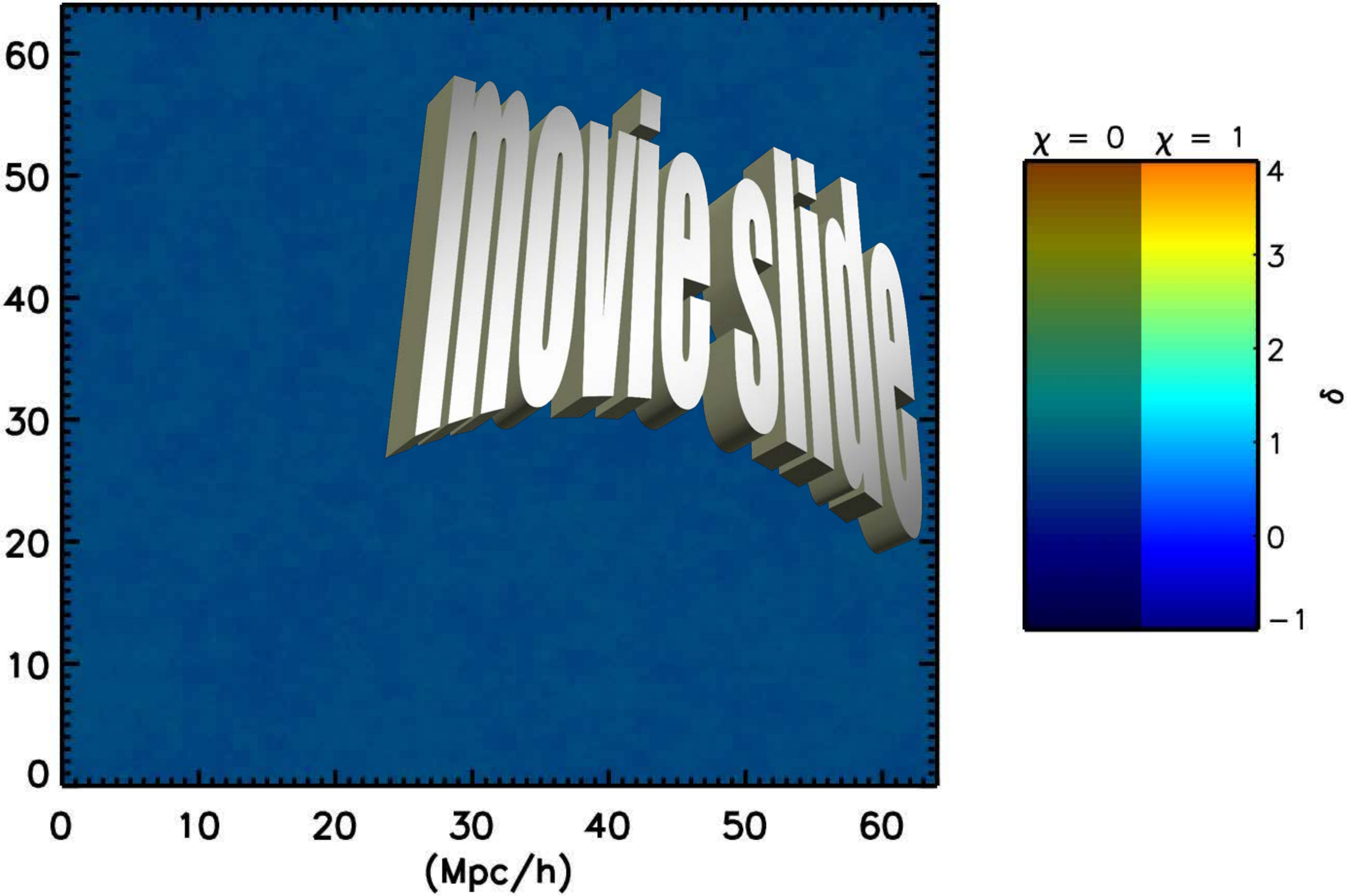
- (left) the local cosmic web in the atomic gas ;
- (middle) red regions denote very hot, supernova-powered superbubbles, while yellow-orange regions show the long-range impact of photo-heating by starlight;
- (right) ionized hydrogen fraction [dark red (dark blue) = ionized (neutral)].

# Reionization of the Local Universe: Witnessing our Own Cosmic Dawn

**Shapiro, Ocvirk, Aubert, Iliev, Teyssier, Gillet, Yepes, Gottloeber, Choi, Park, D'Aloisio, Sullivan +**

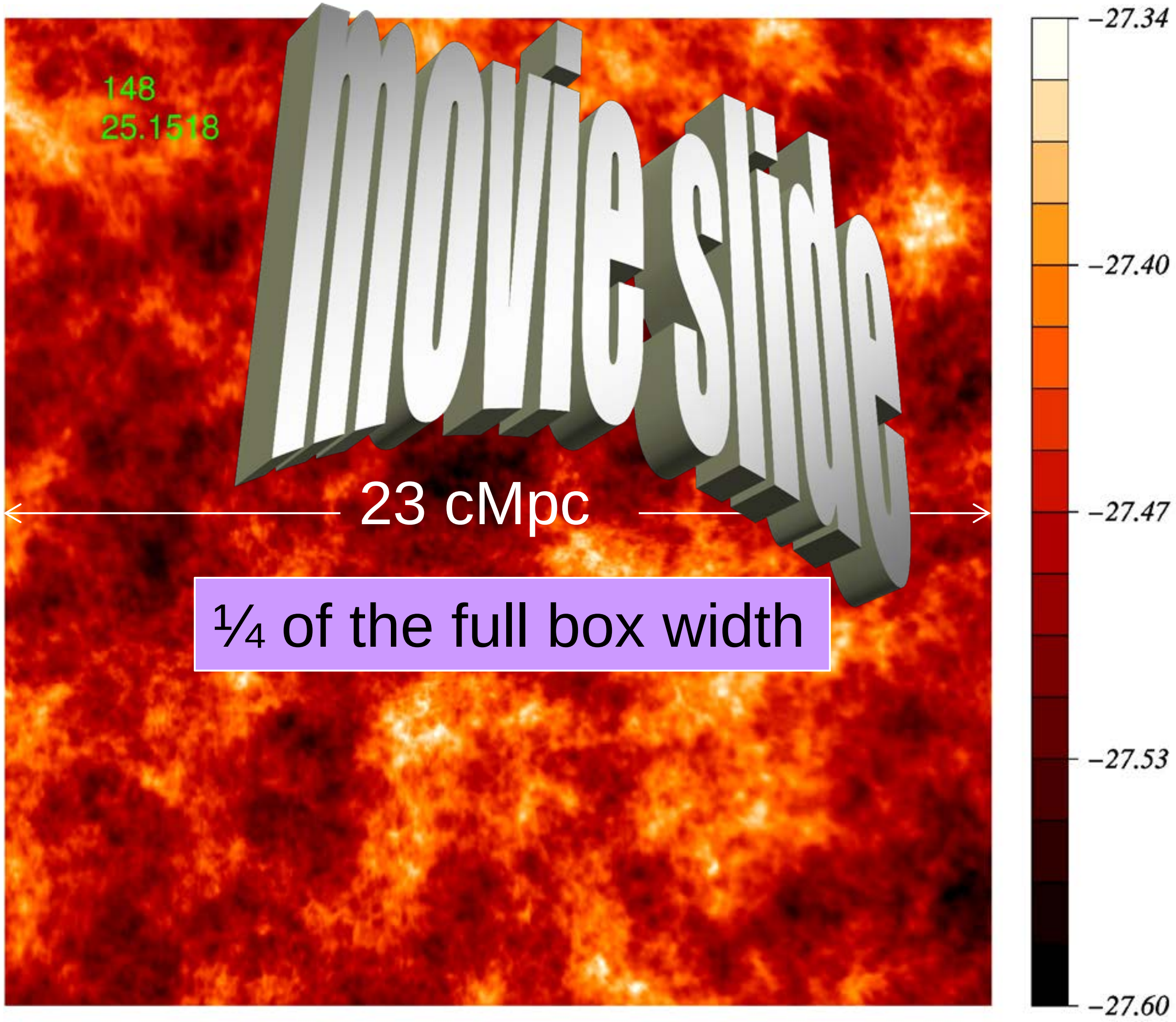
Ionization Field




movie slide
60
50
40
30
20
10
0
0
10
20
30
40
50
60
(Mpc/h)
χ = 0
χ = 1
4
3
2
1
0
−1
δ

# Reionization of the Local Universe: Witnessing our Own Cosmic Dawn

Ionizing Radiation Mean Intensity J



23 cMpc

¼ of the full box width

# Reionization of the Local Universe: Witnessing our Own Cosmic Dawn

Gas Temperature

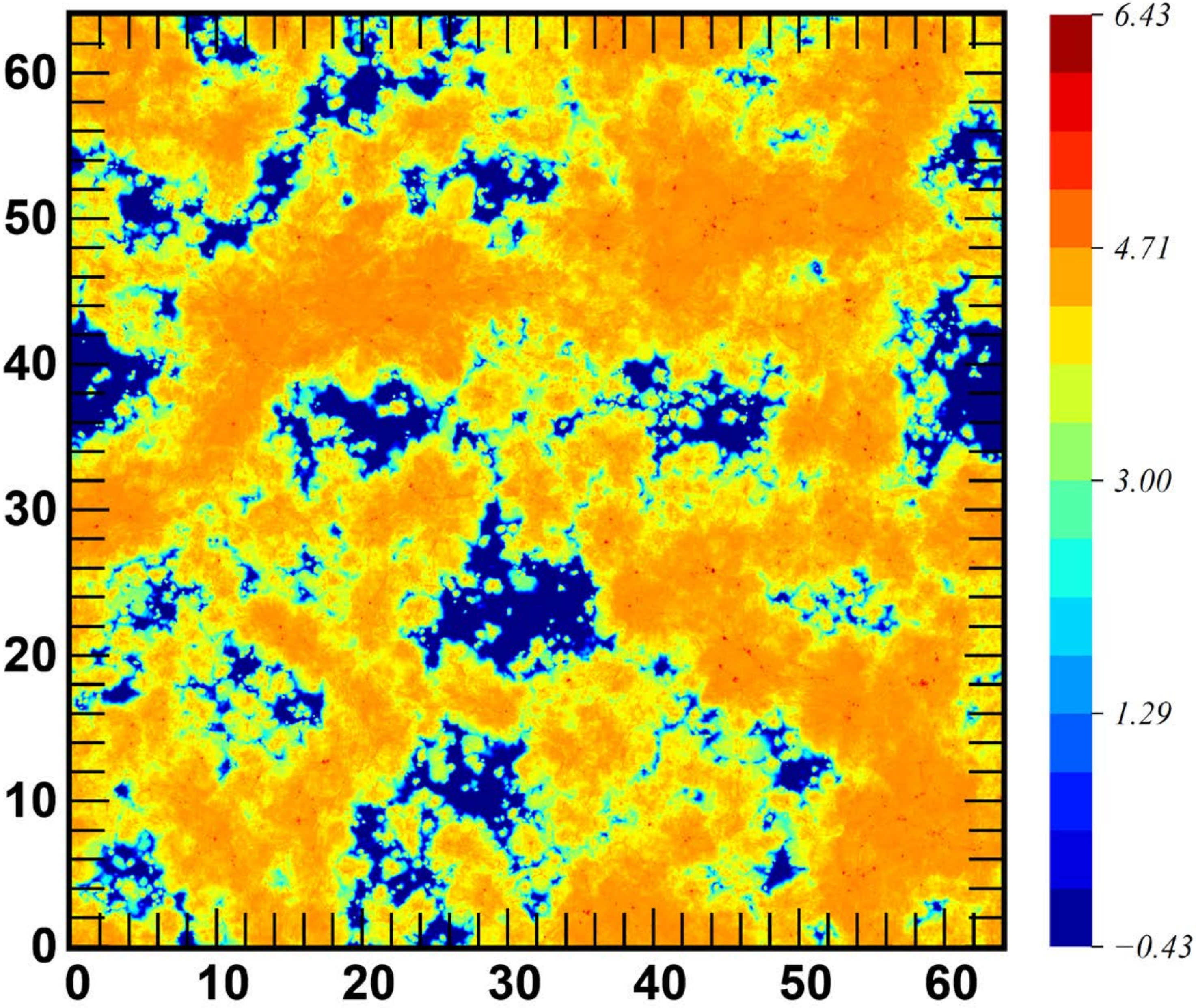
23 cMpc

¼ of the full box width

RAMSES-CUDATON simulation

- Box size = 91 cMpc
- Grid size = $(4096)^3$ cells
- N-body particles = $(4096)^3$
- Min halo mass ~ $10^8$ solar masses

FULL-SIZED RUN:
91 cMpc box: a spatial slice;
@ z ~ 6, with x ~ 50%



log10(temperature)

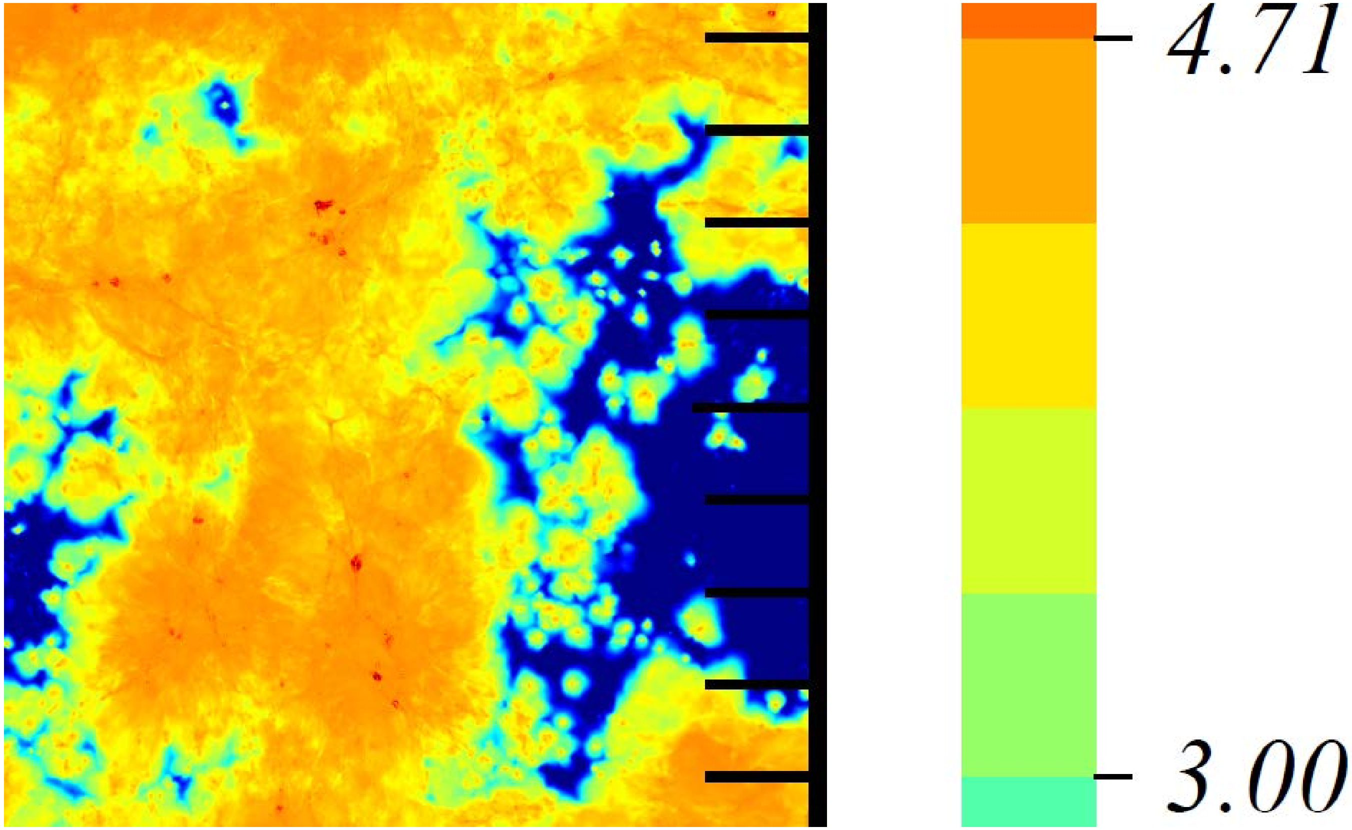
- red regions denote very hot, supernova-powered superbubbles, while yellow-orange regions show the long-range impact of photo-heating by starlight;

RAMSES-CUDATON simulation

- Box size = 91 cMpc
- Grid size = $(4096)^3$ cells
- N-body particles = $(4096)^3$
- Min halo mass ~ $10^8$ solar masses

FULL-SIZED RUN:
91 cMpc box: a spatial slice;
@ z ~ 6, with x ~ 50%

Zoom-in x 4



log10(temperature)

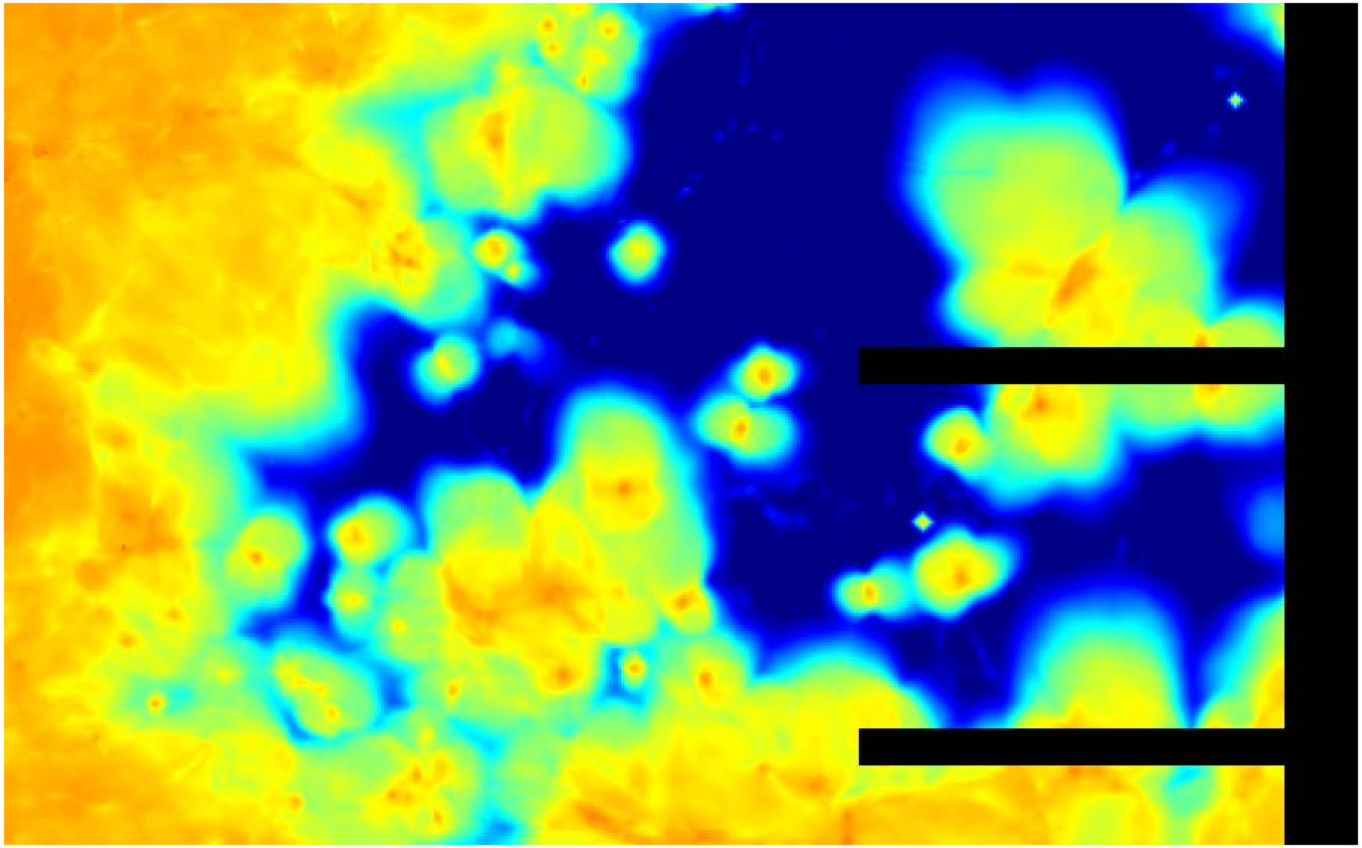
- red regions denote very hot, supernova-powered superbubbles, while yellow-orange regions show the long-range impact of photo-heating by starlight;

RAMSES-CUDATON simulation

- Box size = 91 cMpc
- Grid size = $(4096)^3$ cells
- N-body particles = $(4096)^3$
- Min halo mass ~ $10^8$ solar masses

FULL-SIZED RUN:
91 cMpc box: a spatial slice;
@ z ~ 6,  with x ~ 50%

Zoom-in x 16



log10(temperature)

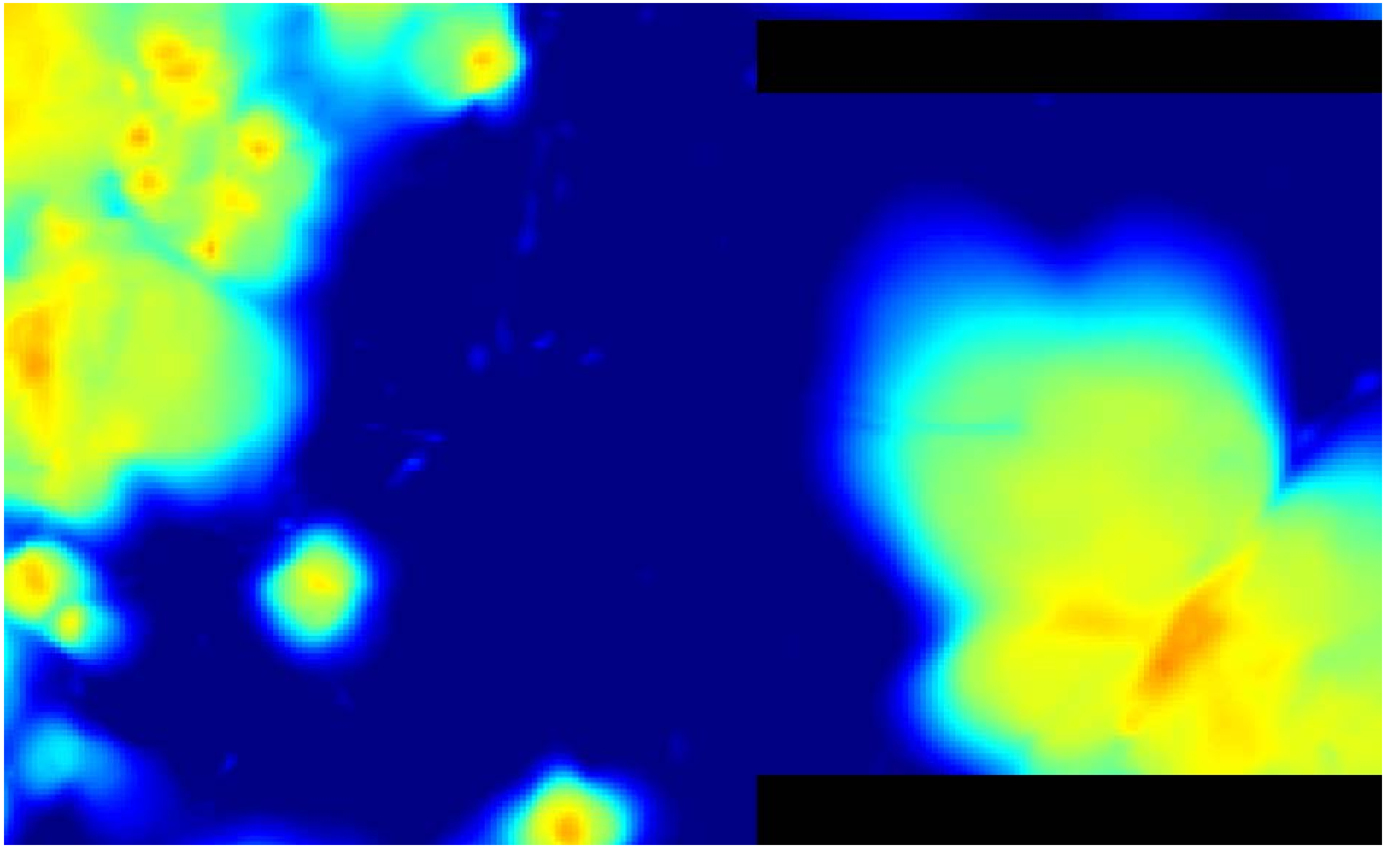
- red regions denote very hot, supernova-powered superbubbles, while yellow-orange regions show the long-range impact of photo-heating by starlight;

RAMSES-CUDATON simulation

- Box size = 91 cMpc
- Grid size = $(4096)^3$ cells
- N-body particles = $(4096)^3$
- Min halo mass ~ $10^8$ solar masses

FULL-SIZED RUN:
91 cMpc box: a spatial slice;
@ z ~ 6,  with x ~ 50%

Zoom-in x 32



log10(temperature)

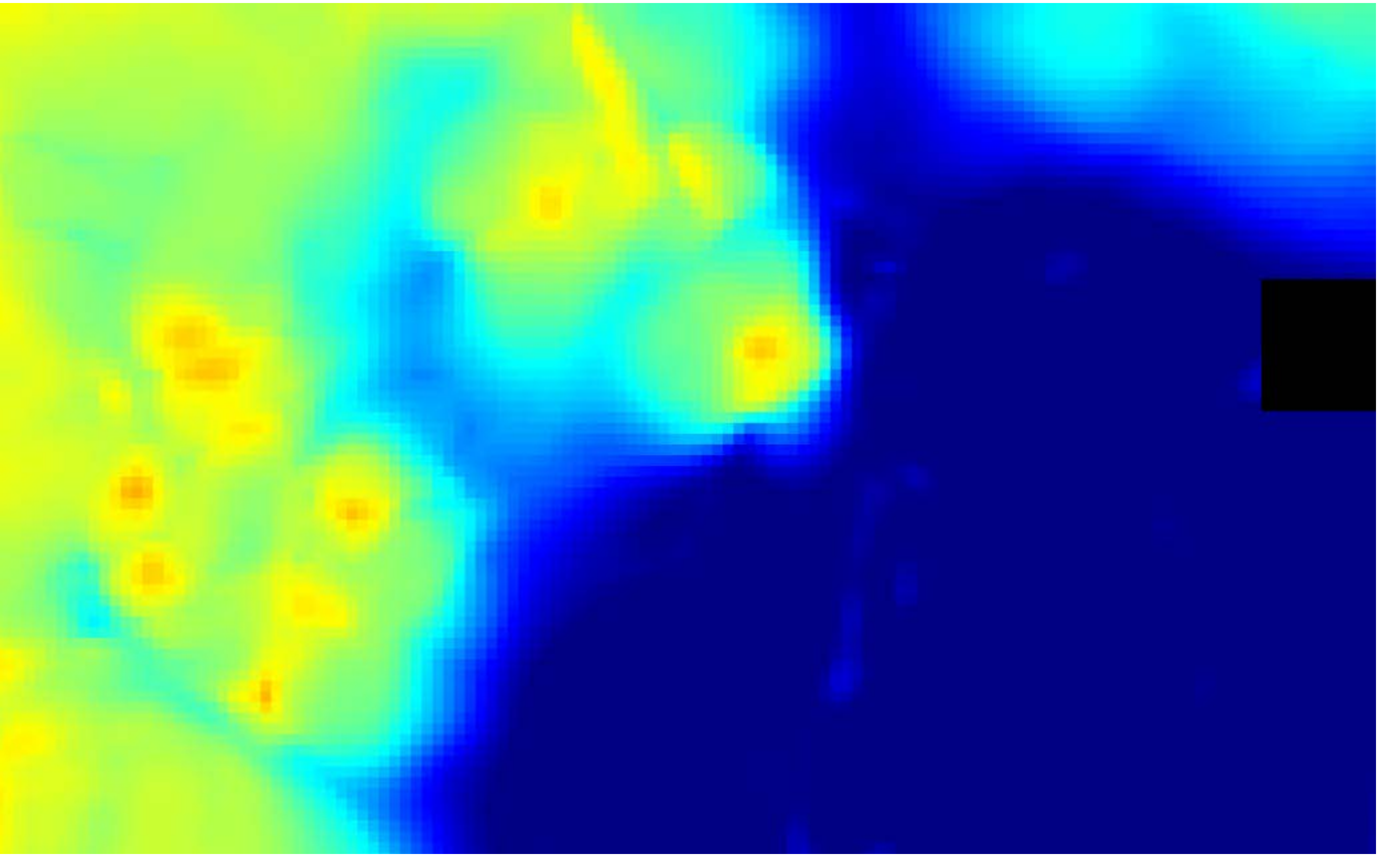
- red regions denote very hot, supernova-powered superbubbles, while yellow-orange regions show the long-range impact of photo-heating by starlight;

RAMSES-CUDATON simulation

- Box size = 91 cMpc
- Grid size = $(4096)^3$ cells
- N-body particles = $(4096)^3$
- Min halo mass ~ $10^8$ solar masses

FULL-SIZED RUN:
91 cMpc box: a spatial slice;
@ z ~ 6, with x ~ 50%

Zoom-in x 64



log10(temperature)

- red regions denote very hot, supernova-powered superbubbles, while yellow-orange regions show the long-range impact of photo-heating by starlight;

Zoom-In (4 $h^{-1}$ cMpc)$^3$ Subvolume = (full simulation volume/4096)

# Selected Cut-out

RAMSES-CUDATON simulation

- Box size = 91 cMpc
- Grid size = $(4096)^3$ cells
- N-body particles = $(4096)^3$
- Min halo mass ~ $10^8$ solar masses

ZOOM-IN ON THE LOCAL GROUP AT Z = 0

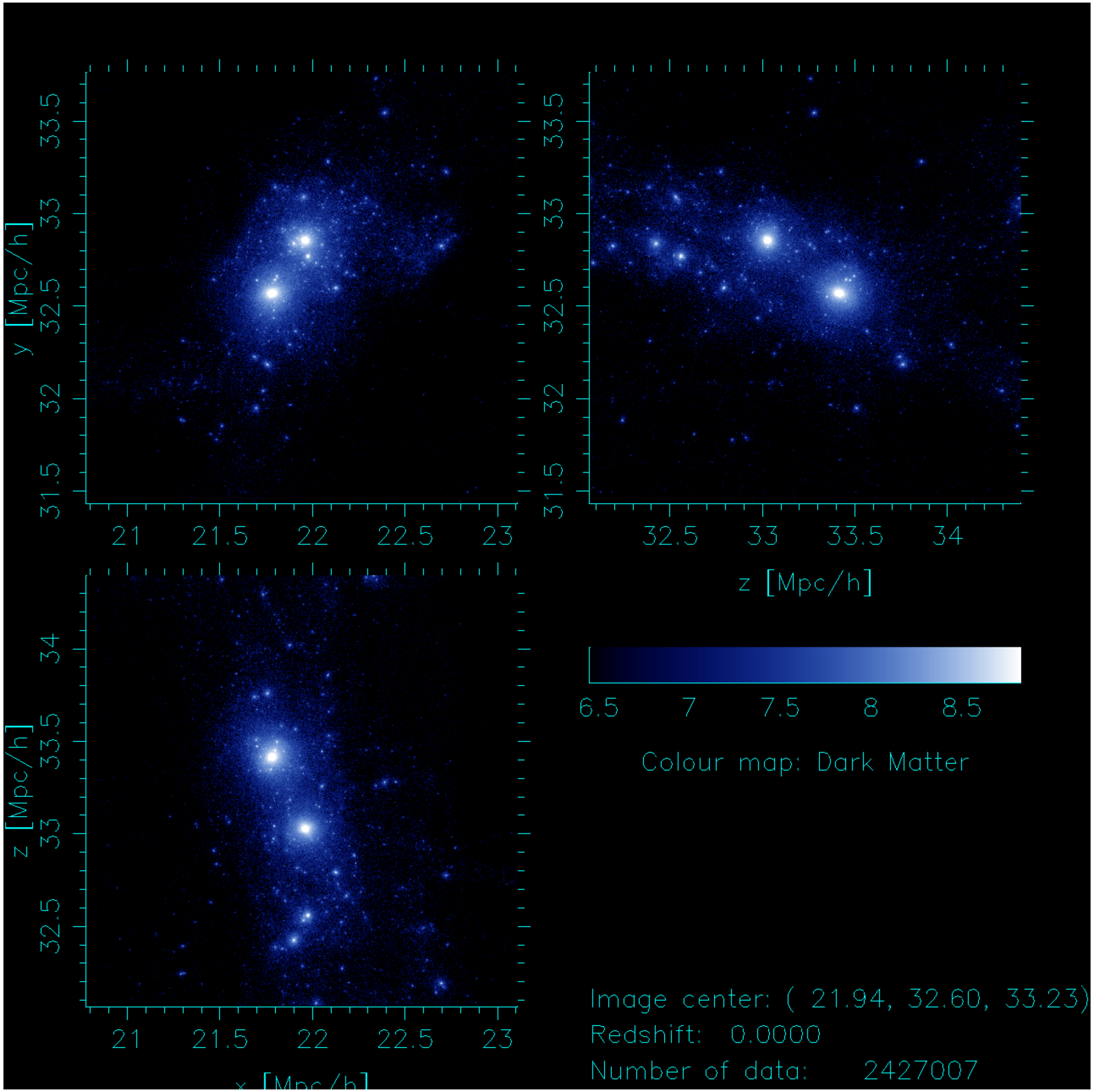
Zoom-In (4 $h^{-1}$ cMpc)$^3$ Subvolume = (full simulation volume/4096)

# Selected Cut-out

RAMSES-CUDATON simulation

- Box size = 91 cMpc
- Grid size = $(4096)^3$ cells
- N-body particles = $(4096)^3$
- Min halo mass ~ $10^8$ solar masses

ZOOM-IN ON LOCAL GROUP AT Z = 0



# Reionization of the Local Universe: Witnessing our Own Cosmic Dawn

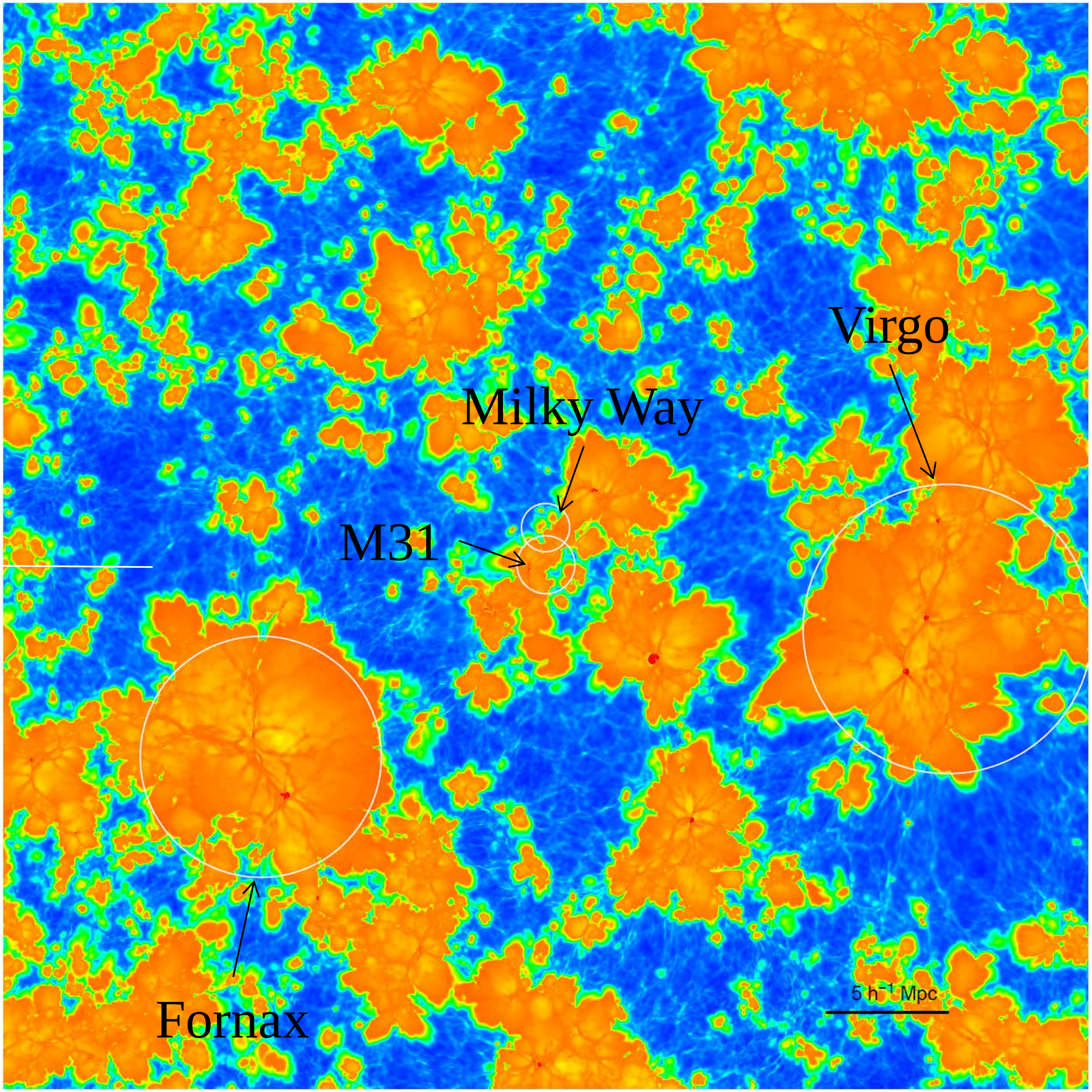
Gas Temperature
at
$z = 6.15$
in the supergalactic
YZ plane
of the
Local Group

Circles indicate progenitors of Virgo, Fornax, M31, and the MW

Orange is photoheated, photoionized gas;

Red is SN-shock-heated;

Blue is cold and neutral



Zoom-In (4 $h^{-1}$ cMpc)$^3$ Subvolume = (full simulation volume/4096)

# Selected Cut-out

RAMSES-CUDATON simulation

- Box size = 91 cMpc
- Grid size = $(4096)^3$ cells
- N-body particles = $(4096)^3$
- Min halo mass ~ $10^8$ solar masses

Look at the Dark Matter at the end of reionization

cutou M stud tmovie_sampler.mpg

movie slide

Zoom-In (4 $h^{-1}$ cMpc)$^3$ Subvolume = (full simulation volume/4096)

# Selected Cut-out

RAMSES-CUDATON simulation

- Box size = 91 cMpc
- Grid size = (4096)$^3$ cells
- N-body particles = (4096)$^3$
- Min halo mass ~ 10$^8$ solar masses

movie slide

Zoom-In (4 $h^{-1}$ cMpc$)^3$ Subvolume = (full simulation volume/4096)

# Selected Cut-out

RAMSES-CUDATON simulation

- Box size = 91 cMpc
- Grid size = $(4096)^3$ cells
- N-body particles = $(4096)^3$
- Min halo mass ~ $10^8$ solar masses

See a map of the ionized gas density evolve thru the EOR in this region

cutout100_xion_rho.mpg

movie slide

Zoom-In (4 $h^{-1}$ cMpc)$^3$ Subvolume = (full simulation volume/4096)

# Selected Cut-out

RAMSES-CUDATON simulation

- Box size = 91 cMpc
- Grid size = (4096)$^3$ cells
- N-body particles = (4096)$^3$
- Min halo mass ~ 10$^8$ solar masses

See a map of the ionized gas density evolve thru the EOR in one of the selected cut-outs

cutout100_x

Movie Slide

This cut-out reionizes itself

Zoom-In (4 $h^{-1}$ cMpc)$^3$ Subvolume = (full simulation volume/4096)

# Selected Cut-out

RAMSES-CUDATON simulation

- Box size = 91 cMpc
- Grid size = $(4096)^3$ cells
- N-body particles = $(4096)^3$
- Min halo mass ~ $10^8$ solar masses

See a map of the ionized gas density evolve thru the EOR in another cut-out region

cutout101_

movie slide

Zoom-In (4 $h^{-1}$ cMpc)$^3$ Subvolume = (full simulation volume/4096)

# Selected Cut-out

RAMSES-CUDATON simulation

- Box size = 91 cMpc
- Grid size = $(4096)^3$ cells
- N-body particles = $(4096)^3$
- Min halo mass ~ $10^8$ solar masses

See a map of the ionized gas density evolve thru the EOR in another cut-out region

cutout101_x

movie slide

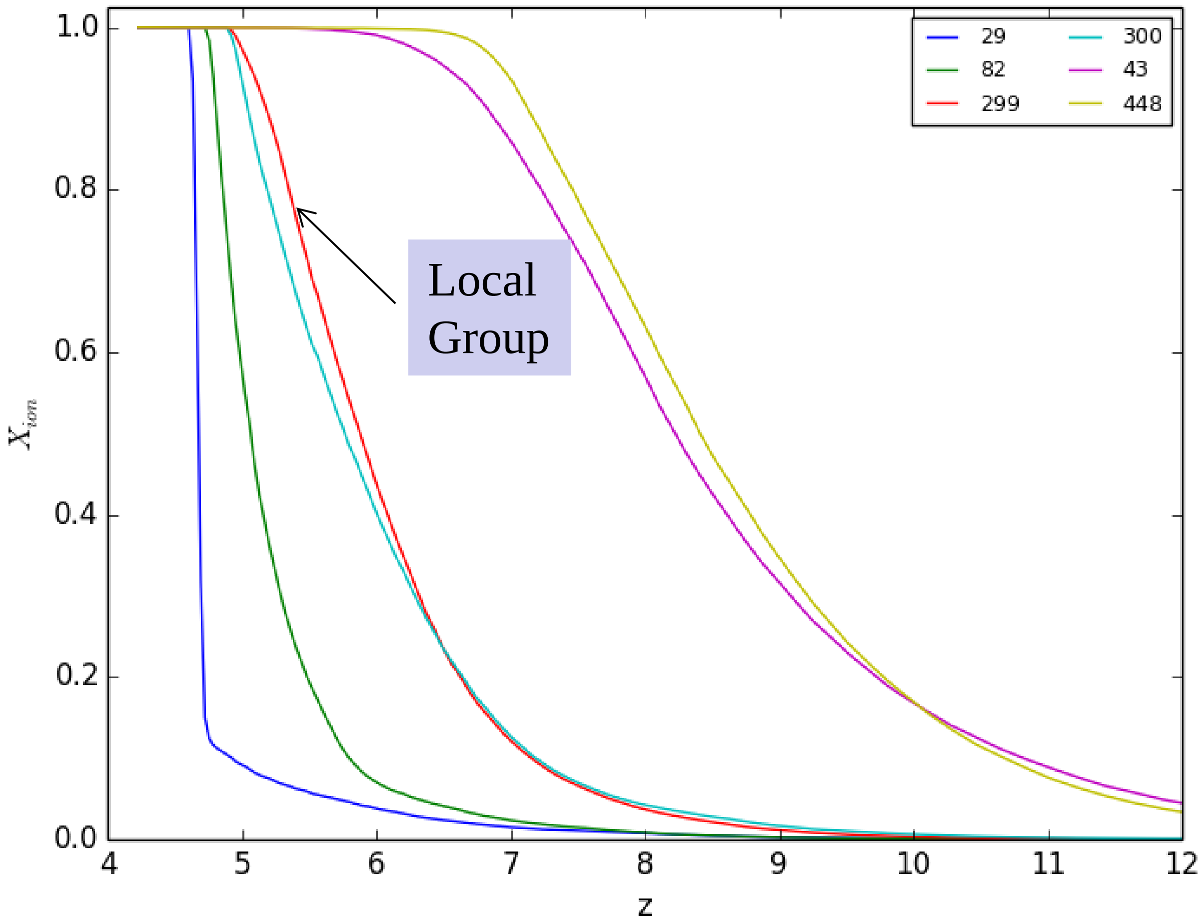
This cut-out is reionized by external sources, as the matter in this cut-out falls toward the source of its reionization.

# Zoom-In (4 $h^{-1}$ cMpc)$^3$ Subvolumes = (full simulation volume/4096)

## Selected Cut-outs

RAMSES-CUDATON simulation

- Box size = 91 cMpc
- Grid size = (4096)$^3$ cells
- N-body particles = (4096)$^3$
- Min halo mass ~ $10^8$ solar masses

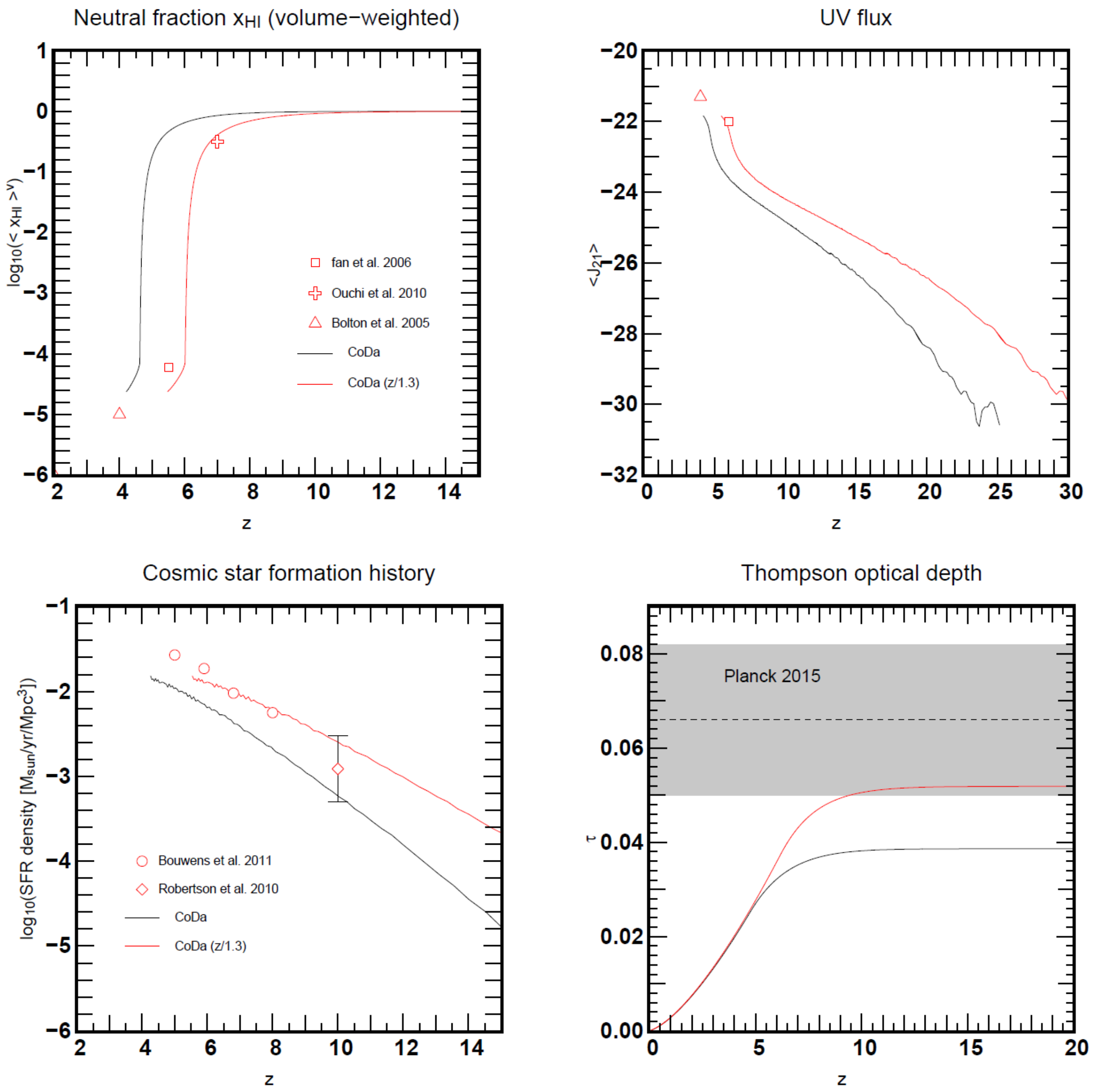


Local Group

Sub-regions with reionization histories that ended gradually were reionized by ***internal sources***, while those whose histories finished abruptly were reionized by ***external sources***.

# Reionization of the Local Universe: Witnessing our Own Cosmic Dawn

- Efficiencies set from smaller-box simulations prove slightly low, so reionization ends a bit late: $z_{rei} < 5$
- But if we let $z \rightarrow z * 1.3$, there is good agreement with observable constraints



Neutral fraction $x_{HI}$ (volume−weighted)

UV flux

Cosmic star formation history

Thompson optical depth

# Reionization of the Local Universe: Witnessing our Own Cosmic Dawn

**Shapiro, Ocvirk, Aubert, Iliev, Teyssier, Gillet, Yepes, Gottloeber, Choi, Park, D'Aloisio, Sullivan +**

Reionization suppresses star formation rate in dwarf galaxies, for M < $10^9$ solar masses

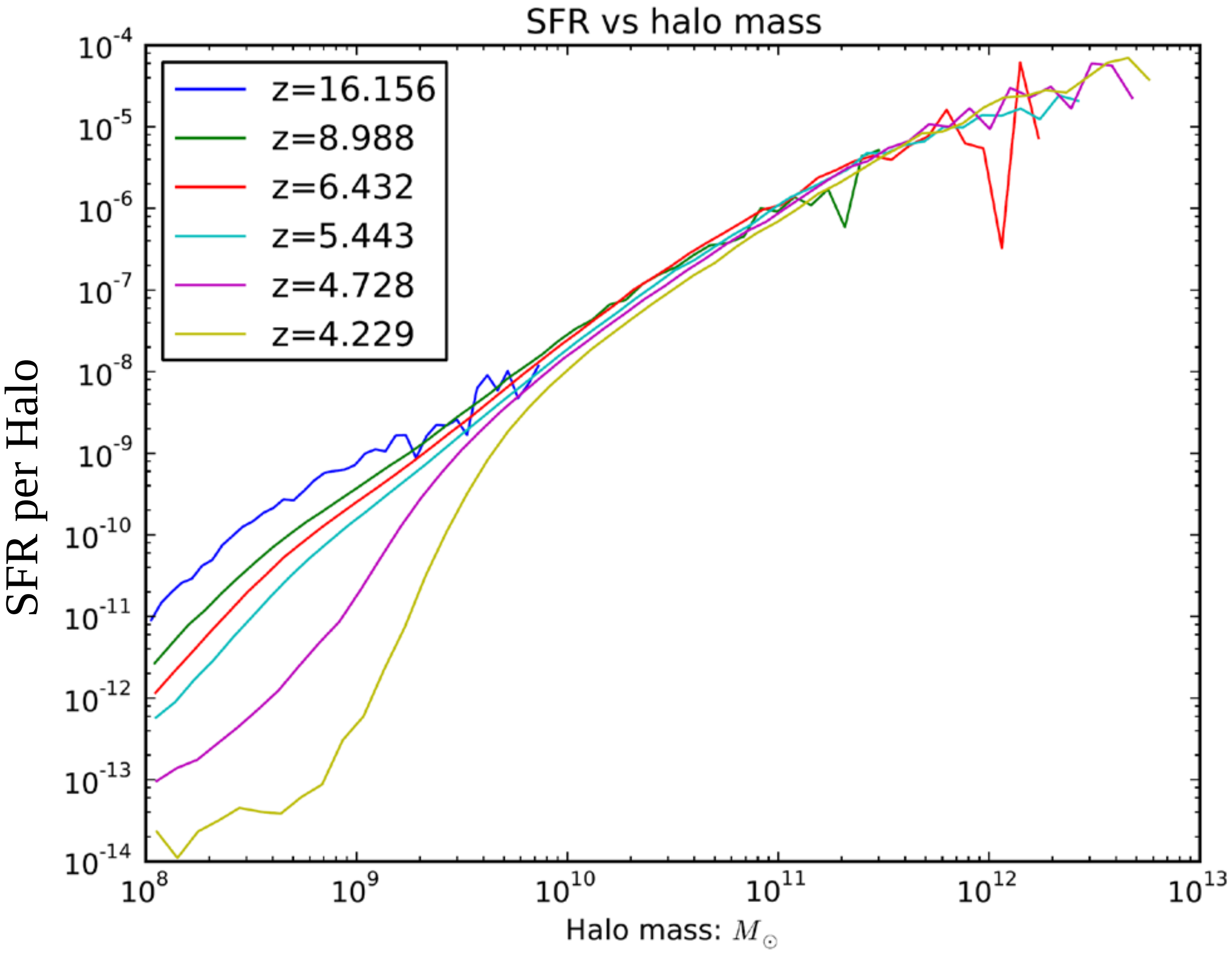
- photoionization-heating & SN remnant shock-heating raises gas pressure

- Gas pressure of heated gas resists gravitational binding into the low-mass galaxies

➔ lowers the cold, dense baryon gas fraction

➔ lowers the SFR per unit halo mass

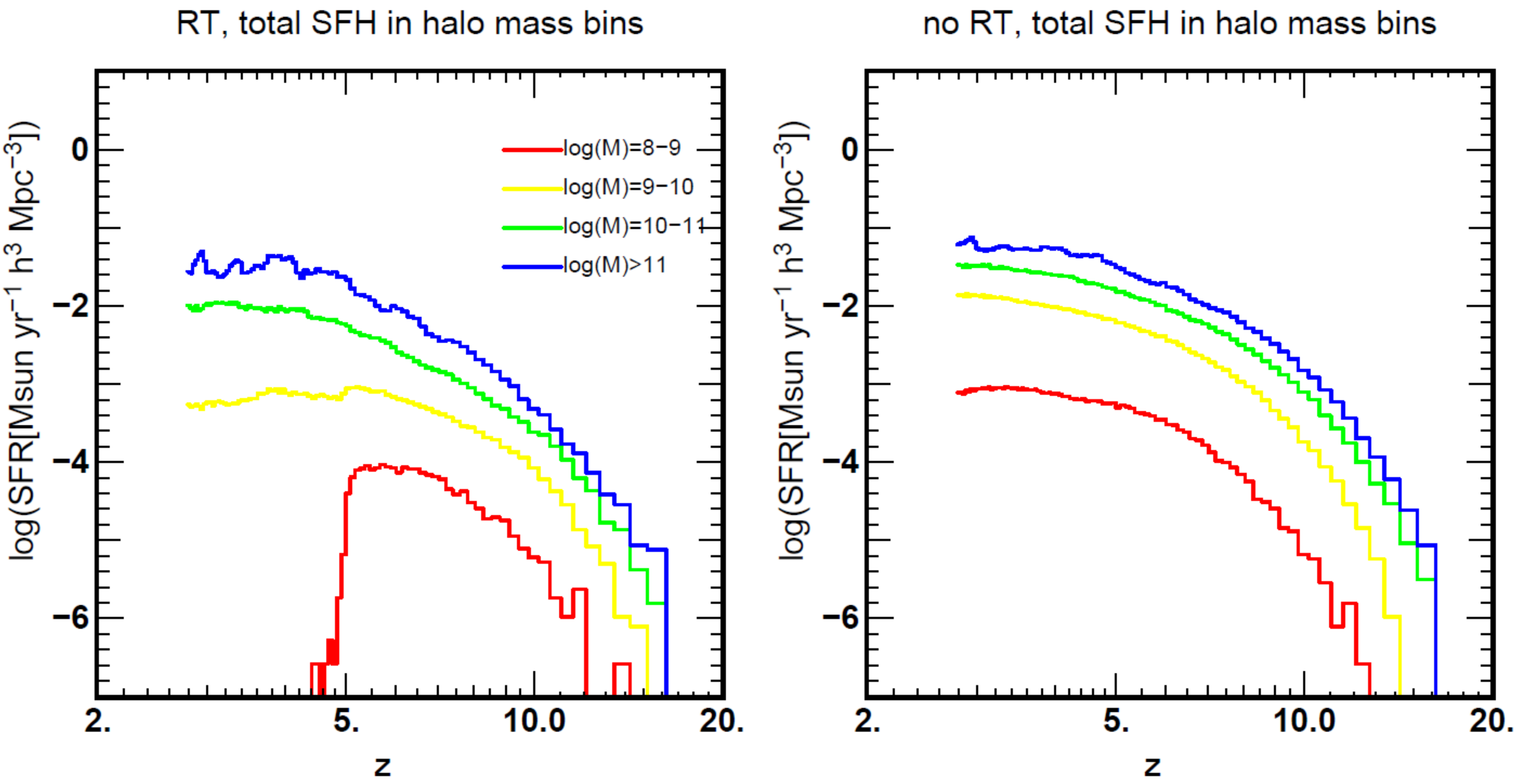
- Low-mass atomic cooling halos (LMACHs) are most suppressed



- SFR $\propto M^\alpha$ , $\alpha \sim 5/3$ for M > $10^{10}$ solar masses, but drops sharply below M ~ 3 X $10^9$ below z ~ 6

# Reionization of the Local Universe: Witnessing our Own Cosmic Dawn

**Shapiro, Ocvirk, Aubert, Iliev, Teyssier, Gillet, Yepes, Gottloeber, Choi, Park, D'Aloisio, Sullivan +**



- Star Formation Rate attributed to halo mass bins in which stars are found at a fixed late time, after reionization ends

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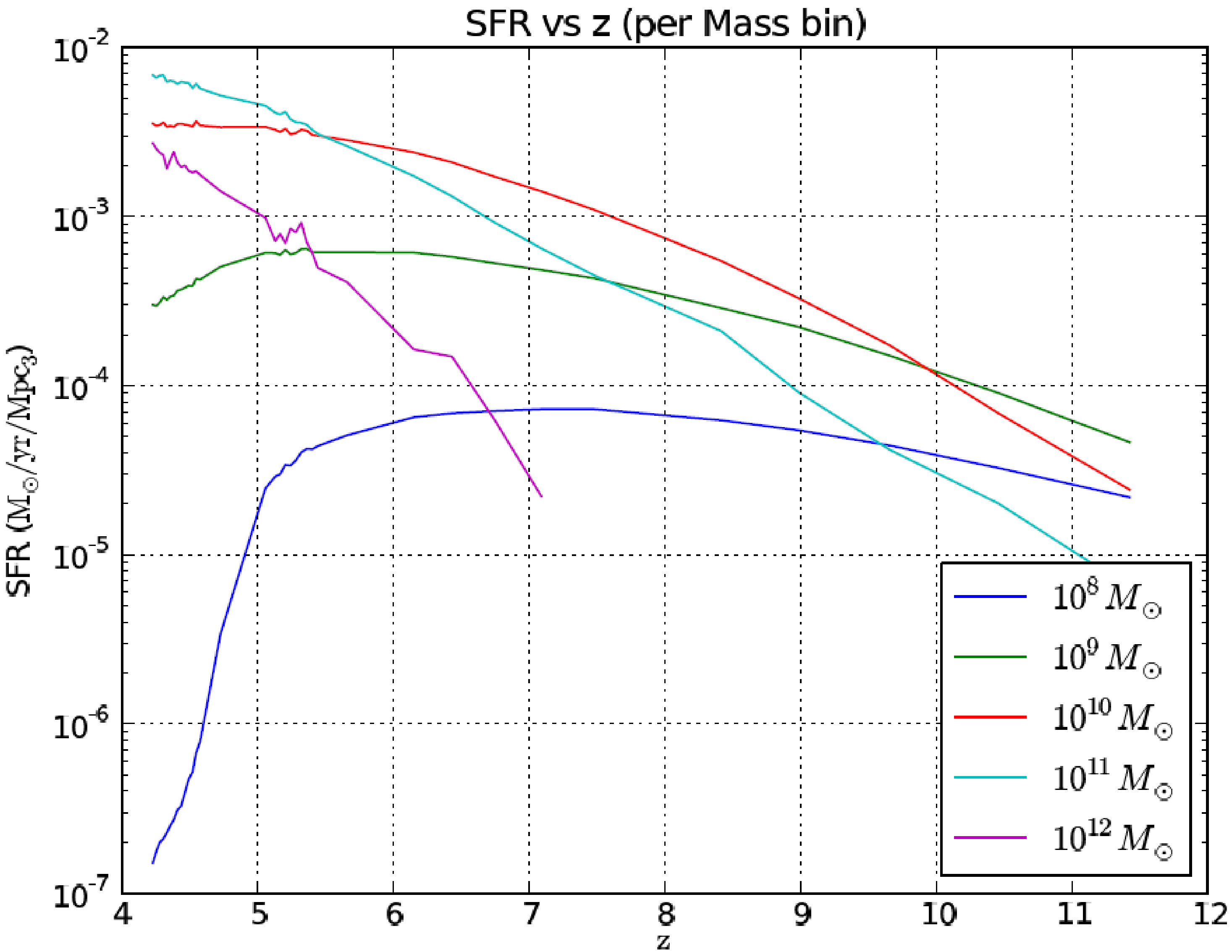

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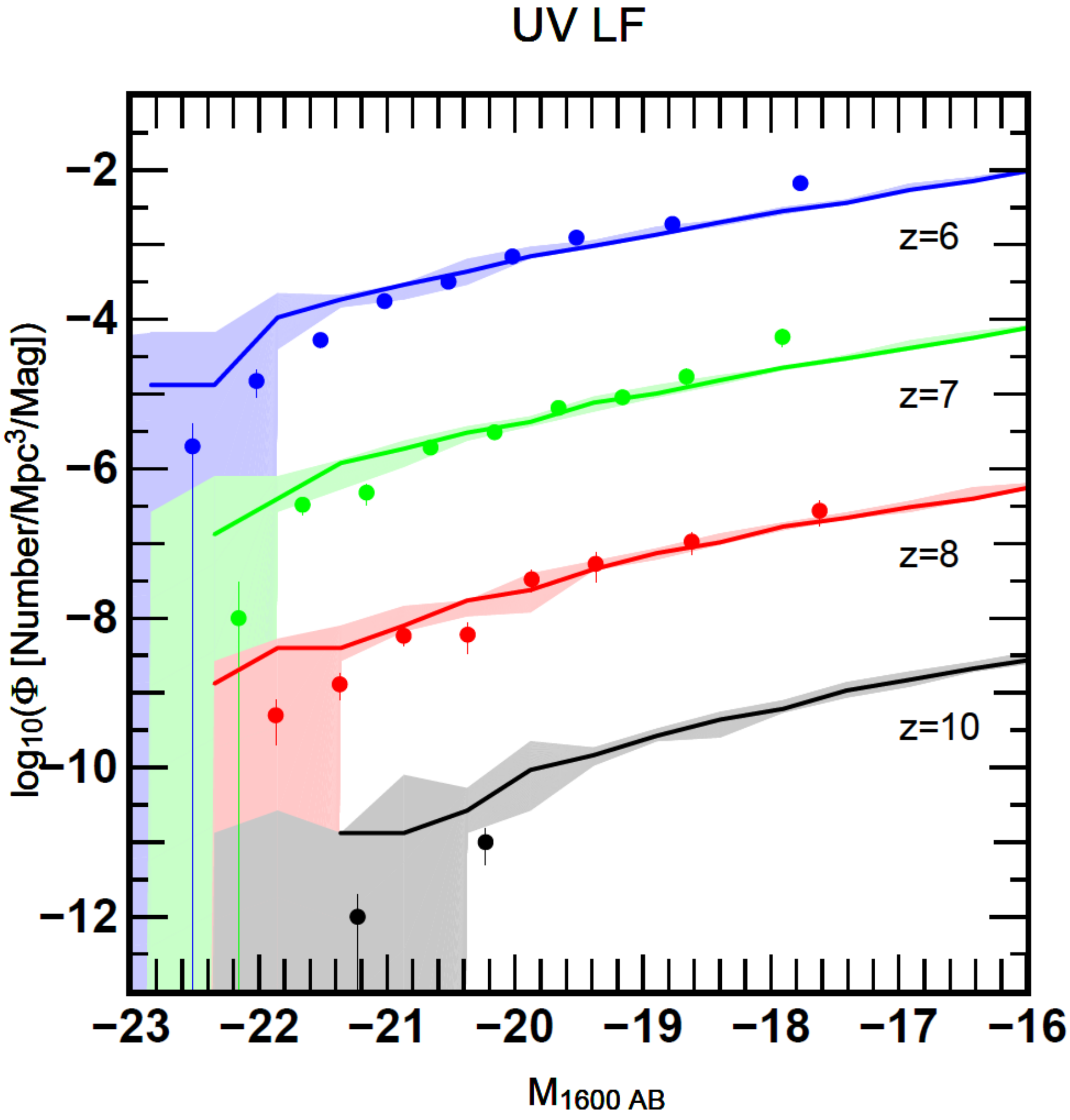
UV Luminosity Function
vs.
Observations from
Bouwens et al. (2014)

- Full circles are from Bouwens et al. (2014)
- Shaded areas and thick lines show the envelope and median of the LFs of 5 equal, independent subvolumes 50/h cMpc
- $M_{AB1600}$ magnitudes computed using lowest metallicity SSP models of Bruzual & Charlot (2003), scaled to same ionizing photons released per 10 Myr
- Shift simulation z ➔ z * 1.3



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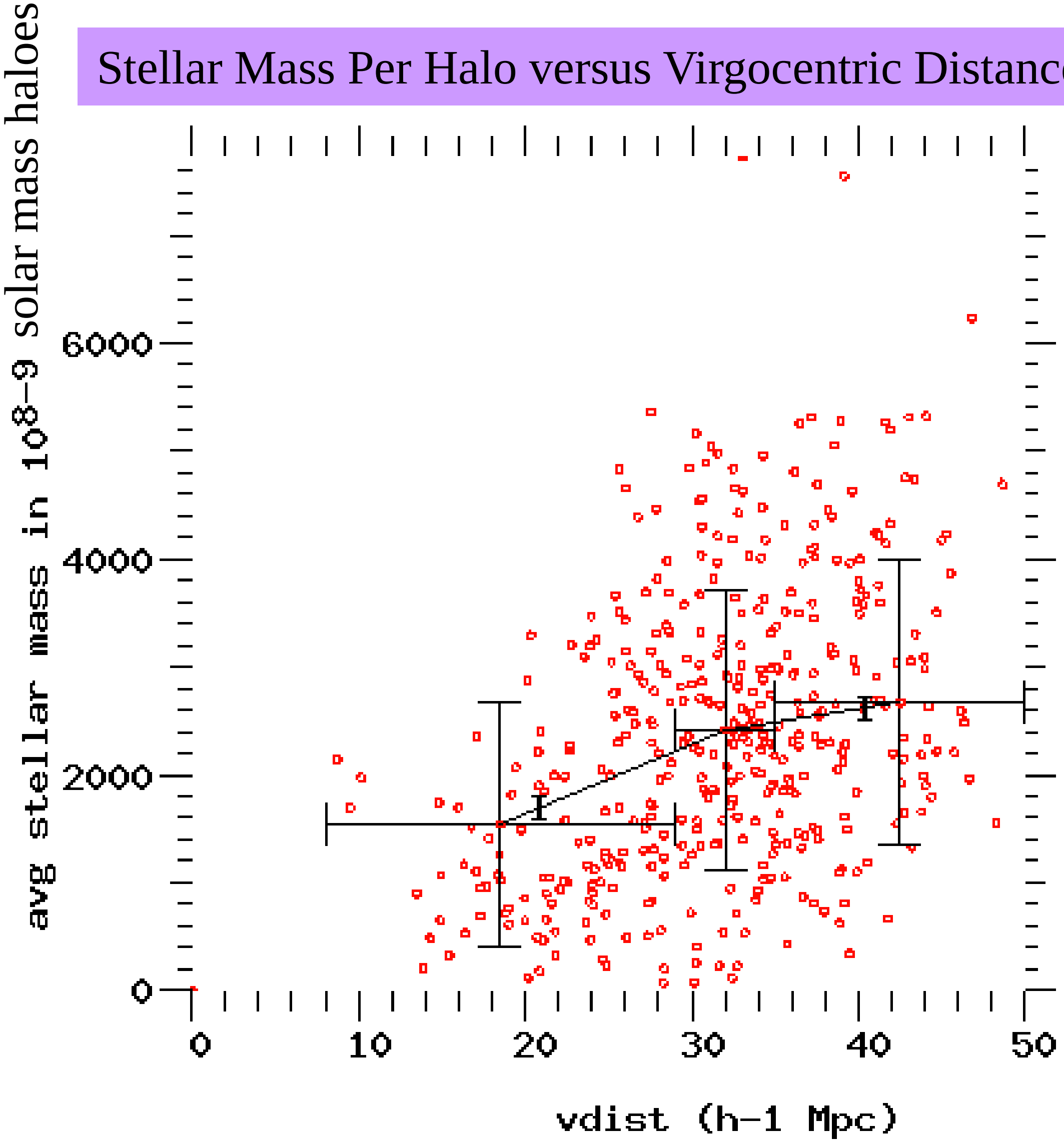
Stellar Mass Per Halo versus Virgocentric Distance



Reionization suppresses star formation rate in dwarf galaxies, for M < $10^9$ solar masses

- Suppression varies with location
- Suppression decreases with increasing distance from a density peak like that which made the Virgo cluster , whose influence can extend over 10's of cMpc

➔ Large-scale structure leaves an imprint on the SFR in dwarf galaxies correlated over 10's of Mpc

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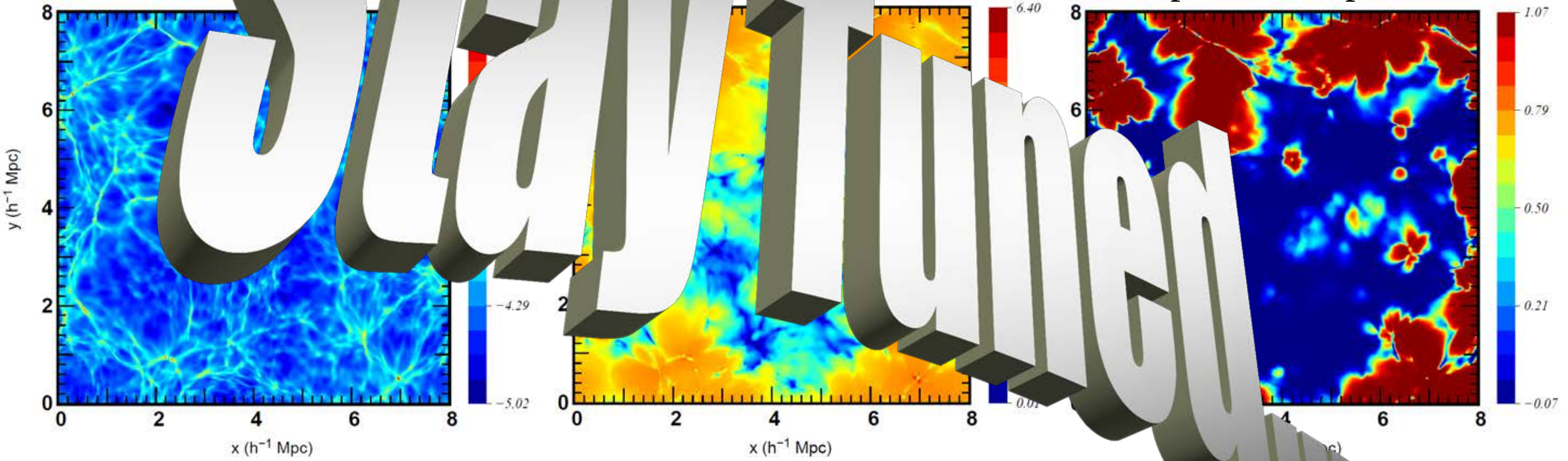
RAMSES-CUDAT N simulation
- Box size = 91
- Grid size = el x ~ 20 cKpc
- N-body pa 3 ~64 billion
- Min halo m $10^8$ ol 0 arts

TITAN Supercomputer requirements
- # steps/run = 2000 CPU (+800,000 GPU)
- # CPU cores (+ # GPUs) = 131,072 (+ 8192)
- # CPU hrs = 2.1 million node hrs ~ 11 days

Stay Tuned...

TEST RUN: 11 cMpc box: a spatial slice



log10(density) log10(temperature) ionized n fraction

- (left) the local cosmic web in the atomic gas ;
- (middle) red regions denote very hot, supernova-powered superbubbles, while yellow-orange regions show the long-range impact of photo-heating by starlight;
- (right) ionized hydrogen fraction [dark red (dark blue) = ionized (neutral)].

PEACE and Happy Anniversary !