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

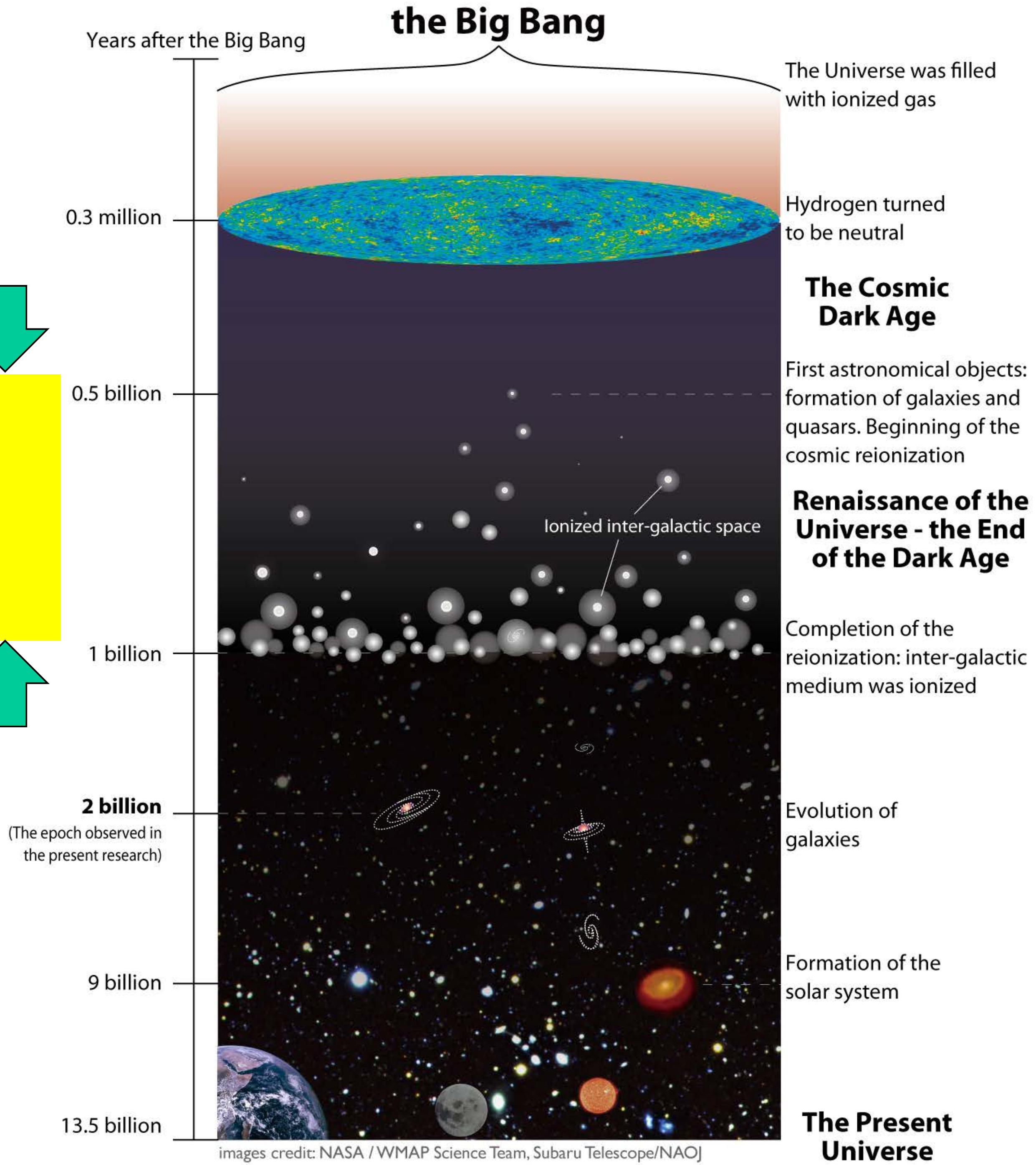
Paul Shapiro
The University of Texas at Austin

Collaborators in the new work described today include:

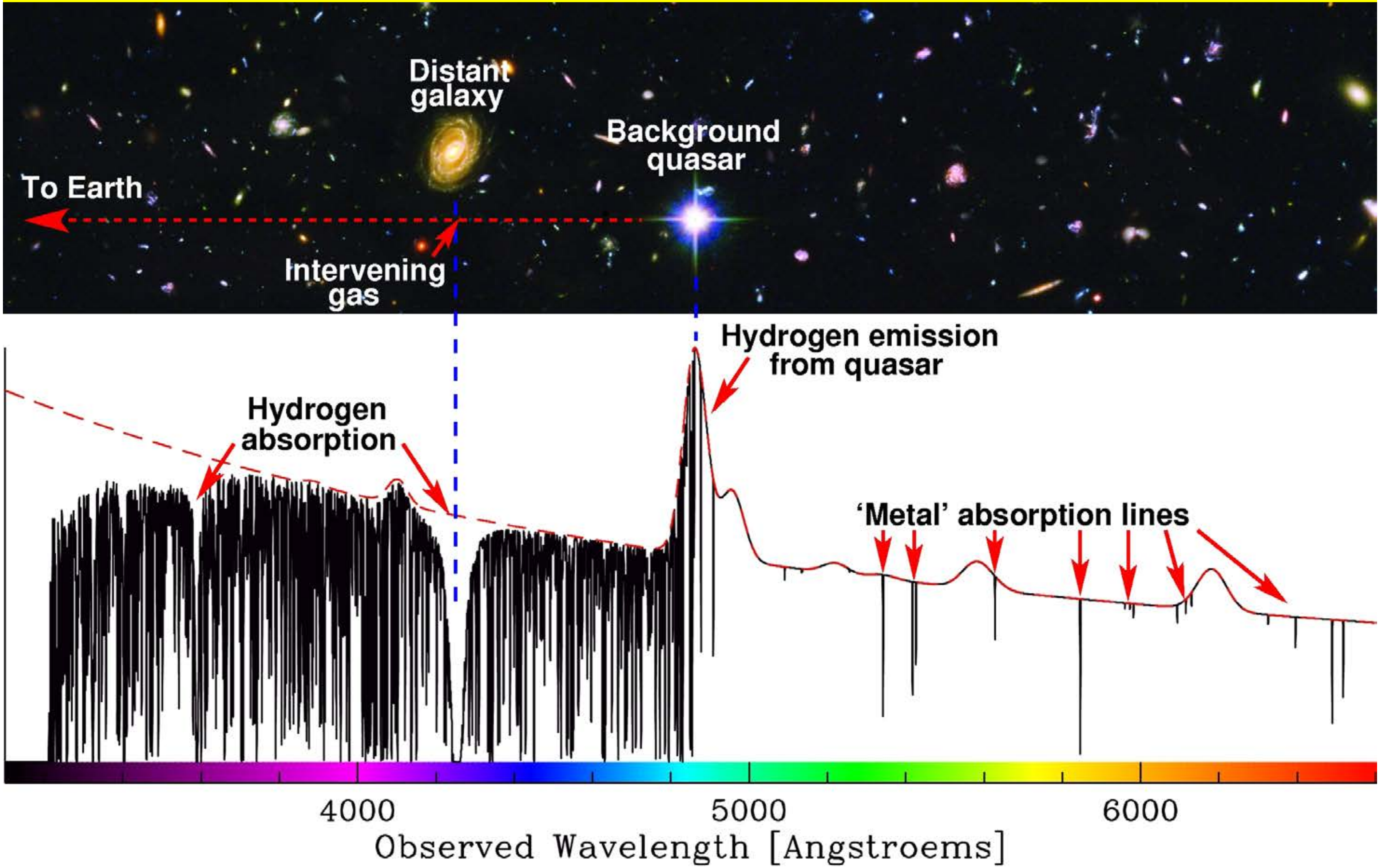
Pierre Ocvirk[3], Dominique Aubert[3], Nicolas Gillet[3], Ilian Iliev[2], Romain Teyssier[4], Gustavo Yepes[5], Stefan Gottloeber[6], Junhwan Choi[1], Hyunbae Park[1], Anson D'Aloisio[1], David Sullivan[2], Yehuda Hoffman[7], Alexander Knebe[5], Timothy Stranex[4]
(1)U Texas at Austin (2)U Sussex (3)U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

SC15
Austin, Texas, November 18, 2015

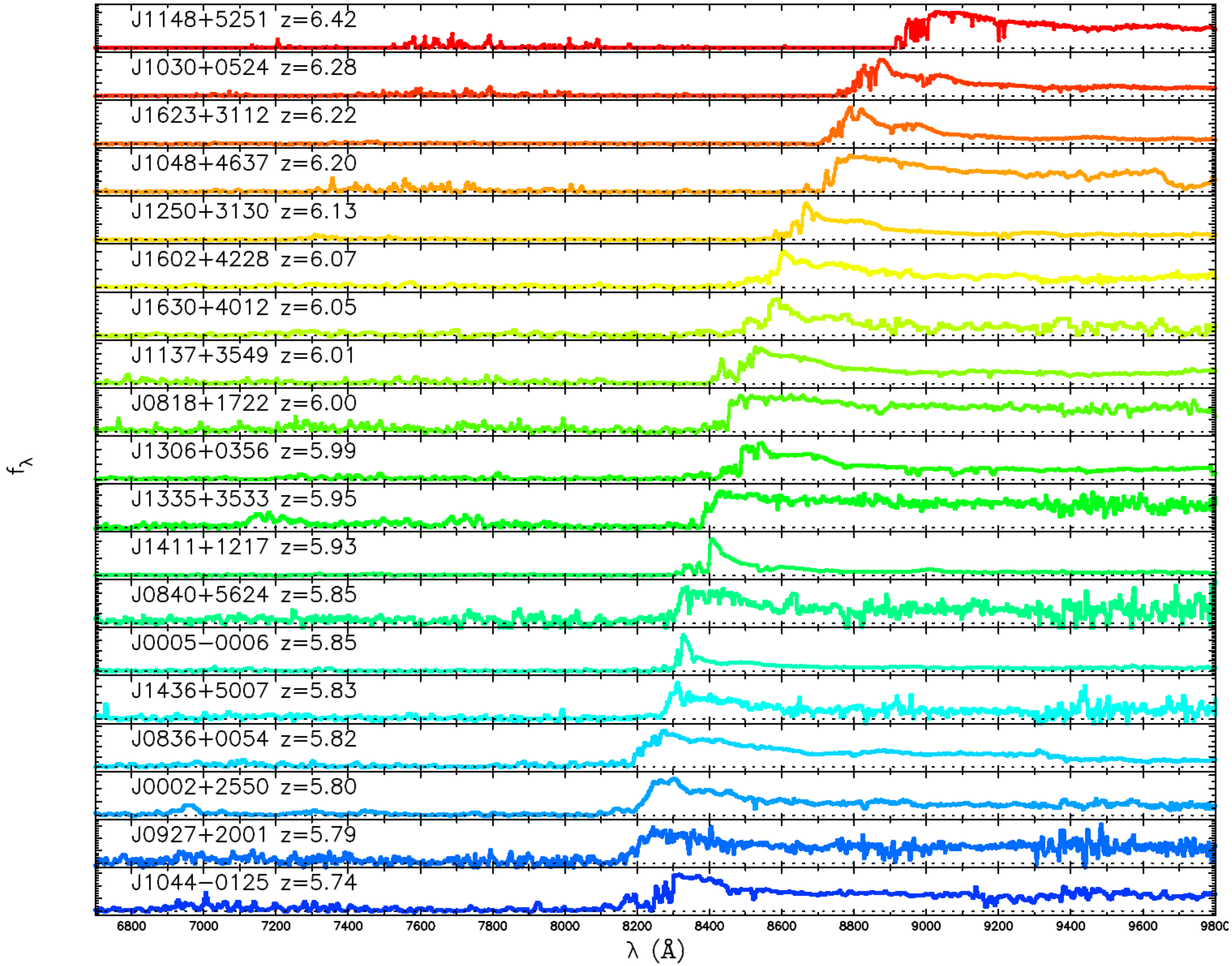
The Epoch of Reionization



Intergalactic H atoms scattered light from distant quasars ➔ quasar absorption spectra sample the intervening neutral H atoms



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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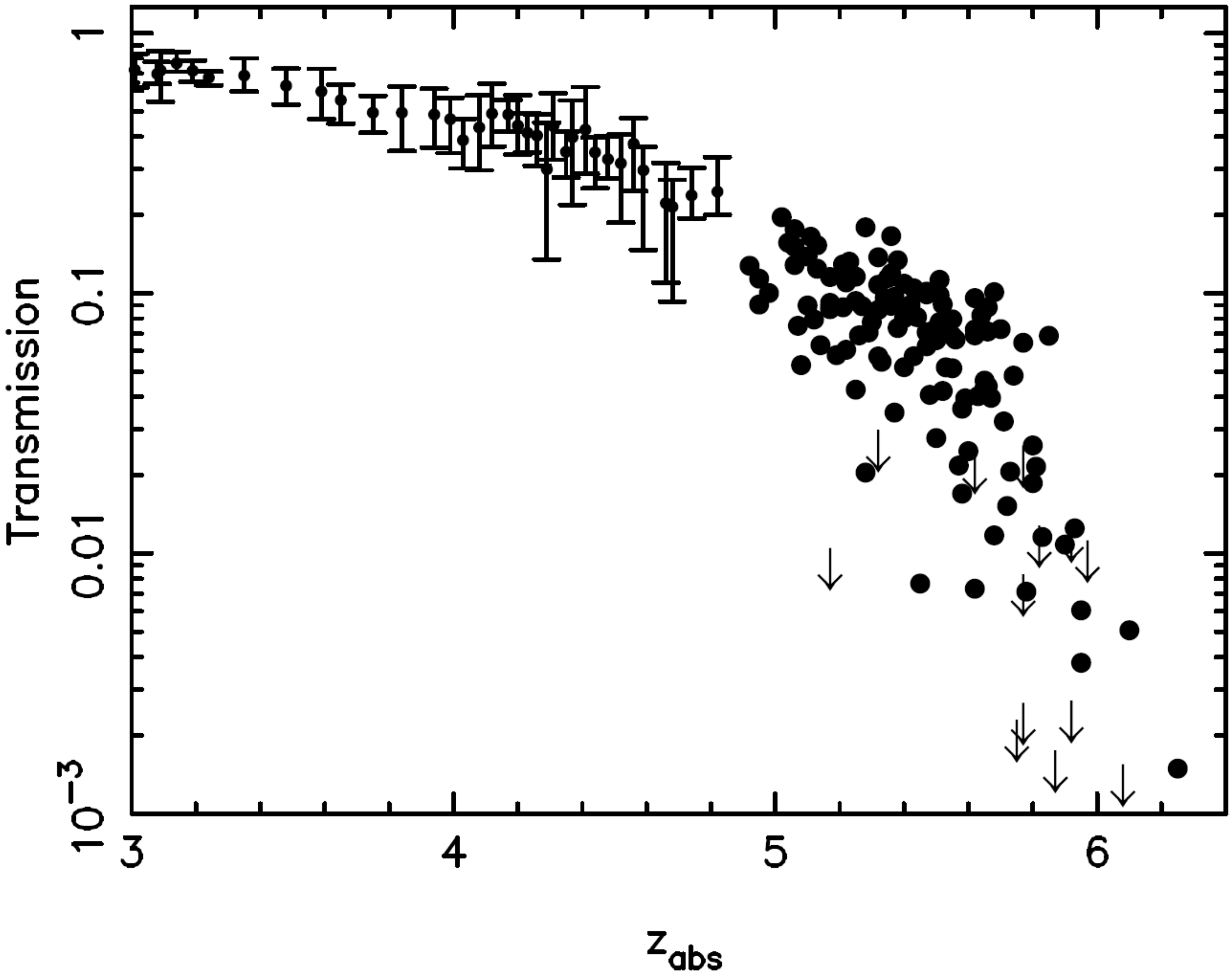


Fan et al (2006)

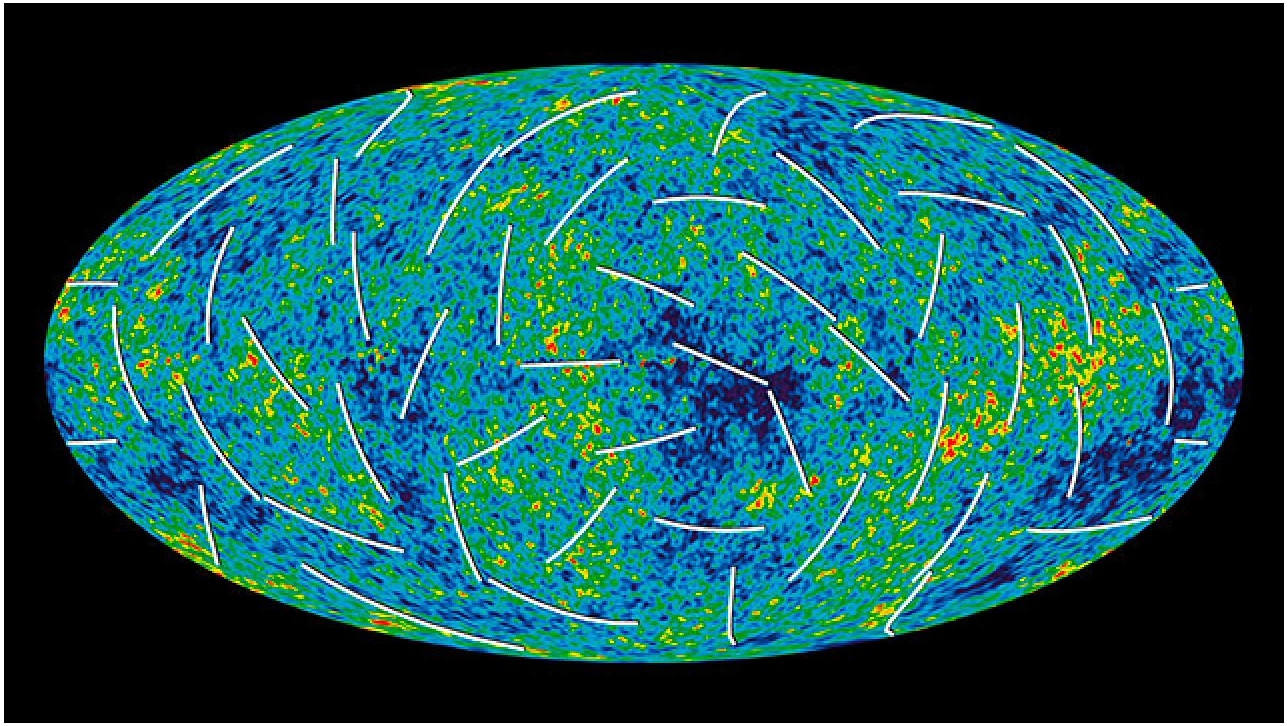
The Epoch of Reionization

- 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.

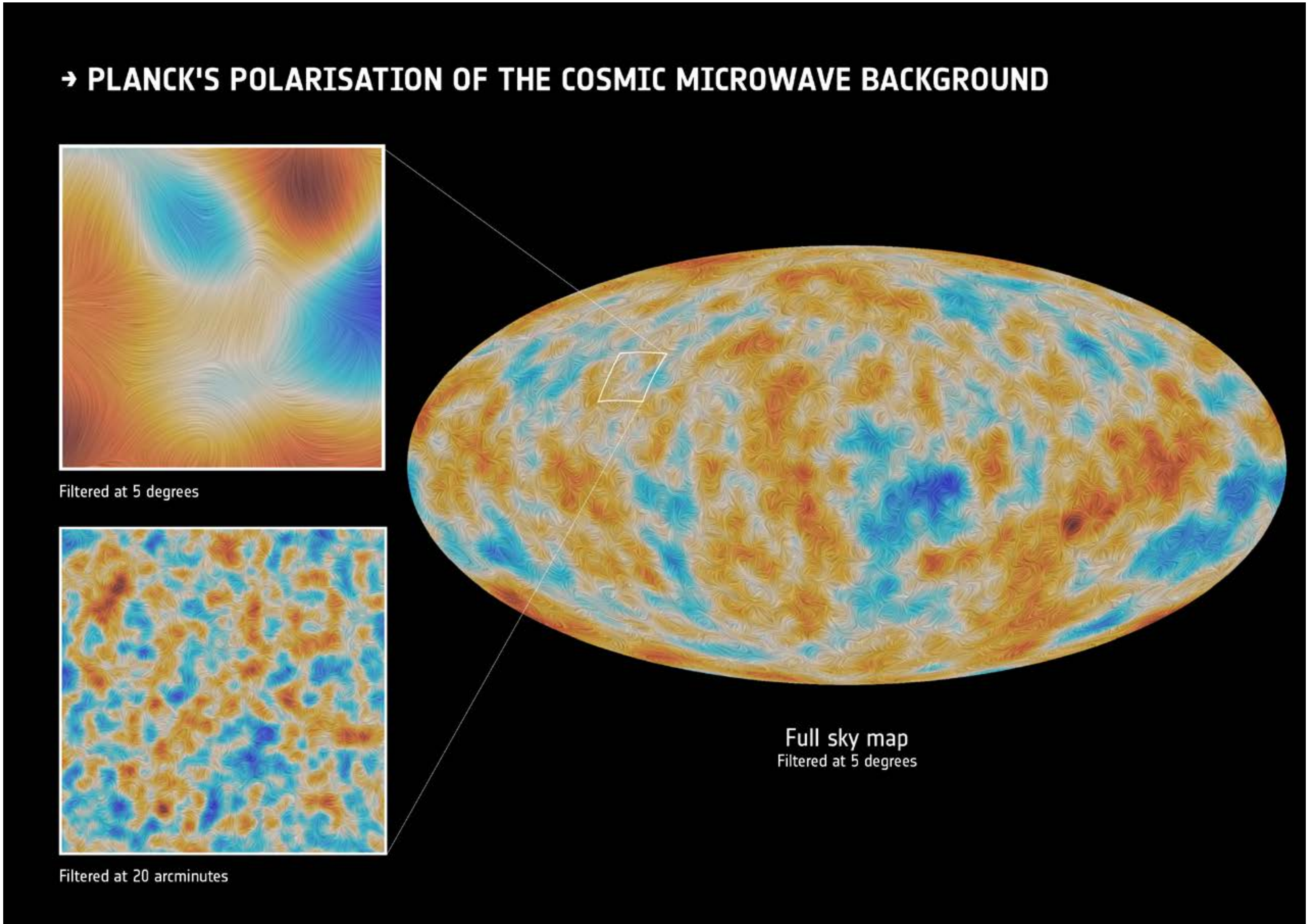
  ===> universe experienced an "epoch of reionization" before this.
- Sloan Digital Sky Survey quasars have been observed at $z > 6$ whose absorption spectra show dramatic increase in the H I fraction at this epoch as we look back in time.

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

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



The Epoch of Reionization

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  ===> 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

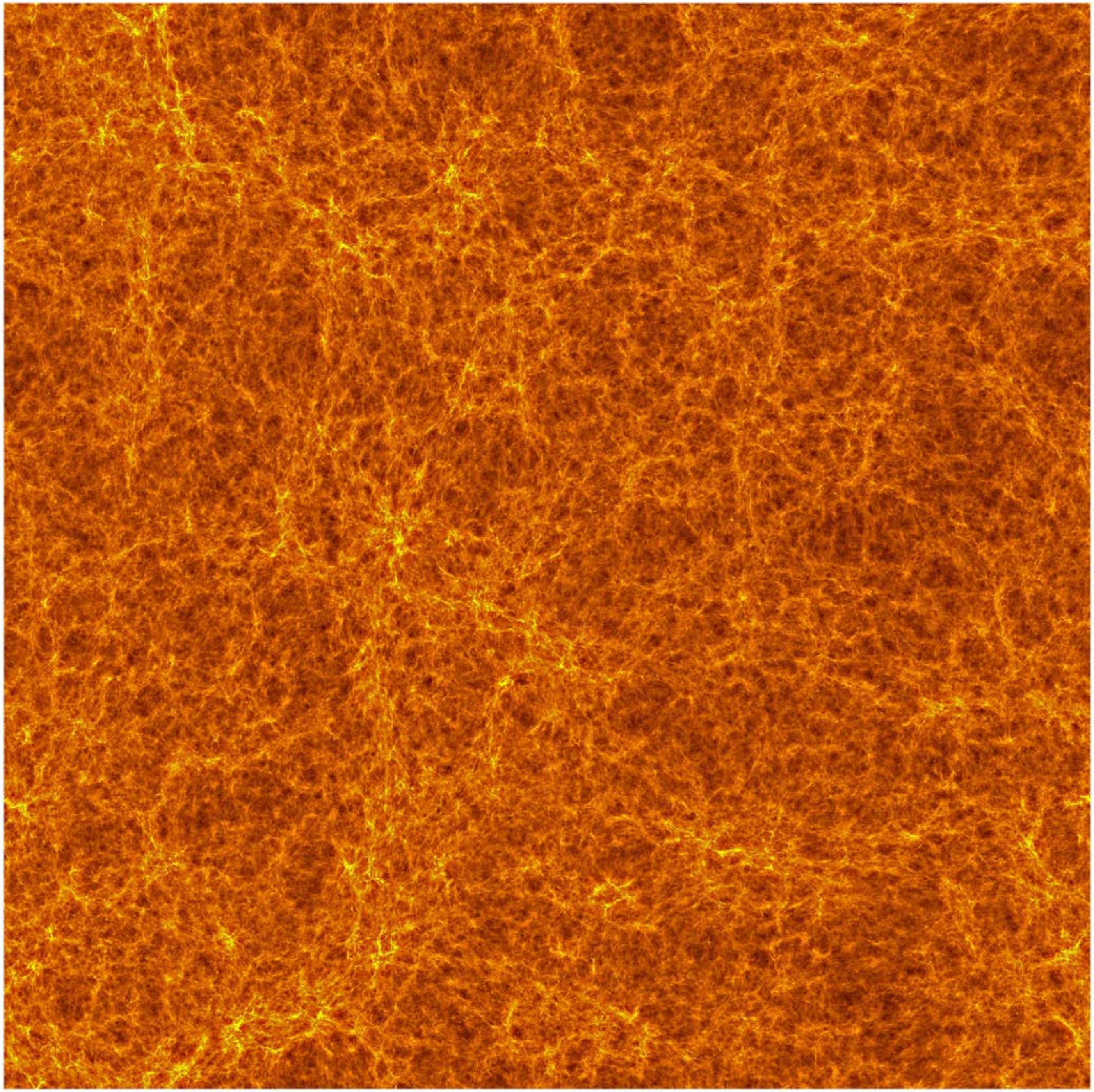
  ===> reionization already substantial by $z \gtrsim 9$

Structure formation in ΛCDM at z = 10

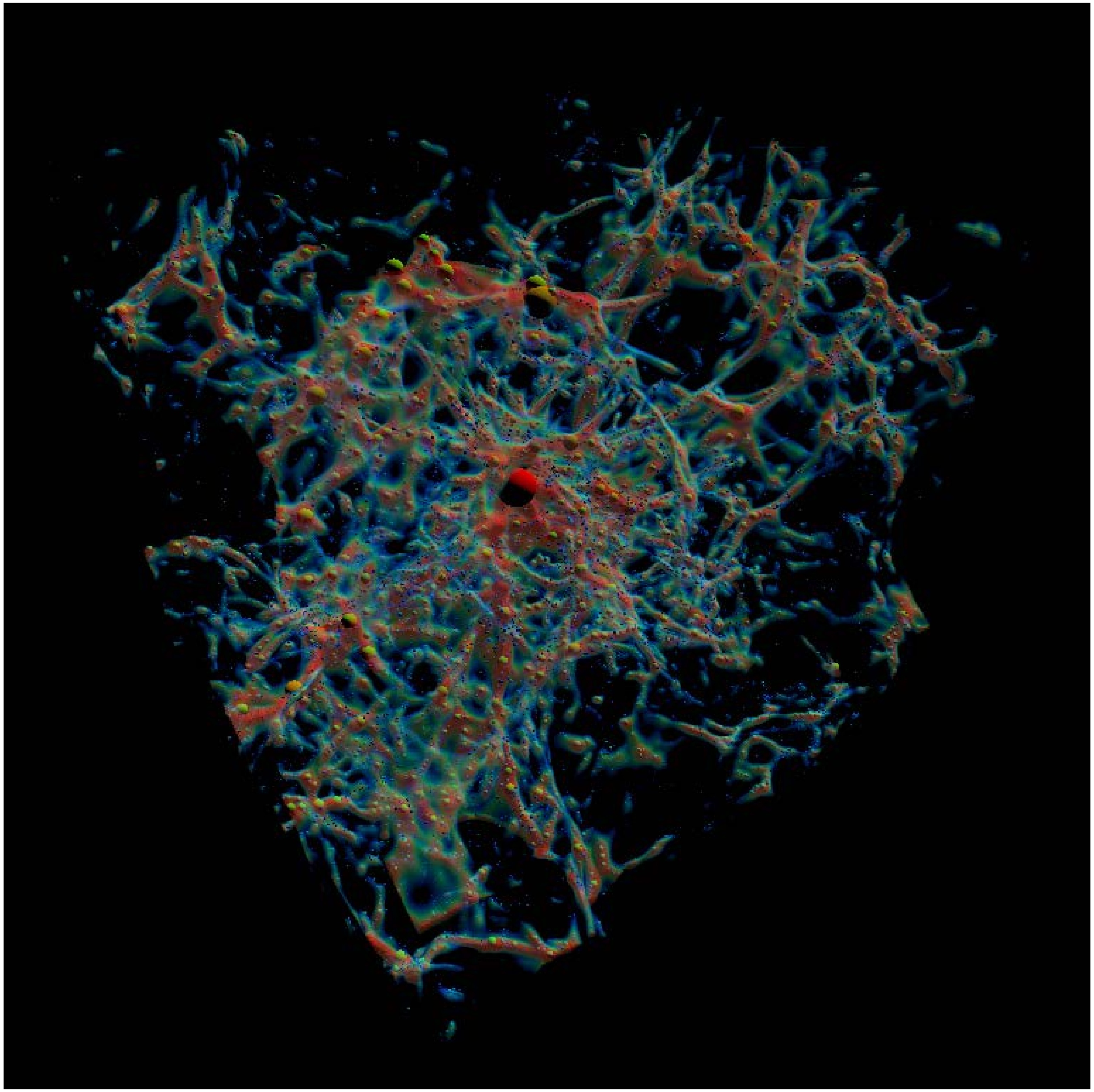
simulation volume = $(100\ h^{-1}\mathrm{Mpc})^3$, comoving

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



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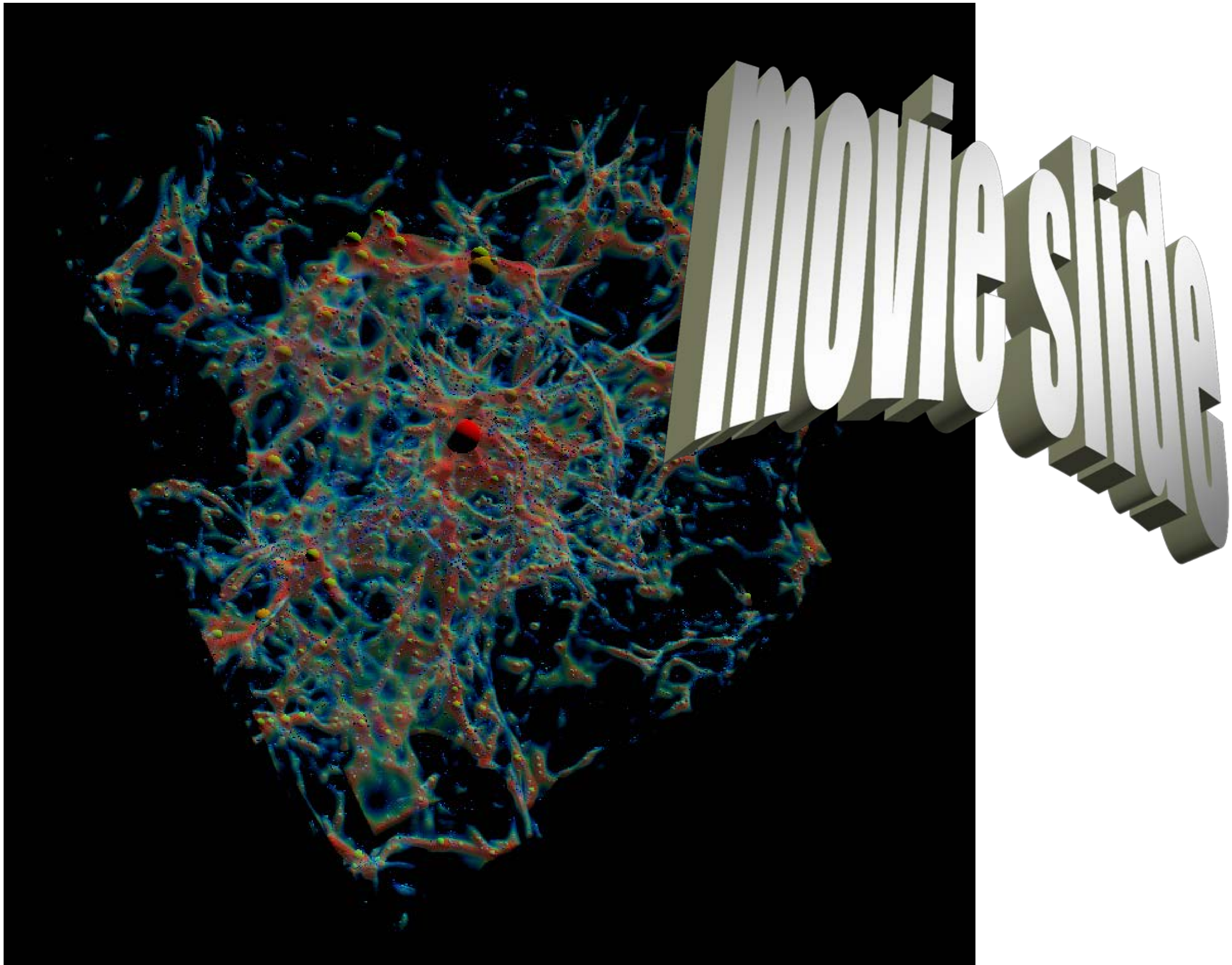


Self-Regulated Reionization

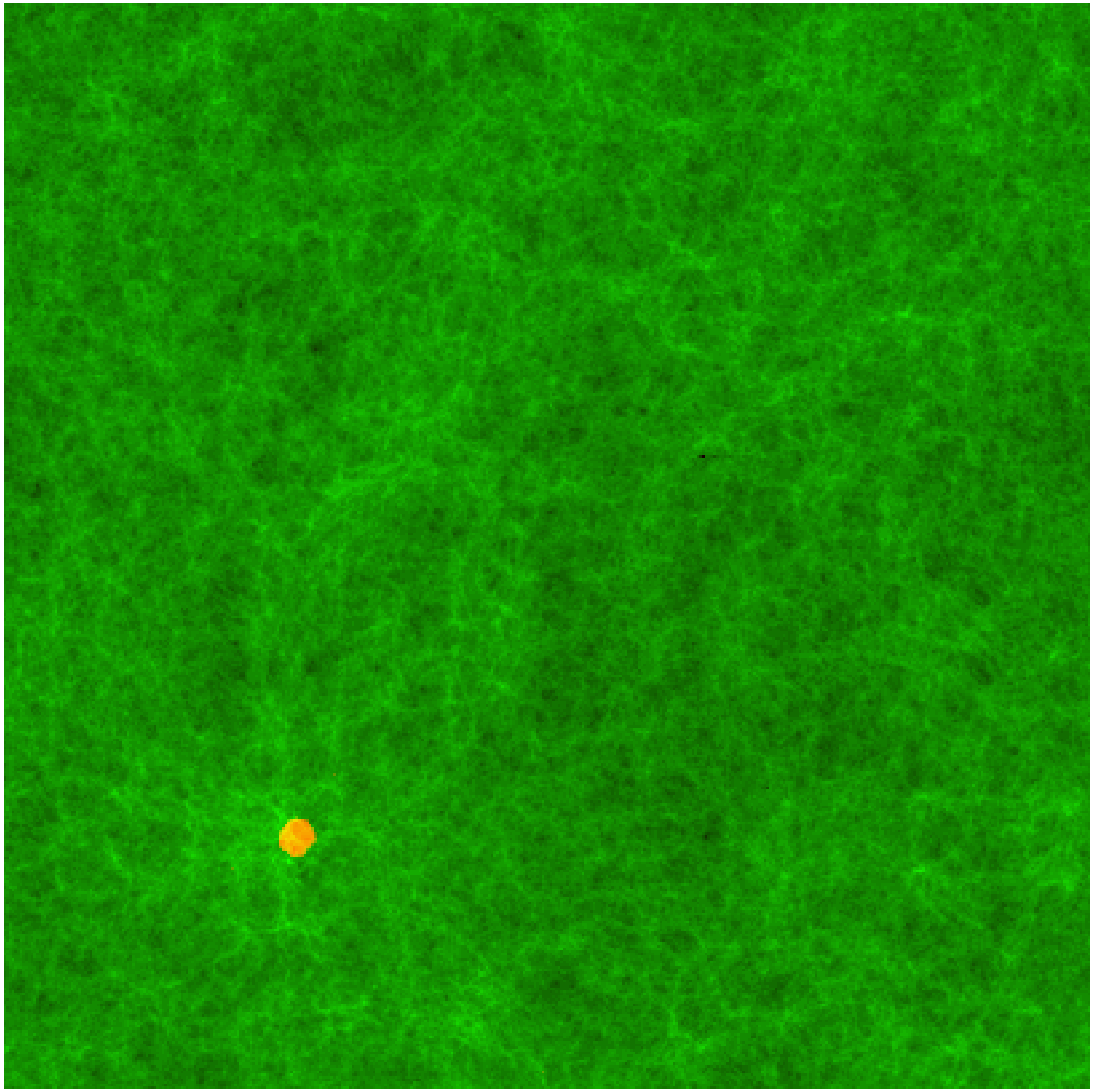
Iliev, Mellema, Shapiro, & Pen (2007), MNRAS, 376, 534; (astro-ph/0607517)

•Jeans-mass filtering ➔ low-mass source halos ($M < 10^9\ M_{solar}$) cannot form inside H II regions ;

•50 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 $z_{ov} = 7.5$.



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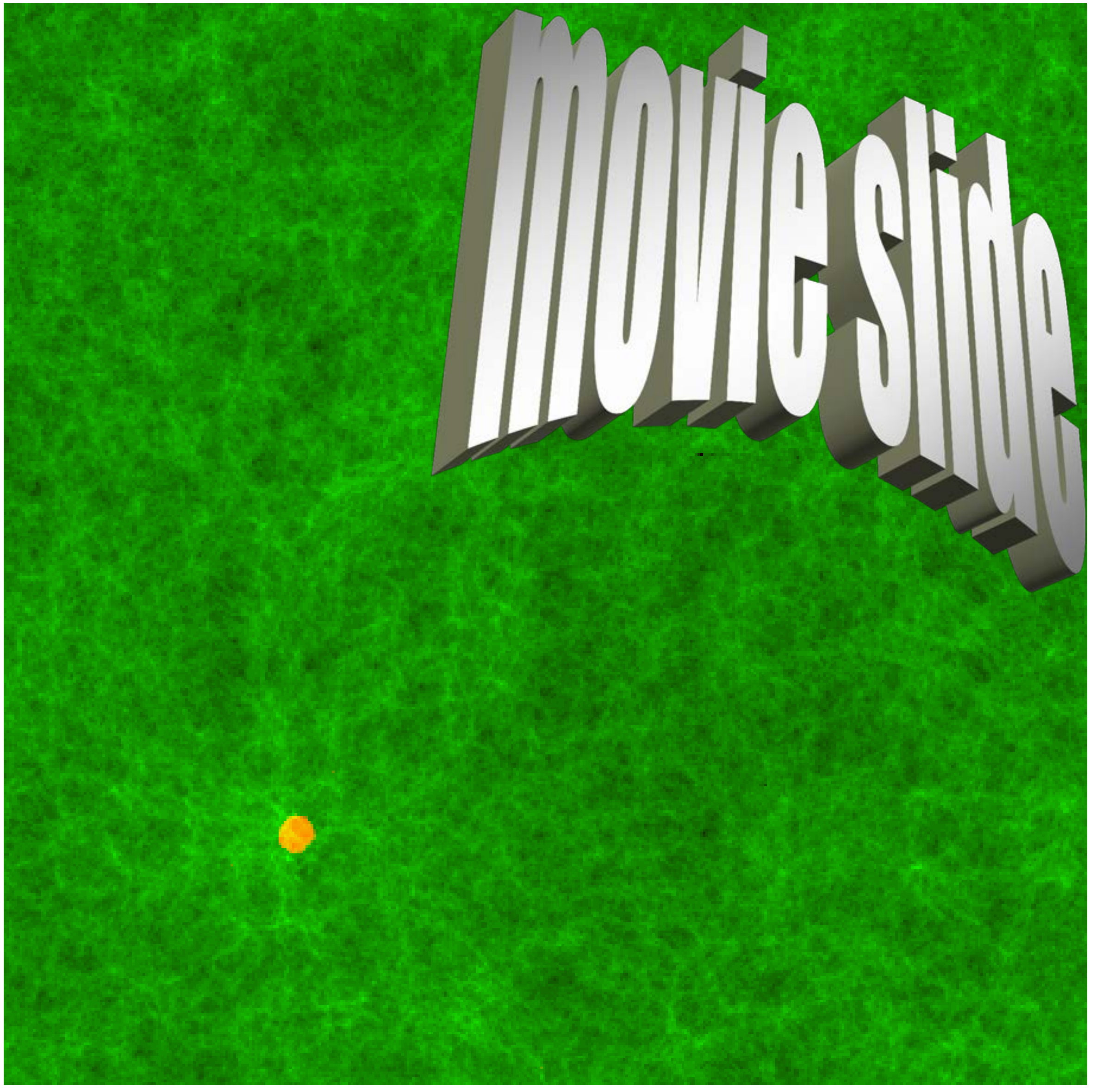
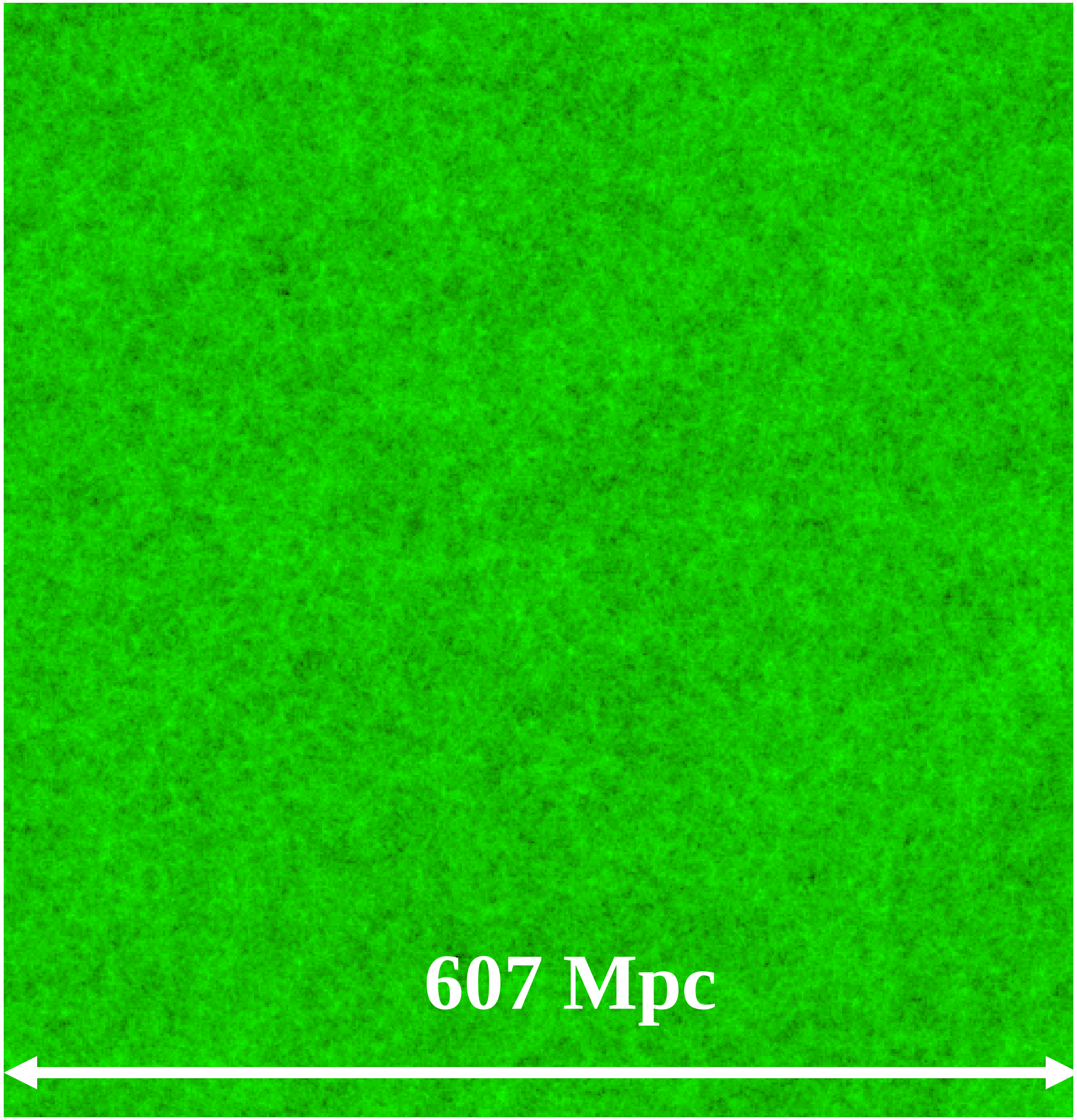
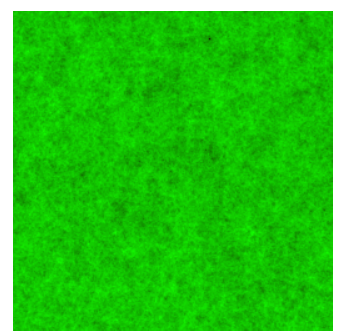


Large-scale, self-regulated reionization by atomic-cooling halos

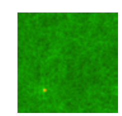
Three generations of simulation



163 Mpc



50 Mpc



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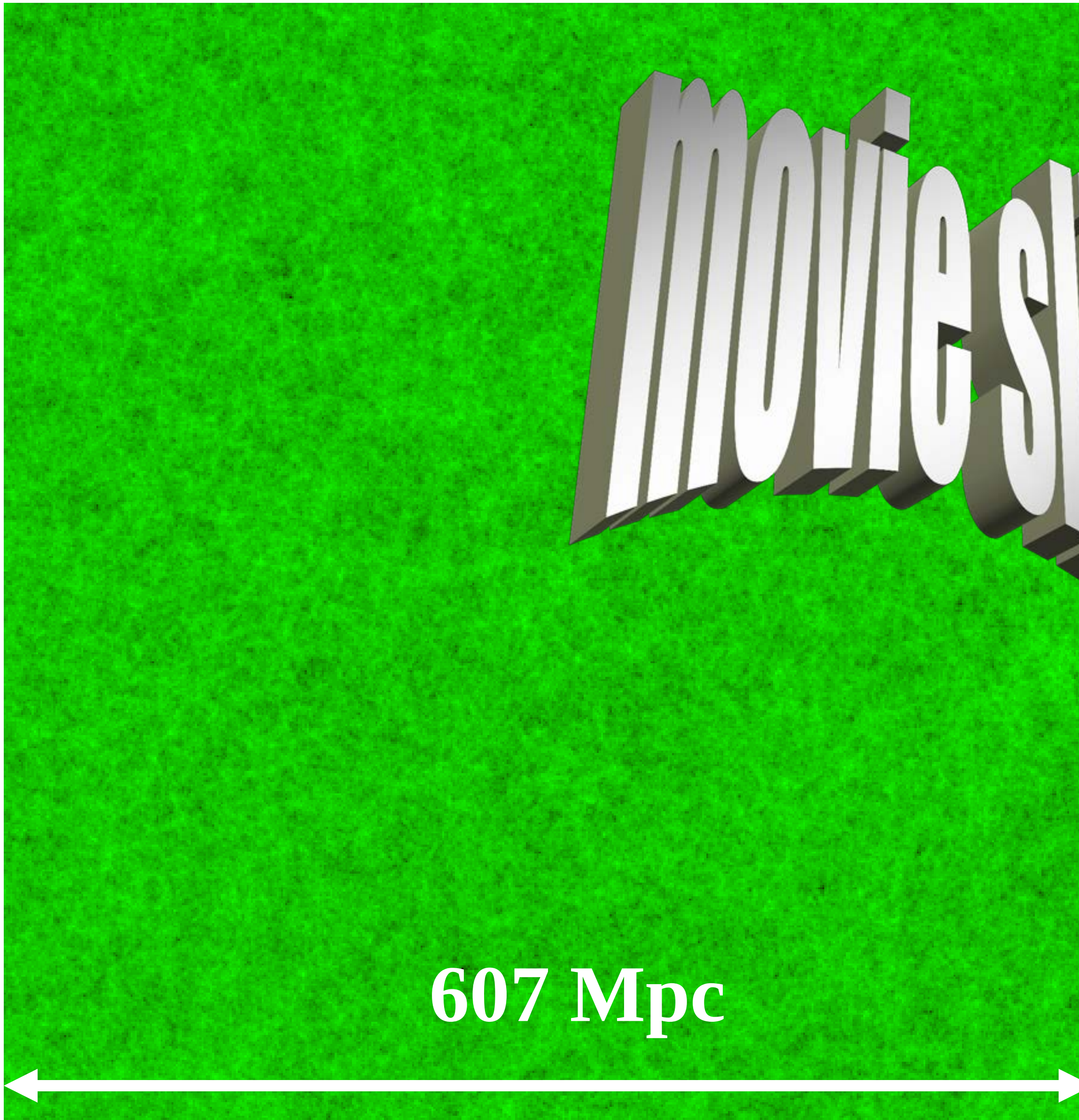

Three generations of simulation

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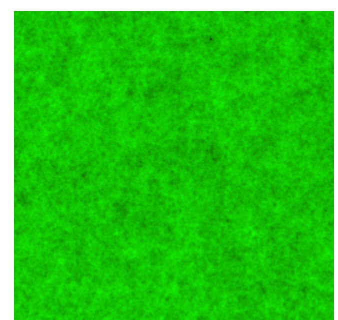
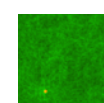


50 Mpc



Reionization of the Local Universe

Part II

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Austin, Texas, November 18, 2015

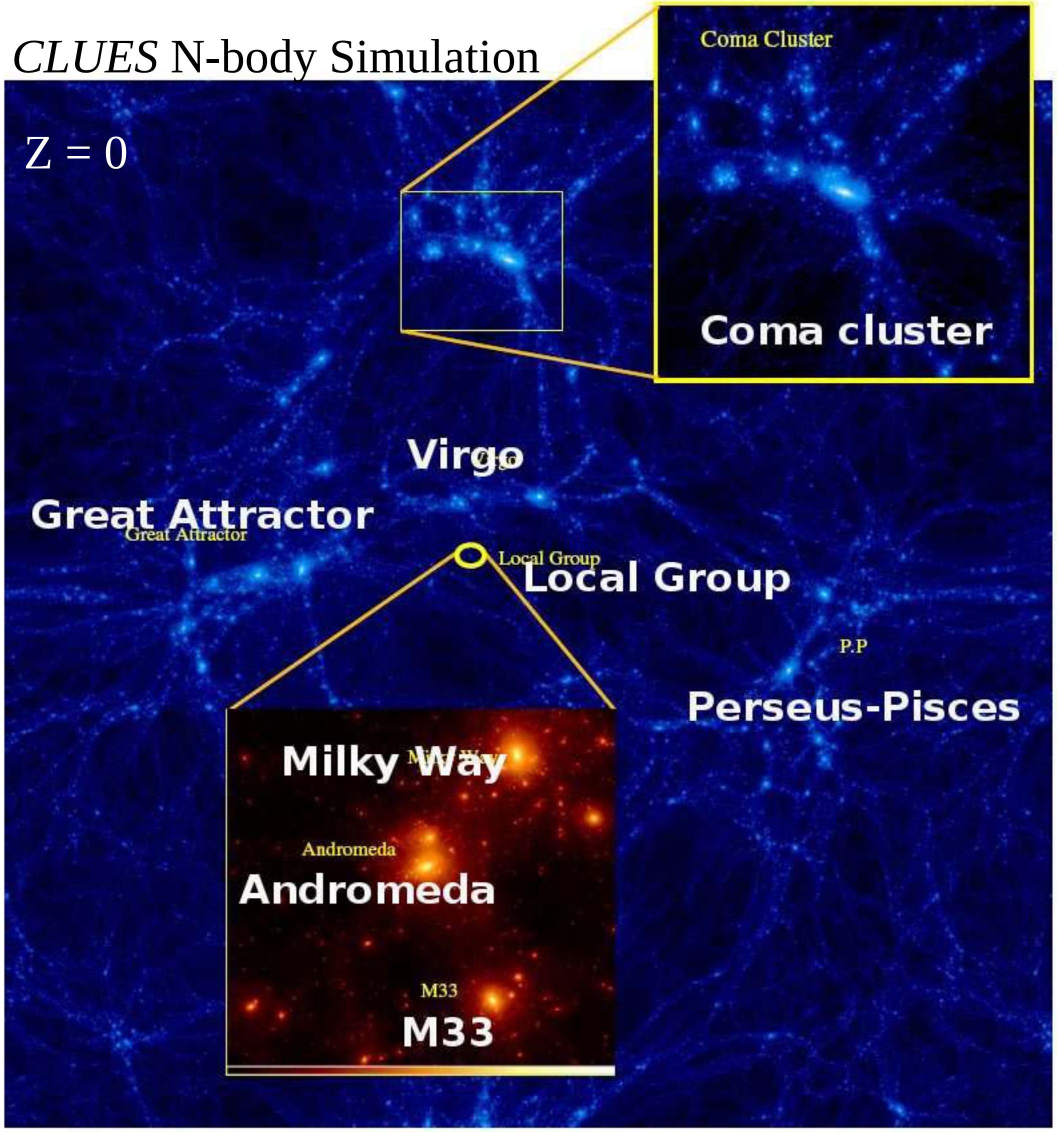
Reionization of the Local Universe: Witnessing our Own Cosmic Dawn

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?

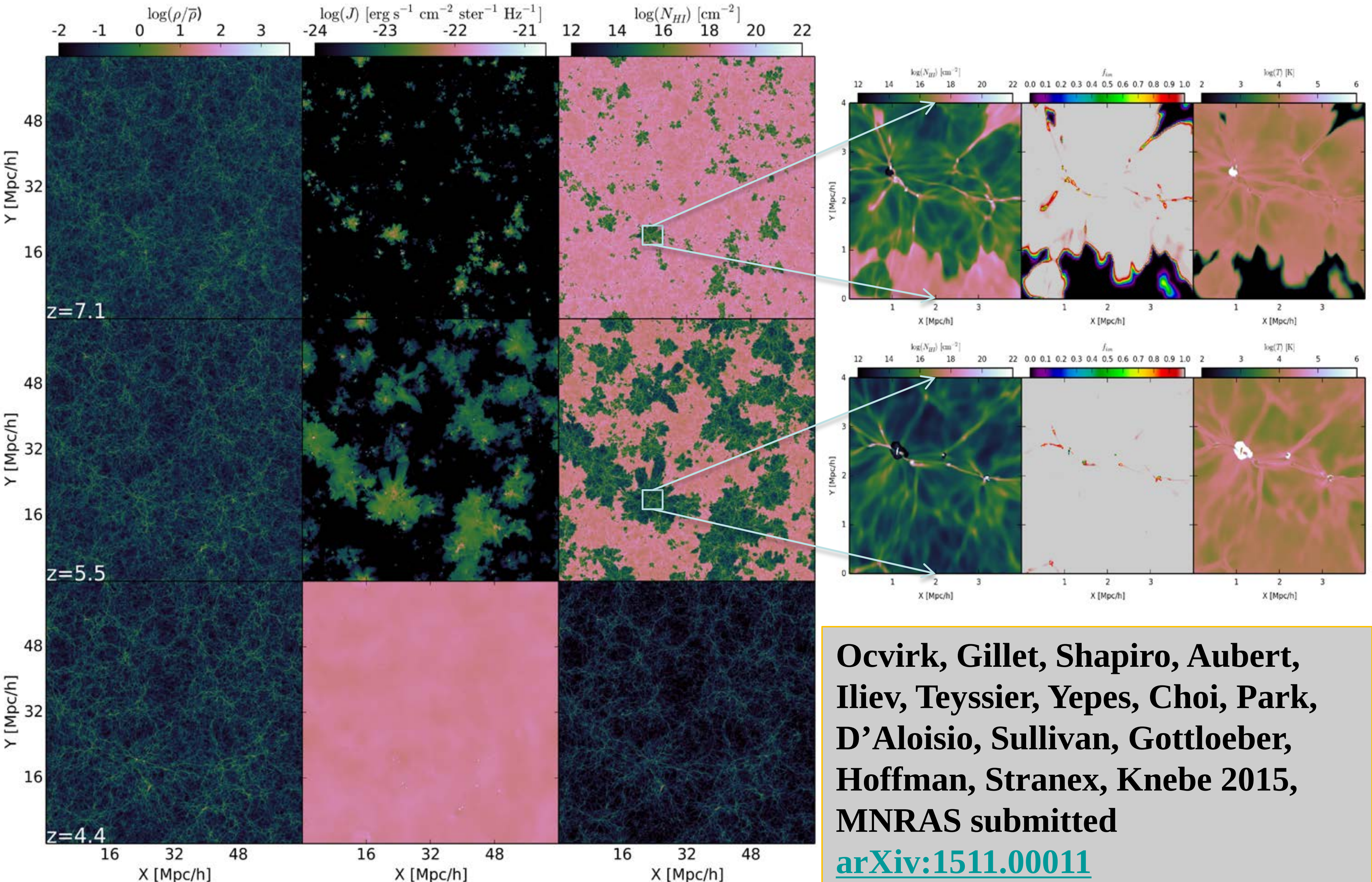
A: Simulate the coupled radiation-hydro-N-body problem of reionization ➔ galaxy formation with ionization fronts that swept across the IGM in the first billion years of cosmic time, in a volume 91 Mpc on a side centered on the Local Group.

CLUES N-body Simulation



229 cMpc

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



Ocvirk, Gillet, Shapiro, Aubert, Iliev, Teyssier, Yepes, Choi, Park, D'Aloisio, Sullivan, Gottloeber, Hoffman, Stranex, Knebe 2015, MNRAS submitted

arXiv:1511.00011

Reionization of the Local Universe: Witnessing our Own Cosmic Dawn

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

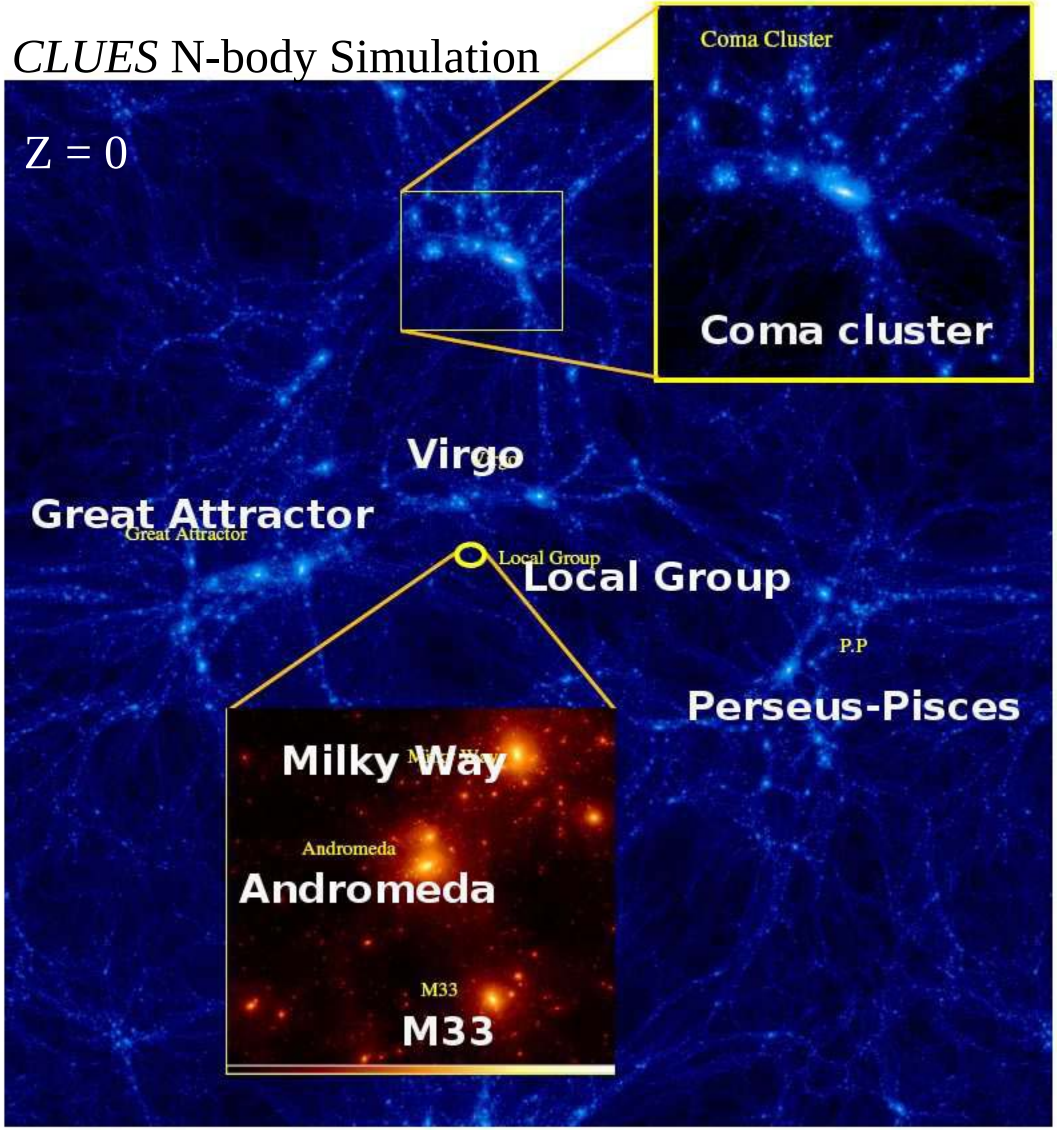
What makes this possible now?

1) Initial Conditions:
- 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

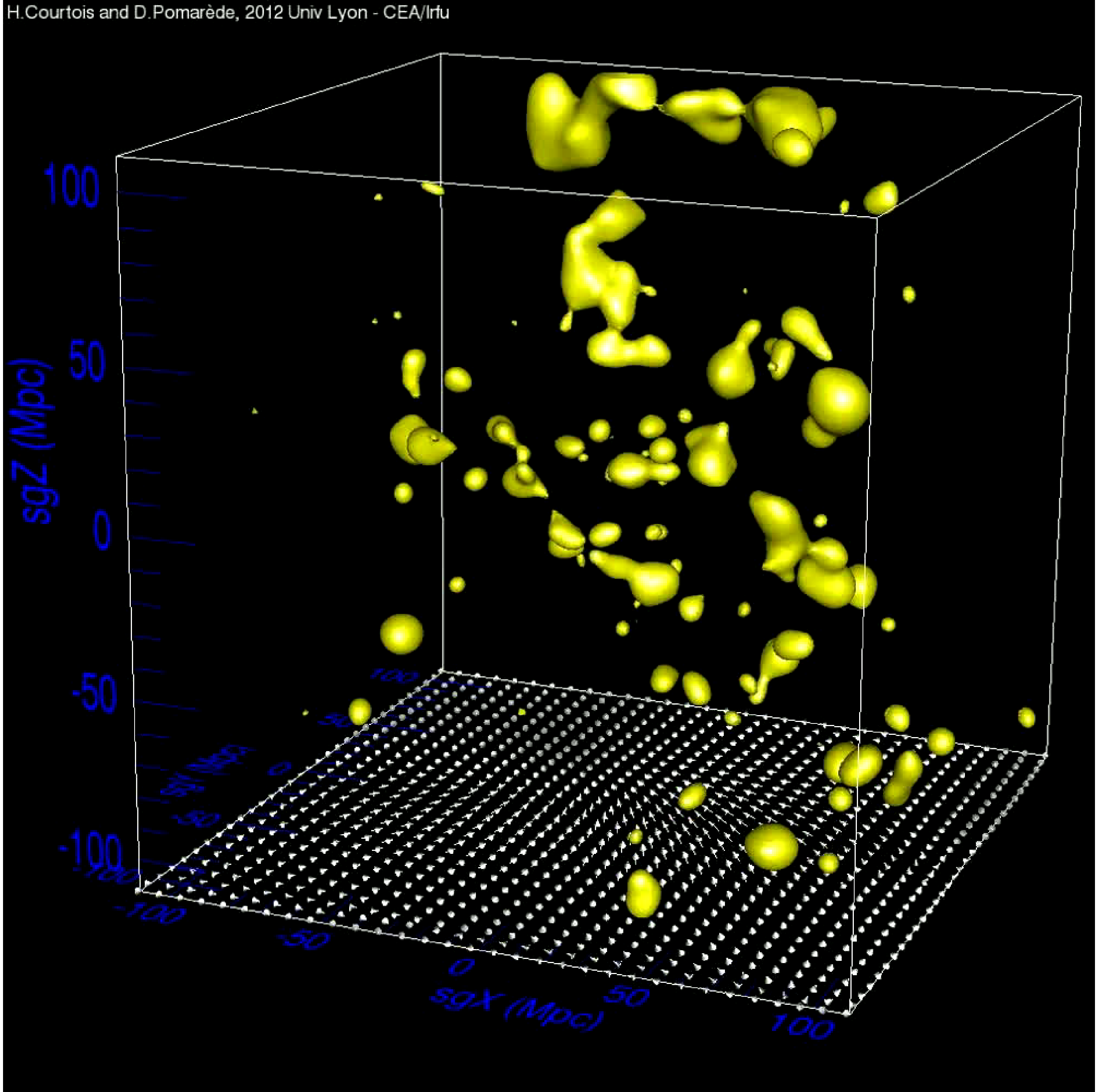
- This reproduces observed features of our local Universe, including the Local Group and nearby galaxy clusters.

- Add higher frequency modes for small-scale structure

CLUES N-body Simulation



229 cMpc


H.Courtois and D.Pomarède, 2012 Univ Lyon - CEA/Irfu
sgZ (Mpc)
100
50
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-50
-100
sgX (Mpc)
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-50
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50
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sgY (Mpc)
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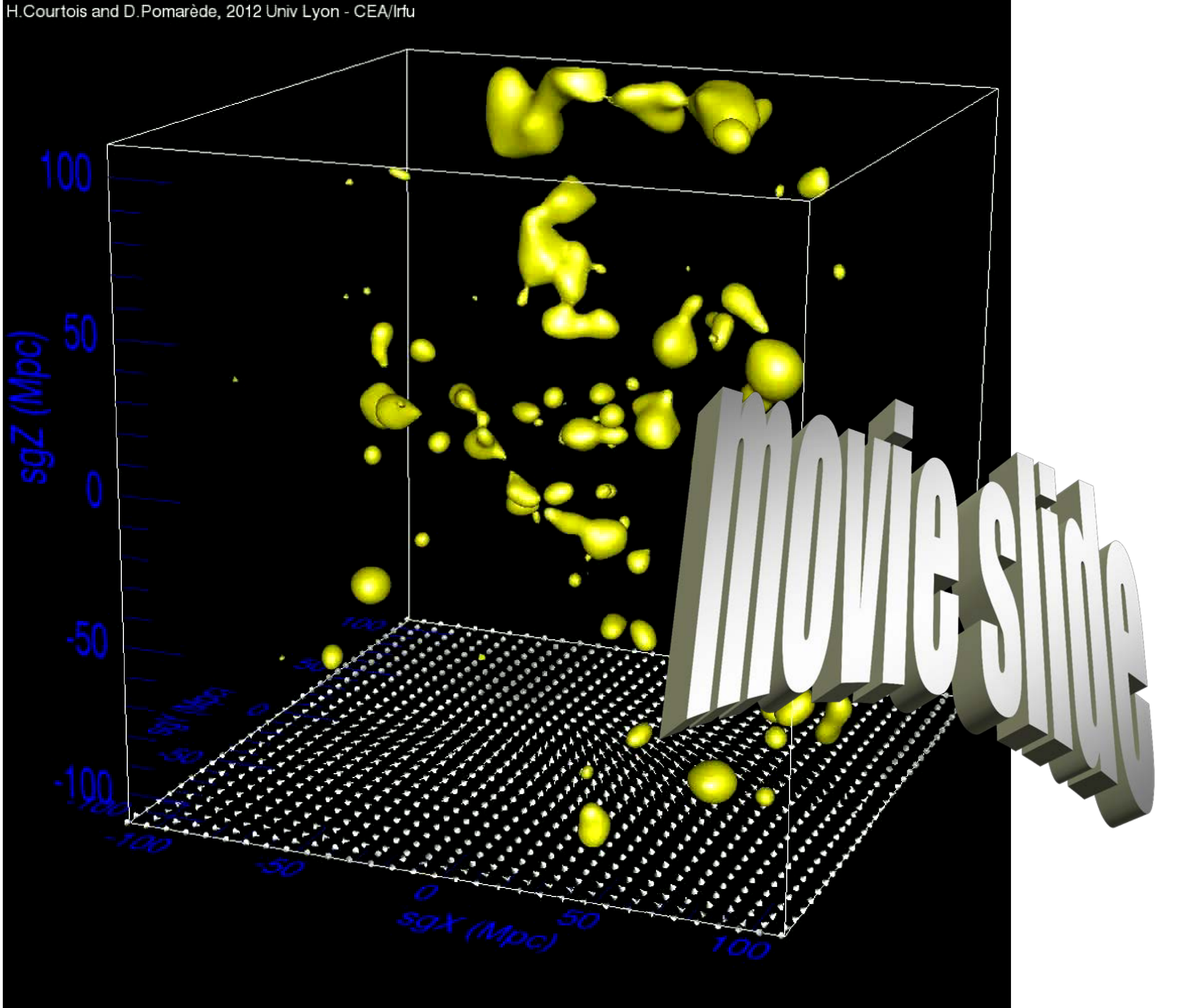
-50
-100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sgZ (Mpc)
100
50
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-100
-50
0
50
100
Movie Slide

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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

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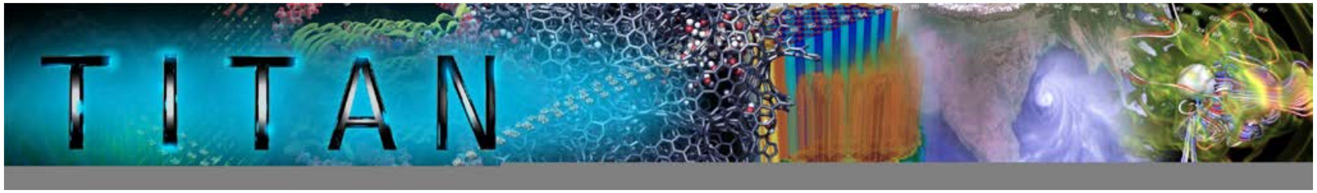
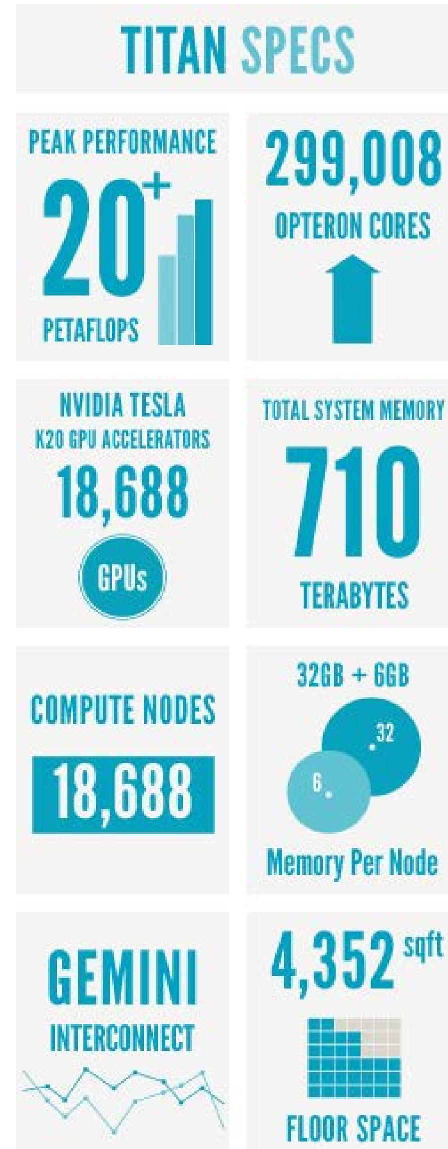


TITAN by the numbers:

- 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



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RAMSES-CUDATON simulation

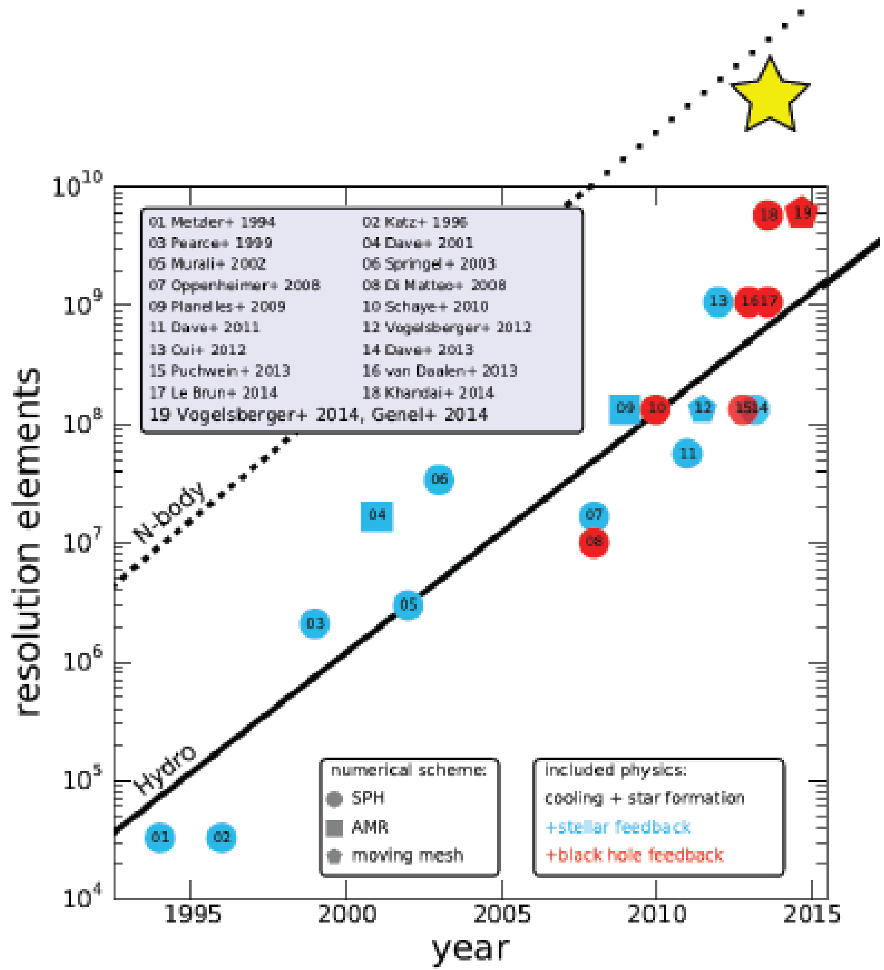
- Box size = 91 cMpc
- Grid size = $(4096)^3$ cells, $\Delta x \sim 20$ cKpc
- N-body particles = $(4096)^3 \sim 64$ billion
- Min halo mass ~ 10^8 M_solar ~300 particles

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)

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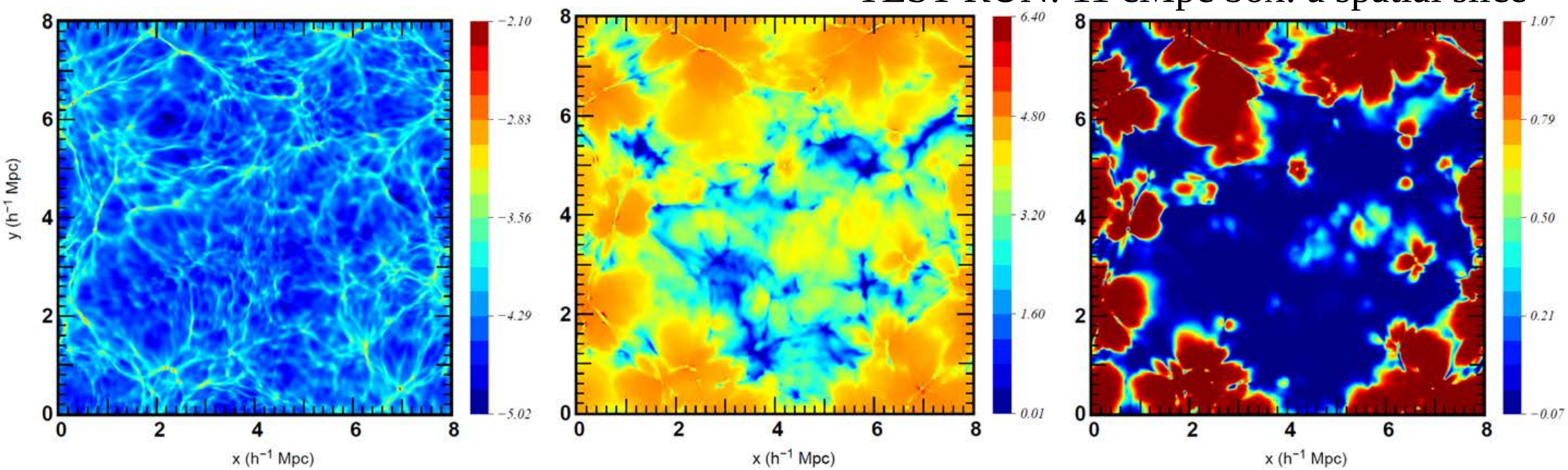
TEST RUN: 11 cMpc box: a spatial slice



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

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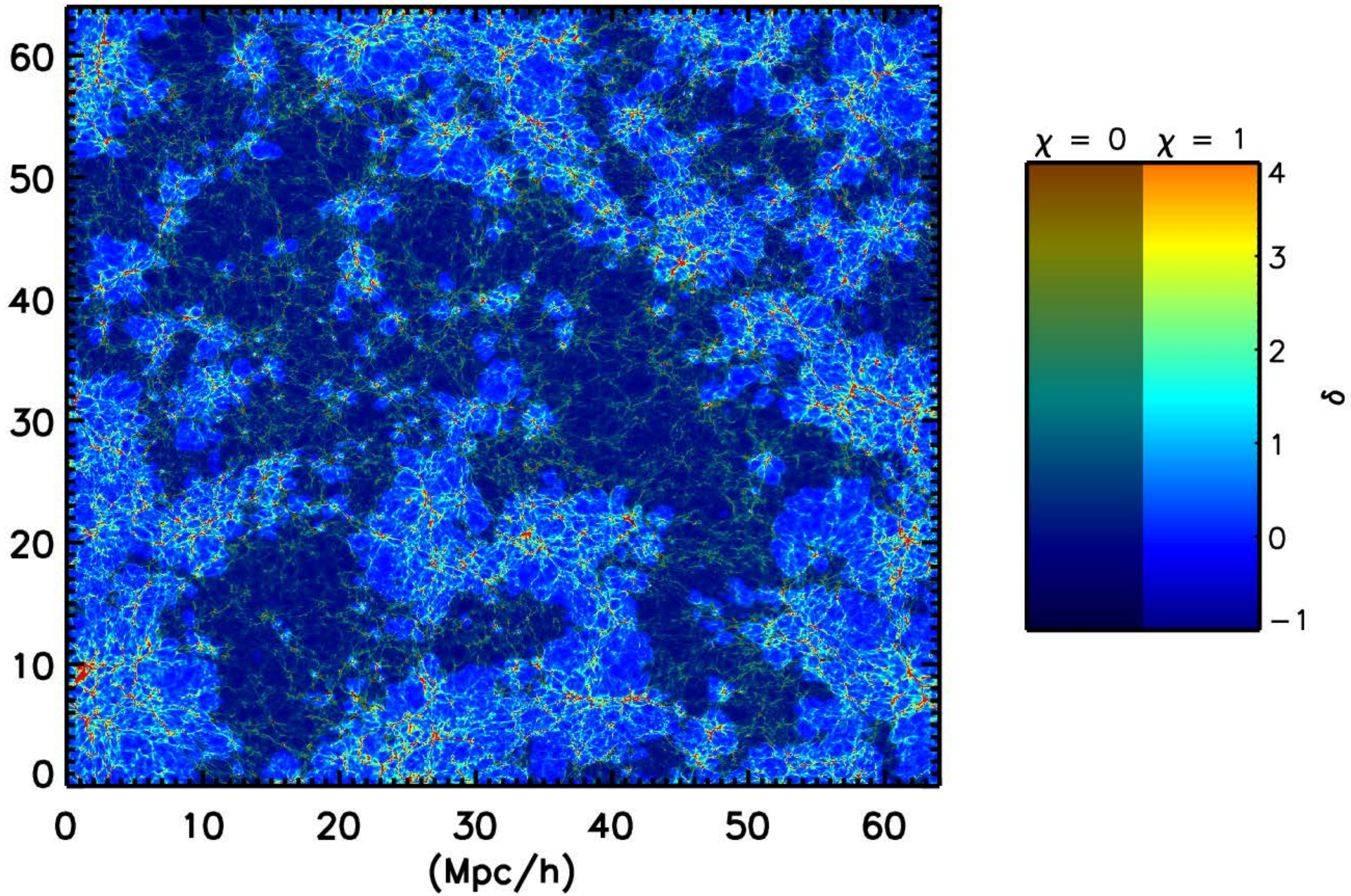
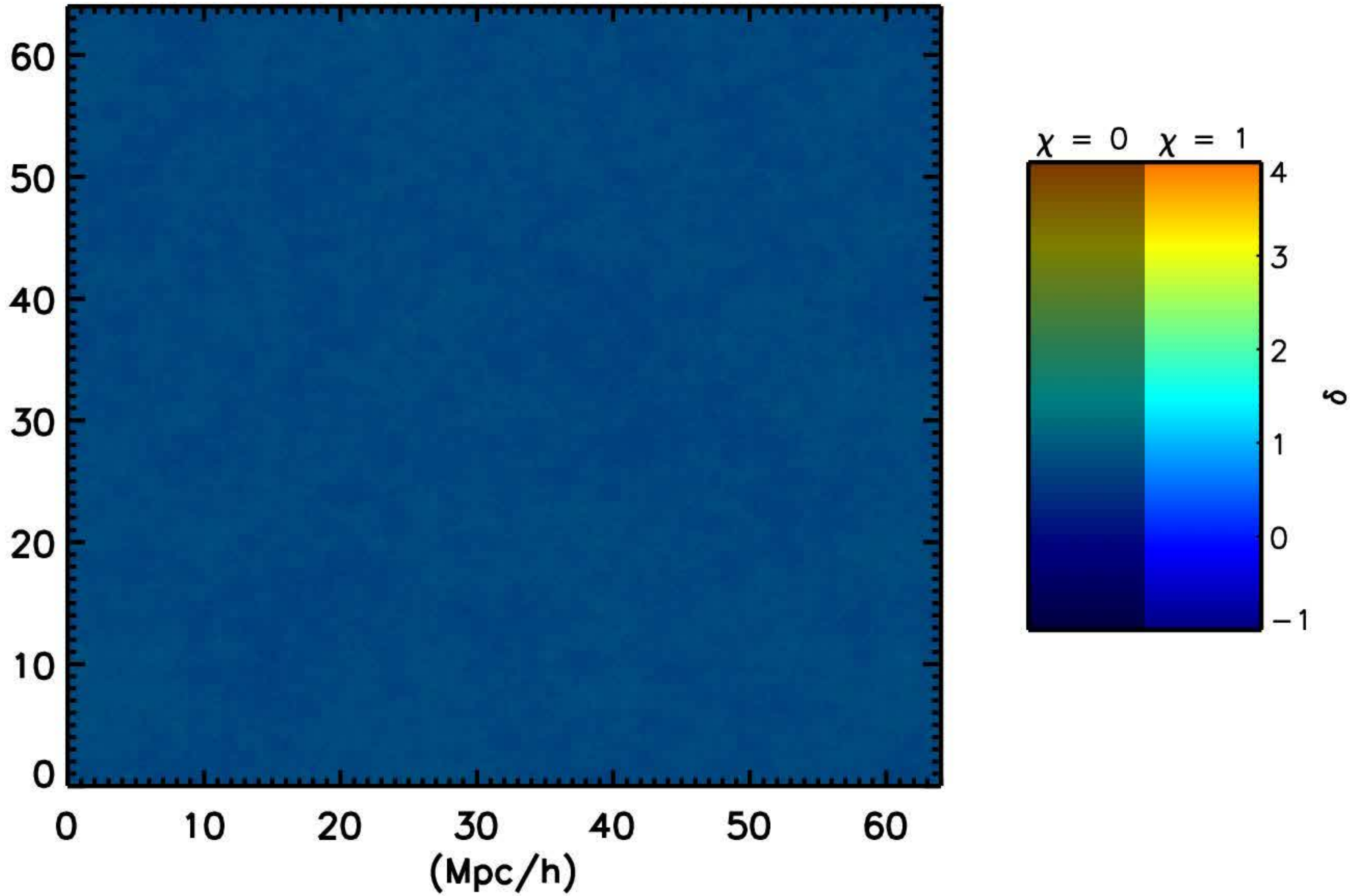
Ionization Field





60
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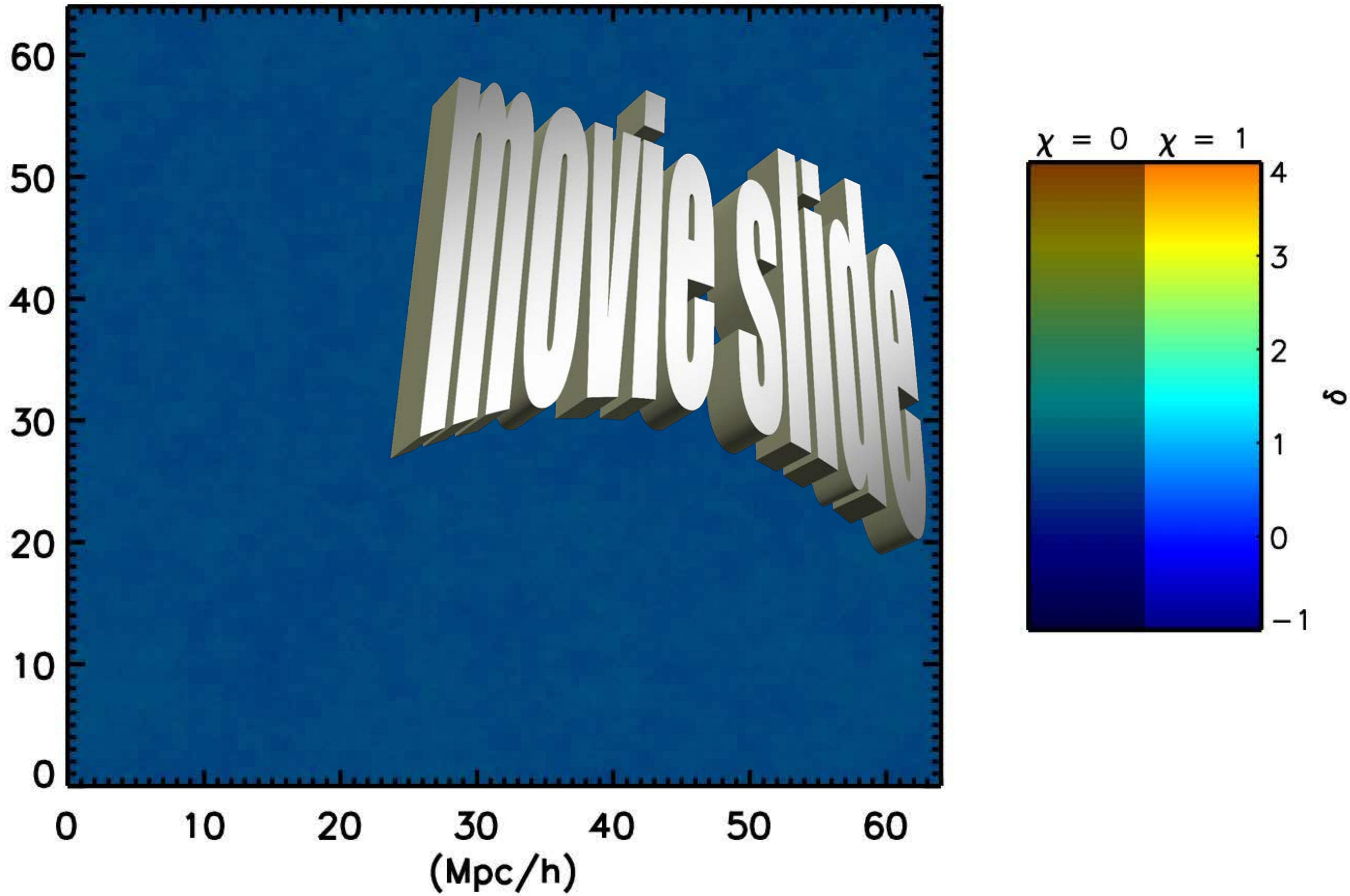
(Mpc/h)
χ = 0
χ = 1
4
3
2
1
0
−1
δ



Movie Slide
60
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40
50
60
(Mpc/h)
χ = 0
χ = 1
4
3
2
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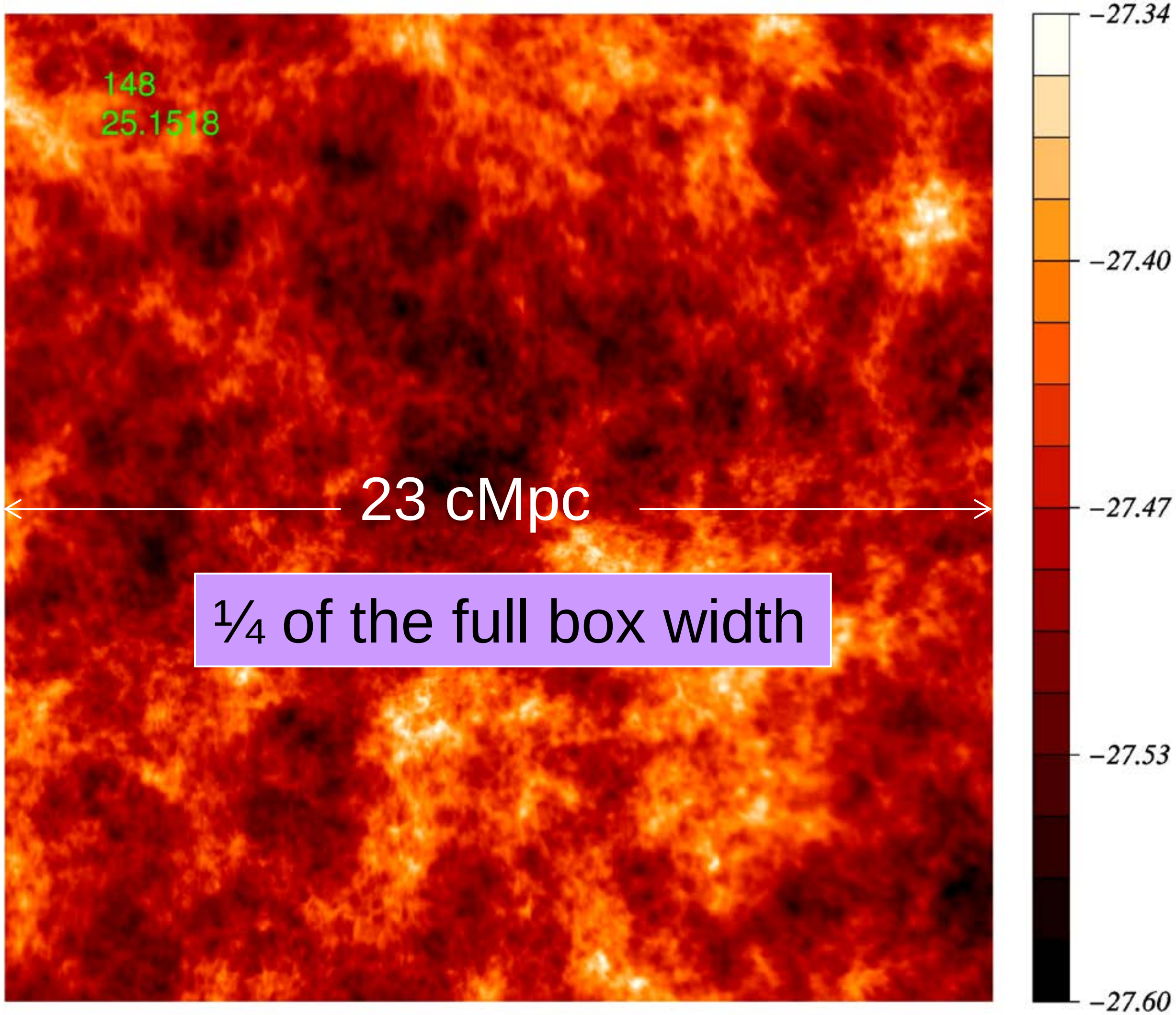
0
−1
δ

Reionization of the Local Universe: Witnessing our Own Cosmic Dawn

Ionizing Radiation Mean Intensity J



Reionization of the Local Universe: Witnessing our Own Cosmic Dawn

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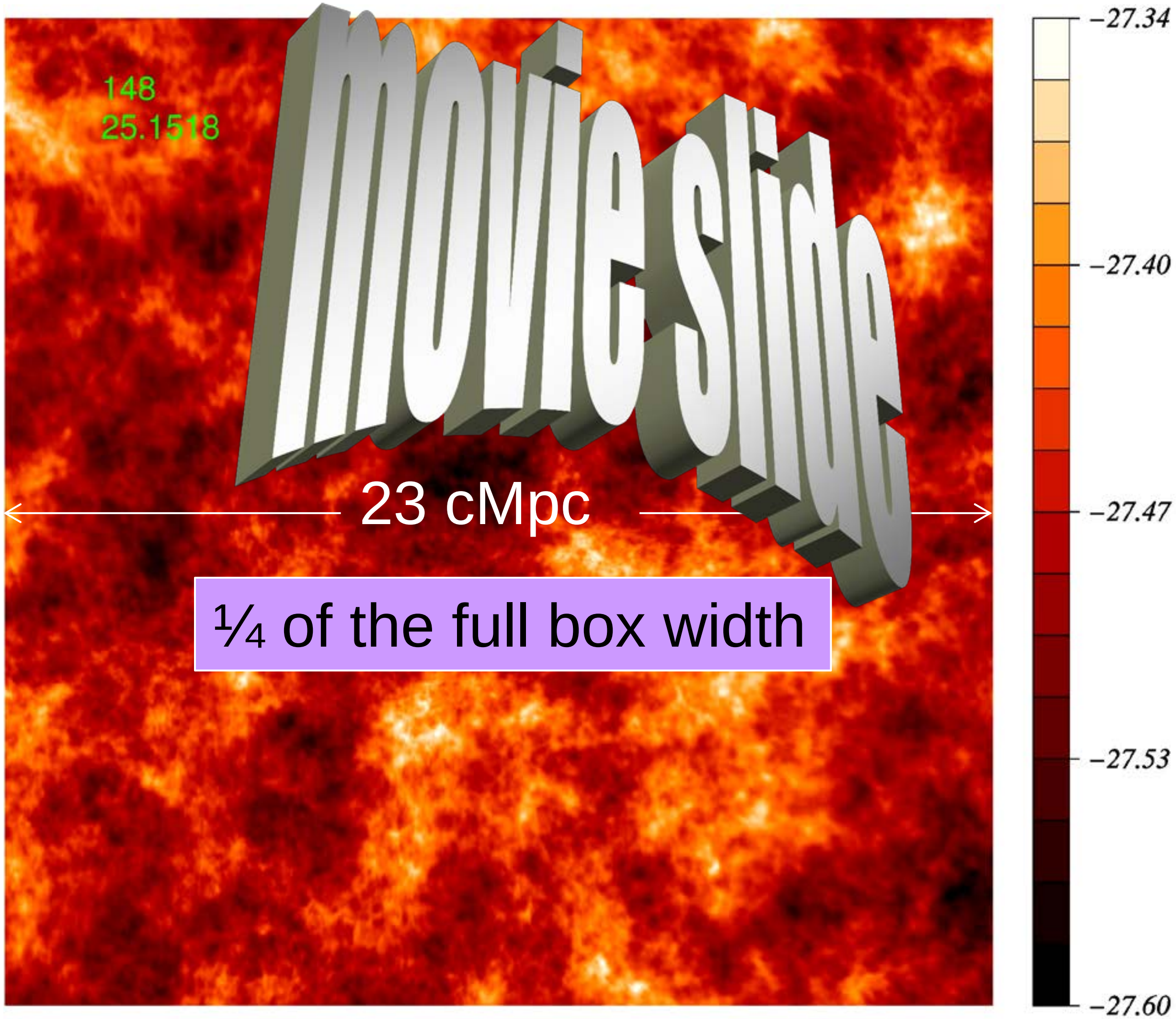
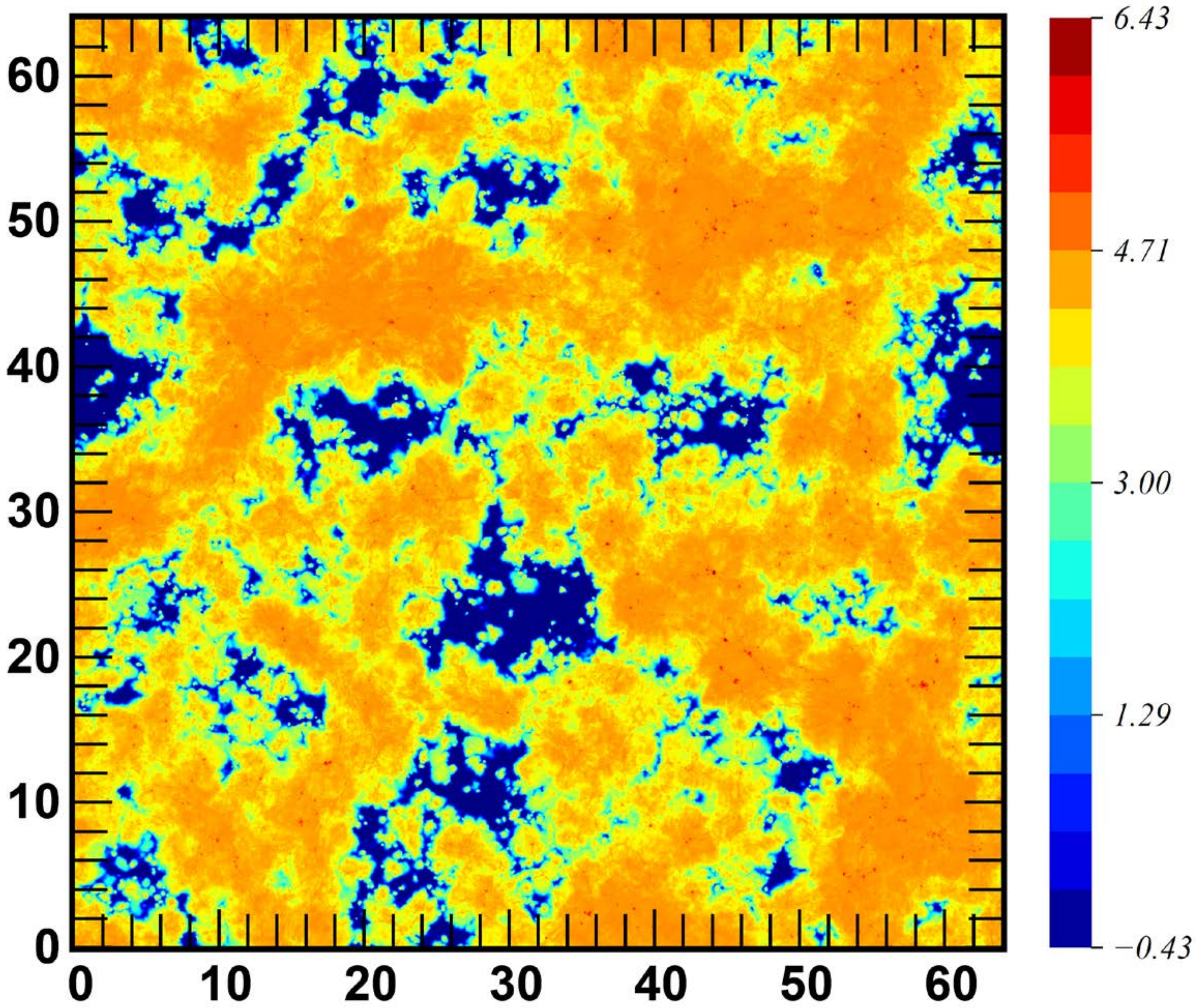


RAMSES-CUDATON simulation

- 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;

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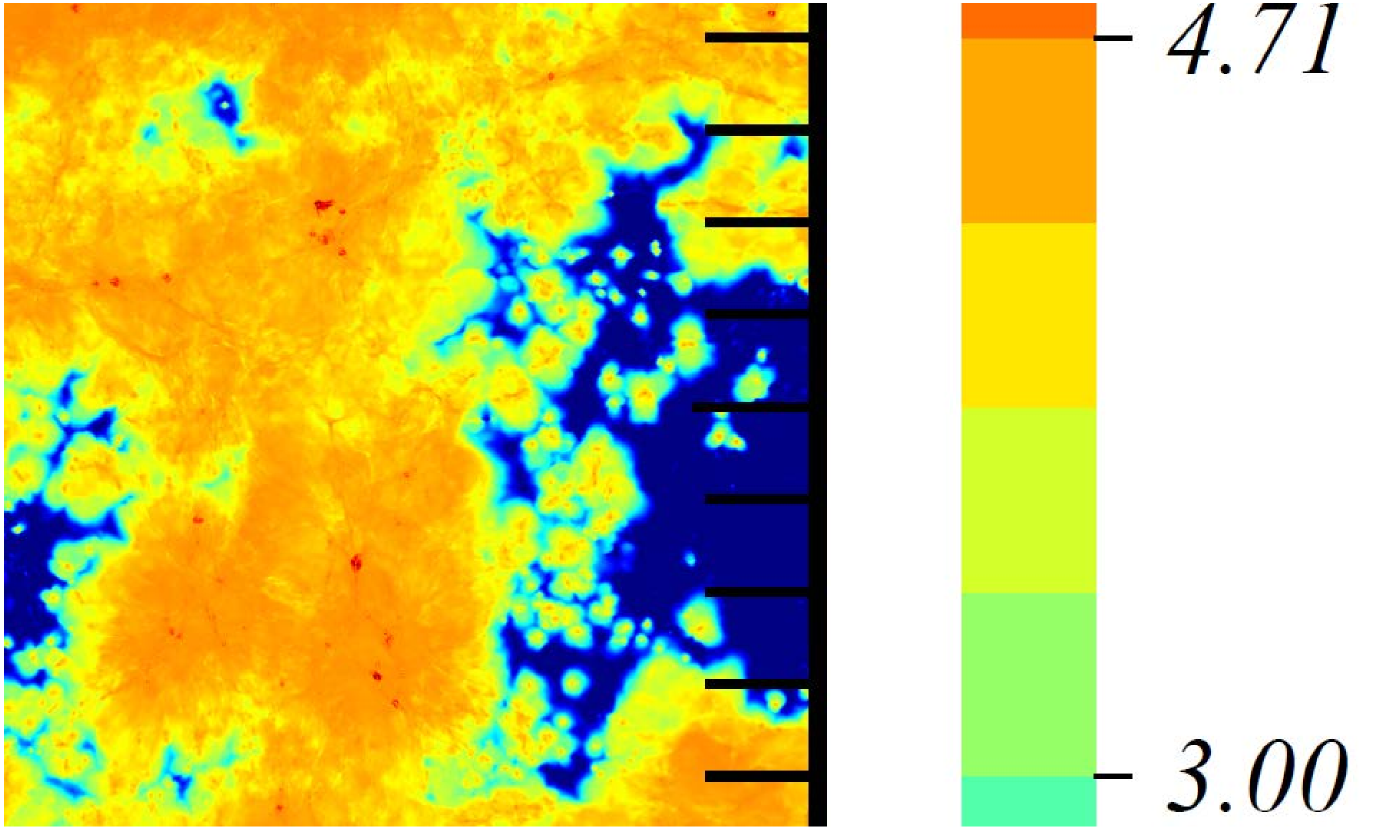
Zoom-in x 4



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91 cMpc box: a spatial slice;
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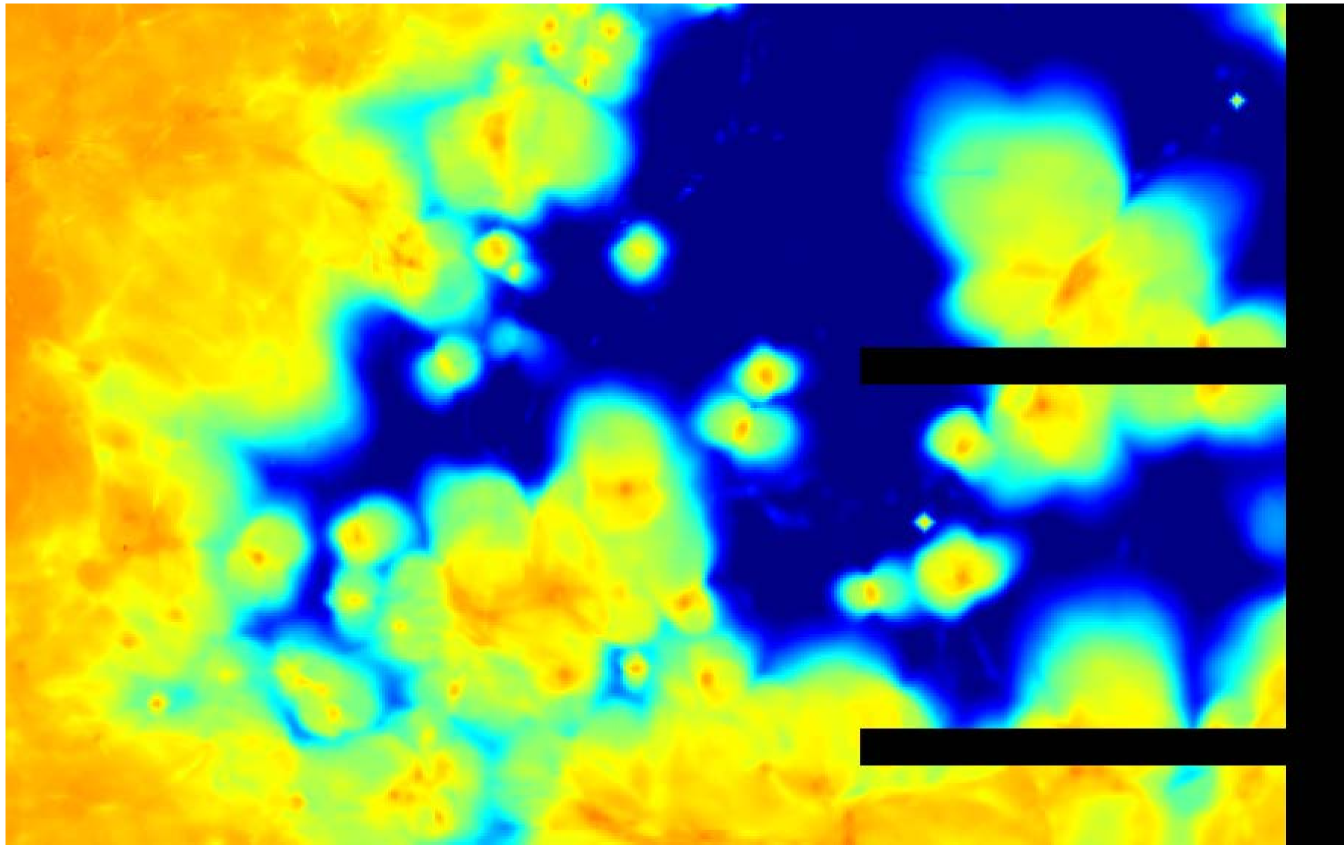
Zoom-in x 16



log10(temperature)

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RAMSES-CUDATON simulation

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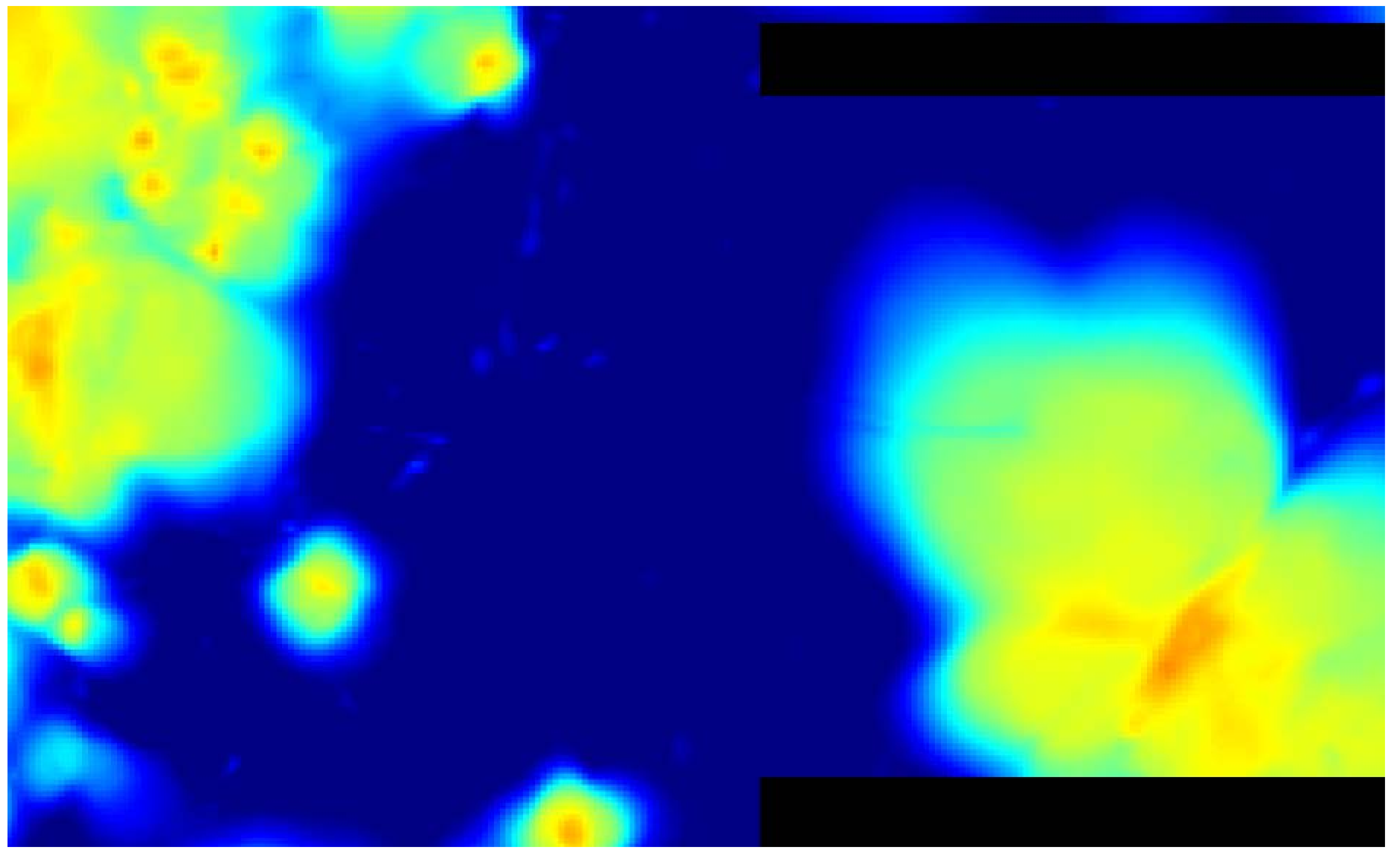
FULL-SIZED RUN:
91 cMpc box: a spatial slice;
@ z ~ 6, with x ~ 50%

Zoom-in x 32



log10(temperature)

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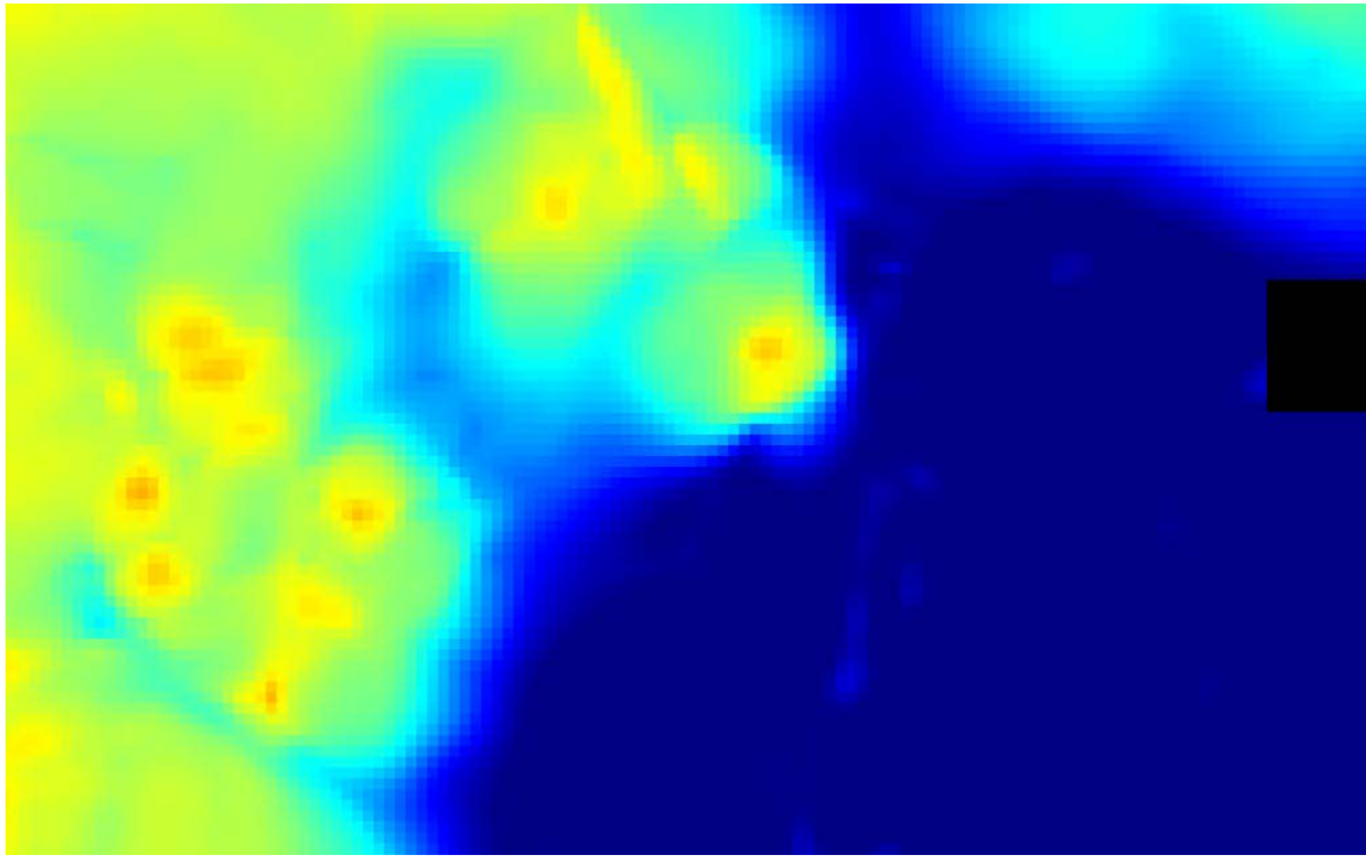
RAMSES-CUDATON simulation

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

Selected Cut-out

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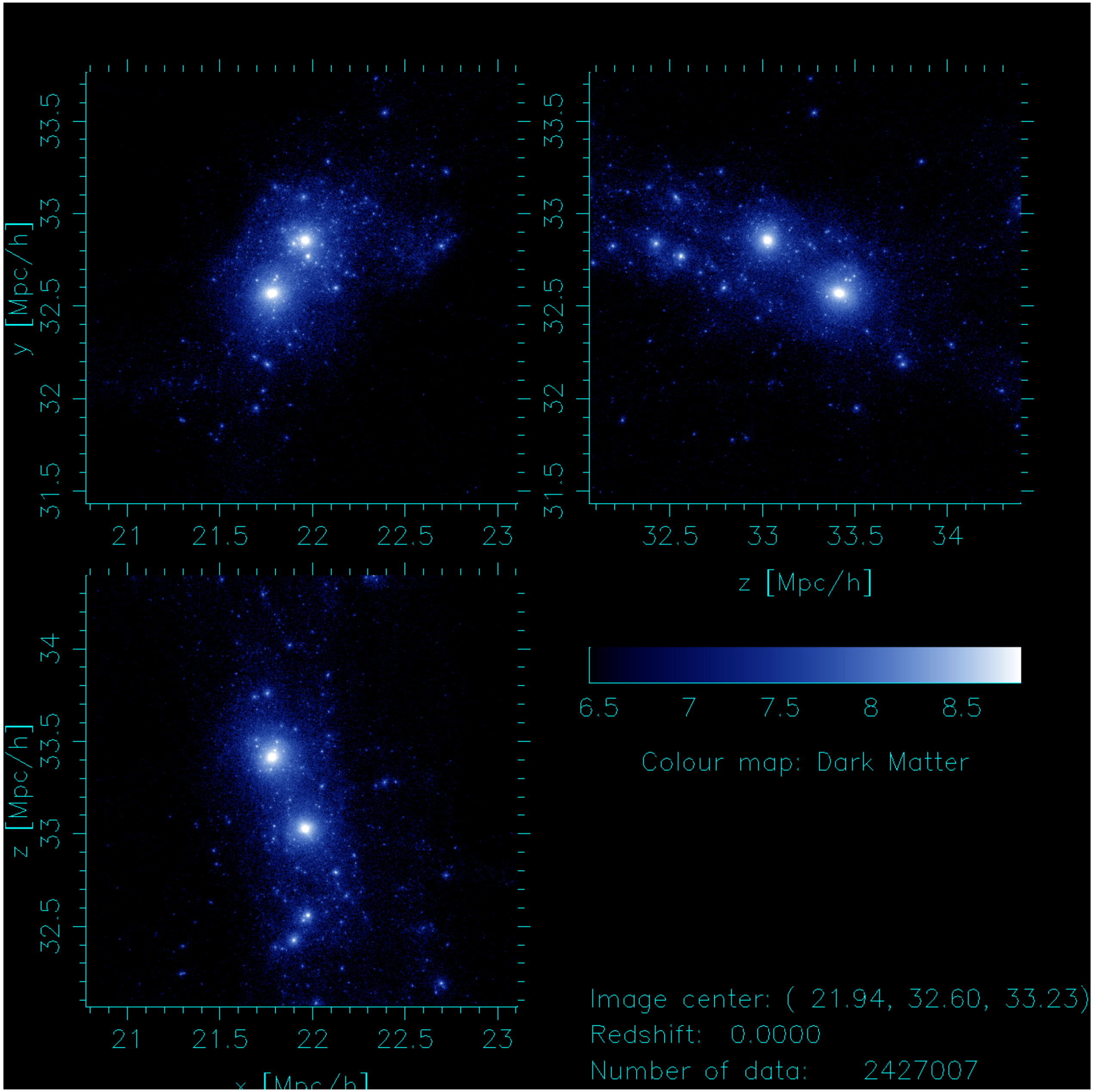
- Min halo mass ~ 10^8 solar masses

ZOOM-IN ON LOCAL GROUP AT Z = 0



Reionization of the Local Universe: Witnessing our Own Cosmic Dawn

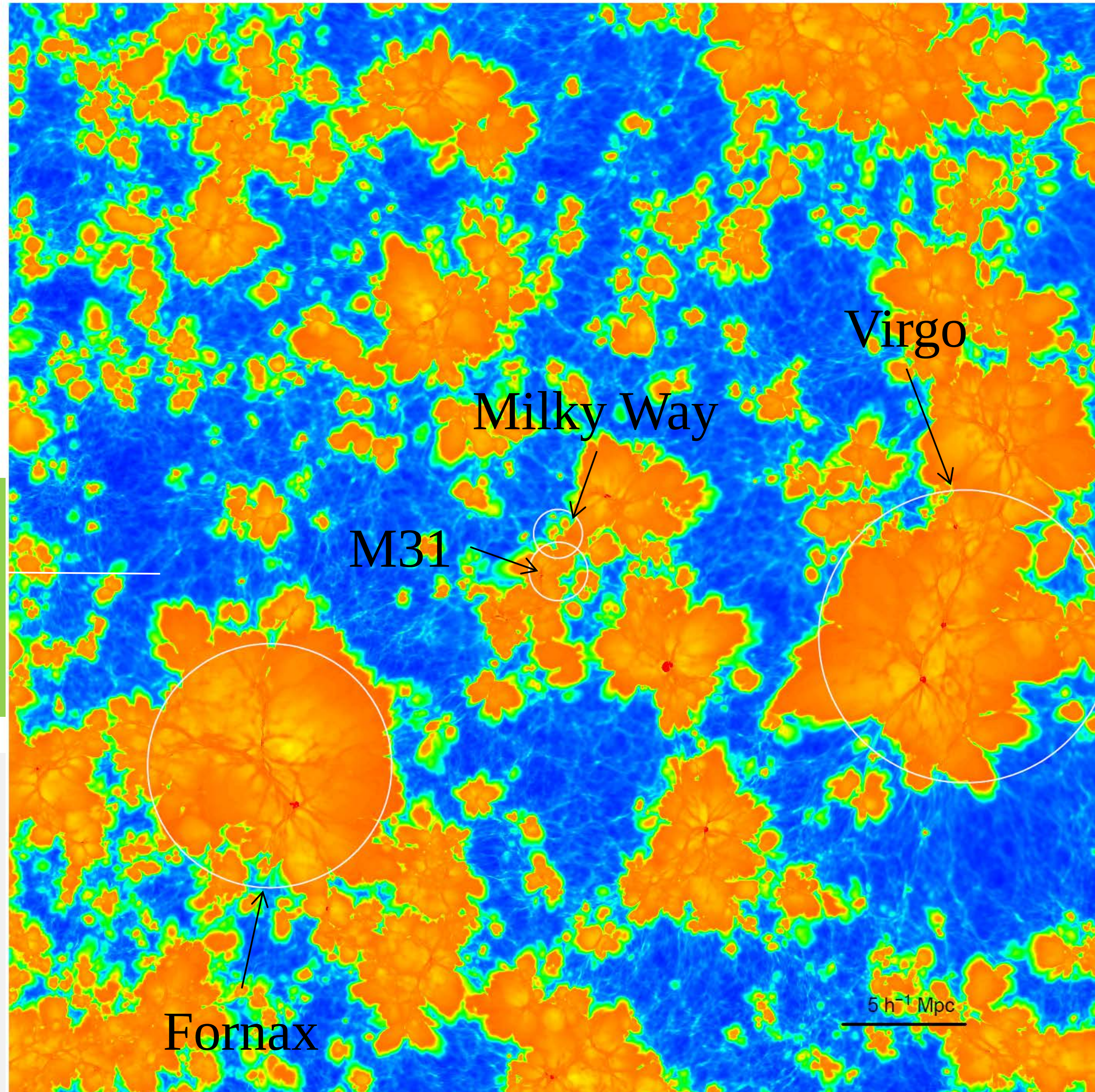
Gas Temperature
at
z = 6.15
in the supergalactic
YZ plane
of the
Local Group

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



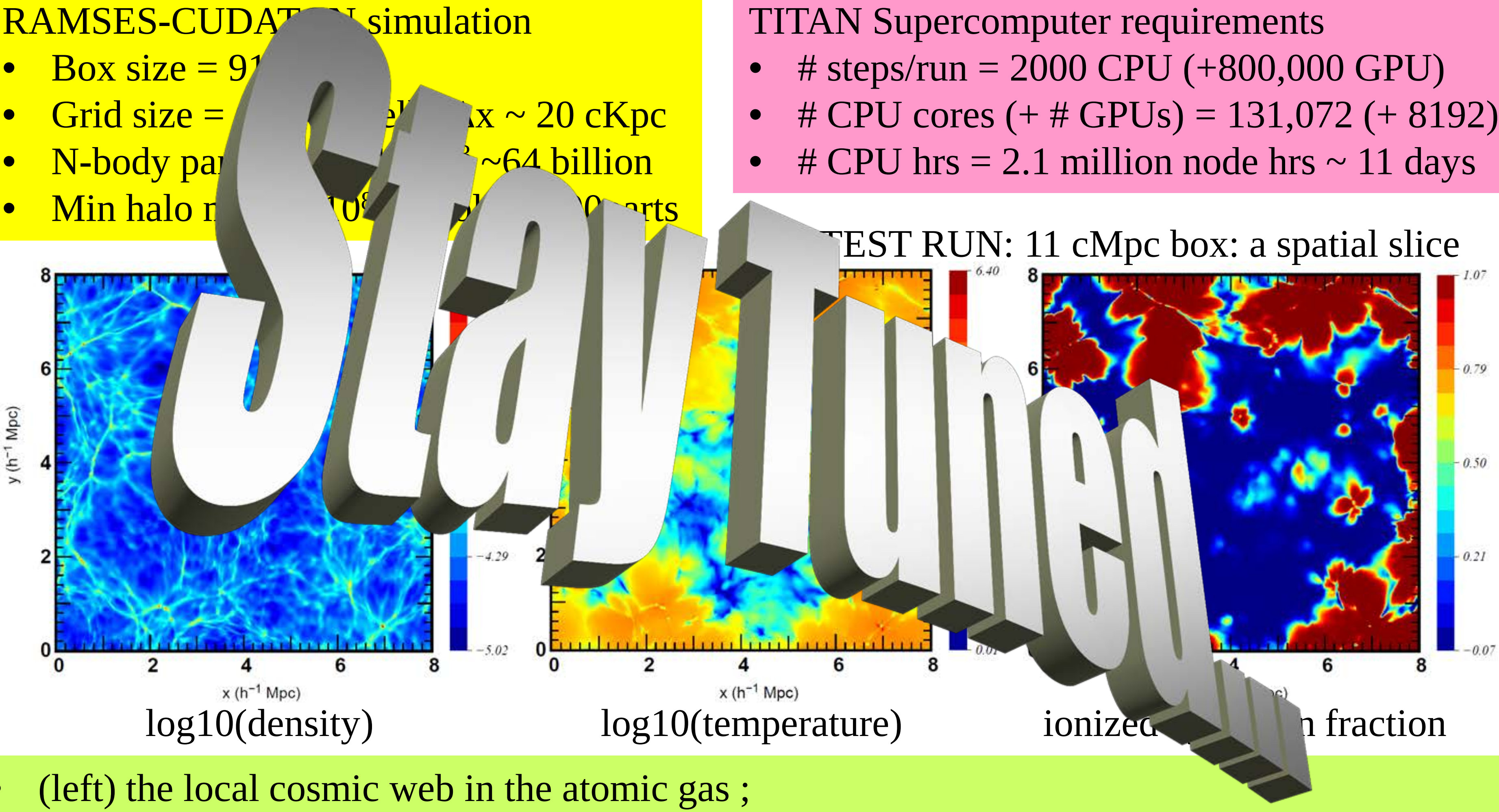
Reionization of the Local Universe: Witnessing our Own Cosmic Dawn

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

RAMSES-CUDAT N simulation
- Box size = 91
- Grid size = el x ~ 20 cKpc
- N-body pa ~64 billion
- Min halo 10 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

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)].