Simulating the Reionization of the Local Universe with Radiation-Hydrodynamics

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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

CLUES 2015, Copenhagen, May 9 , 2015

Self-Regulated Reionization

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

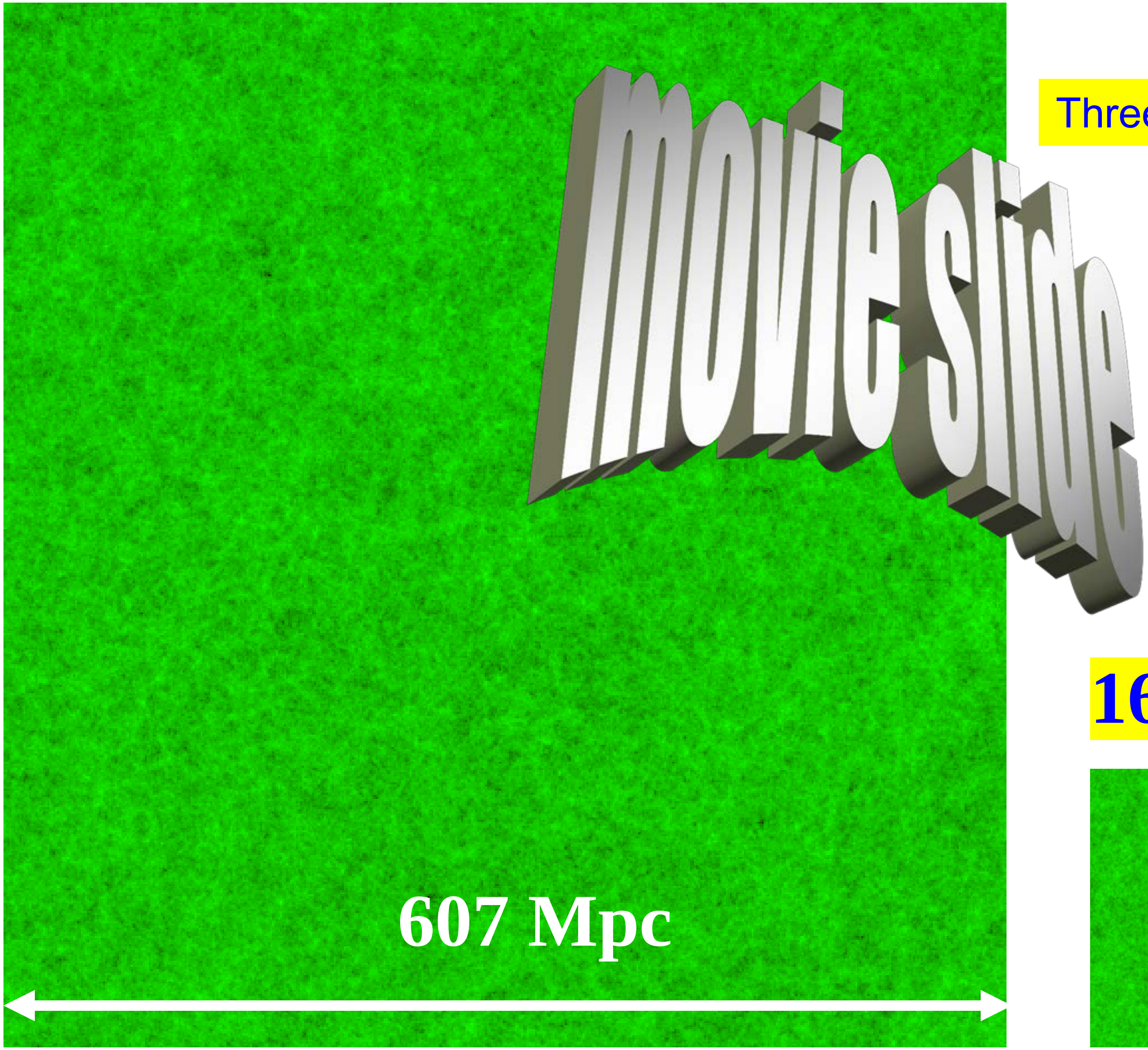
•Jeans-mass filtering ➔ low-mass source halos ($M < 10^9\ M_{solar}$) cannot form inside H II regions ;

•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);

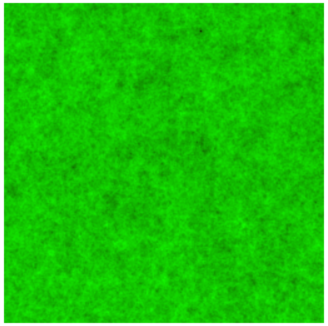
• Evolution: z=21 to z_{ov} = 7.5.

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

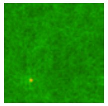


Three generations of simulation

163 Mpc



50 Mpc



Reionization of the Local Universe: Witnessing our Own Cosmic Dawn

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

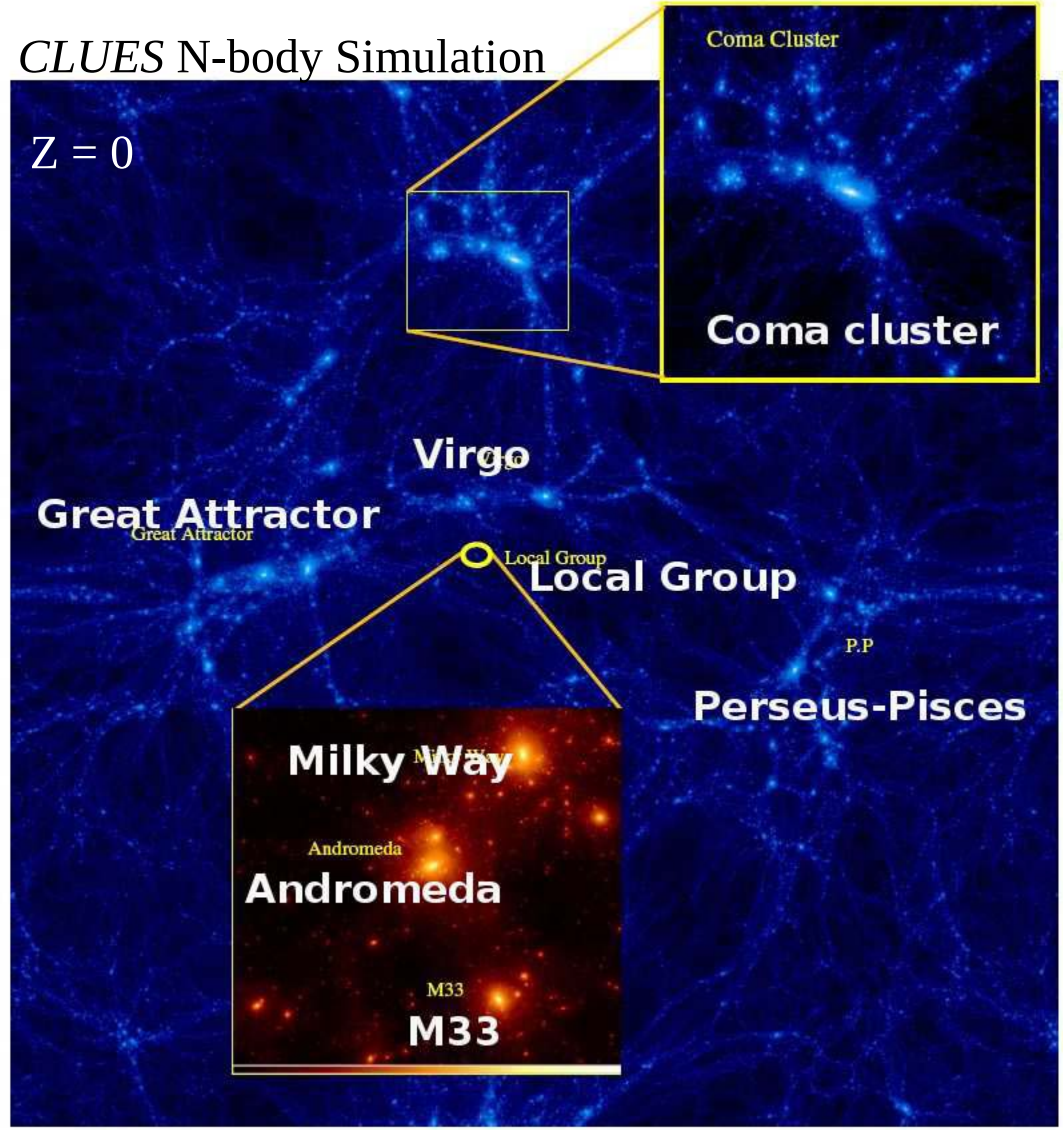
Q: Did reionization leave an imprint on the Local Group galaxies we can observe today?

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?

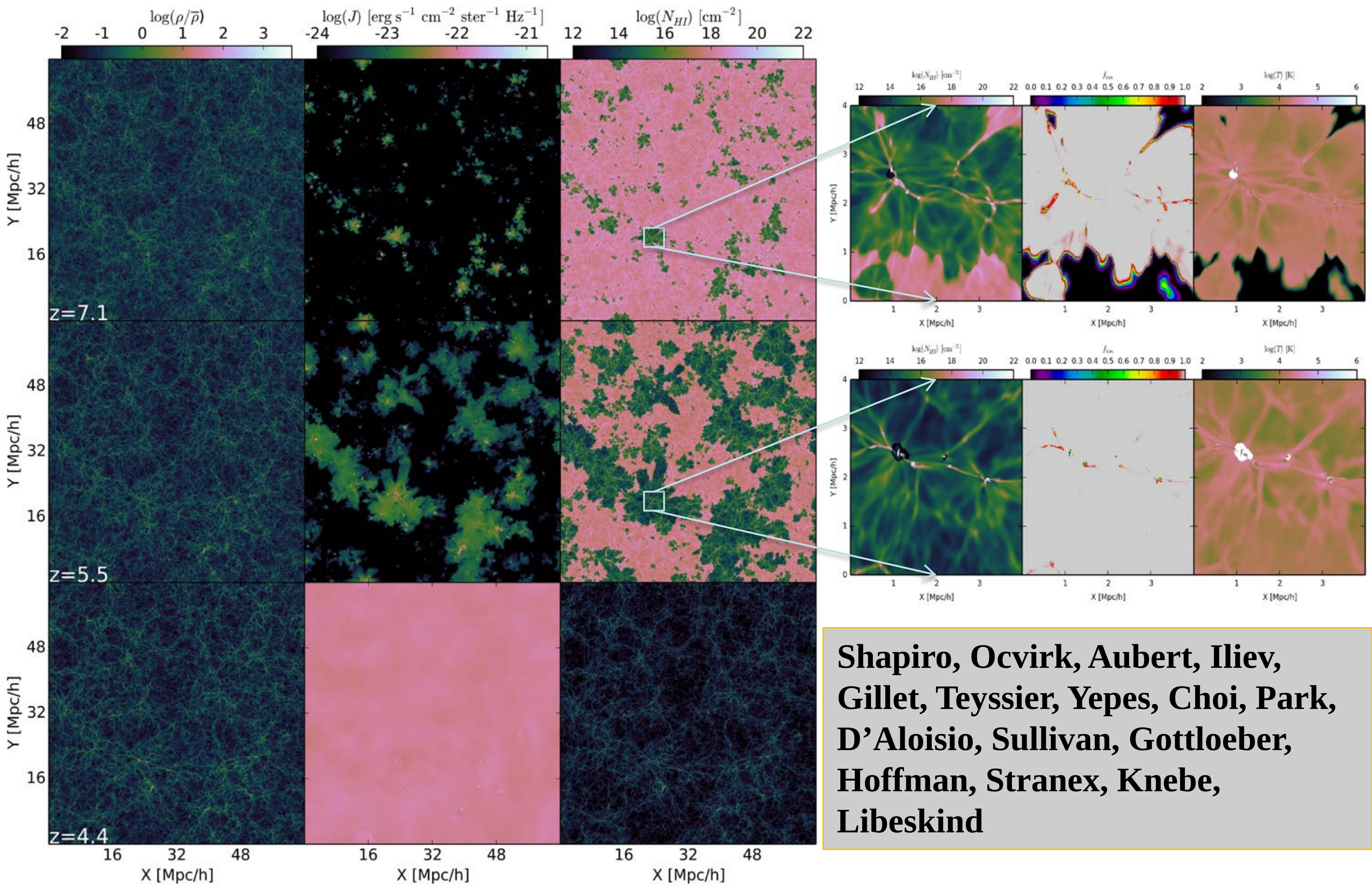
A: Simulate the coupled radiation-hydro-N-body problem of reionization ➔ galaxy formation with ionization fronts that swept across the IGM in the first billion years of cosmic time, in a volume 91 Mpc on a side centered on the Local Group.

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



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

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What makes this possible now?

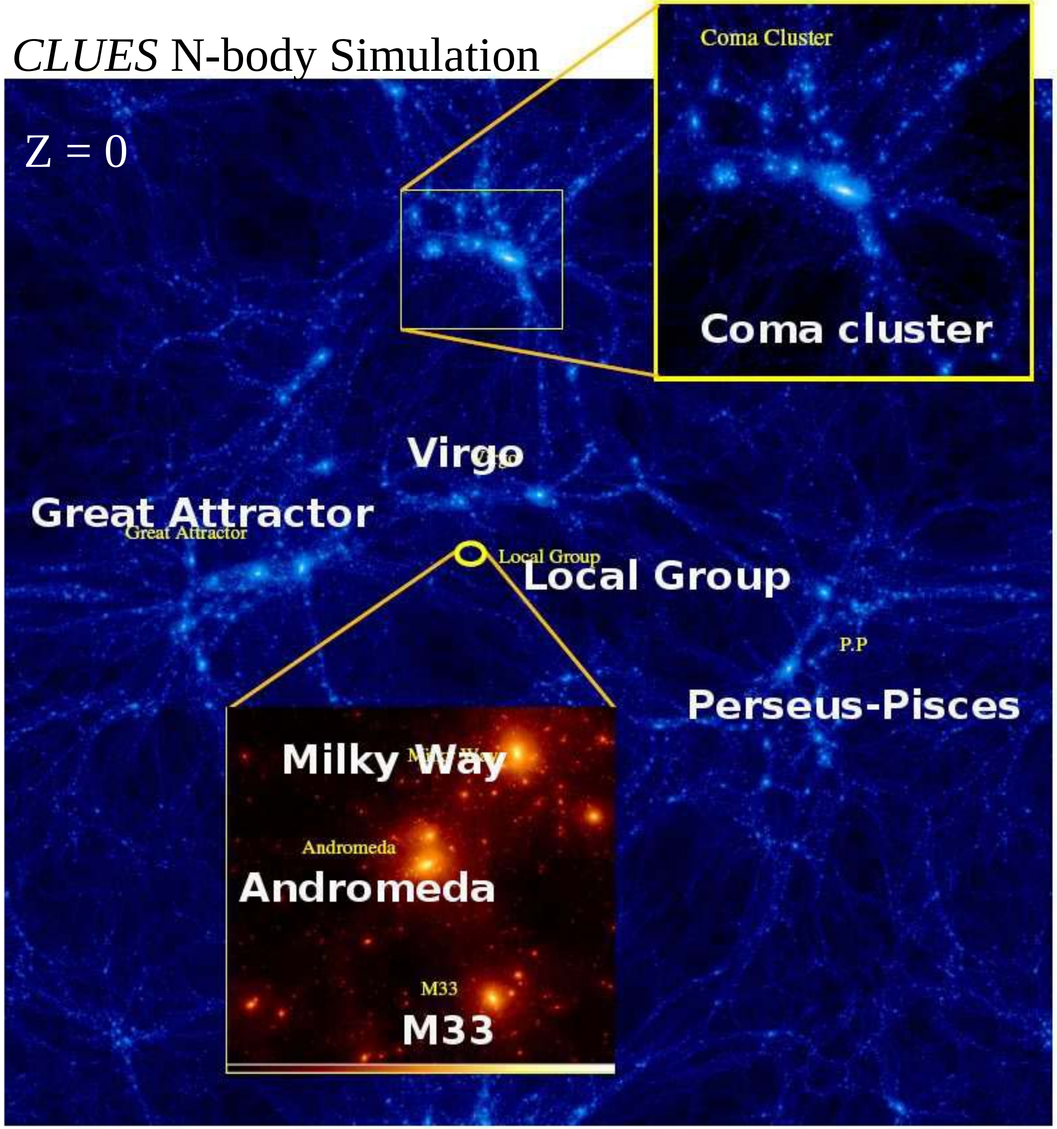
1) Initial Conditions:

- 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

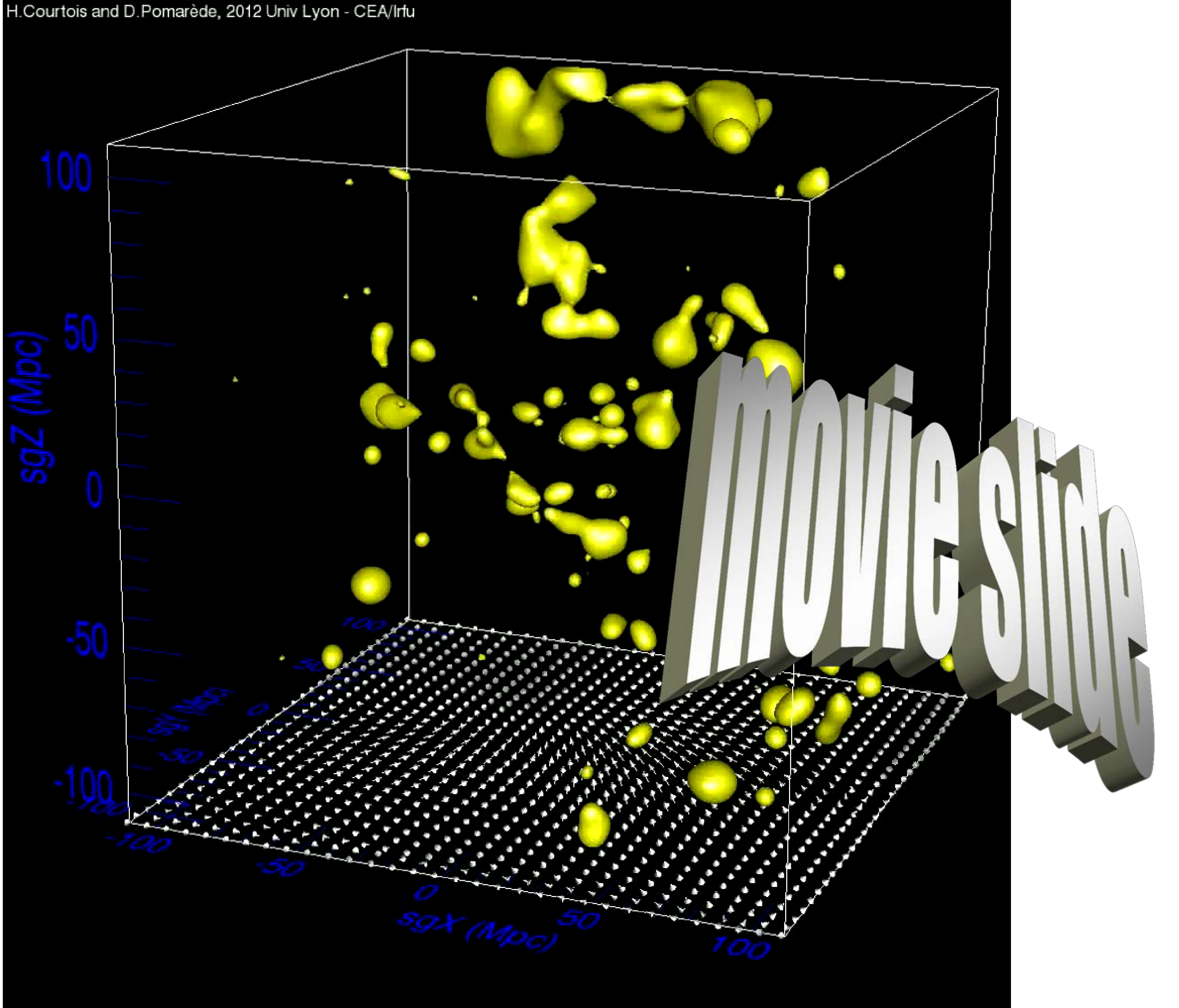
- This reproduces observed features of our local Universe, including the Local Group and nearby galaxy clusters.

- 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
0
-50
-100
sgX (Mpc)
-100
-50
0
50
100
movie slide

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What makes this possible now?

2) <u>New Hybrid (CPU + GPU) numerical method</u> **+** <u>New Hybrid (CPU + GPU) supercomputer</u>

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

- Gravity solver is Particle – Mesh code with a 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** (**GPU**s) = **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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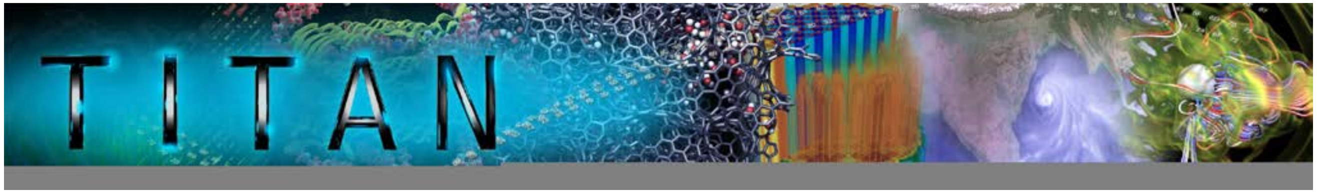
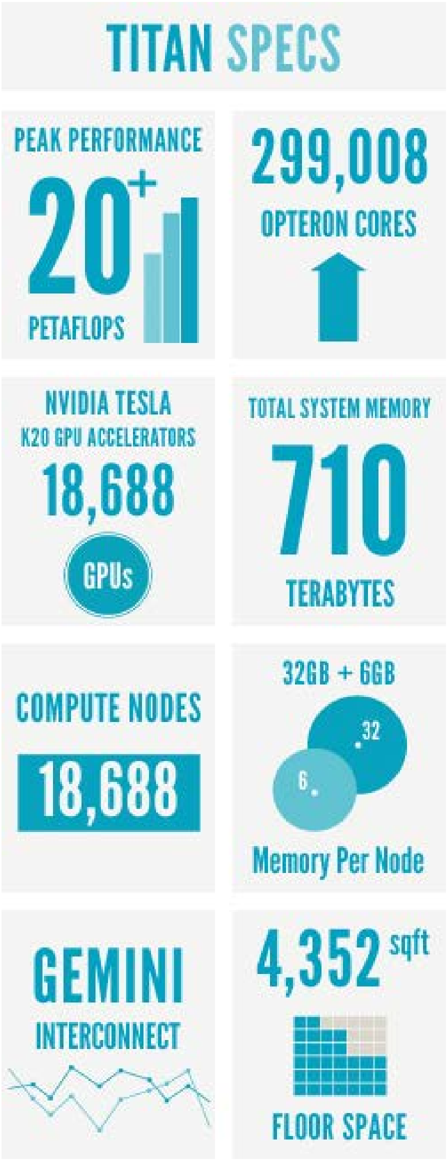


TITAN by the numbers:

- 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



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 +

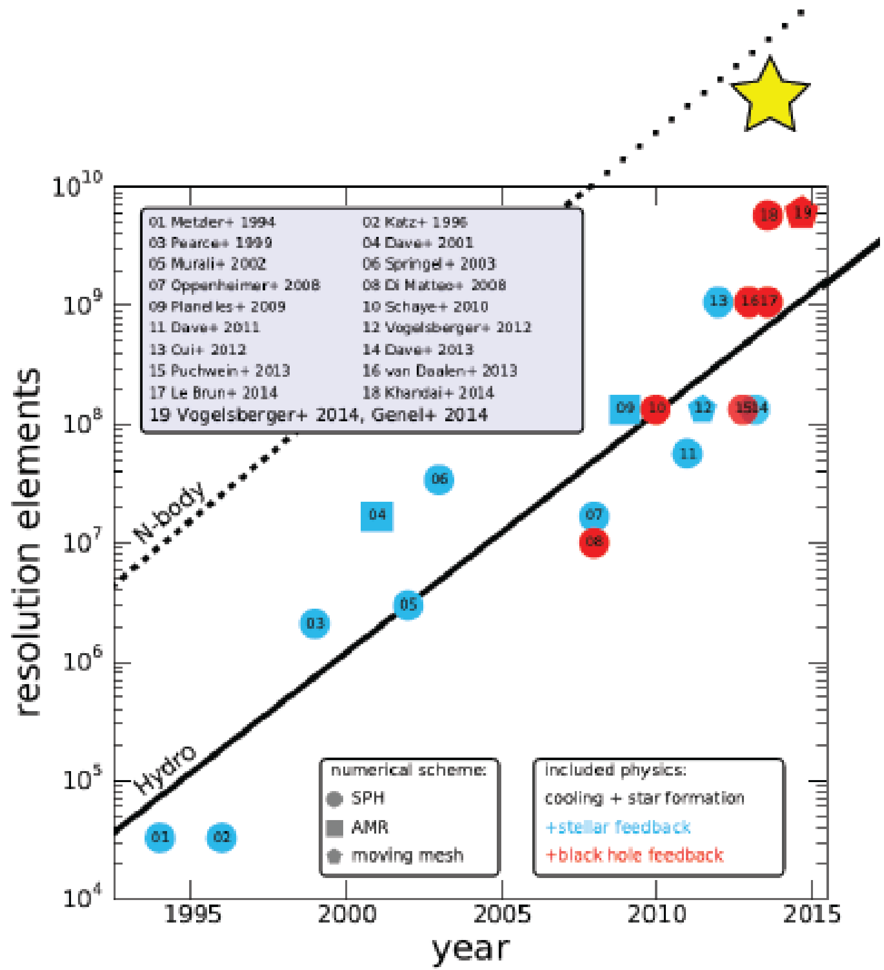
RAMSES-CUDATON simulation

- 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)

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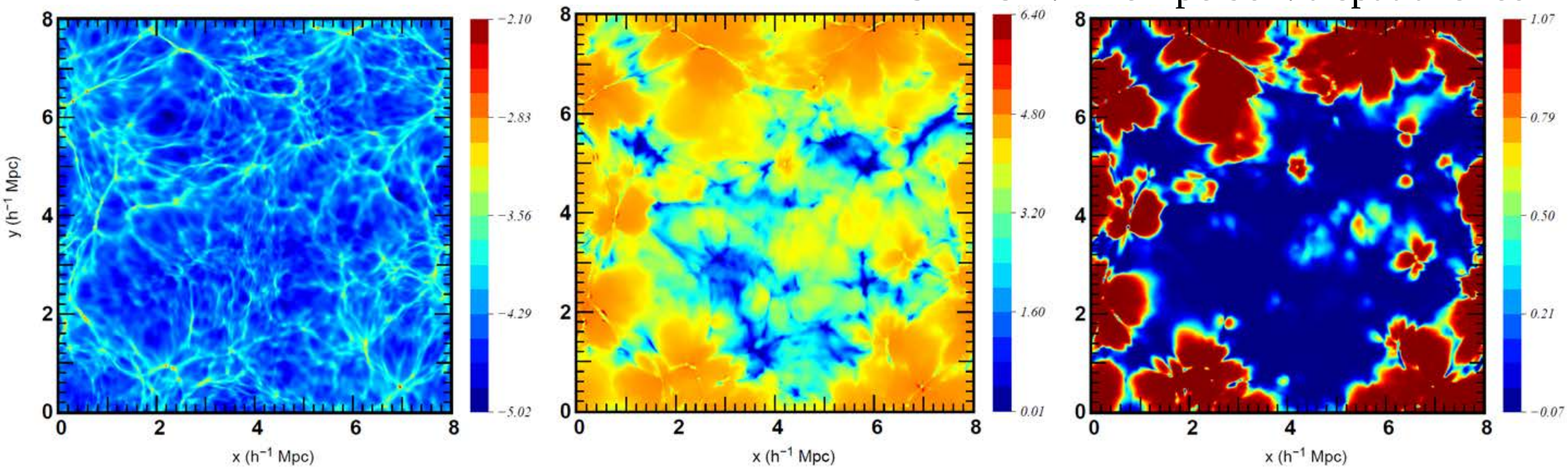
TEST RUN: 11 cMpc box: a spatial slice



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)].

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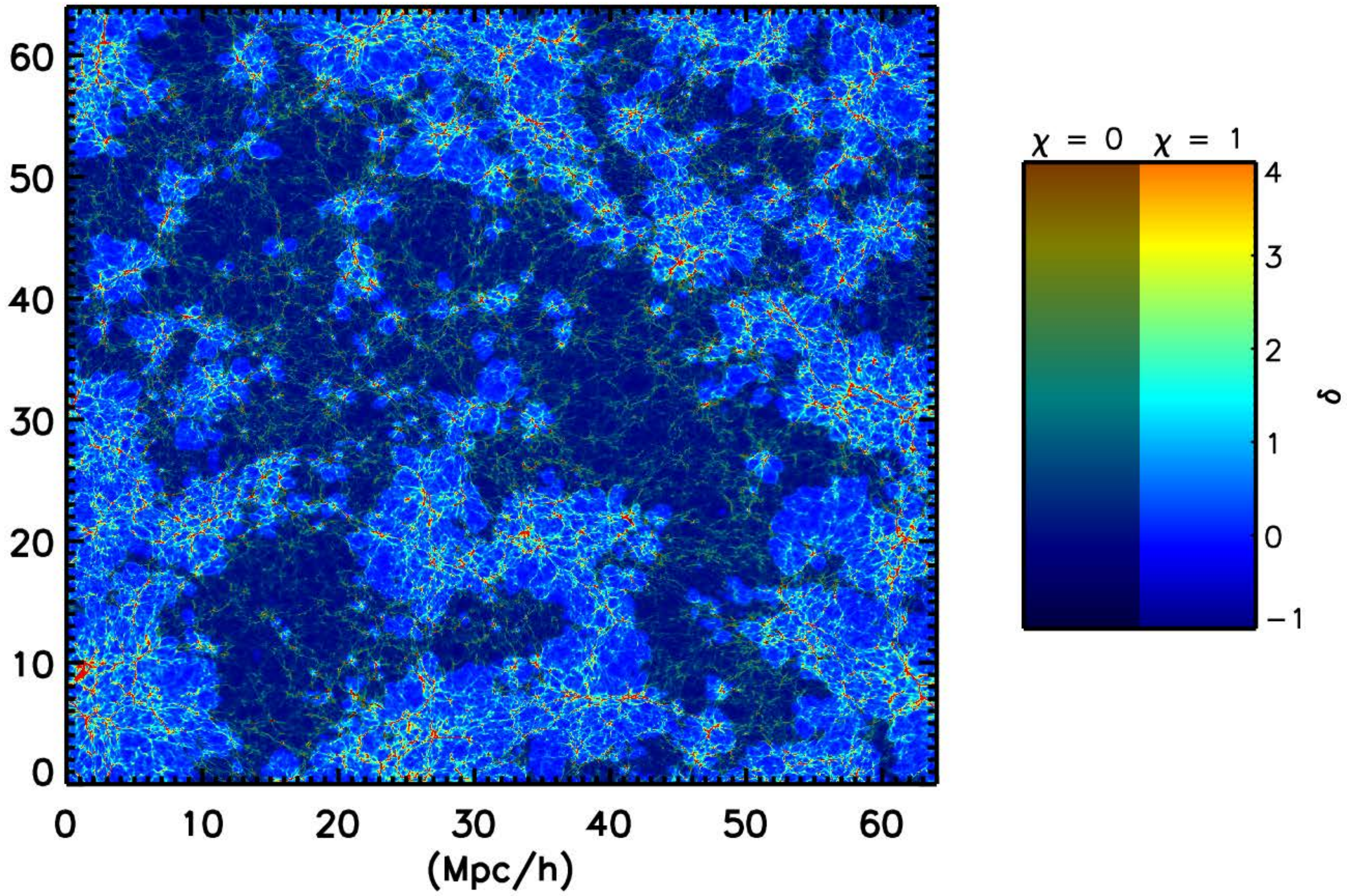
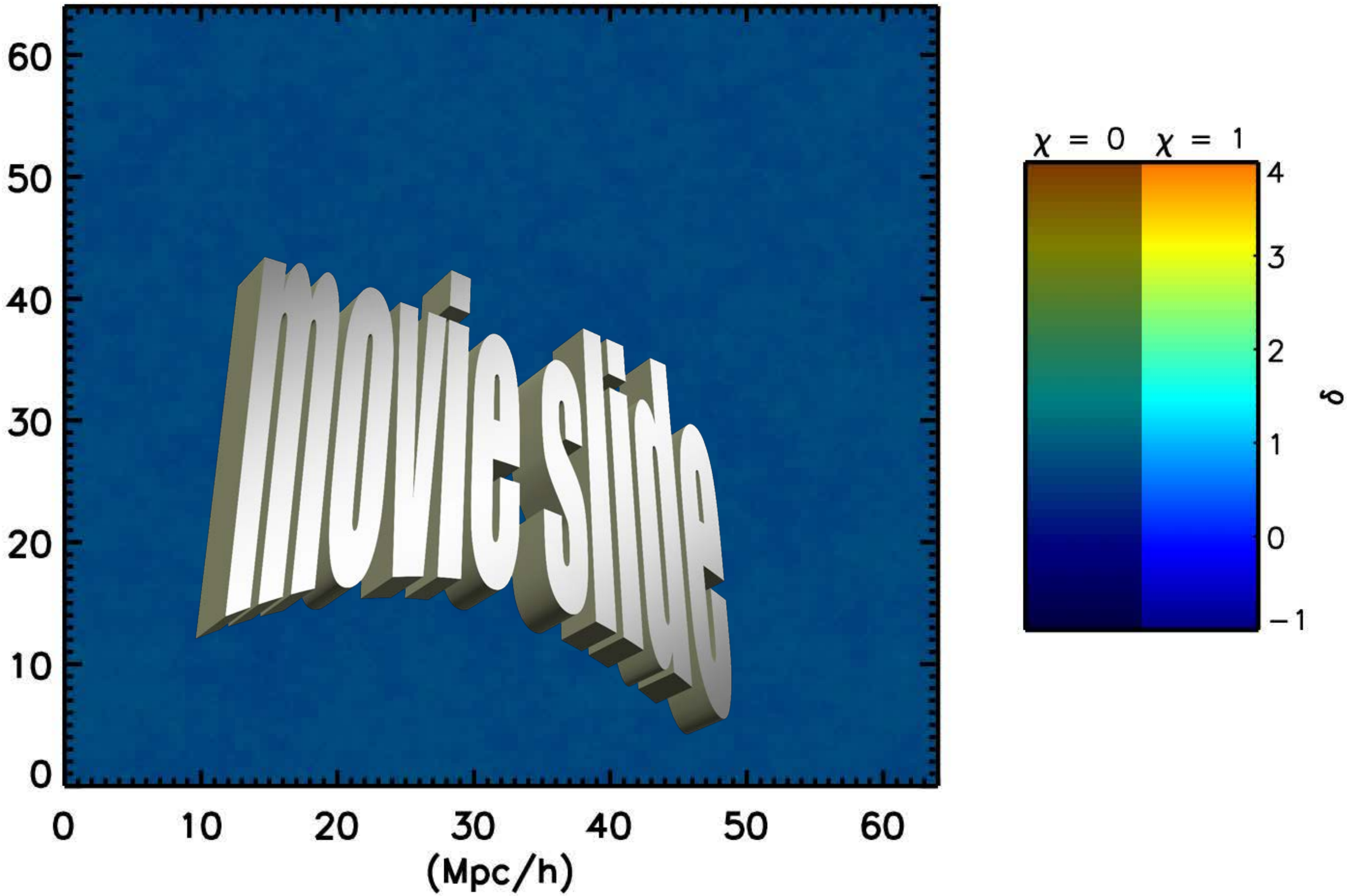
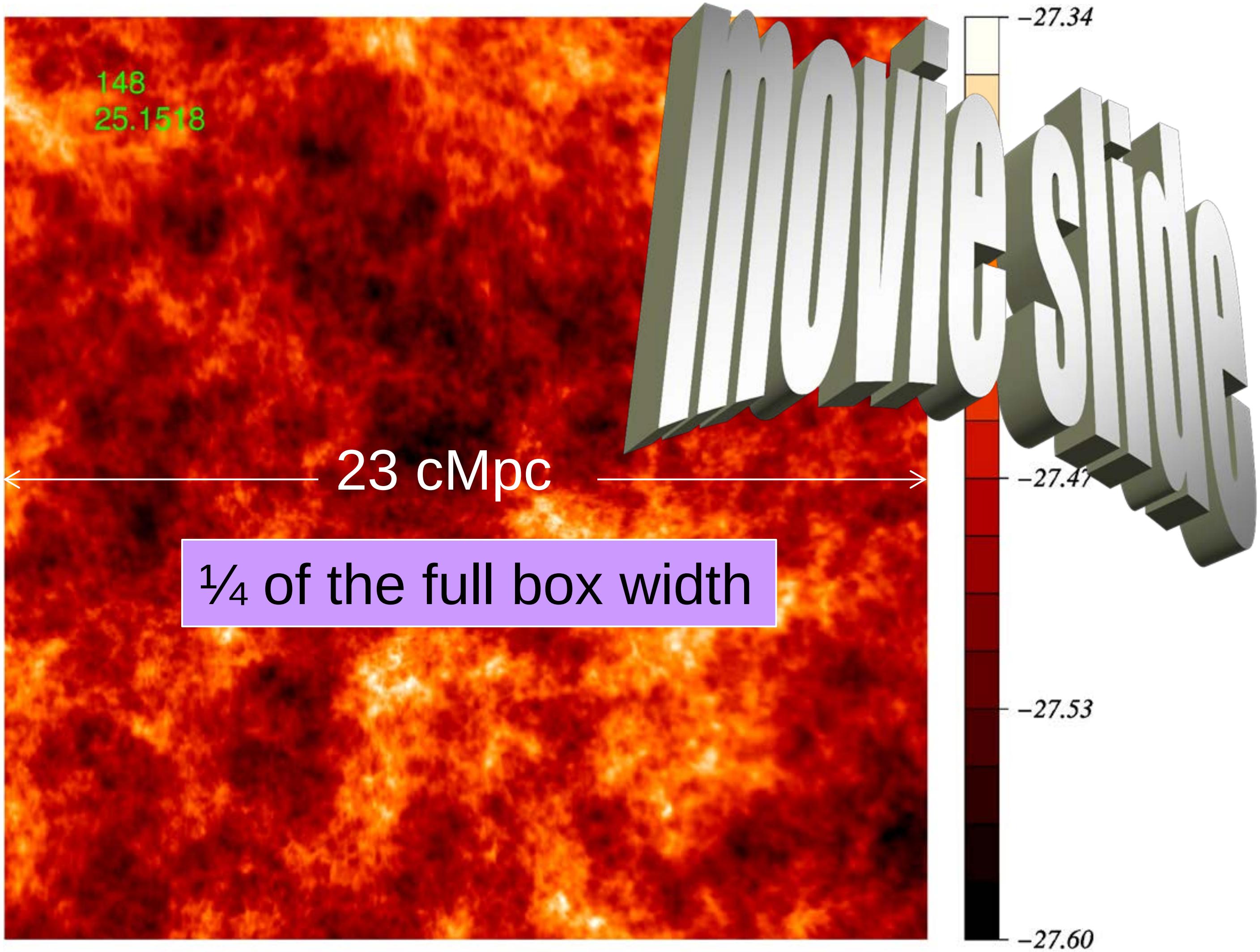
Ionization Field




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



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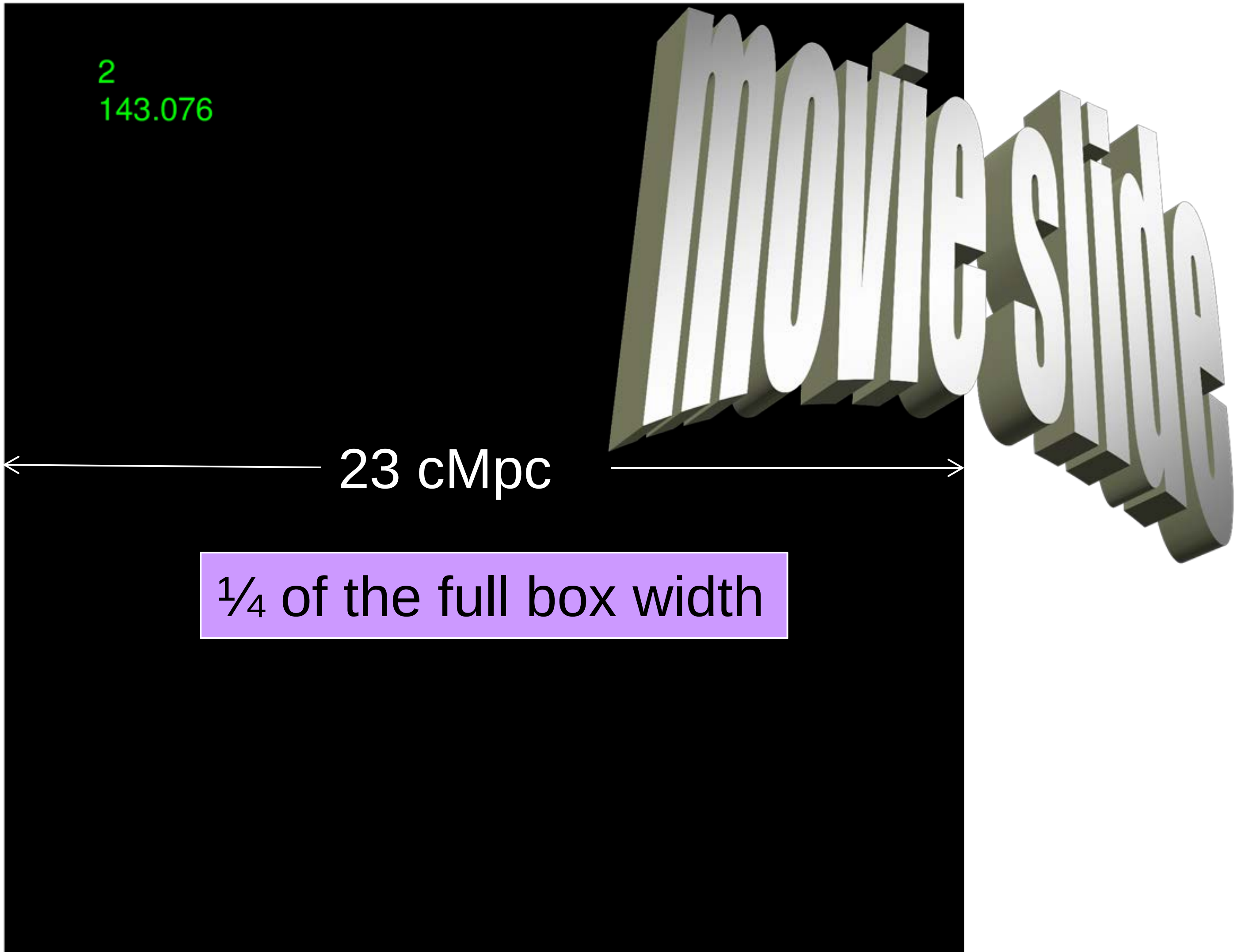
Gas Temperature



¼ of the full box width

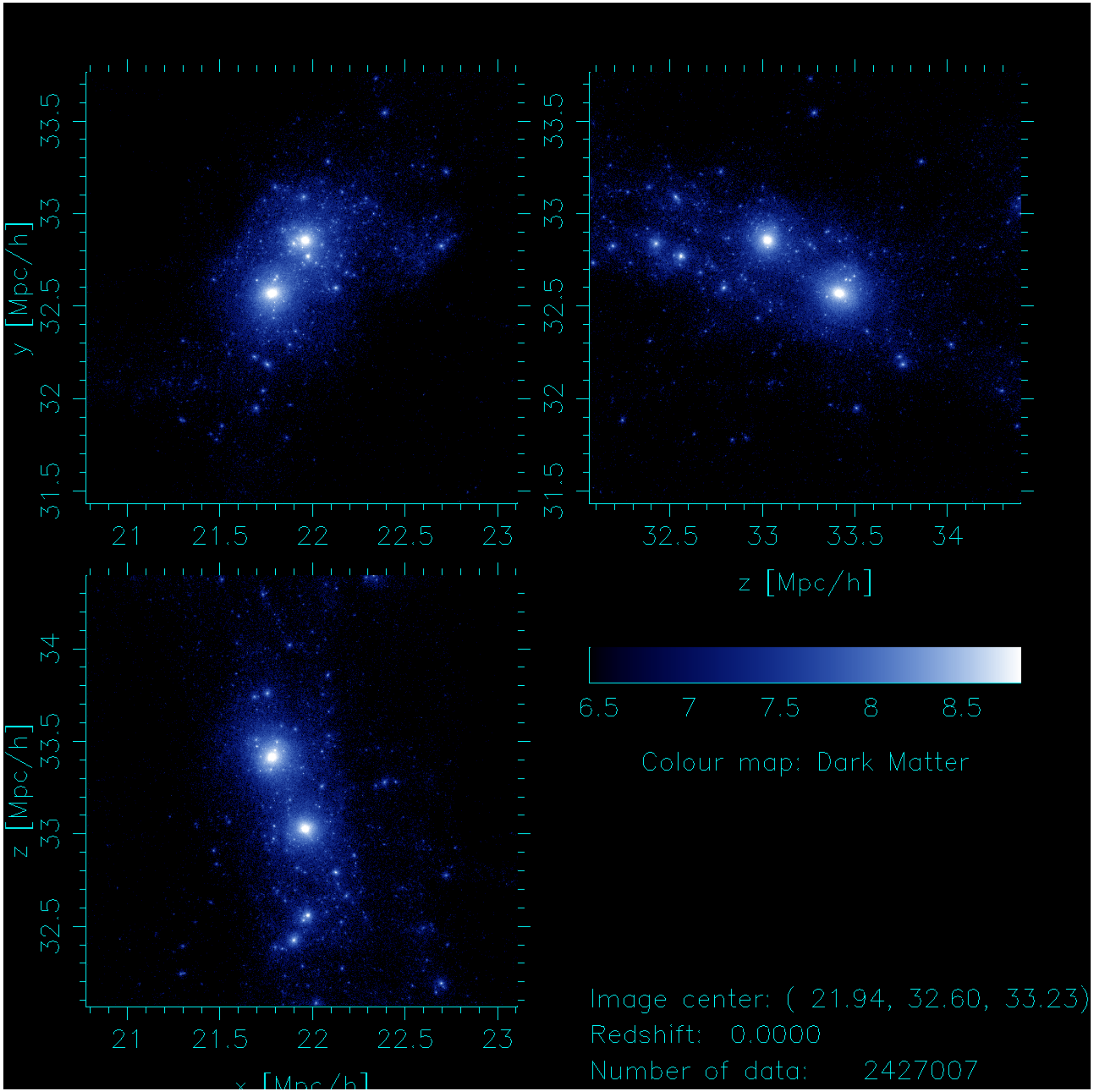
Zoom-In $(4\ h^{-1}\ cMpc)^3$ Subvolume = (full simulation volume/4096)

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

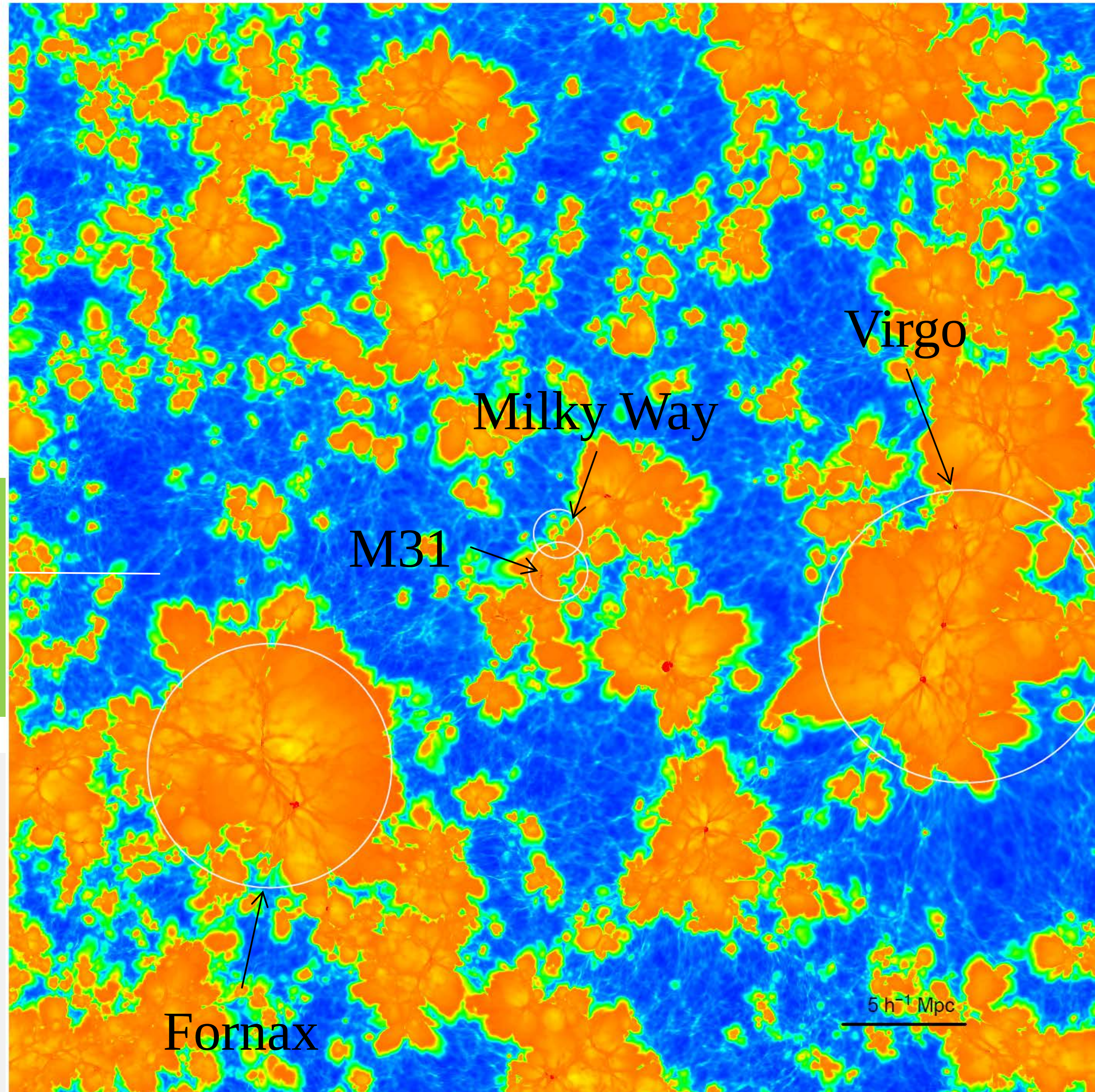
Gas Temperature
at
z = 6.15
in the supergalactic
YZ plane
of the
Local Group

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



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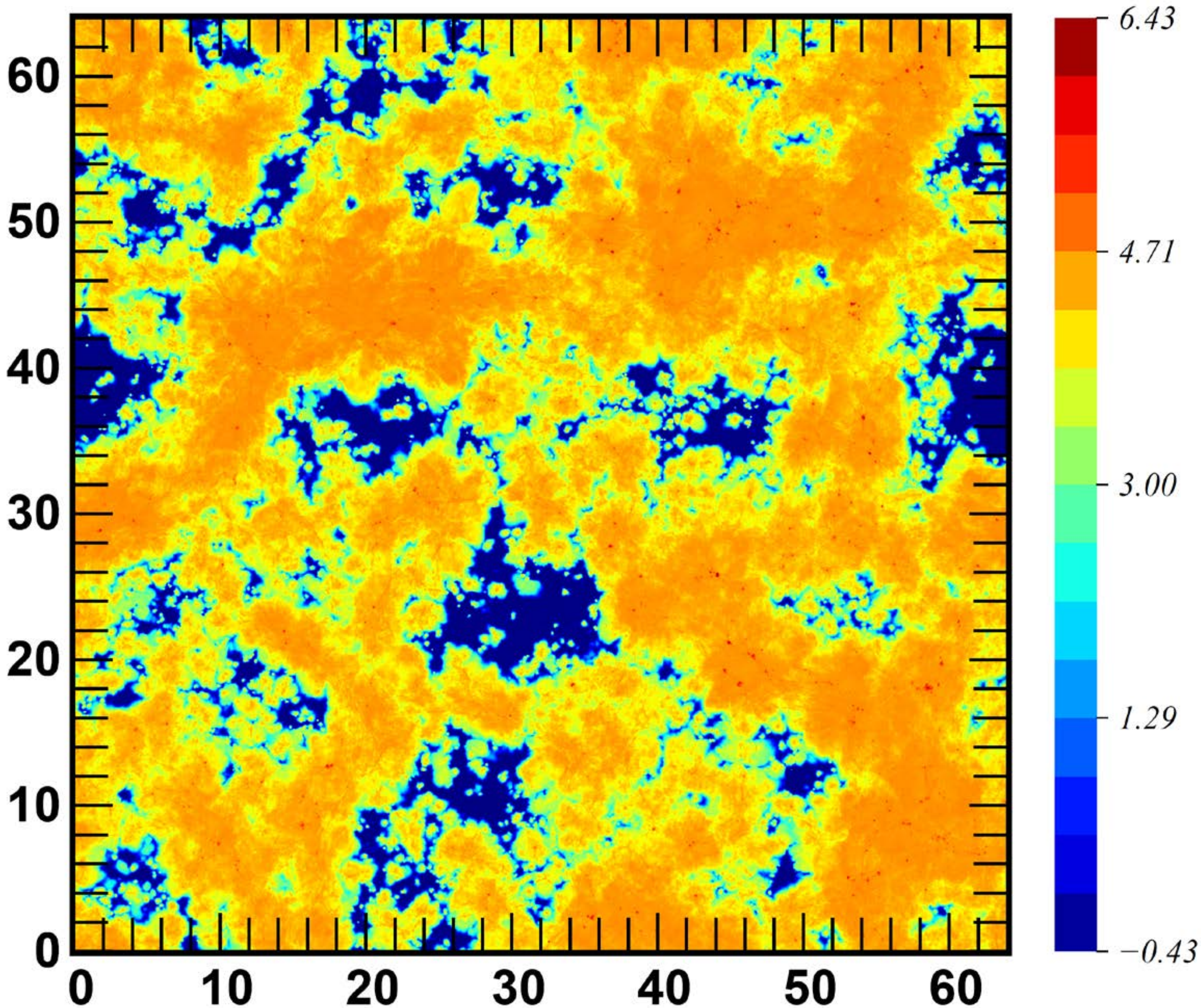
- Min halo mass ~ 10^8 solar masses

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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- Grid size = $(4096)^3$ cells
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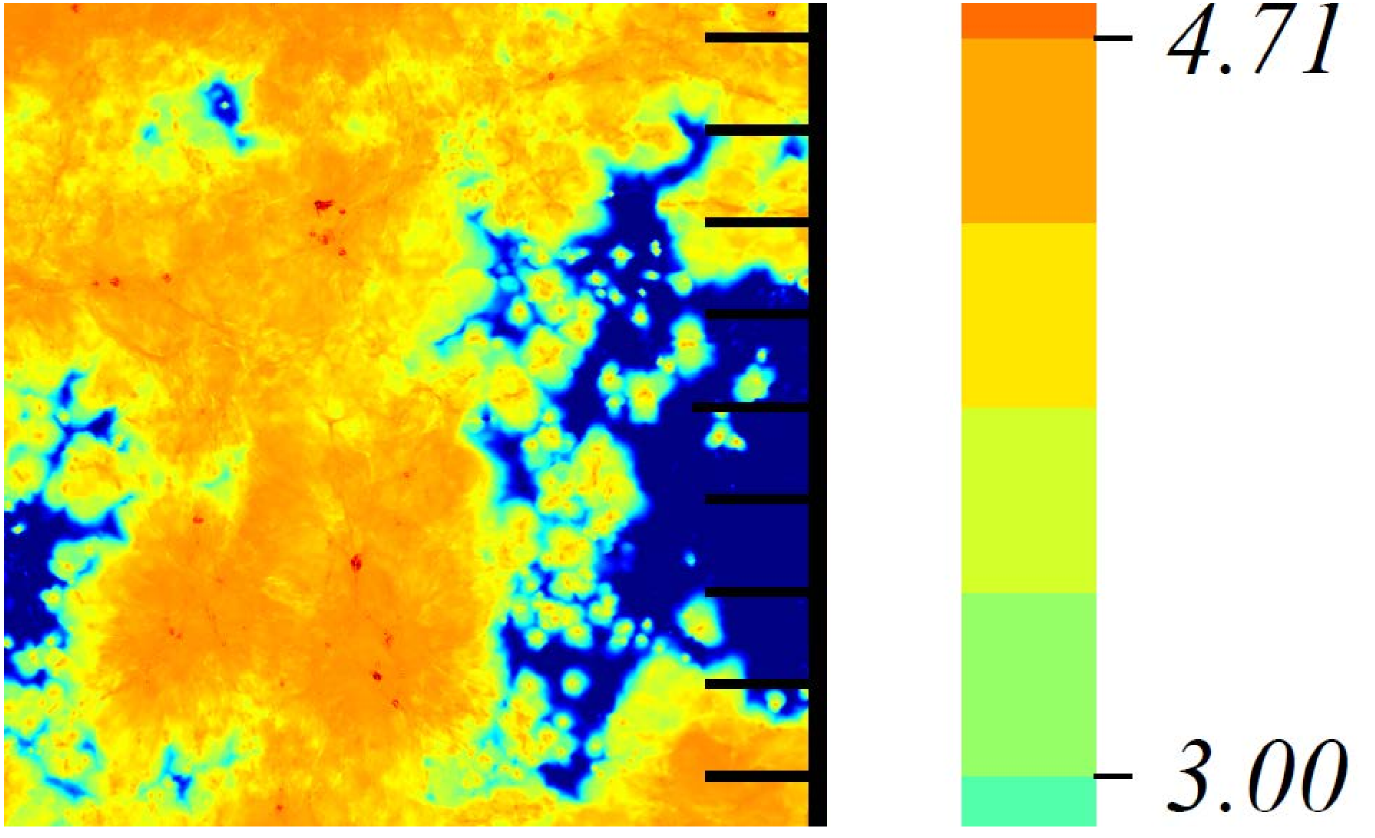
- Min halo mass ~ 10^8 solar masses

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

Zoom-in x 4



log10(temperature)

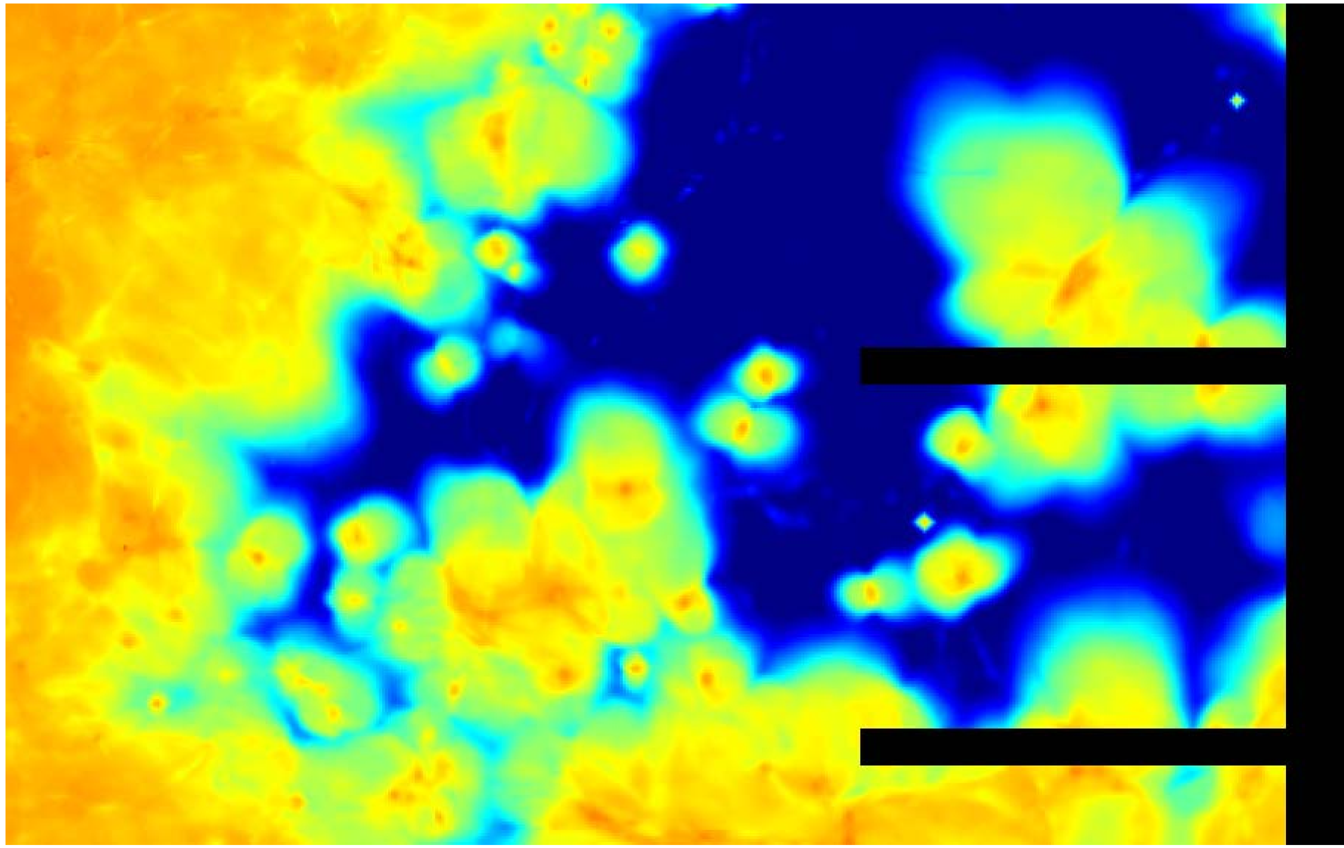
- red regions denote very hot, supernova-powered superbubbles, while yellow-orange regions show the long-range impact of photo-heating by starlight;

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)

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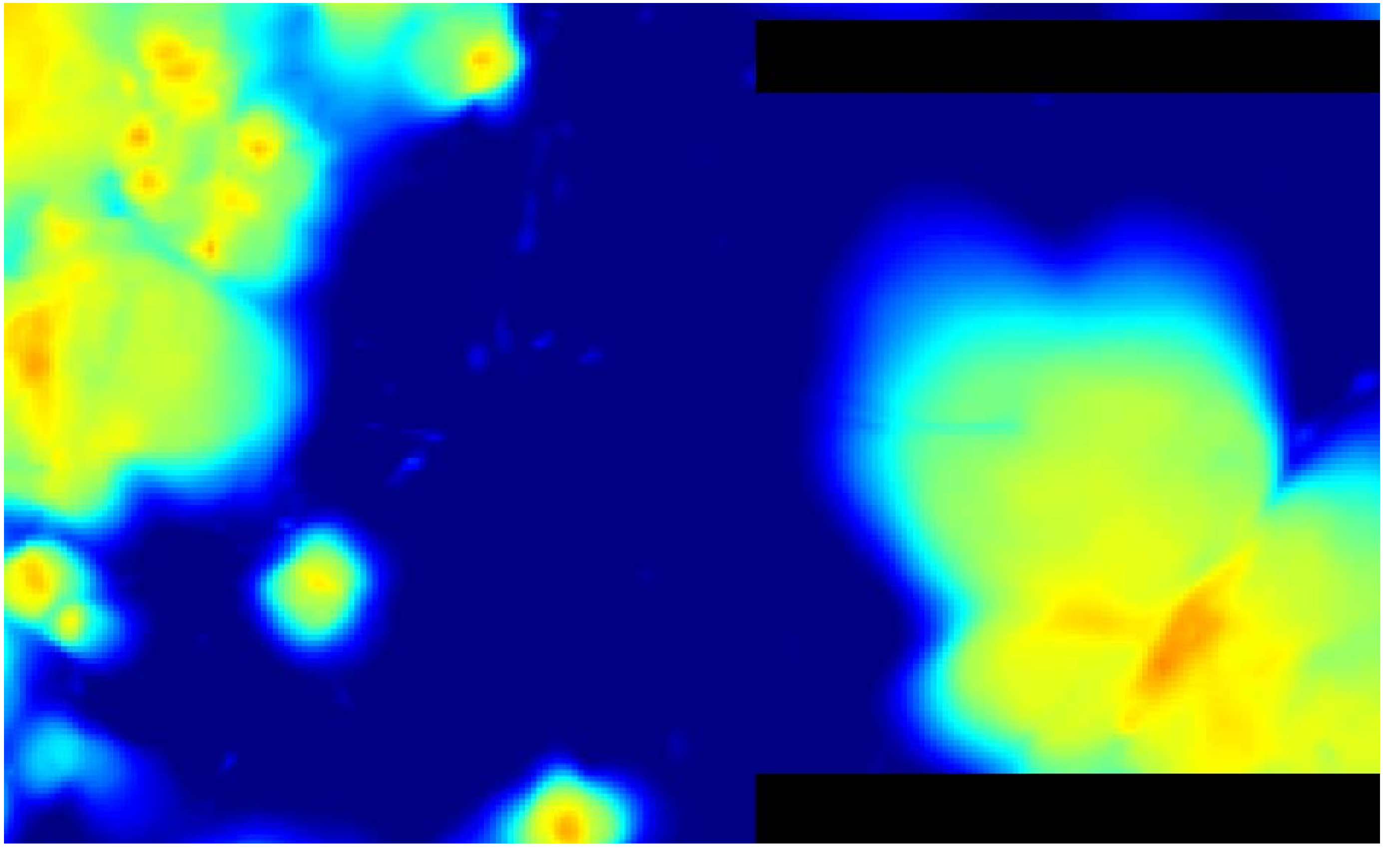
RAMSES-CUDATON simulation

- 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)

Zoom-in x 32



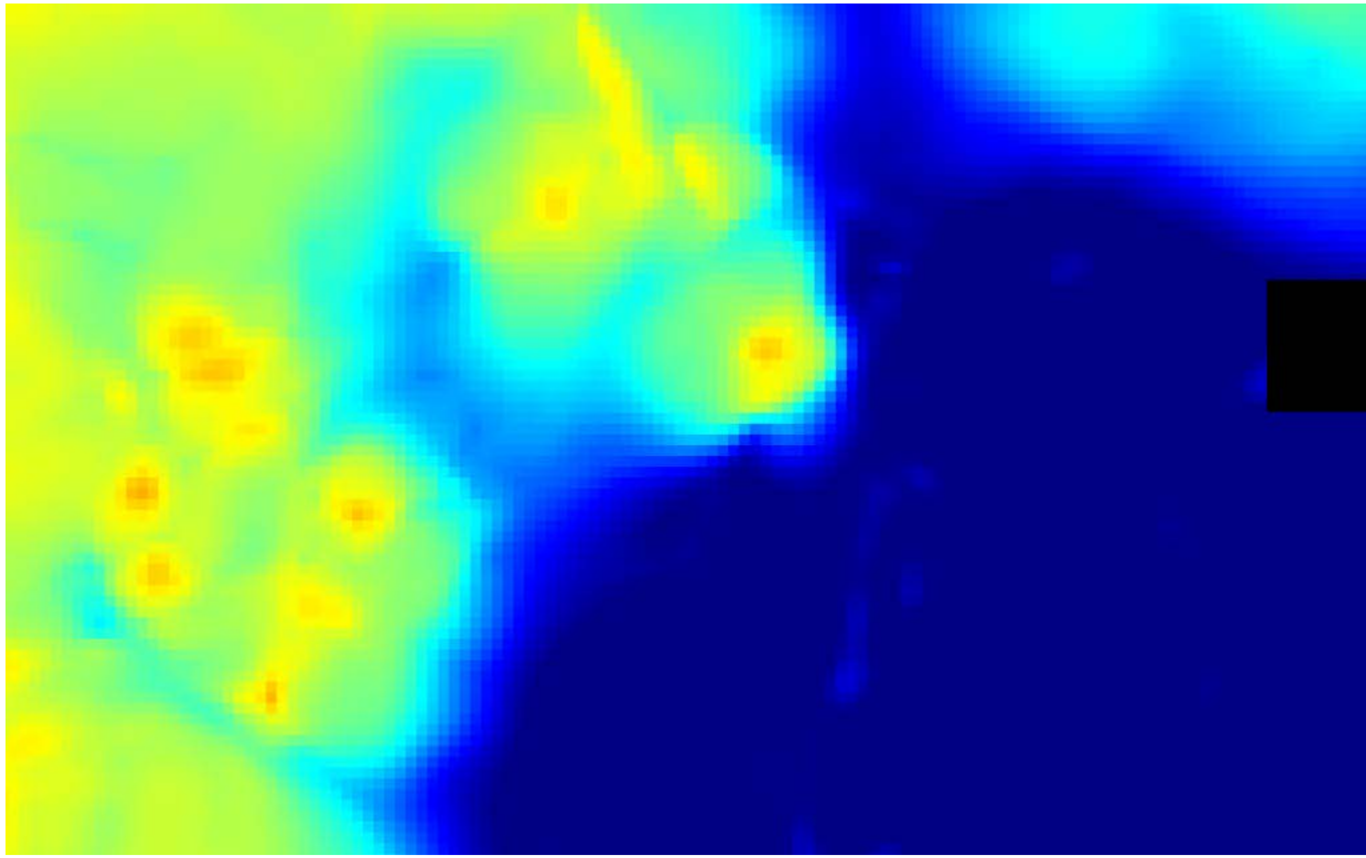
- red regions denote very hot, supernova-powered superbubbles, while yellow-orange regions show the long-range impact of photo-heating by starlight;

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

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ZOOM-IN ON THE LOCAL GROUP AT Z = 0

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

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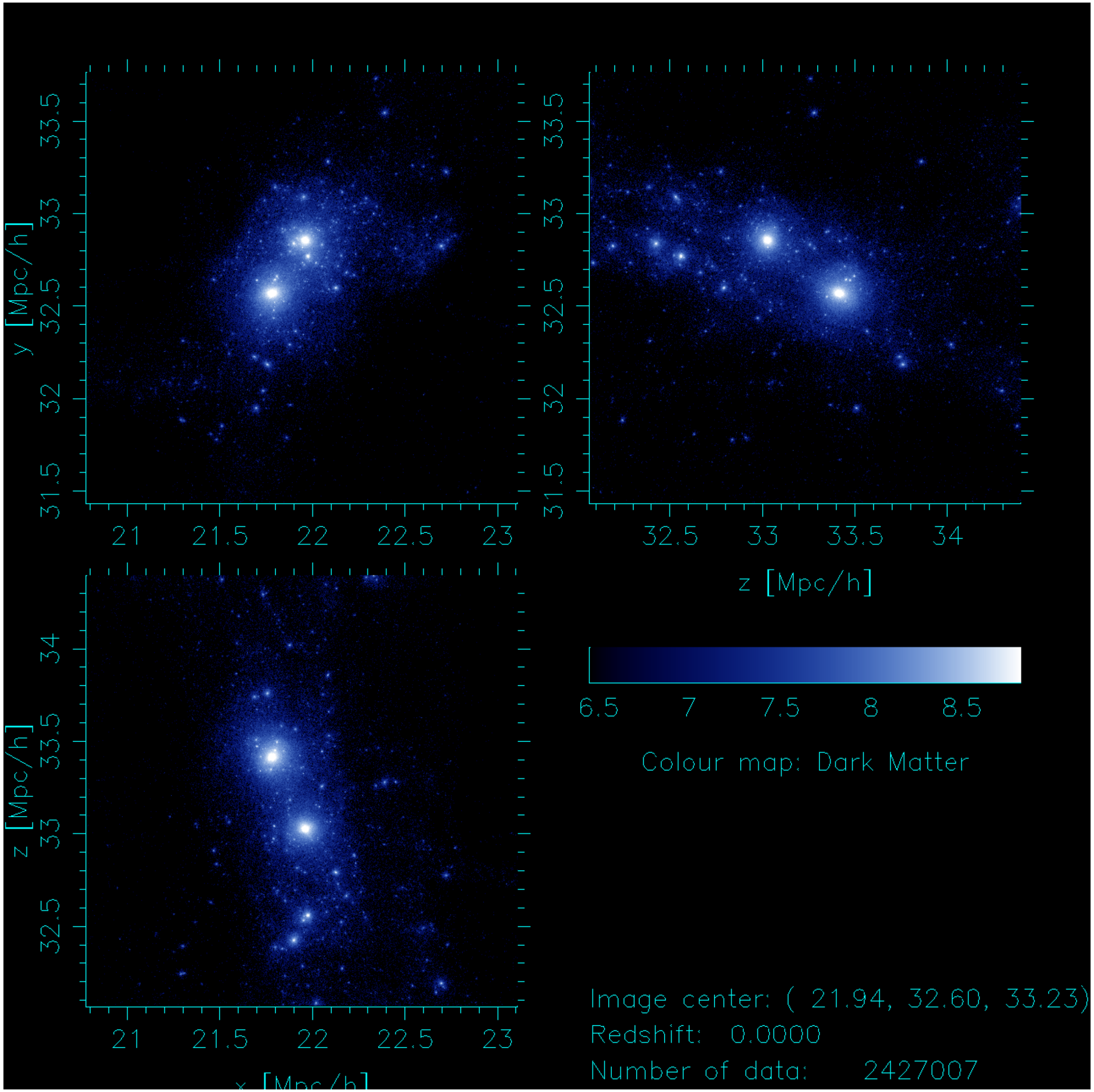


Zoom-In (4 h^{-1} cMpc)^3 Subvolume = (full simulation volume/4096)

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 this region

cutout100_xion_rho.mpg

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_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

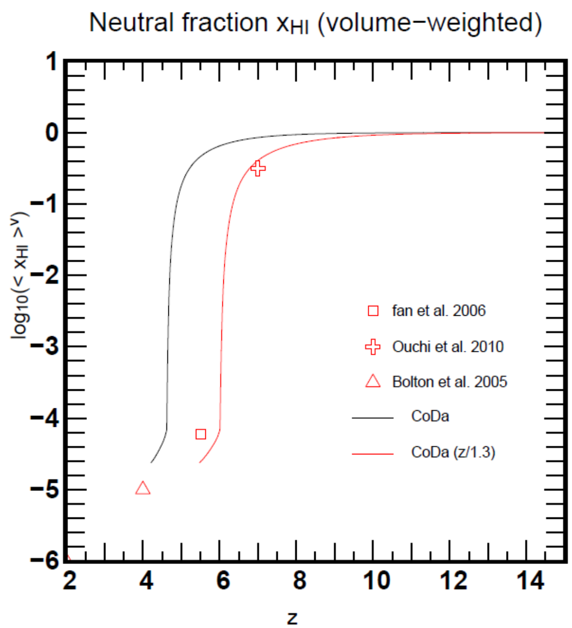
See a map of the ionized gas density evolve thru the EOR in another cut-out region

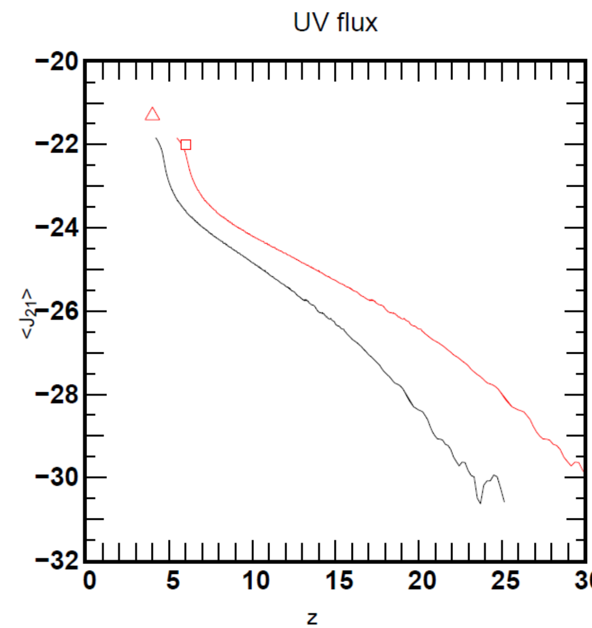
cutout101_xion_rho.mpg

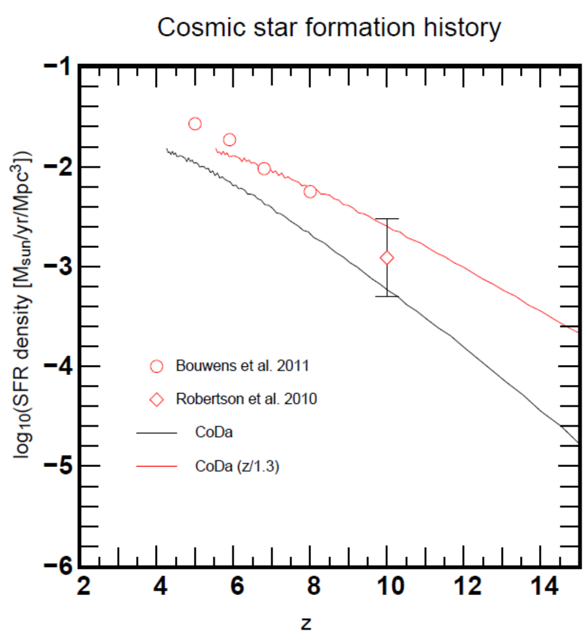
This cut-out is reionized by external sources, as the matter in this cut-out falls toward the source of its reionization.

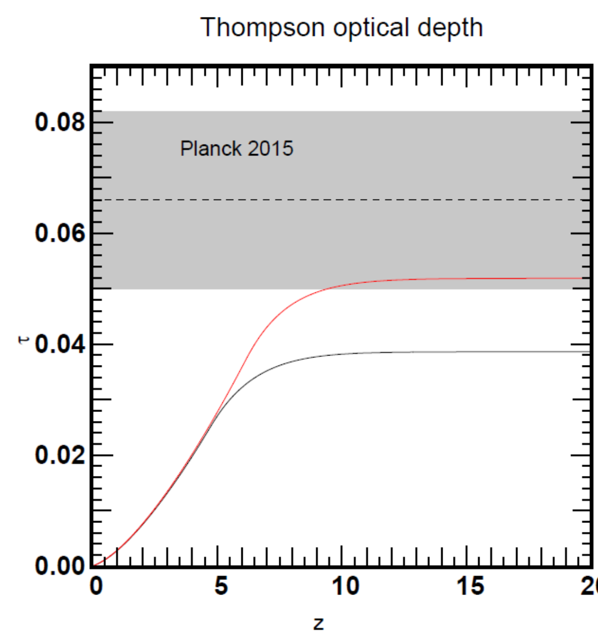
Reionization of the Local Universe: Witnessing our Own Cosmic Dawn

- 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









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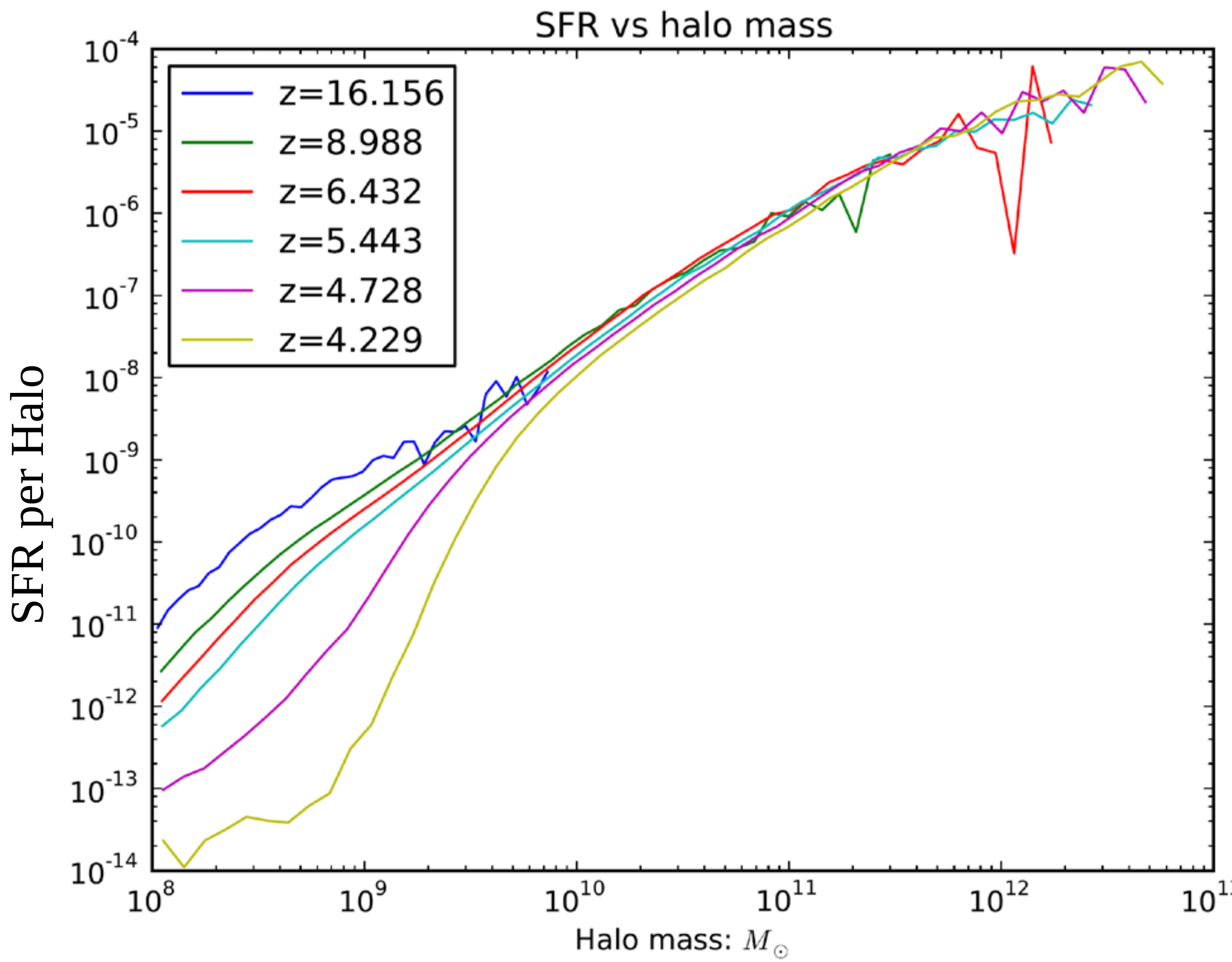
Reionization suppresses star formation rate in dwarf galaxies, for M < 10^9 solar masses

- 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

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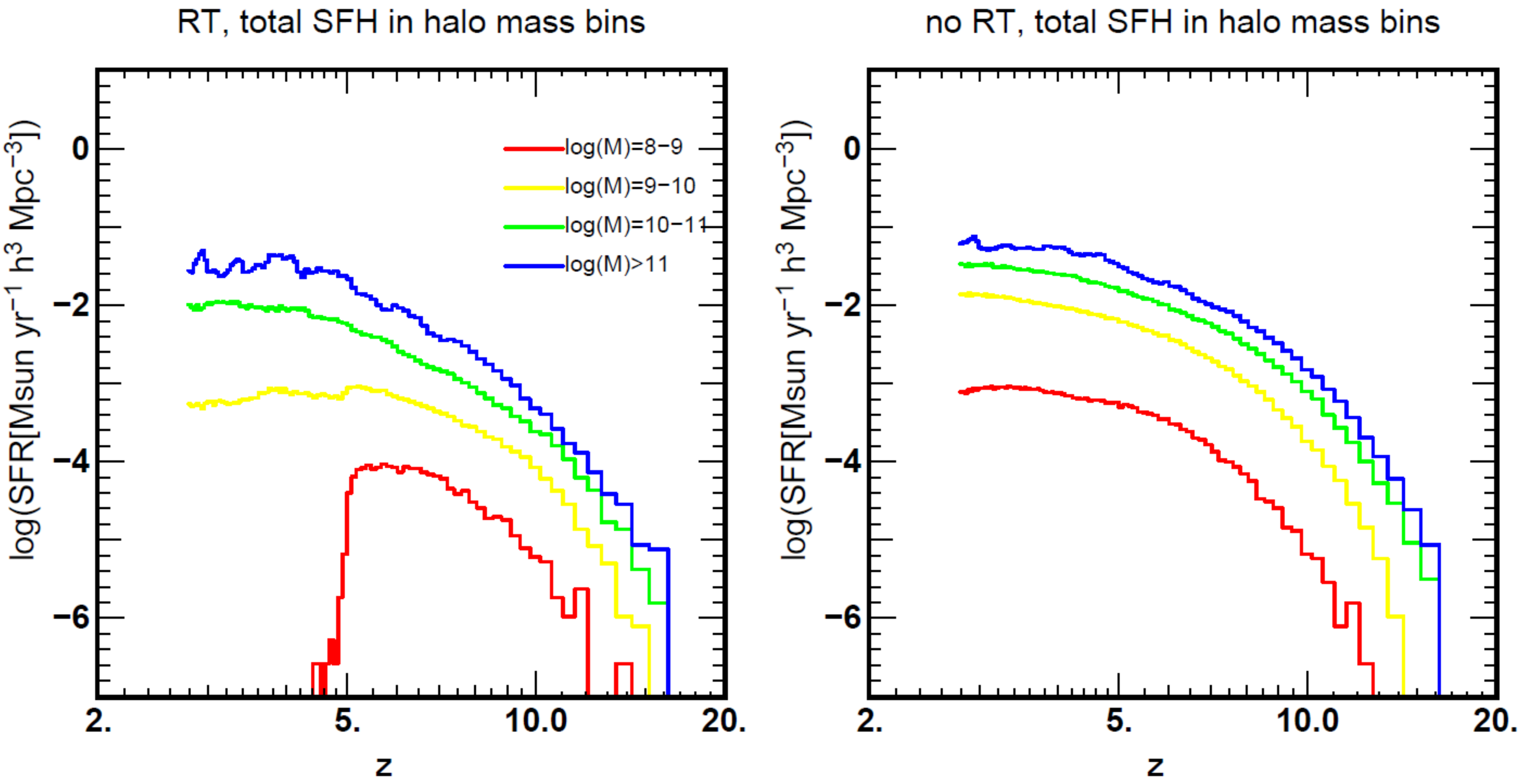

- Star Formation Rate attributed to halo mass bins in which stars are found at a fixed late time, after reionization ends

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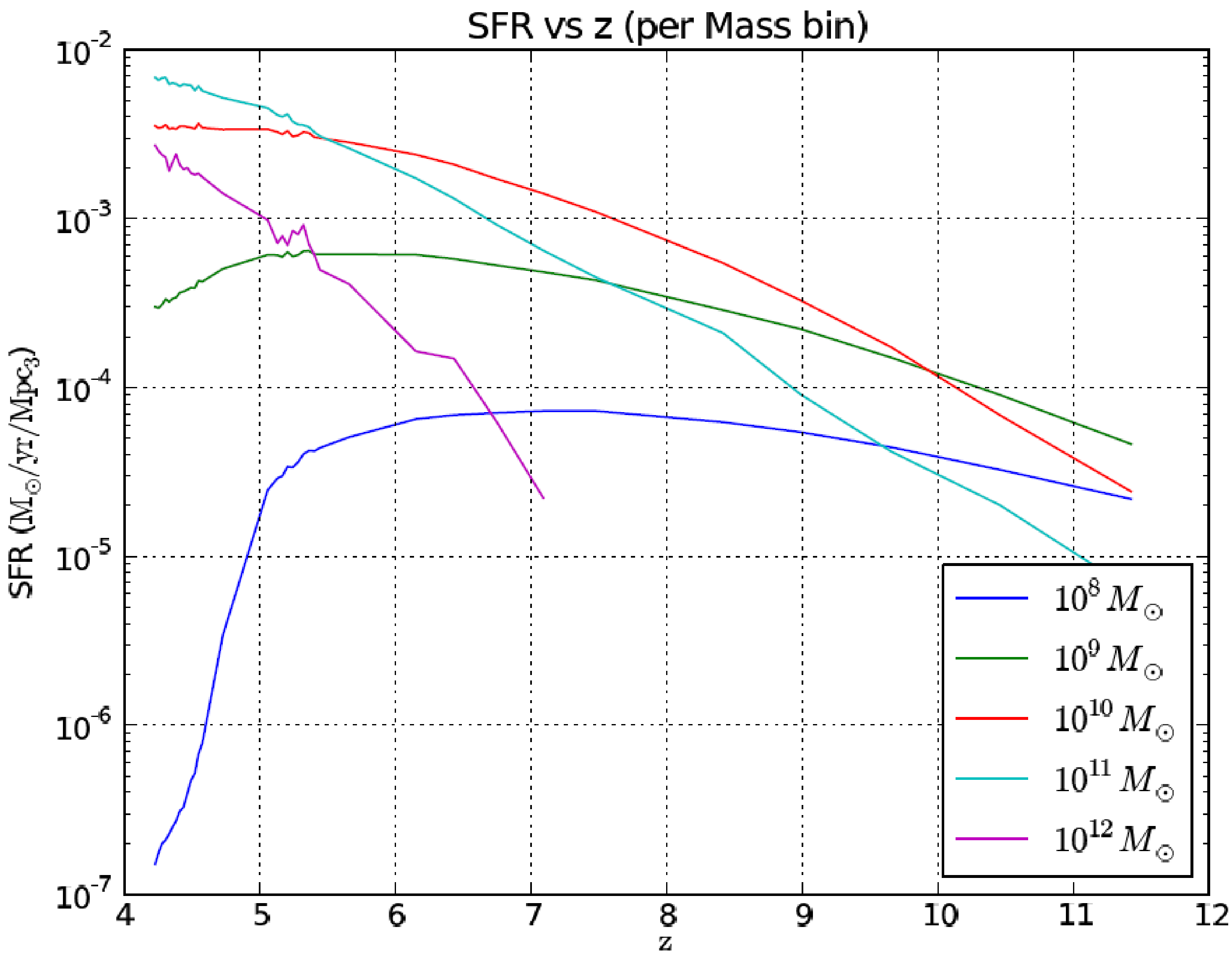

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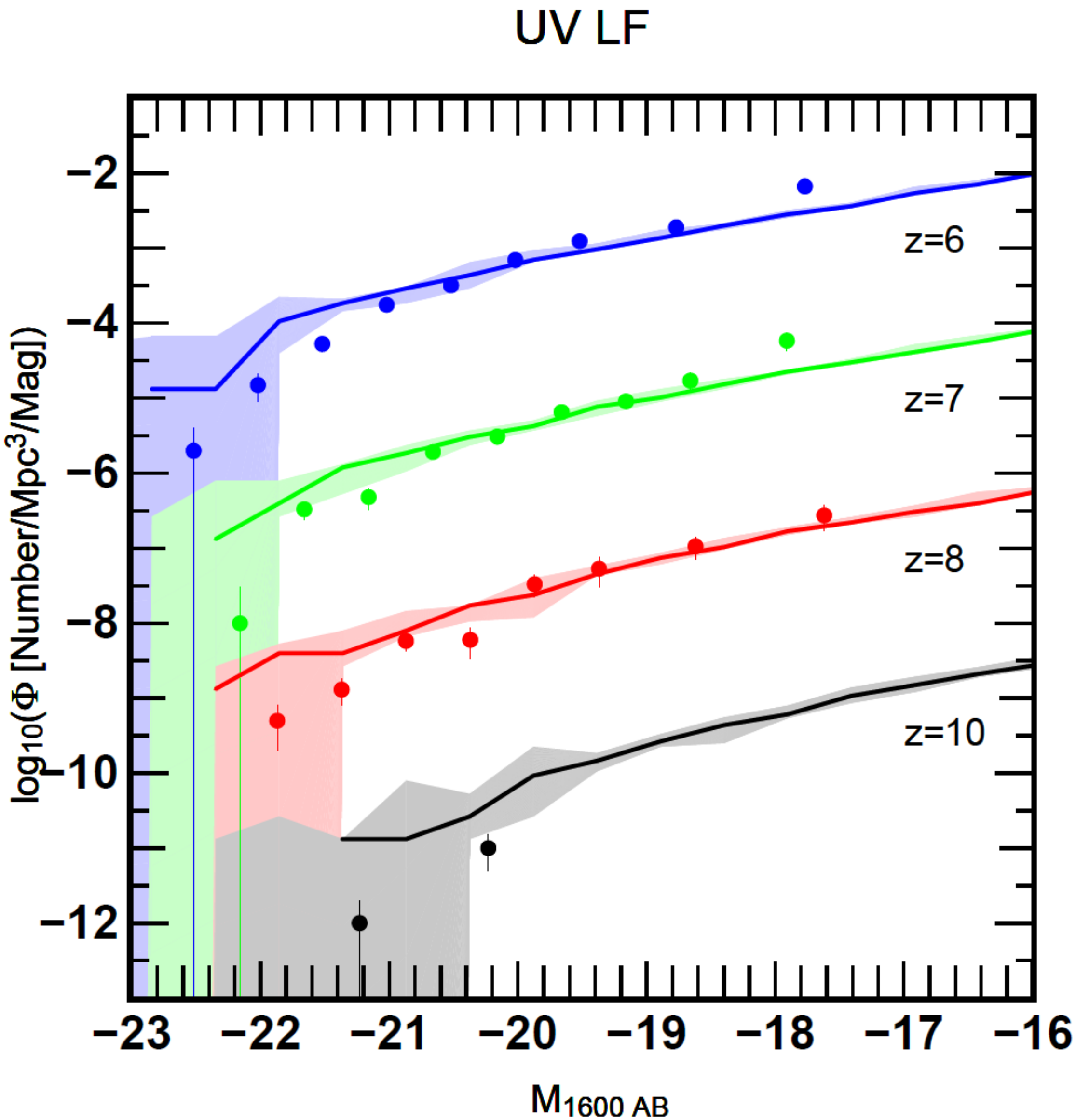
UV Luminosity Function vs. Observations from Bouwens et al. (2014)

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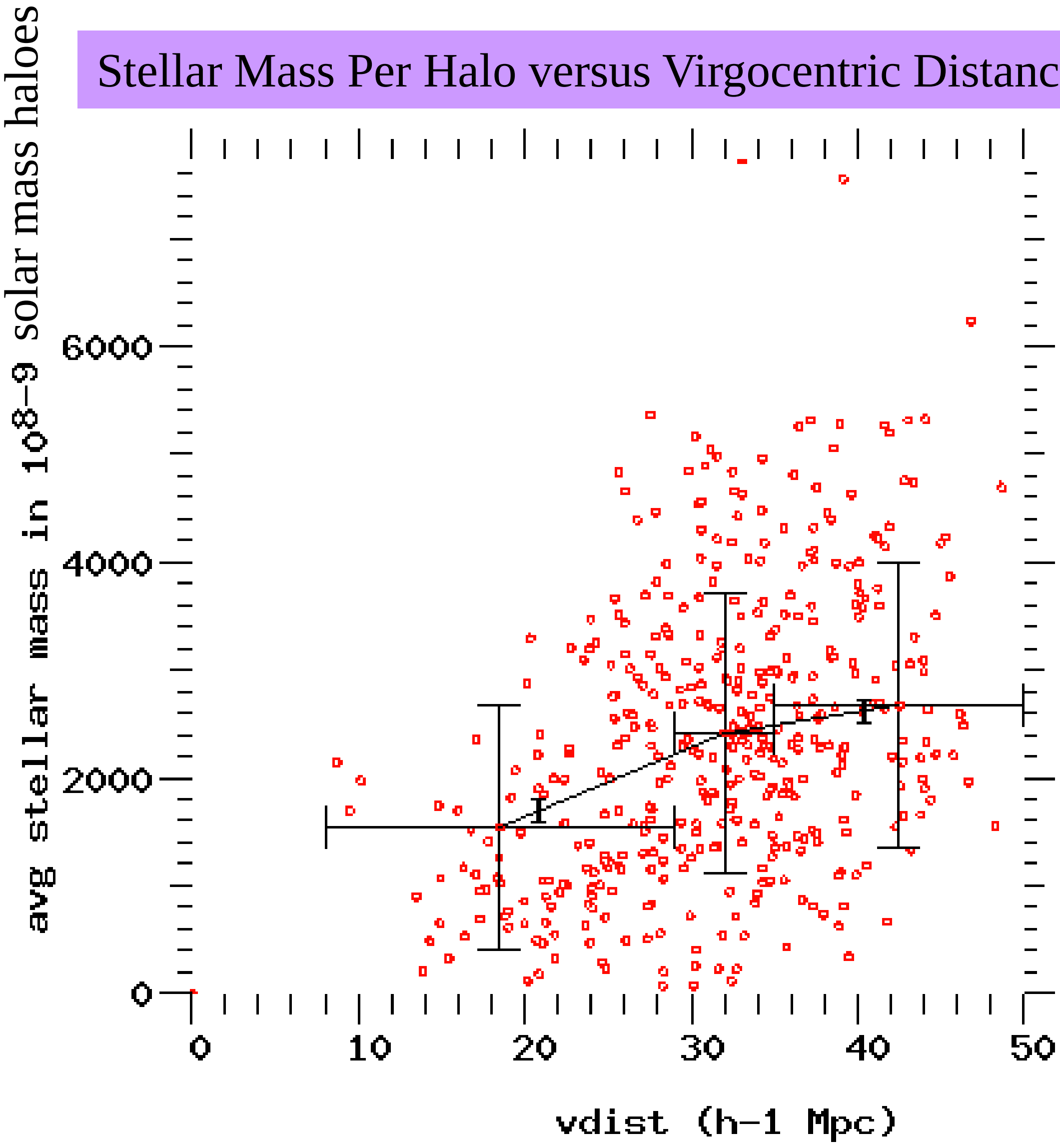
Reionization suppresses star formation rate in dwarf galaxies, for M < 10^9 solar masses

- 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

Stellar Mass Per Halo versus Virgocentric Distance



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RAMSES-CUDAT... N simulation
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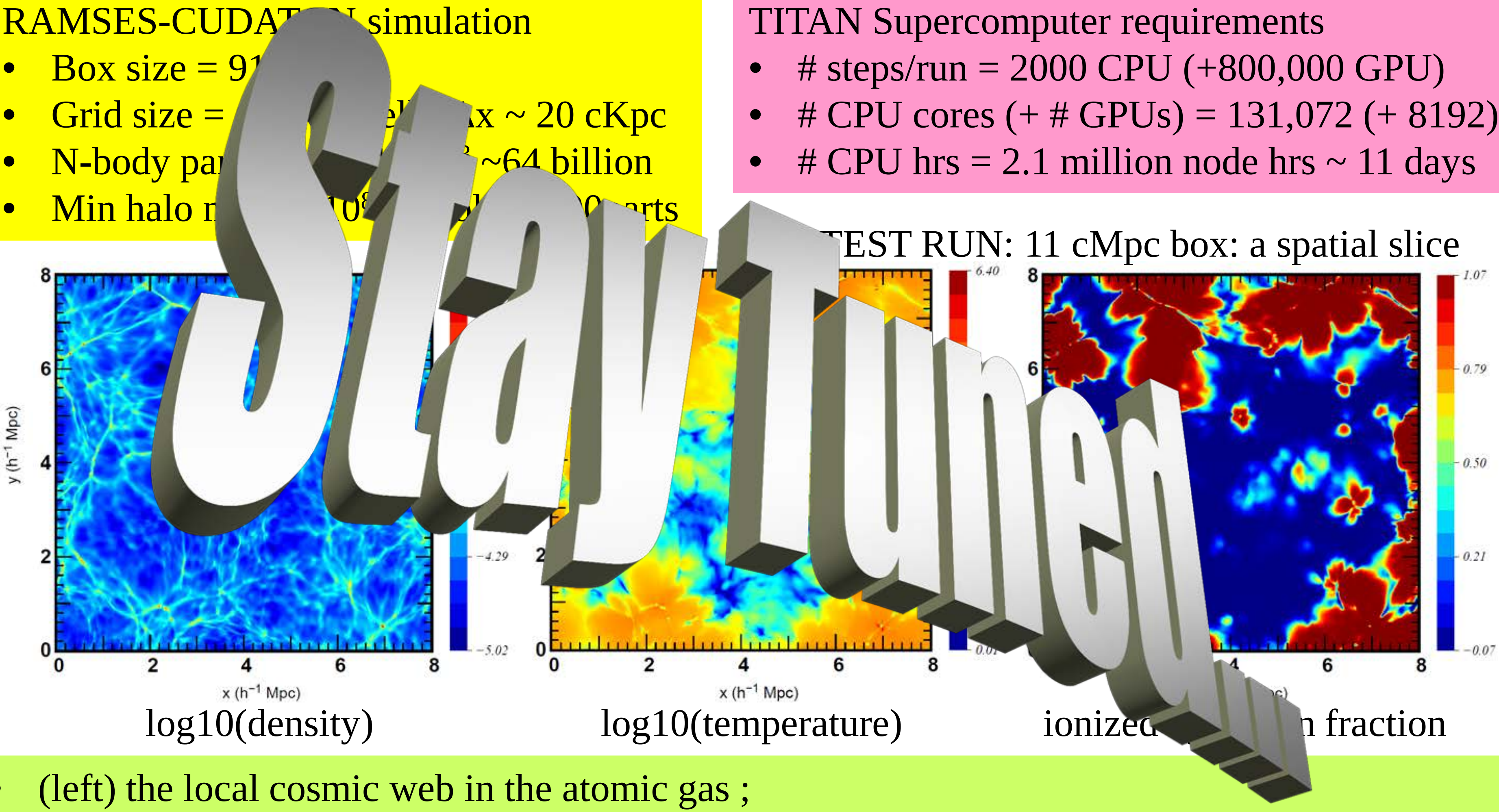
- Grid size = ... el... x ~ 20 cKpc
- N-body par... 3 ~64 billion
- Min halo m... 10^8 ... l... 0 ... arts

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

...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)].