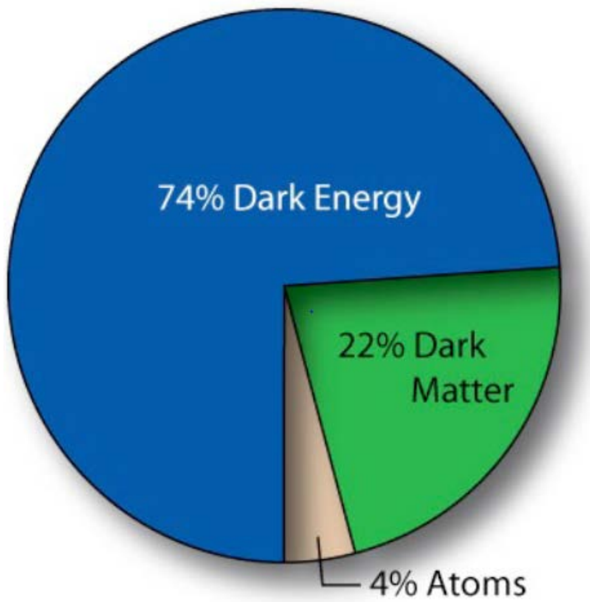


Simulating the 4% Universe

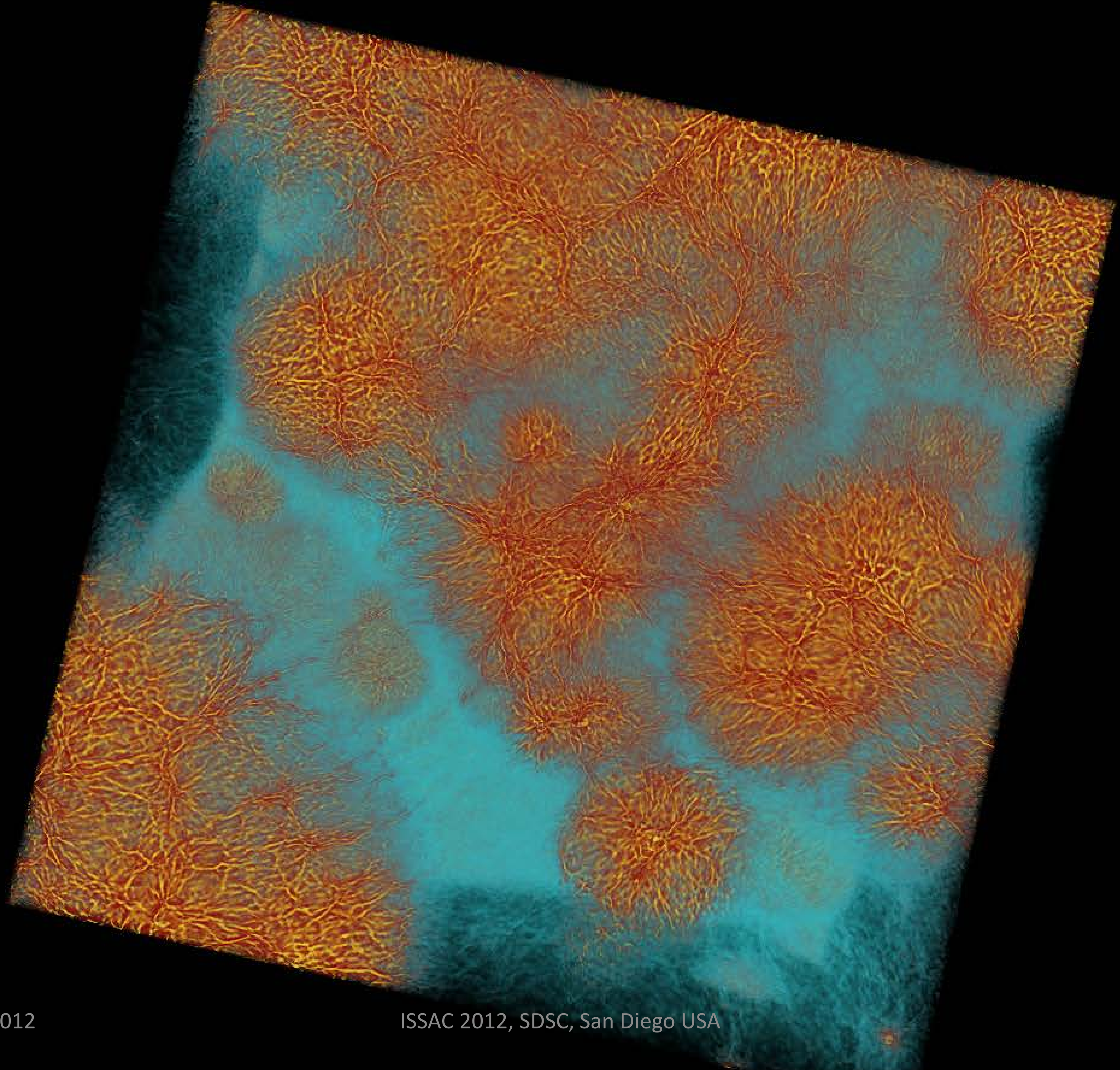
Hydro-cosmology simulations and data analysis

Michael L. Norman
SDSC/UCSD

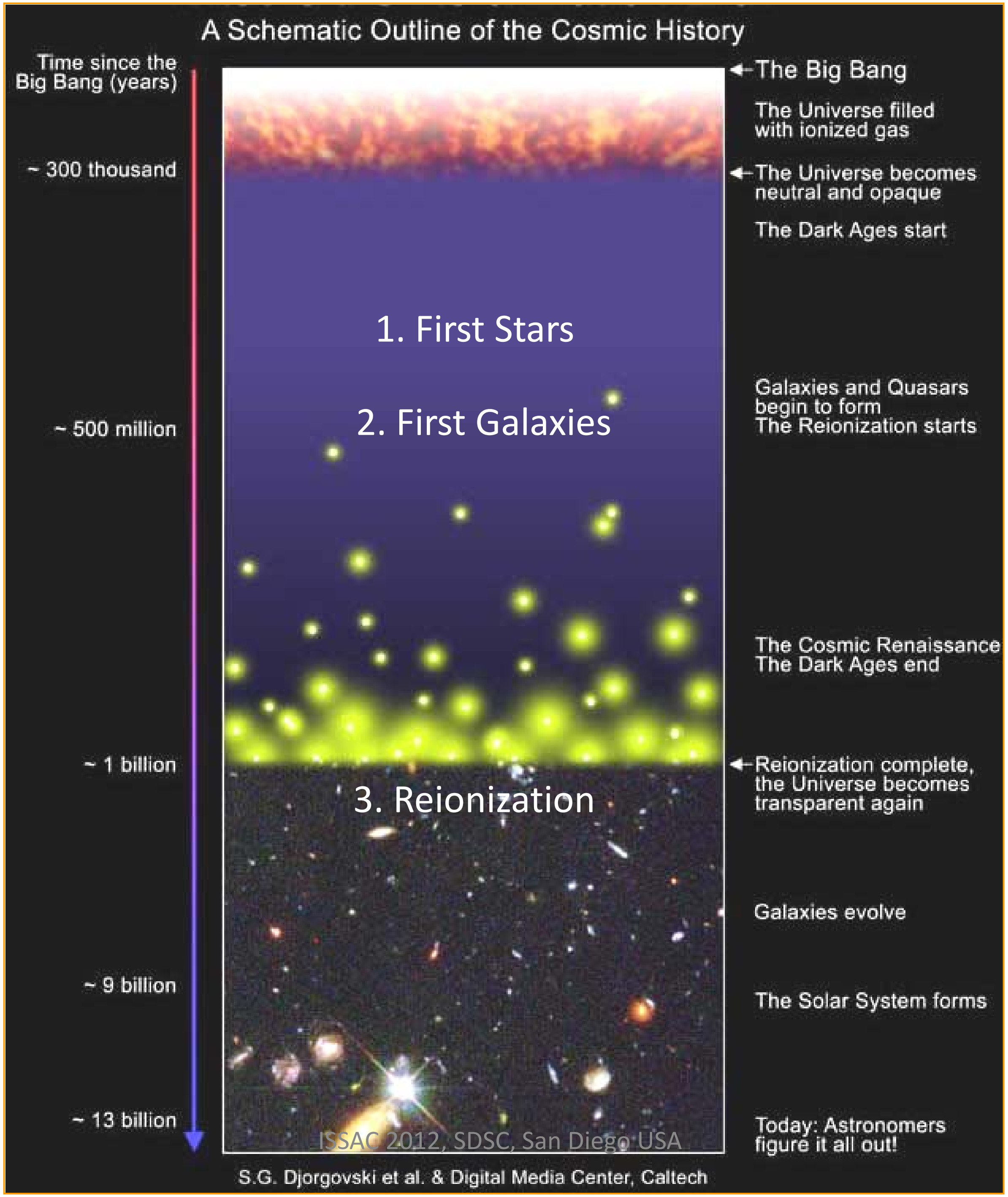
Lecture Plan

- Lecture 1: Hydro-cosmology simulations of baryons in the *Cosmic Web*
  - Lyman alpha forest (LAF)
  - Baryon Acoustic Oscillation (BAO)

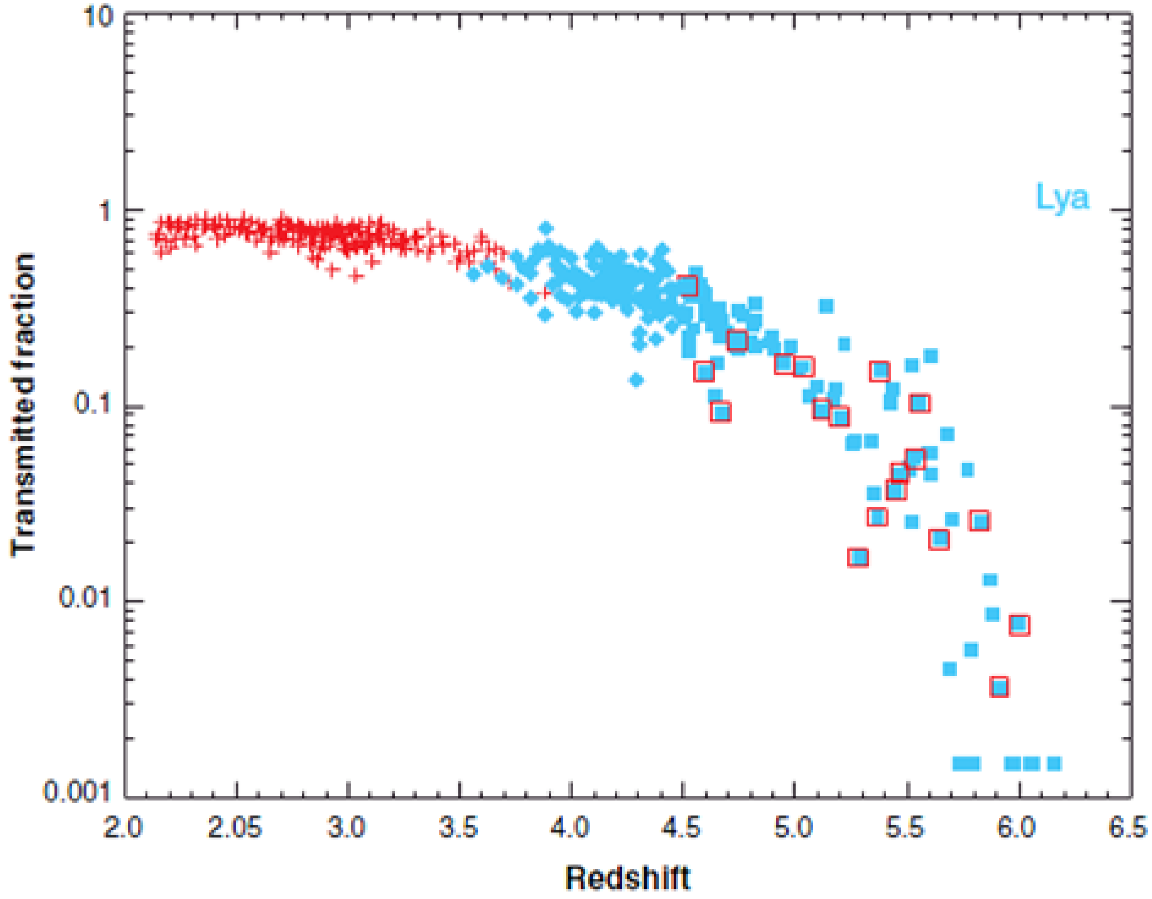
- Lecture 2: Radiation hydro-cosmology simulations of *Cosmic Renaissance*
  - Epoch of Reionization (EOR)
  - First Galaxies



Cosmic Renaissance



When did reionization complete?



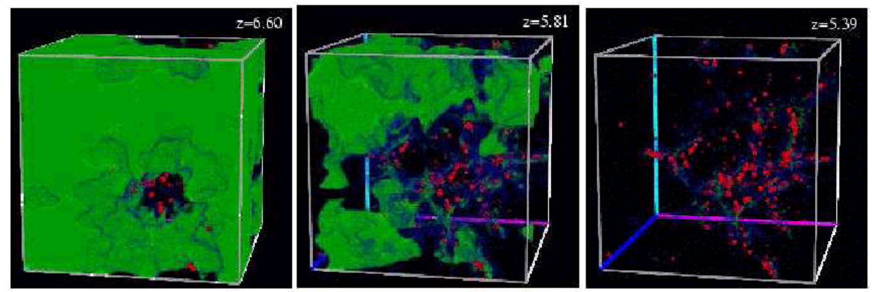
Fan, Carilli & Keating (2006)

Scientific Goals

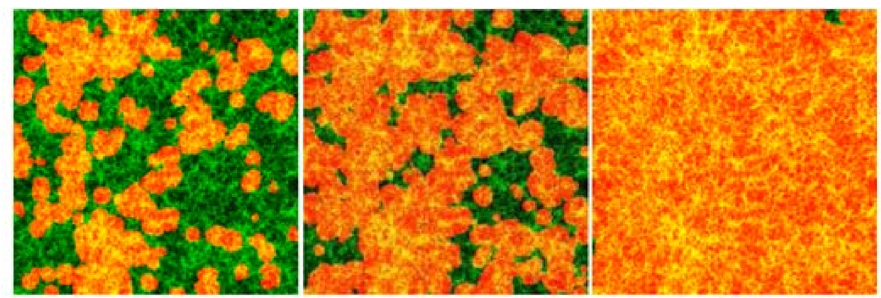
- Connect reionization to first galaxies through *direct numerical simulations*
- Some Questions
  - How does reionization proceed?
  - Is the observed high-z galaxy population sufficient to reionize the Universe?
  - How is galaxy formation and the IGM modified by reionization?
  - How good are the analytic and semi-numerical models of reionization?

Three generations of cosmological reionization simulations

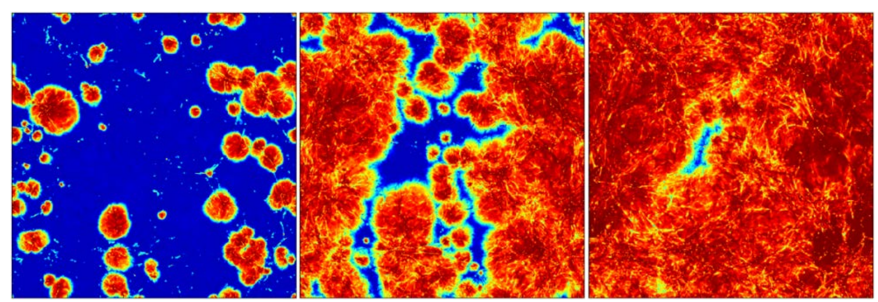
- 1. Local self-consistent
  - (small boxes < 10 Mpc)
  - CRHD+SF+ionization+heating
  - e.g., Gnedin 2000, Razoumov et al. 2002



- 2. Global post-processing
  - (large boxes > 100 Mpc)
  - N-body + RT
  - e.g., Iliev et al. 2006



- 3. Global self-consistent
  - (large boxes > 100 Mpc)
  - CRHD+SF+ionization+heating
  - Norman et al. 2012, in prep.

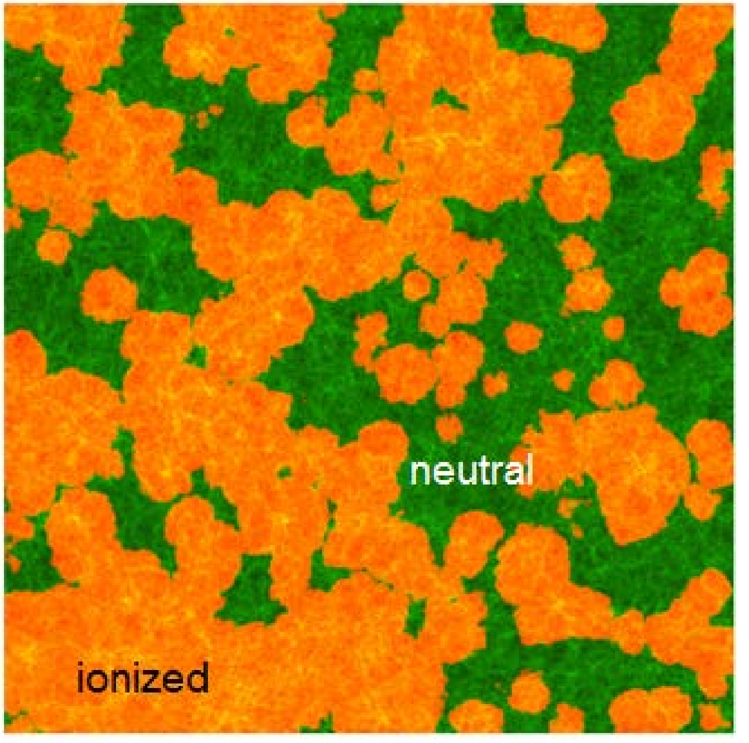


Post-processing Approach

- Pioneered by Sokasian et al. (2003) and "perfected" by Iliev, Shapiro, et al. (2006+)
- Recipe:
  - Perform high resolution N-body DM simulation in large volume (L>100 Mpc/h)
  - Assign ionizing flux to every halo by some prescription
  - Post-process snapshots of the density field, sampled onto a coarse grid, with a ray-tracing radiative transfer code, assuming baryons trace DM
  - Sources and gas clumping factor "coarse grained" on the mesh
  - No radiative feedback on source population or intergalactic gas

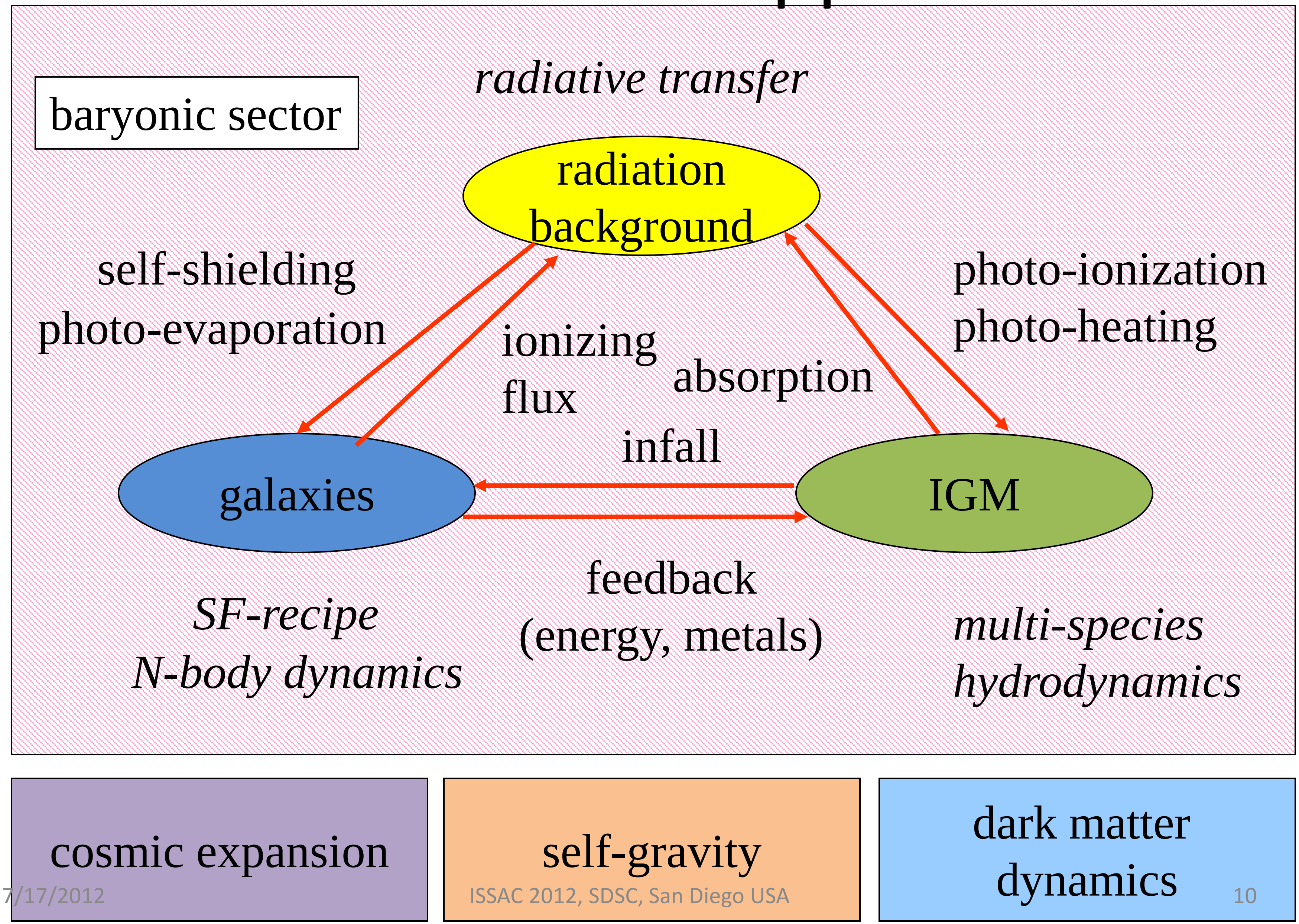
Post-processing Approach

- Key insights
  - reionization proceeds from the "inside-out" (i.e., from overdense to underdense regions)
  - reionization is "rapid" ($\Delta z \sim 2$)
- However
  - redshift of overlap is *not predicted*, but can be "dialed in" since it depends critically on assumed (M_{halo}/L_{ion}) and f_{esc}
  - minimum halo mass cutoff a free parameter



Iliev et al. (2006)

Self-Consistent Approach



https://code.google.com/p/enzo

enzo
Astrophysical Adaptive Mesh Refinement

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Links

Welcome to Enzo!

Here you will find the latest public release of Enzo, an adaptive mesh refinement (AMR), grid-based hybrid code (hydro + N-Body) which is designed to do simulations of cosmological structure formation. It can also be used for astrophysical fluid dynamics simulations more generally.

Enzo development is supported by grants AST-0808184 and OCI-0832662 from the National Science Foundation.

Please visit the Enzo Homepage at http://enzo-project.org/ to learn more about the Enzo project.

How To Get Enzo And Get Started

Documentation

Documentation is provided in every checkout of Enzo. A current build of the documentation is also available online at http://enzo-project.org/doc/ .

At the 2010 Enzo Users' Workshop, we also had a number of presentations and tutorials, many of which were recorded. These are all available online.

Enzo Community

Enzo is a community supported code, written by and for active researchers in the field of Astrophysics. Please join the users' mailing list or the developers' mailing list to tell us about interesting things you've done with Enzo, ask for help, and meet the rest of the community.

Enzo 2.1

Enzo 2.1.x Releases

What does “direct simulation” mean?

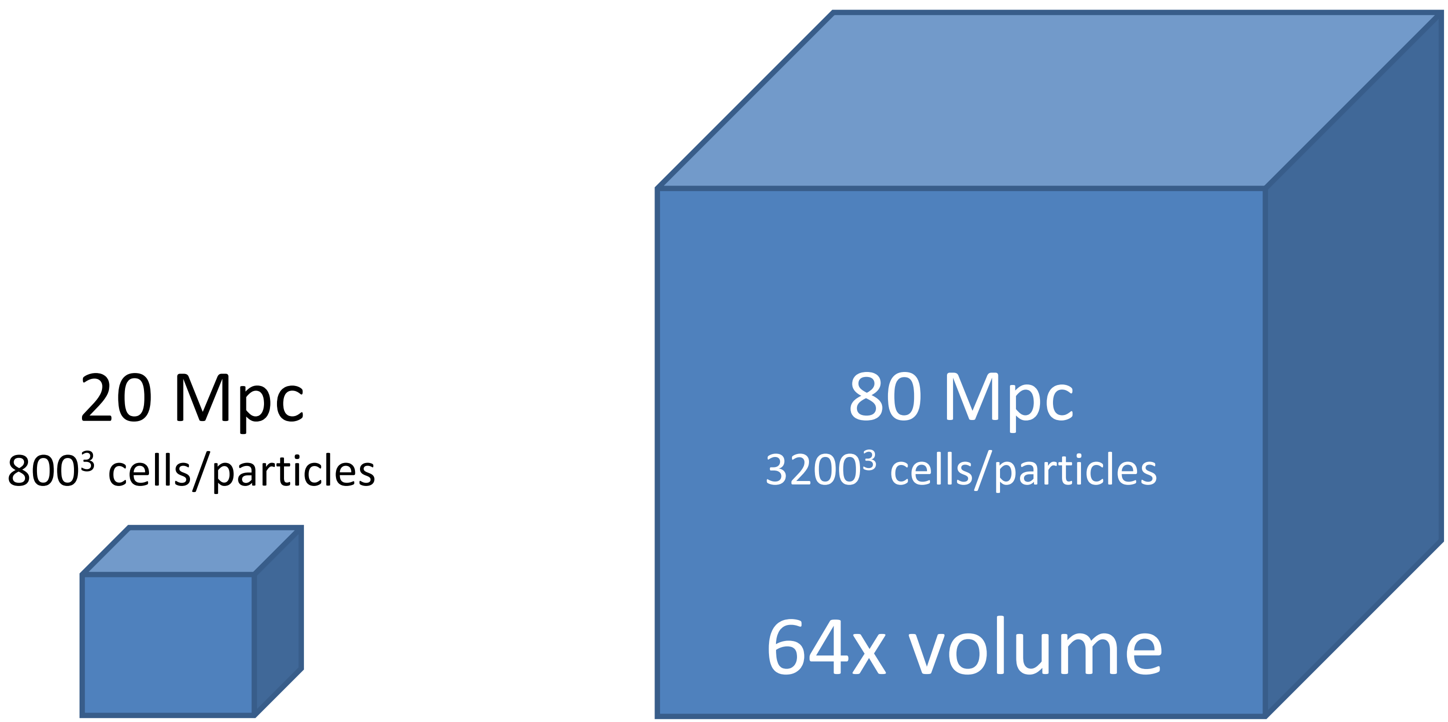
- *All physical processes are simulated at the same mass and spatial resolution*
  - DM, gas dynamics
  - parameterized star formation and feedbacks
  - radiation sources and transport
  - ionization/recombination/photoevaporation
- Only subgrid model is SF, which is calibrated to observations (Bouwens et al.)
- Advantage: sources and sinks of ionizing radiation and radiative feedback effects are simulated directly
- Disadvantage: very costly to bridge scales; some still missing (minihalos)

Two Simulations Differing only in Volume

ΛCDM, WMAP7

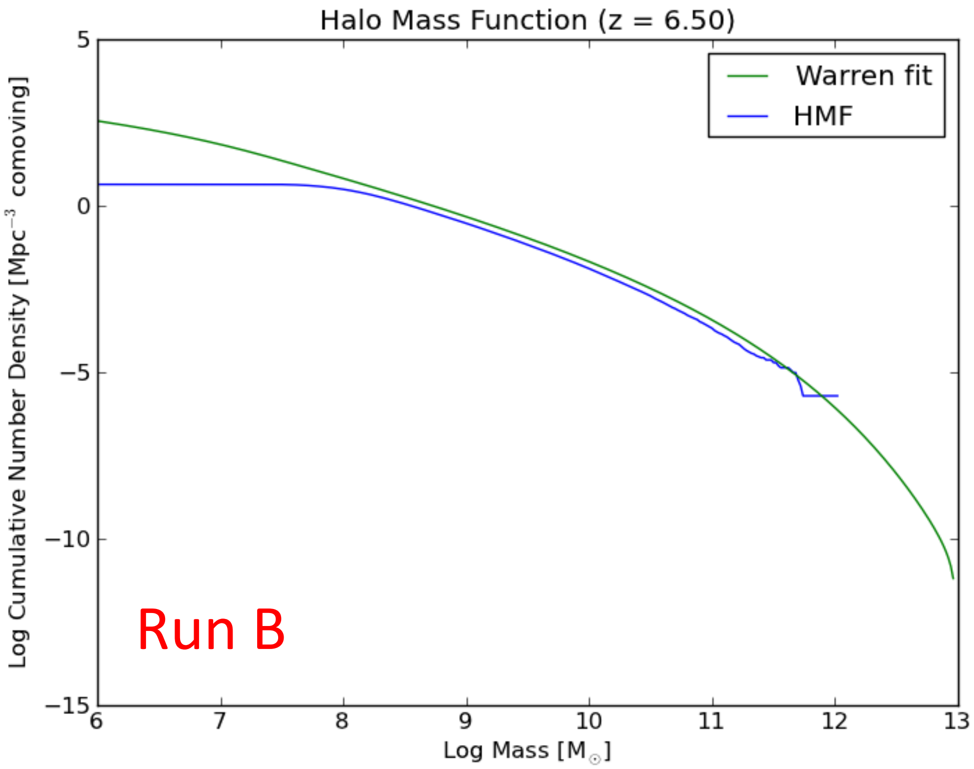
Run A
"¼ scale simulation"

Run B
"Renaissance Simulation"



Run A and Run B have identical mass and spatial resolution, physics, ICs, etc.

Mass and Spatial Resolution

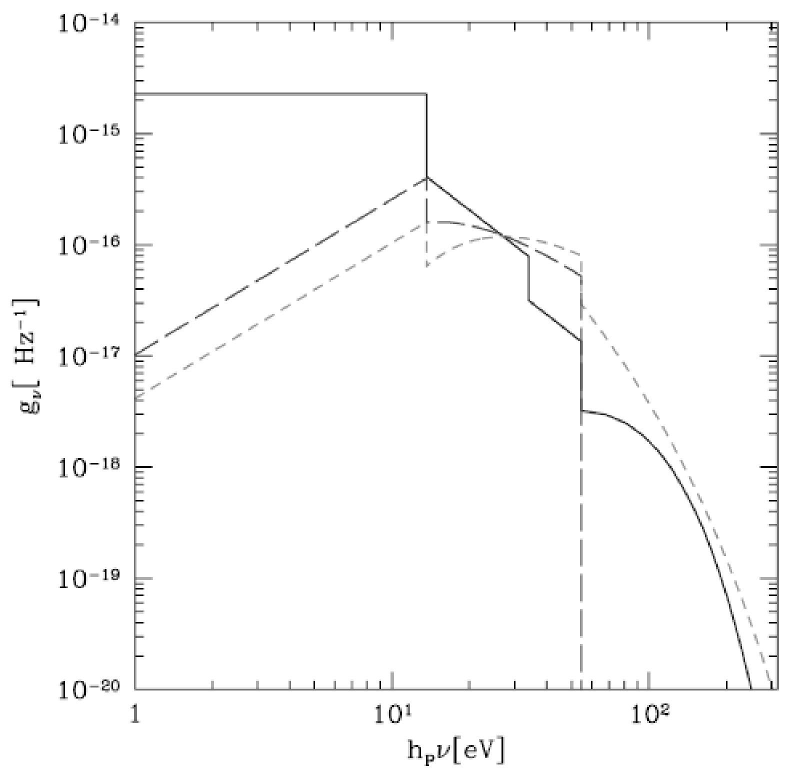


GOALS

- HMF complete to ~10^8 M_s to include dwarfs
  - Sets "minimal" mass and spatial resolution
  - $M_p = 5 \times 10^5\ M_s$
  - Δx=25 ckpc
- Simulate *largest volume possible* with available computer resources

Numerical Methods

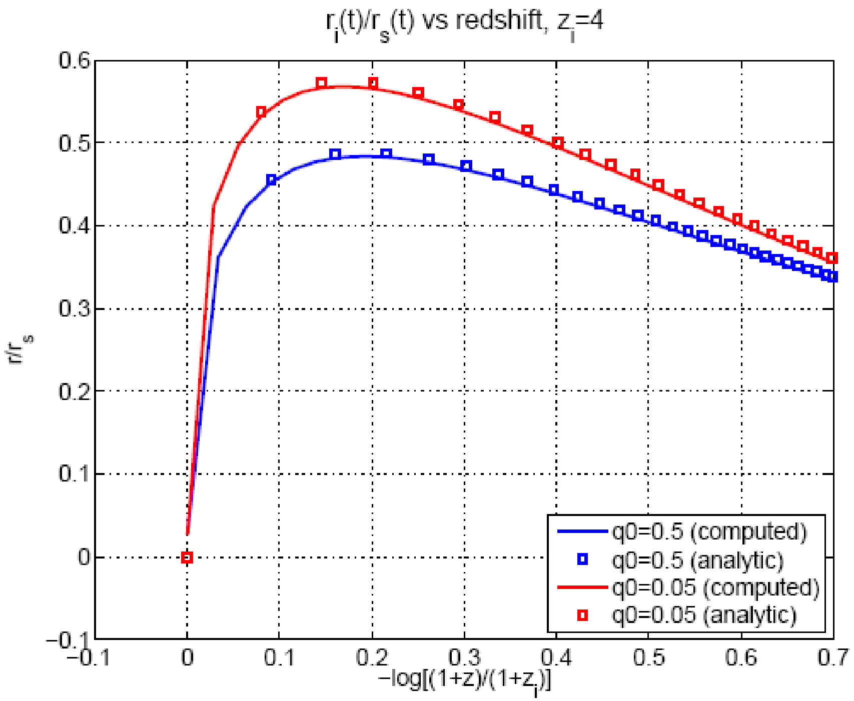
- We use Enzo V2.1 in non-AMR mode http://enzo.googlecode.com
  - 6 species fluid dynamics: PPM
  - Dark matter dynamics: Particle-Mesh
  - Gravity: FFTs
- Radiation transport: implicit flux-limited diffusion, coupled to gas ionization and energy equation (Reynolds et al. 2009)
- Star formation & SN feedback: modified Cen & Ostriker 92 with "distributed feedback" (Smith et al. 2011)
  - Calibrated to Bouwens et al. (2011) SFRD
- UV radiative feedback: Pop II SED from Ricotti, Gnedin & Shull 2002



1. Population II, metallicity $Z = 0.04\ Z_\odot$, evolutionary tracks evolved to $t = 1$ Gyr, continuous star formation (SF) law, and a Salpeter initial mass function (IMF) with star masses between $1\ M_\odot < M_* < 100\ M_\odot$ (Leitherer et al. 1995). Wolf-Rayet stars are responsible for the substantial EUV emission in this SED.

Tests of Radiation Solver
Reynolds et al. (2009)

- Correct I-front speeds are obtained even at low resolution due to *implicit coupling* of rad. transfer, ionization, and gas heating



Shapiro & Giroux '87 analytic test problem

Results

- Run A (1/4 scale simulation)
  - Ionizing photons per H atom
  - Adequacy of MHR estimate

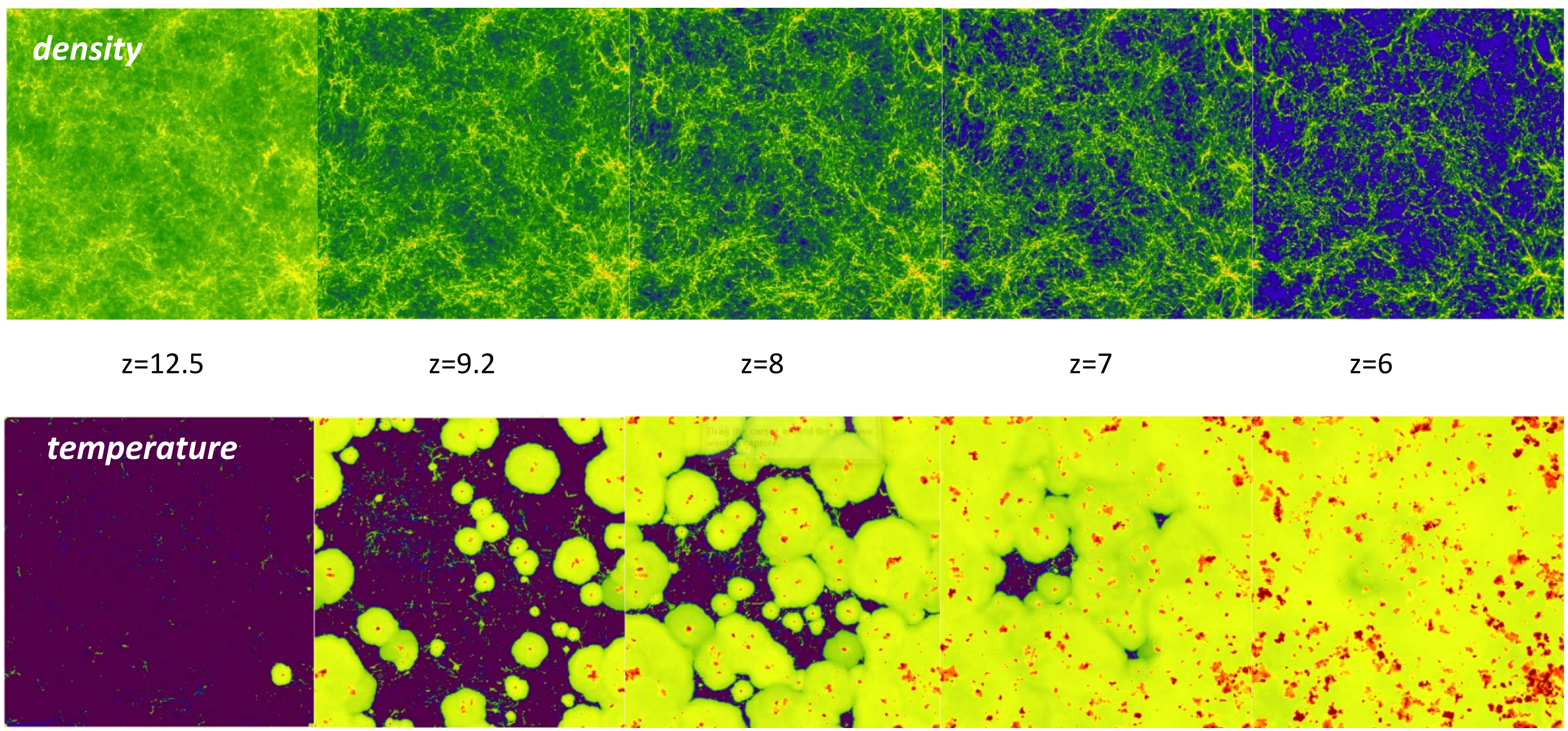
- Run B (Renaissance Simulation)
  - Role of large scale power
  - Suppression of star formation in low mass halos due to radiative feedback

ENZO radiation hydrodynamic cosmic reionization

G. So, M. Norman, R. Harkness (UCSD), D. Reynolds (SMU)

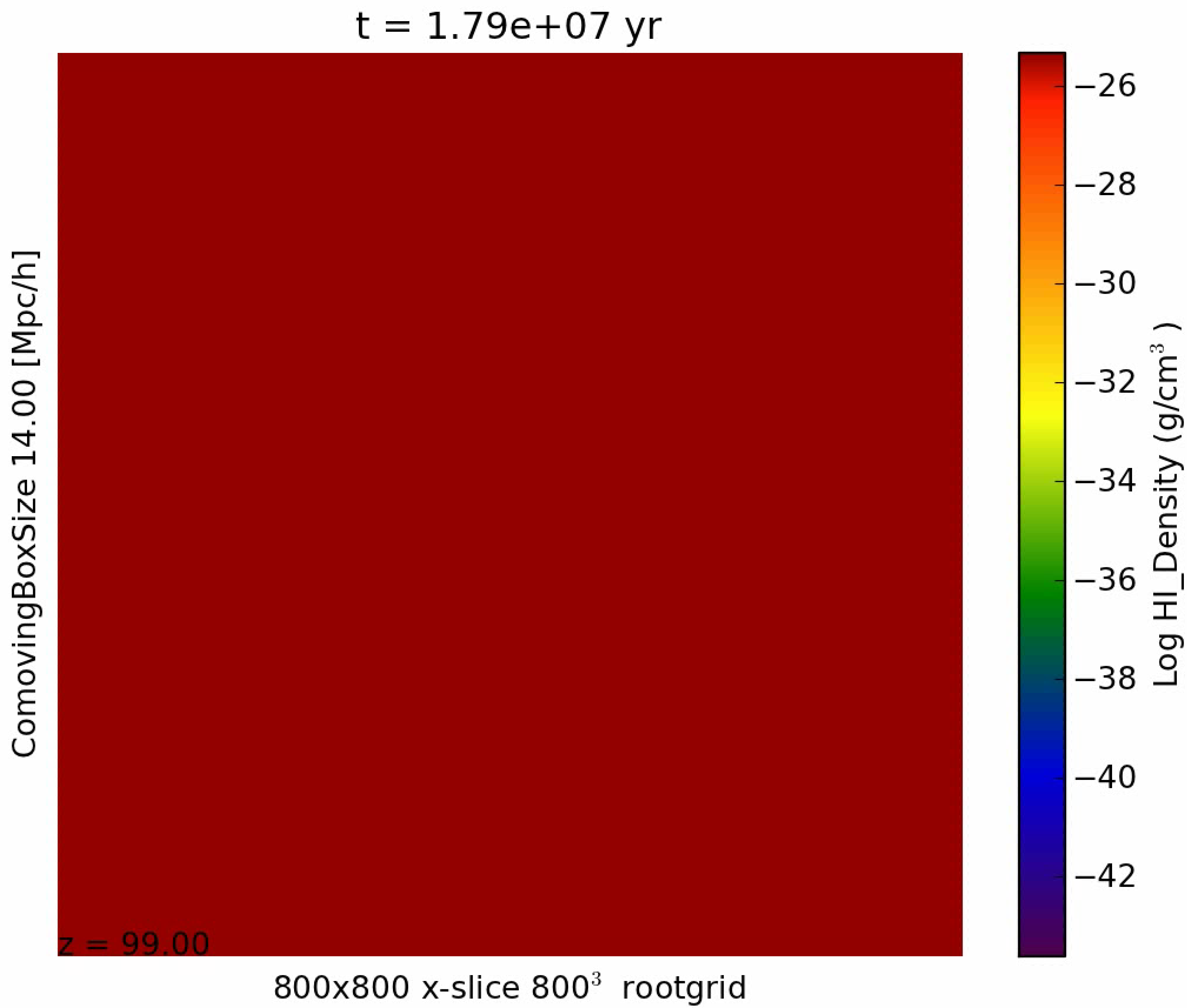
Redshift/time evolution of density and temperature

800^3/20 Mpc/512 core

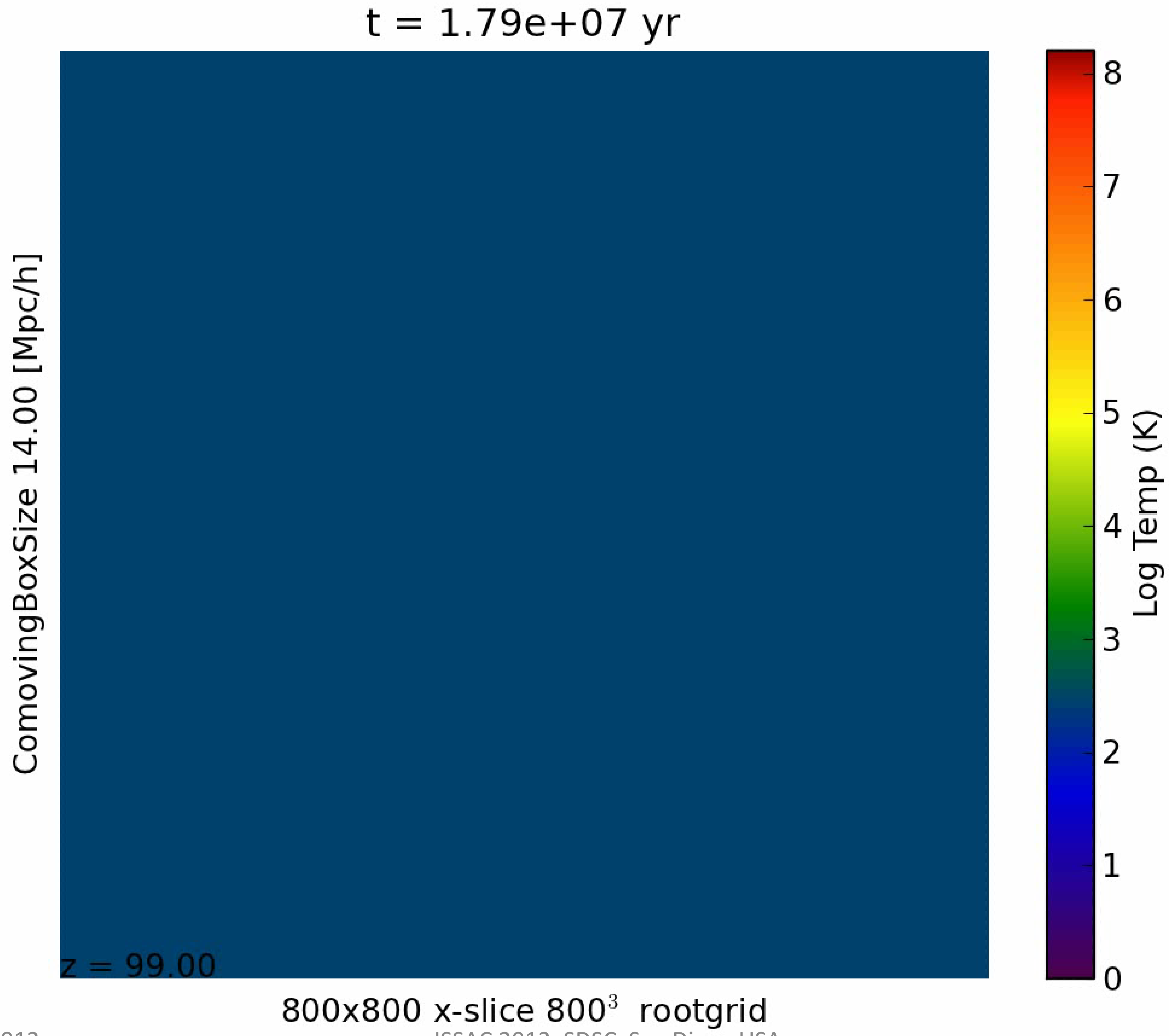


z=12.5 z=9.2 z=8 z=7 z=6

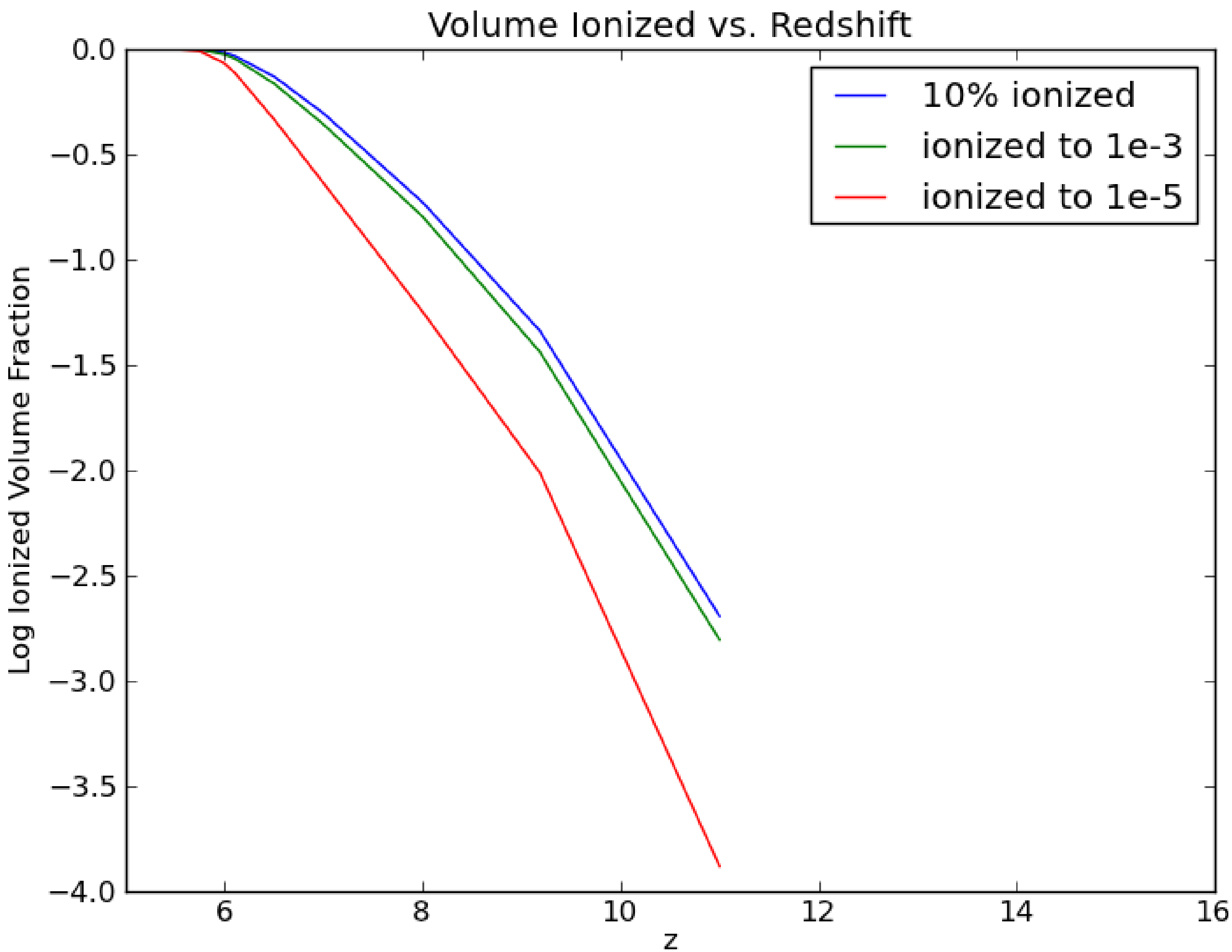
t=362 Myr t=552 Myr t=664 Myr t=792 Myr t=969 Myr



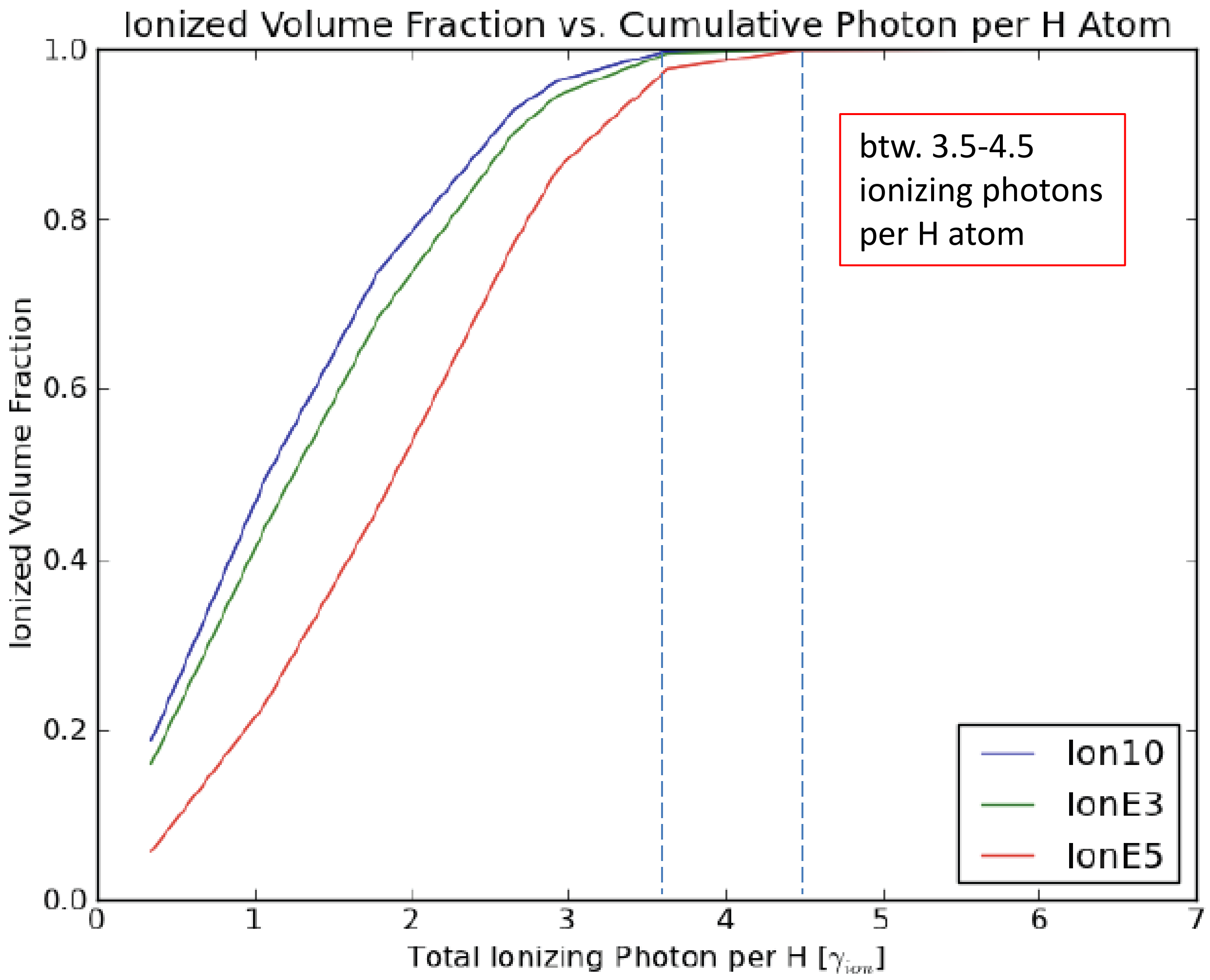
t = 1.79e+07 yr
ComovingBoxSize 14.00 [Mpc/h]
z = 99.00
800x800 x-slice 800^3 rootgrid
Log HI_Density (g/cm^3)
−26
−28
−30
−32
−34
−36
−38
−40
−42


t = 1.79e+07 yr
ComovingBoxSize 14.00 [Mpc/h]
z = 99.00
800x800 x-slice 800^3 rootgrid
8
7
6
5
4
3
2
1
0
Log Temp (K)

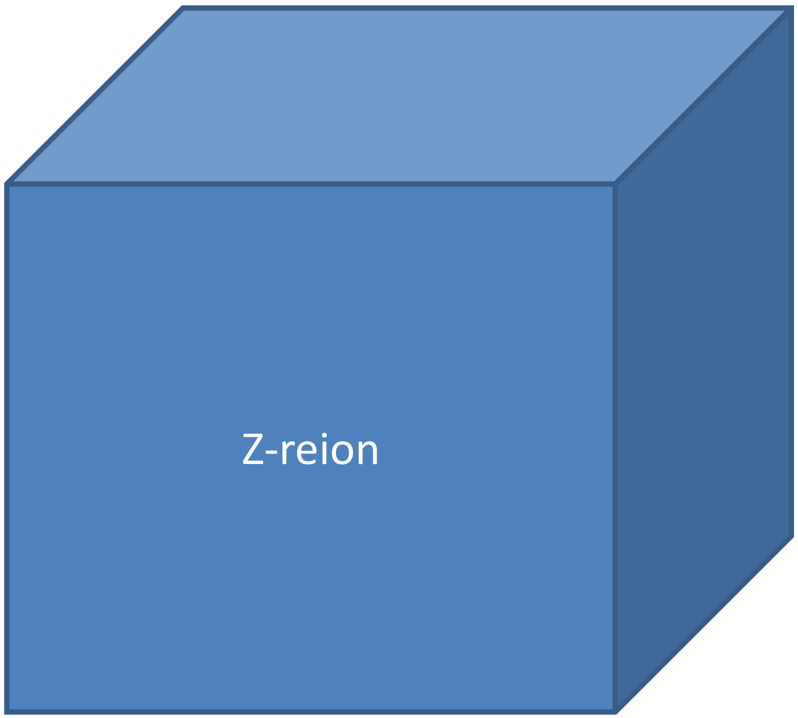
Ionized Volume Fraction



Photons per H atom



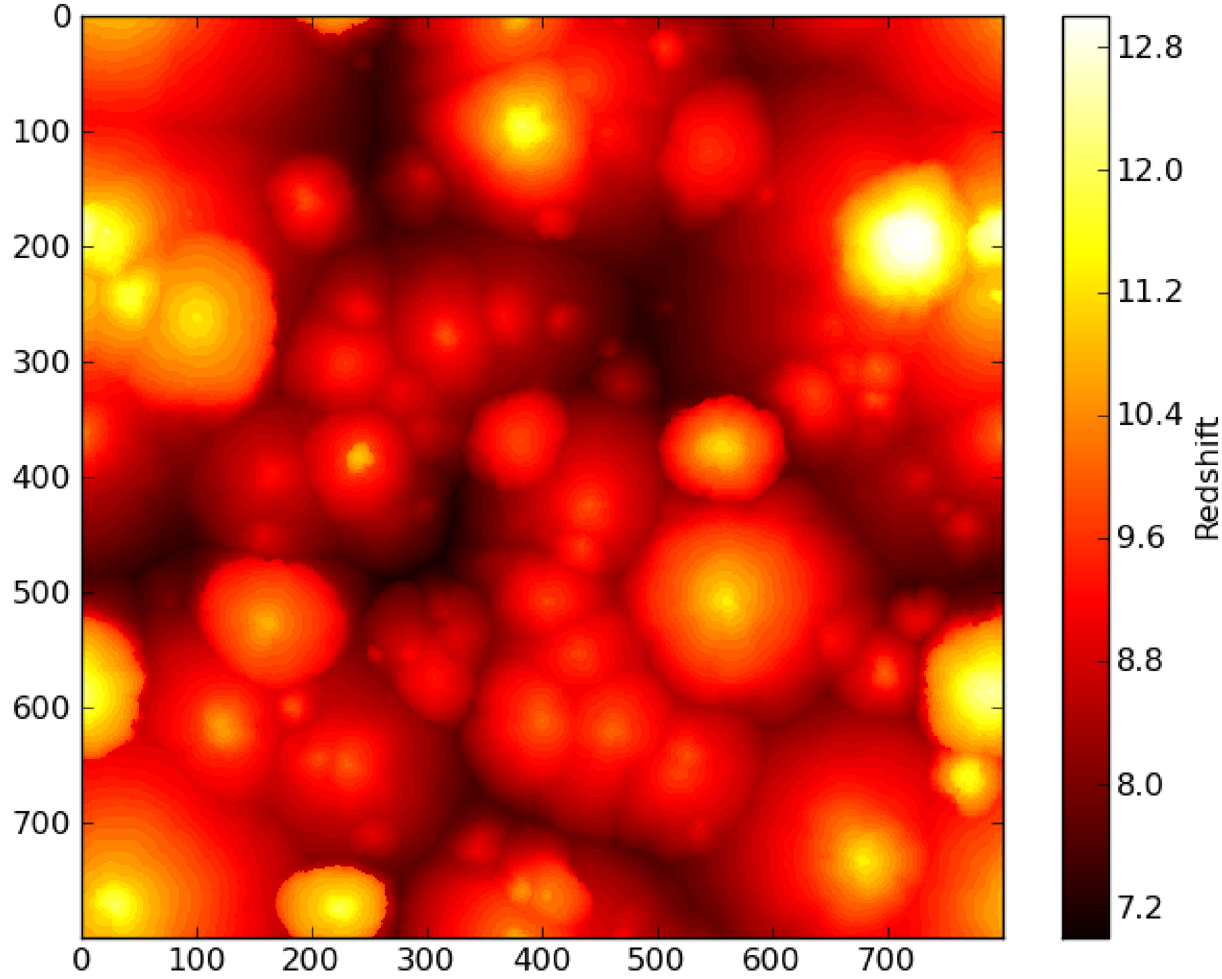
Visualizing "Inside-Out" Reionization: Z-reion Cube



- Every cell contains the redshift when it was first photo-ionized
- yt script:
  - Loop over all redshift outputs (80) and test if $f_{HII}>0.9$
  - Uses nested parallel objects to divide up the work on 256 cores
  - 56 sec on Gordon including IO

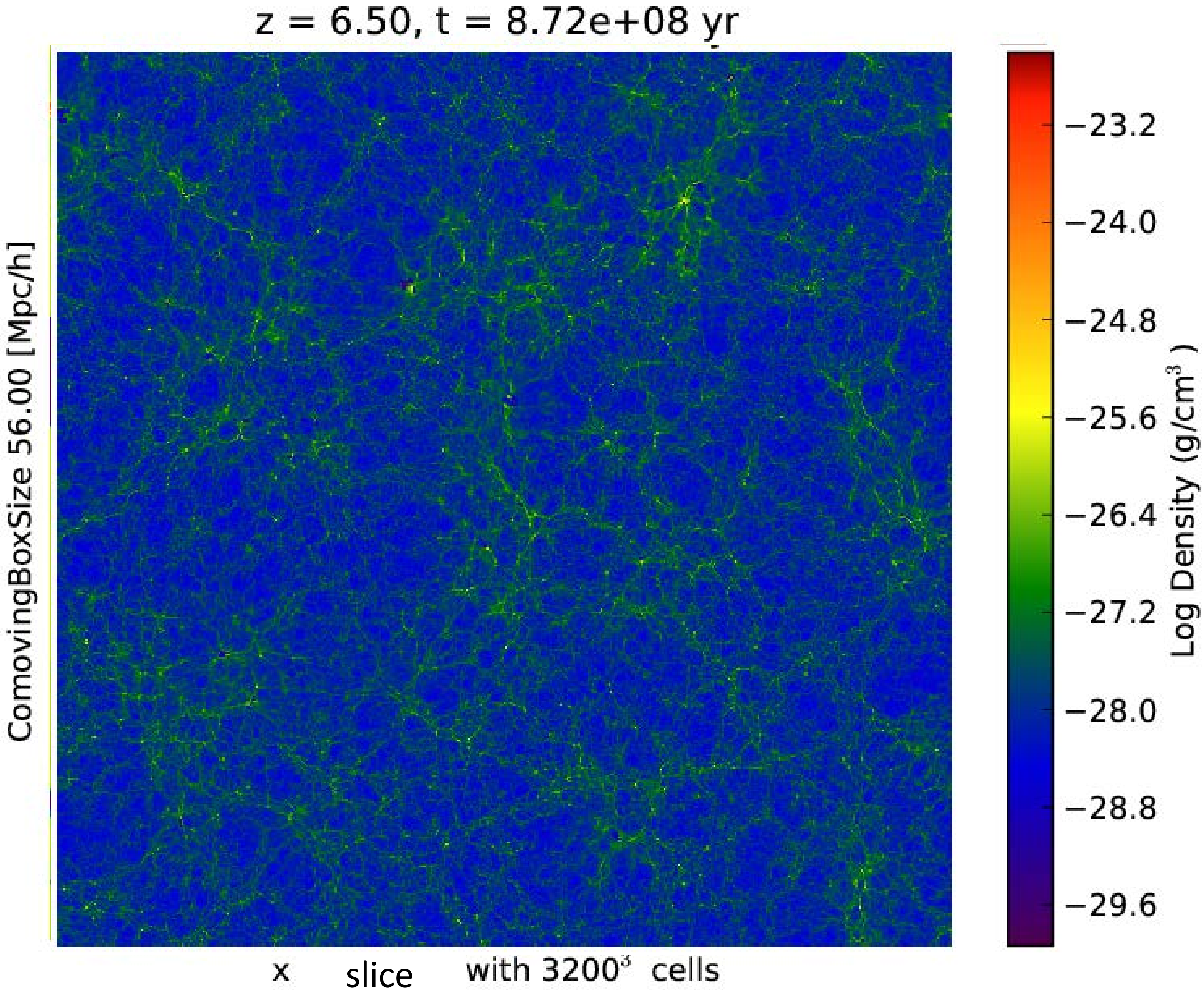
```
from yt.mods import *
from yt.utilities.parallel_tools.parallel_analysis_interface \
    import communication_system
import h5py, glob, time

@derived_field(name = "IonizedHydrogen",
               units = r"\frac{\rho_{HII}}{rho_H}")
def IonizedHydrogen(field, data):
    return data["HII_Density"]/(data["HI_Density"]+data["HII_Density"])

base = "/oasis/projects/nsf/uic221/ux455076/SED800/Dumps"
filenames = glob.glob("%s/DD*/*.hierarchy" % base)
filenames.sort()
ts = TimeSeriesData.from_filenames(filenames, parallel = 8)

ionized_z = na.zeros((800, 800, 800), dtype="float32")

t1 = time.time()
for pf in ts.piter():
    z = pf.current_redshift
    for g in parallel_objects(pf.h.grids, njobs = 16):
        i1, j1, k1 = g.get_global_startindex() # Index into our domain
        i2, j2, k2 = g.get_global_startindex() + g.ActiveDimensions
        # Look for the newly ionized gas
        newly_ion = ((g["IonizedHydrogen"] > 0.999)
                   & (ionized_z[i1:i2,j1:j2,k1:k2] < z))
        ionized_z[i1:i2,j1:j2,k1:k2][newly_ion] = z
        g.clear_data()

print "Iteration completed  %0.3e" % (time.time()-t1)
comm = communication_system.communicators[-1]
for i in range(800):
    ionized_z[i,:,:] = comm.mpi_allreduce(ionized_z[i,:,:], op="max")
    print "Slab % 3i has minimum z of %0.3e" % (i, ionized_z[i,:,:].max())
t2 = time.time()
print "Completed.  %0.3e" % (t2-t1)

if comm.rank == 0:
    f = h5py.File("IonizationCube.h5", "w")
    f.create_dataset("/z", data=ionized_z)
```

Result



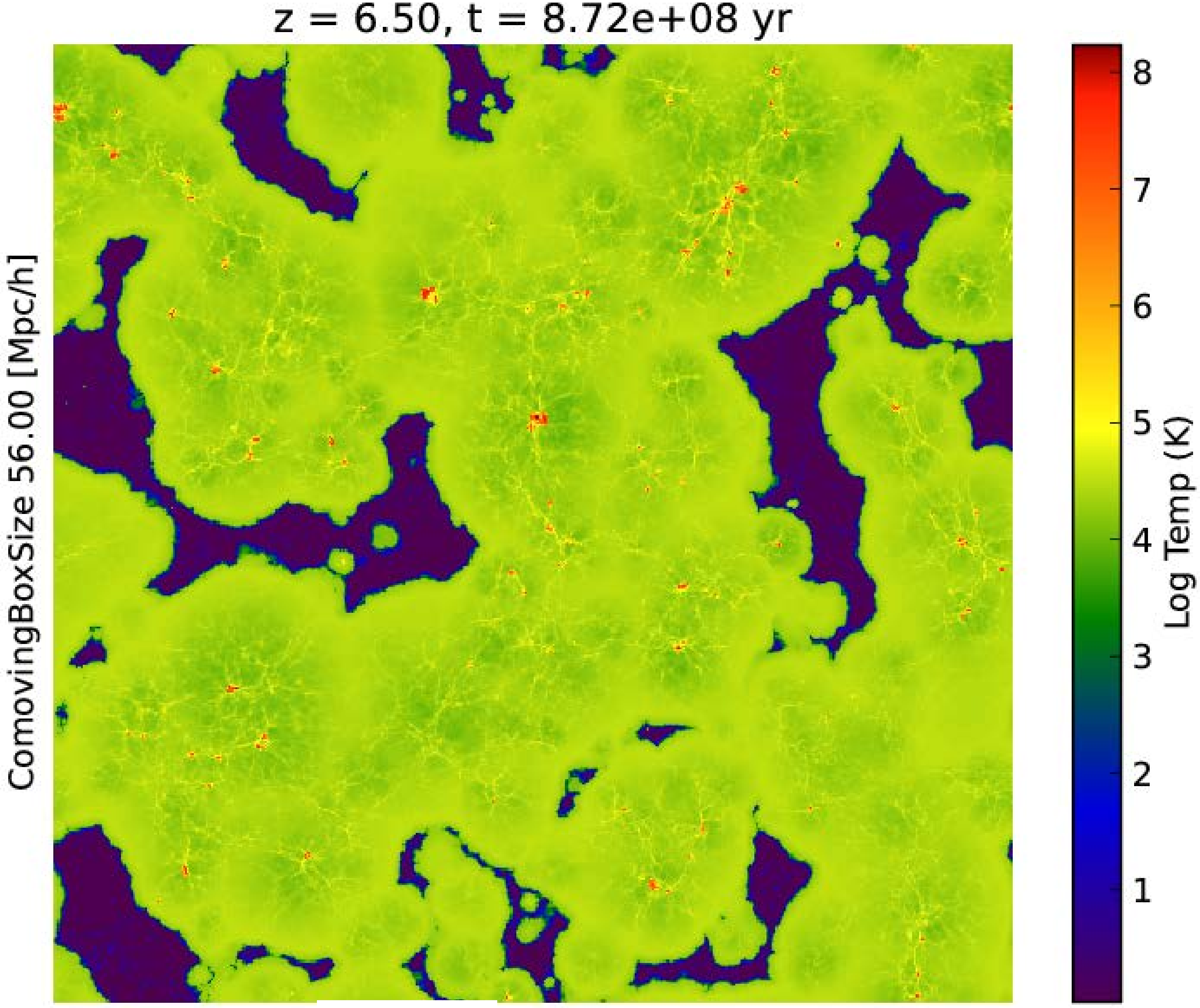
0
100
200
300
400
500
600
700
0
100
200
300
400
500
600
700
12.8
12.0
11.2
10.4
9.6
8.8
8.0
7.2
Redshift

Effective of Large Scale Power



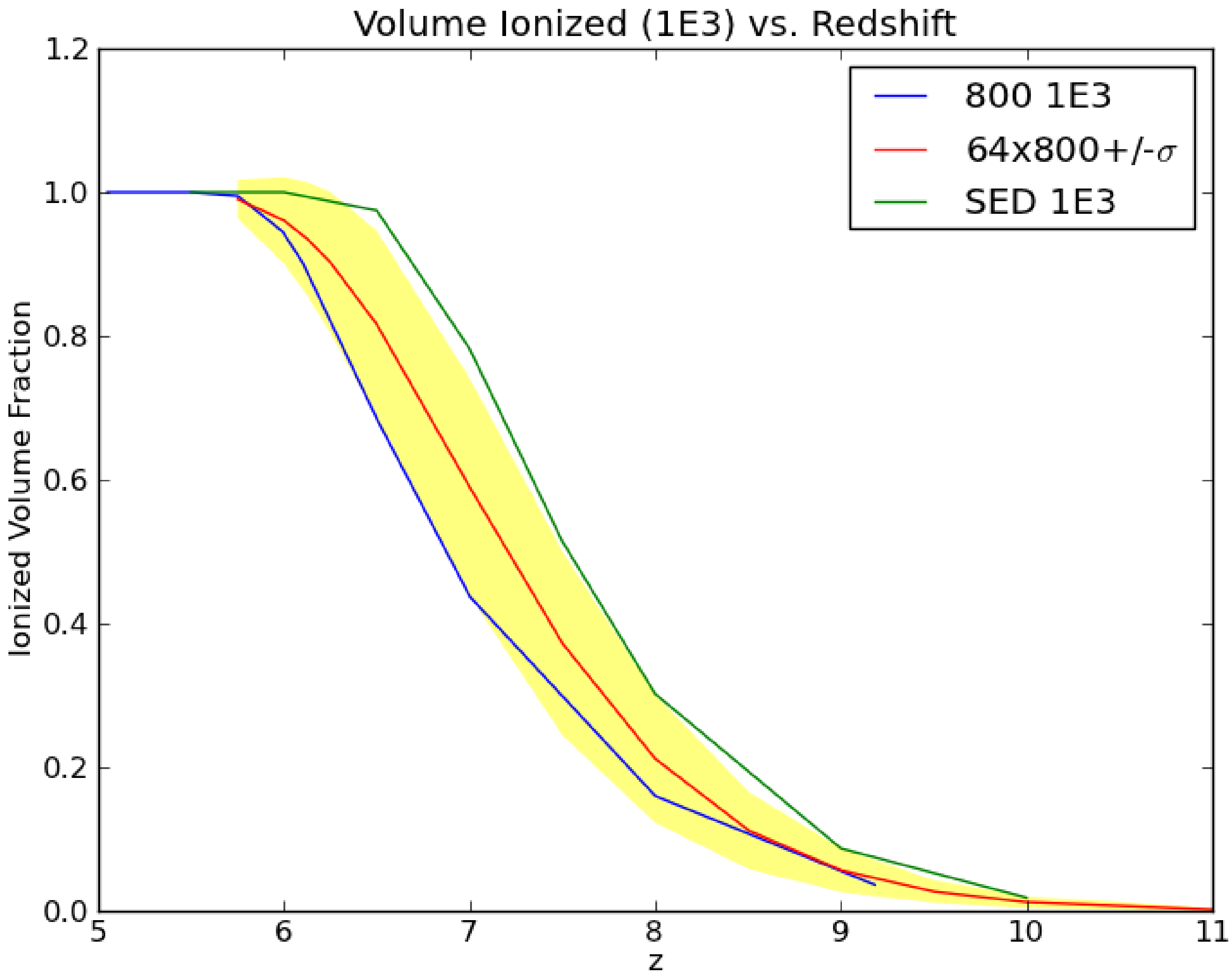
slice

Effective of Large Scale Power



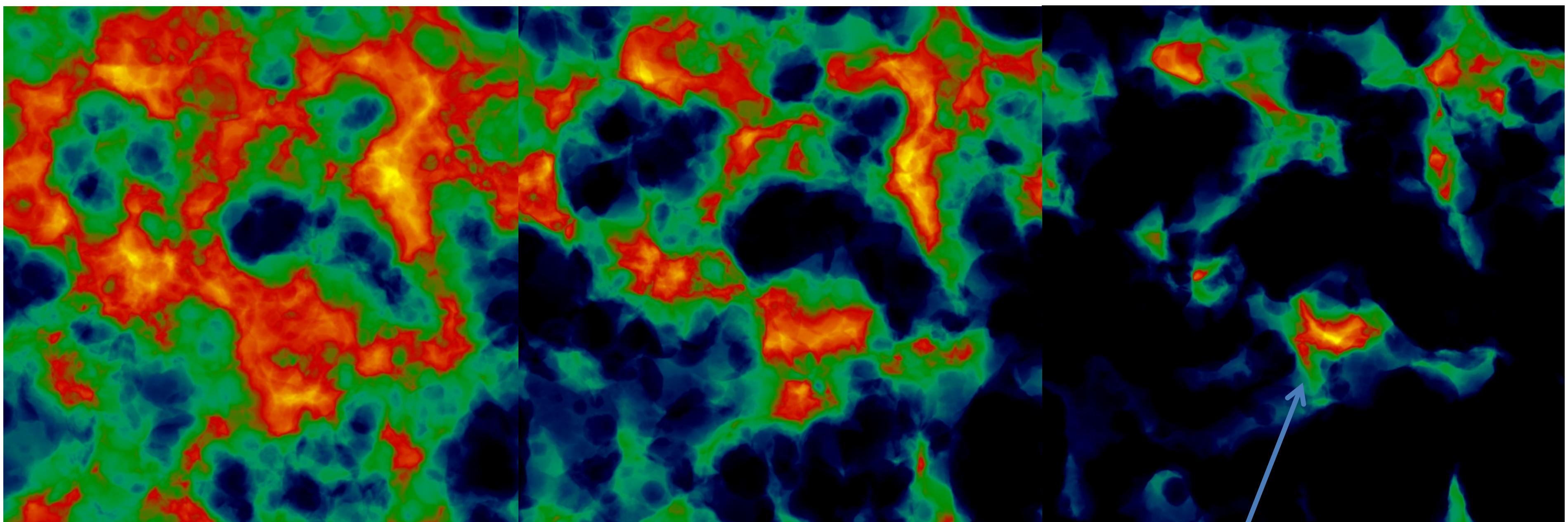
x slice with 3200^3 cells

Effect of large scale power



HI going, going, gone....

Z=7 Z=6.5 Z=6.05

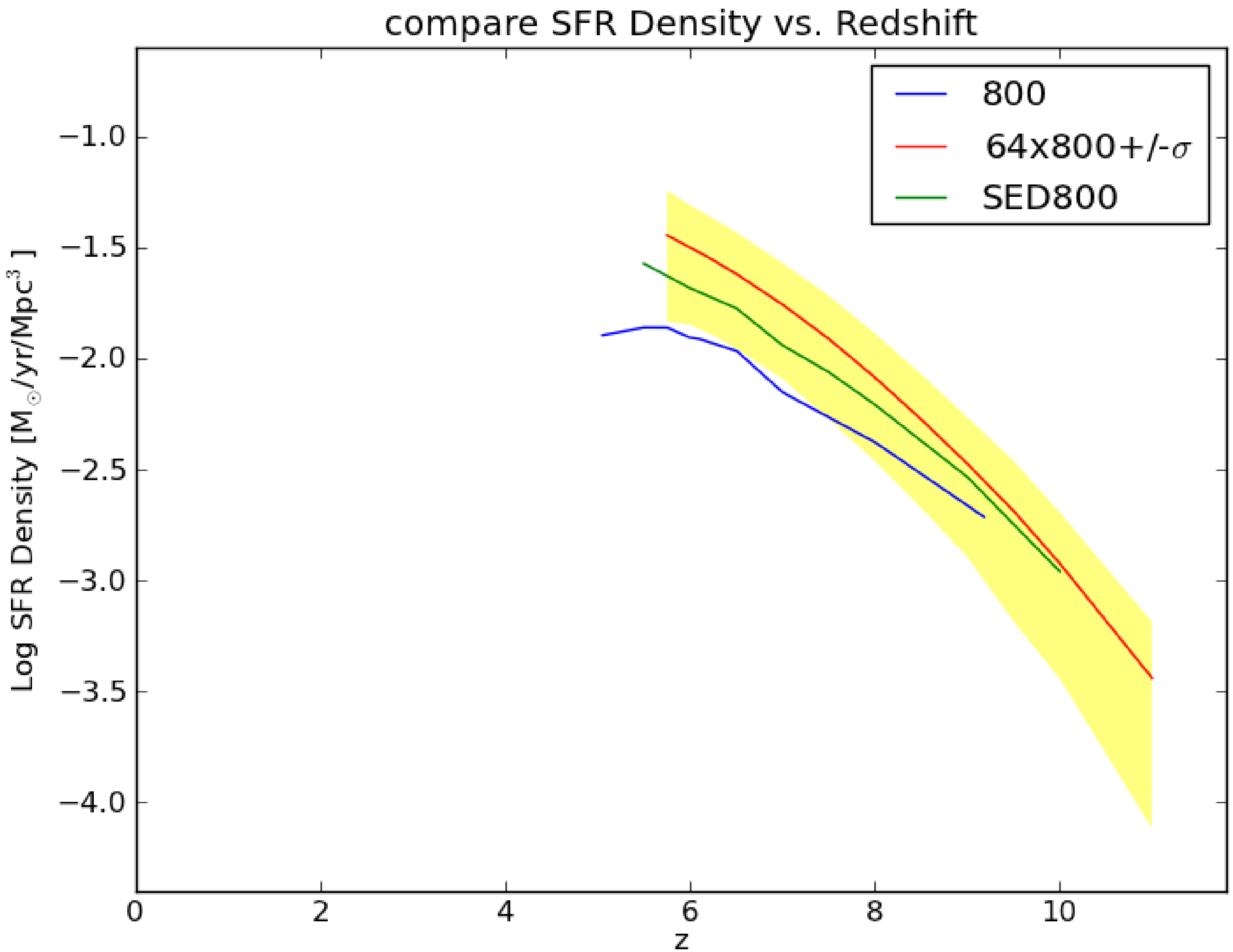


80 cMpc

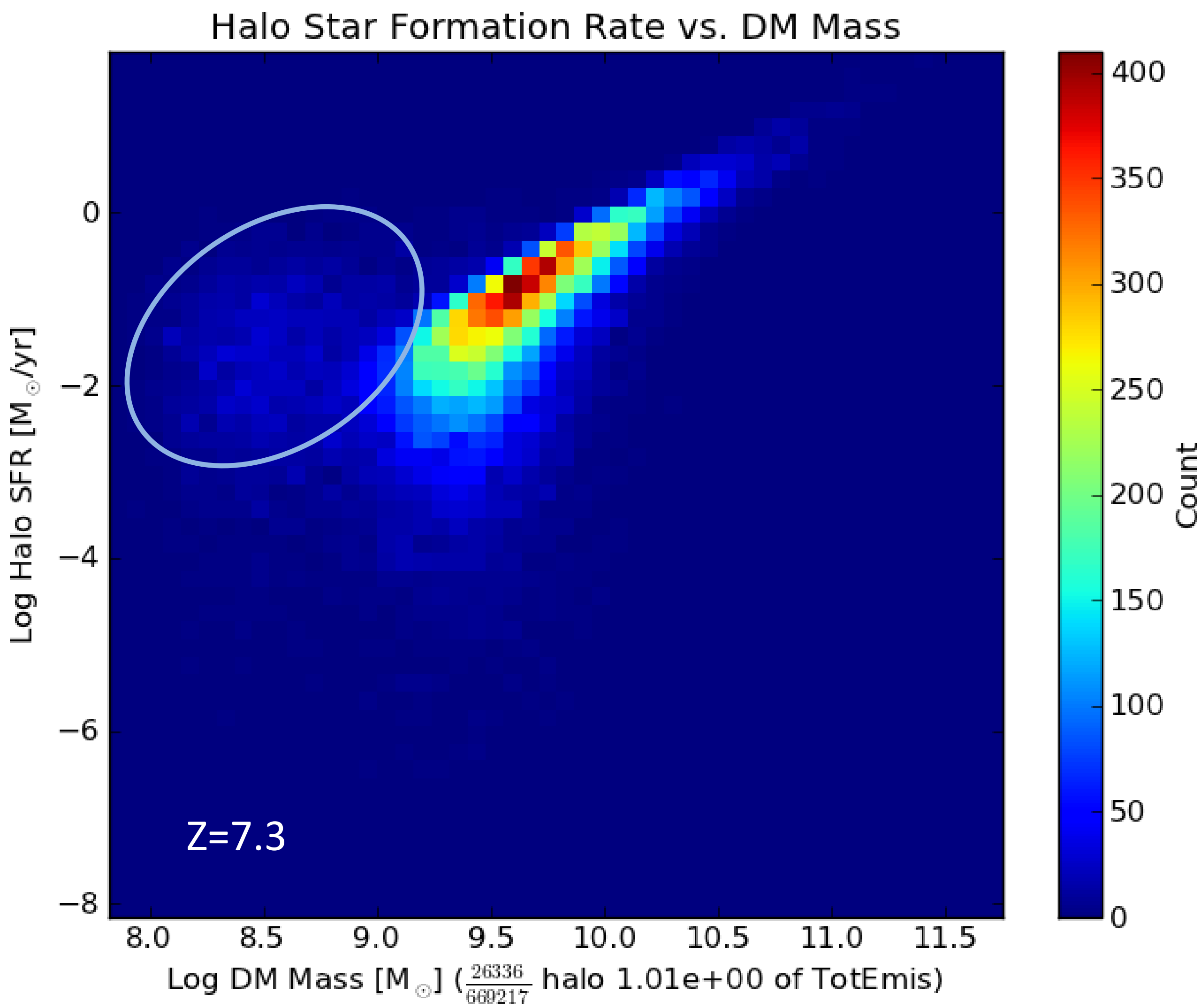
Projected HI fraction

Large-scale neutral patches before overlap

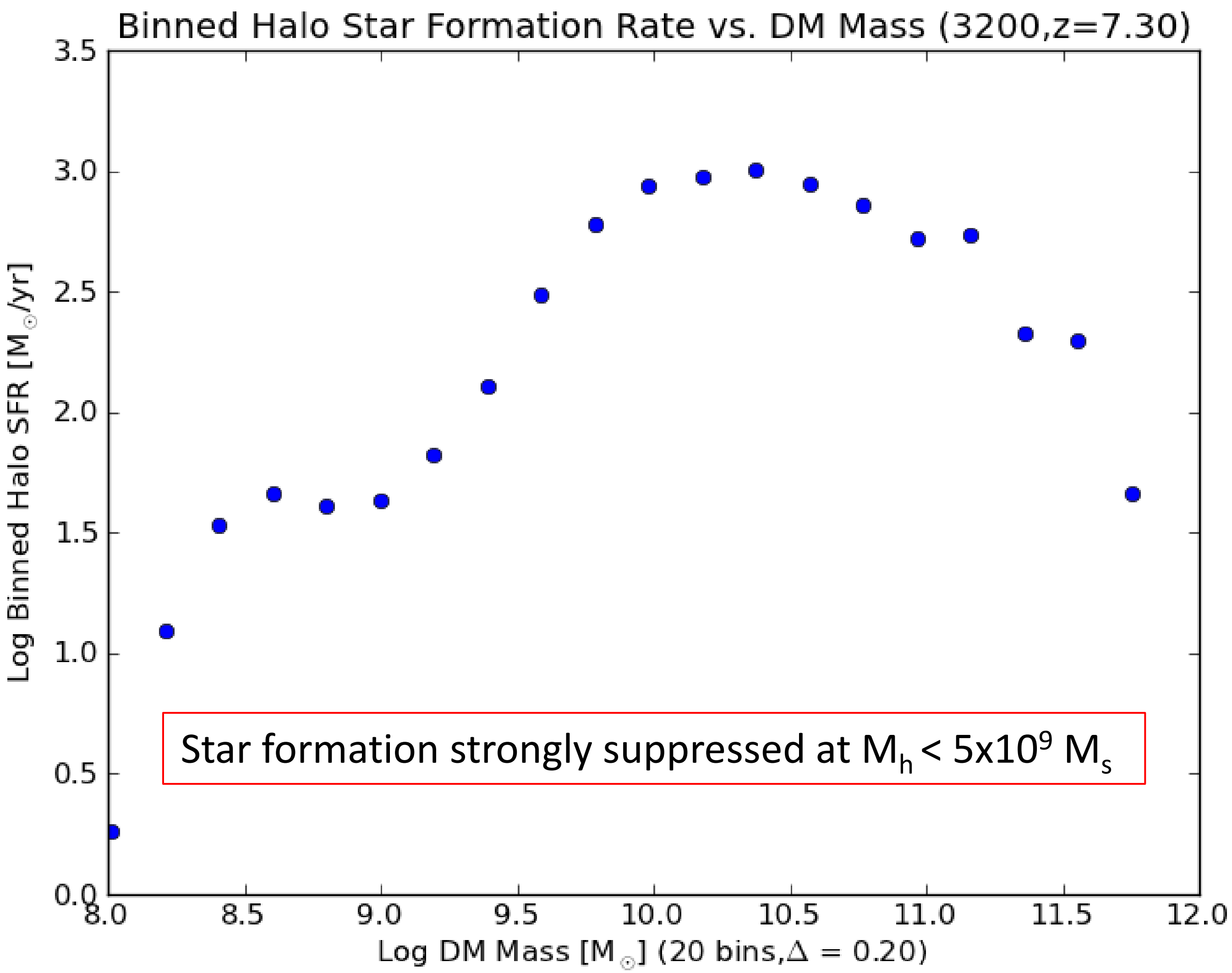
Effect of large scale power



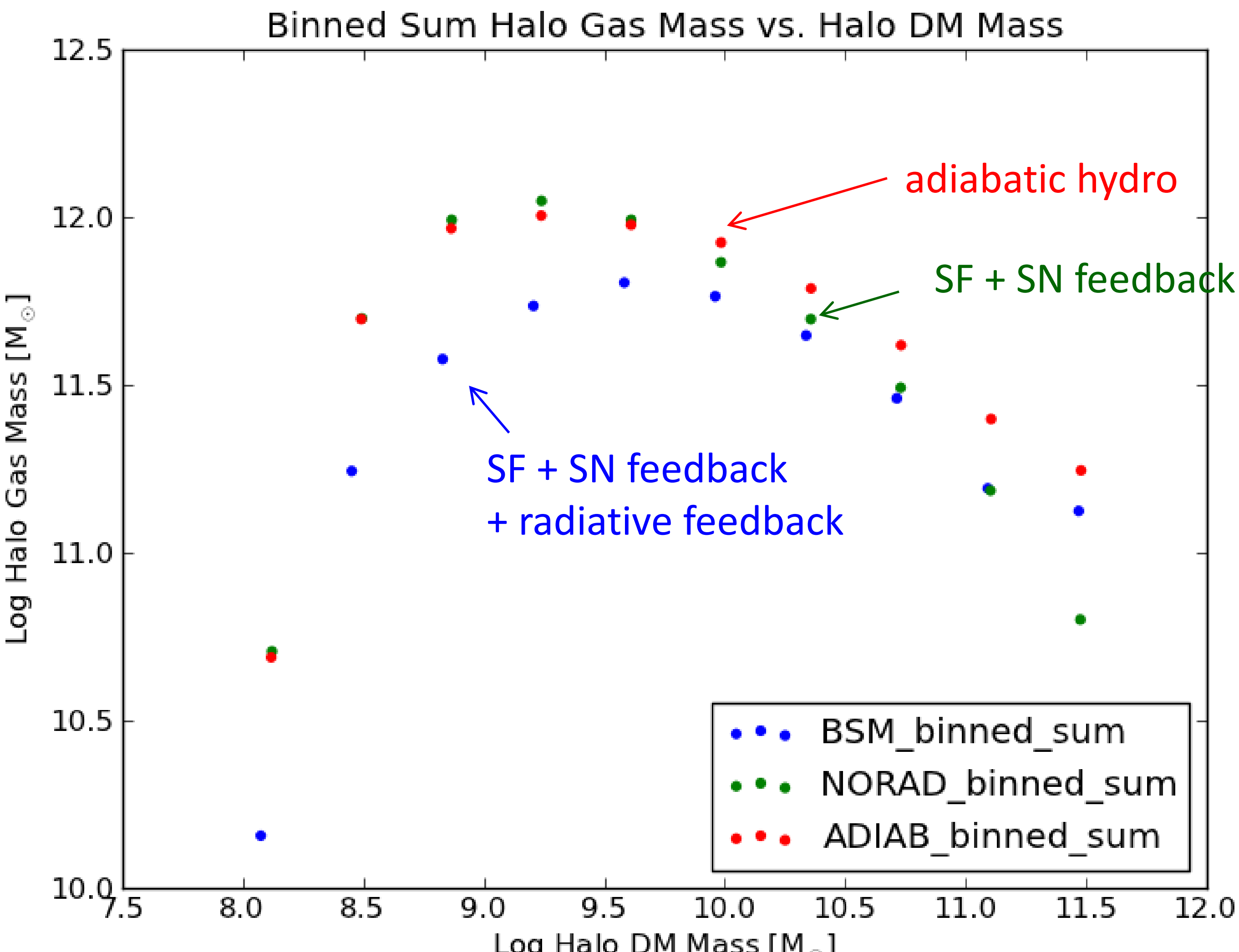
Where is the star formation happening?



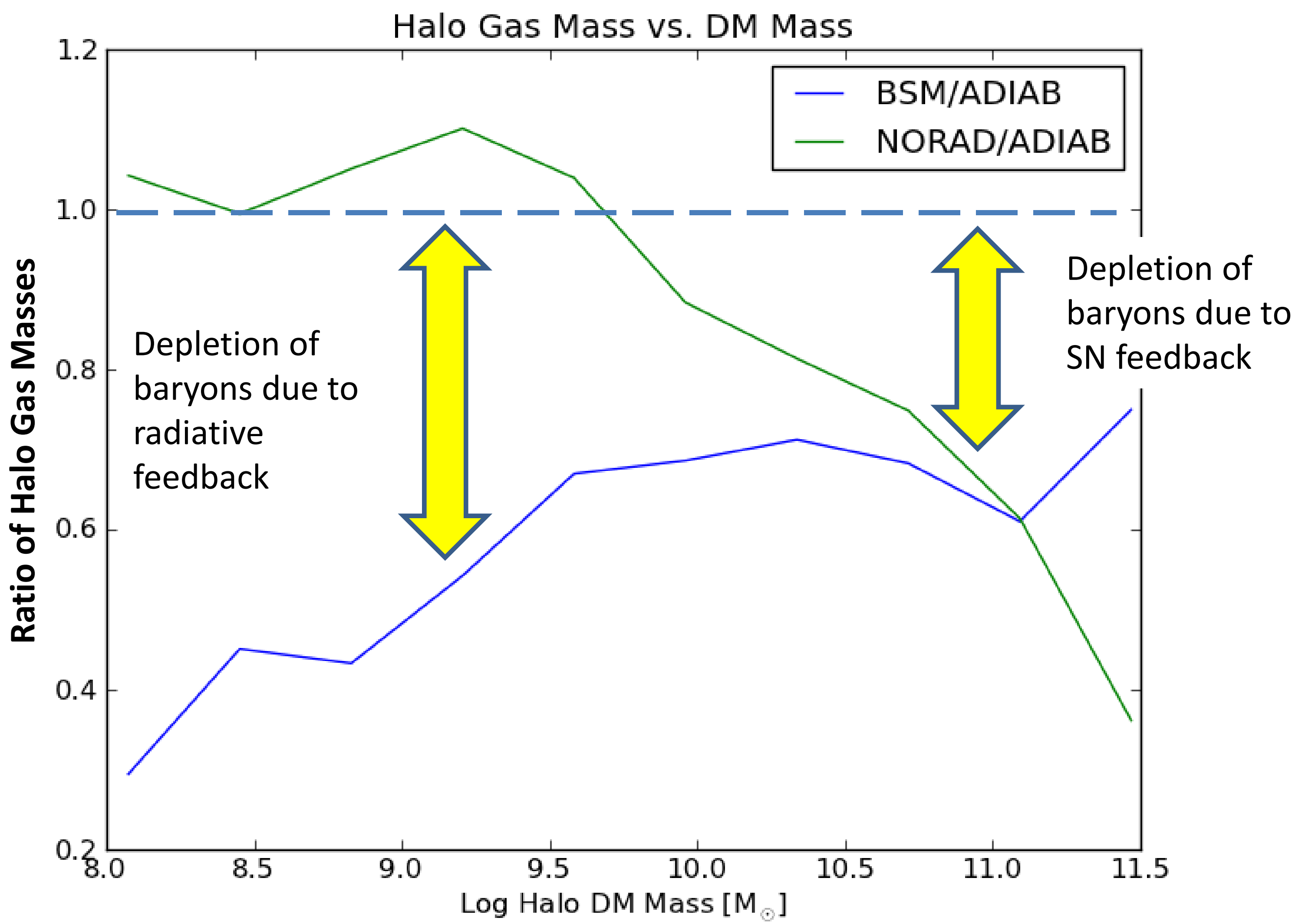
Where is the star formation happening?



Is this a resolution effect? NO



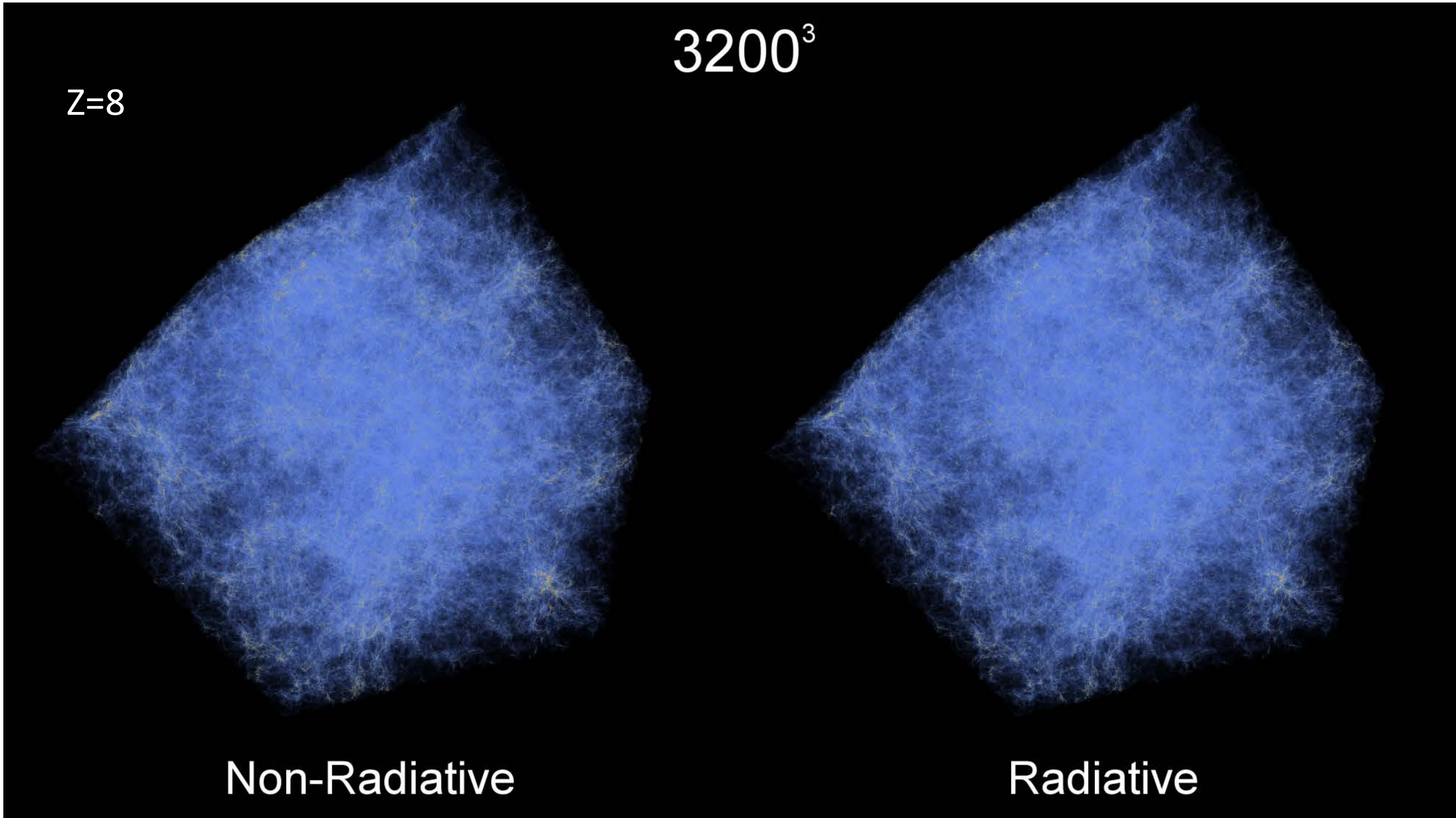
Is this a resolution effect? NO



Visualizing Jeans Smoothing

M. Norman, G. So, R. Harkness (UCSD), D. Reynolds (SMU)

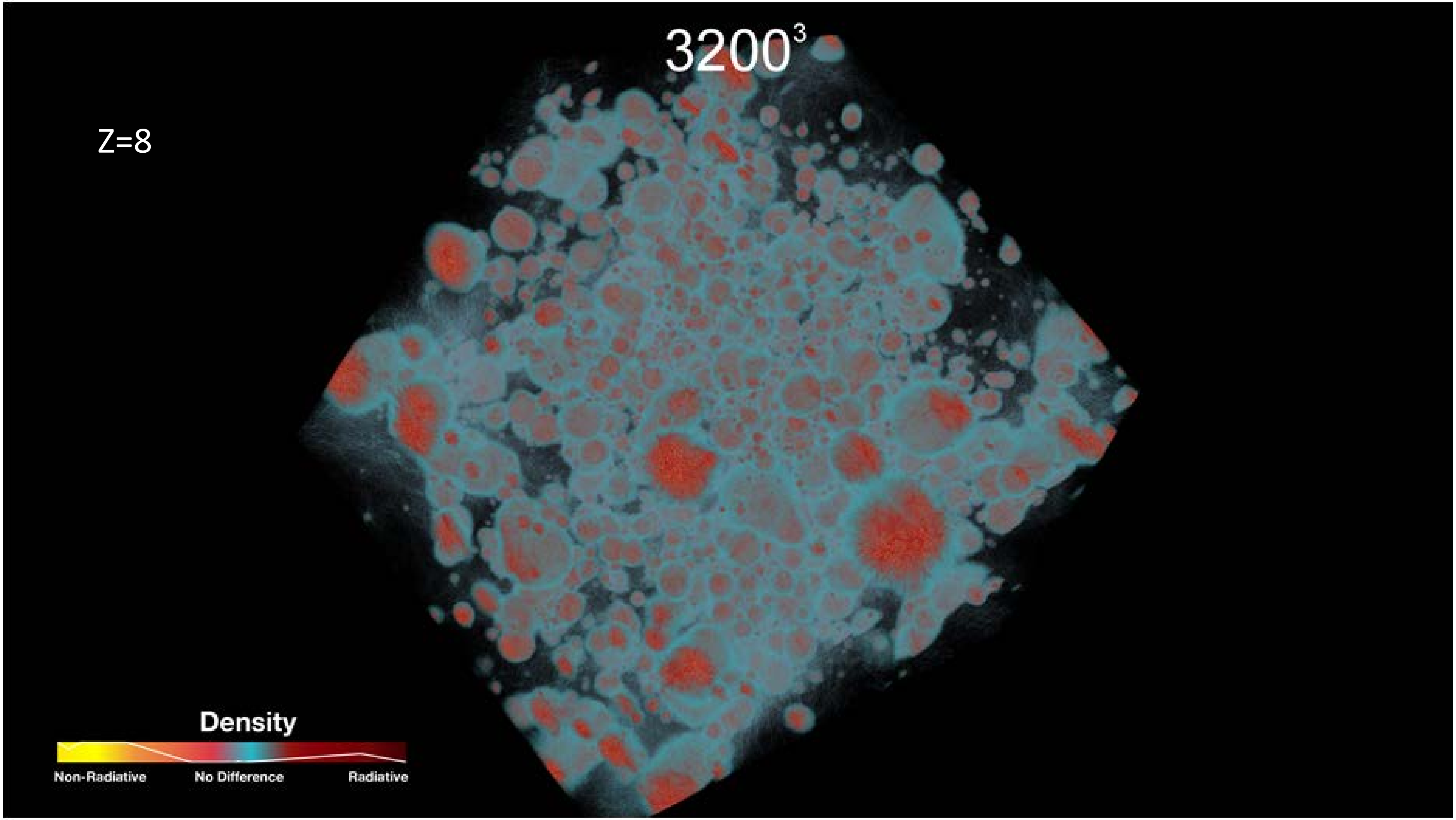
Density fields from RHD and non-RHD models



Visualization by J. Insley (ANL) & R. Wagner (SDSC)

Visualizing Jeans Smoothing

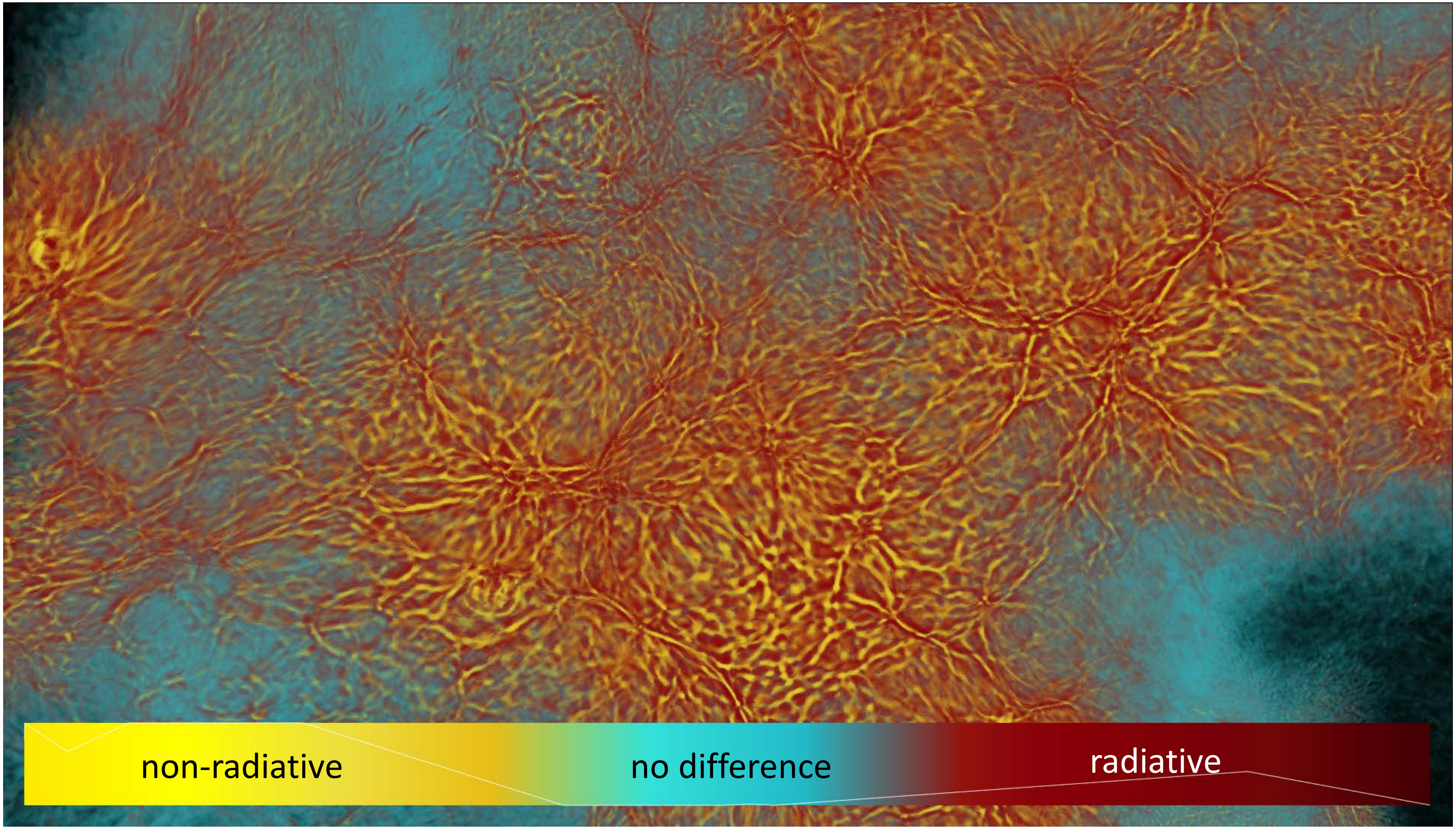
Normailzed density difference between RHD and non-RHD models



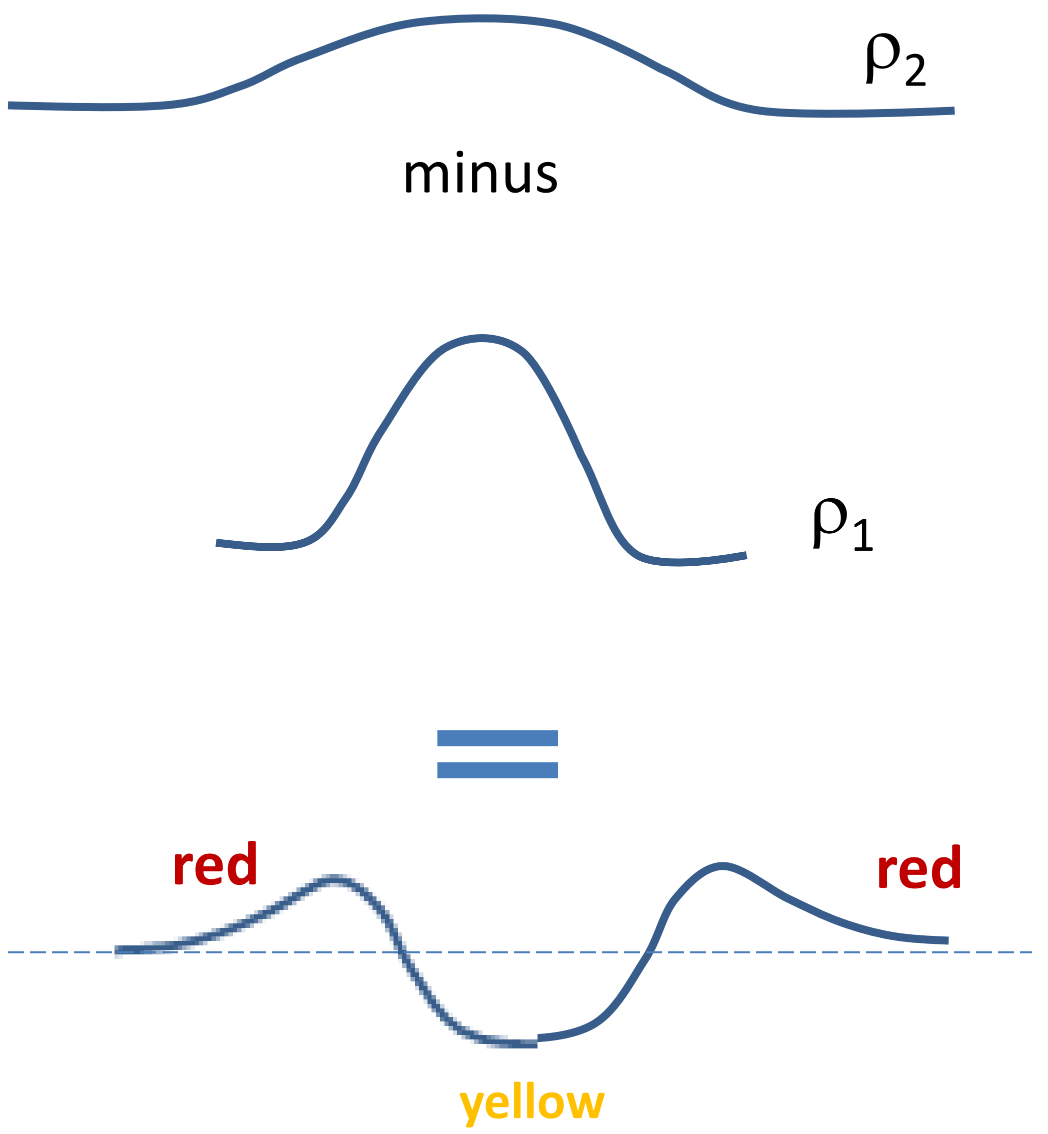
Visualization by J. Insley (ANL) & R. Wagner (SDSC)

Visualizing Jeans Smoothing

Normailzed density difference between RHD and non-RHD models



Visualization by J. Insley (ANL) & R. Wagner (SDSC)



radiative density dist.

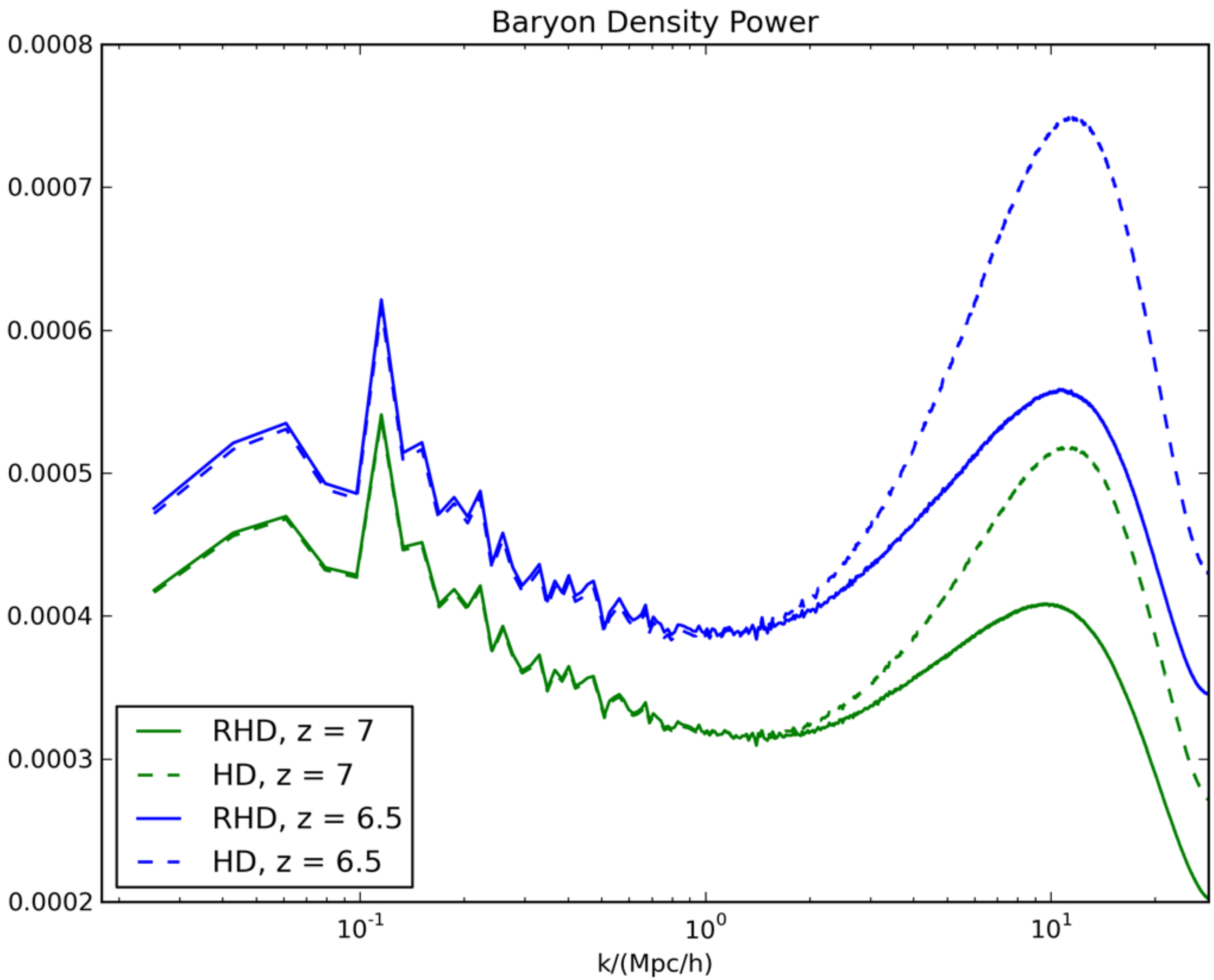
non-radiative density dist.

normalized density difference

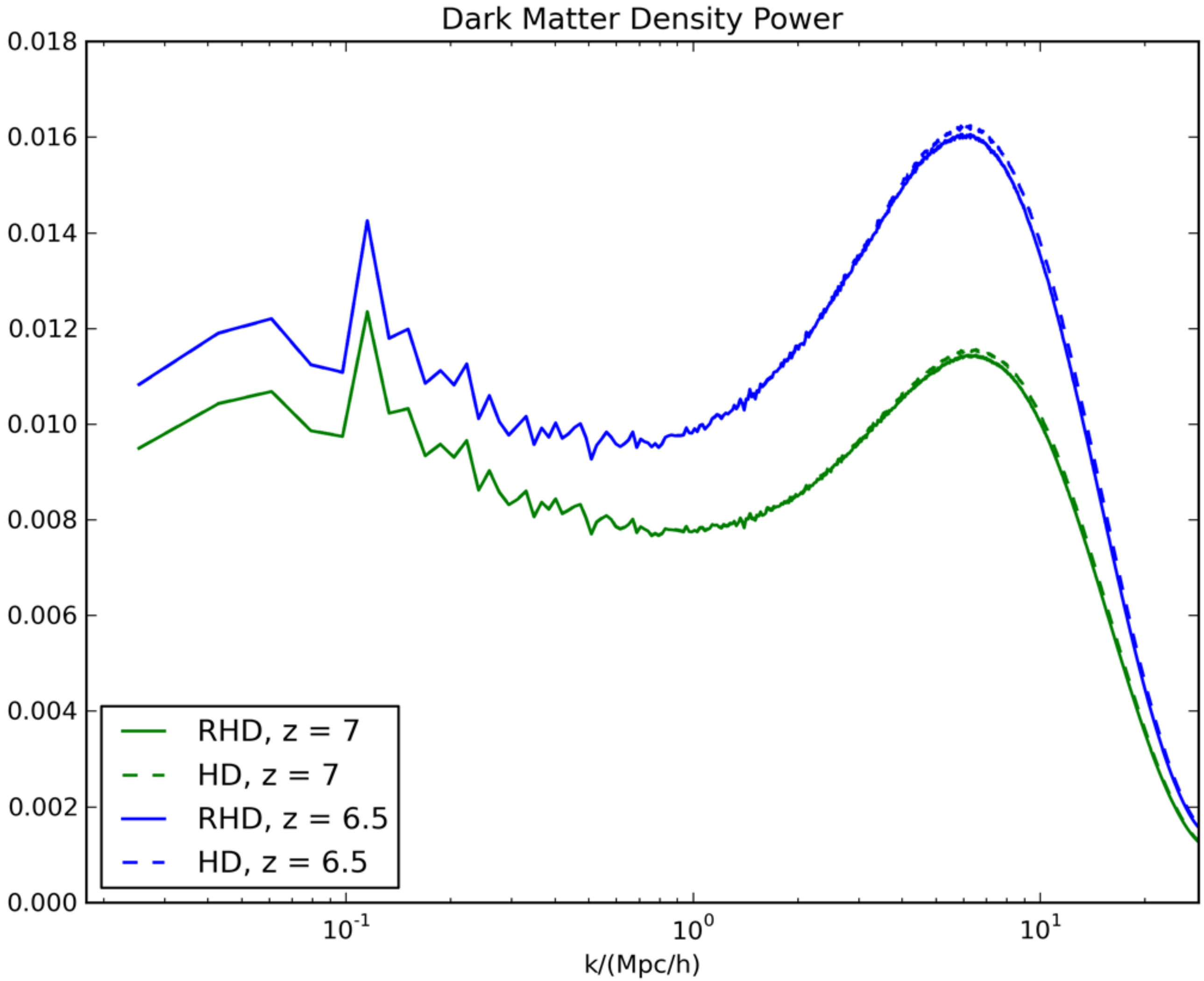
$$\frac{\rho_2 - \rho_1}{\rho_2 + \rho_1}$$

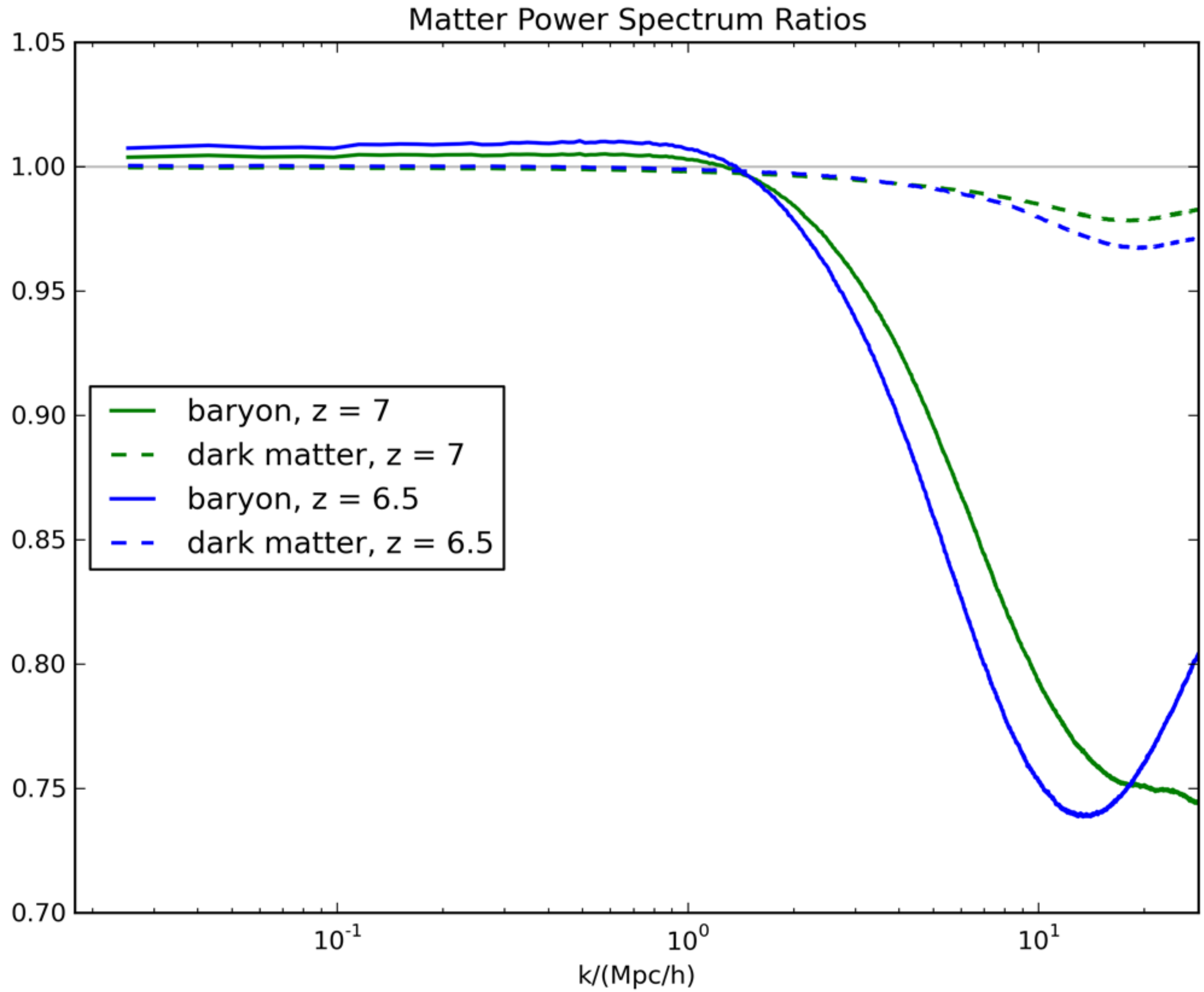
Go to movie

Jeans Smoothing



Effect on Dark Matter Power





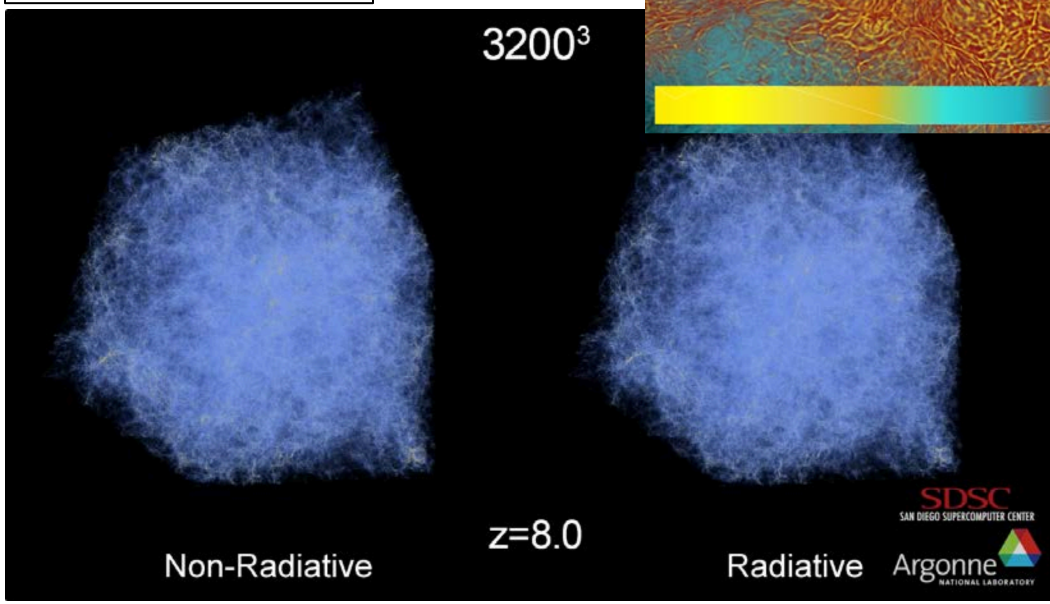
Matter Power Spectrum Ratios
1.05
1.00
0.95
0.90
0.85
0.80
0.75
0.70
10^{-1}
10^{0}
10^{1}
k/(Mpc/h)
baryon, z = 7
dark matter, z = 7
baryon, z = 6.5
dark matter, z = 6.5

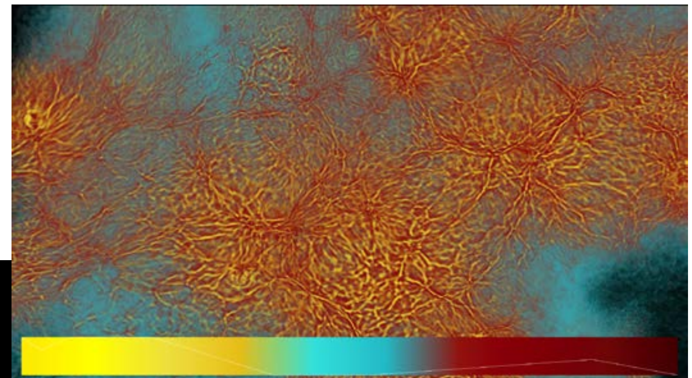
Cosmology simulation matter power spectrum measurement using vSMP

We have run two large (3200^3 uniform grid) simulations, with and without radiation hydrodynamics, to measure the effect of the light from the first stars on the evolution of the universe. To quantitatively compare the matter distribution of each simulation, we use radially binned 3D power spectra.

- 2 simulations
- 3200^3 uniform 3D grids
- 244GiB+ per field
- 15k+ files each

Individual simulations

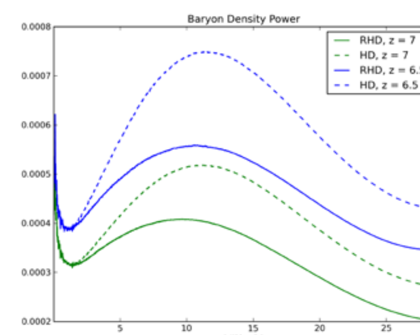




Difference

- Ran existing OpenMP-threaded code
- ~256GiB memory used
- ~5 ½ hours per field
- 0 development effort

Power spectra



Source: *Rick Wagner, Michael L. Norman. SDC. Used by permission. 2012*

Summary: by the numbers

- *Direct RHD simulation* of reionization now feasible in reasonably large volumes
- *Reionization completes* at z ~ 6 using the observed SFRD (Bouwens et al. 2011)
- *Larger box begins reionization sooner*, because of rare peaks, but completes reionization at the same redshift (self-regulation?)
- *Full reionization* requires ~ 4 photons/H atom
- *MHR formula provides a good estimator* of when reionization will occur provided global HII clumping factor is used (dense gas not excluded)
- Radiative feedback suppresses star formation in halos $M_h < 5 \times 10^9 M_s$ due to baryon depletion arising from *Jeans smoothing*
- *Large-scale patches* (>10 Mpc) of HI remain as late as z=5.8, which may be observable in LAE correlation function