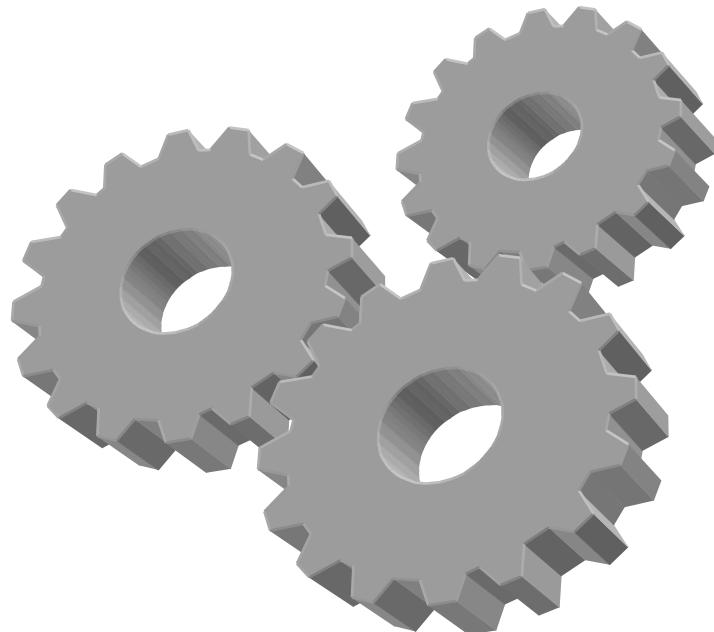


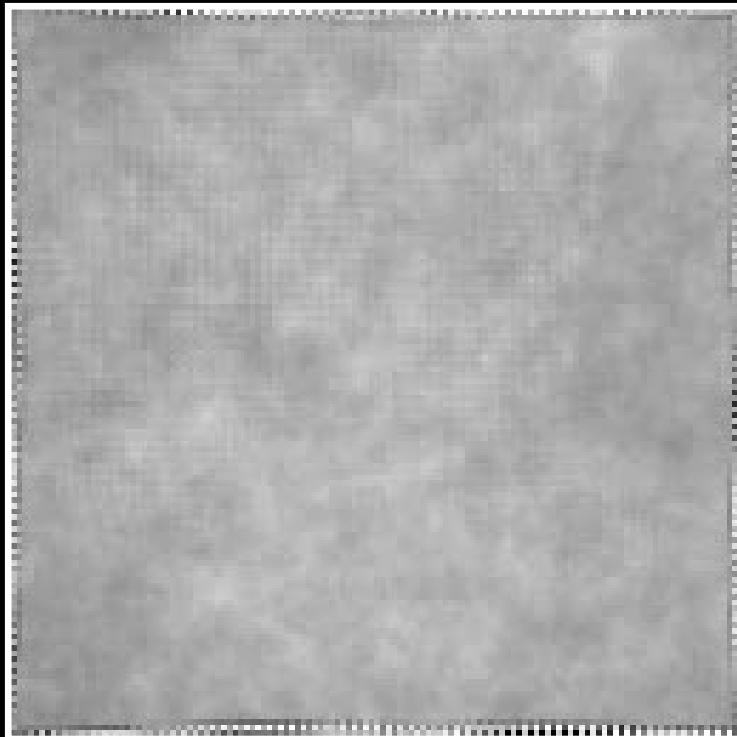
# Cosmological Structure Formation II

Michael L. Norman  
Laboratory for Computational  
Astrophysics  
[mnorman@cosmos.ucsd.edu](mailto:mnorman@cosmos.ucsd.edu)

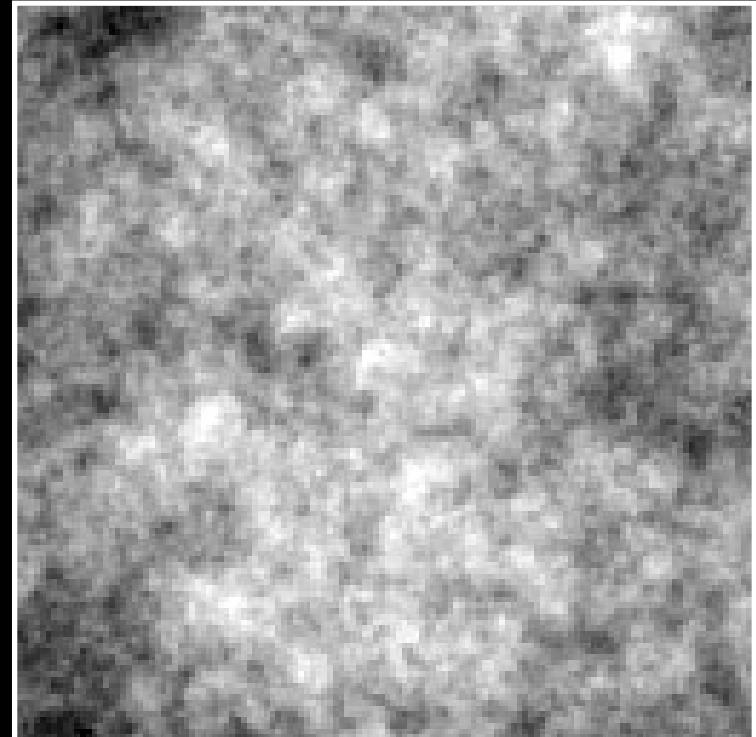


# Hydrodynamic Cosmology

# Baryons: The Tail of the Dog

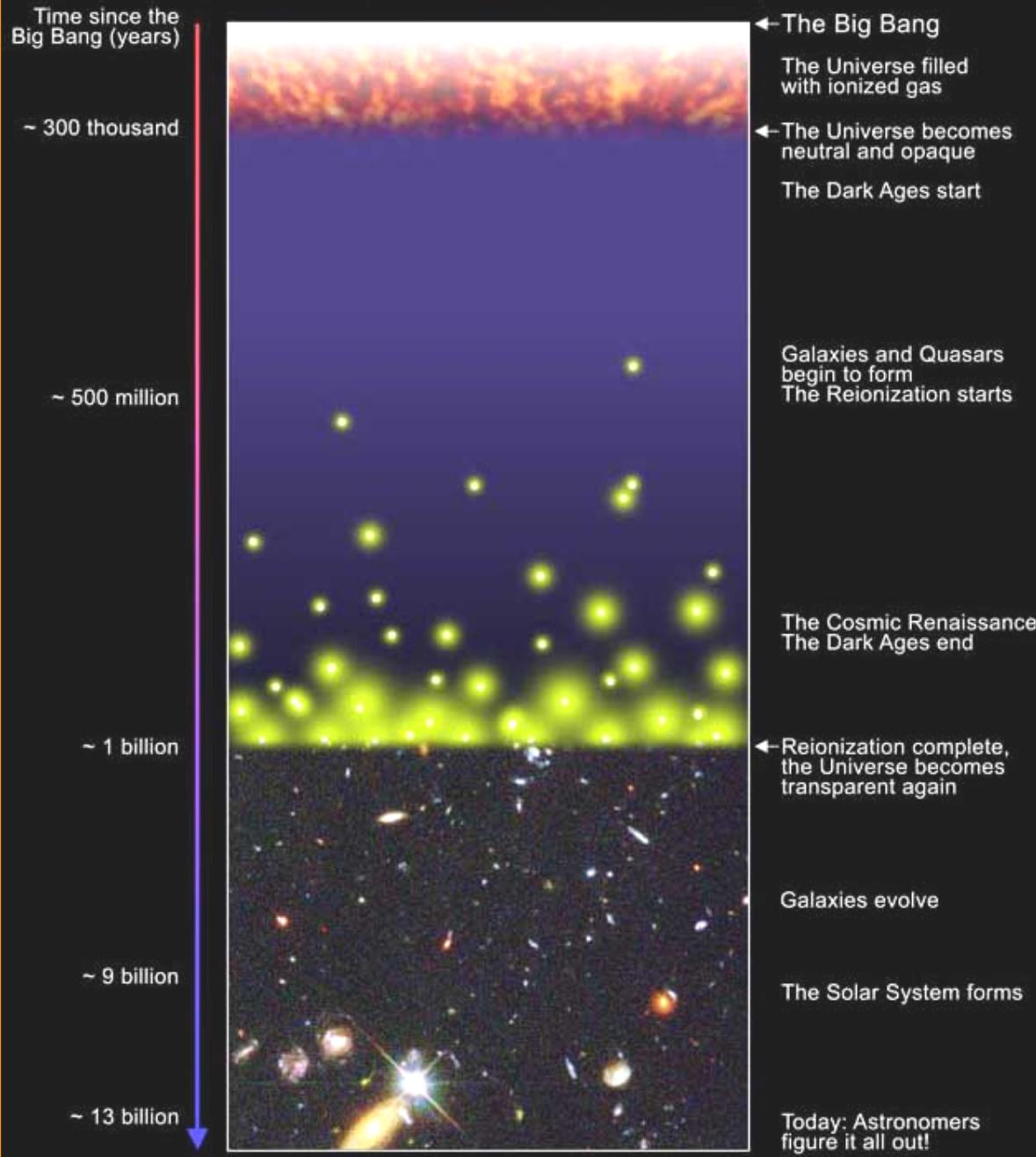


Dark matter



Gas

## A Schematic Outline of the Cosmic History



baryonic universe

*radiative transfer*

self-shielding  
photo-evaporation

galaxies

*SF-recipe*  
*N-body dynamics*

radiation  
background

ionizing  
flux      absorption

infall

photo-ionization  
photo-heating

IGM

feedback  
(energy, metals)

*multi-species*  
*hydrodynamics*

cosmic expansion

self-gravity

dark matter  
dynamics



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Physics Authors News Bread Illinois

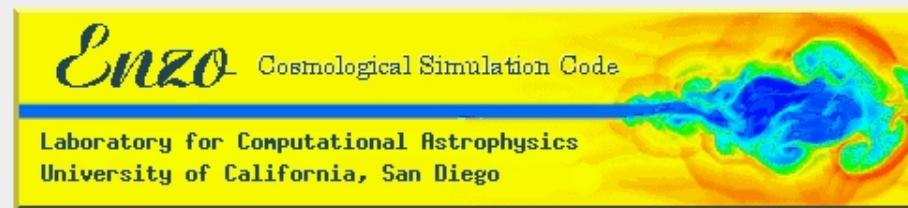
Search...

Skins Web 65°

Address http://cosmos/enzo/

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## General

- [Description](#)
- [Features](#)
- [Authors](#)
- [Acknowledgements](#)

## Software

- [License](#)
- [Requirements](#)
- [Download](#)
- [Code](#)

## Development

## Documentation

- [User Guide](#)
- [Cookbook/Tutorial](#)
- [Developer Guide](#)

## General Information

### Description

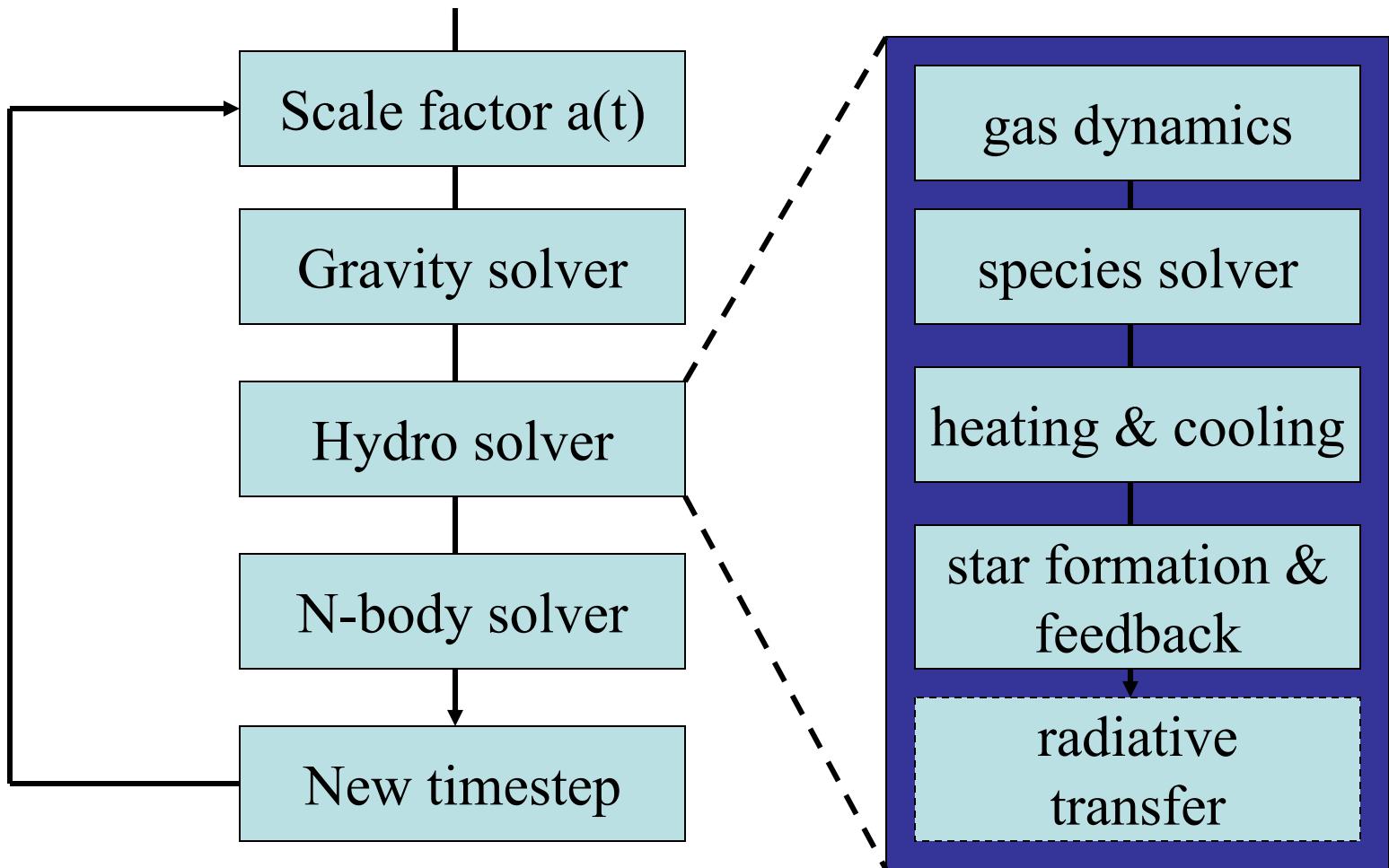
Enzo is an adaptive mesh refinement (AMR), grid-based hybrid code (hydro + N-Body) which is designed to do simulations of cosmological structure formation. It uses the algorithms of Berger & Collela to improve spatial and temporal resolution in regions of large gradients, such as gravitationally collapsing objects. The Enzo simulation software is incredibly flexible, and can be used to simulate a wide range of cosmological situations with the physics packages described below (see [Features](#)).

Enzo has been parallelized using the MPI message-passing library and can run on any shared or distributed memory parallel supercomputer or PC cluster. Simulations using as many as 1024 processors have been successfully carried out on the San Diego Supercomputing Center's Blue Horizon, an IBM SP.

Enzo is scheduled to be released into the public domain in October 2003. For more information please contact [enzo-l@ucsd.edu](mailto:enzo-l@ucsd.edu) at the [Laboratory for Computational Astrophysics](#).

### Features

# Main Loop of Hydrodynamic Cosmology Code



# Cosmological Hydrodynamics

$$\frac{\partial \rho_b}{\partial t} + \nabla \cdot (\rho_b v_b) + 3 \frac{\dot{a}}{a} \rho_b = 0$$

Euler's equations

$$\frac{\partial \rho_b v_{b,i}}{\partial t} + \nabla \cdot [(\rho_b v_{b,i}) v_b] + 5 \frac{\dot{a}}{a} \rho_b v_{b,i} = - \frac{1}{a^2} \frac{\partial p}{\partial x_i} - \frac{\rho_b}{a^2} \frac{\partial \phi}{\partial x_i}$$

$$\frac{\partial e}{\partial t} + \nabla \cdot (e v_b) + p \nabla \cdot v_b + 3 \frac{\dot{a}}{a} (e + p)_b = \Gamma - \Lambda$$

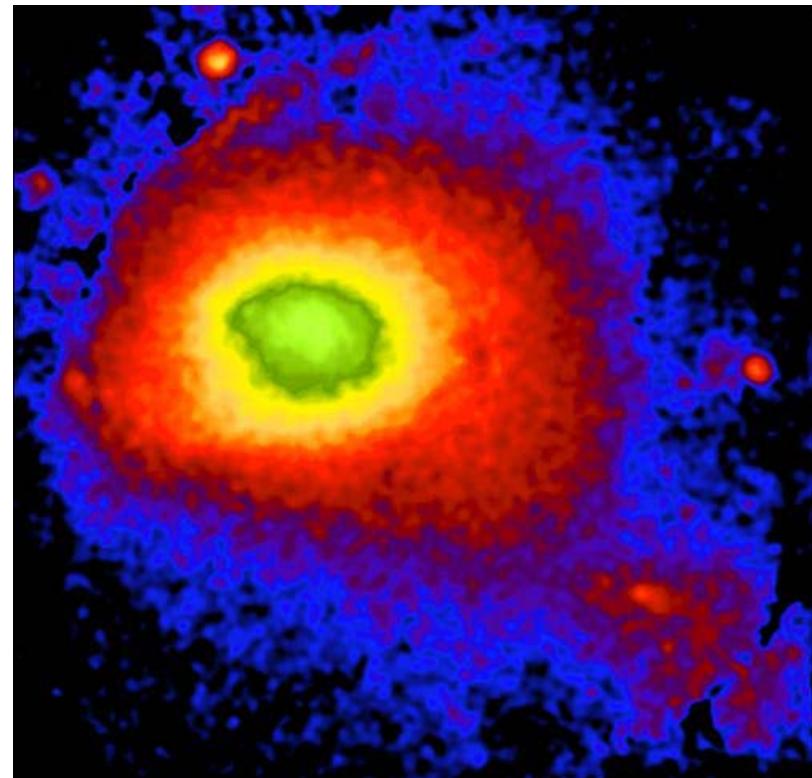
multispecies chemical kinetics

$$\frac{\partial \rho_i}{\partial t} + \nabla \cdot (\rho_i v_b) + 3 \frac{\dot{a}}{a} \rho_i = \pm \sum_j \sum_l k_{jl}(T) \rho_j \pm \sum_j I_j \rho_j$$

# Sample Applications

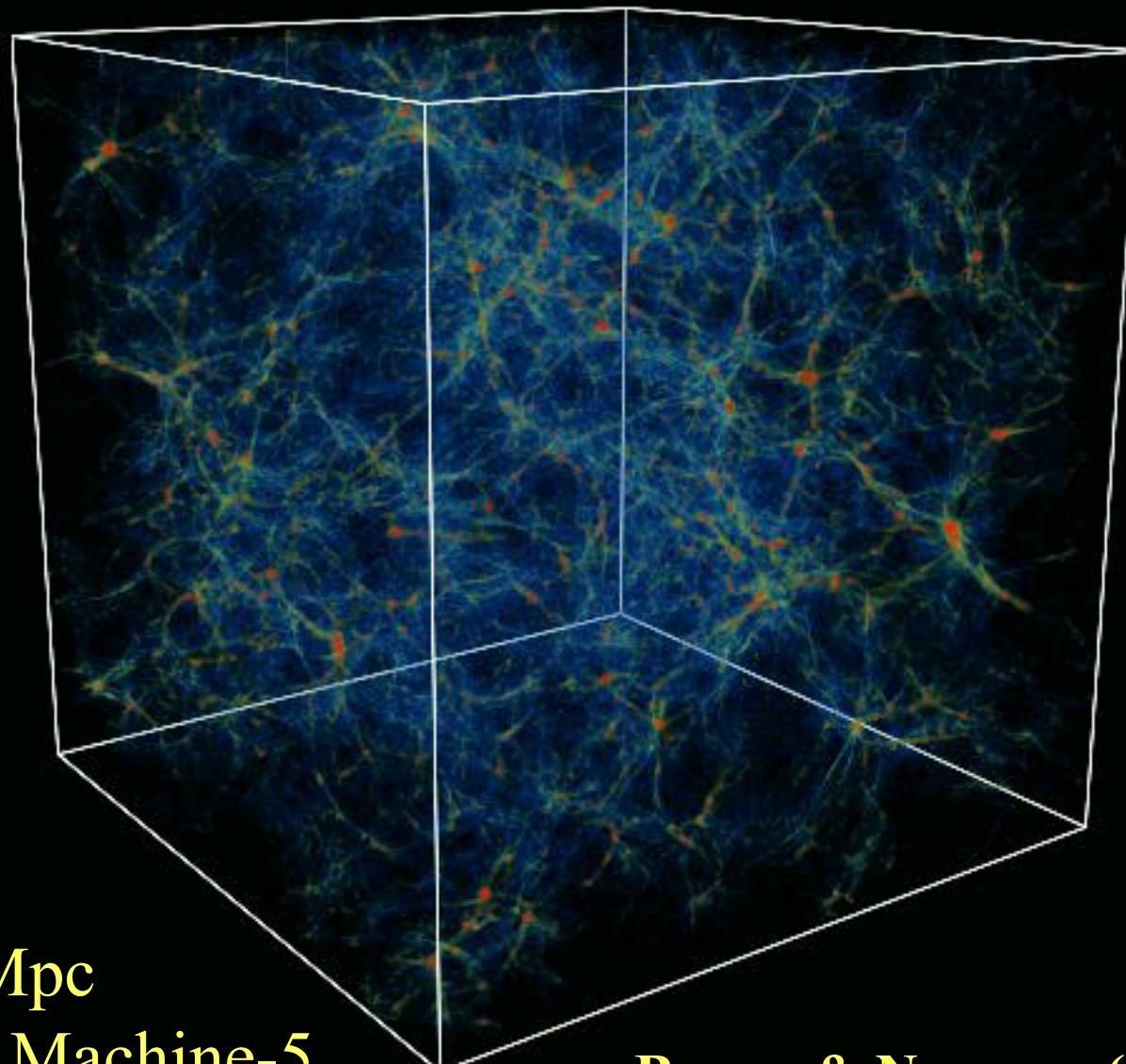
# X-Ray Clusters

- Hot, x-ray emitting gas bound to a cluster of galaxies
- Extremely luminous in x-ray
- T easily measured
- T and M tightly correlated
  - $n(T,z) \rightarrow n(M,z)$
- Cosmological probes of  $P(k)$ ,  $\Omega_m$ ,  $\Omega_b$  and  $\Omega_\Lambda$



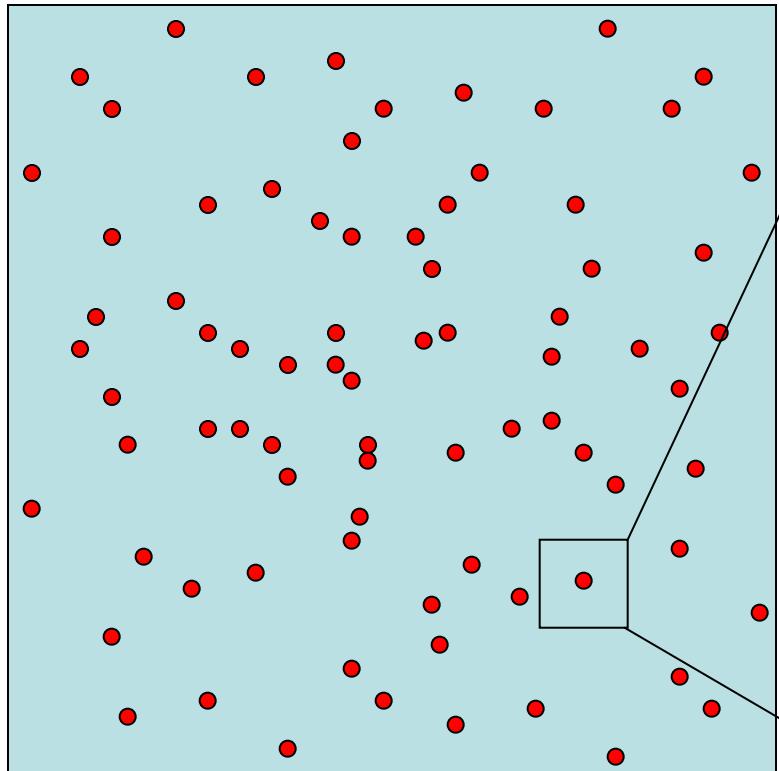
**Coma Cluster**  
**ROSAT (Boehringer et al)**

# X-Cluster Statistics on $512^3$ Grid

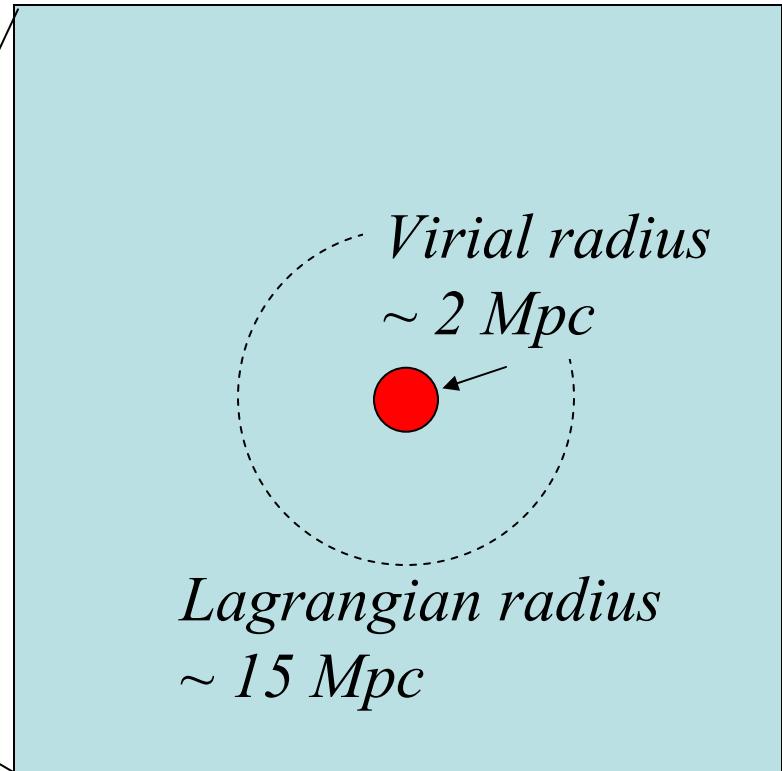


# Technical Difficulty: Range of Scales

*Survey volume*



*Tidal neighborhood*



← 500 Mpc →

← 50 Mpc →

# Idealized Cluster ICM

virialization shock

$$R \sim R_{\text{vir}}$$

adiabatic halo:

$$t_{\text{cool}} > t_{\text{Hubble}}$$

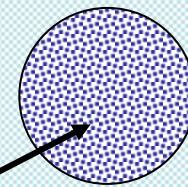
supernovae heating <<  
gravitational heating

non-adiabatic core:

$$t_{\text{cool}} \leq t_{\text{Hubble}}$$

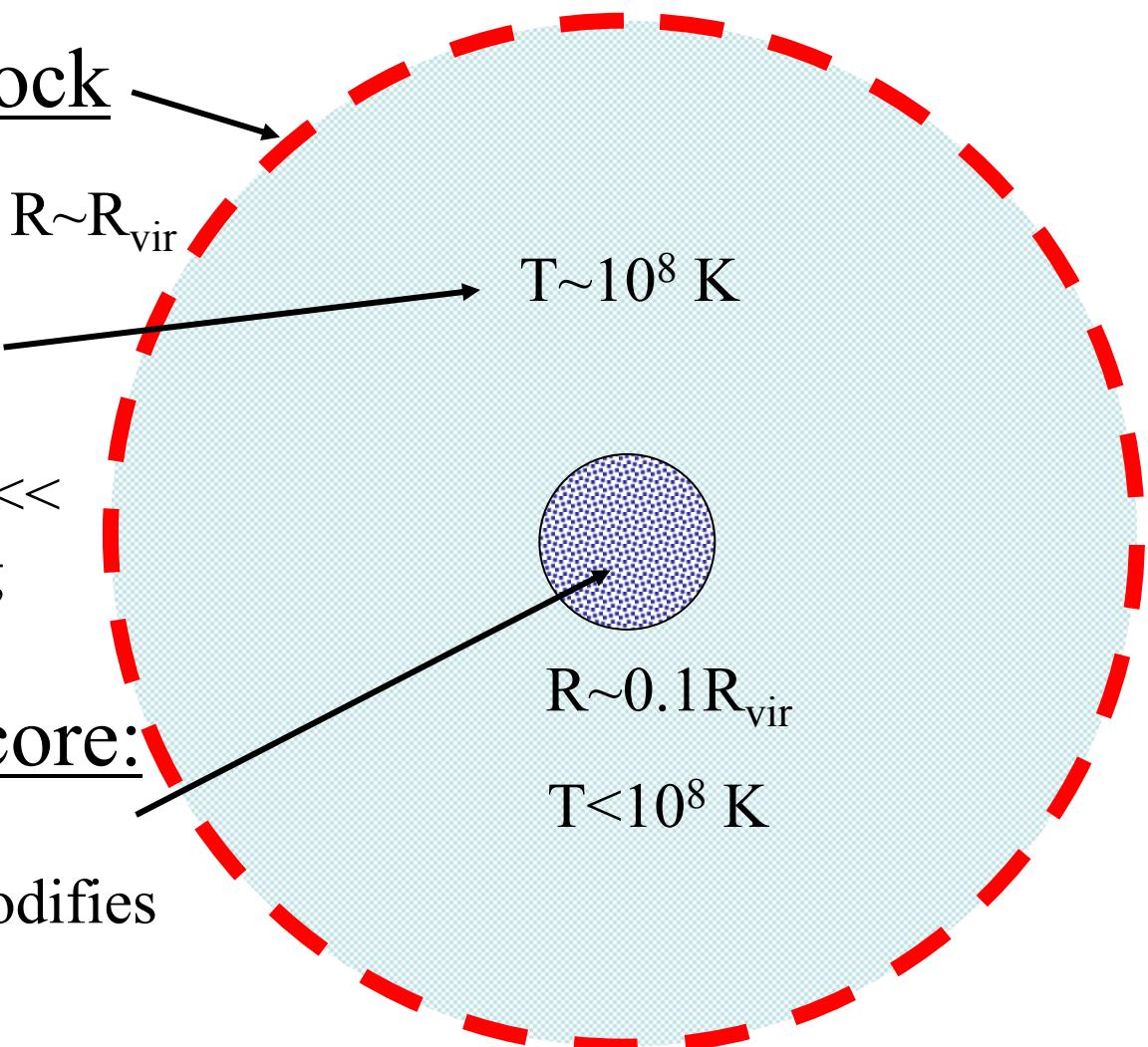
radiative cooling modifies  
entropy profile

$$T \sim 10^8 \text{ K}$$

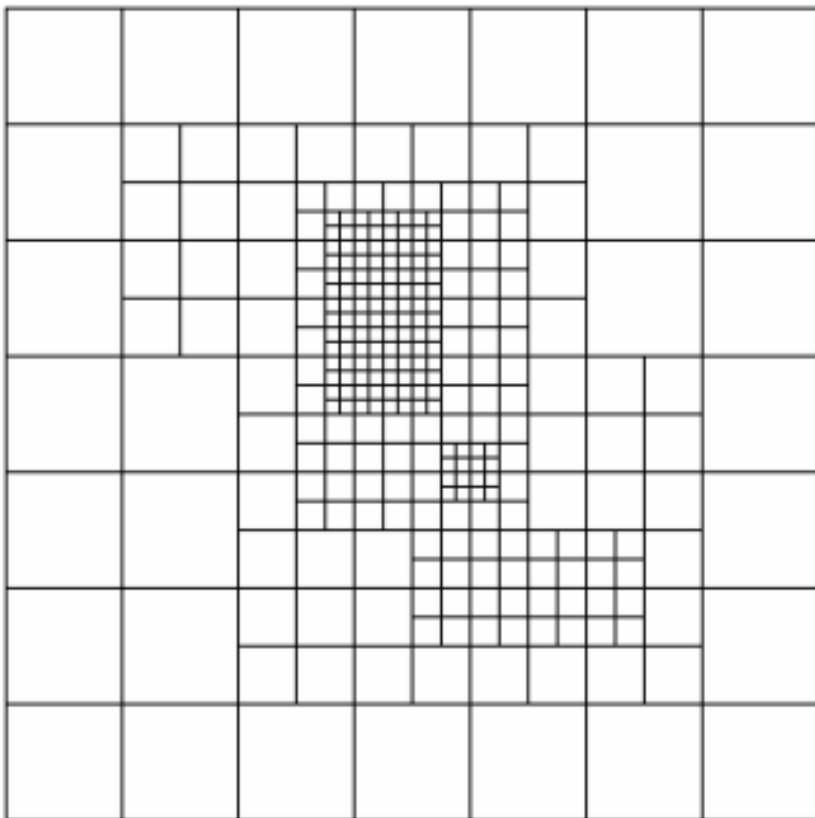


$$R \sim 0.1 R_{\text{vir}}$$

$$T < 10^8 \text{ K}$$

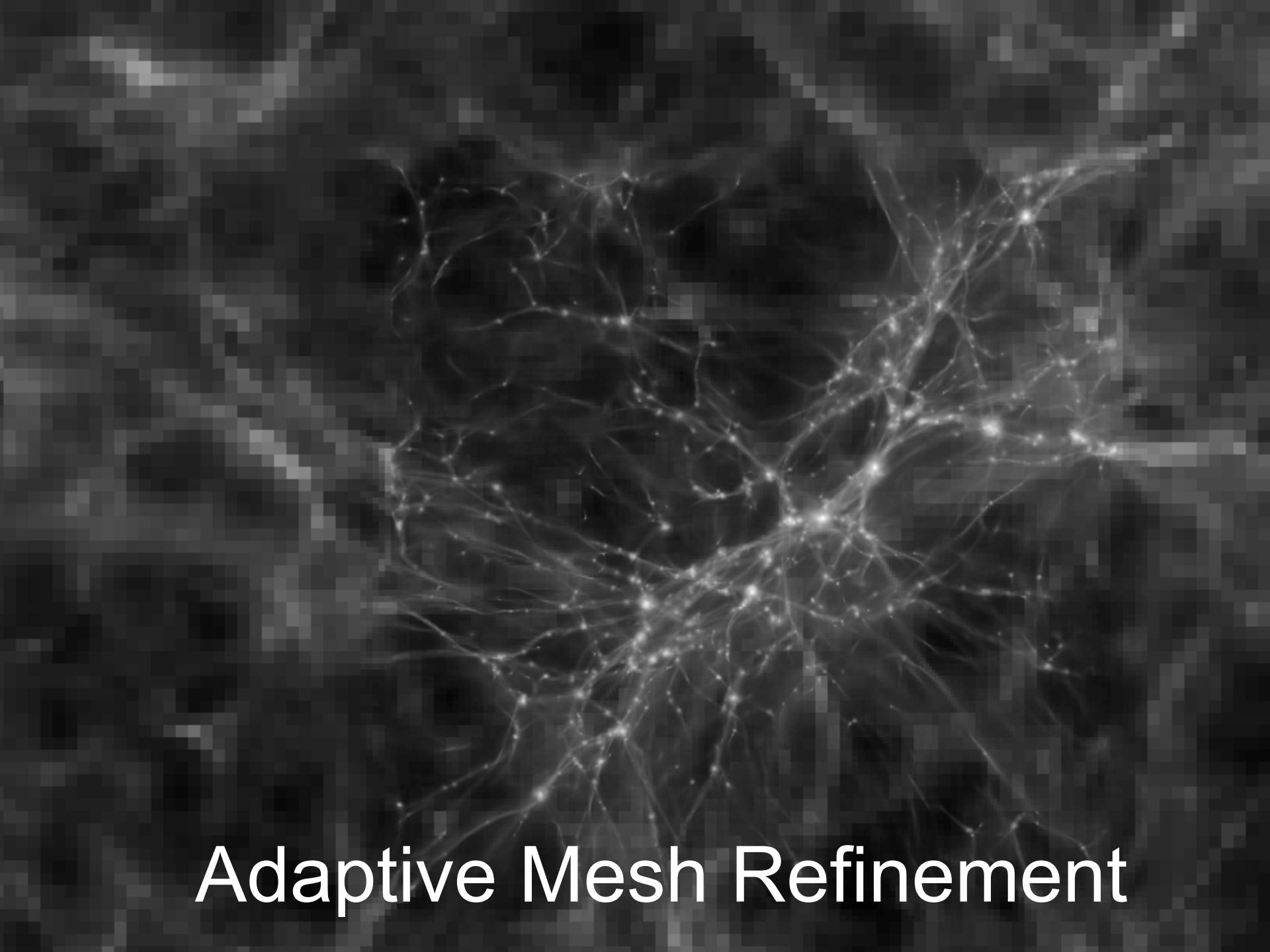


# Adaptive Mesh Refinement



Refine cell spacing  
*locally and automatically* based  
on any combination  
of *physical or numerical criteria*

=> *can resolve all relevant length and timescales*

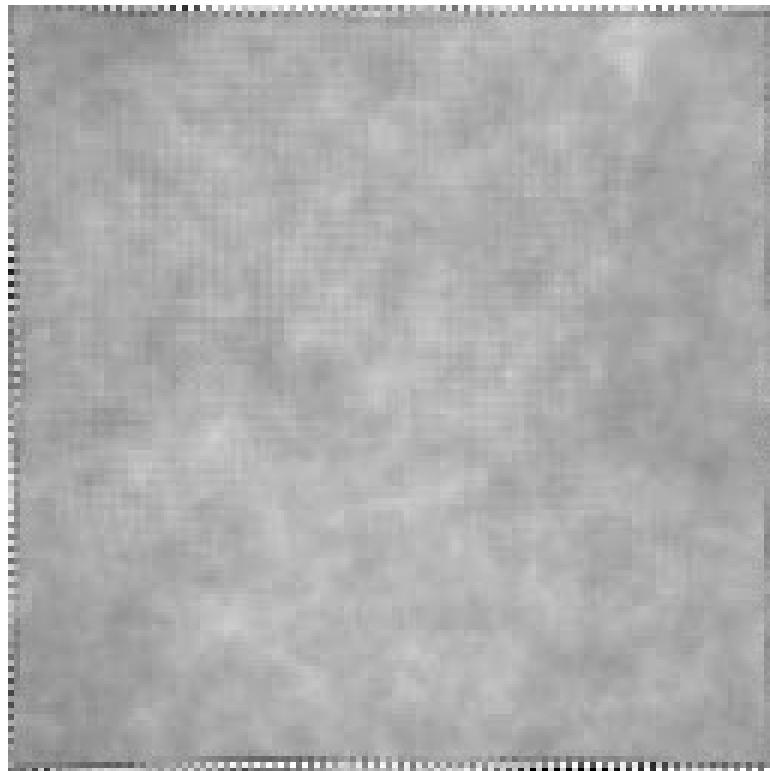


# Adaptive Mesh Refinement

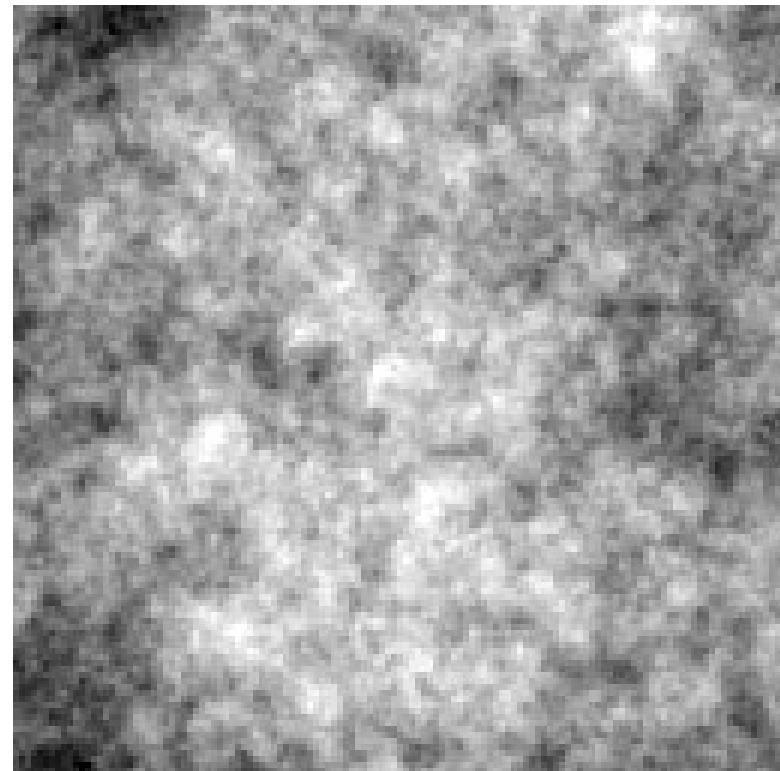
# Formation of an X-ray Cluster

## $256^3$ AMR (adiabatic)

Dark matter



Baryons



← →  
16 Mpc  
(comoving)

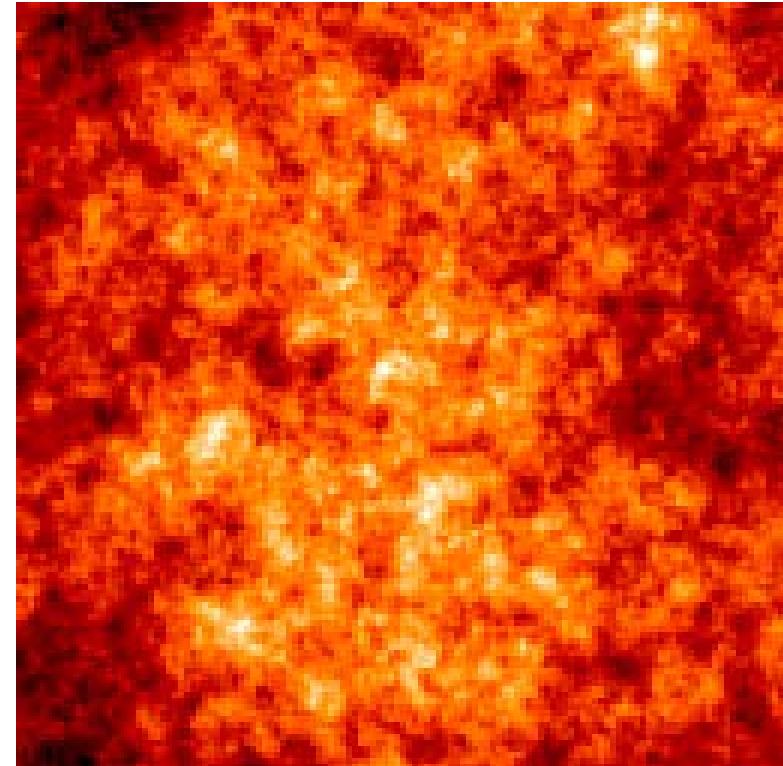
# Formation of an X-ray Cluster

## $256^3$ AMR (adiabatic)

Temperature



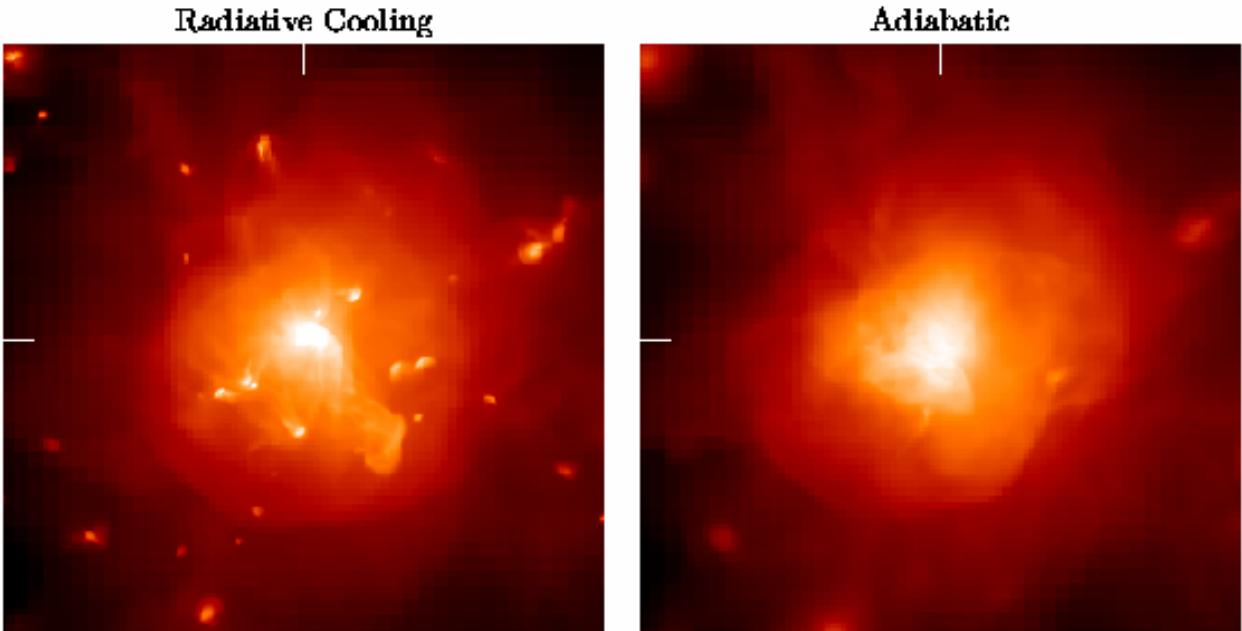
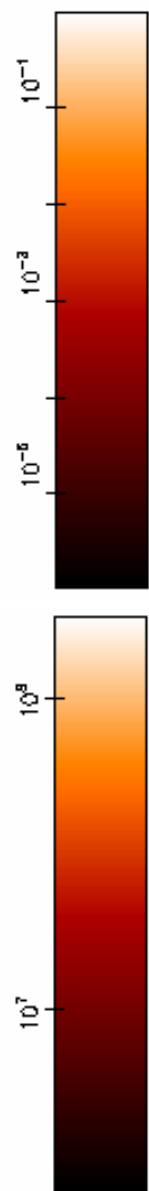
X-ray surface brightness



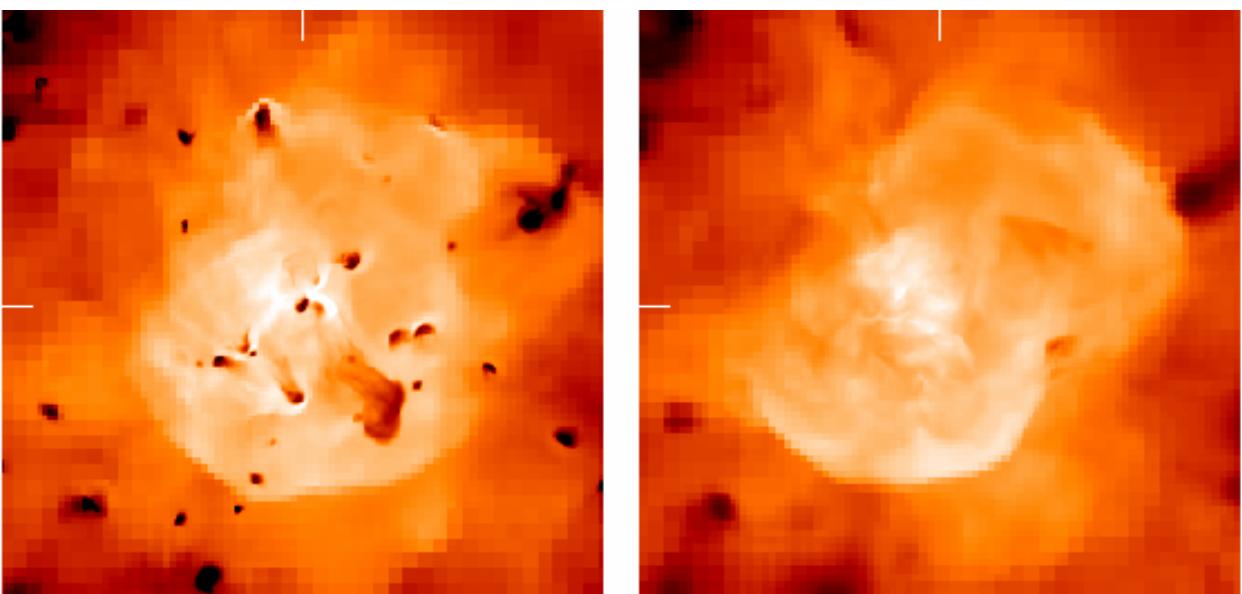
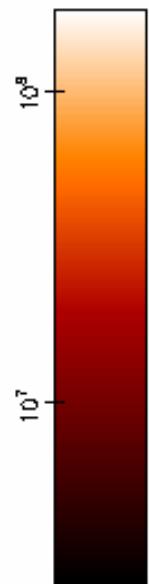
← →  
16 Mpc  
(comoving)

C1  
 $z=0$

$\log(S_x)$



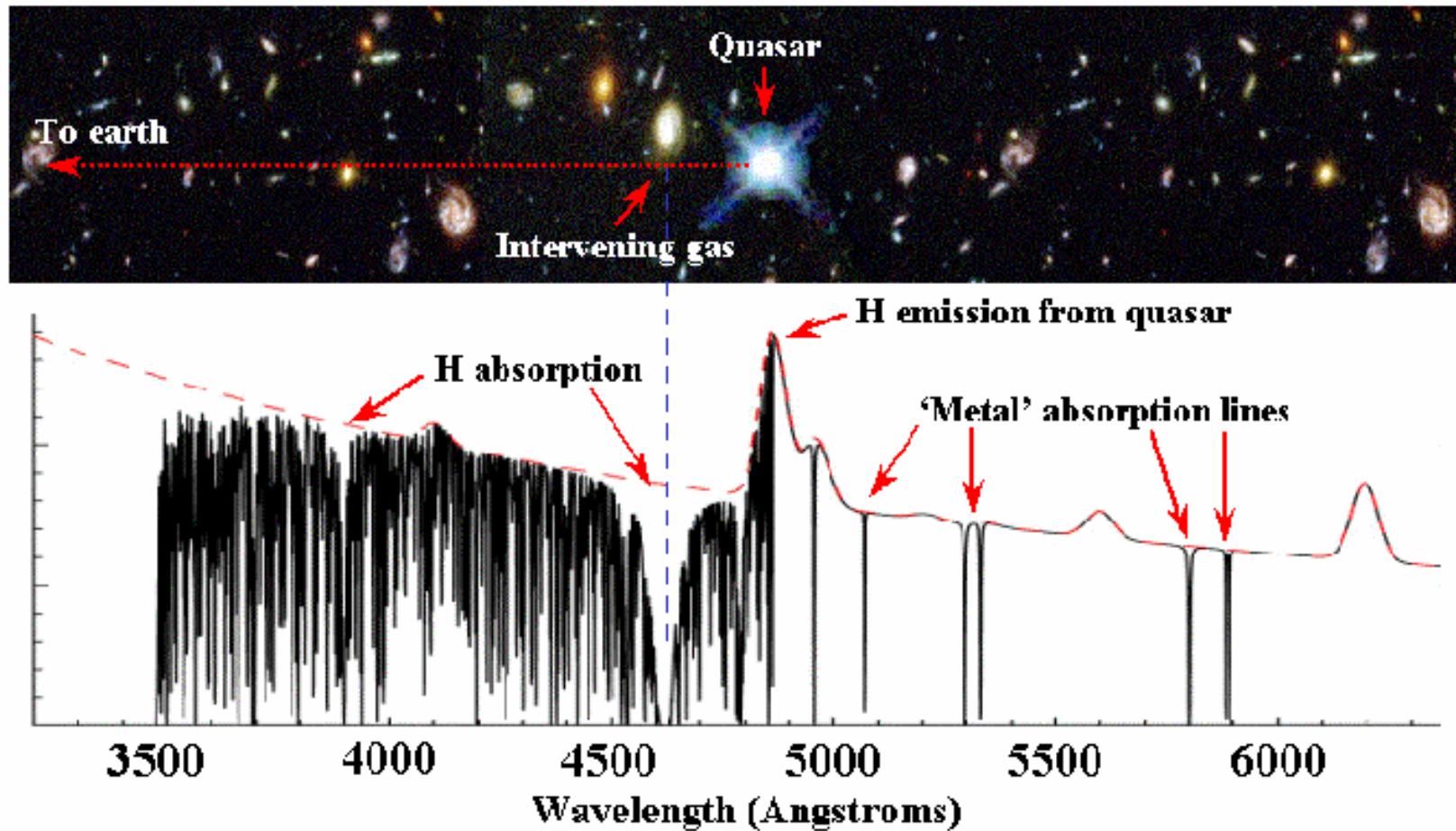
$\log(T_x)$



back

Motl et al. (2002)

# The Intergalactic Medium



Source: M. Murphy

# Physical Origin of Ly $\alpha$ Forest

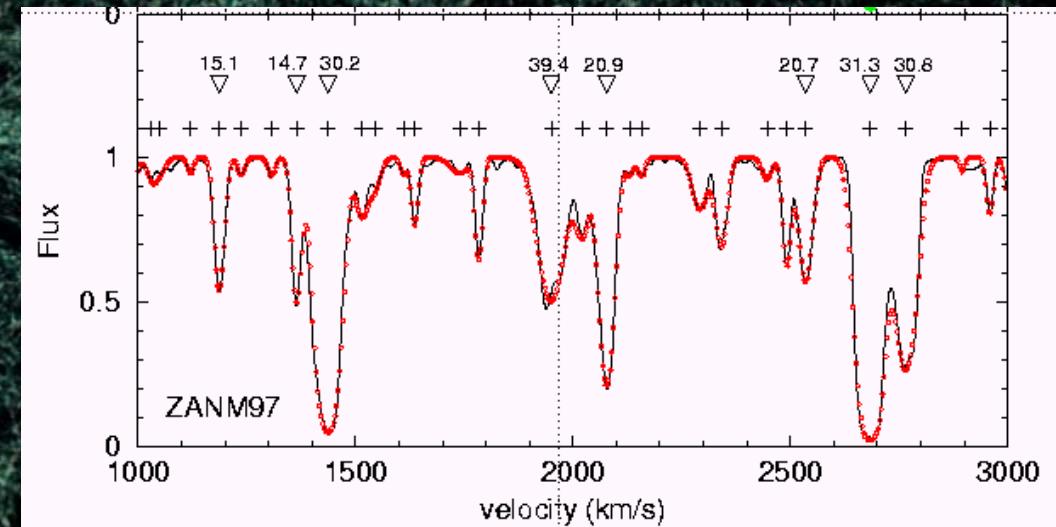
$N=1024^3$

$L=54 \text{ Mpc}/h$

Earth

quasar

Simulated HI absorption spectrum



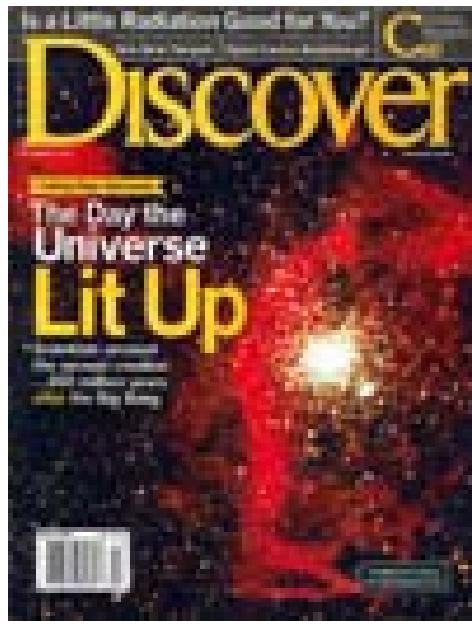
Baryon Overdensity,  $z=3$

# Precision cosmology using the Lyman $\alpha$ forest

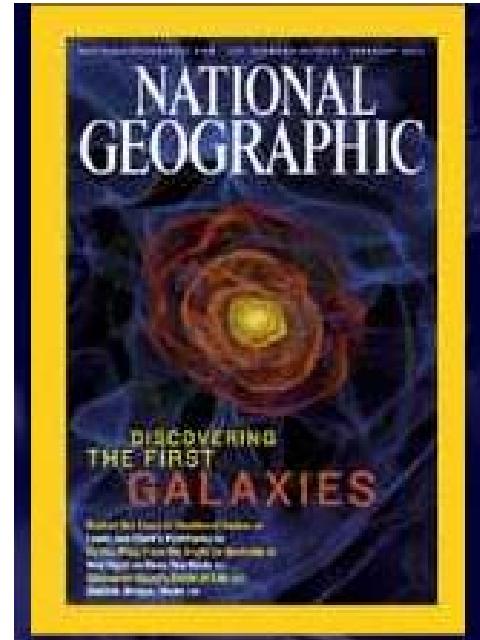
- Absorption spectrum is a 1D map of neutral hydrogen along LOS
- Assuming gas is in ionization equilibrium with known UV background, have 1D map of baryons along LOS
- Baryons closely follow dark matter, hence have 1D map of total mass density along LOS
- Many LOS sample matter power spectrum  $P(k)$
- Simulations provide mapping between absorption spectra and  $P(k)$

# Simulating the Formation of the First Star in the Universe

**Nov. 2002**



**Feb. 2003**

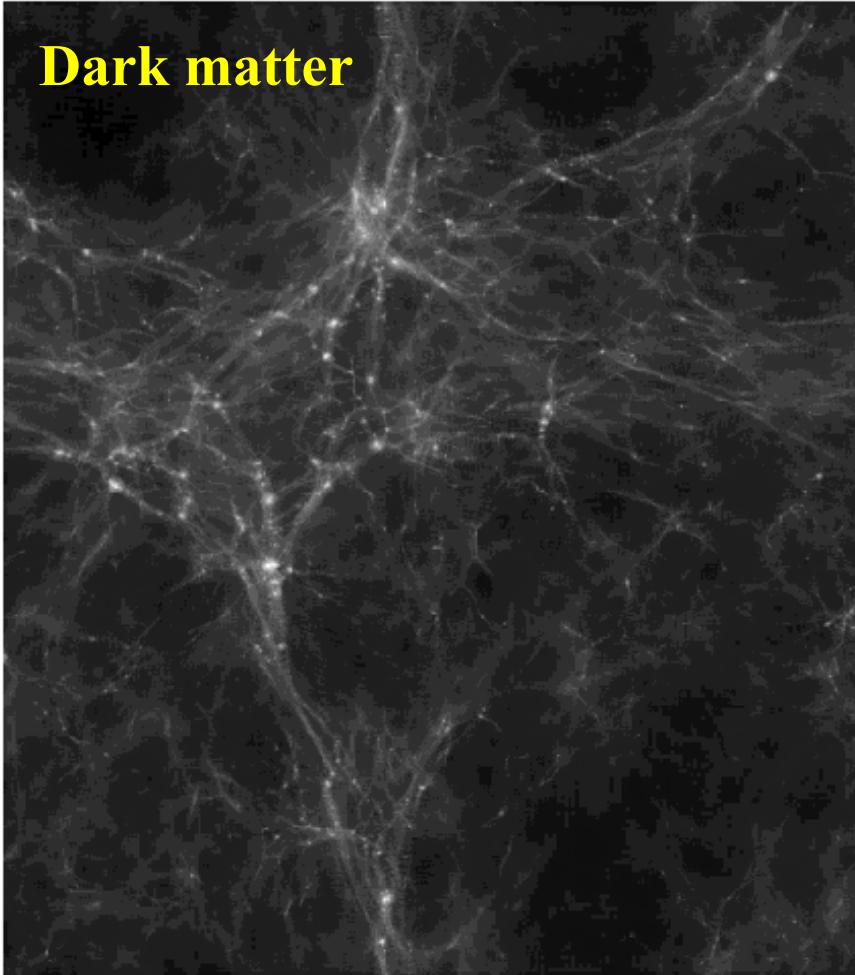


Tom Abel, Greg Bryan & MN

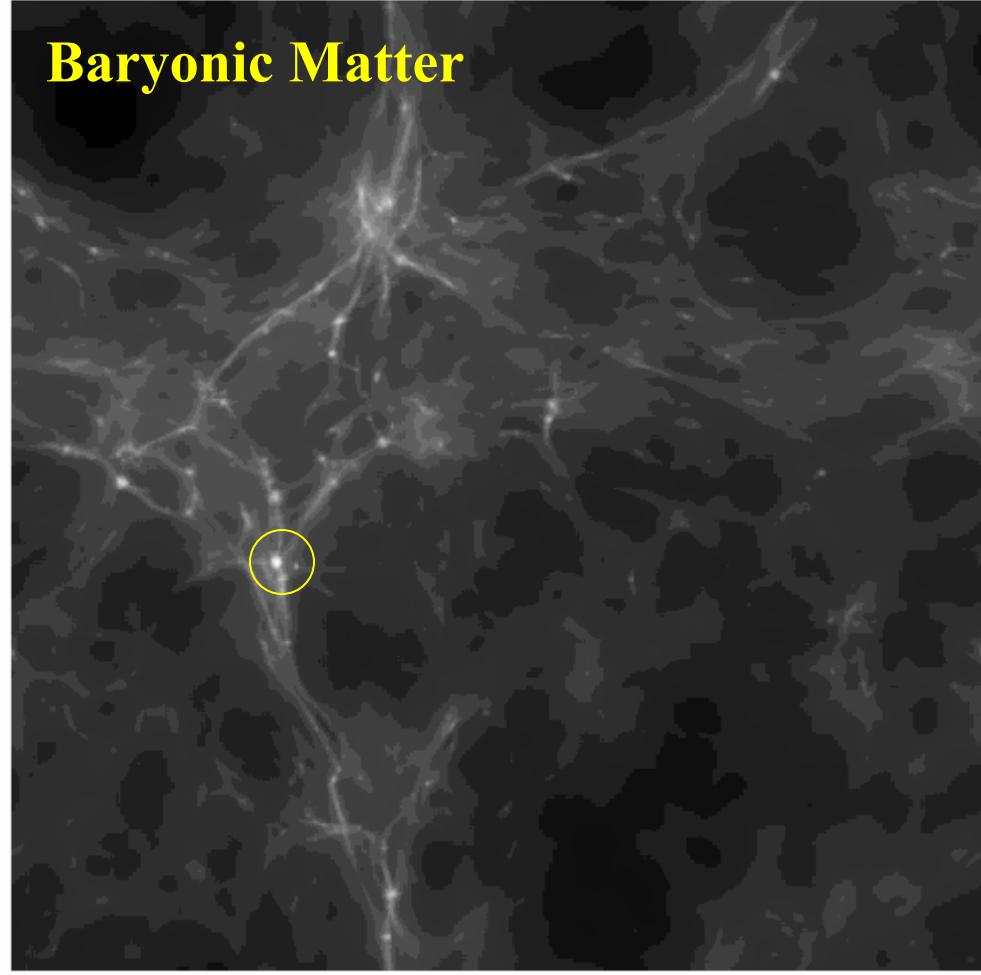
<http://www.TomAbel.com>

# The Universe at $z=20$

**Dark matter**



**Baryonic Matter**

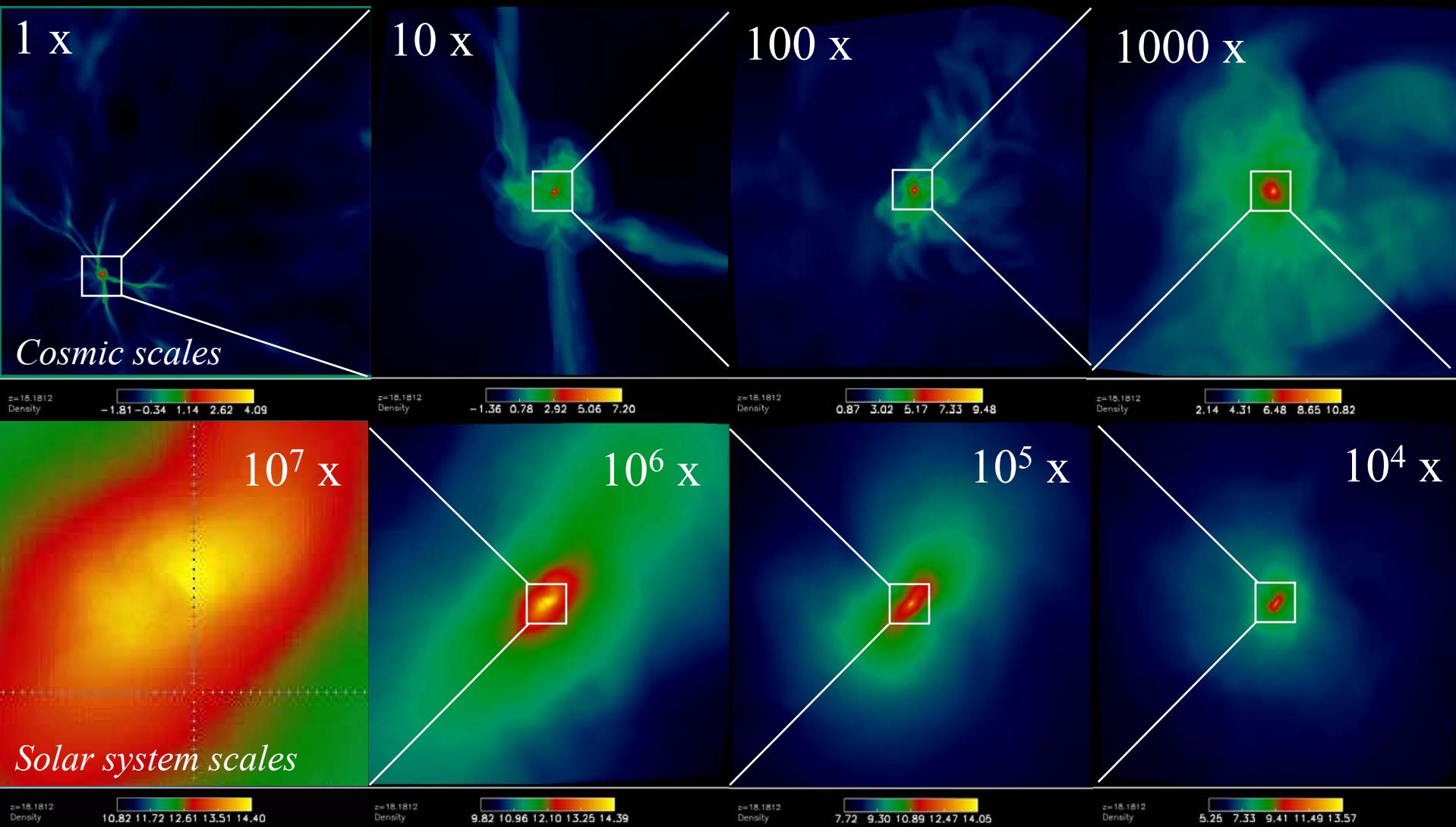


0.1 Mpc (comoving)

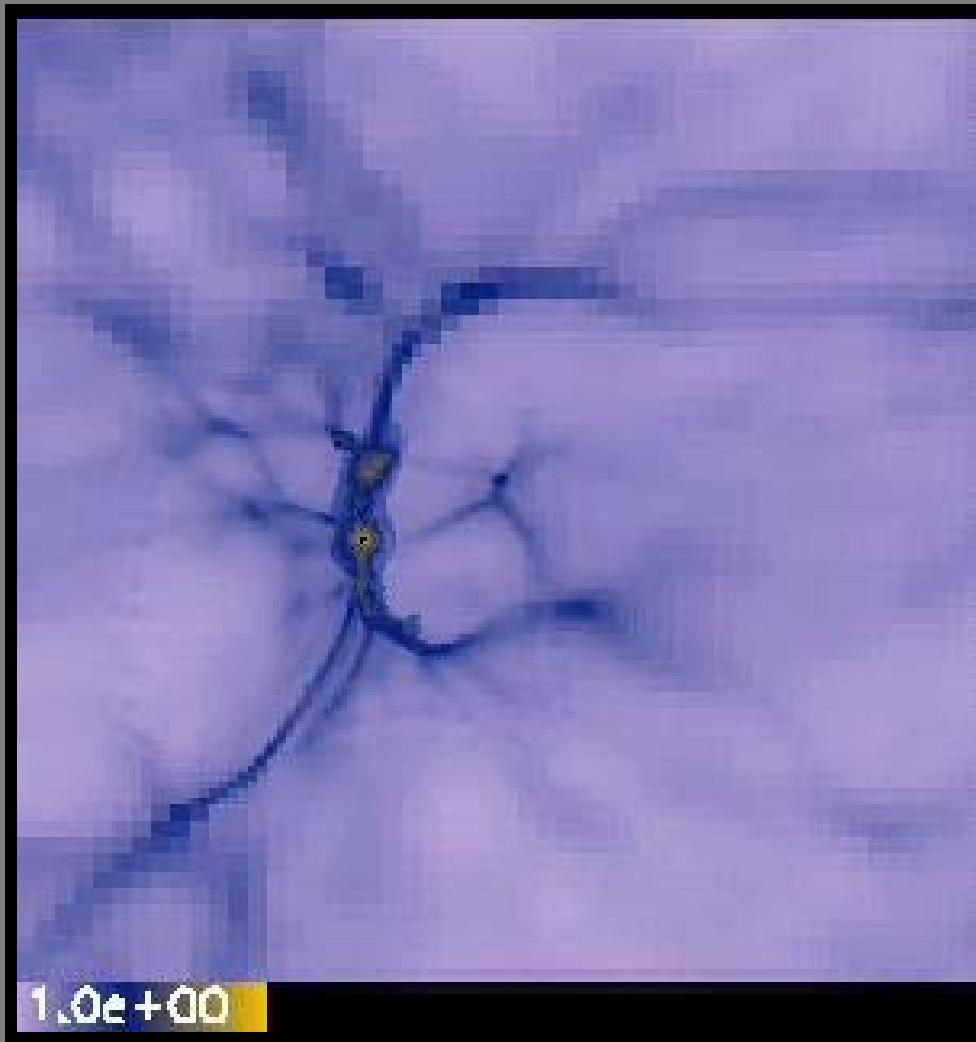
# Formation of First Stars

## Adaptive Mesh Refinement Simulation

Abel, Bryan & Norman (2001)



# Cosmic Zoom In



# Impact of the First Stars

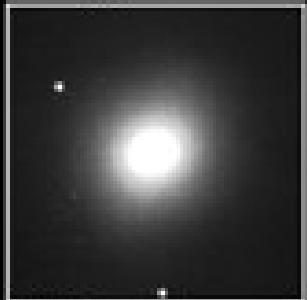
- The first stars are massive, extremely luminous, and short lived
- They either explode as supernovae or collapse to form the first black holes, or both
- Early reionization and reheating of the intergalactic medium (WMAP)
- Chemical enrichment of the intergalactic medium



# Formation and Evolution of Galaxies

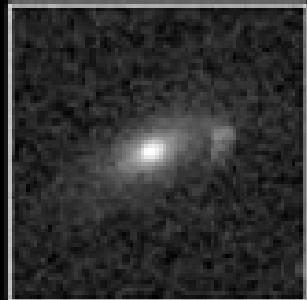
# Age of the Universe

Today: 14 Billion Years    9 Billion Years

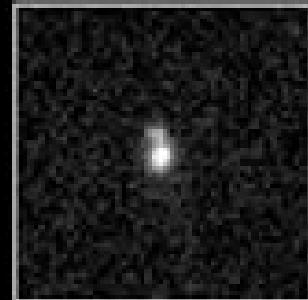


Elliptical

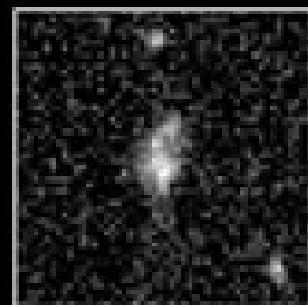
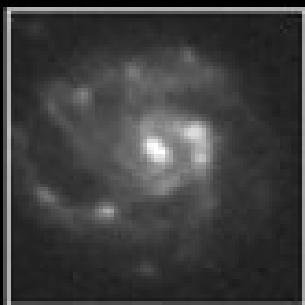
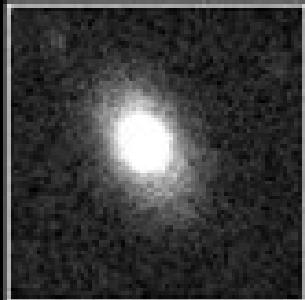
5 Billion Years



2 Billion Years



Spiral



## Galaxies: Snapshots in Time

HST · WFPC2



SPACE  
TELESCOPE  
SCIENCE  
INSTITUTE



# Hydrodynamic Simulation of Galaxy Formation

M. Norman, G. Bryan & B. O'Shea

# Star formation and feedback recipe (Cen & Ostriker 1992)

- for each cell with overdensity  $\rho_b / \bar{\rho}_b > \eta$
- check whether 3 criteria are satisfied:

$$\nabla \cdot \vec{v}_b < 0 \Rightarrow \text{contracting}$$

$$t_{cool} < t_{dyn} \equiv \sqrt{3\pi / 32G\rho_{tot}} \Rightarrow \text{cooling rapidly}$$

$$m_b > m_{Jeans} \equiv G^{-3/2} \rho_b^{-1/2} C^3 \left[ 1 + \frac{\delta\rho_d}{\delta\rho_b} \right]^{-3/2}$$

$\Rightarrow$  gravitationally unstable

- if so, convert fraction  $f^* \Delta t / t_{dyn}$  of gas to collisionsless star particle

# **Evolution of the Universe: Large Scale Structure and Galaxy Formation**

Grand Challenge Cosmology Consortium

**Michael Norman, NCSA**

**Brian O'Shea, NCSA**

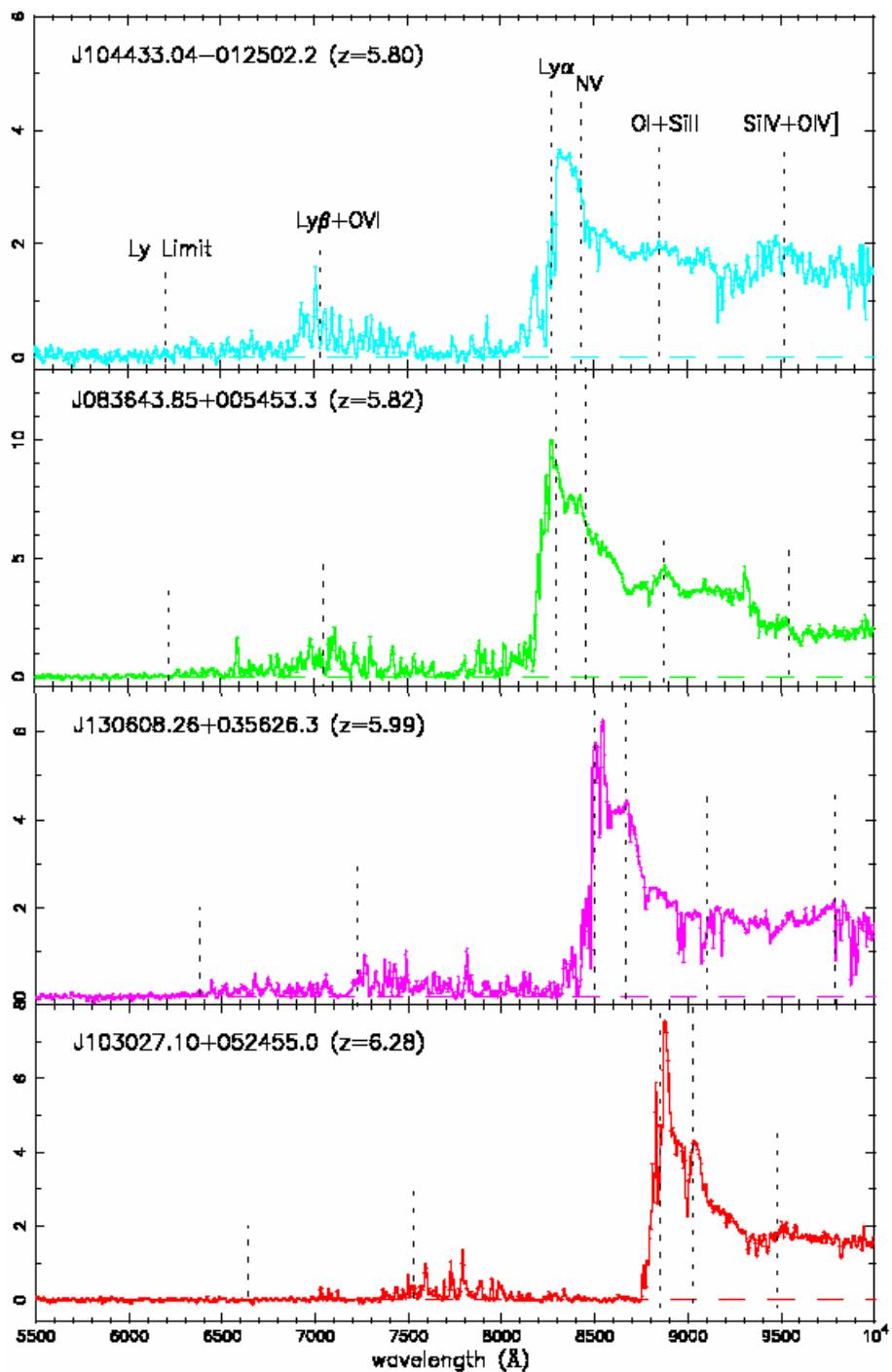
**Greg Bryan, Princeton**

HDTV Visual Excerpt from "Runaway Universe"

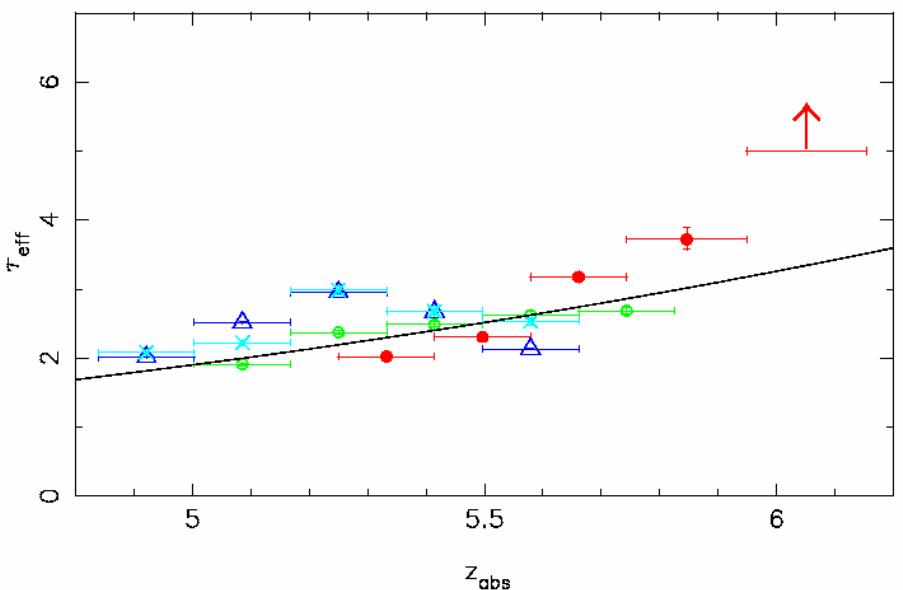
**Courtesy NOVA/WGBH, PBS**

**Thomas Lucas Productions**

# Epoch of reionization seen?



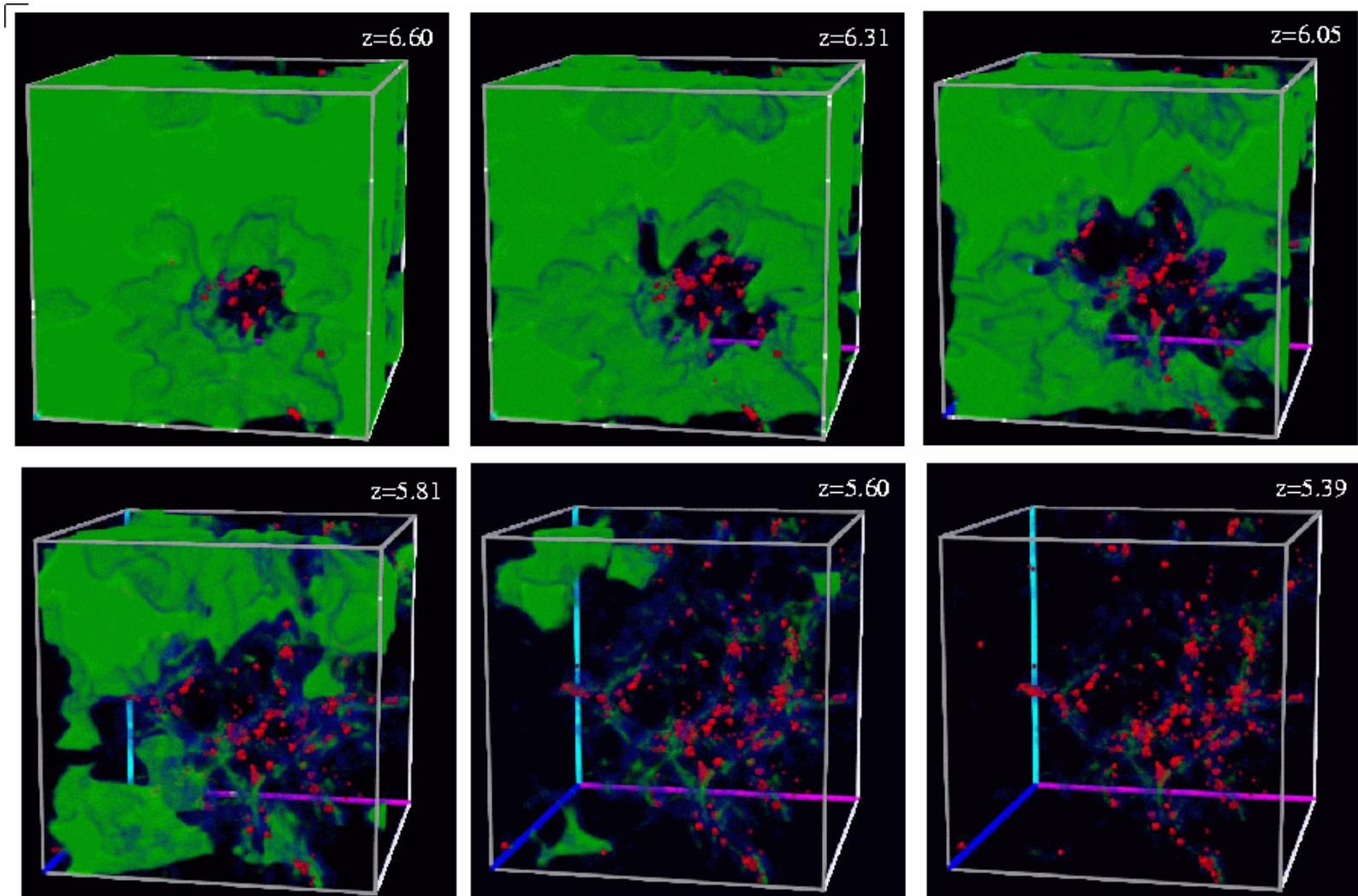
GP optical depth vs. z



Becker et al. (2001)  
SDSS Collaboration

# Reionization of IGM by High-z Galaxies

Razoumov et al. (2002)



# Gunn-Peterson optical depth vs. z

