Cosmological Structure Formation II

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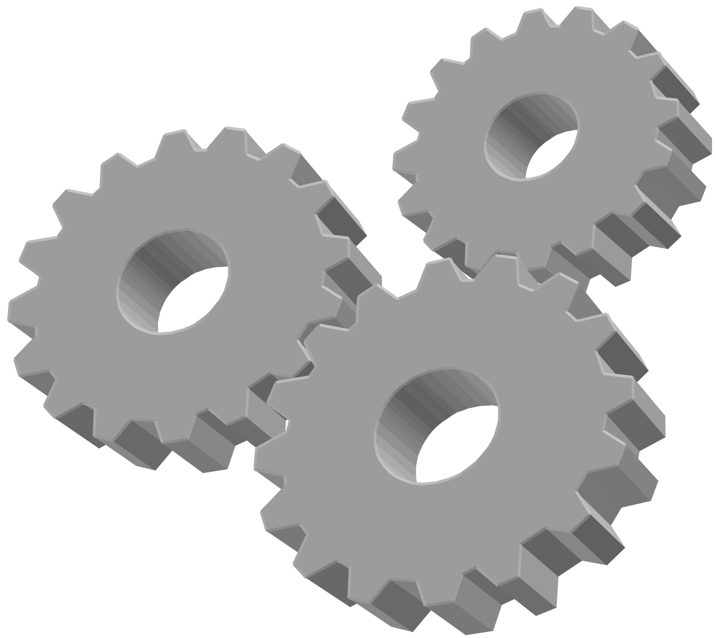
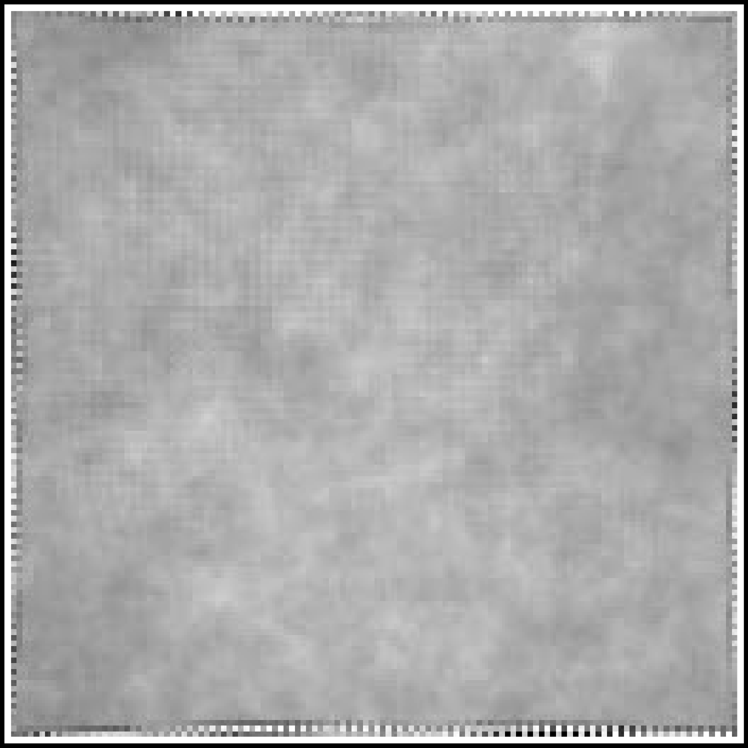
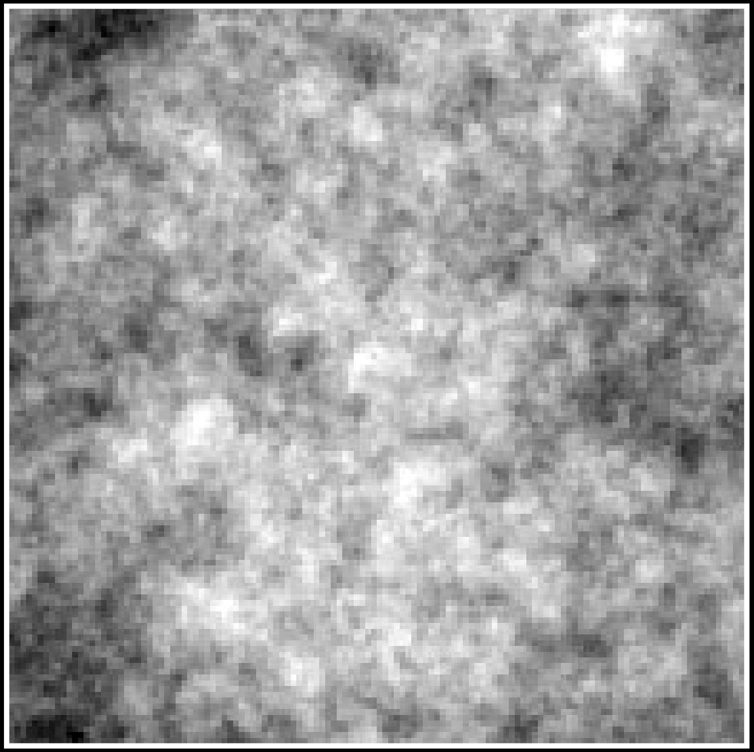


Hydrodynamic Cosmology

Baryons: The Tail of the Dog

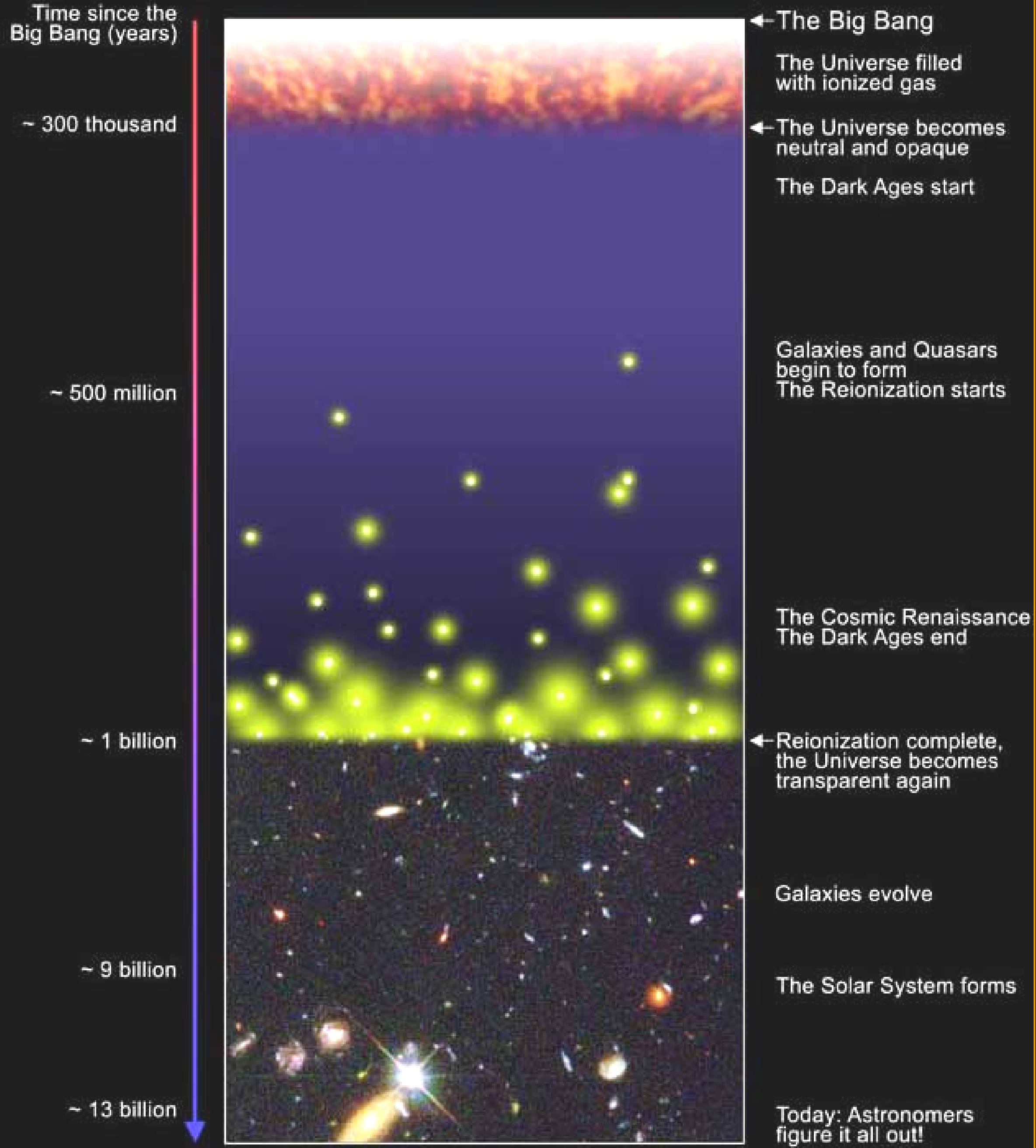


Dark matter

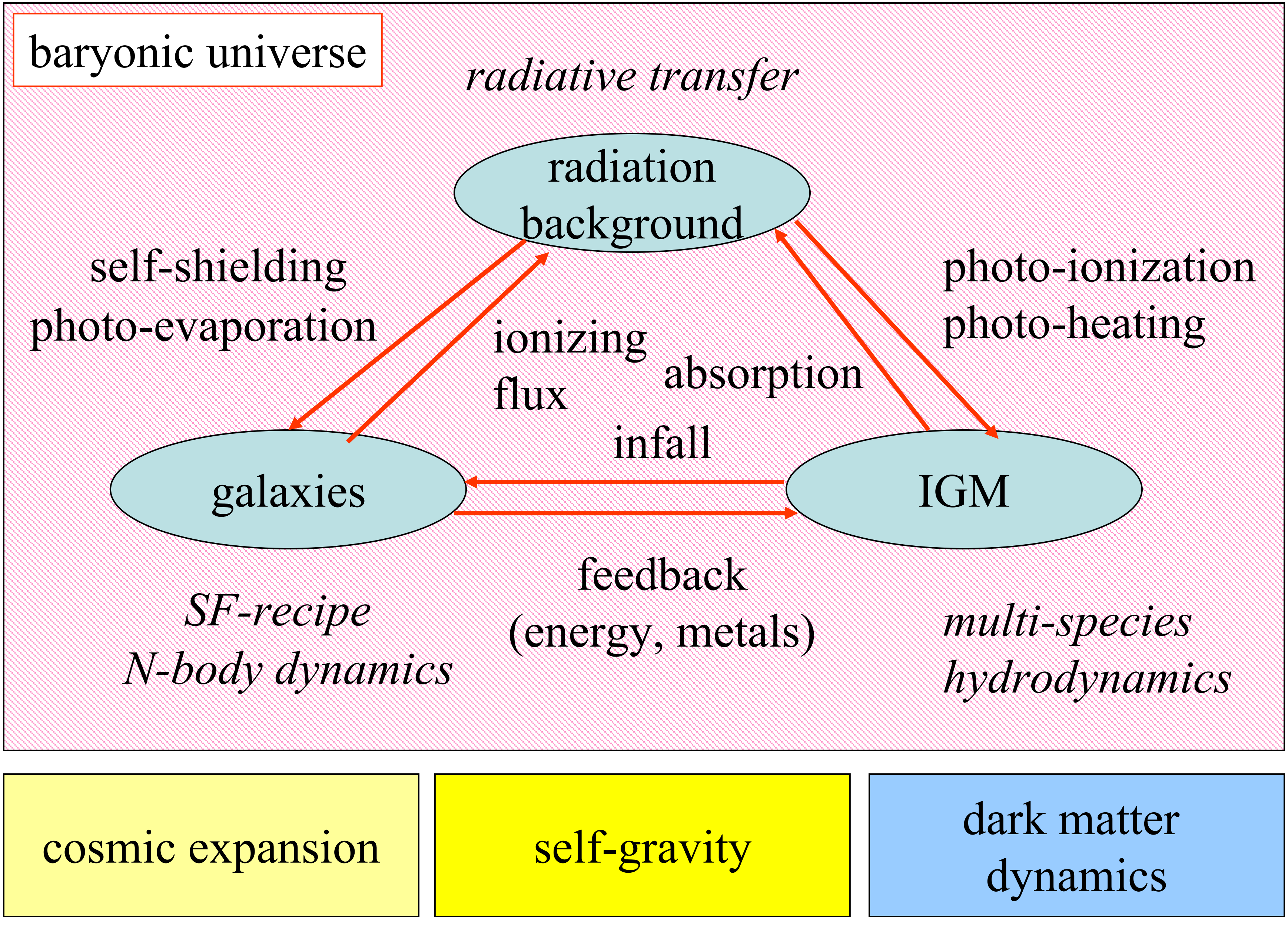


Gas

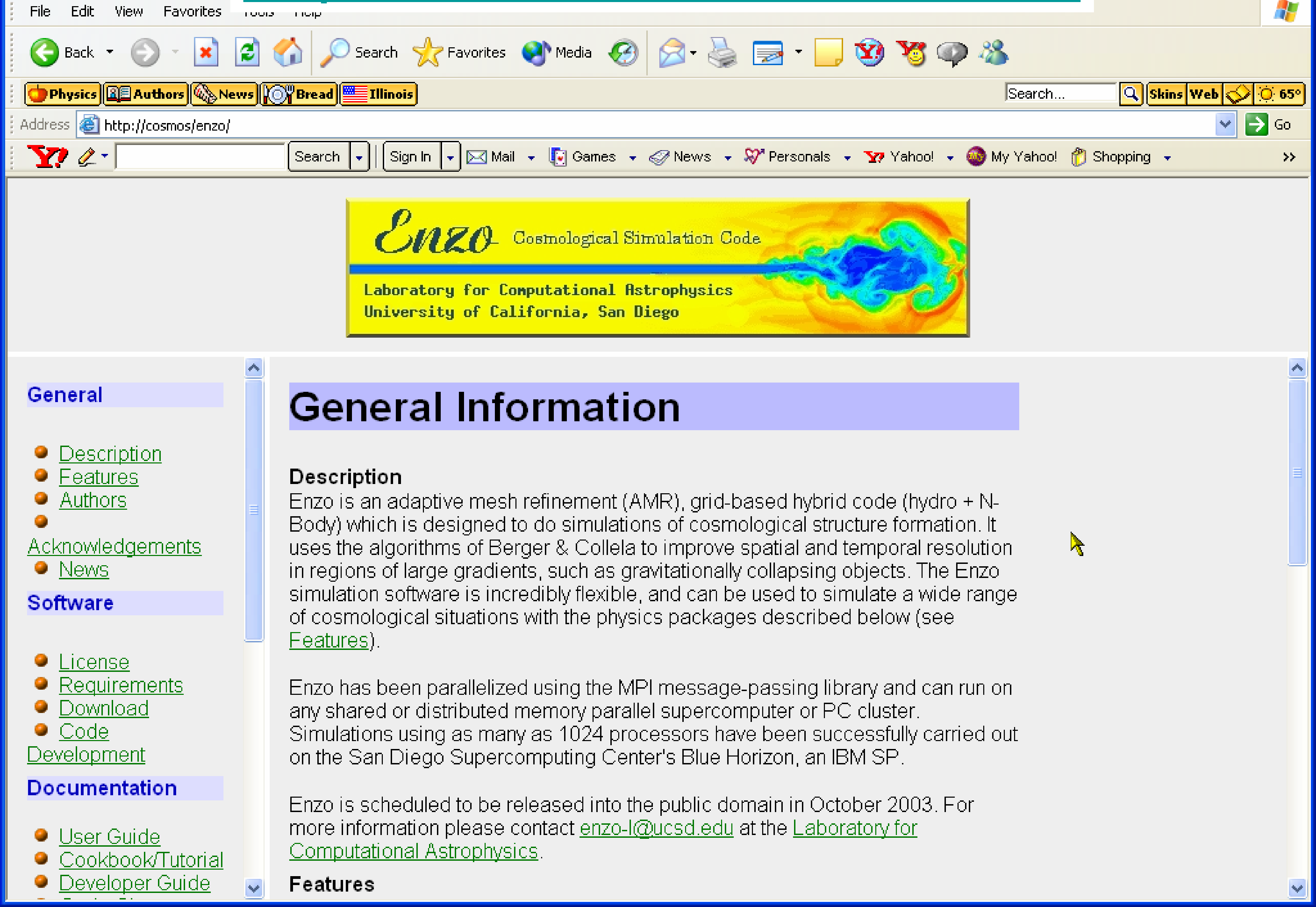
A Schematic Outline of the Cosmic History



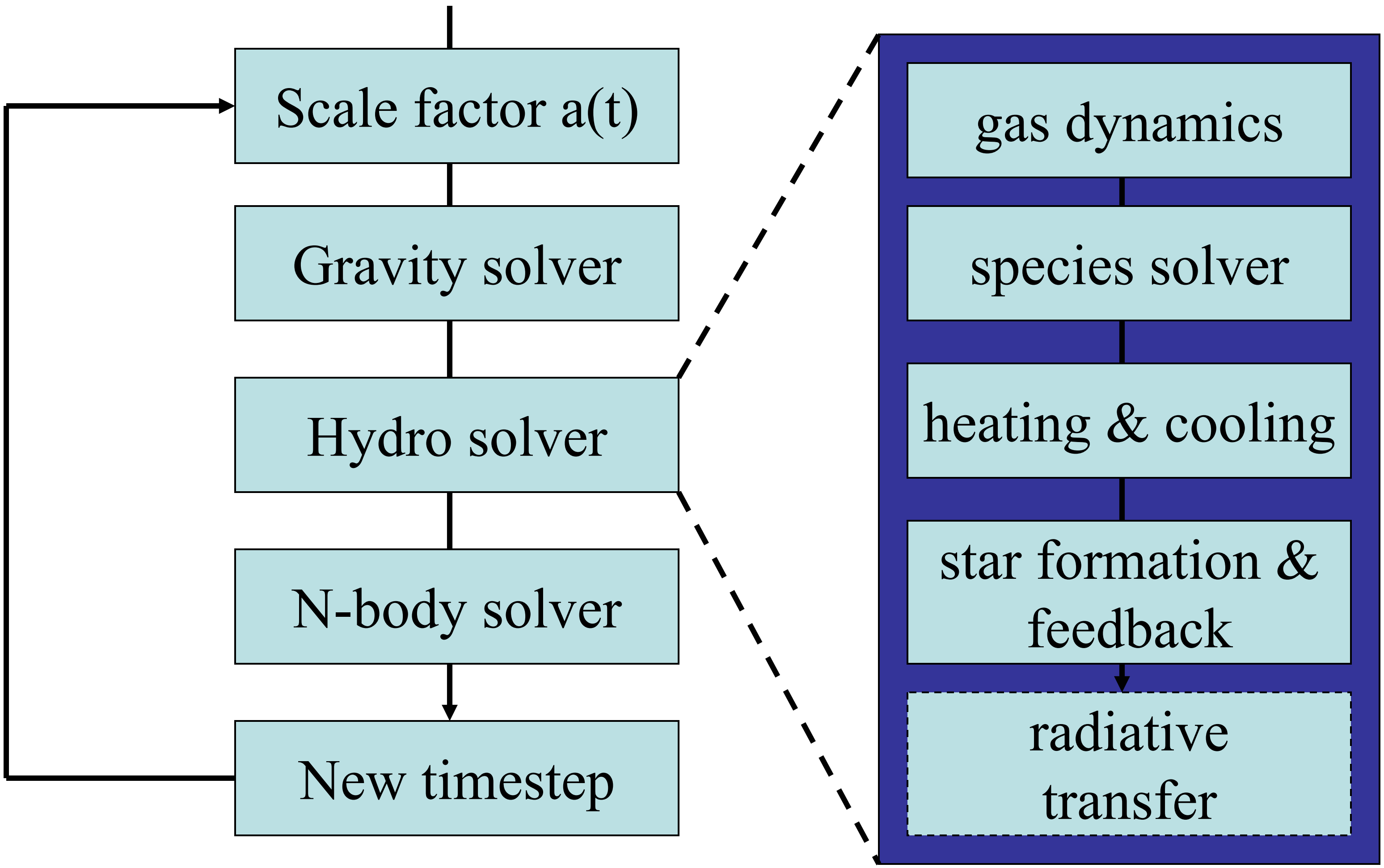
S.G. Djorgovski et al. & Digital Media Center, Caltech


baryonic universe
radiative transfer
radiation background
self-shielding
photo-evaporation
ionizing flux
absorption
photo-ionization
photo-heating
infall
galaxies
IGM
feedback (energy, metals)
SF-recipe
N-body dynamics
multi-species hydrodynamics
cosmic expansion
self-gravity
dark matter dynamics

http://cosmos.ucsd.edu/enzo



Main Loop of Hydrodynamic Cosmology Code



Cosmological Hydrodynamics

Euler's equations

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

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

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

multispecies chemical kinetics

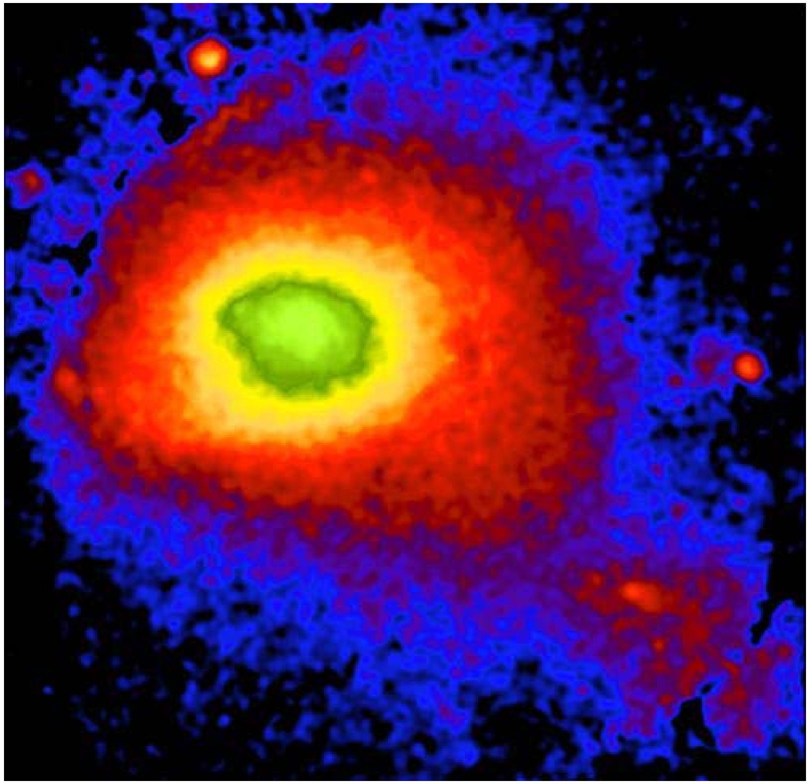
$$\frac{\partial \rho_i}{\partial t} + \nabla \cdot (\rho_i v_b) + 3\frac{\dot{a}}{a}\rho_i = \pm \sum_j \sum_l k_{jl}(T)\rho_j \pm \sum_j I_j \rho_j$$

Sample Applications

	dark matter	gas	radiative cooling	ionization	molecules	star formation	feedback	rad. Xfer
X-ray clusters	X	X	X					
Intergalactic medium	X	X	X	X				
First stars	X	X	X	X	X			
Galaxy formation	X	X	X	X		X	X	
Reionization of IGM	X	X	X	X		X	X	X

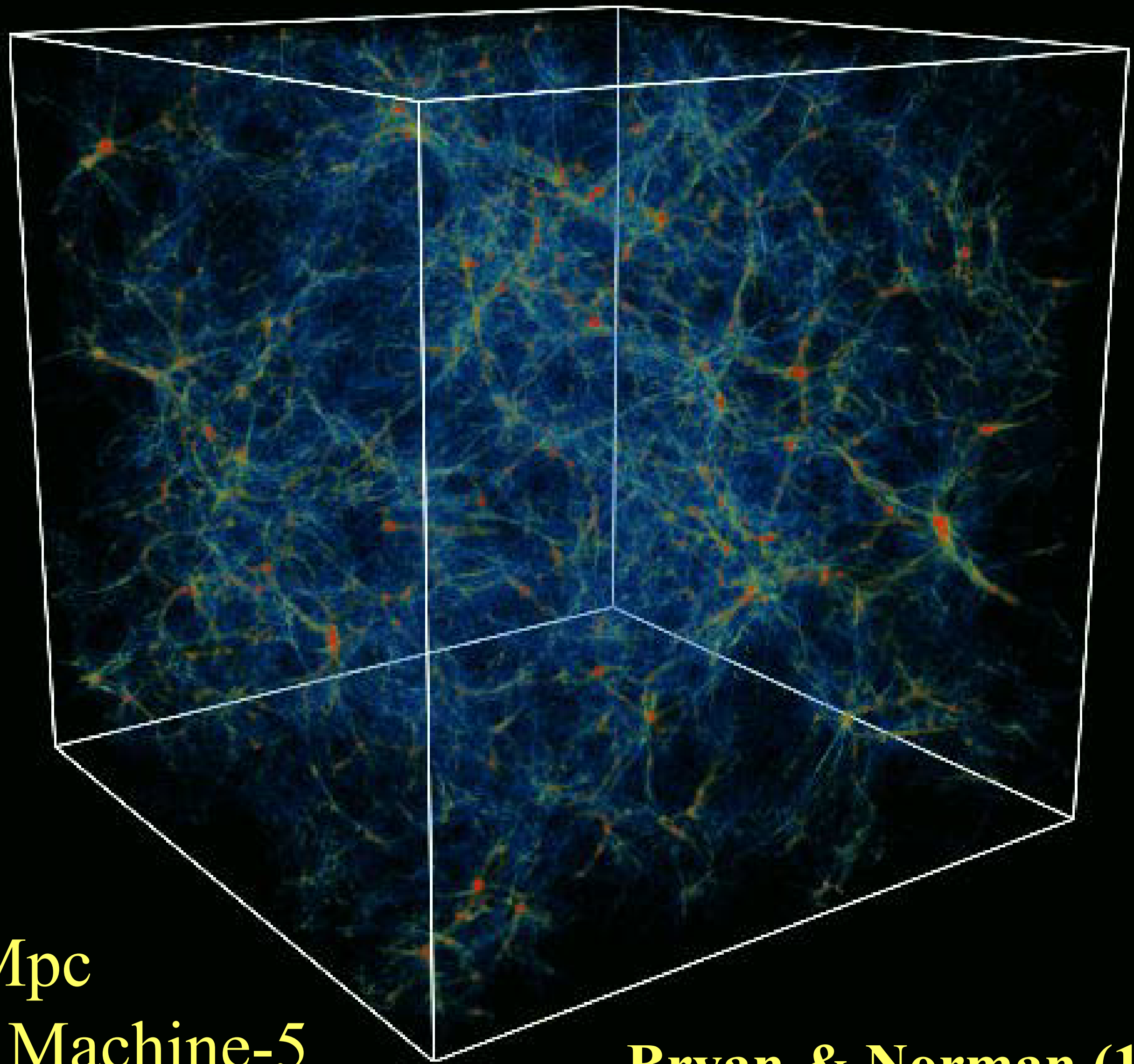
X-Ray Clusters

- 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 $P(k)$, Ω_m, Ω_b and Ω_Λ



Coma Cluster
ROSAT (Boehringer et al)

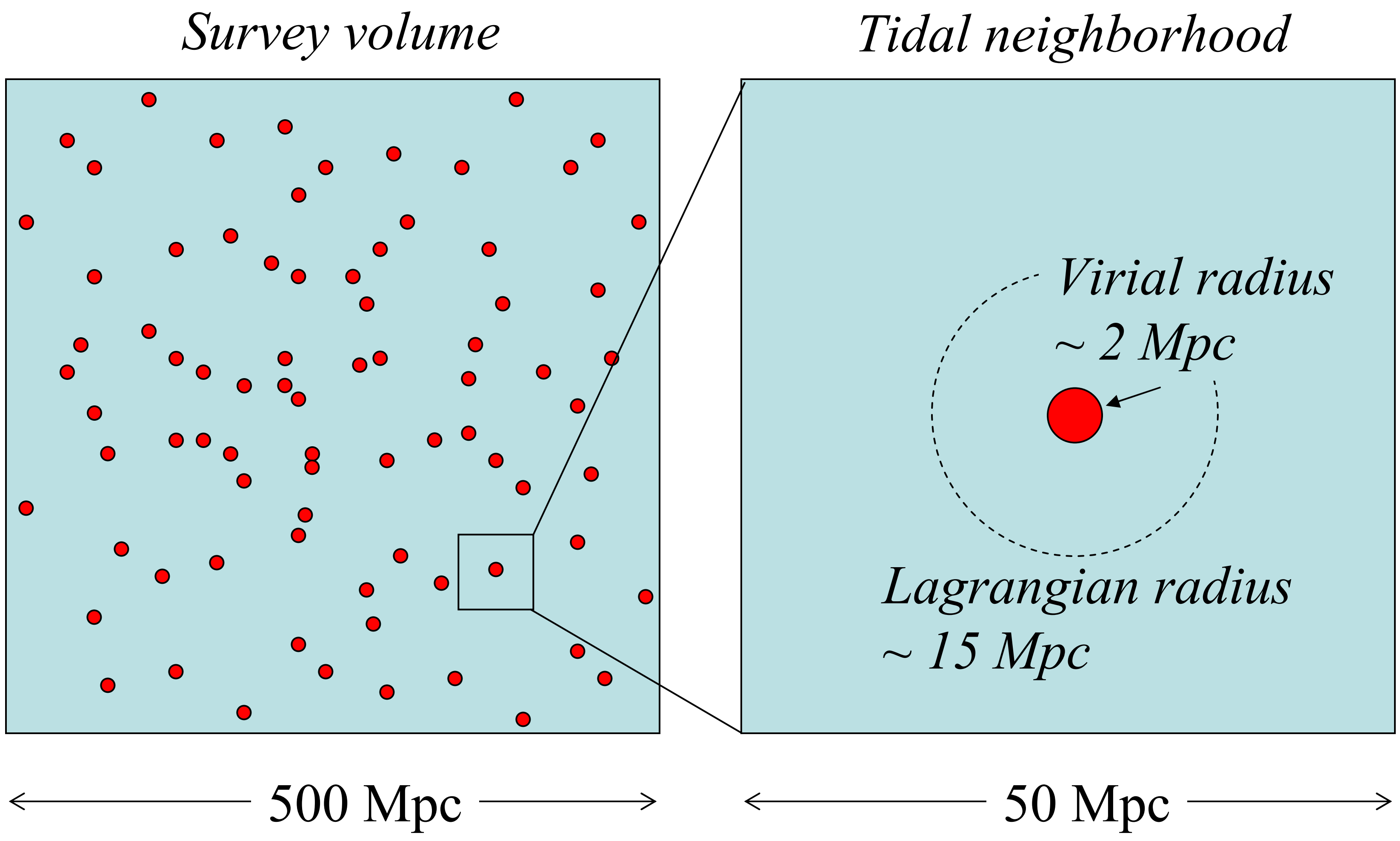
X-Cluster Statistics on 512^3 Grid



CHDM
L=170 h^{-1} Mpc
Connection Machine-5

Bryan & Norman (1994, 1998)

Technical Difficulty: Range of Scales



Idealized Cluster ICM

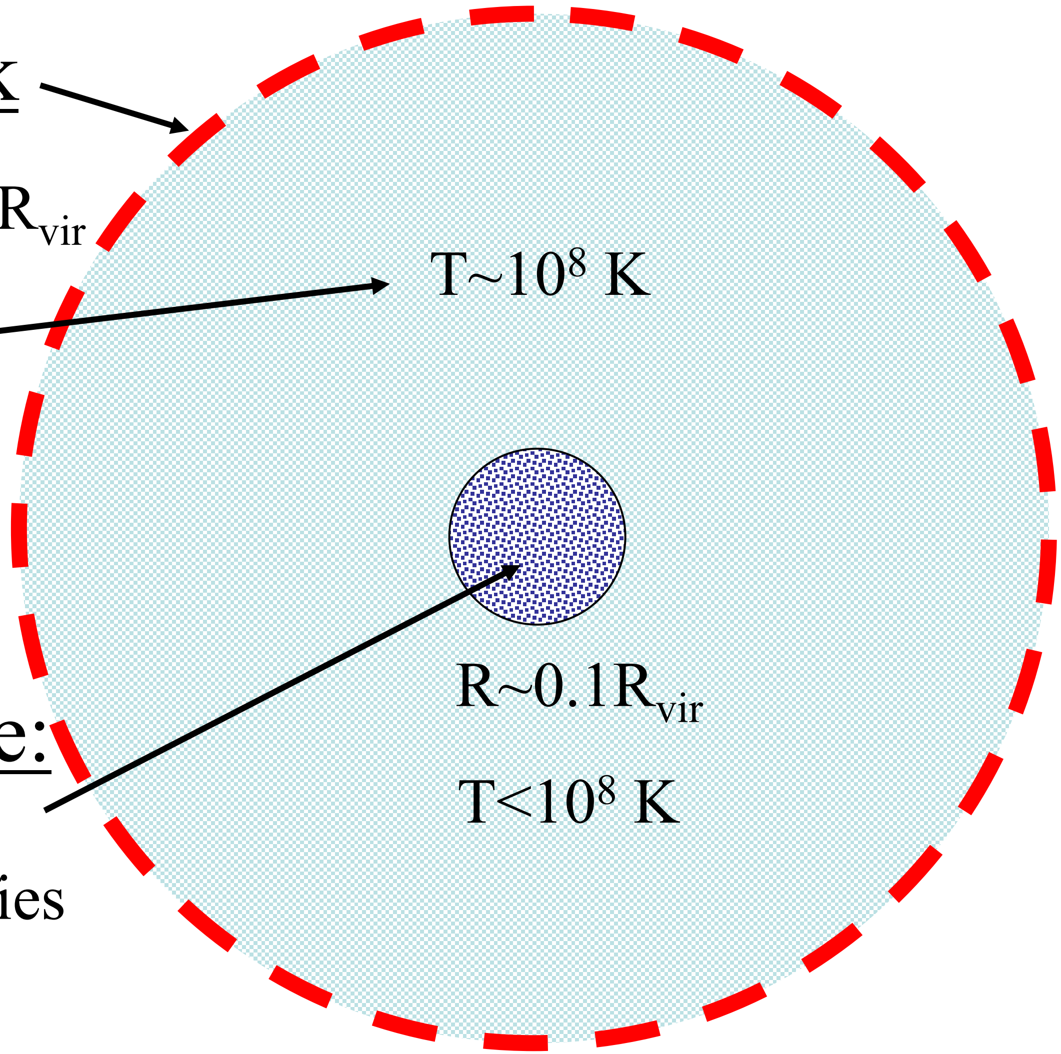
virialization shock

$R \sim R_{vir}$

adiabatic halo:

$t_{cool} > t_{Hubble}$

supernovae heating << gravitational heating

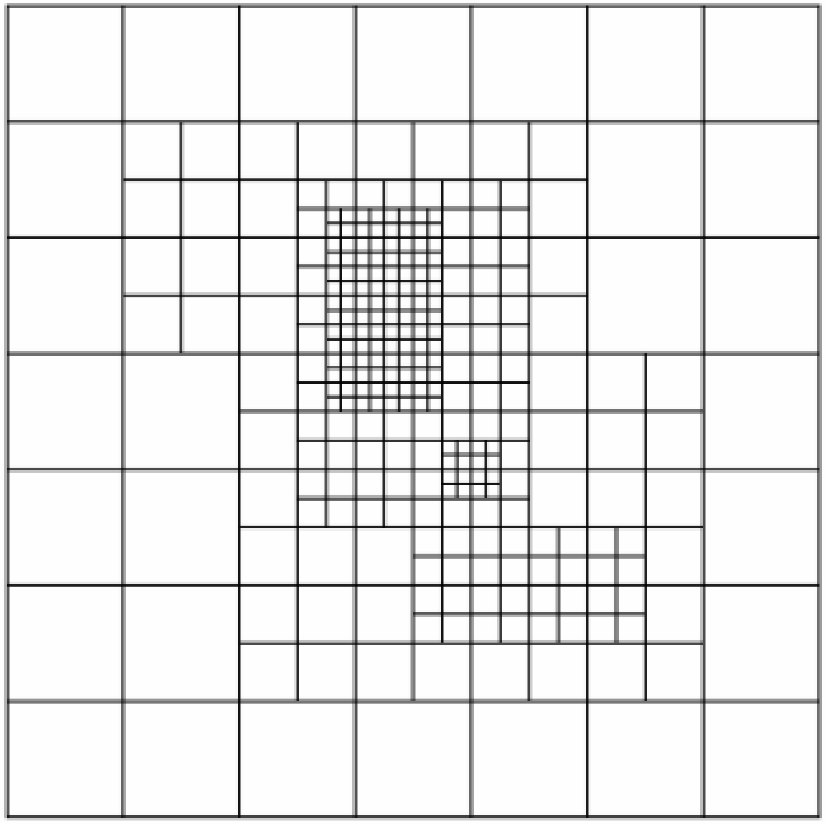


non-adiabatic core:

$t_{cool} <= t_{Hubble}$

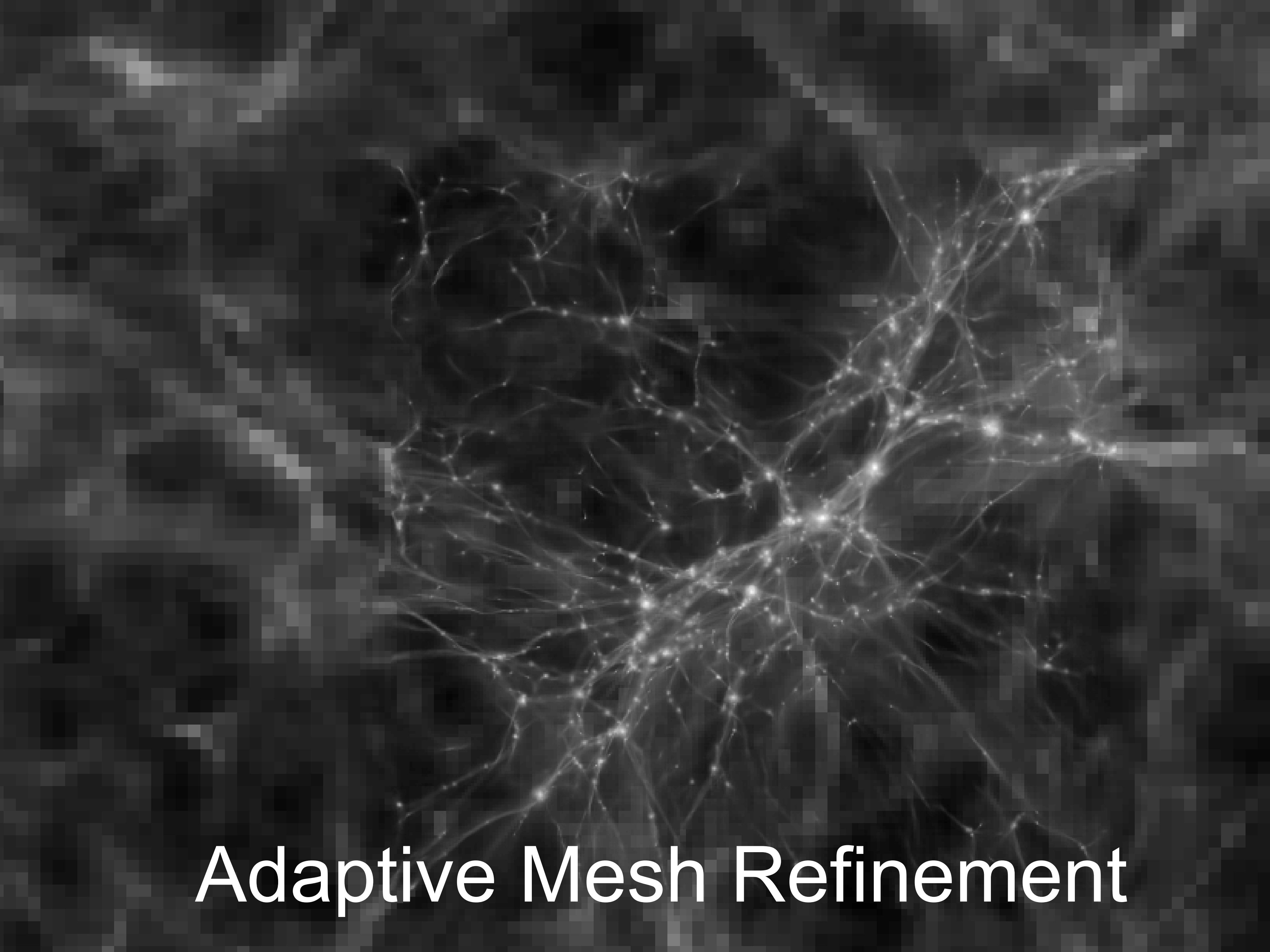
radiative cooling modifies entropy profile

Adaptive Mesh Refinement



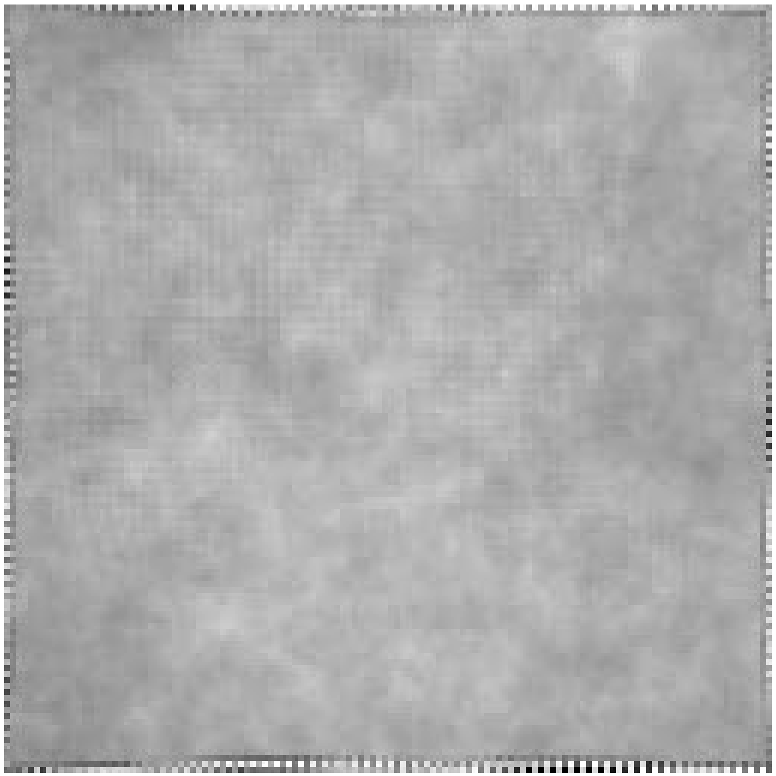
Refine cell spacing *locally and automatically* based on any combination of *physical or numerical criteria*

=> can resolve all relevant length and timescales

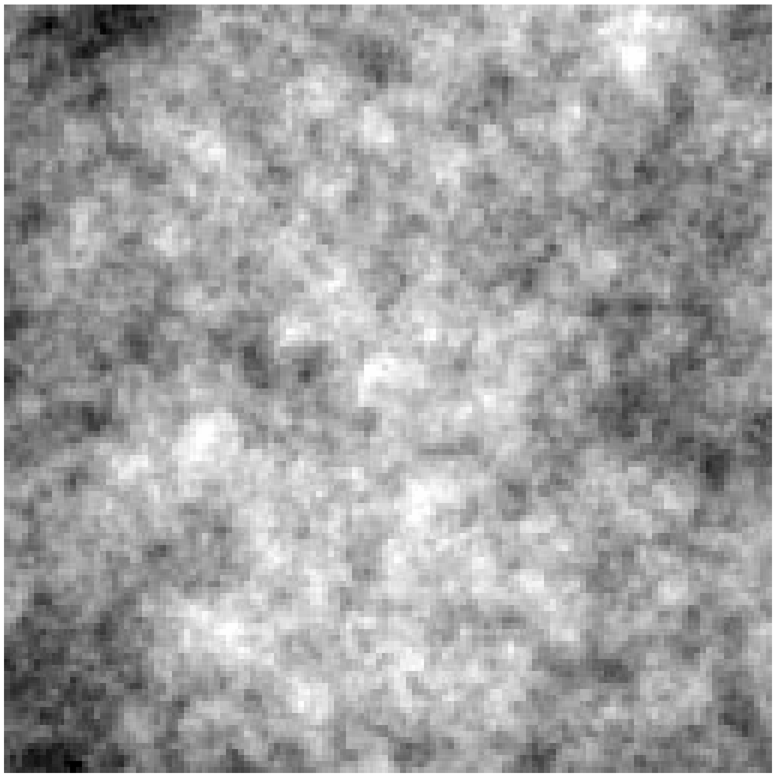

Adaptive Mesh Refinement

Formation of an X-ray Cluster
256^3 AMR (adiabatic)

Dark matter



Baryons

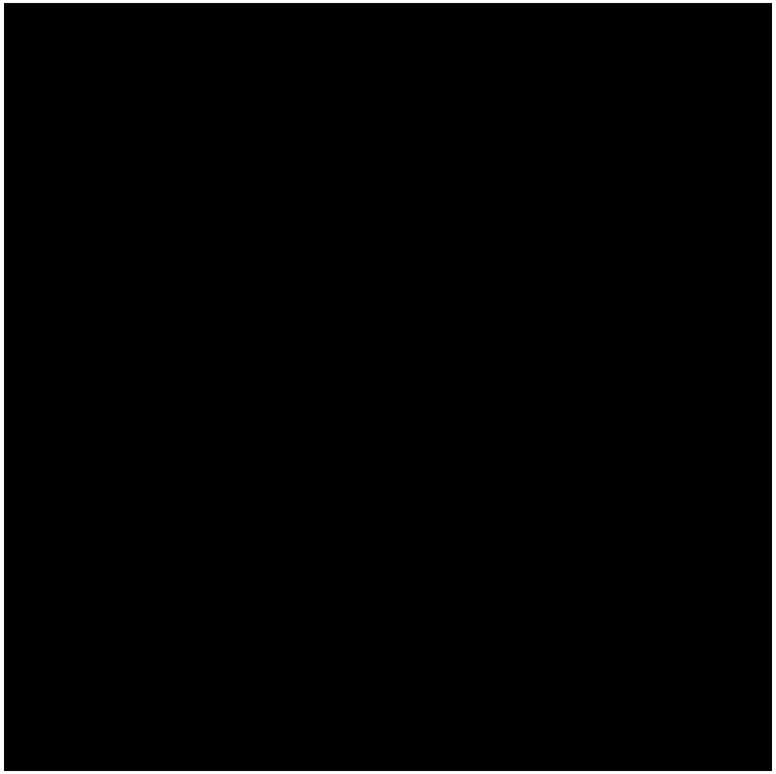


← 16 Mpc (comoving) →

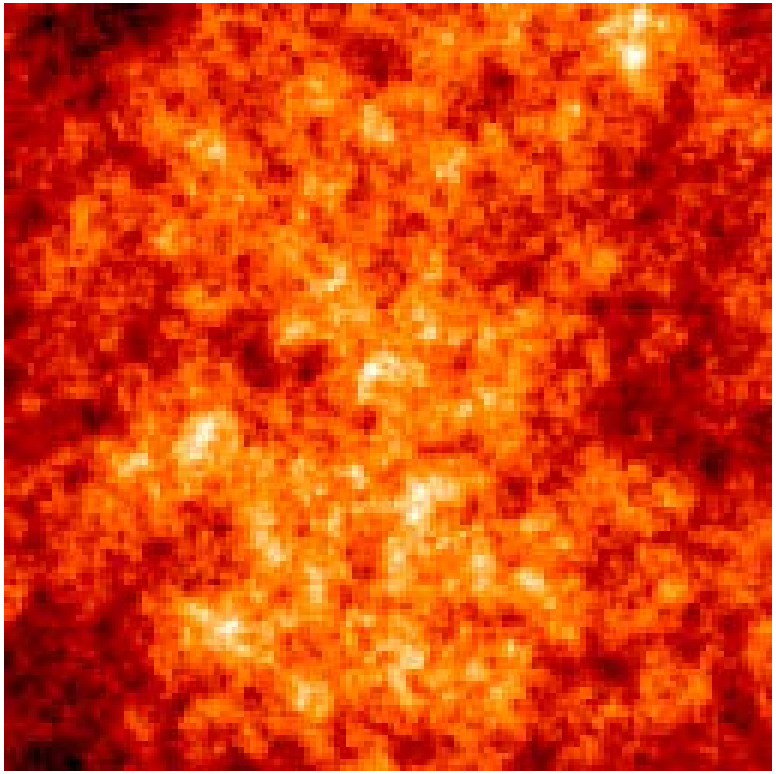
Formation of an X-ray Cluster

256^3 AMR (adiabatic)

Temperature



X-ray surface brightness



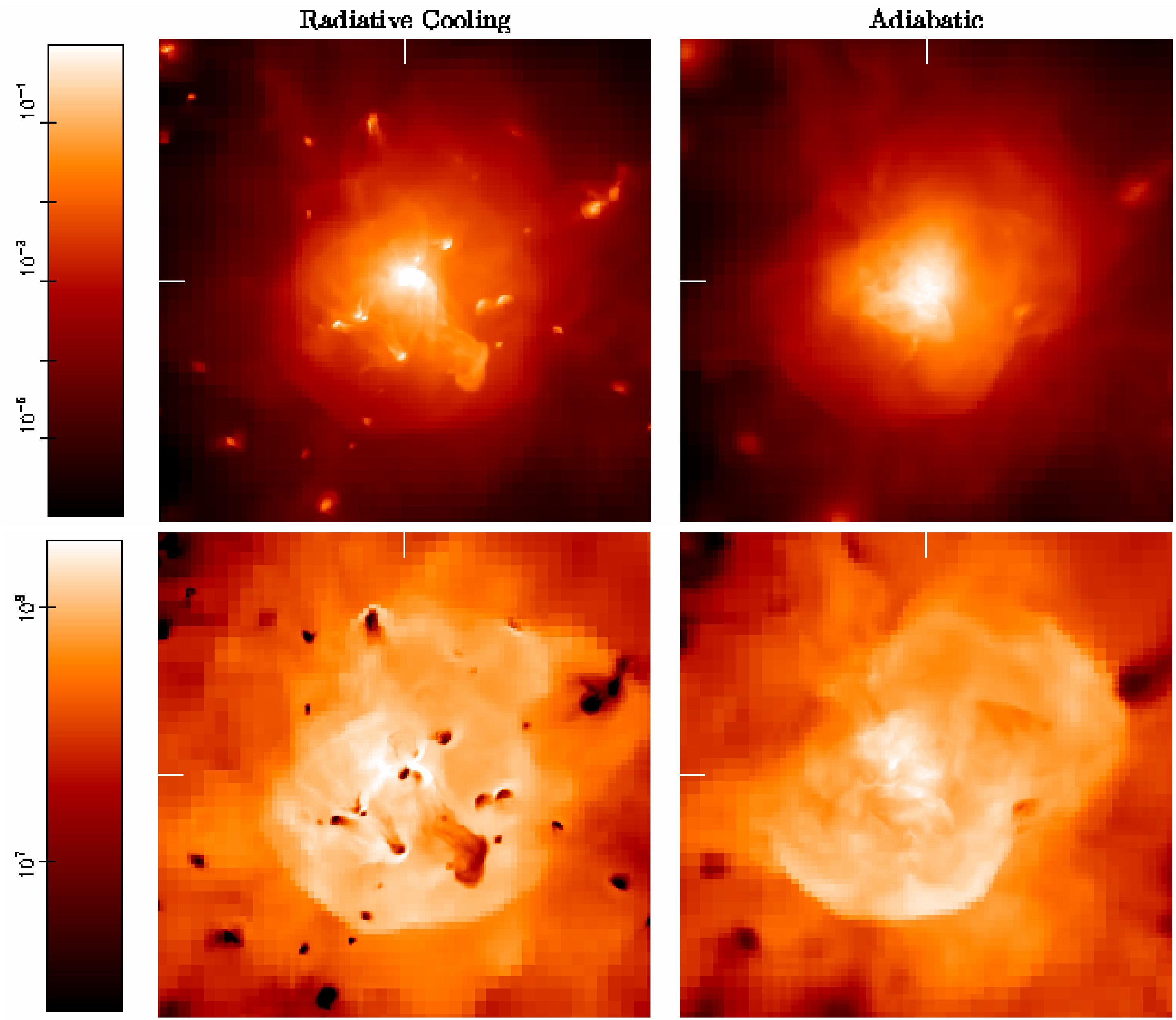
← 16 Mpc →

(comoving)

C1
z=0

log(S_x)

log(T_x)



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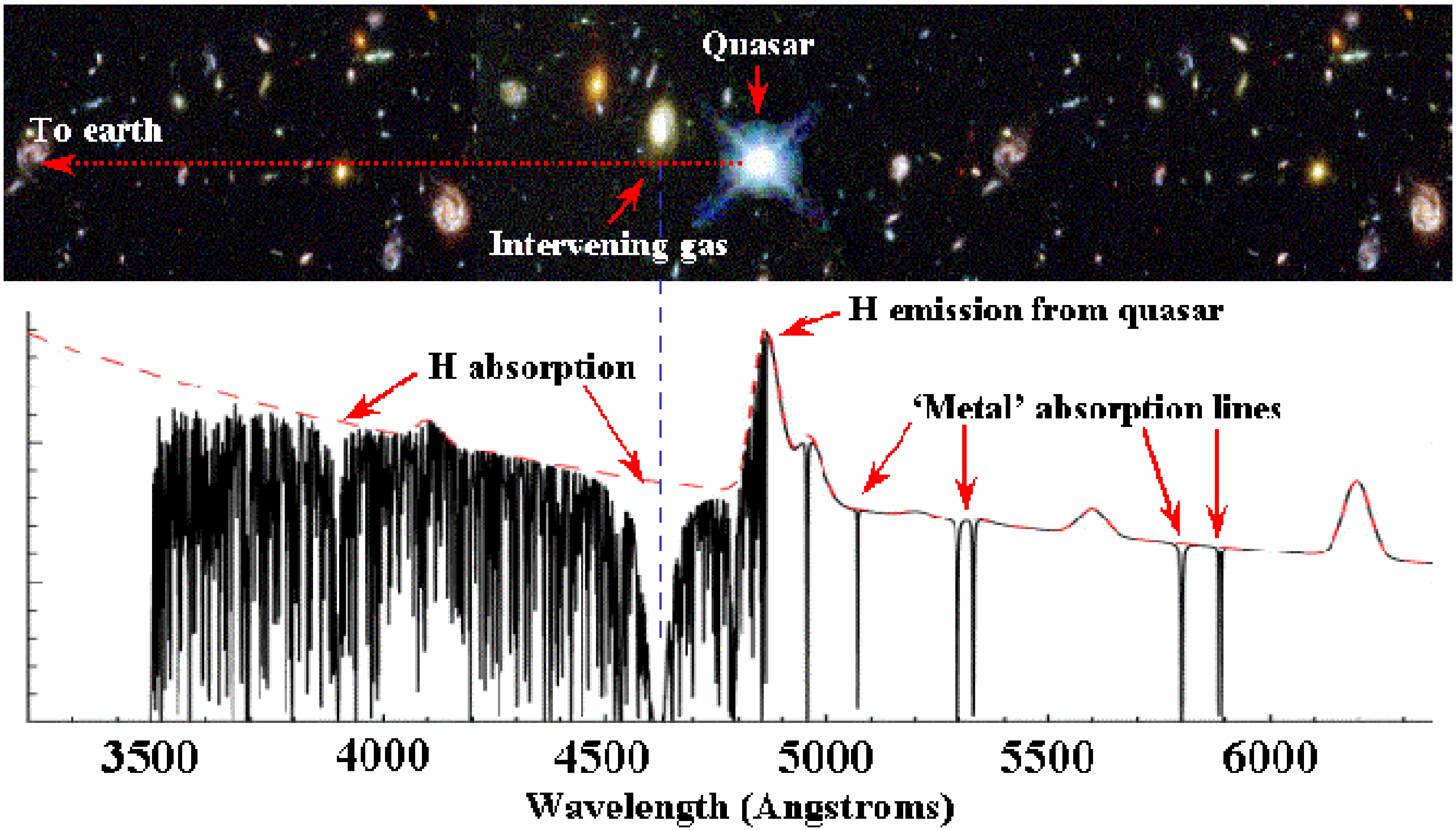
Motl et al. (2002)

The Intergalactic Medium



Source: M. Murphy

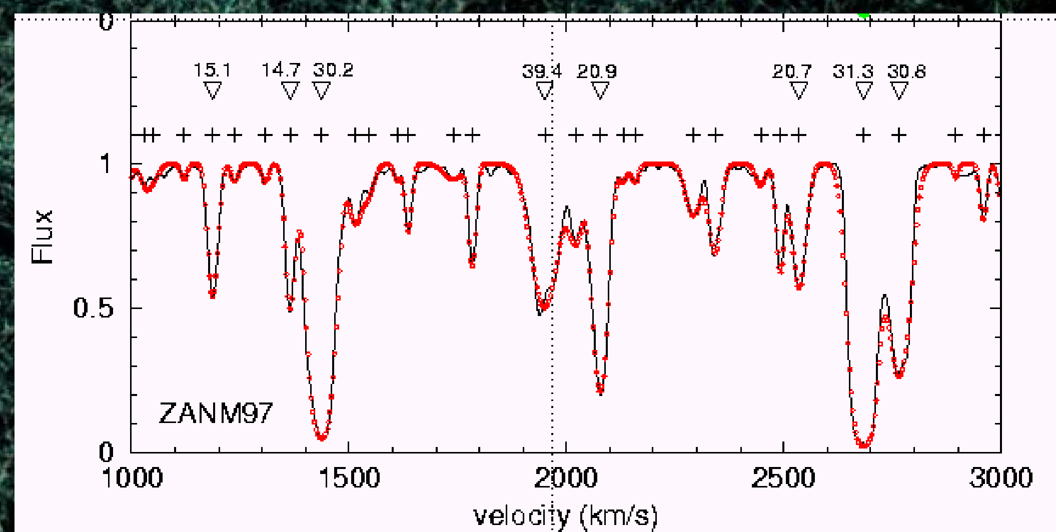
Physical Origin of Ly α Forest

quasar

$N=1024^3$

$L=54$ Mpc/h

Simulated HI absorption spectrum



Earth

Baryon Overdensity, z=3

Precision cosmology using the Lyman α 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)

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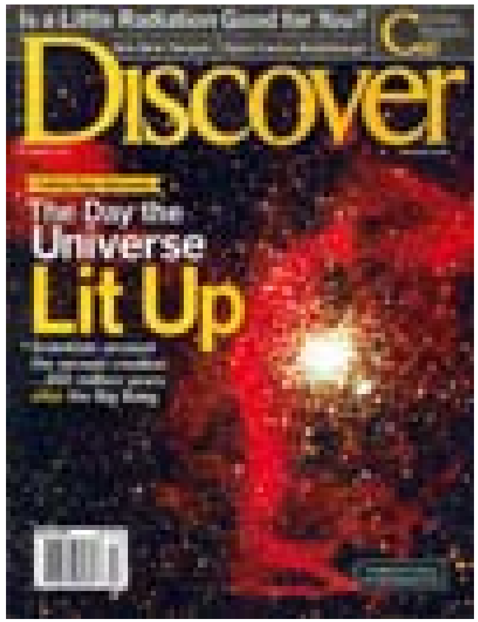
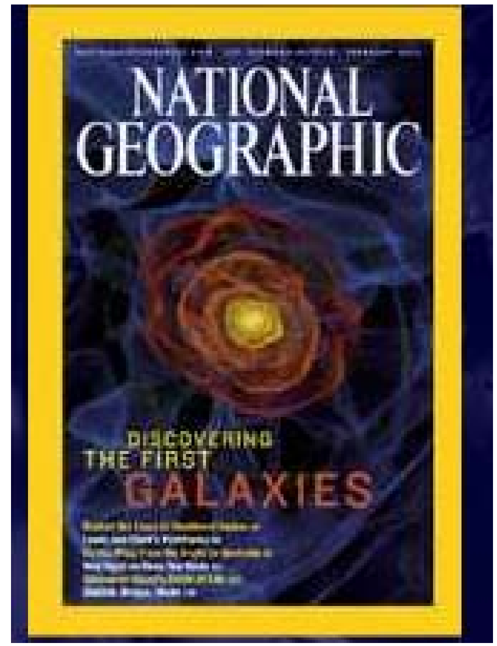
Simulating the Formation of the First Star in the Universe

Nov. 2002



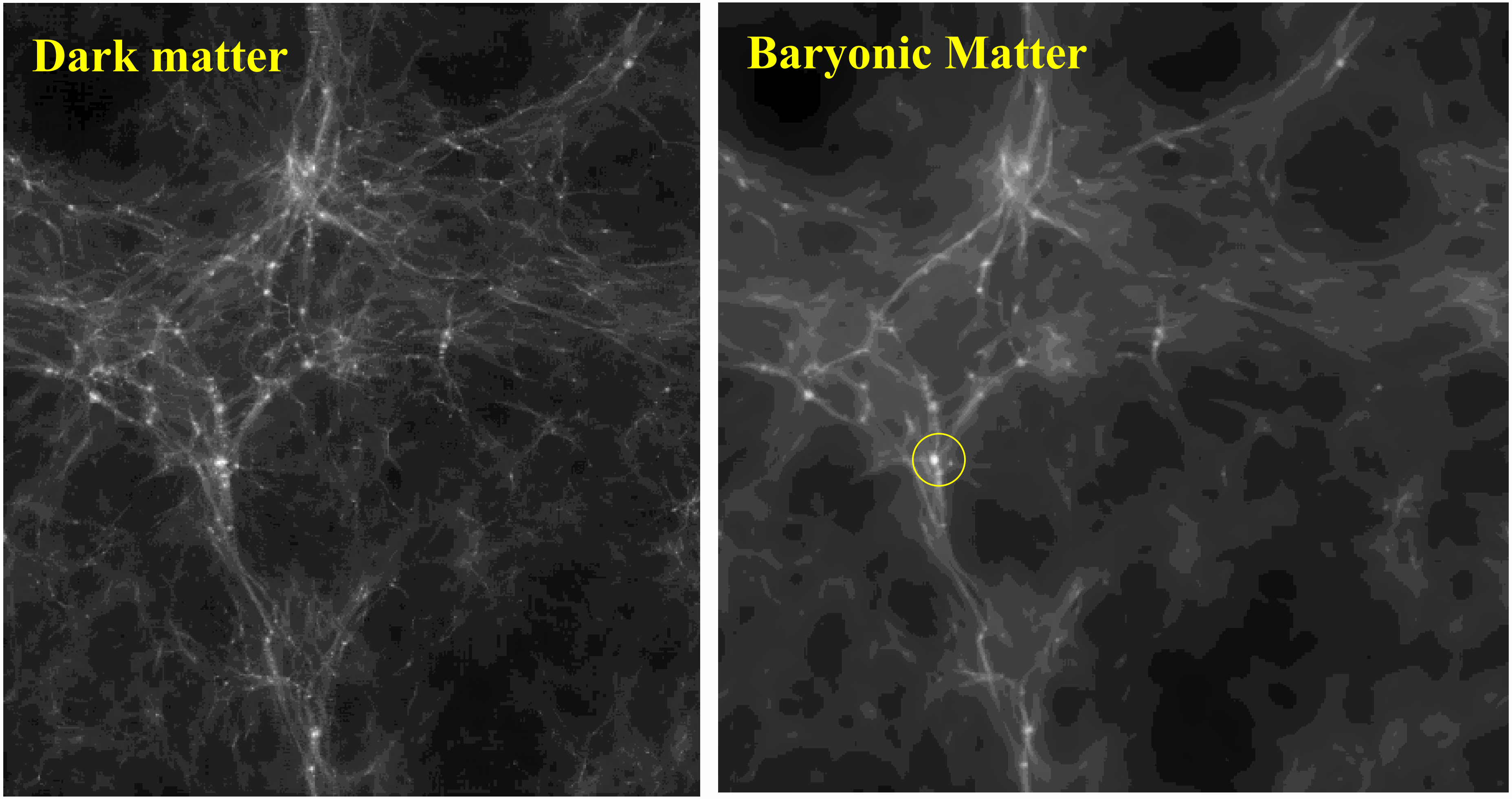


Feb. 2003

Tom Abel, Greg Bryan & MN

http://www.TomAbel.com

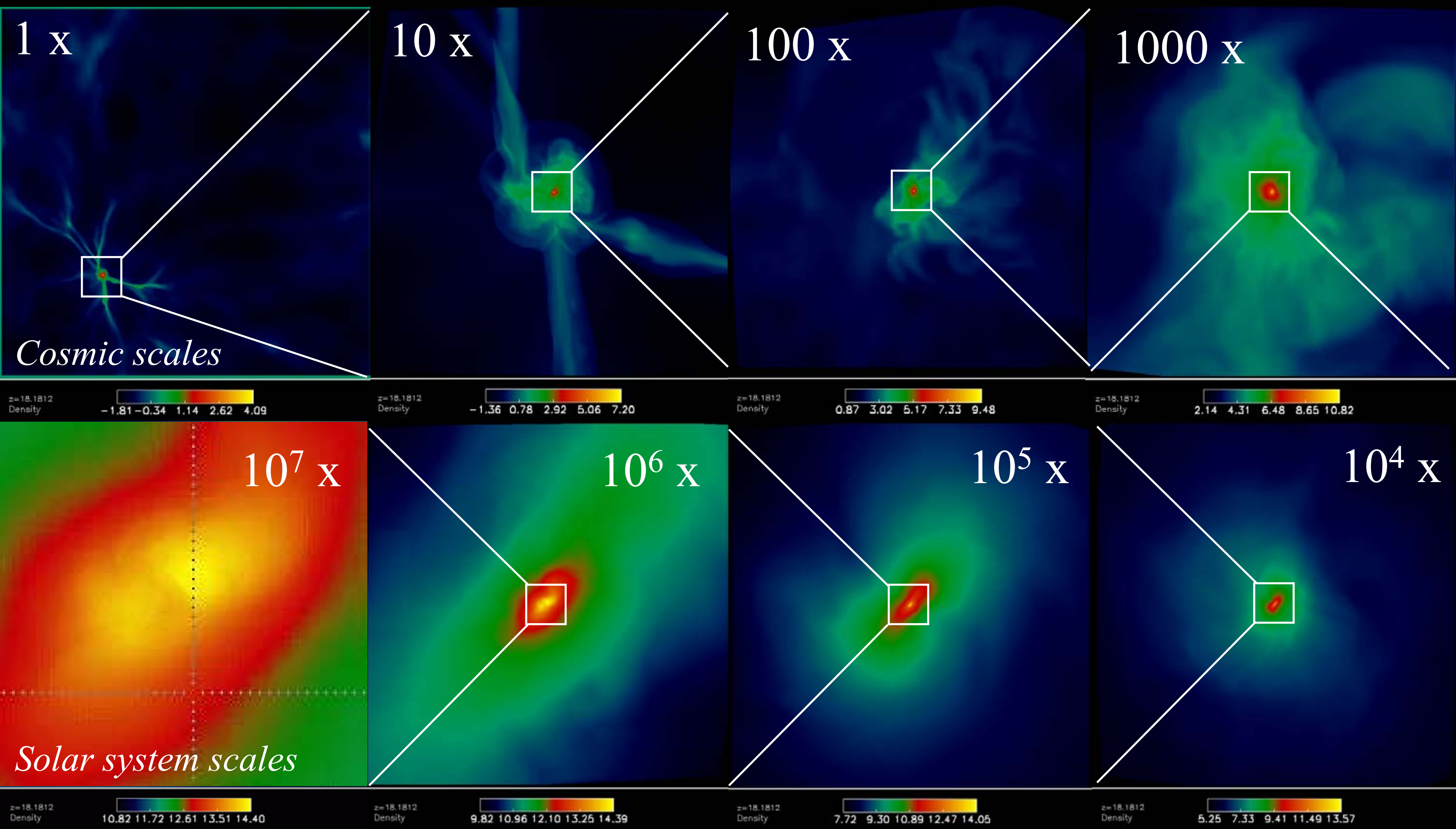
The Universe at z=20



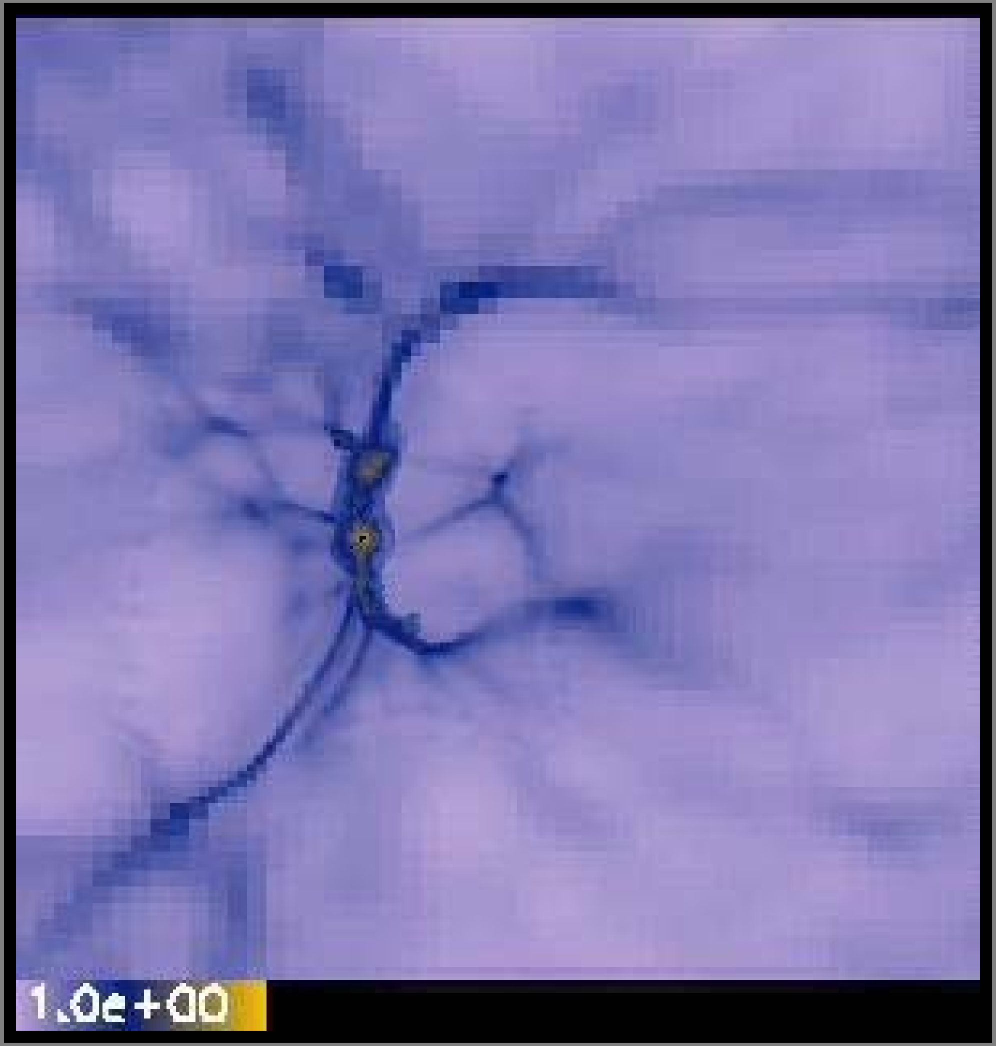
0.1 Mpc (comoving)

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
- The 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

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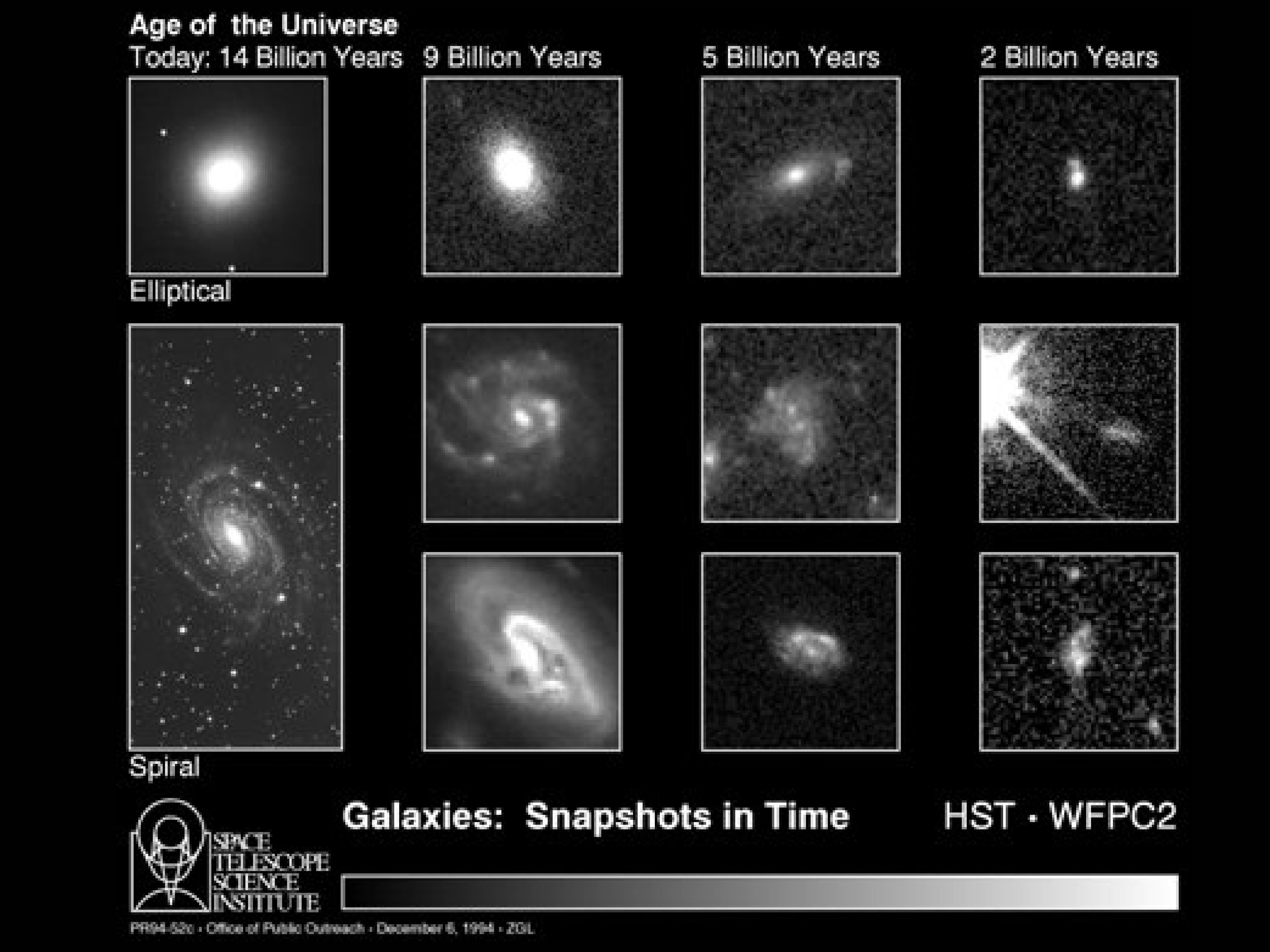
Formation and Evolution of Galaxies



Age of the Universe
Today: 14 Billion Years
9 Billion Years
5 Billion Years
2 Billion Years
Elliptical
Spiral
Galaxies: Snapshots in Time
HST · WFPC2
SPACE TELESCOPE SCIENCE INSTITUTE
PR94-52c · Office of Public Outreach · December 6, 1994 · ZGL

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 $\rho_b / \overline{\rho}_b > \eta$
- check whether 3 criteria are satisfied:

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

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

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

$$\Rightarrow \text{gravitationally unstable}$$

- 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"

Courtesty NOVA/WGBH, PBS
Thomas Lucas Productions

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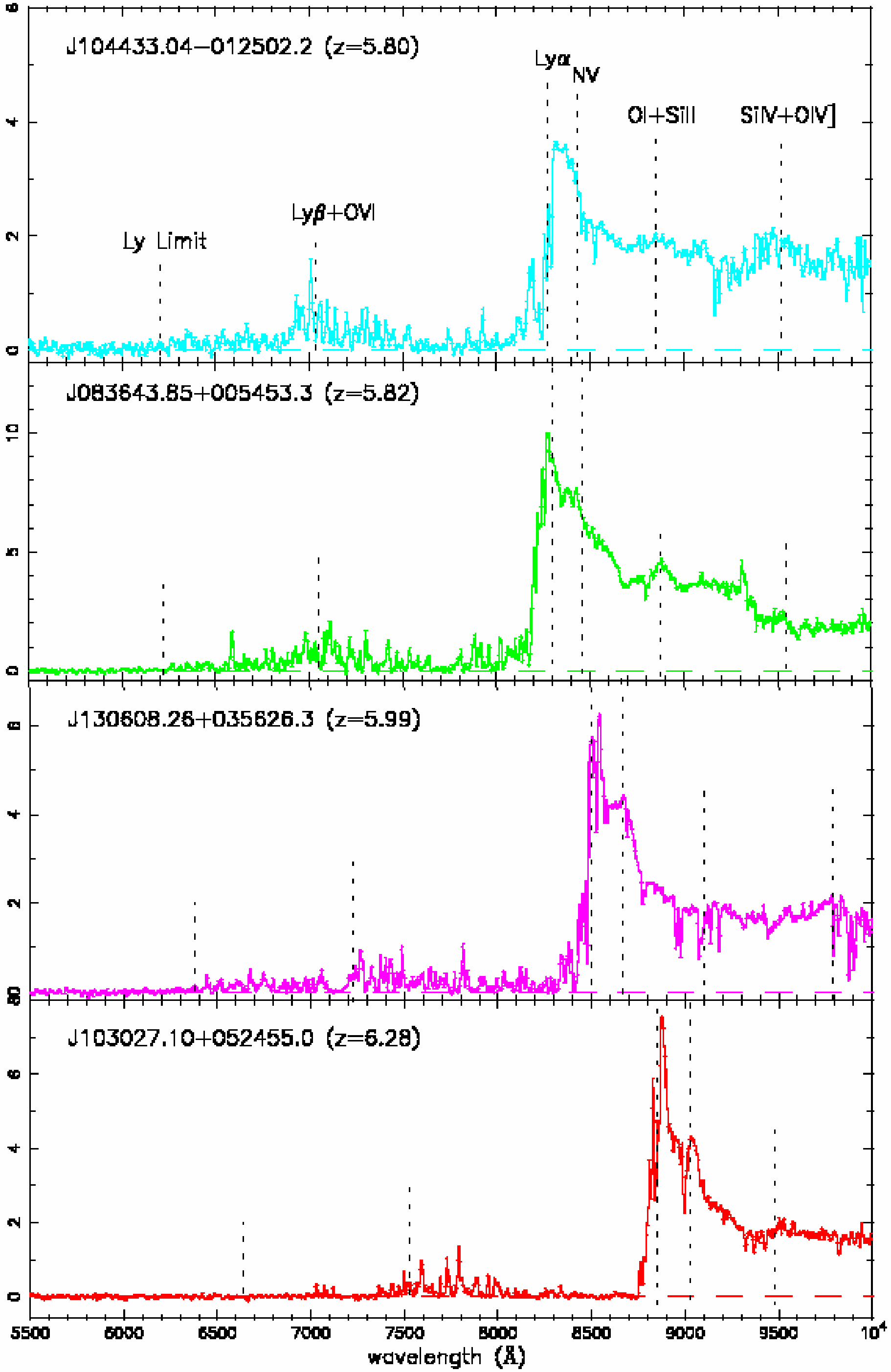
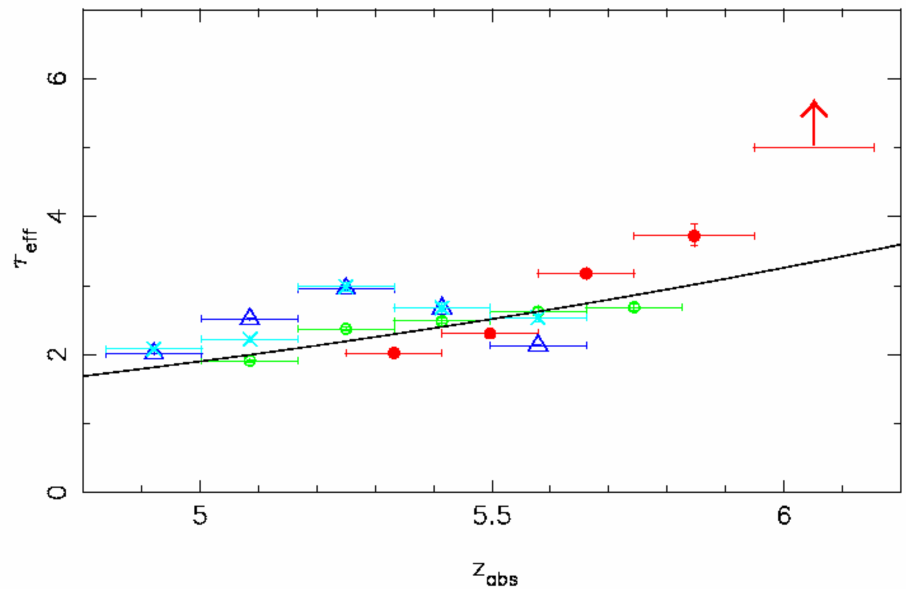
Epoch of reionization seen?



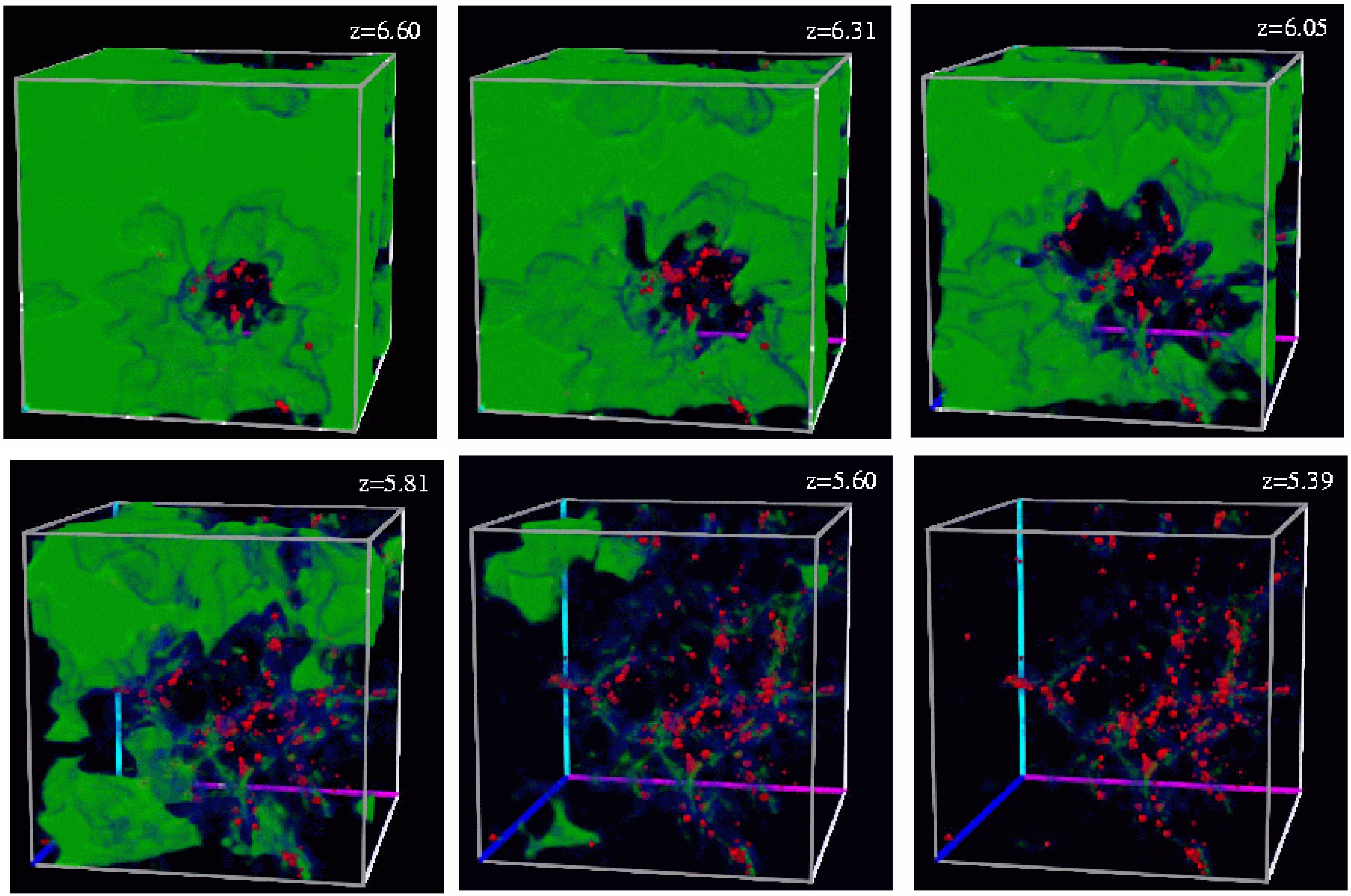
GP optical depth vs. z



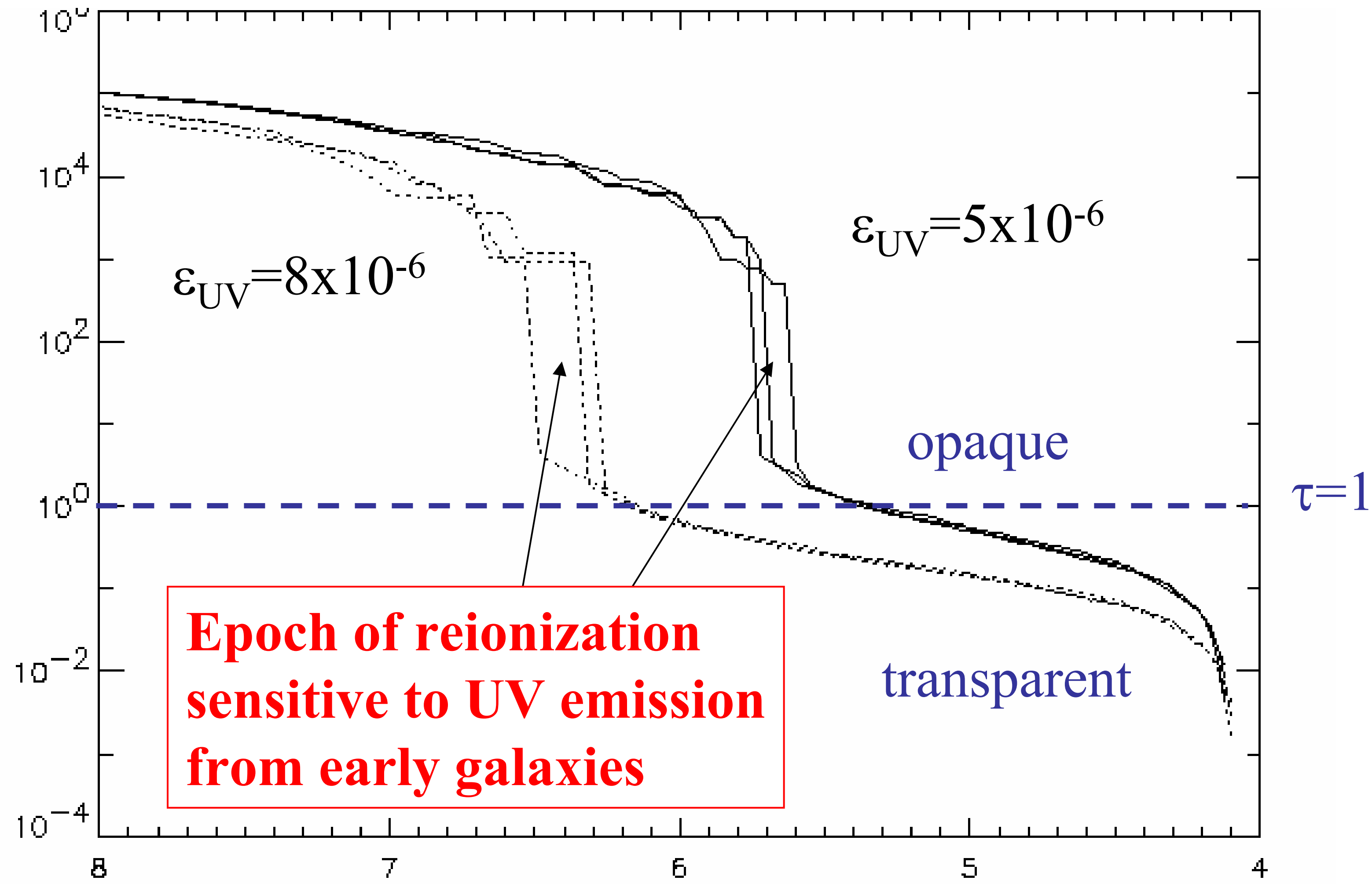
Becker et al. (2001)
SDSS Collaboration

Reionization of IGM by High-z Galaxies

Razoumov et al. (2002)



Gunn-Peterson optical depth vs. z



Razoumov et al. (2002)

z