

Formation of Large-Scale Structure and the Hot IGM

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Outline

- ❖ The Computation of the Evolution of the Universe is an Initial Value Problem Amenable to
- ❖ Numerical Simulations
- ❖ Formation of LSS and Evolution of Cosmic Gas
- ❖ Conclusions

The Universe is an Initial Value Problem.....

- ❖ *Globally*, the universe evolves according to the Friedman equation

$$H^2 = \left(\frac{da}{dt} \right)^2 = \frac{8\pi G}{3} \Omega_m r_{crit} \pm \frac{k}{a^2} + \frac{\Lambda}{3}$$

The diagram illustrates the components of the Friedmann equation. Four arrows point from labels to specific terms:

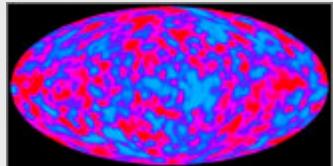
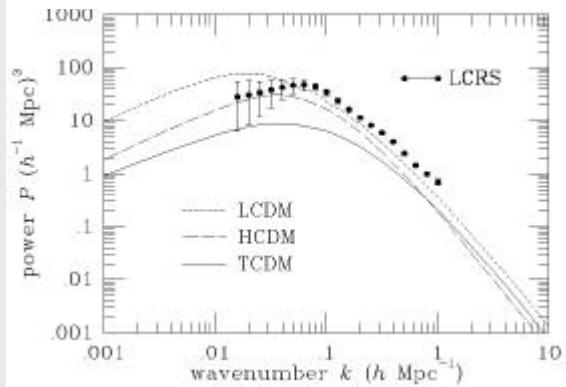
- An arrow points from "Hubble constant" to the term $\left(\frac{da}{dt} \right)^2$.
- An arrow points from "scale factor a(t)" to the term $\left(\frac{da}{dt} \right)^2$.
- An arrow points from "density parameter" to the term $\frac{8\pi G}{3} \Omega_m r_{crit}$.
- An arrow points from "cosmological constant" to the term $\frac{\Lambda}{3}$.

The Universe is an Initial Value Problem.....

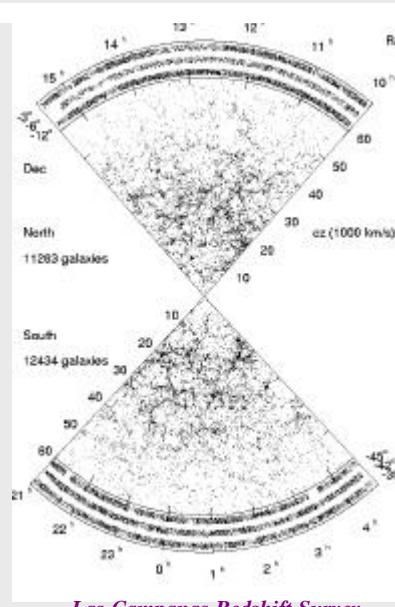
- ❖ *Locally*, it obeys Newtonian equations of gravitational dynamics for:
 - collisionless dark matter (CDM, HDM)
 - primordial gas (baryons)
- ❖ Atomic, molecular, and radiative processes important for the formation of stars, galaxies and galaxy clusters from gas

Initial Conditions

- ❖ Gaussian random field $\delta\rho(\mathbf{x})$
- ❖ Linear power spectrum $P(k)$

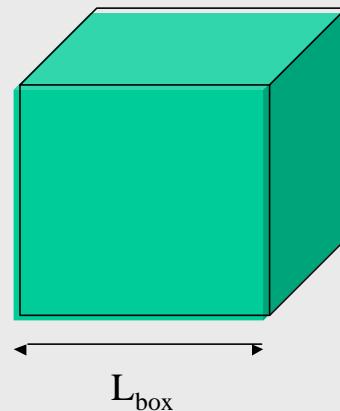


*COBE
+BOOMERANG
+MAXIMA
+ ...*

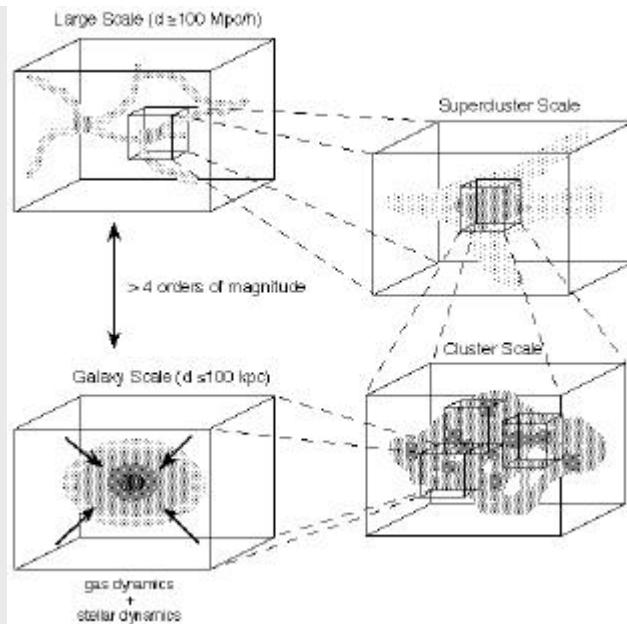


Computing the Universe Using Numerical Simulations

- ❖ Transformation to
comoving coordinates
 $x=r/a(t)$
- ❖ comoving cube,
periodic boundary
conditions
- ❖ $L_{\text{box}} \gg \lambda_{\text{nl}}$



Multiscale Challenge

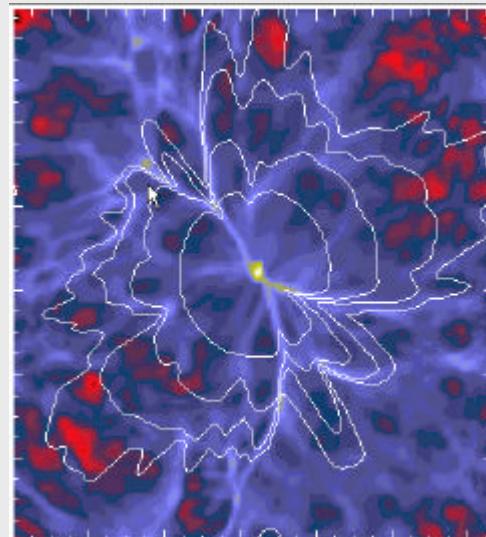


dynamic range requirement:
 $> 10^4$ spatial
 $> 10^9$ mass

http://zeus.ncsa.uiuc.edu:8080/GC3_Overview.html

Multiphysics Challenge

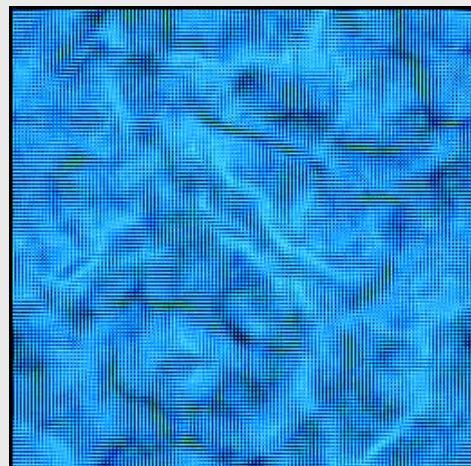
- ❖ Important physical processes
 - ✓ gravity
 - ✓ cosmic expansion
 - ✓ collisionless dark matter
 - ✓ gas dynamics
 - ✓ atomic/molecular physics
 - ✓ radiation transfer
 - ✓ photoionization
 - magnetic fields



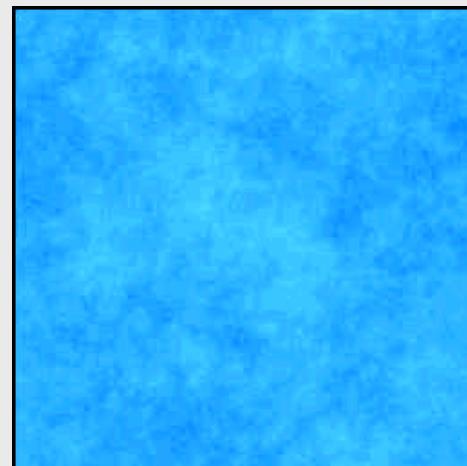
*quasar photoionization region
(T. Abel & M. Norman, NCSA)*

Evolution of Intergalactic Gas

dark matter density
($40 < z < 0$)



baryonic gas density
($40 < z < 0$)

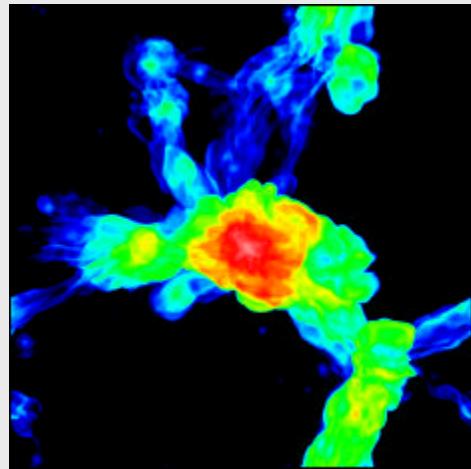


64Mpc

Animation (double click)

Cen, Bode, Ostriker & Xu (1996, <http://astro.princeton.edu/~bode/TVD/index.htm>)

Shocking of IGM

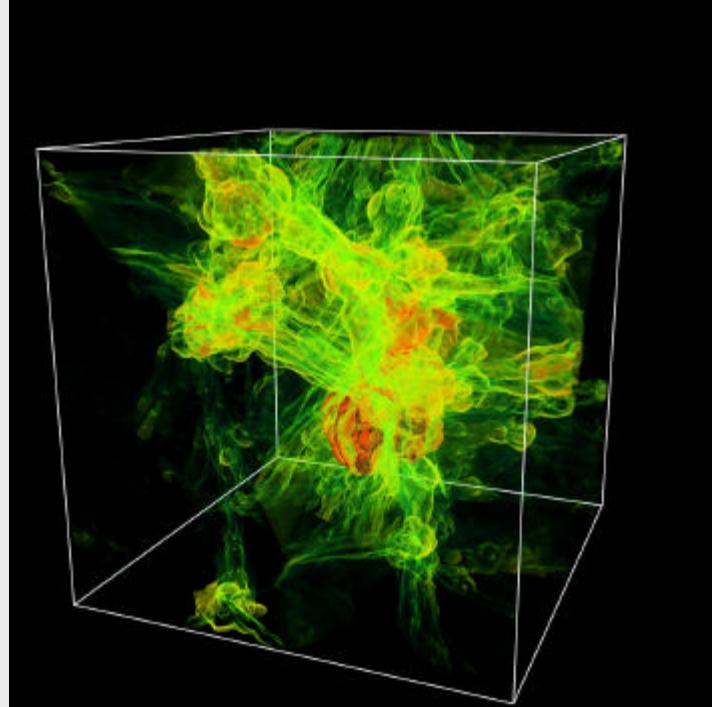


$\log(T)$ at $z=0$

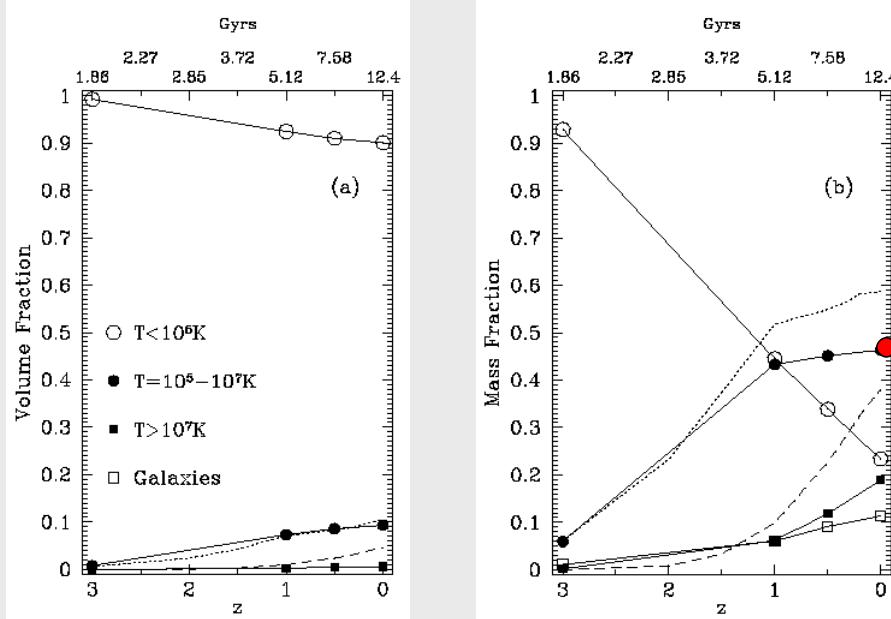


Animation (double click)

Shocking of IGM

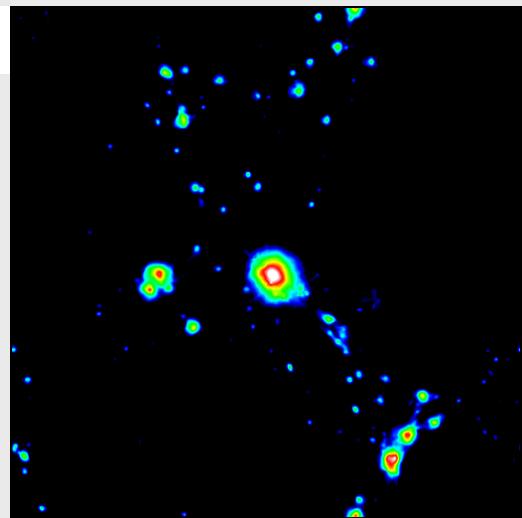


Baryon Budget



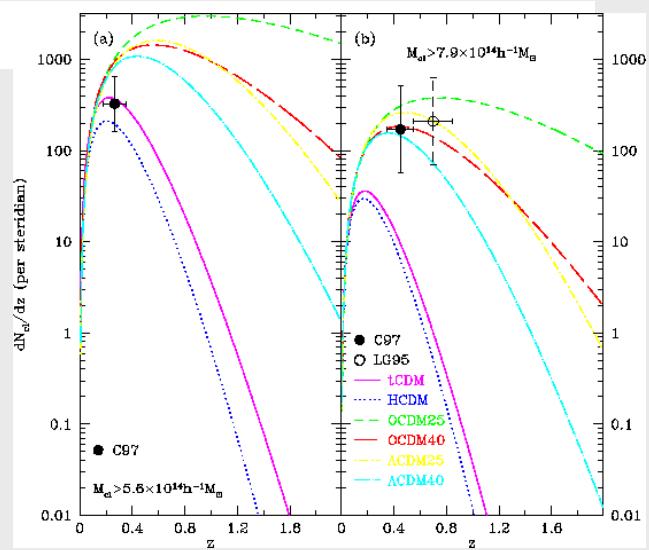
Cen & Ostriker (1999, ApJ, 514, 1)

The T>10⁷K Gas: X-ray Clusters



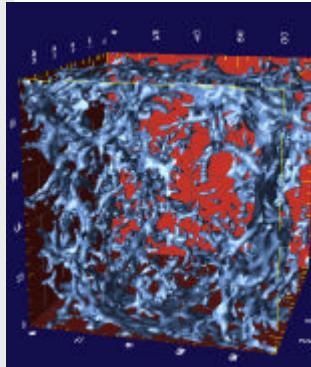
Cen, Bode, Ostriker & Xu (1996)

Evolution of X-ray Clusters

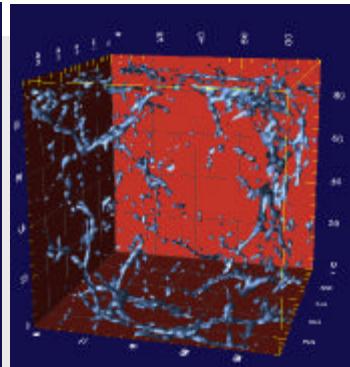


Cen (1998, ApJ,
509, 16)

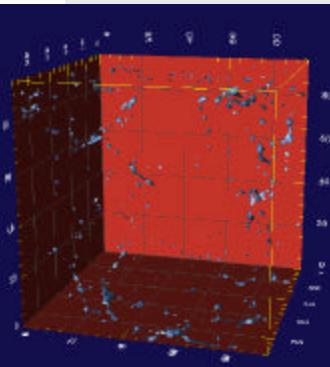
The T<10⁵K Gas: The Lyman Alpha Forest



$\rho=3$

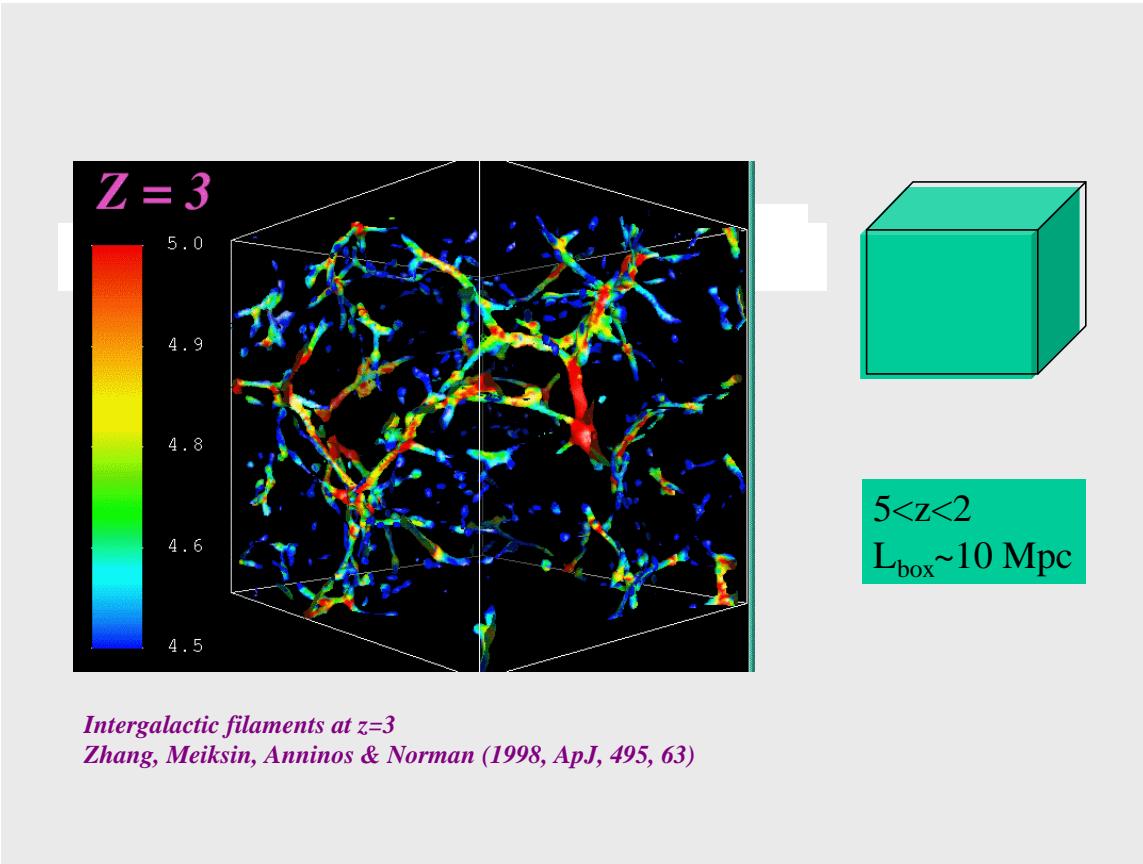


$\rho=10$

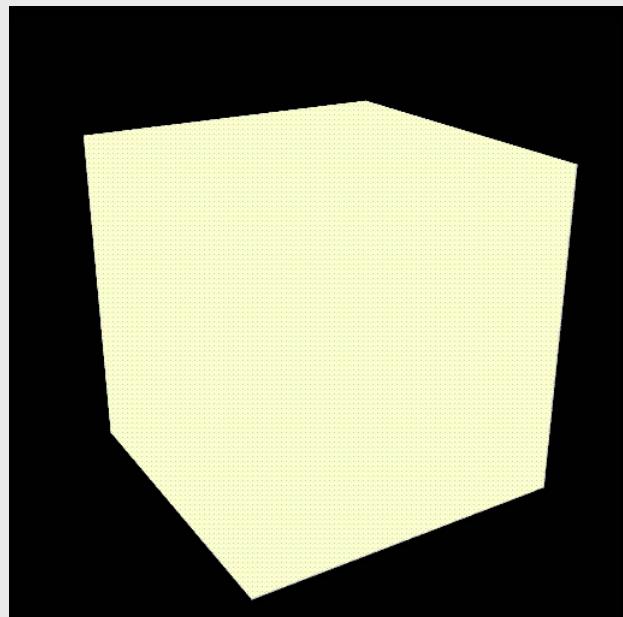


$\rho=30$

*Intergalactic filaments at $z=3$, $L_{box}=10\text{Mpc}$
Cen and Simcoe (1997, ApJ, 483, 8)*



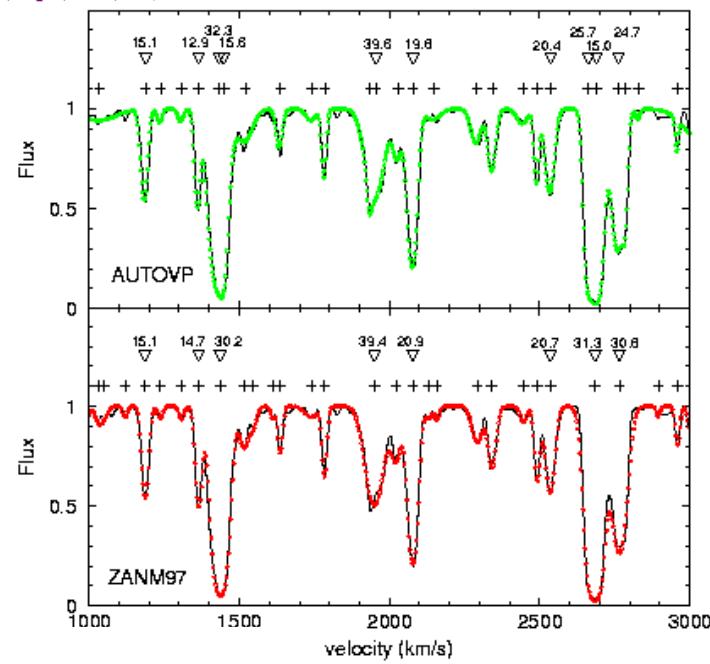
Evolution of neutral gas



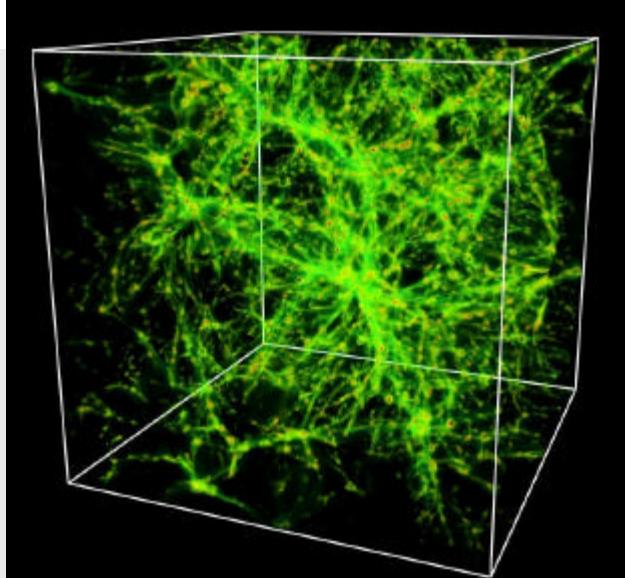
*Cen et. al (2000,
in preparation)*

Synthetic Ly α absorption spectrum

Bryan et al. (1999, ApJ, 517, 13)



T=10⁵-10⁷K Gas: Warm-Hot Intergalactic Medium (WHIM)

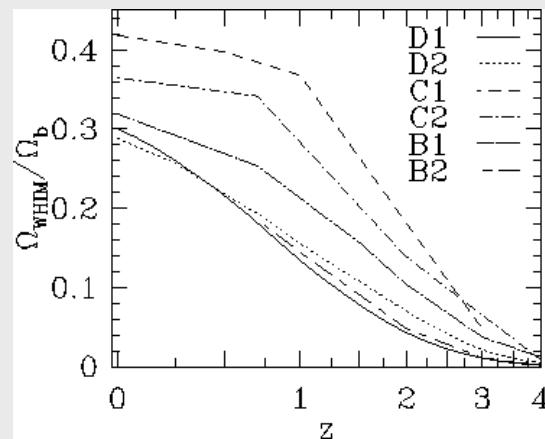


$L_{\text{box}} = 100 \text{Mpc}/h$

*Hot and warm gas in the
Intergalactic medium
Cen & Ostriker (1999,
ApJ, 514, 1)*

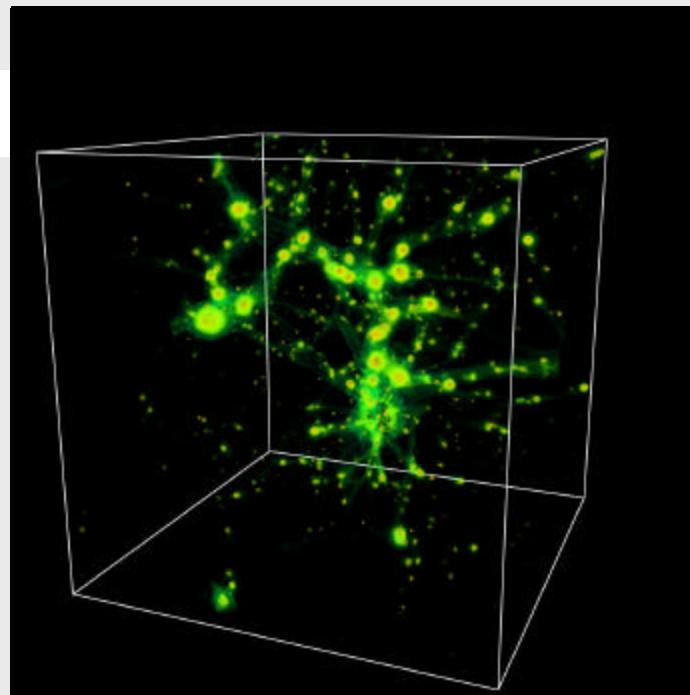
WHIM results are robust

Dave et al. (2000, astro-ph/0007217)



Physical reason:
 $\langle T \rangle \sim (H L_{nl})^2$

Evolution of WHIM



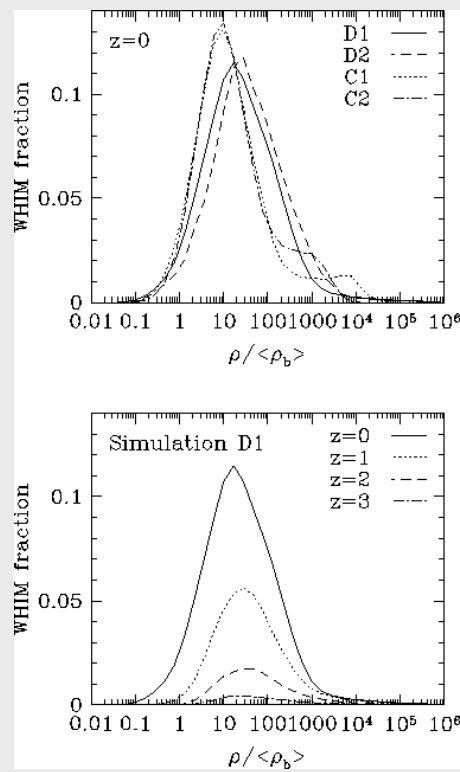
$z=6 \rightarrow 0$

$L_{\text{box}} = 25 \text{Mpc}/h$

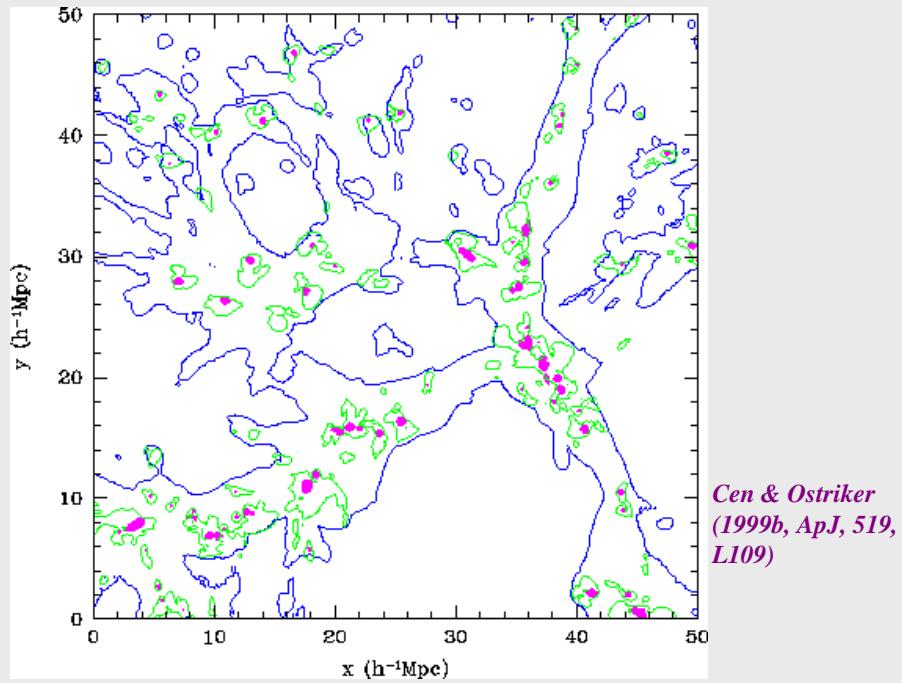
*Cen & Ostriker (2000,
in preparation)*

Density of the WHIM gas

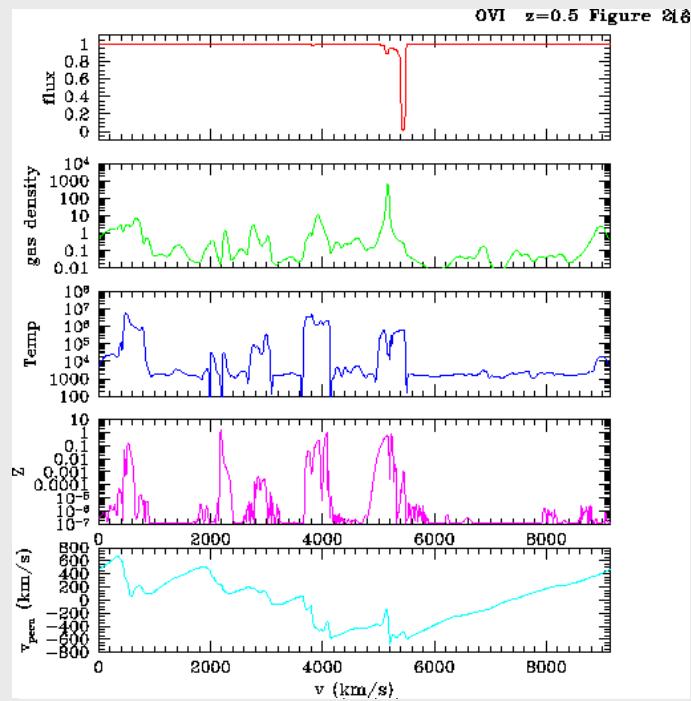
Dave et al. (2000, astro-ph/0007217)



Galaxies, WHIM and Metals



Observing the WHIM I: Absorption



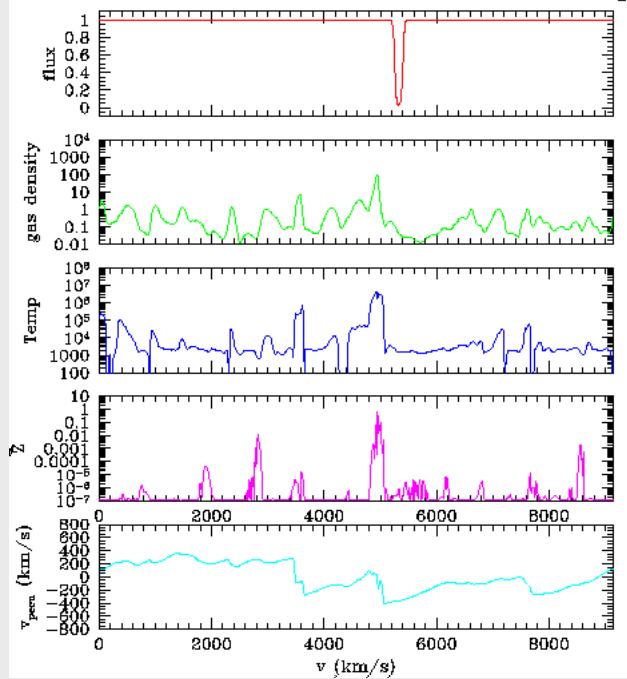
OVI line

$d\eta/dz \sim 1$

Cen et al. (2000,
in preparation)

OVII line

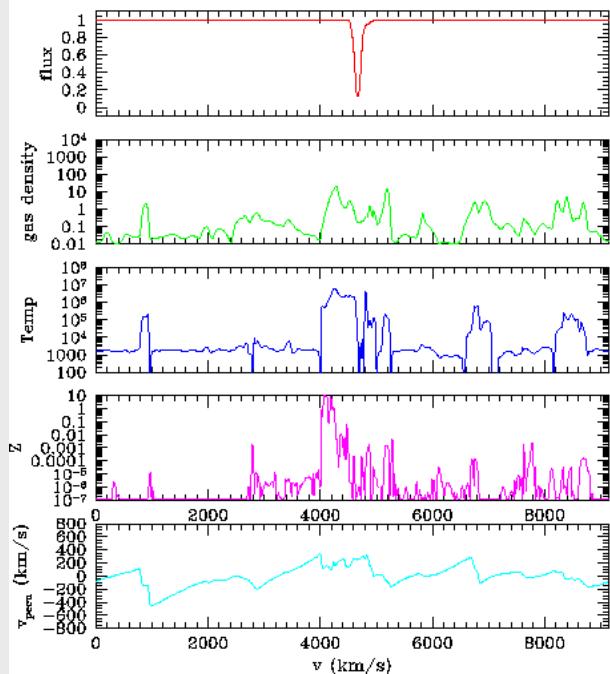
OVII z=0.5 Figure 24



dn/dz~1

OVIII line

OVIII z=0.5 Figure 19



$dn/dz \sim 1$

Observing the WHIM II: Emission

- ❖ Individual emission
- ❖ X-ray background

Conclusions

- ❖ The Warm-Hot Intergalactic Medium is 40% of the total baryon today, an inevitable consequence of formation of large-scale structure
- ❖ It may be best detected in absorption lines; Chandra may be able to see them; Con-X? Yes!