Investigating the Cosmological Impact of Expanding Radio Galaxies on Large-Scales

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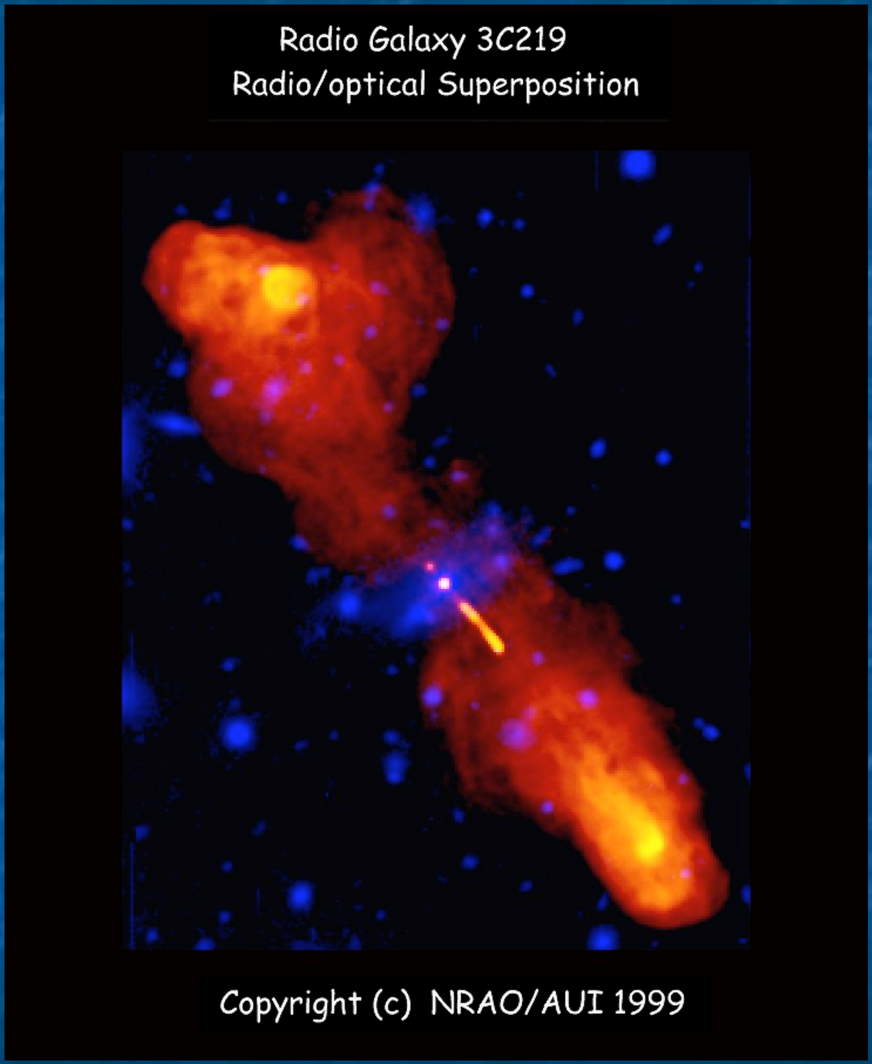
Outline

- Introduction
- Modeling galaxy formation & large-scale structures in simulations

- My work :

  Radio Galaxies expanding in a Cosmological Volume
  - Methodology
  - Simulations
  - Results : Volume Filling Fraction, Magnetic Field
  - Conclusions

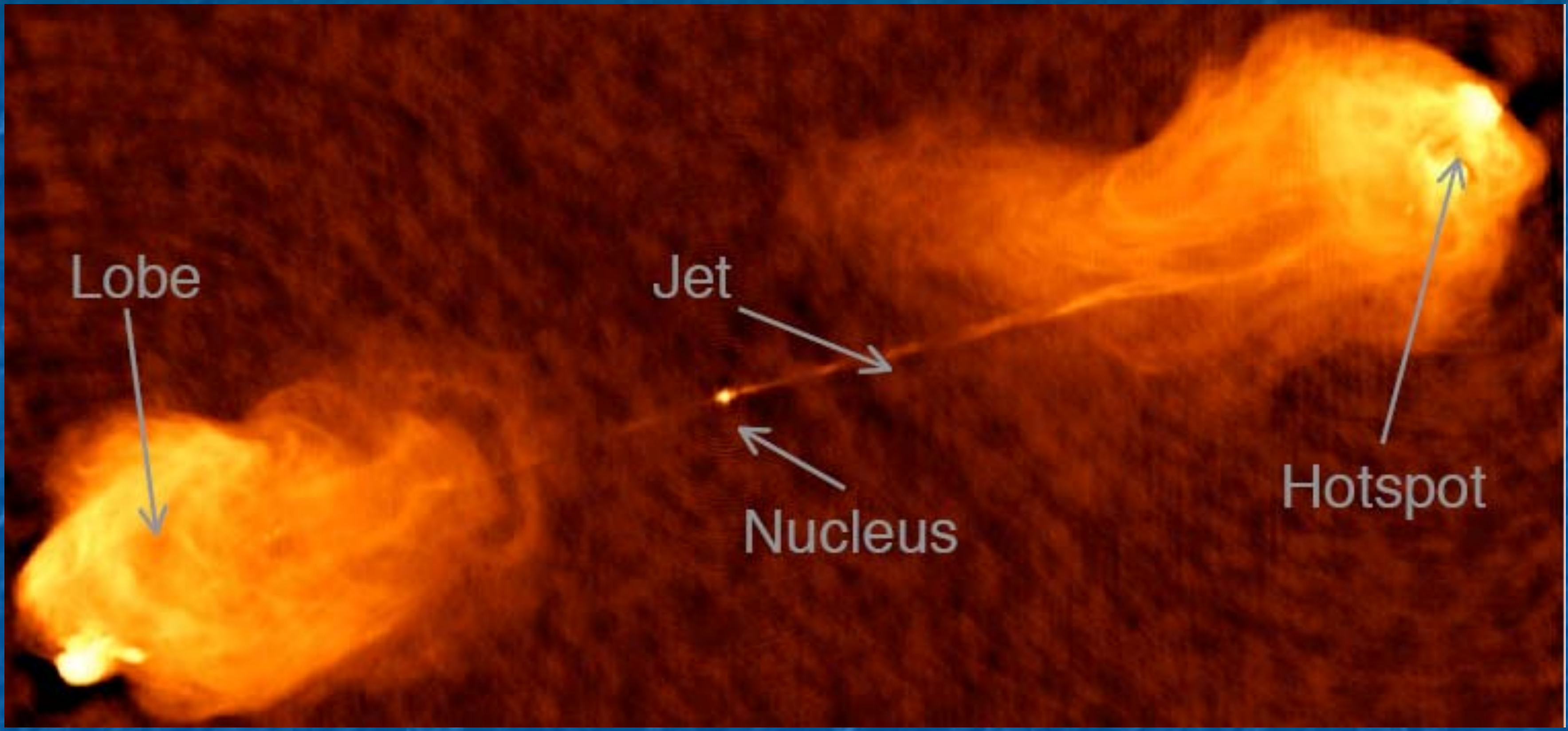
Radio Galaxy (RG)



- A class of AGN
  - SMBH at centers of active galaxies radiate huge amounts of energy ⇒ AGN
- Strong radio emission, in a pair of lobes / cocoons extending over 100s of kpc - Mpc
  - Synchrotron radiation ⇒ e-'s in lobe magnetic field
- Mostly hosted by giant elliptical galaxies

http://www.cv.nrao.edu/~abridle/images/3c219lonopt_large.jpg

RG Structure (Cygnus A)



Chris Carilli (Perley R. A., Dreher J. W. & Cowan J. J., 1984, ApJ, 285, 35L)

Co-Evolution (of Galaxies & AGN)

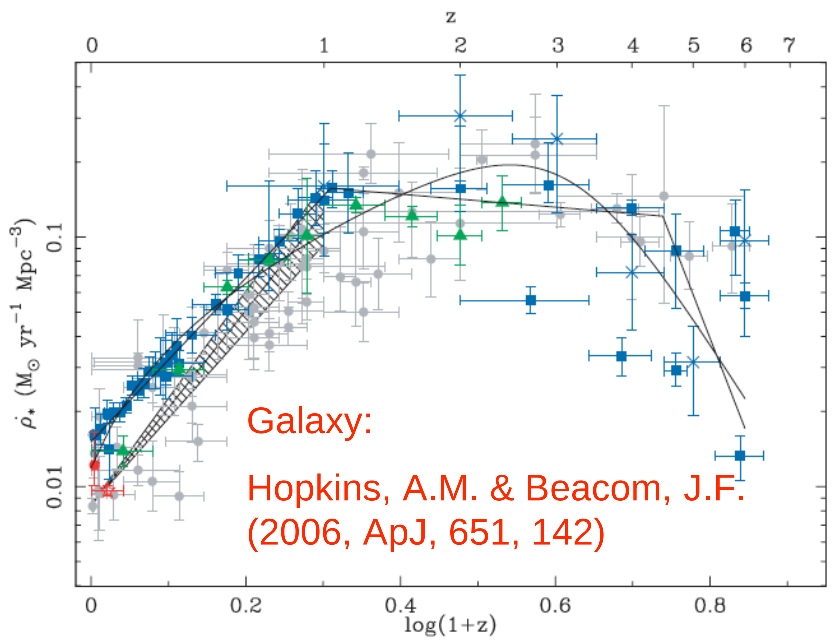


FIG. 1.— Evolution of SFR density with redshift. Data shown here have been scaled, assuming the SalA IMF. The gray points are from the compilation of Hopkins (2004). The hatched region is the FIR (24 μm) SFH from Le Floc'h et al. (2005). The green triangles are FIR (24 μm) data from Pérez-González et al. (2005). The open red star at $z = 0.05$ is based on radio (1.4 GHz) data from Mauch (2005). The filled red circle at $z = 0.01$ is the Hα estimate from Hanish et al. (2006). The blue squares are UV data from Baldry et al. (2005), Wolf et al. (2003), Arnouts et al. (2005), Bouwens et al. (2003a, 2003b, 2005a), Bunker et al. (2004), and Ouchi et al. (2004). The blue crosses are the UDF estimates from Thompson et al. (2006). Note that these have been scaled to the SalA IMF, assuming they were originally estimated using a uniform Salpeter (1955) IMF. The solid lines are the best-fitting parametric forms (see text for details of which data are used in the fitting). Although the FIR SFH of Le Floc'h et al. (2005) is not used directly in the fitting, it has been used to effectively obscuration-correct the UV data to the values shown, which are used in the fitting. Note that the top logarithmic scale is labeled with redshift values, not $(1 + z)$.

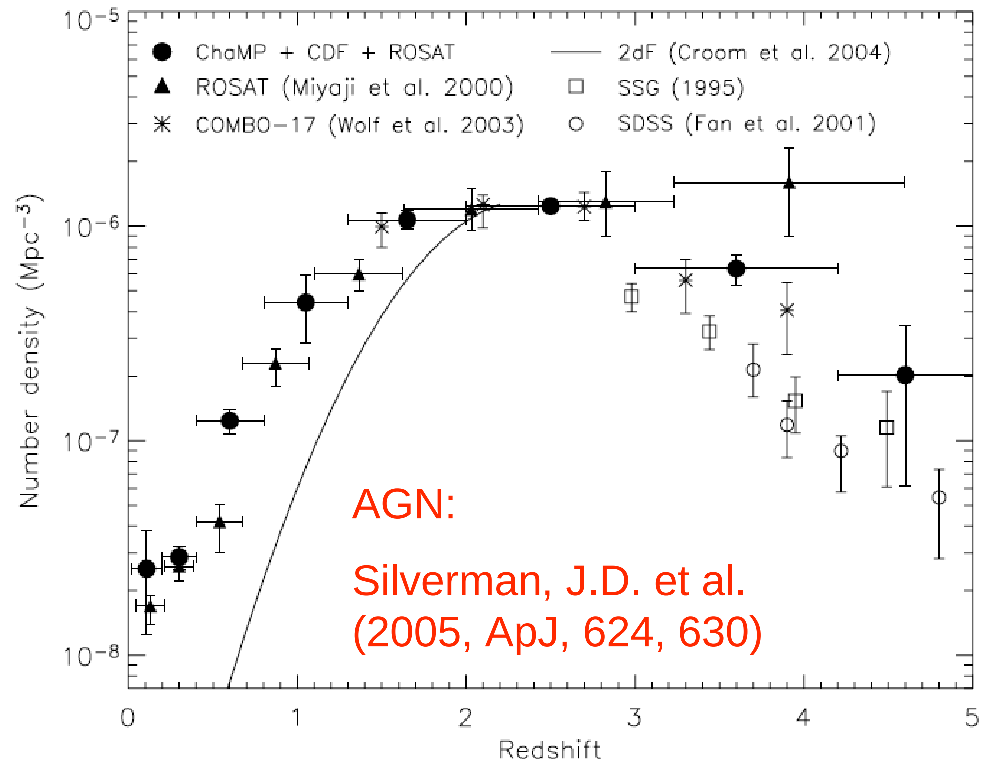


FIG. 9.— Comoving space density of 217 *Chandra* + *ROSAT* AGNs selected in the soft (0.5–2.0 keV) band with log $L_X > 44.5$ compared to the optical surveys. The optical space densities have been scaled to match the X-ray points at $z = 2.5$ for ease of comparison.

- Can we link up the cosmological evolution of galaxy & AGN populations?

How do AGN affect their Large-Scale Environment?

- Radiated energy is fed back & coupled to the surroundings
- Mechanical outflow

Galaxy Formation Modeling

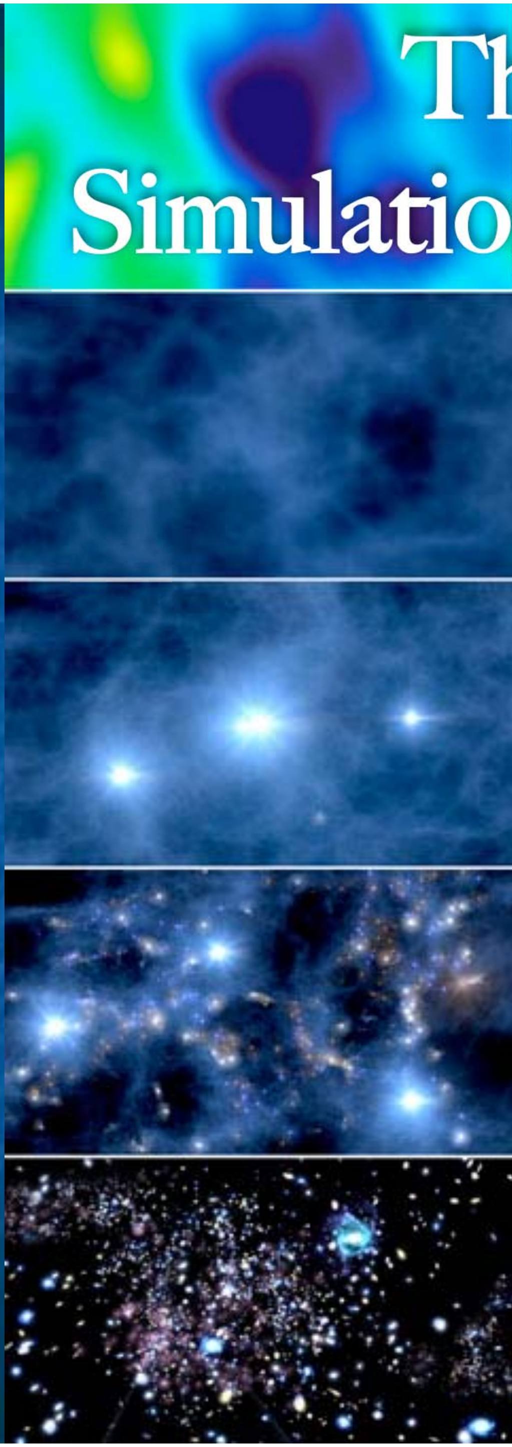
Cosmological (Hydrodynamic) Simulations

Large Scale Structure Formation

ΛCDM Universe ⇒ CDM (cold dark matter) + Cosmological constant / Dark energy

- Quantum fluctuations shortly after the Big Bang give rise to primordial density perturbations in the early radiation and matter density fields
- Inflation expands the perturbations, which form the seeds for later growth
- Gravitational clumping of matter from these initial density fluctuations ⇒ Structures grow
- Main forces driving evolution
  - Gravity : affects dark matter and baryons
  - Gas dynamics : only baryons

The Universe in a Box: Simulations of Large Scale Structures



- Run on Computers
- Purpose: Model the growth of structures
- Bridge gap between observations of early epochs
  - Oldest stars: 10^9 after Big Bang
  - CMBR: radiation from $3x10^5$ yrs after
- Simulations are the only experiments to verify theories of the origin and evolution of the Universe
- Can run many experiments over cosmic epochs in practical times

How do we Simulate? -- Basics

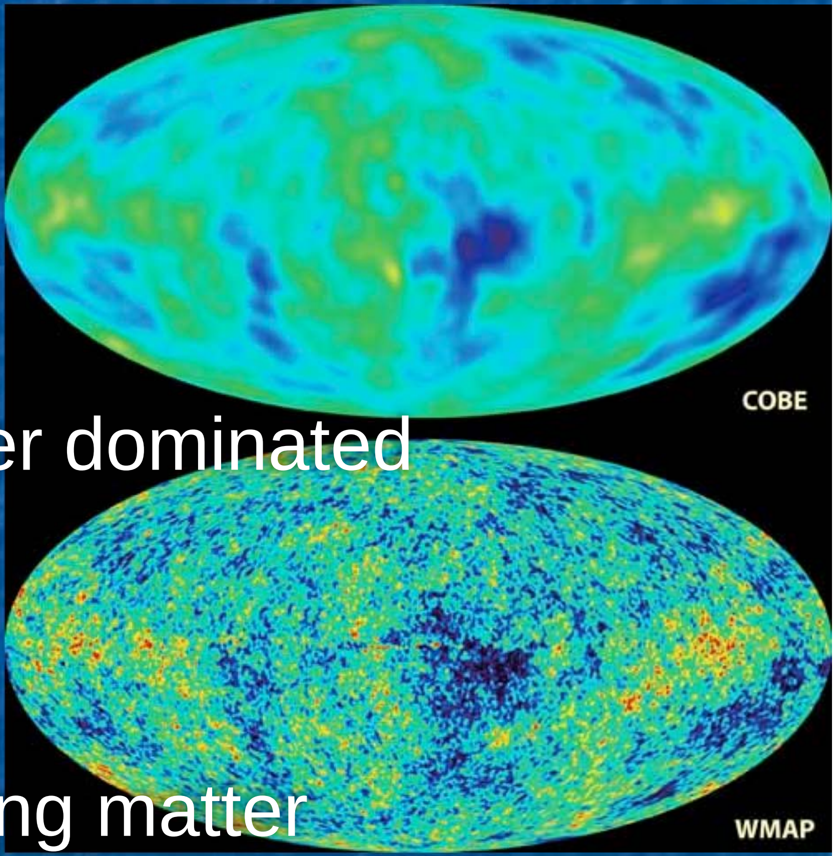
- A computational box ⇔ the Universe
- Particles in the box ⇔ matter in the Universe
- Assume: can model LSS in terms of massive particles each representing about 10^8 - 10^9 $M_{\odot}$
- Physical laws governing the nature determines the dynamics of the particles in the box
- Cosmological simulation → tool to investigate the evolution of millions of particles
- To run these simulations we need supercomputers
  - High speed and high processing power
  - Weeks to months of time

How do we Simulate? -- Procedures

- A two-fold process:
  - Generate the initial conditions for the density fluctuations
  - Evolve computational box using non-relativistic equations for particle dynamics
    - Follow the non-linear evolution of the early density fields using numerical methods
- <u>Goal:</u> get the final particle distribution consistent with observations of the Universe

Initial Condition

- Cosmological model well constrained by obs.
  - CMBR (WMAP)
  - SN
  - Galaxy clusters
  - Gravitational lensing



- Flat, dark-energy & dark-matter dominated
- Primordial density fluctuations
  - Gaussian
- Set initial condition of underlying matter distribution using ΛCDM parameters

Galaxy Simulation Physics

- Dark matter (dissipation-less, collision-less)
  - Gravity-only
  - Particle N-body method
- Baryon / Gas evolution
  - Gravity + Hydrodynamics
- Add source & sink terms / sub-grid physics
  - Radiative cooling and heating of gas
  - Star formation and stellar feedback
  - AGN Accretion & Feedback
- Numerically integrate dynamical equations

Simulation Volume

- The computational box has Hubble expansion just like the real Universe
  - Always encompasses the same mass

- The expansion is taken out from computations, s.t. the box appears static
- Coordinate system that expands (or co-moves) with the Universe (the comoving coordinates) is used

N-body (Collision-less)

- N number of particles
  - Dark matter (+ Baryons)
- Gravitational interactions only
- Equations of particle motion

$$\frac{d\vec{x}}{dt} = \vec{u}$$

$$\frac{d\vec{u}}{dt} = -\nabla\Phi$$

- Poisson's equation

$$\nabla^2\Phi = 4\pi G\rho$$

- During late evolution the relevant velocities are non-relativistic

Hydrodynamics (Baryons)

- Collisional particles with ideal gas properties
- Mass

$$\frac{\partial \rho}{\partial t} + \vec{\nabla} \cdot \left(\rho \vec{u} \right) = 0$$

- Momentum

$$\frac{\partial \vec{u}}{\partial t} + \left(\vec{u} \cdot \vec{\nabla} \right) \vec{u} = -\vec{\nabla} \Phi - \frac{\vec{\nabla} P}{\rho}$$

- Energy

$$\frac{\partial E}{\partial t} + \vec{\nabla} \cdot \left[\left(E + P \right) \vec{u} \right] = -\rho \vec{u} \cdot \vec{\nabla} \Phi$$

- Equation of state, $\varepsilon = f(\rho, P)$
  - Ideal gas

$$\varepsilon = \frac{1}{\left(\gamma - 1 \right)} \frac{P}{\rho}$$

  - Polytropic

$$P = K \rho^{\gamma}$$

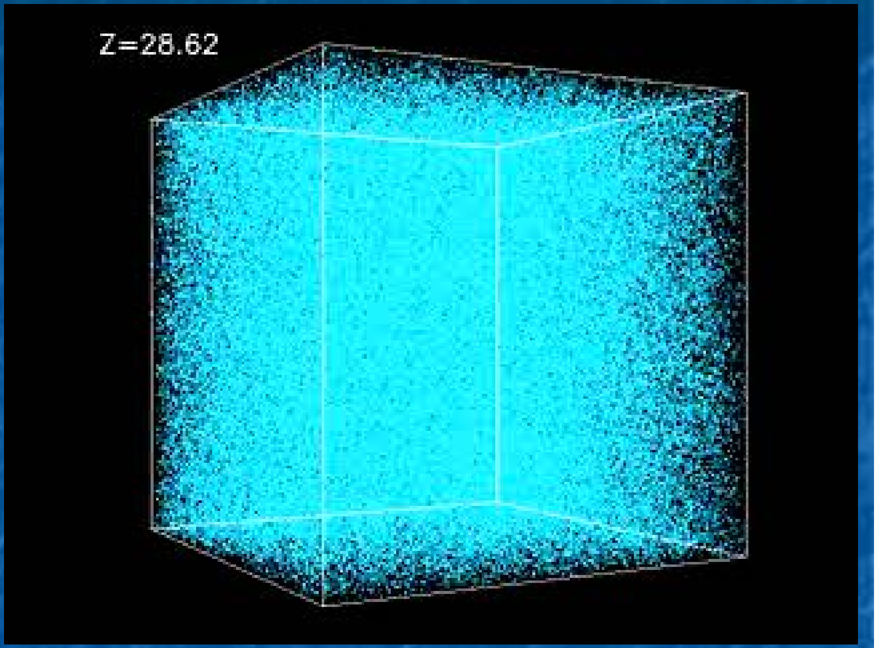
Successful Results

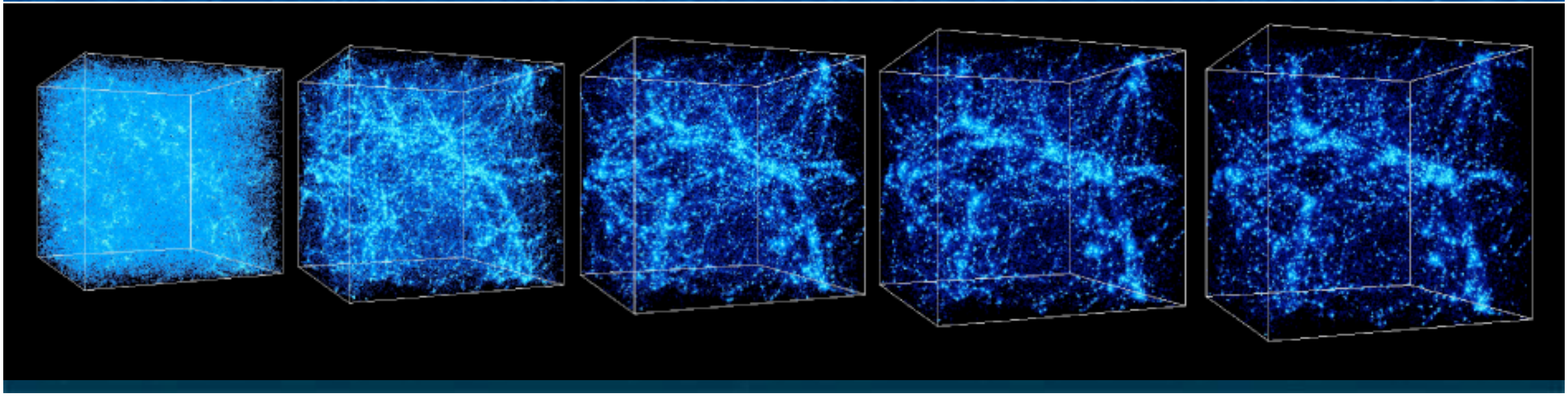
- Hierarchical Structure Formation
  - Can reproduce the distribution and structure of galaxies in very large scales as seen in observations
- On small scales
  - Stellar evolution, black holes, star clusters
- Distribution of matter in the Universe
  - Collapse via gravitational forces into filaments. Galaxies form in these filaments
- Galaxy clustering at all z (z~0, z~1, z~4-5) observed in large scale surveys is well reproduced

Large-Scale Filaments

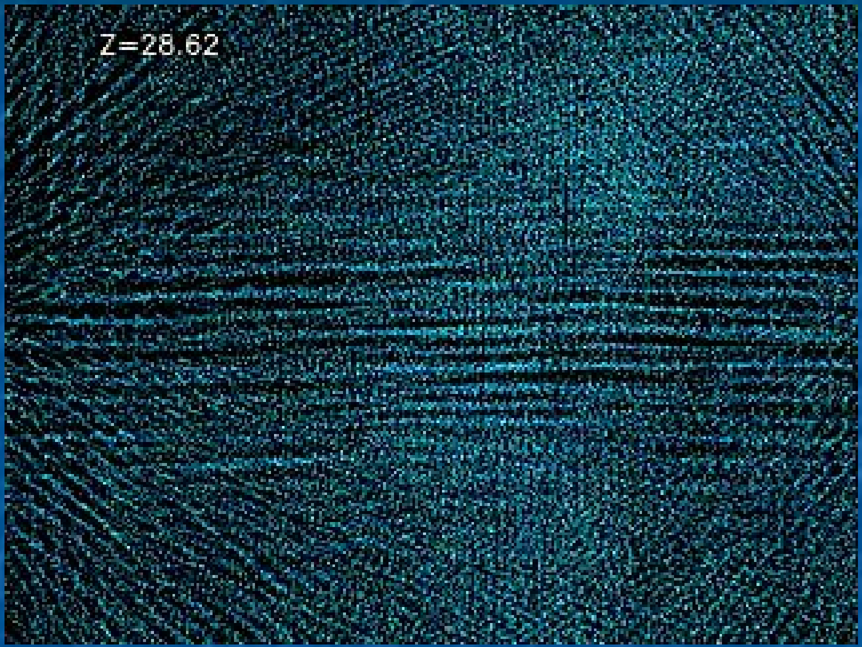
- A (43 Mpc)^3 box
- From z = 30 to z = 0

- Frames below show structure forming from z = 10 to the present

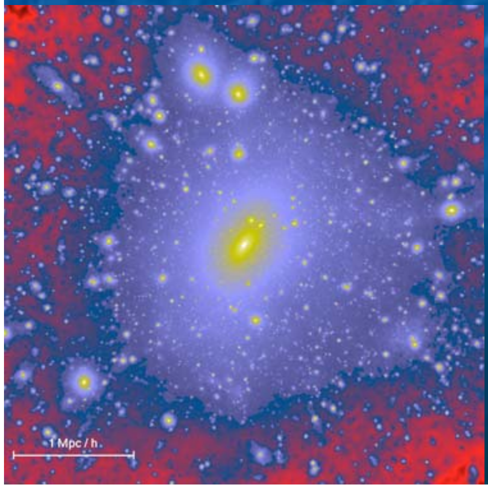


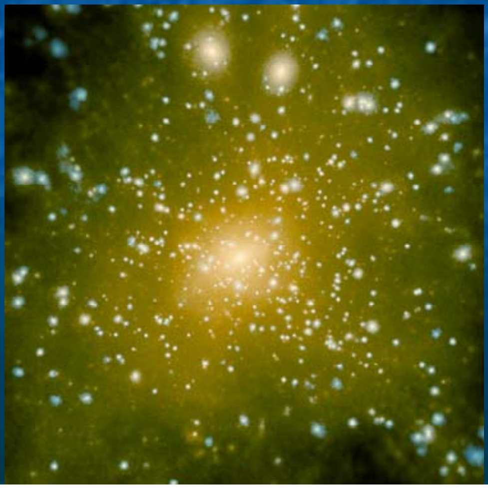


Formation of a Galaxy Cluster



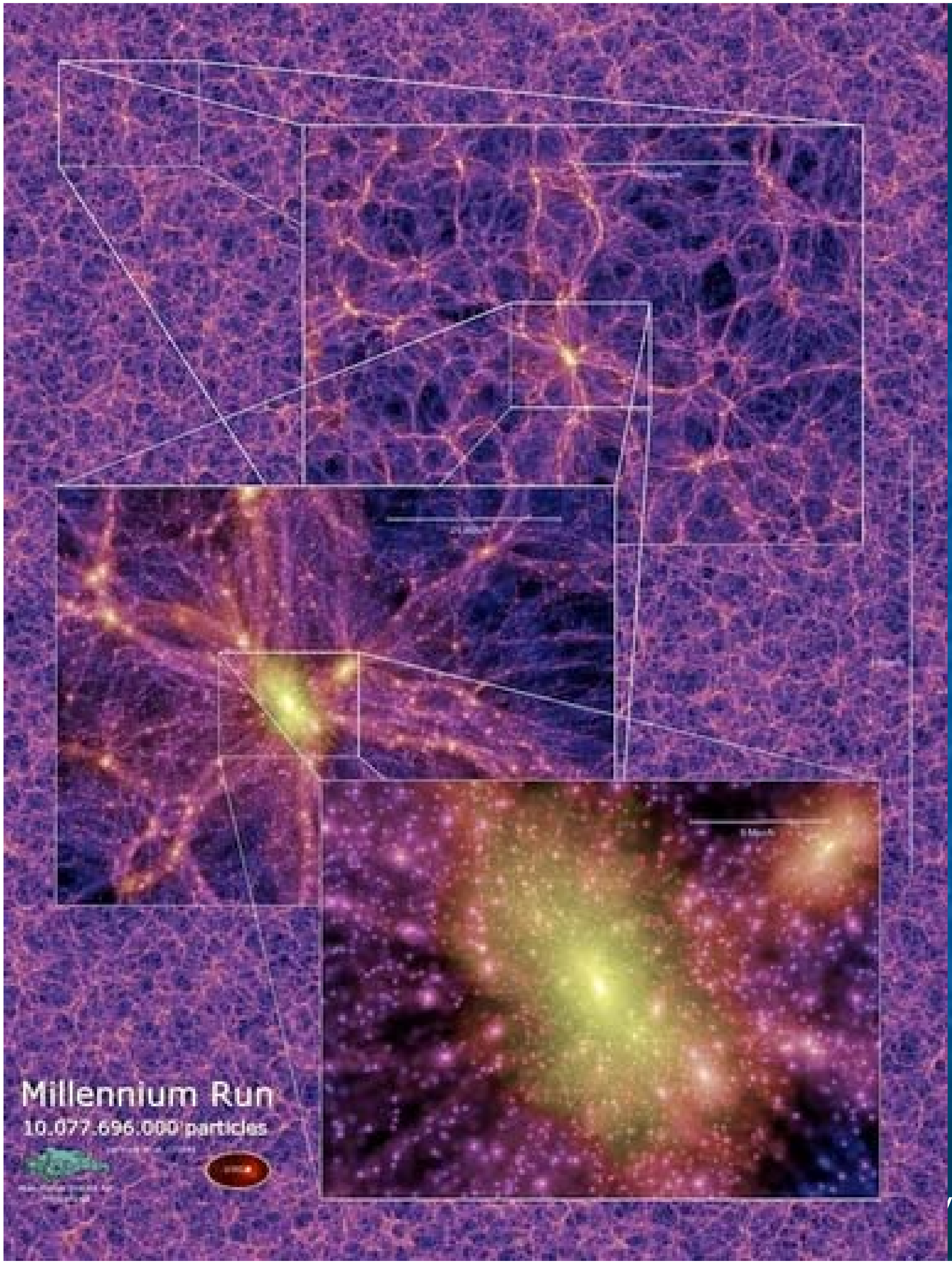
- 4.3 Mpc region of box
- The formation of a cluster proceeds hierarchically
  - Small-mass objects form first at z > 5
  - Quickly grow in size and violently merge with each other, creating increasingly larger and larger system
- This galactic "cannibalism" continues up to z=0





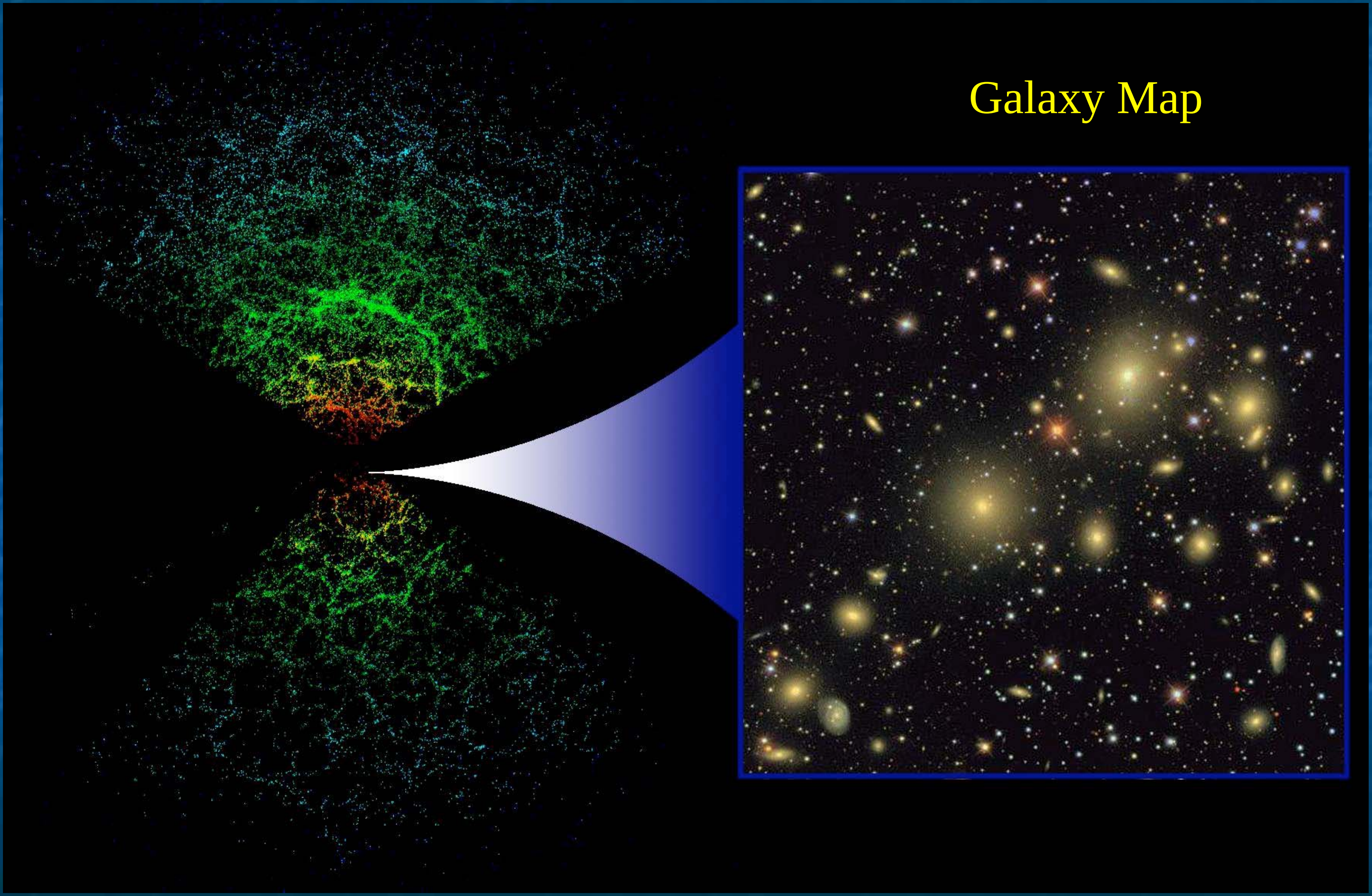
The Millennium Simulation

- One of the largest cosmological N-body run
  - Dark matter only
  - Gravity only, no hydrodynamics
- Done by the Virgo Consortium
  - Springel et al. 2005, Nature, 435, 629
- Box comoving side = 500 h^{-1} Mpc
- $2160^3 \sim 10^{10}$ particles
- Particle mass = 8.6 x 10^8 h^{-1} $M_{\odot}$
- Comoving softening length, $\varepsilon = 5\ h^{-1}$ kpc
- From $z = 127$ to $z = 0$
- Took 28 days on 512 CPUs



- A projected density field for a 15 Mpc/h thick slice of the z=0 output
- The overlaid panels zoom in by factors of 4 in each case, enlarging the regions indicated by the white squares

Sloan Digital Sky Survey



My work on :

Radio Galaxies
Expanding in a Cosmological Volume
& Impact on Large-Scales

Motivation

- Space density of RGs peaked during Quasar Era ($1.5 < z < 3$)
- Influence the formation & evolution of galaxies, & the intergalactic medium (IGM)
- How much volume of the Universe do the radio lobes occupy ?
- Possible impact in the filled volumes :
  - Trigger star formation by compressing proto-galactic gas
    - Rees – 1989; De-Young – 1991, Gopal-Krishna & Wiita – 2001
  - Heat / displace galactic gas $\Rightarrow$ quench star formation
  - Spread magnetic field into IGM
  - Enrich IGM with metals $\Rightarrow$ modify cooling rate of star-forming gas
  - Affect the matter power spectrum

Previous Work

- Volume filling fraction of radio lobes
  - Gopal-Krishna & Wiita, P.J. 2001, ApJ, 560, L115
  - Barai, P. & Wiita, P.J. 2007, ApJ, 658, 217B

As a fraction of the WHIM

Improvement

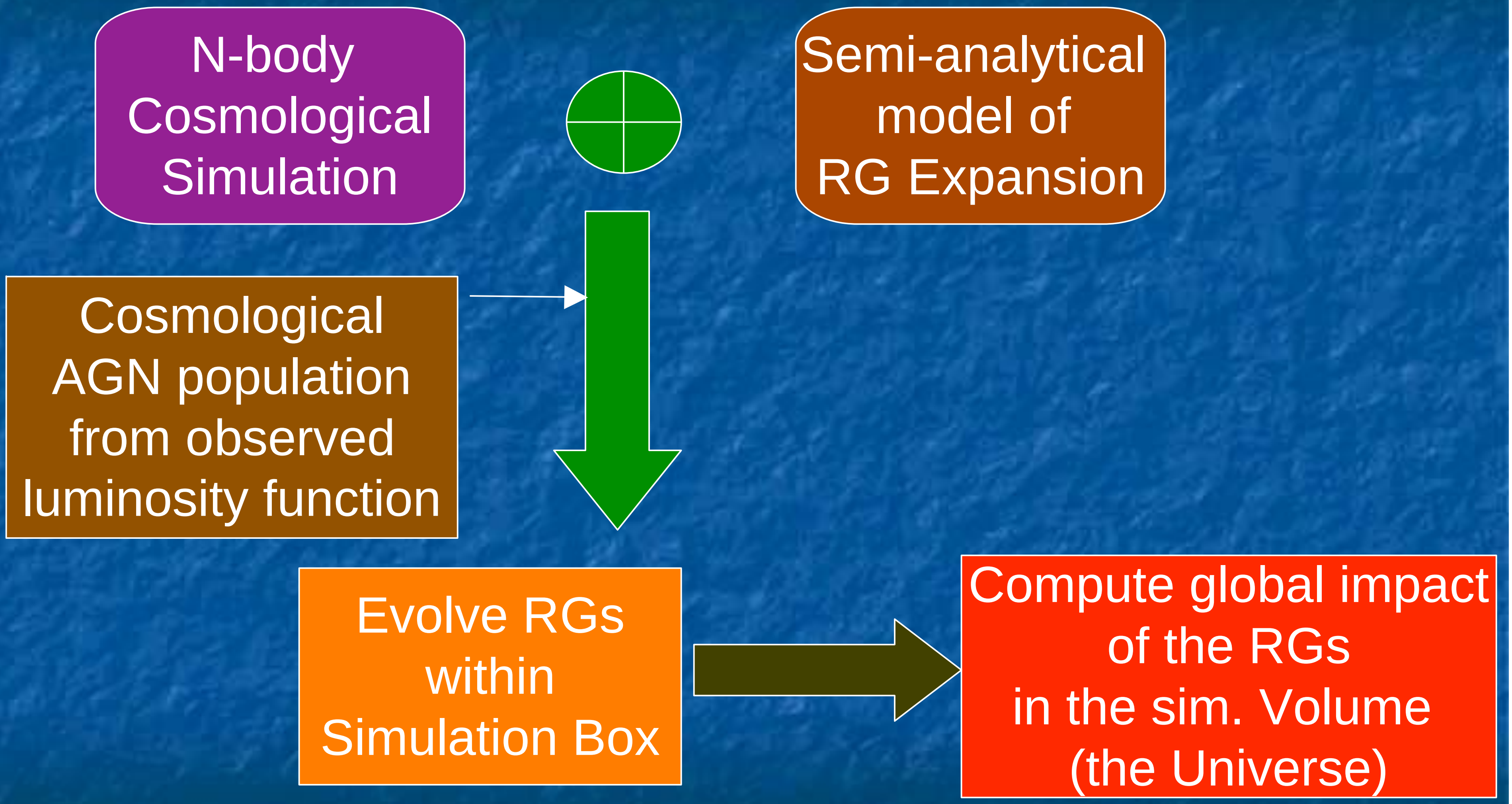
➢ Self-consistent Cosmological Simulations, as a fraction of overdense volume

Goal

- Probe the large-scale impact of RGs over the Hubble time

- Compute the volume fraction filled by expanding lobes of the cosmological population of RGs
  - Energy Density
  - Magnetic field
  - Matter power spectrum

Methodology



Cosmological Simulation

- N-body simulations of a cosmological volume
- *P^3M* (particle- particle / particle-mesh) code
  - Written by Prof. Hugo Martel (Université Laval)

- Box size (comoving) = 256 h^{-1} Mpc
- 256^3 particles, 512^3 grid

- Evolve from z = 25 up to z = 0
- ΛCDM model (WMAP5)

Redshift & Luminosity Distribution

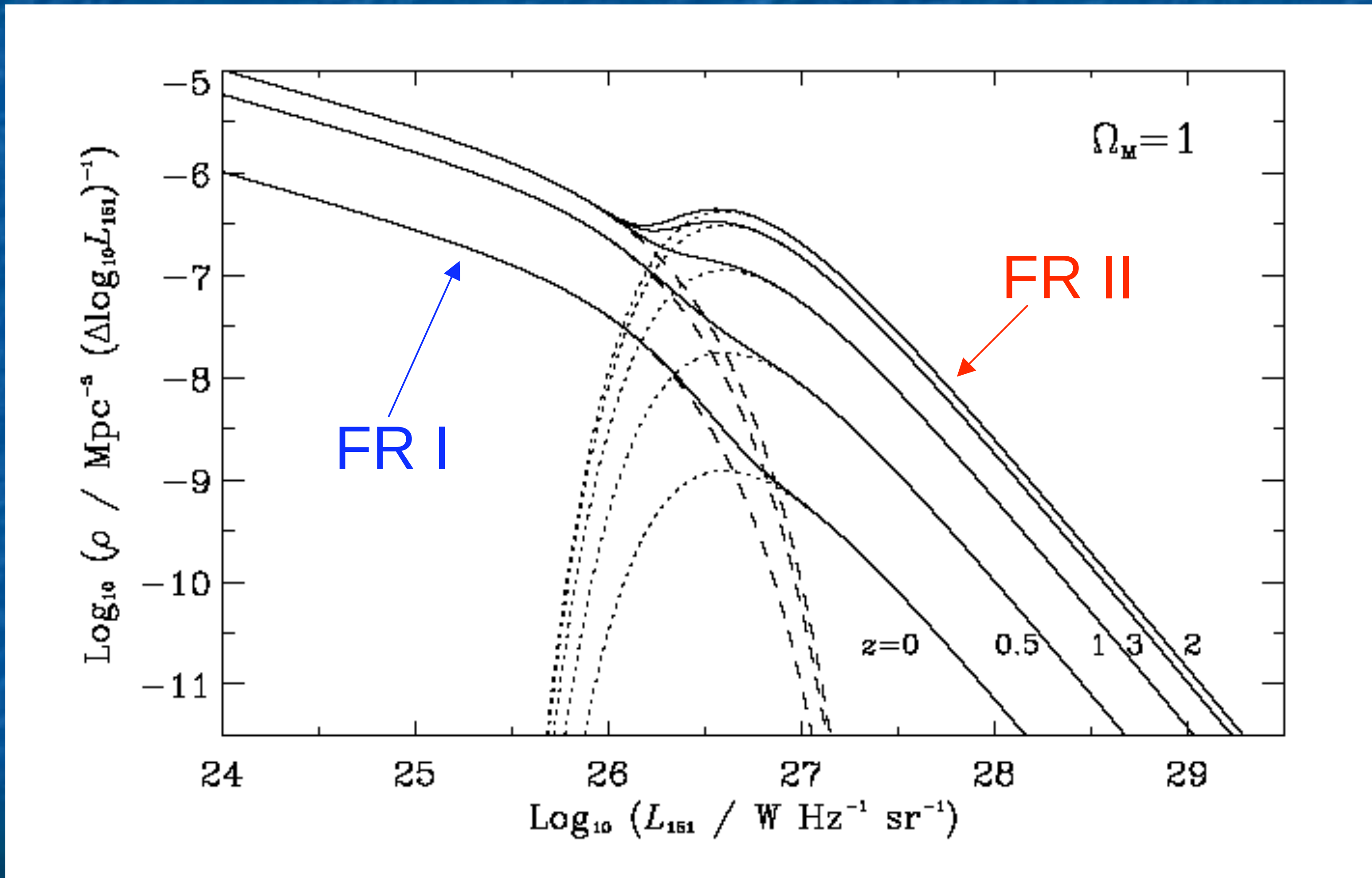
- Radio Luminosity Function, $\rho(L, z)$
  - From observed low-frequency 3CRR, 6CE and 7CRS complete samples
- Number of RGs : $$dN(L,z) = \rho(L,z)d[\log_{10} L]V_{box}$$
- Jet kinetic power : [Koerding, E.G. et al. 2008, MNRAS,383, 277]

$$\log\left[Q_0(\mathrm{erg\ s^{-1}})\right] = 19.1 + \log\left[L_{151}(\mathrm{W\ Hz^{-1}\ sr^{-1}})\right]$$

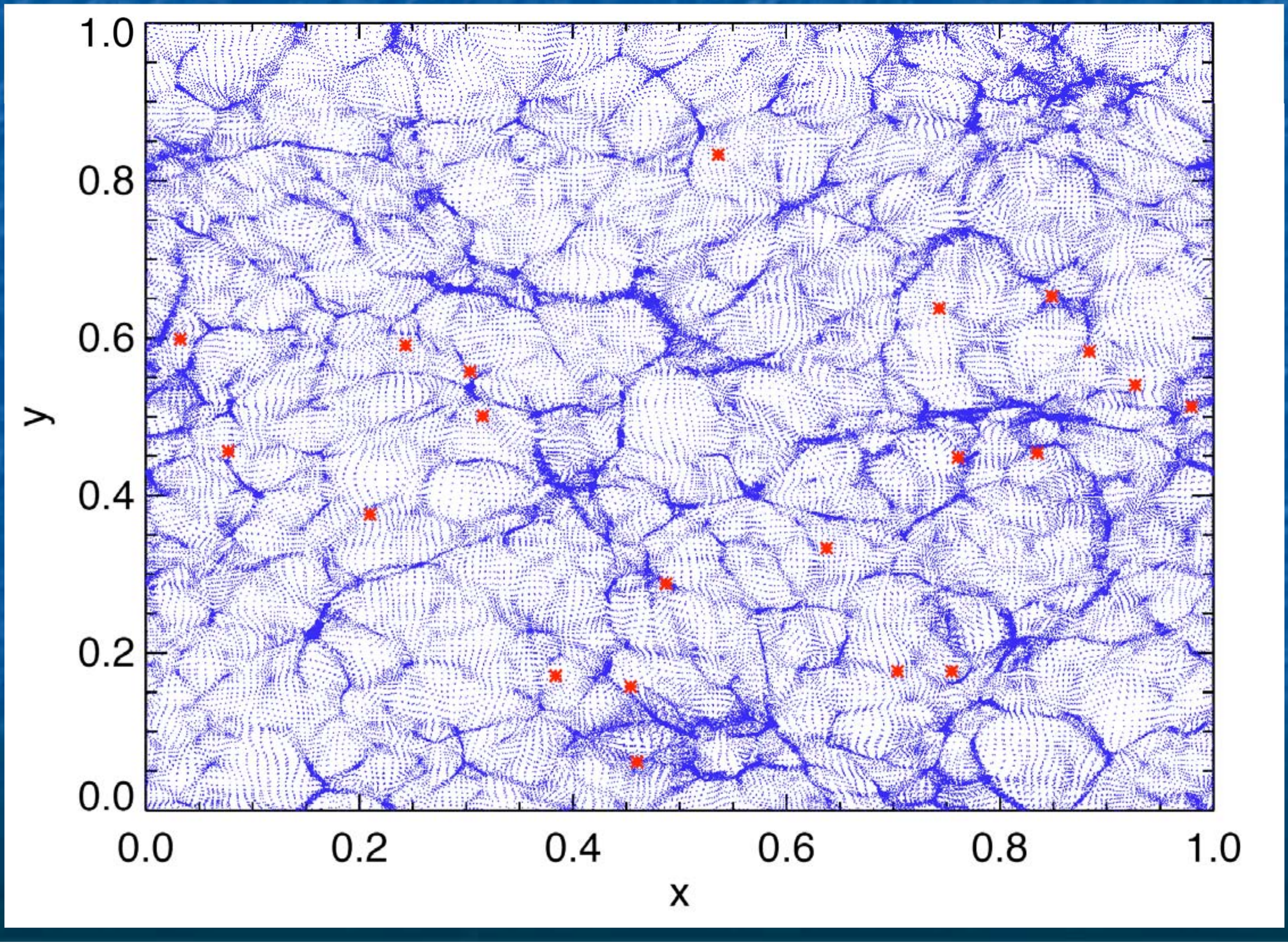
- RG lifetime
  - Fixed : τ_{RG} = 10, 100, 500 Myr
  - Variable : $$\tau_{RG} \propto 1/\sqrt{Q_0}$$
    - Daly, R.A. & Guerra E.J. (2002, AJ, 124, 1831)
    - Daly, R.A. et al. (2009, ApJ, 691, 1058)

Radio Luminosity Function

(Willott et al. 2001, MNRAS, 322, 536)



- Locate RGs in high-density mesh (PM) cells selected randomly
  - Cell density > 5 × mean density of simulation box
- Fig : Locations of new-born RGs in a slice of box at z = 0.5
  - Blue - Particles (PM), Red - RGs



Ambient Medium for RG Expansion

- Assume: baryonic gas distribution follows dark matter in the simulation box
- Ambient gas density :

$$\rho_x(z,\vec{r}) = \frac{\Omega_B}{\Omega_M}\rho_M(z,\vec{r})$$

- Pressure :

$$p_x(z,\vec{r}) = \frac{\rho_x(z,\vec{r})KT_x}{\mu}$$

- Temperature (assuming a photoheated medium)

$$T_x = 10^4 \text{ K}$$

- Mean molecular mass :

$$\mu = 0.611 \text{ a.m.u.}$$

Phases Of RG Evolution

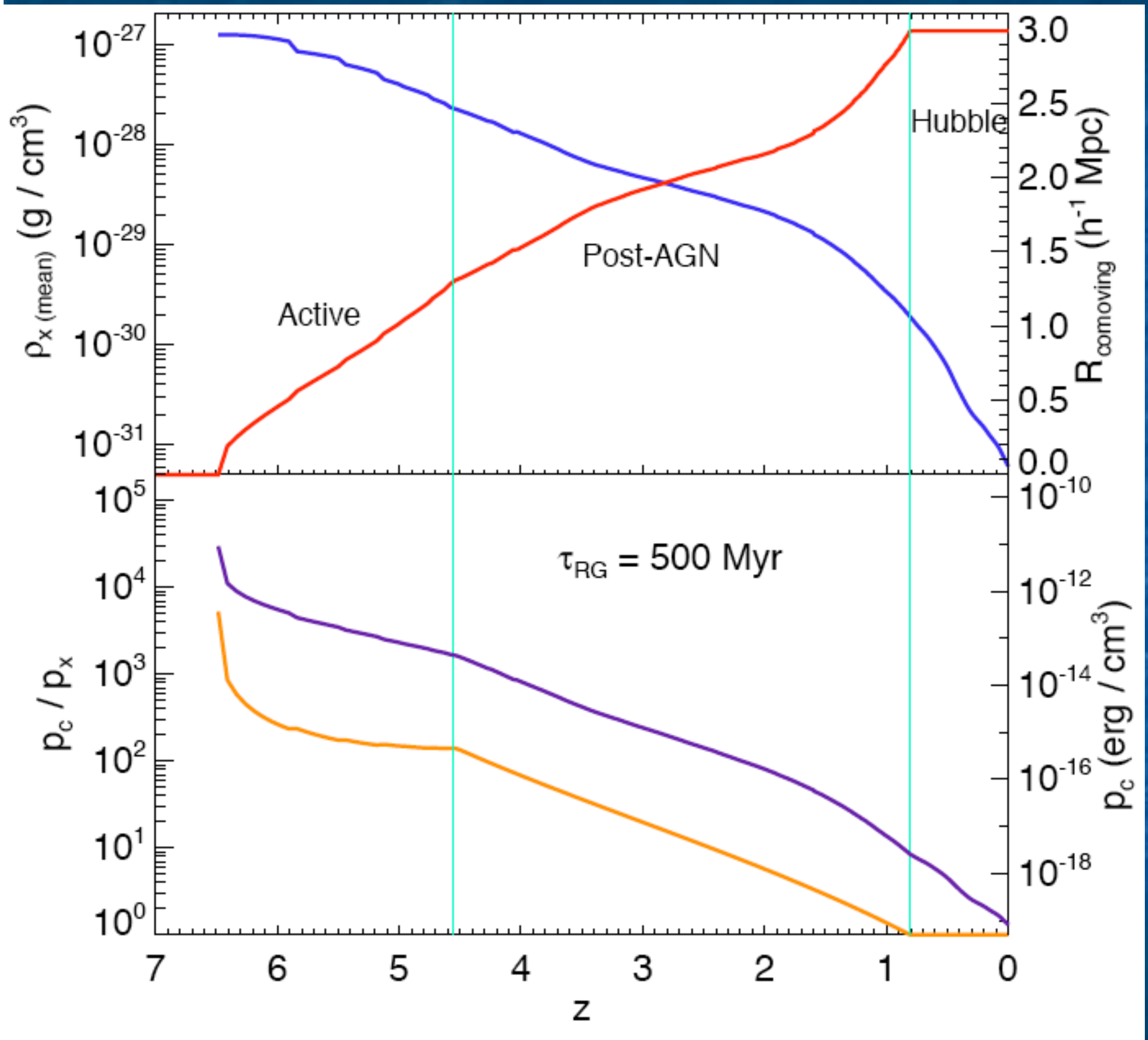
Active Life

- Central SMBH is actively accreting
- Self-similar RG expansion (cylindrical shape)
- Highly overpressured : $p_c >> p_x$

Post-Activity Phase

- SMBH is no more active ⇒ dead RG
- When overpressured, $p_c > p_x$
  - Sedov-Taylor expansion with adiabatic loss
  - Spherical shape
- When reach pressure equilibrium, $p_c = p_x$
  - Passive Hubble evolution, R_{comoving} = Constant

Evolution of a Single RG



Top:

external density & comoving radius.

Bottom:

Overpressure & Cocoon Pressure.

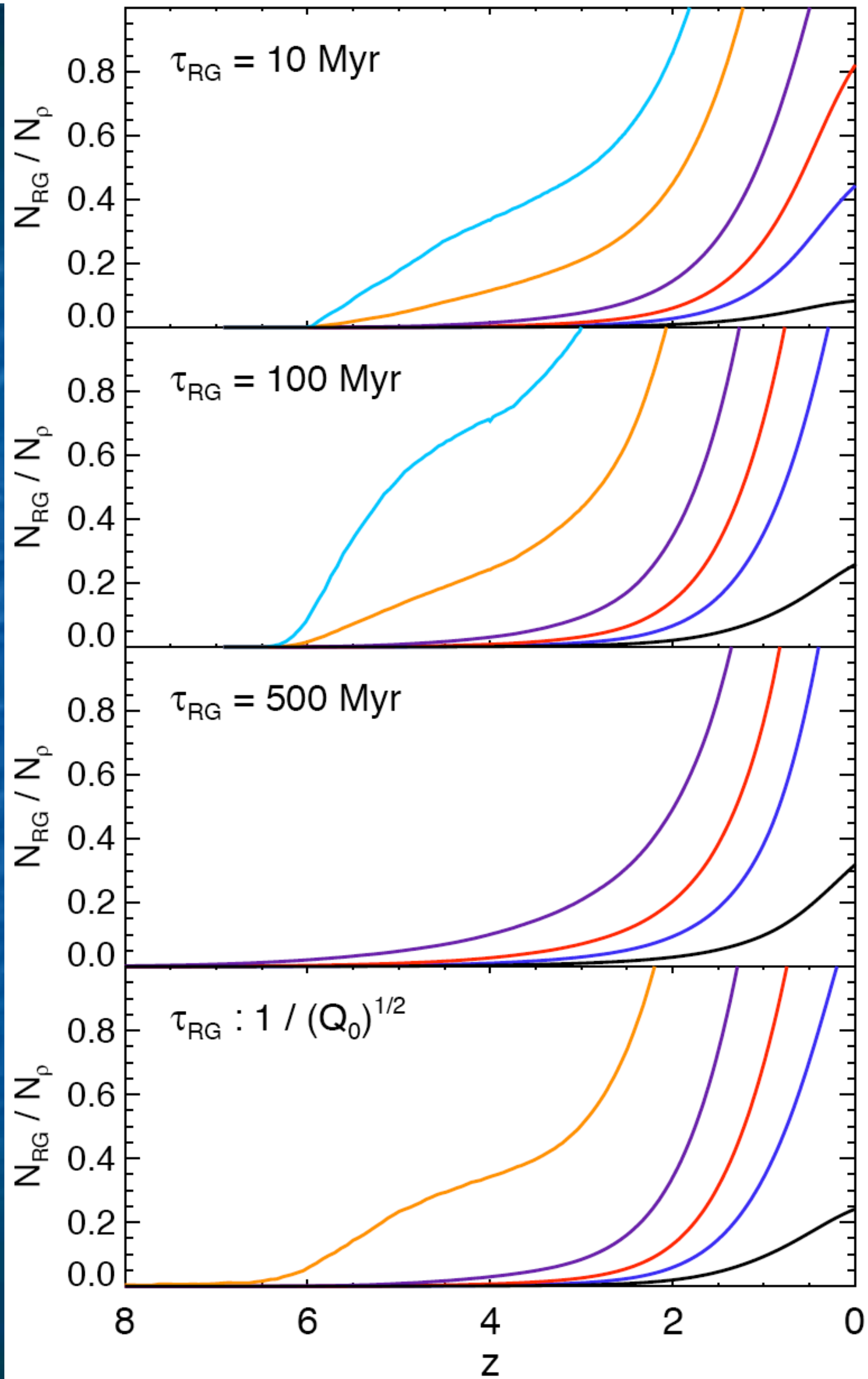
Vertical blue lines separate phases of expansion: Active, Post-AGN and Hubble.

Volume of Box Filled

- Count mesh cells in the simulation box occurring inside the volume of one/more RG cocoon
- Total number of filled cells, N_{RG}
  $\Rightarrow$ total volume of box occupied by RGs
- Express the total volume filled as a fraction of volumes of various overdensities in the box

$$N_{\rho} = N\left(\rho > C\rho_{mean}\right)$$

$$\rho_{mean} = \left(1+z\right)^{3}\Omega_{M}\,\frac{3H_0^2}{8\pi G}$$



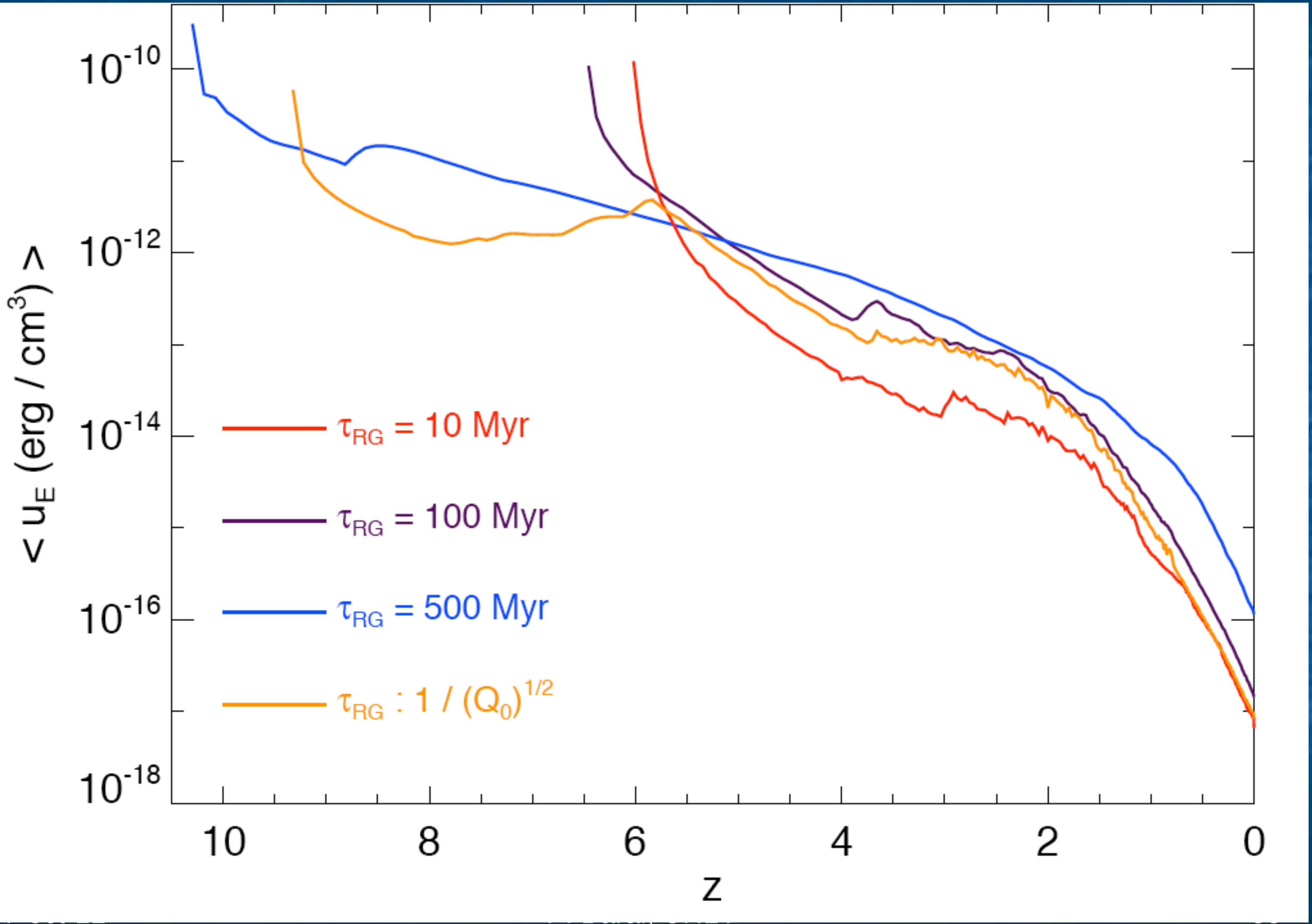
Fractional Volumes of box of various overdensities filled by RGs

(N_ρ *with* C = *0, 1, 2, 3, 5, 7)*

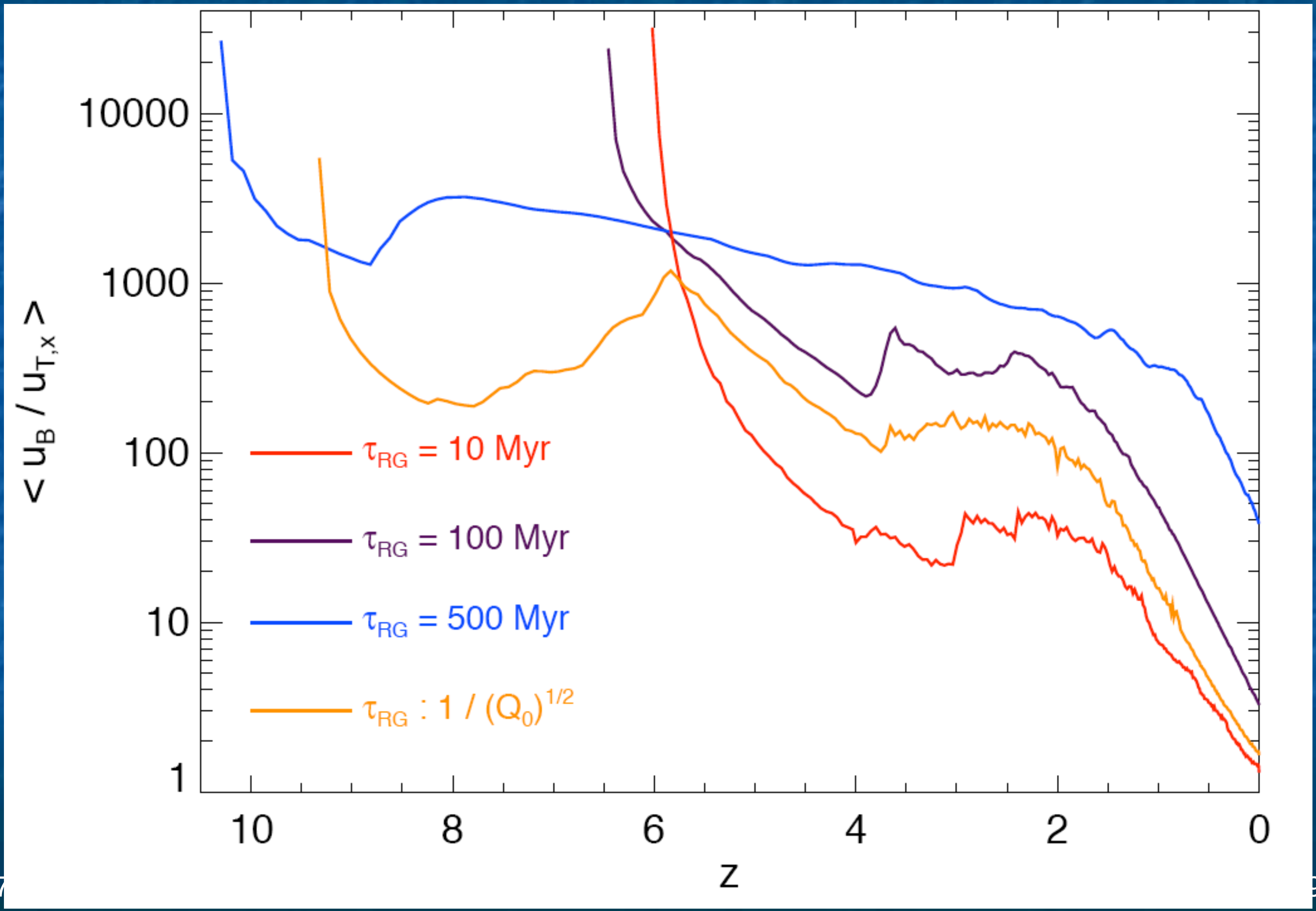
Global Average Values

- Cocoon energy density : $u_E = 3p_c$
- Magnetic energy density : $u_B = \frac{u_E}{2} = \frac{B_c^2}{8\pi}$
- Mean thermal energy density of ambient medium : $\overline{u}_{T,x} = \frac{3\overline{\rho}_x kT_x}{2\mu}$
- Volume-weighted average : $\langle \mathrm{A} \rangle = \frac{\sum \mathrm{A} V_{RG}}{\sum V_{RG}}$

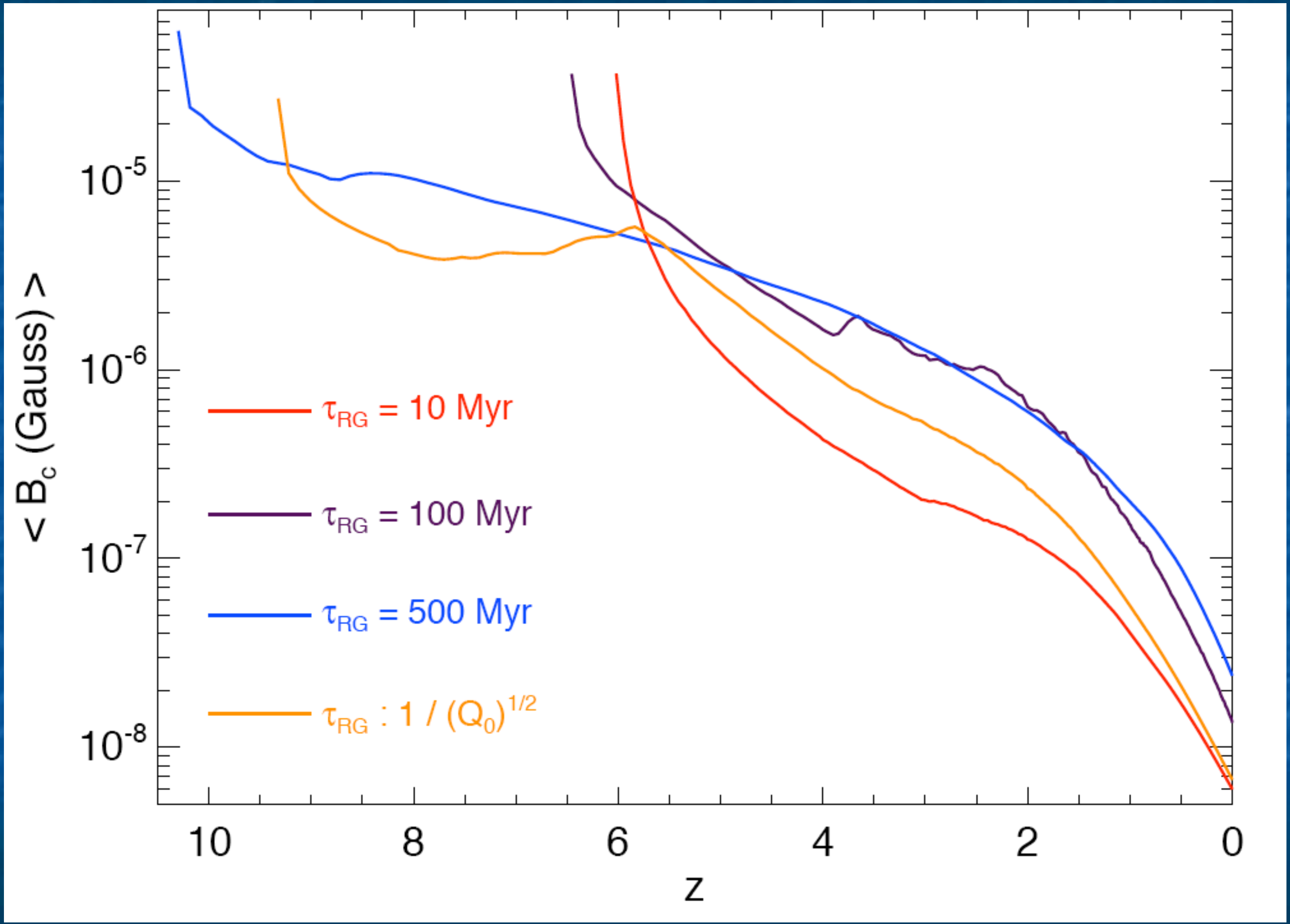
Total Energy Density Inside RG Cocoon Volumes



Ratio of Magnetic Energy Density to Mean External Thermal Energy Density



Equipartition Magnetic Field Within RG Filled Volumes



Matter Power Spectrum, $P(k)$

$$\delta(\vec{x}) = \frac{\rho(\vec{x}) - \bar{\rho}}{\bar{\rho}}$$

$$\delta(\vec{k}) = \text{Fourier Transform}\left[\delta(\vec{x})\right]$$

$$\vec{k} = [i, j, k]\frac{2\pi}{L_{\text{box}}}$$

$$P(k) = \frac{V_{box}}{N^6}\left|\delta(\vec{k})\right|^2$$

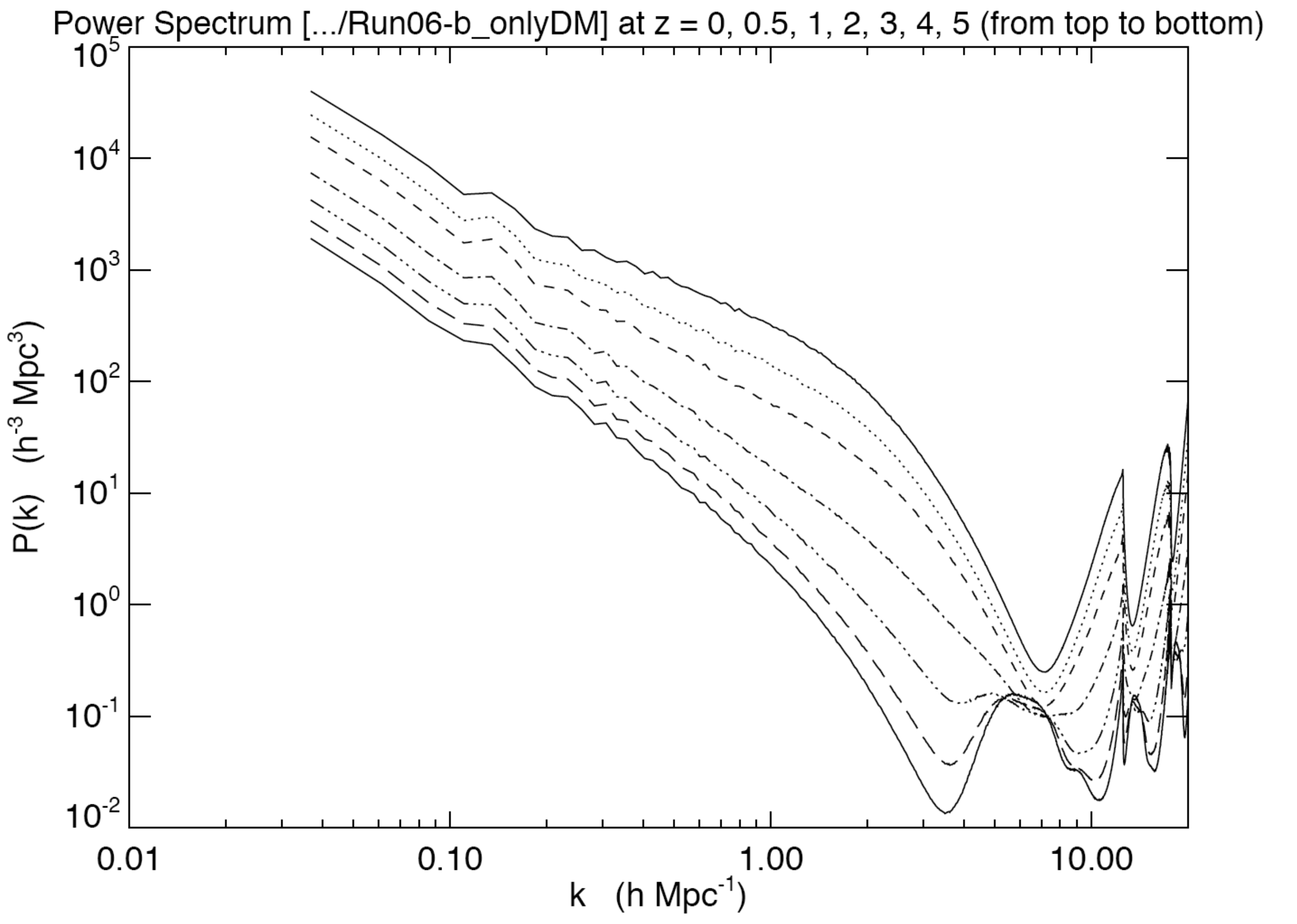
- Baryons are displaced from interior cells of RG volume and collected in the boundary cells
- η = Efficiency of baryon stripping
- Increased density of boundary cells:

$$\rho_{new,bound} = \rho_{old,bound} + \left(\frac{\Omega_B}{\Omega_M}\right)\left(\frac{\eta}{N_{bound}}\right)\sum_{1}^{N_{in}} \rho_{old,in}$$

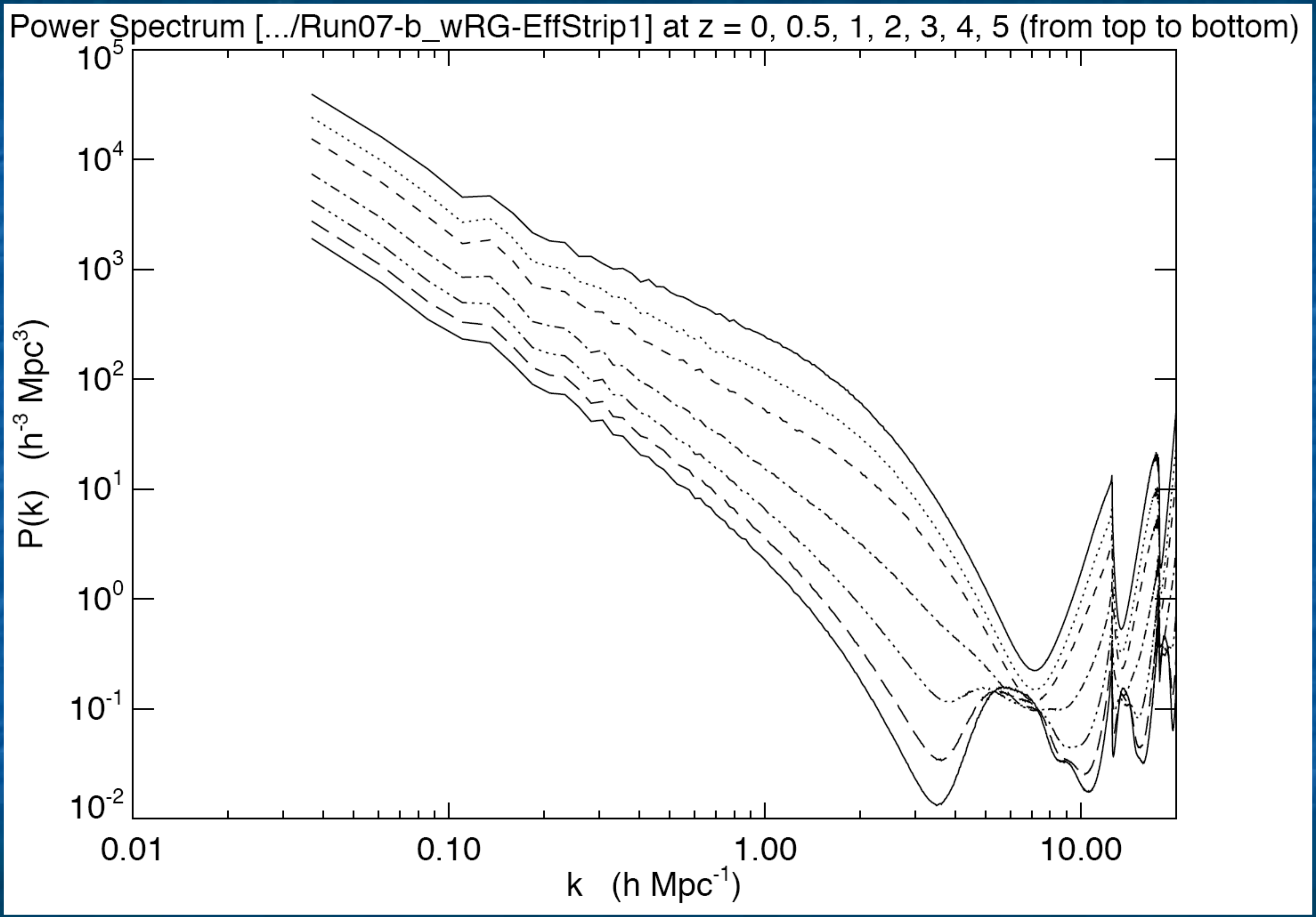
- Decreased density of interior cells:

$$\rho_{new,in} = \rho_{old,in} - \left(\frac{\Omega_B}{\Omega_M}\right)\eta\rho_{old,in}$$

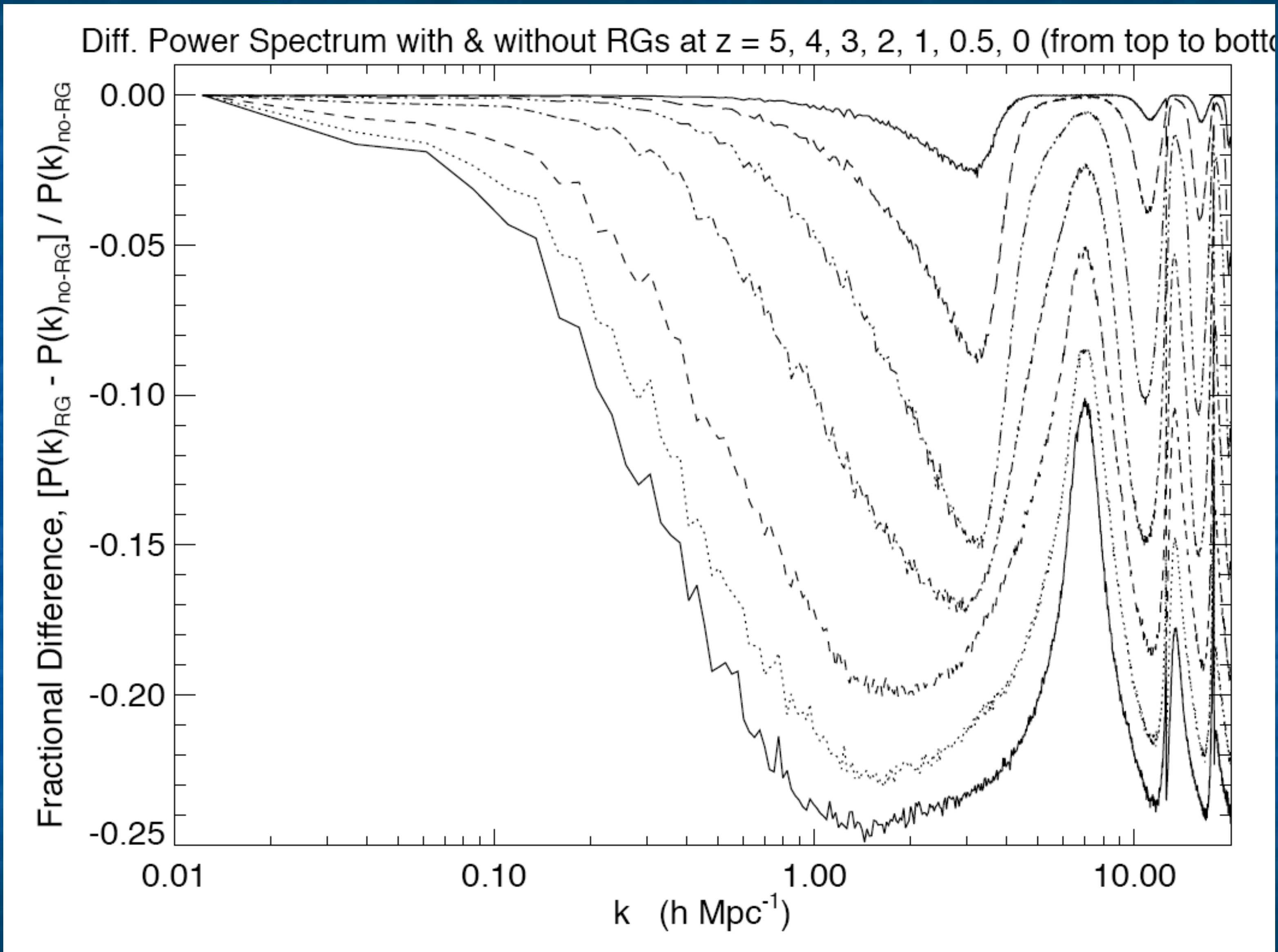
Baryons Unperturbed by RGs



Baryons Displaced by RGs (η = 1)



Difference Caused by RGs



Summary

- Implemented a semi-analytical model of RG expansion in N-body simulations
- Results [Barai, P. 2008, ApJ, 682, L17]
  - RG lobes pervade 10 – 30 % of the total volume by the present
  - Few cases occupy 100% of the overdense regions by z~0.3
  - Volume averaged quantities in the filled regions at z = 0
    - Energy Density ~ 10^{-17} erg cm^{-3}
    - Magnetic field ~ 10^{-8} Gauss

- Ongoing & Future work :
  - Matter power spectrum (upto 25% decrease at z=0)
  - Compton y-parameter of the Sunyaev-Zeldovich effect
  - Acceleration of cosmic rays, Reionization, …, etc, …

Extra Slides

Active Life

- Self-similar RG expansion
  - Cylindrical shape with length $2R_h$, radius R_0
- Jet advance $$\frac{Q_0}{A_h c} = \rho_x \left(\frac{dR_h}{dt} \right)^2$$
- Energy $$E_c = 2Q_0 t_{age}$$
- Pressure $$p_c V_{RG} = (\Gamma_c - 1) E_c$$
  - Relativistic cocoon plasma with $\Gamma_c = 4/3$
- Sideways shock
- Overpressured : $p_c >> p_x$ $$p_c = \rho_x \left(\frac{dR_0}{dt} \right)^2$$

Post-Activity Evolution

- Spherical Expansion when overpressured, $p_c > p_x$
  - Sedov-Taylor adiabatic expansion

$$R_c = \xi_0 \left(\frac{E_c t_{age}^2}{\overline{\rho}_x} \right)^{1/5}$$

  - Total energy during active-life

$$E_c = 2 Q_0 \tau_{RG}$$

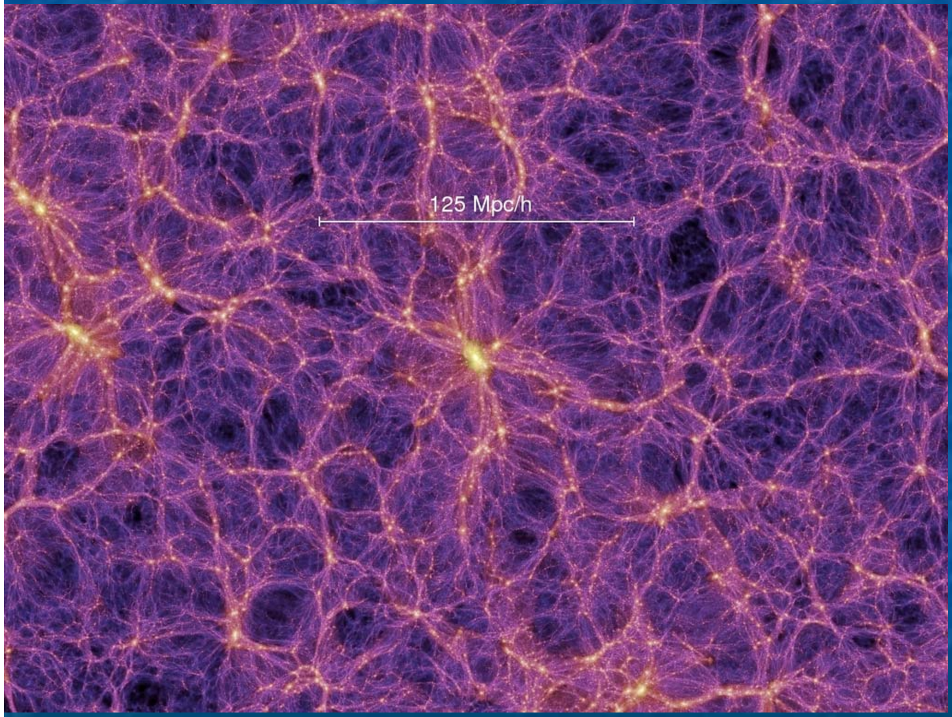
  - Adiabatic loss

$$p_c R_c^{3\Gamma_x} = \text{constant}$$

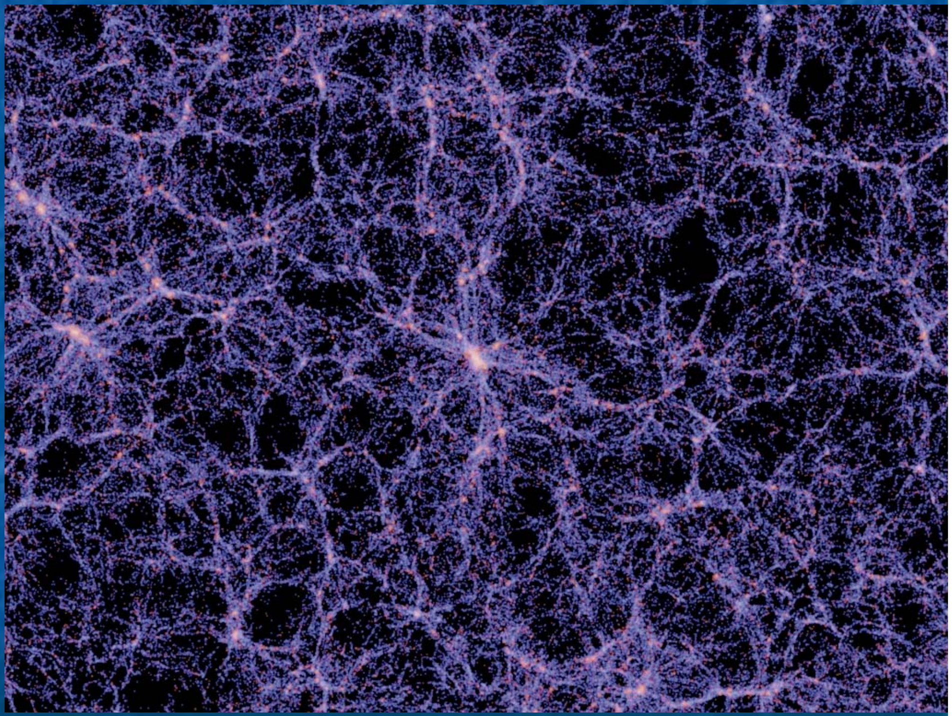
  - Spherical RG cocoon expansion
- When reach pressure equilibrium, $p_c = p_x$
  - Passive Hubble evolution, R_{comoving} = Constant

The Large-scale Matter Distribution in the Millennium Simulation

Dark Matter



Galaxies



Comoving Coordinate, x(t)

- Coordinate moving with the Hubble flow
- Distance between 2 points measured now, at $z = 0$
- Remains constant for objects in Hubble expansion

$$x(t) = \frac{r(t)}{a(t)}$$

$$r = \int_{t_{emit}}^{t_{now}} \frac{c\,dt'}{a(t')}$$

- *r(t)* = Proper Distance
- *a(t)* = Scale factor of the Universe