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

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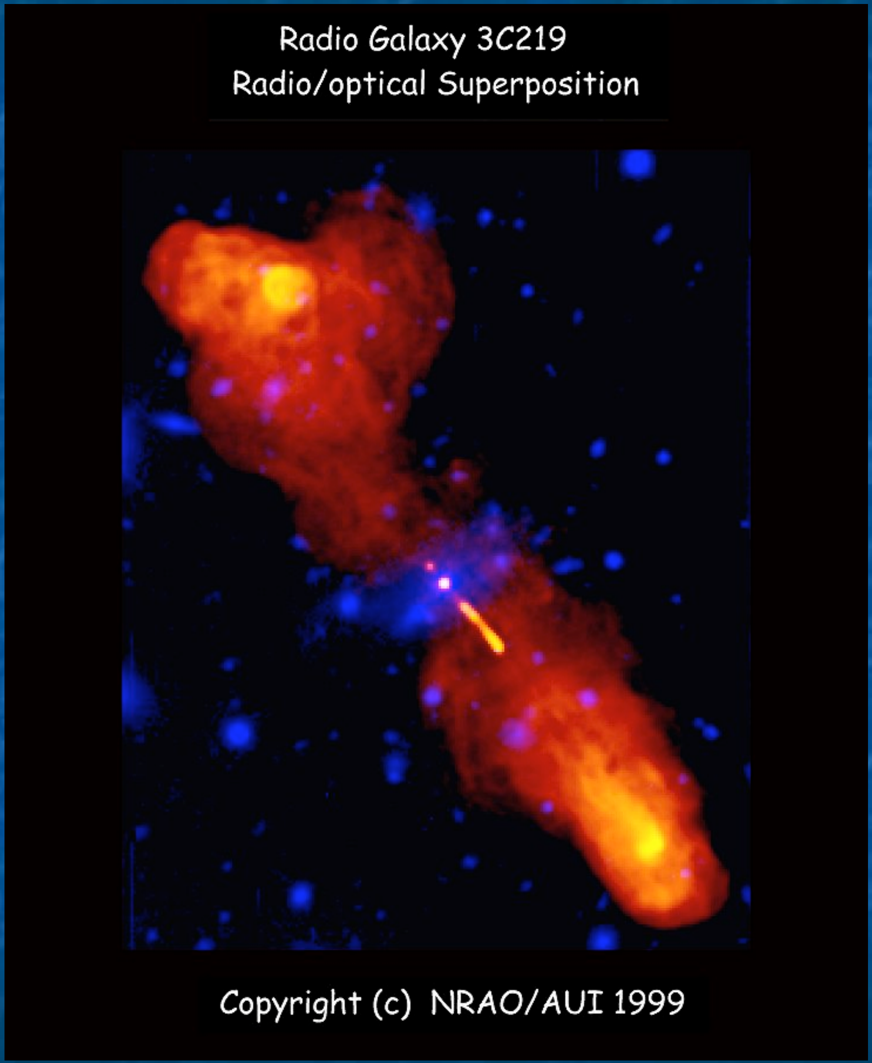
Radio Galaxy



- A class of AGN
  - SMBH at centers of active galaxies radiate huge amounts of energy $\Rightarrow$ AGN
- Strong radio emission, in a pair of lobes / cocoons extending over 100s of kpc - Mpc
- Mostly hosted by giant elliptical galaxies

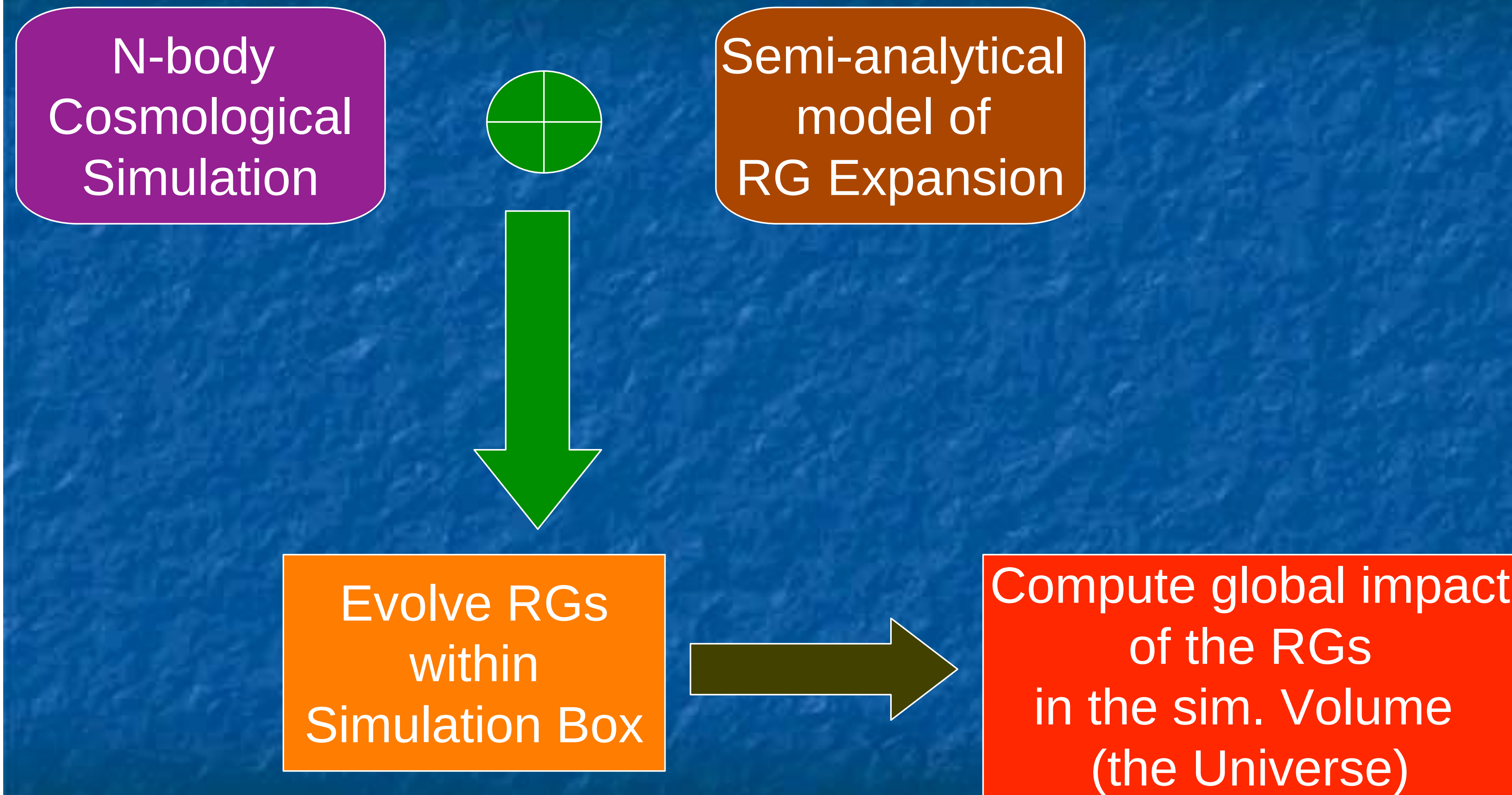
Motivation & Wider Implications

- Expanding RGs affected galaxy formation & evolution during the Quasar Era ($1.5 < z < 3$)
- Goal : Probe the large-scale impact of the cosmological population of RGs over the Hubble time

- How much volume of the Universe do the radio lobes occupy ?
- Possible impact in the filled volumes :
  - Trigger star formation

    Rees – 1989; De-Young – 1991, Gopal-Krishna & Wiita – 2001
  - Spread magnetic field into IGM
  - Metal enrichment of the IGM ⇒ (Joël Germain's talk)
  - Affect the Matter Power Spectrum

Methodology



Cosmological Simulation

- N-body simulations of a cosmological volume
- *PM* (particle-mesh) code
  - Written by Hugo Martel

- 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

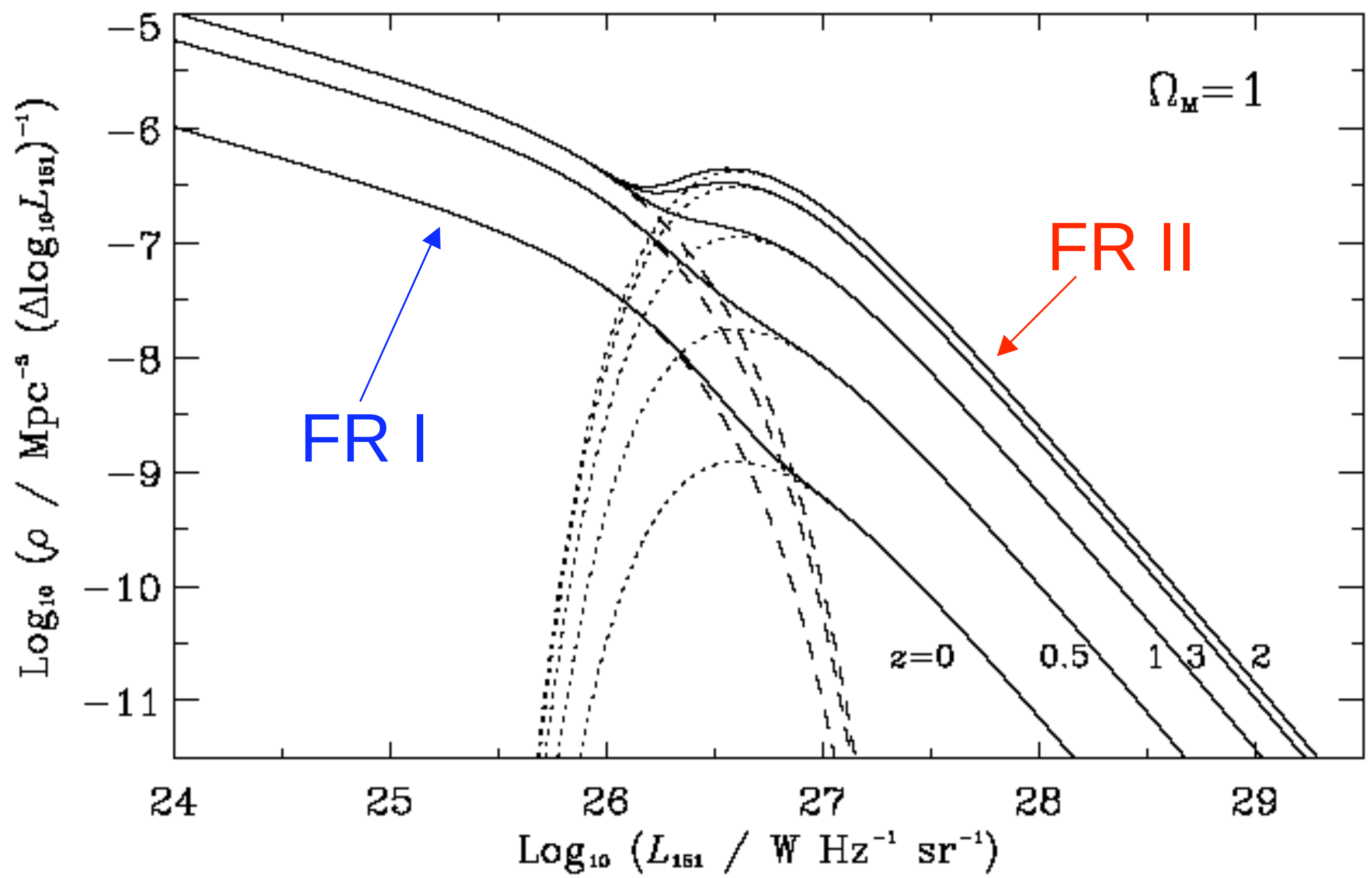
- Radio Luminosity Function, $\rho(L, z)$
  - From observed low-frequency 3CRR, 6CE and 7CRS complete samples
- Number of RGs : $dN(L,z) = \rho(L,z)d[\log_{10} L]V_{box}$
- Jet kinetic power : [Koerding, E.G. et al. 2008, MNRAS,383, 277]

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

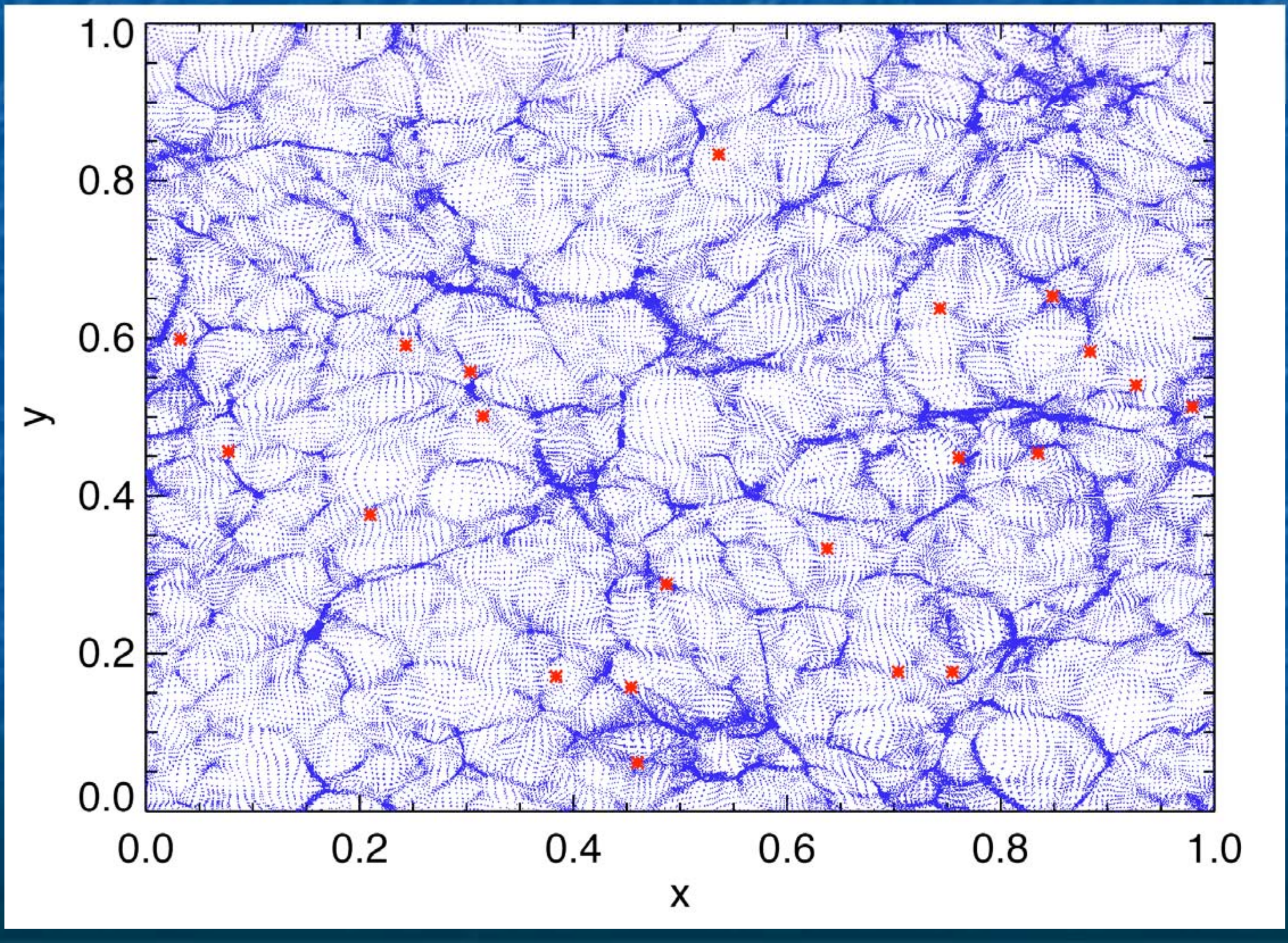
- RG lifetime
  - Fixed : τ_{RG} = 10, 100, 500 Myr
  - Variable : $\tau_{RG} \propto 1/\sqrt{Q_0}$
    - Daly, R.A. & Guerra E.J. (2002, AJ, 124, 1831)
    - Daly, R.A. et al. (2009, ApJ, 691, 1058)

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

<u>Active Life</u>

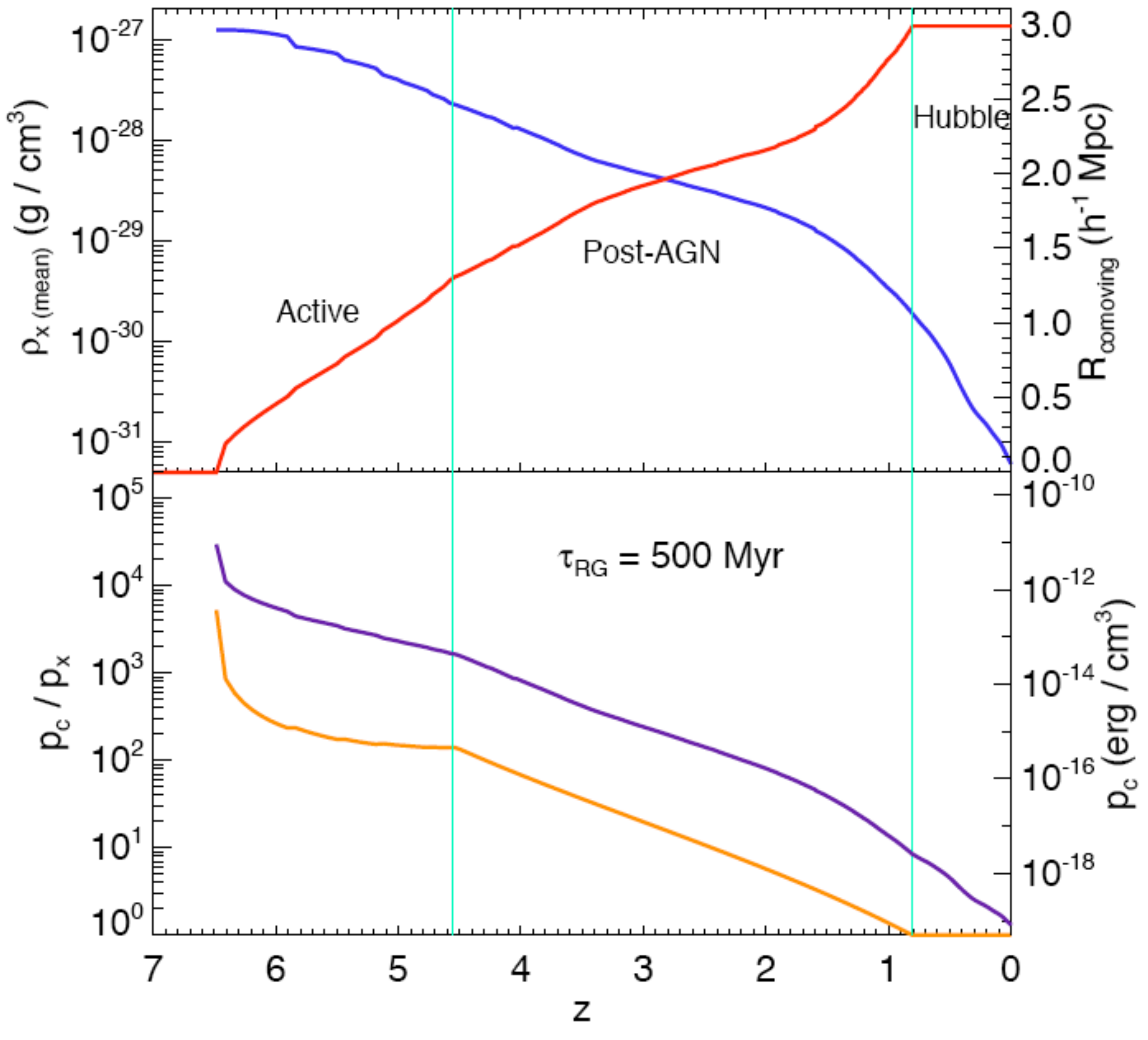
- Central SMBH is actively accreting
- Self-similar RG expansion (cylindrical shape)
- Highly overpressured : $p_c >> p_x$

<u>Post-Activity Phase</u>

- SMBH is no more active $\Rightarrow$ 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.

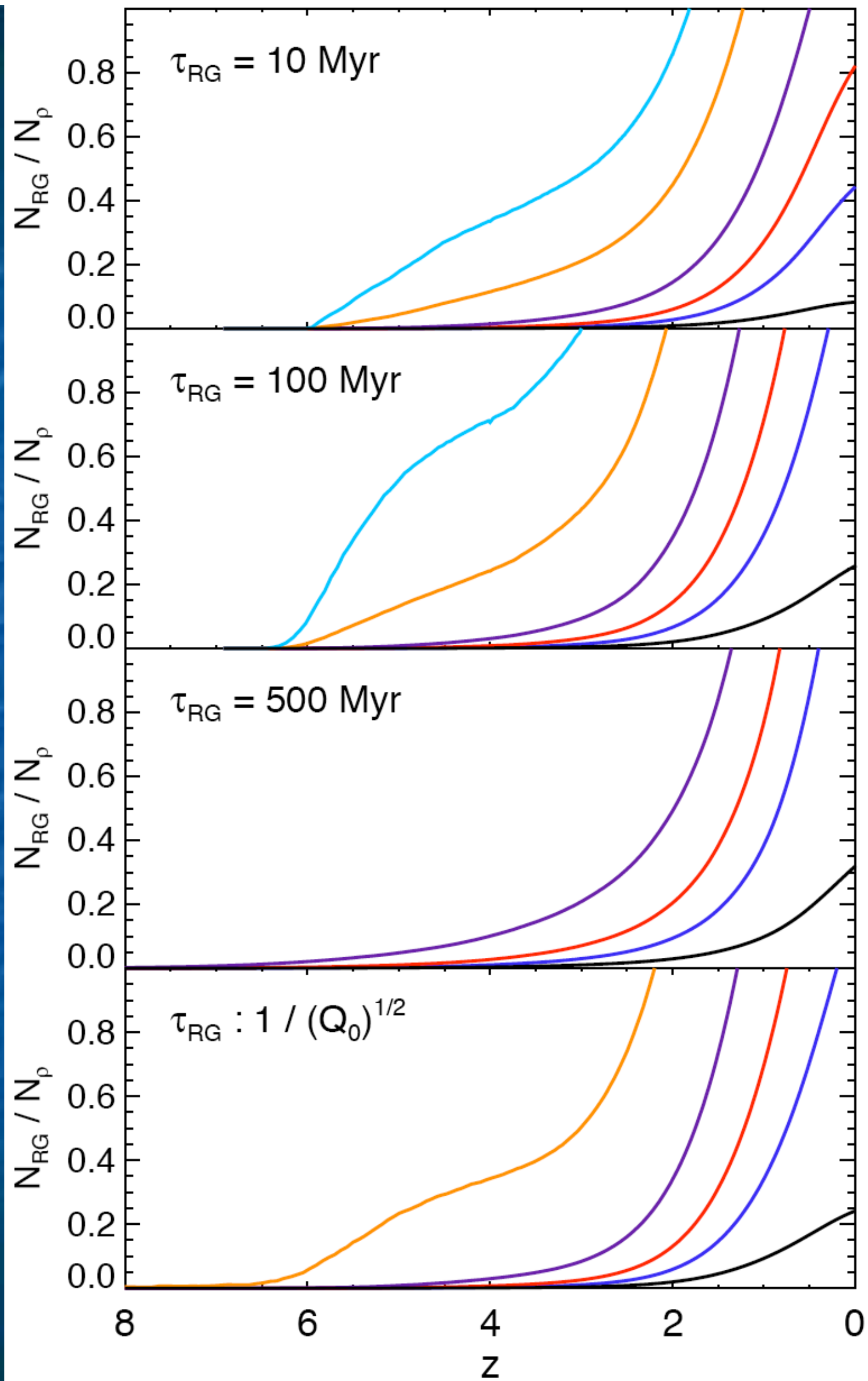
Vertical blue lines separate phases of expansion: Active, Post-AGN and Hubble.

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

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

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



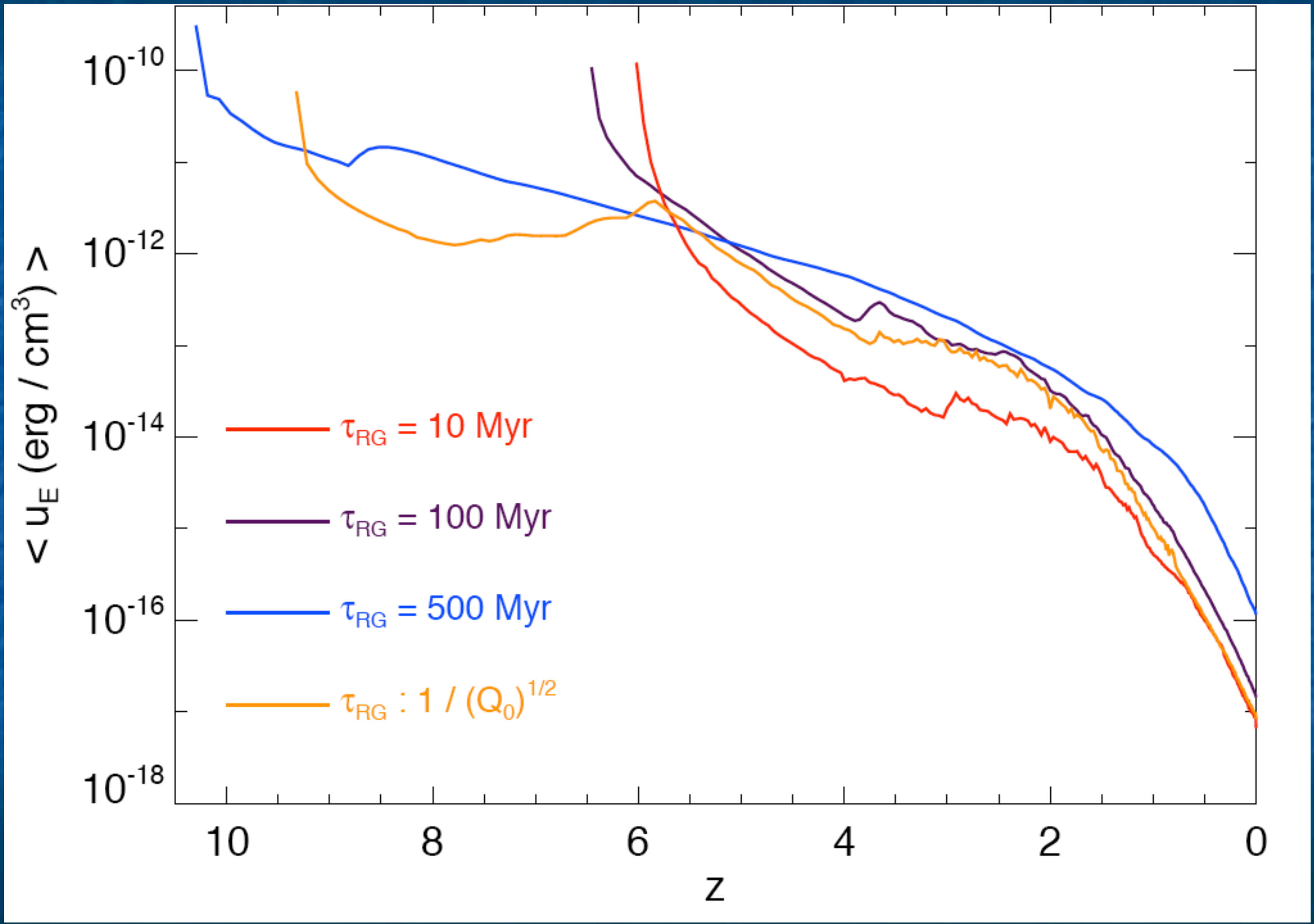
Fractional Volumes of box of various overdensities filled by RGs

(N_ρ *with* C = *0, 1, 2, 3, 5, 7)*

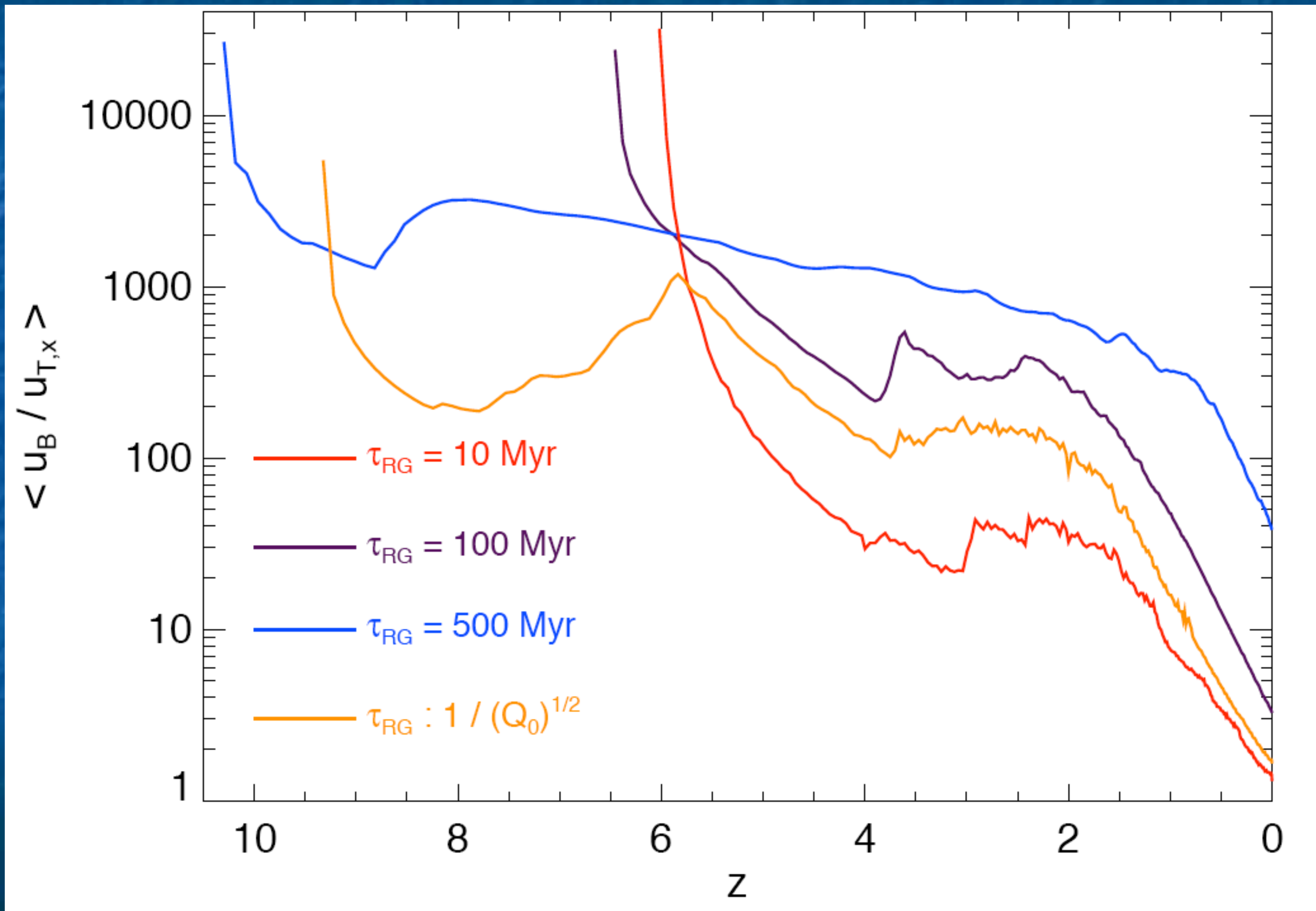
Global Average Values

- 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 : $\overline{u}_{T,x} = \frac{3\overline{\rho}_x k T_x}{2\mu}$
- Volume-weighted average : $\langle \mathrm{A} \rangle = \frac{\sum \mathrm{A} V_{RG}}{\sum V_{RG}}$

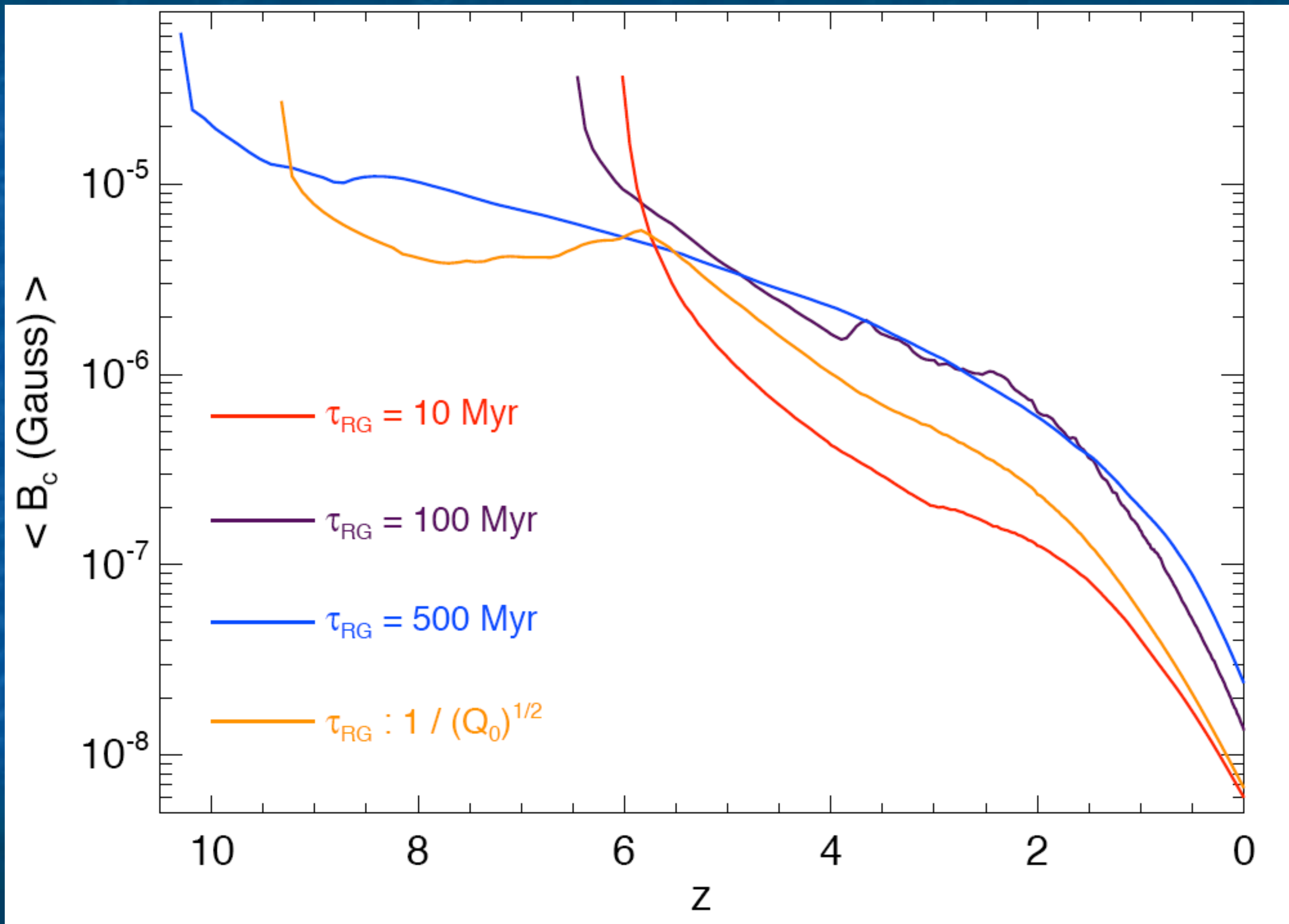
Total Energy Density Inside RG Cocoon Volumes



Ratio of Magnetic Energy Density to Mean External Thermal Energy Density



Equipartition Magnetic Field Within RG Filled Volumes



Matter Power Spectrum, $P(k)$

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

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

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

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

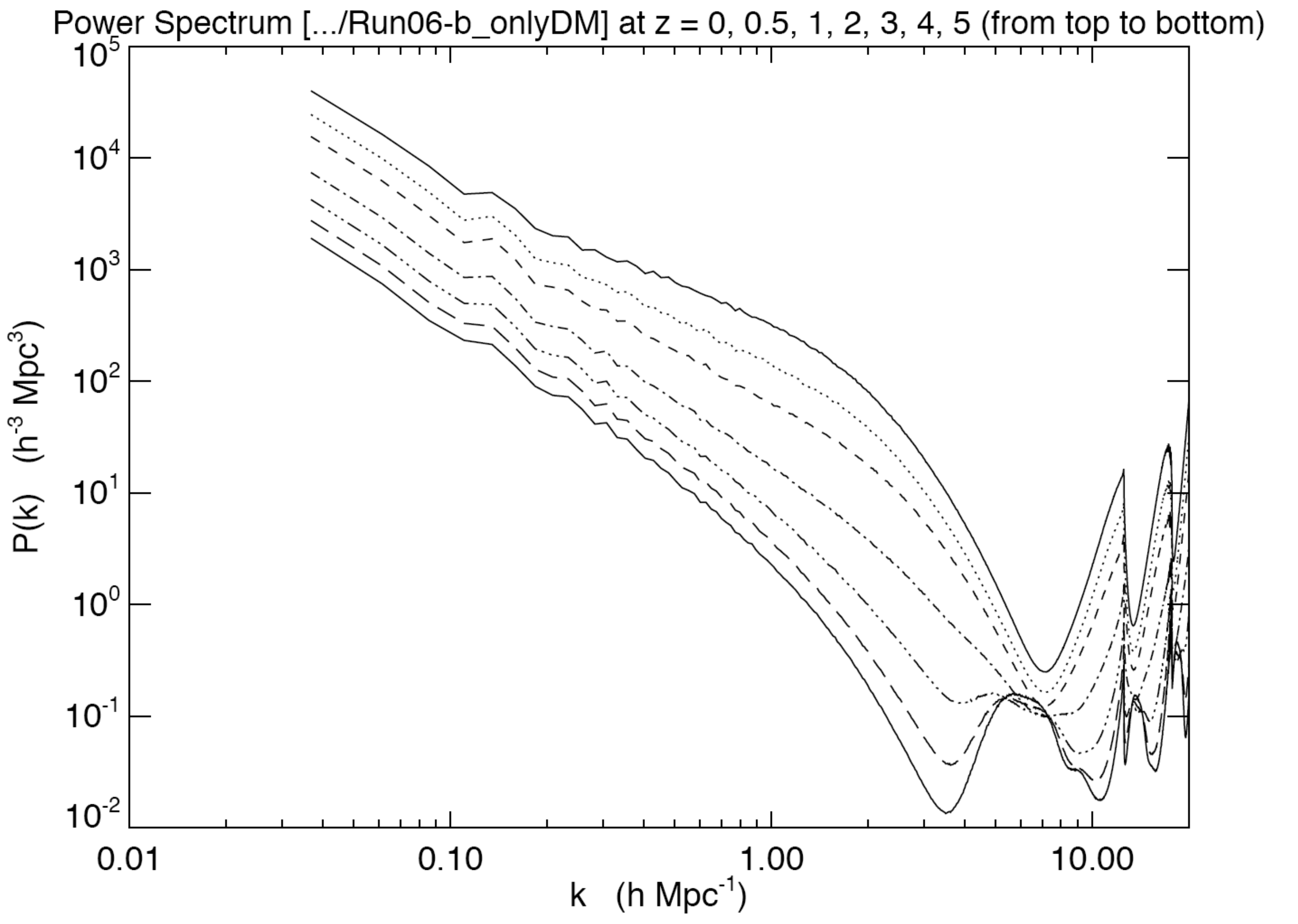
- Baryons are displaced from interior cells of RG volume and collected in the boundary cells
- η = Efficiency of baryon stripping
- Increased density of boundary cells:

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

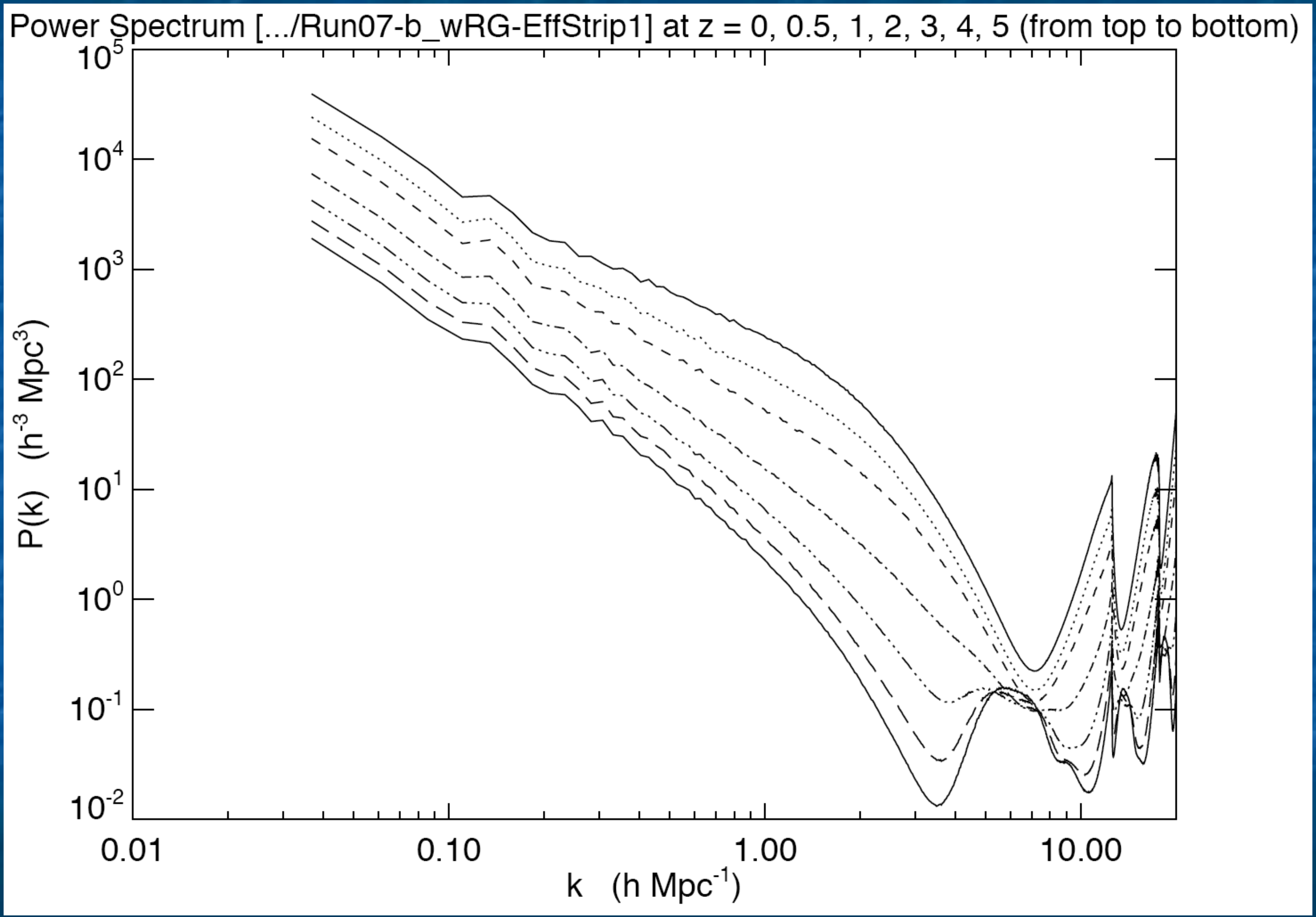
- Decreased density of interior cells:

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

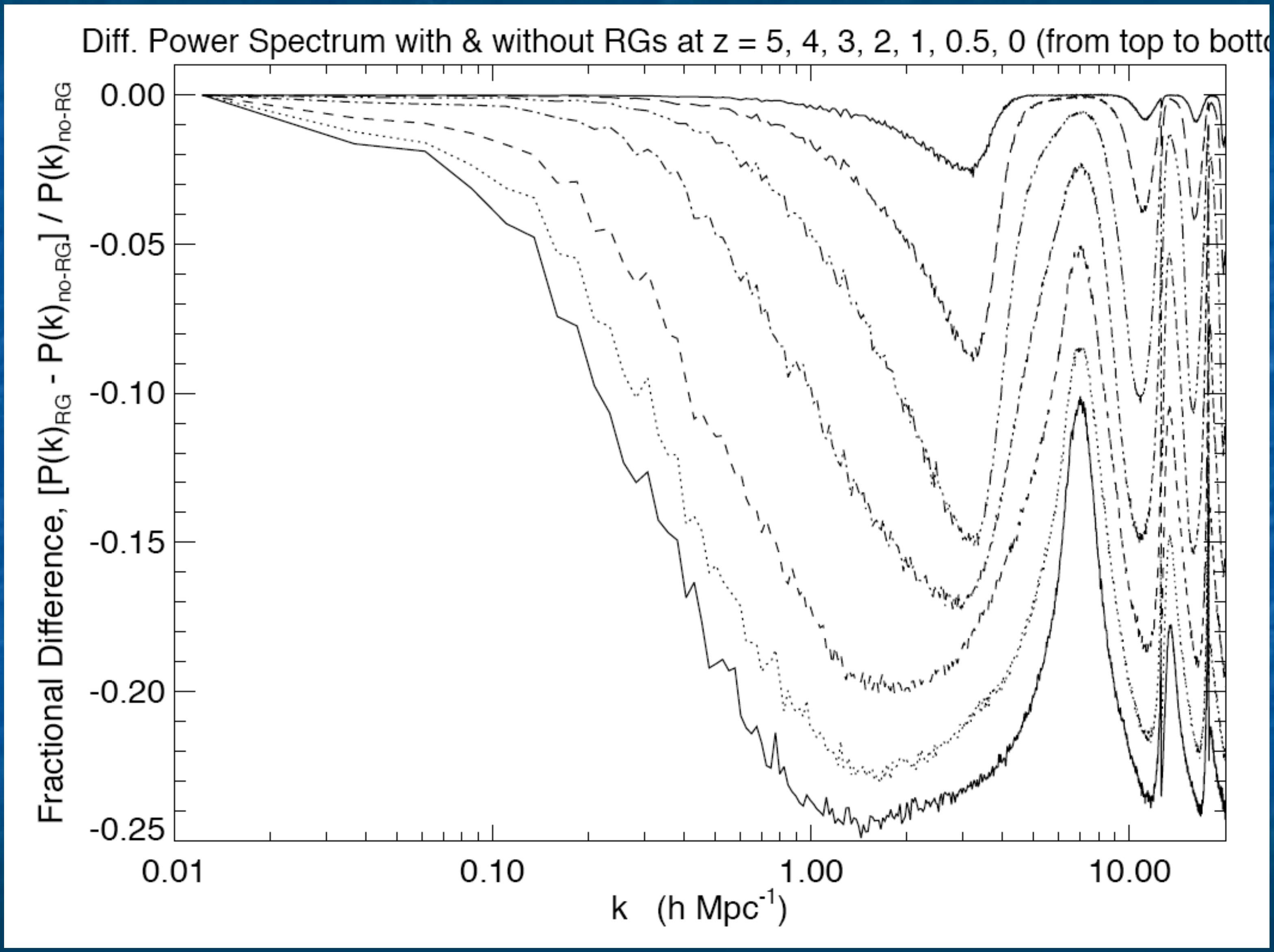
Baryons Unperturbed by RGs



Baryons Displaced by RGs (η = 1)



Difference Caused by RGs



Summary

- Implemented a semi-analytical model of RG expansion in N-body simulations
- Published results [Barai, P. 2008, ApJ, 682, L17]
  - RG cocoons 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

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

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

$$p_c = \rho_x \left(\frac{dR_0}{dt} \right)^2$$

- Overpressured : $p_c >> p_x$

Post-Activity Evolution

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

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

  - 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