Cosmological Simulations of AGN Outflows Propagating Anisotropically on Large Scales

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Introduction

- Outflows observed in a large fraction of Active Galactic Nuclei (AGN)

- Goal :

  Investigate the large-scale impact of the cosmological population of AGN outflows over the Hubble time

  - Metal enrichment of the IGM
  - Volume fraction of the Universe enriched

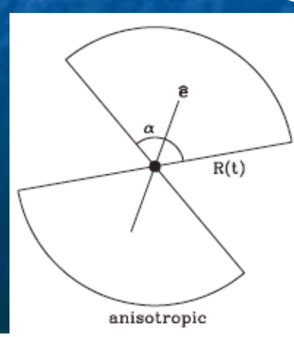
Motivation

- Previous studies
  - Furlanetto & Loeb 2001, ApJ, 556, 619
  - Scannapieco & Oh 2004, ApJ, 608, 62
  - Levine & Gnedin 2005, ApJ, 632, 727
  - Barai, 2008, ApJ, 682, L17

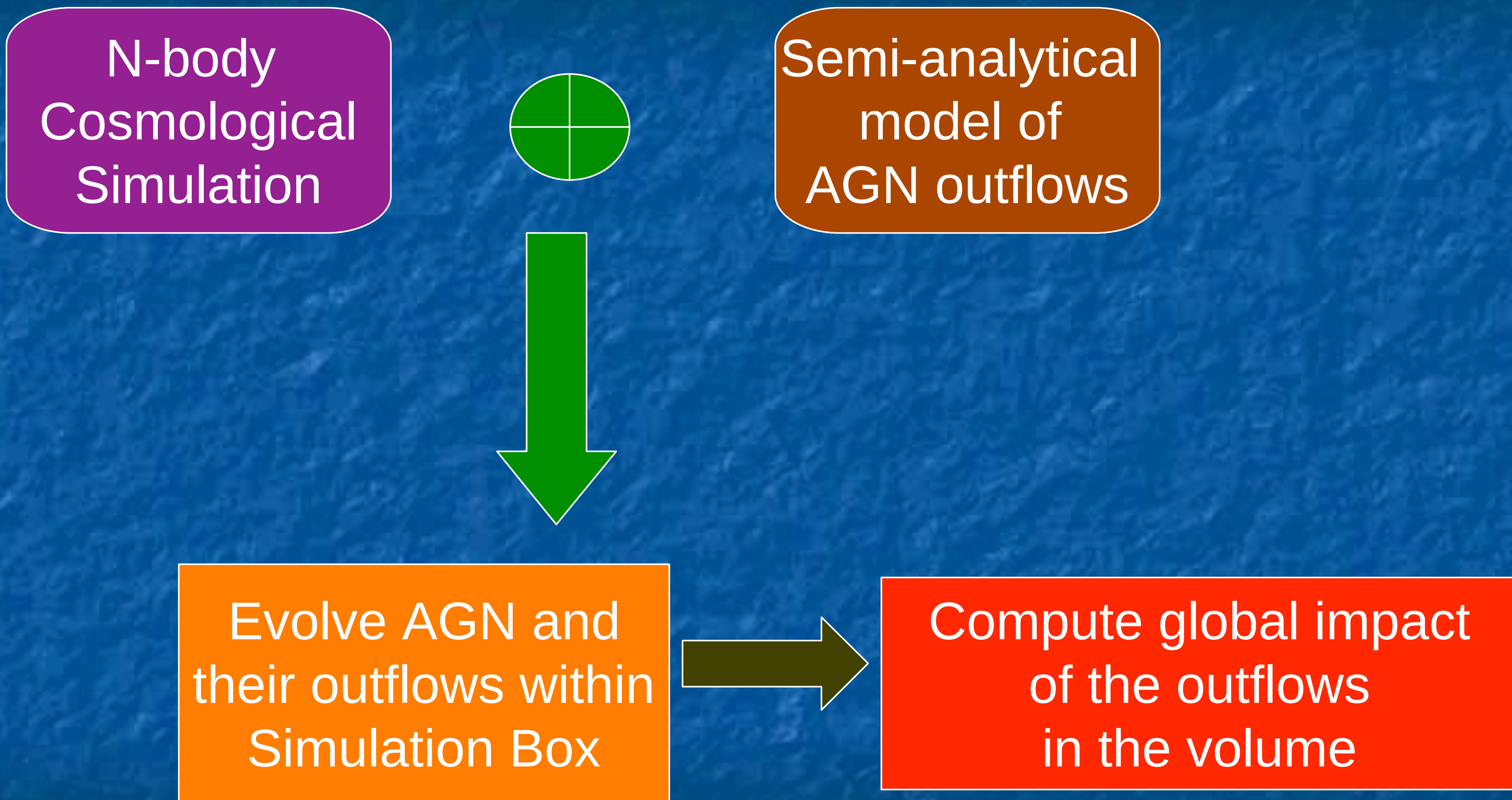
Spherical Outflow

Our Improvement

- Anisotropically expanding outflow
- Track enrichment history of IGM



Methodology



Cosmological Simulation

- N-body simulations of a cosmological volume
- *P^3M* (particle-particle/particle-mesh) code

- Box size (comoving) = 128 h^{-1} Mpc
- 256^3 particles, 512^3 grid

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

Redshift & Luminosity Distribution

- Observed AGN bolometric luminosity function
  (Hopkins, Richards & Hernquist 2007, ApJ, 654, 731)

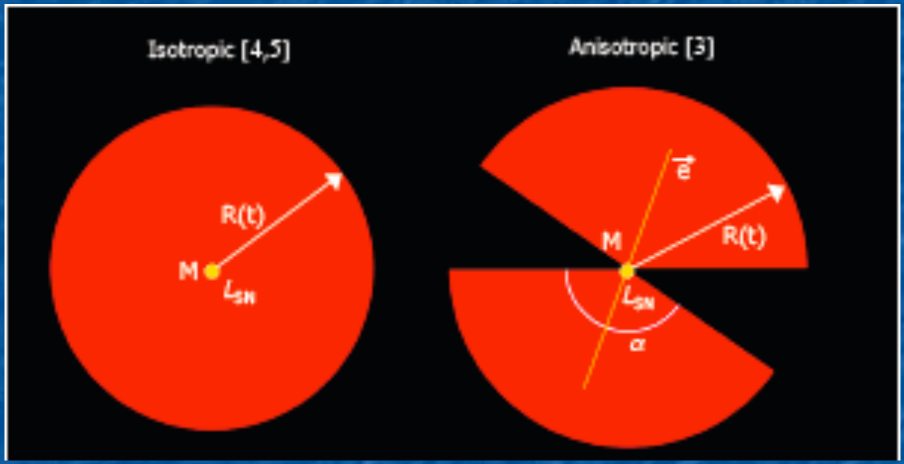
$$\varphi(L) = \frac{\varphi_*}{(L/L_*)^{\gamma_1} + (L/L_*)^{\gamma_2}}$$

- Constant AGN lifetime, $T_{\rm AGN} = 10^8$ yr
- Fraction of AGN hosting outflows = 0.6
  - (Ganguly, R. & Brotherton, M.S. 2008, ApJ, 672, 102)

- Total number of sources from QLF = 1535362
- Locate AGN at local density peaks within simulation box

Outflow Geometry

- Bipolar Spherical Cone (Pieri, Martel & Grenon 2007, ApJ, 658, 36)



$$r \le R$$
$$0 \le \theta \le \frac{\alpha}{2} \text{ ,or, } \left(\pi - \frac{\alpha}{2}\right) \le \theta < \pi$$
$$0 \le \phi < 2\pi$$

$$V = \frac{4}{3}\pi R^3\left(1 - \cos\frac{\alpha}{2}\right)$$

- Expands anisotropically in large scales
  - Away from over-dense regions, into under-dense regions
  - Follows path of Least Resistance --- Direction along which density drops the fastest

Semi-analytical Model for Outflow

- Outflow expansion :

$$\ddot{R} = \frac{4\pi R^2}{M_S}\left(1 - \cos\frac{\alpha}{2}\right)\left(p_T + p_B - p_x\right) - \frac{G}{R^2}\left(M_d + M_{gal} + \frac{M_S}{2}\right) + \Omega_\Lambda H^2 R - \frac{\dot{M}_S}{M_S}\left(\dot{R} - v_p\right)$$

Pressure gradient | Gravitational deceleration | Cosmological constant | Drag force

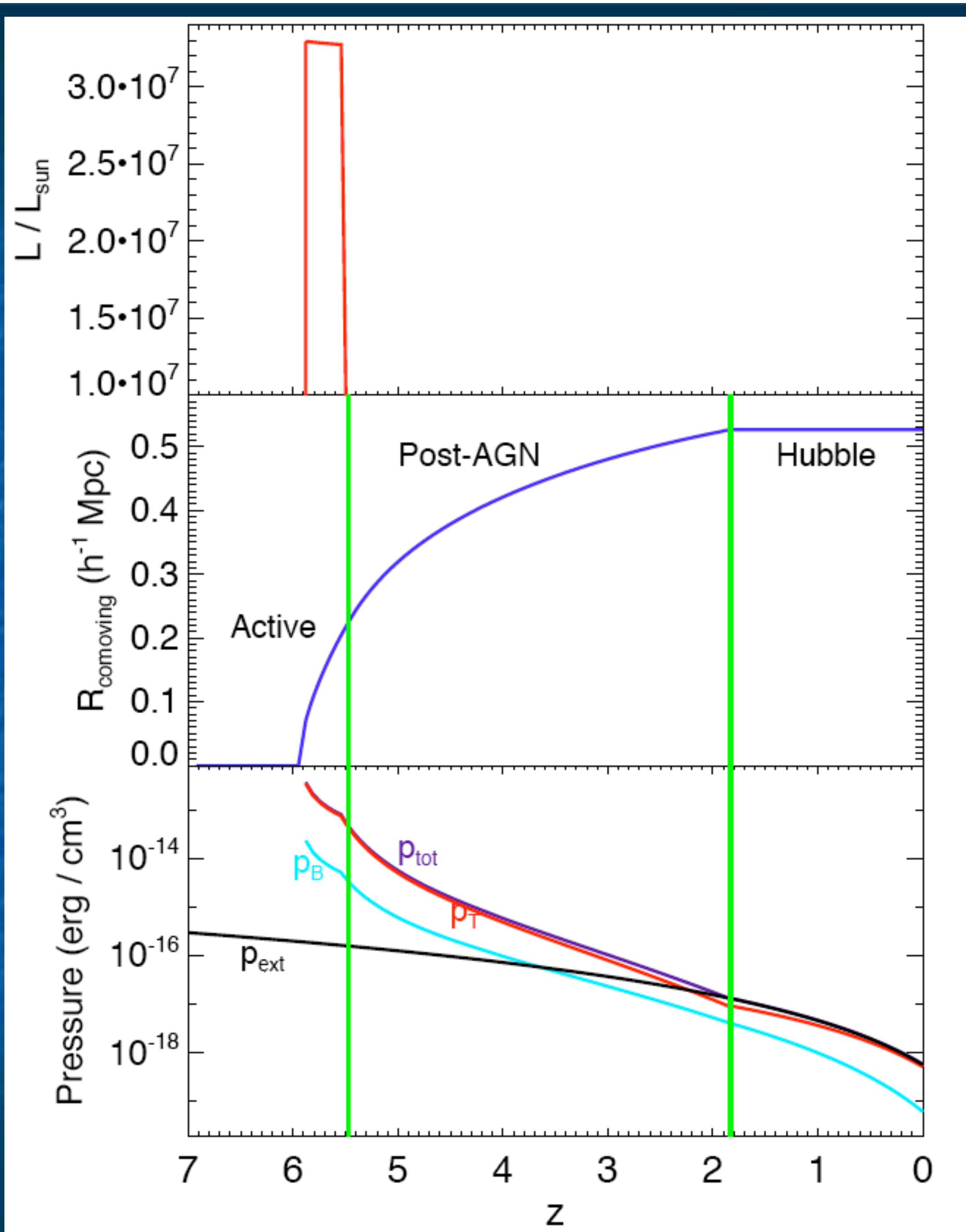
- Thermal pressure :

$$\dot{p}_T = \frac{\Lambda}{2\pi R^3\left[1 - \cos(\alpha/2)\right]} - 5 p_T \frac{\dot{R}}{R}$$

Thermal energy injection | Outflow expansion

- Magnetic pressure :

$$\dot{p}_B = \frac{\varepsilon_B L_{AGN}}{4\pi R^3\left[1 - \cos(\alpha/2)\right]} - 4 p_B \frac{\dot{R}}{R}$$



Evolution of a single outflow.

Top: total luminosity.

Middle: Comoving radius.

Bottom: Pressures (external IGM, magnetic, thermal and total outflow).

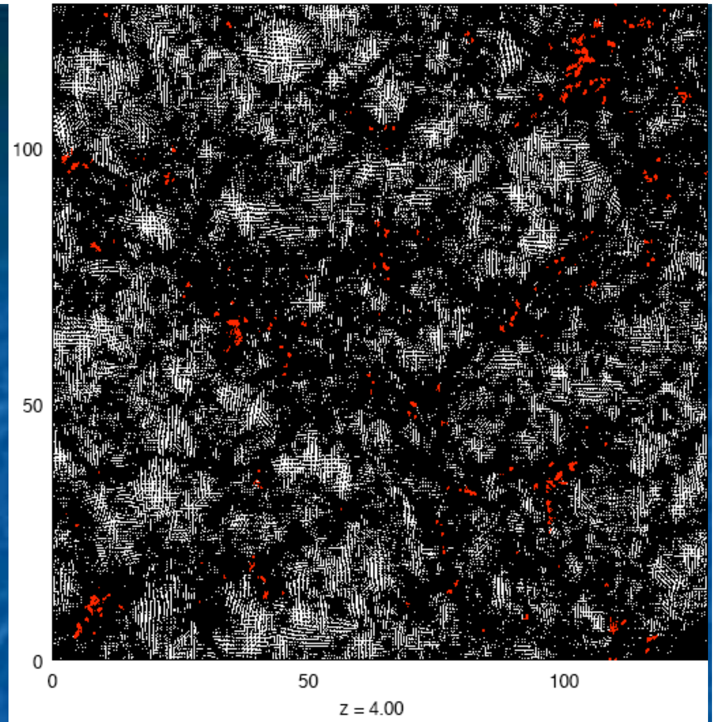
Vertical green lines separate phases of expansion: active, post-AGN and Hubble.

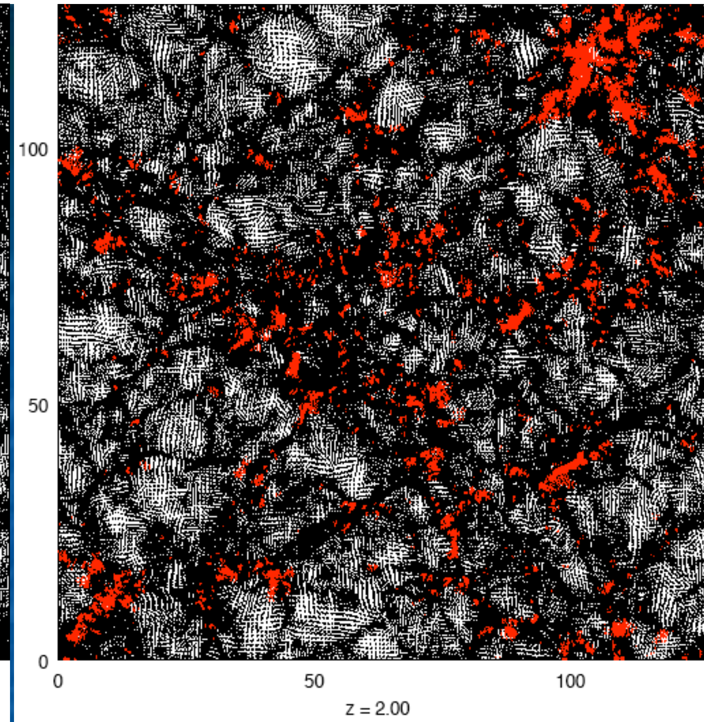
Metal Enrichment

- Metals produced by AGN host galaxy are spread to the surrounding IGM by outflows

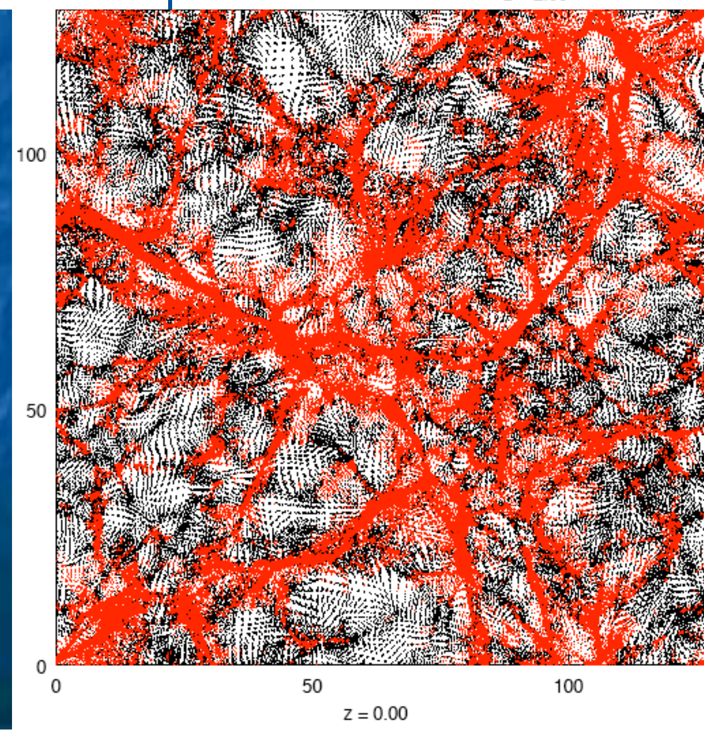
- Particles (of PM code) intercepted by each outflow volume are flagged as enriched
  - For all the outflows existing in the box
  - At every redshift

  $\Rightarrow$ Enrichment history of IGM





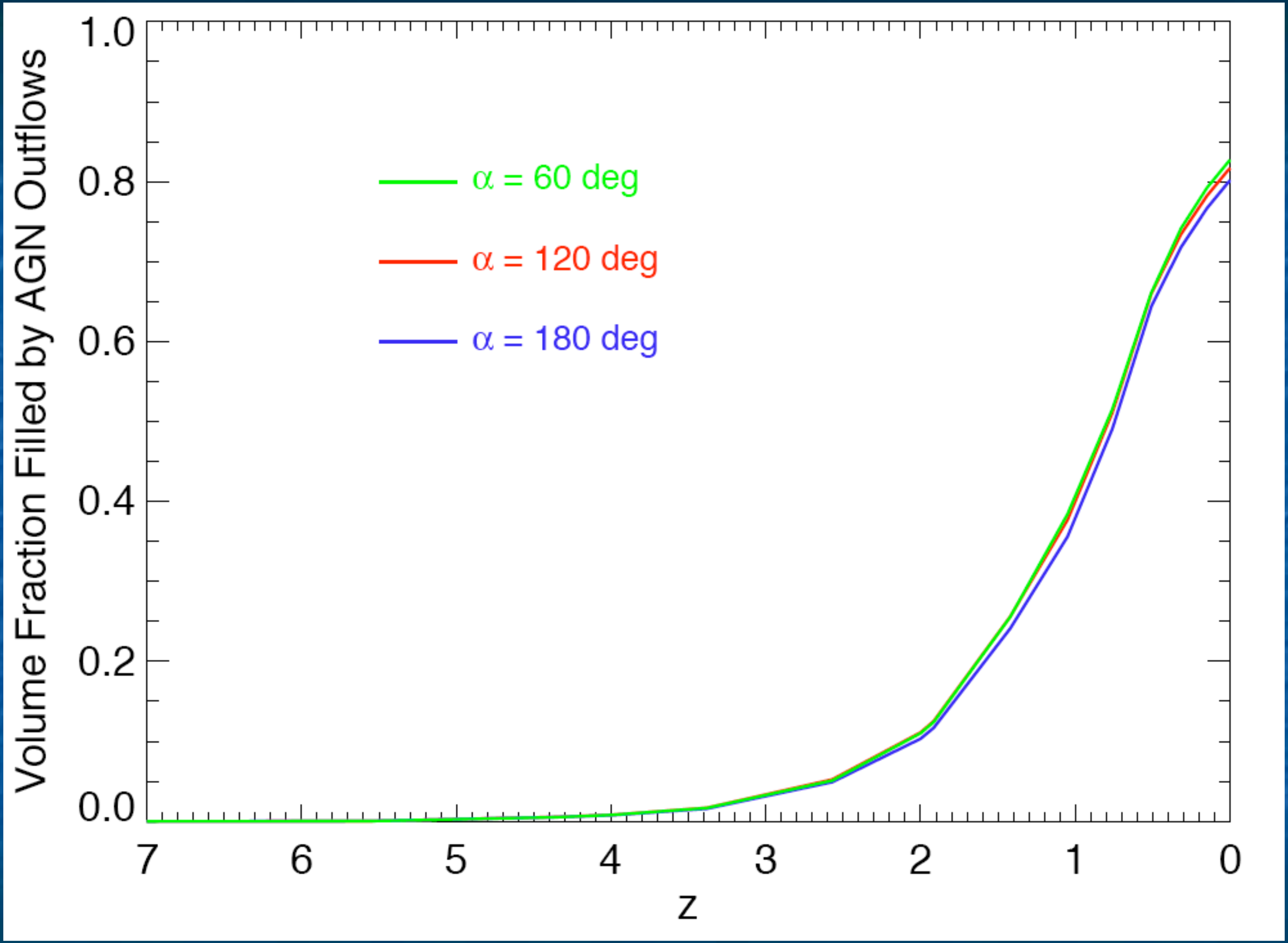
A 4 Mpc wide slice of the box at different redshifts. Black dots: Non-enriched particles. Red dots: Enriched particles.



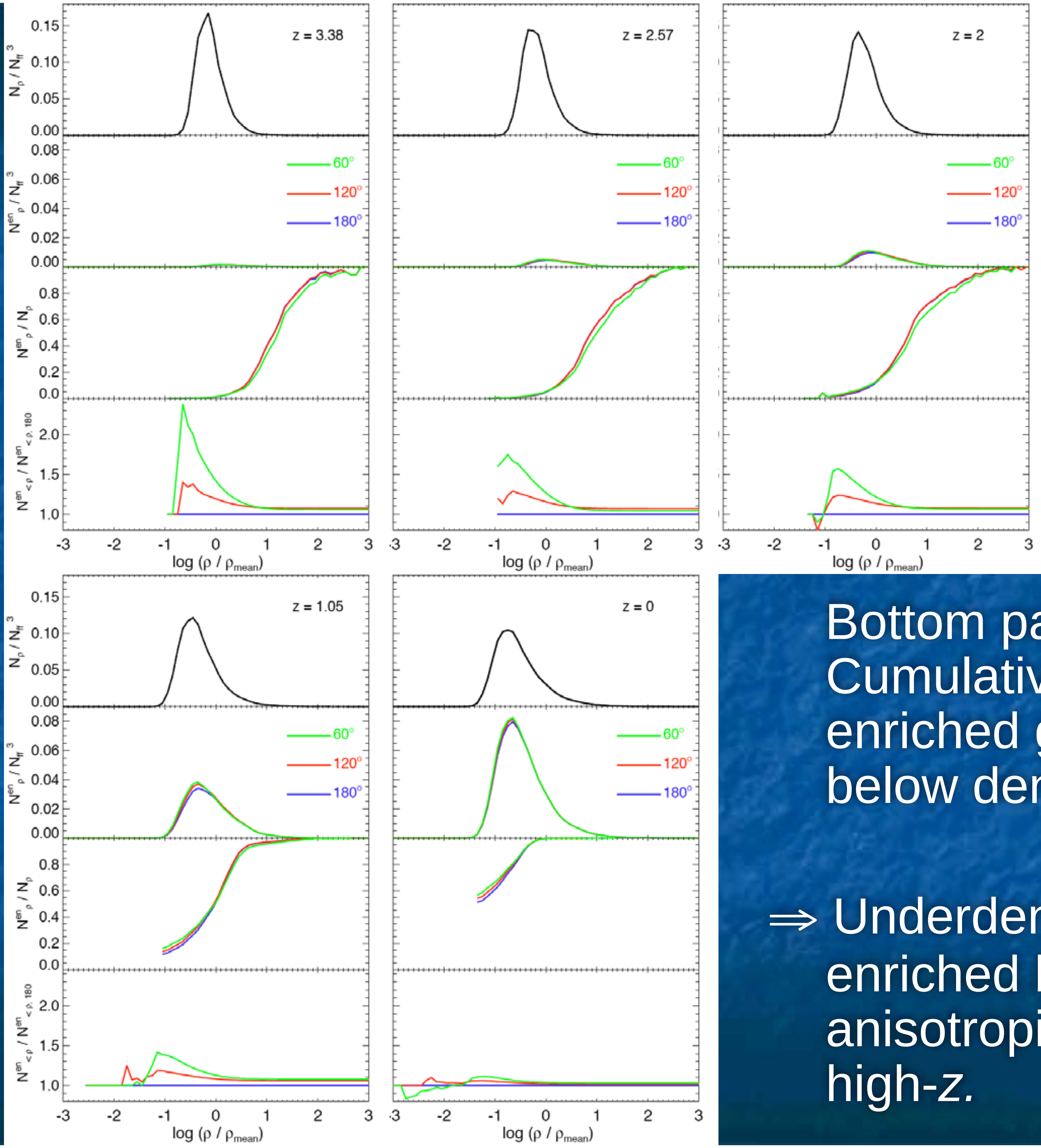
Compute IGM Volume Enriched

- Use SPH smoothing algorithm
  $\Rightarrow$ Get density on a grid $N_{ff}^3 = 256^3$
- Each particle
  - Ascribed a Smoothing Length h
  - Extends over a spherical volume of radius $1.7h$

- Count mesh cells (of N_{ff} grid) occurring inside the spherical volume of one/more enriched particles
- Total number of enriched cells, N_{AGN}
  $\Rightarrow$ Enriched volume of box
- Volume fraction of box enriched by outflows
  $= N_{AGN} / N_{ff}^3$



Volume fractions enriched (for different opening angles).



Bottom panel: Cumulative number of enriched grid points below density threshold.

⇒ Underdense regions enriched by more anisotropic outflows at high-*z*.

Summary

- Implemented a semi-analytical model of anisotropic AGN outflows in N-body simulations

- AGN outflows are found to enrich 80% of the volume of the Universe by the present
- Low-density regions preferentially enriched by more anisotropic outflows

➢ Future work :

Track values of metal abundances in the IGM, and plot iso-metallicity contours.

References

- Furlanetto, S.R. & Loeb, A. 2001, ApJ, 556, 619 (FL01)
- Ganguly, R. & Brotherton, M.S. 2008, ApJ, 672, 102
- Hopkins, P.F., Richards, G.T. & Hernquist, L. 2007, ApJ, 654, 731
- Levine, R. & Gnedin, N.Y. 2005, ApJ, 632, 727
- Pieri, M. M., Martel, H. & Grenon, C. 2007, ApJ, 658, 36 (PMG07)
- Scannapieco, E. & Oh, S.P. 2004, ApJ, 608, 62

Direction of Least Resistance (DLR)

- In large-scale filamentary structures, outflow direction is obtained from pressure of surrounding medium

<u>Implementation</u>

- Find DLR around density peaks
- Taylor expansion of density around a peak inside sphere of radius R★
- Rotate Cartesian coordinates to make cross-terms vanish

$$\delta\left(x', y', z'\right) = \delta_{peak} - Ax'^2 - By'^2 - Cz'^2$$

- Largest of the coefficients A, B, C ⇒ DLR

Ambient Medium for AGN Outflows

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

All Sources in Box from QLF. $N_{AGN,total}$ = 1535362.