Metal Enrichment of the Intergalactic Medium by Anisotropic AGN Outflows on Cosmological Scales

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The Monster's Fiery Breath: Feedback in Galaxies, Groups, and Clusters

Introduction

- Outflows observed in a large fraction of AGN
- Influence the formation & evolution of galaxies, large-scale structures, & the intergalactic medium (IGM)
  - Enrich IGM with metals → modify cooling rate of star-forming gas
  - Eject proto-galactic gas by ram pressure stripping → suppress further star / galaxy formation
- 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

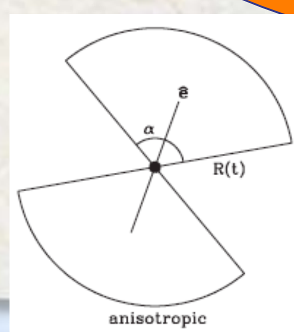
Motivation

- 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

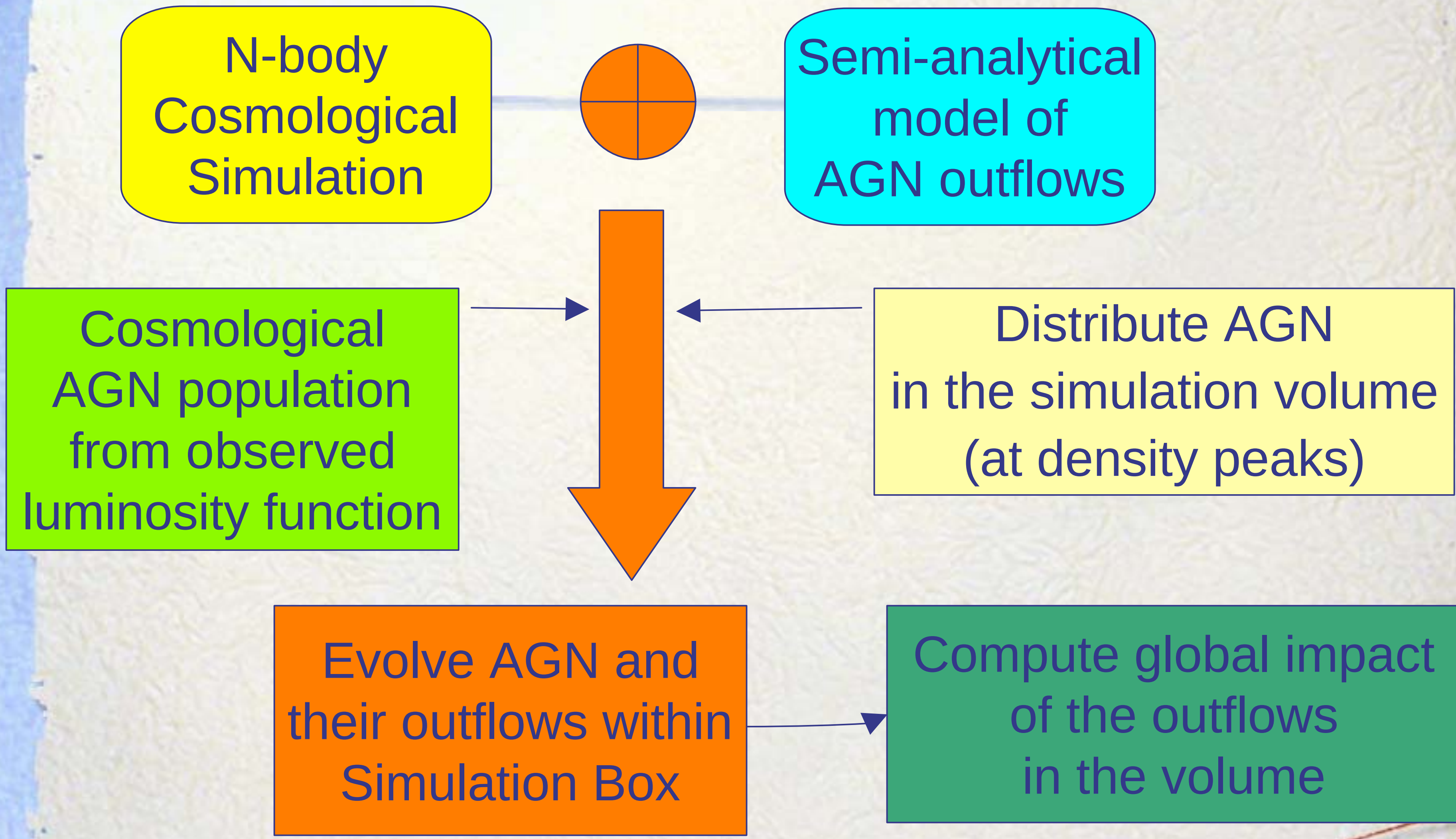
Spherical Outflow

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)

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

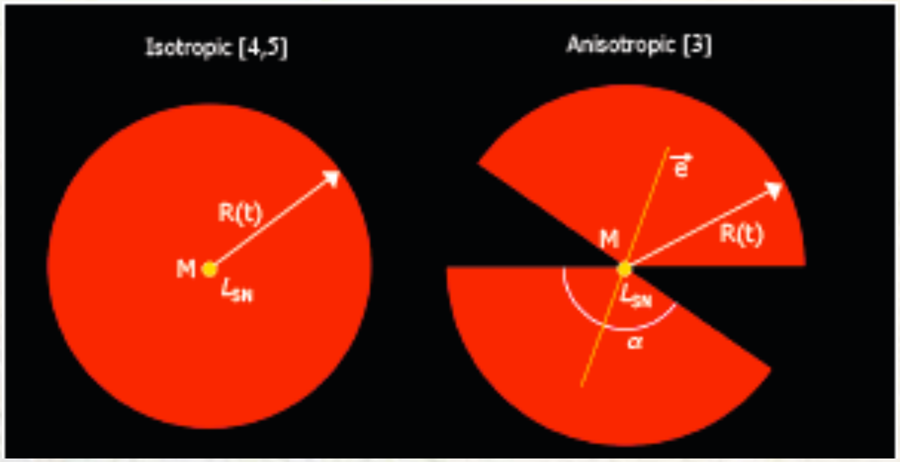
- Fraction of AGN hosting outflows = 0.6
  - (Ganguly, R. & Brotherton, M.S. 2008, ApJ, 672, 102)

- Using, AGN lifetime, $T_{AGN} = 10^8$ yr,
  Total number of sources from QLF = 1,535,362

- Locate AGN at local density peaks within simulation box

Outflow Geometry

- <u>Bipolar Spherical Cone</u> (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

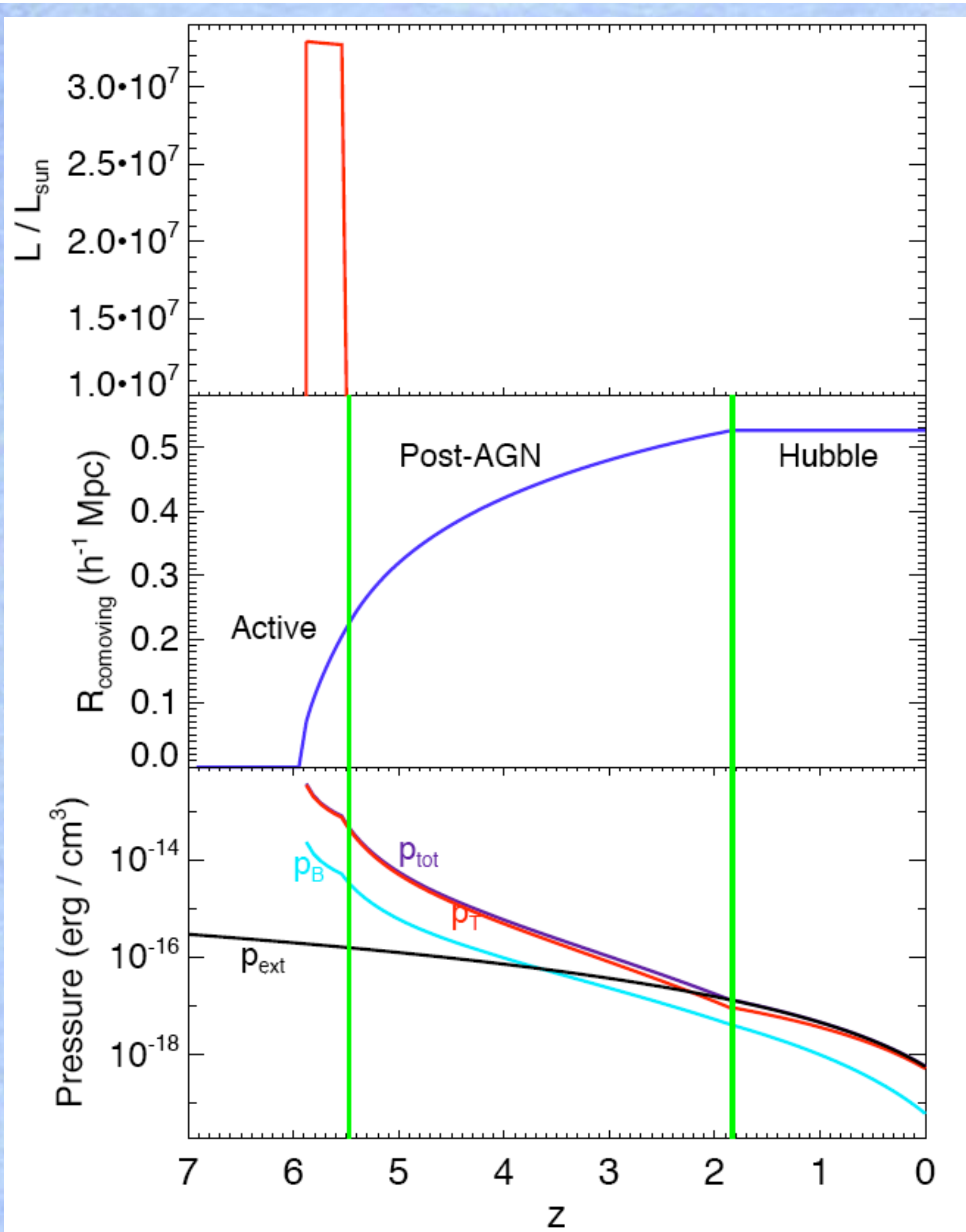
- Thermal pressure :

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

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).

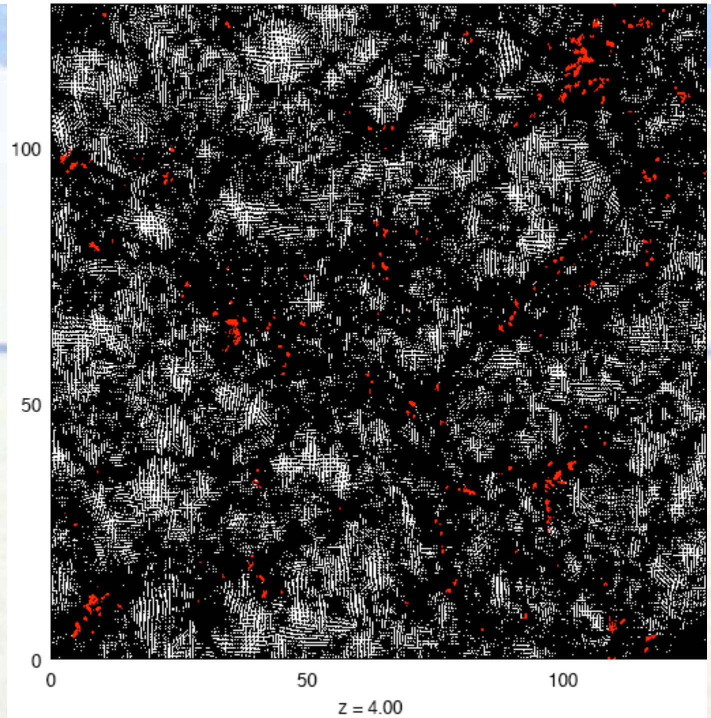
Vertical green lines separate phases of expansion: active, post-AGN and Hubble.

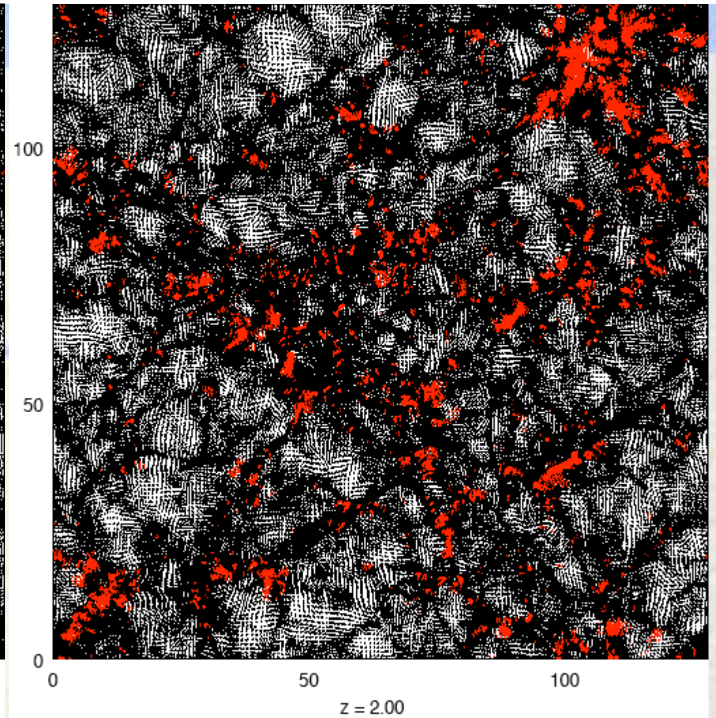
Metal Enrichment

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

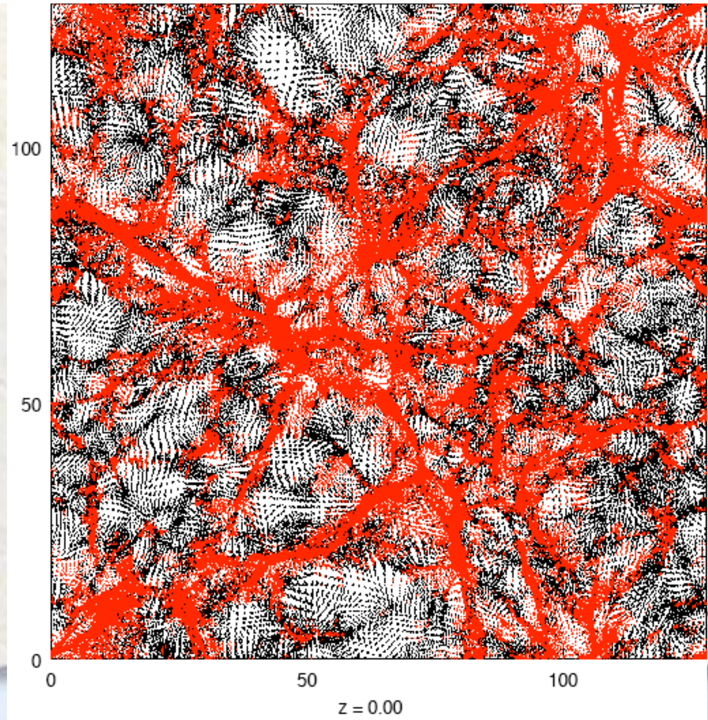
- Particles (of P^3M code) intercepted by each outflow volume are flagged as enriched
  - For all the outflows existing in the box
  - At every redshift

$\Rightarrow$ Enrichment history of IGM





A slice of the box (128/h Mpc × 128/h Mpc × 4/h Mpc) at different redshifts.



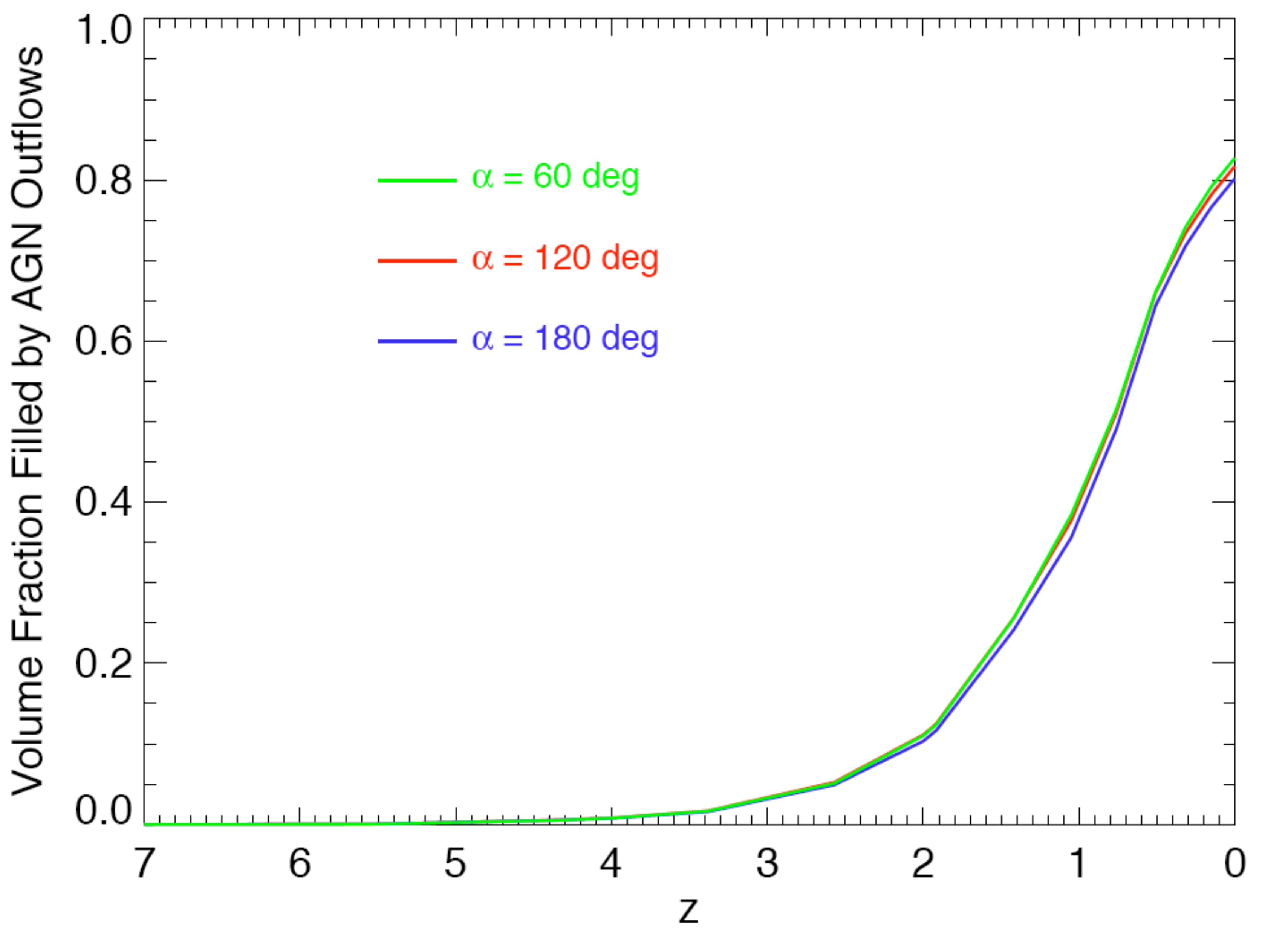
Black dots: Non-enriched particles.

Red dots: Enriched particles.

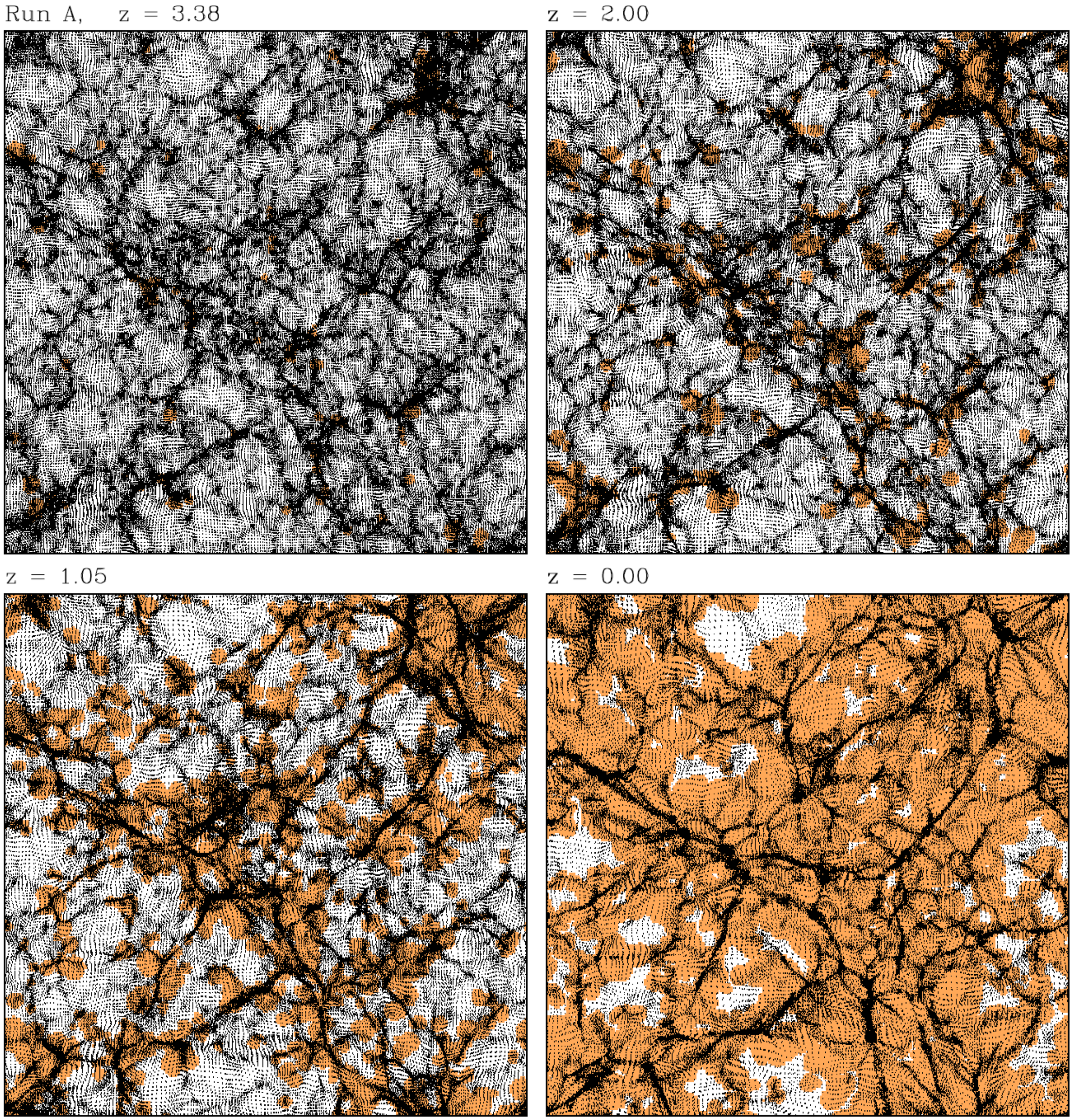
Compute IGM Volume Enriched

- Use SPH smoothing algorithm
  ⇒ 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}
  ⇒ Enriched volume of box
- Volume fraction of box enriched by outflows
  $= N_{AGN} / N_{ff}^3$



Volume fractions enriched (for different opening angles)

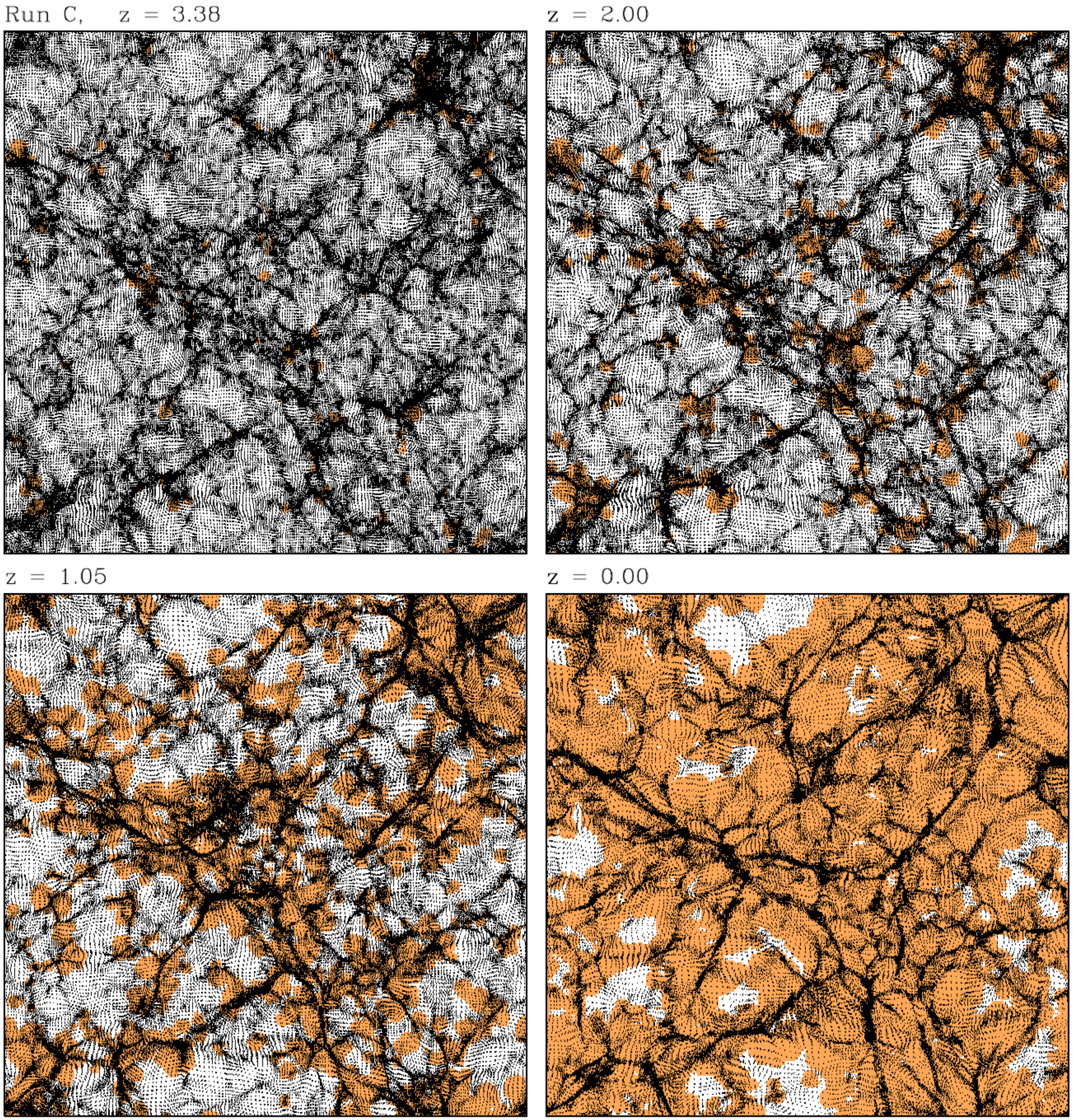


Evolution of metal distribution in a slice
(128/h Mpc × 128/h Mpc × 2/h Mpc).

Orange : enriched volumes.

Black dots : P^3M particles.

α = 180°

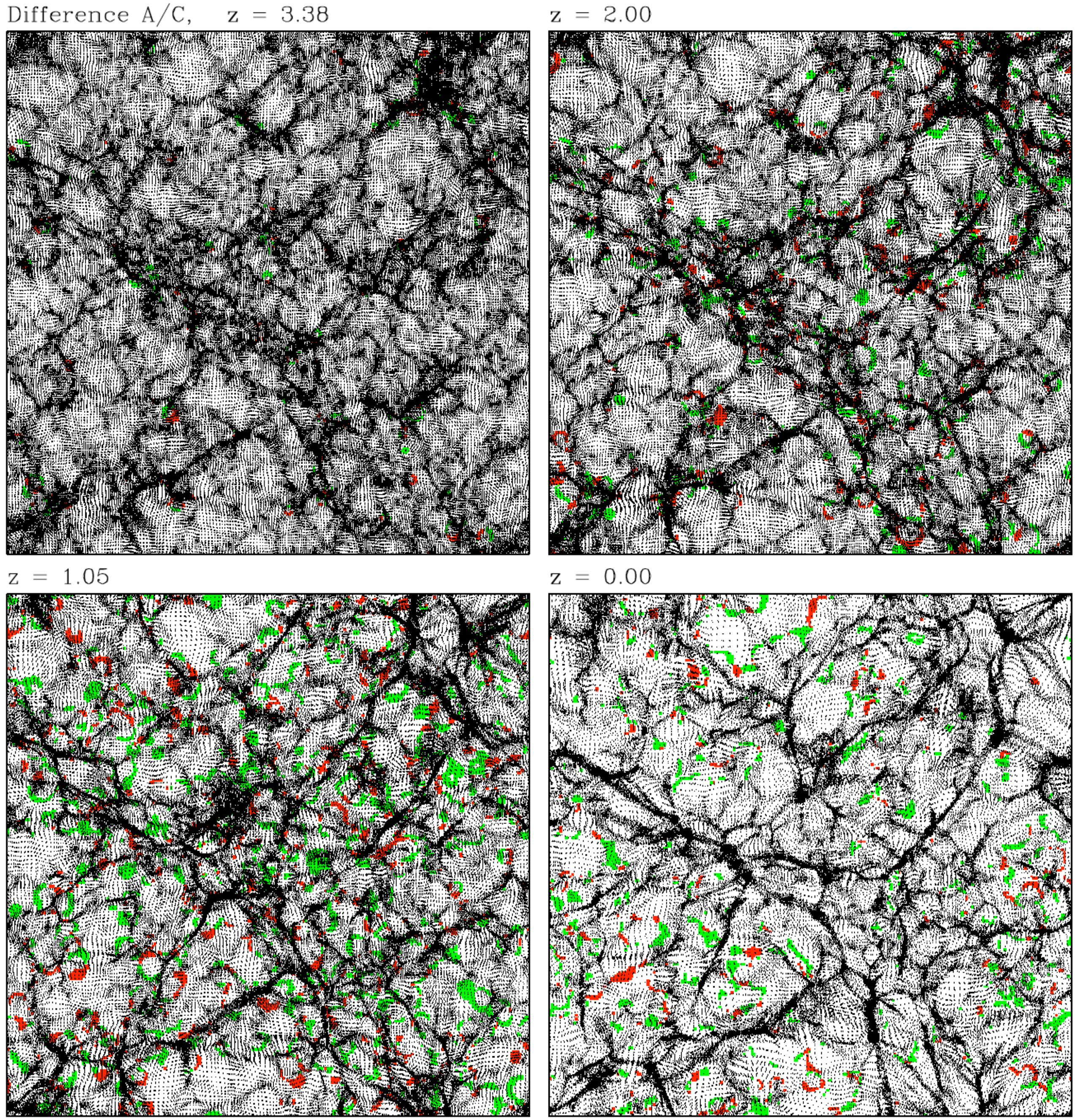


Evolution of metal distribution in a slice (128/h Mpc × 128/h Mpc × 2/h Mpc).

Orange : enriched volumes.

Black dots : P^3M particles.

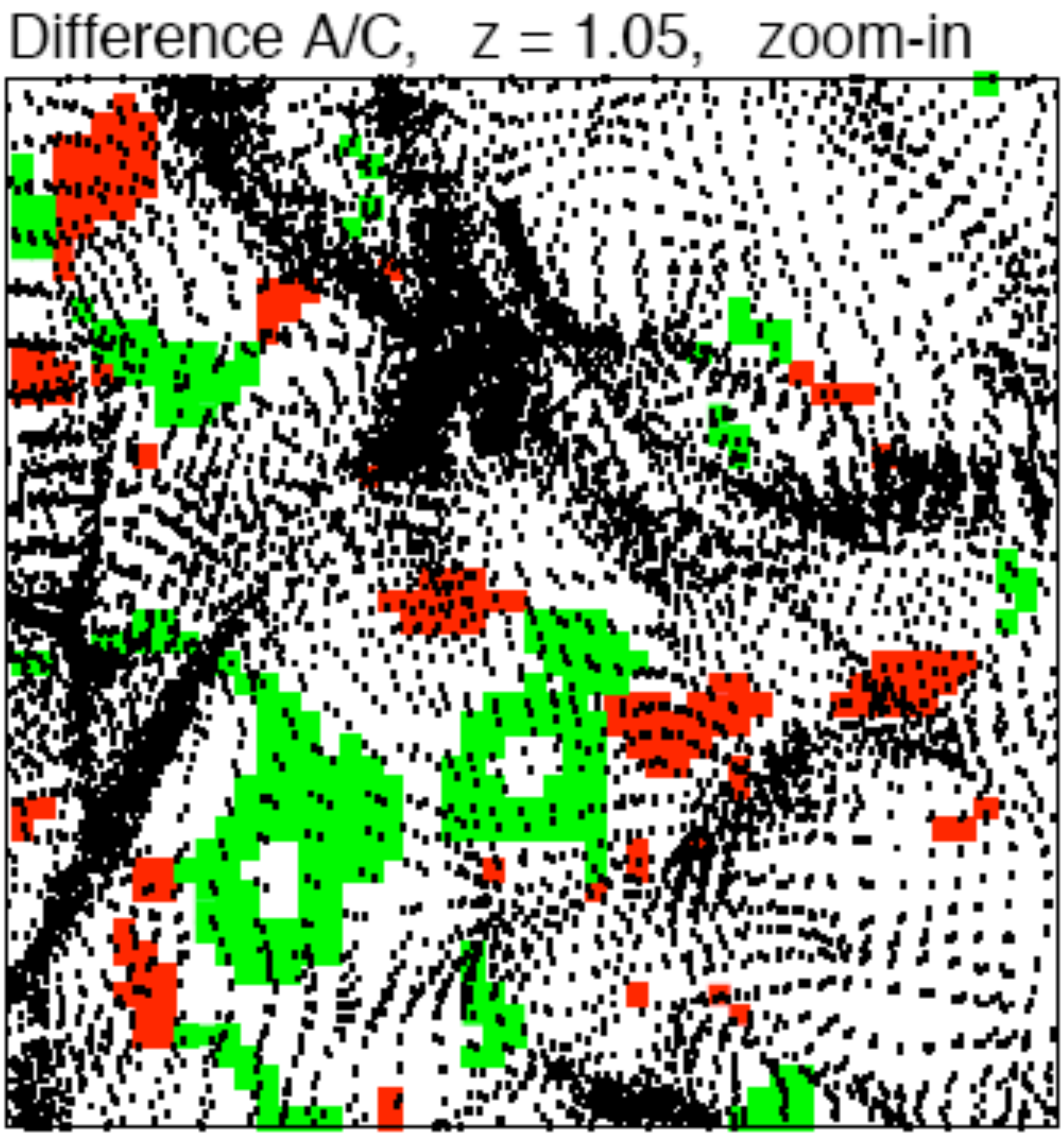
α = 60°



Differential enrichment map between α = 180° and α = 60°.

Red : regions enriched with 180°, but not 60°.

Green : regions enriched with 60°, but not 180°.



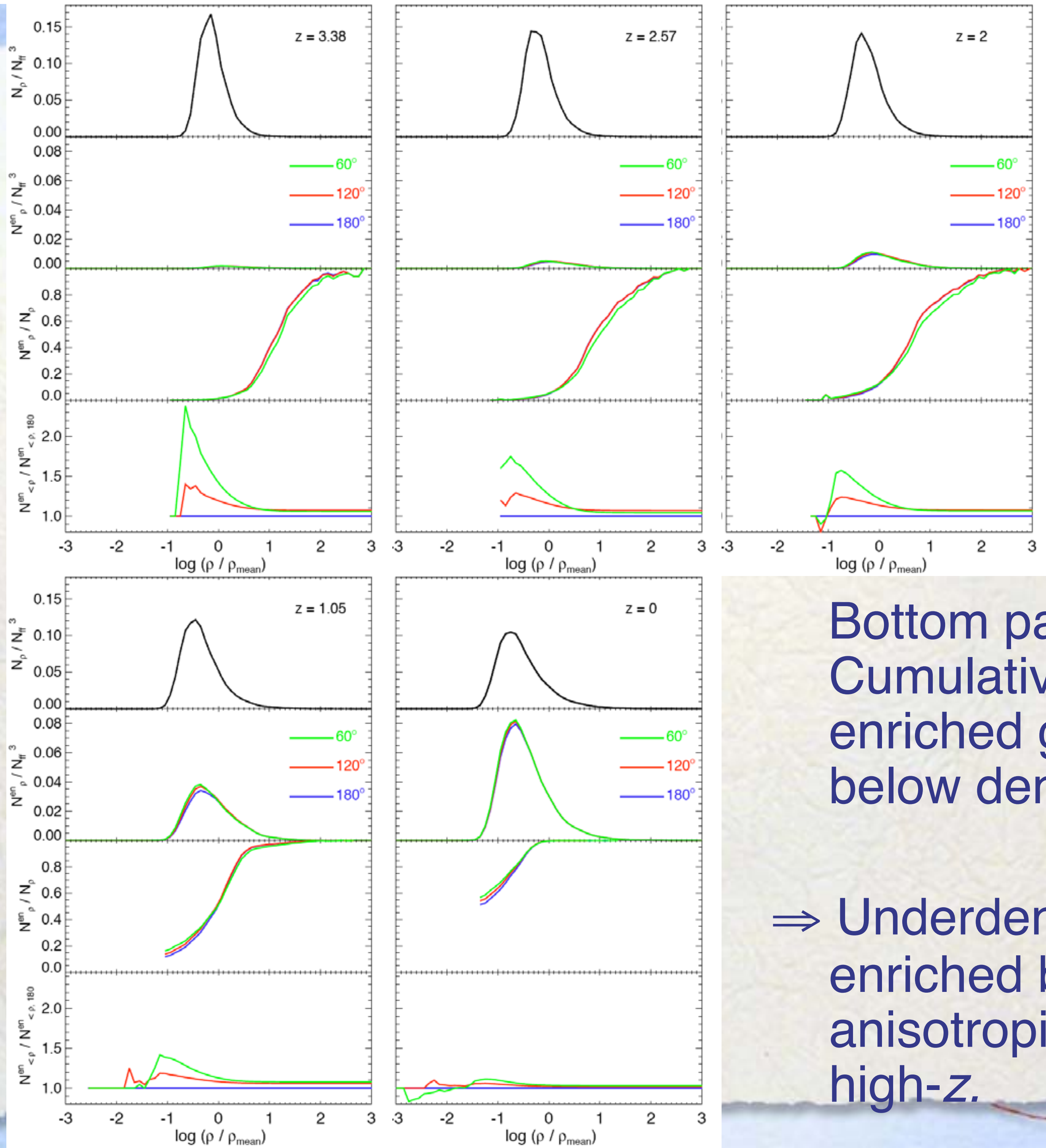
Differential enrichment map between $\alpha = 180°$ and $\alpha = 60°$.

Red : regions enriched with 180°, but not 60°.

Green : regions enriched with 60°, but not 180°.

$z = \mathbf{1.05}$

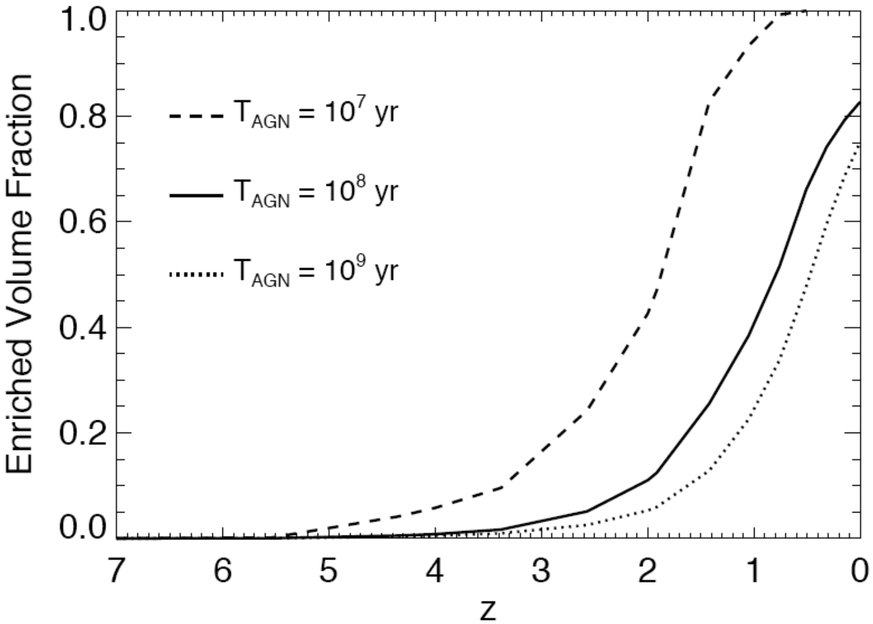
Green areas tend to be in more underdense regions than red areas.



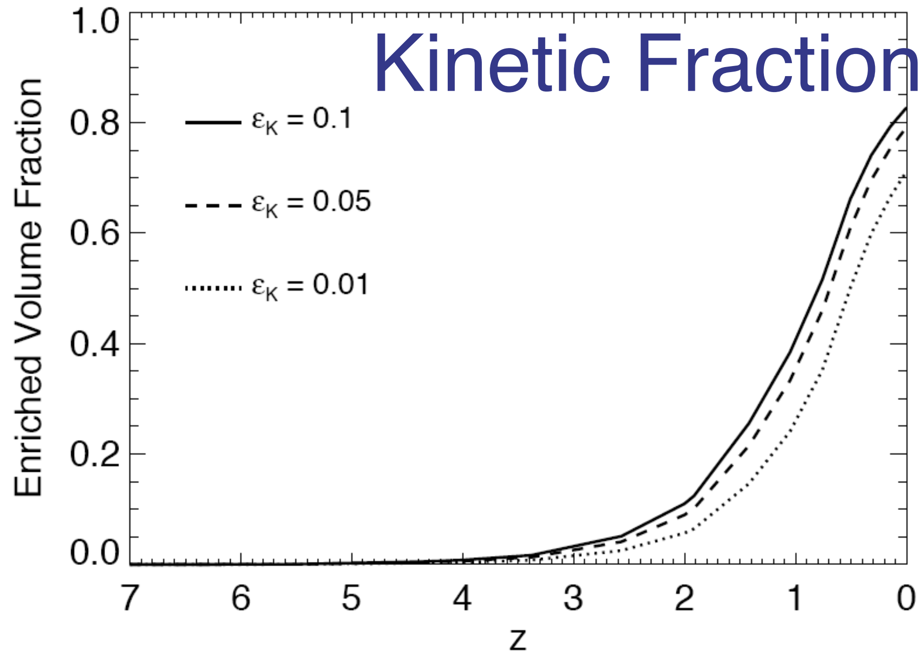
Bottom panel: Cumulative number of enriched grid points below density threshold.

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

Lifetime

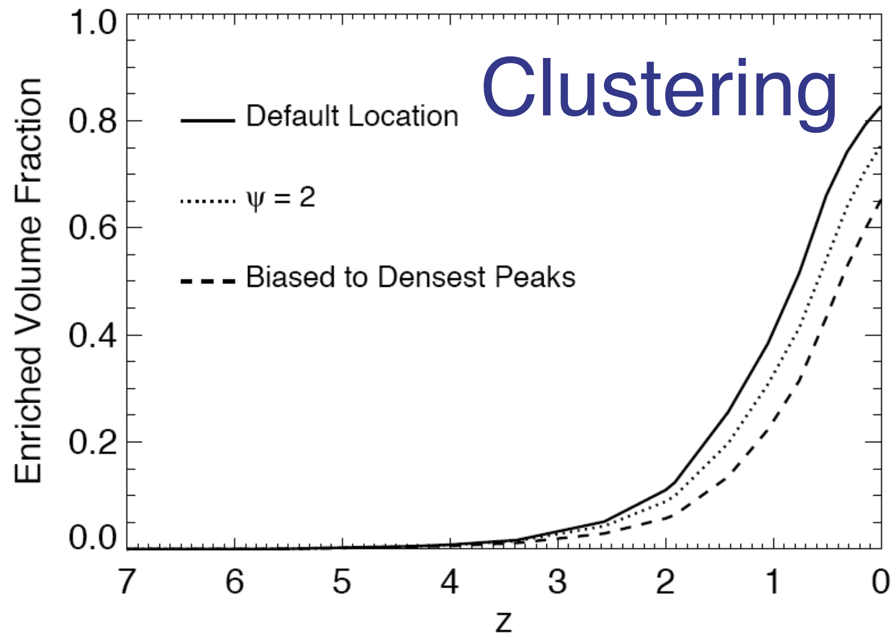


Kinetic Fraction



Exploring more Parameters :

Clustering



Parameters of Simulation Runs & Final Enriched Volume Fractions

Run	α ($^\circ$)	$T_{\rm AGN}$ (yr)	ϵ_K	Bias in Location	$N_{\rm rich}/N^3_{\rm ff}(z=0)$
A	180	10^8	0.10	$\times$	0.80
B	120	10^8	0.10	$\times$	0.82
C	60	10^8	0.10	$\times$	0.83
D	60	10^7	0.10	$\times$	1.00
E	60	10^9	0.10	$\times$	0.75
F	60	10^8	0.05	$\times$	0.79
G	60	10^8	0.01	$\times$	0.71
H	60	10^8	0.10	$\surd$	0.75
I	60	10^8	0.10	$\surd$	0.65

Summary (arXiv:0905.3560)

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

- The resulting enriched volume fractions are relatively small at $z > 2.5$,

  & then grow rapidly afterward to enrich 65% – 100% volume (for different model parameters) of the Universe by the present

- Under-dense regions preferentially enriched by more anisotropic outflows

➢ In progress : Compute metallicity values of the IGM

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

Implementation

- 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

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

- Largest of the coefficients A, B, C $\Rightarrow$ DLR

Ambient Medium for AGN Outflows

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

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

- Pressure :

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

- 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.